Characterization of the genetic architecture of infant and early childhood BMI

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Abstract

Early childhood obesity is a growing global concern, however the role of common genetic variation on infant and child weight development is unclear. Here, we identify 46 loci associated with early childhood BMI at specific ages, matching different child growth phases, and representing four major trajectory patterns. We perform GWAS across 12 time points from birth to eight years in 28,681 children and their parents (27,088 mothers and 26,239 fathers) in the Norwegian Mother, Father and Child Cohort Study. Monogenic obesity genes are enriched near identified loci, and several complex association signals near *LEPR*, *GLP1R*, *PCSK1*, and *KLF14* point toward a major influence for common variation affecting the leptin-melanocortin system in early life, providing a link to putative treatment strategies. We also demonstrate how different polygenic risk scores transition from birth to adult profile through early child growth. In conclusion, our results offer a fine-grained characterization of a changing genetic landscape sustaining early childhood growth.

Main

Physical growth is an indicator and predictor of both present and future health. Deviations from a child's growth trajectory may indicate health issues with life-long implications. Growth in infancy and early childhood is thus monitored closely by parents and health care professionals. Body mass index (BMI) changes substantially with age following a characteristic pattern. From birth, BMI increases rapidly until it reaches a maximum at the age of nine months, followed by a gradual decline towards a minimum at around 5-6 years of age. These two points are often labelled the adiposity peak (AP) and adiposity rebound (AR)[1,2], respectively. Early increase in BMI is associated with diabetes, earlier puberty, risk of obesity in adolescence and adulthood, a major public health issue worldwide[3–5], and the many complications that follow. Only 38% of adults with class II/III obesity (BMI ≥ 35 kg/m²) present normal weight during childhood[6], and 90% of all children defined as obese at age three years remain obese during adolescence[7]. As sustainable weight reduction has proved difficult[8], proactive therapeutic strategies enabling early prevention of obesity are sorely needed, thus a better understanding of the fundamental mechanisms regulating early growth is needed.

Heritability estimates for BMI in twin studies range from 40 to 70% and vary with age[9,10]. Genetic variants strongly influence the risk of obesity, in a complex relationship with behavioural and lifestyle factors[11]. Common genetic variants explain 17 to 27% of the heritability of BMI[12–14]. The genetics of early weight development is therefore of prime scientific interest for children's health, but also as a predictor for adult obesity. The largest genome-wide association study (GWAS) on adult BMI identified 941 independent loci in over 700,000 individuals, explaining ~6% of the phenotypic variation[15]. In children, where sample sizes have been much smaller, considerably less is known about the genetics of BMI. Recent meta-analyses suggest an overlap with adult

BMI[16–18], while studies estimating age-dependent genetic contribution have revealed low correlation in infancy and early childhood that gradually increases with age[12]. Additionally, transient genetic association with early BMI during infancy and early childhood has been identified by us and others[19,20], suggestive of rapid changes in the genetic architecture of BMI during early growth. Still, how the genetics of BMI transitions from birth to adiposity rebound, where the genetic signature of an adult-like obesity emerges, remains unknown.

While GWAS studies performed in very large numbers of adults have been highly successful in discovering common variants of small effect sizes, studies on children with morbid obesity have been more successful at identifying rare genetic variants causing early-onset monogenic and syndromic forms of obesity[21,22]. Recently, there has been a growing recognition that monogenic and polygenic forms of obesity are not discrete entities. Genetic studies point towards shared biological pathways and the influence of both rare and polygenic variation to disease risk at both ends of the spectrum[23–25]. A recent investigation of severe childhood obesity found an excess burden of rare, predicted deleterious, variants involving genes near adult obesity loci[26]. Variants with different penetrance were detected in genes in the leptin/melanocortin pathway, a major determinant of satiety and energy expenditure. Interestingly, GWASs suggest that the *LEP-LEPR* axis is also central to BMI development during infancy and childhood[19,20].

In this study, we investigated the association of common variation with BMI from birth to eight years of age through a longitudinal analysis in the Norwegian Mother, Father and Child Cohort Study (MoBa)[27]. Using this unique pregnancy-based open-ended cohort with dense harmonized phenotypes and genotypes from both parents and children, we present a detailed characterization of the rapidly changing genetic landscape of BMI during the first eight years of life.

Results

BMI from 28,681 children was measured at birth, 6 weeks, 3, 6, 8 months, and 1, 1.5, 2, 3, 5, 7, and 8 years of age (Supplementary Table 1). At each time point, we conducted linear mixed model regression analyses on standardized BMI under an additive genetic model, followed by approximate conditional and joint multiple single-nucleotide polymorphism (SNP) analyses to identify independent signals[28], resulting in 46 independent loci reaching genome-wide significance ($p < 5 \times 10^{-8}$) for at least one time point (Table 1 and Supplementary Table 2). Of these, 29 are novel, i.e. do not have any nearby proxy SNPs (r2>0.6) that are genome-wide significant in recent birth weight and adult BMI meta-analyses[15,29].

Four major association trajectory clusters

We investigated the dynamics of the associations for the 46 loci by projecting their effect size estimates over time onto a basis of reference profiles (Figure 1). We also compared the effect size estimates with published meta-analyses at birth[29] (Figure 2), investigated the long-term association of the 46 loci during adolescence in the Avon Longitudinal Study of Parents and Children (ALSPAC) cohort[1,30] (Figure 3), and in adulthood from parents in MoBa and published summary statistics of BMI[15] (Figure 2). The variants displayed different trajectories (Figure 1C), demonstrating how the genetics of early childhood BMI is an age-dependent combination of interweaved signals. We define four major clusters of profiles (Figure 1E, see methods for details), which we hypothesize to represent distinct biological processes.

The *Birth* cluster represents nine loci previously associated with birth weight[29]. Our longitudinal analysis showed that the association near *SH2B3*, *CCNL1*, *GPSM1*, *GCK,* and *DLG4* quickly vanishes after birth, indicating that these loci are conferring pure prenatal influences, while loci near *ESR1*, *DLK1*, and *HHEX* seem to influence growth also postnatally (Figure 1 and

Figure 2). The trajectory of *ADCY5*, known primarily as a type 2 diabetes (T2D) locus, is remarkable in presenting a strong association at birth which persists during infancy and childhood, but almost no association with adult BMI[15] (Figure 2 and Figure 3).

The *Transient* cluster represents 21 independent signals with no effect at birth, peak association during infancy or early childhood, and little or no effect after the adiposity rebound. None of the SNPs in this cluster reach genome-wide significance ($p < 5 \times 10^{-8}$) in the largest adult BMI meta-analysis to date[15] (Figure 1 and Figure 2), and among SNPs that reach $p < 1 \times 10^{-5}$, three out of four have opposite direction of effect on BMI in adults compared to infancy (*LEPR*(rs10493377), *MLXIPL*(rs17145750) and *KLF14*(rs287621)). Conversely, of the variants previously implicated in birth weight, only one (*PTCH1*(rs28457693)) is present in this cluster. Thus, this cluster represents biological mechanisms with distinct effects on BMI development in infancy and childhood. The other phenotypes associated with the loci in this cluster are primarily anthropometric traits (Figure 1 and Supplementary Table 3), yet the majority (11 of 21) are not known to be associated with adult traits.

The *Early Rise* cluster represents 12 loci showing a gradually stronger association with BMI from infancy into childhood, they plateau around adiposity rebound and maintain some effect until age seven to eight years. This cluster includes variants associated with self-estimated comparative height and size at age ten years in the UK Biobank, as well as traits related to adult body composition, which supports the hypothesis of a more persisting effect. However, while the effect sizes for approximately half of the variants in this cluster are consistent throughout adolescence and towards adulthood, the effect vanishes for the other half. Eventually, only two SNPs in this cluster (*ADCY3(rs11676272)* and *TNNI3K(rs10493544)*) reach genome-wide significance in the largest adult BMI study[15], and one (*AC105393.2(rs77165542)*) with no proxy in Yengo et al[15] showed an association with BMI in the parents in MoBa, the nine others show no association with adult BMI *per se* (Figure 1 and Figure 2).

The *Late Rise* cluster, represents four loci (*FTO(rs17817288)*, *MC4R(rs78263856)*, *SEC16B(rs545608),* and *FAIM2(rs7132908)*) that show little to no association prior to adiposity rebound where they exhibit a rapid increase contrasting with the other clusters. The variants in the *Late Rise* cluster are in high LD with loci reported in a previous study on childhood BMI consisting mainly of children measured at age six to ten years[16] and with adult BMI[15] (Figure 2). The observed upward trajectory therefore yields effects that seem to persist during adolescence and remain significant into adulthood.

Effect trajectories of known birth weight and adult BMI SNPs

The density of the overall distribution of trajectory profiles in MoBa for all previously detected birth weight and adult BMI SNPs[15,29] along with the density of the 46 early growth loci detected in this study is depicted in Figure 1H: the trajectories for birth weight and adult BMI segregate to the left and right sides of the space defined by the reference profiles, respectively, while the early growth BMI is dominated by transient profiles. In contrast to the association profiles in our *Birth* cluster, the birth weight variants mostly display trajectories persisting or rising throughout childhood. Conversely, variants associated with adult BMI present a strong concentration of late rising profiles, suggesting that better power at late ages would provide a higher number of variants in this cluster.

Trajectory agreement between the MoBa and ALSPAC cohorts

The trajectories of the effect size estimates are generally consistent between the two cohorts (Figure 3 and Extended Data Fig. 1). However, ALSPAC estimates in early childhood present high standard errors due to smaller sample size especially during infancy and early childhood (Supplementary Table 1). Despite this modest power, a sign-test shows that the directions of effect at the peak-effect time points from the MoBa cohort are highly consistent between MoBa and ALSPAC, both cumulatively (n = 40/45 consistent, $p < 10^{-7}$) and for each of the four clusters

(Birth: 9/9, Transient: 18/20, Early Rise: 9/12, and Late Rise: 4/4). Considerably larger sample size is needed to enable formal replication at individual loci.

SNP heritability and genetic correlation

We estimated SNP-based heritability and genetic correlation between various traits and BMI at all time points using LD score regression. The heritability estimates vary with age in a pattern mirroring childhood BMI curves (Extended Data Fig. 2 and Supplementary Table 4). Overall, the phenotypes assessed display age-dependent genetic correlation patterns with BMI, with lower correlation from six months to three years (Extended Data Fig. 3 and Supplementary Table 4). Birth weight adjusted for maternal effect presents a high correlation with BMI at birth (r_g: 0.89, se: 0.061, $p < 1 \times 10^{-47}$) that decreases quickly in infancy and throughout childhood, whereas for indirect maternal effects, the correlation is initially lower but increases from one year onwards. While obesity-related traits in general show constant correlation levels before accelerating at three years, *comparative body size at age 10* in the UK Biobank, in which participants reported being thinner or plumper than average at age ten years, presents a rapid linear increase throughout development from birth to seven years (r_g: 0.86, se: 0.06, $p < 9 \times 10^{-53}$), which is in line with the observed overlap of this phenotype with the *Early* and *Late Rise* clusters. Higher childhood BMI correlates with younger age of menarche and taller stature in early puberty, indicating a strong genetic correlation between childhood BMI and early pubertal development. Despite 11 of the 46 top hits having previously been associated with adult height (Supplementary Table 3), the overall genetic correlation with adult height is close to zero for all time points. The well-known inverse relationship of T2D with fetal growth vanishes quickly after birth and the genetic correlation of BMI with glycaemic traits varies rapidly throughout childhood.

Monogenic obesity and the leptin/melanocortin pathway

We further investigated whether genes involved in monogenic obesity are overrepresented in the vicinity of the loci. Out of 42 genes used in routine testing for monogenic and severe early onset obesity, seven reside within 250 kb of one of the 46 top hits (overrepresentation $p < 1.01 \times 10^{-7}$) (Supplementary Table 5). Six of these seven genes encode proteins participating in the leptin/melanocortin pathway (*LEP*, *LEPR* (three signals), *PCSK1* (two signals), *POMC, ADCY3*, and *MC4R*) providing compelling support for the importance of this pathway also in normal growth. Apart from *MC4R*, the associated variants belong to the *Transient* and *Early Rise* clusters, showing that mechanisms at play act very early after birth, some of which in a narrow age window (Extended Data Fig. 4).

Key roles for variants in the LEP *and* LEPR *loci*

The strongest association with BMI across all time points is the intronic variant rs2767486 with peak association at six months in the *LEPR* locus (*Transient* cluster, eaf: 16%, β: 0.14, se: 0.012, $p < 6.4 \times 10^{-34}$), presenting a transient association profile that peaks at six months, in agreement with previous reports[19,20]. Conditional and joint multiple-SNP analysis revealed two additional independent signals in this locus (Supplementary Table 6 and Extended Data Fig. 5). The previously described association with rs10487505 in *LEP*[19] was assigned to the *Early Rise* cluster. Its child BMI-increasing allele is associated with lower plasma leptin levels adjusted for BMI in adults[31], and our results suggest that the association with BMI is specific to childhood.

Established BMI variants near ADCY3 *and* MC4R

Both *ADCY3* and *MC4R* are implicated in Mendelian forms of obesity and polygenic BMI in adults and children and expressed in the hypothalamus where they are important for central regulation of energy homeostasis[15,32–34]. The well-known non-synonymous variant rs11676272

in *ADCY3* was the second strongest locus overall for infant and childhood BMI, peaking at one year (*Early Rise* cluster). The variant rs78263856 upstream of *MC4R* belongs to the *Late Rise* cluster with effects on BMI appearing from two years of age, with peak at seven years, and lasting into adult life (Figure 2).

***Novel variants near* PCSK1**

We identified two independent loci near the monogenic obesity gene *PCSK1*[35,36] (belonging to the transient cluster) (Extended Data Fig. 5). *PCSK1* encodes the prohormone convertase 1/3 (PC1/3), highly expressed in the hypothalamic arcuate nucleus regulating food intake and body weight[37]. No previous phenotypic associations are reported for the lead SNP rs6899303, but the variant is a strong pQTL for PC1/3[38]. The second signal, tagged by rs263377, displays its strongest association at one year (*Transient* cluster), and associates with multiple adult anthropometric traits including fat-free body mass in the UK Biobank ($p < 1.84 \times 10^{-9}$). None of the two variants are in LD with the *PCSK1* missense variant rs6235 associated with insulin and adult BMI-related traits[23]. The hypothalamic PC1/3 expression is high in two leptin-sensitive neuronal populations: proopiomelanocortin (POMC)-expressing neurons, and neuropeptide Y (NPY) and agouti-related peptide (AgRP)-expressing neurons. In the periphery, PC1/3 is highly expressed in specific ghrelin-expressing endocrine cells in the stomach, the α- and β-cells of the islets of Langerhans in the pancreas, and various intestine enteroendocrine cells. These play an important role in appetite, glucose homeostasis, and nutrient assimilation by secreting several PC1/3 products including ghrelin, insulin, and proglucagon-derived peptides such as the hormone glucagon-like peptide-1 (GLP-1).

Three novel variants in* GLP1R *with effect on infant BMI

GLP-1 is released in the small intestines in response to food intake. It interacts with GLP1R, abundant in hypothalamic regions regulating feeding behavior[39], inducing satiety. It is an incretin

with insulinotropic effects in response to oral food intake. GLP-1 improves glucose-stimulated insulin secretion by interacting with β-cell GLP1R. We identified three independent signals at the *GLP1R* locus belonging to the *Transient* cluster (Extended Data Fig. 5). The strength of association increased for all three variants when analysed together, in particular for rs1820721 (at six months $p_{cojo} < 5.3 \times 10^{-21}$). None of the three SNPs have been associated with childhood or adult BMI. However, the BMI-increasing alleles at rs2268657 and rs2268647 are both associated with lower *GLP1R* expression in stomach, pancreas, and adipose tissues (GTEx). Interestingly, the BMI increasing allele at rs2268657 has previously been associated with faster gastric emptying rate[40], suggesting that *GLP1R* variants may affect childhood BMI through higher digestion rate, in line with its function in the treatment of T2D.

***Maternal influences at birth for* SH2B3*,* HHEX*, and* ADCY5**

For each of the 46 independent loci, we extended the association model using the parental genotypes, and conducted child-mother-father trio- and haplotype-resolved analyses. For most loci, the child effect at peak remains after conditioning on the maternal and paternal genotypes, with no noticeable parental effect (Figure 4). However, for five variants, different patterns emerged: three loci from the *Birth* cluster *SH2B3* (rs7310615), *HHEX* (rs11187129), and *ADCY5* (rs11708067), and two from the *Transient* cluster near *KLF14* (rs287621 and rs12672489).

For the *ADCY5* and *HHEX* loci, associated with T2D and birth weight, the trio analysis demonstrated opposing fetal and maternal effects, as already observed for birth weight[29], and no effect from the father (Supplementary Table 7). This differs from the *SH3B2* locus, where the trio analysis indicated a dual and directionally consistent effect from both maternal and fetal alleles on birth BMI. The association trajectory of these three birth weight loci illustrates how the

maternal genome provides heterogeneous indirect effects on fetal growth that vanish after birth with different dynamics (Figure 4 and Supplementary Table 7).

Age-dependent association with imprinting patterns near KLF14

We identified two variants associated with childhood BMI upstream of *KLF14,* rs287621 and rs12672489 separated by a recombination hotspot. Maternal imprinting has been demonstrated for *KLF14* in T2D[41], with risk alleles associated with increased fasting insulin, reduced high-density lipoprotein (HDL)-cholesterol, and decreased expression in adipocyte in adults, only when inherited from mothers[41,42]. Our haplotype analysis revealed that the association for both variants is driven by the maternally inherited allele throughout infancy, with little to no contribution from the paternal allele and the non-transmitted alleles (Figure 4 and Supplementary Table 7), consistent with imprinting effects. While rs287621 is associated with several adult phenotypes, the strongest known association for rs12672489 is *comparative body size at age 10* in the UK Biobank ($p < 3.5 \times 10^{-7}$), showing that this variant influences childhood growth despite residing outside of the region critical for adult traits. eQTL studies have linked variants to the abundance of *KLF14* transcript in adipose tissue[43] and a variant near *KLF14* has been associated with lower plasma leptin levels[44], offering a mechanistic hypothesis and yet another putative link between leptin regulation and weight gain in infancy.

Polygenic transition across infancy and childhood

We constructed polygenic risk scores (PRS) to assess the ability of PRSs of BMI and related traits to stratify BMI and obesity during infancy and early childhood, Strong age-dependent gradients were found with opposing patterns for birth weight and BMI-related traits (Figure 5, Extended Data Fig. 6, and Supplementary Table 8 and 9).

For the birth weight-based PRS, the difference in standardized BMI between the 1st and 10th decile is 0.7 at birth (Figure 5), declines considerably already at six weeks, and subsequently

stabilizes. This residual and lasting association of the birth weight PRS supports an overlap between genetic variants influencing birth weight and BMI development in infancy and childhood. Furthermore, the top risk score decile captures an elevated and consistent share of obese children, even until seven to eight years, where it performs similarly to scores trained on childhood BMI and obesity (Extended Data Fig. 6).

The PRS based on adult BMI displays a shift from three to eight years, where the difference in standardized BMI between the 1st and 10th decile rapidly grows (Figure 5) and variance explained increases from 0.4 to 5.3% (Extended Data Fig. 6). In the top risk decile, 13% of children were obese at age eight years, corresponding to a 2.6 times higher risk compared to the median at this age, and a 7.4 times higher risk compared to the bottom risk decile. The PRSs based on previous childhood BMI and obesity studies display similar patterns as adult BMI, albeit with lower variance explained (Extended Data Fig. 6). These studies thus mainly capture the genetics of BMI after adiposity rebound, where the adult architecture is already dominating. Results from both the BMI adjusted and unadjusted T2D PRSs show an inverse correlation between BMI at birth and later T2D. However, while this effect quickly vanishes for the unadjusted T2D PRS, children in the top risk decile for BMI-adjusted T2D-risk maintain lower BMI throughout infancy, possibly reflecting the key role of insulin metabolism during early growth[45] (Extended Data Fig. 6, Supplementary Table 8).

Age-stratified PRS improves prediction of childhood BMI

None of the PRS models above capture the BMI development during infancy and the first years of childhood. We evaluated the improvement in performance of PRS models when training on the time-resolved GWAS-results generated in this study compared to models trained on adult BMI using a set of 1,096 children in MoBa that were not included in the GWAS. Age-specific modelling vastly improved the variance explained by the PRS during infancy, especially around the adiposity peak at six months, where R^2 increased from 1.5% using results from adult BMI to

6.4% using age-specific results (Extended Data Fig. 6, Supplementary Table 8). We also tested the predictive ability of the 21 variants in the *Transient* cluster, which peaked between six months and 1.5 years (p-value < 1×10^{-5}), and explained between 3.0 and 4.5% of the variance during this age span. Hence, the identified variants in the *Transient* cluster alone explain a substantial proportion of the variance in BMI around the adiposity peak. Tracking the share of children in the different risk score strata at each time point yielded interweaved trajectories illustrative of the dramatic changes in the genetics of BMI (Extended Data Fig. 6).

Discussion

The association of common genetic variation with BMI changes rapidly during infancy and early childhood, which are stages of life characterized by rapid development and drastic changes in the environment, body composition, and metabolism. From the 46 independent loci that we associate with childhood BMI, 29 are not associated with birth weight or adult BMI in large meta-analyses. We propose to group the genetic association with early BMI into four main clusters that align well with the phases of early growth (Figure 1): the *Birth* cluster, characterized by loci mainly acting on fetal growth; the *Transient* and *Early Rise* clusters that affect BMI development during the key transitions around adiposity peak and rebound; and finally the *Late Rise* cluster of loci that come into play later in childhood and have persisting influence on BMI into adult life. It is important to note that the assignment of variants to clusters can be misled by uncertainty in effect size estimates, especially at later ages, uneven distribution of time points, and depends on predefined reference curves. Although the ALSPAC trajectories and summary statistics from adult BMI studies are consistent with our results, further research with larger sample sizes is needed to refine the temporal profiles of these loci and their clustering.

Most of the variants that we discovered show age-specific transient effects and thus would not be identified from GWASs in other age groups. Conversely, early rising loci display gradually stronger effects after birth lasting into pre-pubertal age. These loci may be particularly important

for processes preceding puberty onset, which is supported by the LD score regression profiles that show gradually increasing genetic correlation between BMI at three to eight years of age and early puberty, higher stature at age 10-12 years, and shorter relative length increase after age 12 years. The age-specific association patterns demonstrate a major change in the underlying genetic architecture of childhood BMI pre and post adiposity rebound, where a shift in association trajectories, genetic correlations, PRS prediction power, and heritability occurs. This is further underlined by the large overlap between variants identified in adult BMI and late childhood, but lower overlap with earlier childhood.

An important step in the search for more effective intervention and treatment strategies for childhood and adolescence obesity is to improve our understanding of the genetic and molecular mechanisms influencing BMI development before childhood obesity develops, typically at five years of age, to select predisposed children for targeted intervention. Our results point to the substantial inherited variability influencing key genes in the hypothalamic signalling pathway previously known for their role in Mendelian morbid obesity. In addition to replicating the association with variants in *LEP/LEPR*[19,20], we identify two novel variants in *LEPR* and variants near *PCSK*1, *ADCY3* and *MC4R*, all known monogenic obesity genes and central to the hypothalamic signalling pathway. All show age-dependent influences during early childhood. Thus, our findings are highly suggestive of energy intake and expenditure being central to controlling BMI during early childhood, especially before five years of age. Notably, many of these genes are already targets for treatment in Mendelian disease, such as leptin-replacement treatment for LEP deficiency and MC4R-agonists for LEPR, PCSK1 and POMC deficiency[46–48]. As more genes implicated in monogenic obesity are found to harbour common variants associated with BMI, the notion that monogenic and polygenic obesity share underlying etiologies is strengthened.

The identification of three novel signals within *GLP1R* offers another important link to putative treatment opportunities. The bidirectional gut-brain-axis connecting the enteric with the central nervous system plays a vital role in informing the brain of peripheral energy status. However, relatively few genetic variants associated with genes with direct or indirect roles in gastrointestinal functions have been associated with childhood obesity. First, the discovery of three novel independent associations in *GLP1R* not picked up in the much bigger meta-analyses on adult BMI is advocating for distinctly different underlying biology driving early BMI development. Second, it iterates on the importance of hypothalamic signalling and further establishes the importance of common variation in genes related to the gut-brain-axis in development of early childhood BMI. Finally, increased understanding of GLP-1 signalling in early childhood BMI development is particularly important as GLP1R is a pharmaceutical target for treating adult obesity[49] and recently showed promising results for treating obesity in adolescence[50]. A study of patients treated with the GLP1R agonist liraglutide found alterations in brain activity related to highly desirable food cues and reduced activity in areas of the brain involved in the reward system[51]. Mice injected with liraglutide show increased energy expenditure through stimulation of brown adipocyte thermogenesis acting through hypothalamic processes[52]. Animal studies have shown that GLP1Rs located in the brain mediate the effect of liraglutide on weight loss. A previous study found that knocking down *GLP1R* in the brain eliminated the effect of liraglutide, while knocking down the same receptor in the peripheral nervous system did not reduce its efficacy significantly[53]. *GLP1R* expression in adipose tissue has also been linked to increased insulin sensitivity[54].

Combined, these results point towards a key role for the central melanocortin system for appetite and energy expenditure early in life, and in particular highlights the POMC system as a putative drug target. This shows that well-powered GWASs of BMI performed in young children can identify novel genes, proteins, and pathways not found in adult GWASs, with putative potential for obesity treatment. However, translating GWAS findings into function is challenging

388 and for most of the discovered loci, more research is needed to reveal the precise molecular
389 and physiological mechanisms involved.
390 Child-mother-father trio analyses revealed that the association for two independent loci near
391 *KLF14* is driven by the maternal transmitted allele only, suggesting that the paternal allele is
392 silenced. Maternal imprinting for variants in *KLF14* has previously been identified for T2D and
393 one of our variants tag the same signal, while the other appears as a novel second imprinting
394 effect acting on KLF14 in early childhood. Additionally, our PRS analysis using a T2D reference
395 study finds persistently low BMI during childhood for children in the highest decile of BMI-
396 adjusted T2D PRS, and it is tempting to ascribe these late effects on childhood BMI to
397 mechanisms acting through insulin and glucose metabolism given the numerous studies
398 associating *KLF14* with T2D. However, alleles in high LD with the infant BMI and T2D risk
399 increasing alleles were recently associated with lower plasma leptin levels adjusted for BMI[44],
400 offering yet another putative link between leptin regulation and weight gain in infancy.
401 Polygenic risk prediction provides opportunities to estimate an individual-level genetic liability
402 and may potentially be used for early identification of children with considerable risk for
403 developing obesity. Here, we show striking differences in BMI between children in the top and
404 bottom deciles of an adult-BMI based PRS concurrent with timing of the adiposity rebound.
405 Notably, the effect estimates in MoBa are almost identical to what was previously described for
406 British children from ALSPAC[12], suggesting that this score is transferable between
407 Scandinavian and British children. We also show that the PRS can identify children at
408 considerably higher risk of being obese already from five years of age. As much as 13% of
409 children in the top decile could be defined as obese at age eight years, corresponding to a
410 seven fold higher risk compared to the bottom risk decile (Figure 5). The shift in genetic
411 architecture before age five years renders PRSs based on adult BMI inferior to age-resolved
412 scores during infancy. The testing in our independent sample demonstrates that BMI in the
413 earlier years of life is shaped by a complex interplay and transitions from both age restricted and

more long-term genetic influences that have to be taken into consideration when evaluating a child's growth pattern and the potential for targeted interventions. Although both sensitivity and specificity of current PRS for obesity still are low[24], PRS stratification may help identify selected groups of children that benefit more from early intervention or tailored treatment.

Our study sample consists of a single cohort of northern European descent and further research is needed to evaluate the generalisation of the results to other populations. However, the larger size of the current MoBa release, the availability of parental data and the homogeneous phenotyping allowed us to perform much more detailed time-resolved analyses than typically possible in a meta-analysis involving studies performed under different protocols and data collection timepoints. The age-dependent association patterns identified here illustrate the importance of early age sampling, and the need for unifying data collection and measurements across cohorts to balance the putative benefit from increased sample size without introducing considerable variance in the phenotyping.

In conclusion, our results provide a fine-grained understanding of the changing genetic landscape regulating BMI from birth to eight years. The identified loci represent clusters of association trajectories that reflect various phases of growth and highlight a fundamental role of pathways involved in appetite regulation and energy metabolism in both normal growth and rare syndromic obesity. These results demonstrate a strong genetic drive ensuring that children gather the energy necessary to sustain healthy growth.

Methods

Study population

The Norwegian Mother, Father and Child Cohort Study (MoBa) is an open-ended cohort study that recruited pregnant women in Norway from 1999 to 2008. Approximately 114,500 children, 95,200 mothers, and 75,000 fathers were enrolled in the study from 50 hospitals all across Norway[27]. Anthropometric measurements of the children were carried out at hospitals at birth and during routine visits in the primary health care system by trained nurses at 6 weeks, 3, 6, 8 months, and 1, 1.5, 2, 3, 5, 7, and 8 years of age. Parents later transcribed these measurements to questionnaires. In 2012, the project SELECTionPREDISPOSED and Better Health by Harvesting Biobanks (HARVEST) randomly selected 11,490 umbilical cord blood DNA samples from the biobank of this study for family triad genotyping, excluding samples matching any of the following criteria: (1) stillborn, (2) deceased, (3) twins, (4) non-existing data at the Norwegian Medical Birth Registry, (5) missing anthropometric measurements at birth in Medical Birth Registry, (6) pregnancies where the mother did not answer the first questionnaire (as a proxy for higher dropout rate), and (7) missing parental DNA samples. In 2016, HARVEST randomly selected a second set of 8,900 triads using the same criteria. The same year NORMENT selected 5,910 triads with the same selection criteria as HARVEST, and extended this with 3,209 triads in 2018. Additionally, a study from 2014 genotyped 1,062 ADHD cases among the children and in 2015 a study genotyped 5,834 randomly selected parents.

Genotyping

Genotyping of the samples was performed in seven different batches on different Illumina platforms over a period of four years. SELECTionPREDISPOSED (an ERC AdG-supported University of Bergen project) and HARVEST genotyped using Illumina HumanCoreExome-12

v.1.1 and HumanCoreExome-24 v.1.0 arrays for 6,938 and 4,552 triads, respectively, at the Genomics Core Facility located at the Norwegian University of Science and Technology, Trondheim, Norway. The second wave of genotyping in HARVEST genotyped using Illumina's Global Screening Array v.1.0 for all 8,900 triads at the Erasmus University Medical Center in Rotterdam, Netherlands. NORMENT genotyped 5,910 triads using InfiniumOmniExpress-24v1.2 in 2016 and 3,209 samples using GSA24-v1.0 in 2018. The 1,062 ADHD cases were genotyped using InfiniumOmniExpress-24v1.2 in 2014 and the 5,834 randomly selected controls using HumanOmniExpress-24-v1.0. All were genotyped at deCODE genetics, Reykjavik, Iceland. The Genome Reference Consortium Human Build 37 (GRCh37) reference genome was used for all annotations.

Genotypes were called in Illumina GenomeStudio v.2011.1 for the 11,490 triads part of HARVEST and v.2.0.3 for the remaining batches. Cluster positions were identified from samples with call rate ≥ 0.98 and GenCall score ≥ 0.15. We excluded variants with low call rates, signal intensity, quality scores, and deviation from Hardy-Weinberg equilibrium (HWE) based on the following QC parameters: call rate < 98 %, cluster separation < 0.4, 10% GC-score < 0.3, AA T Dev > 0.025, HWE p-value < 1×10^{-6}. Samples were excluded based on call rate < 98 % and heterozygosity excess > 4 SD. Study participants with non-Norwegian ancestry were excluded after merging with ancestry reference samples from the HapMap project (ver. 3).

Pre-phasing and imputation

Prior to imputation, insertions and deletions were removed to make the dataset congruent with Haplotype Reference Consortium (HRC) v.1.1 imputation panel using HRC Imputation preparation tool by Will Rayner version 4.2.5. Allele, marker position, and strand orientation

were updated to match the reference panel. Pre-phasing was conducted locally using Shapeit v2.790[55]. Imputation was performed at the Sanger Imputation Server with positional Burrows-Wheeler transform[56] and HRC version 1.1 as reference panel.

Phenotypes

Length/height and weight values were extracted from hospital records through the Norwegian Medical Birth Registry for measurements at birth, and from the study questionnaires for remaining time points. In addition, pregnancy duration in days calculated from ultrasound due date was obtained from the Norwegian Medical Birth Registry. Length and weight values were inspected at each age and those provided in centimetre or gram instead of meter and kilogram, respectively, were converted. Extreme outliers, typically an error in handwritten text parsing or a consequence of incorrect units, were excluded. A value x was considered as an extreme outlier if $x > m + 2 \times (perc_{99} - m)$ or $x < m - 2 \times (m - perc_1)$, where m represents the median within the age group and $perc_1$ and $perc_{99}$ the 1st and 99th percentiles, respectively.

Outlier detection and missing value imputation

For all children in MoBa (n > 100,000), length and weight curves were inspected for outlying values, missing values were imputed, and artefacts causing the length of kids to decrease were corrected[19]. Length and weight values presenting an extreme peak or an extreme gap were removed. Missing values preceded and followed by at least two measurement points were imputed by interpolating over the growth curve. Length curves were adjusted to prevent peaks to cause length decrease[19]. These steps were conducted iteratively until no data point was changed, as detailed in Extended Data Fig. 7. Finally, for all children and all time points presenting both length and weight values, the BMI was computed.

Sample selection

From the total set of growth curves, only the genotyped children passing genotype QC were retained. In addition, the following pregnancies were excluded: 1) pregnancies strictly shorter than 37 full gestational weeks (259 days); 2) plural pregnancies; 3) ADHD excess cases ; 4) outliers in the PCA of the genotypes. The set of ADHD excess cases were defined as the additional cases included by the ADHD case/control study. Outliers in the PCA represented 6% of the cohort, and were excluded to reduce the risk of systematic bias due to population stratification[57]. The resulting set of 28,681 children was used in genetic association and is referred to in the following as the *full set* of children. From this, we built a set of child-mother-father trios by selecting children who had both parents genotyped, with parents passing genotype QC and belonging to the central cluster in the PCA of the genotypes. If the members of two different trios were related according to an Identity by descent (IBD) analysis (PI_HAT > 0.1), one trio was randomly excluded. The resulting set of 23,538 trios is referred to in the following as the *set of unrelated trios.* Allele frequencies and linkage disequilibrium (LD) are estimated based on the parents in the *set of unrelated trios*.

Phenotypes standardization

For the *full set* of children, at each time point, the BMI was standardized using the generalized additive model for location, scale and shape (GAMLSS) v5.1-7 (gamlss.com) in R v. 3.6.1 (2019-07-05) -- "Action of the Toes". Two GAMLSS models based on a Log Normal distribution were fitted separately for boys and girls, using pregnancy duration as covariate, as detailed in Table 2. Note that the models of early BMI include a non-linear dependency on pregnancy duration, but the non-linear terms had to be removed after six months to ensure the convergence of GAMLSS. GAMLSS models were fitted solely on children from the *set of unrelated trios*. The models obtained were used to compute standardized BMI values for the *full*

set of children using the 'centiles.pred' function of GAMLSS (Supplementary Table 10). All effect sizes are expressed relative to the standardized phenotypes. A child was considered obese if the standardized BMI was strictly higher than qnorm(0.95) where *qnorm* represents the quantile function of the standard normal distribution.

Genetic association

The association between the genotypes and the standardized phenotypes using linear mixed models was conducted using BOLT-LMM v2.3.4[58] in the *full set* of children using genotyping batch, sex, pregnancy duration, and ten principal components as covariates. LD scores were taken from samples of European ancestry in the 1000 Genomes Project[59], and the genetic map files embedded with BOLT-LMM. The GRM was calculated using a set of high quality markers having both MAF > 0.05 and INFO score > 0.98. A genetic variant was deemed genome-wide significant if presenting a p-value $< 5 \times 10^{-8}$ at any given time point. At all loci reaching genome-wide significance, approximate conditional and joint multiple single-nucleotide polymorphism (SNP) analyses were conducted using COJO in GCTA 1.93.2b[28]. Throughout all analyses, the age at peak association refers to the age of lowest p-value in the association with BMI, and the effect allele refers to the BMI-increasing allele at age at peak association.

Effect size estimates for the top hits in ALSPAC

Age, weight, and height of children were obtained from the ALSPAC cohort[1,30], which corresponds to 15,454 pregnancies, resulting in 15,589 fetuses. Of these 14,901 were alive at 1 year of age. We jointly used both self-reported values and measurements from the Children in Focus (CiF) group as obtained from the ALSPAC cohort. Please note that the study website contains details of all the data that is available through a fully searchable data dictionary and variable search tool (see Data Availability).

Only children listed in the set of unrelated children as provided by the cohort were used. BMI values were computed unless already provided. Values were binned at birth, around 4 and 8 months, around 1, 1.5, 2, and 2.5 years, and around every year from 3 to 18 years of age. When multiple values for the same child were present in the same bin, the one closest to its individual BMI curve was retained. BMI values were standardized using GAMLSS as done for MoBa. Genotypes were extracted using PLINK 1.9 and a linear association between genotypes and standardized BMI was conducted in R.

Obesity gene enrichment analysis

The gene enrichment analysis around the 46 top hits was conducted using the union of two panels of genes implicated in monogenic and severe early onset obesity: Blueprint Genetics Monogenic Obesity Panel (test code KI1701) (blueprintgenetics.com/tests/panels/endocrinology/monogenic-obesity-panel) consisting of 36 genes, and Genomics England severe early-onset obesity panel v.2.2 consisting of 32 genes (panelapp.genomicsengland.co.uk/panels/130). The union of the two resulted in 42 genes used in analysis. A list containing gene locations for hg19 were obtained from PLINK 1.9 resources (cog-genomics.org/plink/1.9/resources). The list contained 25,303 unique genes used in the analysis. A 500 kb window was used to identify genes in the vicinity of the top hits. The significance for the enrichment of monogenic genes compared to random sampling was estimated using the distribution function of the Hypergeometric distribution *via* the function *phyper* from the R package stats.

Comparison with adult BMI in MoBa

Pre-pregnancy BMI values were computed using self-reported height and weight for the parents who were genotyped, passed QC, and excluding outliers in the PCA of the genotypes (27,088 mothers and 26,239 fathers), yielding 26,062 and 22,719 values for mothers and fathers,

573 respectively. As detailed in Supplementary Table 10, BMI values were standardized using
574 GAMLSS for mothers and fathers separately, using their birth year as covariate, as a proxy for
575 age. Like for children, GAMLSS models were fitted solely on parents from the *set of unrelated*
576 *trios*, and used to compute standardized values for all parents, *i.e.* including related parents.
577

The association between parent BMI and genotypes was computed for mothers and fathers separately, using BOLT-LMM v2.3.4[58] as done for the children. The covariates used were the genotyping batch, birth year, and ten principal components.

Clustering of association profiles

For each of the 46 independent genome-wide significant variants, alleles were aligned so that the association with standardized BMI is positive at the age of peak association. Effect sizes for all time points were then combined into an association profile for this variant, *i.e.* a vector $\beta = (\beta_{birth}, \beta_{6w}, \ldots, \beta_{8y})$). Reference effect size over time profiles corresponding to an association at birth waning afterwards, and an increasing association after one year of age towards adulthood were built using equations 1 and 2, respectively.

$$x_1(age) = 10^{-3\frac{age}{365.25}} \quad (1)$$

$$x_2(age) = 0 \text{ if age} < 365.25, \left(\frac{age-365.25}{7 \times 365.25}\right)^2 \text{ else} \quad (2)$$

Where x_1 and x_2 represent the reference profiles and *age* is the age at a given time point in days. Please note that these reference profiles are predefined constructs and their parameterization can influence the clustering. They were not tuned towards specific outcomes to avoid overfitting. The association profiles of each variant were then projected onto these reference profiles, by fitting a linear model:

$$\beta \sim x_1 + x_2 + 1 \quad (3)$$

The resulting projection is shown in Figure 1B. The profiles of equation 1 and 2 correspond to the curves on the West and South cardinal directions of Figure 1B, the profiles in all other cardinal and intercardinal directions correspond to linear combinations of these two, yielding eight reference profiles: (SE) early fall and late rise, (E) early fall, (NE) early and late fall, (N)

late fall, (NW) early rise and late fall, (W) early rise, (SW) early rise and late rise, and (S) late rise.

Each variant was plotted on Figure 1B using the sum of the absolute values of the effect size over time as radial coordinate, hence avoiding dependency on the reference profiles for this coordinate, and the relative association with x_1 and x_2 to define the angular coordinate, as described in equations 4 and 5, respectively.

$$\rho = \Sigma|\beta| \quad (4)$$

$$\theta = -atan2(\beta_{x_2}, \beta_{x_1}) + \theta_0 \quad (5)$$

Where ρ represents the radial coordinate, θ the angular coordinate, β_{x_1} and β_{x_2} the association between the genetic association profile and the reference profiles x_1 and x_2, respectively, and θ_0 a constant.

Each association profile was plotted after normalization to the association level at age at peak in Figure 1C using the angular coordinate θ as baseline on the ordinate.

A cardinal or intercardinal cluster was defined for each of the eight reference profiles corresponding to the cardinal and intercardinal directions in Figure 1B. Every cardinal and intercardinal cluster was assigned a first element chosen to be the variant with the angular coordinate θ closest to the direction (i.e. most correlated to that profile). The other variants were then assigned to a cluster based on their angular nearest neighbour, yielding the clustering displayed by the dendrogram of Figure 1D. Finally, as illustrated in Figure 1E, the cardinal and intercardinal clusters were grouped into four main clusters: (Birth) SE + E + NE; (Transient) N + NW; (Early rise) W; and (Late Rise) SW + S.

Mapping to pathways

The lead SNP of the 46 independent loci were submitted to the Ensembl Variant Effect Predictor (VEP)[60]. All proteins coded by genes reported with a consequence other than

downstream_gene_variant, *upstream_gene_variant*, or *intergenic_variant* were retained as potentially affected by a given variant. If no such gene was found, the protein coded by the closest gene within 500 kb was retained. Proteins were matched to Reactome[61] using PathwayMatcher[62]. Then, for each of the four main clusters, we built the smallest set of top-level pathways that explained the protein set returned by the VEP analysis, and counted the number of variants in this cluster affecting a protein in one of these top-level pathways (Figure 1F). Results for each SNP are reported in Supplementary Table 3.

Mapping to other traits

For each SNP, other associated traits were extracted using PhenoScanner[63,64]. PhenoScanner was queried using *EUR* and an R^2 threshold of 0.8 for proxies and *5e-8* as p-value threshold. Synonymous terms were grouped, and, for each of the four main clusters, the number of variants mapping to a given trait relative to the number of variants in the cluster was plotted in Figure 1G. Results for each SNP are reported in Supplementary Table 3.

Comparison with birth weight and adult BMI

Summary statistics on birth weight and adult BMI were obtained from Warrington *et al.*[29]and Yengo *et al.*[15], respectively. Variants were matched by rsid. For the variants with no match, proxies were sought using LDproxy (ldlink.nci.nih.gov) using a window of 500 kb, CEU as reference population, and an R^2 threshold of 0.2, and alleles were aligned. From the 46 top hits, variants were considered novel if there were no nearby proxy SNP in high LD (r2>0.6) with the lead SNPin Warrington *et al.*[29] and Yengo *et al.*[15] that had a p-value lower than 5×10^{-8}. For comparisons, for each of the 46 top hits, the variant in Warrington *et al.*[29] and Yengo *et al.*[15] with the lowest p-value with an LD R^2 value higher or equal to 0.2 was extracted. Summary statistics for all variants in the three data sets are available in Supplementary Table 11.

Subsequently, for all variants associated with own birth weight in Warrington *et al.*[29], and all variants associated with adult BMI in Yengo *et al.*[15], the association profile in MoBa was extracted and the angular coordinate of Figure 1B was computed by projecting onto the reference profiles as before. The angular density of each study was subsequently computed using sliding windows over θ, normalized to the number of variants in each study, and plotted in Figure 1H.

Child-mother-father trio and haplotype analysis

At all time points, for all 46 independent genome-wide significant variants, the association with the children's genome was conditioned on the genomes of the parents in the set of unrelated trios using the linear model described in equation 6.

$$bmi \sim child + mother + father + 1 \quad (6)$$

Where *bmi* refers to the standardized BMI of the child at a given time point, and child, mother, and father the number of tested alleles (hard call genotypes) for this variant in the child, mother, and father genomes, respectively.

Taking advantage of the phasing of the children's genotypes, we could infer the parent-of-origin of the genotyped alleles as done by Chen et al.[65]. This results in an alternative model that allows studying the association per haplotype in the set of unrelated trios, as detailed in equation 7.

$$bmi \sim MnT + MT + FnT + FT + 1 \quad (7)$$

Where *MnT* and *MT* refer to the number of tested alleles non-transmitted and transmitted by the mother to the child, respectively. Similarly, *FnT* and *FT* refer to the number of tested alleles non-transmitted and transmitted by the father to the child, respectively.

For a given variant, the share of Mendelian errors in the set of unrelated trios was estimated using trios presenting a homozygous parent. Then, a Mendelian error results in a value of -1 or +2 in the non-transmitted allele count. The share of Mendelian error was estimated by

comparing the number of such erroneous genotypes to the number of trios with a homozygous parent expected from the tested allele frequency. When the estimated share of Mendelian errors was over 50%, the alleles of the children were swapped.

For the chromosome X, no filtering was done based on ploidy, when only one chromosome was found the allele was assumed to be inherited from the mother. Note that the chromosome X was not phased, yielding a high share of Mendelian errors, approximately 50%, indicative of a random assignment of children alleles. Haplotype analysis was therefore not possible for the variant on chromosome X, while trio analysis is unaffected by this.

For both models, the same covariates were used as for the genetic association analysis using BOLT-LMM, *i.e.* genotyping batch, sex, gestational age, and ten principal components, and both phenotypes and genotypes were adjusted for covariates in the same way as BOLT-LMM does. Haplotype and trio analyses were conducted using TrioGen v. 0.5.0 (github.com/mvaudel/TrioGen) in the OpenJDK Runtime Environment (Zulu 8.20.0.5-linux64) (build 1.8.0_121-b15). Summary statistics for all variants are available in Supplementary Table 7.

LD score regression

LD score regression was performed with LD Hub v.1.9.0 using LDSC v.1.0.027 using all markers remaining after filtering on the provided SNP-list as recommended by the LD Hub authors. A total of 1,215,001 markers remained after filtering. All available phenotypes were selected for correlation analyses. Results for all variables along with heritability and QC reports are available in Supplementary Table 4.

Polygenic risk scores (PRS)

PRSs were calculated using PRSice-2 v. 2.3.0 (prsice.info). For scores based on study results from previous meta-analyses, the results were obtained from EGG (egg-consortium.org) for birth weight, childhood BMI and childhood obesity, GIANT for adult BMI (portals.broadinstitute.org/collaboration/giant), and DIAGRAM (diagram-consortium.org) for type 2 diabetes (T2D). PRSs were calculated separately for all time points per phenotype using ten principal components, sex, gestational age, and genotyping batch as covariates. Samples without a valid BMI measurement for a specific age were excluded from the analysis at that age, but would be included in analyses of other ages should BMI measurement be available. Among the samples reaching analysis at any age; none had missing genotype data since only markers available in HRC 1.1 were used in the analyses and none of the samples had missing covariates. The target dataset provided to PRSice included all markers available after imputation as hard-called genotypes, but were filtered to only include variants present in the respective reference data used in the respective analysis (supplying beta weights for each variant). Variants were excluded by LD-pruning using the target dataset and default settings for PRSice (250kb clump window, r2 threshold of 0.1, no p-value threshold). In the resulting set of samples and markers multiple PRS models are generated and fitted by gradually incrementing the inclusion p-value by 5e-5. Finally, the assessed PRS models were ranked by p-value of model fit. The PRS model with the best fit at each age was used in downstream stratification analyses. From the *full set* of children, one in each pair of samples with PI_HAT > 0.1 was removed at random, leaving 25,113 samples for the PRS analyses. Time-resolved scores used age-specific summary results from the primary analyses as base with the independent set of 1,062 samples from MoBa as target. Here, ten principal components, sex, and gestational age were used as covariates. Defaults were used for all other parameters. A PRS report as formalised by Wand et al.[66] is available in Supplementary Table 12.

Figures

All figures in the manuscript were generated in R version 3.6.1 (2019-07-05) -- "Action of the Toes" (R-project.org). In addition to the base packages, the following packages were used: tidyr version 1.1.0, janitor version 2.0.1, conflicted version 1.0.4, glue version 1.4.0, stringr version 1.4.0, dplyr version 1.0.0, scico version 1.1.0, RColorBrewer version 1.1-2, ggplot2 version 3.3.2, ggrepel version 0.8.2, grid version 3.6.1, gtable version 0.2.0, patchwork version 1.1.1, phenoscanner version 1.0, ggfx version 0.0.0.900.

Data availability

The full GWAS summary statistics for all time points are available for download at www.fhi.no/en/studies/moba/for-forskere-artikler/gwas-data-from-moba. Access to genotypes and phenotypes from the Norwegian Mother, Father and Child Cohort Study (MoBa) is subject to controlled access by the Norwegian Institute of Public Health in accordance with national and international regulations. Conditions of access including contact details for requests can be found at the Norwegian Institute of Public Health website (fhi.no/en/studies/moba).

HRC or 1000G Imputation preparation and checking: well.ox.ac.uk/~wrayner/tools

Sanger Imputation Service, imputation.sanger.ac.uk

LD Score repository, data.broadinstitute.org/alkesgroup/LDSCORE

GTEx, the Genotype-Tissue Expression portal, gtexportal.org

Birth weight reference data (Warrington et al 2019[29]), http://egg-consortium.org/BW5/Fetal_BW_European_meta.NG2019.txt.gz

Adult BMI reference data (Yengo et al 2018[15]), http://portals.broadinstitute.org/collaboration/giant/images/c/c8/Meta-analysis_Locke_et_al%2BUKBiobank_2018_UPDATED.txt.gz

Type 2 diabetes (Mahajan et al 2018[67]), https://www.diagram-consortium.org/downloads.html

- T2D GWAS meta-analysis - Unadjusted for BMI
  Published in Mahajan et al 2018[67]
- T2D GWAS meta-analysis - Adjusted for BMI
  Published in Mahajan et al 2018[67]

Childhood obesity (Bradfield et al 2019[18]),

http://egg-consortium.org/Childhood_Obesity_2019/CHILDHOOD_OBESITY.TRANS_ANCESTRAL.RESULTS.txt.gz

Childhood BMI (Felix et al 2015[16]), http://egg-consortium.org/Childhood_BMI/EGG_BMI_HapMap_DISCOVERY.txt.gz

The ALSPAC data dictionary and variable search tool, http://www.bristol.ac.uk/alspac/researchers/our-data

Ethics

Informed consent was obtained from all study participants. The administrative board of the Norwegian Mother, Father and Child Cohort Study led by the Norwegian Institute of Public Health approved the study protocol. The establishment of MoBa and initial data collection was based on a license from the Norwegian Data Protection Agency and approval from The Regional Committee for Medical Research Ethics. The MoBa cohort is currently regulated by the Norwegian Health Registry Act. The study was approved by The Regional Committee for Medical Research Ethics (#2012/67).

Ethical approval for the study was obtained from the ALSPAC Ethics and Law Committee and the Local Research Ethics Committees. Informed consent for the use of data collected via questionnaires and clinics was obtained from participants following the recommendations of the ALSPAC Ethics and Law Committee at the time. Consent for biological samples has been collected in accordance with the Human Tissue Act (2004).

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All analyses were performed using digital labs in HUNT Cloud at the Norwegian University of Science and Technology, Trondheim, Norway. We are grateful for outstanding support from the HUNT Cloud community.

Author contributions

Ø.H., M.V., P.R.N. and S.J. designed the study. Ø.H. and M.V. analysed the data. Ø.H., M.V., and S.J. interpreted the data. J.J., J.B., G.P.K., T.R.K., P.M., C.S., O.A.A. contributed to sample acquisition and genotyping. J.J. and J.B. assisted with genotype quality control. P.S.N., C.F., I.L.K., B.B.J., B.J., and P.R.N. critically revised the manuscript for important intellectual content. Ø.H., M.V., and S.J. wrote the manuscript. All authors participated in preparing the manuscript by reading and commenting on drafts before submission. P.R.N. and S.J. acquired the funding.

Competing interests

OAA is a consultant to HealthLytix. The other authors declare no competing interests.

Figure Legends

Figure 1 - Longitudinal association effect size profiles for the 46 top hits. *(A) Age span of the early childhood developmental stages covered by this association study with BMI. (B) Quadrant plot of the 46 top hits where the radial and angular coordinates of a SNP respectively indicate the magnitude and shape of the effect size profile over time. Inserts at cardinal and intercardinal directions indicate the association profile represented by a given angular coordinate. (C) Effect sizes at the different time points grouped by profile similarity, with the vertical position of the profile corresponding to the angular position in panel B. (D) Dendrogram of the effect size profiles clustering. (E) Grouping of effect size profiles into four main clusters:* Birth*,* Transient*,* Early Rise*, and* Late Rise*. Inserts to the left indicate the association profiles in each cluster. (F) Overlap with top-level biological pathways. Bars represent the number of variants in a cluster mapping a given pathway. (G) Comparisons with other GWAS studies present in PhenoScanner. Bars represent the number of variants associated with a trait (p-value 5 × 10^{-8}). (H) Angular density of beta profiles for variants associated with birth weight (blue), and adult BMI (red), compared to early BMI (green) according to [29],[15], and this study, respectively, and processed as in 1B. See the* Clustering of association profiles *section of the methods for details on how the different panels are built. See Supplementary Table 1 for the number of samples at each time point.*

Figure 2 - Comparison with previous studies on birth weight and adult BMI. *(A) Heatmap of the effect size for the 46 top hits from birth to adulthood. Variants are ordered vertically according to Figure 1C. The estimated effect size for association with birth weight (BW) Warrington* et al.[29] *(column 1), BMI during early growth (this study, MoBa cohort, column 2-12), BMI during preadolescence and adolescence (this study, ALSPAC cohort, column 13-17), and adult BMI (this study, mothers and fathers of the MoBa cohort (column 18-19) and Yengo* et al.[15] *(last column)) is displayed in each cell. The cell colour represents the estimated effect size and the text colour represents the unadjusted p-value. Empty cells indicate that no proxy could be found for the given variant in the given study. See methods for details. (B) Estimated effect size for association with birth weight[29] and adult BMI[15] plotted against the estimated effect size at the age of peak association during early growth (this study). Dashed line indicates equal effect sizes in both studies. The colour represents the age of peak association, as defined as the age with lowest p-value. Variants are grouped according to their profile cluster as defined in Figure 1E. Thick and thin error bars represent one standard error estimate on each side of the effect size estimate and 95% confidence intervals, respectively. Note that for the sake of readability,* GCK *at birth is plotted in an insert with a different scale, and the axes might crop the 95% confidence intervals. See Supplementary Table 1 for the number of samples at each time point, the methods for the statistical analysis.*

Figure 3 - MoBa effect trajectories **overlayed with association profiles obtained from ALSPAC.** *Effect size estimates for (A)* ADCY5 - *rs11708067, (B)* LEPR - *rs2767486, (C)* GLP1R - *rs1820721, (D)* KLF14 - *rs287621*, and (E) FTO - *rs17817288 obtained in the MoBa and ALSPAC cohorts. The quadrant plots to the left display the shape of the effect size estimate over time as obtained in Figure 1B, for both cohorts, between birth and eight years of age. The effect size estimates are plotted at each age to the right using line and ribbons for MoBa and point and error bars for ALSPAC. Note that to maintain readability of earlier time points, the scale of the x axis is not linear. Thick and thin error bars/ribbons represent one standard error estimate on each side of the effect size estimates and 95% confidence intervals, respectively. See Supplementary Table 1 for the number of samples at each age bin.*

***Figure 4* - Trio- and haplotype-resolved association profiles.** *(A) Effect size estimate for the conditional allelic association of the child, mother, and father with child standardized BMI for each of the 46 variants at age at peak association. Here, child, mother, and father genotypes are conditioned on each other, see methods for details. (B) Association profile for birth weight loci known to present both maternal and fetal effect on birth weight. Effect size estimates of the association with child standardized BMI are represented for the child and the mother from birth to two years of age (fathers were included in the model, but not displayed for readability). Unadjusted p-values represent the significance of the association with the number of effect alleles in the child, mother, and father in a joint model, and thus differ from the p-values of the GWAS. (C) Association profiles with child standardized BMI from birth to eight years of age for two variants upstream of* KLF14 *in a model combining the child, mother, and father alleles into four haplotypes: (MnT) allele non-transmitted from mother to child; (MT) allele transmitted from mother to child; (FT) allele transmitted from father to child; and (FnT) allele non-transmitted from father to child. FnT is not represented here for readability, all results are available in Supplementary Table 4. Unadjusted p-values represent the significance of the association with the number of effect alleles for each haplotype in a joint model. (D) Regional plot for the unadjusted p-values of association with the MT and FT haplotypes, top and bottom, respectively, in the haplotype-resolved model. The first and second locus, to the left and right, respectively, are annotated with a red diamond and SNPs coloured according to the LD* R^2*. The coordinates of the nearest exon coding for* KLF14 *are annotated at the bottom. Thick and thin error bars and ribbons represent one standard error estimate on each side of the effect size estimates and 95% confidence intervals, respectively. See Supplementary Table 1 for the number of samples at each time point, the methods for the statistical analysis.*

Figure 5 - Polygenic risk score (PRS) analyses. *(A and B) Mean standardized BMI of children in this study at each time point after stratification in PRS deciles using PRS trained using summary statistics from meta-analyses (bottom), and relative risk of obesity for children at a given time point in the top and bottom PRS deciles in red and blue, respectively, compared to the entire cohort (top), where obesity is defined as belonging to the top 5 BMI percentile. PRS training was performed using summary statistics for (A) birth weight from Warrington* et al.[29] *and (B) adult BMI from Yengo* et al.[15]*. (C and D) Zoom on the stratification by birth weight PRS and adult BMI PRS at birth and eight years, respectively. The density of scores in this study is plotted with the different deciles colored from left to right. Below, the relative risk of obesity for children in each decile.relative to the entire cohort is plotted with the share of obese children in each decile annotated. At the bottom is plotted the mean standardized BMI of children in each decile. All error bars represent 95% confidence intervals. See Supplementary Table 1 for the number of samples at each time point.*

Table legends

Table 1 - Association summary statistics for the top hits. *Loci are ordered according to chromosomal position. SNP: rsid of the SNP with lowest p-value at age at peak association. Chr, Position: chromosome and position of the SNP in GRCh37 coordinates. EA, OA, EAF: effect allele, other allele, and effect allele frequency estimate in MoBa, where the effect allele is the BMI-raising allele at age of peak association. Age: age at peak association defined as age with lowest association p-value. Name: locus name based on the nearest gene or previous naming in the literature. Beta, SE, P-value: effect size, standard error, and unadjusted p-value estimates for the association with standardized BMI at age at peak. Cluster: Cluster corresponding to the effect size profile over time. Membership to multiple signals loci, and previous association of the lead SNP with birth weight (BW) in Warrington* et al.[29]*, adult BMI (aBMI) in Yengo* et al.[15]*, or both are annotated with superscripts. See Supplementary Table 1 for the number of samples at each time point, the methods for the statistical analysis.*

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Name	SNP	Chr	Position	EA	OA	EAF	Age	Beta	SE	P-value	Cluster
LEPR	rs10493377	*1*	65,879,252	A	G	53%	1.5 y	0.057	0.010	2.20E-09*	Transient
LEPR	rs10889551	*1*	65,906,137	G	A	65%	1 y	0.088	0.010	5.20E-19*	Transient
LEPR	rs2767486	*1*	65,991,203	G	A	16%	6 m	0.143	0.012	6.40E-34*	Transient
TNNI3K	rs10493544[aBMI]	*1*	74,983,835	T	C	43%	8 m	0.054	0.009	1.40E-08	Early Rise
SEC16B	rs545608[aBMI]	*1*	177,899,121	C	G	23%	8 y	0.088	0.016	3.20E-08	Late Rise
NR5A2	rs2816985	*1*	200,072,966	G	A	45%	3 m	0.059	0.009	5.40E-11	Transient
AC105393.2	rs77165542	*2*	430,975	C	T	98%	1.5 y	0.187	0.032	3.50E-09	Early Rise
ADCY3	rs11676272[aBMI]	*2*	25,141,538	G	A	49%	1 y	0.089	0.009	2.80E-22	Early Rise
ADCY5	rs11708067[BW]	*3*	123,065,778	G	A	23%	Birth	0.079	0.010	5.20E-16	Birth
CCNL1	rs1482853[BW]	*3*	156,798,473	C	A	60%	Birth	0.099	0.008	5.90E-32	Birth
LCORL	rs2610989[BW]	*4*	18,022,834	T	C	26%	1.5 y	0.060	0.011	5.50E-08*	Early Rise
HHIP	rs1032296	*4*	145,434,688	T	C	38%	6 m	0.052	0.009	1.10E-08	Transient
PCSK1	rs6899303	*5*	95,650,975	C	A	63%	6 m	0.057	0.009	5.30E-11*	Transient
PCSK1/CAST	rs263377	*5*	95,884,775	A	G	41%	1 y	0.054	0.010	2.90E-08*	Transient
GLP1R	rs2268657	*6*	39,020,542	T	C	51%	3 m	0.056	0.009	8.40E-10*	Transient
GLP1R	rs2268647	*6*	39,043,178	T	C	50%	1 y	0.048	0.009	2.60E-07*	Transient
GLP1R	rs1820721	*6*	39,110,046	A	C	49%	6 m	0.061	0.009	7.20E-12*	Transient
UBE3D	rs209421	*6*	83,523,684	G	T	26%	6 m	0.073	0.010	5.40E-13	Transient
ESR1	rs7772579[BW]	*6*	152,042,502	A	C	70%	Birth	0.065	0.009	5.90E-13	Birth
OPRM1	rs1772945	*6*	154,312,285	A	G	56%	8 m	0.056	0.009	3.20E-09	Transient
GCK	rs78412508[BW]	*7*	44,223,858	G	A	99%	Birth	0.376	0.047	4.00E-15	Birth
MLXIPL	rs17145750	*7*	73,026,378	C	T	84%	6 m	0.070	0.012	6.80E-09	Transient
LEP	rs10487505	*7*	127,860,163	C	G	49%	1.5 y	0.056	0.009	3.20E-09	Early Rise
KLF14	rs287621	*7*	130,435,181	T	C	26%	6 m	0.064	0.010	3.70E-10*	Transient
KLF14	rs12672489	*7*	130,483,555	C	T	75%	1.5 y	0.067	0.011	2.10E-09*	Early Rise
HNF4G	rs117212676	*8*	76,632,003	A	G	2%	6 m	0.166	0.030	1.80E-07*	Early Rise
PTCH1	rs28457693[BW]	*9*	98,217,348	G	A	13%	6 m	0.073	0.013	2.40E-08	Transient
GPSM1	rs28642213[BW]	*9*	139,248,082	A	G	27%	Birth	0.062	0.010	4.70E-11	Birth
HHEX	rs11187129[BW]	*10*	94,429,907	C	T	46%	Birth	0.047	0.008	2.10E-08	Birth
PLCE1	rs1830890	*10*	96,019,501	G	A	32%	3 y	0.067	0.012	1.30E-08	Early Rise
SCGB1A1	rs1985927	*11*	62,193,537	C	T	73%	8 m	0.060	0.011	6.80E-09	Early Rise
EHBP1L1	rs2298615	*11*	65,352,062	T	C	23%	6 w	0.071	0.012	5.40E-09	Transient
RP11-405A12.2	rs2728641	*12*	20,111,569	C	T	48%	3 m	0.050	0.009	1.90E-08	Transient
FAIM2	rs7132908[aBMI]	*12*	50,263,148	A	G	40%	8 y	0.081	0.014	3.30E-09	Late Rise
RP11-690J15.1	rs6538845	*12*	98,544,888	C	T	48%	3 m	0.055	0.009	1.50E-09	Early Rise

SH2B3	rs7310615[Both]	*12*	111,865,049	G	C	55%	Birth	0.050	0.009	6.50E-09	Birth
NCOR2	rs3741508	*12*	124,812,678	T	G	86%	8 m	0.083	0.013	1.20E-09	Transient
DLK1	rs75806555	*14*	101,189,448	C	T	86%	Birth	0.074	0.012	2.10E-09	Birth
SH3GL3	rs2585058	*15*	84,284,552	G	A	53%	8 m	0.063	0.009	8.60E-12	Transient
FTO	rs17817288[aBMI]	*16*	53,807,764	G	A	49%	8 y	0.095	0.013	1.30E-12	Late Rise
KIAA0895L	rs111810144	*16*	67,216,110	T	C	3%	8 m	0.147	0.025	5.20E-09	Early Rise
DLG4	rs739669[BW]	*17*	7,122,377	A	G	62%	Birth	0.072	0.009	4.70E-17	Birth
MC4R	rs78263856[aBMI]	*18*	58,042,821	T	C	95%	7 y	0.150	0.027	3.80E-08	Late Rise
RIN2	rs148252705	*20*	17,851,179	T	C	97%	3 m	0.157	0.029	2.60E-08	Transient
EFCAB8	rs13038017	*20*	31,467,551	C	T	53%	1 y	0.054	0.009	1.20E-08	Early Rise
PTCHD1-AS	rs5926278	*X*	23,296,291	T	C	2%	3 m	0.149	0.027	4.80E-08	Transient

* locus with multiple signals, independent and significant after conditional and joint analysis
[BW] Variant associated with birth weight according to Warrington *et al.*, 2019.
[aBMI] Variant associated with adult BMI according to Yengo *et al.*, 2018.
[Both] Variant associated with both birth weight and adult BMI according to Warrington *et al.*, 2019, and Yengo *et al.*, 2018, respectively.

A

Newborn
Infant
Toddler
Child

B

H

Birth Weight
Early BMI
Adult BMI

C

ADCY5 (rs11708067)
SH2B3 (rs7310615)
CCNL1 (rs1482853)
GPSM1 (rs28642213)
GCK (rs78412508)
DLG4 (rs739669)
ESR1 (rs7772579)
DLK1 (rs75806555)
HHEX (rs11187129)
EHBP1L1 (rs2298615)
RIN2 (rs148252705)
PTCHD1-AS (rs5926278)
RP11-405A12.2 (rs2728641)
NCOR2 (rs3741508)
OPRM1 (rs1772945)
LEPR (rs10493377)
MLXIPL (rs17145750)
PTCH1 (rs28457693)
PCSK1 (rs6899303)
NR5A2 (rs2816985)
GLP1R (rs2268657)
UBE3D (rs209421)
GLP1R (rs2268647)
LEPR (rs10889551)
HHIP (rs1032296)
LEPR (rs2767486)
CAST (rs263377)
GLP1R (rs1820721)
SH3GL3 (rs2585058)
KLF14 (rs287621)
KLF14 (rs12672489)
EFCAB8 (rs13038017)
SCGB1A1 (rs1985927)
LCORL (rs2610989)
RP11-690J15.1 (rs6538845)
KIAA0895L (rs111810144)
ADCY3 (rs11676272)
PLCE1 (rs1830890)
LEP (rs10487505)
HNF4G (rs117212676)
AC105393.2 (rs77165542)
TNNI3K (rs10493544)
FAIM2 (rs7132908)
SEC16B (rs545608)
MC4R (rs78263856)
FTO (rs17817288)

Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

D

E

Birth
Transient
Early Rise
Late Rise

F

Signal Transduction
Metabolism
Transcription
Metabolism of proteins
Developmental Biology
Neuronal System
Immune System
Hemostasis
Small molecules transport

Signal Transduction
Metabolism
Transcription
Metabolism of proteins
Developmental Biology
Vesicle-mediated transport
ECM organization
Chromatin organization

Metabolism
Signal Transduction
Neuronal System
Small molecules transport

Metabolism of proteins
Vesicle-mediated transport
DNA Repair

G

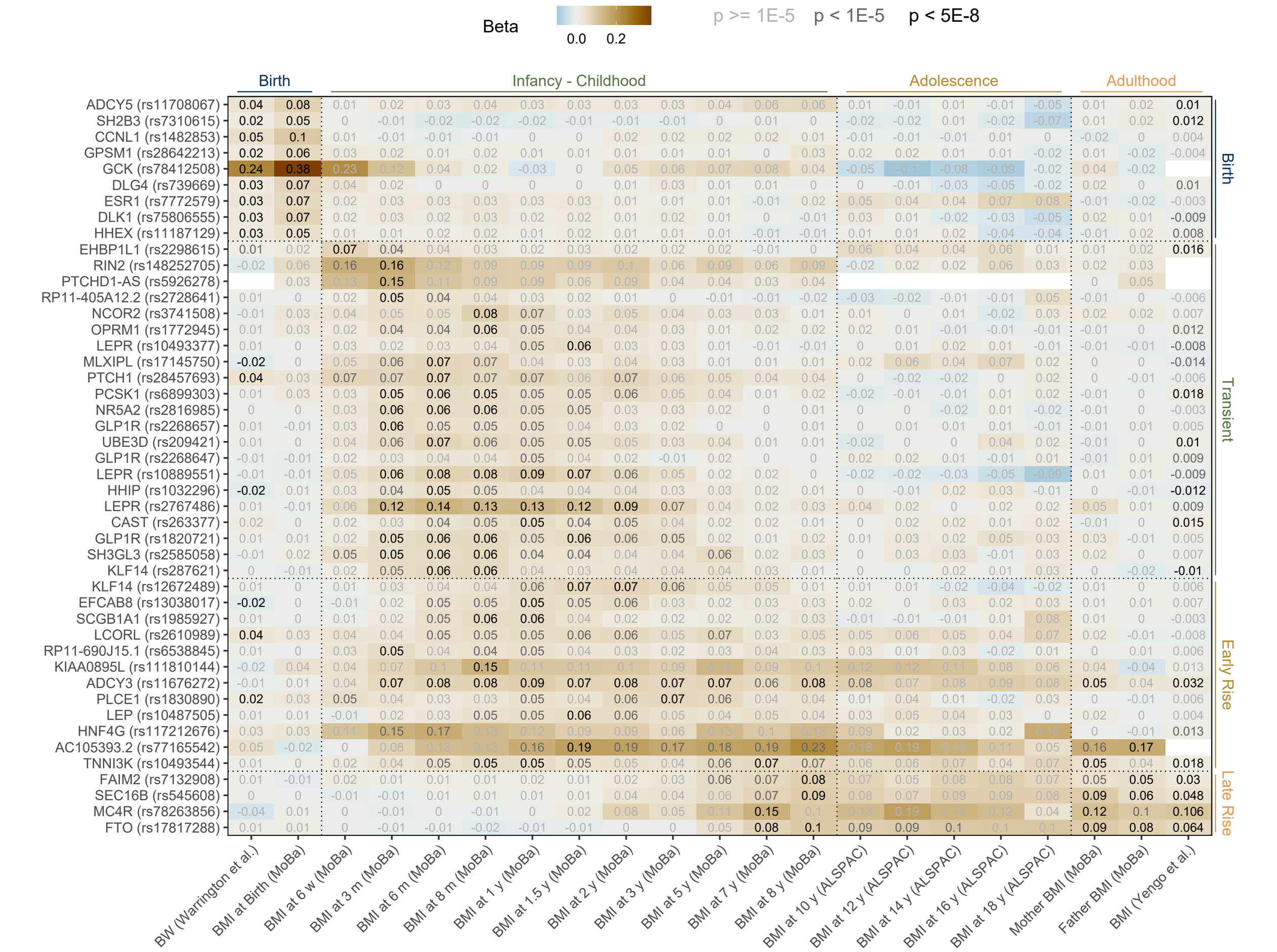
Birth weight
Height
BMI
Type 2 diabetes
Height (10 y)
Platelet
H. bone mineral dens.
Diabetes
Diabetes (Father)
Eosinophil
Eosinophil basophil
HbA1c
Glycated hemoglobin
IBD
Impedance

Impedance
Weight
Fat-free mass
Hip circumference
Height
Basal metabolic rate
Height (10 y)
Expiration
Body size (10 y)
Fat percentage
Platelet
HDL
Leptin
Red cell
Reticulocyte

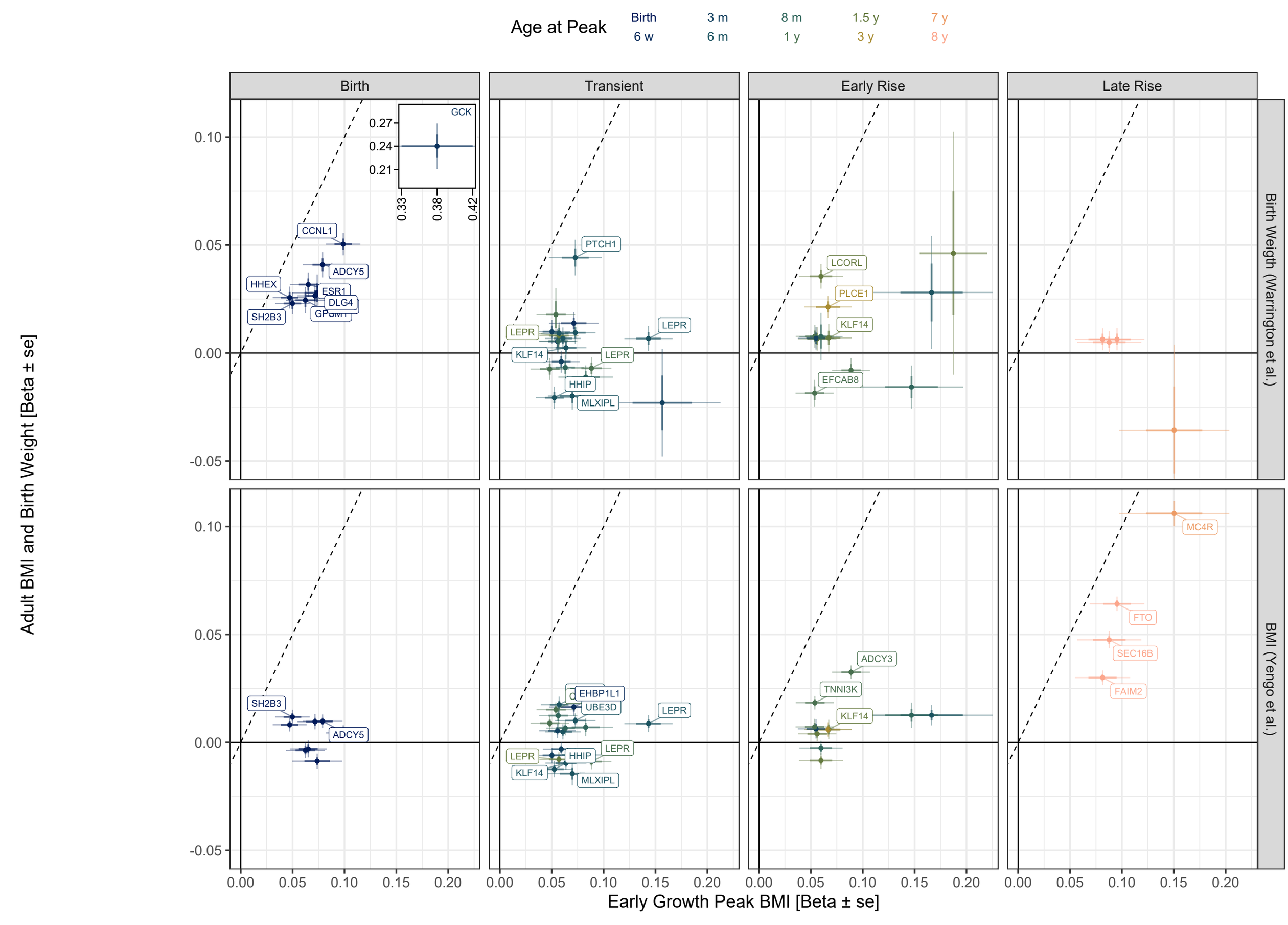
Weight
Height (10 y)
Body size (10 y)
Impedance
Fat-free mass
Basal metabolic rate
Hip circumference
BMI
Fat percentage
Waist circumference
Fat mass
Menarche
Height
Expiration
Blood pressure

Impedance
Weight
Fat-free mass
Basal metabolic rate
Hip circumference
Body size (10 y)
BMI
Fat percentage
Waist circumference
Fat mass
Menarche
BMI (Childhood)
Obesity
Obesity (Childhood)
Height (10 y)

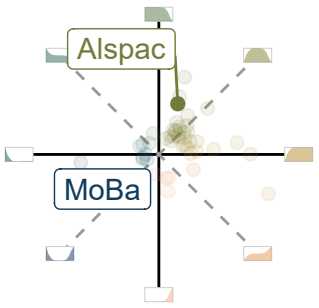
A

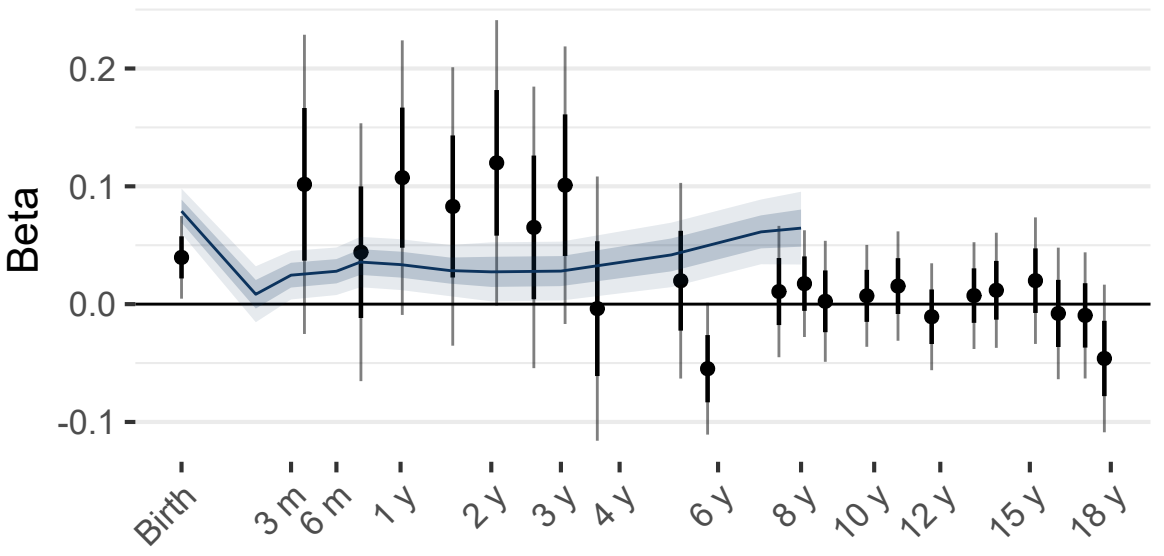

Beta
0.0
0.2
p >= 1E-5
p < 1E-5
p < 5E-8
Birth
Infancy - Childhood
Adolescence
Adulthood
ADCY5 (rs11708067) 0.04 0.08 0.01 0.02 0.03 0.04 0.03 0.03 0.03 0.03 0.04 0.06 0.06 0.01 -0.01 0.01 -0.01 -0.05 0.01 0.02 0.01
SH2B3 (rs7310615) 0.02 0.05 0 -0.01 -0.02 -0.02 -0.02 -0.01 -0.01 -0.01 0 0.01 0 -0.02 -0.02 0.01 -0.02 -0.07 0.01 0.02 0.012
CCNL1 (rs1482853) 0.05 0.1 0.01 -0.01 -0.01 -0.01 0 0 0.02 0.02 0.02 0.02 0.01 -0.01 -0.01 -0.01 0.01 0 -0.02 0 0.004
GPSM1 (rs28642213) 0.02 0.06 0.03 0.02 0.01 0.02 0.01 0.01 0.01 0.01 0.01 0 0.03 0.02 0.02 0.01 0.01 -0.02 0.01 -0.02 -0.004
GCK (rs78412508) 0.24 0.38 0.23 0.12 0.04 0.02 -0.03 0 0.05 0.06 0.07 0.08 0.04 -0.05 -0.1 -0.08 -0.09 -0.02 0.04 -0.02
DLG4 (rs739669) 0.03 0.07 0.04 0.02 0 0 0 0 0.01 0.03 0.01 0.01 0 0 -0.01 -0.03 -0.05 -0.02 0.02 0 0.01
ESR1 (rs7772579) 0.03 0.07 0.02 0.03 0.03 0.03 0.03 0.03 0.01 0.01 0.01 -0.01 0.02 0.05 0.04 0.04 0.07 0.08 -0.01 -0.02 -0.003
DLK1 (rs75806555) 0.03 0.07 0.02 0.03 0.02 0.03 0.02 0.02 0.01 0.02 0.01 0 -0.01 0.03 0.01 -0.02 -0.03 -0.05 0.02 0.01 -0.009
HHEX (rs11187129) 0.03 0.05 0.01 0.01 0.02 0.02 0.01 0.02 0.01 0.01 0.01 -0.01 -0.01 0.01 0.01 0.02 -0.04 -0.04 -0.01 0.02 0.008
EHBP1L1 (rs2298615) 0.01 0.02 0.07 0.04 0.04 0.03 0.02 0.03 0.02 0.02 0.02 -0.01 0 0.06 0.04 0.04 0.06 0.01 0.01 0.02 0.016
RIN2 (rs148252705) -0.02 0.06 0.16 0.16 0.12 0.09 0.09 0.09 0.1 0.06 0.09 0.06 0.09 -0.02 0.02 0.02 0.06 0.03 0.02 0.03
PTCHD1-AS (rs5926278) 0.03 0.13 0.15 0.11 0.09 0.09 0.06 0.09 0.04 0.04 0.03 0.04 0 0.05
RP11-405A12.2 (rs2728641) 0.01 0 0.02 0.05 0.04 0.04 0.03 0.02 0.01 0 -0.01 -0.01 -0.02 -0.03 -0.02 -0.01 -0.01 0.05 -0.01 0 -0.006
NCOR2 (rs3741508) -0.01 0.03 0.04 0.05 0.05 0.08 0.07 0.03 0.05 0.04 0.03 0.03 0.01 0.01 0 0.01 -0.02 0.03 0.02 0.02 0.007
OPRM1 (rs1772945) 0.01 0.03 0.02 0.04 0.04 0.06 0.05 0.04 0.04 0.03 0.01 0.02 0.02 0.02 0.01 -0.01 -0.01 -0.01 -0.01 0 0.012
LEPR (rs10493377) 0.01 0 0.03 0.02 0.03 0.04 0.05 0.06 0.03 0.03 0.01 -0.01 -0.01 0 0.01 0.02 0.01 -0.01 -0.01 -0.01 -0.008
MLXIPL (rs17145750) -0.02 0 0.05 0.06 0.07 0.07 0.04 0.03 0.04 0.03 0.01 0.01 0.01 0.02 0.06 0.04 0.07 0.02 0 0 -0.014
PTCH1 (rs28457693) 0.04 0.03 0.07 0.07 0.07 0.07 0.07 0.06 0.07 0.06 0.05 0.04 0.04 0 -0.02 -0.02 0 0.02 0 -0.01 -0.006
PCSK1 (rs6899303) 0.01 0.03 0.03 0.05 0.06 0.05 0.05 0.05 0.06 0.05 0.04 0.01 0.02 -0.02 -0.01 -0.01 0.01 0.02 -0.01 0 0.018
NR5A2 (rs2816985) 0 0 0.03 0.06 0.06 0.06 0.05 0.05 0.03 0.03 0.02 0 0.01 0 0 -0.02 0.01 -0.02 -0.01 0 -0.003
GLP1R (rs2268657) 0.01 -0.01 0.03 0.06 0.05 0.05 0.05 0.04 0.03 0.02 0 0 0.01 0 0.01 0.01 0.01 -0.01 -0.01 0.01 0.005
UBE3D (rs209421) 0.01 0 0.04 0.06 0.07 0.06 0.05 0.05 0.05 0.03 0.04 0.01 0.01 -0.02 0 0 0.04 0.02 -0.01 0 0.01
GLP1R (rs2268647) -0.01 -0.01 0.02 0.03 0.04 0.04 0.05 0.04 0.02 -0.01 0.02 0 0 0.02 0.02 0.01 -0.01 0.01 -0.01 0.01 0.009
LEPR (rs10889551) -0.01 -0.01 0.05 0.06 0.08 0.08 0.09 0.07 0.06 0.05 0.02 0.02 0 -0.02 -0.02 -0.03 -0.05 -0.09 0.01 0.01 -0.009
HHIP (rs1032296) -0.02 0.01 0.03 0.04 0.05 0.05 0.04 0.04 0.04 0.03 0.03 0.02 0.01 0 -0.01 0.02 0.03 -0.01 0 -0.01 -0.012
LEPR (rs2767486) 0.01 -0.01 0.06 0.12 0.14 0.13 0.13 0.12 0.09 0.07 0.04 0.02 0.03 0.04 0.02 0 0.02 0.02 0.05 0.01 0.009
CAST (rs263377) 0.02 0 0.02 0.03 0.04 0.05 0.05 0.04 0.05 0.04 0.02 0.02 0.01 0 0.02 0.02 0.01 0.02 -0.01 0 0.015
GLP1R (rs1820721) 0.01 0.01 0.02 0.05 0.06 0.06 0.05 0.06 0.06 0.05 0.02 0.01 0.02 0.01 0.03 0.02 0.05 0.03 0.03 -0.01 0.005
SH3GL3 (rs2585058) -0.01 0.02 0.05 0.05 0.06 0.06 0.04 0.04 0.04 0.04 0.06 0.02 0.03 0 0.03 0.03 -0.01 0.03 0.02 0 0.007
KLF14 (rs287621) 0 -0.01 0.02 0.05 0.06 0.06 0.04 0.03 0.04 0.04 0.04 0.03 0.01 0 0 0.02 0.01 0.03 0 -0.02 -0.01
KLF14 (rs12672489) 0.01 0 0.01 0.03 0.04 0.04 0.06 0.07 0.07 0.06 0.05 0.05 0.01 0.01 0.01 -0.02 -0.04 -0.02 0.01 0 0.006
EFCAB8 (rs13038017) -0.02 0 -0.01 0.02 0.05 0.05 0.05 0.05 0.06 0.03 0.02 0.03 0.03 0.02 0 0.03 0.02 0.03 0.01 0.01 0.007
SCGB1A1 (rs1985927) 0.01 0 0.01 0.02 0.05 0.06 0.06 0.04 0.02 0.02 0.02 0.02 0.03 -0.01 -0.01 -0.01 0.01 0.08 0.01 0 -0.003
LCORL (rs2610989) 0.04 0.03 0.04 0.04 0.05 0.05 0.05 0.06 0.06 0.05 0.07 0.03 0.05 0.05 0.06 0.05 0.04 0.07 0.02 -0.01 -0.008
RP11-690J15.1 (rs6538845) 0.01 0 0.03 0.05 0.04 0.04 0.05 0.04 0.03 0.02 0.03 0.04 0.03 0.03 0.01 0.03 -0.02 0.01 0 0.01 0.006
KIAA0895L (rs111810144) -0.02 0.04 0.04 0.07 0.1 0.15 0.11 0.11 0.1 0.09 0.14 0.09 0.1 0.12 0.12 0.11 0.08 0.06 0.04 -0.04 0.013
ADCY3 (rs11676272) -0.01 0.01 0.04 0.07 0.08 0.08 0.09 0.07 0.08 0.07 0.07 0.06 0.08 0.08 0.07 0.08 0.09 0.08 0.05 0.04 0.032
PLCE1 (rs1830890) 0.02 0.03 0.05 0.04 0.03 0.03 0.05 0.04 0.06 0.07 0.06 0.04 0.04 0.01 0.04 0.01 -0.02 0.03 0 -0.01 0.006
LEP (rs10487505) 0.01 0.01 -0.01 0.02 0.03 0.05 0.05 0.06 0.06 0.05 0.04 0.05 0.04 0.03 0.05 0.04 0.03 0 0.02 0 0.004
HNF4G (rs117212676) 0.03 0.03 0.11 0.15 0.17 0.13 0.12 0.09 0.09 0.06 0.13 0.1 0.13 0.09 0.02 0.03 0.02 0.16 0 -0.01 0.013
AC105393.2 (rs77165542) 0.05 -0.02 0 0.08 0.13 0.13 0.16 0.19 0.19 0.17 0.18 0.19 0.23 0.18 0.19 0.16 0.11 0.05 0.16 0.17
TNNI3K (rs10493544) 0.01 0 0.02 0.04 0.05 0.05 0.05 0.05 0.05 0.04 0.06 0.07 0.07 0.06 0.06 0.07 0.04 0.07 0.05 0.04 0.018
FAIM2 (rs7132908) 0.01 -0.01 0.02 0.01 0.01 0.01 0.02 0.01 0.02 0.03 0.06 0.07 0.08 0.07 0.05 0.08 0.08 0.07 0.05 0.05 0.03
SEC16B (rs545608) 0 0 -0.01 -0.01 0.01 0.01 0.01 0.01 0.04 0.04 0.06 0.07 0.09 0.08 0.07 0.09 0.09 0.08 0.09 0.06 0.048
MC4R (rs78263856) -0.04 0.01 0 -0.01 0 -0.01 0 0.02 0.08 0.05 0.11 0.15 0.1 0.13 0.19 0.14 0.12 0.04 0.12 0.1 0.106
FTO (rs17817288) 0.01 0.01 0 -0.01 -0.01 -0.02 -0.01 -0.01 0 0 0.05 0.08 0.1 0.09 0.09 0.1 0.1 0.1 0.09 0.08 0.064
Birth
Transient
Early Rise
Late Rise
BW (Warrington et al.)
BMI at Birth (MoBa)
BMI at 6 w (MoBa)
BMI at 3 m (MoBa)
BMI at 6 m (MoBa)
BMI at 8 m (MoBa)
BMI at 1 y (MoBa)
BMI at 1.5 y (MoBa)
BMI at 2 y (MoBa)
BMI at 3 y (MoBa)
BMI at 5 y (MoBa)
BMI at 7 y (MoBa)
BMI at 8 y (MoBa)
BMI at 10 y (ALSPAC)
BMI at 12 y (ALSPAC)
BMI at 14 y (ALSPAC)
BMI at 16 y (ALSPAC)
BMI at 18 y (ALSPAC)
Mother BMI (MoBa)
Father BMI (MoBa)
BMI (Yengo et al.)

B

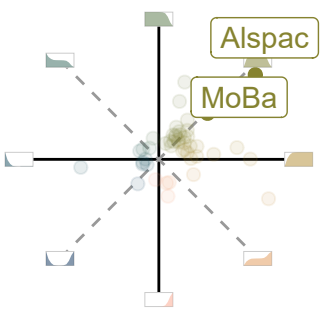

Age at Peak
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
3 y
7 y
8 y
Birth
Transient
Early Rise
Late Rise
GCK
0.27
0.24
0.21
0.33
0.38
0.42
CCNL1
ADCY5
HHEX
ESR1
DLG4
SH2B3
PTCH1
LEPR
KLF14
HHIP
MLXIPL
LCORL
PLCE1
EFCAB8
MC4R
FTO
SEC16B
FAIM2
EHBP1L1
UBE3D
ADCY3
TNNI3K
0.10
0.05
0.00
-0.05
0.00
0.05
0.10
0.15
0.20
Adult BMI and Birth Weight [Beta ± se]
Early Growth Peak BMI [Beta ± se]
Birth Weigth (Warrington et al.)
BMI (Yengo et al.)

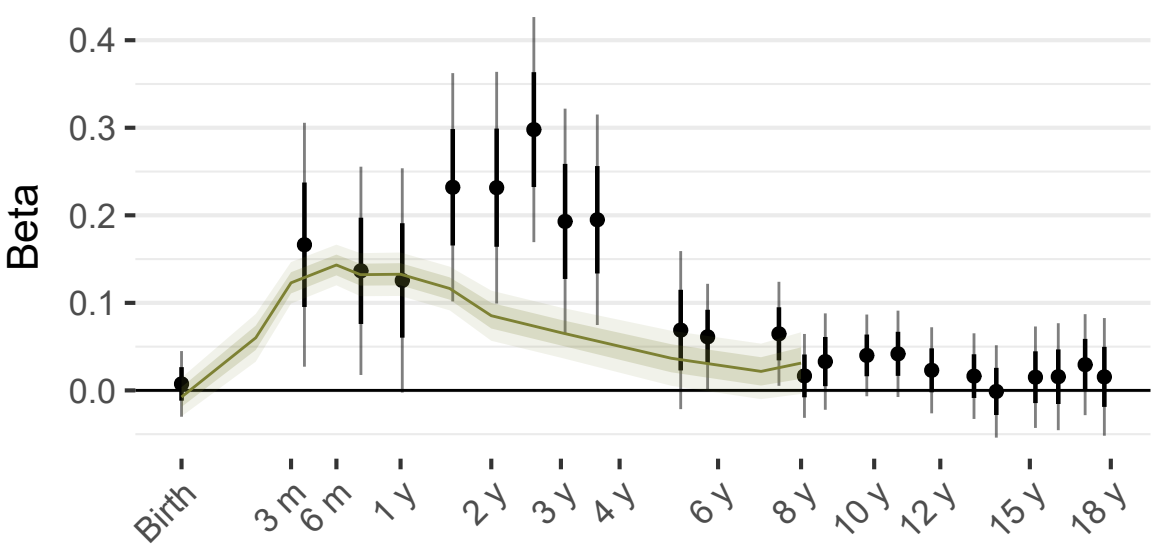
A


Alspac
MoBa

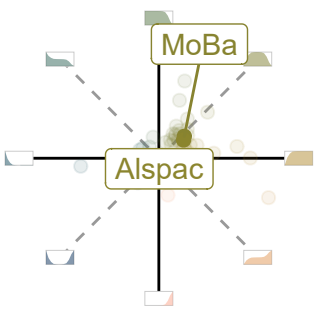

Beta
0.2
0.1
0.0
-0.1
Birth
3 m
6 m
1 y
2 y
3 y
4 y
6 y
8 y
10 y
12 y
15 y
18 y

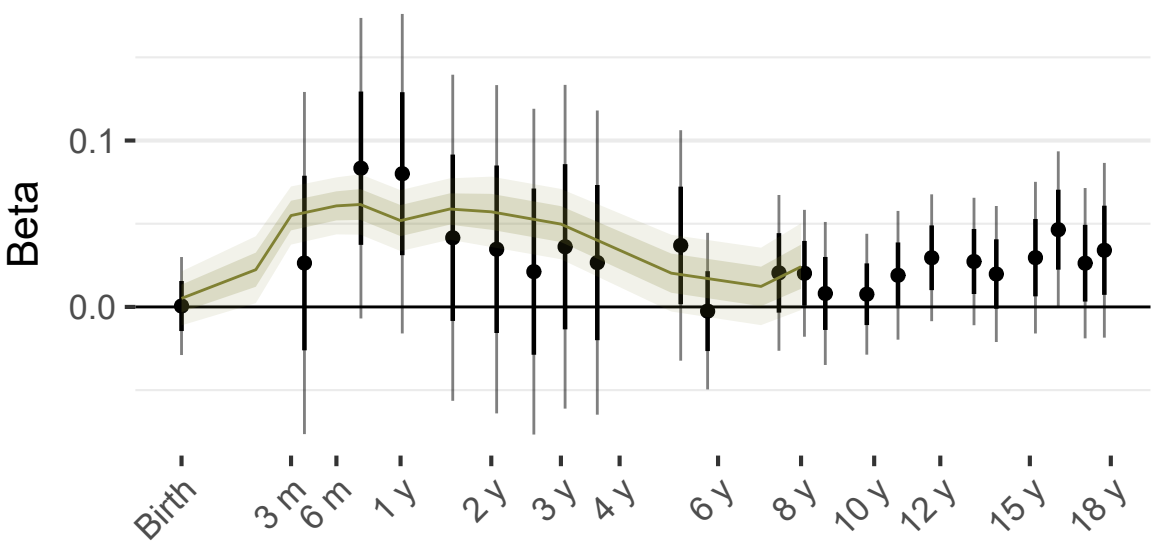
B


Alspac
MoBa

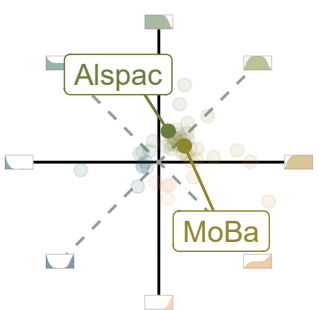

Beta
0.4
0.3
0.2
0.1
0.0
Birth
3 m
6 m
1 y
2 y
3 y
4 y
6 y
8 y
10 y
12 y
15 y
18 y

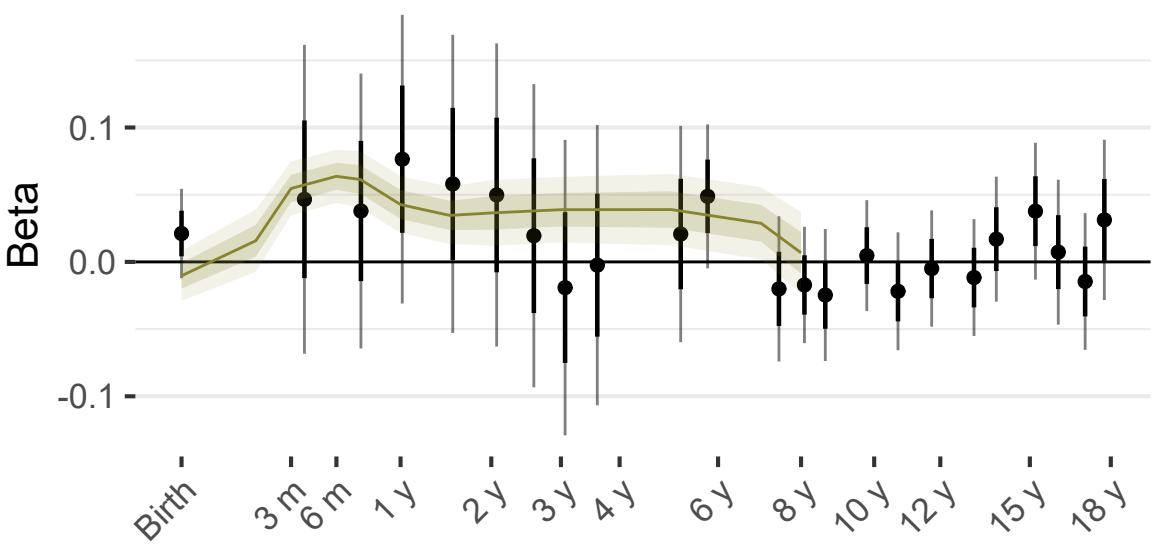
C


MoBa
Alspac

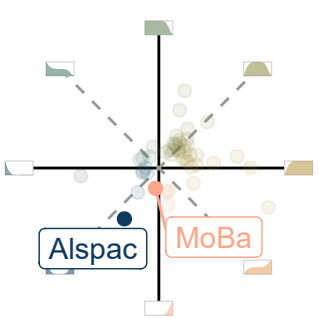

Beta
0.1
0.0
Birth
3 m
6 m
1 y
2 y
3 y
4 y
6 y
8 y
10 y
12 y
15 y
18 y

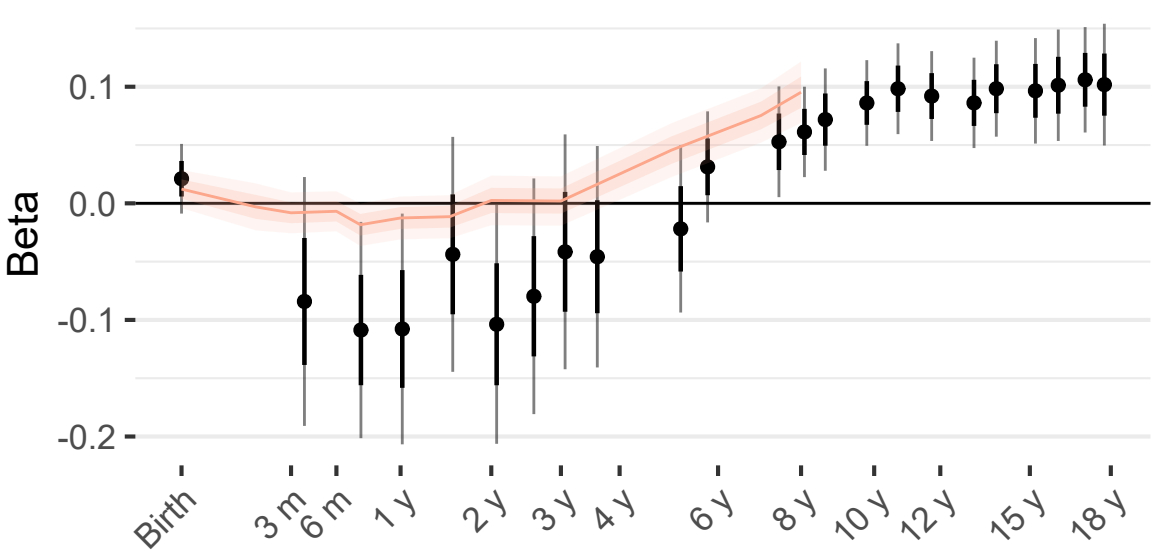
D


Alspac
MoBa

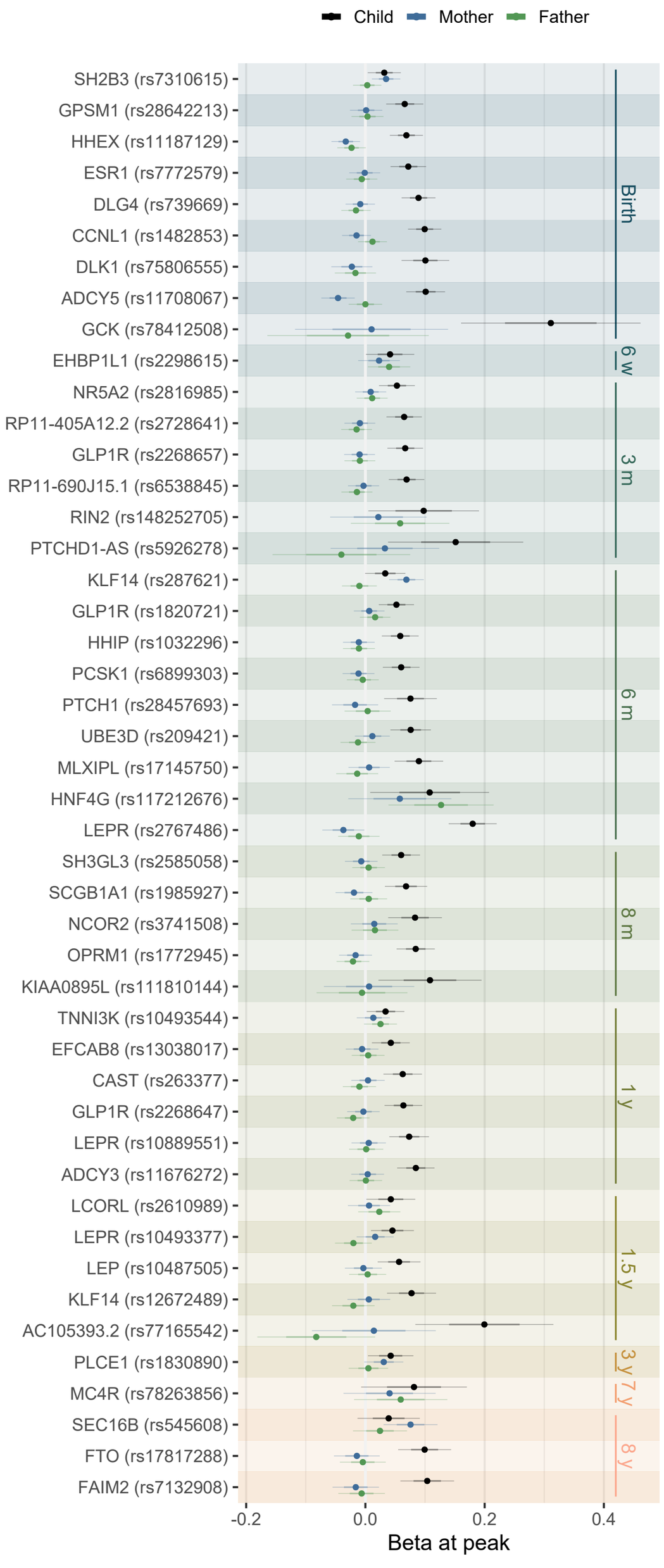

Beta
0.1
0.0
-0.1
Birth
3 m
6 m
1 y
2 y
3 y
4 y
6 y
8 y
10 y
12 y
15 y
18 y

E

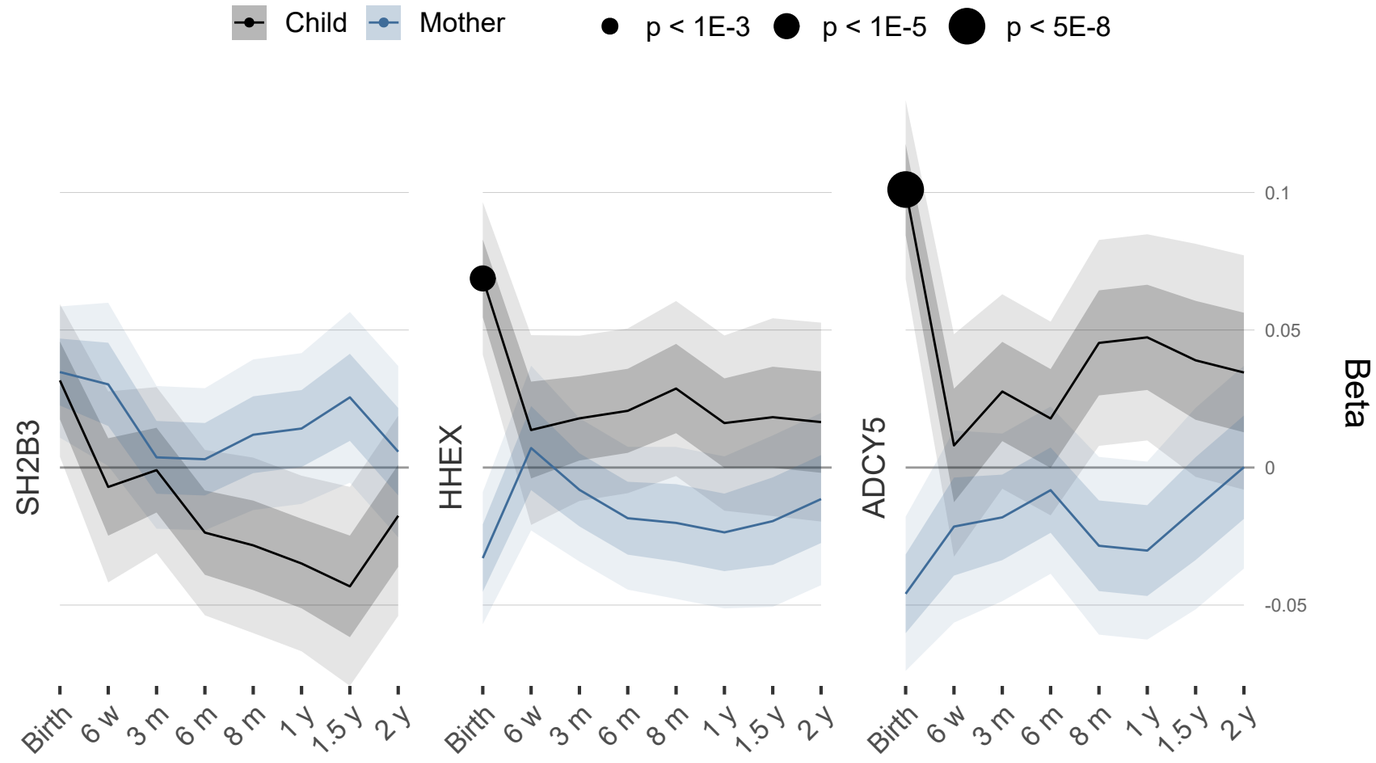

Alspac
MoBa


Beta
0.1
0.0
-0.1
-0.2
Birth
3 m
6 m
1 y
2 y
3 y
4 y
6 y
8 y
10 y
12 y
15 y
18 y

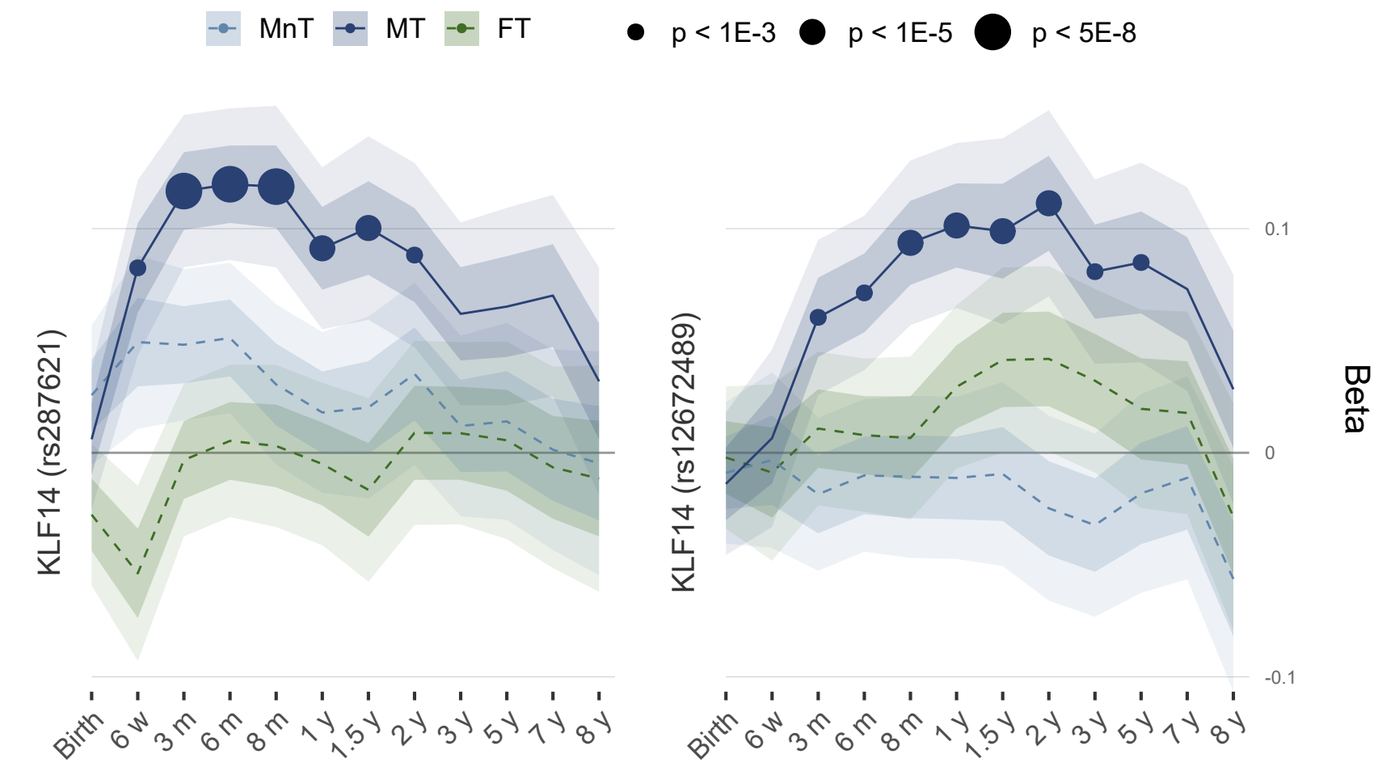
A


Child
Mother
Father
SH2B3 (rs7310615)
GPSM1 (rs28642213)
HHEX (rs11187129)
ESR1 (rs7772579)
DLG4 (rs739669)
CCNL1 (rs1482853)
DLK1 (rs75806555)
ADCY5 (rs11708067)
GCK (rs78412508)
EHBP1L1 (rs2298615)
NR5A2 (rs2816985)
RP11-405A12.2 (rs2728641)
GLP1R (rs2268657)
RP11-690J15.1 (rs6538845)
RIN2 (rs148252705)
PTCHD1-AS (rs5926278)
KLF14 (rs287621)
GLP1R (rs1820721)
HHIP (rs1032296)
PCSK1 (rs6899303)
PTCH1 (rs28457693)
UBE3D (rs209421)
MLXIPL (rs17145750)
HNF4G (rs117212676)
LEPR (rs2767486)
SH3GL3 (rs2585058)
SCGB1A1 (rs1985927)
NCOR2 (rs3741508)
OPRM1 (rs1772945)
KIAA0895L (rs111810144)
TNNI3K (rs10493544)
EFCAB8 (rs13038017)
CAST (rs263377)
GLP1R (rs2268647)
LEPR (rs10889551)
ADCY3 (rs11676272)
LCORL (rs2610989)
LEPR (rs10493377)
LEP (rs10487505)
KLF14 (rs12672489)
AC105393.2 (rs77165542)
PLCE1 (rs1830890)
MC4R (rs78263856)
SEC16B (rs545608)
FTO (rs17817288)
FAIM2 (rs7132908)
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
3 y
7 y
8 y
-0.2
0.0
0.2
0.4
Beta at peak

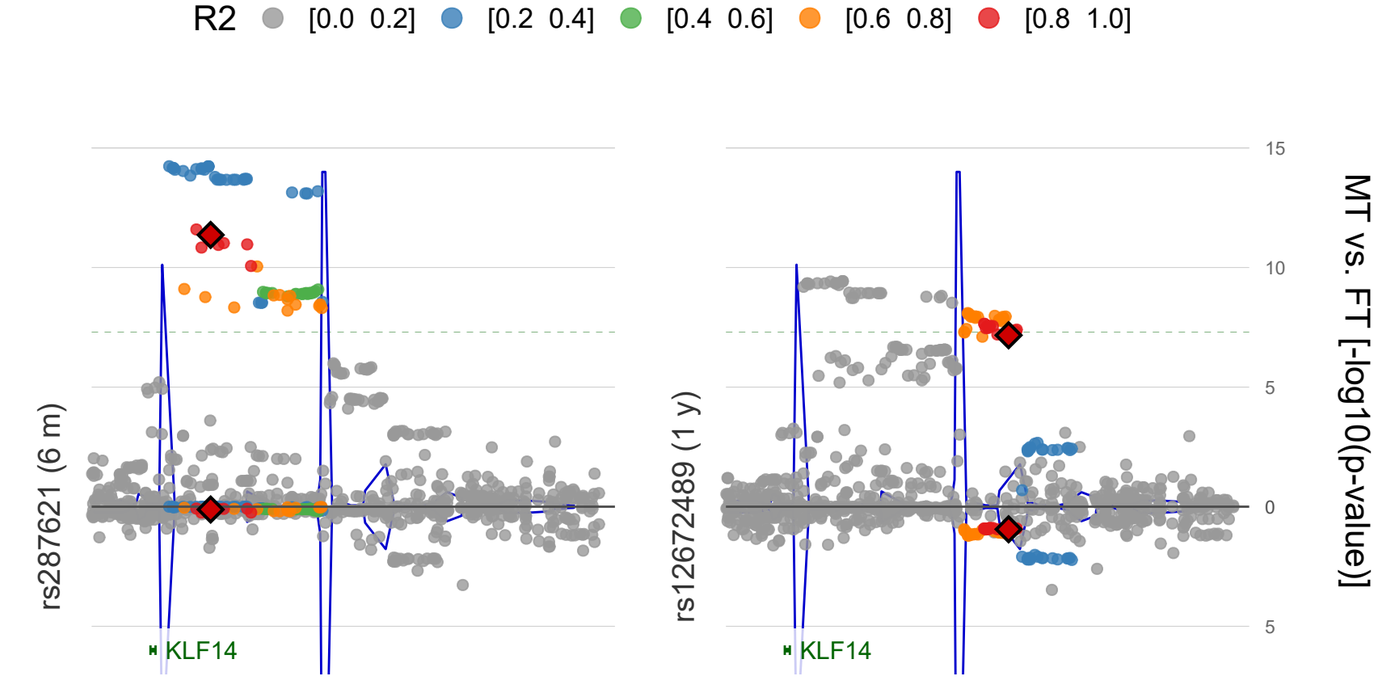
B


Child
Mother
p < 1E-3
p < 1E-5
p < 5E-8
SH2B3
HHEX
ADCY5
0.1
0.05
0
-0.05
Beta
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y

C


MnT
MT
FT
p < 1E-3
p < 1E-5
p < 5E-8
KLF14 (rs287621)
KLF14 (rs12672489)
0.1
0
-0.1
Beta
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

D


R2
[0.0 0.2]
[0.2 0.4]
[0.4 0.6]
[0.6 0.8]
[0.8 1.0]
rs287621 (6 m)
rs12672489 (1 y)
KLF14
15
10
5
0
5
MT vs. FT [-log10(p-value)]

A

Birth Weight (Warrington et al.)

C

Birth 6 w 3 m 6 m 8 m 1 y 1.5 y 2 y 3 y 5 y 7 y 8 y

Relative Risk

2 1 0.5

BMI

0.4 0.2 0 -0.2 -0.4

B

Adult BMI (Yengo et al.)

D

Birth 6 w 3 m 6 m 8 m 1 y 1.5 y 2 y 3 y 5 y 7 y 8 y

Relative Risk

2 1 0.5

BMI

0.4 0.2 0 -0.2 -0.4

C

Birth Weight (Warrington et al.)

PRS Density

Relative Risk [Birth]

2 1 0.5

2% 3% 3% 4% 4% 5% 5% 6% 6% 8%

BMI [Birth]

0.4 0.2 0 -0.2 -0.4

D

Adult BMI (Yengo et al.)

PRS Density

Relative Risk [8 y]

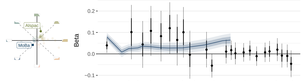
2 1 0.5

2% 2% 3% 4% 5% 6% 6% 8% 10% 13%

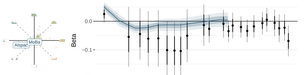
BMI [8 y]

0.4 0.2 0 -0.2 -0.4

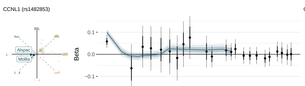
ADCY5 (rs11706067)



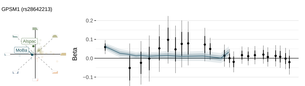
SH2B3 (rs7310615)



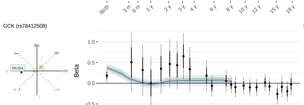
CCNL1 (rs1482853)



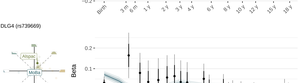
GPSM1 (rs28642213)



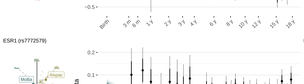
GCK (rs78412508)



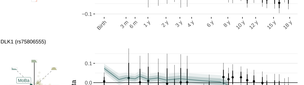
DLG4 (rs739669)



ESR1 (rs7772579)



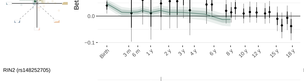
DLK1 (rs75806555)



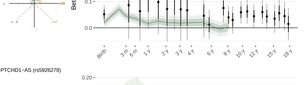
HHEX (rs11187129)

EHBP1L1 (rs2298615)

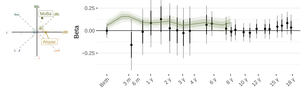
RIN2 (rs148252705)



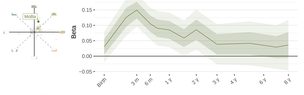
PTCHD1-AS (rs5926278)



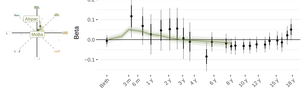
RP11-405A12.2 (rs2728641)



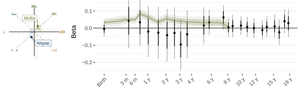
NCOR2 (rs3741508)



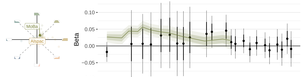
OPRM1 (rs1772945)



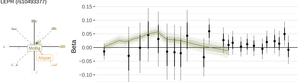
LEPR (rs10493377)



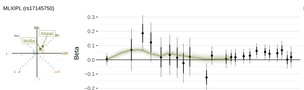
MLXIPL (rs17145750)



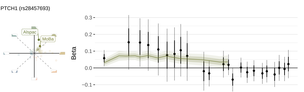
PTCH1 (rs28457693)



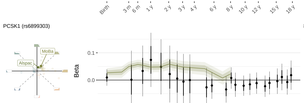
PCSK1 (rs6899303)



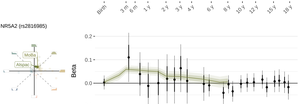
NR5A2 (rs2816985)



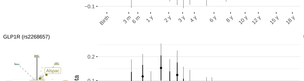
GLP1R (rs2268657)



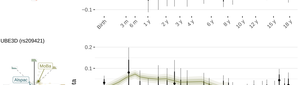
UBE3D (rs209421)



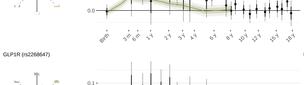
GLP1R (rs2268647)



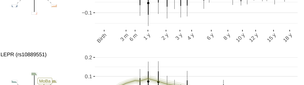
LEPR (rs10889551)



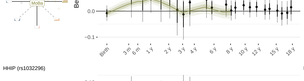
HHIP (rs1032296)



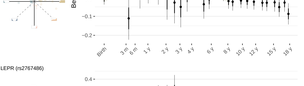
LEPR (rs2767486)



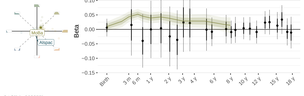
CAST (rs263377)



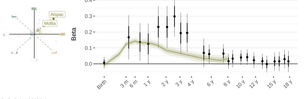
GLP1R (rs1820721)



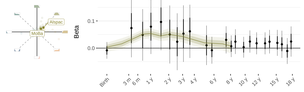
SH3GL3 (rs2585058)



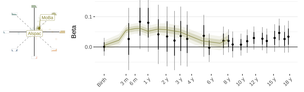
KLF14 (rs287621)



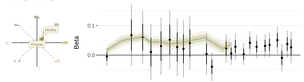
KLF14 (rs12672489)



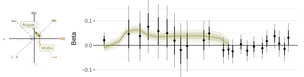
EFCAB8 (rs13038017)



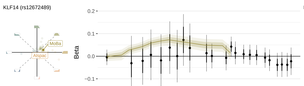
SCGB1A1 (rs1985927)



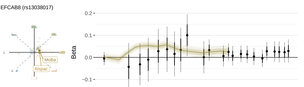
LCORL (rs2610989)



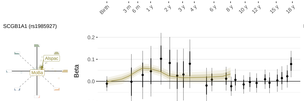
RP11-690J15.1 (rs6538845)



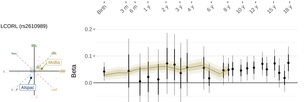
KIAA0895L (rs111810144)



ADCY3 (rs11676272)

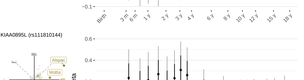


PLCE1 (rs1830890)



LEP (rs10487505)

HNF4G (rs117212676)



AC105393.2 (rs7165542)

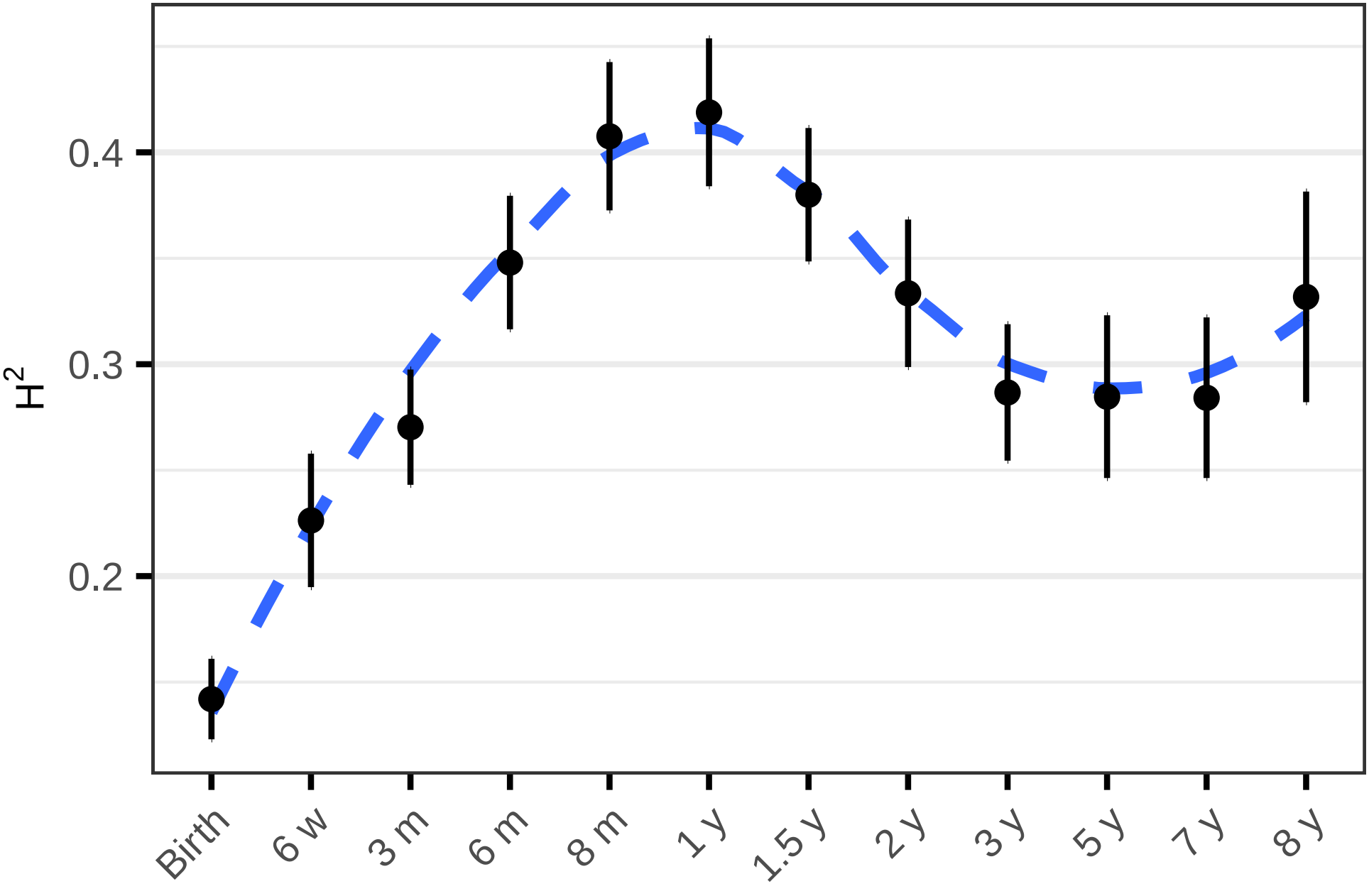
TNNI3K (rs10493544)

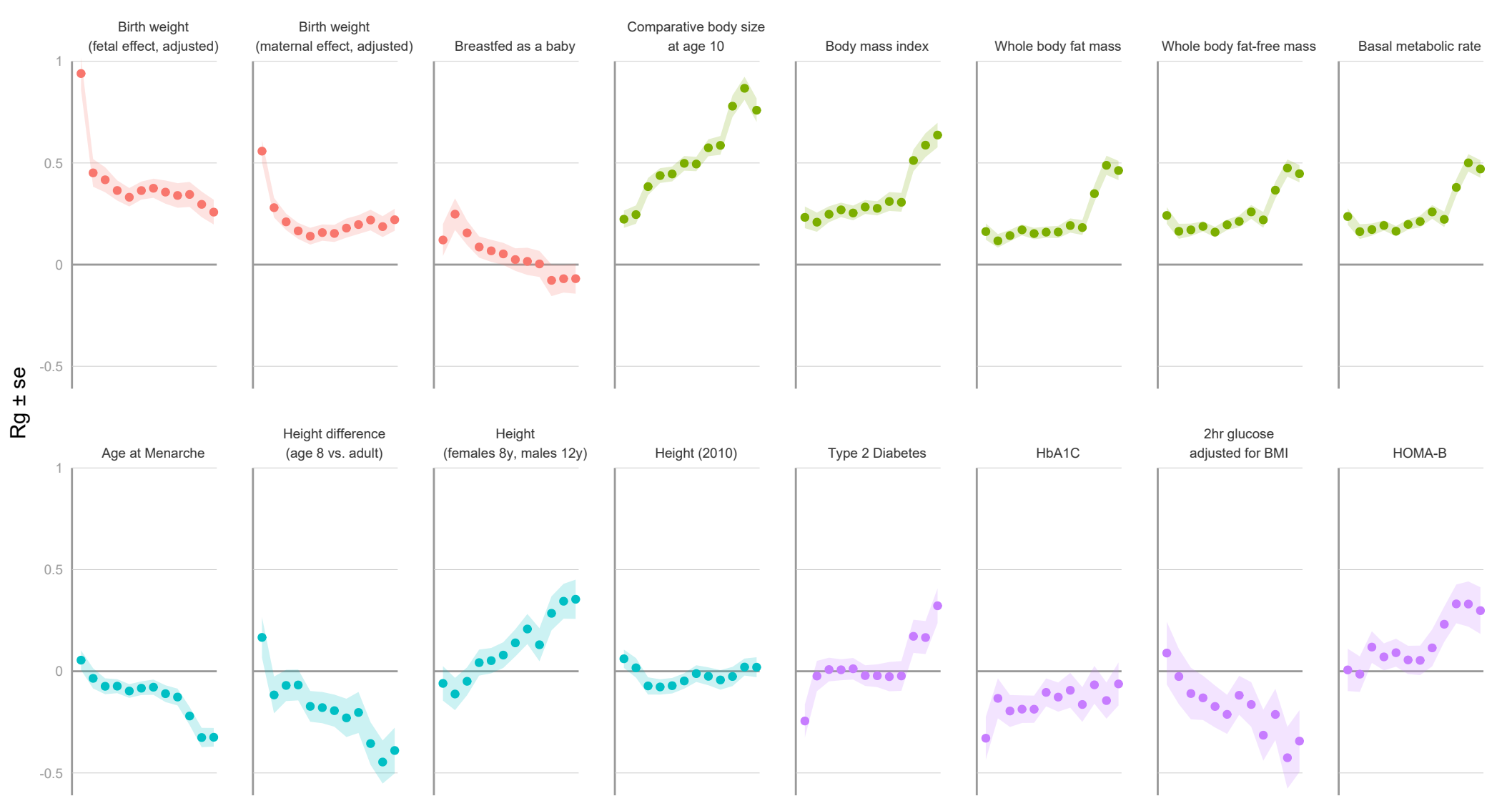
FAIM2 (rs7132908)

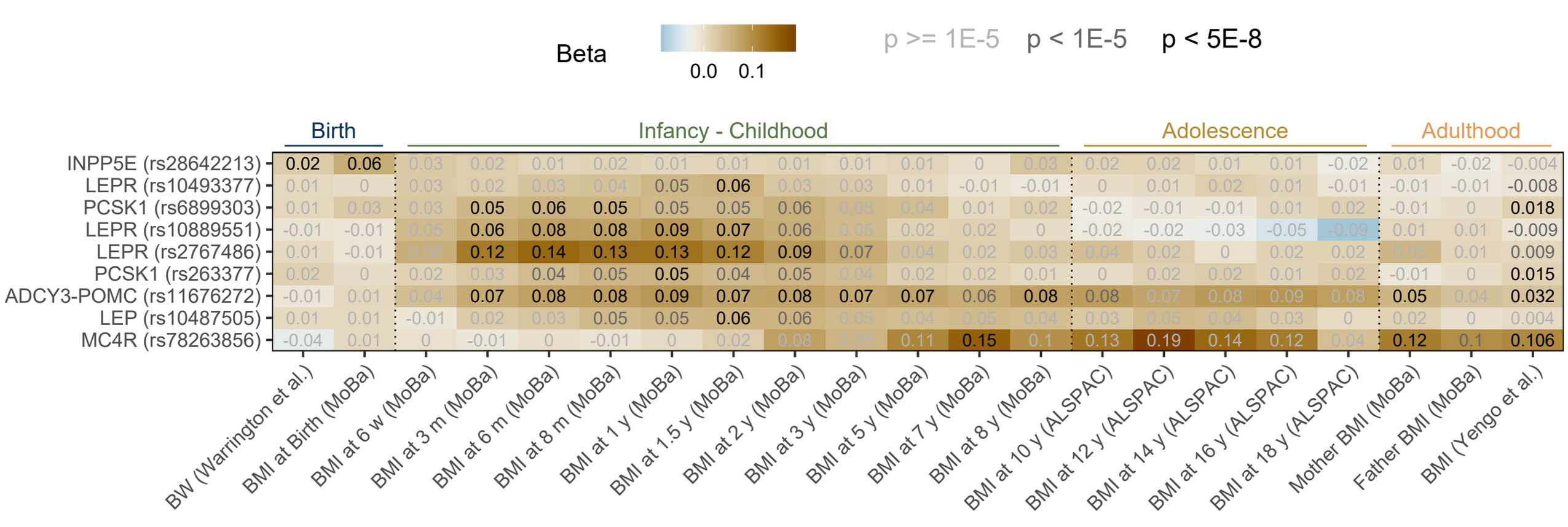
SEC16B (rs545608)

MC4R (rs78263856)

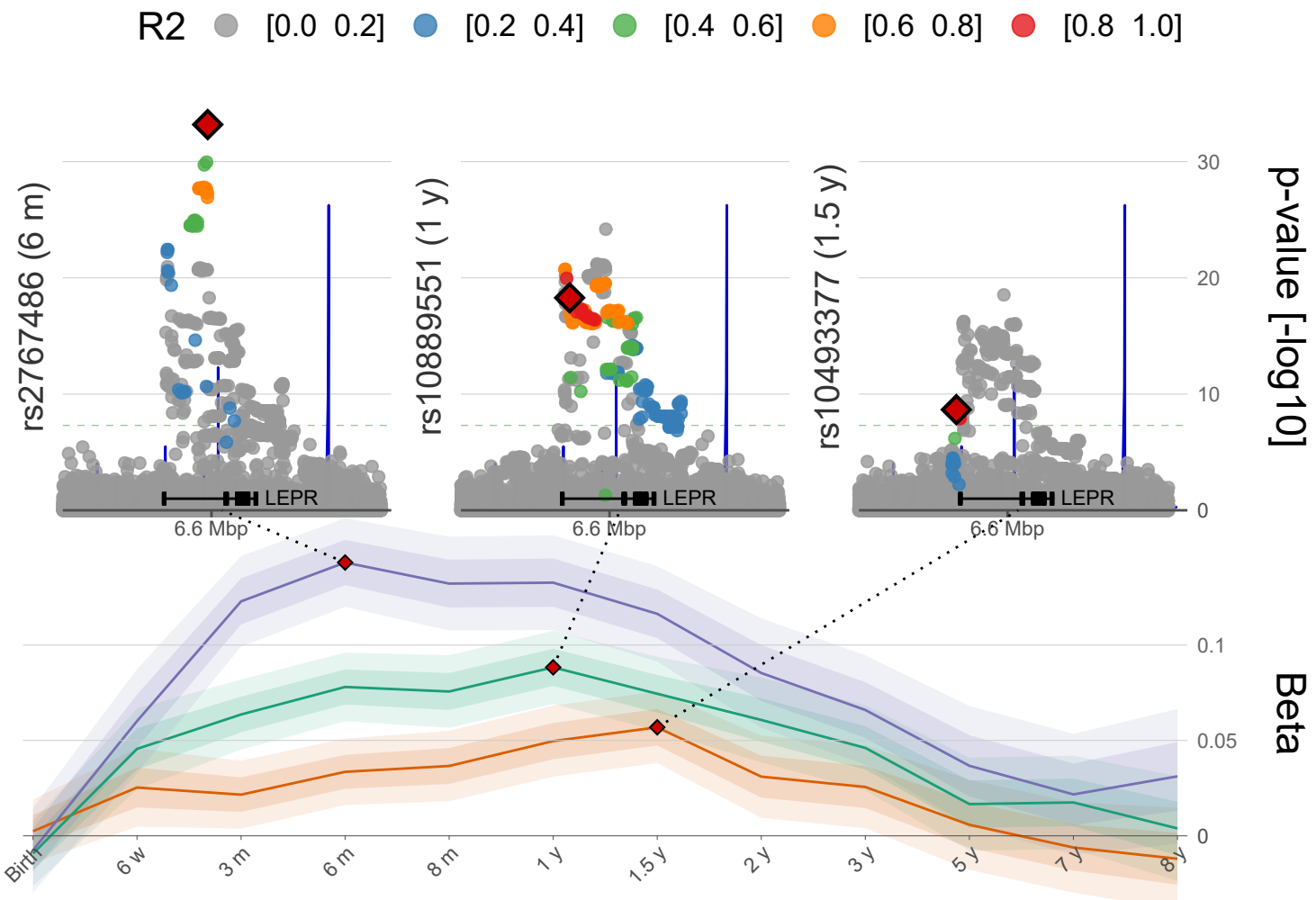
FTO (rs17817288)


0.4
0.3
0.2
H^2
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

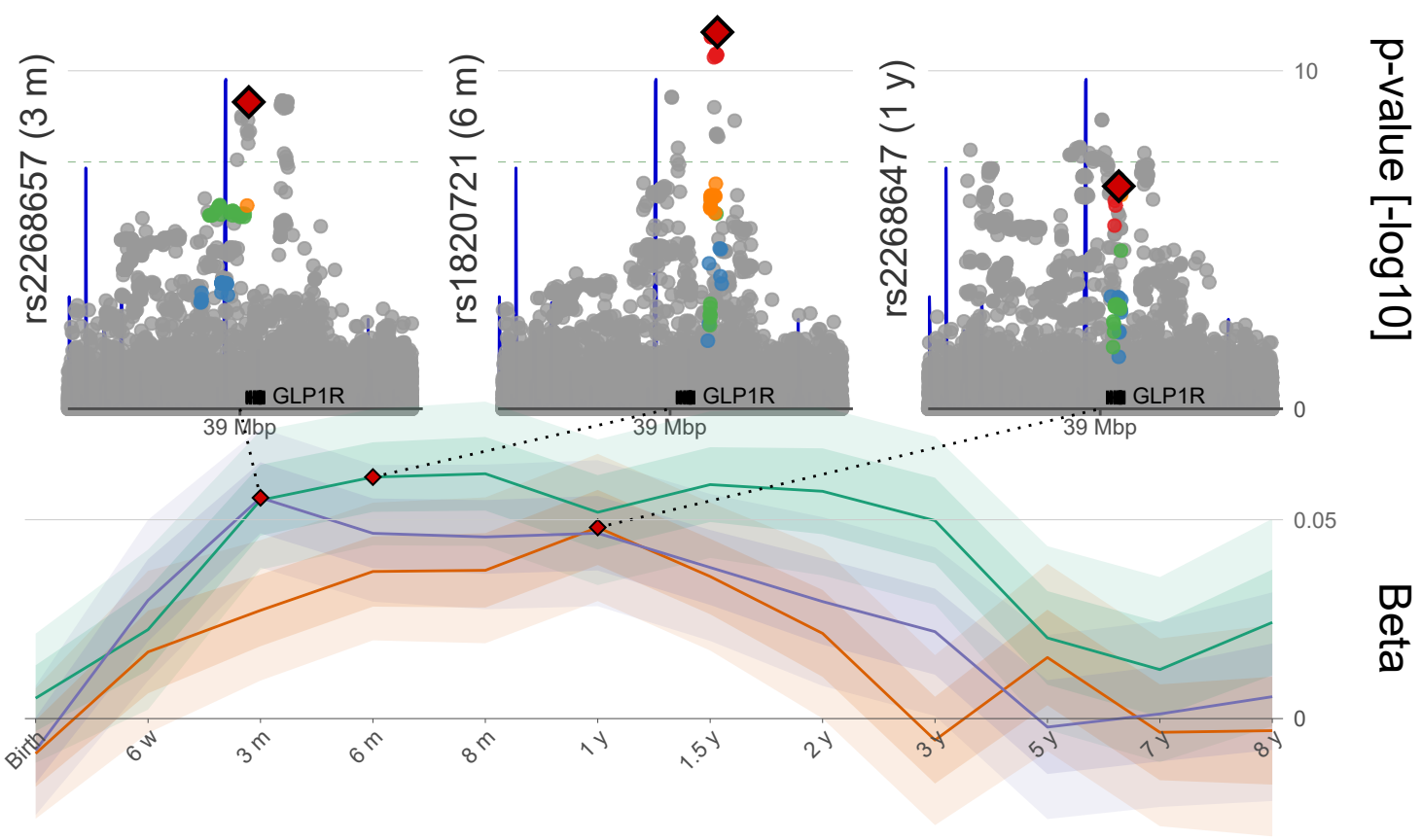

Birth weight
(fetal effect, adjusted)
Birth weight
(maternal effect, adjusted)
Breastfed as a baby
Comparative body size
at age 10
Body mass index
Whole body fat mass
Whole body fat-free mass
Basal metabolic rate
Age at Menarche
Height difference
(age 8 vs. adult)
Height
(females 8y, males 12y)
Height (2010)
Type 2 Diabetes
HbA1C
2hr glucose
adjusted for BMI
HOMA-B
Rg ± se
1
0.5
0
-0.5


Beta
0.0
0.1
p >= 1E-5
p < 1E-5
p < 5E-8
Birth
Infancy - Childhood
Adolescence
Adulthood
INPP5E (rs28642213) 0.02 0.06 0.03 0.02 0.01 0.02 0.01 0.01 0.01 0.01 0.01 0 0.03 0.02 0.02 0.01 0.01 -0.02 0.01 -0.02 -0.004
LEPR (rs10493377) 0.01 0 0.03 0.02 0.03 0.04 0.05 0.06 0.03 0.03 0.01 -0.01 -0.01 0 0.01 0.02 0.01 -0.01 -0.01 -0.01 -0.008
PCSK1 (rs6899303) 0.01 0.03 0.03 0.05 0.06 0.05 0.05 0.05 0.06 0.05 0.04 0.01 0.02 -0.02 -0.01 -0.01 0.01 0.02 -0.01 0 0.018
LEPR (rs10889551) -0.01 -0.01 0.05 0.06 0.08 0.08 0.09 0.07 0.06 0.05 0.02 0.02 0 -0.02 -0.02 -0.03 -0.05 -0.09 0.01 0.01 -0.009
LEPR (rs2767486) 0.01 -0.01 0.06 0.12 0.14 0.13 0.13 0.12 0.09 0.07 0.04 0.02 0.03 0.04 0.02 0 0.02 0.02 0.05 0.01 0.009
PCSK1 (rs263377) 0.02 0 0.02 0.03 0.04 0.05 0.05 0.04 0.05 0.04 0.02 0.02 0.01 0 0.02 0.02 0.01 0.02 -0.01 0 0.015
ADCY3-POMC (rs11676272) -0.01 0.01 0.04 0.07 0.08 0.08 0.09 0.07 0.08 0.07 0.07 0.06 0.08 0.08 0.07 0.08 0.09 0.08 0.05 0.04 0.032
LEP (rs10487505) 0.01 0.01 -0.01 0.02 0.03 0.05 0.05 0.06 0.06 0.05 0.04 0.05 0.04 0.03 0.05 0.04 0.03 0 0.02 0 0.004
MC4R (rs78263856) -0.04 0.01 0 -0.01 0 -0.01 0 0.02 0.08 0.05 0.11 0.15 0.1 0.13 0.19 0.14 0.12 0.04 0.12 0.1 0.106
BW (Warrington et al.)
BMI at Birth (MoBa)
BMI at 6 w (MoBa)
BMI at 3 m (MoBa)
BMI at 6 m (MoBa)
BMI at 8 m (MoBa)
BMI at 1 y (MoBa)
BMI at 1.5 y (MoBa)
BMI at 2 y (MoBa)
BMI at 3 y (MoBa)
BMI at 5 y (MoBa)
BMI at 7 y (MoBa)
BMI at 8 y (MoBa)
BMI at 10 y (ALSPAC)
BMI at 12 y (ALSPAC)
BMI at 14 y (ALSPAC)
BMI at 16 y (ALSPAC)
BMI at 18 y (ALSPAC)
Mother BMI (MoBa)
Father BMI (MoBa)
BMI (Yengo et al.)

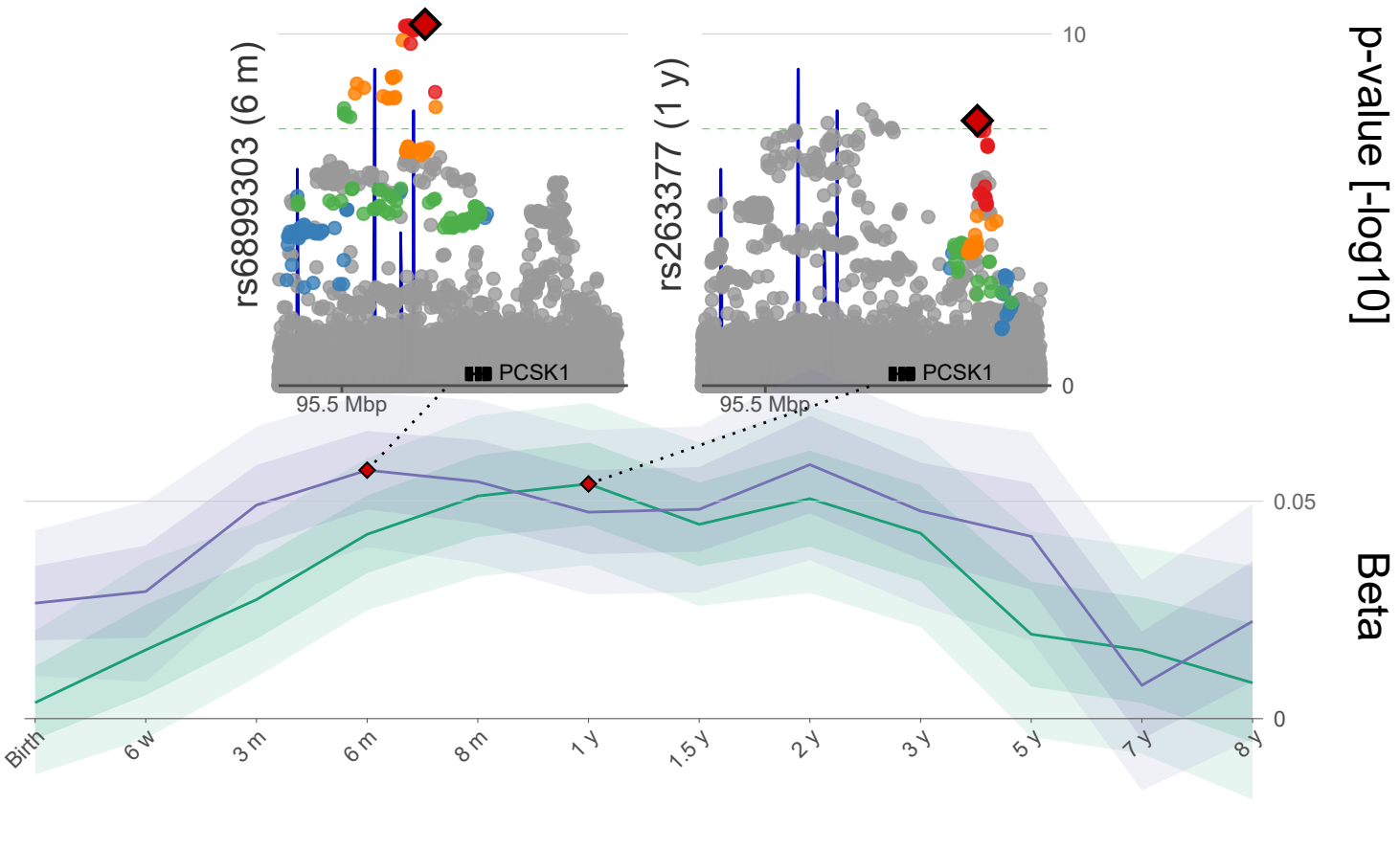
A


R2
[0.0 0.2]
[0.2 0.4]
[0.4 0.6]
[0.6 0.8]
[0.8 1.0]
rs2767486 (6 m)
rs10889551 (1 y)
rs10493377 (1.5 y)
LEPR
6.6 Mbp
30
20
10
0
p-value [-log10]
0.1
0.05
0
Beta
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

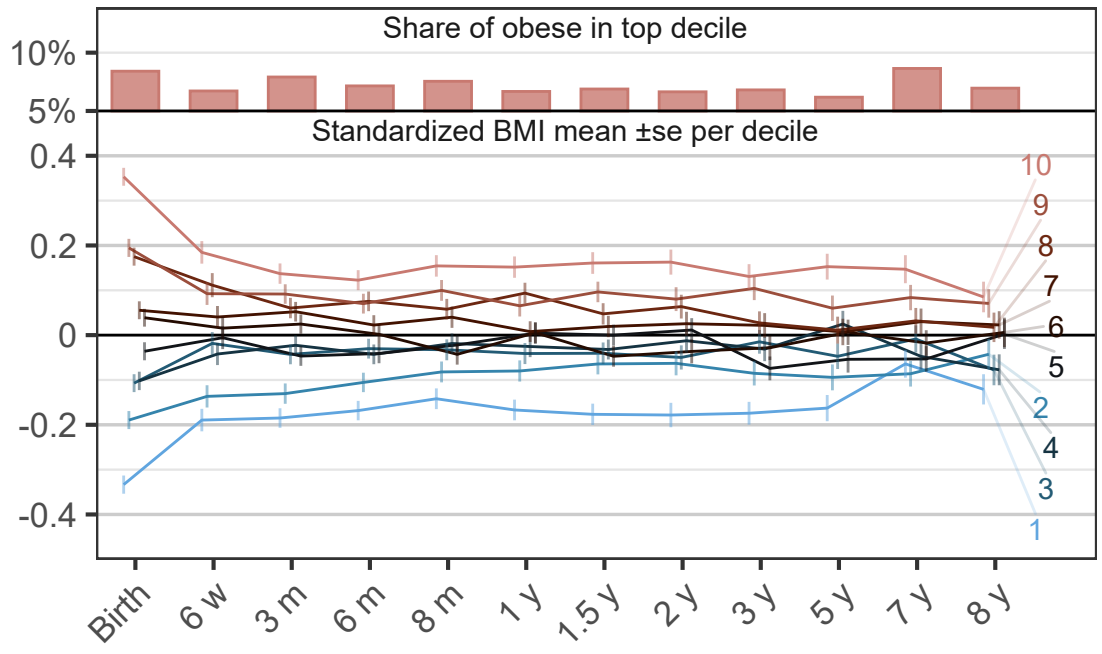
B


rs2268657 (3 m)
rs1820721 (6 m)
rs2268647 (1 y)
GLP1R
39 Mbp
10
0
p-value [-log10]
0.05
0
Beta
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

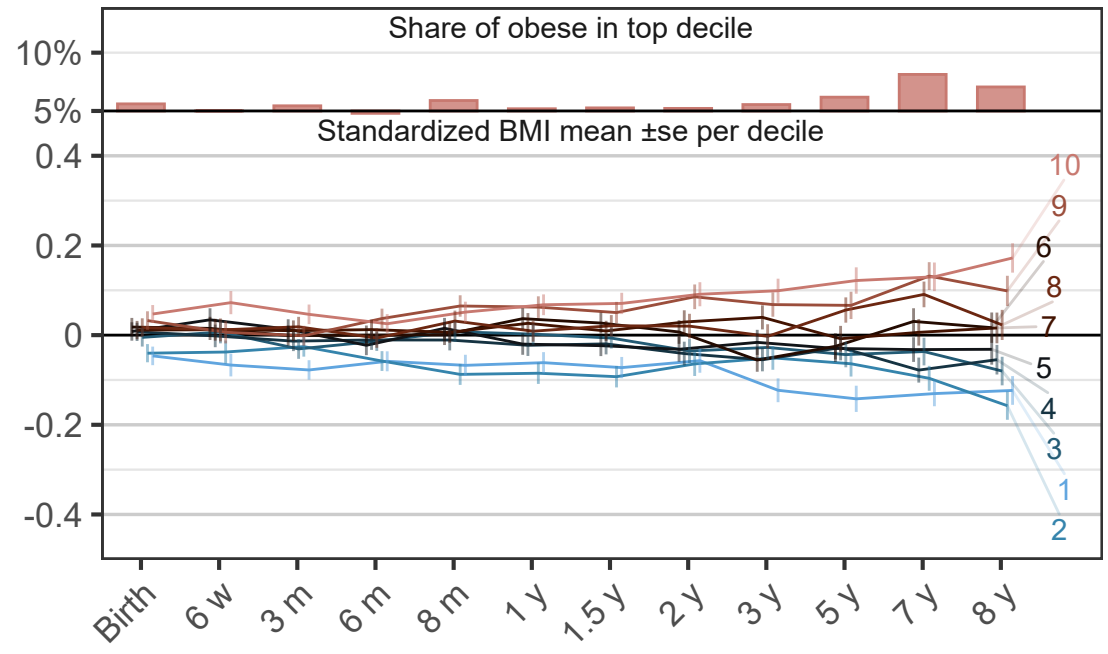
C


rs6899303 (6 m)
rs263377 (1 y)
PCSK1
95.5 Mbp
10
0
p-value [-log10]
0.05
0
Beta
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

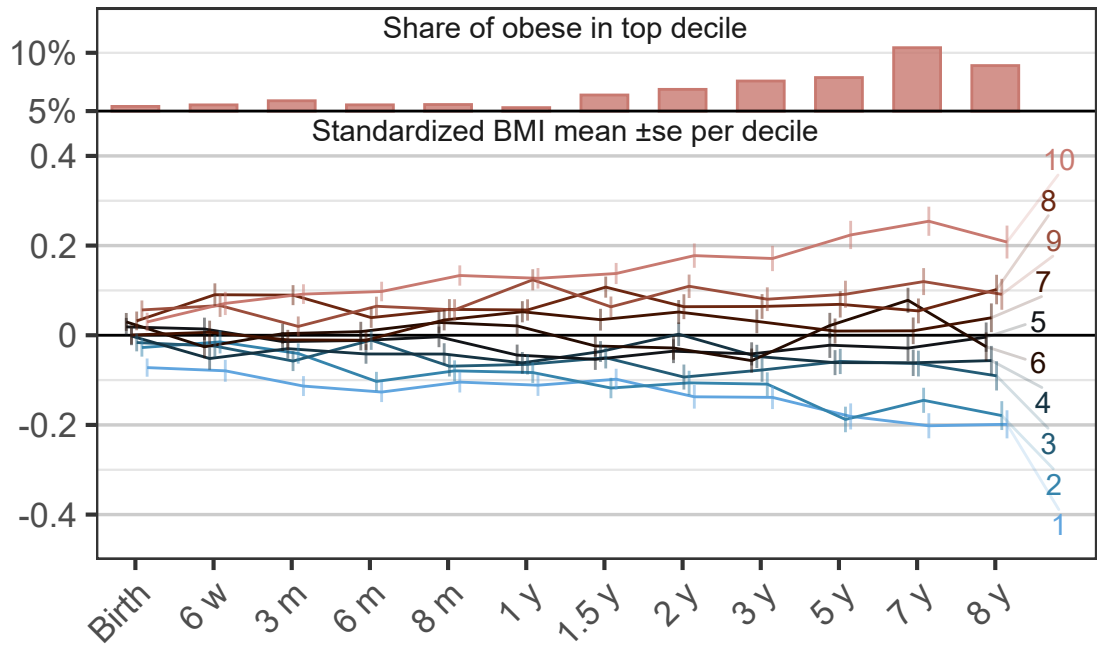
A


Birth Weight
Share of obese in top decile
10%
5%
Standardized BMI mean ±se per decile
0.4
0.2
0
-0.2
-0.4
10
9
8
7
6
5
2
4
3
1
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

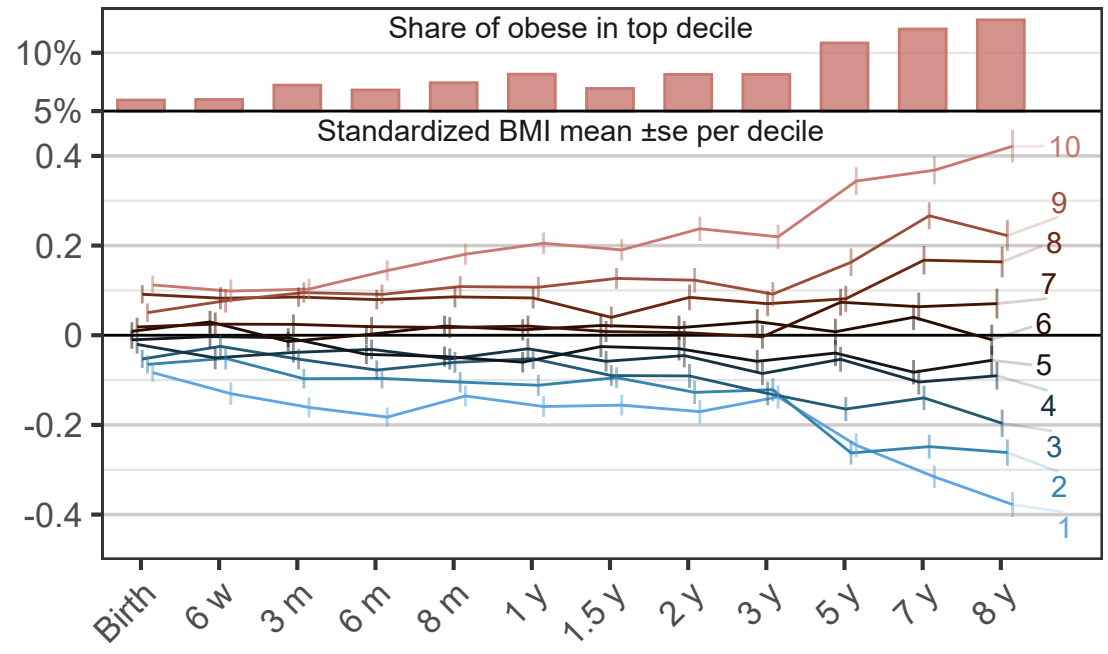
B


Childhood Obesity
Share of obese in top decile
10%
5%
Standardized BMI mean ±se per decile
0.4
0.2
0
-0.2
-0.4
10
9
6
8
7
5
4
3
1
2
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

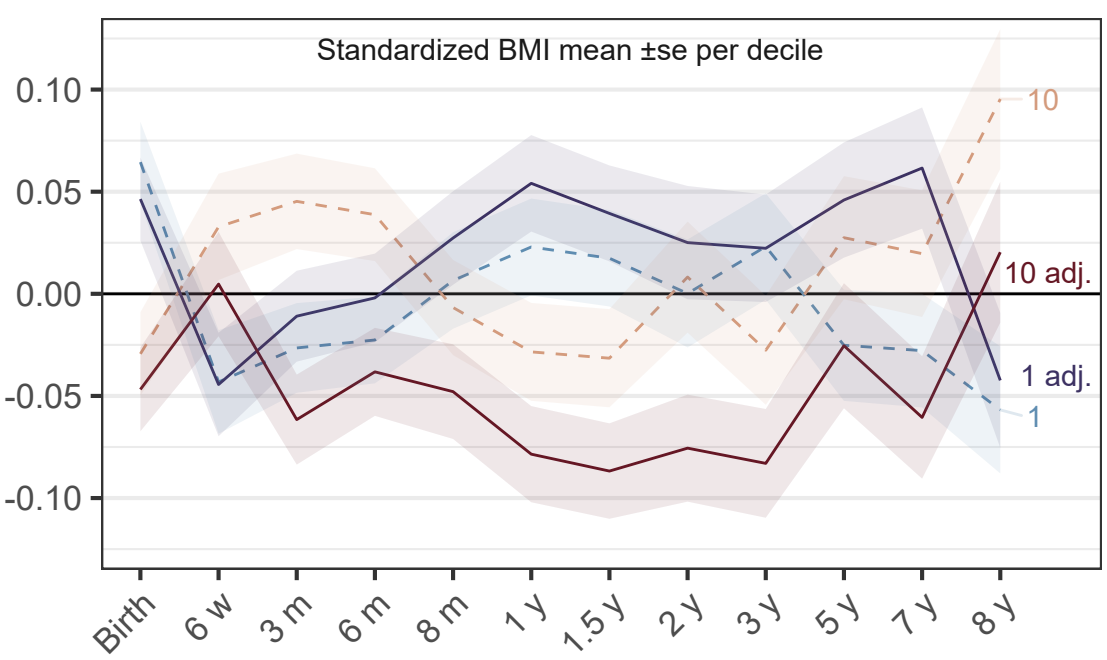
C


Childhood BMI
Share of obese in top decile
10%
5%
Standardized BMI mean ±se per decile
0.4
0.2
0
-0.2
-0.4
10
8
9
7
5
6
4
3
2
1
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

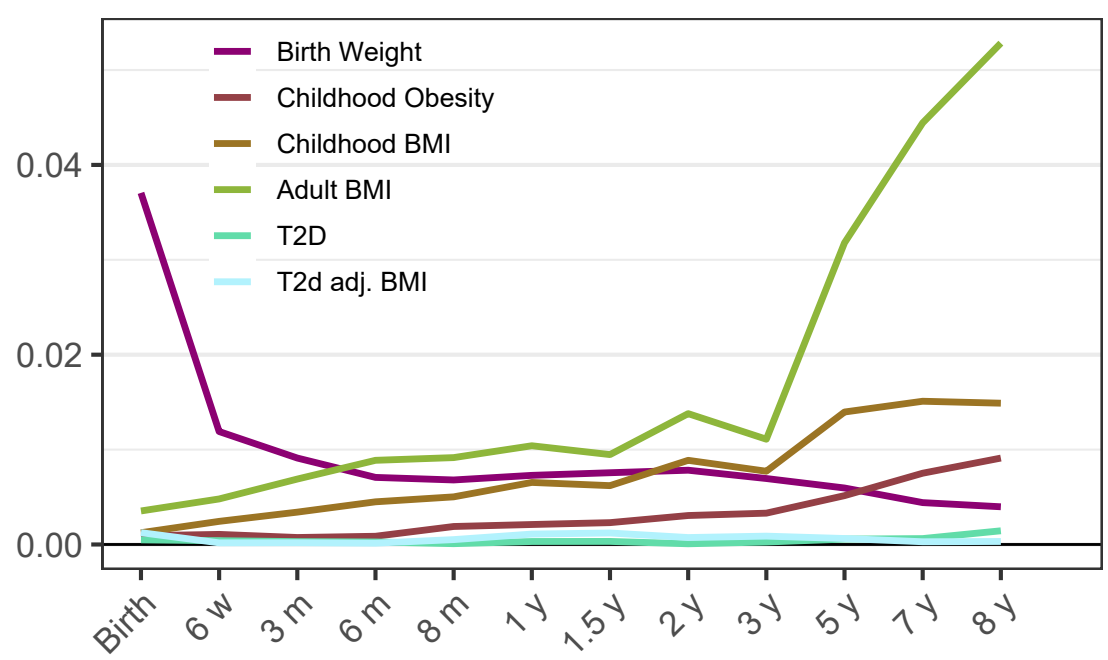
D


Adult BMI
Share of obese in top decile
10%
5%
Standardized BMI mean ±se per decile
0.4
0.2
0
-0.2
-0.4
10
9
8
7
6
5
4
3
2
1
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

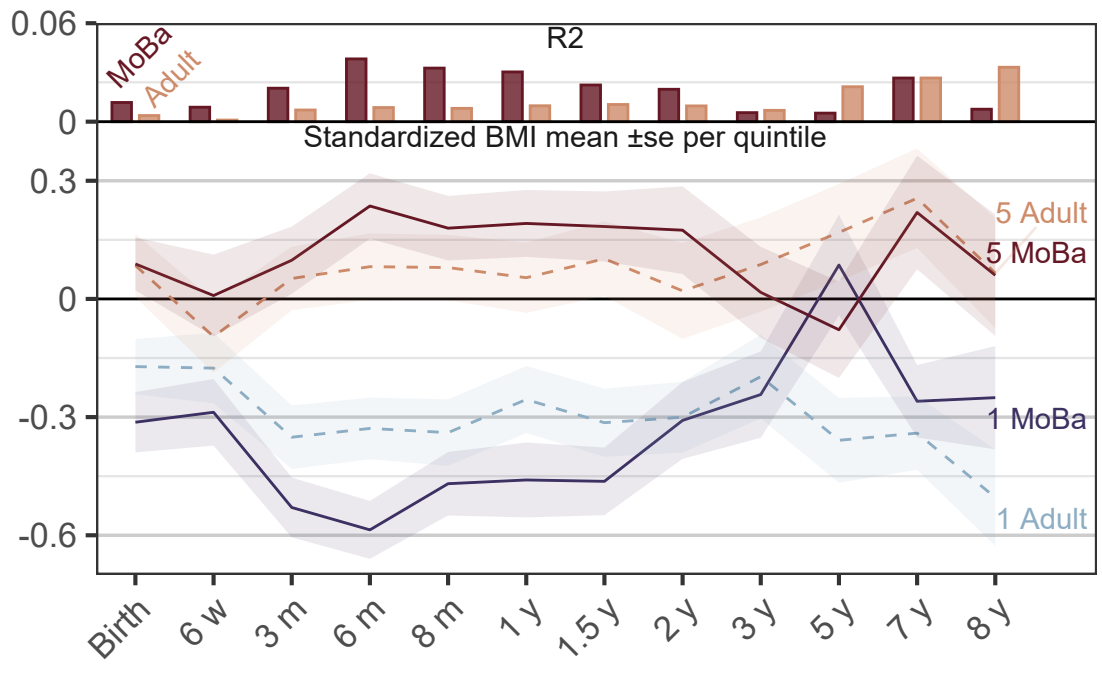
E


T2D and T2D adjusted for BMI
Standardized BMI mean ±se per decile
0.10
0.05
0.00
-0.05
-0.10
10
10 adj.
1 adj.
1
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

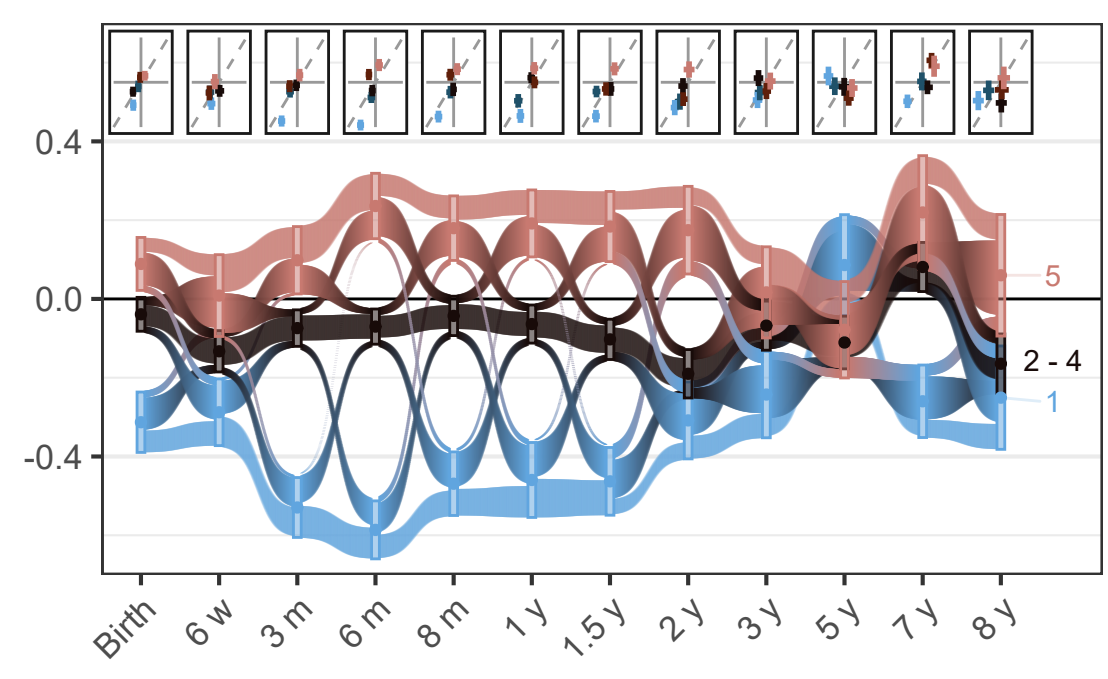
F

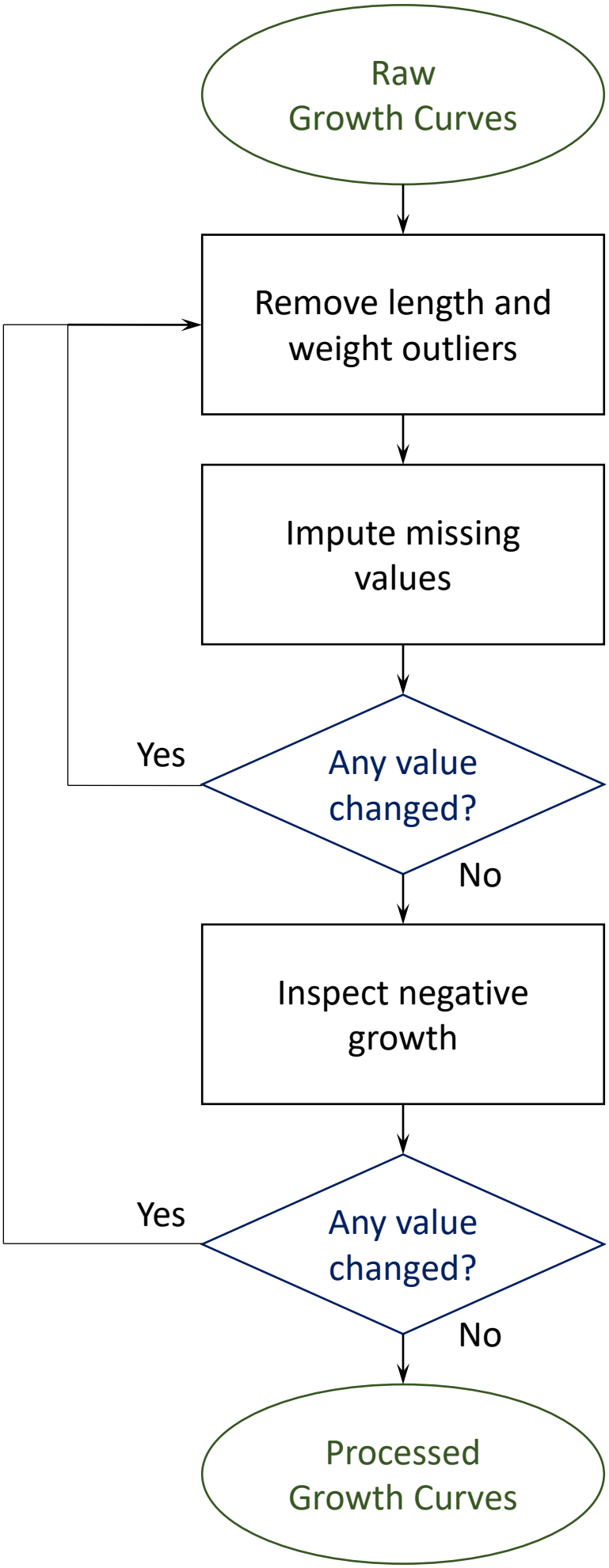

R2
Birth Weight
Childhood Obesity
Childhood BMI
Adult BMI
T2D
T2d adj. BMI
0.04
0.02
0.00
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

G


Time-resolved MoBa BMI vs. Adult BMI
0.06
0
MoBa
Adult
R2
Standardized BMI mean ±se per quintile
0.3
0
-0.3
-0.6
5 Adult
5 MoBa
1 MoBa
1 Adult
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y

H


Time-resolved MoBa BMI
0.4
0.0
-0.4
5
2 - 4
1
Birth
6 w
3 m
6 m
8 m
1 y
1.5 y
2 y
3 y
5 y
7 y
8 y


Raw
Growth Curves
Remove length and
weight outliers
Impute missing
values
Any value
changed?
Yes
No
Inspect negative
growth
Any value
changed?
Yes
No
Processed
Growth Curves