

ACT–Planck data and phase transitions from a viable no-scale Standard Model completion

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Motivation

We look for a completion of the SM that is **classically scale invariant** (CSI): no mass parameter appears in the Lagrangian, and all scales are generated by dimensional transmutation.

- ▶ In these theories symmetry breaking is *radiative*, and this **always** gives a *first-order* phase transition¹ — which releases **gravitational waves**.
- ▶ Observing them would be a clean signal of new physics: *the SM predicts no such transition*.
- ▶ But a first-order PT forces us to build a cosmology around it. In the literature this is called a **“rollercoaster cosmology”**²: inflation happens in two stages, separated by a radiation-dominated era.

What the model predicts

inflationary observables (n_s , r) and **gravitational-wave observables** — from the *same* parameters.

There are particle-physics predictions too, but at energies well beyond collider reach.

¹ E. Witten, Nucl. Phys. B **177** (1981) 477.

² G. D’Amico and N. Kaloper, arXiv:2011.09489.

Radiative symmetry breaking: the model-independent picture

Scale invariance forbids every mass term, so the classical potential is **purely quartic**:

$$V_{\text{cl}}(\varphi) = \frac{1}{4!} \lambda_{abcd} \varphi_a \varphi_b \varphi_c \varphi_d, \quad V_{\text{tot}}(\varphi, T) = \underbrace{V_{\text{cl}}(\varphi)}_{\text{tree}} + \underbrace{V_q(\varphi)}_{\text{one loop, } T=0} + \underbrace{V_T(\varphi, T)}_{\text{thermal}}.$$

At some scale $\tilde{\mu}$ a *flat direction* appears: along $\varphi_a = n_a \chi$ one has $V_{\text{cl}} = \frac{1}{4} \lambda_\chi \chi^4$ with $\lambda_\chi(\tilde{\mu}) = 0$. There the tree-level term vanishes, the one-loop term takes over and generates the minimum:³

$$\boxed{V_q(\chi) = \frac{\bar{\beta}}{4} \left[\log \frac{\chi}{\chi_0} - \frac{1}{4} \right] \chi^4} \quad \langle \chi \rangle = \chi_0, \quad m_\chi = \sqrt{\bar{\beta}} \chi_0, \quad V_0 \equiv \frac{\bar{\beta} \chi_0^4}{16},$$

where $\bar{\beta} > 0$ is the beta function of the quartic that vanishes at $\tilde{\mu}$.

³ S. R. Coleman and E. J. Weinberg, Phys. Rev. D **7** (1973) 1888; E. Gildener and S. Weinberg, Phys. Rev. D **13** (1976) 3333.

Finite temperature: the thermal potential and ϵ

The plasma contributes, bosons and fermions through their own thermal functions:

$$V_T(\chi, T) = \frac{T^4}{2\pi^2} \left[\sum_B n_B J_B \left(\frac{m_B^2(\chi)}{T^2} \right) + \sum_F n_F J_F \left(\frac{m_F^2(\chi)}{T^2} \right) \right]$$

Expanding them, the potential of the **improved supercool expansion**⁴ is

$$\bar{V}_{\text{eff}}(\chi, T) \simeq \frac{m^2(T)}{2} \chi^2 - \frac{k(T)}{3} \chi^3 - \frac{\lambda(T)}{4} \chi^4$$

$$m^2(T) = \frac{g^2 T^2}{12},$$

$$g^2 \equiv \sum_b n_b m_b^2(\chi)/\chi^2 + \sum_f m_f^2(\chi)/\chi^2,$$

$$k(T) = \frac{\tilde{g}^3 T}{4\pi},$$

$$\tilde{g}^3 \equiv \sum_b n_b m_b^3(\chi)/\chi^3,$$

$$\lambda(T) = \bar{\beta} X,$$

$$X \equiv \log \frac{\chi_0}{T},$$

$$\epsilon \equiv \frac{g^4}{6 \bar{\beta} X}$$

⁴ A. Salvio, arXiv:2602.20246.

A specific realisation: gauged $U(1)_{B-L}$

Beyond-SM field content: three right-handed neutrinos N_i (ν oscillations, dark matter, baryon asymmetry⁵) and one scalar A carrying lepton number, since scale invariance forbids explicit Majorana masses. The Abelian symmetry acting on A is gauged: anomaly freedom makes it $U(1)_{B-L}$.⁶

$$\begin{aligned}\mathcal{L}_{\text{matter}} = & \mathcal{L}_{\text{SM}}^{\text{ns}} + D_\mu A^\dagger D^\mu A + \bar{N}_j i \not{D} N_j - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} \\ & + \left[Y_{ij} L_i H N_j + \frac{1}{2} y_{ij} A N_i N_j + \text{h.c.} \right] - \lambda_a |A|^4 + \lambda_{ah} |A|^2 |H|^2\end{aligned}$$

With gravity — this is the Lagrangian we use for inflation

$$\mathcal{L} = \mathcal{L}_{\text{matter}} - \frac{1}{2} f(\varphi) R - \Lambda_0, \quad f(\varphi) \equiv M_P^2 + 2\xi_a |A|^2 + 2\xi_h |H|^2$$

The non-minimal couplings ξ_a, ξ_h are dimensionless: *scale invariance does not forbid them*, so they must be there.

⁵ T. Asaka and M. Shaposhnikov, Phys. Lett. B **620** (2005) 17.

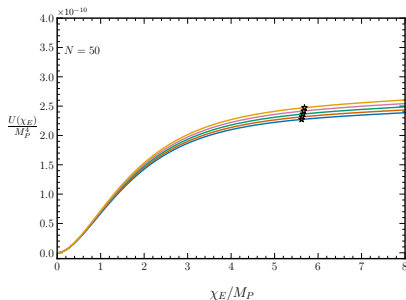
⁶ S. Iso, N. Okada and Y. Orikasa, Phys. Lett. B **676** (2009) 81.

Inflation: scale invariance gives the plateau for free

Since $\xi\chi^2 R$ is allowed, a Weyl transformation $g_{\mu\nu} \rightarrow (M_P^2/f)g_{\mu\nu}$ brings us to the Einstein frame with

$$U = M_P^4 \frac{V}{f^2}, \quad f = M_P^2 + \xi\chi^2 \quad \Rightarrow \quad U \xrightarrow{\xi\chi^2 \gg M_P^2} \frac{M_P^4 \bar{\beta}}{4\xi^2} \log \frac{\chi}{\chi_0}.$$

The $1/f^2$ suppression turns it into a **plateau**: exactly what a high n_s requires.⁷



- ▶ the measured $P_{\mathcal{R}}$ fixes $\bar{\beta}(\xi)$; benchmarks at $\xi \sim 10^4$
- ▶ ξ_h large and negative keeps the Higgs inert
- ▶ stars: field value N e-folds before the end of inflation.

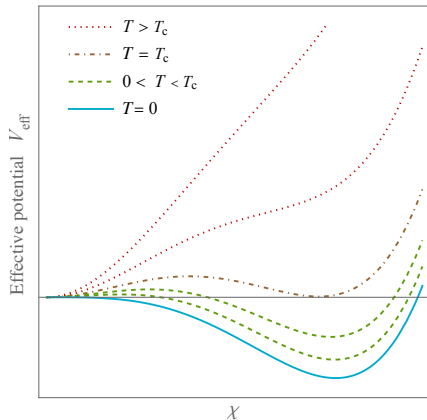
⁷ K. Kannike, A. Racioppi and M. Raidal, JHEP **06** (2014) 154; A. Joti *et al.*, JHEP **07** (2017) 058.

Reheating: the field gets trapped

The portal λ_{ah} gives χ a small component along the physical Higgs, so the inflaton decays into SM particles and reheats the universe to

$$T_{\text{rh}} \gg \chi_0$$

This is all we need: T_{rh} far exceeds the critical temperature above which RSB does not occur so χ is **trapped at** $\chi = 0$.



The nucleation temperature

Once trapped, the vacuum energy $V_0 = \bar{\beta}\chi_0^4/16$ soon dominates over radiation and a **second, purely thermal, inflationary stage** begins, at a rate

$$H_t = \frac{\sqrt{\bar{\beta}} \chi_0^2}{4\sqrt{3} M_P}.$$

The false vacuum decays by *tunnelling*: bubbles of true vacuum nucleate per unit volume at a rate

$$\Gamma_v \simeq T^4 e^{-S_3/T}, \quad S_3 = \text{action of the } O(3) \text{ bounce}.$$

Definition

The transition becomes effective when roughly one bubble nucleates per Hubble volume per Hubble time. The temperature at which this happens is the **nucleation temperature**:⁸

$$\Gamma_v(T_n) \simeq H_t^4$$

.

⁸ A. Salvio, JCAP **04** (2023) 051 [arXiv:2302.10212].

Without a gauged $B - L$: the bubbles are diluted

With only N_i and A as new fields, χ couples too weakly to the plasma: g is small, S_3/T stays too large, and **no T_n exists**. Bubbles are diluted faster than they nucleate.

Why not just let gravity do it?

It *can*⁹: for $\xi \gg 1/(12\pi^2)$ the curvature is a *negative* correction,

$$m_{\text{eff}}^2 \longrightarrow m^2 - 12\xi H_t^2,$$

which can be driven to zero, so the transition always completes.

The subtle point

The N_t e-folds of the thermal stage must be *subtracted* from the slow-roll count: observables are evaluated at $N \simeq N_e - N_t$, and $N \simeq 50$ is where they work.

But the price is the e-fold count

$$N_t \simeq \log \frac{g T_{\text{eq}}}{12\sqrt{\xi} H_t} \sim \mathcal{O}(20\text{--}30)$$

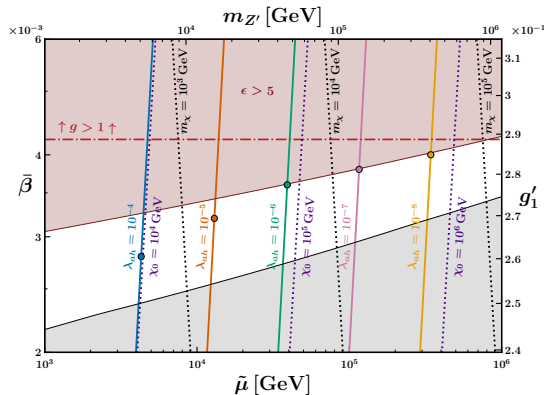
i.e. N_e some tens above 60.¹⁰

⁹ A. Salvio, Phys. Lett. B **852** (2024) 138639.

¹⁰ A. R. Liddle and S. M. Leach, Phys. Rev. D **68** (2003) 103503.

Gauging $B - L$: a viable parameter space

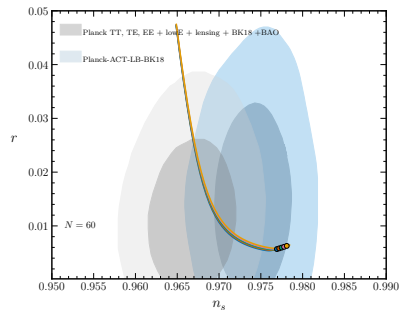
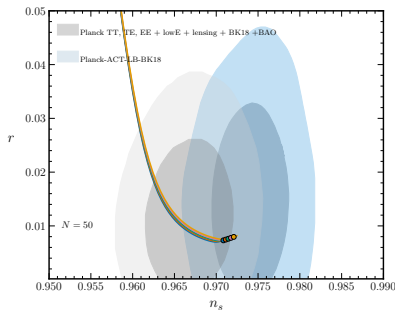
With g'_1 sizeable, $\bar{\beta} = 96g_1'^4/(4\pi)^2$ and $g = 2\sqrt{3}g'_1$: the transition completes on its own, $N_t = 5-7$, and $N_e = N + N_t \simeq 55-60$.



BM	$\bar{\beta}$	χ_0 [GeV]	T_n [GeV]	N_t
blue	0.0028	9.7×10^3	0.35	7
orange	0.0032	2.8×10^4	4.1	6
green	0.0036	8.3×10^4	30	5
pink	0.0038	2.4×10^5	88	5
yellow	0.0040	7.1×10^5	2.4×10^2	5

- ▶ two parameters only: both axes are g'_1 (left/right) and $\tilde{\mu}$ (bottom/top)
- ▶ boundaries: perturbativity $g < 1$, and $\epsilon < 5$
- ▶ the dots are the sampled benchmarks

The resulting inflationary predictions



grey: Planck+BK18+BAO¹¹ blue: Planck-ACT-LB+BK18¹² prediction: $r \simeq 7 \times 10^{-3}$

The point

With $N_t \simeq 5-7$, the CMB pivot sits at $N \simeq 50$ (left panel) and the model is compatible **at 1σ with both Planck/BK18 and ACT**, for $N_e = 55-60$.

¹¹ Planck Collab., Astron. Astrophys. **641** (2020) A10; BICEP/Keck Collab., Phys. Rev. Lett. **127** (2021) 151301.

¹² ACT Collab., JCAP **11** (2025) 062 [arXiv:2503.14452].

Conclusions

- ▶ A **fully realistic classically scale-invariant** completion of the SM: three right-handed neutrinos, one scalar A , and a gauged $U(1)_{B-L}$. It accounts for neutrino oscillations, dark matter and the baryon asymmetry, and the hierarchy is generated by *dimensional transmutation*.
- ▶ Radiative symmetry breaking makes the phase transition **necessarily first order and strongly supercooled** — so the cosmology is necessarily non-standard.
- ▶ **Gauging $B - L$ is what makes it work**: the transition completes without gravitational assistance, so the thermal stage costs only $N_t \simeq 5-7$ e-folds instead of several tens.
- ▶ Those e-folds shift the CMB pivot to $N \simeq 50$, and there the model sits at 1σ with **both Planck/BK18 and ACT**, for a total $N_e = 55-60$.
- ▶ **Predictions**: $r \simeq 7 \times 10^{-3}$, a gravitational-wave background in the **LISA** band, $\lesssim 1\%$ of dark matter in primordial black holes,¹³ and a $B - L$ Z' at 10^4-10^6 GeV — beyond collider reach, but the CMB and the GW spectrum probe the *same* parameters.

Thank you for your attention!

¹³ A. Salvio, JCAP **12** (2023) 046 [arXiv:2307.04694]; I. K. Banerjee, F. Rescigno and A. Salvio, JCAP **07** (2025) 007.

Backup slides

The dominant one-loop contribution is the Z' vector, so in $\overline{\text{MS}}$

$$V_q(\chi) \simeq \frac{3}{64\pi^2} m_{Z'}^4(\chi) \left[\log \frac{m_{Z'}^2(\chi)}{\tilde{\mu}^2} - \frac{5}{6} \right], \quad m_{Z'}(\chi) = 2g'_1\chi.$$

Matching to $V_q = \frac{\bar{\beta}}{4} \left[\log \frac{\chi}{\chi_0} - \frac{1}{4} \right] \chi^4$ gives *both*

$$\bar{\beta} \approx \frac{96g_1'^4}{(4\pi)^2}, \quad \chi_0 \approx \tilde{\mu} \frac{e^{1/6}}{2g_1'}, \quad m_\chi \approx \frac{\sqrt{6}}{2\pi} e^{1/6} g_1' \tilde{\mu}, \quad m_{Z'} \approx e^{1/6} \tilde{\mu},$$

Backup slides

Decomposing the doublets into real fields,

$$H = e^{i\pi_i \tau_i} \begin{pmatrix} 0 \\ h/\sqrt{2} \end{pmatrix}, \quad A \equiv \frac{a}{\sqrt{2}} e^{i\pi_a},$$

the unitary-gauge potential involves only the two gauge-invariant fields h and a , and these are related to χ and the observed Higgs $\mathcal{H}$ by

$$\begin{cases} a = \chi \cos \alpha - \mathcal{H} \sin \alpha \\ h = \chi \sin \alpha + \mathcal{H} \cos \alpha \end{cases} \quad \tan \alpha \equiv \sqrt{\frac{\lambda_{ah}}{2\lambda_h}}.$$

The conditions imposed at $\tilde{\mu}$ are

$$\lambda_{ah} = 2\sqrt{\lambda_a \lambda_h}, \quad v = \sin \alpha \chi_0.$$

Backup slides

After the Weyl transformation the scalar-tensor part reads

$$\mathcal{L}_{st} = M_P^2 \left[\frac{\partial_\mu \varphi \partial^\mu \varphi}{2f} + \frac{3 \partial_\mu f \partial^\mu f}{4f^2} \right] - U - \frac{M_P^2}{2} R, \quad U = M_P^4 \frac{V}{f^2}.$$

- ▶ the $3(\partial f)^2/4f^2$ term is why χ is not canonically normalised: one introduces χ_E with the appropriate $d\chi_E/d\chi$;
- ▶ with ξ_h large and *negative*, the term $-\xi_h |H|^2 R$ with $R > 0$ gives H a large positive effective mass: it stays pinned, inflation is single-field, and EW-vacuum metastability is simultaneously harmless;
- ▶ standard slow-roll then gives $n_s = 1 - 6\epsilon_V + 2\eta_V$, $r = 16\epsilon_V$, $P_{\mathcal{R}} = U/(24\pi^2 M_P^4 \epsilon_V)$, with $P_{\mathcal{R}} = (2.10 \pm 0.03) \times 10^{-9}$ imposed.

Backup slides

In the fast-reheating approximation,

$$T_{\text{rh}} \approx \left(\frac{45 \Gamma_{\chi_E}^2 M_P^2}{4\pi^3 g_*(T_{\text{rh}})} \right)^{1/4},$$

and one of the main channels is into a top pair,

$$\Gamma_{\chi_E \rightarrow t\bar{t}} \approx \left(\frac{d\chi}{d\chi_E} \right)_{\chi=\chi_{\text{max}}}^2 \frac{3y_t^2 \sin^2 \alpha}{16\pi} M_{\text{eff}},$$

where M_{eff} is the maximal value of $d^2U/d\chi_E^2$, attained at χ_{max} .

For the benchmarks this channel *alone* reheats the universe to at least $\sim 10^{10} \text{ GeV} \gg \chi_0$. A precise calculation is not needed: only $T_{\text{rh}} \gg \chi_0$ matters, and it holds by many orders of magnitude.

Note also that reheating requires $\sin \alpha \neq 0$: the same tilt of the flat direction that breaks the electroweak symmetry is what allows the inflaton to decay into SM particles.

Backup slides

For the supercool expansion potential the bounce equation is parameter-free after rescaling, $u'' + \frac{2}{\rho}u' = u - u^3$, giving

$$S_3 = c_3 \frac{m(T)}{\lambda(T)}, \quad c_3 = 18.8973, \quad \implies \quad \frac{S_3}{T} = \frac{c_3 g}{\sqrt{12} \bar{\beta} X} \equiv \frac{a}{X}.$$

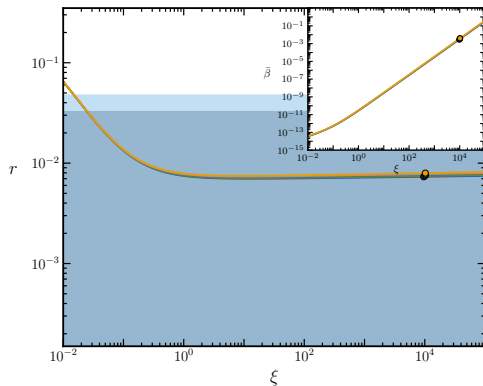
Imposing $\Gamma_v \simeq H_t^4$, i.e. $S_3/T = 4 \log(T/H_t)$, gives a quadratic equation

$$4X^2 - cX + a = 0, \quad a = \frac{c_3 g}{\sqrt{12} \bar{\beta}} = \frac{K}{Y g^3}, \quad c = 2 \log \frac{48 M_P^2}{\bar{\beta} \chi_0^2} = 2 \log \frac{L}{Y g^4},$$

with $K = (4\pi)^2 c_3 / \sqrt{12}$, $L = 48(4\pi)^2 M_P^2 / \chi_0^2$, and $X_n = (c - \sqrt{c^2 - 16a})/8$.

A solution exists only if $c^2 \geq 16a$.

Backup slides



- ▶ imposing the measured $P_{\mathcal{R}}$ turns $\bar{\beta}$ into a function of ξ (inset)
- ▶ r saturates at $\simeq 7 \times 10^{-3}$ for $\xi \gtrsim 10$
- ▶ the benchmarks need $\bar{\beta} \sim 3 \times 10^{-3}$, i.e. g'_1 sizeable $\Rightarrow \xi \sim 10^4$

Unitarity

In Higgs inflation such a large ξ breaks perturbative unitarity at M_P/ξ — but that is the cutoff *around the minimum*. During inflation the background is $\chi \gg M_P/\xi$ and the cutoff is much larger. We checked the same holds here.

Backup slides

The size of the cubic relative to the quadratic is small only when *many* incoherent species contribute ($\tilde{g}^3/g^3 \lesssim 1/\sqrt{N}$). Here $N = 1$: $\tilde{g}/g = 3^{-1/6} = 0.83$. So the cubic is kept non-perturbatively:

$$S_3 = \frac{3\pi m^3}{k^2} F(\tilde{\lambda}), \quad \tilde{\lambda} \equiv \frac{\lambda m^2}{k^2}, \quad F(\tilde{\lambda}) = \frac{1 + e^{-1/\sqrt{\tilde{\lambda}}}}{2/9 + \tilde{\lambda}},$$

and nucleation becomes the *non-polynomial* equation $a_1 - a_2 \tilde{\lambda} = F(\tilde{\lambda})$, with a_1, a_2 independent of T .

Backup slides

With $R_b \sim 1/m$ and $m \equiv gT/\sqrt{12}$, gravity is negligible when

$$m \gg \max\left(\sqrt{12|\xi|}, \frac{1}{\pi}\right) H_t \quad \Longleftrightarrow \quad T \gg \frac{12\sqrt{\xi} H_t}{g}.$$

If instead this fails and $\xi \gg 1/(12\pi^2)$, the curvature acts as a *negative* correction to the effective mass of χ and the transition always completes eventually, but only after

$$N_t \simeq \log \frac{g T_{\text{eq}}}{12\sqrt{\xi} H_t} \sim \mathcal{O}(20\text{--}30) \text{ e-folds.}$$

- ▶ orange benchmark: $m \simeq 1.1 \text{ GeV}$ vs. $\sqrt{12\xi} H_t \simeq 9 \times 10^{-10} \text{ GeV} \Rightarrow \text{ratio} \sim 10^9$ — satisfied by nine orders of magnitude;
- ▶ $\xi < 0$ *impedes* the transition, giving even larger N_t ;
- ▶ $\xi \lesssim 1/(12\pi^2)$ also gives larger N_t , since the r.h.s. decreases with ξ .

Hence the analysis is restricted to the curvature-irrelevant regime.

Backup slides

Vacuum energy of the trapped phase:

$$V(0) - V(\chi_0) = \frac{\bar{\beta}\chi_0^4}{16} \implies H_t^2 = \frac{\bar{\beta}\chi_0^4}{48M_P^2} \implies H_t = \frac{\sqrt{\bar{\beta}}\chi_0^2}{4\sqrt{3}M_P}.$$

Onset of vacuum domination:

$$\frac{\pi^2}{30}g_*T_{\text{eq}}^4 = \frac{\bar{\beta}\chi_0^4}{16} \implies T_{\text{eq}} = \left(\frac{15\bar{\beta}\chi_0^4}{8\pi^2g_*}\right)^{1/4} \simeq 0.05\chi_0.$$

Duration: at fixed H_t the scale factor grows exponentially while $T \propto 1/a$, so

$$N_t = \log \frac{a_n}{a_{\text{eq}}} = \log \frac{T_{\text{eq}}}{T_n} = X_n - \log \frac{\chi_0}{T_{\text{eq}}} \simeq X_n - 3.$$

Check (orange): $\chi_0 = 2.8 \times 10^4$, $\bar{\beta} = 0.0032 \Rightarrow T_{\text{eq}} = 1.34 \times 10^3$ GeV; with $T_n = 4.1$ GeV, $N_t = \log(326) = 5.8 \simeq 6$. ✓

Backup slides

The history is

$$\underbrace{\text{slow-roll}}_N \rightarrow \underbrace{\text{reheating, } T_{\text{rh}} \gtrsim 10^{10} \text{ GeV}}_{\text{fast}} \rightarrow \underbrace{\text{radiation domination}}_{\text{many e-folds}} \rightarrow \underbrace{\text{thermal inflation}}_{N_t} \rightarrow \text{FOPT}$$

- ▶ CMB scales exit the horizon during the *first* stage, but all subsequent expansion — including the N_t e-folds of the second — brings them back inside today;
- ▶ hence observables must be evaluated at $N \simeq N_e - N_t$;
- ▶ with $N_t = 5\text{--}7$ and $N_e = 55\text{--}60$ this gives $N \simeq 50$;
- ▶ at $N = 50$ the model predicts $n_s \simeq 0.971$: inside *both* the Planck/BK18 and the ACT contours.

Without the second stage the model would prefer $N = 60$ and sit at higher n_s .

Backup slides

- ▶ Strength: $\alpha \equiv 30\rho(T_n)/(\pi^2 g_* T_n^4) \gg 1$
- ▶ Inverse duration: $\beta/H_n \simeq 4\text{--}6$ from the improved expansion. A small β/H means a *strong* signal.
- ▶ Peak frequency today scales as $f_{\text{peak}} \propto (\beta/H_n)T'_{\text{rh}}$. For $\chi_0 = 10^4\text{--}10^6$ GeV this lands in the **mHz** band = LISA.
- ▶ PBHs: $f_{\text{PBH}} \lesssim 1\%$ of dark matter for $\chi_0 \sim 10^5$ GeV.
- ▶ Spectra extracted from the model-independent results of Salvio '23 and Banerjee–Rescigno–Salvio '24, not recomputed here.

Backup slides

The single jump $\chi : 0 \rightarrow \chi_0$ breaks *three* symmetries at once:

- ▶ $U(1)_{B-L}$ **completely** — the Goldstone π_a is eaten by the Z' ;
- ▶ the electroweak group, since $v = \sin \alpha \chi_0$ — *this is the electroweak phase transition*, here strongly first order;
- ▶ classical scale invariance — χ is the corresponding pseudo-Goldstone (dilaton), light because the breaking is only anomalous: $m_\chi = \sqrt{\bar{\beta}}\chi_0$.

Degrees of freedom: A (2) + massless Z' (2) $\rightarrow$ massive Z' (3) + χ (1).

particle	mass	orange benchmark
Z'_{B-L}	$2g'_1\chi_0$	1.5×10^4 GeV
χ	$\sqrt{\bar{\beta}}\chi_0$	1.6×10^3 GeV
N_i	$y_{ij}\chi_0/\sqrt{2}$	$\ll$ EW
W, Z , quarks, leptons	$\propto v = \sin \alpha \chi_0$	SM values

Before the transition *everything* is massless. Note $m_\chi/m_{Z'} = \sqrt{6}g'_1/(2\pi) \simeq 0.10$, independently of χ_0 .

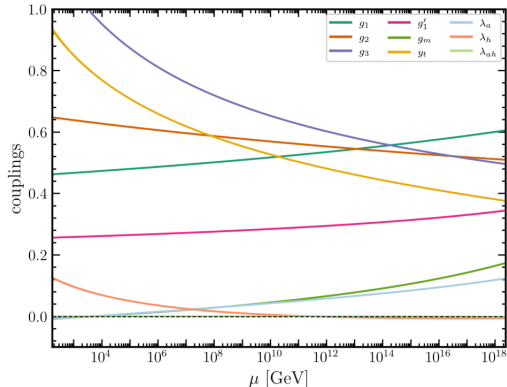
Backup slides

One-loop RGEs of the full model; initial conditions = blue benchmark. Two of them:

$$\frac{dg'_1}{d \ln \mu} = \frac{1}{(4\pi)^2} \left(12g_1'^3 + \frac{32}{3} g_1'^2 g_m + \frac{41}{6} g_1' g_m^2 \right)$$

$$\frac{d\lambda_a}{d \ln \mu} = \frac{1}{(4\pi)^2} \left(20\lambda_a^2 + 2\lambda_{ah}^2 - \sum_j y_j^4 + 96g_1'^4 \right. \\ \left. - 48\lambda_a g_1'^2 + 2\lambda_a \sum_j y_j^2 \right)$$

The $+96g_1'^4$ is precisely $\bar{\beta}$; λ_a crossing zero at $\tilde{\mu}$ is the flat direction. The Landau pole of g'_1 sits at $\Delta \log \mu \simeq 90$, while only $\simeq 32$ is needed to reach M_P — so the binding constraint is $g = 2\sqrt{3}g'_1 < 1$, not the pole.



Backup slides

The full gauge group is $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$, and

$$D_\mu = \partial_\mu + ig_3 T^\alpha G_\mu^\alpha + ig_2 T^a W_\mu^a + ig_Y Y B_\mu + i[g_m Y + g'_1(B-L)]B'_\mu,$$

with $B'_{\mu\nu} \equiv \partial_\mu B'_\nu - \partial_\nu B'_\mu$ the field strength of $U(1)_{B-L}$.

field	$B-L$
quarks	+1/3
charged leptons, ν	-1
N_i	-1
A	+2
H	0

- ▶ anomaly freedom requires exactly the three N_i : without them a gauged $B-L$ would be inconsistent;
- ▶ $Q_{B-L}(A) = +2$ follows from $\frac{1}{2}y_{ij}AN_iN_j$, and gives $m_{Z'}(\chi) = 2g'_1\chi$;
- ▶ g_m is the kinetic mixing between $U(1)_Y$ and $U(1)_{B-L}$: it is set to a negligible value at $\tilde{\mu}$, but is regenerated by the running and so is kept in the RGEs.

Since $m_{Z'}/g'_1 = 2\chi_0 \gtrsim 20$ TeV, the Z' is far above the LHC reach: the phenomenology of this model is cosmological, not collider-based.

Backup slides

$$J_B(x) \equiv \int_0^\infty dp \quad p^2 \log \left(1 - e^{-\sqrt{p^2+x}} \right) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}x - \frac{\pi}{6}x^{3/2} - \frac{x^2}{32} + \dots$$

$$J_F(x) \equiv \int_0^\infty dp \quad p^2 \log \left(1 + e^{-\sqrt{p^2+x}} \right) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}x - \frac{x^2}{32} + \dots$$

Note that only J_B has an $x^{3/2}$ term: this is why the cubic term of $\bar{V}_{\text{eff}}$ — and hence $\tilde{g}$ — receives no fermionic contribution.