Unifying inflation with the axion, dark matter, baryogenesis and the seesaw mechanism

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The aim:

Introduce a theory, “SMASH”, that addresses several problems in particle physics and cosmology, providing a consistent picture of the evolution of the Universe.

The plan:

Discussion of the problems.

Definition of the model.

Discussion of how the model addresses the problems.

What terrestrial experiments told us

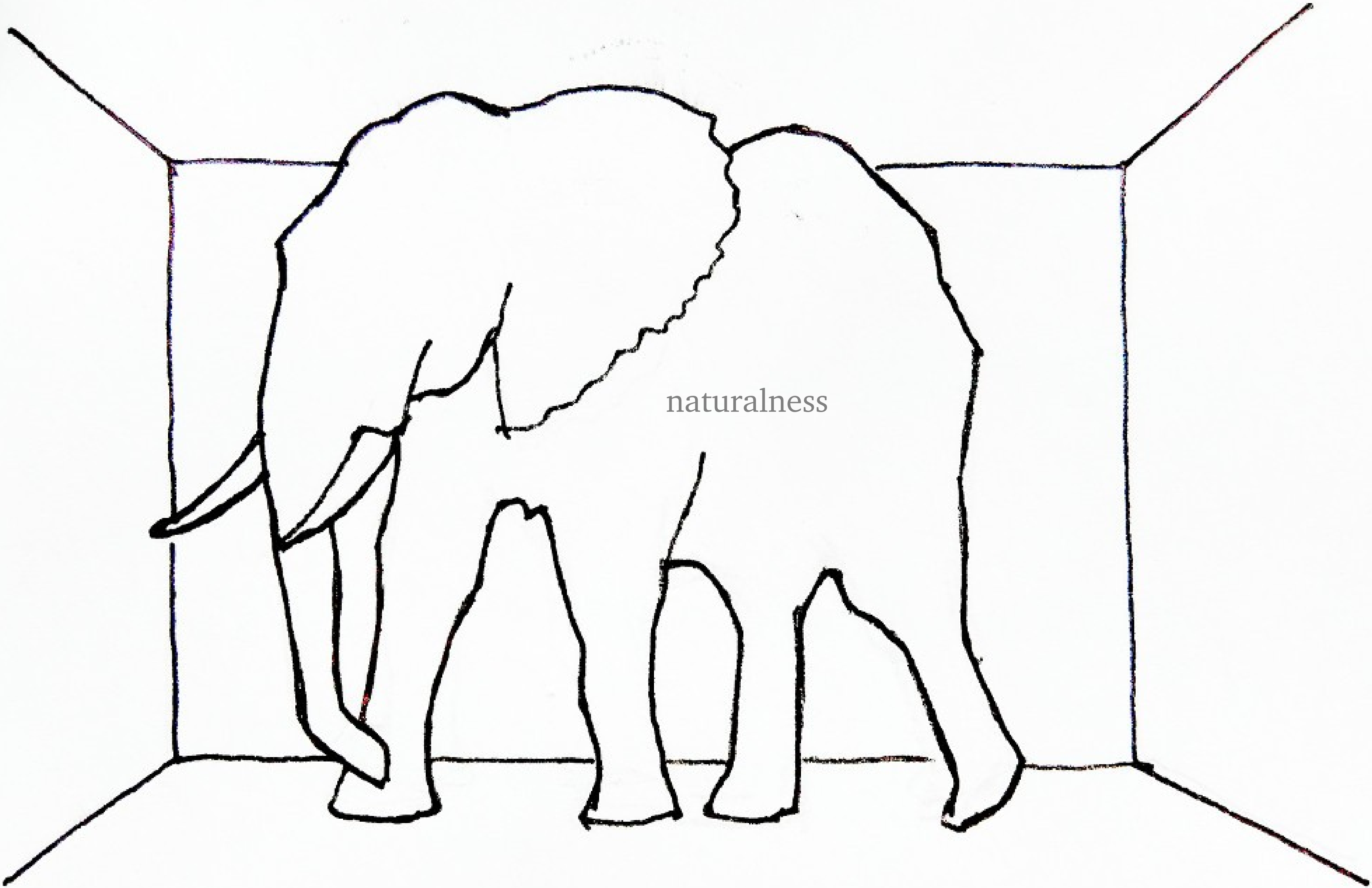
The Standard Model plus neutrino masses is able to explain the overwhelming majority of terrestrial experiments.

The SM is a consistent theory. The Higgs potential extrapolated at large field values has an instability around $\Lambda_I \sim 10^{11}$ GeV for the central values of α_s, m_t, m_h, but this is not necessarily a problem in flat space-time due to the long lifetime of the electroweak vacuum.

Open questions relevant for this talk and directly connected with observables in particle physics experiments:

Origin of small neutrino masses (as required by oscillation data and cosmological observations)

CP problem: Absence of CP violation in the strong interactions (potentially observable in the neutron´s dipole moment)


naturalness

The truth is out there

Cosmological data show that we live in a spatially flat, nearly homogeneous universe with accelerated expansion. CMB temperature map points towards density perturbations with a common origin (hence the peak structure in the power spectrum)

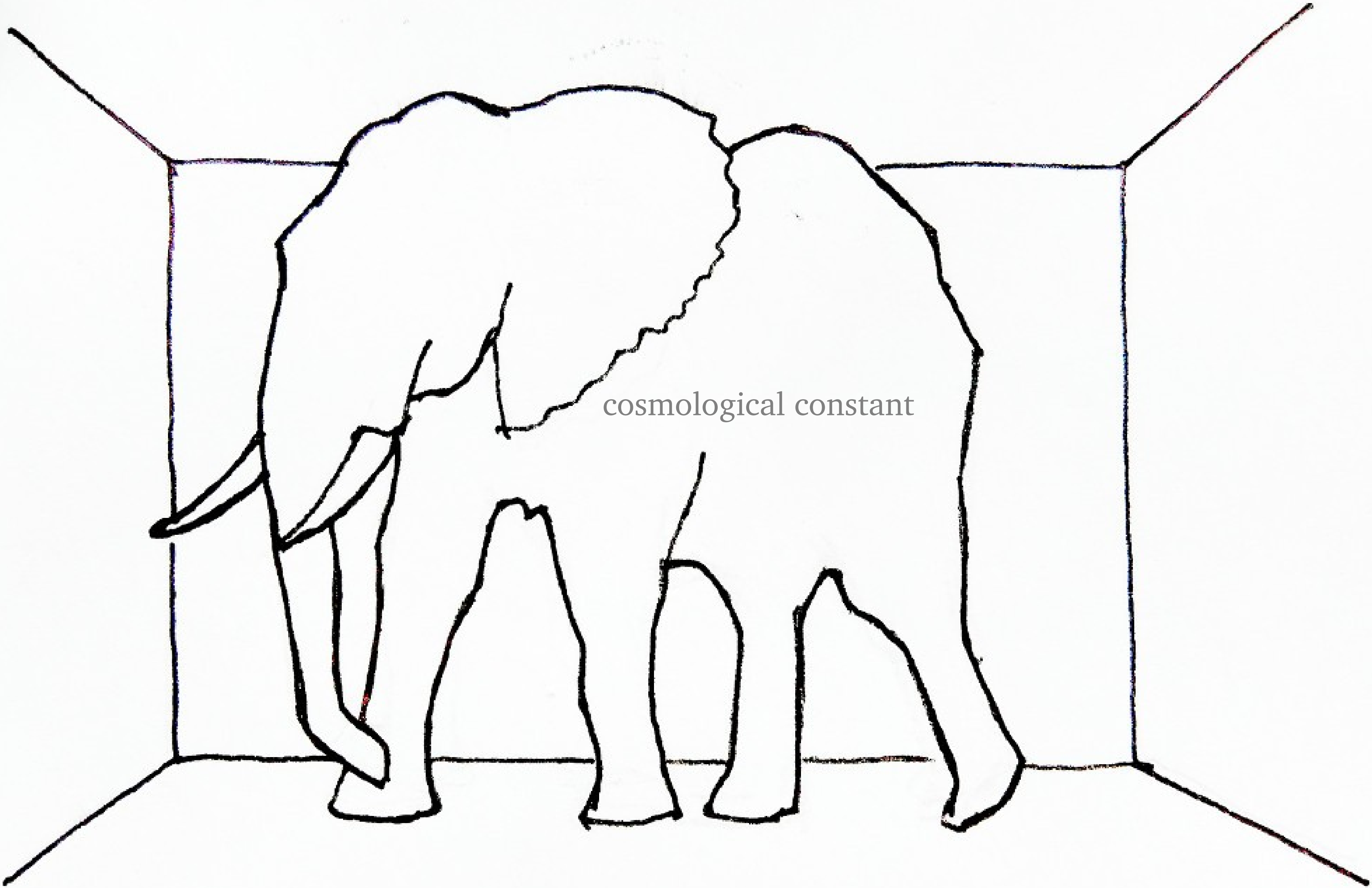
The paradigm is the ΛCDM model with an early period of inflation:

SM + dark matter + cosmological constant + inflationary sector.

During inflation, spacetime's curvature is large and the Higgs instability can be a problem!

Open questions relevant for this talk

What plays the role of the inflaton?
What makes up dark matter?
What is the mechanism of baryogenesis?
How is the Higgs stabilized during inflation?


cosmological constant

All those problems… all those solutions

Zero T	Inflation	Scalar inflaton
	Higgs stability	Scalar interactions
	Small neutrino masses	Seesaw models, radiative mass generation
	CP problem	Axion, Nelson-Barr
Finite T	Dark matter	WIMP, sterile neutrinos, axion
	Baryogenesis	Electroweak baryogenesis, leptogenesis, Affleck-Dine…

Abridged problem dictionary

Inflation. Period of accelerated expansion needed to explain the isotropy and homogeneity of the Universe.

A slowly-rolling scalar field with positive potential energy can drive accelerated expansion. Could it be the Higgs [Bezrukov,Shaposhnikov]??

Higgs inflation problem: Lack of predictivity! [Barbon, Espinosa, Burgess, Lee, Trott]

$$S_{HI} = \int d^4x\sqrt{-g}\left[\mathcal{L}_{SM} - \frac{M^2}{2}R - \xi H^\dagger H R\right]$$

After a Weyl rescaling the theory becomes that of a minimally coupled scalar, with unitarity-breaking derivative interactions suppressed by a cutoff

$$\Lambda = \frac{M}{\xi} \sim \frac{M_P}{\xi}$$

Canonical normalization of the scalar leads to an exponentially flat potential, giving the correct spectrum of density perturbations for $\xi \sim 10^5\sqrt{\lambda_H} \sim 10^4$

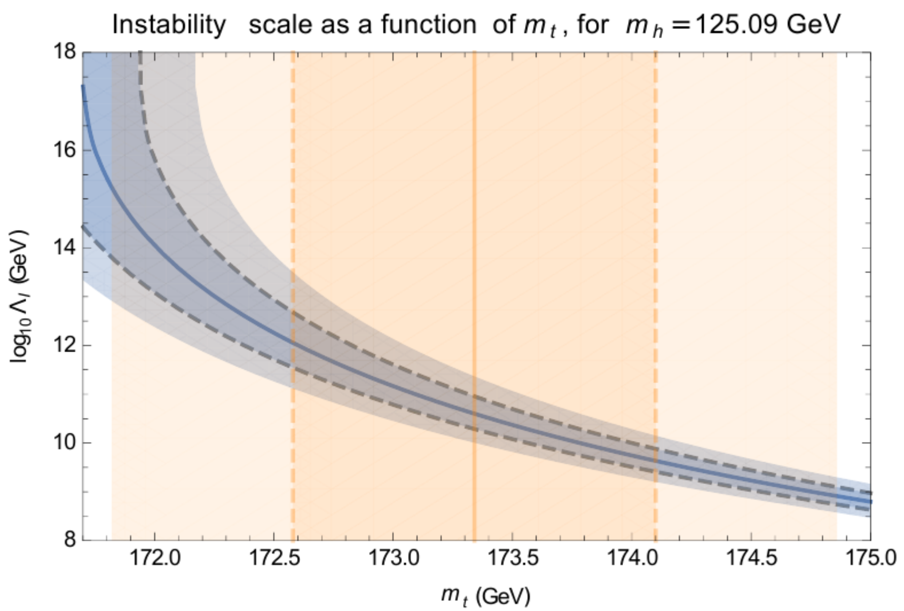
Physics curing unitarity above the cutoff $<< M$ can feed back into the potential (through virtual effects) at field values $<< M_p$, invalidating predictions.

Abridged problem dictionary

Higgs stability problem. At large field values, including quantum corrections,

$$h \equiv \sqrt{2}H^0, \quad V_{SM}(h) \sim \frac{\lambda(h)}{4}h^4, \quad \frac{\partial \lambda}{\partial \log h} = \beta_\lambda \sim -\frac{3y_t^4}{8\pi^2} < 0$$

$\lambda(h)$ fixed by Higgs mass at low h, but becomes negative (and so does the potential) at $h \sim \Lambda_I \sim 10^{11}$GeV.



Not necessarily a problem in a low-curvature background, but quantum fluctuations during inflation can drive the Higgs over the edge

$$\Delta h \sim \frac{\mathcal{H}}{2\pi} > \Lambda_I, \quad \mathcal{H} = \frac{\dot{a}}{a}$$

Can be fixed in theories with modified β_λ or boundary condition for $\lambda(h)$.

Also increasing the effective Higgs mass during inflation.

Abridged problem dictionary

Neutrino mass problem. Neutrino oscillation data imply that neutrinos are massive, yet the masses are tiny. Why?

$$\sum_i m_{\nu,i} < 0.23\,\mathrm{eV} \quad \text{[PLANCK 2015]}, \quad |\Delta m^2_{ij}| < 3\times 10^{-3}\,\mathrm{eV}^2 \quad \text{[NuFIT 2016]}$$

Can be explained e.g. with see-saw mechanism

$$\mathcal{L} \supset -G_{ij} L_i H^\dagger E_j - F_{ij} L_i \epsilon H N_j - \frac{1}{2} M_{ij} N_i N_j \quad \Rightarrow m_\nu = \frac{1}{2} F M^{-1} F^\top v^2$$

CP problem. QCD has a chiral anomaly, implying the existence of a physical CP violating phase $\theta_{\rm phys}$

$$\mathcal{L}_{QCD} \supset \frac{g^2\theta}{16\pi^2} \mathrm{Tr}\,\tilde{G}_{\mu\nu} G^{\mu\nu}, \quad \theta_{\rm phys} = \theta - \arg\det M_q$$

Measurements of the neutron's dipole moment imply $|\theta_{\rm phys}| < 10^{-11}$ [Kim 09]

Can be explained if $\theta_{\rm phys}$ becomes dynamical, with potential stabilized at origin: axion solution.

$$\mathcal{L} \supset \frac{g^2(\theta + \frac{A(x)}{f})}{16\pi^2} \mathrm{Tr}\,\tilde{G}_{\mu\nu} G^{\mu\nu}, \quad \theta_{\rm phys} \to \theta_{\rm phys}(x) = \theta + \frac{A(x)}{f} - \arg\det M_q$$

Abridged problem dictionary

Dark matter. Galactic rotation curves and the CMB power spectrum imply the existence of non-baryonic matter in the Universe, which SM particles cannot account for.

$$\Omega_B = 0.05, \quad \Omega_{DM} = 0.26 \quad \text{[Planck 2015]}$$

Modelled by new, mostly neutral and mostly stable particles. Have to ensure they end up with the proper abundance. WIMPS, sterile neutrinos, axions...

Baryogenesis. The known Universe is overwhelmingly made of matter rather than antimatter, although physical laws don't establish a fundamental distinction.

$$\eta = \frac{n_B}{n_\gamma} = \frac{n_b - \overline{n}_b}{n_\gamma} = 6.1 \times 10^{-10} \quad \text{[Cyburt et al, 2015 Planck data]}$$

Can be generated if one has violations of CP, B and thermal equilibrium.

Leptogenesis: Out-of-equilibrium decays of heavy sterile neutrinos.

Baryogenesis: Out-of-equilibrium processes around an expanding bubble in a first-order phase transition.

Relating solutions

CP problem plus dark matter	Abbot et al, Dine et al, Preskill et al,…
Neutrino masses plus axion	Dias et al, Kim, Mohapatra et al, Berezhiani, Shafi et al, Langacker et al, Shin, He et al, Celis et al, Bertolini et al, Ng et al, Carvajal et al, Clarke et al, Ahn et al,…
Neutrino masses plus inflation	Boucenna et al, Budhi et al ,…
Inflation plus dark matter	Lerner, McDonald, Kahlhofer,…
Inflation plus dark matter plus CP problem	Fairbairn & Marsh,…

Non-minimal list of minimal models of the Universe

νMSM [Asaka, Blanchet, Shaposhnikov]

SM+ RH neutrinos (Inflaton=Higgs, DM=RH neut)

Salvio [Salvio]

SM+KSVZ axion+ RH neutrinos (Inflaton=Higgs, DM=axion)

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nMSM [Davoudiasl, Kitano, Li, Murayama]

SM+two real scalars+RH neutrinos (Inflaton, DM: scalars)

Non-minimal list of minimal models of the Universe

		νMSM	Salvio	nMSM	SMASH
Zero T	Inflation	⚠	⚠	✔	✔
	Stability	✘	✔	⚠	✔
	ν masses	✔ (tuning)	✔	✔	✔
	CP	✘	✔	✘	✔
Finite T	DM	✔	✔	✔	✔
	Baryogenesis	✔	✔	✔	✔
	New scales	M_a	M_a, f_A	M_a, m^2_S,m^2_ϕ	f_A

S.M.A.S.H

A minimal model providing a consistent, predictive picture of:

Particle physics from the electroweak to the Planck scale

Cosmology from inflation to today

Highlights:

A single new scale, playing a role in dark matter, the CP problem and baryogenesis

Predictive inflation free from unitarity concerns

Detailed understanding of parameter space yielding stability

Detailed understanding of reheating and post-inflationary history

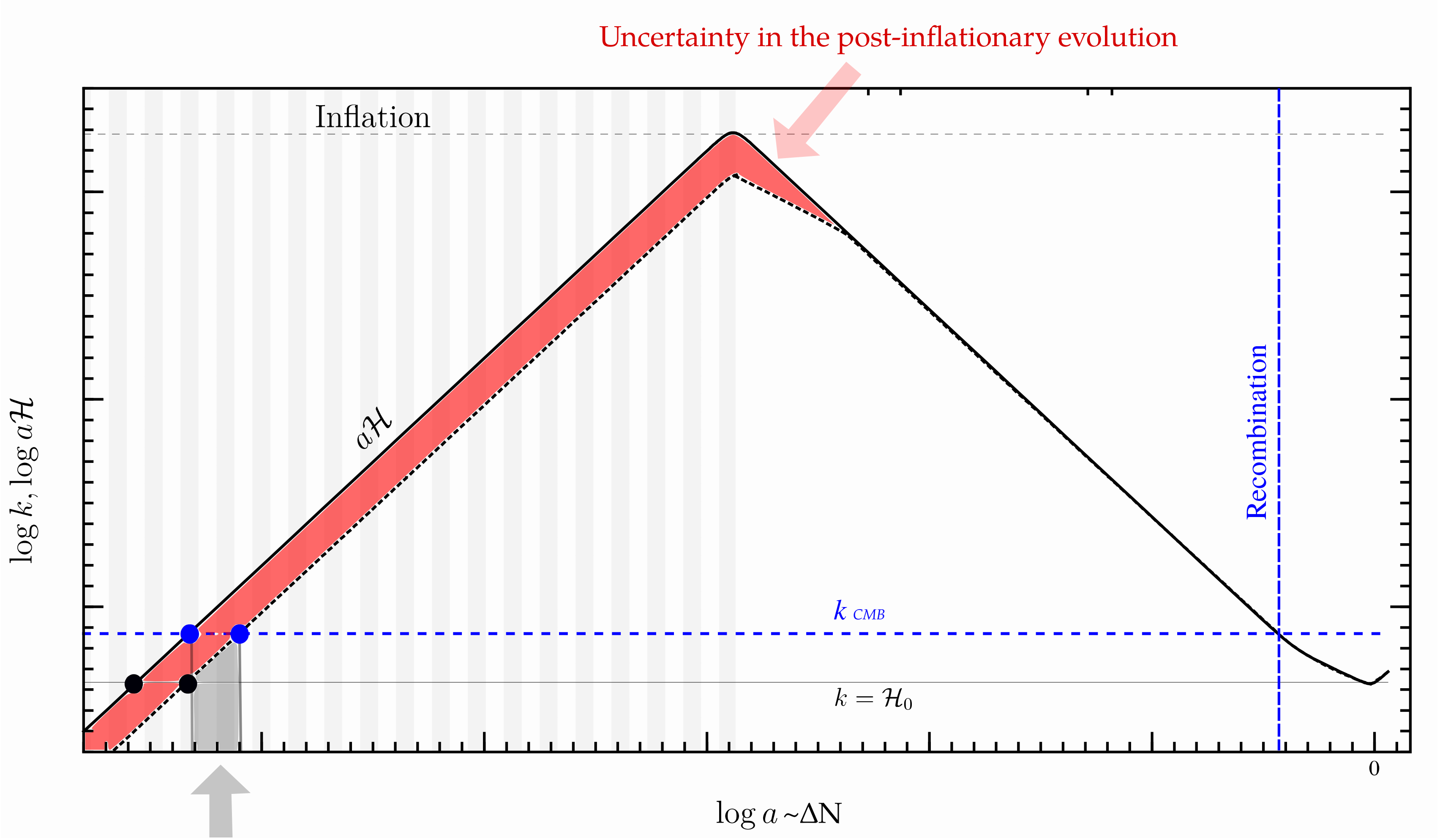
Accurate predictions for cosmological parameters and the axion mass in reach of future experiments

Why care about a minimal model at all?

Predictivity!

Knowing the full particle content of a model fixes the post-inflationary history of the Universe, in particular the relation between length scales observed in the sky today and the moment at which the corresponding perturbations were generated during inflation. This implies precise predictions for cosmological observables an can help rule out classes of models with common features.

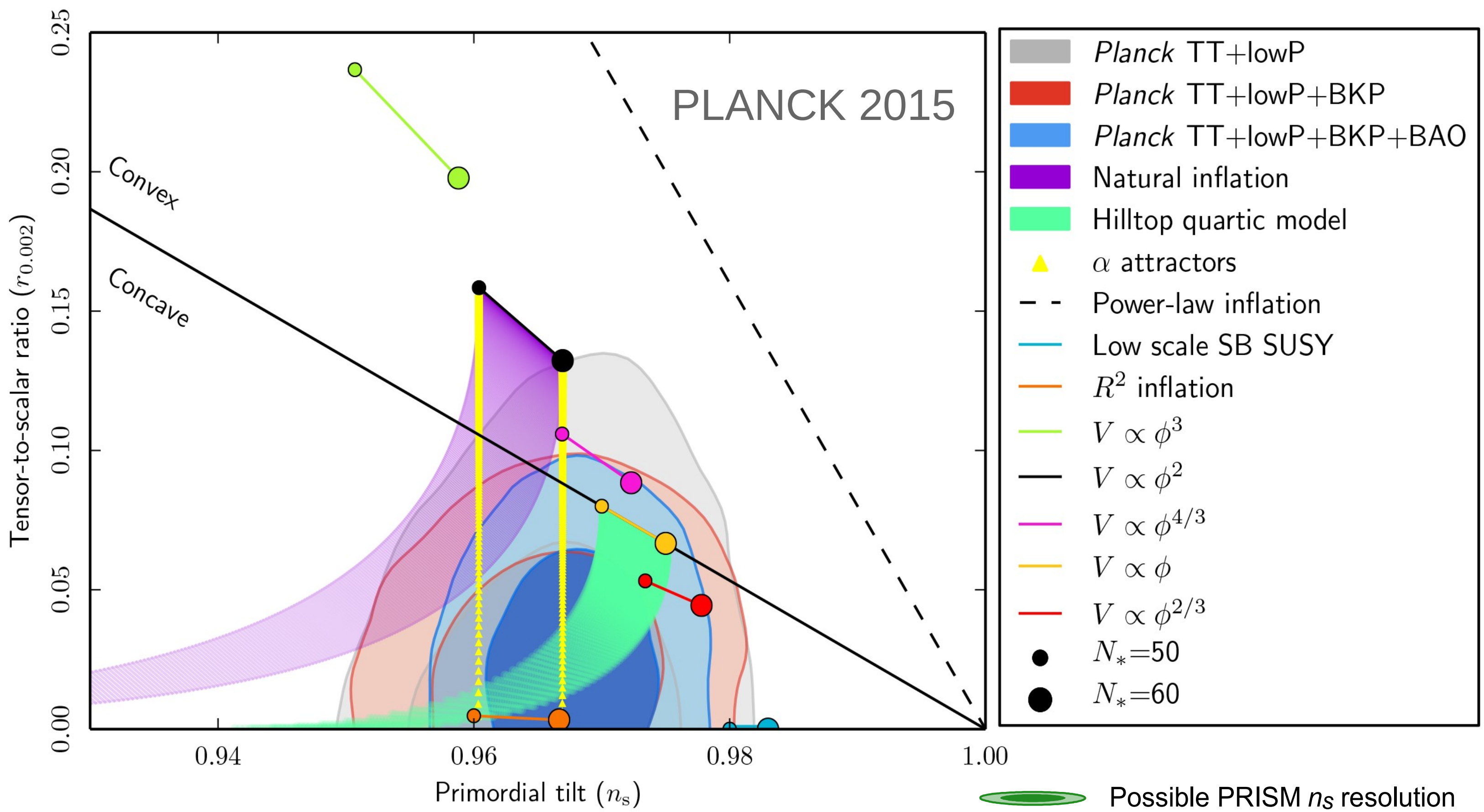
Why care about a minimal model at all?



Uncertainty in the number of efolds/inflationary predictions!

Why care about a minimal model at all?

Uncertainties show up in the predictions for inflationary parameters



Future precision: $r \sim 0.001$, $\Delta n_s \sim \pm\, 0.002$ (LiteBird, PRISM)

Building up SMASH

5 problems addressed with 3 new types of particles.

A new scalar σ playing a role in inflation is motivated by the lack of predictivity of Higgs inflation. σ can release the Higgs from the burden of inflating the Universe, avoiding the unitarity problem enforced by the large Higgs quartic.

As a bonus, the scalar can stabilize the Higgs direction. Moreover, if the scalar gets a large VEV, it can have an enhanced stabilizing effect thanks to the threshold mechanism [Lebedev, Elias-Miró et al]

A singlet scalar which gets a large VEV v_σ can be part of the KSVZ axion solution to the CP problem! To implement this, we consider a pair of Weyl fermions $Q, \tilde{Q}$ in the (anti)fundamental of SU(3).

The axion (contained in the phase of σ), can give us dark matter for free.

The large axion VEV v_σ can play te role of the seesaw scale. Thus we add RH neutrinos N_i coupling to the axion.

SMASH recap

$$\mathcal{L} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm yuk}^{SM}$$

$$- \left[\frac{M^2}{2} + \xi_H\, H^\dagger H + \xi_\sigma\, |\sigma|^2\right] R$$

$$-\lambda_H \left(H^\dagger H - \frac{v^2}{2}\right)^2 - 2\lambda_{H\sigma}\left(H^\dagger H - \frac{v^2}{2}\right)\left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)$$

STABILITY

$$-\lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)^2 - [y\sigma\tilde{Q}Q + y_{Q_{d\,i}}\sigma Q d_i + c.c]$$

CP PROBLEM

INFLATION

$$-[F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + c.c.]$$

SEESAW AND LEPTOGENESIS

Most general, renormalizable Lagrangian compatible with the following global PQ symmetry:

q	u	d	L	N	E	Q	$\tilde{Q}$	σ
$1/2$	$-1/2$	$-1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	$-1/2$	1

Zero T problems: inflation

$$S \supset -\int d^4x\sqrt{-g}\left[\left(\frac{M^2}{2}+\xi_H\,H^\dagger H+\xi_\sigma\,\sigma^*\sigma\right)R+V(H,\sigma)\right],\quad M_P^2=M^2+\xi_H v^2+\xi_\sigma v_\sigma^2$$

$$H(x)=\frac{1}{\sqrt{2}}\begin{pmatrix}0\\ h(x)\end{pmatrix},\quad |\sigma(x)|=\frac{\rho(x)}{\sqrt{2}},\quad \phi(x)=(h(x),\rho(x))\,.$$

Going to the Einstein frame

$$\tilde{g}_{\mu\nu}(x)=\Omega^2(h(x),\rho(x))\,g_{\mu\nu}(x),\qquad \Omega^2=1+\frac{\xi_H(h^2-v^2)+\xi_\sigma(\rho^2-v_\sigma^2)}{M_P^2},$$

$$S^{(\mathrm{E})}_{\mathrm{SMASH}}\supset\int d^4x\sqrt{-\tilde{g}}\left[-\frac{M_P^2}{2}\tilde{R}+\frac{1}{2}\sum_{i,j}^{1,2}\mathcal{G}_{ij}\tilde{g}^{\mu\nu}\partial_\mu\phi_i\partial_\nu\phi_j-\tilde{V}\right],\quad \tilde{V}(h,\rho)=\frac{V(h,\rho)}{\Omega^4}$$

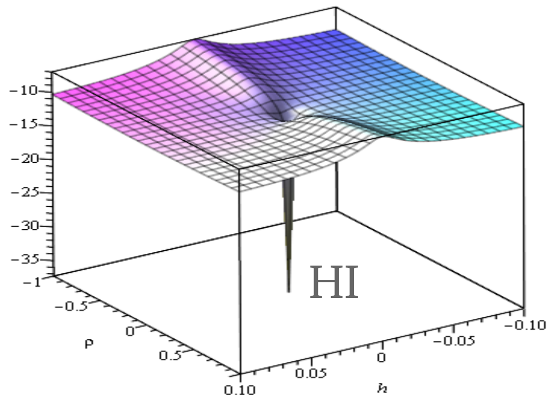
The large field potential has valleys which act as inflationary attractors.

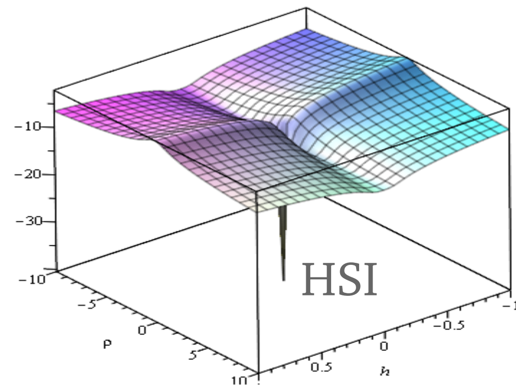
$$\kappa_H\equiv\lambda_{H\sigma}\xi_H-\lambda_H\xi_\sigma\,,$$
$$\kappa_\sigma\equiv\lambda_{H\sigma}\xi_\sigma-\lambda_\sigma\xi_H$$

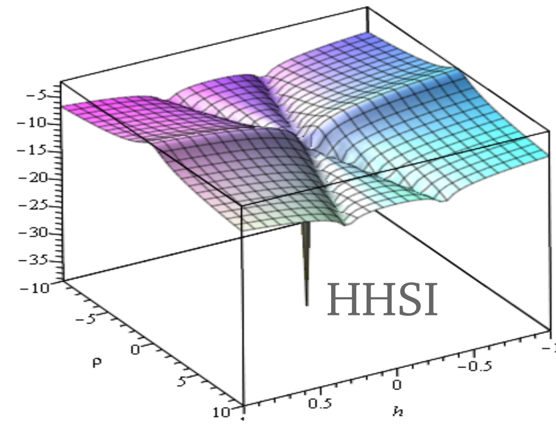
sign(κ_H)	sign(κ_σ)	Inflation
+	+	HI *or* HSI
+	−	HI
−	+	HSI
−	−	HHSI

HI: Higgs inflation
HSI: Hidden scalar inflation
HHSI: Higgs-Hidden scalar inflation

Zero T problems: inflation







Along the valleys one can treat inflation as a dynamical problem in one field dimension. After the Weyl transformation, for $\xi_H \ll 1$ (discarding HI) one has

$$V(\chi) = \frac{\lambda}{4}\phi(\chi)^4 \left(1 + \xi_\sigma \frac{\phi(\chi)^2}{M_P^2}\right)^{-2} \qquad \lambda \to \begin{cases} \lambda_\sigma, & \text{HSI} \\ \tilde{\lambda}_\sigma \equiv \lambda_\sigma - \frac{\lambda_{H\sigma}^2}{\lambda_H}, & \text{HHSI} \end{cases}$$

For a canonically normalized field $\phi \to \chi$ the resulting potential becomes exponentially flattened at large field values

$$\xi_\sigma \gg 1: \qquad \tilde{V}(\chi) \simeq \frac{\lambda}{4\xi_\sigma^2} M_P^4 \left[1 - \exp\left(-\sqrt{\frac{2}{3}}\frac{\chi}{M_P}\right)\right]^2,$$

$$\xi_\sigma \ll 1: \qquad \tilde{V}(\chi) \simeq \frac{\lambda}{4\xi_\sigma^2} M_P^4 \left[\tanh\left(\sqrt{\frac{\xi}{b}}\frac{\chi}{M_P}\right)\right]^4$$

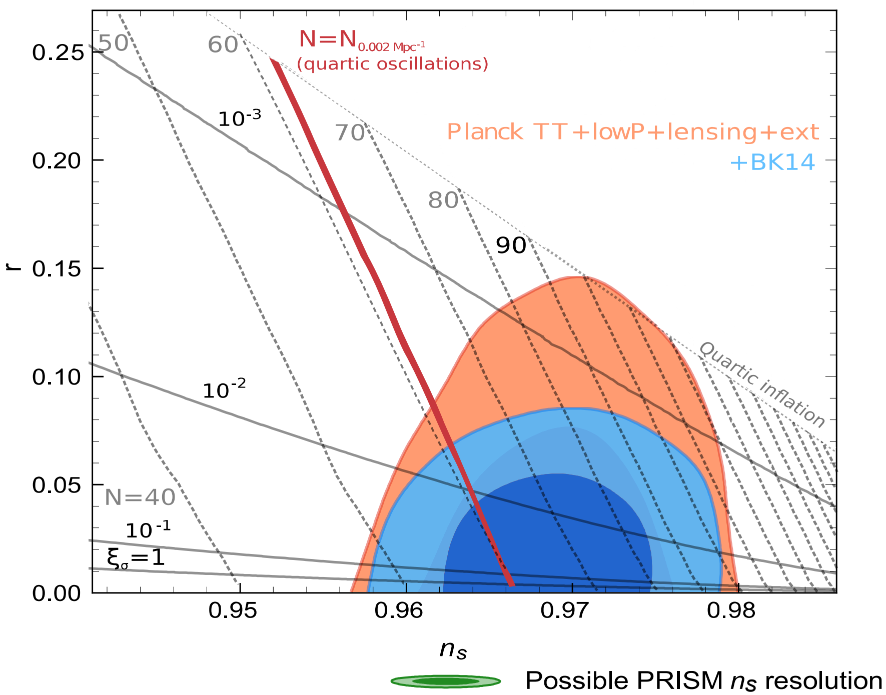
Zero T problems: inflation

Power spectrum of scalar density perturbations:

$$\langle \mathcal{R}_k \mathcal{R}'_k \rangle = \frac{16\pi^5}{k^3}\delta^{(3)}(k+k')\Delta^2_{\mathcal{R}}(k), \quad \Delta^2_{\mathcal{R}}(k) = A_s(k_*)\left(\frac{k}{k_*}\right)^{n_s(k_*)-1}$$

n_s: spectral index. Similarly one can define an amplitude $A_t(k_*)$ for tensor perturbations, and the tensor-to-scalar ratio r

$$r(k_*) = \frac{A_s(k_*)}{A_t(k_*)} \qquad \alpha = \frac{dn_s(k_*)}{d\log k_*}$$



Predictive inflation window:

$$2\times 10^{-3} \lesssim \xi_\sigma \lesssim 1 \Rightarrow 10^{-9} \gtrsim \lambda \gtrsim 10^{-13}$$

In this case one has

$$\alpha \sim 10^{-3(4)}$$

$r \sim 10^{-3}$ can be probed by experiments like PRISM, LiteBird

$\alpha \sim 10^{-3}$ can be probed by 21 cm line.

Zero T problems: stability

We demand positivity of the effective potential for all field values up to Planckian scales. This avoids unstable classical attractors and fluctuation-induced instabilities.

Stability in Higgs direction: endangered by top Yukawa.

$$\beta_{\lambda_H} \supset -\frac{3y_t^4}{8\pi^2}$$

Threshold stabilization mechanism.

The SM potential near the EW vacuum must match the SMASH potential along the valley line

$$\frac{\partial V(h,\rho)}{\partial \rho} = 0$$

(equivalently, SM recovered when integrating out ρ)

This gives, at low scales, $\lambda_H = \lambda_H^{SM} + \delta, \;\; \delta \equiv \frac{\lambda_{H\sigma}^2}{\lambda_\sigma}$ clearly favouring stability

at large field values when V is dominated by quartics.

Zero T problems: stability

Stability in σ direction: endangered by Yukawas of RH neutrinos.

$$\beta_{\lambda_\sigma} \supset -\frac{1}{16\pi^2}\mathrm{Tr}[YY^\dagger YY^\dagger]$$

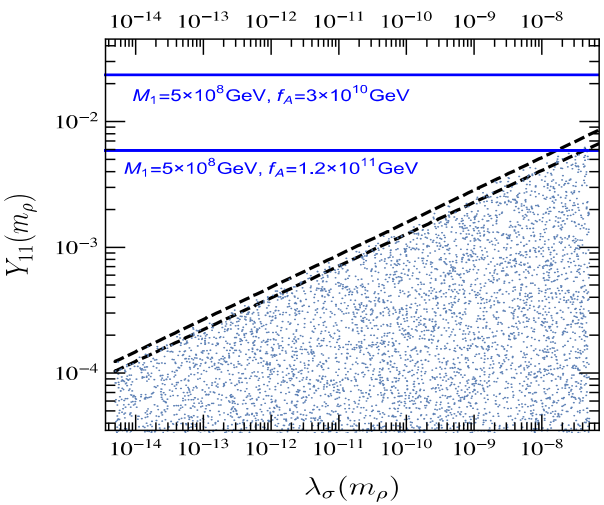
Accounting for quadratic interactions, (relevant in the potential energy valleys) the stability conditions are:

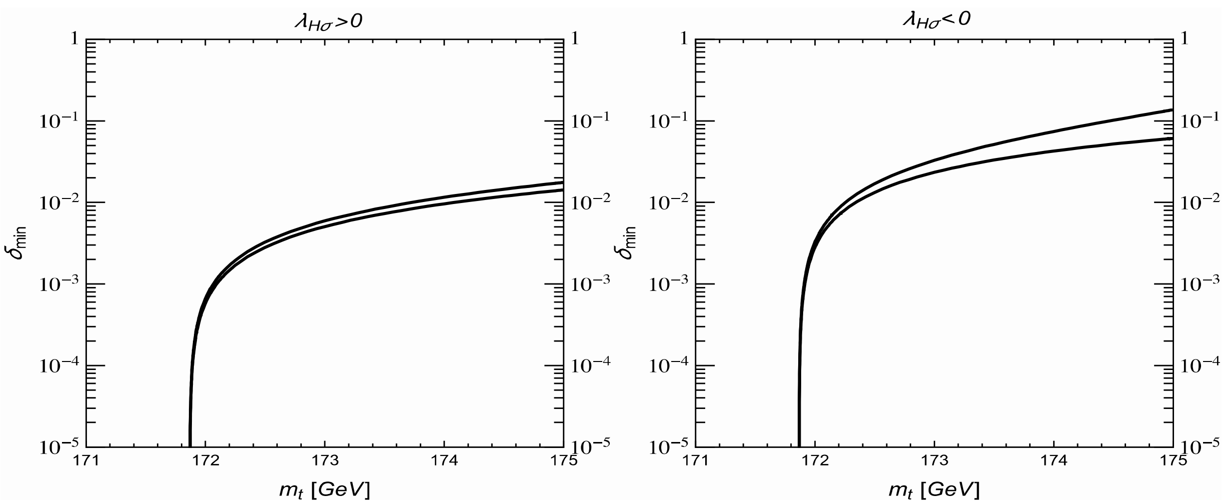
$$\lambda_{H\sigma} < 0: \quad \tilde\lambda_H, \tilde\lambda_\sigma > 0 \quad \text{for all} \quad h\,.$$

$$\lambda_{H\sigma} > 0: \quad \begin{cases} \tilde\lambda_H, \tilde\lambda_\sigma > 0, & \text{for} \quad h < \sqrt{2}\Lambda_h \\ \lambda_H, \lambda_\sigma > 0, & \text{for} \quad h > \sqrt{2}\Lambda_h \end{cases}$$

$$\tilde\lambda_\sigma \equiv \lambda_\sigma - \frac{\lambda_{H\sigma}^2}{\lambda_H},\ \tilde\lambda_H \equiv \lambda_H - \delta$$

$$\Lambda_h^2 = \frac{\lambda_{H\sigma}}{\lambda_H} v_\sigma^2$$





Typical δ around 0.01. With typical $\lambda_\sigma \sim 10^{-10}$ from inflation, we have $\lambda_{H\sigma} \sim 10^{-6}$

Zero T problems: strong CP

KSVZ axion solution.

The axion is the Goldstone boson of the PQ symmetry broken by the VEV v_σ . Since the vector quarks $Q, \tilde{Q}$ are charged under PQ and SU(3), the PQ symmetry is anomalous, which enforces at low energies a coupling between the axion and gauge fields that mimics the θ term.

q	u	d	L	N	E	Q	$\tilde{Q}$	σ
$1/2$	$-1/2$	$-1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	$-1/2$	1

The axion is the phase of σ: $\sigma(x) = \frac{1}{\sqrt{2}}\left[v_\sigma + \rho(x)\right] e^{iA(x)/v_\sigma}$

Under a PQ transformation, $\delta_{\rm PQ} A = v_\sigma \alpha$ while the effective action has an anomaly,

$$\delta_{PQ}\mathcal{L}_{\rm eff} = \frac{g^2\alpha}{16\pi^2}{\rm Tr}\tilde{G}_{\mu\nu}G^{\mu\nu} + \frac{g'\alpha^2}{32\pi^2}\frac{2}{3}\tilde{B}_{\mu\nu}B^{\mu\nu}$$

Mimicked by effective Lagrangian $(f_A \equiv v_\sigma)$

$$\mathcal{L}_{\rm eff,A} = \frac{1}{2}\partial_\mu A \partial^\mu A + \frac{\partial_\mu A}{f_A}\sum_i q_i(\psi_i^\dagger \bar{\sigma}^\mu \psi_i) - \frac{g^2 A}{16\pi^2 f_A}{\rm Tr}\,\tilde{G}_{\mu\nu}G^{\mu\nu} - \frac{g'^2 A}{32\pi^2 f_A}\frac{2}{3}\tilde{B}_{\mu\nu}B^{\mu\nu}$$

Zero T problems: strong CP

The total effective Lagrangian now involves θ in combination with the axion

$$\mathcal{L}_{eff} \supset \frac{g^2}{16\pi^2}\left(\theta - \frac{A(x)}{f_A}\right) \mathrm{Tr}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$$

Nonperturbative QCD effects generate a potential for $\tilde{A}(x) = f_A\theta - A(x)$, stabilizing it at zero and thus solving the strong CP problem.

$$V(\tilde{A}) \equiv -\frac{1}{\mathcal{V}} \ln \frac{Z_{QCD}(\theta)}{Z_{QCD}(0)}\bigg|_{\theta\to\tilde{A}/f_A} \qquad m_A^2 \equiv \frac{\partial^2 V(A)}{\partial A^2}\bigg|_{A=0} = \frac{\chi}{f_A^2}.$$

The topological susceptibility χ can be calculated with chiral perturbation theory or in the lattice, with recent agreement. The latest lattice results give [Borsanyi et al]

$$m_A = 57.0(7)\left(\frac{10^{11}\mathrm{GeV}}{f_A}\right)\mu\mathrm{eV}.$$

The SMASH axion couples to photons, nucleons and neutrinos. Below Λ_{QCD}:

$$\mathcal{L}_A \supset -\frac{\alpha}{8\pi} C_{A\gamma}\frac{A}{f_A} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}C_{AN}\frac{\partial_\mu A}{f_A}\,\overline{\psi}_N\gamma^\mu\gamma_5\psi_N - \frac{1}{4}\frac{\partial_\mu A}{f_A}\,\overline{\nu}_i\gamma^\mu\gamma_5\nu_i,$$

$$C_{A\gamma} = -1.25, C_{Ap} = -0.47, C_{An} = -0.02$$

Zero T problems: neutrino masses

Small neutrino masses follow from the standard type I seesaw mechanism, with the see-saw scale set by the VEV v_{σ}.

$$\mathcal{L} \supset -[F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + c.c.]$$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & F v \\ F^T v & Y\, v_\sigma \end{pmatrix}$$

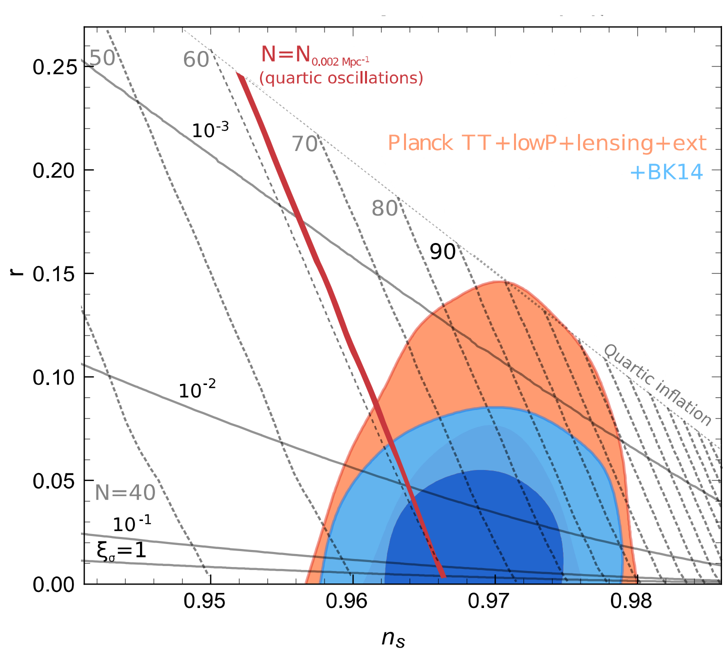
$$m_\nu = -M_D M_M^{-1} M_D^T = -\frac{F\, Y^{-1}\, F^T}{\sqrt{2}}\ \frac{v^2}{v_\sigma} = 0.04\,\text{eV} \left(\frac{10^{11}\,\text{GeV}}{v_\sigma}\right) \left(\frac{-F\, Y^{-1}\, F^T}{10^{-4}}\right) .$$

Towards finite T problems: reheating

After inflation ends, in predictive models with $\xi_\sigma \lesssim 1$, the background oscillates in a quartic potential. The resulting stress-energy tensor behaves as a radiation fluid.

$$\phi(t) \sim \phi_0(t) \cos\left[\omega(t) t\right], \quad \phi_0(t) = \frac{\phi_{\rm end}}{a(t)}, \quad \omega(t) = 1.69\sqrt{\lambda}\phi_0(t).$$

The background can be viewed as a condensate of particles with energy $\omega(t)$.
It can lose energy by decays or many-body processes. With decay chains ending in very light particles, the produced particles are relativistic and radiation domination continu



Radiation domination starts right after inflation, and there is no matter-dominated reheating stage.

This allows accurate predictions for ns, r.

Towards finite T problems: reheating

Reheating in SMASH is subtle!

Production of bosons is expected to dominate, thanks to resonant multibody effects.

However, production channels of bosonic SM particles are closed except when the background approaches the origin! This renders the usual perturbative reheating estimates invalid. Remember: Inflation & stability $\Rightarrow \lambda_\sigma \sim 10^{-10}, \lambda_{H\sigma} \sim 10^{-6}$

HSI, $\lambda_{H\sigma} > 0$

Inflaton σ is a condensate particles with energy $\omega(t) \sim \sqrt{\lambda_\sigma}\phi_0(t)$

can produce Higgses, with $m_h(t) \sim \sqrt{\lambda_{H\sigma}}\phi_0(t)|\cos\omega t|$

HHSI, $\lambda_{H\sigma} < 0$

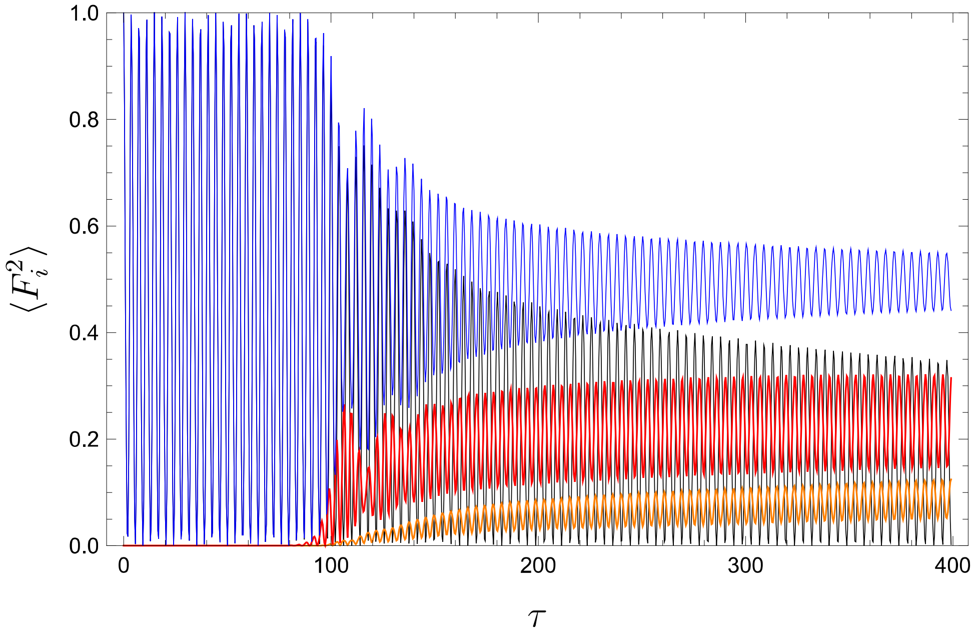
Inflaton is a condensate of *h* and σ, with $\omega(t) \sim \sqrt{\tilde{\lambda}_\sigma}\phi_0(t)$

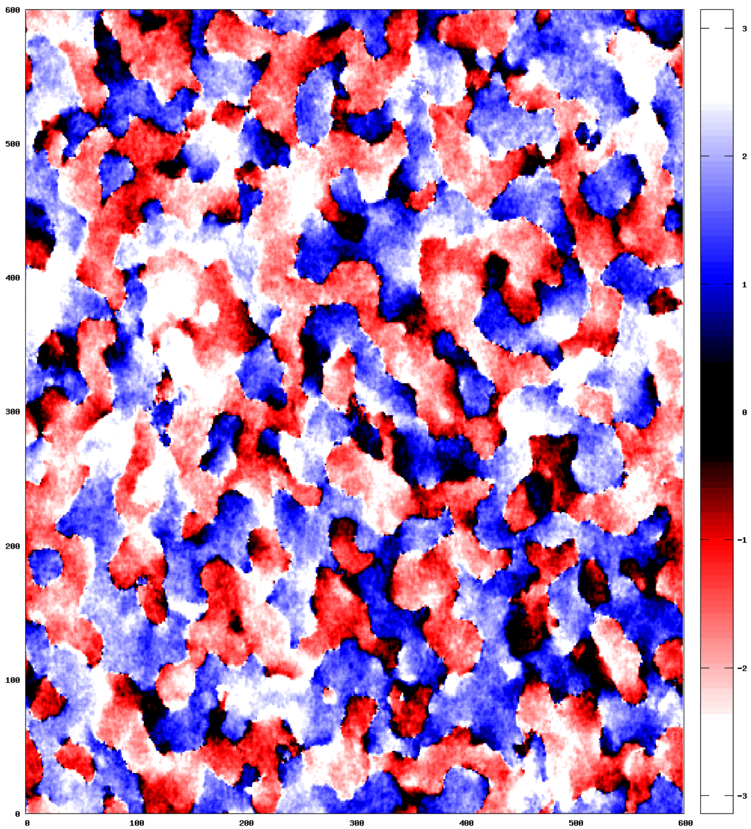
Can produce: Higgses as above, W,Z bosons, with $m_W(t) \sim \frac{g}{2}\sqrt{\frac{|\lambda_{H\sigma}|}{\lambda_H}}\phi_0(t)|\cos\omega t|$

Finite T problems: preheating

Closed production of bosonic SM particles implies enhanced resonant production of σ excitations in a phase of preheating.

Our own lattice simulations in HSI, show $<\sigma^2>$ reaching a constant value, and the PQ symmetry undergoing a nonthermal restoration for $f_A < 4 \times 10^{16}$ GeV.





Towards finite T problems: reheating

SM radiation production in HSI ($\lambda_{H\sigma} > 0$) after preheating

Preheating induces a constant <σ^2>, closing production of Higgs particles until quadratic interactions become important and the PQ symmetry is broken. The energy of σ excitations is shared between axions and modulus excitations, which end up decaying. This yields an unacceptable amount of dark radiation:

$$\Delta N_{\rm eff}^{\rm HSI} = O(1) \quad \text{vs} \quad N_{\rm eff} = 3.04 \pm 0.18 \quad \text{[Planck 2015]}$$

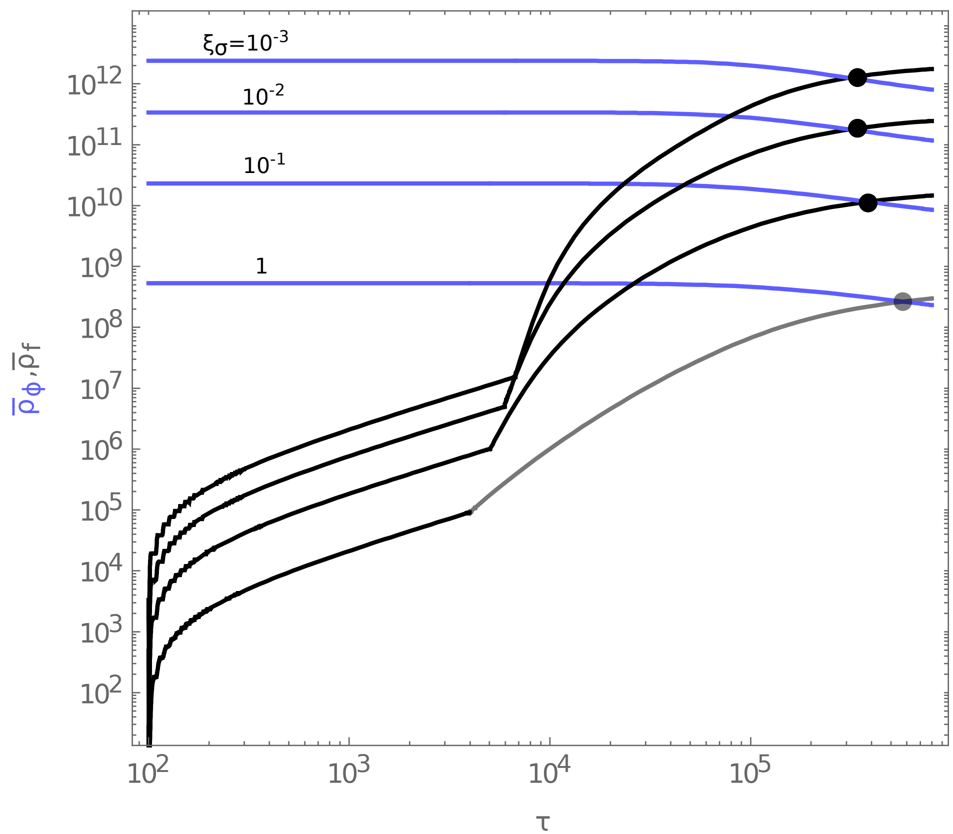
SM radiation production in HHSI ($\lambda_{H\sigma} < 0$) after preheating

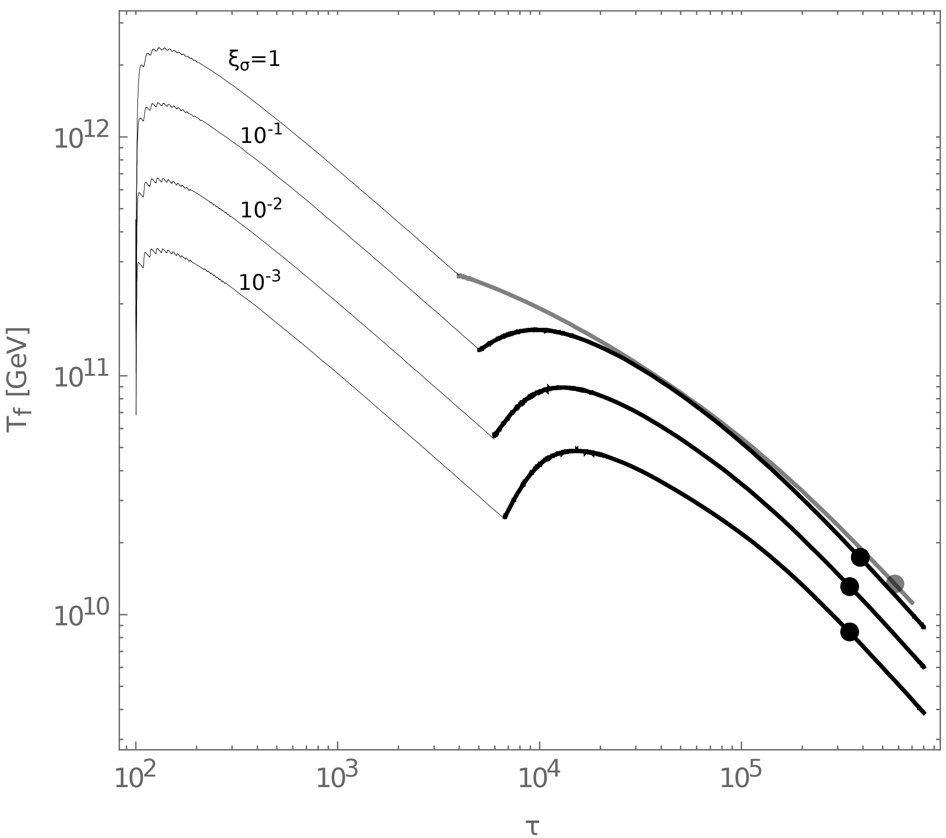
The condensate has a Higgs component. Inefficient production of Higgs excitations prevents the complete blocking of the W,Z channel.

Decays of W, Z into light fermions prevent resonant production, yet when the light particles thermalize there is an interesting feedback mechanism enhancing the energy loss of the condensate. Modelling this with Boltzmann equations accounting for backreaction we estimate reheating temperatures

$$T_R \sim 10^{10}\,\text{GeV}$$

Towards finite T problems: reheating





Finite T problems: baryogenesis

The reheating temperatures around 10^{10} GeV in HHSI are enough to allow for thermal leptogenesis. This relies on:

- Production of a lepton asymmetry from the out-of-equilibrium decays of a population of RH neutrinos with initial thermal abundances.

- Conversion of part of the lepton asymmetry into net baryon number by sphaleron processes in chemical equilibrium.

In SMASH RH neutrinos get a mass at the PQ phase transition, retaining throughout an equilibrium abundance because typically $M/T_c \lesssim 1$.

RH neutrinos can also annihilate, yet decays dominate in the relevant parameter space. Thus one can in principle have a vanilla leptogenesis scenario.

Generically this requires $M \gtrsim 5 \times 10^8\,\mathrm{GeV}$ [Buchmuller,Davidson]. This is borderline compatible with stability in the σ direction, but easy to overcome with a very mild resonant enhancement [Pilaftsis].

Finite T problems: axion dark matter

Near the QCD phase transition, axions become nonrelativistic and behave like dark matter.

From our preheating simulations, the PQ symmetry is restored after inflation for $f_A < 4 \times 10^{16}$ GeV. This implies a unique prediction between f_A and the dark matter abundance. Scenarios with $f_A > 4 \times 10^{16}$ GeV are ruled out by isocurvature constraints.

2 sources of axion production.

Realignment mechanism. The axion condensate (which acquires stochastic initial conditions after PQ restoration) oscillates and behaves as dark matter. Recent progress in finite T lattice QCD calculations allow a precise calculation of abundance [Borsanyi et al].

Decays of axionic strings and domain walls. Axionic strings along which the PQ symmetry remains restored are unstable, and their decay produces axion excitations.

$$\Omega_A h^2 \approx 0.12 \Rightarrow 3 \times 10^{10}\,\text{GeV} \lesssim f_A \lesssim 1.2 \times 10^{11}\,\text{GeV} \quad ; \quad 50\,\mu\text{eV} \lesssim m_A \lesssim 200\,\mu\text{eV}$$

Axion dark radiation

In HHSI, the reheating temperature $T_R \sim 10^{10}$ GeV allows for relativistic axion excitations to thermalize with the SM bath and acquire an equilibrium abundance.

These relativistic axions decouple from the bath at

$$T_A^{\mathrm{dec}} \sim 1.7 \times 10^9 \ \mathrm{GeV} \left(\frac{f_A}{10^{11} \ \mathrm{GeV}} \right)^{2.246} ,$$

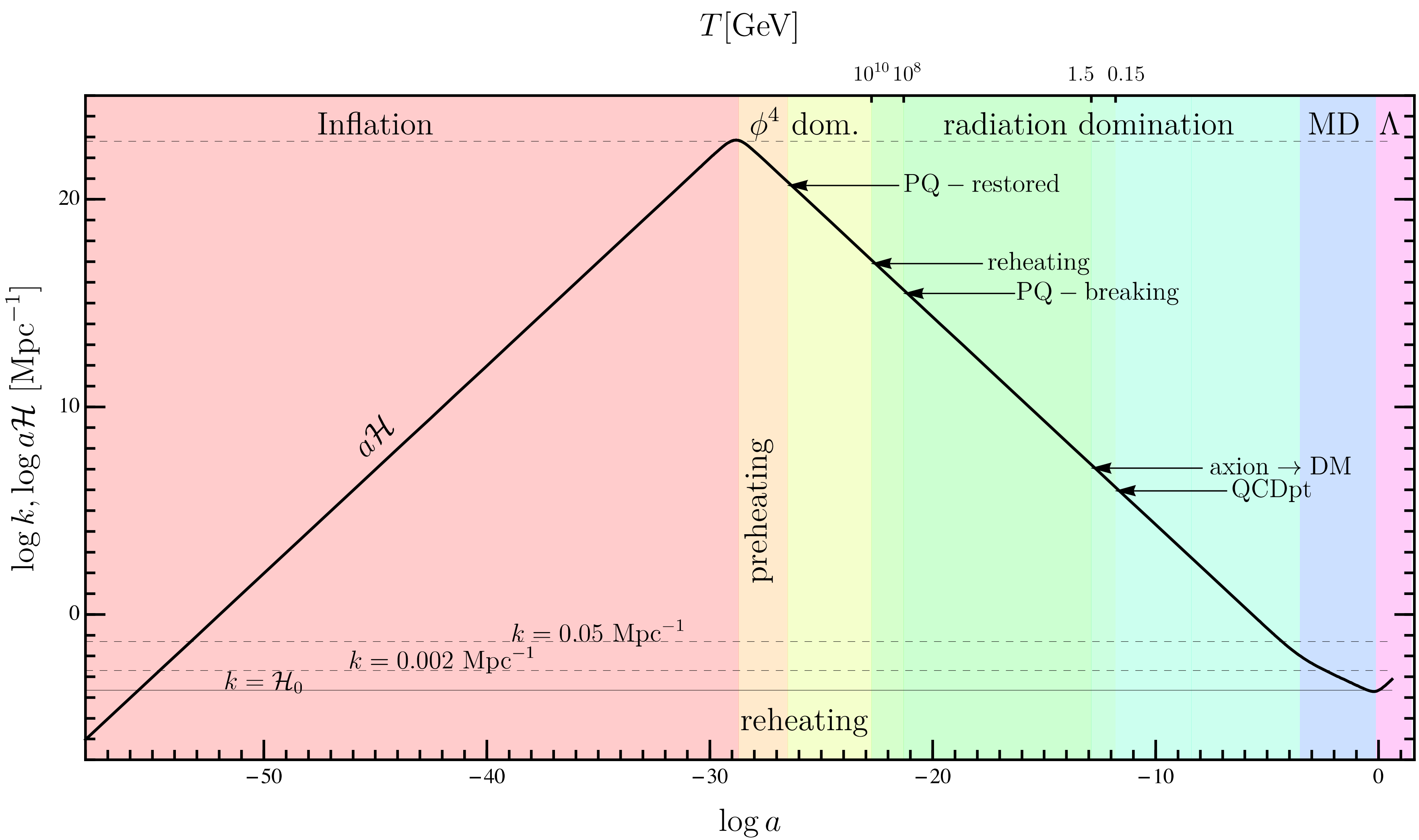
and imposing entropy conservation one predicts

$$\Delta N_\nu^{\mathrm{eff}} \simeq 0.0268 \ \left(\frac{427/4}{g_{*s}(T_A^{\mathrm{dec}})} \right)^{4/3}$$

Could be probed by future CMB polarization experiments.

$$N_{\mathrm{eff}} = 3.04 \pm 0.18 \quad [\mathrm{Planck} \ \ 2015]$$

SMASHy history of the Universe



Summary

SMASH offers a consistent history of the universe, with the following features:

Provides predictive inflation.

Solves the Higgs instability problem

Addresses the smallness of neutrino masses

Solves the CP problem

Explains the origin of the baryon asymmetry

Includes a dark matter candidate

The model introduces a single new scale: the axion decay constant.

The existence of regions of parameter space in which the above is satisfied is nontrivial, and we have performed detailed analyses.

Summary: predictions

Axion mass and coupling to photons in reach of upcoming experiments (MADMAX, CULTASK)

$$50\,\mu\text{eV} \lesssim m_A \lesssim 200\,\mu\text{eV}, |C_{A\gamma}| = 1.25(4)$$

Precise predictions for cosmological observables n_s, r, $\alpha \lesssim 10^{-3}$, $N_{eff} \sim 0.03$ which can be further constrained by experiments (PRISM, LiteBird, 21cm measurements)