SMASH

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1608.05414 & 1610.01639
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Advances in theoretical cosmology in the light of data

21/07/2017, Nordita

Unifying Inflation with the Axion, Dark Matter, Baryogenesis, and the Seesaw Mechanism

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(Received 22 August 2016; revised manuscript received 22 November 2016; published 15 February 2017)

A minimal extension of the standard model (SM) with a single new mass scale and providing a complete and consistent picture of particle physics and cosmology up to the Planck scale is presented. We add to the SM three right-handed SM-singlet neutrinos, a new vectorlike color triplet fermion, and a complex SM-singlet scalar σ that stabilizes the Higgs potential and whose vacuum expectation value at $\sim 10^{11}$ GeV breaks lepton number and a Peccei-Quinn symmetry simultaneously. Primordial inflation is produced by a combination of σ (nonminimally coupled to the scalar curvature) and the SM Higgs boson. Baryogenesis proceeds via thermal leptogenesis. At low energies, the model reduces to the SM, augmented by seesaw-generated neutrino masses, plus the axion, which solves the strong *CP* problem and accounts for the dark matter in the Universe. The model predicts a minimum value of the tensor-to-scalar ratio $r \simeq 0.004$, running of the scalar spectral index $\alpha \simeq -7 \times 10^{-4}$, the axion mass $m_A \sim 100\ \mu\text{eV}$, and cosmic axion background radiation corresponding to an increase of the effective number of relativistic neutrinos of ~ 0.03. It can be probed decisively by the next generation of cosmic microwave background and axion dark matter experiments.

DOI: 10.1103/PhysRevLett.118.071802

1. Who is the dark matter?

2. Who is the inflaton?

3. Matter/anti-matter asymmetry

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 10^{-9}$$

(CMB)

$$n_p / n_{\bar{p}} \sim 10^4$$

(Galactic cosmic rays)

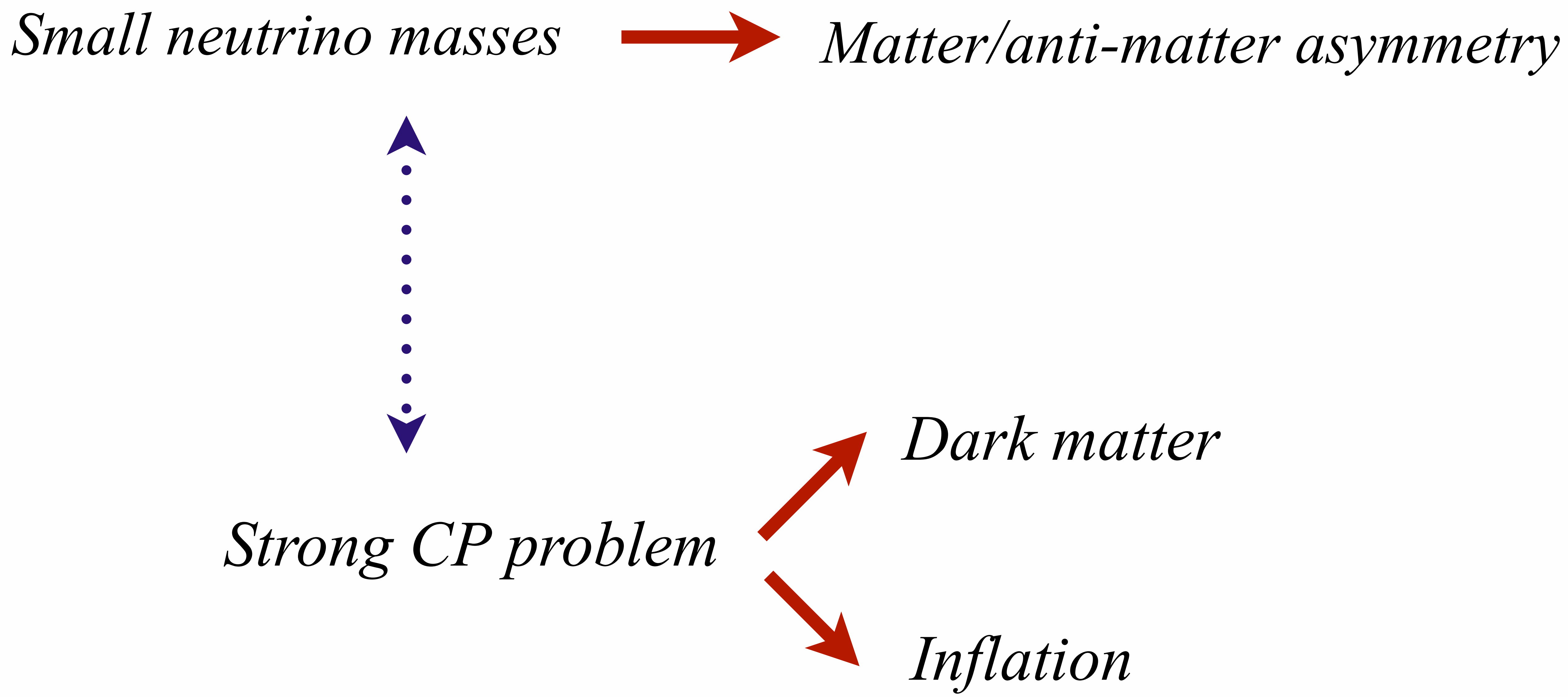
4. Smallness of the neutrino masses $\sum m_\nu \lesssim 0.2\,\mathrm{eV}$

5. Strong CP problem

$$\mathcal{L}_{\mathrm{QCD}} \in -\frac{\theta_0}{32\pi^2} G\tilde{G}$$

$$\theta \equiv \theta_0 - \arg(\det M) \lesssim 10^{-10}$$

(neutron e.d.m.)


Small neutrino masses
Matter/anti-matter asymmetry
Dark matter
Strong CP problem
Inflation

S*tandard*

M*odel*

A*xion*

S*ee-saw*

H*iggs [portal inflation]*

SMASH = SM +

★ Three singlet neutrinos: N_i

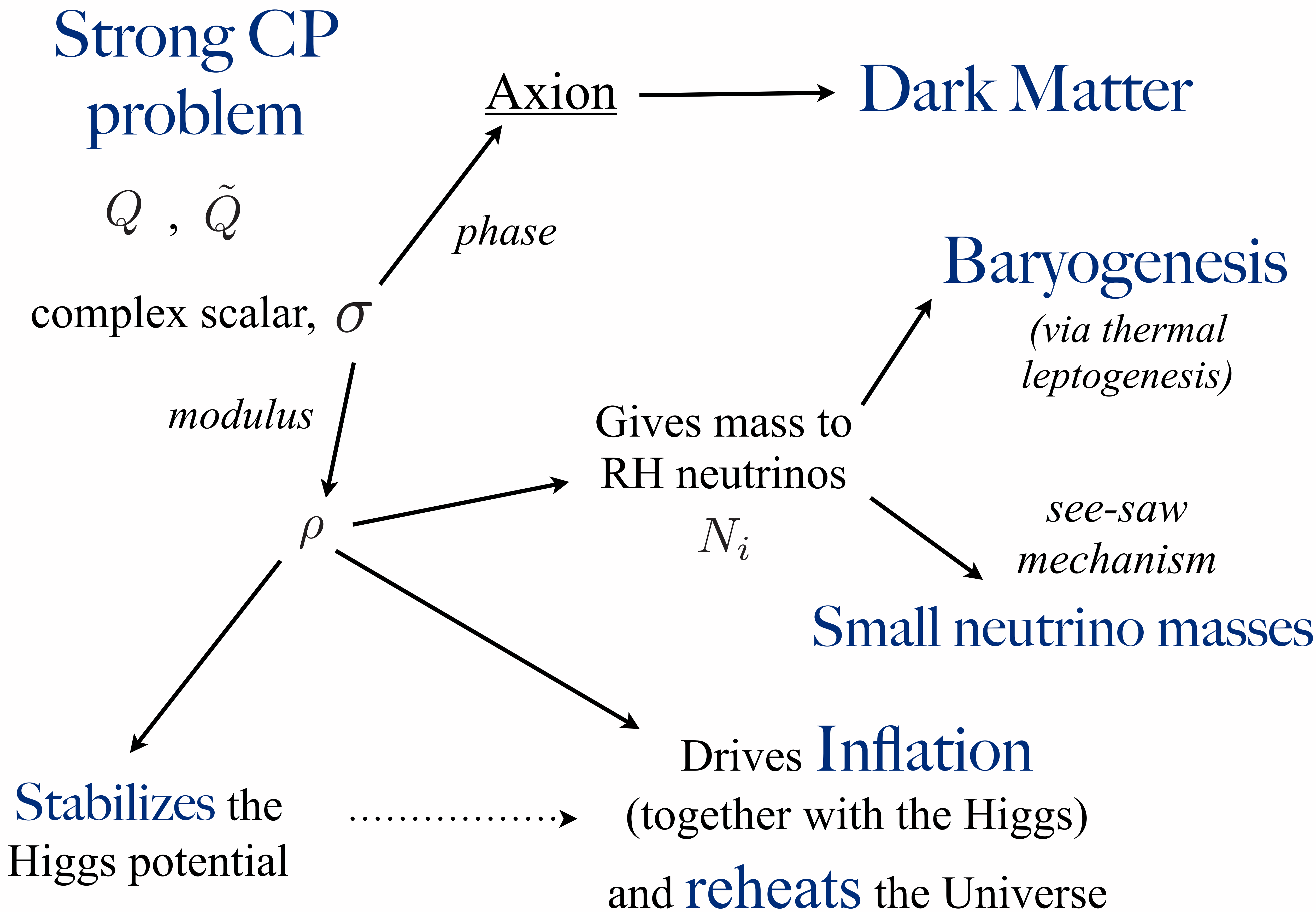
★ A complex scalar: σ

★ Two Weyl fermions: Q and $\tilde{Q}$ in the $\mathbf{3}$ and $\bar{\mathbf{3}}$ of $SU(3)_c$

Dias, Machado, Nishi, Ringwald and Vaudrevange 2014

★ New $U(1)$ symmetry: PQ and lepton number

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


Strong CP problem
Q , $\tilde{Q}$
complex scalar, σ
phase
Axion
Dark Matter
modulus
ρ
Gives mass to RH neutrinos N_i
Baryogenesis
(via thermal leptogenesis)
see-saw mechanism
Small neutrino masses
Stabilizes the Higgs potential
Drives Inflation
(together with the Higgs)
and reheats the Universe

SM

$$\mathcal{L} \supset - \Big[Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j$$

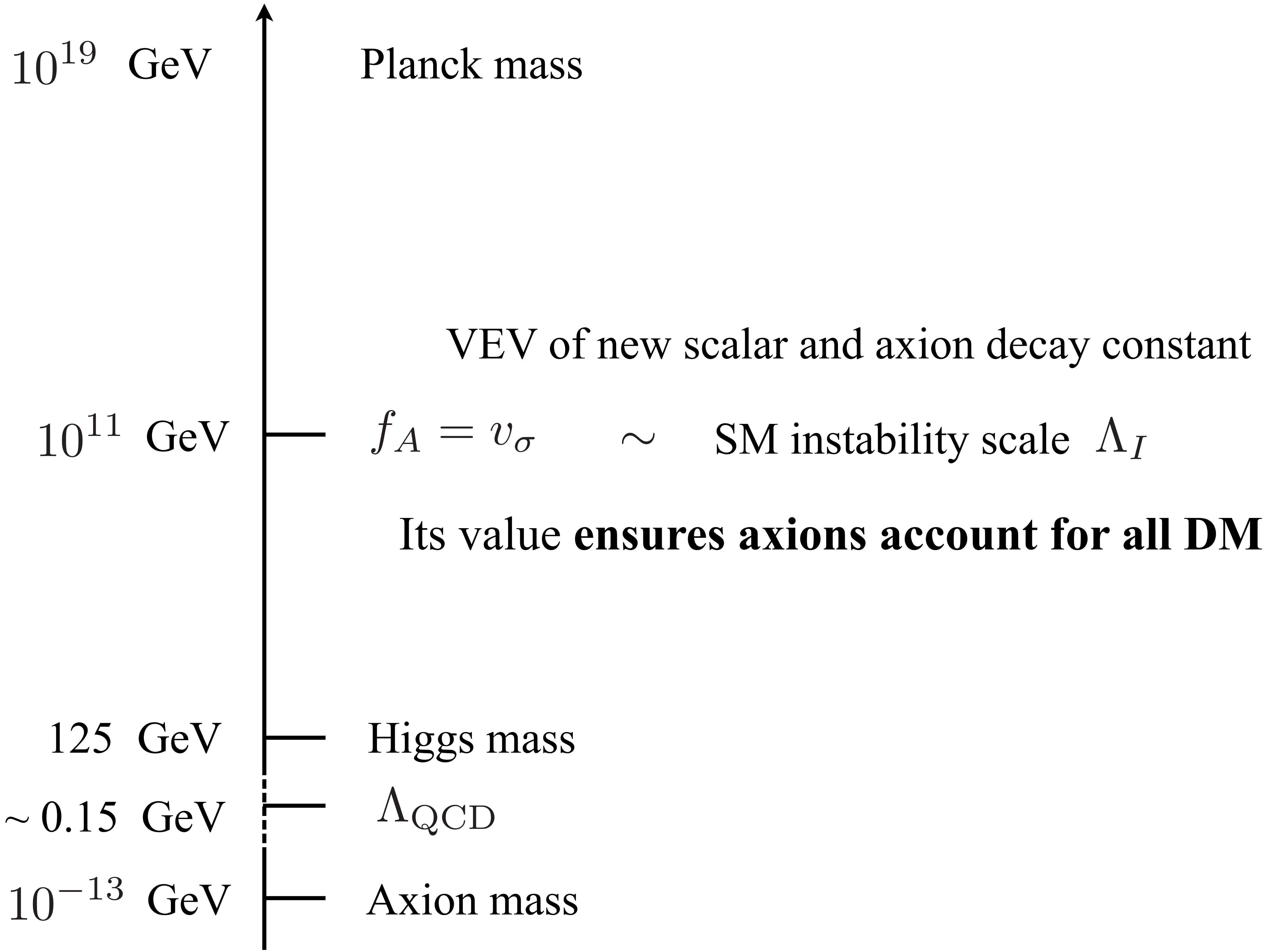
Neutrino masses

$$+ y \, \tilde{Q} \sigma Q + \; y_{Q_{d\,i}} \sigma Q d_i + h.c. \Big] \, ,$$

Strong CP problem (and DM)

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

Stability, inflation and reheating


10^{19} GeV
Planck mass
VEV of new scalar and axion decay constant
10^{11} GeV
$f_A = v_\sigma \quad \sim$ SM instability scale Λ_I
Its value **ensures axions account for all DM**
125 GeV
Higgs mass
~ 0.15 GeV
$\Lambda_{\rm QCD}$
10^{-13} GeV
Axion mass

Axion mass: $m_A = (57.2 \pm 0.7)\left(\frac{10^{11}\mathrm{GeV}}{f_A}\right)\mu\mathrm{eV}$

Borsanyi et al. 2016 from lattice QCD

$$\frac{M_{N_i}}{Y} \sim \frac{m_Q}{y} \sim \frac{m_\rho}{\sqrt{\lambda_\sigma}} \sim v_\sigma + \mathcal{O}(v) \sim 10^{11}\mathrm{GeV}$$

Upper limit on Yukawas $Y,\ y$ for stability

Typically: $10^{-13} \lesssim \frac{\lambda_\sigma}{5} \lesssim 10^{-10}$ from inflation

The strong CP problem

$$\mathcal{L}_{\rm QCD} \in -\frac{\theta_0}{32\pi^2}\, G\tilde{G}$$ breaks CP

$$\theta \equiv \theta_0 - \arg(\det M)$$

Invariant under chiral transformations

Quark mass matrix

$$\theta \lesssim 10^{-10}$$

from neutron e.d.m.

Solution?

e.g. another transformation under which $\delta S \propto \int G\,\tilde{G}$

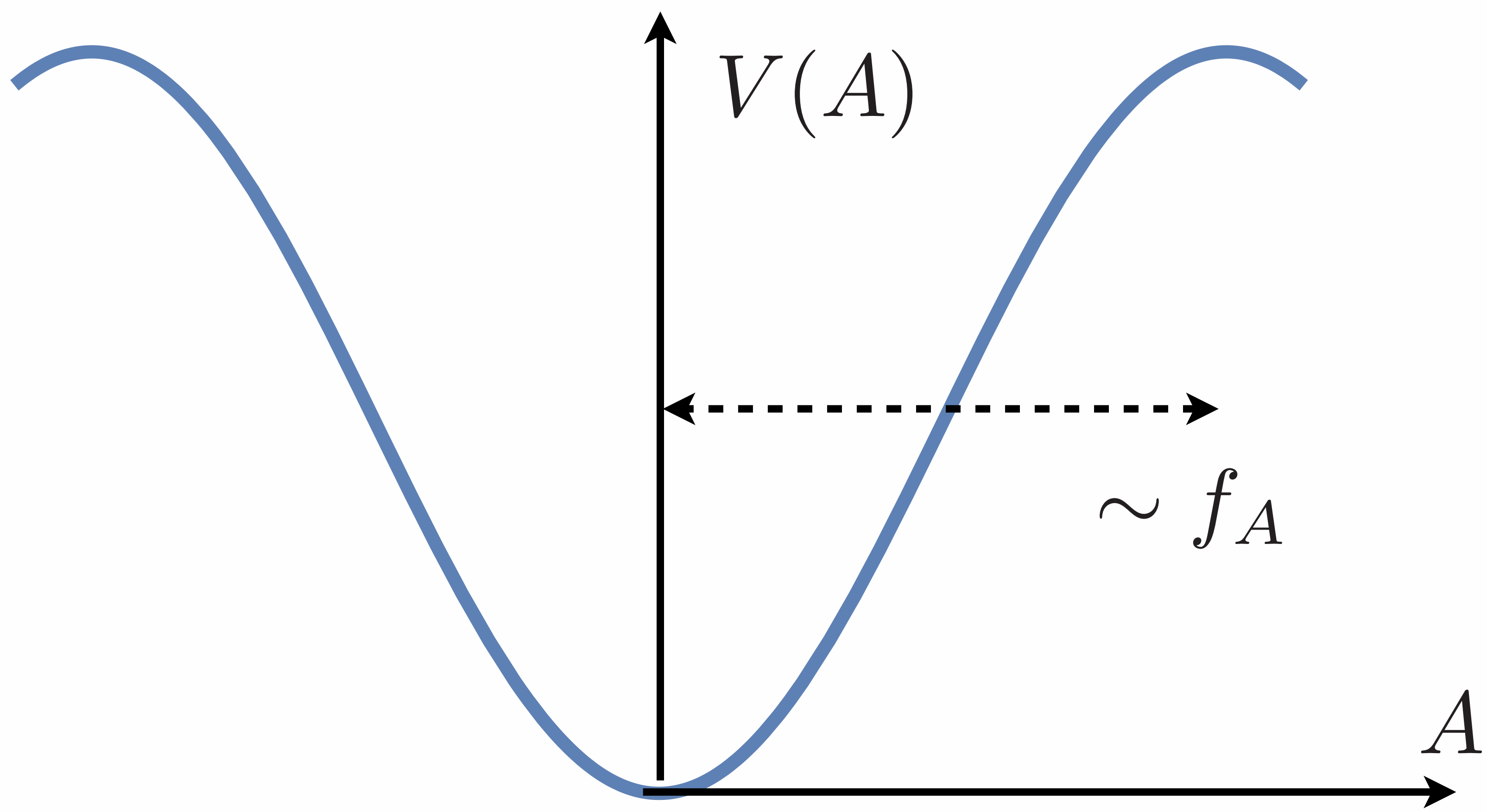
making θ unphysical.

Global sym. that is anomalous under SU(3)c

(but there is no such symmetry in the SM)

The axion

$$\mathcal{L} \in \frac{1}{2}\partial_\mu A\,\partial^\mu A + i\frac{A}{32\pi^2}G\tilde{G} + V(A)$$



The axion potential is generated by non-perturbative QCD physics

KSVZ-like axion

$$\mathcal{L} \in \frac{1}{2}\partial_\mu A\,\partial^\mu A + i\frac{A}{32\pi^2}G\tilde{G} + V(A)$$

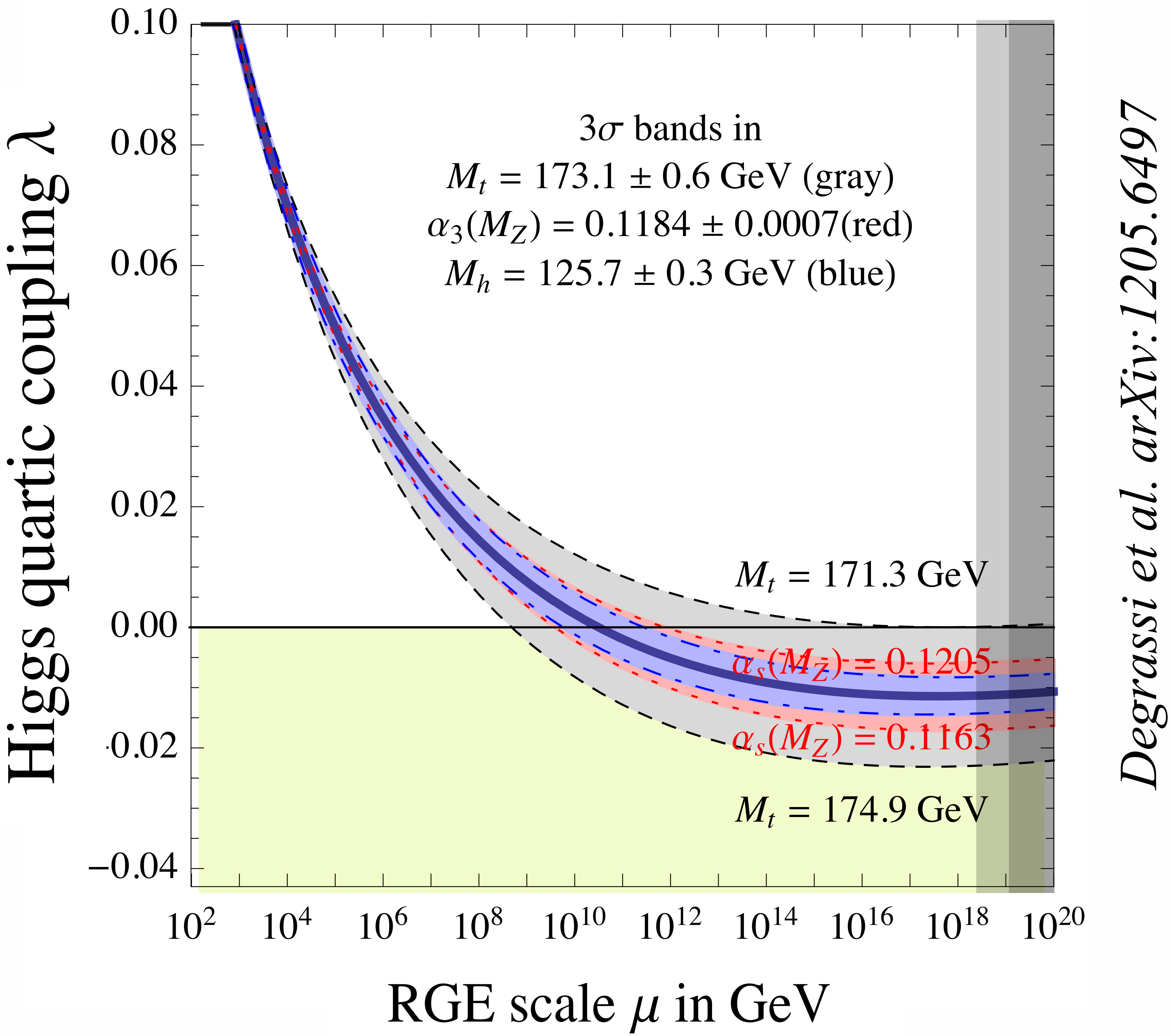
The coupling of the axion to QCD is a dim. 5 operator.

$$\frac{1}{2}\partial_\mu\sigma\,\partial^\mu\sigma^* + \lambda_\sigma\left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)^2 + y\,\tilde{Q}\sigma Q + \ h.c.$$

$$\sigma \to e^{i\alpha}\,\sigma\,, \quad Q \to e^{-i\frac{\alpha}{2}\gamma_5}\,Q\,, \quad \alpha = A/v_\sigma$$

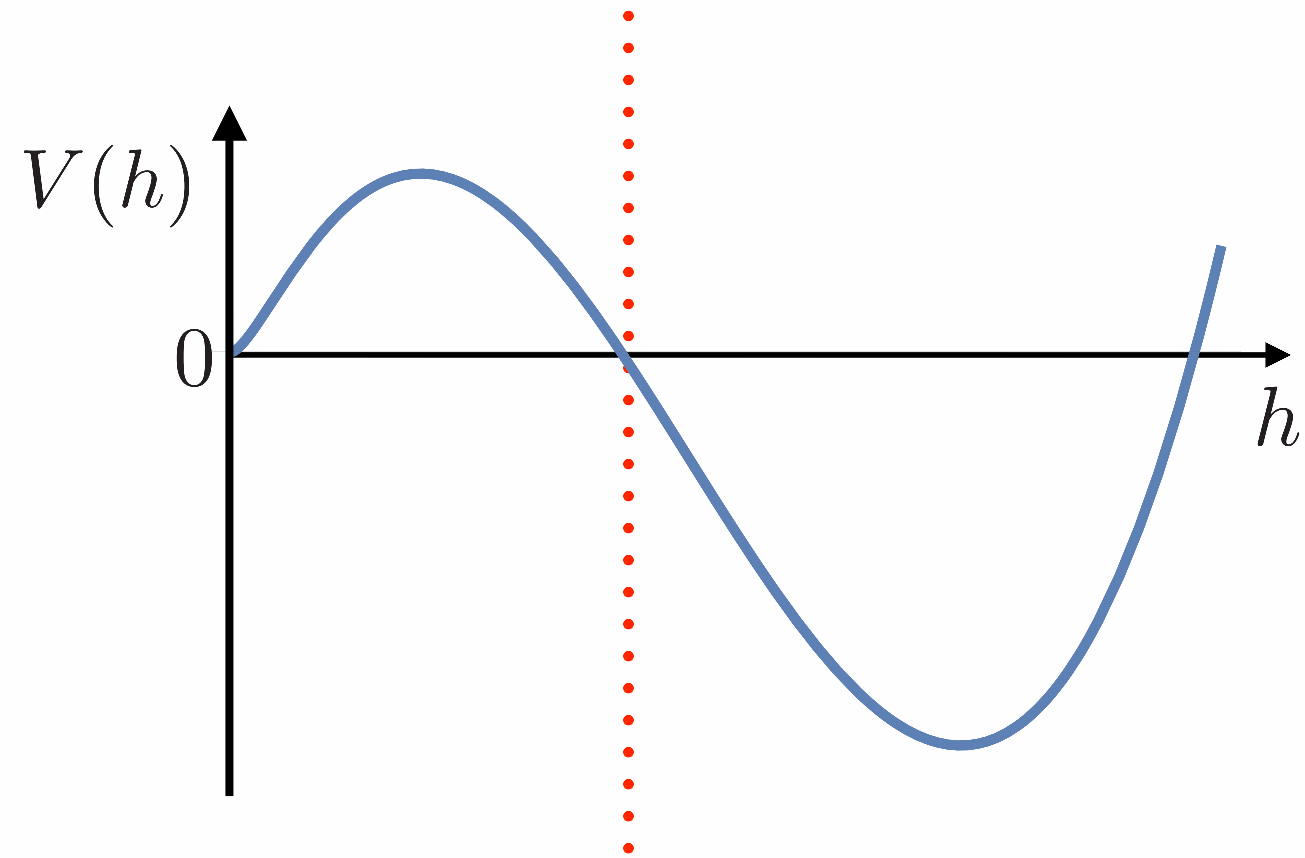
and integrate out Q and $|\sigma|$ below $v_\sigma = f_A$

Inflation and the SM instability



Inflation and the SM instability

$$V(h) \simeq \frac{\lambda_H(h)}{4} h^4$$



$\Lambda_I \sim 10^{11}\mathrm{GeV}$

Fluctuations during inflaton:

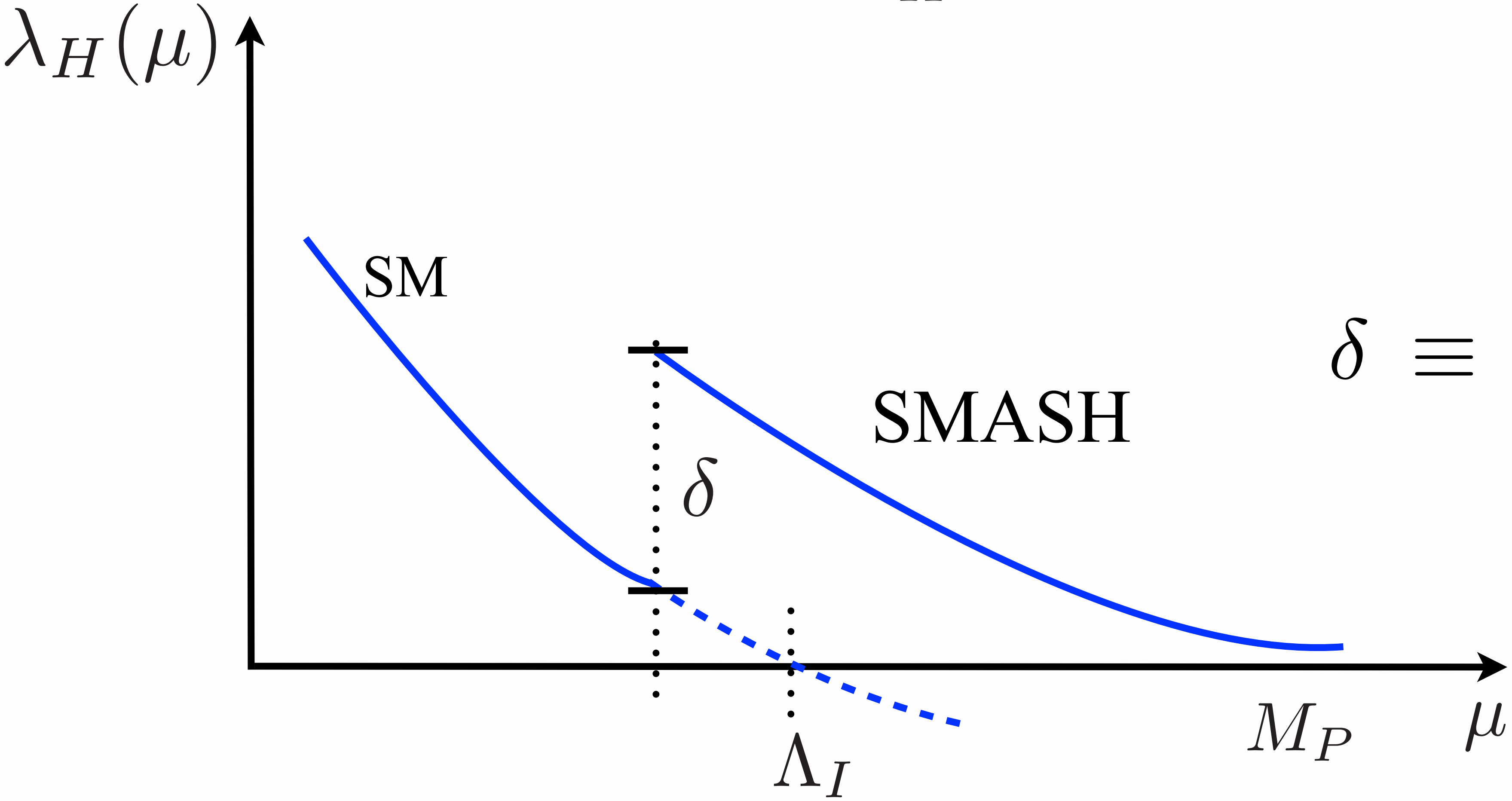
$$\sqrt{\langle h^2 \rangle} \sim \mathcal{H} \sim 10^{-5} M_P \sim 10^{14}\mathrm{GeV} \gg \Lambda_I$$

Threshold stabilization

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

At low energies, below the mass of $|\sigma|$

$$\lambda_H^{(SM)} = \lambda_H - \delta$$



$$\delta \equiv \lambda_{H\sigma}^2/\lambda_\sigma \sim 10^{-2}$$

Inflation from the Higgs?

$$S \supset - \int d^4x \sqrt{-g} \left[\frac{M^2}{2} + \xi_H \, H^\dagger H + \quad \ldots \quad \right] R$$

$$\tilde{V} \sim \frac{\lambda_H}{\xi_H^2} M_P^4$$

CMB temperature fluctuations $\longrightarrow$ $\xi_H \sim 10^5 \sqrt{\lambda_H} \sim 10^4$

Breaking of perturbative unitarity:

$$\Lambda_U = \frac{M_P}{\xi_H} \sim 10^{14}\,\mathrm{GeV} \ll \frac{M_P}{\sqrt{\xi_H}} \sim 10^{16}\,\mathrm{GeV}$$

Inflation with the new singlet

$$S \supset -\int d^4x\sqrt{-g}\left[\frac{M^2}{2} + \xi_H\, H^\dagger H + \xi_\sigma\, \sigma^*\sigma\right] R\,,$$

$$\tilde{V} \sim \frac{\lambda}{\xi_\sigma} M_P^4, \quad \xi_\sigma \lesssim 1$$ and also $$\xi_H \lesssim 1$$

$$\boxed{\lambda_{H\sigma} > 0 \longrightarrow \text{inflaton} = |\sigma|\ , \ \lambda = \lambda_\sigma}$$

$\lambda_{H\sigma} < 0 \longrightarrow$ $\text{inflaton} = |\sigma|$ + small Higgs component,

$$\lambda = \lambda_\sigma - \lambda_{H\sigma}^2/\lambda_H$$

Reheating after inflation

A small Higgs component in the inflaton of SMASH guarantees successful reheating

$$N_\nu^{\mathrm{eff}} = 3.04 \pm 0.18$$

from CMB and BAO data

$\lambda_{H\sigma} > 0\,, \quad T_R \sim 10^7$ GeV

Axions remain decoupled from thermal bath

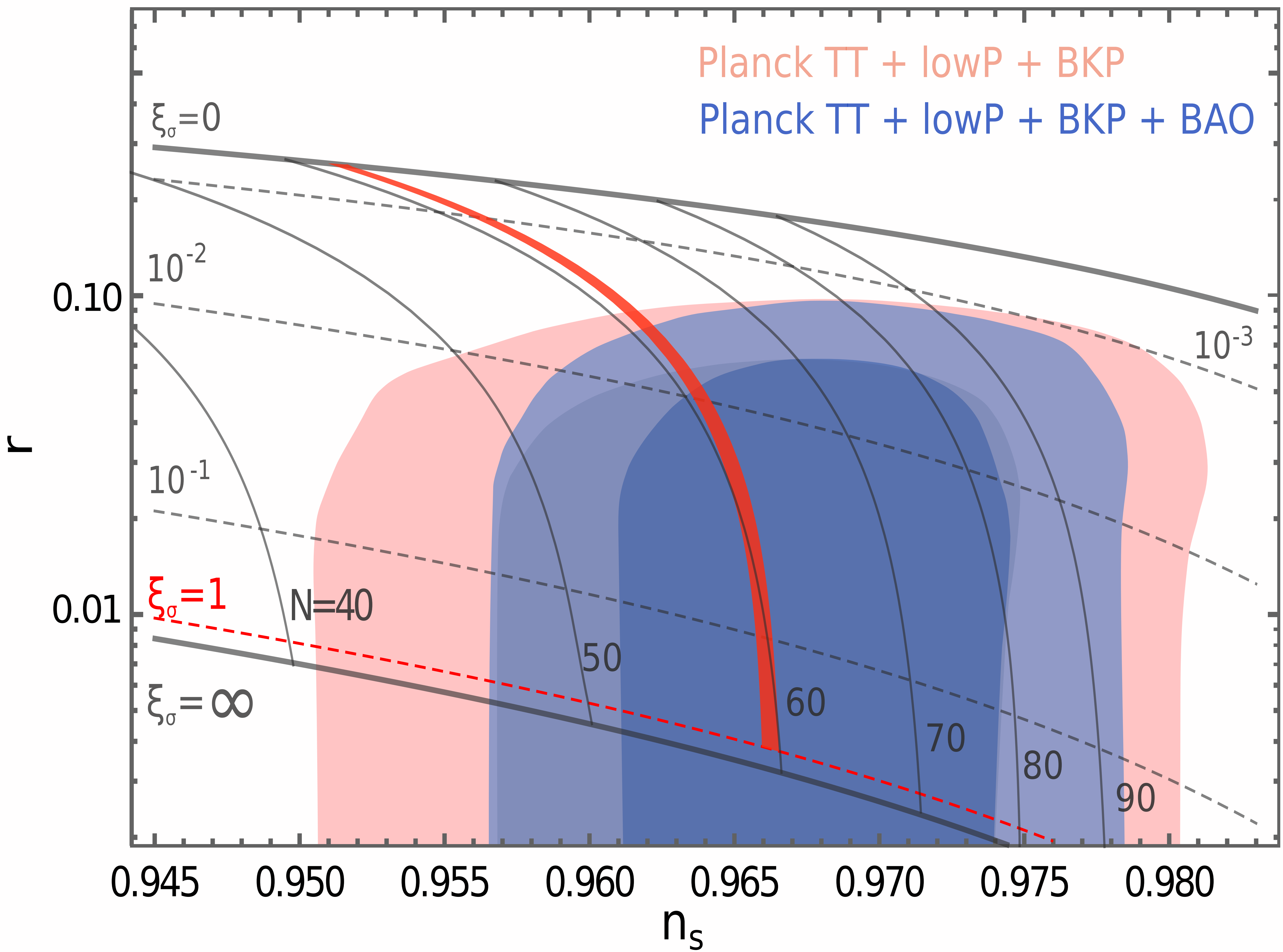
$$\Delta N_{\mathrm{eff}} \sim 1$$

Too much axion radiation

$\lambda_{H\sigma} < 0\,, \quad T_R \sim 10^{10}$ GeV

$$\Delta N_{\mathrm{eff}} \sim 0.03$$

CMB S4, Simons O. ...



Planck TT + lowP + BKP
Planck TT + lowP + BKP + BAO
ξσ=0
10-2
10-3
10-1
ξσ=1
N=40
50
60
70
80
90
ξσ=∞
0.10
0.01
r
0.945
0.950
0.955
0.960
0.965
0.970
0.975
0.980
ns

Primordial spectrum

CMB + unitarity: $0.004 \lesssim r \lesssim 0.07$

(CORE, LiteBird, Pixie, CMB S4)

$$5 \times 10^{-13} \lesssim \lambda \lesssim 5 \times 10^{-10}$$

Small non-Gaussianities and isocurvature

$$0.962 \lesssim n_s \lesssim 0.966$$

Spectral index running: $\alpha \simeq -7 \times 10^{-4}$

(21 cm line of neutral Hydrogen)

Axion dark matter

$\lambda_{H\sigma} < 0$: SSB of PQ symmetry after inflation

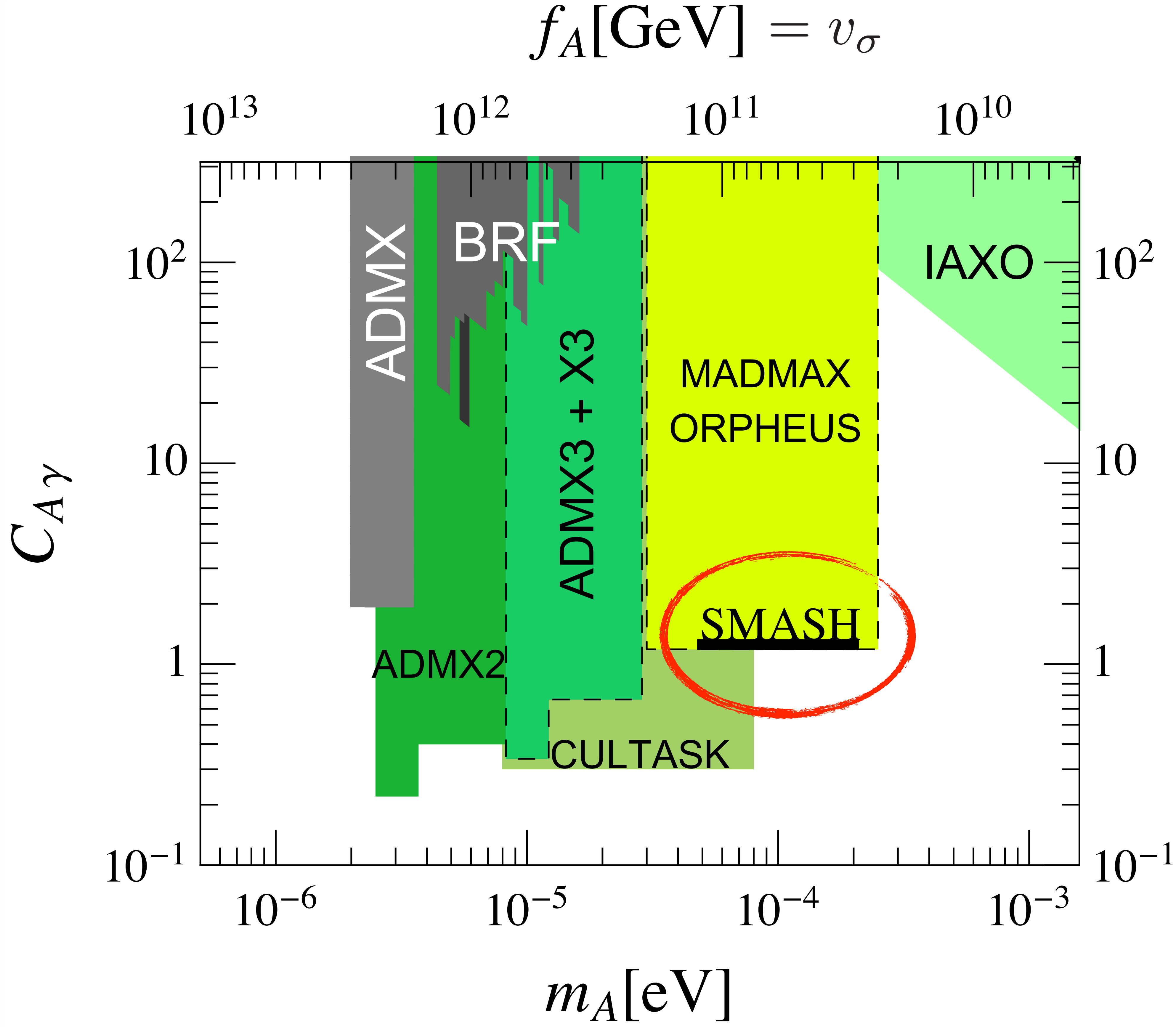
vacuum misalignment: $\ddot{A} + 3\mathcal{H}\dot{A} + m_A^2 A = 0$

and decay of Peccei-Quinn strings

$$3 \times 10^{10}\,\mathrm{GeV} \lesssim v_\sigma \lesssim 1.2 \times 10^{11}\,\mathrm{GeV},$$

$$\downarrow$$

$$50\,\mu\mathrm{eV} \lesssim m_A \lesssim 200\,\mu\mathrm{eV}$$



$f_A[\mathrm{GeV}] = v_\sigma$
10^{13}
10^{12}
10^{11}
10^{10}
ADMX
BRF
ADMX3 + X3
MADMAX
ORPHEUS
IAXO
SMASH
ADMX2
CULTASK
10^2
10
1
10^{-1}
$C_{A\gamma}$
10^{-6}
10^{-5}
10^{-4}
10^{-3}
$m_A[\mathrm{eV}]$

SMASH

Solves **the strong CP problem** with a *KSVZ-like* ***axion,***

explains:

the nature of **dark matter** *(*with ***the axion)***,

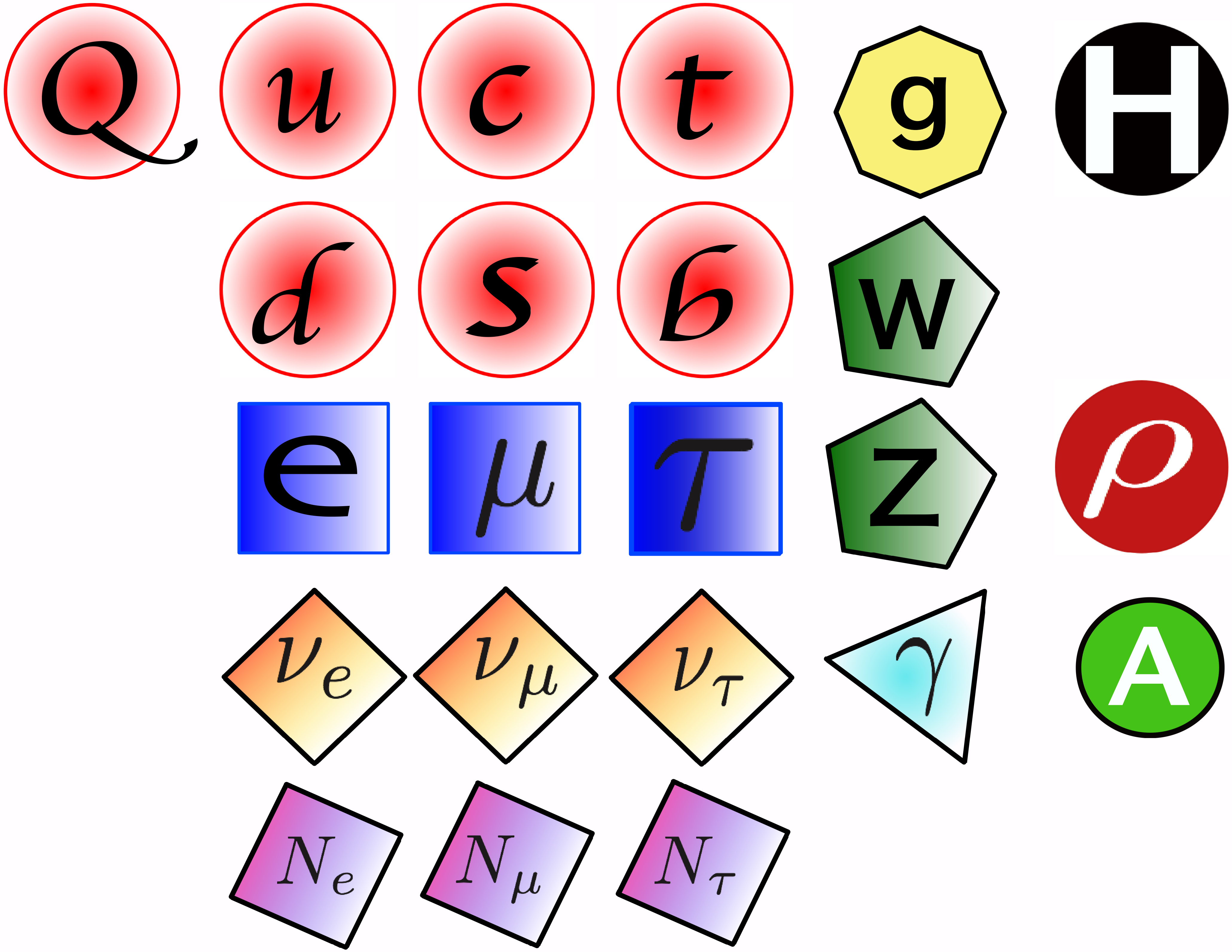
the smallness of neutrino masses *(through* ***the see-saw)***,

baryogenesis *(*via ***leptogenesis)***

and

gives a candidate for **primordial inflation**.

SMASH



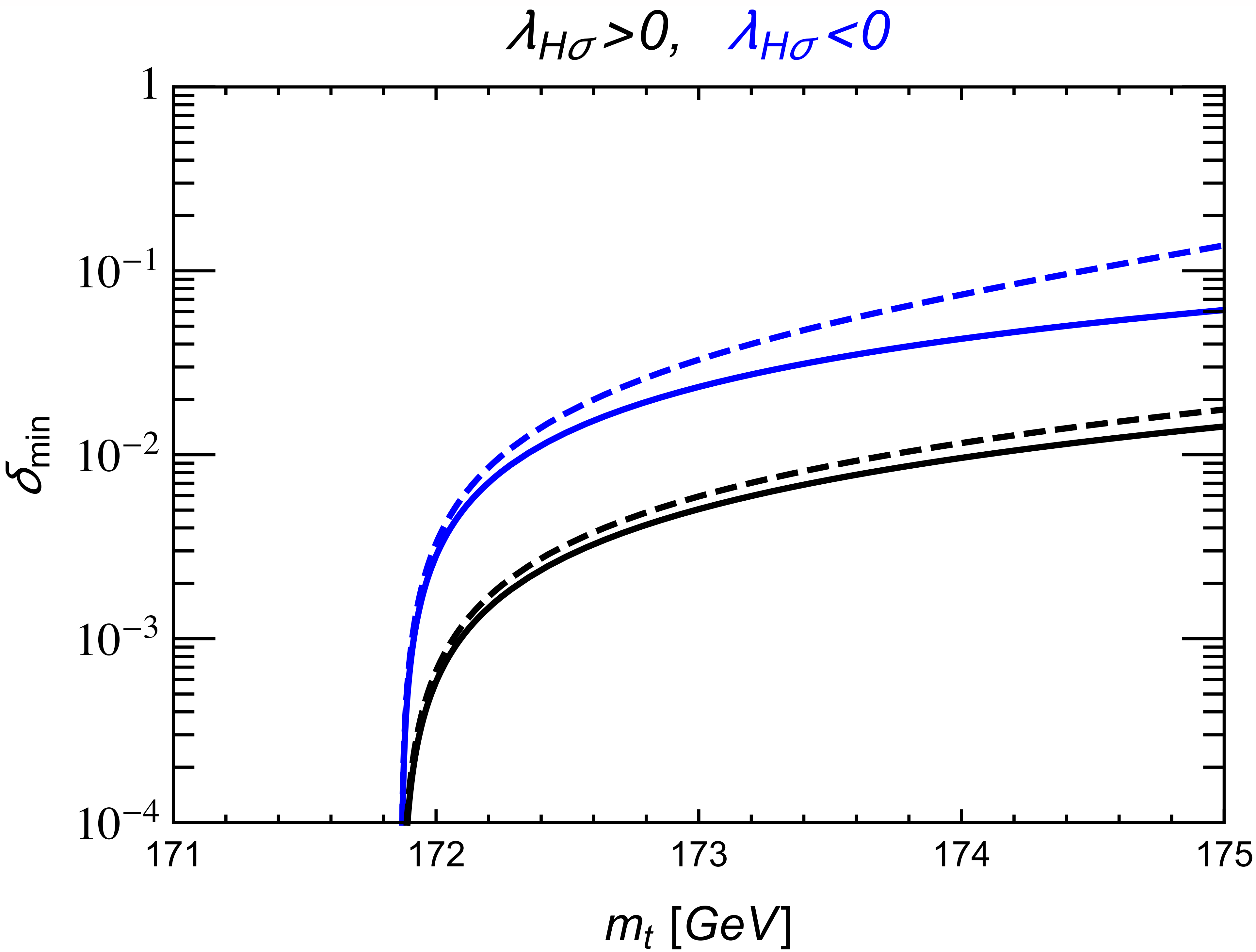
Neutrino masses, from see-saw

$$F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j$$

σ takes a large VEV $v_\sigma \sim 10^{11}\,\mathrm{GeV}$

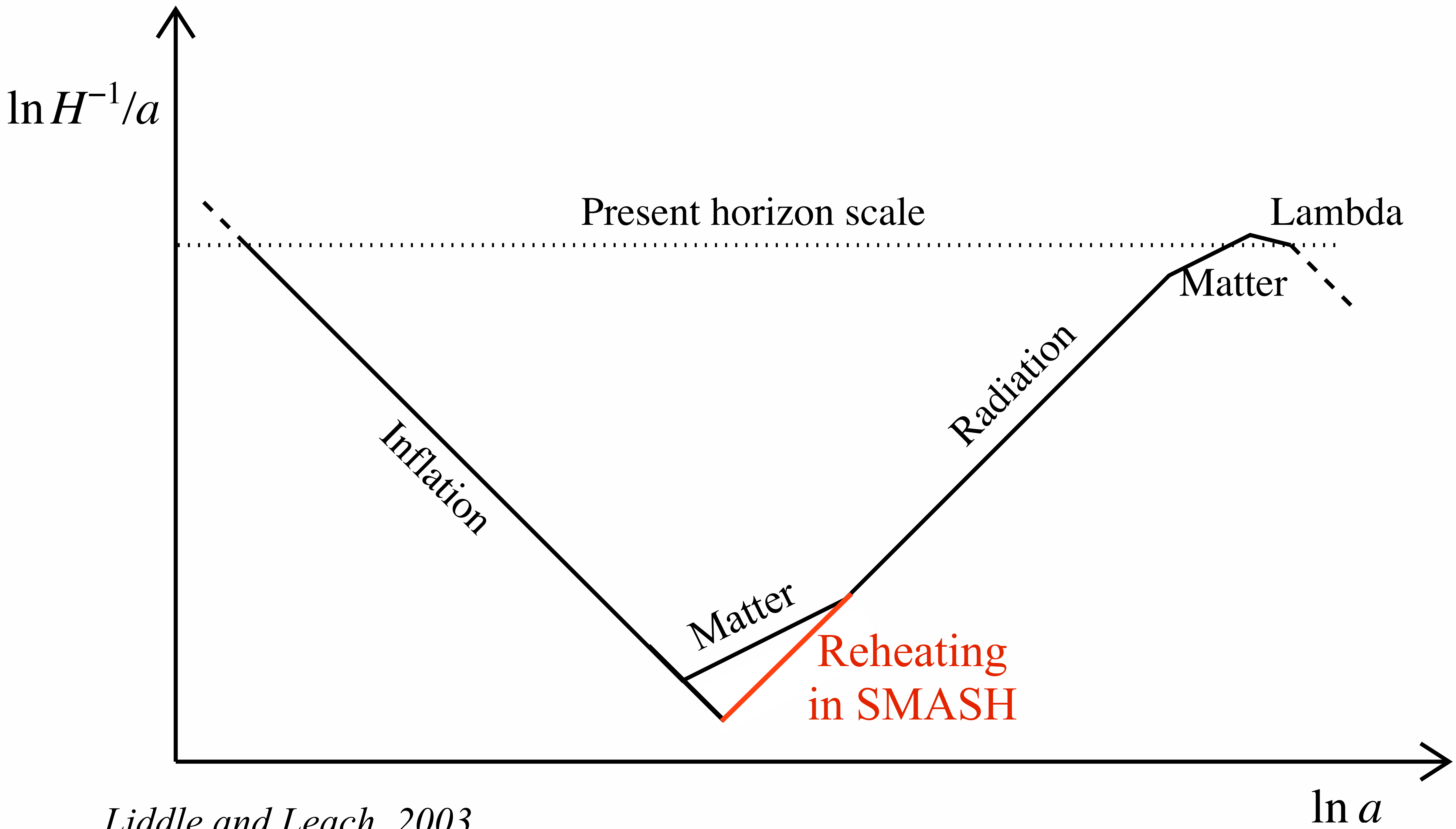
$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & F v \\ F^T v & Y\, v_\sigma \end{pmatrix}$$

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

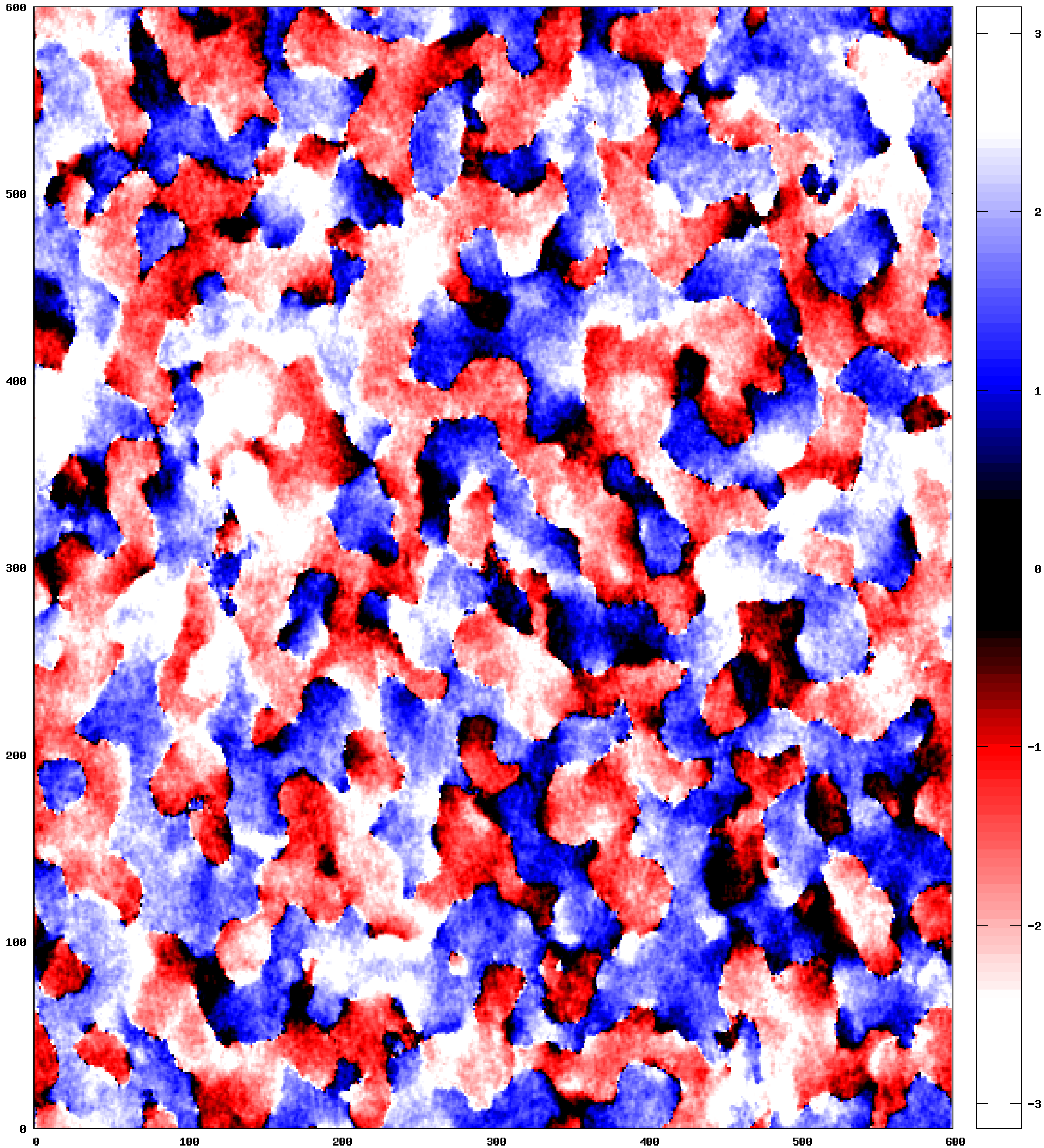


$\mu = m_\rho$ (solid) and $\mu = 30 M_P$ (dashed)

Reheating with a quartic potential



Liddle and Leach, 2003



Preheating

Parametric resonance of fluctuations of σ

θ

PQ symmetry non-thermally restored after ~14 oscillations

Matter/anti-matter asymmetry

Obtained from thermal leptogenesis:

Fukugita and Yanagida, 1986

Vanilla leptogenesis:

Hierarchical RH neutrino mass spectrum $3M_1 \lesssim M_3 \sim M_2$

(determined by the Yukawas in our case)

For a thermal distribution of the lightest RH neutrino and neglecting flavour effects, the observed baryon asymmetry is generated if

$$M_1 \gtrsim 5 \times 10^8 \text{ GeV}; \qquad (M_D M_D^T)_{11}/M_1 \lesssim 10^{-3}\,\text{eV}$$

Davidson and Ibarra, 2002

Buchmüller, di Bari and Plumacher 2002

For larger RH masses, resonant leptogenesis may occur

Pilaftsis and Underwood, 2003