SMASH: how to unify inflation with the axion, dark matter, baryogenesis and the see-saw

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Minimal extension of the SM for:

1. Inflation
2. Baryogenesis
3. Dark matter
4. Smallness of neutrino masses
5. Strong CP problem

Basic structure

1. Inflation
2. Baryogenesis
3. Dark matter
4. Smallness of neutrino masses
5. Strong CP problem

An example of minimality: $\nu\,\mathrm{Minimal\,SM}$

$\mathrm{SM}\,+$ Three singlet neutrinos, N_i , with Majorana masses

- Small masses of SM neutrinos from see-saw
- The lightest N_i is a DM candidate with ~ keV mass
- Baryogenesis from oscillations of the two heavier N_i

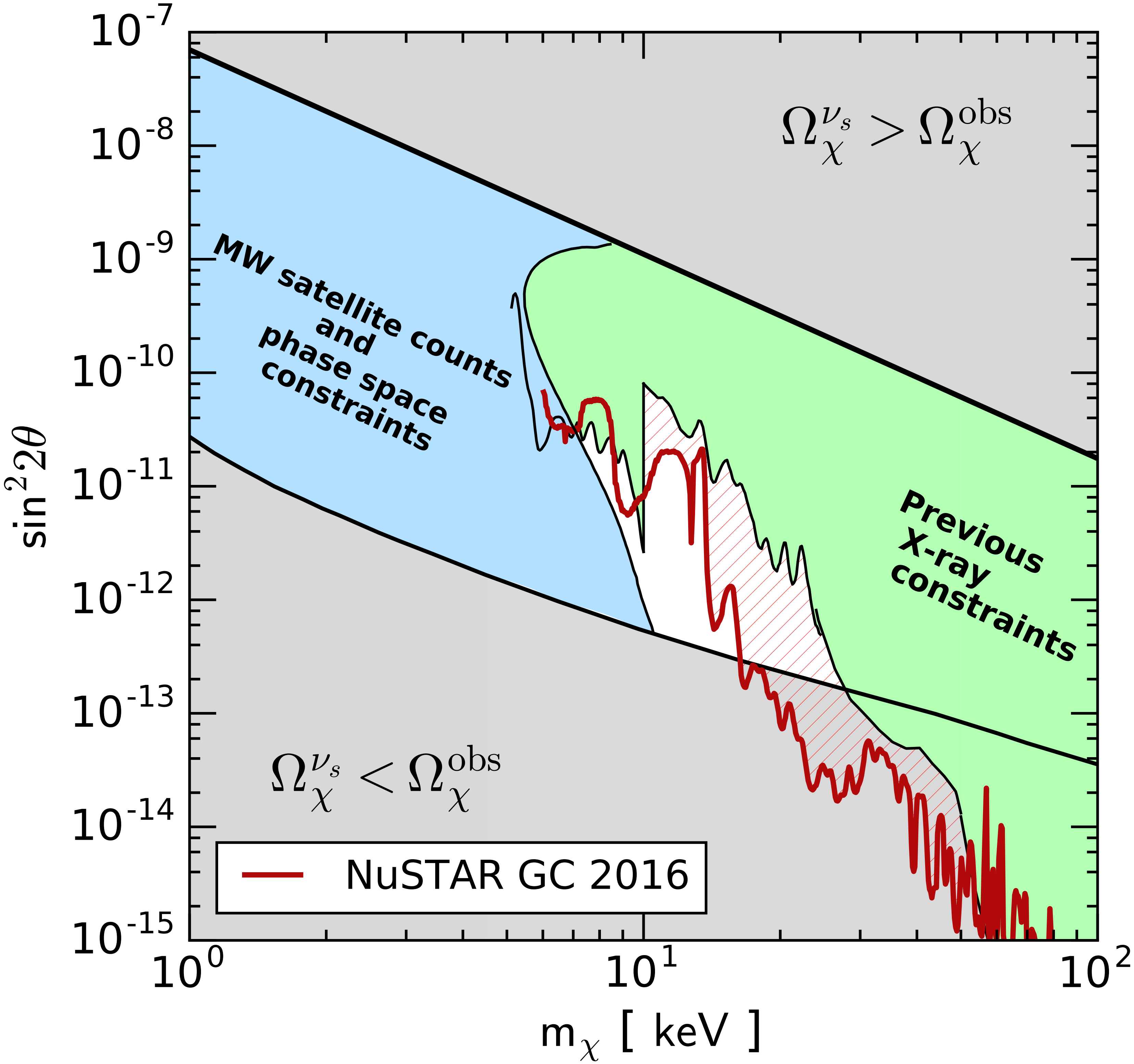
Asaka, Blanchet and Shaposhnikov 2005

- The Higgs, non-minimally coupled to gravity, gives inflation

Bezrukov and Shaposhnikov 2008

νMSM

1. inflation 
2. baryogenesis ✓
3. dark matter (now small window, *Perez et al. 2016*)
4. smallness of neutrino masses ✓
5. strong CP problem ✗



νMSM dark matter

NuSTAR

Observations of the Galactic Center to search for X-ray lines from the radiative decays of sterile neutrino DM.

$$\chi \to \gamma\,\nu$$

For sterile neutrino dark matter in νMSM, only a tiny window remains near $m_\chi \simeq 10 - 16\,\mathrm{keV}$.

Perez et al. 1609.00667

νMSM

inflation

1. Higgs inflation 

- Negative SM potential at large field values

- Perturbative unitarity breaking $\longrightarrow$ Loss of predictivity

SMASH

Standard Model -
Axion -
See-saw -
Higgs portal (inflation)

SMASH = SM +

★ Three singlet neutrinos, N_i

★ A complex singlet, σ

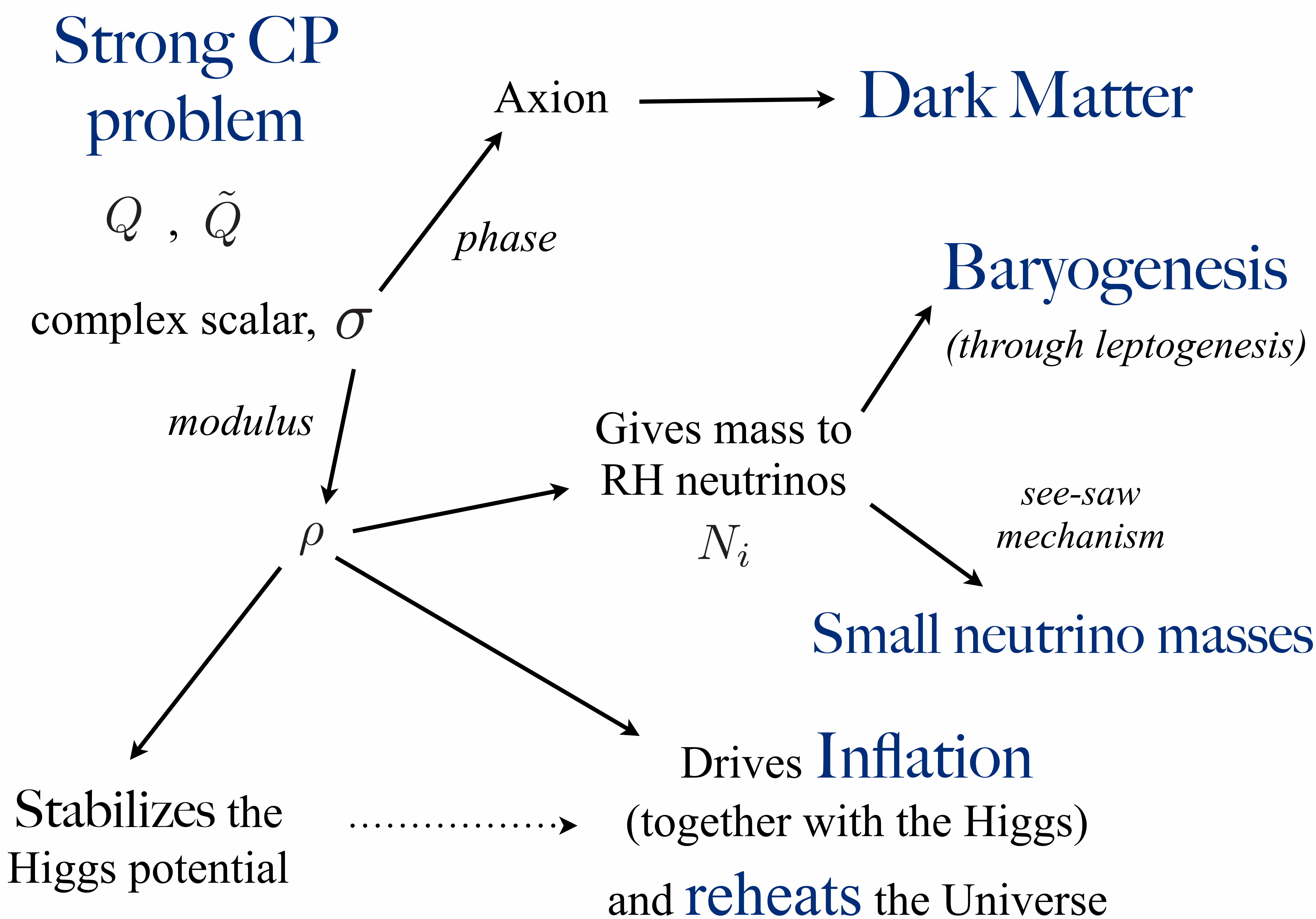
★ Q and $\tilde{Q}$ in the fund. and anti-fund. reps. of $SU(3)_c$

(with hypercharges -1/3 and 1/3, allowing them to decay into SM quarks)

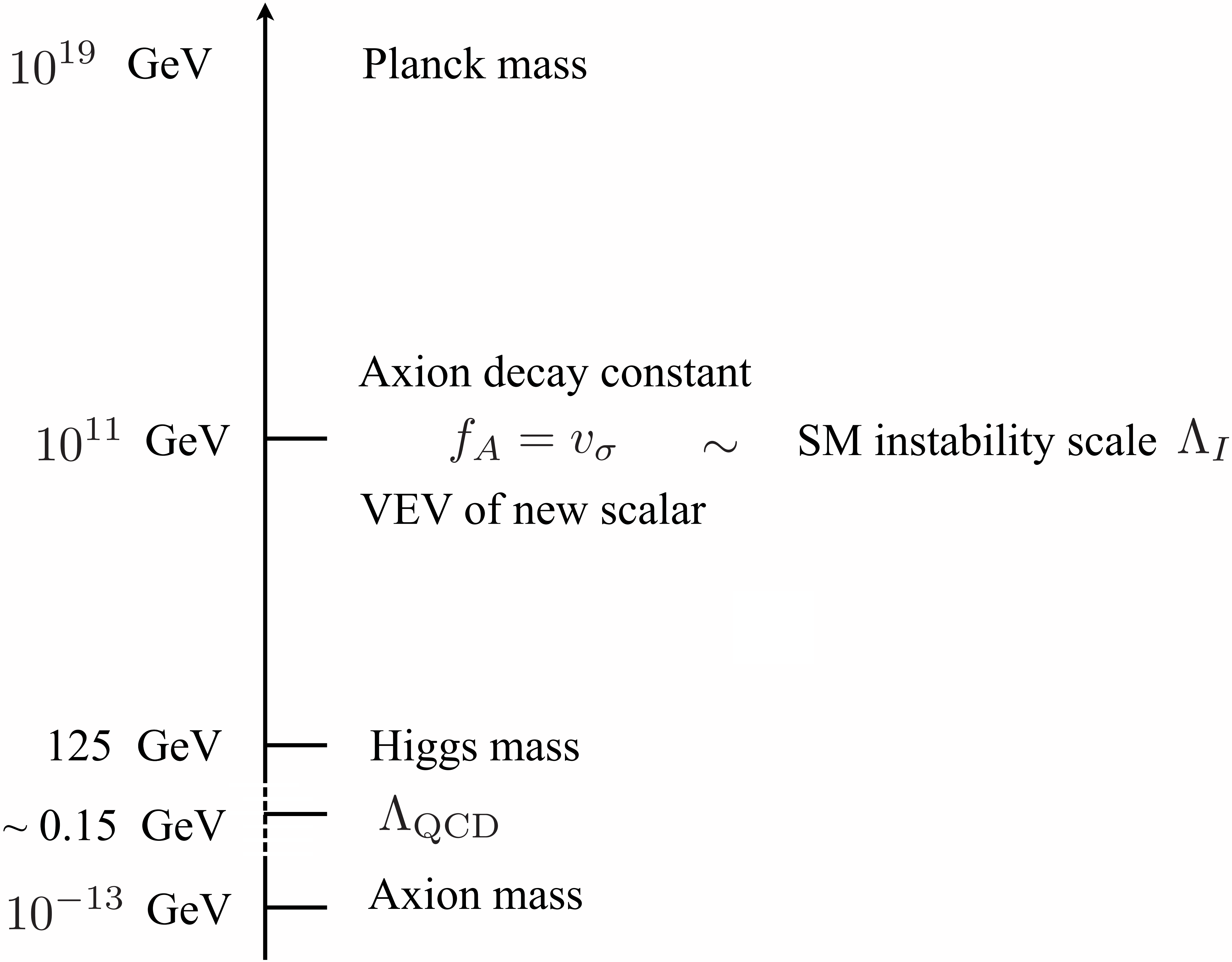
Dias, Machado, Nishi, Ringwald and Vaudrevange 2014

★ New global $U(1)$ symmetry with charges:

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
(through leptogenesis)
see-saw mechanism
Small neutrino masses
Stabilizes the Higgs potential
Drives Inflation
(together with the Higgs)
and reheats the Universe


10^{19} GeV
Planck mass
Axion decay constant
10^{11} GeV
$f_A = v_\sigma$ $\sim$ SM instability scale Λ_I
VEV of new scalar
125 GeV
Higgs mass
~ 0.15 GeV
Λ_{QCD}
10^{-13} GeV
Axion mass

Mass spectrum from a single new scale, f_A

$v_\sigma = f_A \sim 10^{11}\mathrm{GeV}$ ensures all the DM is in axions

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

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

Yukawa couplings and potential:

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

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

See-saw

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

Couplings to gravity:

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

Inflation

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 $v_\sigma \sim 10^{11}\,\mathrm{GeV}$

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

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

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.

Solutions?

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)

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

The KSVZ axion

Kim-Shifman-Vainshtein-Zakharov 1979

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

UV completion ?

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

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

Redefine Q with a chiral transformation of parameter $\alpha = \frac{A}{v_\sigma}$

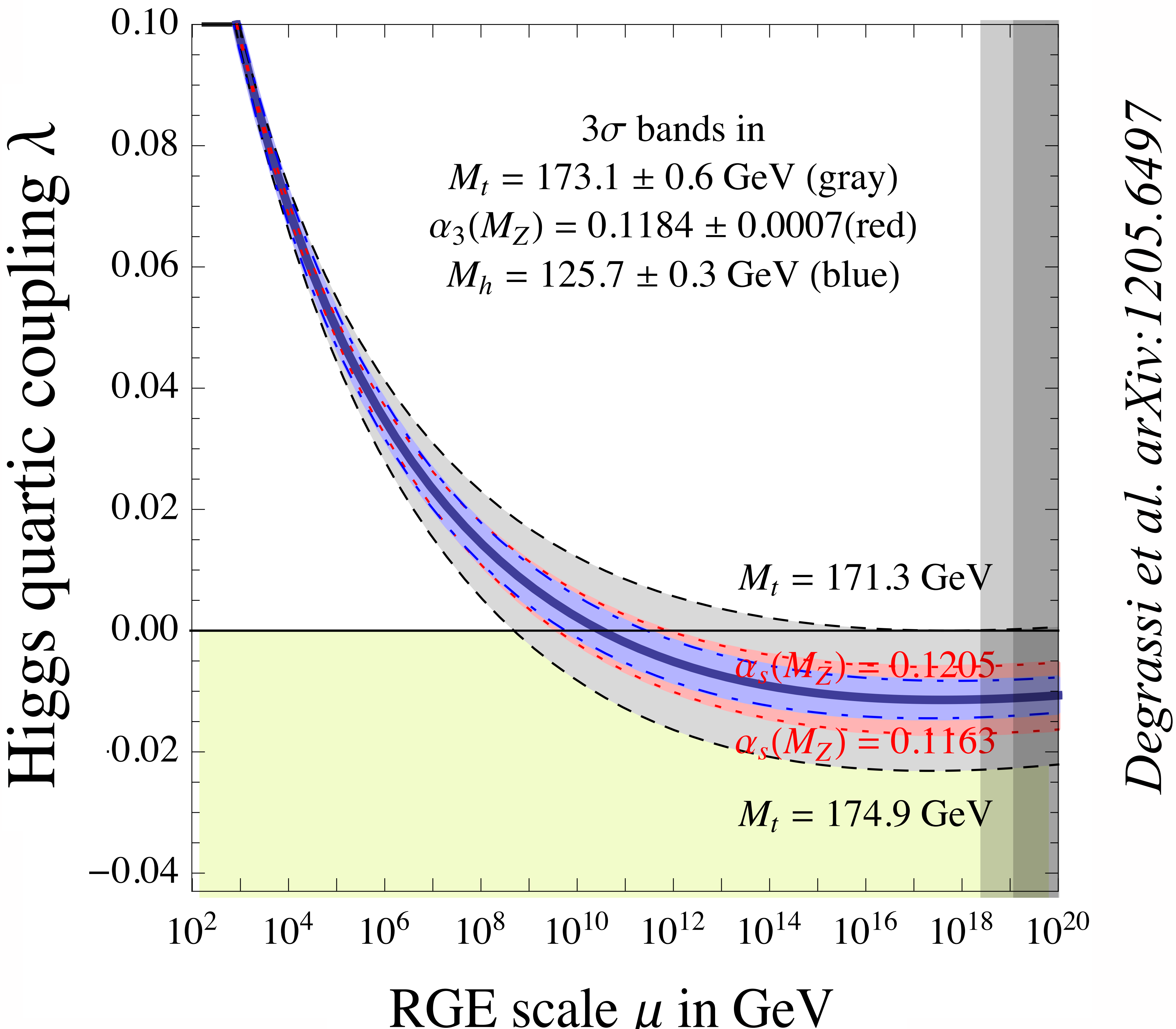
and integrate out Q and $|\sigma|$ below v_σ

$$\sigma(x) = \frac{1}{\sqrt{2}}\left[v_\sigma + \rho(x)\right] e^{iA(x)/v_\sigma}$$

Solving the strong CP problem gives us
a DM candidate (the axion, A) and
a heavy scalar, ρ, relevant for inflation and stability

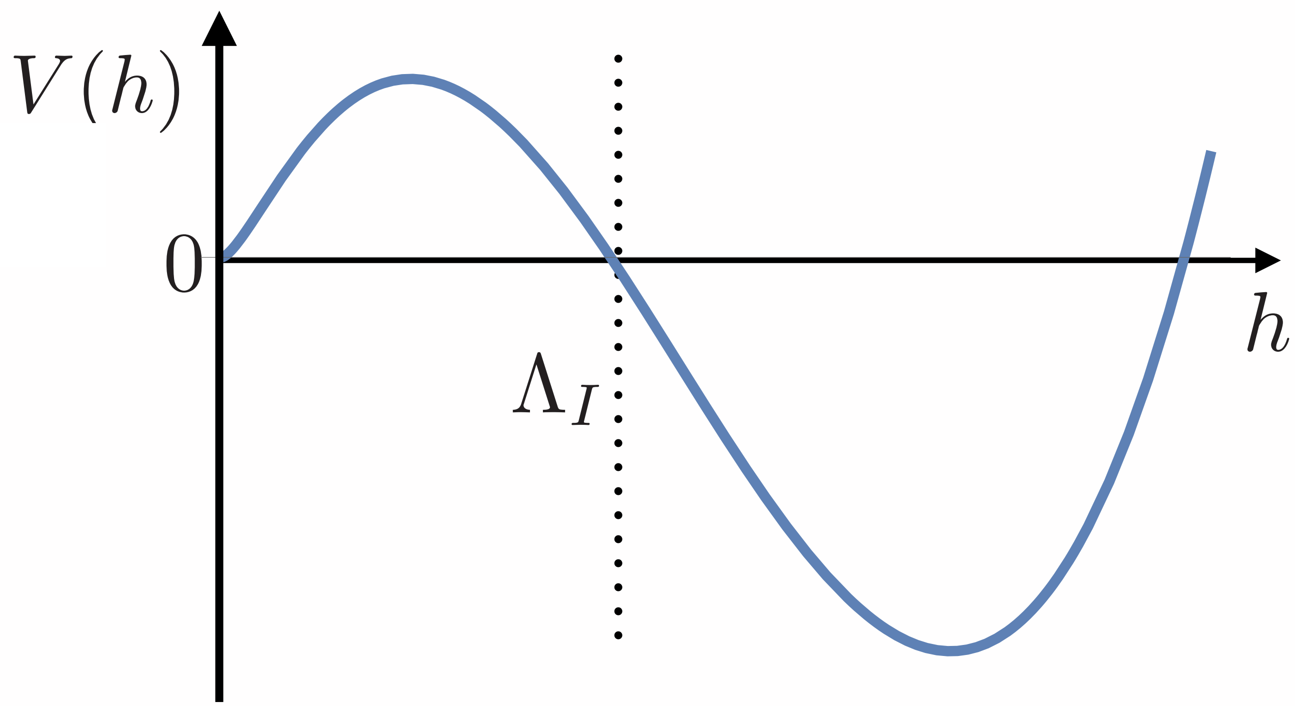
Inflation and the SM
as a motivation for SMASH

Inflation and the SM instability



Inflation and the SM instability

Higgs potential: $V(h) \simeq \dfrac{\lambda_H(h)}{4} h^4, \quad \beta_{\lambda_H} \sim \dfrac{1}{16\pi^4}\left(-y_t^4 + \cdots\right)$



$$V(h) < 0 \quad \text{at} \quad h = \Lambda_I \sim 10^{11}\text{GeV}$$

Inflation and the SM instability

Two problems

1) Higgs Inflation

If the Higgs has to inflate the Universe $(\nu\mathrm{MSM})$
its potential **must** be positive

2) Quantum fluctuations of the Higgs:

Even if the Higgs is not the inflaton

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

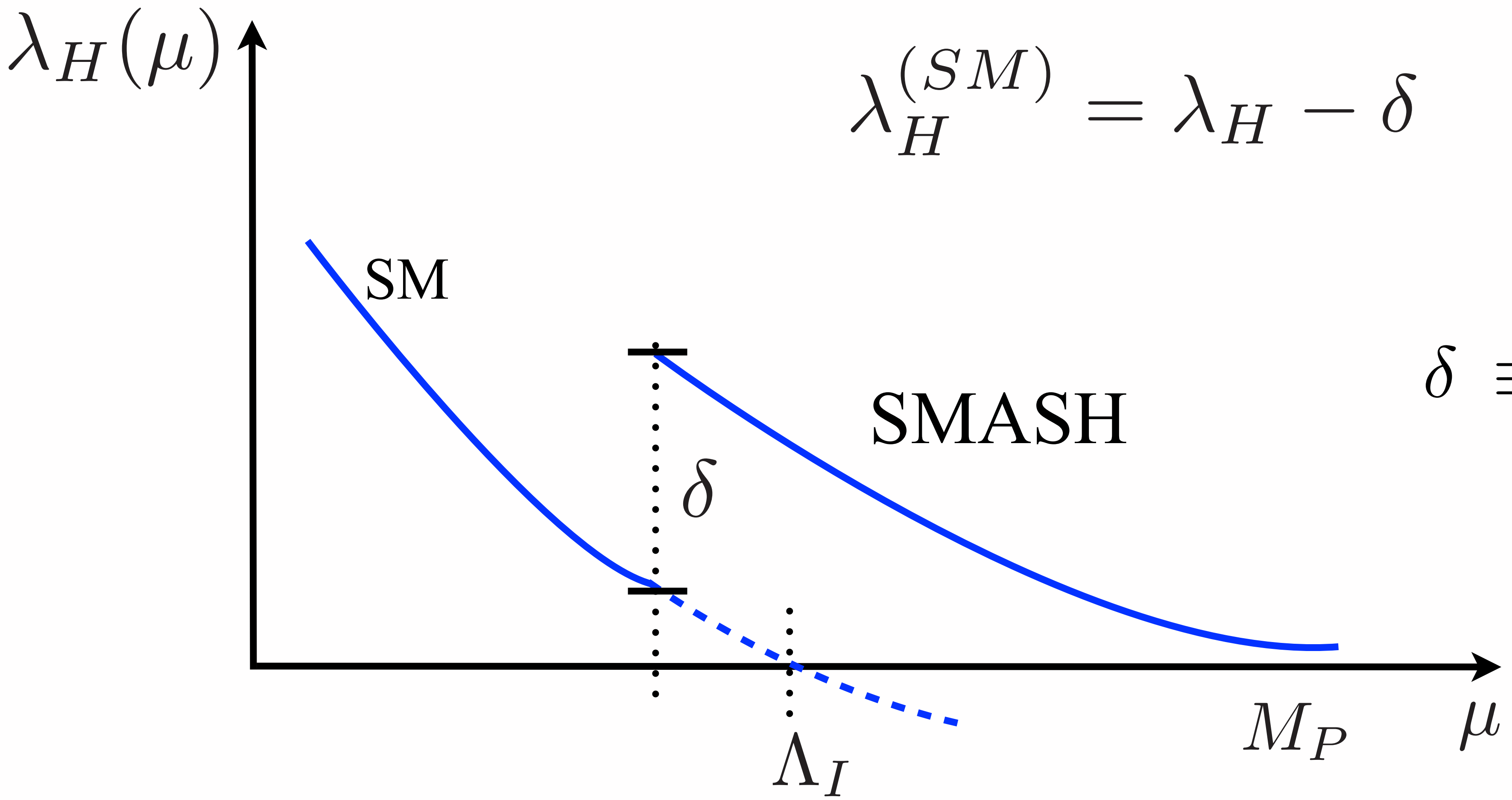
Threshold stabilization

Lebedev 2012
Elias-Miro et al. 2012

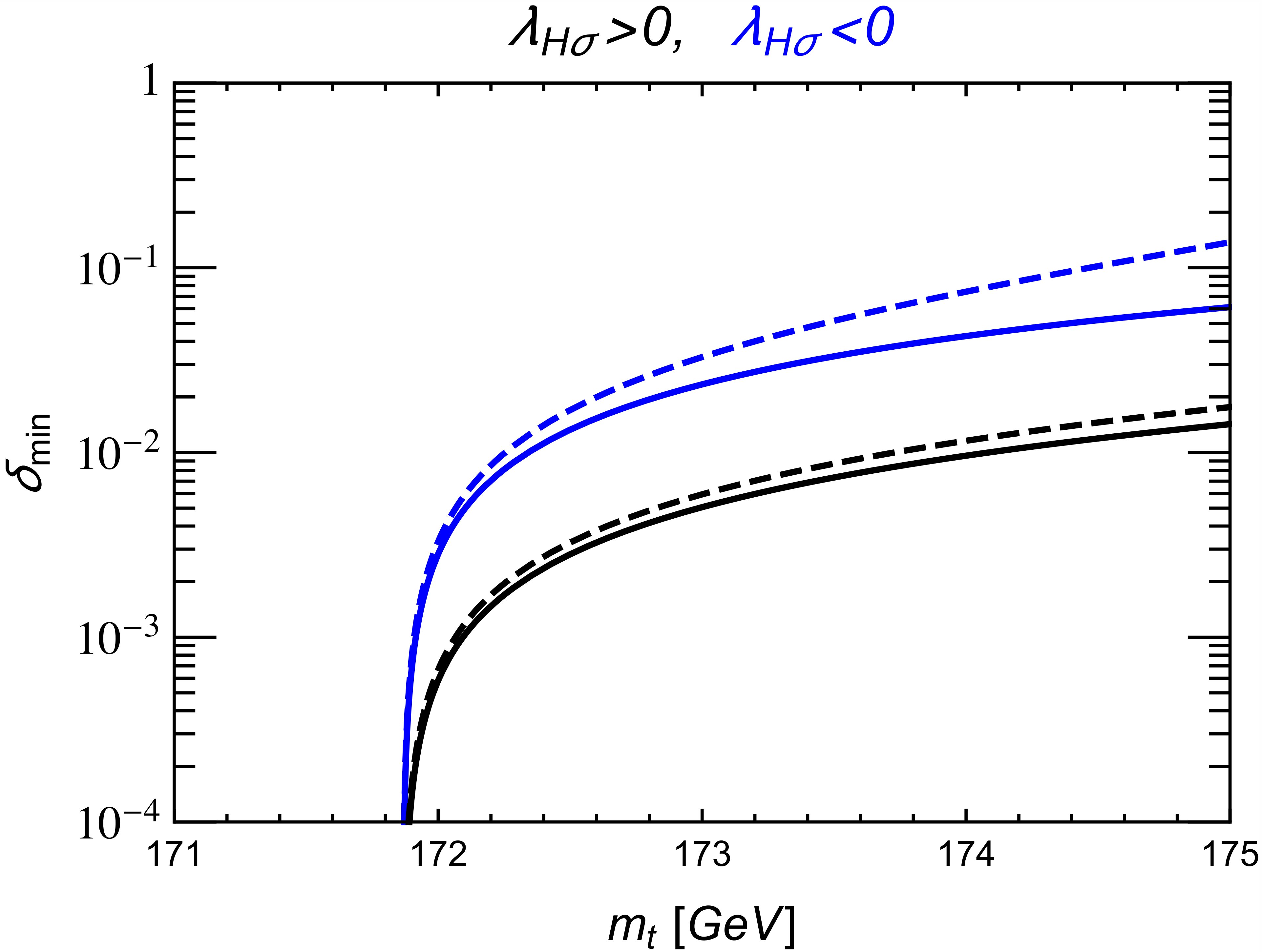
$$V(H,\sigma) = \lambda_H \left(H^\dagger H - \frac{v^2}{2}\right)^2 + \lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)^2 + 2\lambda_{H\sigma}\left(H^\dagger H - \frac{v^2}{2}\right)\left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)$$

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

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



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



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

Stability conditions

Higgs direction

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

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

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

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

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$|\sigma|$ direction

$$\beta_{\lambda_\sigma} \sim \frac{1}{16\pi^4}\left(-Y^4 - y^4 + \cdots\right)$$

$$\frac{y^4 + Y^4}{16\pi^2} \lesssim \frac{\lambda_\sigma}{\log(h/m_{|\sigma|})}$$

Higgs inflation and perturbative unitarity

$$-\int d^4x\sqrt{-g}\left(\frac{M_P^2}{2}+\xi_H\, H^\dagger H\right)R+\int d^4x\sqrt{-g}\left(\partial_\mu H^\dagger \partial^\mu H - V(H^\dagger H)\right)$$

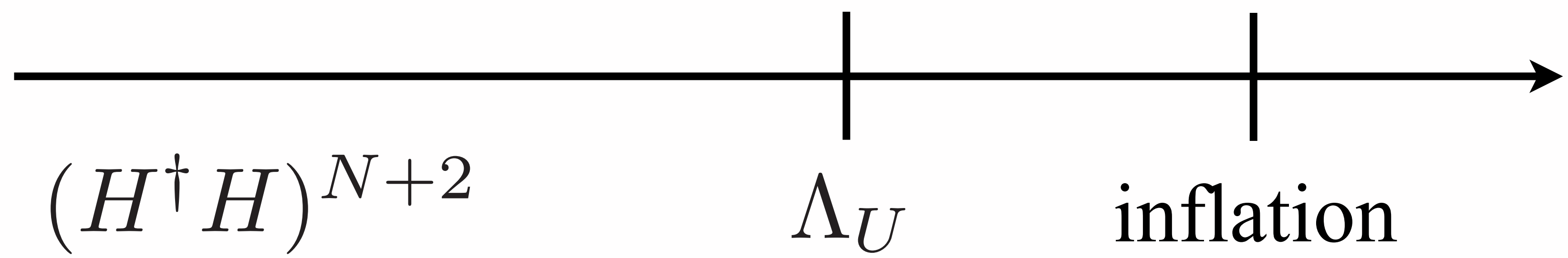
$$\tilde{V} \sim \frac{\lambda_H}{\xi_H^2} M_P^4 \qquad\qquad \xi_H \sim 10^5 \sqrt{\lambda_H} \sim 10^4$$

Unitarity breaking

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

To restore unitarity physics must change at or below Λ_U ,
very likely altering the inflationary dynamics
and its predictions

Loss of unitarity in Higgs inflation



$$\mathcal{O} \sim \frac{(H^\dagger H)^{N+2}}{{\Lambda_U}^{2N}}$$

$$h \sim \frac{M_P}{\sqrt{\xi_H}} \to \mathcal{O} \sim \frac{M_P^{2(N+2)}}{{\xi_H}^{N+2}{\Lambda_U}^{2N}} \sim \xi_H^{N-2} M_P^4$$

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

$$\frac{\mathcal{O}}{V} \sim \frac{\xi_H^N}{\lambda_H} \gg 1$$

The inflationary predictions depend critically on the potential shape

$$\mathcal{H} \sim \frac{\sqrt{V}}{M_P} \sim \sqrt{\lambda_H}\, \Lambda_U$$

Loss of unitarity in Higgs inflation

Roles of the Higgs →

- Unitarize gauge boson scattering
- Give masses by SSB
- Inflation?

Simple solution: the other field

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

$$\lambda_\sigma \ll 1$$

$$\Lambda_U \sim M_P/\xi_\sigma \sim M_P$$

Inflation with the new singlet

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

ξ_H and ξ_σ are always generated radiatively

$$\tilde{V}(\chi) = \frac{\lambda}{4}\rho(\chi)^4\left(1 + \xi_\sigma \frac{\rho(\chi)^2}{M_P^2}\right)^{-2}$$

Same effective potential, two possibilities:

$$\lambda_{H\sigma} > 0 \longrightarrow \quad \rho = |\sigma|\,, \quad \lambda = \lambda_\sigma$$

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

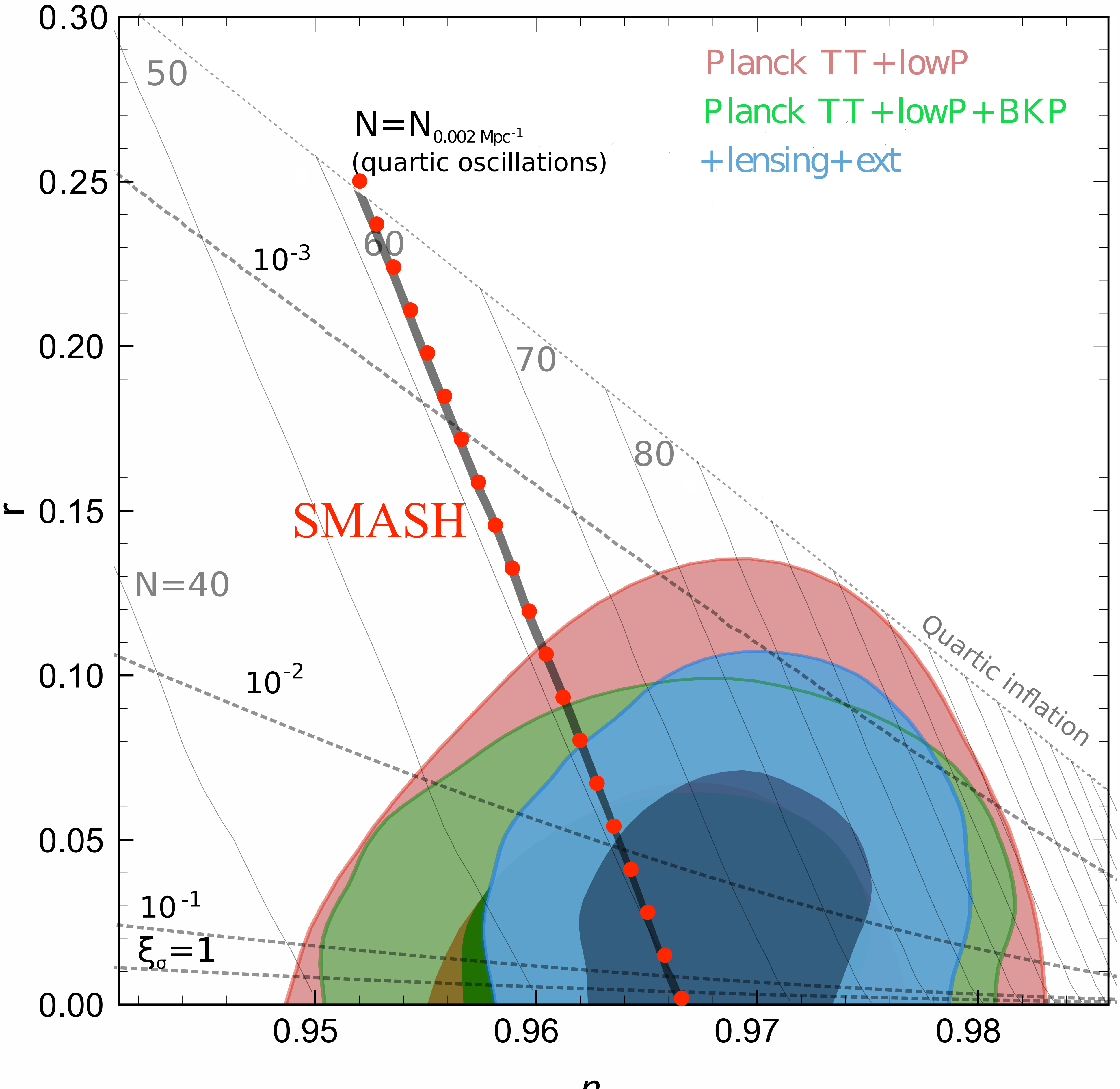
$$\lambda = \lambda_\sigma - \lambda_{H\sigma}^2/\lambda_H$$

SMASH

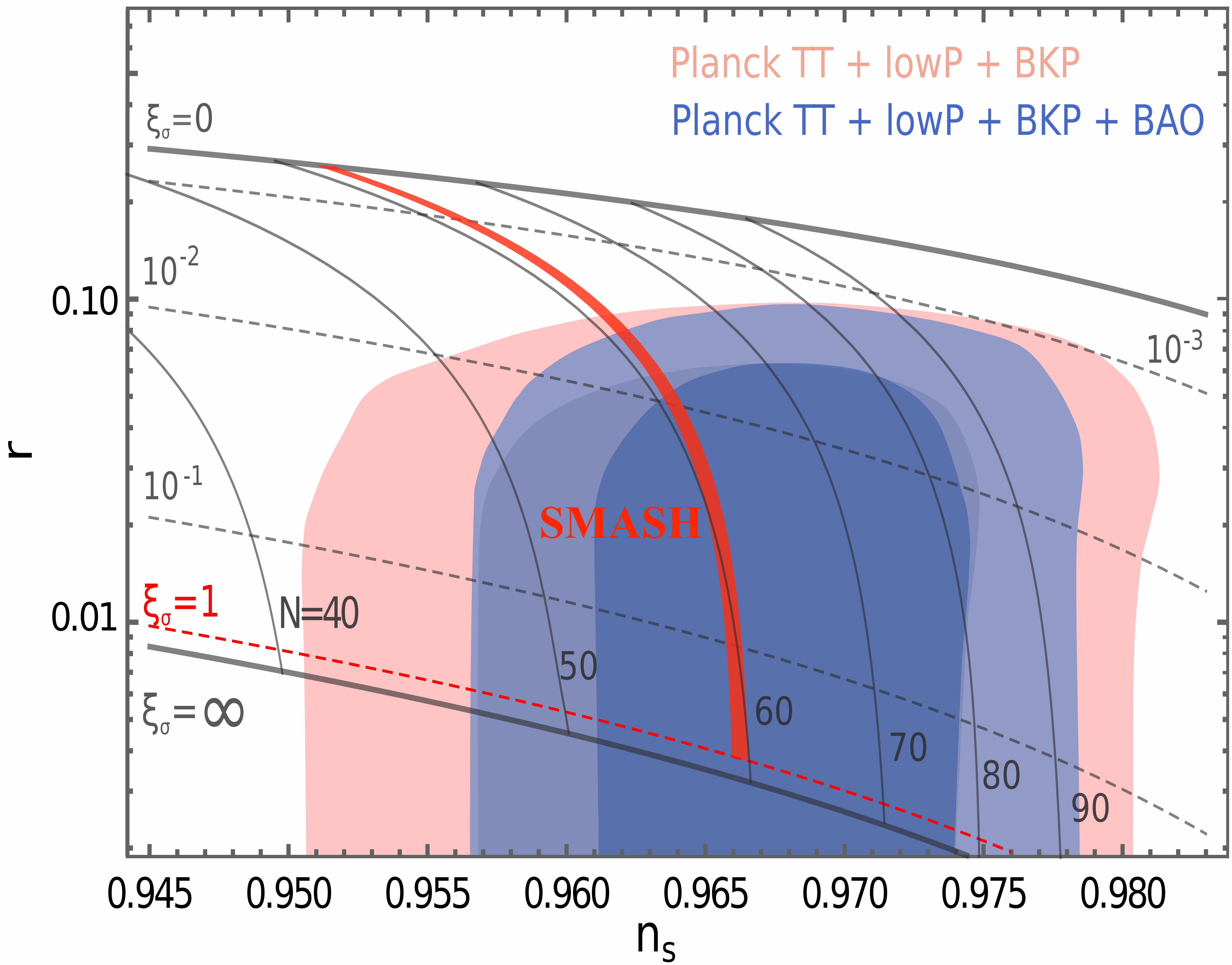
is

a model of particle physics and cosmology
from the electroweak scale to the Planck scale
and from inflation until today

Reheating process is fully computable $\longrightarrow$ Precise CMB predictions



Planck TT+lowP
Planck TT+lowP+BKP
+lensing+ext
N=N0.002 Mpc-1
(quartic oscillations)
SMASH
Quartic inflation
N=40
50
60
70
80
10-3
10-2
10-1
ξσ=1
r
ns
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.95
0.96
0.97
0.98



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

Predictions from inflation

From the CMB: $r \lesssim 0.07$ and $\xi_\sigma \sim 10^5 \sqrt{\lambda}$

From unitarity: $\xi_\sigma \lesssim 1 \longrightarrow 0.004 \lesssim r$

CORE
LiteBird
Pixie

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

Small non-Gaussianities, and isocurvature

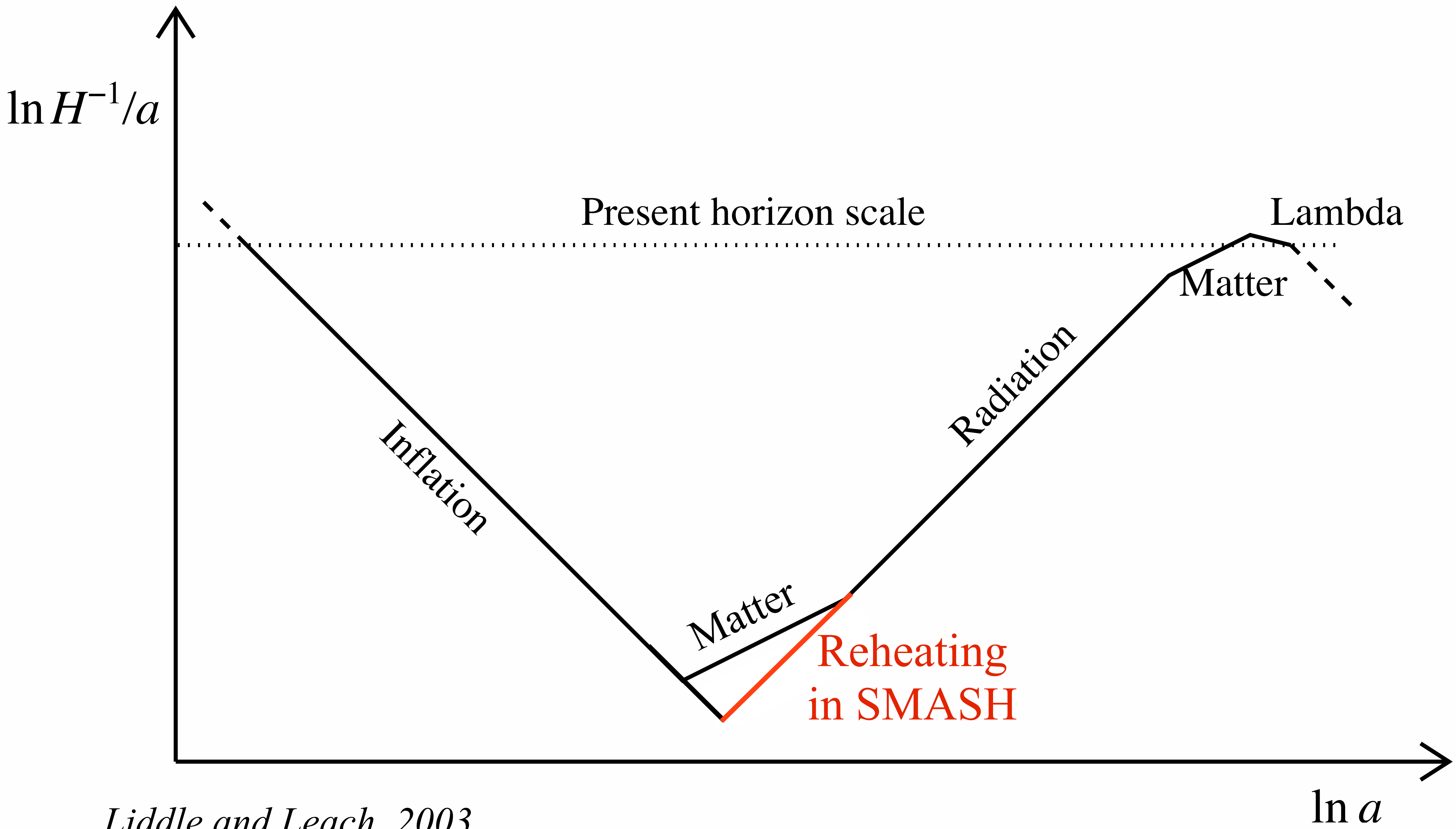
Scalar spectral index running $\alpha \simeq -7 \times 10^{-4}$

21 cm line of neutral Hydrogen

Specific range of spectral index $0.962 \lesssim n_s \lesssim 0.966$

Quartic potential ⟶ Radiation domination

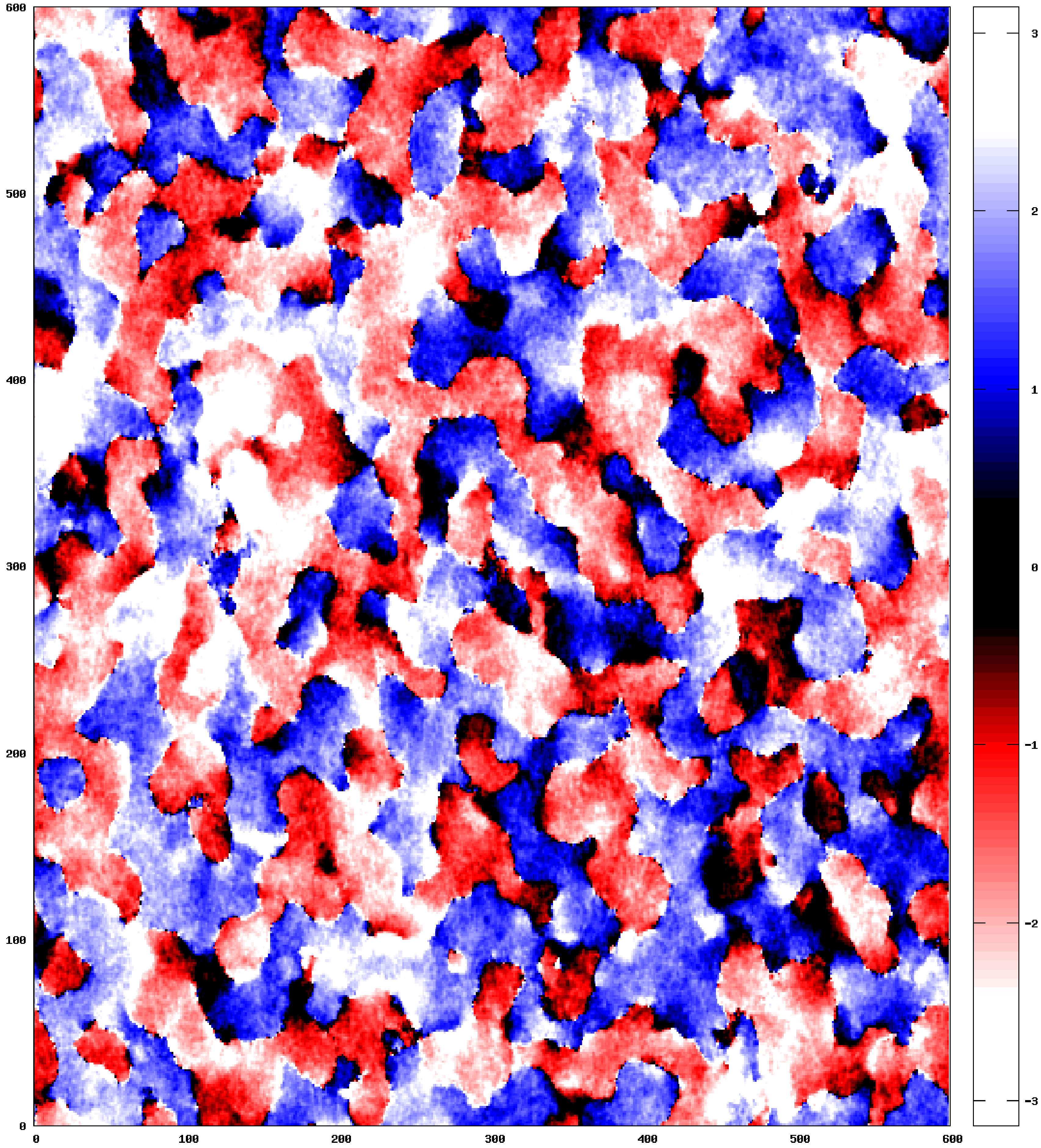
$$N_e(k) \simeq \log \frac{a_{\rm eq}\, H_{\rm eq}}{a_0\, H_0} - \frac{1}{4} \log \frac{3\, H_{\rm eq}^2}{M_P^2} - \log \frac{k}{a_0\, H_0} + \frac{1}{2} \log \frac{V_k}{M_P^4} + \frac{1}{4} \log \frac{M_P^4}{V_{\rm end}}$$



Liddle and Leach, 2003

Preheating

Parametric resonance of fluctuations of σ



θ

PQ symmetry non-thermally restored after ~14 oscillations

After preheating: Reheating

A small Higgs component in the inflaton
of SMASH is crucial for successful reheating

Two possibilities:

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

Axions remain decoupled
from thermal bath

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

Too much axion radiation

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

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

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

from CMB and BAO data

Axion dark matter

$\lambda_{H\sigma} < 0$ Inflaton = new singlet + a bit of Higgs

SSB of PQ symmetry after inflation

- vacuum misalignment mechanism

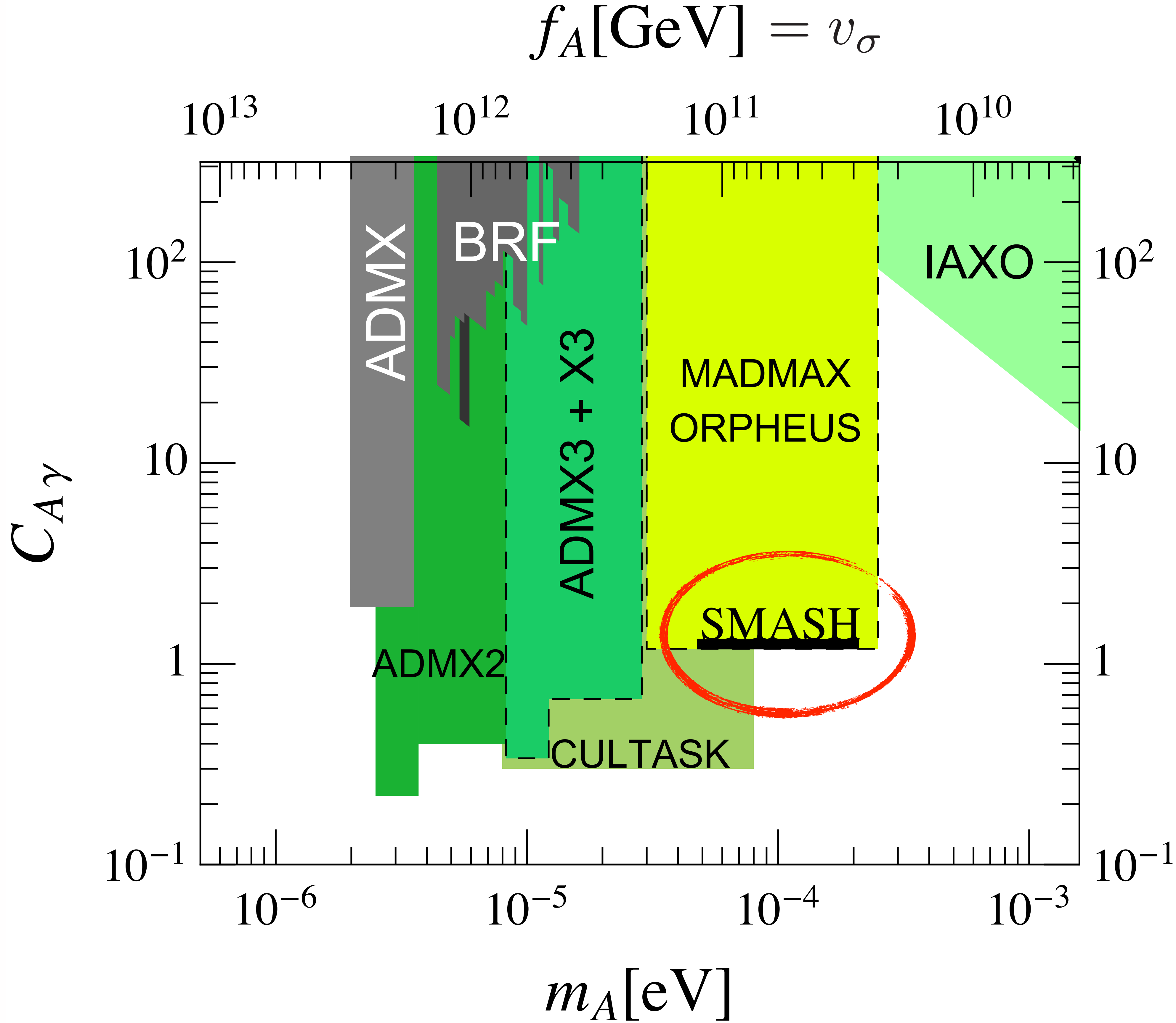
$$\ddot{A} + 3\mathcal{H}\dot{A} + m_A^2\, A = 0$$

- decay of Peccei-Quinn strings

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

Axion mass window

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



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

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

Summary

SMASH ~ SM + KSVZ + RH ν

Solves

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

and explains:

the smallness of neutrino masses, by ***the see-saw**;*

the nature of dark matter, which is ***the axion***;

baryogenesis, via ***leptogenesis***

&

and the origin of ***primordial inflation***.

Summary

Testing SMASH

CMB and LSS:

Spectral index and running, tensor-to-scalar ratio, Neff

Axion dark matter:

Axion-photon coupling and mass