Solving five problems of particle physics and cosmology in one stroke

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Exploring the energy ladder of the universe

Extension of the SM addressing

1. inflation

2. baryogenesis

3. dark matter

4. smallness of neutrino masses

5. strong CP problem

νMSM

SM + Three singlet neutrinos, N_i , with Majorana masses

- Small masses of left-handed neutrinos from the see-saw mechanism

- The lightest of the N_i is a DM candidate with ~ keV mass

- Baryon asymmetry is generated by oscillations of the two heavier N_i

Asaka, Blanchet and Shaposhnikov 2005

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

Bezrukov and Shaposhnikov 2008

νMSM

1. inflation

2. baryogenesis

3. dark matter

4. smallness of neutrino masses

5. strong CP problem

νMSM

1. inflation
2. baryogenesis ✓
3. dark matter ✓
4. smallness of neutrino masses ✓
5. strong CP problem

νMSM

1. inflation
2. baryogenesis ✓
3. dark matter ✓
4. smallness of neutrino masses ✓
5. ~~strong CP problem~~

νMSM

1. inflation 

2. baryogenesis ✓

3. dark matter ✓

4. smallness of neutrino masses ✓

~~5. strong CP problem~~

νMSM

1. inflation

a) Negative effective potential at large Higgs values

b) Loss of unitarity (due to large non-minimal coupling)
and (consequently) lost of predictive power

Burgess, Lee and Trott 2009
Barbón and Espinosa 2009

~~5. strong CP problem~~

SMASH!

Standard Model - Axion - See-saw - Hidden scalar

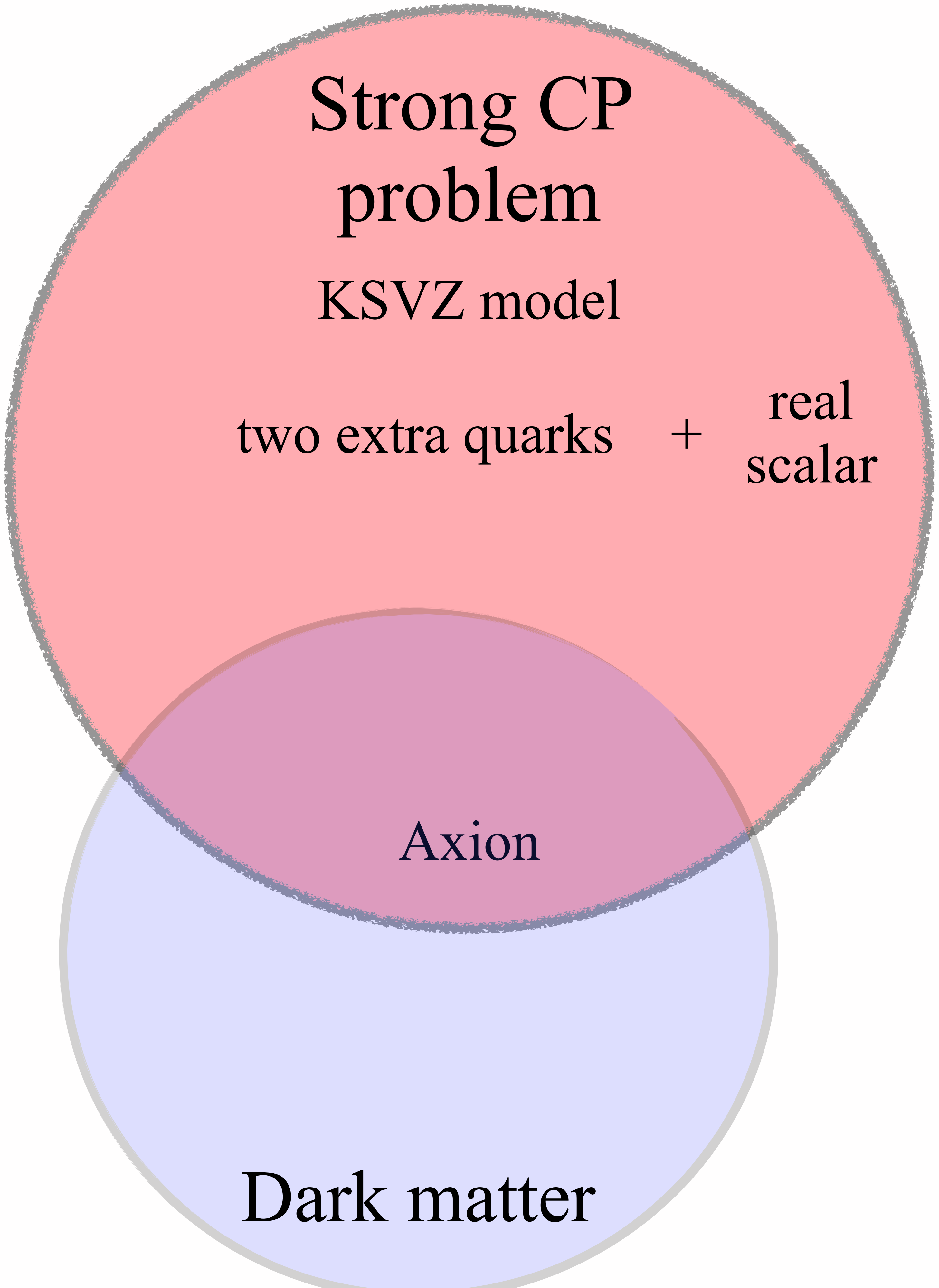
SMASH

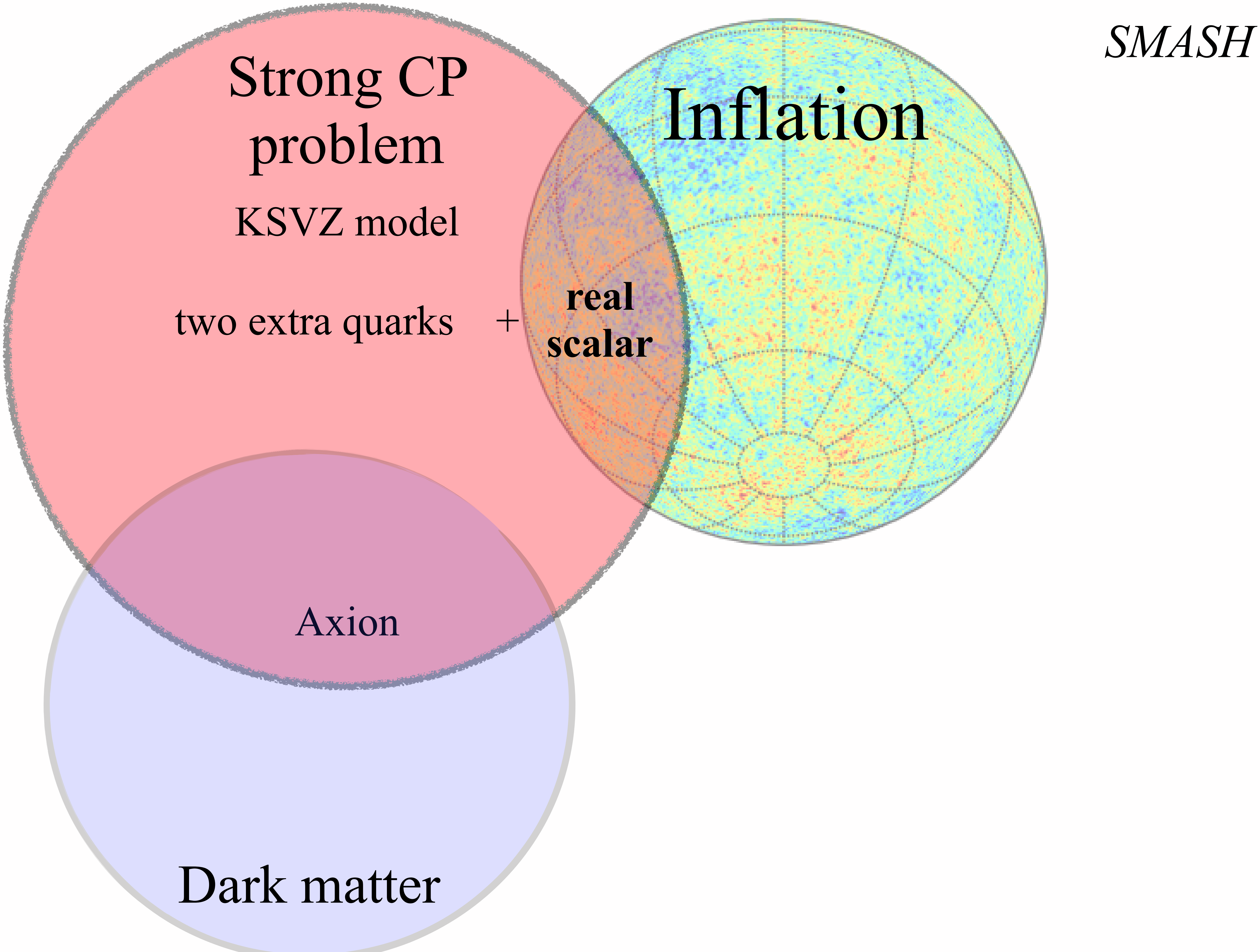
Strong CP problem

KSVZ model

complex scalar + two extra quarks

SMASH


Strong CP problem
KSVZ model
two extra quarks
+
real scalar
Axion
Dark matter


SMASH
Strong CP problem
KSVZ model
two extra quarks + real scalar
Inflation
Axion
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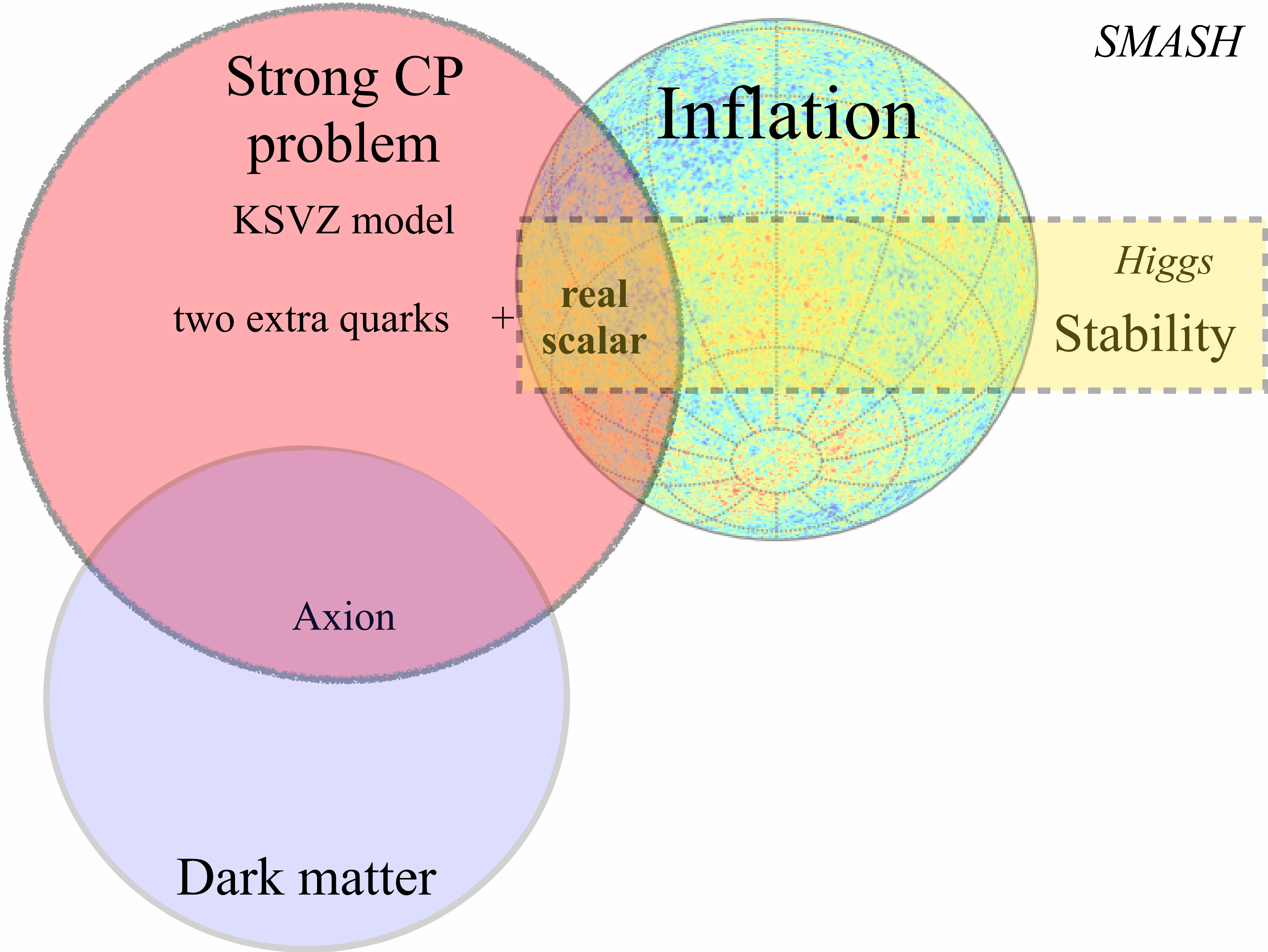
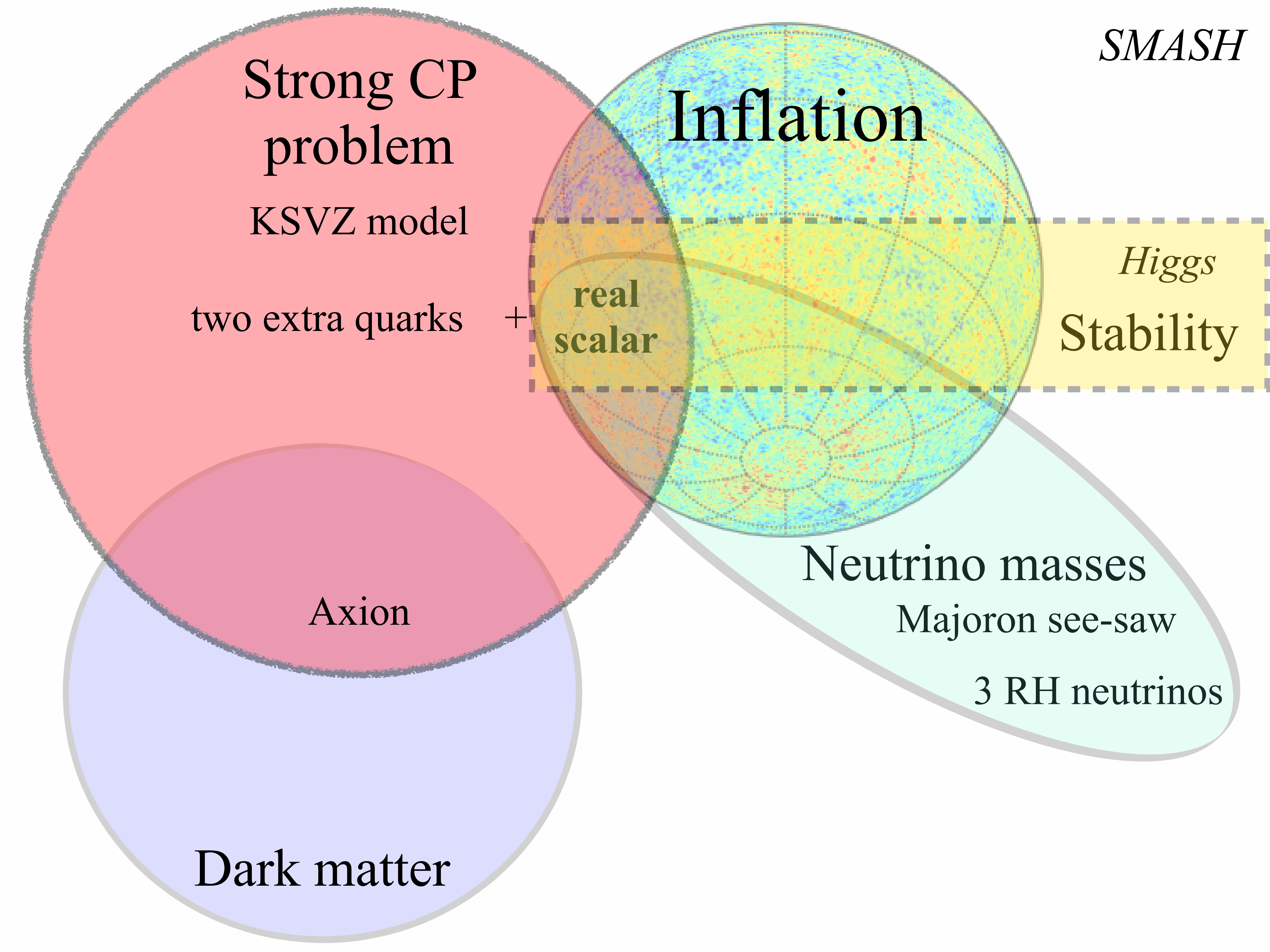
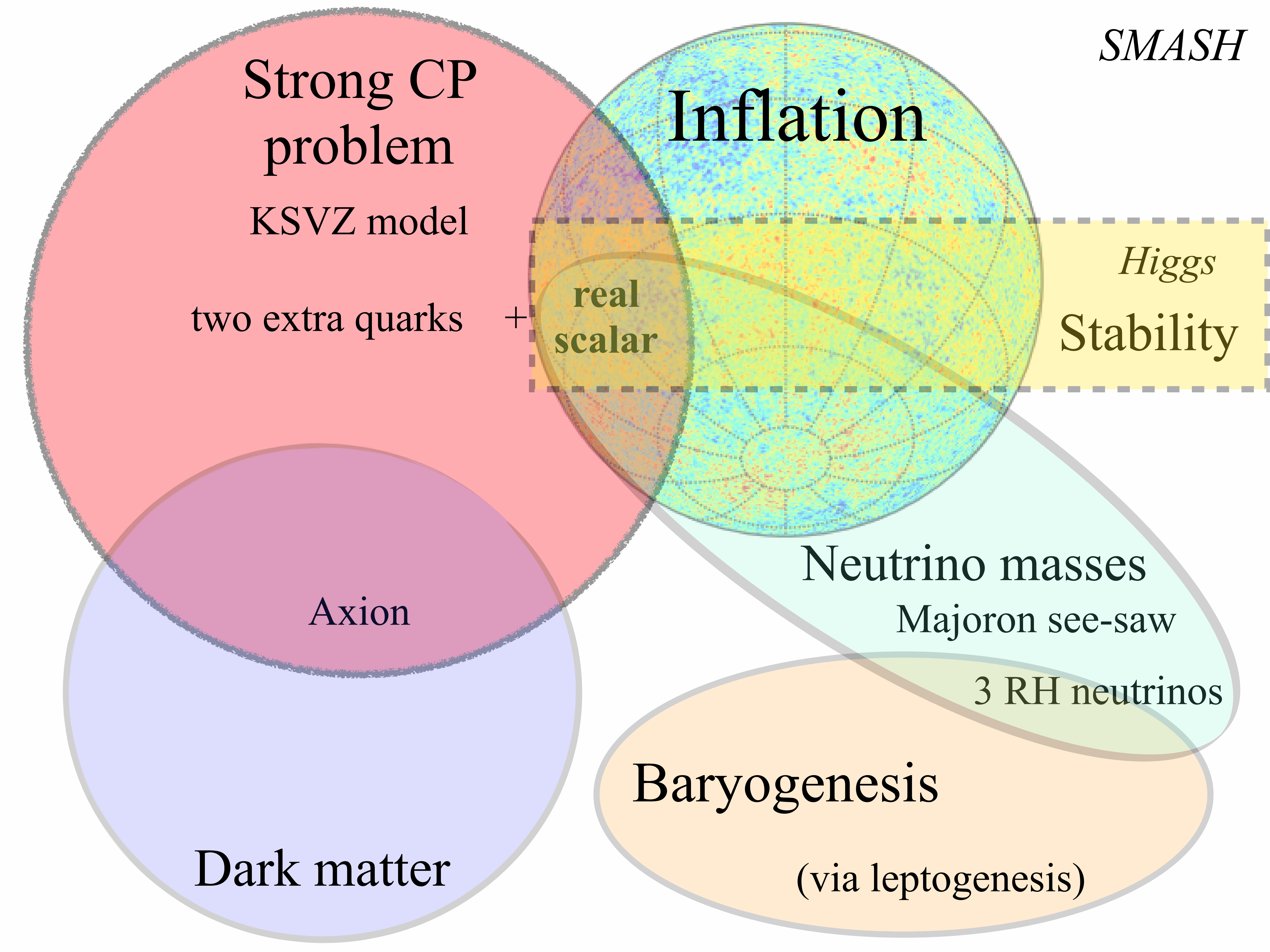


SMASH
Strong CP problem
KSVZ model
two extra quarks
+
real scalar
Inflation
Higgs
Stability
Axion
Dark matter


SMASH
Strong CP problem
KSVZ model
two extra quarks
+
Inflation
real scalar
Higgs
Stability
Neutrino masses
Majoron see-saw
3 RH neutrinos
Axion
Dark matter


SMASH
Strong CP problem
KSVZ model
two extra quarks
+
real scalar
Inflation
Higgs
Stability
Neutrino masses
Majoron see-saw
3 RH neutrinos
Axion
Baryogenesis
(via leptogenesis)
Dark matter

SMASH = SM +

- A complex singlet, σ → axion → DM; → inflaton, couples to Higgs → see-saw, baryogenesis
- Three singlet neutrinos, N_i → see-saw, baryogenesis
- Q and $\tilde{Q}$ in the fund. and anti-fund. reps. of $SU(3)_c$ and hypercharges $-1/3$ and $1/3$

(allowing them to decay into SM quarks)

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

Yukawa couplings and potential:

$$\mathcal{L} \supset -\left[Y_{u\,ij} q_i \epsilon H u_j + Y_{d\,ij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j \right.$$

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

Neutrino masses

Strong CP problem and DM

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

Strong CP problem, DM, inflation and stability

Couplings to gravity:

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

Inflation

SMASH Lagrangian

Proposed in
Dias, Machado, Nishi, Ringwald and Vaudrevange (2014)
to relate the PQ symmetry breaking scale to the see-saw scale

It did not consider inflation

A similar model was proposed by *Salvio (2015)*.
Same field content, but extra quark without hypercharge $\longrightarrow$ standard see-saw
Higgs as the inflaton

Neutrino masses

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

σ takes a large VEV v_σ

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

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

The strong CP problem

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

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

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

from neutron e.d.m.

Invariant under chiral transformations

quark mass matrix

Solution: another transformation under which $\delta S \propto \int G\,\tilde{G}$,

making θ unphysical.

Example: global sym that is anomalous under SU(3)c

But there is no global symmetry with this property in the SM

The KSVZ axion

$$\mathcal{L} \in \frac{1}{2}\partial_\mu a\, \partial^\mu a + i\frac{a}{32\pi^2} G\tilde{G} \qquad\qquad a \to a + c\,, \quad \partial_\mu c = 0$$

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 $\alpha = \dfrac{a}{v_\sigma}$

and integrate out Q and $|\sigma|$ below v_σ (large VEV)

Axion mass

Can be computed using chiral perturbation theory

$$m_a \sim m_\pi \frac{f_\pi}{v_\sigma} \,, \quad v_\sigma = f_A$$

$$m_a = \left(\frac{10^{12}\mathrm{GeV}}{v_\sigma} \right) (5.70 \pm 0.07)\, \mu\mathrm{e}V$$

(at zero temperature)

Grilli di Cortona, Hardy, Pardo Vega, Villadoro (2016)

Matter/anti-matter asymmetry

obtained from thermal leptogenesis:

Fukugita and Yanagida, 1986

Example:

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

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

Davidson and Ibarra, 2002

Buchmüller, di Bari and Plumacher 2002

For smaller RH masses, resonant leptogenesis may occur

Pilaftsis and Underwood, 2003

Stability of the effective potential and inflation

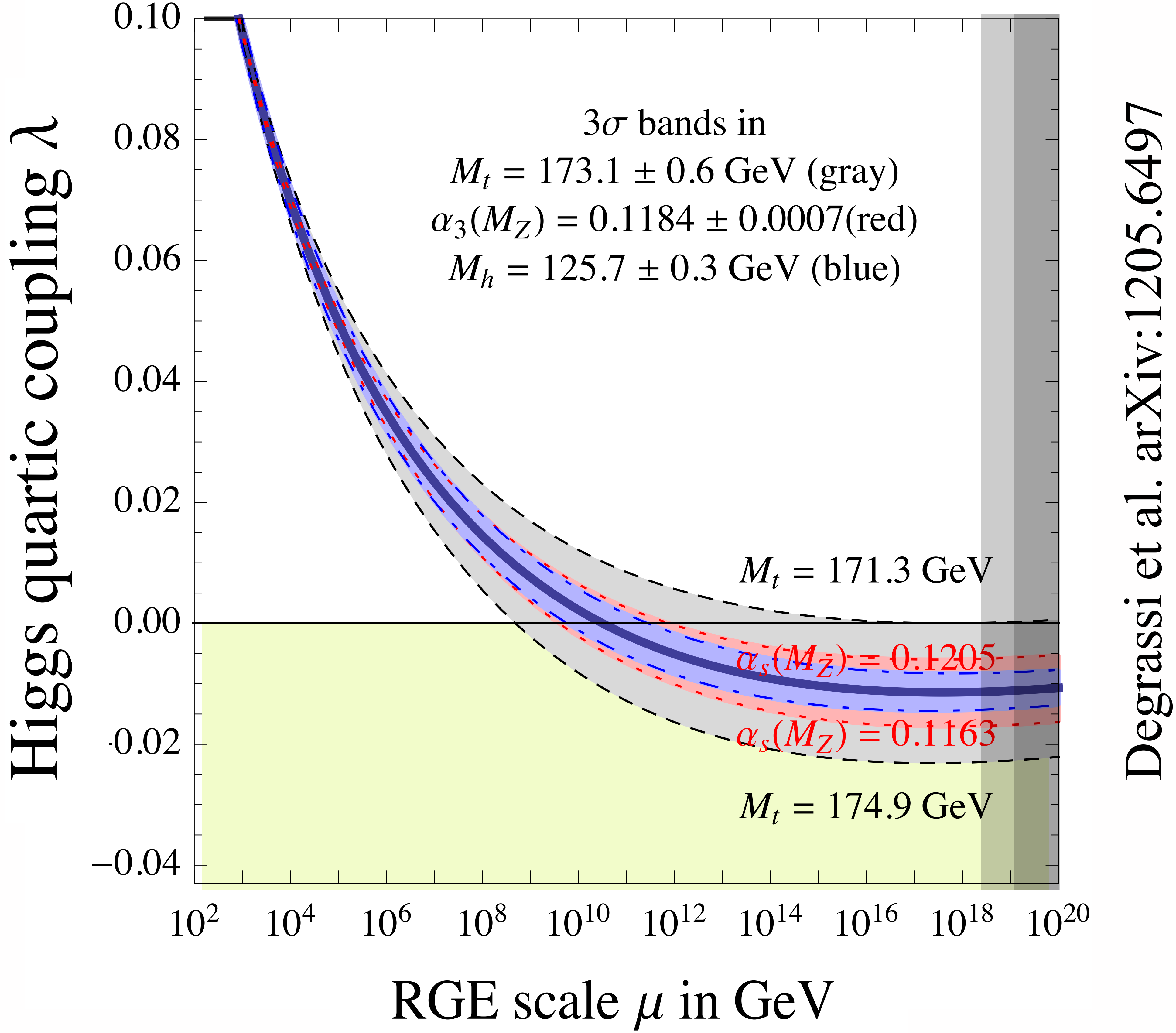
$$V(H,\sigma) = \lambda_H \left(H^\dagger H - \frac{v^2}{2}\right)^2 + \lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)^2 + 2\lambda_{H\sigma}\left(H^\dagger H - \frac{v^2}{2}\right)\left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)$$

<u>Absolute stability</u>: the potential is positive everywhere

- Safe choice to avoid quantum tunneling during inflation

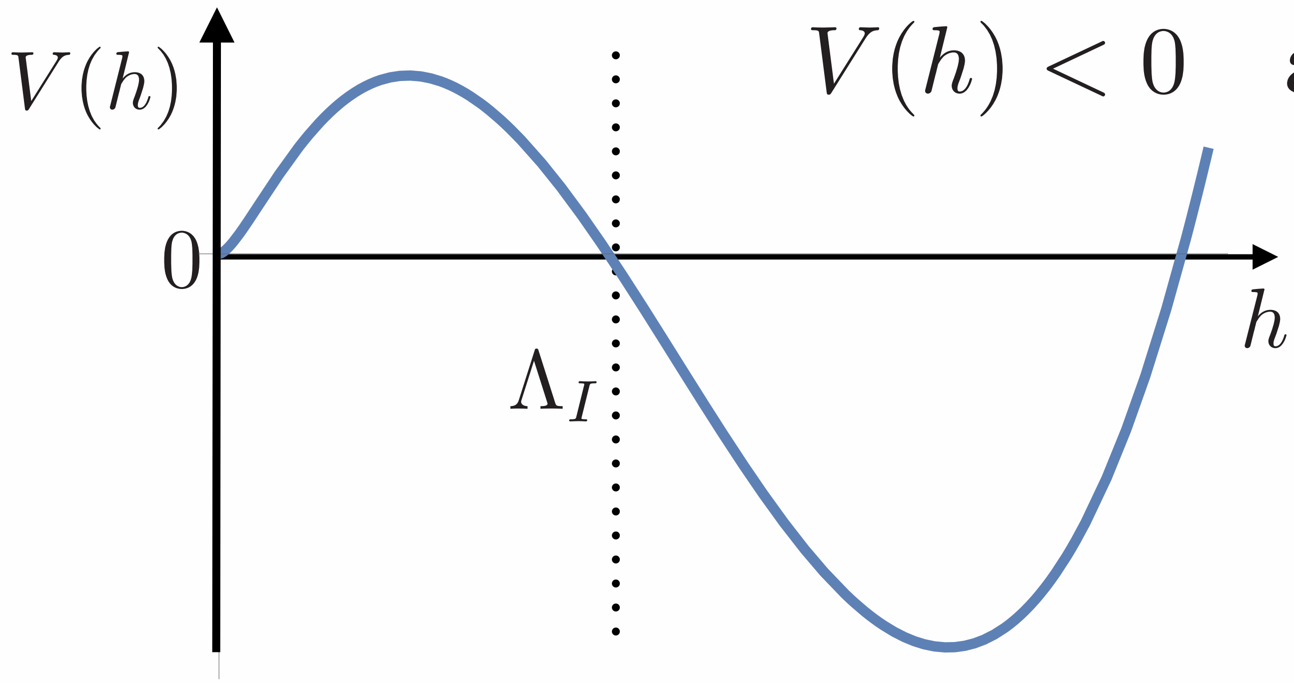
- Required if we want inflation to occur along the direction where an instability may develop. E.g. Higgs inflation

- If there is an instability, inflation might occur away from it, but quantum fluctuations still need to be under control



Higgs quartic coupling λ
RGE scale μ in GeV
3σ bands in
M_t = 173.1 ± 0.6 GeV (gray)
$\alpha_3(M_Z)$ = 0.1184 ± 0.0007(red)
M_h = 125.7 ± 0.3 GeV (blue)
M_t = 171.3 GeV
$\alpha_s(M_Z)$ = 0.1205
$\alpha_s(M_Z)$ = 0.1163
M_t = 174.9 GeV
Degrassi et al. arXiv:1205.6497
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
−0.04
10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20}

Inflation and the Higgs



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

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

Quantum fluctuations of the Higgs:

$$\sqrt{\langle h^2 \rangle} \sim H \sim \frac{\sqrt{V_{\inf}(\phi)}}{M_P} \sim 10^{-5} M_P \sim 10^{14}\text{GeV} \gg \Lambda_I$$

$$M_P = 1/\sqrt{8\pi G} \simeq 2.435 \cdot 10^{18}\,\text{GeV}$$

Stability

$$V = m_H^2 H^\dagger H + \frac{m_S^2}{2} S^2 + \frac{\lambda}{2}(H^\dagger H)^2 + \frac{\lambda_S}{4!} S^4 + \frac{\lambda_{SH}}{2} H^\dagger H S^2$$

At large field values, $V > 0$ requires:

$$\lambda > 0\,, \quad \lambda_S > 0\,, \quad \lambda_{SH} > -\sqrt{\lambda\lambda_S/3}$$

$$\beta_\lambda = \frac{1}{16\pi^2}\left[-12y_t^4 + \lambda\left(-\frac{9}{5}g_1^2 - 9g_2^2 + 12y_t^2\right) + \frac{27}{100}g_1^4 + \frac{9}{10}g_2^2 g_1^2 + \frac{9}{4}g_2^4 + 12\lambda^2 + \lambda_{SH}^2\right]$$

$$\beta_{\lambda_S} = \frac{1}{16\pi^2}\left[3\lambda_S^2 + 12\lambda_{SH}^2\right]$$

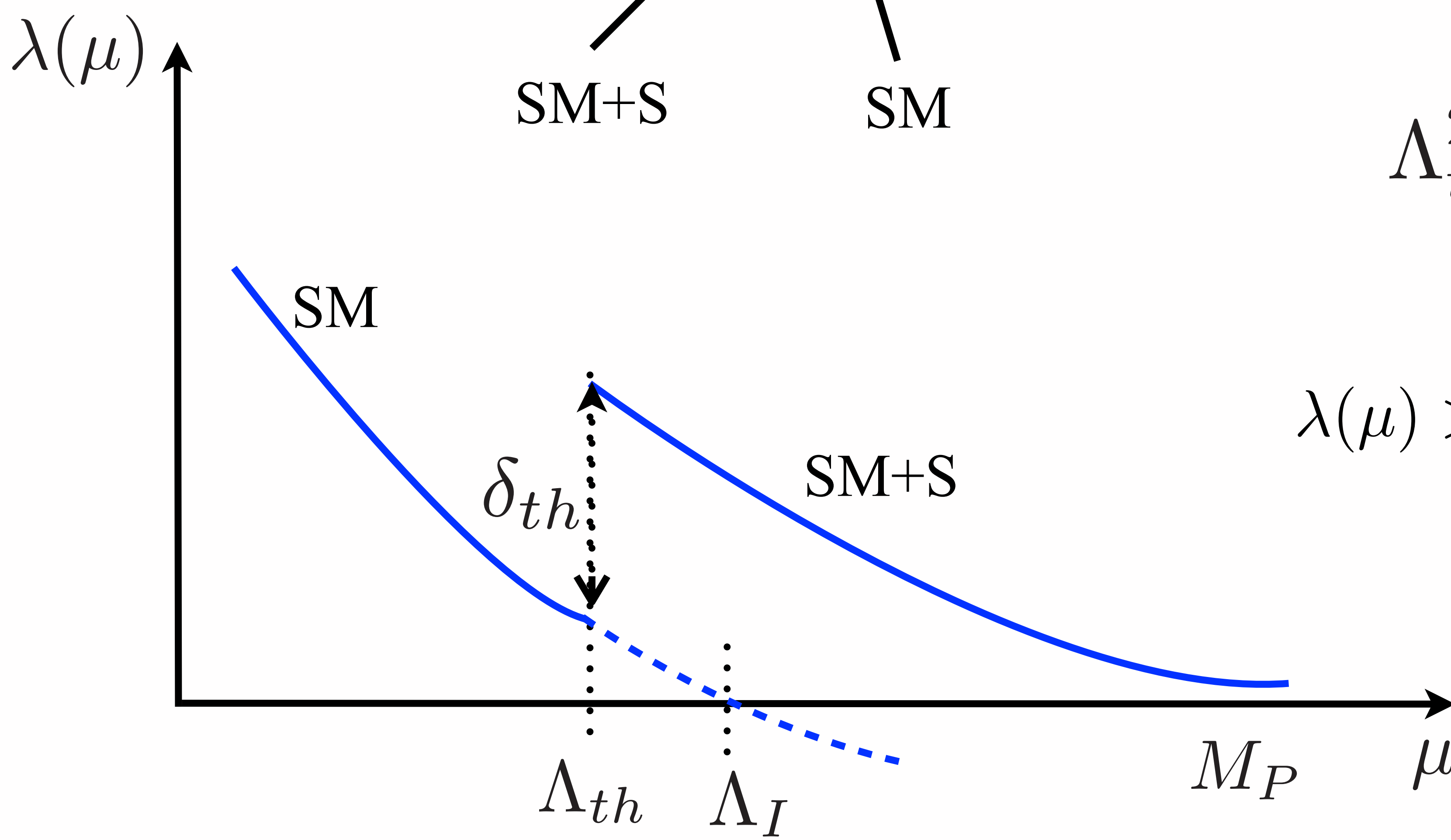
$$\beta_{\lambda_{SH}} = \frac{1}{16\pi^2}\left[\lambda_{SH}\left(-\frac{9}{10}g_1^2 - \frac{9}{2}g_2^2 + 6\lambda + \lambda_S + 6y_t^2\right) + 4\lambda_{SH}^2\right]$$

Threshold stabilization

$$V = m_H^2 H^\dagger H + \frac{m_S^2}{2} S^2 + \frac{\lambda}{2}(H^\dagger H)^2 + \frac{\lambda_S}{4!} S^4 + \frac{\lambda_{SH}}{2} H^\dagger H S^2$$

$$\tilde{\lambda} = \lambda - \frac{3\lambda_{SH}^2}{\lambda_S} = \lambda - \delta_{th}$$

SM+S　　SM



$$\Lambda_{th}^2 \sim |m_S^2| < \Lambda_I^2$$

$$\lambda(\mu) > \begin{cases} \delta_{th} & \text{for} \quad \mu \lesssim \Lambda_{th} \\ 0 & \phantom{\text{for}} \quad \mu \gg \Lambda_{th} \end{cases}$$

Lebedev 2012
Elias-Miro, Espinosa, Giudice, Lee, Strumia 2012

Inflation with a new singlet

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

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

ξ_H and ξ_σ are always generated radiatively

Newton's constant depends on the VEVs and on ξ_H and ξ_σ

$$M_P^2 = M^2 + \xi_H v^2 + \xi_\sigma v_\sigma^2.$$

The stability of the effective potential does not depend on ξ_H and ξ_σ

- They do not affect the running of the quartic couplings.
- In Jordan frame: effective masses, do not affect vacua existence
- In Einstein frame: the potential is proportional to their squares

Einstein Frame at tree-level

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

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

$$\int d^4x\sqrt{-\tilde{g}}\left[-\frac{M_P^2}{2}\tilde{R} + \frac{1}{2}\sum_{i,j}^{1,2}\mathcal{G}_{ij}\tilde{g}^{\mu\nu}\partial_\mu\phi_i\partial_\nu\phi_j - \tilde{V}\right]$$

$$\tilde{V}(h,\rho) = \frac{1}{\Omega^4(h,\rho)}\left[\frac{\lambda_H}{4}\left(h^2 - v^2\right)^2 + \frac{\lambda_\sigma}{4}\left(\rho^2 - v_\sigma^2\right)^2 + \frac{\lambda_{H\sigma}}{2}\left(h^2 - v^2\right)\left(\rho^2 - v_\sigma^2\right)\right]$$

inflationary potential for large fields $\sim \lambda\dfrac{M_P^4}{4\,\xi^2}$

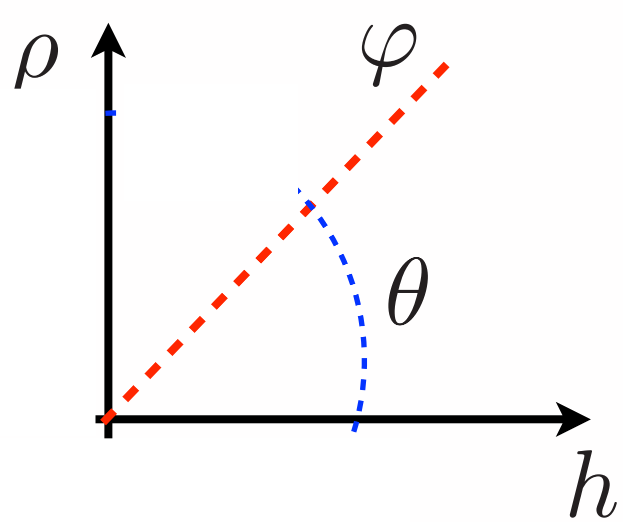
Example, Higgs inflation: $\xi_H\, h^2 \gg M_P^2$ and $\xi_H \gg 1/6$

Canonically normalized field in Einstein frame: χ_H

$$\tilde{V}_{\rm HI} \simeq \frac{\lambda_H}{4}\frac{M_P^4}{\xi_H^2}\left[1 - \exp\left(-\sqrt{\frac{2}{3}}\frac{\chi_h}{M_P}\right)\right]^2 ,$$

Polar coordinates: $h = \varphi\cos\theta$, $\rho = \varphi\sin\theta$, for large φ

$$\tilde{V} \simeq \frac{\lambda_H \cos^4\theta + \lambda_\sigma \sin^4\theta + 2\lambda_{H\sigma}\cos^2\theta\sin^2\theta}{4\left(\xi_H\cos^2\theta + \xi_\sigma\sin^2\theta\right)^2} M_P^4$$



Extrema for $\theta = 0,\quad \pi/2$ and

$$\frac{\rho}{h} = \sqrt{-\frac{\lambda_H}{\lambda_{H\sigma}}} + \mathcal{O}\left(\frac{\xi_H}{\xi_\sigma}\right)$$

Amplitude of primordial perturbations

$$\tilde{V}_{\text{eff}} \simeq \frac{\tilde{\lambda}_{\text{eff}}}{4} M_P^4 \left[1 - \exp\left(-\sqrt{\frac{2}{3}}\frac{|\chi_{\text{eff}}|}{M_P}\right)\right]^2$$

$$\tilde{\lambda}_{\text{eff}} = \left\{ \frac{\lambda_H}{\xi_H^2} \, , \frac{\lambda_\sigma}{\xi_\sigma^2} \, , \left(\lambda_\sigma - \frac{\lambda_{H\sigma}^2}{\lambda_H}\right) \frac{1}{\xi_H^2} \right\} \sim 10^{-10}$$

Higgs inflation

Sigma inflation

Mixed direction

$\xi_H \sim 10^5 \sqrt{\lambda_H} \sim 10^4$, problematic

Recall also: if the potential is unstable, no inflation at large field

Loss of unitarity

$$\xi_H \sim 10^5 \sqrt{\lambda_H} \sim 10^4$$

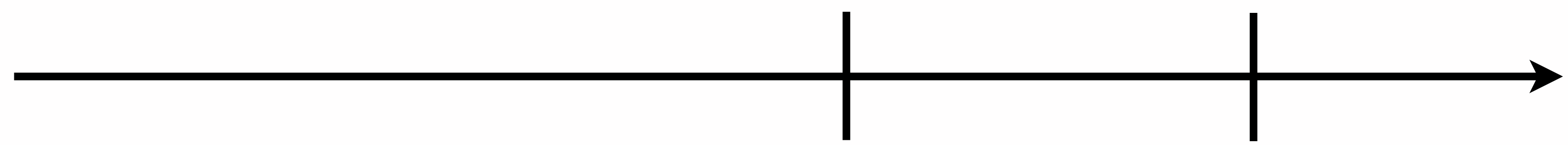
$$\Lambda_U = \frac{M_P}{\xi_H} \sim 10^{14}\,\mathrm{GeV} \ll \frac{M_P}{\sqrt{\xi_H}} \sim 10^{16}\,\mathrm{GeV}$$

To restore unitarity something must occur at or below Λ_U, very likely altering the inflationary dynamics

Roles of the Higgs in the SM

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

Loss of unitarity



$$\frac{(H^\dagger H)^{N+2}}{{\Lambda_U}^{2N}} \qquad \Lambda_U \qquad \text{inflation}$$

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

$$V \sim \frac{\lambda_H}{\xi_H^2} M_P^4 \qquad\qquad \frac{\mathcal{O}}{V} \sim \frac{\xi_H^N}{\lambda_H} \gg 1$$

The inflationary predictions depend critically on the potential shape

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

Free the Higgs from the burden of inflating!

$$\Lambda_U = \frac{M^2 + \xi_\sigma\, v_\sigma^2 + 6\xi_\sigma^2\, v_\sigma^2}{\xi_\sigma \sqrt{M^2 + \xi_\sigma\, v_\sigma^2}}\,, \qquad M_P^2 \simeq M^2 + \xi_\sigma\, v_\sigma^2$$

$$\xi_\sigma \gg 1 \quad \text{and} \quad \xi_\sigma v_\sigma^2 \sim M_P^2/6 \;\rightarrow\; \Lambda_U \sim M_P$$

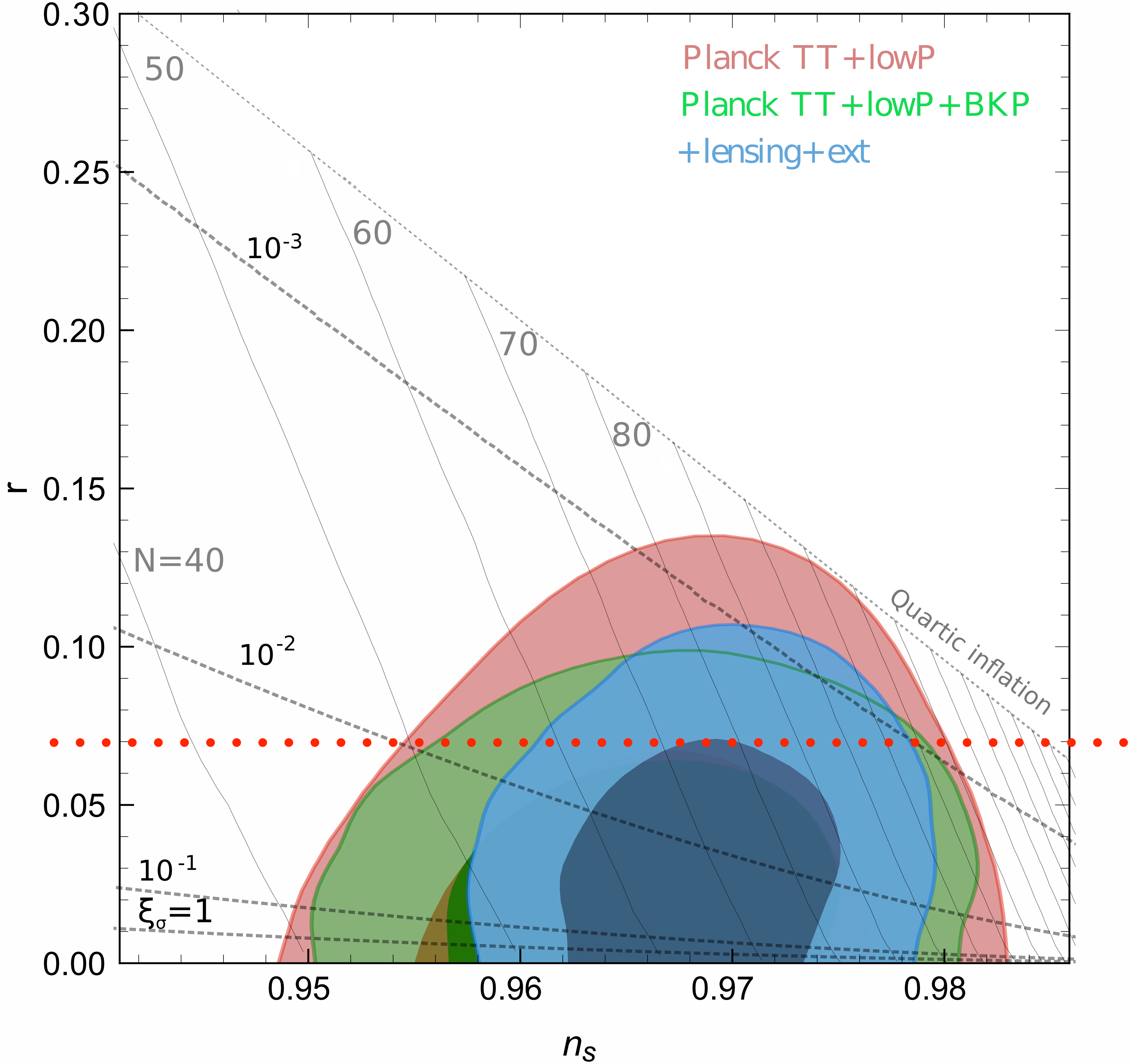
Giudice, Min-Lee

$$v_\sigma \lesssim 10^{15}\mathrm{GeV} \gg 10^{12}\mathrm{GeV}$$

Instead: $\xi_H \ll \xi_\sigma \lesssim 1 \rightarrow M_P \sim M \quad \text{and} \quad \Lambda_U \sim M_P$

$\sigma \sim M_P$ as in usual "large field" models

$$\tilde{V}_{\text{eff}} \simeq \frac{\tilde{\lambda}_{\text{eff}}}{4} M_P^4 \left[\tanh\left(\sqrt{\frac{\xi_\sigma}{a}}\frac{|\chi_\rho|}{M_P}\right)\right]^4$$



Planck TT+lowP
Planck TT+lowP+BKP
+lensing+ext
0.30
0.25
0.20
0.15
0.10
0.05
0.00
r
0.95
0.96
0.97
0.98
n_s
50
60
70
80
N=40
10^{-3}
10^{-2}
10^{-1}
$\xi_\sigma=1$
Quartic inflation

Axion dark-matter

1. PQ symmetry restored after inflation $T_{\max} > f_A > T_c$

- vacuum misalignment
- decay of strings and domain walls

$$f_A(\Omega_{A,c}h^2 = 0.12) \simeq 7.0 \times 10^{10}\,\mathrm{GeV} \times \frac{1 - 0.084(n-8)}{(n/8)^{1.1}}$$

n depends on the behaviour of the axion mass with temperature and can be between ~2 and ~10

$$5 \times 10^{10}\,\mathrm{GeV} < f_A < 5 \times 10^{11}\,\mathrm{GeV}$$

Axion dark-matter

2. PQ symmetry NOT restored after inflation $T_{\max} < T_c$

- vacuum misalignment

Isocurvature perturbations below current bounds (~3%) if

$$f_A < 10^{14}\mathrm{GeV}$$

Conclusion

Solving

the strong CP problem**,** by ***the KSVZ axion***

and explaining

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

we can identify

the dark matter*,* which is ***the QCD axion***,

obtain

baryogenesis*,* via ***leptogenesis***

and explain

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

All we need is to extend the SM with:

a complex singlet, a heavy quark and three RH neutrinos