Unifying inflation with the axion, dark matter, baryogenesis and the see-saw mechanism

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1608.05414

29/09/2016

DESY Theory Workshop

Simple 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

Asaka, Blanchet and Shaposhnikov 2005

- Small neutrino masses from the see-saw mechanism
- The lightest of the N_i is a DM candidate with ~ keV mass
- Baryon asymmetry from oscillations of the two heavier N_i

- Does not solve the strong CP problem
- Inflation ?

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

Bezrukov and Shaposhnikov 2008

Problems of Higgs 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

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 $SU(3)_c$

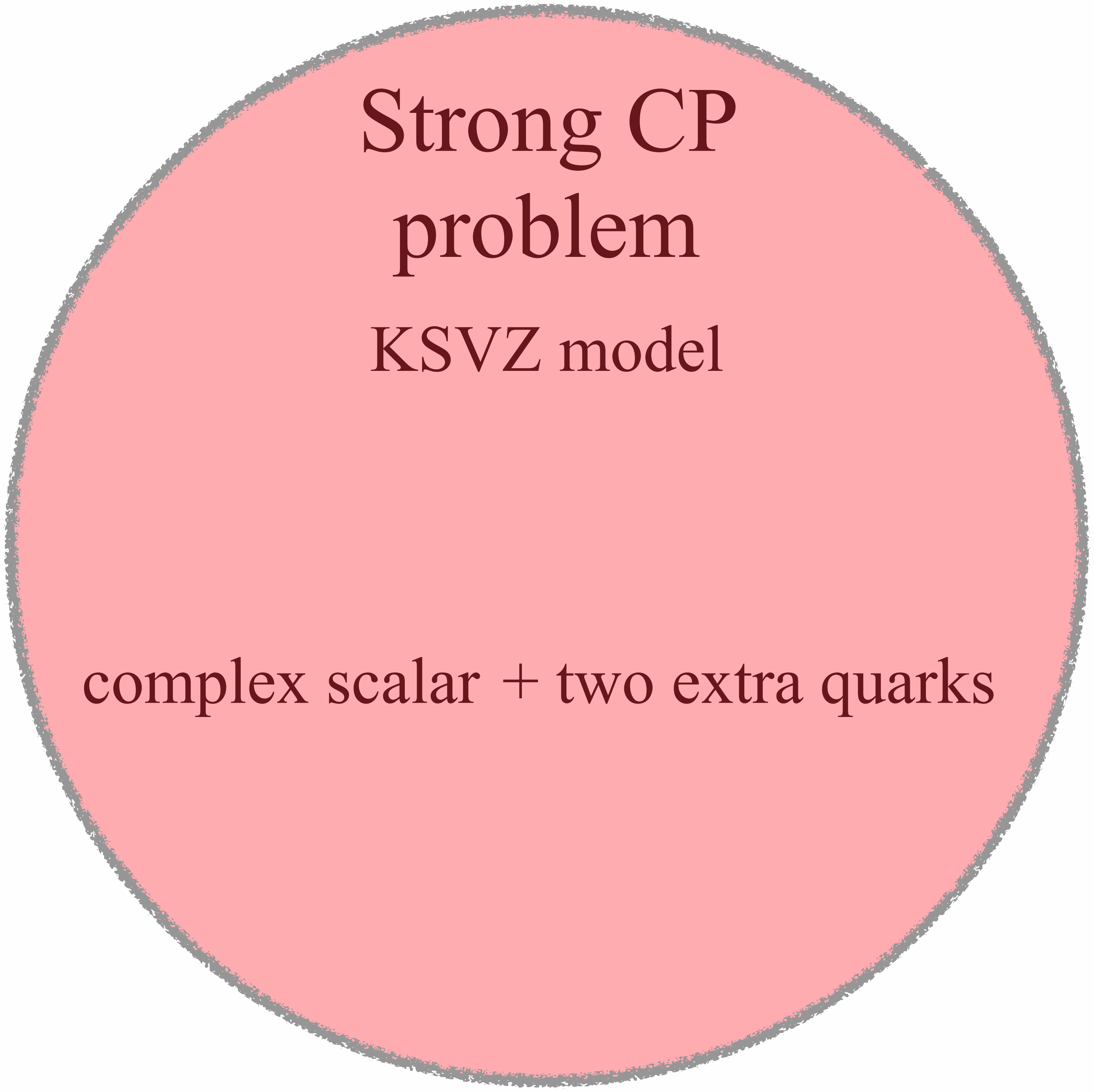
(with hypercharges -1/3 and 1/3, allowing them to decay)

Dias, Machado, Nishi, Ringwald and Vaudrevange (2014)

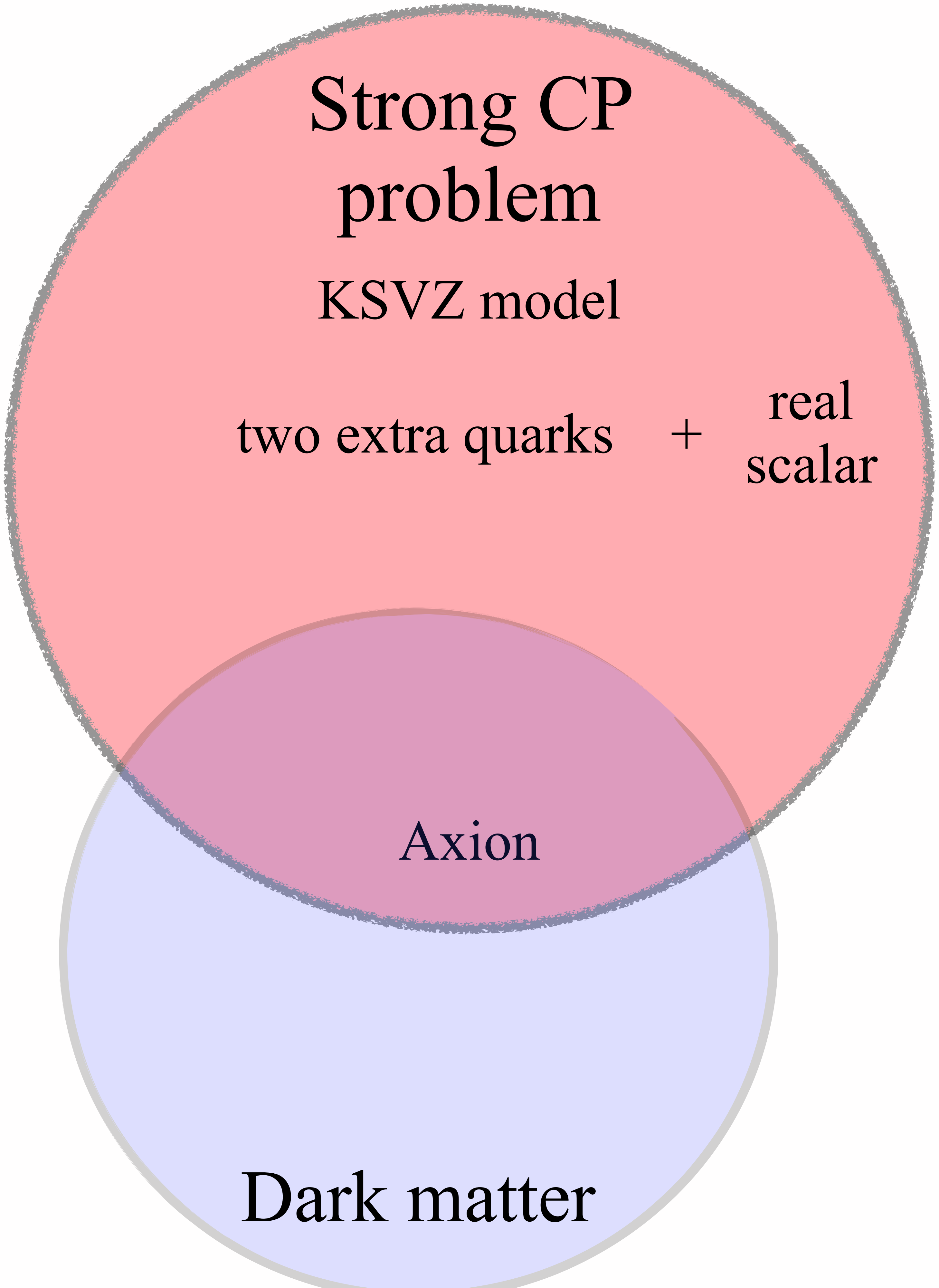
New global $U(1)$ PQ symmetry with charges:

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

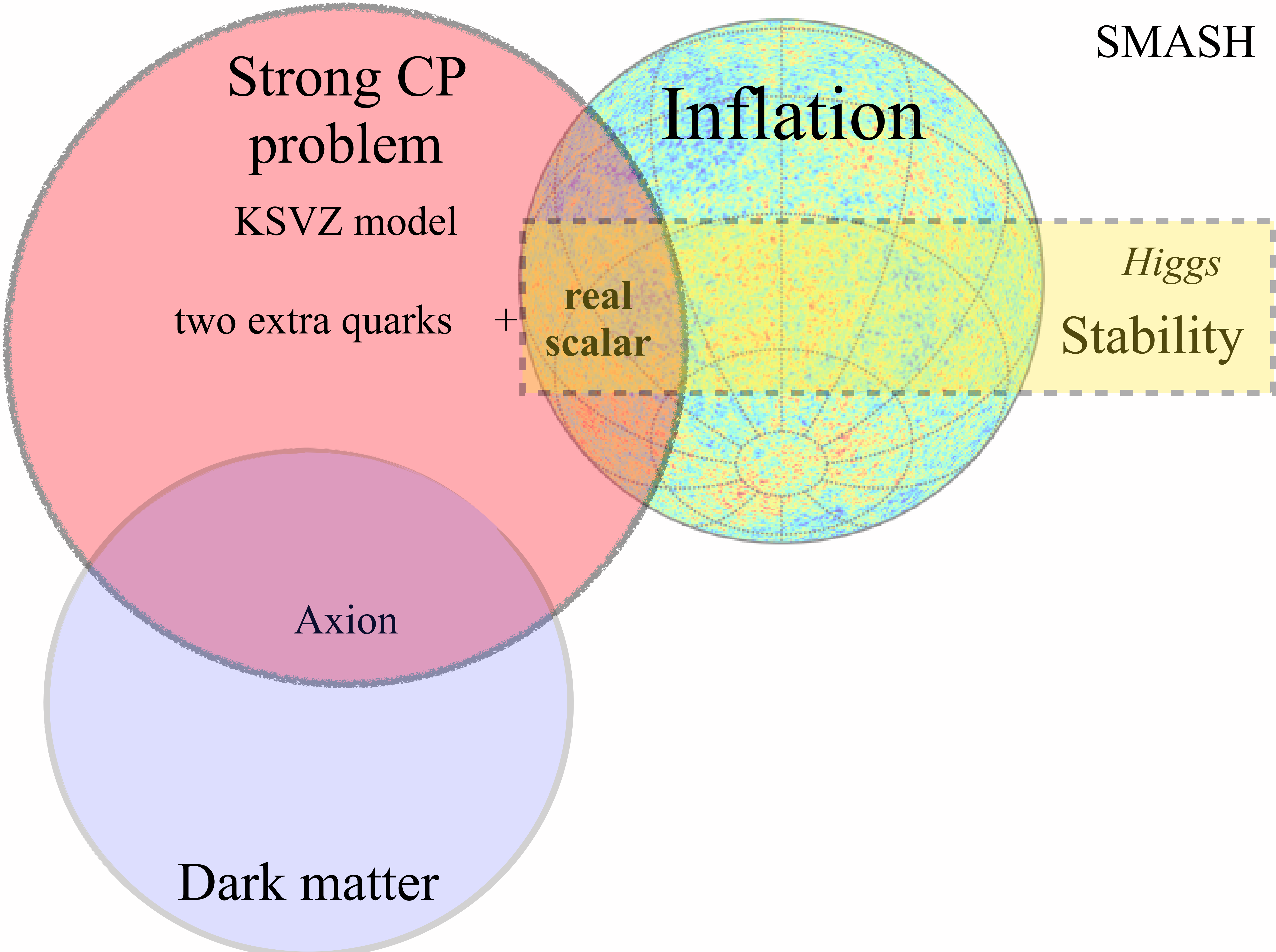
SMASH

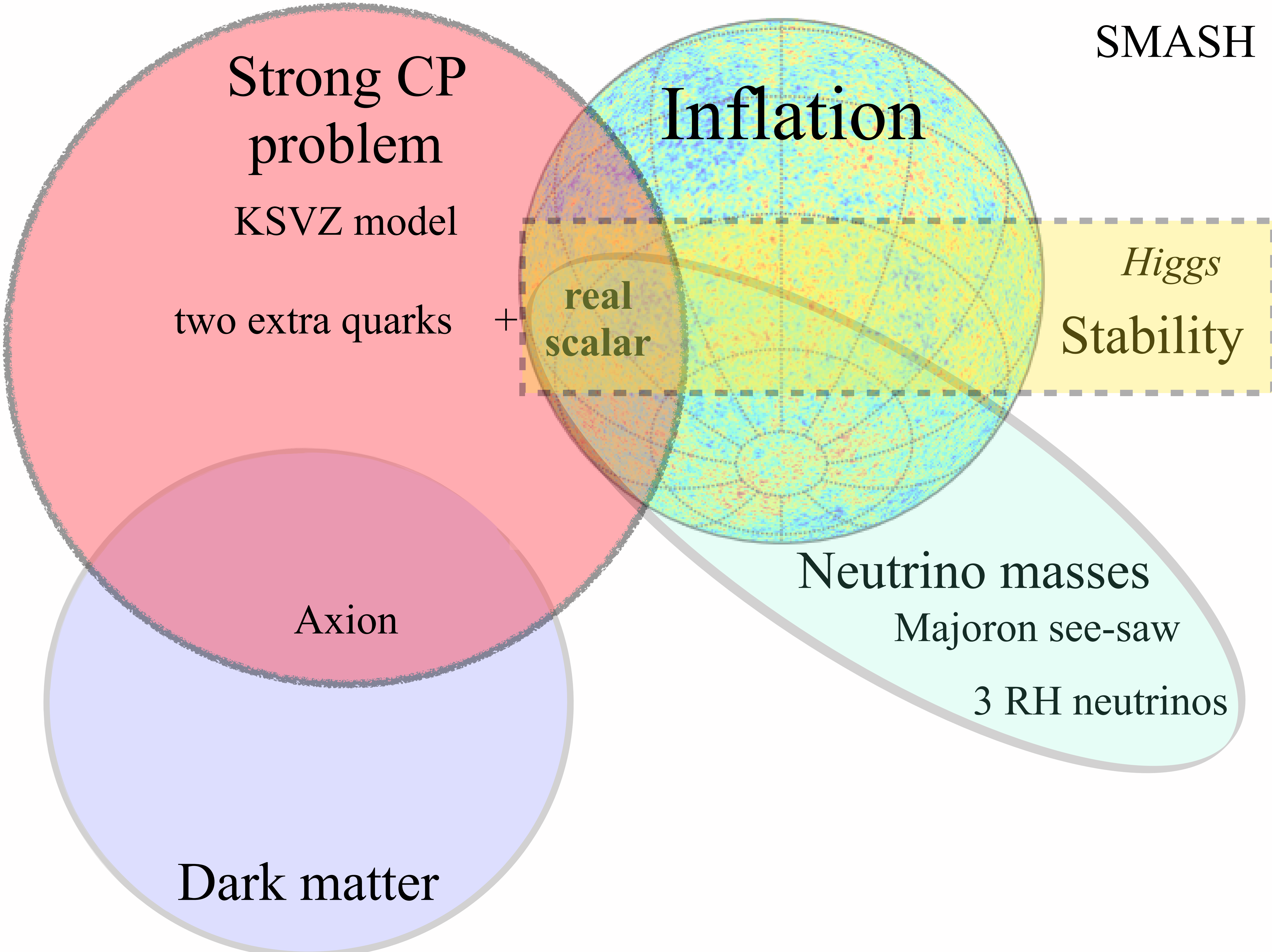

Strong CP
problem
KSVZ model
complex scalar + two extra quarks

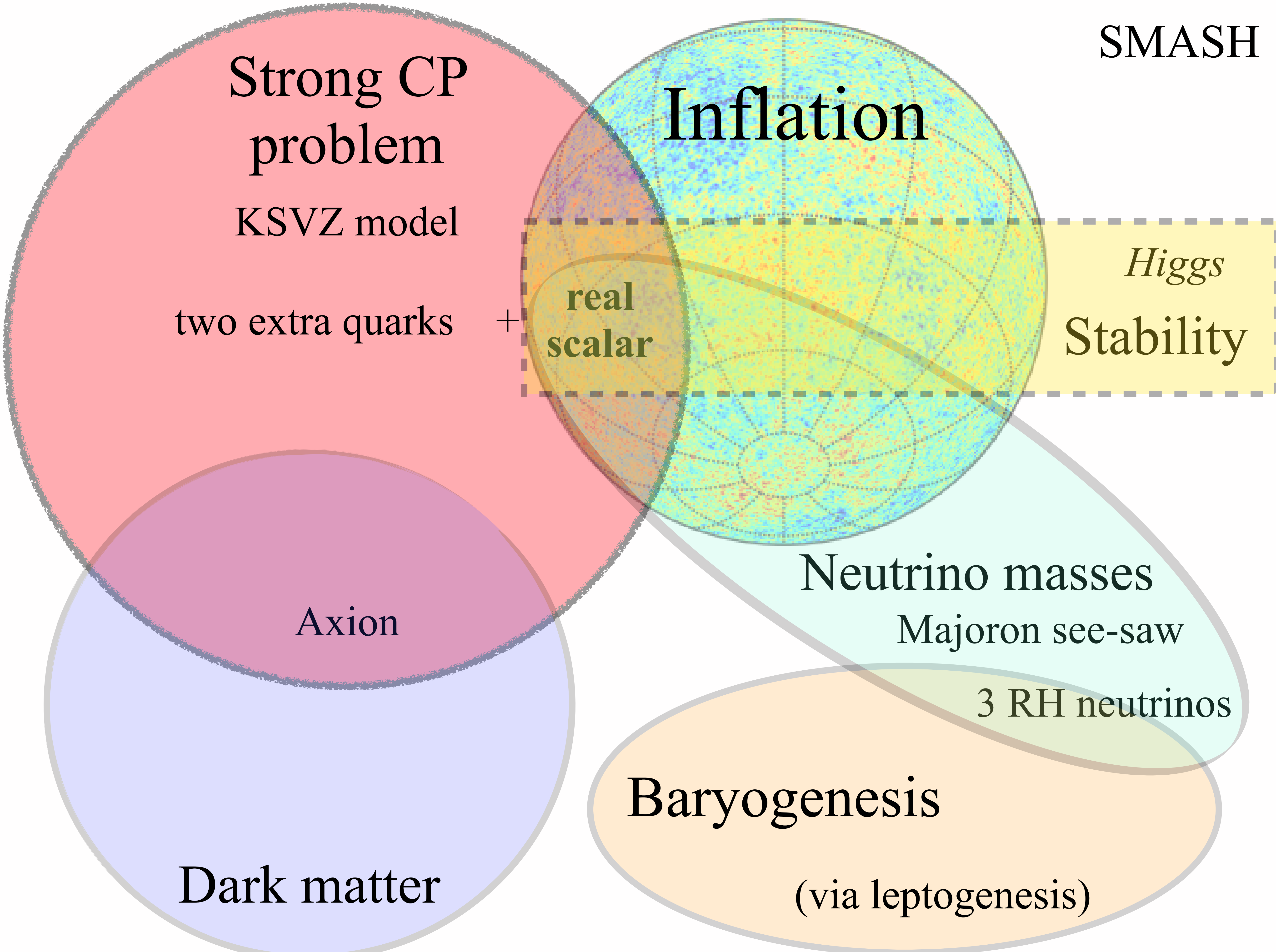
SMASH



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
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

Yukawa couplings and potential:

$$\mathcal{L} \supset -\Big[Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j$$
$$+ y\,\tilde{Q}\sigma Q + y_{Q_{d}i} \sigma Q d_i + h.c.\Big] ,$$

Neutrino masses and DM

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:

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

Inflation

The strong CP problem

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

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

θ ↑ Invariant under chiral transformations

M ↑ quark mass matrix

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

from neutron e.d.m.

Solution requires a transformation under which $\delta S \propto \int G\tilde{G}$

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

(there is no such sym. in the SM)

The KSVZ axion

Kim-Shifman-Vainshtein-Zakharov (1979)

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

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)

Scalar potential and inflation

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

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

ξ_H and ξ_σ are generated radiatively. $\quad M_P^2 = M^2 + \xi_H v^2 + \xi_\sigma v_\sigma^2.$

Higgs inflation & perturbative unitarity

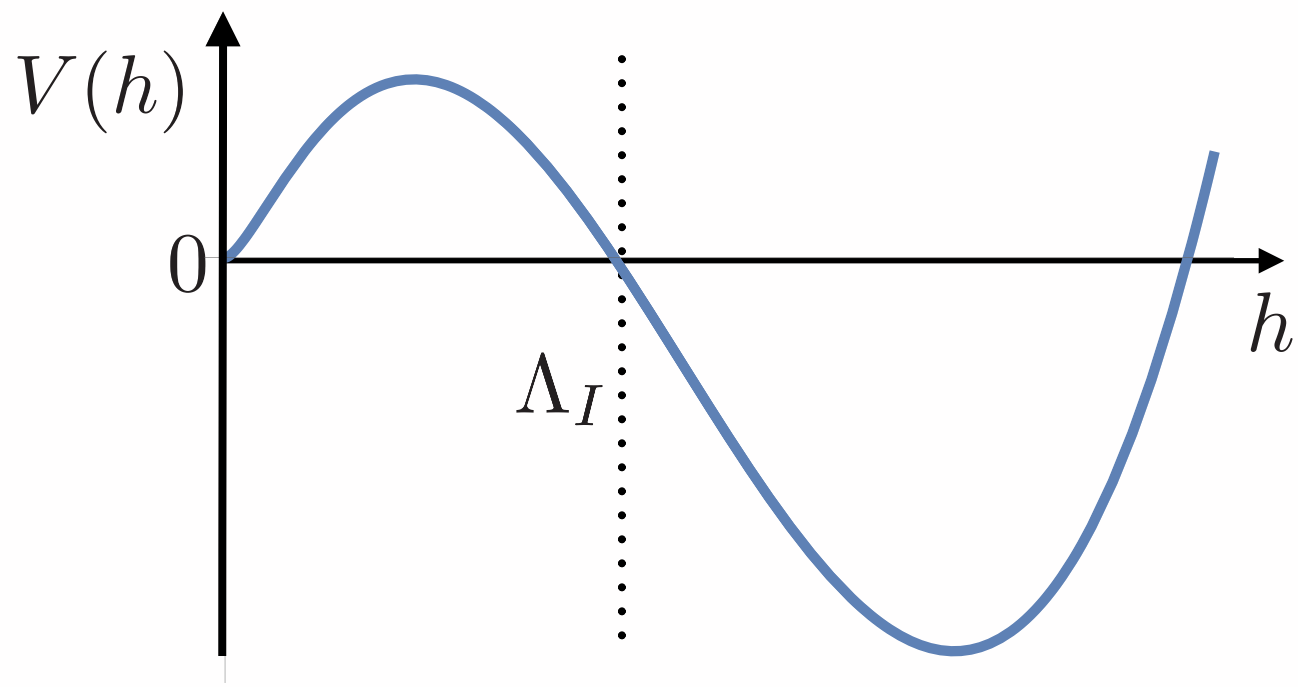
$$\xi_H \sim 10^5\sqrt{\lambda_H} \sim 10^4$$

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

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

Inflation and the SM instability

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



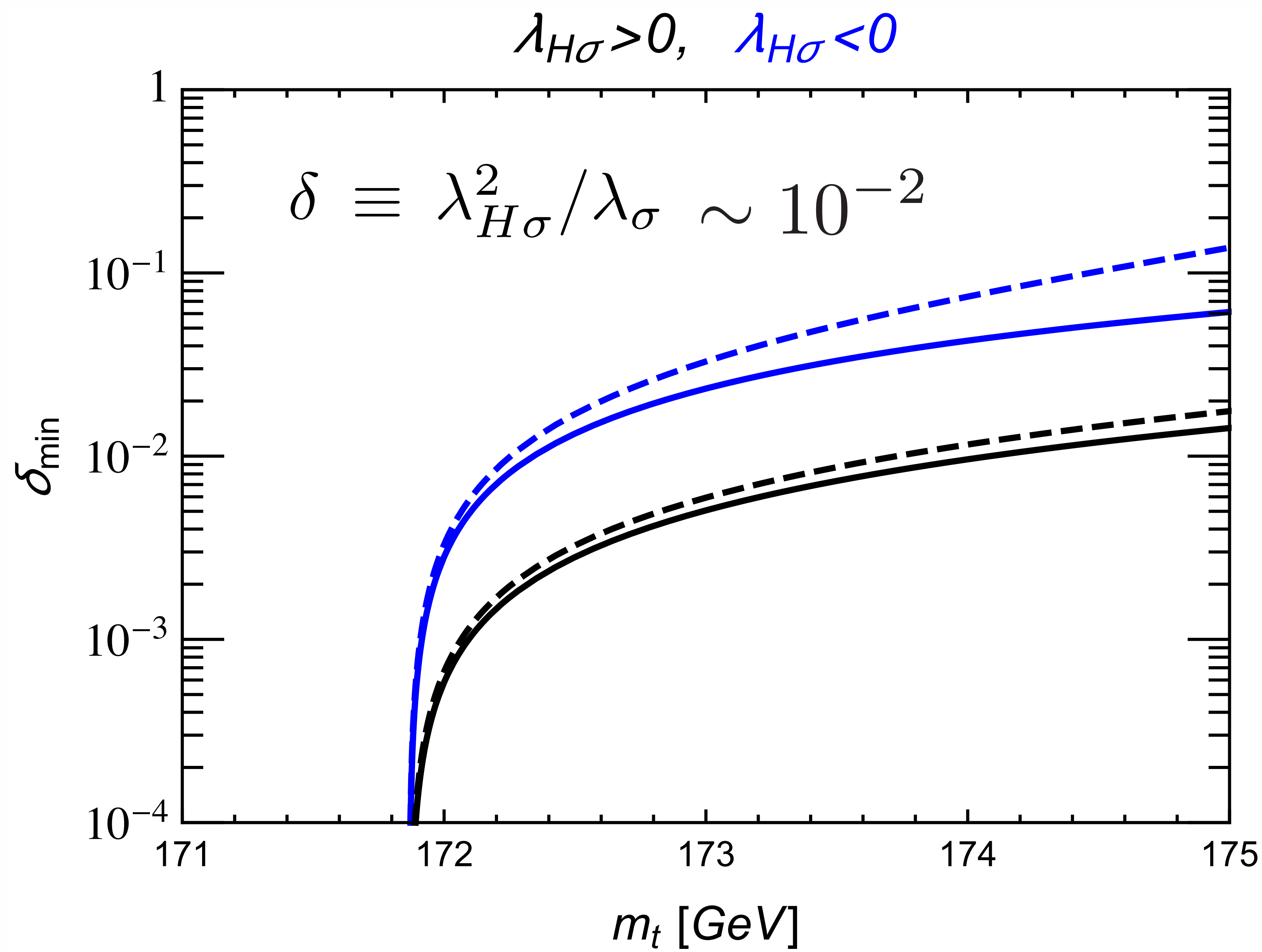
Quantum fluctuations of the Higgs:

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

Threshold stabilization

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

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



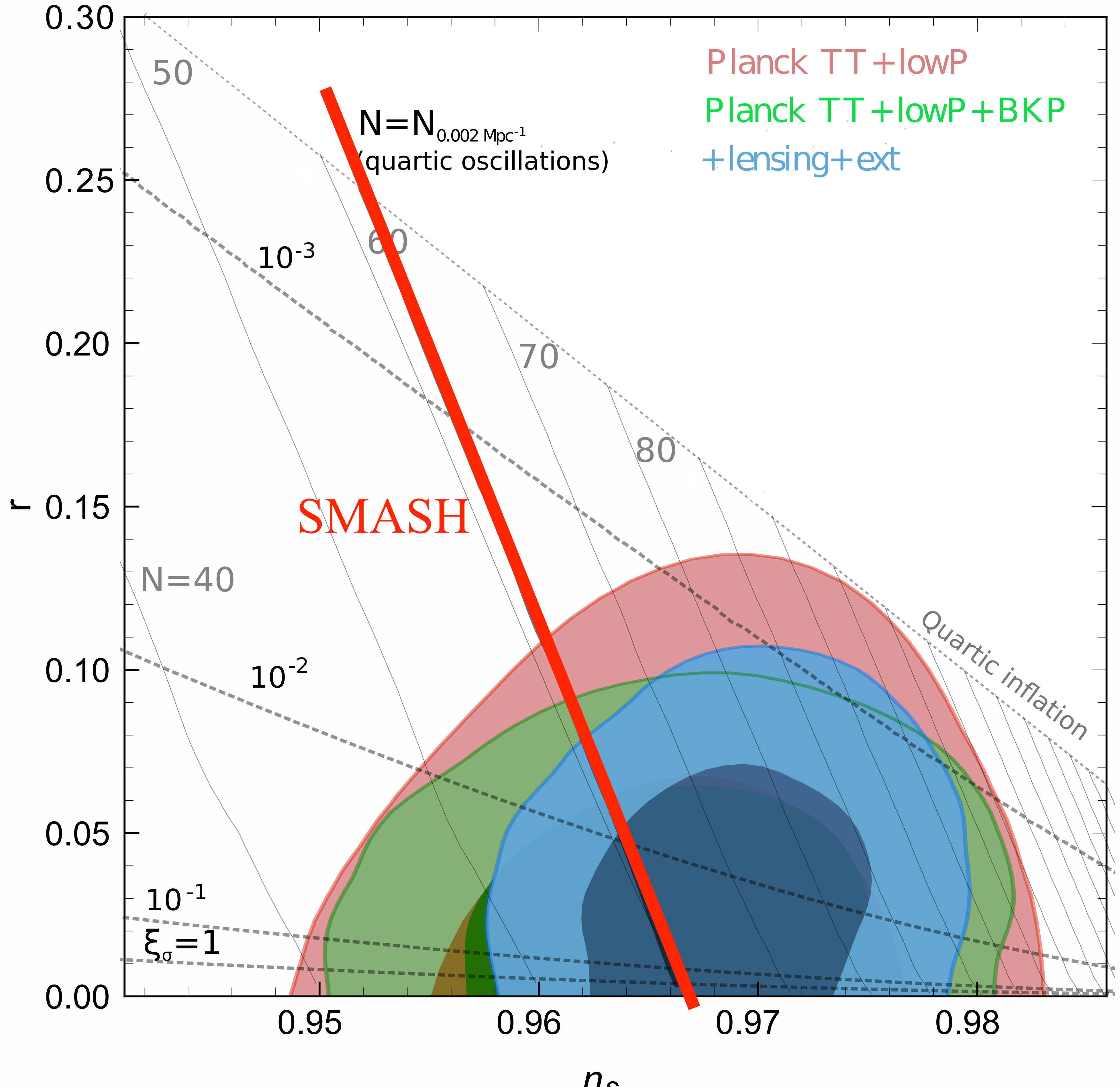
Inflation in SMASH

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

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

or

$$\lambda_{H\sigma} < 0 \longrightarrow \begin{array}{l} \rho = |\sigma| + \text{ small Higgs component} \\ \lambda = \lambda_\sigma - \lambda_{H\sigma}^2/\lambda_H \end{array}$$



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

Reheating & dark radiation

Inflation ends for $\rho \sim \mathcal{O}(M_P)$

and the inflaton oscillates in a quartic potential

$\lambda_{H\sigma} > 0$, $T_R \sim 10^7$ GeV $\quad \Delta N_{\rm eff} \sim 1$ Too much axion radiation

$\lambda_{H\sigma} < 0$, $T_R \sim 10^{10}$ GeV $\quad \Delta N_{\rm eff} \sim 0.03$ ✓

Axion dark matter

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

PQ symmetry restored after inflation

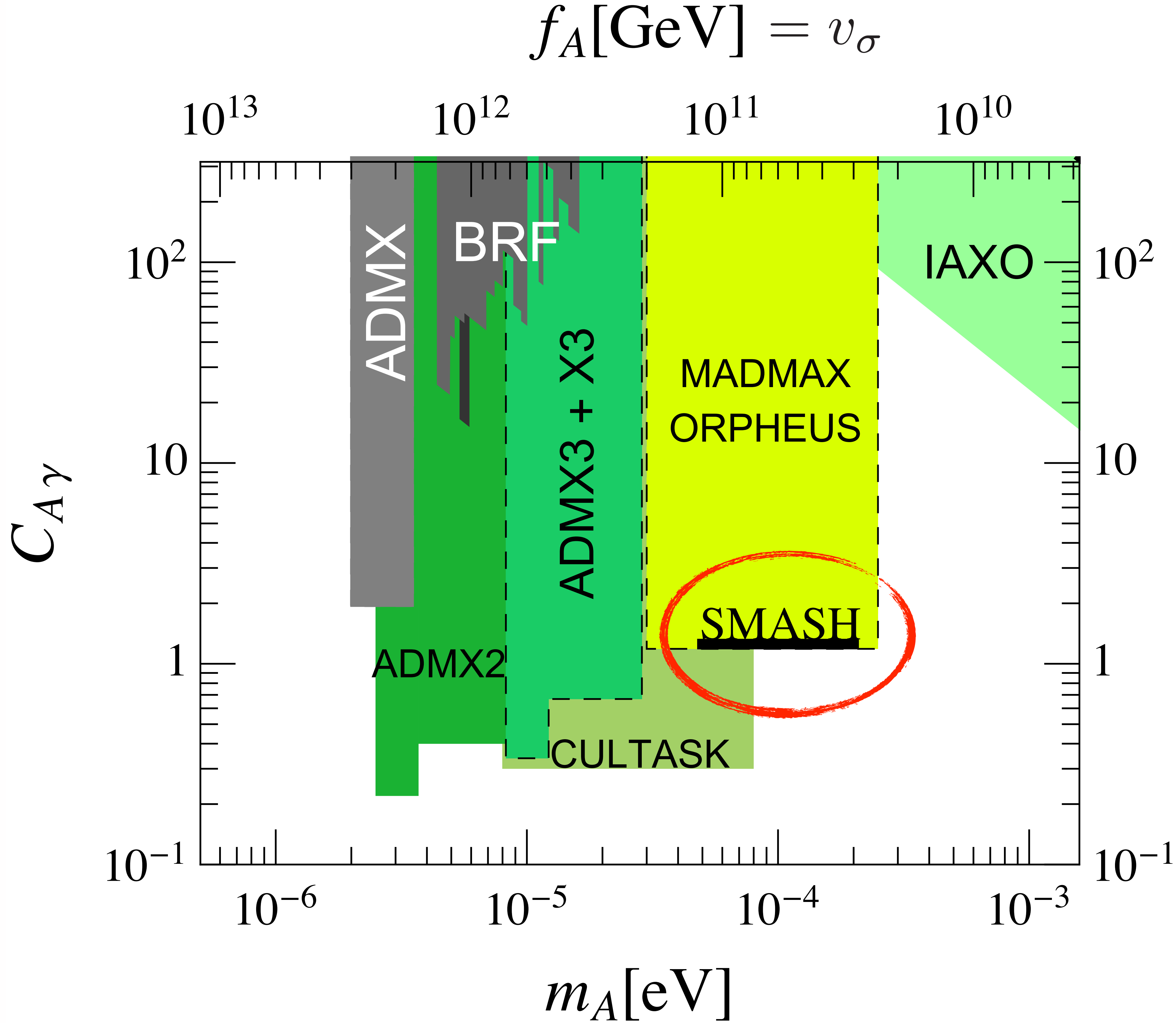
$$3 \times 10^{10}\,\text{GeV} \lesssim v_\sigma \lesssim 1.2 \times 10^{11}\,\text{GeV},$$

- vacuum misalignment mechanism
- decay of strings and domain walls

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

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

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



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

Conclusion

“ SMASH = SM + KSVZ + RHν ”

Solves

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