SM*A*S*H.

A Minimal Model for Particle Physics and Cosmology.

Andreas Ringwald (DESY)

Dark Matter from aeV to ZeV
3rd IBS-MultiDark-IPPP Workshop
Lumley Castle, UK
21-25 November 2016

[Guillermo Ballesteros, Javier Redondo, AR, Carlos Tamarit, 1608.05414; 1610.01639]

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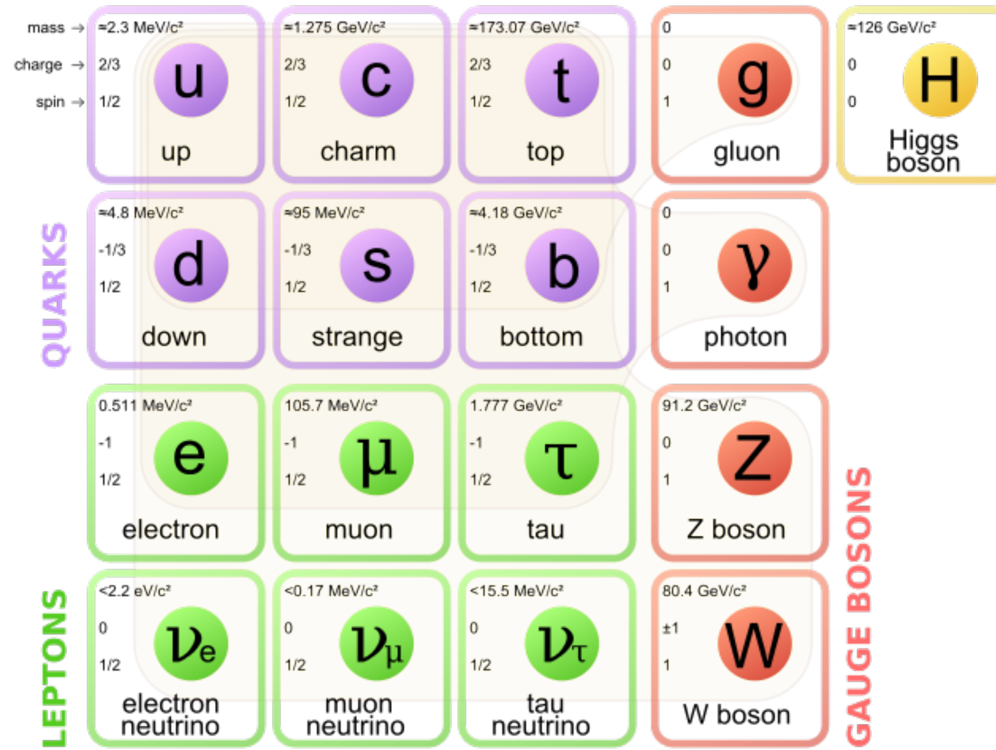
The Quest for a Minimal Model of Particle Cosmology

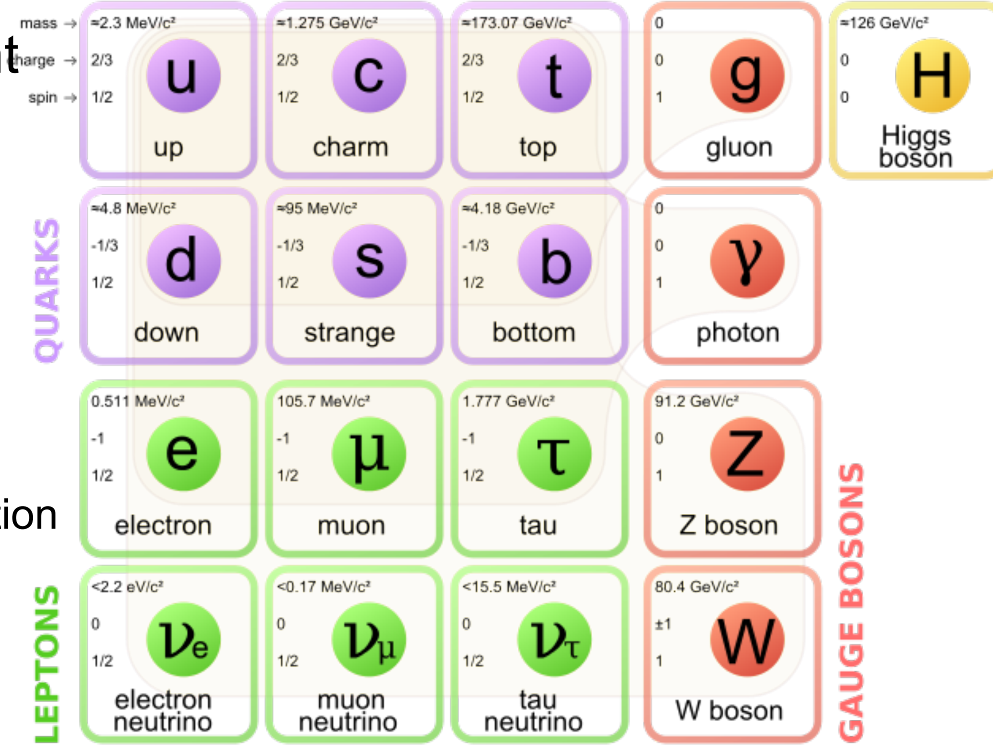
- Discovery of Higgs boson marks completion of SM particle content



[wikipedia]

The Quest for a Minimal Model of Particle Cosmology

- Discovery of Higgs boson marks completion of SM particle content
- Observations in particle physics, astrophysics and cosmology point to existence of BSM particles
  1. Neutrino oscillations
  2. Baryon asymmetry
  3. Dark matter
  4. Inflation
  5. Non-observation of strong CP violation



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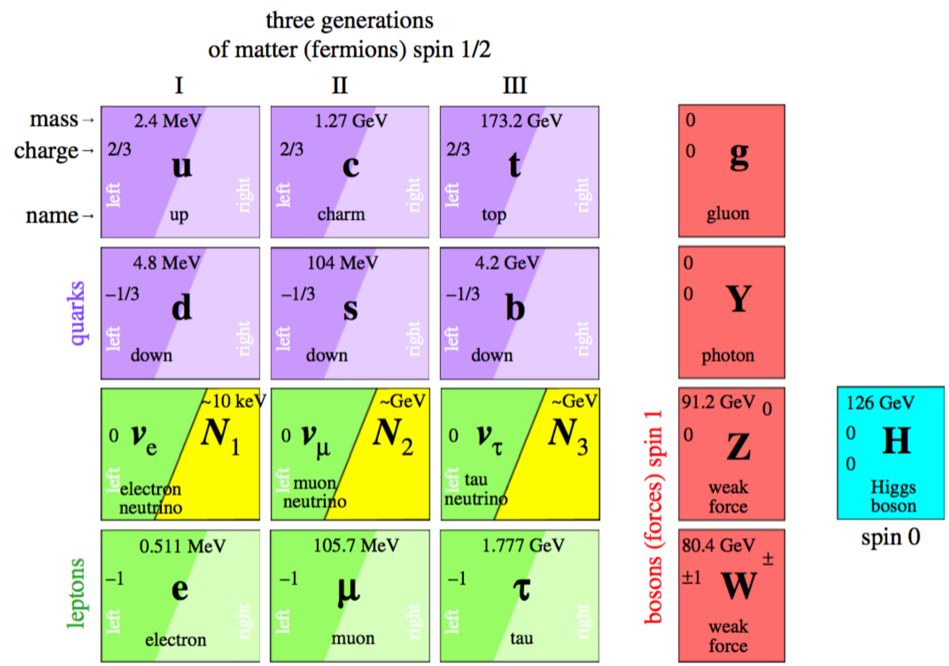

[M. Shaposhnikov, *Phil. Trans. R. Soc. A* **373** (2014) 0038]

- Problems 1.-4. solved in νMSM:
  - Minimal SM extension by light right-handed singlet neutrinos [Asaka, Shaposhnikov `05]

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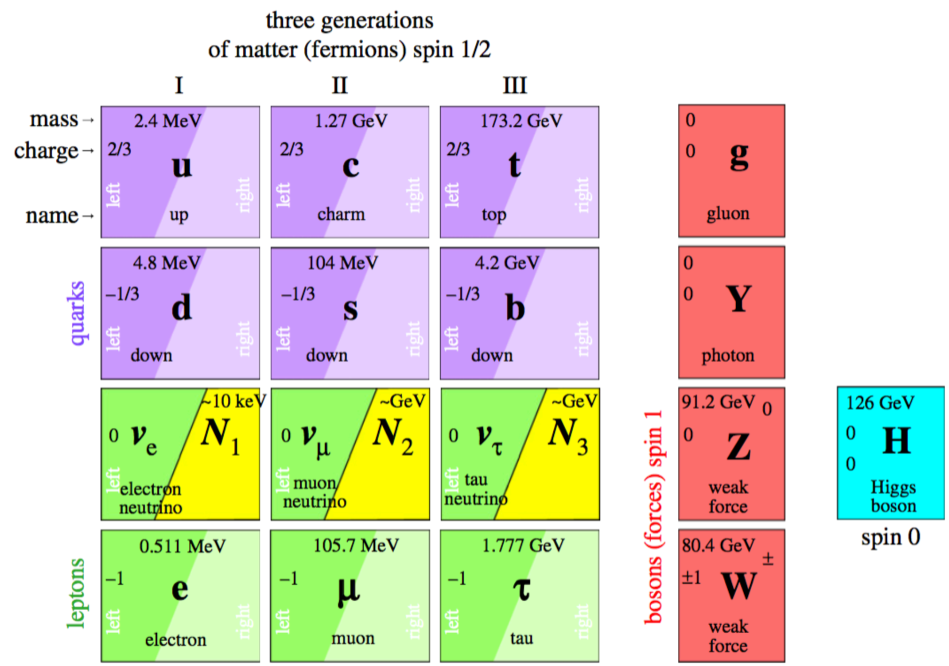

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- Problems 1.-4. solved in νMSM:
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  - Allowing for large, $\xi_H \sim 10^5 \sqrt{\lambda_H}$, non-minimally coupling of Higgs to Ricci scalar: Higgs Inflation [Bezrukov, Shaposhnikov `08]

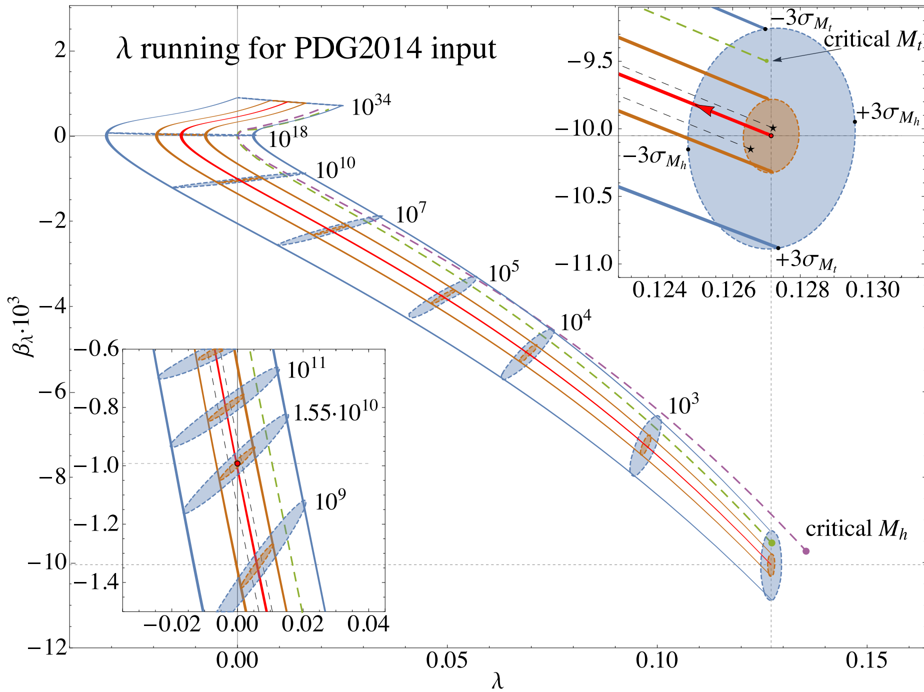
$$S \supset -\int d^4x\sqrt{-g}\,\xi_H\, H^\dagger H\, R$$

The Quest for a Minimal Model of Particle Cosmology

- Success of $\nu\mathrm{MSM}$ threatened:
  - For $\xi_H \sim 10^4$, perturbative unitarity breaks down well below the scale of inflation, rendering predictions unreliable

    [Barbon,Espinosa 09; Burgess et al. 09; Kehagias et al. 14]
  - Higgs inflation cannot be realised if Higgs quartic coupling λ_H runs negative at large (Planckian) field values

    [Degrassi et al. 12; Bezrukov et al. 12; Bednyakov et al. 15]
- Can be avoided by extending field content of $\nu\mathrm{MSM}$ by Hidden complex Scalar (HS) charged under new global U(1) symmetry that is spontaneously broken



[Bednyakov et al. 15]

The Quest for a Minimal Model of Particle Cosmology

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

- Role of the inflaton can now be played by modulus $|\sigma|^2 = \rho^2/2$ of HS or a mixture of latter with the modulus of the Higgs
  - Required non-minimal coupling $\xi_\sigma \sim 10^5\sqrt{\lambda_\sigma}$ to fit amplitude of CMB temperature fluctuations can be of order unity, for $\lambda_\sigma \sim 10^{-10}$, raising scale of unitarity violation to M_P

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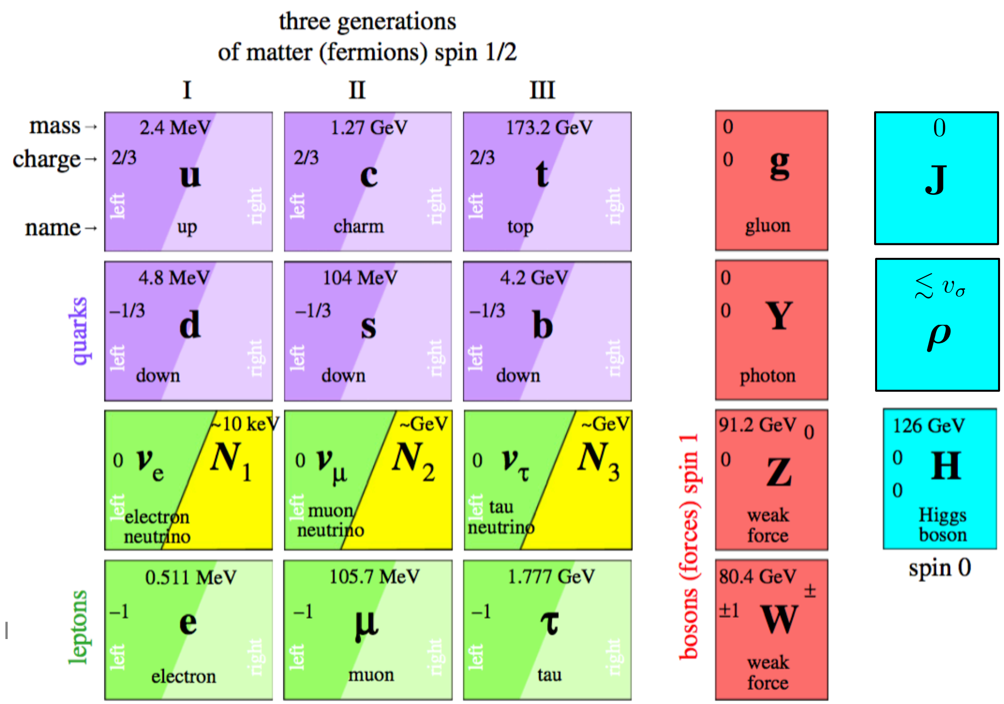
- Hidden scalar stabilizes scalar potential through Higgs portal coupling
  - Gives extra positive contribution to beta function of Higgs quartic

    [Gonderinger et al. 10]
  - Generates tree-level threshold effect on Higgs quartic coupling that can stabilize scalar potential

    [Lebedev 12; Elias-Miro et al. 12]



The Quest for a Minimal Model of Particle Cosmology

- Promote the new U(1) symmetry to a lepton symmetry

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

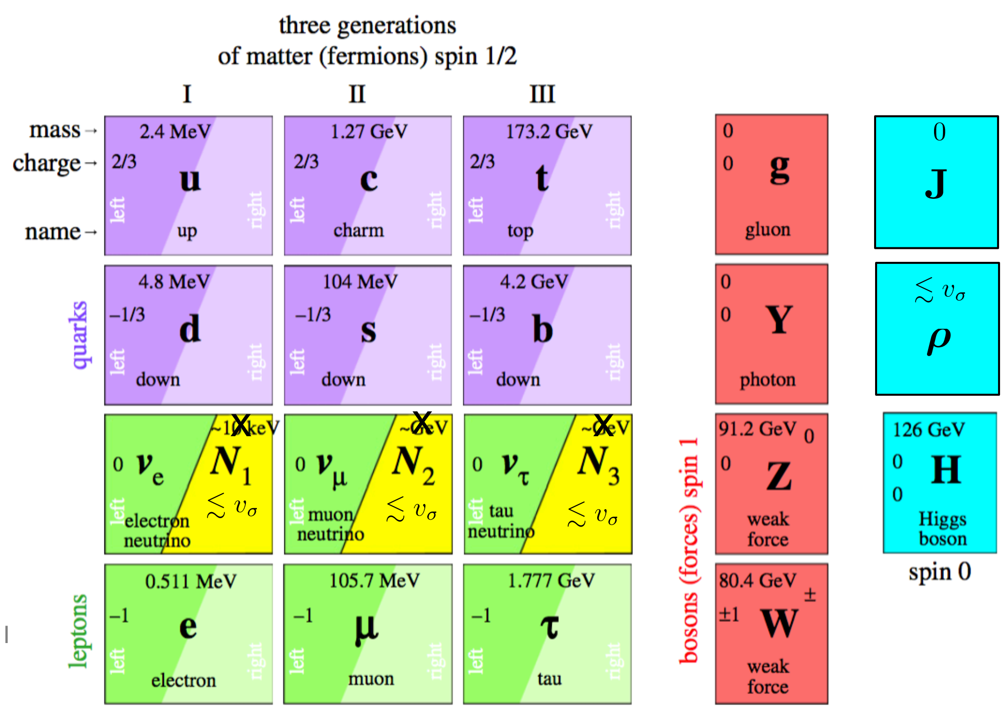
L	N	σ
$1/2$	$-1/2$	1

  - Naturally small active neutrino masses if VEV large:

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

  - Simplest thermal leptogenesis (out of equilibrium decay of lightest RHN) works

- DM possibilities:
  - Higgs portal (ρ) dark matter
  - Majoron (J) dark matter, if it gets mass from explicit U(1) breaking terms due to gravitational effects [Boucenna et al. 14]



The Quest for a Minimal Model of Particle Cosmology

- Add further vector-like quark with chiral charge assignment under hidden U(1), rendering the latter to a Peccei-Quinn symmetry [Shin `88; Dias et al. `14]

$$\mathcal{L} \supset -\left[F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + y\, \tilde{Q} \sigma Q + y_{Q_d}{}_i \sigma Q d_i + h.c.\right]$$

SM * Axion * See-saw * Higgs portal inflation

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

SM*A*S*H

[Ballesteros,Redondo, AR,Tamarit, 1608.05414]

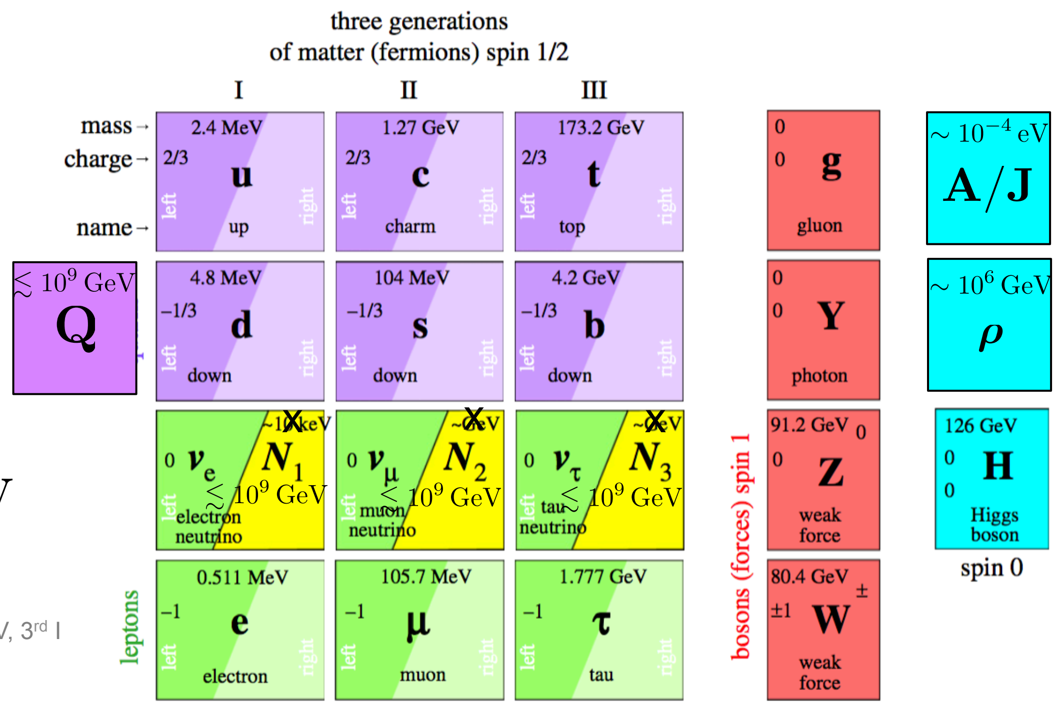
- NG boson A/J has coupling

$$\mathcal{L}_A \supset -\frac{\alpha_s}{8\pi} \frac{A}{v_\sigma} G^c_{\mu\nu} \tilde{G}^{c,\mu\nu}$$

- Strong CP problem solved
- Axion = Majoron

$$f_A = v_\sigma \qquad m_A \sim f_\pi m_\pi / f_A$$

- Axion = DM, if $v_\sigma \sim 10^{11}\,\mathrm{GeV}$



Higgs Portal Inflation

- Non-minimal couplings stretch scalar potential in Einstein frame; makes it convex and asymptotically flat at large field values

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

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

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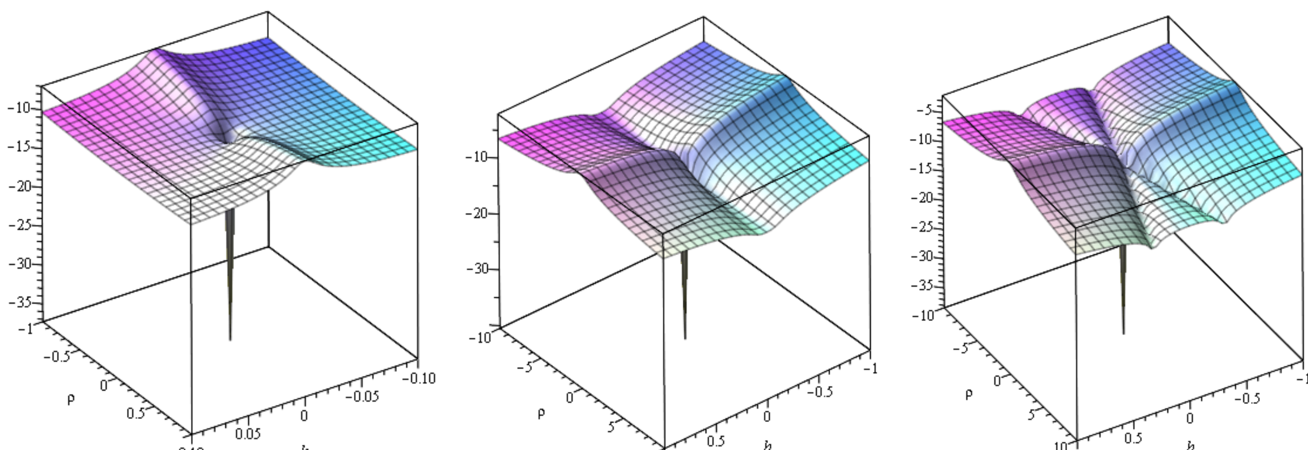
- Potential has valleys = attractors for Higgs Inflation (HI), Hidden Scalar Inflation (HSI) or mixed Higgs Hidden Scalar Inflation (HHSI), depending on relative signs of $\kappa_H \equiv \lambda_{H\sigma}\xi_H - \lambda_H\xi_\sigma\,,\quad \kappa_\sigma \equiv \lambda_{H\sigma}\xi_\sigma - \lambda_\sigma\xi_H$



sign(κ_H)	sign(κ_σ)	Inflation
$+$	$-$	HI
$-$	$+$	HSI
$-$	$-$	HHSI

Higgs Portal Inflation

- CMB observables

$$A_s = (2.20 \pm 0.08) \times 10^{-9}\,,$$
$$n_s = 0.967 \pm 0.004\,,$$
$$r < 0.07$$

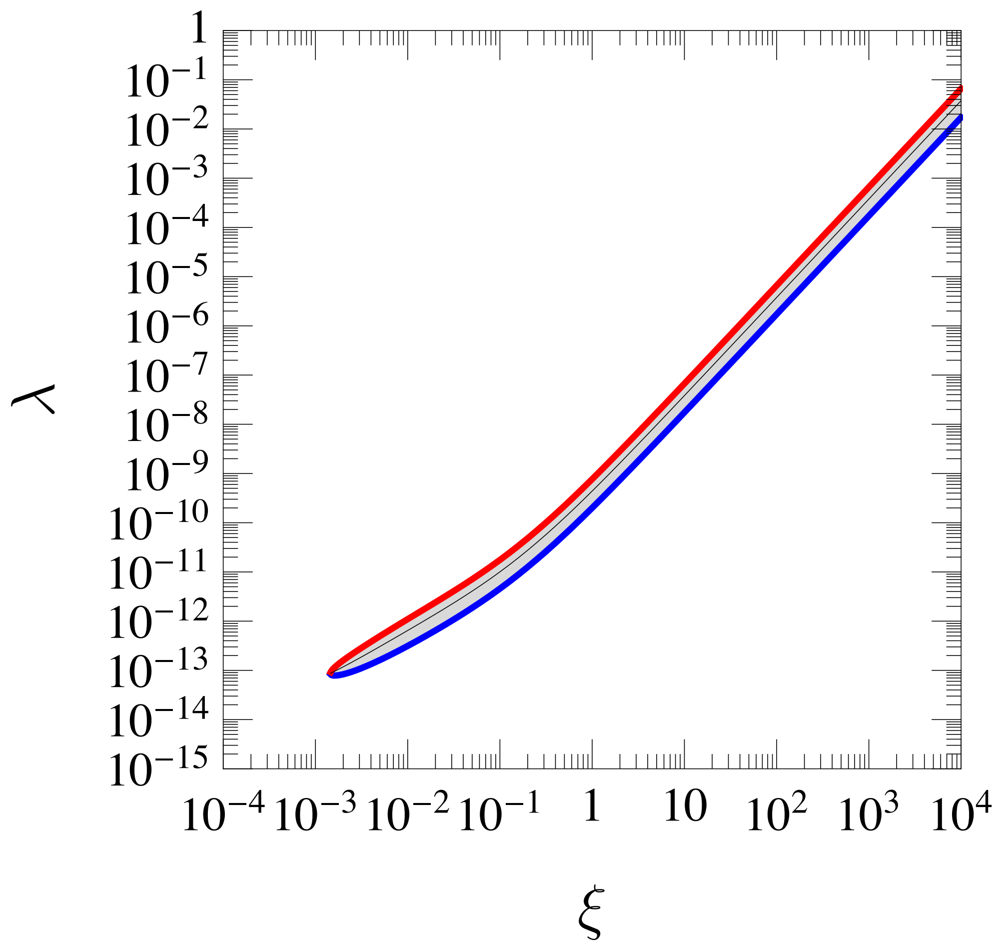
can be fit for any

$$\xi \simeq 2 \times 10^5 \sqrt{\lambda} \gtrsim 10^{-3}$$

where

$$\xi \equiv \begin{cases} \xi_H\,, & \text{for HI,} \\ \xi_\sigma\,, & \text{for HSI,} \\ \xi_\sigma\,, & \text{for HHSI} \end{cases}$$

$$\lambda \equiv \begin{cases} \lambda_H\,, & \text{for HI,} \\ \lambda_\sigma\,, & \text{for HSI,} \\ \lambda_\sigma \left(1 - \frac{\lambda_{H\sigma}^2}{\lambda_\sigma \lambda_H}\right)\,, & \text{for HHSI} \end{cases}$$



[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

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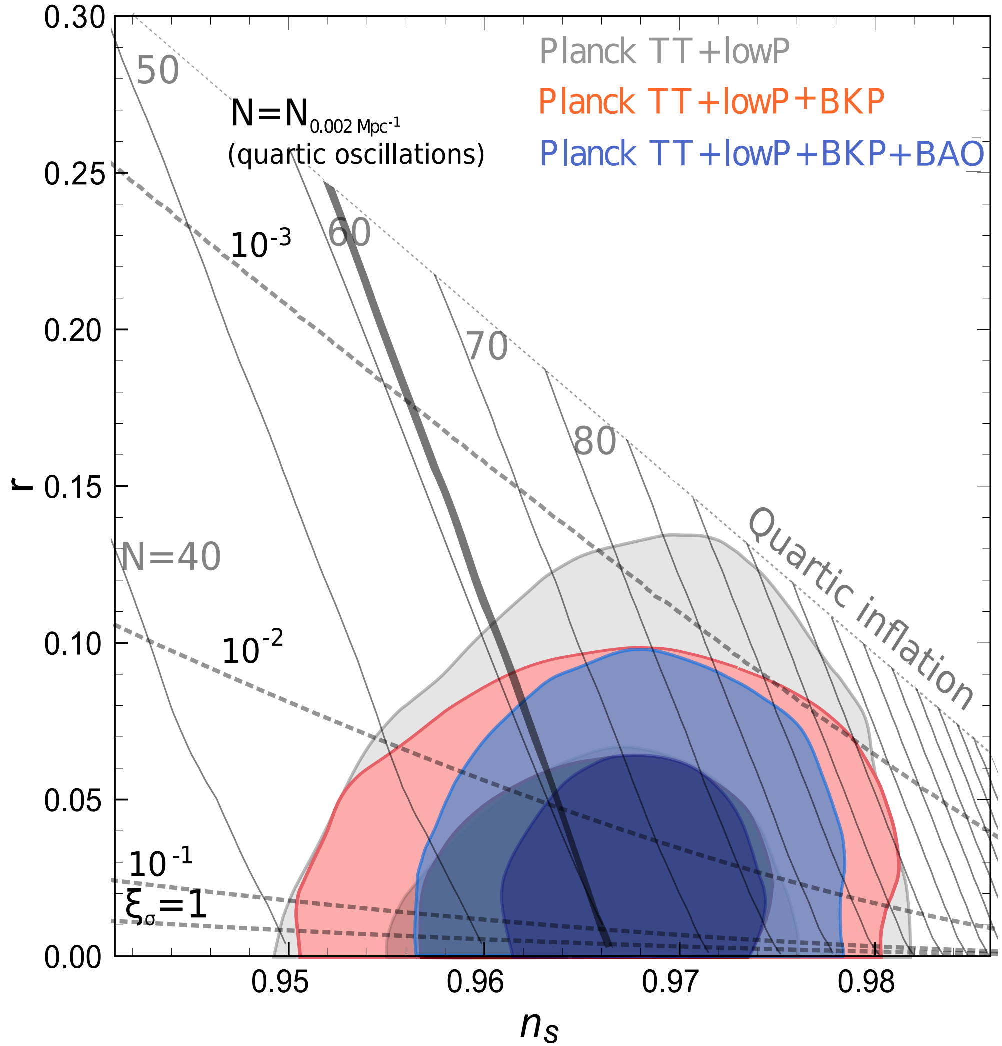


Higgs Portal Inflation

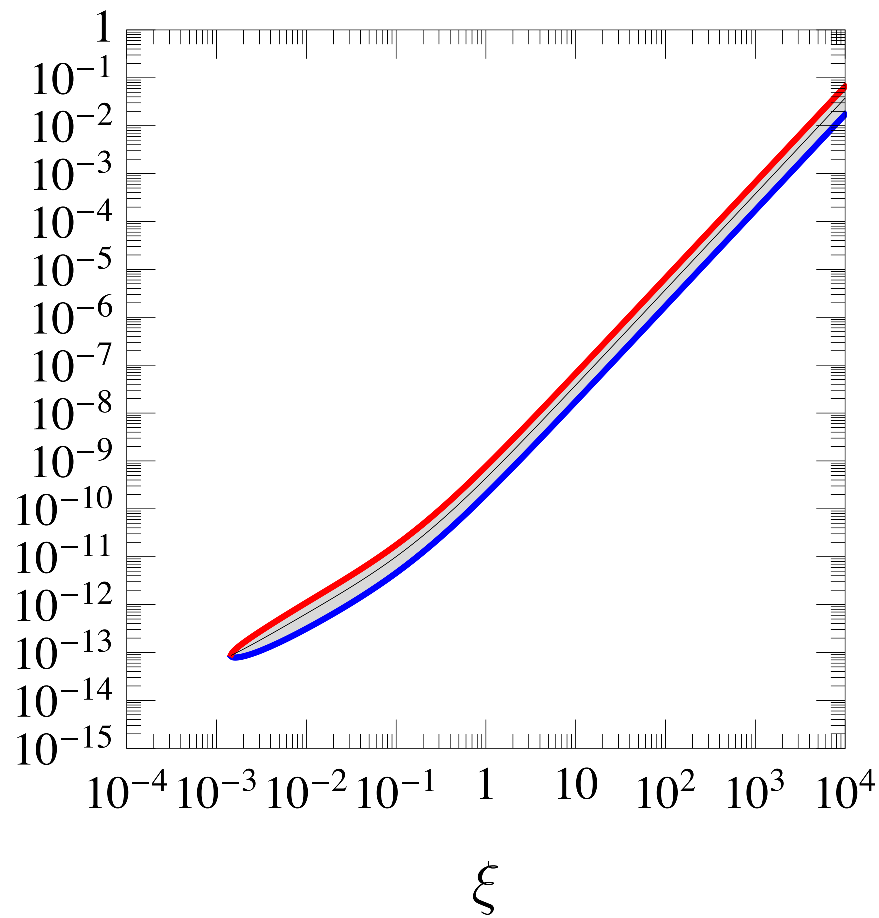
- HI requires huge non-minimal coupling of the Higgs:

$$\xi_H \sim 2 \times 10^5 \sqrt{\lambda_H(\sim M_P)} \sim 2 \times 10^4$$

- Perturbative unitarity lost in HI

$$\Lambda_U \sim \frac{M_P}{\xi_H} \sim 10^{14}\,\mathrm{GeV} \ll \tilde{V}^{1/4}(h_I) \sim 10^{16}\,\mathrm{GeV}$$

- No unitarity problem in HSI/HHSI, if $\lambda_\sigma, \tilde{\lambda}_\sigma \lesssim 10^{-10}$, since then $\xi_\sigma \lesssim 1$



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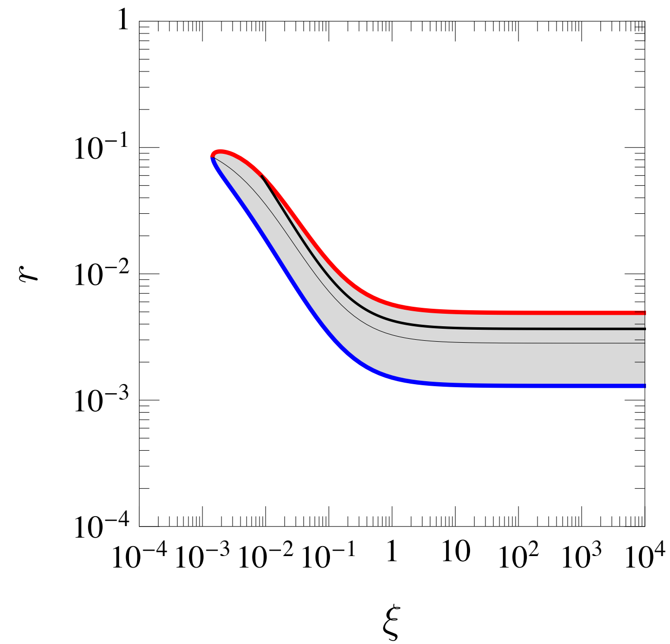
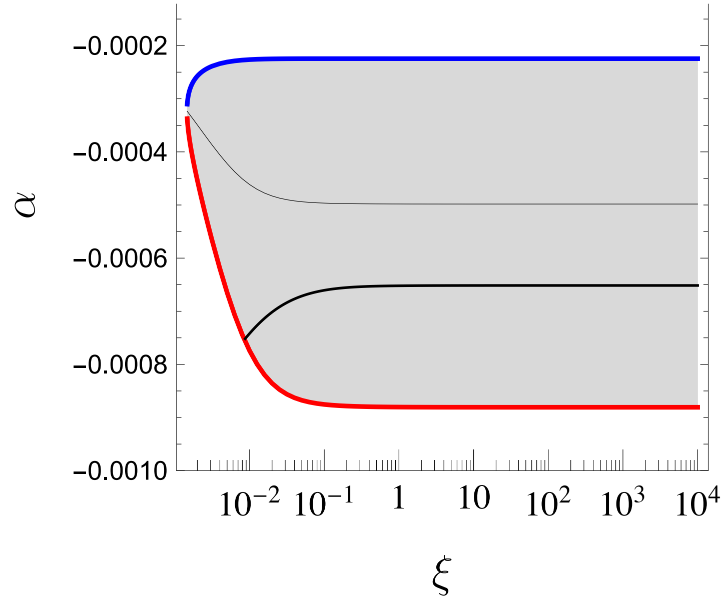
- Predicted tensor/scalar ratio in reach of CMB-S4 and LiteBird
- Predicted running of spectral index in reach of 21 cm H emission line observatory





Stability

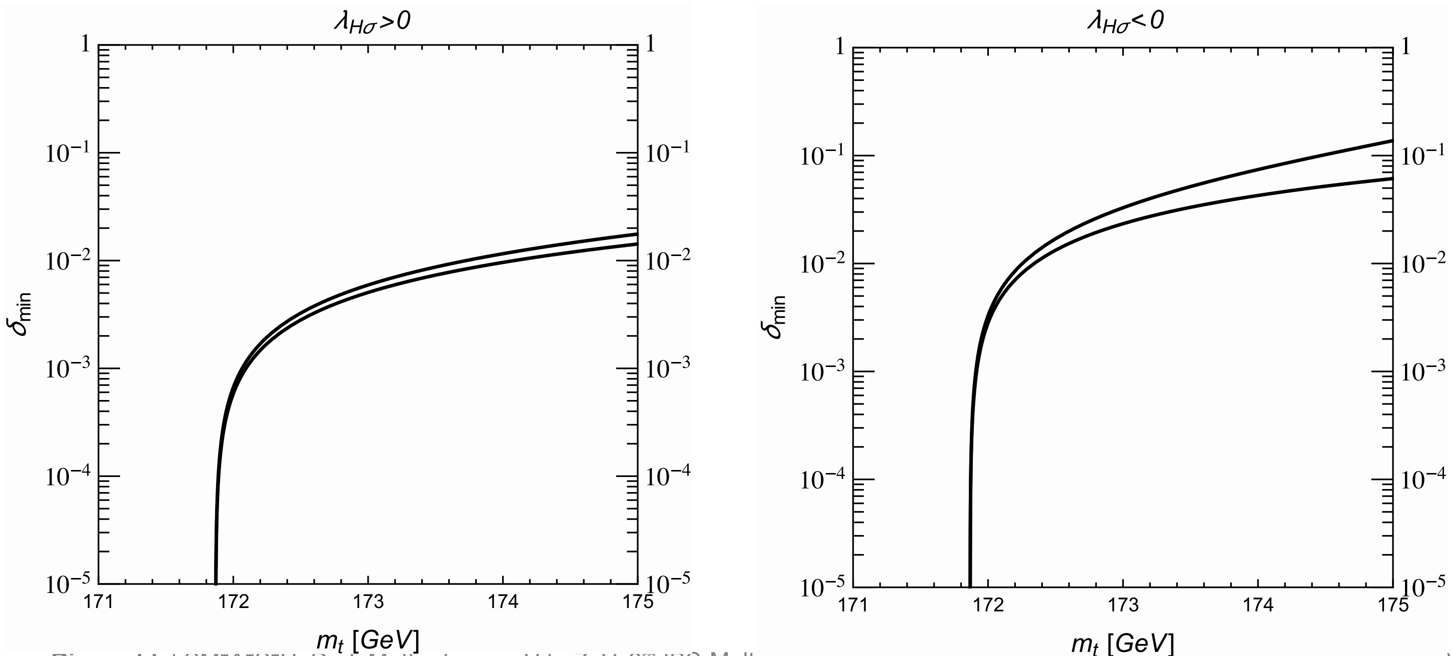
> SM-singlet scalar σ helps to stabilize scalar potential in Higgs direction through threshold effect associated with Higgs portal

- When ρ integrated out, Higgs portal gives negative contribution ot Higgs quartic,

$$\bar{\lambda}_H(m_h) = \lambda_H - \lambda_{H\sigma}^2/\lambda_\sigma\big|_{\mu=m_h}$$

- At energies above m_ρ, true (and larger!) value of λ_H is revealed by integrating ρ in

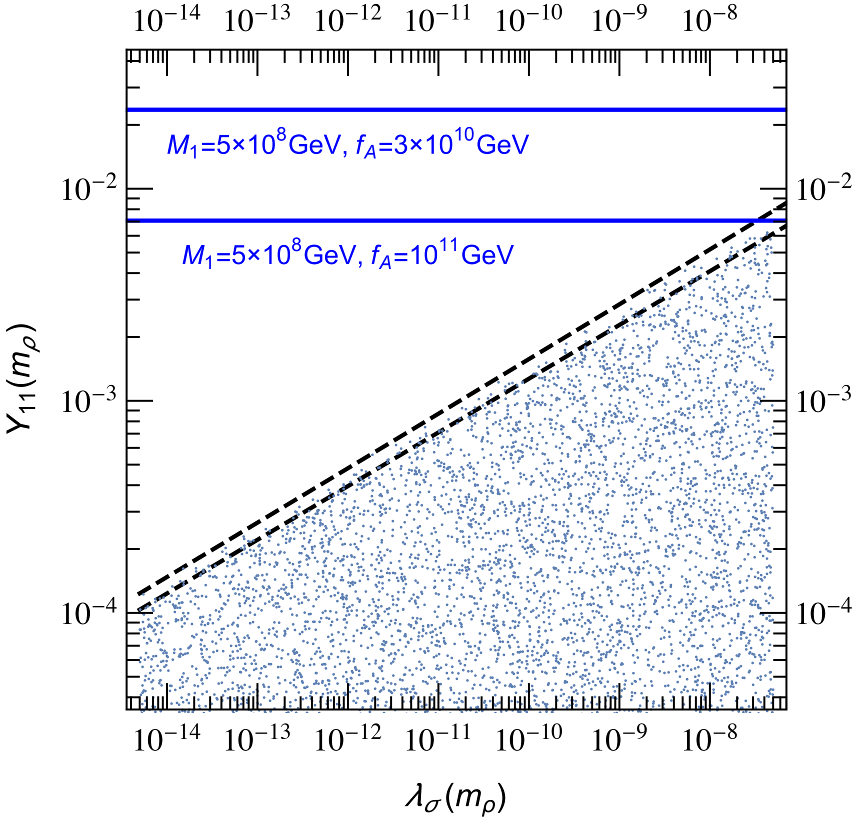
> Minimum required $\delta = \lambda_{H\sigma}^2/\lambda_\sigma\big|_{\mu=m_h}$ to stabilize up to Planck scale:

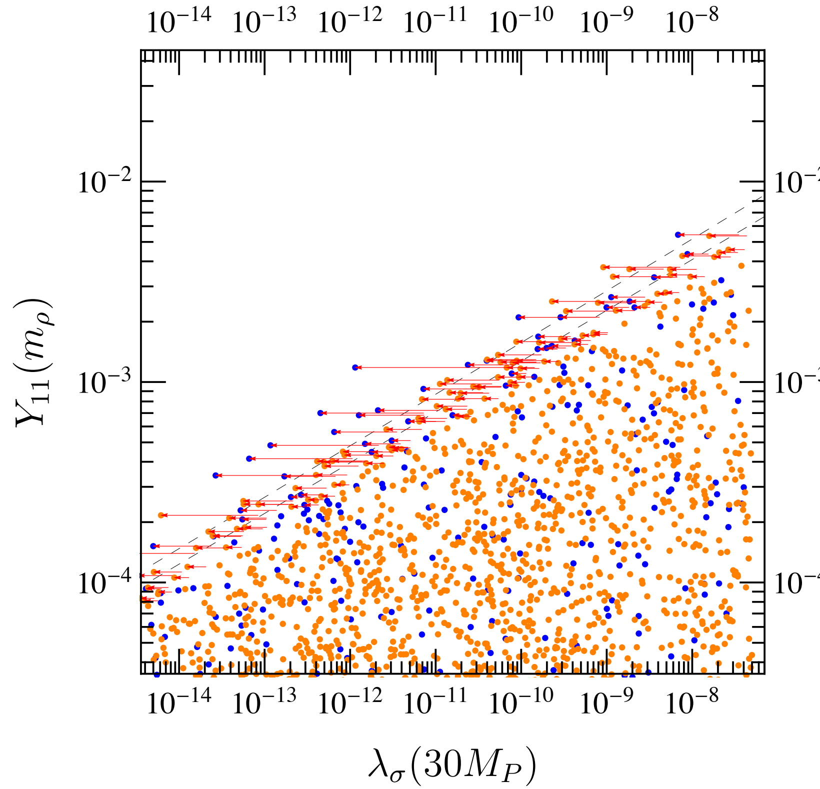


Stability

- Stability in σ direction threatened by quantum corrections due to right-handed neutrinos and exotic quark, unless

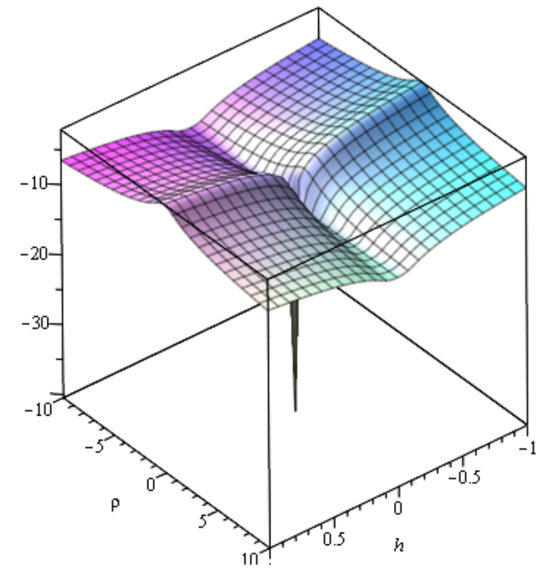
$$\sum Y_{ii}^4 + 6y^4 \lesssim 16\pi^2 \lambda_\sigma / \log\left(30 M_P / \sqrt{2\lambda_\sigma} v_\sigma\right)$$

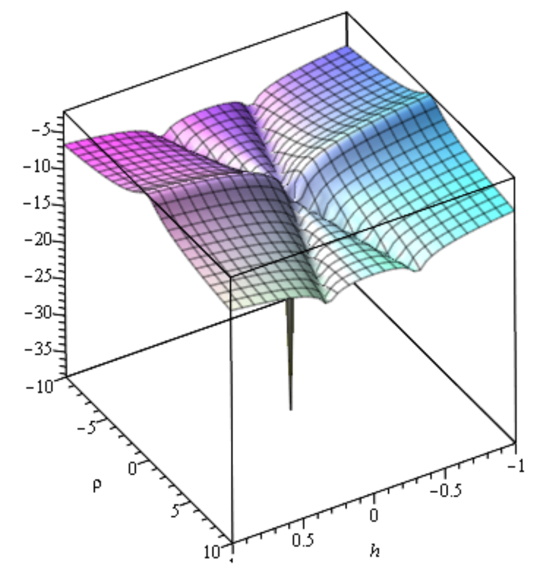




Reheating

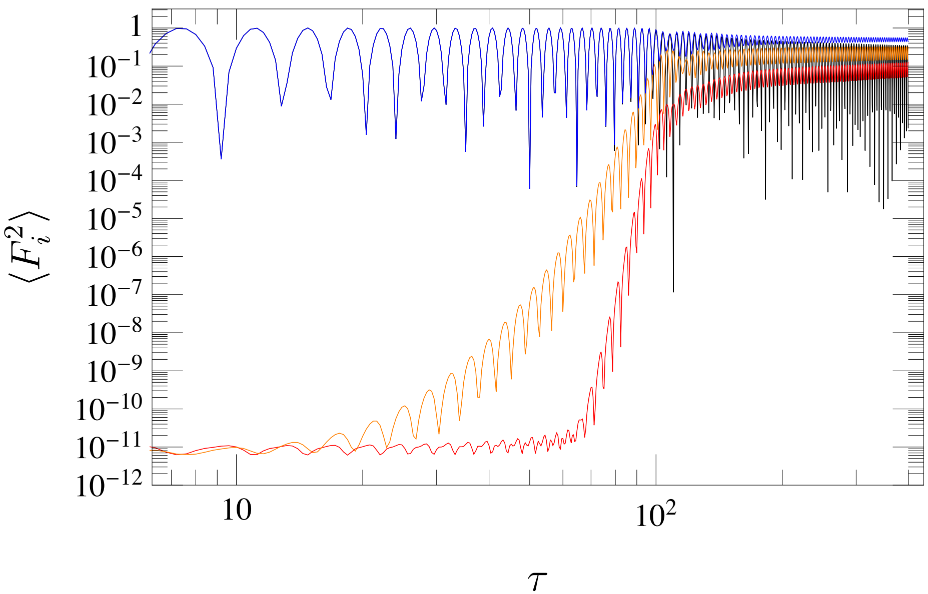
- SMASH complete model: evolution after inflation can be calculated
- Fundamental questions:
  - PQ symmetry restored after inflation?
  - Reheating temperature large enough for successful thermal leptogenesis?
- Both in HSI and HHSI with $\xi_\sigma \lesssim 1$, slow-roll inflation ends at a value of $\rho \sim \mathcal{O}(M_P)$
- Inflaton starts to undergo Hubble-damped oscillations in a quartic potential, with Universe expanding as in a radiation-dominated era

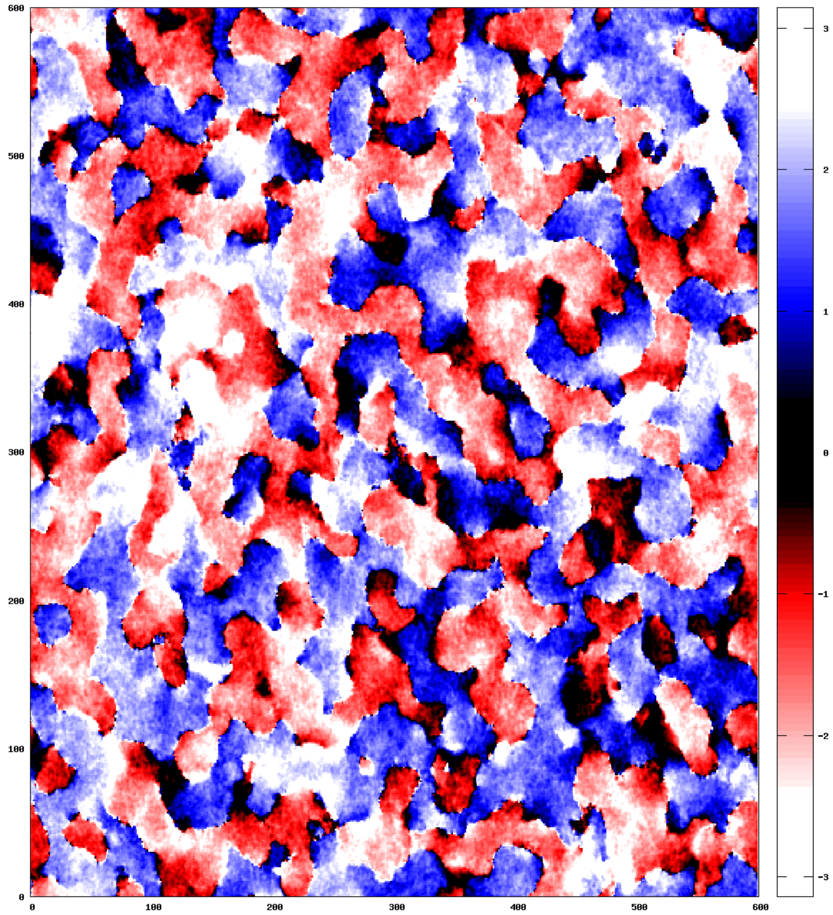




Reheating

- Preheating:
  - Fluctuations of hidden scalar grow fast due to parametric resonance while inflaton background oscillates in its quartic potential
  - PQ symmetry restored after about 14 full oscillations





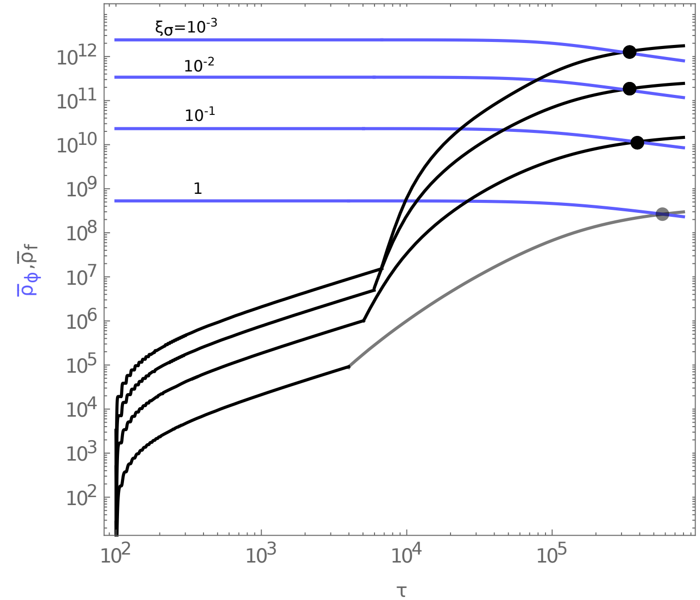
Reheating

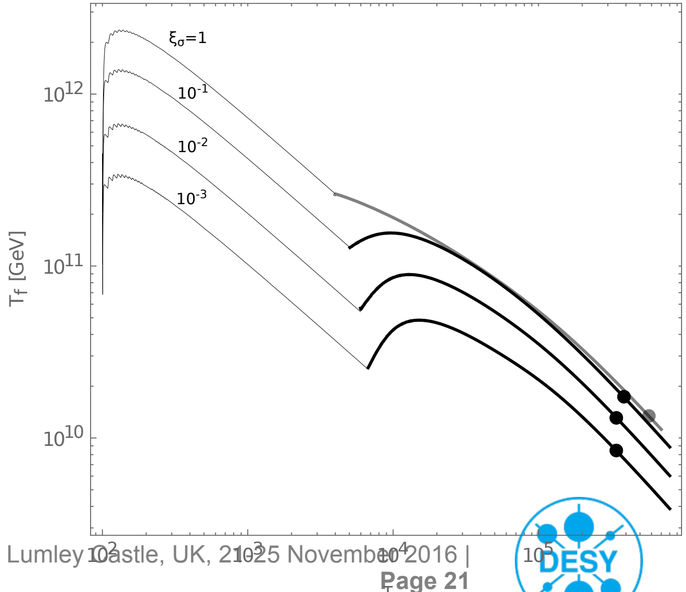
- Perturbative reheating:
  - HSI: Large induced particle masses quench inflaton decays or annihilations into SM particles, resulting in low reheating temperature and too much cosmic axion background (CAB) radiation

$$T_R \sim 10^7\,\mathrm{GeV}\, v_{11} \lambda_{10}^{3/8} \delta_3^{-1/8}$$

$$\Delta N_\nu^{\rm eff} \sim (\delta_3 v_{11}/\lambda_{10})^{-1/6}$$

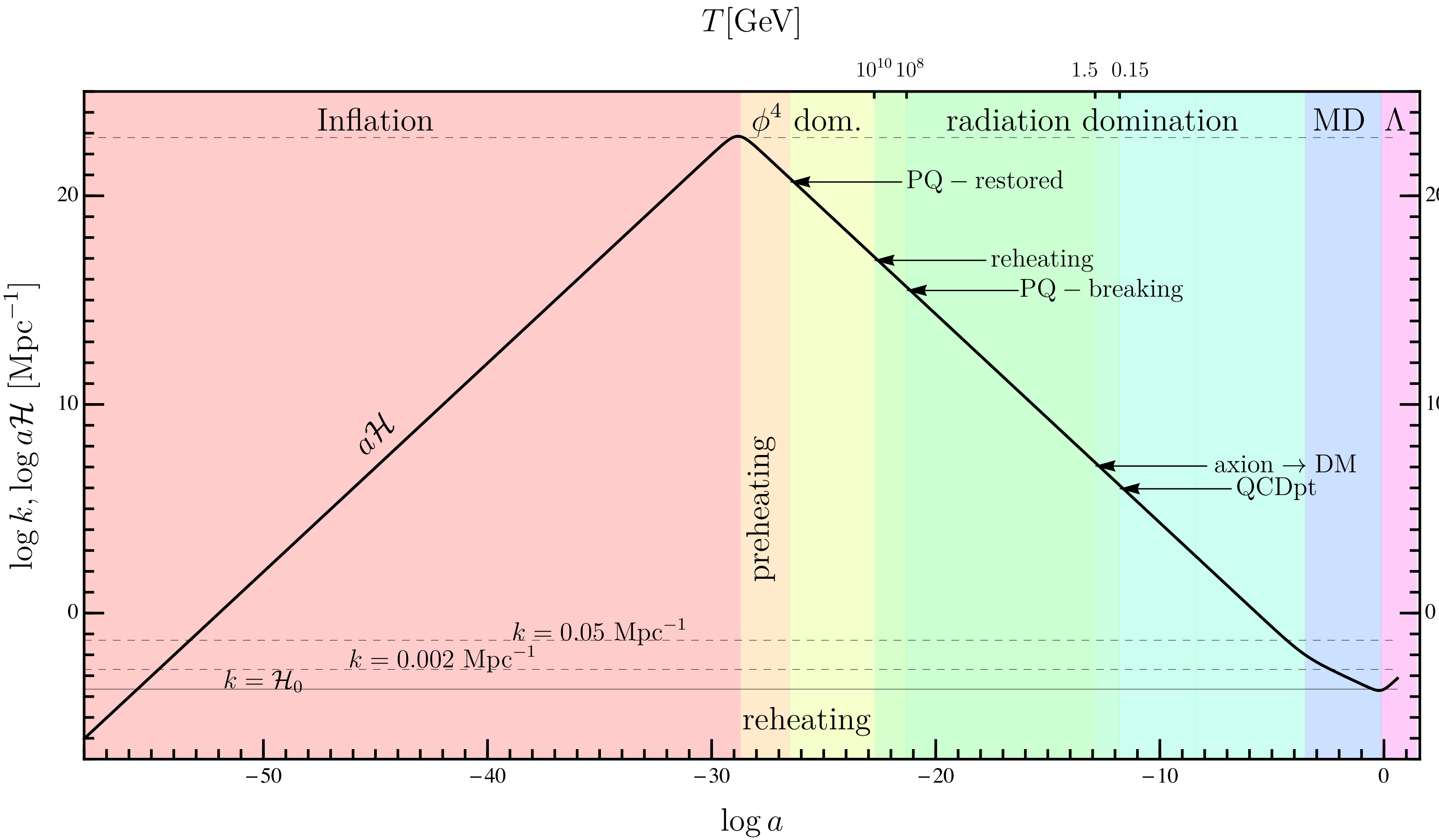
  - HHSI: Higgs component of inflaton allows for production of SM gauge bosons, resulting in high reheating temperature (sufficient for thermal leptogenesis) and $\Delta N_\nu^{\rm eff} \simeq 0.03$
- CAB in reach of future CMB polarization experiment





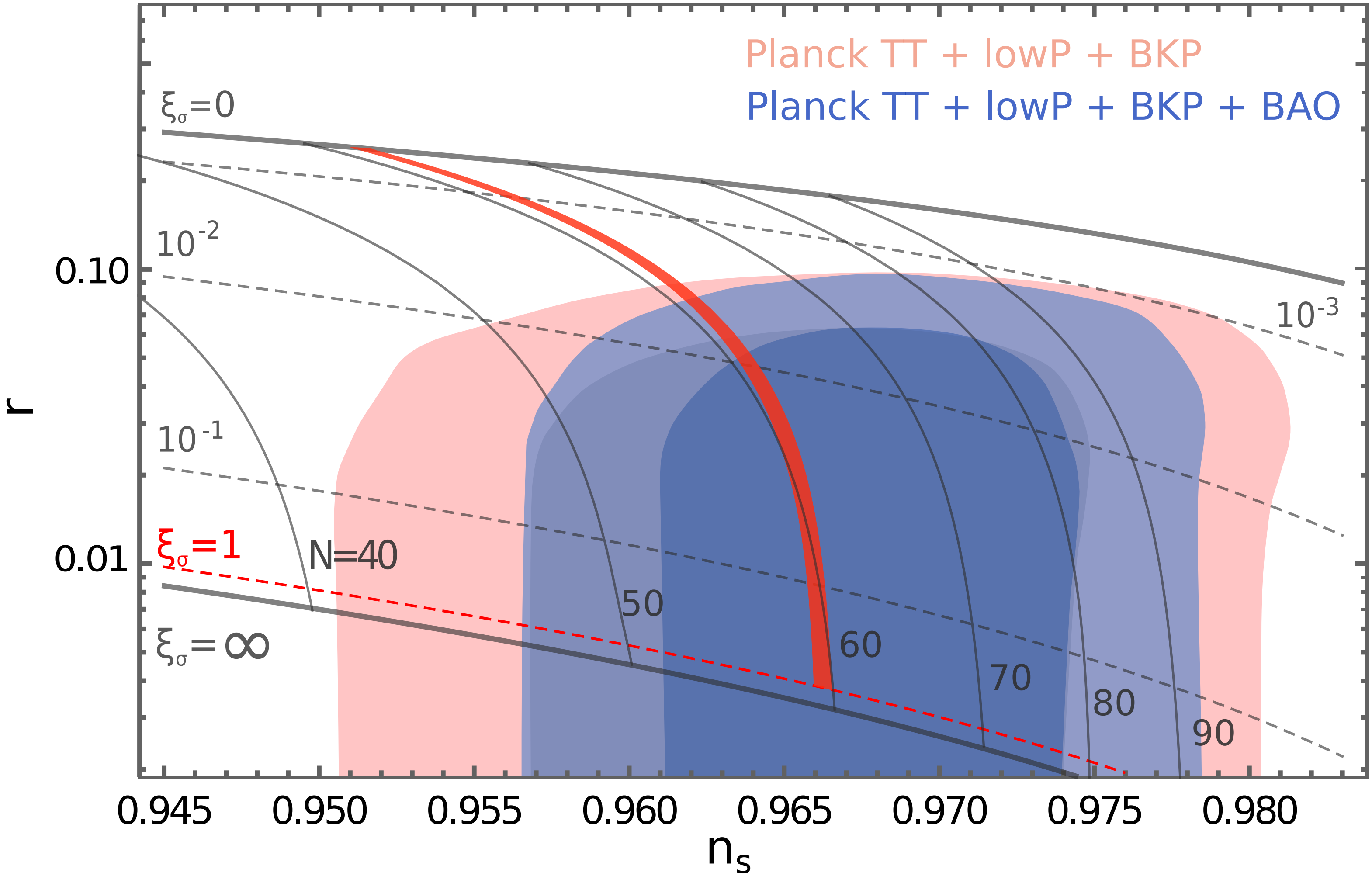
Reheating

> Universe expands as in a radiation-dominated era (w=1/3) from the end of inflation until matter-radiation equality



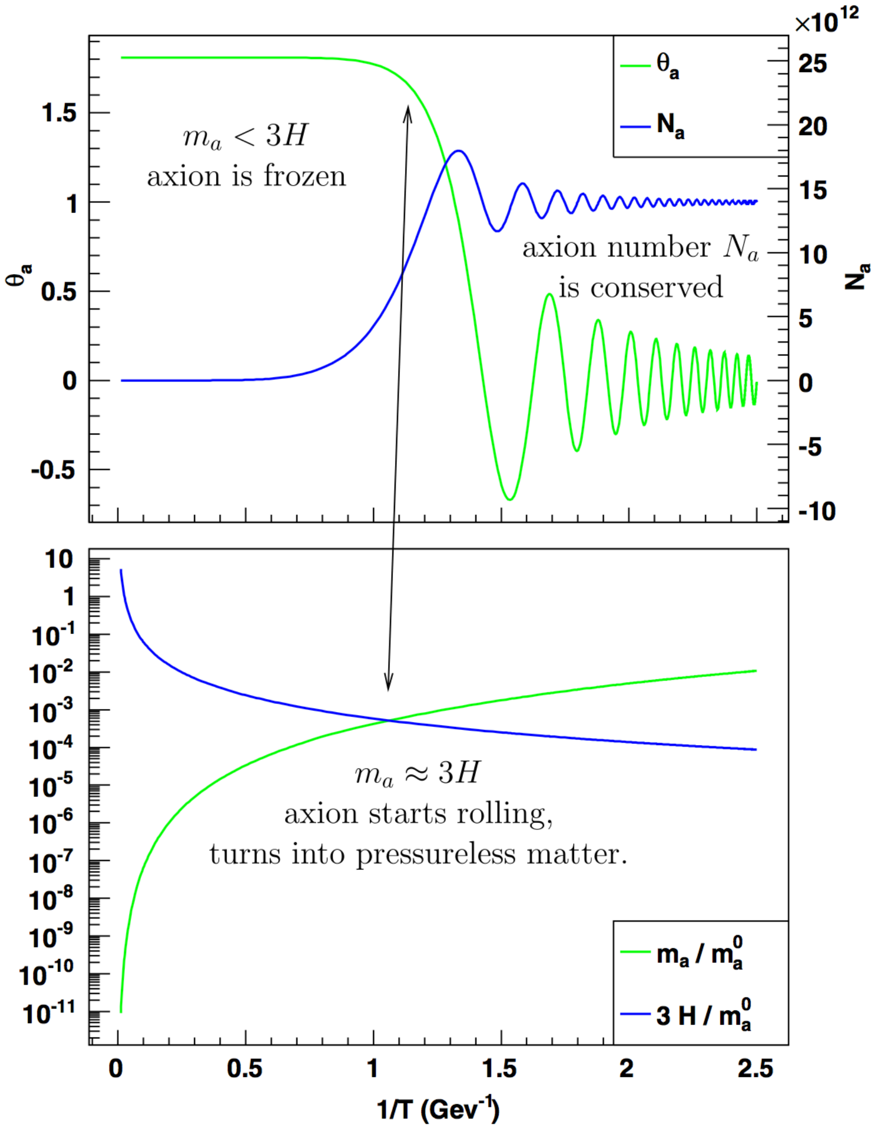
Reheating

- Sharp prediction of r vs n_s for fixed pivot scale k:



Axion Dark Matter

- SMASH predicts post-inflationary PQ breaking and thus one-to-one relation $m_A \Leftrightarrow \Omega_A$
- Mechanisms of production:
  - Vacuum realignment



[Wantz,Shellard 09]

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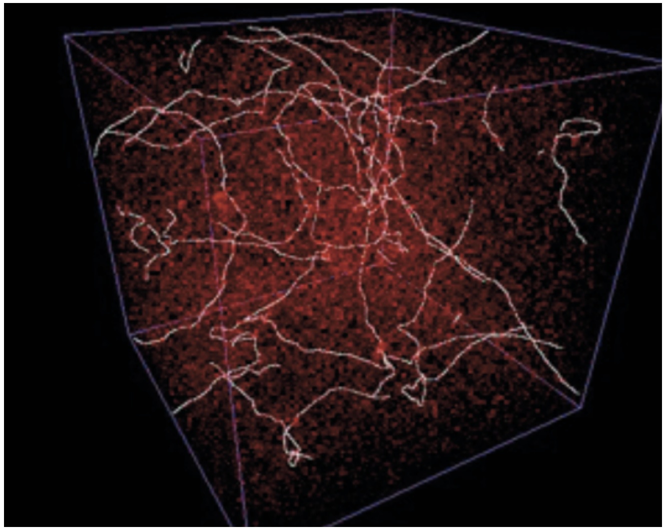
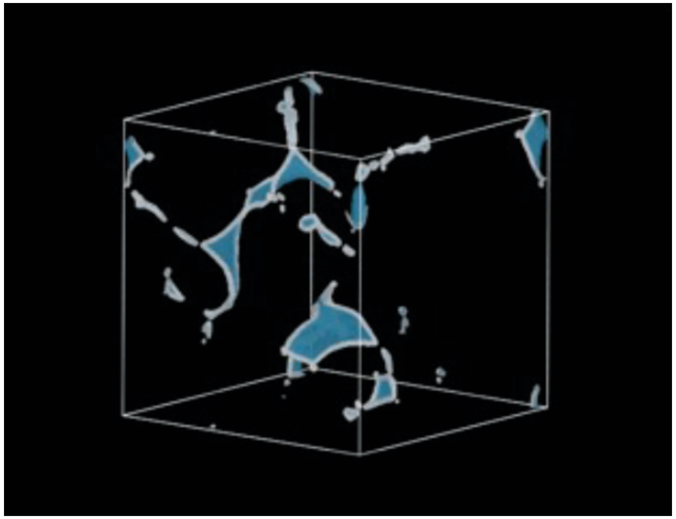
$$\Omega_{A,\mathrm{tot}}h^2 = \Omega_{A,\mathrm{real}}h^2 + \Omega_{A,\mathrm{string}}h^2 + \Omega_{A,\mathrm{wall}}h^2$$





[Hiramatsu et al. 12]

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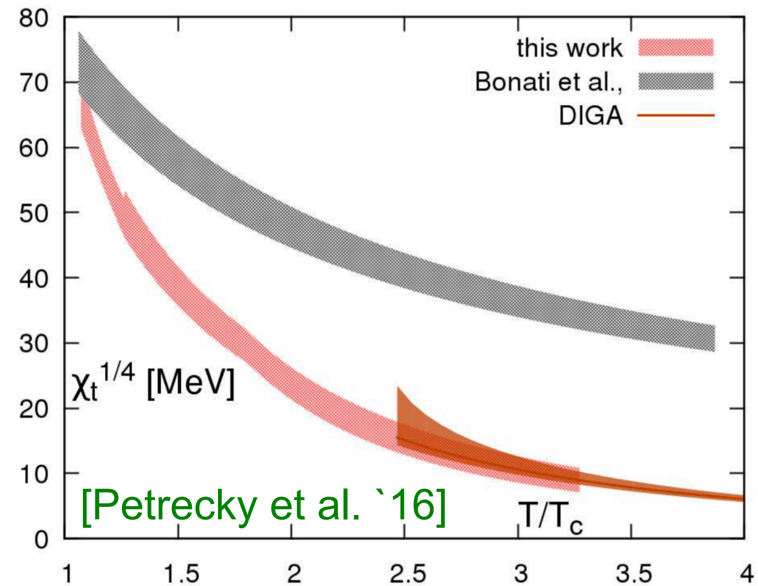
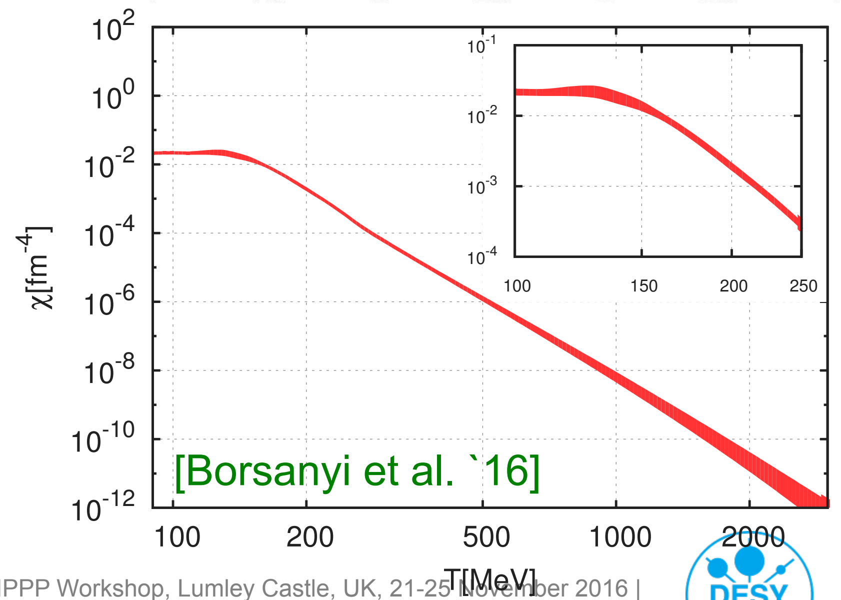
- DM prediction depends critically on temperature dependence of axion mass, $m_A(T) f_A = \sqrt{\chi(T)}$
- QCD lattice calculations of topological susceptibility $\chi(T)$
  - Estimates using dilute instanton gas approximation surprisingly accurate





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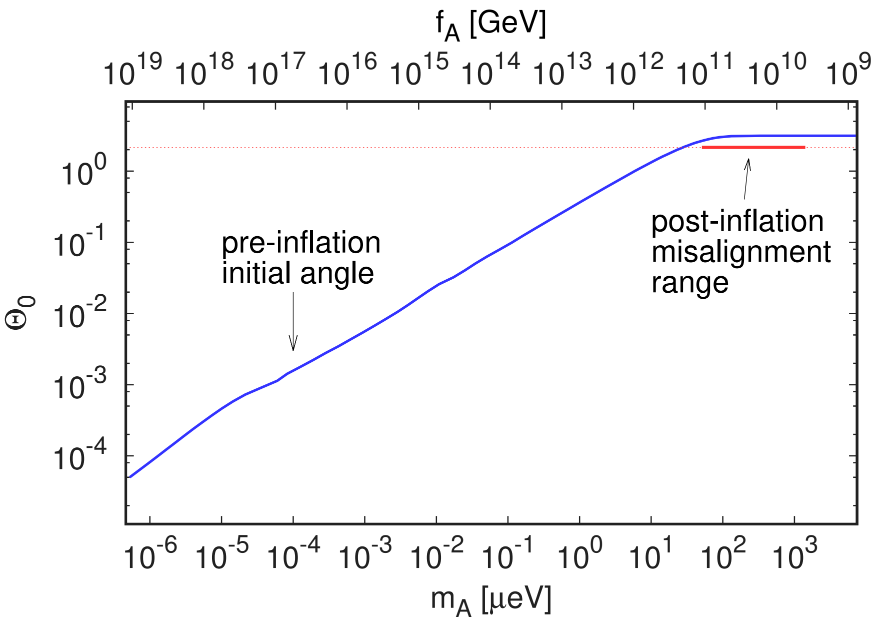


[Borsanyi et al. `16]

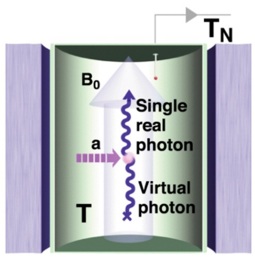
- Axion dark matter window:

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

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

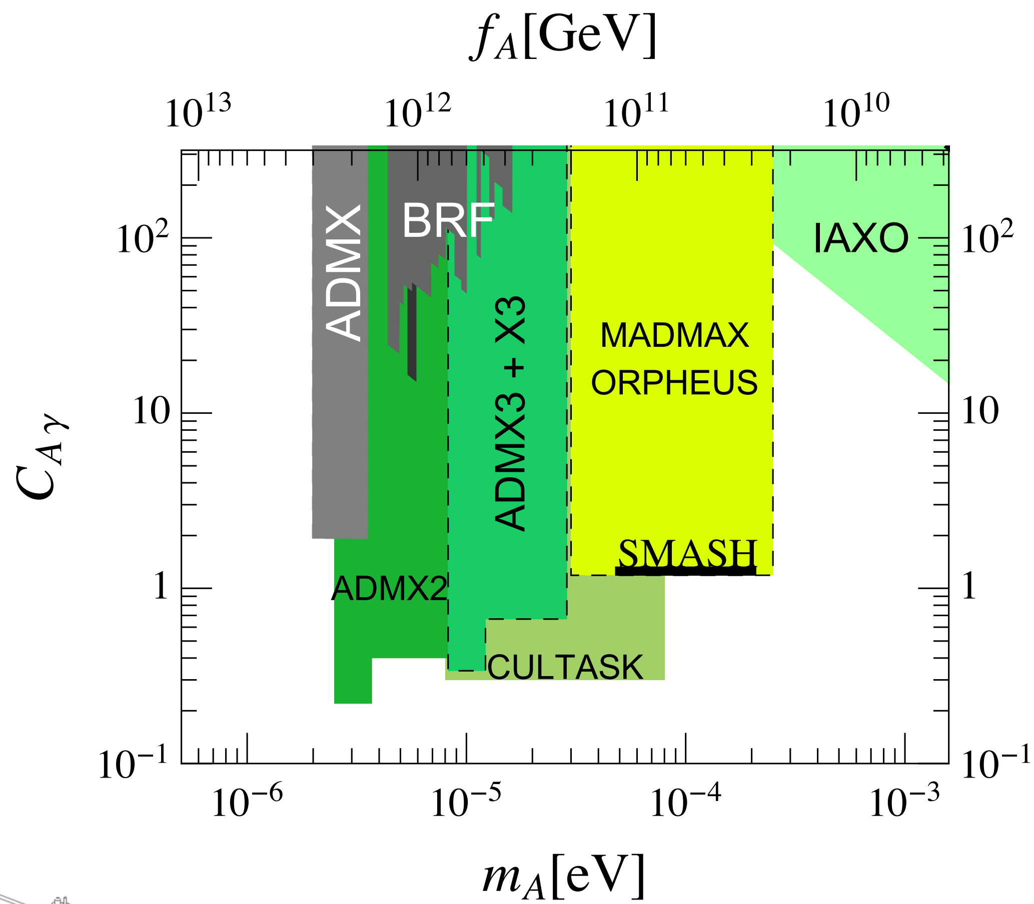
Axion Dark Matter

- Presently operating (ADMX) and planned next generation experiments based on RF cavities not able to cover whole mass range



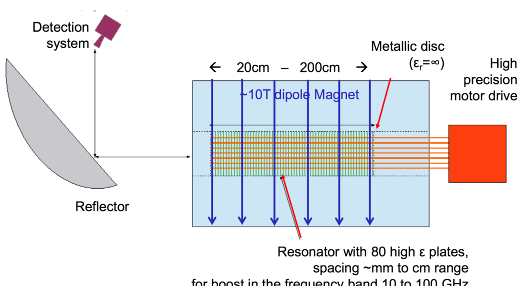
[Sikivie `83]

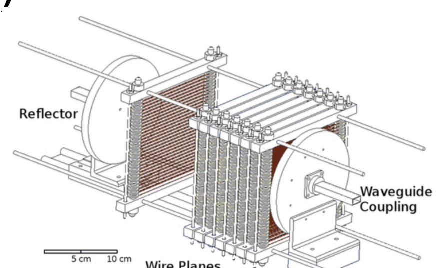
$$P_{\rm out} \sim g^2 \mid \mathbf{B}_0 \mid^2 \rho_{\rm DM} V Q / m_a$$



[Ballesteros et al. 1608.05414]

- More promising: Experiments exploiting open dielectric or FP resonators (MADMAX,...)





Conclusions

- Remarkably simple extension of SM involving just one new dimension-ful scale provides solution of five fundamental problems

  1. Neutrino oscillations
  2. Baryon asymmetry
  3. Dark matter
  4. Inflation
  5. Non-observation of strong CP violation

SM*A*S*H

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

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

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

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

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

INFLATION

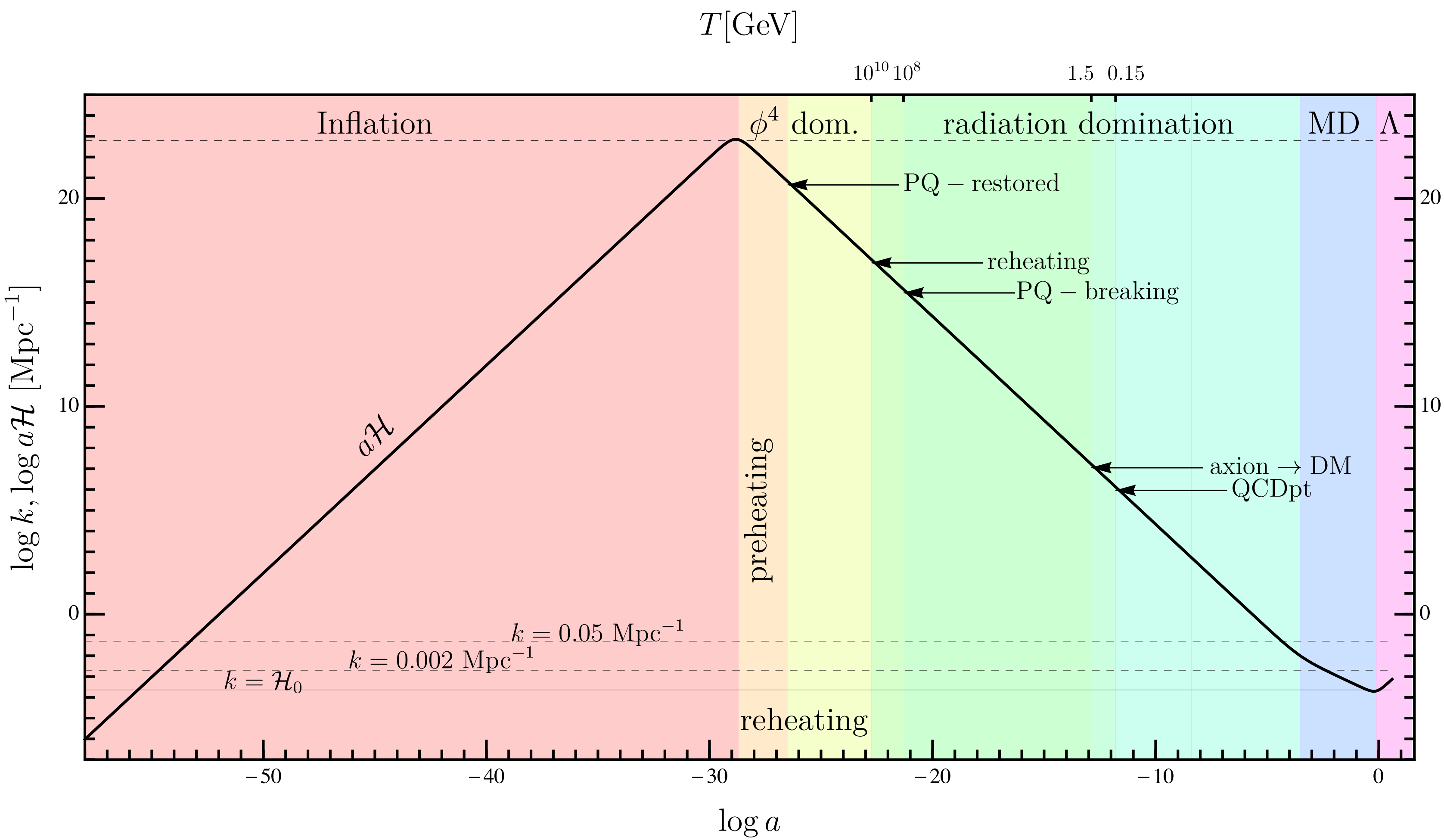
STABILITY

CP PROBLEM

SEESAW AND LEPTOGENESIS

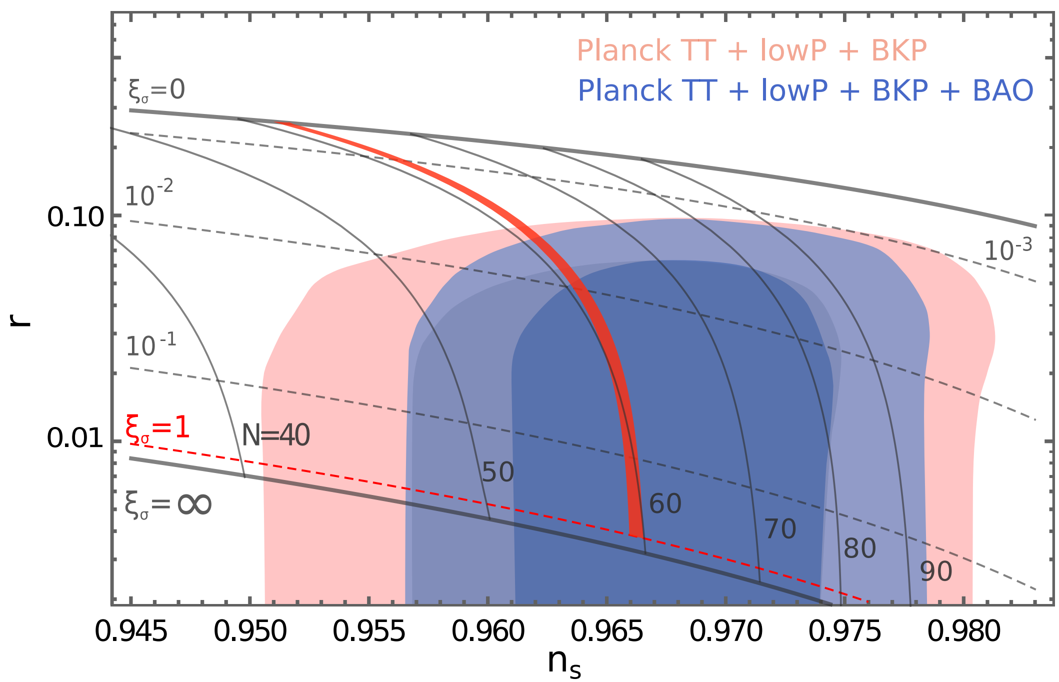
Conclusions

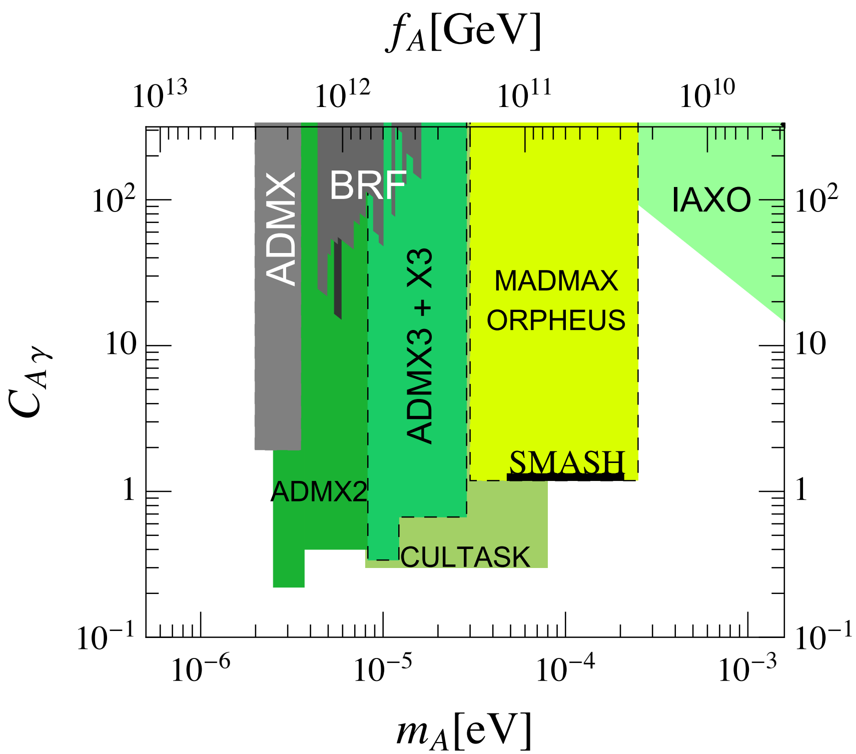
- A complete and consistent history of the Universe:



Outlook

- Firm predictions ($r, \alpha, \Delta N_\nu^{\rm eff}$, axion DM) in reach of upcoming CMB and axion DM experiments:





Outlook

- Variants of SMASH?
  - DFSZ axion model instead of KSVZ axion model?
  - Other variants of the see-saw mechanism?
  - Relaxation mechanism to solve naturalness problems (hierarchy problem, cosmological constant problem) inherent to SMASH?
- Ultraviolet completion of SMASH including quantum gravity?
  - Embedding in string theory?