SM*A*S*H

Standard Model * Axion * See-saw * Hidden scalar inflation

Andreas Ringwald (DESY)

12th Patras Workshop on Axions, WIMPs and WISPs
Jeju Island, South Korea
20 – 24 June 2016

[Guillermo Ballesteros, Javier Redondo, AR, Carlos Tamarit, arXiv:1606.nnnn]

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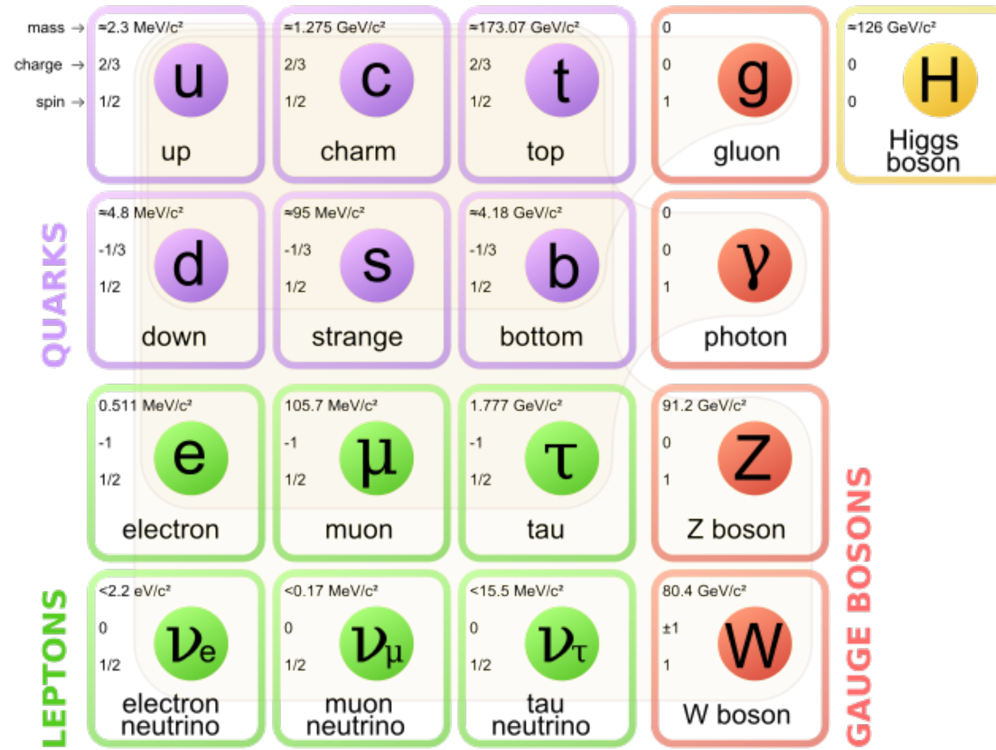
The Quest for a Minimal Model of Particle Cosmology

- Discovery of Higgs boson marks completion of SM particle content

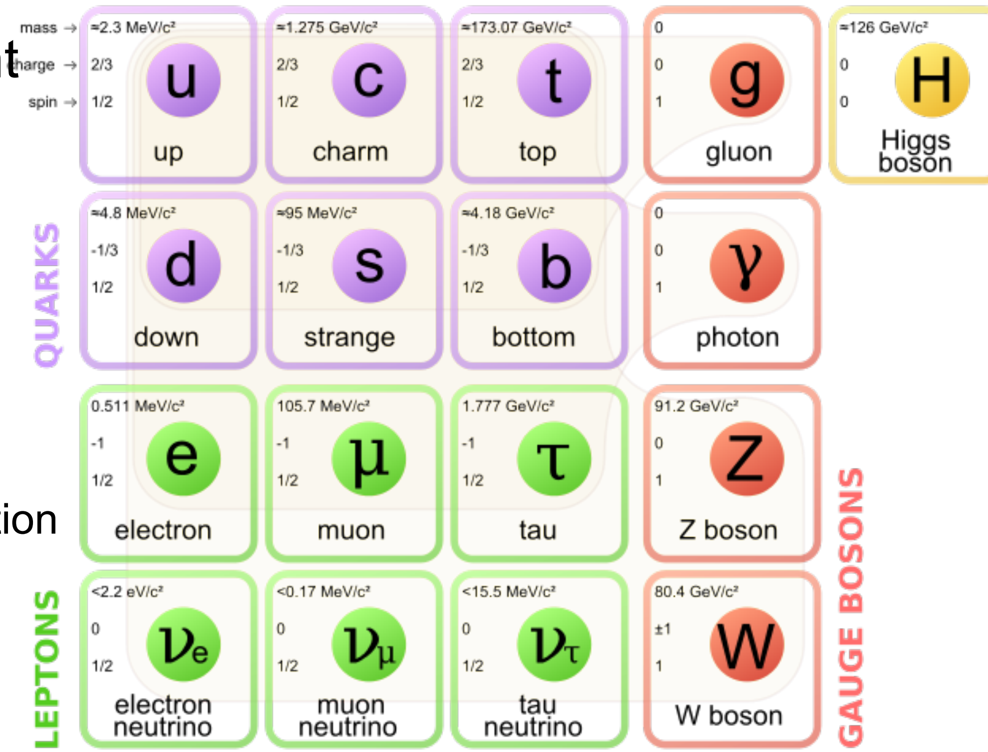


[wikipedia]

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



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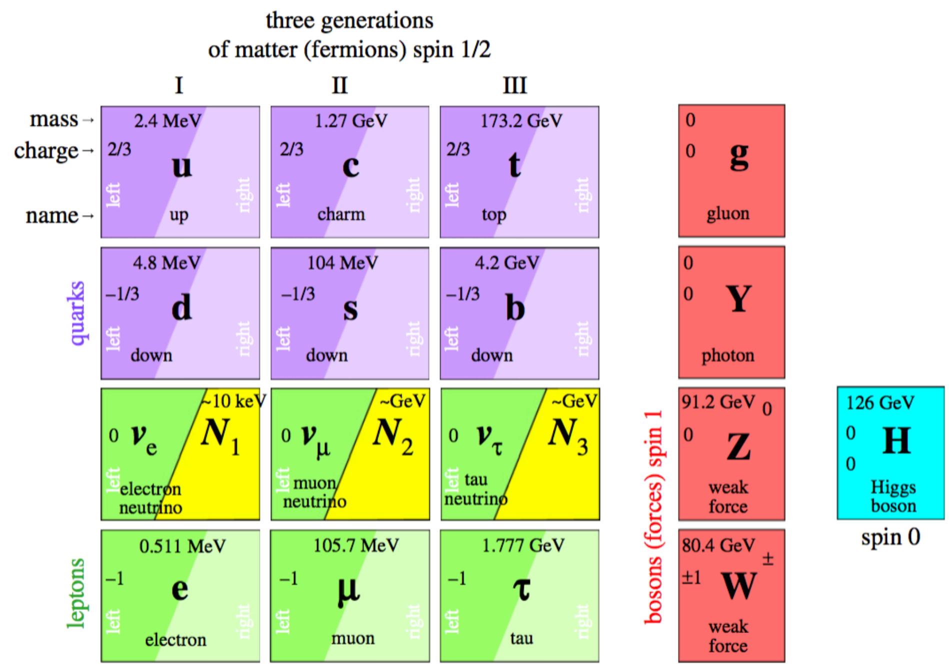

[M. Shaposhnikov, *Phil. Trans. R. Soc. A* **373** (2014) 0038]

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

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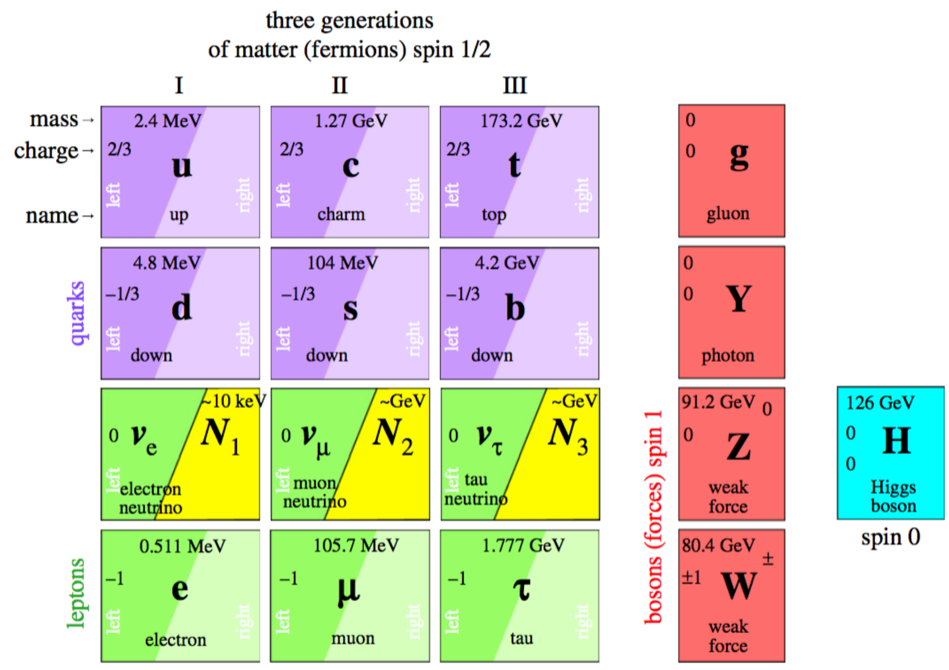

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- Problems 1.-4. solved in νMSM:
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  - Allowing for (very large, $\xi_H \sim 10^5 \sqrt{\lambda_H}$) non-minimally coupling of Higgs to Ricci scalar [Bezrukov, Shaposhnikov `08]

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

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The Quest for a Minimal Model of Particle Cosmology

- Success of inflation in $\nu\mathrm{MSM}$ threatened:
  - For $\xi_H \sim 10^4$, perturbative unitarity breaks down during inflation or, at the very least, during reheating, rendering predictions unreliable

    [Barbon,Espinosa 09; Burgess et al. 09; Kehagias et al. 14]

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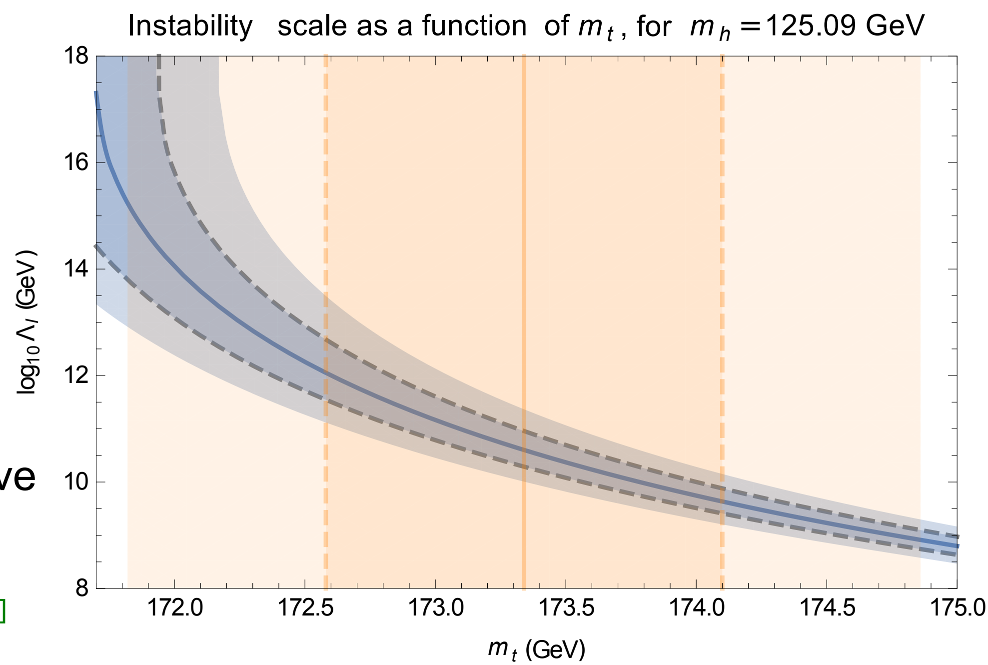

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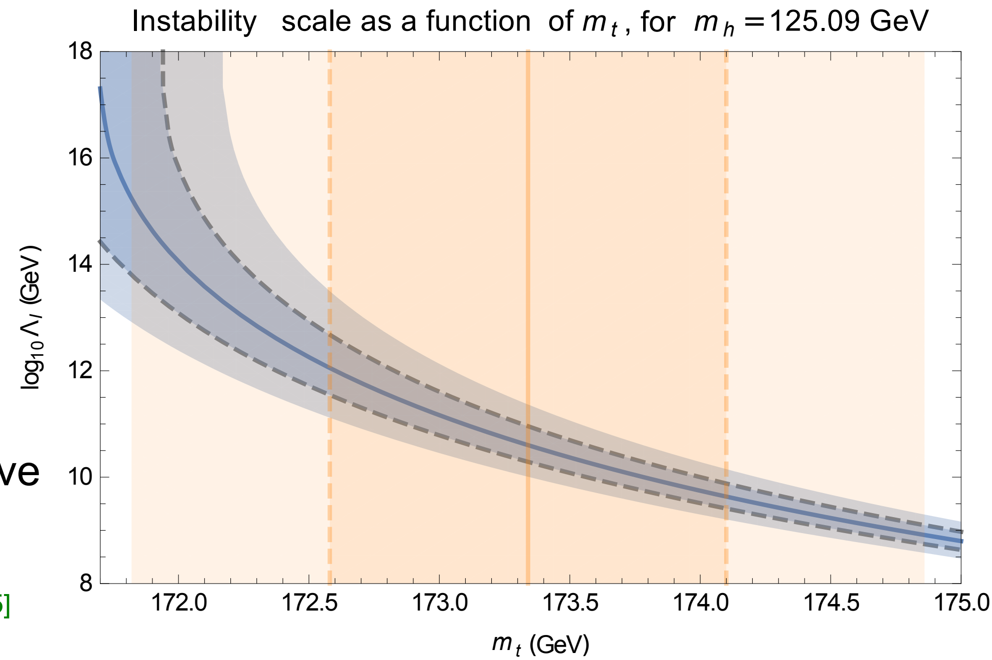

- Can be avoided by introducing hidden complex scalar charged under new global U(1) symmetry that is spontaneously broken

[Ballesteros,Redondo, AR,Tamarit, arXiv:1606.nnnn]

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

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- Role of the inflaton can now be played by $|\sigma| = \rho/\sqrt{2}$ or a mixture 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 make potential absolutely stable if $v_\sigma < \Lambda_I \sim 10^{11}\,\mathrm{GeV}$

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

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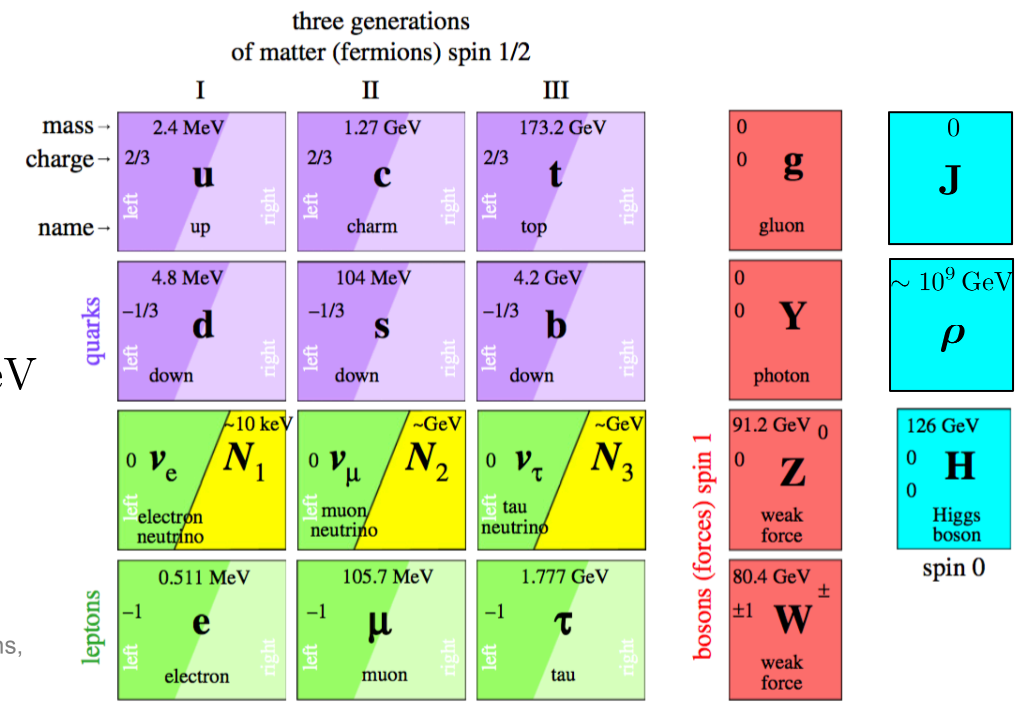
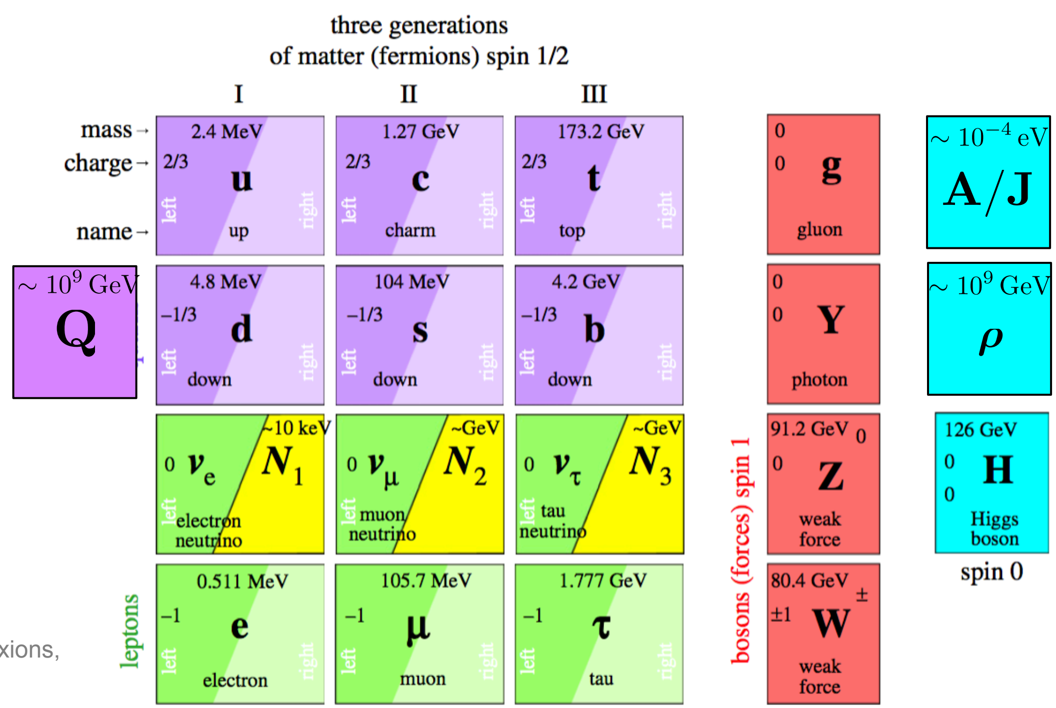


The Quest for a Minimal Model of Particle Cosmology

- Add vector-like quark with chiral charge assignment under hidden U(1), rendering the latter to a Peccei-Quinn symmetry as in KSVZ axion model

$$\mathcal{L} \supset -\left[Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + y\, \tilde{Q} \sigma Q + y_{Qd\,i} \sigma Q d_i + h.c. \right],$$

q	u	d	Q	$\tilde{Q}$	σ
$1/2$	$-1/2$	$-1/2$	$-1/2$	$-1/2$	1



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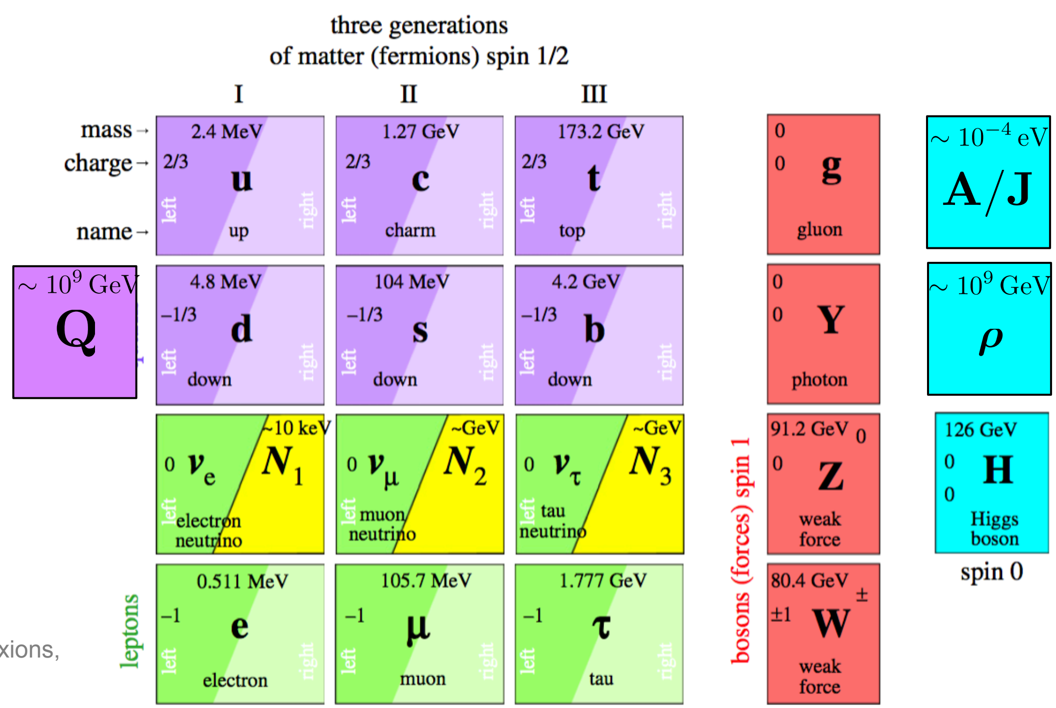

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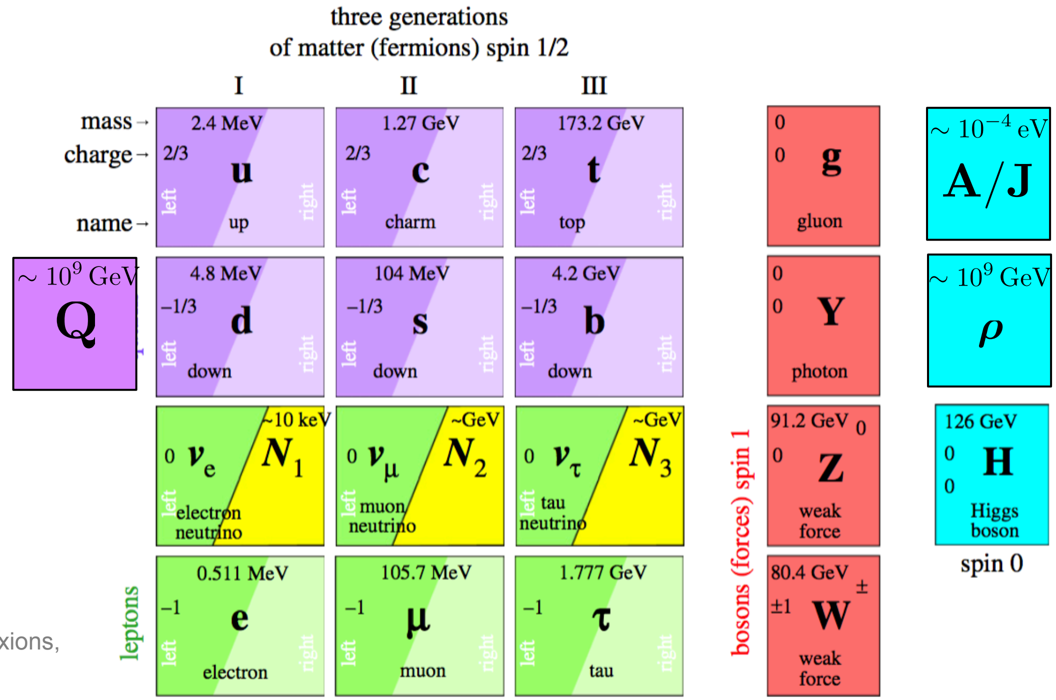
- Angular scalar excitation:
  - NG boson A/J has coupling $\mathcal{L}_A \supset -\frac{\alpha_s}{8\pi}\frac{A}{v_\sigma} G^c_{\mu\nu}\tilde{G}^{c,\mu\nu}$
  - Strong CP problem solved!
  - A/J decay constant: $f_A = v_\sigma$
  - Mass $m_A \sim f_\pi m_\pi / f_A$



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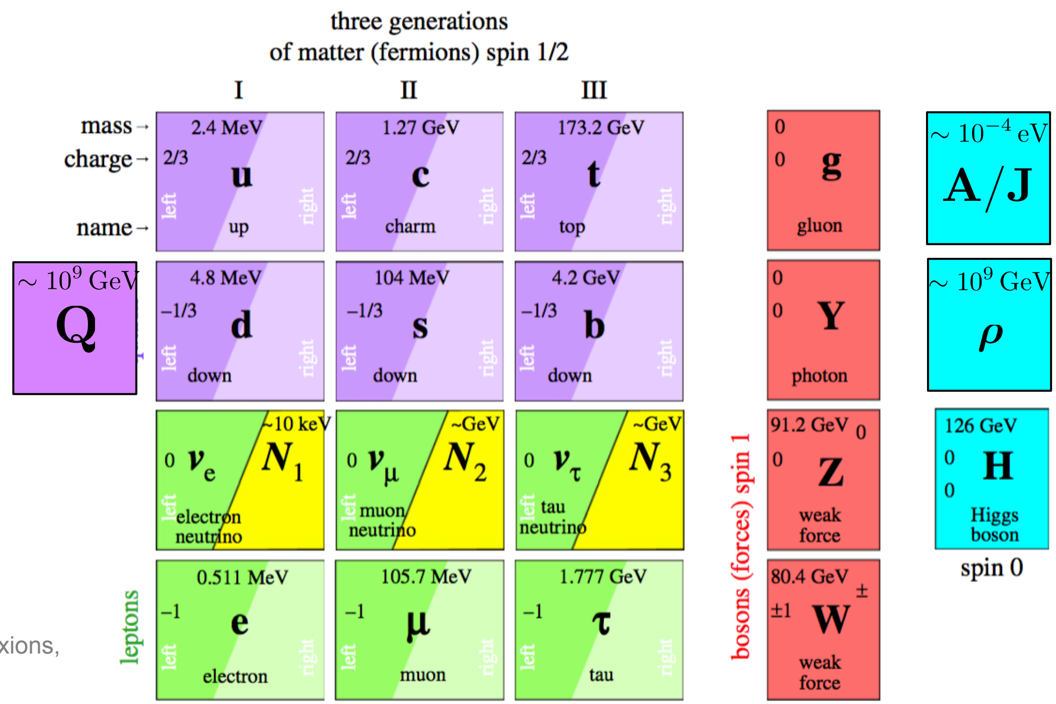
- Axion cold DM plus sterile neutrino warm DM



The Quest for a Minimal Model of Particle Cosmology

- Unify PQ U(1) symmetry with lepton symmetry: give also the SM leptons and the right-handed neutrinos PQ charges [Dias et al. `14]

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  - Determines Majorana masses
  - Explains smallness of active neutrino masses by see-saw relation

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

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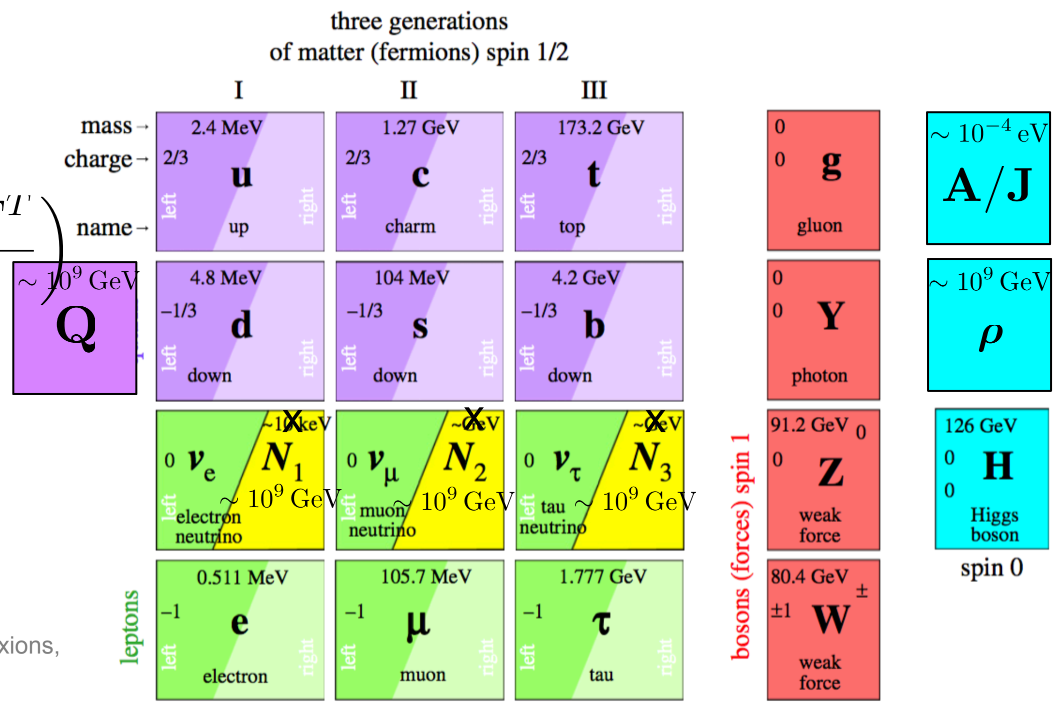

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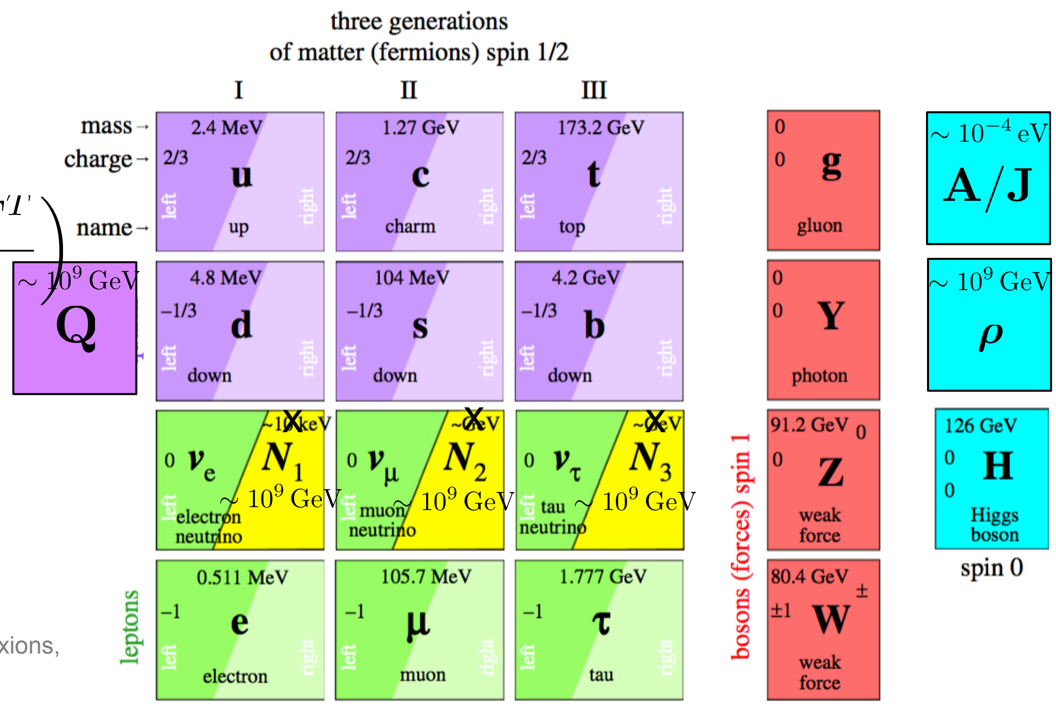

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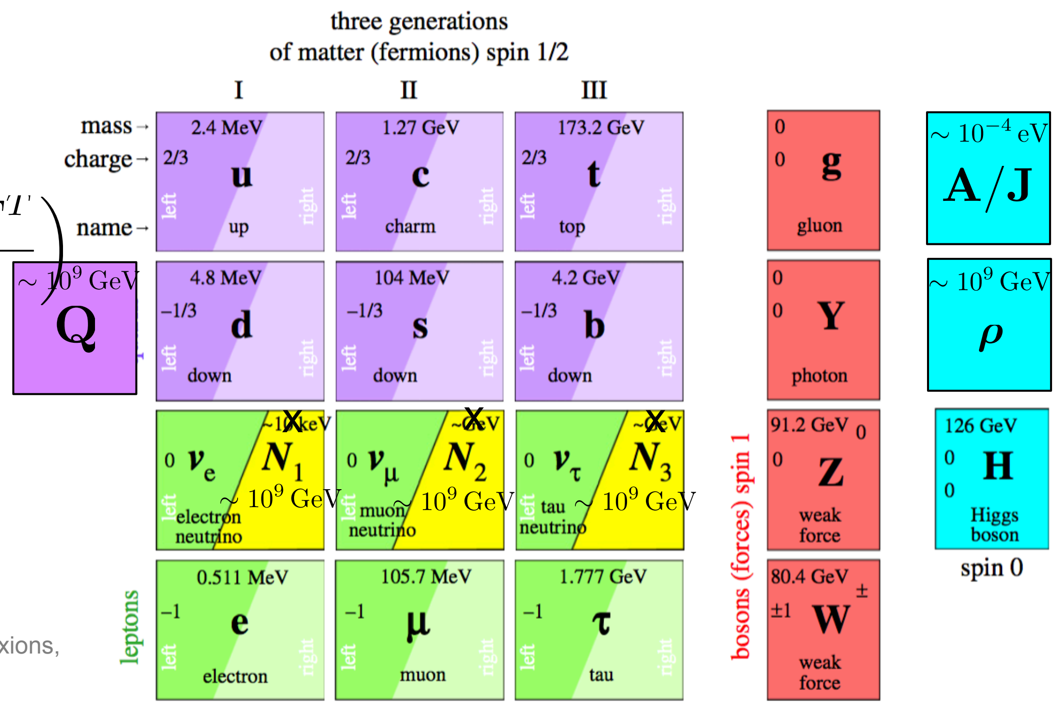

Inflation: Higgs Inflation, Hidden Scalar Inflation, ...

- Non-minimal couplings: stretching of the scalar potential in Einstein frame which makes it convex and asymptotically flat at large field values

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

$$\Omega^2 = 1 + \frac{\xi_H (h^2 - v^2) + \xi_\sigma (\rho^2 - v_\sigma^2)}{M_P^2}$$

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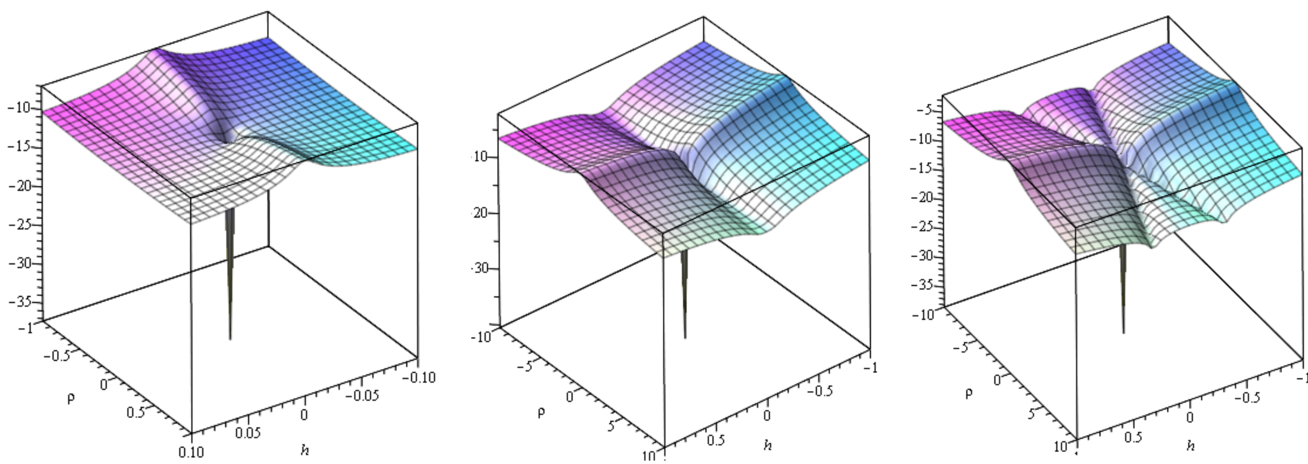
- Potential has valleys allowing for Higgs Inflation (HI), Hidden Scalar Inflation (HSI) or mixed Higgs Hidden Scalar Inflation (HHSI), depending on relative signs of $\kappa_H \equiv \lambda_{H\sigma}\xi_H - \lambda_H\xi_\sigma\,,\quad \kappa_\sigma \equiv \lambda_{H\sigma}\xi_\sigma - \lambda_\sigma\xi_H$



$\mathrm{sign}(\kappa_H)$	$\mathrm{sign}(\kappa_\sigma)$	Inflation
$+$	$-$	HI
$-$	$+$	HSI
$-$	$-$	HHSI

Inflation: Confronting with Observations

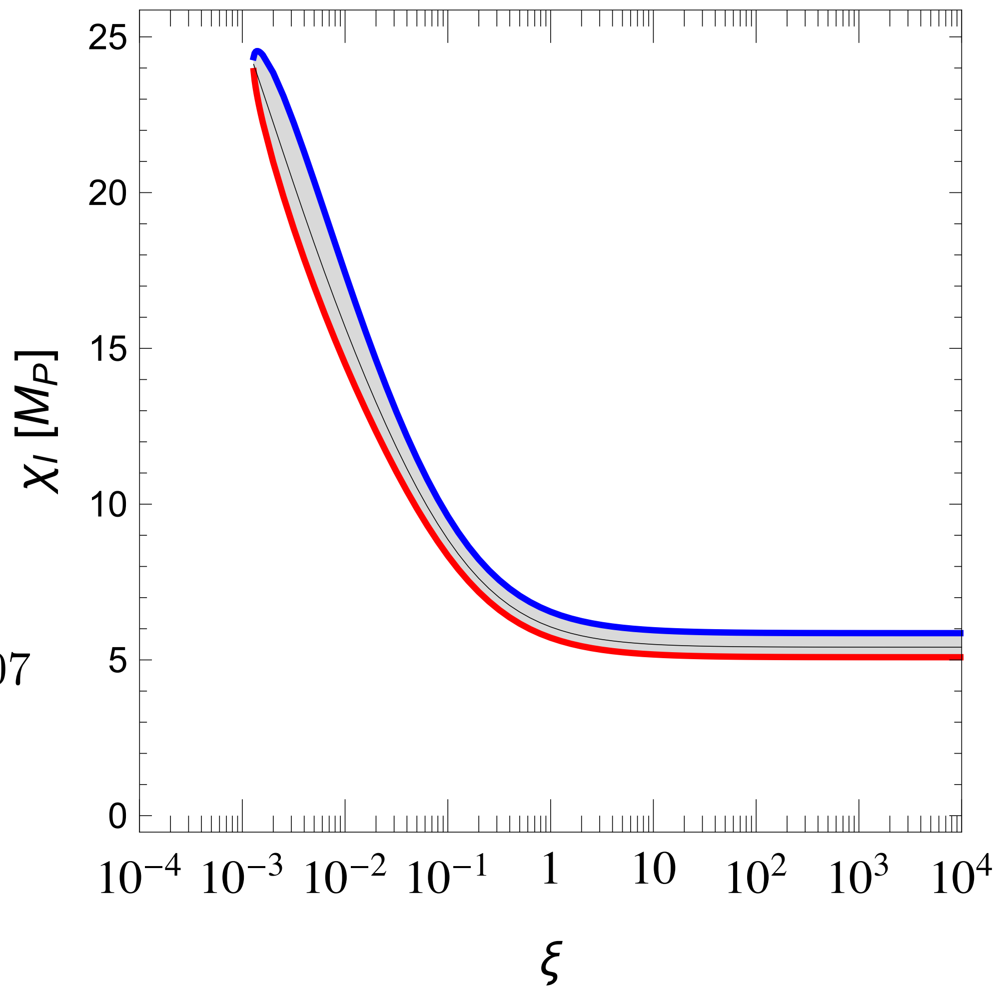
- Adjusting χ_I, CMB observables

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

can be fit for any $\xi \gtrsim 10^{-3}$

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

- Smaller non-minimal coupling excluded by upper limit on $r < 0.07$



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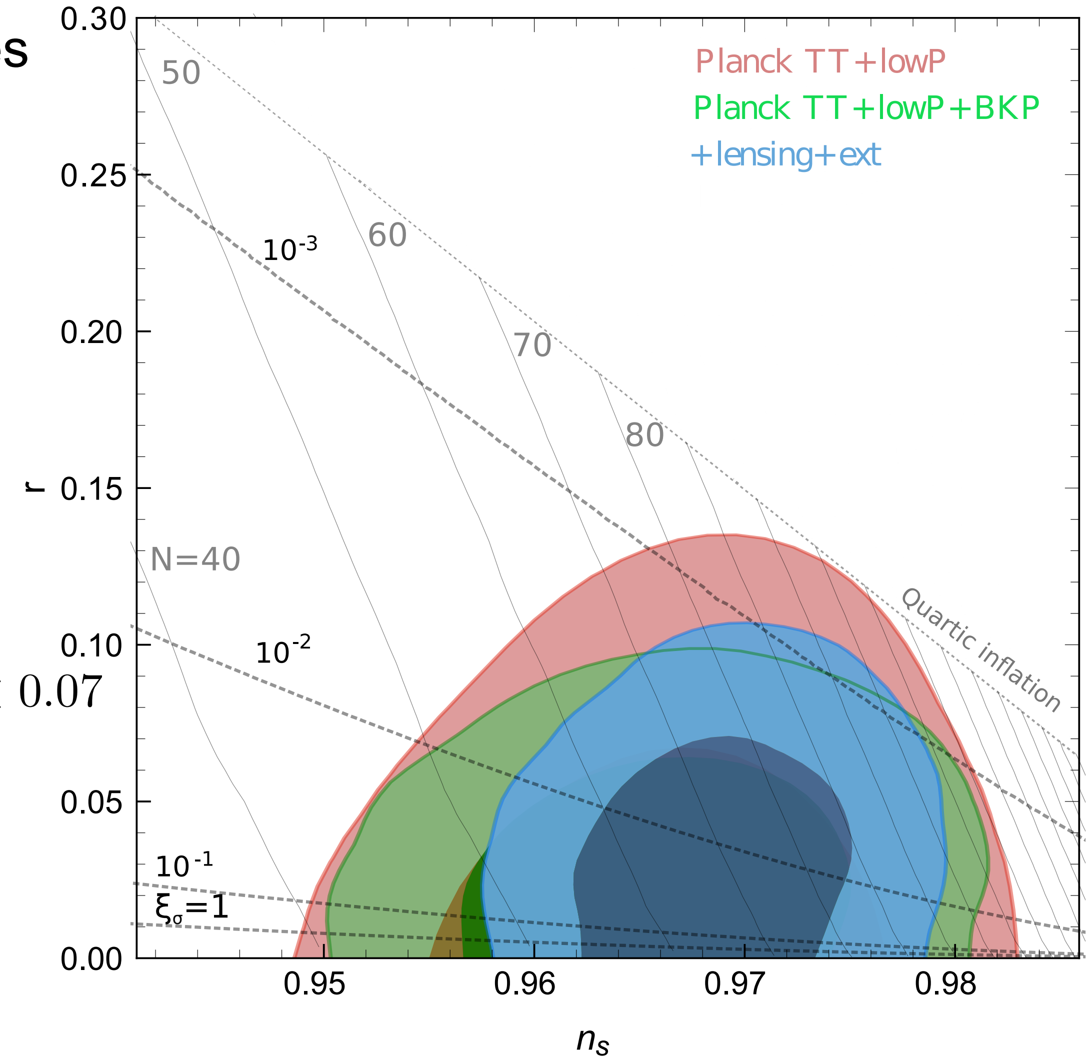
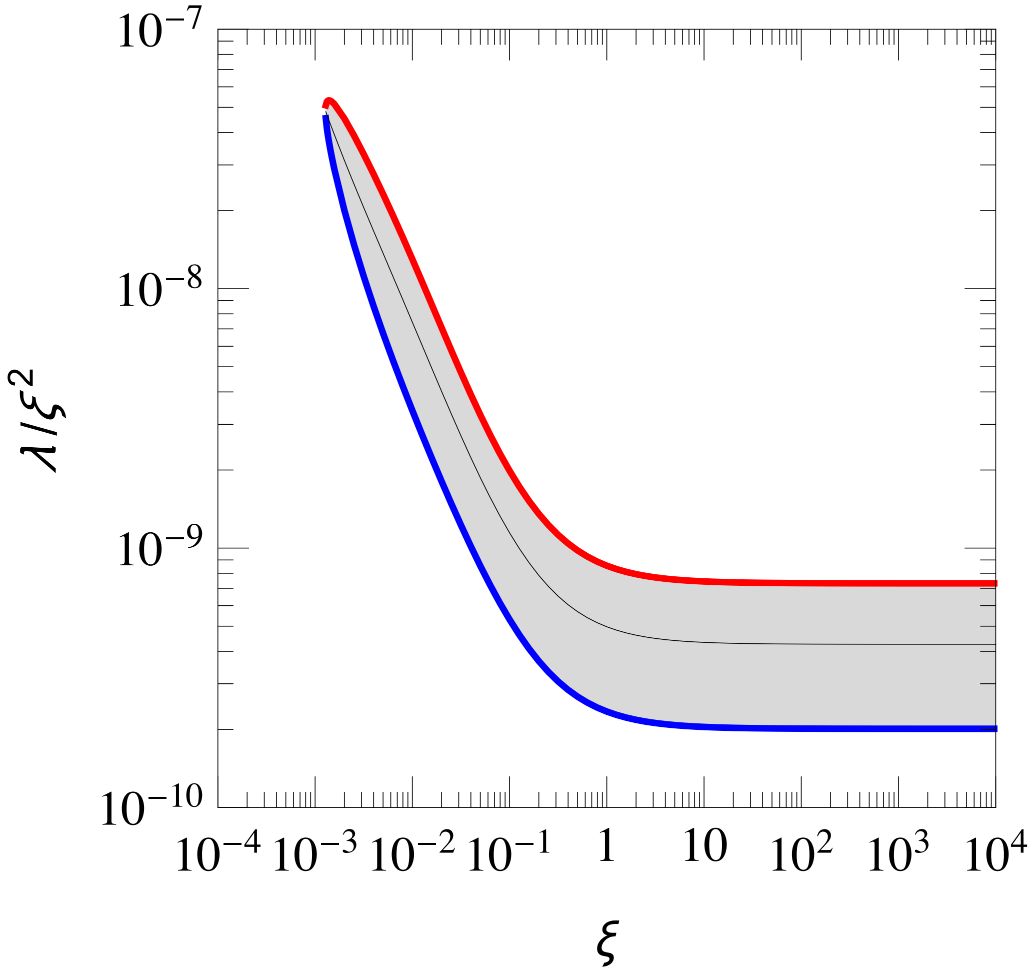


Inflation: Confronting with Observations

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

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

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



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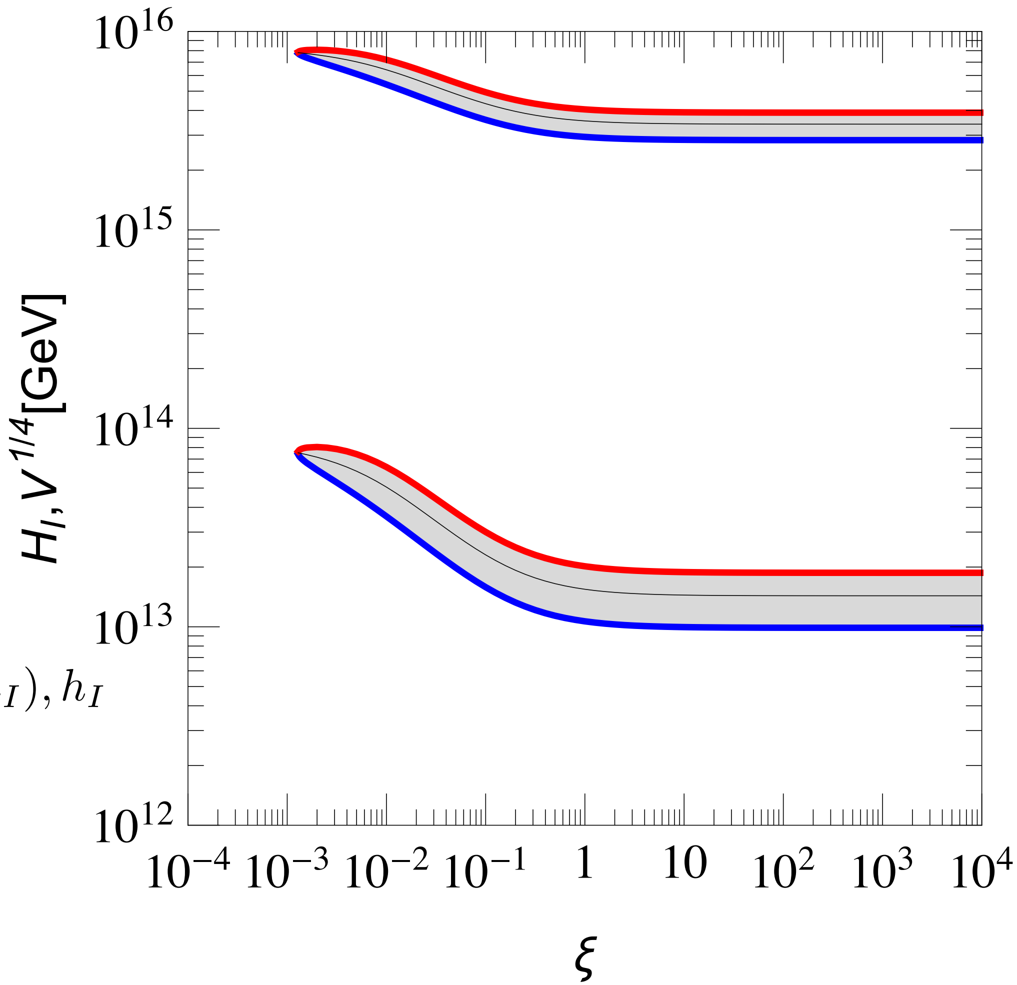
$$\Lambda_U \sim \frac{M_P}{\xi_H} \sim 10^{14}\ \text{GeV} \sim H_I \ll \tilde V^{1/4}(h_I), h_I$$



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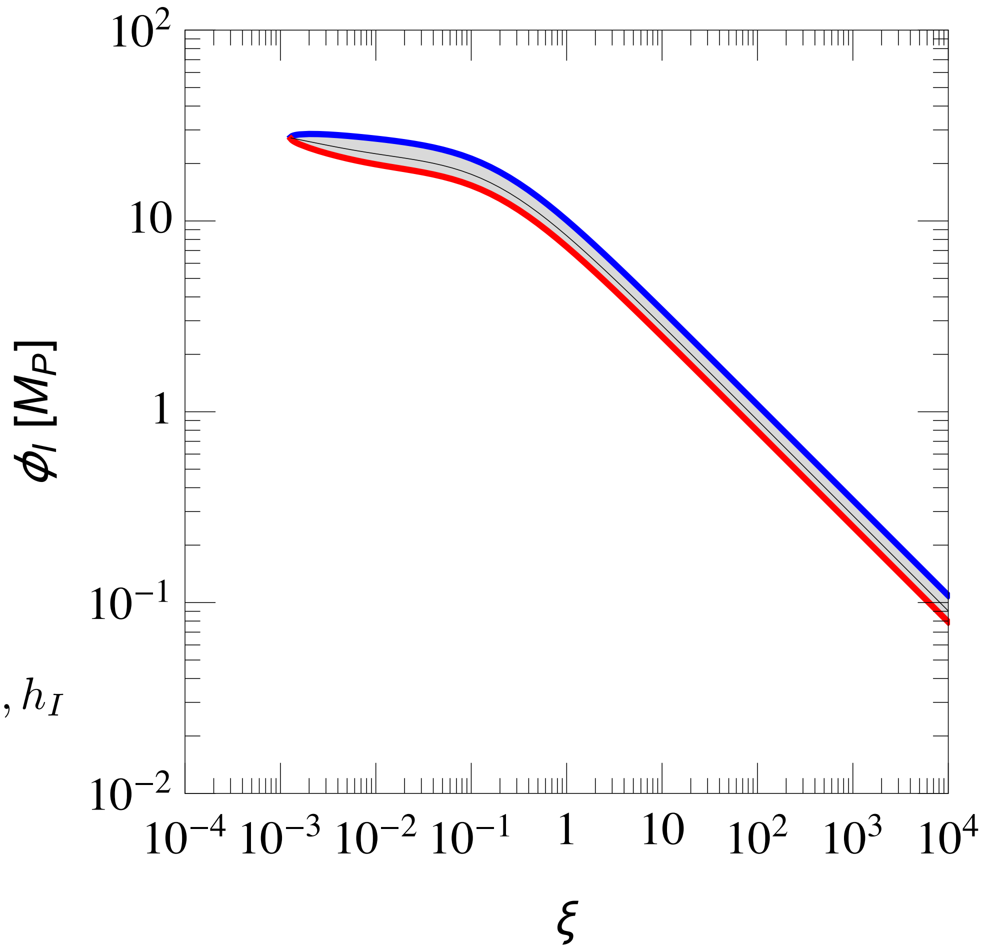


Inflation: Confronting with Observations

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

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

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

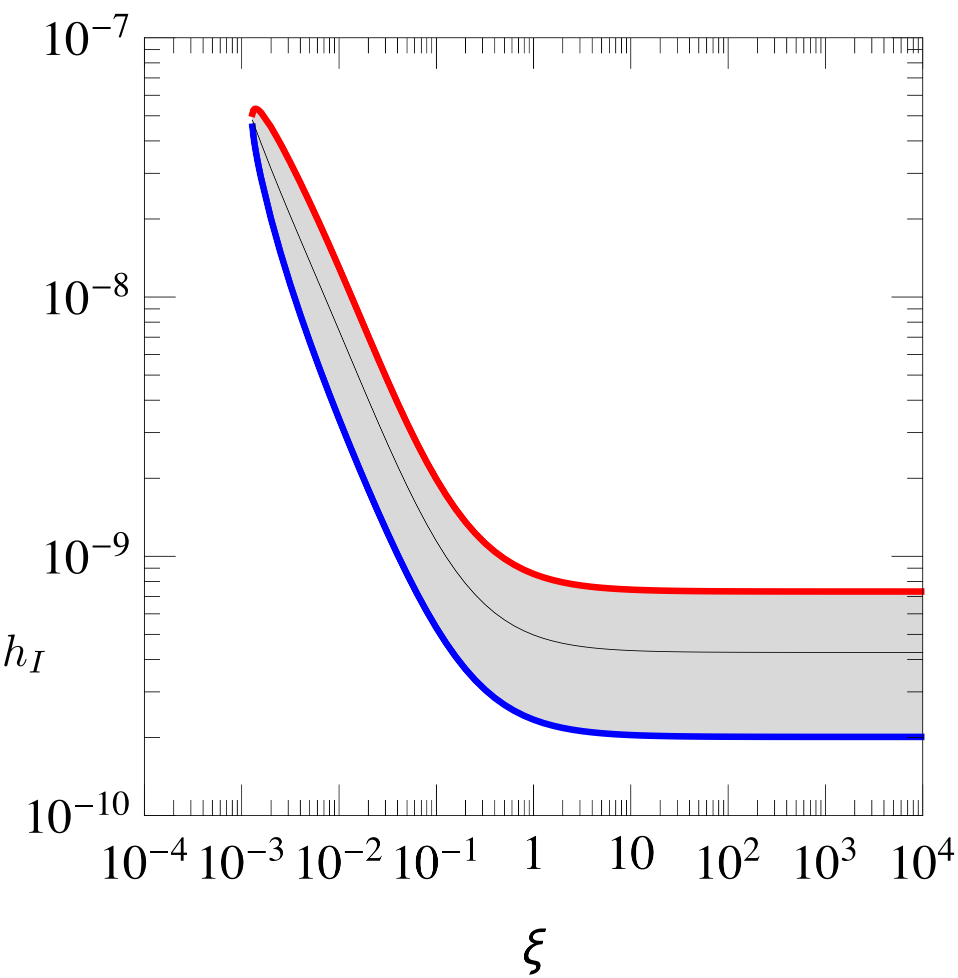
- Perturbative unitarity lost in HI

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

- Can be of order one for HSI or HHSI; e.g. $\xi_\sigma = 1$ requires

$$\lambda_\sigma, \tilde{\lambda}_\sigma = (4.1^{+3.0}_{-2.1}) \times 10^{-10}$$

- No unitarity problem in HSI/HHSI!

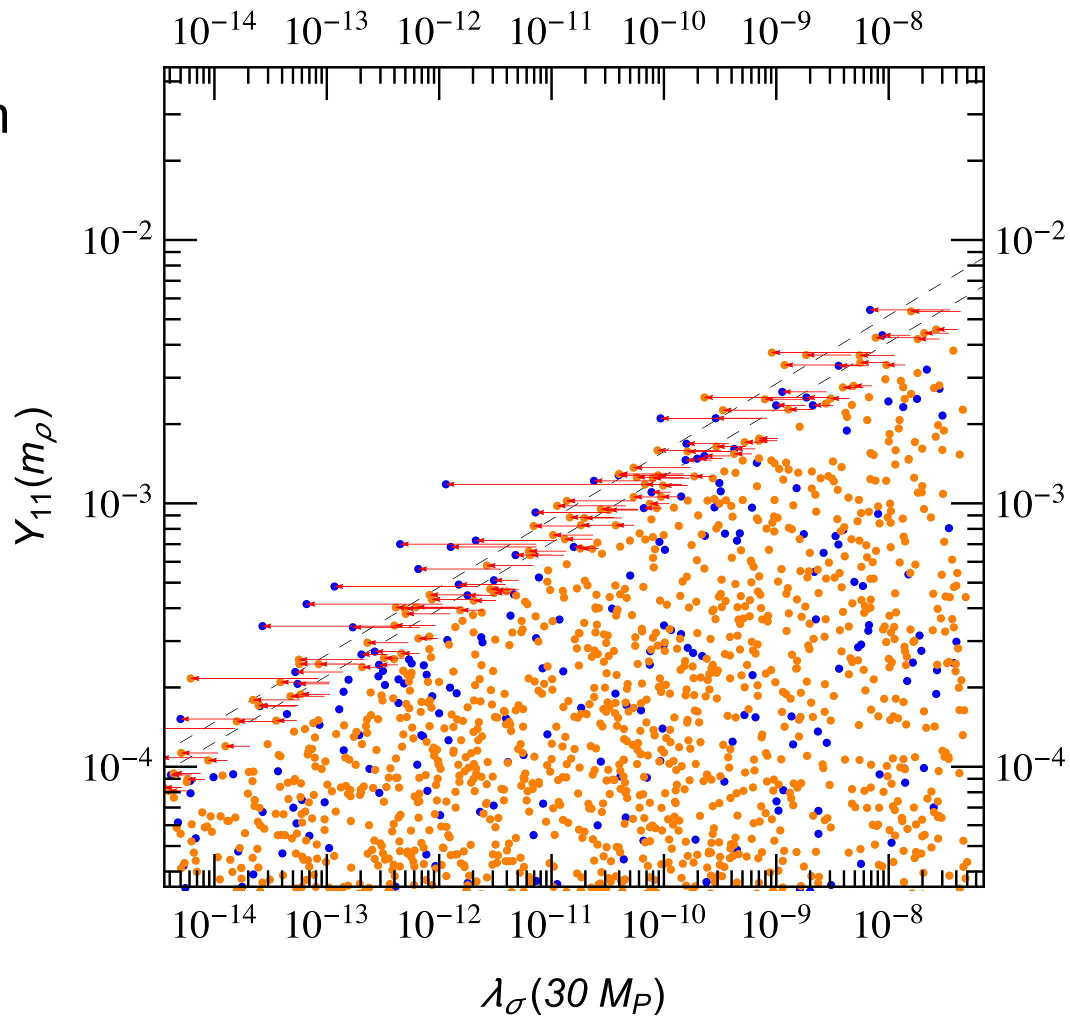


Stability

- Determine range of parameters in SMASH for which effective scalar potential is positive up to the large values of scalar fields required to have successful inflation
- Instabilities in effective scalar potential can arise from fermionic quantum corrections in both scalar directions, driving quartic couplings towards negative values and rendering potential unstable for large field values
  - Along Higgs direction: instability driven by top Yukawa coupling
  - Along hidden scalar direction: instability driven by Yukawas of RH neutrinos and exotic quark

Stability: Scan $(\lambda_\sigma, \lambda_{H\sigma} > 0, Y_{11}, y = Y_{11}, f_A)$ with $m_t = 172.38$ GeV

- Stability in the hidden scalar direction enforces a minimum of λ_σ at a given scale, as a function of $M_i/f_A = Y_{ii}/\sqrt{2}$



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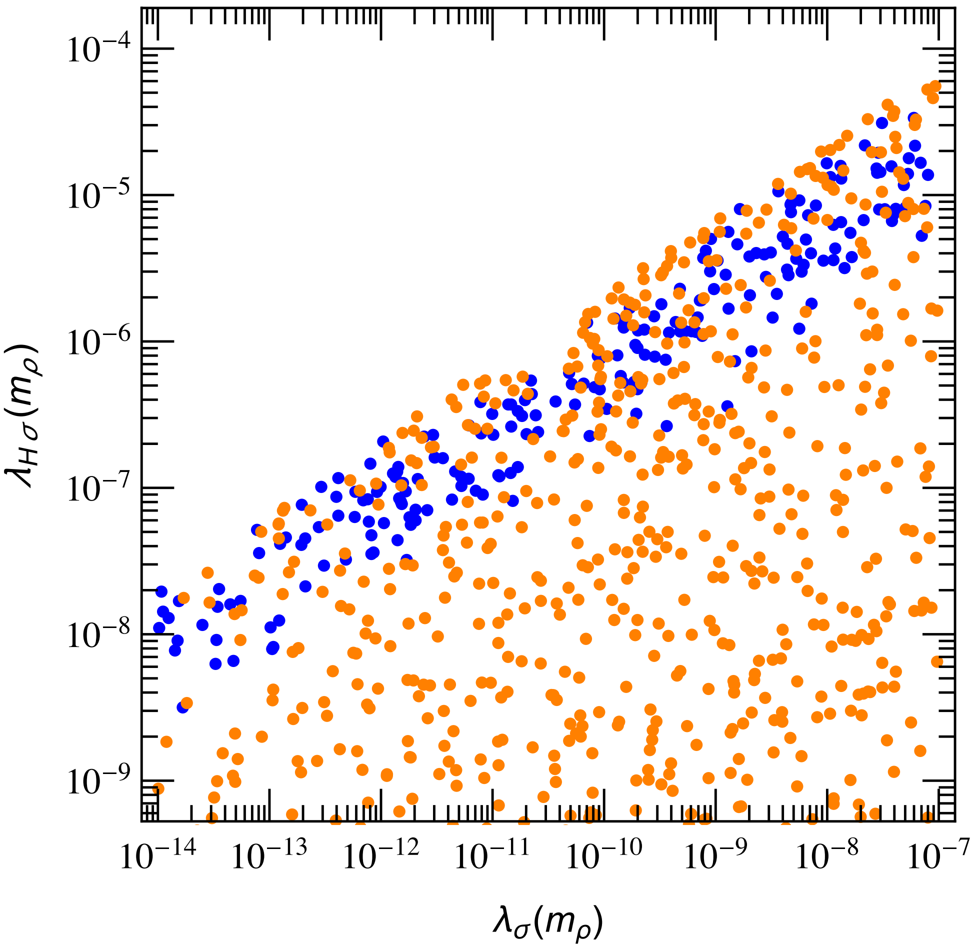
- Stability in the hidden scalar direction enforces a minimum of λ_σ at a given scale, as a function of $M_i/f_A = Y_{ii}/\sqrt{2}$
- Stability in the Higgs direction can be obtained from the threshold mechanism w/o RG effects by adjusting portal coupling
  - Higgs quartic measured at low energies,
    $\overline{\lambda}_H(m_h) = \lambda_H(m_h) - \lambda_{H\sigma}^2/\lambda_\sigma\big|_{\mu=m_h}$
  - Fundamental quartic λ_H can stay positive up to large energies if threshold correction $\delta \equiv \lambda_{H\sigma}^2/\lambda_\sigma$ sufficiently large



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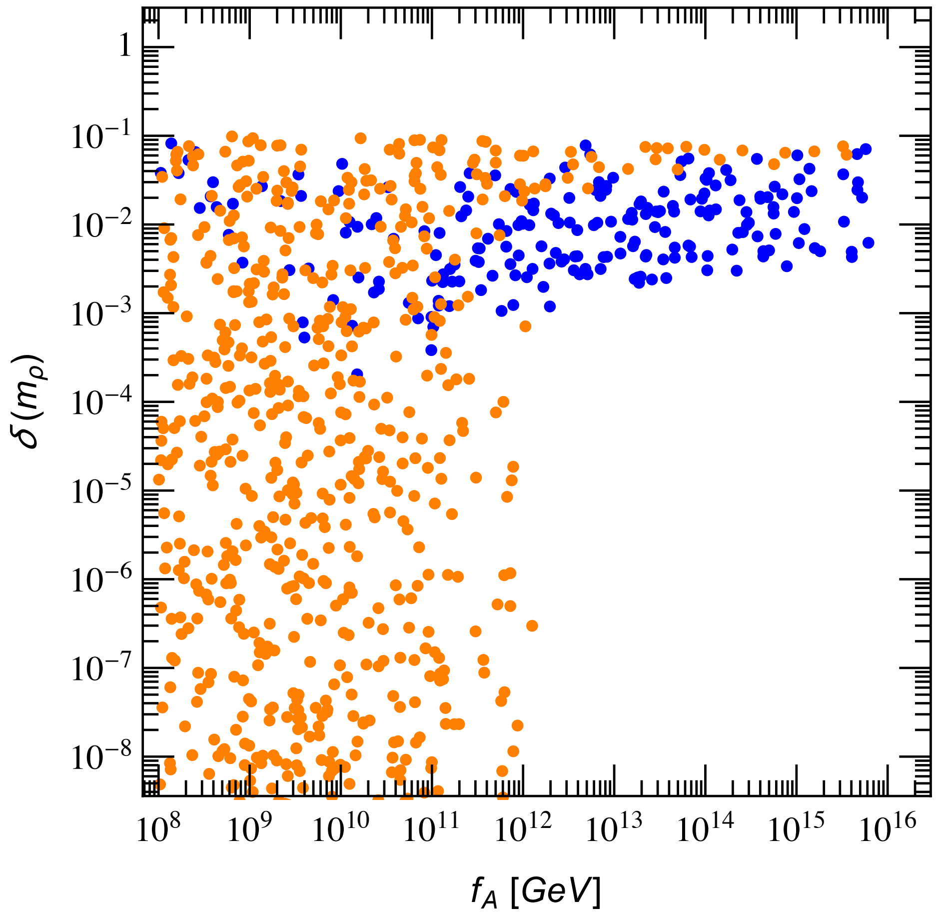


Reheating

> Mechanism of reheating in SMASH well defined: coupling of inflaton to SM either known or well constrained

> Fundamental questions:

- Is PQ symmetry restored after inflation?
- Is reheating temperature large enough for successful thermal leptogenesis?

> Reheating proceeds in two steps:

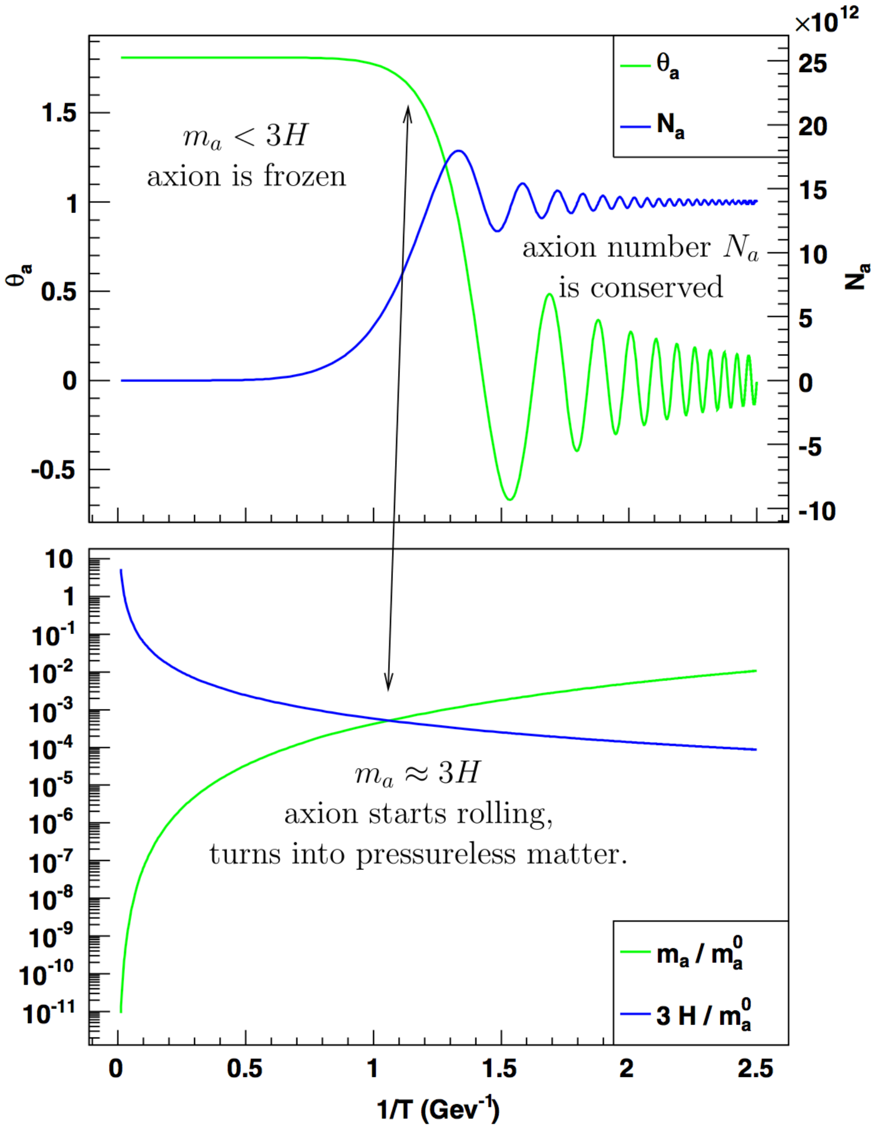
- Preheating: Fluctuations of hidden scalar grow fast due to parametric resonance while HS-inflaton oscillates in its quartic potential. PQ symmetry effectively restored for $f_A \lesssim 10^{16}\,\mathrm{GeV}$
- Perturbative reheating: HS fluctuations thermalize quickly and decay into SM particles once their decay rate goes above the Hubble rate. In stabilised parameter region, $10^{11}\,\mathrm{GeV} \sim T_R \gg T_c \sim 2\lambda_\sigma^{1/4} f_A \sim 10^9\,\mathrm{GeV}$

> PQ thermally restored phase continues for a few e-folds and then PQ symmetry is spontaneously broken

> Leptogenesis proceeds by out of equilibrium decays of RHNs

Axion Dark Matter

- In postinflationary PQ SB scenario: one-to-one relation between axion mass and relic abundance
- Mechanisms of production:
  - Vacuum realignment

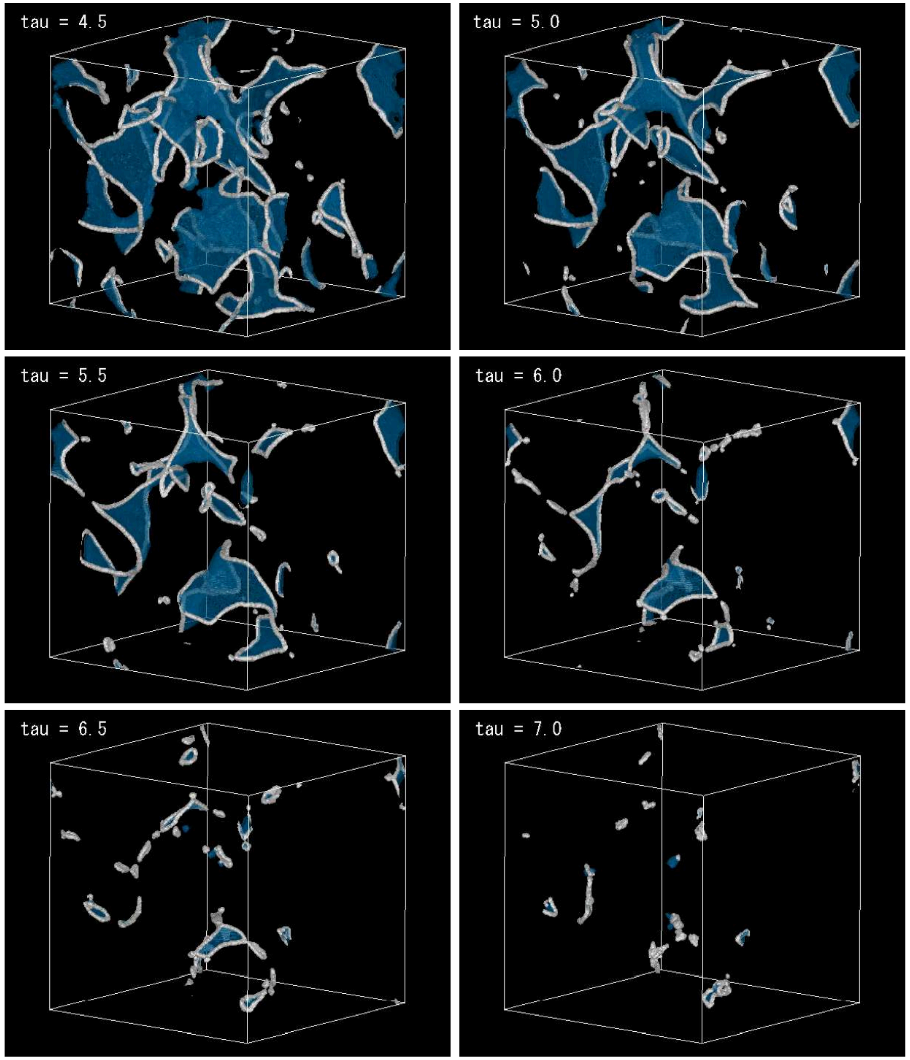


[Wantz,Shellard 09]

Axion Dark Matter

- In postinflationary PQ SB scenario: one-to-one relation between axion mass and relic abundance
- Mechanisms of production:
  - Vacuum realignment
  - Decay of topological defects (domain walls and strings)

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



[Hiramatsu et al. 12]

Axion Dark Matter

- In postinflationary PQ SB scenario: one-to-one relation between axion mass and relic abundance
- Mechanisms of production:
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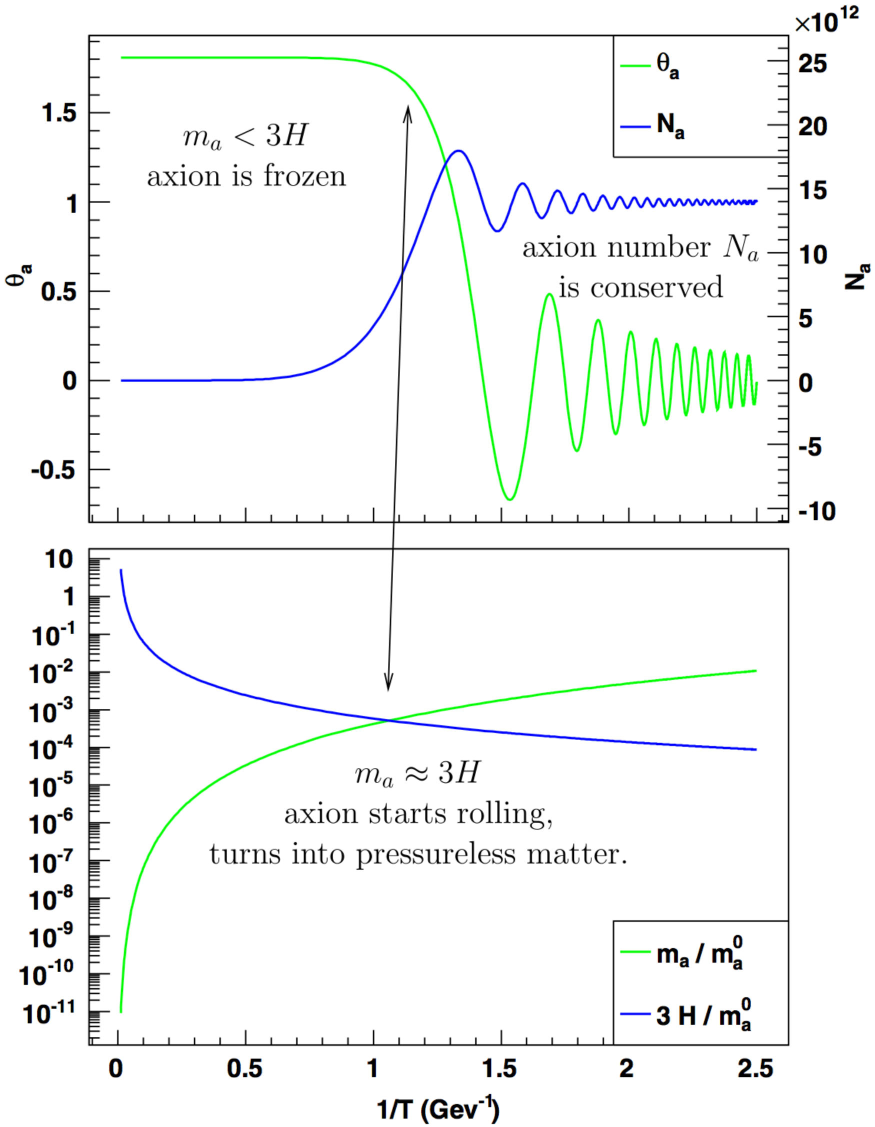
$$\Omega_{A,\mathrm{tot}}h^2 = \Omega_{A,\mathrm{real}}h^2 + \Omega_{A,\mathrm{string}}h^2 + \Omega_{A,\mathrm{wall}}h^2$$

- Key quantity entering prediction: Temperature dependence of axion mass, $m_A(T) f_A = \sqrt{\chi(T)}$
- Exploiting Dilute Instanton Gas Approximation (DIGA) or Instanton Liquid Model (ILM):

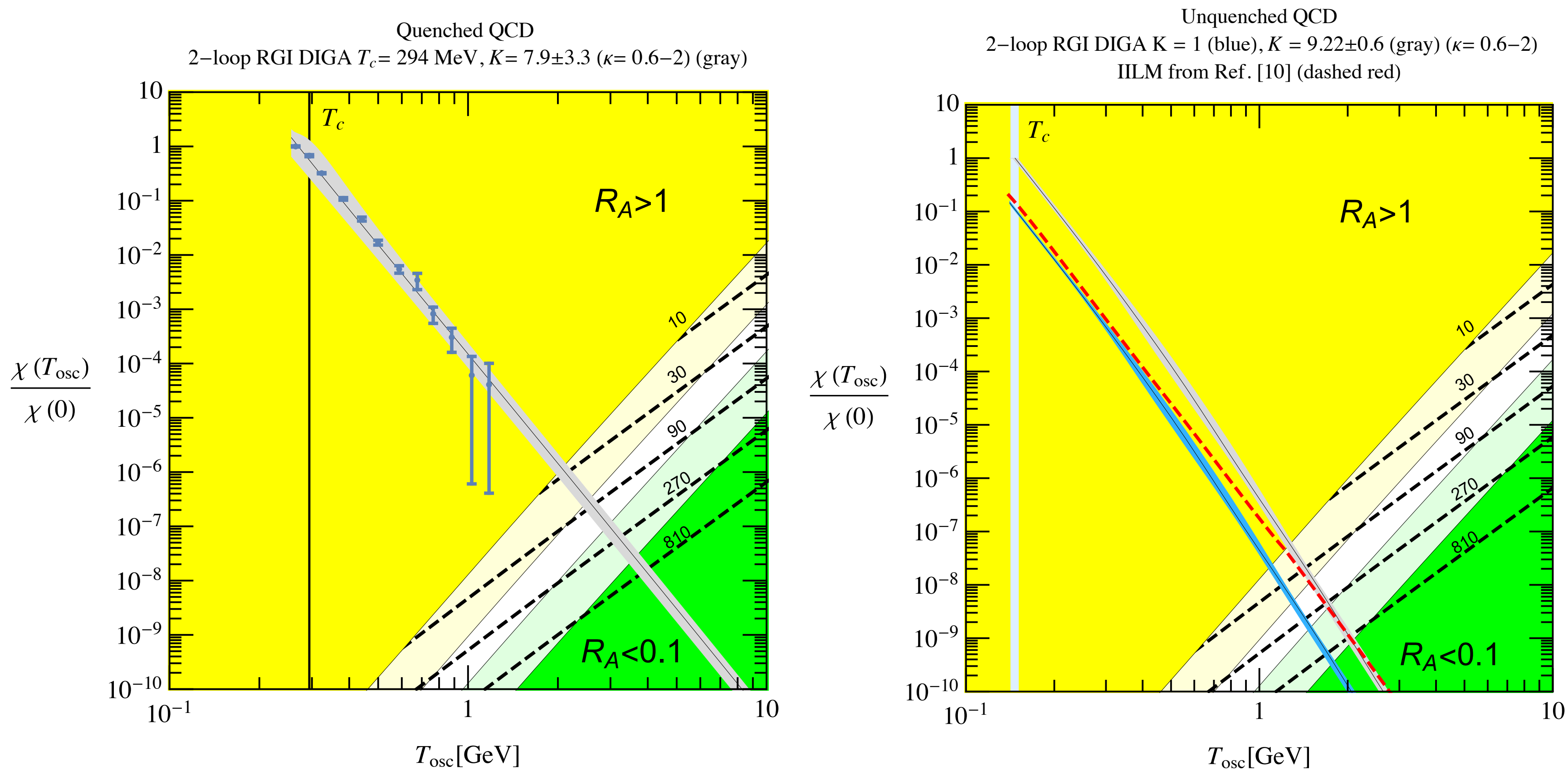
$$m_A \approx (0.8\text{–}1.3) \times 10^{-4}\,\mathrm{eV}$$



[Wantz,Shellard 09]

Axion Dark Matter: Uncertainties

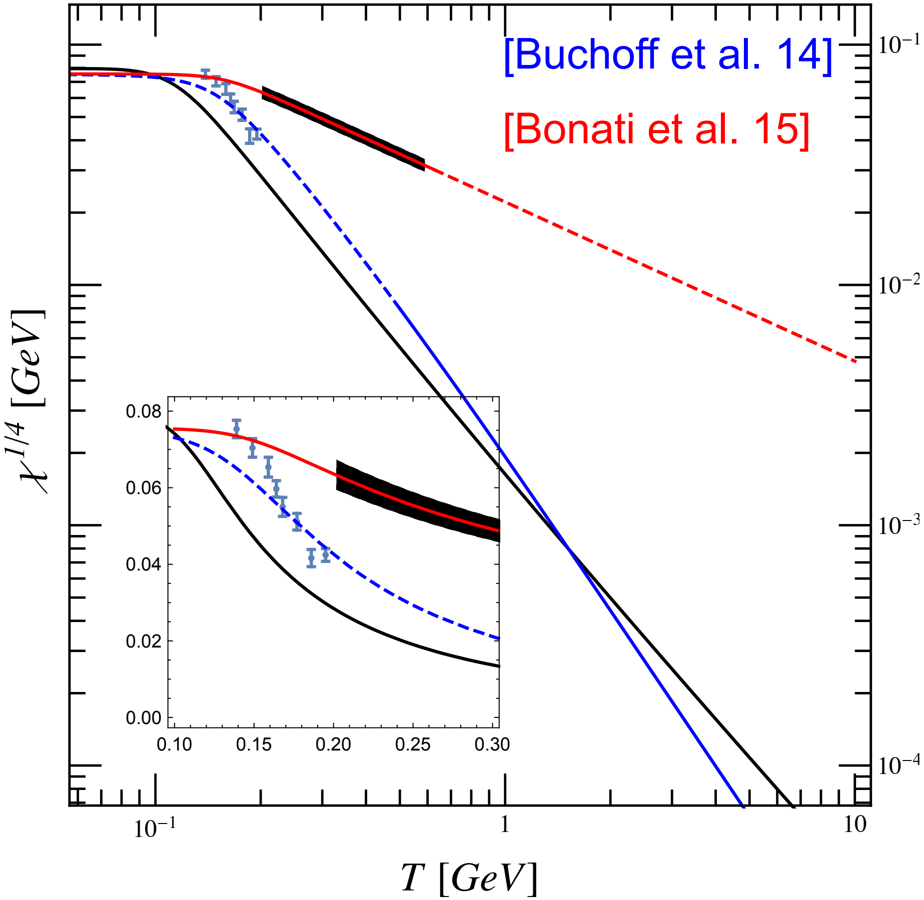
- First principle determination of temperature dependence of axion mass from topological susceptibility measured on the lattice, $m_A(T) f_A = \sqrt{\chi(T)}$

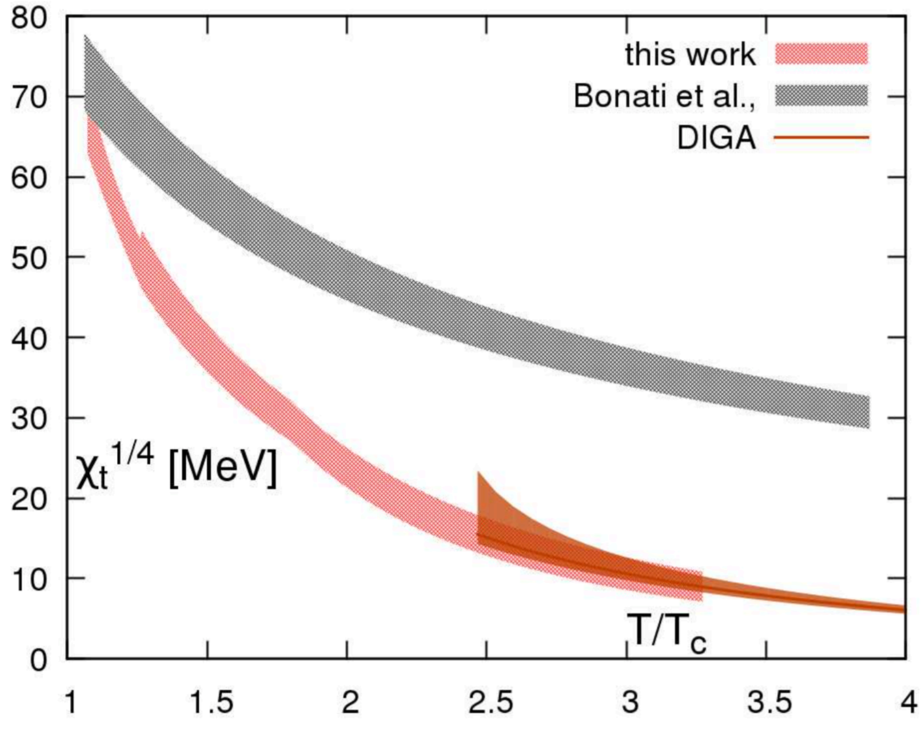


[Borsanyi et al. 15]

Axion Dark Matter: Uncertainties

- Differing lattice results in full QCD:



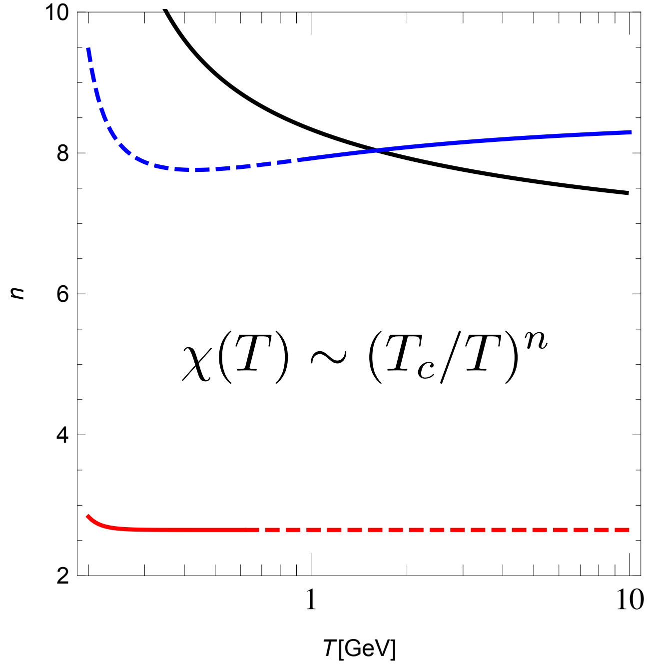


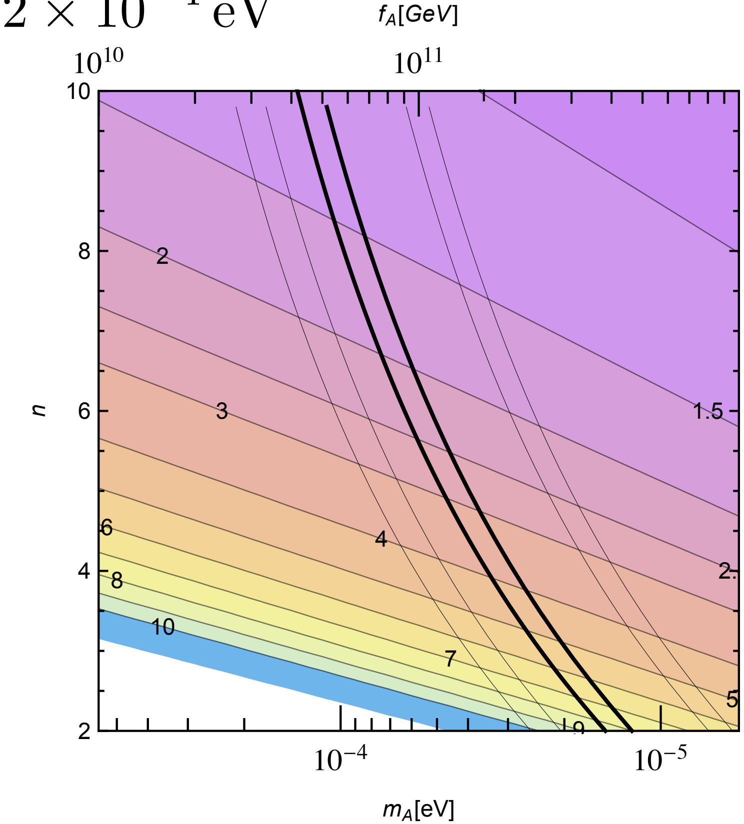
[Petreczky et al. 15]

Axion Dark Matter: Uncertainties

- Resulting uncertainty in axion mass relevant for dark matter:

$$10^{-5}\,\text{eV} \lesssim m_A \lesssim 2\times 10^{-4}\,\text{eV}$$





- Can be narrowed by improving lattice results on topological susceptibility and predictions of axions radiated from strings

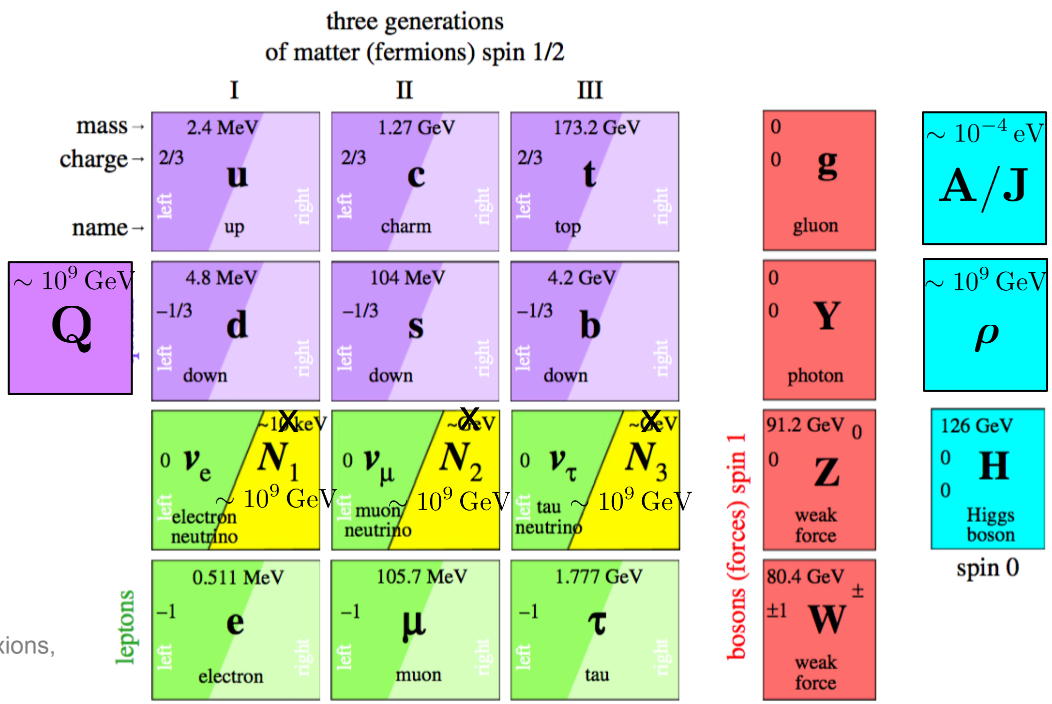
Summary

> Remarkably simple extension of the SM provides solution of five fundamental problems of particle physics and cosmology

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

SM*A*S*H

[Ballesteros,Redondo, AR,Tamarit, arXiv:1606.nnnn]

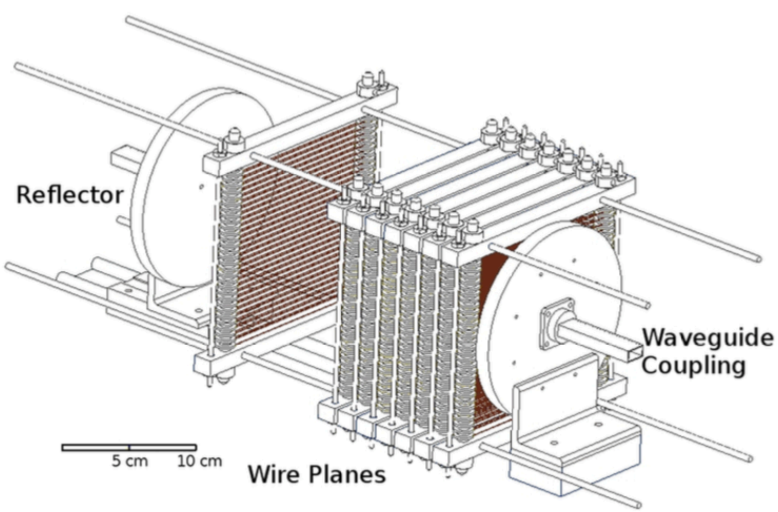


Summary

- Crucial predition: Dark matter comprised of axions with mass in range

$$10^{-5}\,\mathrm{eV} \lesssim m_A \lesssim 2 \times 10^{-4}\,\mathrm{eV}$$

- Can be tested experimentally in next decade by new direct detection experiments, such as the Orpheus or MADMAX haloscopes



First prototype setup at MPI