SM*A*S*H

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

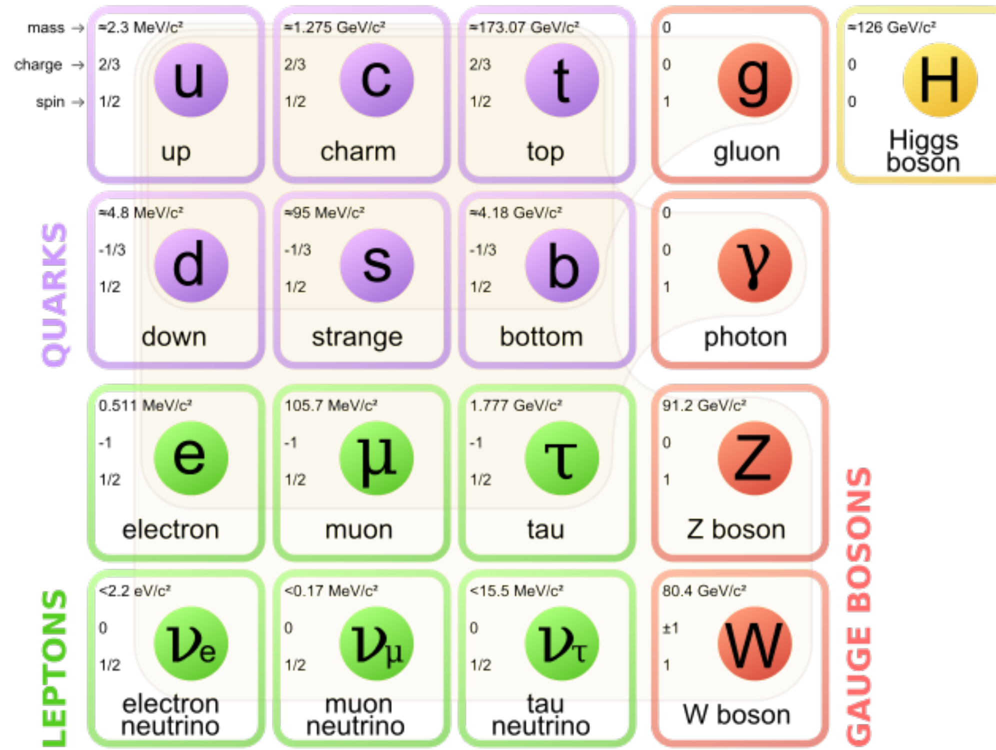
Andreas Ringwald (DESY)

From the Vacuum to the Universe
Kitzbühel, Austria
26 June – 1 July 2016

[Guillermo Ballesteros, Javier Redondo, AR, Carlos Tamarit, arXiv:1607.nnnn]

The Quest for a Minimal Model of Particle Cosmology

- Discovery of Higgs boson marks completion of SM particle content



[wikipedia]

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- Discovery of Higgs boson marks completion of SM particle content
- Observations in particle physics, astrophysics and cosmology point to existence of BSM particles

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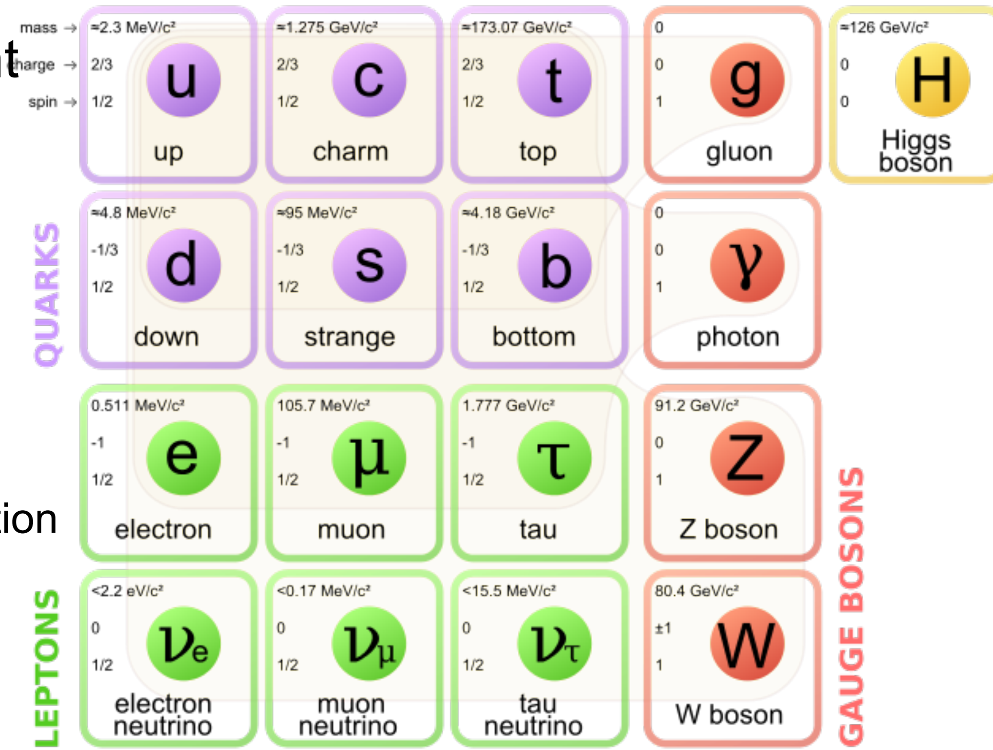
  2. Baryon asymmetry
  3. Dark matter
  4. Neutrino flavour oscillations
  5. Non-observation of strong CP violation



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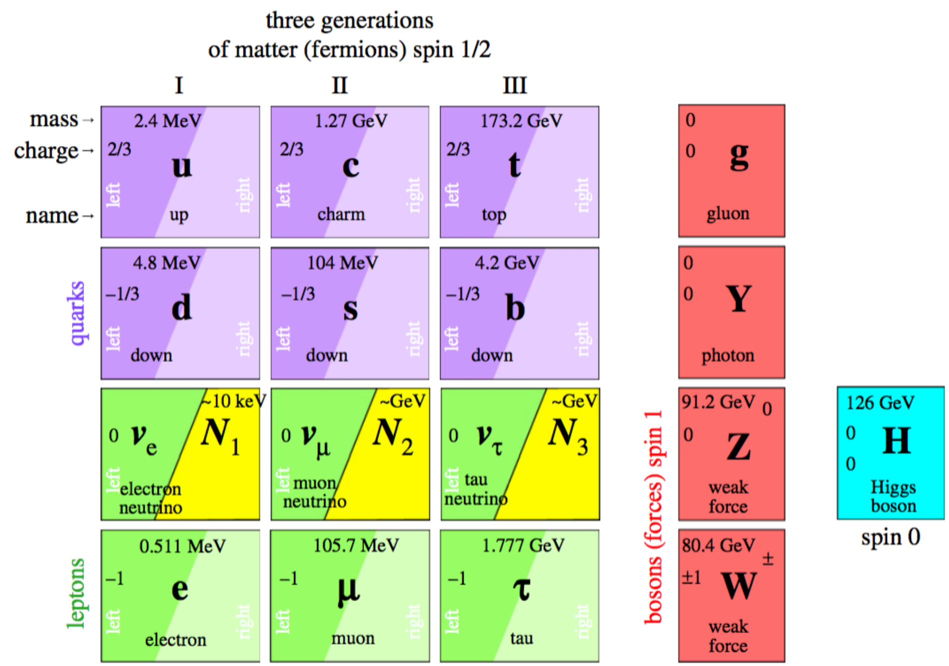

[M. Shaposhnikov, *Phil. Trans. R. Soc. A* **373** (2014) 0038]

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

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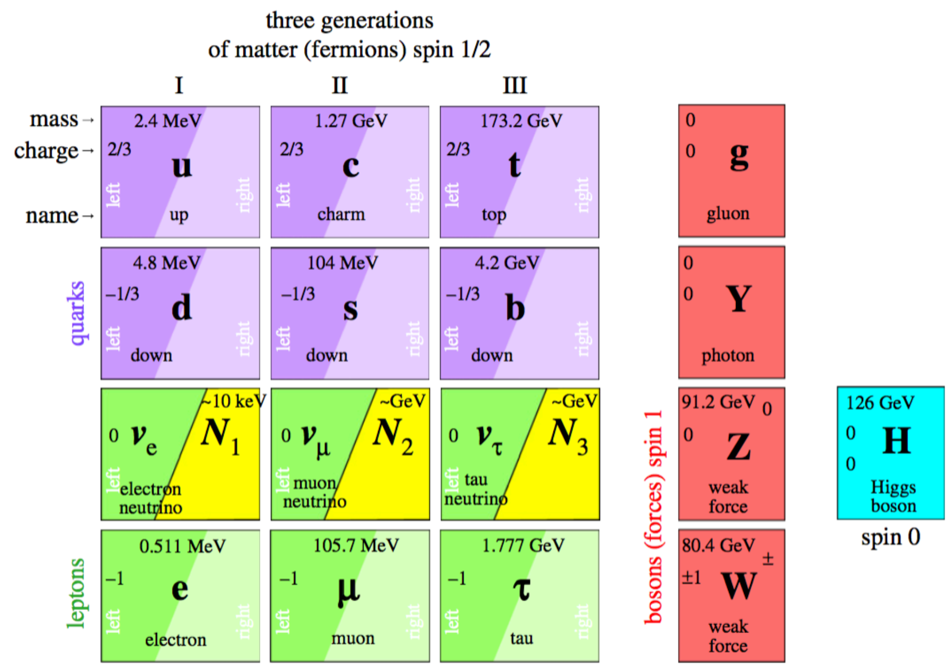

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  - Allowing for large, $\xi_H \sim 10^5 \sqrt{\lambda_H}$, non-minimally coupling of Higgs to Ricci scalar [Bezrukov, Shaposhnikov `08]

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

The Quest for a Minimal Model of Particle Cosmology

- Success of inflation in νMSM 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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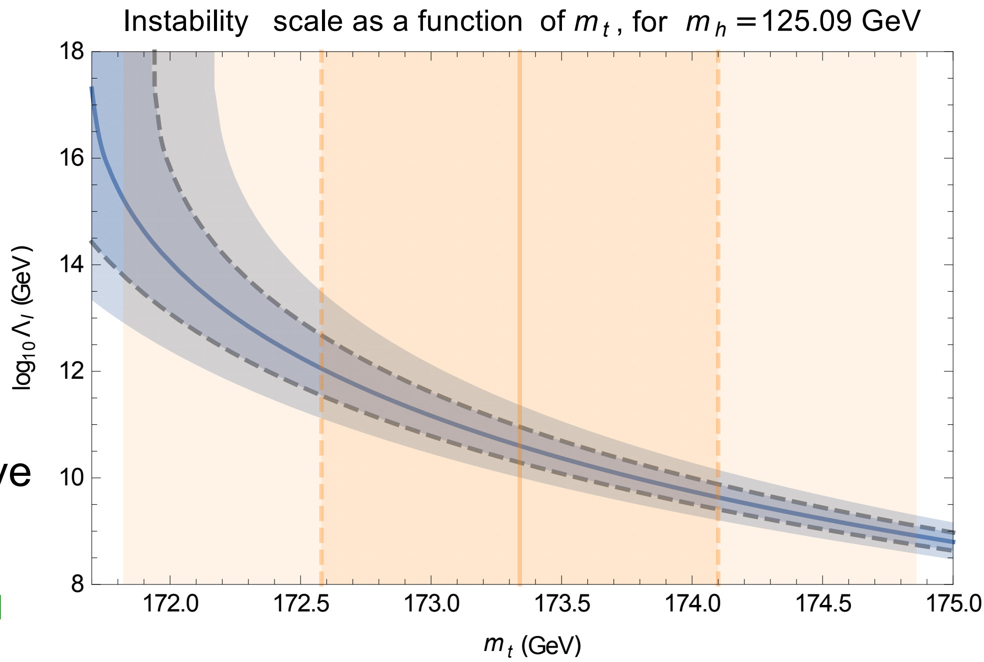

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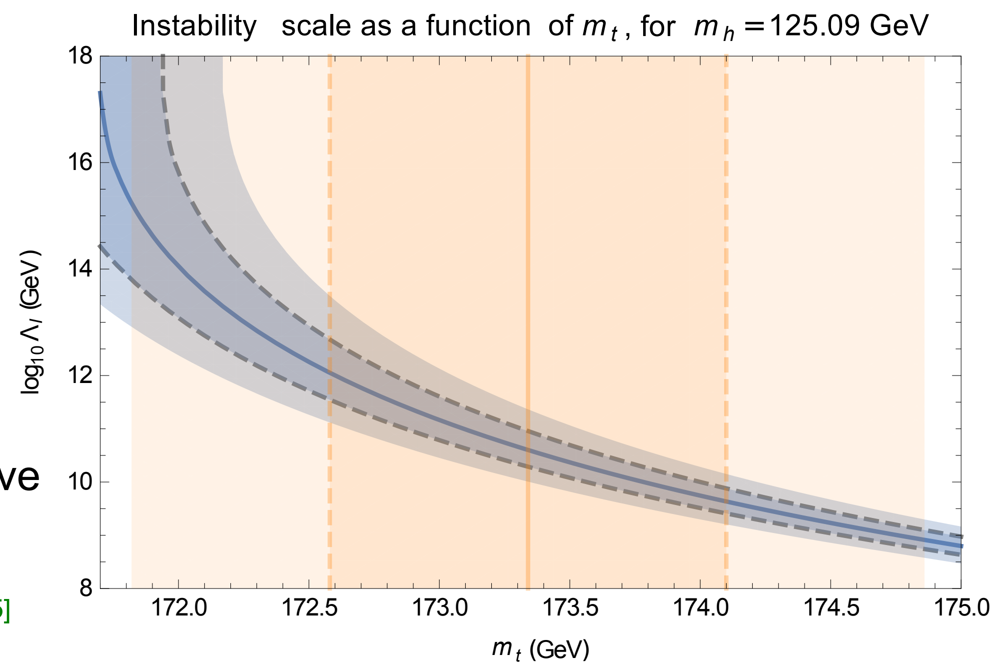

- Can be avoided by introducing Hidden complex Scalar (HS) charged under new global U(1) symmetry that is spontaneously broken

[Ballesteros,Redondo, AR,Tamarit, arXiv:1607.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 modulus $|\sigma| = \rho/\sqrt{2}$ 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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  - 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 absol-utely stable if $v_\sigma < \sqrt{\lambda_H/\lambda_{H\sigma}}\, \Lambda_I$

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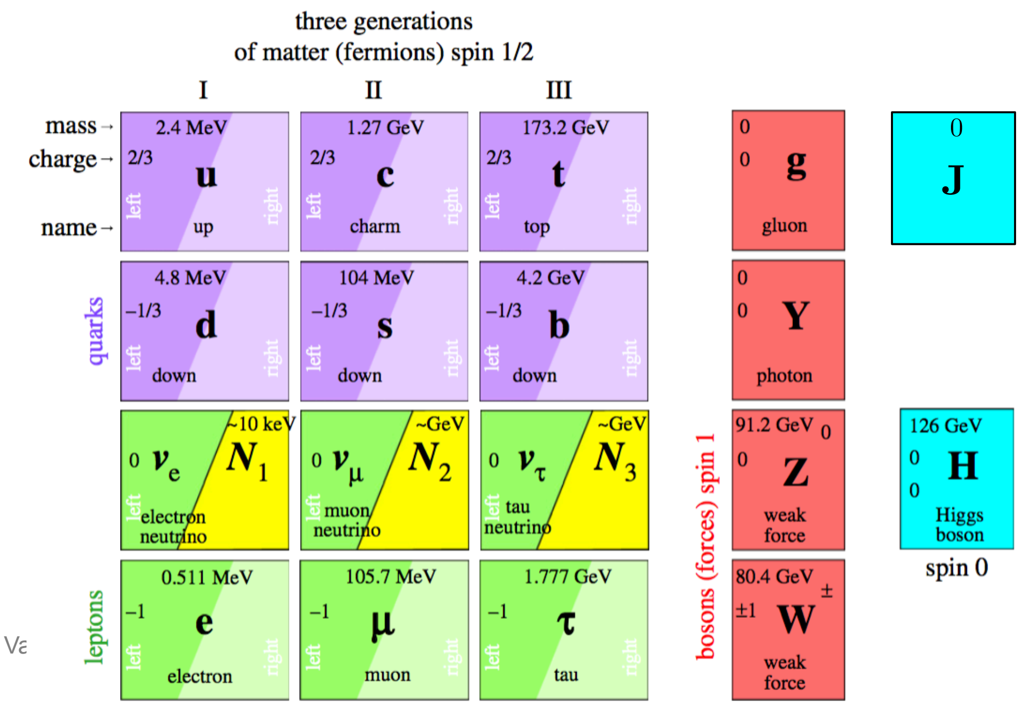
    [Lebedev 12; Elias-Miro et al. 12]
- Angular scalar excitation:
  - NG boson J



The Quest for a Minimal Model of Particle Cosmology

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

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

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

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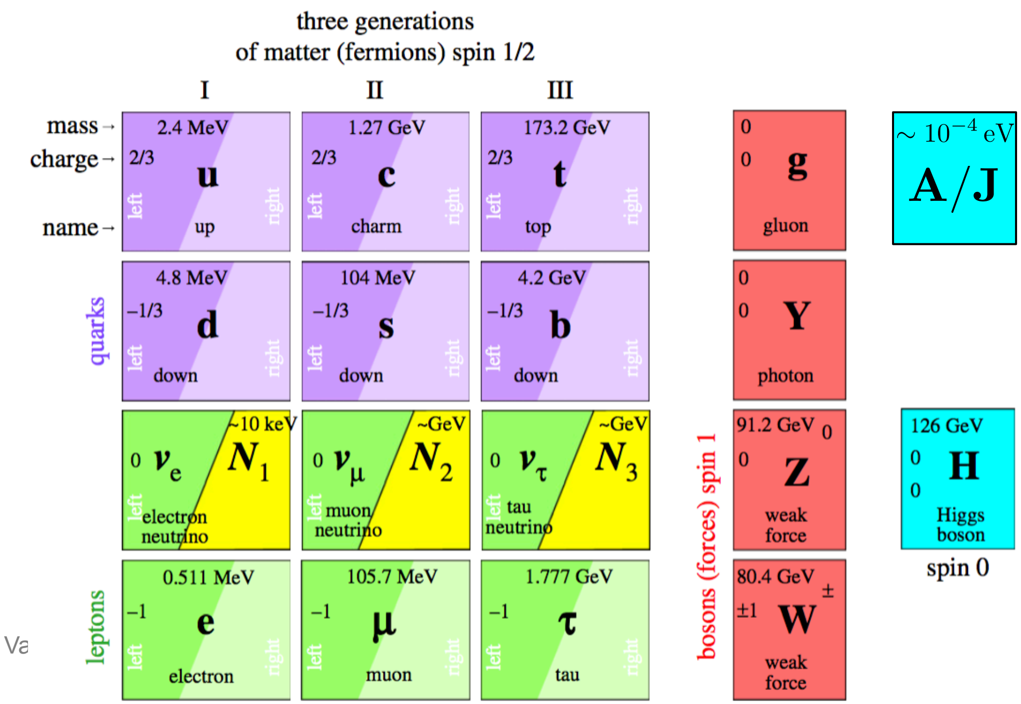

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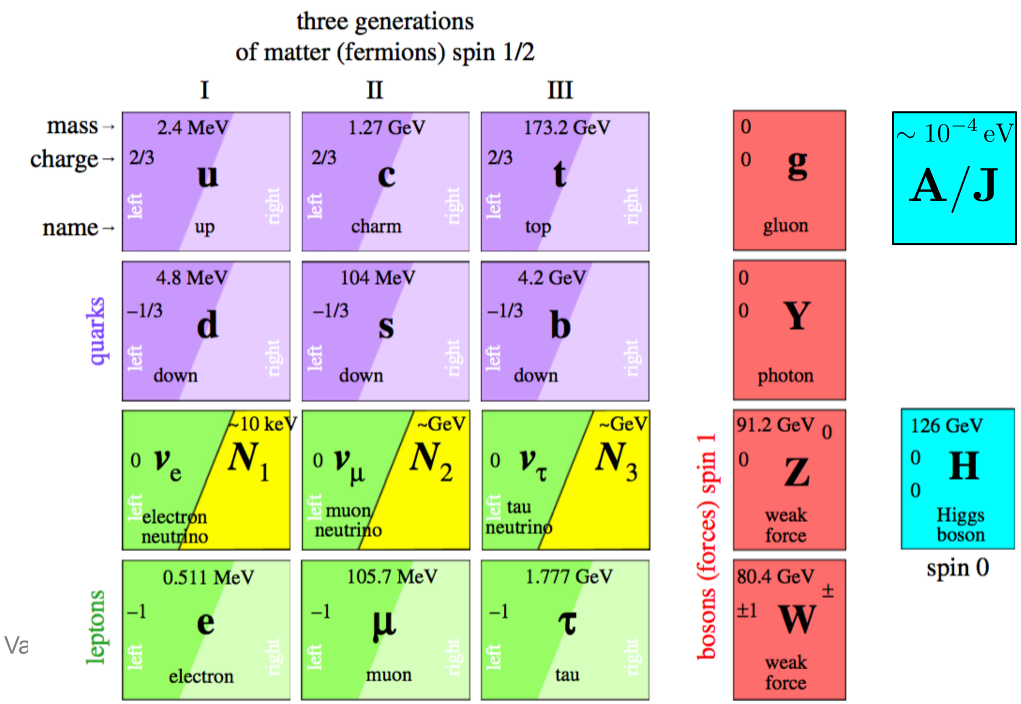
  - NG boson A/J has coupling
    $$\mathcal{L}_A \supset -\frac{\alpha_s}{8\pi} \frac{A}{v_\sigma} G^c_{\mu\nu} \tilde{G}^{c,\mu\nu}$$
  - Strong CP problem solved!
  - A/J decay constant: $f_A = v_\sigma$
  - Mass $m_A \sim f_\pi m_\pi / f_A$



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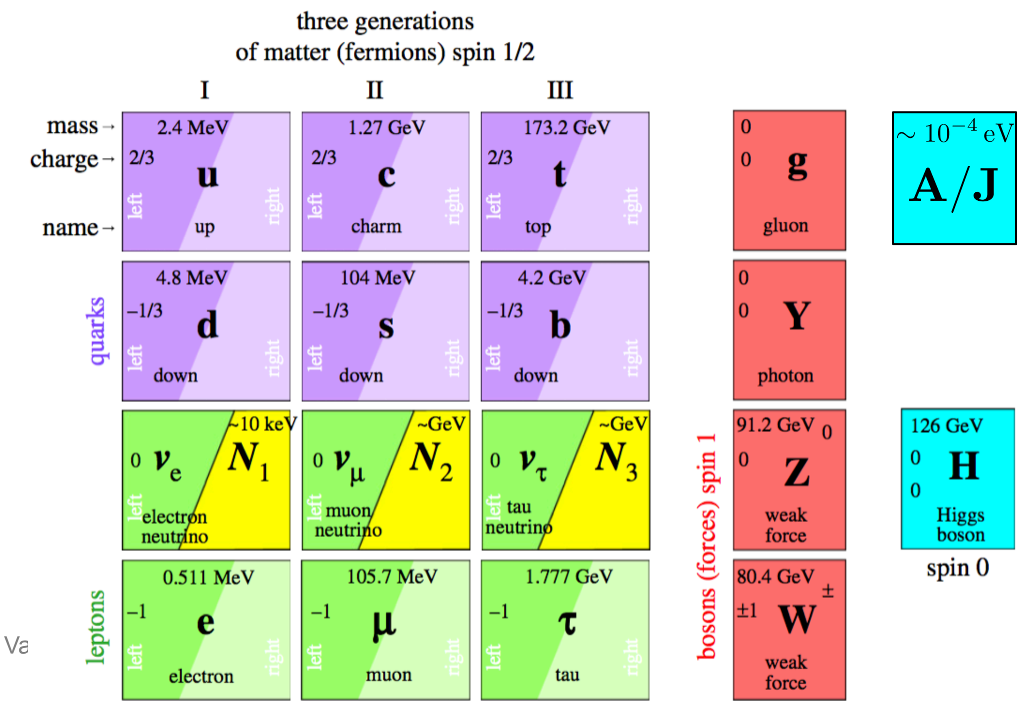
- Axion cold DM plus sterile neutrino warm DM



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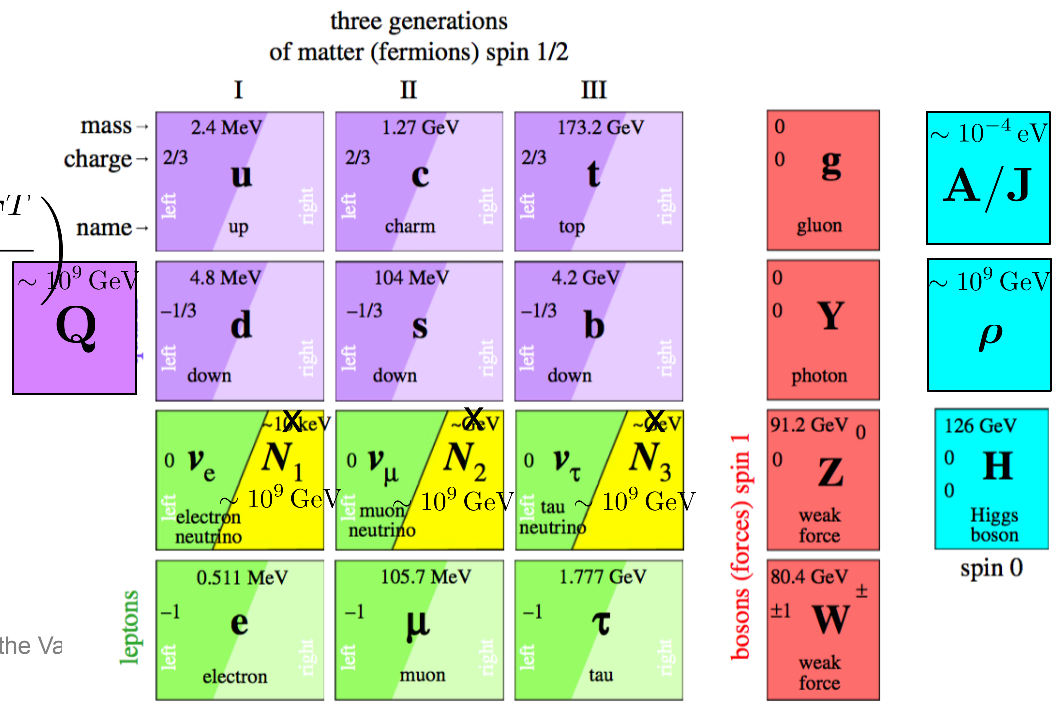

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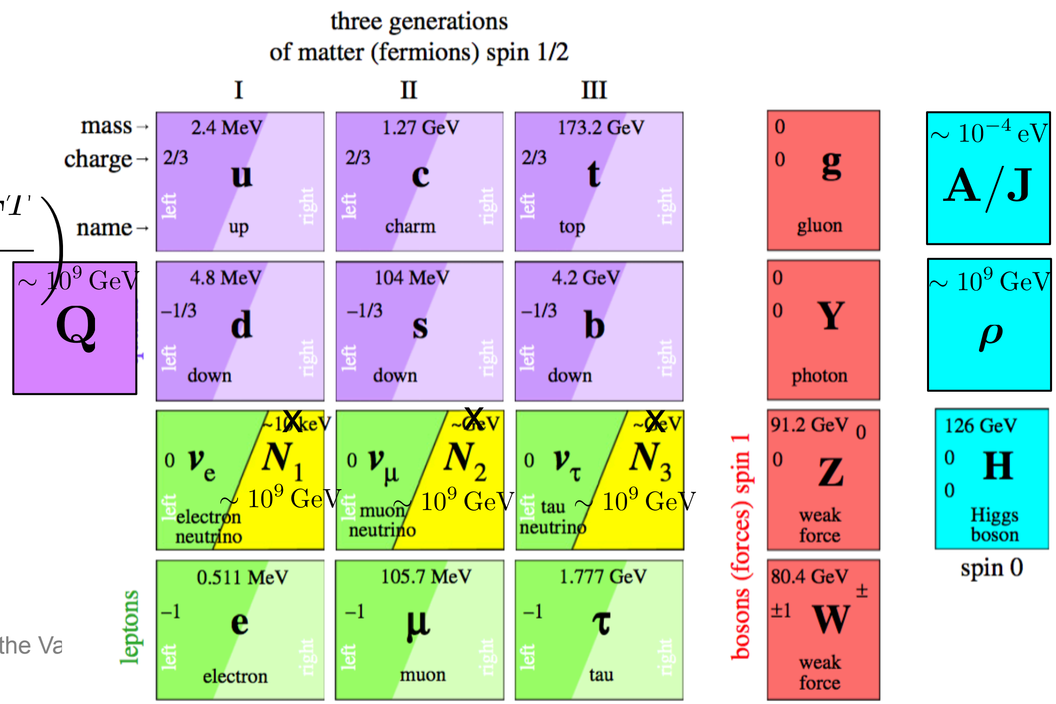

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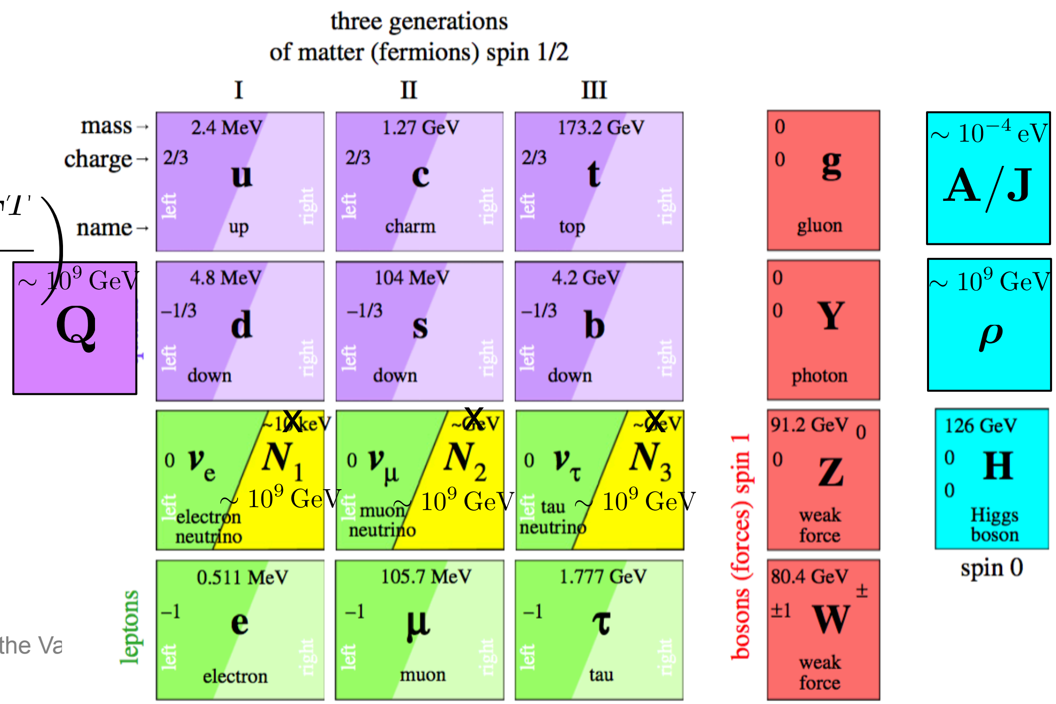

Inflation: Higgs Inflation, Hidden Scalar Inflation, ...

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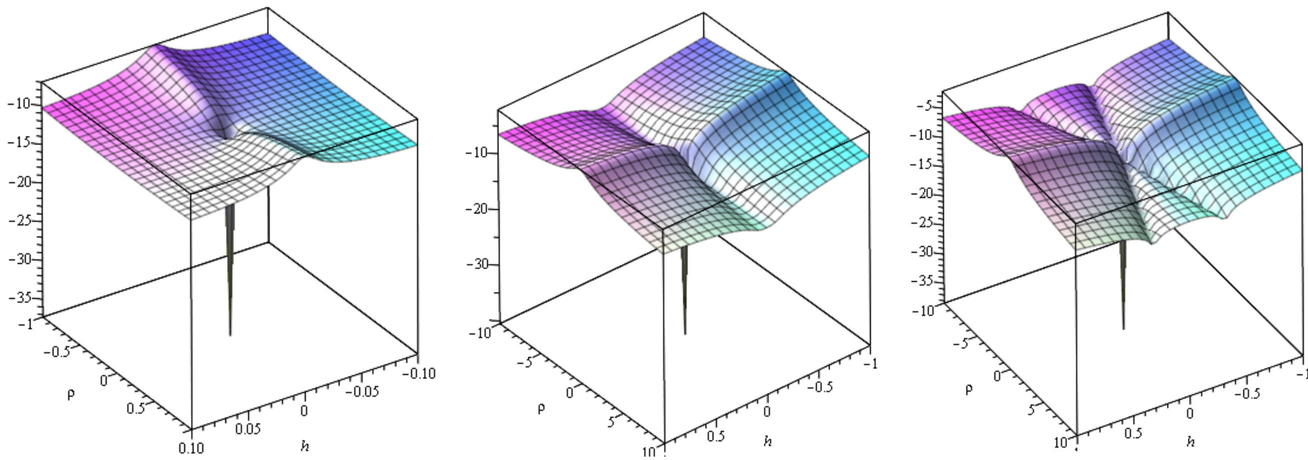
- Potential has valleys =attractors for Higgs Inflation (HI), Hidden Scalar In-flation (HSI) or mixed Higgs Hidden Scalar Inflation (HHSI), depending on relative signs of $\kappa_H \equiv \lambda_{H\sigma}\xi_H - \lambda_H\xi_\sigma\,,\quad \kappa_\sigma \equiv \lambda_{H\sigma}\xi_\sigma - \lambda_\sigma\xi_H$



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

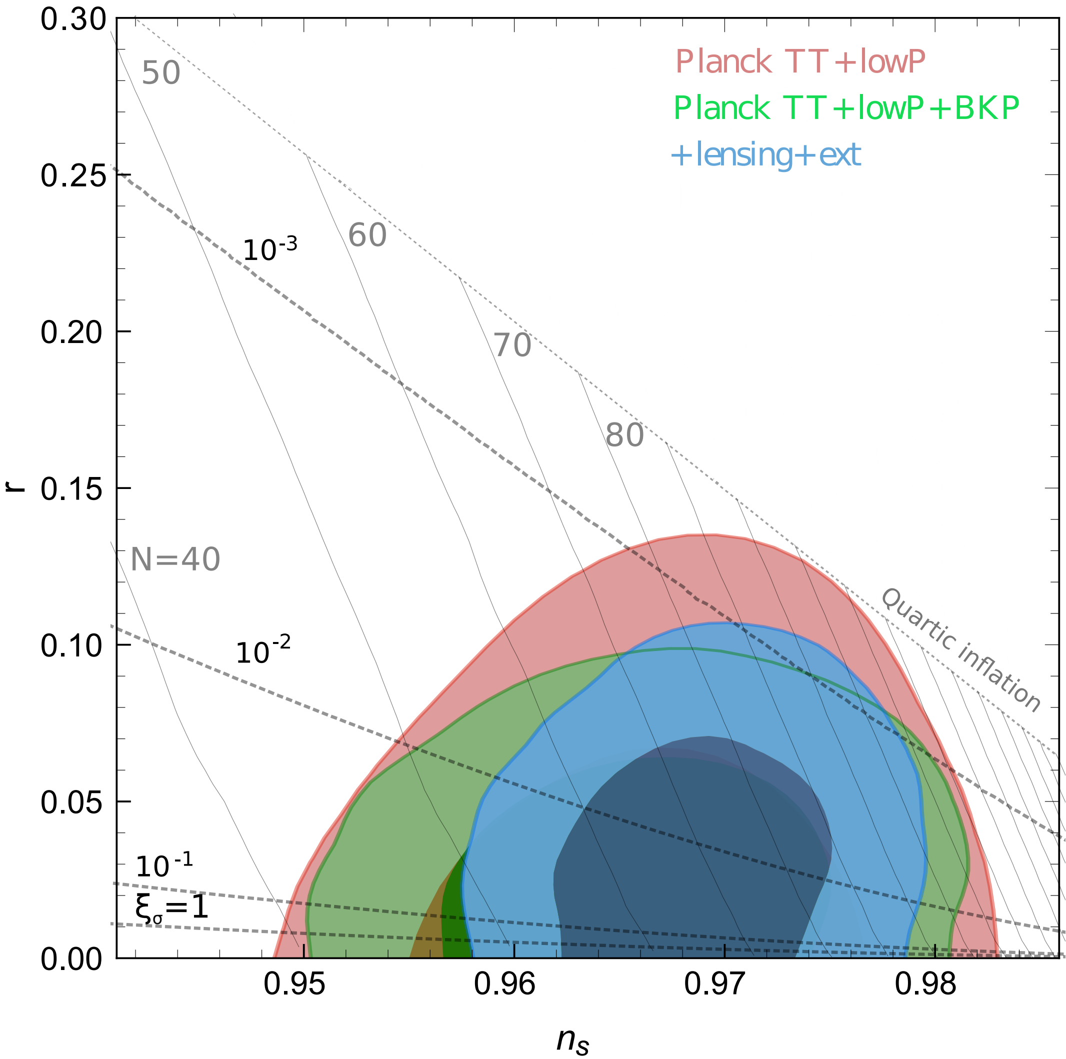
Inflation: Confronting with Observations

> 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 $\xi \gtrsim 10^{-3}$

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



Inflation: Confronting with Observations

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

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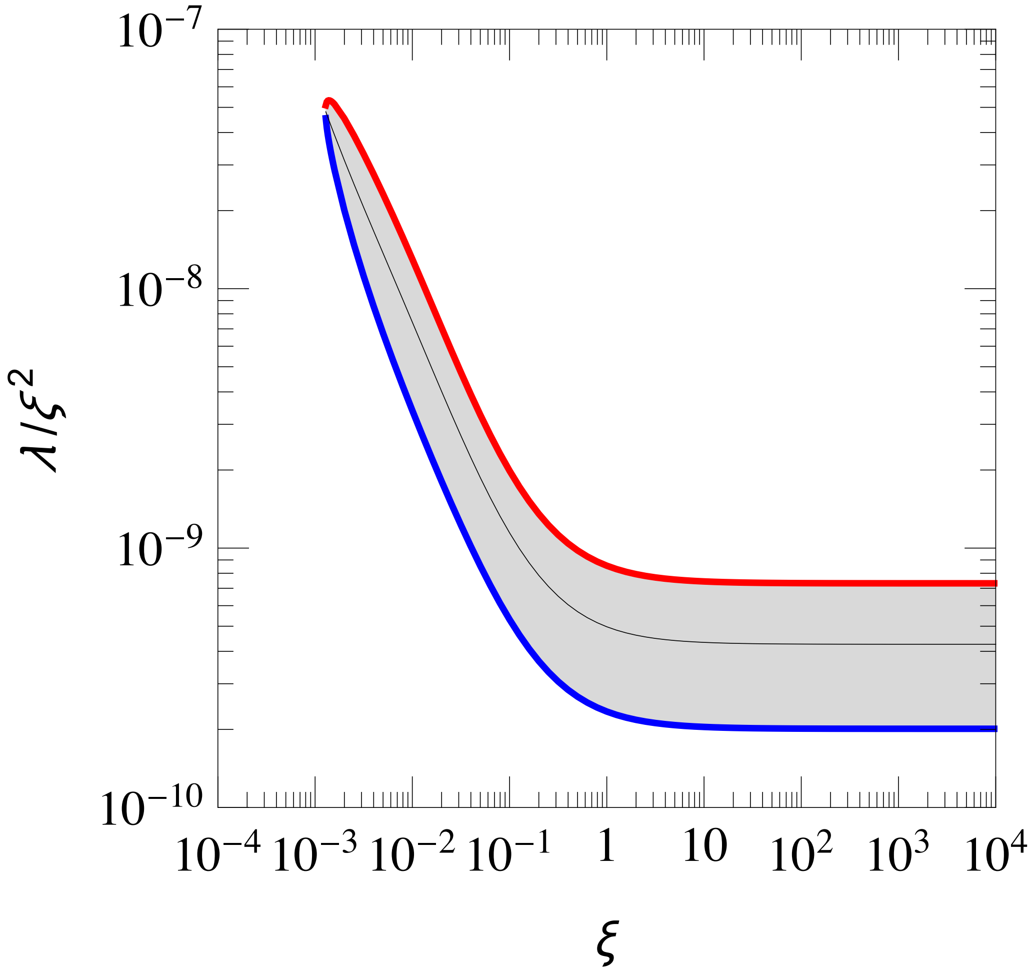
$$\xi_H \sim 2 \times 10^5 \sqrt{\lambda_H(\sim M_P)} \sim 2 \times 10^4$$



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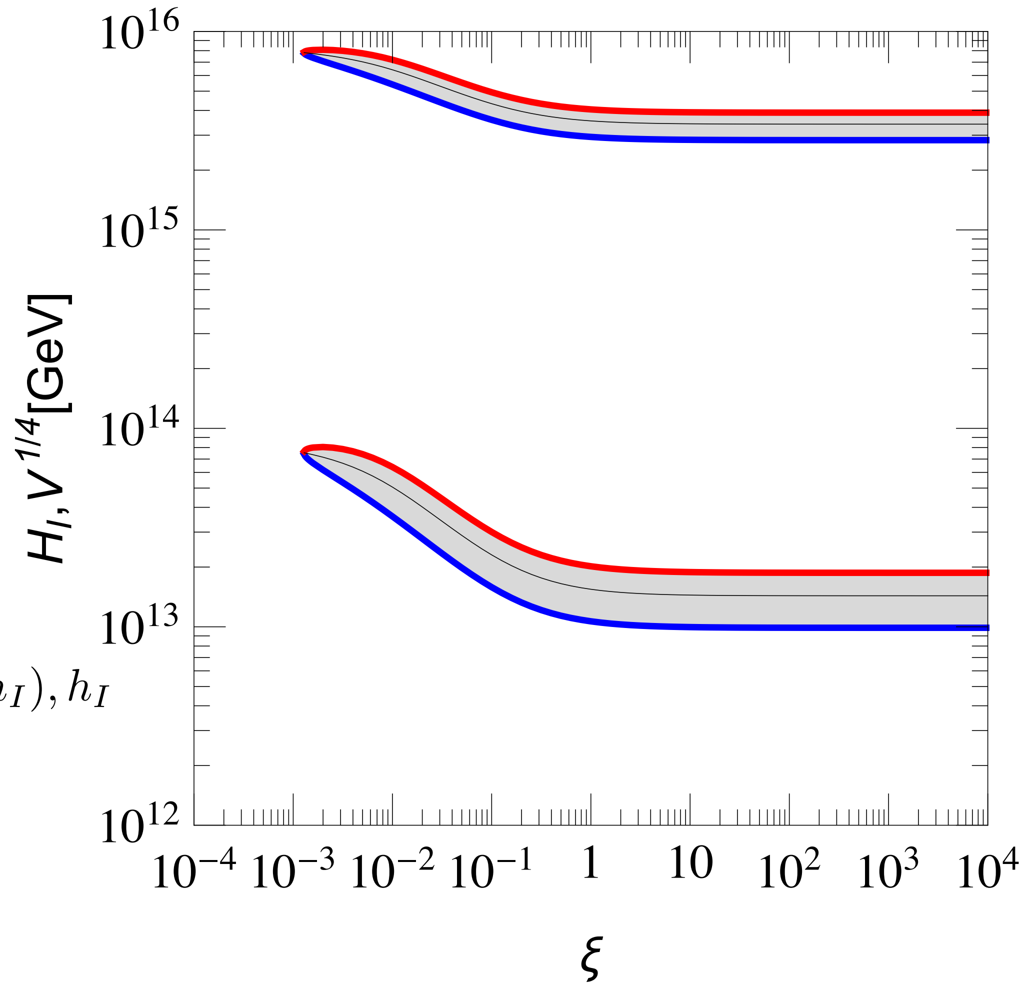
$$\Lambda_U \sim \frac{M_P}{\xi_H} \sim 10^{14}\ \text{GeV} \sim H_I \ll \tilde{V}^{1/4}(h_I), h_I$$



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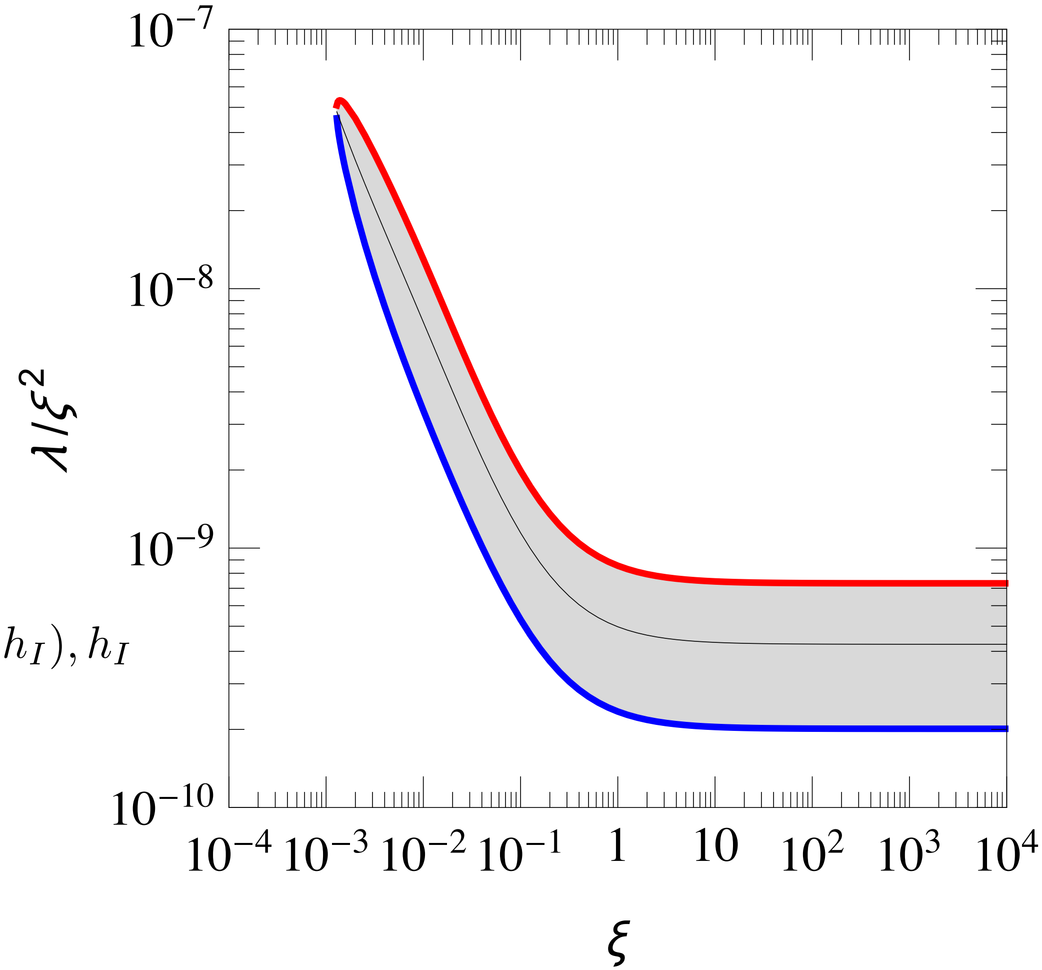
- Can be of order one for HSI or HHSI; e.g. $\xi_\sigma = 1$ requires

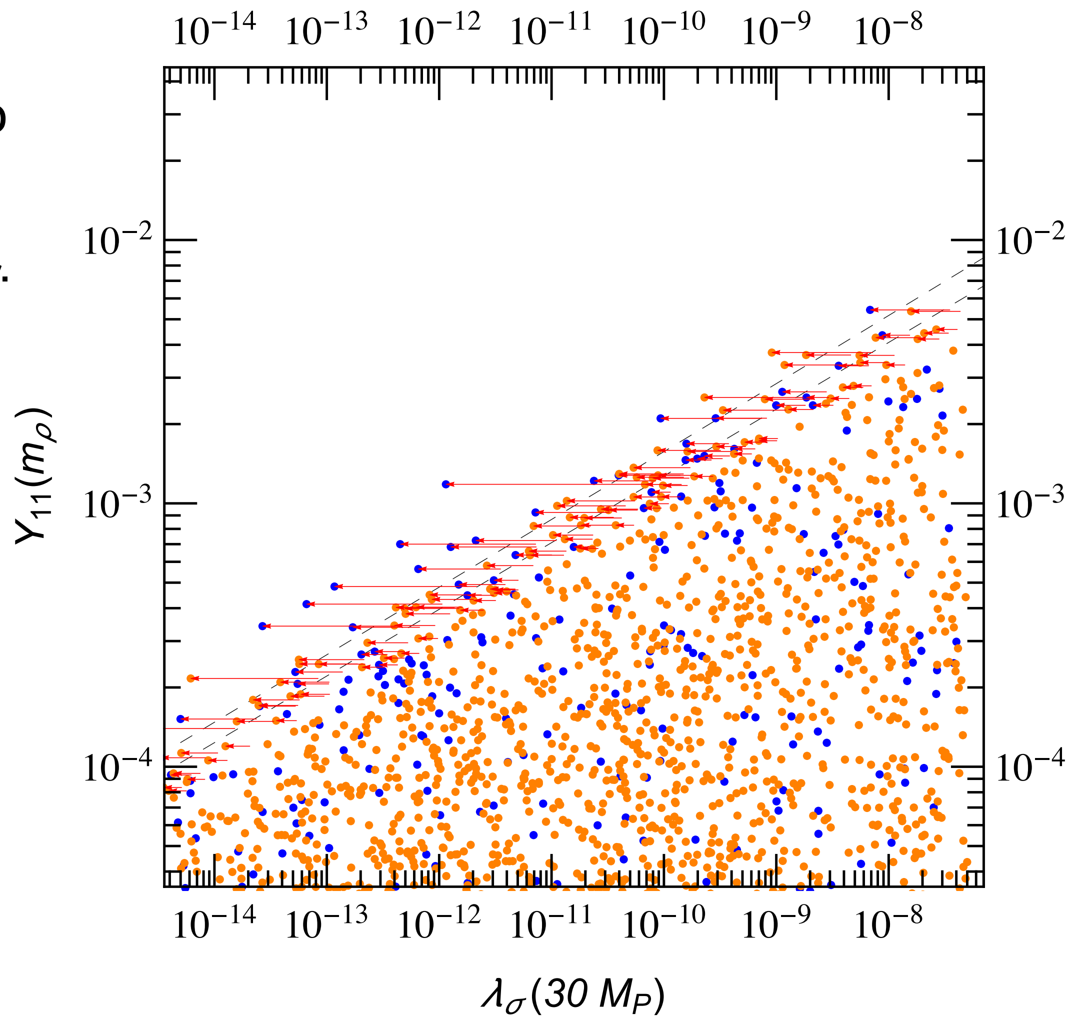
$$\lambda_\sigma, \tilde{\lambda}_\sigma = (4.1^{+3.0}_{-2.1}) \times 10^{-10}$$

- No unitarity problem in HSI/HHSI!



Stability

- Effective scalar potential in SMASH can be positive up to the Planck scale
- Stability in HS direction enforces a maximum on Yukawas of RH neutrinos



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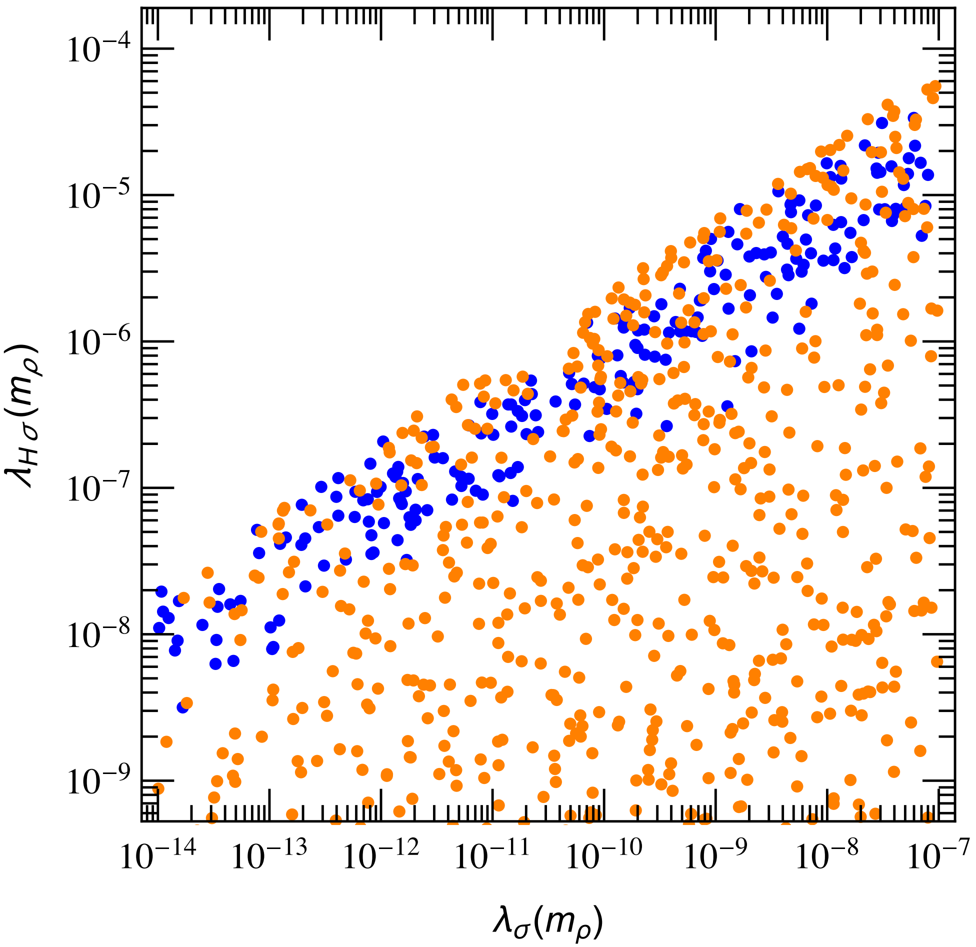
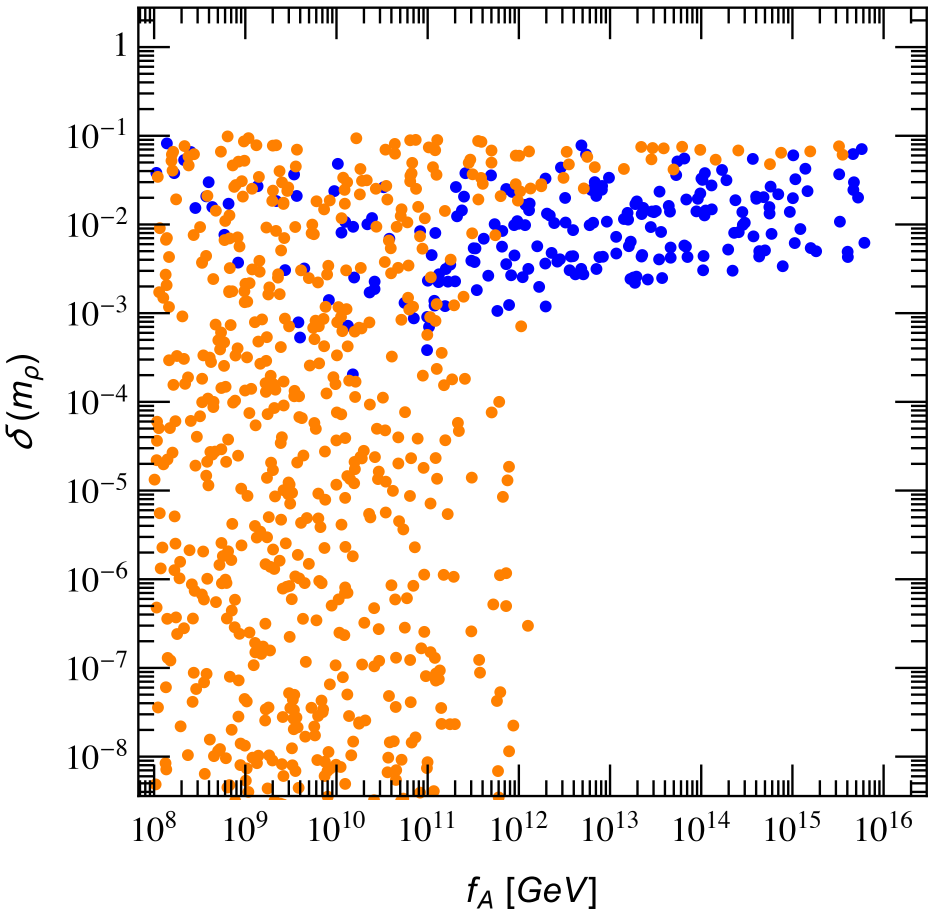
- Stability in HS direction enforces a maximum on Yukawas of RH neutrinos
- Stability in Higgs direction enforces maximum on Higgs portal coupling



Stability

- Effective scalar potential in SMASH can be positive up to the Planck scale
- Stability in HS direction enforces a maximum on Yukawas of RH neutrinos
- Stability in Higgs direction enforces maximum on Higgs portal coupling and a maximum on f_A

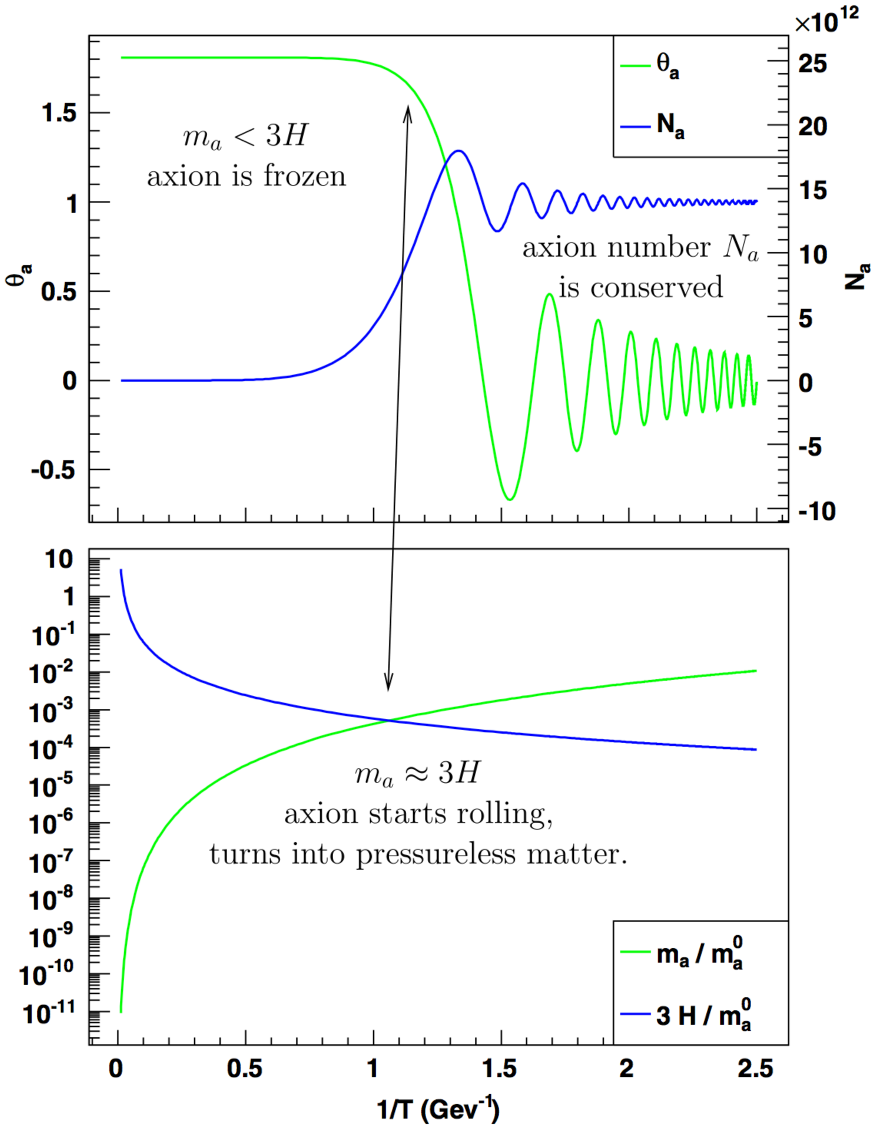


Reheating

- Mechanism of reheating in SMASH well defined: proceeds via the Higgs portal
- 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 dump their energy 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

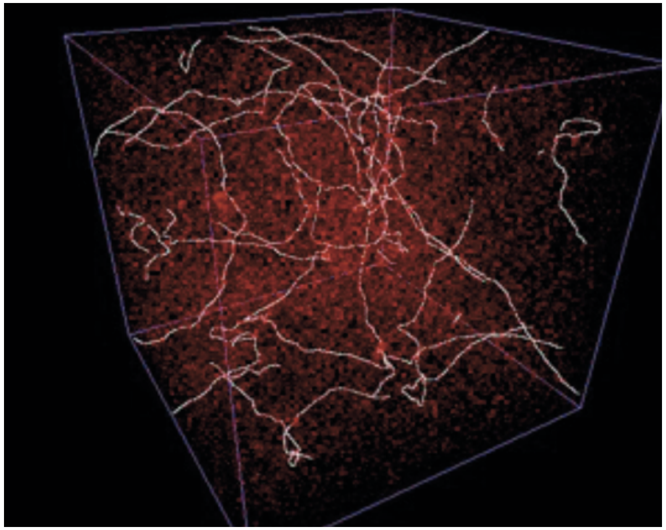


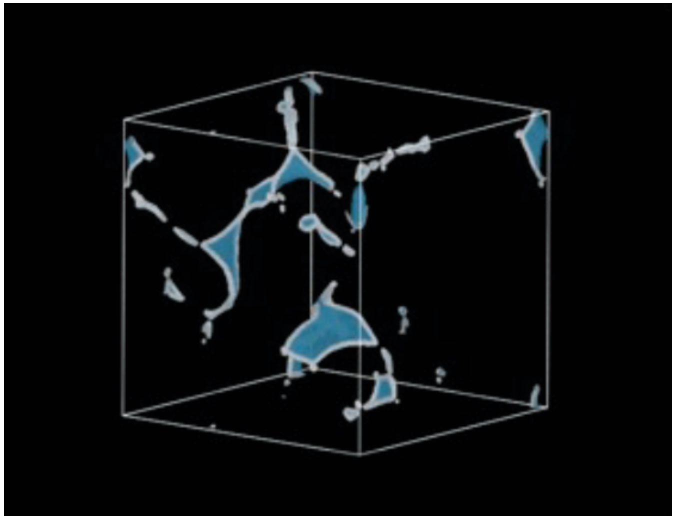
[Wantz,Shellard 09]

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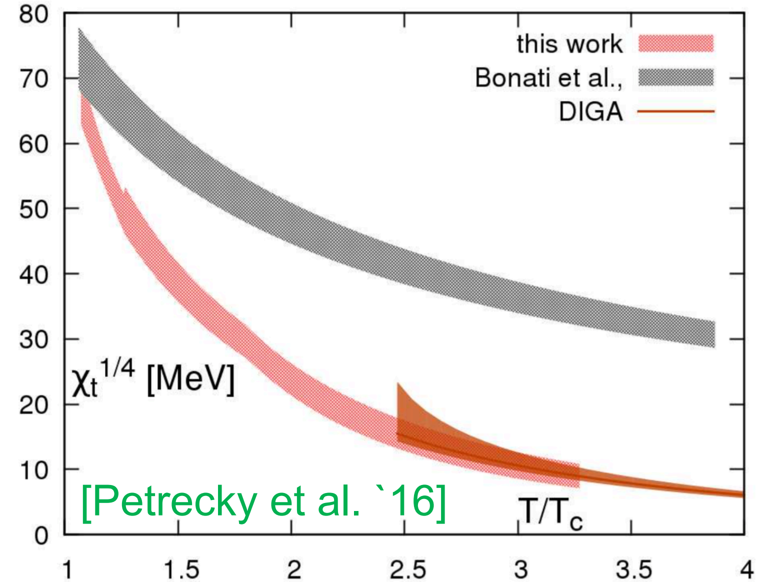
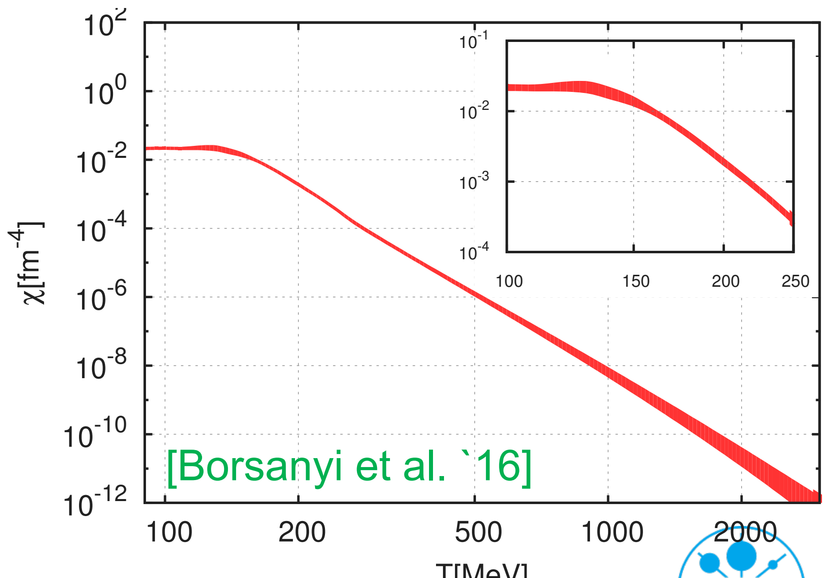
$$\Omega_{A,\mathrm{tot}}h^2 = \Omega_{A,\mathrm{real}}h^2 + \Omega_{A,\mathrm{string}}h^2 + \Omega_{A,\mathrm{wall}}h^2$$

- Key quantity entering prediction: Temperature dependence of axion mass, $m_A(T) f_A = \sqrt{\chi(T)}$





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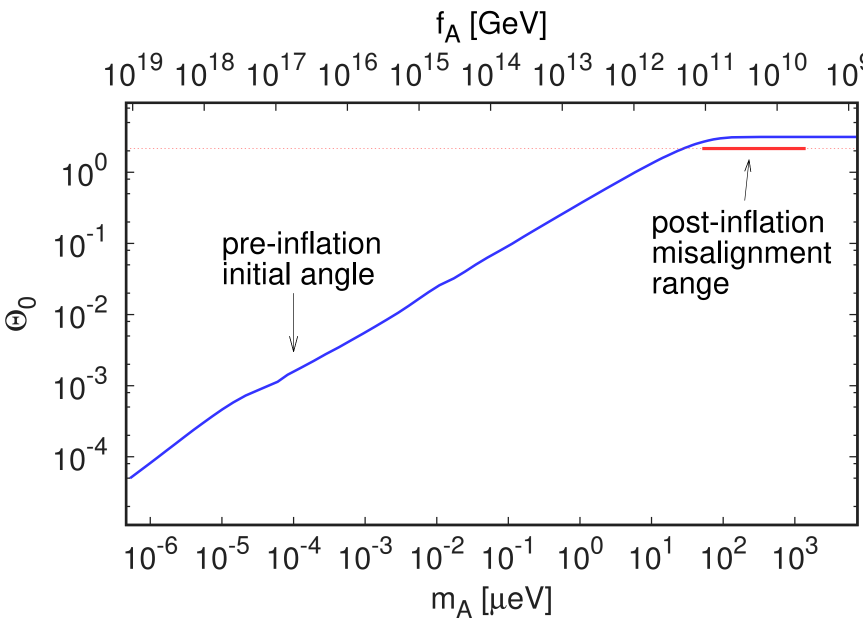
$$\Omega_{A,\rm tot}h^2 = \Omega_{A,\rm real}h^2 + \Omega_{A,\rm string}h^2 + \Omega_{A,\rm wall}h^2$$

- Key quantity entering prediction: Temperature dependence of axion mass, $m_A(T) f_A = \sqrt{\chi(T)}$
- For a 100%/50%/1% contribution from misalignment; remainder from topological defects:

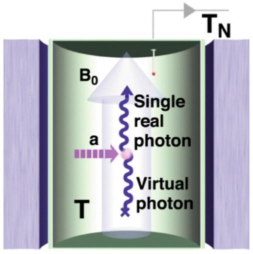
$$m_A = 28(2)/50/1500\,\mu\mathrm{eV}$$



[Borsanyi et al. \`16]

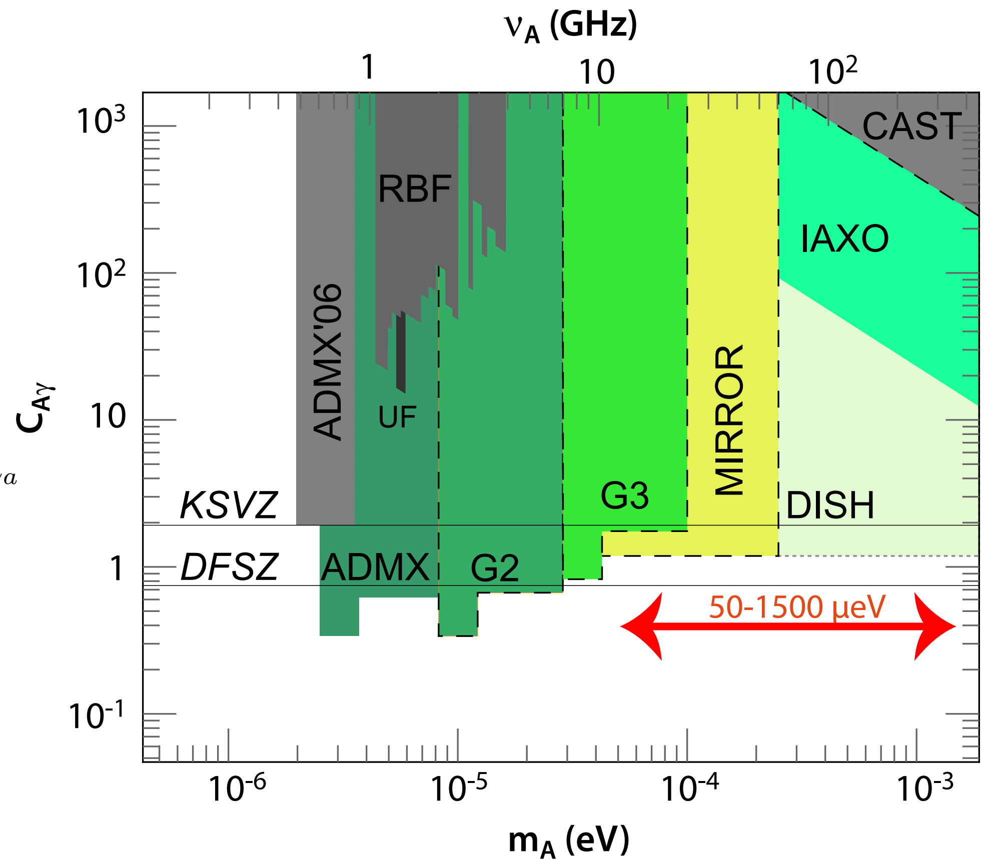
Axion Dark Matter Experiments Checking SMASH

- Presently operating (ADMX) and planned next generation experiments based on RF cavities (G2, G3) not able to cover whole mass range



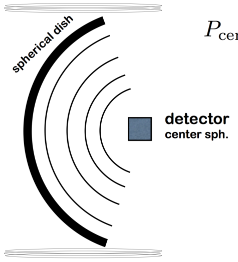
[Sikivie `83]

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



[Borsanyi et al. `16]

- More promising: Experiments exploiting dielectric mirrors or antenna dishes



$$P_{\rm center} \approx \langle |\mathbf{E}_a|^2 \rangle A_{\rm dish} \sim \chi^2 \rho_{\rm CDM} A_{\rm dish}$$
$$\sim 10^{-26} \left(\frac{\rm B}{\rm 5T} \frac{c_\gamma}{2} \right)^2 \frac{\rm A}{\rm 1m^2} {\rm Watt}$$

[Horns et al. `13]

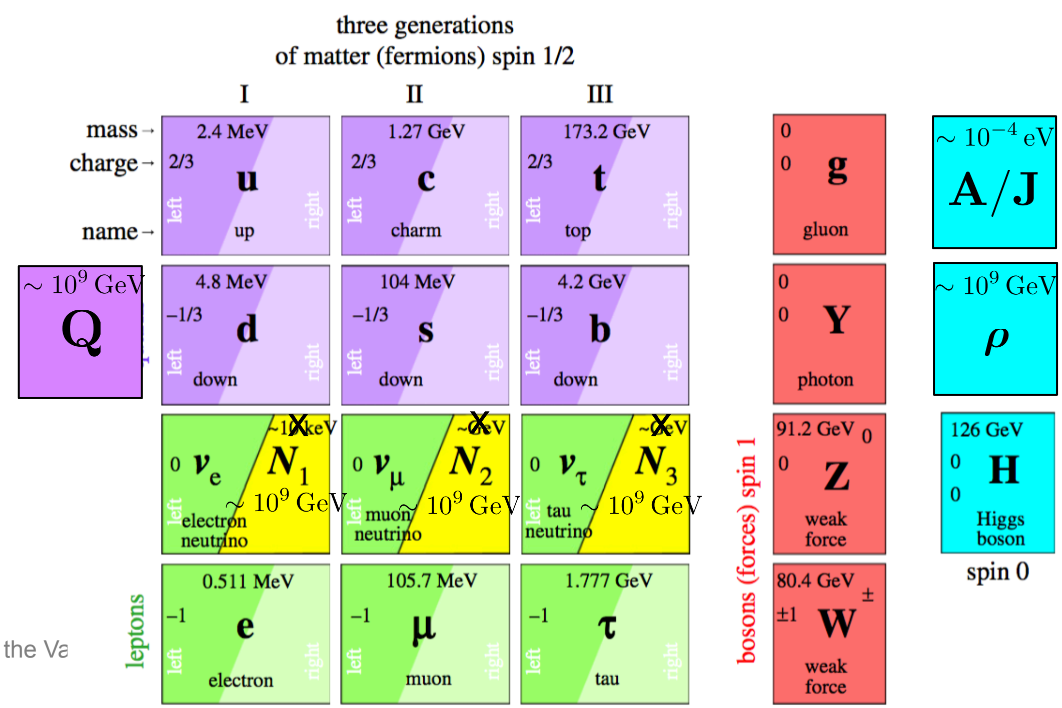
Summary

- 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

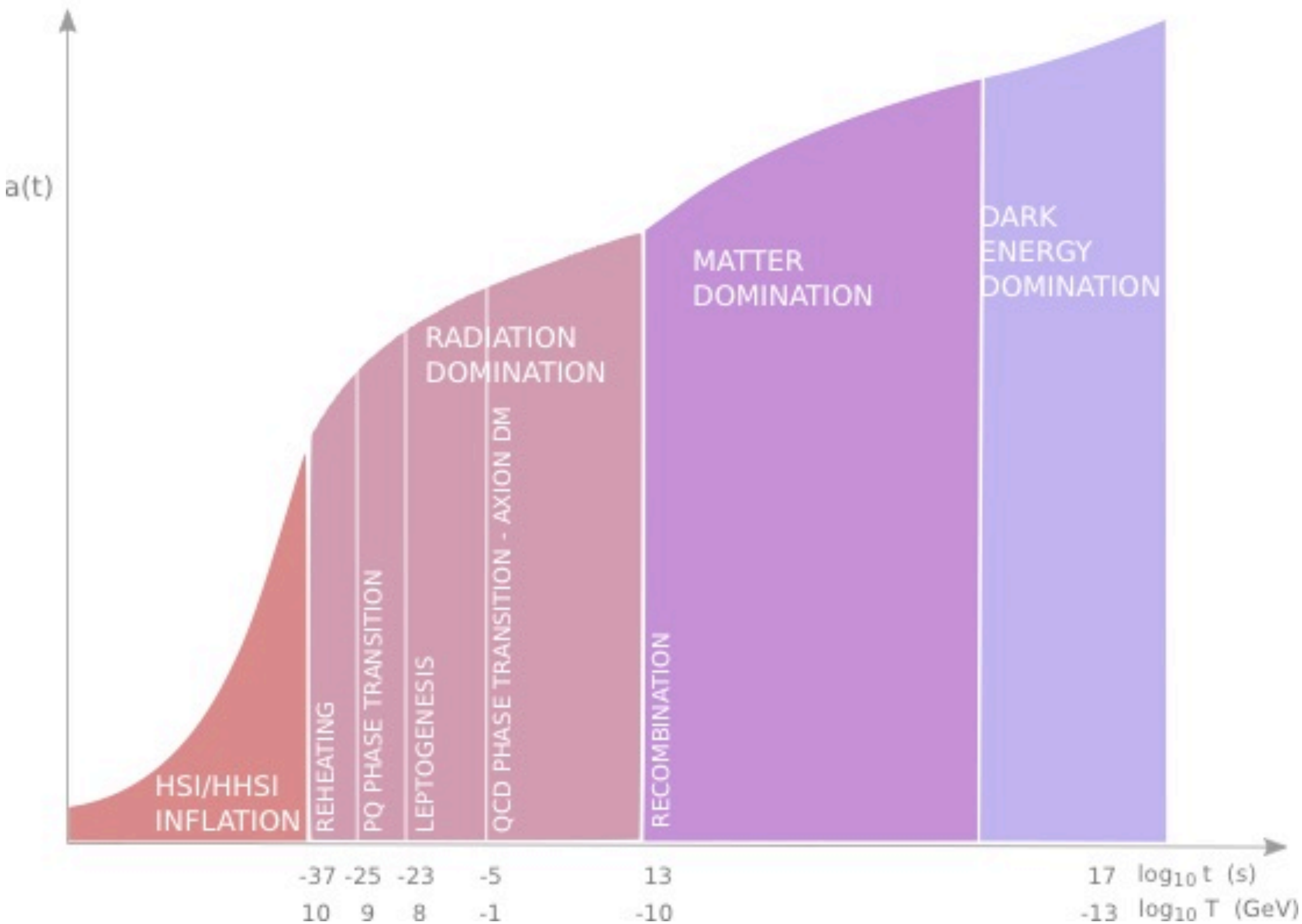
SM*A*S*H

[Ballesteros,Redondo, AR,Tamarit, arXiv:1607.nnnn]



Conclusions

> SMASHy history of the universe:



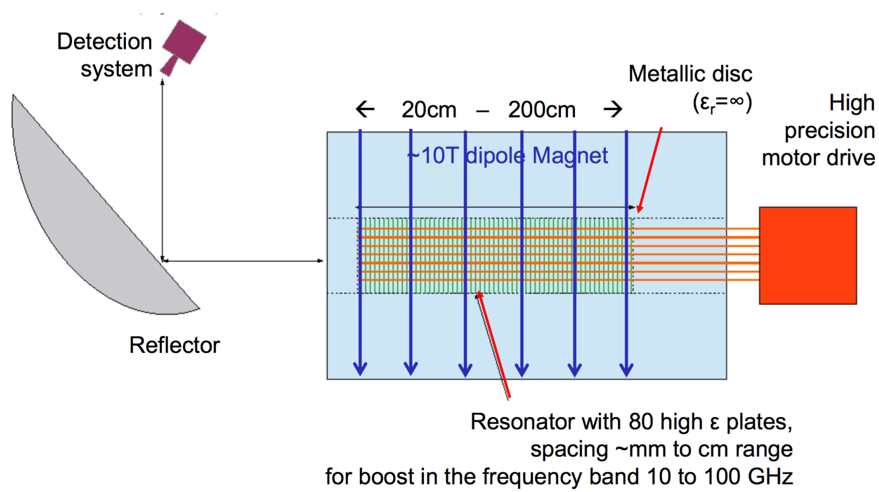
Summary

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

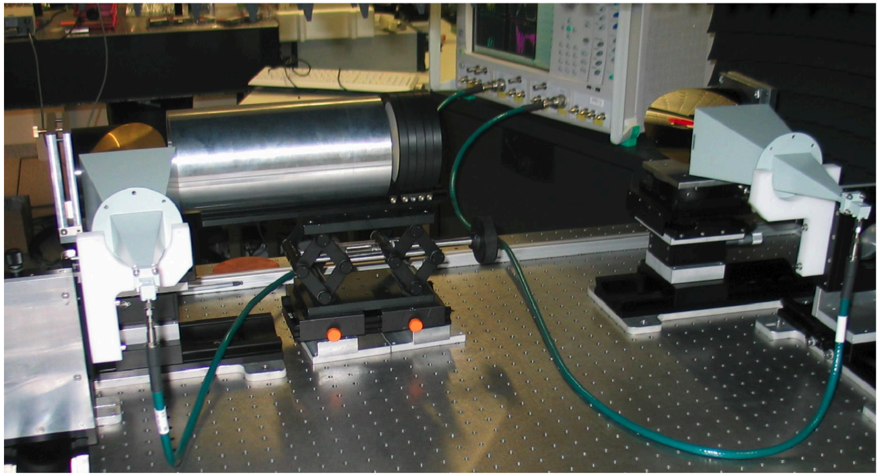
$$m_A = (50 \div 1500)\,\mu\text{eV}$$

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

Experimental idea



First prototype setup at MPI



[Caldwell et al. 15]