The Hunt for the Axion.

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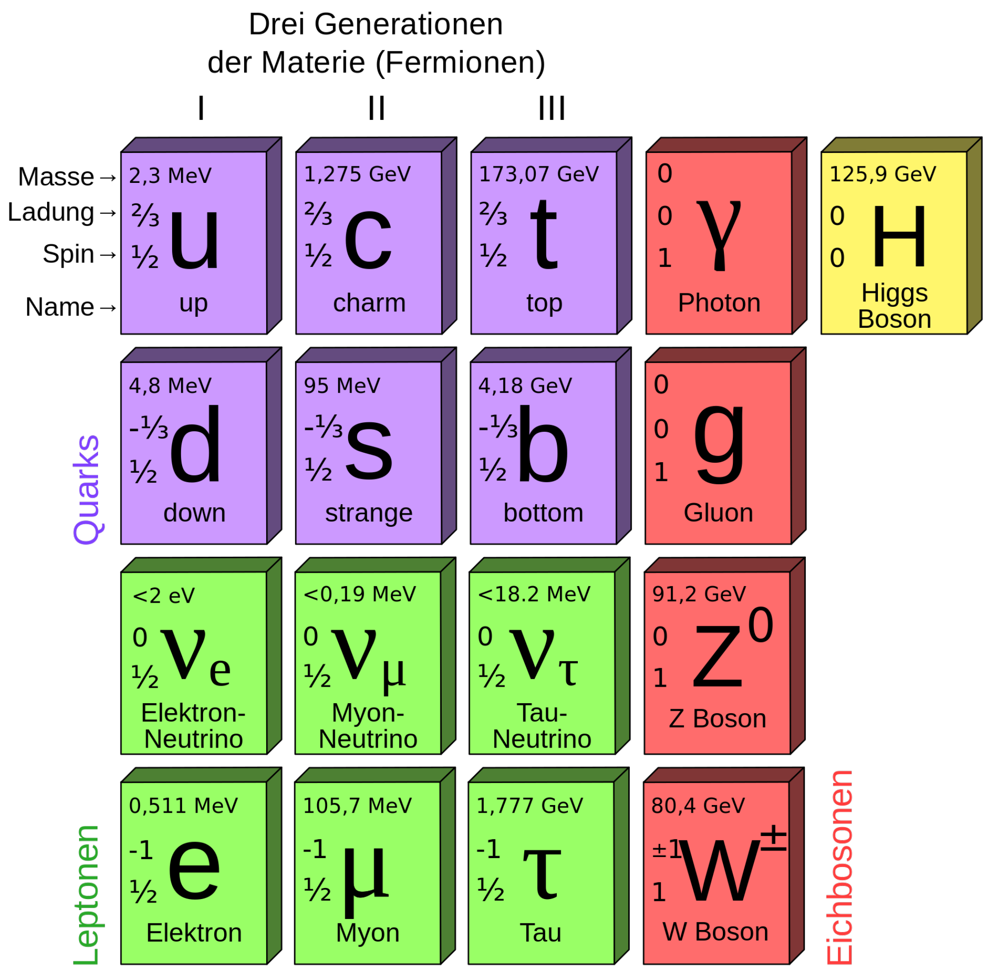
DESY

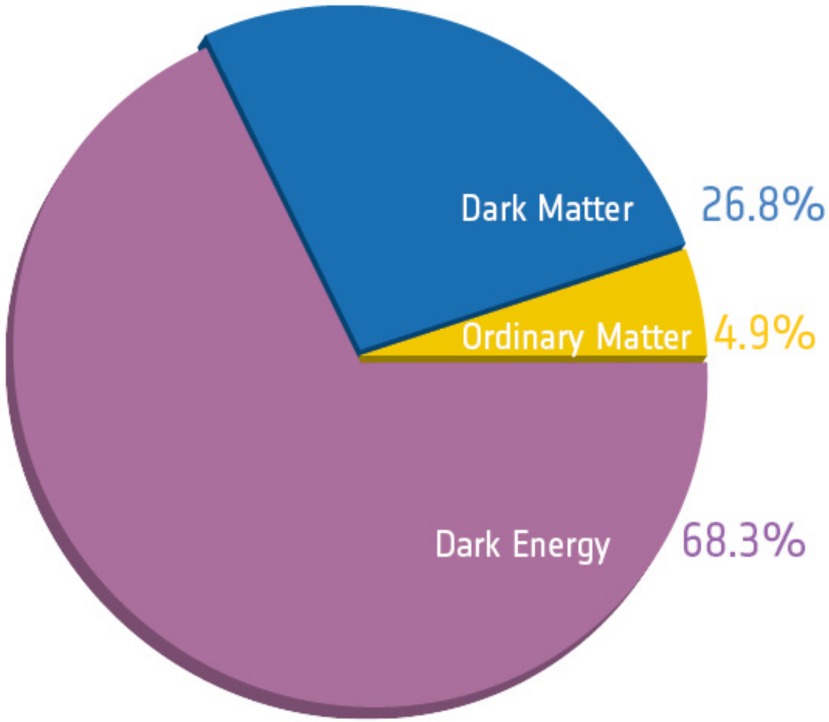
Strong Case for Physics beyond the Standard Model

- Standard Model (SM) describes interactions of all known particles with remarkable accuracy



Strong Case for Physics beyond the Standard Model

- Standard Model (SM) describes interactions of all known particles with remarkable accuracy
- Big fundamental problems in particle physics and cosmology seem to require new physics
  - Dark matter
  - Neutrino masses and mixing
  - Baryon asymmetry
  - Inflation
  - Strong CP problem



[PLANCK]

Strong CP Problem

> Most general gauge invariant Lagrangian of QCD:

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\,q - \frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

- Parameters: strong coupling α_s, quark masses $\mathcal{M}_q = {\rm diag}(m_u, m_d, \ldots)$ and theta angle θ [Belavin et al. \`75;´t Hooft 76;Callan et al. \`76;Jackiw,Rebbi \`76]

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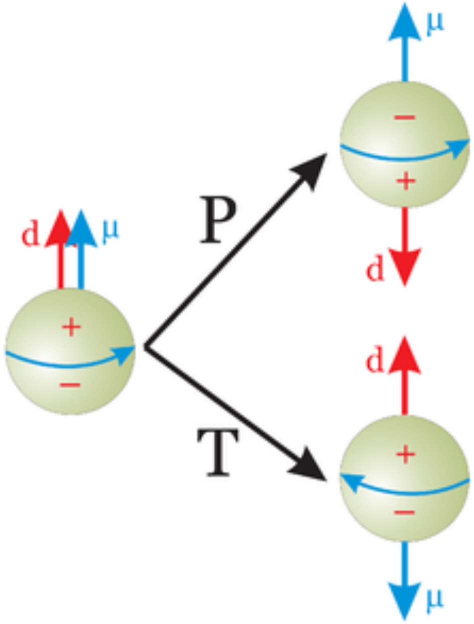

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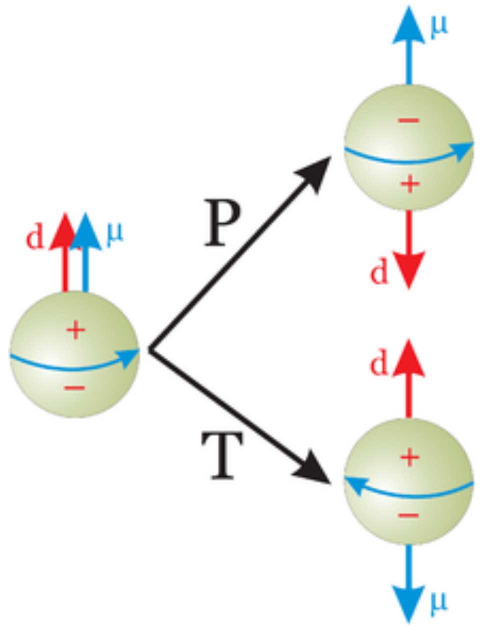
$$d_n \sim \frac{1}{m_n^2}\frac{m_u m_d}{m_u + m_d}\,\theta\, e \sim 6\times 10^{-17}\ \theta\ e\,\mathrm{cm}$$



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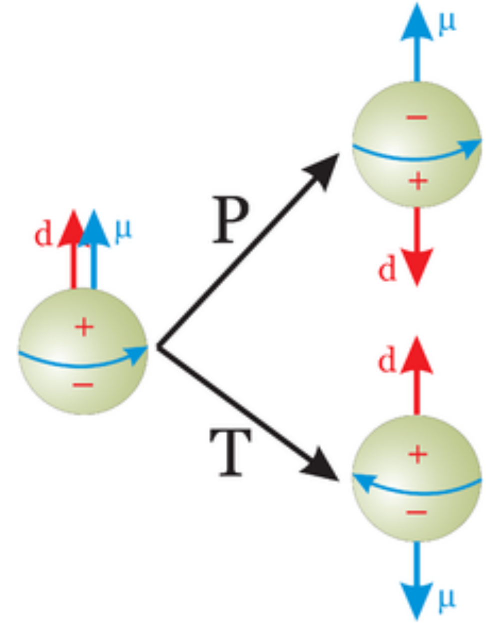

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- Experiment: [Baker et al. 06]

$$|d_n| < 2.9\times 10^{-26}\ e\,{\rm cm} \Rightarrow |\theta| < 10^{-9}$$

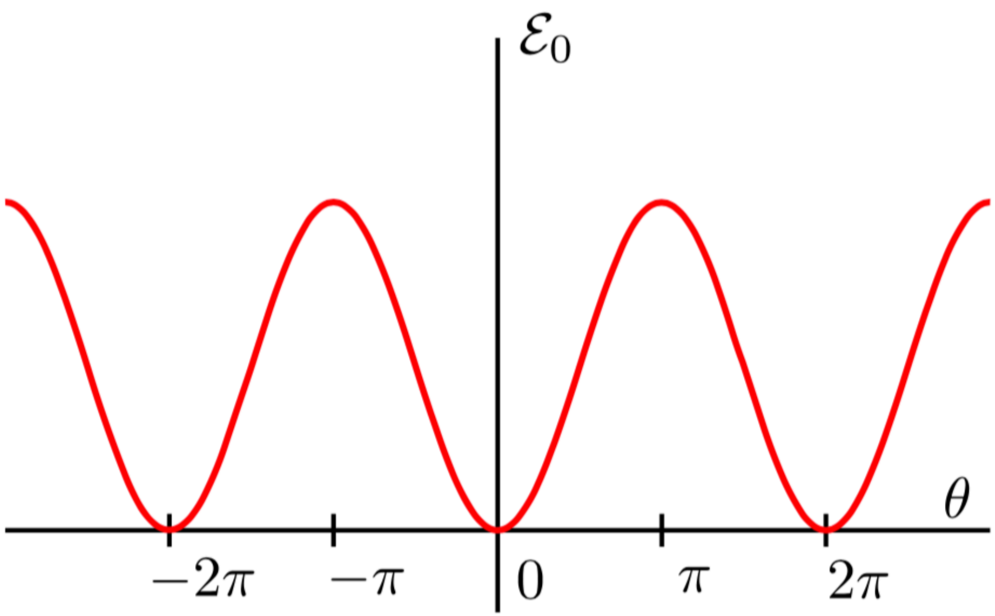
Axionic Solution of Strong CP Problem

- Peccei-Quinn (PQ) solution of strong CP problem based on observation that the vacuum energy in QCD has localised minimum at $\theta = 0$:

$$\epsilon_0(\theta) \simeq \Sigma(m_u + m_d)\left(1 - \frac{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos\theta}}{m_u + m_d}\right)$$

[Di Vecchia,Veneziano `80; Leutwyler,Smilga 92]

$$\Sigma = -\langle \bar{u}u \rangle = -\langle \bar{d}d \rangle$$



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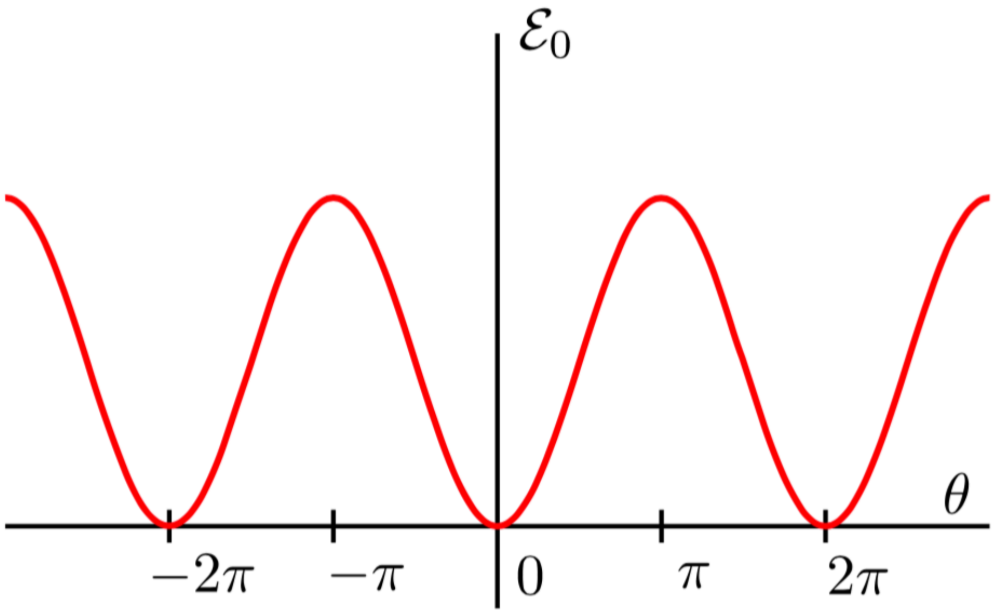
- If θ were a dynamical field, its vev would be zero



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- Add to SM angular field $\theta_A(x) \equiv A(x)/f_A$, respecting a shift symmetry $\theta_A(x) \to \theta_A(x) + \text{const.}$, broken only by coupling to topological density,

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\left[\theta + \theta_A(x)\right] G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}$$

  - Can eliminate θ by shift $\theta_A(x) \to \theta_A(x) - \theta$; effective potential $V(\theta_A) \equiv \epsilon_0(\theta_A)$ predicts vanishing vev, $\langle\theta_A(x)\rangle = 0$, i.e. P, T, and CP conserved [Peccei,Quinn 77]
  - Particle excitation of A: Nambu-Goldstone boson "axion" [Weinberg 78; Wilczek 78]
  - Mass

$$m_A \simeq \frac{\sqrt{\Sigma}}{f_A}\sqrt{\frac{m_u m_d}{m_u + m_d}} \simeq \frac{m_\pi f_\pi}{f_A}\frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\ \text{meV}\left(\frac{10^9\ \text{GeV}}{f_A}\right)$$

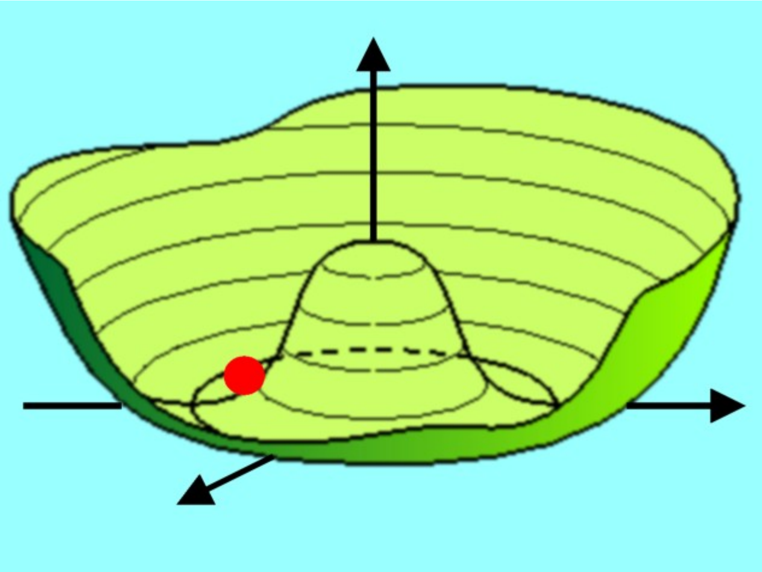
  and strength of its interactions with SM controlled by decay constant f_A

Renormalizable UV Completion of SM Predicting Axion

- A singlet complex scalar field σ featuring a global $U(1)_{\rm PQ}$ symmetry is added to SM
- Symmetry is broken by vev $\langle\sigma\rangle = v_{\rm PQ}/\sqrt{2}$

$$\sigma(x) = \frac{1}{2}\left(v_{\rm PQ} + \rho(x)\right) {\rm e}^{{\rm i}A(x)/v_{\rm PQ}}$$

  - Excitation of modulus: $m_\rho \sim v_{\rm PQ}$
  - Excitation of angle: NGB $m_A = 0$



[Raffelt]

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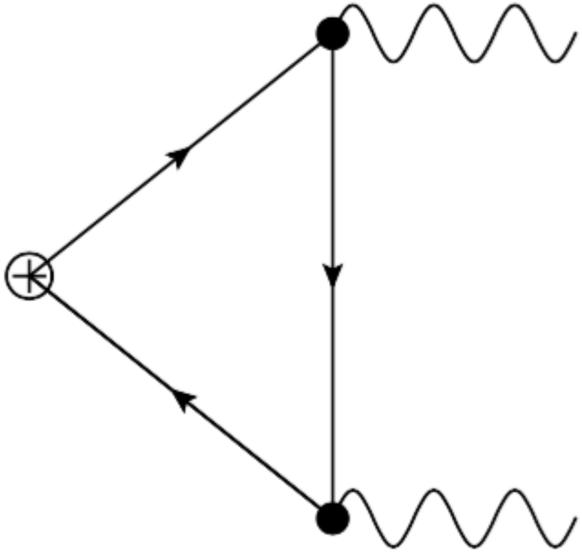
- Quarks (SM or extra) carry PQ charges such that $U(1)_{\rm PQ}$ is anomalously broken due to gluonic triangle anomaly

$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} = -\frac{\alpha_s}{8\pi}\, N\, G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} - \frac{\alpha}{8\pi}\, E\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$



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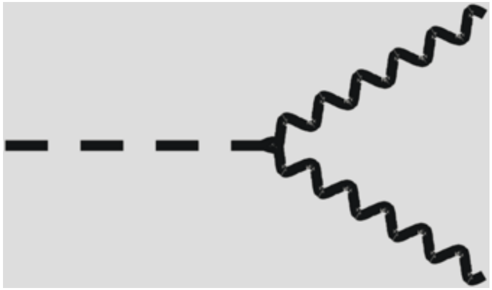

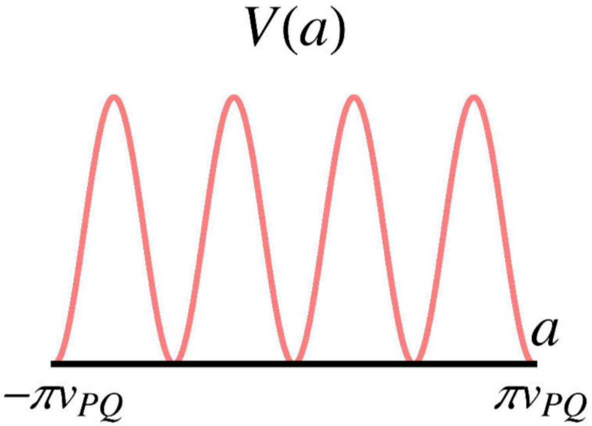

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- Low energy effective field theory at energies below v ($\ll v_{\rm PQ}$), but above $\Lambda_{\rm QCD}$: [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{A(x)}{f_A} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} - \frac{\alpha}{8\pi}\frac{E}{N}\frac{A(x)}{f_A} F_{\mu\nu}\tilde{F}^{\mu\nu}; \qquad f_A = v_{\rm PQ}/N$$

Axion Couplings to SM at Energies Below QCD Scale

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu A \partial^\mu A - \frac{1}{2} m_A^2 A^2 - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A} A\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{Af}}{f_A}\partial_\mu A\, \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

- Axion mass: $m_A = 57.0(7)\left(\frac{10^{11}\,\mathrm{GeV}}{f_A}\right)\mu\mathrm{eV}$

[Grilli di Cortona et al. `16 ; Borsanyi et al. `16]

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- Couplings of axion to SM suppressed by powers of

$$f_A = v_{\mathrm{PQ}}/N \gg v = 246\,\mathrm{GeV}$$

rendering the axion „invisible“ [Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]

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- Photon coupling: $C_{A\gamma} = \frac{E}{N} - 1.92(4)$ [Kaplan 85;Srednicki `85]
- Nucleon couplings: [Grilli di Cortona et al. `16]

$$C_{Ap} = -0.47(3) + 0.88(3)C_{Au} - 0.39(2)C_{Ad} - 0.038(5)C_{As} - 0.012(5)C_{Ac} - 0.009(2)C_{Ab} - 0.0035(4)C_{At}\,,$$

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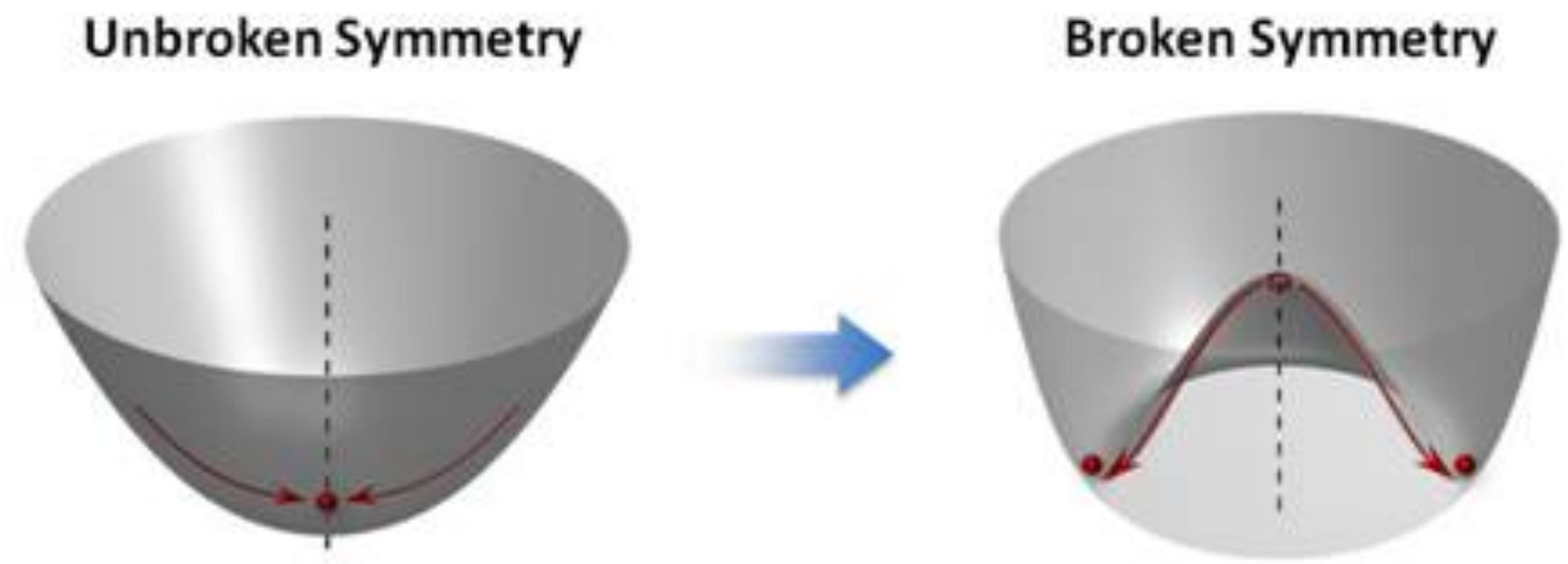
- Electron coupling very model-dependent

Axion Cold Dark Matter

- Axion field is born after PQ symmetry breaking, $T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N f_A$



[Peking University]

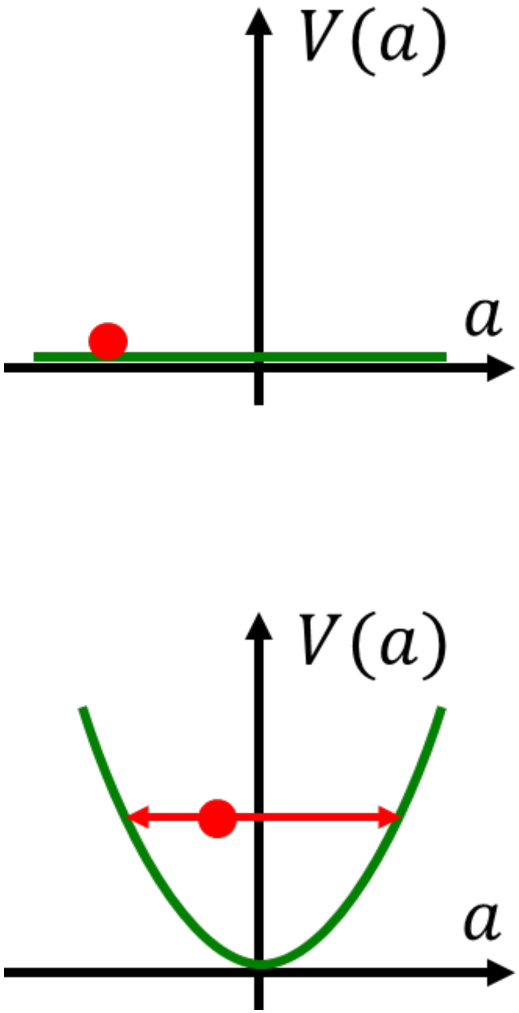
Axion Cold Dark Matter

> DM from vacuum realignment:

[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

- In causally connected region at phase transition, axion takes random initial value and is frozen at this value
- Later when $H(T) \sim m_A(T)$, axion field starts to oscillate around zero; behaves like cold dark matter:

$$w_A = p_A/\rho_A \simeq 0$$



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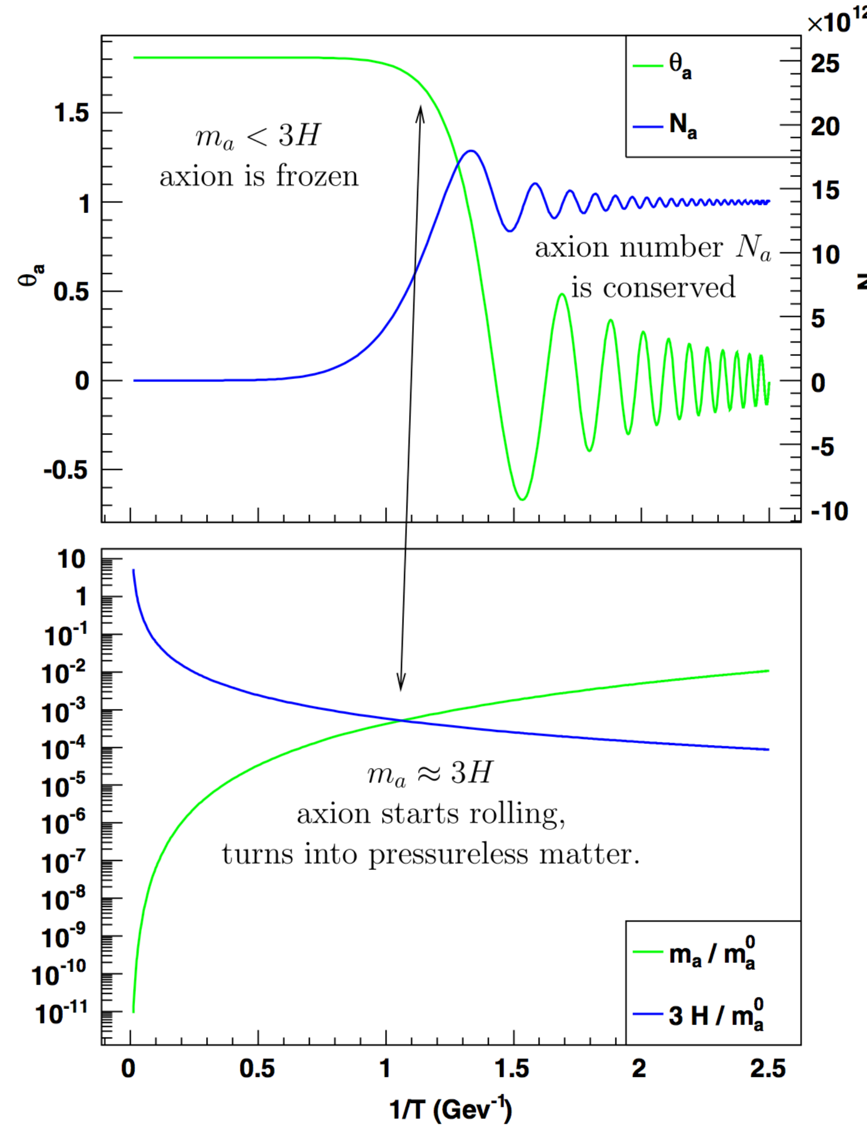

[Wantz,Shellard `09]

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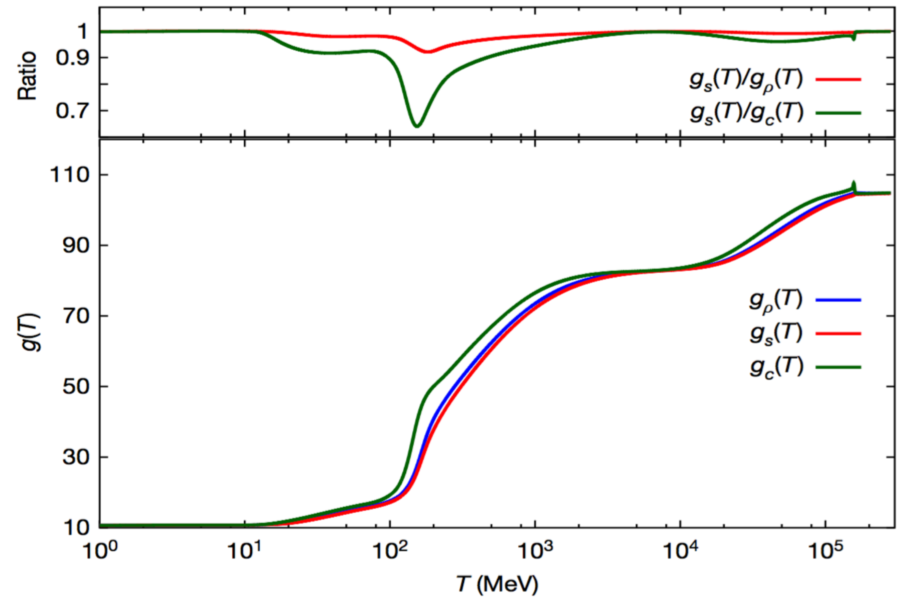
- Crucial lattice QCD input for prediction of axion DM abundance:
  - Equation of state at temperatures around 1 GeV: determines $H(T)$



[Borsanyi et al., Nature `16 [1606.0794]]

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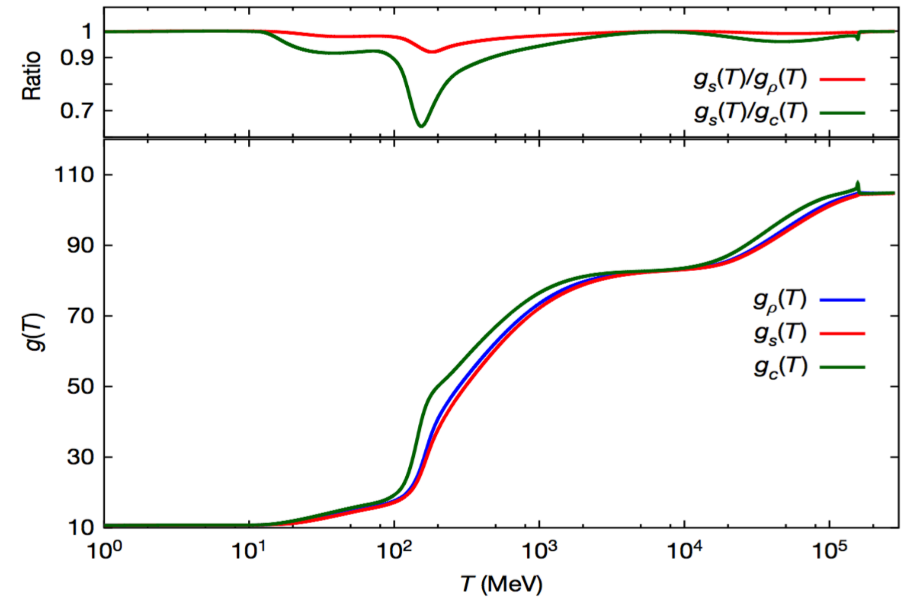


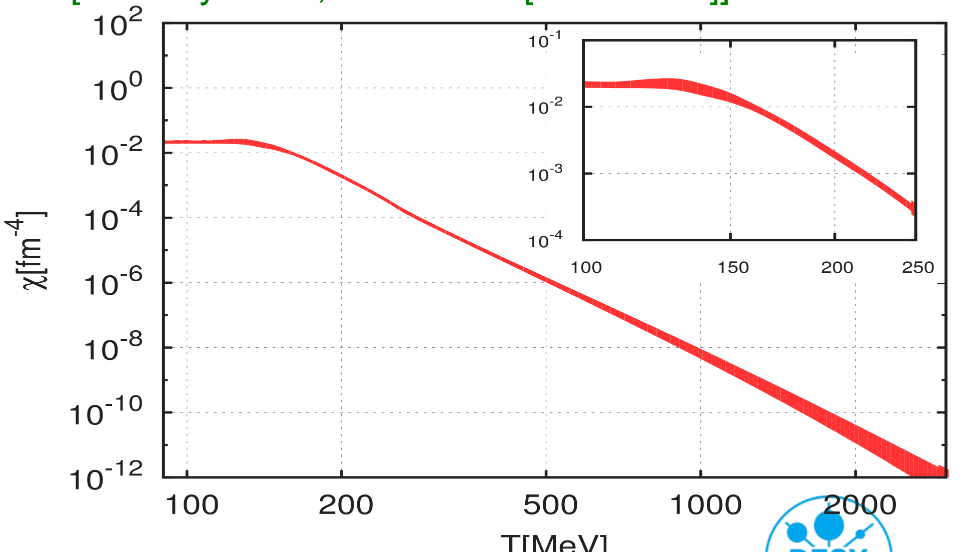
[Borsanyi et al., Nature `16 [1606.0794]]

> Crucial lattice QCD input for prediction of axion DM abundance:

- Equation of state at temperatures around 1 GeV: determines $H(T)$
- Topological susceptibility:

$$\chi(T) \equiv \int d^4x \langle q(x)q(0)\rangle_T$$

determines $m_A^2(T) = \chi(T)/f_A^2$

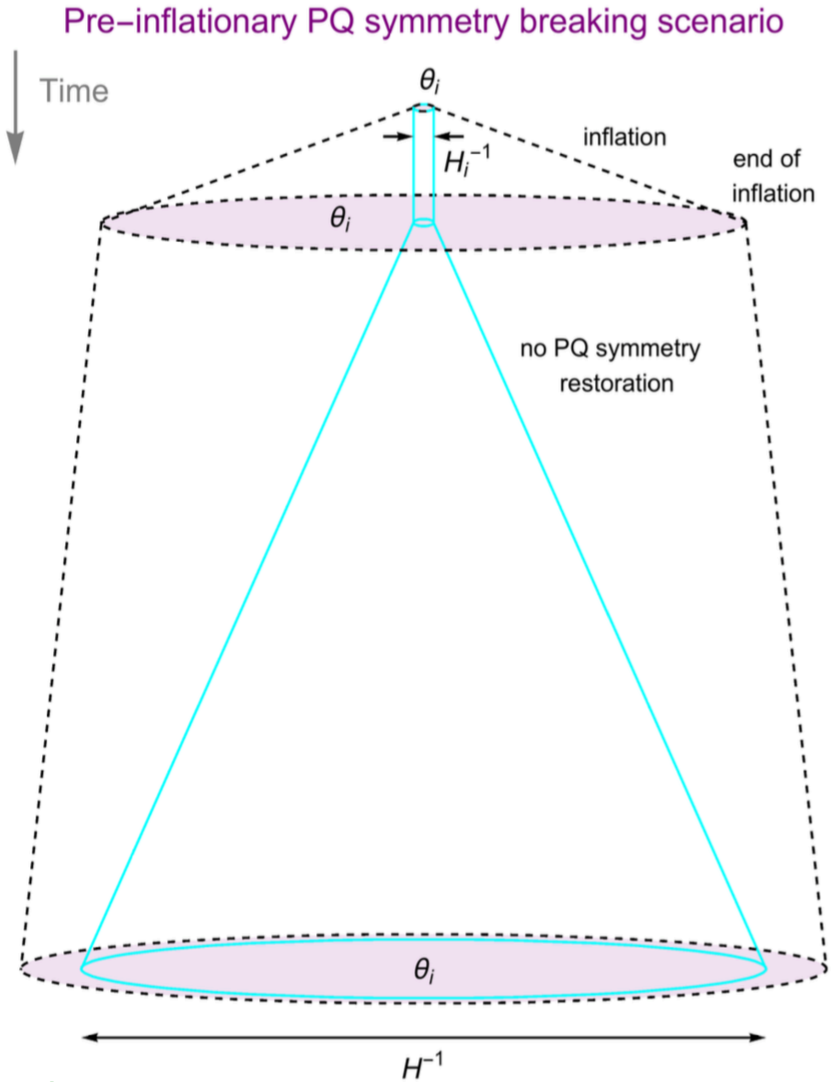


Axion Cold Dark Matter

- If PQ symmetry broken before or during inflation and not restored afterwards (pre-inflationary PQ breaking scenario)

[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

  - Random initial axion value in patch which becomes observable universe



[Saikawa]

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  - Random initial axion value in patch which becomes observable universe
  - Axion CDM density depends on single initial angle and f_A

$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{f_A}{9 \times 10^{11}\ {\rm GeV}} \right)^{1.165} \theta_{\rm i}^2$$

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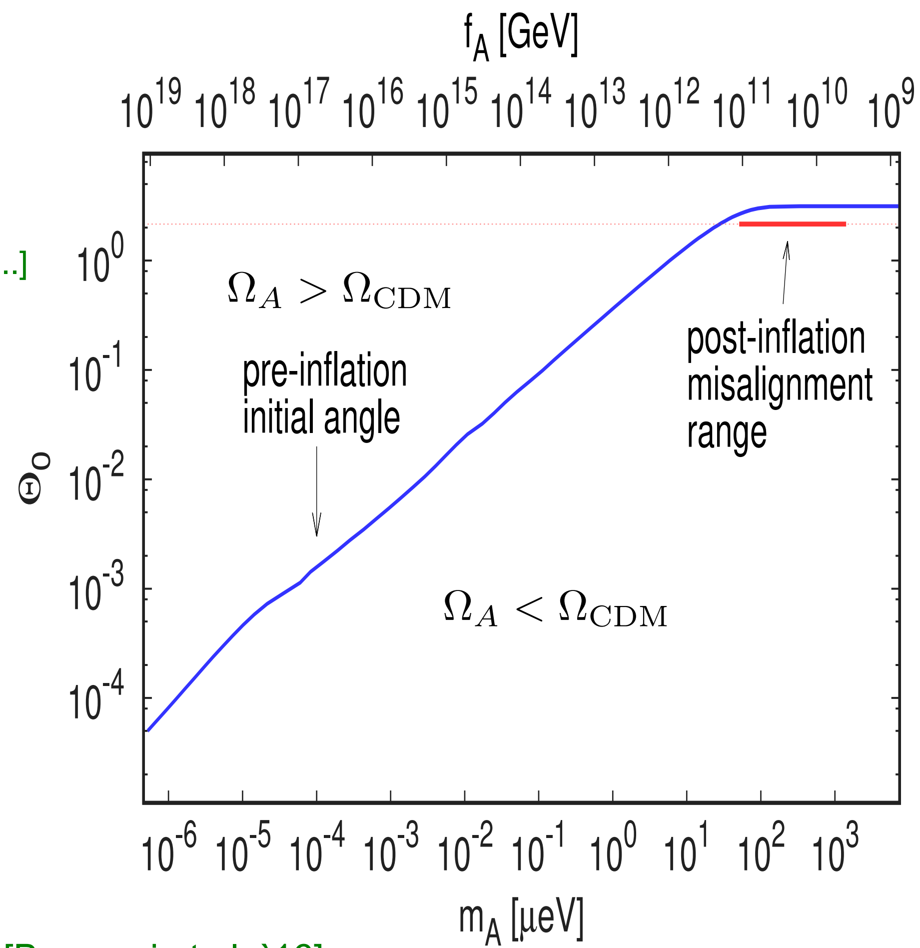
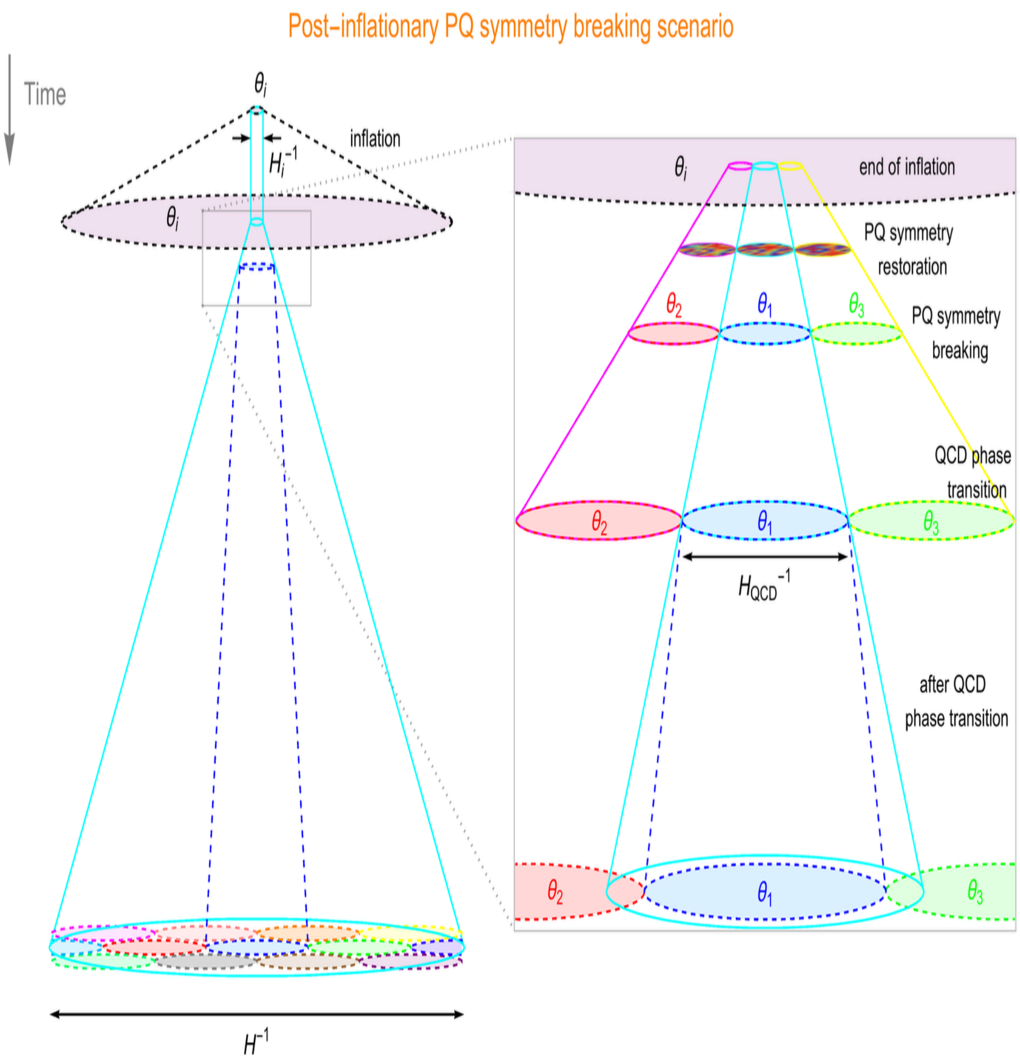


[Borsanyi et al. `16]

Axion Cold Dark Matter

- If Peccei-Quinn symmetry restored after inflation (post-inflationary PQ breaking scenario)
  - Initial axion values at points of post-inflationary causal contact are random; naive average:

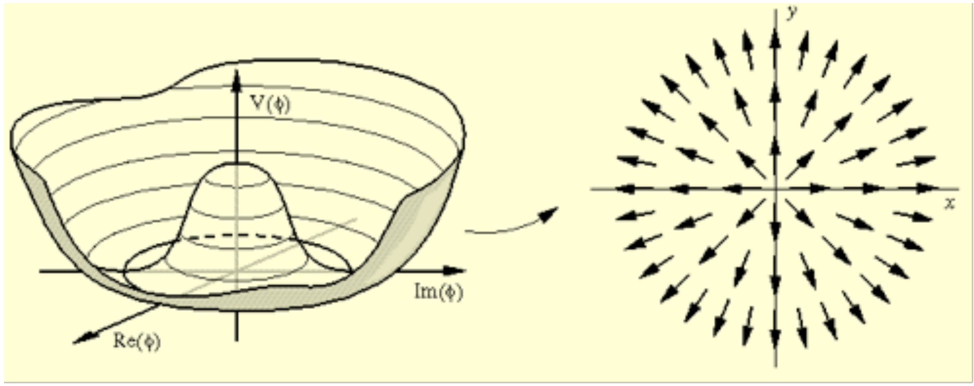
$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{30\ \mu\text{eV}}{m_A}\right)^{1.165}$$



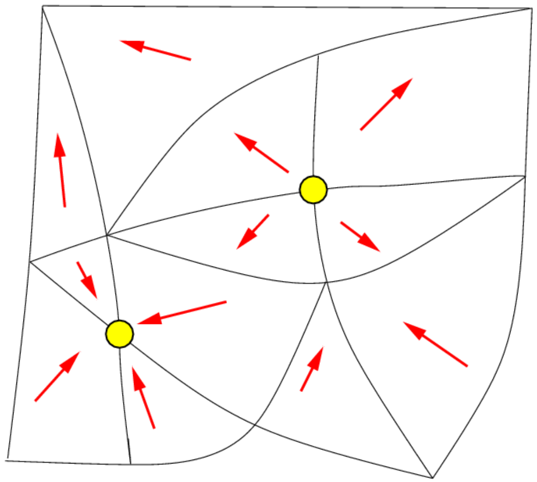
[Saikawa]

Axion Cold Dark Matter

- If Peccei-Quinn symmetry re-stored after inflation (post-in-flationary PQ breaking scena-rio)
  - Initial axion values at points of post-inflationary causal contact are random
  - At PQ phase transition, network of axionic cosmic strings created by Kibble mechanism



[ctc.cam.ac.uk]



[Uhlmann et al. `10]

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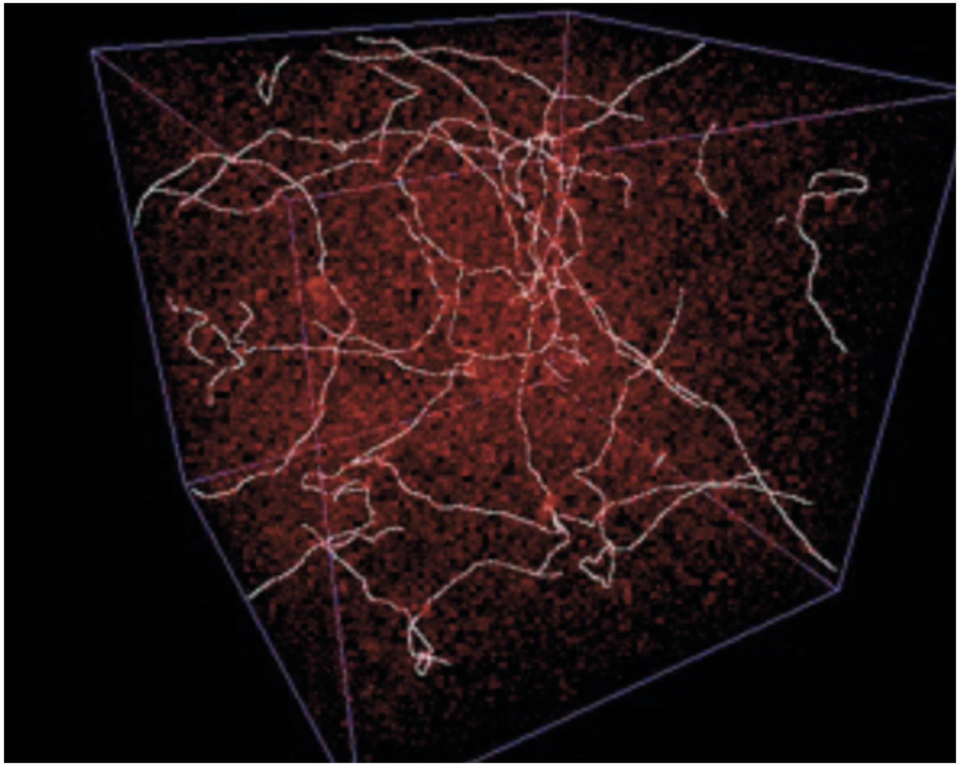

[Hiramatsu et al.]

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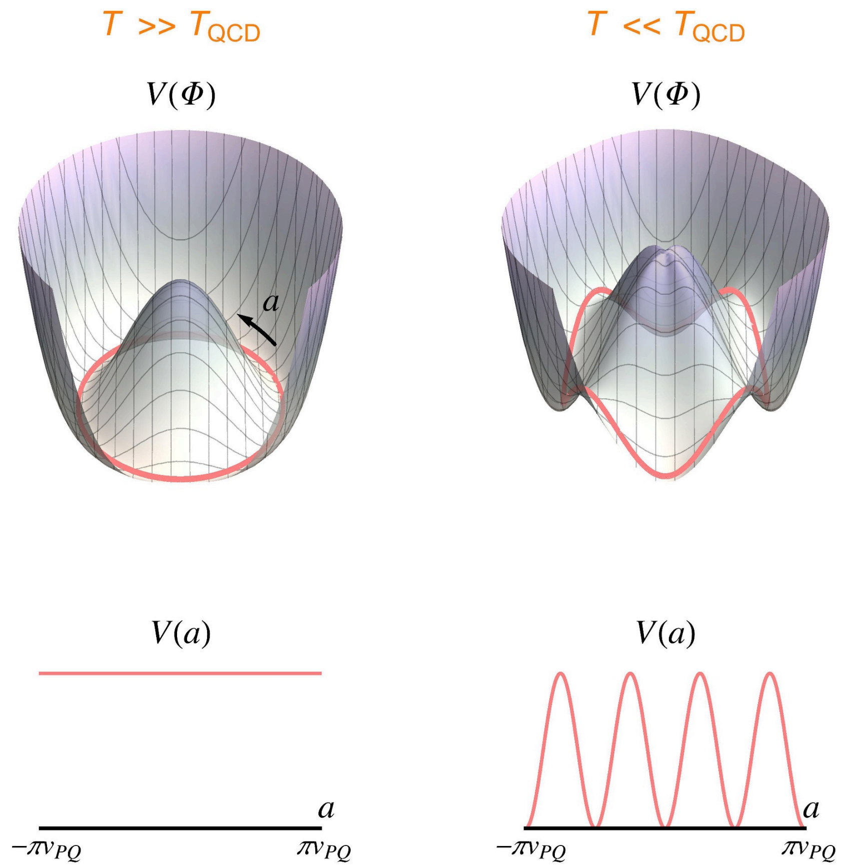
  - Initial axion values at points of post-inflationary causal contact are random
  - At PQ phase transition, network of axionic cosmic strings created by Kibble mechanism
  - Around QCD phase transition, axion potential develops,

$$V(A,T) = \chi(T)\left[1-\cos\left(N\frac{A}{v_{\rm PQ}}\right)\right]$$



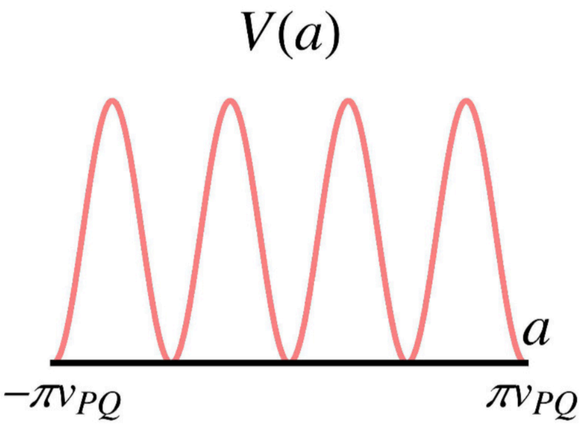
[Saikawa]

Axion Cold Dark Matter

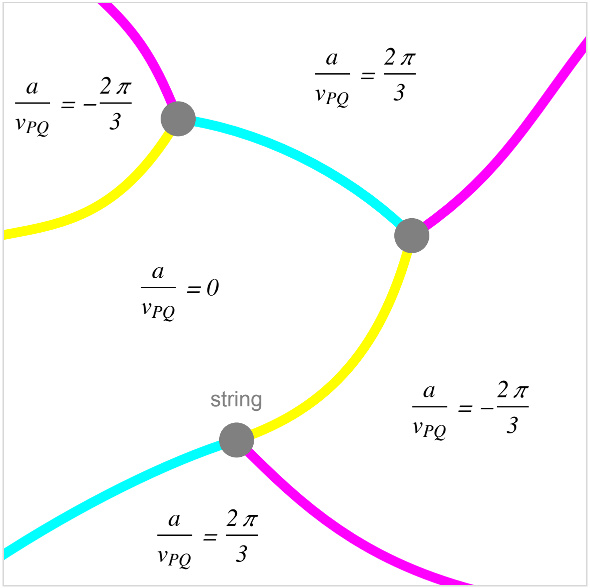
- If Peccei-Quinn symmetry restored after inflation (post-inflationary PQ breaking scenario)
  - Initial axion values at points of post-inflationary causal contact are random
  - At PQ phase transition, network of axionic cosmic strings created by Kibble mechanism
  - Around QCD phase transition, axion potential develops,

$$V(A,T) = \chi(T)\left[1 - \cos\left(N\frac{A}{v_{\rm PQ}}\right)\right]$$

N domain walls end at string



[Saikawa]



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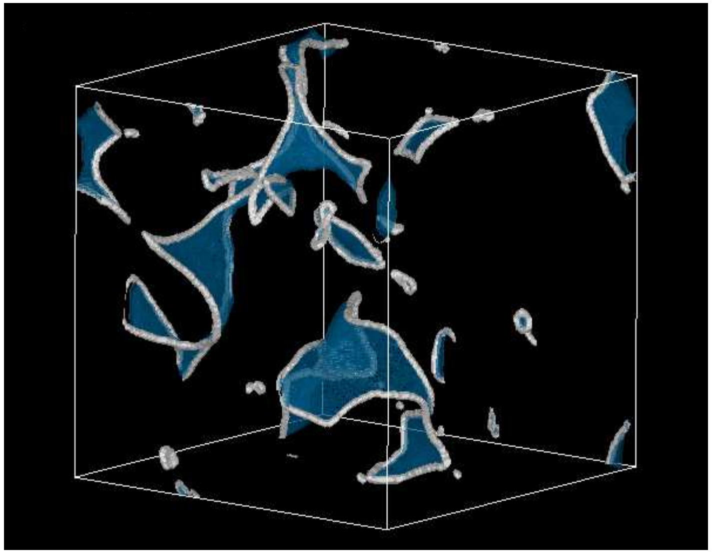
$N=1$



[Hiramatsu et al.]

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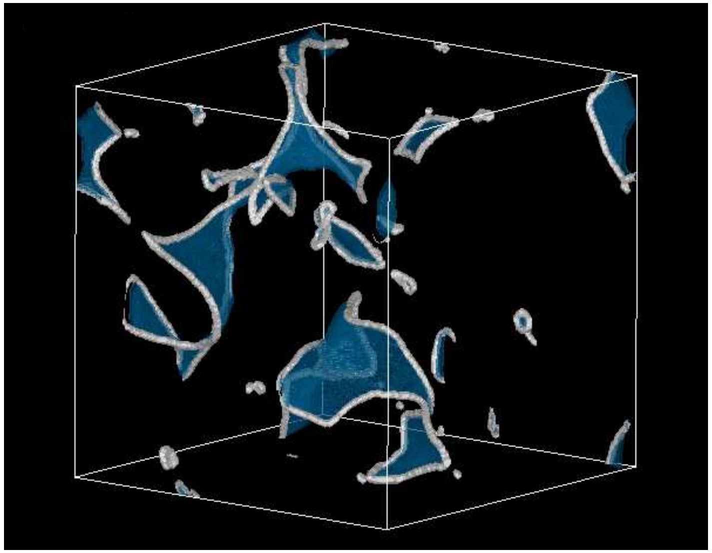
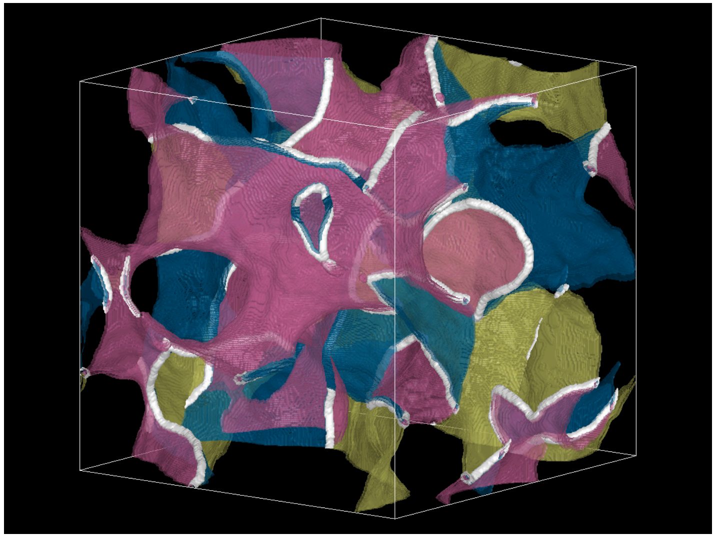
  N domain walls end at string

  - $N = 1$: String-wall system decays
  - $N > 1$: Domain wall problem

$N = 1$



$N = 3$



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Axion Cold Dark Matter

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  - For $N = 1$, exploiting results from field theoretic lattice simulations, updated to latest determination of topological susceptibility, find CDM explained for

$$m_A \approx (30\text{–}200)\ \mu\text{eV}$$

[Hiramatsu et al. 11,12,13;
Kawasaki,Saikawa,Segikuchi 15;
Borsanyi et al. 16;
Ballesteros et al. 16]

Large uncertainty due to extrapolation of string tension to physical value

  - New method allows to simulate directly at physical string tension, resulting in

$$m_A = (26.2 \pm 3.4)\ \mu\text{eV}$$

[Klaer,Moore `17]

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[Klaer,Moore `17]

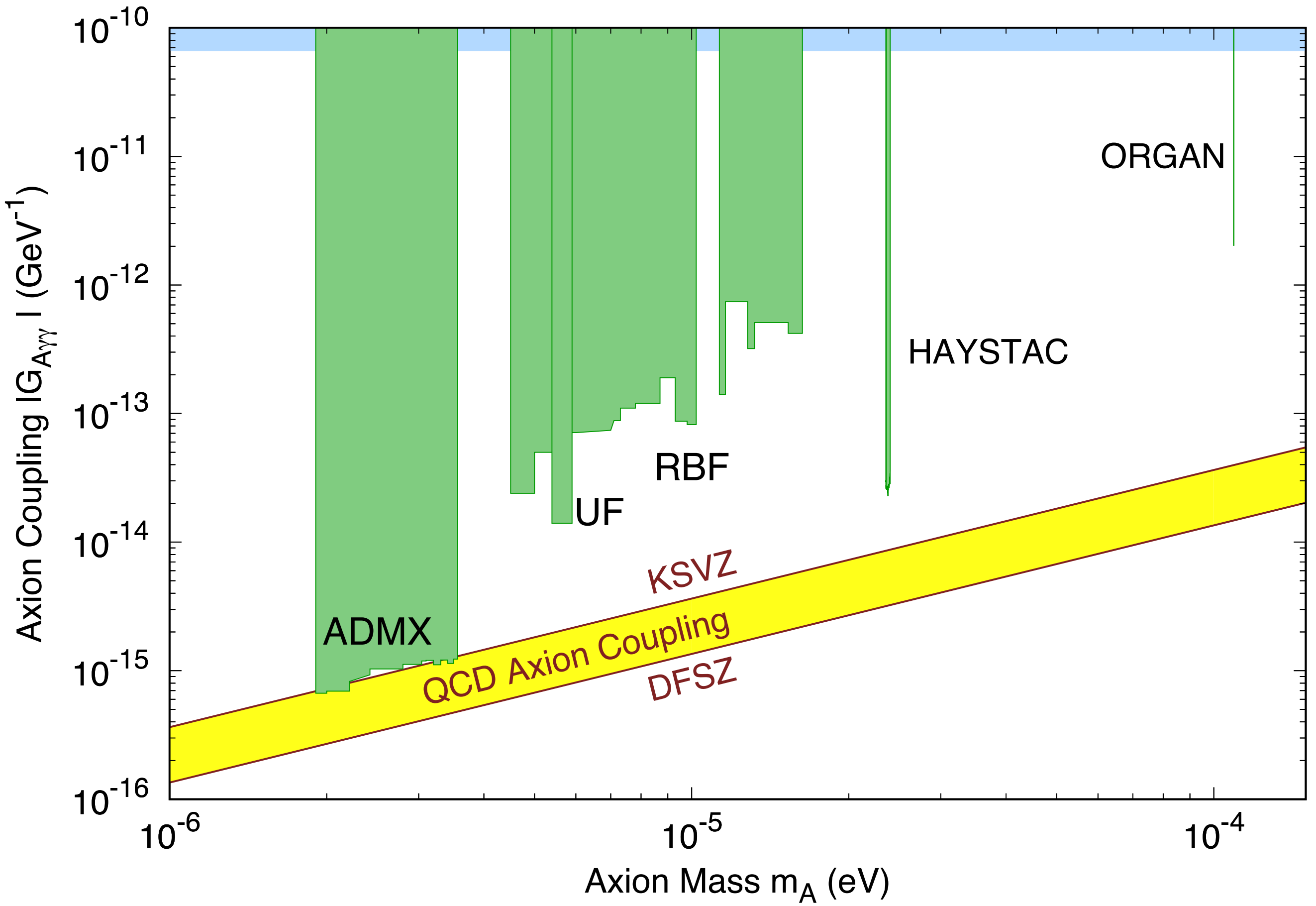
- For $N > 1$, domain wall problem can be avoided if PQ symmetry explicitely broken, e.g. by Planck suppressed operators, $\mathcal{L} \supset g M_{\rm P}^4 \left(\sigma/M_{\rm P}\right)^{\mathcal{N}} + \text{h.c.}$, for $\mathcal{N} = 9, 10$,

$$0.2\,\text{meV} \lesssim m_A \lesssim 50\,\text{meV}$$

[AR,Saikawa `16; Giannotti et al `17]

Axion Dark Matter Direct Detection Experiments

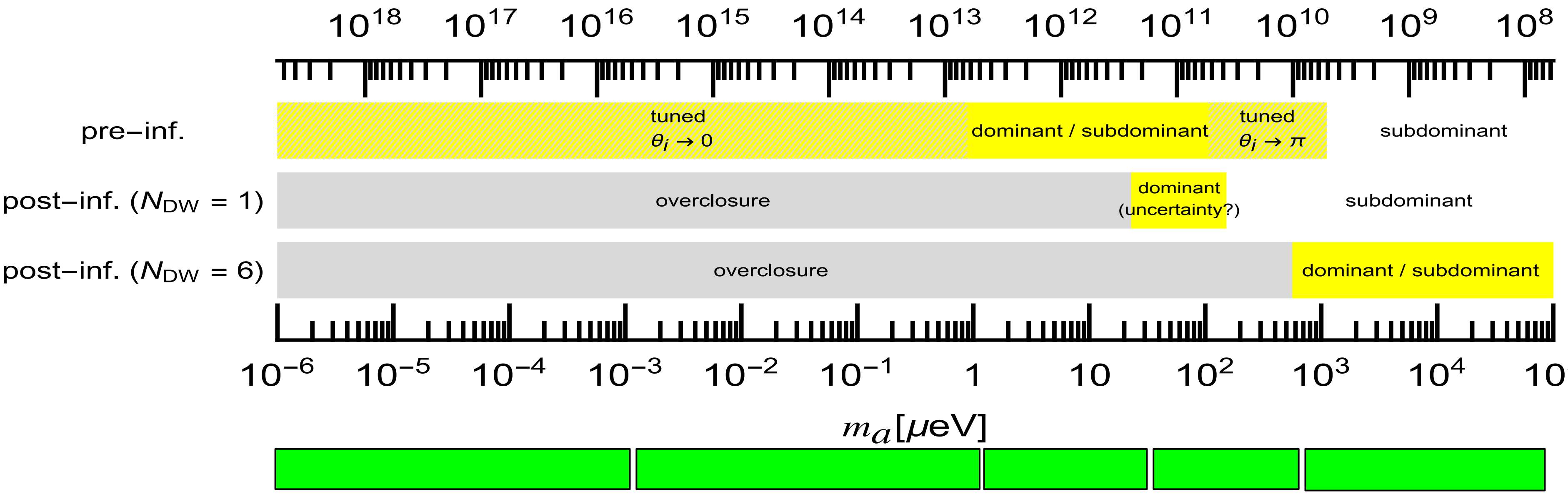
- Current bounds from axion dark matter experiments:



[AR,Rosenberg,Rybka (PDG RPP) `17]

Axion Dark Matter Direct Detection Experiments

- Upcoming generation of axion dark matter direct detection experiments can probe entire mass range: f_a[GeV]



CASPEr

ABRACADABRA

KLASH

ADMX

HAYSTAC

CAST-CAPP

CULTASK

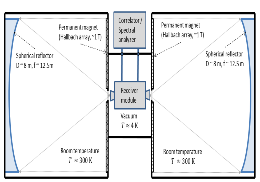
MADMAX

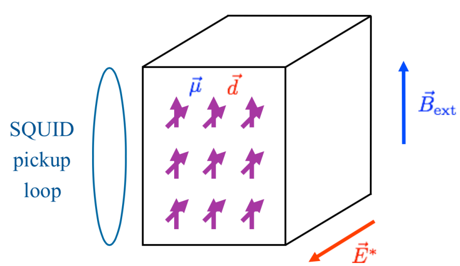
ORPHEUS

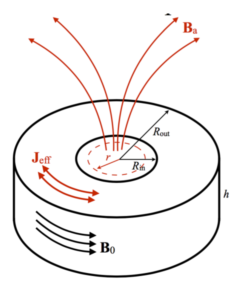
ORGAN

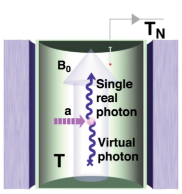
QUAX

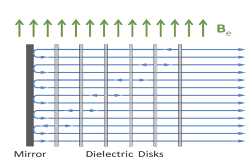
BRASS





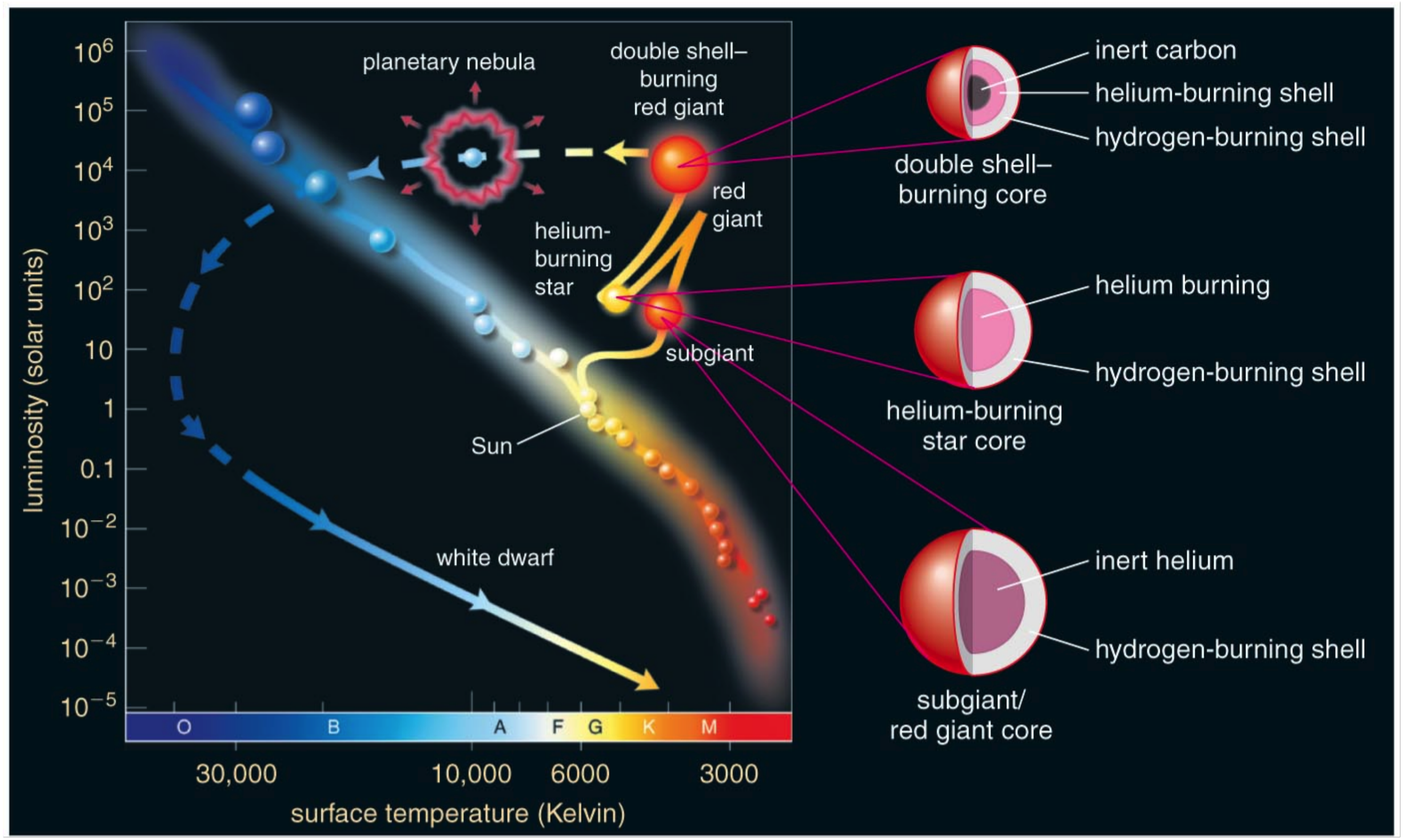






Astro-Hints for the Axion: Energy Losses of Stars?

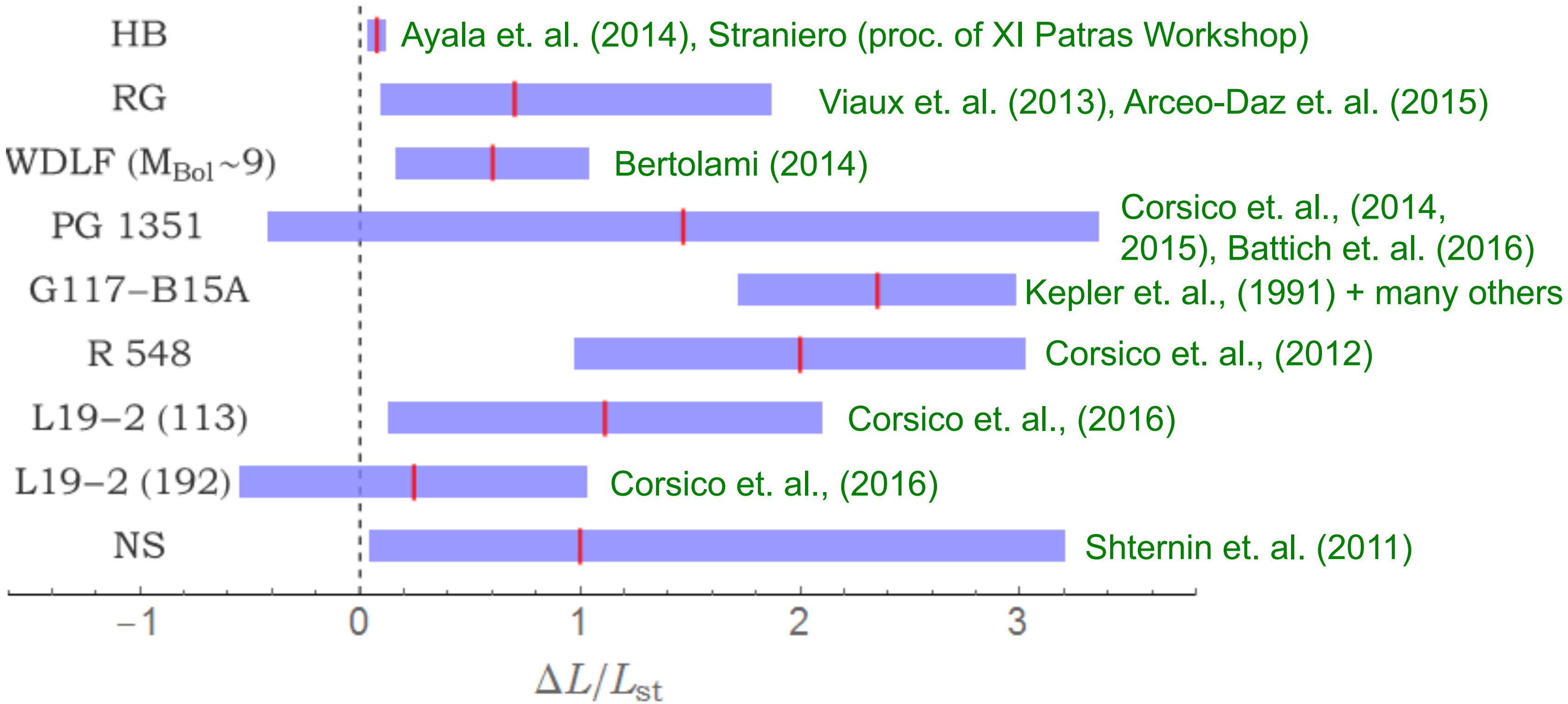
- Evolution of stars (Main Sequence – Red-Giant (RG) – Helium Burning (HB) – White Dwarf (WD)) sensitive to additional energy losses



[Copyright Addison Wesley]

Astro-Hints for the Axion: Energy Losses of Stars?

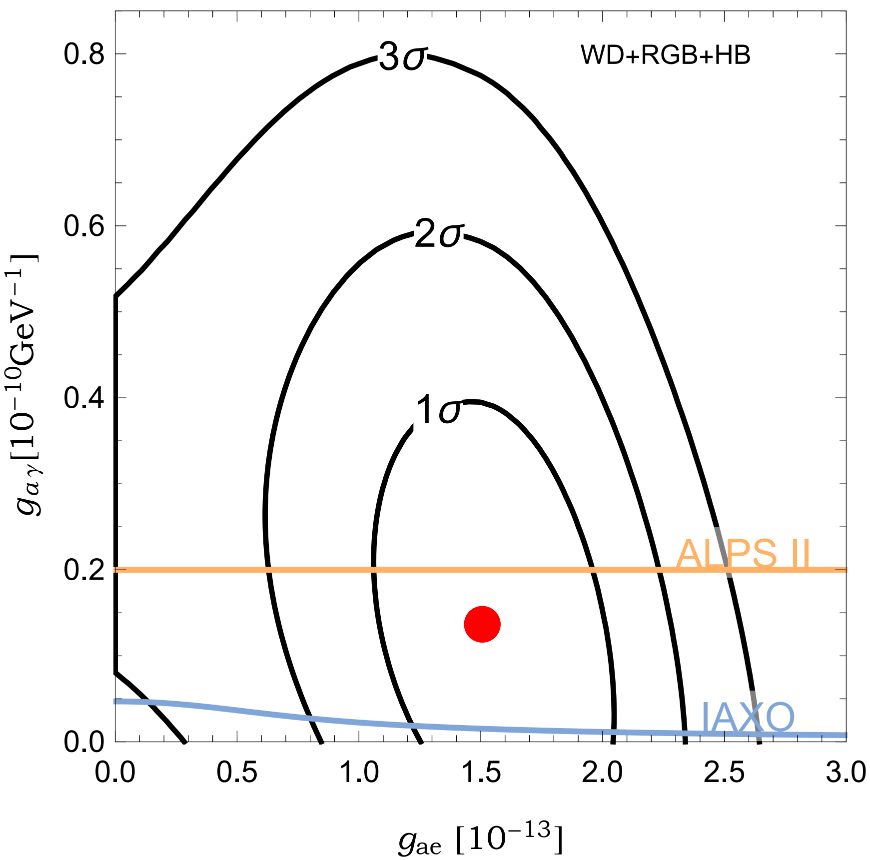
- Practically every stellar systems seems to be cooling faster than predicted by models



[Giannotti, Irastorza, Redondo, AR ‘15; Giannotti, Irastorza, Redondo, AR, Saikawa ‘17]

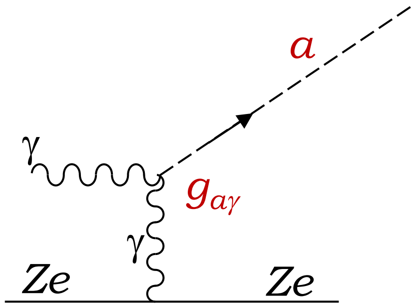
Astro-Hints for the Axion: Energy Losses of Stars?

- Excessive energy losses of HBs, RG, WDs can be explained at one stroke by production of axion/ALP with coupling to photons and electrons:

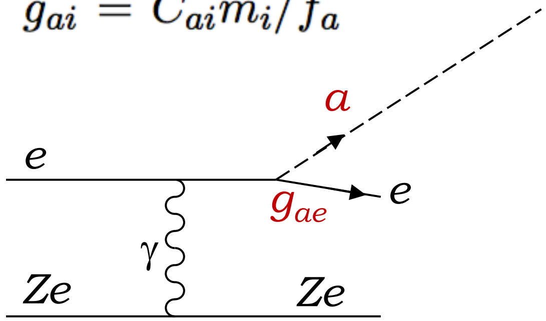


[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

$$g_{a\gamma} = C_{a\gamma}\alpha/(2\pi f_a)$$



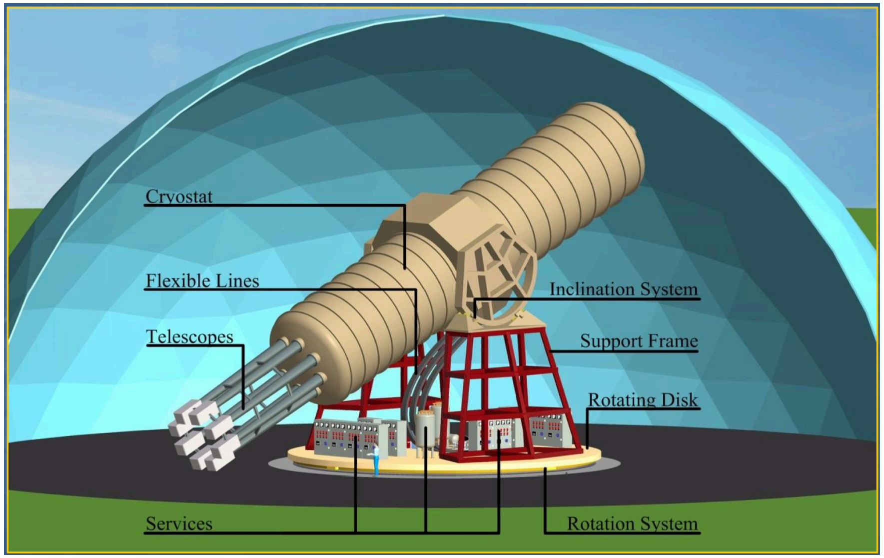
$$g_{ai} = C_{ai} m_i / f_a$$



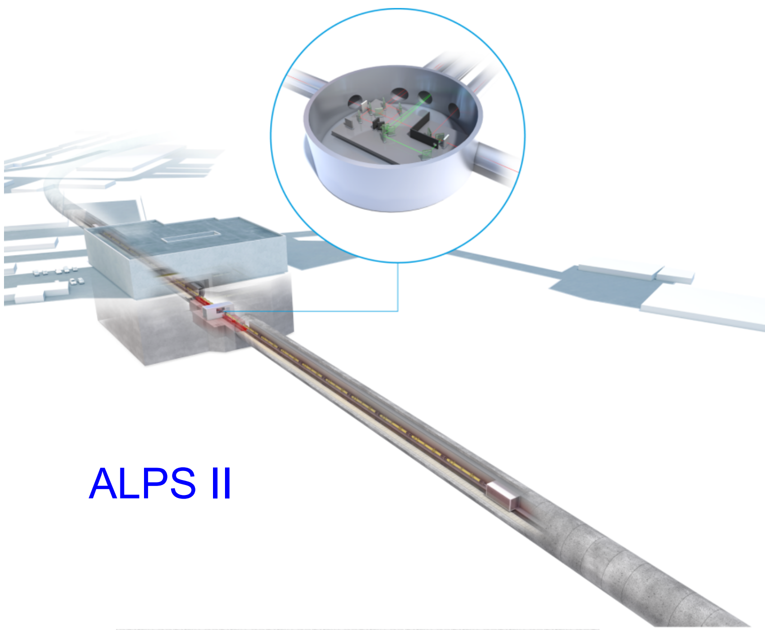
Astro-Hints for the Axion: Energy Losses of Stars?

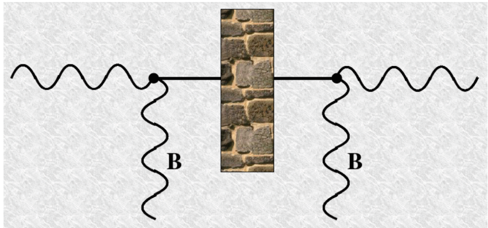
- Excessive energy losses of HBs, RG, WDs can be explained at one stroke by production of axion/ALP with coupling to photons and electrons and probed by next generation experiments:

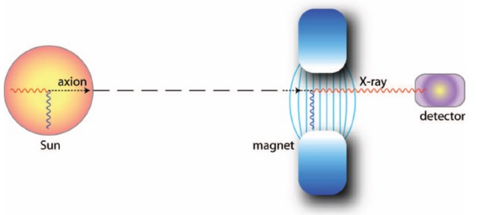
IAXO



ALPS II

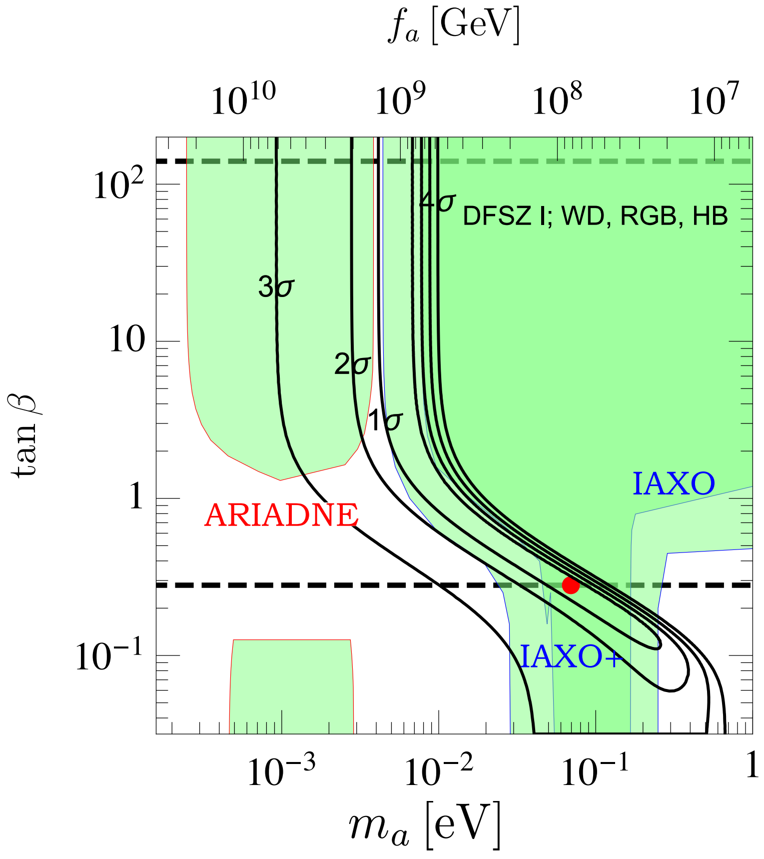






Astro-Hints for the Axion: Energy Losses of Stars?

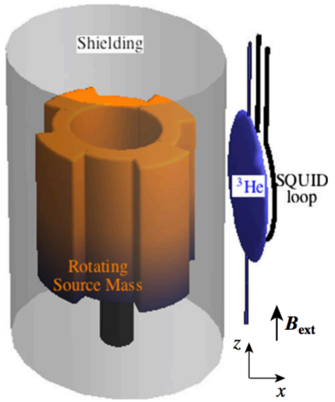
- Excessive energy losses of HBs, RG, WDs can be explained at one stroke by production of axion with coupling to photons and electrons, e.g. for DFSZ axion model:



$$f_a = \frac{v_{PQ}}{6}, \qquad \tan\beta = \frac{v_u}{v_d}$$

$$C_{a\gamma} = \frac{8}{3} - 1.92(4), \qquad C_{ae} = \frac{1}{3}\sin^2\beta$$

ARIADNE



[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

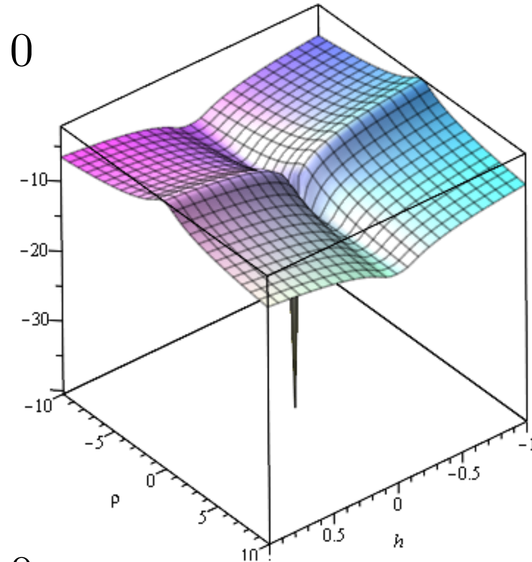
Unifying Inflation and Dark Matter with PQ Field

- $|\,\sigma\,| = \rho/\sqrt{2}$ or mixture with Higgs modulus may play role of inflaton, if it has non-minimal coupling to gravity,

$$S \supset -\int d^4x\sqrt{-g}\;\xi_\sigma\,\sigma^*\sigma R$$

[Fairbairn,Hogan,Marsh `14]

$\lambda_{H\sigma} > 0$



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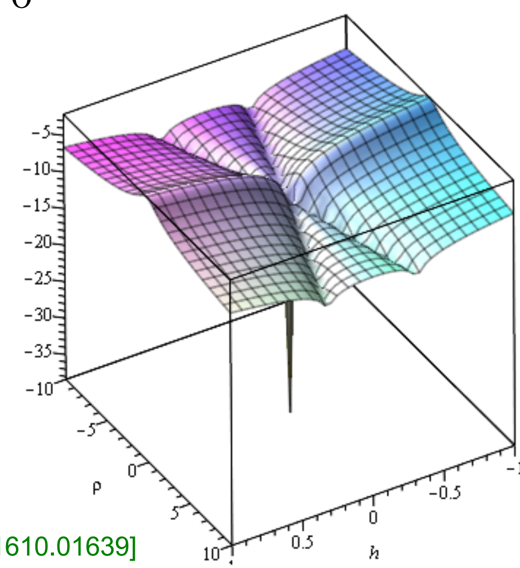

[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

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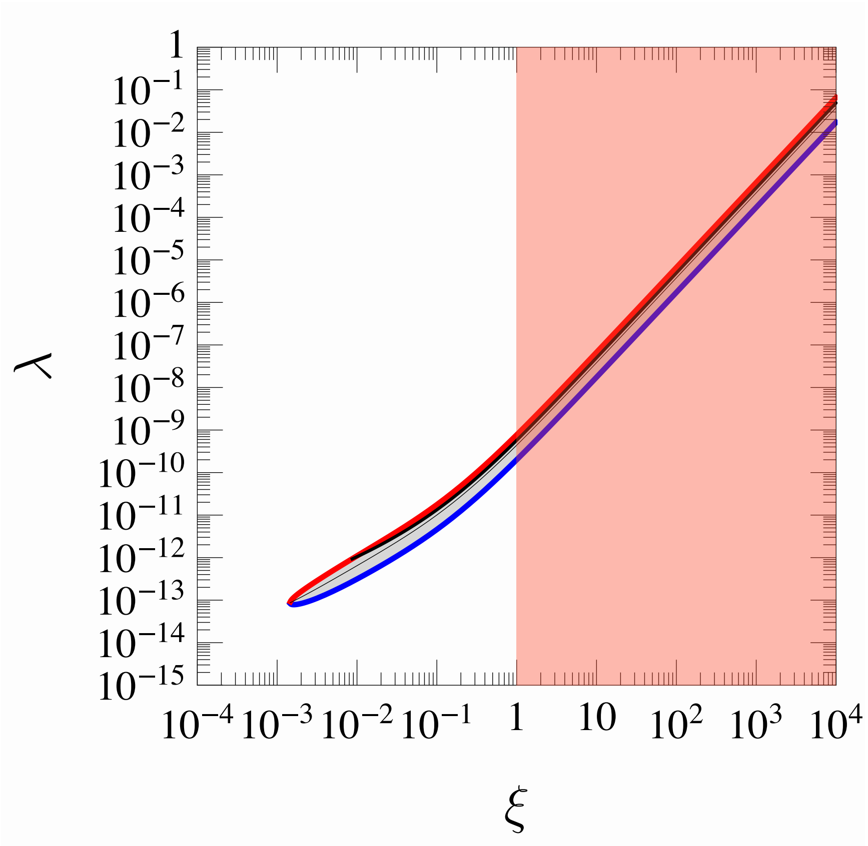
[Fairbairn,Hogan,Marsh `14]

- CMB observables

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

fit by

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



[Ballesteros,Redondo, AR,Tamarit `16]

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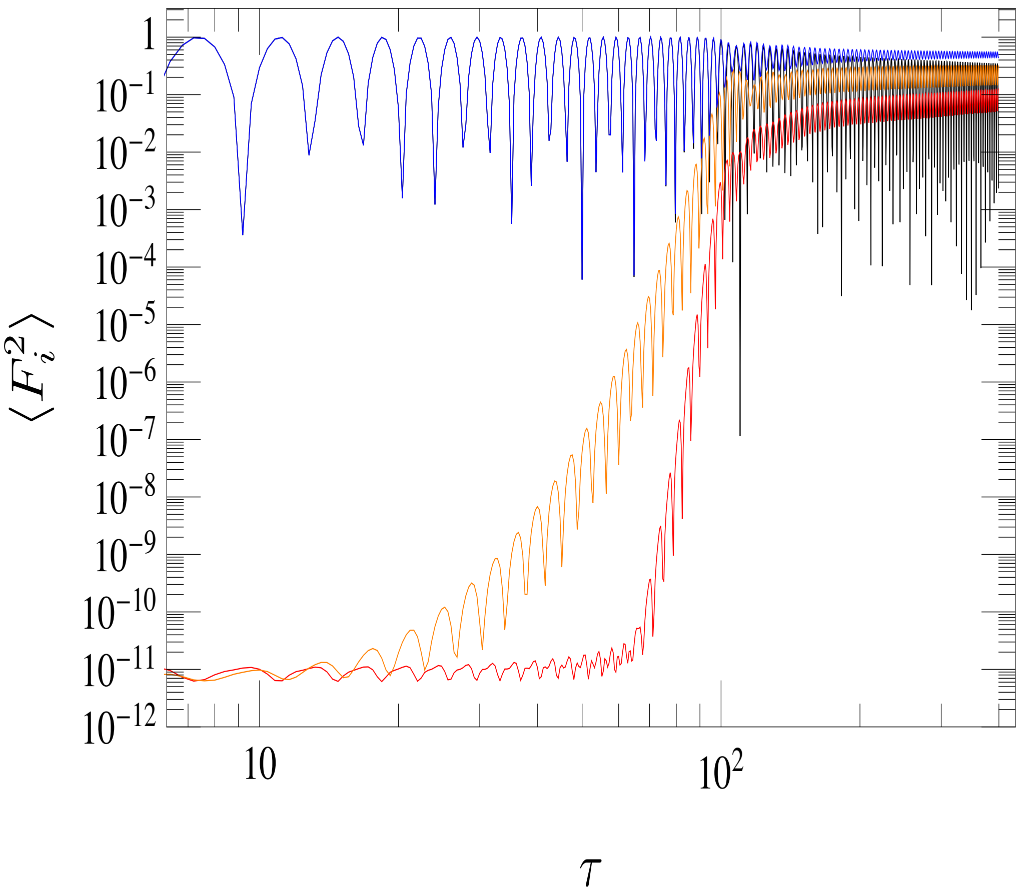
- PQ symmetry restored after inflation already in preheating stage when PQ field undergoes Hubble damped oscillations in quartic potential
- Axion mass in classic window:

$$30\,\mu\mathrm{eV} \lesssim m_A \lesssim 50\,\mathrm{meV}$$



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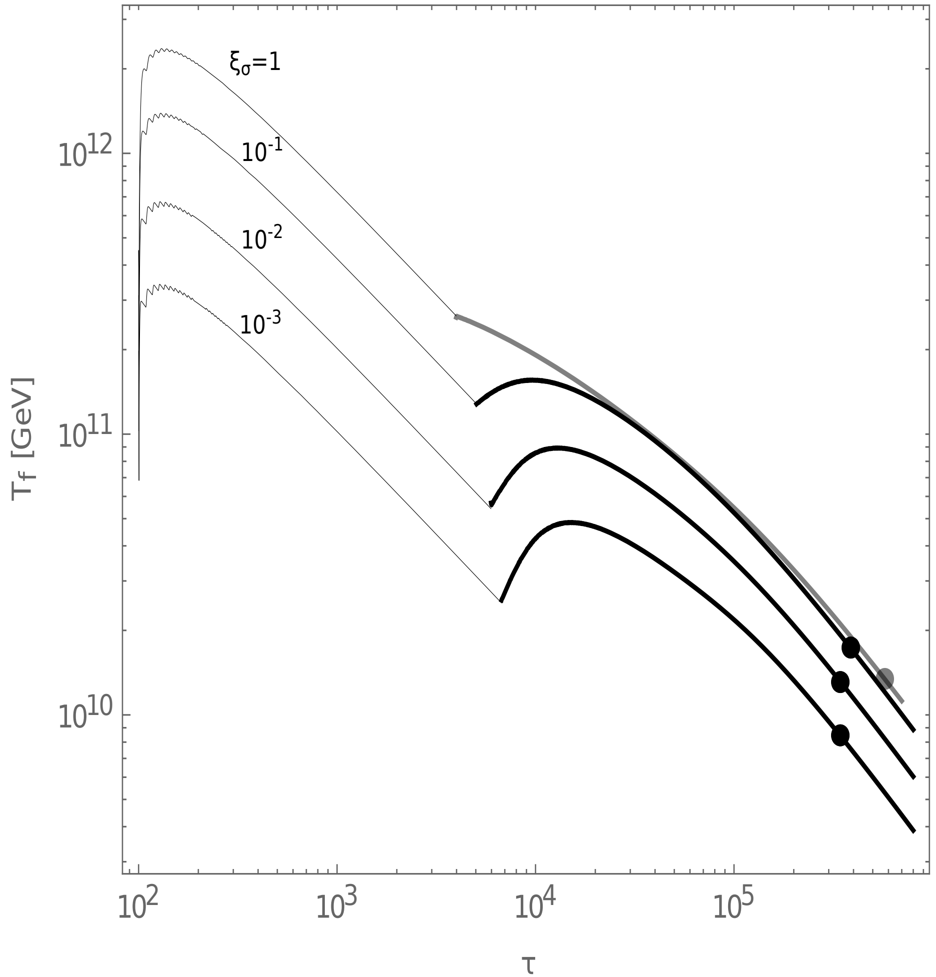
- Large reheating temperature
  - $10^{10}\,\text{GeV}$ for mixed PQ scalar/Higgs inflation $(\lambda_{H\sigma} < 0)$

- Axion dark radiation:

$$\Delta N_\nu^{\text{eff}} \simeq 0.03$$



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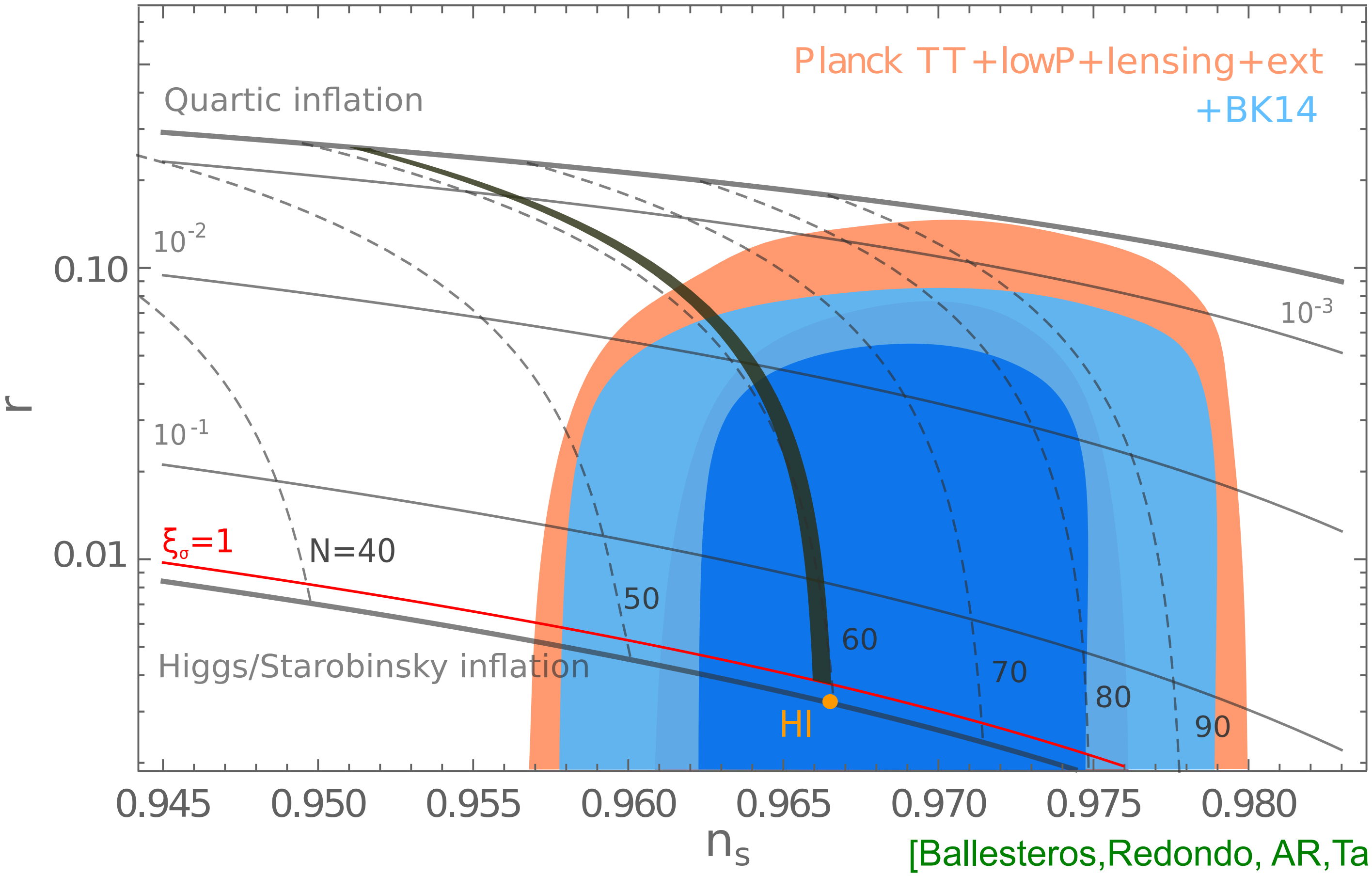
Unifying Inflation and Dark Matter with PQ Field

- Sharp prediction of r vs n_s for fixed pivot scale, e.g. $k_0 = 0.002\ \mathrm{Mpc}^{-1}$



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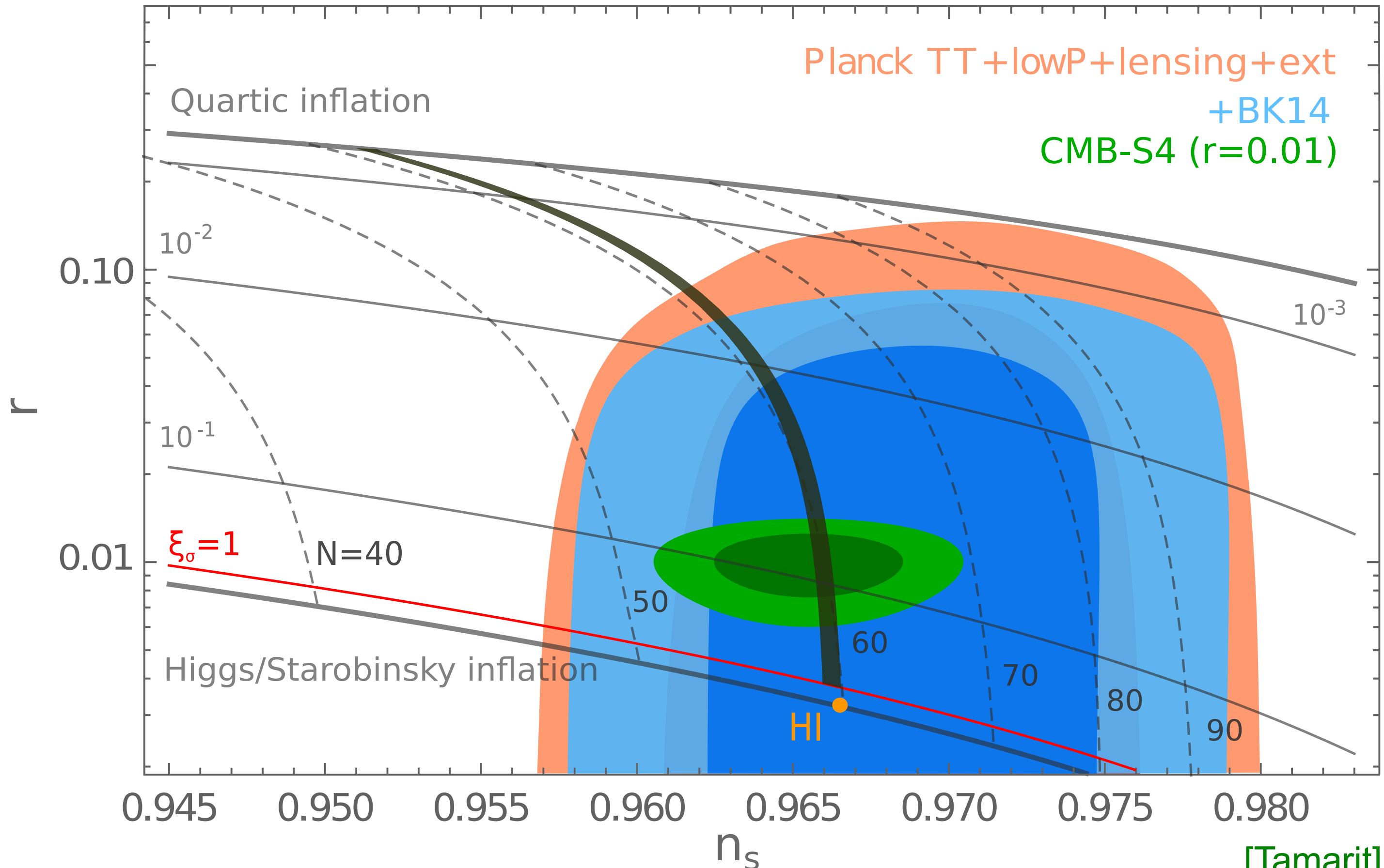


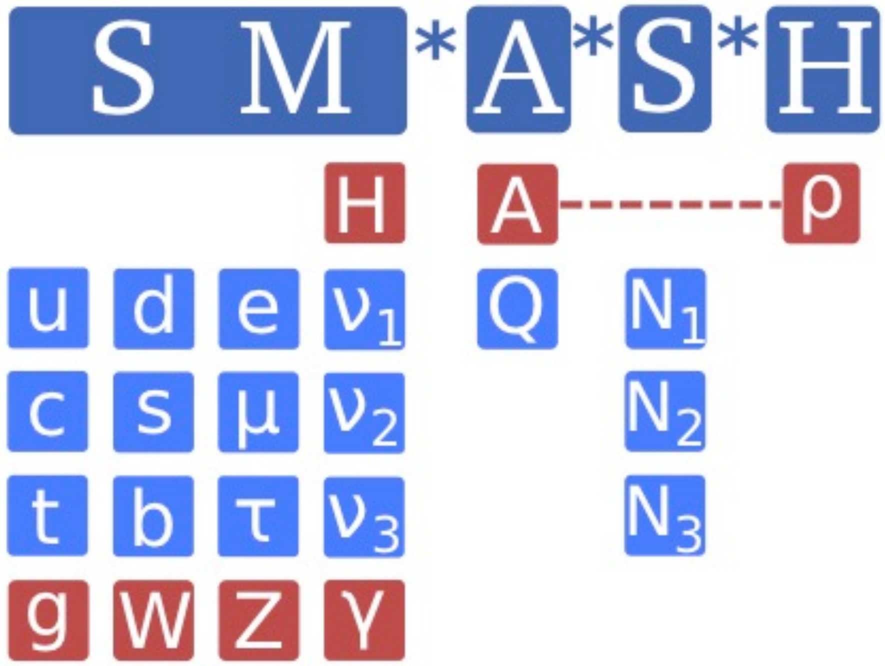
[Tamarit]

- Can be probed by next generation CMB experiments (e.g. CMB-S4)

Unifying Inflation, Dark Matter, and Seesaw with PQ Field

- Augmenting axion models with three SM singlet neutrinos, getting their Majorana masses also through the vev $v_\sigma = N f_A$
  - no strong CP problem
  - dark matter
  - inflation
  - neutrino masses and mixing
  - baryogenesis via leptogenesis

[Dias et al. `14; Ballesteros et al. `16]



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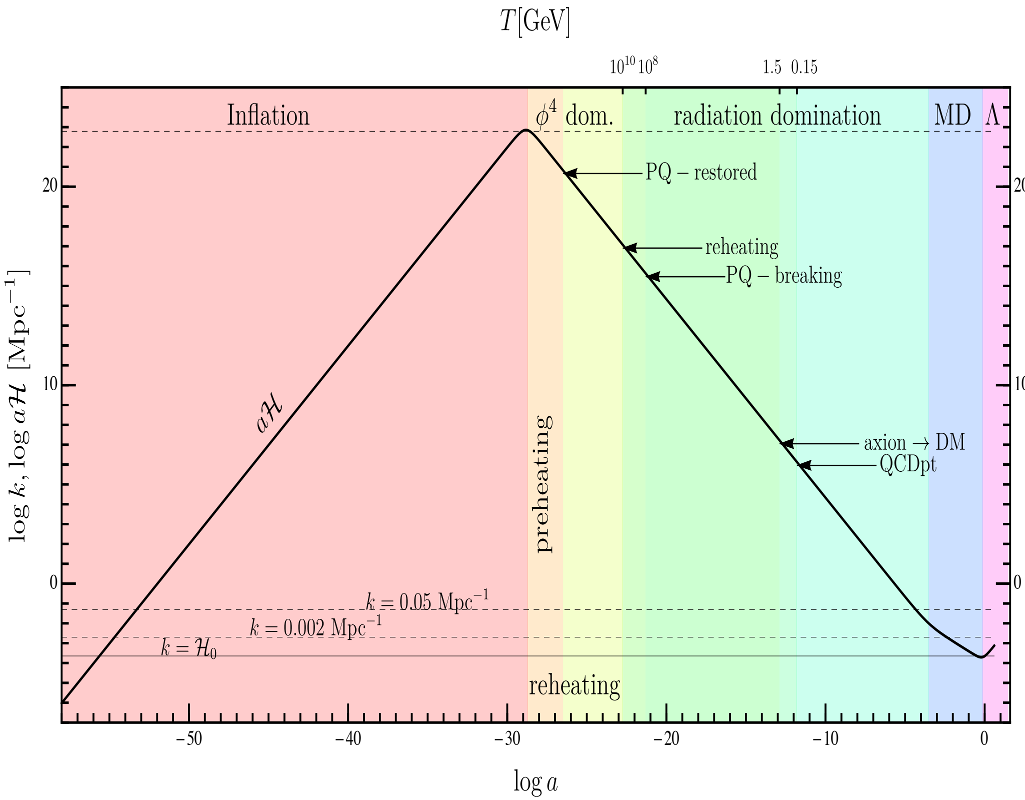

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- Complete and consistent history of the universe from inflation to now

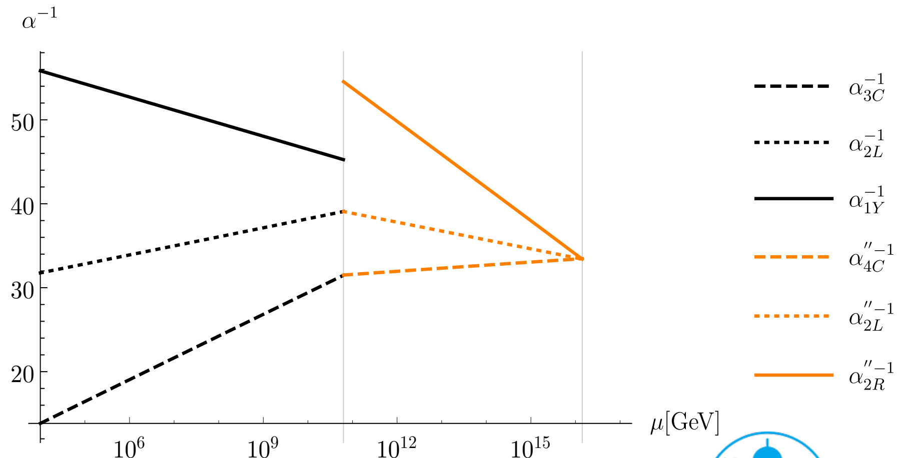
- $SO(10)$ GUT SMASH?

  [Ernst,AR,Tamarit in prep.]

- Minimal $SO(10) \times U(1)_{\rm PQ}$ models:

	16_F	$\overline{126}_H$	10_H	210_H	45_H	S	10_F	N
Model 1	1	-2	-2	4	–	–	–	3
Model 2.1	1	-2	-2	0	4	–	–	3
Model 2.2	1	-2	-2	0	4	–	-2	1
Model 3.1	1	-2	-2	0	–	4	–	3
Model 3.2	1	-2	-2	0	–	4	-2	1

$$SO(10) \xrightarrow{M_{\rm U}-210_H} SU(4)_C \times SU(2)_L \times SU(2)_R$$
$$\xrightarrow{M_{\rm BL}-\overline{126}_H} SU(3)_C \times SU(2)_L \times U(1)_Y$$
$$\xrightarrow{M_Z-10_H} SU(3)_C \times U(1)_{\rm em}$$



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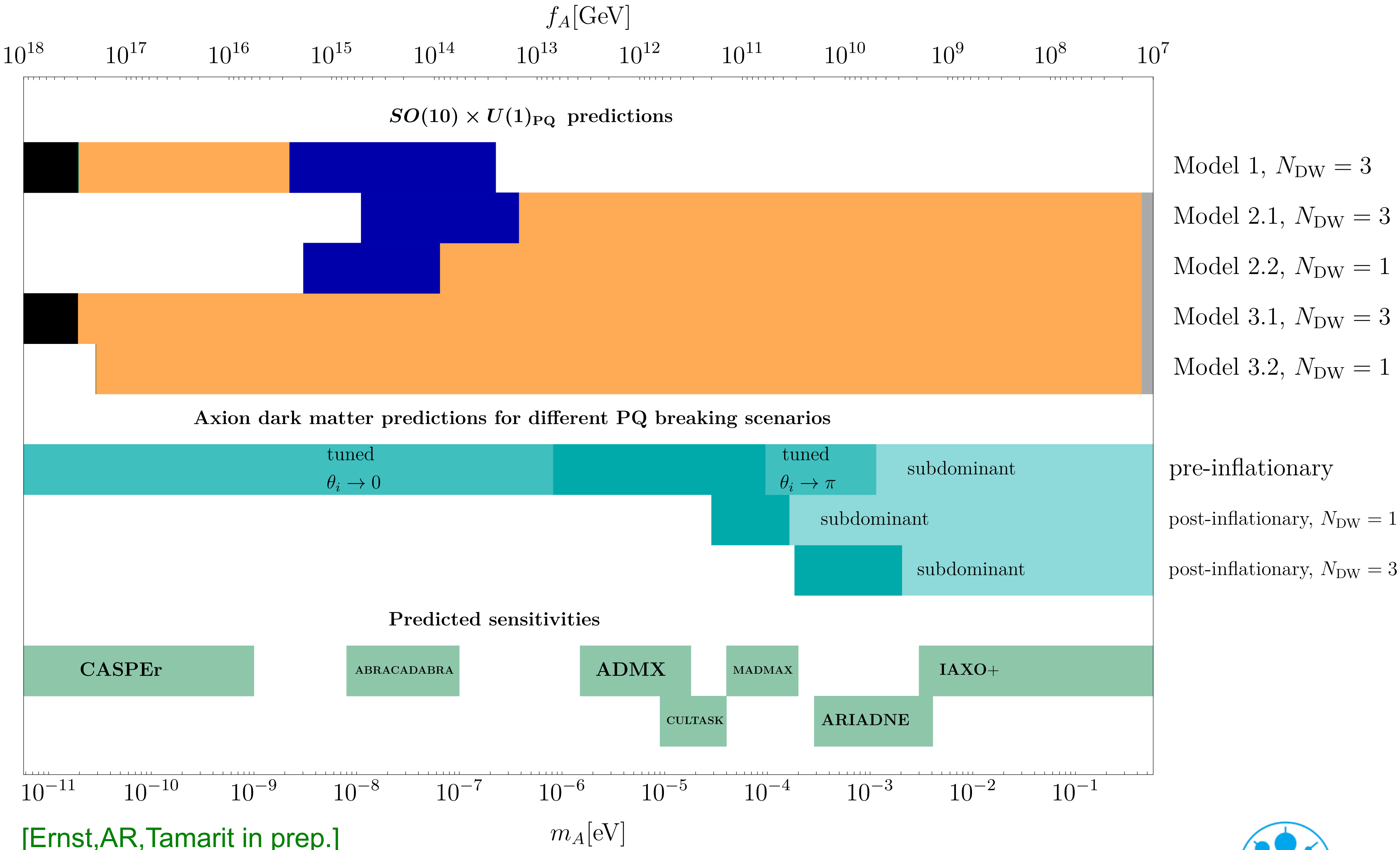
Model 3.1	1	-2	-2	0	–	4	–	3
Model 3.2	1	-2	-2	0	–	4	-2	1

- 16_F automatically features:
  - Neutrino masses and mixing
  - Baryogenesis via leptogenesis
- PQ extension adds
  - Predictivity of fermion masses/mixing
  - Solution of strong CP problem
  - Axion dark matter

[Bajc et al. 06; Altarelli,Meloni 13; Babu,Khan 15]

Unifying Inflation, Dark Matter, and Seesaw with PQ Field

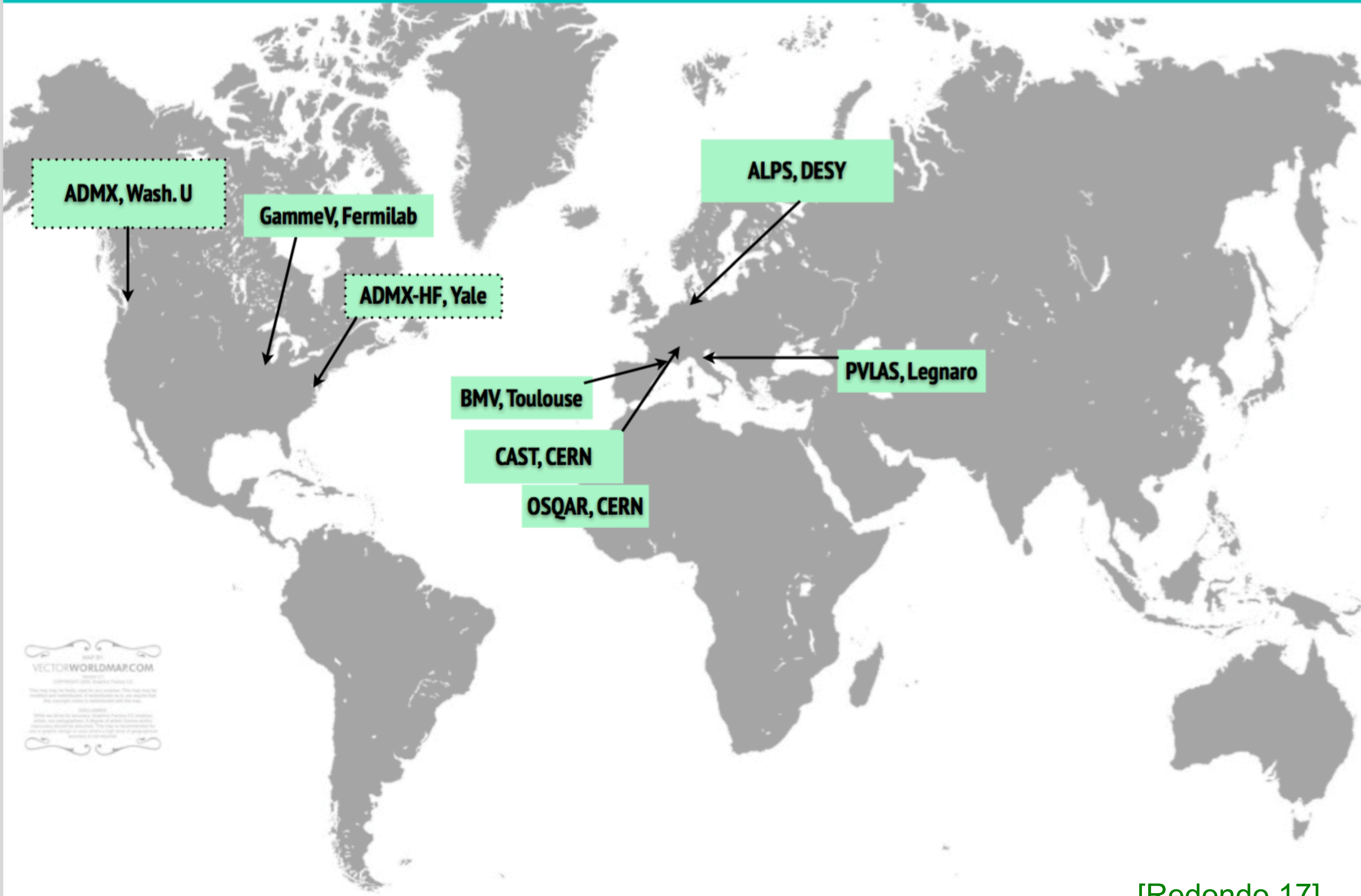


[Ernst,AR,Tamarit in prep.]

Conclusions

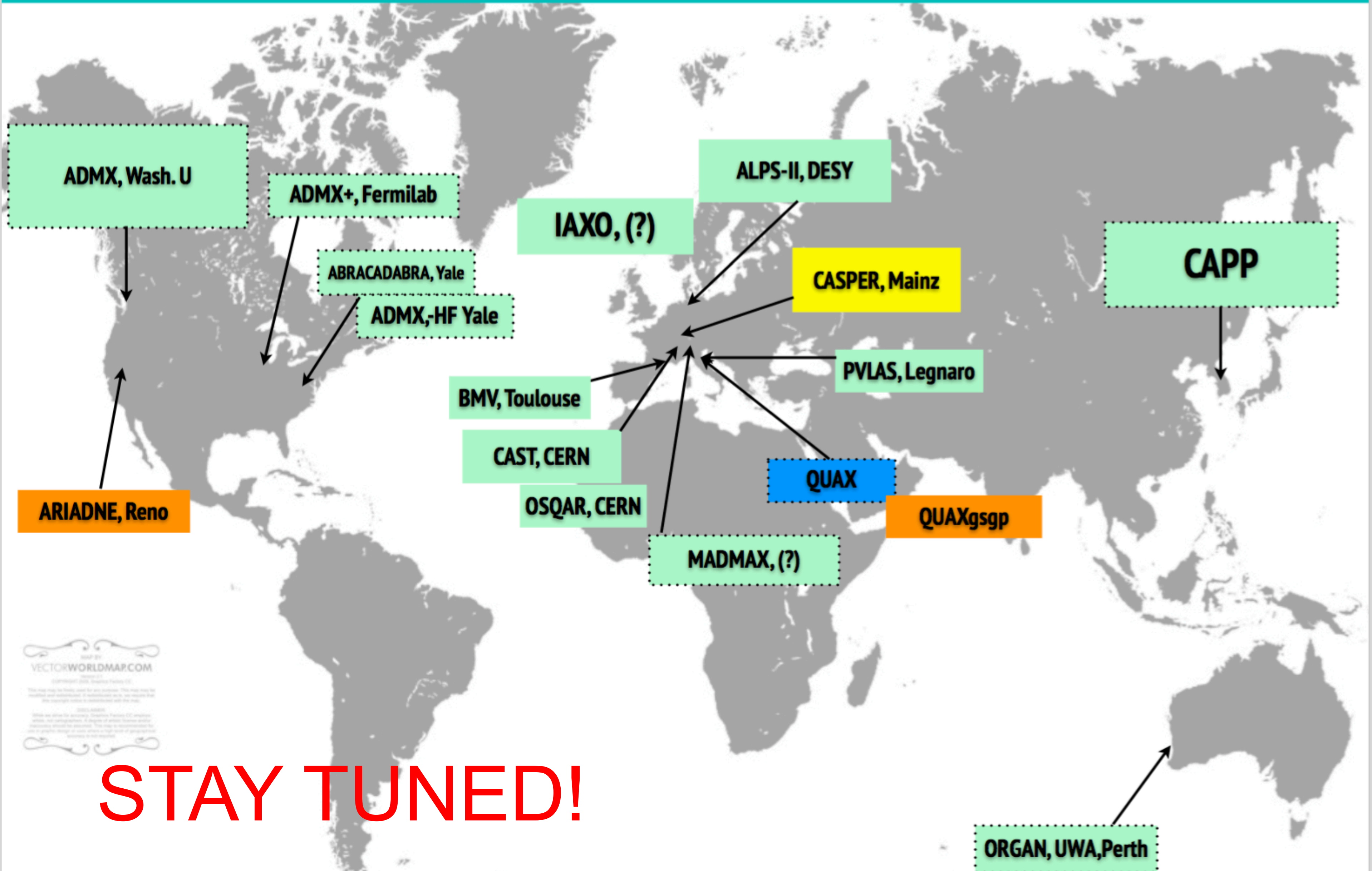
- Strong physics case for axion:
  - Axion occurs naturally as NG boson from breaking of well motivated symmetry
  - Solution of strong CP problem
  - Candidate for dark matter
  - PQ field may even provide inflaton
  - Explanation of excessiv energy losses of
- Strong motivation for experimental searches of axions
- Number of axion experiments strongly growing

Lab experiments 2011



[Redondo 17]

Lab experiments 2017

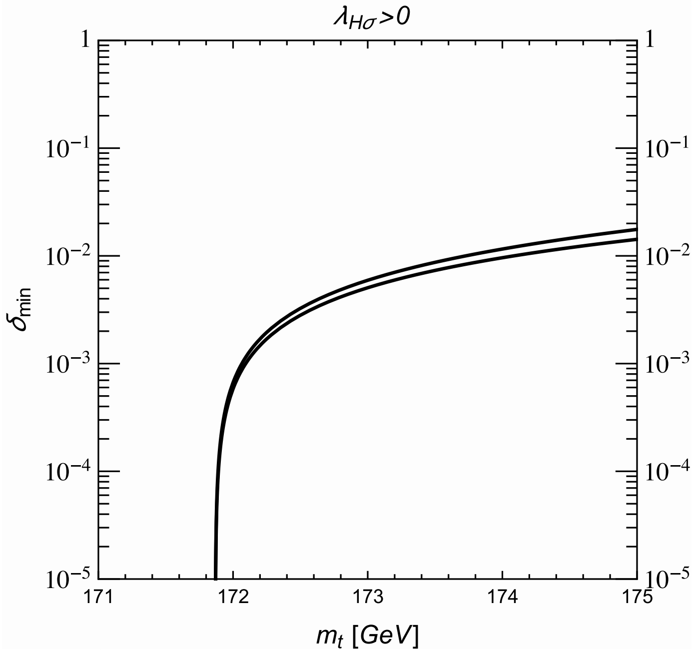


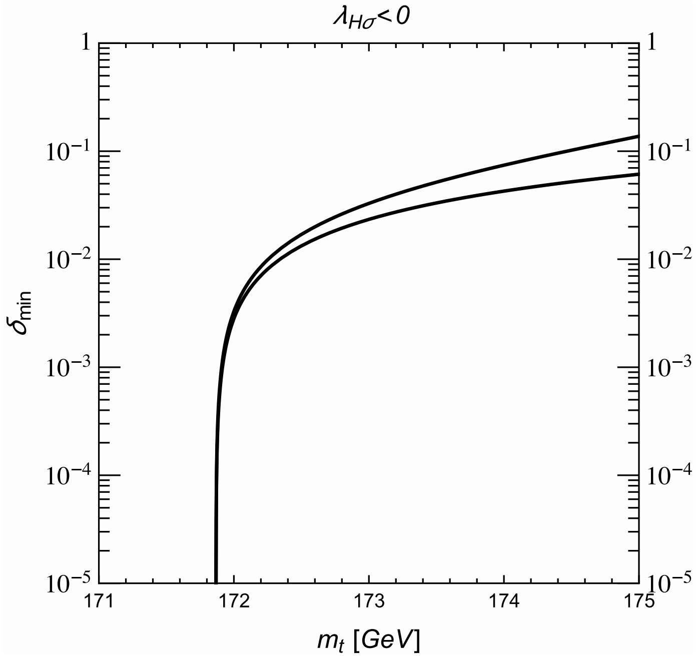
STAY TUNED!

[Redondo 17]

Back-Up: Vacuum 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,
$$\overline{\lambda}_H(m_h) = \lambda_H - \lambda_{H\sigma}^2/\lambda_\sigma\big|_{\mu=m_h}$$
  - 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:

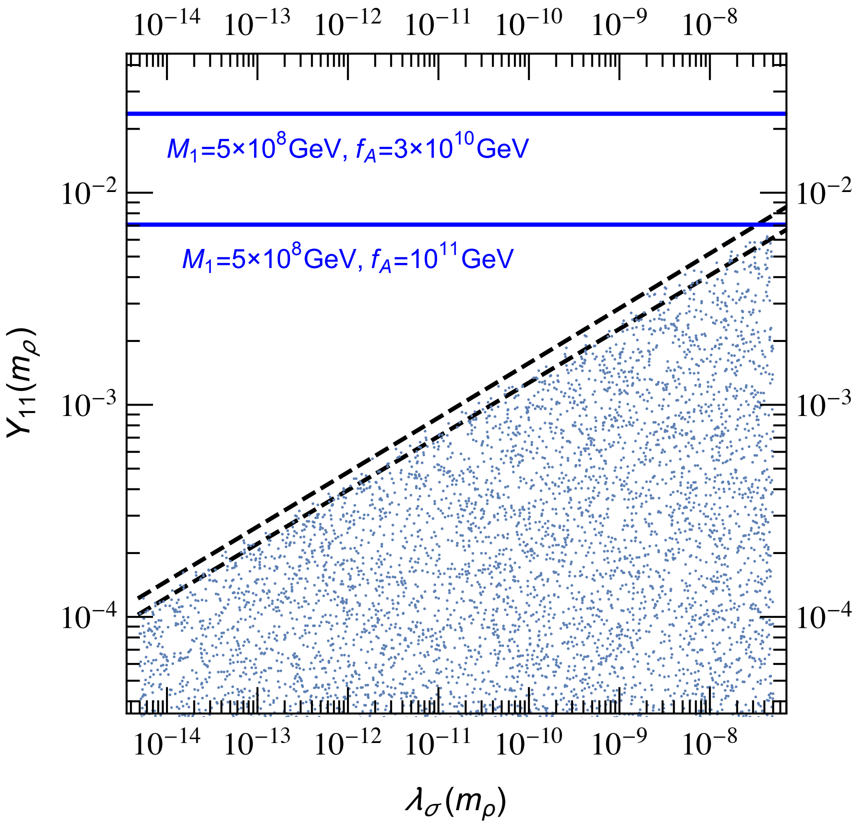


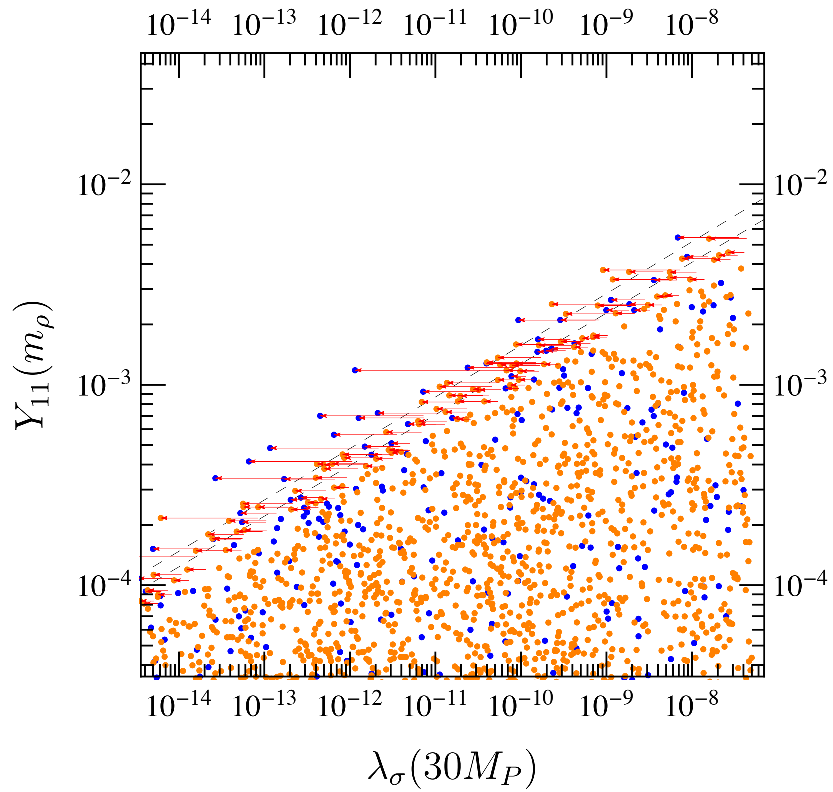


Back-Up: Vacuum Stability

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

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





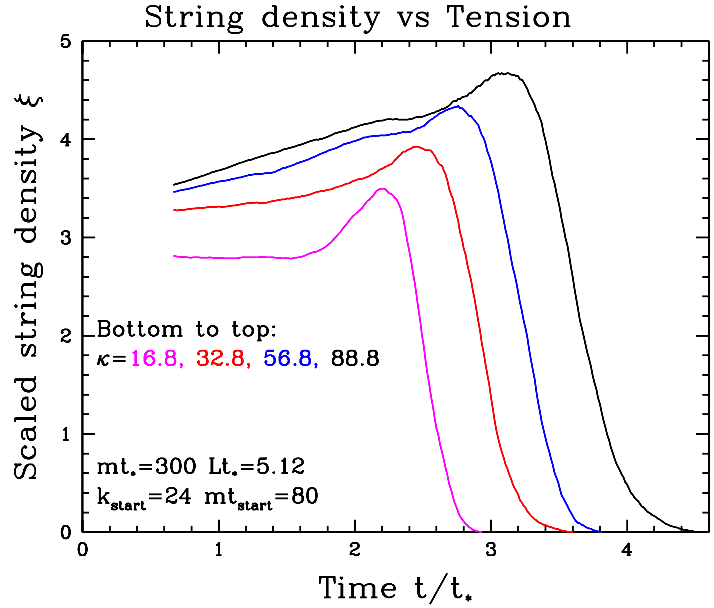
Back-Up: DM Axion Mass in Post-Inflationary PQSB Case

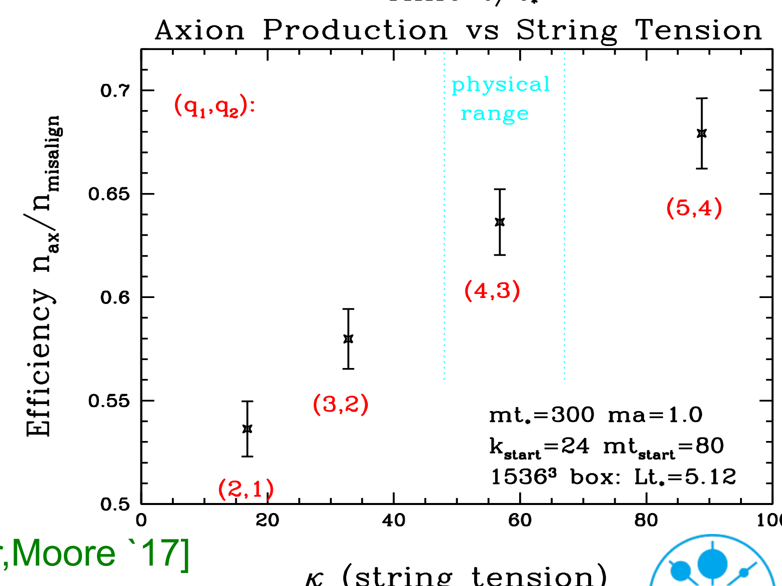
$$\kappa = \ln(\sqrt{2\lambda_\sigma} v_{\rm PQ}/H) \in [48, 67]$$

controls string tension

- For large κ, string's long-range interactions become less important relative to string evolution under tension
  - For $\kappa \gg 1$, string behavior should go over to that of local (Nambu-Goto) strings
  - Simulation of evolution of PQ field alone can be done only at $\kappa < 7$
- New method: exploit UV extension of PQ field theory reducing in IR to Nambu-Goto string plus axion
- Axion production smaller than angle-average of ``realignment'' mechanism

$$m_A = 26.2 \pm 3.4\,\mu\text{eV}$$

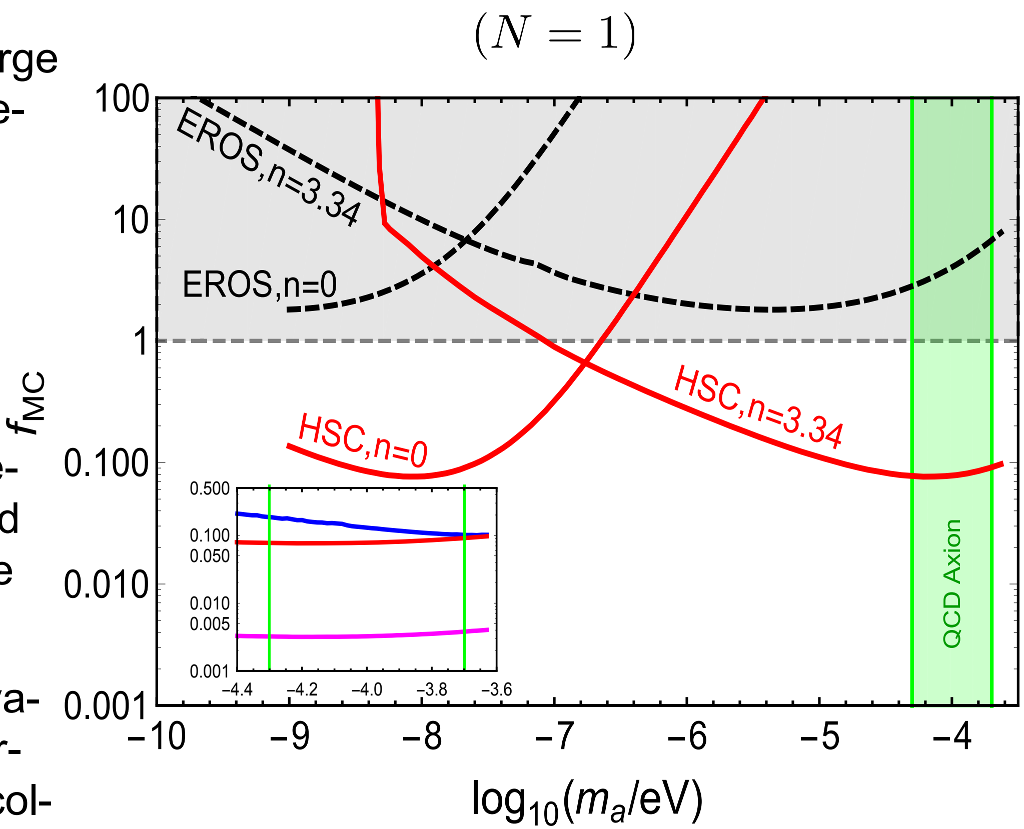




[Klaer,Moore `17]

Back-Up: Axion Miniclusters

- Recall axion cosmology in post-inflationary PQSB scenario:
  - At PQSB, topological defects and large amplitude axion field fluctuations present on scales of order the horizon
  - Kibble mechanism smoothes axion field on horizon scale until around QCD phase transition, when mass becomes relevant
  - At this epoch, topological defects decay (assume $N = 1$), and axion field left with large amplitude isocurvature fluctuations on the horizon scale
  - At matter-radiation equality, isocurvature perturbations converted into curvature perturbations, and promptly collapse into dense bound structures of DM known as axion miniclusters (MC) [Hogan,Rees `88;Kolb,Tkachev `93]
- Gravitational Microlensing by MC



[Fairbairn et al. `17]