Saxion/Higgs Inflation and Axion Dark Matter

Andreas Ringwald
Planck 2018
Bonn, 21-25 May 2018

Axionic Solution of Strong CP Puzzle

In a nutshell …

- Add to SM Nambu-Goldstone field, $\theta(x) \equiv A(x)/f_A \in [-\pi, \pi]$, respecting a non-linearly realized $U(1)_{\rm PQ}$ symmetry ($\theta(x) \to \theta(x) + {\rm const.}$), broken by coupling to gluonic topological charge density: [Peccei,Quinn 77]

$$\mathcal{L} \supset -\theta(x)\, q(x)\,; \qquad q(x) \equiv \frac{\alpha_s}{8\pi}\, G^b_{\mu\nu}(x)\tilde{G}^{b,\mu\nu}(x)$$

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

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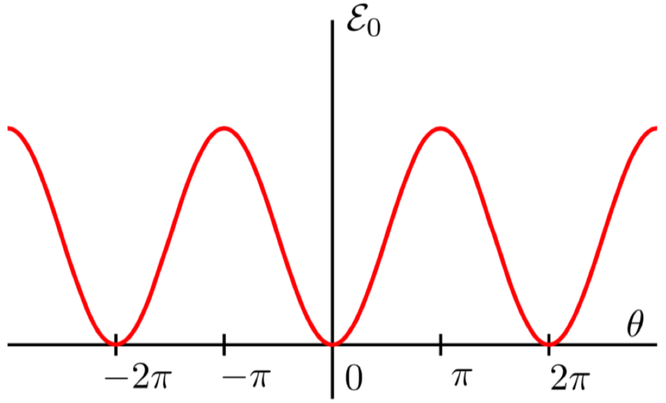
  - Effective potential at energies below $\Lambda_{\rm QCD}$ has absolute minimum at $\theta = 0$ and thus predicts vanishing vev, $\langle\theta(x)\rangle = 0$
    No strong CP violation in vacuum [Vafa,Witten 84]



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

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

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

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    No strong CP violation in vacuum [Vafa,Witten 84]
  - Particle excitation: pseudo Nambu-Goldstone boson "axion" [Weinberg 78; Wilczek 78]
  - Topological susceptibility in QCD, $\chi \equiv \int d^4x \langle q(x) q(0)\rangle$, determines mass in units of decay constant: $m_A = \sqrt{\chi}/f_A$
  - Recent precise determination (ChPT; lattice QCD):

$$m_A = 57.0(7)\left(\frac{10^{11}\,{\rm GeV}}{f_A}\right)\mu{\rm eV}$$

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

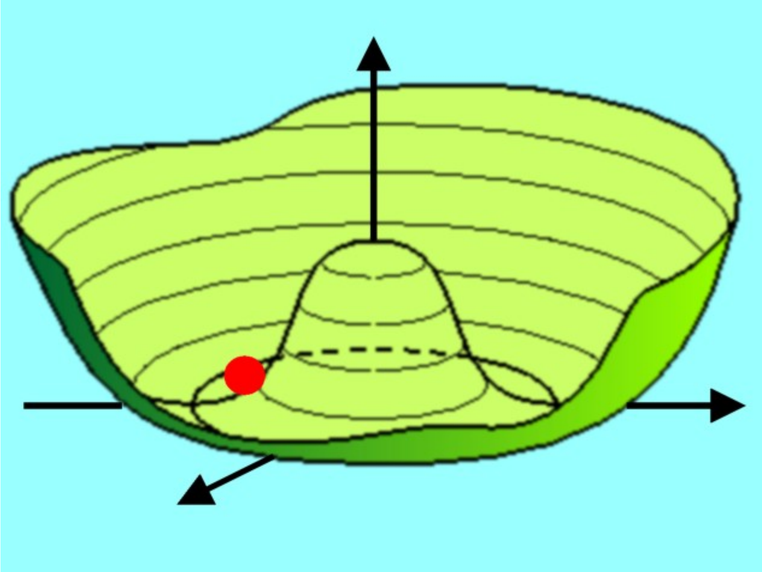
Peccei-Quinn Extension of Standard Model

UV completions yielding axion

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

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

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



[Raffelt]

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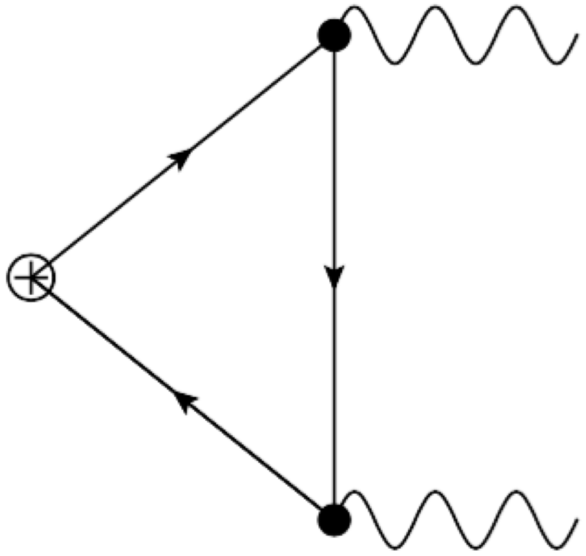
$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} \supset -\frac{\alpha_s}{8\pi} N\, G^b_{\mu\nu} \tilde{G}^{b,\mu\nu}$$



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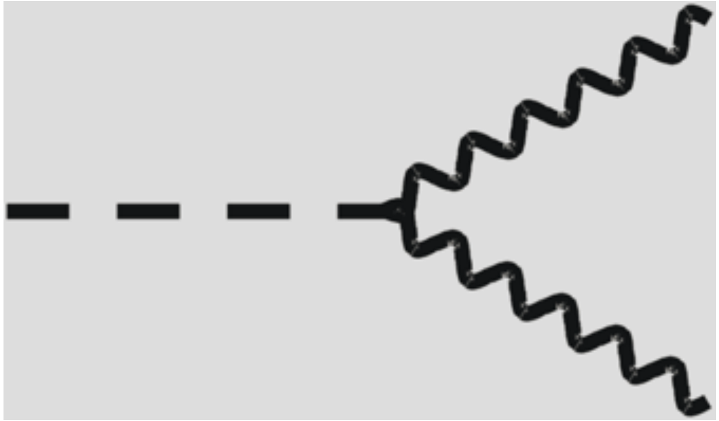
- Low energy effective field theory at energies below $\Lambda_{\rm QCD}$ but above $v\ (\ll v_{\rm PQ})$: [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\,\theta(x)\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}\,; \qquad \theta(x) = A(x)/f_A\,; \qquad f_A = v_{\rm PQ}/N$$

[Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]



Saxion/Higgs Inflation

Exploiting modulus of PQ field or mixture of it with Higgs modulus to solve horizon and flatness puzzle

- Take into account non-minimal coupling of Higgs and PQ field to gravity, [Fairbairn,Hogan,Marsh `14]

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

  - Generated anyway radiatively even if set to zero at some scale

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

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

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

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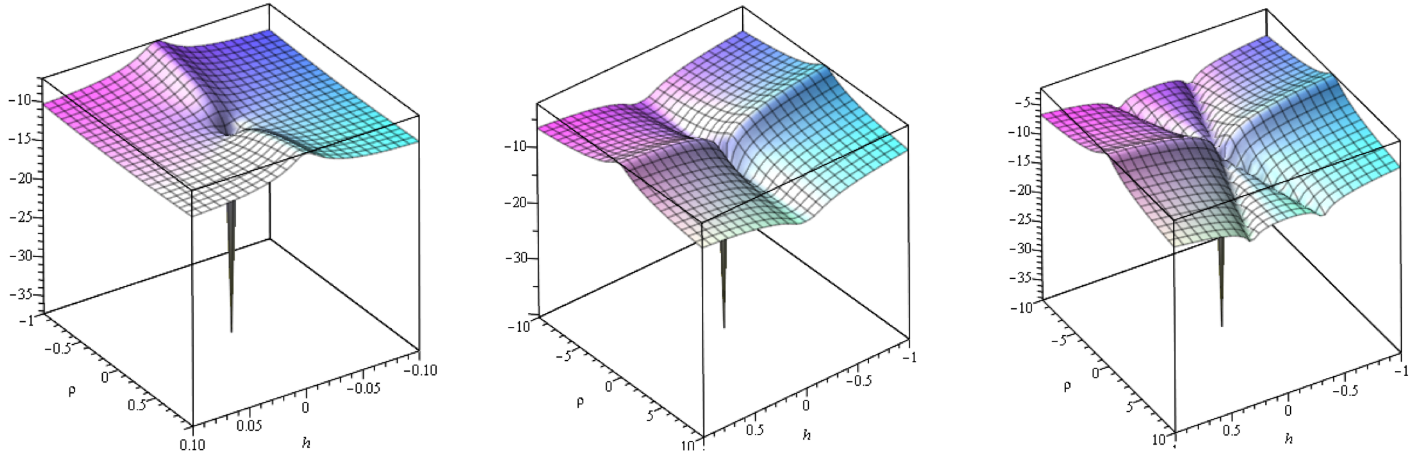
- Potential has valleys = attractors for Higgs Inflation (HI), Saxion Inflation (SI) or mixed Saxion/Higgs Inflation (SHI), depending on relative signs of $\kappa_H \equiv \lambda_{H\sigma}\xi_H - \lambda_H\xi_\sigma\,, \quad \kappa_\sigma \equiv \lambda_{H\sigma}\xi_\sigma - \lambda_\sigma\xi_H$



$\mathrm{sign}(\kappa_H)$	$\mathrm{sign}(\kappa_\sigma)$	Inflation
$+$	$-$	HI
$-$	$+$	SI
$-$	$-$	SHI

[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

Saxion/Higgs Inflation

Exploiting modulus of PQ field or mixture of it with Higgs modulus to solve horizon and flatness puzzle

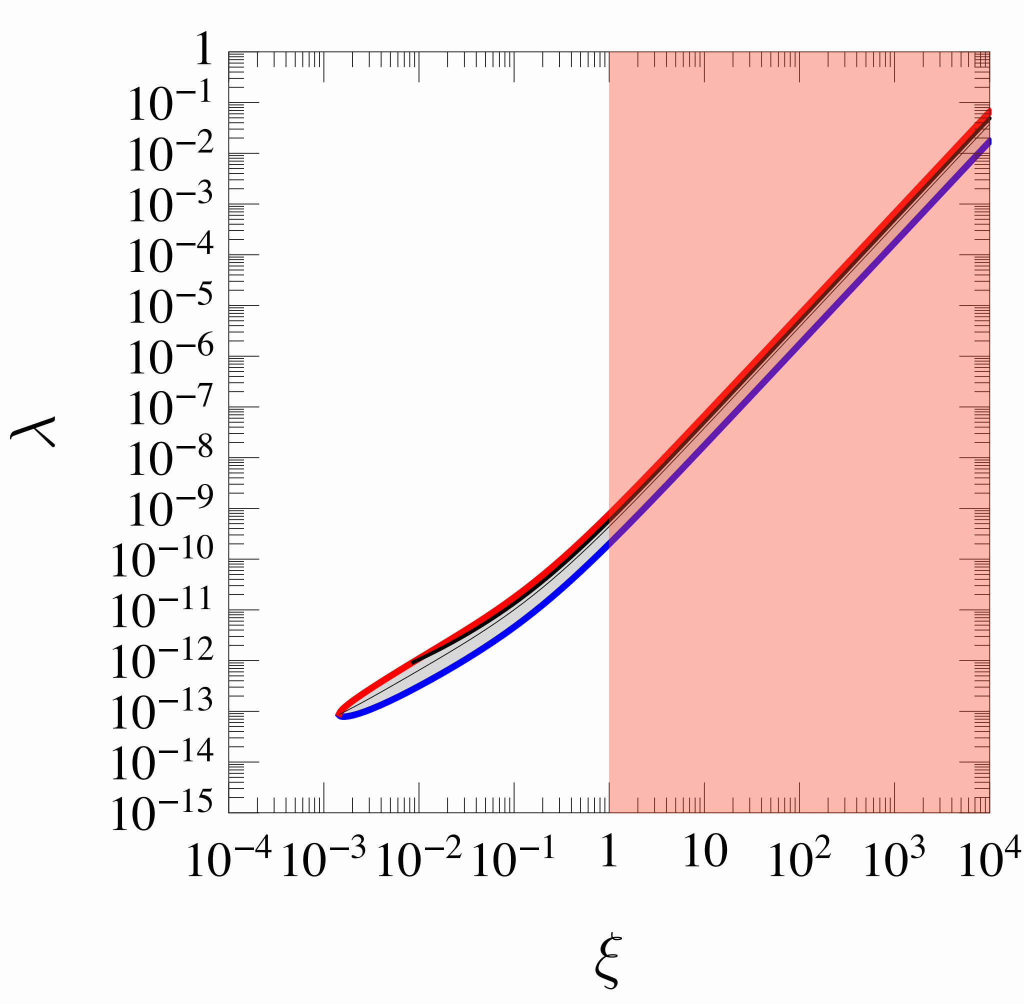
- Characteristics of primordial density fluctuations inferred from CMB temperature fluctuations

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

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

where
$$\xi = \begin{cases} \xi_H\,, & \text{for HI} \\ \xi_\sigma\,, & \text{for SI} \\ \xi_\sigma\,, & \text{for SHI} \end{cases}$$
$$\lambda = \begin{cases} \lambda_H\,, & \text{for HI} \\ \lambda_\sigma\,, & \text{for SI} \\ \lambda_\sigma \left(1 - \frac{\lambda_{H\sigma}^2}{\lambda_\sigma \lambda_H}\right)\,, & \text{for SHI} \end{cases}$$

- HI has unitarity problem
- SI and SHI have no unitarity problem if $\lambda_\sigma, \tilde{\lambda}_\sigma \lesssim 10^{-10}$



[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

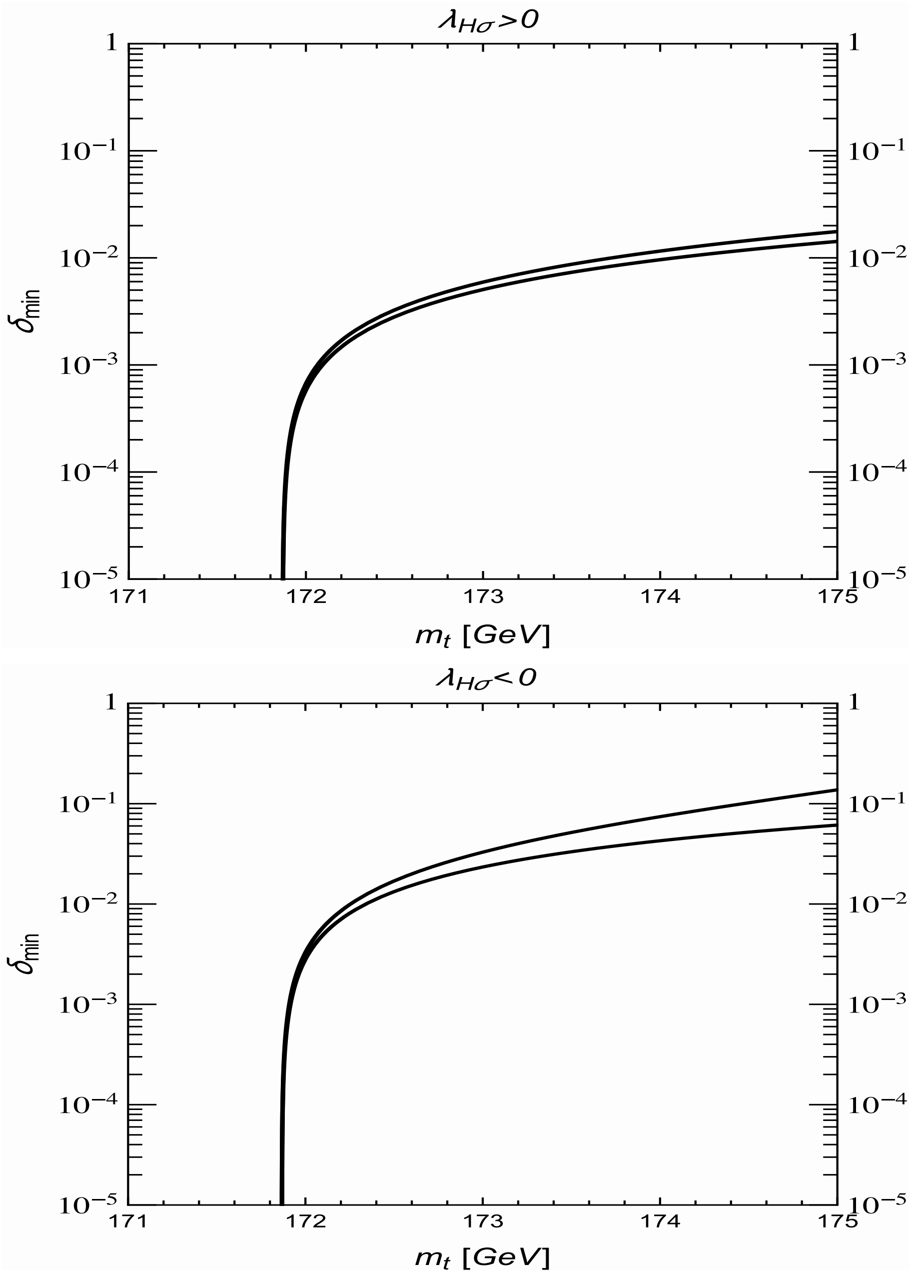
Saxion/Higgs Inflation

Modulus of PQ field or mixture with Higgs modulus as inflaton

- Stability up to Planck scale?
  - 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 to 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
  - Stability up to Planck scale ensured if $\delta = \lambda_{H\sigma}^2/\lambda_\sigma\big|_{\mu=m_h}$ exceeds a minimum value dependent on top mass



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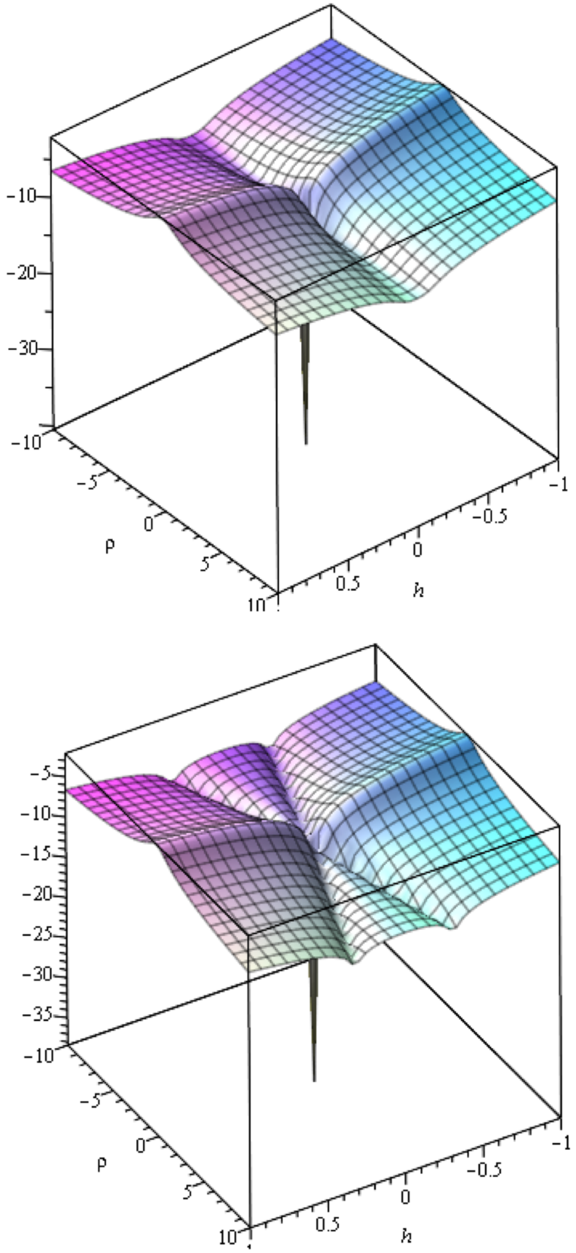
Modulus of PQ field or mixture with Higgs modulus as inflaton

- Both in SI and SHI 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 quasi-quartic potential, with Universe expanding as in a radiation-dominated era



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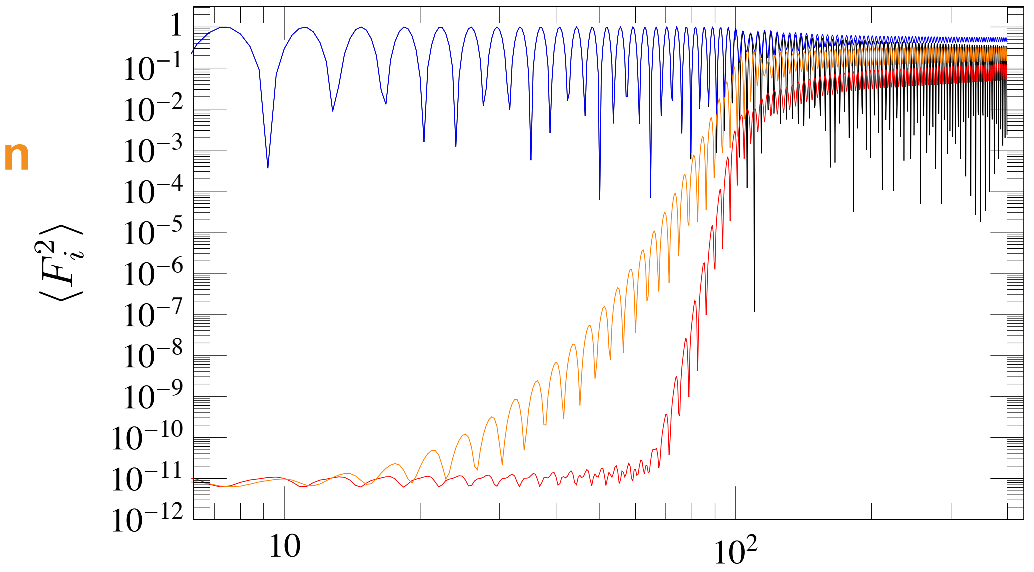
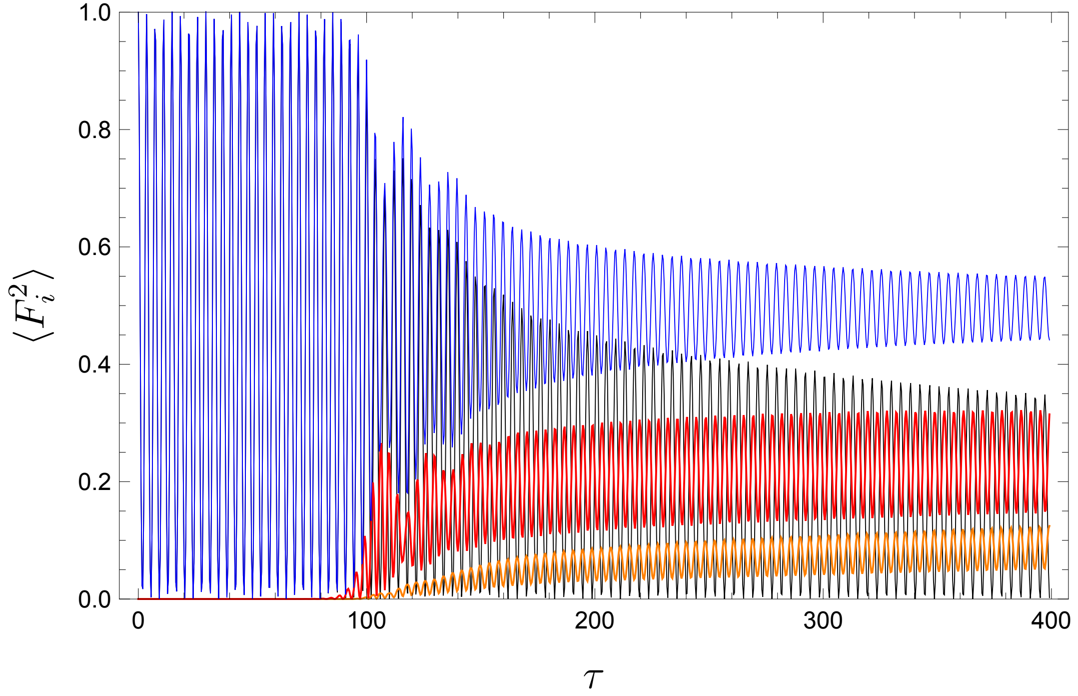
- For $f_A \lesssim 10^{16}\,\mathrm{GeV}$, PQ symmetry restored after few oscillations





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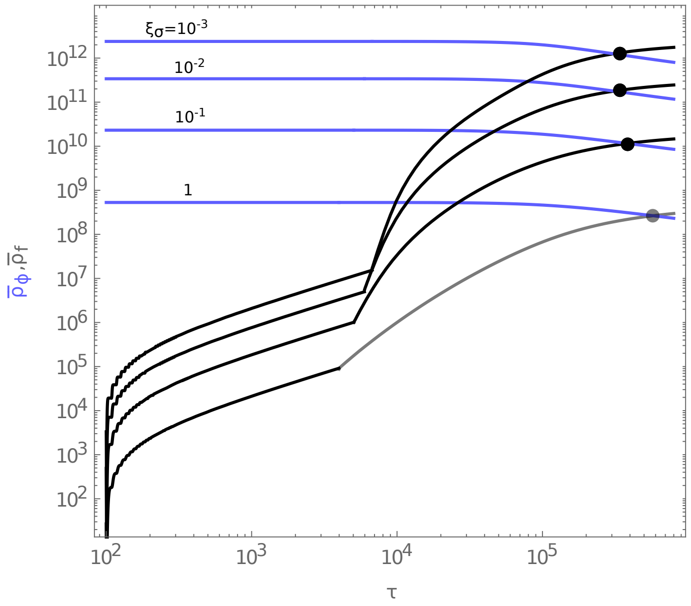
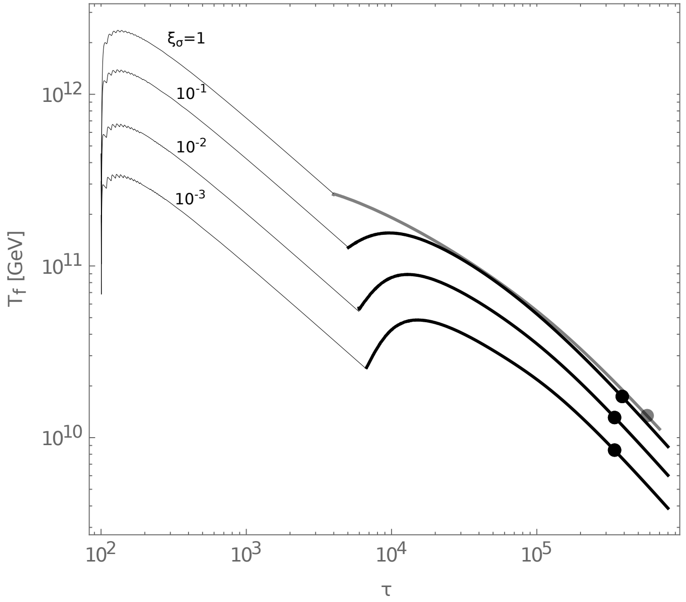
- **SI:** Large induced particle masses quench inflaton decays or annihilations into SM particles

  $T_R \sim 10^7\,\mathrm{GeV} v_{11} \lambda_{10}^{3/8} \delta_3^{-1/8} \quad \Delta N_\nu^{\mathrm{eff}} \sim (\delta_3 v_{11}/\lambda_{10})^{-1/6}$
- **SHI:** Higgs component of inflaton allows for production of SM gauge bosons

  $T_R \sim 10^{10}\,\mathrm{GeV} \qquad \Delta N_\nu^{\mathrm{eff}} \simeq 0.0268 \left(\frac{427/4}{g_{*s}(T_A^{\mathrm{dec}})}\right)^{4/3}$





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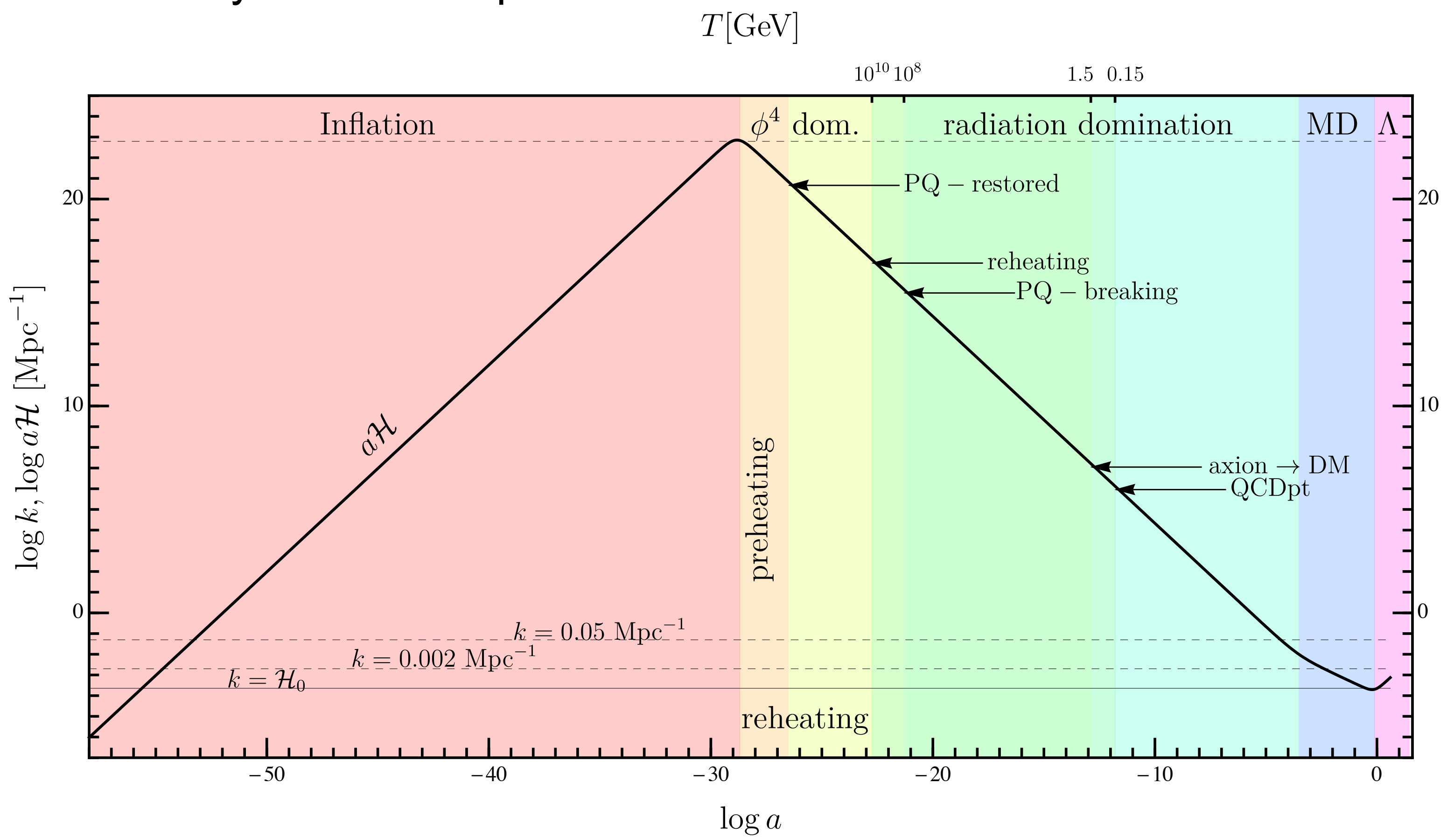
Saxion/Higgs Inflation

Modulus of PQ field or mixture with Higgs modulus as inflaton

- Expansion and thermal history of universe predicted



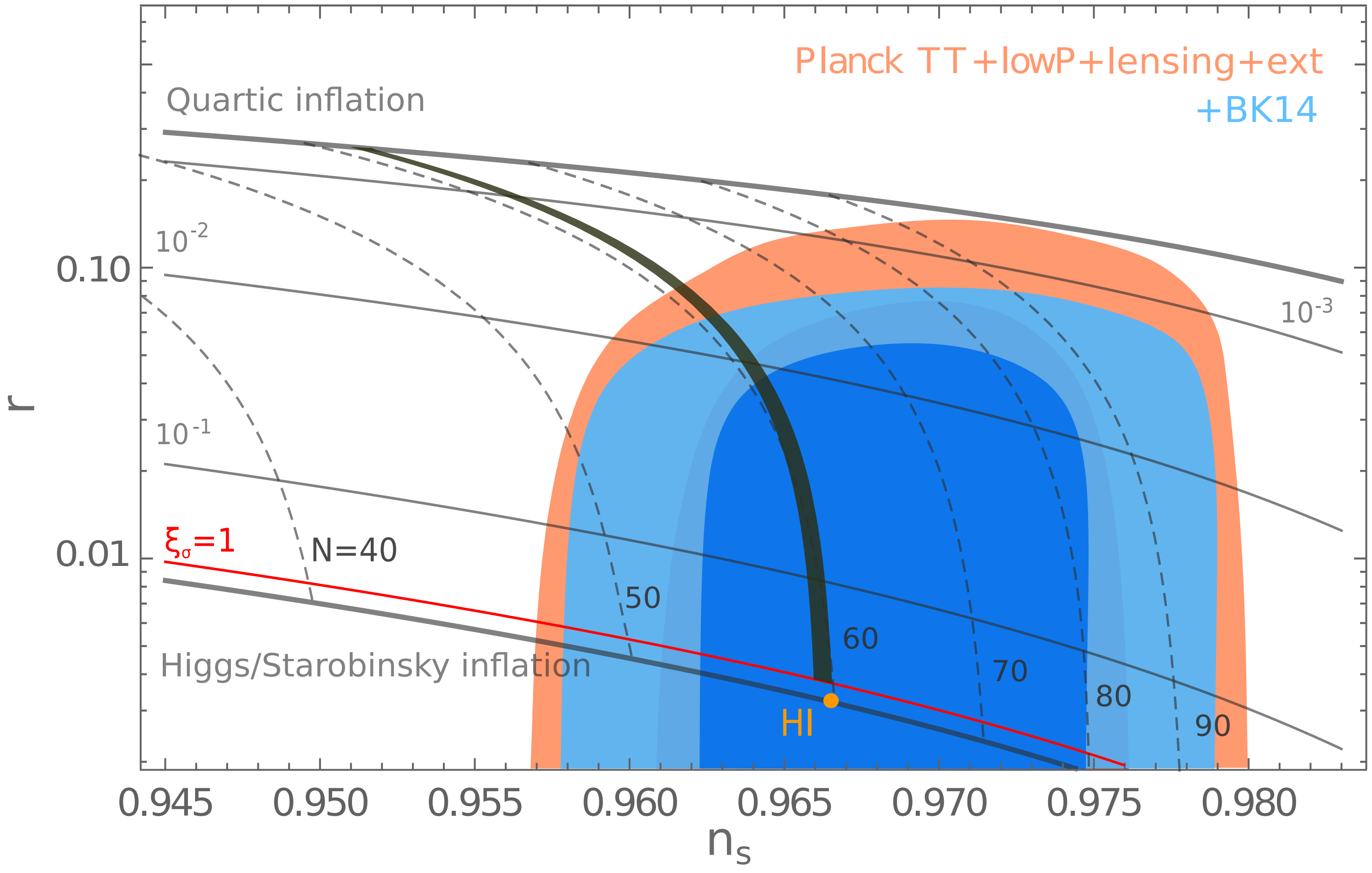
- Number of e-folds $N(k)$ from the time a given comoving scale k leaves horizon until end of inflation predicted

[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

Saxion/Higgs Inflation

Modulus of PQ field or mixture with Higgs modulus as inflaton

- Sharp prediction of r vs n_s:



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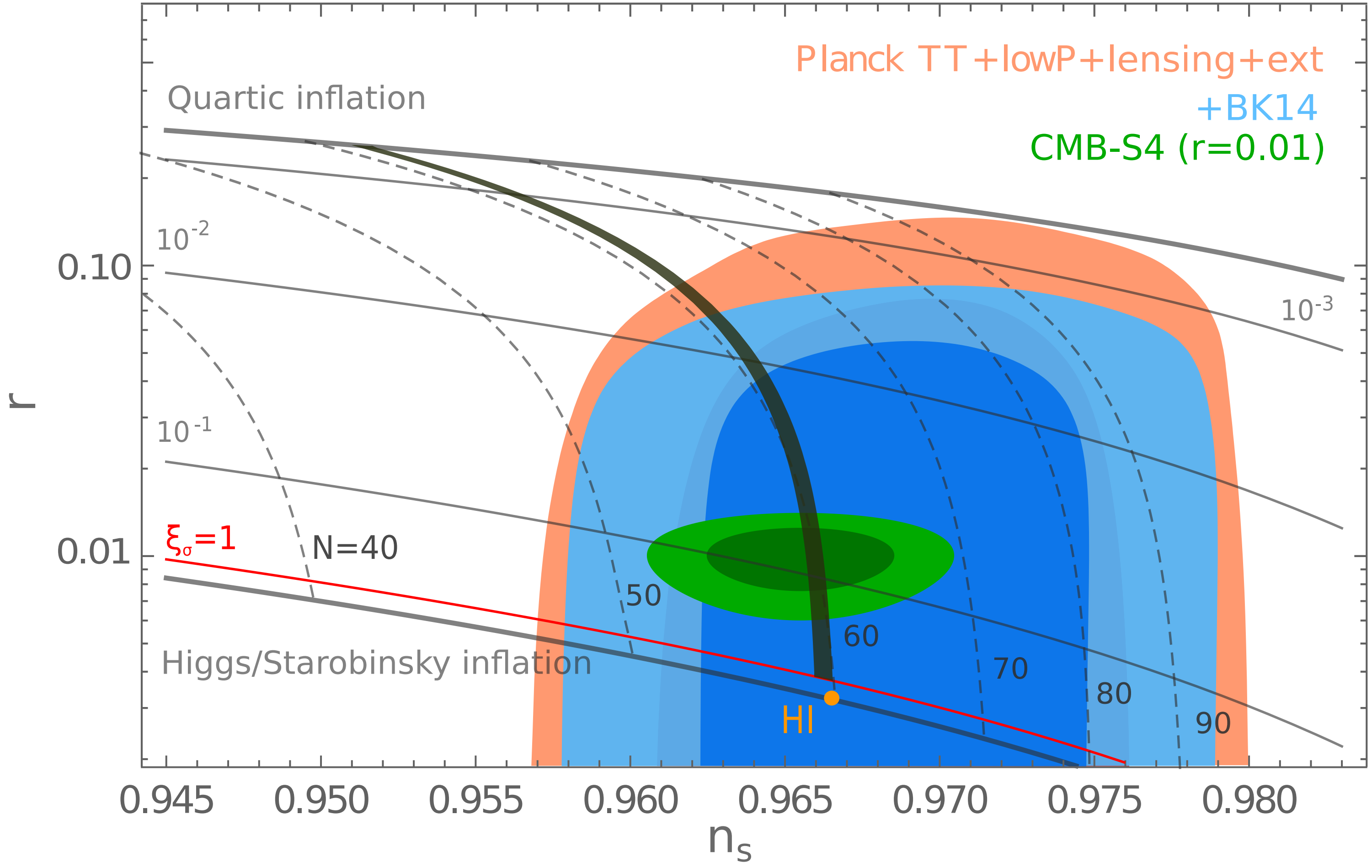
Saxion/Higgs Inflation

Modulus of PQ field or mixture with Higgs modulus as inflaton

- Sharp prediction of r vs n_s can be probed by upcoming CMB experiments (e.g. CMB-S4):



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Axion Dark Matter

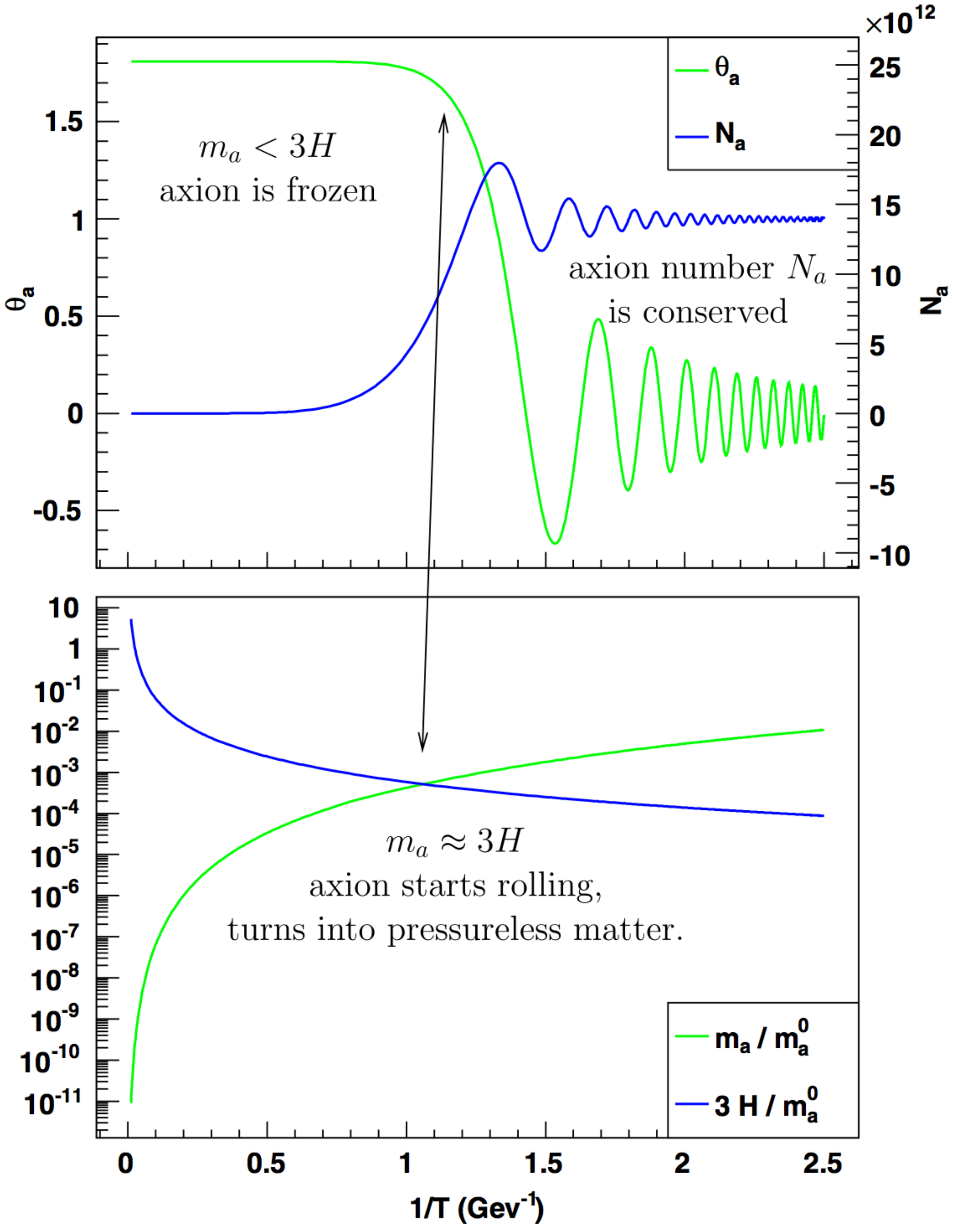
Predictions of post-inflationary PQ SB scenarios

- PQ phase transition takes place at

$$T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N f_A$$

- Axion takes random initial values in causally connected domains
- Later when $H(T) \sim m_A(T)$, axion field starts to oscillate around minimum of potential; behaves like cold dark matter: $w_A = p_A/\rho_A \simeq 0$

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



[Wantz,Shellard `09]

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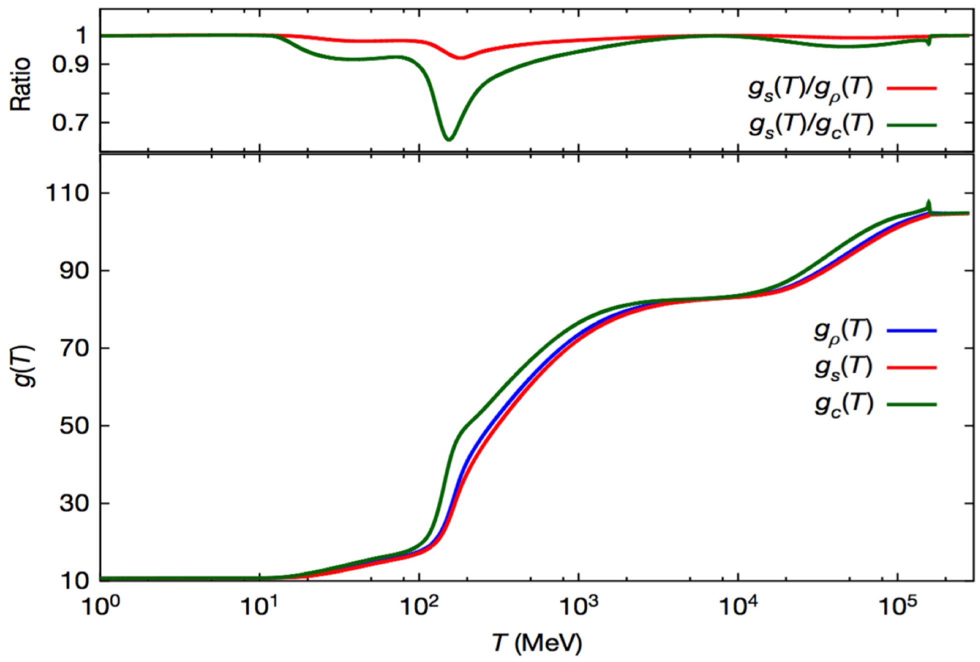
- QCD input from lattice:
  - Equation of state $\Rightarrow H(T)$



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

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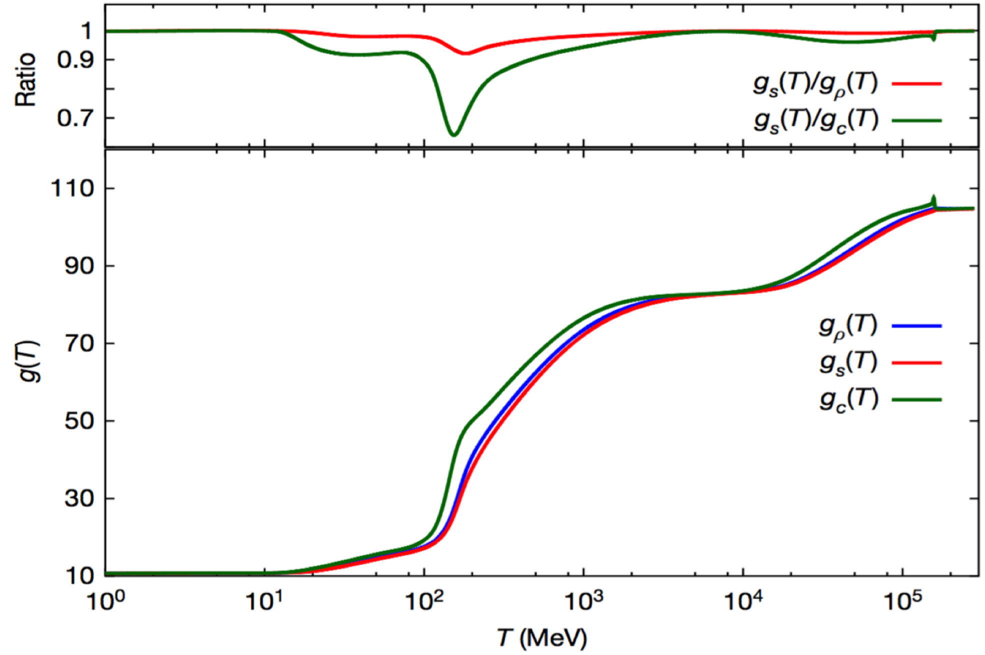
  - Topological susceptibility $\Rightarrow m_A(T)$



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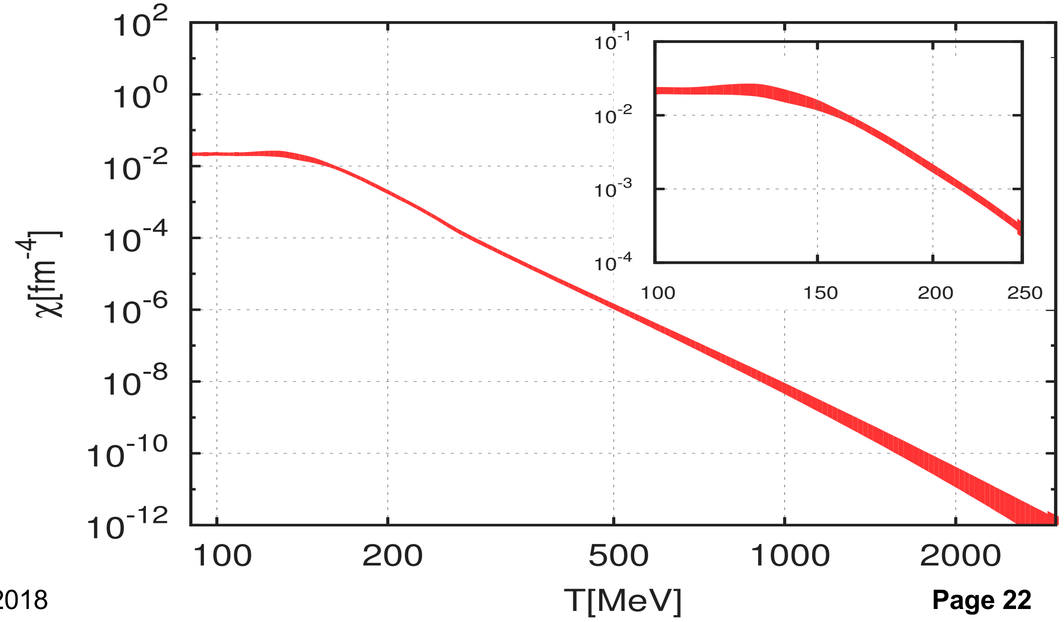


Axion Dark Matter

Predictions of post-inflationary PQ SB scenarios

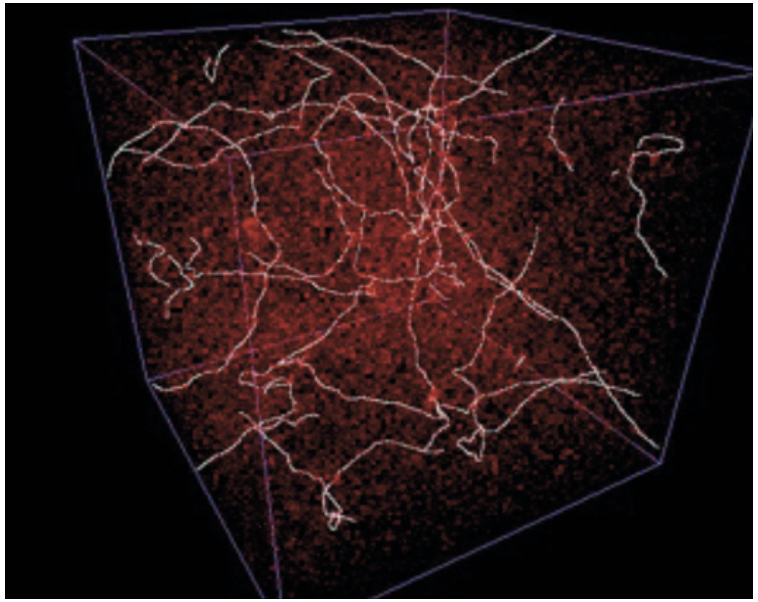
- Averaging over random initial axion field values

$$\Omega_A^{(\mathrm{VR})} h^2 = (3.8 \pm 0.6) \times 10^{-3} \left(\frac{f_A}{10^{10}\,\mathrm{GeV}} \right)^{1.165}$$

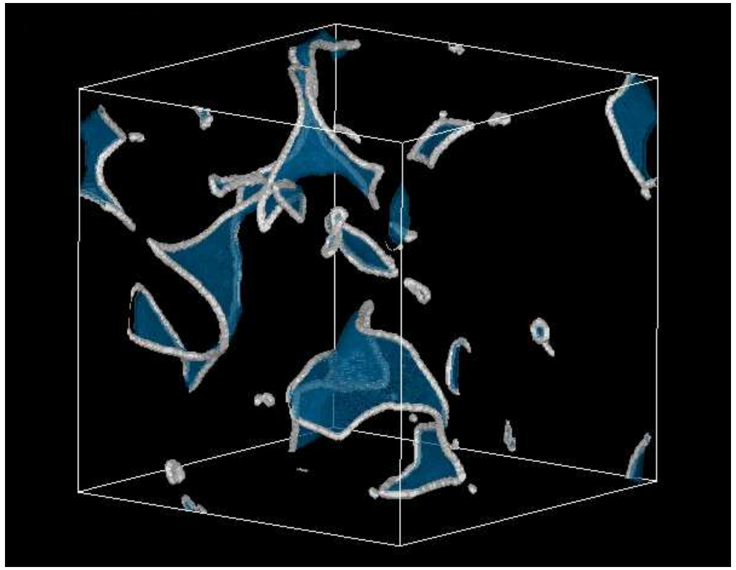
- Does not exceed observed CDM abundance for

$$m_A > 28(2)\,\mu\mathrm{eV}$$

- Axions also produced by collapse of network of topological defects – strings and domain-walls –
  - Need field theoretic simulations to determine their contribution to dark matter



[Hiramatsu et al.]



Axion Dark Matter

Predictions of post-inflationary PQ SB scenarios

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

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

$$f_A \approx (3.8 - 9.9) \times 10^{10}\,\mathrm{GeV} \quad \Leftrightarrow \quad m_A \approx (58 - 150)\ \mu\mathrm{eV}$$

  - Still large unknown theoretical error because simulations can be done only at unrealistic values of the string tension
  - Result from new simulation technique designed to work directly at high string tension: [Klaer,Moore `17]

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

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  - Further simulations by other groups are under way to clarify the issue
- For $N>1$, domain wall problem can be avoided if PQ symmetry explicitely broken, e.g. by Planck suppressed operators, $\mathcal{L} \supset g M_{\rm P}^4\,(\sigma/M_{\rm P})^{\mathcal{N}} + \mathrm{h.c.}$, for $\mathcal{N} = 9, 10$,

$$4.4 \times 10^7\,(1.3 \times 10^9)\,\mathrm{GeV} < f_A < 1 \times 10^{10}\,\mathrm{GeV} \ \Leftrightarrow\ 0.56\,\mathrm{meV} < m_A < 130\,(4.5)\,\mathrm{meV}$$

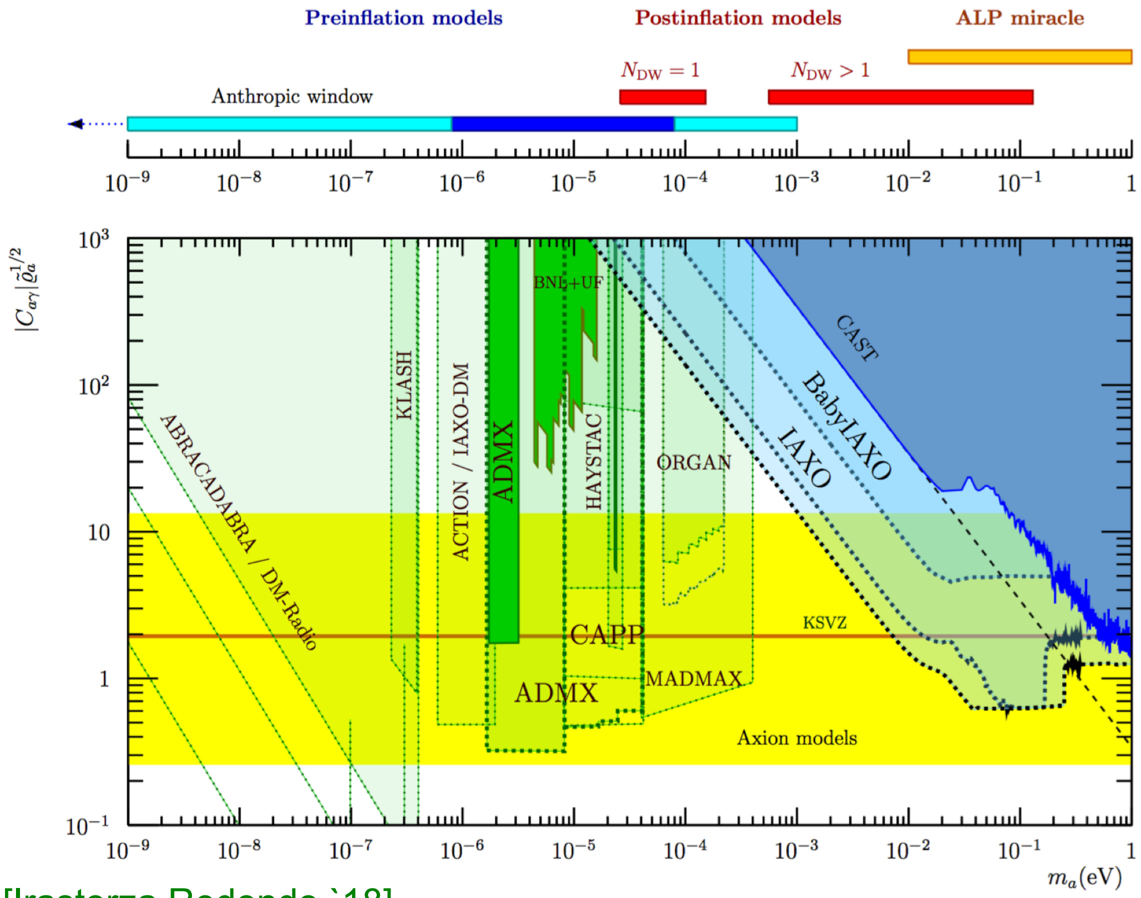
[Kawasaki,Saikawa,Sekiguchi `15; AR,Saikawa `16]

  - May postulate discrete symmetry to forbid lower dimensional operators e.g. [Dias et al. `14]
  - A DFSZ axion ($N=6$) in this mass range explains excessive stellar energy losses [Giannotti,Irastorza,Redondo,AR,Saikawa`17]

Axion Dark Matter

Predictions of post-inflationary PQ SB scenarios

- Mass range will be probed in near future:

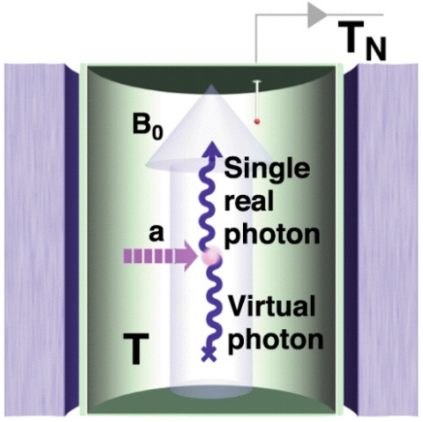


[Irastorza,Redondo `18]

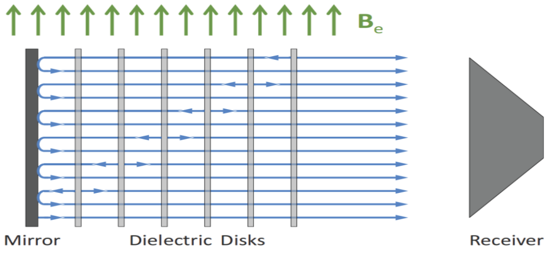
HAYSTAC

CAPP

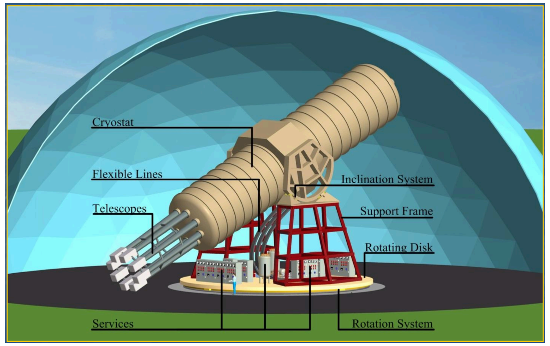
ORGAN



MADMAX



IAXO



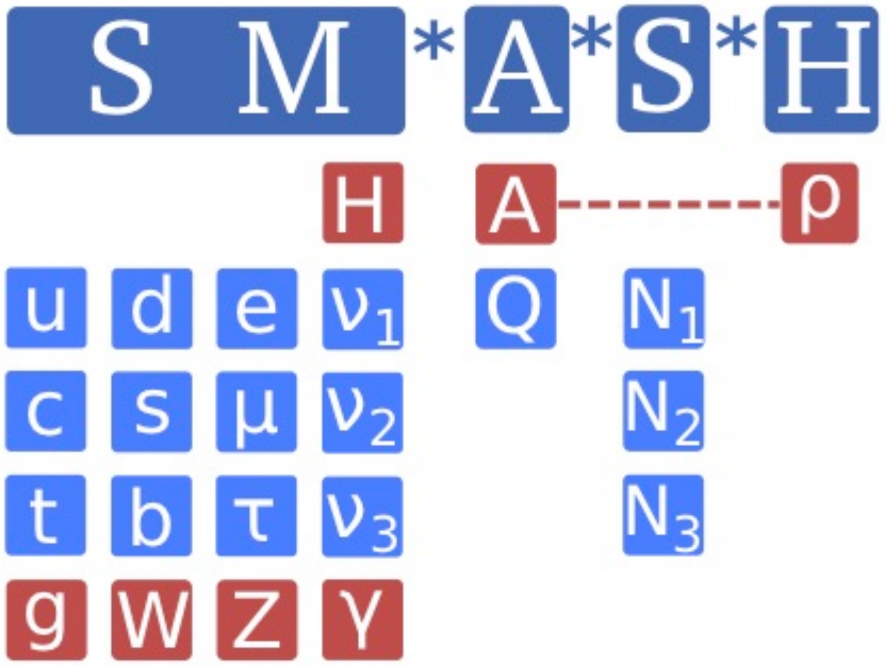
Unifying Inflation, Dark Matter, and Seesaw with PQ Field

One SM*A*S*H to rule them all ...

- Extension of SM to PQSM plus three SM singlet neutrinos, getting their Majorana masses also through PQ 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]

SM*Axion*Seesaw*Higgs Portal Inflation



Unifying Inflation, Dark Matter, and Seesaw with PQ Field

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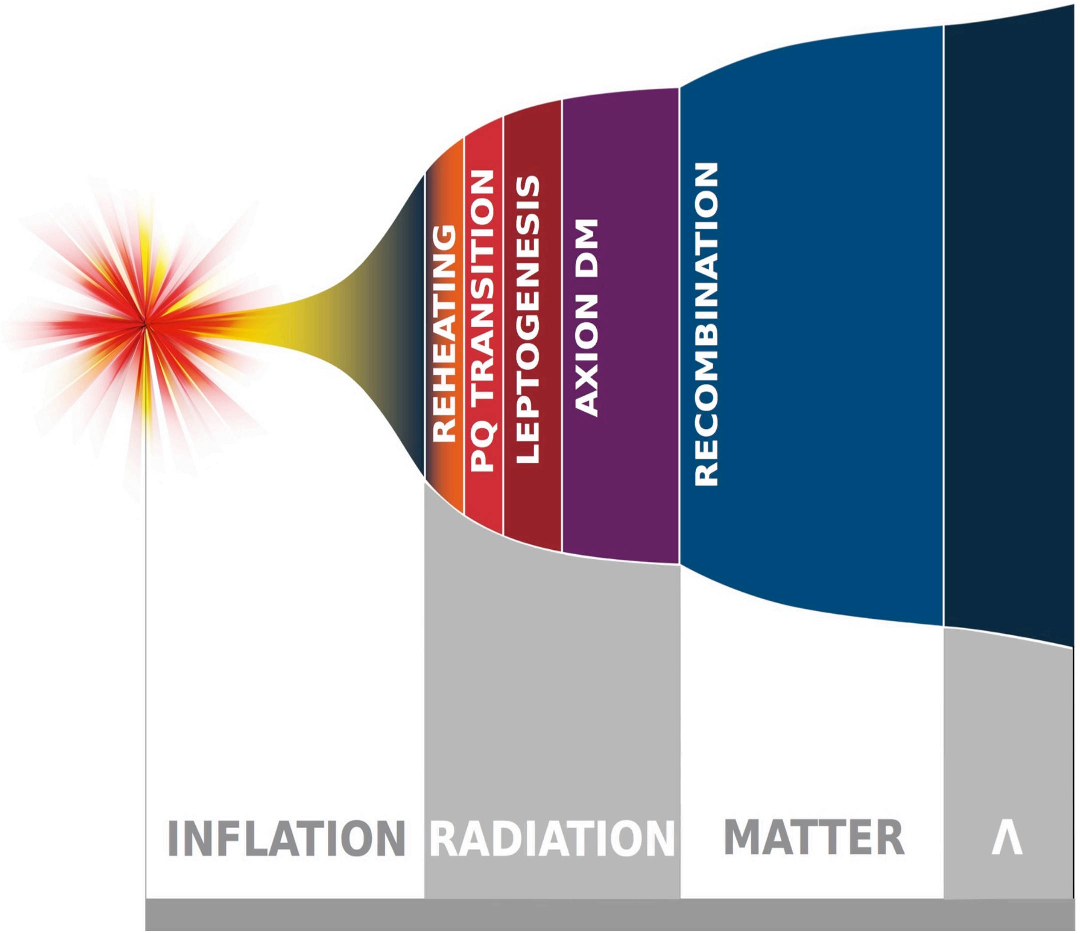
[Dias et al. `14; Ballesteros et al. `16]

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



[desy.de]

Summary

- PQ extensions of SM very attractive:
  - Axion solves strong CP puzzle
  - Axion is dark matter candidate (for $f_A \gtrsim 10^8\,\mathrm{GeV} \;\Leftrightarrow m_A \lesssim 60\,\mathrm{meV}$)
  - Saxion/Higgs is inflaton candidate (for $1 \gtrsim \xi_\sigma \simeq 2\times 10^5 \sqrt{\lambda_\sigma} \gtrsim 10^{-3}$)
- PQSM with saxion/Higgs inflation very predictive and thus experimentally testable in near future:
  - CMB observatories: $r \gtrsim 0.004;\quad \Delta N_{\rm eff}^{\nu} \gtrsim 0.03$
  - Axion dark matter experiments: $m_A \gtrsim 30\,\mu\mathrm{eV}$

STAY TUNED!

Back-Up: Topological Susceptibility

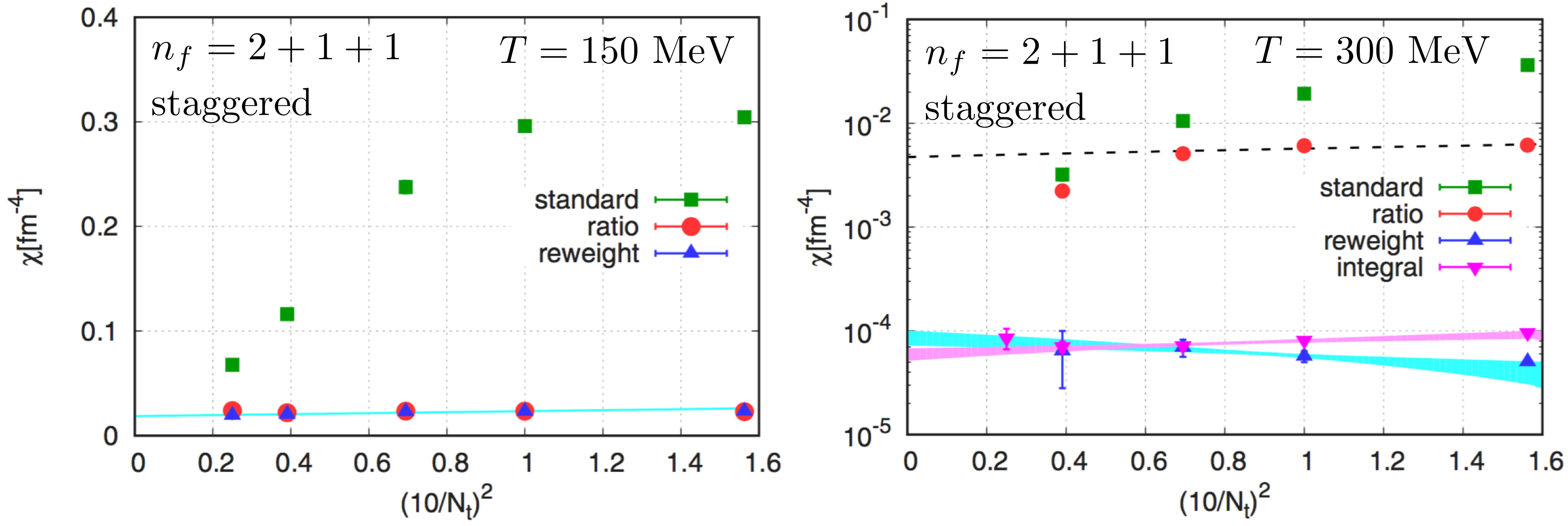
- Topological susceptibility notoriously difficult to calculate on lattice
  1. Large cutoff effects when exploiting action with non-chiral quarks to calculate topo-logical observables
  2. Tiny topological susceptibility needs extremely long simulation threads to observe enough changes of topological sectors
- Solutions of these problems:

[Borsanyi et al. `16]

  1. Eigenvalue reweighting technique: Substitute topology related eigenvalues of non-chiral quark Dirac operator with its corresponding eigenvalues in continuum
  2. Fixed sector integral technique: Measure logarithmic differential of topological sus-ceptibility which is related to quantities to be measured in fixed topological sectors. Then integrate.

Back-Up: Topological Susceptibility

- Comparison of lattice spacing dependence of topological susceptibility determined via different methods:



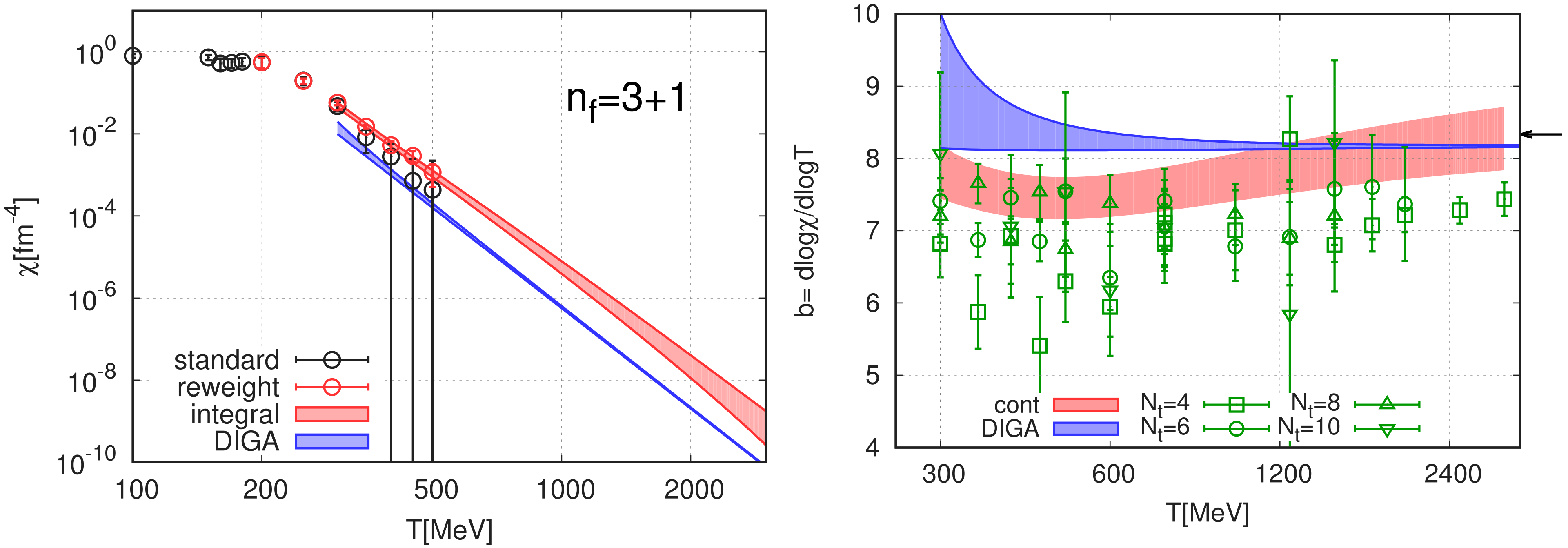
[Borsanyi et al. `16]

- At high temperatures, brute force („standard“) method and ratio method suffer from strong cutoff effects

Back-Up: Topological Susceptibility

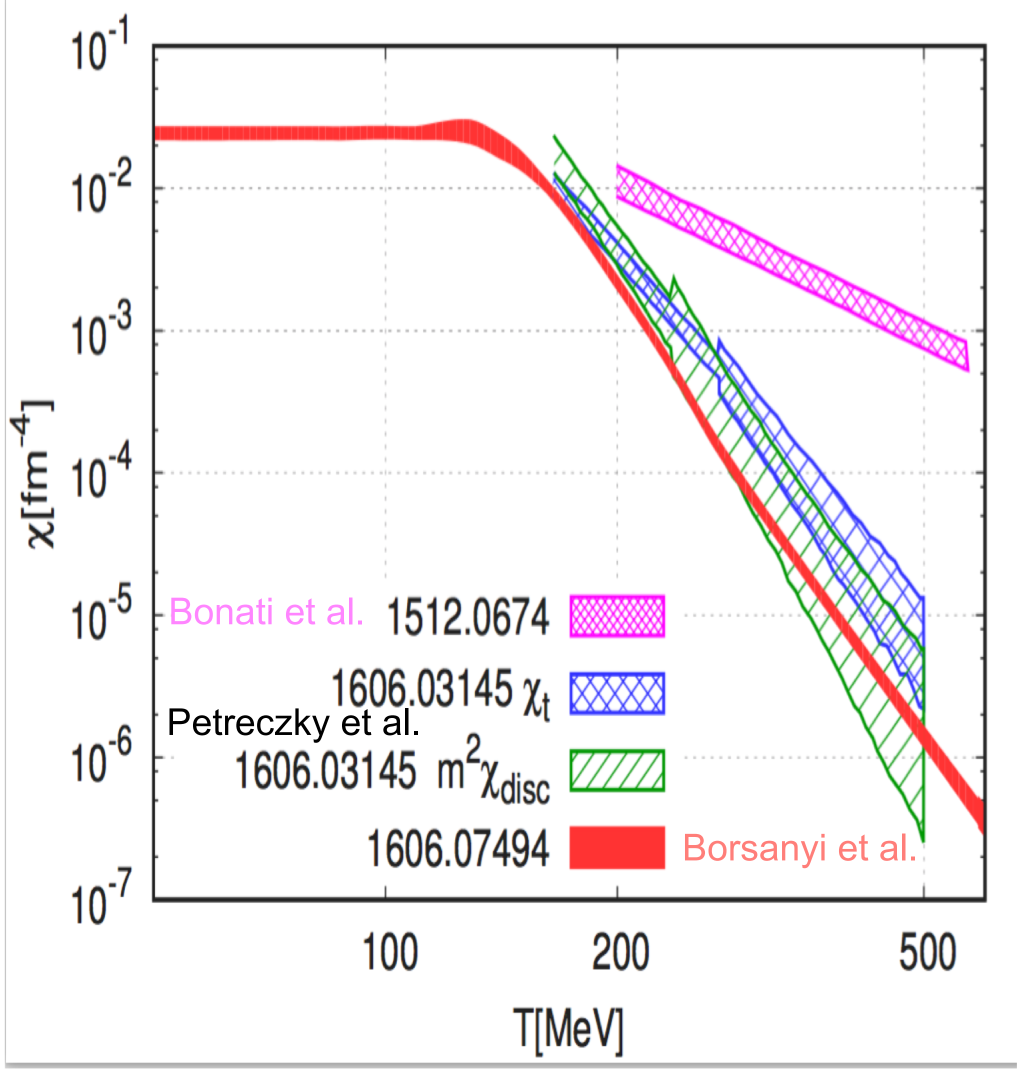
- Result:

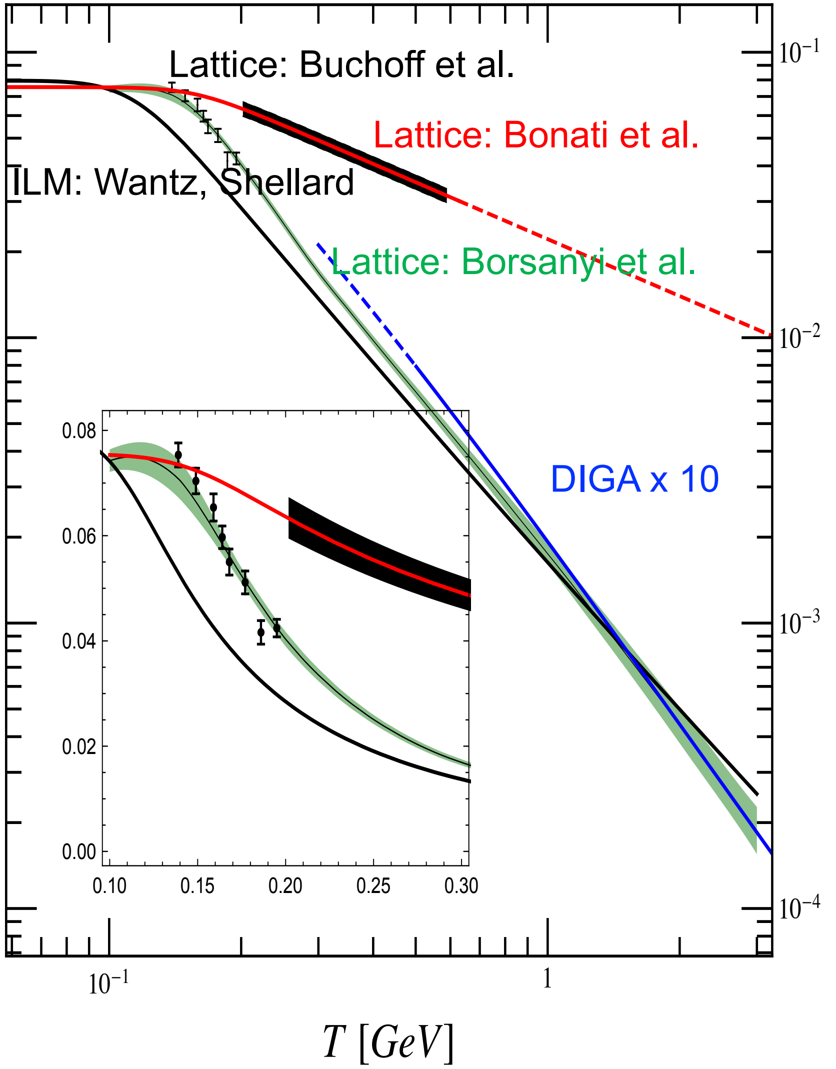
[Borsanyi et al. `16]



- Temperature slope close to dilute instanton gas approximation (DIGA)
- DIGA underestimates topological susceptibility by overall normalization „K factor“ of order ten (should be improved in two-loop DIGA)

Back-Up: Topological Susceptibility





[Borsanyi `16]

[Ballesteros,Redondo, AR,Tamarit `16]

Back-Up: DM Axion Mass in Post-Inflationary PQ SB Scenario

- For $\kappa \gg 1$, string's interactions with the long range PQ field ($\propto f_A^2$) become less important relative to string evolution under tension ($\propto f_A^2 \kappa$)
- For $\kappa \gg 1$, string behavior should approach that of infinitely thin, i.e. local Nambu-Goto strings
- New method: exploit UV extension of PQ field theory, with additional comp-lex scalar and additional local U(1) symmetry, [Klaer,Moore `17]

$$T_{\rm str} = \pi f_A^2 \kappa$$
$$\kappa = \ln(\sqrt{2\lambda_\sigma} f_A / H)$$

$$\mathcal{L} = \mathcal{L}_{\rm NG} + \mathcal{L}_{\rm GS} + \mathcal{L}_{\rm KR}\,,$$
$$\mathcal{L}_{\rm NG} = \bar\kappa \pi f_A^2 \int d\sigma \sqrt{y'^2(\sigma)(1 - \dot y^2(\sigma))}\,,$$
$$\mathcal{L}_{\rm GS} = f_A^2 \int d^3x\, \partial_\mu\theta \partial^\mu\theta\,,$$
$$\mathcal{L}_{\rm KR} = \int d^3x\, A_{\mu\nu} j^{\mu\nu}\,,$$
$$H_{\mu\nu\alpha} = f_A \epsilon_{\mu\nu\alpha\beta}\partial^\beta\theta = \partial_\mu A_{\nu\alpha} + {\rm cyclic}\,,$$
$$j^{\mu\nu} = -2\pi f_A \int d\sigma\, \left(v^\mu y'^\nu - v^\nu y'^\mu\right) \delta^3(x - y(\sigma))$$

$$-\mathcal{L}(\varphi_1,\varphi_2,A_\mu) = \frac{1}{4e^2}F_{\mu\nu}F^{\mu\nu} + \Big|(\partial_\mu - iq_1A_\mu)\varphi_1\Big|^2 + \Big|(\partial_\mu - iq_2A_\mu)\varphi_2\Big|^2 + \frac{m_1^2}{8v_1^2}\left(2\varphi_1^*\varphi_1 - v_1^2\right)^2 + \frac{m_2^2}{8v_2^2}\left(2\varphi_2^*\varphi_2 - v_2^2\right)^2 + \frac{\lambda_{12}}{2}\left(2\varphi_1^*\varphi_1 - v_1^2\right)\left(2\varphi_2^*\varphi_2 - v_2^2\right)$$

Back-Up: DM Axion Mass in Post-Inflationary PQ SB Scenario

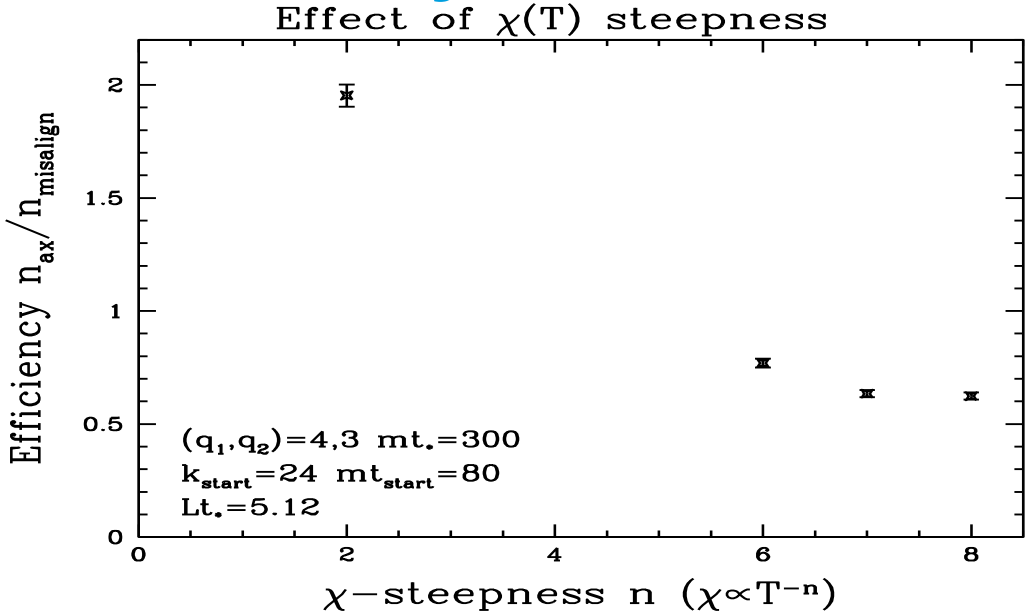
- Exploiting lattice results on topological susceptibility of [Borsanyi et al. `16] :

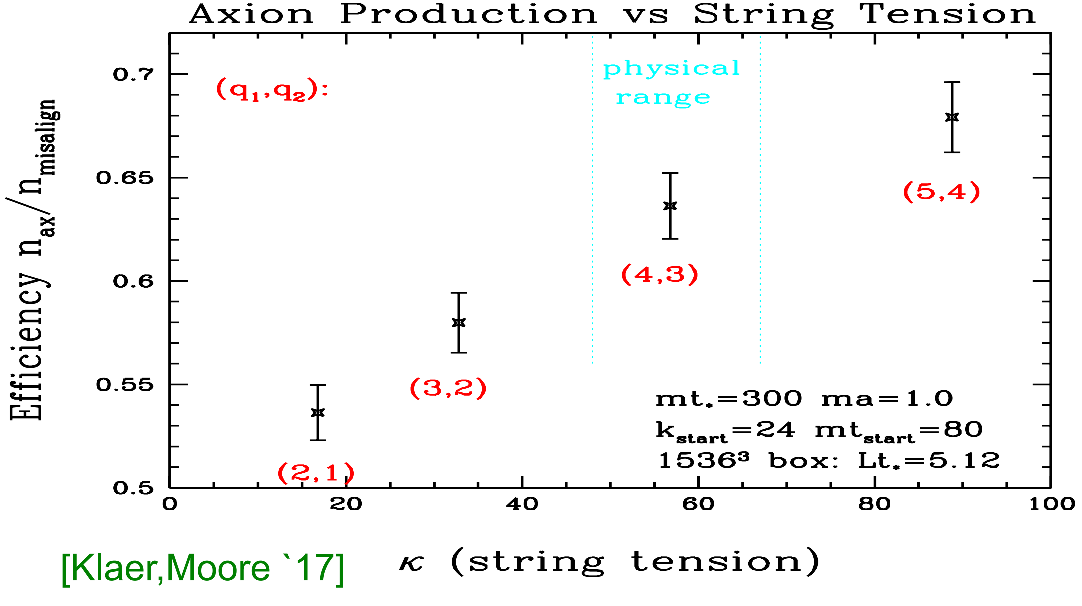
$$m_A = 26.2 \pm 3.4\,\mu\mathrm{eV}$$ [Klaer,Moore `17]

- Axion production efficiency smaller than angle-average of ``realignment'' mechanism

$$\Omega_A^{\rm vr} h^2 = 0.12 \left(\frac{29.7\ \mu\mathrm{eV}}{m_A}\right)^{1.165}$$

  - Simple sum
    $$\Omega_A^{\rm tot} = \Omega_A^{\rm vr} + \Omega_A^{\rm string+wall}$$
    double counts
    - Energy in domain walls is the energy of field misalignment, from values $\theta \sim \pi$

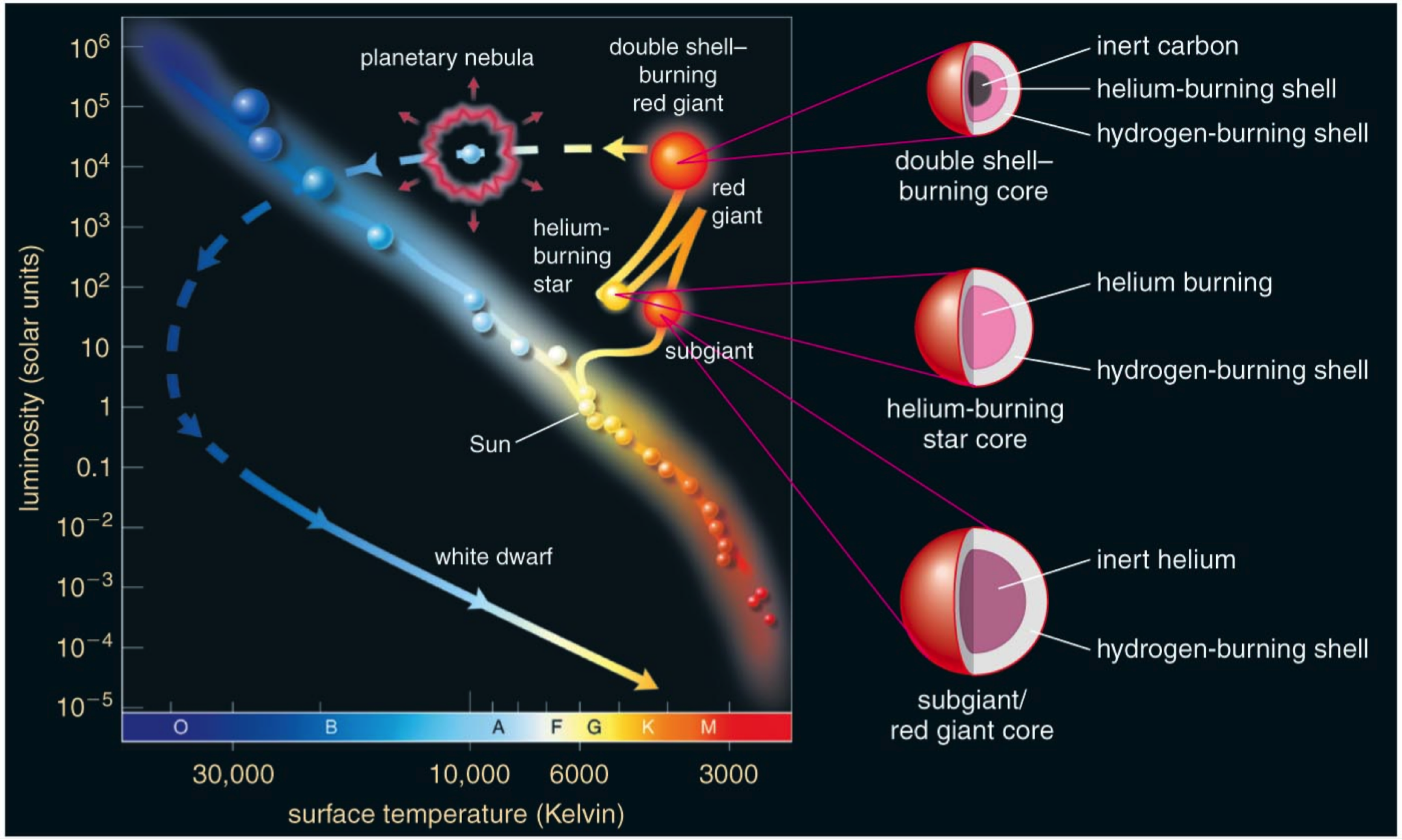




[Klaer,Moore `17]

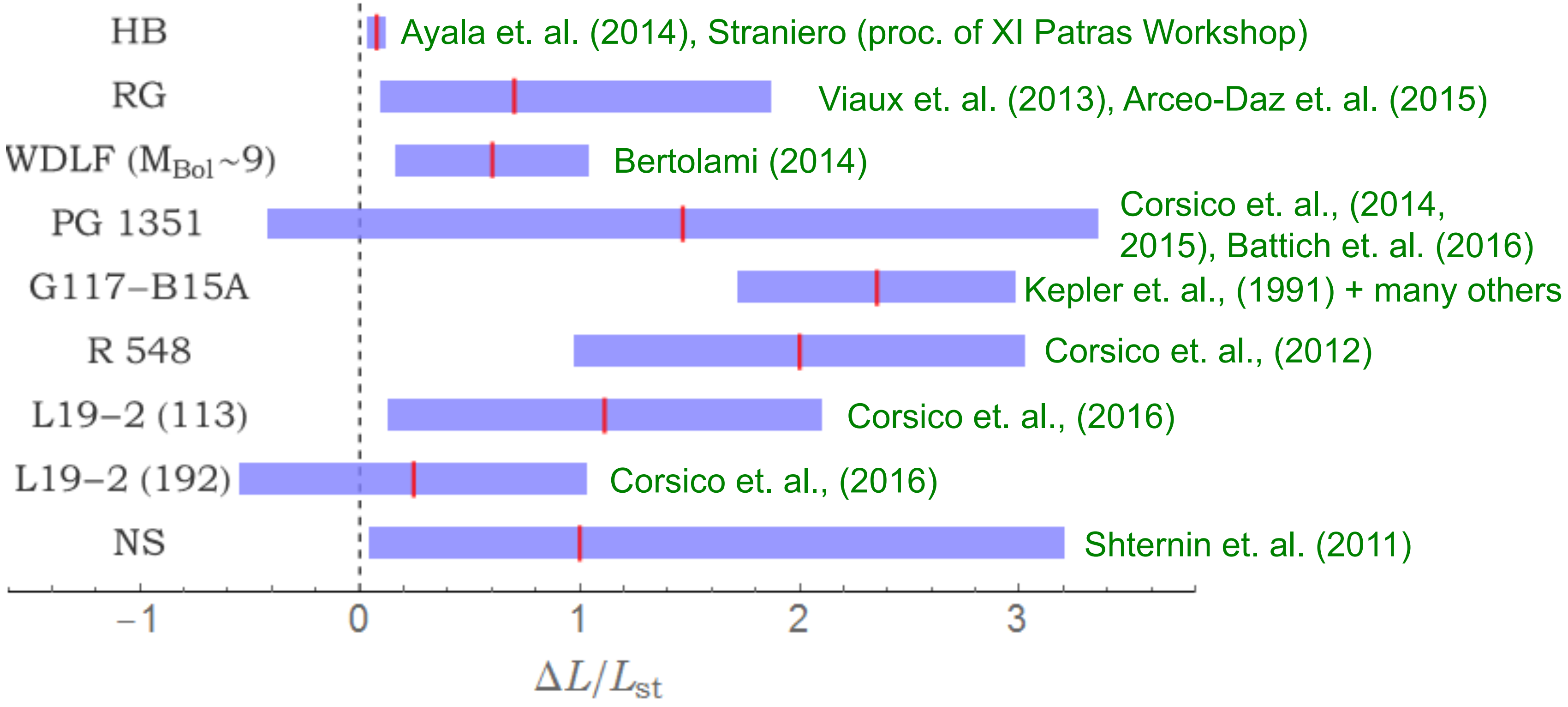
Back-Up: Energy Losses of Stars?

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



Back-Up: Energy Losses of Stars?

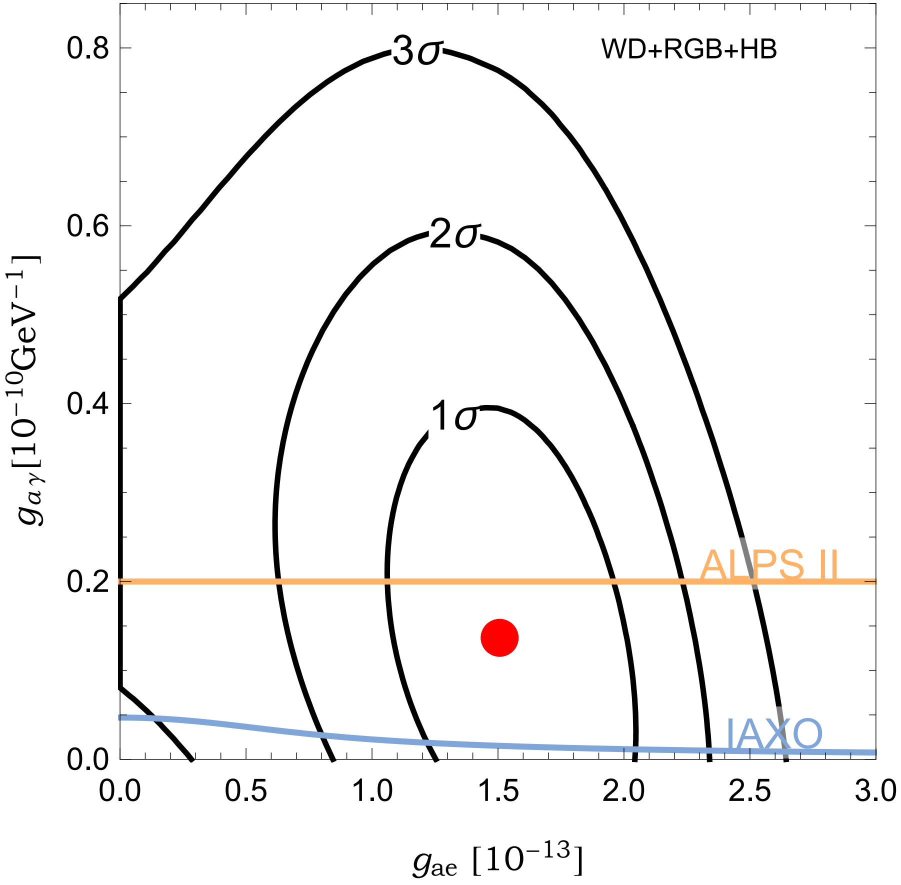
- Practically every stellar systems seems to be cooling faster than predicted by models



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

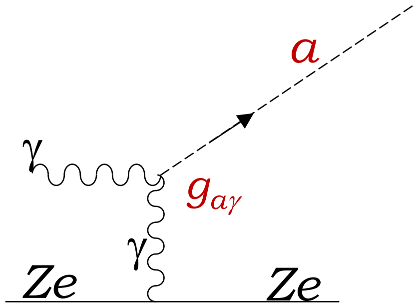
Back-Up: Energy Losses of Stars?

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

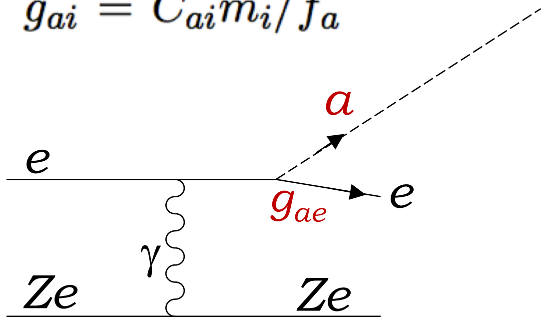


[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

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



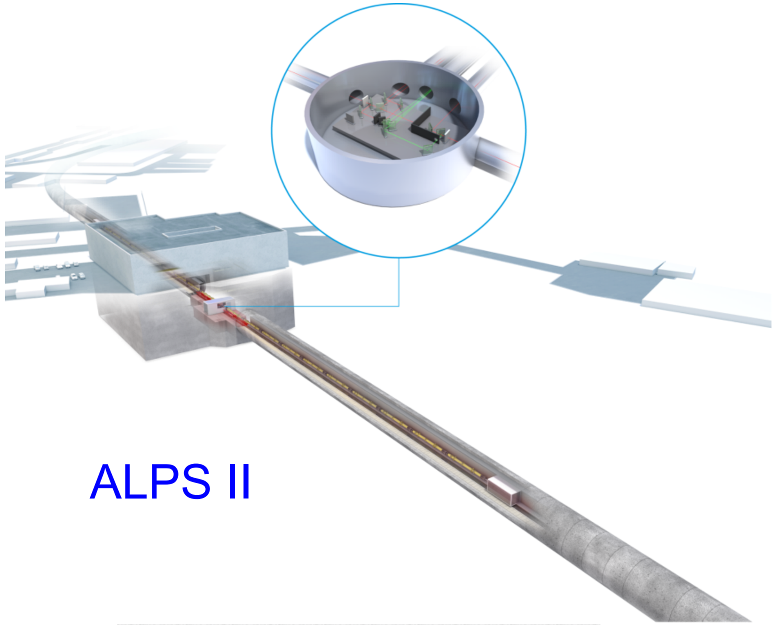
$$g_{ai} = C_{ai} m_i / f_a$$

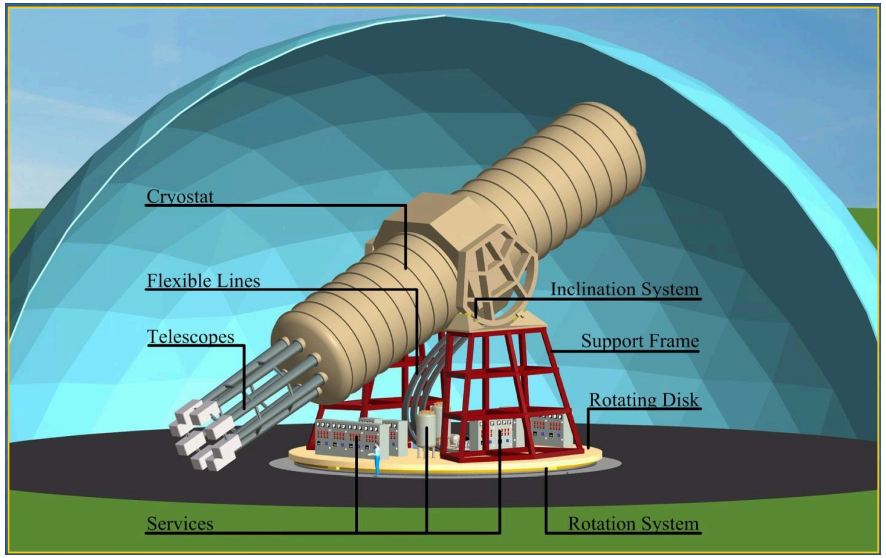


Back-Up: Energy Losses of Stars?

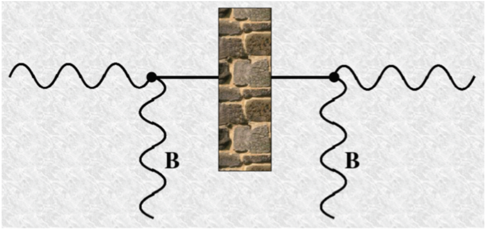
- Excessive energy losses of HBs, RG, WDs can be explained at one stroke by production of axion/ALP with coupling to photons and electrons and probed by next generation experiments:

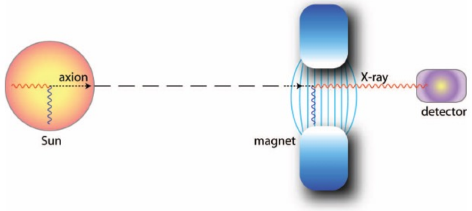
IAXO





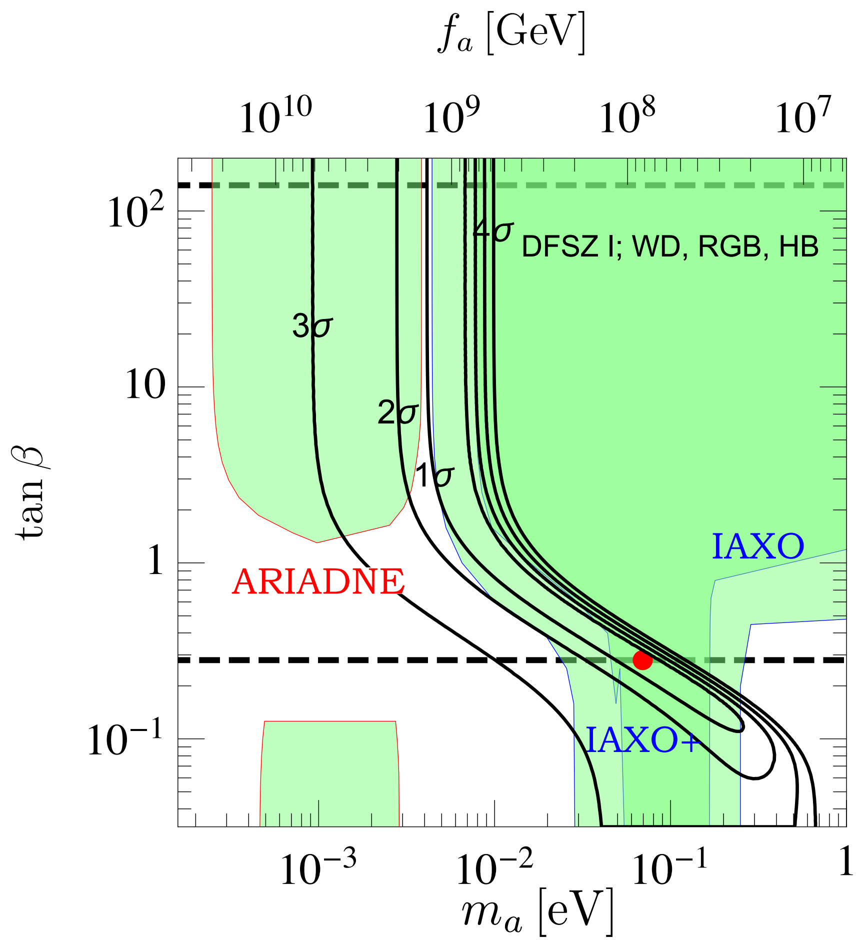
ALPS II





Back-Up: 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:

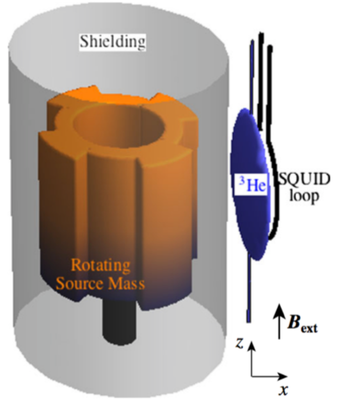


[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

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

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

ARIADNE



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

- $SO(10)$ GUT SMASH?

[Ernst,AR,Tamarit `18 and in prep.]

  - Minimal scalar sector predicts GUT-scale decay constant
  - Need to extend scalar sector in order to accommodate smaller decay constant

Minimal $SO(10) \times U(1)_{\mathrm{PQ}}$ 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