Axion Models.

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HELMHOLTZ
ASSOCIATION

DESY

Kim-Shifman-Vainshtein-Zakharov (KSVZ) Model

- Add singlet complex scalar field σ featuring a global $U(1)_{\rm PQ}$ symmetry to Standard Model (SM)

- Parameters in most general scalar potential such that symmetry spontaneously broken in vacuum:

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

- For $\lambda_H, \lambda_\sigma > 0$ and $\lambda_{H\sigma}^2 < \lambda_H \lambda_\sigma$, minimum of potential attained at:

$$\langle H^\dagger H\rangle = v^2/2, \qquad \langle|\sigma|^2\rangle = v_{\rm PQ}^2/2$$

- Expansion about VEV:

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

  - Excitation of modulus: $m_\rho = \sqrt{2\,\lambda_\sigma}\, v_{\rm PQ} + \mathcal{O}\left(\frac{v}{v_{\rm PQ}}\right)$
  - Excitation of angle (Nambu-Goldstone Boson (NGB)): $m_A = 0$

- Low energy effective field theory: SM + massless non-interacting NGB

Kim-Shifman-Vainshtein-Zakharov (KSVZ) Model

[Kim 79;Shifman,Vainshtein,Zakharov 80]

- Add color-triplet, electroweak singlet fermion $Q = (Q_L, Q_R)$
- PQ scalar and exotic quark are assumed to transform under $U(1)_{\rm PQ}$ as

$$\sigma \to e^{i\alpha}\sigma\,, \qquad Q_L \to e^{i\alpha/2} Q_L\,, \qquad Q_R \to e^{-i\alpha/2} Q_R$$

- Invariant Lagrangian:

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu \sigma^* \partial^\mu \sigma - V(H,\sigma) + \frac{i}{2}\overline{Q}\partial_\mu \gamma^\mu Q - y\overline{Q}_L \sigma Q_R$$

- After PQ symmetry breaking, integrate out modulus: $\left[\sigma(x) = \frac{v_{\rm PQ}}{\sqrt{2}} e^{iA(x)/v_{\rm PQ}}\right]$

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu A \partial^\mu A + \frac{i}{2}\overline{Q}\partial_\mu \gamma^\mu Q - y\frac{v_{\rm PQ}}{\sqrt{2}} e^{iA/v_{\rm PQ}}\overline{Q}_L Q_R$$

- Redefining fermion by local transformation,

$$Q_L \to e^{iA/2v_{\rm PQ}} Q_L; \quad Q_R \to e^{-iA/2v_{\rm PQ}} Q_R$$

we obtain:

$$\mathcal{L} \supset \frac{1}{2}\left(\partial_\mu A\right)^2 + \frac{i}{2}\overline{Q}\partial_\mu \gamma^\mu Q - y\frac{v_{\rm PQ}}{\sqrt{2}}\overline{Q}_L Q_R + \frac{1}{2}\frac{\partial_\mu A}{v_{\rm PQ}}\overline{Q}\gamma^\mu \gamma_5 Q$$

Kim-Shifman-Vainshtein-Zakharov (KSVZ) Model

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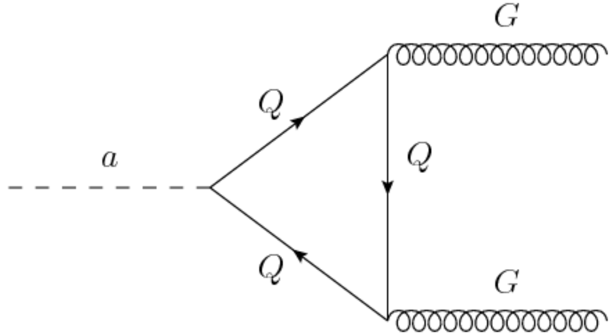
- Coupling of axion with exotic color-triplet gives rise to effective interaction with gluons via triangle anomaly:

$$\mathcal{L} \supset -\frac{1}{2}\frac{A}{v_{\rm PQ}}\partial_\mu\left(\overline{Q}\gamma^\mu\gamma_5 Q\right) = -\frac{\alpha_s}{8\pi}\frac{A}{v_{\rm PQ}} G^c_{\mu\nu}\tilde{G}^{c\,\mu\nu}$$



- Integrating out heavy color-triplet, end up with effective theory at scales much below PQ scale $v_{\rm PQ}$, but above QCD scale $\Lambda_{\rm QCD}$:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial^\mu A\,\partial_\mu A - \frac{\alpha_s}{8\pi}\frac{A}{v_{\rm PQ}} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}$$

Kim-Shifman-Vainshtein-Zakharov (KSVZ) Model

- Indeed model with space-time dependent theta parameter:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu A)^2 - \frac{\alpha_s}{8\pi}\frac{A}{f_A} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}; \qquad f_A = v_{\rm PQ}$$

- Anomalous coupling can be reshuffled by quark field redefinition,

$$q = \left(\begin{array}{c} u \\ d \end{array}\right) \to e^{i\gamma_5 \frac{A}{f_A}\frac{Q_A}{2}} \left(\begin{array}{c} u \\ d \end{array}\right), \qquad {\rm tr}\, Q_A = 1$$

yielding, taking into account anomaly of chiral currents of light quarks,

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial_\mu A)^2 - \bar{q}_L M_A q_R + 6\,{\rm tr}\left(Q_A Q^2\right) \frac{\alpha}{8\pi}\frac{A}{f_A} F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}\frac{\partial_\mu A}{f_A}\,\bar{q}\gamma^\mu\gamma_5 Q_A q$$

$$M_A = e^{i\frac{A}{2f_A}Q_A} M_q\, e^{i\frac{A}{2f_A}Q_A}, \qquad M_q = \left(\begin{array}{cc} m_u & 0 \\ 0 & m_d \end{array}\right), \qquad Q = \left(\begin{array}{cc} \frac{2}{3} & 0 \\ 0 & -\frac{1}{3} \end{array}\right)$$

- Anomalous coupling to QCD encoded in phase dependence of quark mass matrix of lightest quarks

[Di Vecchia,Veneziano `80;Georgi,Kaplan,Randall 86;di Cortona et al. 16]

Kim-Shifman-Vainshtein-Zakharov (KSVZ) Model

- At leading order in chiral expansion all non-derivative dependence on axion contained in mass terms:

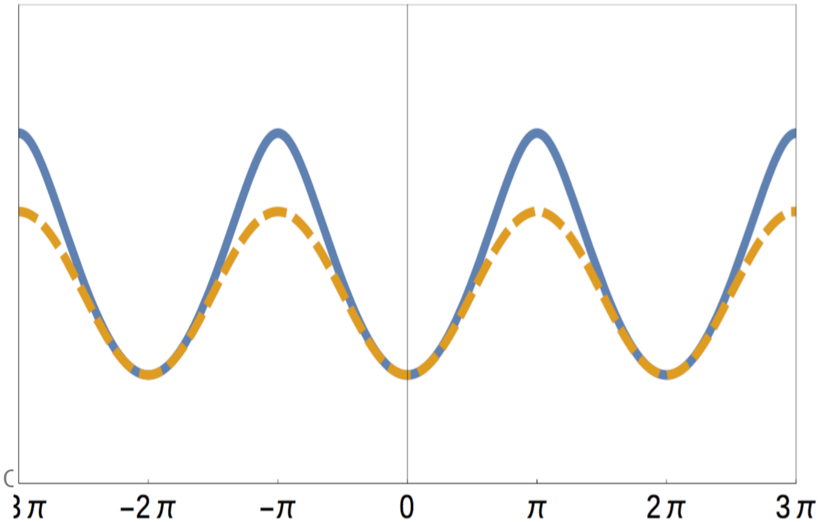
$$\mathcal{L}_{p^2} \supset 2B_0 \frac{f_\pi^2}{4} \mathrm{tr}\left(U M_A^\dagger + M_A U^\dagger\right) \; ; \quad U = e^{i\Pi/f_\pi} \; ; \quad \Pi = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}$$

- Choosing $Q_A = M_q^{-1}/\mathrm{tr}(M_q^{-1})$ to avoid mass mixing between the axion and the neutral pion, one finds for axion potential and mass:

$$V(A) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{A}{2 f_A}\right)}$$

$$m_A^2 = \frac{d^2 V}{dA^2}_{|A=0} = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_A^2}$$

- Strong CP problem solved ($\langle A \rangle = 0$)



[di Cortona et al. `16]

Kim-Shifman-Vainshtein-Zakharov (KSVZ) Model

- Low energy interactions of KSVZ axion:

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial_\mu A)^2 - V(A) - C_{A\gamma}\frac{\alpha}{8\pi}\frac{A}{f_A}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{\partial_\mu A}{f_A}\sum_N C_{AN}\bar{N}\gamma^\mu\gamma_5 N$$

  - Potential:

$$V(A) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{A}{2f_A}\right)}$$

  - Coupling to photon:

$$C_{A\gamma} = -\frac{2}{3}\frac{4m_d + m_u}{m_d + m_u} \simeq -1.92$$

[Kaplan 85;Srednicki `85]

  - Coupling to nucleons:

$$C_{Ap} = -0.47(3)\,, \qquad C_{An} = -0.02(3)$$

[di Cortona et al. `16]

A Minimal Model of Particle Physics and Cosmology

- Unify PQ U(1) symmetry with lepton symmetry: add three right-handed SM-singlet neutrinos to KSVZ like model [Shin 87; Dias et al. `14]

$$\mathcal{L} \supset -\Big[Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j$$
$$+ y\,\tilde{Q}\sigma Q + y_{Q_d\,i} \sigma Q d_i + h.c. \Big]$$

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

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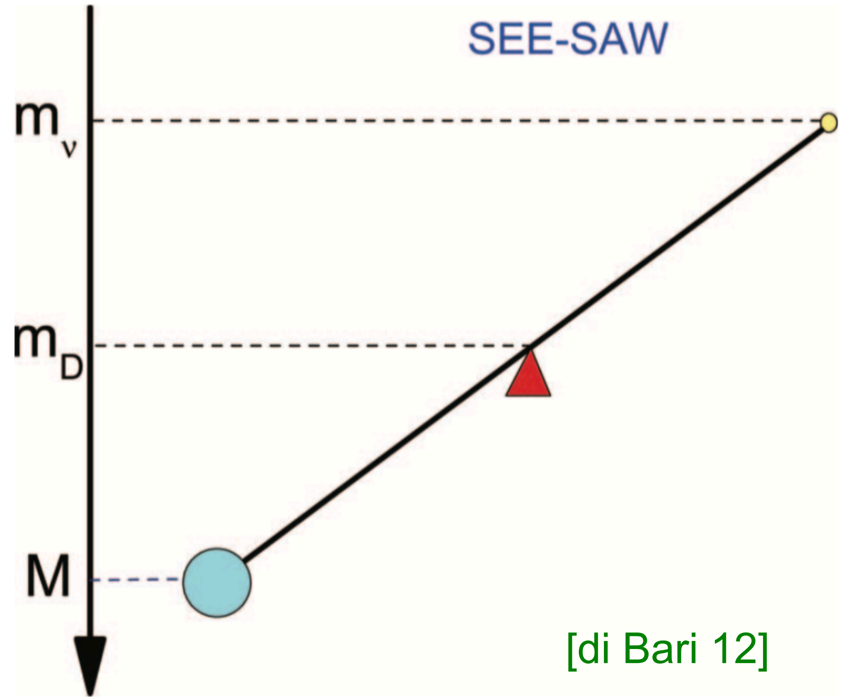
1. No strong CP problem
2. Axion dark matter
3. See-saw explanation of active neutrino masses

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



[di Bari 12]

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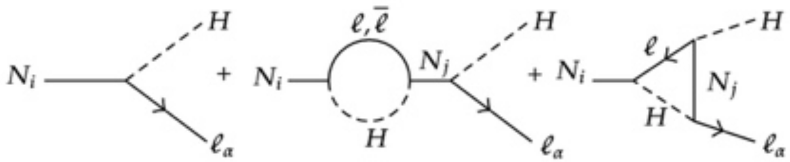

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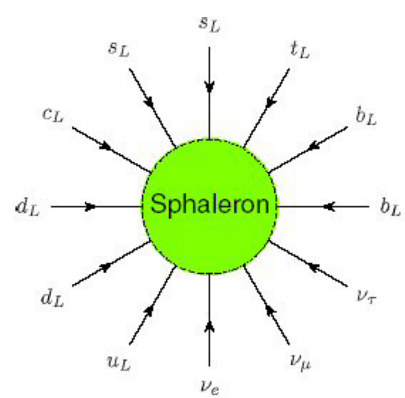
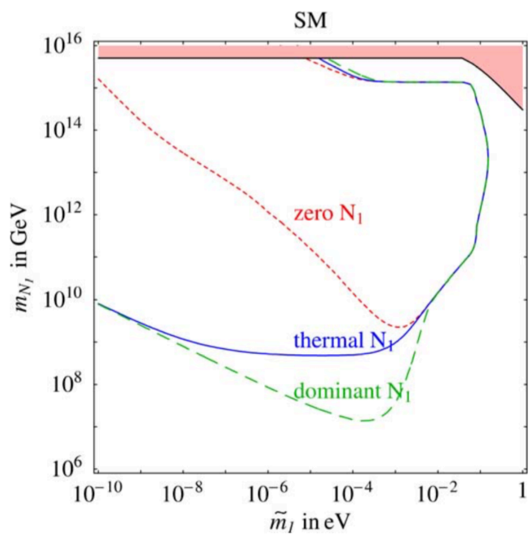
4. Explains matter-anti-matter asymmetry by thermal leptogenesis



[Buchmüller et al. 04]



[Giudice et al. 04]

A Minimal Model of Particle Physics and Cosmology

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SM * Axion * See-saw * Higgs portal inflation

[Ballesteros,Redondo, AR,Tamarit, 1608.05414]

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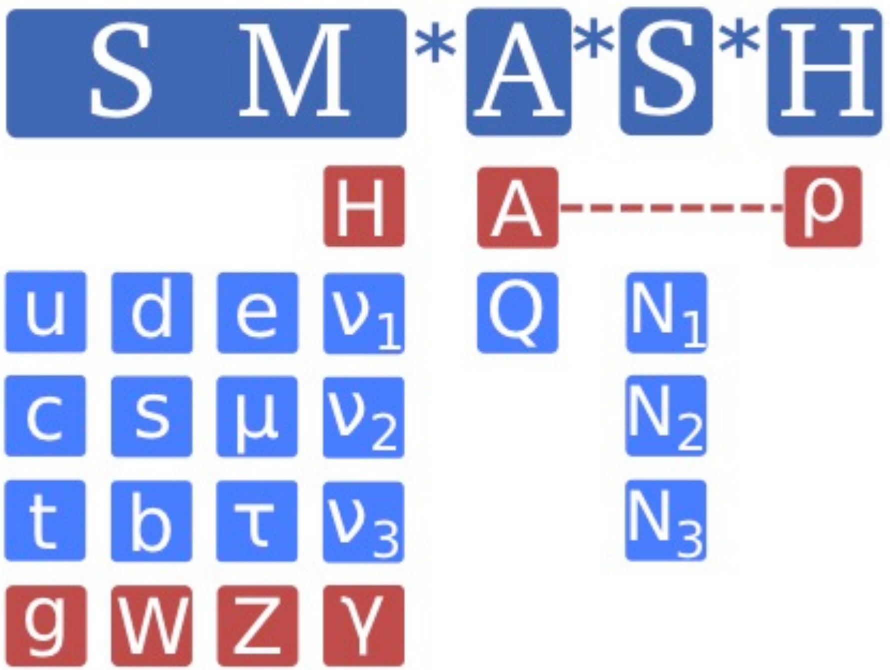

Higgs Portal Inflation in SMASH

- Allow for non-minimal coupling of Higgs and PQ scalar to gravity,

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

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

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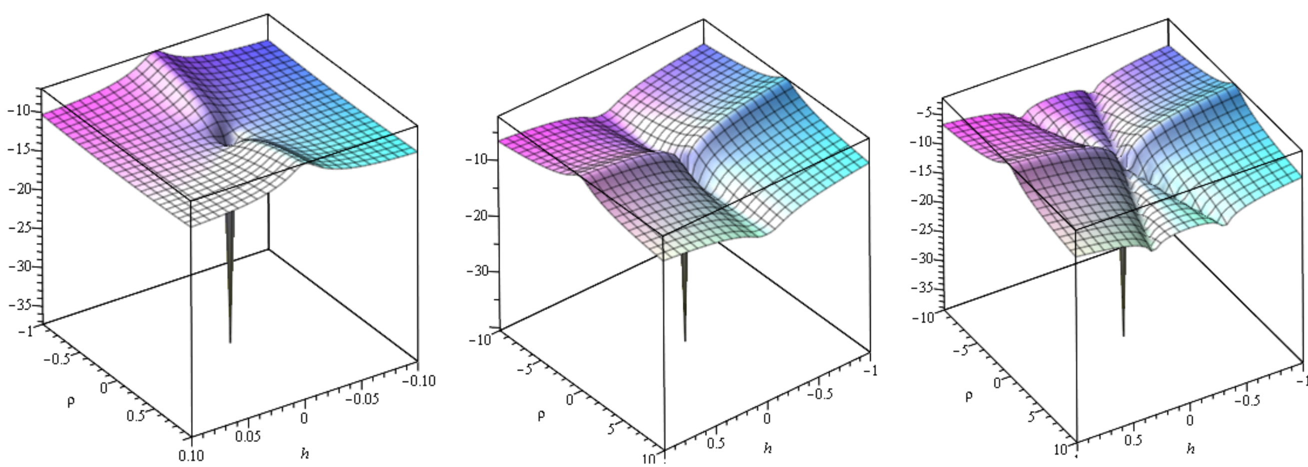
- Potential has valleys = attractors for Higgs Inflation (HI), Hidden Scalar Inflation (HSI) or mixed Higgs Hidden Scalar Inflation (HHSI), depen-ding on relative signs of $\kappa_H \equiv \lambda_{H\sigma}\xi_H - \lambda_H\xi_\sigma\,, \quad \kappa_\sigma \equiv \lambda_{H\sigma}\xi_\sigma - \lambda_\sigma\xi_H$



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

[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

Higgs Portal Inflation in SMASH

- CMB observables

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

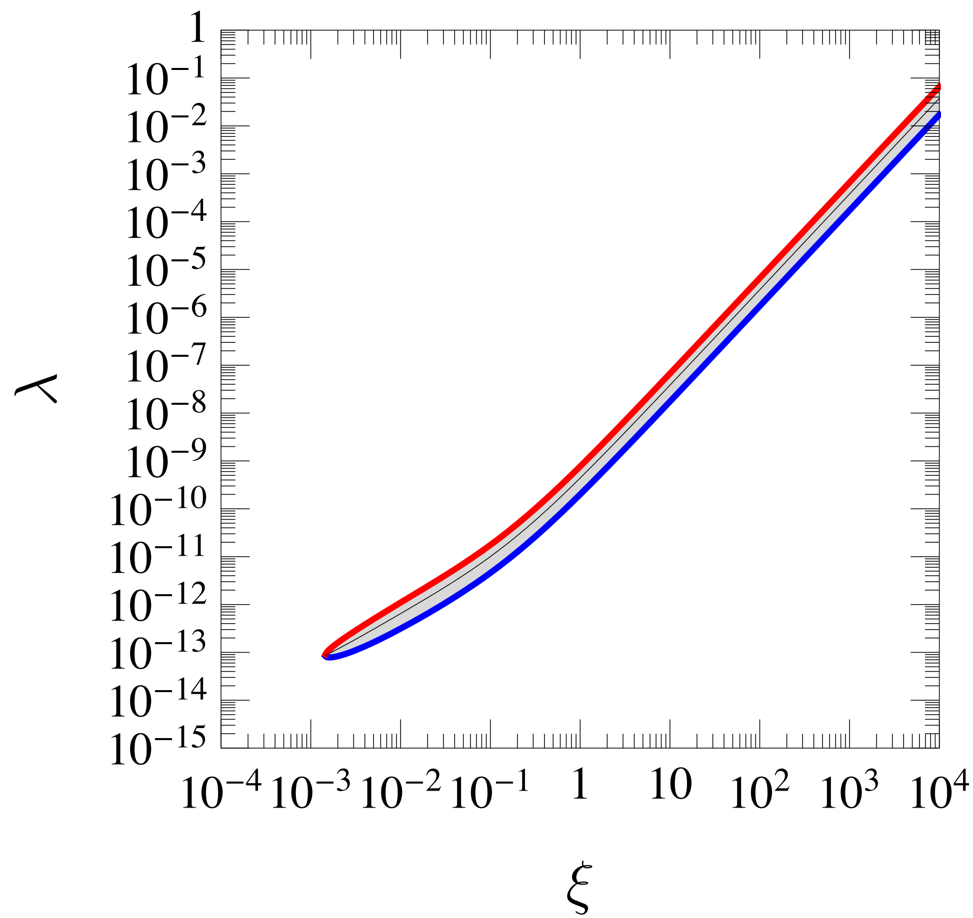
fit by

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

where

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

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



[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

Higgs Portal Inflation in SMASH

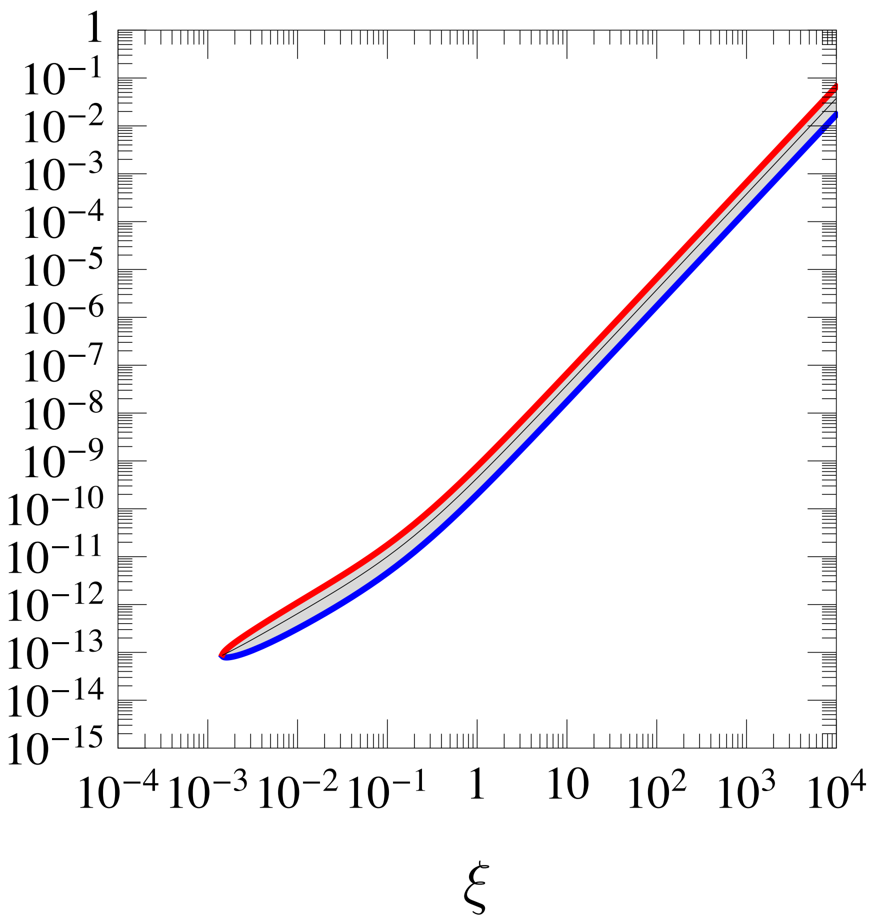
- **HI** requires huge non-minimal coupling of the Higgs:

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

- Perturbative unitarity lost in **HI**

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

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



[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

Reheating in SMASH

- Fundamental questions:
  - PQ symmetry restored after inflation?
  - Reheating temperature large enough for successful thermal leptogenesis?
- SMASH complete model: evolution after inflation can be calculated

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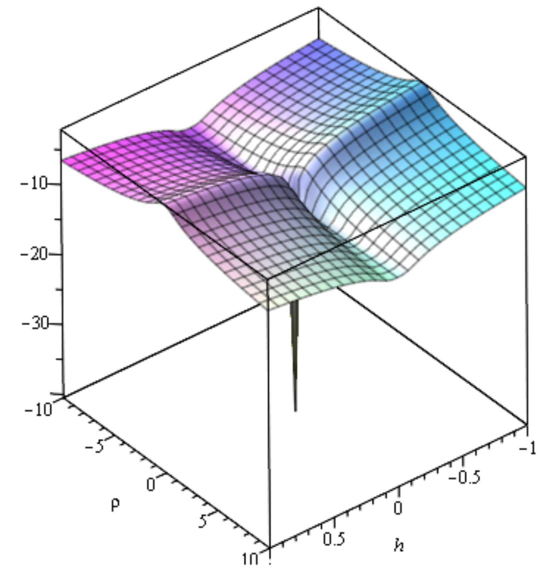
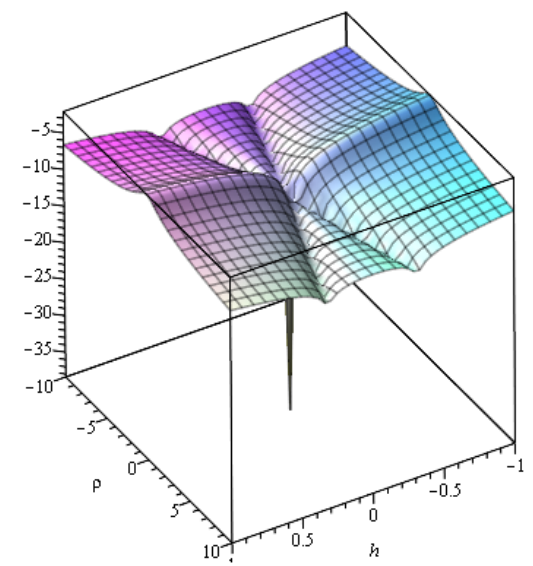
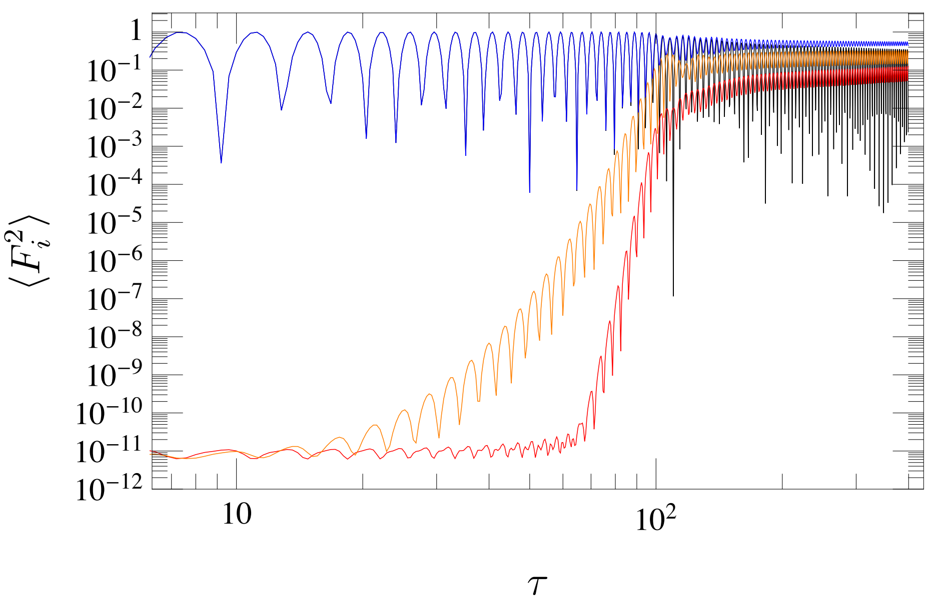
  - Reheating temperature large enough for successful thermal leptogenesis?
- SMASH complete model: evolution after inflation can be calculated
- Both in HSI and HHSI with $\xi_\sigma \lesssim 1$, slow-roll inflation ends at a value of $\rho \sim \mathcal{O}(M_P)$
- Inflaton starts to undergo Hubble-damped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

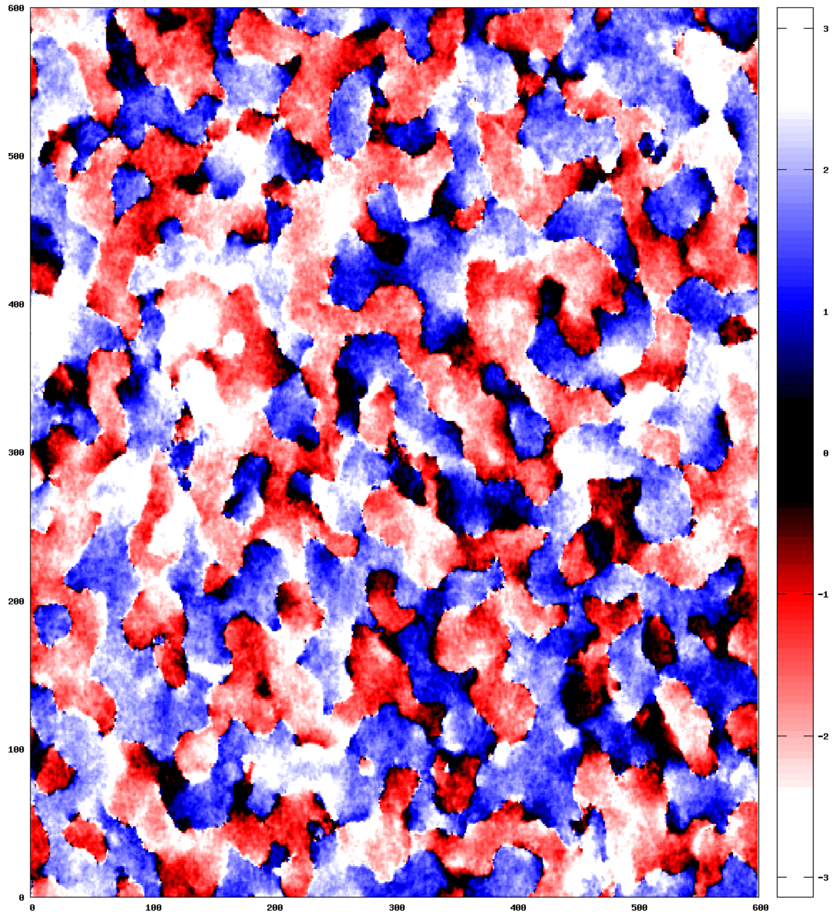




Reheating in SMASH

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





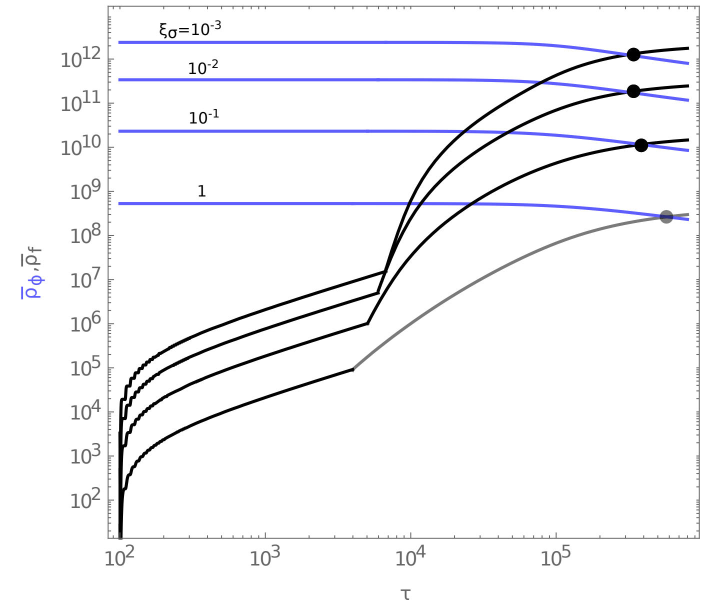
Reheating in SMASH

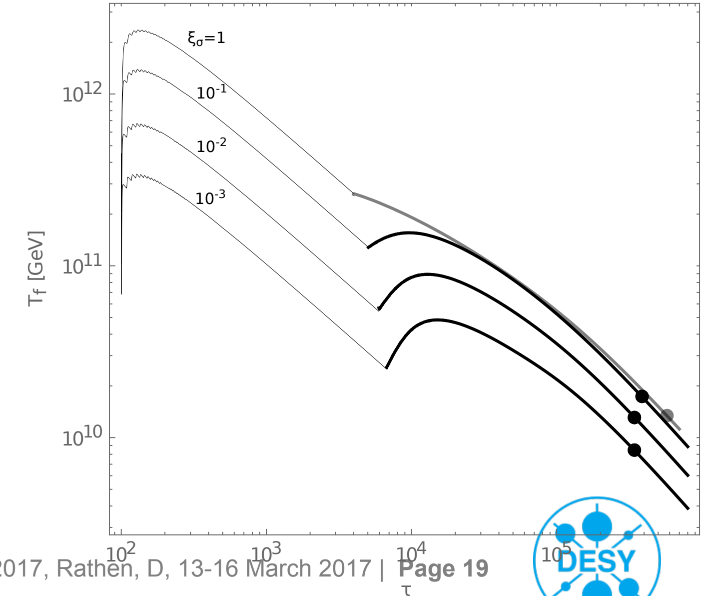
- Perturbative reheating:
  - HSI: Large induced particle masses quench inflaton decays or annihilations into SM particles, resulting in low reheating temperature and too much cosmic axion background (CAB) radiation

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

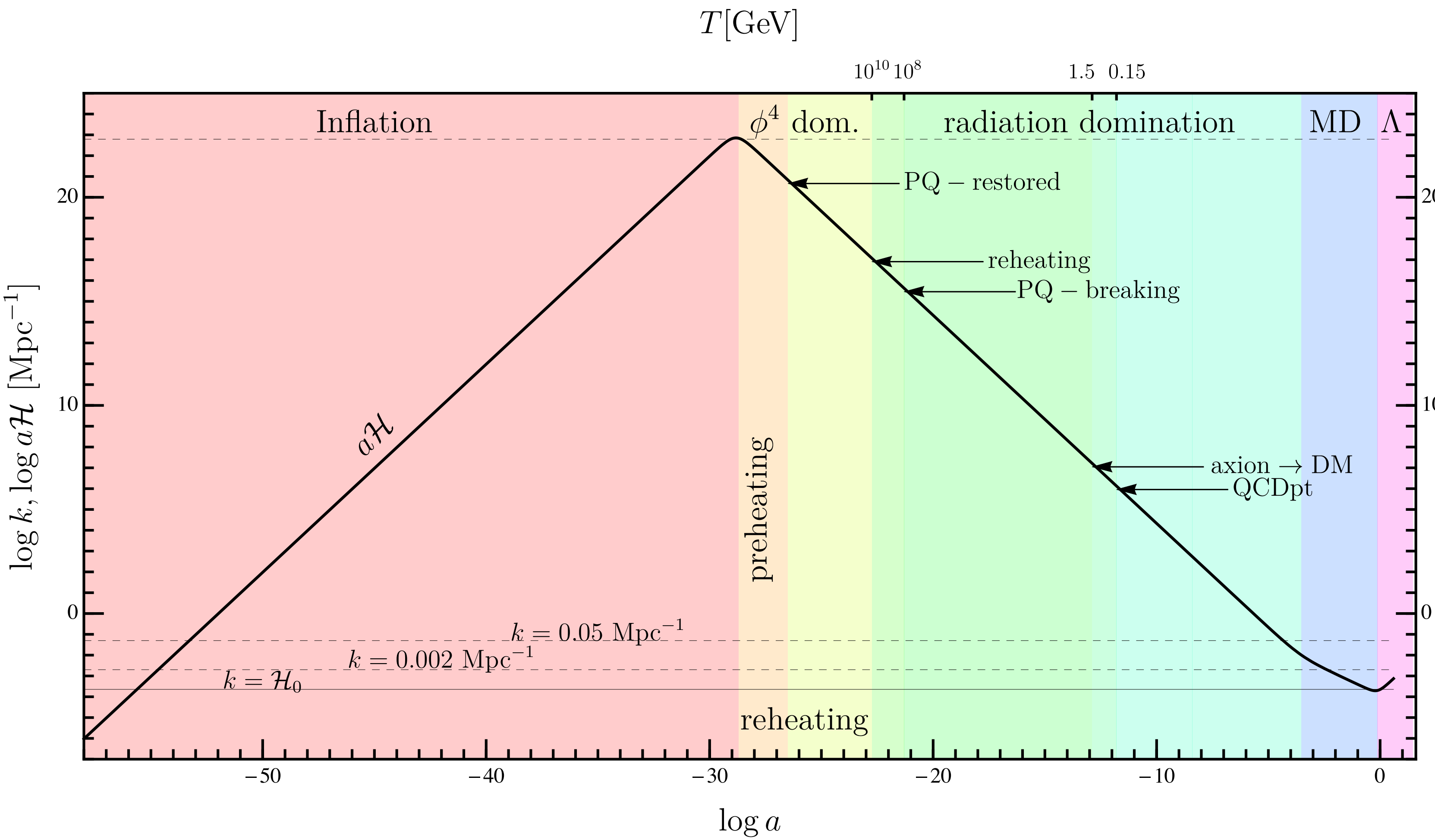
$$\Delta N_\nu^{\rm eff} \sim (\delta_3 v_{11}/\lambda_{10})^{-1/6}$$

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



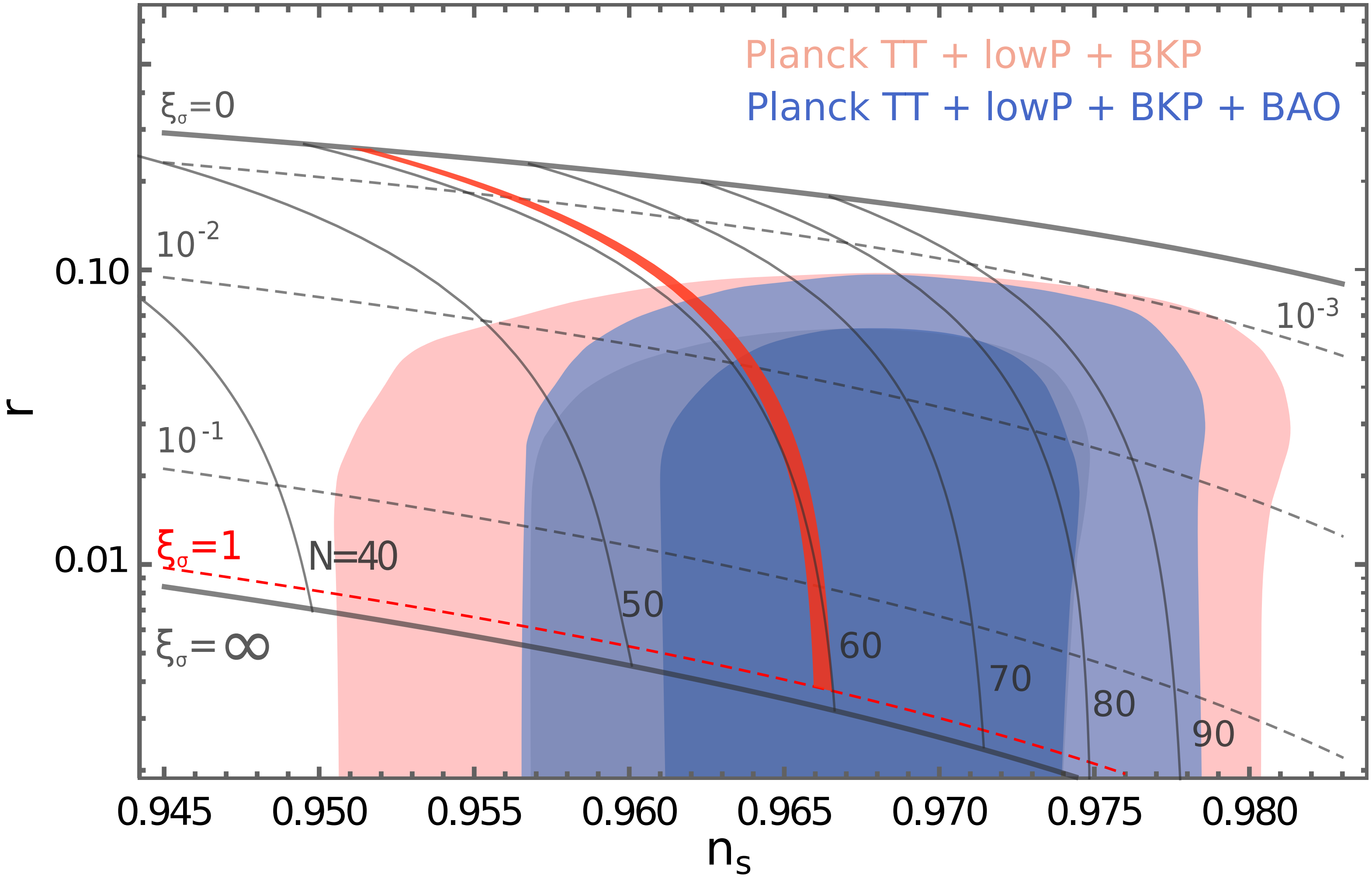


History of Universe in SMASH



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

History of Universe in SMASH



- Sharp prediction of r vs n_s for fixed pivot scale, e.g. $k_0 = 0.002\ \mathrm{Mpc}^{-1}$
- Can be probed decisively by next generation CMB experiments

Axion Dark Matter in SMASH

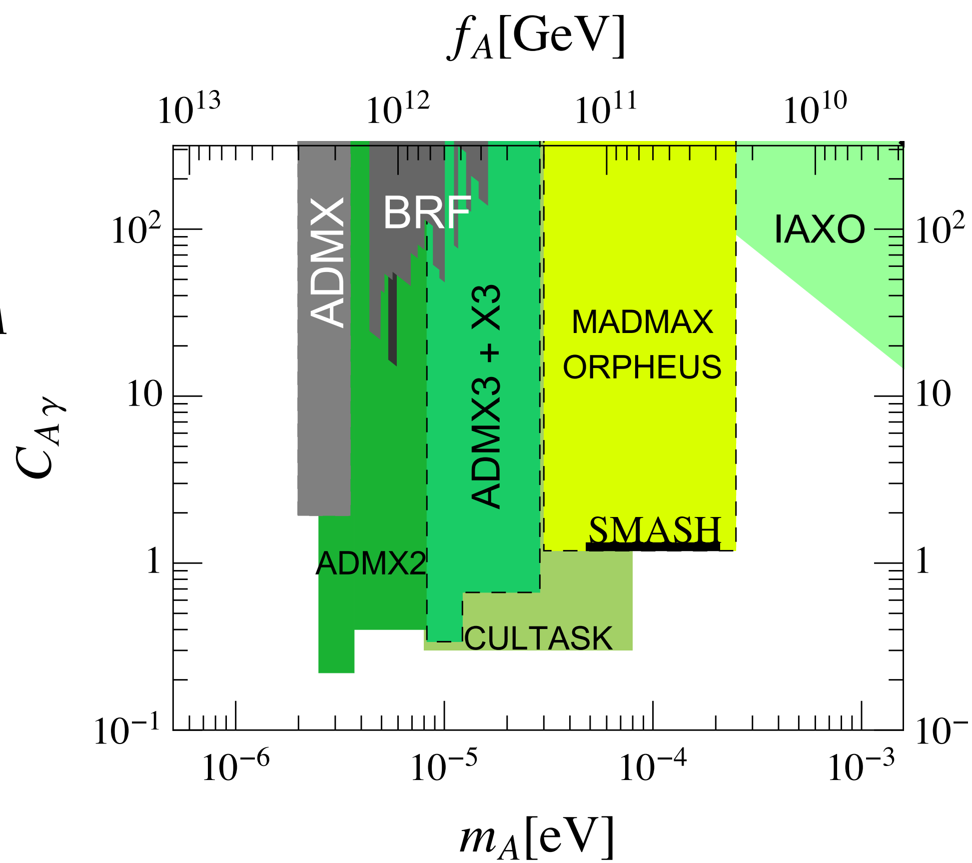
- SMASH predicts post-inflationary PQ breaking and thus one-to-one relation $m_A \Leftrightarrow \Omega_A$
- Dark matter abundance fixes symmetry breaking scale $v_\sigma = f_A$

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

and thus axion mass

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

- In reach of proposed axion dark matter experiments (MADMAX, ORPHEUS)



[Ballesteros,Redondo, AR,Tamarit, 1608.05414]

Dine-Fischler-Srednicki-Zhitnitskyi (DFSZ) Model

[Zhitnitsky 80;Dine,Fischler,Srednicki 81]

- Type II Higgs Doublet Model:

$$\mathcal{L}_Y = Y_{ij}\bar{q}_{iL}H_d d_{jR} + \Gamma_{ij}\bar{q}_{iL}\tilde{H}_u u_{jR} + h.c.$$

- Fields are supposed to transform under PQ symmetry as:

$$\begin{aligned}
\sigma &\to e^{i\alpha}\sigma\,, \\
H_d &\to e^{iX_d\alpha}H_d\,, \\
H_u &\to e^{-iX_u\alpha}H_u\,, \\
d_{iR} &\to e^{-iX_d\alpha}d_{iR}\,, \\
u_{iR} &\to e^{-iX_u\alpha}u_{iR}
\end{aligned}$$

- Yukawa interactions as well as most general scalar potential,

$$V(\sigma) = -\mu_\sigma^2|\sigma|^2 + \lambda_\sigma|\sigma|^4 + \lambda_3 H_d^\dagger H_u\sigma^2$$

invariant, if $X_u + X_d = 2$

- Anomalous divergence of PQ current:

$$\partial^\mu J_\mu^{\rm PQ} = -6\,\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} - 16\,\frac{\alpha}{8\pi}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Dine-Fischler-Srednicki-Zhitnitskyi (DFSZ) Model

- Low energy effective Lagrangian below EW, but above QCD scale:

$$\mathcal{L}_{\rm eff} = \frac{1}{2}\partial_\mu A \partial^\mu A - \frac{\alpha_s}{8\pi}\frac{A}{f_A} G^c_{\mu\nu}\tilde{G}^{c,\mu\nu} - \frac{\alpha}{8\pi}\frac{8}{3}\frac{A}{f_A} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{\partial_\mu A}{f_A}\sum_f C_f \bar{f}\gamma^\mu\gamma_5 f$$

$$f_A = \frac{v_{\rm PQ}}{6}; \qquad C_{Ae} = C_{Ad} = \frac{\sin^2\beta}{3}; \qquad C_{Au} = \frac{\cos^2\beta}{3}; \qquad \tan\beta = \frac{v_u}{v_d}$$

- Low energy effective Lagrangian below QCD scale:

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial_\mu A)^2 - V(A) - C_{A\gamma}\frac{\alpha}{8\pi}\frac{A}{f_A}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{\partial_\mu A}{f_A}\sum_f C_{Af}\bar{f}\gamma^\mu\gamma_5 f$$

  - Photon coupling

$$C_{A\gamma} = \frac{8}{3} - \frac{2}{3}\frac{4m_d + m_u}{m_d + m_u}$$

[Kaplan 85;Srednicki `85]

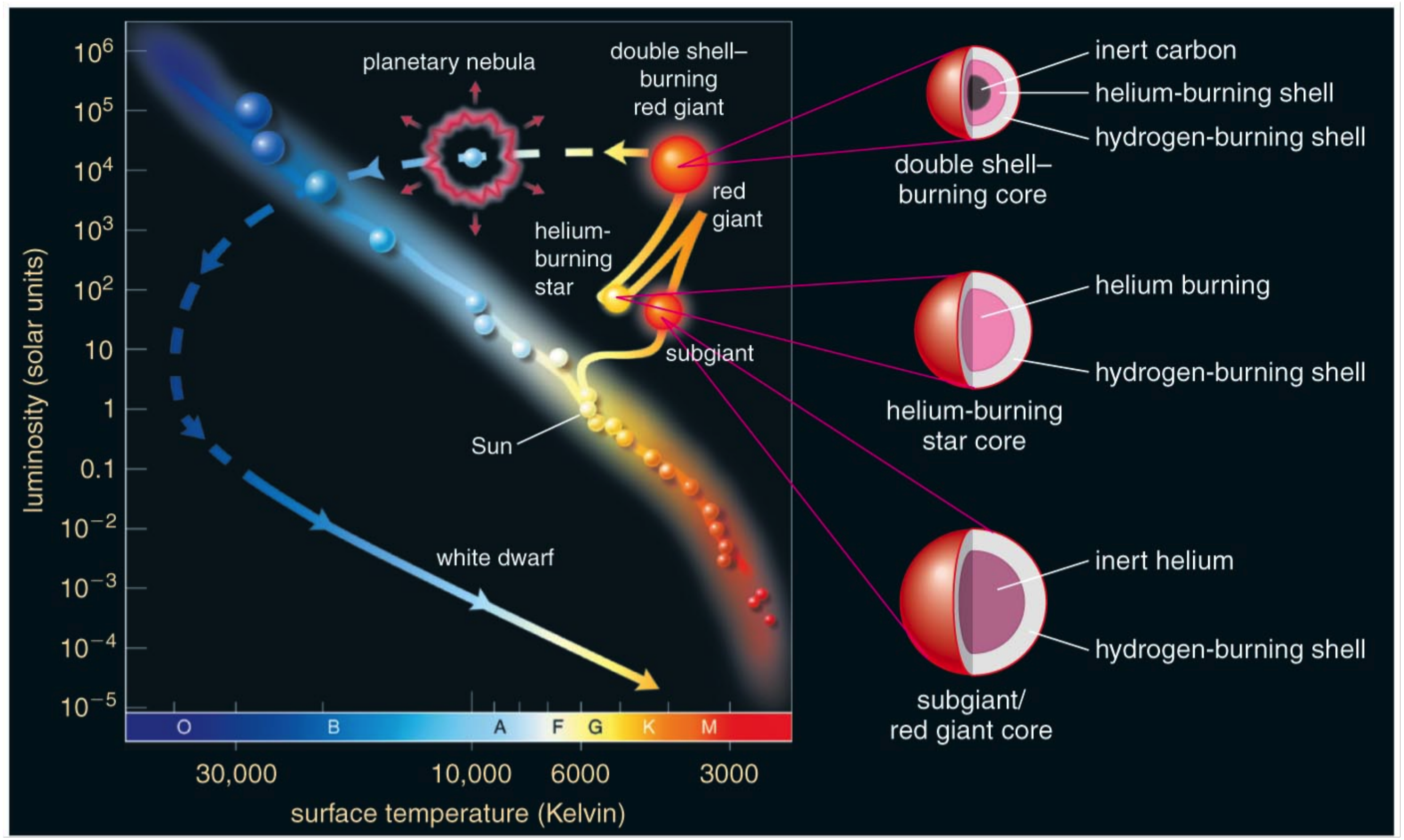
  - Nucleon coupling

[di Cortona et al. `16]

$$C_{Ap} = -0.435\sin^2\beta + (-0.182 \pm 0.025)\,; \qquad C_{An} = 0.414\sin^2\beta + (-0.16 \pm 0.025)$$

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

- Modest hints for excessive energy losses of stars in various evolutionary stages



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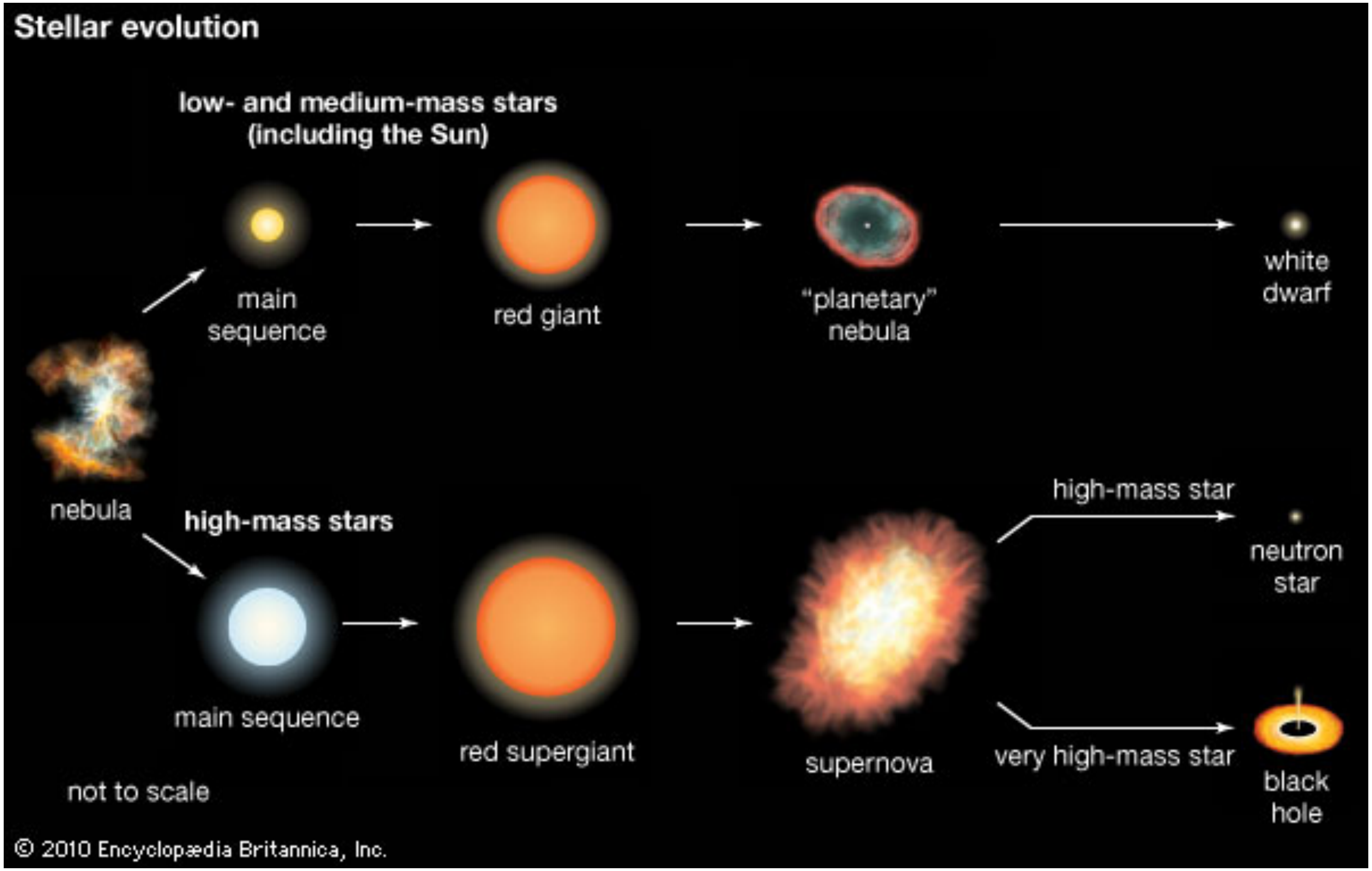
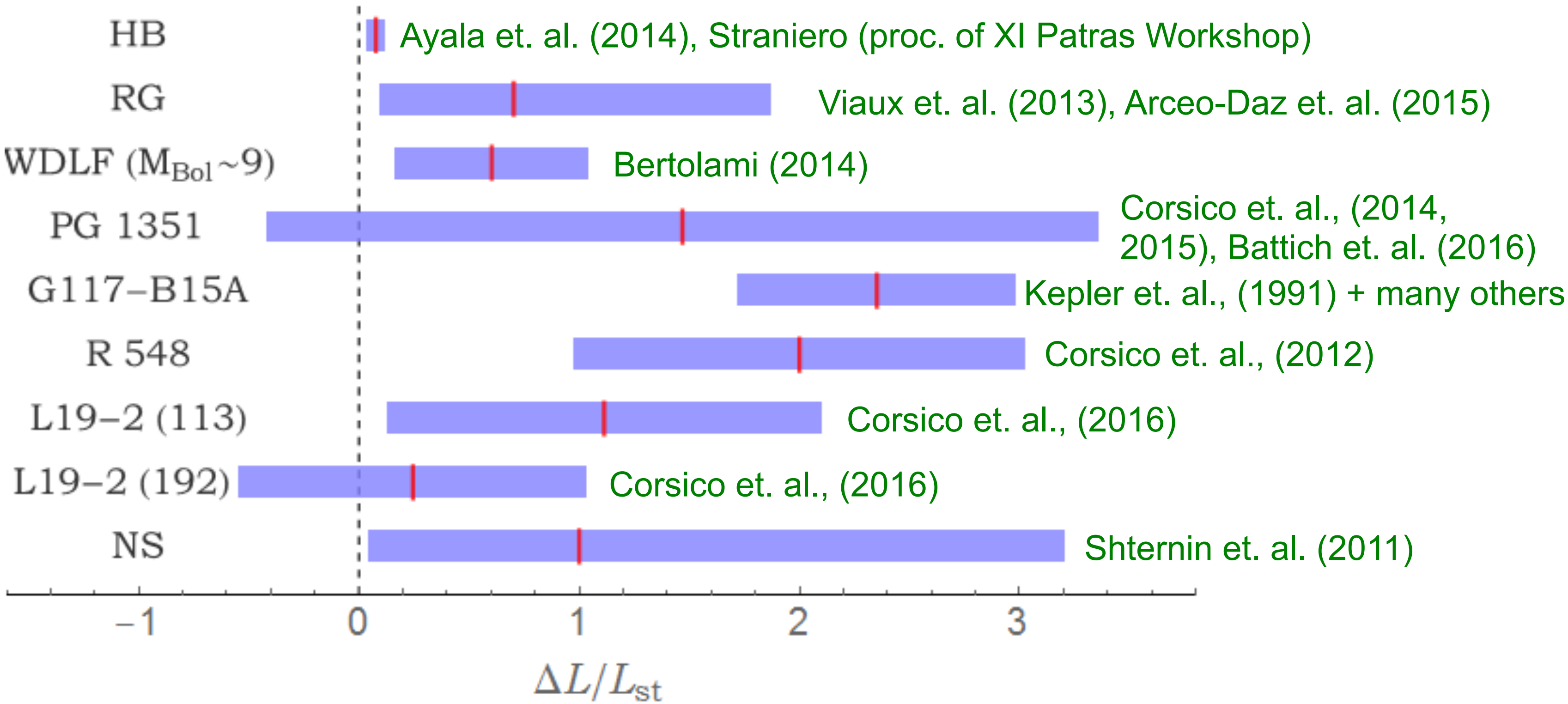
Astro-Hints for the Axion: Energy Losses of Stars?

- Modest hints for excessive energy losses of stars in various evolutionary stages



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

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

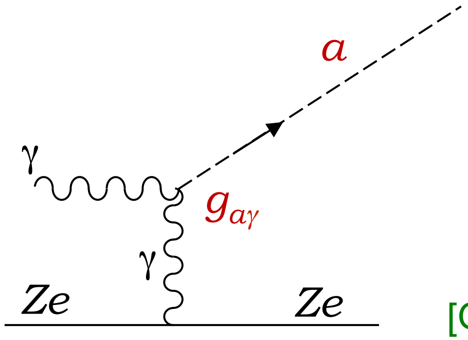


[Giannotti, Irastorza, Redondo, AR (2015); Giannotti, Irastorza, Redondo, AR (in preparation)]

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

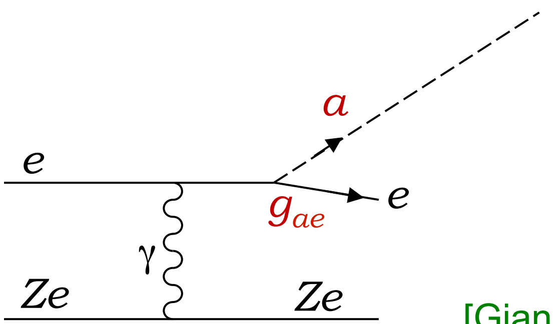
> Excessive energy losses of HBs, RG, WDs, NS can be explained at one stroke by production of axion with coupling to photons, electrons, quarks:

- Primakoff production of axions in Helium Burning stars (HBs) and Red Giants (RG)



[Giannotti `16]

- Bremsstrahlung off electrons in White Dwarfs (WD) and RGs

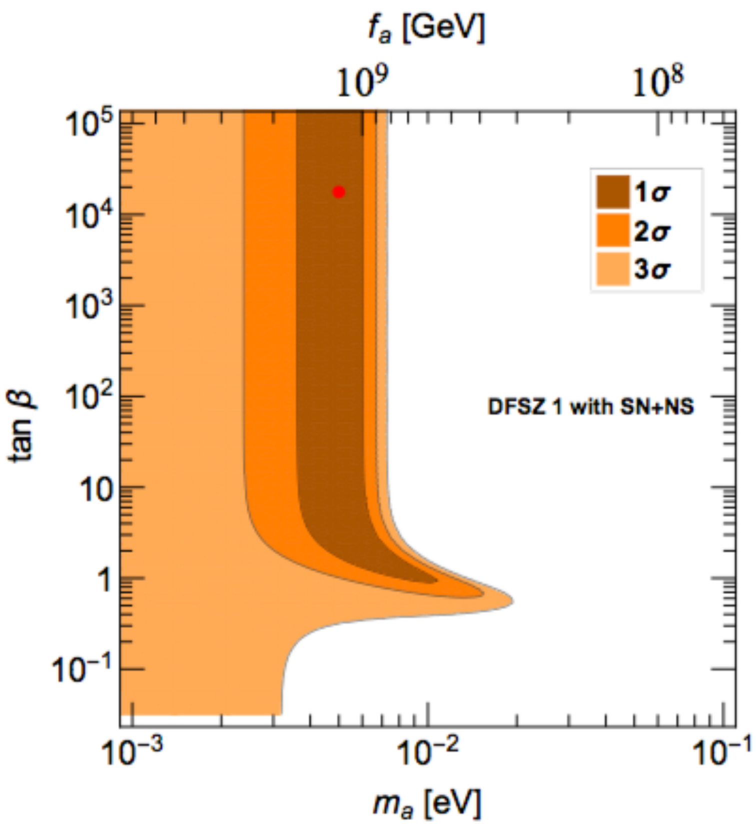


[Giannotti `16]

- Bremsstrahlung off neutrons in Neutron Stars (NS)

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

> Excessive energy losses of HBs, RG, WDs, NS can be explained at one stroke by production of axion with coupling to photons, electrons, nucleons, like in DFSZ axion model:



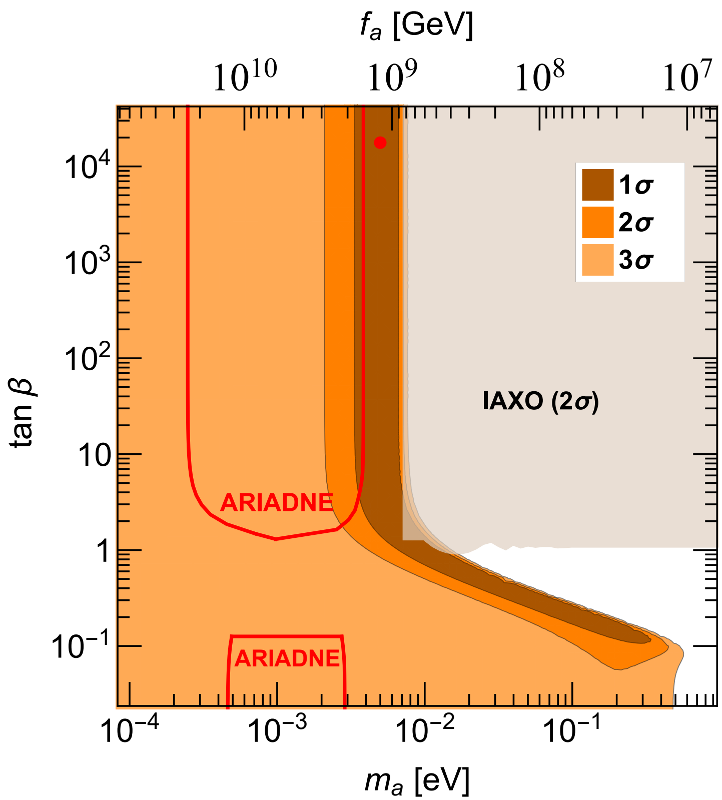
$$C_{A\gamma} = \frac{8}{3} - 1.92(4)\,,$$
$$C_{Ae} = \frac{1}{3}\sin^2\beta\,,$$
$$C_{Ap} = -0.435\sin^2\beta + (-0.182 \pm 0.025)\,,$$
$$C_{An} = 0.414\sin^2\beta + (-0.16 \pm 0.025)$$

$$\tan\beta = v_u/v_d$$

[Giannotti,Irastorza,Redondo,AR,Saikawa in preparation]

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

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



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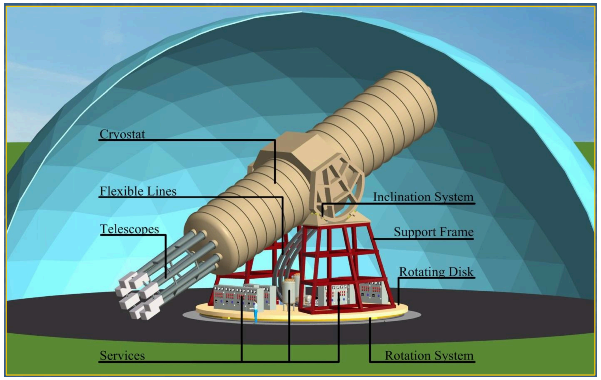

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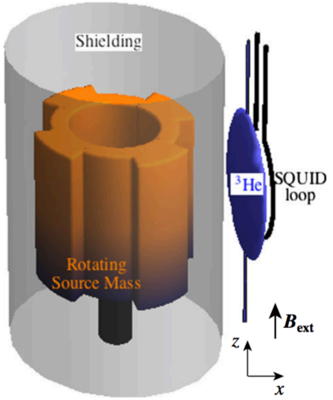
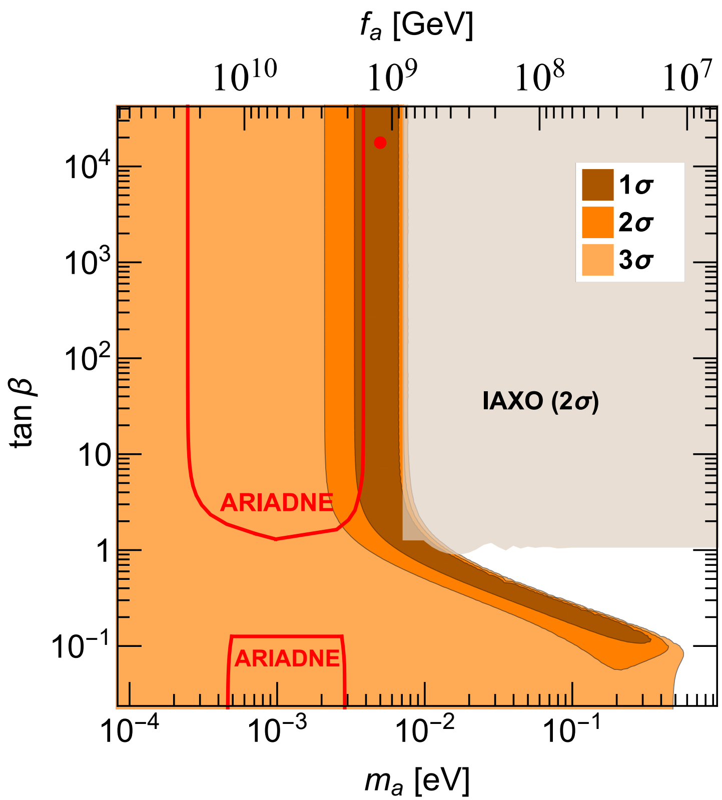
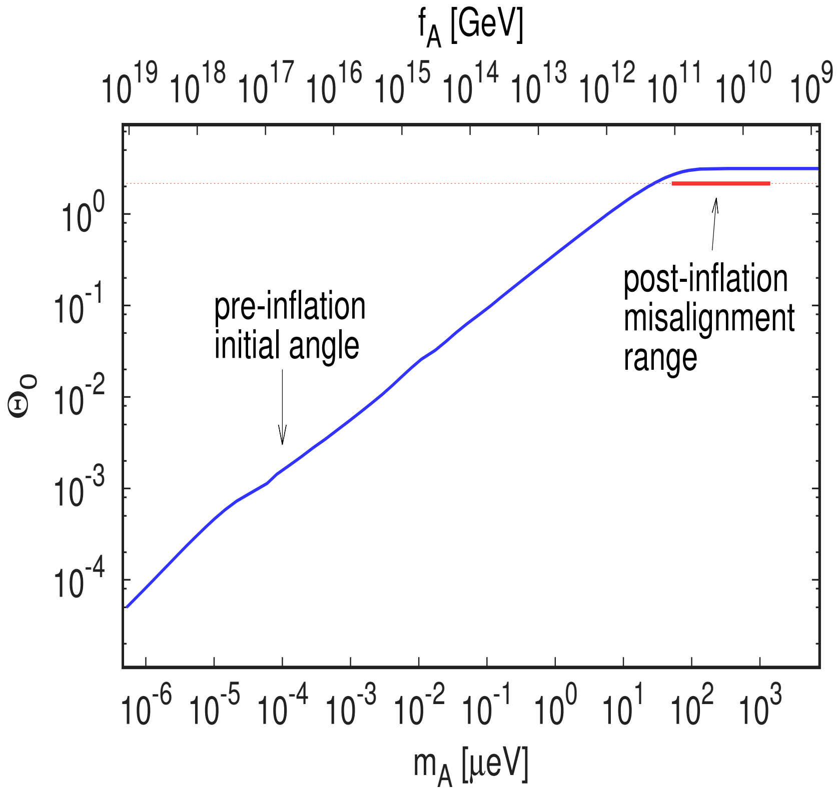


[Giannotti,Irastorza,Redondo,AR,Saikawa in preparation]

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

> Can be also dark matter:





[Giannotti,Irastorza,Redondo,AR,Saikawa in preparation]

[Borsanyi et al. `16]

Summary

- Axion mass in units of decay constant very well determined
- Couplings to photons, nucleons, electrons model dependent
  - Photon and nucleon coupling in units of decay constant typically of order one
  - Coupling to electrons in units of decay constant may be suppressed
- PQ scalar may play the role of the inflaton: axion models may solve at one stroke strong CP problem, dark matter and inflation
- Axion in meV mass range may explain at the same time also hints of excessive stellar energy losses
- Thursday: Axion/ALP Experiments