One SMASH to Rule Them All

A Minimal Model for Particle Physics and Cosmology

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GRK 2044 Seminar
Albert-Ludwigs-Universität, Freiburg, Germany
17 June 2020

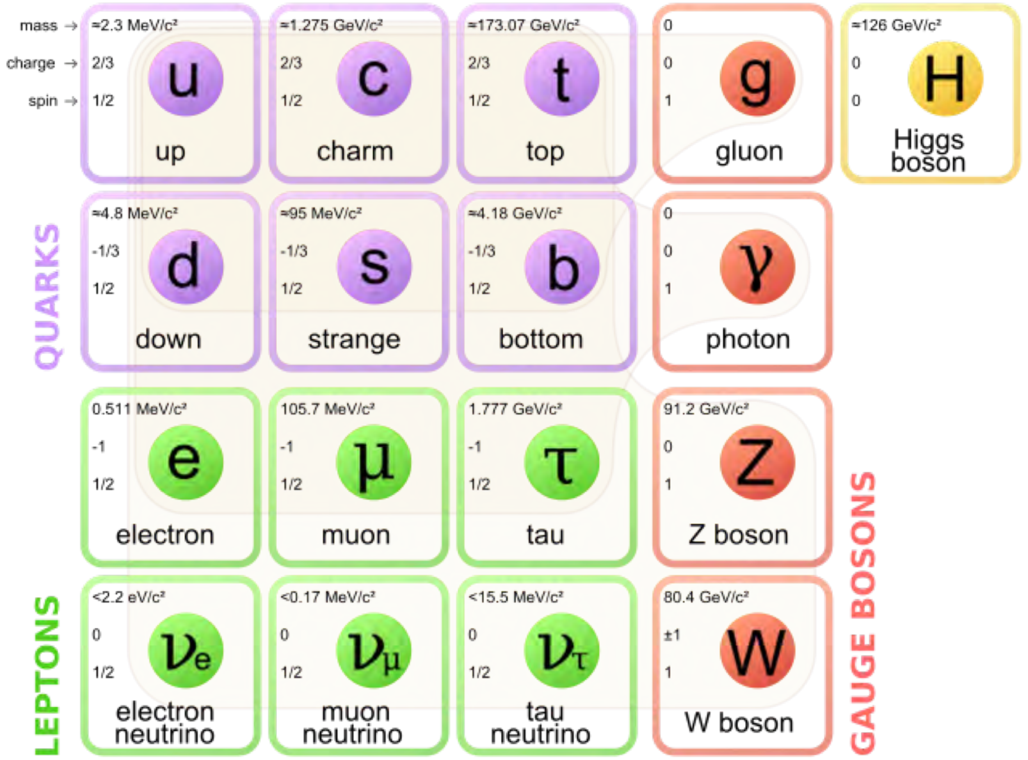
[Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; arXiv:1610.01639; AR, Saikawa, Tamarit, in preparation]
[Ballesteros, AR, Tamarit, Welling, in preparation]

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

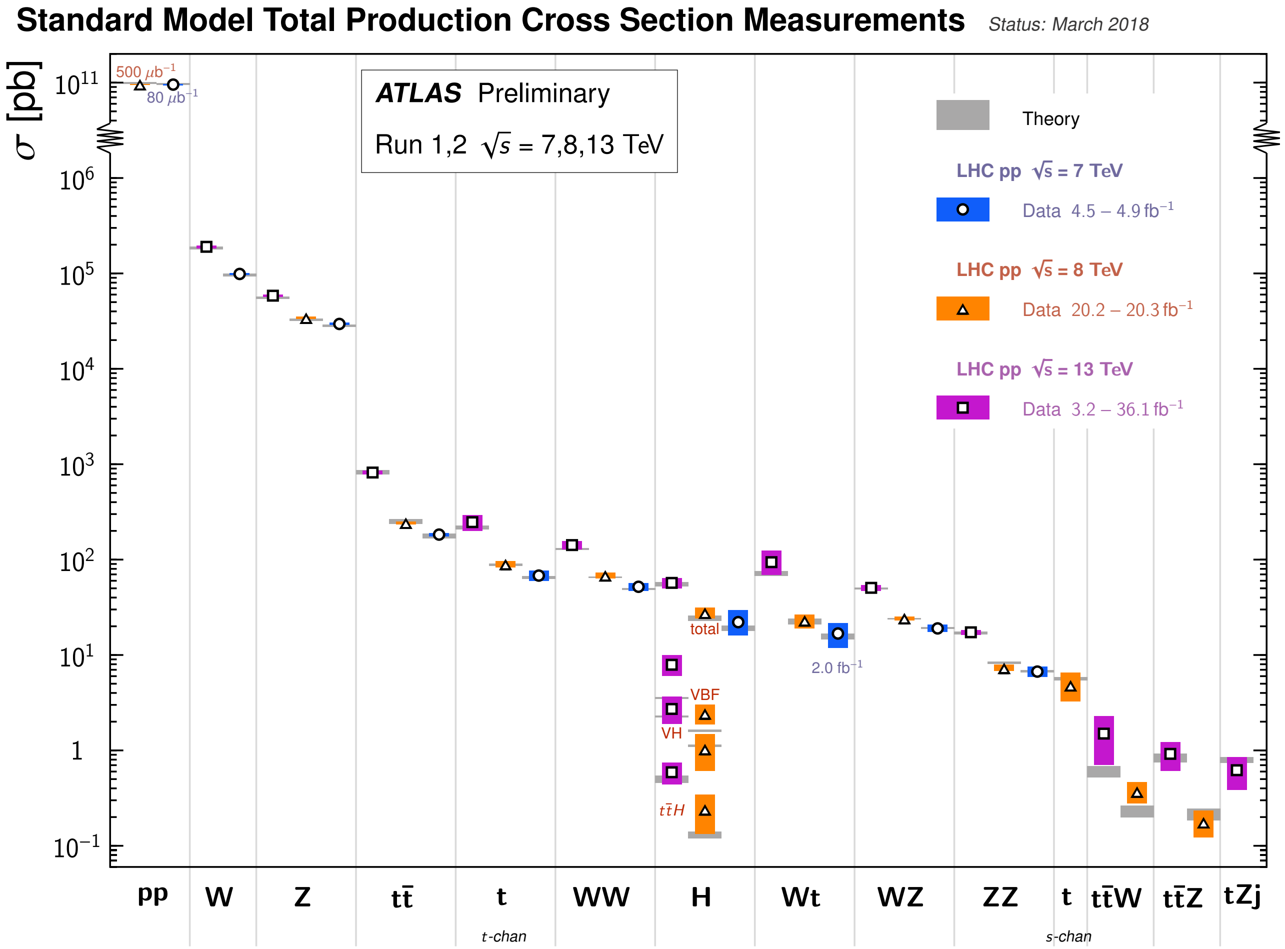
DESY.

The Standard Model of Particle Physics

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



[wikipedia]



[twiki.cern.ch]

The Big Five

- Big fundamental problems in particle physics and cosmology seem to require physics beyond SM

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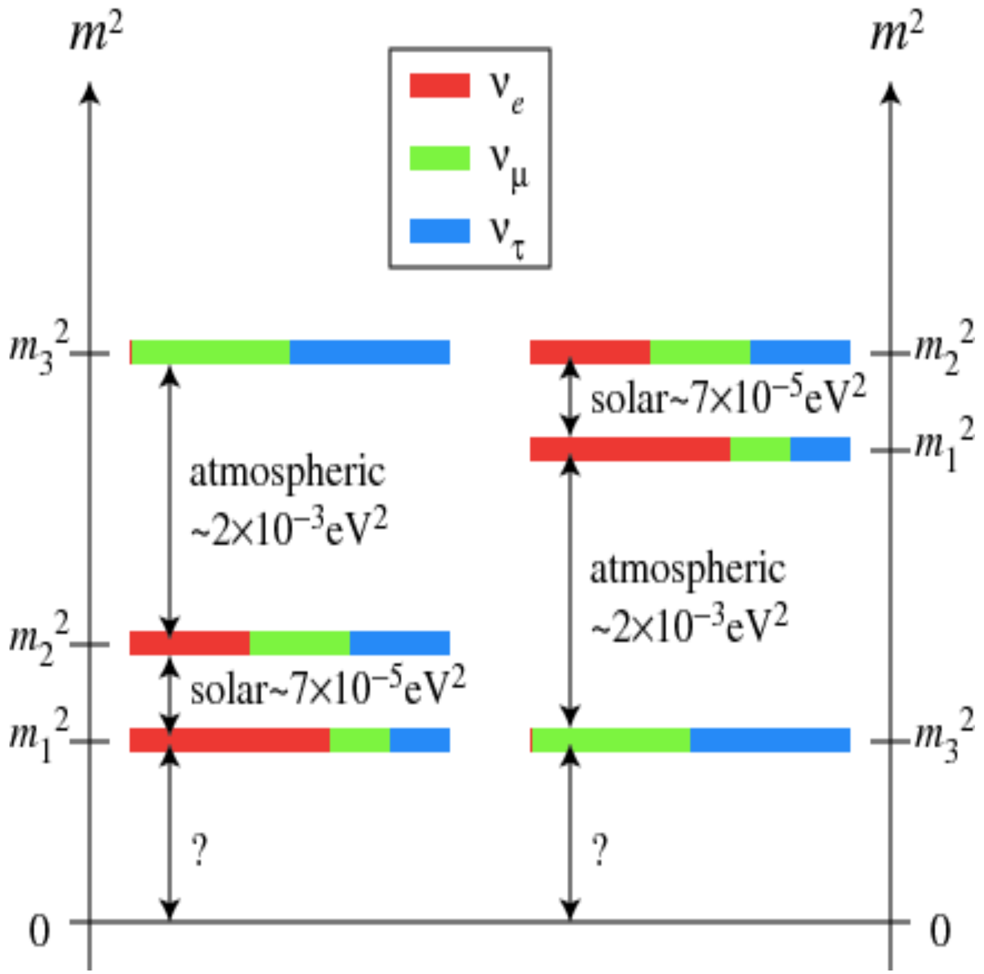
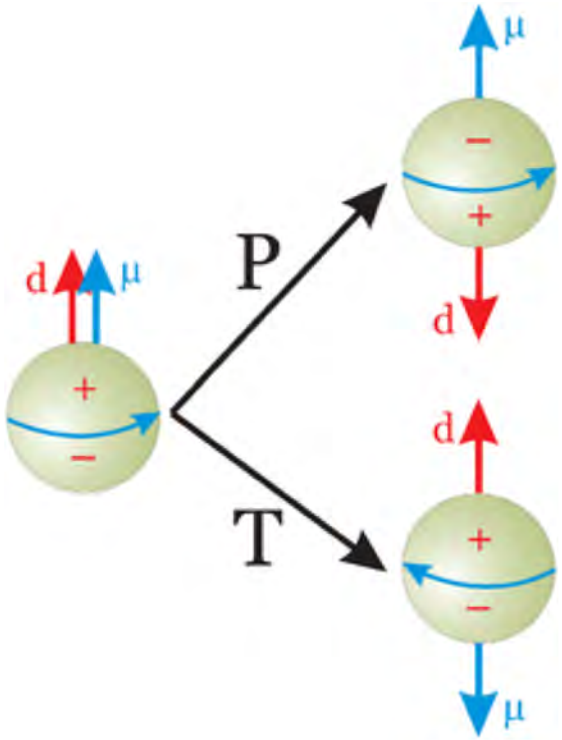
   1. **Neutrino masses and mixing**



[King et al. 13]

The Big Five

- Big fundamental problems in particle physics and cosmology seem to require physics beyond SM
  1. Neutrino masses and mixing
  2. **Strong CP problem**



- Most general gauge invariant Lagrangian of QCD contains topological theta-term:

[Belavin et al. \`75;´t Hooft 76;Callan et al. \`76;Jackiw,Rebbi \`76]

$$\mathcal{L}_{\rm QCD} \supset -\frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}$$

- Theta-term $\propto G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a\cdot\mathbf{B}^a$ violates P and T, and thus CP
- Most sensitive probe of P and T violation in flavor conserving interactions: electric dipole moment of neutron
  - Prediction: [Crewther,Di Vecchia,Veneziano,Witten 79;...; Pospelov,Ritz 00]

$$d_n(\overline{\theta}) = 2.4(1.0)\times 10^{-16}\,\overline{\theta}\,e\,{\rm cm}$$

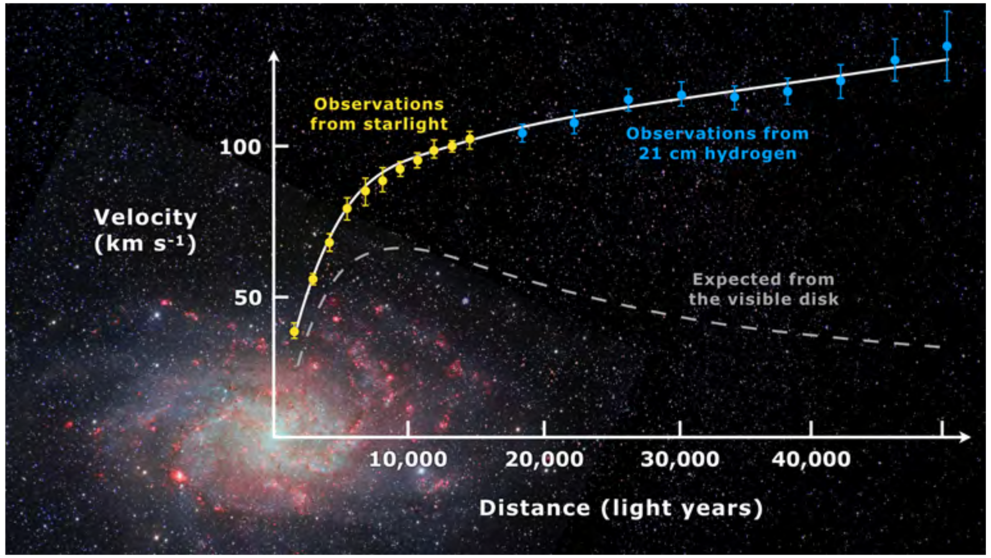
  - Experiment: [Abel et al. 20] $[\overline{\theta}\equiv\theta + \arg\det(\mathcal{M}_u\mathcal{M}_d)]$

$$|d_n| < 1.8\times 10^{-26}\,e\,{\rm cm}$$

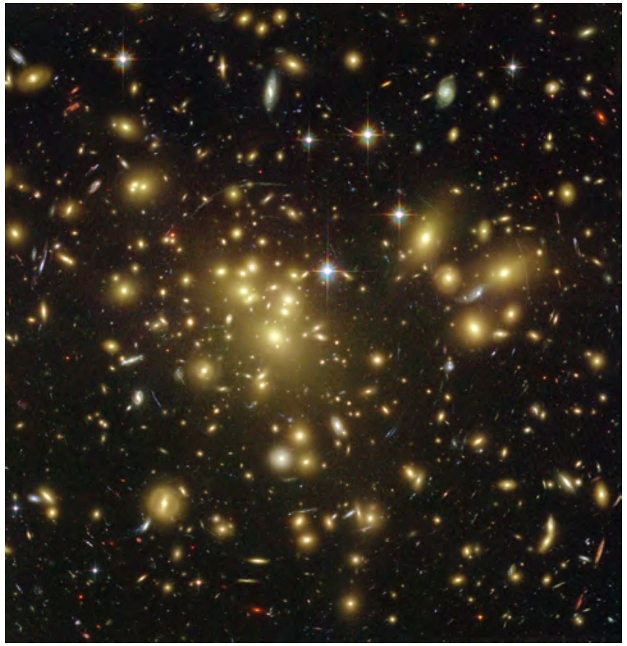
- Strong CP problem: $|\overline{\theta}| < 10^{-10}$

The Big Five

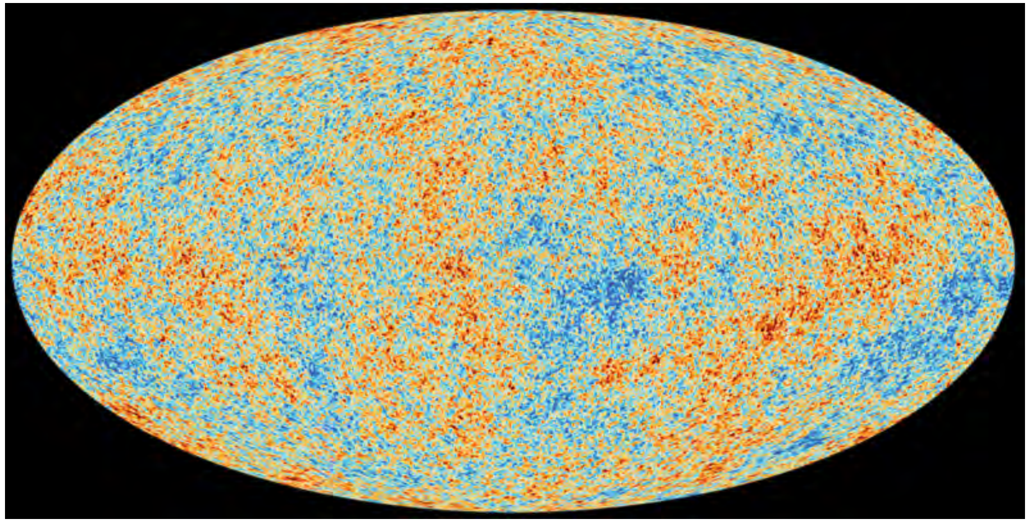
- Big fundamental problems in particle physics and cosmology seem to require physics beyond SM
  1. Neutrino masses and mixing
  2. Strong CP problem
  3. **Dark matter**



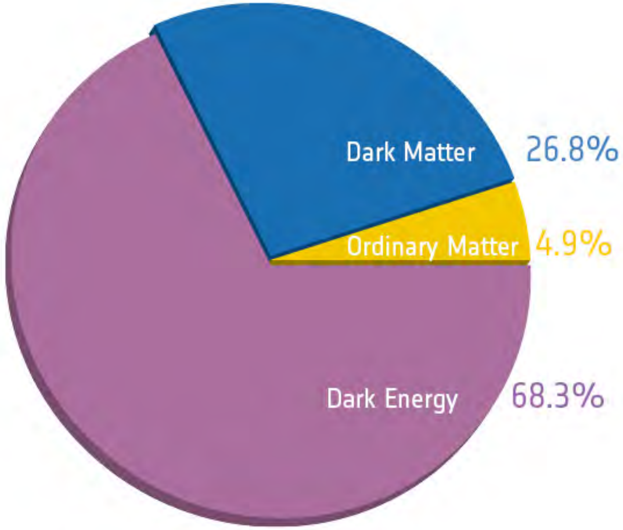
[Mario De Leo, Wikipedia]



[NASA, Wikipedia]



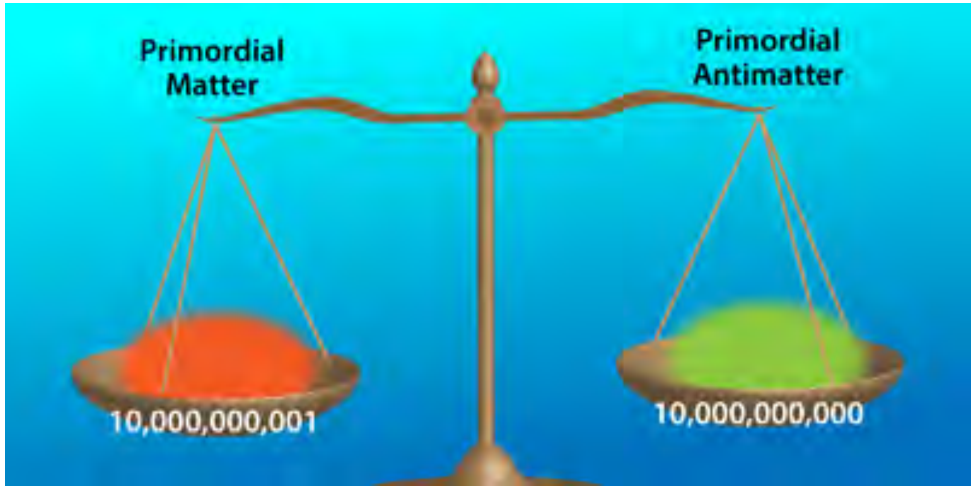
[PLANCK]



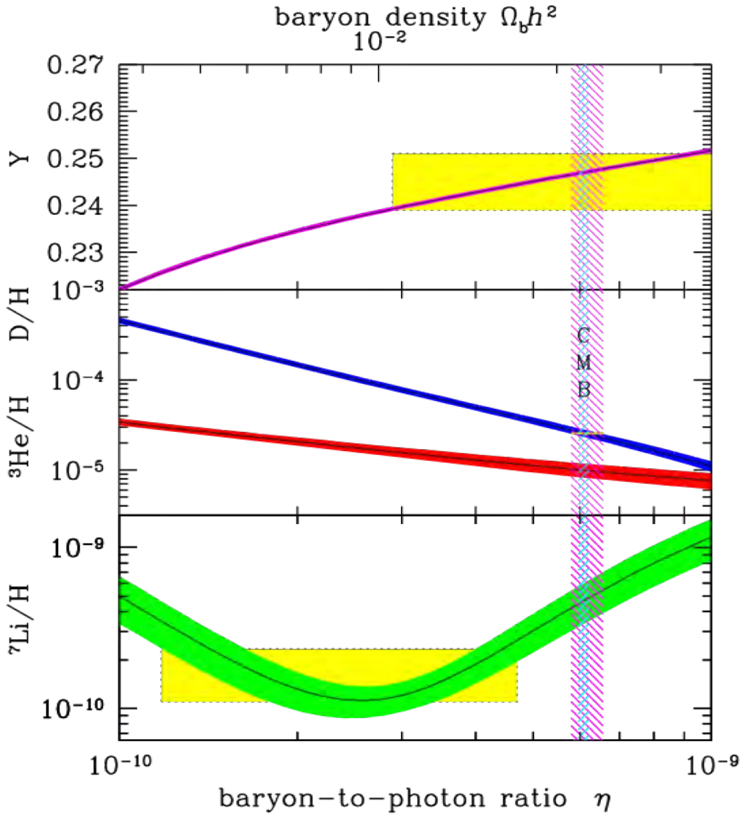
The Big Five

- Big fundamental problems in particle physics and cosmology seem to require physics beyond SM

1. Neutrino masses and mixing
2. Strong CP problem
3. Dark matter
4. **Baryon asymmetry**



[APS]



[PDG]

The Big Five

- Big fundamental problems in particle physics and cosmology seem to require physics beyond SM
  1. Neutrino masses and mixing
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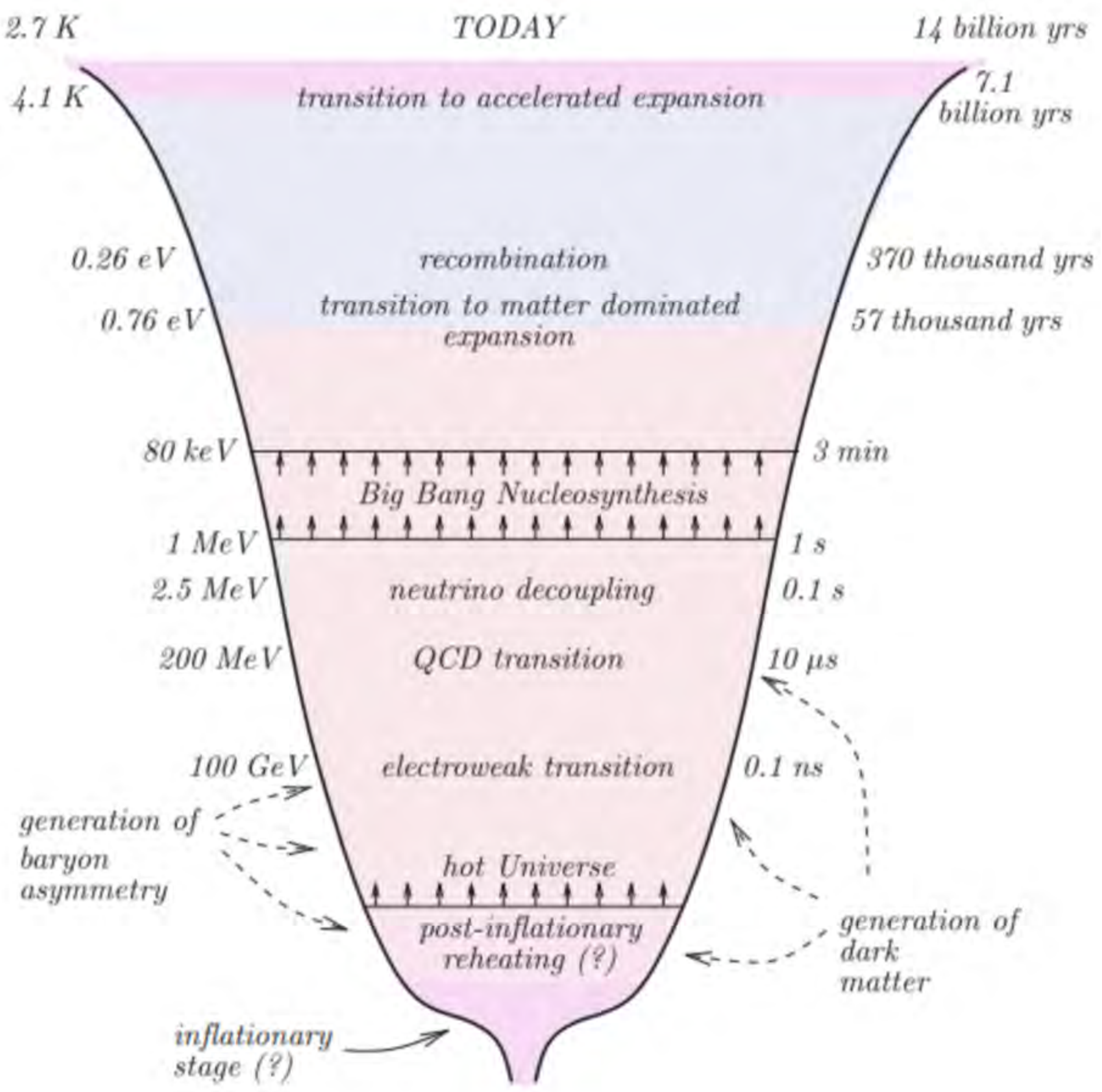
  4. Baryon asymmetry
  5. **Inflation**

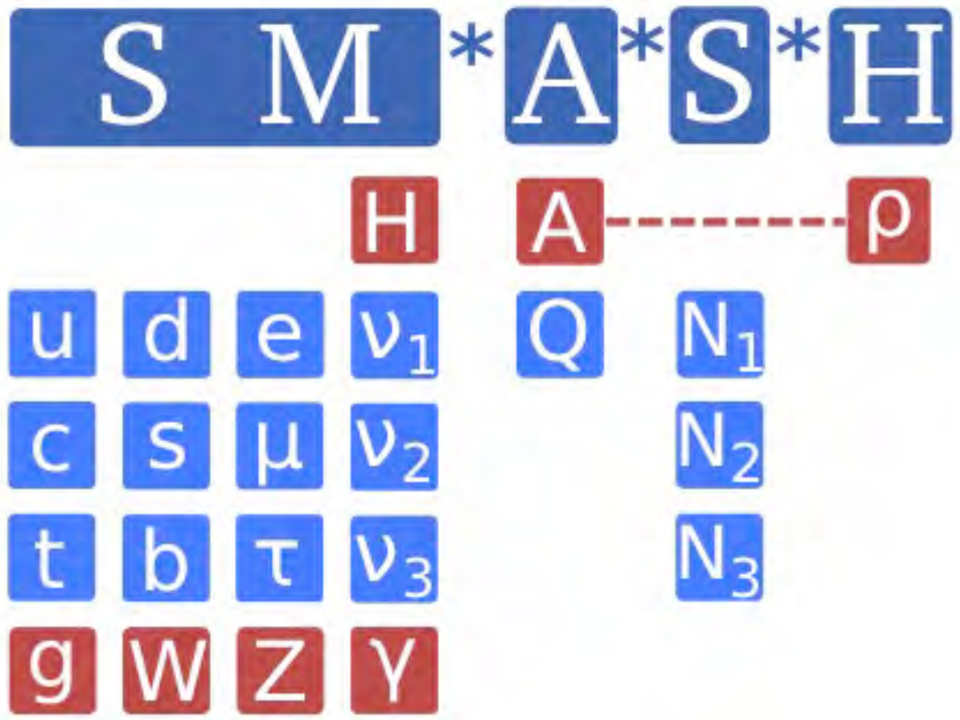


The Big Five

- Big fundamental problems in particle physics and cosmology seem to require physics beyond SM
  1. Neutrino masses and mixing
  2. Strong CP problem
  3. Dark matter
  4. Baryon asymmetry
  5. Inflation
- These problems may be solved in one smash in a minimal extension of the SM by
  - 3 right-handed SM singlet neutrinos N_i
  - 1 SM singlet complex scalar $\sigma(x) = \frac{1}{\sqrt{2}}(v_\sigma + \rho(x))\, \mathrm{e}^{iA(x)/v_\sigma}$
  - 1 vector-like extra quark Q

  dubbed **SM*A*S*H**

  Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]



Minimal Solution of Neutrino Masses and Mixing Problem

Seesaw mechanism

- Extend SM by three right-handed SM singlet neutrinos N_i ($L = (\ell, \nu_\ell)^T$)

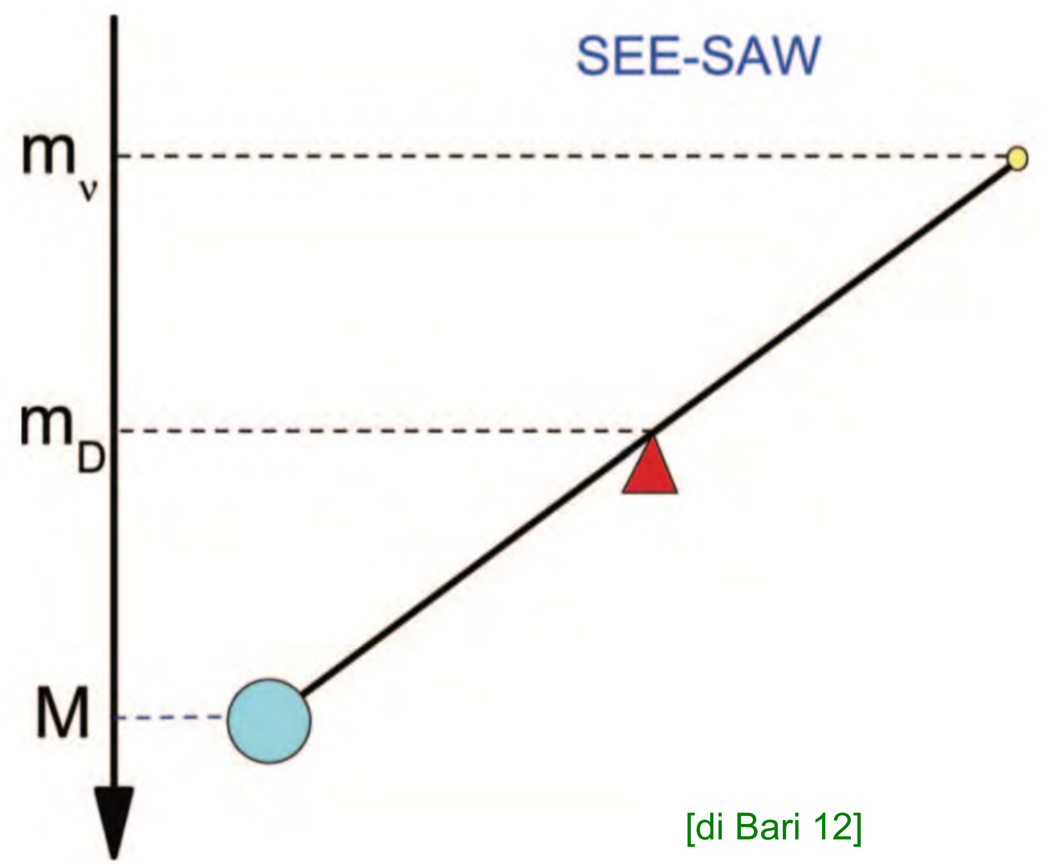
$$\mathcal{L} \supset -\left[F_{ij} L_i \epsilon H N_j + \frac{1}{2} M_{ij} N_i N_j + h.c.\right]$$

- In see-saw limit, $M \gg m_D \equiv Fv/\sqrt{2}$, with $v = 246\ \mathrm{GeV}$, the neutrino mass eigenstates split into
  - a heavy set with masses M_i constituted by the N_i
  - a light set with masses

$$m_\nu = \frac{1}{2} F \frac{v^2}{M} F^T = 0.03\ \mathrm{eV}\ F \frac{10^{15}\ \mathrm{GeV}}{M} F^T$$

constituted by mixtures of ν_ℓ

[Minkowski 77; Gell-Mann,Ramond,Slansky 79; Yanagida 79]



[di Bari 12]

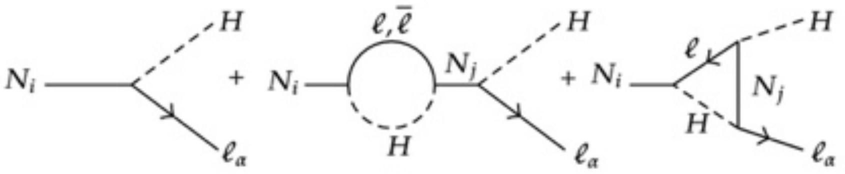
Minimal Solution of Baryogenesis Problem

Baryogenesis via leptogenesis

- Extend SM by three right-handed SM singlet neutrinos N_i $(L = (\ell, \nu_\ell)^T)$

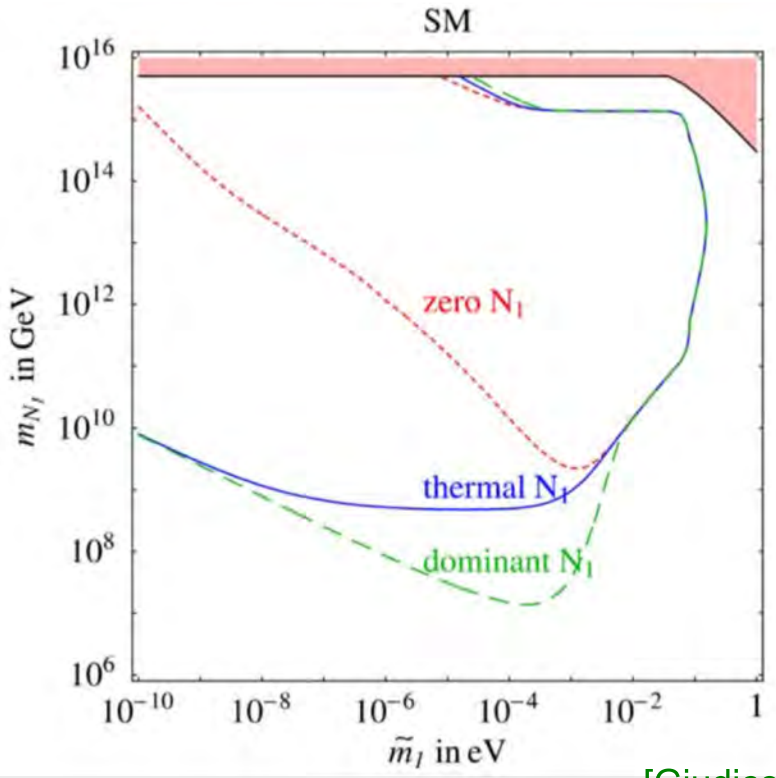
$$\mathcal{L} \supset -\left[F_{ij} L_i \epsilon H N_j + \frac{1}{2} M_{ij} N_i N_j + h.c.\right]$$

- For large $M_i \gg v = 246\ \mathrm{GeV}$, baryon asymmetry generated via leptogenesis [Fukugita,Yanagida 80]
  - At $T \sim M_i$, out-of-equilibrium CP and L violating decays of N_i generate lepton number

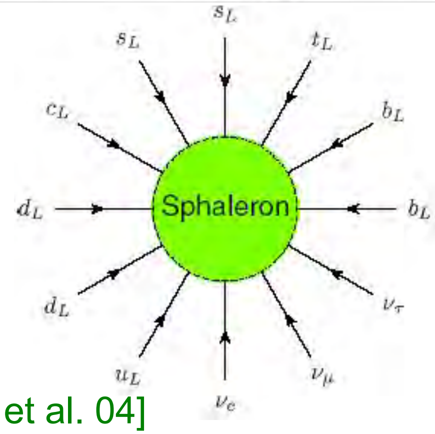


[Sheng Fong et al. 12]

  - At $T \sim v$, electroweak B+L violating, but B-L conserving sphaleron processes turn lepton number into baryon number



[Giudice et al. 04]



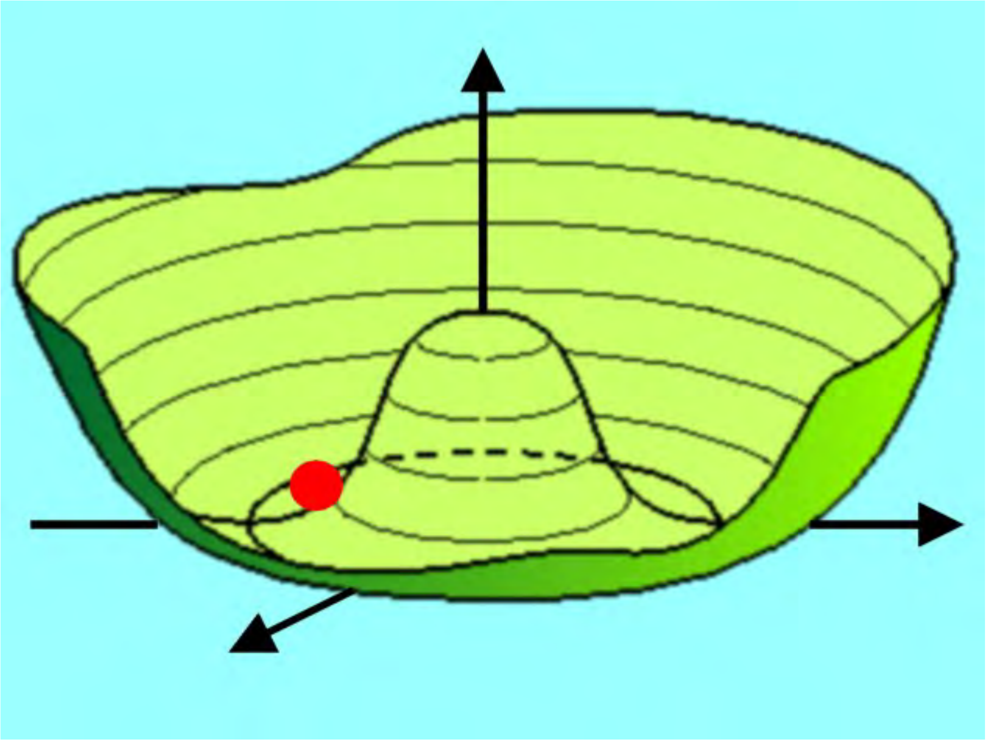
[Buchmüller et al. 04]

Minimal Solution of Strong CP Problem

Peccei-Quinn mechanism

- Extend particle content further by vector-like exotic quark [Kim 79;Shifman,Vainshtein,Zakharov 80]
- Introduce global U(1) symmetry which is broken by VEV $\langle\sigma\rangle = v_\sigma/\sqrt{2}$ of SM-singlet complex scalar;
  - Excitation of modulus: $m_\rho \propto v_\sigma$
  - Excitation of argument: $m_A \ll v_\sigma$

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



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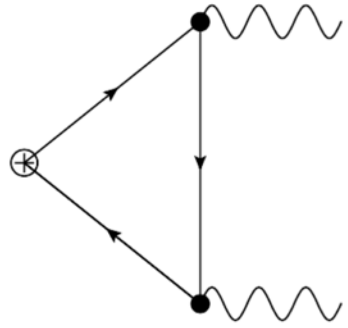
- Charges of exotic quark such that U(1) broken by gluonic triangle anomaly: A axion [Weinberg 79; Wilczek 79]

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

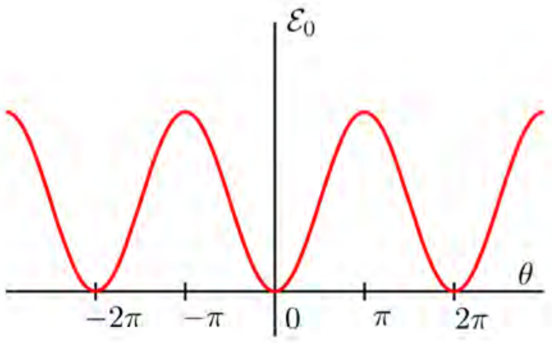


[Shin 88; Dias et al. 14; Ballesteros et al. 16]

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

- No strong CP problem, since axion field acts as space-time dependent theta parameter:

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{A(x)}{f_A} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}; \qquad f_A = v_\sigma$$



- QCD dynamics: $\langle A(x)\rangle = 0$ [Peccei,Quinn 78] ; $m_A = 57.0(7)\left(\frac{10^{11}\mathrm{GeV}}{f_A}\right)\mu\mathrm{eV}$

Minimal Solution of DM Problem

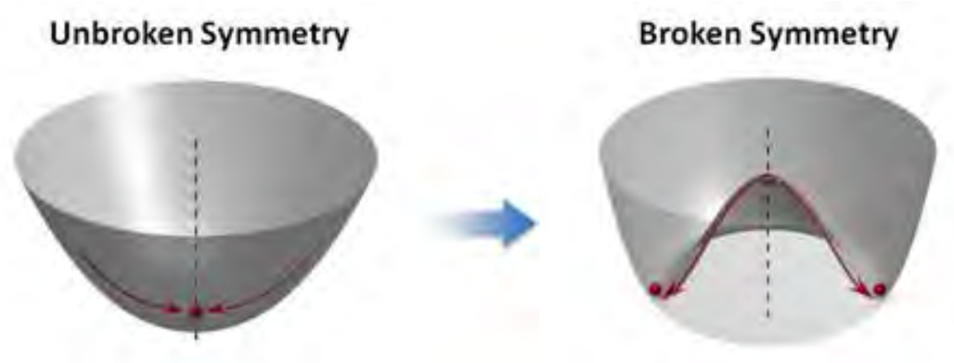
Axion as DM candidate

- Axion born after PQ phase transition,

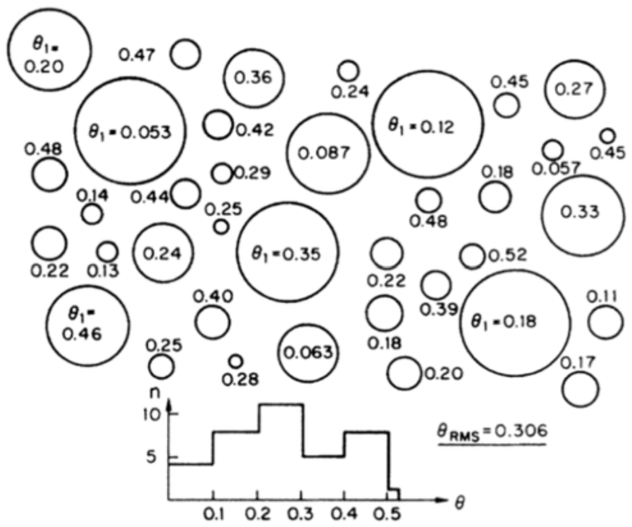
$$T \lesssim T_c^{\mathrm{PQ}} \sim v_{\mathrm{PQ}} = N f_A$$

- Axion takes random initial values in causally connected domains

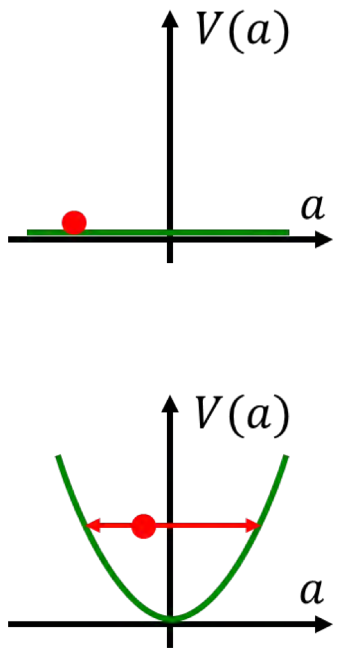
- Frozen as long as Hubble expansion rate exceeds mass, $H(T) > m_A(T)$



[Peking University]



[Turner `86]



[Raffelt]

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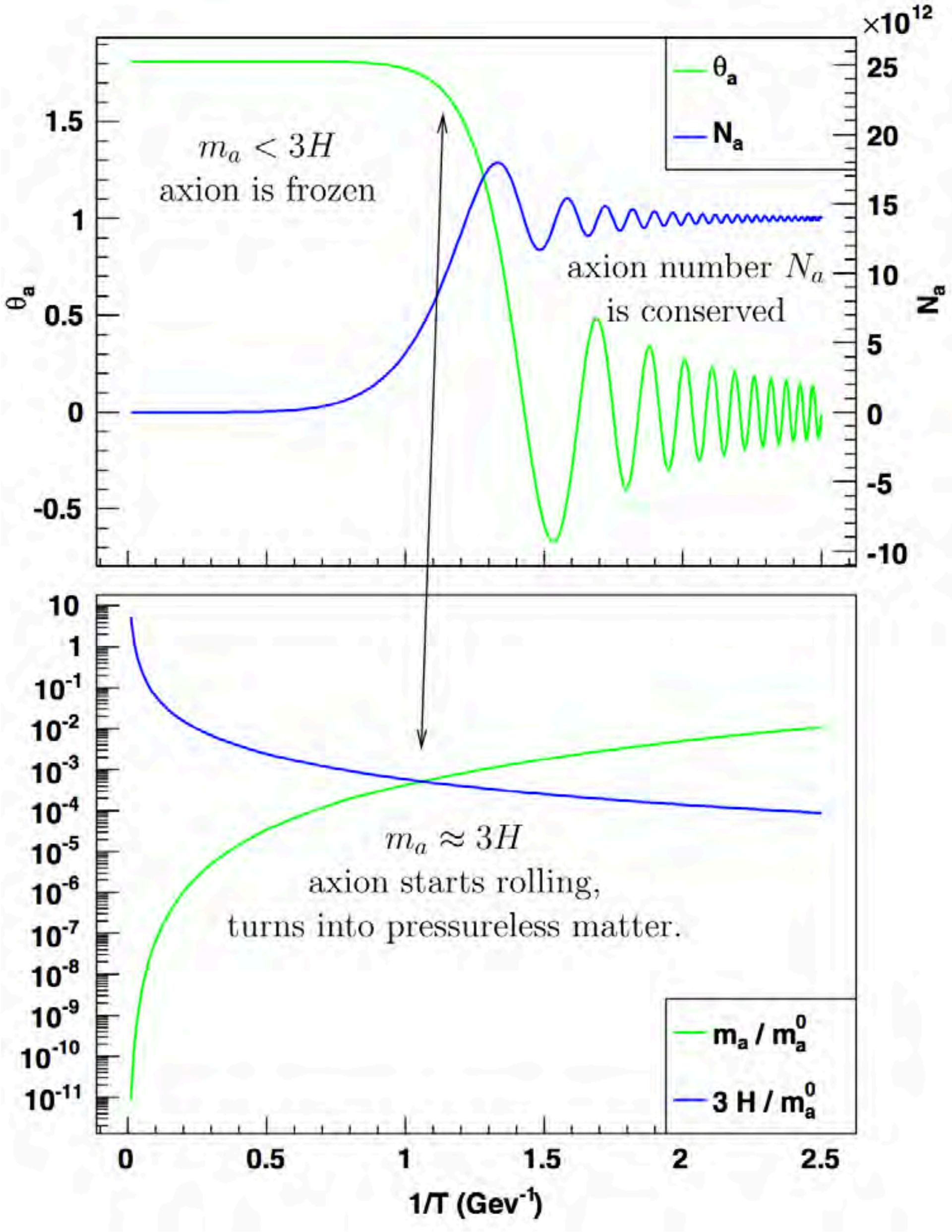
- When $H(T) \sim m_A(T)$, axion field starts to oscillate around minimum of potential; behaves like cold dark matter: $w_A = p_A/\rho_A \simeq 0$

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



[Wantz,Shellard `09]

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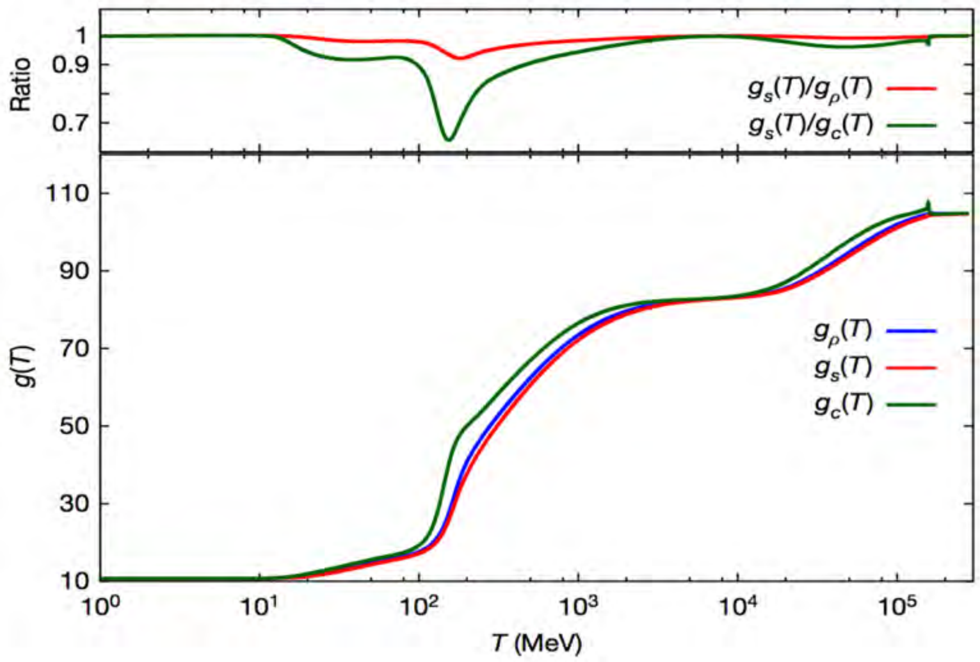
- QCD input from lattice:
  - Equation of state $\Rightarrow H(T)$



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

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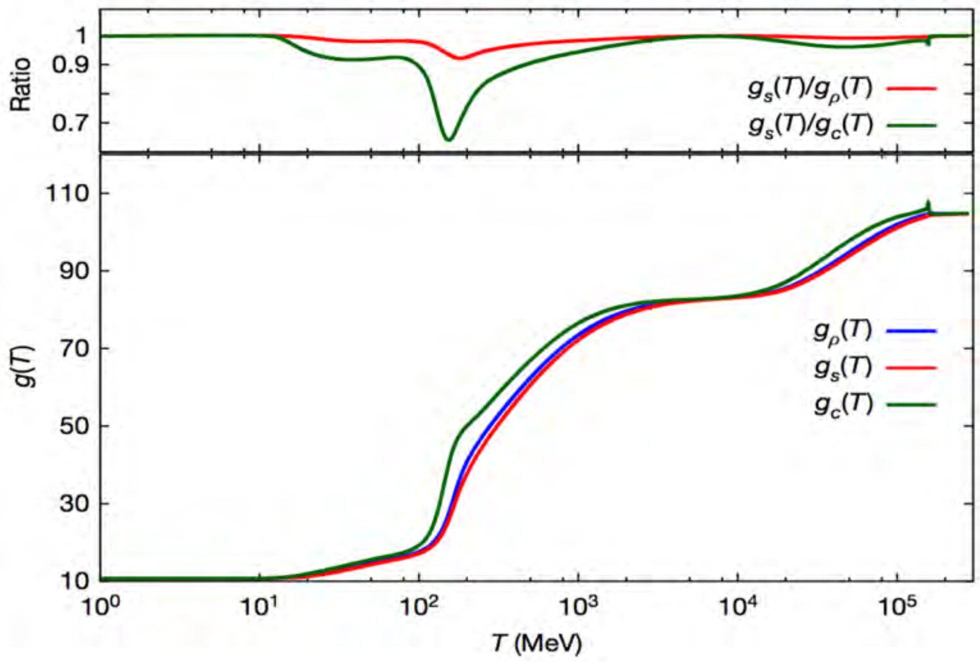
- QCD input from lattice:
  - Equation of state $\Rightarrow H(T)$
  - Topological susceptibility $\Rightarrow m_A(T) = \sqrt{\chi(T)}/f_A$



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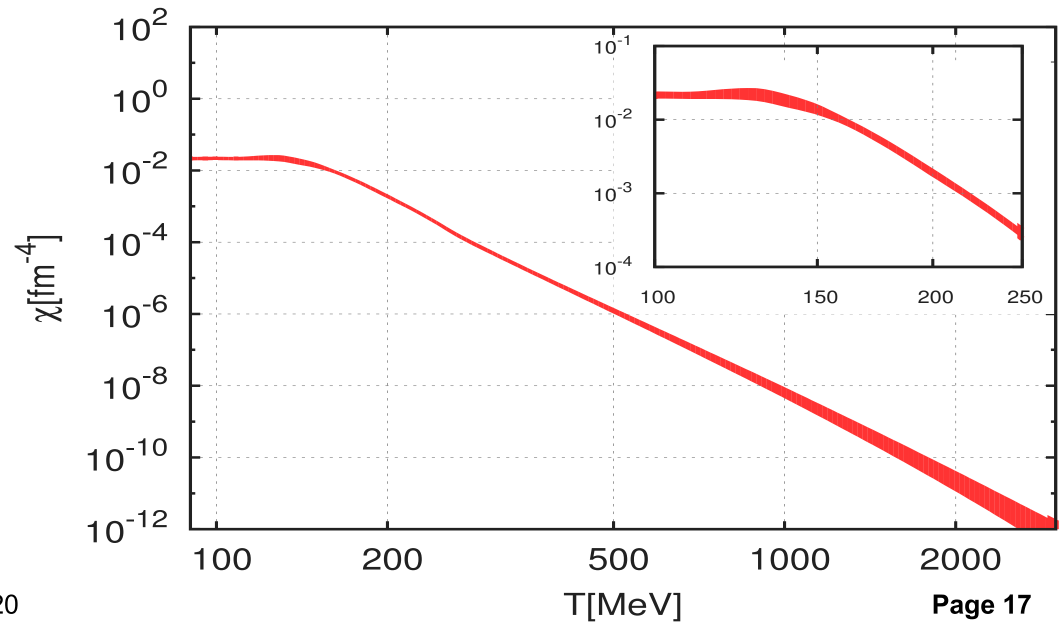
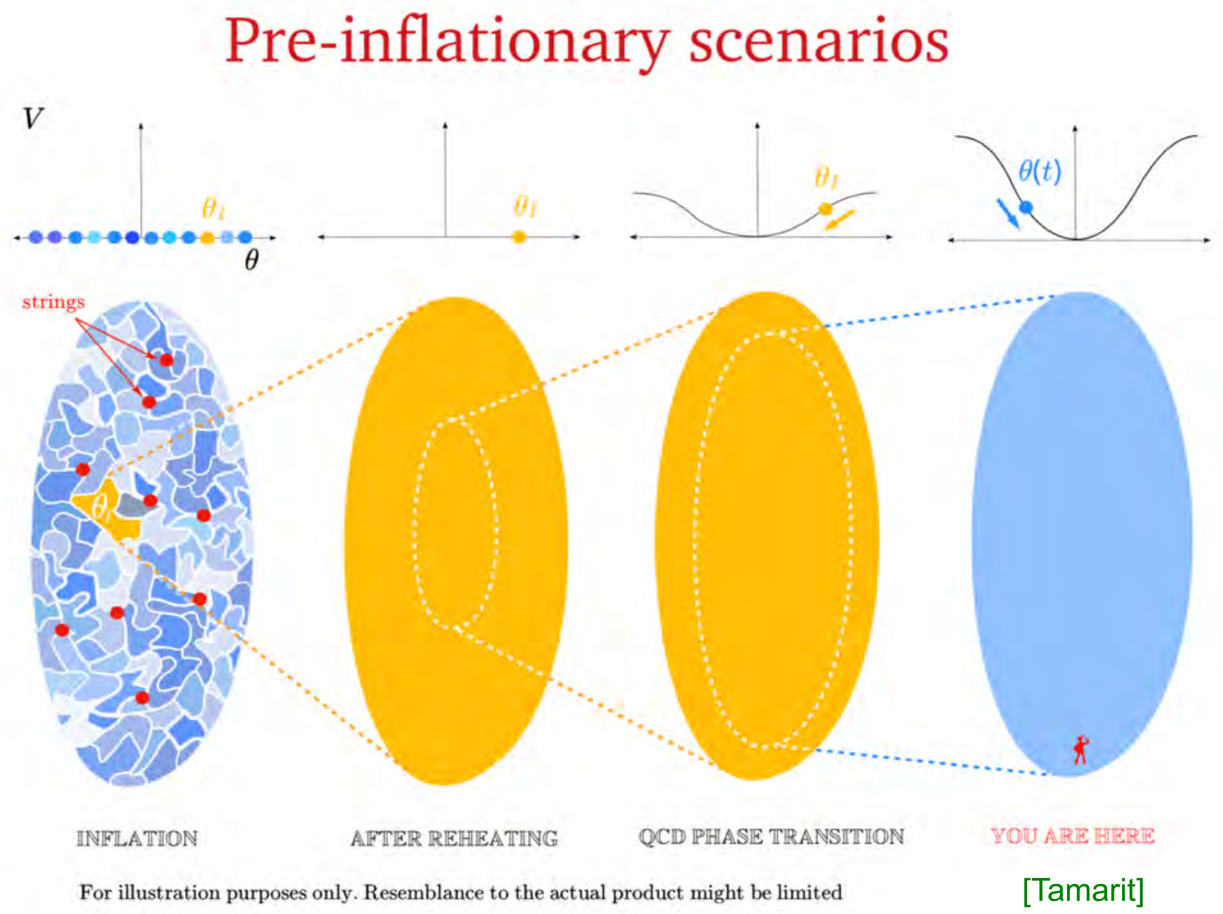


Minimal Solution of DM Problem

Axion as DM candidate

- If PQ symmetry broken before or during inflation $(f_A > H_I/(2\pi))$ and not restored afterwards
  - Axion CDM density depends on single initial value in patch which becomes observable universe and f_A



[Tamarit]

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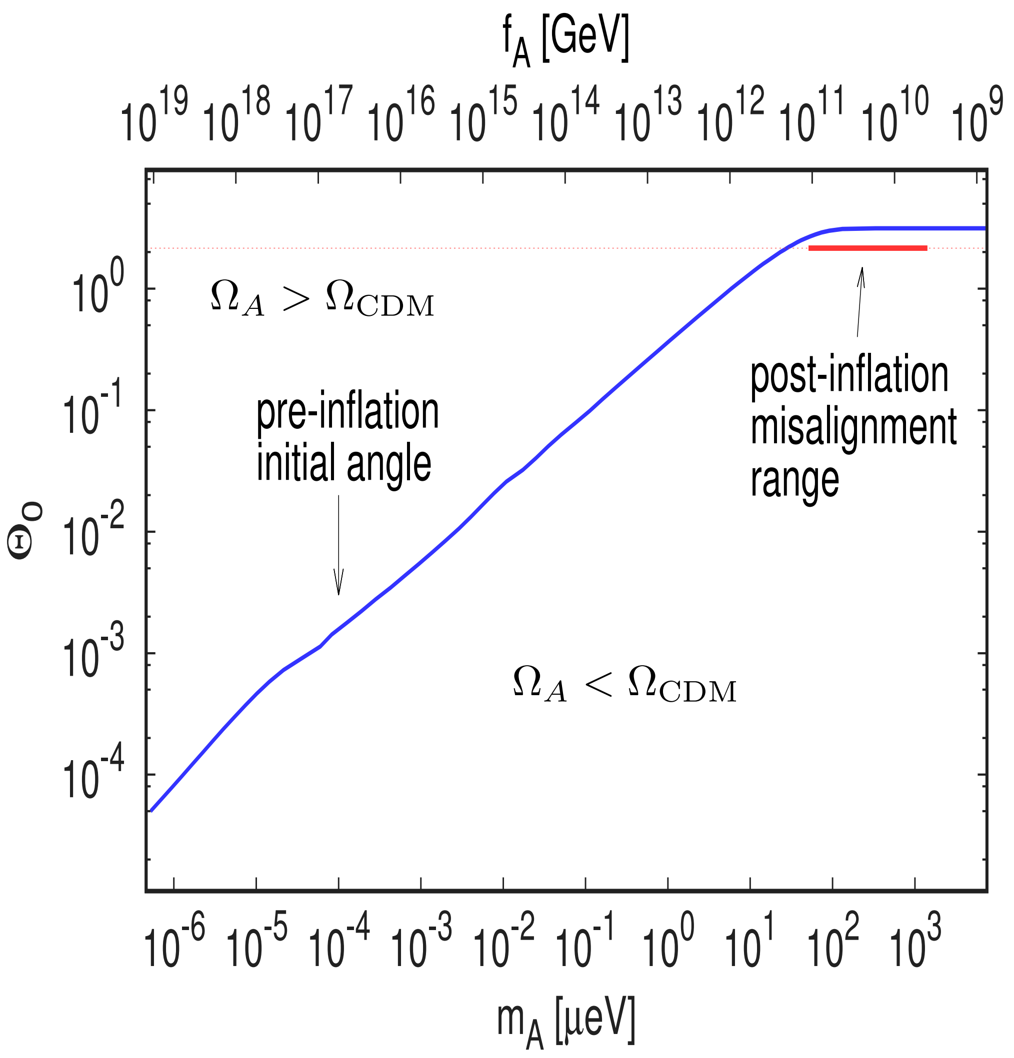
$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{f_A}{9\times 10^{11}\ {\rm GeV}}\right)^{1.165} \theta_{\rm i}^2$$

$$\approx 0.12 \left(\frac{6\ \mu{\rm eV}}{m_A}\right)^{1.165} \theta_{\rm i}^2\,,$$



[Borsanyi et al., Nature `16]

Minimal Solution of DM Problem

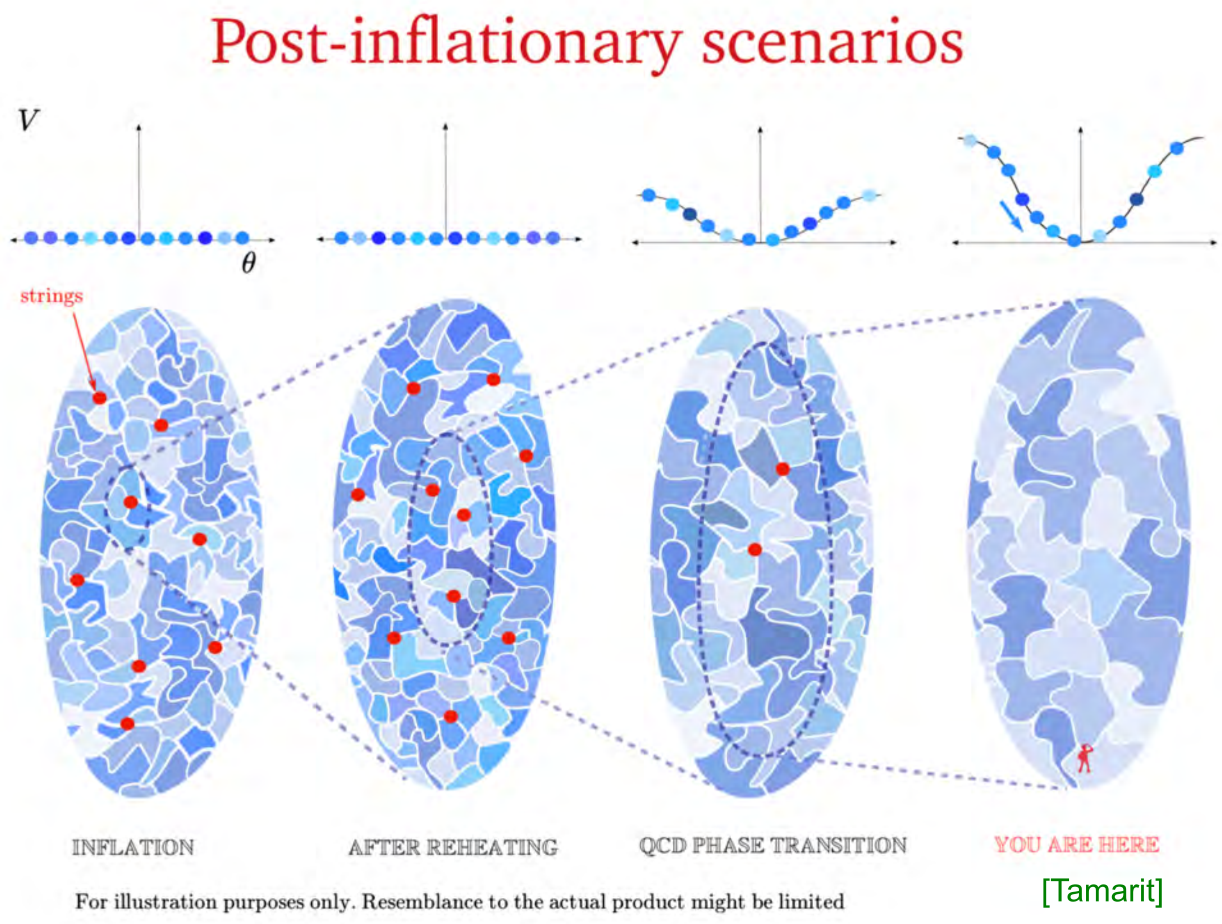
Axion as DM candidate

- Averaging over random initial axion field values

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

- Does not exceed observed CDM abundance for

$$m_A > 28(2)\ \mu{\rm eV}$$ [Borsanyi et al., Nature `16]



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

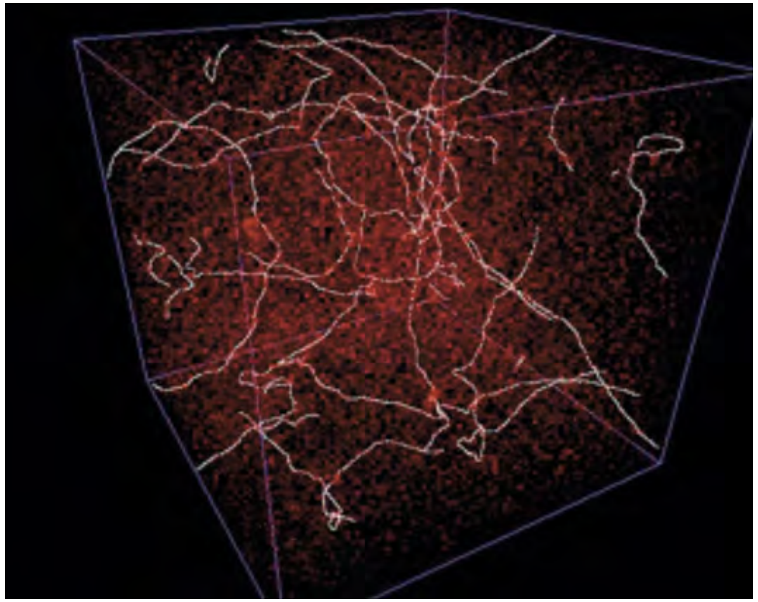
- Axions also produced by collapse of network of topological defects – strings and domain-walls –

- Axion can be 100% of DM for

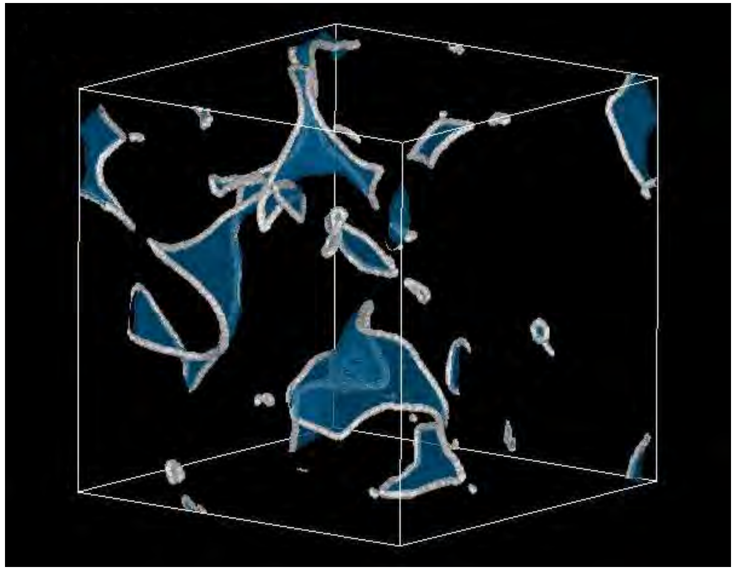
$$m_A \approx 26\ \mu{\rm eV} - 4.4\ {\rm meV}$$

$$f_A \approx 1.3 \times 10^9\ {\rm GeV} - 2.2 \times 10^{11}\ {\rm GeV}$$

[Hiramatsu et al. 11,12,13;
Kawasaki,Saikawa,Segikuchi 15;
Ballesteros et al. 16;
AR,Saikawa `16;
Klaer,Moore `17;
Gorghetto,Hardy,Villadoro `18;
Buschmann et al. 19;
Hindmarsh 19]



[Hiramatsu et al.]



One SM*A*S*H to Rule Them All

- Field content suffices to solve all five big problems in one stroke:

SM * Axion * See-saw * Higgs portal inflation

[Ballesteros,Redondo, AR,Tamarit, 1608.05414; 1610.01639]

1. Neutrino masses and mixing

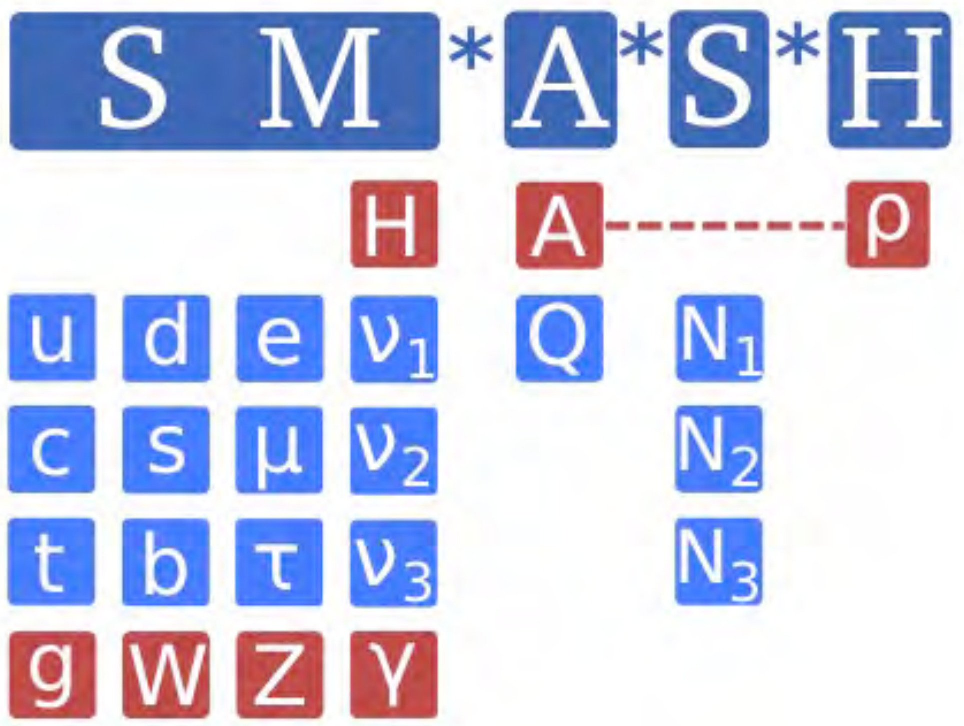
$$m_\nu = 0.04\,\text{eV}\left(\frac{10^{11}\,\text{GeV}}{v_\sigma}\right)\left(\frac{-F\,Y^{-1}\,F^T}{10^{-4}}\right)$$

2. Axionic solution of the strong CP problem

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

$$f_A = v_\sigma$$

3. Axion dark matter
4. Baryogenesis via leptogenesis
5. Inflation



Inflation in SM*A*S*H

Non-minimal chaotic (Higgs) Hidden Scalar inflation

- Take into account unavoidable non-minimal coupling of Higgs and HS field to gravity,

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

- Non-minimal couplings stretch scalar potential in Einstein frame; make 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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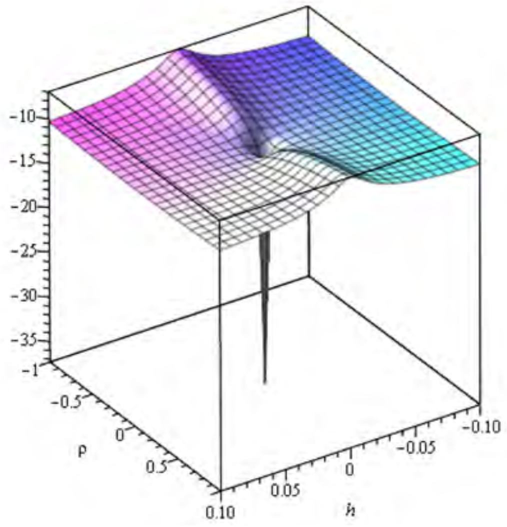
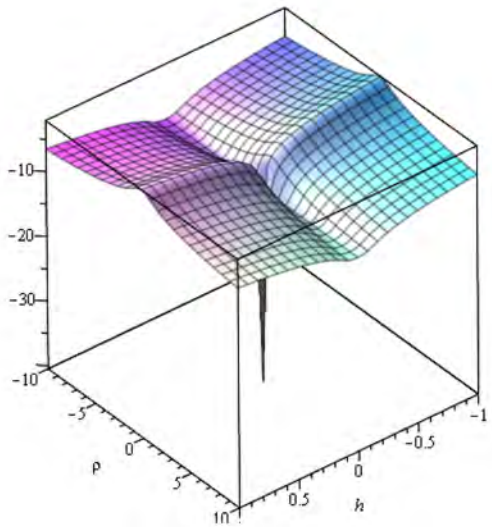
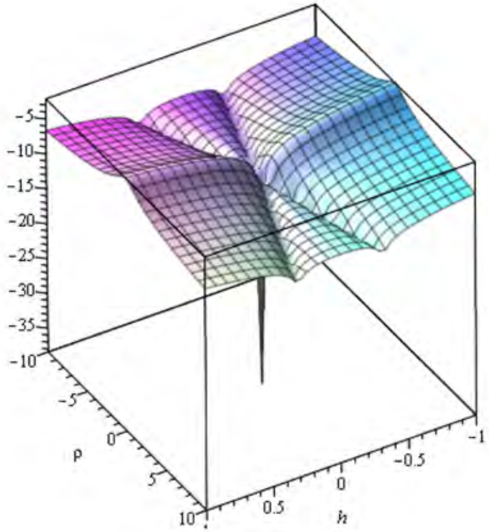
- Non-minimal couplings stretch scalar potential in Einstein frame; make it convex and asymptotically flat at large field values
- Potential has valleys = attractors for Higgs Inflation (HI), Hidden Scalar Inflation (HSI) or mixed Higgs Hidden Scalar Inflation (HHSI), depending on relative signs of $\kappa_H \equiv \lambda_{H\sigma}\xi_H - \lambda_H\xi_\sigma\,, \quad \kappa_\sigma \equiv \lambda_{H\sigma}\xi_\sigma - \lambda_\sigma\xi_H$

sign(κ_H)	sign(κ_σ)	Inflation
$+$	$-$	HI
$-$	$+$	HSI
$-$	$-$	HHSI

Inflation in SM*A*S*H

Non-minimal chaotic (Higgs) Hidden Scalar inflation

- Power spectra of primordial scalar and tensor perturbations, with (from CMB observations)

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

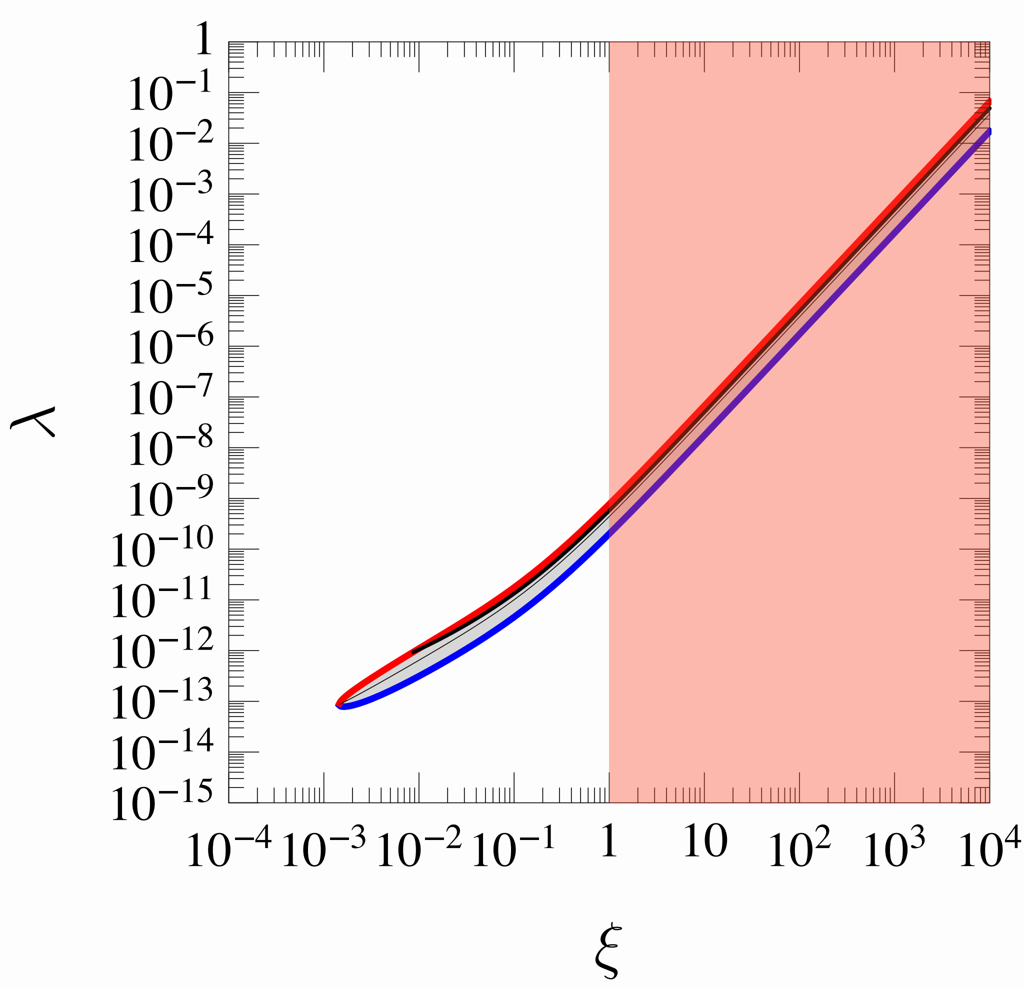
obtained for $\xi \simeq 2 \times 10^5 \sqrt{\lambda} \gtrsim 10^{-3}$

where

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

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

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



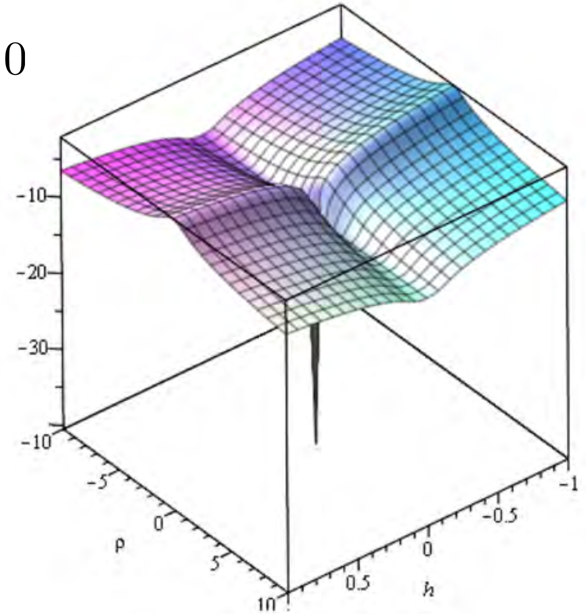
Reheating in SM*A*S*H

PQ symmetry restoration

- 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 quasi-quartic potential, with Universe expanding as in a radiation-dominated era

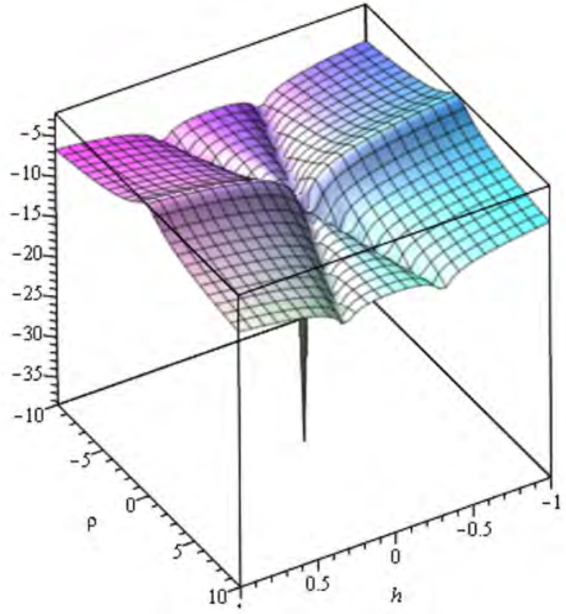
$\lambda_{H\sigma} > 0$

HSI



$\lambda_{H\sigma} < 0$

HHSI



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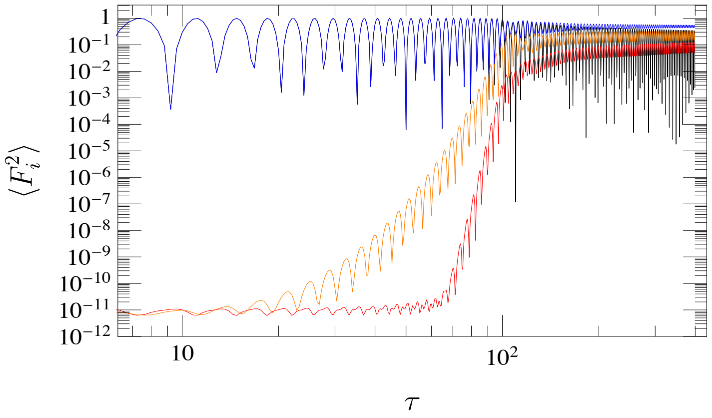
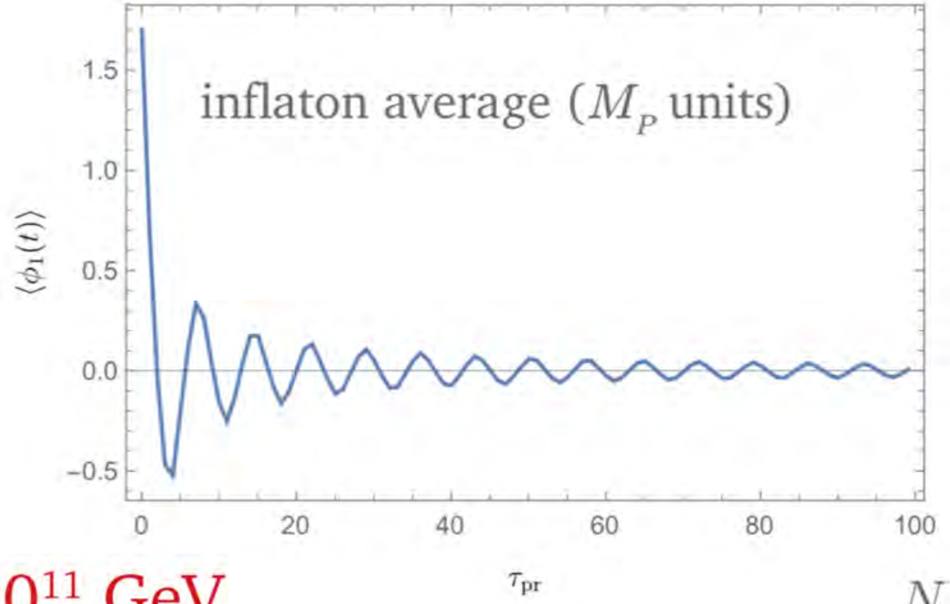
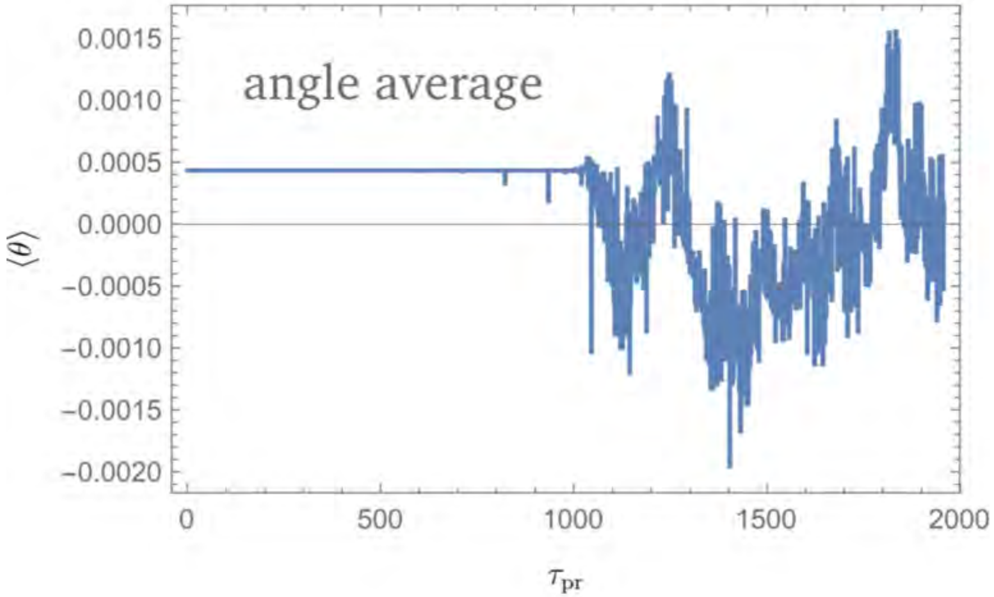
- For $f_A \lesssim 10^{17}\,\mathrm{GeV}$, PQ symmetry restored after inflation





$f = 10^{11}$ GeV



[Ballesteros, AR,Tamarit, Welling in prep.]

Reheating in SM*A*S*H

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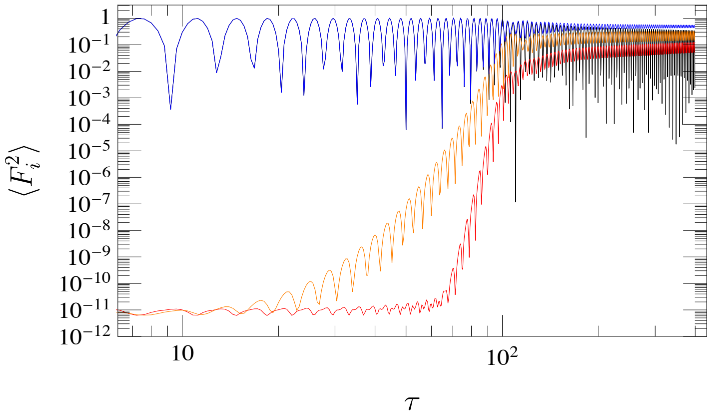
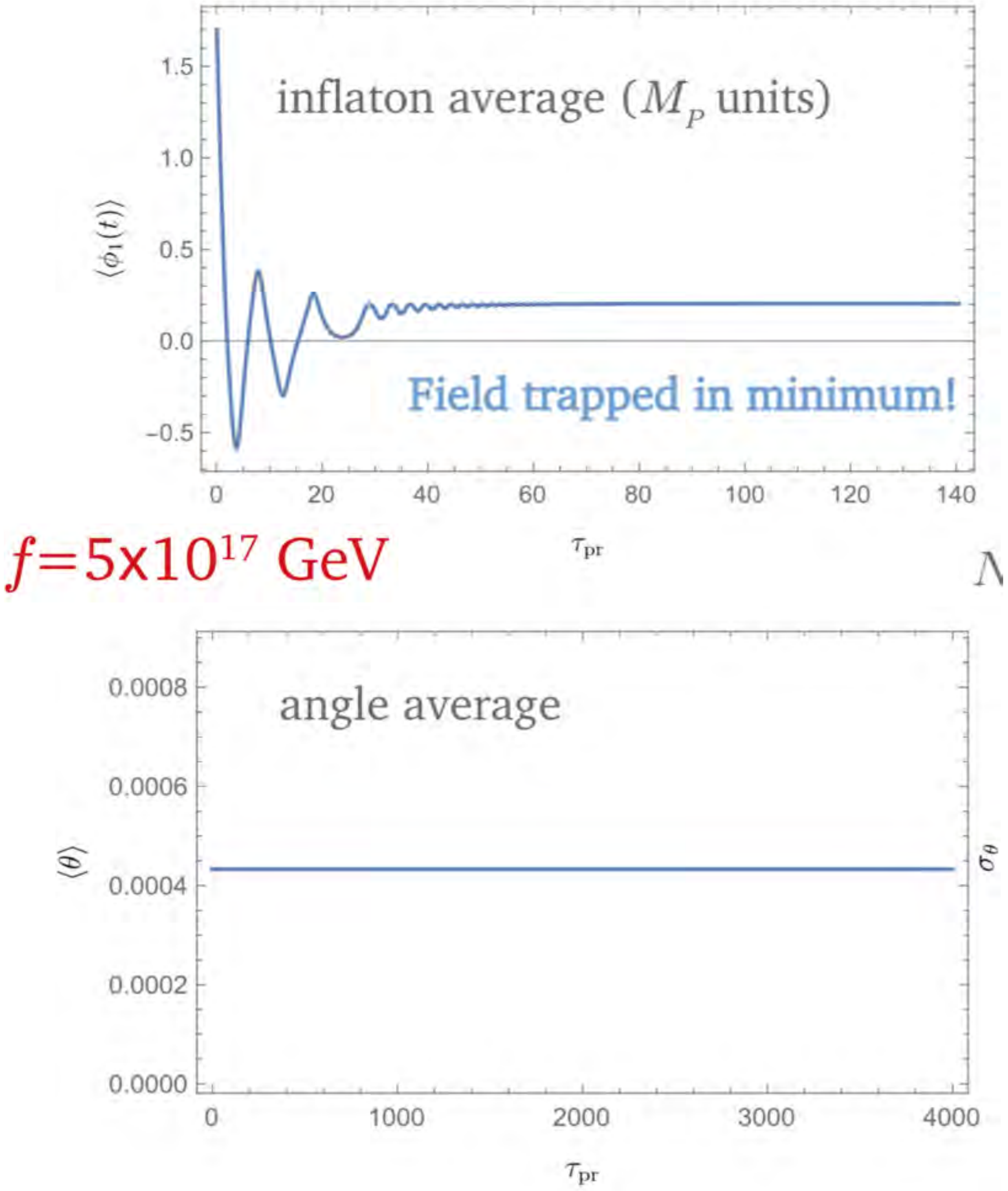


- $f_A \gtrsim 10^{17}\,\mathrm{GeV}$ excluded by PLANCK upper limits on isocurvature fluctuations [Ballesteros, AR,Tamarit, Welling in prep.]



[Ballesteros, AR,Tamarit, Welling in prep.]

Reheating in SM*A*S*H

Reheating temperature and dark radiation

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

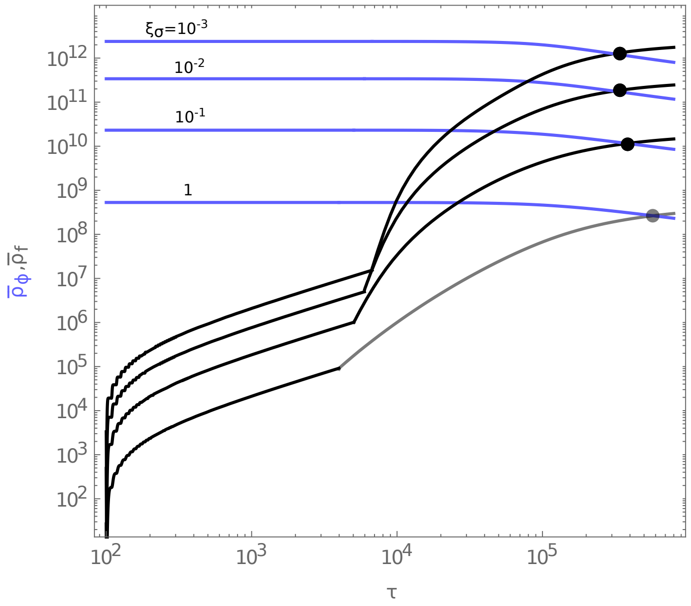
$$T_R \sim 10^7\,\mathrm{GeV}\,v_{11}\lambda_{10}^{3/8}\delta_3^{-1/8}$$

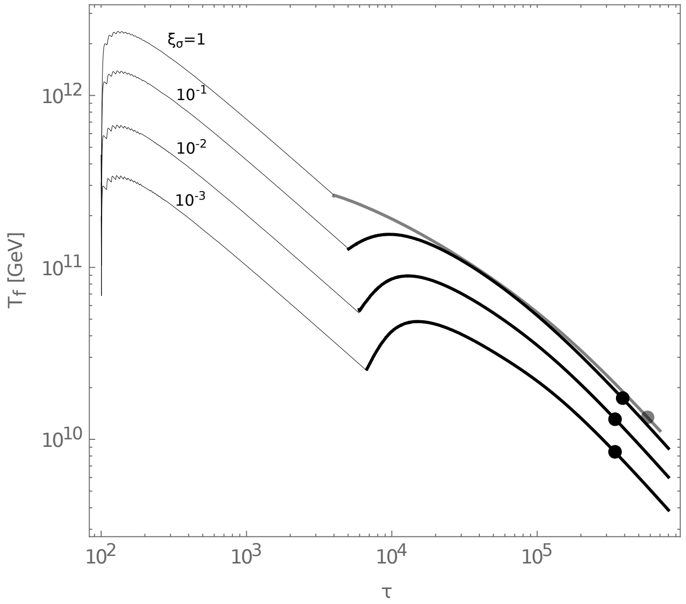
$$\Delta N_\nu^{\mathrm{eff}} \sim (\delta_3 v_{11}/\lambda_{10})^{-1/6}$$

- **HHSI:** Higgs component of inflaton allows for production of SM gauge bosons

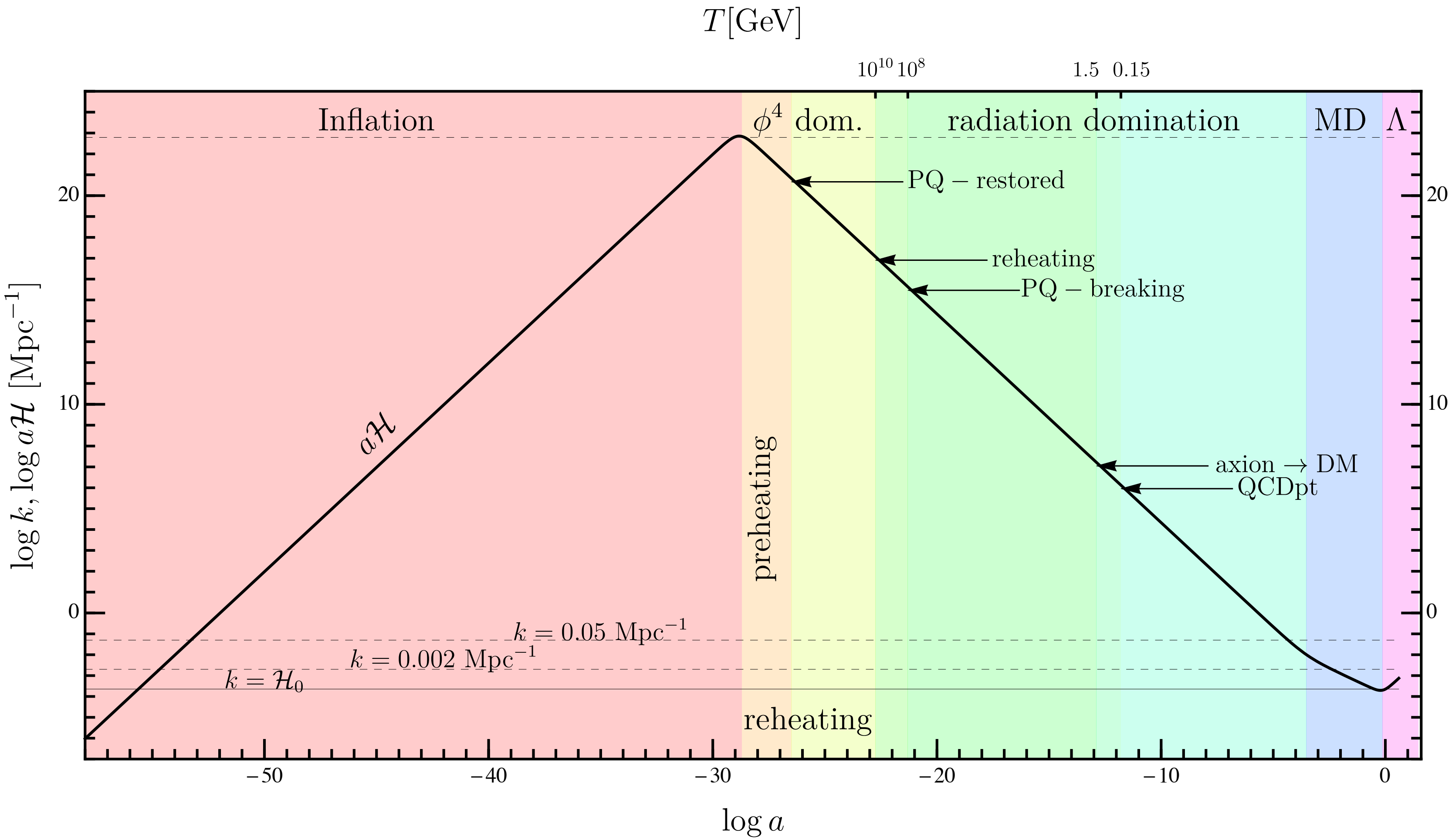
$$T_R \sim 10^{10}\,\mathrm{GeV}$$

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





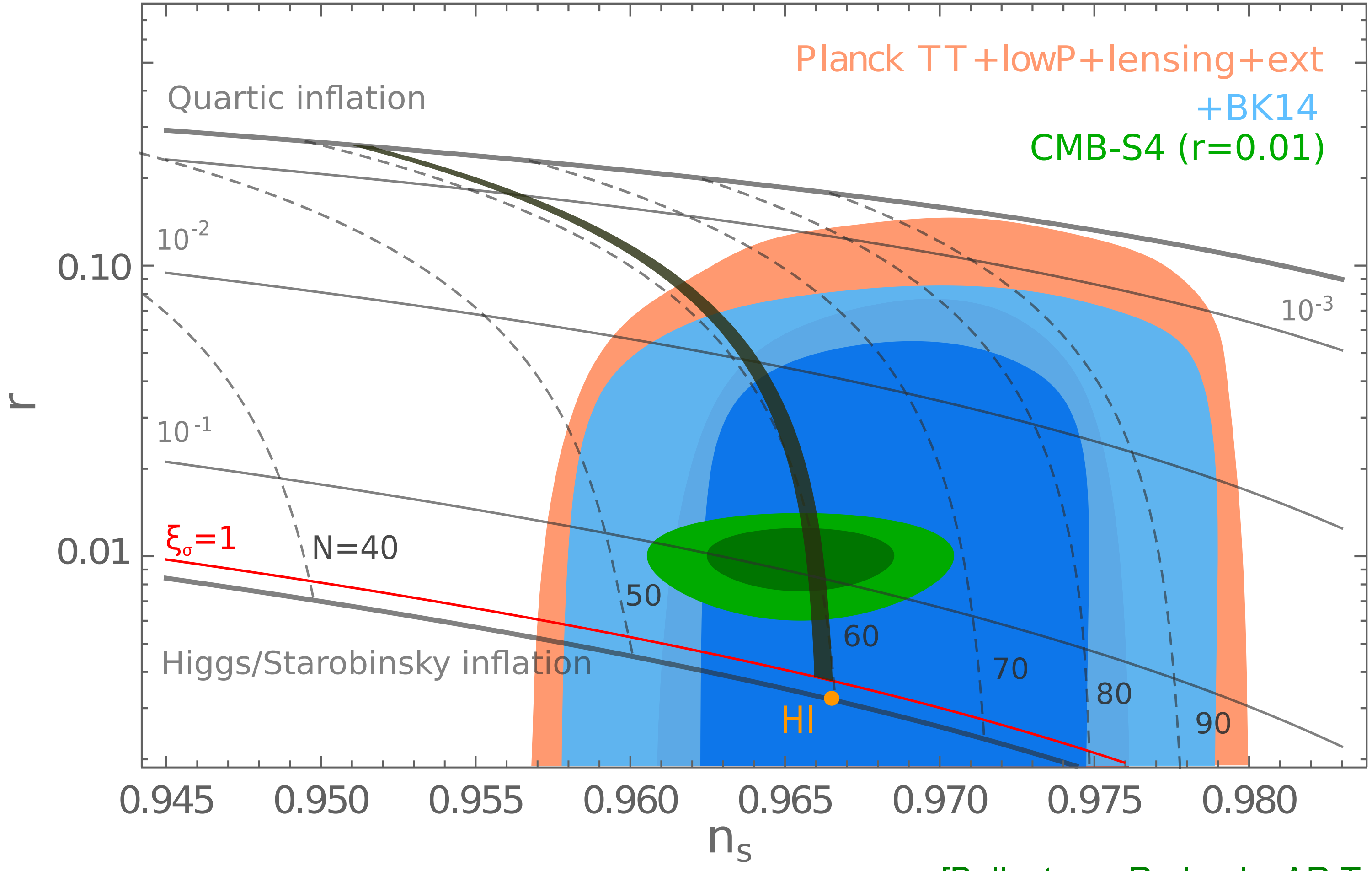
Expansion and Thermal History in SM*A*S*H



- Number of e-folds $N(k)$ from the time a given comoving scale k leaves horizon until end of inflation predicted. Correspondingly sharp prediction of r versus n_s

Primordial Gravitational Waves in SM*A*S*H

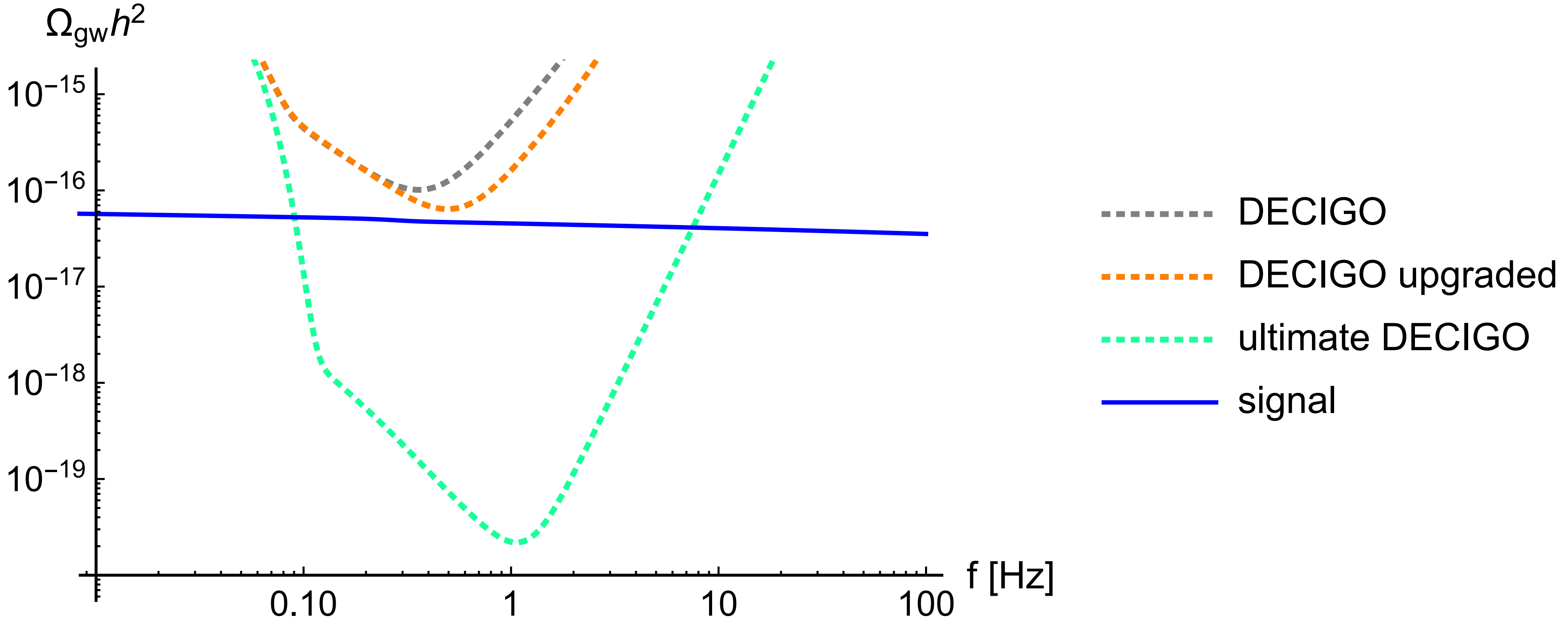
- Can be probed indirectly by upcoming CMB polarization experiments (e.g. CMB-S4):



[Ballesteros,Redondo, AR,Tamarit, 1904.05594]

Primordial Gravitational Waves in SM*A*S*H

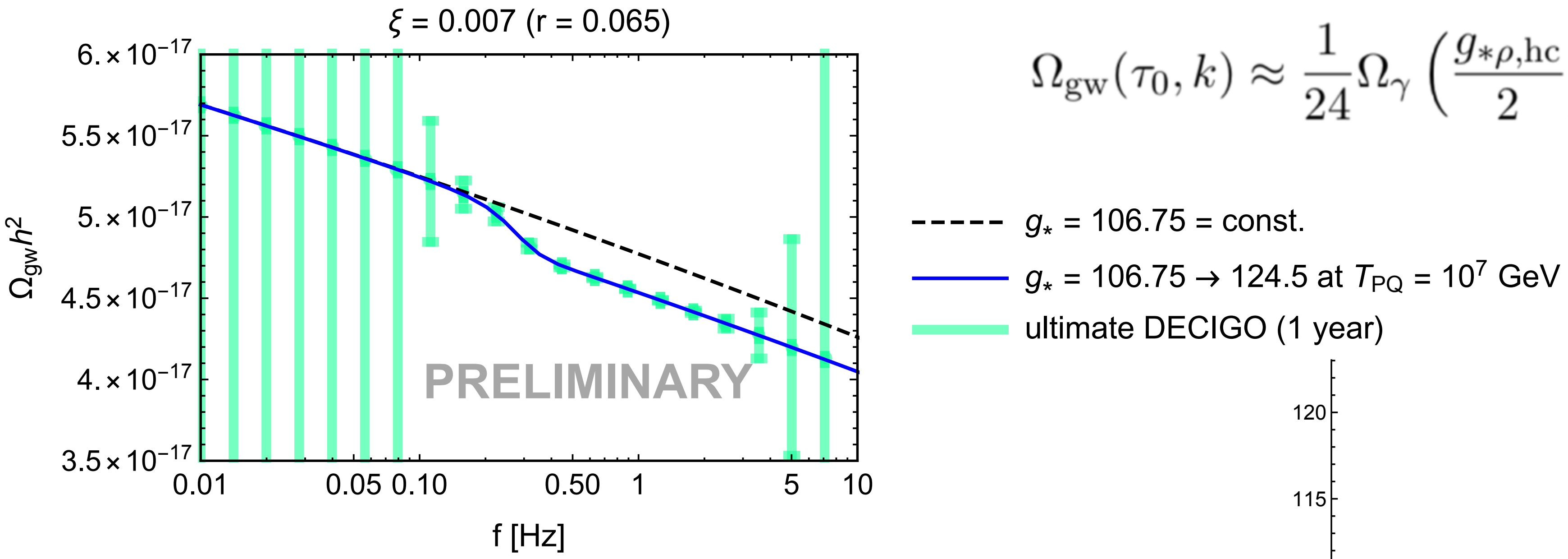
- Can be probed directly by future space-born gravitational wave interferometer (e.g. DECIGO)



[AR, Saikawa, Tamarit, in preparation]

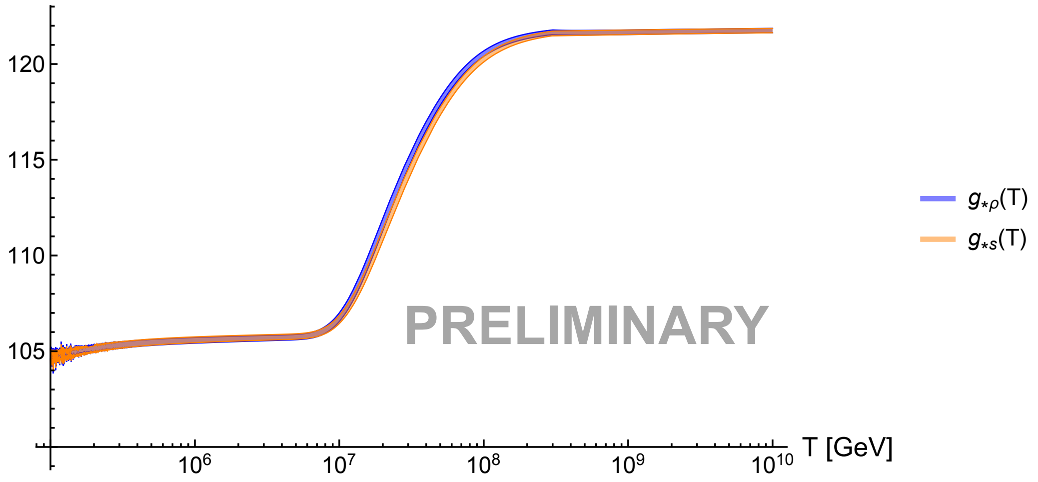
Primordial Gravitational Waves in SM*A*S*H

- Future space-born GW interferometer (e.g. ultimate DECIGO) sensitive to step in primordial GW spectrum due to change of equation of state around the PQ phase transition: [AR, Saikawa, Tamarit, in preparation]



$$\Omega_{\rm gw}(\tau_0,k)\approx\frac{1}{24}\Omega_\gamma\left(\frac{g_{*\rho,\rm hc}}{2}\right)\left(\frac{g_{*s,\rm hc}}{g_{*s,\rm fin}}\right)^{-\frac{4}{3}}\mathcal{P}_T(k)$$

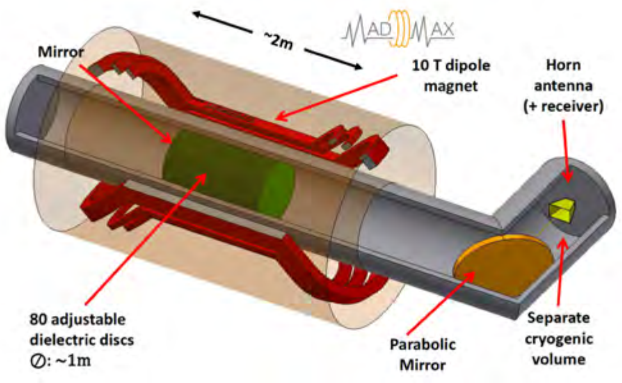
$$f=\frac{k}{2\pi a_0}=\frac{H_{\rm hc}}{2\pi}\frac{a_{\rm hc}}{a_0}\approx 2.65\,{\rm Hz}\left(\frac{g_{*s,\rm fin}}{3.931}\right)^{\frac{1}{3}}\left(\frac{g_{*\rho,\rm hc}}{106.75}\right)^{\frac{1}{2}}\left(\frac{g_{*s,\rm hc}}{106.75}\right)^{-\frac{1}{3}}\left(\frac{T_{\rm hc}}{10^8\,{\rm GeV}}\right)$$



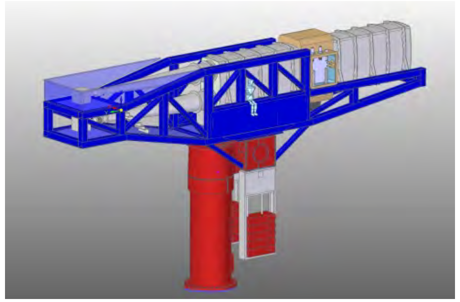
Dark Matter in SM*A*S*H

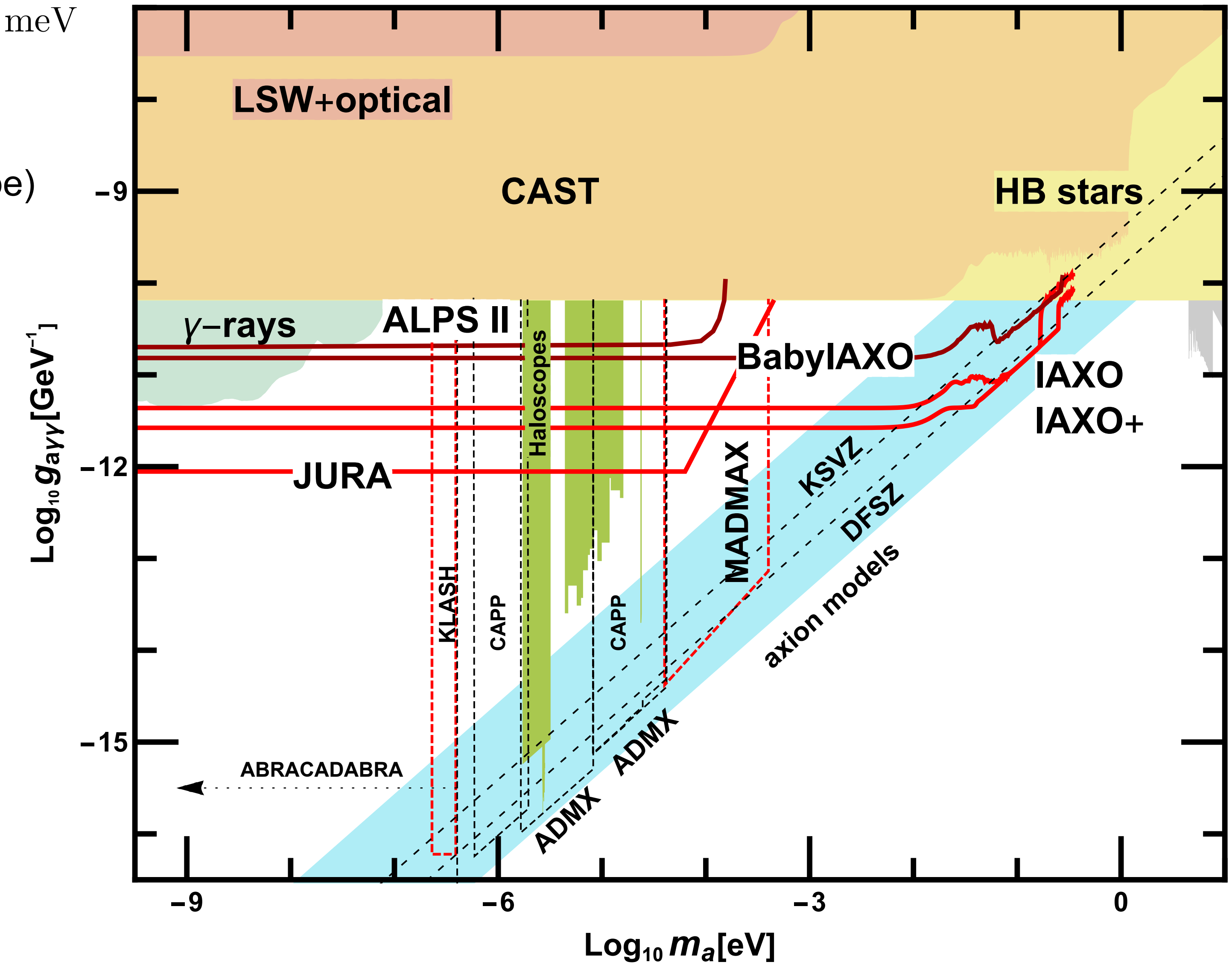
Axion dark matter mass $m_A \approx 25\ \mu\text{eV} - 4.4\ \text{meV}$

- Mass range will be probed in this decade:
  - Axion dark matter direct detection (Haloscope)
    - **MADMAX** @ DESY



  - Solar axion telescope (Helioscope)
    - **(Baby)IAXO** @ DESY



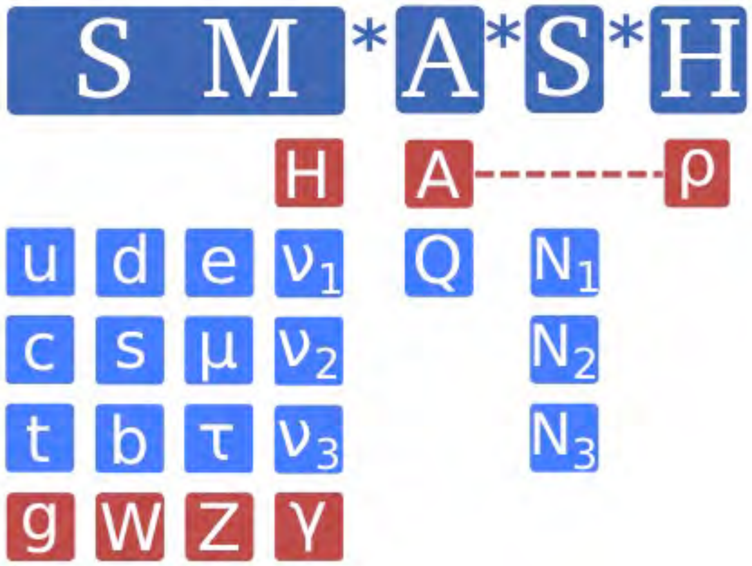


[Desch et al., „A European Strategy Towards Finding Axions and Other WISPs"]

Summary

- Remarkably simple extension of SM involving just one new dimension-full scale provides solution of five fundamental problems:

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



$$\mathcal{L} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm yuk}^{SM}$$

$$- \left[\frac{M^2}{2} + \xi_H \, H^\dagger H + \xi_\sigma \, |\sigma|^2 \right] R$$

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

STABILITY

$$- \lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2} \right)^2 - [y \sigma \tilde{Q} Q + y_{Q d_i} \sigma Q d_i + c.c]$$

INFLATION

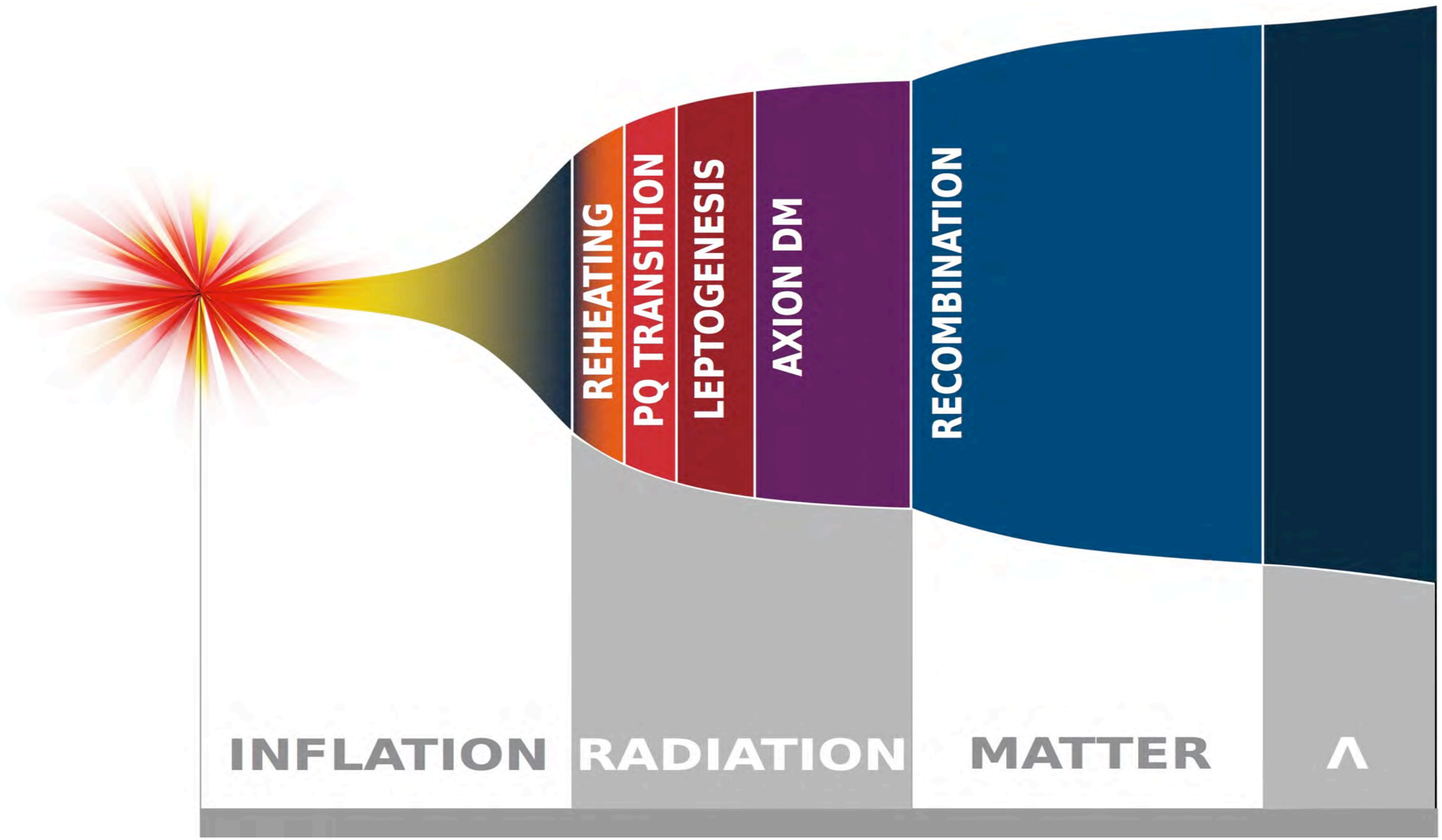
CP PROBLEM

$$-[F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + c.c.]$$

SEESAW AND LEPTOGENESIS

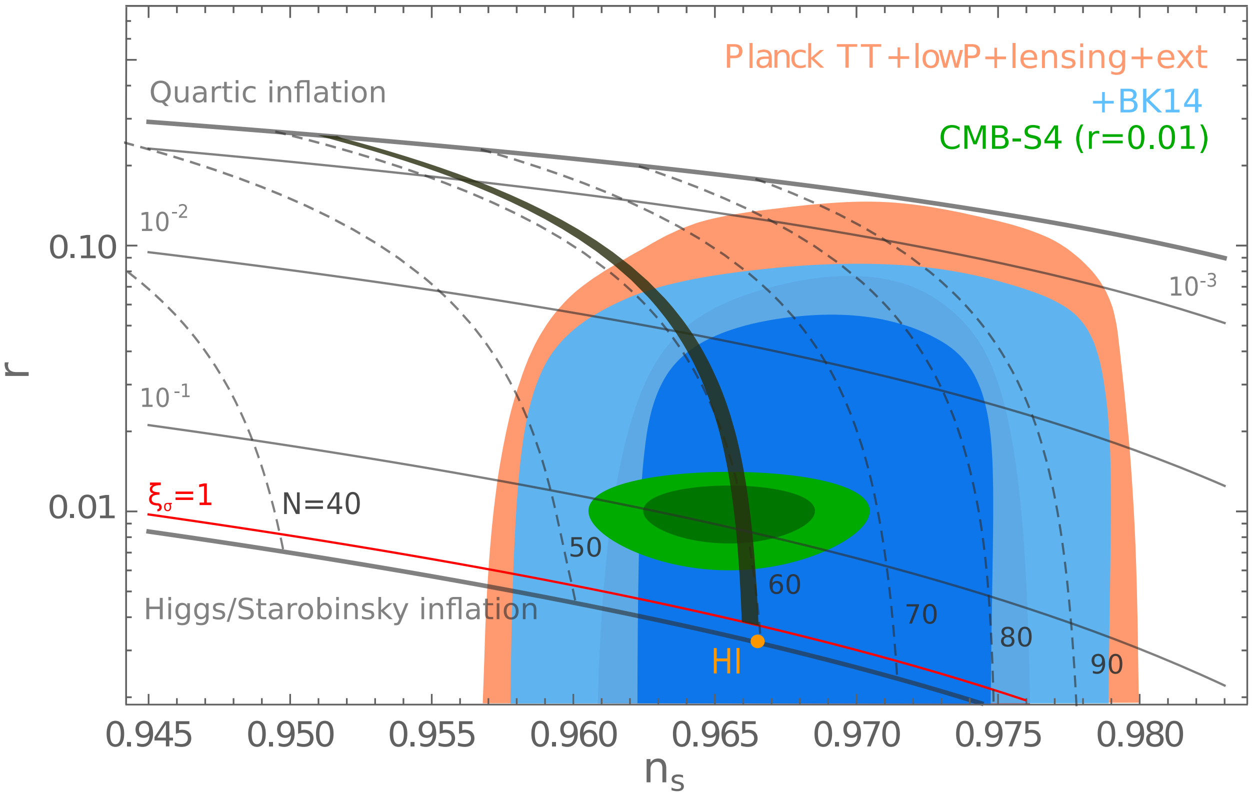
Summary

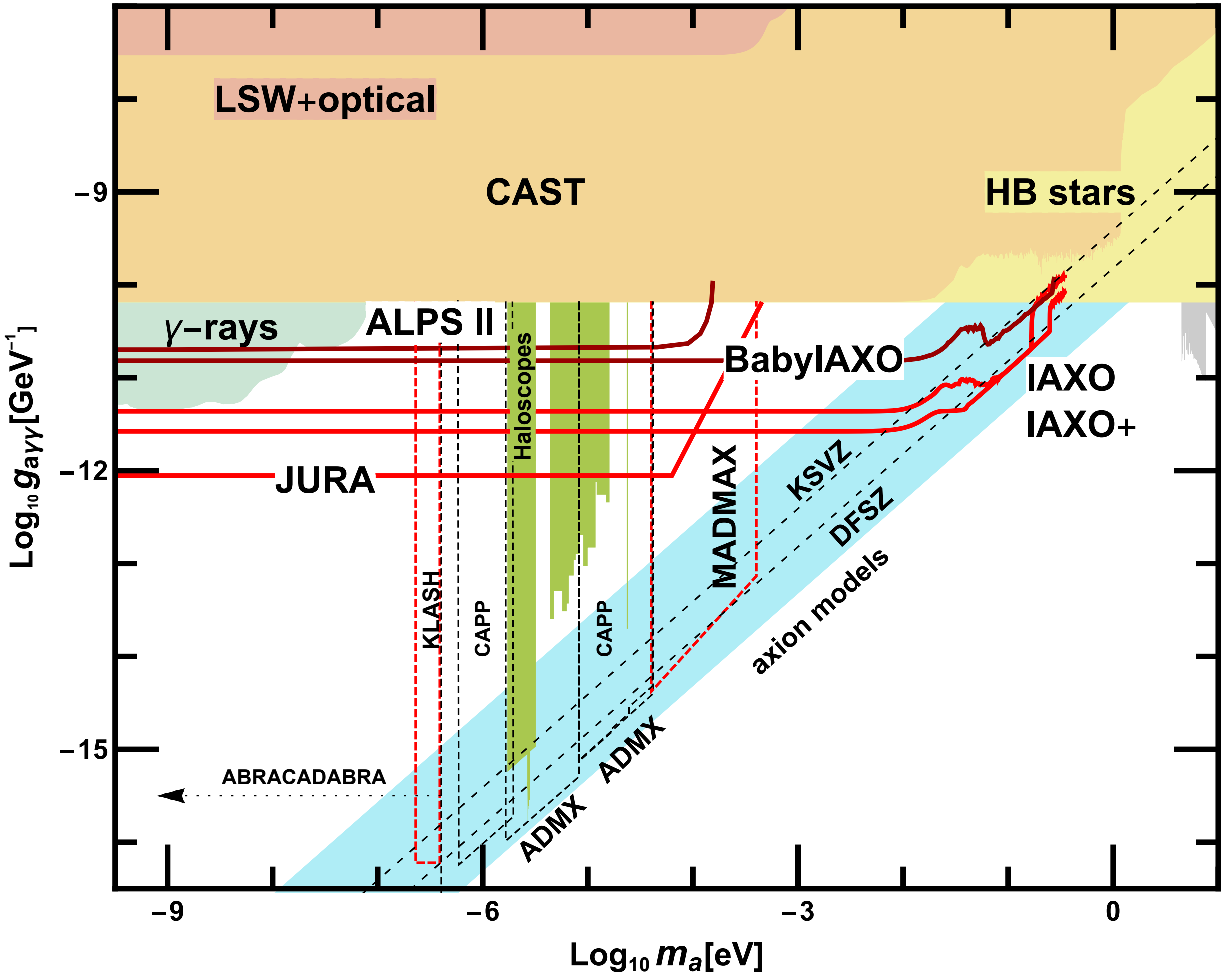
- SM*A*S*H offers self-contained description of cosmology from inflation until today:



Summary

- Firm predictions ($r \gtrsim 0.004,\ \triangle N_{\rm eff}^{\nu} = 0.027,\ m_A \approx 25\ \mu{\rm eV} - 4.4\ {\rm meV}$) in reach of upcoming experiments:



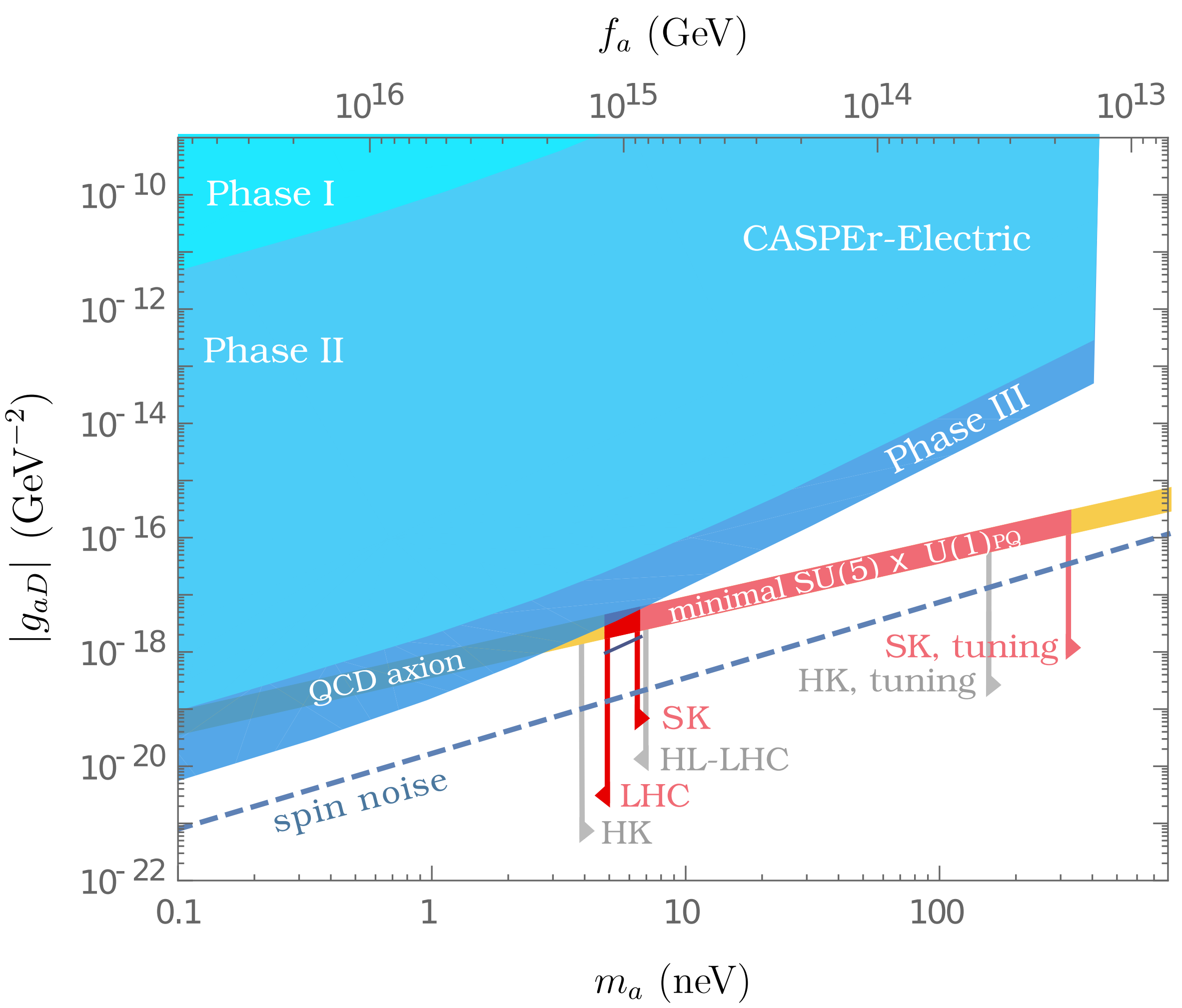


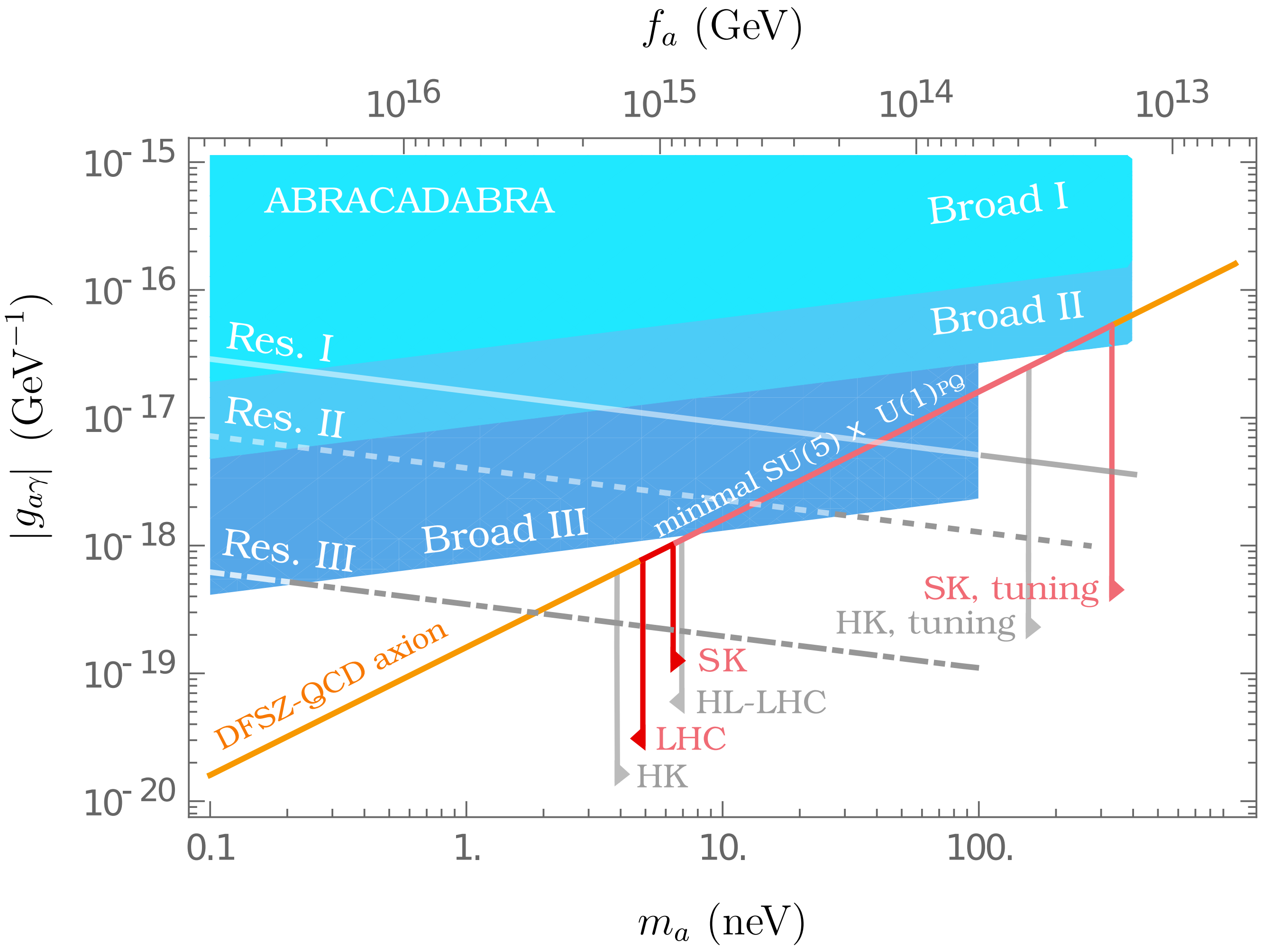
Summary

- Work in progress:
  - Primordial gravitational waves in SMASH [AR, Saikawa, Tamarit, in preparation]
  - Variations of SMASH
    - 2hdSMASH [Dutta, Matlis, Moortgat-Pich, AR, in progress]
    - GUT SMASH [Ballesteros, Di Luzio, AR, Tamarit, Welling, , in progress]

Back Up: Summary

- GUT SMASH opens a further window at neV axion mass which can also be probed in the new decade:

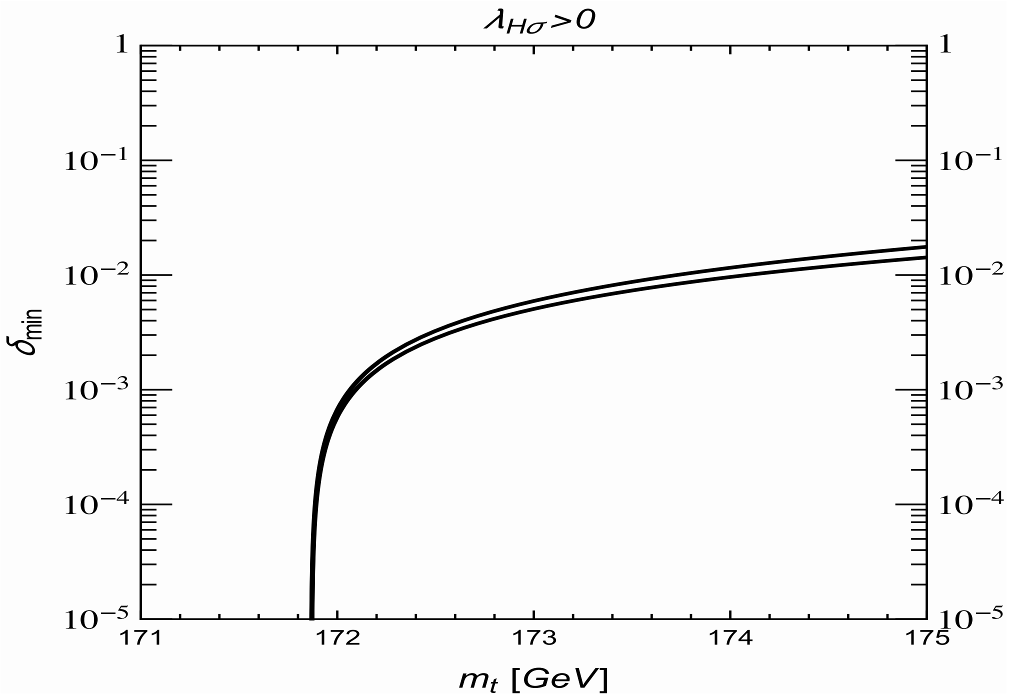


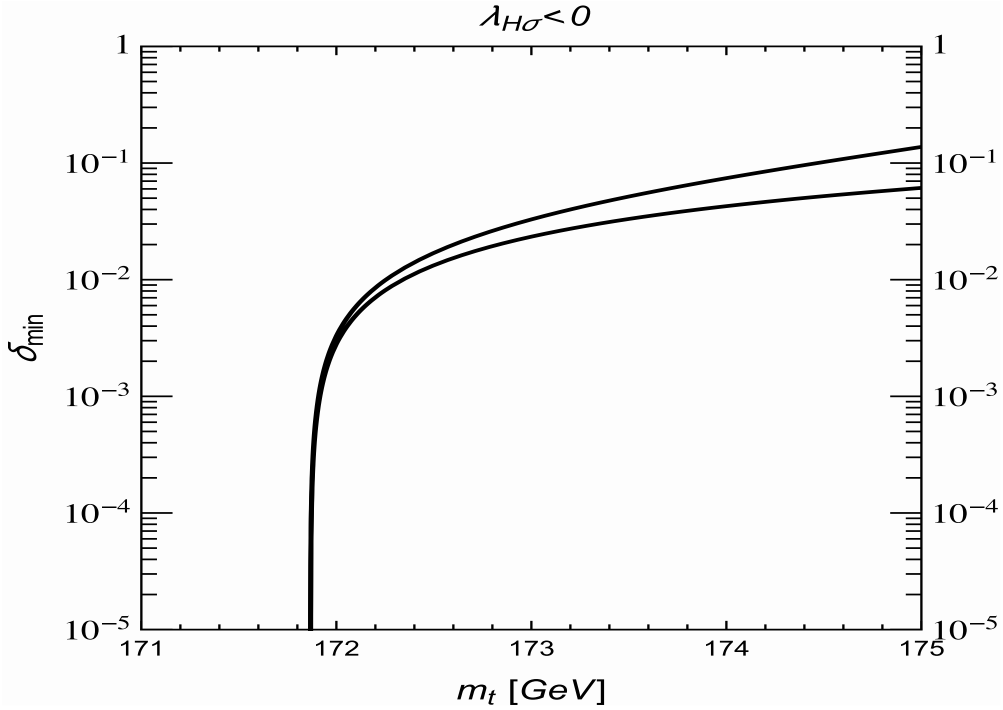


Vacuum Stability in SM*A*S*H

Electroweak vacuum stabilization through Hidden Scalar

- 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:



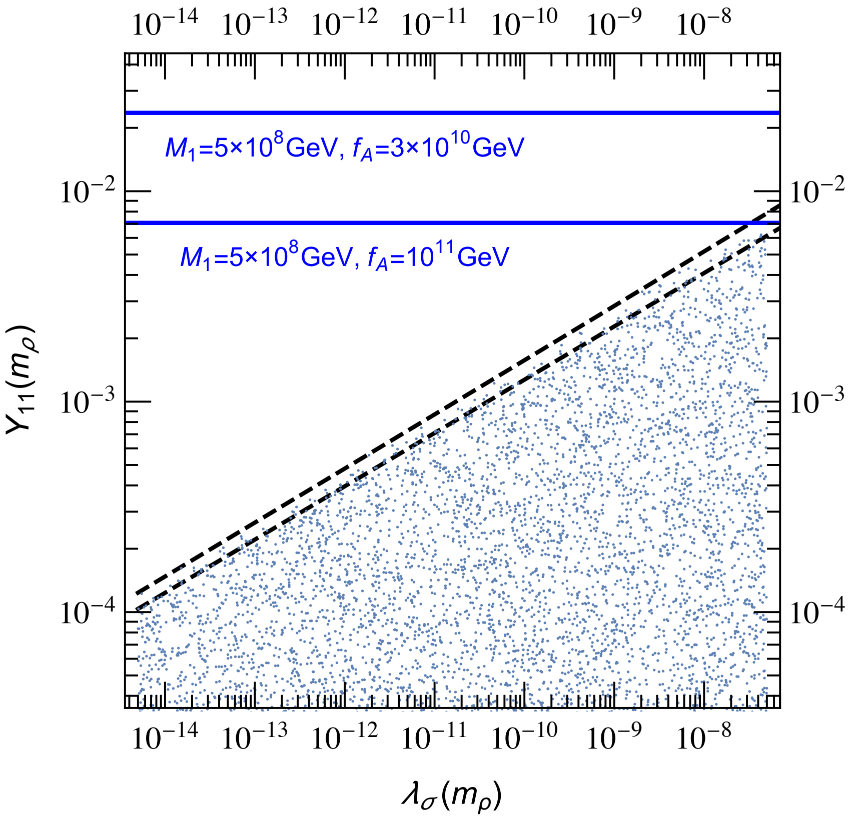


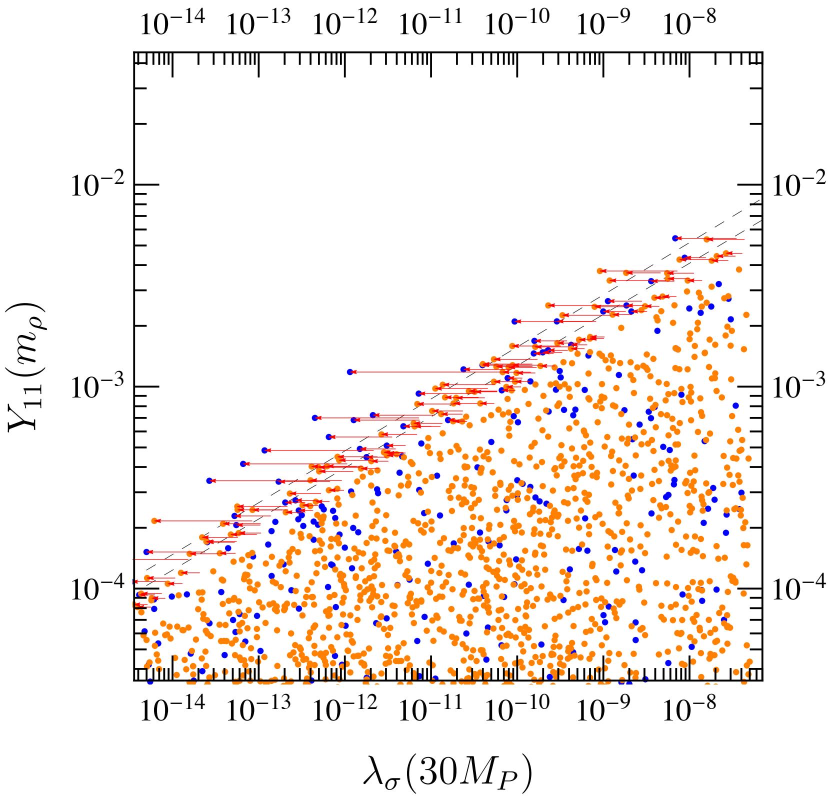
Vacuum Stability in SM*A*S*H

Vacuum stability in PQ scalar direction

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

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





Back Up: Towards a GUT SMASH

Minimal SU(5) GUT

- Original SU(5) model comprised of
  [Georgi, Glashow 74]
  - three copies of 10_F and $\bar{5}_F$ representing chiral SM matter fermions
  - 24_H and 5_H , representing Higgs bosons

$$10_F = \underbrace{\left(\bar{3}, 1, -\frac{2}{3}\right)_F}_{u^c} \oplus \underbrace{\left(3, 2, +\frac{1}{6}\right)_F}_{q} \oplus \underbrace{(1, 1, +1)_F}_{e^c},$$

$$\bar{5}_F = \underbrace{\left(\bar{3}, 1, +\frac{1}{3}\right)_F}_{d^c} \oplus \underbrace{\left(1, 2, -\frac{1}{2}\right)_F}_{\ell},$$

$$24_H = \underbrace{(1, 1, 0)_H}_{S_H} \oplus \underbrace{(1, 3, 0)_H}_{T_H} \oplus \underbrace{(8, 1, 0)_H}_{O_H} \oplus \underbrace{\left(3, 2, -\frac{5}{6}\right)_H}_{X_H} \oplus \underbrace{\left(\bar{3}, 2, +\frac{5}{6}\right)_H}_{\bar{X}_H},$$

$$5_H = \underbrace{\left(3, 1, -\frac{1}{3}\right)_H}_{\mathcal{T}} \oplus \underbrace{\left(1, 2, +\frac{1}{2}\right)_H}_{h},$$

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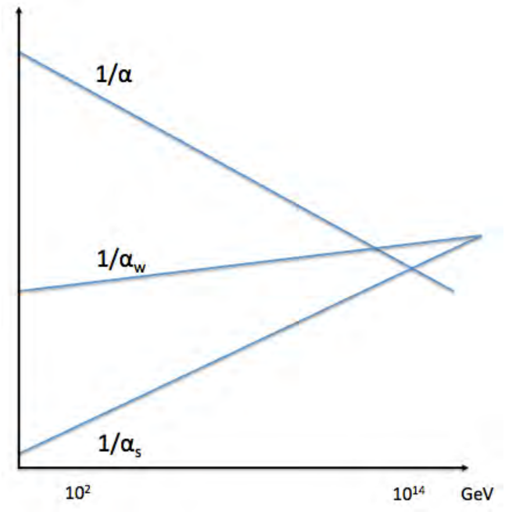

[StackExchange]

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Back Up:

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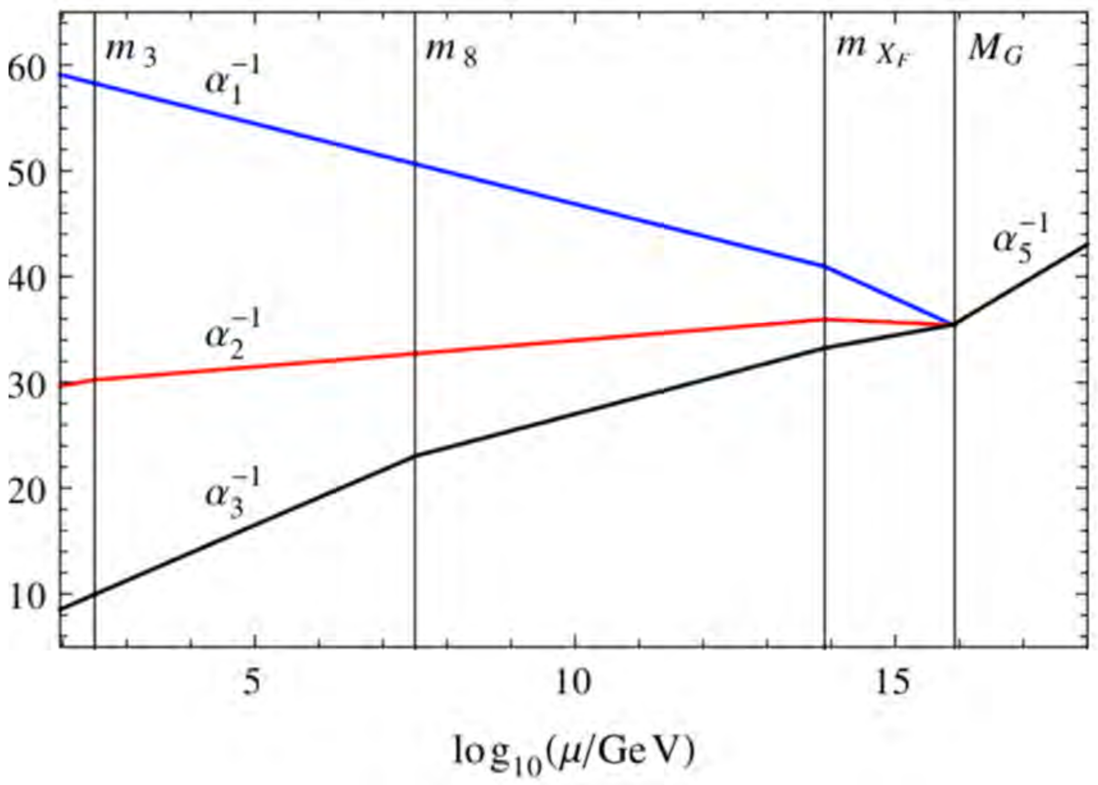

[Di Luzio, Mihaila 13]

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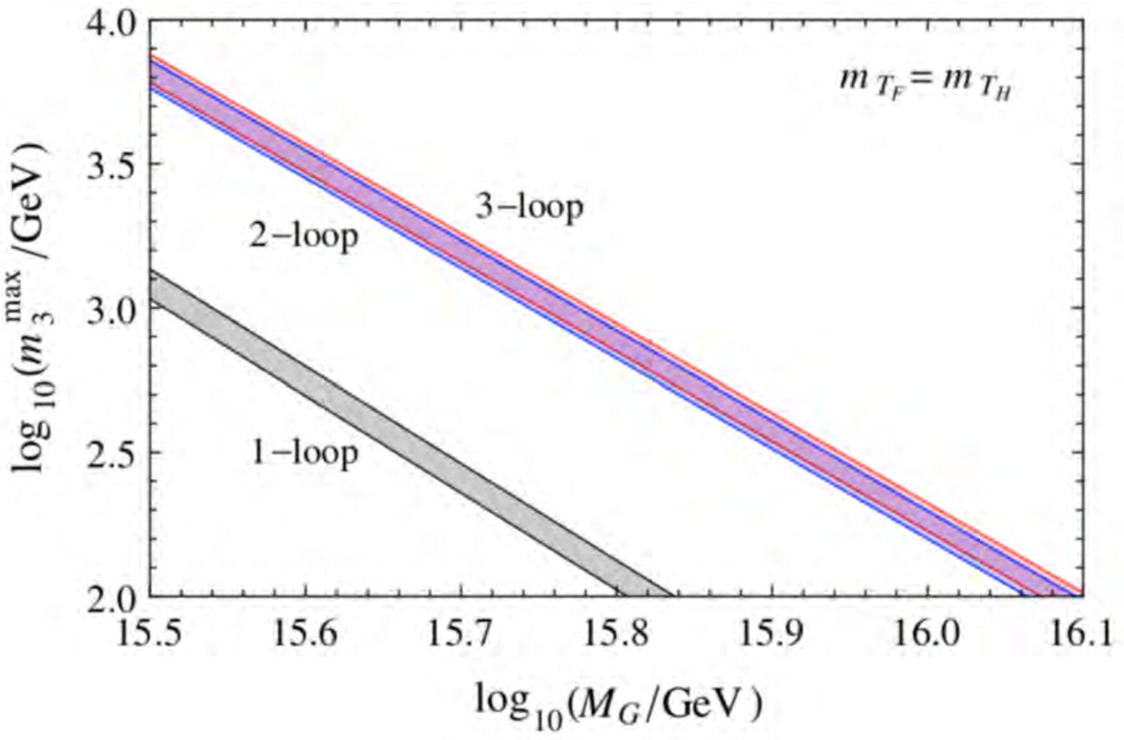
  - Clean correlation between effective electroweak triplet mass m_3 and unification scale M_G



[Di Luzio, Mihaila 13]

$$m_3 = \left(m_{T_F}^4 m_{T_H}\right)^{1/5}$$

Back Up: Towards a GUT SMASH

Axion in minimal SU(5) GUT

- Require that 24_H complex and add $5'_H$
- Impose PQ symmetry:

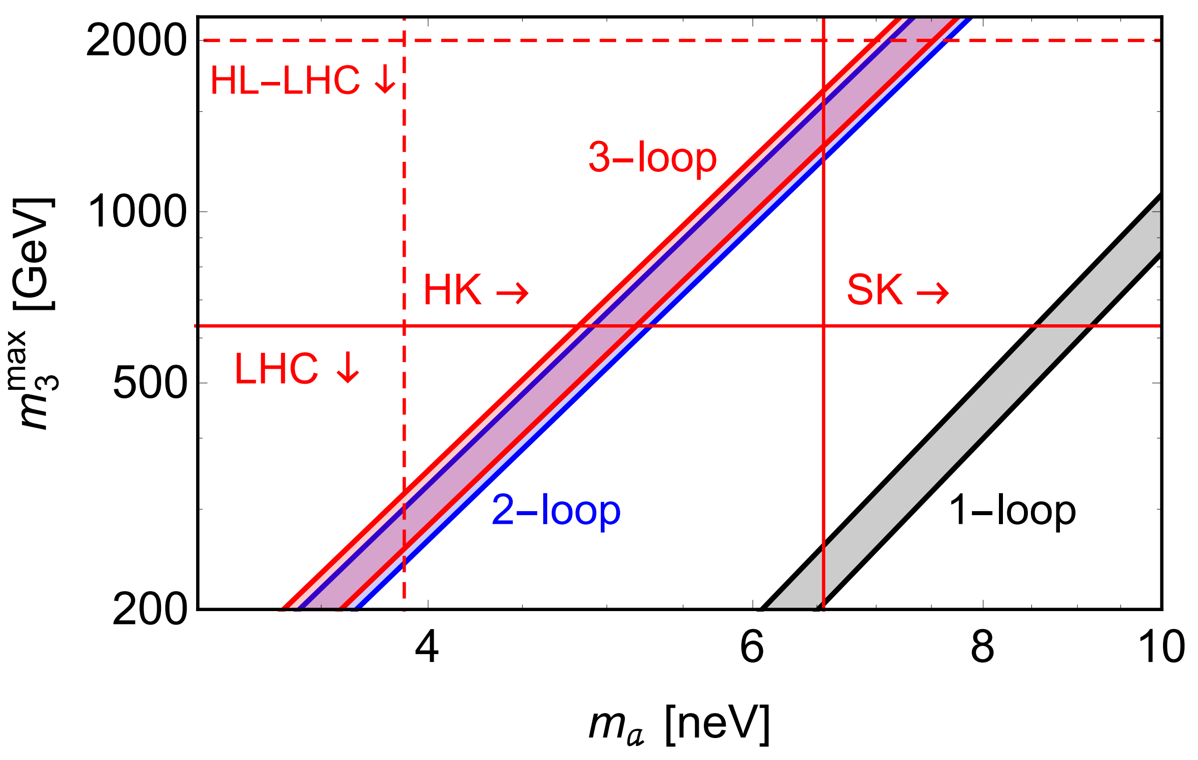
$$\bar{5}_F \to e^{-i\alpha/2}\bar{5}_F,$$
$$10_F \to e^{-i\alpha/2}10_F,$$
$$5_H \to e^{i\alpha}5_H,$$
$$5'_H \to e^{-i\alpha}5'_H,$$
$$24_H \to e^{-i\alpha}24_H,$$
$$24_F \to e^{-i\alpha/2}24_F$$

- Axion decay constant:

$$f_A \simeq \frac{1}{11}\sqrt{\frac{6}{5}}\frac{M_G}{g_5}$$

- Gauge coupling unification, taking into account LHC and Superkamiokande constraints:

$$m_A \in [4.8, 6.6]\ \mathrm{neV}$$



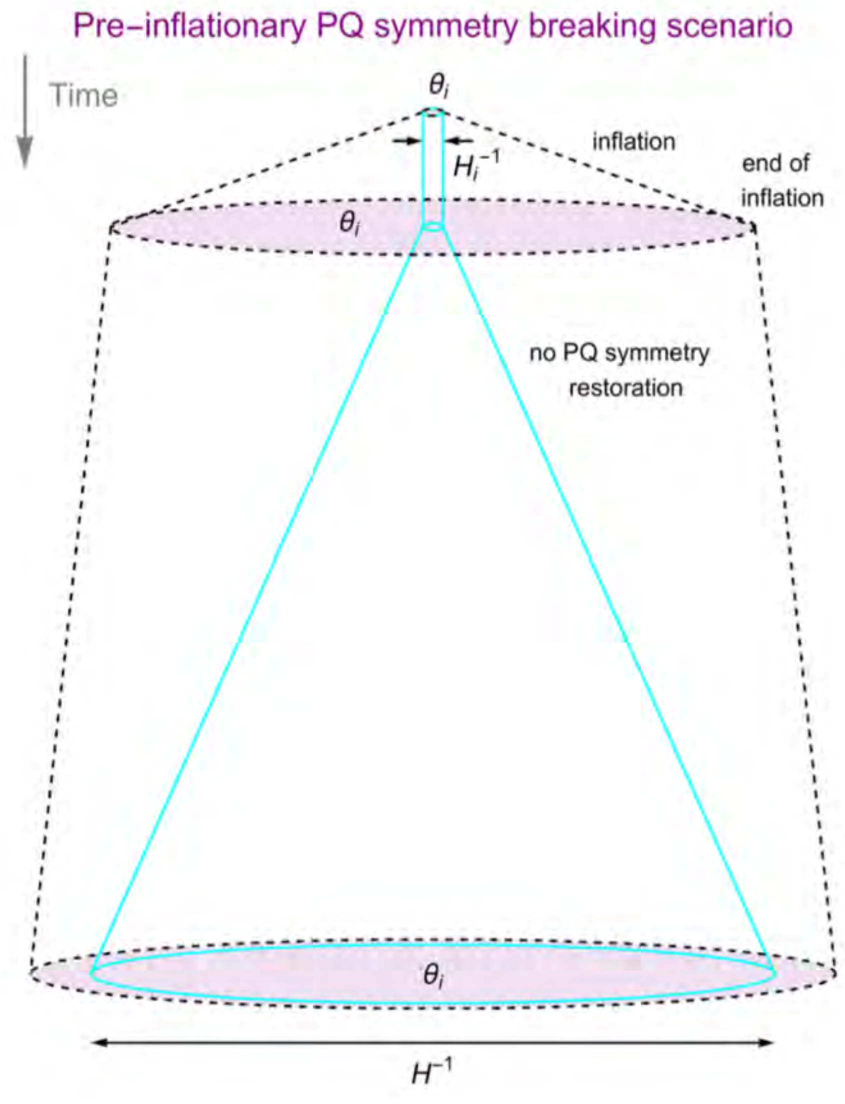
[Di Luzio, AR, Tamarit, arXiv:1807.09769]

Back Up: Towards a GUT SMASH

Axion in minimal SU(5) GUT

- Axion mass in neV range:
  - PQ symmetry has to be broken before inflation and not restored afterwards to avoid DM overabundance
- DM abundance depends not only on mass, but also on the initial value of $\theta_i = A_i/f_A$ inside causally connected region which is inflated to observable universe
- Anthropical selection of initial value to reproduce the observed dark matter abundance needed:

$$\Omega_a h^2 = 0.12 \left(\frac{5.0\ \mathrm{neV}}{m_a}\right)^{1.165} \left(\frac{\theta_{\mathrm{i}}}{1.6\times 10^{-2}}\right)^2$$



[Saikawa]

Back Up: Towards a GUT SMASH

Axion in minimal SU(5) GUT

- Axion mass in neV range:
  - PQ symmetry has to be broken before inflation and not restored afterwards to avoid DM overabundance
- DM abundance depends not only on mass, but also on the initial value of $\theta_i = A_i/f_A$ inside causally connected region which is inflated to observable universe
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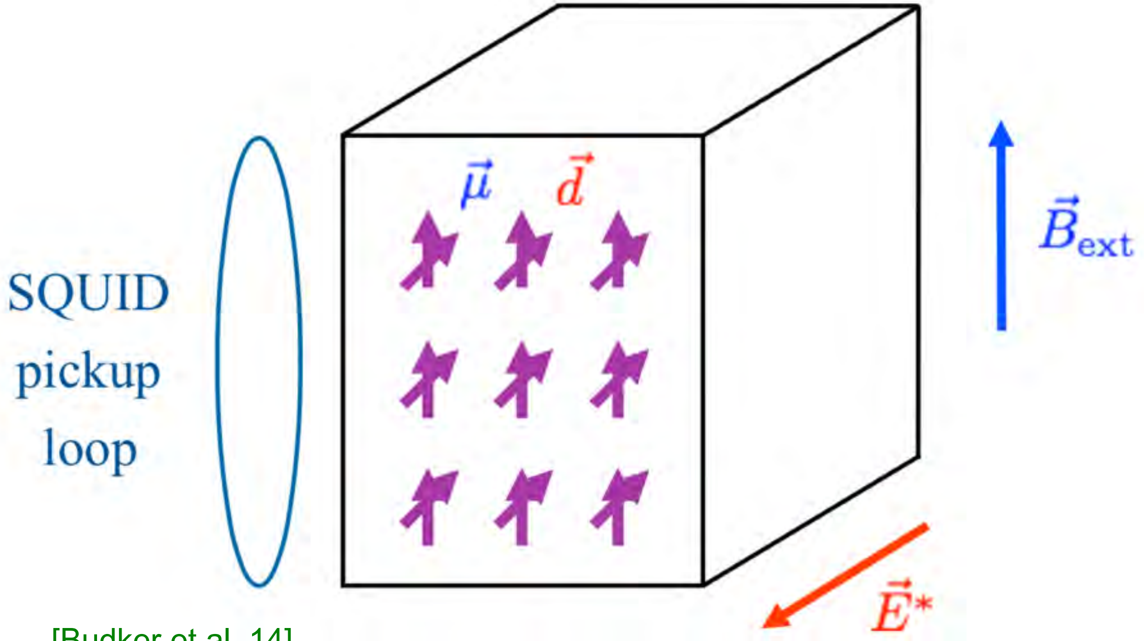
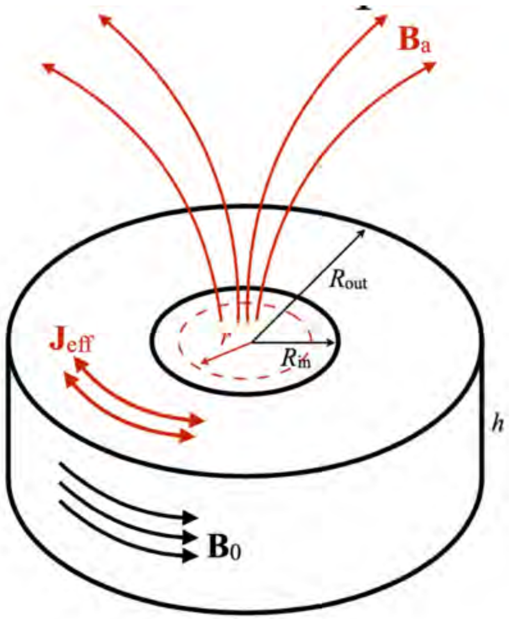
- CASPEr-Electric and ABRACADABRA



[Budker et al. 14]



[Ouellet `16; adapted from Kahn,Safdi,Thaler `16]

Back Up: Towards a GUT SMASH

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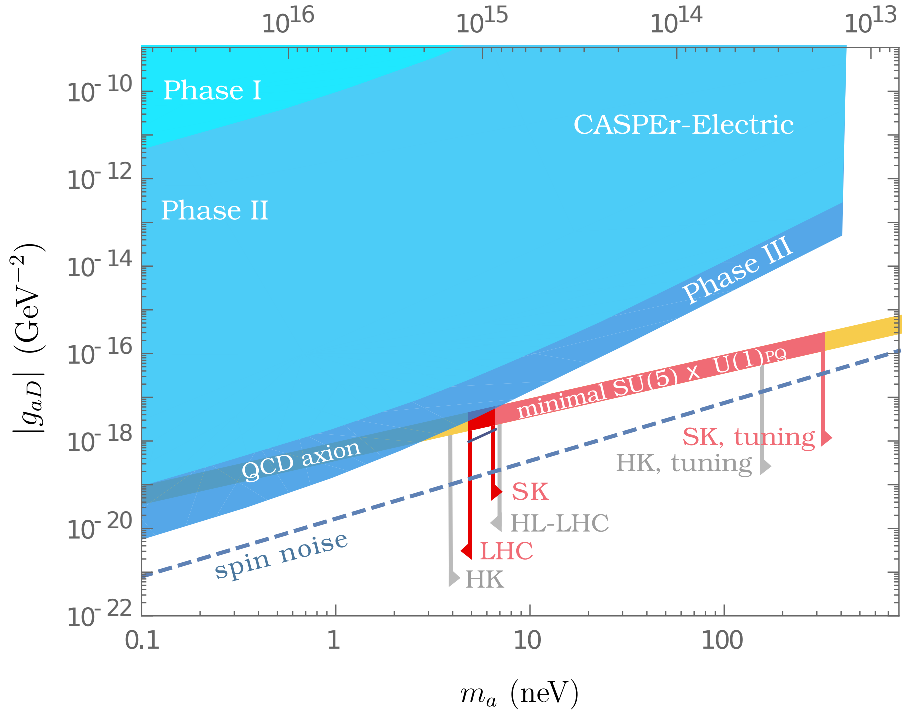
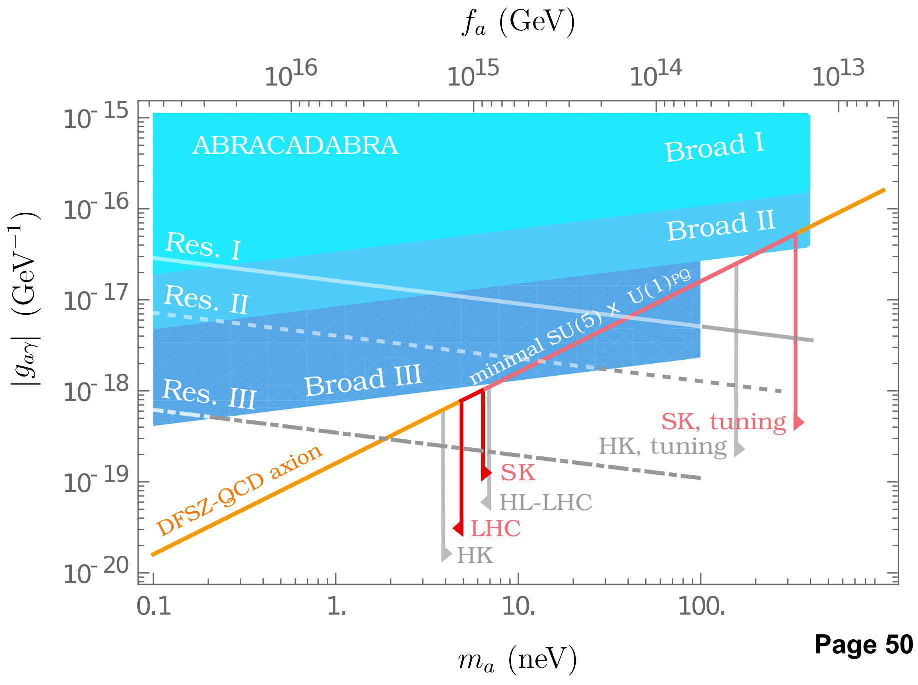
- CASPEr-Electric and ABRACADABRA will probe the relevant parameter space, complementing prospected constraints from HyperKamiokande



[Di Luzio, AR, Tamarit, arXiv:1807.09769]



Back Up: Towards a GUT SMASH

Axion in minimal SU(5) GUT

- Can the modulus of the 24_H in this model be a viable inflaton candidate, taking into account its possible non-minimal coupling to gravity?

[Ballesteros, Di Luzio, AR, Tamarit, Welling, in progress]

$$S \supset -\int d^4x \sqrt{-g}\, \xi_{24_H} \mathrm{Tr}(24_H^2) R$$

  - For $v_{24_H} = M_G/g_5 \gtrsim 10^{17}\,\mathrm{GeV}$, PQ symmetry not restored after inflation
- Can isocurvature constraints be avoided?
  - In a pre-inflationary PQ symmetry scenario, where PQ field is not part of the inflaton:
    - axion is massless field in de Sitter space, leading to isocurvature fluctuations, whose power spectrum freezes at horizon crossing
    - Planck non-observation of isocurvature fluctuations leads to bound on Hubble scale during inflation:

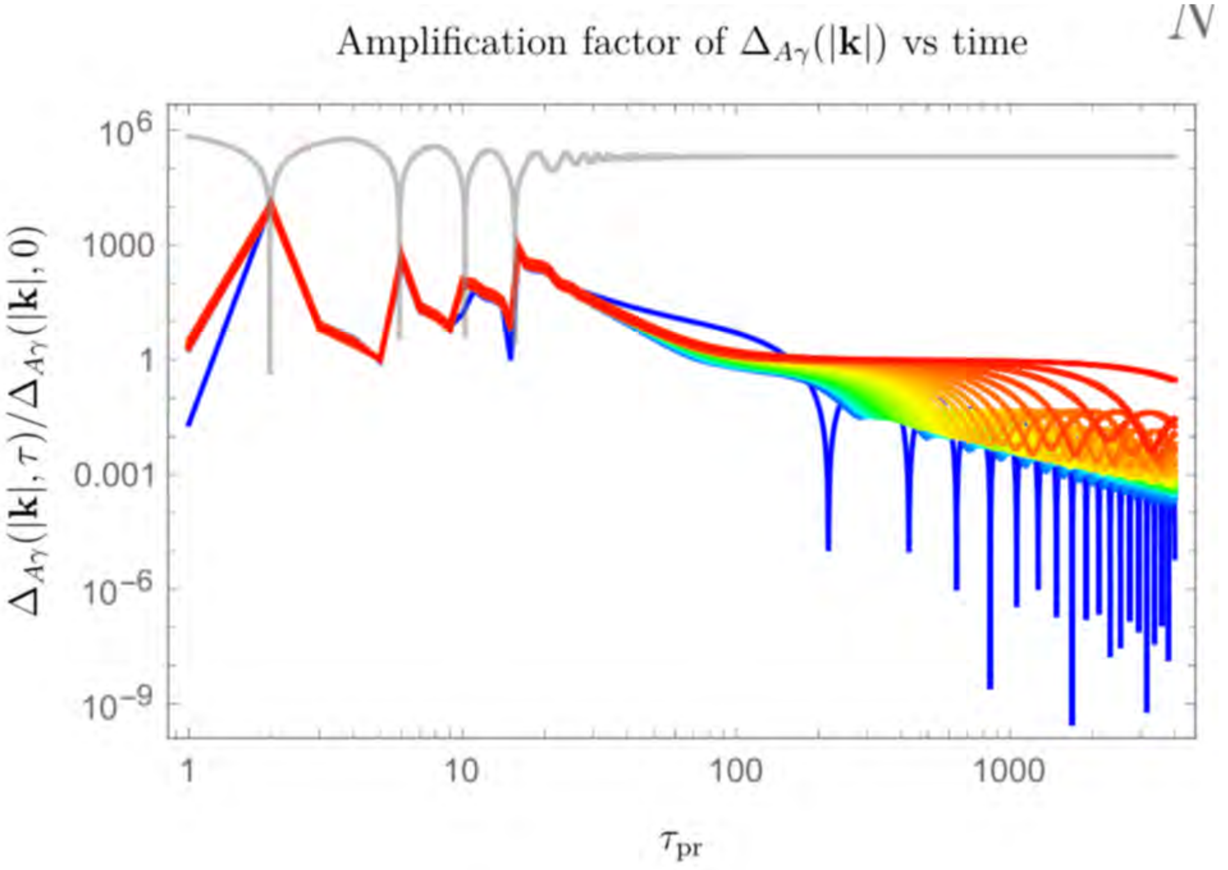
$$H_I < 5.7 \times 10^8\,\mathrm{GeV} \left(\frac{5.0\,\mathrm{neV}}{m_a}\right)^{0.4175}$$

- Bound does not apply in case of non-minimal chaotic 24_H inflation, since axion part of the inflaton and therefore not massless during inflation and reheating

Back Up: Towards a GUT SMASH

Revisiting isocurvature bound

- Work in progress: [Ballesteros, Di Luzio, AR, Tamarit, Welling]
  - Numerical evolution of inflationary perturbations, accounting for nonzero masses; use these as initial conditions for lattice simulations including effects of Higgs decays
  - Derive power spectra for isocurvature perturbation
  - Extrapolate to CMB scales
- Results:
  - Super-horizon isocurvature modes have an initial exponential growth but then decay as 1/a(t)^2
  - Extrapolation to CMB times: competition between initial amplification and later decay
    - As $\Delta_{A\gamma}(|\mathbf{k}|,\tau)a(\tau)^2/\Delta_{A\gamma}(|\mathbf{k}|,0)$ seems to always peak and then oscillate around a constant value, we can establish bound and direct estimate at CMB times



Lower momenta in red, higher momenta in blue
In gray: $10^6\,\phi_1(\tau_{pr})/M_P$

Back Up: Towards a GUT SMASH

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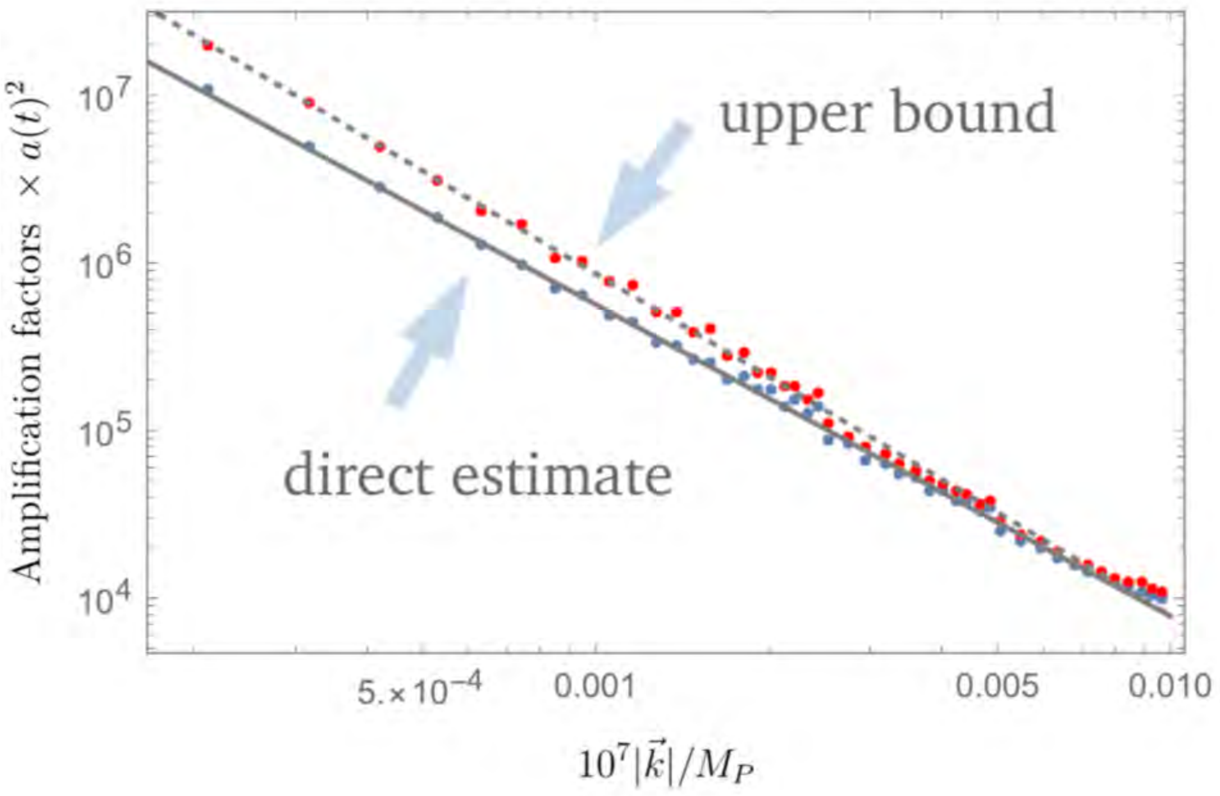
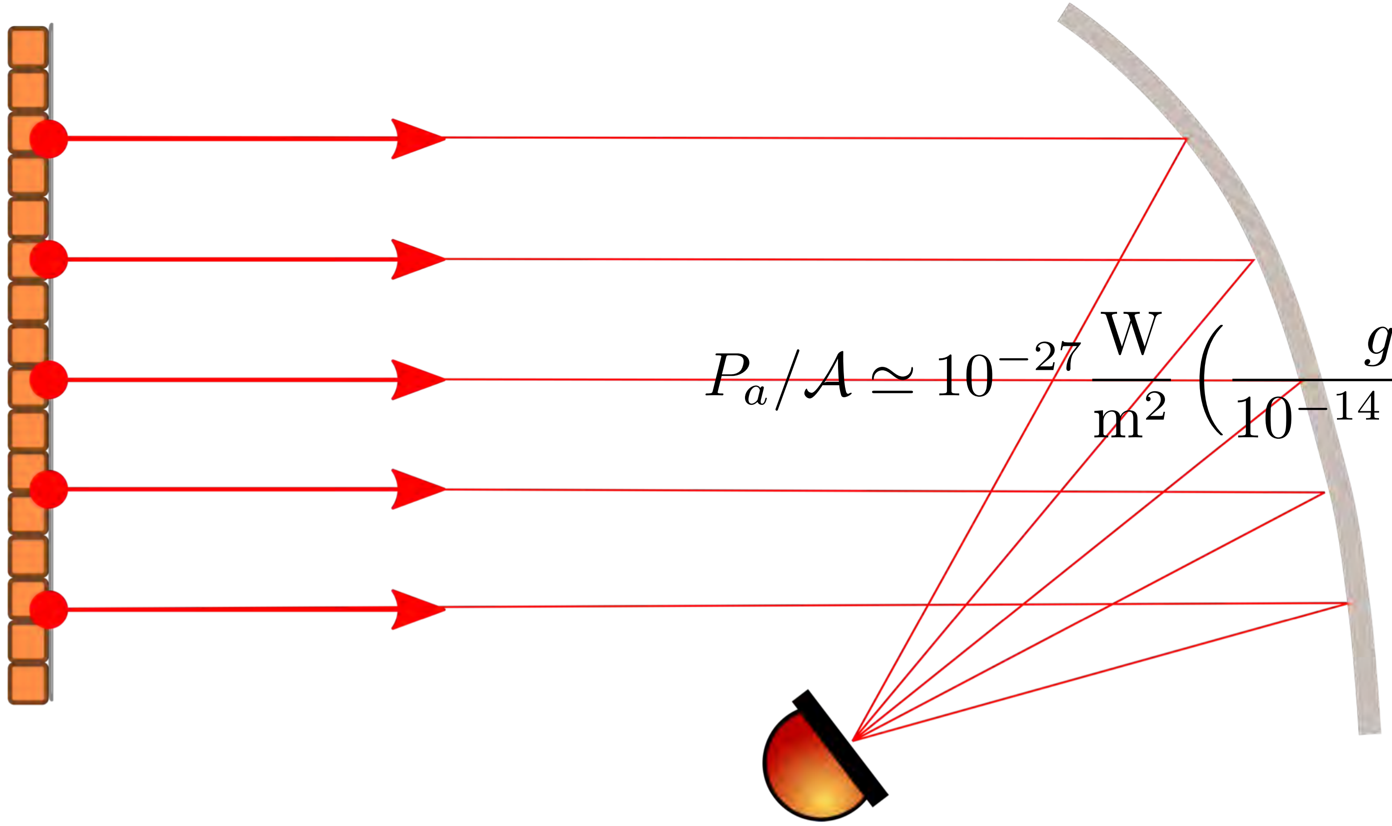
  - If inflaton and axion part of multiplet (>= 6 real scalars), CMB isocurvature bound satisfied (preliminary)



Back Up: Searches for Dark Matter Axions

Dish Antennas

- Oscillating axion/ALP DM in a background magnetic field carries a small electric field component
- A magnetised mirror in axion/ALP DM background radiates photons [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]



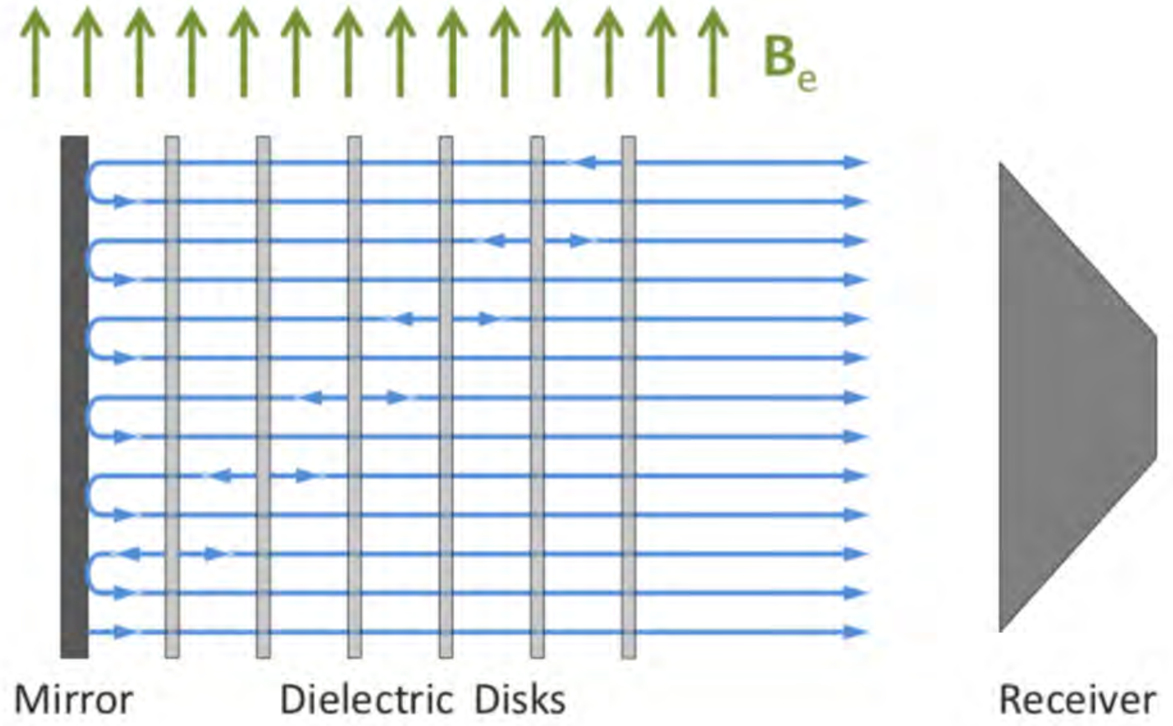
$$P_a/\mathcal{A} \simeq 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{g_{a\gamma}}{10^{-14}\,\mathrm{GeV}^{-1}}\right)^2\left(\frac{10^{-4}\,\mathrm{eV}}{m_a}\right)^2\left(\frac{B}{10\,\mathrm{T}}\right)^2$$

Back Up: Searches for Dark Matter Axions

Dish Antennas

- Boosted dish antenna: Open dielectric resonator
  - Add stack of dielectric disks with $\sim \lambda/2$ spacing in front of mirror (all immersed in magnetic field) [Jaeckel,Redondo 13]
  - Constructive interference of photon part of wave function [Millar,Raffelt,Redondo,Steffen 16]

[Baryakhtar,Huang,Lasenby18]

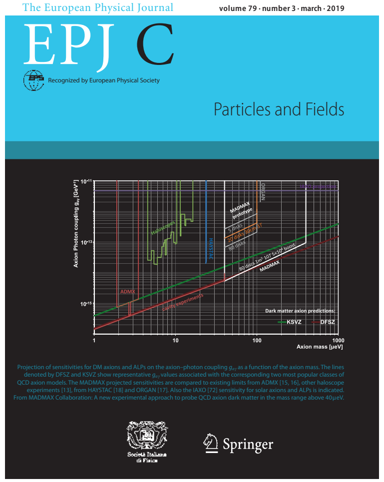


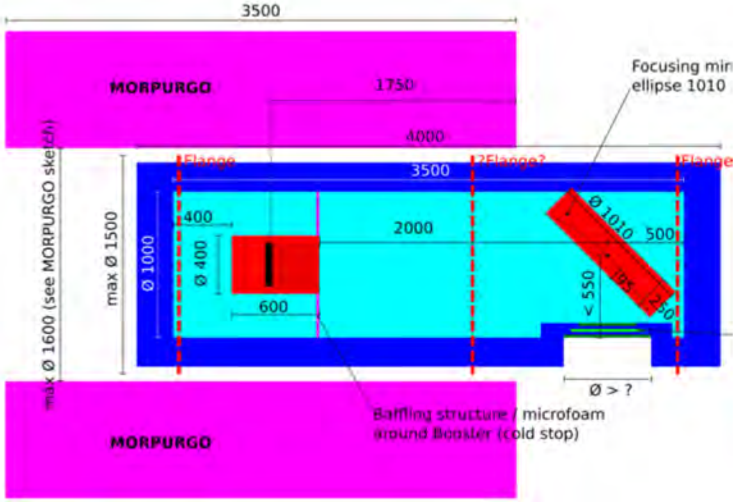
Back Up: Searches for Dark Matter Axions

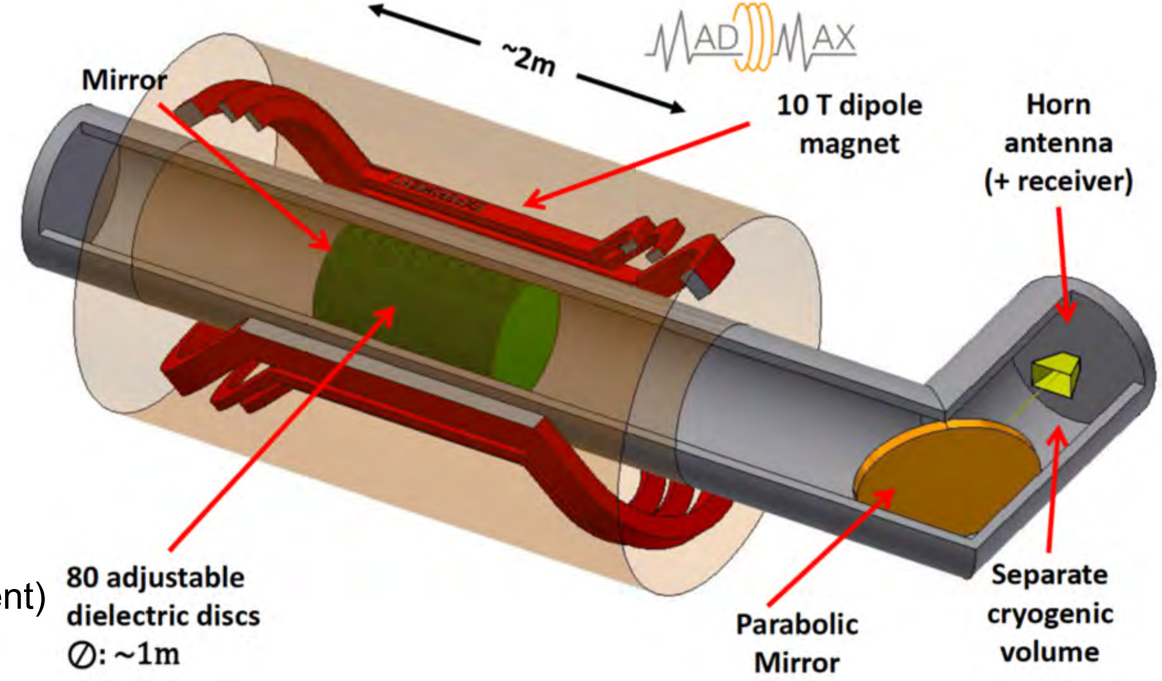
Dish Antennas

- Boosted dish antenna: Proposed MADMAX experiment [Caldwell et al. `16; Bruns et al. 19]

2017 -2019 Design	2020 -2025 Prototype	2025 -2035 Experiment
	@CERN	@DESY







Scaling: Area 1/10 (of final experiment)
discs 1/4
B [T] 1/5

Back Up: Searches for Dark Matter Axions

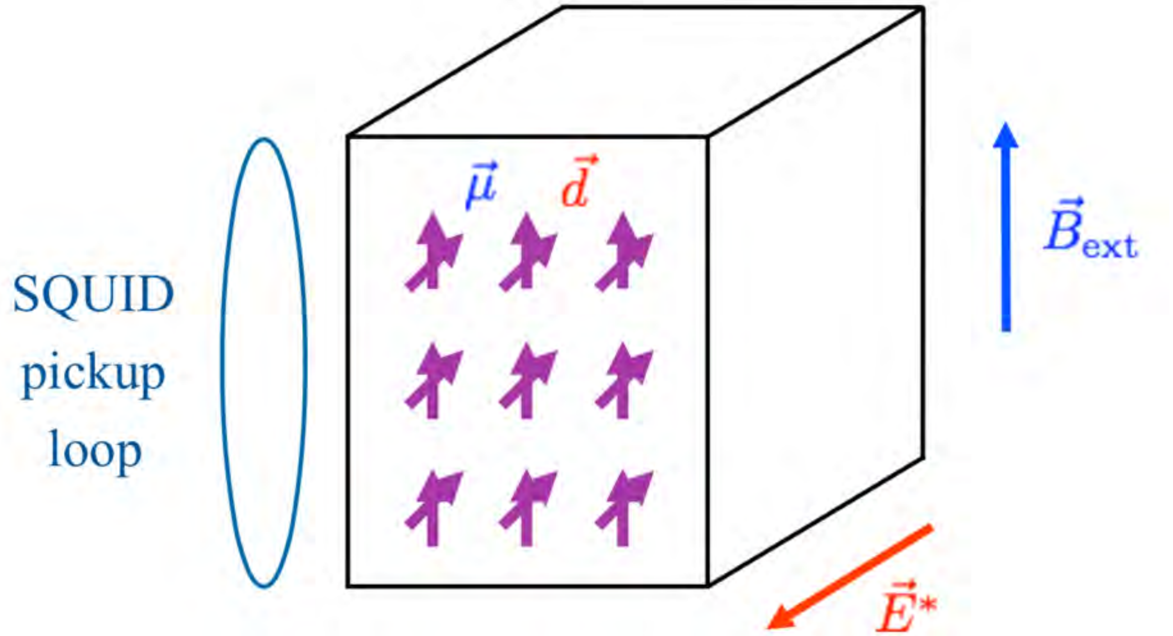
Magnetic Resonance Searches

- Axion DM field induces oscillating NEDMs:

$$d_N(t) = g_d \sqrt{2\rho_{\rm DM}} \cos(m_A t)/m_A$$

  - Place a ferroelectric crystal (permanent electric polarisation fields $\vec{E}^*$) in external $\vec{B}_{\rm ext} \perp E^*$
  - Nuclear spins are polarised along $\vec{B}_{\rm ext}$ and precess at Larmor frequency $\omega_L = 2\mu_N B_{\rm ext}$
  - Interaction $\epsilon_S \vec{d}_N(t) \cdot \vec{E}^*$ of DM induced NEDM with the $\vec{E}^*$-field leads to resonant increase of transverse magnetisation of sample when $\omega_L = m_A$

[Graham,Rajendran 13; Budker et al. 14]



[Budker et al. 14]

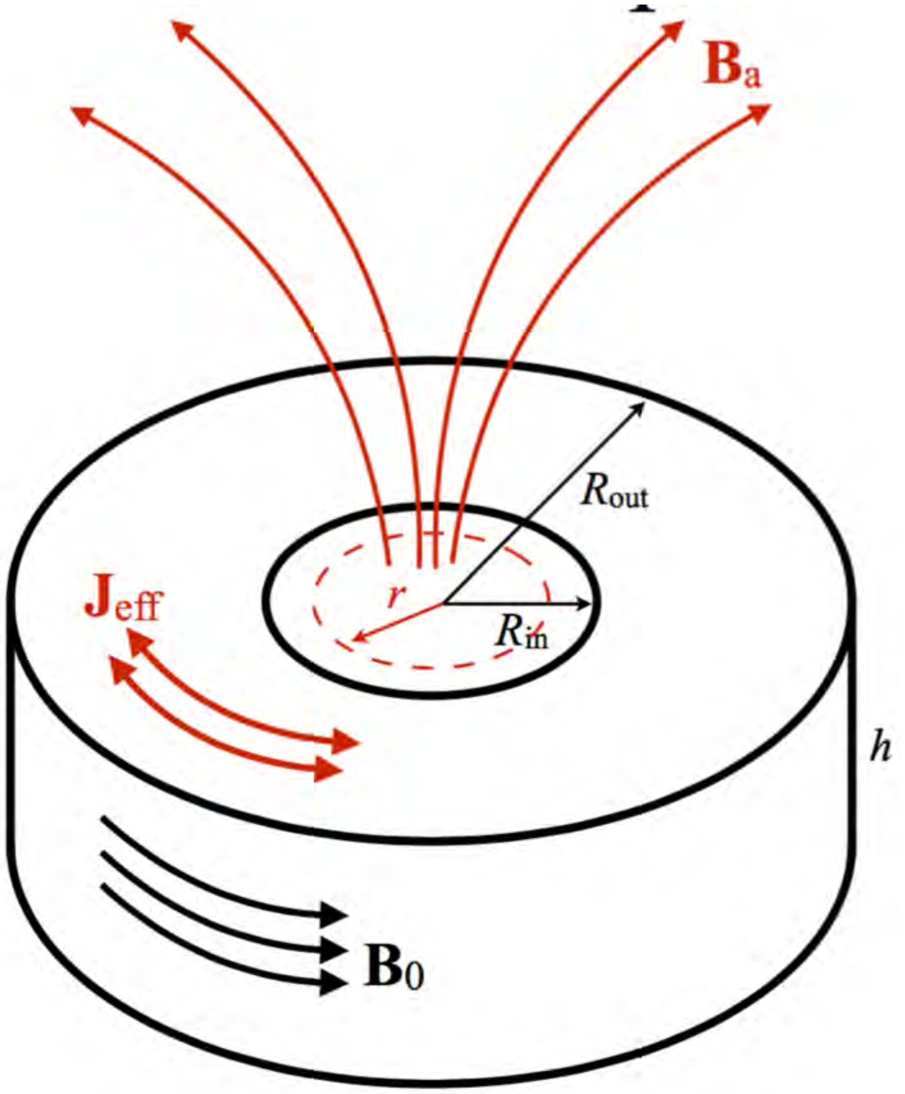
- CASPEr-Electric currently being set-up in Boston

Back Up: Searches for Dark Matter Axions

Searching for Axion-induced Magnetic Fields

[Sikivie,Sullivan,Tanner 14; Kahn,Safdi,Thaler `16]

- ABRACADABRA (MIT) currently being set-up
  - Exploit toroidal magnet with fixed magnetic field:
    - Axion DM generates oscillating effective current around ring
    - ... this generates oscillating magnetic field through center
    - ... this can be detected by pickup loop
- DM-Radio (Stanford): similar experiment in path-finder status [Silva-Feaver et al. 16]



[Ouellet `16; adapted from Kahn,Safdi,Thaler `16]

Back Up: Searches for Dark Matter Axions

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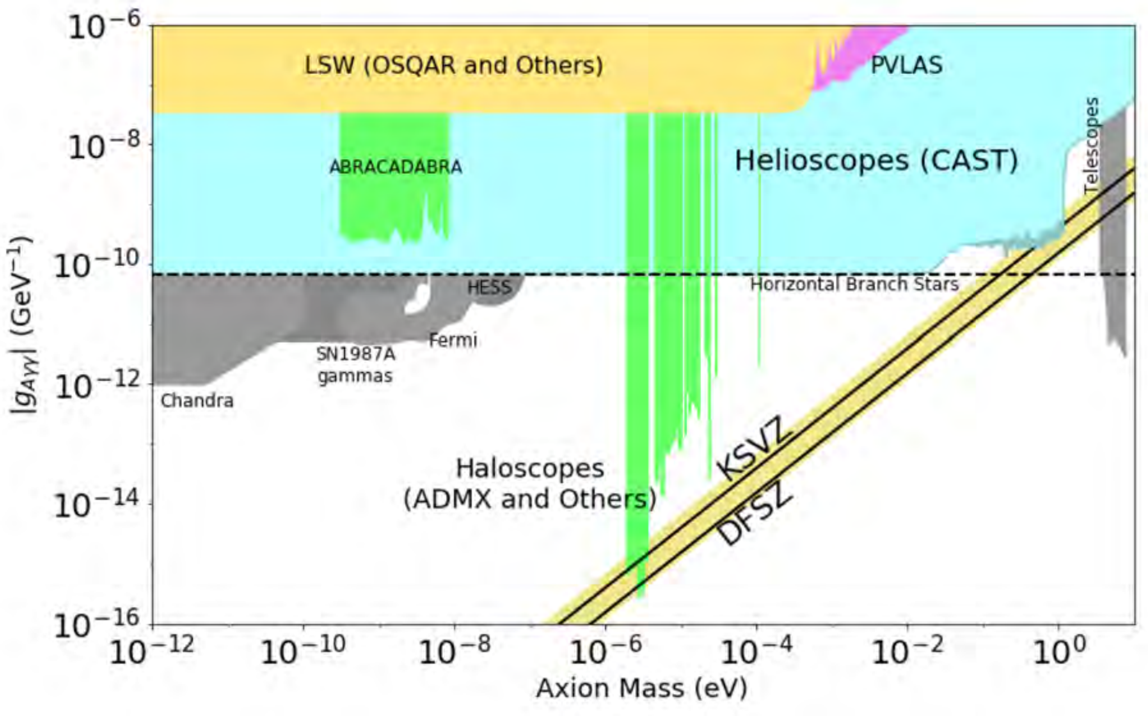
ABRACADABRA-10 cm Run 1:

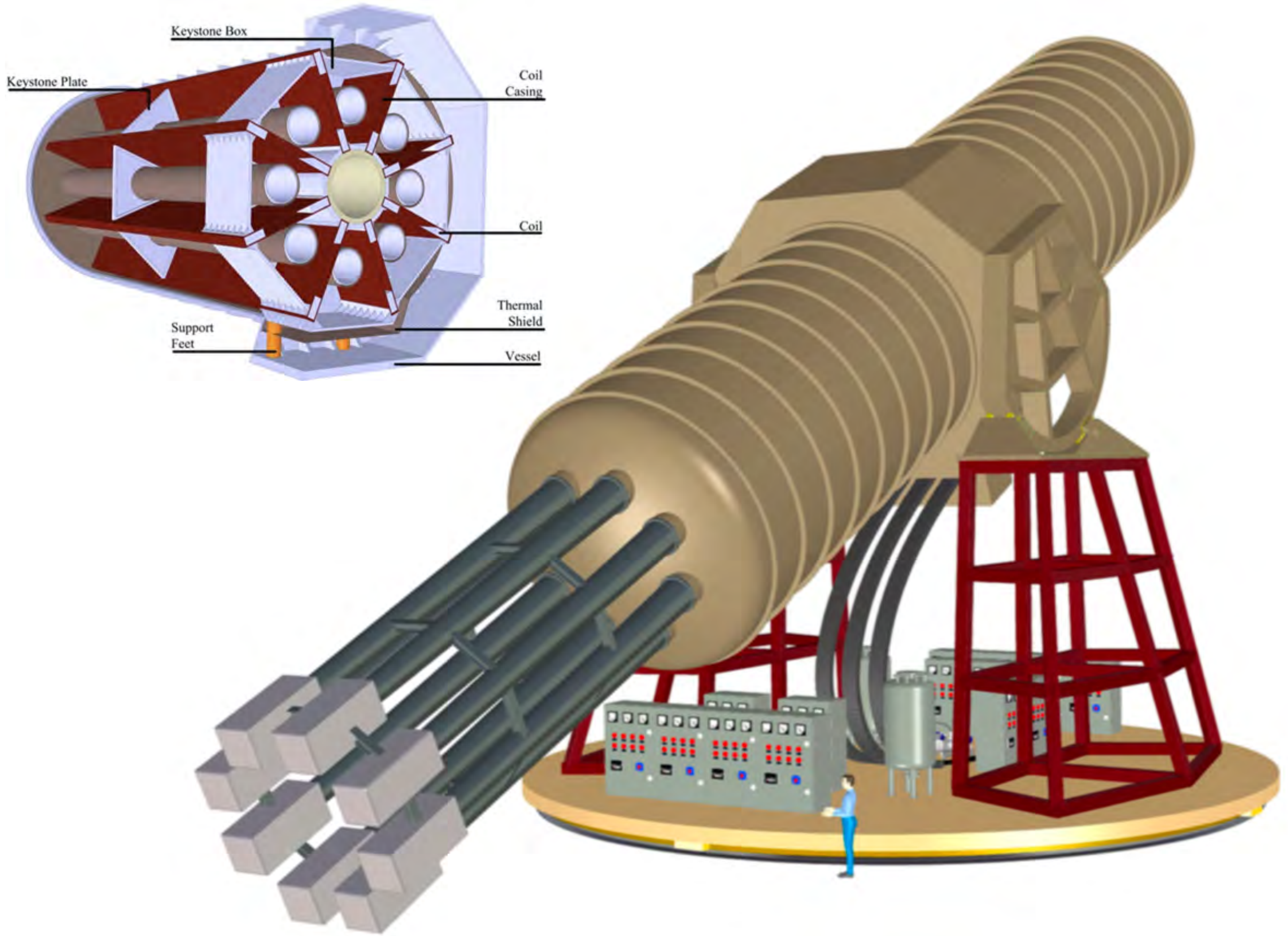


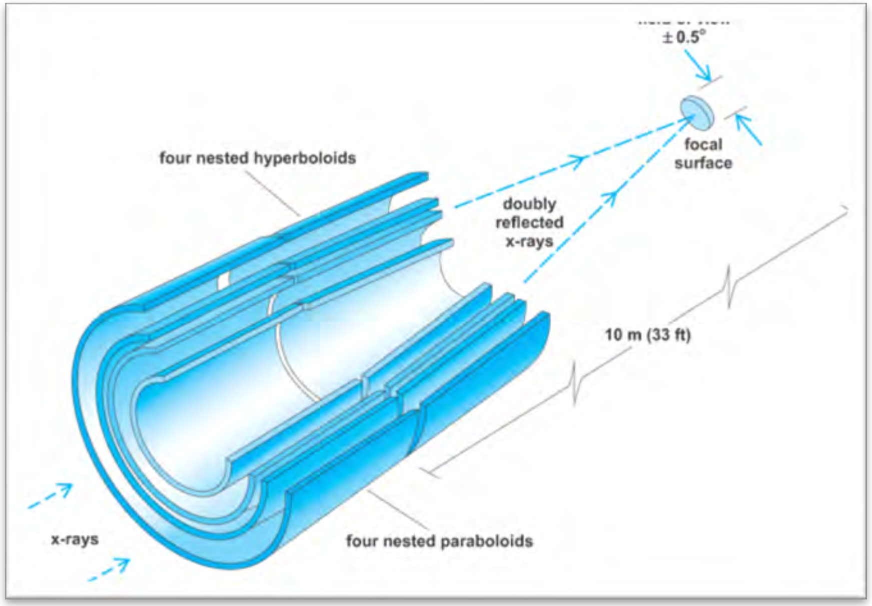
[AR,Rybka,Rosenberg in 2019 update PDG RPP]

Back Up: Searches for Solar Axions

- International Axion Observatory (IAXO)
  - Large toroidal 8-coil magnet L = ~20 m
  - 8 bores: 600 mm diameter each
  - 8 X-ray telescopes + 8 detection systems
  - Rotating platform with services
- Proposed site: DESY

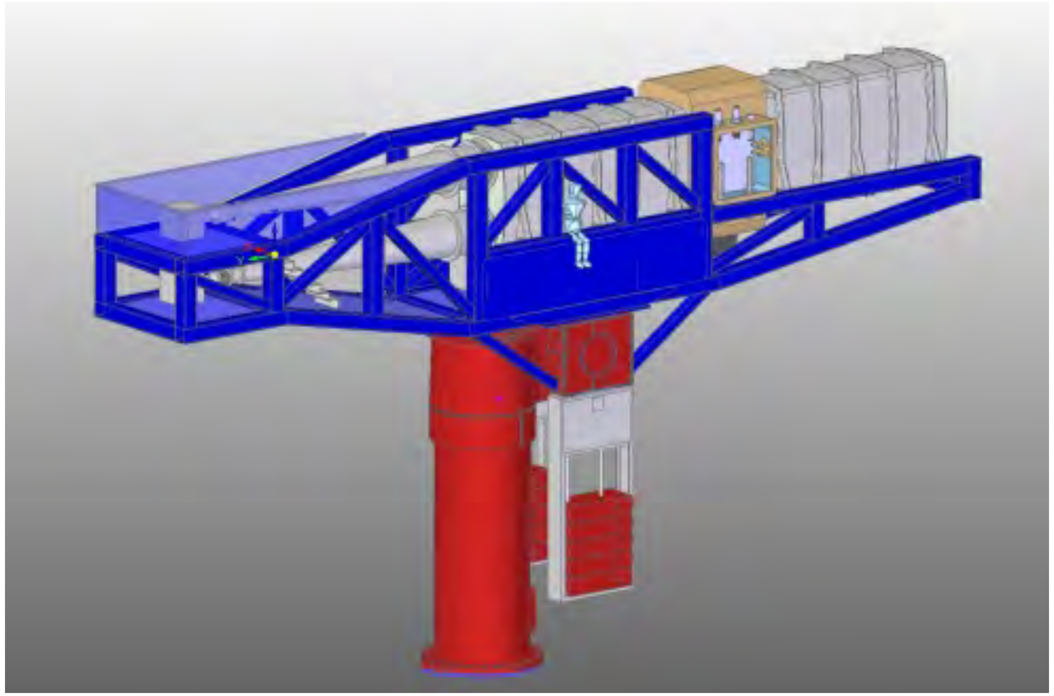
[IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]

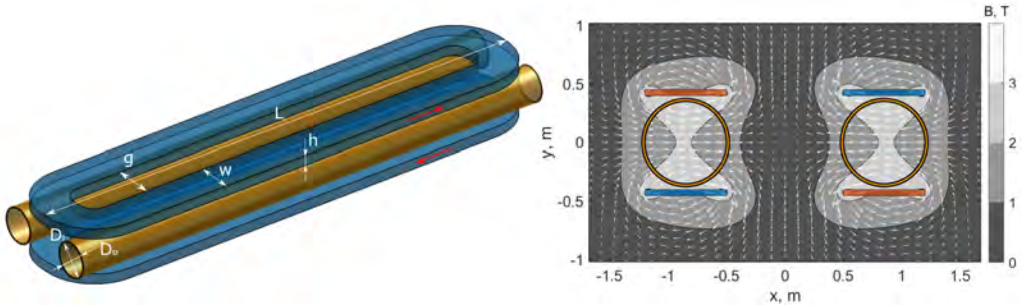




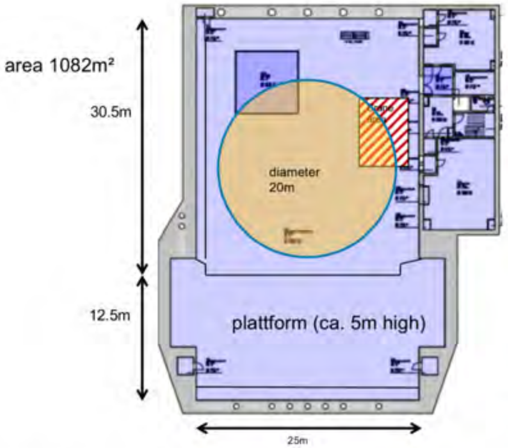
Back Up: Searches for Solar Axions

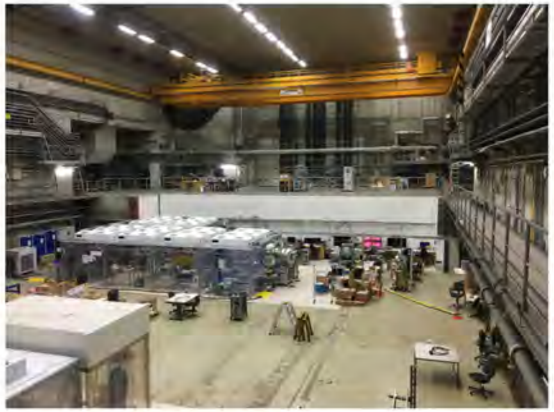
- Prototype for IAXO: BabyIAXO
  - Two bores of dimensions similar to final IAXO bores
  - Detection lines representative of final ones
  - Test & improve all systems
- Magnet technical design ongoing at CERN





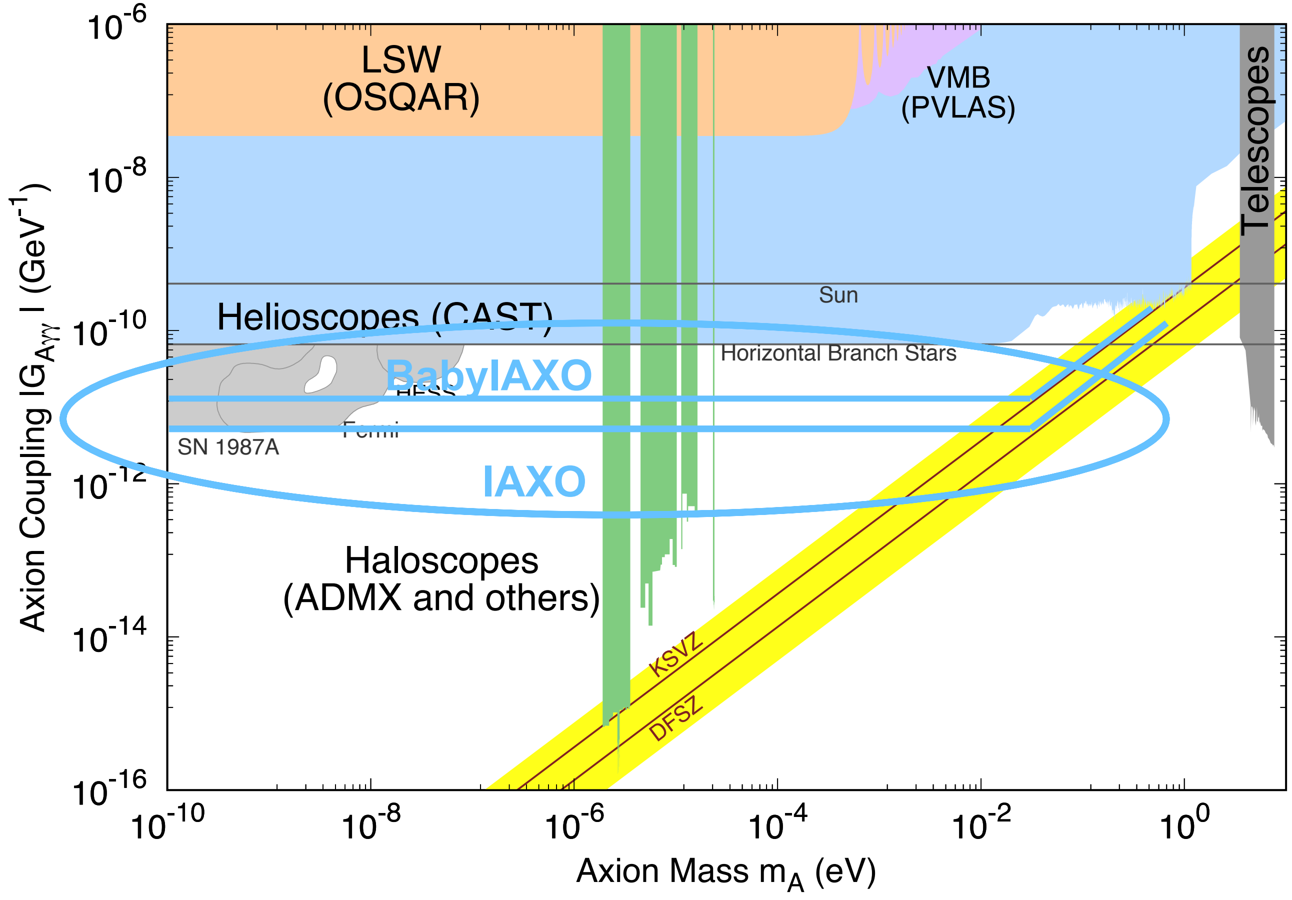
- Funded mainly via Irastorza: ERC-AvG 2017 IAXO+
- Site: HERA South Hall at DESY
- Construction may start in 2020
- Data taking may start in 2024





Back Up: Searches for Solar Axions

- (Baby)IAXO probes meV mass QCD axion and covers most of parameter space relevant for astro hints

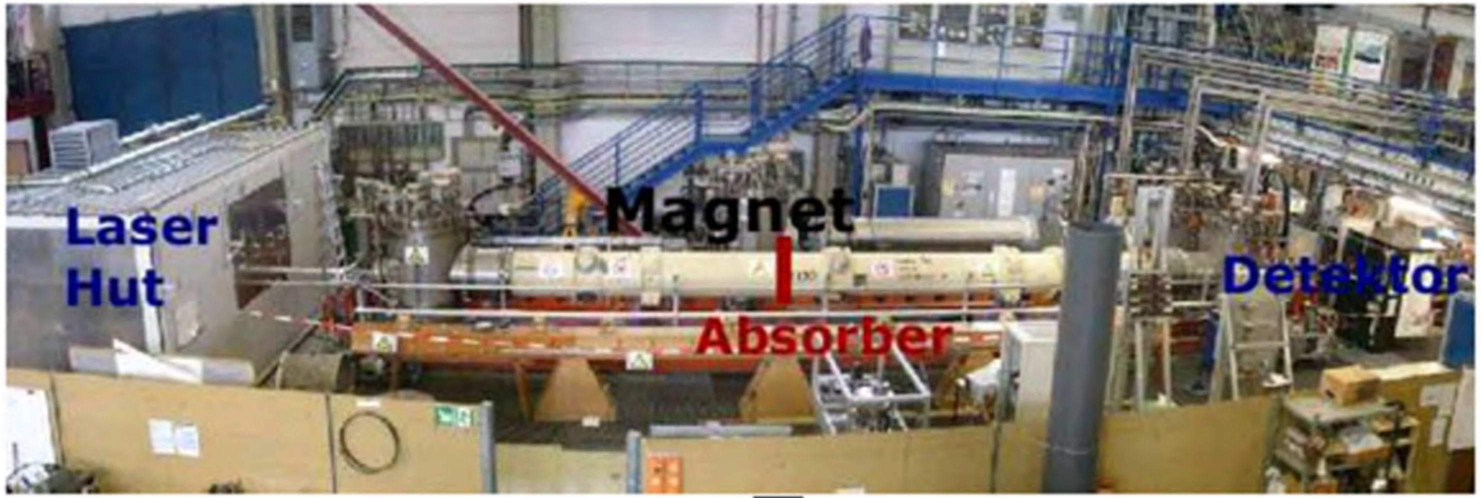


Light-Shining-through-a-Wall Searches

[Sikivie 1983, Ansel'm 1985, van Bibber et al. 1987]

- ALPS I @ DESY (in collaboration with AEI Hannover and U Hamburg)

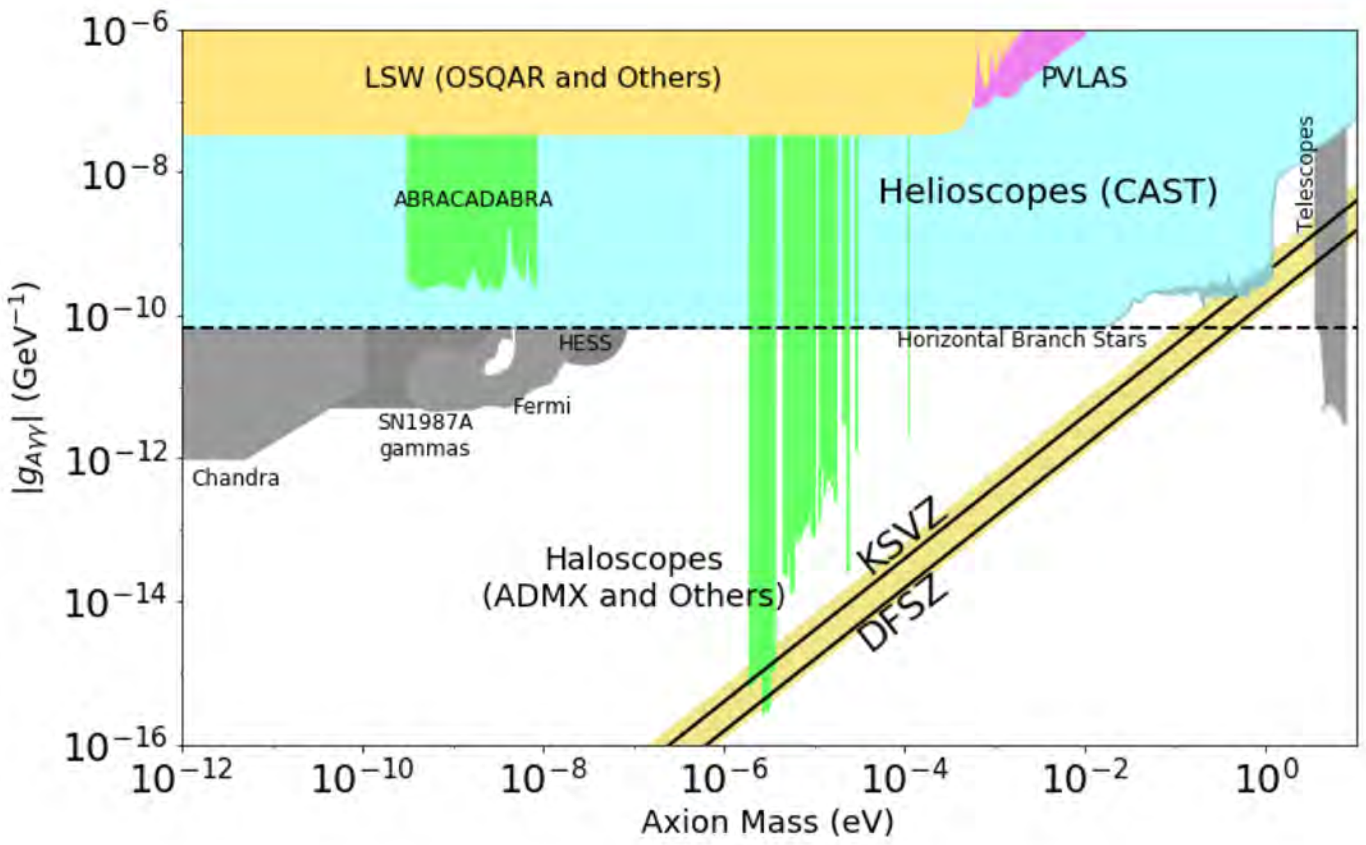
[AR 03;....;Ehret et al. 10]



$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

Light-Shining-through-a-Wall Searches

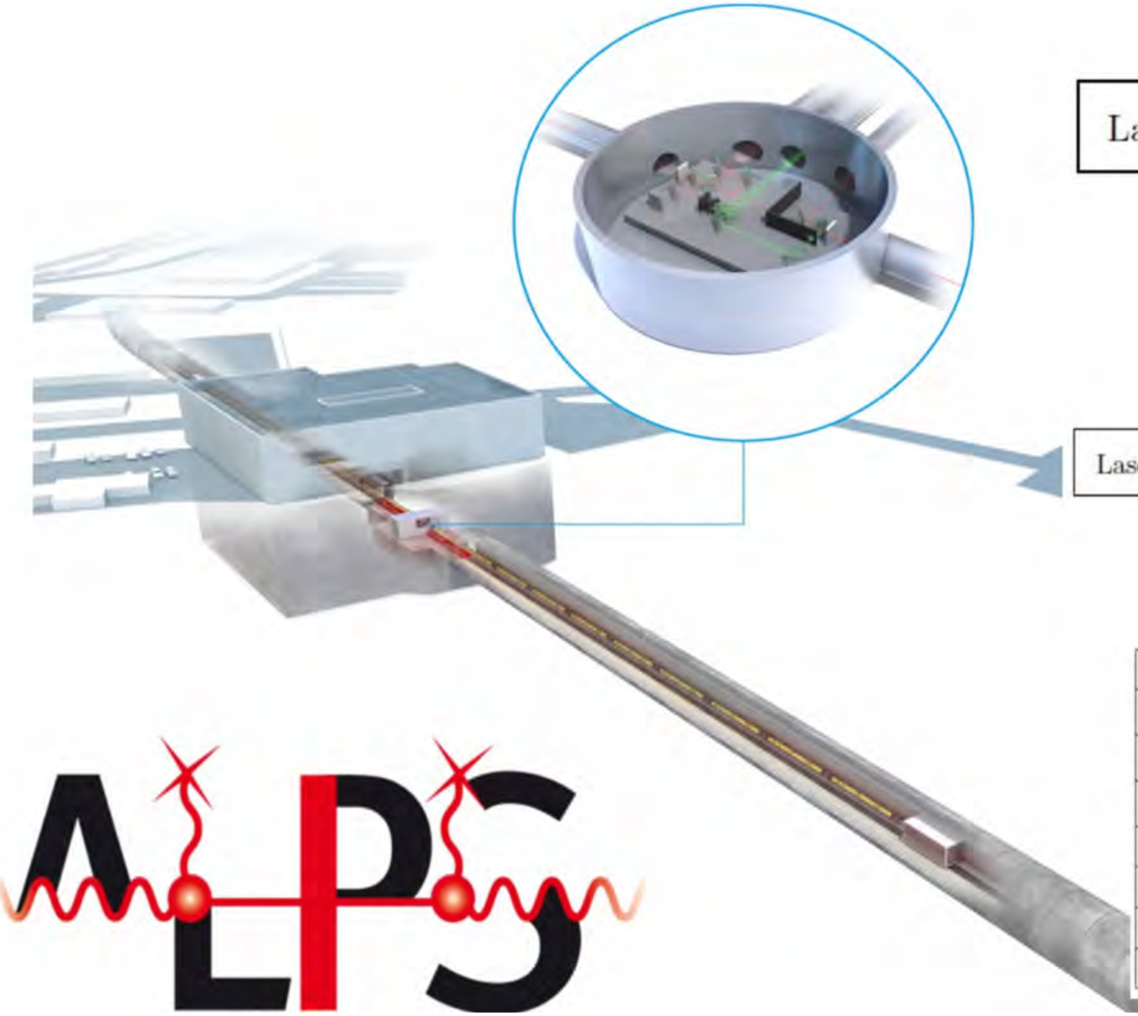
- ALPS I @ DESY (in collaboration with AEI Hannover and U Hamburg) [AR 03;...;Ehret et al. 10]
  - LSW experiments ALPS I and OSQAR @ CERN give currently the best purely laboratory limit on low mass axions:

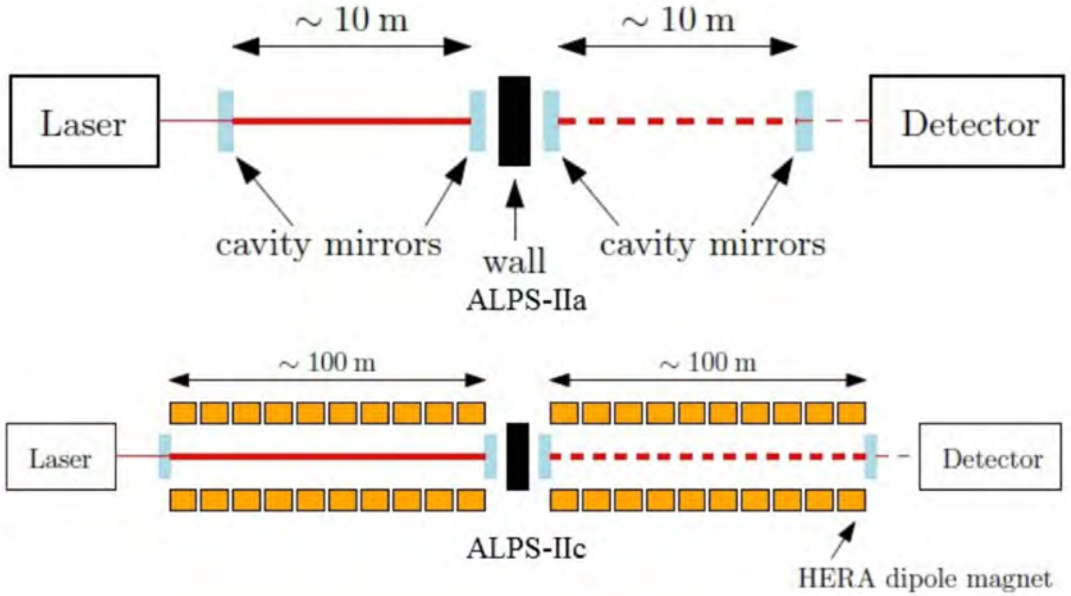


[AR,Rybka,Rosenberg in 2019 update PDG RPP]

Light-Shining-through-a-Wall Searches

- ALPS II @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz) [Bähre et al (ALPS II TDR) 13]





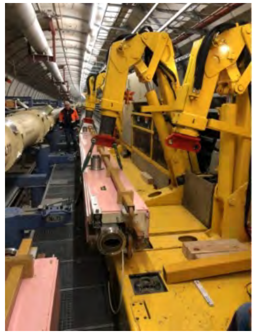
Parameter	Scaling	ALPS I	ALPS IIc	Sens. gain
Effective laser power P_{laser}	$g_{a\gamma} \propto P_{laser}^{-1/4}$	1 kW	150 kW	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC P_{RC}	$g_{a\gamma} \propto P_{reg}^{-1/4}$	1	40,000	14
BL (before& after the wall)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
Detector efficiency QE	$g_{a\gamma} \propto QE^{-1/4}$	0.9	0.75	0.96
Detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	0.0018 s^{-1}	0.000001 s^{-1}	2.6
Combined improvements				3082

Light-Shining-through-a-Wall Searches

ALPS II at DESY

DESY

- HERA tunnel on about 300 m cleared



Albert Einstein Institute Hannover

UF UNIVERSITY of FLORIDA

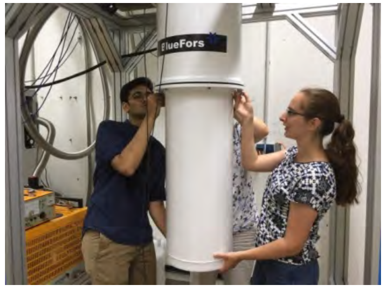
HEISING-SIMONS FOUNDATION

- 24 magnets straightened and tested; first magnets installed

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

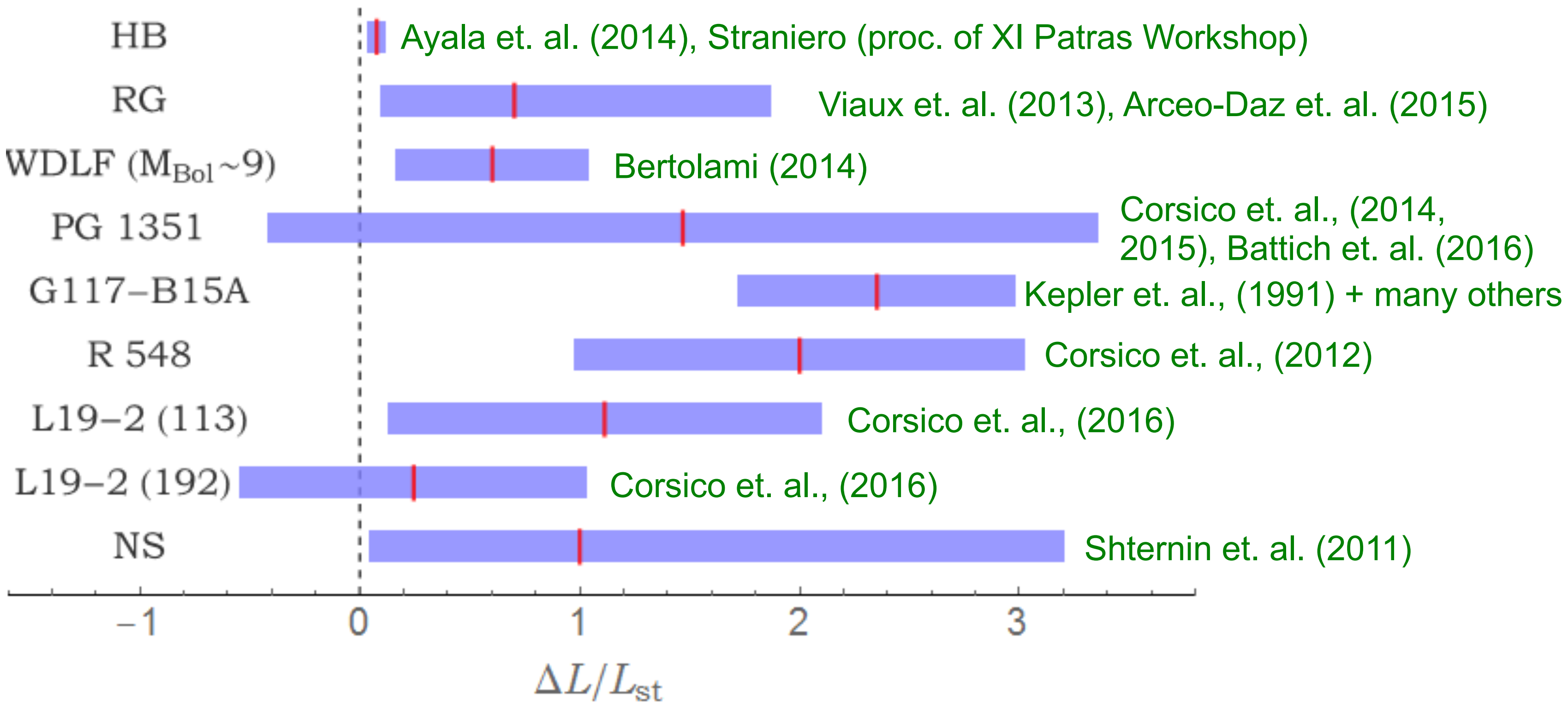
- Construction will be finished end of 2020
- Data taking 2021 and 2022



Back Up: Astrophysical Hints for Axions/ALPs

Excessive stellar energy losses

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

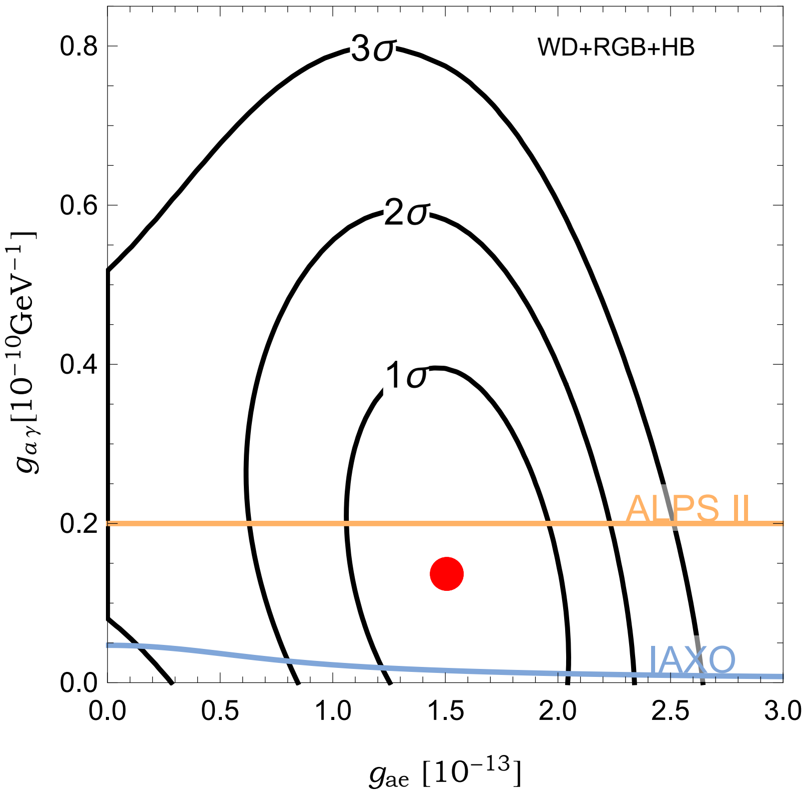


[Giannotti, Irastorza, Redondo, AR '15; Giannotti, Irastorza, Redondo, AR, Saikawa '17]

Back Up: Astrophysical Hints for Axions/ALPs

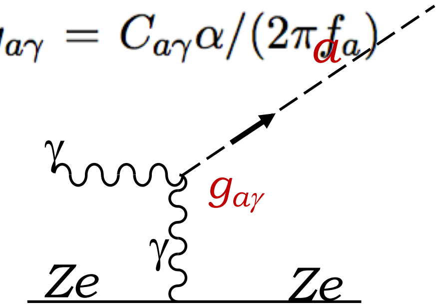
Excessive stellar energy losses

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

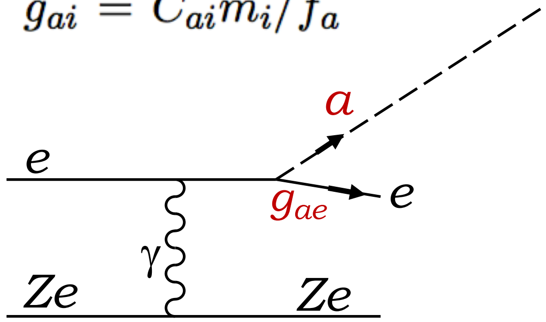


[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

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



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



Back Up: Astrophysical Hints for Axions/ALPs

Excessive stellar energy losses

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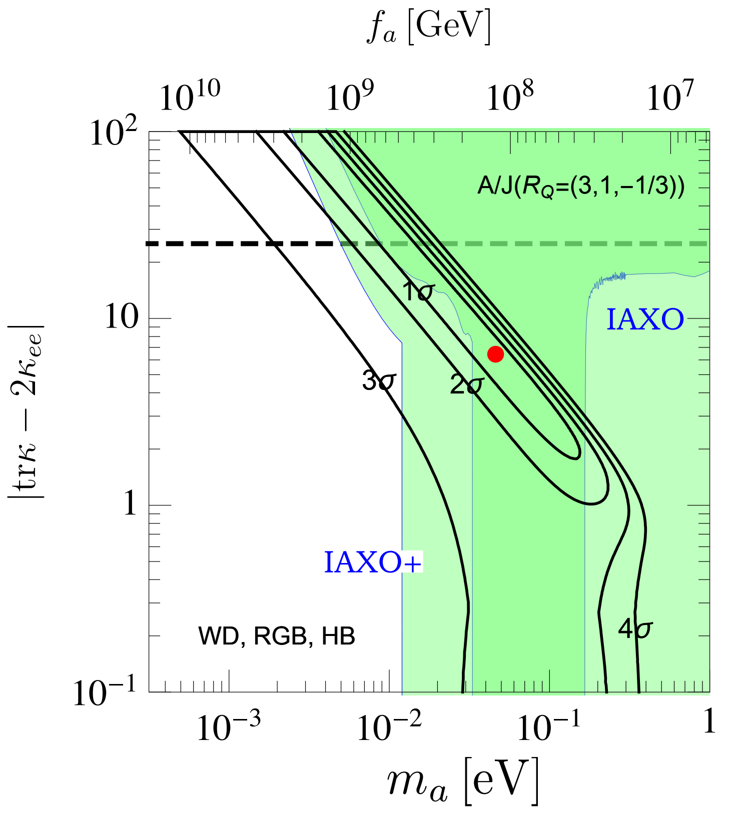

[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

$$C_{a\gamma} = \frac{2}{3} - 1.92(4)$$

$$C_{ae}^{A/J} \simeq -\frac{1}{16\pi^2 N}(\mathrm{tr}\kappa - 2\kappa_{ee})$$

$$\kappa \equiv \frac{m_D m_D^\dagger}{v^2}$$