WISP Dark Matter Theory.

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Latest Results in Dark Matter Searches
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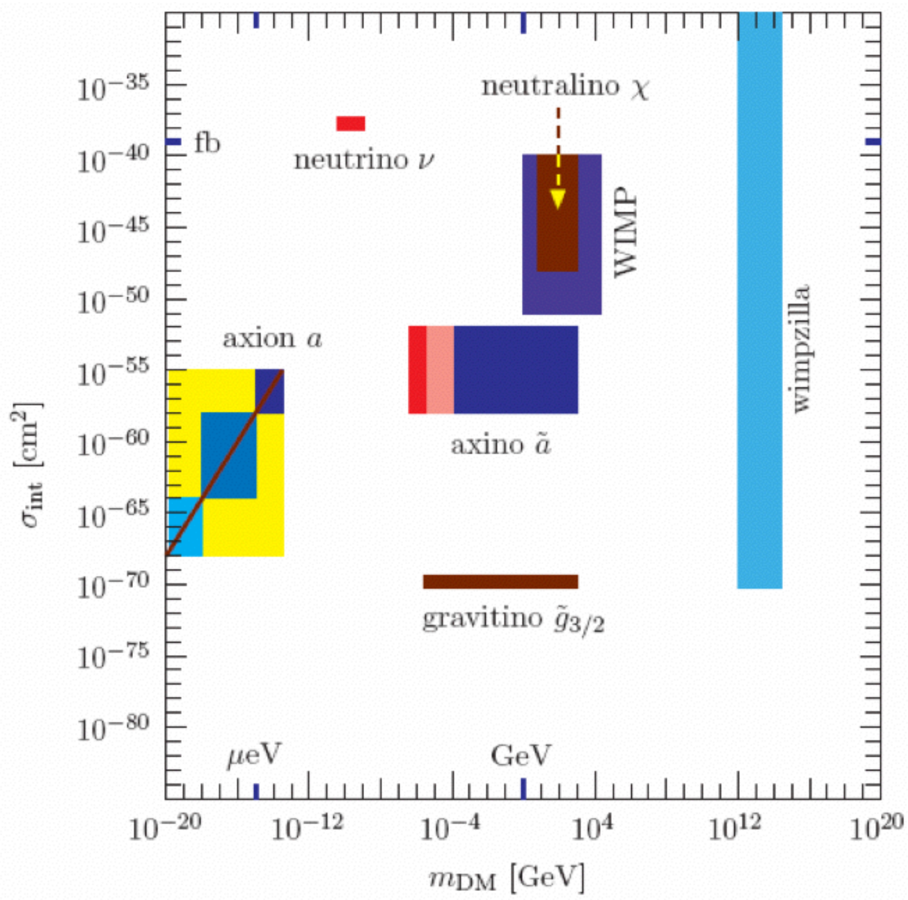
Introduction

- Plenty of dark matter (DM) candidates spanning huge parameter range in masses and couplings
- Two classes stand out because of their convincing physics case and the variety of experimental and observational probes:
  - Weakly Interacting Massive Particles (WIMPs), such as neutralinos
  - Very Weakly Interacting Slim (=ultra-light) Particles (WISPs), such as axions, axion-like particles and hidden photons



[Kim,Carosi `10]

Theoretically favored WISP candidates

> Pseudo Nambu-Goldstone bosons:

- "Axion-Like Particles" (ALPs) arising from breaking of global U(1) symmetries at high energy scale f_a; $a(x)$ angular part of complex SM singlet Higgs-like field
  - Low energy effective field theory has shift symmetry $a(x) \to a(x) + \mathrm{const.}$, forbidding explicit mass terms, $\propto m_a^2 a^2(x)$, in the Lagrangian
  - Effective couplings to SM particles suppressed by powers of high energy scale f_a , e.g. coupling to photons, $\mathcal{L} \supset -\frac{\alpha}{8\pi} C_{a\gamma} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$
- Examples:
  - Axion from breaking of global chiral symmetry; axion field acts as dynamical theta parameter, $\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \underbrace{\frac{A}{f_A}}_{\bar\theta} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$ [Peccei,Quinn 77; Weinberg 78; Wilczek 78]
  spontaneously relaxing to zero, $\langle A \rangle = 0$ (thus CP conserved in strong interactions)
    - mass due to chiral symmetry breaking, $m_A \sim m_\pi f_\pi / f_A$
  - Majoron from breaking of global lepton number symmetry [Chikashige et al. 78]
    - high scale explains small neutrino mass, $m_\nu \sim v^2/f_L$ [Langacker et al. 86]
  - Familon from breaking of family symmetry [Wilczek 82]
  - Closed string ALPs: Kaluza-Klein zero modes of 10D antisymmetric tensor fields in string theory, $f_a \sim M_s$ [Witten 84; Conlon 06; Cicoli,Goodsell,AR 12]

Theoretically favored WISP candidates

> Hidden U(1) gauge bosons:

- "Hidden" or "dark" photons (HPs): vector bosons of a local U(1) gauge theory under which SM particles are uncharged
  - Gauge symmetry forbids explicit mass terms; mass generated via
    - Higgs mechanism: $m_{\gamma'} \sim g_h v_h$
    - Stückelberg mechanism: topological mass
  - Suppressed couplings to SM particles; e.g. kinetic mixing with the photon: [Holdom 86]

$$\mathcal{L} \supset -\frac{\chi}{2} F'_{\mu\nu} F^{\mu\nu}; \qquad \chi \sim \frac{e\, g_h}{16\pi^2}$$

- Examples:
  - U(1) factors from breaking of grand unified gauge group
  - Often occur in low energy effective field theories from string theory: [Goodsell,AR 10]
    - Heterotic string: hidden U(1)s arising from breaking of 10D $E_8 \times E'_8$, expect $\chi \sim 10^{-4}$
    - Type II string (brane world scenarios):
      - RR U(1)s: KK zero modes arising in 4D decomposition of 10D form fields
      - Brane localized U(1)s: massless excitations of space-time filling D-branes wrapping cycles in extra dimensions [Abel et al. 08;Goodsell et al. 09;Cicoli et al. 11]

$$\chi \sim \frac{e}{16\pi^2}\left(\frac{M_s}{M_P}\right)^{2/3}; \qquad \frac{M_s^2}{M_P} \lesssim m_{\gamma'}^{\rm st} \lesssim M_s$$

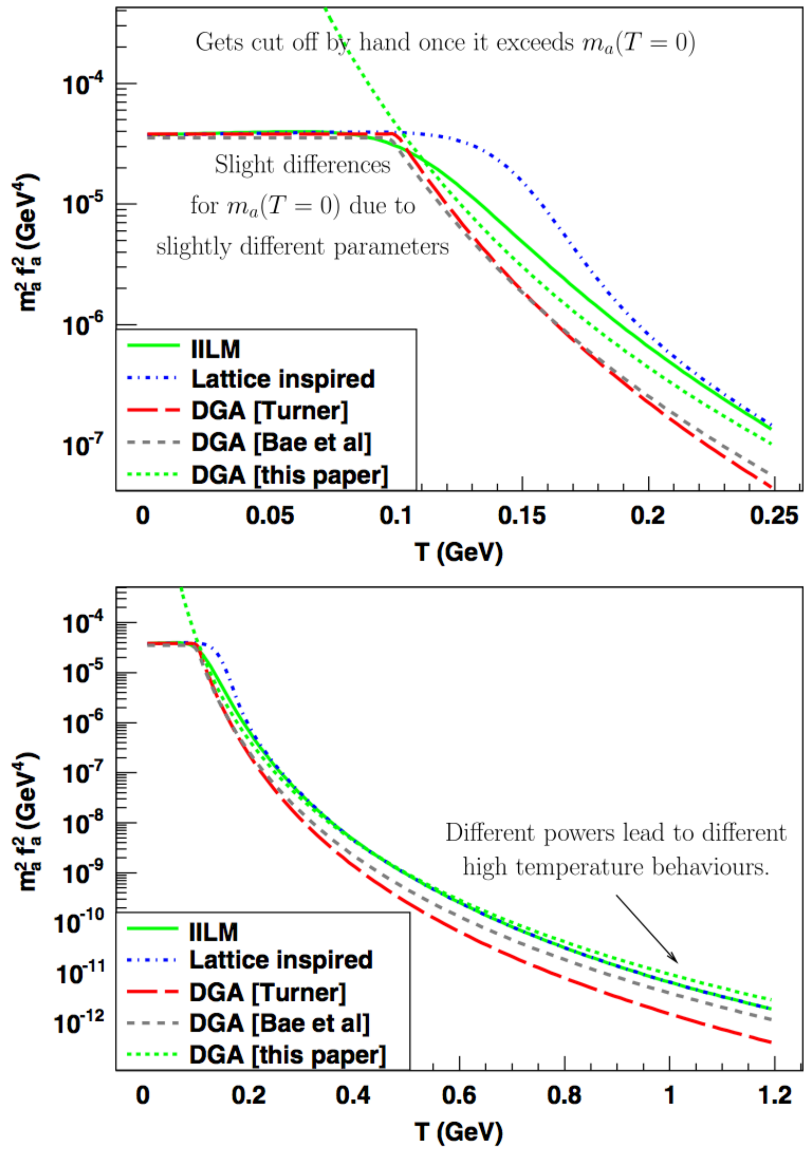
Axion/ALP cold dark matter via vacuum-realignment

- At $T < f_a$, axion or ALP field

$$\theta_a(x) = a(x)/f_a \in [-\pi, \pi]$$

satisfies

$$\ddot{\theta}_a + 3H(T)\dot{\theta}_a - \nabla^2\theta_a/R^2 + m_a^2(T)\sin\theta_a = 0$$



[Wantz,Shellard 0910.1066]

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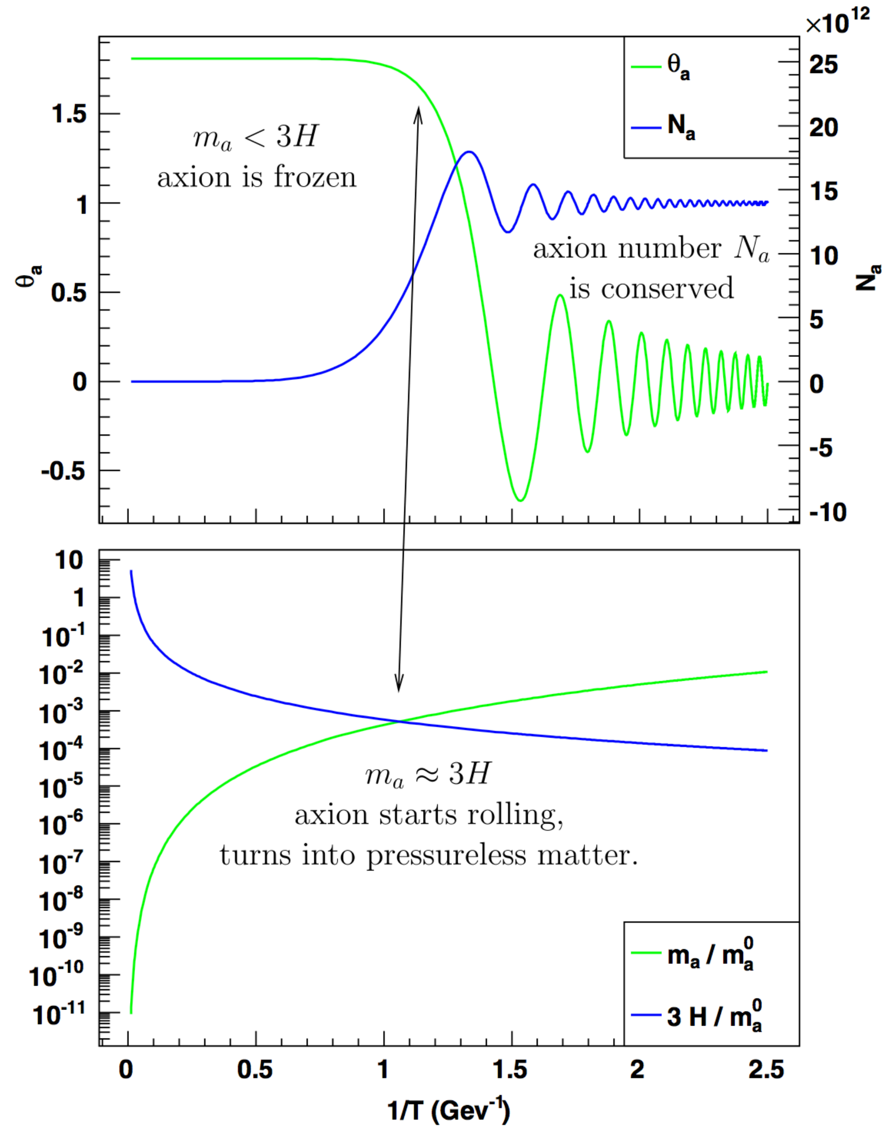
  - First, at $3\,H > m_a$, Hubble friction freezes field at initial value
  - Then, at $3\,H(T_{\rm osc}) \simeq m_a(T_{\rm osc})$, field feels pull of mass towards $\theta_a = 0$
  - Oscillating zero mode corresponds to coherent state of many nonrelativistic axions or ALPs. After a few oscillations,

$$\overline{N}_a = \overline{\rho}_a R^3/m_a = \text{const.}$$

and therefore

$$\overline{\rho}_a(T_0) \simeq \overline{\rho}_a(T_{\rm osc}) \frac{m_a(T_0)}{m_a(T_{\rm osc})} \frac{s(T_0)}{s(T_{\rm osc})}$$



[Wantz,Shellard 0910:1066]

Axion/ALP cold dark matter via vacuum-realignment

- In standard cosmology, oscillations start during radiation dominated phase. Then [Preskill et al. 83; Abbott,Sikivie 83; Dine,Fischler 83]

$$\Omega_a h^2 \simeq 0.016 \sqrt{\frac{m_a(T_0)}{\mathrm{eV}}} \sqrt{\frac{m_a(T_0)}{m_a(T_{\rm osc})}} \mathcal{F}(T_{\rm osc}) \left(\frac{f_a}{10^{11}\,\mathrm{GeV}} \right)^2 \mathcal{A}(\langle \overline{\theta_a^2} \rangle) \langle \overline{\theta_a^2} \rangle$$

where $\mathcal{F}(T_{\rm osc}),\ \mathcal{A}(\langle \overline{\theta_a^2} \rangle)$ are smooth and of order one

- Predictions for $\langle \overline{\theta_a^2} \rangle \equiv \langle \overline{\theta}_a \rangle^2 + \sigma^2_{\overline{\theta}_a}$ depend on whether phase transition occured before/after inflation, more accurately on whether

$$f_a > / < \max \left(\underbrace{\frac{H_I}{2\pi}}_{T_{\rm GH}}, \underbrace{\epsilon_{\rm eff}\, E_I = \epsilon_{\rm eff} \sqrt{\sqrt{\frac{3}{8\pi}} M_{\rm Pl}\, H_I}}_{T_{\rm max}} \right)$$

- In first case: $\langle \overline{\theta}_a \rangle \in [-\pi, \pi], \quad \sigma_{\overline{\theta}_a} = H_I/(2\pi f_a)$
- In second case: $\langle \overline{\theta}_a \rangle = 0, \quad \sigma_{\overline{\theta}_a} = \pi/\sqrt{3}$

Axion/ALP cold dark matter via vacuum-realignment

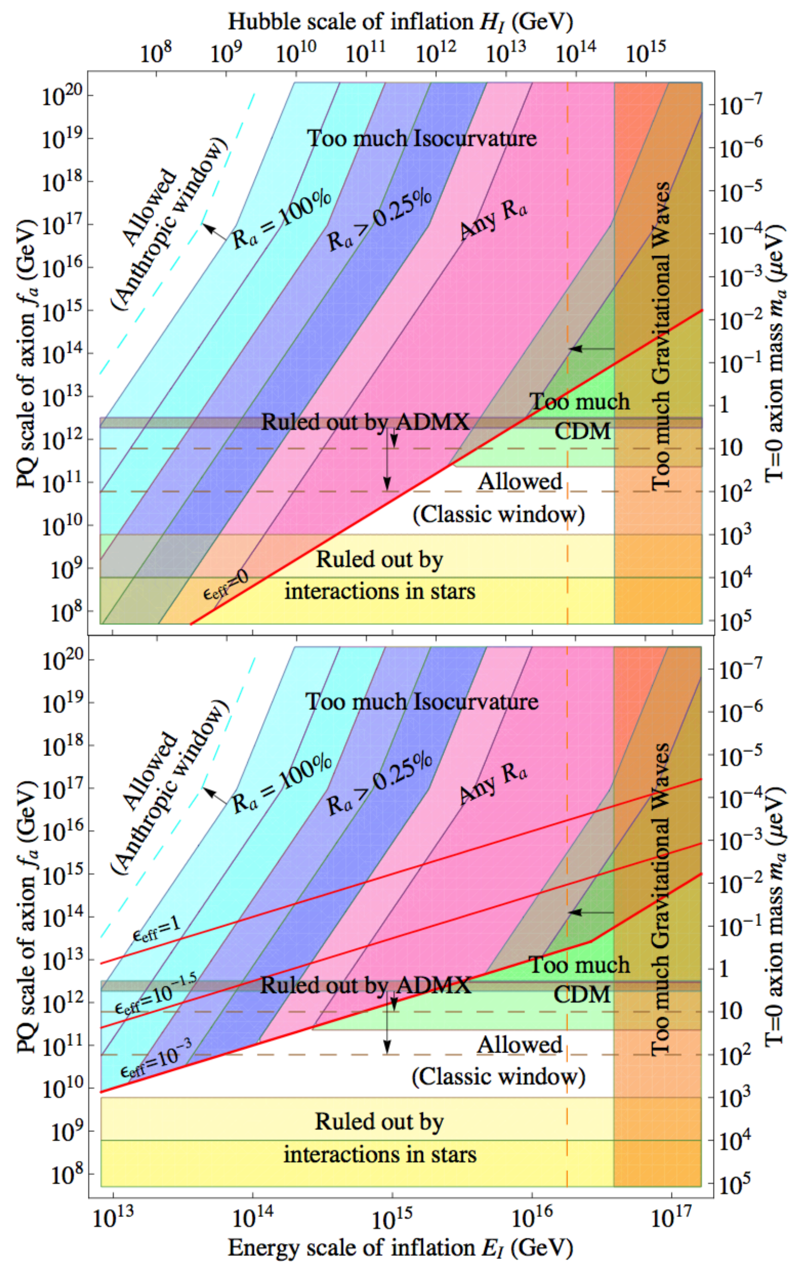
- If $f_a > \max\left(H_I/(2\pi), \epsilon_{\rm eff}\, E_I\right)$, quantum fluctuations $\delta\overline{\theta}_a = H_I/(2\pi f_a)$ of the axion/ALP lead to isocurvature (= entropy) fluctuations in CMB, with nearly scale-invariant power spectrum

$$\mathcal{P}_i(k) \simeq \left(\frac{\Omega_a}{\Omega_d}\right)^2 \begin{cases} \frac{H_I^2}{\pi^2 f_a^2 \langle\overline{\theta}_a\rangle^2}, & \text{for } \langle\overline{\theta}_a\rangle^2 \gg \left(\frac{H_I}{2\pi}\right)^2, \\ 2, & \text{for } \langle\overline{\theta}_a\rangle^2 \ll \left(\frac{H_I}{2\pi}\right)^2, \end{cases}$$

- Non-observation rules out existence of axion/ALP, unless

$$H_I \lesssim 10^{13}\,\mathrm{GeV}$$

[Fox et al. hep-th/0409059; Beltran et al. hep-ph/0606107; Hertzberg et al. 0807.1726; Visinelli,Gondolo 0903.4377; Hamann et al. 0904.0647; Wantz,Shellard 0910.1066]



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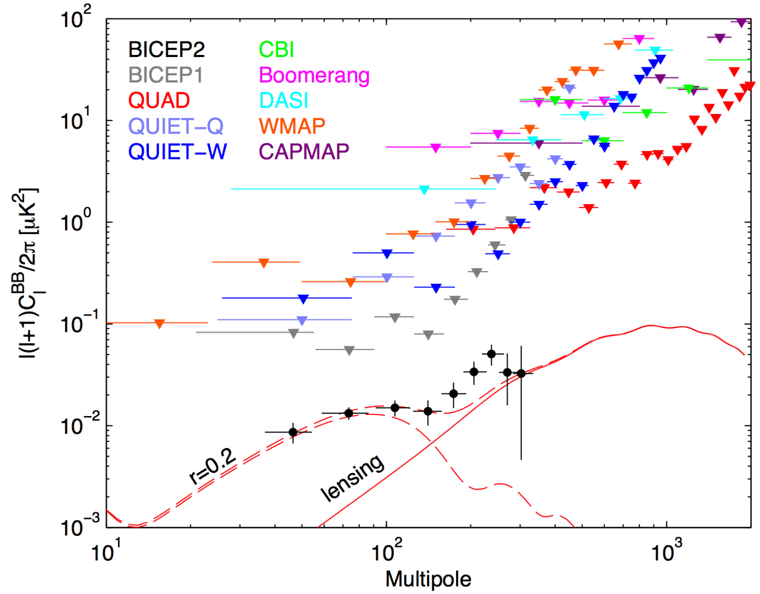
- Detection of $\mathcal{P}_t/\mathcal{P}_s \equiv r = 0.20^{+0.07}_{-0.05}$ by BICEP2 implies

$$H_I \simeq \frac{1}{4}\sqrt{A_s r \pi} M_{\rm Pl} = 1.1\times 10^{14}\,\mathrm{GeV}\left(\frac{r}{0.2}\right)^{1/2}$$



[BICEP2 1403.3985]

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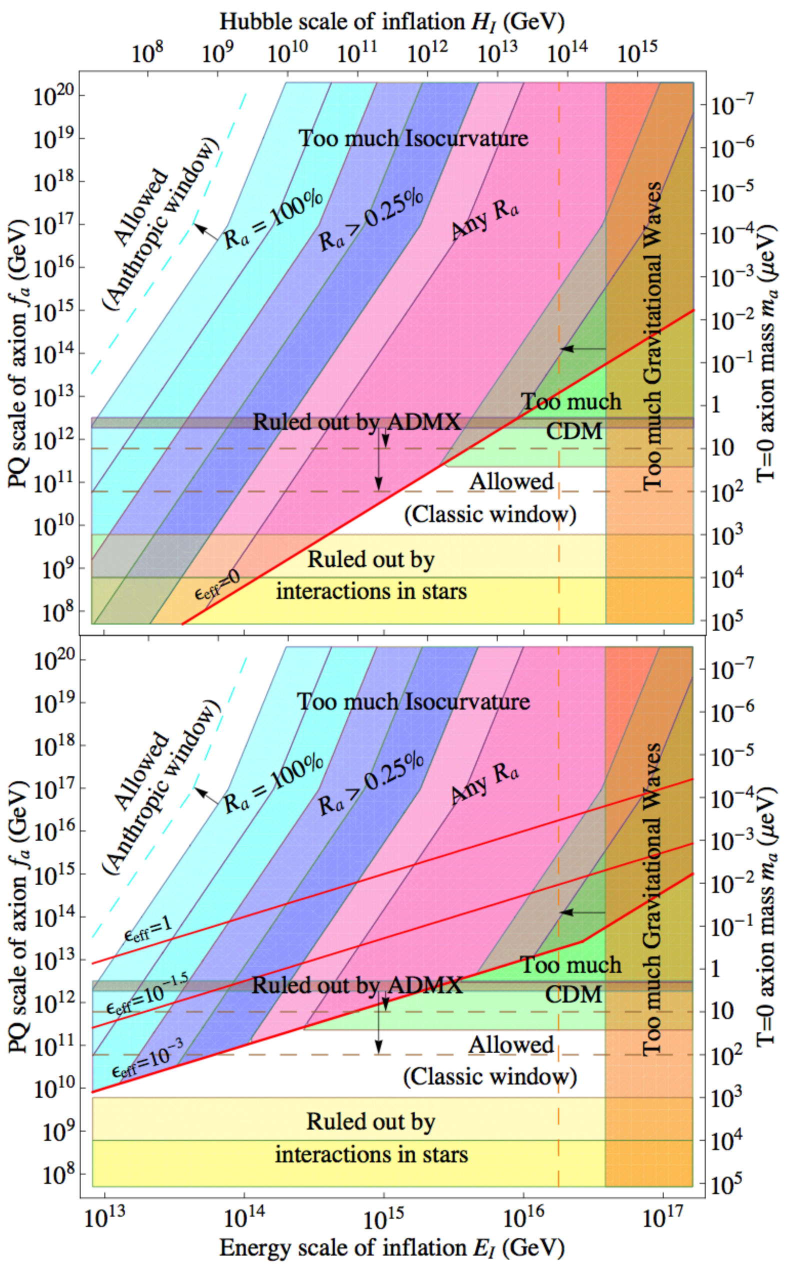
- $f_a > 1.8\times 10^{13}\,\text{GeV}$ strongly disfavored
  [Fox et al. hep-th/0409059; Higaki et al. 1403.4186; Marsh et al. 1403.4216; Visinelli,Gondolo 1403.4594]

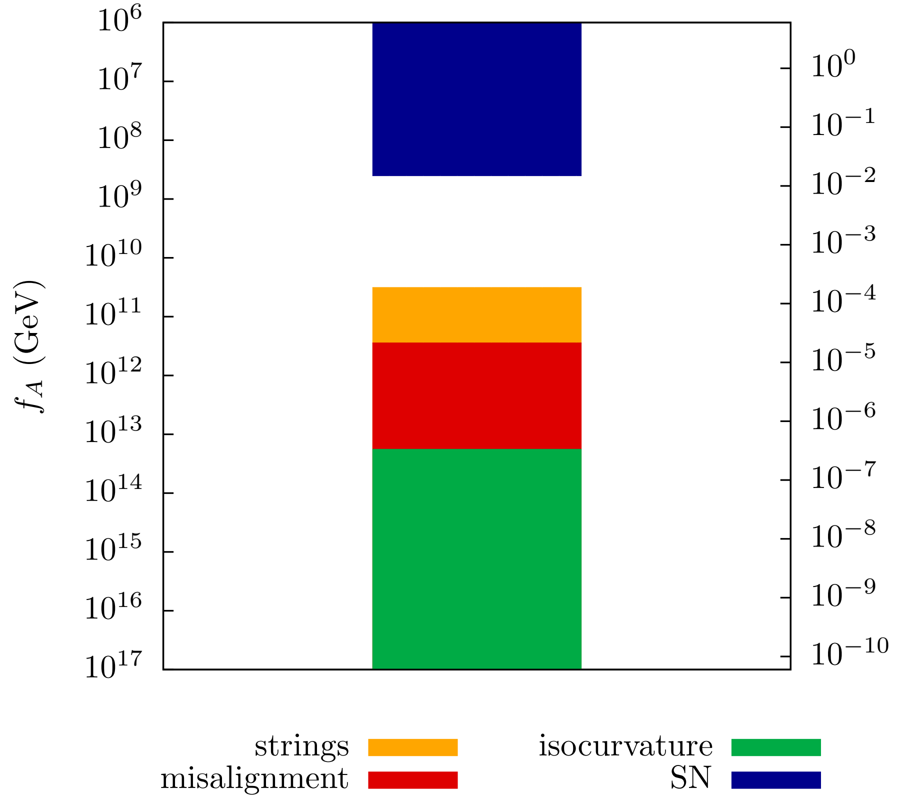


Ways around isocurvature bound?

- f_a much larger during inflation than today [Linde,Lyth ´90; Linde ´91]
  - Easily implementable in SUSY, since potential of PQ scalar determining $f_a \sim v_{\rm PQ}$ relatively flat
  - Non-minimal coupling to gravity [Folkerts,Germani,Redondo 1304.7270]
- m_a much larger during inflation than today
  [Anisimov,Dine hep-ph/0405256; Jeong,Takahashi 1304.8131; Higaki et al. 1403.4186]

Axion/ALP search space after BICEP2

- Scenarios with $f_a < \max\left(H_I/(2\pi), \epsilon_{\rm eff}\, E_I\right)$ unaffected by isocurvature bound
- In this case, also axions/ALPs string decay contribute to cold dark matter
- Axion/ALP search space favorably small if BICEP2 confirmed
  [Visinelli,Gondolo 1403.4594; Di Valentino et al. 1405.1860; Döbrich,Payez,AR 1405.nnnn]



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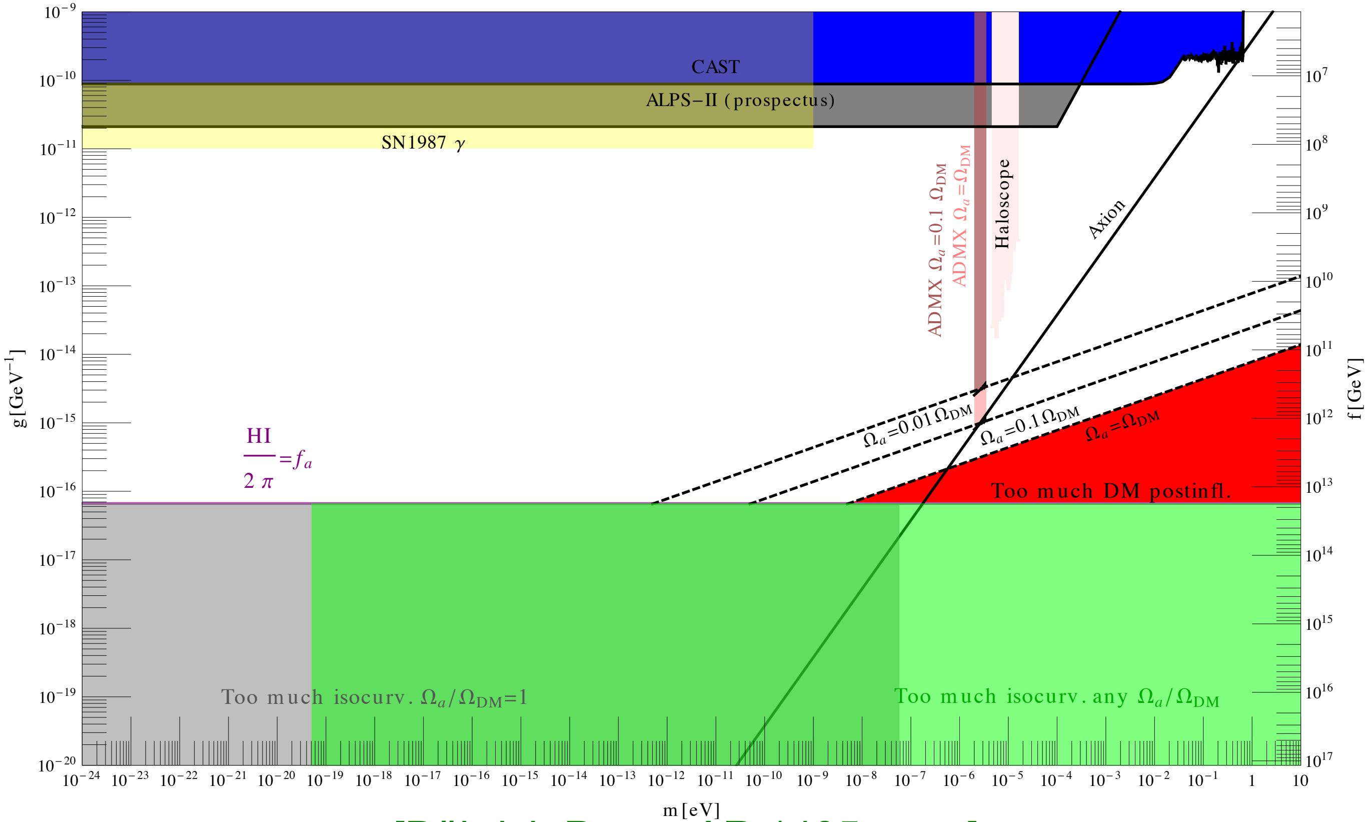
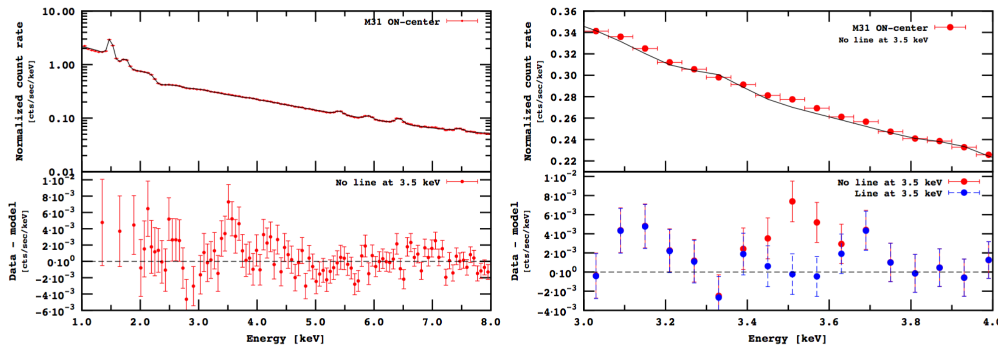


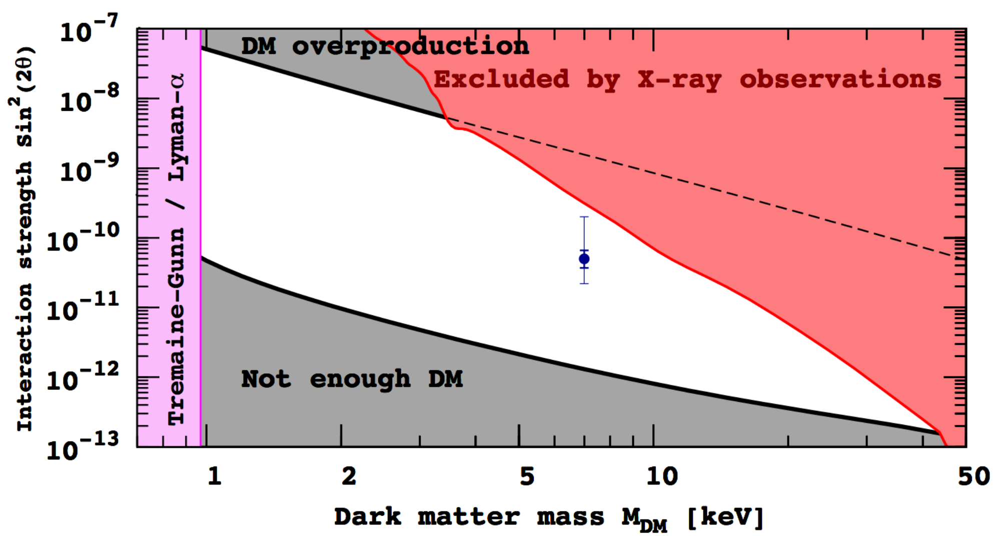
[Döbrich,Payez,AR 1405.nnnn]

Astrophysical hints on ALPs: Decaying ALP dark matter

- Unidentified 3.55 keV line from galaxy clusters and from Andromeda and Perseus recently found [Bulbul et al. 1402.2301, Boyarski et al.1402.4119]
  - Brightness profile compatible with decaying dark matter
- Various interpretations in terms of dark matter decaying into photons
  - Sterile neutrinos
  - ALPs
  - Axinos
  - Excited states of dark matter



Boyarski et al.1402.4119



Astrophysical hints on ALPs: Decaying ALP dark matter

- Decaying 7.1 keV mass ALP interpretation [Higaki,Jeong,Takahashi 1402.6965; Jaeckel,Redondo,AR 1402.7335]
  - Required life-time

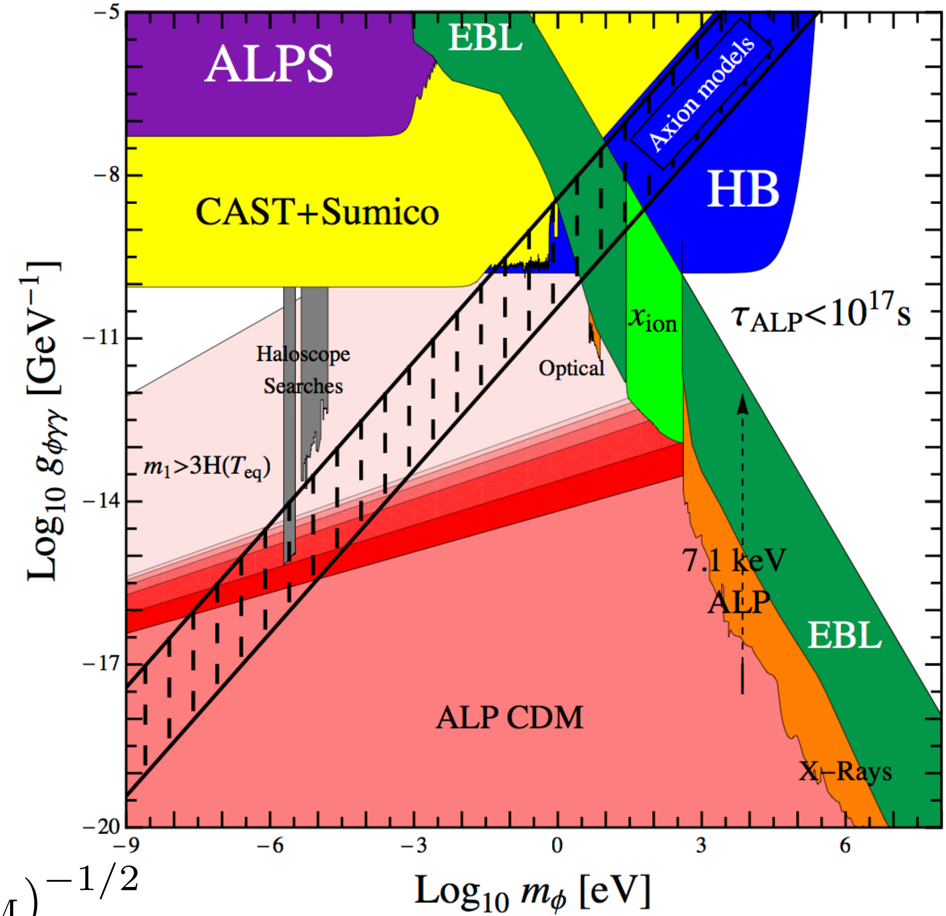
$$\tau_a = 4 \times 10^{27 \div 28}\,\mathrm{s} \times (\rho_a/\rho_{\mathrm{DM}})$$

  - For an ALP, with photon coupling

$$\mathcal{L} \supset \underbrace{\frac{1}{4}\frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a}}_{g_{a\gamma}}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

lifetime given by $\tau_a = \dfrac{64\pi}{g_{a\gamma}^2 m_a^3}$

  - Thus required coupling and scale



$$g_{a\gamma} \sim 10^{-(17\div 18)}\ \mathrm{GeV}^{-1} \times (\rho_a/\rho_{\mathrm{DM}})^{-1/2}$$

$$f_a \sim 10^{14\div 15}\ \mathrm{GeV} \times C_{a\gamma} \times (\rho_a/\rho_{\mathrm{DM}})^{1/2}$$

Jaeckel,Redondo,AR 1402.7335

Astrophysical hints on ALPs: Decaying ALP dark matter

> Intermediate scale ALP + HP model for the 3.55 keV line [Jaeckel et al. 1402.7335]

- Assuming post-inflationary PQ symmetry breaking, predicted ALP dark matter fraction

$$\frac{\rho_a}{\rho_{\rm DM}} \simeq 0.13 \times \left(\frac{m_a}{7.1\,{\rm keV}}\right)^{\frac{1}{2}} \left(\frac{f_a}{10^9\,{\rm GeV}}\right)^2 (1 + c_a^{\rm strings})$$

- Corresponding two photon coupling too large for $C_{a\gamma\gamma} \sim 1$; need rather $C_{a\gamma\gamma} \sim 10^{-(5\div 6)}$

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma\gamma}}{f_a} = 10^{-12}\,{\rm GeV} \times C_{a\gamma\gamma}\left(\frac{10^9\,{\rm GeV}}{f_a}\right)$$

- If ALP resides in hidden sector, and couples to two hidden photons (HPs) via

$$\mathcal{L} \supset -\frac{1}{2}\chi F^{\mu\nu} X_{\mu\nu} - \frac{1}{4}\underbrace{\frac{\alpha_X}{2\pi}\frac{C_{a\gamma'\gamma'}}{f_a}}_{g_{a\gamma'\gamma'}} a\, X^{\mu\nu}\tilde{X}_{\mu\nu}$$

- Then, after removing mixed kinetic term by field redifinition $X^\mu \to X^\mu + \chi A^\mu$

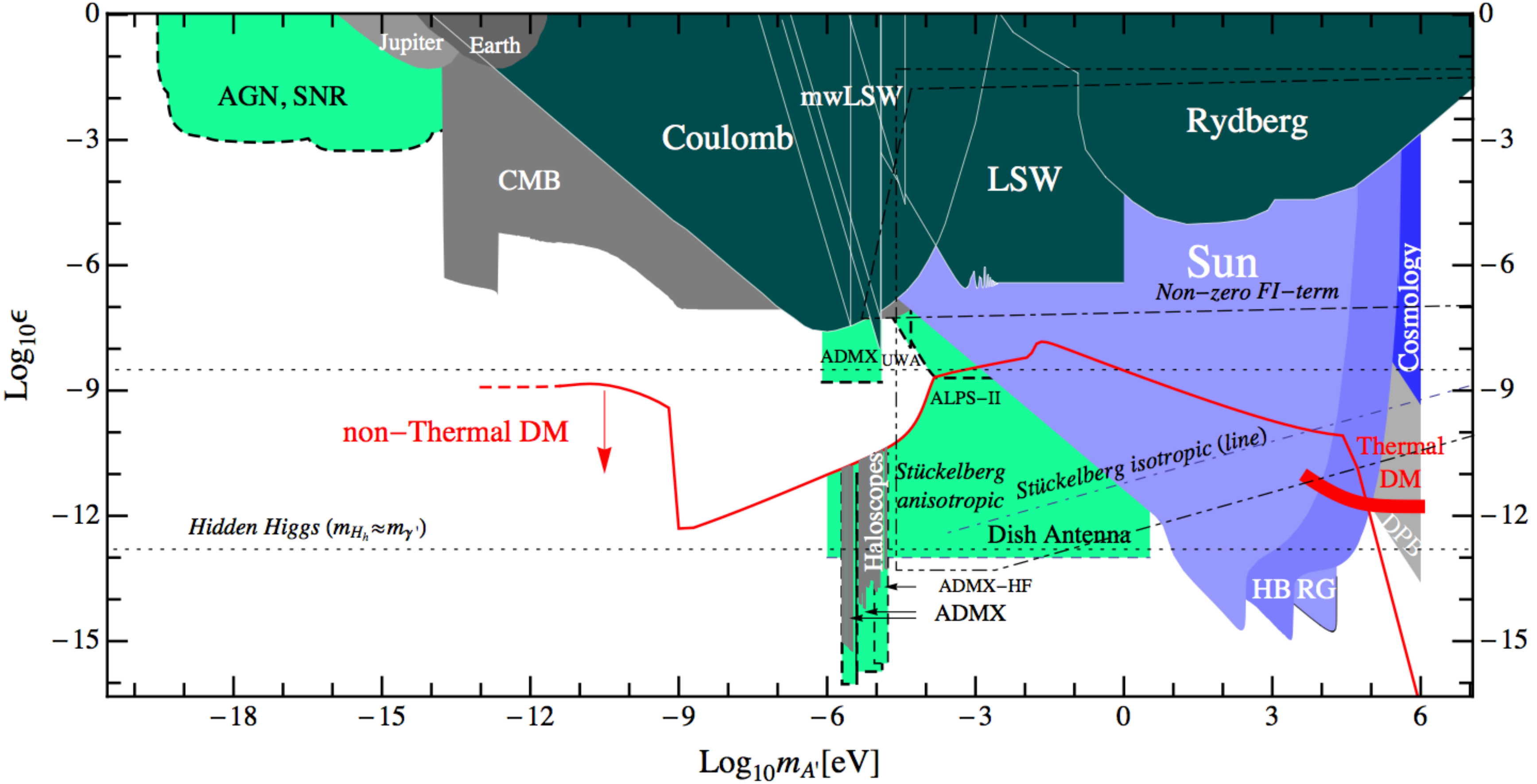
$$\mathcal{L} \supset \frac{1}{2}\underbrace{\frac{\alpha_X}{2\pi}\frac{\chi}{f_a}}_{g_{a\gamma\gamma'}} a\, F^{\mu\nu}\tilde{X}_{\mu\nu} + \frac{1}{4}\underbrace{\frac{\alpha_X}{2\pi}\frac{\chi^2}{f_a}}_{g_{a\gamma\gamma}} a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$

- The decay $a \to \gamma + \gamma'$ gives rise to a line; required parameter range

$$g_{a\gamma\gamma'} = \frac{\alpha_X}{2\pi}\frac{\chi}{f_a} \simeq 10^{-18}\,{\rm GeV} \times \left(\frac{\alpha_X}{\alpha}\right)\left(\frac{\chi}{10^{-6}}\right)\left(\frac{10^9\,{\rm GeV}}{f_a}\right)$$

Astrophysical hints on ALPs: Decaying ALP dark matter

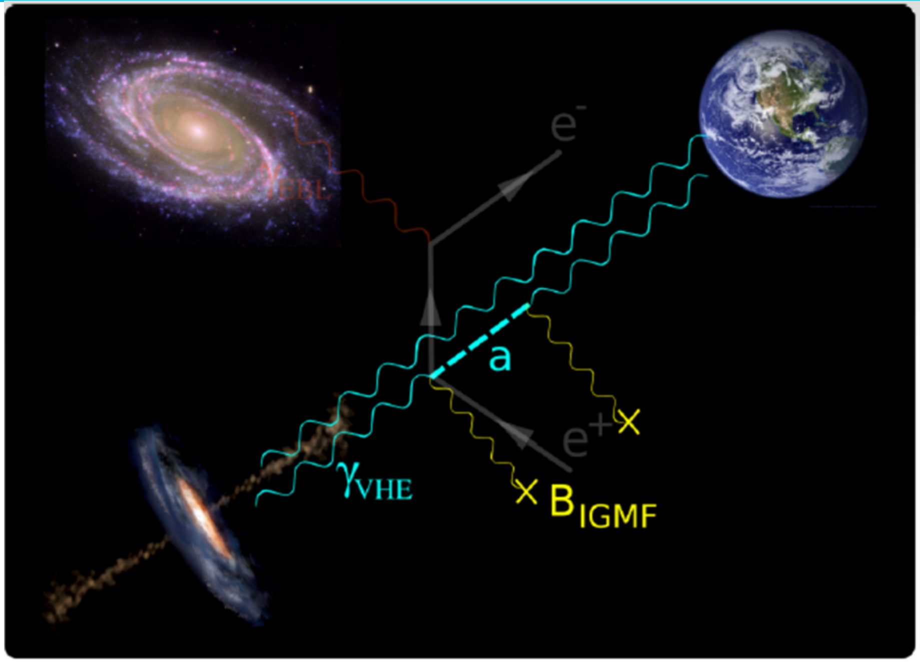
> If required HP has a small mass, it can be searched for e.g. in CMB:



[Essig et al. 1311.0029]

Astrophysical hints on ALPs: Cosmic VHE transparency

- Gamma ray spectra from distant AGNs should show an energy and red-shift dependent exponential attenuation, due to pair production at Extragalactic Background Light (EBL)
- Attenuation recently observed by Fermi-LAT and H.E.S.S.
- At $\tau \gtrsim 2$, however, hints for anomalous gamma transparency, from IACT and Fermi-LAT data [Aharonian et al. 07; Aliu et al. 08;...;Horns,Meyer 12;...]
- Possible explanation: photon <-> ALP conversions in magnetic fields [De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer,Horns,Raue 13]



[Manuel Meyer 12]

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma\gamma}}{f_a} \gtrsim 10^{-12}\ \mathrm{GeV}^{-1}$$

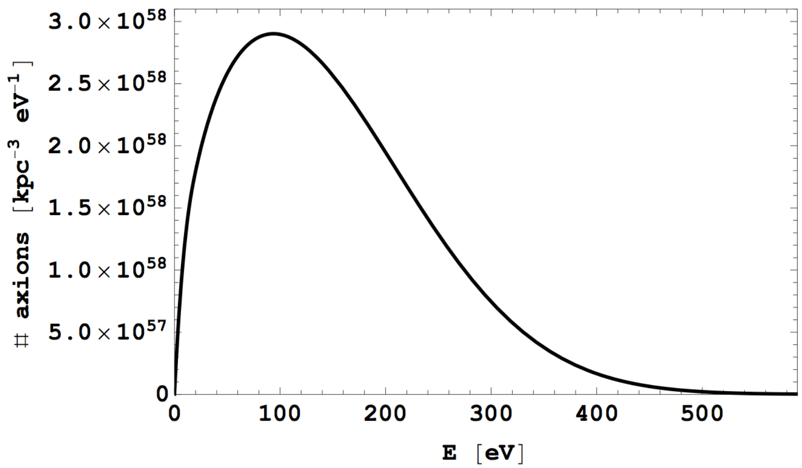
$$f_a \lesssim 10^{9}\ \mathrm{GeV} \times C_{a\gamma\gamma}$$

$$m_a \lesssim 10^{-7}\ \mathrm{eV}$$

Astro hints on ALPs: Cosmic ALP background radiation

- Hints of dark radiation ($\triangle N_{\rm eff}$) in CMB
- Dark radiation comprised by ALPs may be generated by modulus (scalar partner of pseudoscalar ALP) decay. Spectrum peaked at around 100 eV, for modulus mass $\sim 10^6\,\mathrm{GeV}$

  [Cicoli,Conlon,Quevedo 12; Higaki,Takahashi 12]

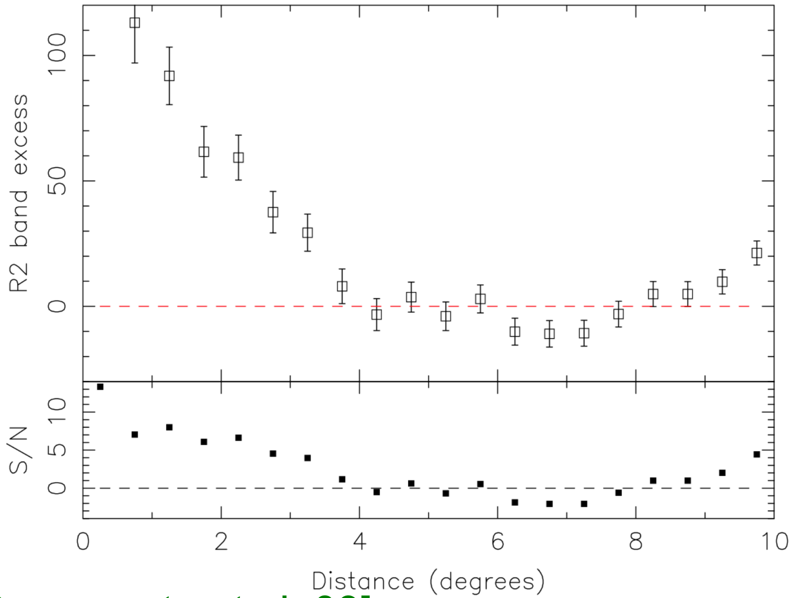


[Angus et al. 13]

- ALP conversion to photon in magnetic fields of galaxy clusters, e.g. Coma, may explain observed soft X-ray excess if [Marsh,Conlon 13; Angus et al. 13]

$$g_{a\gamma\gamma} \gtrsim \sqrt{0.5/\triangle N_{\rm eff}} \times 1.4\times 10^{-13}\,\mathrm{GeV}^{-1}$$

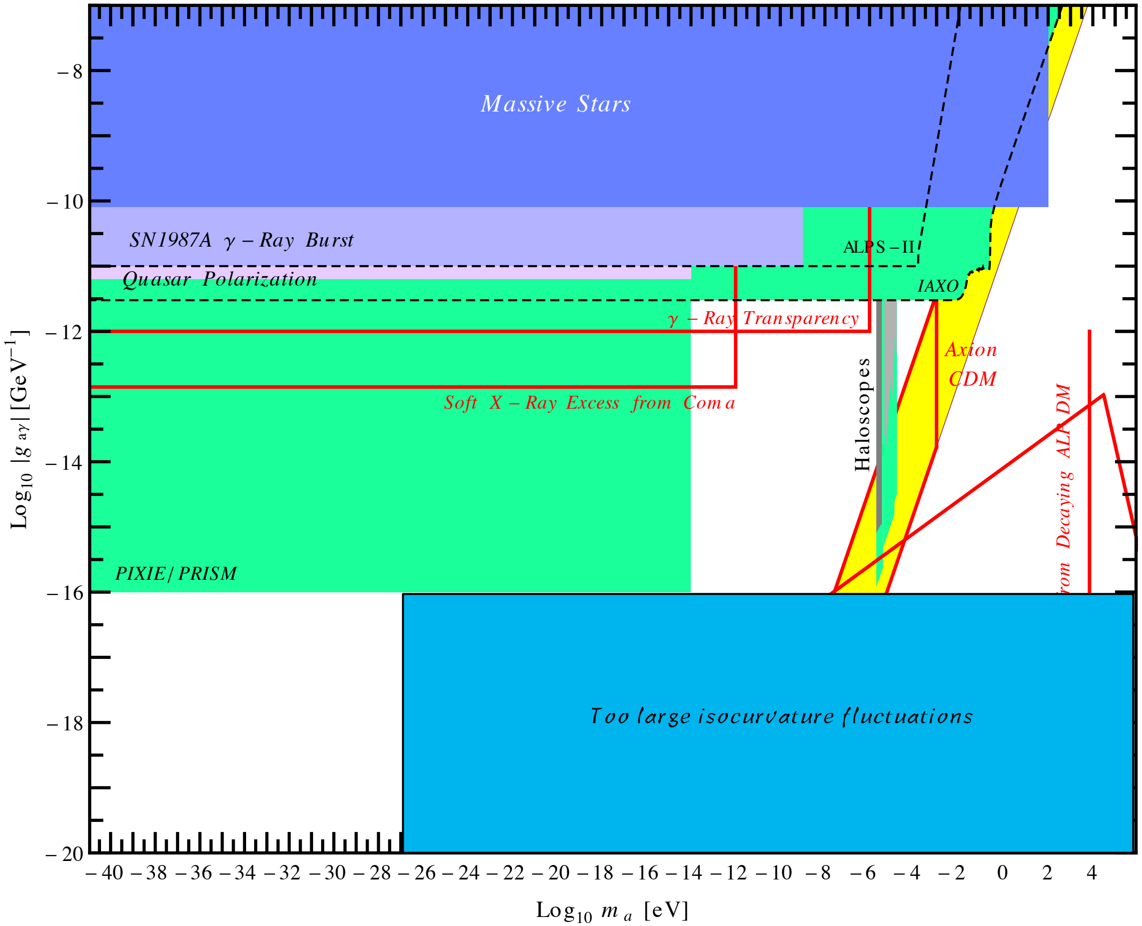
$$\text{for}\quad m_a \lesssim 10^{-12}\,\mathrm{eV}$$



[Bonamente et al. 09]

Astrophysical hints on ALPs

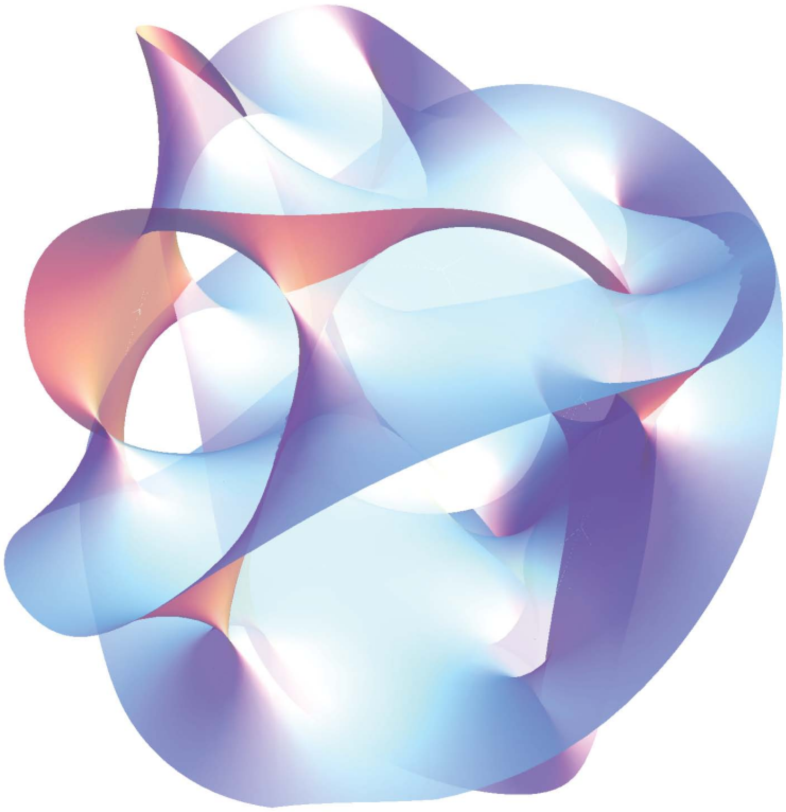
- Astrophysical hints suggest the existence of (2-3) extra ALPs in addition to the axion, all with an intermediate scale decay constant $f_{a_i} \sim 10^9\,\mathrm{GeV}$



[adapted from Dias,Machado,Nishi,AR,Vaudrevange 1403.5760]

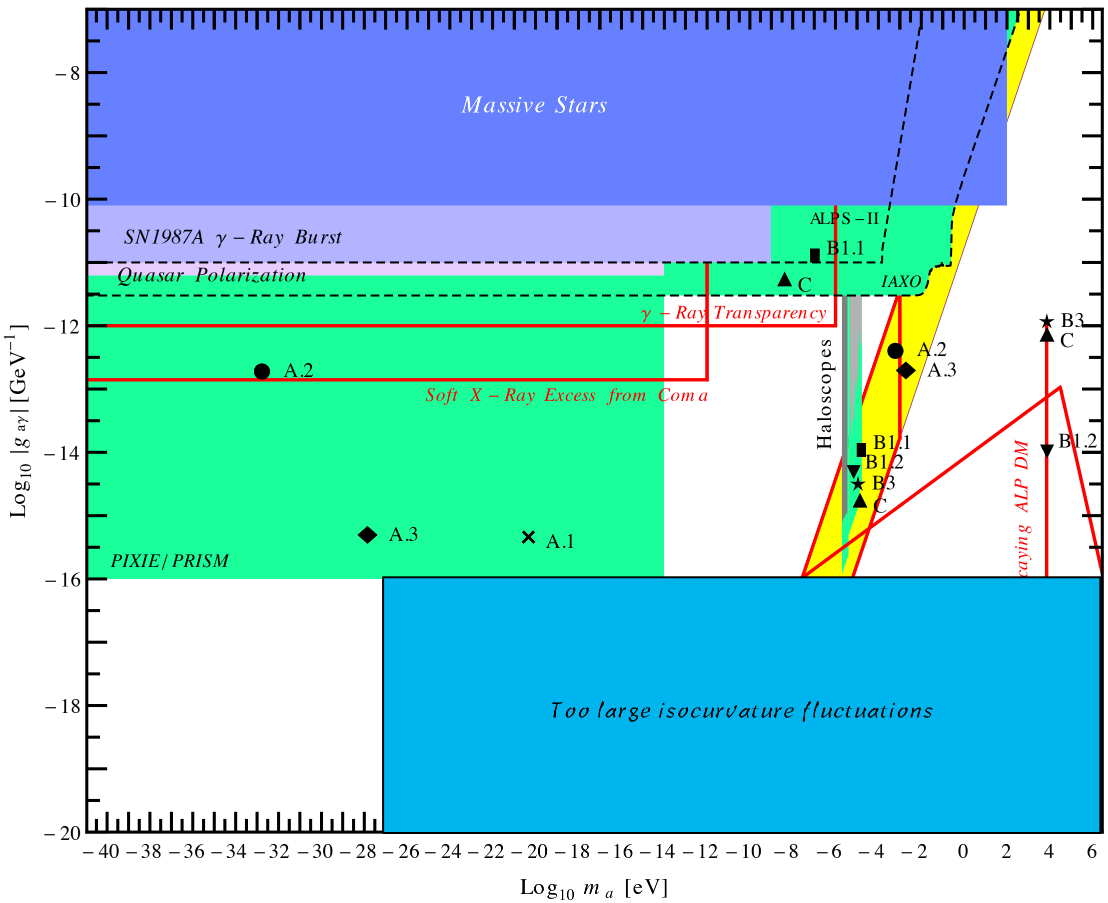
UV completions featuring ALPs: String axiverse

- 4D low-energy effective field theory emerging from string theory predicts natural candidates for the axion, often even an `axiverse´, containing many additional ALPs
  - KK zero modes of 10D antisymmetric tensor fields, the latter belonging to the massless spectrum of the bosonic string
    - shift symmetry from gauge invariance in 10D; # ALPs depends on topology;
    - PQ scale of order the string scale, i.e. GUT scale, $10^{16}\ \mathrm{GeV}$,in the heterotic string case; typically lower, the intermediate scale, $10^{10}\ \mathrm{GeV}$, in IIB compactifications realising brane worlds with large extra dimensions [Witten 84; Conlon 06; Arvanitaki et al. 09; Acharya et al. 10; Cicoli, Goodsell, AR 12]
  - NGBs from accidental PQ symmetries appearing as low energy remnants of discrete symmetries from compactification, PQ scale decoupled from string scale [Lazarides,Shafi 86; Choi et al. 09; AR,Vaudrevange in prep.]



UV completions featuring accidental PQ symmetries

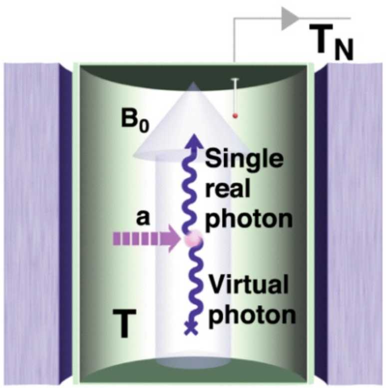
- Purely field theoretic UV extensions of SM featuring several accidental PQ symmetries yield benchmarks

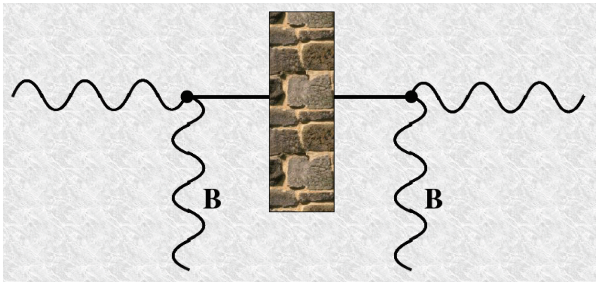


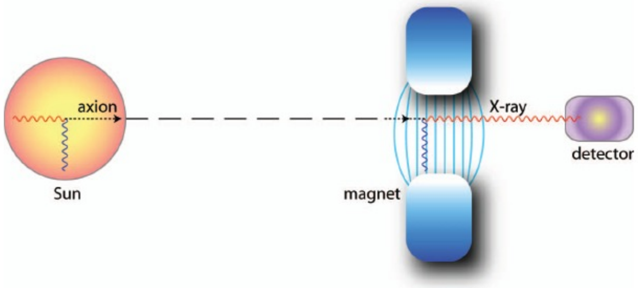
[adapted from Dias,Machado,Nishi,AR,Vaudrevange 1403.5760]

Laboratory searches for WISPs

- Sizeable part of parameter range of interest can be accessed in this decade with terrestrial searches based on WISP photon oscillations (requiring presence of strong magnetic fields in case of axions/ALPs)
  - Haloscopes: direct detection of DM WISPs [Sikivie ’83]
  - Light-shining-through-a-wall: production and detection of WISPs [Anselm ‘85; van Bibber et al ‘87]
  - Helioscopes: detection of solar WISPs [Sikivie ’83]







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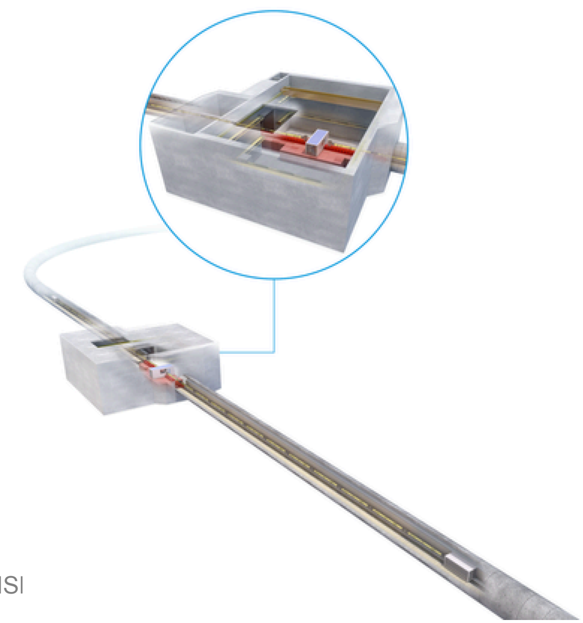
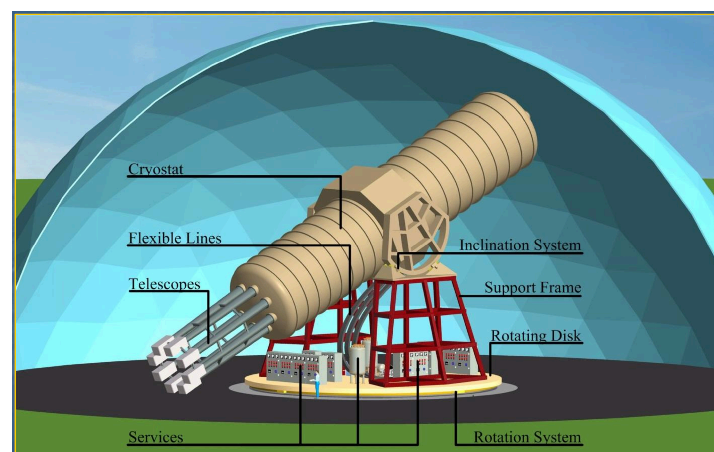
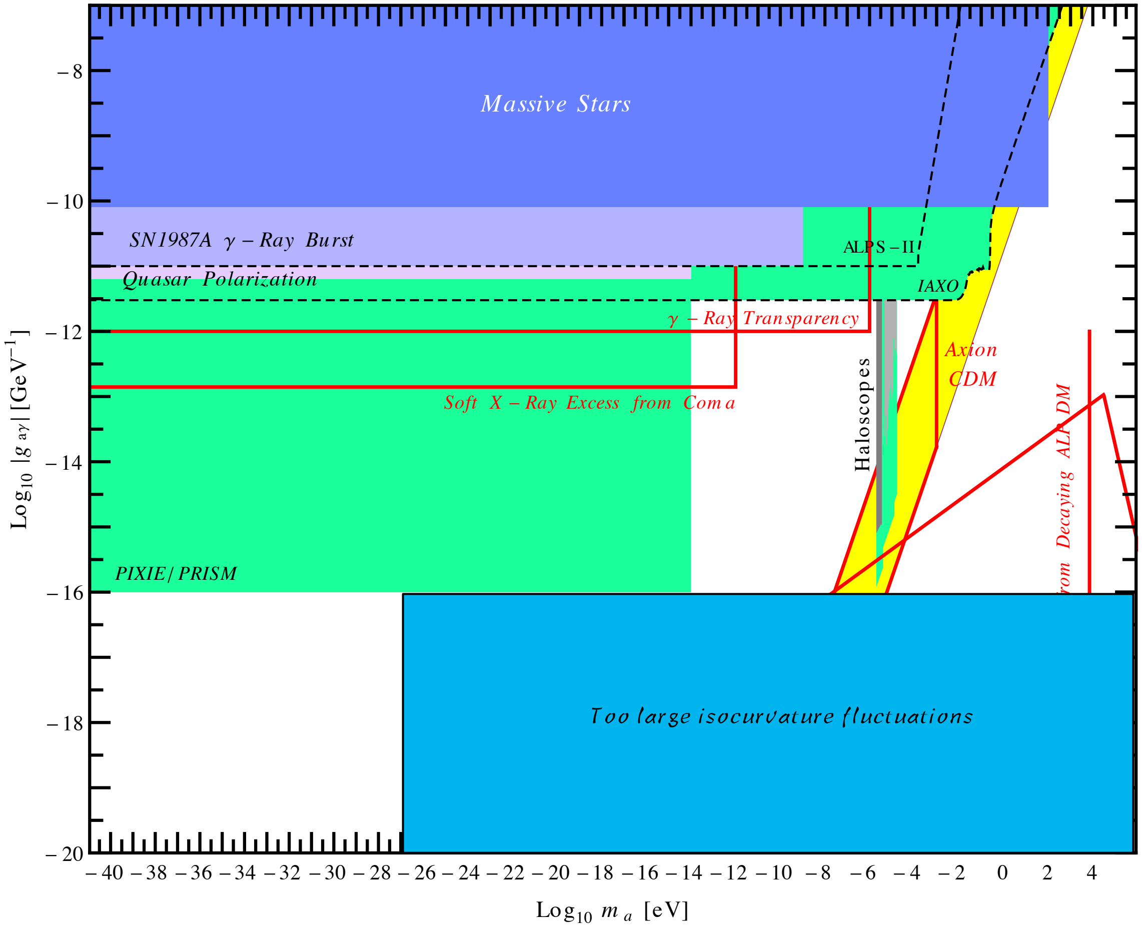
  - Light-shining-through-a-wall: production and detection of WISPs: ALPS II (DESY), ...
  - Helioscopes: detection of solar WISPs: IAXO (?), ...





Laboratory searches for WISPs

> Sizeable part of parameter range of interest can be accessed in this decade with terrestrial searches based on WISP photon oscillations



[adapted from Dias,Machado,Nishi,AR,Vaudrevange 1403.5760]

Summary

- Strong physics case for WISPs, in particular axion and ALPs:
  - Solution of strong CP problem gives particularly strong motivation for existence of axion
  - For intermediate scale decay constant, $10^9\,\mathrm{GeV} \lesssim f_A, f_a \lesssim 10^{12}\,\mathrm{GeV}$, axion and ALPs are natural cold dark matter candidates
  - In many theoretically appealing UV completions of SM, in particular in completions arising from strings, there occur intermediate scale axions and ALPs automatically
  - ALPs can explain the anomalous transparency of the universe for (V)HE gamma rays
  - ALPs may explain soft X-ray excesses from galaxy clusters
  - 7.1 keV ALP may explain unidentified X-ray line from Andromeda and galaxy clusters
- Intermediate scale region in axion and ALPs parameter space can be tackled in the upcoming decade by a number of experiments:
  - Haloscopes
  - Light-shining-through-a-wall experiments
  - Helioscopes
- Stay tuned!