# Axions and axion-like particles.

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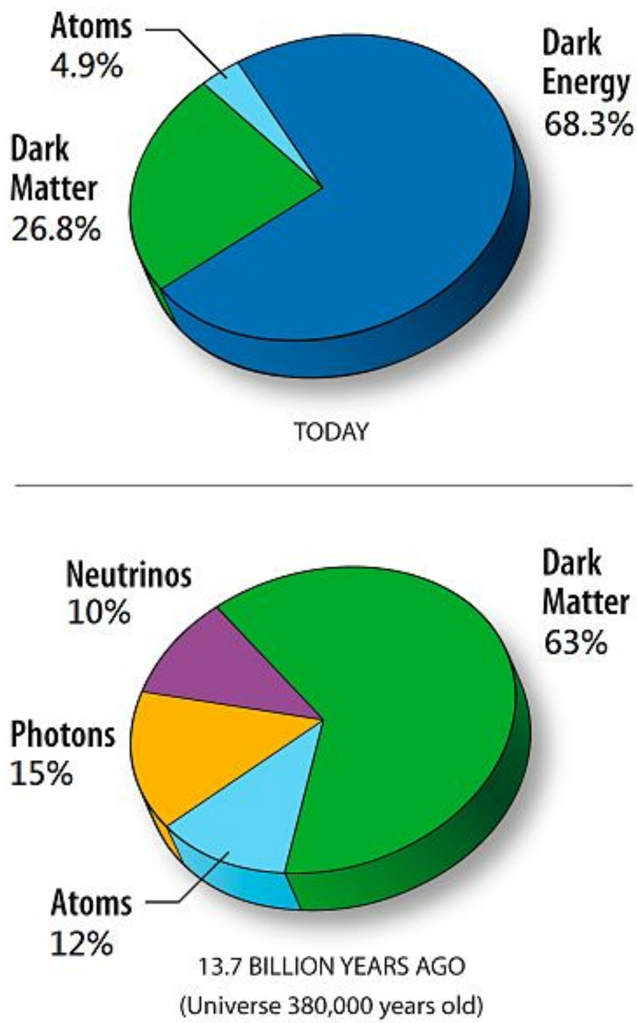
HELMHOLTZ ASSOCIATION

DESY

# Strong case for particles beyond the Standard Model

- Standard Model (SM) of particle physics describes basic properties of known matter and forces
- SM not a complete and fundamental theory:
  - No satisfactory explanation for values of its many parameters
  - No quantum theory of gravity
  - No explanation of the origin of the dark sector of the universe




[wikipedia]

# Strong case for particles beyond the Standard Model

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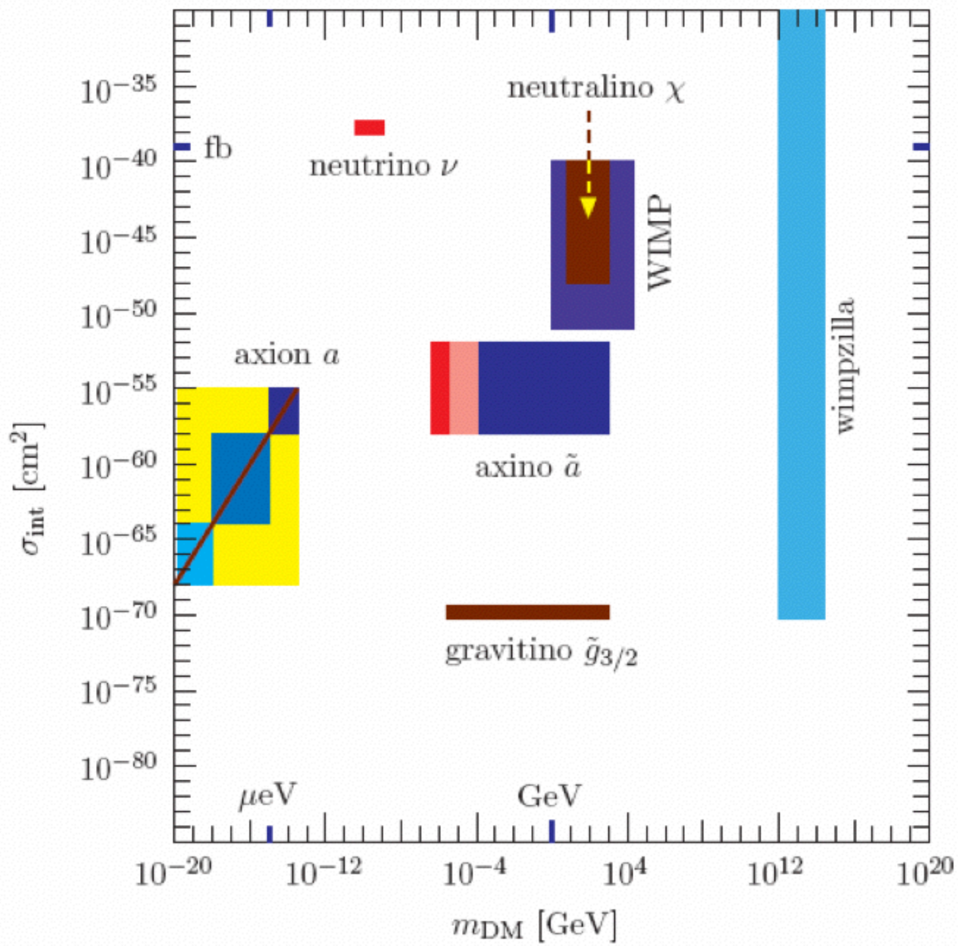
- SM not a complete and fundamental theory:
  - No satisfactory explanation for values of its many parameters
  - No quantum theory of gravity
  - No explanation of the origin of the dark sector of the universe
- Well-motivated SM extensions provide dark matter candidates:
  - Neutralinos and other Weakly Interacting Massive Particles (WIMPs)
  - Axions and other very Weakly Interacting Slim (=ultra-light) Particles (WISPs)




(Kim,Carosi 10)

# Theoretically favored WISP candidates

> Nambu-Goldstone bosons arising from SSB of global U(1)s at scale $f_a$

- Low energy effective field theory has shift symmetry $a(x) \to a(x) + \text{const.}$, 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 $f_a$

- Examples:
  - Axion from breaking of global chiral symmetry; axion field acts as dynamical theta para-meter, [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \underbrace{\frac{A}{f_A}}_{\bar{\theta}} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

spontaneously relaxing to zero, $\langle A \rangle = 0$ (thus CP conserved)

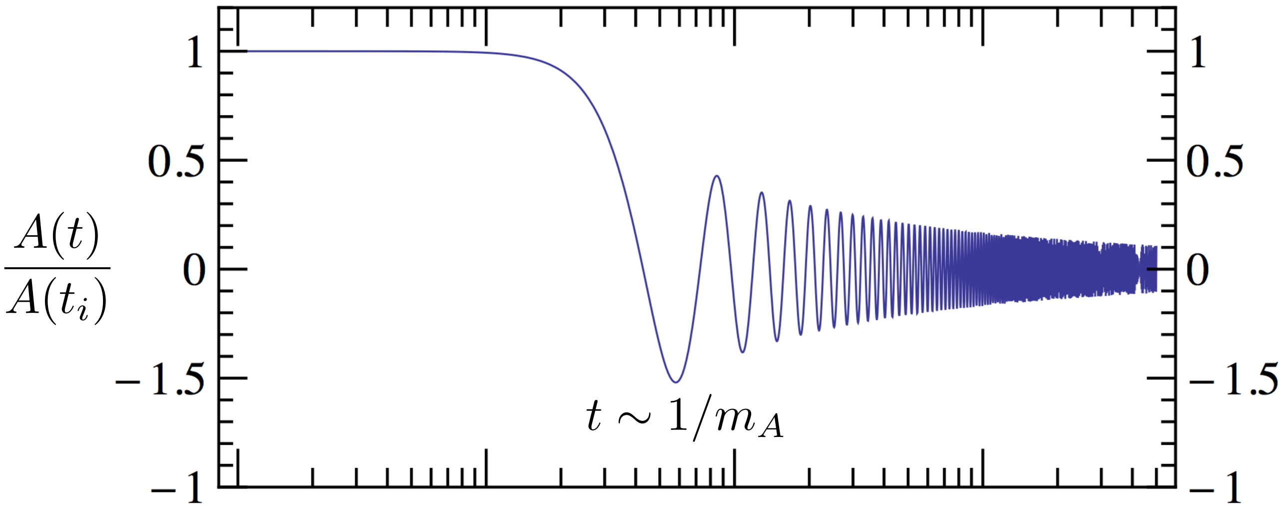
- mass due to chiral symmetry breaking $m_A \sim m_\pi f_\pi / f_A$
- has universal coupling to photons, $\mathcal{L} \supset -\frac{\alpha}{8\pi} C_0 \frac{A}{f_A} F_{\mu\nu} \tilde{F}^{\mu\nu}$

  - 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 axion and axion-like particles: 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]

- Axion-like particle (ALP): no coupling to gluons, but nonzero coupling to photons

# Physics case for axions and ALPs: Cold dark matter

- For $f_A \gtrsim 10^9\,\mathrm{GeV}$, axions produced pre-dominantly non-thermally in the early universe
- Vacuum-realignment: [Preskill et al. 83; Abbott,Sikivie 83; Dine,Fischler 83]
  - Homogeneous mode of axion field frozen at random initial value, $A(t_i) = \theta_i\, f_A$, because of cosmic expansion, as long as $t \lesssim 1/m_A$. Later, at $t > 1/m_A$, axion field oscillates around zero.




  - Classical, spatially coherent oscillating fields = coherent state of extremely non-relativistic dark matter, i.e. cold dark matter

# Physics case for axions and ALPs: Cold dark matter

- If PQ phase transition before inflation and no dilution by late decays of particles beyond SM,

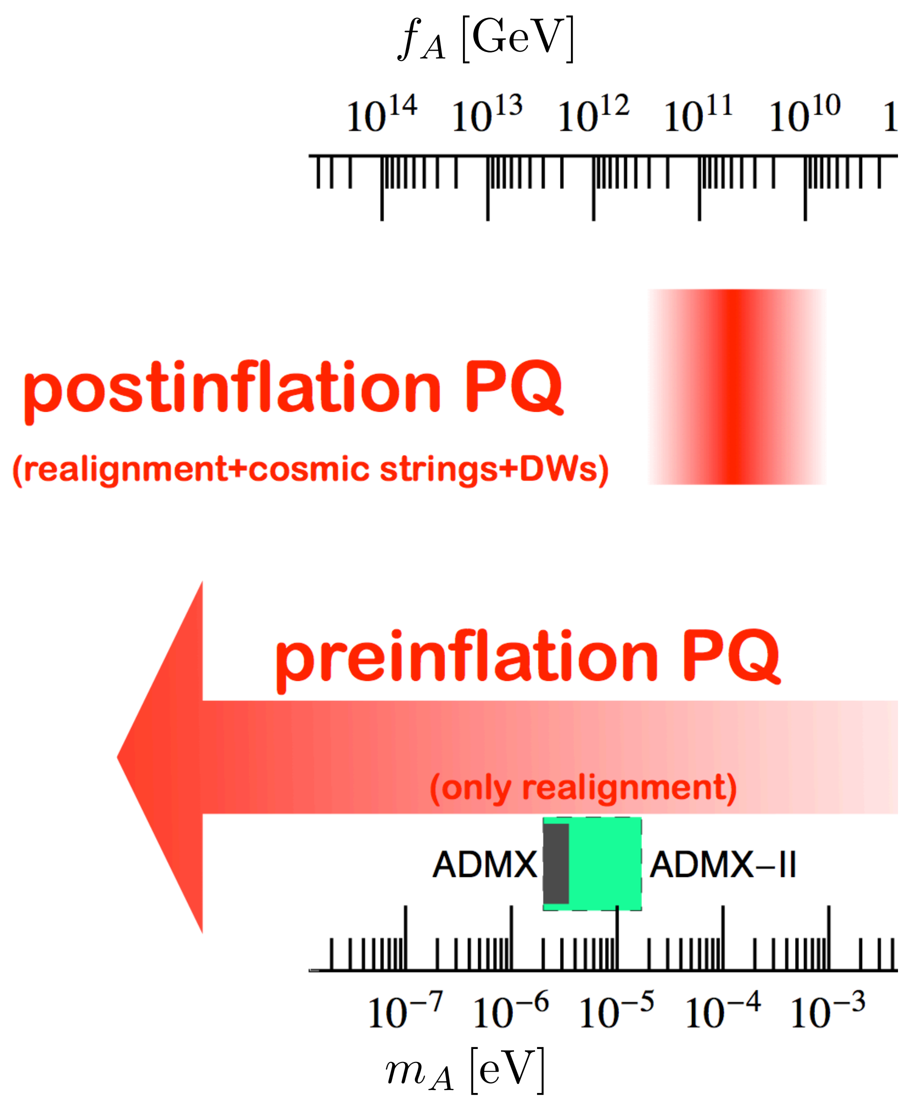
$$\Omega_A^{\rm vr} h^2 \approx 0.11 \left( \frac{f_A}{5 \times 10^{11}\ {\rm GeV}} \right)^{1.184} F\, \bar\Theta_{\rm i}^2$$
$$= 0.11 \left( \frac{12\ \mu{\rm eV}}{m_A} \right)^{1.184} F\, \bar\Theta_{\rm i}^2 ,$$

- If PQ phase transition after inflation, initial misalignment angles take on different values in different patches of universe; average

$$\Omega_A^{\rm vr} h^2 \approx 0.11 \left( \frac{40\ \mu{\rm eV}}{m_A} \right)^{1.184}$$

  - Decay of cosmic strings and domain walls may provide for additional sources for axion CDM

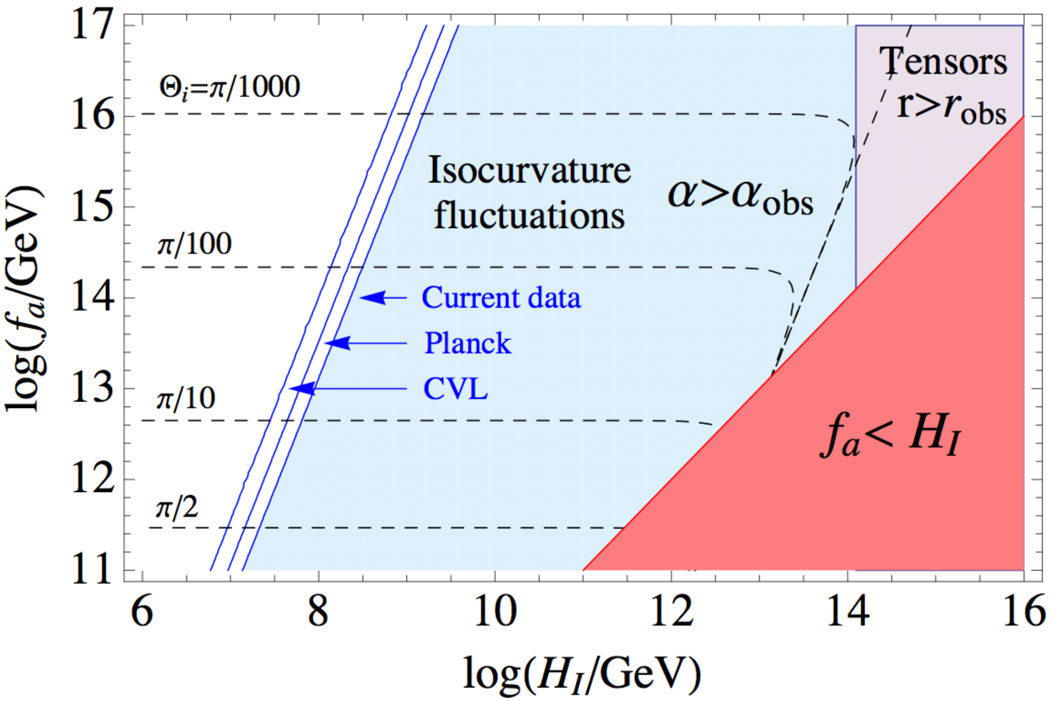
$$\Omega_A^{\rm td} h^2 \approx 0.11 \left( \frac{400\ \mu{\rm eV}}{m_A} \right)^{1.184}$$




[adapted by from Essig et al. 1311.0029]

# Physics case for axions and ALPs: Cold dark matter

- If PQ phase transition before inflation, $f_A > H_I$, axion field present during inflation, leading to isocurvature fluctuations that are severly constrained: only allowed if Hubble scale during inflation smallish




[Hamann,Hannestad,Raffelt,Wong 0904.0647]

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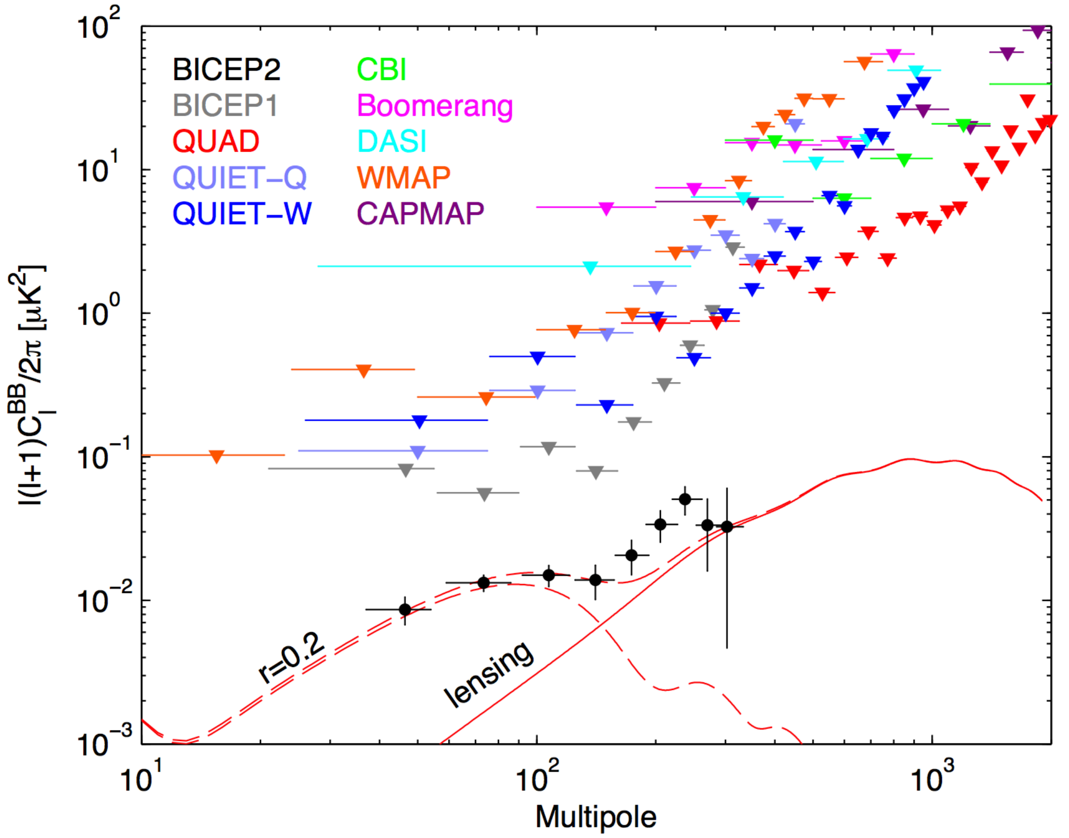
- Detection of tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$ from B-mode power spectrum by BICEP2 implies large

$$H_I = \frac{1}{4}\sqrt{\pi A_S r}\ M_{\rm Pl}$$
$$\simeq 1.33 \times 10^{14}\ {\rm GeV} \left(\frac{A_S}{2.4 \times 10^{-9}}\right)^{1/2} \left(\frac{r}{0.25}\right)^{1/2}$$




[BICEP2 1403.3985]

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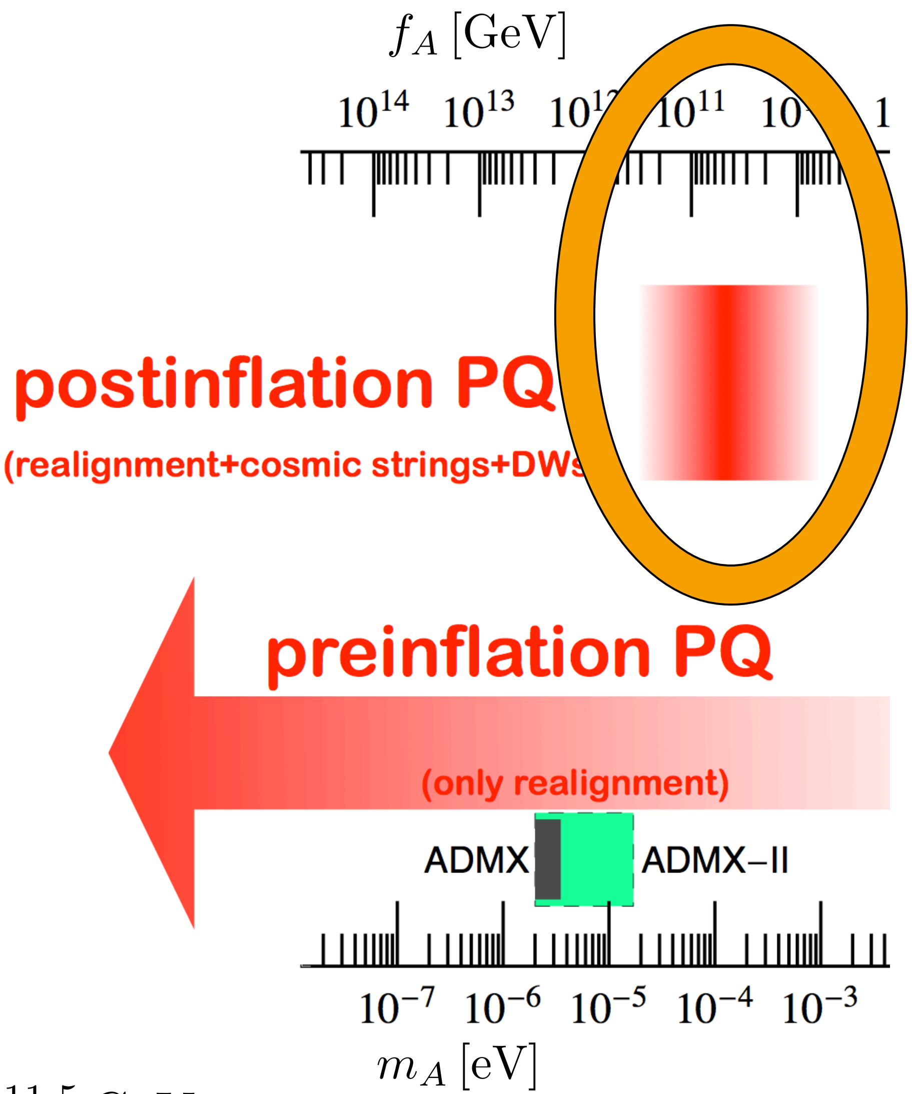
- Axion DM window narrowed to postinflation PQ, $f_A \sim 10^{9.5\div 11.5}\ \mathrm{GeV}$ see also [Marsh et al., 1403.4216]



# Physics case for axions and ALPs: Cold dark matter

- Other bosonic WISPs, such as ALPs or Hidden Photons, are also be produced via the vacuum-realignment mechanism,

[Arias et al. 12]

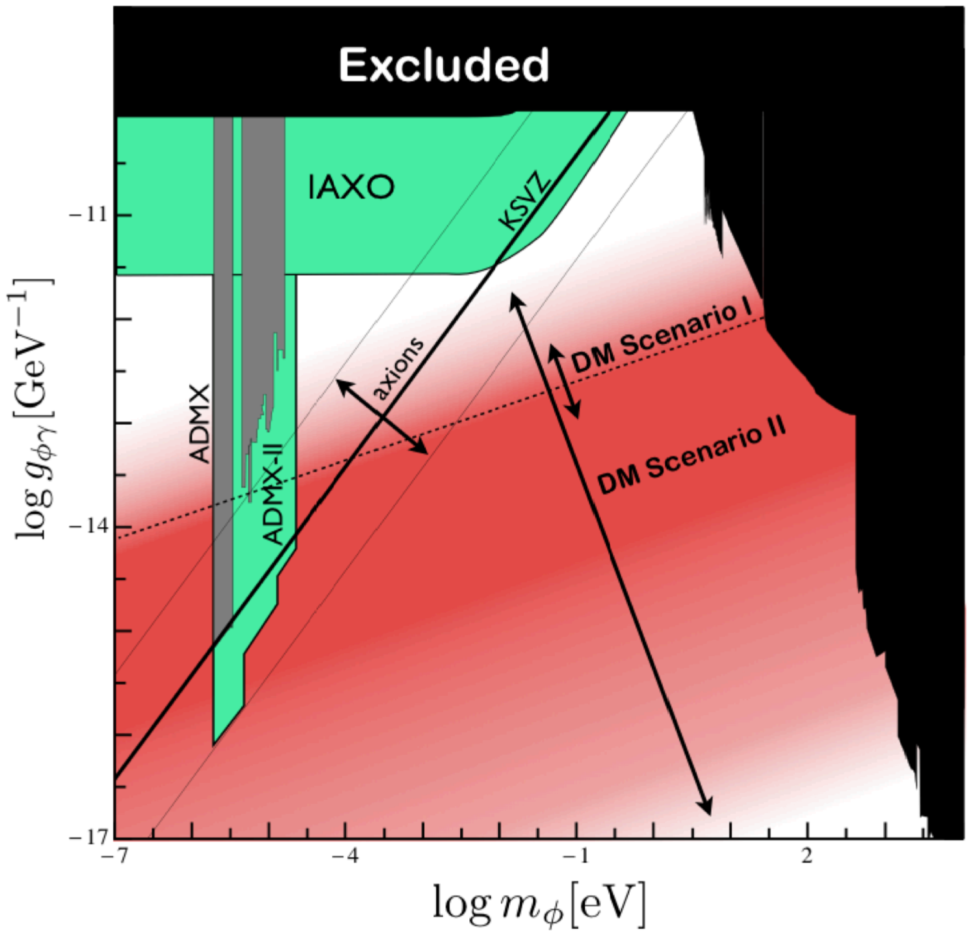
$$\Omega_a h^2 \approx 0.16 \left(\frac{m_a}{\rm eV}\right)^{1/2} \left(\frac{f_a}{10^{11}\ {\rm GeV}}\right)^2 \left(\frac{\theta_i}{\pi}\right)^2$$

- Natural range for axion/ALP CDM: "cosmic axion window",

$$10^9\ {\rm GeV} \lesssim f_A, f_a \lesssim 10^{12}\ {\rm GeV}$$

("intermediate scale")

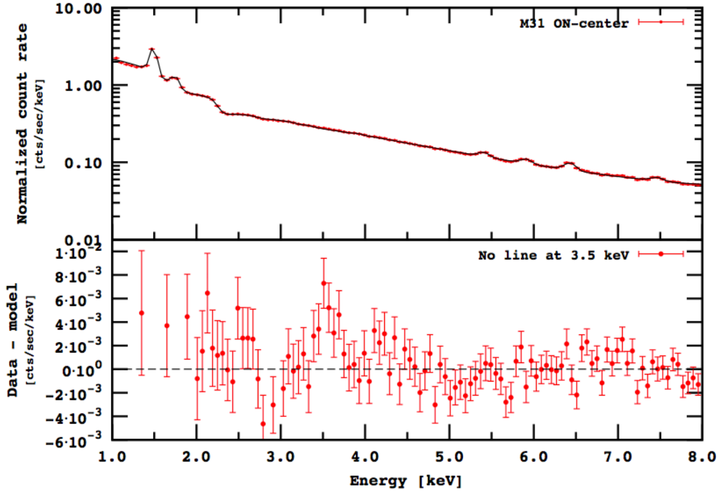
- Large search space for axion and ALP CDM in photon coupling $g_{i\gamma} \sim \alpha/(2\pi f_i)$ vs. mass

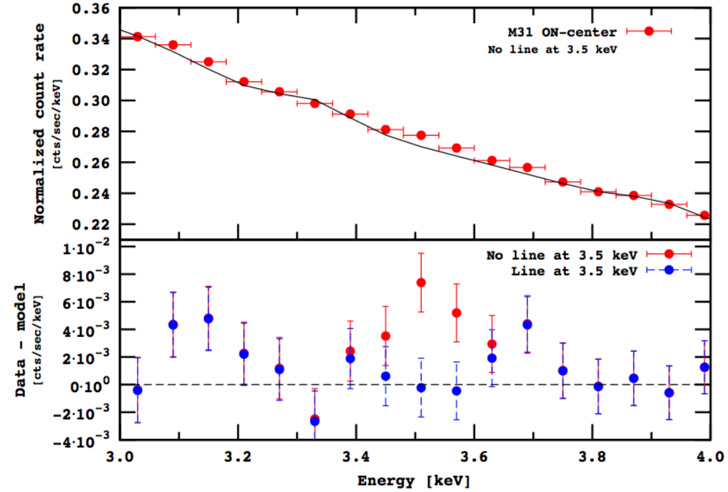



[Döbrich,Redondo 13]

# Physics case for axions and ALPs: Cold dark matter

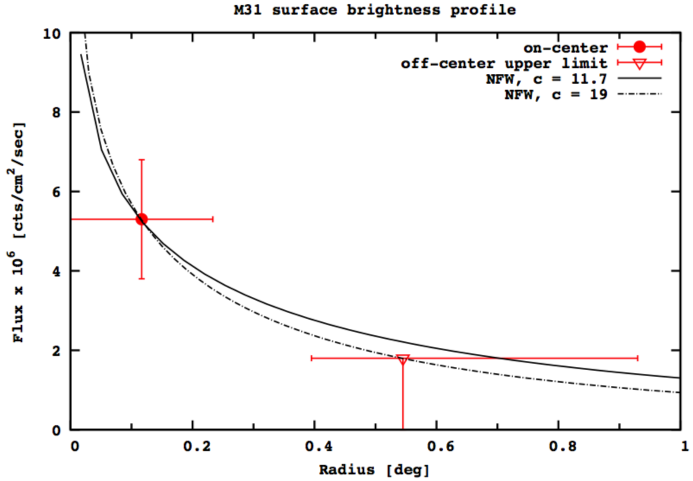
- Unidentified 3.55 keV line from galaxy clusters and from Andromeda and Perseus recently found [Bulbul et al. 1402.2301, Boyarski et al.1402.4119]



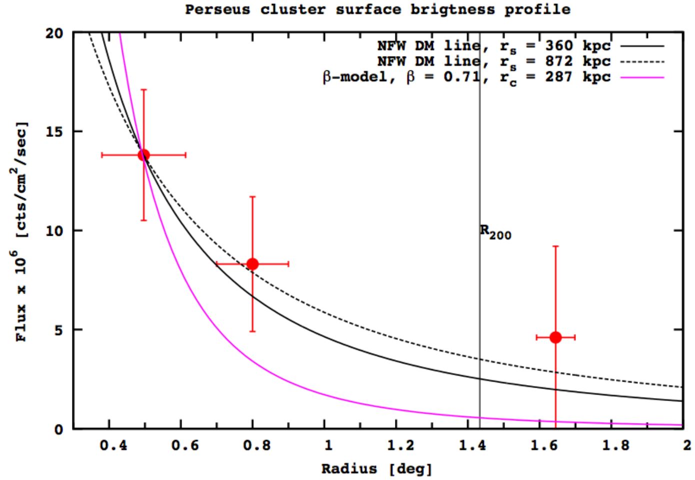




- Brightness profile compatible with decaying dark matter

M31 surface brightness profile




Perseus cluster surface brigtness profile



# Physics case for axions and ALPs: Cold dark matter

- 3.55 keV line may be identified with line from two photon decay of 7.1 keV mass ALP CDM
[Higaki,Jeong,Takahashi 1402.6965; Jaeckel,Redondo,AR 1402.7335]

  - For $x_\phi = \rho_\phi/\rho_{\rm DM}$, required life-time

$$\tau_\phi = \frac{64\pi}{g_{\phi\gamma\gamma}^2 m_\phi^3} = x_\phi \times (4\times 10^{27} - 4\times 10^{28})\,{\rm s}$$

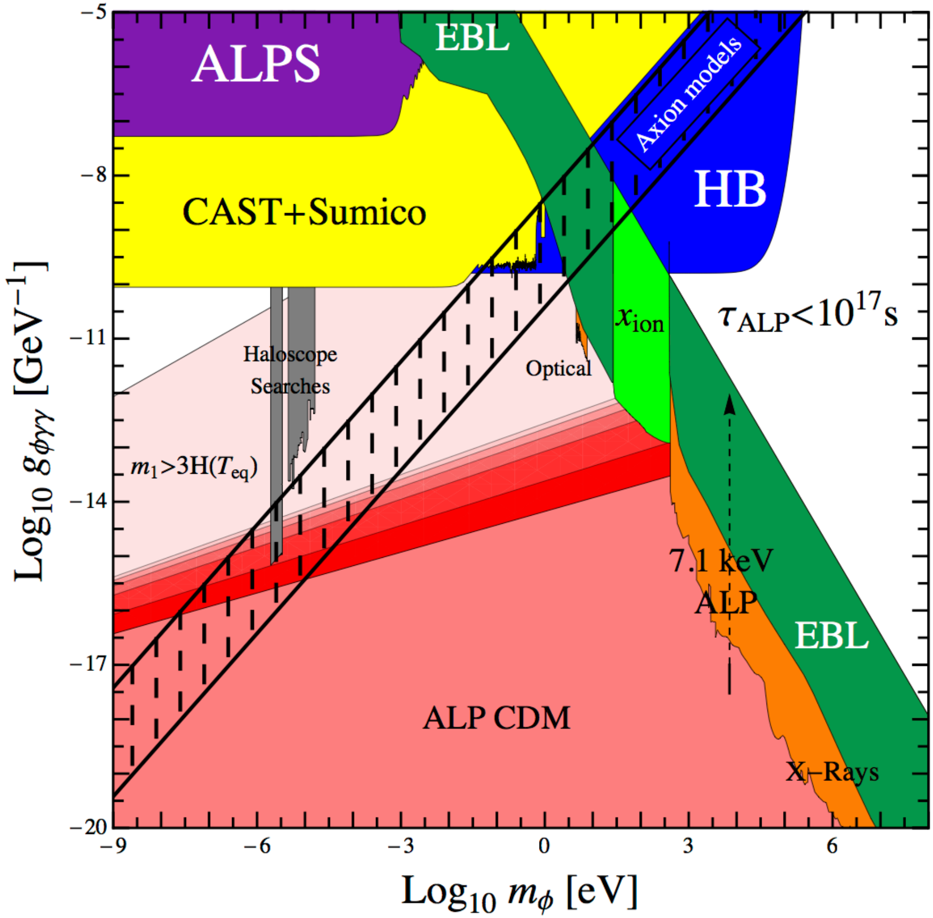
  - Thus required coupling and scale

$$g_{\phi\gamma\gamma} \sim (3\times 10^{-18} - 10^{-12})\,{\rm GeV}^{-1}$$

$$f_\phi \sim (10^9 - 4\times 10^{14})\,{\rm GeV}$$

if one allows $x_\phi$ to be in the range

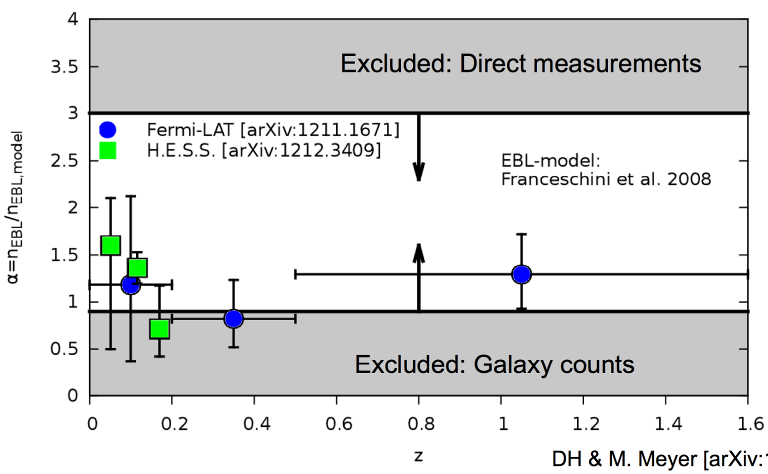
$$x_\phi \sim 10^{-10} - 1$$



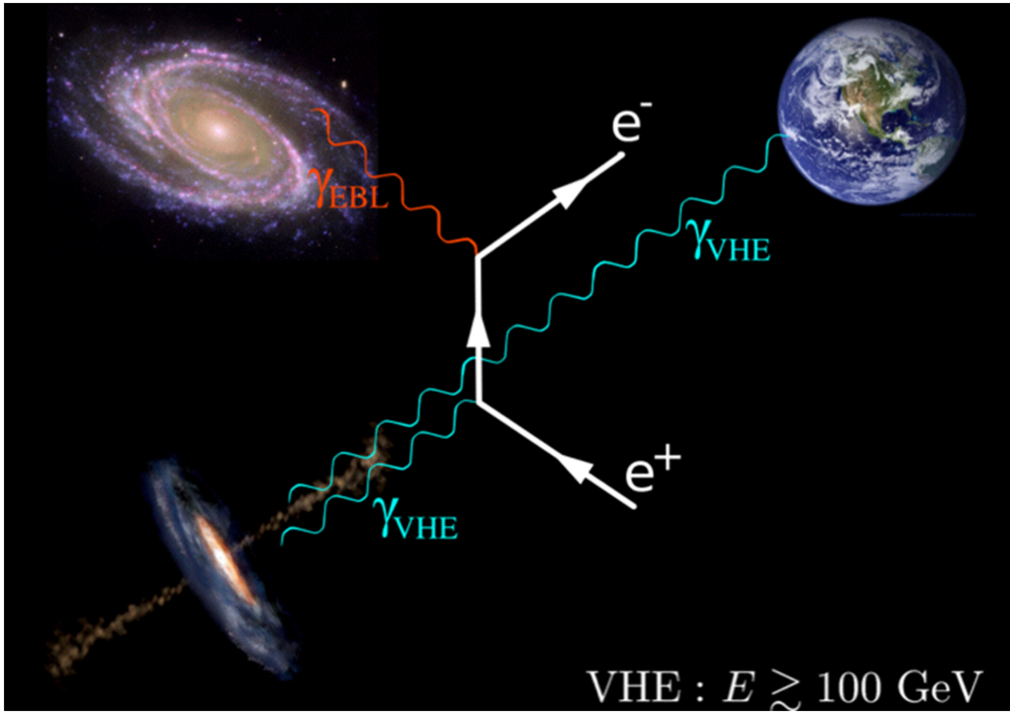

adapted from [Arias et al. 12]

# Physics case for ALPs: Gamma transparency of universe

- 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.




DH & M. Meyer [arXiv:1309.3846]




[Manuel Meyer 12]

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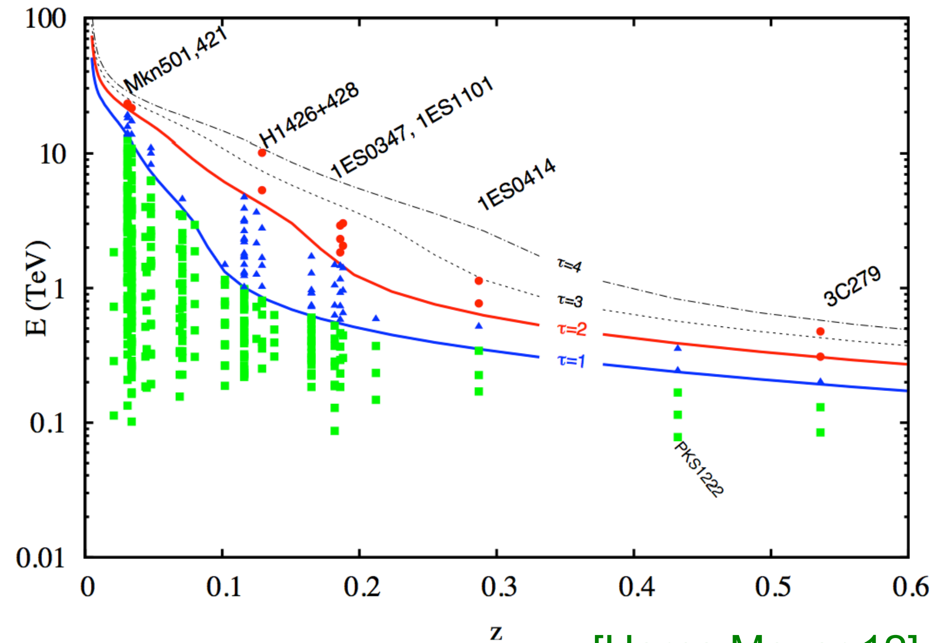
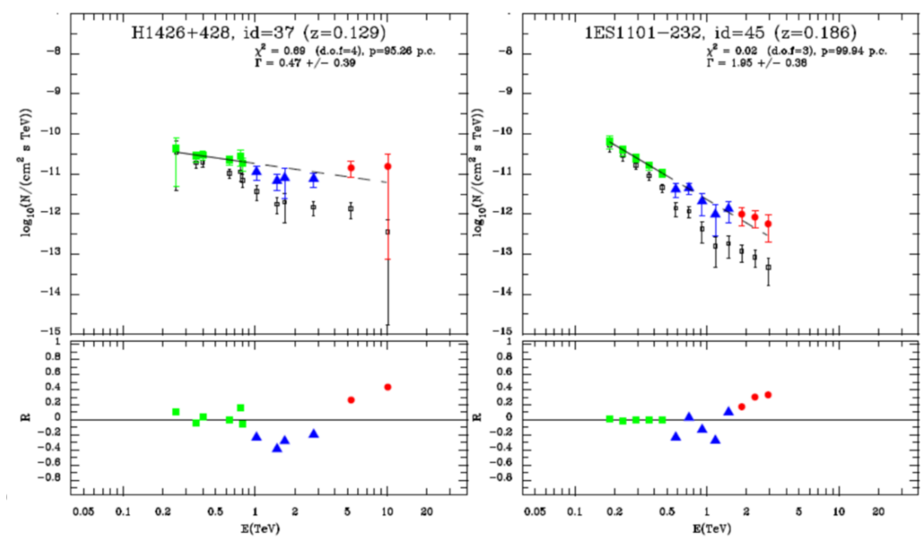
- At $\tau \gtrsim 2$, however, hints for anomalous gamma transparency, from IACT and Fermi-LAT data
  [Aharonian et al. 07; Aliu et al. 08;...;Horns,Meyer 12;...]




[Horns,Meyer 12]



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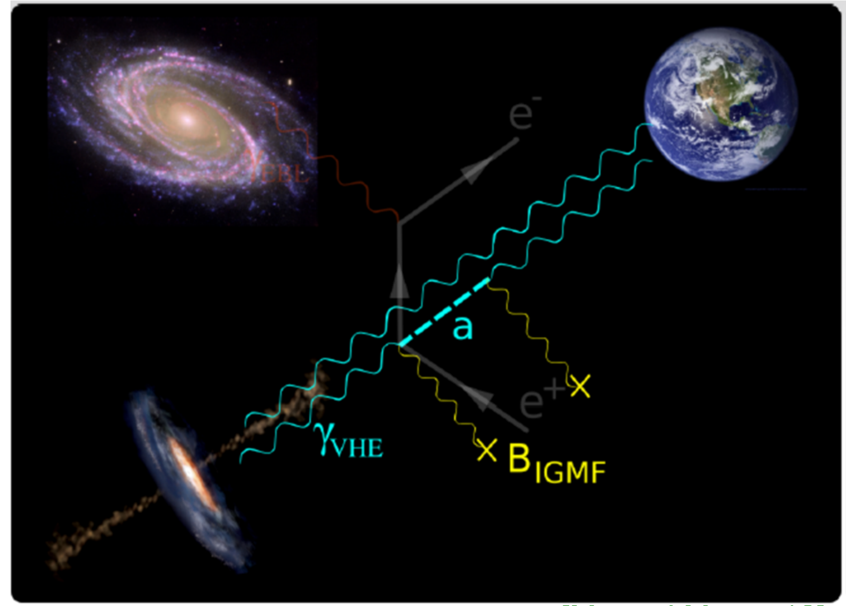
- Possible explanation: photon <-> ALP conversions in magnetic fields [De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer,Horns,Raue 13]

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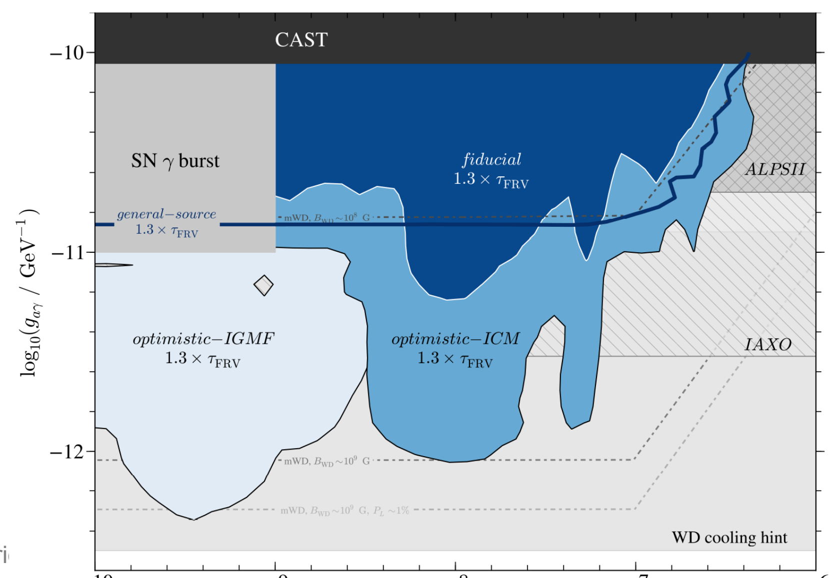



[Meyer,Horns,Raue 13]

# Physics case for ALPs: Cosmic ALP background radiation

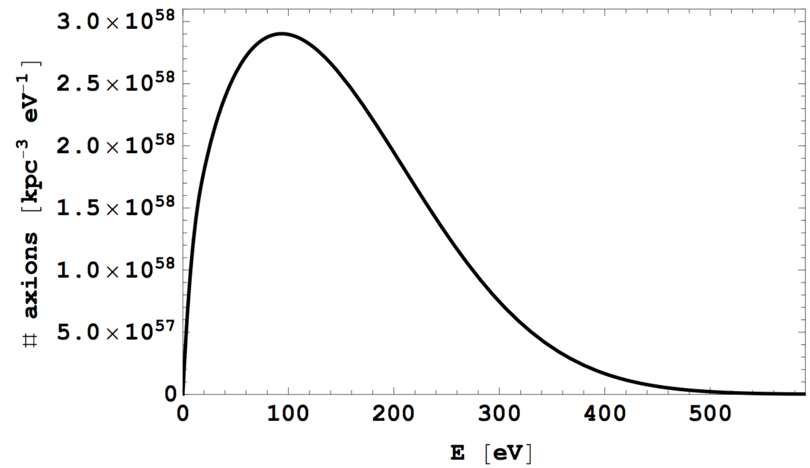
- Hints of dark radiation ($\Delta N_{\rm eff}$)in CMB
- Dark radiation comprised by ALPs may be generated by modulus (scalar partner of pseudoscalar ALP) decay. Spectrum peaked at around 100 eV, for modulus mass $\sim 10^6\,{\rm GeV}$

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

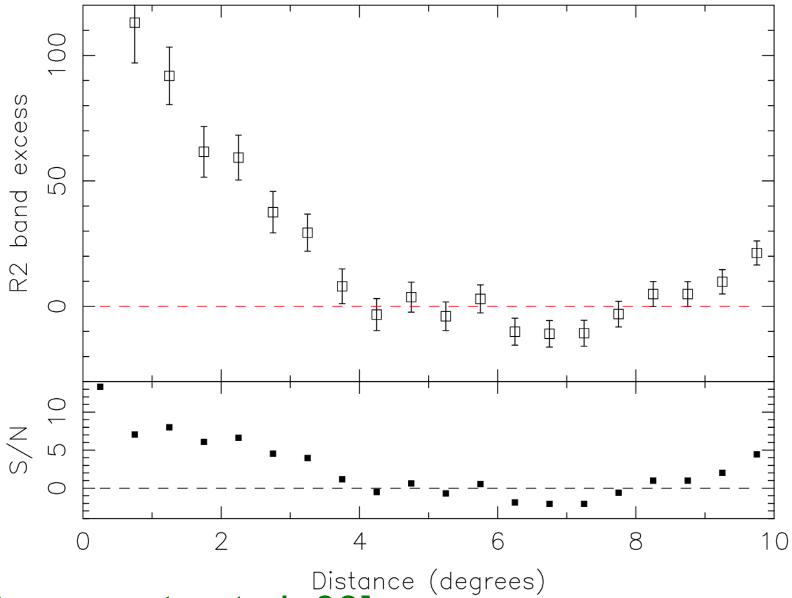
- ALP conversion to photon in magnetic fields of galaxy clusters, e.g. Coma, may explain observed soft X-ray excess if [Marsh,Conlon 13; Angus et al. 13]

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

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



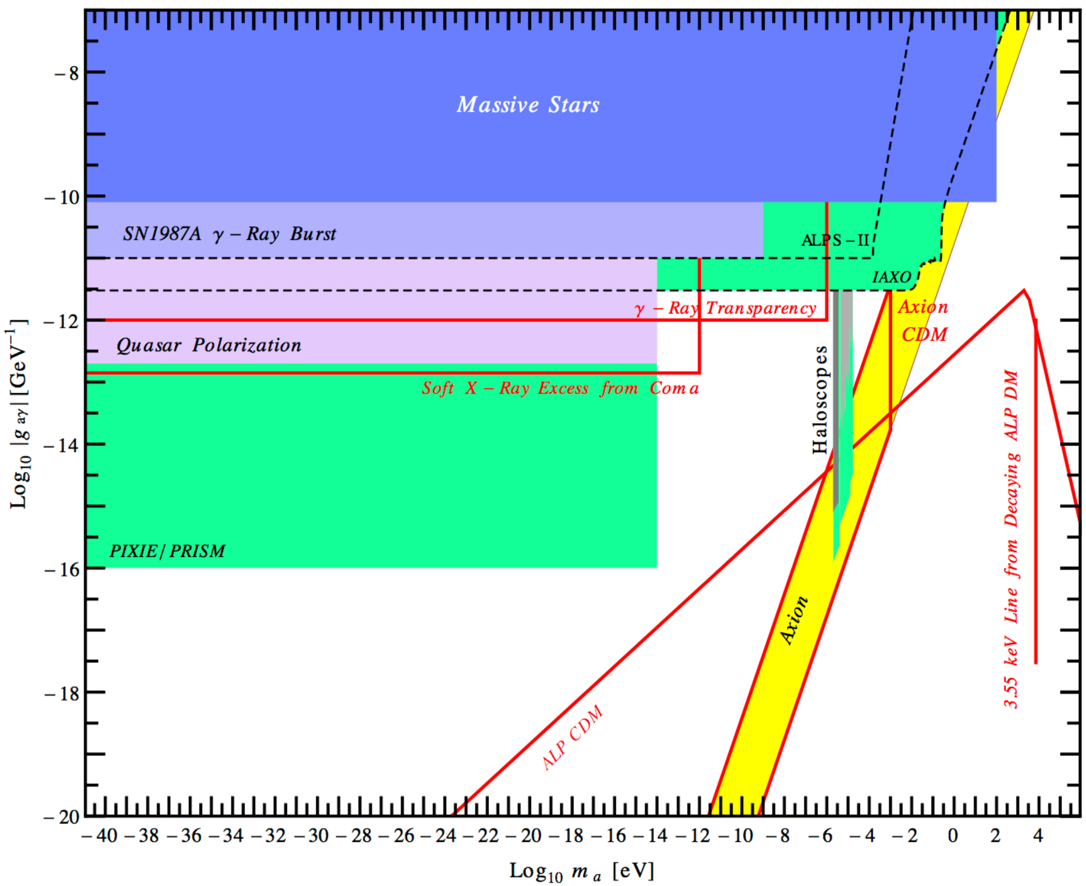

[Angus et al. 13]




[Bonamente et al. 09]

# Physics case for axions and ALPs: Parameters of interest

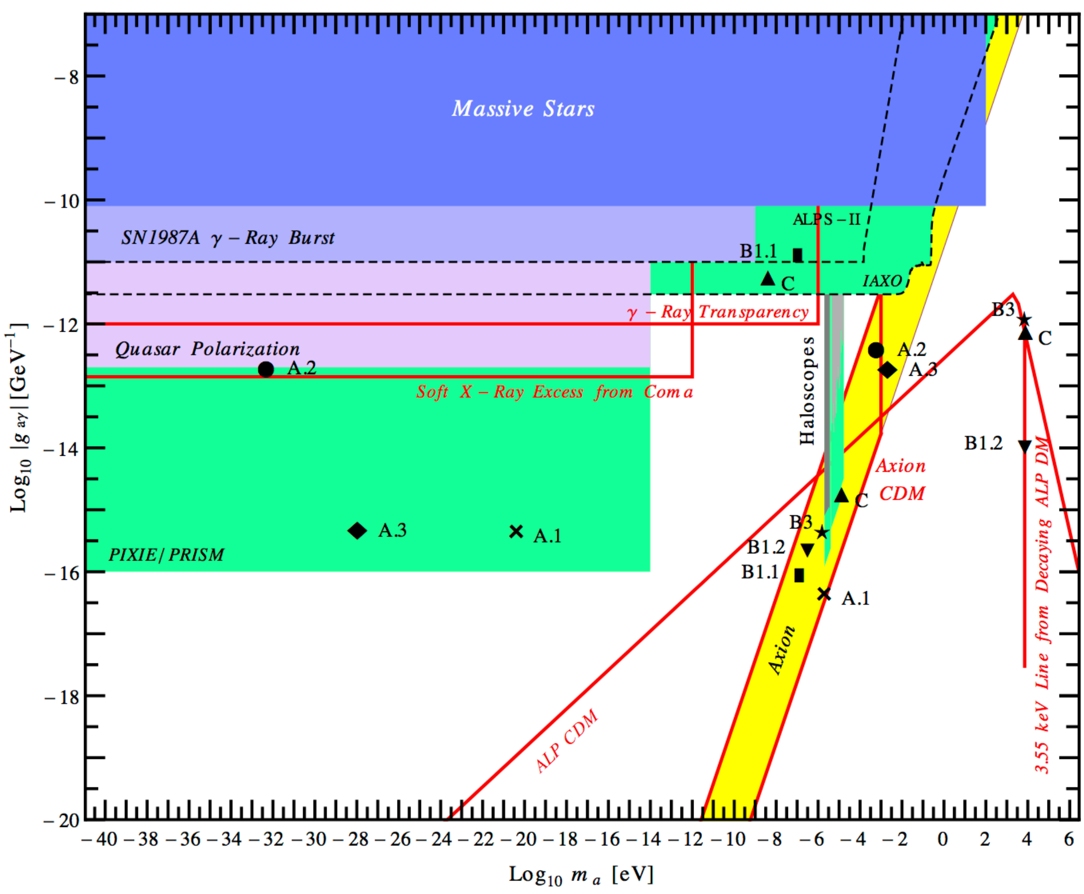
- Strong theoretical, astrophysical, and cosmological motivations for axion and ALPs with intermediate PQ scales




[Dias,Machado,Nishi,AR,Vaudrevange in prep.]

# Physics case for axions and ALPs: Parameters of interest

- Strong theoretical, astrophysical, and cosmological motivations for axion and ALPs with intermediate PQ scales
- UV extensions of SM featuring several accidental PQ symmetries yield axion and ALPs in favored regions of parameter space for intermediate PQ scale
- Part of favored regions can be explored in foreseeable future with haloscopes, e.g. ADMX, light-shining-through-a-wall, e.g. ALPS-II, and helioscopes, e.g. CAST and IAXO

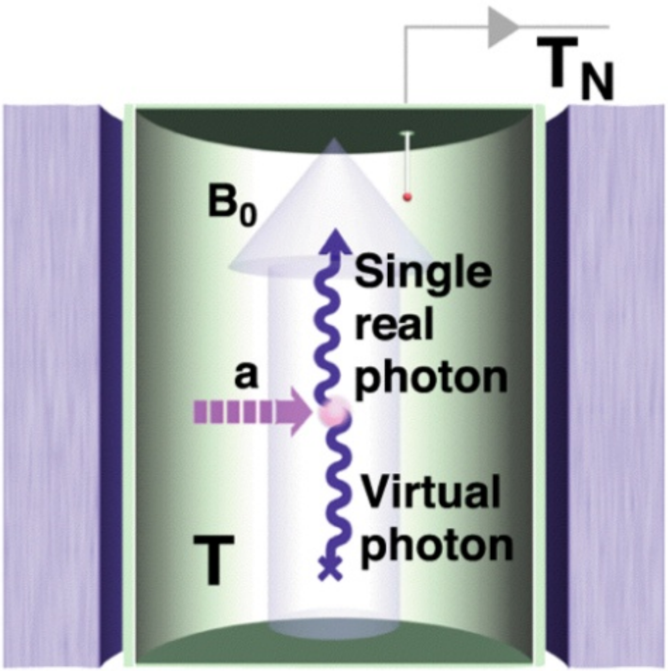



[Dias,Machado,Nishi,AR,Vaudrevange in prep.]

# Haloscope searches: Resonant cavities

> Resonant axion or ALP DM – photon conversion in microwave cavity placed in magnetic field

- Ongoing: ADMX at University of Washington, Seattle, exploiting high Q cavity in 8 T superconducting solenoid; scan starts at 1 GHz towards higher frequencies
- Pilot study: WISPDMX at DESY, Hamburg, exploiting high Q HERA p acceleration ca-vity and H1 solenoid (1.1 T); scan starts at 208 MHz towards higher frequencies

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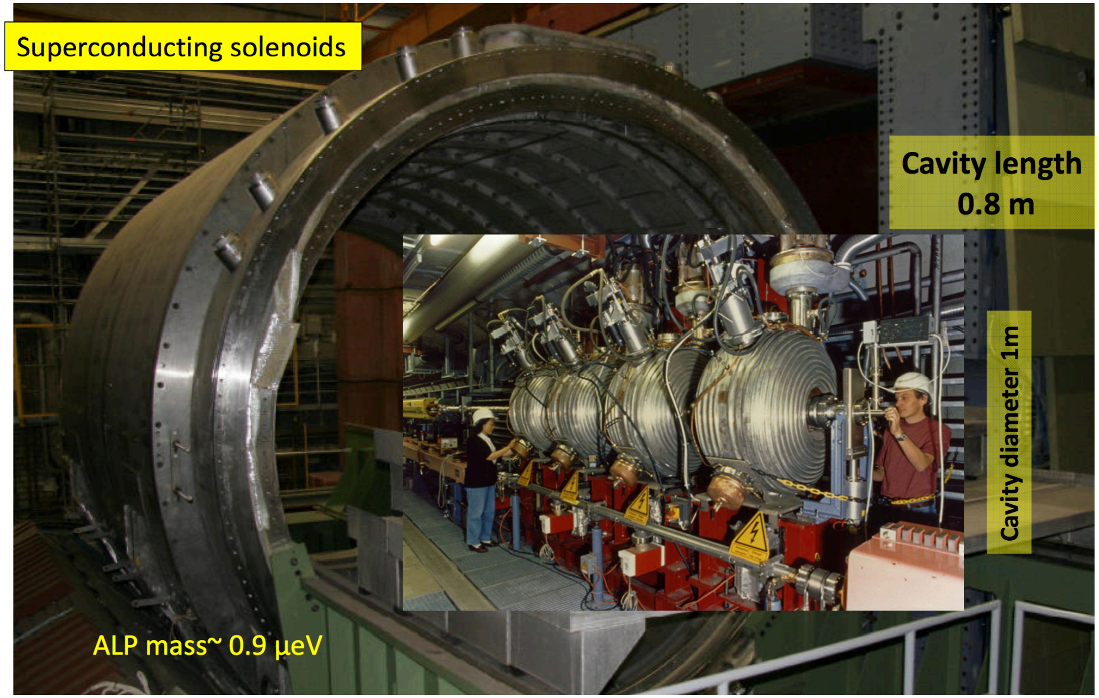

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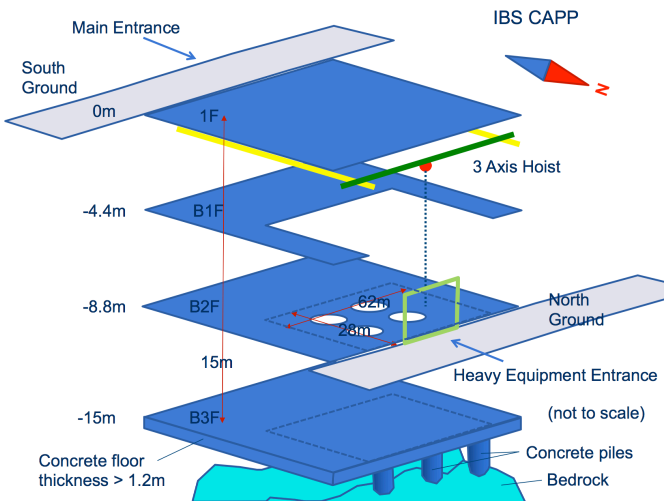
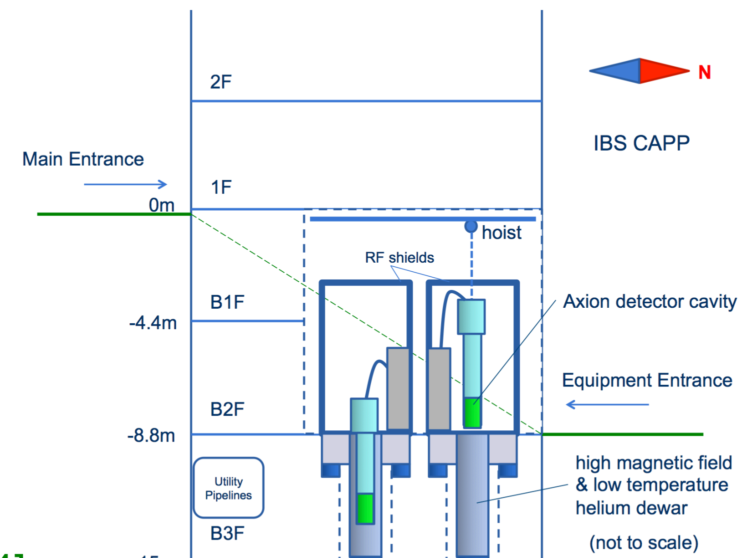
- New Center for Axion and Precision Physics (CAPP) at KAIST (Korea): started R&D towards 25-35 T superconducting solenoids based on high Tc cables (5y, 10M$); aim probing 1-100 micro-eV range



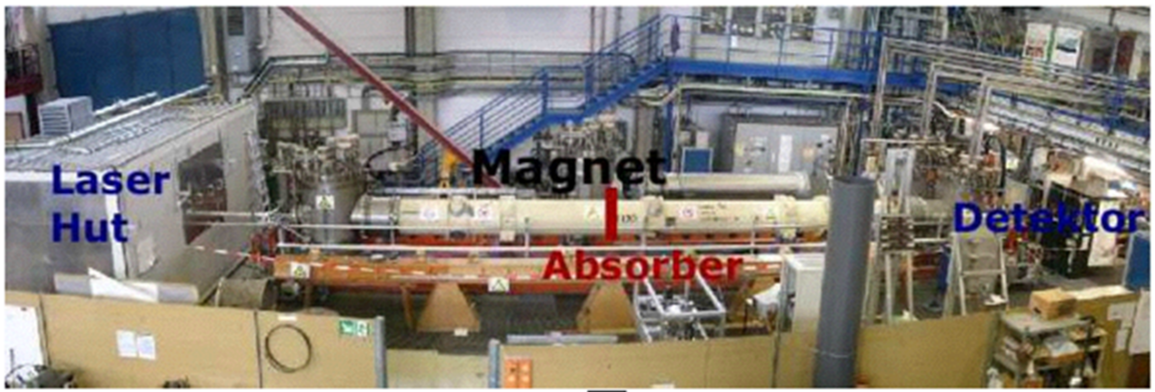




[Semertzidis talk at DESY 02/14]

# Light-shining-through-a-wall searches

> Most sensitive until now: Any Light Particle Search I (ALPS-I) at DESY

- One superconducting HERA dipole (5 T)
- 1.2 kW cw green (2.3 eV) laser
- CCD camera



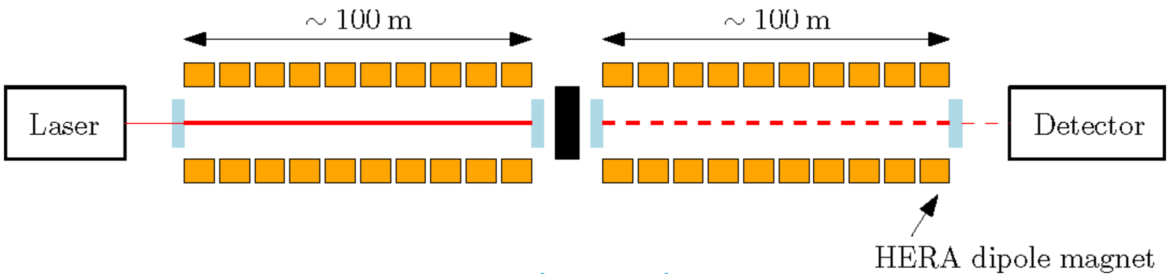


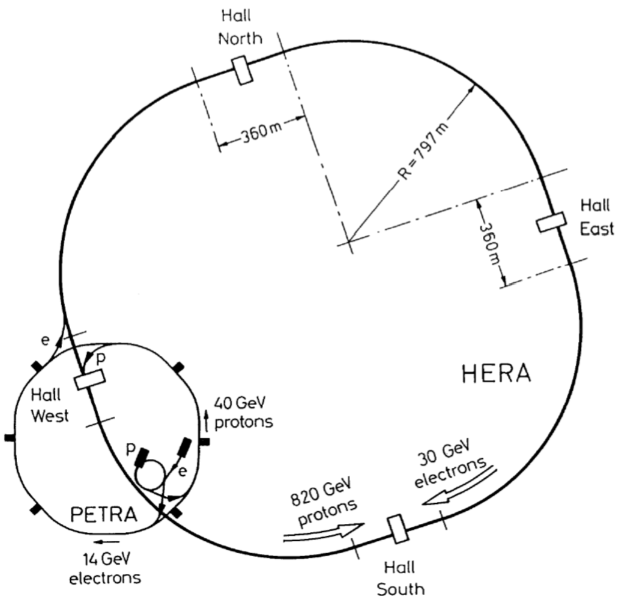
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

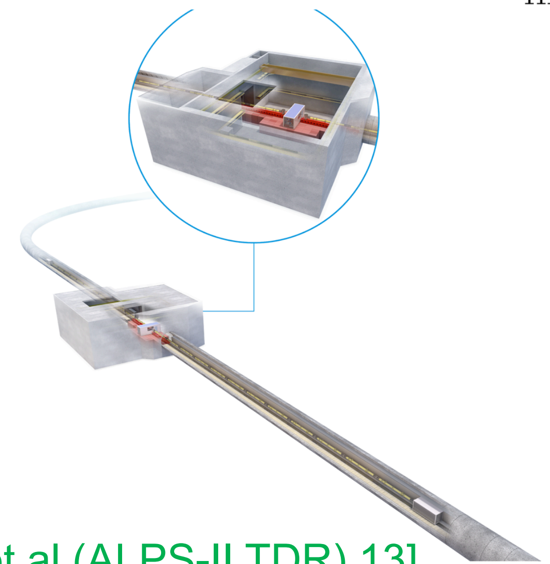
# Light-shining-through-a-wall searches

> Presently being set up: ALPS-II at DESY (data taking planned for 2017)

- 10 + 10 superconducting HERA dipoles
- 150 kW infrared (1.17 eV) laser light stored before wall; resonant regeneration behind wall
- Transition Edge Sensor



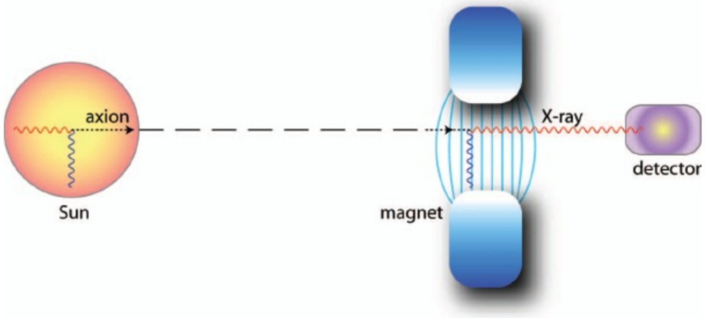



[Bähre et al (ALPS-II TDR) 13]

# Helioscope searches

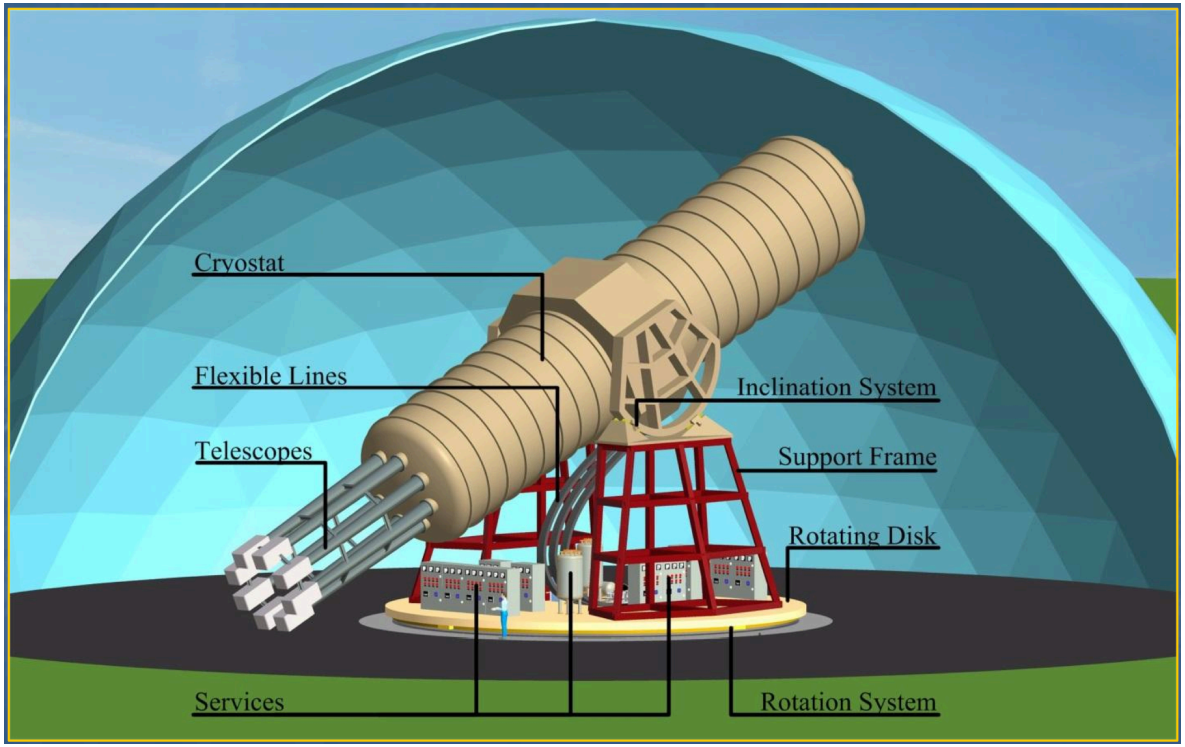
- Most sensitive until now: CERN Axion Solar Telescope (CAST)
  - Superconducting LHC dipole magnet
  - X-ray detectors

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



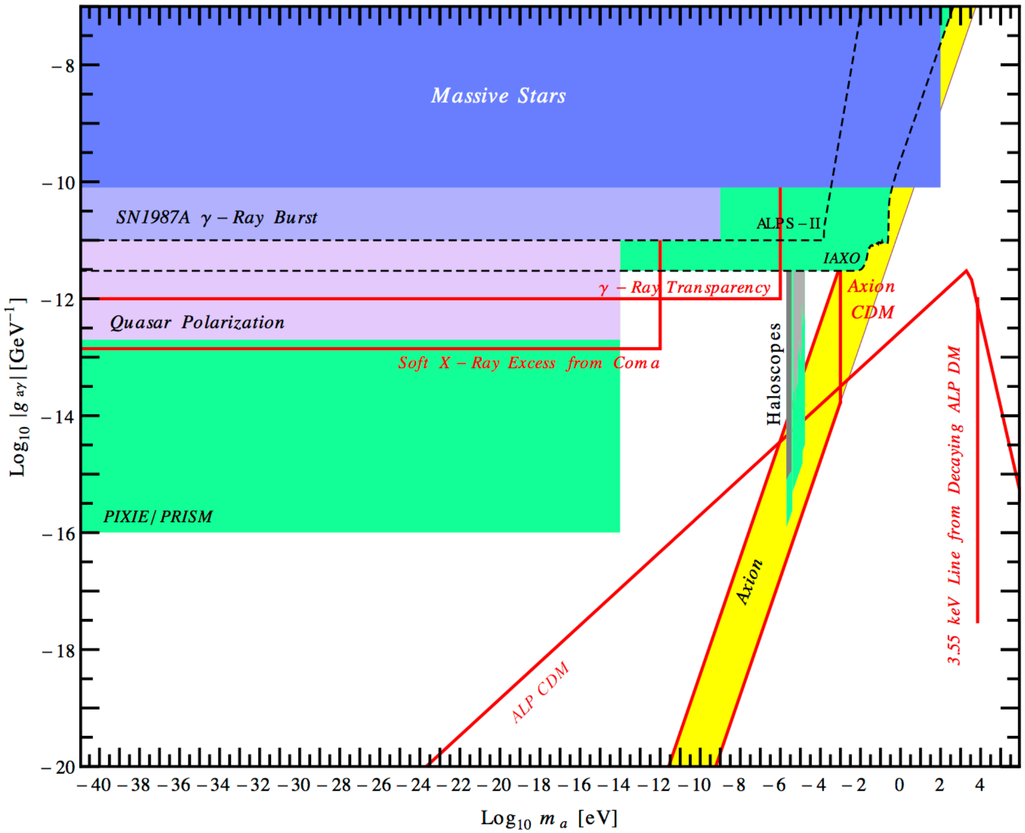

# Helioscope searches

- Proposed successor: International Axion Observatory (IAXO)
  - Dedicated superconducting toroidal magnet with much bigger aperture than CAST
  - Extensive use of X-ray optics
  - Low background X-ray detectors




[Armengaud et al (IAXO CDR) 1401.3233]

# Projected sensitivities for axions and ALPs




> New ideas to cover some persistent holes in favored parameter space have been proposed recently, e,g. for axion/ALP DM at higher mass:

- Horns et al., “Searching for WISPy cold dark matter with a dish antenna”, 1212.2970
- Rybka,Wagner, “A Technique to Search for High Mass Dark Matter Axions”, 1403.3121

# Summary

- Strong physics case for 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!