Case for Axion-Like Particles and their Terrestrial Searches.

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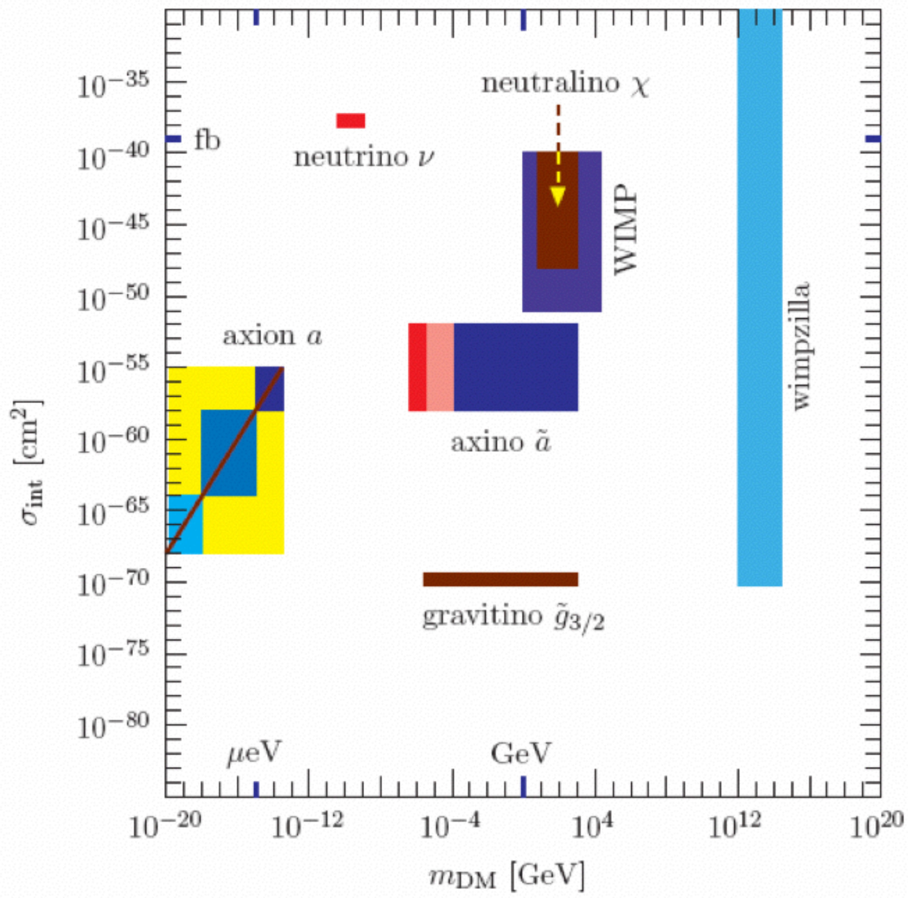
DESY

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
- Plan:
  - Physics case for axions and axion-like particles (ALPs)
  - Terrestrial probes of axions and ALPs



[Kim,Carosi `10]

Physics case for the axion: Strong CP problem

- Most general gauge invariant Lagrangian of QCD up to dimension four:

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\,q - \frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

  - Fundamental parameters of QCD: strong coupling α_s, quark masses m_u, m_d, ..., and theta parameter

$$\overline{\theta} = \theta + \arg\,\det\,\mathcal{M}_q$$

- 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 (EDM) of neutron; experimentally

$$|d_n| < 2.9 \times 10^{-26}\ e\,\mathrm{cm}$$

- Strong CP problem:

$$d_n(\overline{\theta}) \sim \frac{e\overline{\theta} m_u m_d}{(m_u + m_d) m_n^2} \sim 6 \times 10^{-17}\ \overline{\theta}\ e\,\mathrm{cm} \Rightarrow |\overline{\theta}| \lesssim 10^{-9}$$

Physics case for the axion: Strong CP problem

> Peccei-Quinn (PQ) solution of strong CP problem based on observation that the vacuum energy in QCD, inferred from chiral QCD Lagrangian,

$$V(\bar\theta) = \frac{m_\pi^2 f_\pi^2}{2} \frac{m_u m_d}{(m_u + m_d)^2} \bar\theta^2 + \mathcal{O}(\bar\theta^4)$$

has localised minimum at vanishing theta parameter:

If theta were a dynamical field, its vacuum expectation value (vev) would be zero

> Introduce field A(x) as Nambu-Goldstone field arising from the breaking of a global chiral $U(1)_{\rm PQ}$ symmetry featuring a $U(1)_{\rm PQ} \times SU(3)_C \times SU(3)_C$ anomaly. Correspondingly,

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \left(\bar\theta + \frac{A}{f_A}\right) G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

- Can eliminate theta by shift $A(x) \to A(x) - \bar\theta f_A$; QCD dynamics (see above) leads then to vanishing vev, $< A >= 0$, i.e. P, T, and CP conserved
- Particle excitation of A: "Axion" [Weinberg 78; Wilczek 78]
- Mass from mixing with pion: $m_A \sim \frac{m_\pi f_\pi}{f_A} \sim {\rm meV} \times \left(\frac{10^9\,{\rm GeV}}{f_A}\right)$
- Couplings, e.g. $\mathcal{L} \supset -\frac{g_{A\gamma}}{4} A\, F_{\mu\nu}\tilde{F}^{\mu\nu}$, suppressed by f_A, e.g. $g_{A\gamma} \sim \frac{\alpha}{2\pi f_A} \sim 10^{-12}\ {\rm GeV}^{-1} \left(\frac{10^9\,{\rm GeV}}{f_A}\right)$
- For large f_A, ultralight and very weakly interacting [Kim 79; Shifman et al 80; Zhitnitsky 80; Dine et al 81]

Physics case for axion-like particles

> Breaking of other global symmetries lead to additional axion-like particles emerging as Nambu-Goldstone bosons:

- Majoron from breaking of global lepton number symmetry [Chikashige et al. 78]
  - High symmetry breaking scale $f_L \simeq v_L$ explains small active neutrino mass

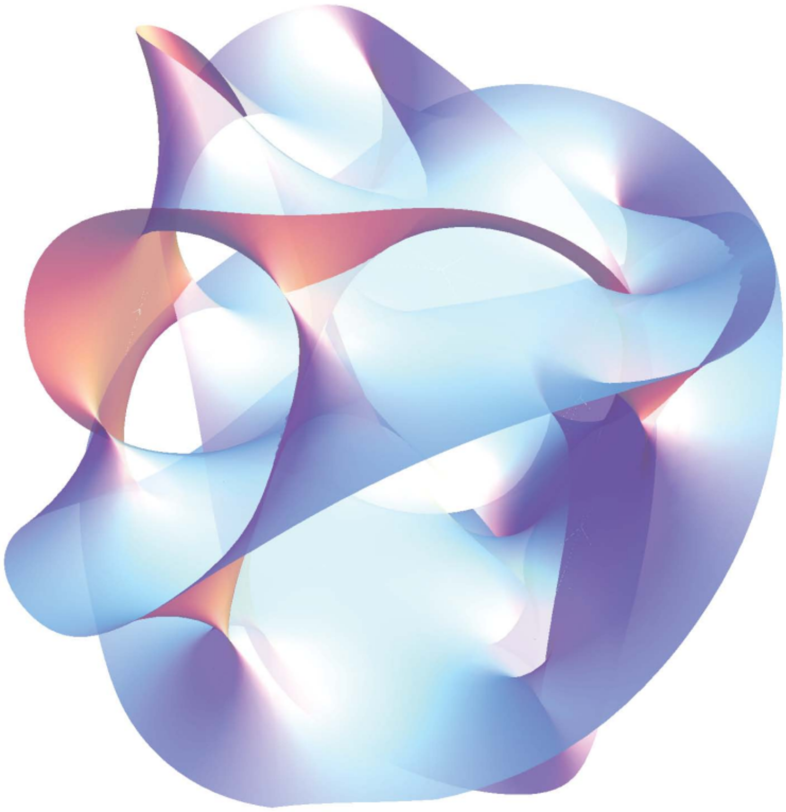
$$m_\nu = -M_D M_M^{-1} M_D^T = -y_D\, y_M^{-1}\, y_D^T\, \frac{v^2}{v_L} = 0.06\,\mathrm{eV} \left(\frac{10^{13}\,\mathrm{GeV}}{v_L}\right) \left(\frac{-y_D\, y_M^{-1}\, y_D^T}{10^{-2}}\right)$$

- Familon from breaking of family symmetry [Wilzcek 82; Berezhiani, Khlopov 90]

- Axion-like particles from string compactifications
  - Closed string axion-like particles
  - Axion-like particles from the breaking of accidental global U(1) symmetries

Physics case for ALPs: String compactifications

- 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} GeV,in the heterotic string case; typically lower, the intermediate scale, 10^{10} 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; Dias et al. in prep.]



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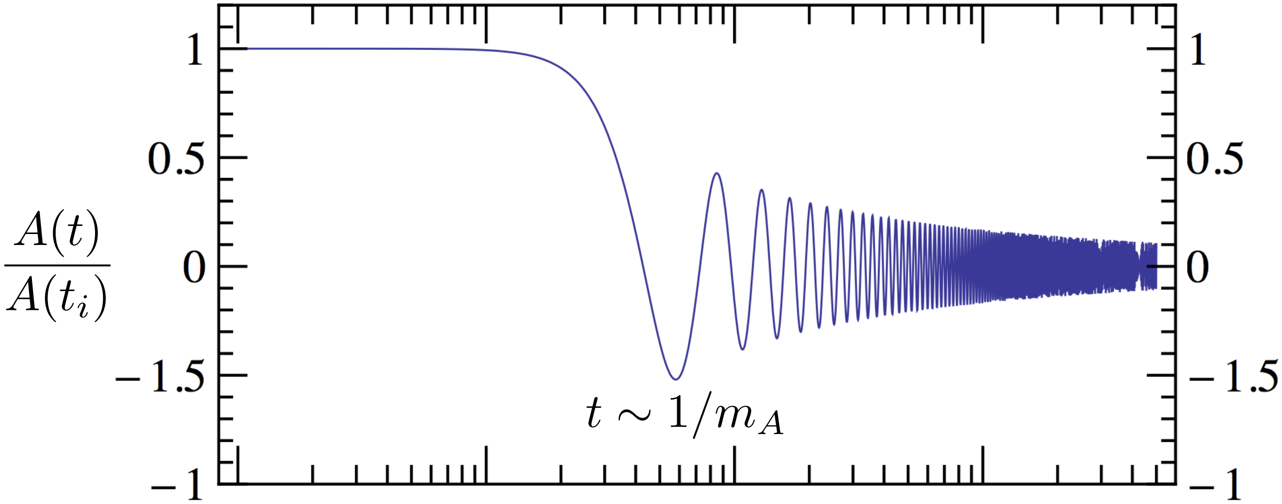
> Theoretically favored symmetry breaking scales for axion and ALPs

- Intermediate scale $f_I \sim \sqrt{v\, M_{\rm Pl}} \sim 10^{10}\,\text{GeV}$
- GUT scale $f_{\rm GUT} \sim 10^{16}\,\text{GeV}$

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 reheating temperature after inflation below f_A and no dilution by late decays of particles beyond SM,

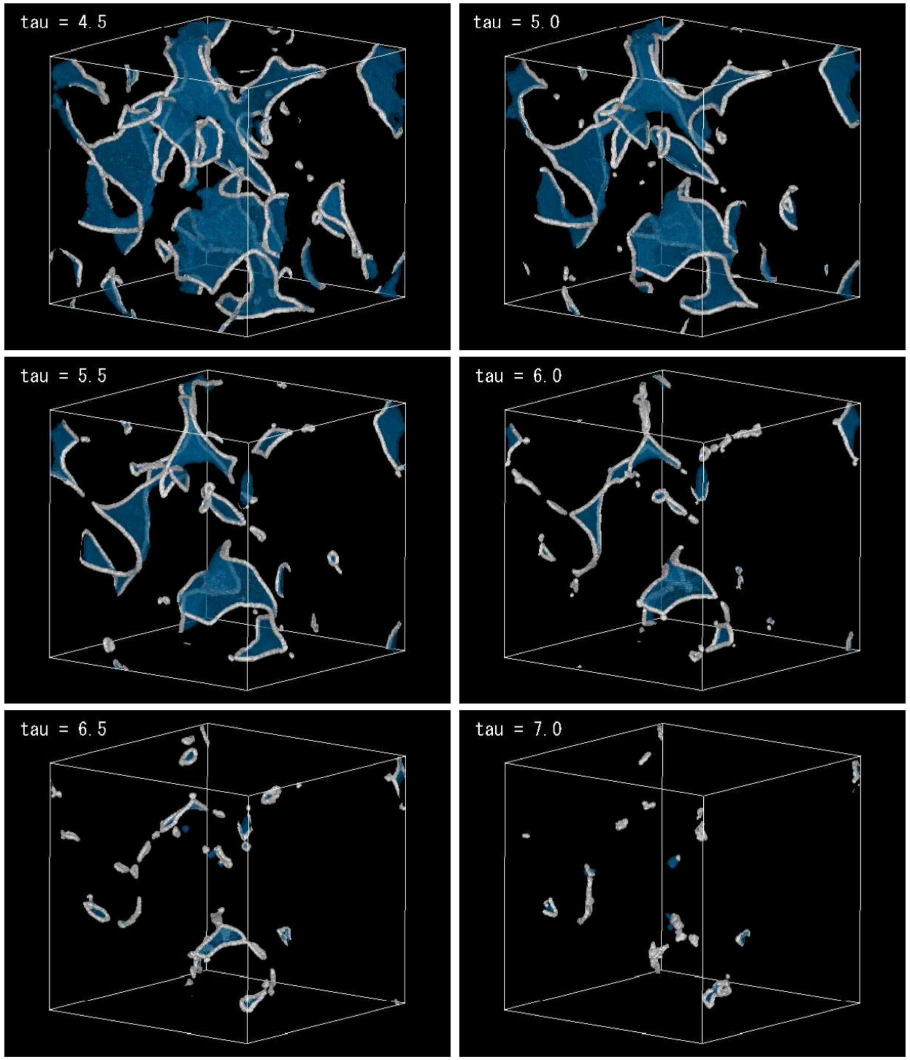
$$\Omega_A^{\rm vr} h^2 \approx 0.11 \left(\frac{f_A}{5 \times 10^{11}\ \text{GeV}} \right)^{1.184} F\,\bar{\Theta}_{\rm i}^2$$
$$= 0.11 \left(\frac{12\ \mu\text{eV}}{m_A} \right)^{1.184} F\,\bar{\Theta}_{\rm i}^2 ,$$

- If reheating temperature after inflation is above f_A, initial misalignment angles take on different values in different patches of universe,

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

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

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



[Hiramatsu et al. 12]

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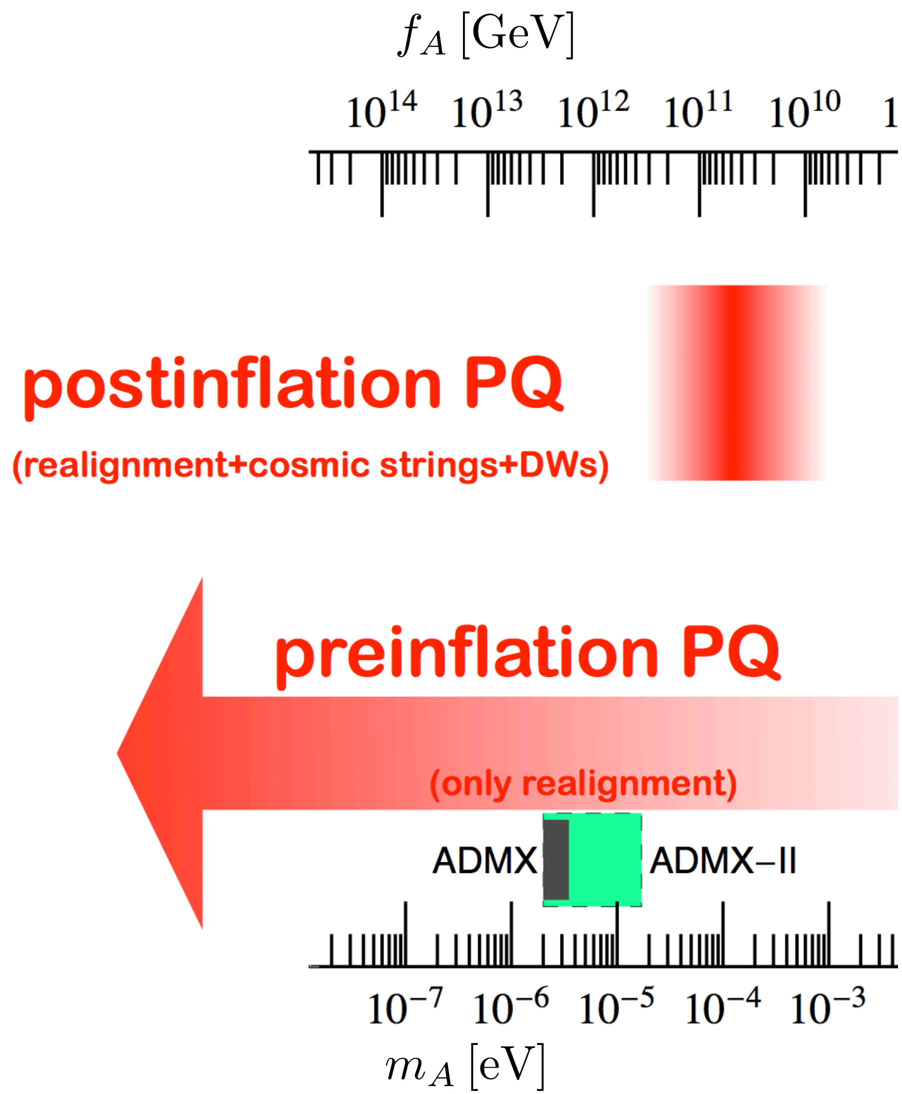


[adapted by from Essig et al. 1311.0029]

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]

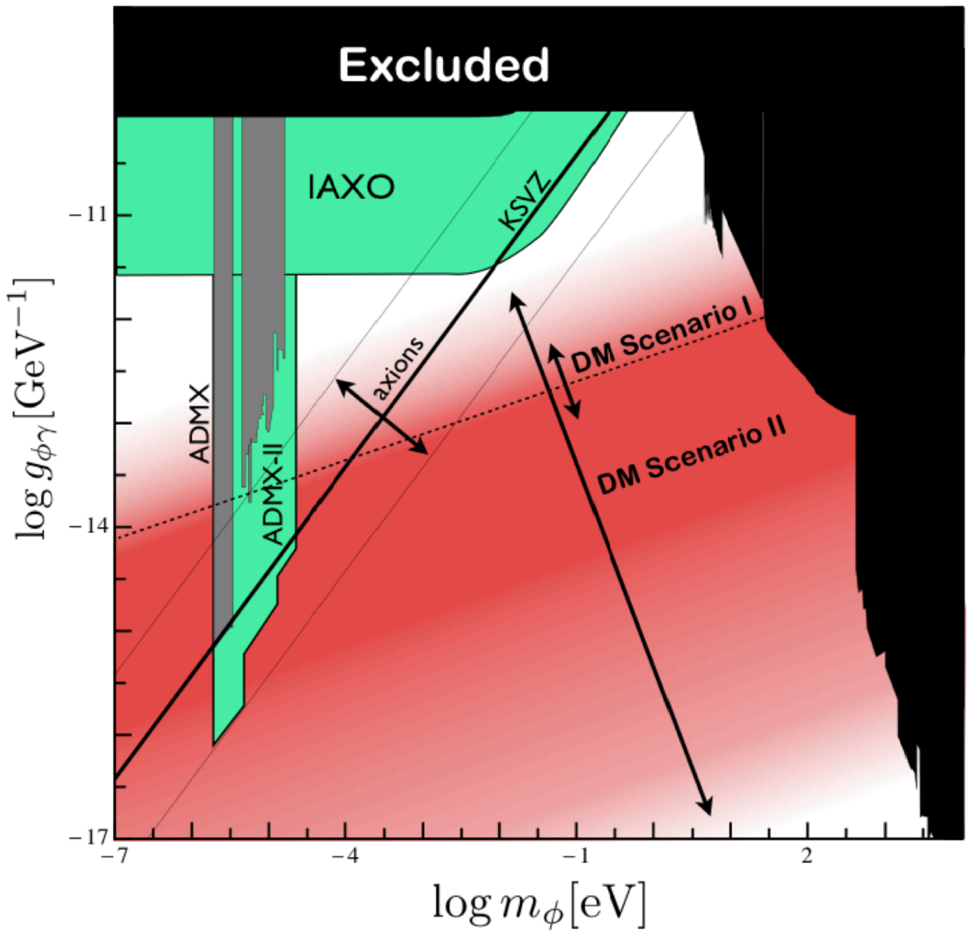
$$\Omega_a h^2 \approx 0.16 \left(\frac{m_a}{\text{eV}}\right)^{1/2} \left(\frac{f_a}{10^{11}\ \text{GeV}}\right)^2 \left(\frac{\theta_i}{\pi}\right)^2$$

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

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

(“intermediate scale”)

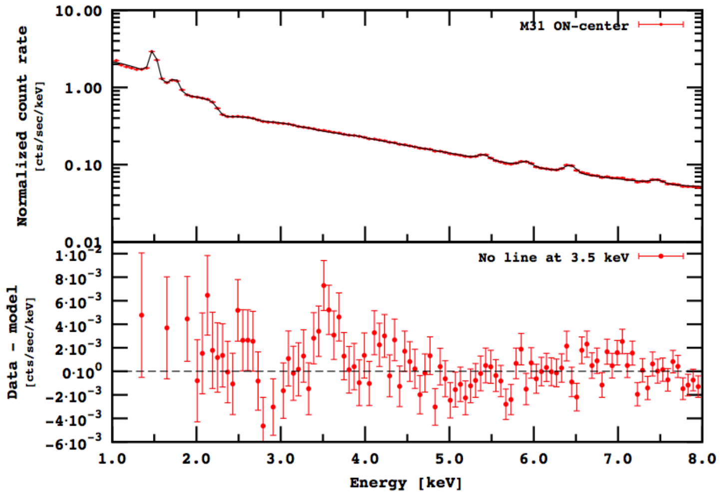
- Large search space for axion and ALP CDM in photon coupling $g_{i\gamma} \sim \alpha/(2\pi f_i)$ vs. mass

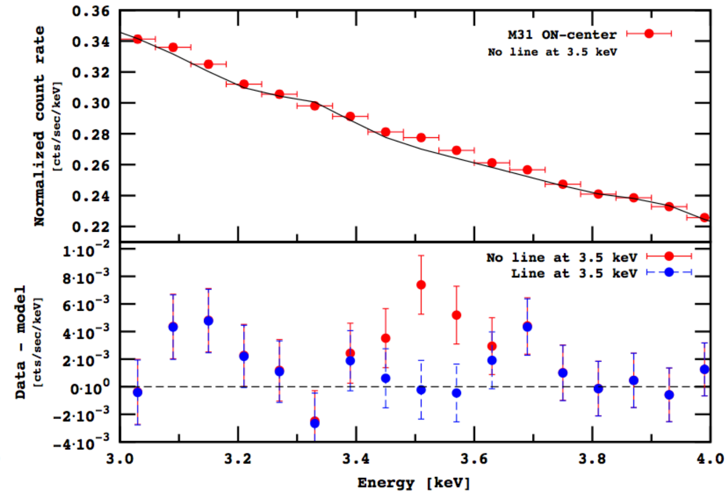


[Döbrich,Redondo 13]

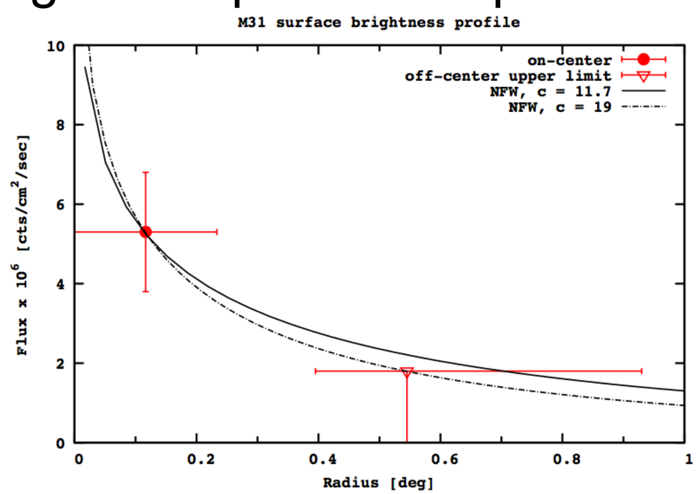
Physics case for axions and ALPs: Cold dark matter

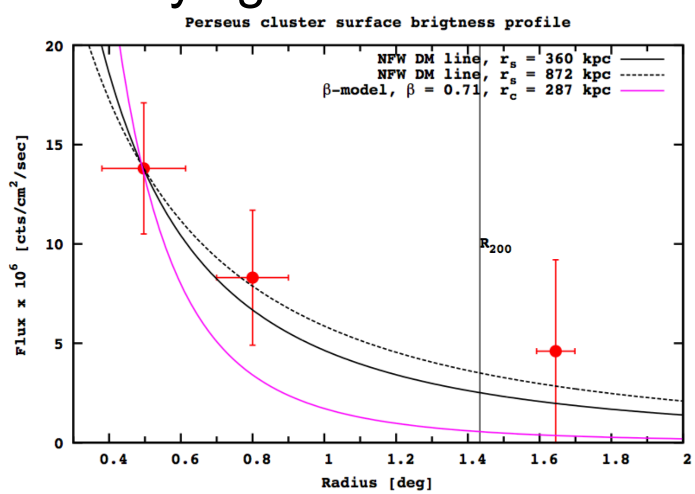
> Unidentified 3.55 keV line from galaxy clusters and from Andromeda recently found [Bulbul et al. 1402.2301, Boyarski et al. 1402.4119]





> Brightness profile compatible with decaying dark matter





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

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

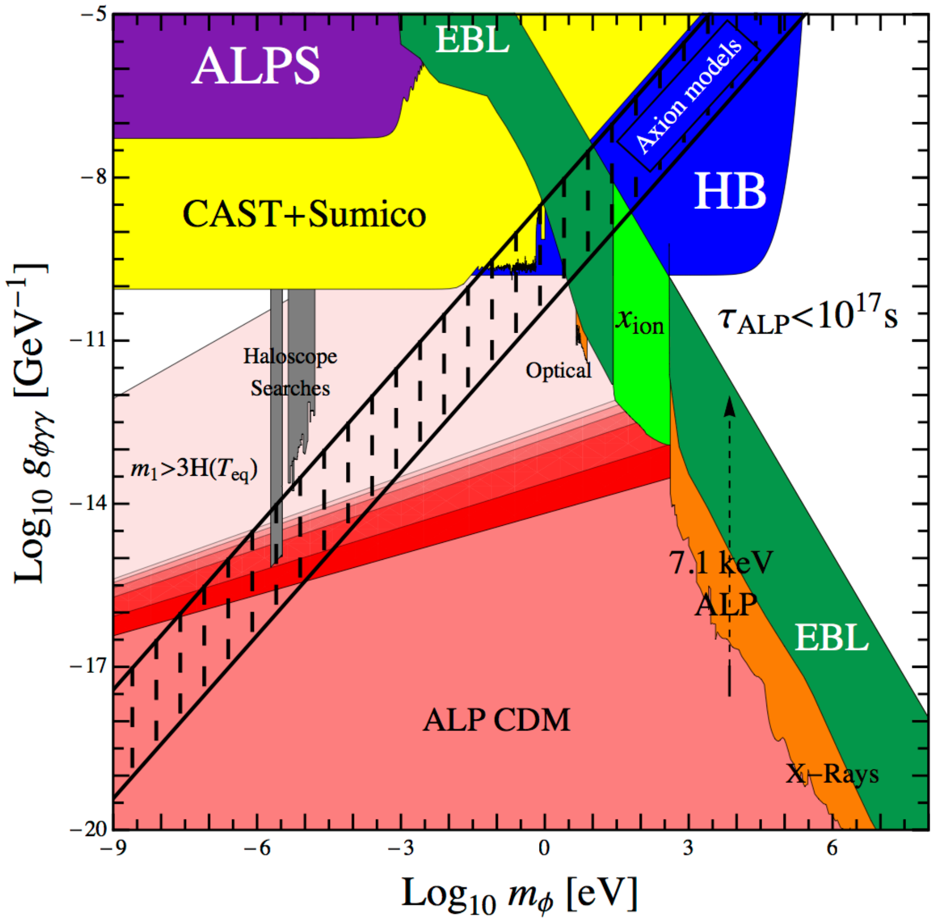
  - Thus required coupling and scale

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

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

if one allows x_ϕ to be in the range

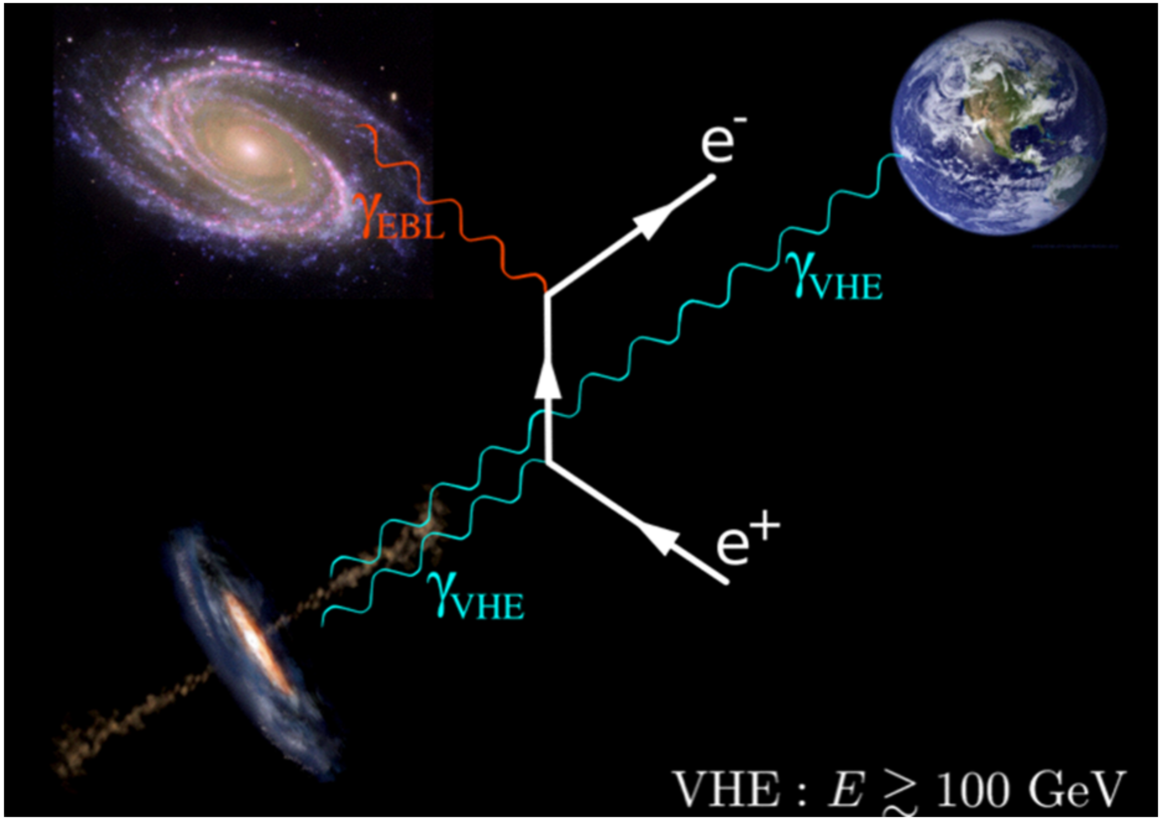
$$x_\phi \sim 10^{-10} - 1$$



adapted from [Arias et al. 12]

Physics case for ALPs: Gamma transparency of universe

- Gamma ray spectra from distant Active Galactic Nuclei (AGN) should show an energy and distance (red-shift) dependent exponential attenuation, $\propto \exp(-\tau(E,z)); \tau(E,z) = \int_0^z dz' \int d\epsilon' \ldots n_{\rm EBL}(\epsilon',z')\sigma_{\gamma\gamma}(E,\epsilon',\ldots)$, due to pair production at Extragalactic Background Light (EBL)



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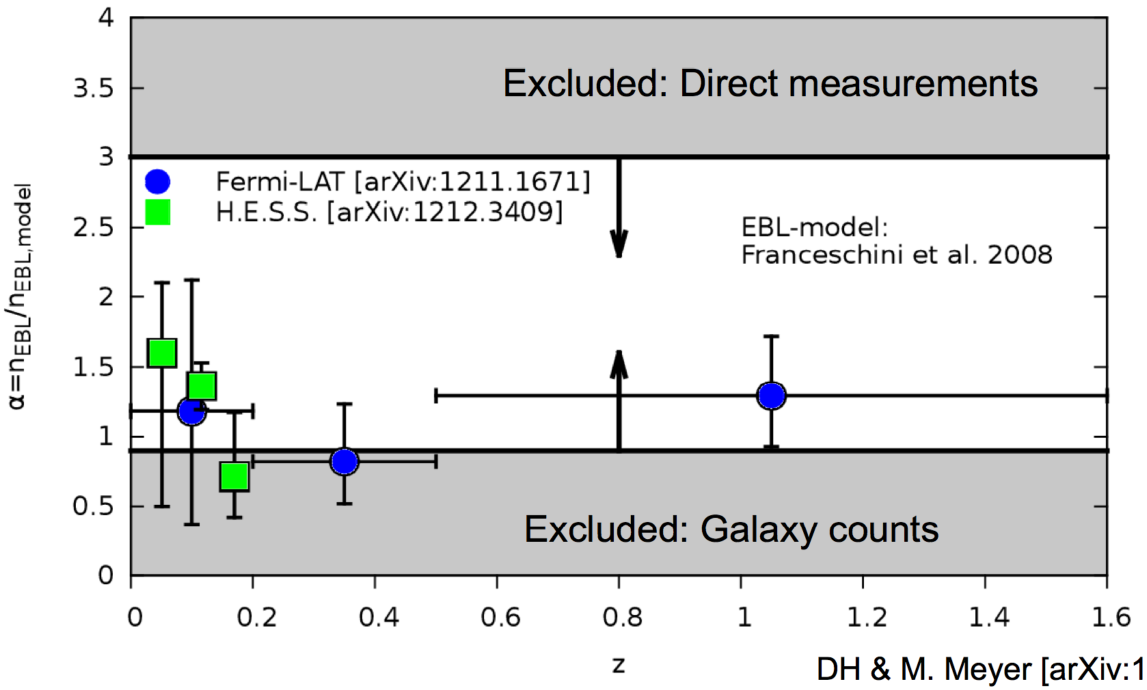
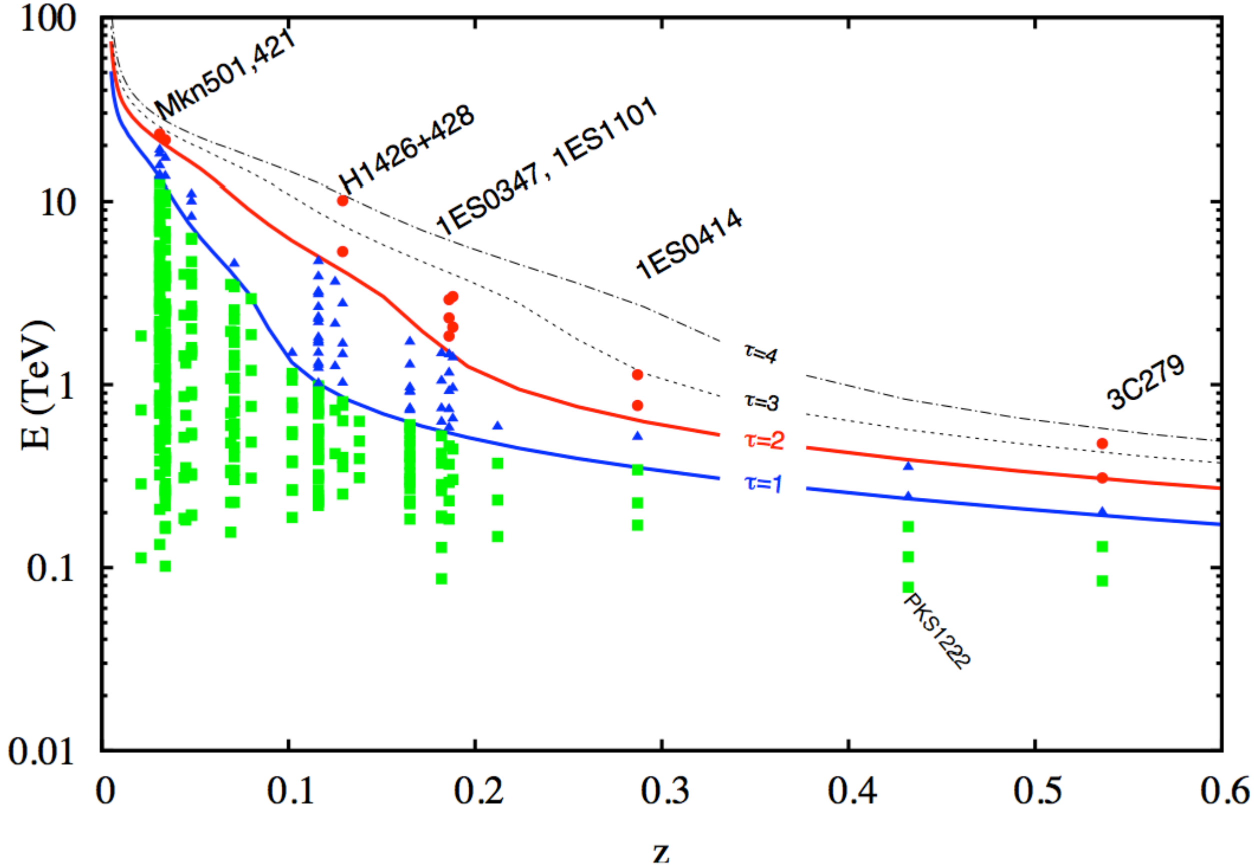
- Attenuation recently been observed by Fermi-LAT and H.E.S.S.



DH & M. Meyer [arXiv:1309.3846]

Physics case for ALPs: Gamma transparency of universe

- 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;...]



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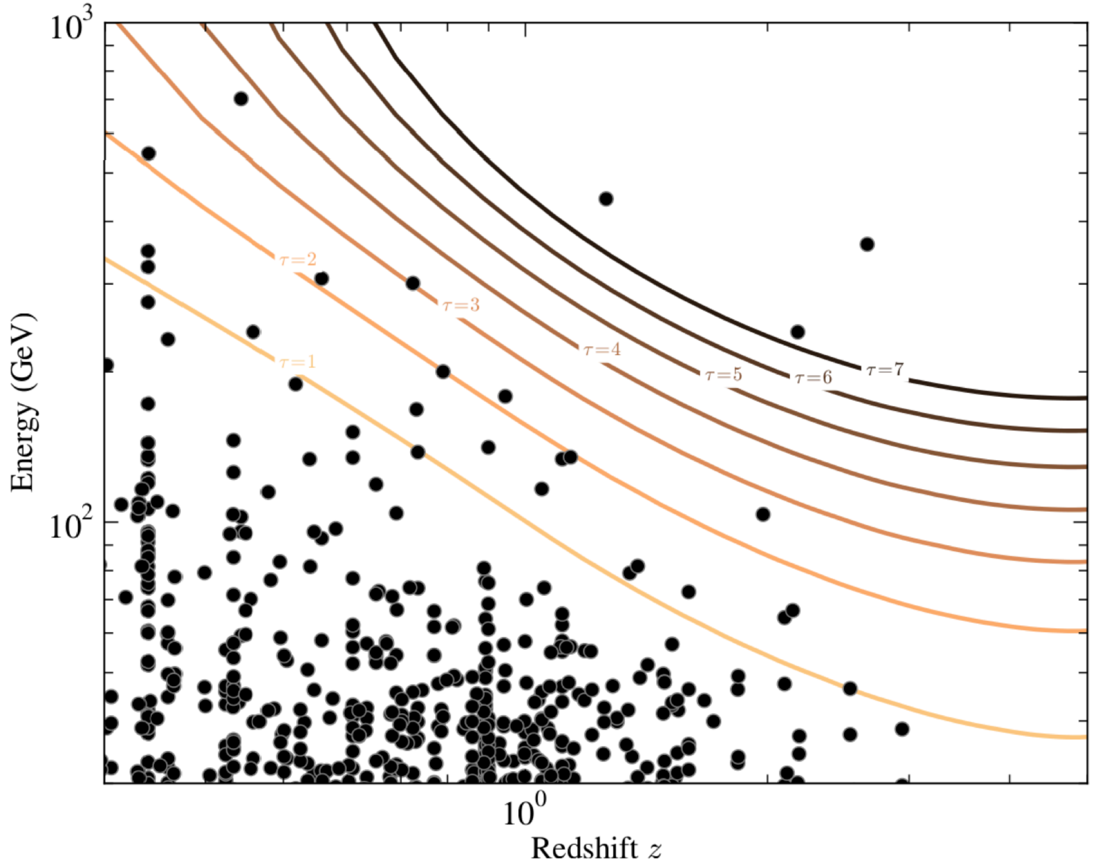

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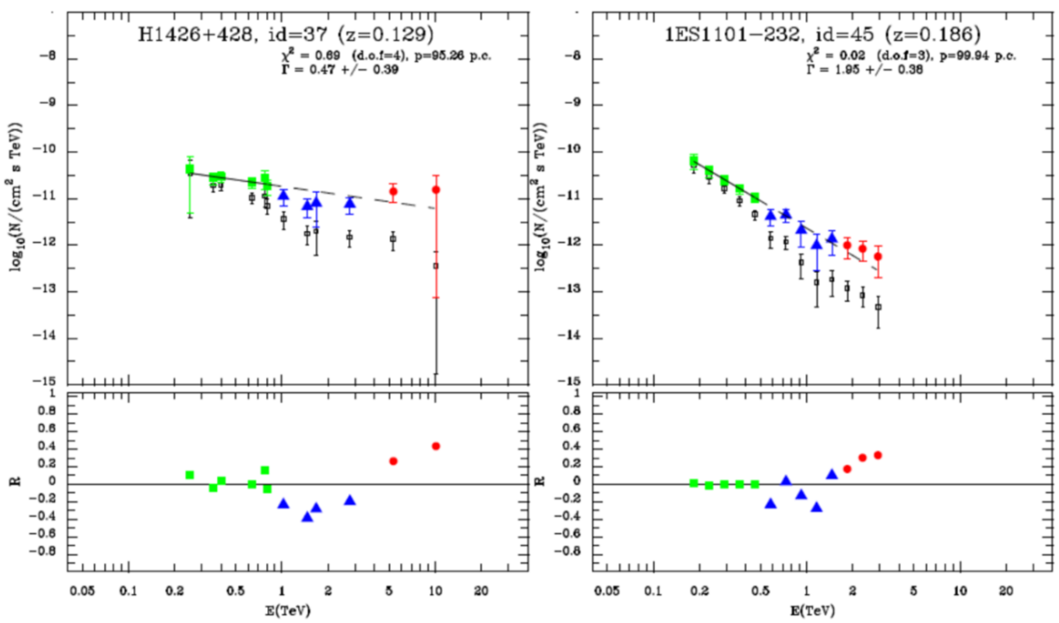
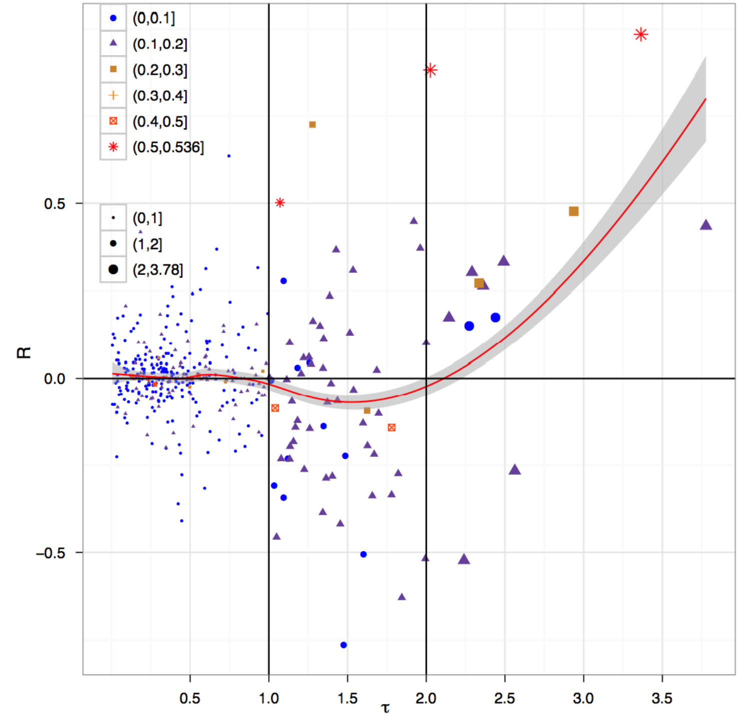


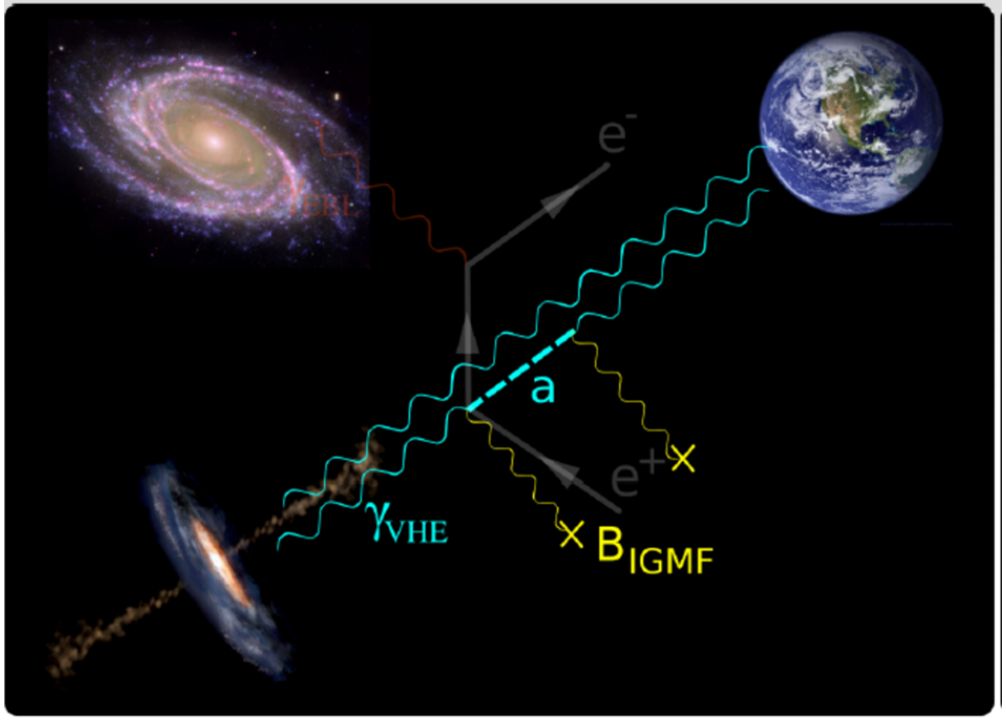


[Horns,Meyer 12]

Physics case for ALPs: Gamma transparency of universe

- Possible explanation in terms of photon <-> ALP conversions in astro-physical magnetic fields with $g_{a\gamma} \gtrsim 10^{-12}\ \mathrm{GeV}^{-1};\ m_a \lesssim 10^{-7}\ \mathrm{eV}$

[De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer,Horns,Raue 13]



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

[Manuel Meyer 12]

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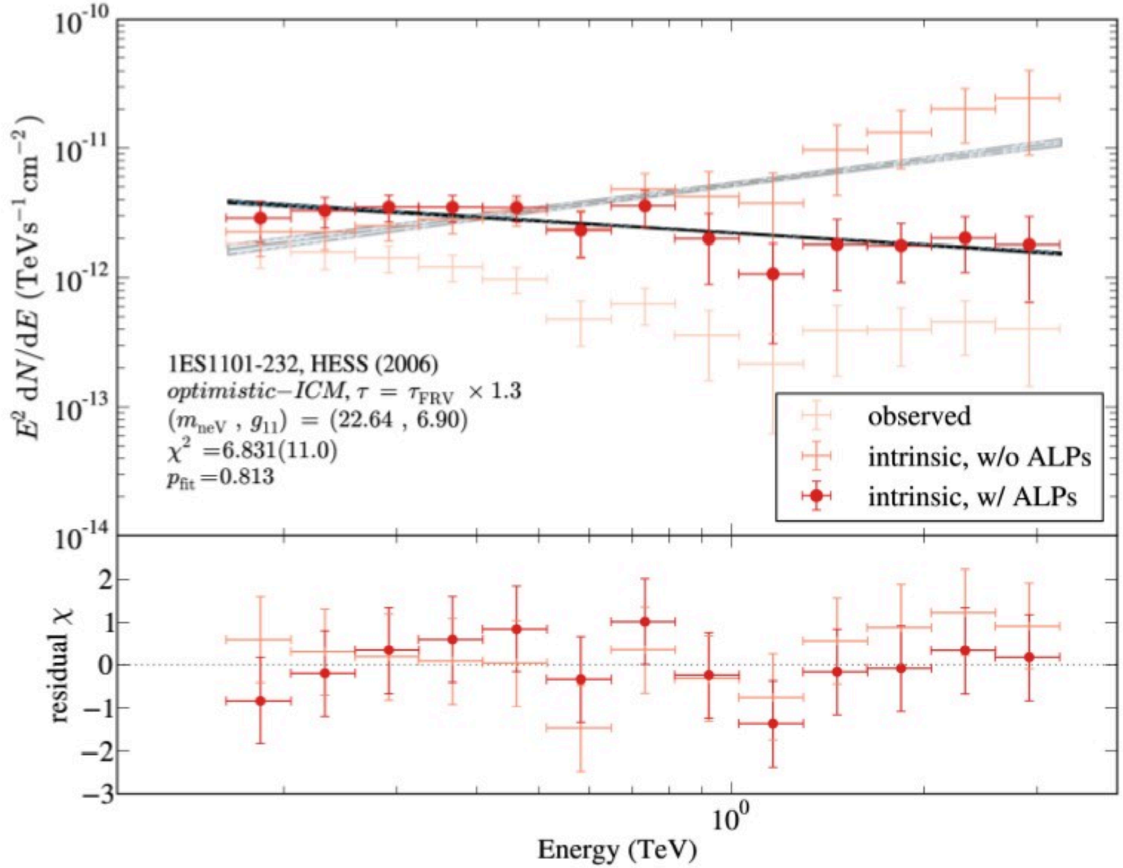

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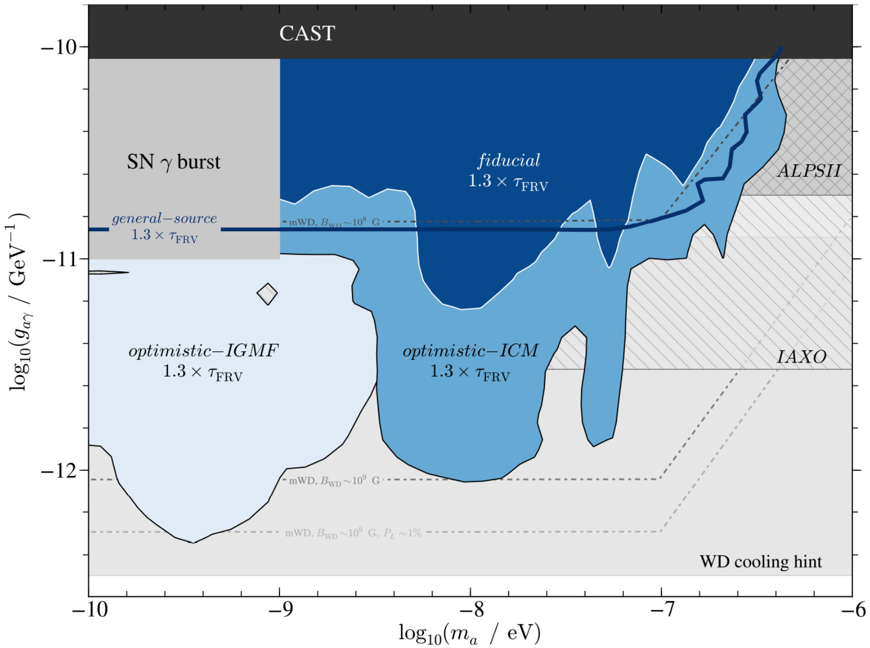


Name	IGMF B^0_{IGMF} (nG)	$\lambda^c_{\mathrm{IGMF}}$ (Mpc)	$n^0_{\mathrm{el,IGM}}$ ($\times 10^{-7}$ cm^{-3})	ICM B^0_{ICMF} (μG)	$\lambda^c_{\mathrm{ICMF}}$ (kpc)	r_{cluster} (Mpc)	$n^0_{\mathrm{el,ICM}}$ ($\times 10^{-3}$ cm^{-3})	r_{core} (kpc)	η
General source			Only conversion in GMF, but $\rho_{\mathrm{init}} = 1/3\mathrm{diag}(e^{-\tau}, e^{-\tau}, 1)$						
Optimistic IGMF	5	50	1	...	...	...	...	...	...
Optimistic ICM	...	...	...	10	10	2	10	200	0.5
Fiducial	0.01	10	1	1	10	2/3	1	...	...

[Meyer,Horns,Raue 13]

Physics case for ALPs: Cooling of white dwarfs

- Anomalous cooling of white dwarfs (WDs) apparent in [Isern et al. 08-12]
  - luminosity function
  - period decrease of pulsating WDs G117-B15A and R548
- Required coupling to the electron

$$\mathcal{L} \supset \frac{\left(g_{Ae}\partial_\mu A + g_{ae}\partial_\mu a\right)}{2m_e}\,\bar{e}\gamma^\mu\gamma_5 e$$

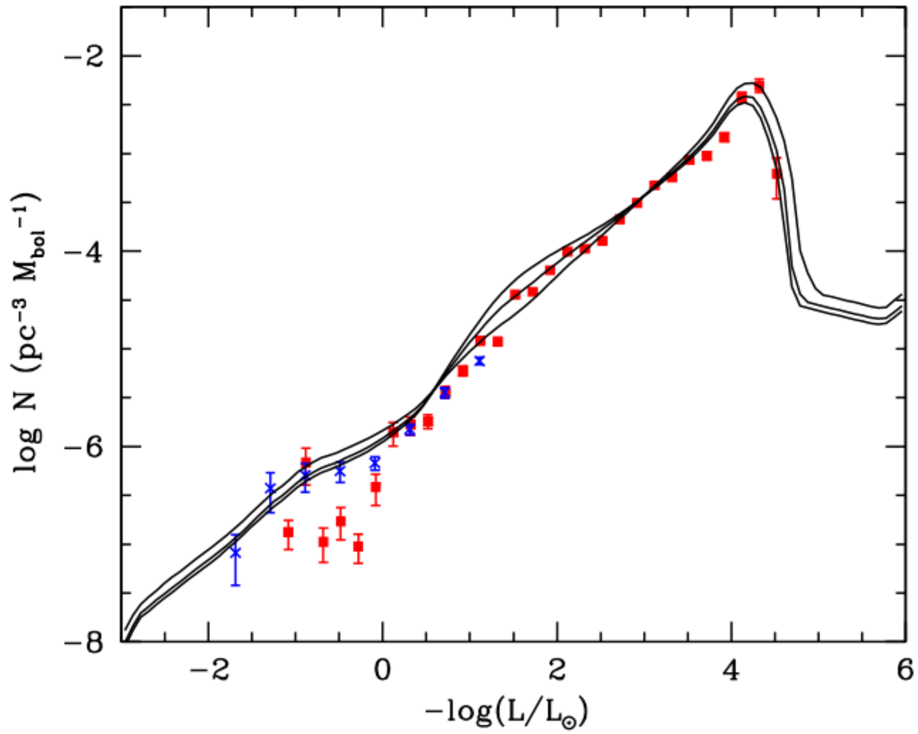
of size

$$|g_{Ae}| \equiv |C_{Ae}|\, m_e/f_A \sim 10^{-13} \quad \text{and/or}$$
$$|g_{ae}| \equiv |C_{ae}|\, m_e/f_a \sim 10^{-13}$$

and thus intermediate scale

$$\frac{f_A}{C_{Ae}}, \frac{f_a}{C_{ae}} \sim 10^9\,\text{GeV}\,,$$

$$\text{for} \quad m_A, m_a \lesssim \text{keV}$$



[Isern 09]

Physics case for ALPs: Cosmic ALP background radiation

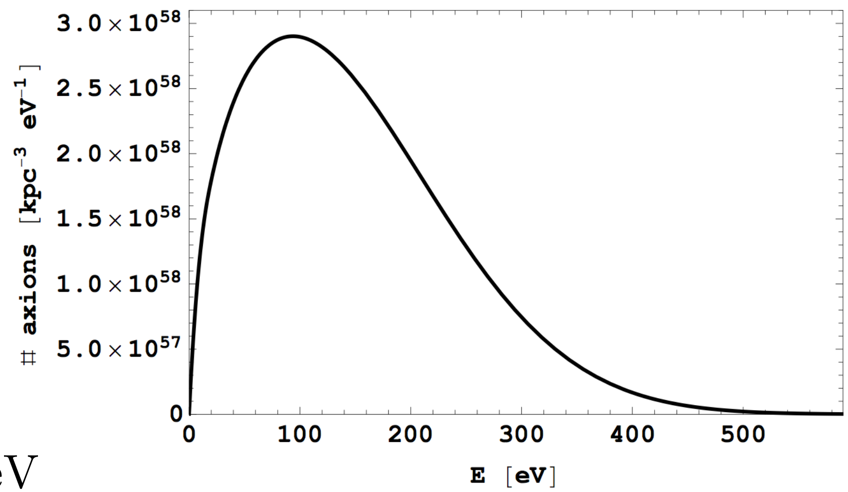
- Hints of dark radiation $\triangle N_{\rm eff}$ in CMB
- Cosmic ALP background radiation may be generated by modulus (scalar partner of pseudoscalar ALP) decay. Spectrum peaked at around 100 eV, for modulus mass expected in IIB string compactifications, $\sim 10^6\,\mathrm{GeV}$

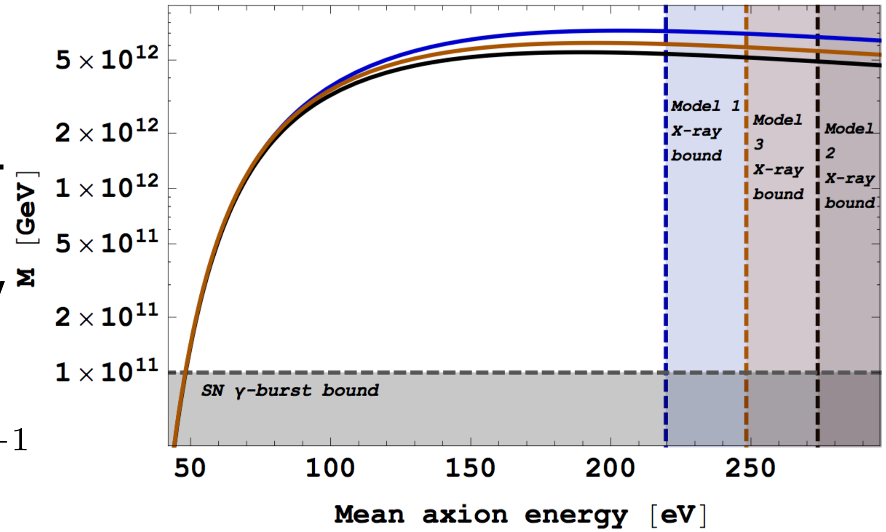
  [Cicoli,Conlon,Quevedo 12; Higaki,Takahashi 12]

- 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]

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

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

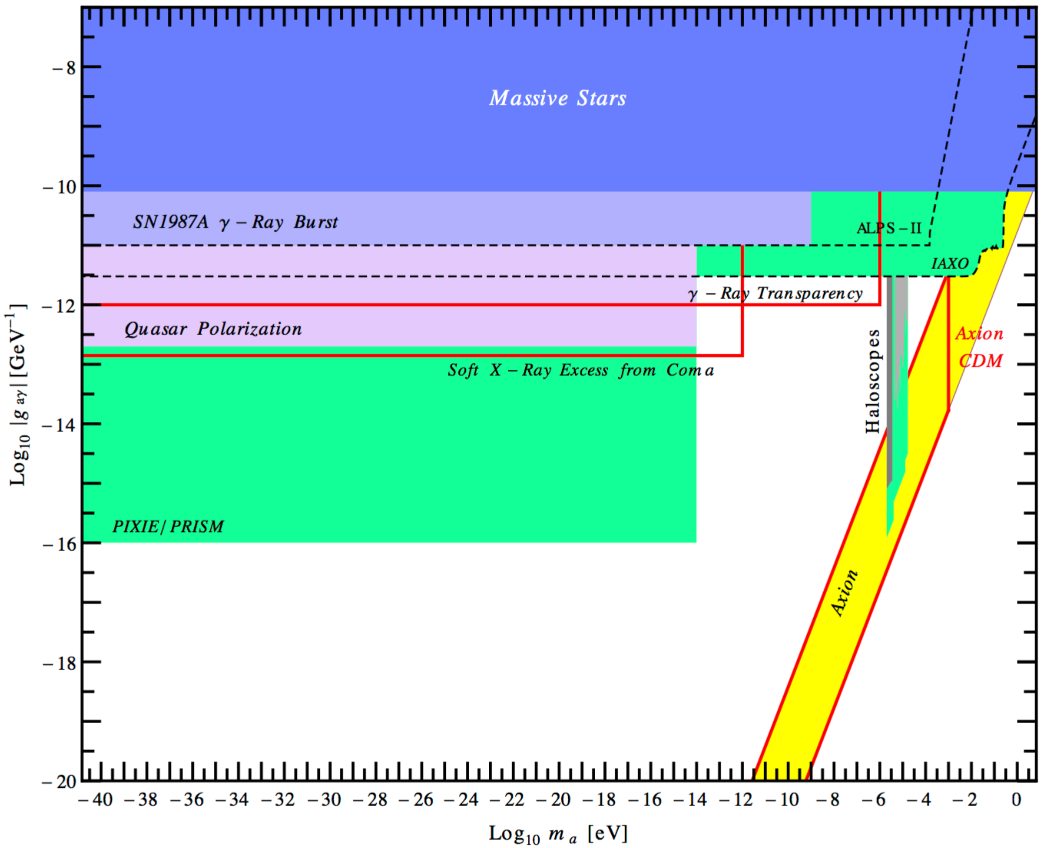




[Angus et al. 13]

Physics case for axions and ALPs: Parameters of interest

- There are allowed regions in parameter space where an ALP can simultaneously explain the gamma ray transparency, the soft X-ray excess from Coma and be a subdominant contribution to CDM



[Dias et al. in prep.]

Physics case for axions and ALPs: Parameters of interest

- In models with several axion-like fields,

$$\mathscr{L} = \frac{1}{2}\,\partial_\mu a_i'\,\partial^\mu a_i' - \frac{\alpha_s}{8\pi}\left(\sum_{i=1}^{n_{\rm ax}} C_{ig}\frac{a_i'}{f_{a_i'}}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\left(\sum_{i=1}^{n_{\rm ax}} C_{i\gamma}\frac{a_i'}{f_{a_i'}}\right) F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\left(\sum_{i=1}^{n_{\rm ax}} C_{ie}\frac{\partial_\mu a_i'}{f_{a_i'}}\right)\bar{e}\gamma^\mu\gamma_5 e$$

the axion is in general a mixture,

$$\frac{A}{f_A} \equiv \sum_{i=1}^{n_{\rm ax}} C_{ig}\frac{a_i'}{f_{a_i'}}$$

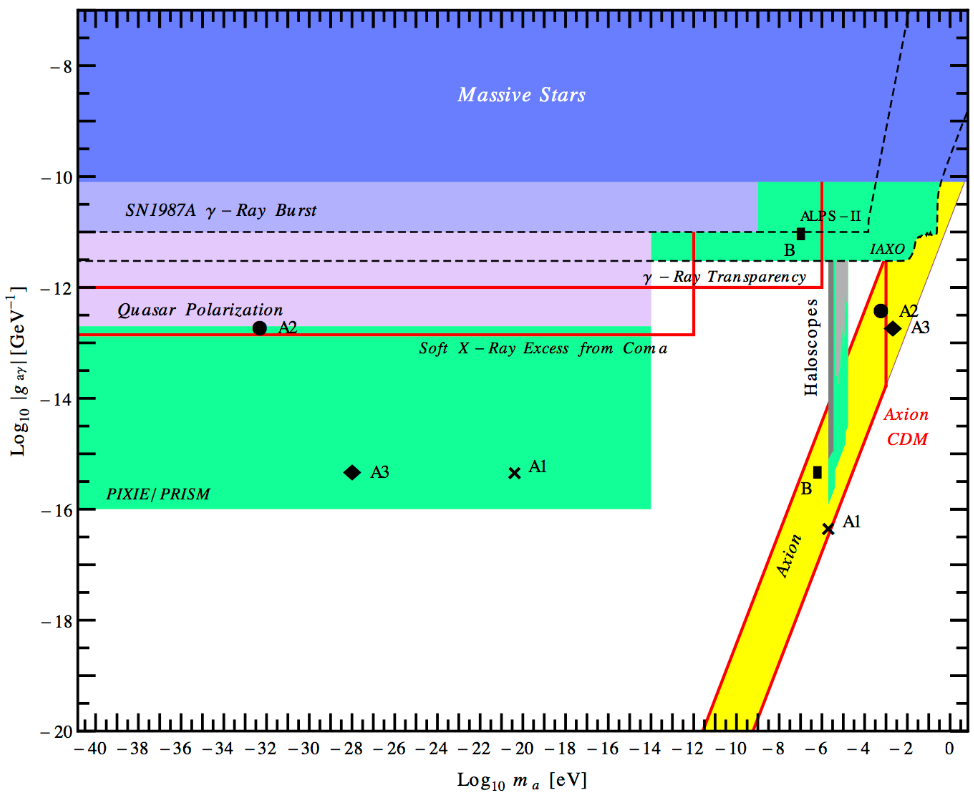
- UV completions with two accidental global chiral U(1)s yield benchmark values

[Dias et al. in prep.]

Model	Input values		Resulting low-energy parameters						
	$v_1 = f_{a_1'}$ [GeV]	$v_2 = f_{a_2'}$ [GeV]	f_A [GeV]	m_A [eV]	m_a [eV]	$\lvert g_{A\gamma}\rvert$ [GeV]$^{-1}$	$\lvert g_{a\gamma}\rvert$ [GeV]$^{-1}$	$\lvert g_{Ae}\rvert$	$\lvert g_{ae}\rvert$
A1	1×10^{13}	1×10^{13}	3×10^{12}	2×10^{-6}	4×10^{-21}	5×10^{-17}	5×10^{-16}	5×10^{-17}	2×10^{-17}
A2	1×10^{10}	1×10^{11}	0.96×10^{10}	6×10^{-4}	5×10^{-33}	4×10^{-13}	2×10^{-13}	1×10^{-15}	5×10^{-15}
A3	1×10^{13}	1×10^{10}	3×10^{9}	2×10^{-3}	1×10^{-28}	2×10^{-13}	5×10^{-16}	5×10^{-14}	2×10^{-17}
B	1×10^{13}	1×10^{9}	1×10^{13}	6×10^{-7}	2×10^{-7}	5×10^{-16}	1×10^{-11}	0	5×10^{-13}

Physics case for axions and ALPs: Favored parameters

Model	Input values		Resulting low-energy parameters						
	$v_1 = f_{a'_1}$ [GeV]	$v_2 = f_{a'_2}$ [GeV]	f_A [GeV]	m_A [eV]	m_a [eV]	$\lvert g_{A\gamma}\rvert$ [GeV]$^{-1}$	$\lvert g_{a\gamma}\rvert$ [GeV]$^{-1}$	$\lvert g_{Ae}\rvert$	$\lvert g_{ae}\rvert$
A1	1×10^{13}	1×10^{13}	3×10^{12}	2×10^{-6}	4×10^{-21}	5×10^{-17}	5×10^{-16}	5×10^{-17}	2×10^{-17}
A2	1×10^{10}	1×10^{11}	0.96×10^{10}	6×10^{-4}	5×10^{-33}	4×10^{-13}	2×10^{-13}	1×10^{-15}	5×10^{-15}
A3	1×10^{13}	1×10^{10}	3×10^{9}	2×10^{-3}	1×10^{-28}	2×10^{-13}	5×10^{-16}	5×10^{-14}	2×10^{-17}
B	1×10^{13}	1×10^{9}	1×10^{13}	6×10^{-7}	2×10^{-7}	5×10^{-16}	1×10^{-11}	0	5×10^{-13}



[Dias et al. in prep.]

DESY

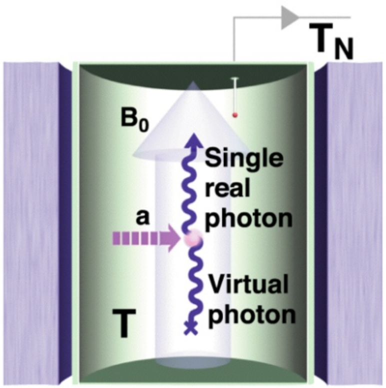
Intermediate scale axions/ALPs may be found in lab exps

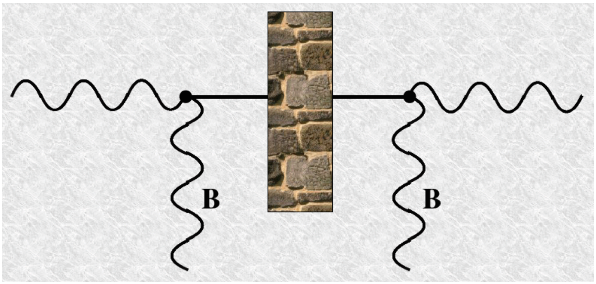
> Axions and ALPs with decay constants in the intermediate scale range

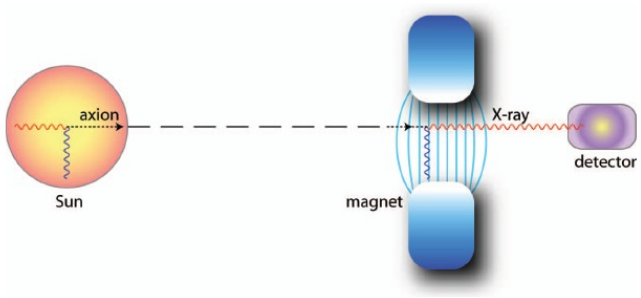
$$10^9\,\mathrm{GeV} \lesssim f_A, f_a \lesssim 10^{12}\,\mathrm{GeV}$$

can be searched for in the laboratory with

- haloscopes: direct detection of DM axions/ALPs [Sikivie 83]
- light-shining-through-a-wall: production and detection of ALPs [Anselm 85; van Bibber et al 87]
- helioscopes: detection of solar axions/ALPs [Sikivie 83]



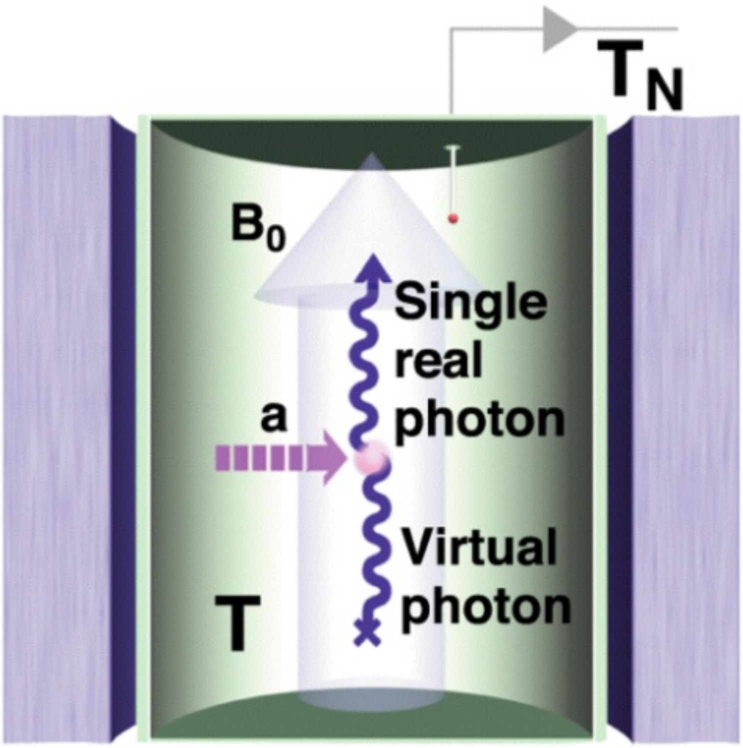




Haloscope searches: Resonant cavities

- Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field [Sikivie 83]

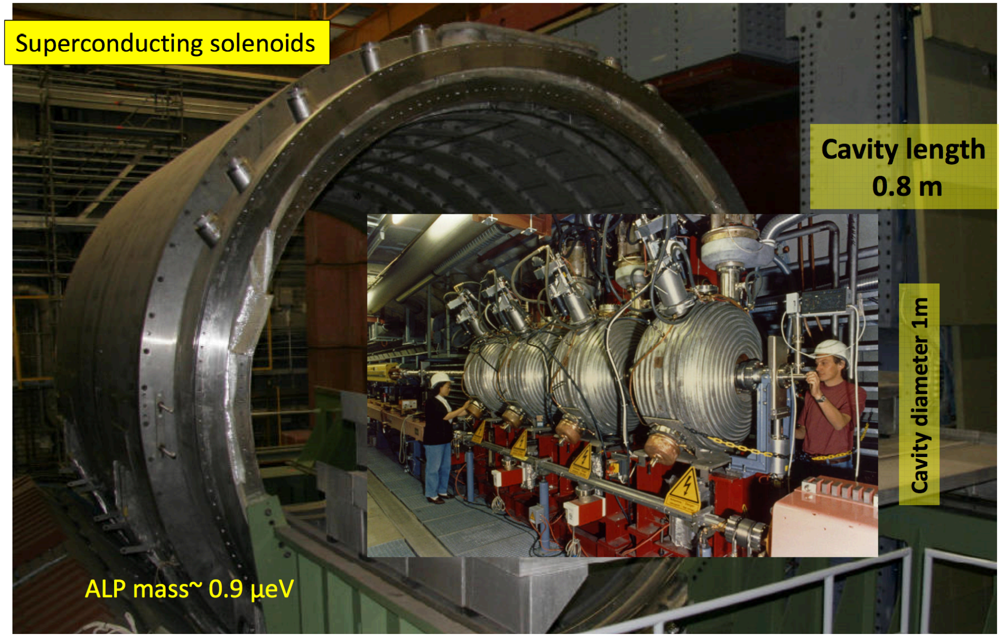
Best sensitivity: mass = resonance frequency $m_a = 2\pi\nu \sim 4\ \mu\text{eV}\left(\frac{\nu}{\text{GHz}}\right)$



$$P_{\text{out}} \sim g^2 \mid \mathbf{B}_0 \mid^2 \rho_{\text{DM}} V Q / m_a$$

Haloscope searches: Resonant cavities

- 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; search starts at 1 GHz towards higher frequencies
  - Pilot study: WISPDMX at DESY, Hamburg, exploiting high Q HERA p acceleration cavity and H1 solenoid (1.1 T); search starts at 208 MHz towards higher frequencies



Haloscope searches: Dish antennas

> Oscillating Axion/ALP DM in a background magnetic field carries a small electric field component

- Equations of motion for a plane wave $\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix} \exp(-i(\omega t - kz)).$

$$\left[(\omega^2 - k^2)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & -g_{a\gamma}|\mathbf{B}|\omega \\ -g_{a\gamma}|\mathbf{B}|\omega & m_a^2 \end{pmatrix}\right]\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}.$$

axion mixes with A-component PARALLEL to the external B-field

- "Dark matter" solution $v = \frac{k}{\omega} \quad ; \quad \omega \simeq m_a(1 + v^2/2 + \ldots)$

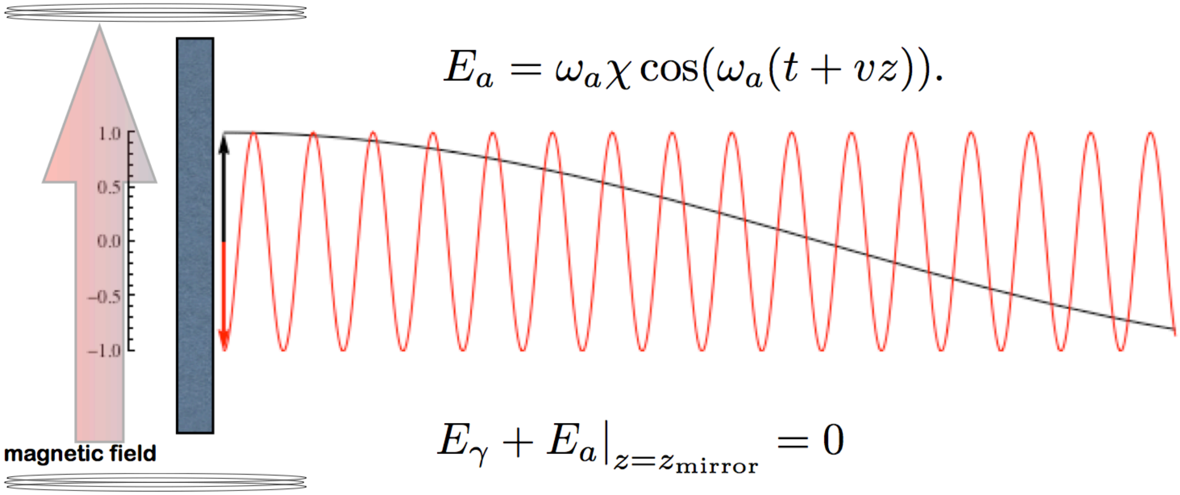
$$\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix}\Bigg|_{\rm DM} \propto \begin{pmatrix} -\chi_a \\ 1 \end{pmatrix} \exp(-i(\omega t - kz)).$$

It has a small E field! $\chi_a \sim \frac{g_{a\gamma}|\mathbf{B}|}{m_a}$

[Redondo: talk at DESY 14]

Haloscope searches: 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



$$E_a = \omega_a \chi \cos(\omega_a (t + vz)).$$

$$E_\gamma + E_a\big|_{z=z_{\rm mirror}} = 0$$

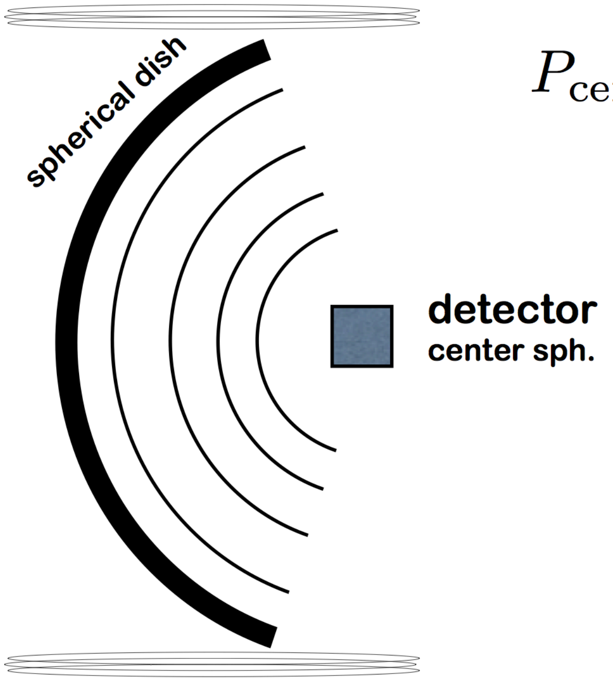
Radiated photon wave $$E_\gamma = -\omega_a \chi \cos(\omega_\gamma (t - z)).$$

whose frequency is $$\omega_\gamma = \omega_a = m_a (1 + v^2/2)$$

[Redondo: talk at DESY 14]

Haloscope searches: 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
- Simple broadband experiment: spherical dish antenna [Horns et al. 12]



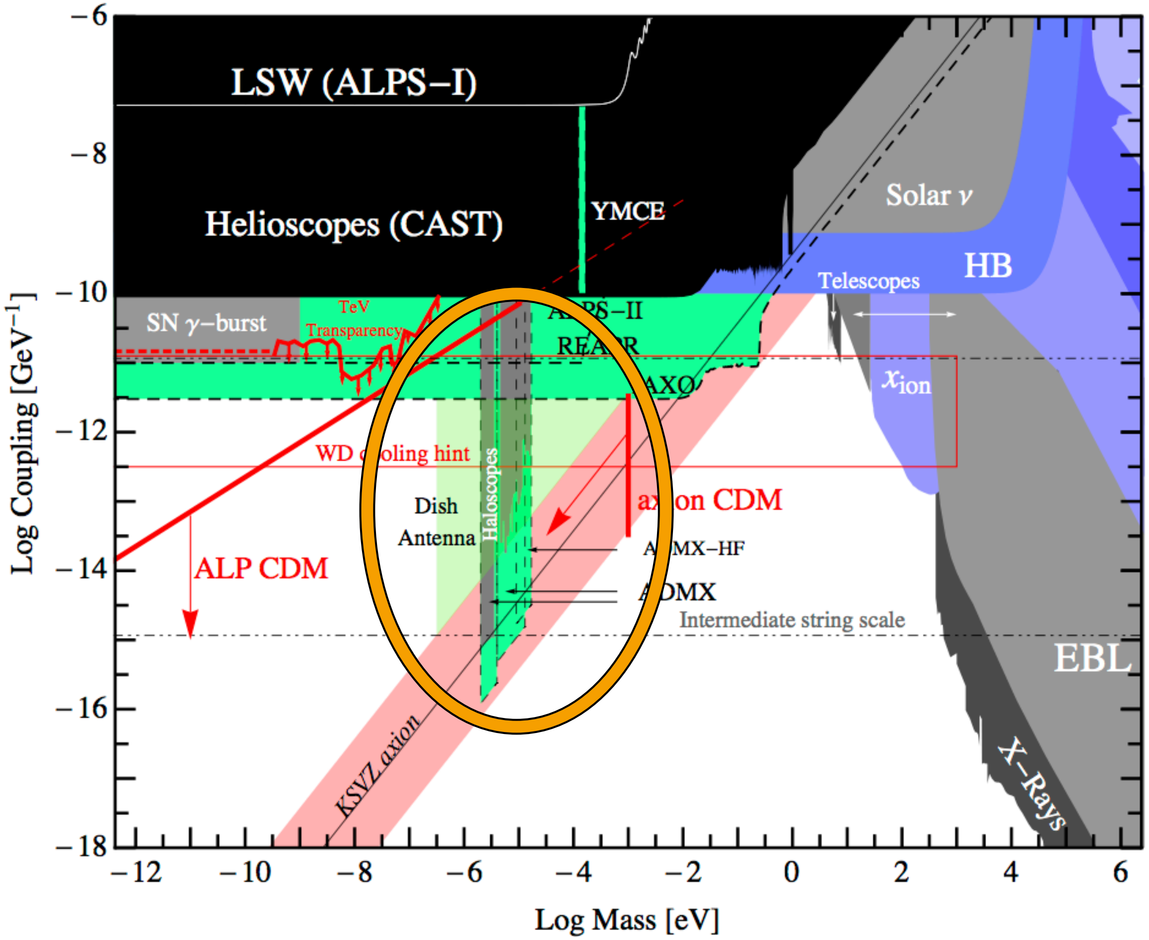
$$P_{\rm center} \approx \langle |\mathbf{E}_a|^2 \rangle A_{\rm dish} \sim \chi^2 \rho_{\rm CDM} A_{\rm dish}$$

$$\sim 10^{-26} \left(\frac{\rm B}{\rm 5T} \frac{c_\gamma}{2} \right)^2 \frac{\rm A}{\rm 1m^2} {\rm Watt}$$

[Redondo: talk at DESY 14]

Haloscope searches: Resonant cavities and dish antennas

- Sensitivity of microwave cavity (ADMX) and dish antenna haloscopes:



[Essig et al. 1311.0029]

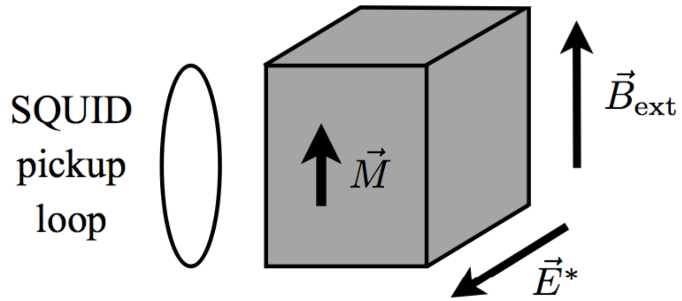
Haloscope searches: Precision magnetometry

- Proposed searches for axion and ALP dark matter exploiting time varying CP-odd nuclear moments acquired by interactions with the background axion dark matter, e.g.

$$d_N \equiv g_{Ad} A(t) \sim e \frac{m_u m_d}{(m_u + m_d) m_N^2} \frac{A(t)}{f_A} \sim 10^{-16} \frac{A(t)}{f_A}\, e\,\mathrm{cm}$$

$$\frac{A(t)}{f_A} \sim \frac{\sqrt{\rho_{\rm DM}}}{m_A f_A} \cos(m_A t) \sim \frac{\sqrt{\rho_{\rm DM}}}{m_\pi f_\pi} \cos(m_A t) \sim 10^{-19} \cos(m_A t)$$

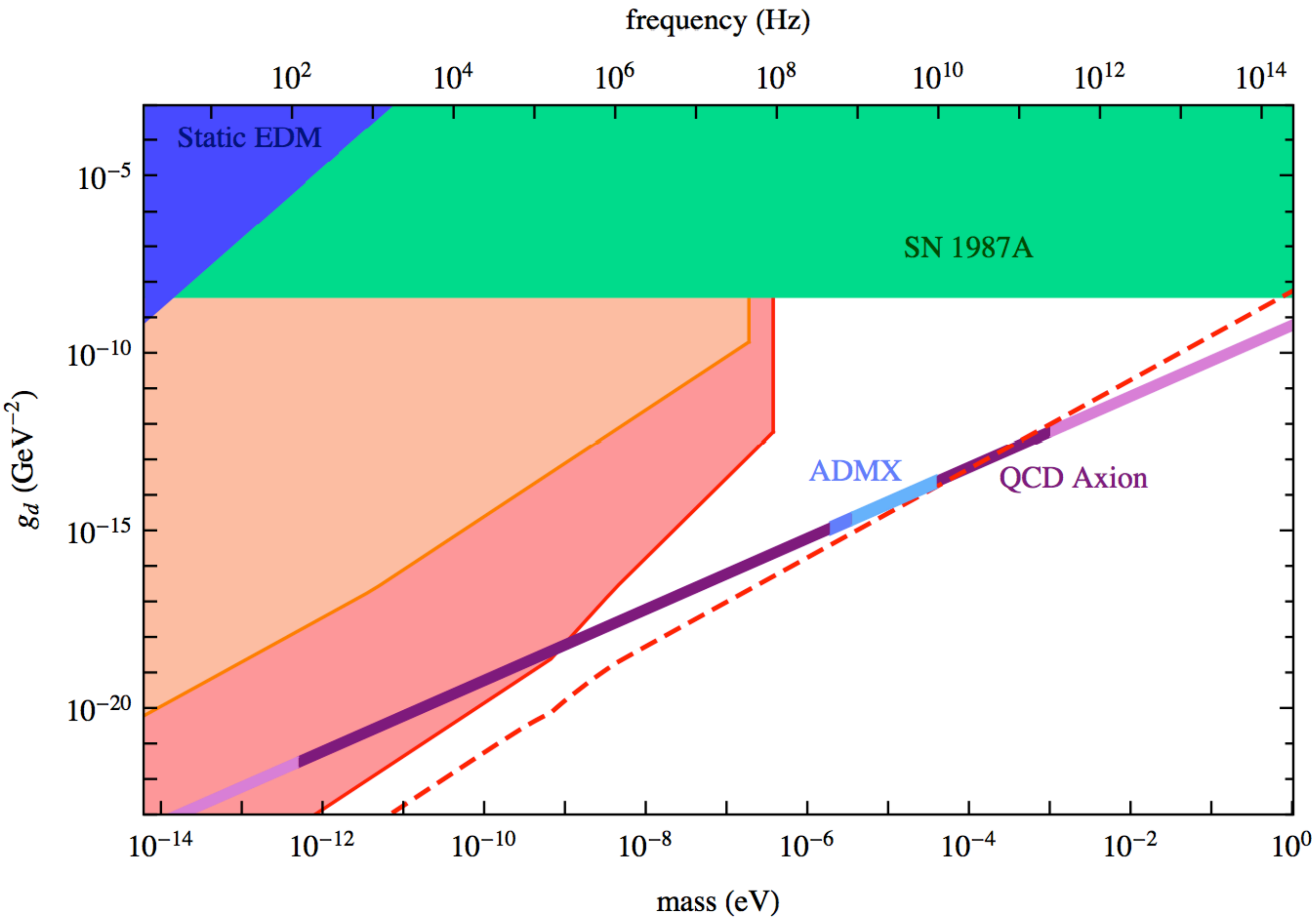
  - Moments cause precession of nuclear spins in material sample in presence of background electric field
  - Can be searched for with precision magnetometry [Graham,Rajendran 13; Budker et al 11]



  - Window of opportunity for GUT scale axions, $m_a \sim m_\pi f_\pi / f_a \sim \mathrm{MHz}\,(10^{16}\,\mathrm{GeV}/f_a)$

Haloscope searches: Precision magnetometry

> Sensitivity of CASPEr (Cosmic Axion Spin Precession Experiment)

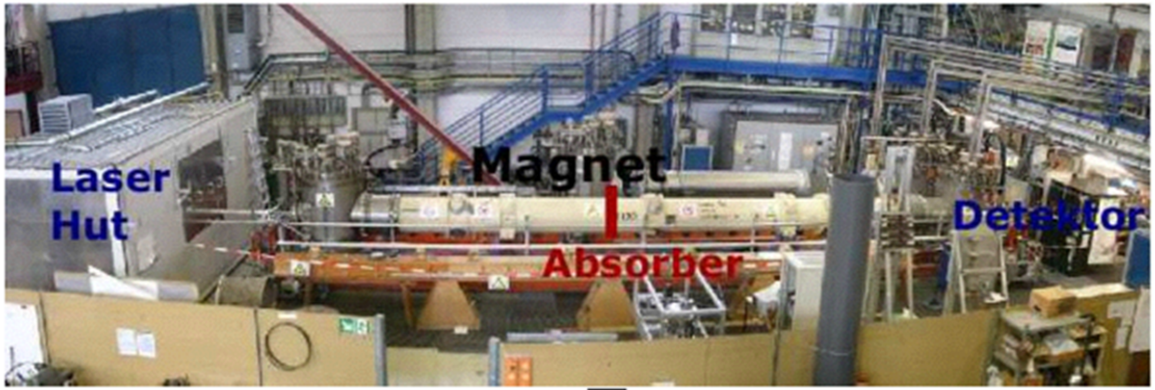


[Budker et al 13]

Light-shining-through-a-wall searches

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

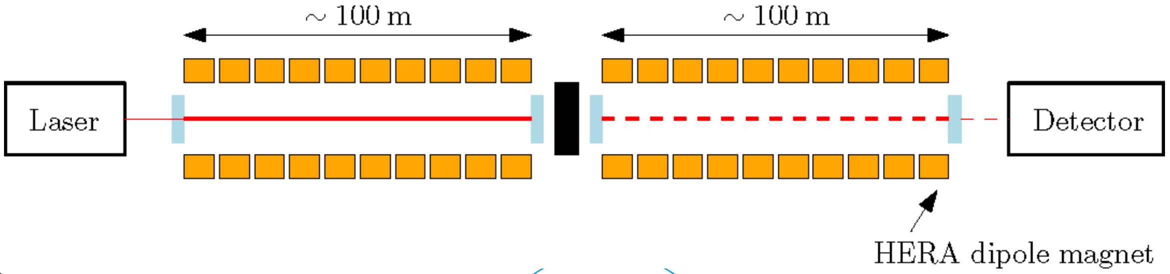
- One superconducting HERA dipole (5 T)
- 1.2 kW cw green (2.3 eV) laser
- CCD camera

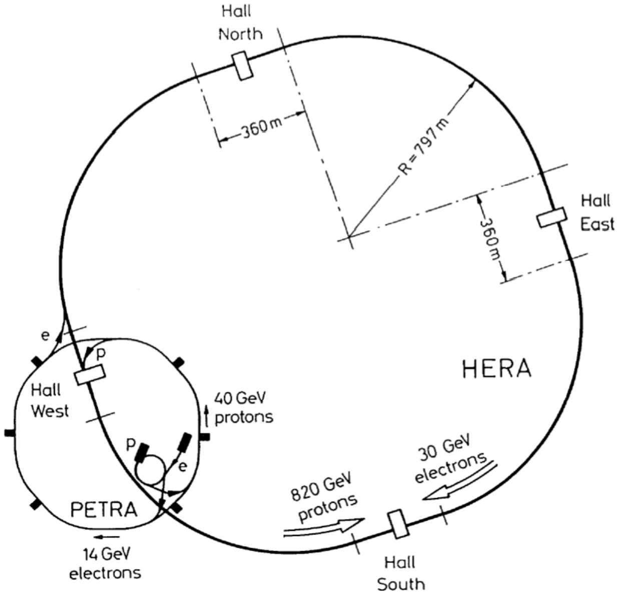


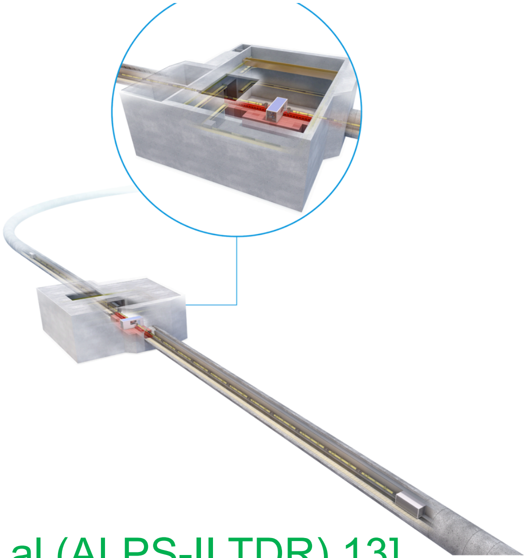
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

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





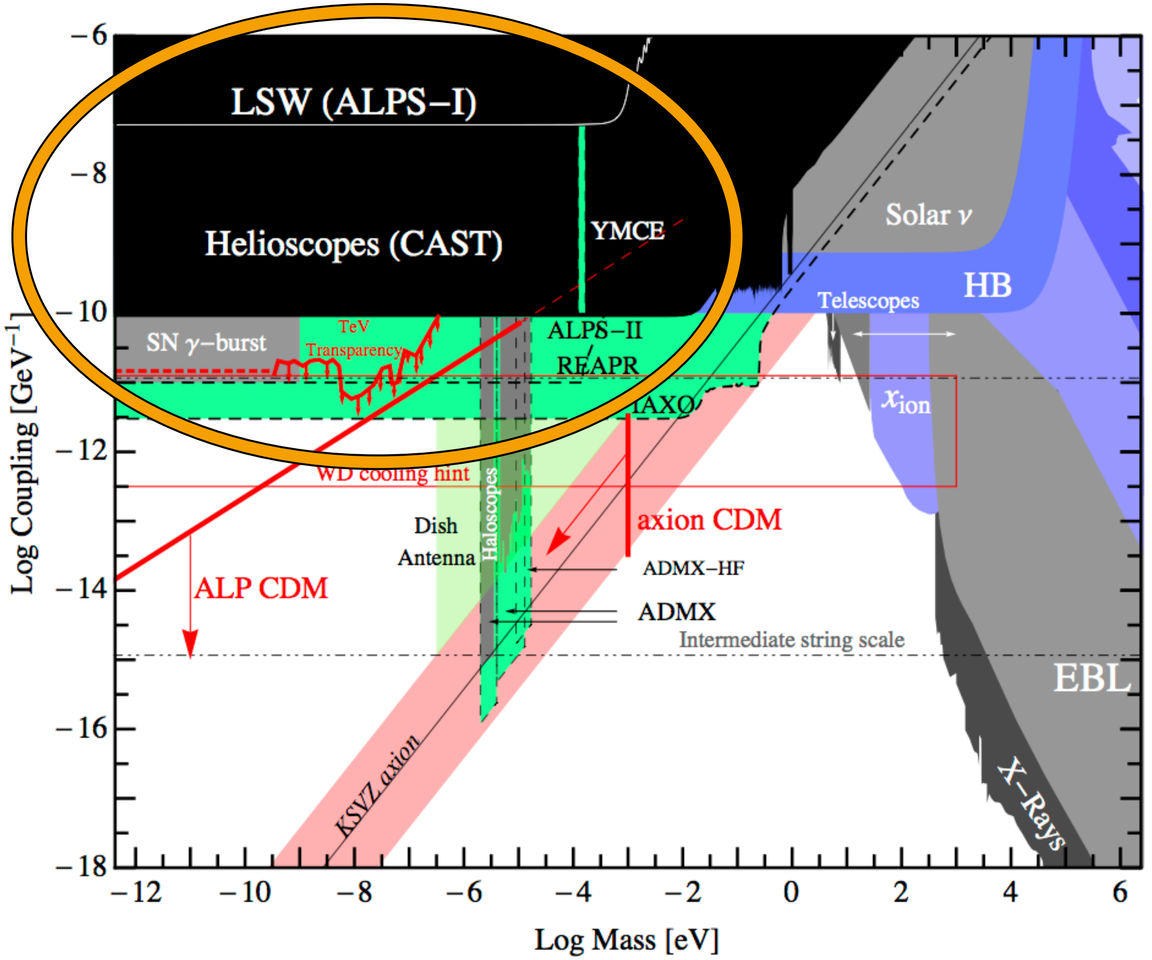


[Bähre et al (ALPS-II TDR) 13]

DESY

Light-shining-through-a-wall searches

- Sensitivity of light-shining-through-a-wall (LSW) searches:

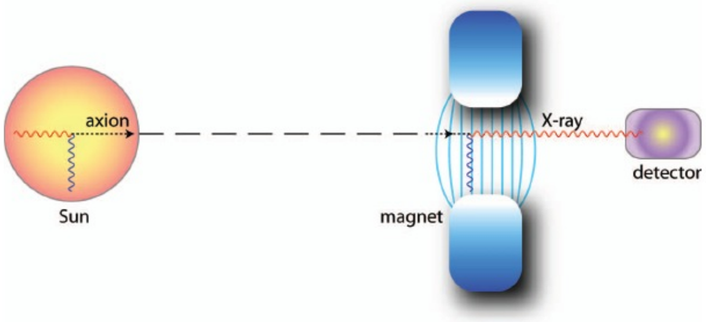


[Essig et al. 1311.0029]

Helioscope searches

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

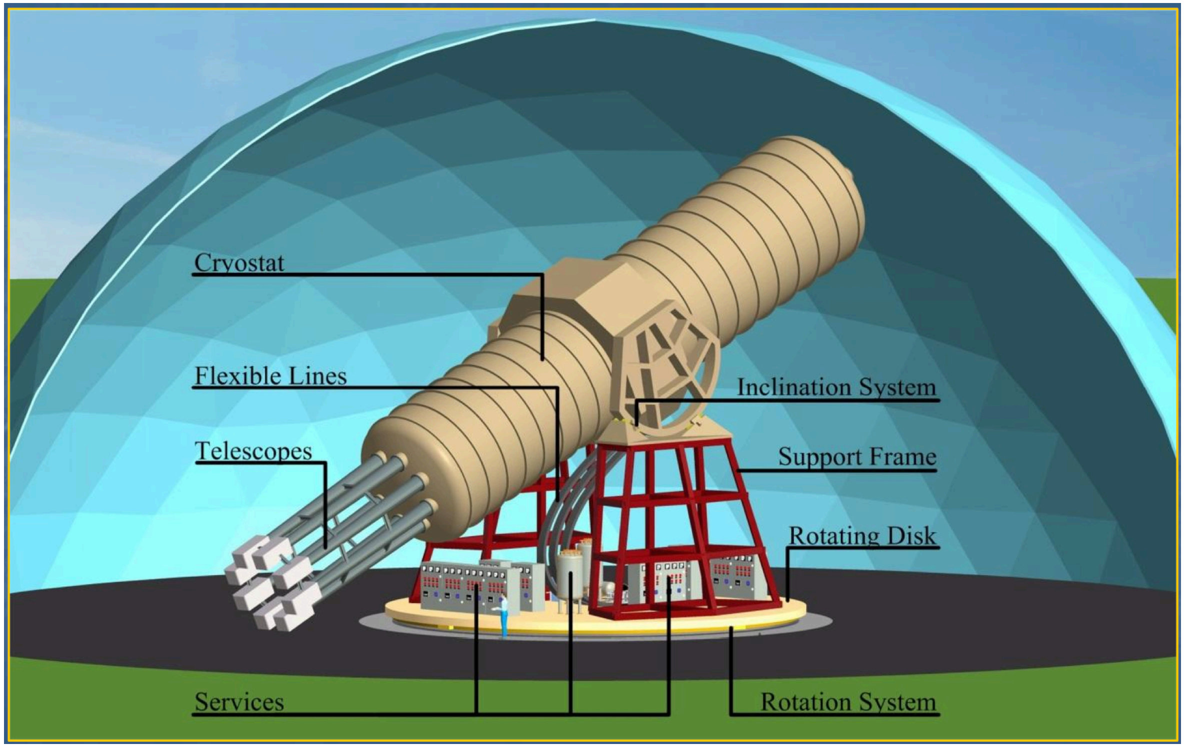
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$



Helioscope searches

> Proposed successor: International Axion Observatory (IAXO)

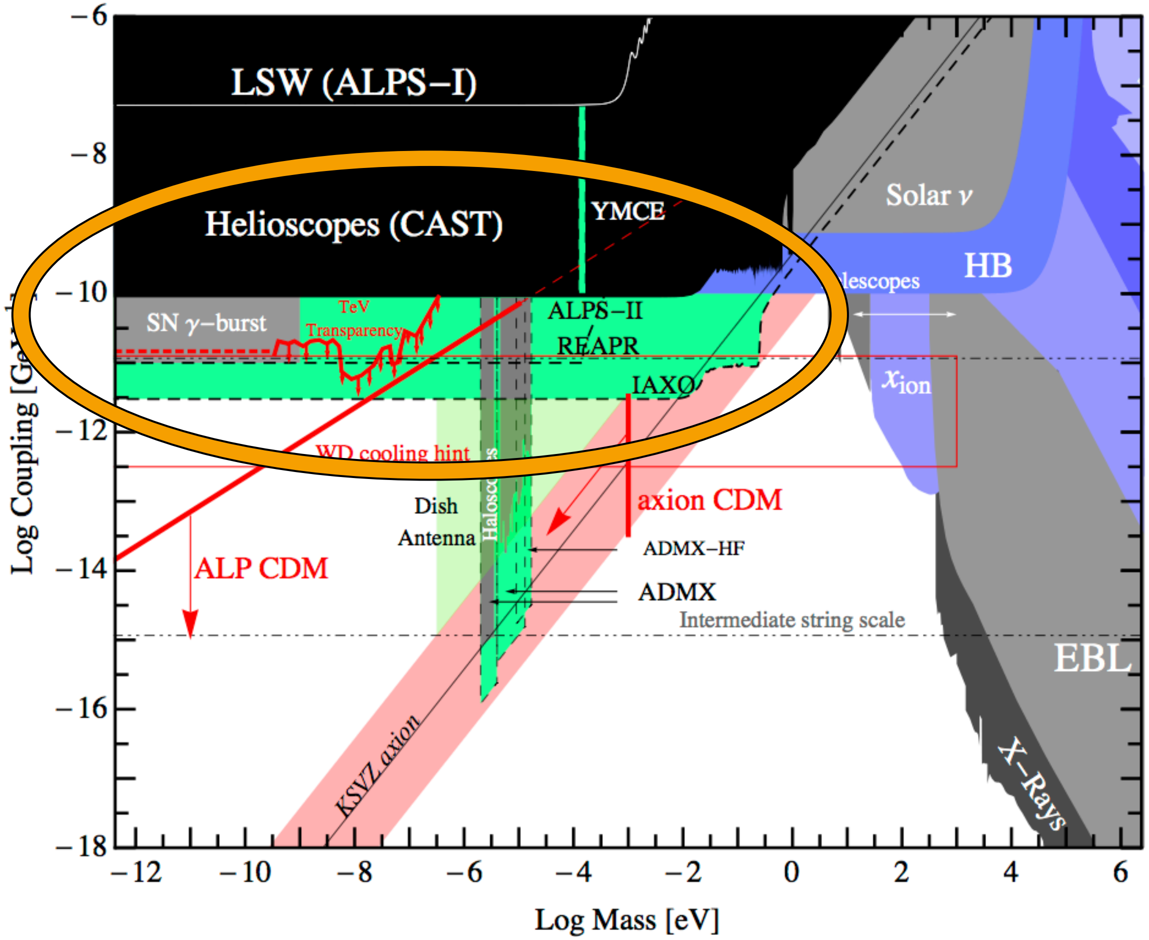
- Dedicated superconducting toroidal magnet with much bigger aperture than CAST
- Extensive use of X-ray optics
- Low background X-ray detectors



[Armengaud et al (IAXO CDR) 1401.3233]

Helioscope searches

> Sensitivity of helioscope searches:



adapted from [Hewett et al 12]

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!