Experimental Searches for Axions and Axion-Like Particles.

Andreas Ringwald (DESY)

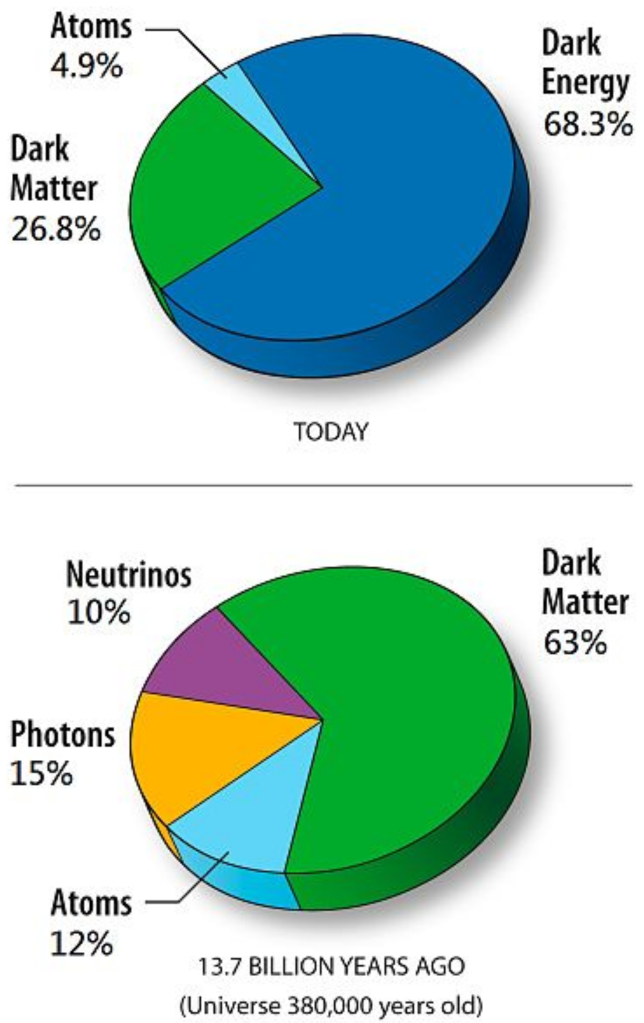
DaMESyFla: CP Violation 50 Years after Discovery
SISSA, Trieste, Italy
22-23 September 2014

HELMHOLTZ ASSOCIATION

DESY

Strong case for particles beyond the Standard Model

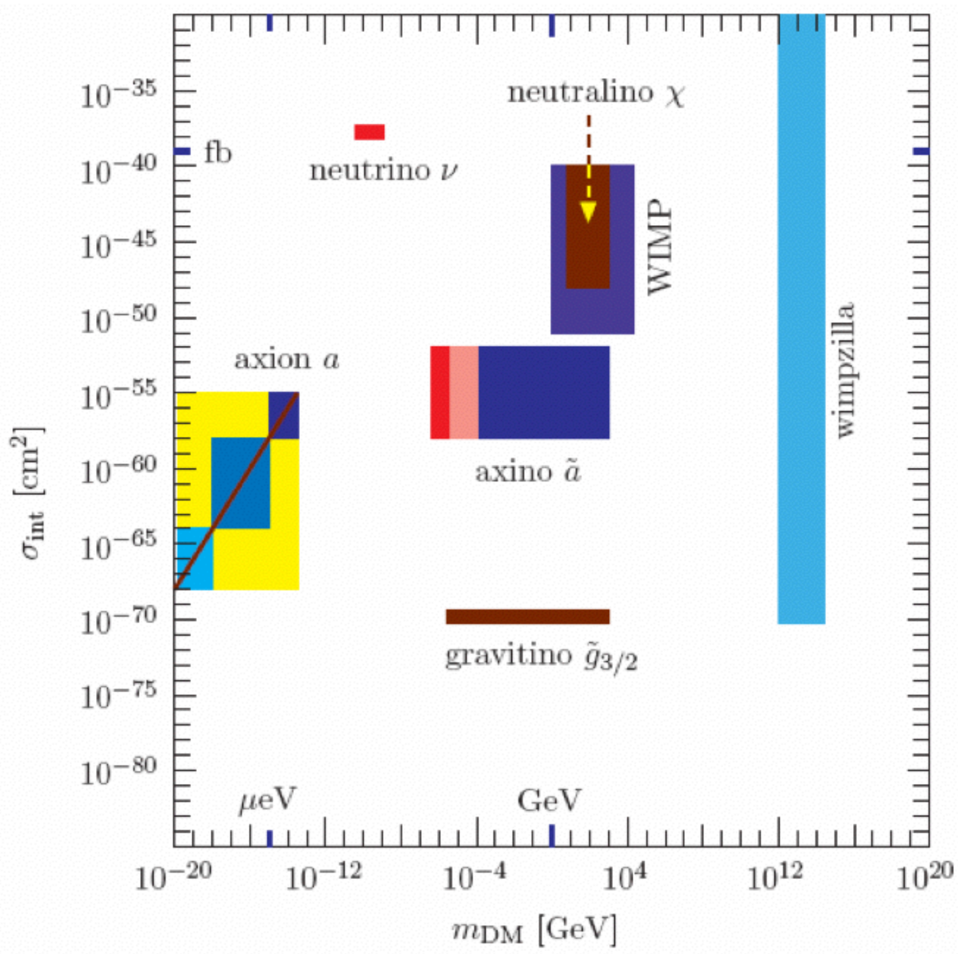
- Standard Model (SM) of particle physics describes basic properties of known matter and forces
- SM not a complete and fundamental theory:
  - No explanation of dark sector



[wikipedia]

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



(Kim,Carosi 10)

Physics case for WISPs: Theoretical motivations

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

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

- Examples:
  - Axion from breaking of global chiral symmetry; axion field acts as dynamical theta parameter, [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)

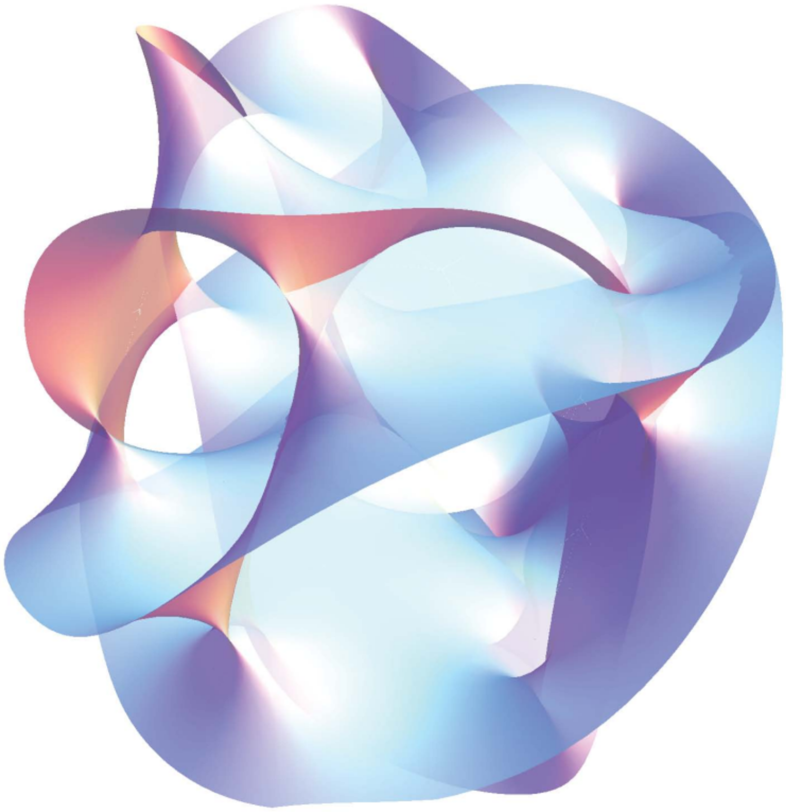
    - mass due to mixing with pion, $m_A \sim m_\pi f_\pi / f_A$
    - has universal coupling to photons, $\mathcal{L} \supset -\frac{\alpha}{8\pi} C_0 \frac{A}{f_A} F_{\mu\nu} \tilde{F}^{\mu\nu}$
  - Majoron from breaking of global lepton number symmetry [Chikashige et al. 78]
    - high scale explains small neutrino mass, $m_\nu \sim v^2/f_L$ [Langacker et al. 86]
  - Familon from breaking of family symmetry [Wilczek 82; Berezhiani,Khlopov 90]

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

$$\mathcal{L} \supset -\frac{\alpha}{8\pi} C_{a\gamma} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Physics case for WISPs: Theoretical motivations

- 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. 14]



Physics case for axions and ALPs: Cold dark matter

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

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

satisfies

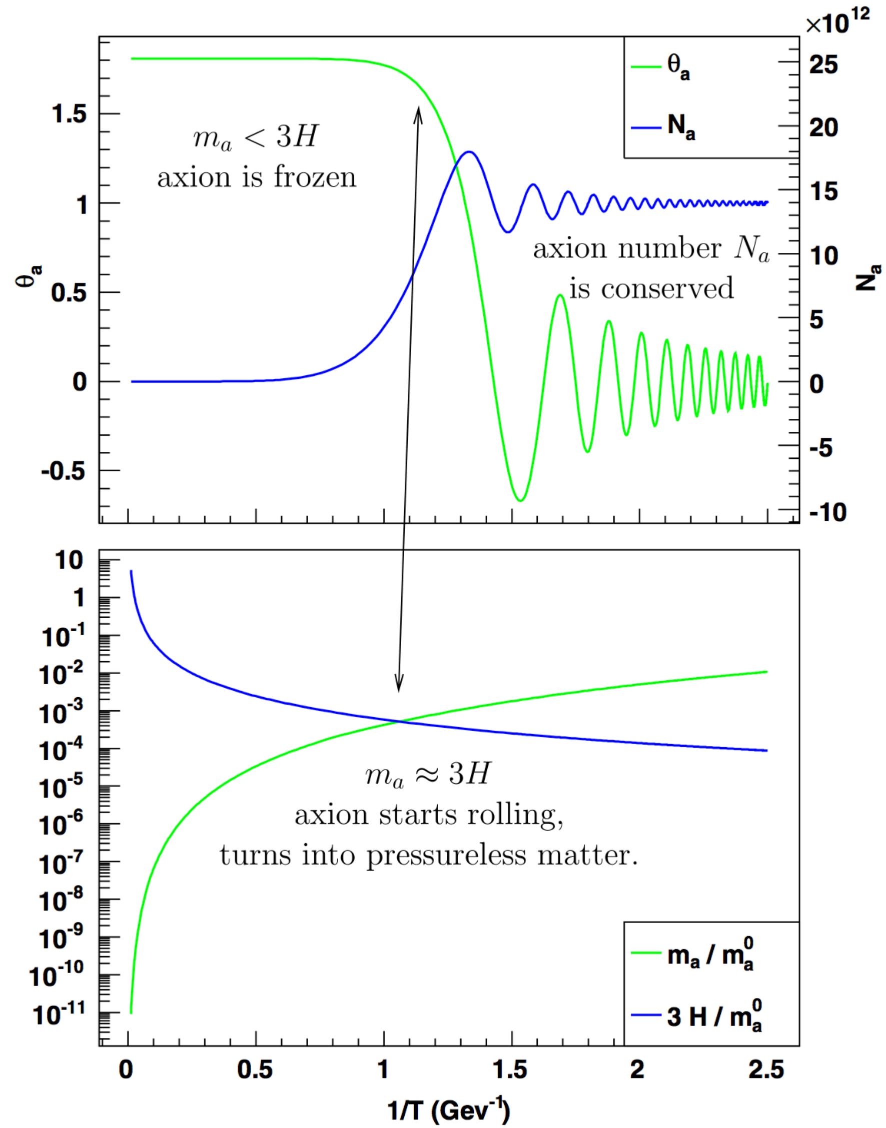
$$\ddot{\theta}_a + 3H(T)\dot{\theta}_a - \nabla^2\theta_a/R^2 + m_a^2(T)\sin\theta_a = 0$$

  - 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]

Physics case for axions and ALPs: Cold dark matter

- In standard cosmology, oscillations start during radiation dominated phase. Then [Preskill et al. 83; Abbott,Sikivie 83; Dine,Fischler 83;...; Arias et al. 12]

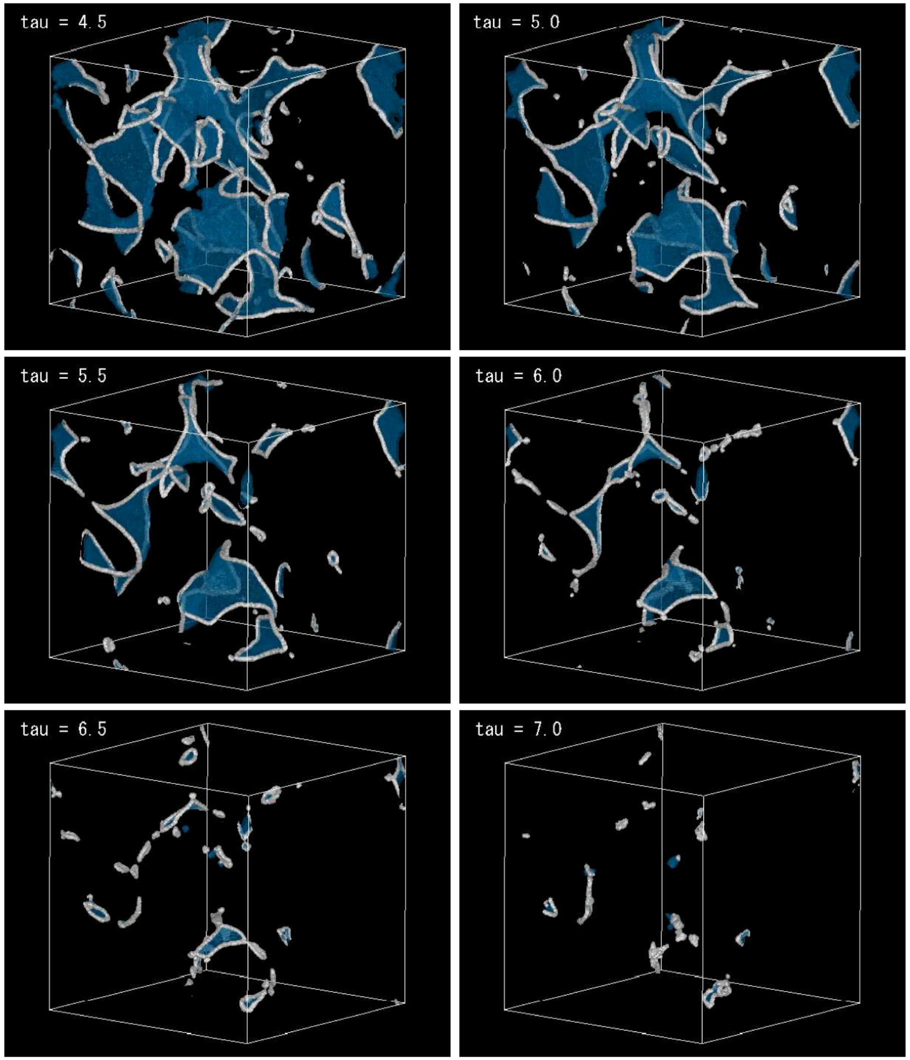
$$\frac{\rho_a^{(\rm vr)}}{\rho_{\rm CDM}}(t_0) \simeq 0.2\,\sqrt{\frac{m_a(t_0)}{\rm eV}}\sqrt{\frac{m_a(t_0)}{m_a(t_{\rm osc})}}\left(\frac{f_a}{10^{11}\,{\rm GeV}}\right)^2\langle\theta_a^2\rangle$$

- Predictions for $\langle\theta_a^2\rangle$ depend on whether spontaneous symmetry breaking (SSB) of global U(1) occured before/after inflation:

$$\langle\theta_a^2\rangle = \begin{cases} \theta_i^2 + \left(\frac{H_I}{2\pi f_a}\right)^2, & \text{if } f_a > \max\left(\frac{H_I}{2\pi}, \epsilon_{\rm eff} E_I\right) \ \text{(pre-infl. SSB)}, \\ \frac{\pi^2}{3}, & \text{if } f_a < \max\left(\frac{H_I}{2\pi}, \epsilon_{\rm eff} E_I\right) \ \text{(post-infl. SSB)}. \end{cases}$$

Physics case for axions and ALPs: Cold dark matter

- In post-infl. SSB scenario, decay of cosmic strings and domain walls provide additional CDM axion and ALPs



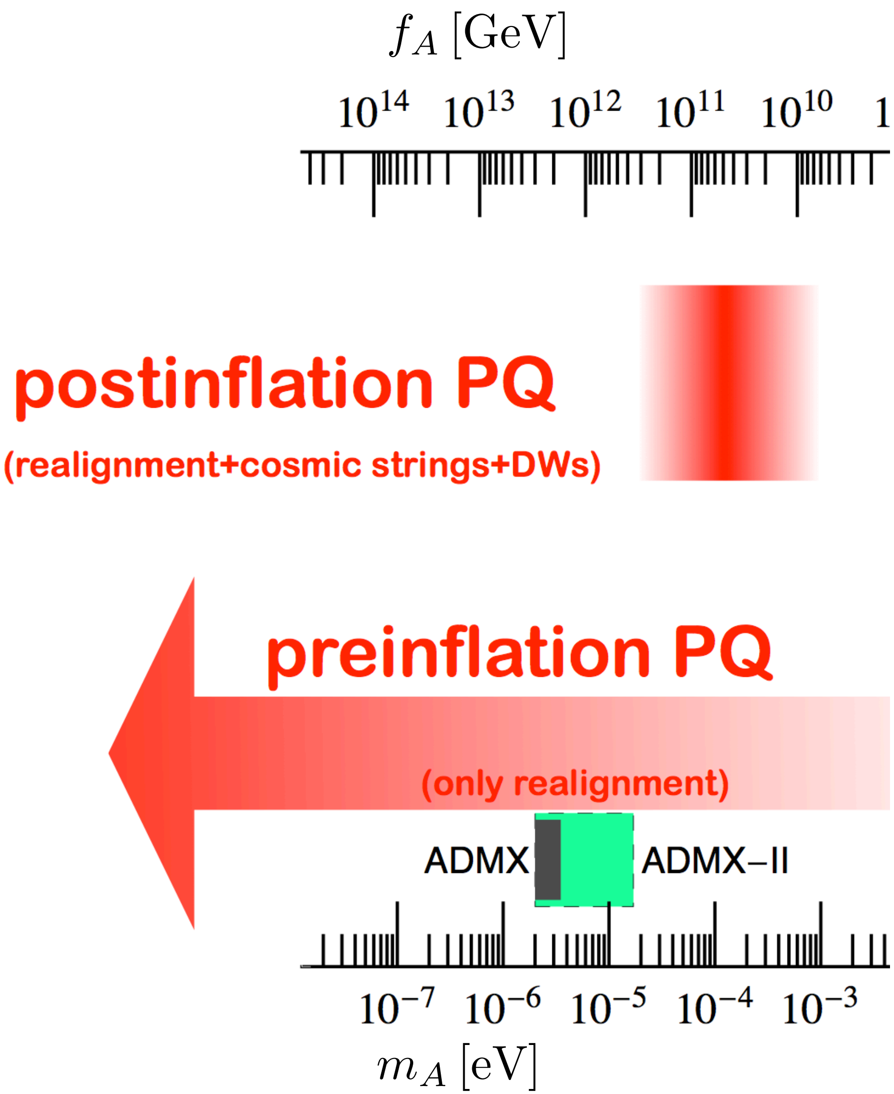
[Hiramatsu et al. 12]

Physics case for axions and ALPs: Cold dark matter

- In post-infl. SSB scenario, decay of cosmic strings and domain walls provide additional CDM axion and ALPs
- Natural range for axion/ALP CDM: "cosmic axion window",

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

("intermediate scale")



[adapted by from Essig et al. 1311.0029]

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

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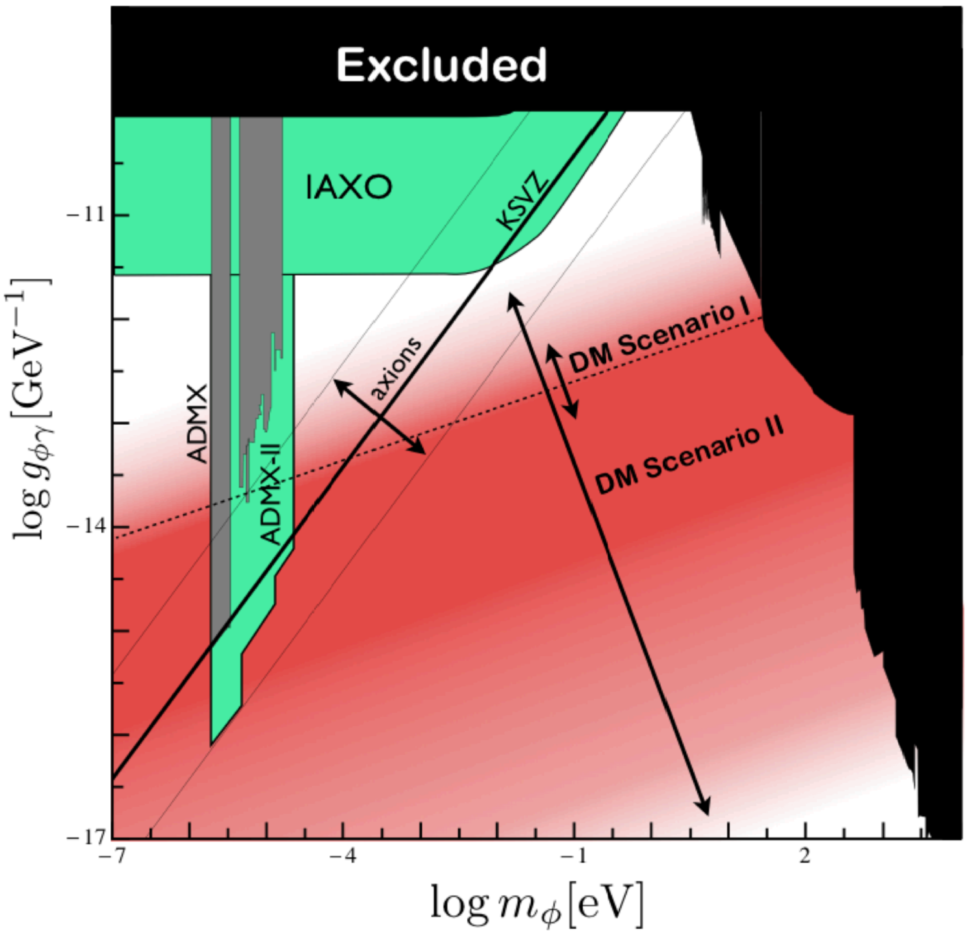
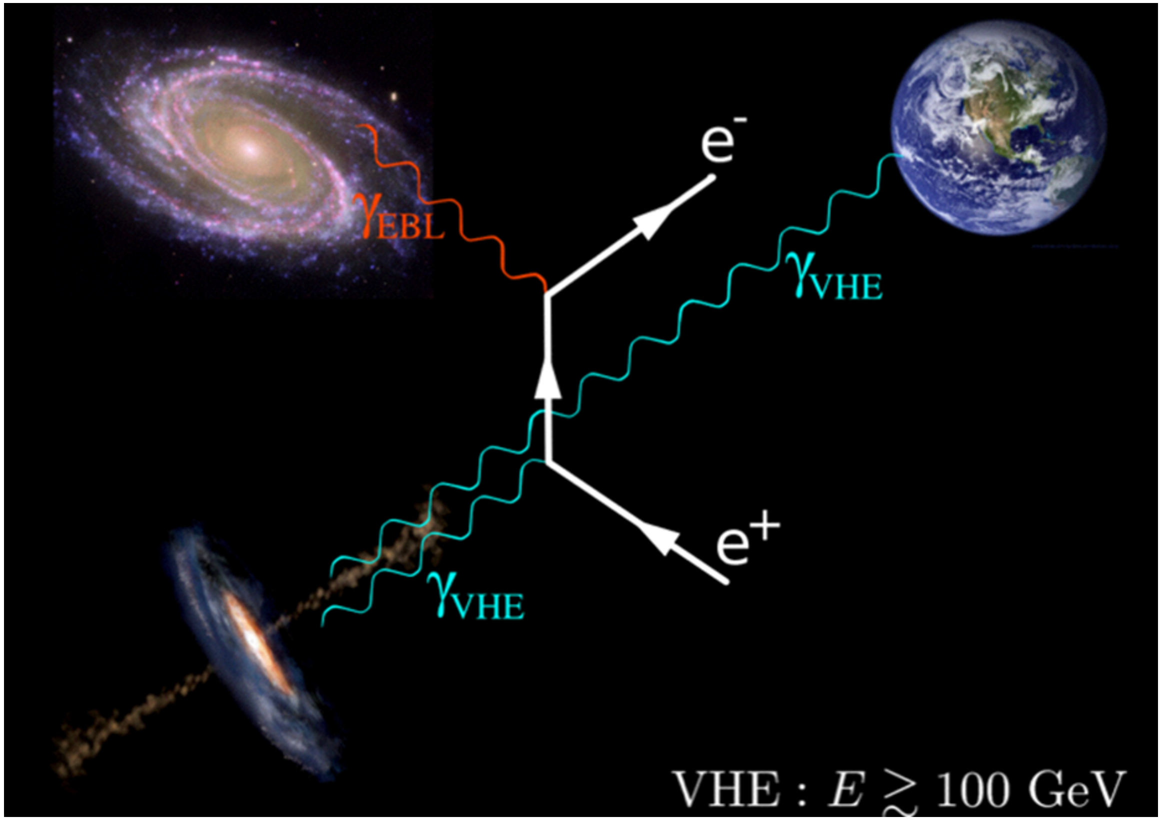
  ("intermediate scale")
- Large search space for axion and ALP CDM in photon coupling $g_{i\gamma} \sim \alpha/(2\pi f_i)$ vs. mass



[Döbrich,Redondo 13]

Physics case for ALPs: Gamma transparency of universe

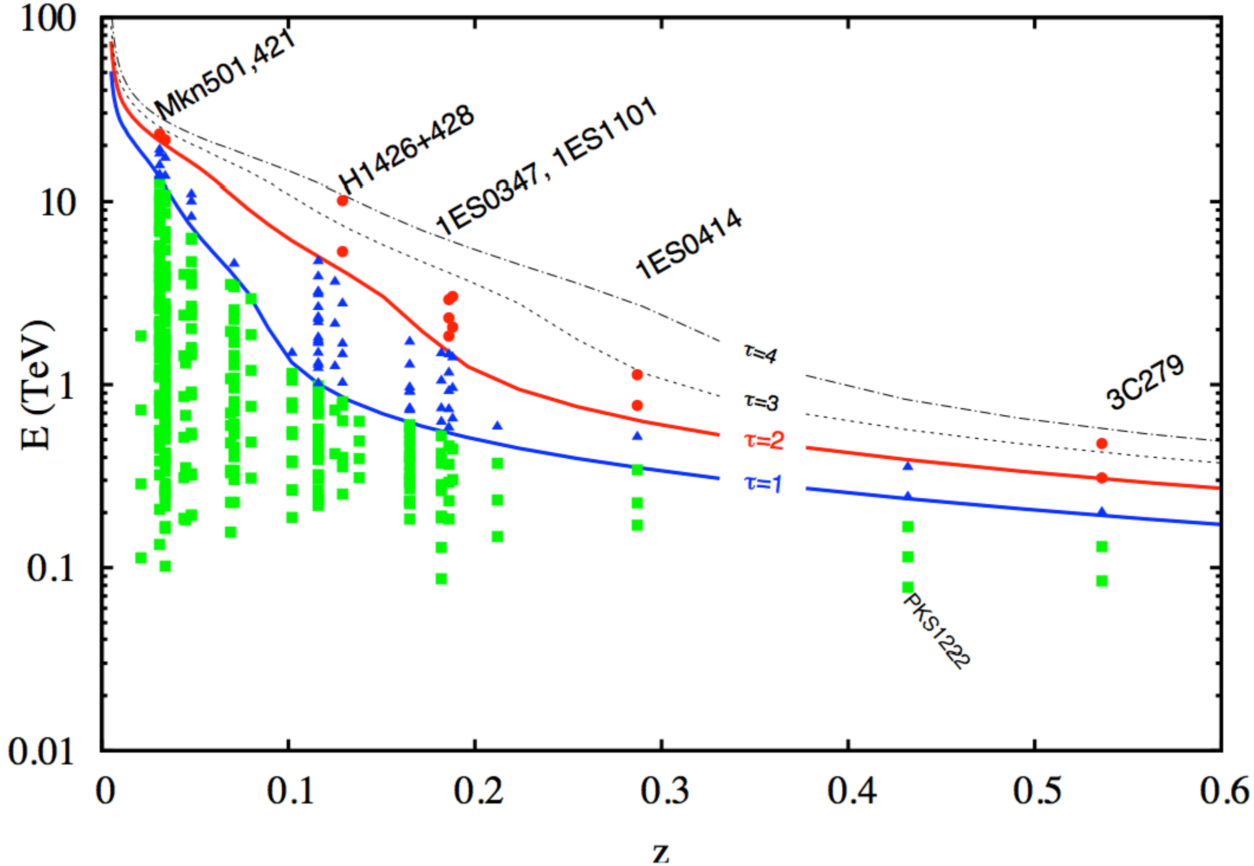
- Gamma ray spectra from distant Active Galactic Nuclei (AGN) should show an energy and distance (red-shift) dependent exponential attenuation, $\propto \exp(-\tau(E,z)); \tau(E,z) = \int_0^z dz' \int d\epsilon' \ldots n_{\rm EBL}(\epsilon',z')\sigma_{\gamma\gamma}(E,\epsilon',\ldots)$, due to pair production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



[Manuel Meyer 12]

Physics case for ALPs: Gamma transparency of universe

- At $\tau \gtrsim 1$, however, evidence for anomalous gamma transparency, from IACT and Fermi data [Aharonian et al. 07; Aliu et al. 08;...; Horns,Meyer 12;...; Rubtsov,Troitsky 14]



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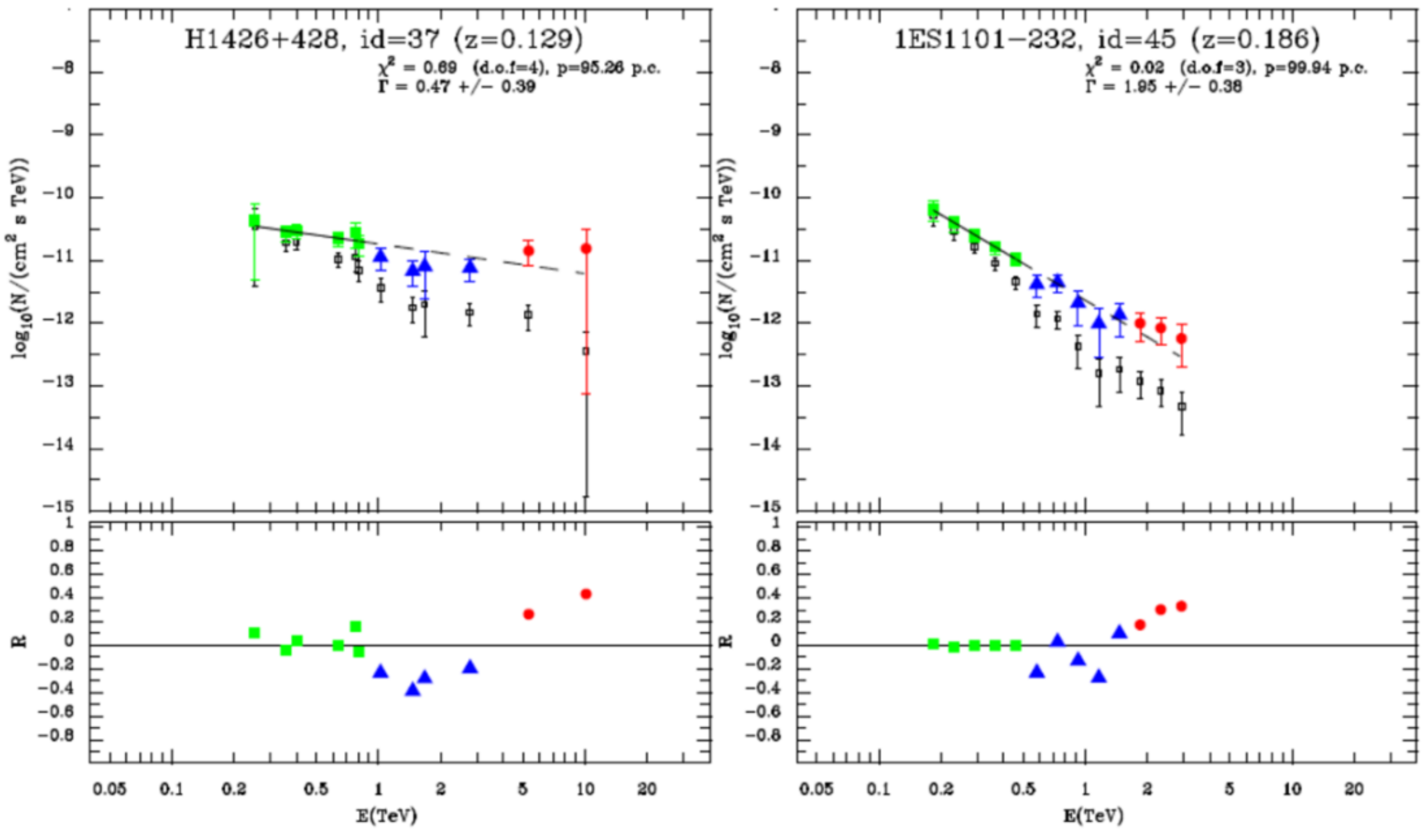
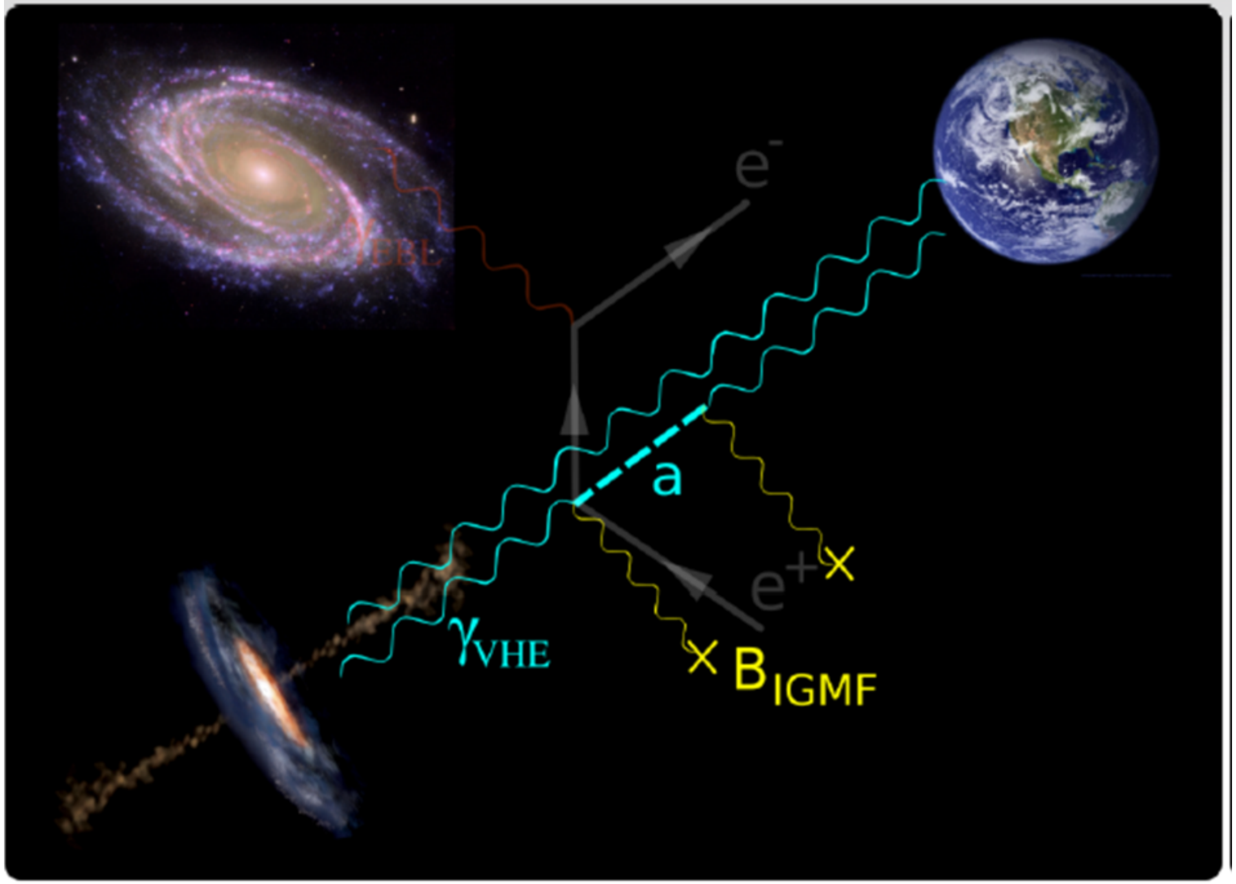


[Horns,Meyer 12]

Physics case for ALPs: Gamma transparency of universe

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



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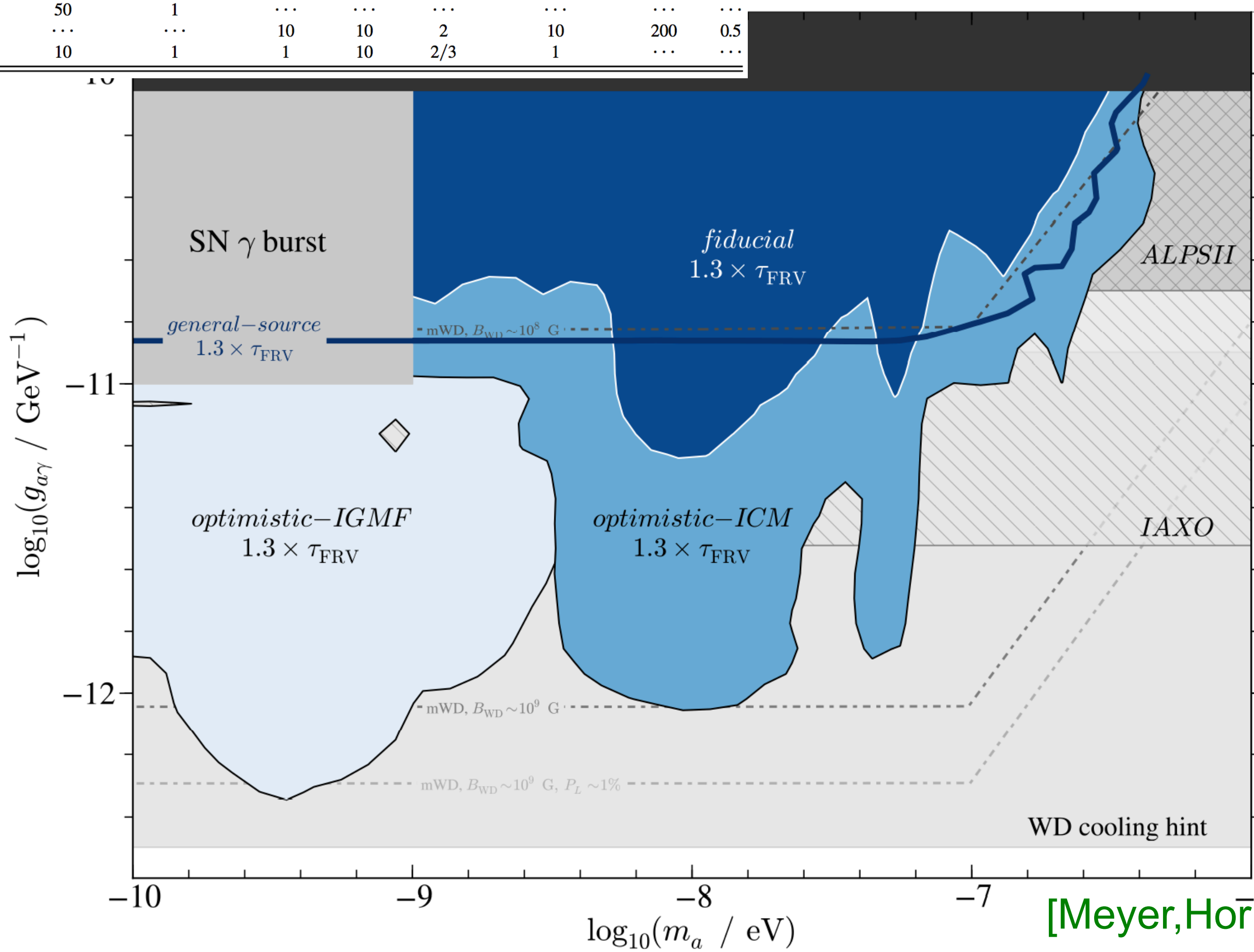
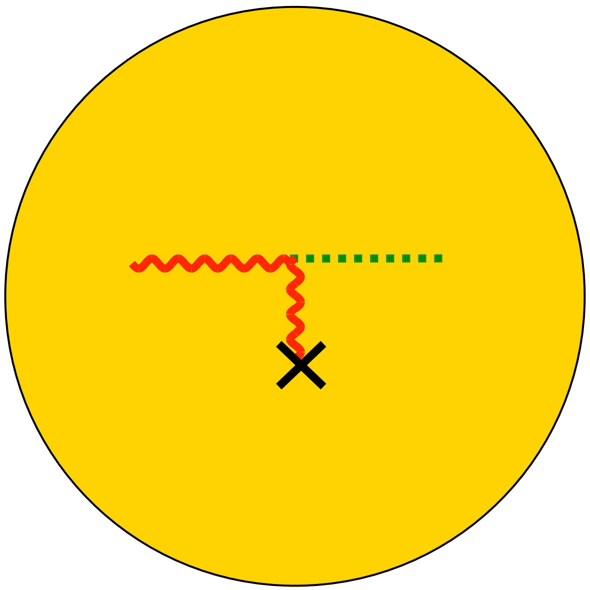
	IGMF			ICM					
Name	$B^0_{\rm IGMF}$ (nG)	$\lambda^c_{\rm IGMF}$ (Mpc)	$n^0_{\rm el,IGM}$ ($\times 10^{-7}$ cm^{-3})	$B^0_{\rm ICMF}$ (μG)	$\lambda^c_{\rm ICMF}$ (kpc)	$r_{\rm cluster}$ (Mpc)	$n^0_{\rm el,ICM}$ ($\times 10^{-3}$ cm^{-3})	$r_{\rm core}$ (kpc)	η
General source	Only conversion in GMF,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

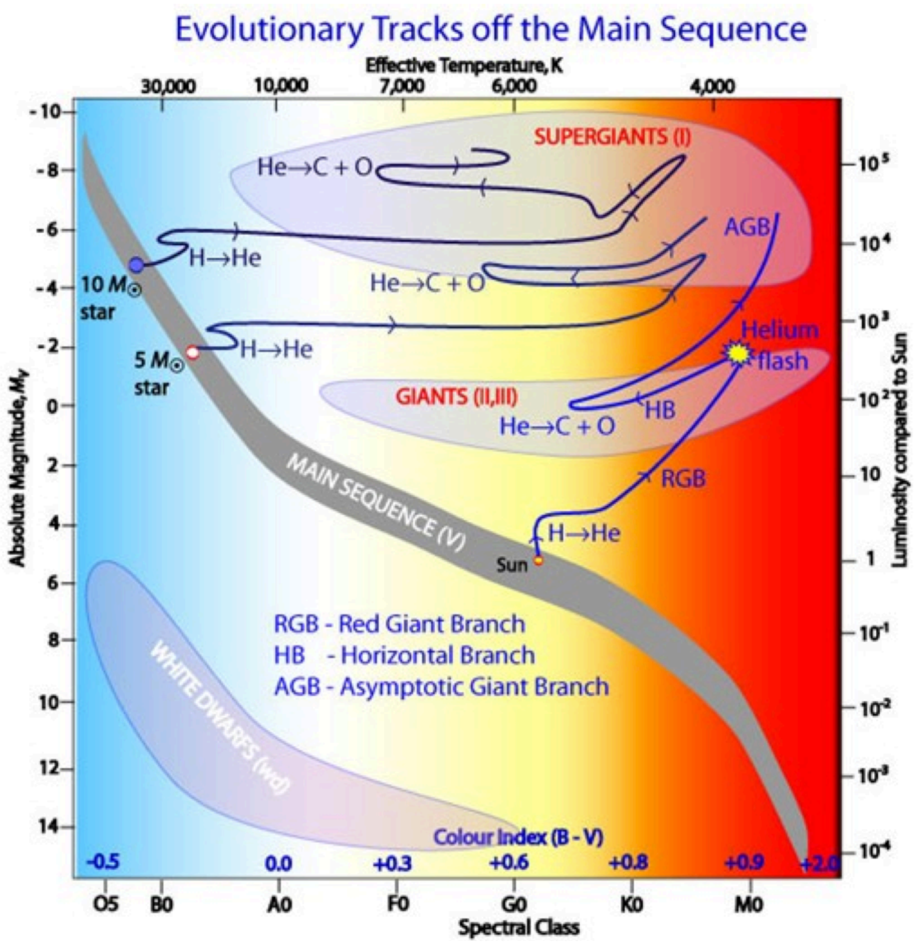


[Meyer,Horns,Raue 13]

Physics case for ALPs: Horizontal branch star cooling

- Star cooling through photon-ALP conversion in stellar cores would reduce ratio of the number of stars in the horizontal and in the red giant branch of old stellar clusters





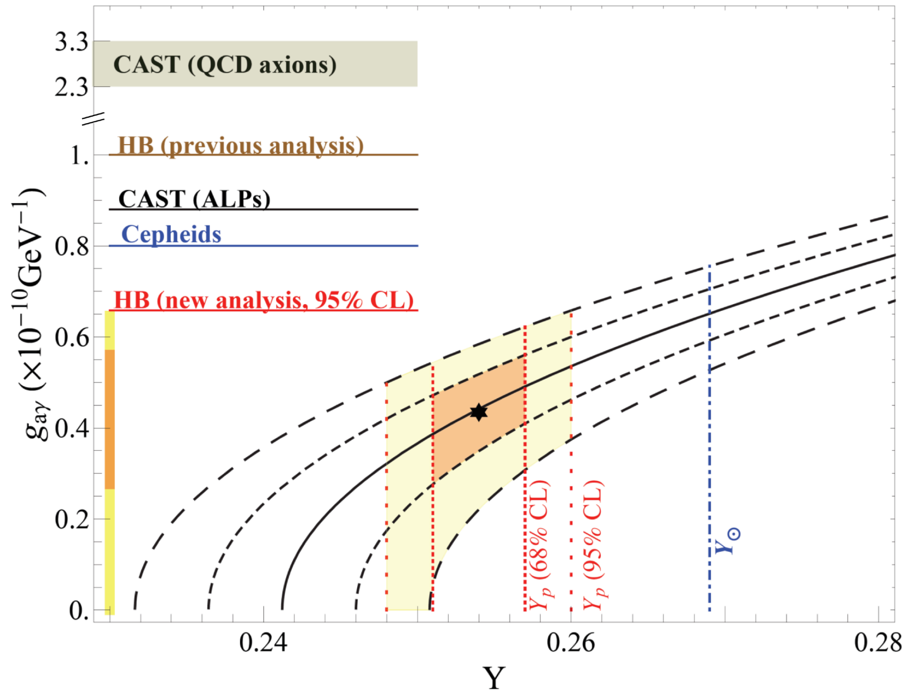
Physics case for ALPs: Horizontal branch star cooling

- Star cooling through photon-ALP conversion in stellar cores would reduce ratio of the number of stars in the horizontal and in the red giant branch of old stellar clusters
- New analysis of sample of 39 Galactic Globular Clusters compared to prediction of state-of-the-art stellar models
  - Small non-zero axion-photon coupling improves the agreement between models and observations,

$$g_{a\gamma} = 0.45^{+0.12}_{-0.16} \times 10^{-10}\ \mathrm{GeV}^{-1}$$

  - Conservative upper limit,

$$g_{a\gamma} < 0.66 \times 10^{-10}\ \mathrm{GeV}^{-1}$$

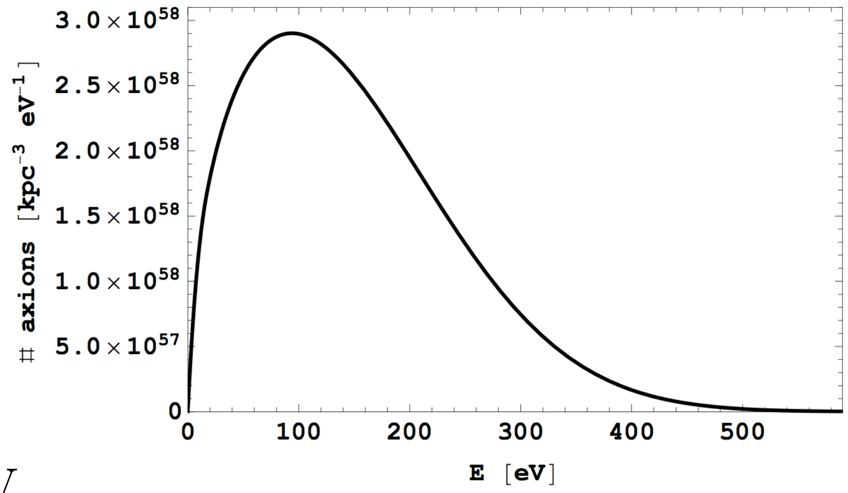


[Ayala,Dominguez,Gianotti,Mirizzi,Straniero 14]

Physics case for ALPs: Cosmic ALP background radiation

- Hints of dark radiation $\triangle N_{\text{eff}}$ 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, $\sim 10^6\,\text{GeV}$

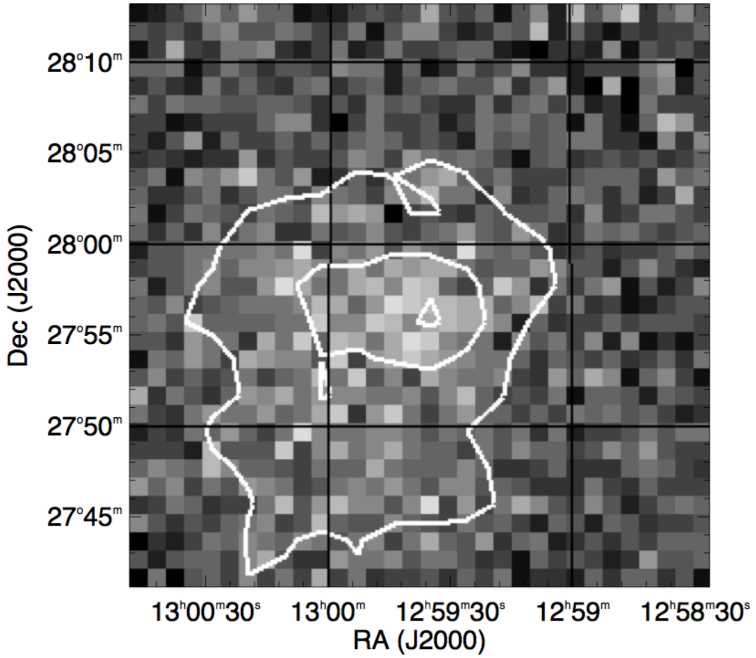
  [Cicoli,Conlon,Quevedo 12; Higaki,Takahashi 12]



- 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]

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

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



[Boyer et al., Soft excess in Coma as observed by EUVE 04]

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

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

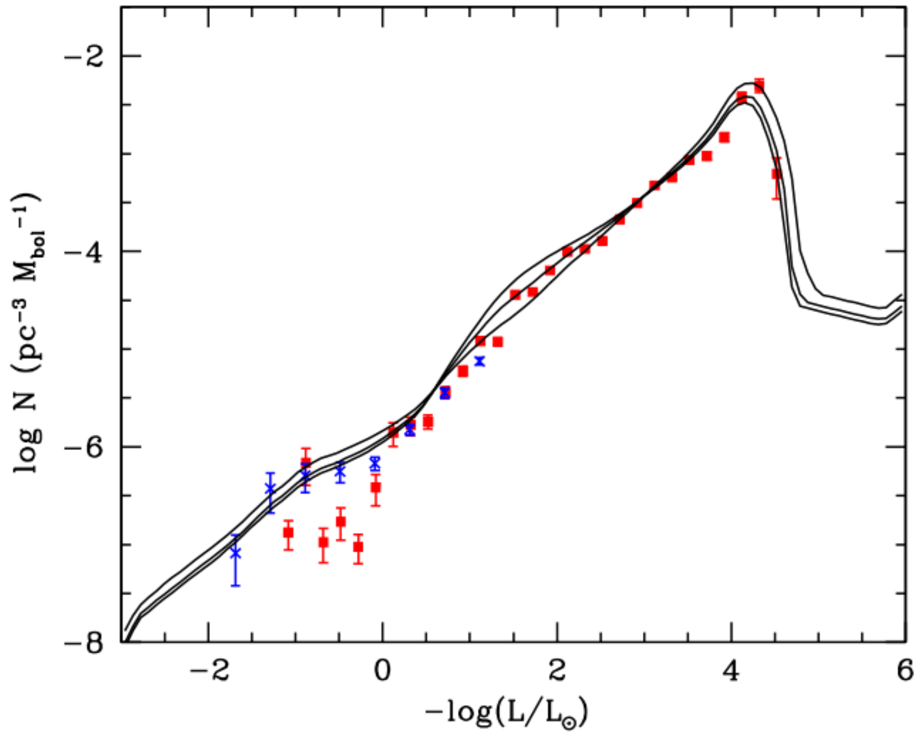
of size

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

and thus intermediate scale

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

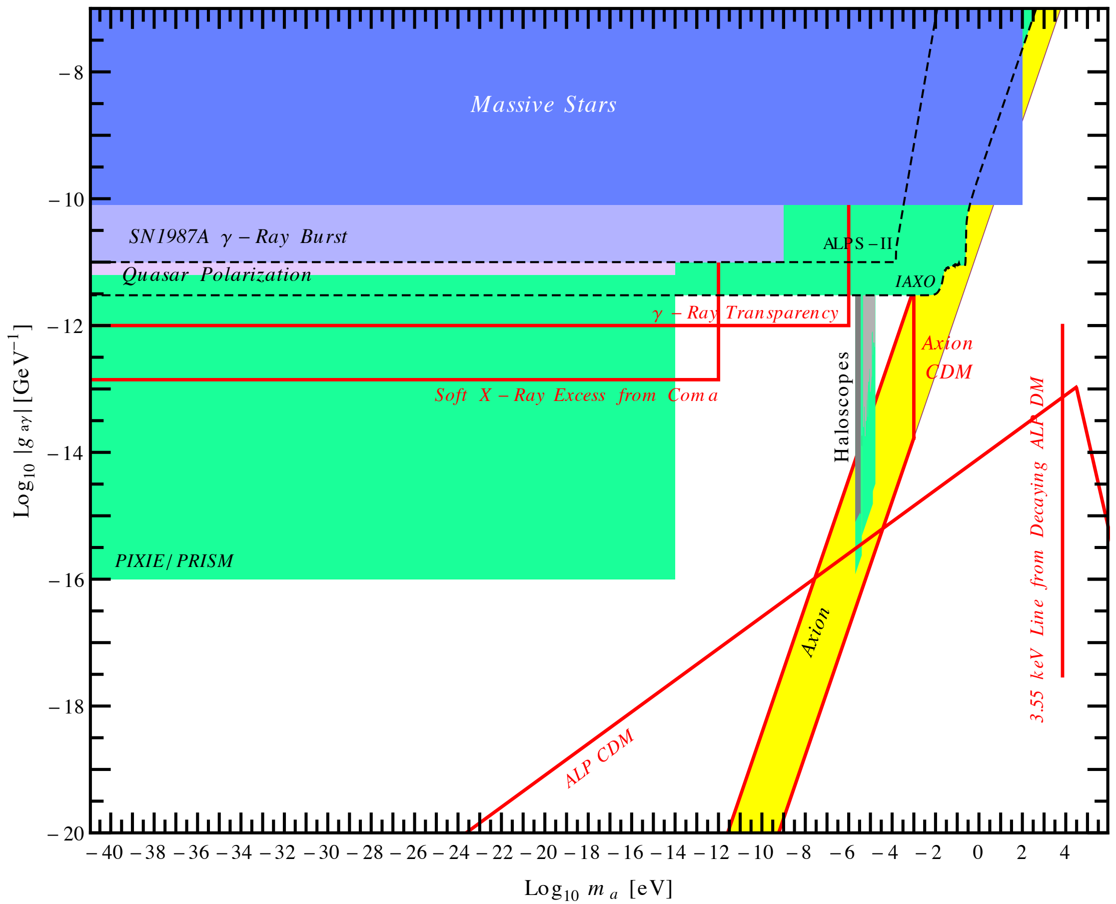
$$\text{for} \quad m_A, m_a \lesssim \text{keV}$$



[Isern 09]

Physics case for ALPs: Summary of astro/cosmo hints

- There are very-well motivated search regions for axions and ALPs:



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

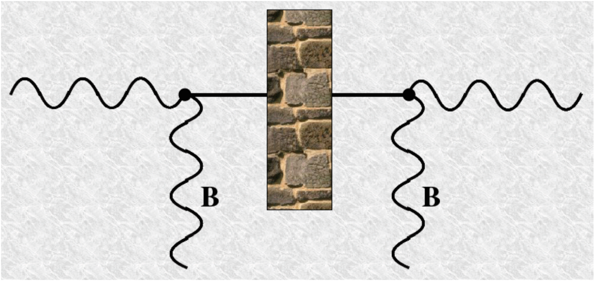
Intermediate scale axions/ALPs may be found in lab exps

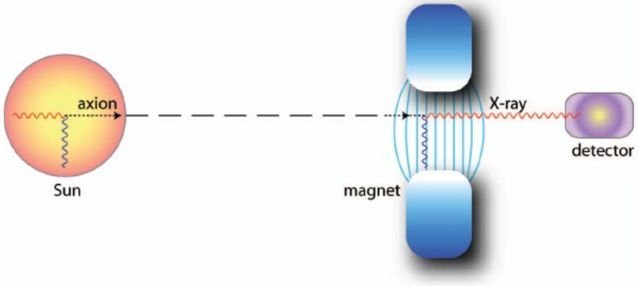
> Axions and ALPs with decay constants in the intermediate scale range

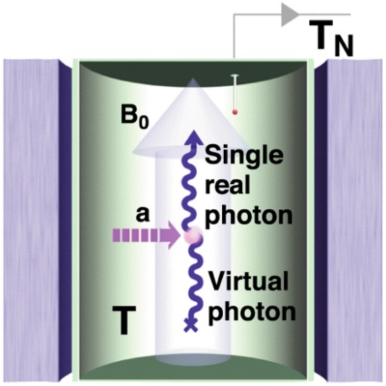
$$10^8\,\mathrm{GeV} \lesssim f_A, f_a \lesssim 10^{12}\,\mathrm{GeV}$$

can be searched for in the laboratory with

- 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]
- haloscopes: direct detection of DM axions/ALPs [Sikivie 83]







Axion/ALP experiments worldwide

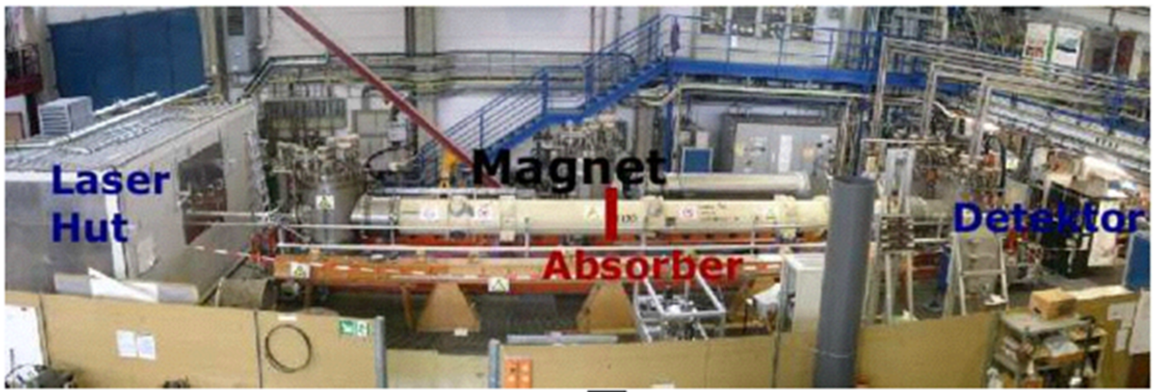
An incomplete selection of (mostly) small-scale experiments:

Experiment	Type	Location	Status
ALPS II	Laboratory experiments, light-shining-through-a-wall	DESY	preparation
CROWS		CERN	finished
OSQAR		CERN	running
REAPR		FNAL	proposed
CAST	Helioscopes	CERN	running
IAXO		?	proposed
SUMICO		Tokyo	running
ADMX	Haloscope	Seattle, NH	running
WISPDMX		DESY	studies

[Lindner `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



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

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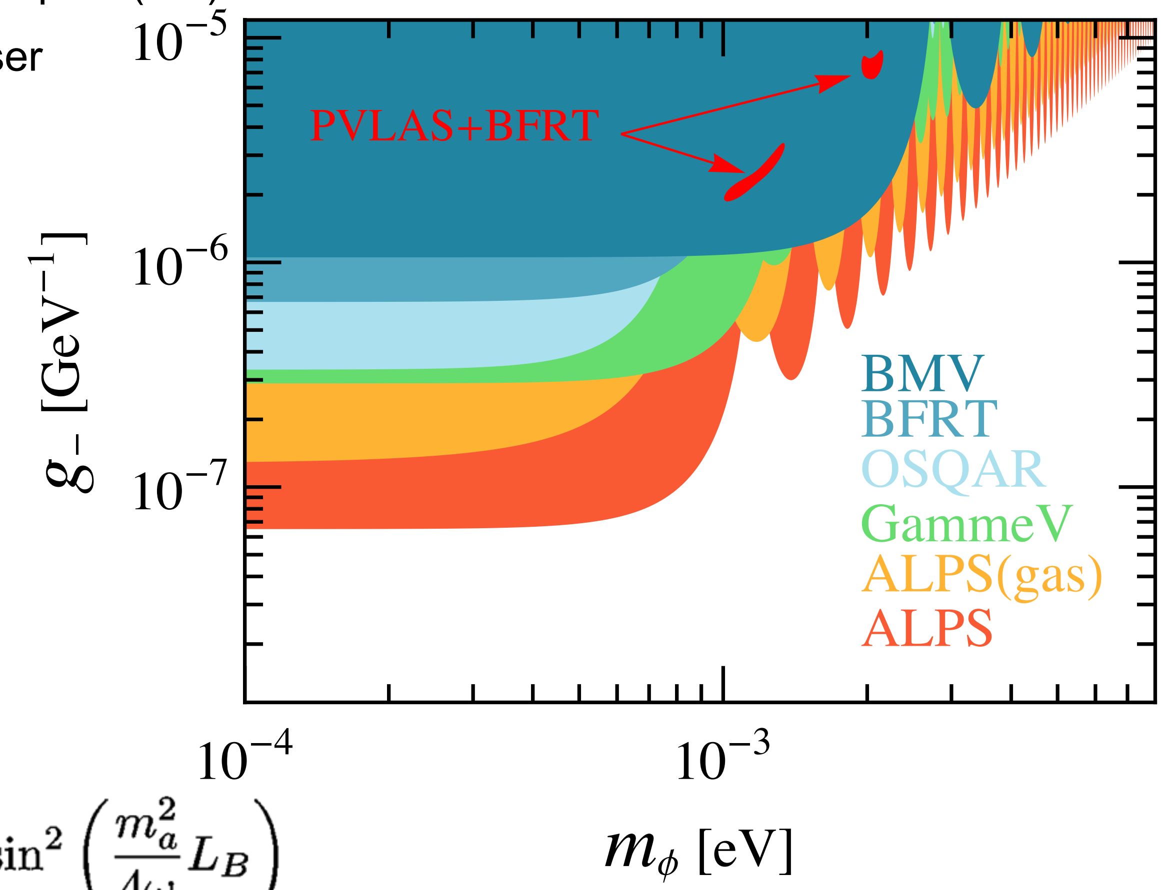
[Ehret et al. (ALPS I) `10]



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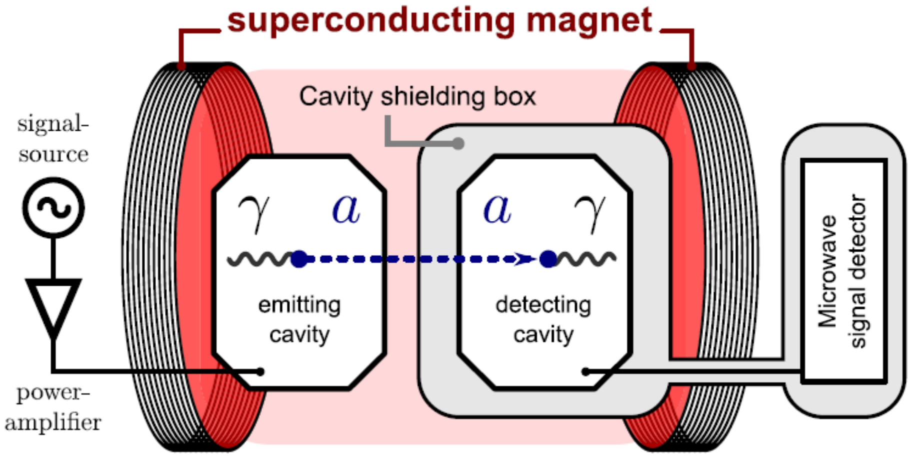
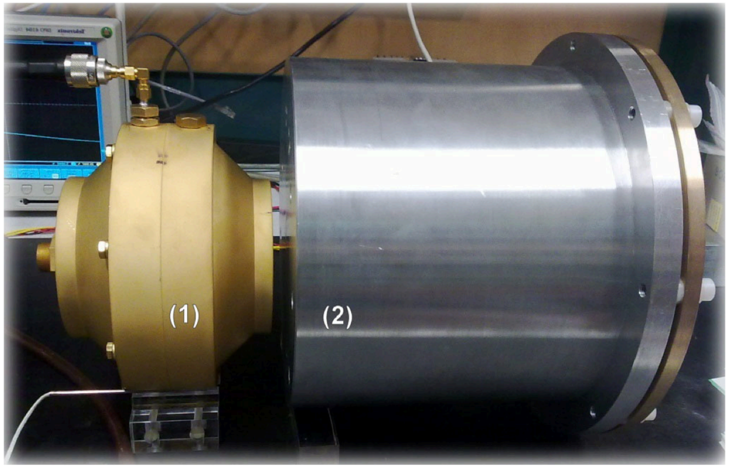
Light-shining-through-a-wall searches

- Microwaves shining through a shielding
  [Hoogeveen 92; Jaeckel,AR `08; Caspers,Jaeckel,AR `09]
- CERN ResOnant Weakly interacting sub-eV particle Search (CROWS)
  [Betz et al. (CROWS) `13]





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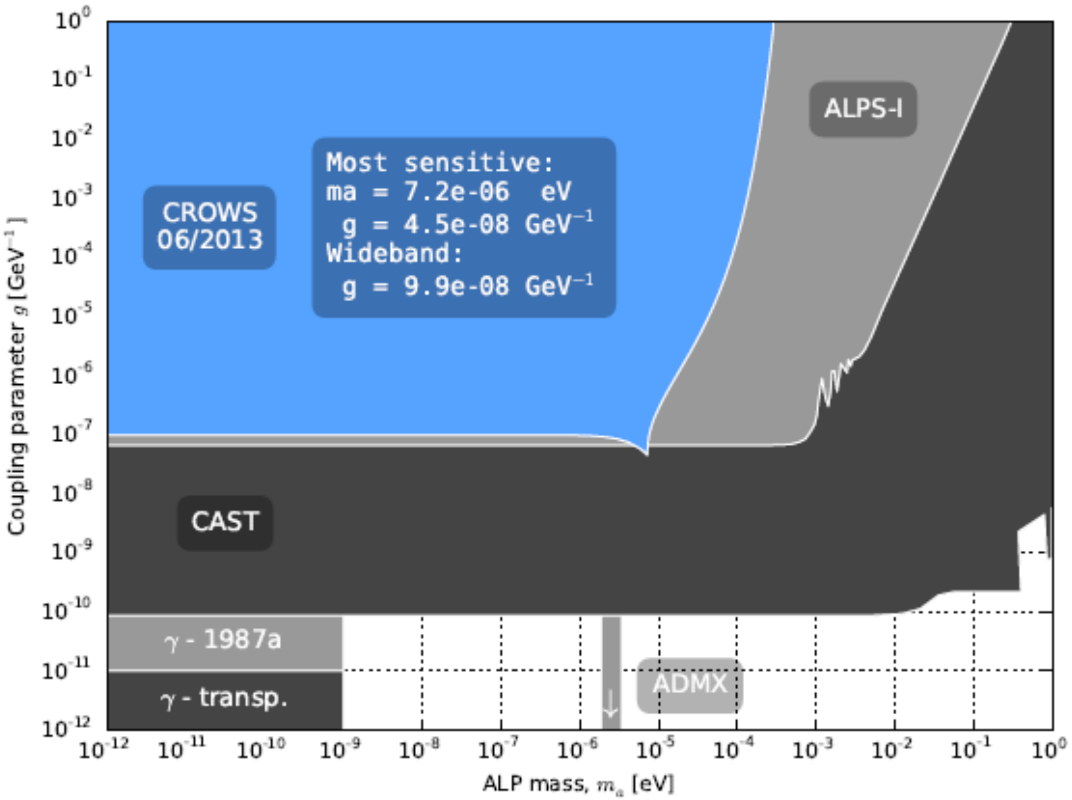
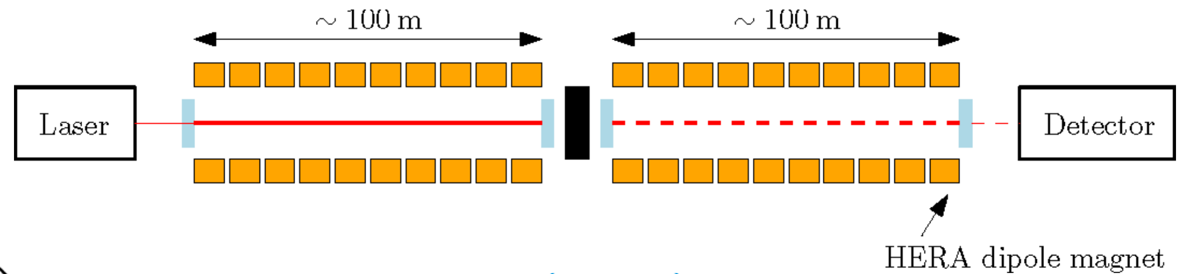
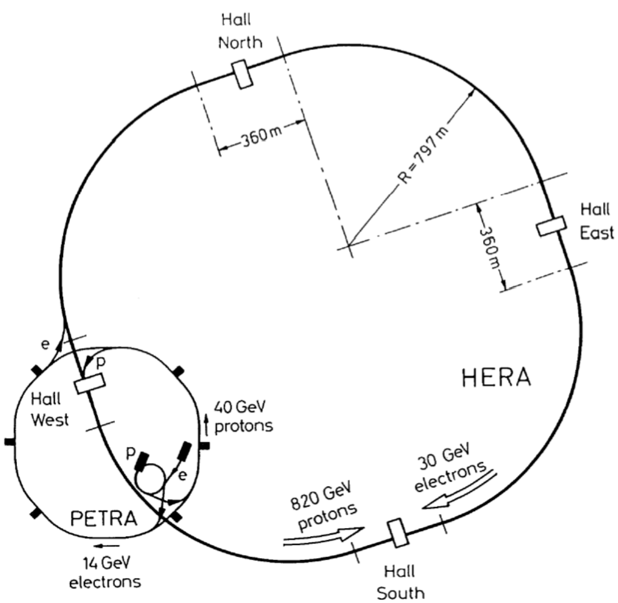
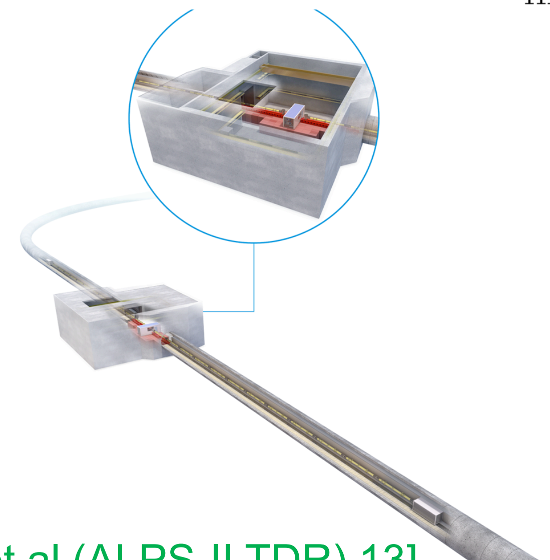


Light-shining-through-a-wall searches

- 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

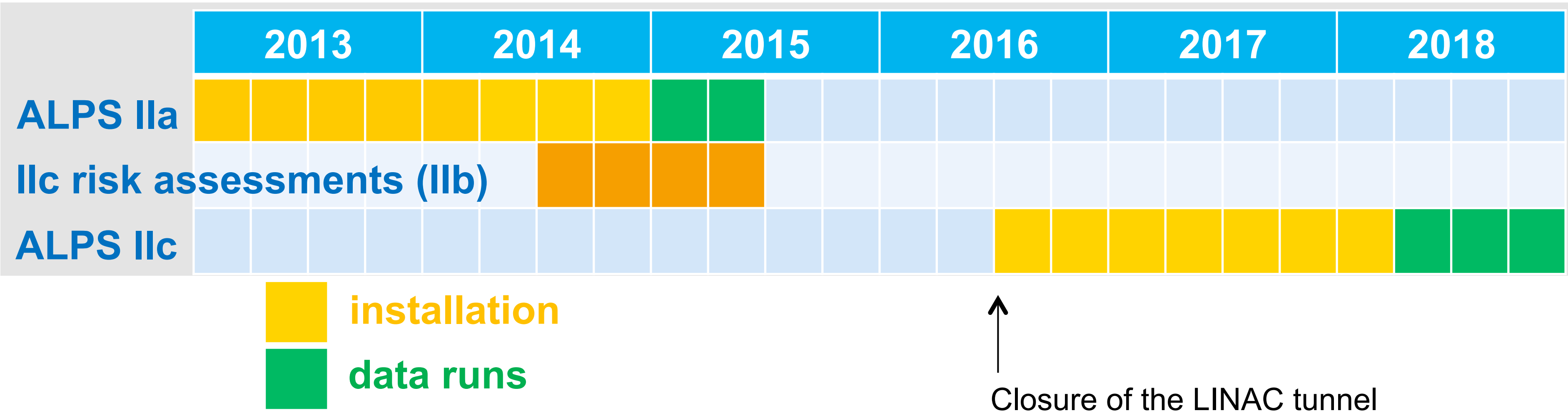






[Bähre et al (ALPS-II TDR) 13]

Light-shining-through-a-wall searches

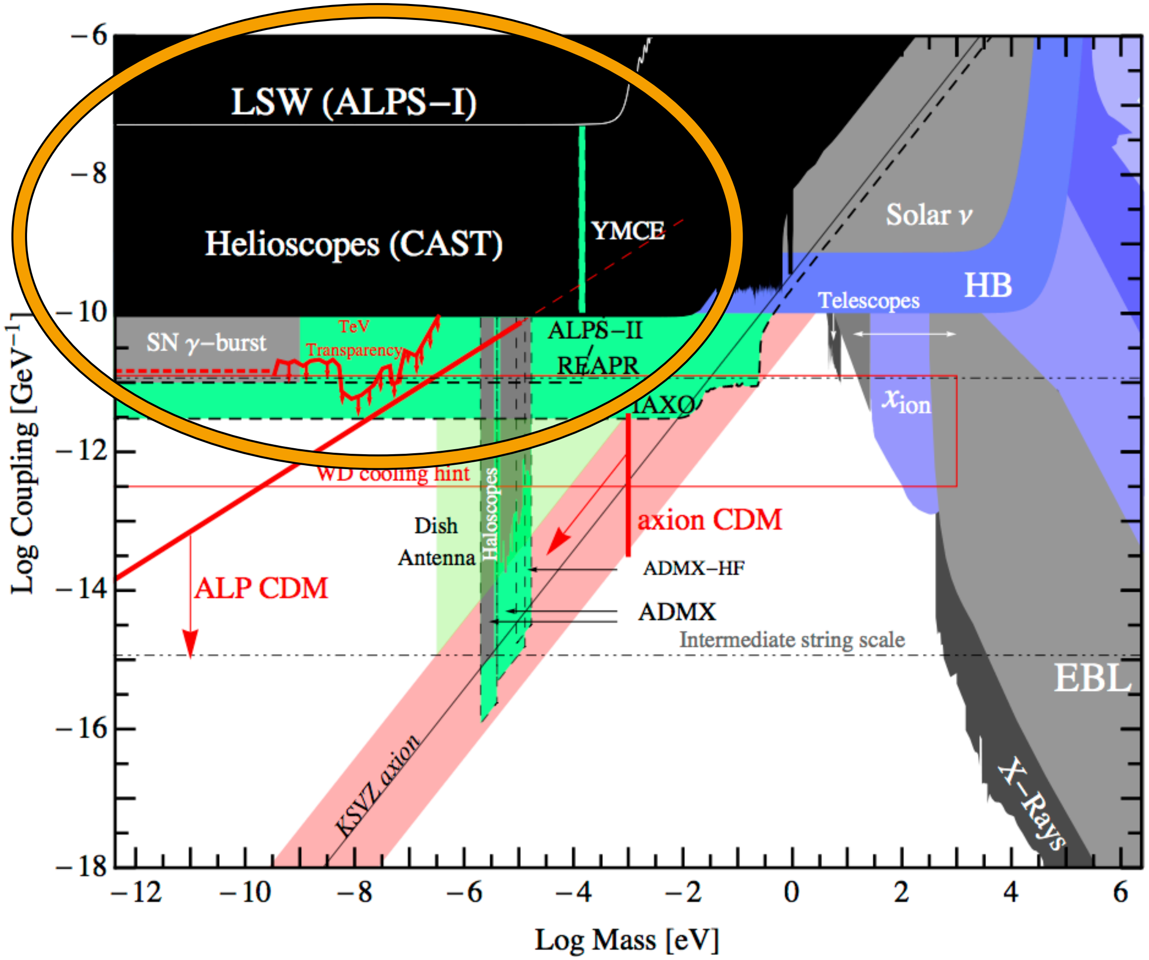


Closure of the LINAC tunnel of the European XFEL project under construction at DESY.

ALPS IIc in 2018
in HERA tunnel

Light-shining-through-a-wall searches

> ALPS II will explore new territory and probe TeV transparency region:



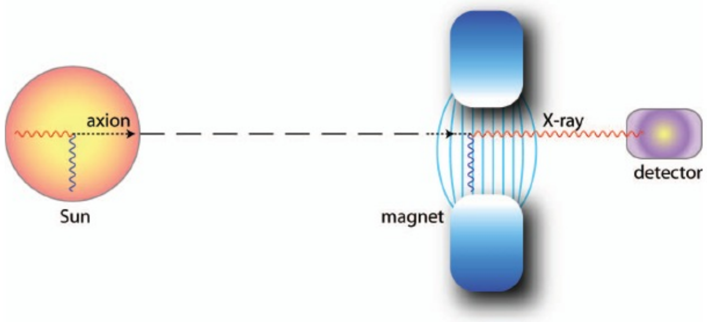
[Essig et al. 1311.0029]

Helioscope searches

> Most sensitive until now: CERN Axion Solar Telescope (CAST)

- Superconducting LHC dipole magnet
- X-ray detectors

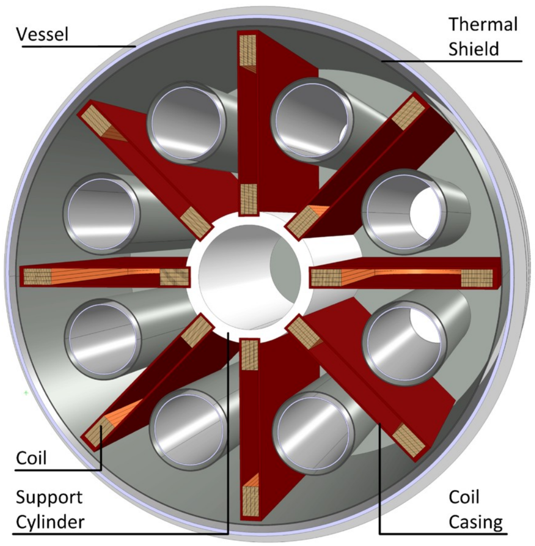
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

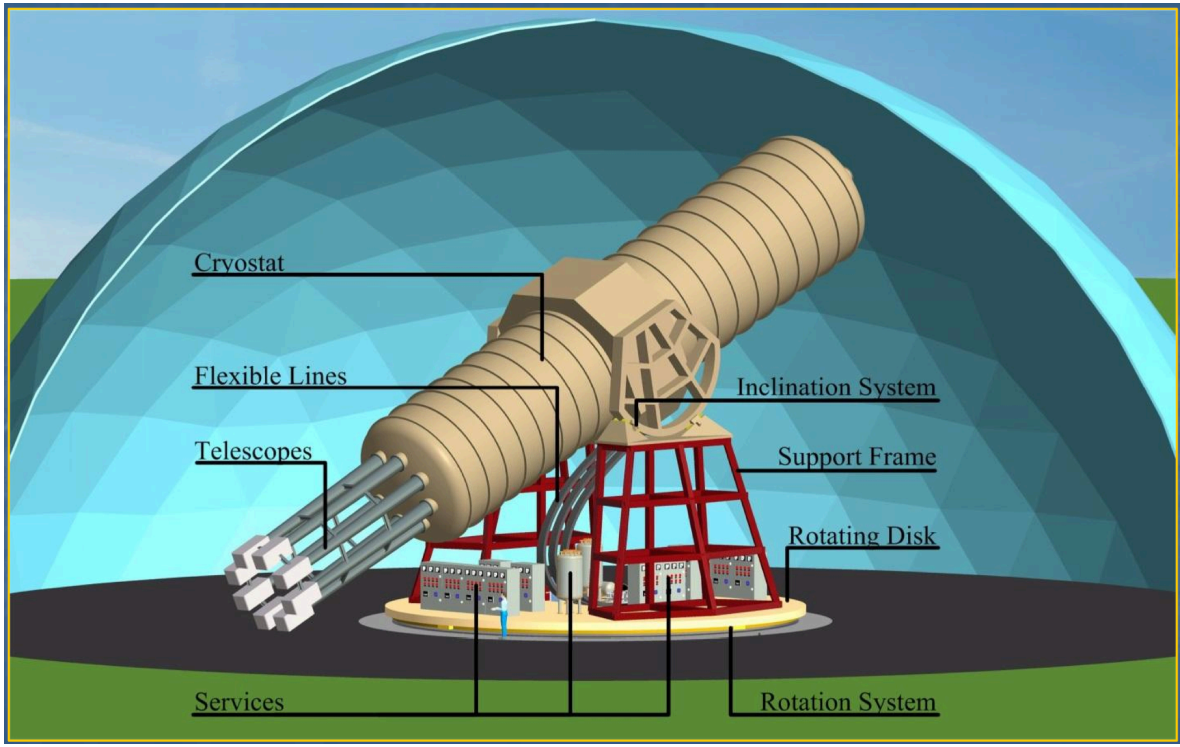


Helioscope searches

> 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

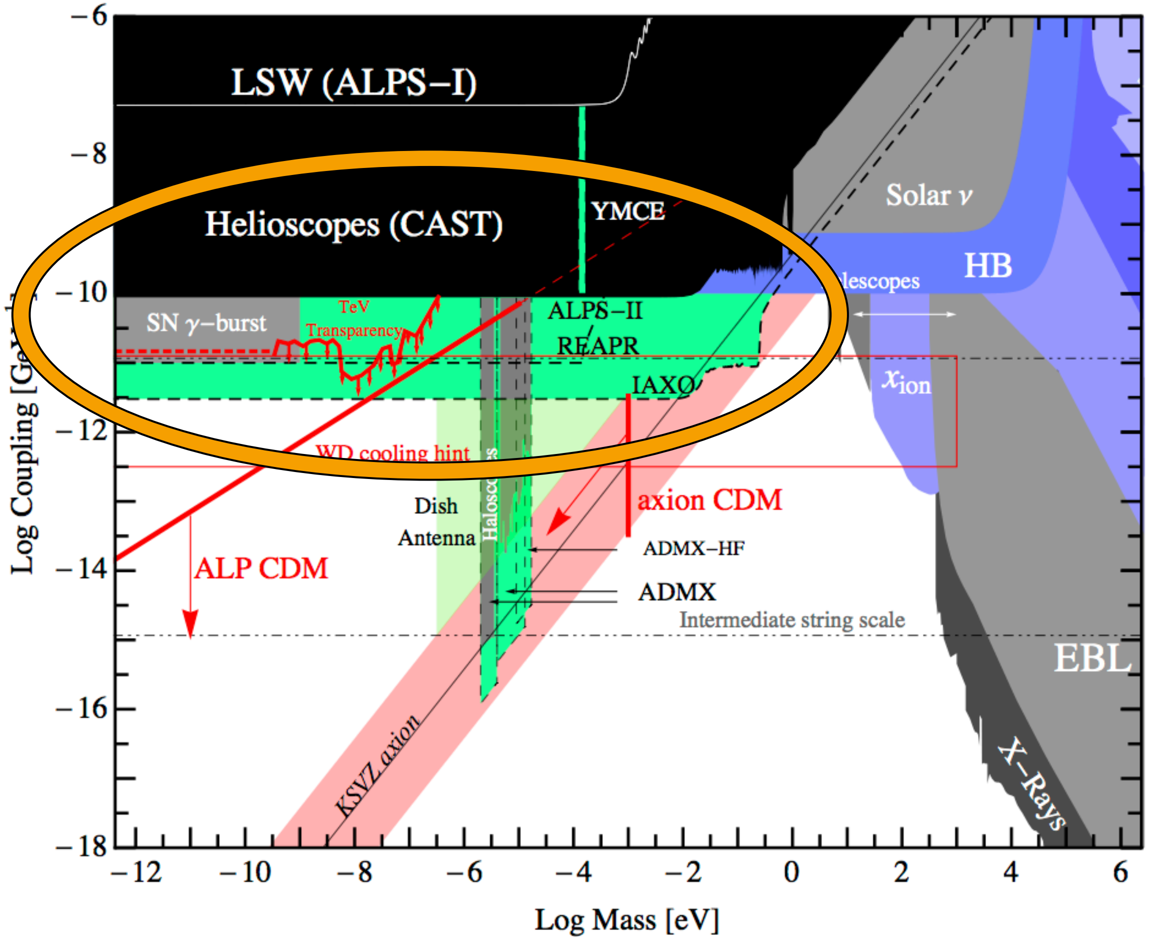




[Armengaud et al (IAXO CDR) 1401.3233]

Helioscope searches

- IAXO will explore new territory, probe TeV transpareny and CAB region:

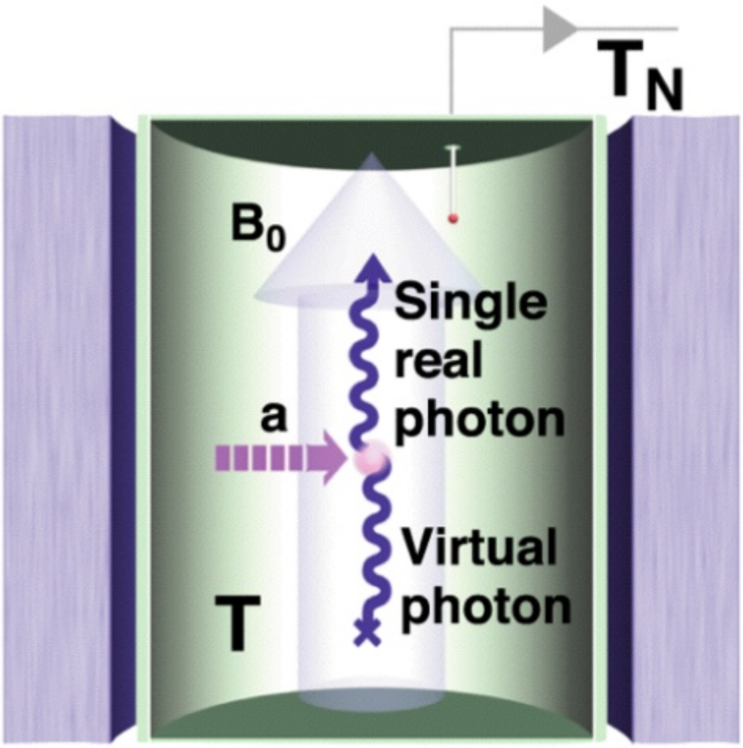


adapted from [Hewett et al 12]

Haloscope searches: Resonant cavities

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

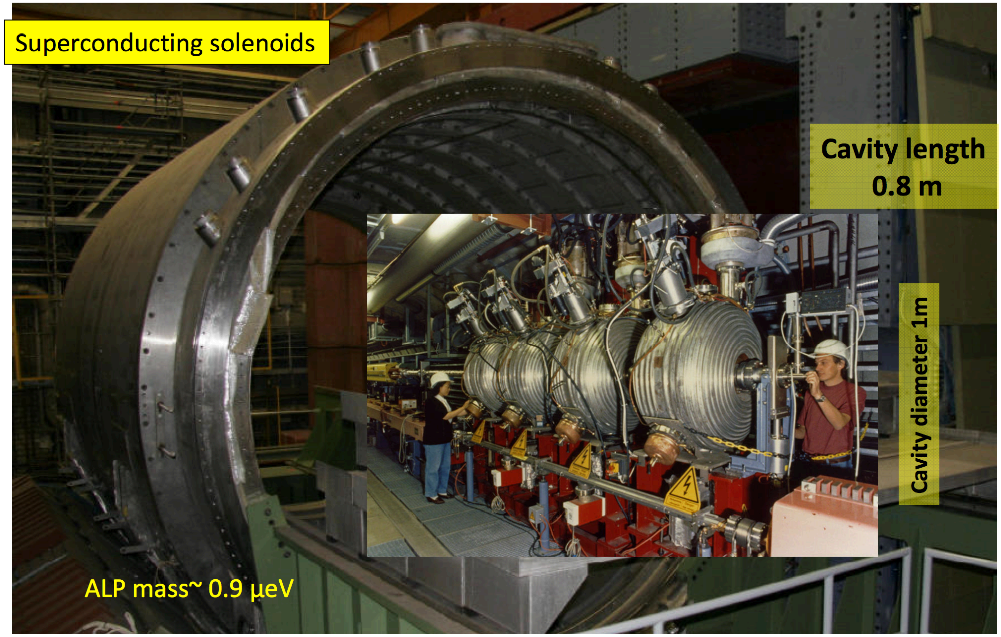
Best sensitivity: mass = resonance frequency $m_a = 2\pi\nu \sim 4\ \mu\text{eV}\left(\frac{\nu}{\text{GHz}}\right)$



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

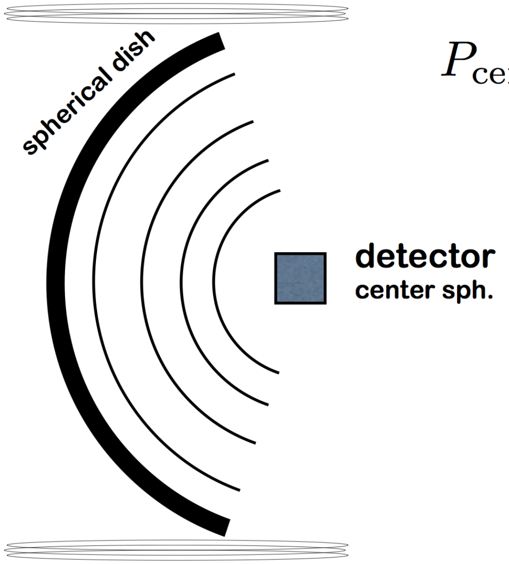
Haloscope searches: Resonant cavities

- 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
- A magnetised mirror in axion/ALP DM background radiates photons
- Simple broadband experiment: spherical dish antenna [Horns et al. 12]



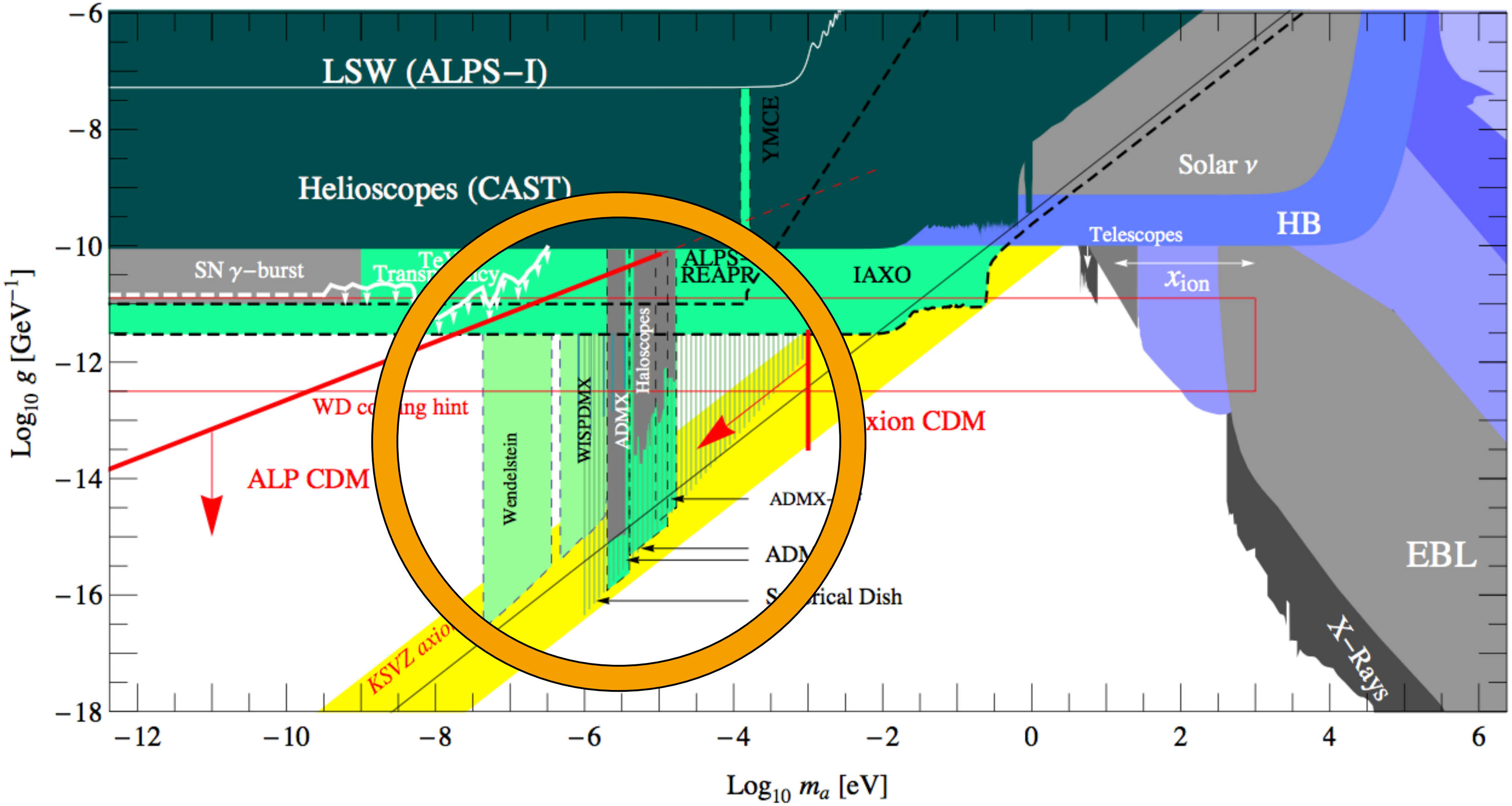
$$P_{\rm center} \approx \langle |\mathbf{E}_a|^2 \rangle A_{\rm dish} \sim \chi^2 \rho_{\rm CDM} A_{\rm dish}$$

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

- Pilot dish experiment at KIT in Karlsruhe presently being setup

Haloscopes: Resonant cavities and broadband searches

> ADMX and proposed broadband searches probe sizeable region:



[Horns,Lindner,Lobanov,AR `13]

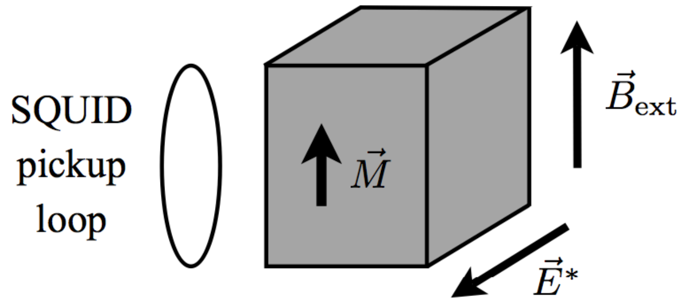
Haloscope searches: Precision magnetometry

- 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.

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

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

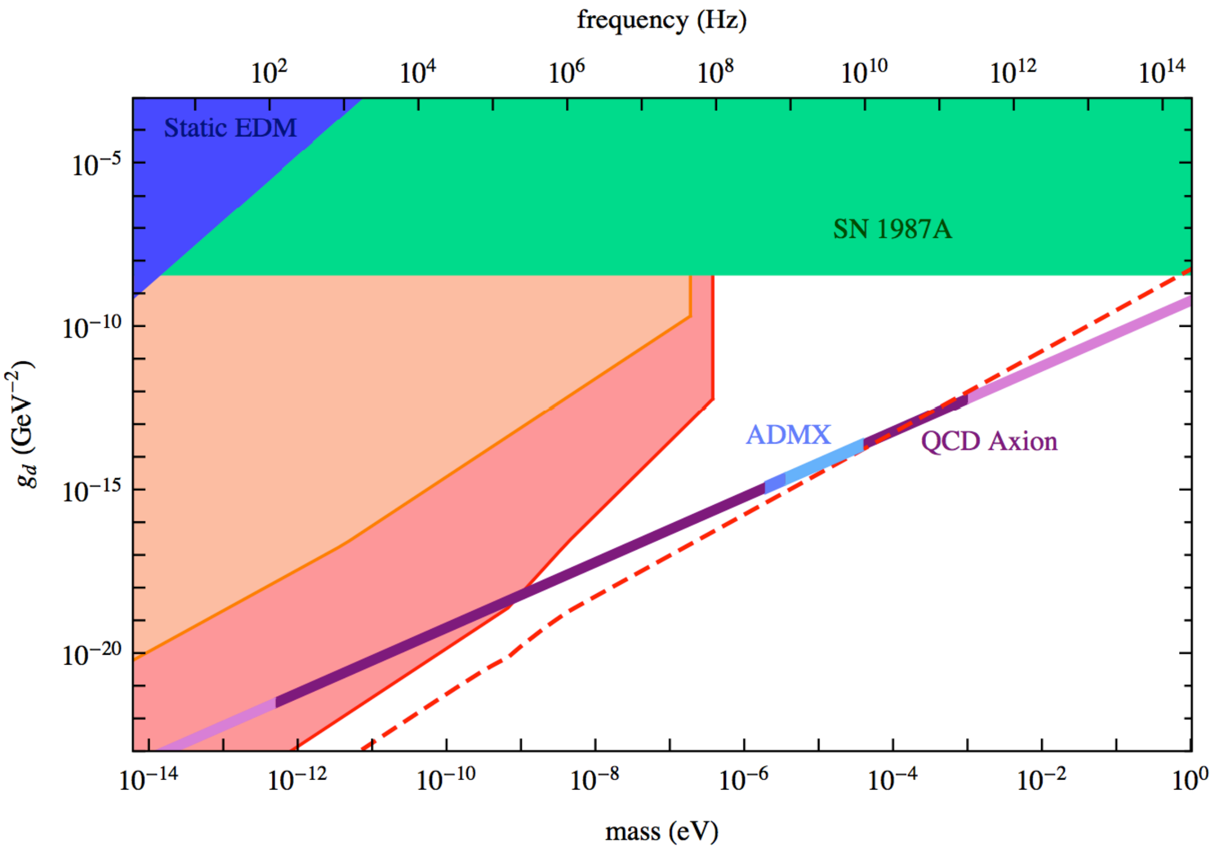
  - Moments cause precession of nuclear spins in material sample in presence of background electric field
  - Can be searched for with precision magnetometry [Graham,Rajendran 13; Budker et al 11]



  - 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) planned to be build at Helmholtz Institute in Mainz



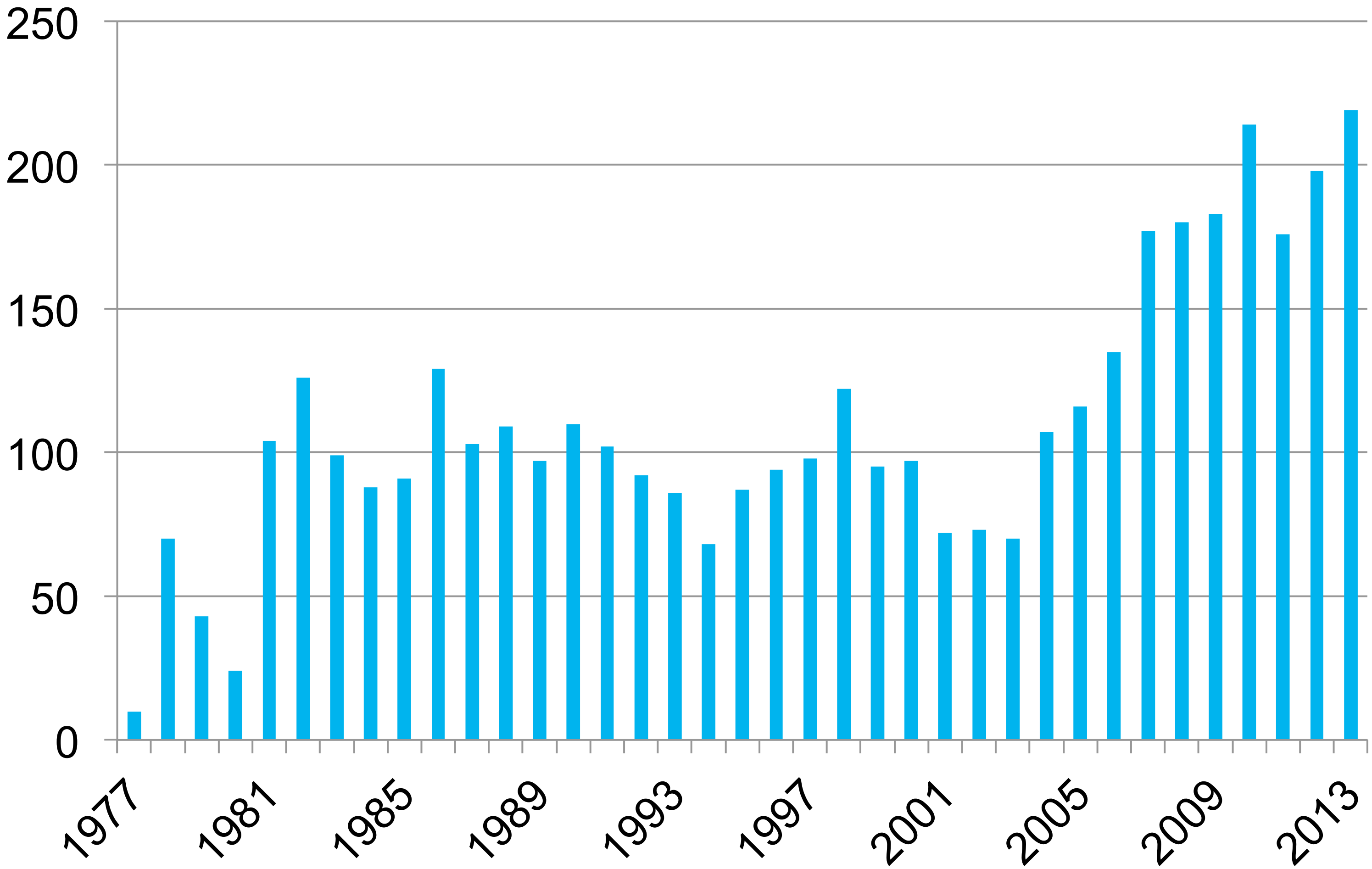
[Budker et al 13]

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, 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 can explain anomalous energy loss of horizontal branch stars
  - ALPs can explain soft X-ray excesses from galaxy clusters
- Intermediate scale region in axion and ALPs parameter space will be tackled in the upcoming decade by a number of experiments:
  - Light-shining-through-a-wall experiments
  - Helioscopes
  - Haloscopes

Good investment: DAX (Dow Jones Axion IndeX) grows!

> inSPIRE: Citation of Peccei-Quinn papers or title axion (and similar)



[Raffelt 14]