The Hunt for Axions.

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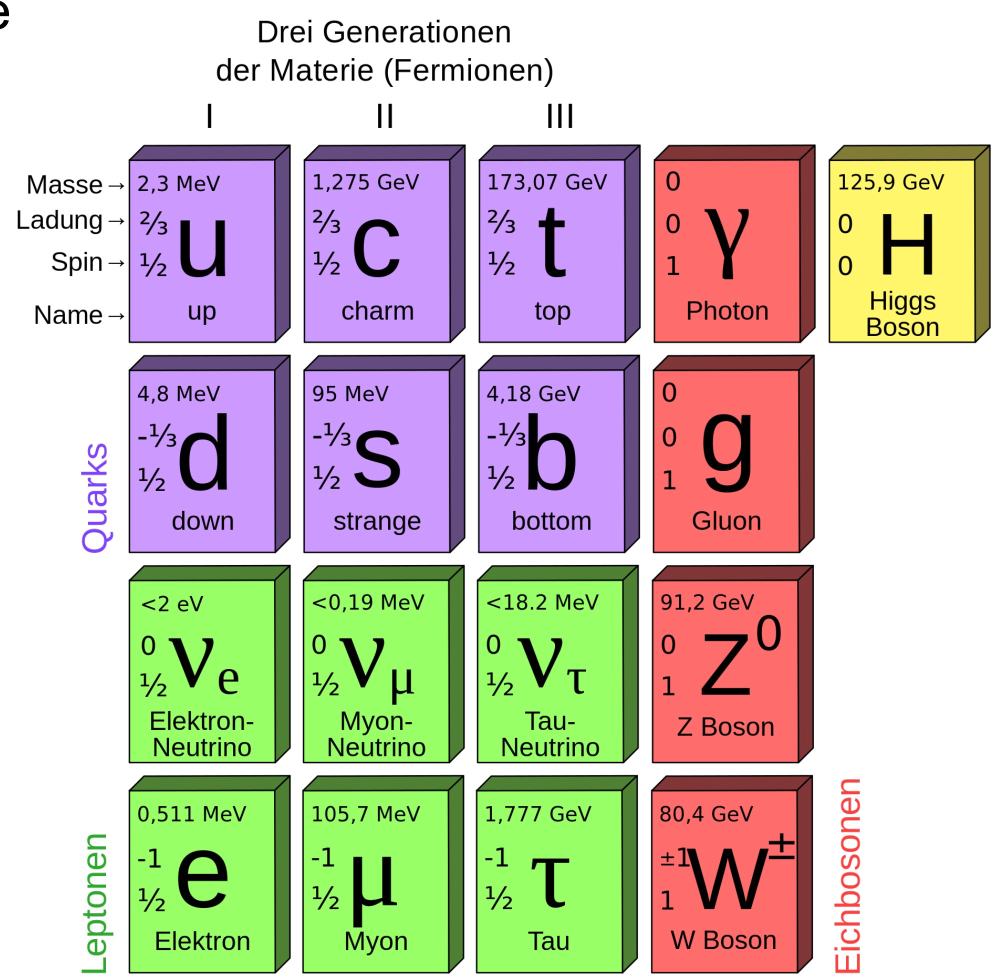
Strong Case for Particles Beyond the Standard Model

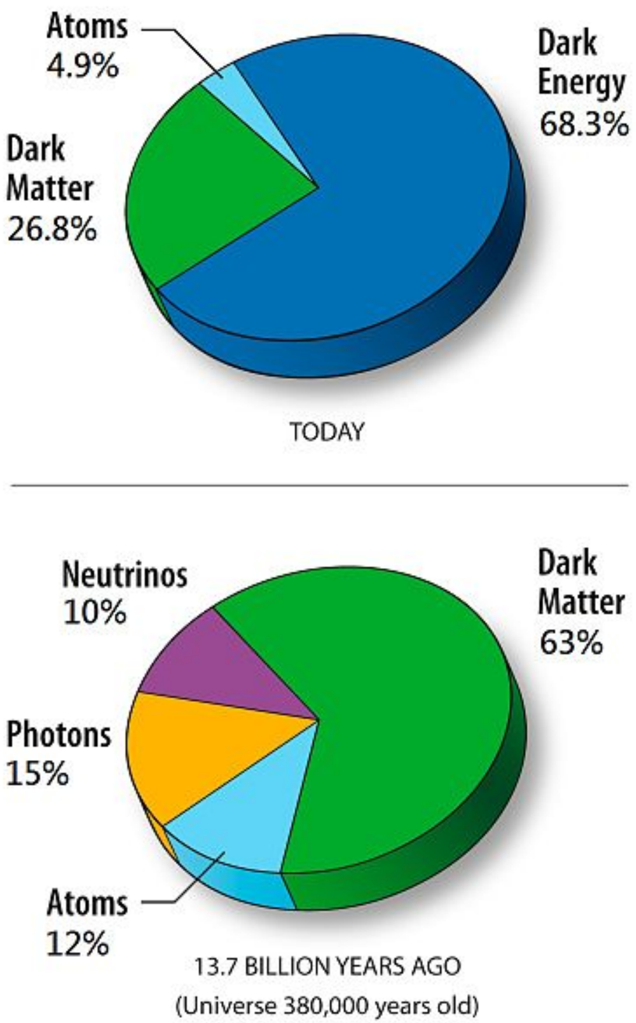
- Standard Model (SM) of particle physics describes properties of known matter and forces to a great precision



[wikipedia]

Strong Case for Particles Beyond the Standard Model

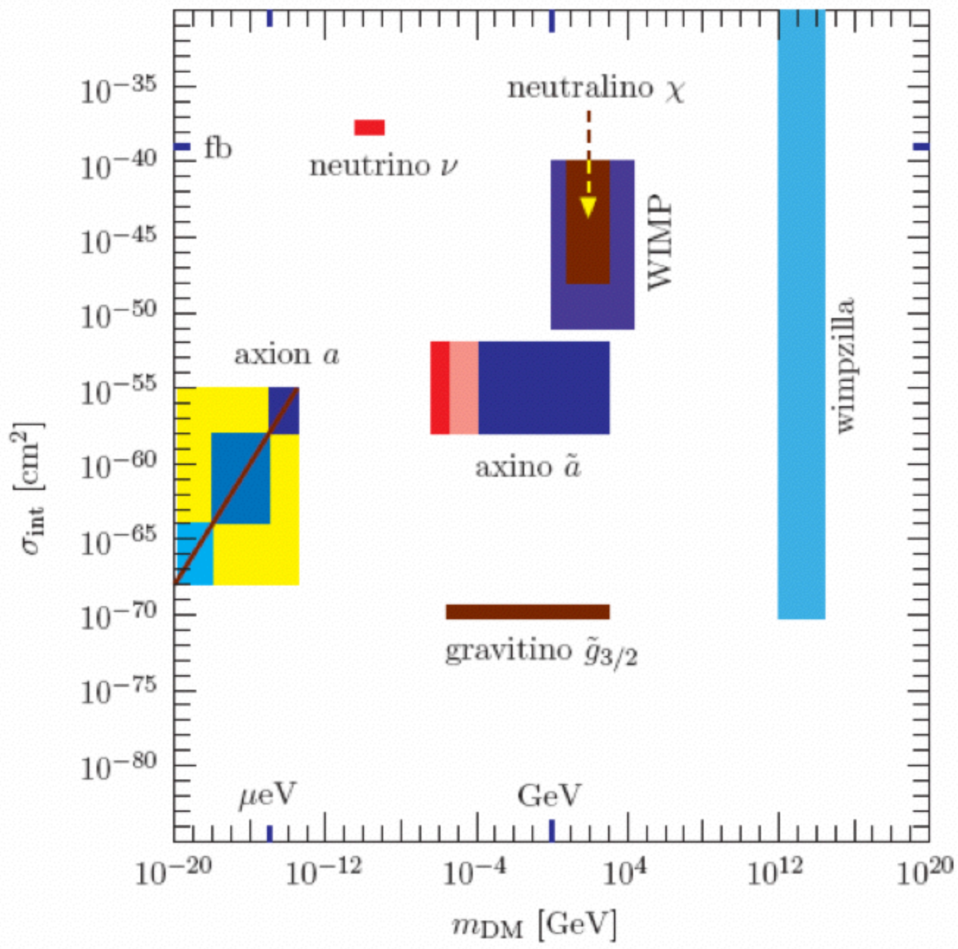
- Standard Model (SM) of particle physics describes properties of known matter and forces to a great precision
- SM not a complete and fundamental theory:
  - No explanation of the origin of dark energy and dark matter (DM)



[wikipedia]

Strong Case for Particles Beyond the Standard Model

- Standard Model (SM) of particle physics describes properties of known matter and forces to a great precision
- SM not a complete and fundamental theory:
  - No explanation of the origin of dark energy and dark matter (DM)
- Plenitude of DM candidates, nota-bly:
  - Weakly Interacting Massive Particles (WIMPs), such as neutralinos
  - Very Weakly Interacting Slim (=ultra-light) Particles (WISPs), such as axions
- Stand out because of their convin-cing physics case and the variety of experimental probes



[Kim,Carosi 10]

Natural Candidates for WISPs: Nambu-Goldstone Bosons

- Nambu-Goldstone boson arising from breaking of global, e.g. U(1), symmetry
- Hidden Higgs field:

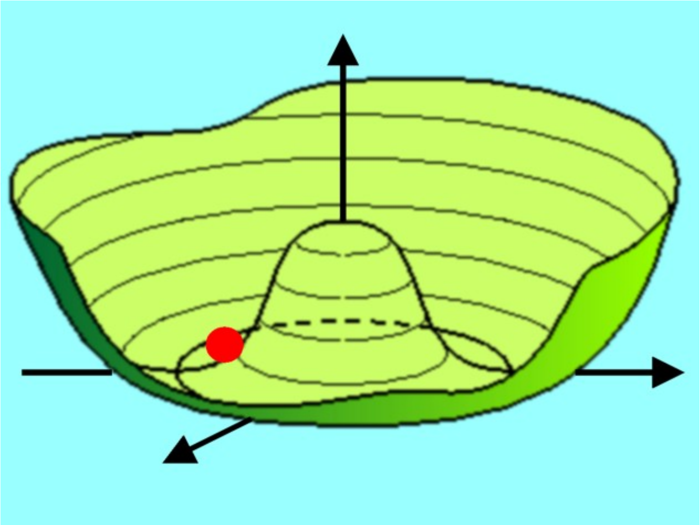
$$H_h(x) = \frac{1}{\sqrt{2}}\left[v_h + h_h(x)\right] \mathrm{e}^{ia(x)/v_h}$$

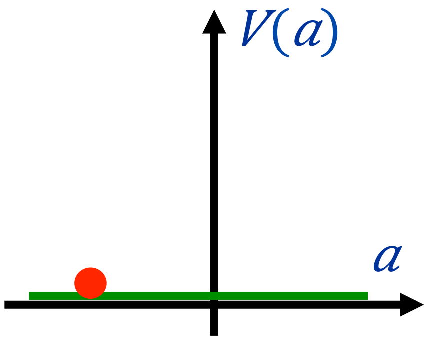
Massive modulus, massless phase:

$$m_{h_h} \sim v_h \qquad m_a = 0$$

- Interactions with SM particles small, if scale of symmetry breaking much larger than SM Higgs vacuum expectation value,

$$v_h \gg v = 246\ \mathrm{GeV}$$



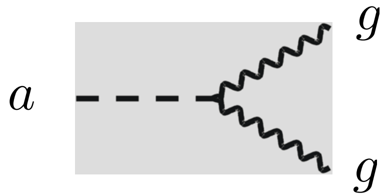


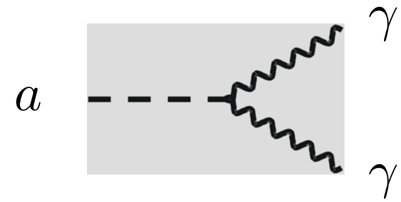
[Raffelt]

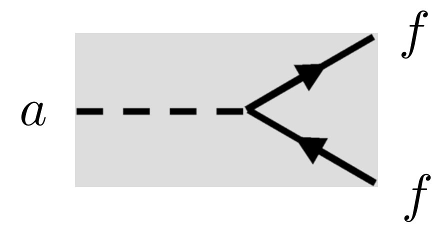
Natural Candidates for WISPs: Nambu-Goldstone Bosons

> Couplings to SM suppressed by powers of $f_a \sim v_h \gg v = 246\ \mathrm{GeV}$

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C_{ag}}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{af}}{f_a}\partial_\mu a\, \overline{\psi}_f \gamma^\mu\gamma_5\psi_f$$







> Coefficients $C_{ag},\ C_{a\gamma}$ determined by loops over particles charged under hidden U(1). C_{af} can arise at tree or loop level.

> Global symmetry not necessarily exact: Nambu-Goldstone boson will acquire a small mass vanishing in the limit that the global hidden symmetry is exact

- Example in SM: Pions .... pseudo Nambu-Goldstone bosons of chiral symmetry breaking in QCD ... mass vanishes for vanishing quark masses

Natural Candidates for WISPs: Nambu-Goldstone Bosons

- Often, there is more than one global symmetry and therefore more than one Nambu-Goldstone boson
  - Global lepton number symmetry: Majoron [Chikashige et al. 78; Gelmini,Roncadelli 80]
  - Global family symmetry: Familon [Wilczek 82; Berezhiani,Khlopov 90]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C'_{ig}}{f_{a'_i}}\, a'_i\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C'_{i\gamma}}{f_{a'_i}}\, a'_i\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C'_{a'_i f}}{f_{a'_i}}\,\partial_\mu a'_i\,\overline{\psi}_f\gamma^\mu\gamma_5\psi_f$$

- The particle corresponding to the linear combination

$$\frac{A(x)}{f_A} \equiv \frac{C'_{ig}}{f_{a'_i}}\, a'_i(x)$$

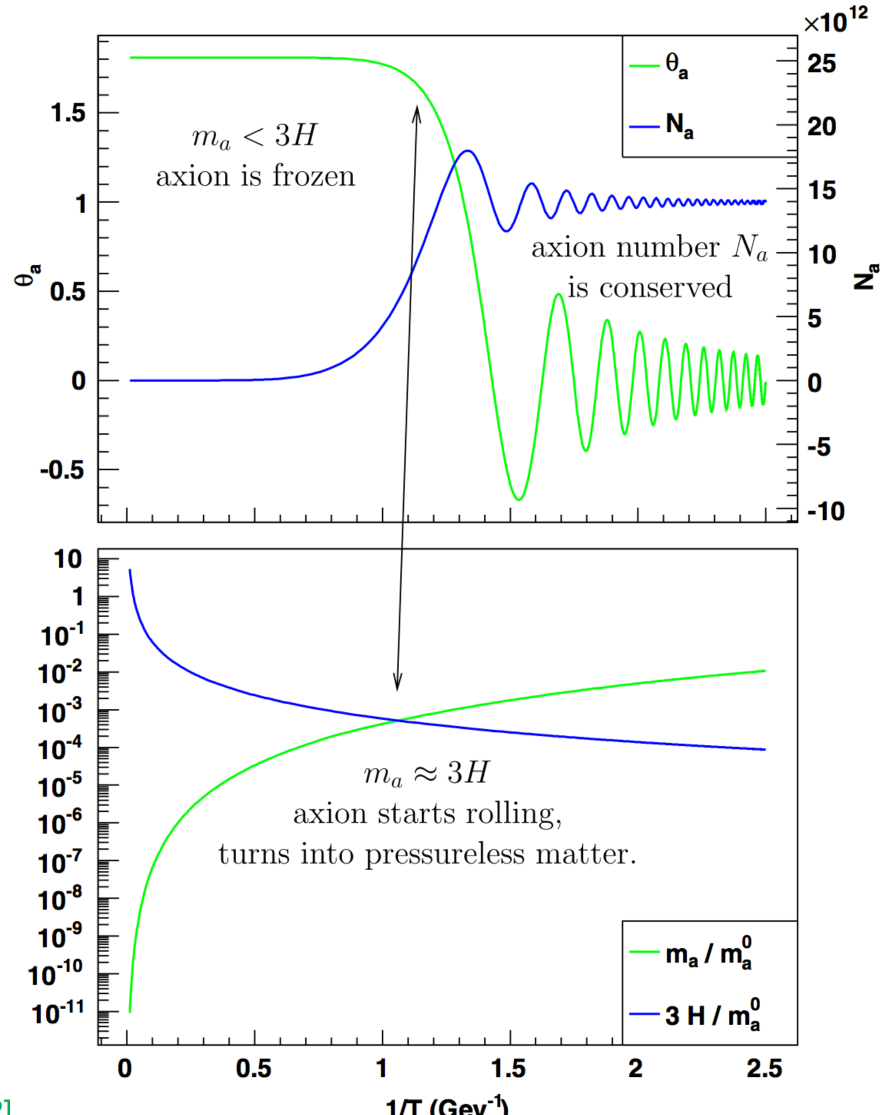
is called Axion (= laundry detergent): it cleans up the strong CP problem

[Peccei,Quinn 77; Weinberg 78; Wilczek 78]

- Particle excitations of the fields orthogonal to the axion field are called Axion-Like-Particles (ALPs)
- String theory suggests a plenitude of ALPs [Witten; Arvanitaki et al., Cicoli,Goodsell,AR]

Axion/ALP Dark Matter?

- In early universe, axion/ALP frozen at random initial value
- Later, field feels pull of mass towards zero and oscillates around it
- Spatially uniform oscillating classical field = coherent state of many, extremely non-relativistic particles = cold dark matter (CDM)



[Preskill et al 83; Abbott,Sikivie 83; Dine,Fischler 83,....;Arias et al. 12]

[Wantz,Shellard 09]

Axion/ALP Dark Matter?

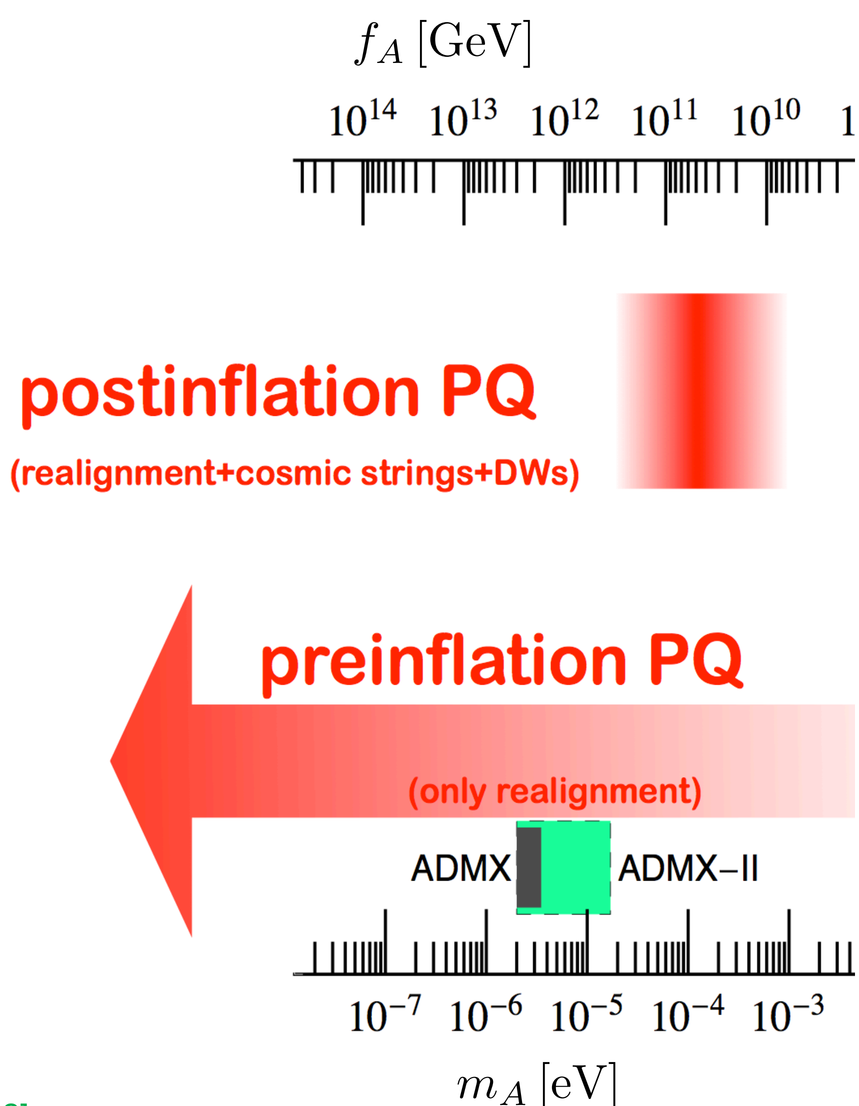
- In early universe, WISP (axion/ALP) frozen at random initial value
- Later, field feels pull of mass to-wards zero and oscillates around it
- Spatially uniform oscillating classical field = coherent state of many, ex-tremely non-relativistic particles = cold dark matter (CDM)
- Energy density proportional to initial field amplitude squared,

$$\rho_a = n_a m_a \sim f_a^2$$

- Axion/ALP CDM prefers:

$$f_a \gtrsim 10^{10\div 12}\ \mathrm{GeV}$$

[Preskill et al 83; Abbott,Sikivie 83; Dine,Fischler 83,....;Arias et al. 12]

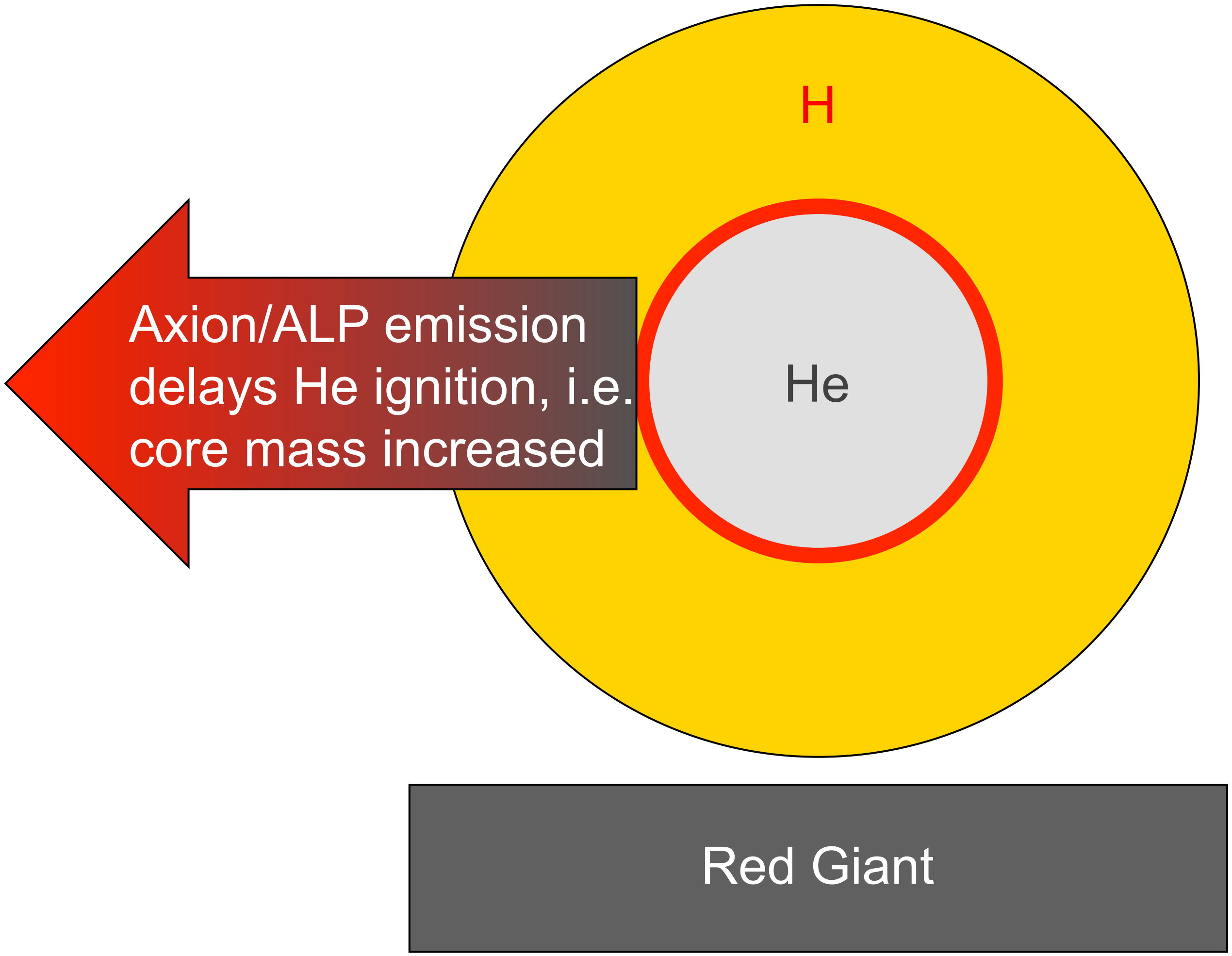


[adapted by from Essig et al. 1311.0029]

Axion/ALP Energy Losses of Stars in Globular Clusters?

- Red Giants (RGs) in globular clusters mildly prefer additional energy losses due to axion/ALP emission via Bremsstrahlung $e + Ze \to Ze + e + a$

[Viaux et al. 13]



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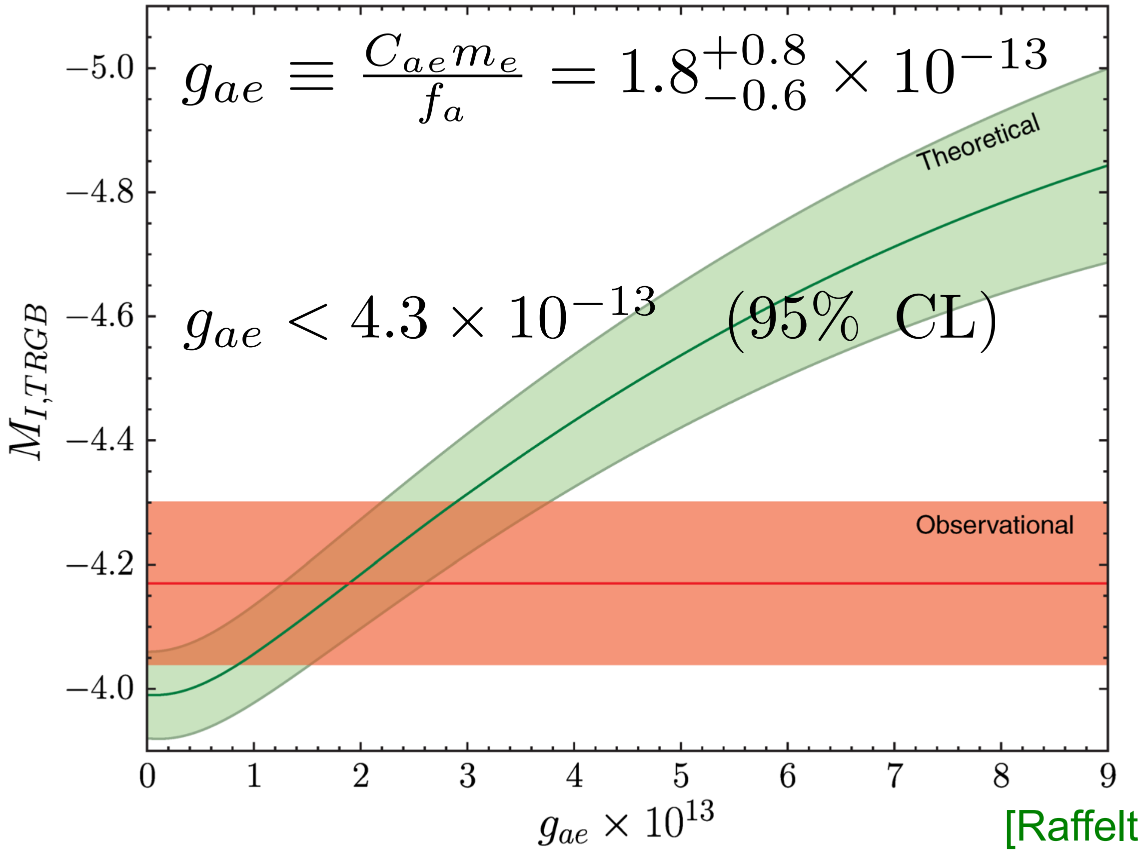


[Raffelt 14]

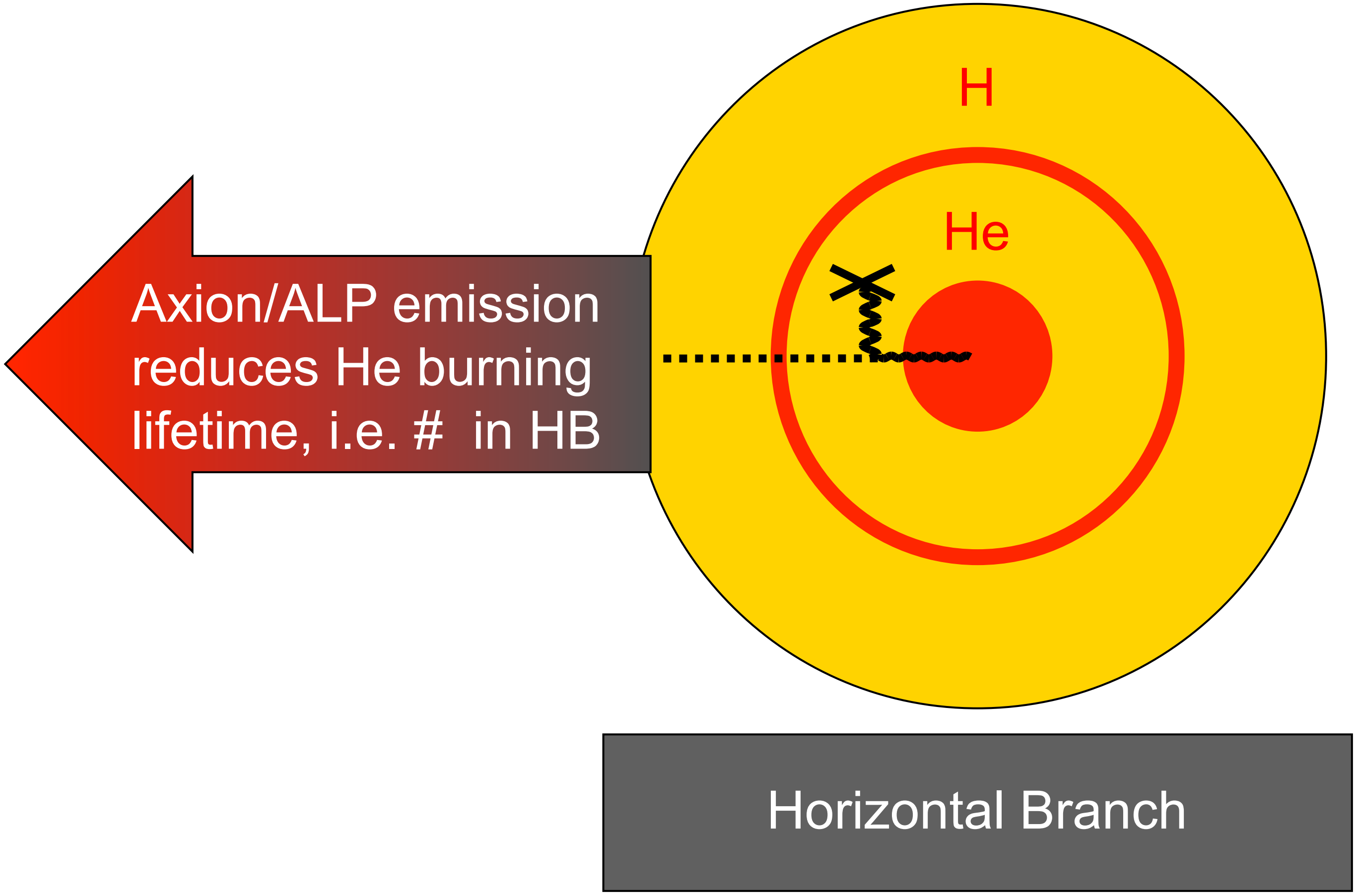
- Mild hints of anomalous energy loss of White Dwarfs (WDs) could also be explained by same parameter values

[Isern et al.]

Axion/ALP Energy Losses of Stars in Globular Clusters?

- Horizontal Branch (HB) stars in globular clusters mildly prefer additional energy losses due to axion/ALP emission via Primakoff $\gamma + Ze \to Ze + a$

[Ayala et al. 14]



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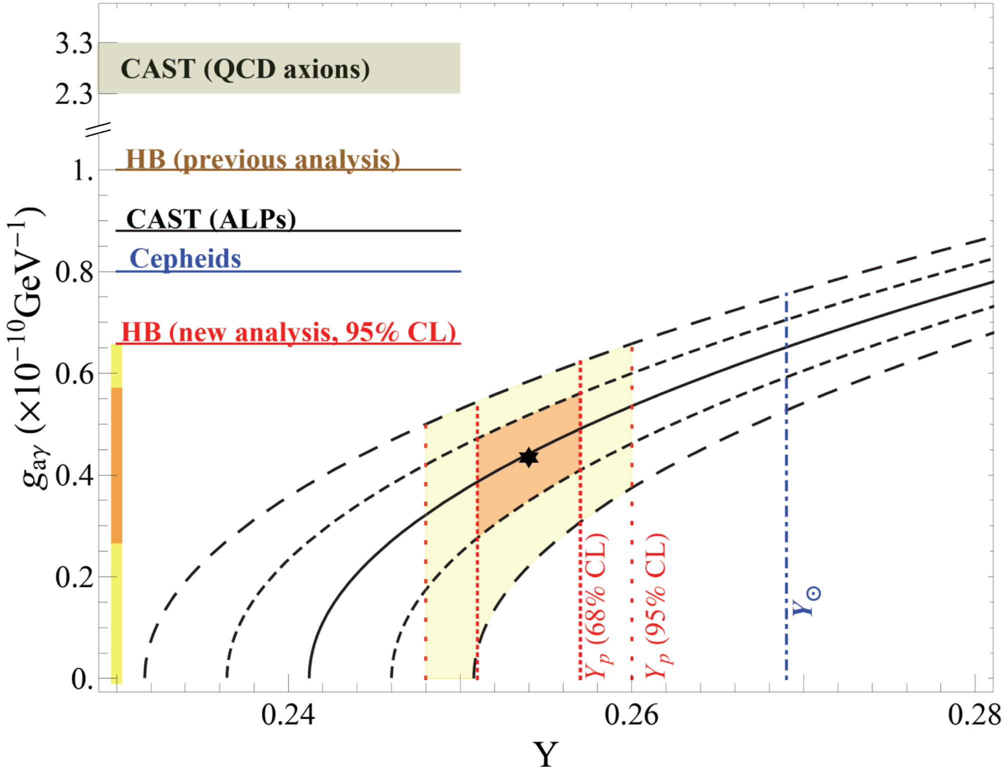
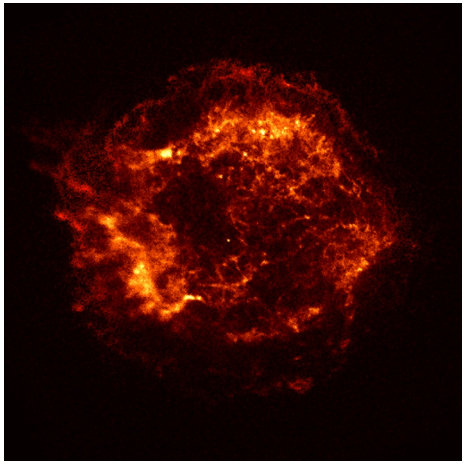


$$g_{a\gamma} \equiv \frac{\alpha C_{a\gamma}}{2\pi f_a} = 0.45^{+0.12}_{-0.16} \times 10^{-10} \text{ GeV}^{-1}$$

$$g_{a\gamma} < 0.66 \times 10^{-10} \text{ GeV}^{-1} \quad (95\% \text{ CL})$$

Axion/ALP Energy Losses of Neutron Star in Cas A?

> Neutron star in Cas A:

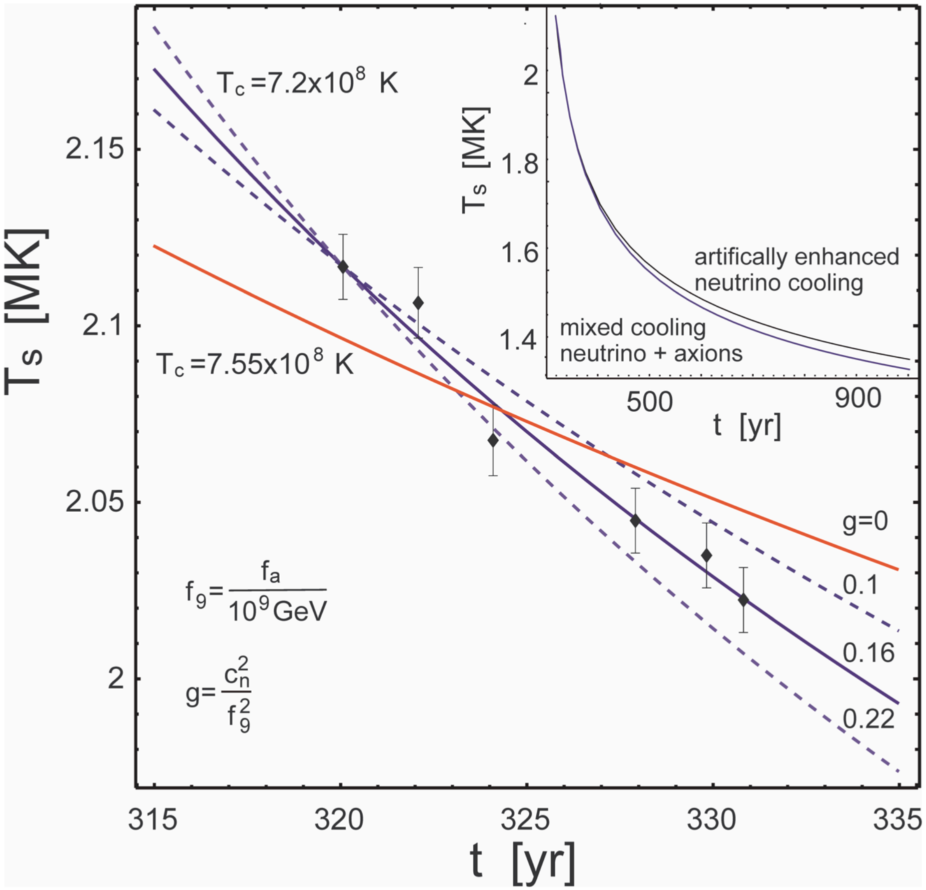


- Measured surface temperature over 10 years reveals unusually fast cooling rate
- Hint on extra cooling by axion/ALP due to nucleon bremsstrahlung

$$N + N \to N + N + a$$

- Required coupling to neutron:

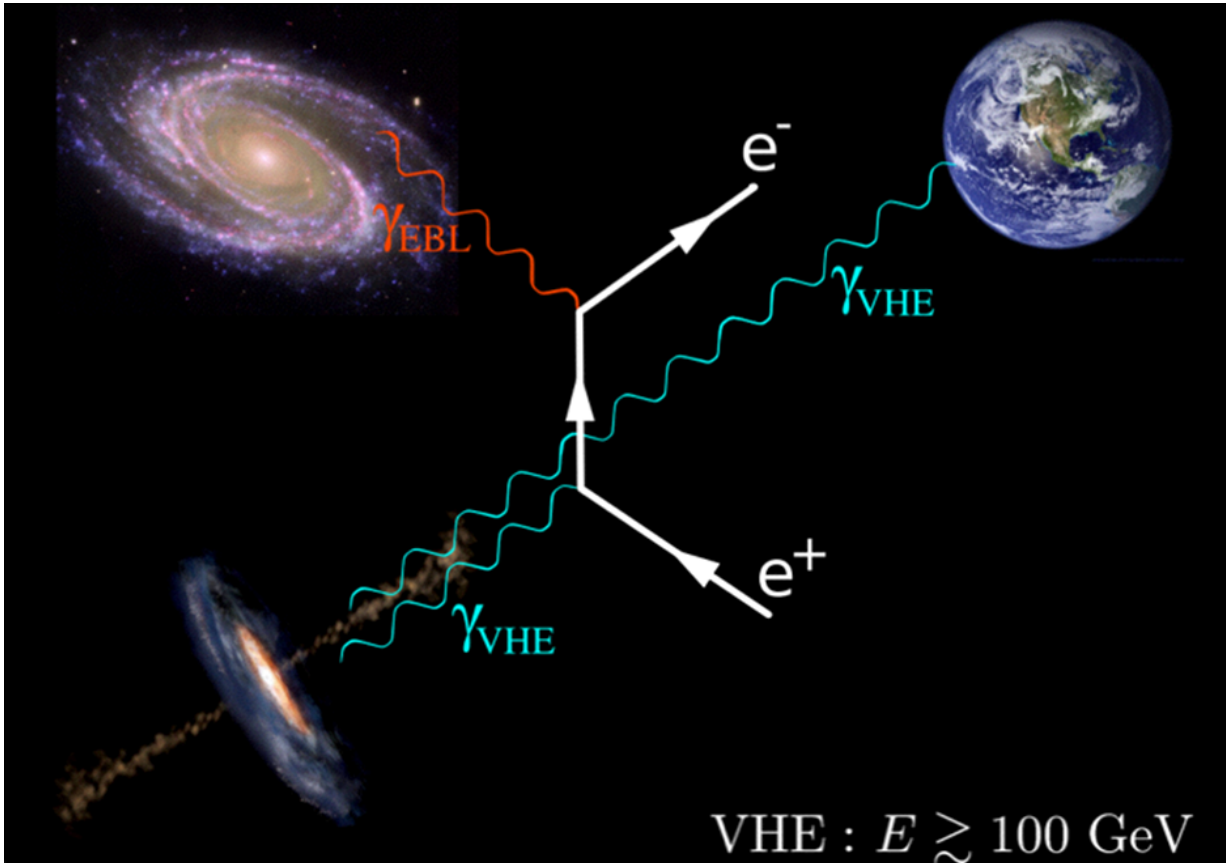
$$g_{an} \equiv \frac{C_{an} m_n}{f_a} \sim 4 \times 10^{-10}$$



[Leinson 14]

Photon – ALP Conversion in Cosmic Magnetic Fields?

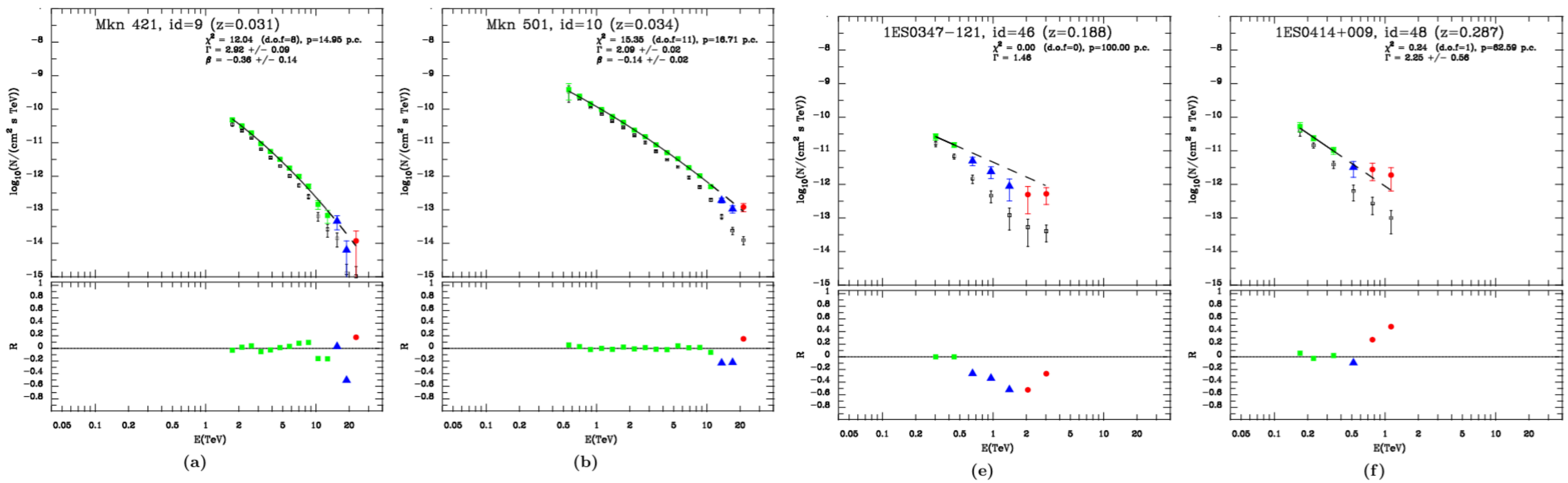
- Gamma ray spectra from distant AGNs should show an energy and red-shift dependent exponential attenuation, due to pair production at Extragalactic Background Light (EBL)

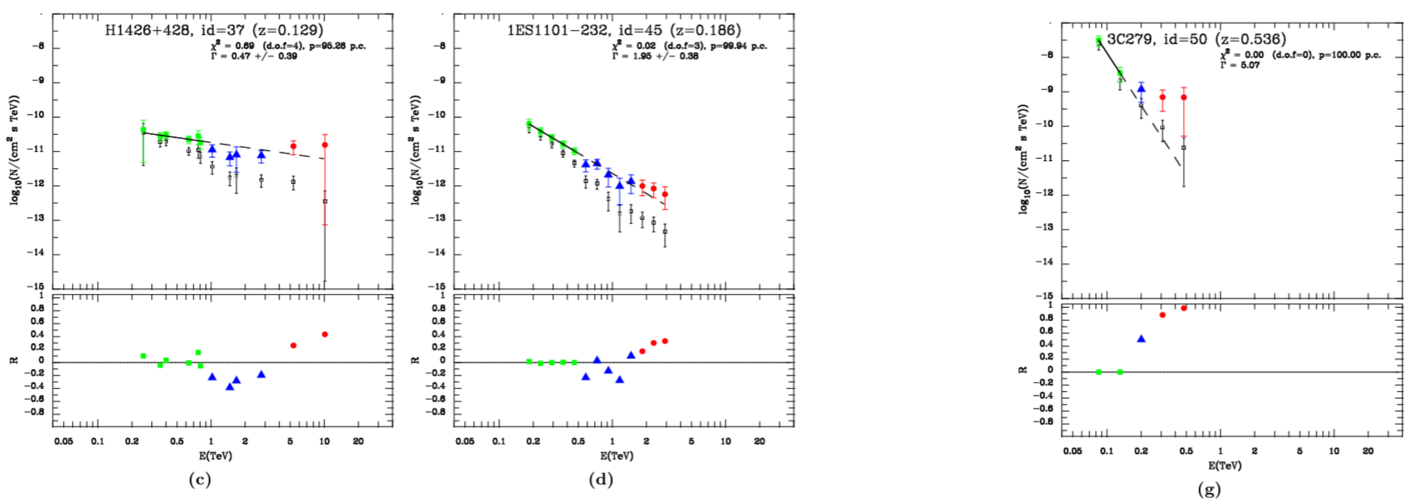


[Manuel Meyer 12]

Photon – ALP Conversion in Cosmic Magnetic Fields?

- Indication of anomalous gamma transparency: attenuation observed by IACT and Fermi-LAT too small [Aharonian et al. 07; de Angelis,Roncadelli et al. 07;...;Horns,Meyer 12;...;Rubtsov,Troitsky 14]

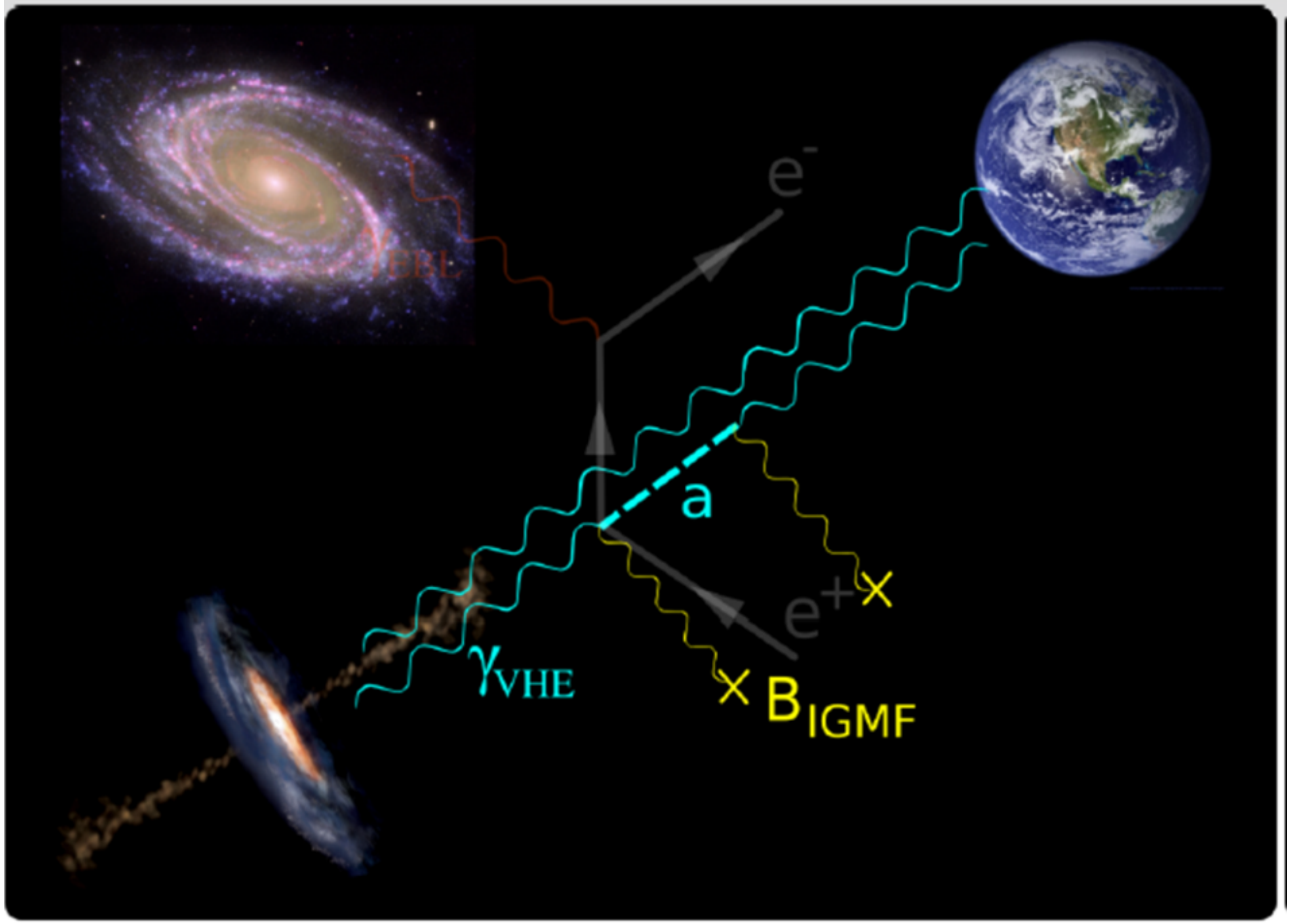




[Horns,Meyer 12]

Photon – ALP Conversion in Cosmic Magnetic Fields?

- 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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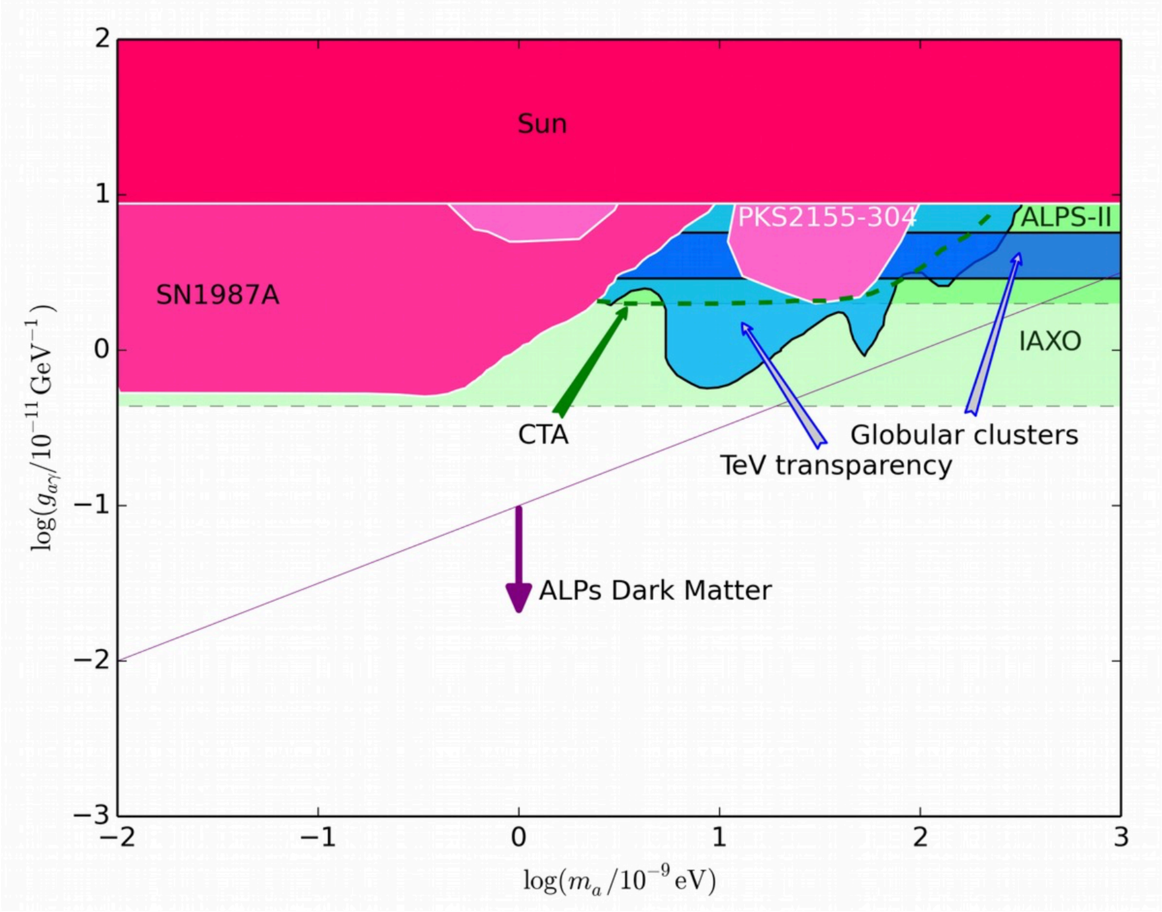
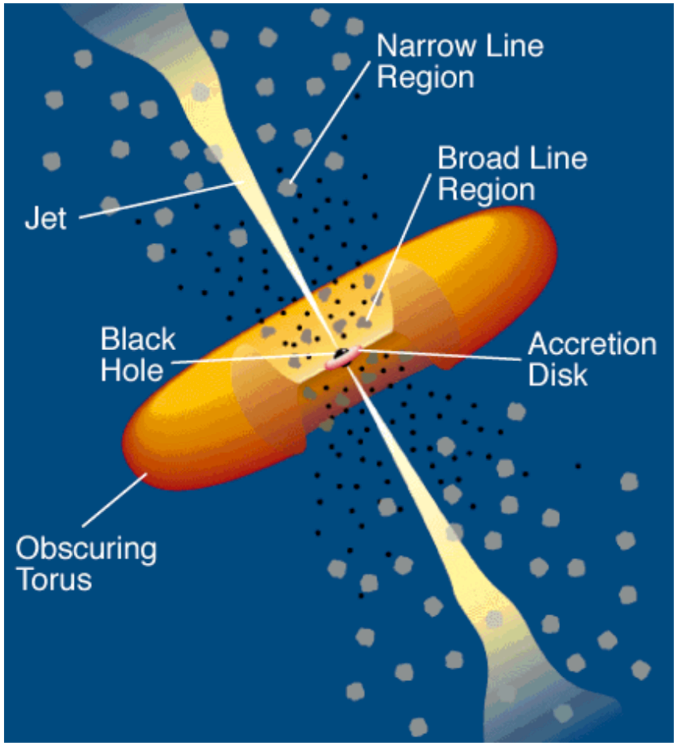


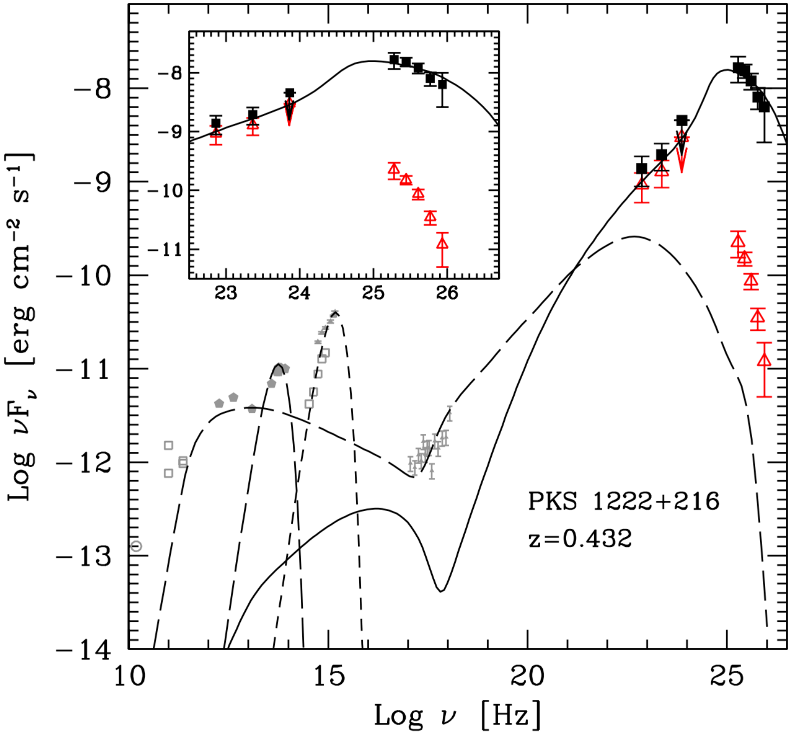
[Horns 15]

- Required photon coupling overlaps with preferred region from HBs in GCs

Photon – ALP Conversion in Cosmic Magnetic Fields?

- Photon-ALP conversion with a strength $g_{a\gamma} \sim \mathrm{few} \times 10^{-11}\ \mathrm{GeV}^{-1}$ explains also puzzling observation of VHE photons from Flat Spectrum Radio Quasars (FSRQs) [Tavecchio,Roncadelli,Galanti,Bonnoli 12]
  - Pair production on UV photons in broad line region should prevent photons produced by the central engine to escape



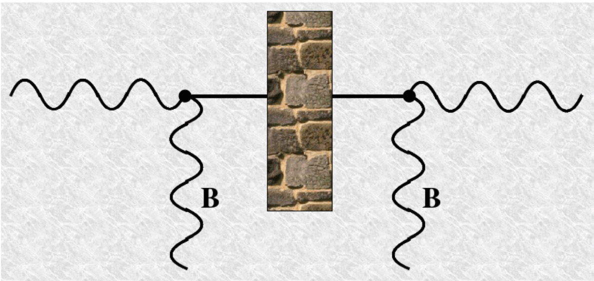


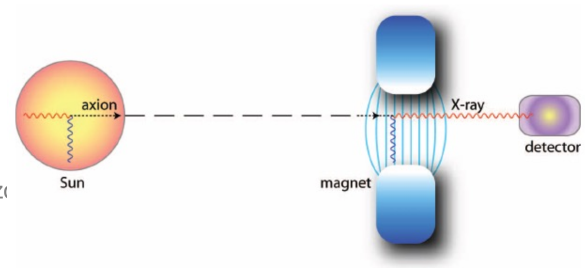
Summary of Astrophysical Hints for Axion/ALPs

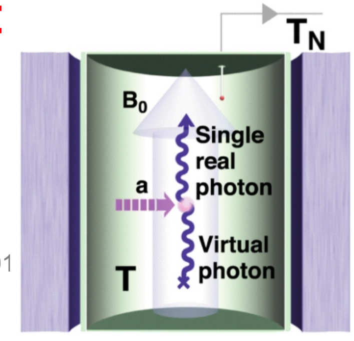
- Symmetry breaking scale inferred from astrophysical hints:
  1. RGs + WDs: $f_a = 3 \times 10^9 \text{ GeV } C_{ae} \left(\frac{2\times10^{-13}}{g_{ae}} \right)$
  2. n star in Cas A: $f_a = 2 \times 10^9 \text{ GeV } C_{an} \left(\frac{4\times10^{-10}}{g_{an}} \right)$
  3. HB stars + AGN spectra: $f_a = 2 \times 10^7 \text{ GeV } C_{a\gamma} \left(\frac{5\times10^{-11} \text{ GeV}^{-1}}{g_{a\gamma}} \right)$
- Astrophysical hints can be explained by
  - ALP with $f_a \sim 10^7 \text{ GeV},\ m_a \lesssim 0.1\ \mu\text{eV},\ C_{a\gamma} \sim 1,\ C_{ae} \sim C_{an} \sim 10^{-2}$
  - Axion with $f_A \sim 10^9 \text{ GeV},\ C_{An} \sim C_{A\gamma} \sim C_{Ae} \sim 1$

  plus

  ALP with $f_a \sim 10^7 \text{ GeV},\ m_a \lesssim 0.1\ \mu\text{eV},\ C_{a\gamma} \sim 1,\ C_{ae} \sim C_{an} \ll 10^{-2}$
- In reach of upcoming generation of terrestrial experiments:







Axion/ALP Experiments Worldwide

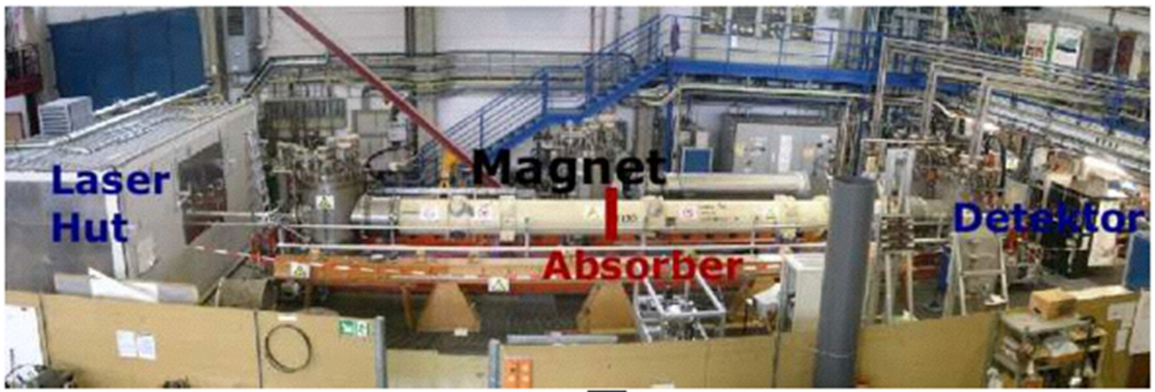
An incomplete selection of (mostly) small-scale experiments:

Experiment	Type	Location	Status
ALPS II	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	Haloscopes	Seattle	running
CASPEr		Mainz	preparation
QUAX		Legnaro	preparation

[adapted from Axel Lindner `14]

Light-shining-through-a-wall Searches

- Any Light Particle Search (ALPS) at DESY (in coll. with LZH, AEI)



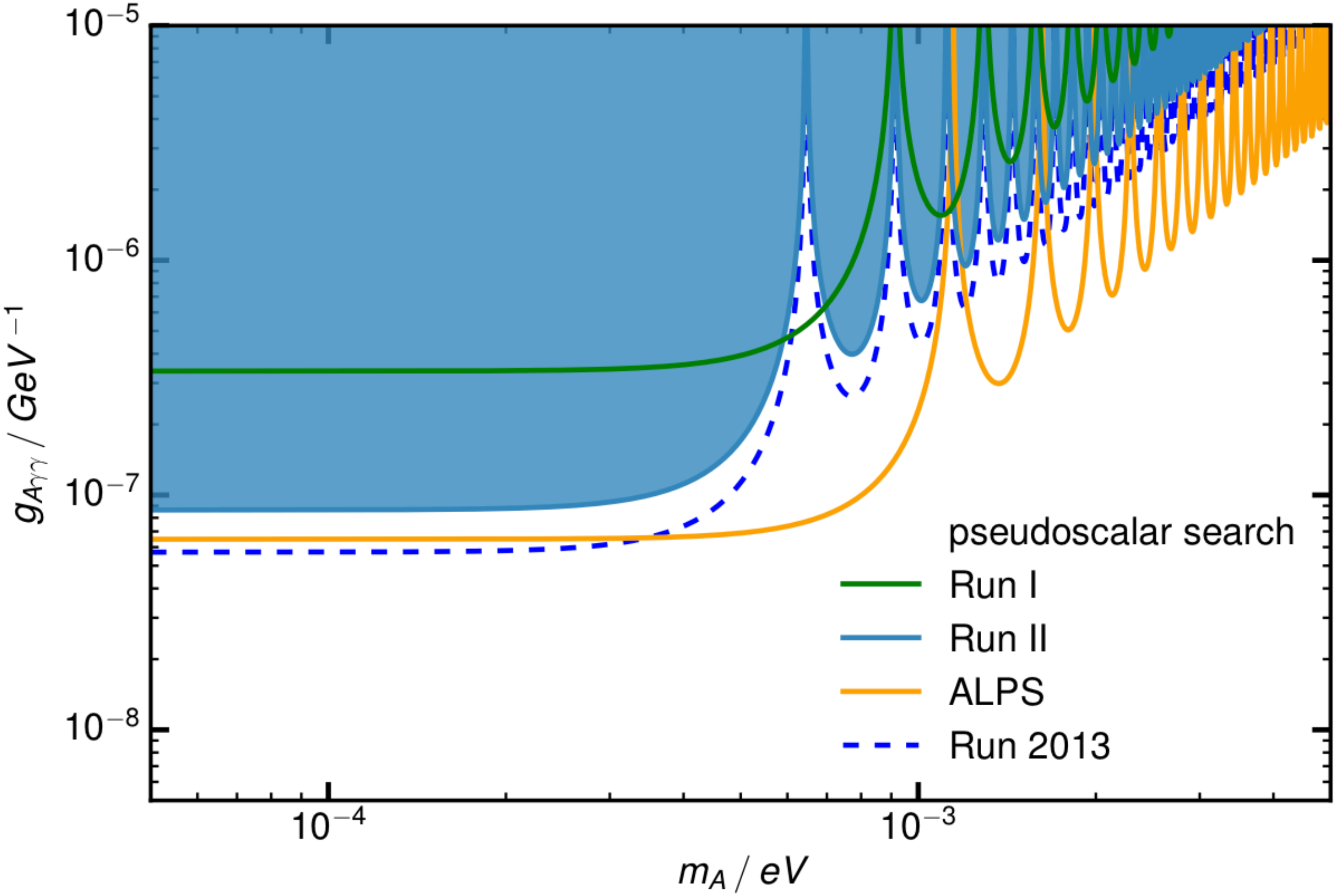
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

[Anselm 85;van Bibber et al. 87]

DESY

Light-shining-through-a-wall Searches

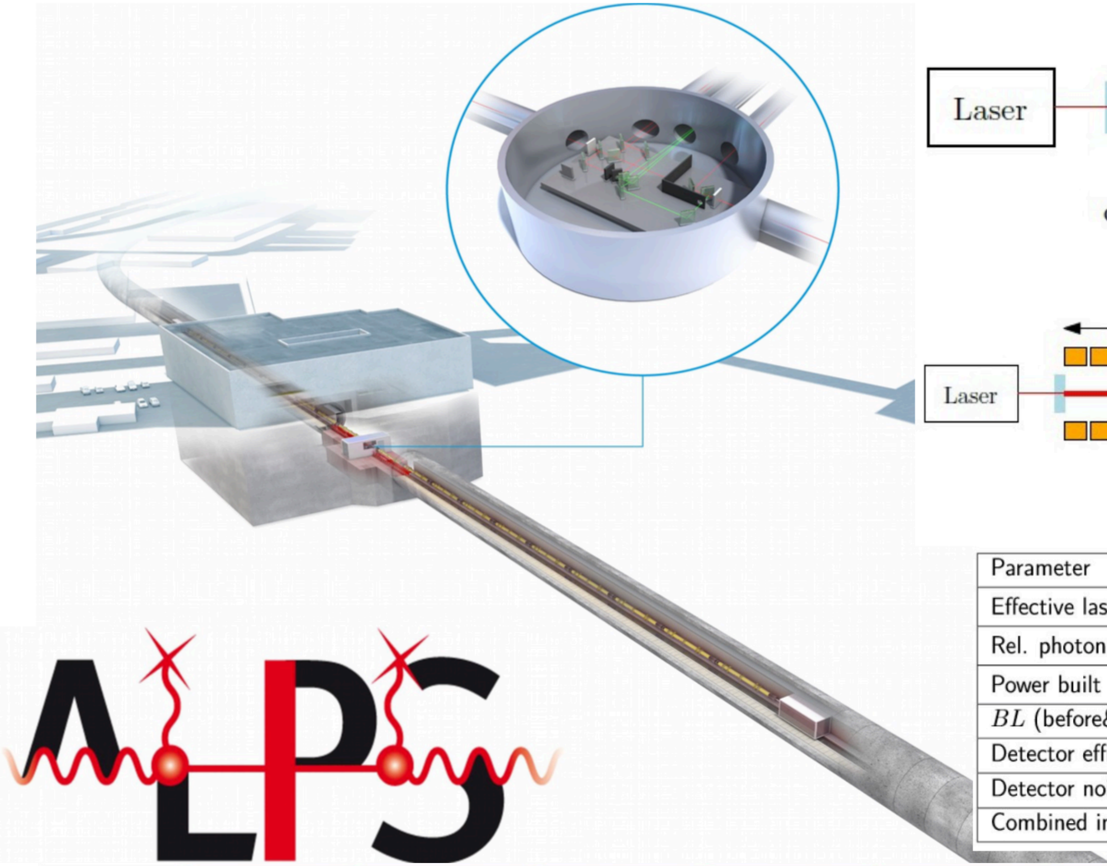
- Currently best limits from LSW: ALPS (DESY) and OSQAR (CERN)

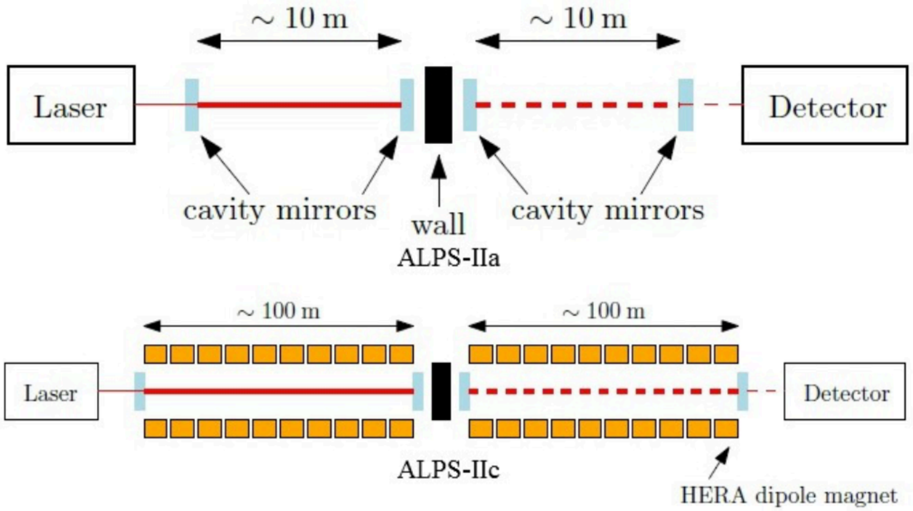


[Balou et al. 14]

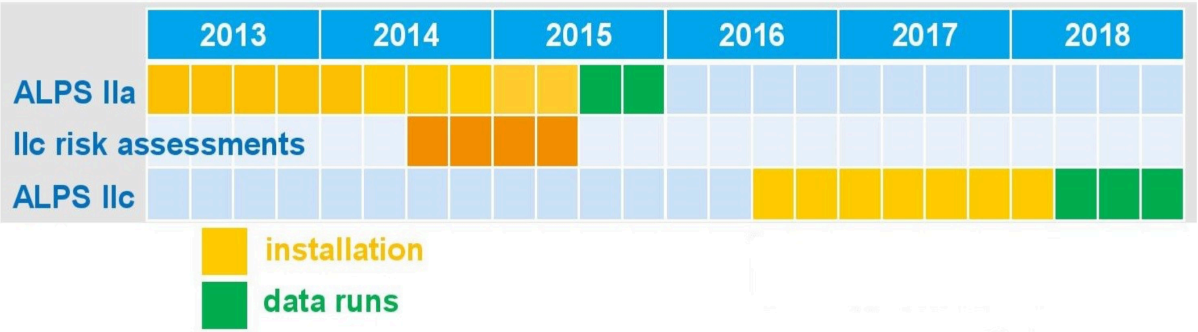
Light-shining-through-a-wall Searches

> ALPS II in prepar. at DESY (in collaboration with UHH, AEI, U Mainz)





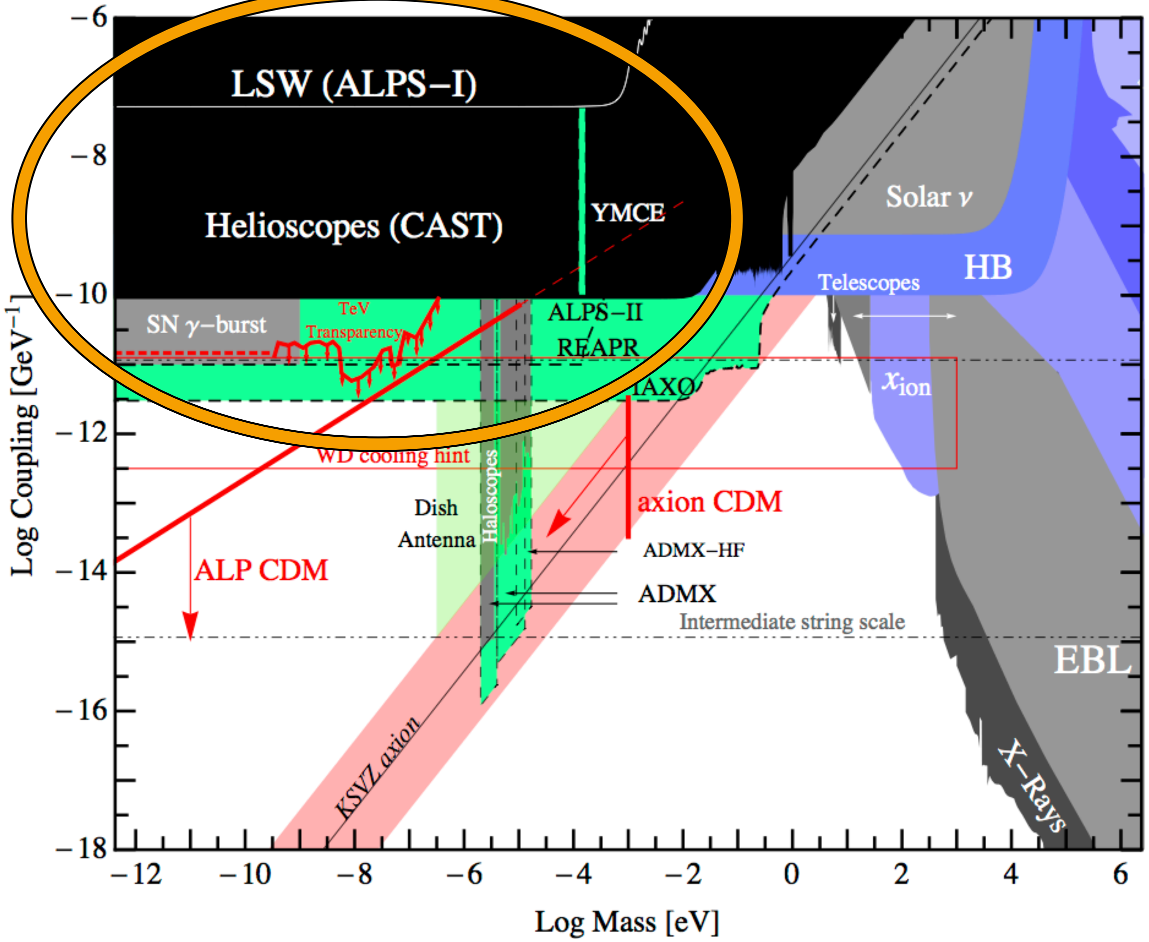
Parameter	Scaling	ALPS I	ALPS IIc	Sens. gain
Effective laser power $P_{\rm laser}$	$g_{a\gamma} \propto P_{\rm laser}^{-1/4}$	1 kW	150 kW	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC $P_{\rm RC}$	$g_{a\gamma} \propto P_{reg}^{-1/4}$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



[Bähre et al (ALPS II TDR) 13]

Light-shining-through-a-wall Searches

- Crucial test of ALP explanation of excessive HB star energy loss and AGN spectra at VHE

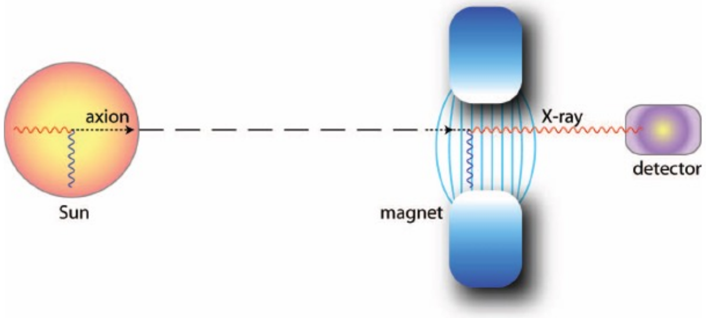


[Essig et al. 1311.0029]

Helioscope Searches

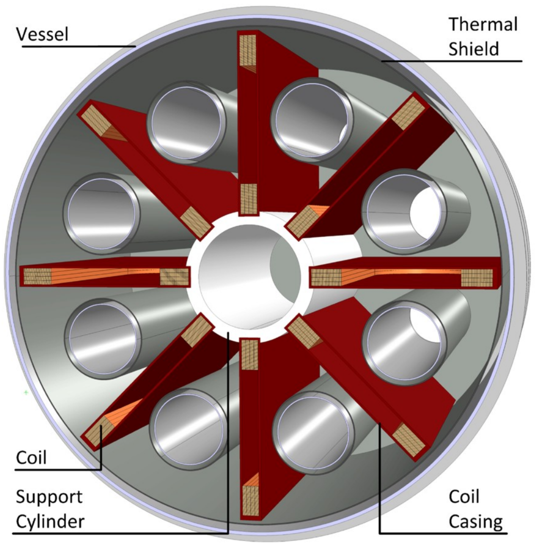
- Most sensitive until now: CERN Axion Solar Telescope (CAST)
  - Superconducting LHC dipole magnet
  - X-ray detectors

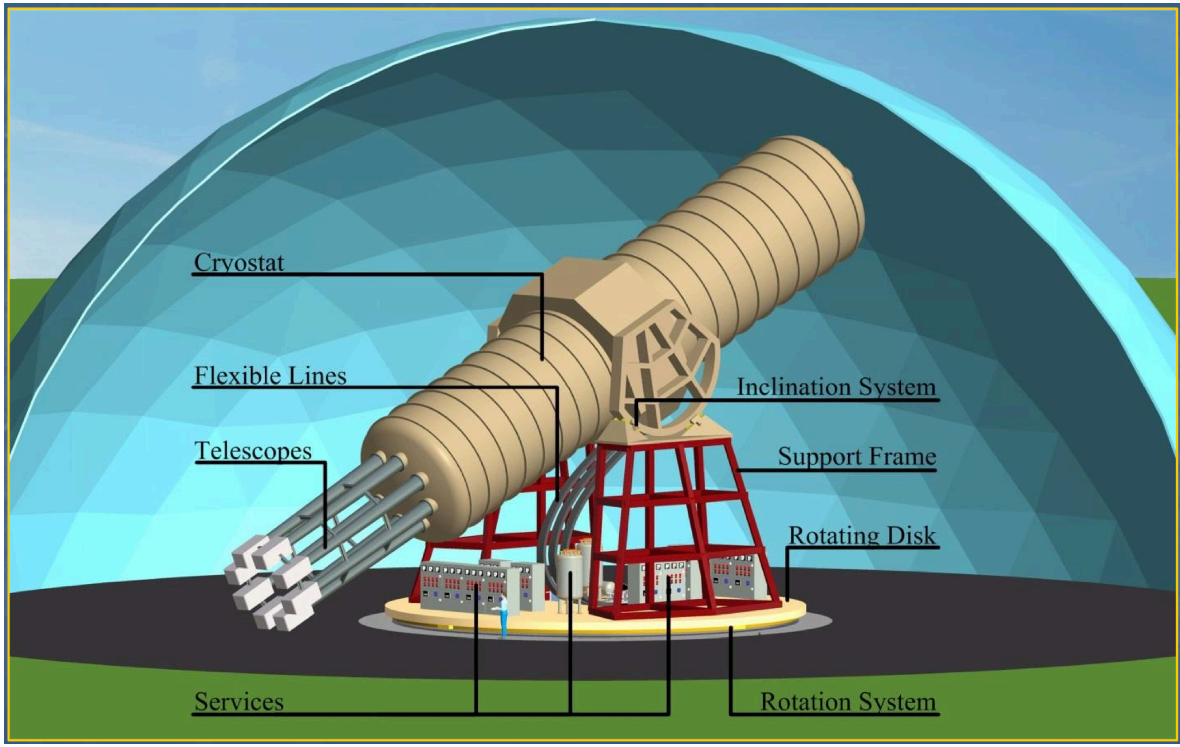
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$



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

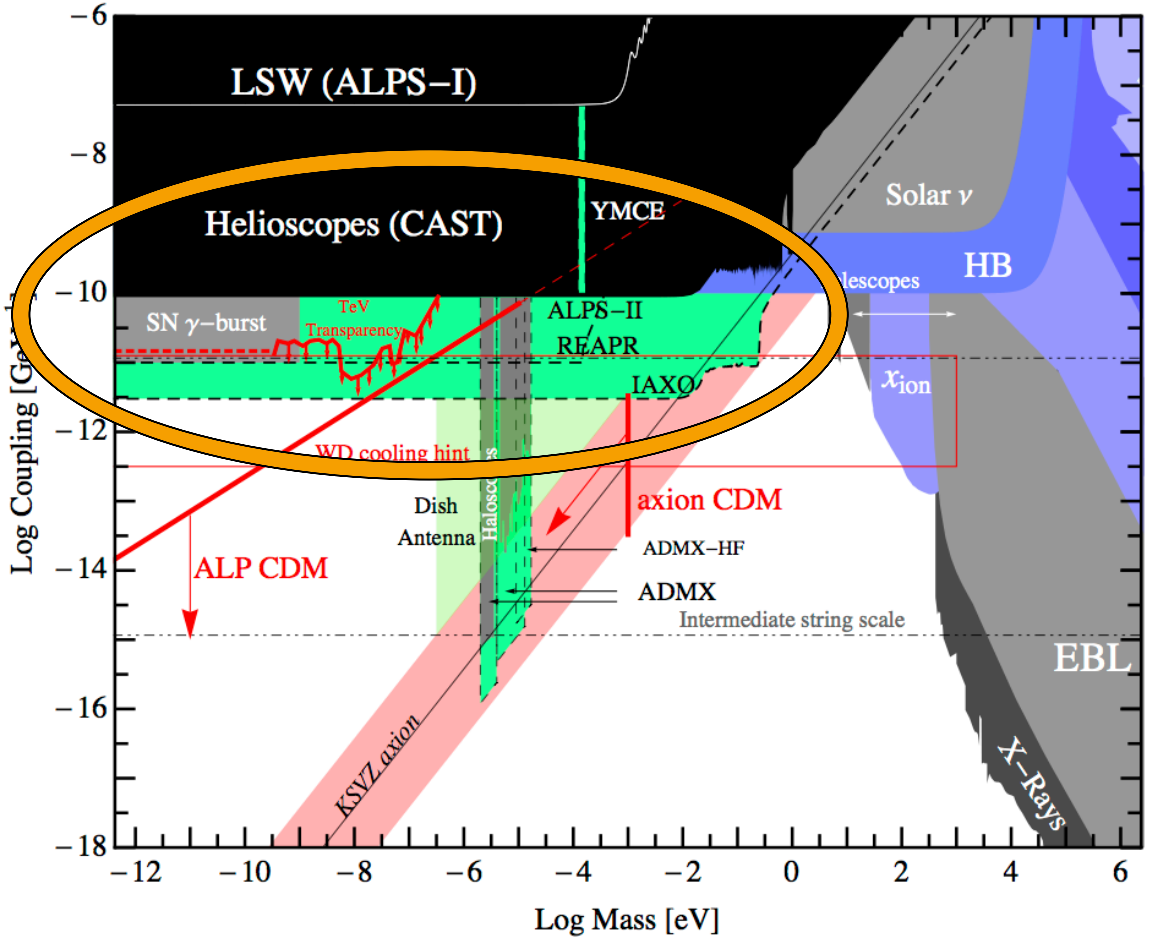




[Armengaud et al (IAXO CDR) 1401.3233]

Helioscope Searches

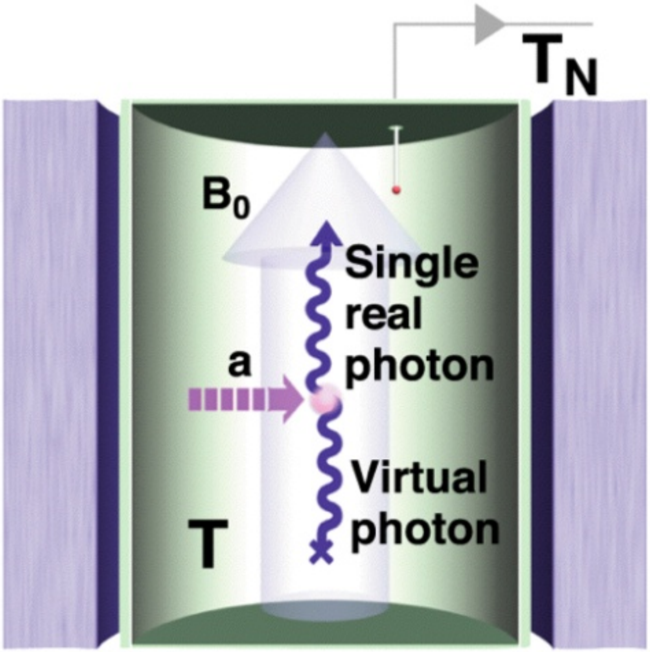
> Crucial test of the axion explanation of the excessive energy losses of RGs, WDs, n star in Cas A and ALP explanation of AGN spectra at VHE



adapted from [Hewett et al 12]

Haloscope Searches: Resonant Cavities

- Direct detection of axion/ALP dark matter!
- Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field [Sikivie 83]



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

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

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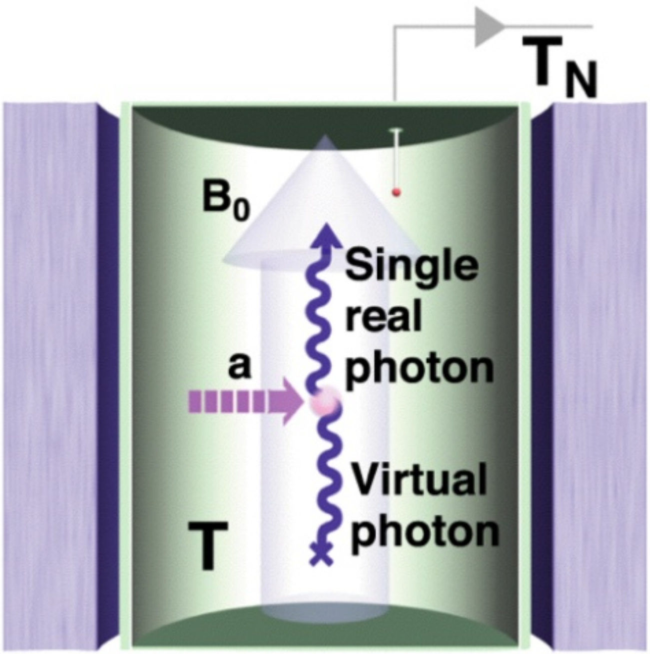
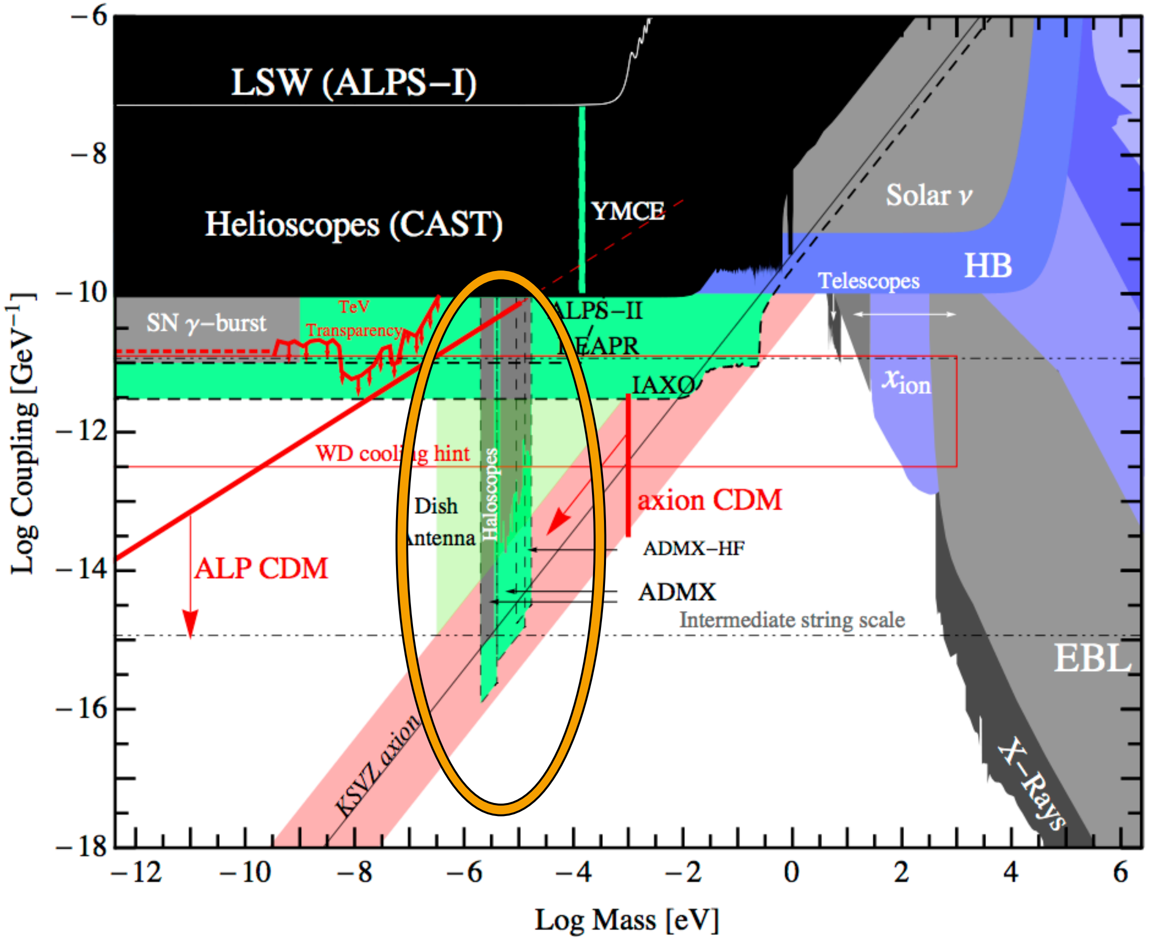


- Best sensitivity: mass = resonance frequency $m_a = 2\pi\nu \sim 4\ \mu\text{eV} \left(\frac{\nu}{\text{GHz}}\right)$
- Ongoing: ADMX (Seattle), exploiting high Q cavity in 8 T SC solenoid

Haloscope Searches: Resonant Cavities

- ADMX able to probe about 1.5 decades in axion/ALP mass:



adapted from [Hewett et al 12]

Haloscopes: MR Searches for Oscillating EDMs

- Axion DM gives all nucleons oscillating electric dipole moments (EDMs)

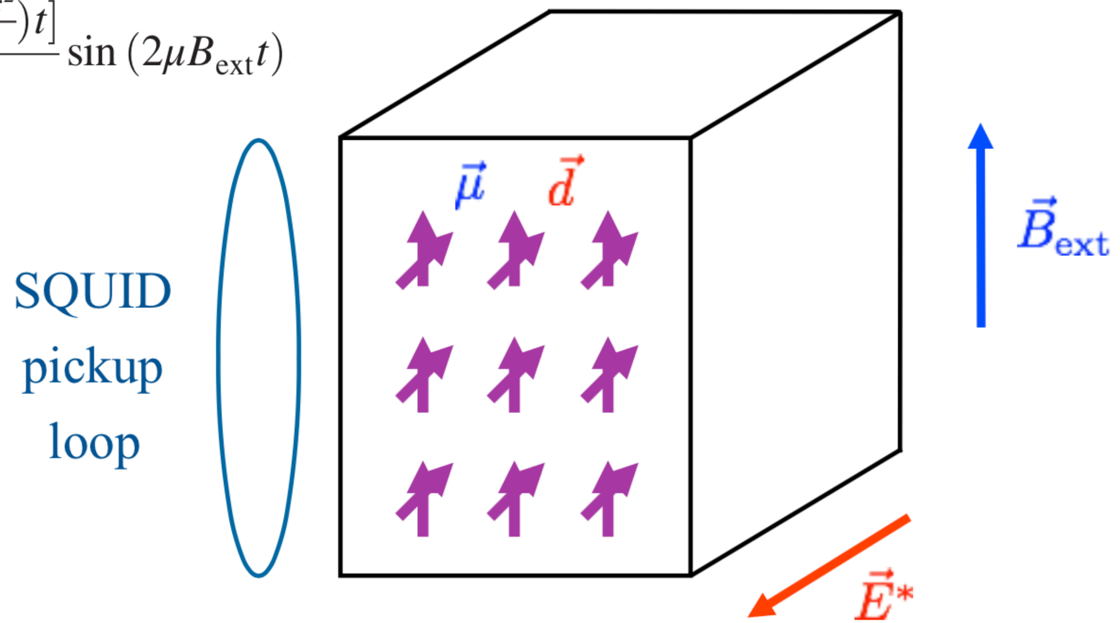
$$d_N \equiv g_{Ad} A(t) \sim e \frac{m_u m_d}{(m_u + m_d) m_N^2} \frac{A(t)}{f_A} \sim 10^{-16} \frac{A(t)}{f_A}\, e\,\mathrm{cm}$$

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

- EDMs cause precession of nuclear spins in a nucleon spin polarized sample in the presence of an electric field

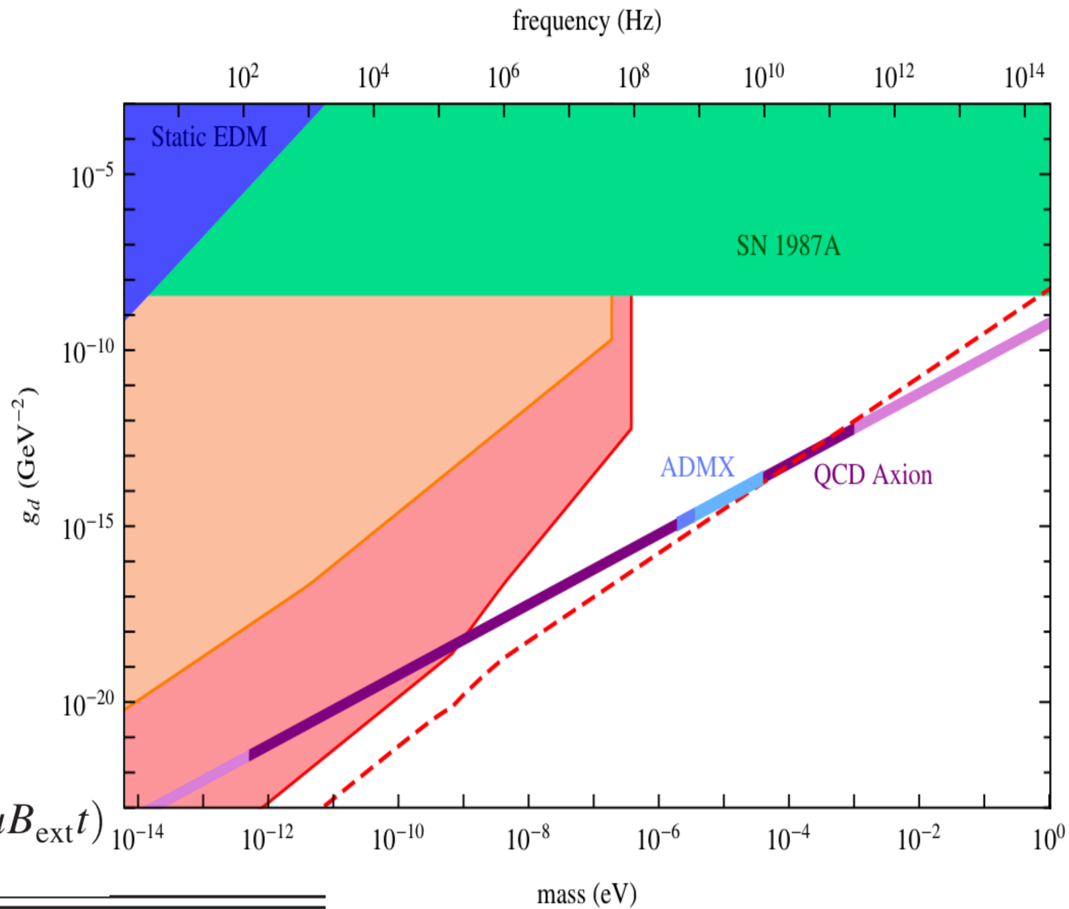
- Resulting transverse magnetisation can be searched for exploiting magnetic resonance (MR) techniques [Budker,Graham,Ledbetter,Rajendran,Sushkov]

$$M(t) \approx n p \mu E^* \epsilon_S d_n \frac{\sin\left[\left(\frac{2\mu B_{\rm ext} - m_a c^2}{\hbar}\right) t\right]}{\frac{2\mu B_{\rm ext} - m_a c^2}{\hbar}} \sin\left(2\mu B_{\rm ext} t\right)$$



Haloscopes: MR Searches for Oscillating EDMs

- Cosmic Axion Spin Precession Experiment (CASPEr) in preparation in Mainz
  - Probes very light axion, from GUT to Planck scale SSB (anthropic axion)
  - Sensitive in a mass/symmetry breaking scale region complementary to ADMX



$$M(t) \approx n p \mu E^* \epsilon_S d_n \frac{\sin[(\frac{2\mu B_{\rm ext} - m_a c^2}{\hbar})t]}{\frac{2\mu B_{\rm ext} - m_a c^2}{\hbar}} \sin(2\mu B_{\rm ext} t)$$

	n	E^*	p	T_2	Max $B_{\rm ext}$
Phase 1	10^{22} cm^{-3}	3×10^8 V/cm	10^{-3}	1 ms	10 T
Phase 2	10^{22} cm^{-3}	3×10^8 V/cm	1	1 s	20 T

[Budker et al. 14]

$$\mathcal{L} \ni -\frac{i}{2} g_d\, a\, \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$

Haloscopes: MR Searches for the Axion/ALP Wind

- The axion/ALP nucleon coupling

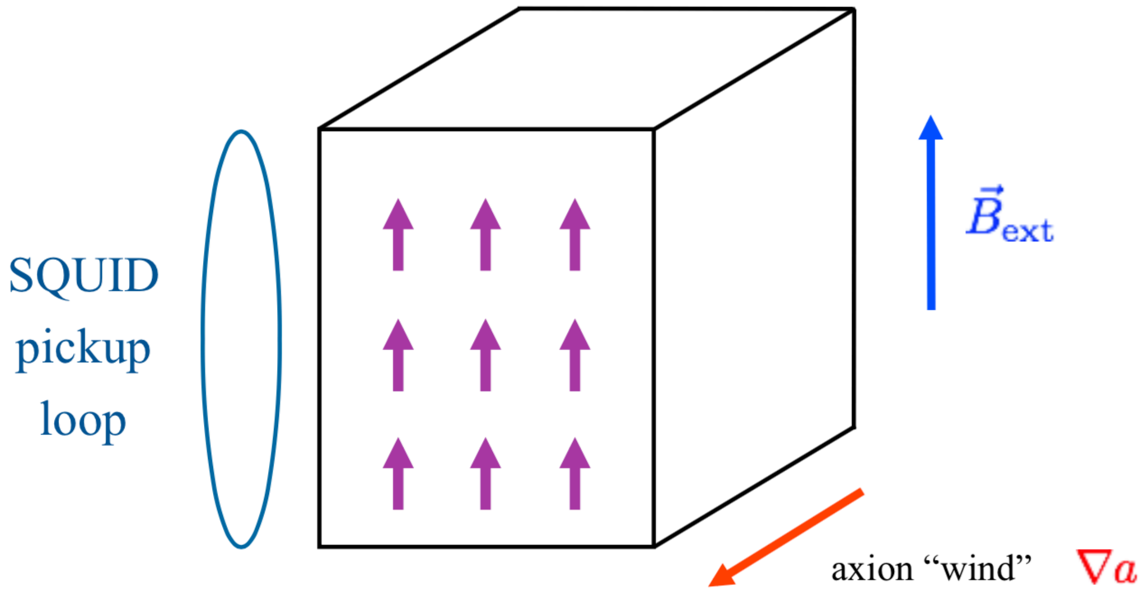
$$g_{aNN}\left(\partial_\mu a\right)\bar{N}\gamma^\mu\gamma_5 N \implies H_N \supset g_{aNN}\vec{\nabla}a.\vec{S}_N$$

  will lead to a spin precession about the axion/ALP DM wind

[Graham,Rajendran 13]

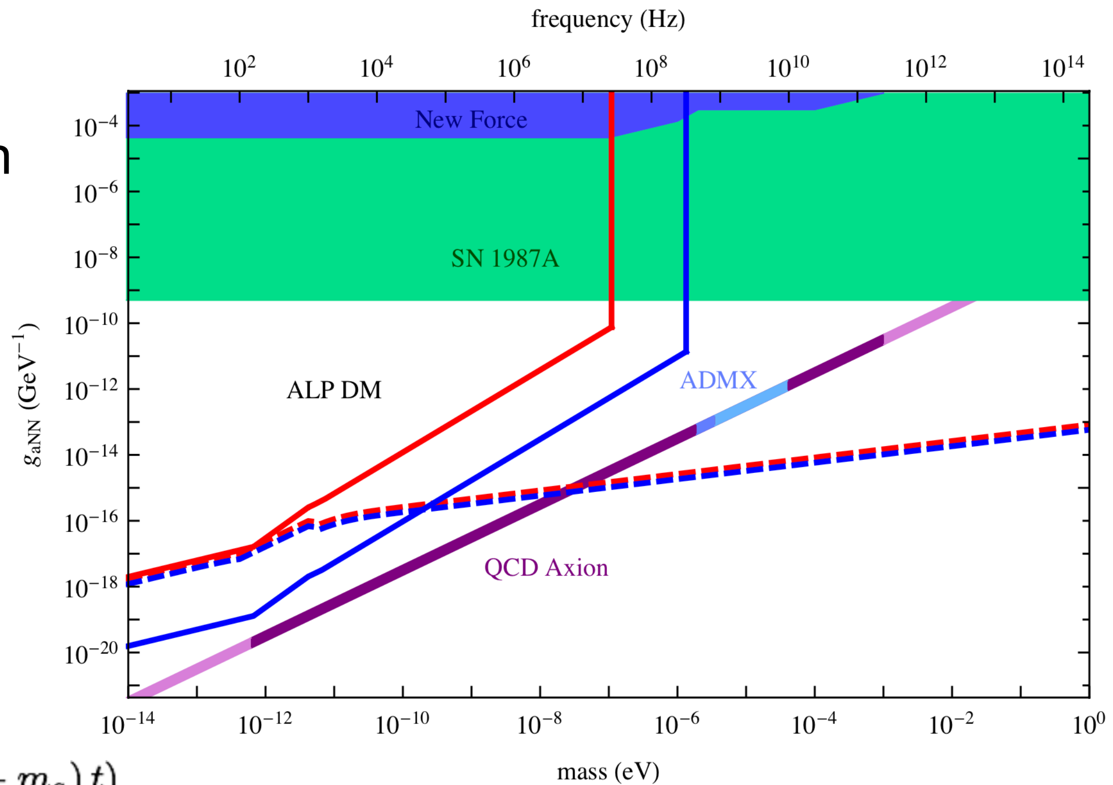
- Resulting magnetisation

$$M(t) \approx n p \mu \left(g_{aNN}\sqrt{2\rho_{DM}}v\right)\frac{\sin\left(\left(2\mu B_{ext}-m_a\right)t\right)}{2\mu B_{ext}-m_a}\sin\left(2\mu B_{ext}t\right)$$



Haloscopes: MR Searches for the Axion/ALP Wind

- Cosmic Axion Spin Precession Experiment (CASPEr) in preparation in Mainz
  - Sensitivity does not reach axion prediction



$$M(t) \approx np\mu \left(g_{aNN} \sqrt{2\rho_{DM}} v \right) \frac{\sin\left(\left(2\mu B_{ext} - m_a \right) t \right)}{2\mu B_{ext} - m_a} \sin\left(2\mu B_{ext} t \right)$$

[Graham,Rajendran 13]

	Element	Density (n)	Magnetic Moment (μ)	T_2	Max. B	Magnetometer Sensitivity
1.	Xe	$1.3 \times 10^{22} \frac{1}{\text{cm}^3}$	$0.35\,\mu_N$	100 s	10 T	$10^{-16} \frac{\text{T}}{\sqrt{\text{Hz}}}$
2.	^{3}He	$2.8 \times 10^{22} \frac{1}{\text{cm}^3}$	$2.12\,\mu_N$	100 s	20 T	$10^{-17} \frac{\text{T}}{\sqrt{\text{Hz}}}$

$$\mathcal{L} \supset g_{aNN} \left(\partial_\mu a \right) \bar{N} \gamma^\mu \gamma_5 N$$

Haloscopes: ESR/MR Searches for the Axion/ALP Wind

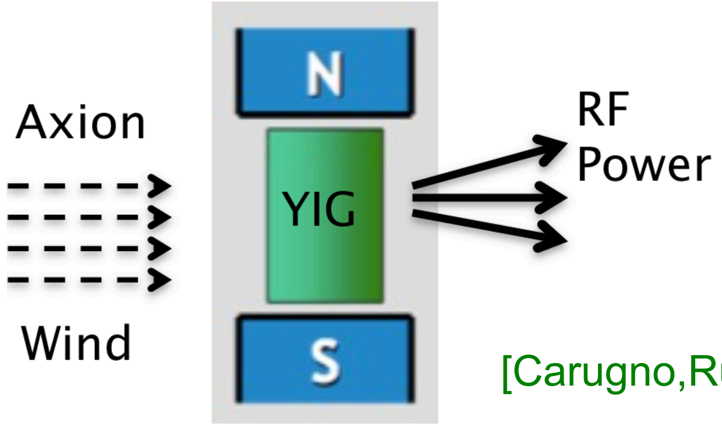
- The axion/ALP electron coupling [Krauss et al. 85;Barbieri et al. 89]

$$\mathcal{L} \supset g_{aee}\, \partial_\mu a \left(\bar{e} \gamma_5 \gamma^\mu e \right)$$

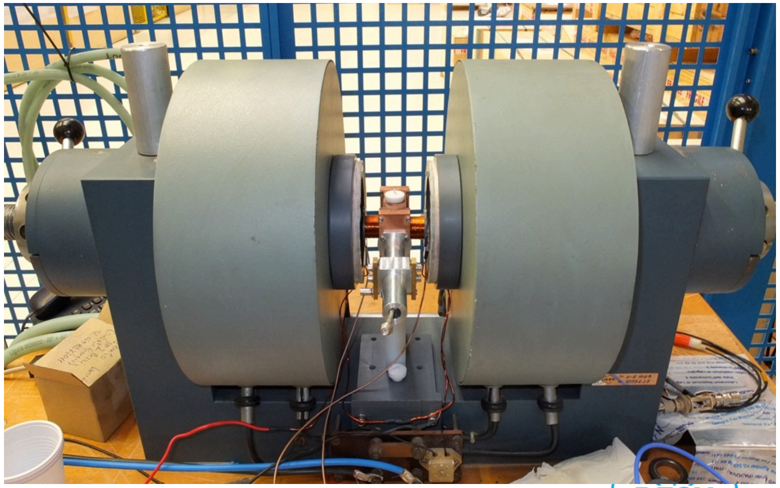
  will also lead to a spin precession about the axion/ALP DM wind

- Larmor frequency and thus sensitivity extended to higher masses by factor $\mu_B/\mu_N \sim m_N/m_e \sim 10^3$

- QUAX (QUaerere AXions) in preparation by INFN (Legnaro, Padua, Torino), Birmingham, Moscow aims to exploit magnetic resonance (MR) inside a magnetized material (Electron Spin Resonance (ESR))



[Carugno,Ruoso et al.]



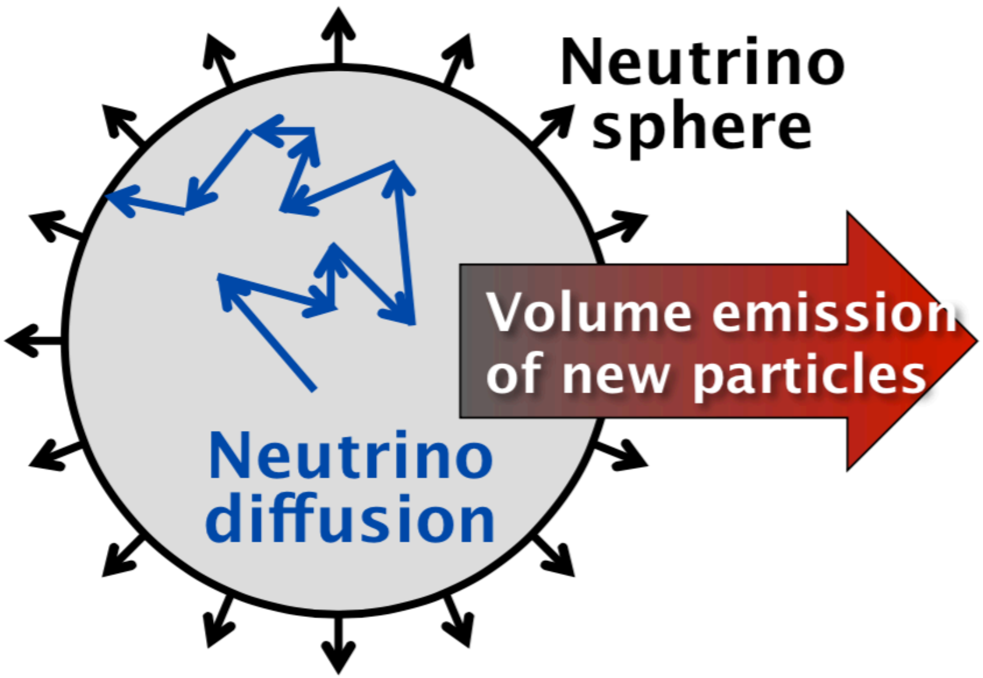
Summary

- Strong physics case for axion and ALPs:
  - Axion and ALPs occur naturally as NG bosons from breaking of well motivated symm.
  - Solution of strong CP problem
  - Candidates for dark matter
  - Explanation of astrophysical hints (energy losses of stars; AGN spectra)
- Large parts in axion and ALPs parameter space can be tackled in the upcoming decade by a number of terrestrial experiments:
  - Light-shining-through-a-wall experiments (ALPS II, ...)
  - Helioscopes (IAXO, ...)
  - Haloscopes (ADMX, CASPEr, QUAX, ...)
- Stay tuned!

Backup: Axion and Neutrino Signal from CC Supernovae

> Late-time neutrino signal most sensitive observable

- Early neutrino burst powered by accretion, not sensitive to volume energy loss
- Late-time neutrino signal associated with neutrino diffusion. Emission of axions would steal energy from the late-time neutrino burst and shorten it



[Raffelt 14]

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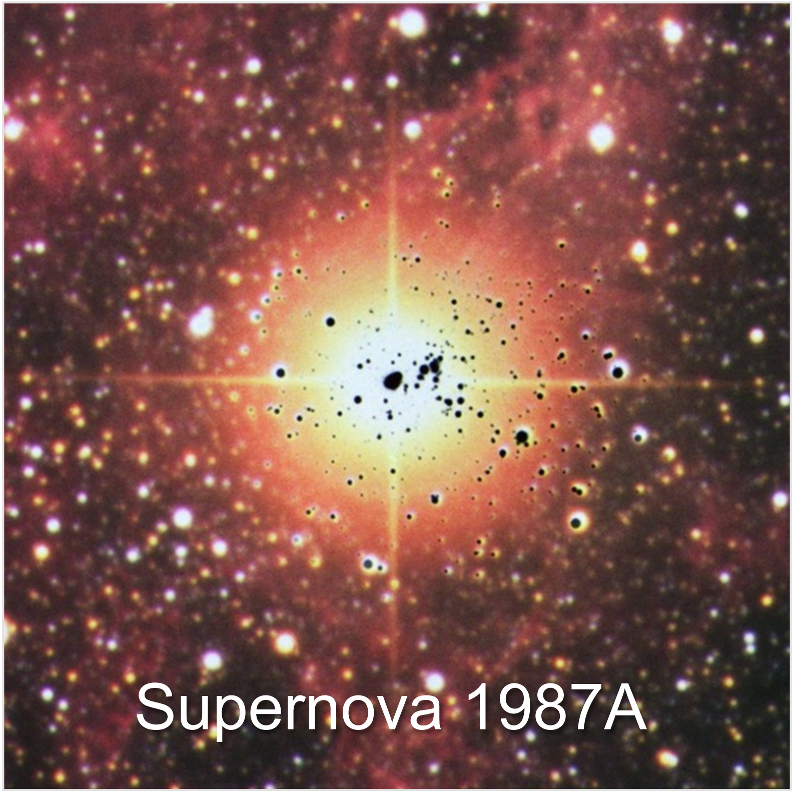

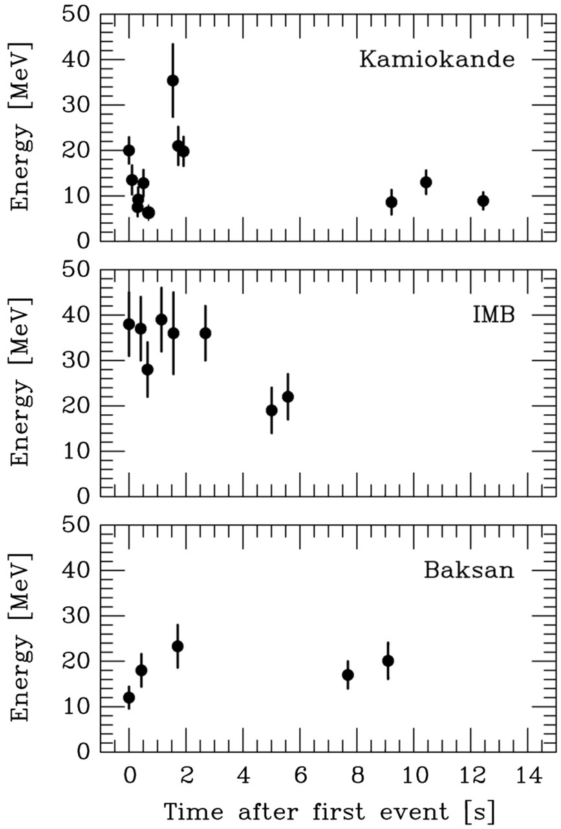

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- Limit on energy loss due to nucleon bremsstrahlung of axions/ALPs in SN 1987 A: [Raffelt 96,08]

$$g_{aN} \equiv \frac{C_{aN} m_N}{f_a} \lesssim 5 \times 10^{-10}, \qquad \text{for} \quad m_a \lesssim \text{MeV}.$$

- Fundamental particle physics opportunity for neutrino telescopes if galactic core-collapse supernova is observed!
- Sensitive in a range of symmetry breaking scale where other experiments have difficulties!

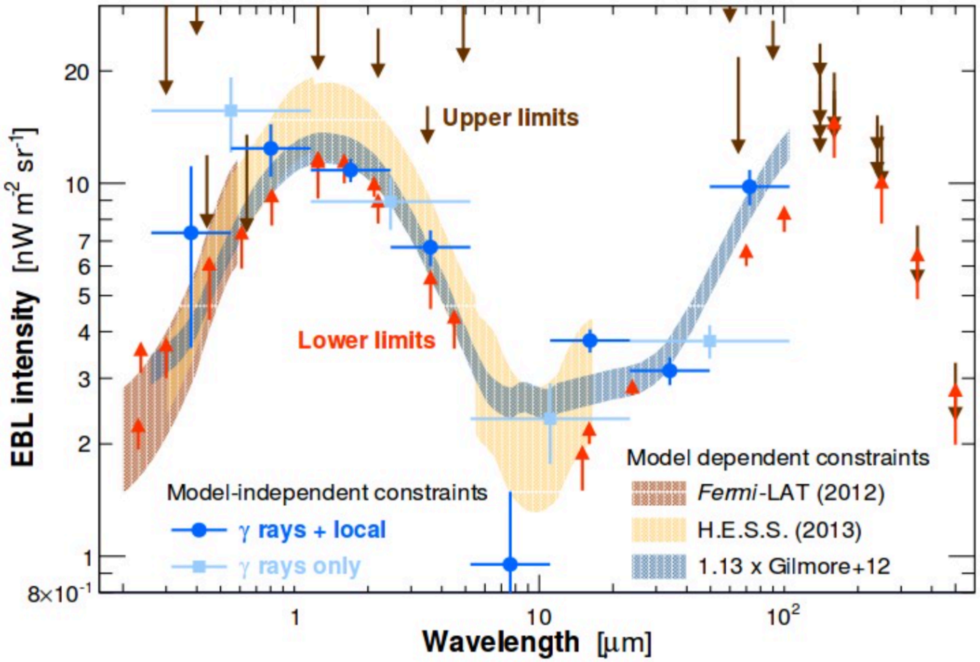
Backup: No Cosmic Pair Production Anomaly?

> Recent claim: no indication of pair production anomaly in VHE AGN spectra [Biteau,Williams 15]

- But then pair productin anomly replaced by EBL anomaly

Deconvolution of the EBL [arXiv:1502.04166]

- Approximate EBL with sums of Gaussians
- Use O(100) spectra
- Tension with models 3-5 σ
- Tension with lower limits from galaxy counts at NIR
- Tension with Fermi-LAT estimate on EBL
- Additionally: too large H_0, too small z for 1424+240



[Horns 15]

Backup: Isocurvature Constraints on Axion/ALPs

- 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 (= entro-py) fluctuations in CMB, with nearly sca-le-invariant power spectrum

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

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

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

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

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

- $f_a > 1.8\times 10^{13}\,\mathrm{GeV}$ strongly disfavored

[Fox et al. hep-th/0409059; Higaki et al. 1403.4186; Marsh et al. 1403.4216; Visinelli,Gondolo 1403.4594]