Hints for Axion Hunts.

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The Ultra-Light Frontier
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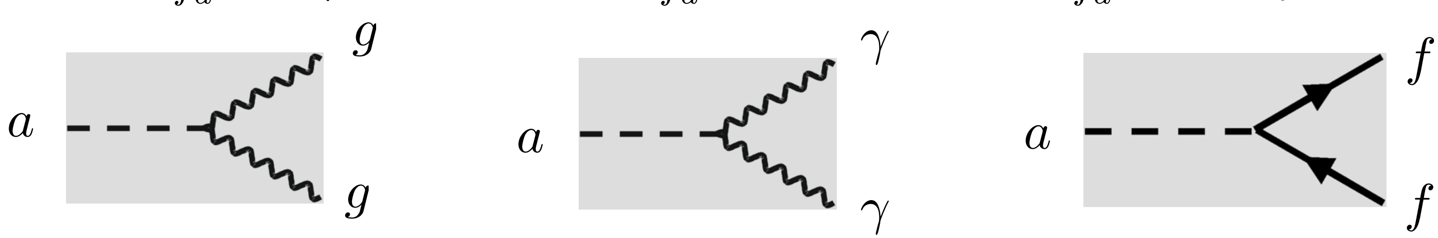
Introduction

- Axion and other Nambu-Goldstone bosons arising from spontaneous breakdown of global symmetries are theoretically well-motivated very weakly interacting ultra-light particles
  - light: (approximate) shift symmetry
  - Very weakly coupled: large symmetry breaking scale: $f_a \sim v_h \gg v = 246\ \mathrm{GeV}$

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



- Coefficients determined by specific ultraviolet extension of SM

Introduction

> 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]

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

> Particle (field) corresponding to the linear combination

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

is called axion: cleans up the strong CP problem

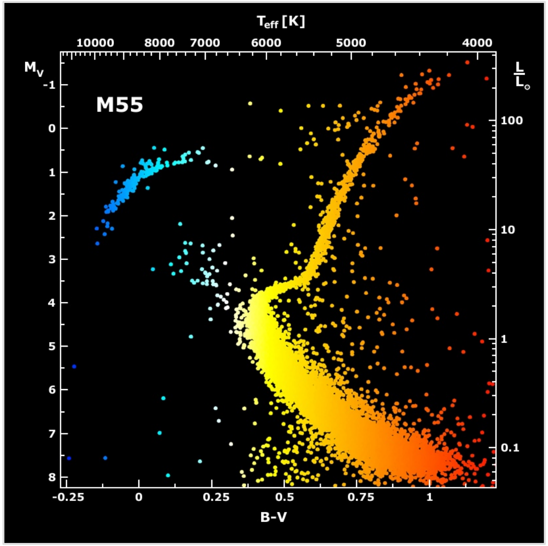
[Peccei,Quinn 77; Weinberg 78; Wilczek 78]

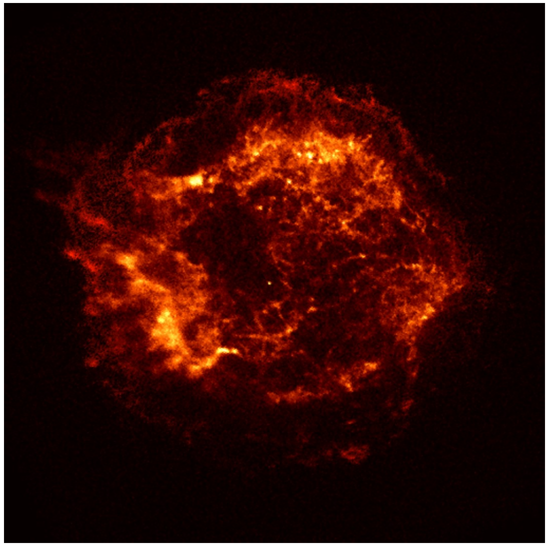
- Mass due to mixing with neutral pion: $m_A \sim m_\pi f_\pi / f_A$

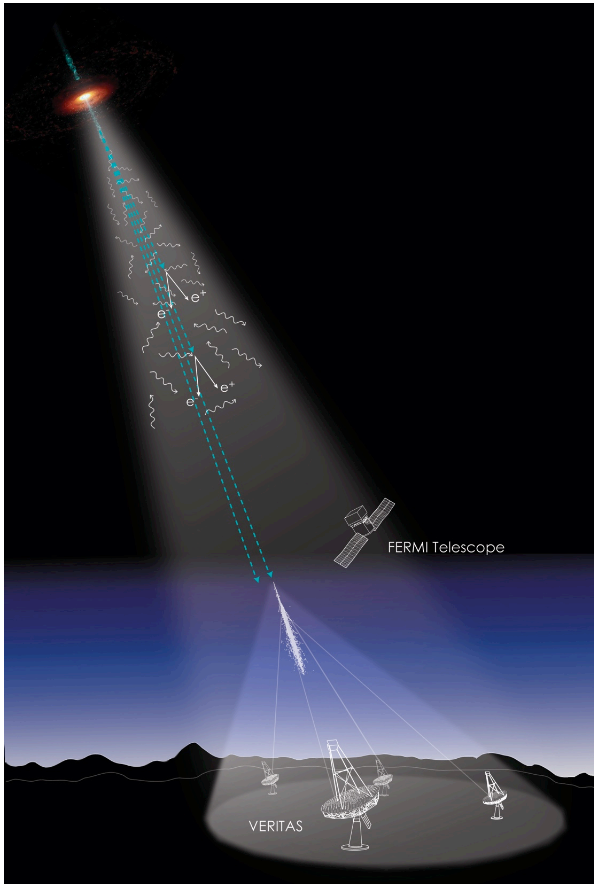
> Particle excitations of the fields orthogonal to the axion field are called Axion-Like-Particles (ALPs)

Introduction

- Marginal hints for excessive energy losses of stars and excessive transparency of the universe for TeV gamma rays





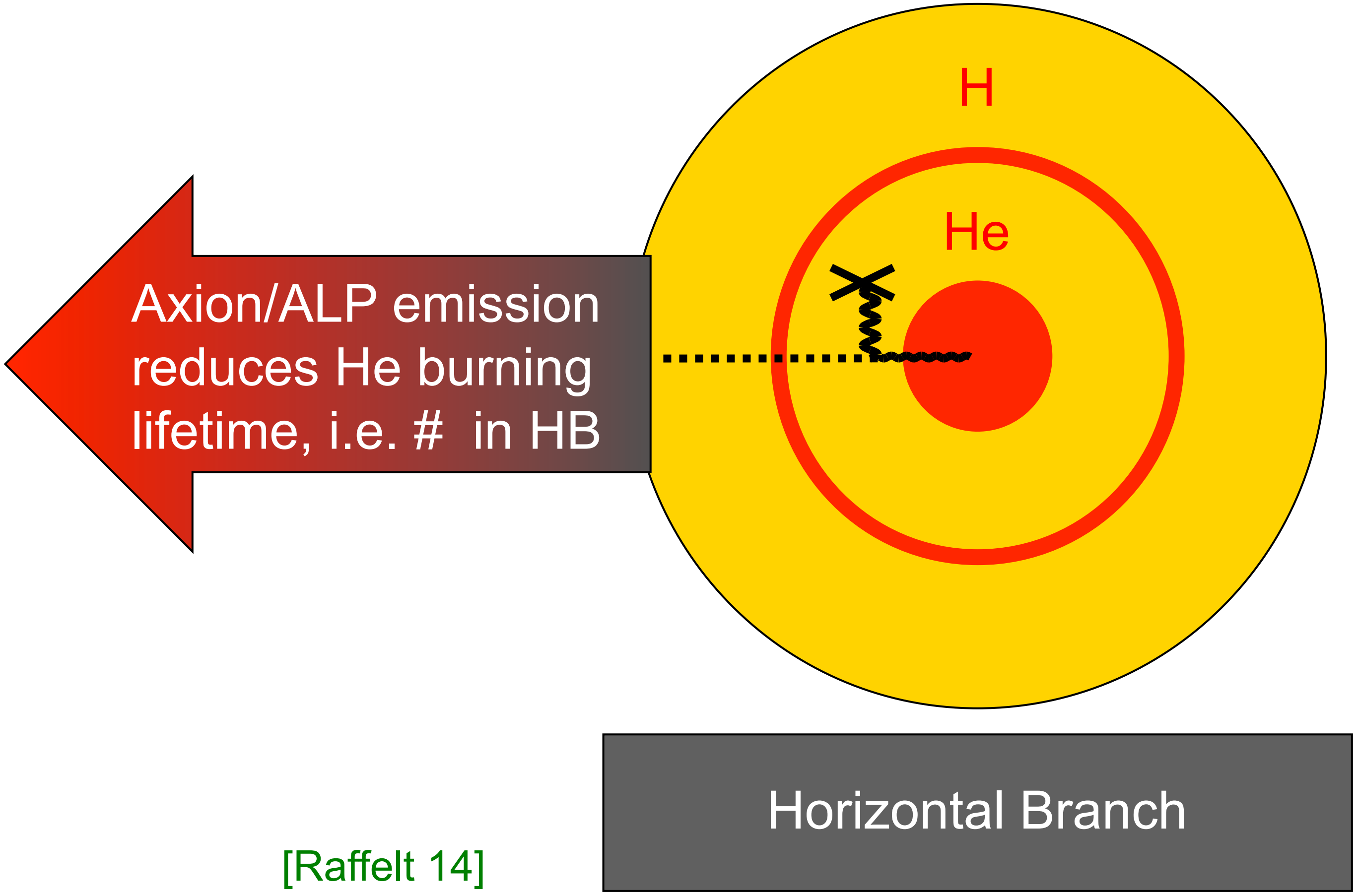


- Signatures of the axion or an ALP?
- Hints for terrestrial hunts!

[phys.org]

Axion/ALP Energy Losses of Stars in Globular Clusters?

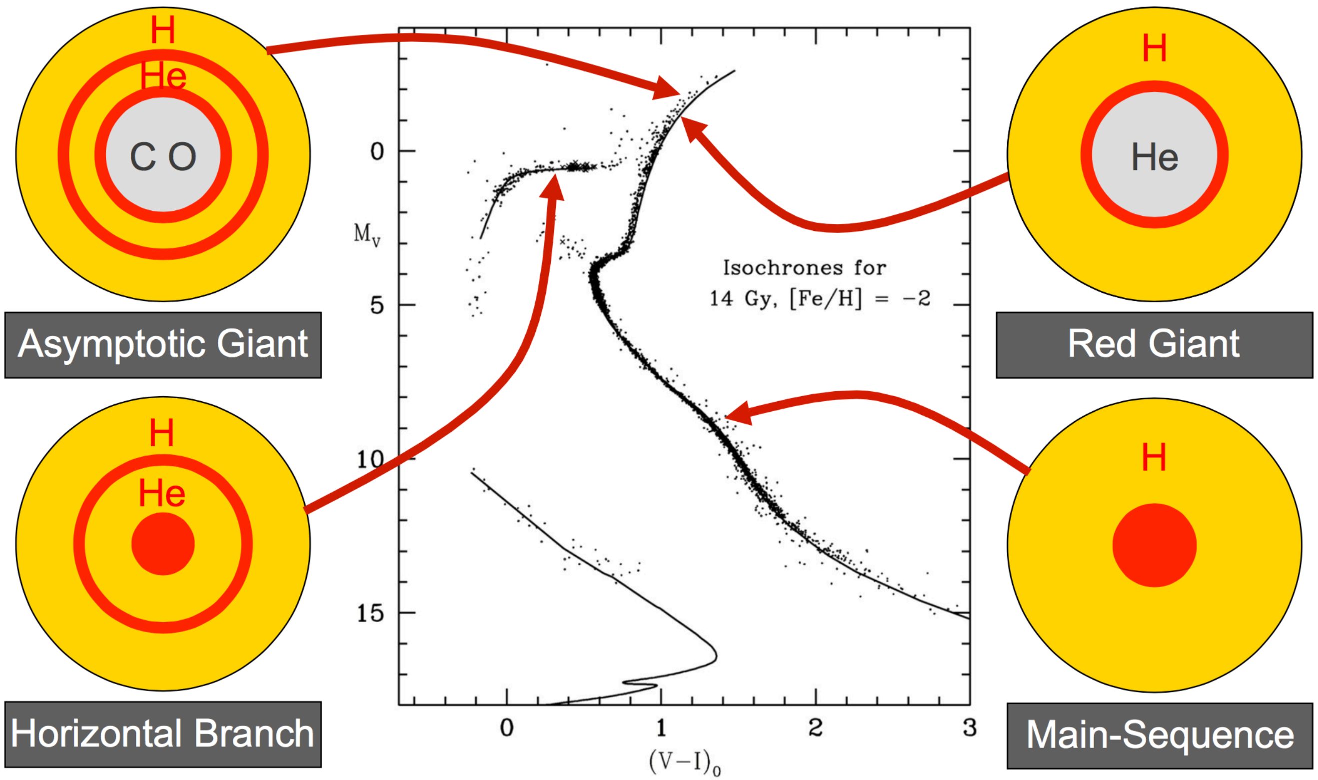
- Horizontal Branch (HB) stars may suffer from additional energy losses through axion/ALP produced via Primakoff $\gamma + Ze \to Ze + a$



[Raffelt 14]

Axion/ALP Energy Losses of Stars in Globular Clusters?

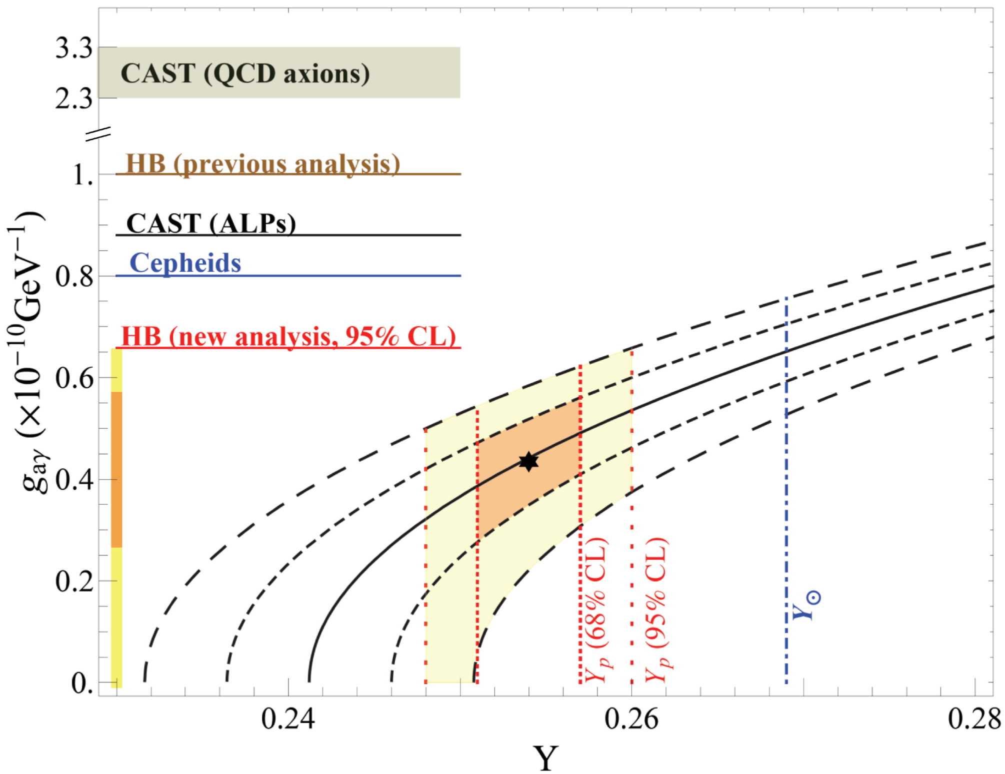
- Horizontal Branch (HB) stars may suffer from additional energy losses through axion/ALP produced via Primakoff $\gamma + Ze \rightarrow Ze + a$
- Signature: Increased ratio of # in HB vs. Red Giant Branch (RGB)



[Raffelt 14]

Axion/ALP Energy Losses of Stars in Globular Clusters?

- Observations mildly prefer excessive energy losses



[Ayala et al. 14]

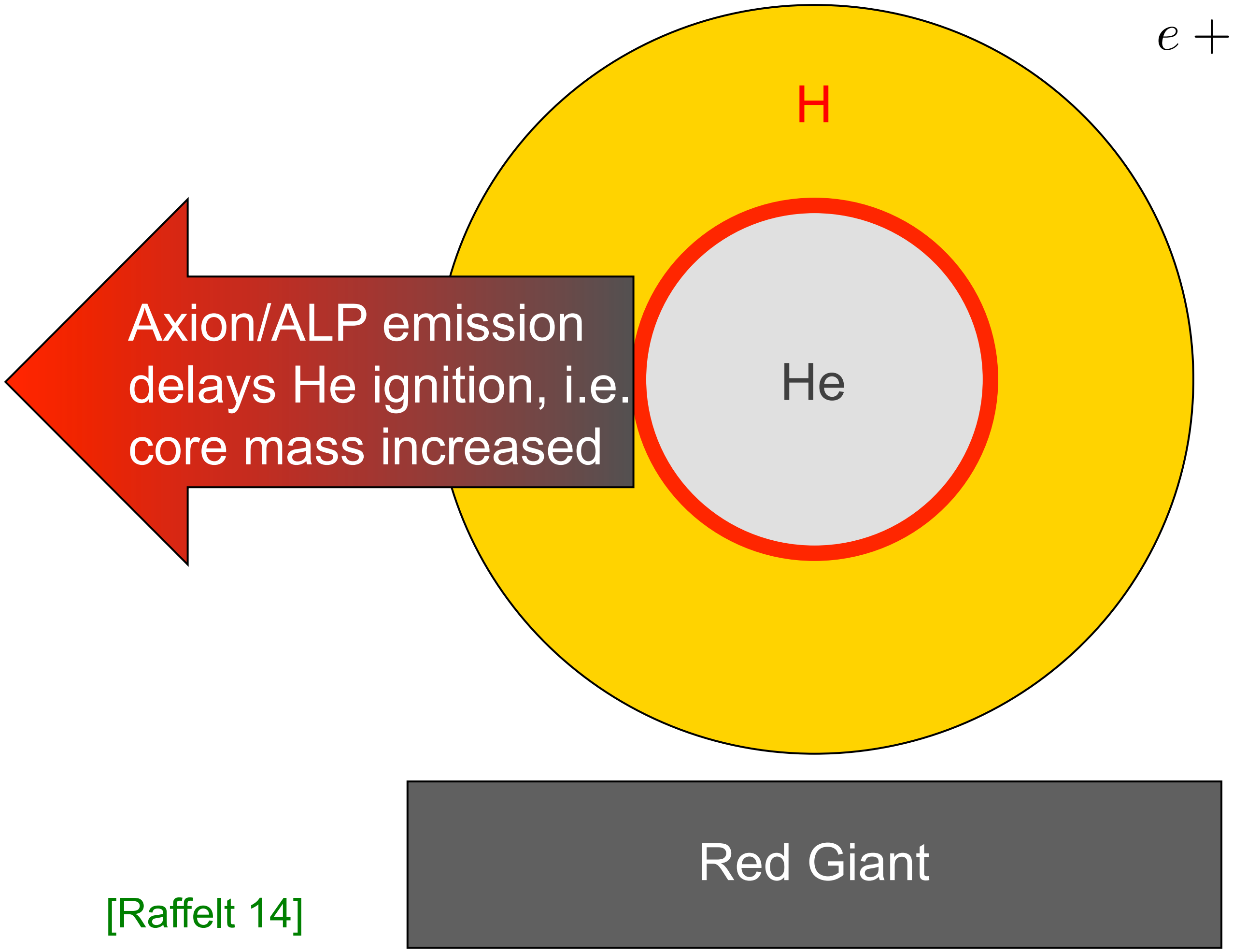
$$g_{a\gamma} \equiv \frac{\alpha\, C_{a\gamma}}{2\pi f_a} = 0.45^{+0.12}_{-0.16} \times 10^{-10}\ \mathrm{GeV}^{-1}$$

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

Axion/ALP Energy Losses of Stars in Globular Clusters?

- Degenerate helium core of Red Giants (RGs) may suffer from additional energy losses through axion/ALP production via Bremsstrahlung:

$$e + Ze \to Ze + e + a$$



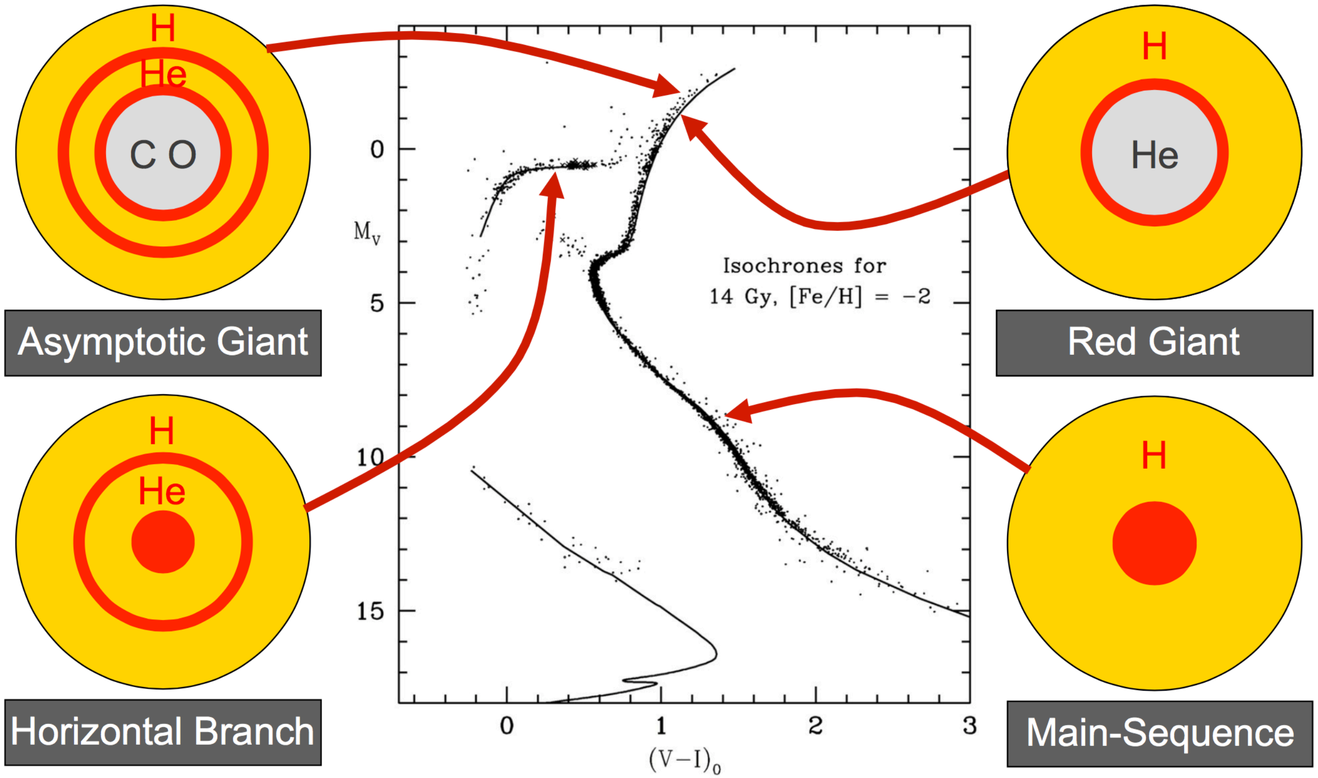
[Raffelt 14]

Axion/ALP Energy Losses of Stars in Globular Clusters?

- Degenerate helium core of Red Giants (RGs) may suffer from additional energy losses through axion/ALP production via Bremsstrahlung:

$$e + Ze \to Ze + e + a$$

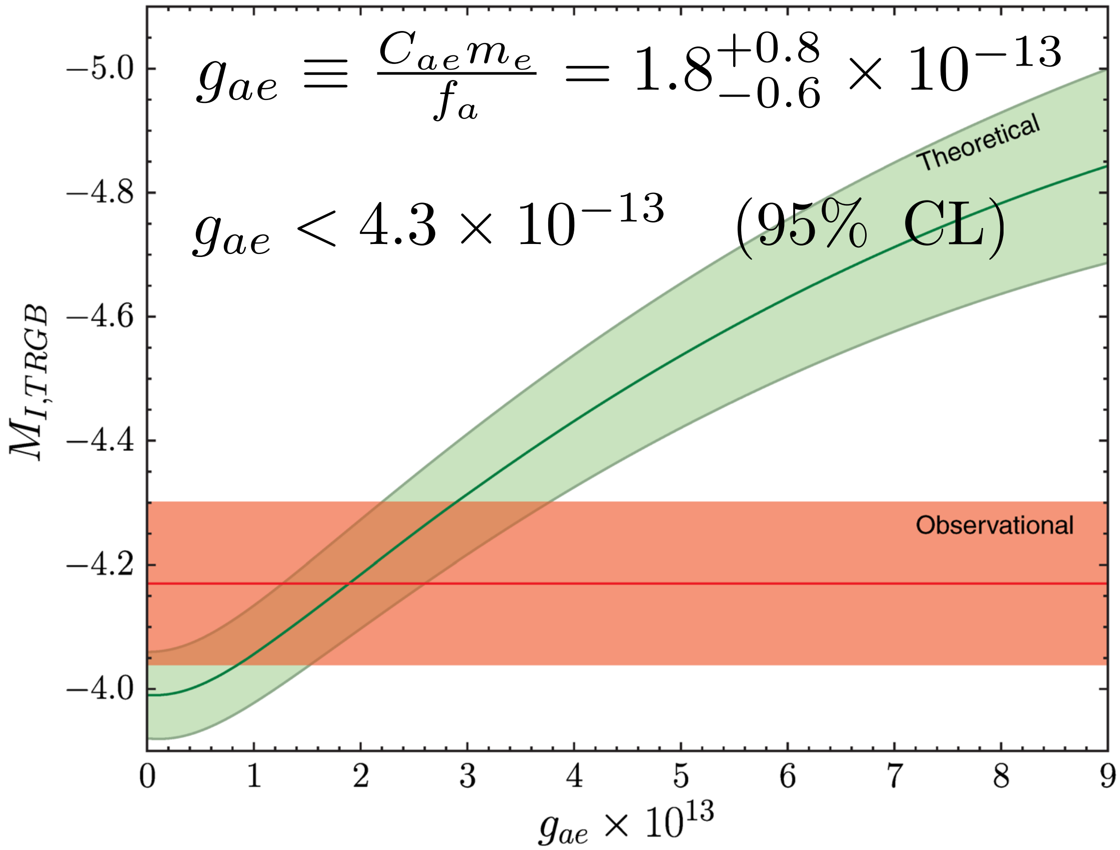
- Signature: RGB extended to larger brightness



[Raffelt 14]

Axion/ALP Energy Losses of Stars in Globular Clusters?

> Observations mildly prefer excessive energy losses:

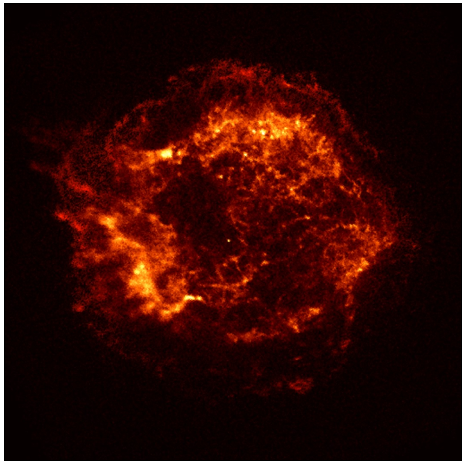


[Viaux et al. 13]

> 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 Neutron Star in Cas A?

- Neutron star in Cas A:



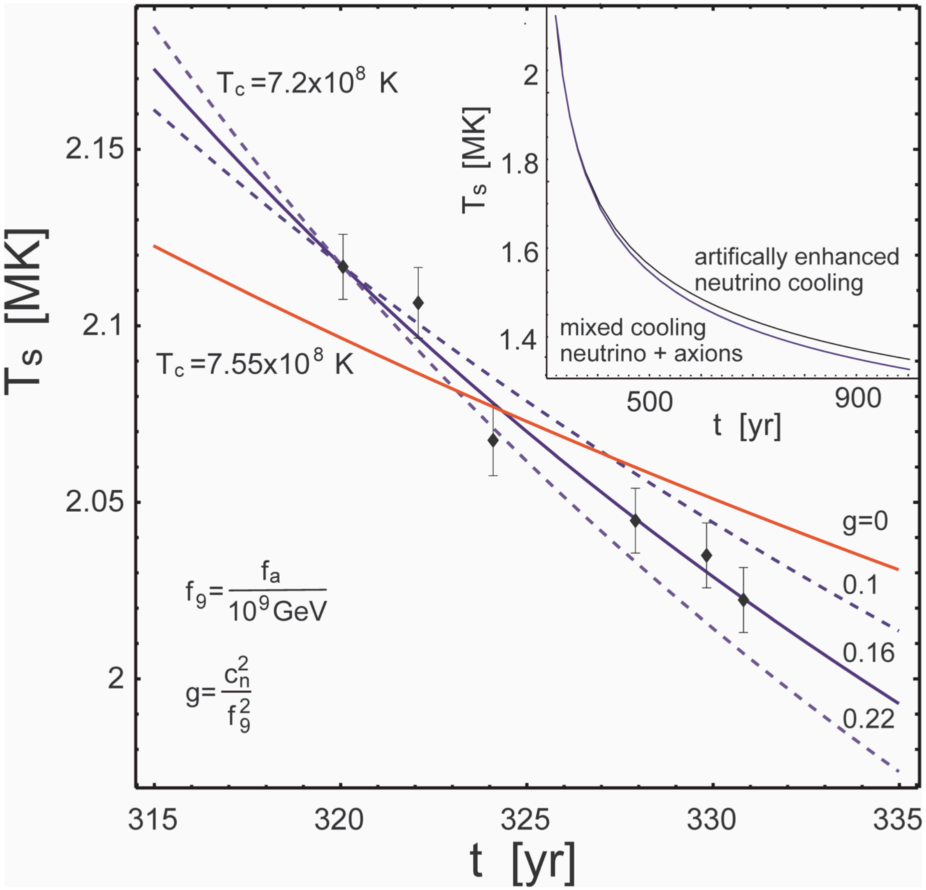
  - Measured surface temperature reveals unusually fast cooling rate
  - Hint on extra cooling by axion/ALP due to nucleon bremsstrahlung

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

  - Required coupling to neutron:

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

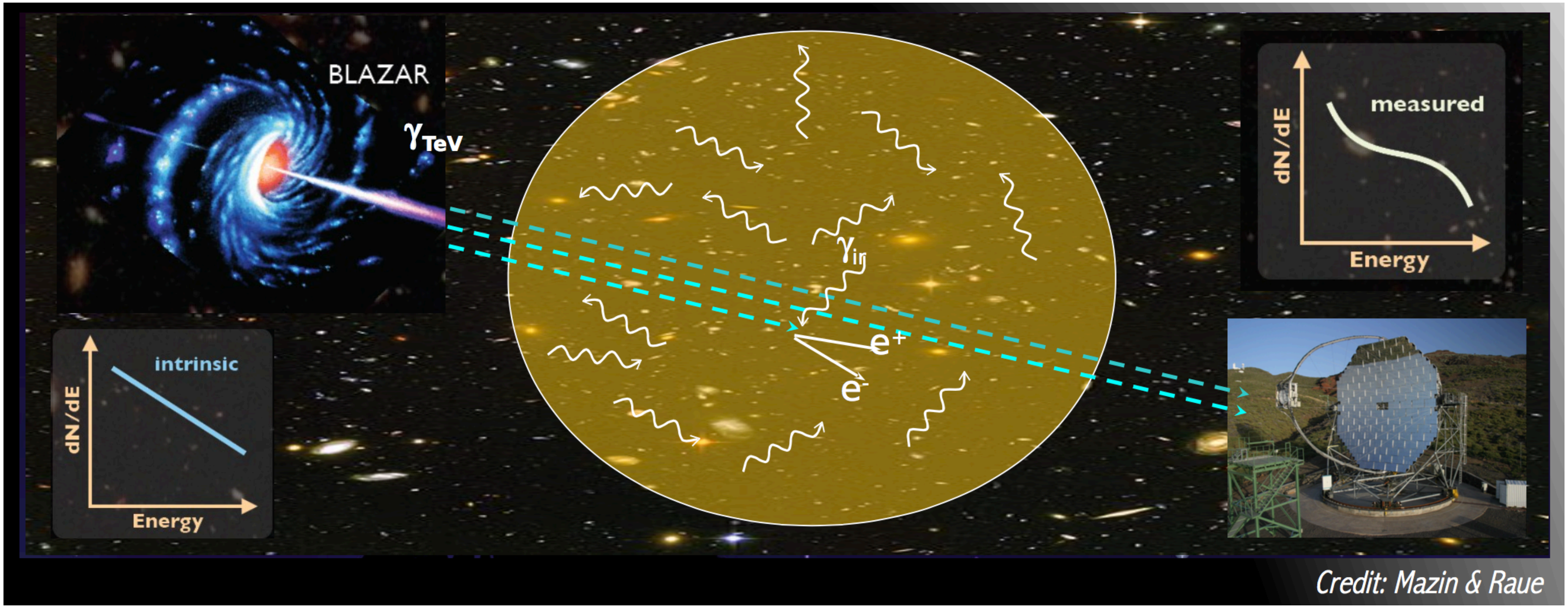
  - Alternative explanation: PT of n condens.



[Leinson 14]

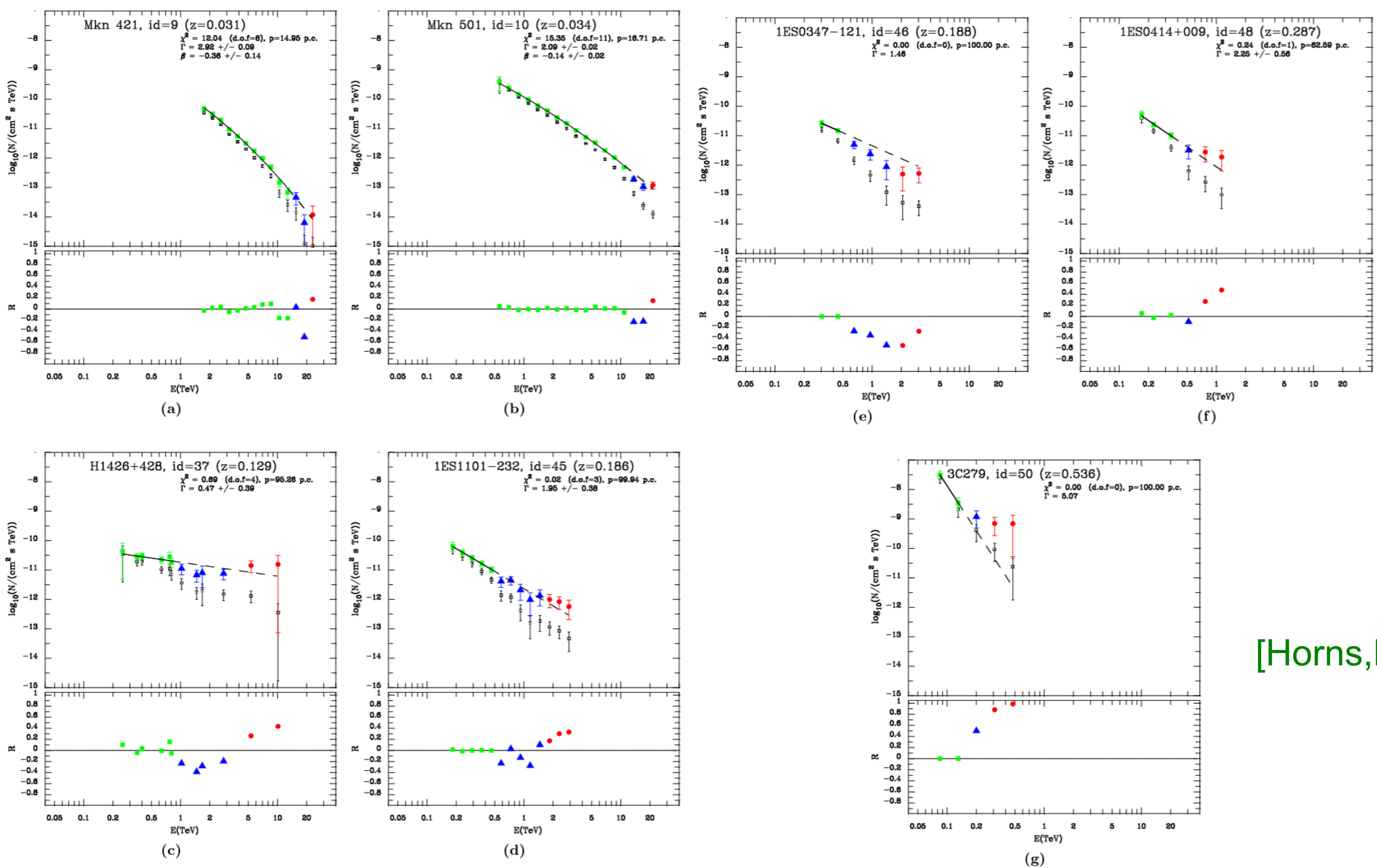
Photon – ALP Conversion in Cosmic Magnetic Fields?

- 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)



Photon – ALP Conversion in Cosmic Magnetic Fields?

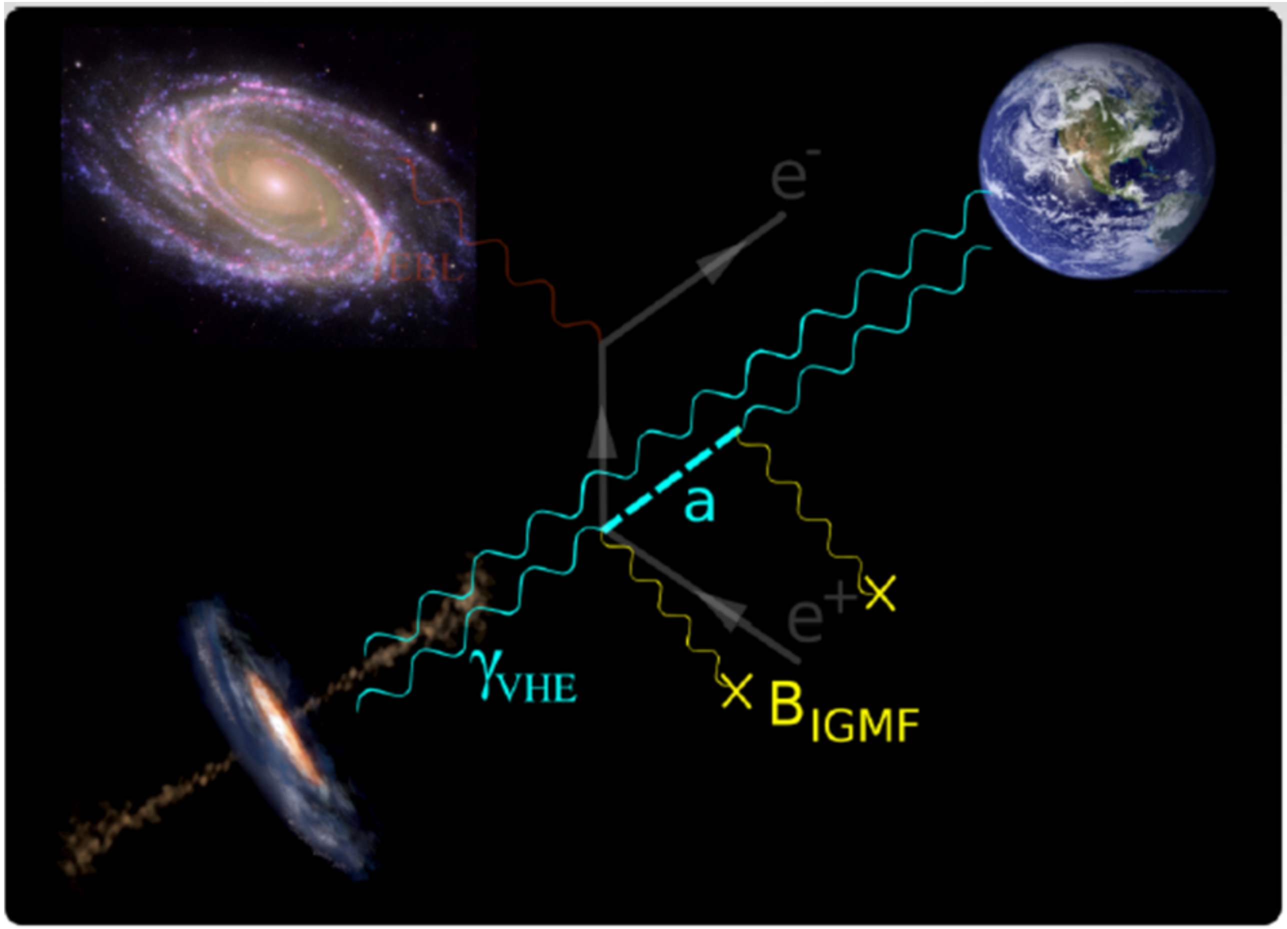
- Indication of anomalous gamma transparency: attenuation observed by IACT and Fermi-LAT too small [Aharonian et al. 07; de Angelis,Roncadelli et al. 07;...;Horns,Meyer 12;...;Rubtsov,Troitsky 14]



[Horns,Meyer 12]

Photon – ALP Conversion in Cosmic Magnetic Fields?

- Possible explanation: photon <-> ALP conversions in magnetic fields; conversion very efficient for sub micro-eV mass (strong mixing)
  [De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer,Horns,Raue 13]



[Manuel Meyer 12]

Photon – ALP Conversion in Cosmic Magnetic Fields?

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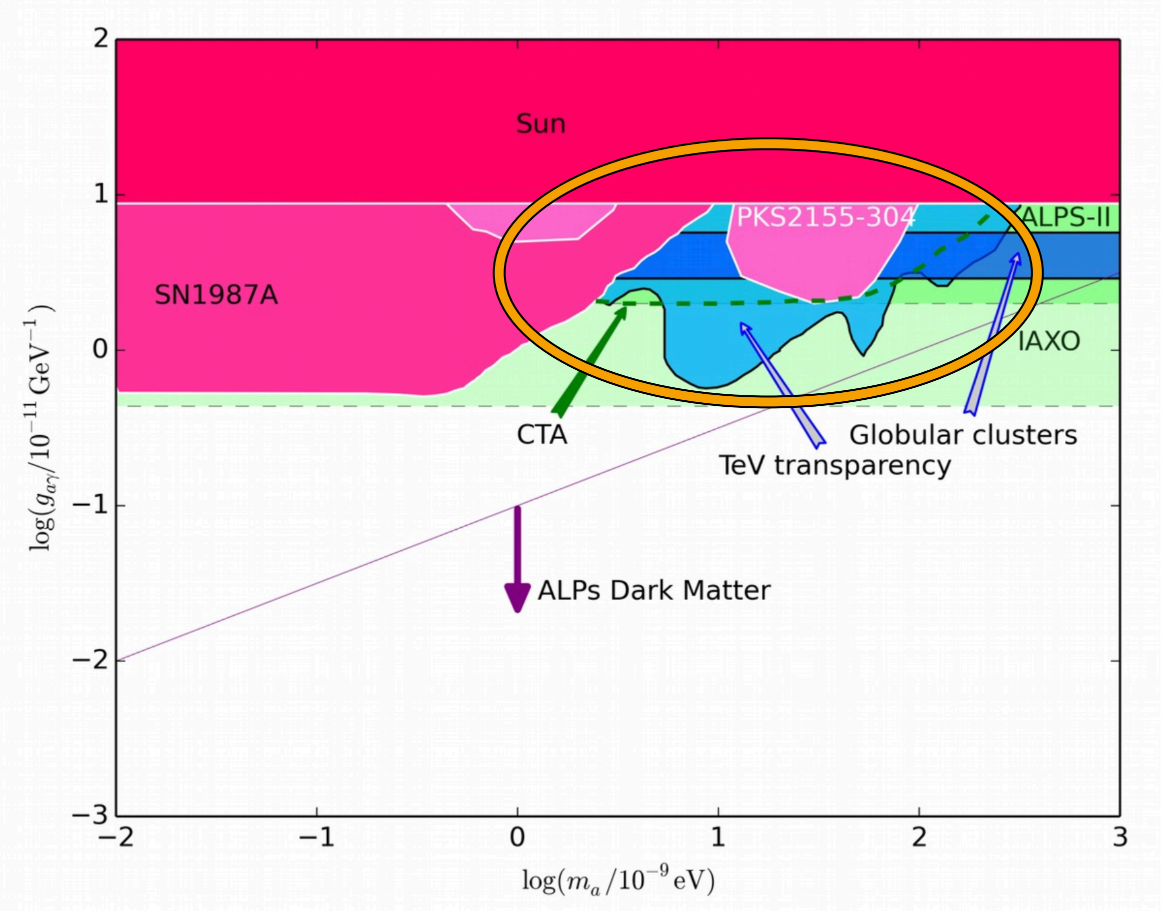
  [De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer,Horns,Raue 13]



[Horns 15]

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

Summary of Astrophysical Hints for Axion/ALPs

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

     plus

     ALP with $f_a \sim 10^7\ \mathrm{GeV},\ m_a \lesssim 0.1\ \mu\mathrm{eV},\ C_{a\gamma} \sim 1,\ C_{ae} \sim C_{an} \ll 10^{-2}$
- ALP from closed string sector of IIB string theory good example for 1.
- 1. and 2. may be checked in upcoming photon regeneration experiments (ALPS II, IAXO, ...)

Closed String ALPs in String Theory

1. Massless bosonic spectrum of closed string sector of string theories in 10D contains form fields satisfying gauge symmetries

MASSLESS SPECTRUM OF STRING THEORIES				
THEORY	DIMENSION	SUPERCHARGES	BOSONIC SPECTRUM	
Heterotic	10	16		$g_{\mu\nu}, B_{\mu\nu}, \phi$
$E_8 \times E_8$				$A_\mu^{i\bar{j}}$ in adjoint representation
Heterotic	10	16		$g_{\mu\nu}, B_{\mu\nu}, \phi$
$SO(32)$				$A_\mu^{i\bar{j}}$ in adjoint representation
Type I	10	16	NS-NS	$g_{\mu\nu}, \phi$
$SO(32)$				$A_\mu^{i\bar{j}}$ in adjoint representation
			R-R	$C_{(2)}$
Type IIB	10	32	NS-NS	$g_{\mu\nu}, B_{\mu\nu}, \phi$
			R-R	$C_{(0)}, C_{(2)}, C_{(4)}$
Type IIA	10	32	NS-NS	$g_{\mu\nu}, B_{\mu\nu}, \phi$
			R-R	$C_{(1)}, C_{(3)}$

[Quevedo `02]

2. Symmetries broken by compactification

3. Kaluza-Klein decomposition contains ALPs, with decay constants determined by string or compactification scale
[Witten 84; Conlon 06; Svrcek,Witten 06]

4. Shift symmetries only violated through non-perturbative effects

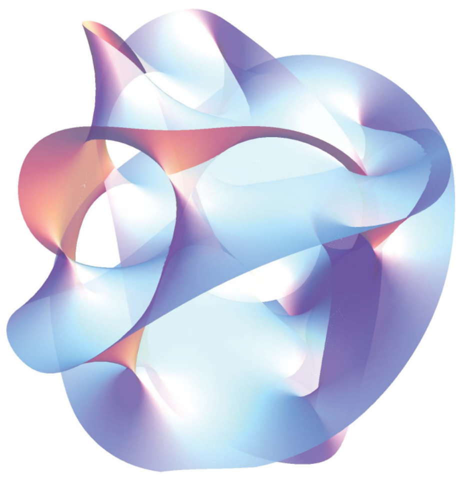
Closed String ALPs in IIB String Theory

> KK reduction (expansion in harmonic forms):

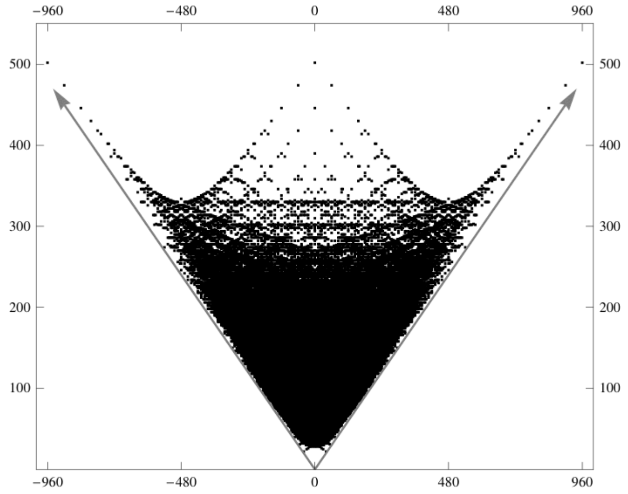
$$C_2 = c^a(x)\omega_a, \quad a = 1, ..., h^{1,1}_-$$

$$C_4 = c_\alpha(x)\tilde{\omega}^\alpha + \ldots, \quad \alpha = 1, ..., h^{1,1}_+$$

> Number of ALPs determined by topology of CY orientifold: number of topologically non-equivalent 2-cycles or 4-cycles



$$h^{1,1} + h^{2,1}$$



[Kreuzer,Skarke]

Figure 1: A plot of the Hodge numbers of the Kreuzer–Skarke list. $\chi = 2(h^{11} - h^{21})$ is plotted horizontally and $h^{11} + h^{21}$ is plotted vertically. The oblique axes bound the region $h^{11} \geq 0$, $h^{21} \geq 0$.

$$2(h^{1,1} - h^{2,1})$$

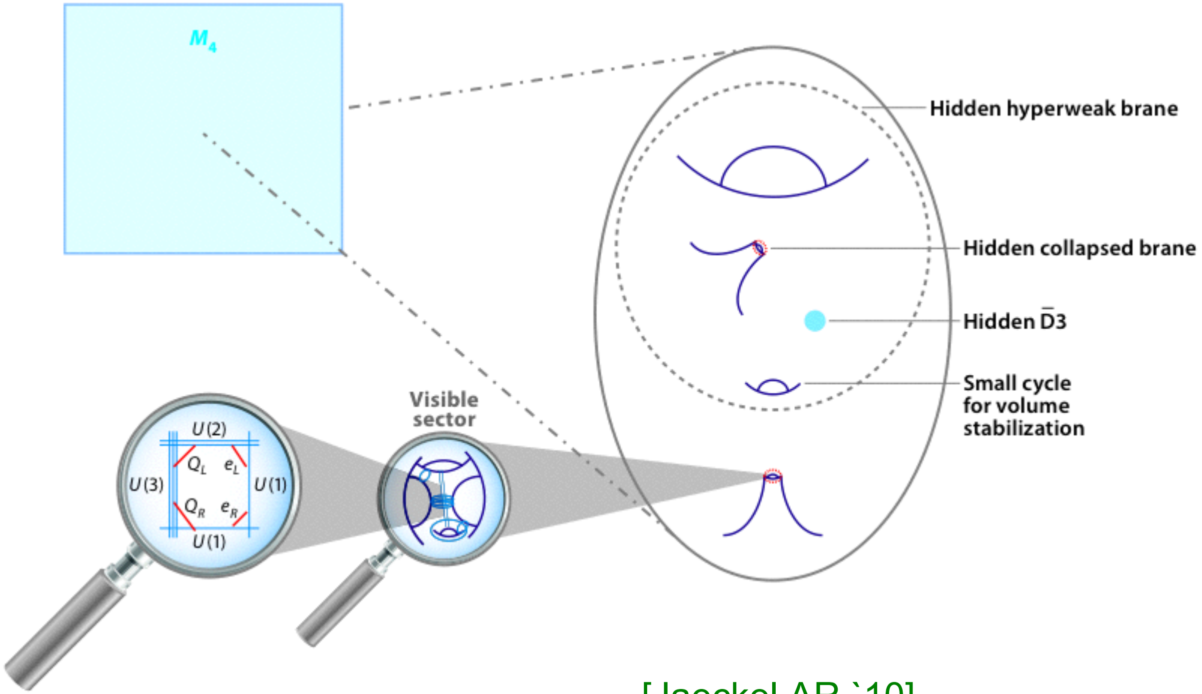
> An axiverse may naturally arise from strings

[Arvanitaki et al. `09]

Closed String ALPs in IIB String Theory

Realisation brane-world scenario

- Visible sector gauge theory realized by stacks of D7 branes wrapping small 4-cycles
- Gravity propagates in the bulk, leading to a string scale $M_s \sim M_P/\sqrt{\mathcal{V}}$ and a KK scale $M_{\rm KK} \sim M_P/\mathcal{V}^{2/3}$ possibly much much smaller than the Planck scale M_P, at the expense of a large compactification volume $\mathcal{V} \gg 1$



[Jaeckel,AR `10]

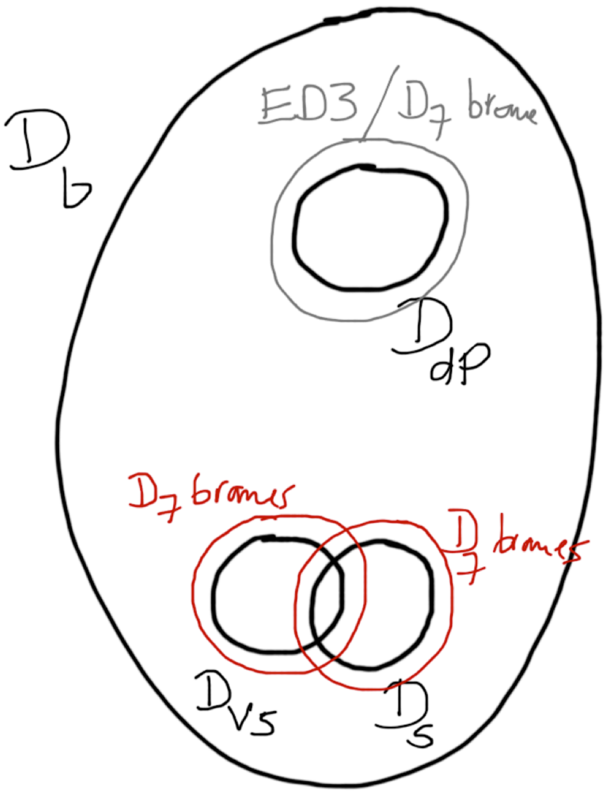
Closed String ALPs in LARGE Volume IIB String Theory

- LVS requires at least four 4-cyles: [Cicoli et al. `11]
  - bulk (large volume) cycle, size fixed perturbatively
  - dP cycle, size fixed non-perturbatively
  - cycle supporting the stack of branes describing the visible sector, size fixed perturbatively
  - cycle supporting a stack of branes providing D-terms to stabilise the volume of the visible cycle
- LVS has at least two light ALPs: [Cicoli, Goodsell, AR, 1206.0819]
  - large volume ALP a'_b with $f_{a'_b} \sim M_{\rm KK} \sim M_P/\mathcal{V}^{2/3}$ small coupling, $C_{b\rm vs} \simeq \mathcal{O}\left(\mathcal{V}^{-2/3}\right)$ $\quad m_{a'_b} \sim m_{3/2}\,{\rm e}^{-c\,n\,\tau_b}$
  - visible sector ALP $a'_{\rm vs}$ with ,

$$f_{a'_{\rm vs}} \sim M_s \sim M_P/\sqrt{\mathcal{V}}$$

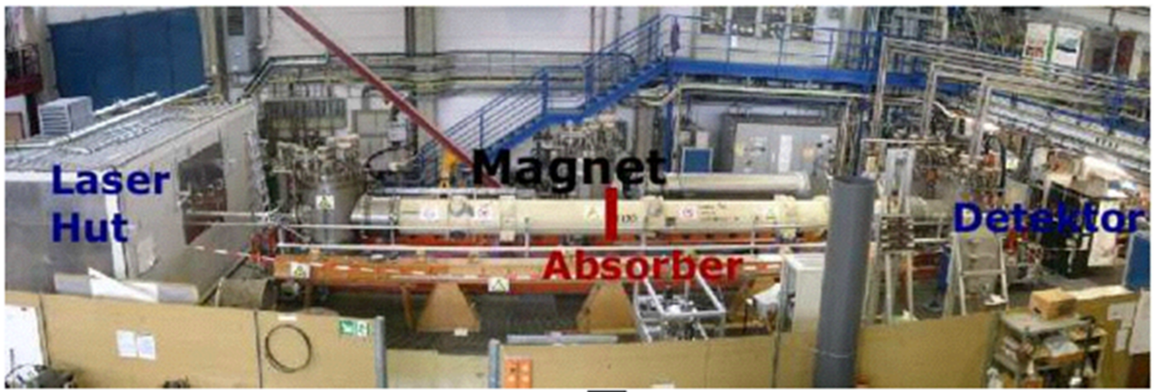
$$m_{a'_{\rm vs}} \sim \frac{M_P}{\mathcal{V}} {\rm e}^{-2\pi n/\alpha}$$

$$C_{a_{\rm vs}\gamma} = \mathcal{O}(1), C_{a_{\rm vs}f} = \mathcal{O}(\alpha)$$



Light-shining-through-a-wall Searches

- Any Light Particle Search (ALPS) at DESY

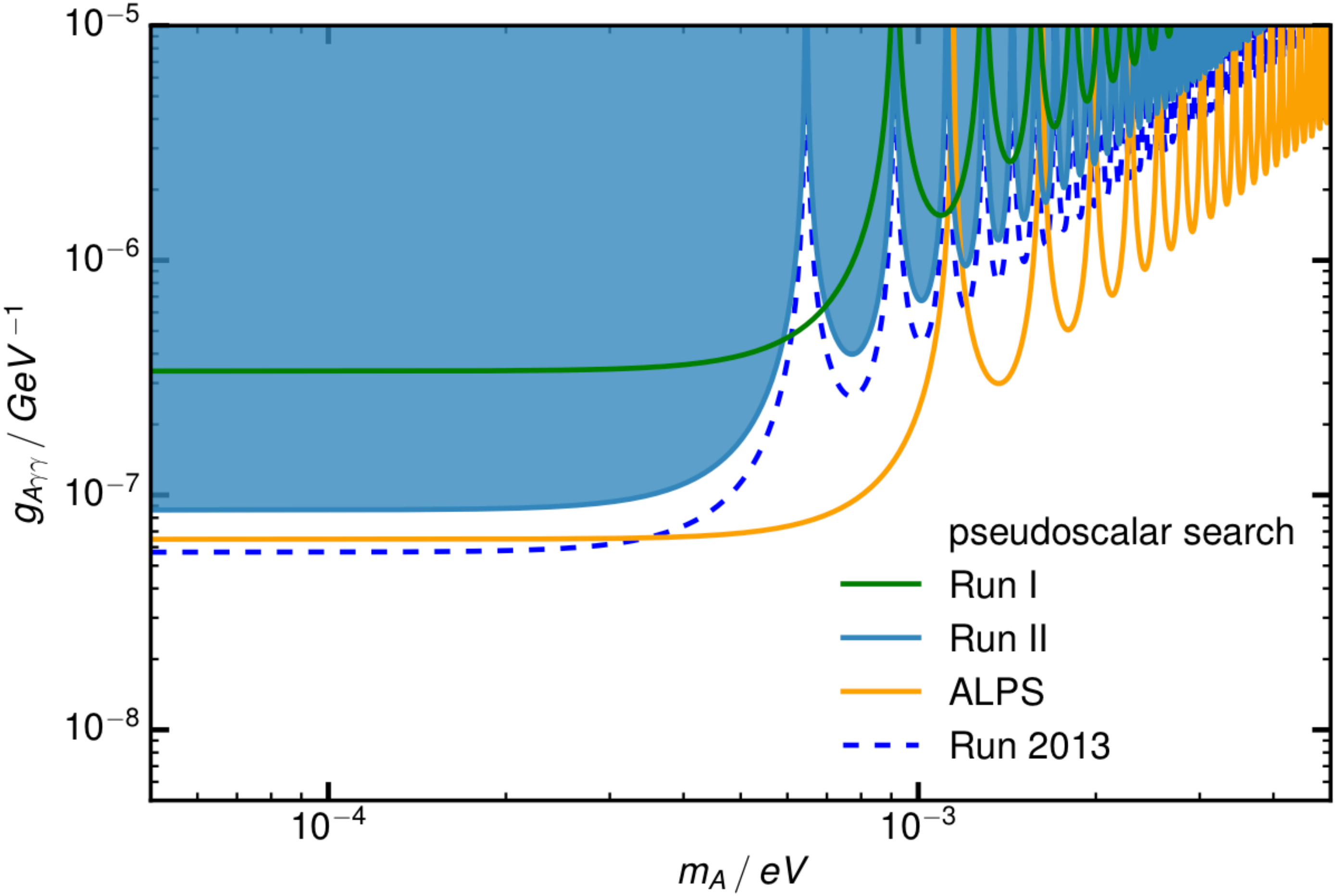


$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

[Anselm 85;van Bibber et al. 87]

Light-shining-through-a-wall Searches

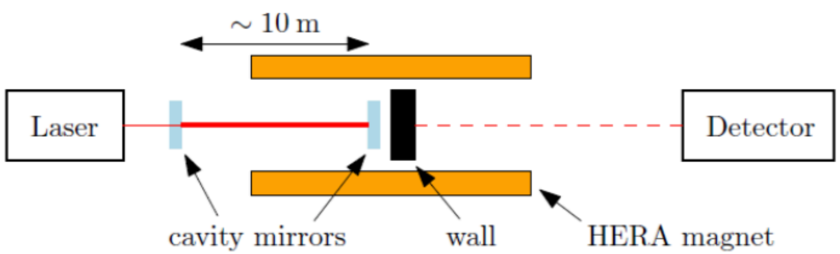
- Currently best limits from LSW: ALPS (DESY) and OSQAR (CERN)



[Balou et al. 14]

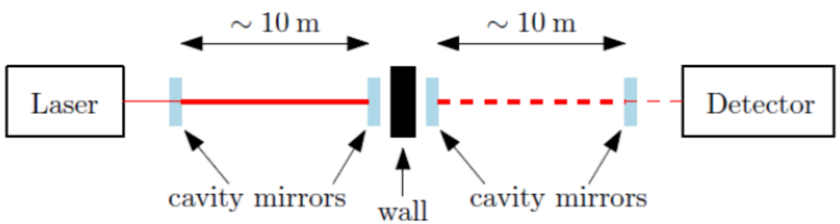
ALPS II: Stages

ALPS I



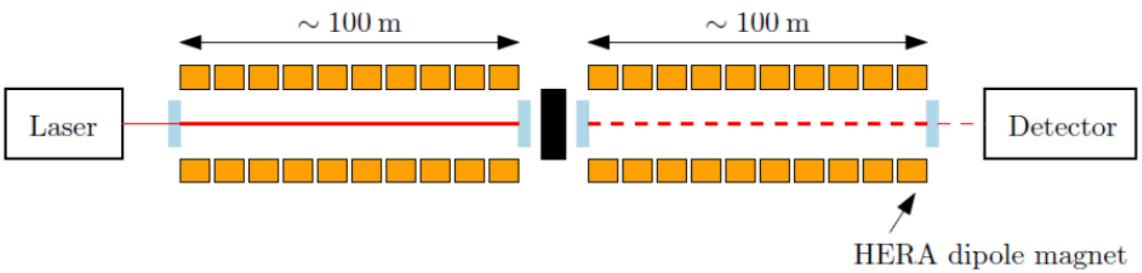
(a) ALPS-I

> **ALPS IIa**



(b) ALPS-IIa

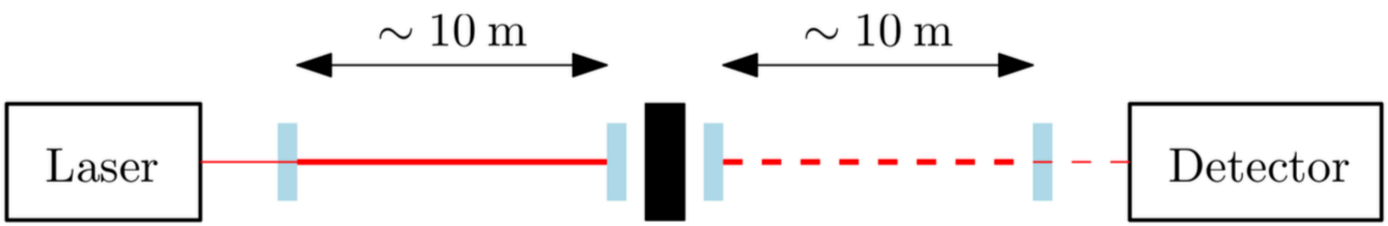
> **ALPS IIc**



(d) ALPS-IIc

ALPS IIa

Development Stage



- **Production-Cavity:**
  - Power Buildup: $\beta_{PC} = 5000$
- **Regeneration-Cavity:**
  - Power Buildup: $\beta_{RC} = 40000$

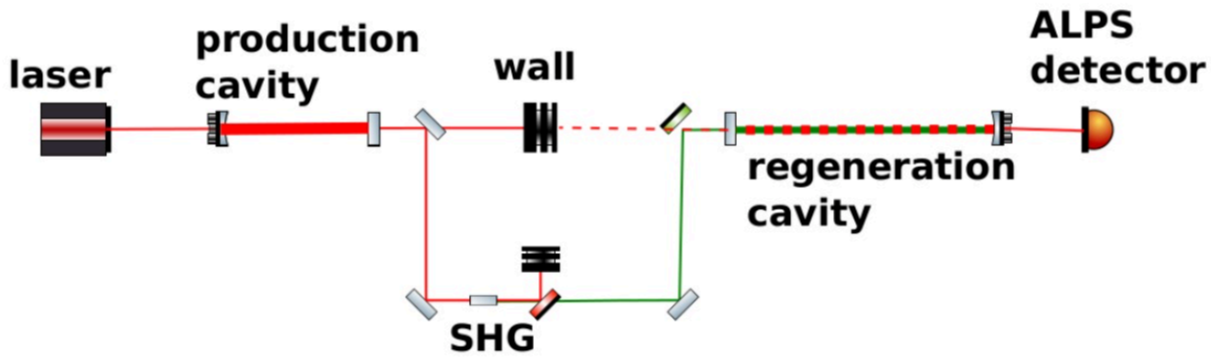
$$\textit{sensitivity} \propto \left(\frac{1}{\beta_{PC} \cdot \beta_{RC}}\right)^{\frac{1}{4}}$$

Sensitivity Gain (ALPS-I $\rightarrow$ II): $\times 3.5 \;\; \times 14$

[Weinsheimer 15]

ALPS IIa: Optics

Conceptual design

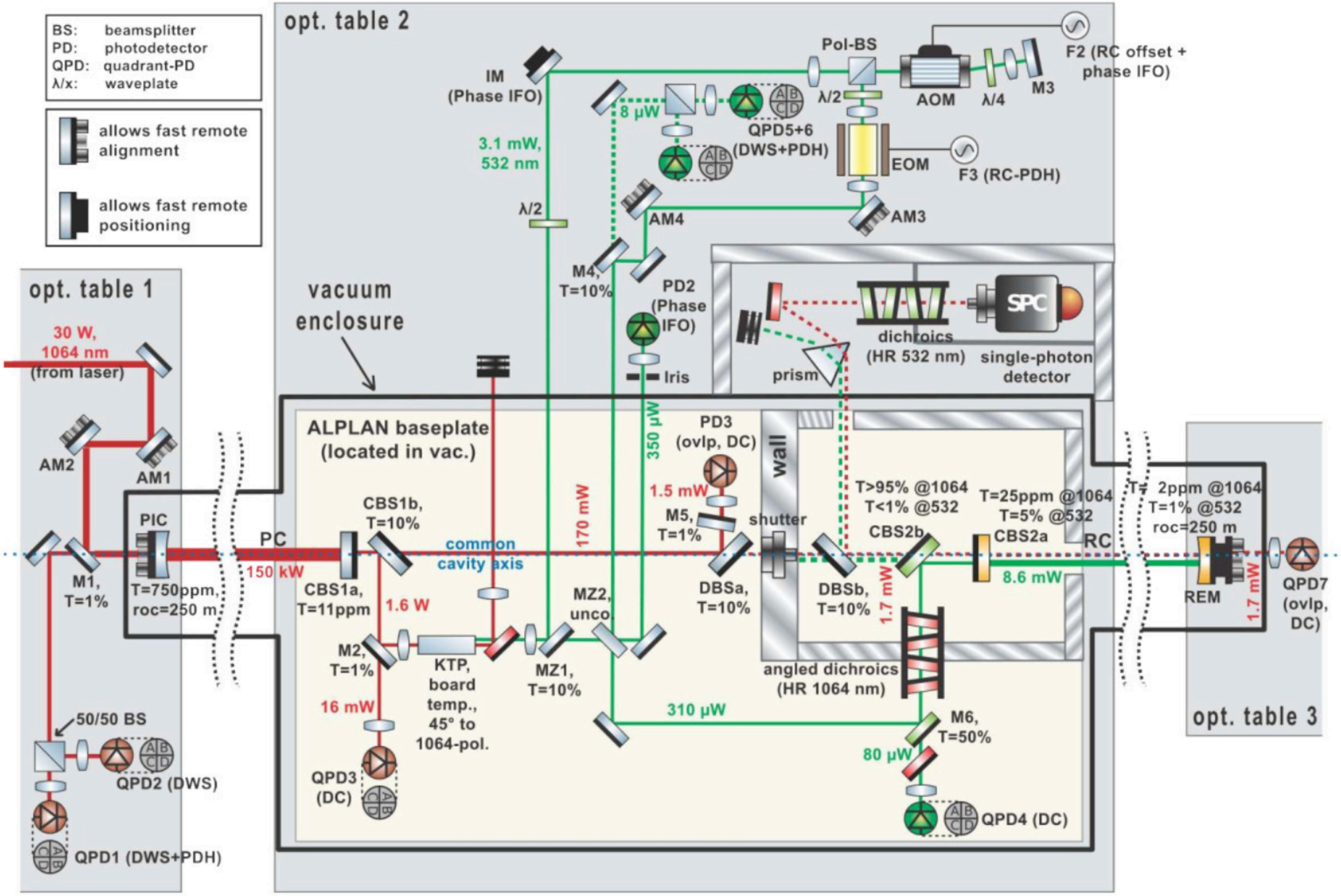


- Stabilize cavities
  - Pound-Drever-Hall
  - Differential-Wavefront-Sensing
- Keep regeneration cavity on resonance with green light
- overlap of cavity modes

ALPs signal: reconverted red photons

[Weinsheimer 15]

ALPS IIa: Optics



[Weinsheimer 15]

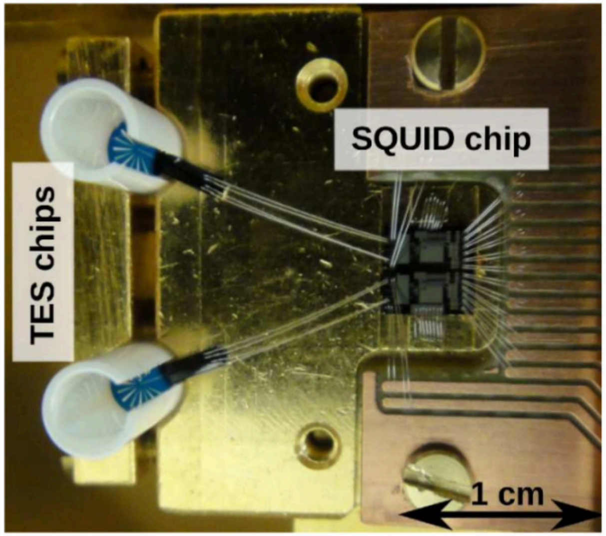
ALPS II: Detector

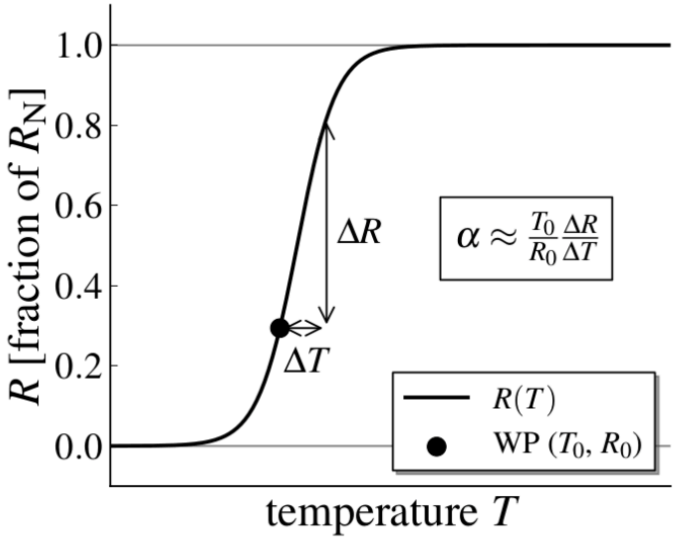
Transition Edge Sensor (TES)

- 25 µm × 25 µm Tungsten-Film
- Microcalorimeter operating at 80 mK

- Signal $\mathcal{O}$(70 nA) read via SQUID
- Intrinsic bkg. rate 10^{-4} Hz
- Energy resolution below 10%

[Weinsheimer 15]

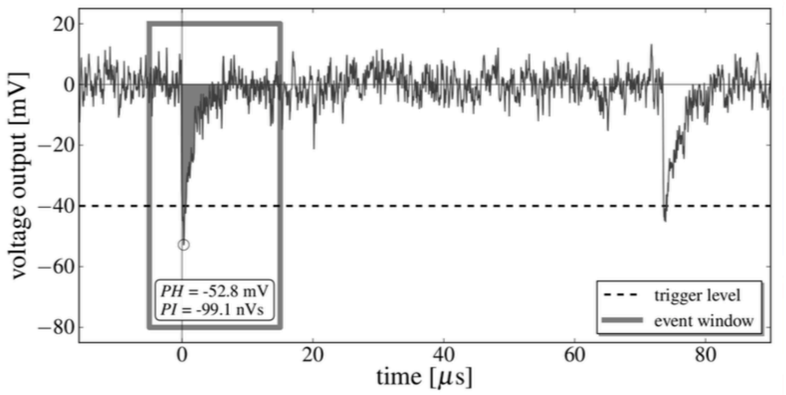


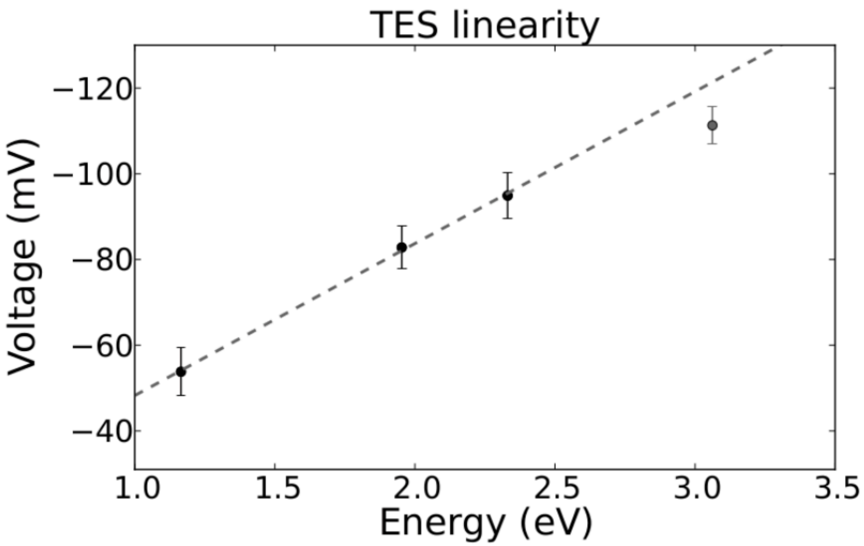


ALPS II: Detector

Performance

- Setting-up operation done!
- Performance paper published [1502.07878]
- Optimized detection efficiency measurement ongoing





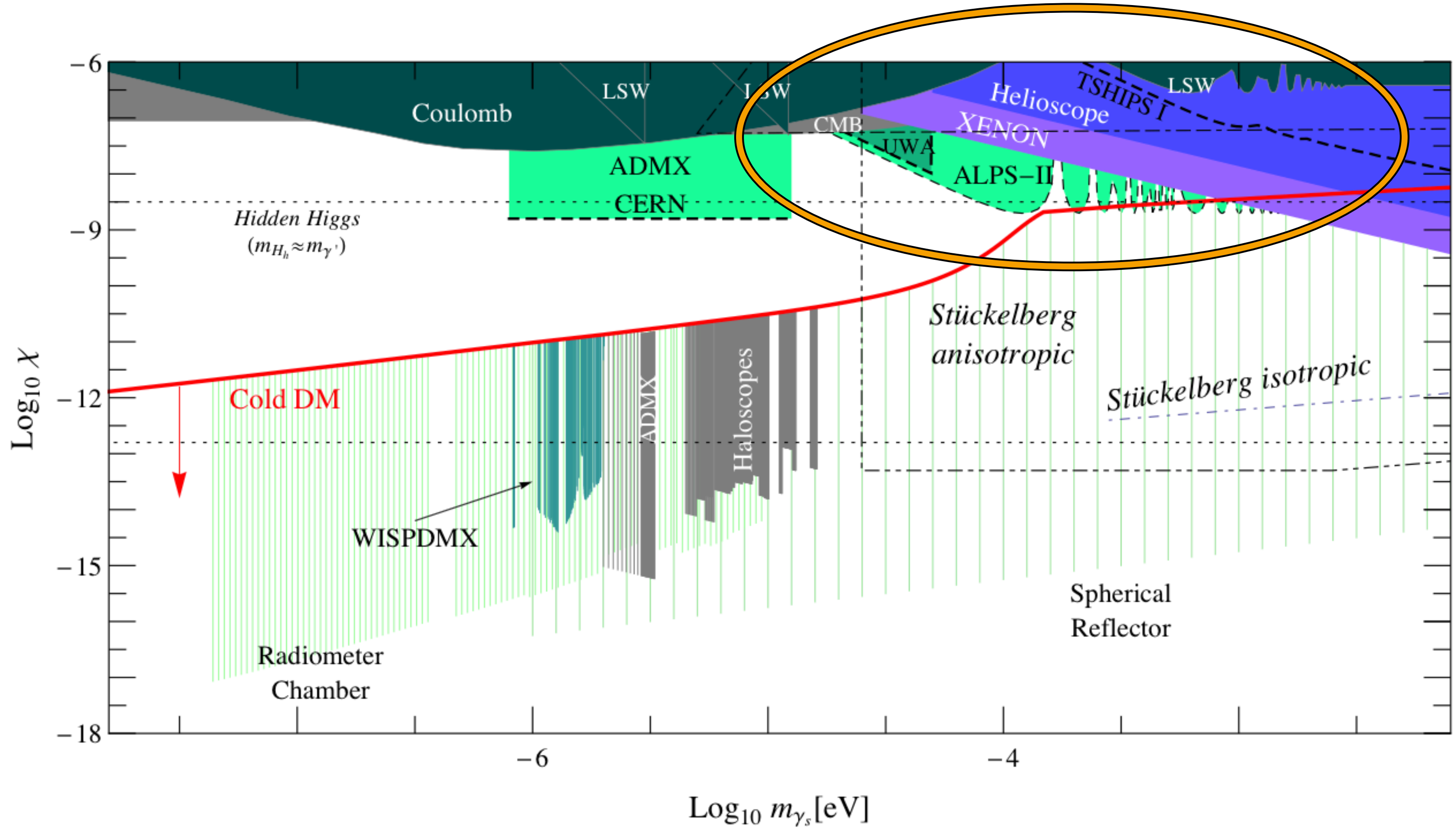
Water circuit

- Heavy contamination lead to Long-Shutdown-1
- Improved (closed cycle) cooling circuit

[Weinsheimer 15]

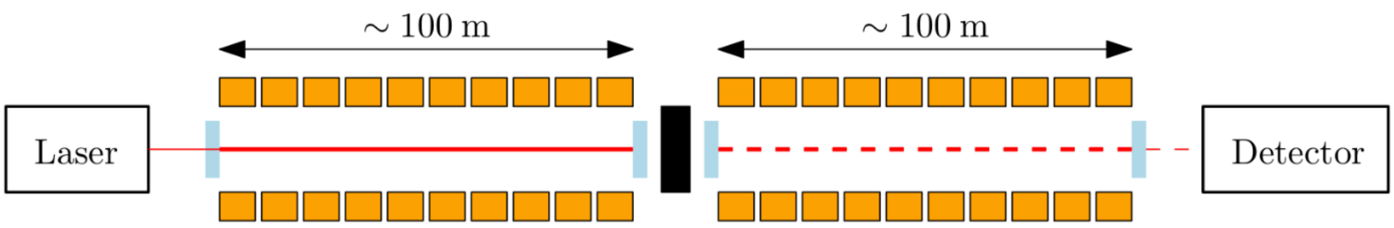
ALPS IIa: Projected Sensitivity

> Discovery potential for hidden photons in 0.1 meV mass region:



[Horns,Lindner,Lobanov,AR 14]

Final Stage



- **Magnetic Length:**
  - $(10 + 10)$ HERA dipoles
  - $BL = 468\,\mathrm{T\,m}$

$$\text{sensitivity} \propto \left(\frac{1}{BL}\right) \cdot \left(\frac{1}{\beta_{PC} \cdot \beta_{RC}}\right)^{\frac{1}{4}}$$

Sensitivity Gain (ALPS-I $\rightarrow$ II): $\times 21$

[Weinsheimer 15]

ALPS IIc: Magnets

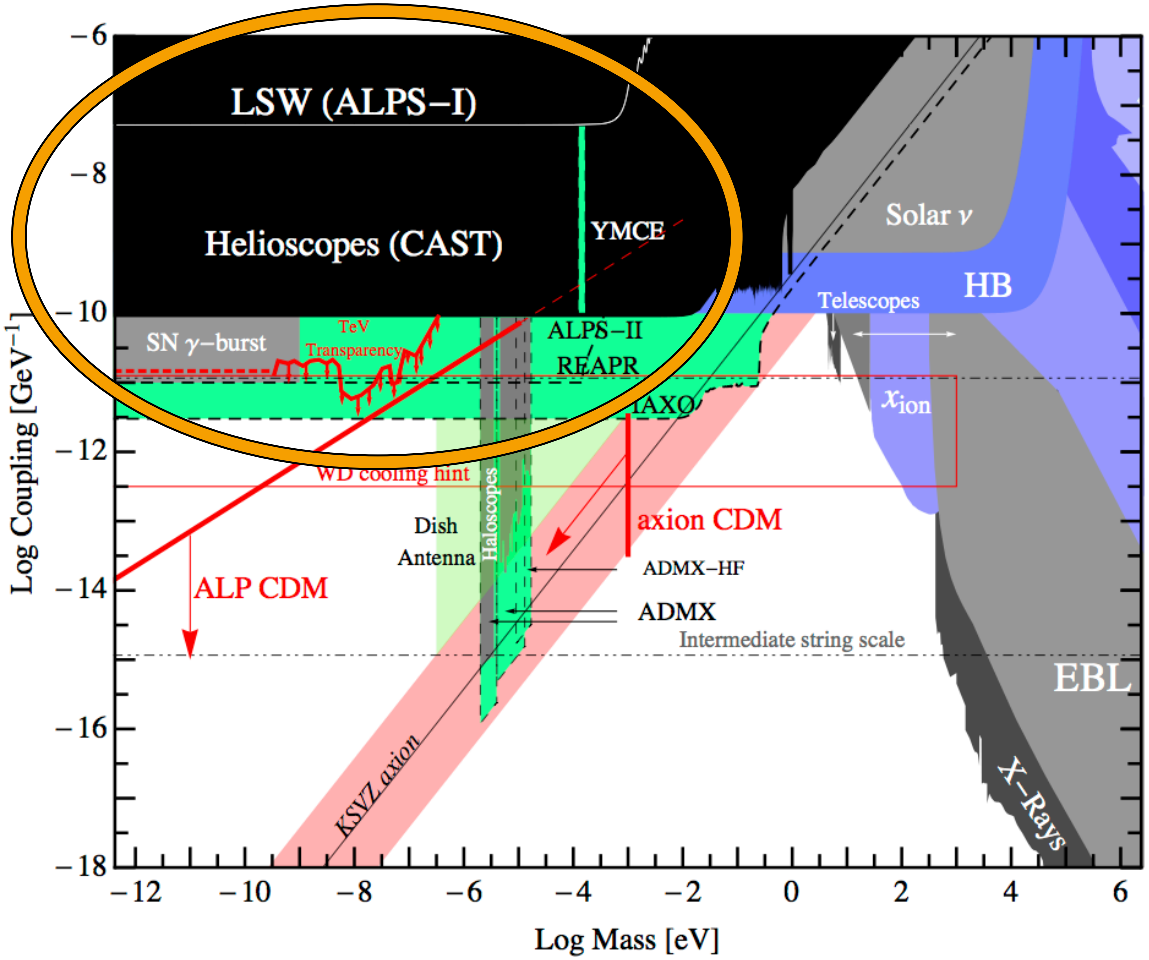
[Weinsheimer 15]

Status & Procedure

- First **straightened** test magnet operated successfully
  - Even with $I > I_{\text{design}}$
- **Second magnet** on test bench
- Successfully operated after 25 y in storage

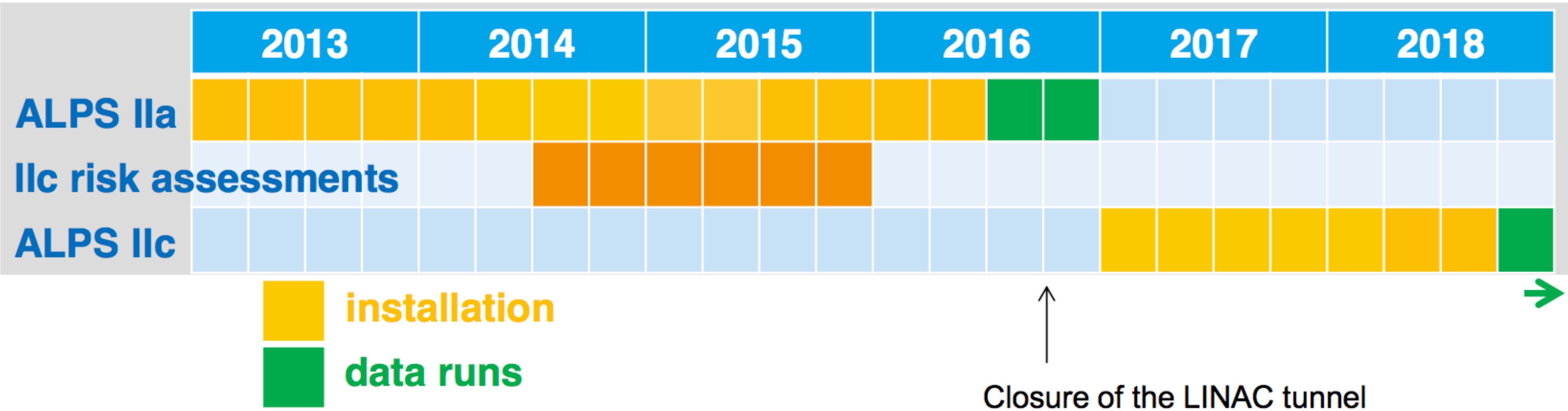
ALPS IIc: Projected Sensitivity

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



[Essig et al. 1311.0029]

ALPS II: Schedule

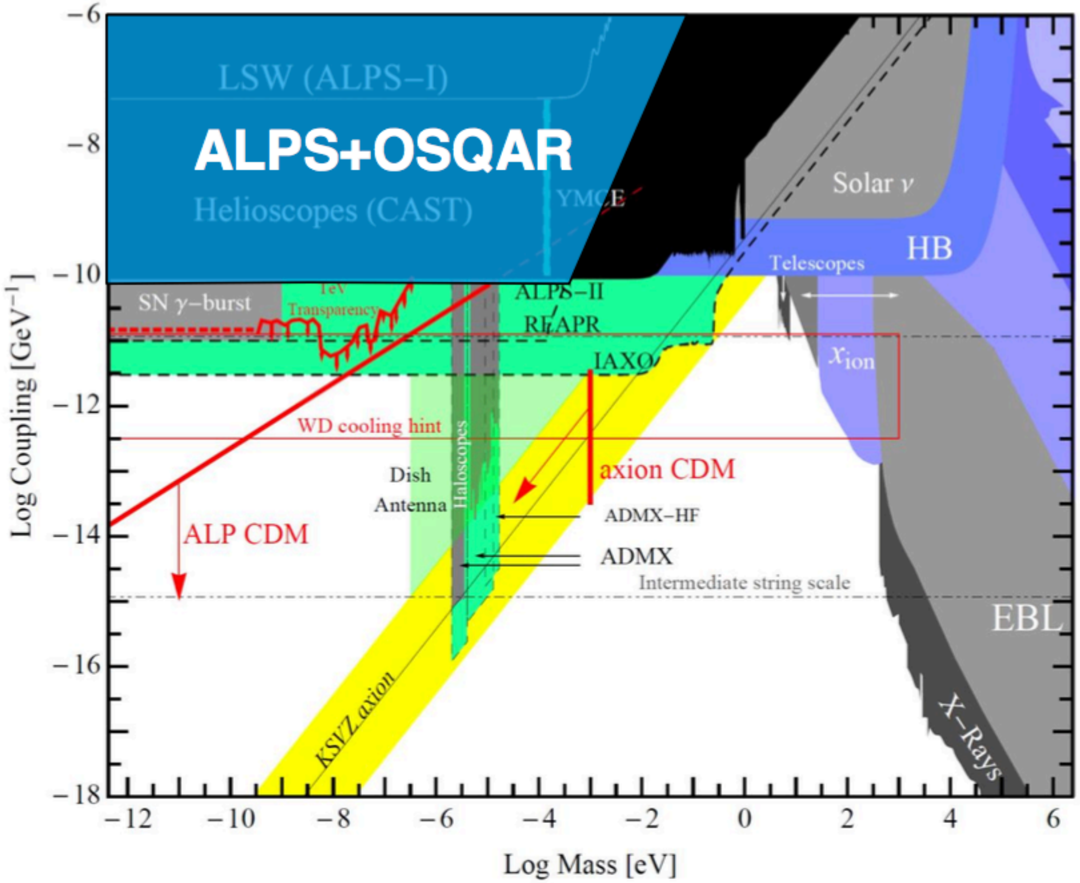


Closure of the LINAC tunnel
of the European XFEL project
under construction at DESY.

ALPS IIc in 2018
in the HERA tunnel

Intermezzo at CERN between ALPS IIa and II?

- Investigating possibility for intermediate data run at CERN with two LHC dipoles (2016/2017) exploiting ALPS II optics and detector



[Lindner 15]

Beyond ALPS II

> Rough estimation with some crucial parameters:

Exp.	Photon flux (1/s)	Photon E (eV)	B (T)	L (m)	B·L (Tm)	PB reg.cav.	Sens. (rel.)	Mass reach (eV)
ALPS I	$3.5 \cdot 10^{21}$	2.3	5.0	4.4	22	1	0.0003	0.001
ALPS II	$1 \cdot 10^{24}$	1.2	5.3	106	468	40,000	1	0.0002
“ALPS III”	$3 \cdot 10^{25}$	1.2	13	400	5200	100,000	27	0.0001
European XFEL	$< 10^{18}$	$1 \cdot 10^{4}$	5.3	106	562	1	0.001	0.01
PW laser	10^{20} 1/pulse	2.3	10^{6}	10^{-5}	10	1	0.0003	0.5

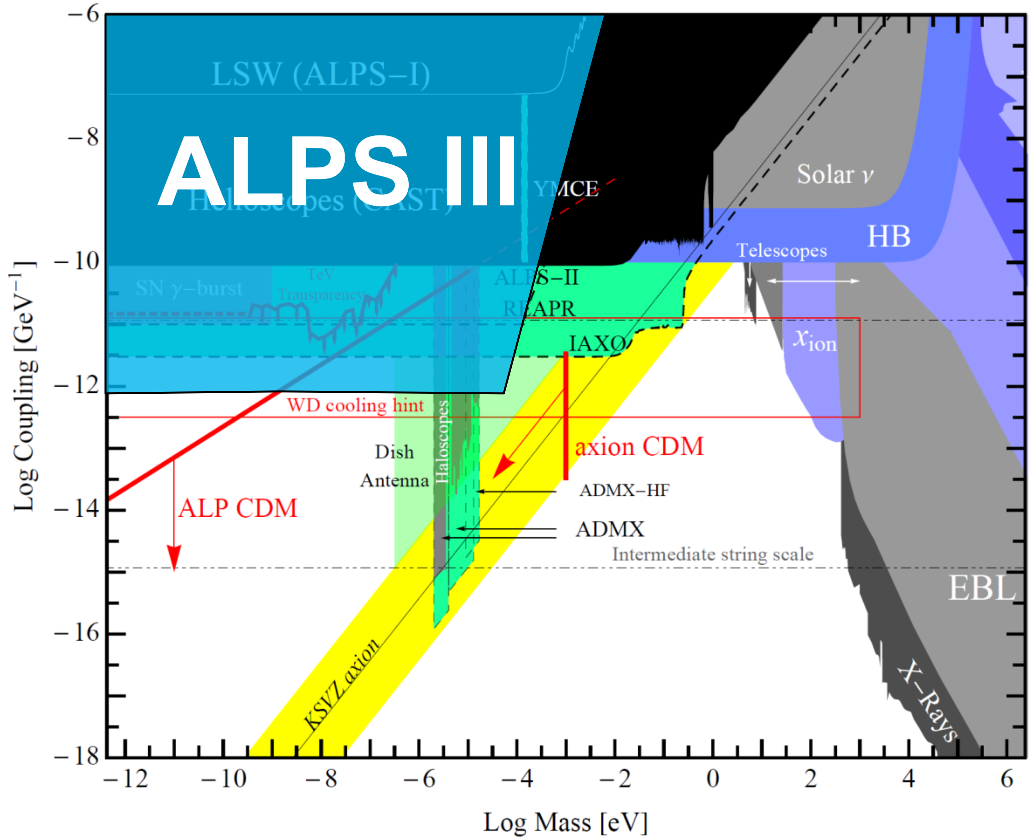
[Lindner 14]

"ALPS III" sensitivity

- With a multi - 10 M€ project one could even probe well beyond the IAXO reach.

However:

- It is to be shown first that ALPS II can be realized.
- Magnets as being developed for an LHC energy upgrade are essential.
- "ALPS III" not before 2025.



[Lindner 14]

ALPS II: Collaboration in 2015

ALPS II is a joint effort of

PhD students, postdocs

- DESY:
  Reza Hodajerdi, Mikhail Karnevskiy, Ernst-Axel Knabbe, Natali Kuzkova, Axel Lindner, Andreas Ringwald, Jan Põld, Richard Stromhagen, Dieter Trines, Klaus Zenker

- Hamburg University:
  Noemie Bastidon, Dieter Horns, Aaron Spector

- AEI Hanover (MPG & Hanover Uni.):
  Robin Bähre, Benno Willke

- Mainz University:
  Matthias Schott, Christoph Weinsheimer

- University of Florida, Gainesville:
  Guido Müller, David Tanner, N.N., N.N.

with strong support from

- neoLASE, PTB Berlin, NIST (Boulder)

Summary

- Strong physics case for axion/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, ...) cf. talk tomorrow by Javier Redondo
  - Haloscopes (ADMX, CASPeR, ...) cf. talk today by Gray Rybka
- Stay tuned!

ALPS IIc

Sensitivity

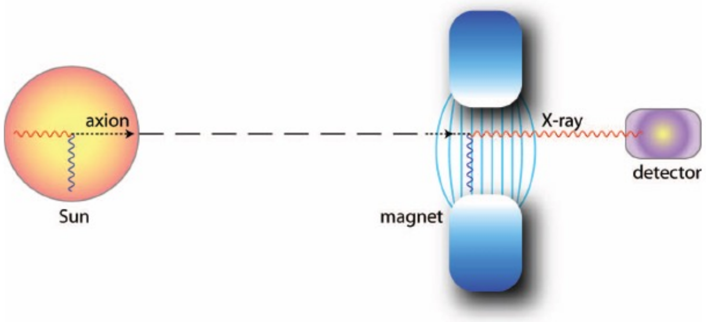
$$S(g_{a\gamma\gamma}) \propto \frac{1}{BL}\left(\frac{DC}{t}\right)^{\frac{1}{8}}\left(\frac{1}{DE \cdot \beta_{PC} \cdot \beta_{RC} \cdot \dot{N}_{\text{prod}}}\right)^{\frac{1}{4}}$$

Parameter	Scaling	ALPS-I	ALPS-IIc	Sens. gain
Effective laser power P_{laser}	$g_{a\gamma} \propto P_{\text{laser}}^{-1/4}$	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_{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	$g_{a\gamma} \propto DC^{1/8}$	$0.0018\,\text{s}^{-1}$	$0.000001\,\text{s}^{-1}$	2.6
Combined improvements				3082

Helioscope Searches

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

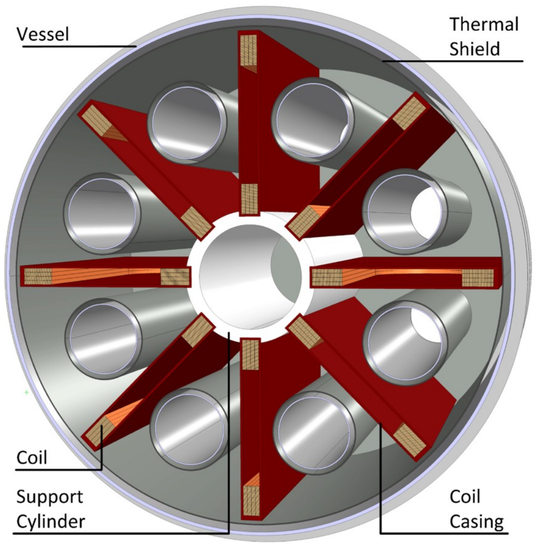
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

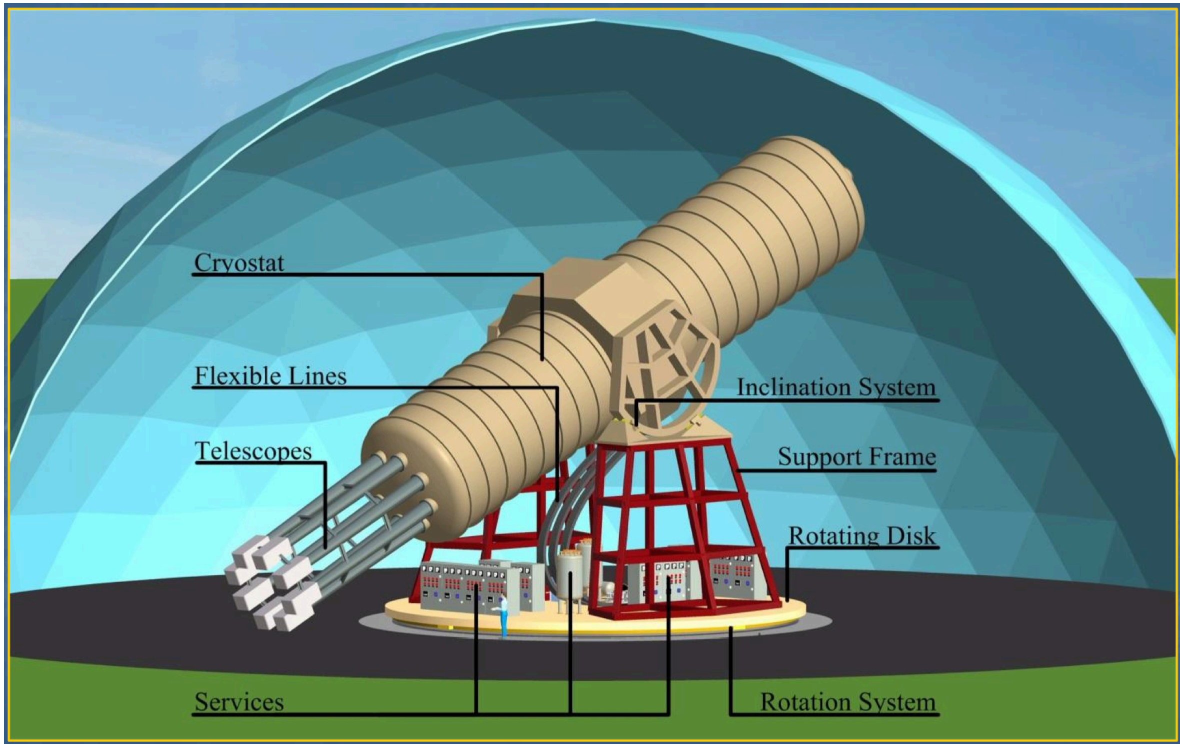


Helioscope Searches

> 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

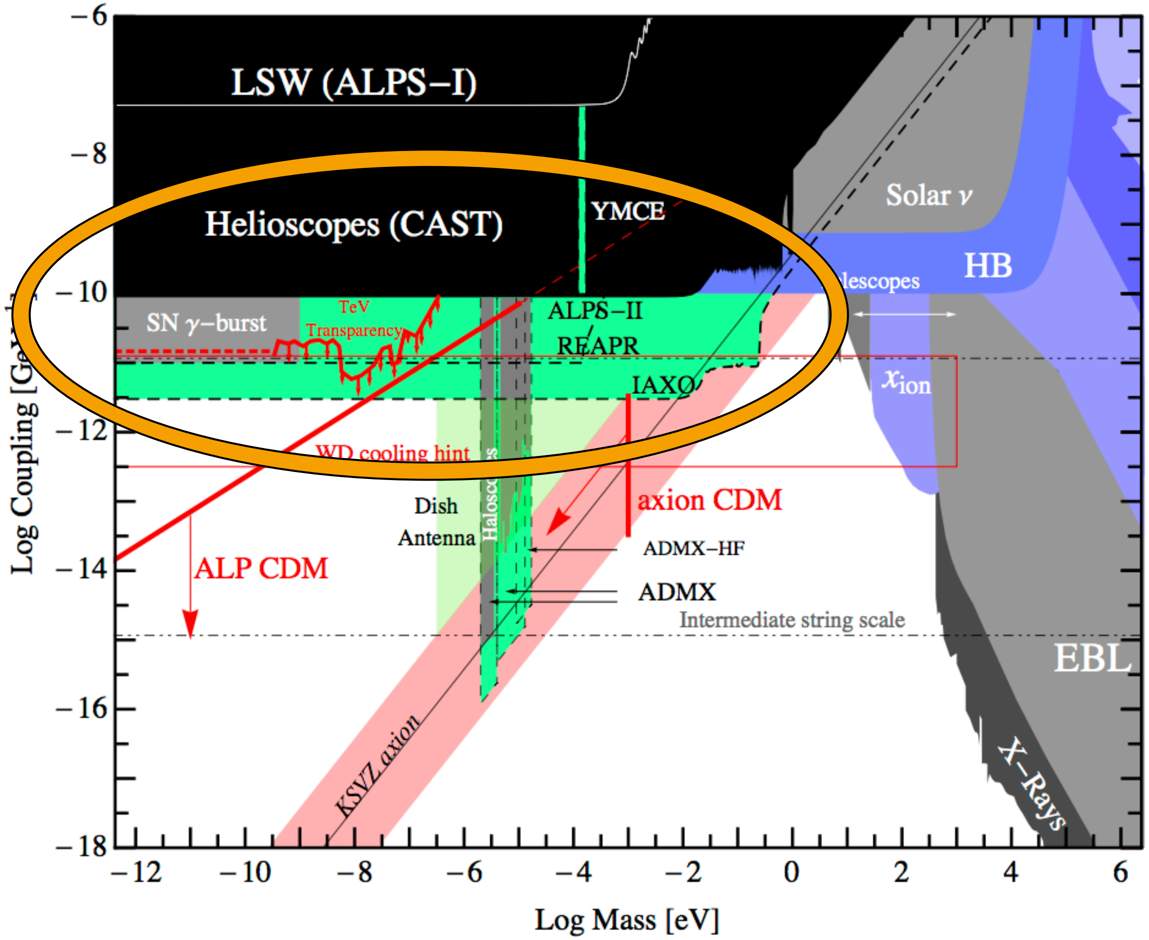




[Armengaud et al (IAXO CDR) 1401.3233]

Helioscope Searches

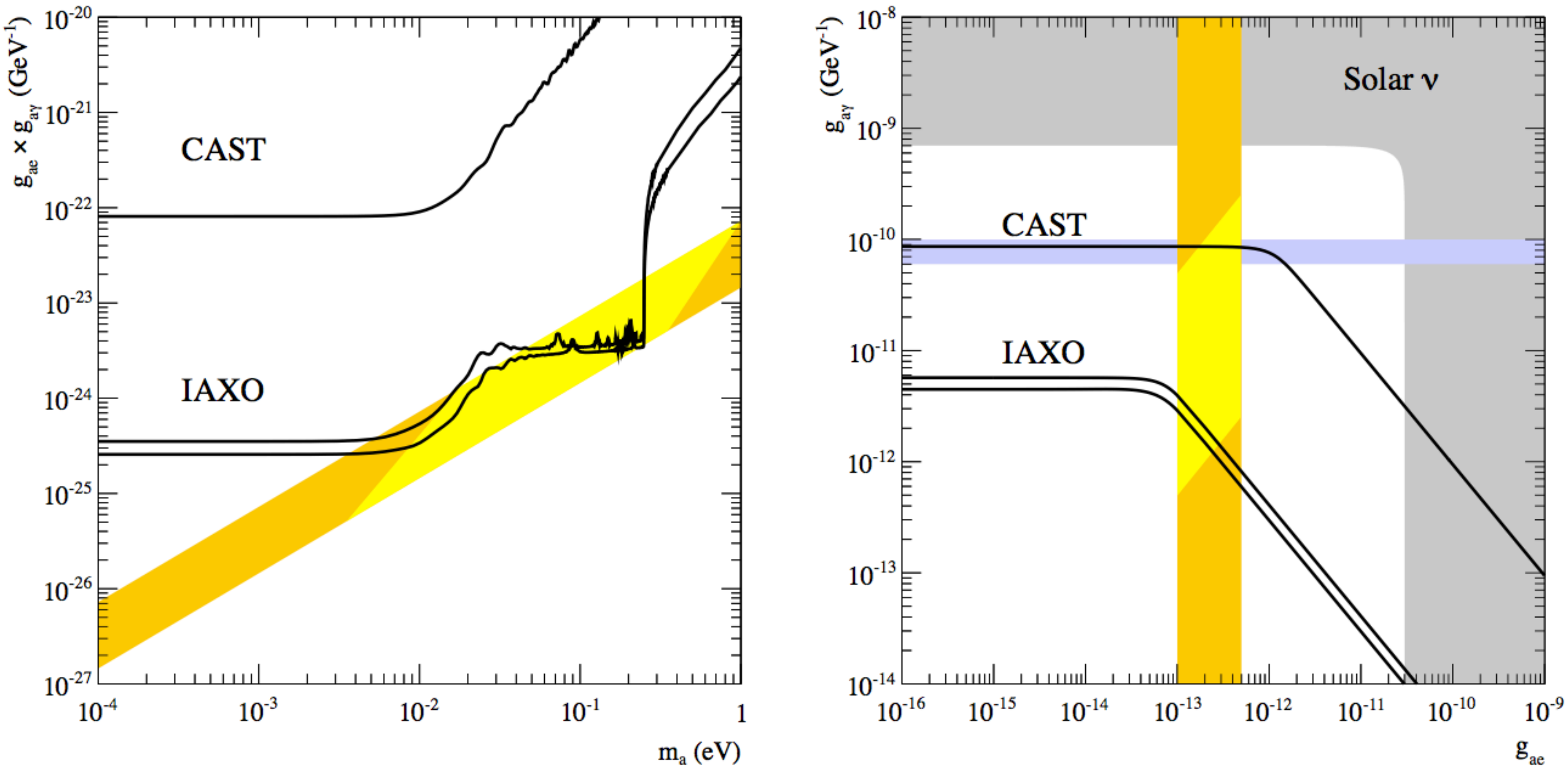
- Crucial test of the axion explanation of the excessive energy losses of RGs, WDs, n star in Cas A and ALP explanation of AGN spectra at VHE



adapted from [Hewett et al 12]

Helioscope Searches

- IAXO may also probe the electron coupling



[LoI IAXO 13]