# The Hunt for ALPs.

**Andreas Ringwald (DESY)**

Particles & Fields Seminar
Department of Physics, University of Oxford
Oxford, UK, 4 February 2016

HELMHOLTZ ASSOCIATION

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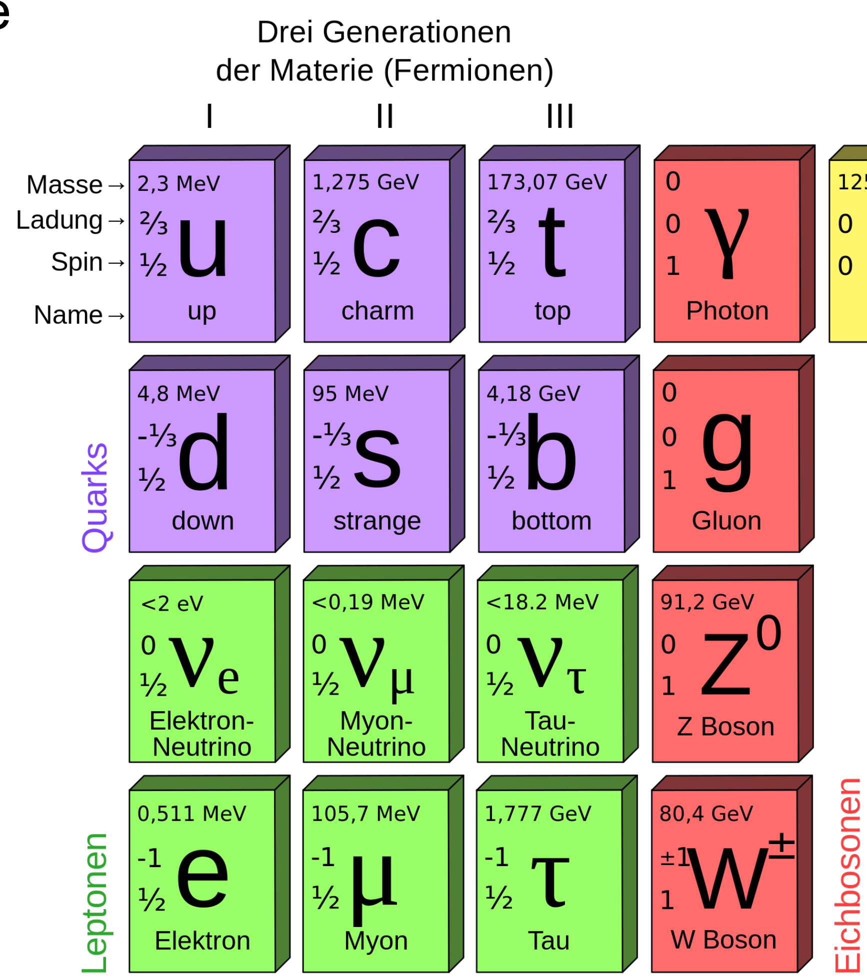
# Strong Case for Particles Beyond the Standard Model

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




[wikipedia]

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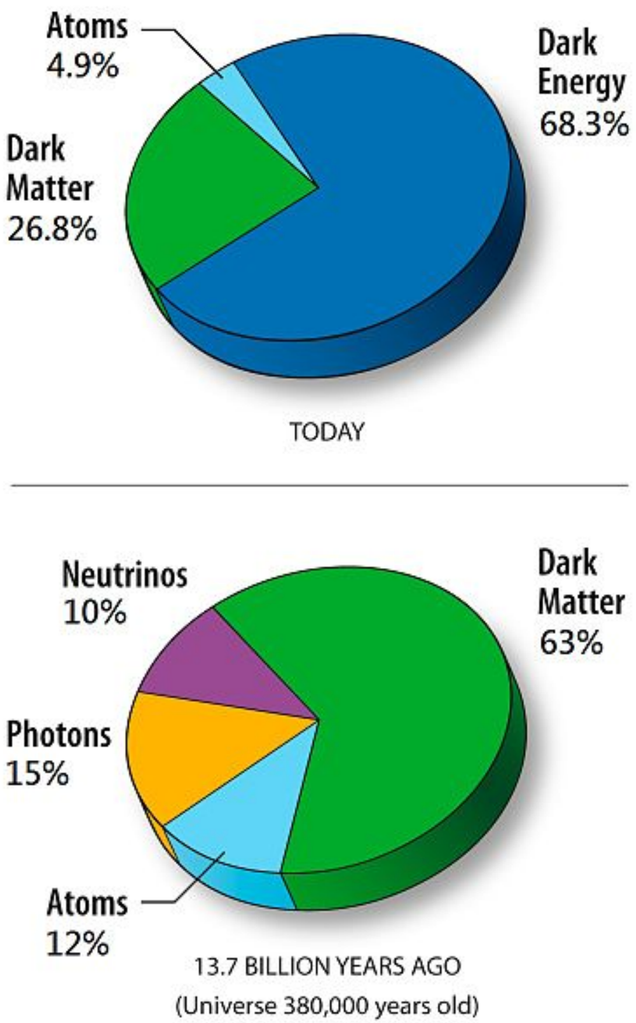
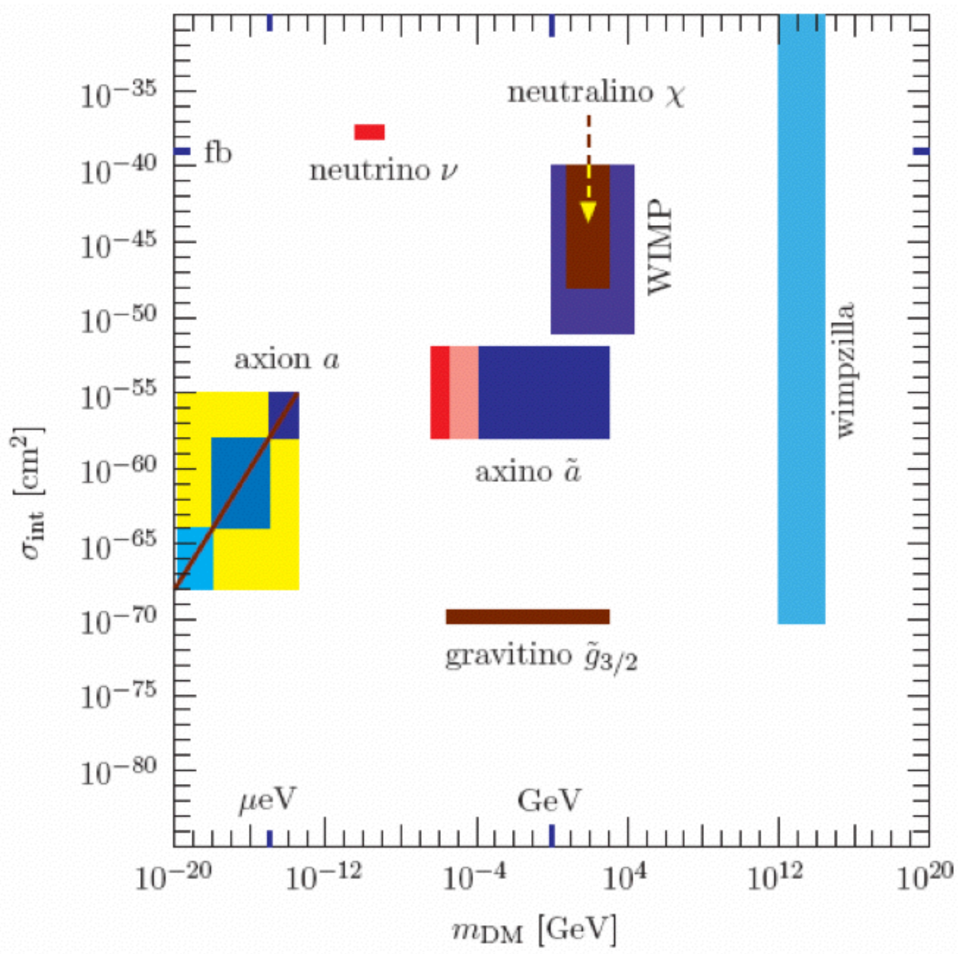
- SM not a complete and fundamental theory:
  - No explanation of the origin of dark energy and dark matter (DM)




[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, notably:
  - Weakly Interacting Massive Particles (WIMPs), such as neutralinos
  - Very Weakly Interacting Slim (=ultra-light) Particles (WISPs), such as axions
- Stand out because of their convincing 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:

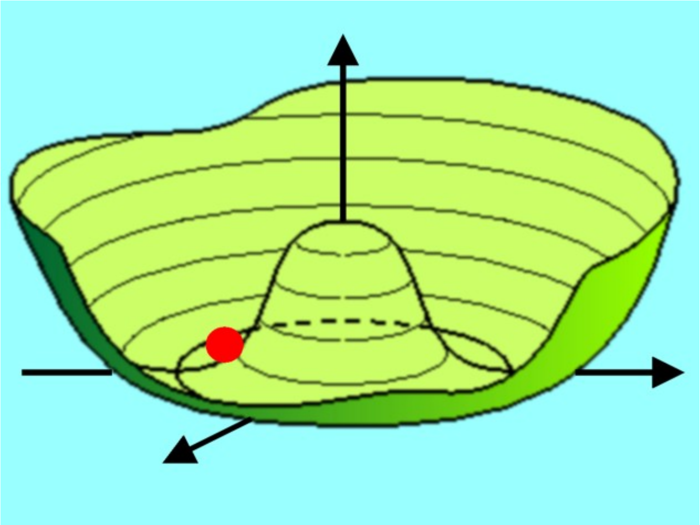
$$H_h(x) = \frac{1}{\sqrt{2}}\left[v_h + h_h(x)\right] \mathrm{e}^{ia(x)/v_h}$$

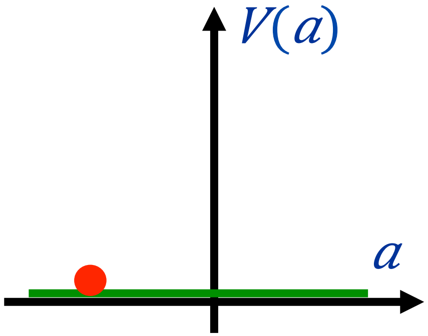
  Massive modulus, massless phase:

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

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

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



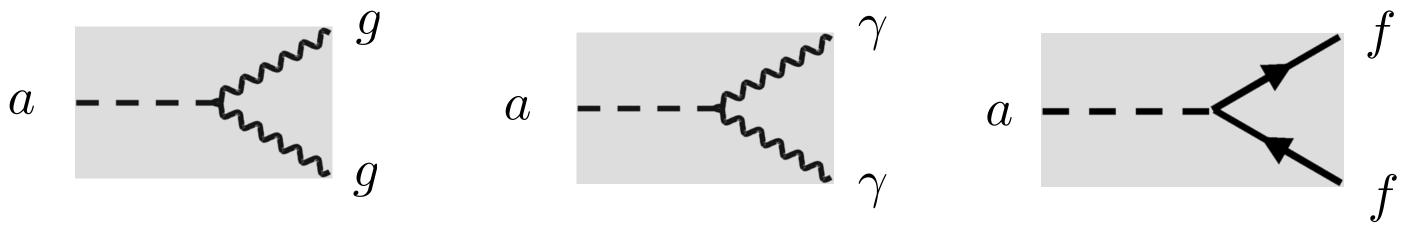



[Raffelt]

# Natural Candidates for WISPs: Nambu-Goldstone Bosons

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

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




- 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)

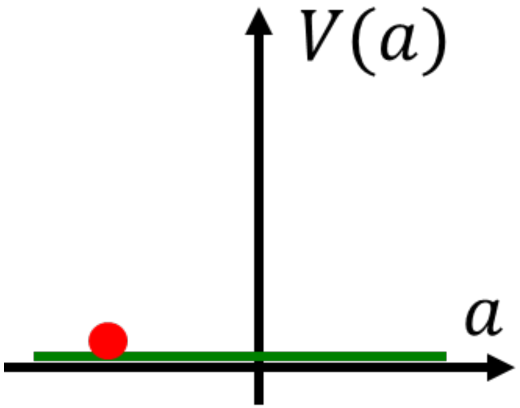
> String theory suggests a plenitude of ALPs [Witten 84; Conlon 06; Arvanitaki,Dimopoulos,Dubovsky,Kaloper,March-Russell 10; Cicoli,Goodsell,AR 12]

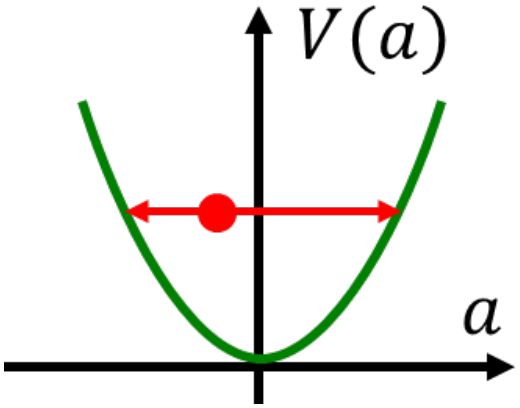
# Axion/ALP Dark Matter

> DM from vacuum realignment:

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

- In early universe, axion/ALP frozen at random initial value
- Later, field feels pull of mass to-wards zero and oscillates around it




[Raffelt]

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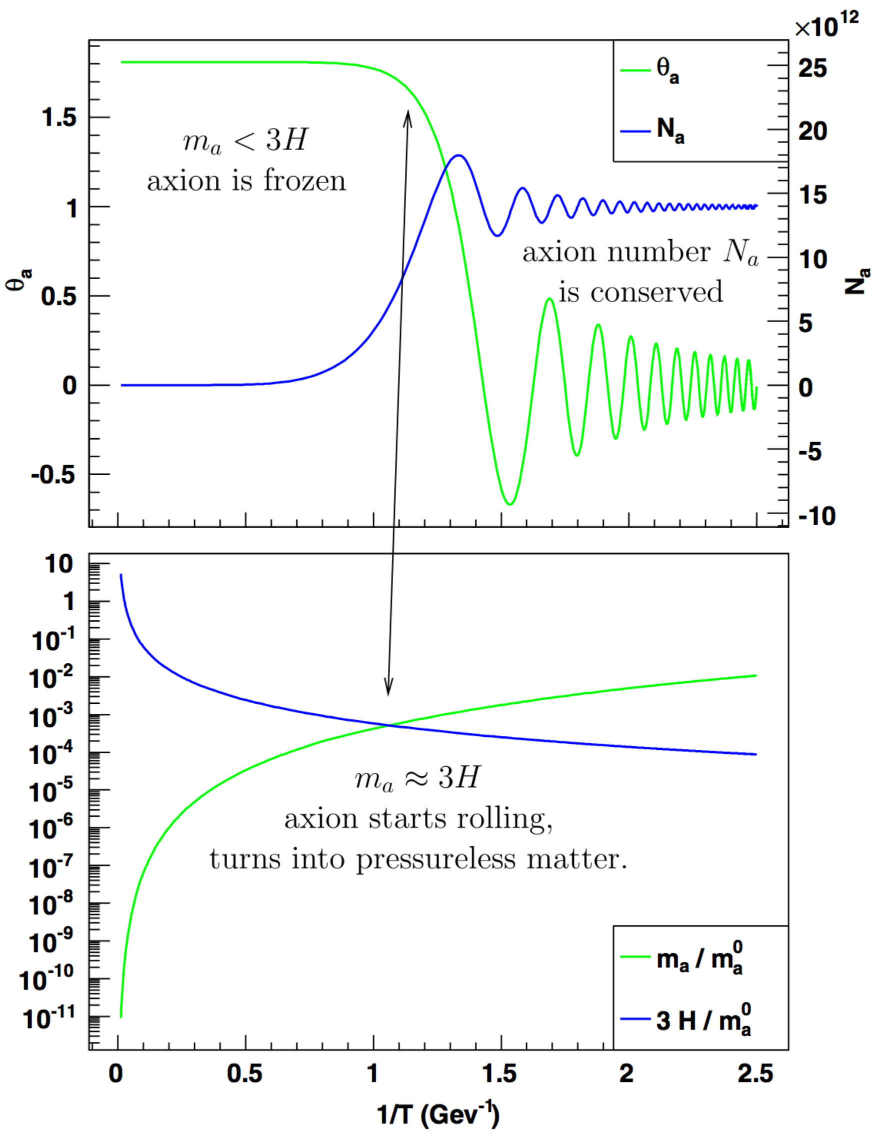
- Spatially uniform oscillating classical field = coherent state of many, extremely non-relativistic particles = CDM




[Wantz,Shellard 09]

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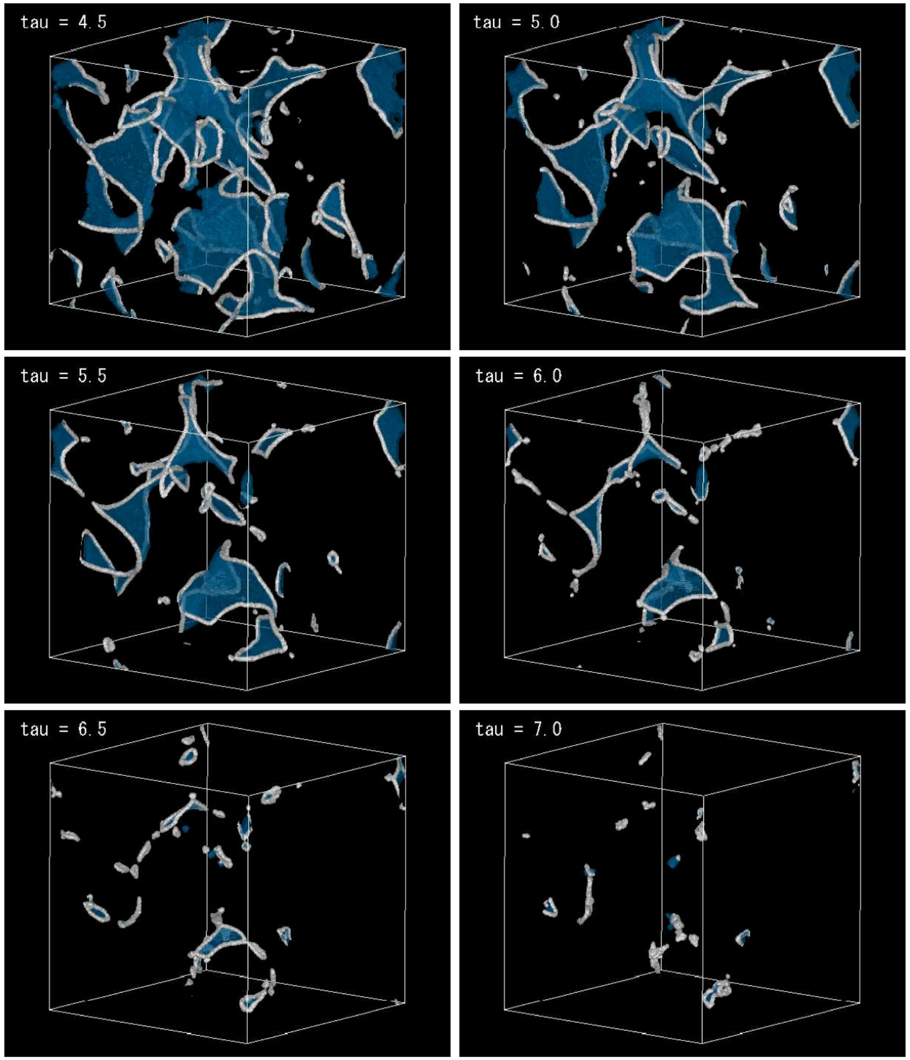
- DM from decay of topological defects




[Hiramatsu et al. 12]

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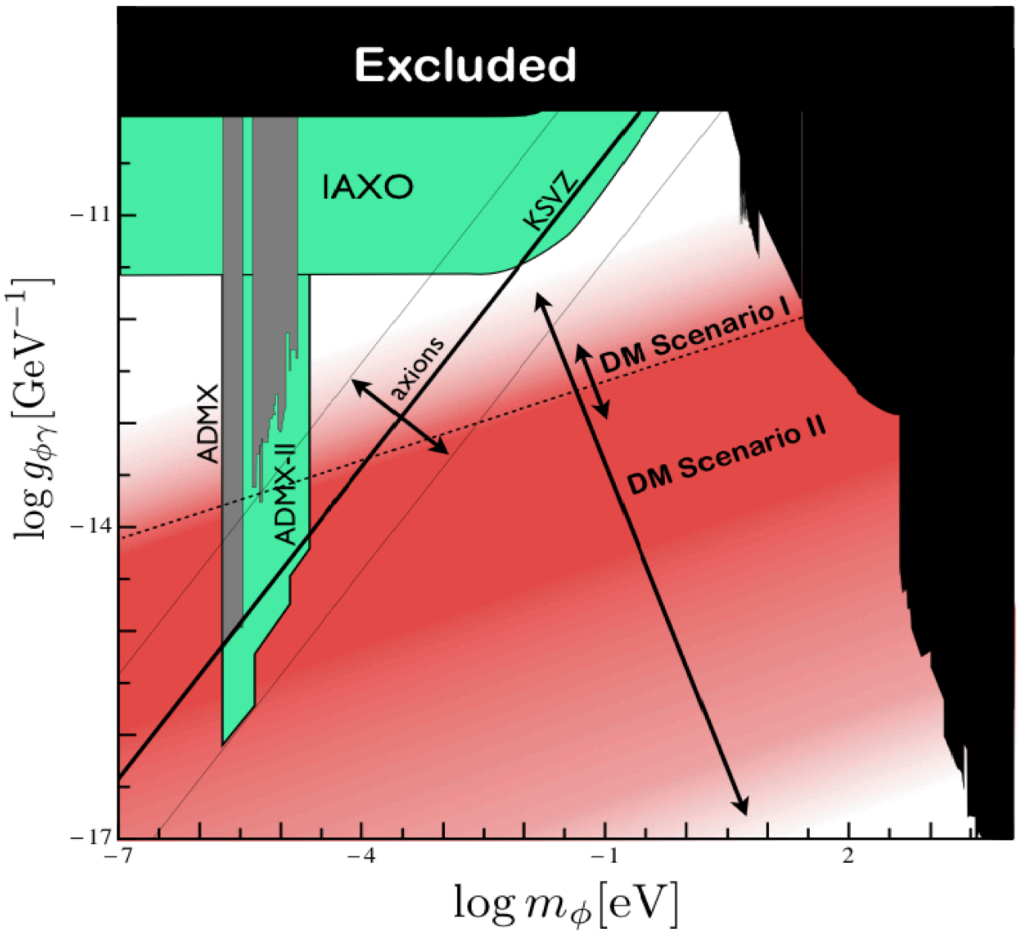
> DM from decay of topological defects

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

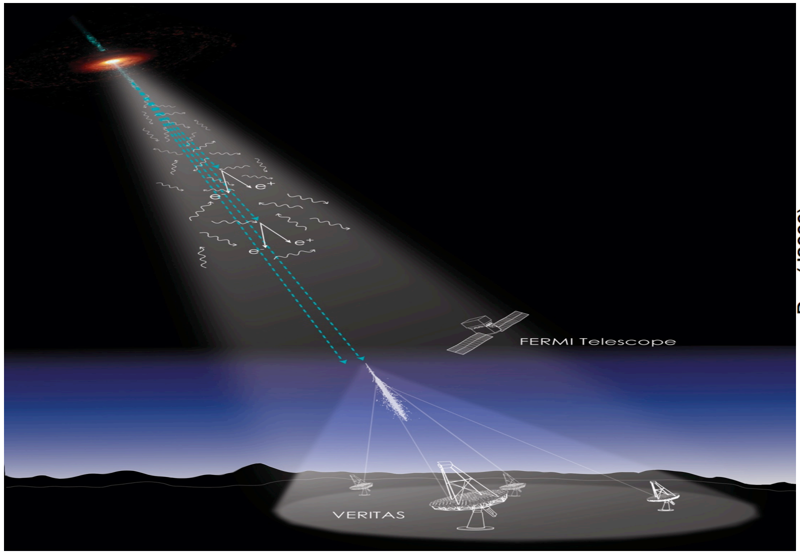
[Arias et al. 12]

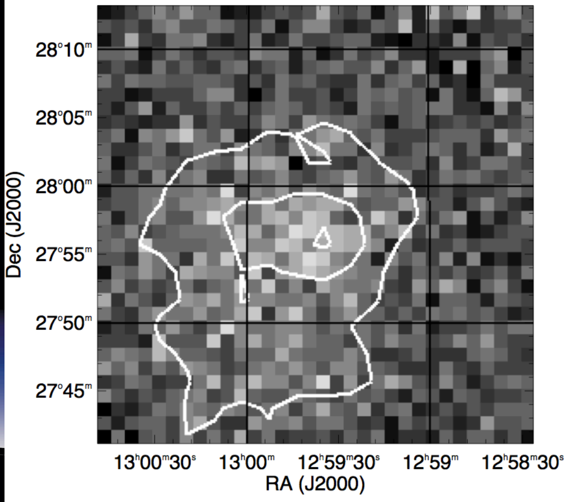



[Döbrich,Redondo 13]

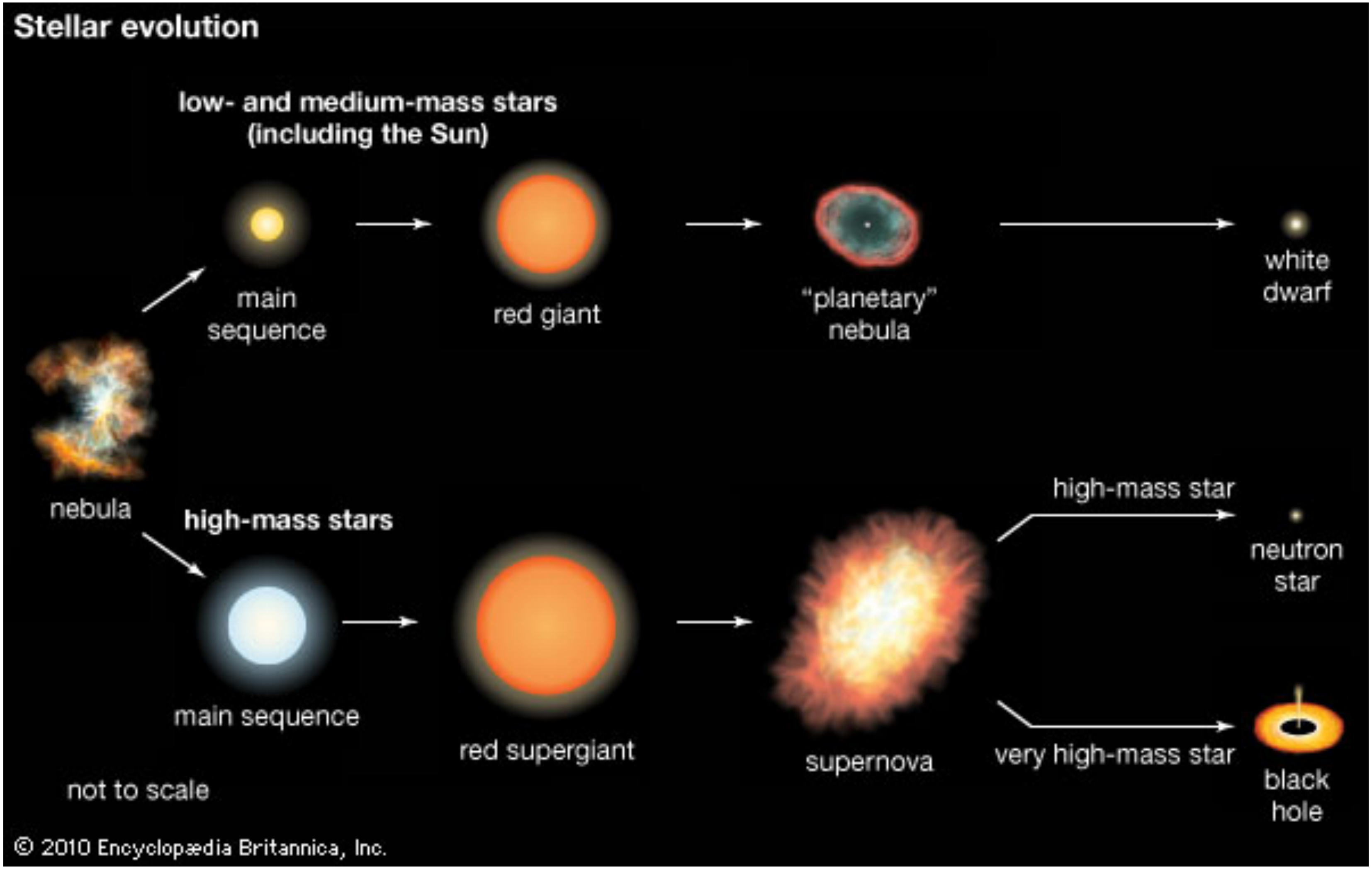
# Astro-Hints on Axion/ALPs?

- Modest hints for excessive
  - energy losses of stars in various evolutionary stages,
  - transparency of the universe for TeV gamma rays,
  - soft X-ray radiation from galaxy clusters



# Hints of Axion/ALP Energy Losses of Stars?



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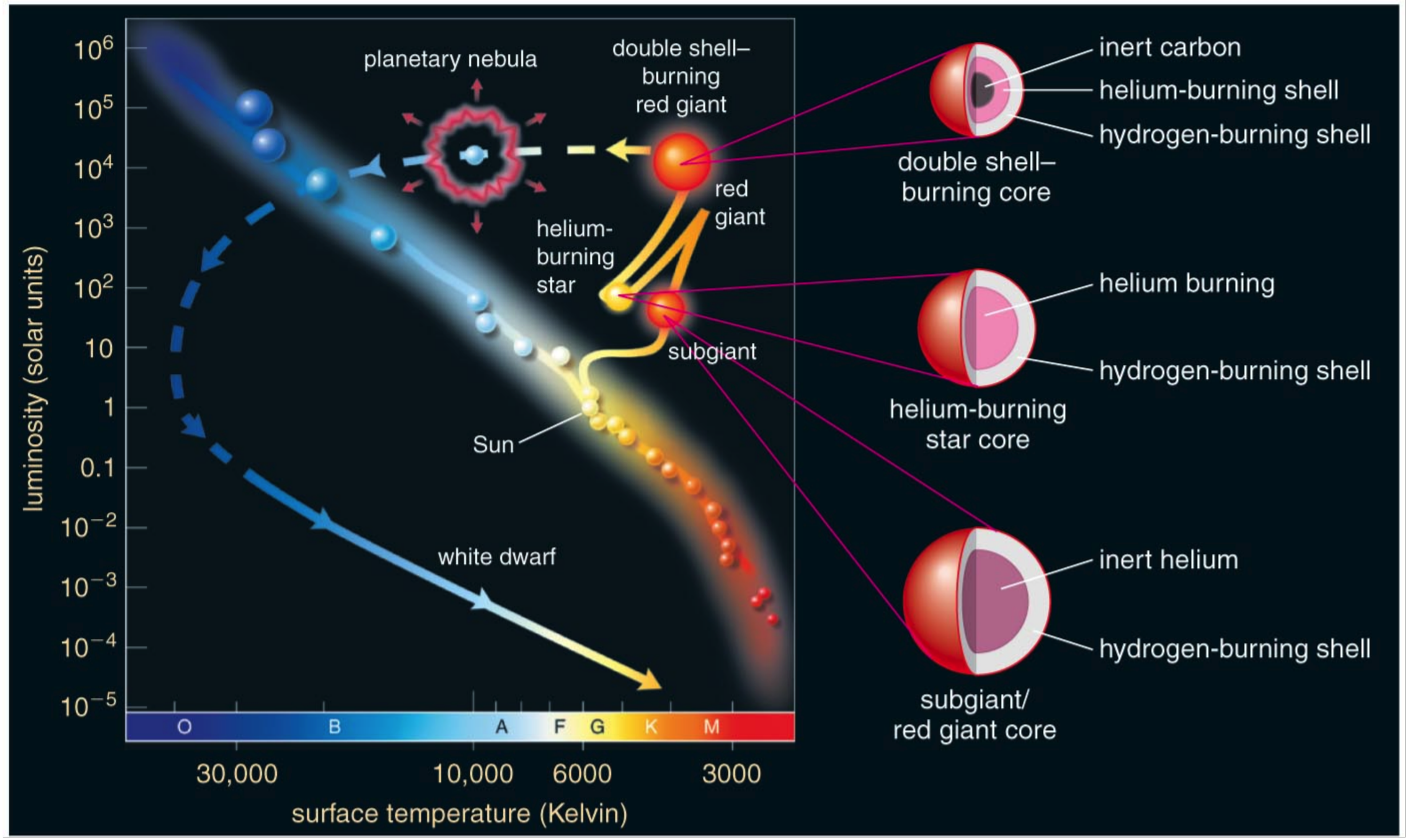

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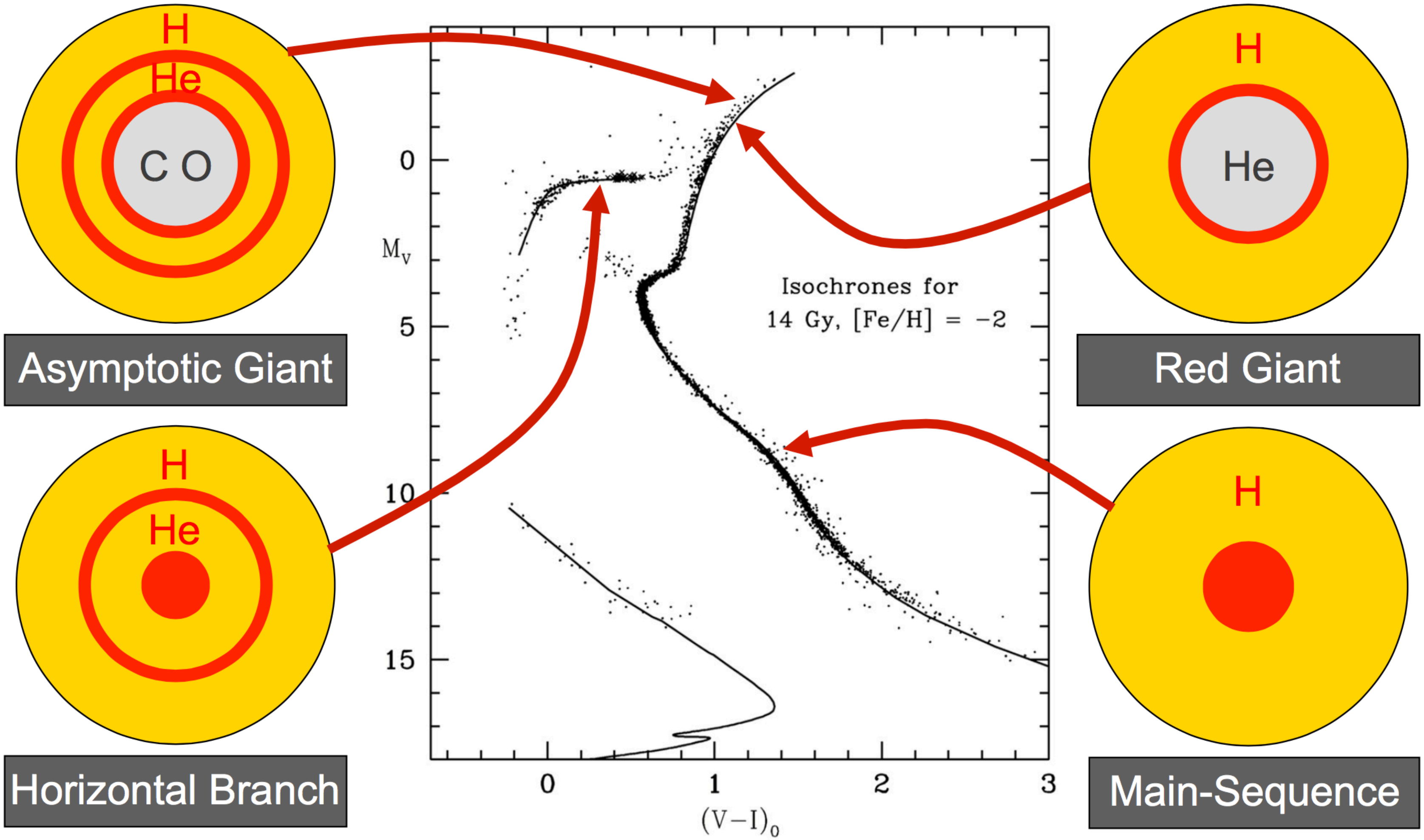
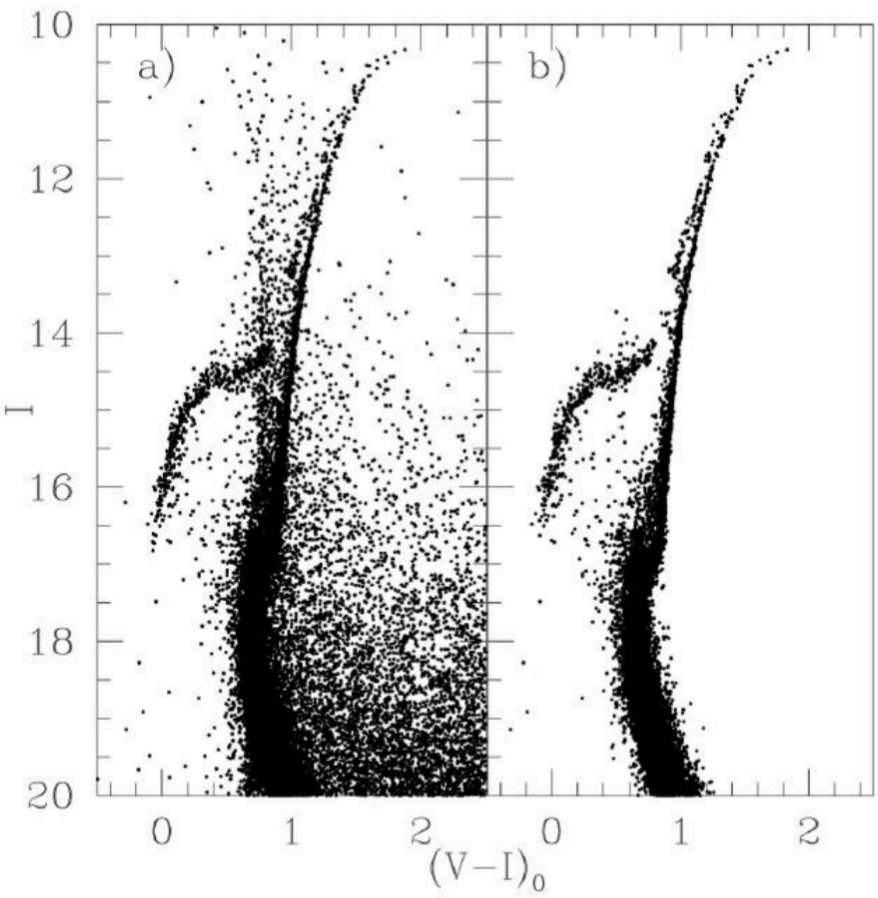



[Raffelt 14]

# Hints of Axion/ALP Energy Losses of Stars?

- RG cooling excess: Brightness of tip of RGB in CM diagram of GC [Viaux et al. 13]
- HB cooling excess: Number of HB stars vs. number of RGB stars in CMD of GC [Ayala et al. 14]




[Viaux et al. 13]

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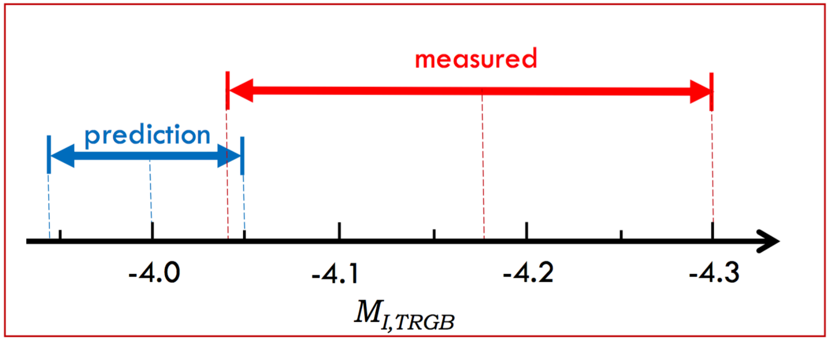


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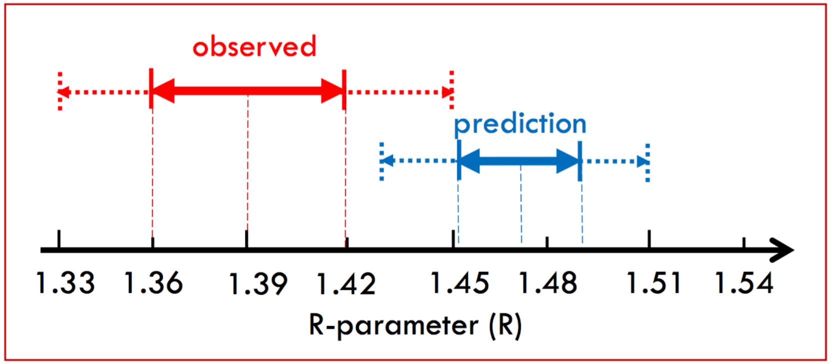


[Giannotti 15]

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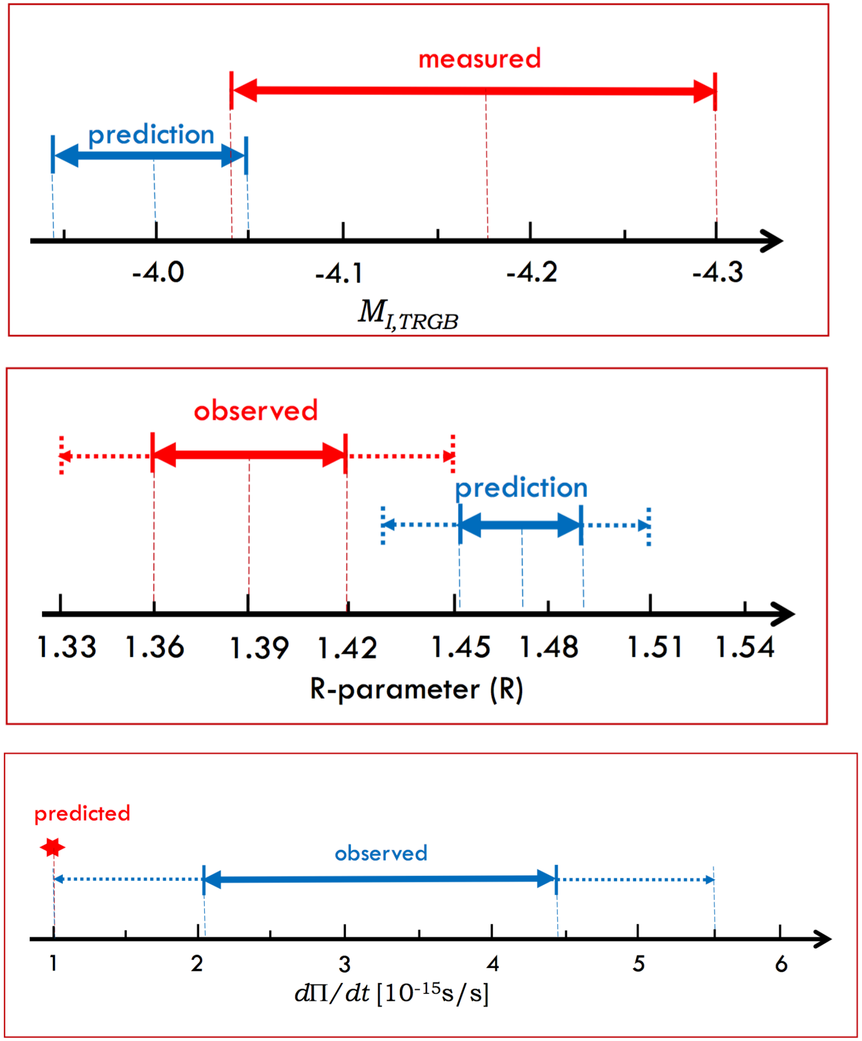
- WD cooling excess:
  - Period decrease of variable WDs [Kepler et al. 91,...]

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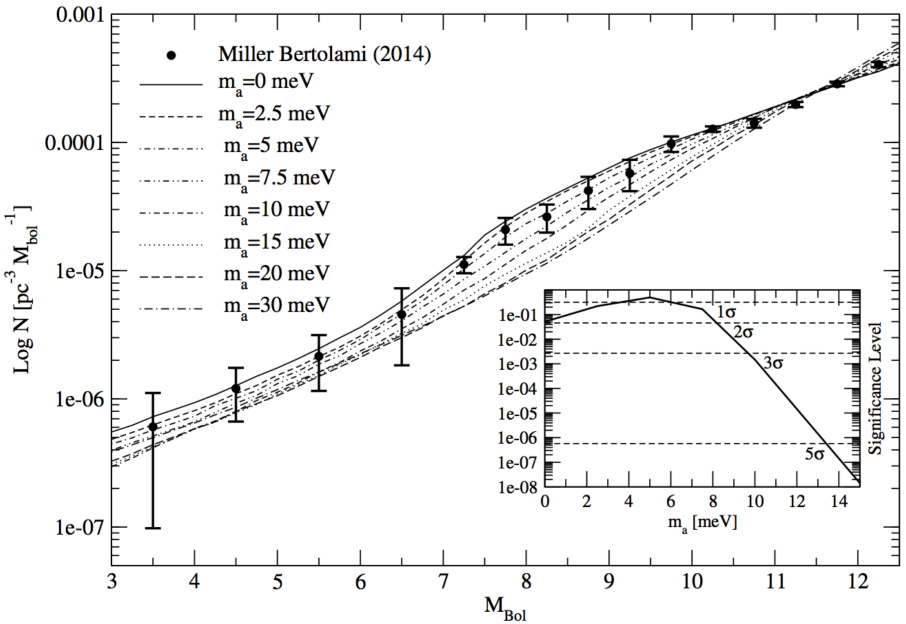
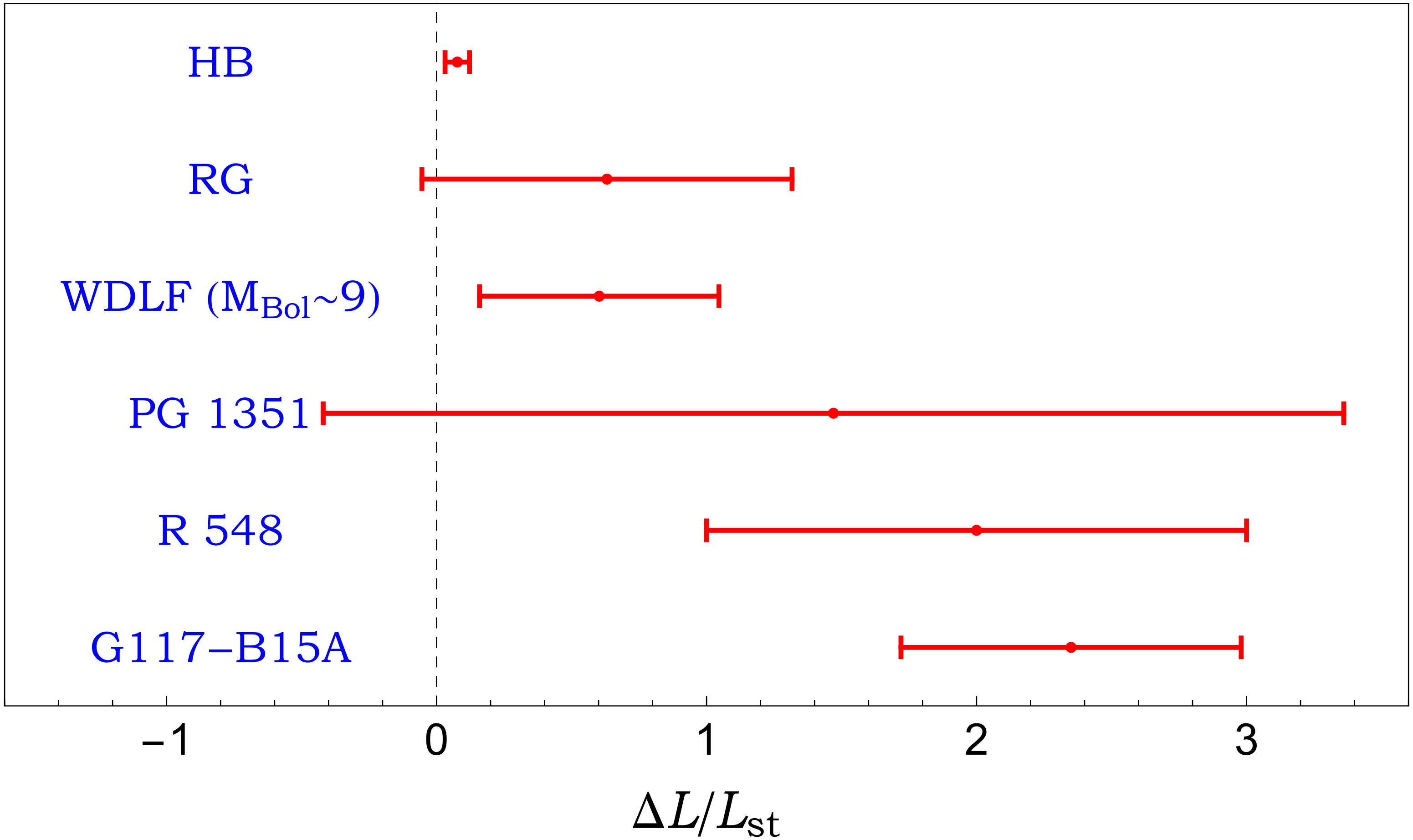
  - White dwarf luminosity function (WDLF) [Isern et al. 08-12]




[Bertolami et al. 15]

# Hints of Axion/ALP Energy Losses of Stars?

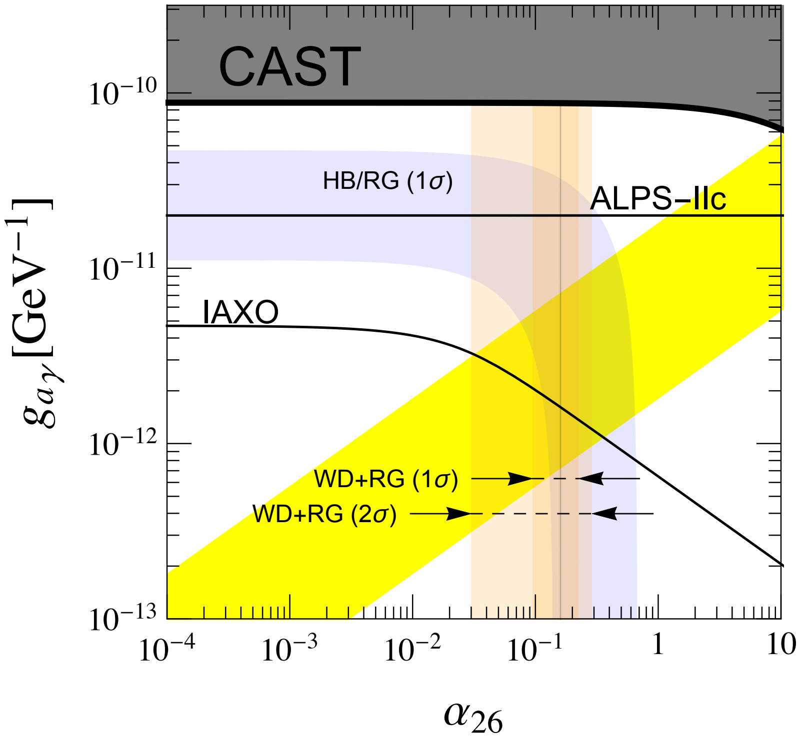
- Systematic tendency of stars to cool more efficiently than predicted:




[Giannotti,Irastorza,Redondo,AR 1512.08108]

# Hints of Axion/ALP Energy Losses of Stars?

- Excessive energy losses of RGs, HBs and WDs can all be explained at one stroke by production and emission of ALP with coupling both to electrons and photons:




$$g_{a\gamma} = C_{a\gamma}\alpha/(2\pi f_a)$$

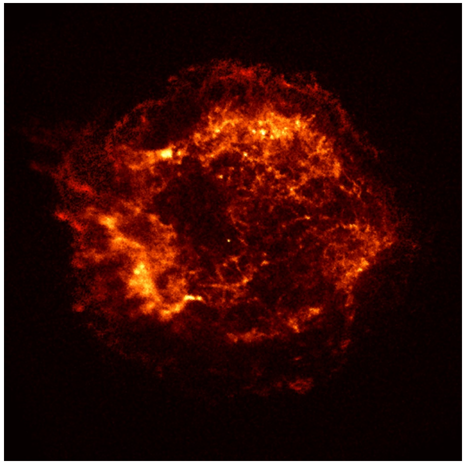
$$\alpha_{26} = g_{ae}^2/(4\pi)/10^{-26}$$

$$g_{ai} = C_{ai} m_i / f_a$$

[Giannotti,Irastorza,Redondo,AR arXiv:1512.08108]

# Hints of Axion/ALP Energy Losses of Stars?

> Neutron star in Cas A:

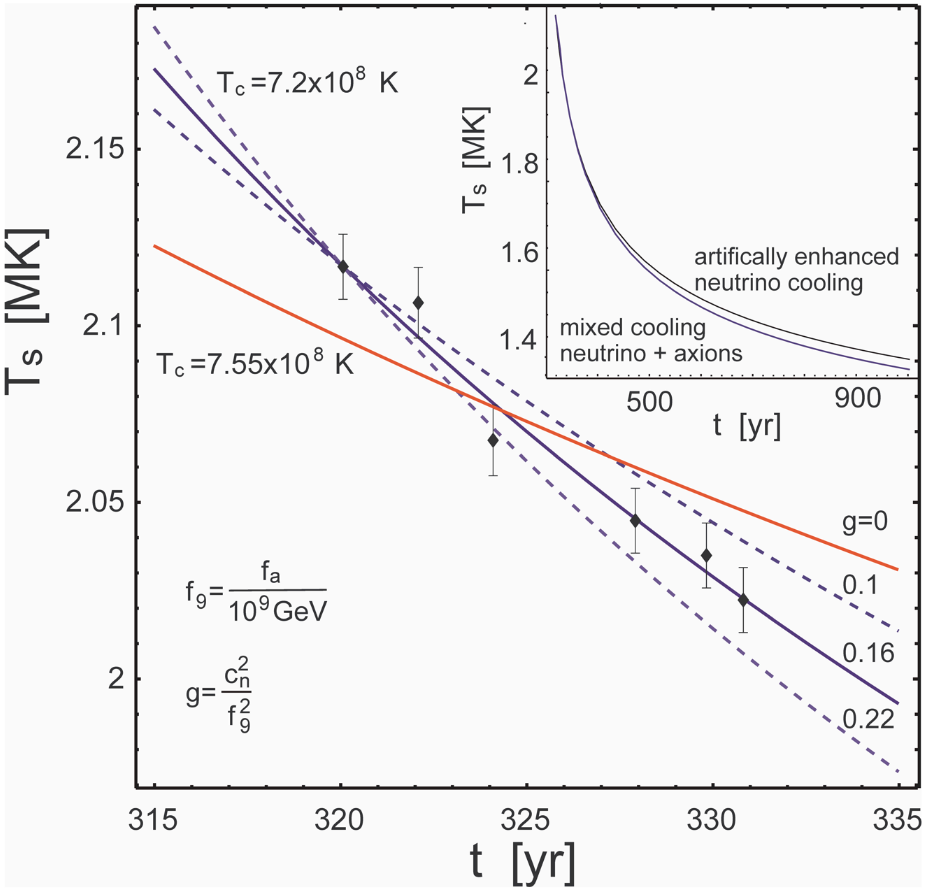


- Measured surface temperature over 10 years reveals unusually fast cooling rate
- Hint on extra cooling by axion/ALP due to nucleon bremsstrahlung

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

- Required coupling to neutron:

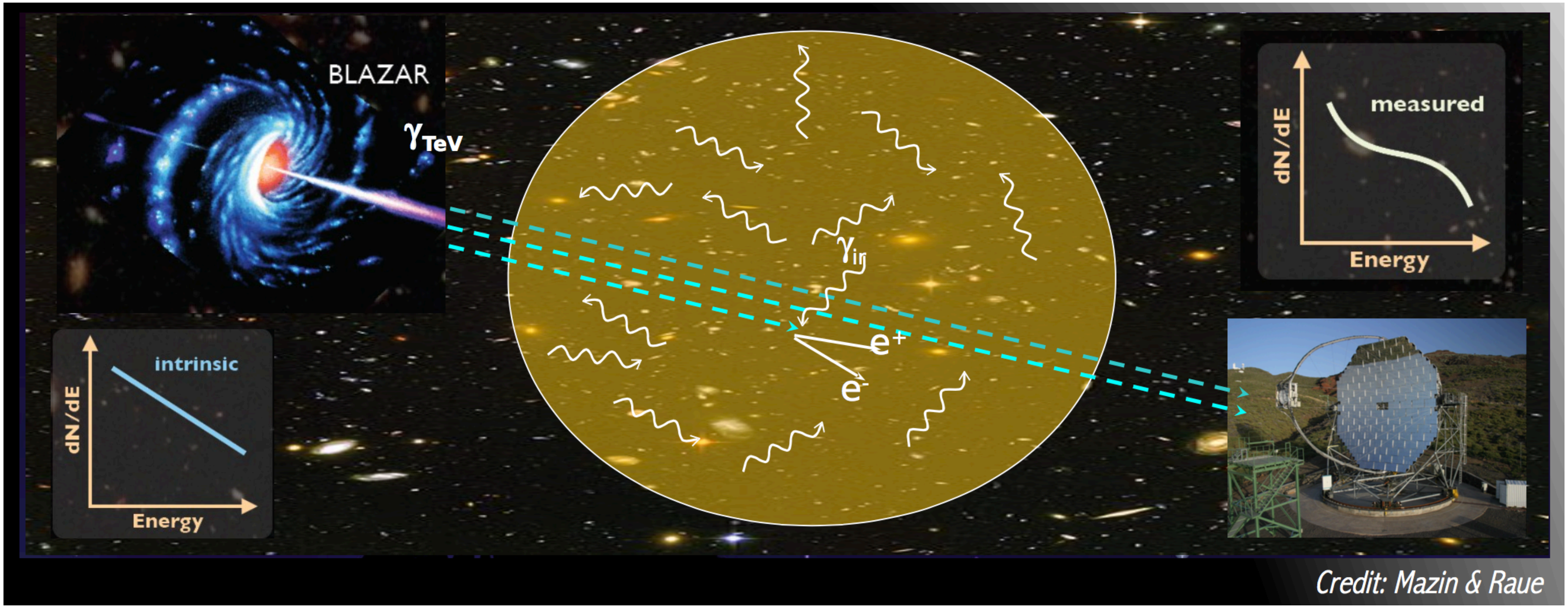
$$g_{an} = (3.8 \pm 3) \times 10^{-10}$$




[Leinson 14]

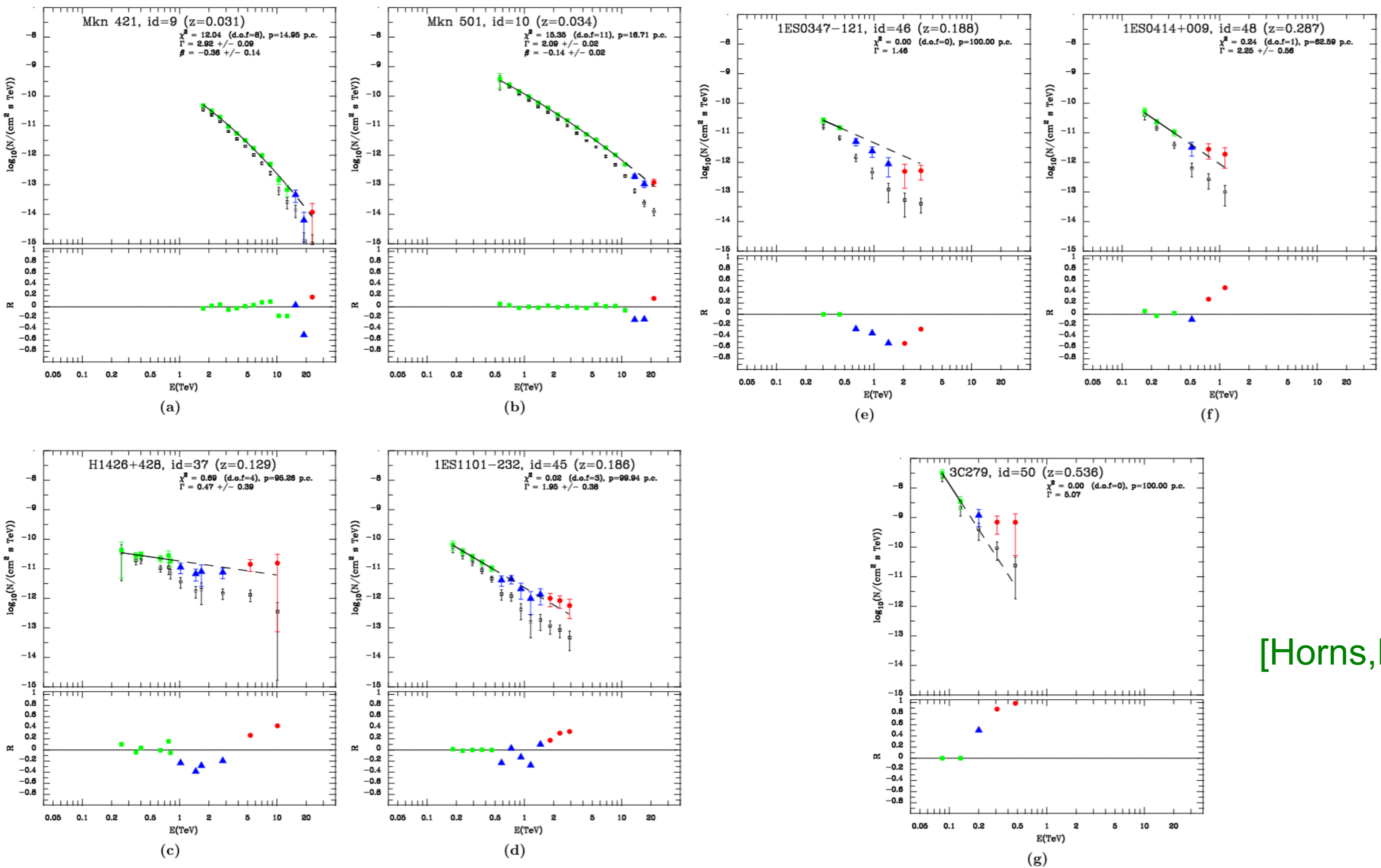
# Photon – ALP Conversion in Cosmic Magnetic Fields?

- 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)



# Photon – ALP Conversion in Cosmic Magnetic Fields?

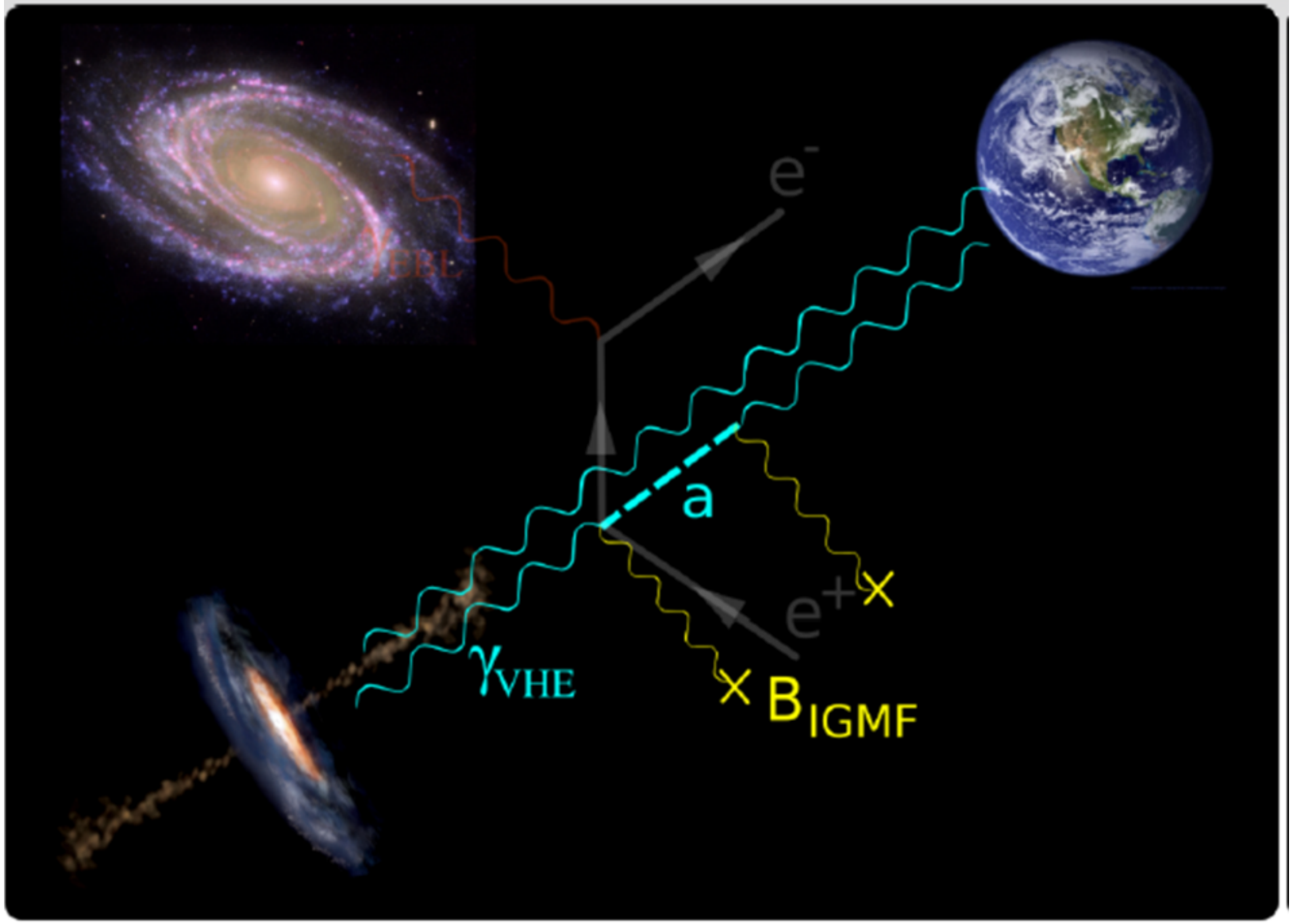
- Indication of anomalous gamma transparency: attenuation observed by IACT and Fermi-LAT too small [Aharonian et al. 07; de Angelis,Roncadelli et al. 07;...;Horns,Meyer 12;...;Rubtsov,Troitsky 14]




[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]




[Manuel Meyer 12]

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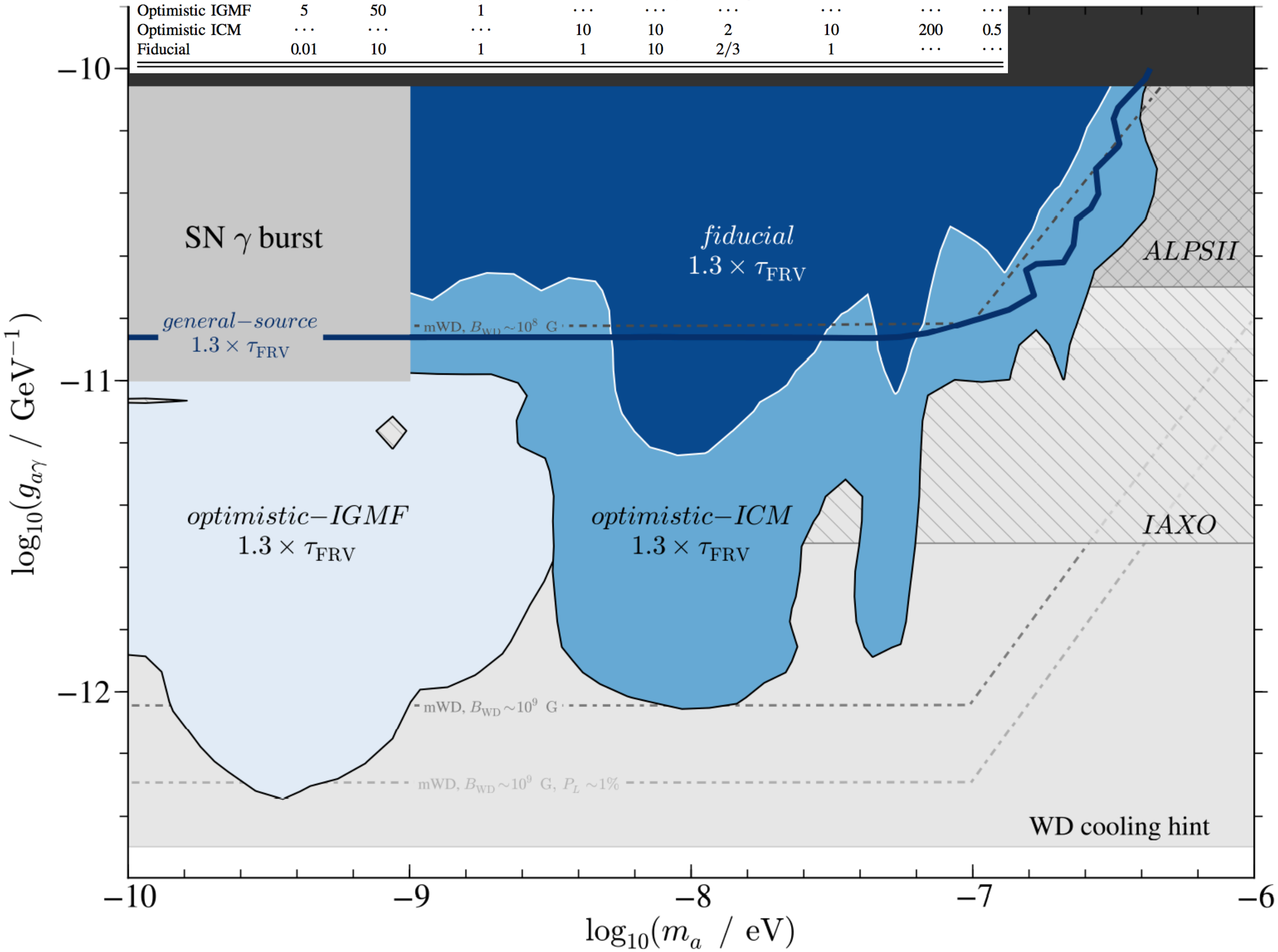
| | IGMF | | | ICM | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Name | $B^0_{\rm IGMF}$ (nG) | $\lambda^c_{\rm IGMF}$ (Mpc) | $n^0_{\rm el,IGM}$ ($\times 10^{-7}$ cm$^{-3}$) | $B^0_{\rm ICMF}$ ($\mu$G) | $\lambda^c_{\rm ICMF}$ (kpc) | $r_{\rm cluster}$ (Mpc) | $n^0_{\rm el,ICM}$ ($\times 10^{-3}$ cm$^{-3}$) | $r_{\rm core}$ (kpc) | $\eta$ |
| 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]



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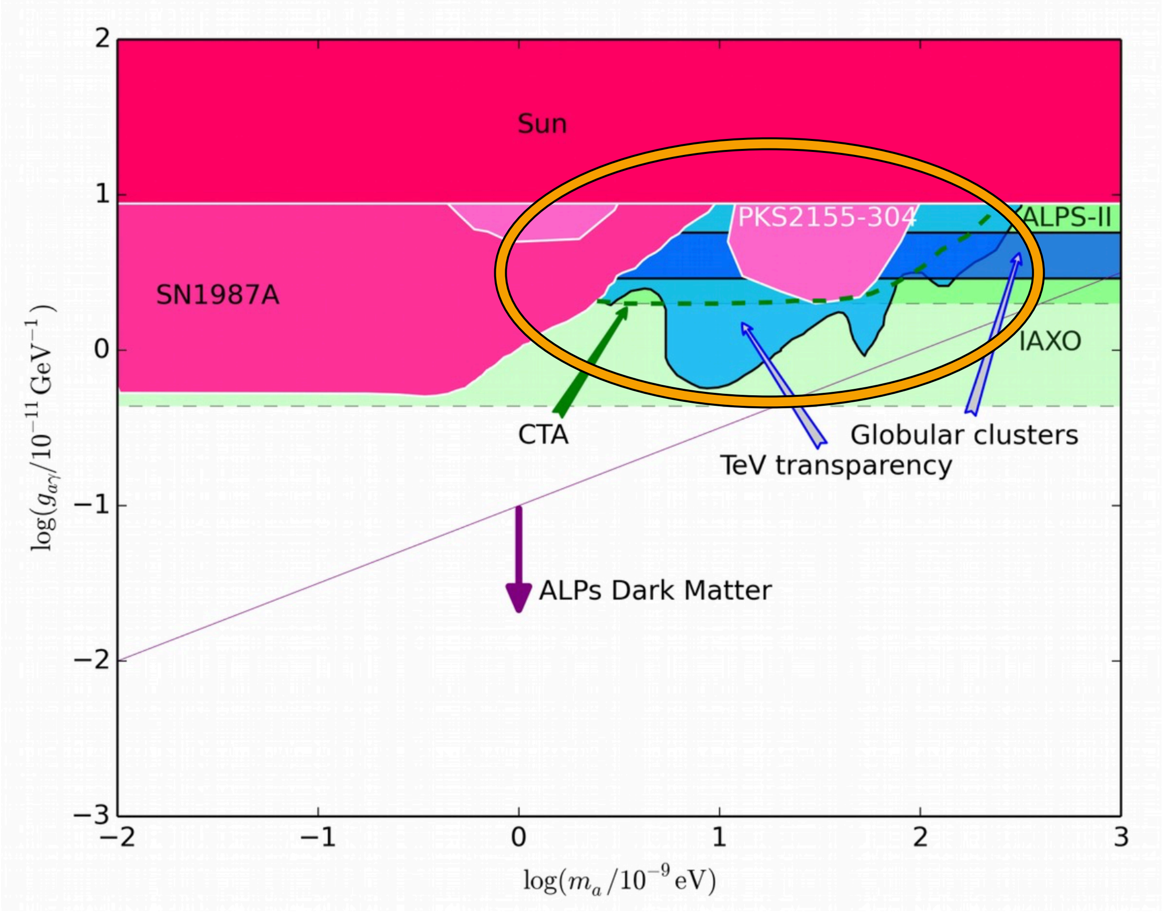


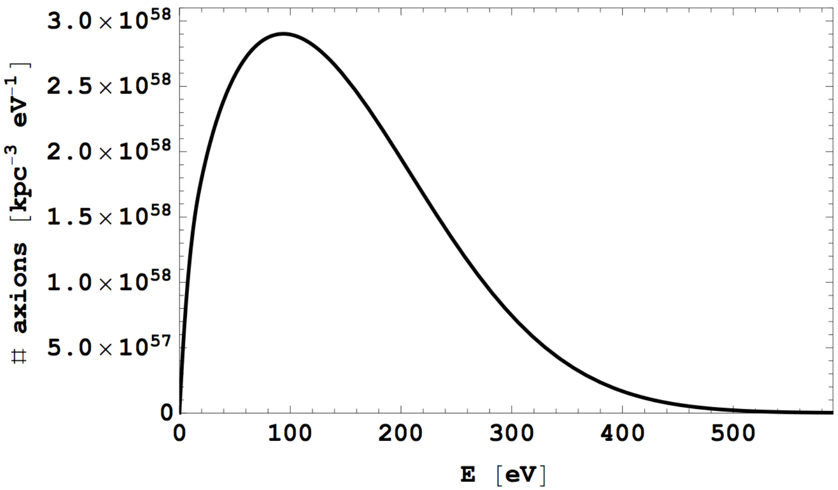

[Horns 15]

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

# Photon – ALP Conversion in Cosmic Magnetic Fields?

- 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]




[Angus et al. 13]

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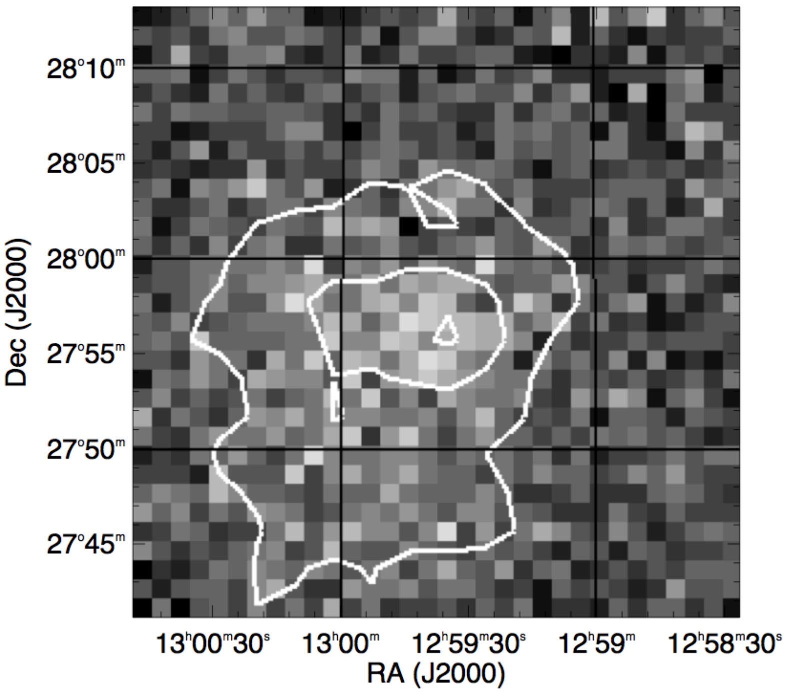
- ALP-photon in magnetic fields of galaxy clusters, e.g. Coma, may explain observed soft X-ray excess [Marsh,Conlon 13; Angus et al. 13]




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

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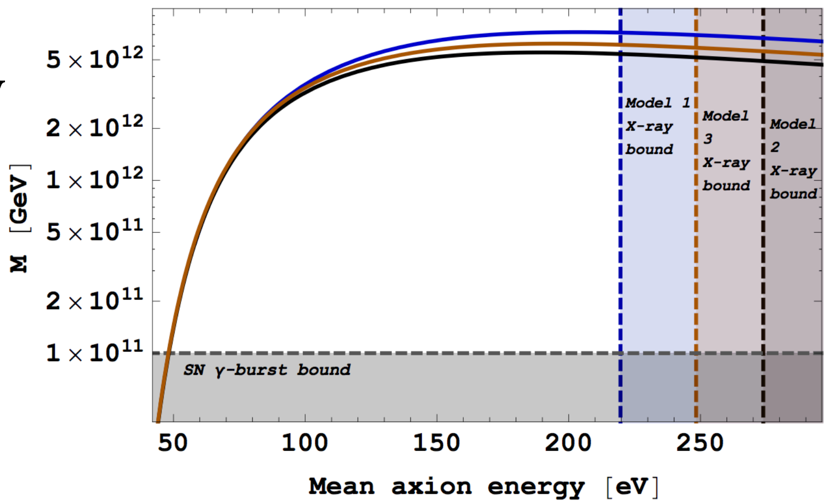


[Angus et al. 13]

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

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

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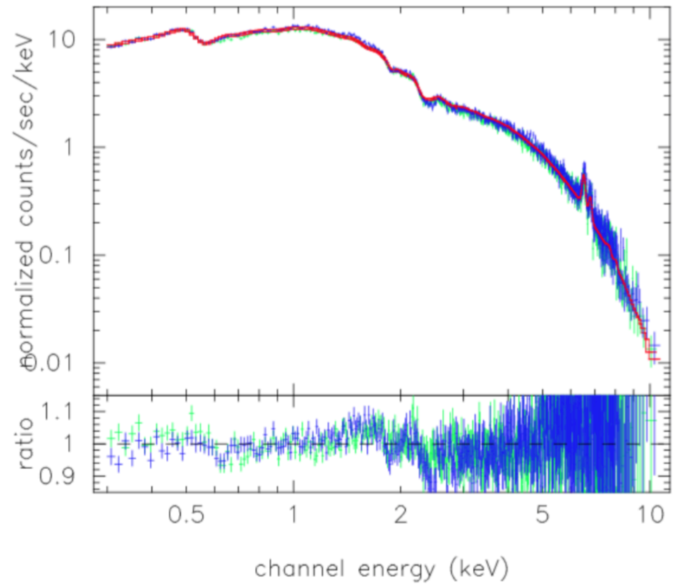
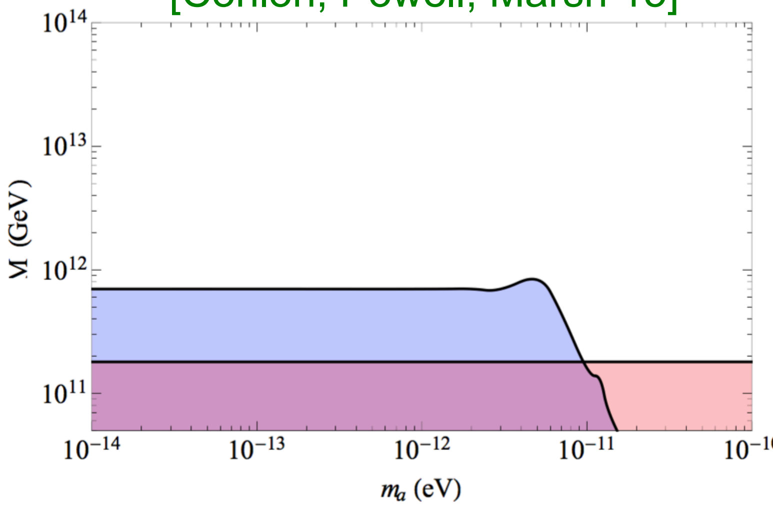
- Photon-ALP conversion leads to spectral deviations of cluster thermal bremsstrahlung spectrum

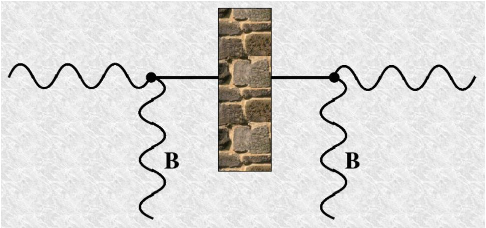



[Conlon, Powell, Marsh 15]

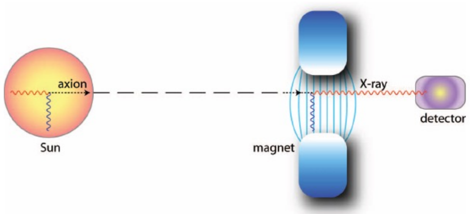


# Hints for Axion/ALPs: Strong Motivation for Hunts

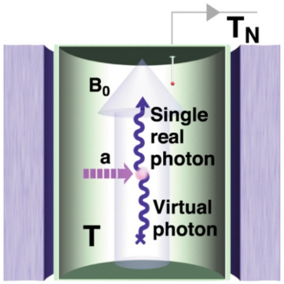
> Light-shining-through-walls



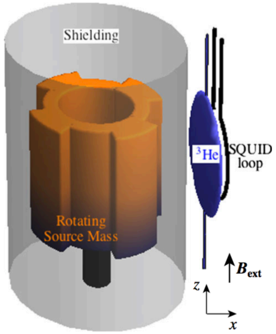

> Helioscopes




> Haloscopes




> Fifth-force searches



# Axion/ALP Experiments Worldwide

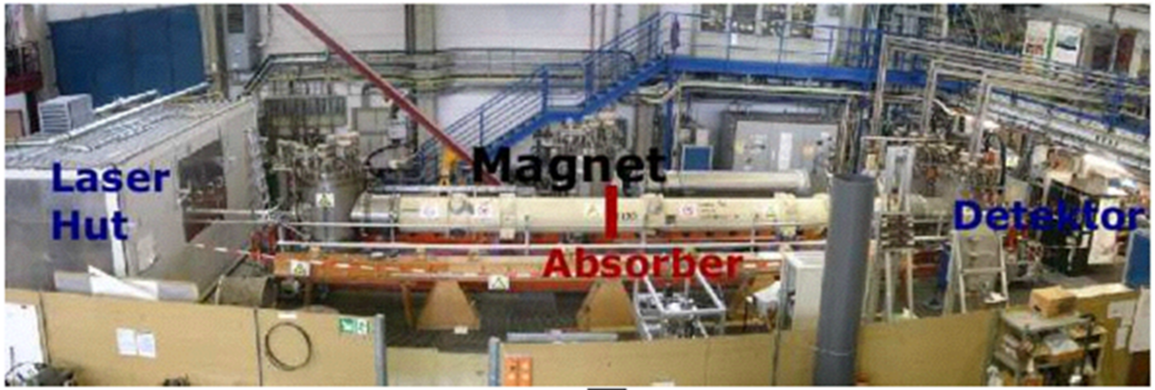
An incomplete selection of (mostly) small-scale experiments:

| 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 AEI, UHH)

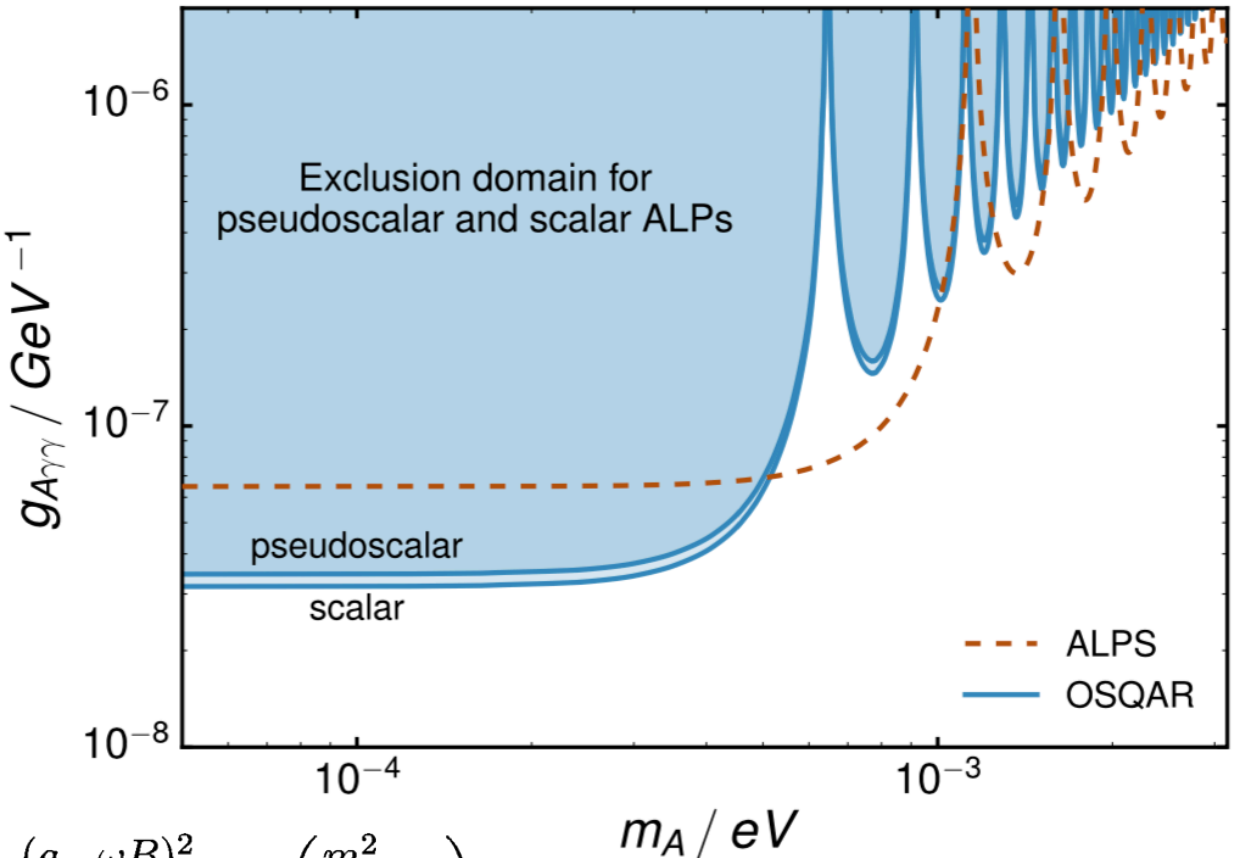




[Anselm 85;van Bibber et al. 87]

# Light-shining-through-a-wall Searches

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

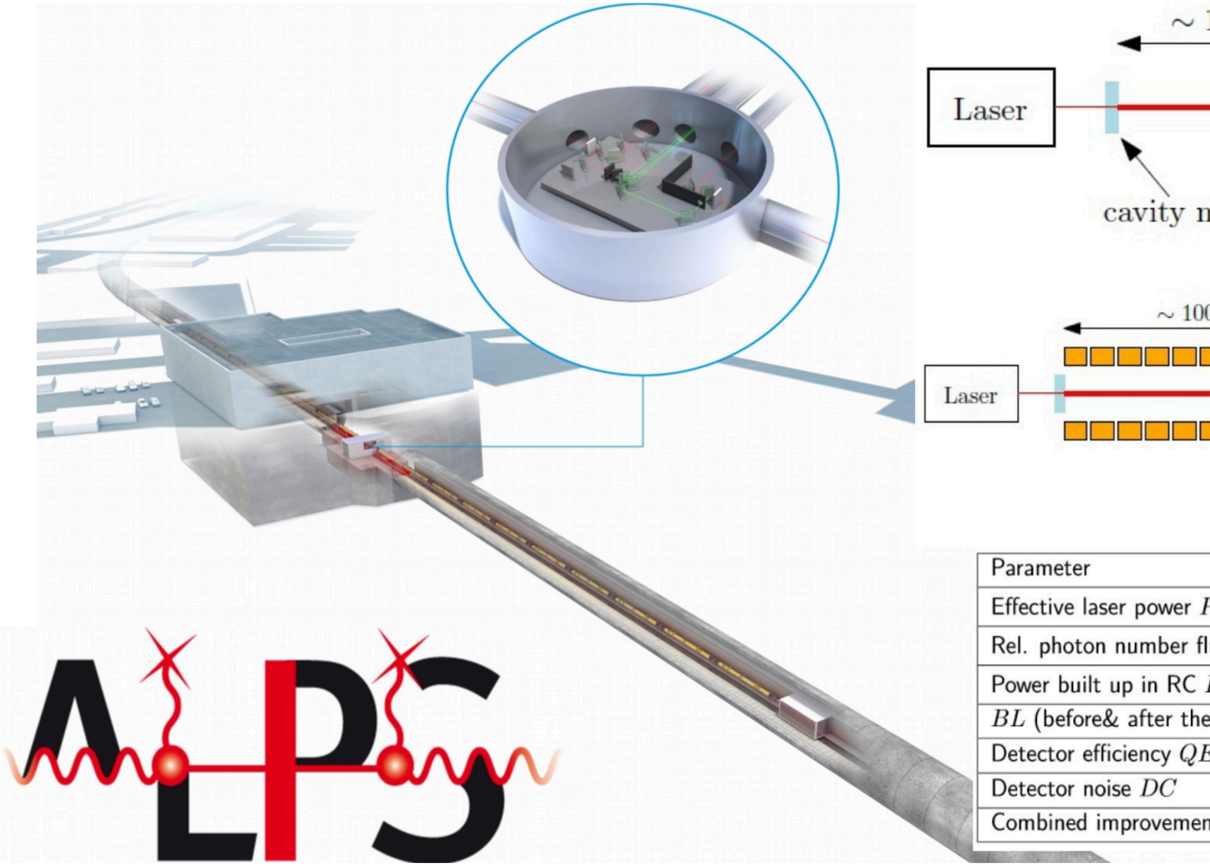


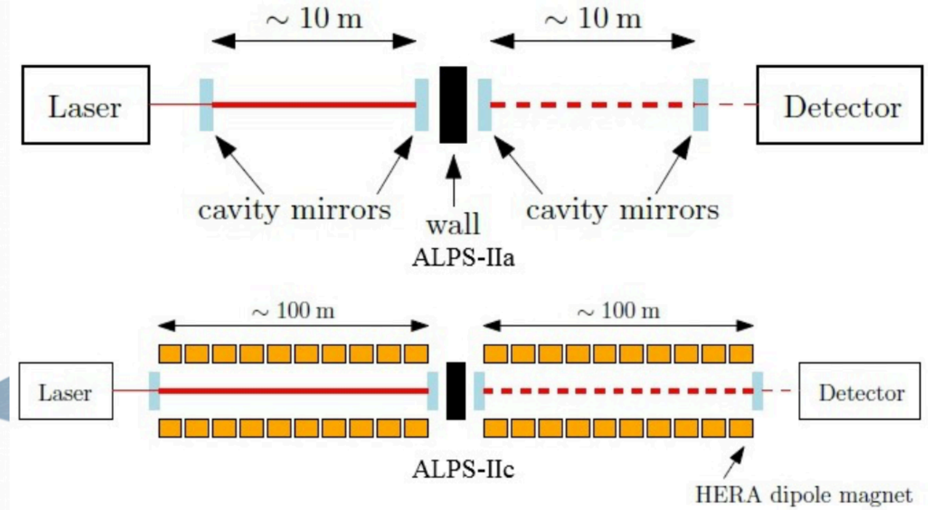

$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

[Ballou et al. 15]

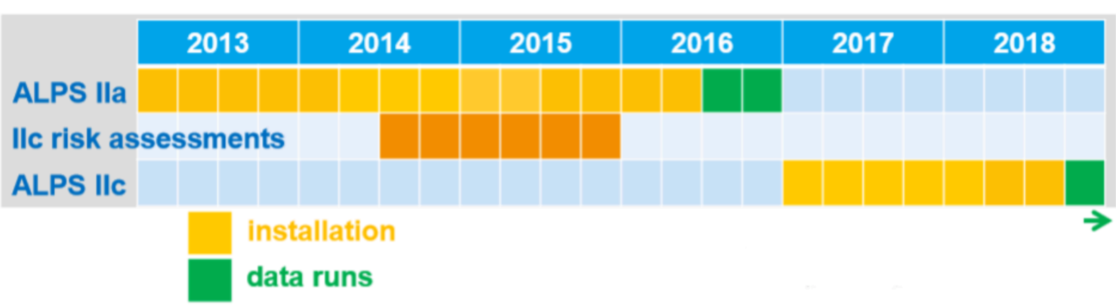
# Light-shining-through-a-wall Searches

> ALPS II at DESY (in coll. with AEI, U FL, UHH, U Mainz)





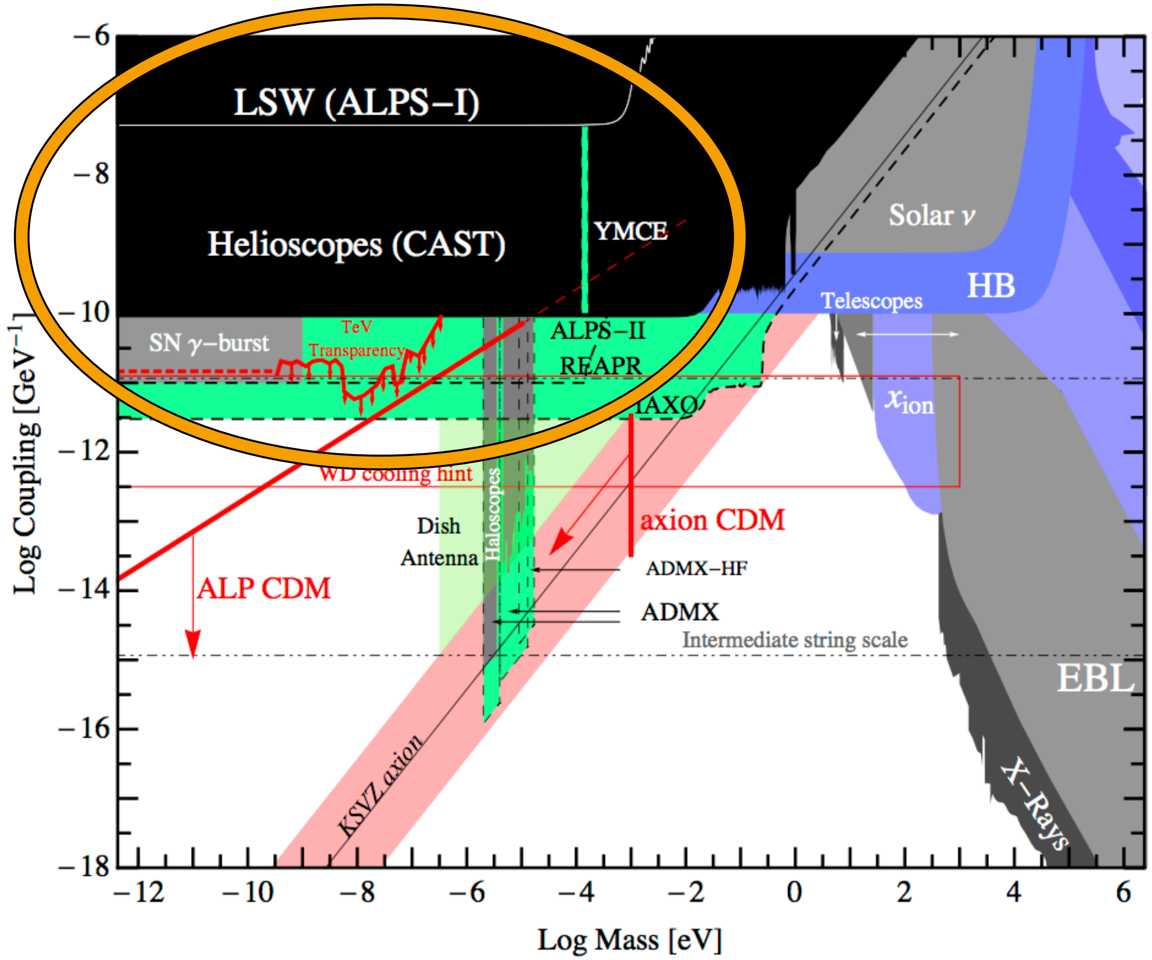

| Parameter | Scaling | ALPS I | ALPS IIc | Sens. gain |
|---|---|---|---|---|
| Effective laser power $P_{\rm laser}$ | $g_{a\gamma} \propto P_{\rm laser}^{-1/4}$ | 1 kW | 150 kW | 3.5 |
| Rel. photon number flux $n_\gamma$ | $g_{a\gamma} \propto n_\gamma^{-1/4}$ | 1 (532 nm) | 2 (1064 nm) | 1.2 |
| 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]

# Light-shining-through-a-wall Searches

> Beyond ALPS II?

| 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 |

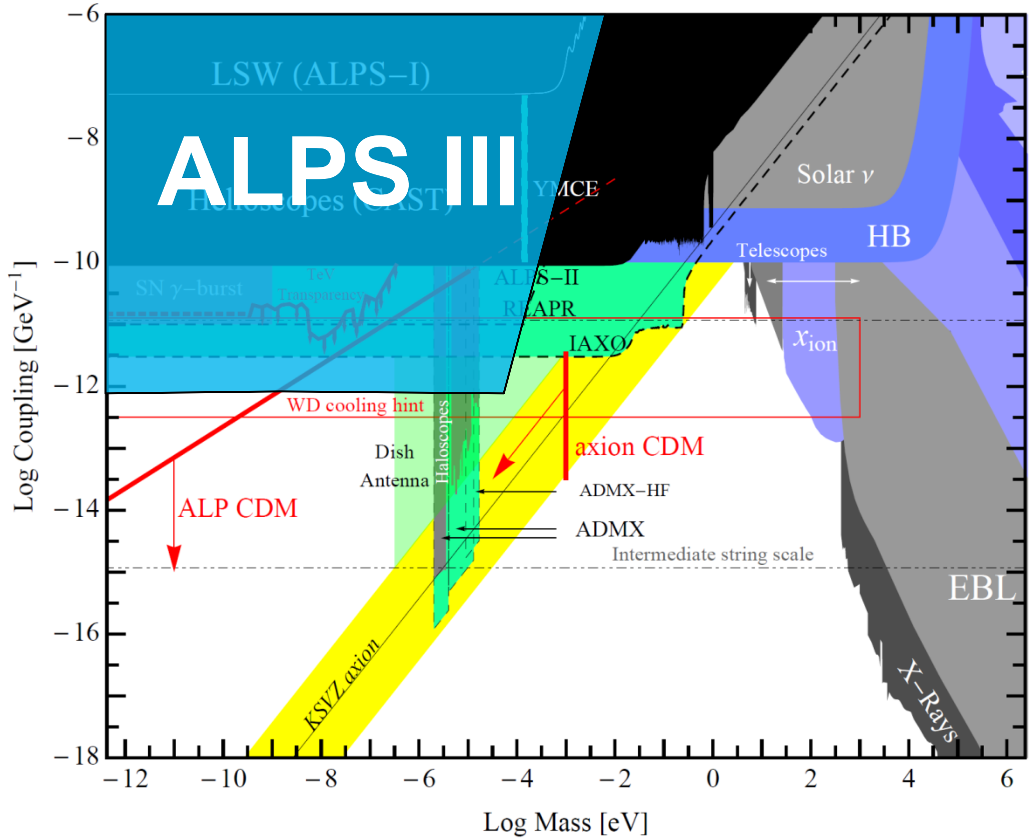
[Lindner 14]

# Light-shining-through-a-wall Searches

- 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 performs as expected
- Magnets as being developed for an LHC energy upgrade are essential
- "ALPS III" not before 2025



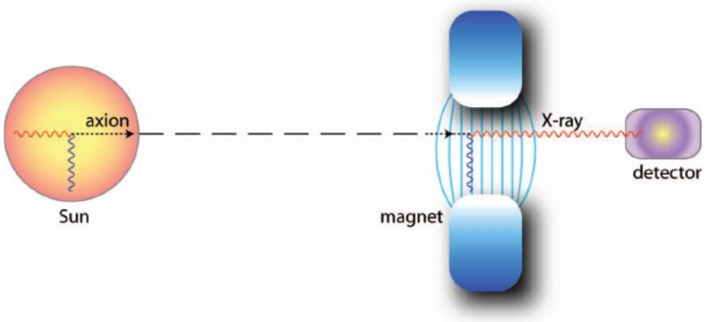

[Lindner 14]

# Helioscope Searches

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

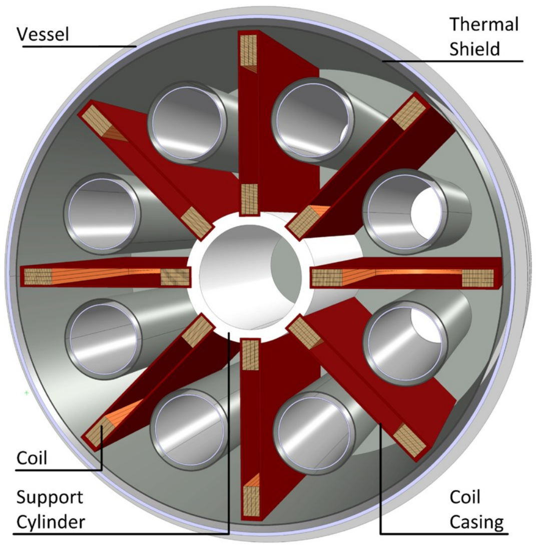
- Superconducting LHC dipole magnet
- X-ray detectors

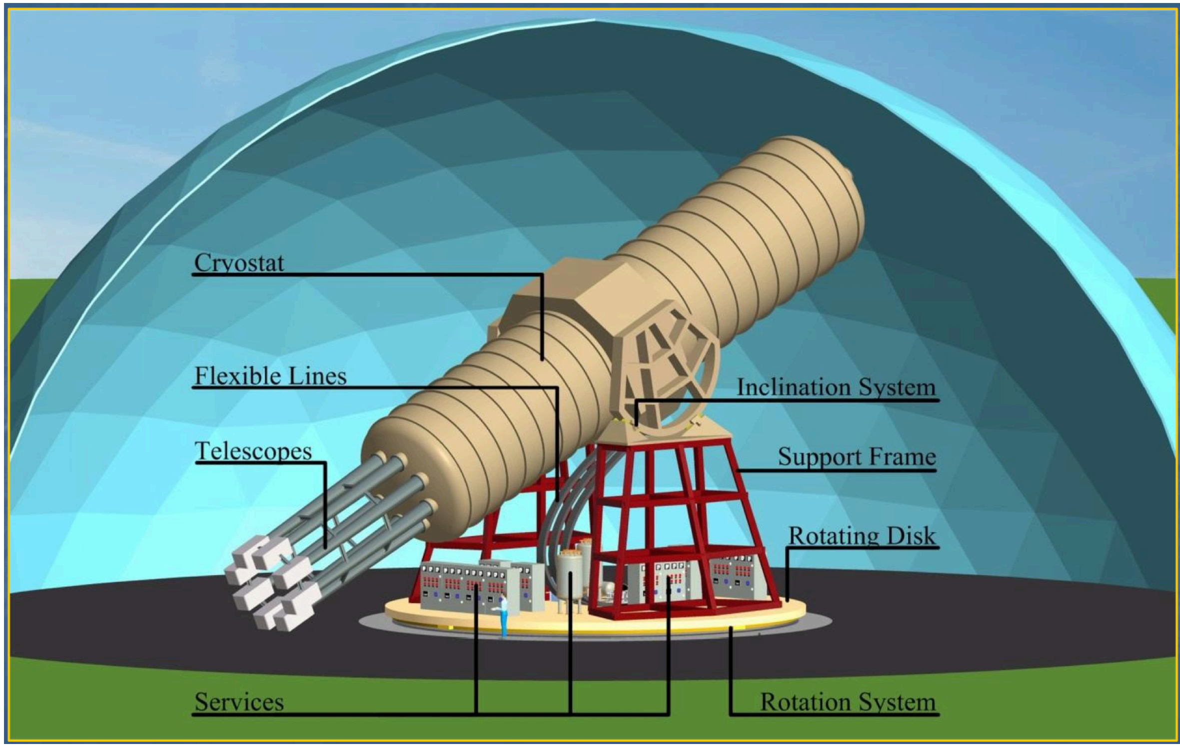
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$




# 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

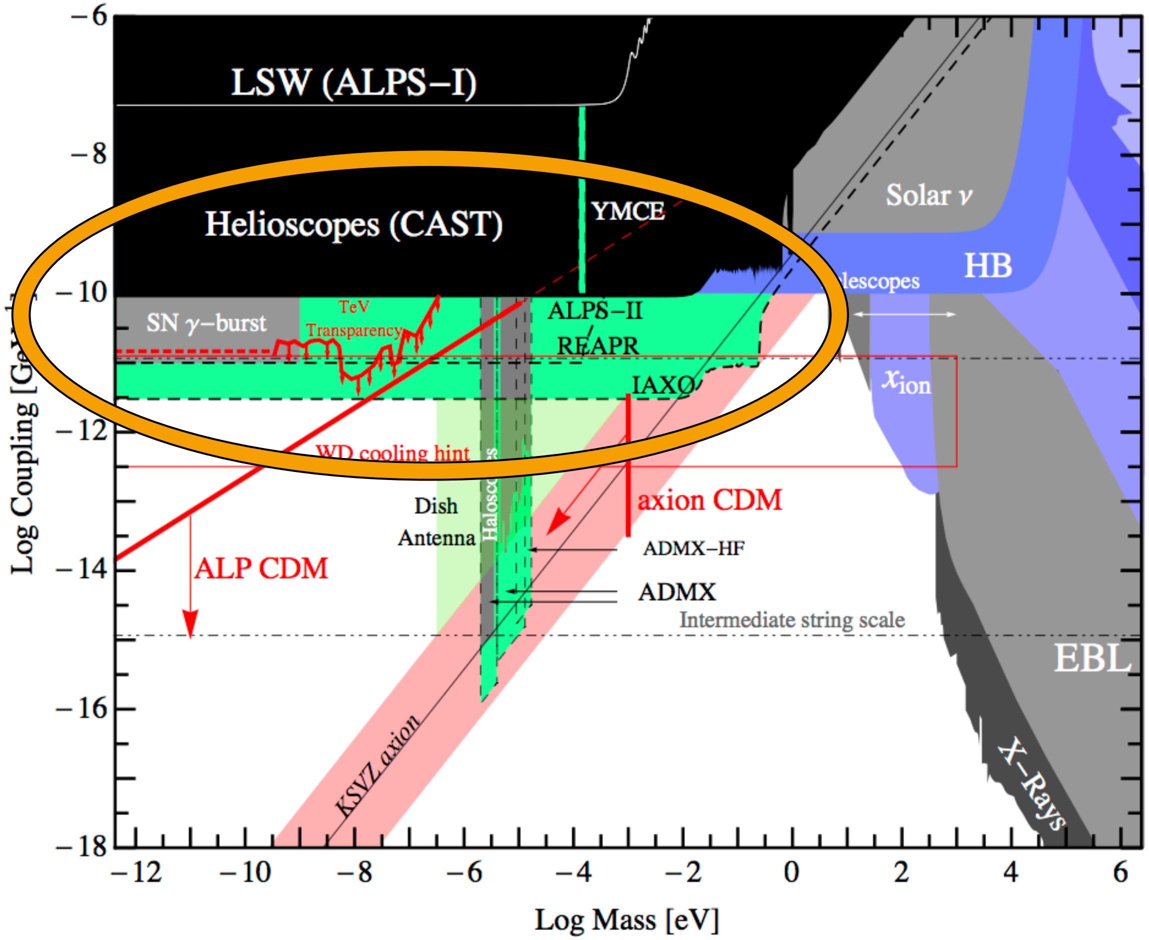



[Armengaud et al (IAXO CDR) 1401.3233]

# 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

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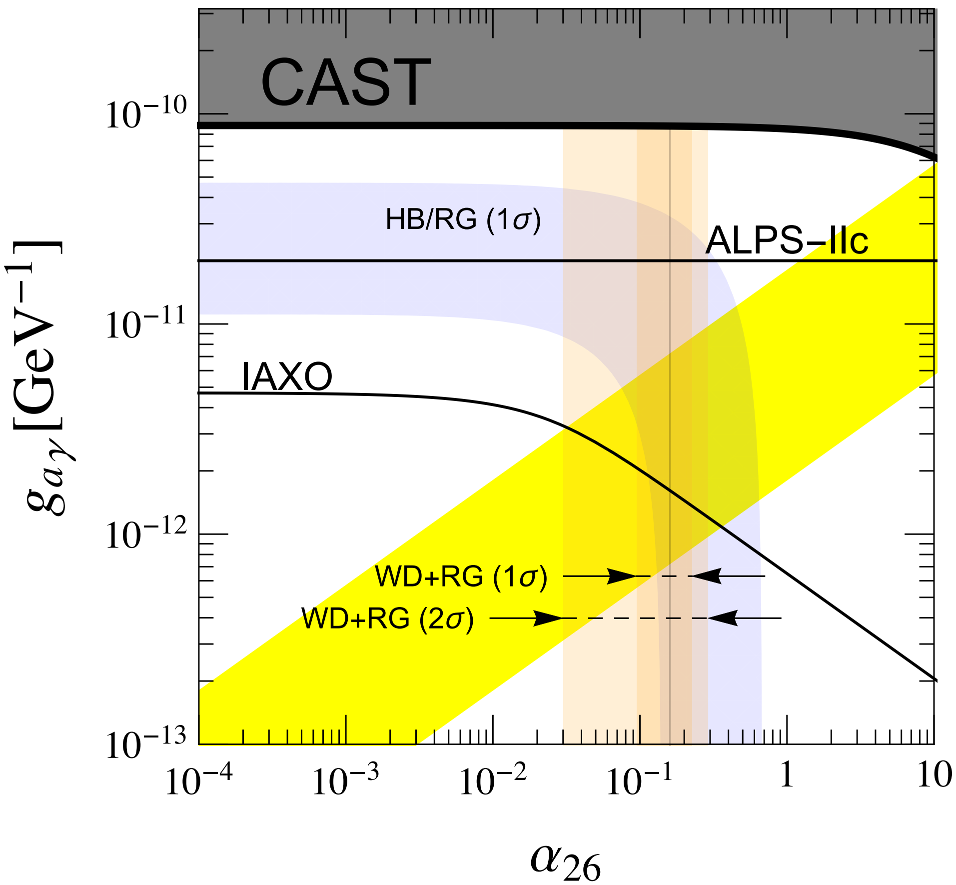
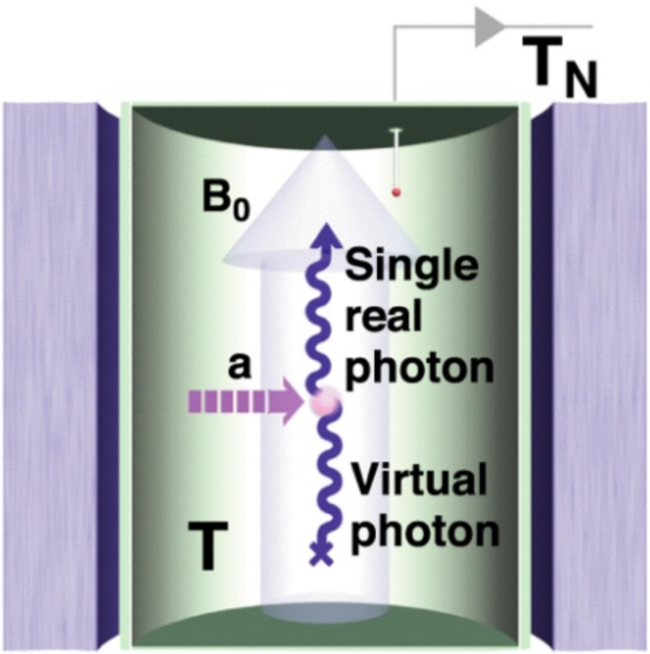



[Giannotti,Irastorza,Redondo,AR arXiv:1512.08108]

# 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 $m_a = 2\pi\nu \sim 4\ \mu\text{eV} \left(\frac{\nu}{\text{GHz}}\right)$

# Haloscope Searches: Resonant Cavities

- Direct detection of axion/ALP dark matter!
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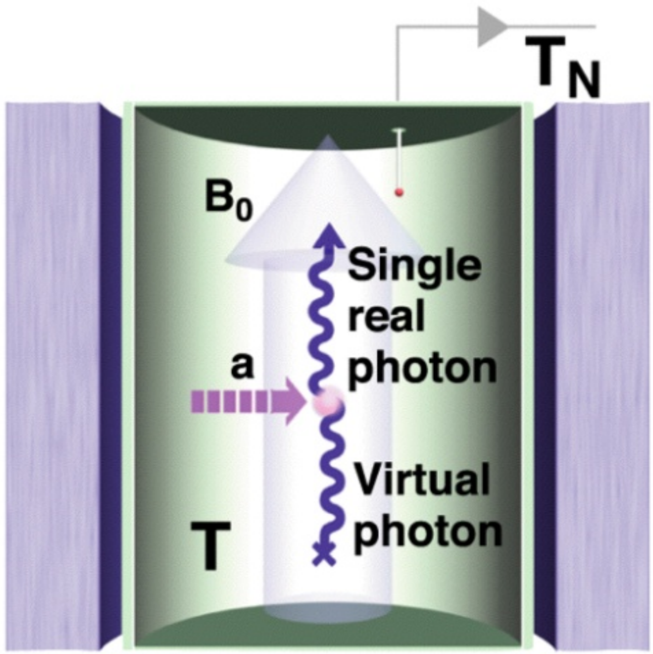


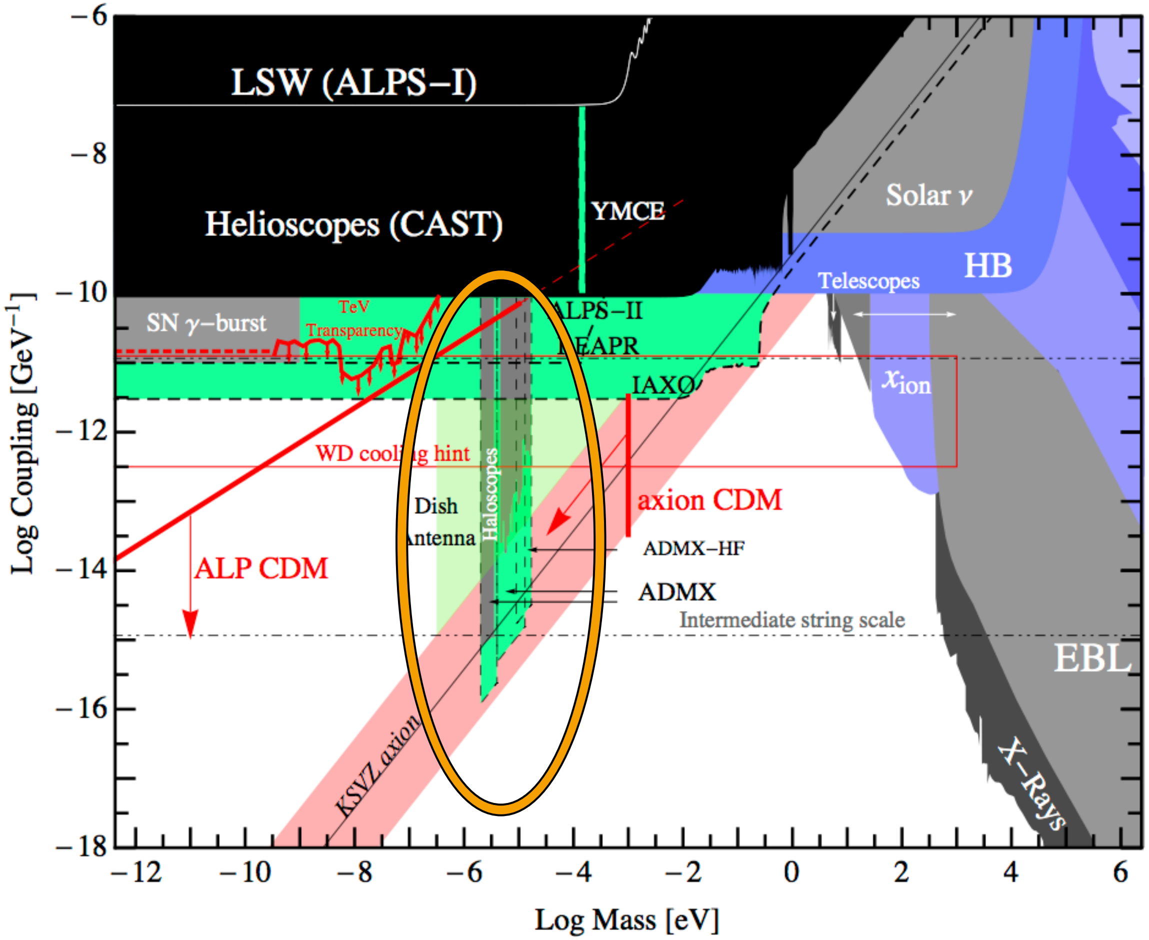

- Best sensitivity: mass = resonance frequency $m_a = 2\pi\nu \sim 4\ \mu\mathrm{eV}\left(\frac{\nu}{\mathrm{GHz}}\right)$
- Ongoing: ADMX (Seattle), exploiting high Q cavity in 8 T SC solenoid



DESY

# Haloscope Searches: Resonant Cavities

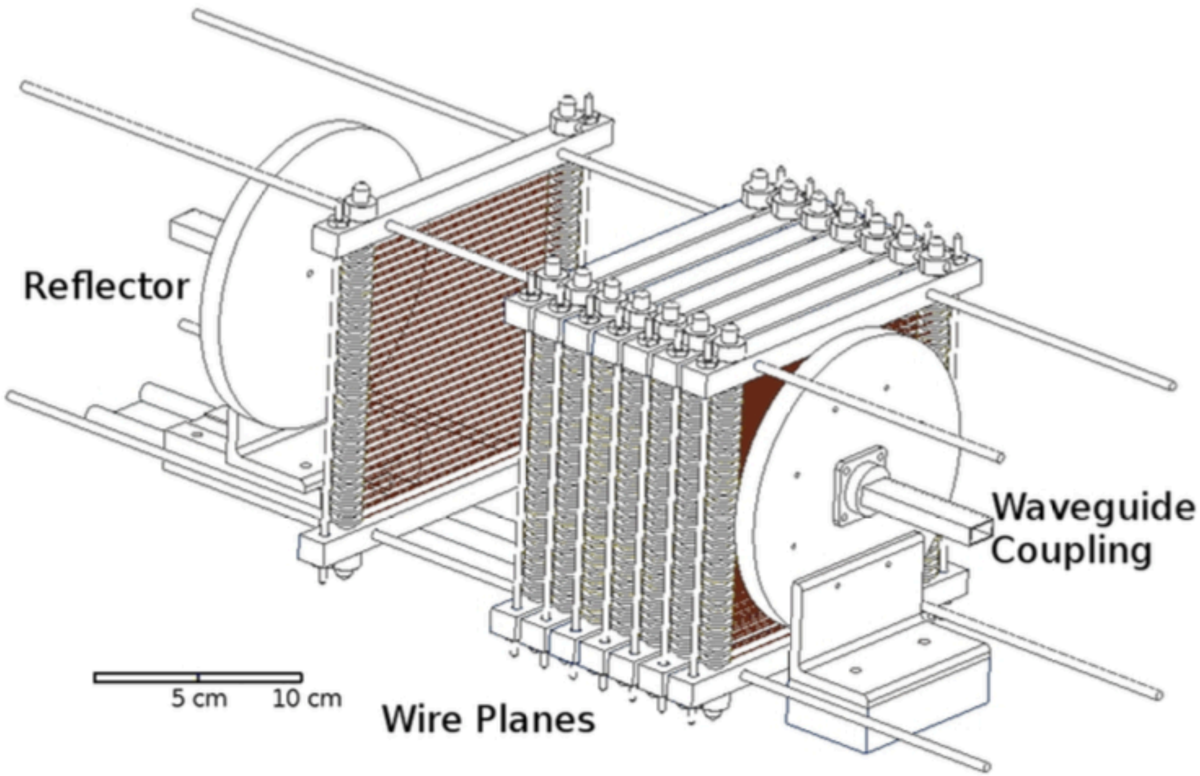
> ADMX able to probe about 1.5 decades in axion/ALP mass:




adapted from [Hewett et al 12]

# Haloscope Searches: Open Resonator

- **Orpheus** (Seattle): [Rybka et al. 15]
  - exploit open Fabry-Perot resonator and series of current wire-planes



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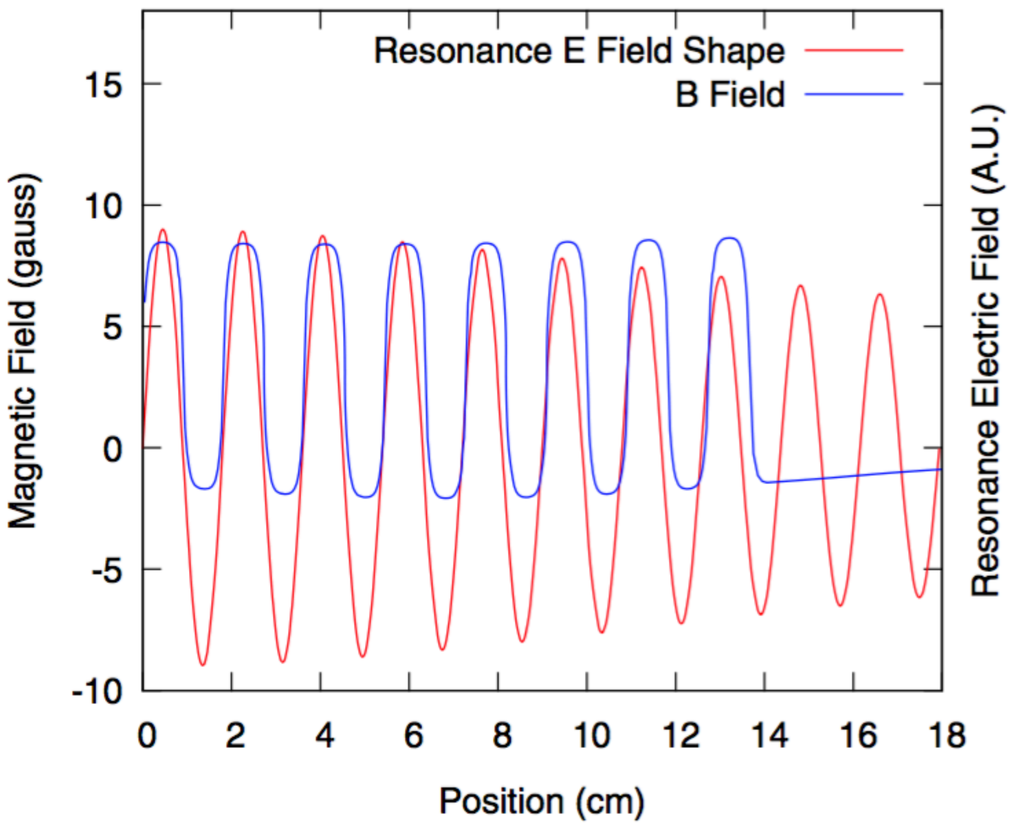
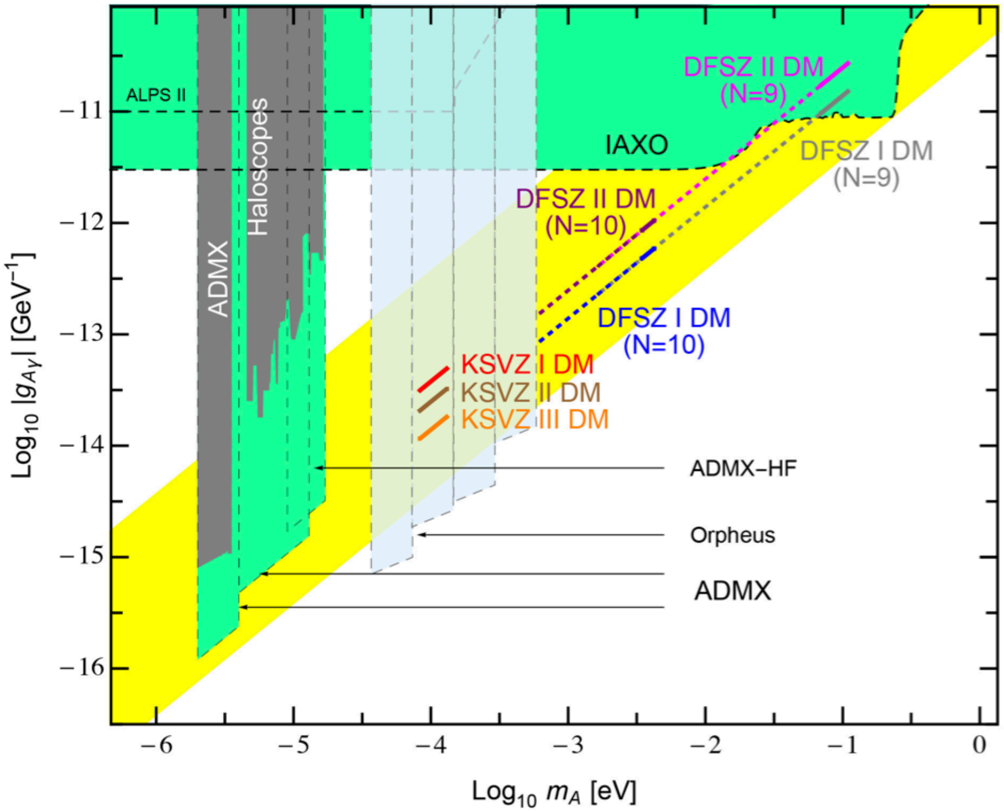


# Haloscope Searches: Open Resonator

- **Orpheus** (Seattle):
  - exploit open Fabry-Perot resonator and series of current wire-planes
  - technique allows to probe higher masses suggested in post-inflationary SSB scenario




[AR, Saikawa 15]

# Haloscope Searches: Dish Antennas

- Oscillating axion/ALP DM in a background magnetic field carries a small electric field component [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]

**- 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** $v = \frac{k}{\omega}$ ; $\omega \simeq m_a(1 + v^2/2 + \ldots)$

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

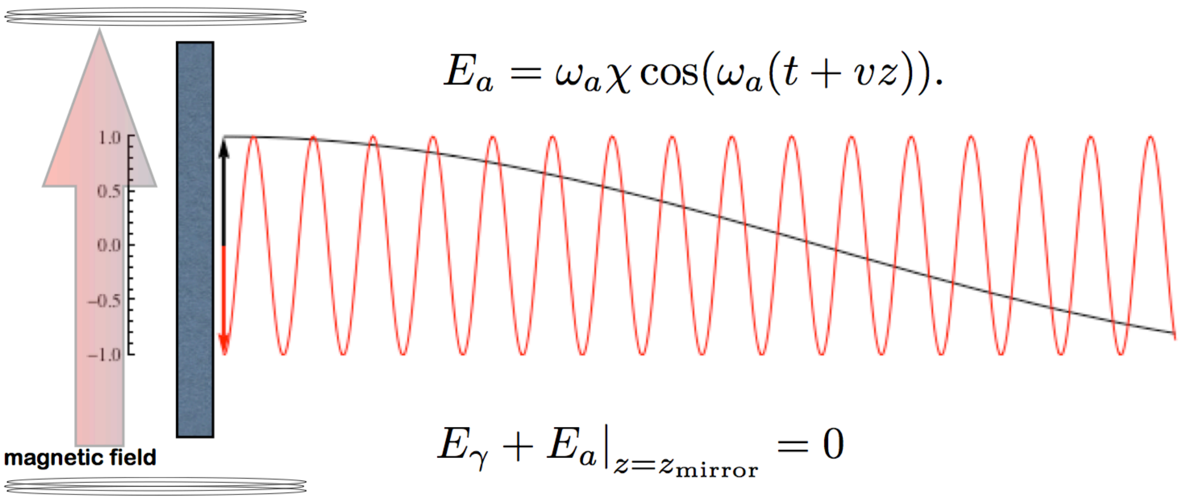
**It has a small E field!**

$$\chi_a \sim \frac{g_{a\gamma}|\mathbf{B}|}{m_a}$$

[Redondo: talk at DESY 14 ]

# Haloscope Searches: Dish Antennas

- Oscillating axion/ALP DM in a background magnetic field carries a small electric field component [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]
- A magnetised mirror in axion/ALP DM background radiates photons




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

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

**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 ]

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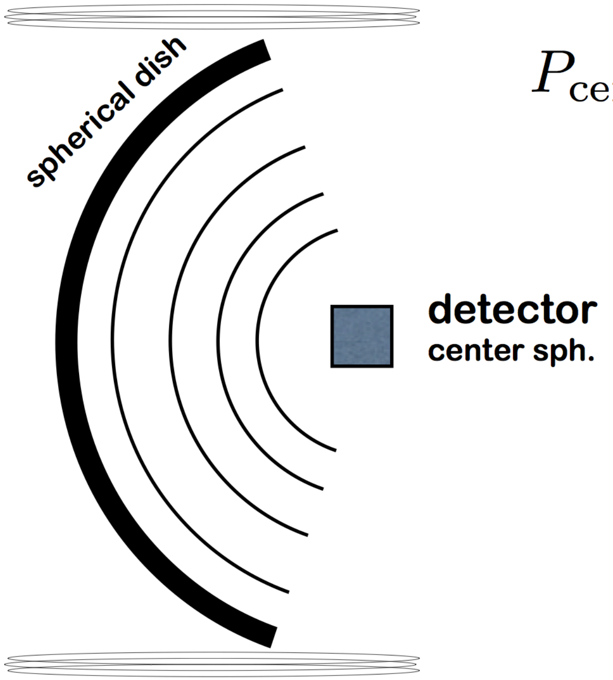
- Oscillating axion/ALP DM in a background magnetic field carries a small electric field component [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]
- A magnetised mirror in axion/ALP DM background radiates photons
- Simple broadband experiment: spherical dish antenna



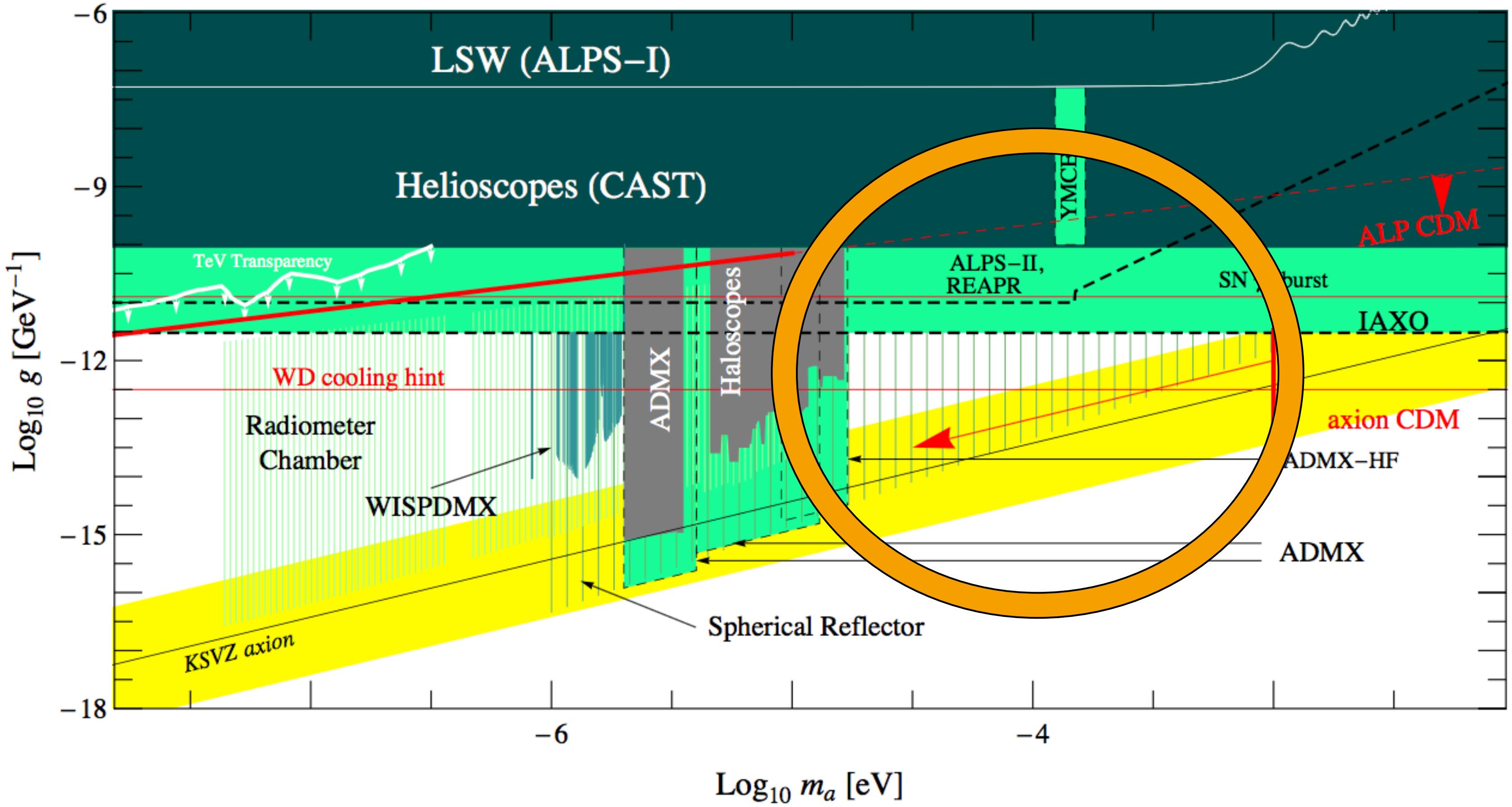

$$P_{\rm center} \approx \langle |\mathbf{E}_a|^2 \rangle A_{\rm dish} \sim \chi^2 \rho_{\rm CDM} A_{\rm dish}$$

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

[Redondo: talk at DESY 14 ]

# Haloscope Searches: Dish Antennas

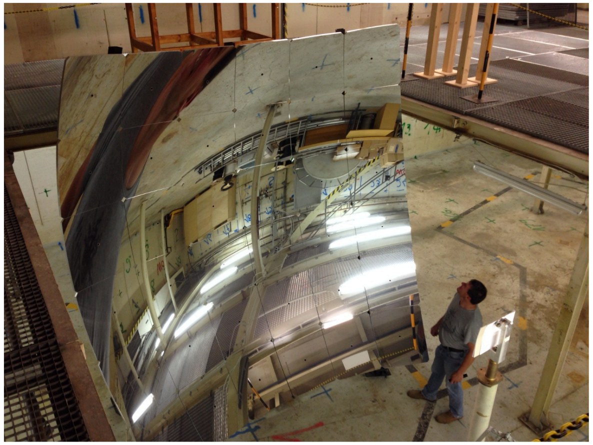
> Dish antenna may probe higher axion/ALP masses:



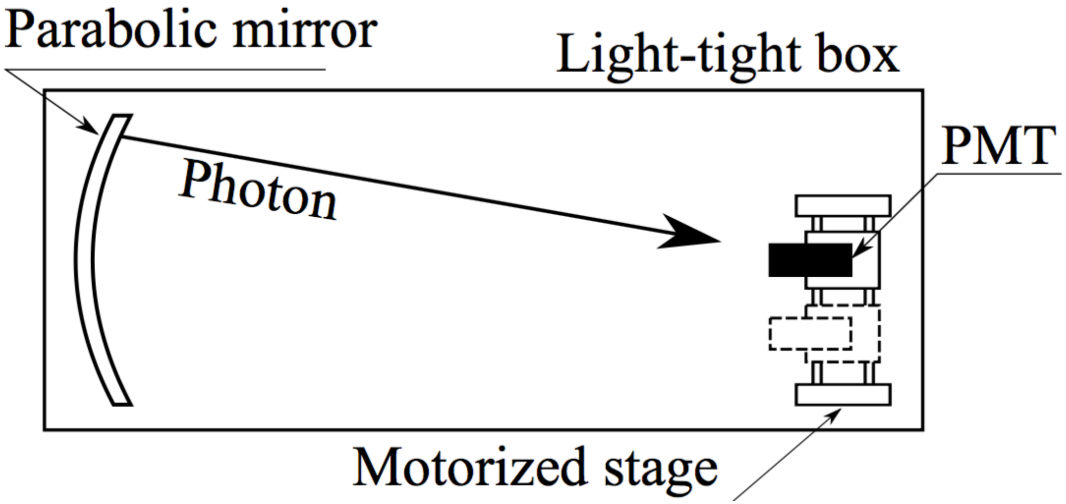

[Horns,Lindner,Lobanov,AR 14]

# Haloscope Searches: Dish Antennas

- Several pilot dish antenna experiments searching for hidden photon DM:



FUNK (Karlsruhe)




??? (Tokyo)

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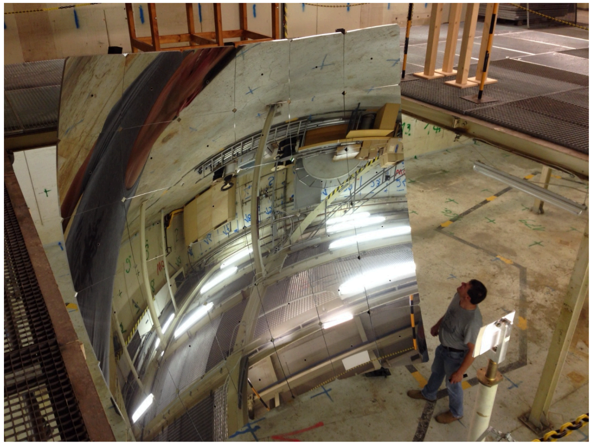

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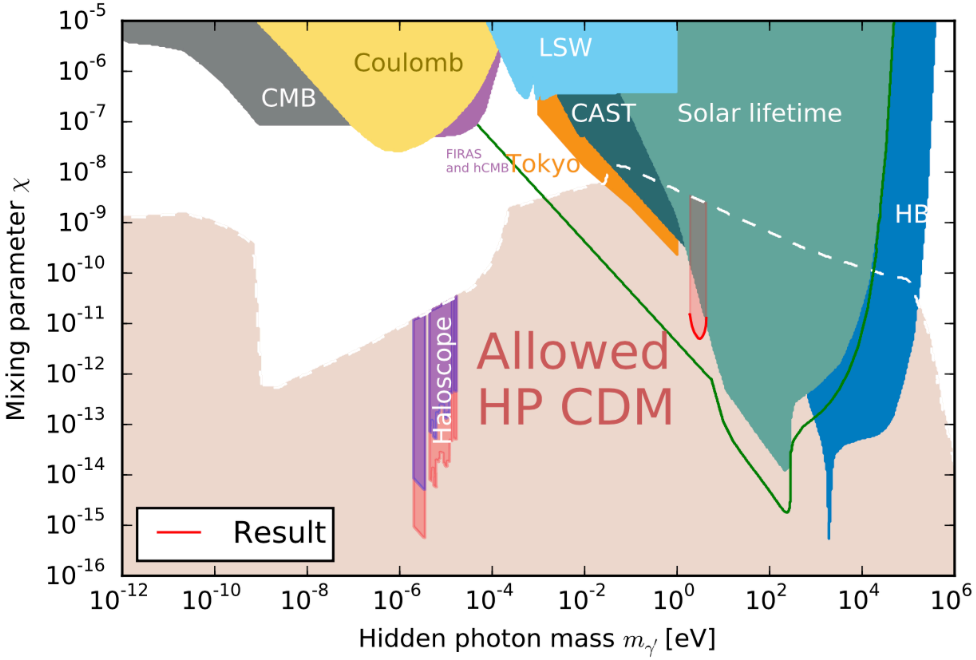


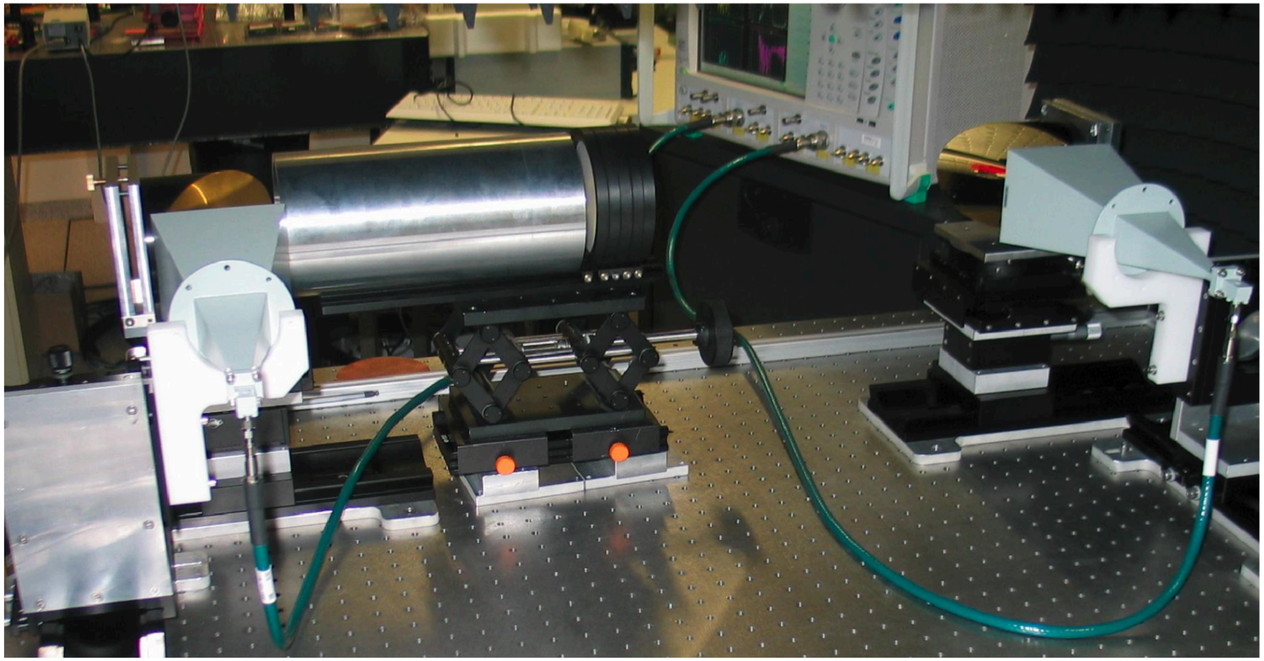

??? (Tokyo)

[Suzuki et al. 15]

# Haloscope Searches: Dish Antennas

- Several pilot dish antenna experiments searching for hidden photon DM:

**First prototype setup at MPI**



??? (MPI Munich)

[Caldwell et al. 15]

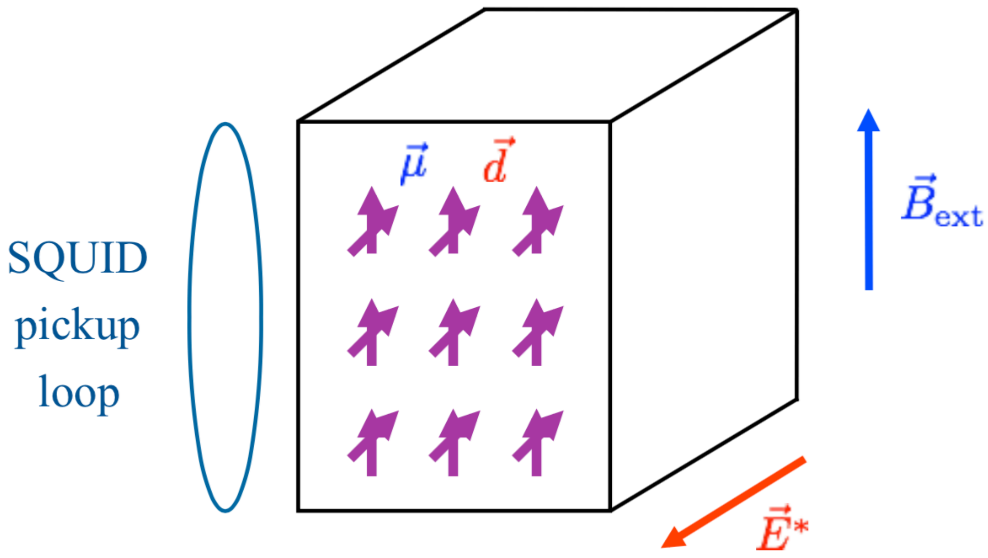
# Haloscopes: Magnetic Resonance Searches

> Galactic axion DM field induces oscillating nuclear EDMs:

$$d_N(t) = g_d \sqrt{\rho_{\rm DM}} \cos(m_a t)/m_a$$

> CASPEr (Mainz):

MRT search for transverse magnetization due to precession of nuclear spins in polarized sample in presence of eletric field




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

[Budker et al. 14]

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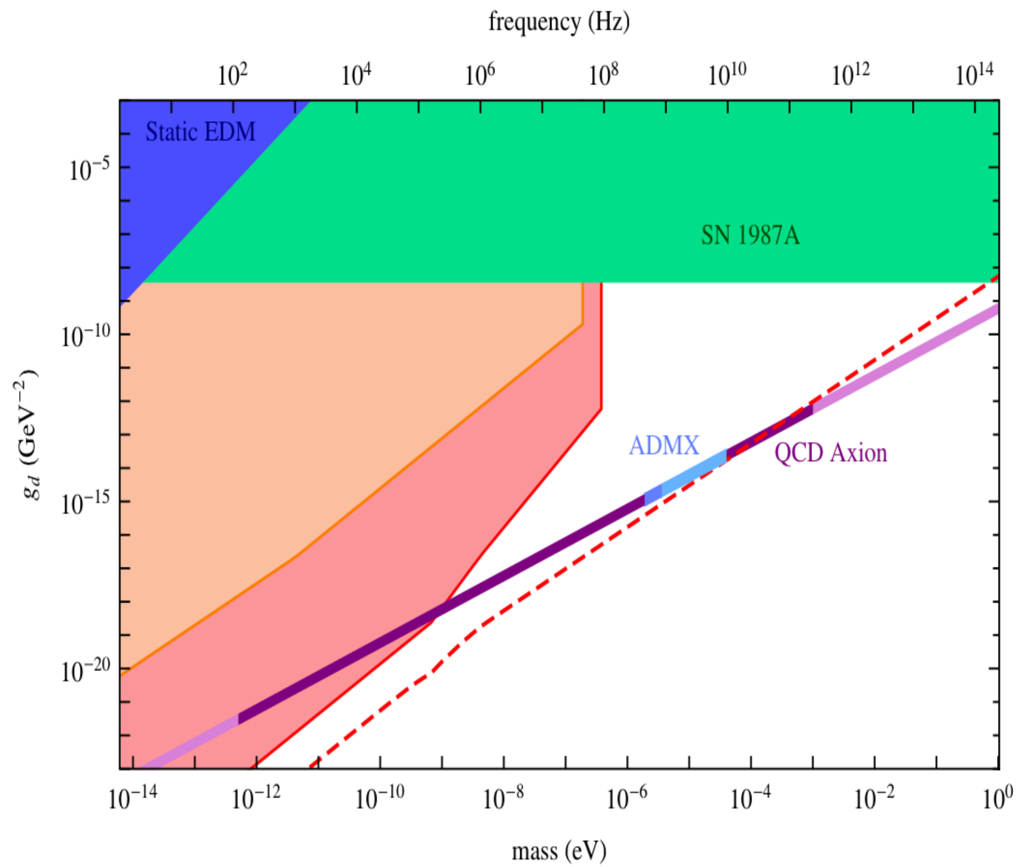


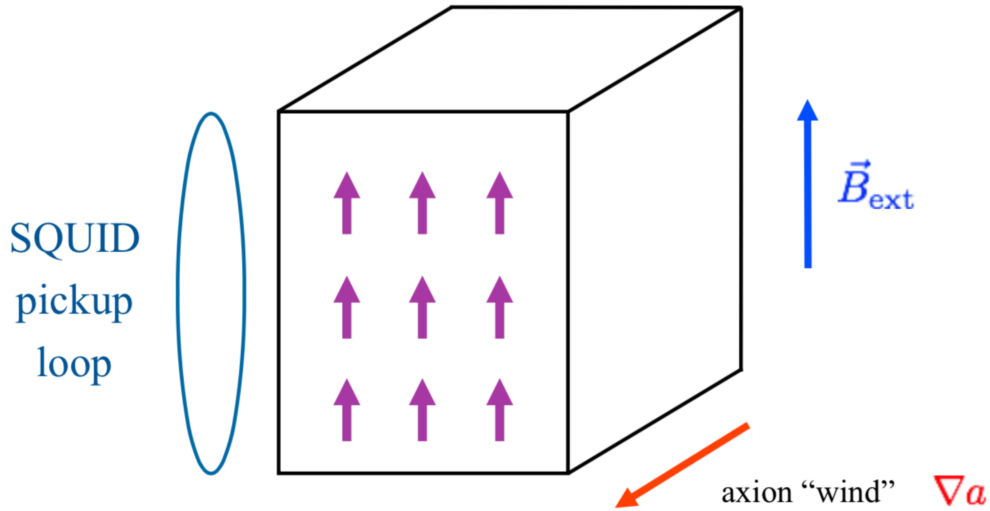

[Budker et al. 14]

| | $n$ | $E^*$ | $p$ | $T_2$ | Max $B_{\rm ext}$ |
|---|---|---|---|---|---|
| Phase 1 | $10^{22}$ cm$^{-3}$ | $3\times10^8$ V/cm | $10^{-3}$ | 1 ms | 10 T |
| Phase 2 | $10^{22}$ cm$^{-3}$ | $3\times10^8$ V/cm | 1 | 1 s | 20 T |

# Haloscopes: Magnetic Resonance Searches

- Axion/ALP nucleon/electron coupling leads to nucleon/ electron spin precession about galactic axion/ALP DM wind
- CASPEr (Mainz):

  MRT search for transverse magnetization due to pre-cession of nuclear spins in polarized sample in DM wind




[Graham,Rajendran 13]

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

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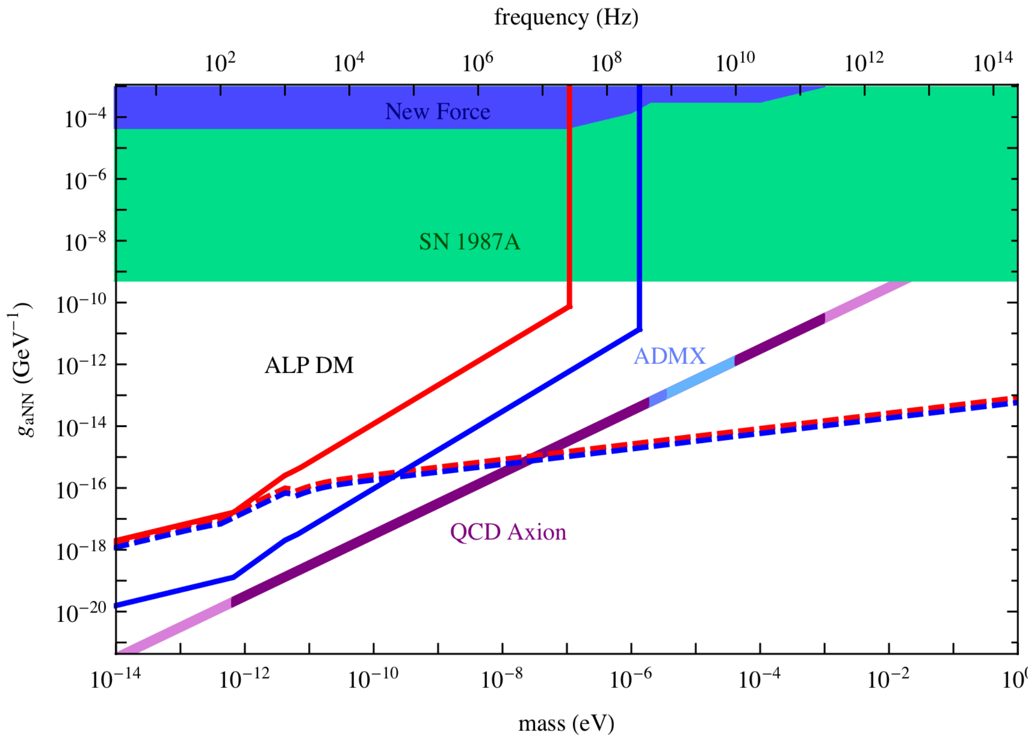


[Graham,Rajendran 13]

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| | Element | Density ($n$) | Magnetic Moment ($\mu$) | $T_2$ | 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 | $10^{-17}\,\frac{\text{T}}{\sqrt{\text{Hz}}}$ |

# Haloscopes: Magnetic Resonance Searches

- Axion/ALP nucleon/electron coupling leads to nucleon/electron spin precession about galactic axion/ALP DM wind
- CASPEr (Mainz):

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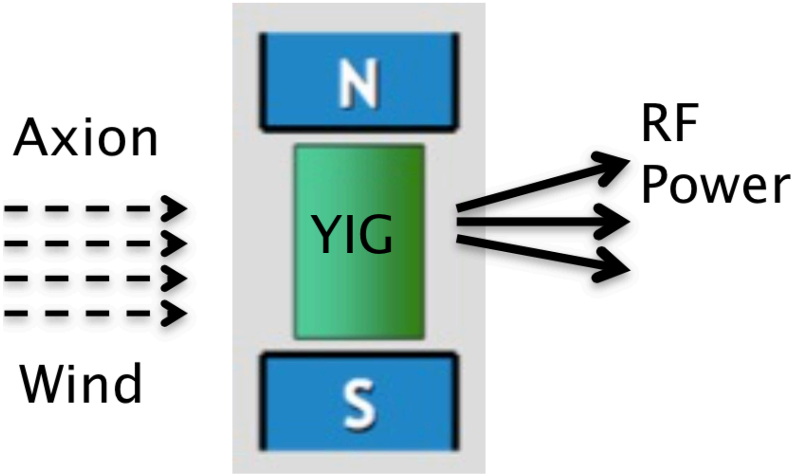
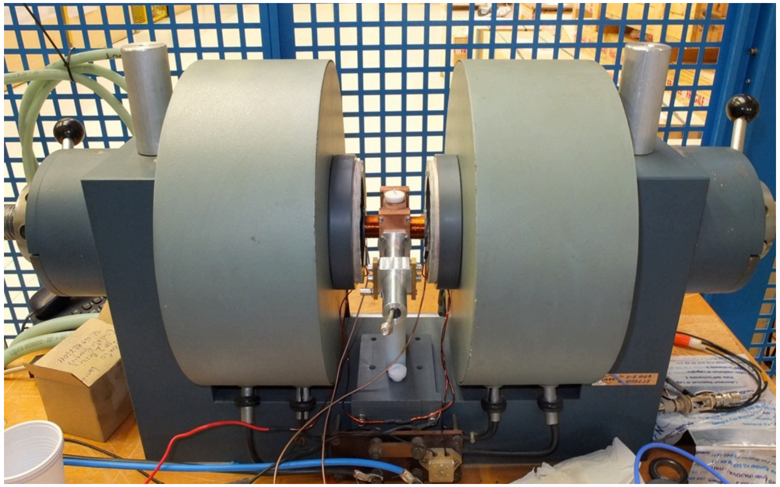
- QUAX (INFN):

  ESRT search



[Ruoso et al. 15]

# Fifth Force: Search for Axion-Mediated Forces

- ARIADNE: Proposed experiment based on precision magnetometry to search for axion-mediated spin-dependent forces
- Combining techniques used in NMR and short-distance tests of gravity

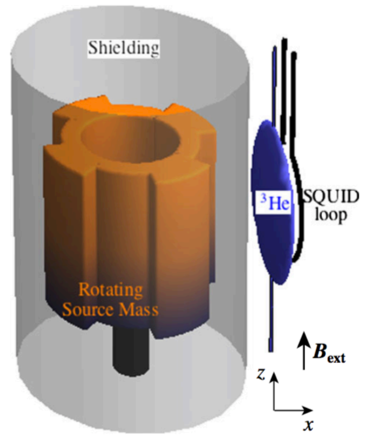
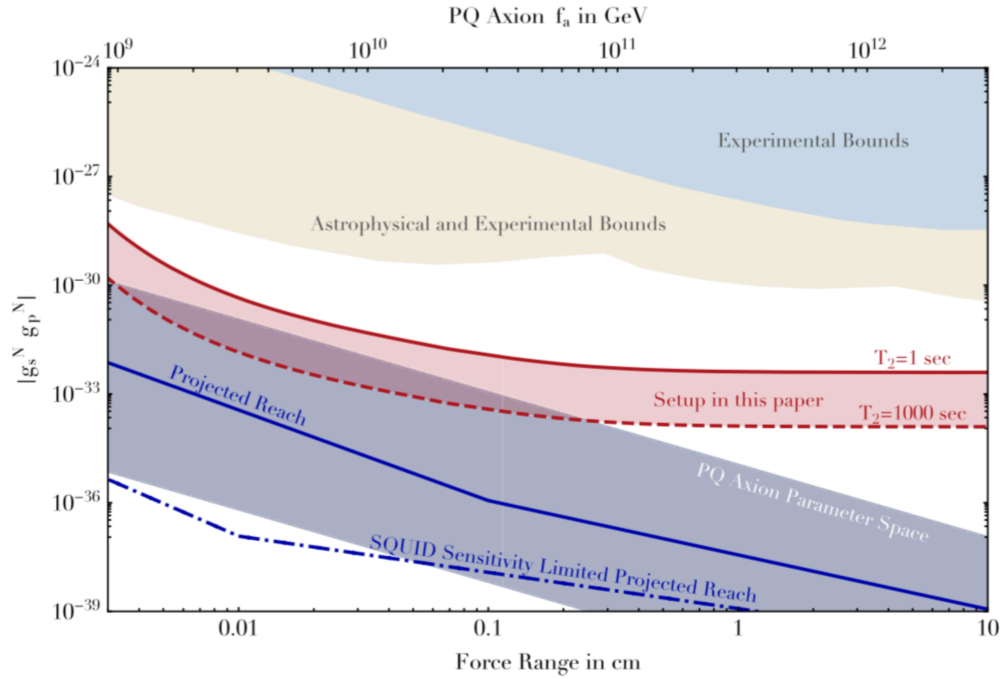



FIG. 1 (color online). A source mass consisting of a segmented cylinder with $n$ sections is rotated around its axis of symmetry at frequency $\omega_{rot}$, which results in a resonance between the frequency $\omega = n\omega_{rot}$ at which the segments pass near the sample and the resonant frequency $2\vec{\mu}_N \cdot \vec{B}_{ext}/\hbar$ of the NMR sample. Superconducting cylinders screen the NMR sample from the source mass and (not shown) the setup from the environment.

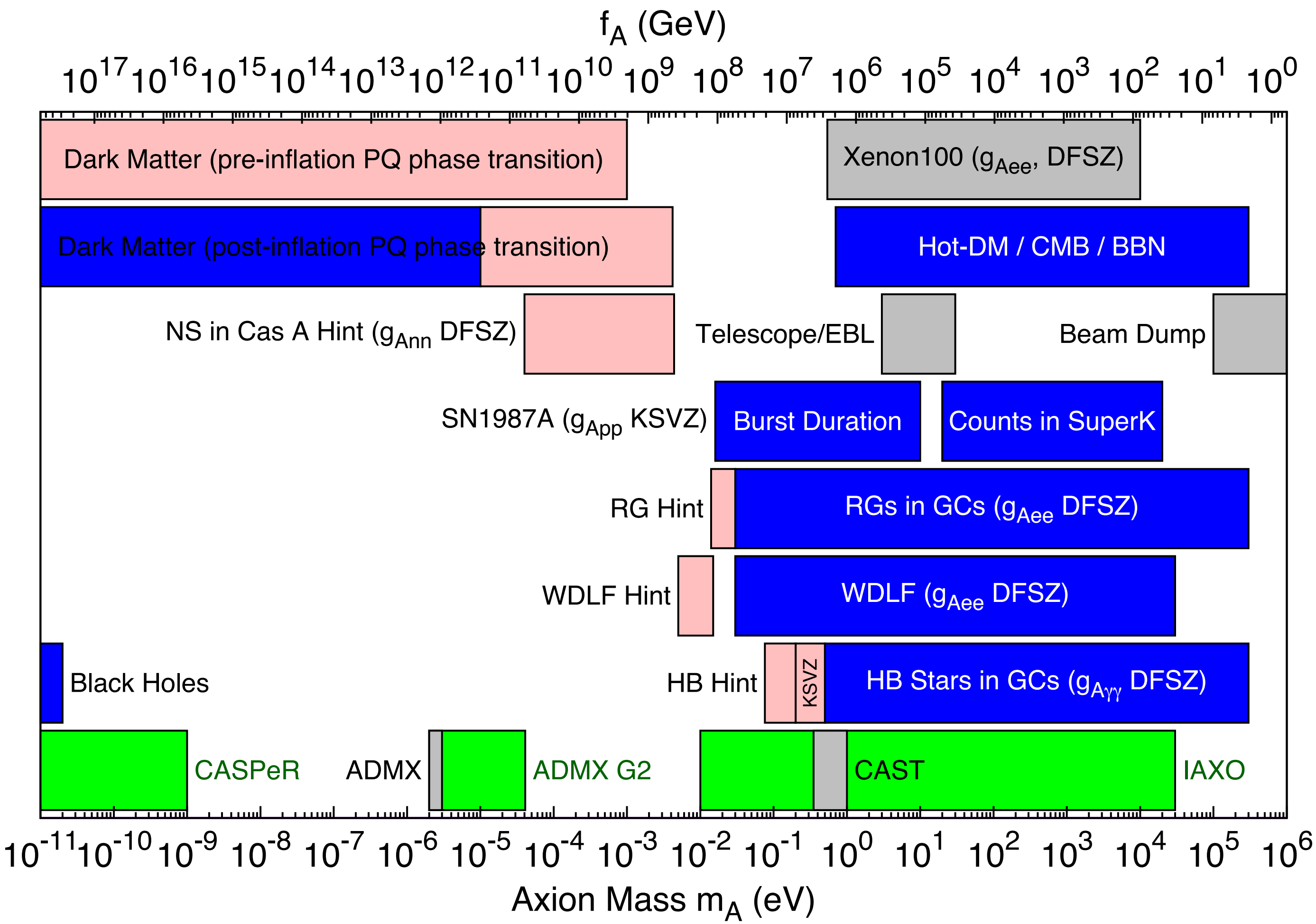



[Arvanitaki, Geraci 14]

# Conclusions

- 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; soft X-rays from clusters)
- 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, ...)
  - Fifth-force experiments (ARIADNE, ...)
- Stay tuned!

# Summary of Astrophysical Hints for Axion/ALPs




[AR,Rosenberg,Rybka, Review of Particle Physics, Update 2016]

# Axion/ALP bounds from Penrose BH superradiance

- If ALP Compton wavelength of order black hole size:
  - Bound states around BH nucleus formed
  - Occupation numbers grow exponentially by extracting rotational energy and angular momentum from the ergosphere
  - Forming rotating Bose-Einstein condensate emitting gravitational waves
  - For BH lighter than 10^7 solar masses, accretion can not replenish spin
- Existence of bosonic WISPs leads to gaps in mass vs. spin plots of rapidly rotating BHs

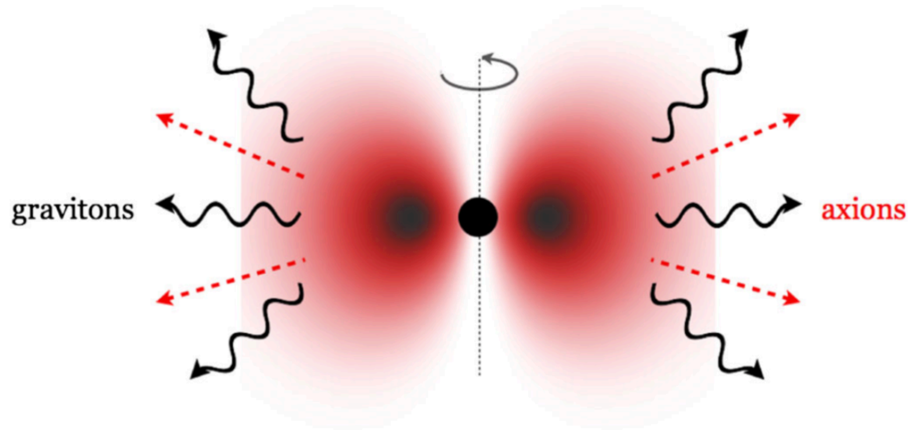



FIG. 1 (color online). *Axionic Black Hole Atom:* The spinning black hole "feeds" superradiant states forming an axion Bose-Einstein condensate. The resulting bosonic atom will emit gravitons through axion transitions between levels and annihilations and will emit axions as a consequence of self-interactions in the axion field.

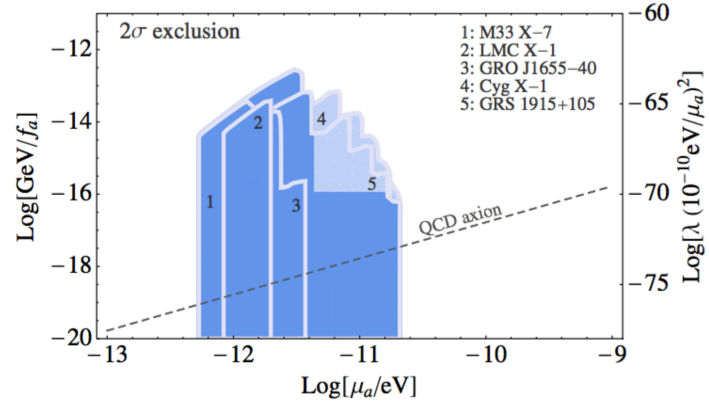
[Arvanitaki,Dimopoulos,Dubovsky,Kaloper,March-Russell 10]

# Axion/ALP bounds from Penrose BH superradiance

- **>** If ALP Compton wavelength of order black hole size:
  - Bound states around BH nucleus formed
  - Occupation numbers grow exponentially by extracting rotational energy and angular momentum from the ergosphere
  - Forming rotating Bose-Einstein condensate emitting gravitational waves
  - For BH lighter than 10^7 solar masses, accretion can not replenish spin
- **>** Existence of bosonic WISPs leads to gaps in mass vs. spin plots of rapidly rotating BHs

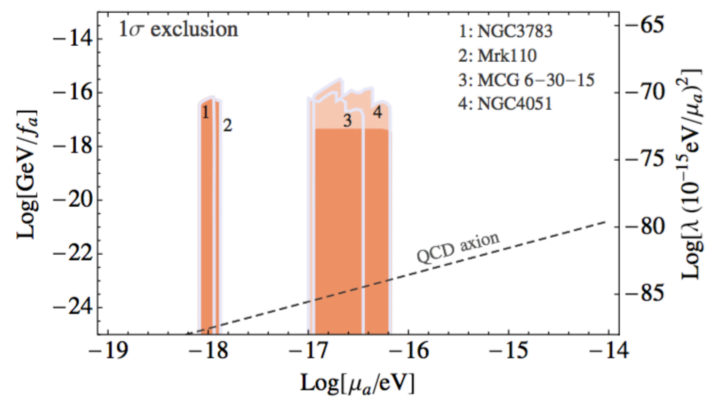
- **>** Stellar BH spin measurements exclude

$$6 \times 10^{-13}\,\mathrm{eV} < m_A < 2 \times 10^{-11}\,\mathrm{eV}$$




(a)

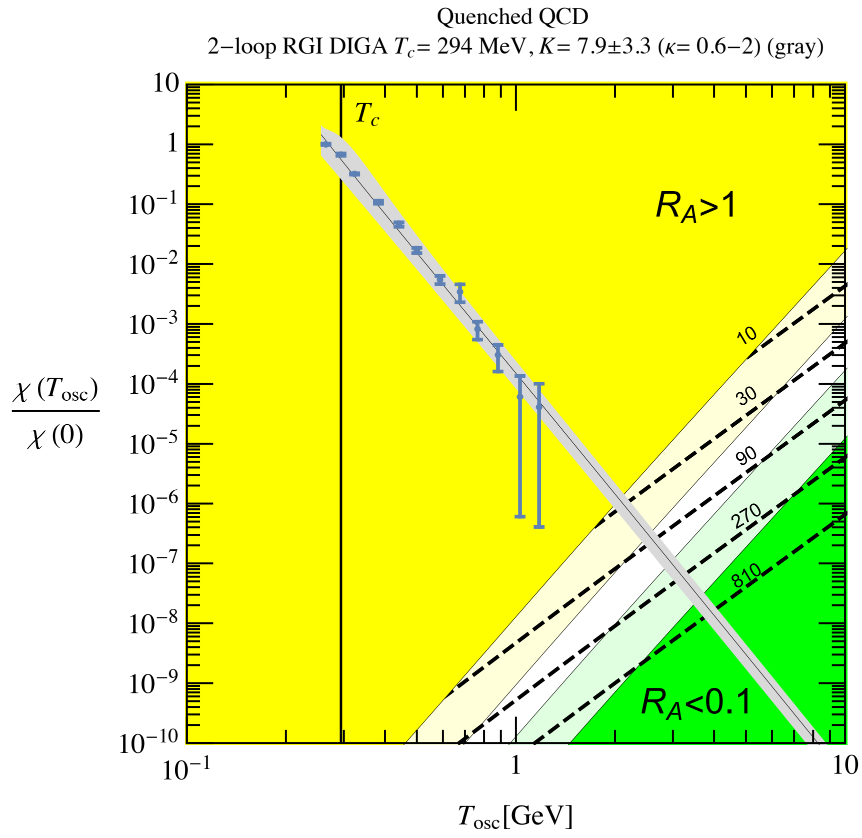
[Arvanitaki et al. 14]

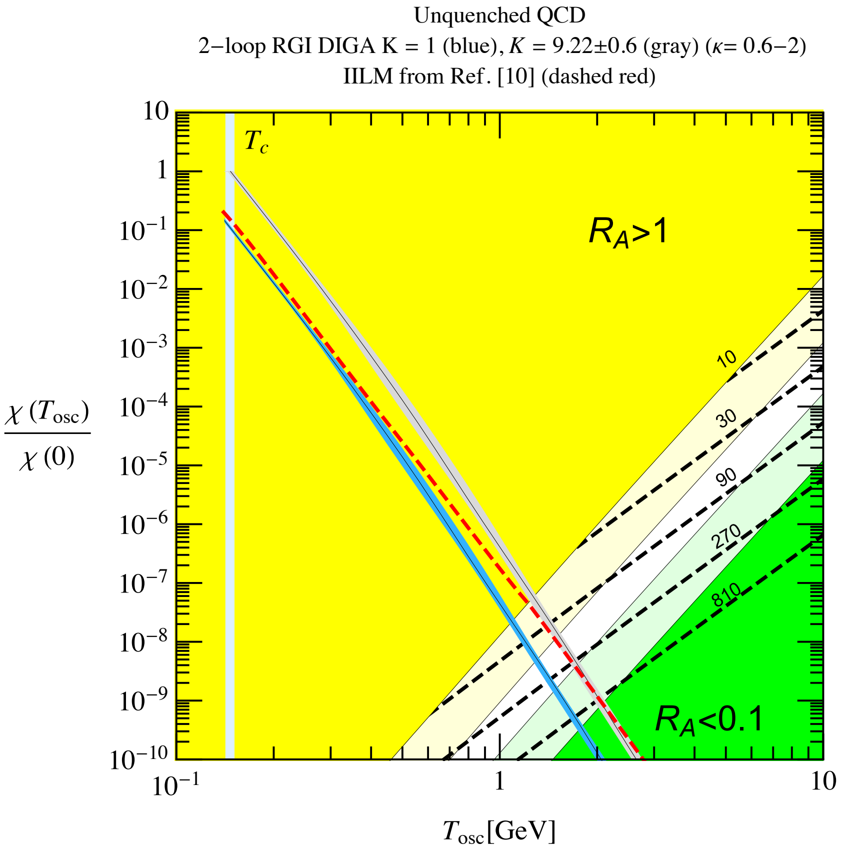



(b)

# Reliability of prediction of axion DM abundance?

- Temperature dependence of axion mass from topological susceptibility:

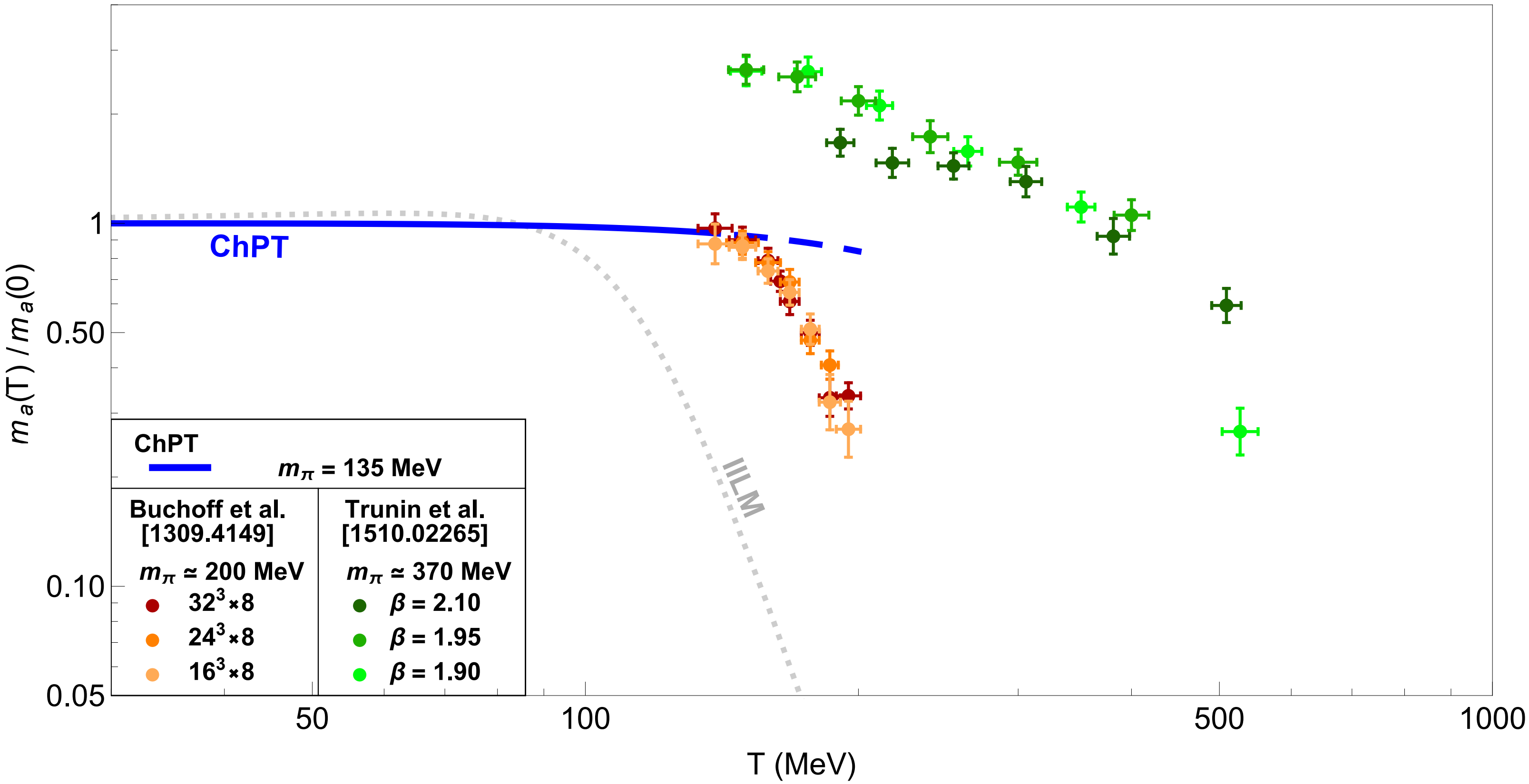



[Borsanyi et al. 15]

# Reliability of prediction of axion DM abundance?

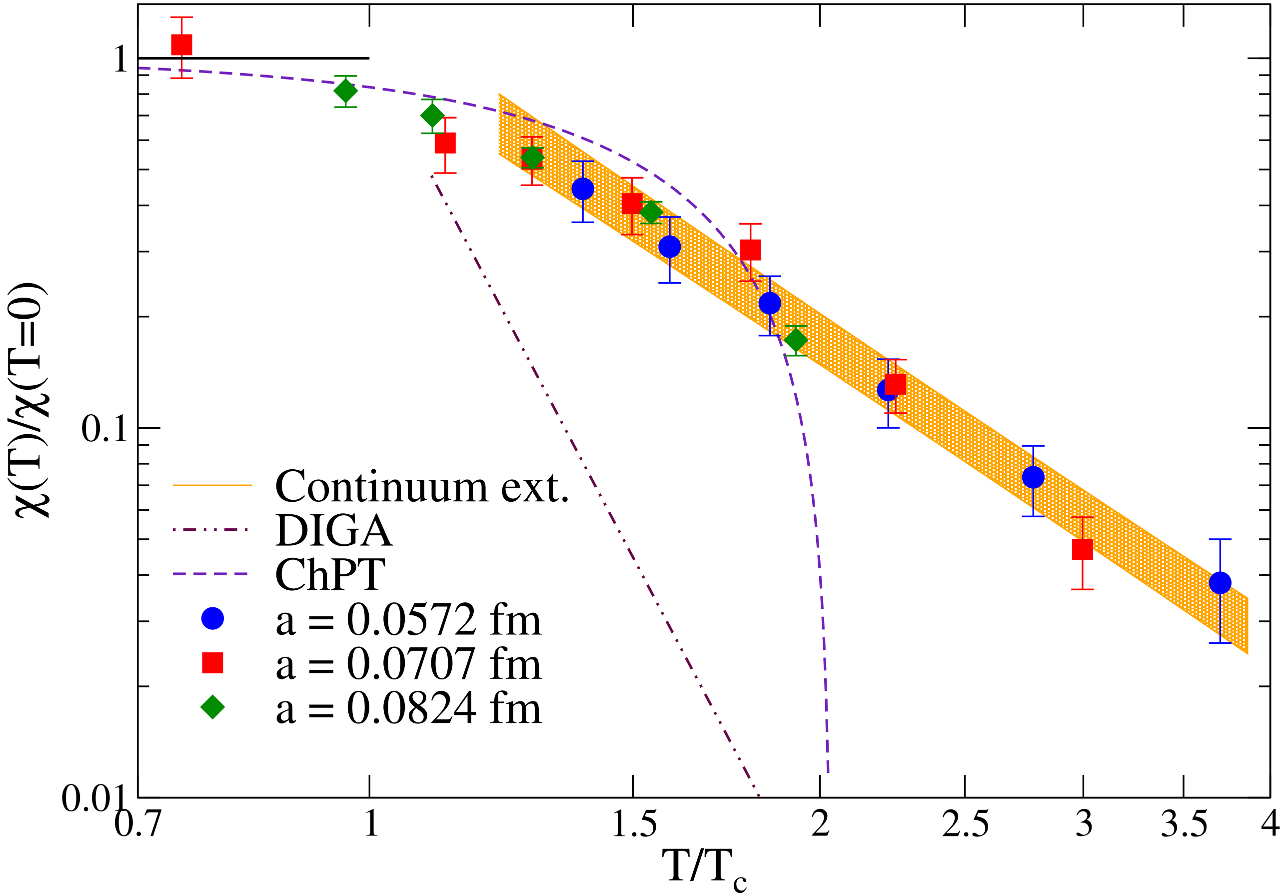
- Full QCD: strong cutoff effects?




[Grilli di Cortona, Hardy, Vega,Villadoro 15]

# Reliability of prediction of axion DM abundance?

> Full QCD: strong cutoff effects?




[Bonati et al. 15]