Science Case for / Physics Goals of ALPS-II.

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for the ALPS Collaboration

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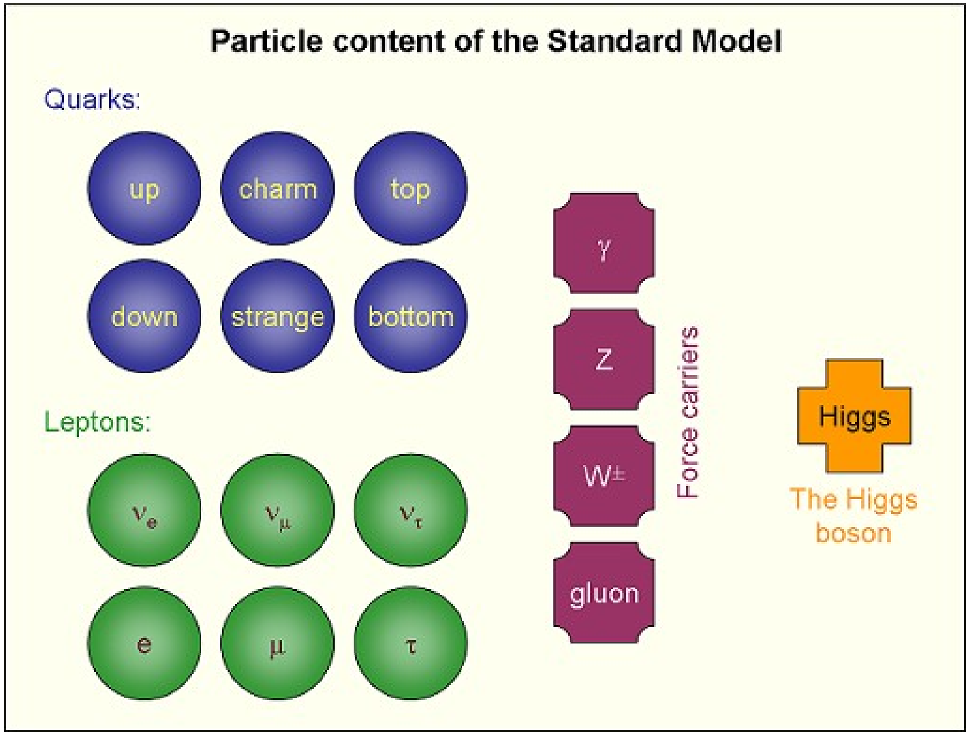
Strong case for particles beyond the Standard Model

- Standard Model (SM) of particle physics describes basic properties of known matter and forces
- SM not a complete and fundamental theory:
  - No satisfactory explanation for values of its many parameters
  - No quantum gravity



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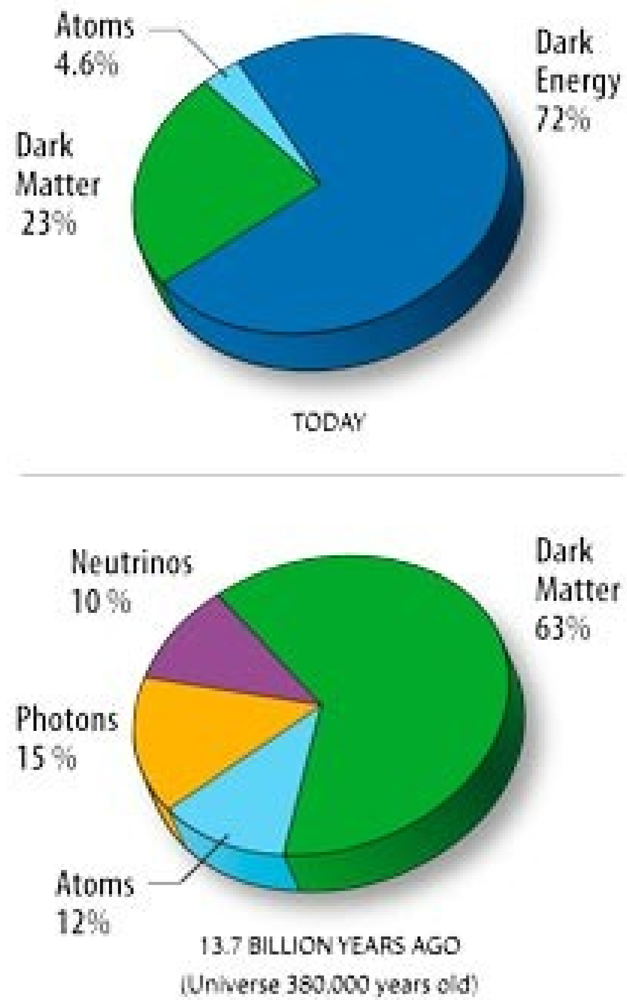

(wikipedia)

Strong case for particles beyond the Standard Model

- Standard Model (SM) of particle physics describes basic properties of known matter and forces
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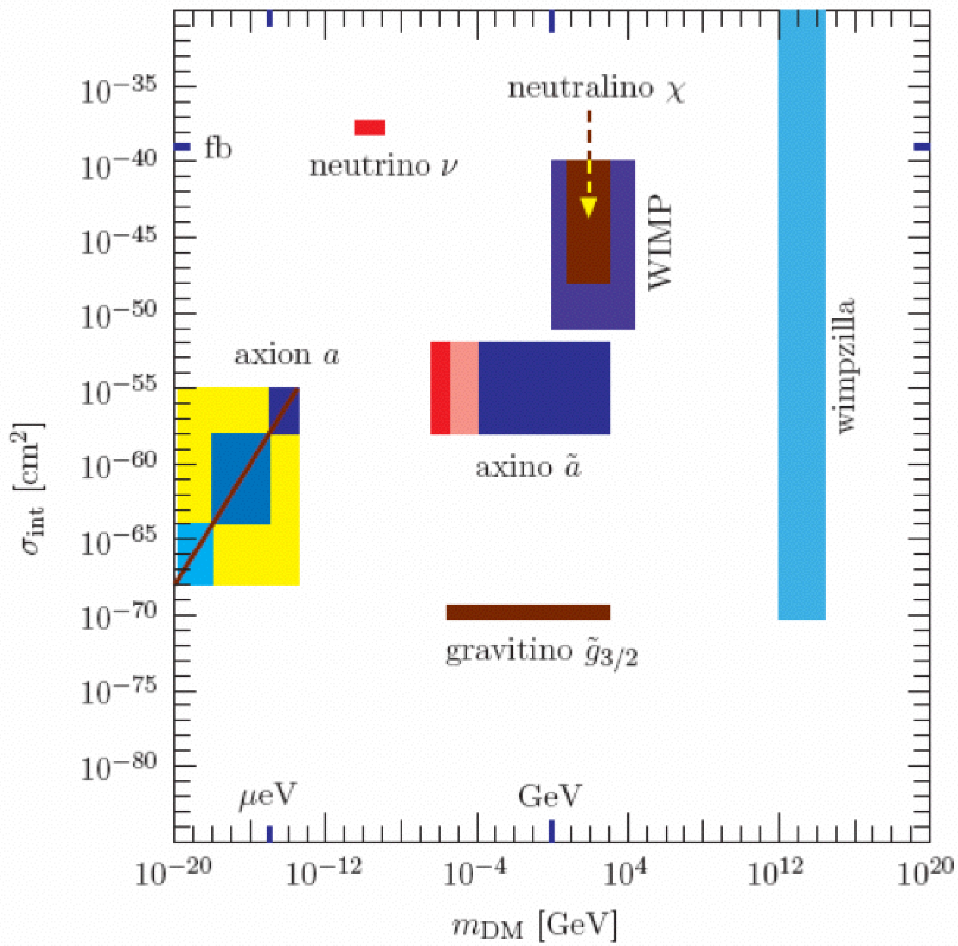
  - No satisfactory explanation for values of its many parameters
  - No quantum gravity
  - No explanation of the origin of dark energy and dark matter
- Leading dark matter candidates:
  - Neutralinos and other Weakly Interacting Massive Particles (WIMPs)
  - Axions and other very Weakly Interacting Slim (=ultra-light) Particles (WISPs)



(Kim,Carosi 10)

Axion and axion-like particles: Theory

> Peccei-Quinn solution of strong CP puzzle: introduce axion field a(x) as dynamical theta parameter, enjoying a shift symmetry, $a \to a + \text{const.}$, broken only by anomalous couplings to gauge fields,

$$\mathcal{L} \supset \frac{1}{2}\,\partial_\mu a\,\partial^\mu a - \frac{\alpha_s}{8\pi}\left(\bar\theta + \frac{a}{f_a}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} C_{a\gamma}\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + \ldots$$

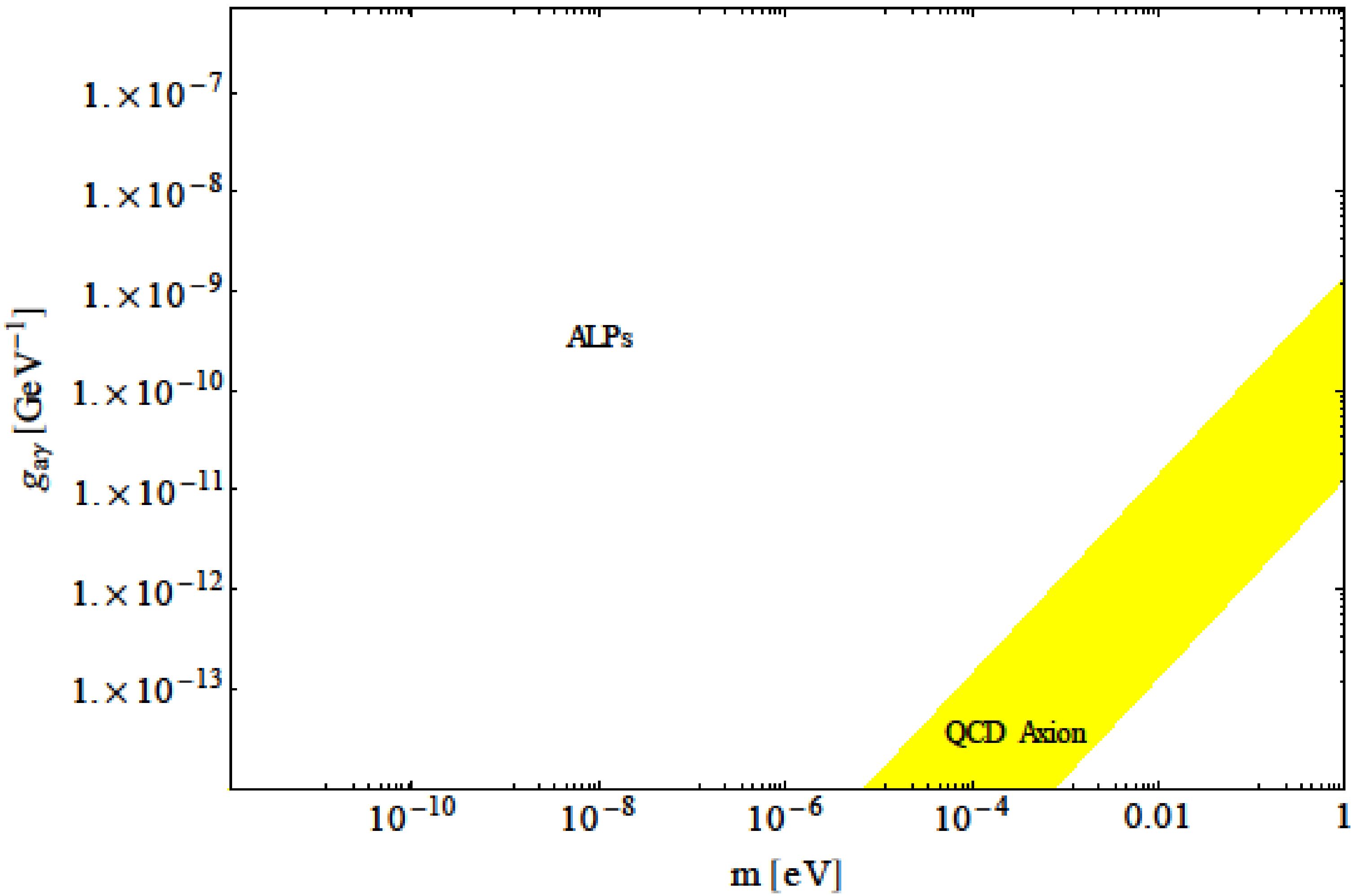
- Effective theta parameter has zero expectation value: no strong CP violation
- Elementary particle excitation of axion field: QCD axion (Weinberg 78; Wilczek 78)
- For large decay constant f_a: prime example of a WISP . . .
  . (Kim 79; Shifman et al 80; Zhitnitsky 80; Dine et al 81)

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(C_{a\gamma} - \frac{2}{3}\,\frac{m_u + 4m_d}{m_u + m_d}\right) \sim 10^{-12}\ \mathrm{GeV}^{-1}\left(\frac{10^9\ \mathrm{GeV}}{f_a}\right)$$

$$m_a = \frac{m_\pi f_\pi}{f_a}\frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\,\mathrm{meV} \times \left(\frac{10^9\ \mathrm{GeV}}{f_a}\right)$$

> Axion-like particles (ALPs) : more axion-like fields $a_i(x)$ with shift symmetry and anomalous couplings to gauge bosons

Axion and axion-like particles: Theory



Axion and axion-like particles: Theory

- In field theoretic extensions of SM, axion and ALP fields realised as phase of complex SM singlet scalar fields whose vacuum expectation values v_i break global anomalous chiral U(1) symmetries

  (Peccei, Quinn 77)

  - At energies much below the symmetry breaking, the low-energy effec-tive field theory is that of (pseudo-)Nambu-Goldstone bosons with decay constants $f_{a_i} \sim v_i$

- In models, in which the global PQ symmetries are not imposed by hand, but in which they appear as automatic consequences of local gauge in-variance, renormalisability and pattern of gauge symmetry breakdown:

  . (Georgi, Hall, Wise 81)

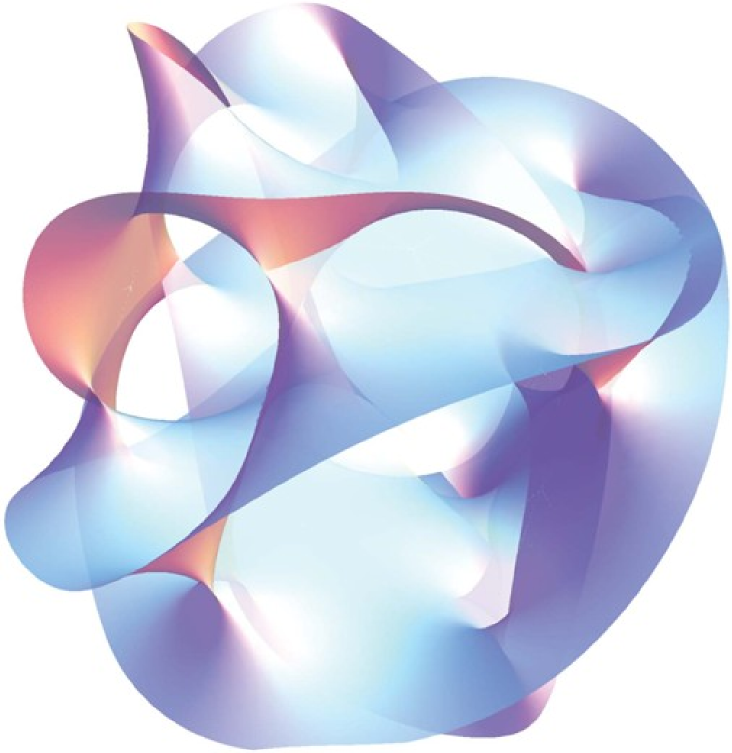
$$f_{a_i} \sim v_i \sim \text{ scale of gauge symmetry breaking}$$

- Big range of possibilities discussed in literature:

$$f_{a_i} \sim v_i \sim 10^{7 \div 16}\,\mathrm{GeV} \Rightarrow g_{i\gamma} \sim 10^{-19} \div 10^{-10}\ \mathrm{GeV}^{-1}$$

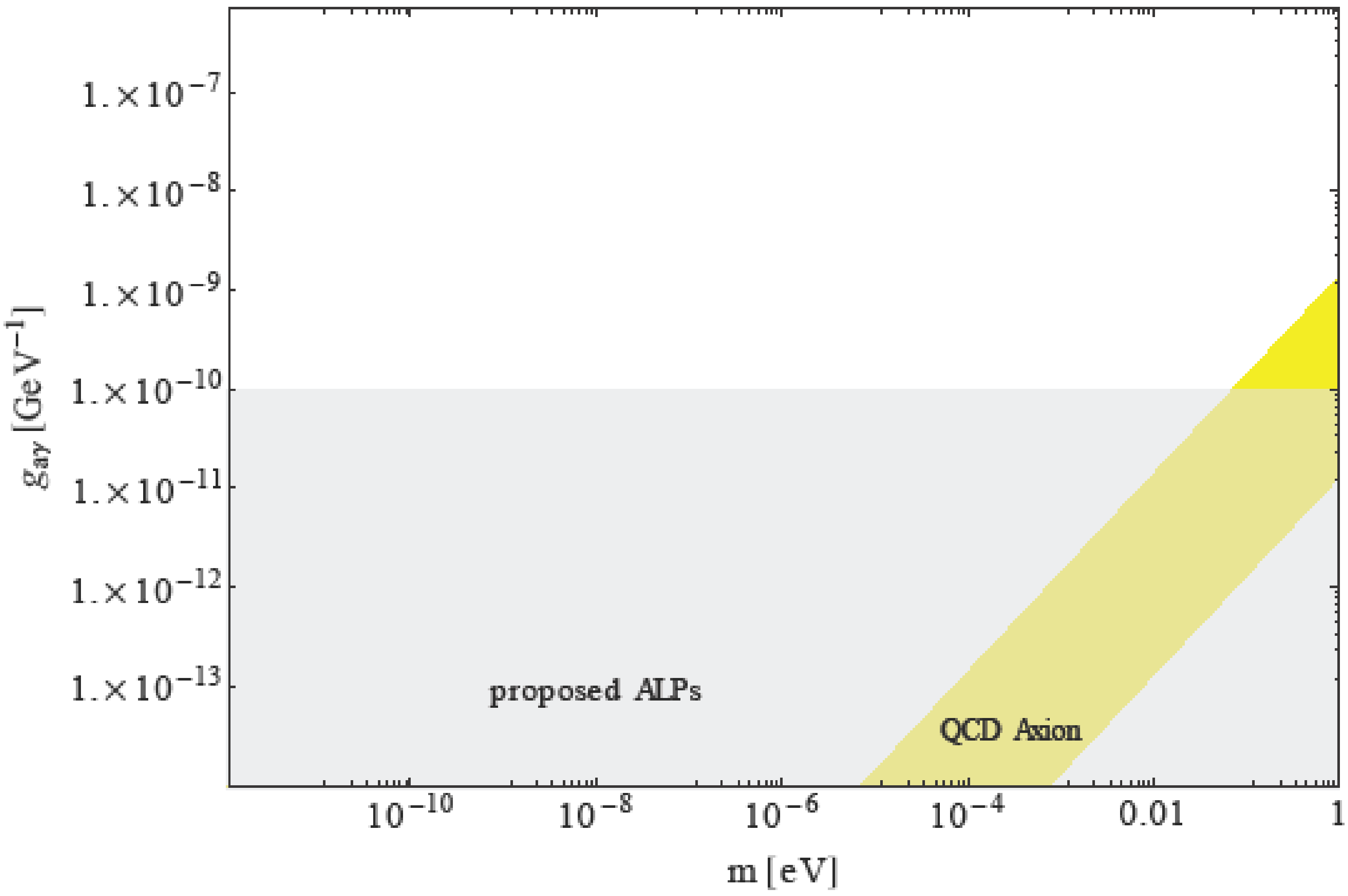
Axion and axion-like particles: Theory

- Particular strong motivation for the existence of the axion and ALPs comes from string theory
- Low-energy effective field theory emerging from string theory predicts natural candidates for the QCD axion, often even an \`axiverse´, containing many additional ALPs
(Witten 84; Conlon 06; Svrcek, Witten 06; Arvanitaki et al 09; Acharya et al 10; Cicoli,Goodsell,AR 12)
- Number of ALPs = number of cycles of extra-dimensional manifold
- Big range of possibilities, since its volume $\mathcal{V}$ can take a range of values:



$$f_{a_i} \sim M_s \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{8\div 18}\ \mathrm{GeV} \Rightarrow g_{i\gamma} \sim 10^{-21} \div 10^{-11}\ \mathrm{GeV}^{-1}$$

Axion and axion-like particles: Theory

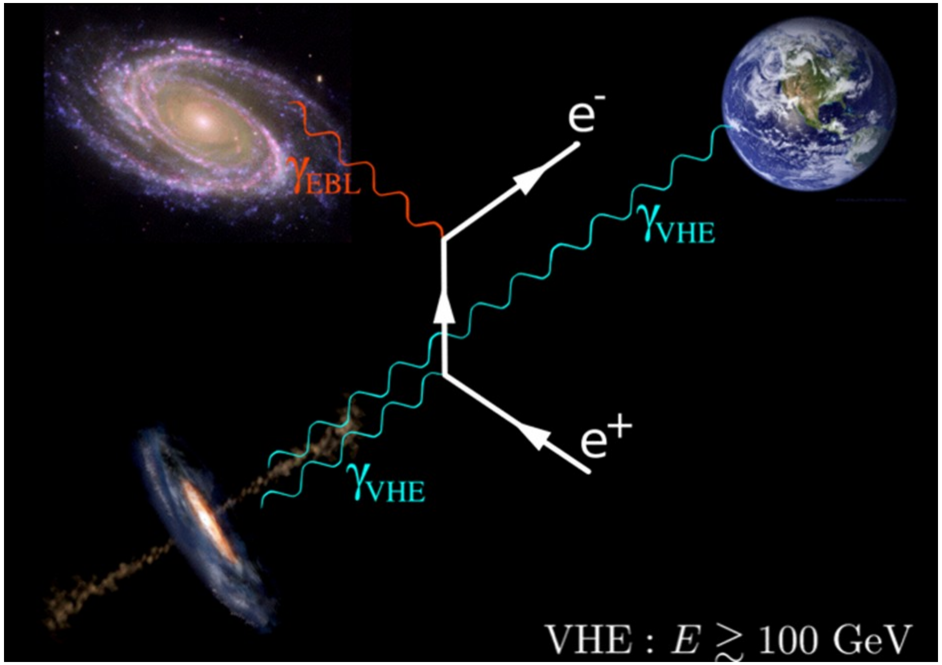


Axion and axion-like particles: Astrophysics

- Strong bounds on axions/ALPs come from their effects on stellar evolution and on the propagation of SM particles through astrophysical environments: (Raffelt 96)
  - Non-observation of an anomalous energy loss of Horizontal Branch (HB) stars due to ALP emission:
  $$g_{i\gamma} \lesssim 10^{-10}\ \mathrm{GeV}^{-1}, \qquad m_{a_i} \lesssim \mathrm{keV}$$
  - Absense of a gamma-ray burst due to axion/ALP-photon conversion in coincidence with neutrinos from SN 1987A: (Brockway et al 96; Grifols et al 96)
  $$g_{i\gamma} \lesssim 10^{-11}\ \mathrm{GeV}^{-1}, \qquad m_{a_i} \lesssim 10^{-9}\ \mathrm{eV}$$
- Just behind the boundary of current bounds, there are intriguing hints suggesting existence of axions and ALPs (Isern et al 08;12)
  - Evidence for a non-standard energy loss in white dwarfs, consistent with the existence of a sub keV mass axion or ALP with
  $$\frac{1}{2}\frac{C_{ie}}{f_{a_i}}\bar{e}\gamma^{\mu}\gamma_5 e\,\partial_{\mu}a_i; \qquad \frac{f_{a_i}}{C_{ie}} = (0.7 \div 2.6)\times 10^{9}\,\mathrm{GeV}$$

Axion and axion-like particles: Astrophysics

- TeV photons from distant Active Galactic Nuclei (AGN) should show absorption features due to e+e- pair production at the Extragalactic Background Light (EBL)



Axion and axion-like particles: Astrophysics

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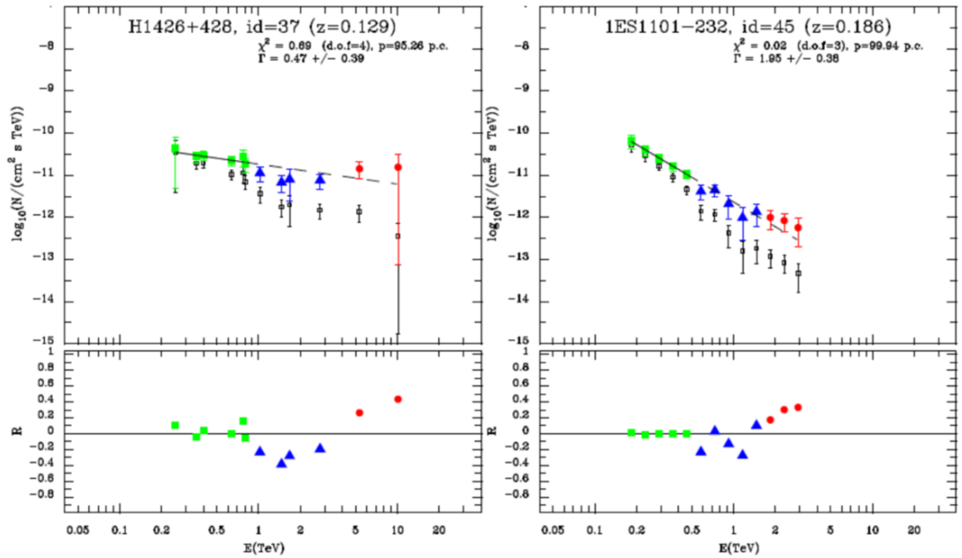
- Not the case: (e.g. Horns,Meyer)
  - Analysis of 50 spectra (HESS, MAGIC, Veritas): minimal EBL, absorption excluded by more than 4 sigma



(Horns,Meyer 12)

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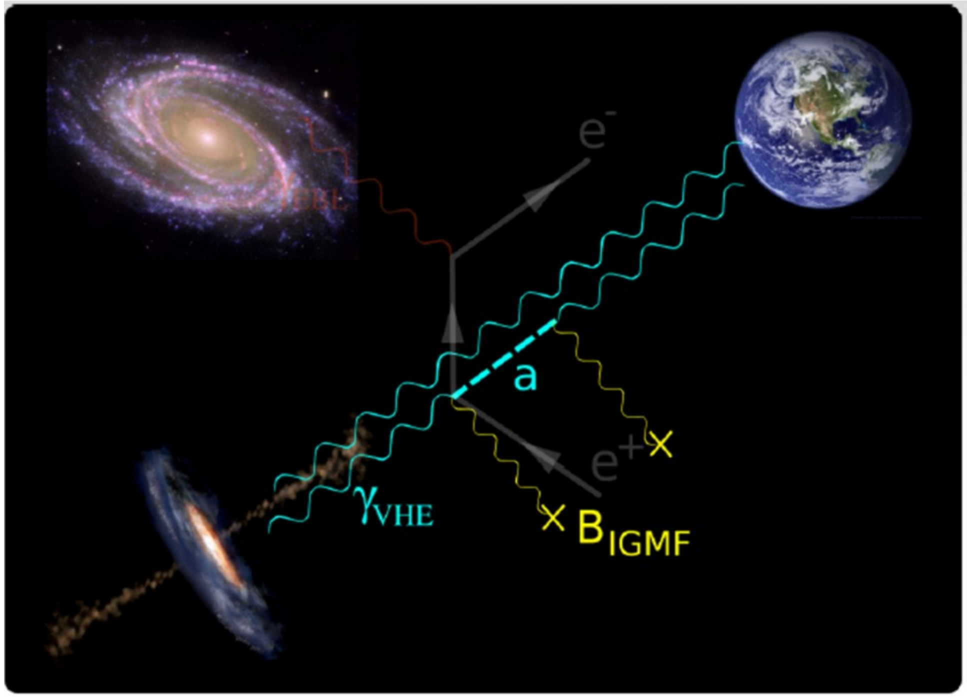
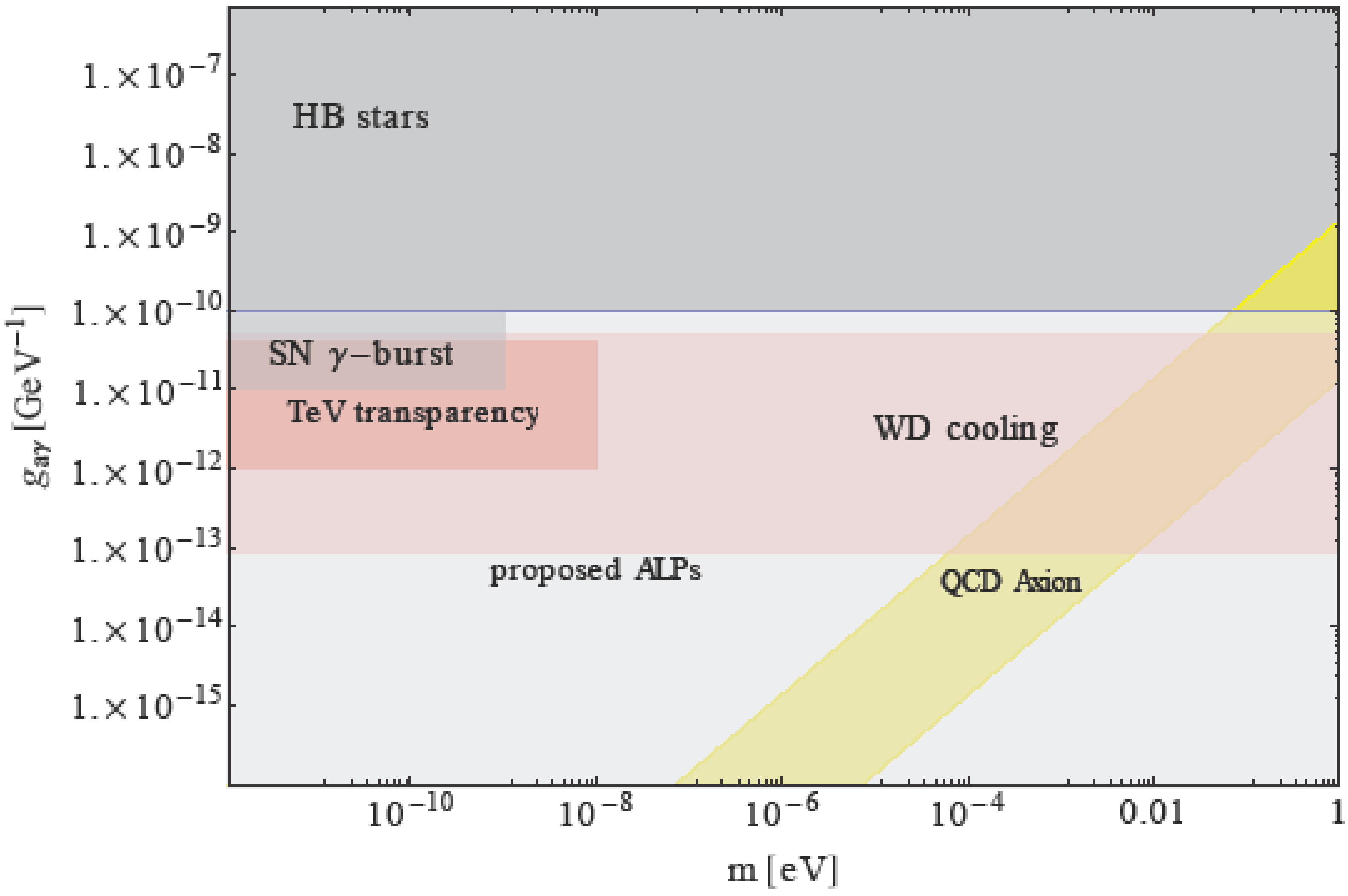
  - Analysis of 50 spectra (HESS, MAGIC, Veritas): minimal EBL, absorption excluded by more than 4 sigma
- Possible explanation in terms of photon <-> ALP conversions in astrophysical magnetic fields (Roncadelli et al 07; Simet et al 08; Sanchez-Conde et al 09; Horns et al 12)



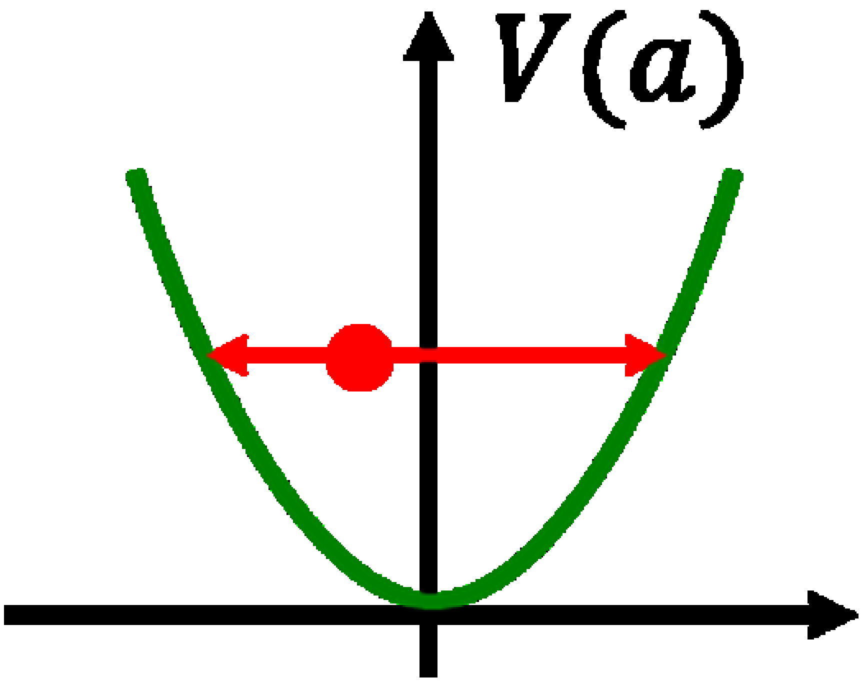
$$g_{i\gamma} \sim 10^{-11}\ \mathrm{GeV}^{-1}, \qquad m_{a_i} \lesssim 10^{-8}\ \mathrm{eV}$$

Axion and axion-like particles: Astrophysics



Axion and axion-like particles: Dark matter

- Axions and other bosonic WISPy cold dark matter may be produced non-thermally via vacuum-realignment in form of classical, spatially coherent oscillating fields = coherent state of extremely non-relativistic dark matter (Preskill et al 83; Abbott,Sikivie 83; Dine,Fischler 83; Cadamuro et al 12)



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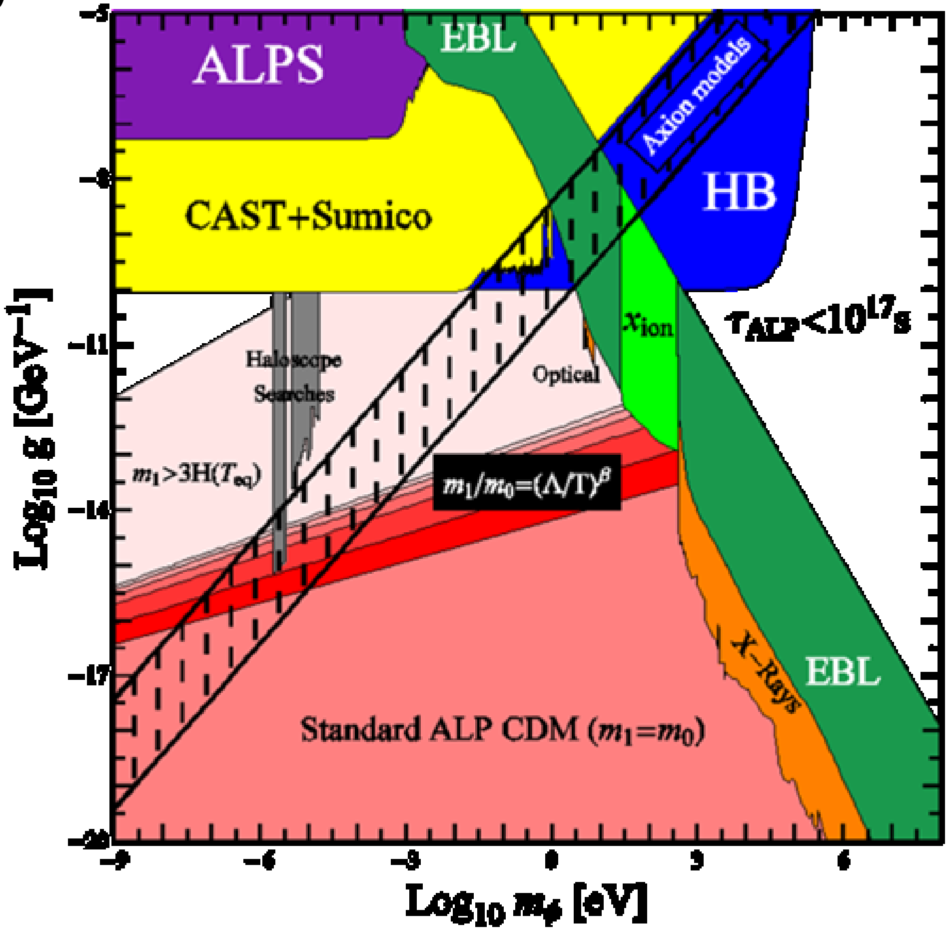
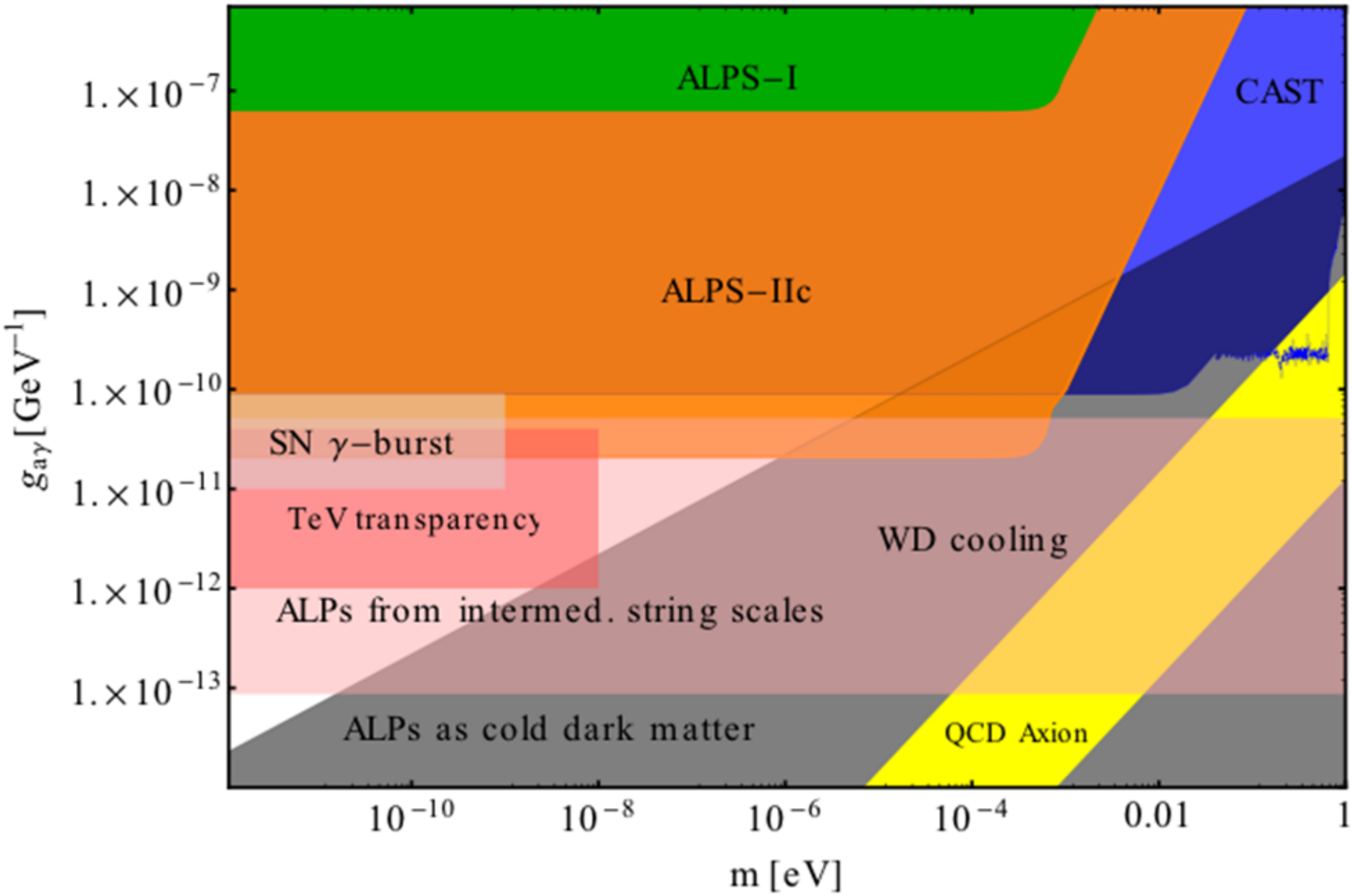
  - Axion (ALPs) can contribute significantly to cold dark matter for $f_a \gtrsim 10^{10}\,\mathrm{GeV}$ (a wider range of parameters)
- Axion or ALP cold dark matter may form rethermalising Bose Einstein Condensate (BEC) (Sikivie,Yang 09; Erken et al. 12; Sikivie 12)
  - Observational evidence for caustic rings of dark matter consistent with BEC, but not with WIMPy dark matter



(Cadamuro et al. 12)

Axion and axion-like particles: Goals of ALPS-IIc

- Chart thus-far unexplored parameter space, surpassing, at low masses, even the limits from the CERN Axion Solar Telescope (CAST)
- Tackle regions which are favored by astrophysical hints, dark matter, and theory



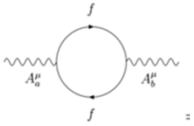
Hidden photons: Theory

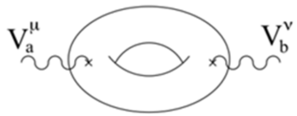
- Most extensions of standard model based on supergravity or superstrings predict "hidden sector" of particles which are very weakly coupled to the "visible sector" standard model particles

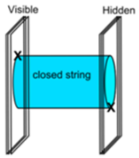
- Hidden-sector Abelian gauge bosons (hidden photons) provide a window to the hidden sector since they can mix kinetically with the visible sector hypercharge U(1) gauge boson,

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\chi}{2}F_{\mu\nu}X^{\mu\nu} + \frac{m_{\gamma'}{}^2}{2}X_\mu X^\mu$$

- Kinetic mixing generated at loop level via messenger exchange (Holdom 86; Dienes et al 97; Abel et al 08; Goodsell et al 09;12; Cicoli et al 11)



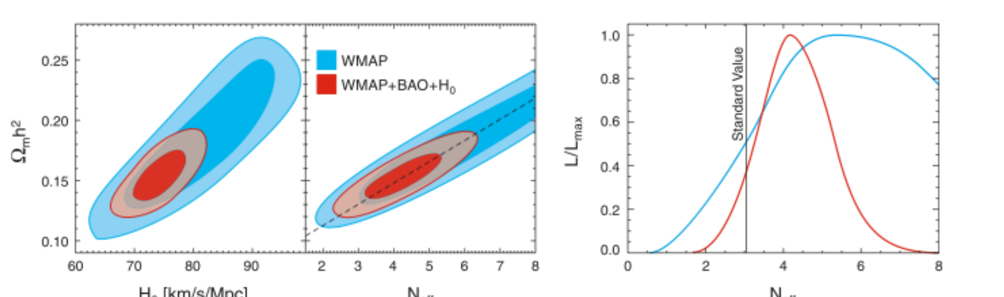




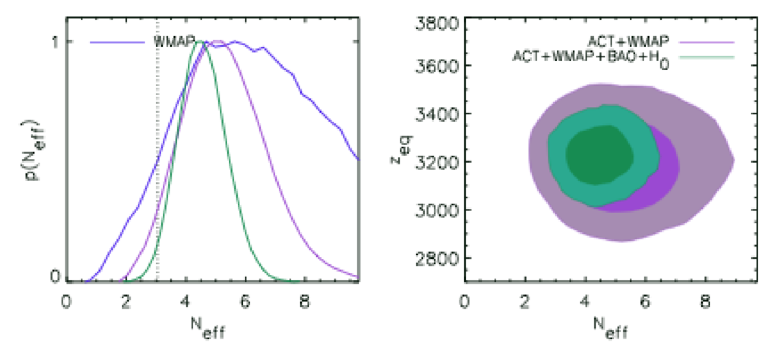
$$10^{-12} \lesssim \chi \sim \frac{e g_h}{16\pi^2} C \lesssim 10^{-3}$$

Hidden photons: Dark radiation

- For meV scale masses, photon <-> hidden photon oscillations occur resonantly after big bang nucleosynthesis, producing a hidden cosmic microwave background, leading to an increase of the cosmic energy density in invisible radiation at decoupling (dark radiation), often quoted as the effective number of neutrino species (Jaeckel,Redondo,AR 08)
- CMB observations seem to favour extra dark radiation:
  (Komatsu et al [WMAP] 10; Dunkley et al [Acatama Cosmology Telescope Collaboration] 10)



[WMAP 7-year Cosmological Interpretation]



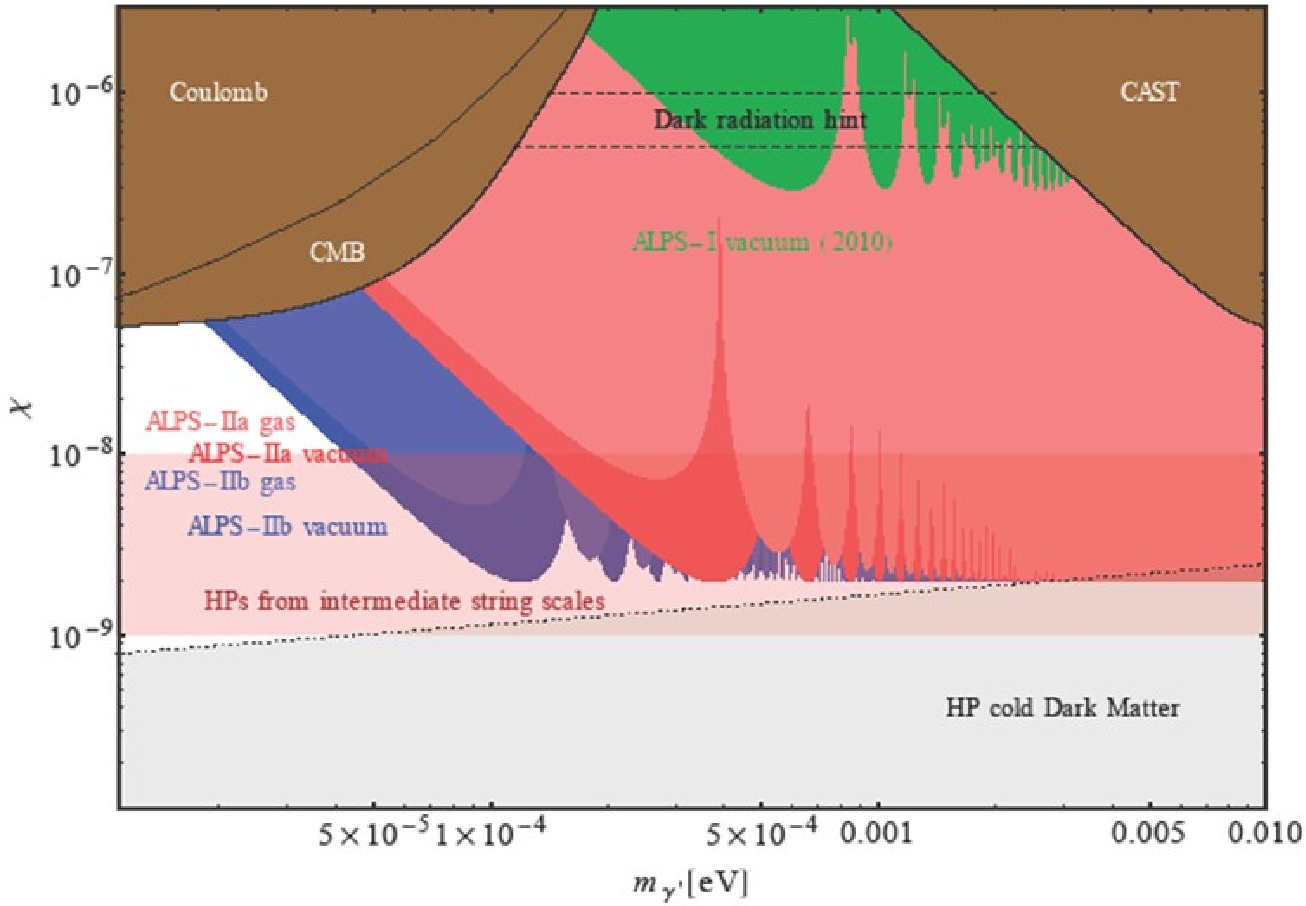
[Atacama Cosmology Telescope:

- Required parameters:

$$\chi \sim 10^{-6}; \qquad m_{\gamma'} \sim \mathrm{meV}$$

Hidden photons: Goals of ALPS-IIa/IIb

- Conclusive test of hidden photon dark radiation hypothesis
- Probe parameter region predicted in intermediate string scale scenarios
- Tackle a fraction of hidden photon dark matter parameter space

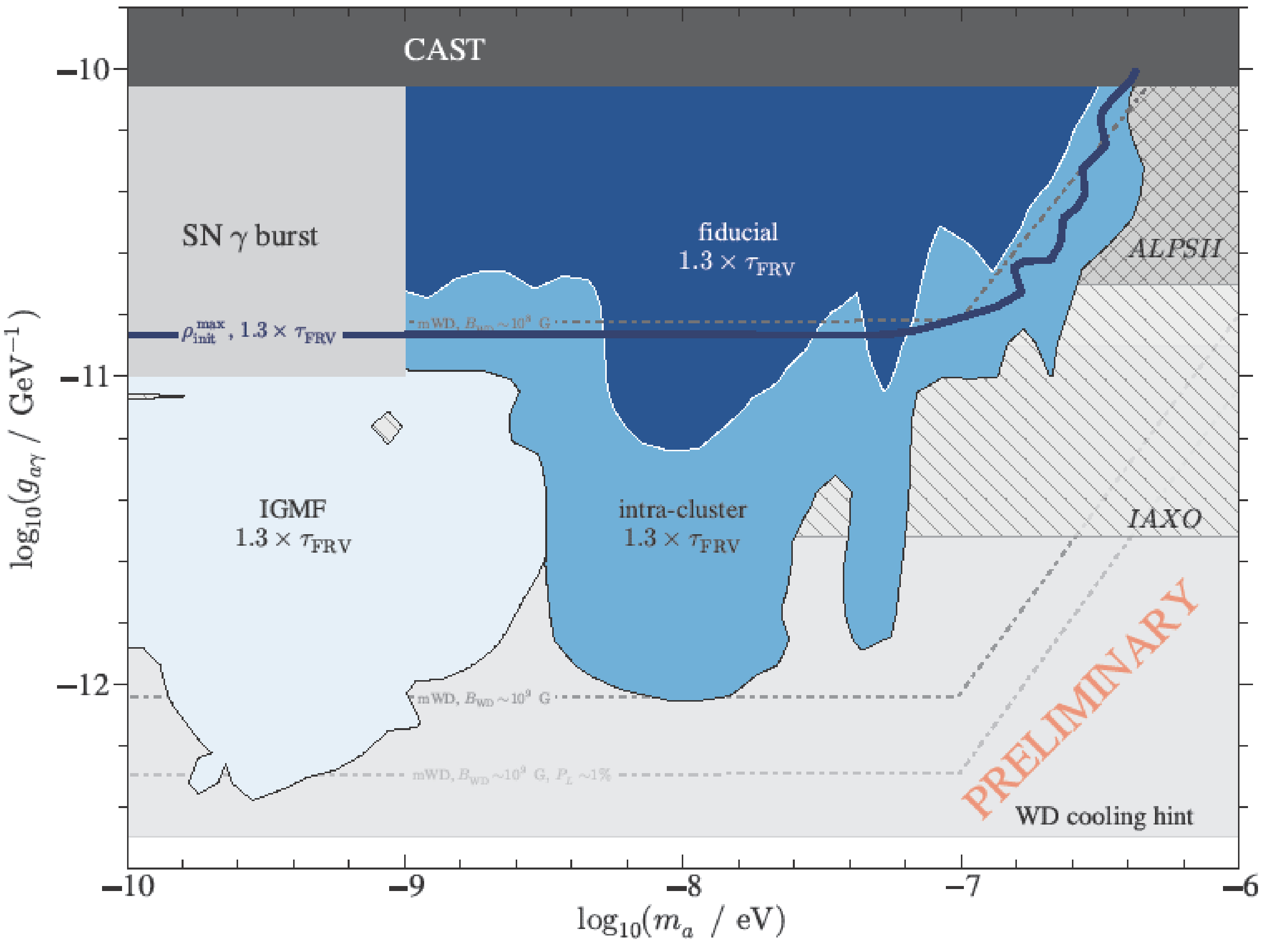


Summary

- Strong physics case for WISPs from theory:
  - Solution of strong CP problem gives particularly strong motivation for existence of QCD axion
  - In many UV completions of SM with a QCD axion, there occur also ALPs
  - Hidden sectors are often exploited in supersymmetric extensions of the SM. In these sectors, hidden photons are very well motivated WISP candidates providing a window to the hidden sector.
- ALPs and hidden photons can solve puzzles in astrophysics and cosmology:
  - Anomalous energy loss of white dwarfs
  - Anomalous transparency of the universe for TeV photons
  - Extra dark radiation
  - WISPy dark matter
- ALPS-II can tackle corresponding regions in WISPy parameter space!

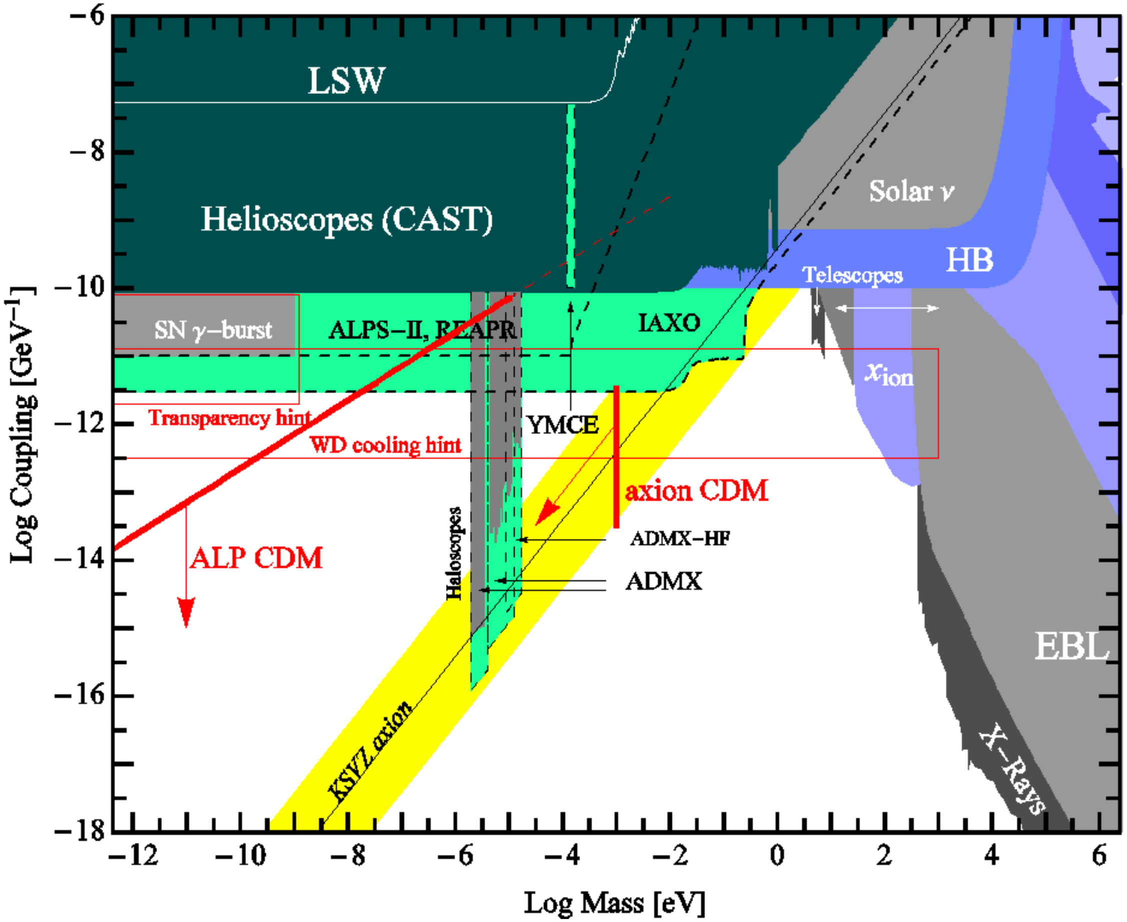
Backup

- Study on ALP explanation of TeV transparency in progress (Horns,Meyer): ALPS-II covers fiducial region



Backup

> Projected axion/ALP sensitivities of other experiments:



(Hewett et al 12)

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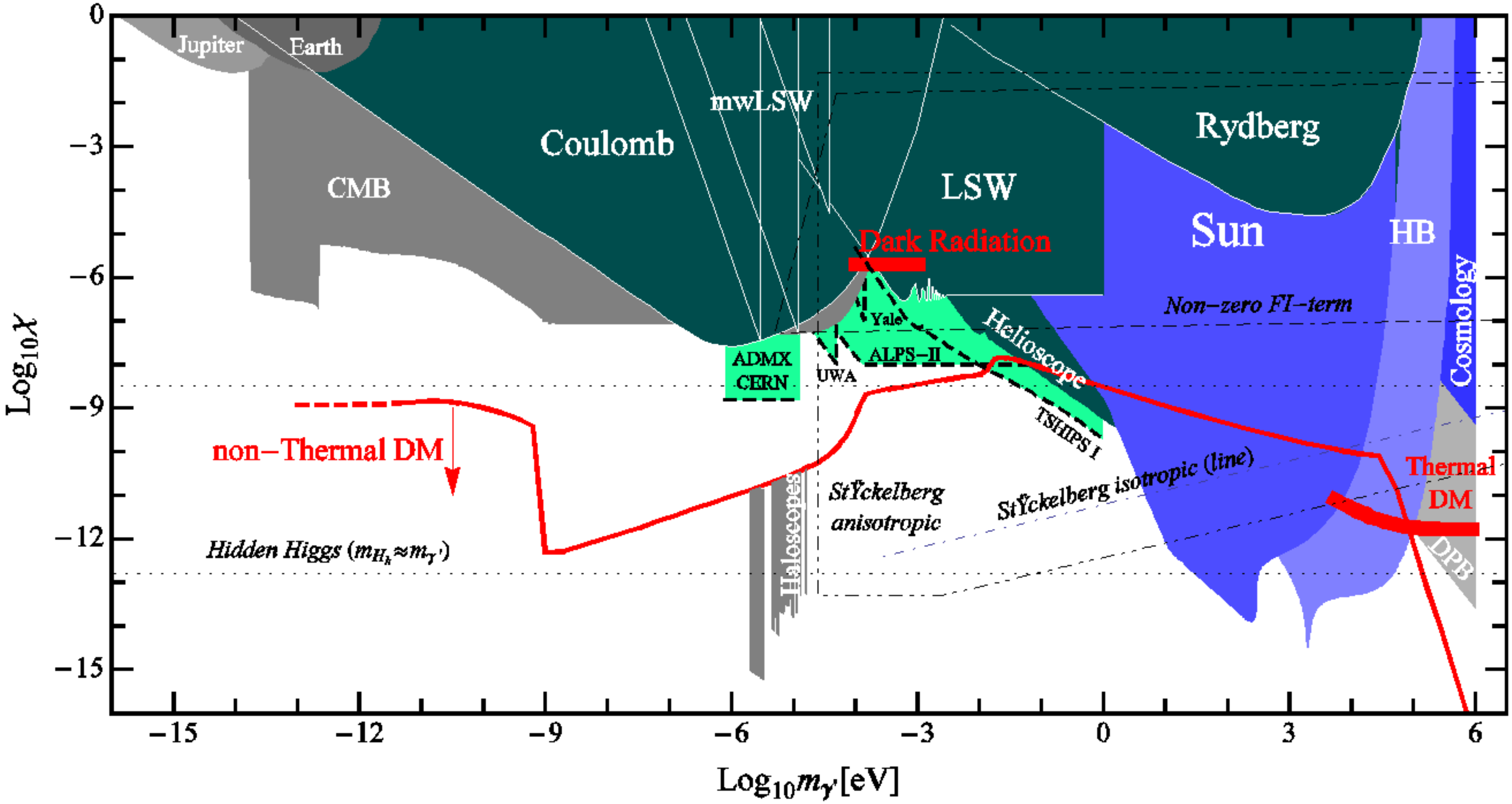

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