Exploring the Dark Sector by Terrestrial Searches for Axions and Other WISPs.

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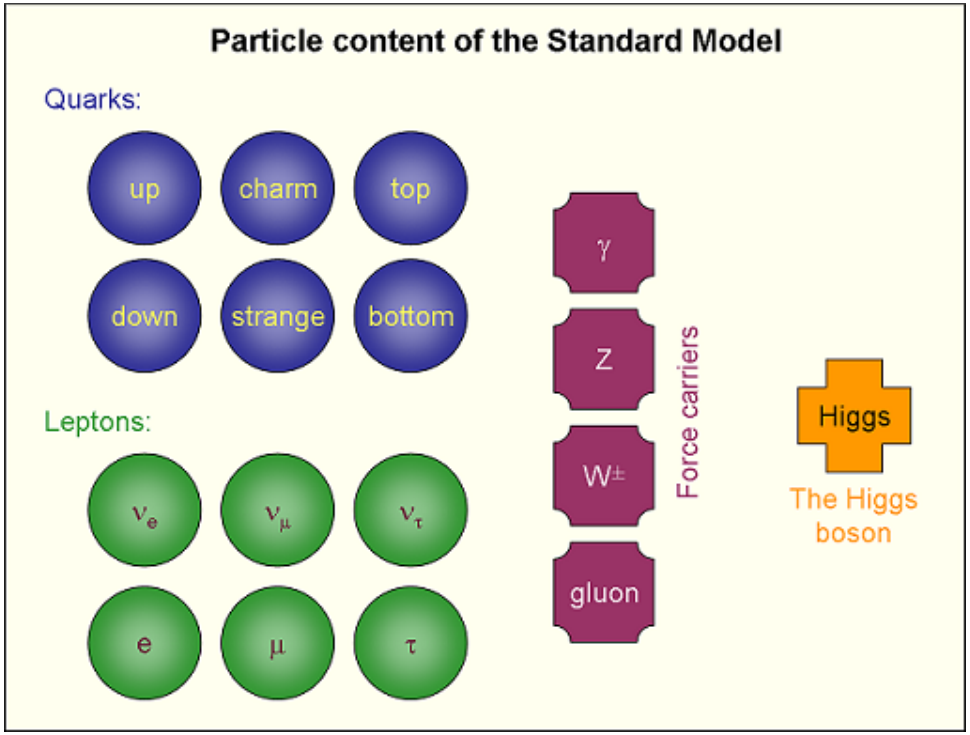
HELMHOLTZ ASSOCIATION

DESY

Strong case for particles beyond the Standard Model

- Standard Model (SM) of particle physics describes basic properties of known matter and forces



Strong case for particles beyond the Standard Model

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$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Dirac} + \mathcal{L}_{\rm mass} + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm gauge/\psi} \,. \tag{1}$$

Here,

$$\mathcal{L}_{\rm Dirac} = i\bar{e}^i_{\rm L}\partial\!\!\!/ e^i_{\rm L} + i\bar{\nu}^i_{\rm L}\partial\!\!\!/ \nu^i_{\rm L} + i\bar{e}^i_{\rm R}\partial\!\!\!/ e^i_{\rm R} + i\bar{u}^i_{\rm L}\partial\!\!\!/ u^i_{\rm L} + i\bar{d}^i_{\rm L}\partial\!\!\!/ d^i_{\rm L} + i\bar{u}^i_{\rm R}\partial\!\!\!/ u^i_{\rm R} + i\bar{d}^i_{\rm R}\partial\!\!\!/ d^i_{\rm R} \,; \tag{2}$$

$$\mathcal{L}_{\rm mass} = -v\left(\lambda^i_e\bar{e}^i_{\rm L}e^i_{\rm R} + \lambda^i_u\bar{u}^i_{\rm L}u^i_{\rm R} + \lambda^i_d\bar{d}^i_{\rm L}d^i_{\rm R} + {\rm h.c.}\right) - M_W^2 W^+_\mu W^{-\mu} - \frac{M_W^2}{2\cos^2\theta_W} Z_\mu Z^\mu \,; \tag{3}$$

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}(G^a_{\mu\nu})^2 - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \mathcal{L}_{WZA} \,, \tag{4}$$

where

$$\begin{aligned} G^a_{\mu\nu} &= \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_3 f^{abc} A^b_\mu A^c_\nu \\ W^\pm_{\mu\nu} &= \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu \\ Z_{\mu\nu} &= \partial_\mu Z_\nu - \partial_\nu Z_\mu \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu \,, \end{aligned} \tag{5}$$

and

$$\begin{aligned} \mathcal{L}_{WZA} = \; & ig_2\cos\theta_{\rm W}\left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu Z^\nu + W^+_{\mu\nu}W^{-\mu}Z^\nu - W^-_{\mu\nu}W^{+\mu}Z^\nu\right] \\ & + ie\left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu A^\nu + W^+_{\mu\nu}W^{-\mu}A^\nu - W^-_{\mu\nu}W^{+\mu}A^\nu\right] \\ & + g_2^2\cos^2\theta_{\rm W}\left(W^+_\mu W^-_\nu Z^\mu Z^\nu - W^+_\mu W^{-\mu}Z_\nu Z^\nu\right) \\ & + g_2^2\left(W^+_\mu W^-_\nu A^\mu A^\nu - W^+_\mu W^{-\mu}A_\nu A^\nu\right) \\ & + g_2 e\cos\theta_{\rm W}\left[W^+_\mu W^-_\nu\left(Z^\mu A^\nu + Z^\nu A^\mu\right) - 2W^+_\mu W^{-\mu}Z_\nu A^\nu\right] \\ & + \frac{1}{2}g_2^2\left(W^+_\mu W^-_\nu\right)\left(W^{+\mu}W^{-\nu} - W^{+\nu}W^{-\mu}\right) \,; \end{aligned} \tag{6}$$

and

$$\mathcal{L}_{\rm gauge/\psi} = -g_3 A^a_\mu J^{\mu a}_{(3)} - g_2\left(W^+_\mu J^\mu_{W^+} + W^-_\mu J^\mu_{W^-} + Z_\mu J^\mu_Z\right) - eA_\mu J^\mu_A \,, \tag{7}$$

where

$$\begin{aligned} J^{\mu a}_{(3)} &= \bar{u}^i\gamma^\mu T^a_{(3)}u^i + \bar{d}^i\gamma^\mu T^a_{(3)}d^i \\ J^\mu_{W^+} &= \frac{1}{\sqrt{2}}\left(\bar{\nu}^i_{\rm L}\gamma^\mu e^i_{\rm L} + V^{ij}\bar{u}^i_{\rm L}\gamma^\mu d^j_{\rm L}\right) \\ J^\mu_{W^-} &= (J^\mu_{W^+})^* \\ J^\mu_Z &= \frac{1}{\cos\theta_{\rm W}}\left[\frac{1}{2}\bar{\nu}^i_{\rm L}\gamma^\mu\nu^i_{\rm L} + \left(-\frac{1}{2} + \sin^2\theta_{\rm W}\right)\bar{e}^i_{\rm L}\gamma^\mu e^i_{\rm L} + (\sin^2\theta_{\rm W})\bar{e}^i_{\rm R}\gamma^\mu e^i_{\rm R}\right. \\ & \quad + \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm L}\gamma^\mu u^i_{\rm L} + \left(-\frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm R}\gamma^\mu u^i_{\rm R} \\ & \quad \left. + \left(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm L}\gamma^\mu d^i_{\rm L} + \left(\frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm R}\gamma^\mu d^i_{\rm R}\right] \\ J^\mu_A &= (-1)\bar{e}^i\gamma^\mu e^i + \left(\frac{2}{3}\right)\bar{u}^i\gamma^\mu u^i + \left(-\frac{1}{3}\right)\bar{d}^i\gamma^\mu d^i \,. \end{aligned} \tag{8}$$

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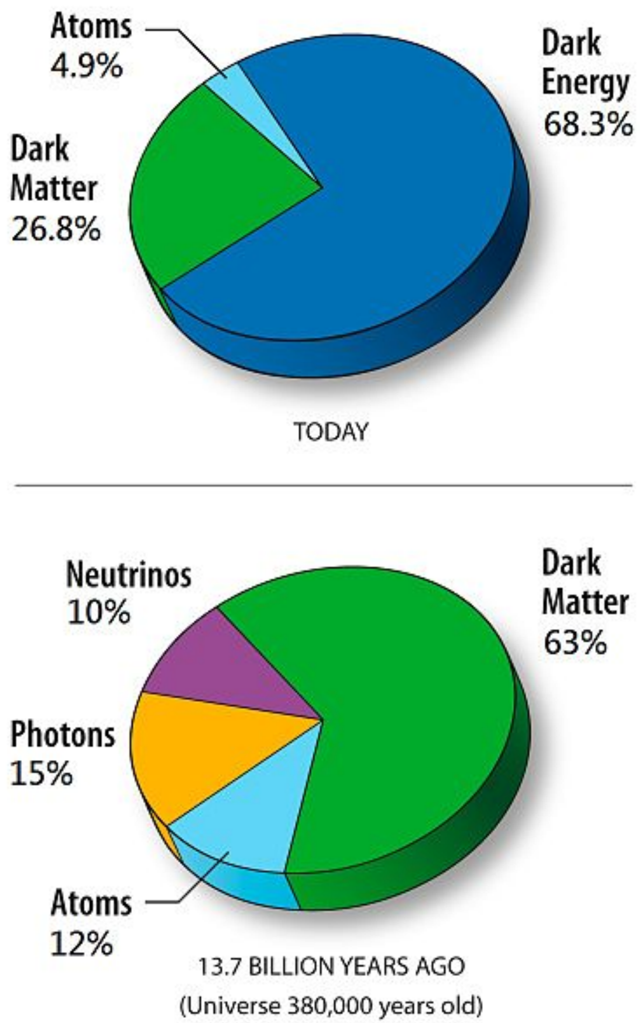
  - No explanation of the origin of the dark sector of the universe



[wikipedia]

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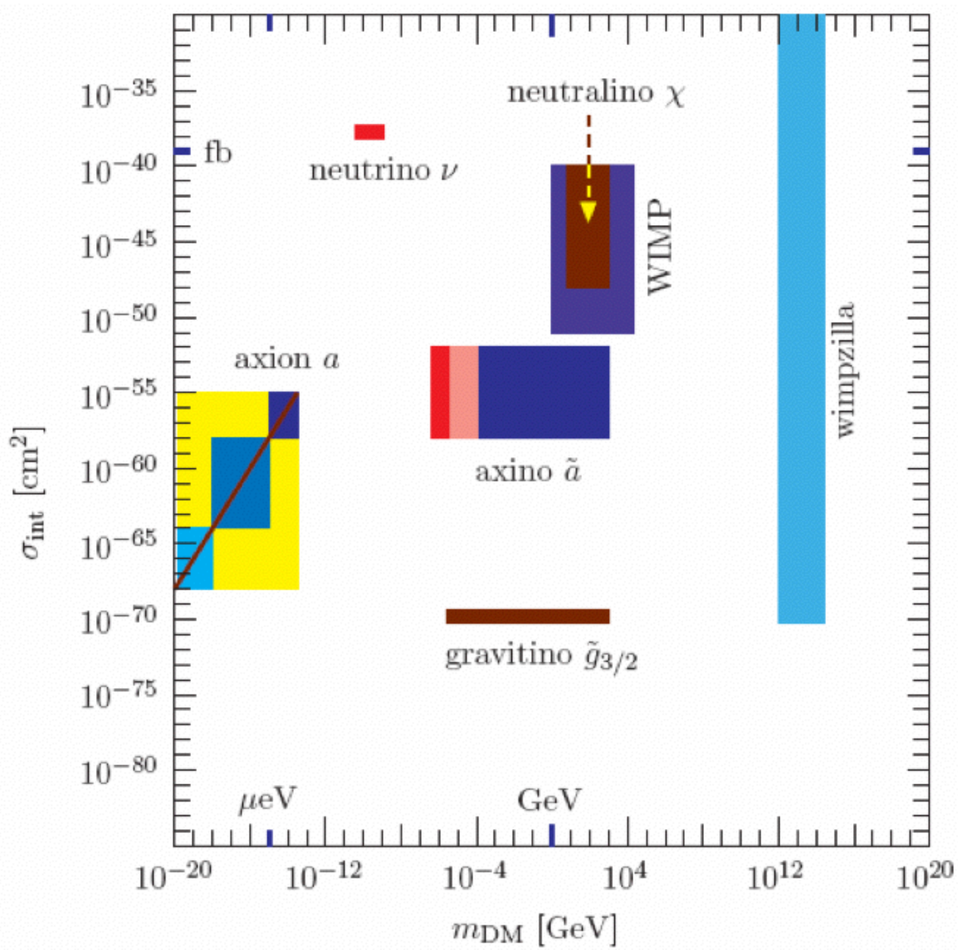
- Well-motivated SM extensions provide dark matter candidates:
  - Neutralinos and other Weakly Interacting Massive Particles (WIMPs)
  - Axions and other very Weakly Interacting Slim (=ultra-light) Particles (WISPs)



(Kim,Carosi 10)

Theoretically favored WISP candidates

Nambu-Goldstone bosons:

- "Axion-Like Particles" (ALPs) arising from breaking of global U(1) symmetries at high energy scale f_a
  - Low energy effective field theory has shift symmetry $a(x) \to a(x) + \mathrm{const.}$, forbidding explicit mass terms, $\propto m_a^2 a^2(x)$, in the Lagrangian
  - Effective couplings to SM particles suppressed by powers of high energy scale f_a , e.g. coupling to photons, $\mathcal{L} \supset -\frac{\alpha}{8\pi} C_{a\gamma} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$
- Examples:
  - Axion from breaking of global chiral symmetry; axion field acts as dynamical theta parameter, $\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \underbrace{C_{ag} \frac{a}{f_a}}_{\theta} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$ [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

    spontaneously relaxing to zero, $\langle a \rangle = 0$ (thus CP conserved in strong interactions)
    - works for any value of f_a
    - mass due to chiral symmetry breaking, $m_a \sim m_\pi f_\pi / f_a$
  - Majoron from breaking of global lepton number symmetry [Chikashige et al. 78]
    - high scale explains small neutrino mass, $m_\nu \sim v_H^2 / f_a$ [Langacker et al. 86]
  - Closed string axions: Kaluza-Klein zero modes of 10D antisymmetric tensor fields in string theory, $f_a \sim M_s$ [Witten 84; Conlon 06; Cicoli,Goodsell,AR 12]

Theoretically favored WISP candidates

> Hidden U(1) gauge bosons:

- "Hidden" or "dark" photons (HPs): vector bosons of a local U(1) gauge theory under which SM particles are uncharged
  - Gauge symmetry forbids explicit mass terms; mass generated via
    - Higgs mechanism: $m_{\gamma'} \sim g_h v_h$
    - Stückelberg mechanism: topological mass
  - Suppressed couplings to SM particles; e.g. kinetic mixing with the photon: [Holdom 86]

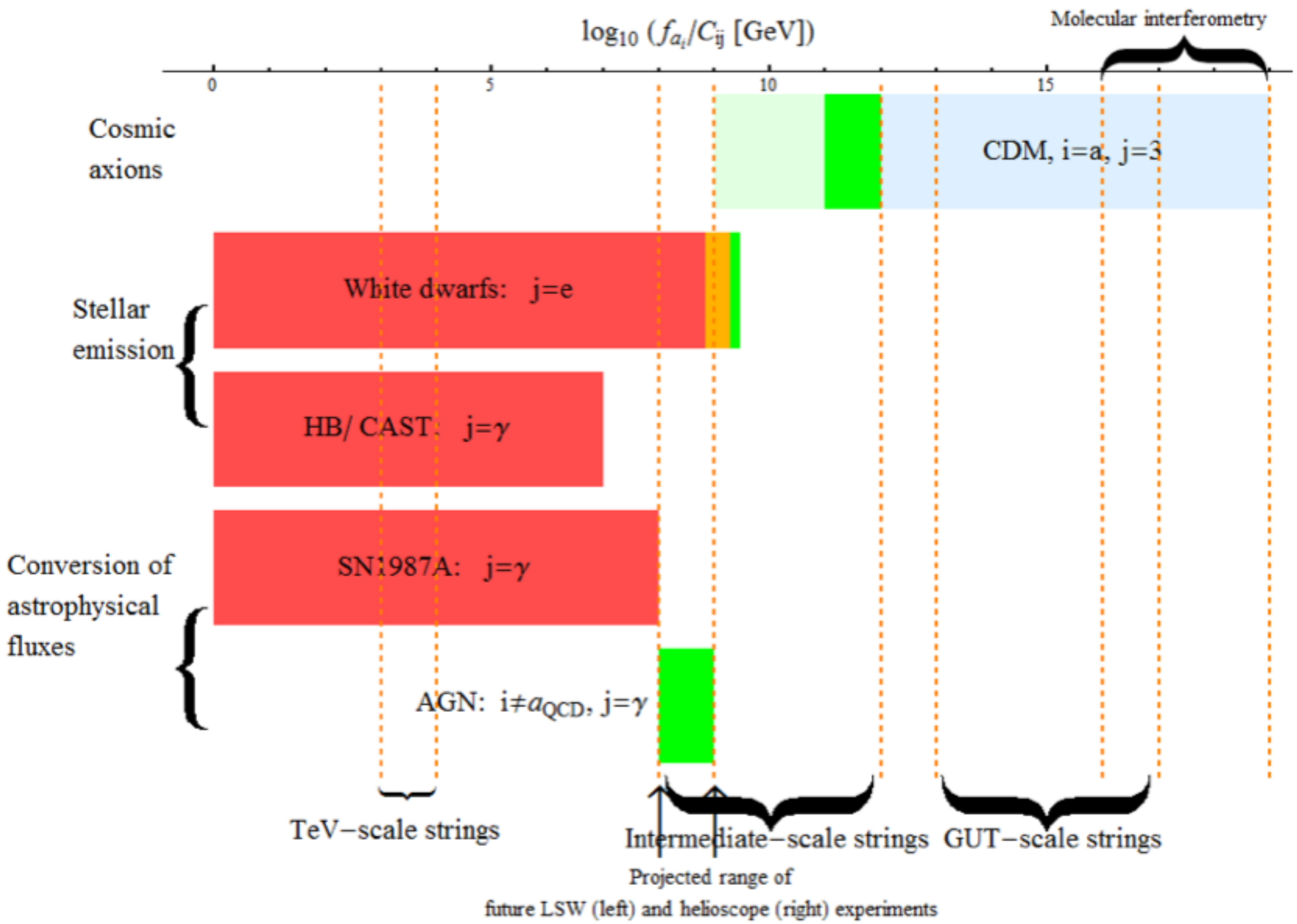
$$\mathcal{L} \supset -\frac{\chi}{2} F'_{\mu\nu} F^{\mu\nu}; \qquad \chi \sim \frac{e\, g_h}{16\pi^2}$$

- Examples:
  - U(1) factors from breaking of grand unified gauge group
  - Often occur in low energy effective field theories from string theory: [Goodsell,AR 10]
    - Heterotic string: hidden U(1)s arising from breaking of 10D $E_8 \times E'_8$, expect $\chi \sim 10^{-4}$
    - Type II string (brane world scenarios):
      - RR U(1)s: KK zero modes arising in 4D decomposition of 10D form fields
      - Brane localized U(1)s: massless excitations of space-time filling D-branes wrapping cycles in extra dimensions [Abel et al. 08;Goodsell et al. 09;Cicoli et al. 11]

$$\chi \sim \frac{e}{16\pi^2} \left(\frac{M_s}{M_P}\right)^{2/3}; \qquad \frac{M_s^2}{M_P} \lesssim m_{\gamma'}^{\rm st} \lesssim M_s$$

Sub keV mass ALPs are really WISPy

- Current constraints on ALPs:



[Cicoli,Goodsell,AR 12]

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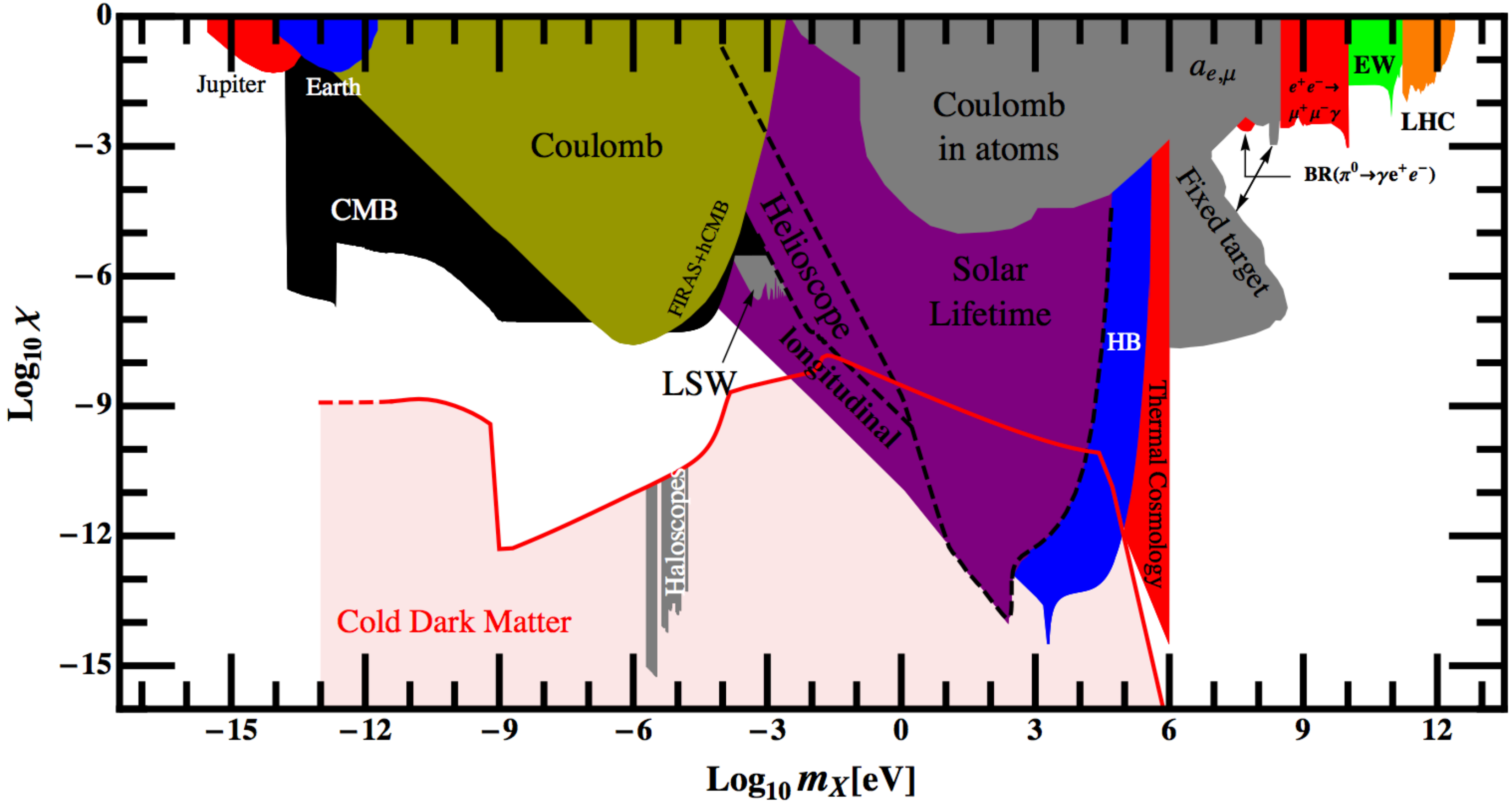
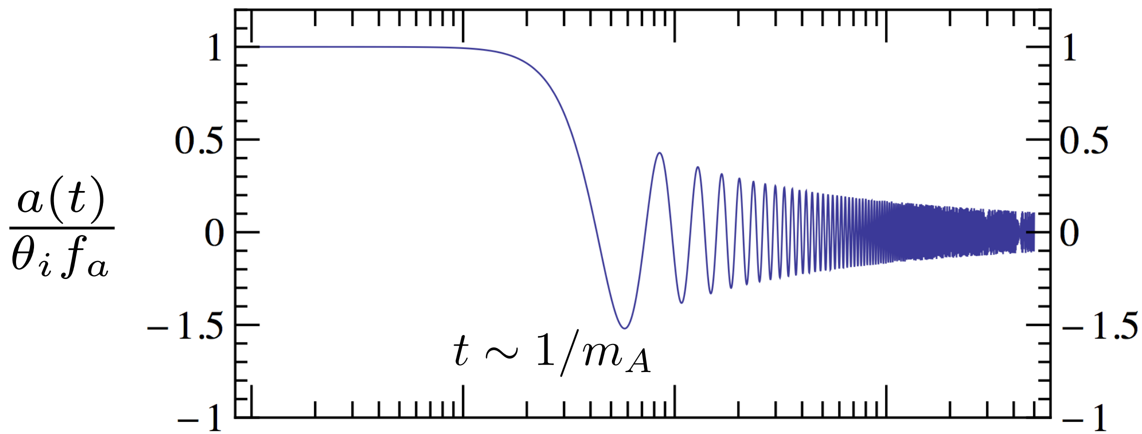


[Jaeckel 13]

WISPy dark matter

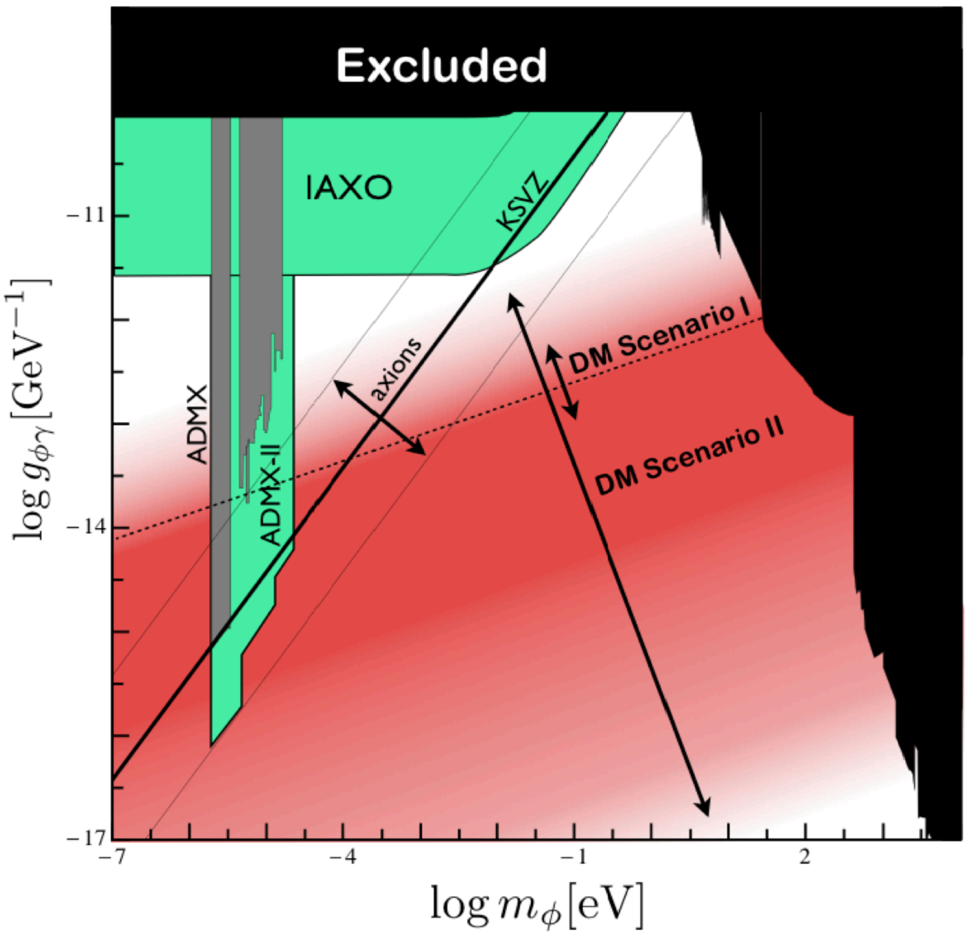
- For $f_a \gtrsim 10^9\,\mathrm{GeV}$, axions and ALPs produced pre-dominantly non-thermally in the early universe and contribute to cold DM
  - Vacuum-realignment: [Preskill et al. 83; Abbott,Sikivie 83; Dine,Fischler 83]
    - Homogeneous mode of axion/ALP field frozen at random initial value, $a(t_i) = \theta_i f_a$, because of cosmic expansion, as long as $t \lesssim 1/m_a$. Later, at $t \gtrsim 1/m_a$, axion/ALP field oscillates around zero; coherent state of non-relativistic dark matter



    - Works also for other bosonic WISPs such as hidden photons [Arias et al. 12]
  - Decay of cosmic strings and domain walls

WISPy dark matter

- Large search space for axion/ALP dark matter [Arias et al. 12]



[Döbrich,Redondo 13]

$$g_{a\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a}$$

- ALP DM Scenario I:

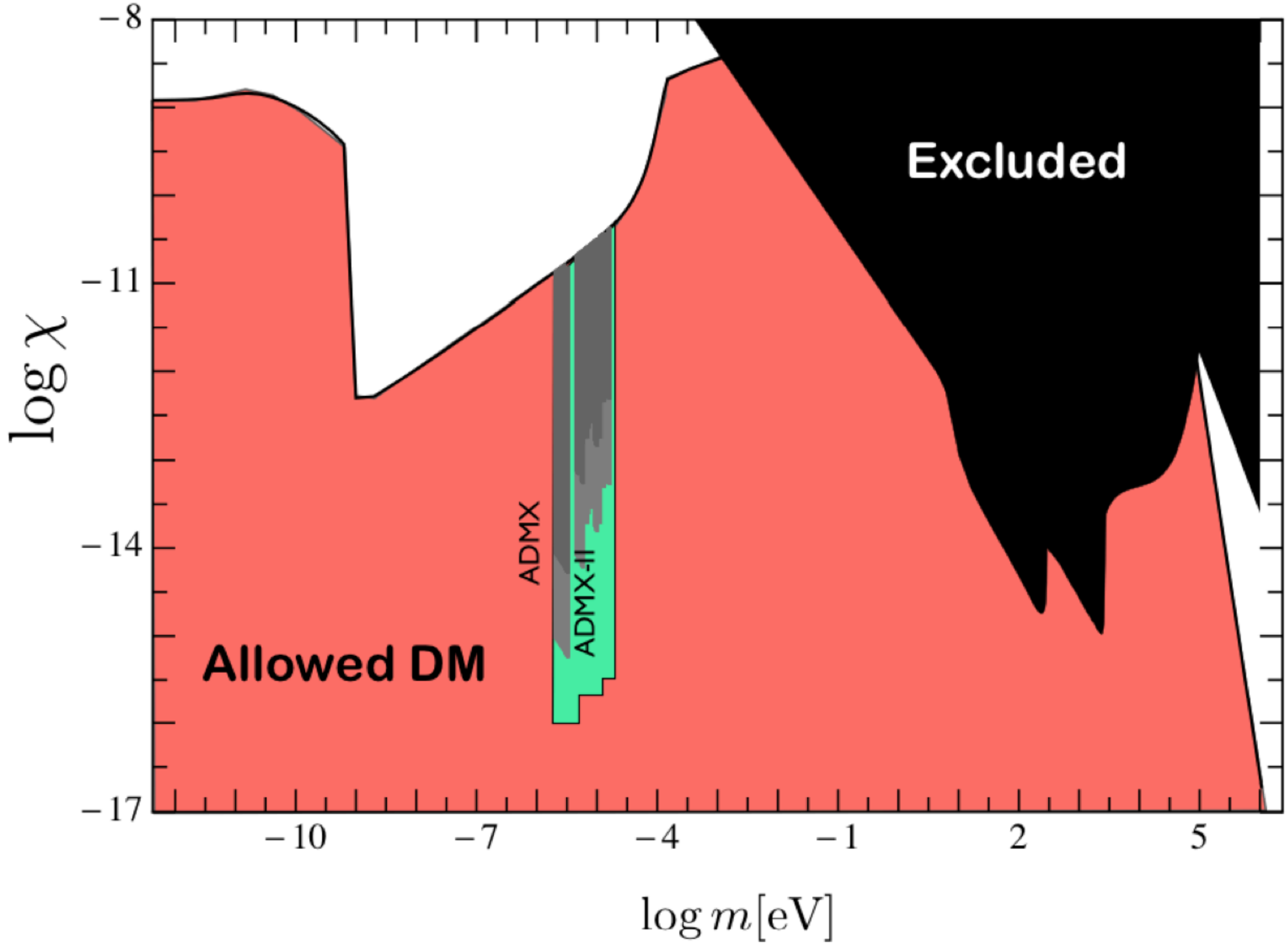
  Symmetry breaking scale smaller than reheating temperature after inflation

- ALP DM Scenario II:

  Symmetry breaking scale larger than reheating temperature after inflation

WISPy dark matter

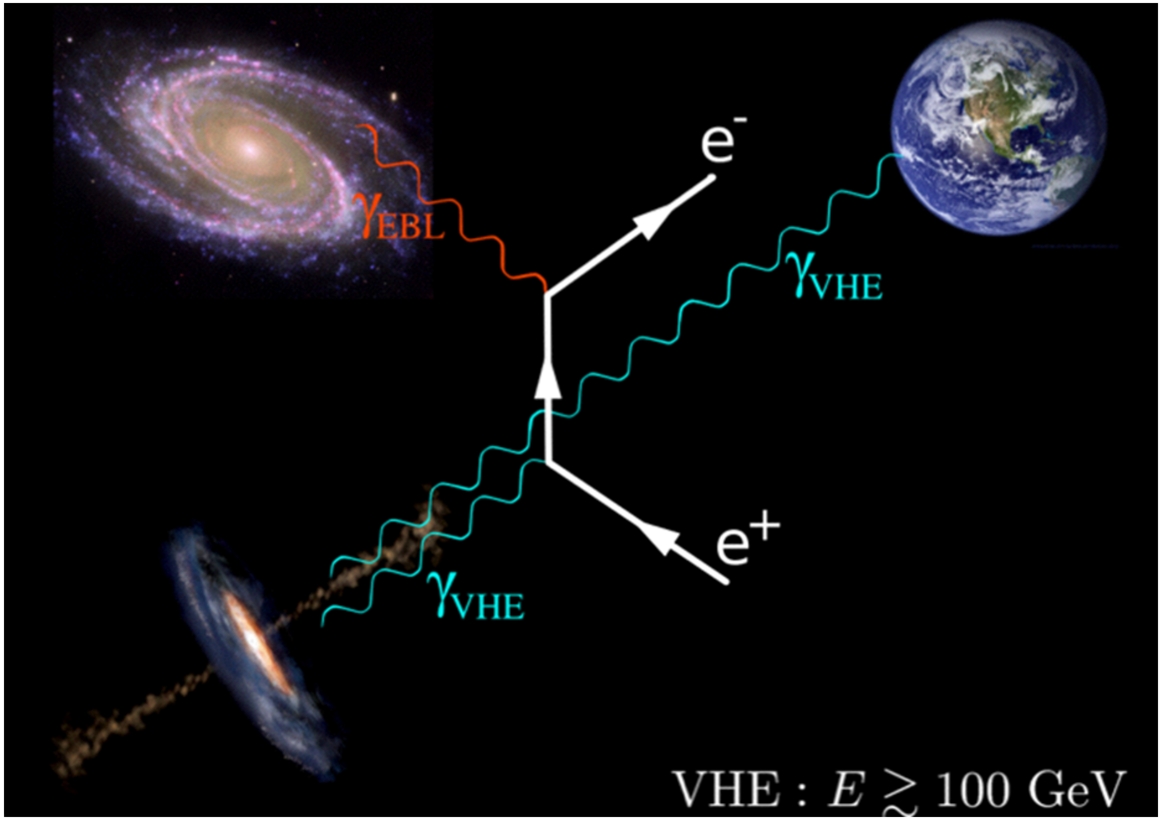
- Large search space for hidden photon dark matter [Arias et al. 12]



[Döbrich,Redondo 13]

Astro hint on ALP: Gamma transparency of universe

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



[Manuel Meyer 12]

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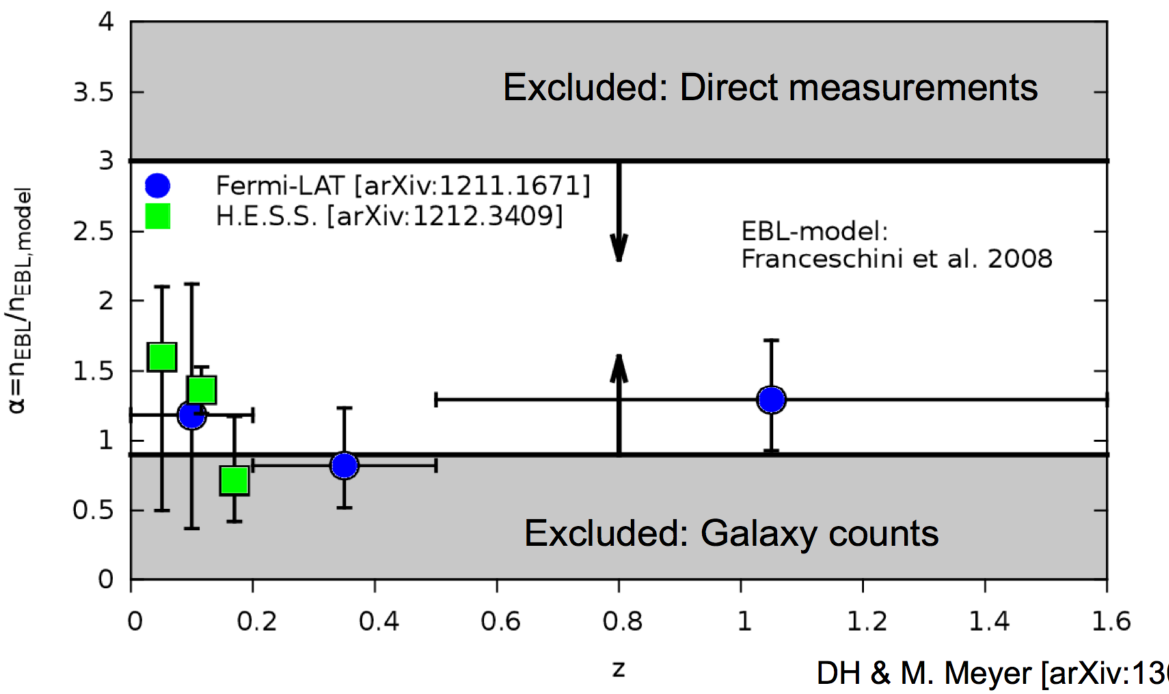
- Attenuation recently been observed by Fermi-LAT and H.E.S.S.



DH & M. Meyer [arXiv:1309.3846]

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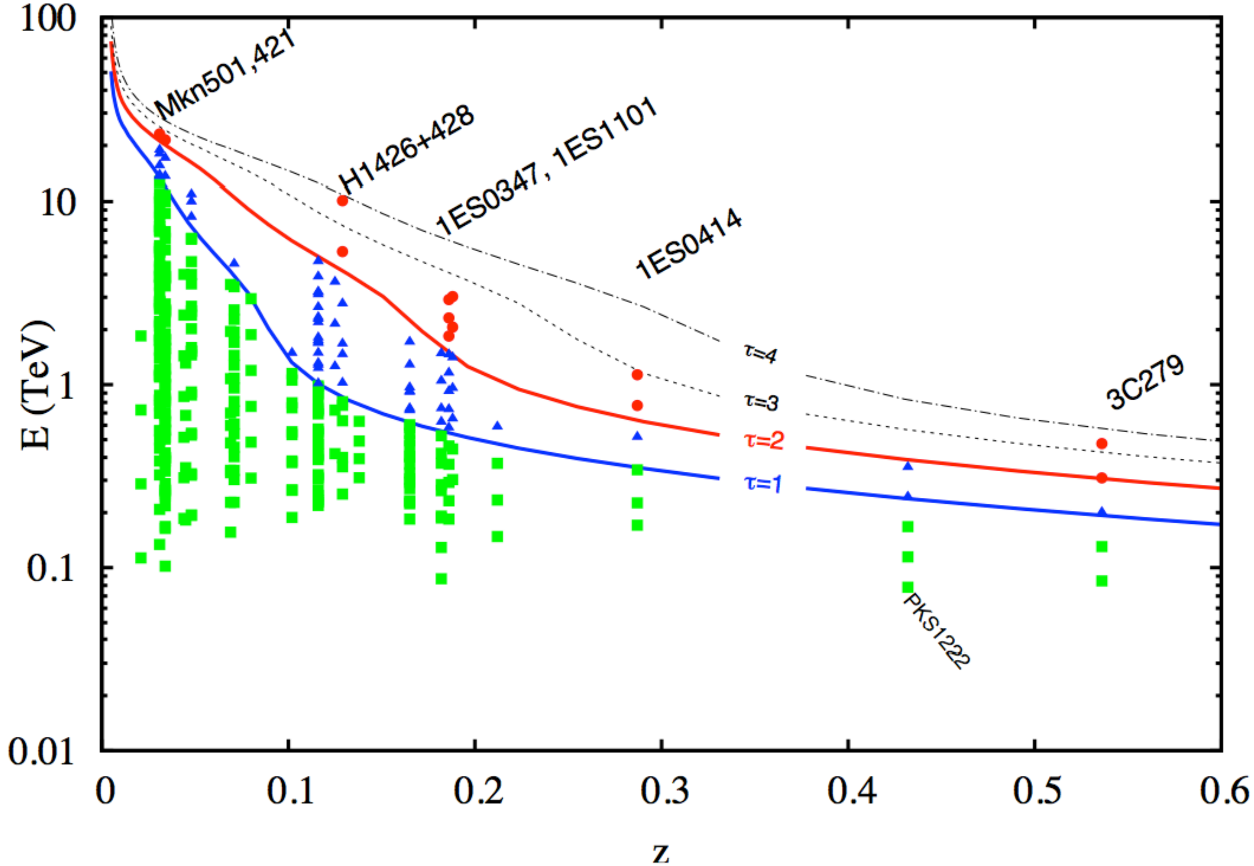
- At $\tau \gtrsim 2$, however, hints for anomalous gamma transparency, from IACT and Fermi-LAT data [Aharonian et al. 07; Aliu et al. 08;...; Horns,Meyer 12;...]



[Horns,Meyer 12]

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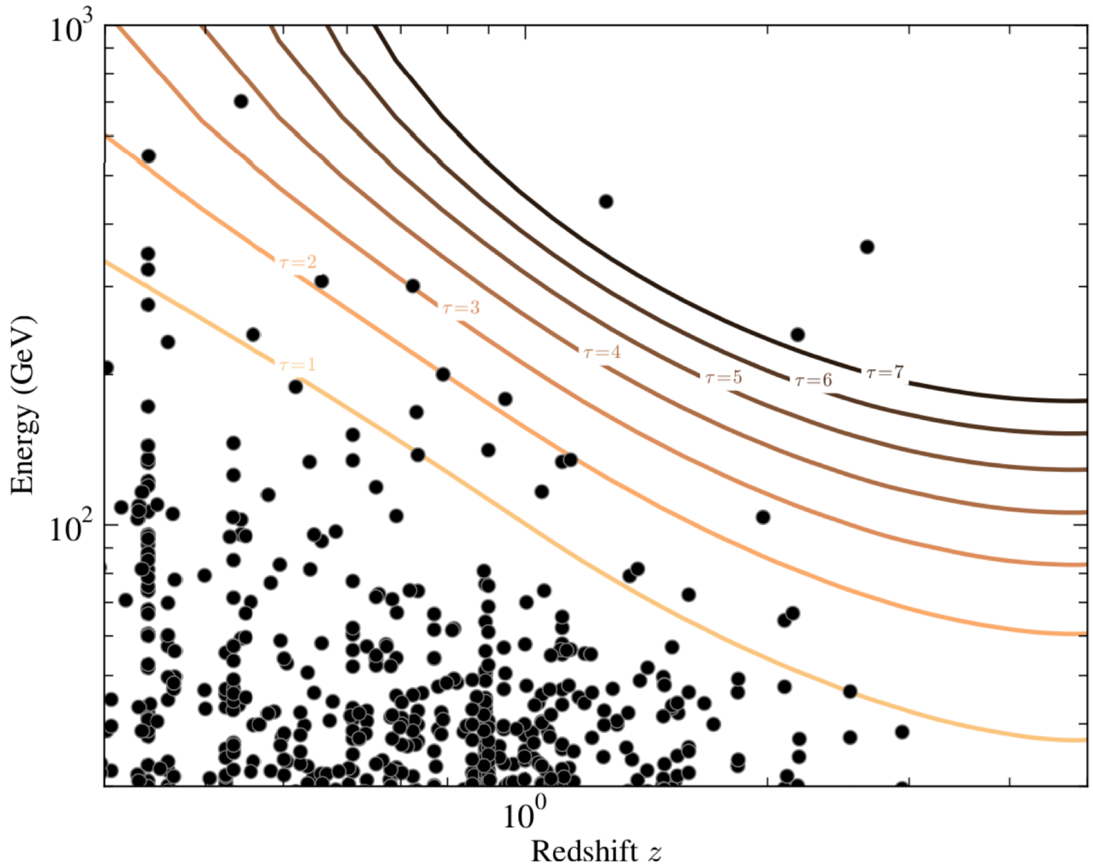

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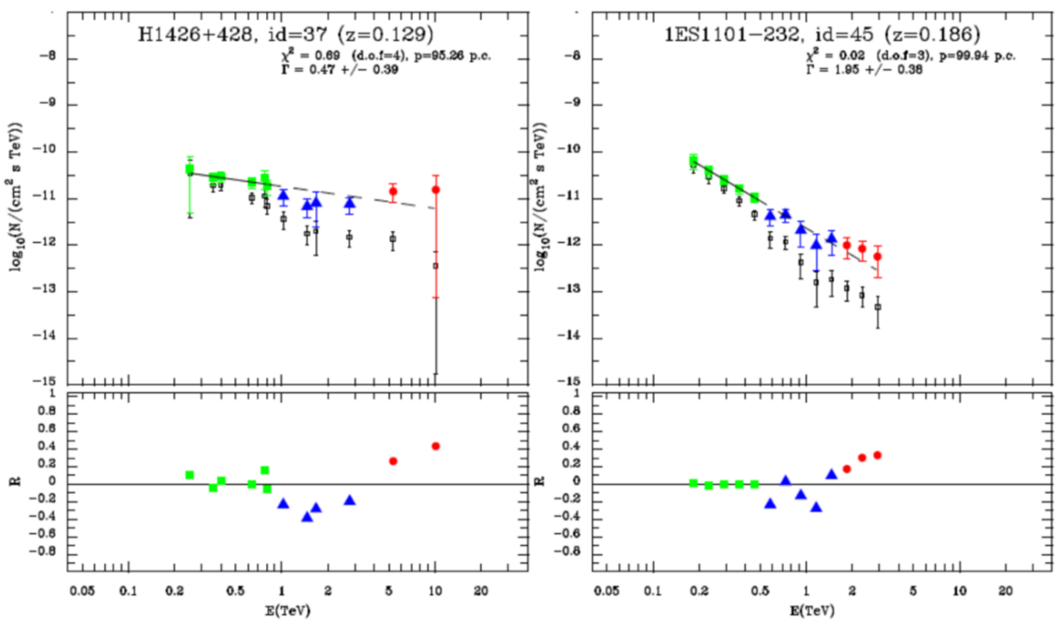
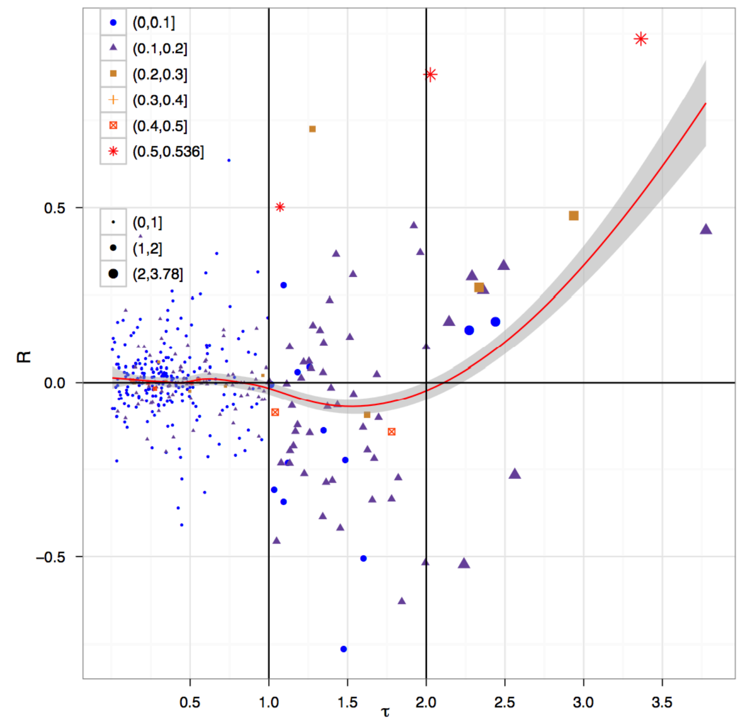


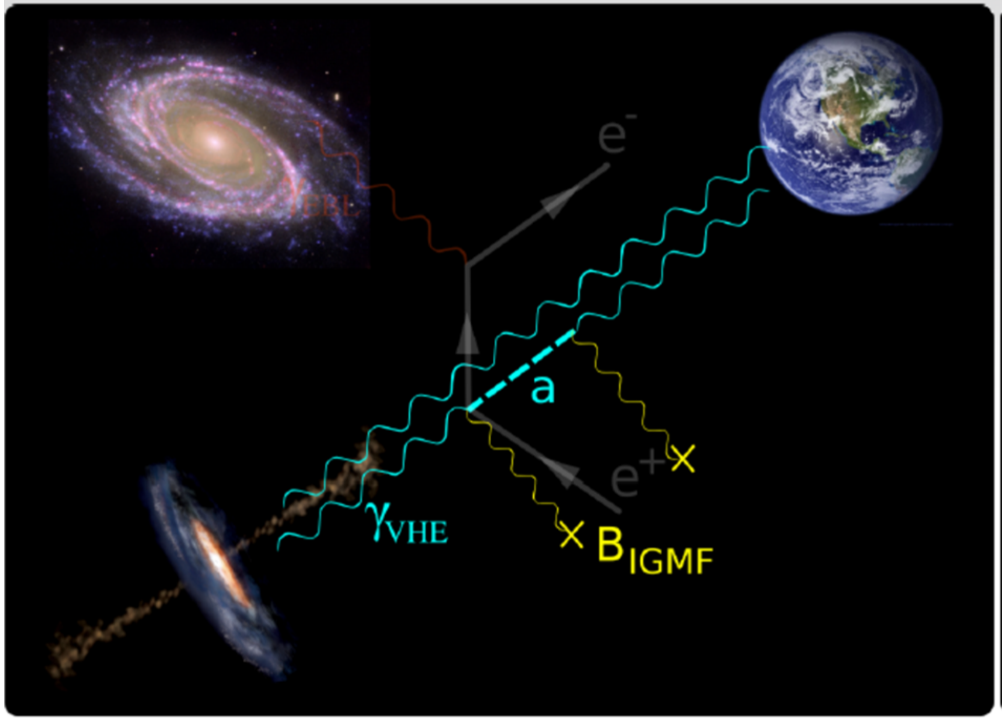


[Horns,Meyer 12]

Astro hint on ALP: Gamma transparency of universe

- Possible explanation in terms of photon <-> ALP conversions in astro-physical magnetic fields with $g_{a\gamma} \gtrsim 10^{-12}\ \mathrm{GeV}^{-1};\ m_a \lesssim 10^{-7}\ \mathrm{eV}$

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



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

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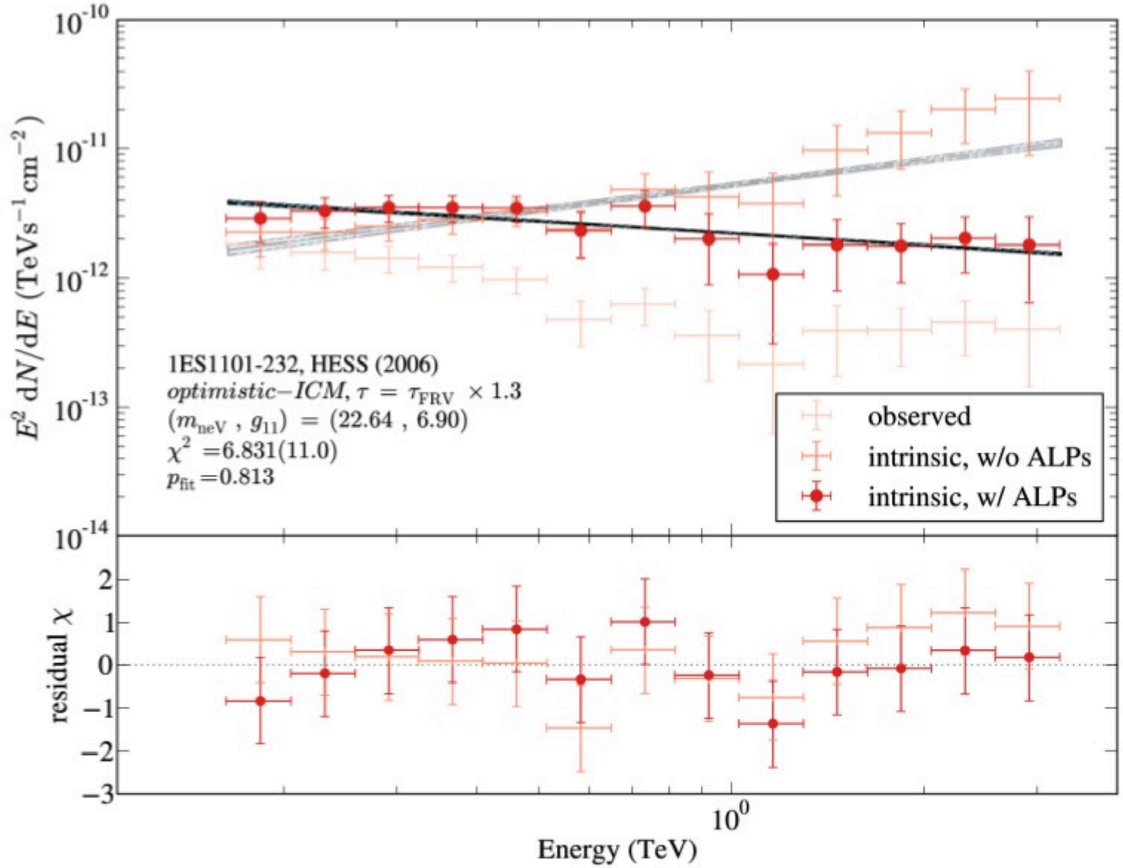

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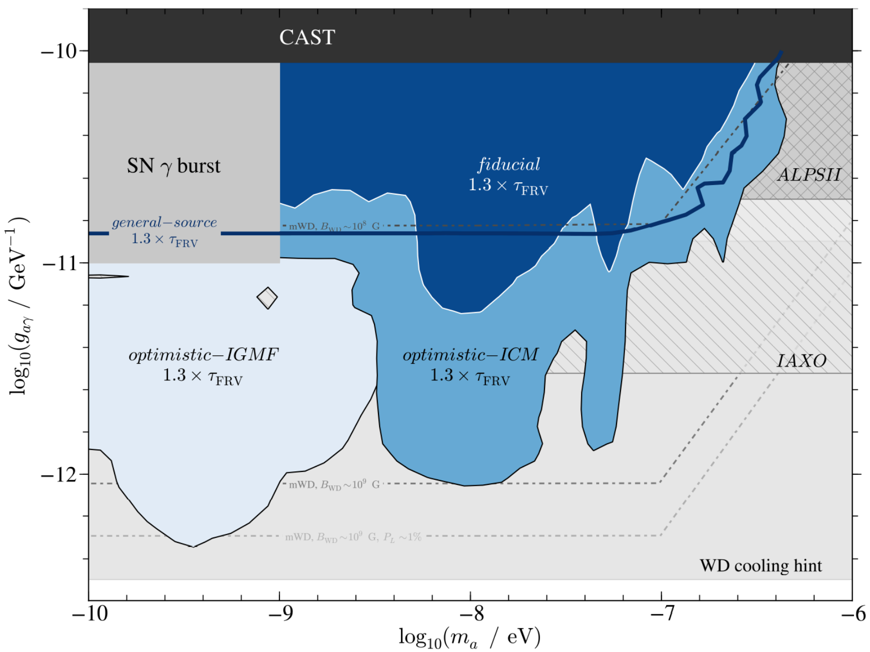
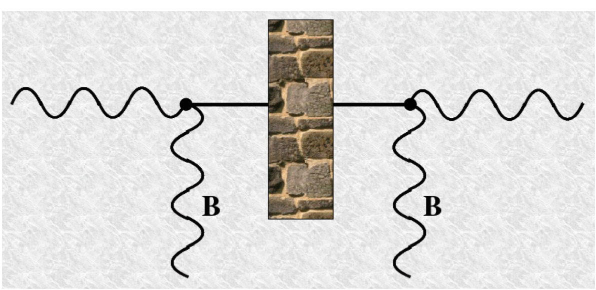


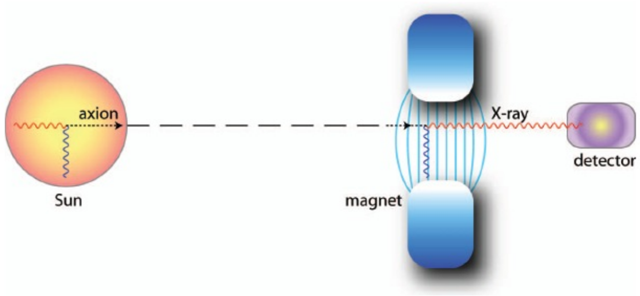
Name	IGMF B^0_{IGMF} (nG)	IGMF $\lambda^c_{\mathrm{IGMF}}$ (Mpc)	IGMF $n^0_{\mathrm{el,IGM}}$ ($\times 10^{-7}$ cm^{-3})	ICM B^0_{ICMF} (μG)	ICM $\lambda^c_{\mathrm{ICMF}}$ (kpc)	ICM r_{cluster} (Mpc)	ICM $n^0_{\mathrm{el,ICM}}$ ($\times 10^{-3}$ cm^{-3})	ICM r_{core} (kpc)	η
General source	Only conversion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

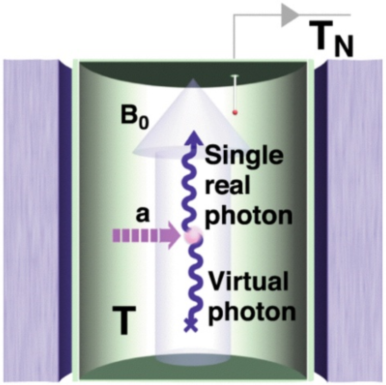
[Meyer,Horns,Raue 13]

Laboratory searches for WISPs

- Sizeable part of parameter range of interest can be accessed in this decade with terrestrial searches based on WISP photon os-cillations (requiring presence of strong magnetic fields in case of axions/ALPs)
  - Light-shining-through-a-wall: production and detection of WISPs [Anselm ‘85; van Bibber et al ‘87]
  - Helioscopes: detection of solar WISPs [Sikivie ’83]
  - Haloscopes: direct detection of DM WISPs [Sikivie ’83]

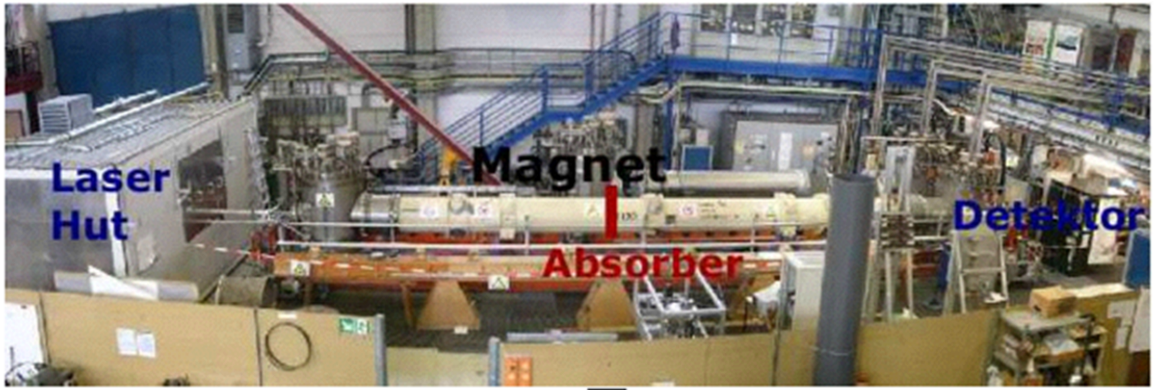


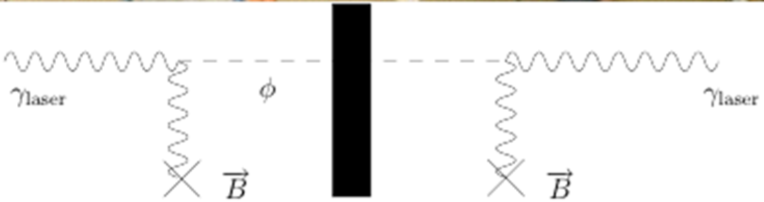




Light-shining-through-a-wall searches

- Most sensitive until now: Any Light Particle Search I (ALPS-I) at DESY
  - One superconducting HERA dipole (5 T)
  - 1.2 kW cw green (2.3 eV) laser light stored before wall in resonant cavity
  - CCD camera





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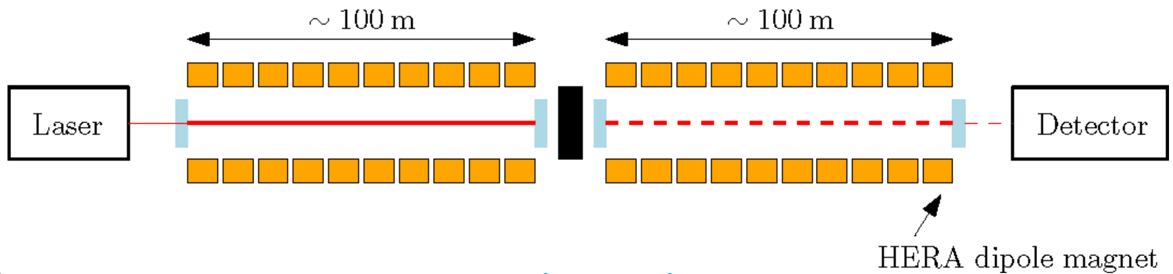
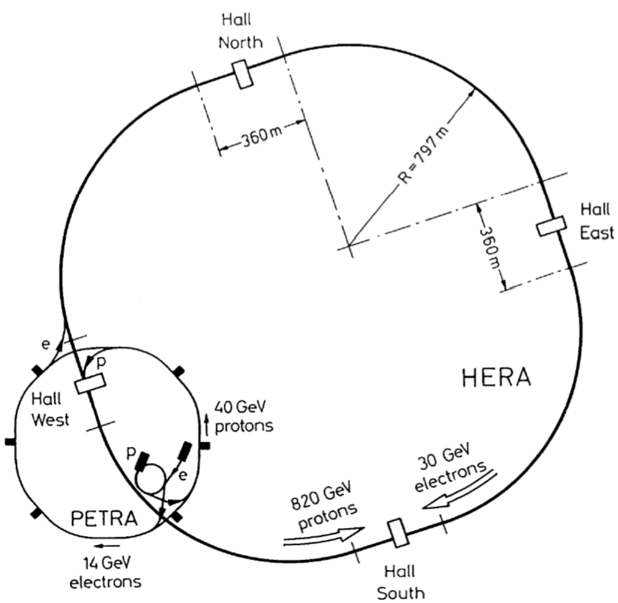
Light-shining-through-a-wall searches

- Presently being set up: ALPS-II at DESY (data taking planned for 2017)
  - 10 + 10 superconducting HERA dipoles
  - 150 kW infrared (1.17 eV) laser light stored before wall; resonant regeneration behind wall
  - Transition Edge Sensor

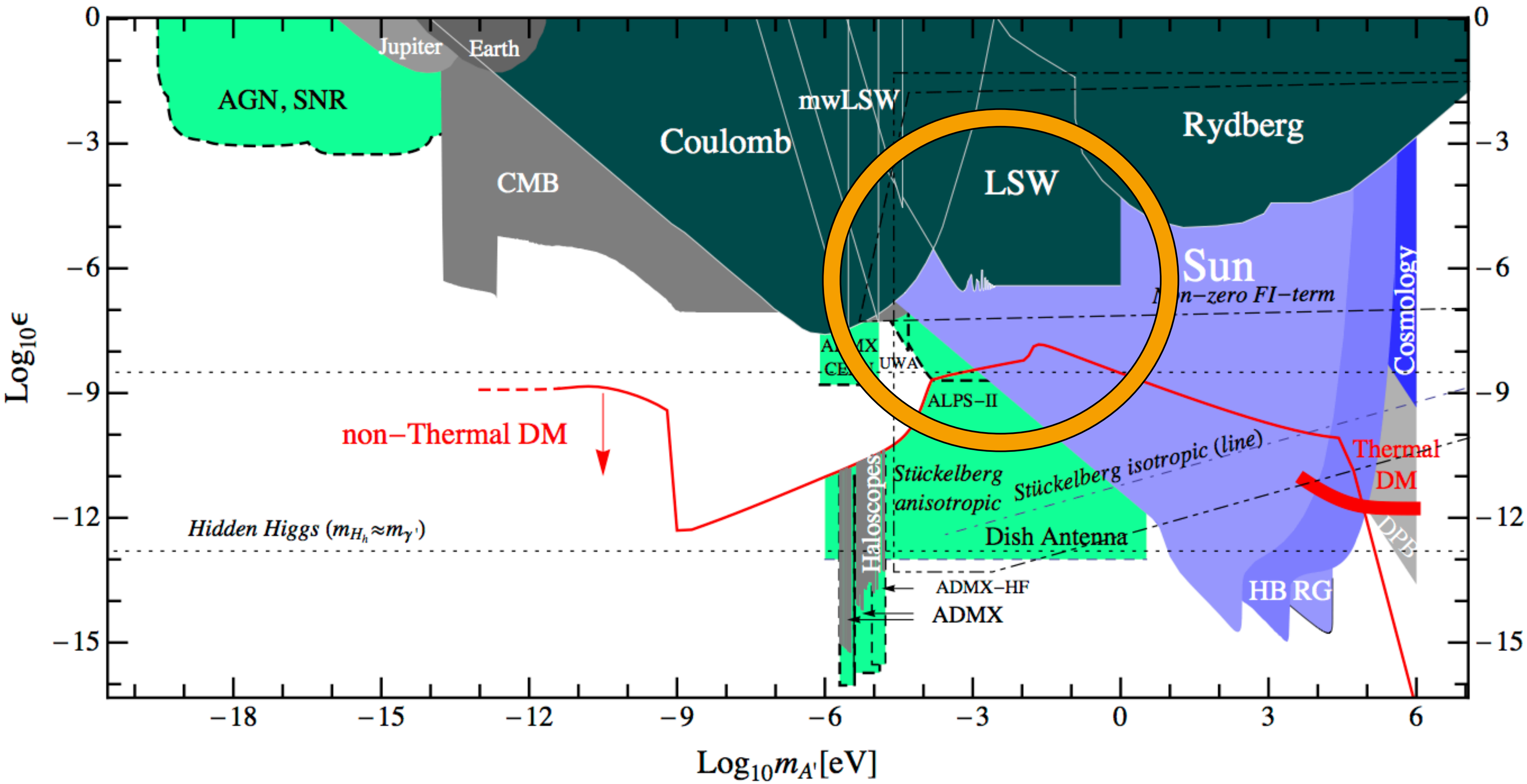




[Bähre et al (ALPS-II TDR) 13]

Light-shining-through-a-wall searches

> Sensitivity of light-shining-through-a-wall (LSW) searches for HPs



adapted from [Hewett et al 12]

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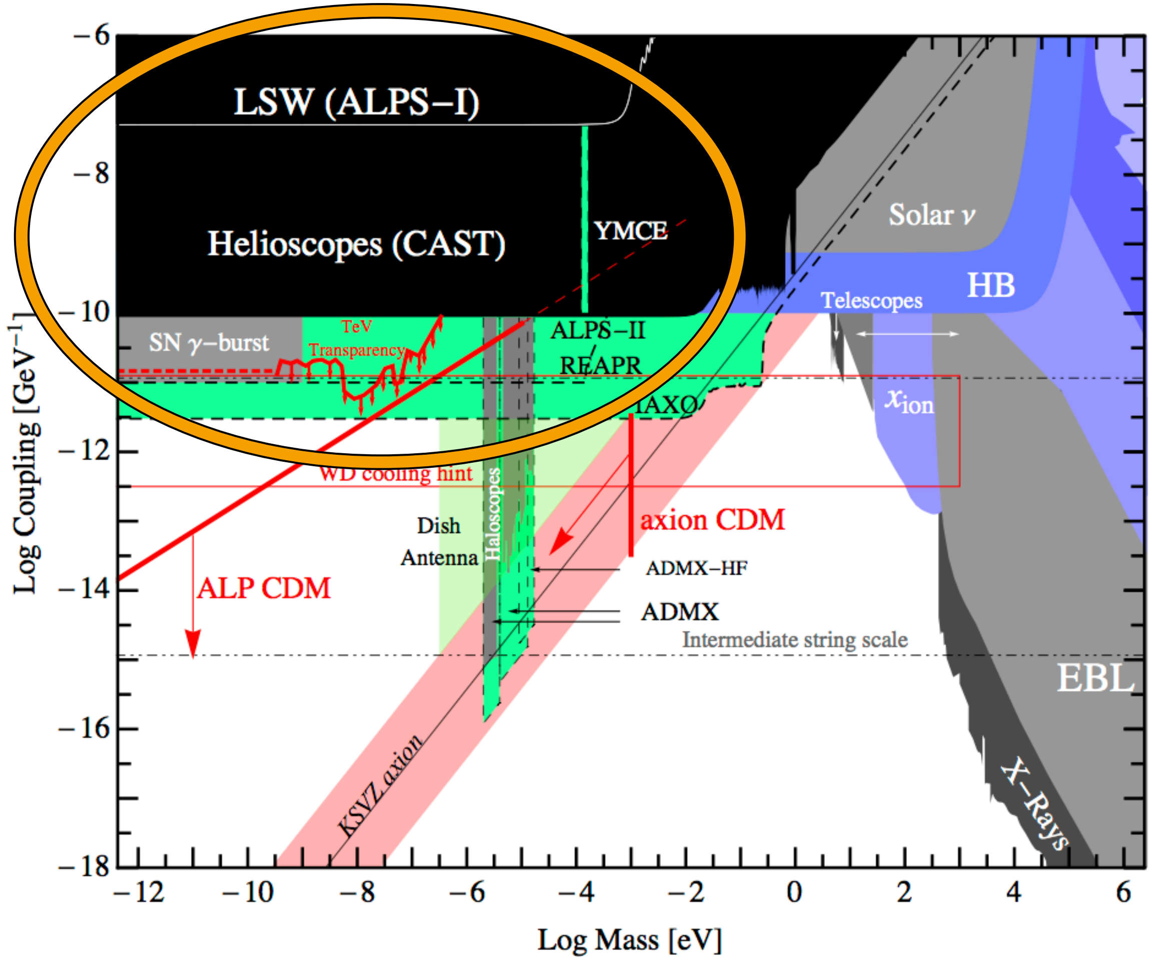


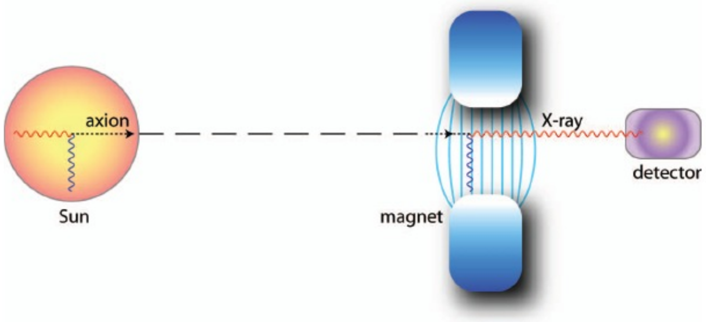
adapted from [Hewett et al 12]

Helioscope searches

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

- Superconducting LHC dipole magnet
- X-ray detectors

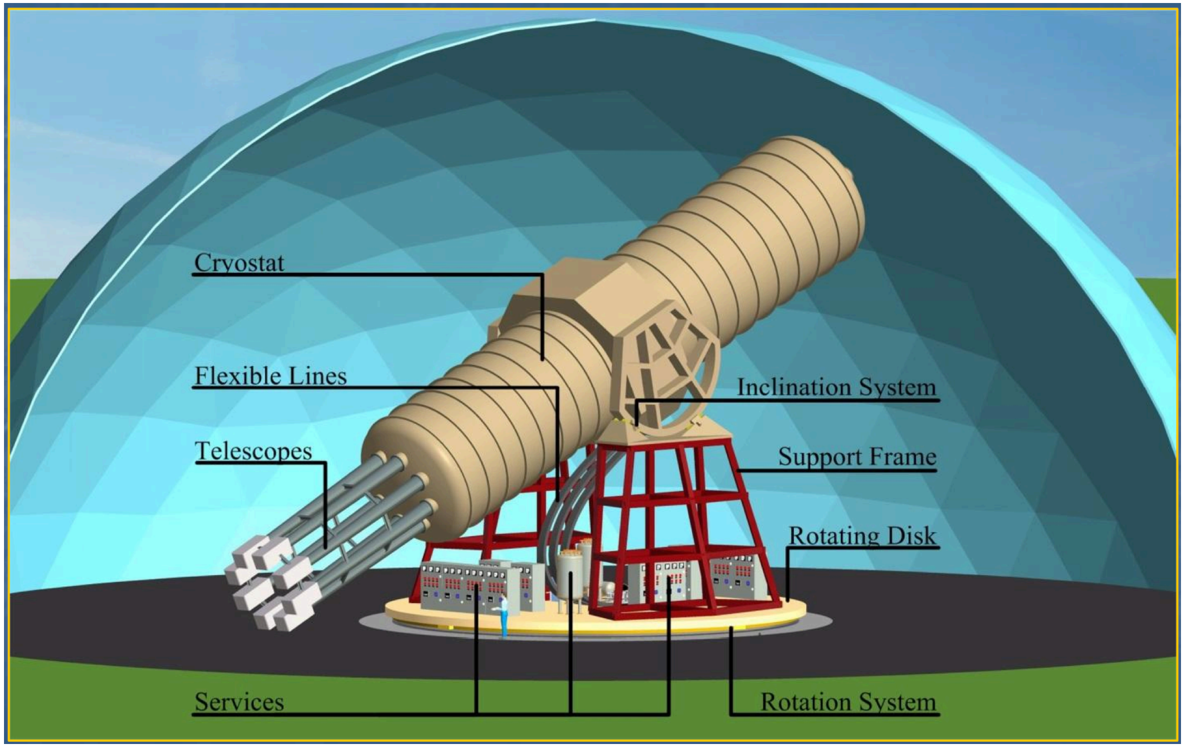
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$



Helioscope searches

> Proposed successor: International Axion Observatory (IAXO)

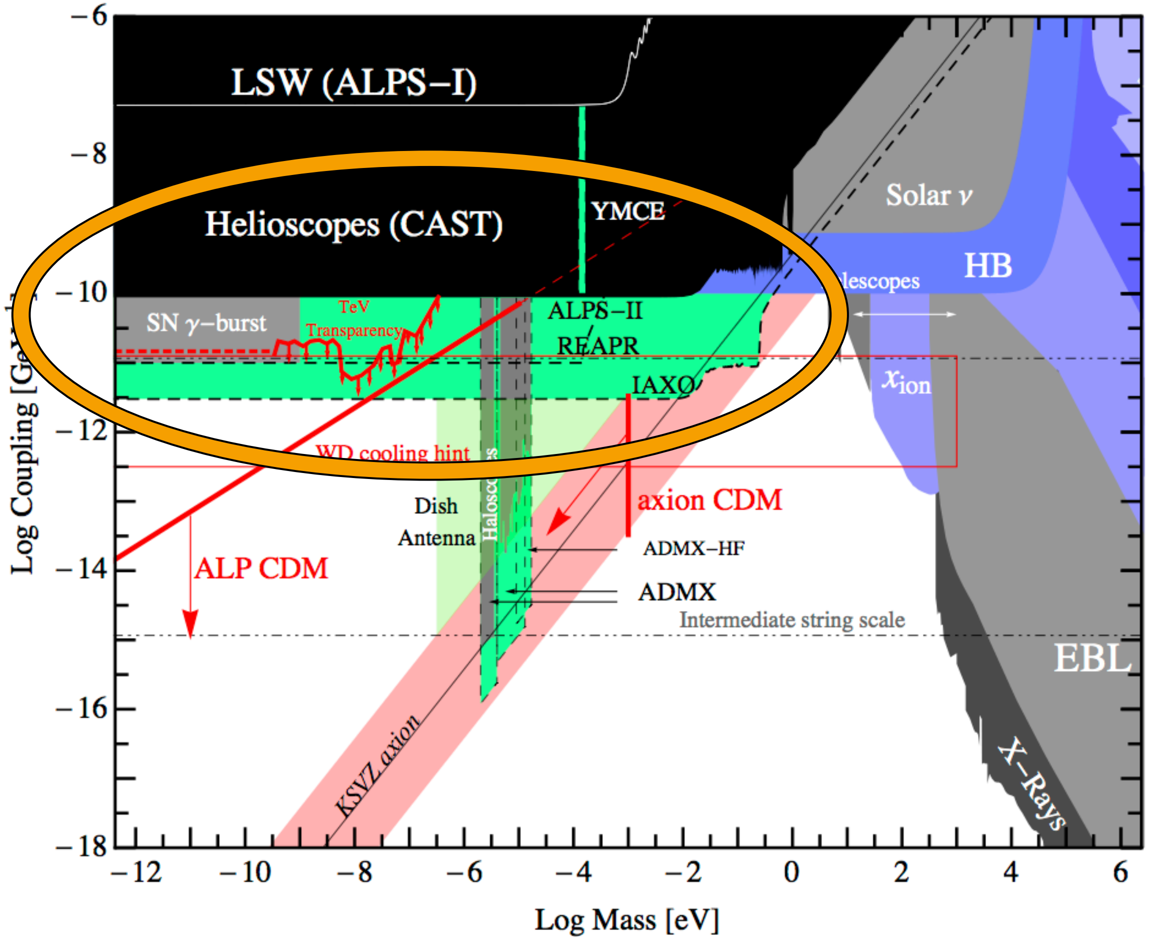
- Dedicated superconducting toroidal magnet with much bigger aperture than CAST
- Extensive use of X-ray optics
- Low background X-ray detectors



[Armengaud et al (IAXO LoI) 13]

Helioscope searches

- Sensitivity of helioscope searches for axions/ALPs:

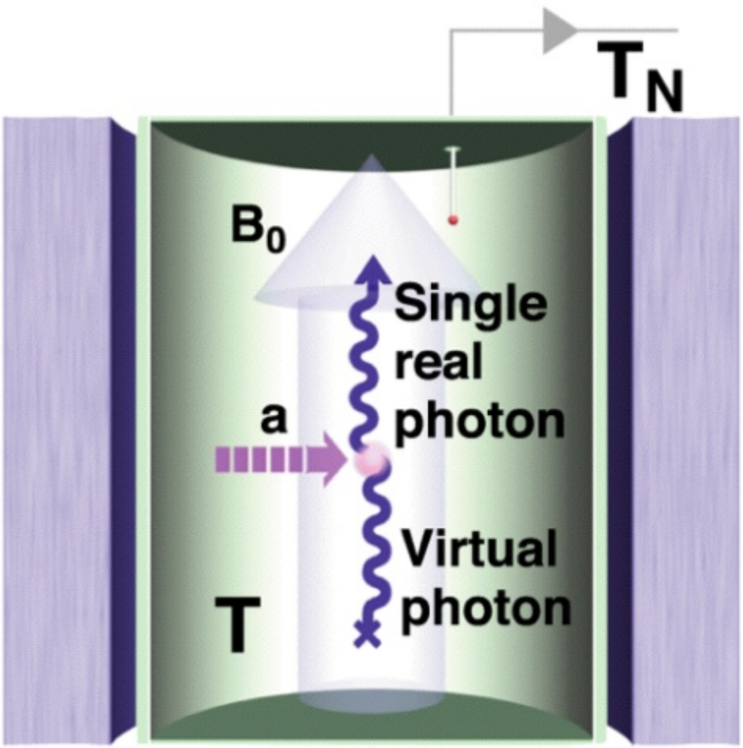


adapted from [Hewett et al 12]

Haloscope searches

- WISP DM – photon conversion in microwave cavity (placed in magnetic field, for axion/ALP search)

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

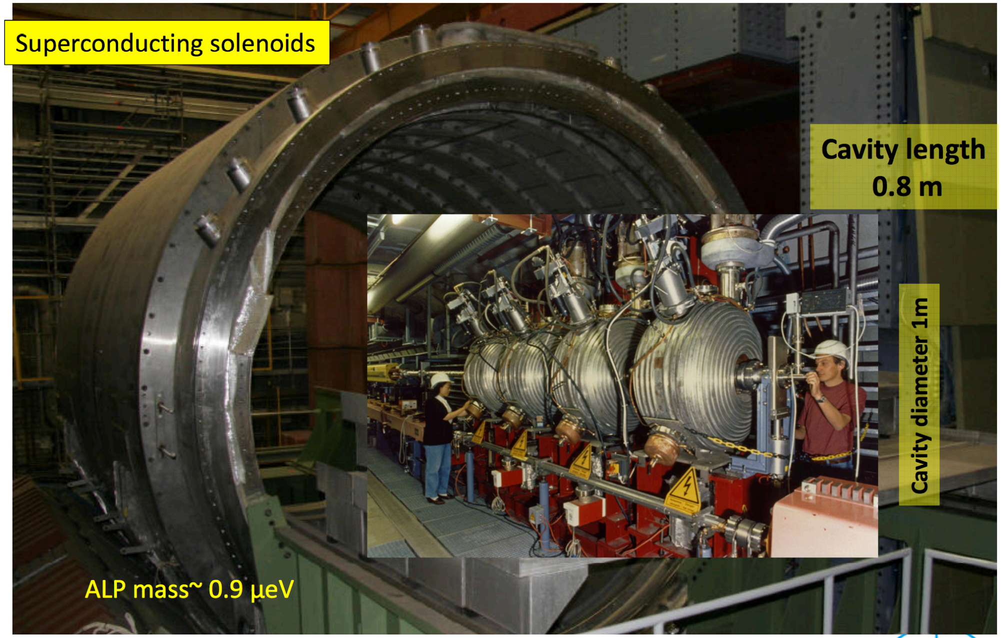


$$P_{\mathrm{out}} \sim \chi^2 m_{\gamma'} \rho_{\mathrm{DM}} V\, Q$$

$$P_{\mathrm{out}} \sim g_{a\gamma}^2\, \mathbf{B}^2 \rho_{\mathrm{DM}} V\, Q/m_a$$

Haloscope searches

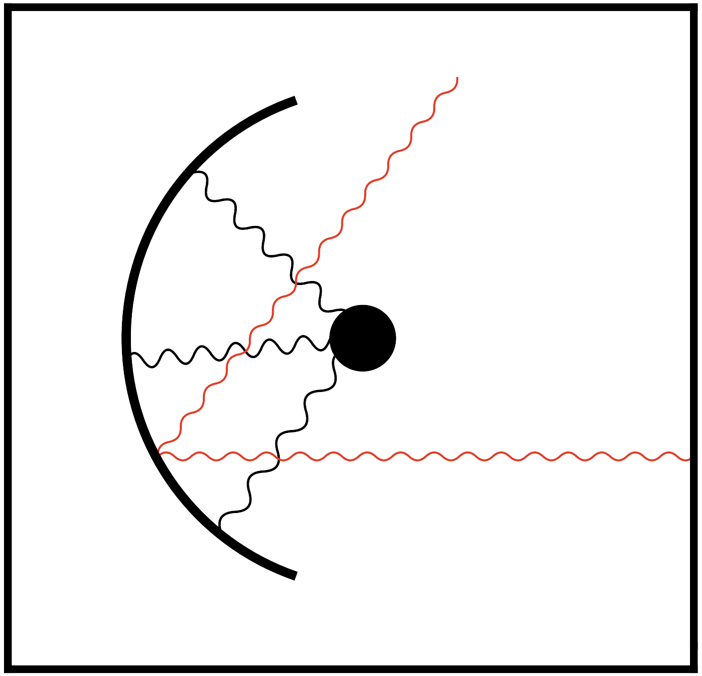
- WISP DM – photon conversion in microwave cavity (placed in magnetic field, for axion/ALP search)
  - Ongoing: ADMX at University of Washington, Seattle, exploiting high Q cavity in 8 T superconducting solenoid; search starts at 1 GHz towards higher frequencies
  - Starting: WISPDMX at DESY, Hamburg, exploiting high Q HERA p acceleration ca-vity; HP DM search starts at 208 MHz towards higher frequencies; later axion/ALP search exploiting H1 solenoid (1.1 T)



Haloscope searches

> Proposed broadband dish antenna search [Horns et al. 12]

- Non-relativistic DM WISPs are converted into monochromatic photons emitted from the surface of a spherical dish antenna (placed in a background magnetic field, in case of axion/ALP)
- Photons are focused in the centre, where a broadband detector is placed

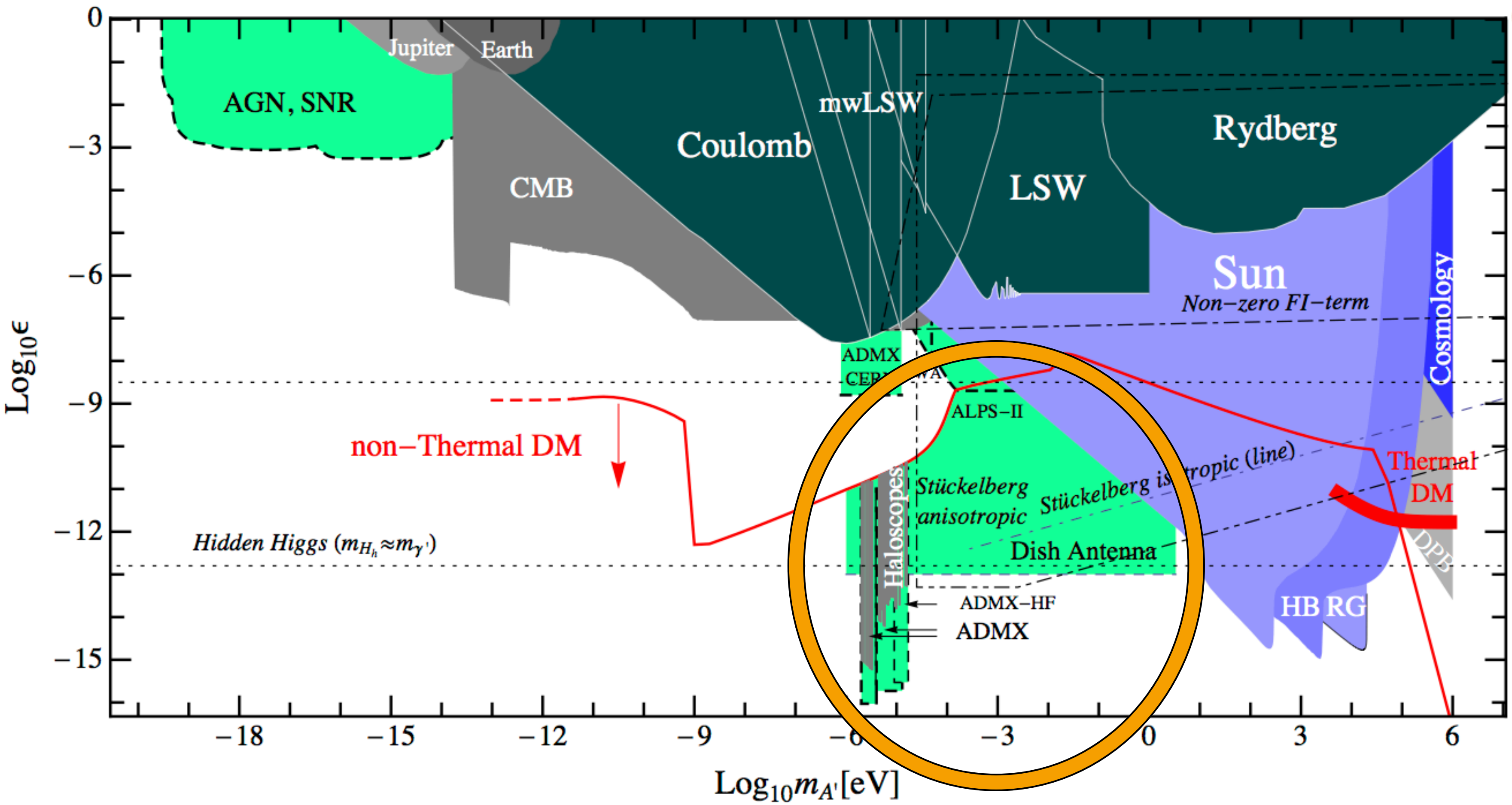


$$P_{\rm center} \sim \chi^2 \rho_{\rm DM} A_{\rm dish}$$

$$P_{\rm center} \sim g_{a\gamma}^2 \, \mathbf{B}^2 \rho_{\rm DM} A_{\rm dish}/m_a^2$$

Haloscope searches

- Sensitivity of microwave cavity (ADMX) and dish antenna haloscopes:



adapted from [Hewett et al 12]

Haloscope searches

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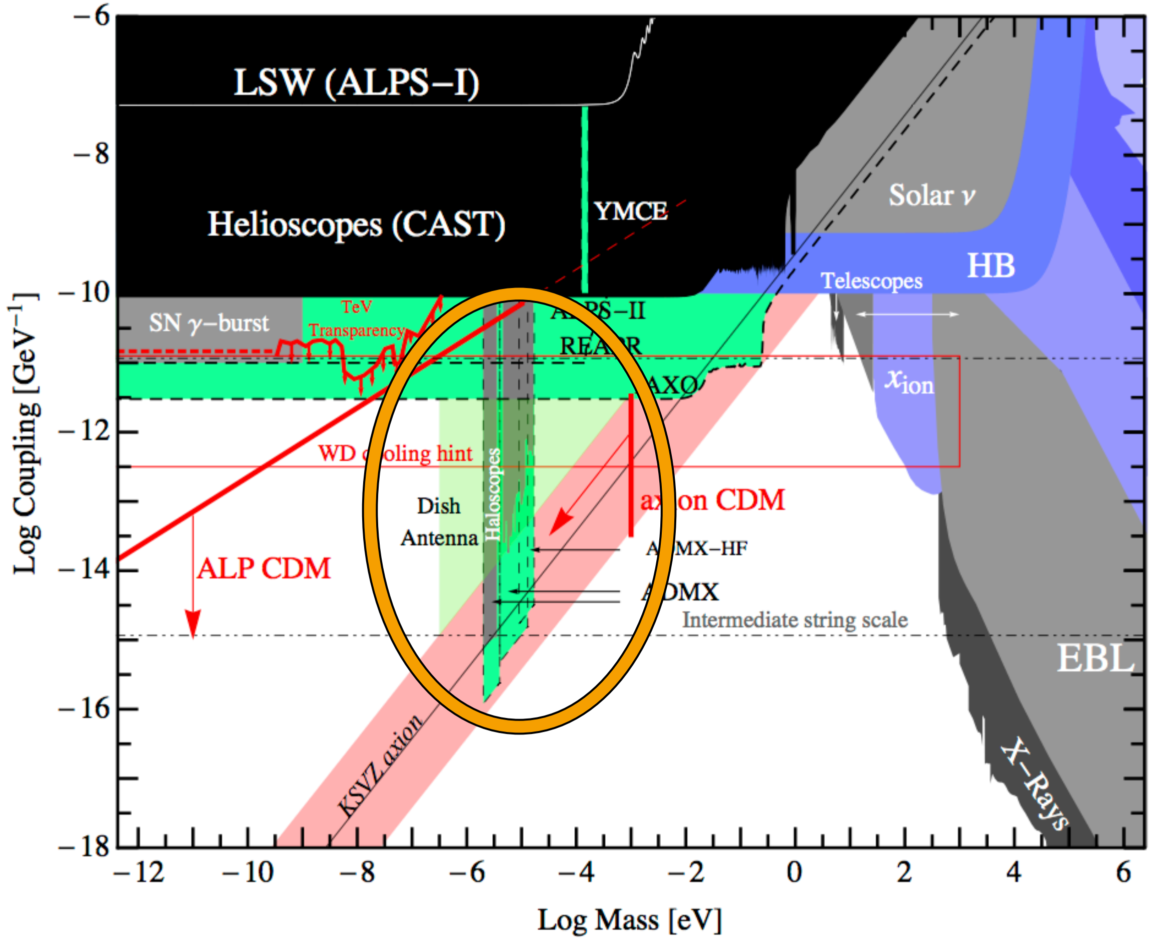


adapted from [Hewett et al 12]

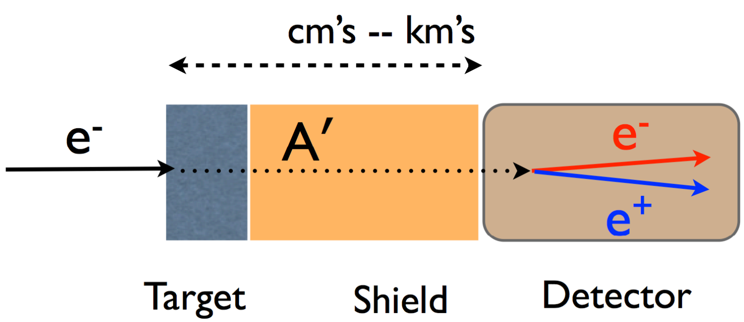
MeV-GeV scale hidden (dark) photon

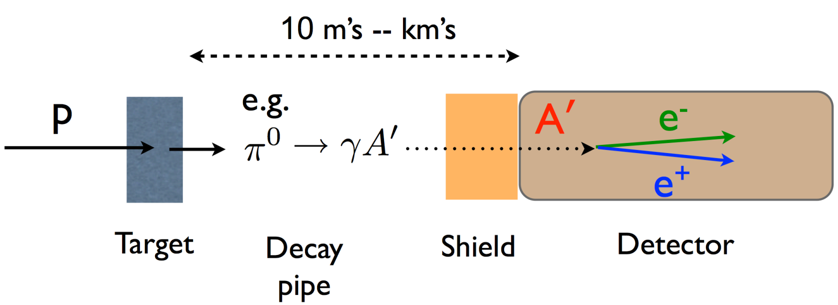
> May explain

- $(g-2)_\mu$ anomaly [Pospelov '08]
- DM `hints´ [Arkani-Hamed et al. '08; Pospelov,Ritz '08;...]
  - in direct detection (DAMA, CoGeNT, CRESST, CDMS vs. XENON) and
  - in cosmic rays (PAMELA, FERMI, AMS)

  if DM charged under hidden U(1)

> Can be checked in beam dump and other fixed-target experiments with intense e or p beams [Bjorken et al. 09;Blümlein,Brunner 11; Gninenko 12; Andreas et al. 12]

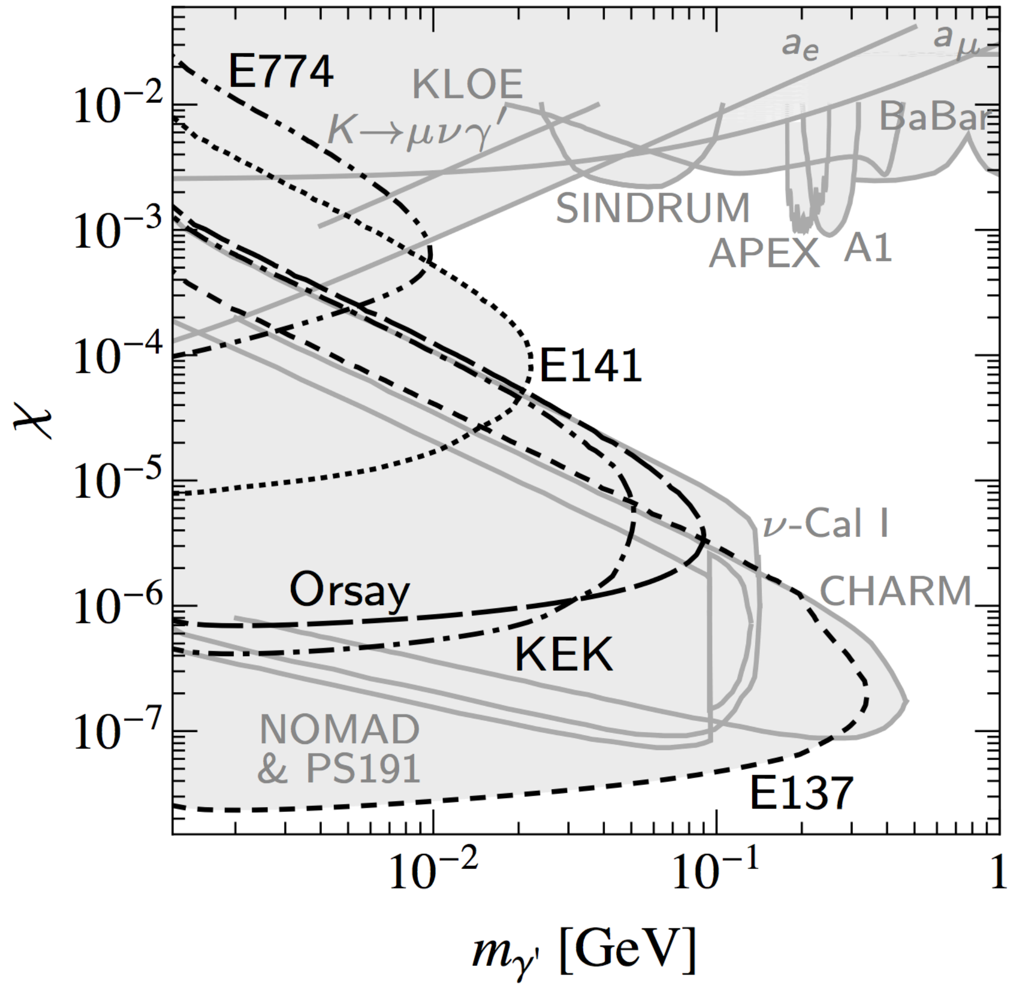




MeV-GeV scale hidden (dark) photon

> Current laboratory constraints:

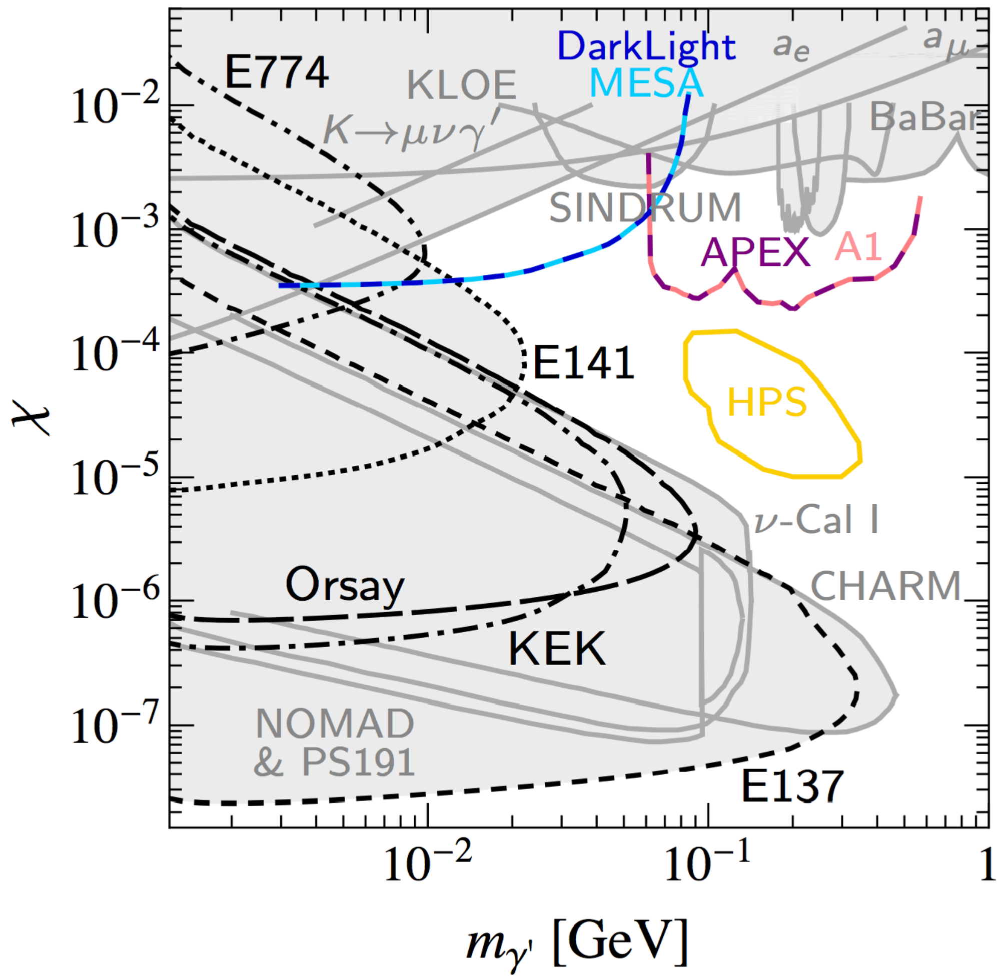
- Electron beam dumps
  [Bjorken,Essig,Schuster 09; Andreas,Niebuhr,AR 12]
  - KEK (1986)
  - SLAC E141 (1987)
  - SLAC E137 (1988)
  - Orsay (1989)
  - Fermilab E774 (1991)
- Proton beam dumps
  [Blümlein,Brunner 11, Gninenko 12]
  - CERN CHARM (1983-86)
  - PS191 (1986)
  - Serpukhov ν-Cal I (1989)
  - CERN NOMAD (2001)



[Andreas]

MeV-GeV scale hidden (dark) photon

- New electron fixed target experiments:
  - MAMI A1
  - JLab APEX
  - JLab HPS
  - JLab DarkLight
  - MESA



[Andreas]

MeV-GeV scale hidden (dark) photon

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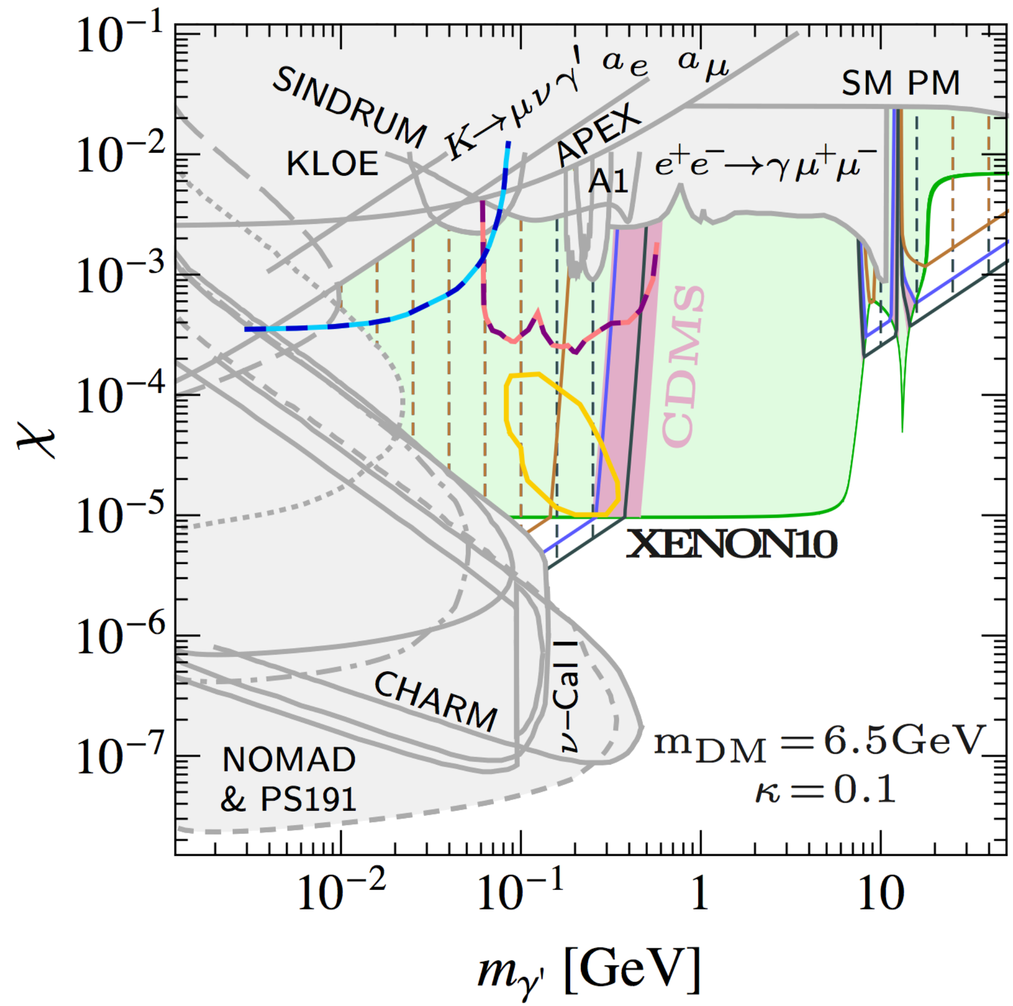


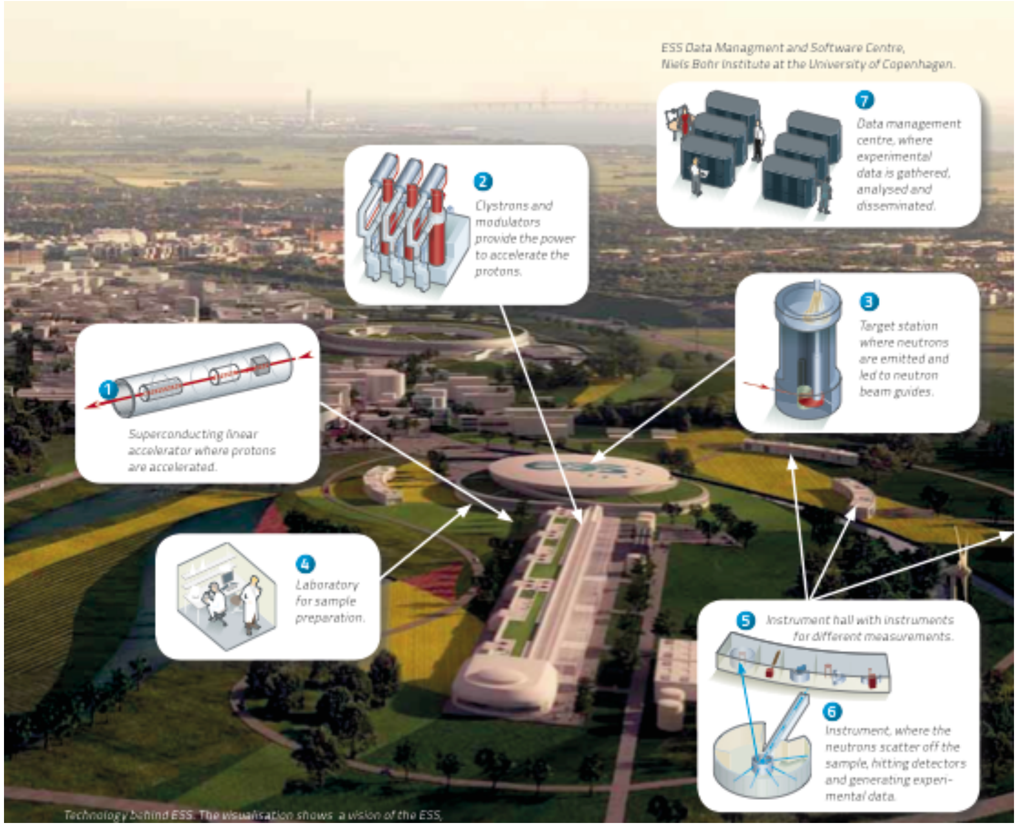
[Andreas,Goodsell,AR '13]

MeV-GeV scale hidden (dark) photon

> New proton beam dumps?

- Presently no dedicated experi-ments planned
- Beam dump at ESS? [Rathsman]
  - Beamparameter:

$$\sim 10^{16}\,\mathrm{pot/s};\ \ E \sim 2\,\mathrm{GeV}$$



[europeanspallationsource.se]

MeV-GeV scale hidden (dark) photon

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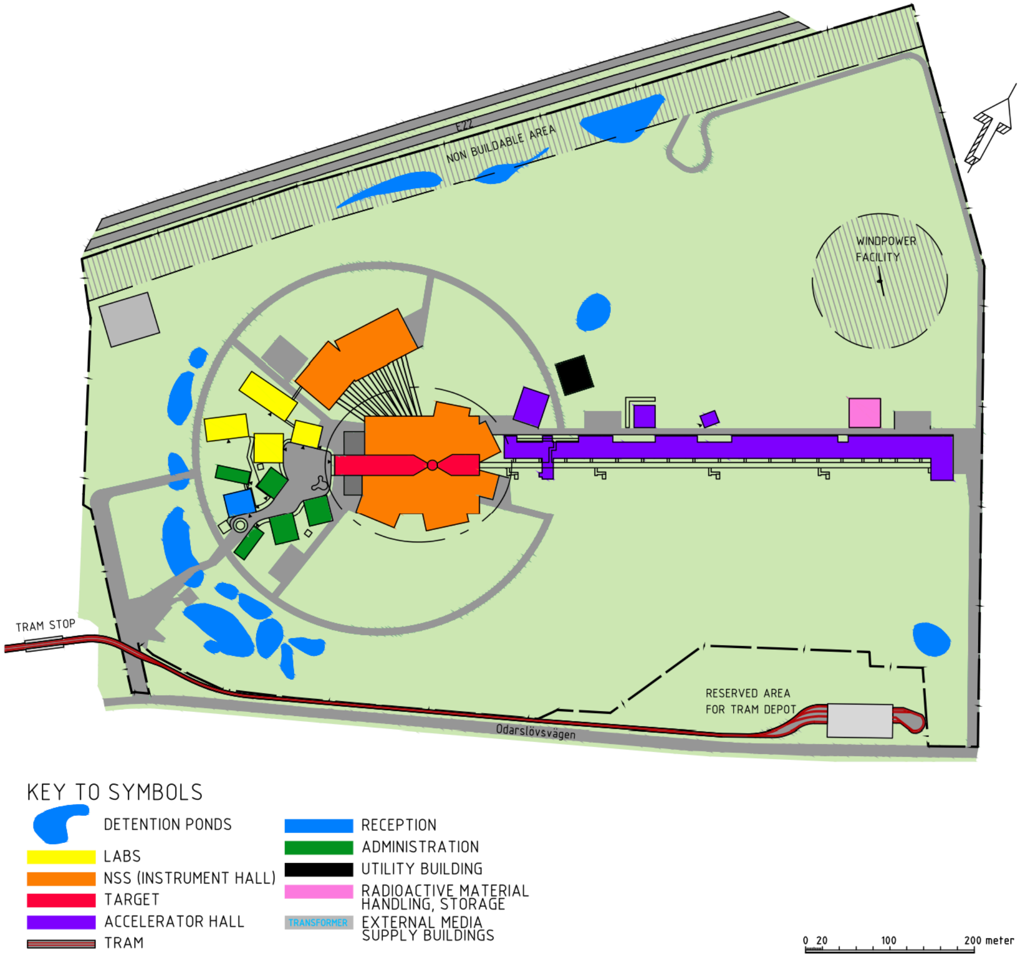


[ESS TDR]

MeV-GeV scale hidden (dark) photon

- New proton beam dumps?
  - Presently no dedicated experiments planned
  - Beam dump at ESS? [Rathsman]
    - Beamparameter:

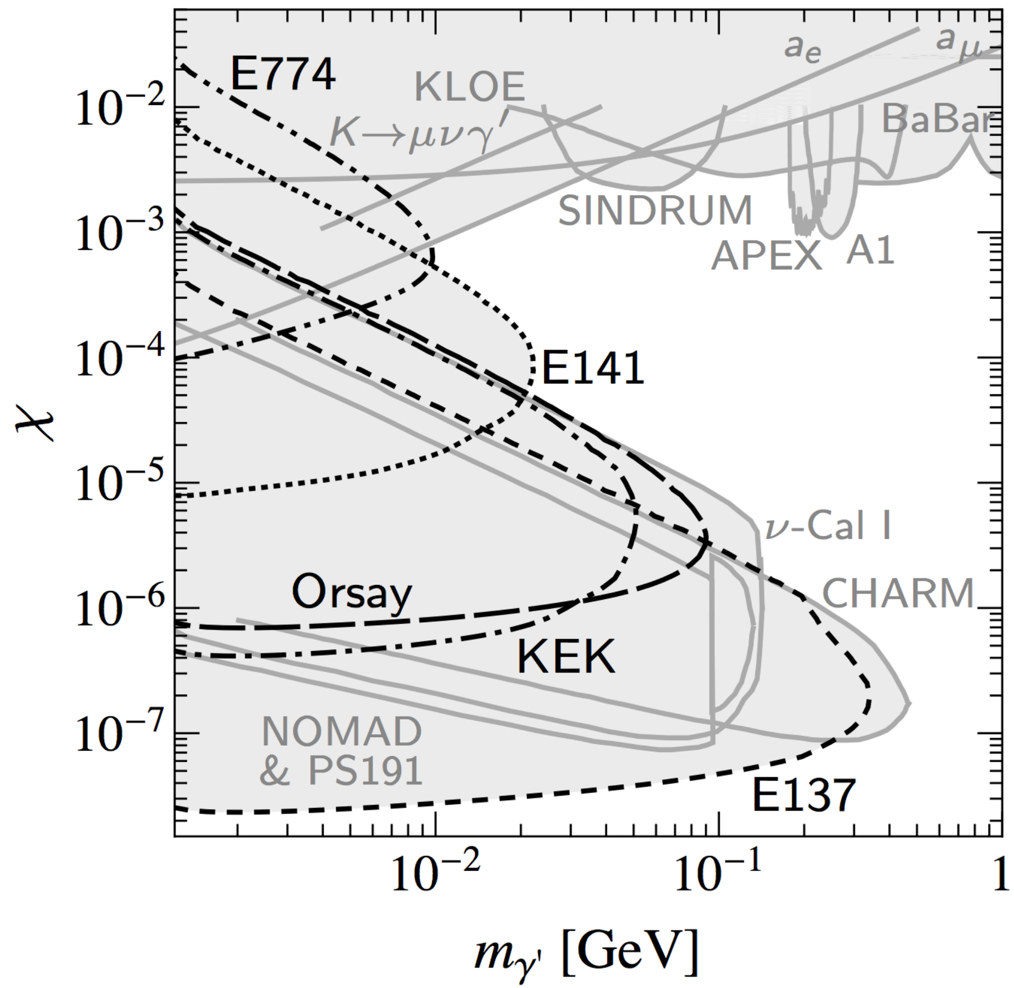
      $\sim 10^{16}\,\mathrm{pot/s};\;\; E \sim 2\,\mathrm{GeV}$
    - Old beam dumps:
      - CHARM

        $2.4 \times 10^{18}\,\mathrm{pot};\;\; E \sim 400\,\mathrm{GeV}$
      - ν-CAL I

        $1.7 \times 10^{18}\,\mathrm{pot};\;\; E \sim 70\,\mathrm{GeV}$
      - NOMAD

        $4.1 \times 10^{19}\,\mathrm{pot};\;\; E \sim 450\,\mathrm{GeV}$
      - PS191

        $8.6 \times 10^{18}\,\mathrm{pot};\;\; E \sim 19.2\,\mathrm{GeV}$



[Andreas]

Summary and conclusions

- The world-wide searches for WIMPy dark matter, including direct detection experiments, searches for WIMPs at colliders, and searches for indirect signals in cosmic rays have reached the decisive stage that within this decade one should see a signal or WIMPs can't make all of DM
- In this case it may well be that the Dark Sector is WISPy
- There is an increasing number of experiments to search for WISPy dark matter with direct WISP dark matter detection experiments and with intense photon, electron and proton beams
- This low energy, high intensity community has still to grow in order to be able to probe all plausible parameter ranges and to be as exhaustive as the WIMP dark matter searches
- Join the party!
- Stay tuned!

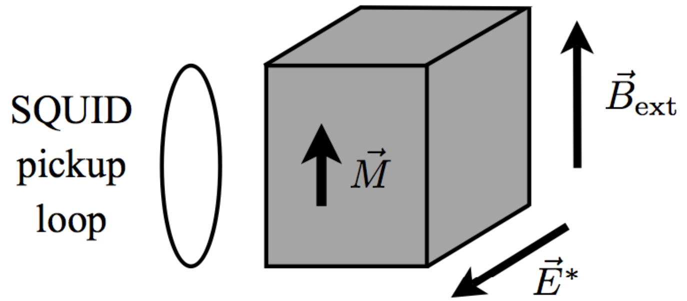
Backup: Haloscope searches

> Proposed searches for axion and ALP dark matter exploiting time varying CP-odd nuclear moments acquired by interactions with the background axion dark matter, e.g.

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

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

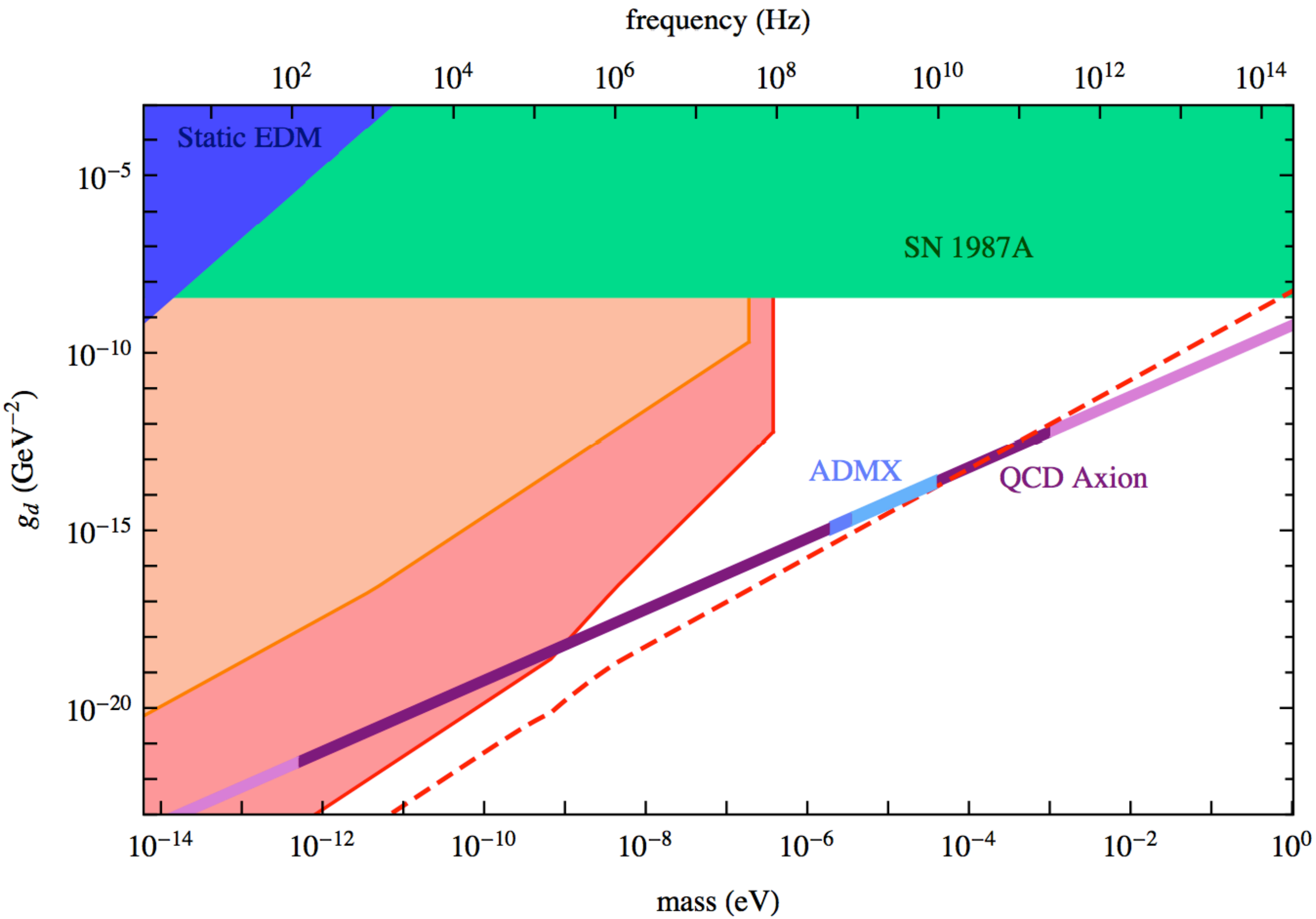
- Moments cause precession of nuclear spins in material sample in presence of background electric field
- Can be searched for with precision magnetometry [Graham,Rajendran 13; Budker et al 11]



- Window of opportunity for GUT scale axions, $m_a \sim m_\pi f_\pi / f_a \sim \mathrm{MHz}\,(10^{16}\,\mathrm{GeV}/f_a)$

Backup: Haloscope searches

- Sensitivity of CASPEr (Cosmic Axion Spin Precession Experiment)



[Budker et al 13]