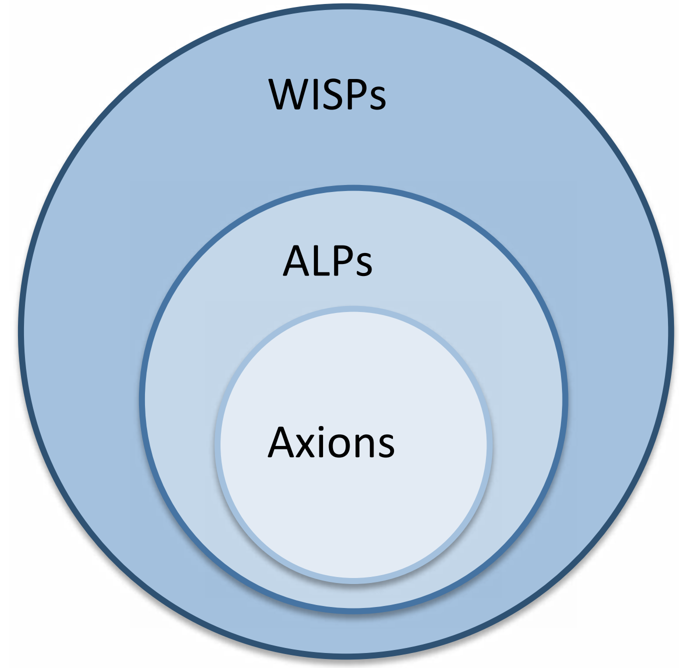
Axions & ALPs (WISPs)

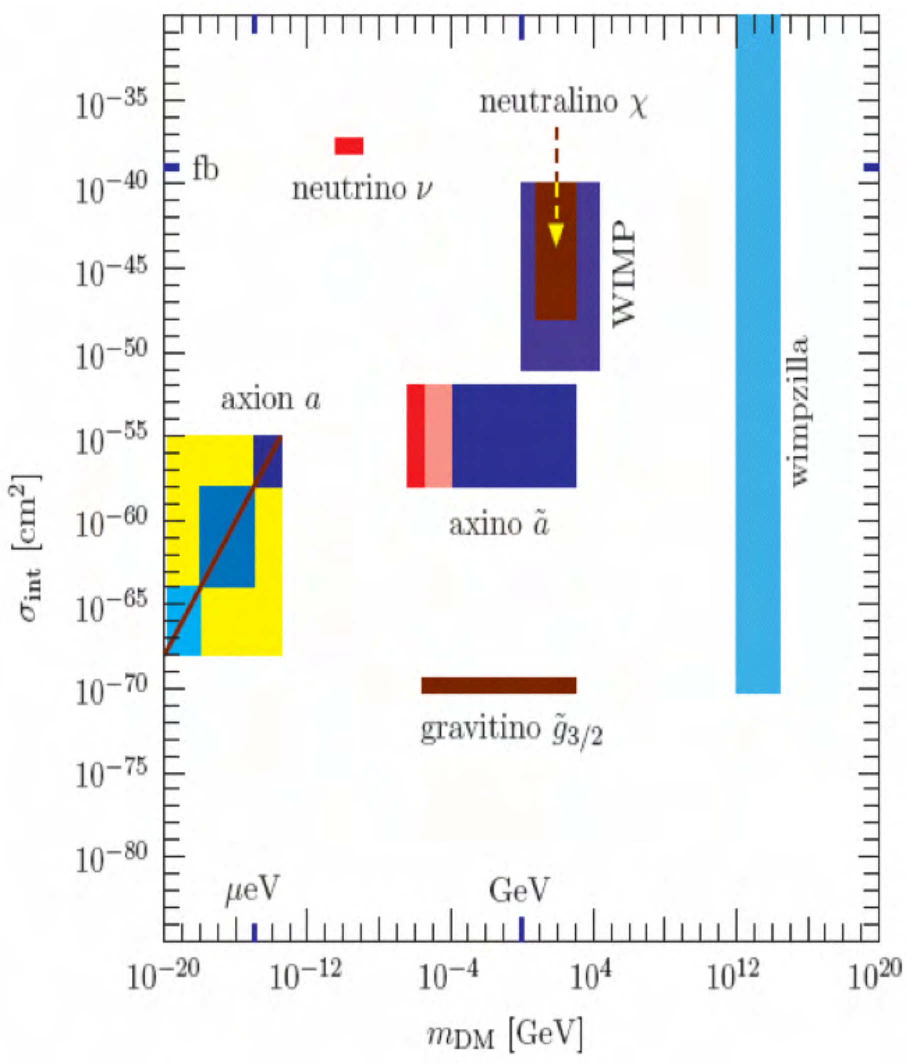


Alessandro De Angelis, INFN/INAF Padova and LIP/IST Lisboa

IDPASC School, Vipava, May 2016

(Credits: D. Horns, S. Parker, G. Raffelt, A. Ringwald, M. Roncadelli)

- Plenty of dark matter (DM) candidates spanning huge parameter range in masses and couplings
- Two classes stand out because of their convincing physics case and the variety of experimental and observational probes:
  - Weakly Interacting Massive Particles (WIMPs), such as neutralinos
  - Weakly Interacting Slim (=ultra-light) Particles (WISPs), such as axions
- Plan:
  - Physics case for axions, axion-like particles (ALPs), WISPs
  - Probes (in the lab, in astroparticle)



WISPs in a nutshell

- Axions. Hypothetical light pseudoscalar postulated to explain the strong CP problem (CP has not a-priori reason to be a symmetry of the QCD Lagrangian; however, CP appears to be conserved in QCD). A SSB at a very-high-energy scale, giving rise to an associated pseudo-scalar boson called the axion, might explain it. Being pseudoscalar (like the π^0), the axion can decay into two photons.

$$g_{a\gamma\gamma} \approx \frac{1}{M} \; ; \; \frac{m_a}{1 \text{ eV}} \sim \frac{1}{\text{M}/(6 \text{ x } 10^6 \text{ GeV})}$$

 Some consequences for cosmological photon propagation (see later).

- ALPs. An extension of axions, relaxing the above relation between mass and coupling.
- Matter in parallel branes; Shadow or Mirror matter. Some theories postulate the presence of matter in parallel branes, interacting with our world only via gravity or a super-weak interaction. In theories popular in the 1960s, a "mirror matter" was postulated to form astronomical mirror objects; the cosmology in the mirror sector could be different from ours, possibly explaining the formation of dark halos. This mirror-matter cosmology has been claimed to explain a wide range of phenomena.

WISPs: why and how

The axion: origins in particle physics

CP symmetry is violated in electroweak interactions; no obvious reason to be conserved in QCD

CP violating term in QCD Lagrangian implies neutron electric dipole moment: $$d_n \simeq \frac{e\,\theta\, m_q}{m_N^2}$$

But measurements place a severe constraint: $$\theta \lesssim 10^{-9}$$

Why is the neutron electric dipole moment (and thus θ) so small?
This is called the **Strong CP Problem**.

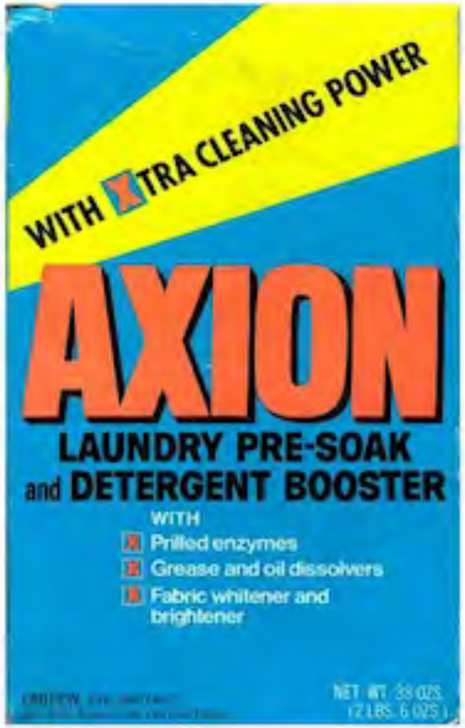
"Simplest" solution: Introduce a $U(1)_{PQ}$ symmetry. This symmetry breaks at some energy scale (f_a); the associated (pseudo) Goldstone boson is the **axion**, which acts as a dynamical CP-conserving field.

Coupling to quarks and gluons gives the axion mass: $g_{a\gamma\gamma} \approx \frac{1}{M}\ ;\ \frac{m_a}{1\ \mathrm{eV}} \sim \frac{1}{\mathrm{M}/(6\ \mathrm{x}\ 10^6\ \mathrm{GeV})}$

Coupling with photons also suppressed by *g*

"Weakly" interacting, small mass particle: **WISP**.

Mechanism by Peccei and Quinn, name by Wilczek




Frank Wilczek

"I named them after a laundry detergent, since they clean up a problem with an axial current."
(Nobel lecture 2004)

The axion can be cold

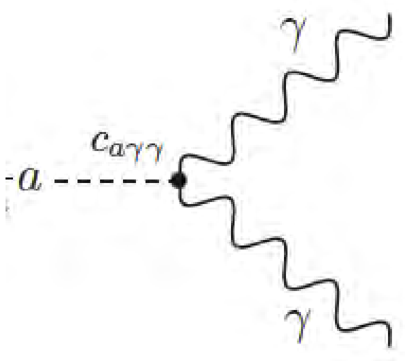
- Both thermal and non thermal production mechanisms are possible
- Thermal decoupling mechanism should dominate for m > 10 meV (HDM)
- Non-thermal production mechanism should dominate for m < 0.1 meV (CDM)
  – During QCD phase transition, free quarks form bound hadrons, and along that a Bose condensate of axions is also formed (Weinberg 1978, Wilczek 1978)

Axion / Photon Coupling

Axion- 2 photon coupling: same formalism as $\pi^0 \rightarrow \gamma\gamma$

Axion-2 photon coupling provides very important experimental and observational access (with minimal model dependence).

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\, a\, \vec{E} \cdot \vec{B}$$



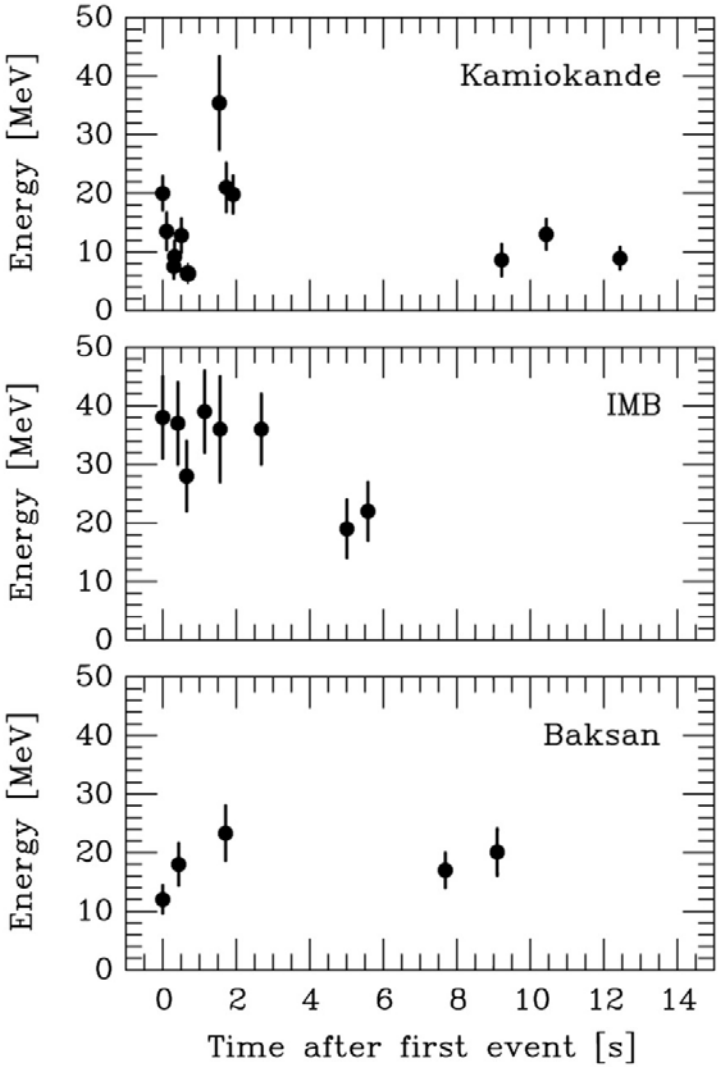
B field can act as 2nd virtual photon to induce axion-photon conversion

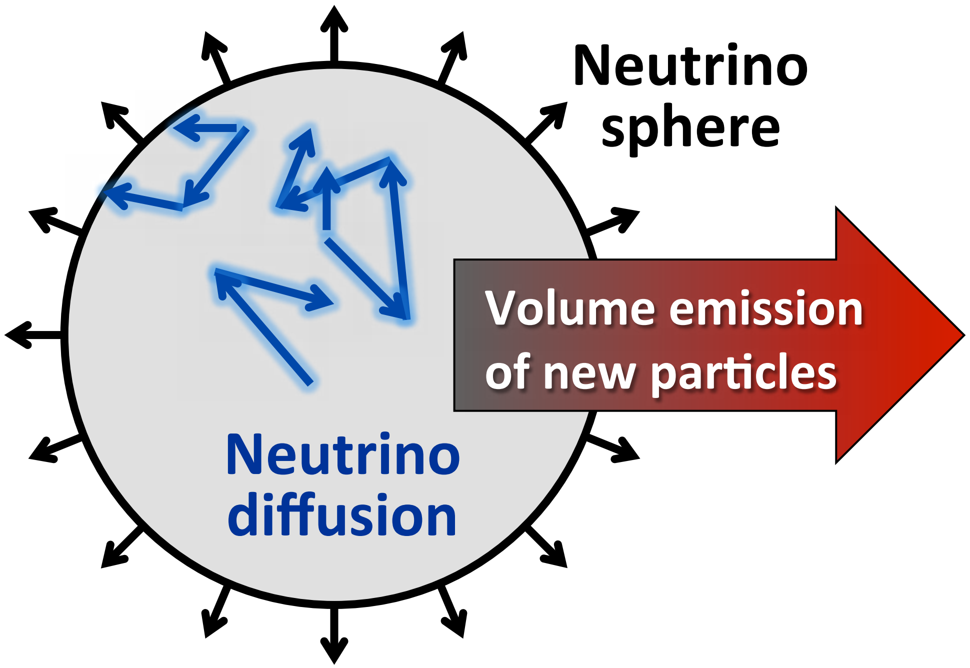
Axion mass dictates photon frequency

Want to test / bind $g_{a\gamma\gamma}$

Constraints from astrophysics

SN 1987A neutrino signal

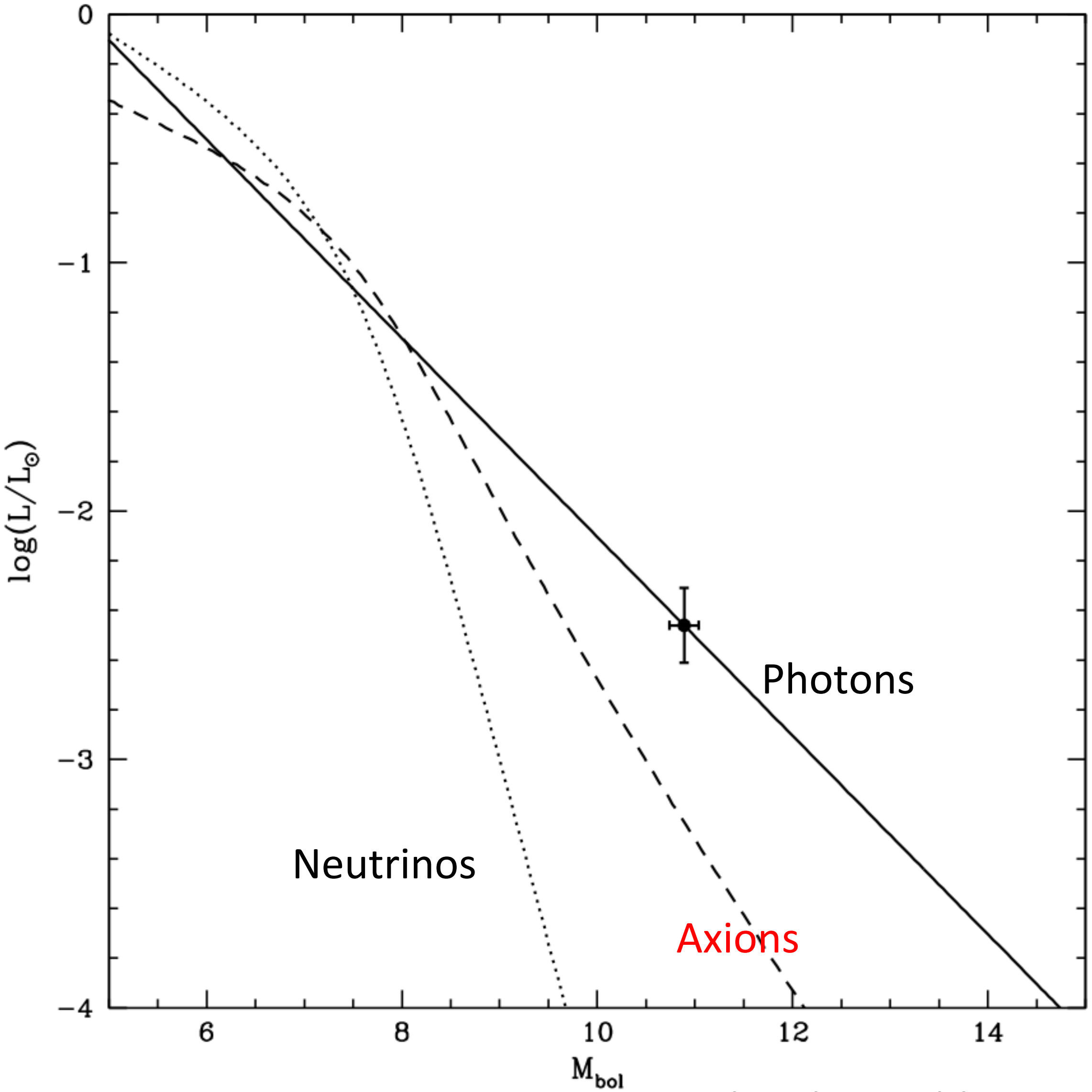




Emission of very weakly interacting particles might "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

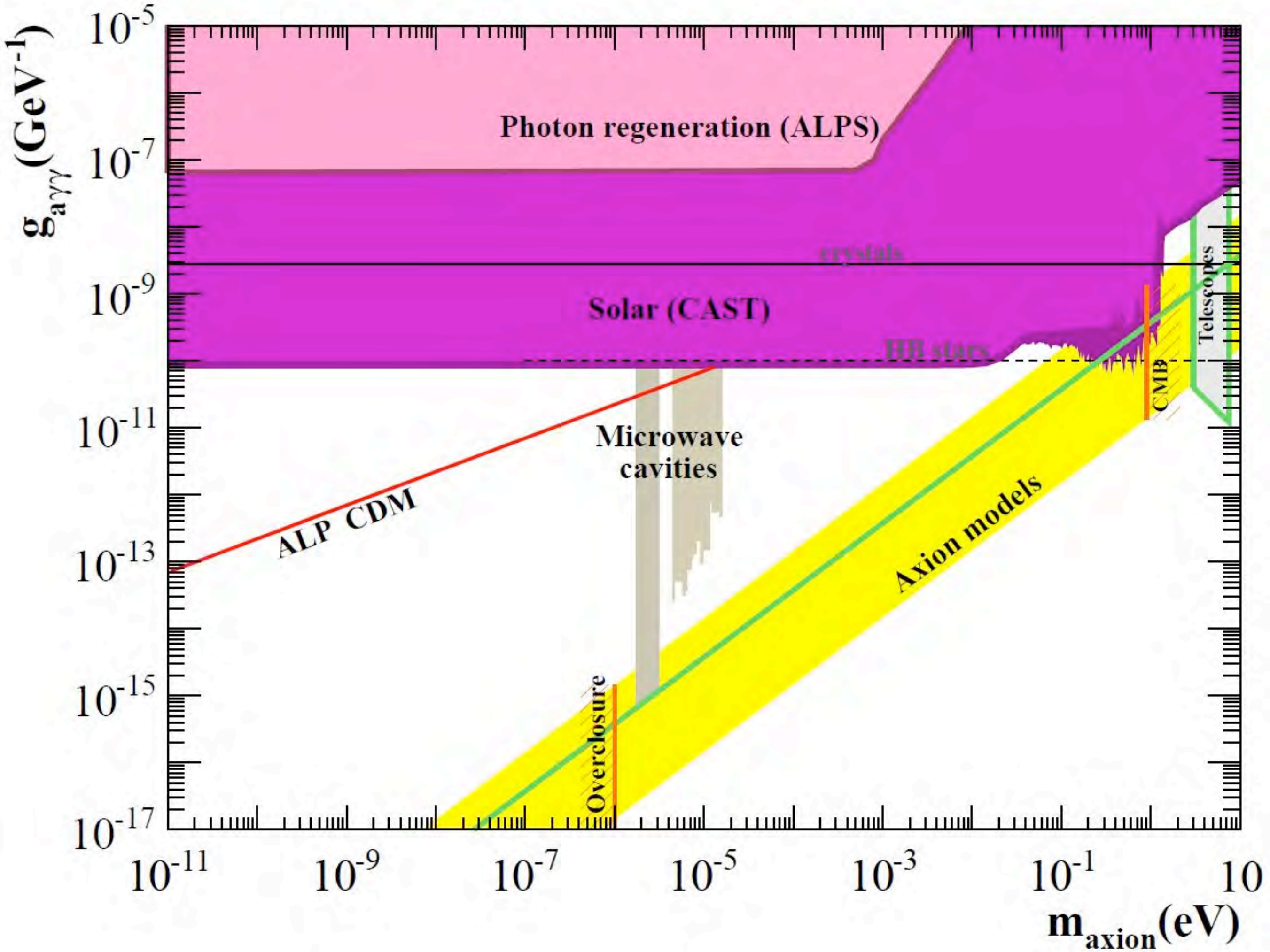
Late-time signal most sensitive observable

Energy loss (Period Change) of White Dwarfs



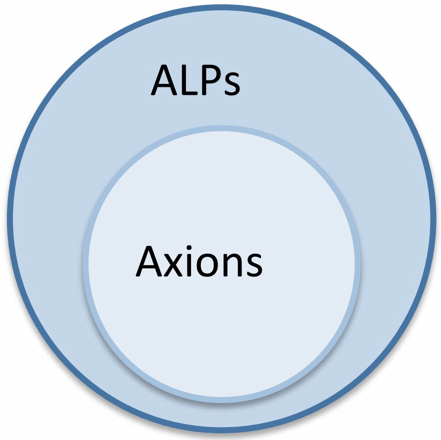
The observable is not very sensitive

Axion Mass / Photon Coupling



From axions to ALPs

- Non-minimal model
- Release the constraint of proportionality
  between mass and coupling



From ALPs to WISPs
example: para-photons in hidden sectors

Different SM extensions introduce “hidden sectors” of particles due to addition of extra symmetries.

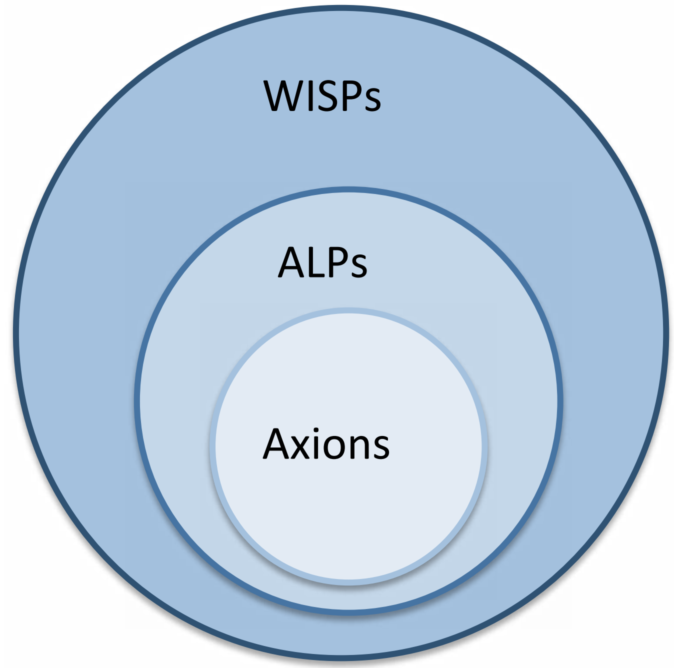
Addition of extra U(1) symmetry interacts very weakly via kinetic mixing of the gauge bosons.

Consequence: Photon – Hidden Sector Photon oscillations

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \boxed{\frac{1}{2}\chi F^{\mu\nu}B_{\mu\nu}} + \frac{1}{2}\left(\frac{c}{\hbar}m_{\gamma\prime}\right)^2 B^{\mu}B_{\mu}$$

Broad range of allowable mass and coupling strength.

Can be formulated as WISP Dark Matter



Experimentalist’s approach: It’s like an axion but without the need for a magnetic field
And no spin formalism is needed

Probing WISPs: laboratory experiments

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

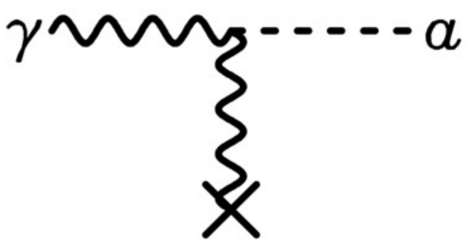
Experimental Tests of the "Invisible" Axion

P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611
(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

Primakoff effect:

Axion-photon transition in external static E or B field
(Originally discussed for π^0
by Henri Primakoff 1951)

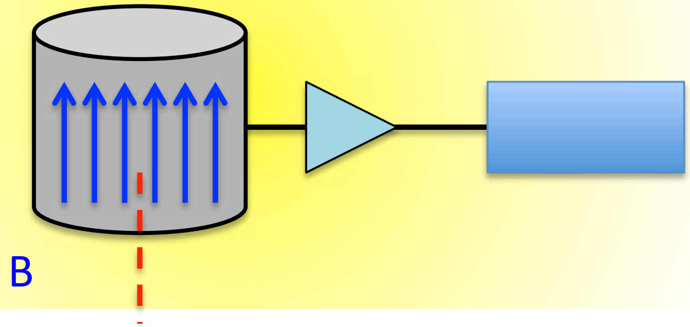


Pierre Sikivie:

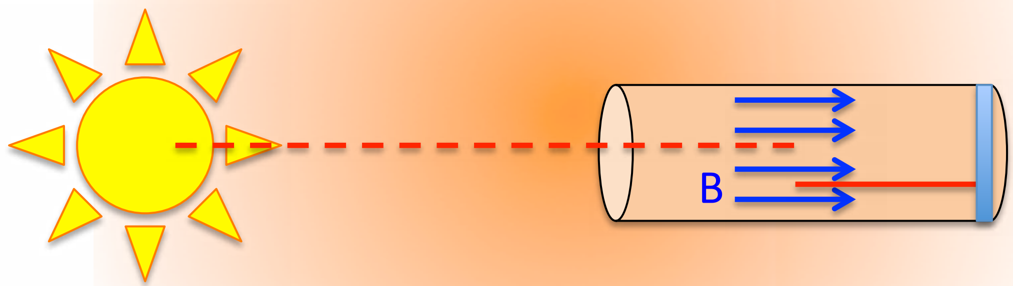
Macroscopic B-field can provide a large coherent transition rate over a big volume (low-mass axions)

- Axion haloscopes:
  Look for dark-matter axions in a cavity
- Axion helioscopes:
  Look at the Sun through a dipole magnet

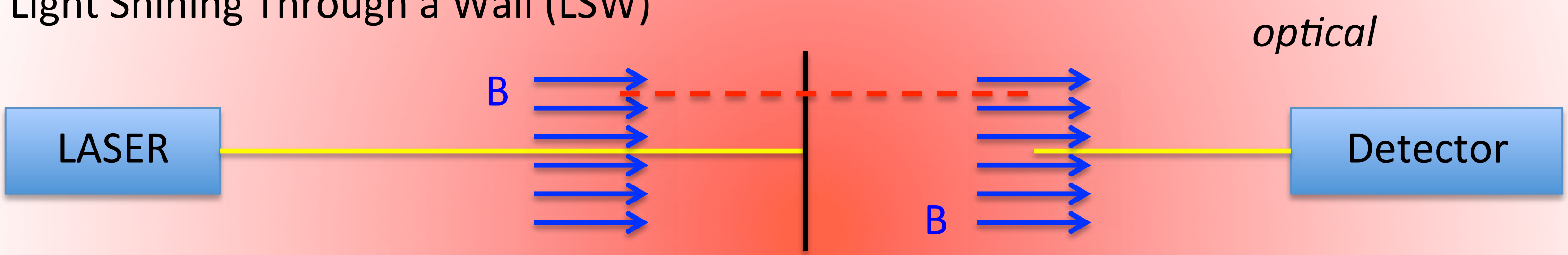
Haloscopes (direct search)
Cavities (birefringence, dichroism)



Helioscopes

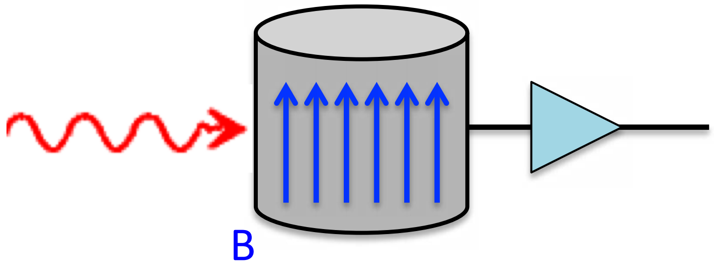


Light Shining Through a Wall (LSW)



Haloscopes Cavities	Helioscopes	Light Shining Through a Wall
		Optical
PVLAS (Legnaro/Trieste) WISPDMX (DESY)	CAST (CERN) TSHIPS (DESY)	OSQAR (CERN) ALPS/ALPS-II (DESY) GammeV/REAPR (Fermilab)
	Sumico (Tokyo)	
		Microwave
	IAXO (?)	
ADMX (UW) ADMX-HF (Yale) CAPP (IBS/KAIST)		ADMX (UW) CROWS (CERN) UWA Yale

Axion haloscopes



Cavity enables resonant enhancement of converted photon signal

$$P_{Sig} = g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) B_0^2 V C Q$$

Expected signal (power in W)

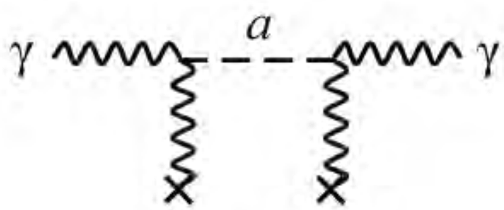
ρ_a – Axion density (~0.3 GeV/cm^3)
m_a – Axion mass
B_0 – Magnetic field strength
V – Cavity volume
C – Form factor (E.B overlap)
Q – Cavity quality factor

Measure power to constrain axion-photon coupling.

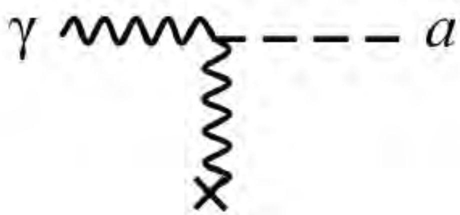
One more good use of cavities

- Detect birefringence/dichroism in "vacuum"
- Physics similar to LSW experiments; technique similar to haloscopes

BIREFRINGENCE i. e. linear polarization becomes ELLIPTICAL with its major axis PARALLEL to the initial polarization.

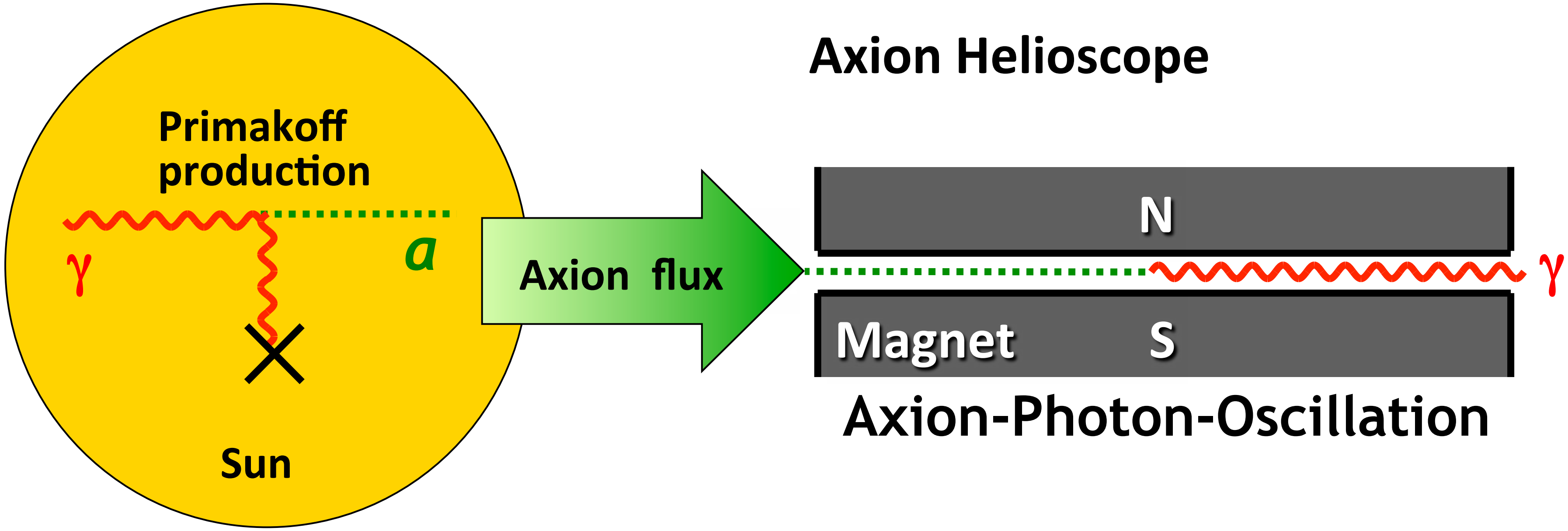


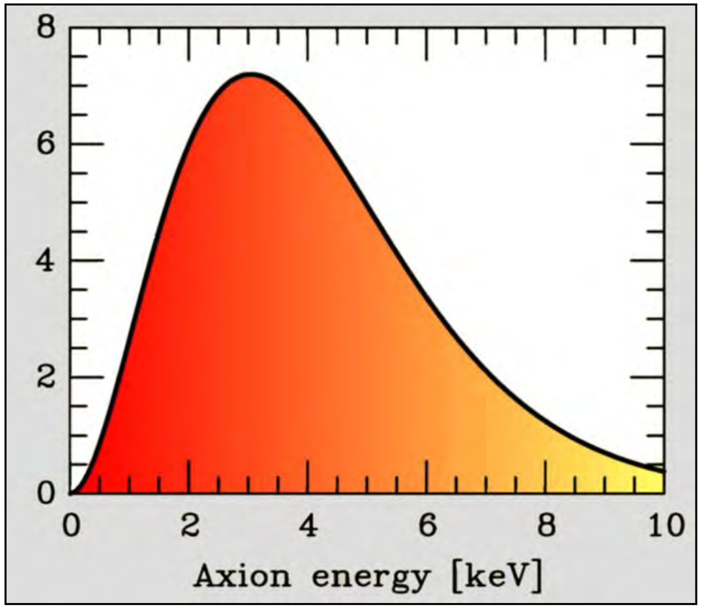
DICHROISM i. e. selective photon ABSORPTION, which causes the ellipse's major axis to be MISALIGNED with respect to the initial polarization.



- Note: birifringence expected also in standard QED vacuum (but not measured, yet)

Helioscopes: search for solar axions



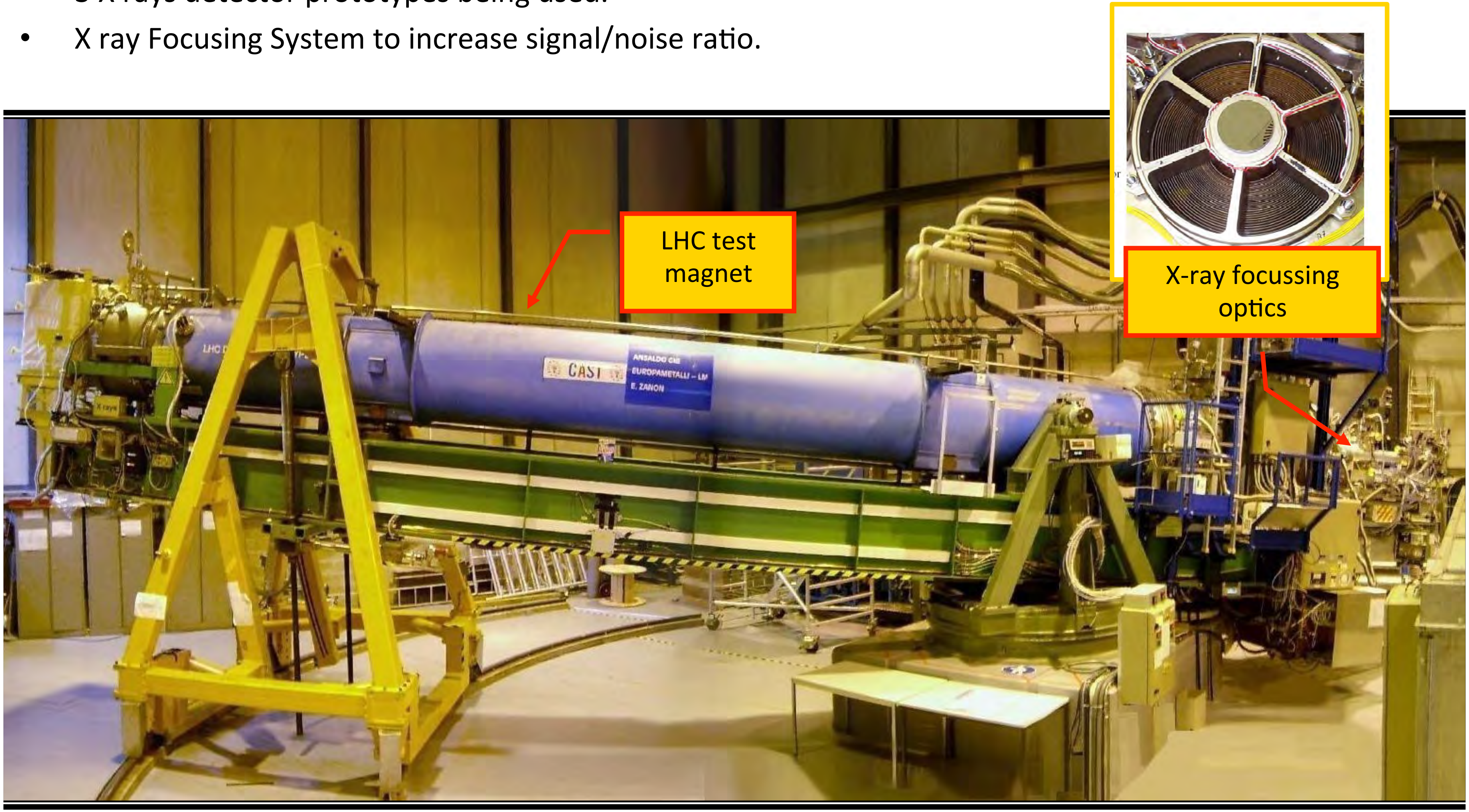


- Tokyo Axion Helioscope ("Sumico") (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST) (Data since 2003)

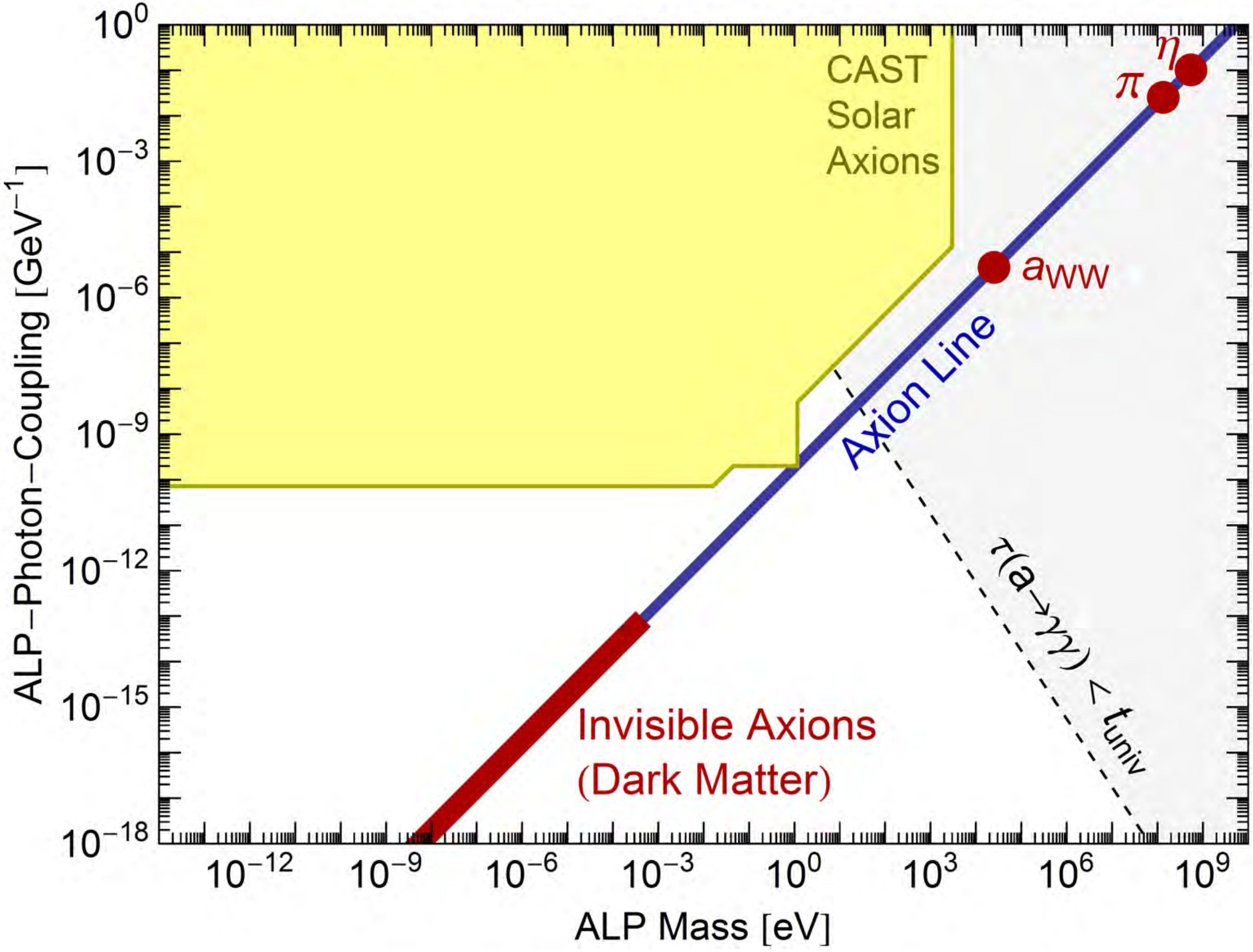
Experimental limits on solar axion flux from dark-matter experiments (SOLAX, COSME, DAMA, CDMS ...)

CAST @ CERN

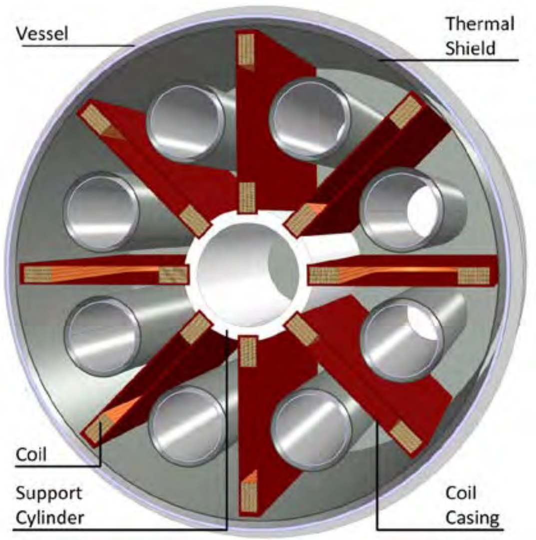
- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 3 X rays detector prototypes being used.
- X ray Focusing System to increase signal/noise ratio.

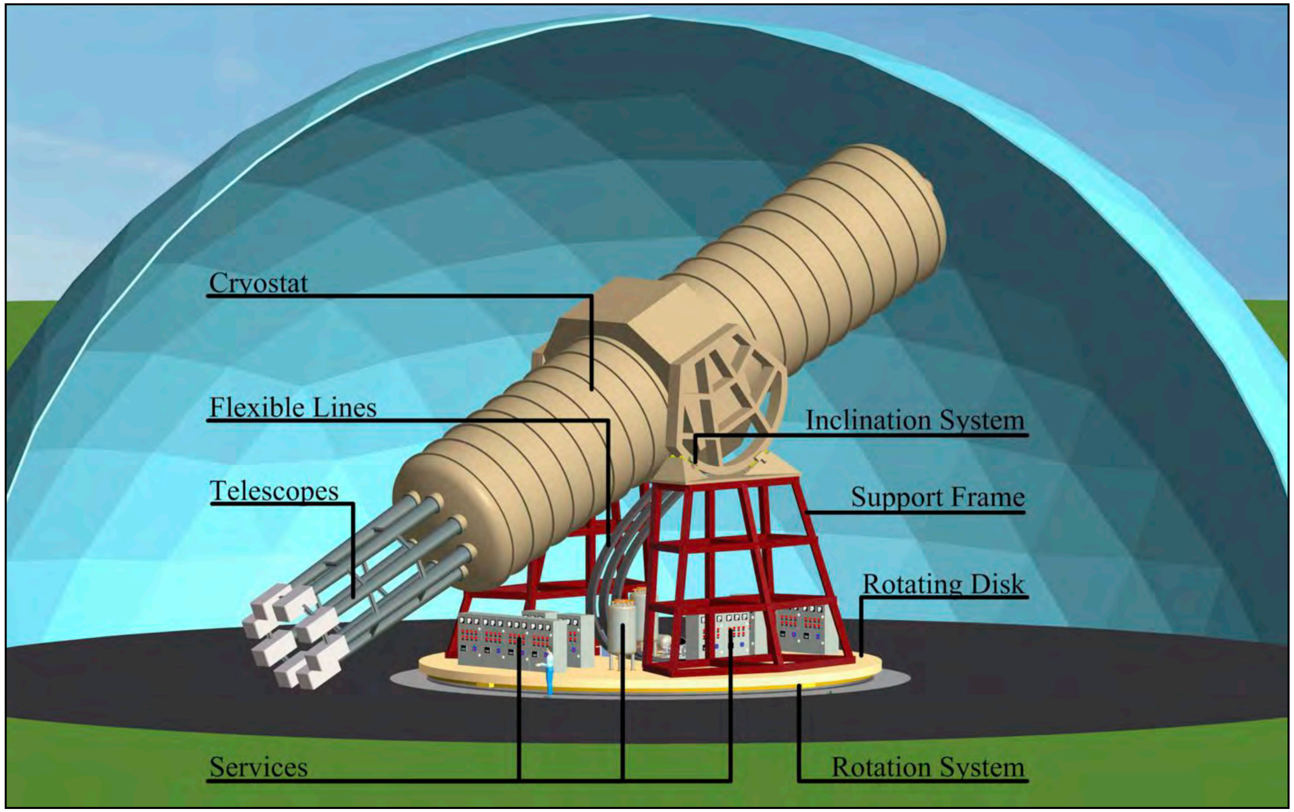


Parameter Space for ALPs



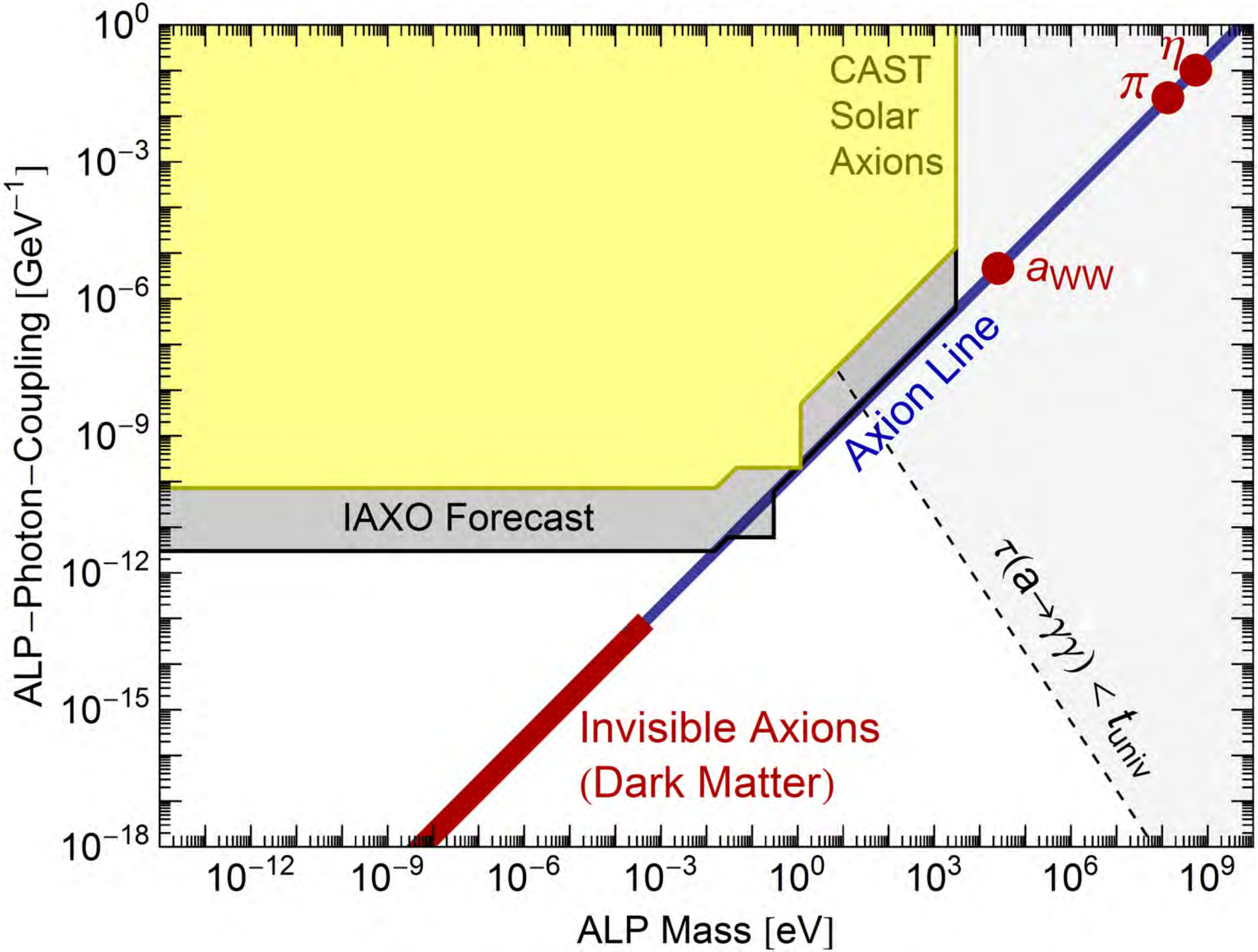
Next Generation Axion Helioscope (IAXO)





Need new magnet w/
– Much bigger aperture: $\sim 1\ m^2$ per bore
– Lighter (no iron yoke)
– Bores at T_{room}

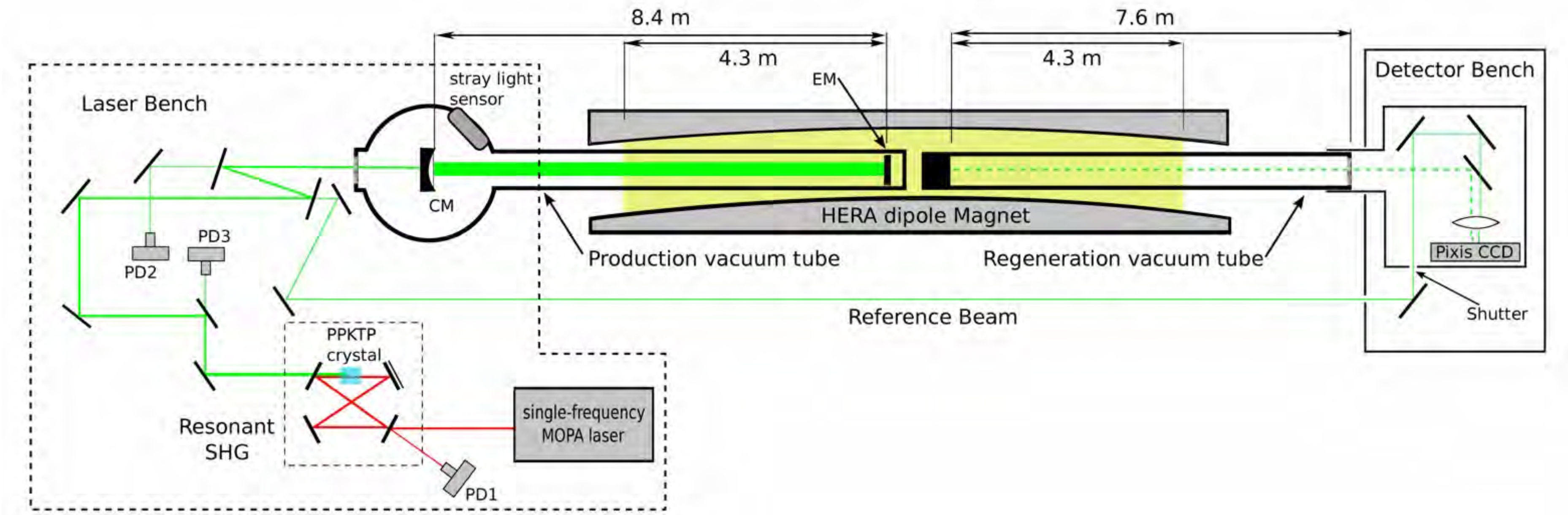
- 5.2 m in diameter and 25 m length. Magnetic field of 5.4 T
- Conceptual Design of the International Axion Observatory (IAXO), arXiv:1401.3233



CAST
Solar
Axions
IAXO Forecast
Axion Line
a_{WW}
π
η
Invisible Axions
(Dark Matter)
$\tau(a\to\gamma\gamma) < t_{univ}$
ALP−Photon−Coupling [GeV^{-1}]
ALP Mass [eV]
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}

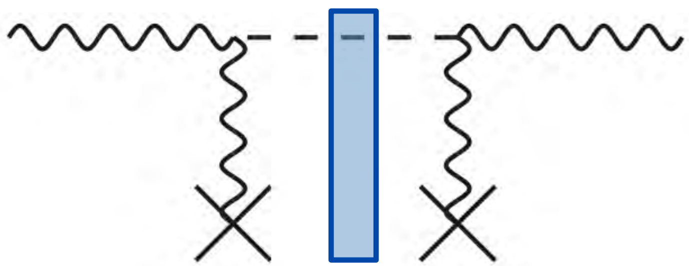
Photon regeneration experiments (LSW)

Ehret et al. (ALPS Collaboration), arXiv:1004.1313

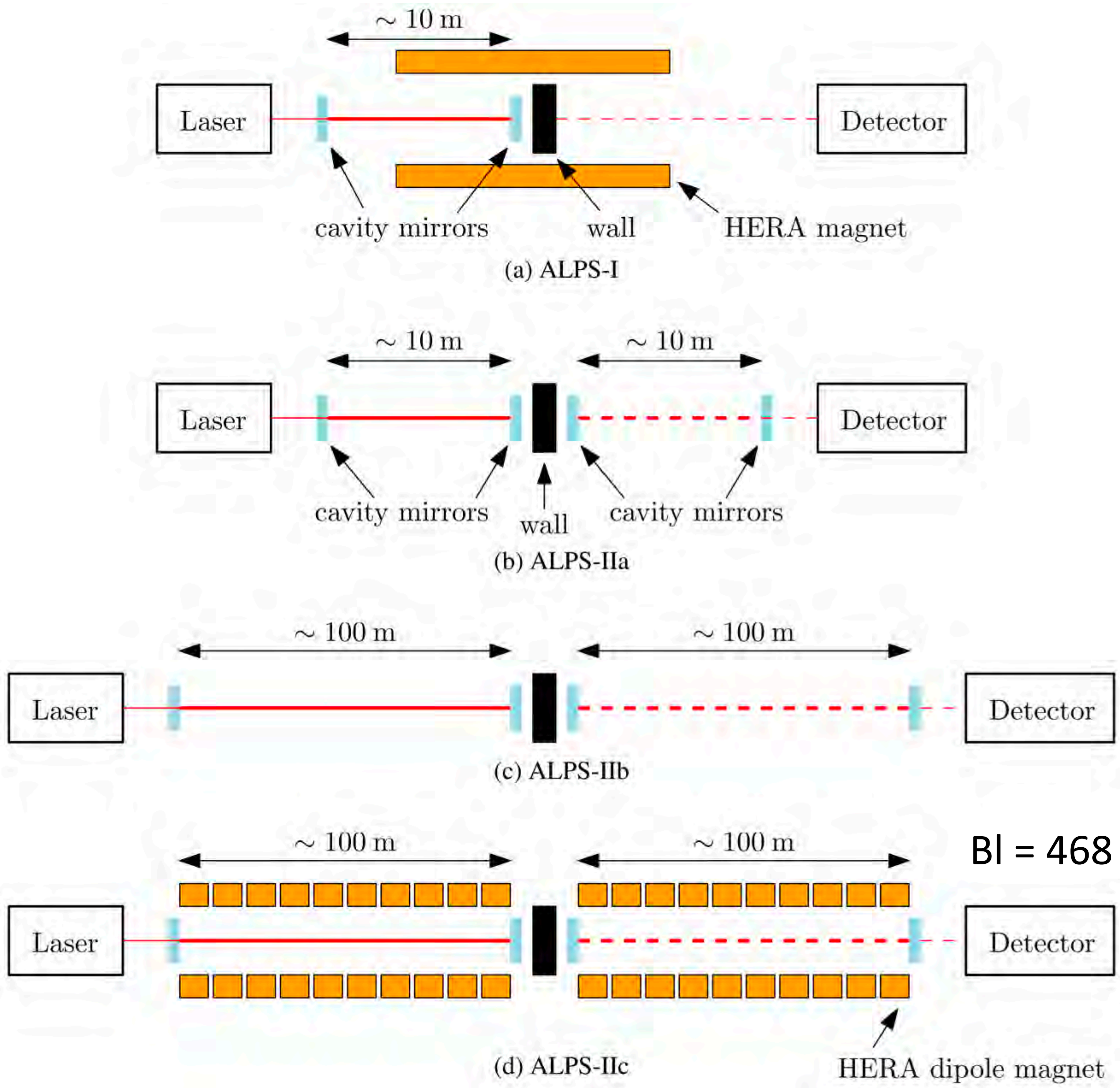


Recent “shining-light-through-a-wall” or vacuum birefringence experiments:

- ALPS (DESY, using HERA dipole magnet)
- BMV (Laboratoire National des Champs Magnétiques Intens, Toulouse)
- BFRT (Brookhaven, 1993)
- GammeV (Fermilab)
- LIPPS (Jefferson Lab)
- OSQAR (CERN, using LHC dipole magnets)
- PVLAS (INFN Trieste/Legnaro)



Any Light Particle Search II (ALPS-II) at DESY



ALPS (finished)

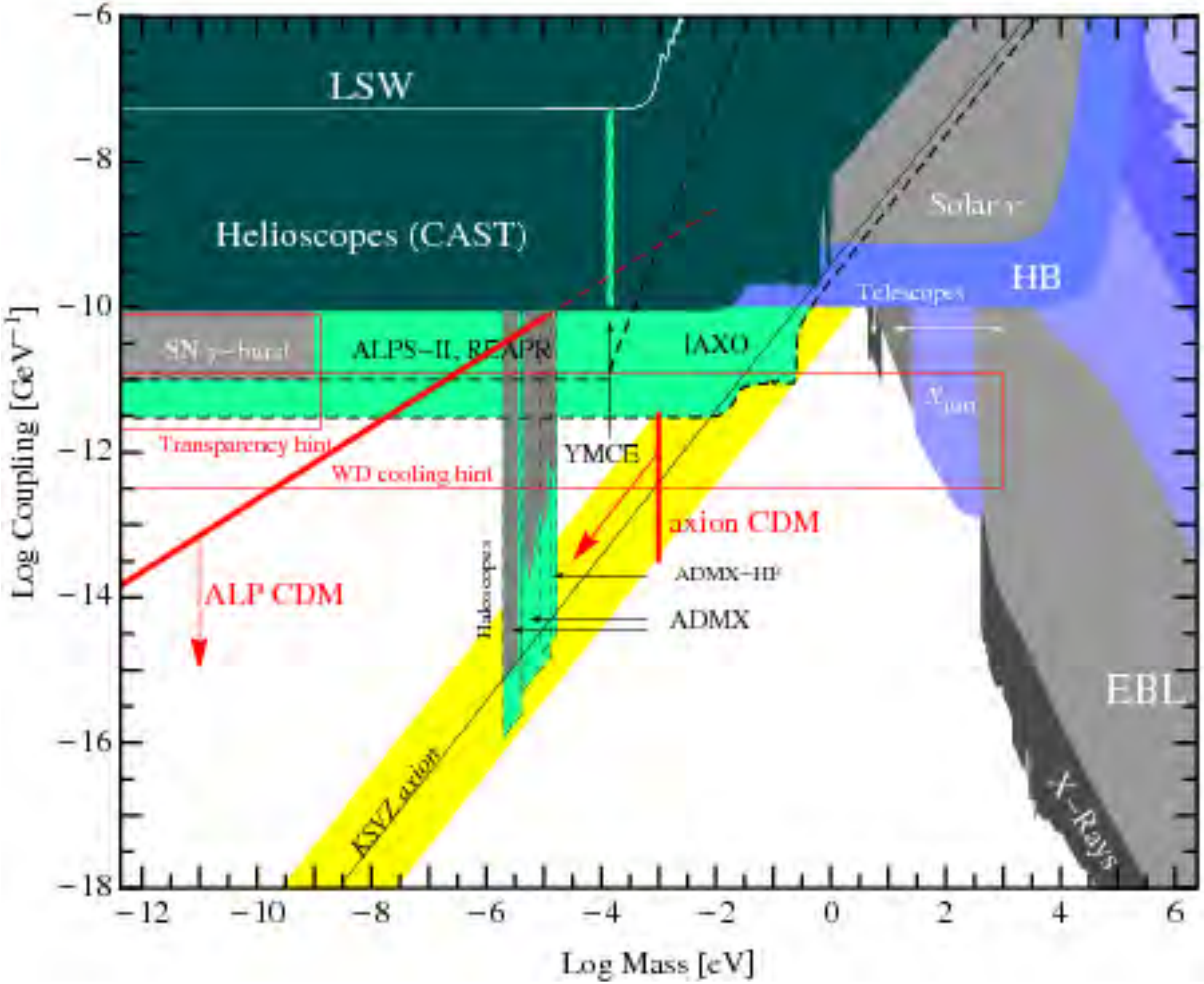
ALPS-IIa (2016)

ALPS-IIb (2017)

Bl = 468 Tm

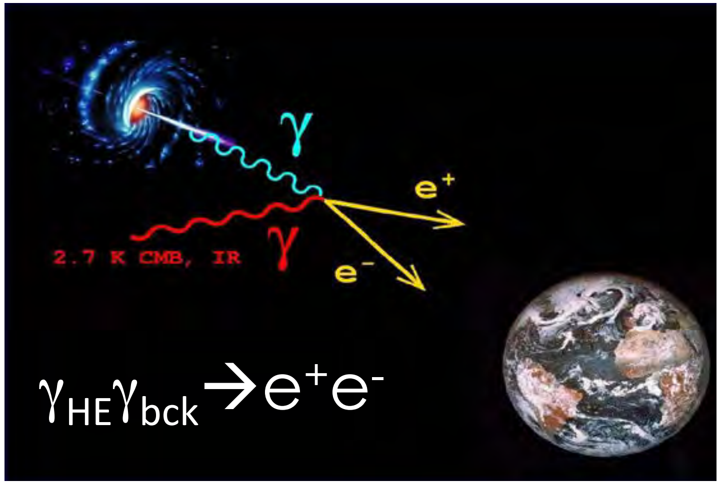
ALPS-IIc (2019)

ALPS-II Technical Design Report, arXiv:1302.5647


LSW
Helioscopes (CAST)
Solar ν
HB
Telescopes
SN γ-burst
ALPS-II, REAPR
IAXO
Transparency hint
WD cooling hint
YMCE
axion CDM
ADMX-HF
ADMX
ALP CDM
Haloscopes
KSVZ axion
EBL
X-Rays
Log Coupling [GeV^{-1}]
Log Mass [eV]
−6
−8
−10
−12
−14
−16
−18
−12
−10
−8
−6
−4
−2
0
2
4
6

WISPs and the cosmological propagation of photons

Attenuation of γ–rays

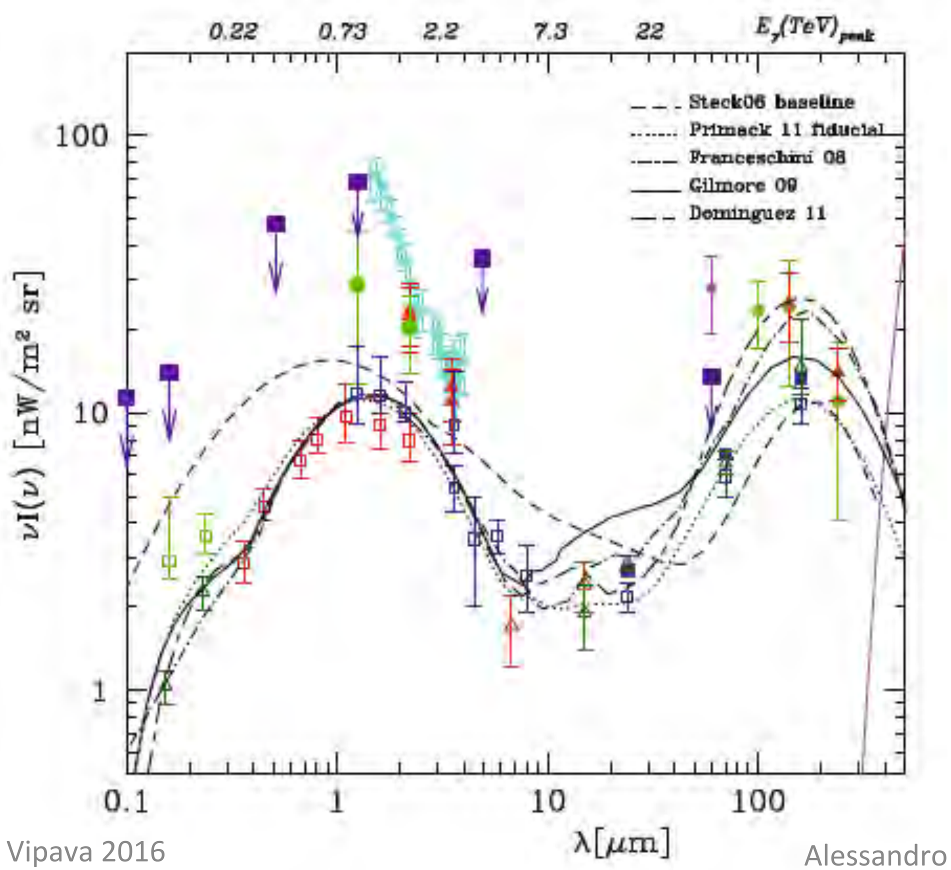


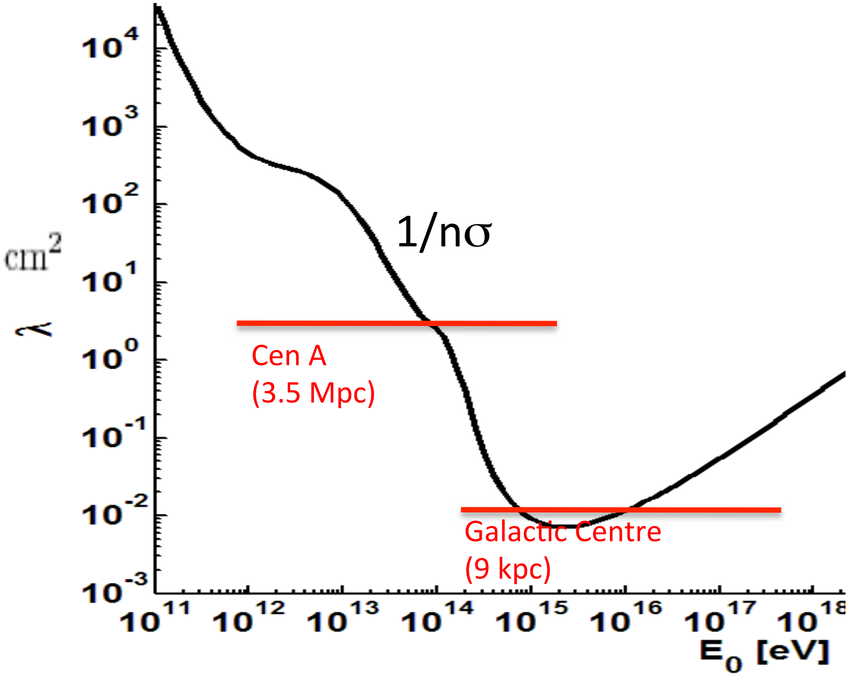
- γ-rays are effectively produced in EM and hadronic interactions
  - Energy spectrum at sources E^{-2}
- are effectively detected by space- and ground-based instruments
- effectively interact with matter, radiation ($\gamma\gamma \rightarrow e^+e^-$) and B-fields
- The interaction with background photons in the Universe attenuates the flux of gamma rays
- The "enemies" of VHE photons are photons near the optical region (Extragalactic Background Light, EBL)

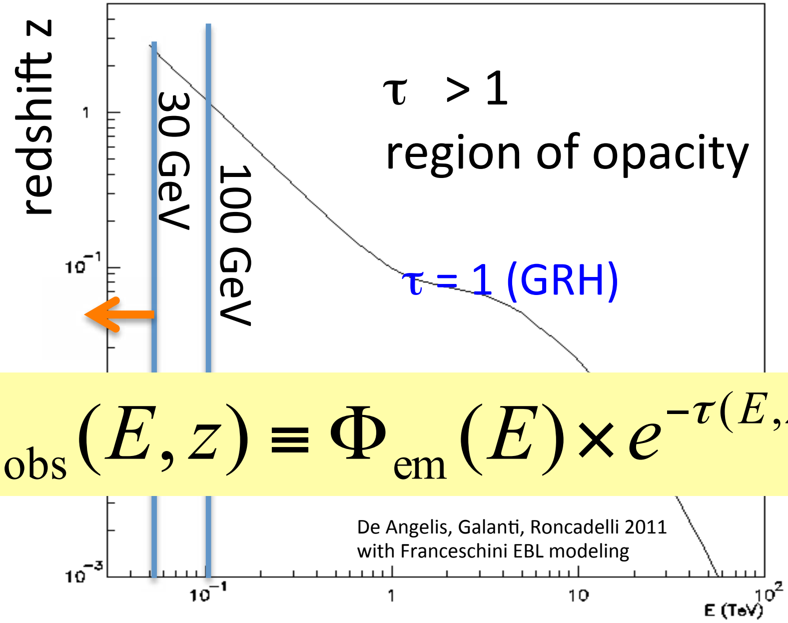
$\gamma_{VHE}\gamma_{bck} \rightarrow e^+e^-$

$\sigma(\beta) \sim$ $$1.25 \cdot 10^{-25}(1-\beta^2) \cdot \left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \mathrm{cm}^2$$

Max for: $$\epsilon \simeq \frac{2m_e^2c^4}{E} \simeq \left(\frac{500\ \mathrm{GeV}}{E}\right) \mathrm{eV}$$





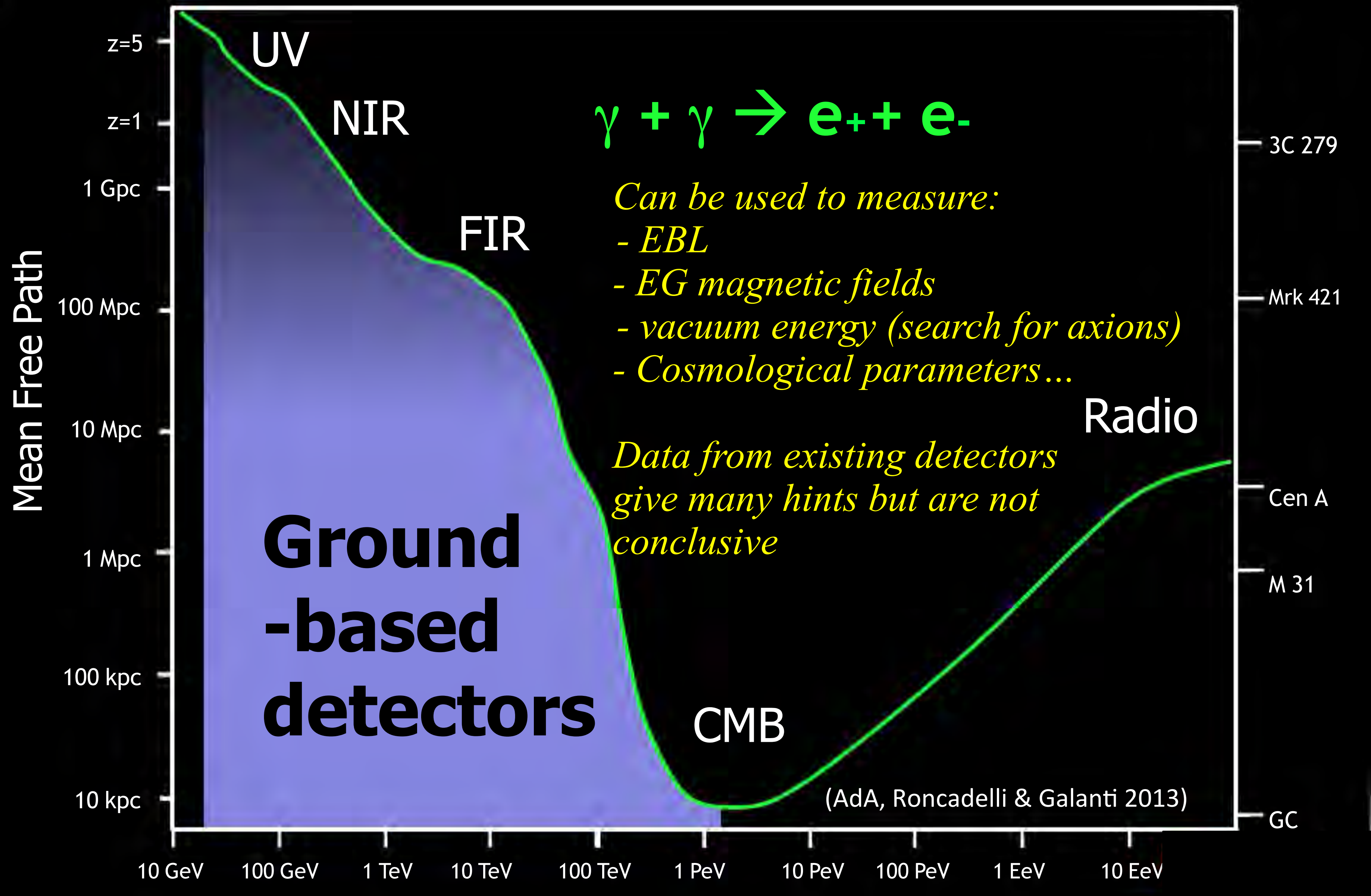


$$\Phi_{obs}(E,z) \equiv \Phi_{em}(E) \times e^{-\tau(E,z)}$$

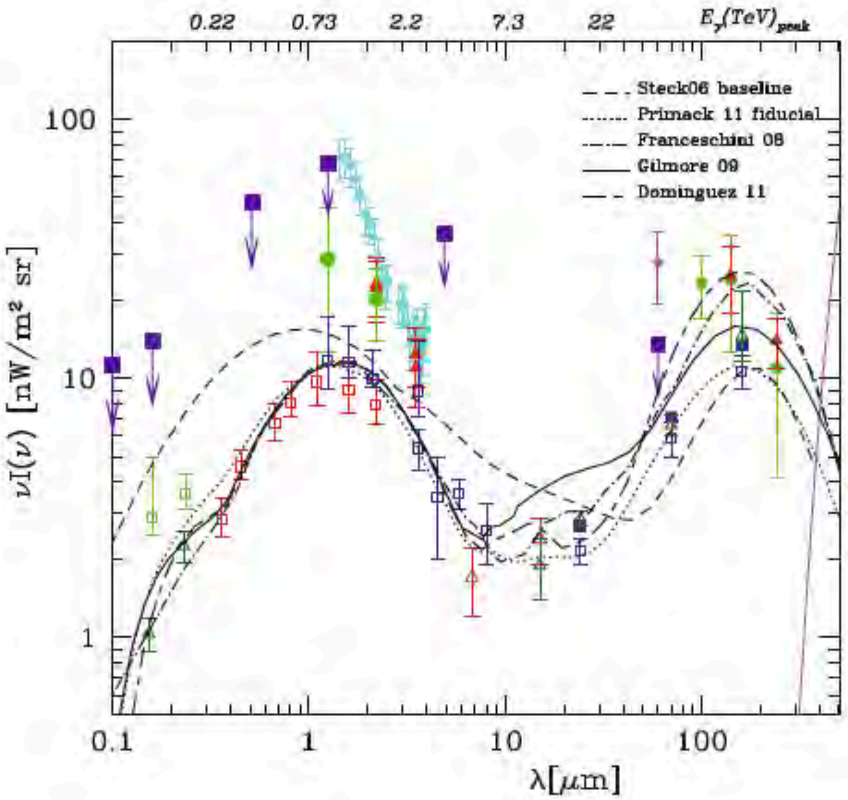
γ ray energy (TeV)

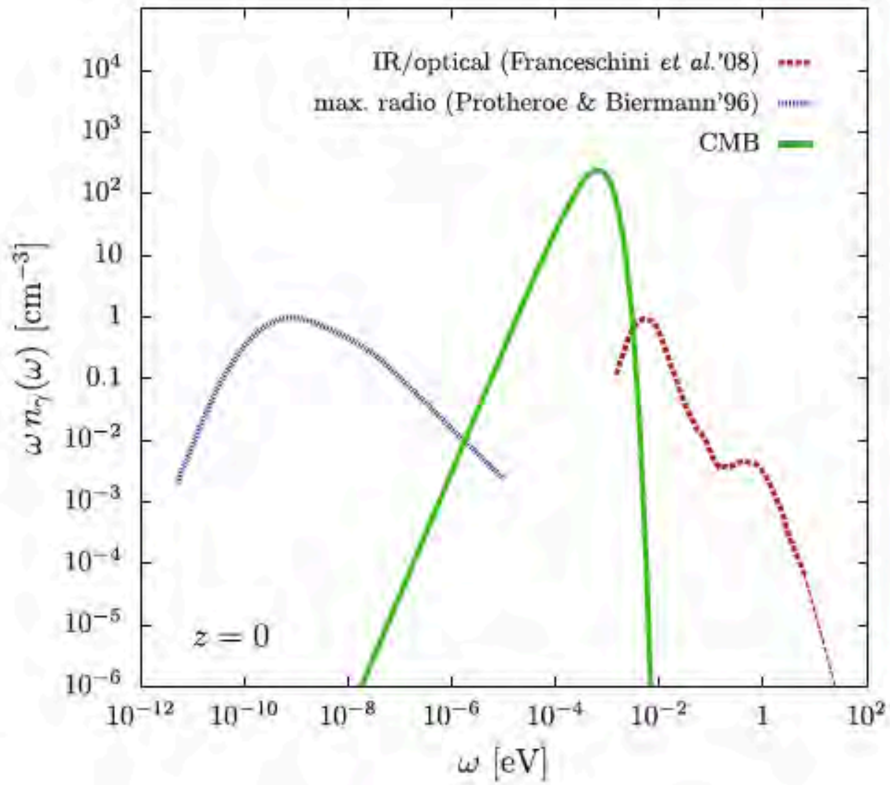
- The diffuse extragalactic background light (EBL) is all the accumulated radiation in the Universe due essentially to star formation processes
  - This radiation covers a wavelength range between ~0.1 and 600 μm (consider the redshift and the reprocessing)
  - After the CMB, the EBL is the second-most energetic diffuse background
- The understanding of the EBL is fundamental
  - To know the history of star formation
  - To model VHE photon propagation for extragalactic VHE astronomy. VHE photons coming from cosmological distances are attenuated by pair production with EBL photons. This interaction is dependent on the SED of the EBL.
- Therefore, it is necessary to know the SED of the EBL in order to study intrinsic properties of the emission in the VHE sources.

The γ horizon: nuisance and resource



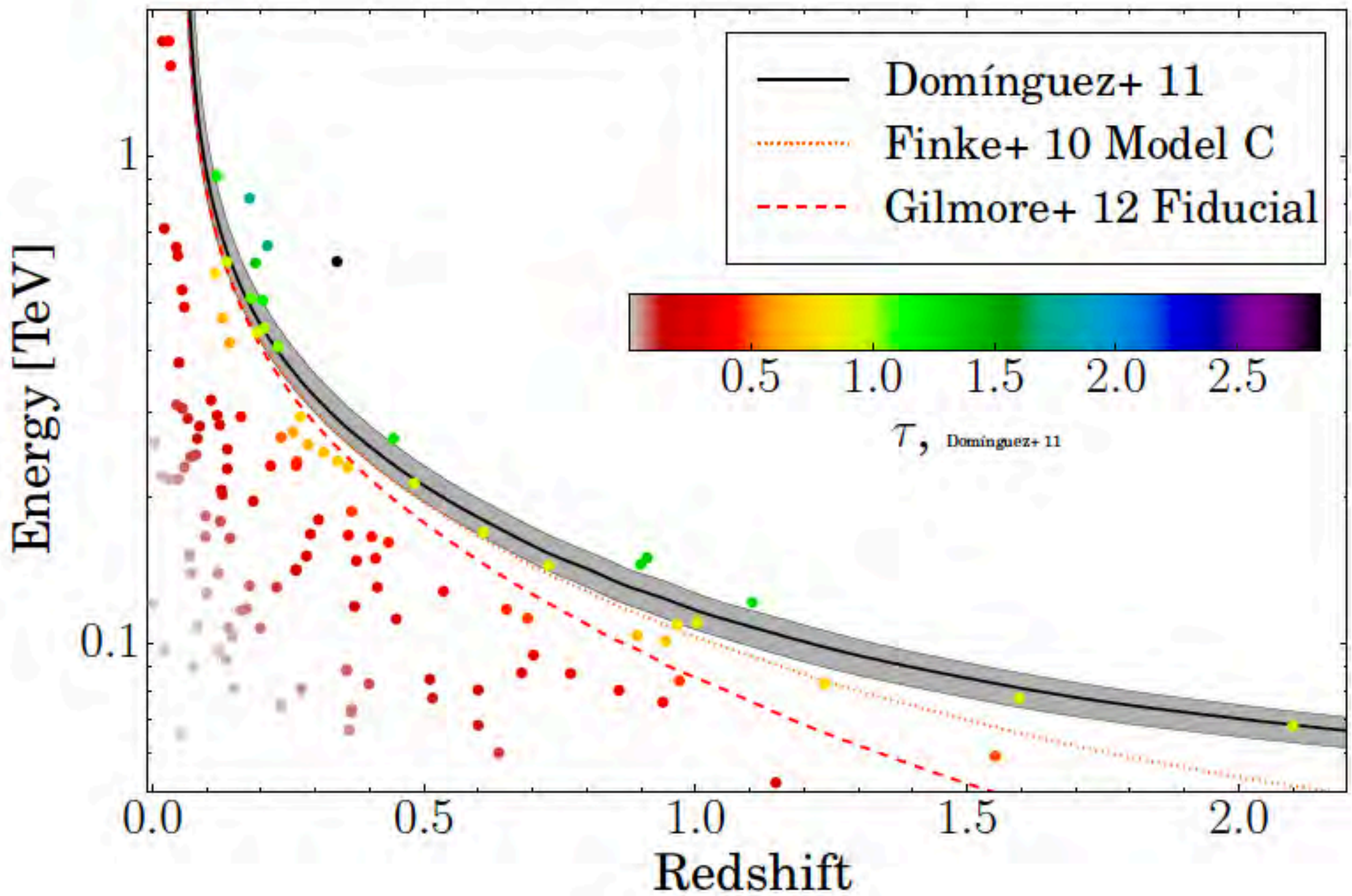
EBL





The EBL affects in particular the signal from extragalactic sources

Fermi 2FHL and gamma horizon



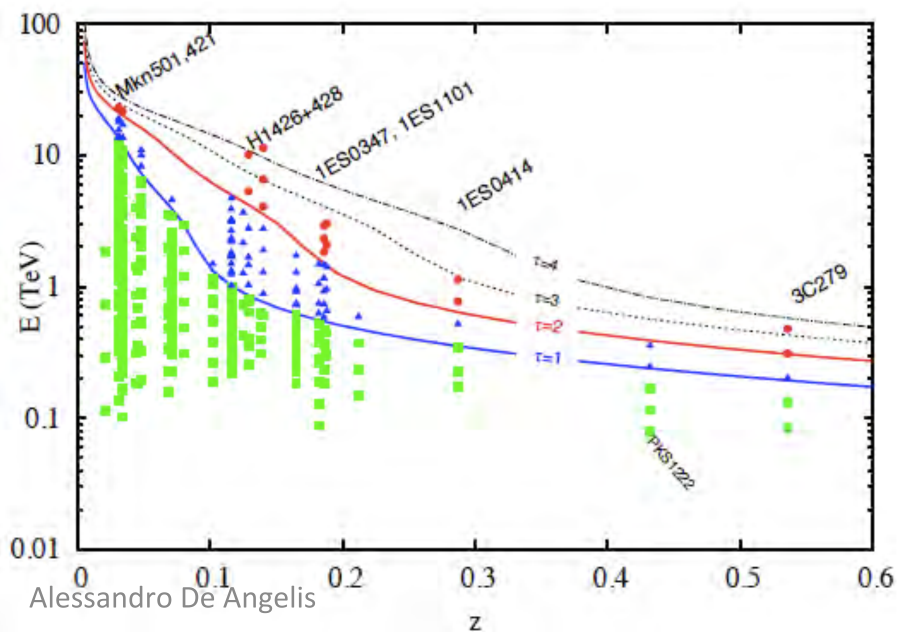
Anomalous effects on cosmological γ propagation

Are our AGN observations consistent with theory?

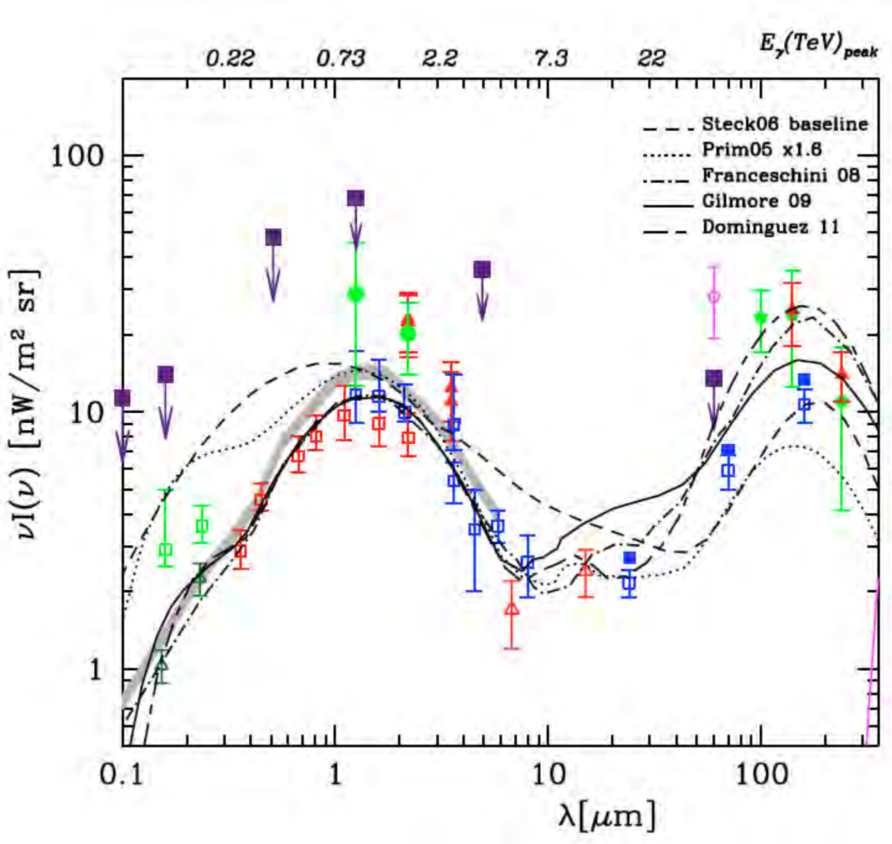
- For each AGN detected, a corresponding lower limit on the optical depth τ is calculated using a minimum EBL model
- Nonparametric test of consistency
- Disagreement with data: overall significance of 4.2 σ

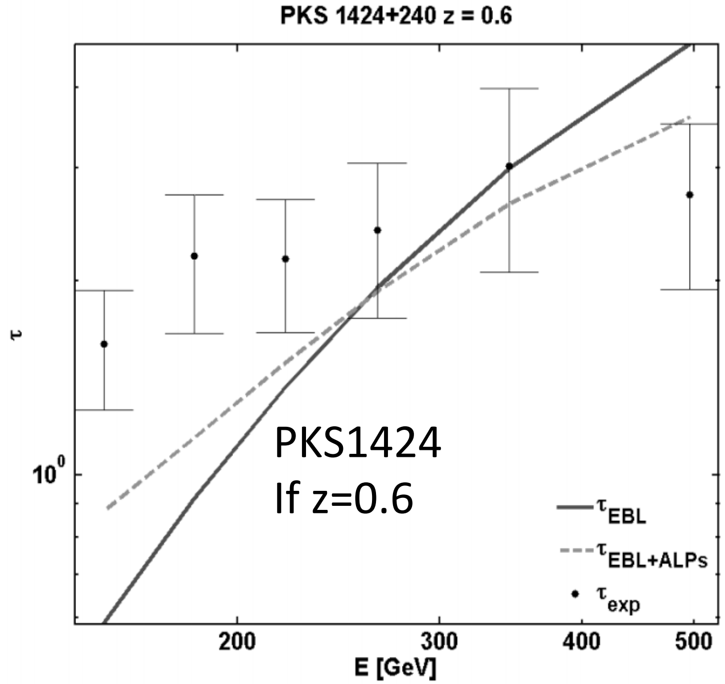
=> <u>Understand experimentally the outliers</u>

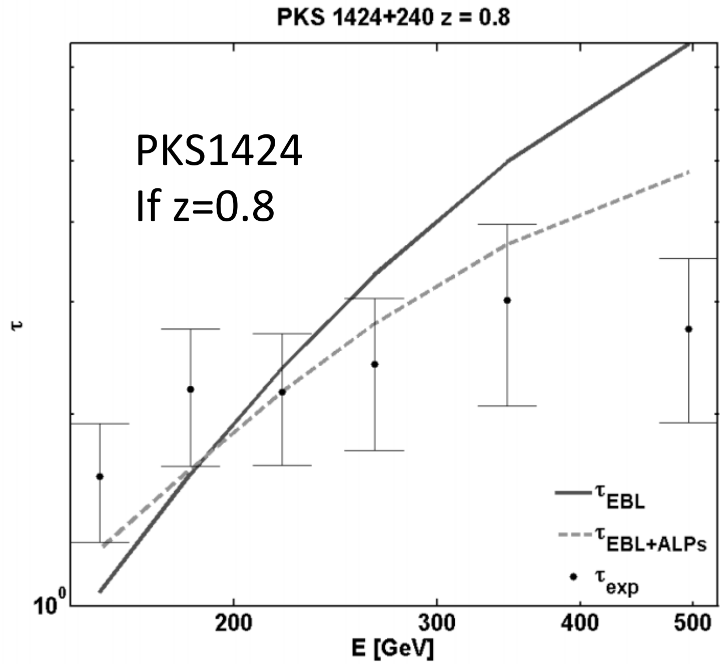
(Horns, Meyer 2011)



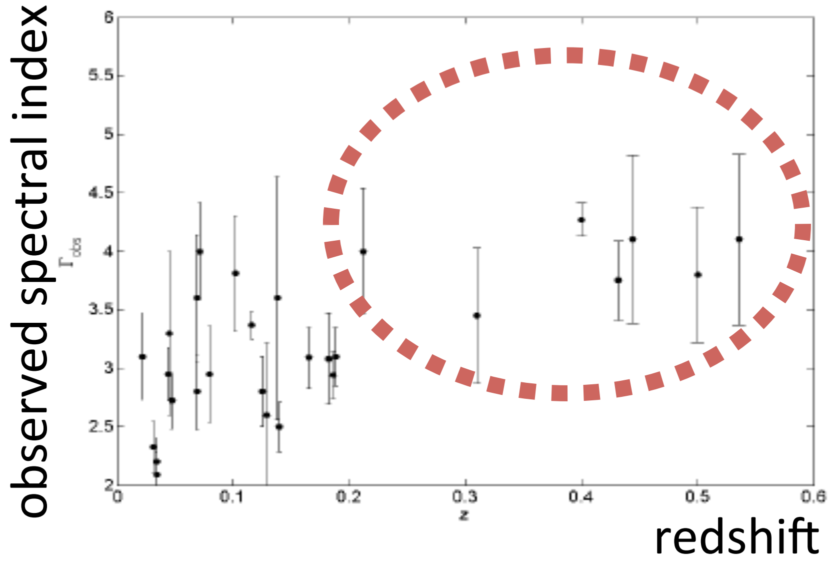
A reminder: EBL rather well constrained, and SED extrapolation from Fermi is possible

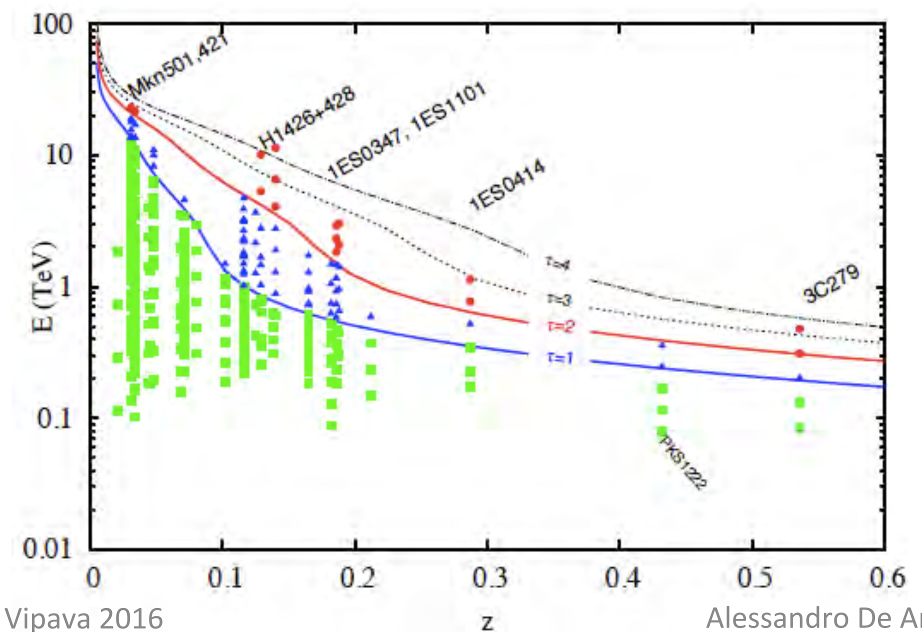






If there is a problem





Explanations from the standard ones

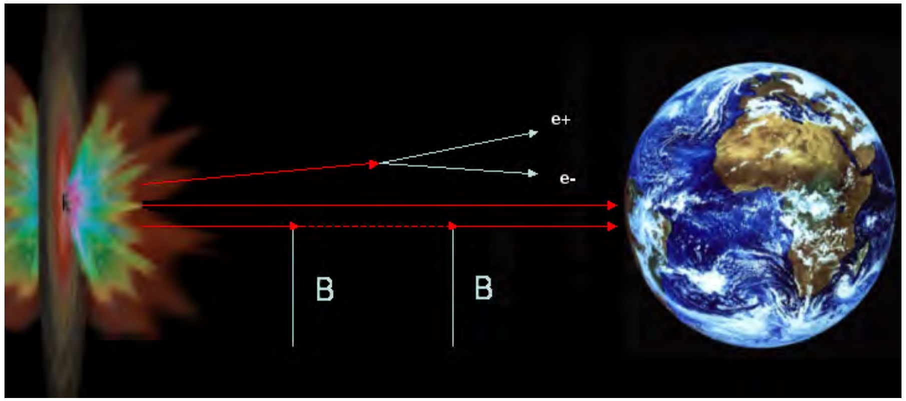
- very hard emission mechanisms with intrinsic slope < 1.5 (Stecker 2008)
- Very low EBL, plus observational bias, plus a couple of "wrong" outliers

to almost standard

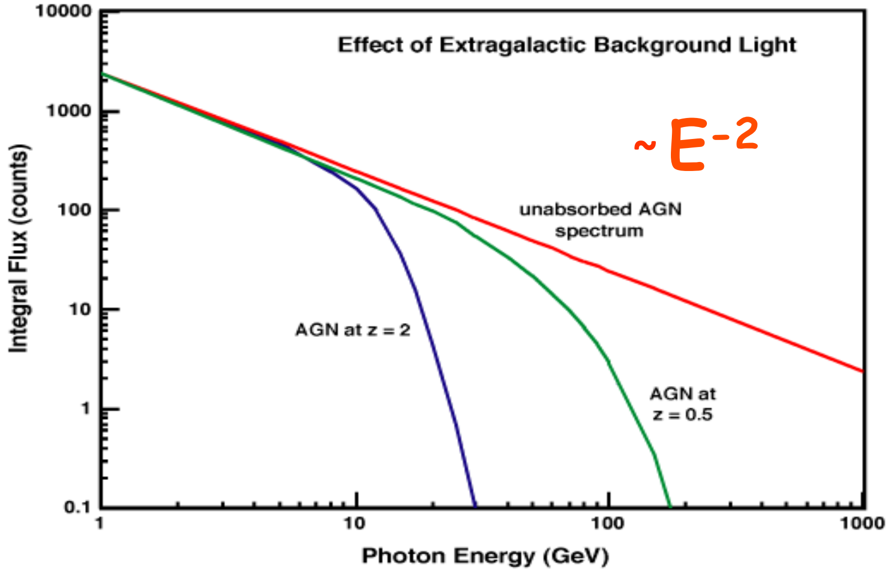
- γ-ray fluxes enhanced by relatively nearby production by interactions of primary cosmic rays or ν from the same source

to possible evidence for new physics

- Oscillation to a light particle coupled to the photon?



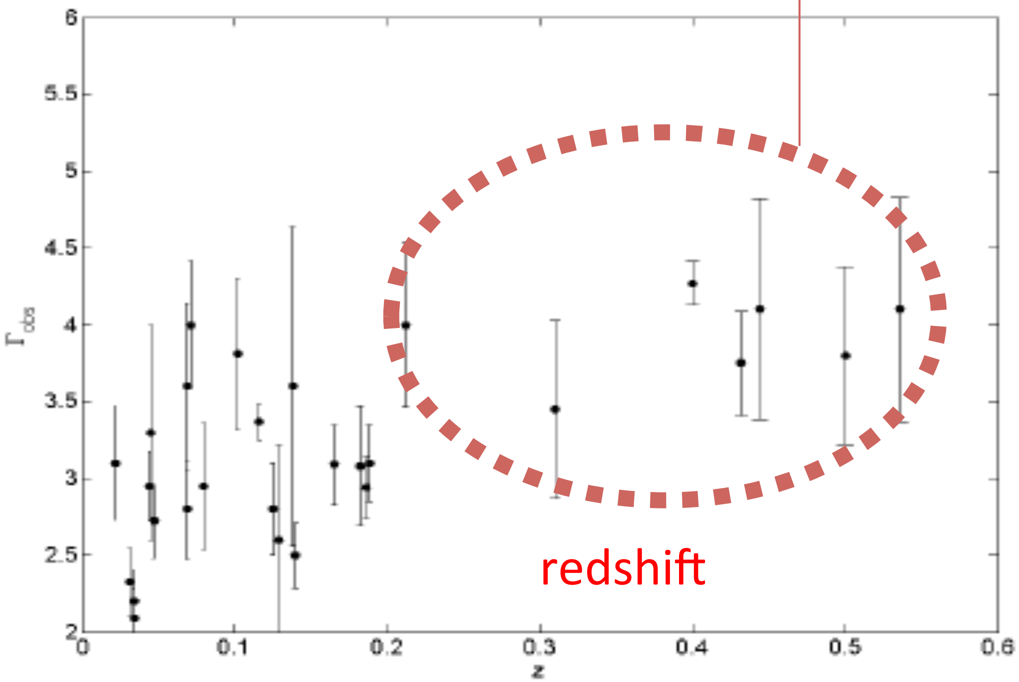
Are our AGN observations consistent with theory?



Measured spectra affected by attenuation in the EBL:

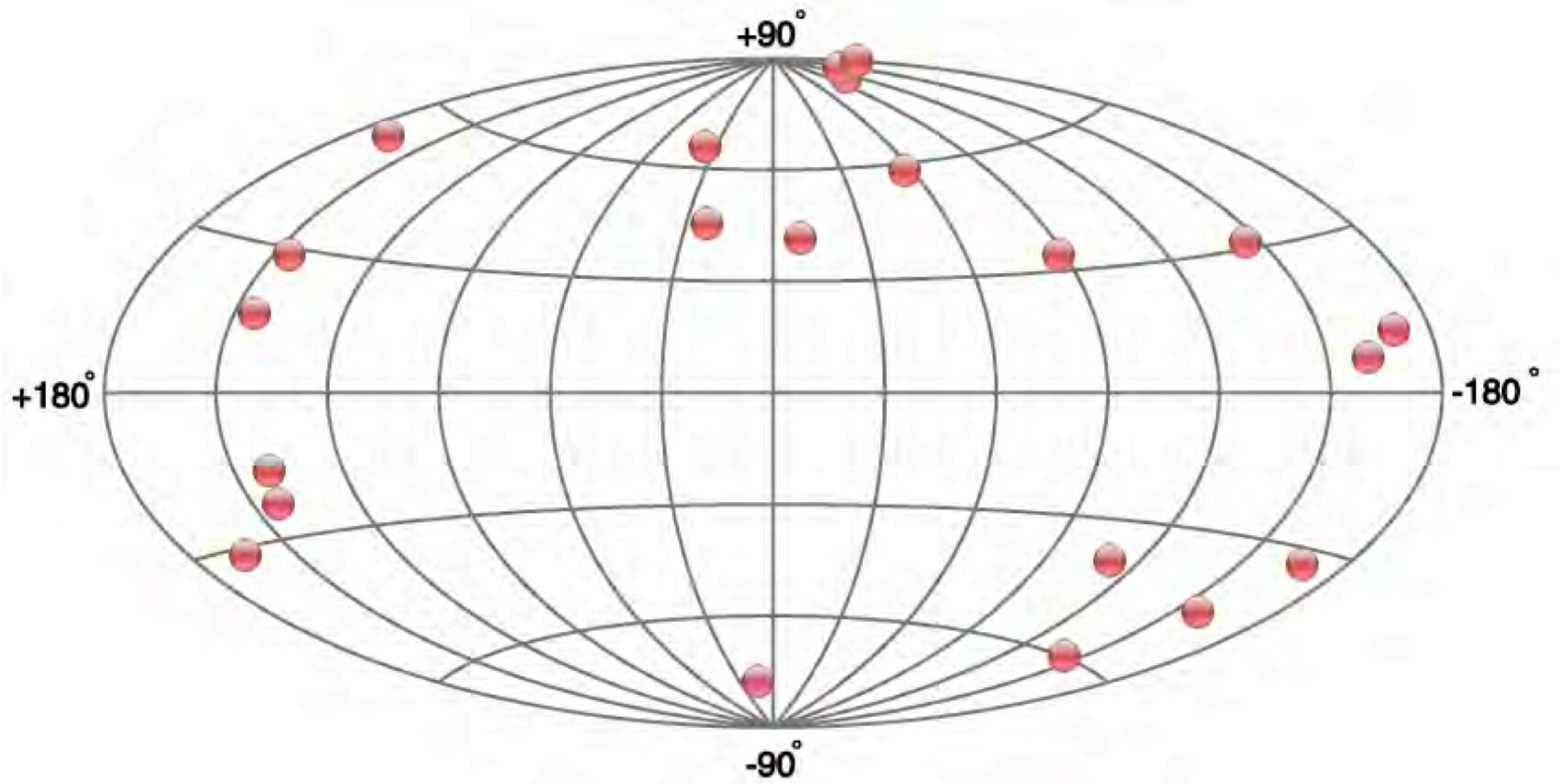
Selection bias?
New physics ?

observed spectral index



(DA, Galanti, Roncadelli; PRD 2011)

VHE gamma sources above z = 0.15



Shining TeV Gamma Rays through the Universe

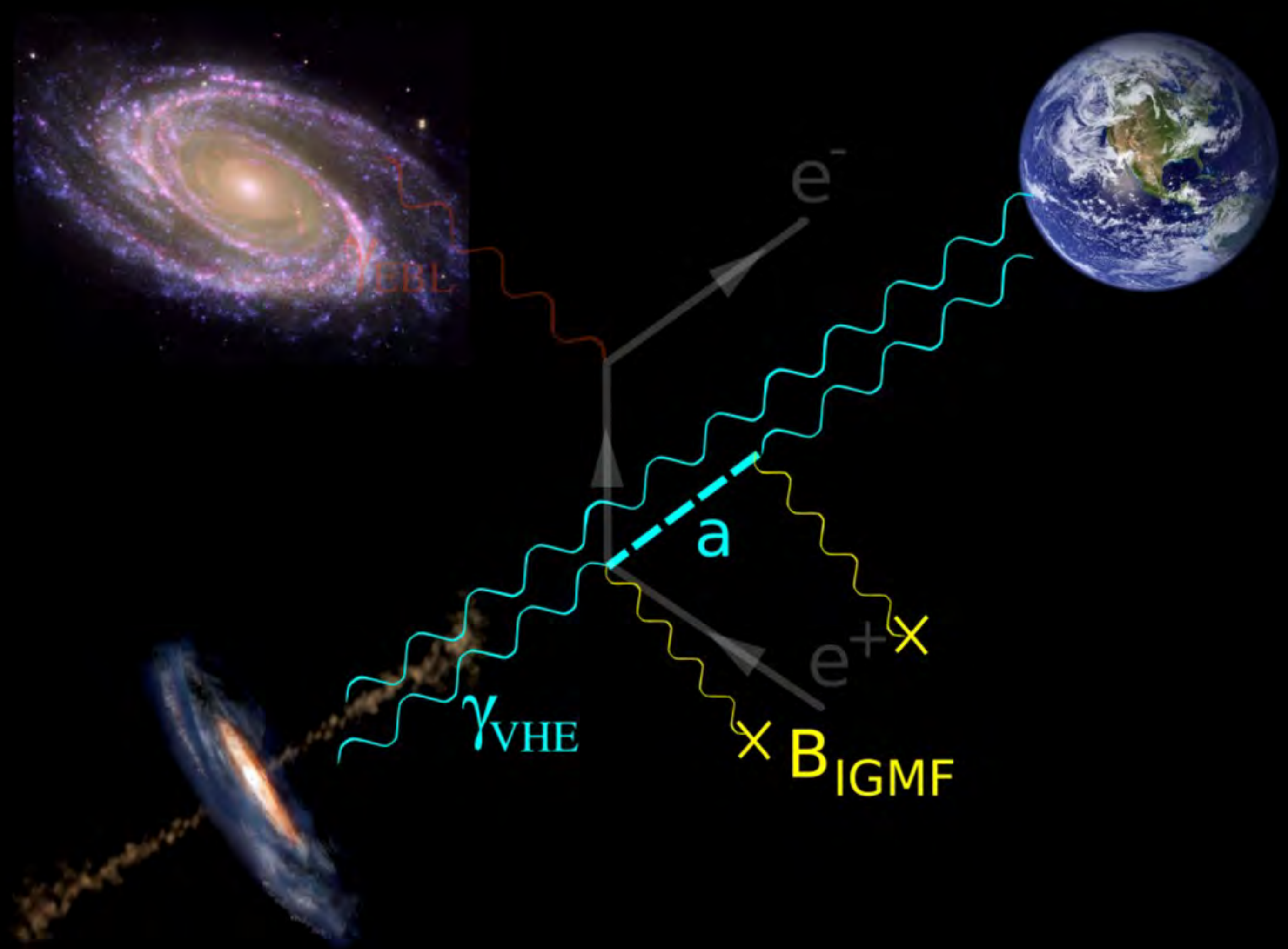
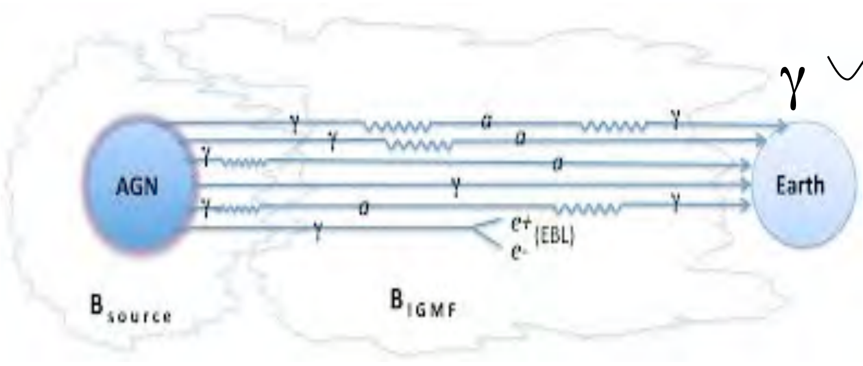
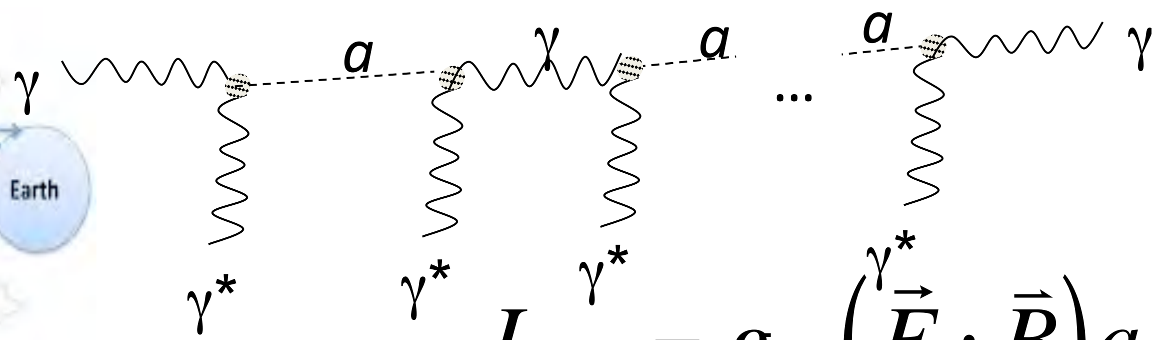


Figure from M. Meyer (Hamburg)

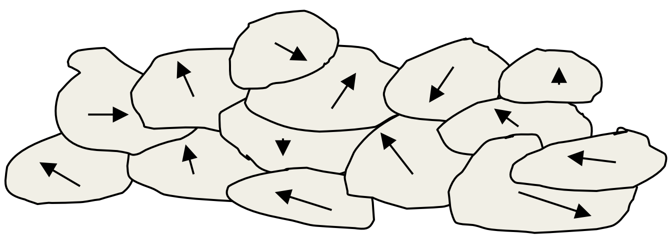
The cosmological photon-axion mixing





$$L_{a\gamma\gamma} = g_{a\gamma}\left(\vec{E}\cdot\vec{B}\right)a$$

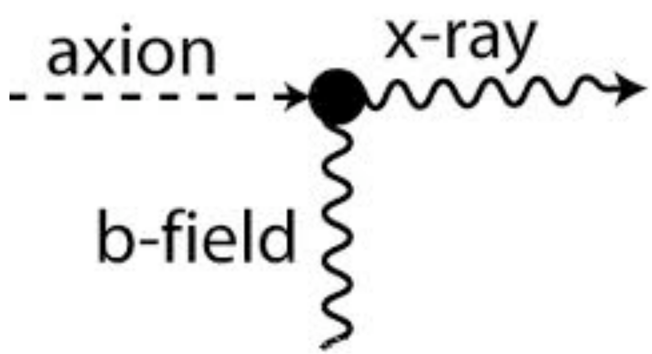
- Magnetic field 1 nG < B < 1fG (AGN halos). Cells of ~ 1 Mpc

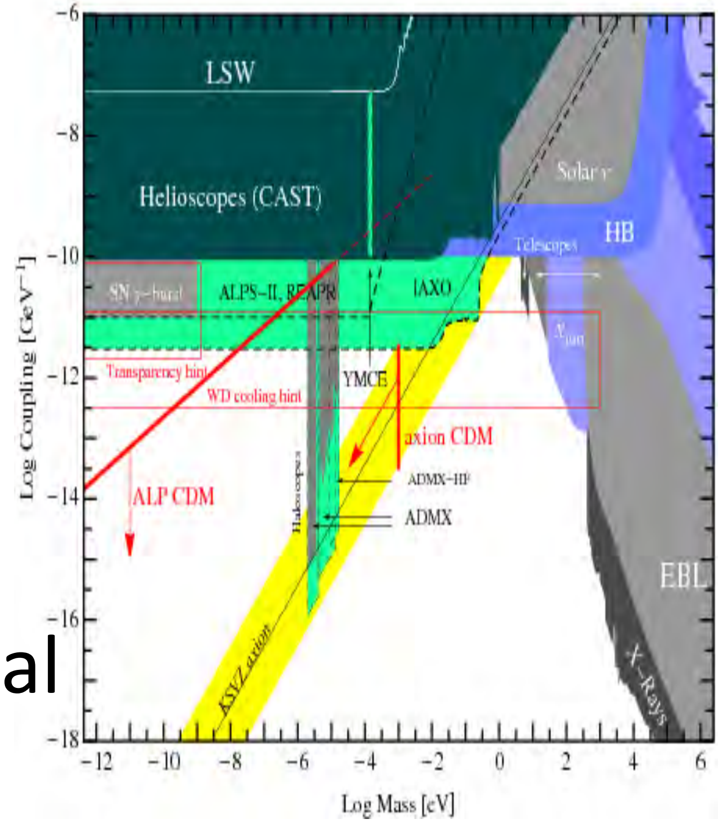


$$P_{\gamma\to a} \approx NP_1$$

$$P_1 \approx \frac{g_{a\gamma}^2 B_T^2 s^2}{4} \approx 2\times 10^{-3}\left(\frac{B_T}{1\mathrm{nG}}\frac{s}{1\mathrm{Mpc}}\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2$$

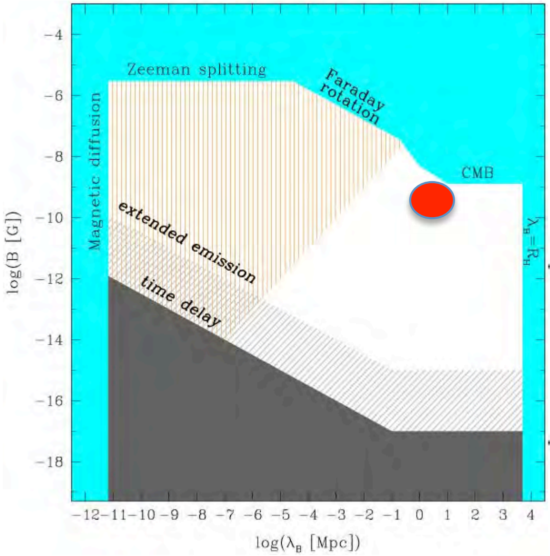
- Photons-ALP mixing could enhance the transparency of the Universe:
  - Photon/ALP mixing in the intergalactic space (DA, Roncadelli & MAnsutti [DARMA], PRD2007)
  - Conversion into axion at the source, reconversion in the Milky Way (Hooper, Simet, Serpico 2008)Axion emission (Simet+, PRD2008)
  - A combination of the above

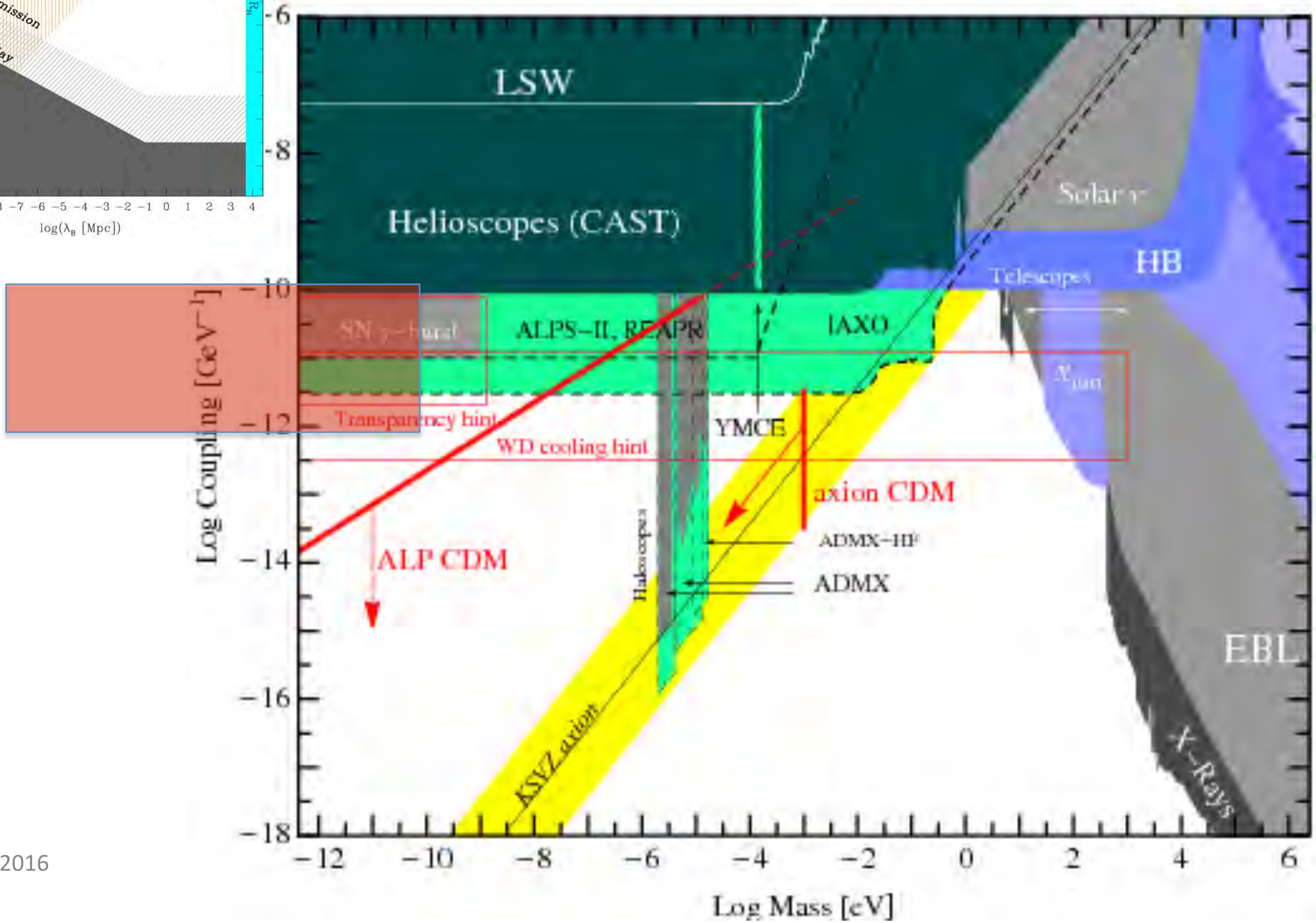




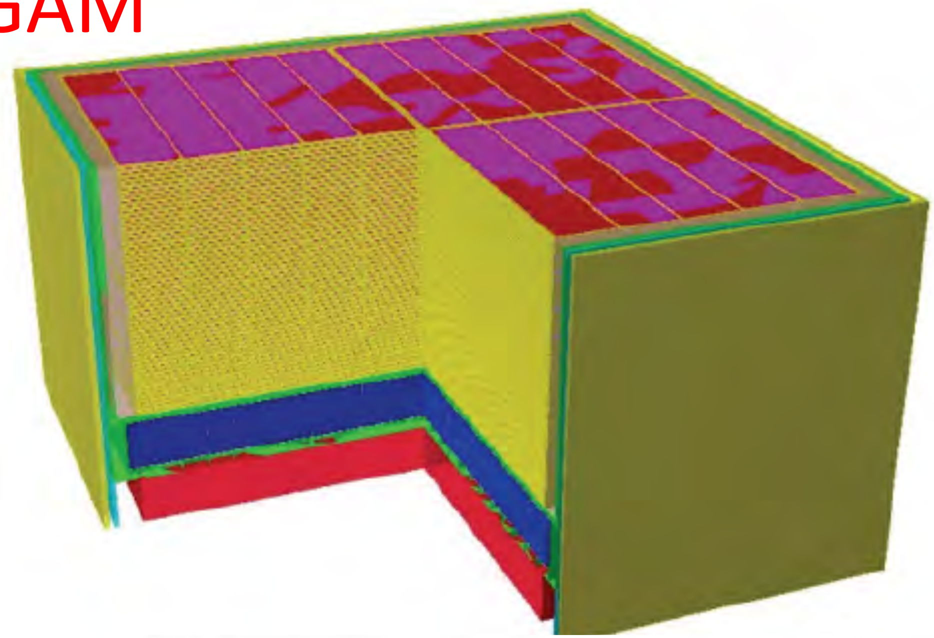
- g < 10^{-10} GeV^{-1} from astrophysical bounds
- m_a < 0.02 eV (direct searches) if standard axion
  - m_a < 1 keV in general
  - m_a < (0.1-1) meV could be CDM

Preferred values for m, g (DARMA)

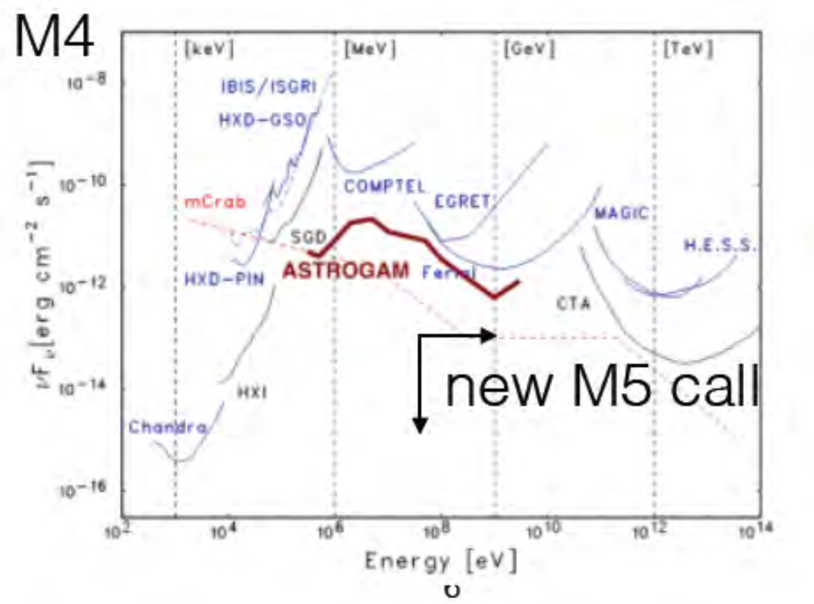


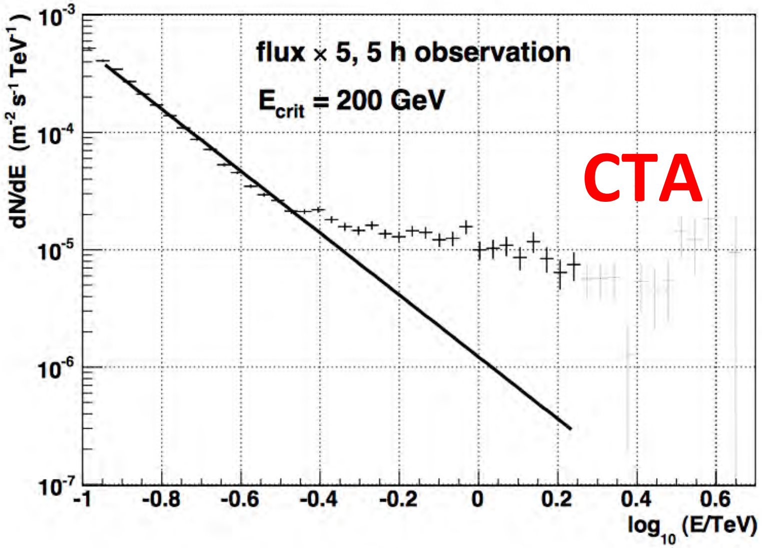


Future gamma-ray experiments sensitive to ALPs: e-ASTROGAM

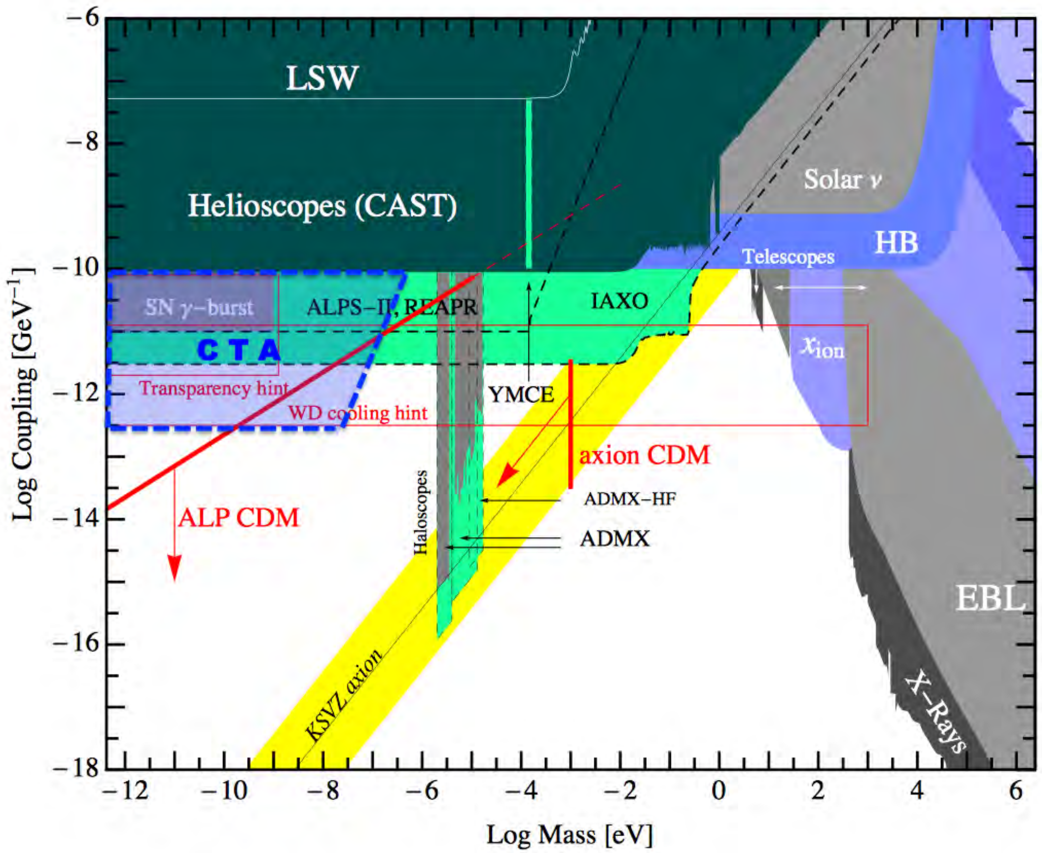


- ALPs can induce localised O(10%) oscillatory modulations in the spectra of photon sources passing through astrophysical magnetic fields
- Ultra-deep observations of galaxy clusters in the keV-MeV-GeV can spot gamma-ray spectral irregularities from AGN
- e-ASTROGAM





Simulated CTA observation
Bright flare from 4C 21.35
0.1 nG IGMF
EBL of Dominguez et al. 2011



Caveat: Other astrophysical processes, e.g. UHECR cascades, can also lead to spectral hardening

Left figure: Doro et al., *Astropart. Phys.* 43, 189; arXiv:1208.5356
Right figure: Sanchez-Conde et al., in prep., adapted from Ringwald, 2012, arXiv:1209.2299

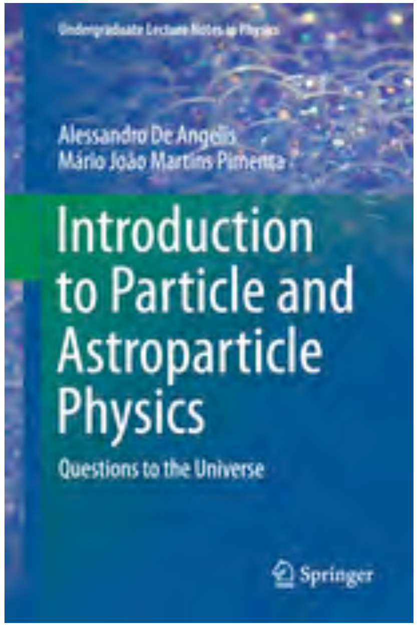
Summary

- Axions (and WISPs) are economical (in the Occam sense) dark matter candidates
- Laboratory and space experiments currently probing viable parameter space
- Some hints, mostly by experiments in gamma astrophysics (anomalous gamma propagation)
- Still no compelling signal, but a lot of activity foreseen
  - IAXO, ALPS2 are the next "big things"
  - CTA, (Fermi) and next gamma-ray experiments in space (e-ASTROGAM) might further test hints

Exercises

- $\gamma\gamma$ -> *e+e-*. Compute the energy threshold for this process as a function of the energy of the target photon, and compare it to the energy for which the absorption of extragalactic gamma-rays is maximal. Analyze in particular the case of the scattering against the CMB, assuming a density of 400 photons/cm^3 for the background CMB photons
- *Mixing photons with paraphotons.* The existence of a neutral particle of tiny mass m, the paraphoton, coupled to the photon, has been suggested to explain possible anomalies in the CMB spectrum and in photon propagation (the mechanism is similar to the one discussed to the photon-axion mixing, but there are no complications related to spin here). Calling ϕ the mixing angle between the photon and the paraphoton, express the probability of oscillation of a photon to a paraphoton as a function of time (note: the formalism is the same as for neutrino oscillations). Supposing that the paraphoton is sterile, compute a reasonable range of values for ϕ and m that could explain an enhancement by a factor of 2 for the signal detected at 500 GeV from the AGN 3C279 at z ~ 0.54.

Minimal bibliography



- https://dl.dropboxusercontent.com/u/44901481/BookAstropart/BookComplete28nov/Exercises/hea_deangelis_syllabus4.htm

- Page on axions and ALPs in the PDG, and references therein