ALP GAMMA-RAY SEARCHES WITH FERMI AND CHERENKOV TELESCOPES

Miguel A. Sánchez-Conde
[KIPAC/SLAC, Stanford]

VISTAS IN AXION PHYSICS
Seattle, WA -- April 23-26, 2012

Photon/axion conversions

- Axion-like particle (ALP): mass and coupling not related.
- ALPs are expected to convert into photons (and vice-versa) in the presence of magnetic fields.

Probability of conversion (Hooper & Serpico 07):

$$P_0 = \frac{1}{1+(E_{crit}/E_\gamma)^2} \sin^2\left[\frac{B\ s}{2\ M}\sqrt{1+\left(\frac{E_{crit}}{E_\gamma}\right)^2}\right] \quad \text{with} \quad E_{crit} \equiv \frac{m^2\ M}{2\ B}$$

≥ 1

Some astrophysical environments fulfill the mixing requirements

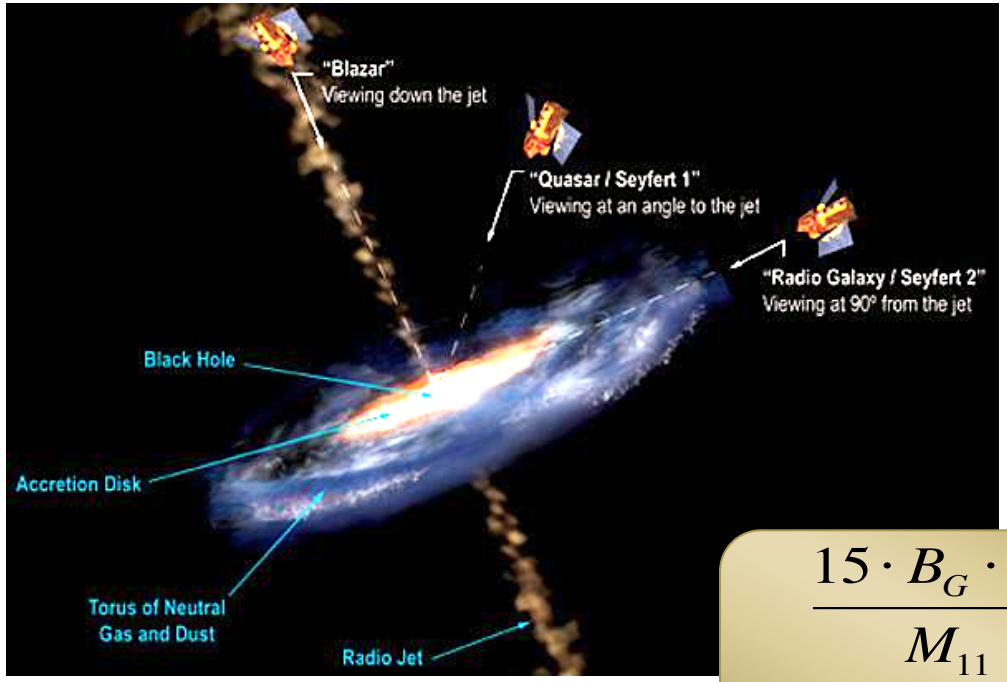
Astrophysical sources with $B_G \cdot s_{pc} \geq 0.01$ will be valid.

$$\frac{15 \cdot B_G \cdot s_{pc}}{M_{11}} \geq 1$$

$M_{11} \geq 0.114$ GeV (CAST limit)

- M_{11}: inverse of the coupling constant ($g_{a\gamma}/10^{11}$ GeV)
- B_G: magnetic field (G)
- s_{pc}: size of the B region (pc)

DO THEY EXIST?



Active Galactic Nuclei (AGNs)

B ~ Gauss

s_{pc} ~ (sub)pc

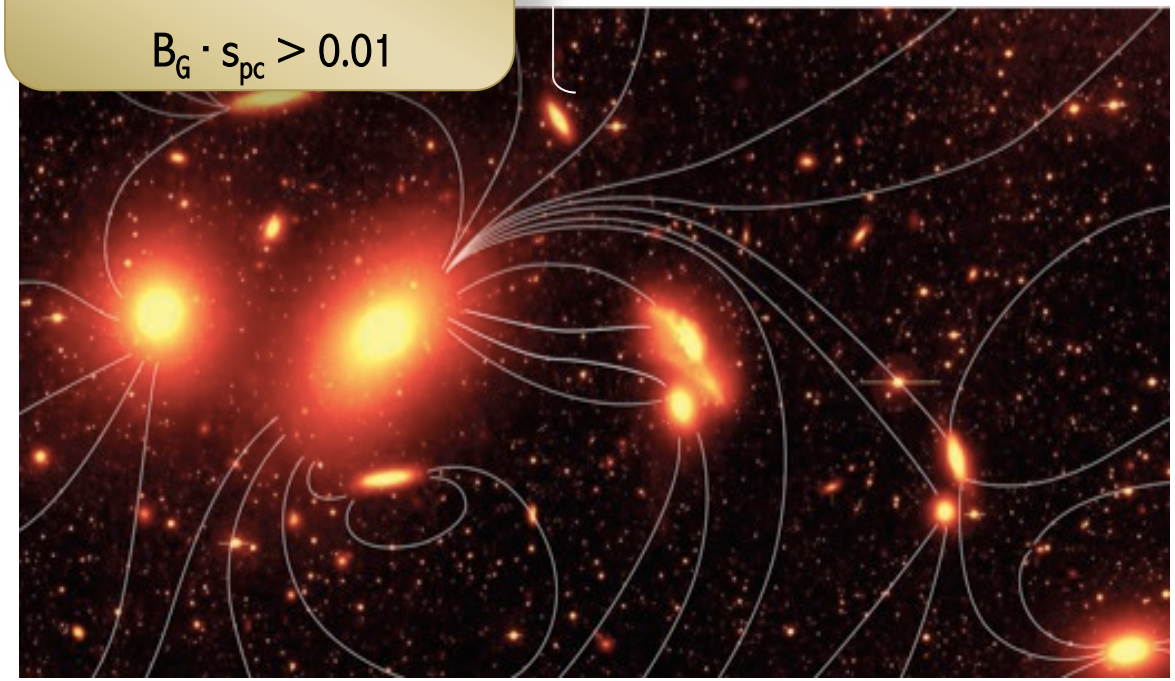
$$\frac{15 \cdot B_G \cdot s_{pc}}{M_{11}} \geq 1$$

$$B_G \cdot s_{pc} > 0.01$$

Intergalactic Magnetic Fields (IGMFs)

B ~ nG

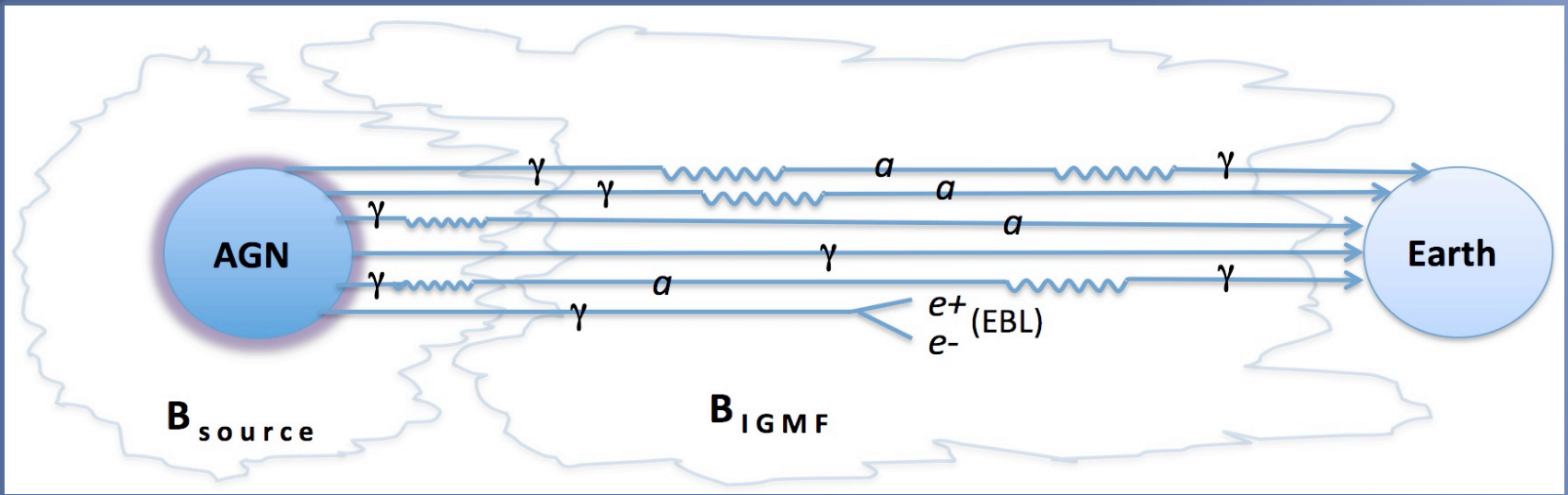
s_{pc} ~ Mpc



Photon/axion conversions in gamma-rays

AGNs located at cosmological distances will be affected by:

A. Source mixing (Hooper & Serpico 07): flux attenuation
B. IGM mixing (De Angelis+07): flux attenuation and/or enhancement.
C. Galactic mixing (Simet+08): flux enhancement.

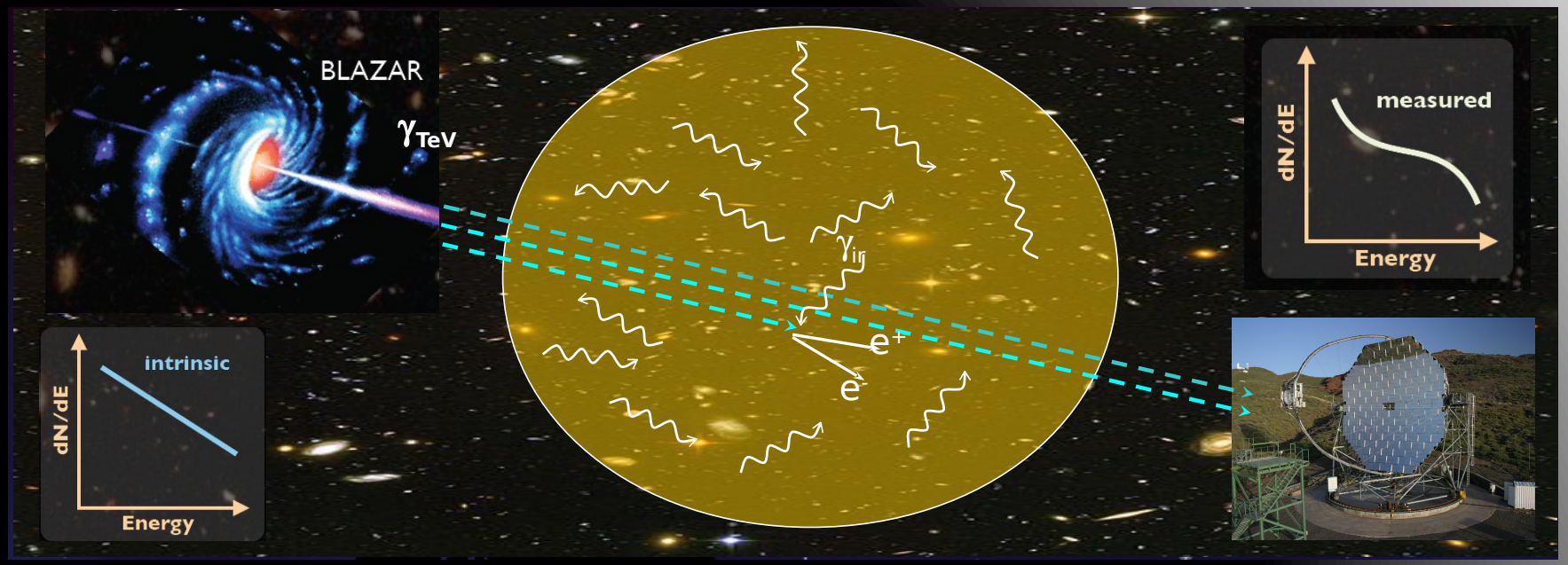


[MASC, Paneque, Bloom, Prada and Domínguez, 2009]

$$E_{crit}(GeV) \equiv \frac{m^2_{\mu eV}\ M_{11}}{0.4\ B_G}$$

Gamma-ray energy range ➡ ultra-light ALPs.

Intergalactic absorption of VHE photons: EBL



Credit: Mazin & Raue

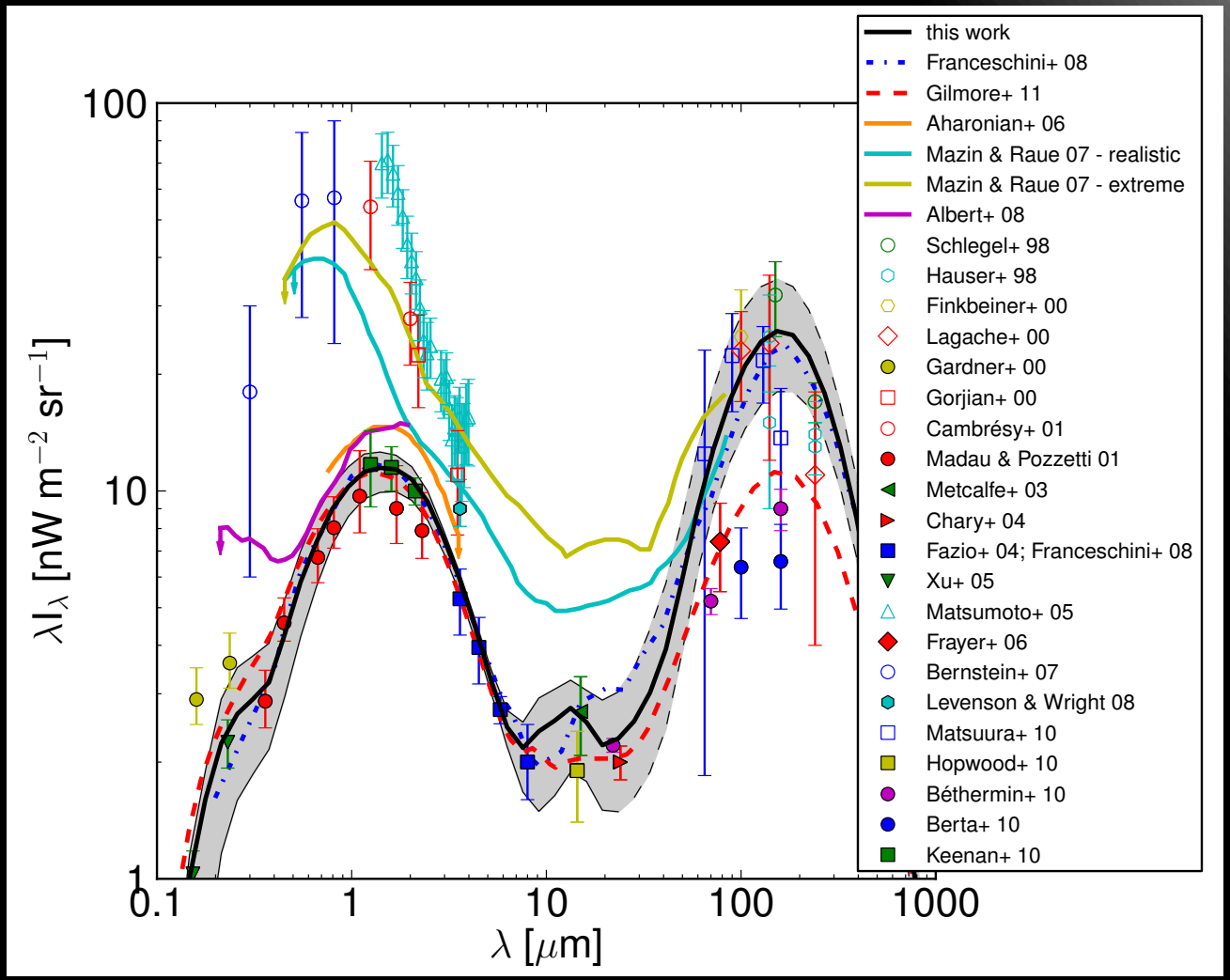
Around the TeV region:

$$\lambda \approx 1.24 \left(\frac{E}{1TeV} \right) \mu m$$

Infrared/optical background photons:
Extragalactic Background Light (EBL)

For a source at redshift 0.5 and 0.5 TeV, attenuation ~2 orders of magnitude!!

State-of-the-art EBL models



The latest EBL models now agree!

Domínguez+10

Gamma-ray observatories

A. On orbit: NASA Fermi satellite
B. From the ground: Imaging Atmospheric Cherenkov telescopes (IACTs)

E. range: 10 MeV - 300 GeV

E. resolution: <10% @ 10 GeV

FoV: ≈2.4 sr

Angular resolution: 0.1°@10 GeV

Fermi/LAT

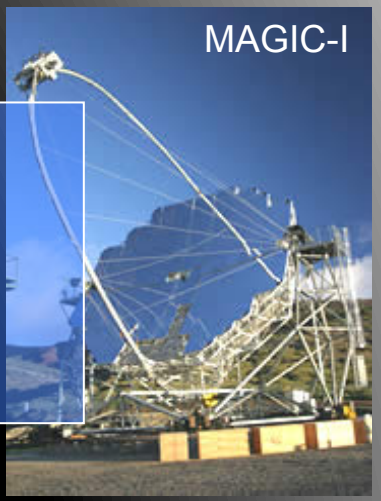
E. range: 100 GeV - 30 TeV

E. resolution: >20%

FOV: ≈ 4 deg.

Angular resolution: ≈ 0.1°

Typical IACT



Leading IACTs at present

MAGIC
(Germany, Italy, Spain)
2003
2 telescopes
17 meters each

Canary Islands, Spain

Tucson, Arizona

VERITAS
(USA & England)
2006
4 telescopes
12 meters each

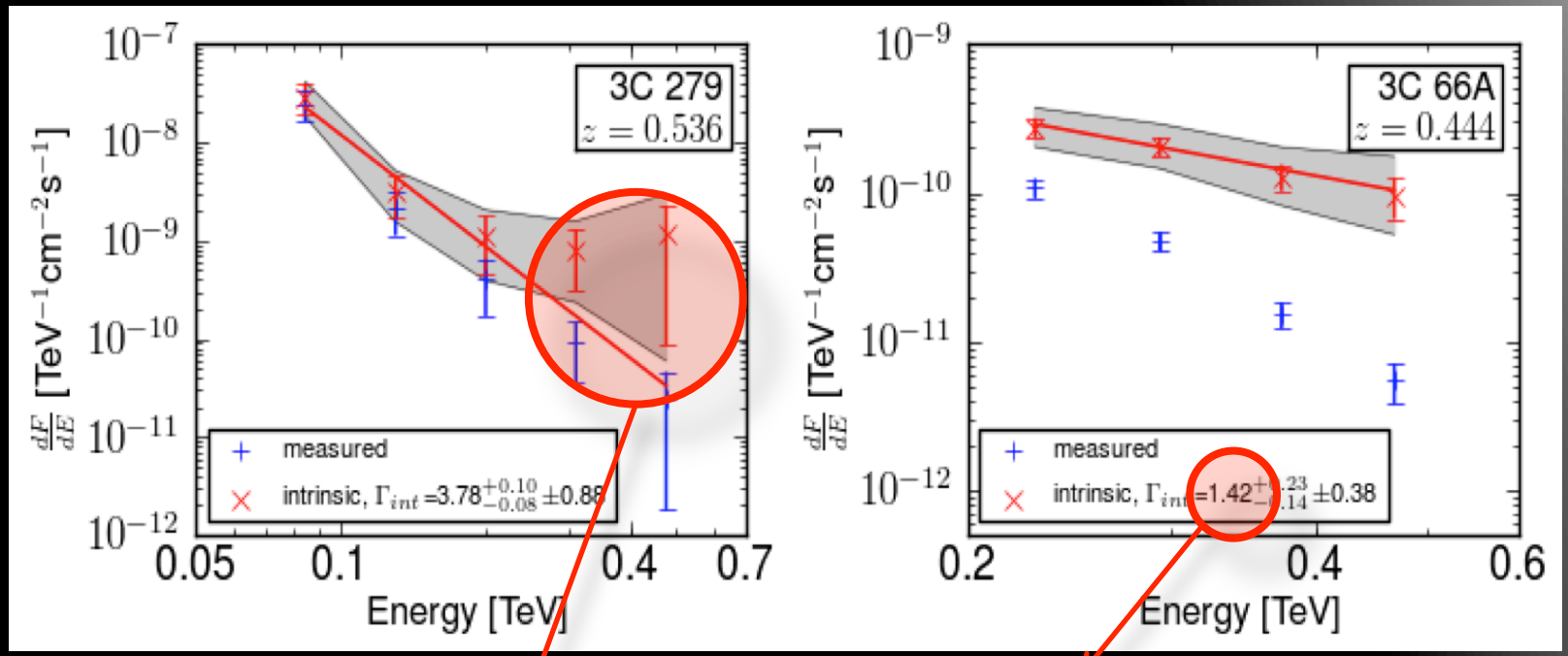
Windhoek, Namibia

HESS
(Germany & France)
2002
4 telescopes
12 meters each

Hints for new physics?

- Some recent gamma-ray observations pose substantial challenges to the conventional models.
  - Intrinsic spectrum deviates from a power-law: pile-up problem (Dominguez+12).
  - Very hard intrinsic spectrum of FSRQs (e.g. Albert+08, Alecsik+11, Wagner+10)
  - Extremely rapid and intense flares (Tavecchio+12).
  - GeV spectral breaks!

[Domínguez et al. 2011]

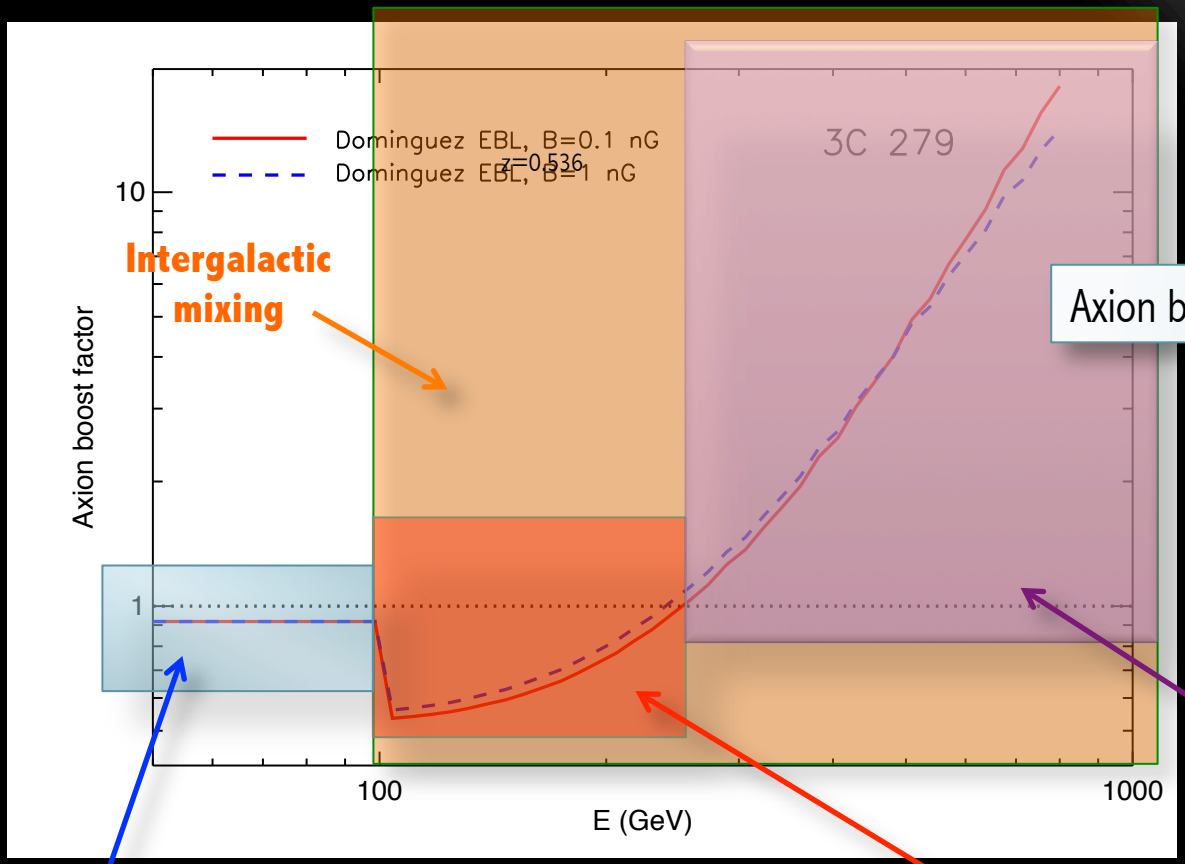


See also Horns+12 !

PILE-UP!

Modeling of AGN emission mechanisms typically assume **spectral index >1.5**

ALPs modify the spectrum of distant AGNs



Intergalactic mixing

Axion boost =(Flux w/ axions) / (Flux w/o axions)

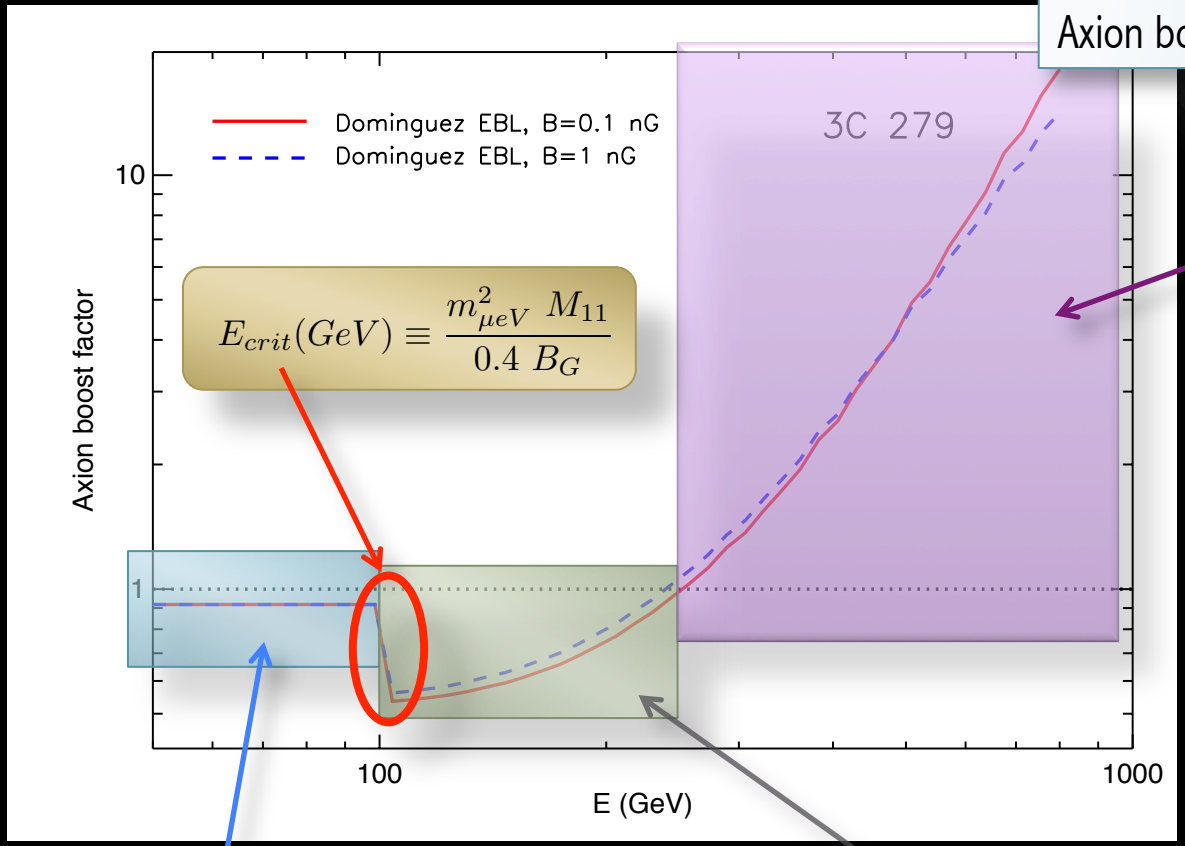
Enhancement due to intergalactic mixing

Attenuation due to source mixing

Attenuation due to intergalactic mixing

- ✓ Larger axion boosts for distant sources.
- ✓ Larger B fields not always lead to larger axion boosts.

Observational strategies with Fermi and IACTs



Axion boost =(Flux w/ axions) / (Flux w/o axions)

IACTs observations

Look for systematic flux **enhancements** at energies where the EBL is important (**hardening** of the spectra expected!).

Distant (z > 0.2) sources at the highest possible energies (>1 TeV), to push EBL models to the extreme.

Source and EBL model dependent, but very important enhancement expected.

Fermi/LAT

Look for flux **drops** in the residuals ("best-model"-data).

Source model dependent.

Powerful, relatively **near** AGNs.

Fermi/LAT and/or IACTs

Look for flux **drops/jumps** in the residuals.

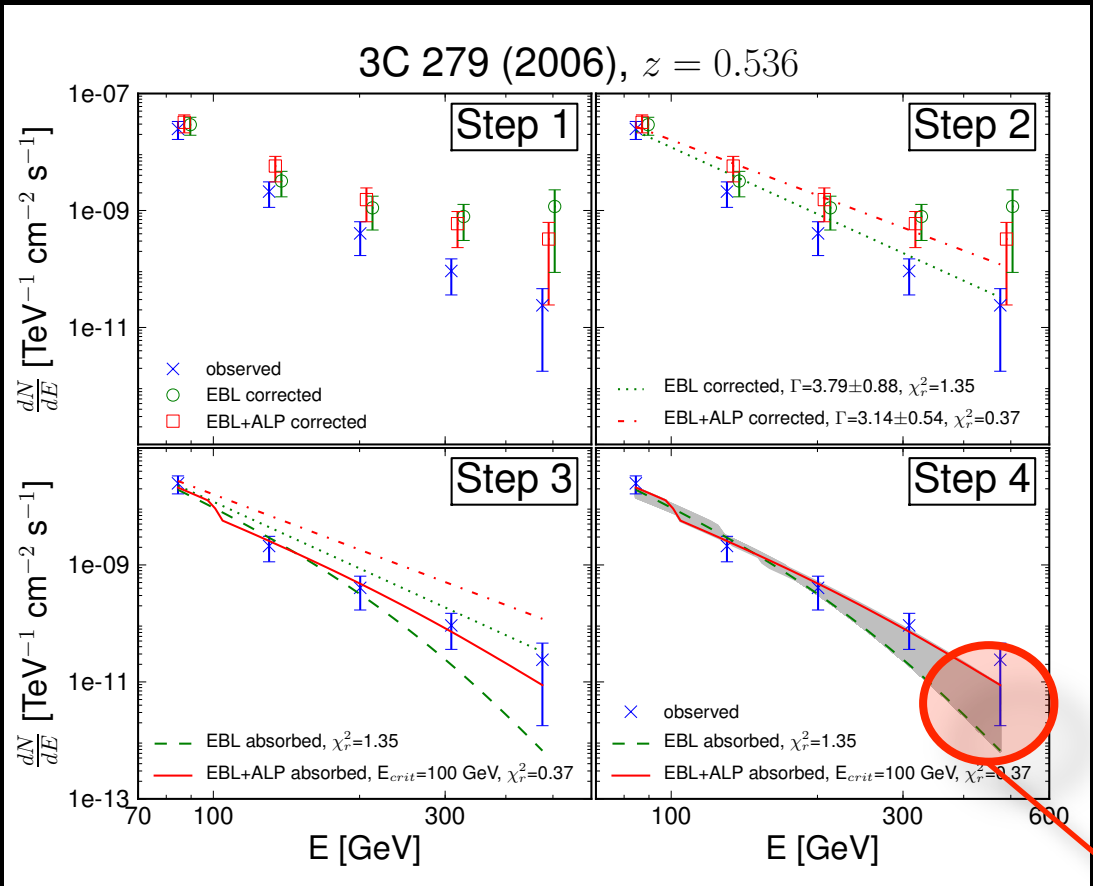
Only depends on the IGMF and axion properties (mass and coupling constant).

Independent of the sources -> CLEAR signature!

ALP imprint in IACT observations of cosmological VHE sources

More high energy photons than expected at the highest energies:
deviation from a power-law? → pile-up

Might ALPs help in offering an alternative explanation?



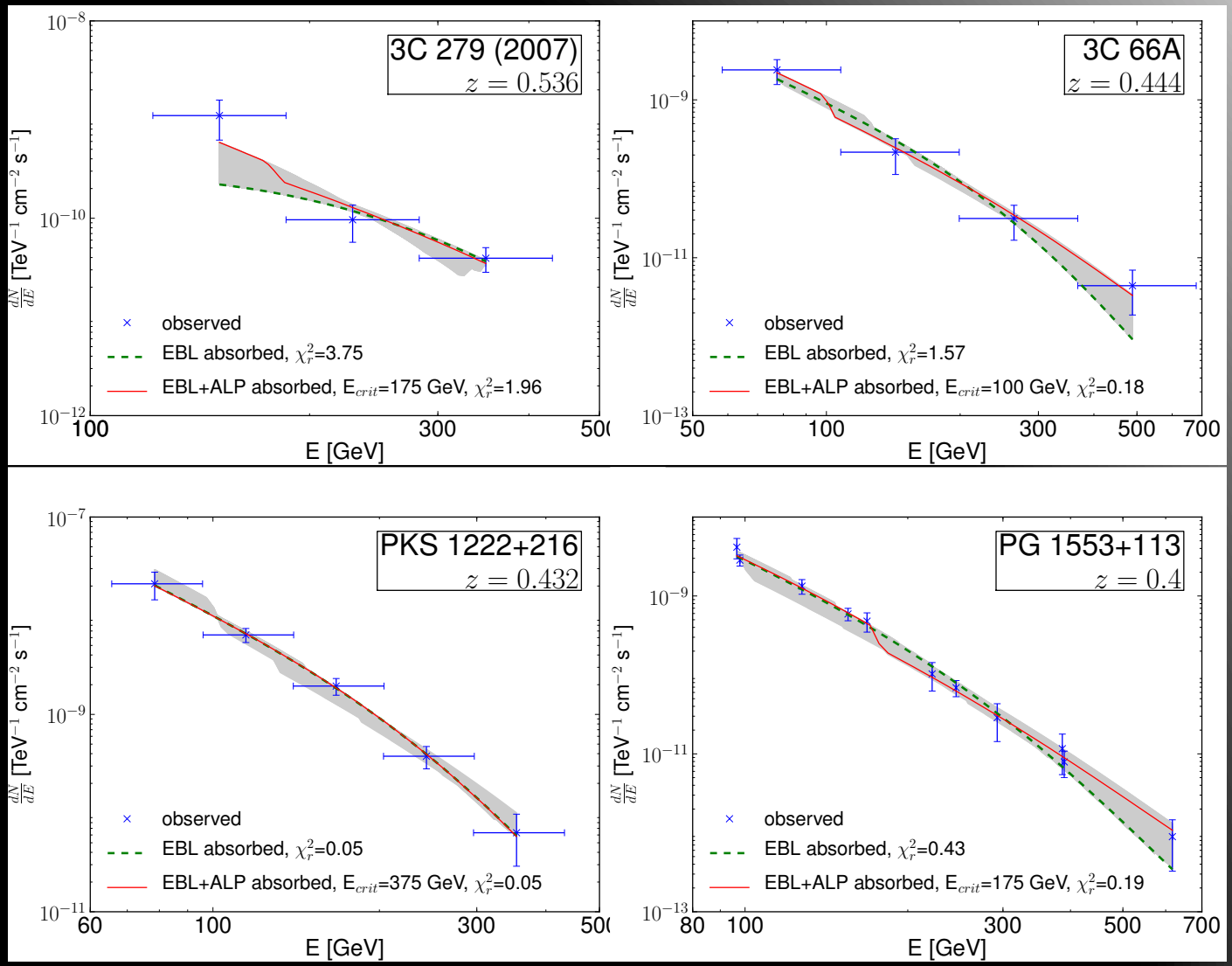
Domínguez, Sánchez-Conde and Prada, JCAP 11 (2011) 020

★ Working hypothesis:

1) Intrinsic spectra of AGNs are well-described by power laws.
2) M_{11} has an optimistic value but still within experimental limits.
3) E_{crit} is within the energy range of present IACTs.
4) The EBL is well described by the Dominguez+11 EBL model.

Source modeling using multi-wavelength SSC fits available in the literature.

PILE-UP!



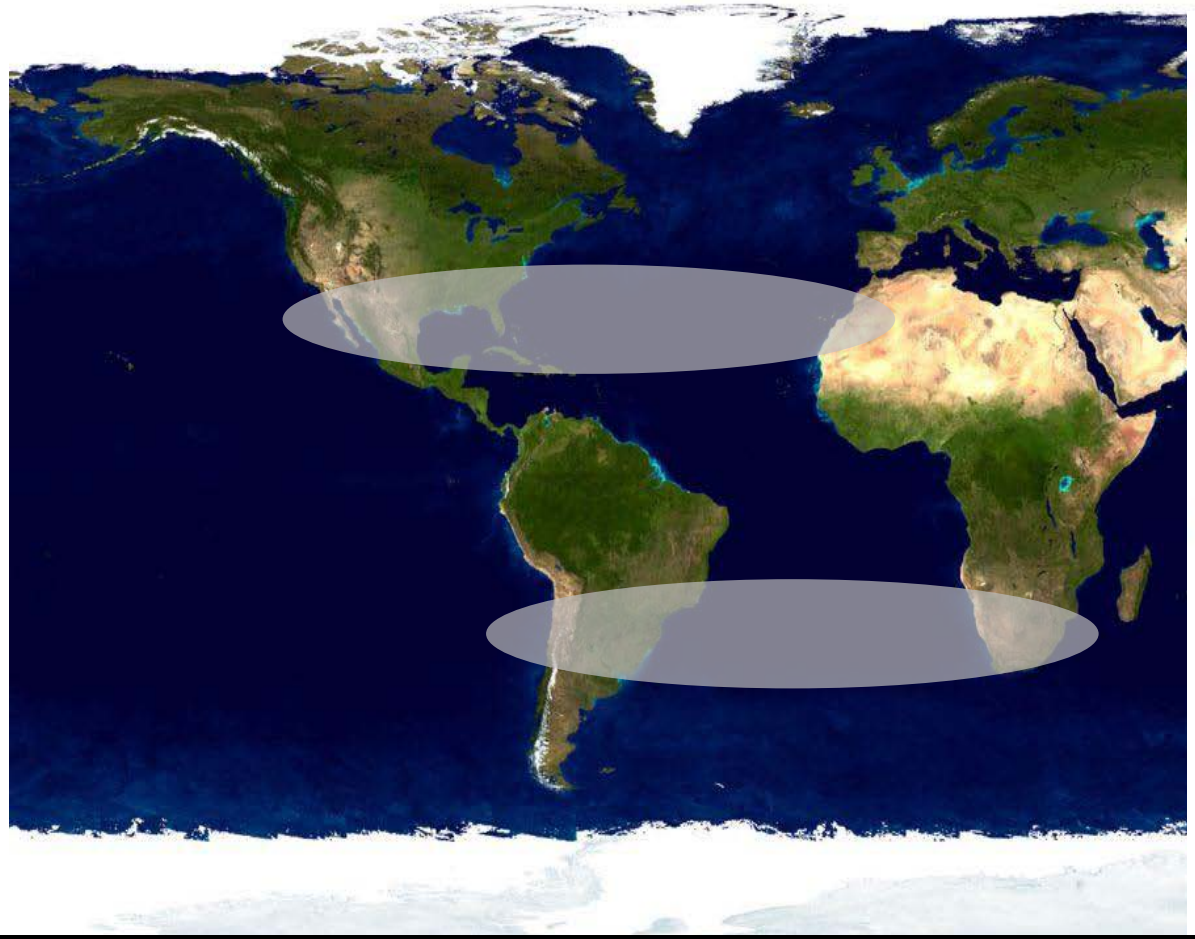
- Low critical energies are preferred.
- ALPs do not introduce any additional effect when no pile-up is present.
- More cases needed!

ALP searches with the future CTA

The CTA project

The concept

- One observatory with two sites for all-sky coverage
- Operated by one single consortium
- Open observatory concept



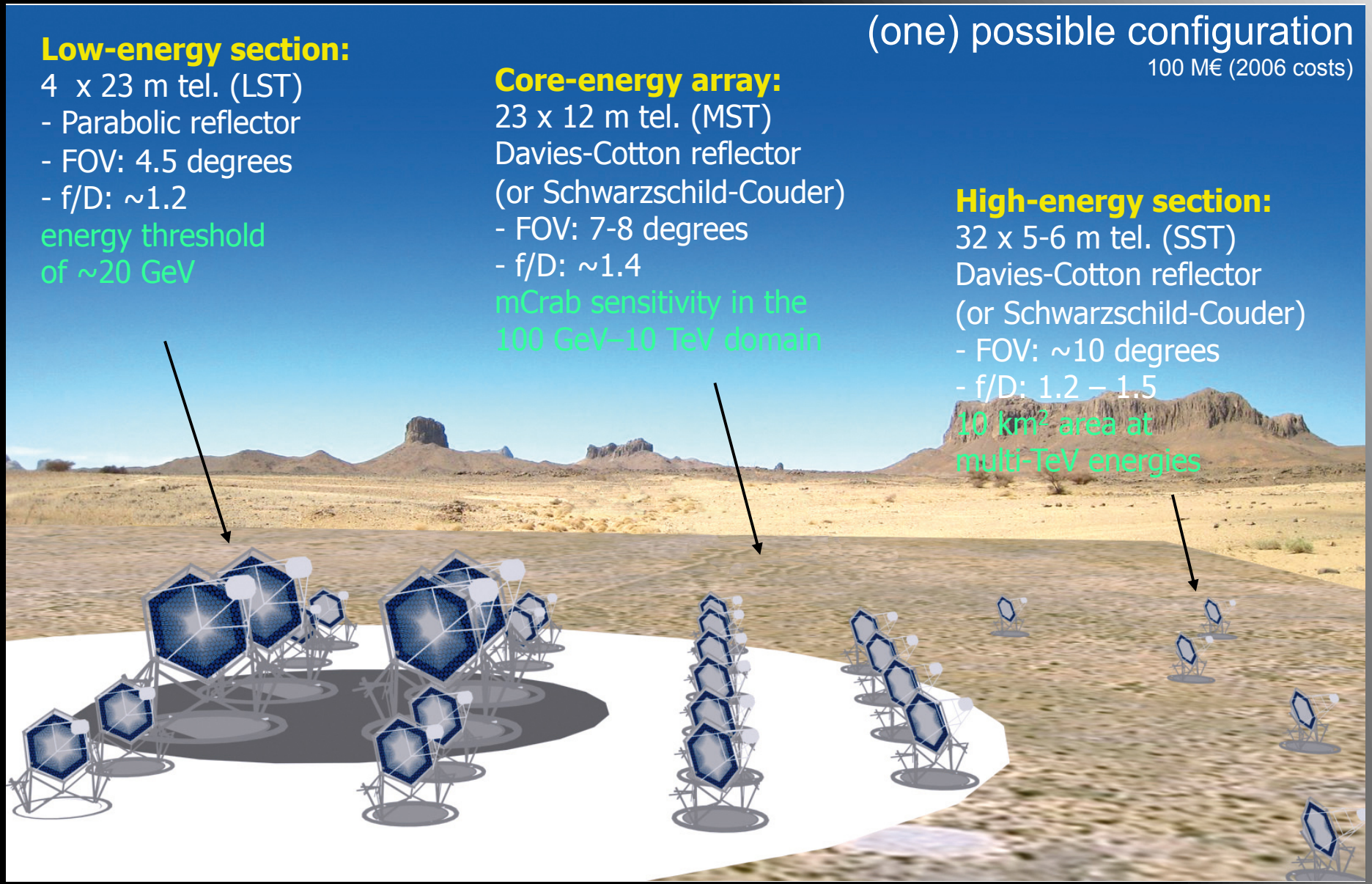
Northern Array (50 ME)

→ complementary to SA for full sky coverage
→ Energy range some 10 GeV .... ~1 TeV
→ Small field of view Mainly extragal. Sources

Southern Array (100 ME)

→ Full energy and sensitivity coverage some 10 GeV .... 100 TeV
→ Angular resolution: 0.02 ... 0.2 deg
→ Large field of view Galactic + Extragal. Sources

CTA layout


(one) possible configuration
100 M€ (2006 costs)
Low-energy section:
4 x 23 m tel. (LST)
- Parabolic reflector
- FOV: 4.5 degrees
- f/D: ~1.2
energy threshold
of ~20 GeV
Core-energy array:
23 x 12 m tel. (MST)
Davies-Cotton reflector
(or Schwarzschild-Couder)
- FOV: 7-8 degrees
- f/D: ~1.4
mCrab sensitivity in the
100 GeV–10 TeV domain
High-energy section:
32 x 5-6 m tel. (SST)
Davies-Cotton reflector
(or Schwarzschild-Couder)
- FOV: ~10 degrees
- f/D: 1.2 – 1.5
10 km² area at
multi-TeV energies

Search of ALPs with CTA

A. González-Muñoz (IFAE), A. Moralejo (IFAE), M.A. Sánchez-Conde (KIPAC/SLAC)

- Test source: PKS 1222+216 , z = 0.432. Second most distant object detected by IACTs.
- Observed by MAGIC in June 2010 in flaring state for 0.5 hours.

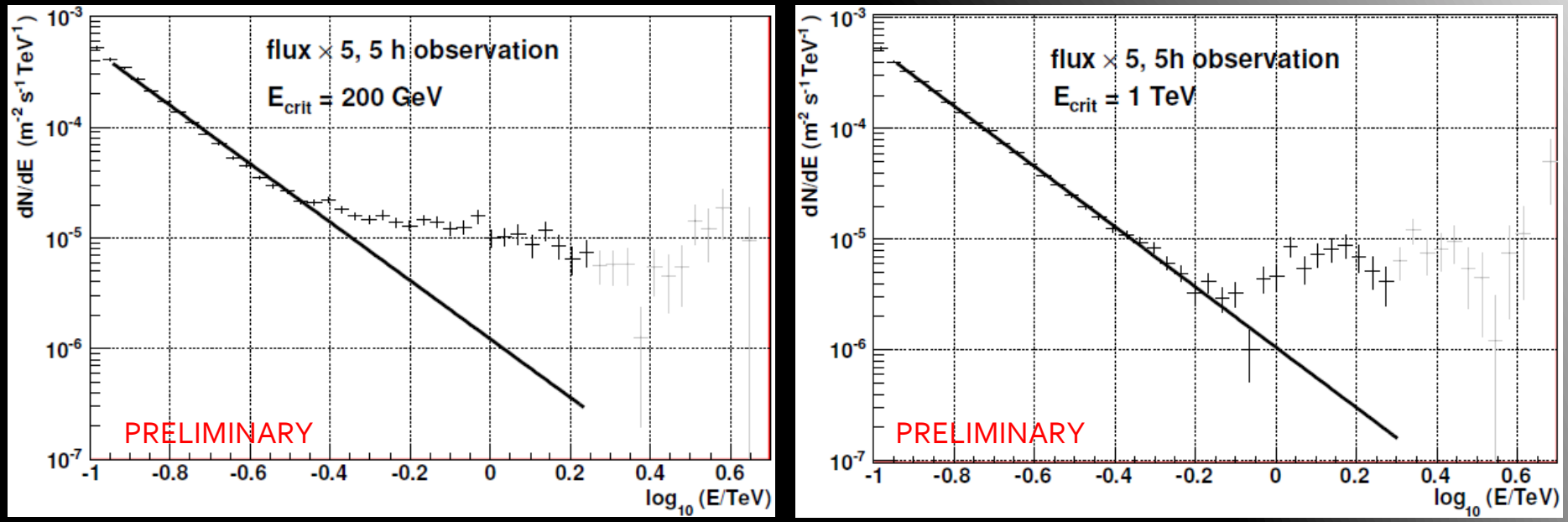
- We assumed an intrinsic power-law spectrum suggested by MAGIC observation:

$$dN/dE = K \times [E/(0.2\ \mathrm{TeV})]^{-2.72}$$, with $K = 1.78 \times 10^{-5}\ \mathrm{m^{-2}\ s^{-1}\ TeV^{-1}}$

- ALP parameters: $M=0.114 \times 10^{11}$ GeV, $m_a \sim 10^{-10}$ eV , $B_{IGMF}=0.1$ nG.
- Domínguez+11 EBL model.
- E_{crit} was scanned in the range 0.1 – 10 TeV in steps of 0.1 TeV.
- Performance files for the CTA candidate array "E".

- This work is part of an special issue to be published in Astroparticle Physics on CTA physics prospects.

Test case: PKS 1222+216



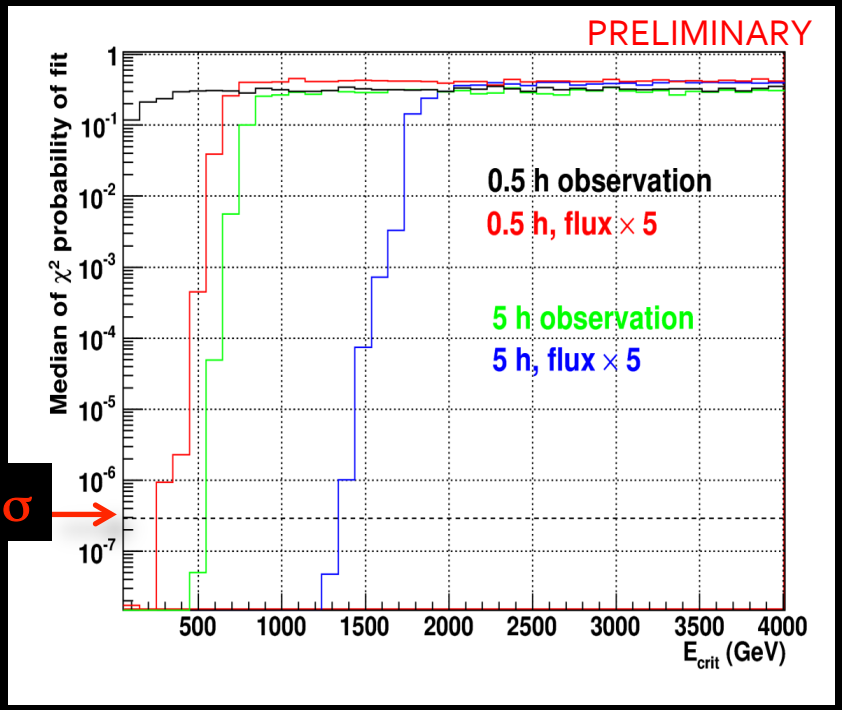
Simulation of a 5-hour CTA observation 5 times more intense than the one recorded by MAGIC

The most suitable energy range for ALP search is that in which the EBL is already present but still with moderate absorption: ~few hundreds GeV to few TeV:

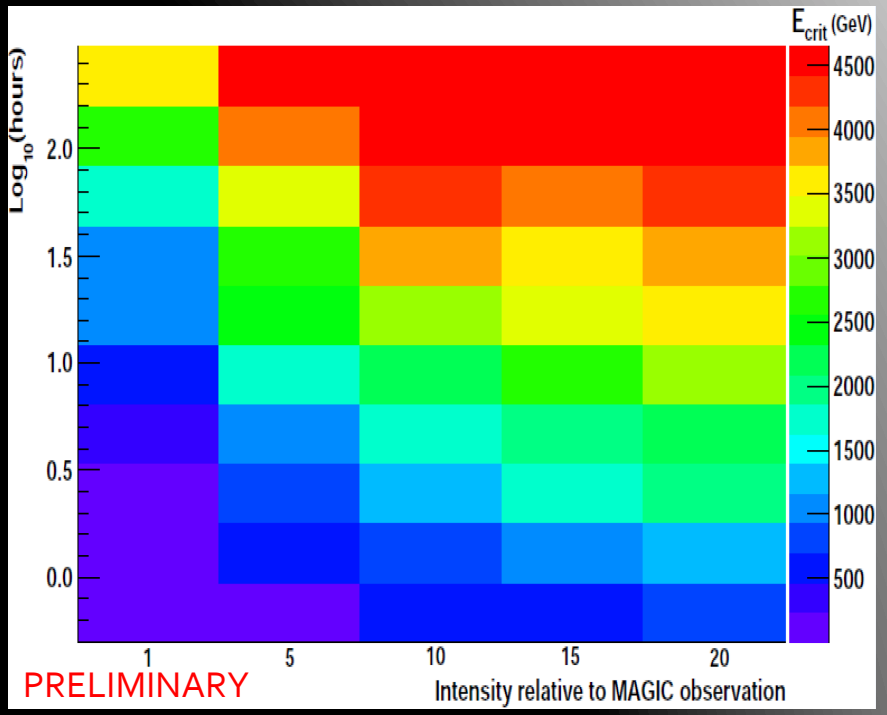
- If EBL is too strong, then ALP *boost* is not enough to make the source observable.
- If EBL is too weak, then no significant boost expected.

Very good detection prospects for CTA!
No so good for current IACTs.

Test case: PKS 1222+216



Median χ^2 of the fit after 1000 trials for each E_{crit}



E_{crit}'s accesible to CTA
(i.e., > 5σ deviation of spectrum w.r.t. the fit)

ALP search also ongoing in Fermi

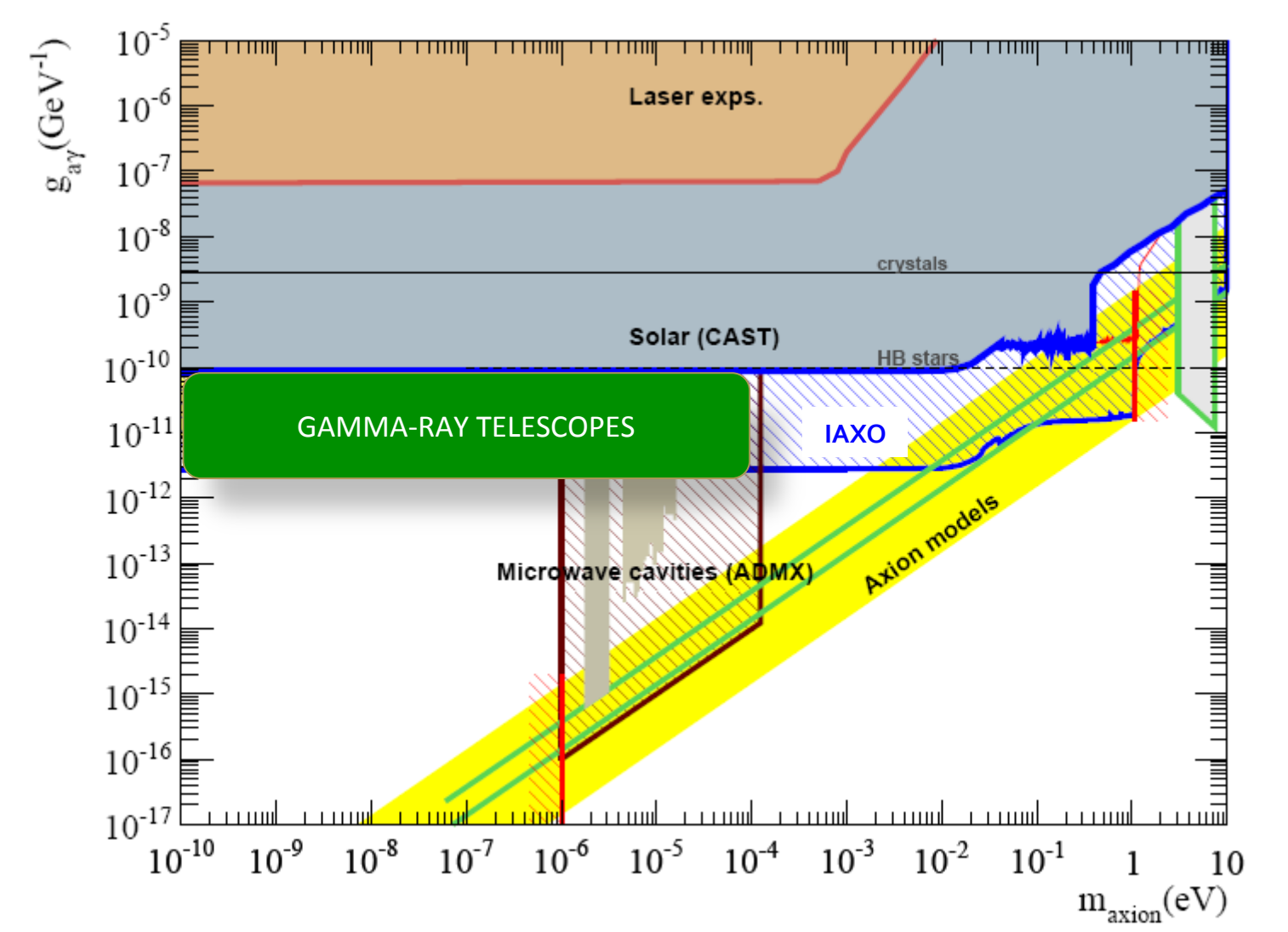
- ✓ The project has just started.
- ✓ Now, defining the best AGN sample and details of the stacking analysis.

- ✓ Different search strategies are being explored:
  - Flux drops at E_{crit} ~ (sub)GeV energies due to source mixing.
  - Flux drops at E_{crit} ~ (sub)TeV energies due to intergalactic mixing.
  - Systematic flux enhancements at the highest possible energies.

- ✓ If no detection, constraints on ALP parameters.

- ✓ Plans to work together with the IACT community.

Fermi + IACTs can explore a region of the ALP parameter space that is difficult to explore otherwise!



[Adapted from Irastorza, this conf.]