THE HUNT FOR AXION-LIKE PARTICLES WITH GAMMA RAYS

Miguel A. Sánchez-Conde

[Oskar Klein Centre for Cosmoparticle Physics, Stockholm University]

Off-the-Beaten-Track DM and Astrophysical Probes of Fundamental Physics

ICTP Trieste, 13-17 April 2015

Photon/axion conversions

- Axions proposed as a by-product of the Peccei-Quinn solution of the strong-CP problem.
- Axion-like particle (ALP): mass and coupling not related.
- Can be suitable dark matter candidates.
- Expected to convert into photons (and vice-versa) in the presence of magnetic fields.

Probability of conversion (e.g.Raffelt & Stodolsky 88, Mirizzi+07):

$$P_0 = (\Delta_B s)^2 \frac{\sin^2(\Delta_{\rm osc} s/2)}{(\Delta_{\rm osc} s/2)^2}.$$

with

$$\Delta_B = \frac{B_t}{2M} \simeq 1.7 \times 10^{-21} M_{11} B_{\rm mG}\ {\rm cm}^{-1},$$

$$\Delta_{\rm osc}^2 \simeq (\Delta_{\rm CM} + \Delta_{\rm pl} - \Delta_a)^2 + 4\Delta_B^2,$$

Photon/axion conversions the main vehicle used in axion searches at present (ADMX, CAST…).

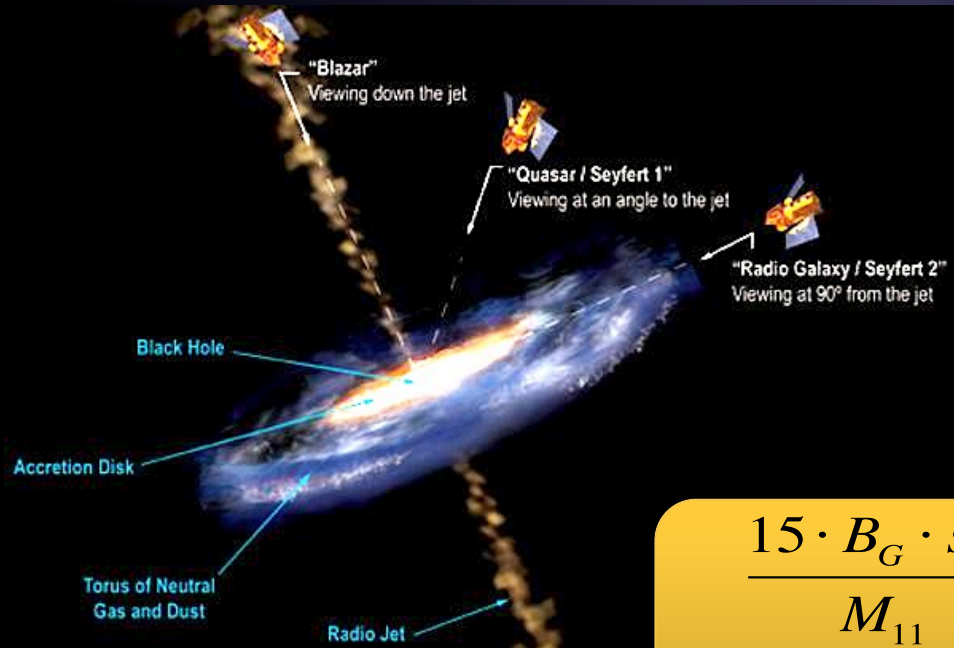
Some astrophysical environments fulfill the mixing requirements

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

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

- M_{11}: coupling constant inverse ($g_{ag}/10^{11}$ GeV)
- B_G: magnetic field (G)
- s_{pc}: size region (pc)

Very diverse astrophysical mixing scenarios are possible…

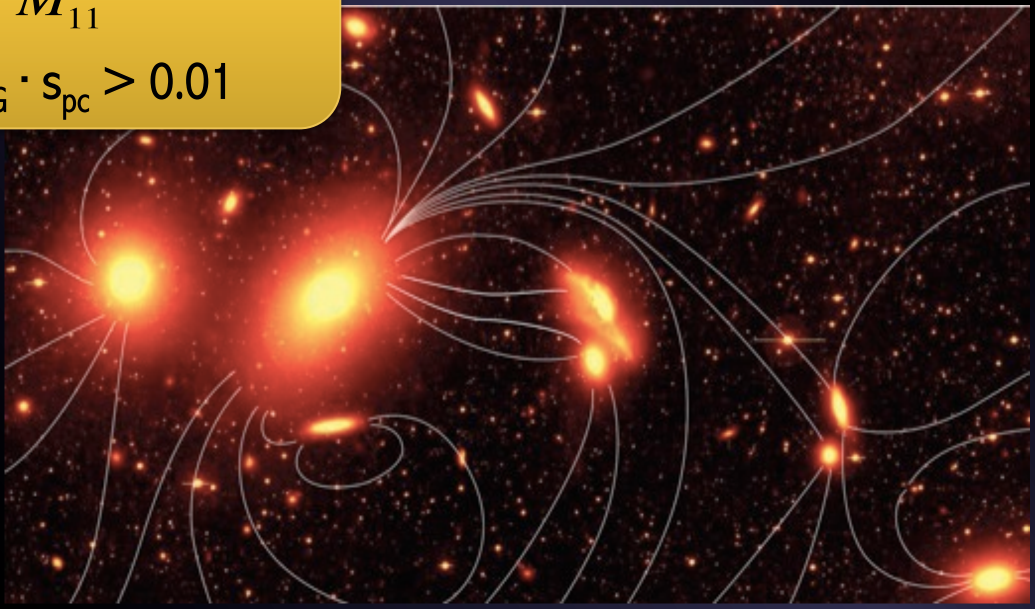


From Active Galactic Nuclei (AGNs)…

B ~ Gauss
s_{pc} ~ (sub)pc

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

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



… to Intergalactic Magnetic Fields (IGMFs)

B ~ nG
s_{pc} ~ Mpc

Astrophysical scenarios for photon/ALP conversions

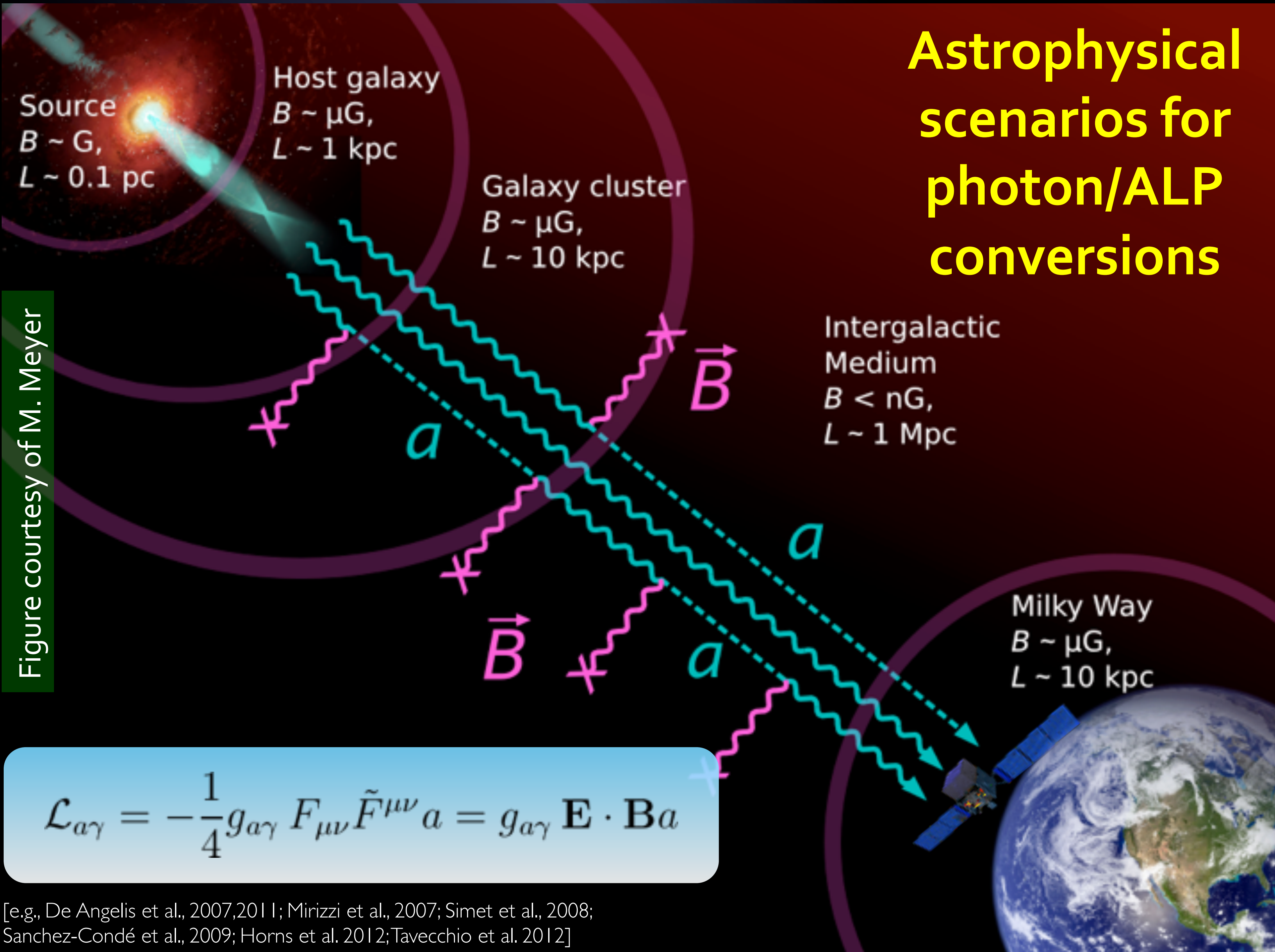


Figure courtesy of M. Meyer

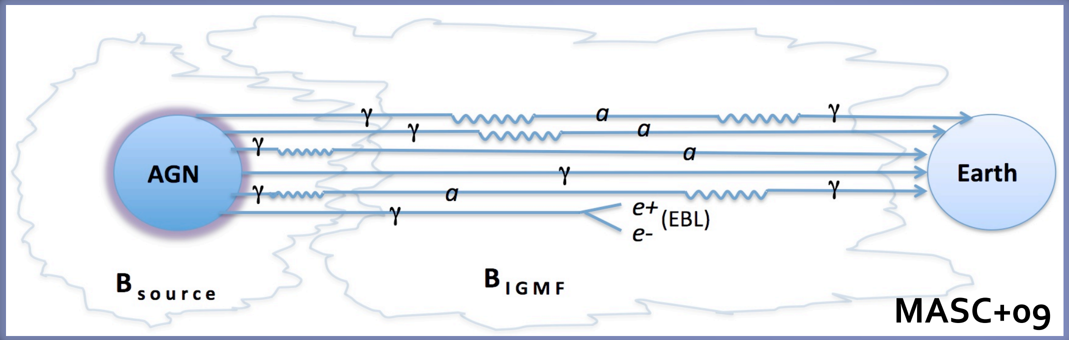
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a$$

[e.g., De Angelis et al., 2007,2011; Mirizzi et al., 2007; Simet et al., 2008; Sanchez-Condé et al., 2009; Horns et al. 2012; Tavecchio et al. 2012]

Photon/ALP conversions in gamma-rays

Many different scenarios already explored in the literature:

- Mixing in the AGN (e.g. Hooper & Serpico 07, Tavecchio+12)
- IGMF mixing (e.g. De Angelis+07, 09, 11)
- AGN+ IGMF mixing (e.g. MASC+09)
- IGMF + Galactic mixing (e.g. Simet+08)
- AGN + cluster+ Galactic mixing (e.g. Meyer+14)



Critical energy for conversion

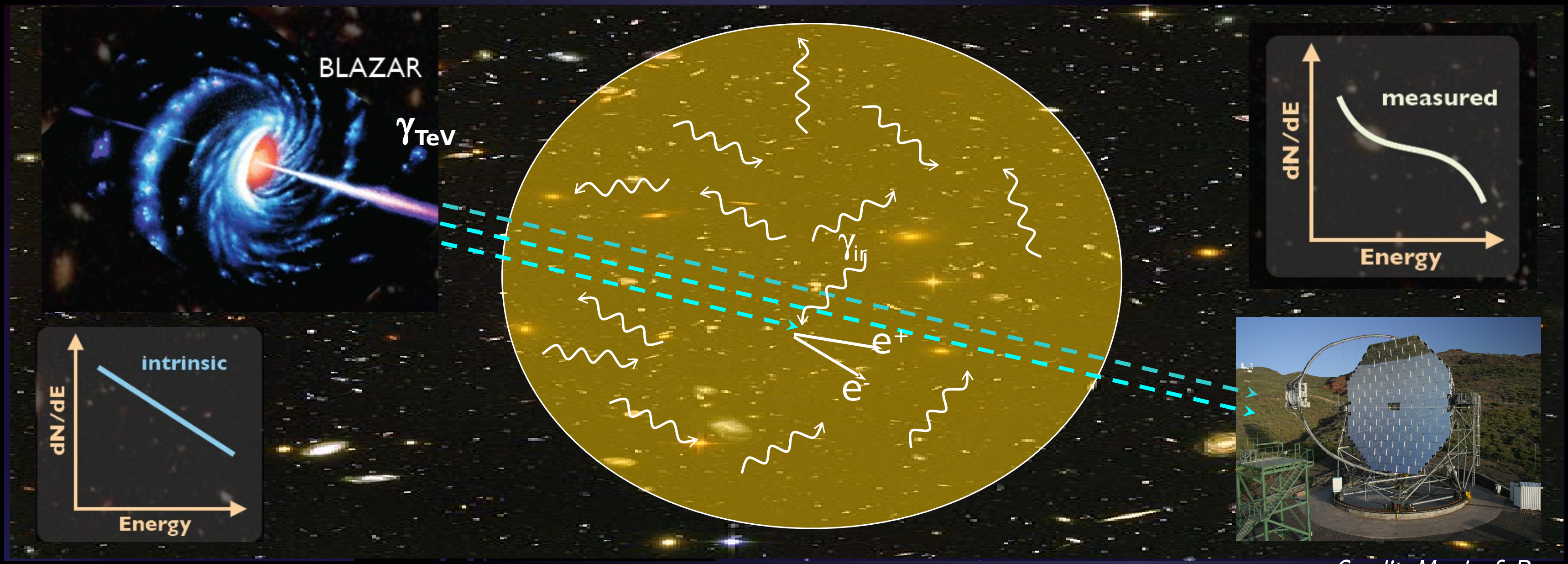
$$E_{crit}(GeV) \equiv \frac{m_{\mu eV}^2 \; M_{11}}{0.4 \; B_G}$$

where $m_{\mu eV} = |m_{ALP} - \omega_{plasma}|$

Gamma-ray energy range ➡ ultra-light ALPs (~10^{-9} eV).

For the same ALP properties, different E_{crit} are expected for each astrophysical scenario.

Intergalactic absorption of gamma-ray photons



Credit: Mazin & Raue

Around TeV energies:

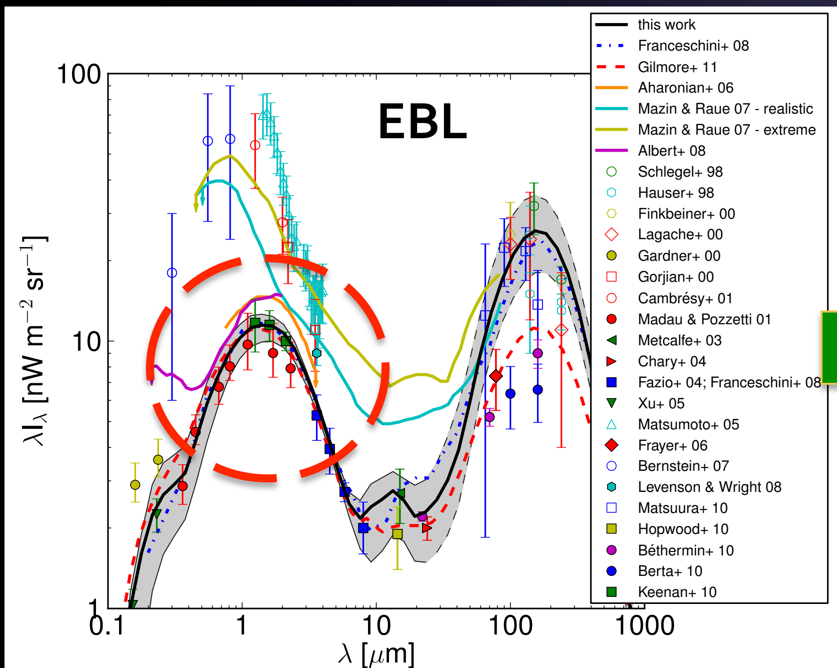
$$\lambda \approx 1.24\left(\frac{E}{1TeV}\right)\mu m$$

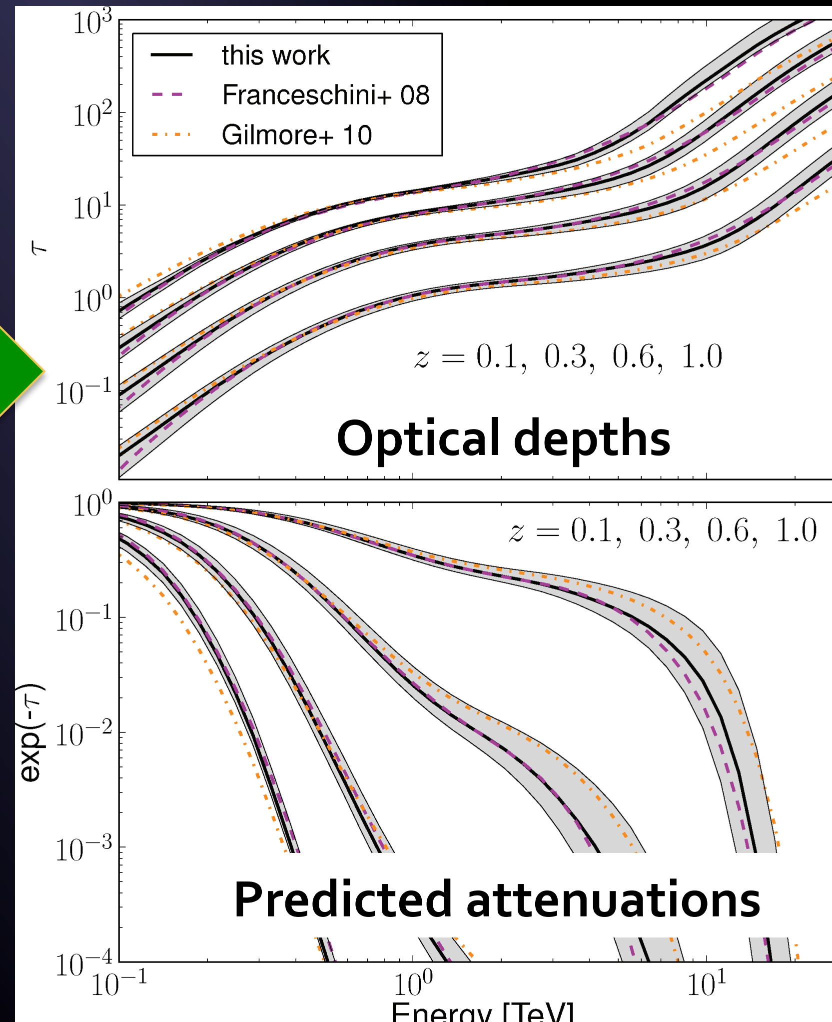
Infrared/optical/UV background photons:
Extragalactic Background Light (EBL)

Flux attenuation: $F_{Earth} = F_{source}\,\mathrm{Exp}[-\tau(E,z)]$ with τ = optical depth

Example: for a source at redshift 0.5 and 0.5 TeV, attenuation ~2 orders of magnitude!!

Optical depth from state-of-the-art EBL models





The most refined EBL models remarkably agree on their predictions for the (sub)TeV regime

Domínguez+11

Hints of new Physics in γ-ray data?

(or why astrophysicists started to care about ALPs)

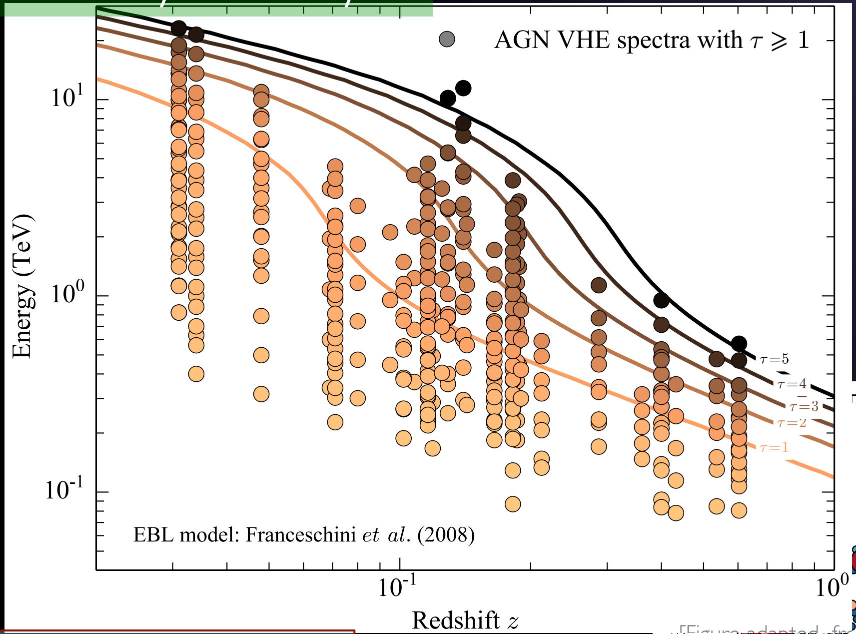
Some gamma-ray observations pose substantial challenges to the conventional astrophysical models, e.g.:

- **Lower opacity of the Universe to gamma rays** than expected (e.g. Aharonian+06, Albert+08, Acciari+11, De Angelis+09,11,13)
- **Too hard intrinsic spectrum of AGNs** (e.g. Albert+08, Wagner+10, Aleksic+11,Tanaka+13, Furniss+13)
- **Intrinsic spectrum deviates from a power-law**: pile-up problem (Dominguez, MASC+12; Furniss+13)
- **Extremely rapid and intense flares in FSRQs:** γγ absorption problem (Tavecchio+12).
- **GeV spectral breaks and dips** (Tanaka+13, Rubtsov & Troitsky 14, Mena & Razzaque 13)

Hints of new Physics in γ-ray data?
LOWER OPACITY TO GAMMA RAYS

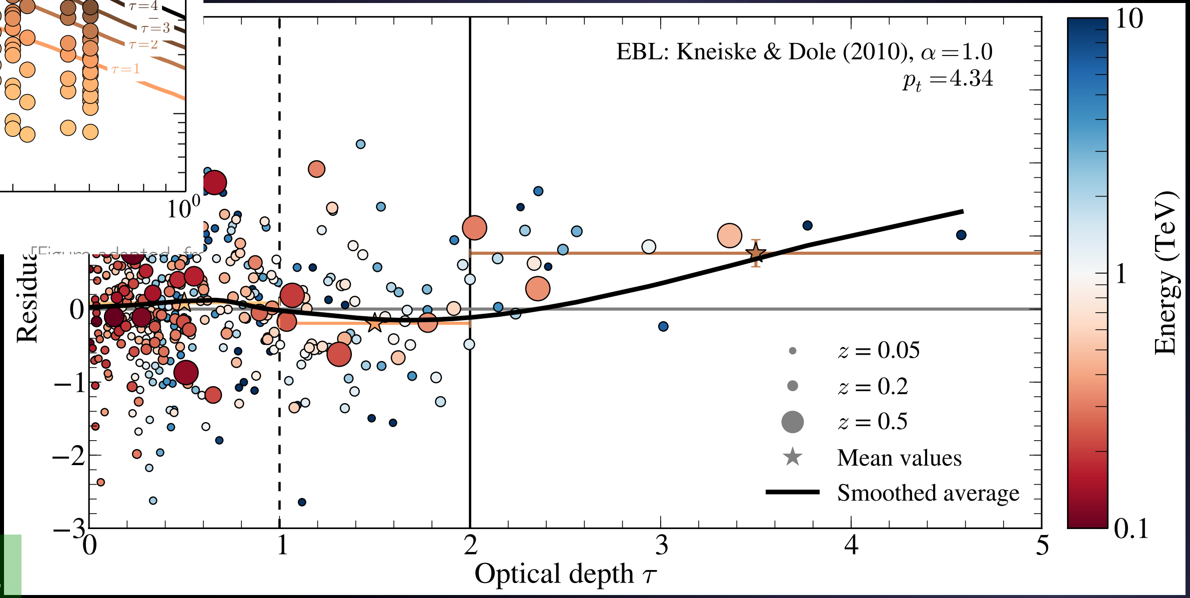
More gamma-ray photons than expected at high optical depths.

Courtesy of M. Meyer



EBL corrected blazar spectra reveals a **2σ-4σ** evidence for overcorrection with EBL models

Increasing number of AGNs at high optical depths.

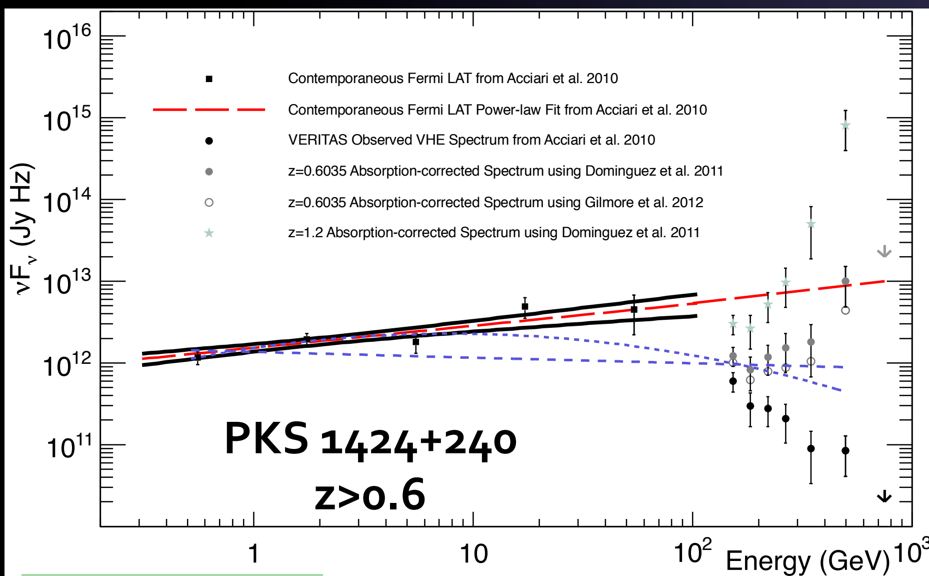


Horns & Meyer+12

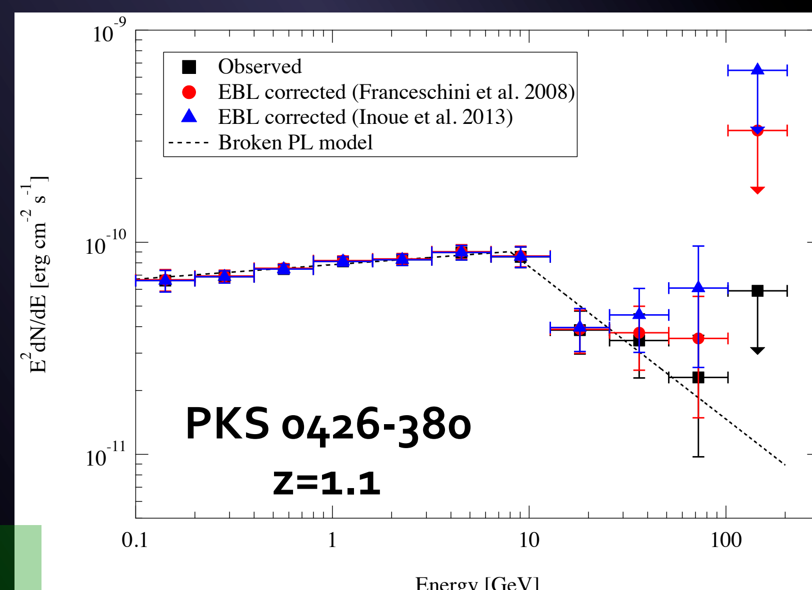
Hints of new Physics in γ-ray data?

SPECTRAL "HARDENING" at high τ

Some de-absorbed, *intrinsic* AGN spectra are best described by power laws with spectral indices smaller than 1.5 – **too "hard" AGN spectra**



Furniss+13c

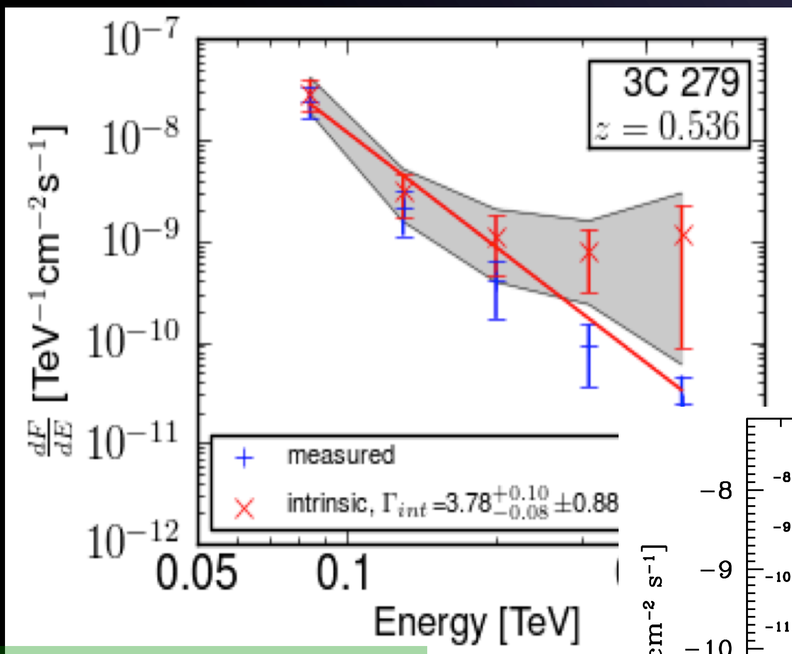


Tanaka+13

Note that the last data points give τ ~ 5 !!

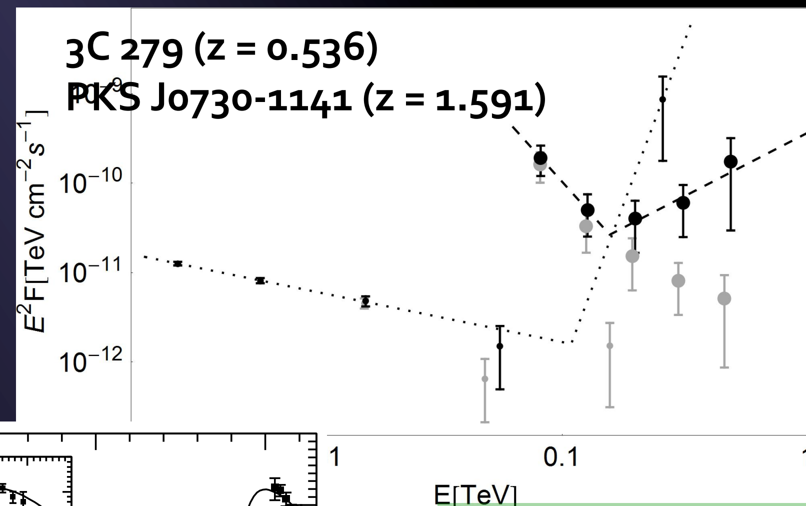
Hints of new Physics in γ-ray data?
MORE ANOMALIES

PILE-UP of photons at the highest energies

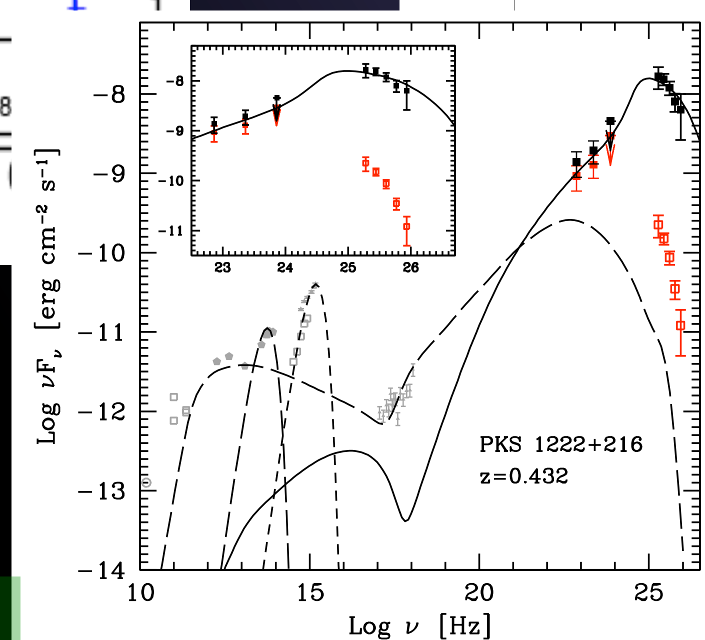


Domínguez, MASC+11

UPTURN at high optical depths



Rubtsov & Troitsky 14

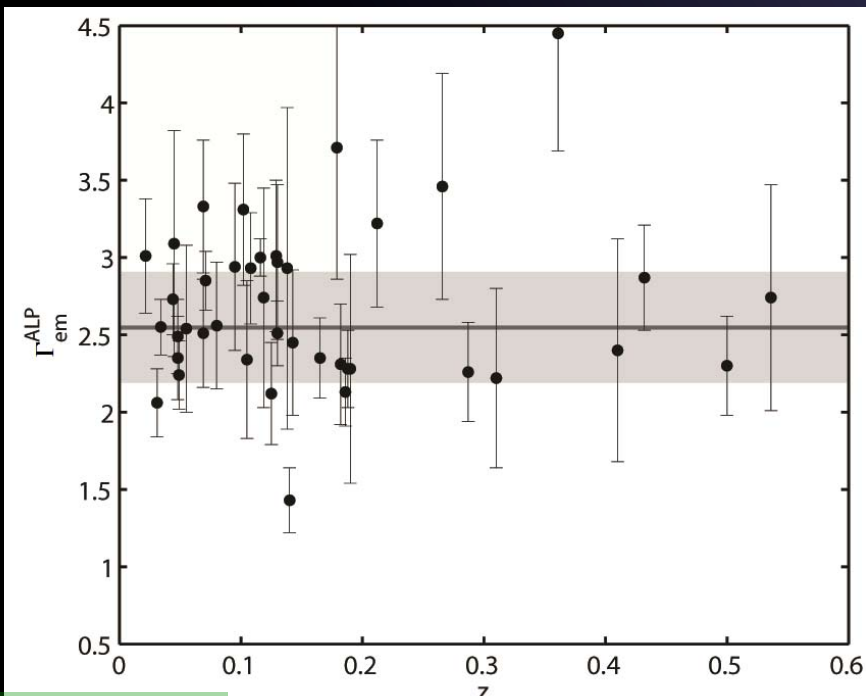


Tavecchio+12

Circumventing **GAMMA-GAMMA ABSORPTION** close to the central engine

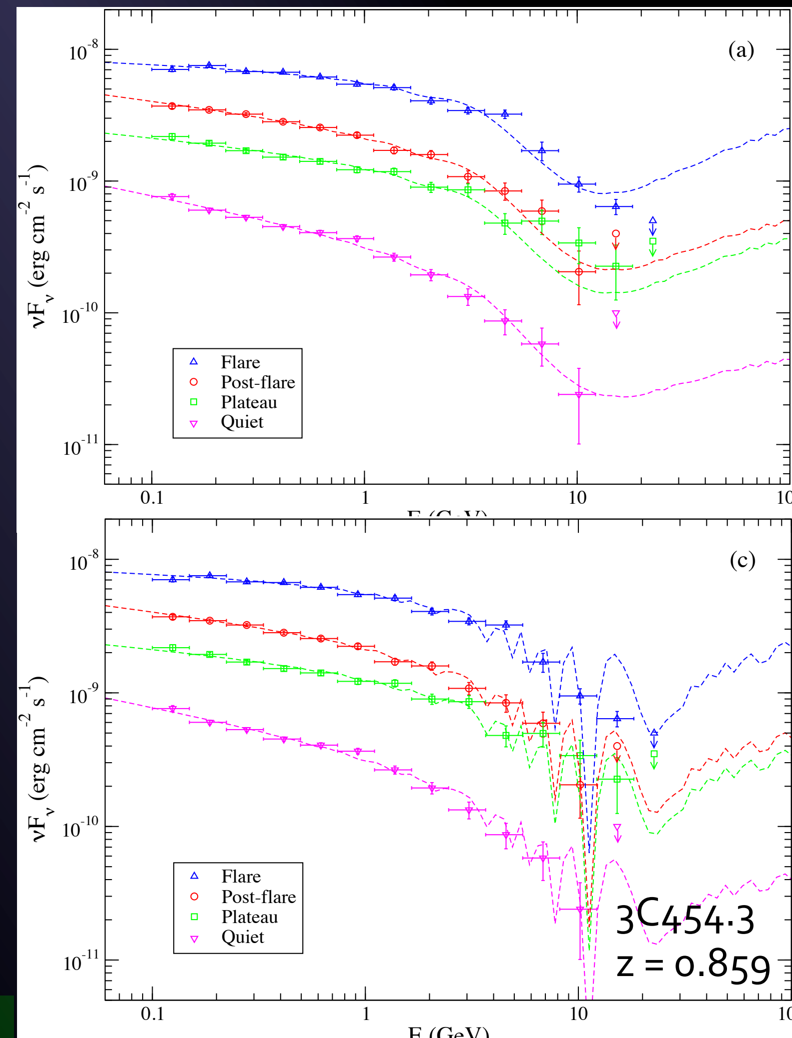
Hints of new Physics in γ-ray data?
MORE ANOMALIES

Unphysical behavior of AGN **spectral index with redshift**



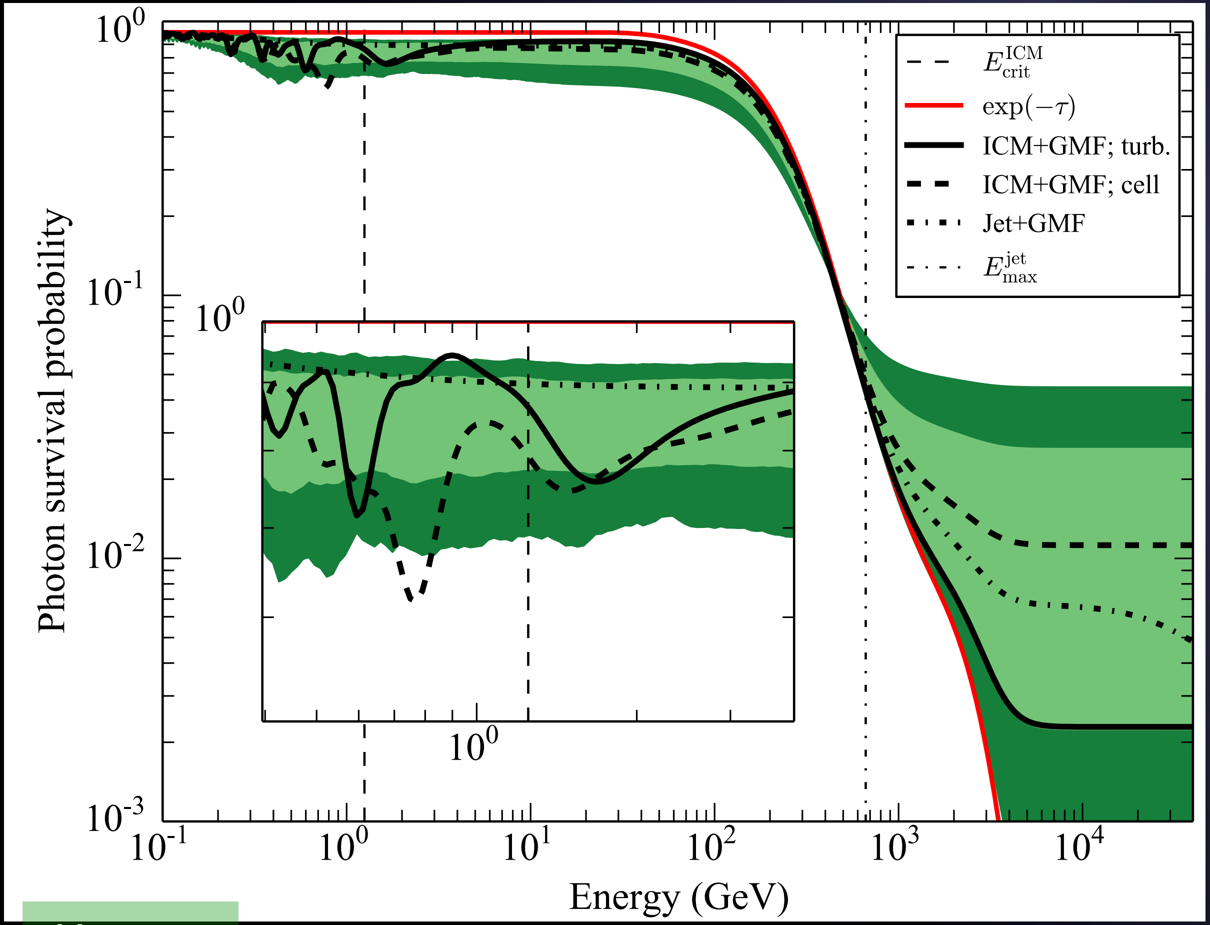
Galanti+15

GeV breaks in AGN spectra



Mena & Razzaque 13

ALPs modify the spectrum of AGNs

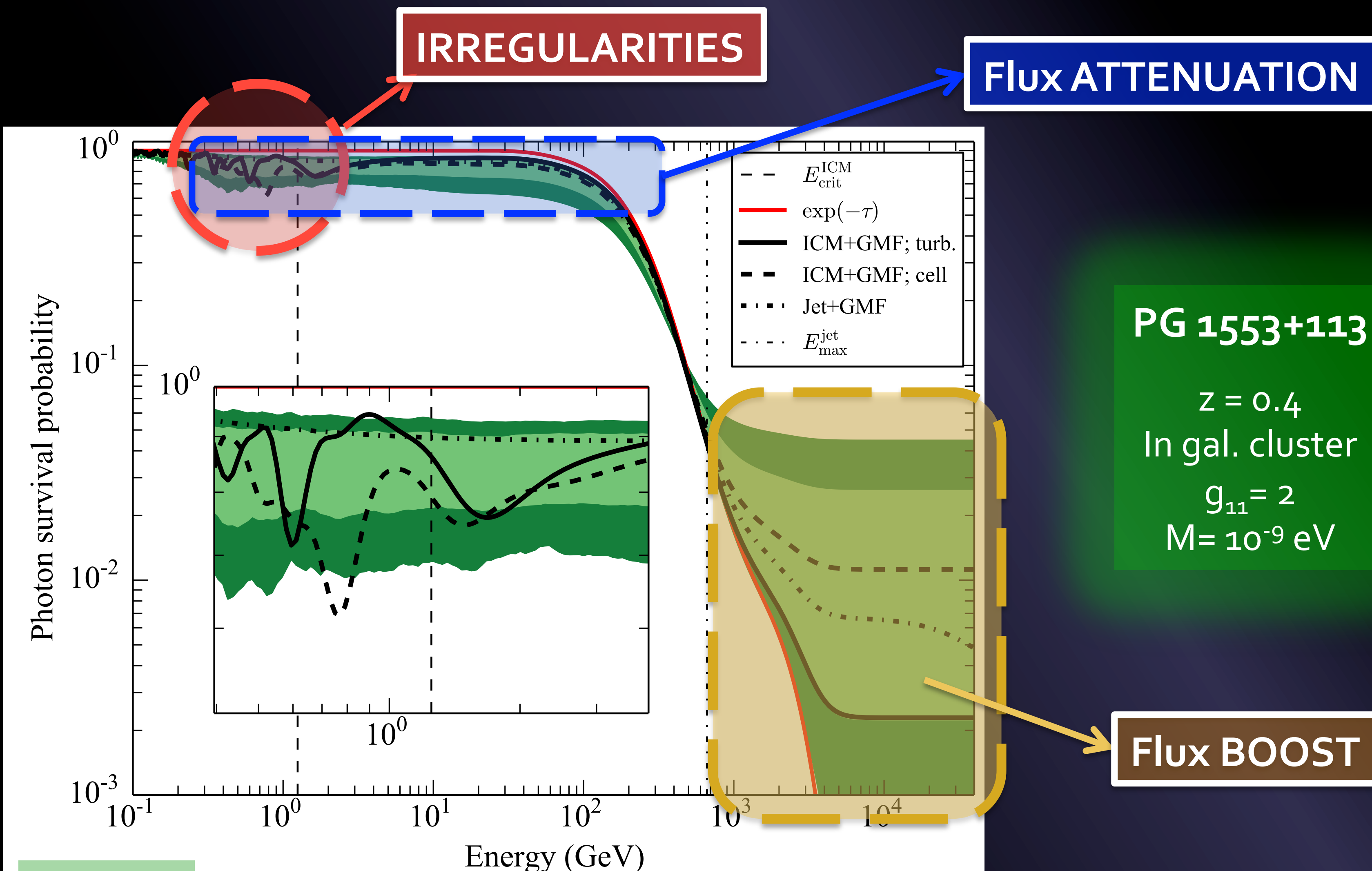


Meyer+14

PG 1553+113

z = 0.4
In gal. cluster
g_{11} = 2
M= 10^{-9} eV

ALPs modify the spectrum of AGNs



PG 1553+113

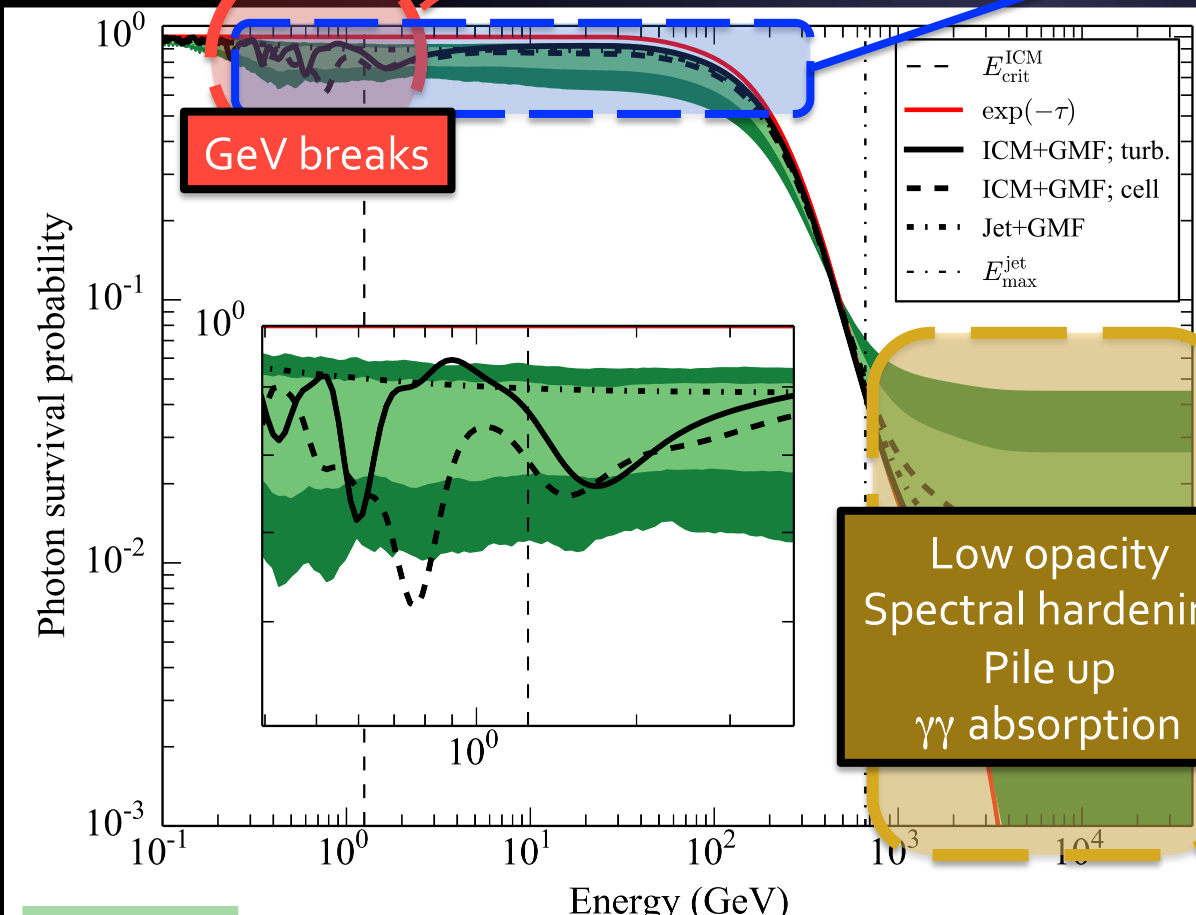
z = 0.4
In gal. cluster
g_{11}= 2
M= 10^{-9} eV

Meyer+14

ALPs could explain these anomalies

IRREGULARITIES

Flux ATTENUATION



Flux BOOST

PG 1553+113

z = 0.4
In gal. cluster
g_{11}= 2
M= 10^{-9} eV

Meyer+14

Present gamma-ray observatories

E. range: 20 MeV - >1 TeV

E. resolution: ~10% @ GeV

FoV: ≈ 2.4 sr

Angular resolution: ~0.2º@10 GeV

Effective area ~ m^2

Fermi-LAT

E. range: 50 GeV - >10TeV

E. resolution: ~20%

FOV: ≈ 4 deg.

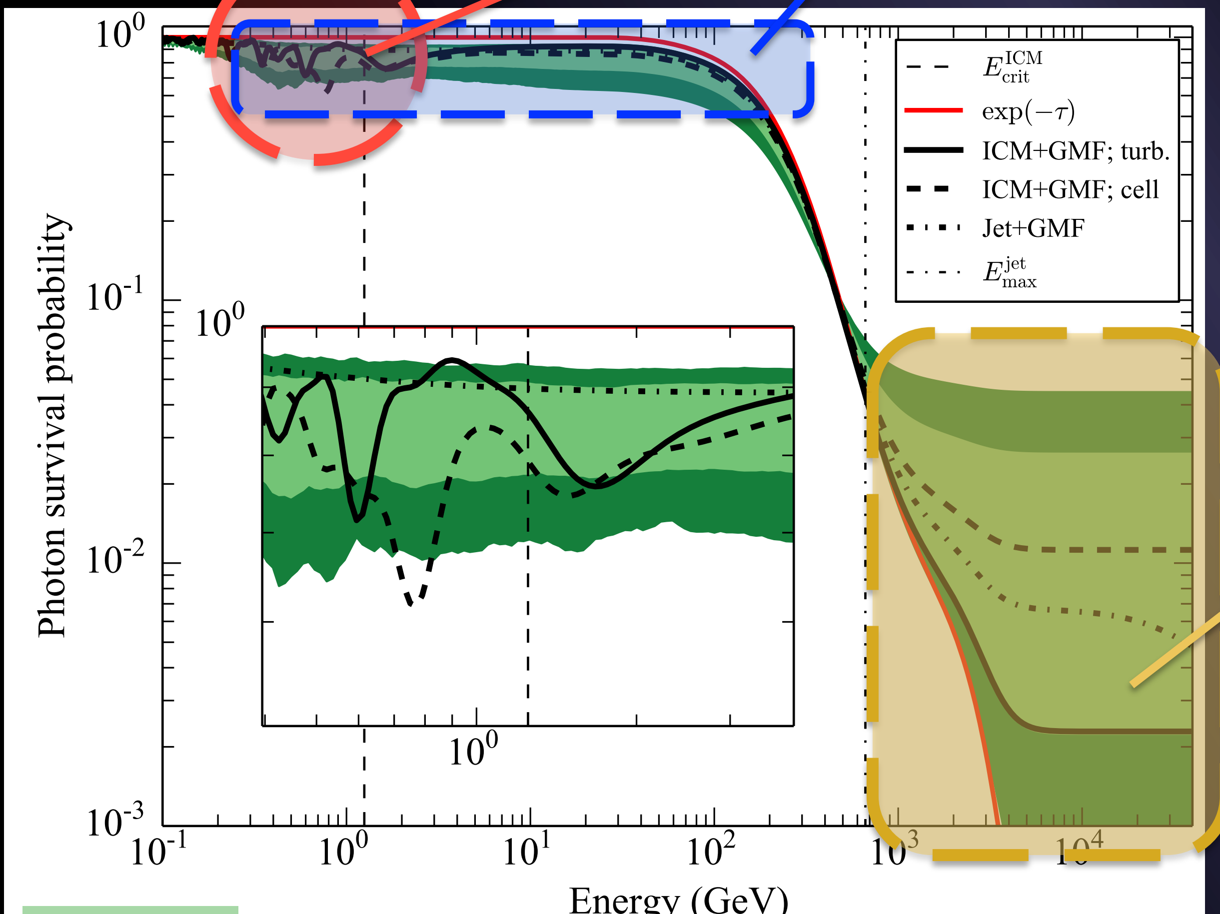
Angular resolution: ≈ 0.1º

Effective area ~ 10^5 m^2

Typical Cherenkov telescope (IACT)

The ALP hunt with Fermi and IACTs

Fermi is more suitable for energies where the EBL is still not at work



Meyer+14

(Ongoing) ALP search with Fermi: PERSEUS GALAXY CLUSTER

- Focus on spectral irregularities

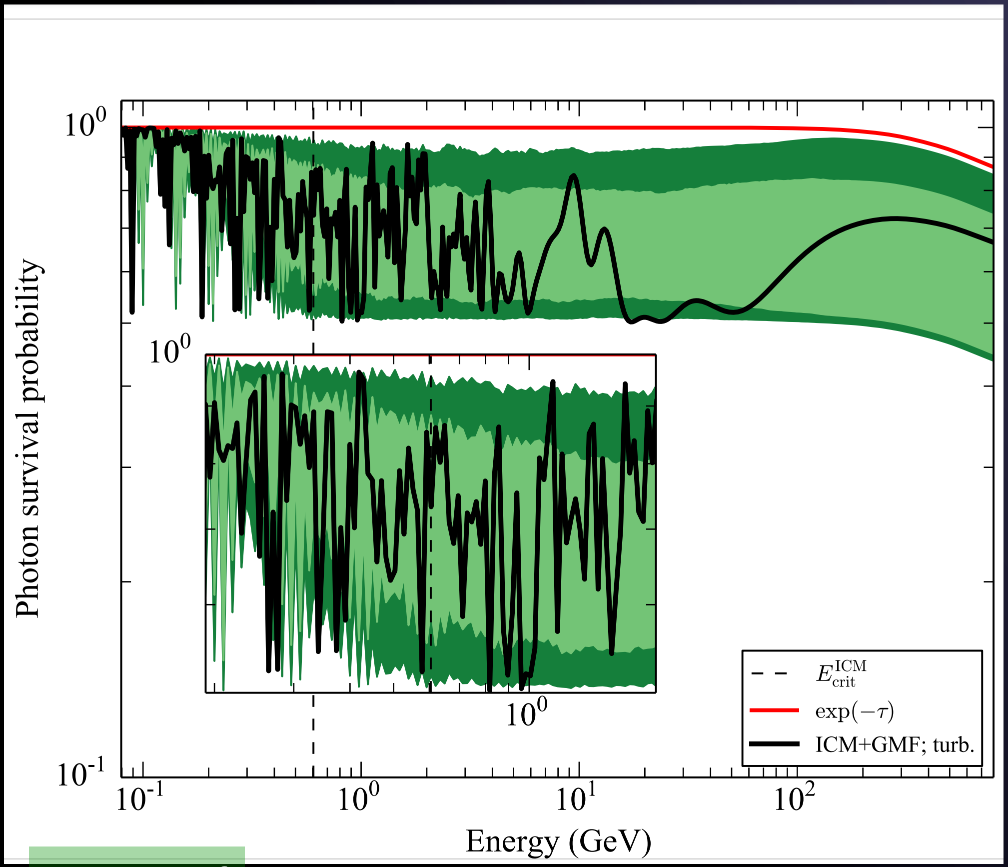
  → no cosmological distances needed.

- PERSEUS galaxy cluster an optimum candidate.
  - Bright radio galaxy NGC 1275 in its center. Seen by Fermi and MAGIC.
  - Estimates of B field ~ 10-20 μG in the center (Taylor+06, Aleksic+10, Aleksic+12). Morphology on large scales unknown.
  - Turbulent B field , follows electron density.
  - Electron density inferred from X-rays (Churazov+03, Fabian+06).

- Cluster and Galactic magnetic fields considered.

Credit: R Jay GaBany
http://www.cosmotography.com/images/ngc1275.html

Example of expected irregularities



Courtesy of
M. Meyer

Parameter	Value
Virial radius	3.3 Mpc
Redshift	0.0179
Coupling	10^{-11} GeV
ALP mass	3 neV
Central B field	15 mG
Coherence Length	10 kpc
Turbulence PL index	-2.80
Maximum B field radius	560 kpc
Electron density	33

Fermi analysis ongoing

Analysis

100 MeV -- 500 GeV
5.7 years of data
Makes uses of the new event data selection, "Pass 8"

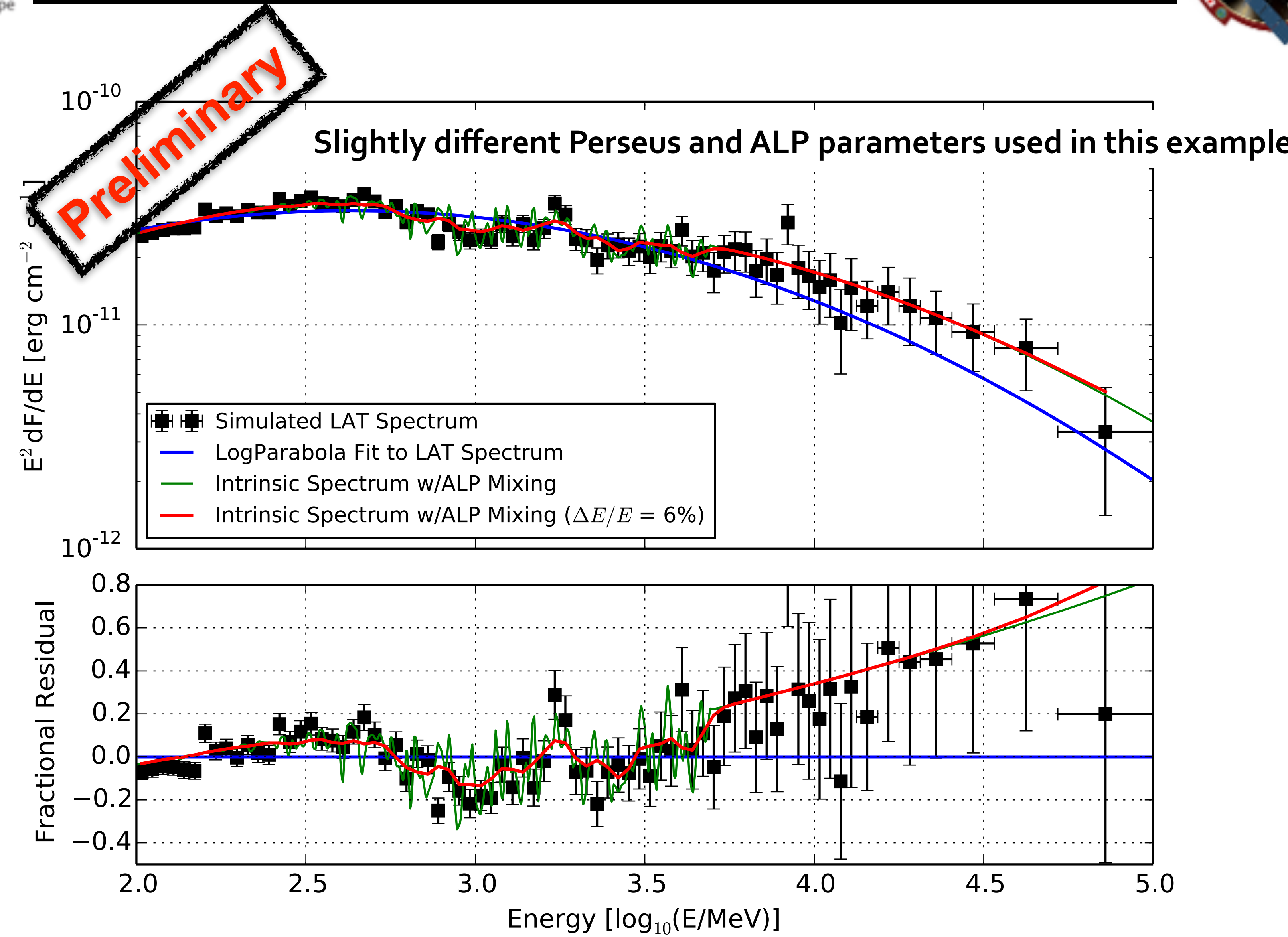
Method

Fit the spectrum of NGC 1275 to a log parabola with and w/o ALPs.
Scan the ALP mass-coupling parameter space
Explore hundreds of B field realizations
Likelihood analysis
Monte Carlo simulations being performed to obtain null distribution.
→ Constraints on the ALP parameter space

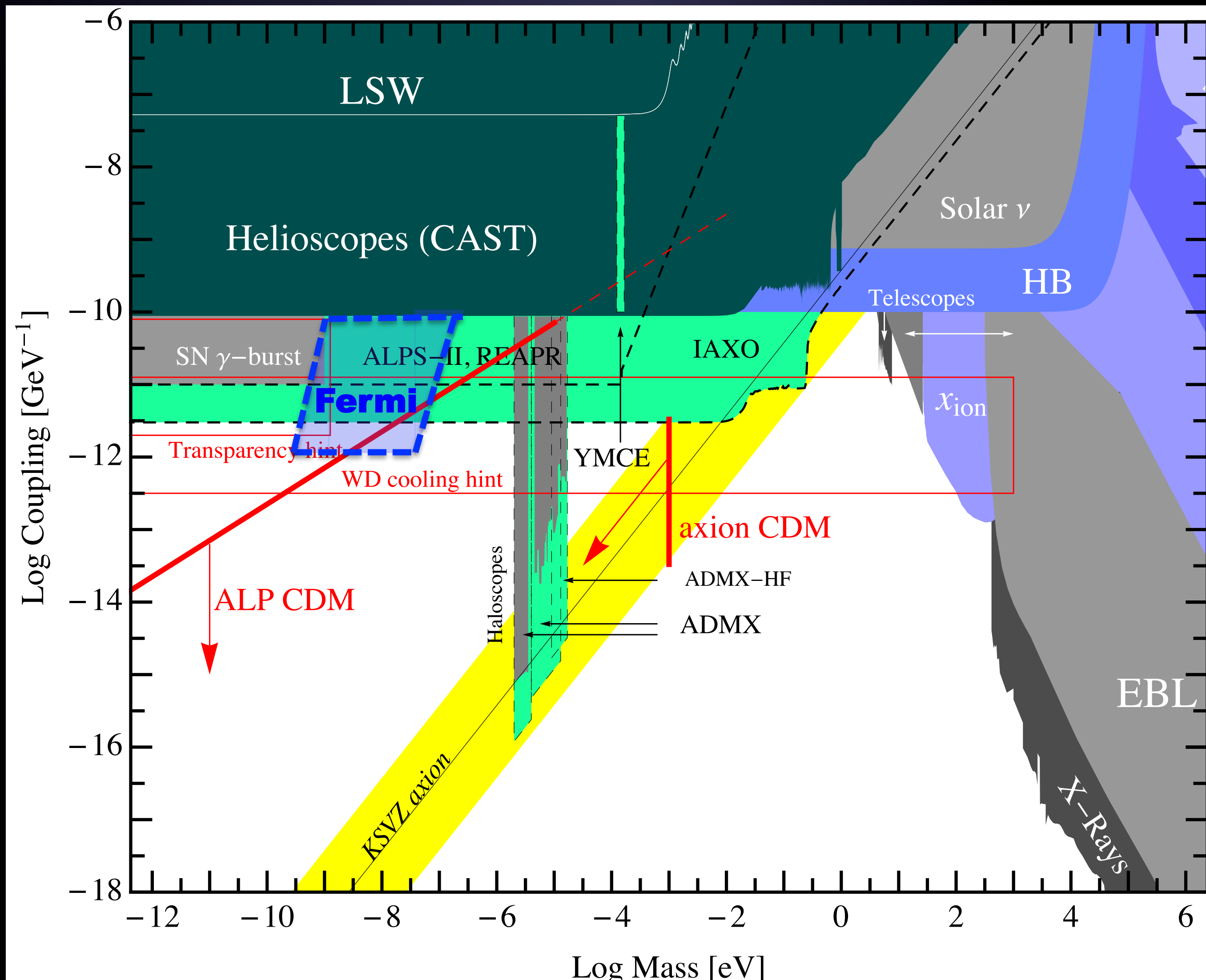
✓ Joint analysis of several AGNs in galaxy clusters possible.

✓ Work will be probably ready by ~ next Fall.

Simulated LAT spectrum of NGC1275 including Axion-like particles



An estimate of the Fermi sensitivity

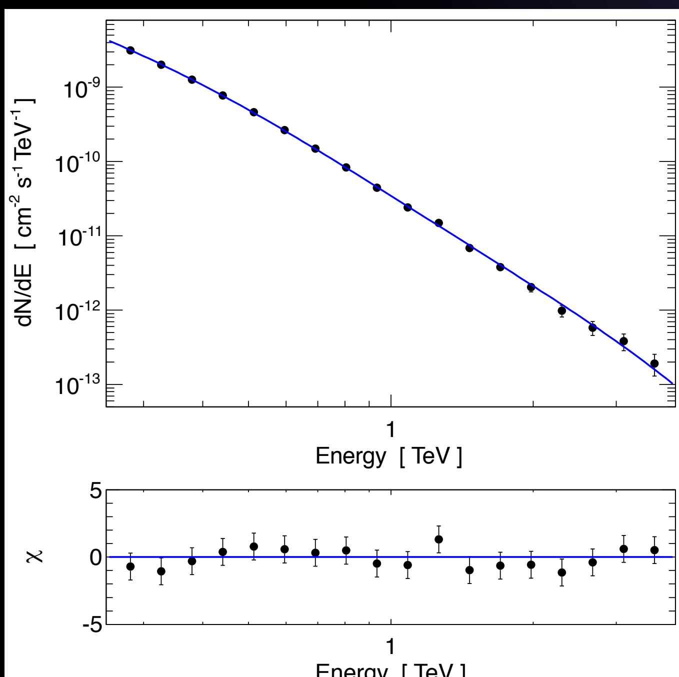


Adapted from Ringwald 2012

The ALP search with H.E.S.S.

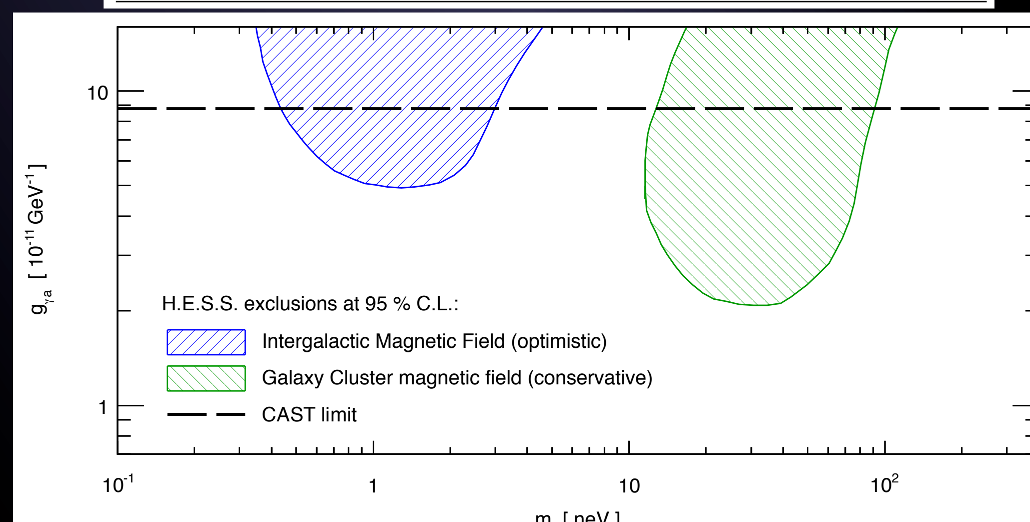
- PKS 2155-304, z = 0.116.
- Located at the center of a galaxy cluster.
- Assume intra-cluster and IGM photon/ALP conversions. Galactic neglected.
- Look for the maximum level of irregularity allowed by the data
  → constraints on the ALP parameter space.

Abramwski+13



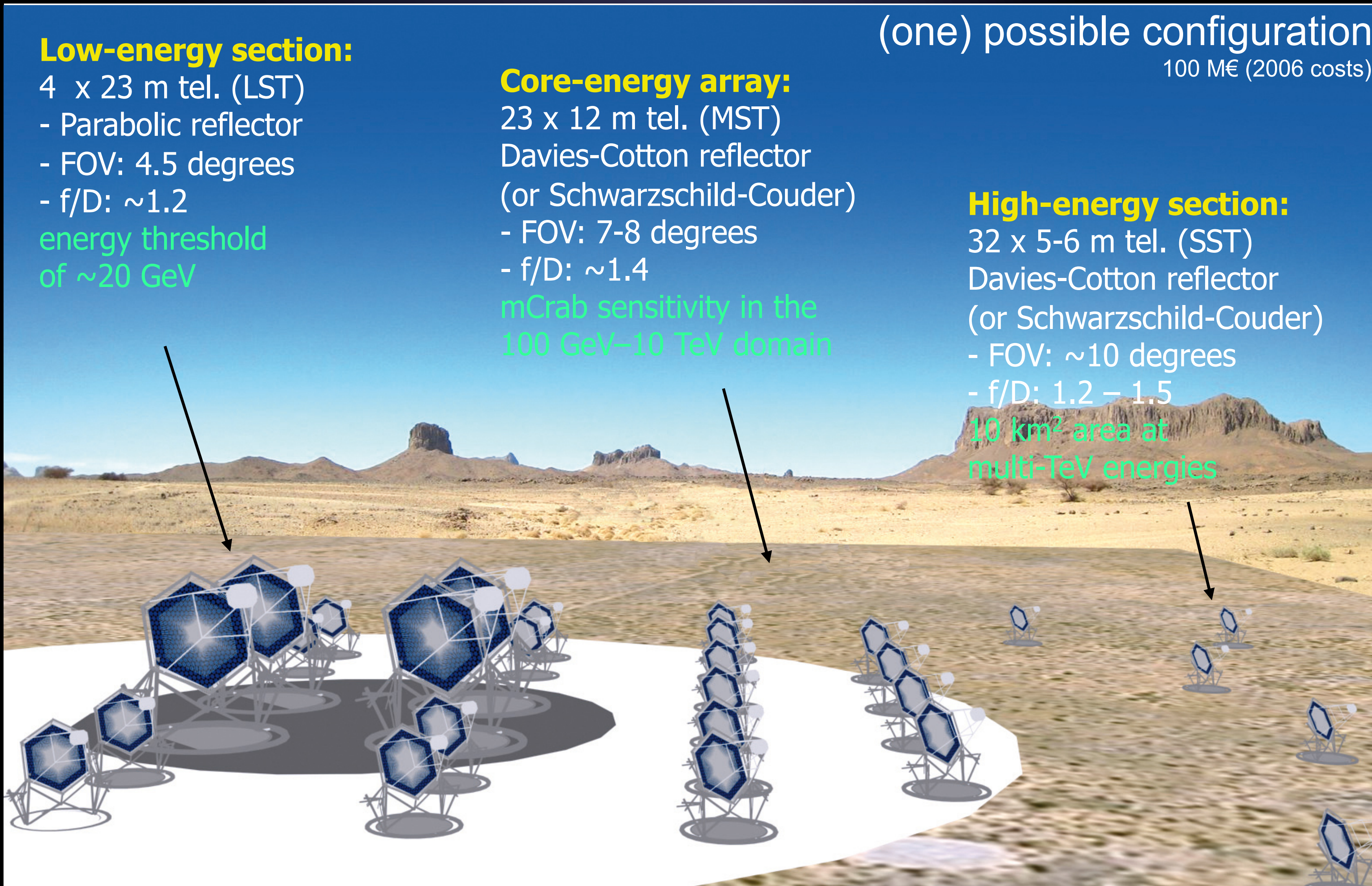
PKS 2155-304 spectrum and residuals of the best-fit model

	Cluster magnetic field	IGMF
B	1 μG	1 nG
L	370 kpc	500 Mpc
L/s	37	528



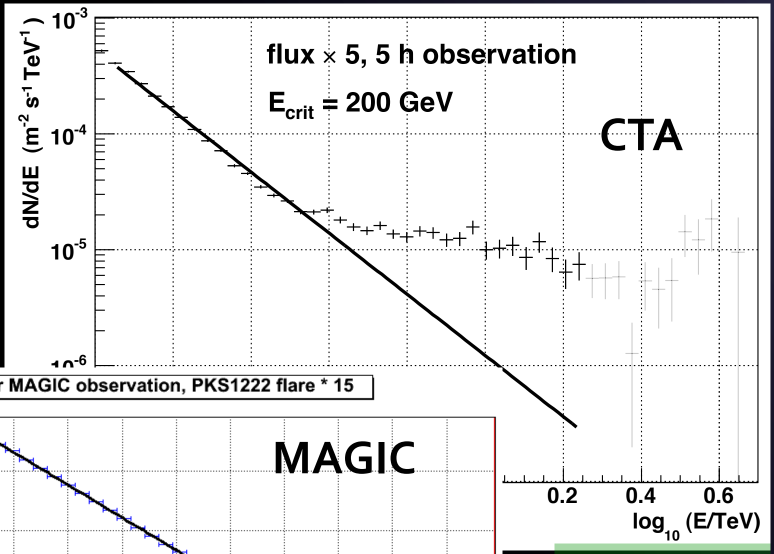
Constraints are derived separately for IGMF and CMF

The future:
Cherenkov Telescope Array (CTA)

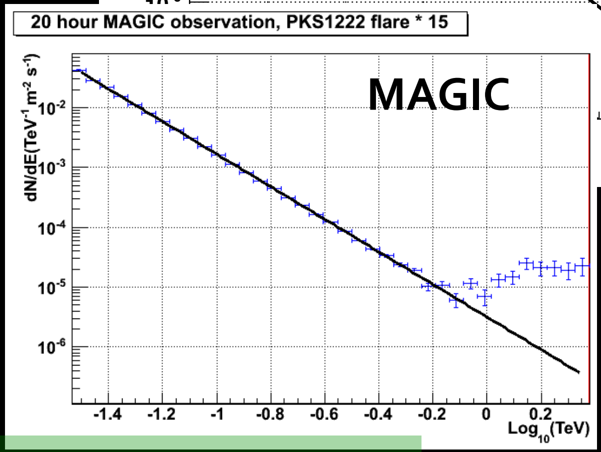


The search of ALPs with CTA

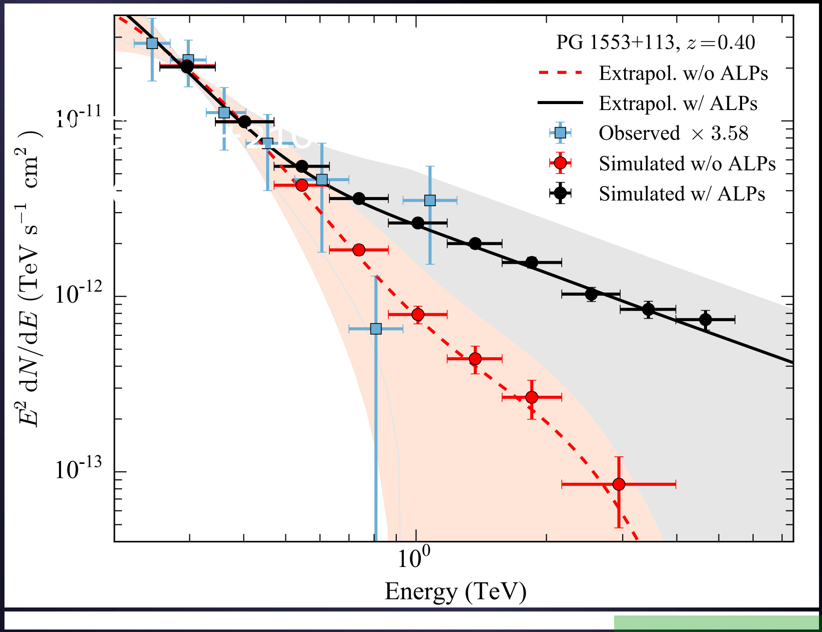
CTA will be the ideal instrument to look for boosts of gamma-ray photons at high optical depths.



Doro+13



González-Muñoz+12

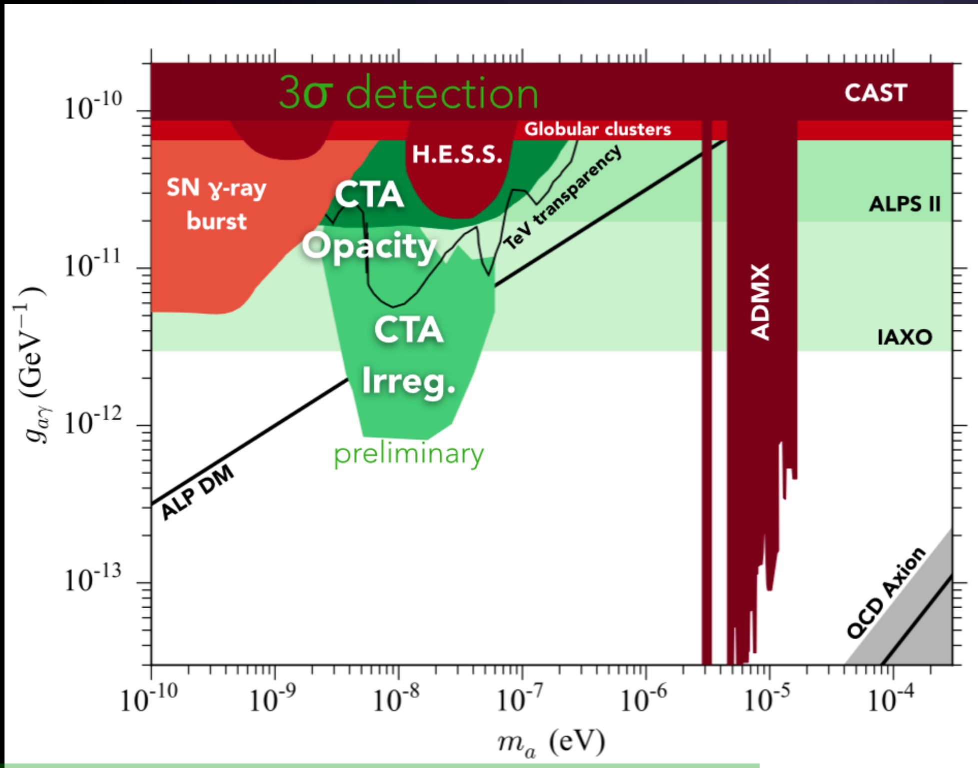


Meyer+14

Possible to reach much higher optical depths w.r.t. current IACTs!

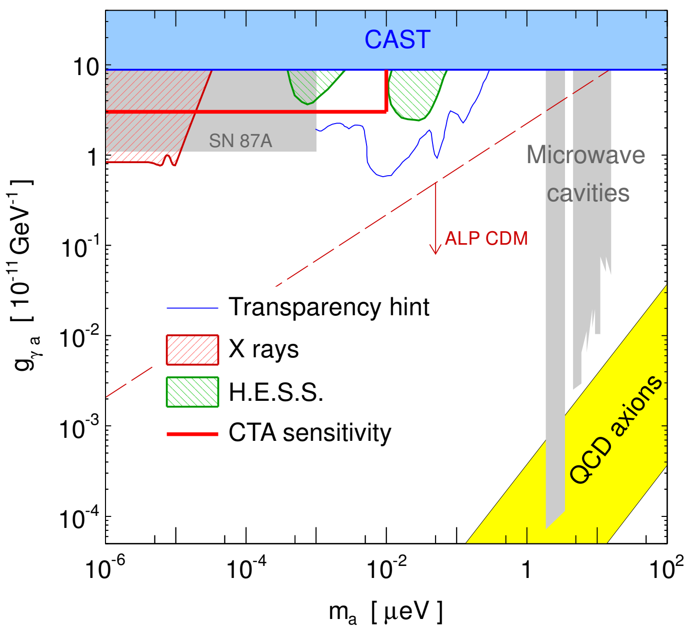
Most promising targets:
Blazars in flaring states at z ~ 0.4

Predicted CTA sensitivity



Meyer+14; Meyer & Wood 15 (preliminary)

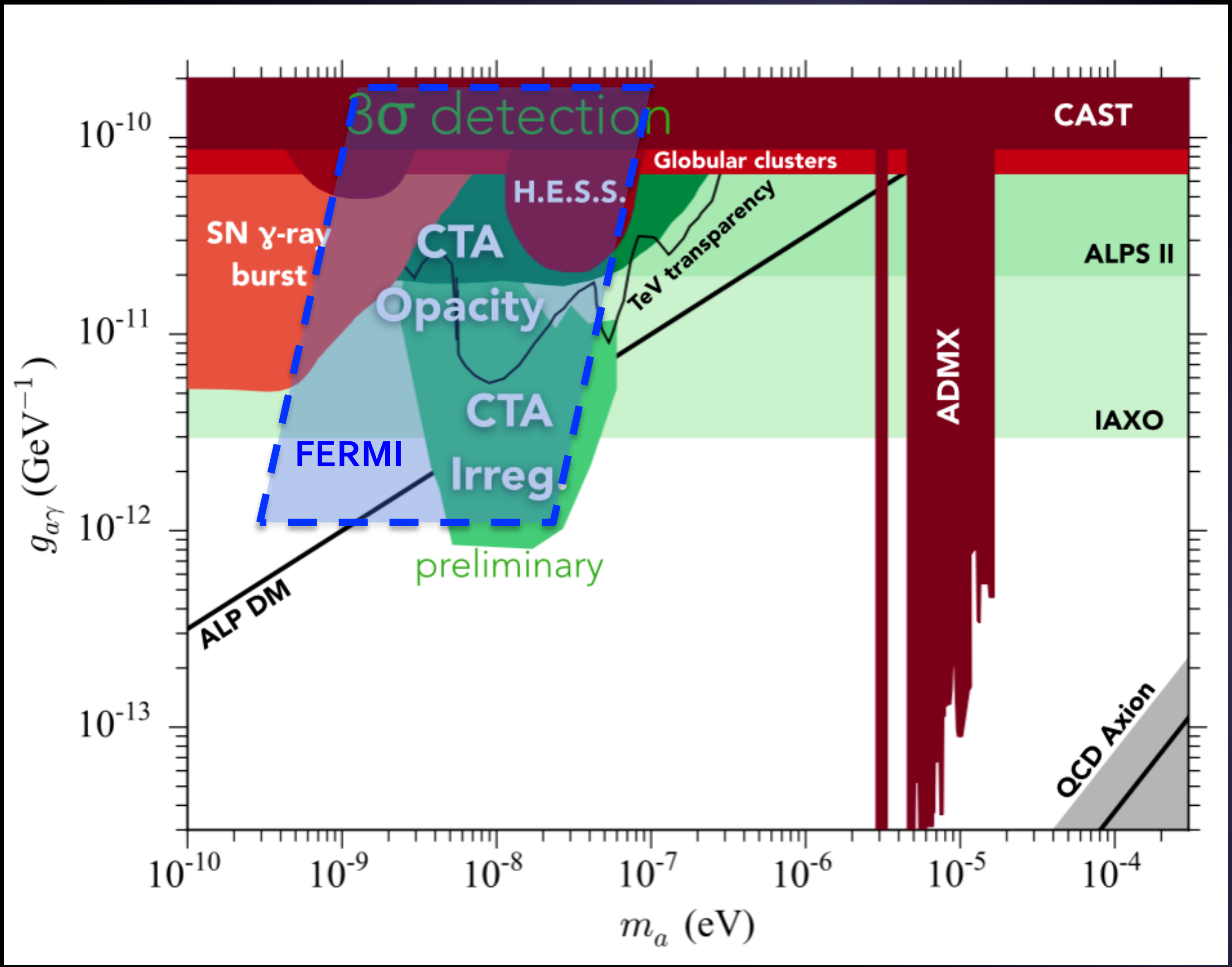
Sensitivity from likelihood ratio test with and w/o axions



→ Other search strategies proposed: '**Anisotropy test**'

Idea: auto-correlation of AGN spectral indices with the Galactic magnetic field (Wouters & Brun 14)

Nice complementarity!



Could reach the ALP DM region

Can test most of the low opacity hint parameter space

[Warning: the Fermi exclusion region should be considered just as a rough first estimate]

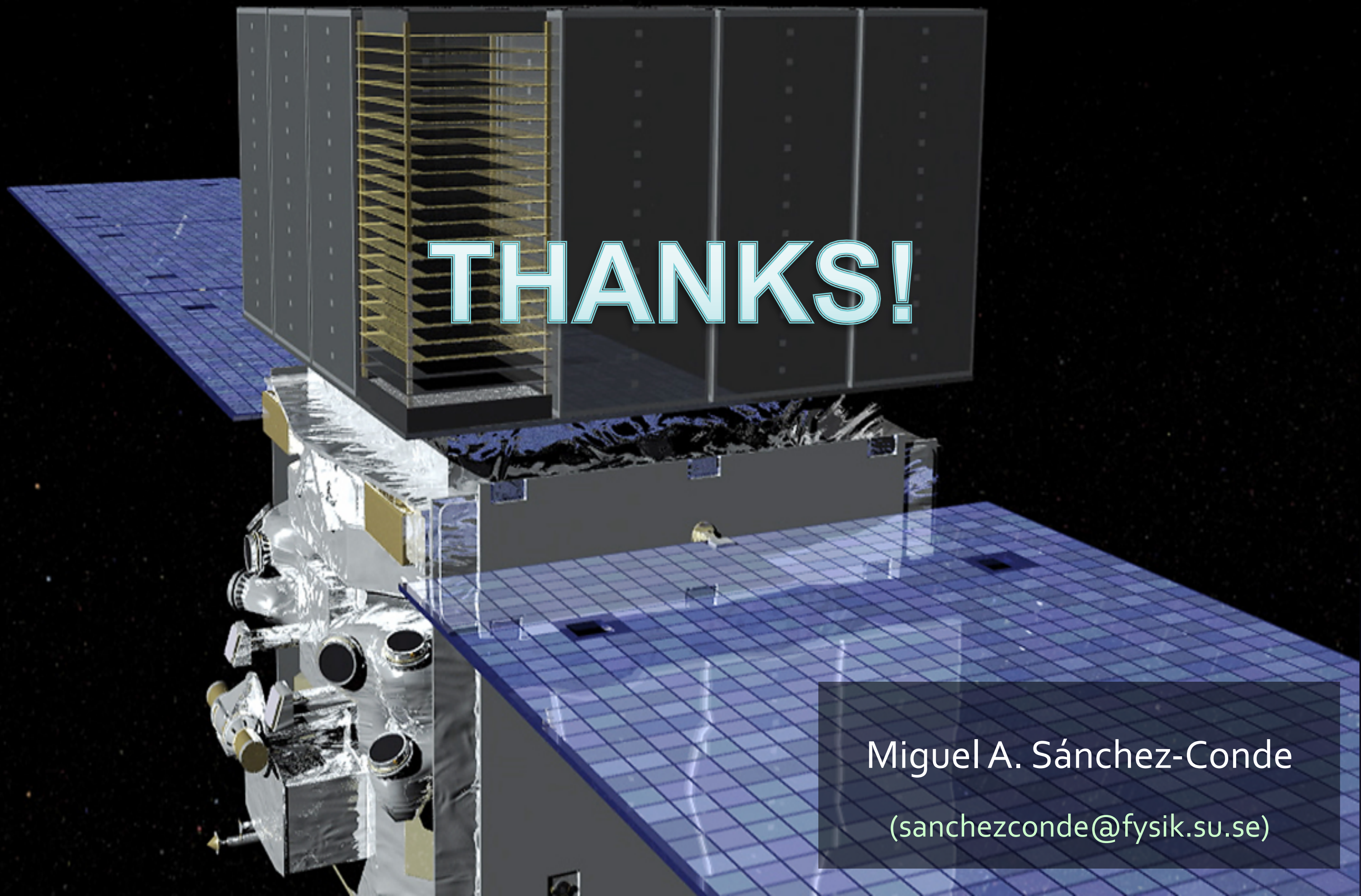
CONCLUDING REMARKS

- Photon/ALP conversions may lead to **very peculiar imprints in the spectra** of astrophysical objects.
- Some **anomalies exist in gamma-ray data** that challenge an explanation in terms of "conventional physics".
- Photon/ALP **conversions could explain** these anomalies.
- ALP search currently ongoing by the **Fermi LAT** collaboration:
  - Spectral irregularities in NGC1275, the central AGN in Perseus.
  - Work in an advanced stage. Could be out by Fall.
- **H.E.S.S.** already looked for ALP-induced spectral irregularities:
  - No hint of ALPs in the data.
  - First constraints in the ALP paramenter space from γ-ray telescopes.
- **CTA** will be able to probe a larger region of the ALP parameter space.
- **Fermi and IACTs nicely complementary** each other and complementary/ competitive to other existent search techniques.

Oskar Klein centre

Stockholm University

MULTIDARK
Multimessenger Approach for Dark Matter Detection



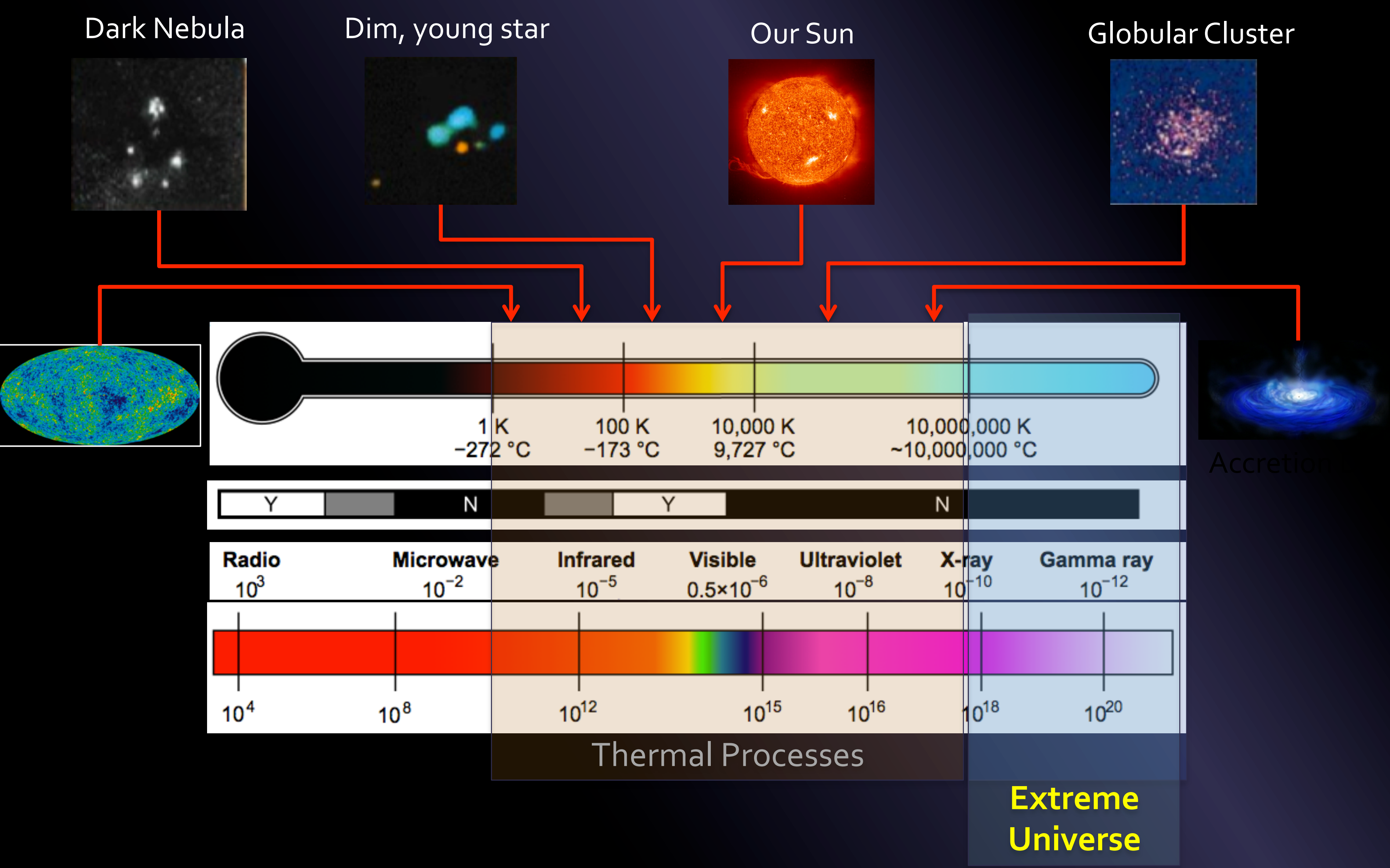
THANKS!

Miguel A. Sánchez-Conde

(sanchezconde@fysik.su.se)

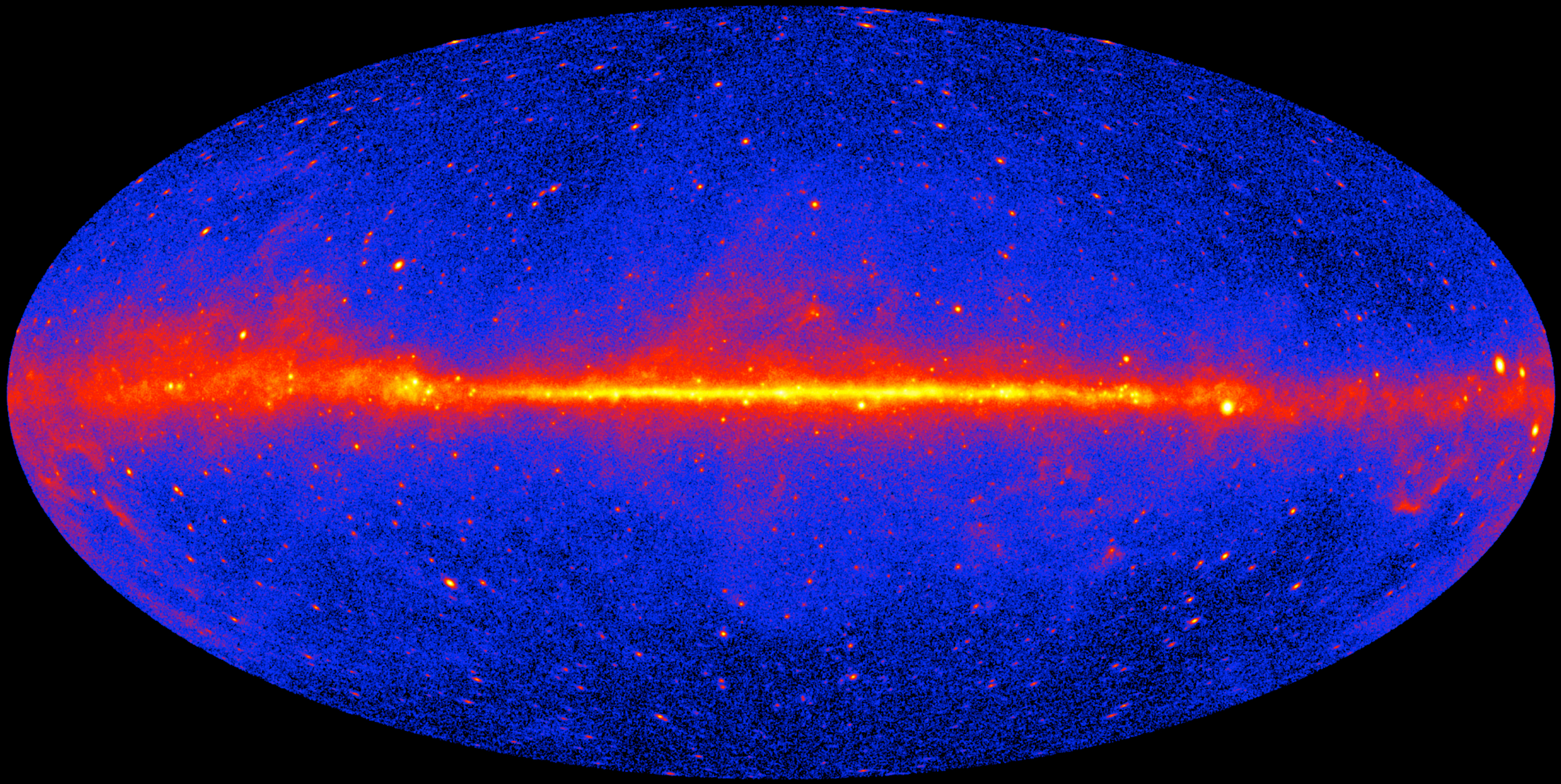
ADDITIONAL MATERIAL

γ-rays probe the extreme non-thermal Universe



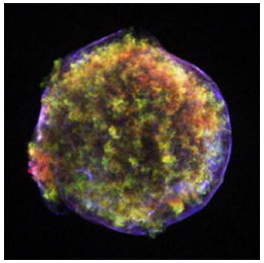
THE GAMMA-RAY SKY above 1 GeV

5 years of Fermi LAT data

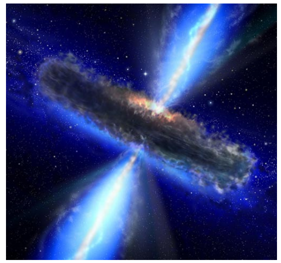


Different mechanisms producing γ–rays

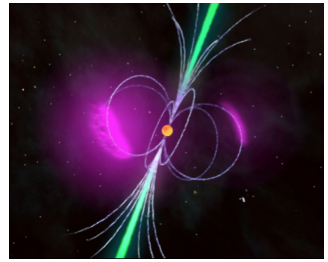
ENERGY SOURCES



Explosions



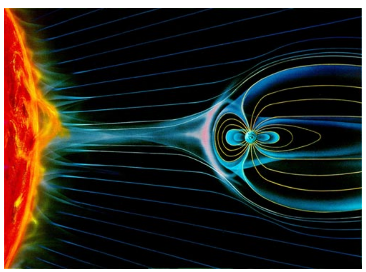
Accretion



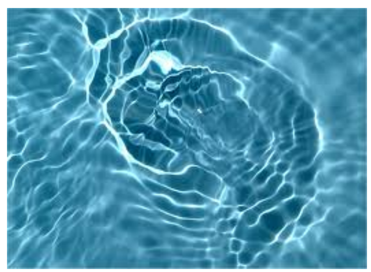
Rotating Fields

Many of these mechanisms will produce radiation at other, non γ-ray, wavelengths

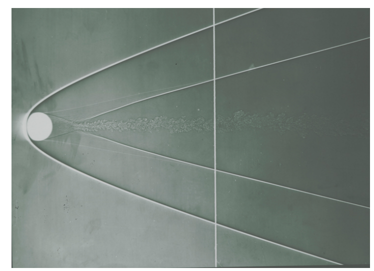
ACCELERATION MECHANISMS



Reconnection

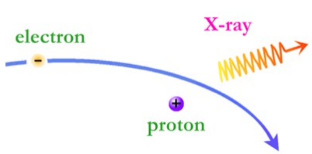


Caustics

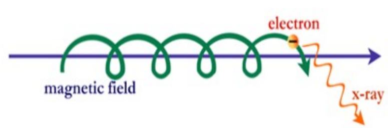


Other Shocks

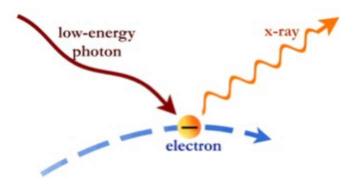
γ-RAY EMISSION MECHANISMS



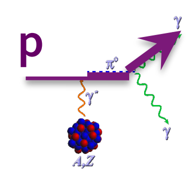
bremsstrahlung



synchrotron

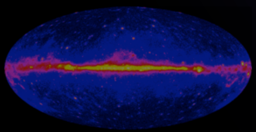


inverse Compton

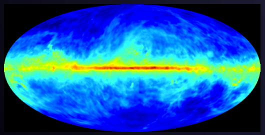


π^0 production

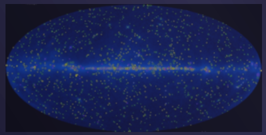
The complexity of the (Fermi) gamma-ray sky



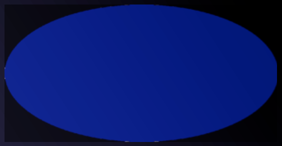
=



+



+

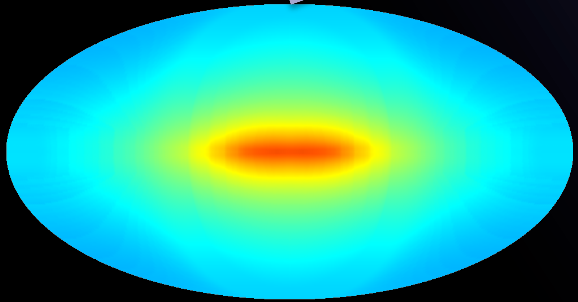


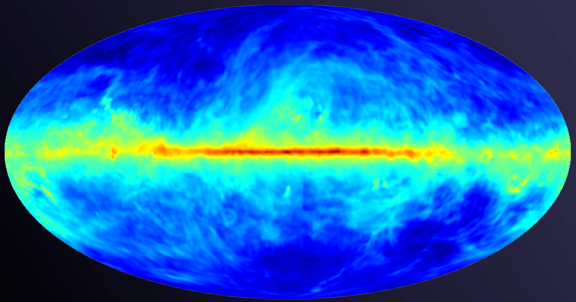
+ ???

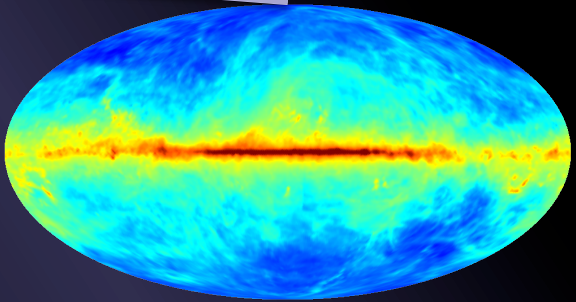
Galactic

Point Sources

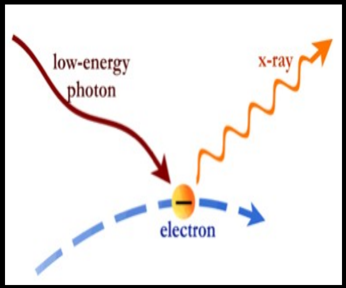
Isotropic



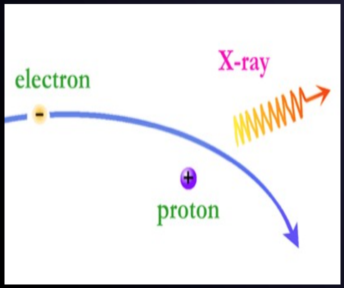




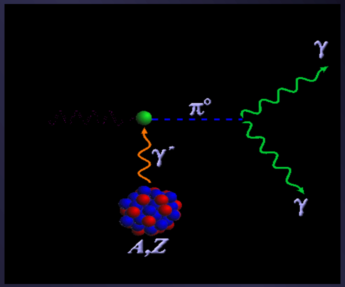
Inverse Compton



Bremsstrahlung

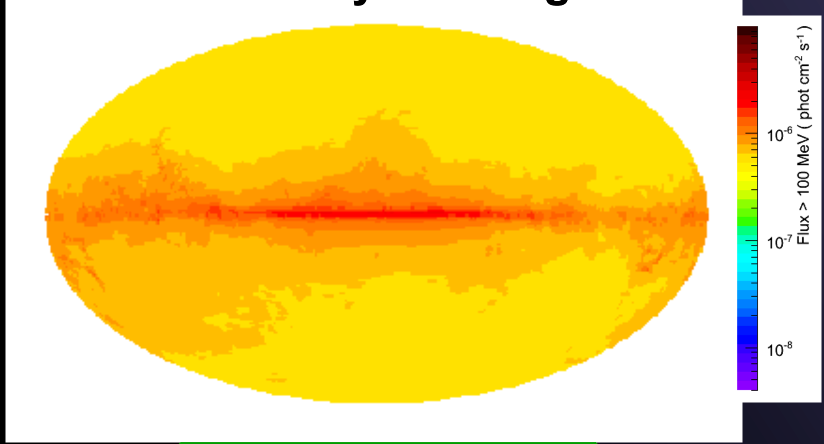


π^o decay



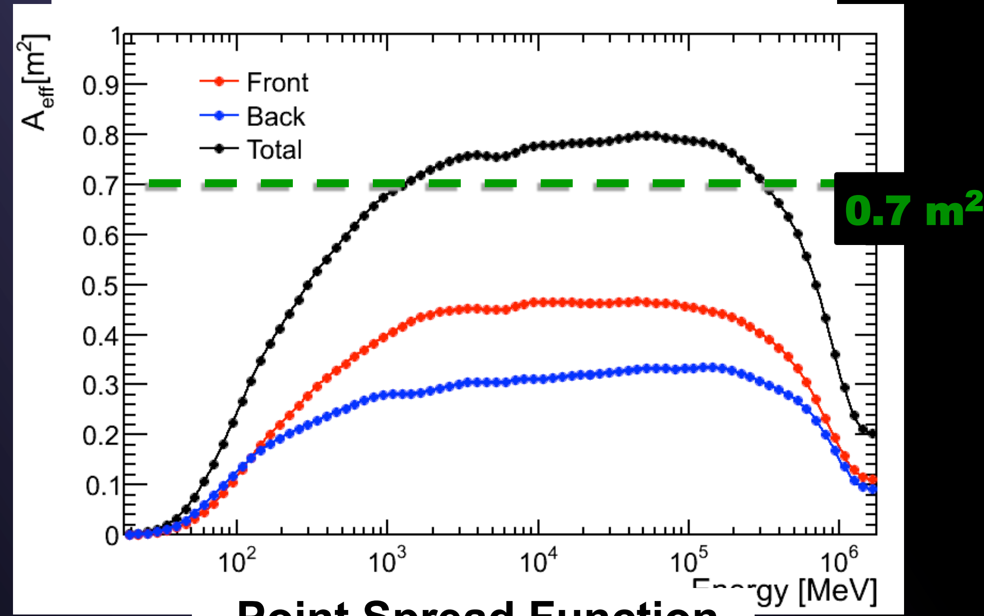
Fermi-LAT performance

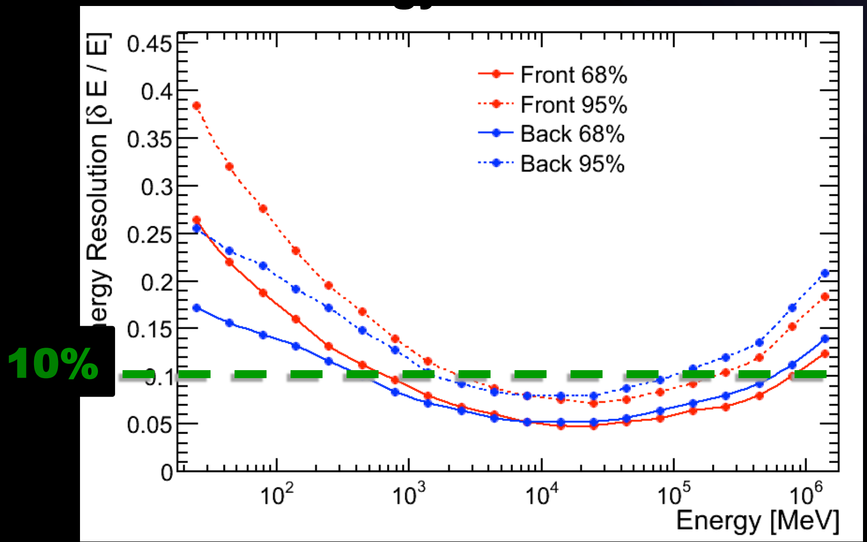
All-Sky Coverage



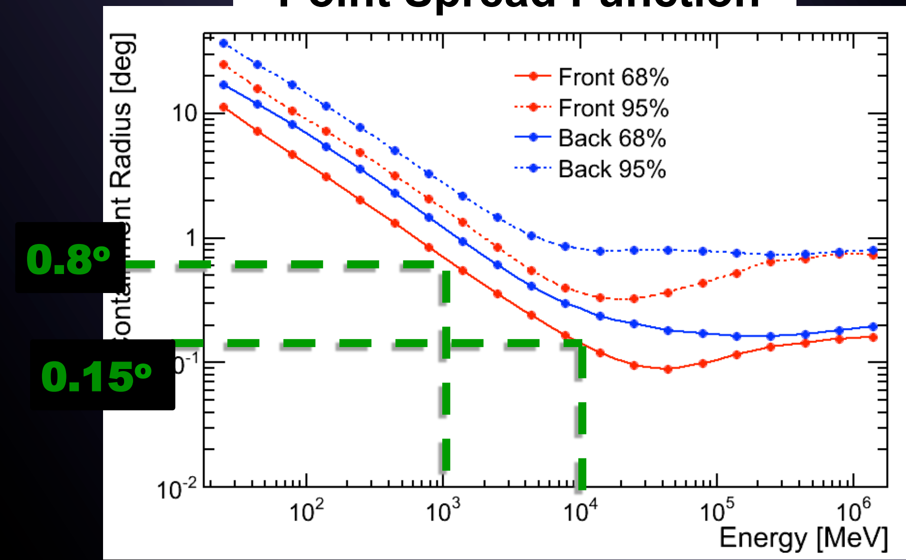
Every ~3 Hours

Effective Area

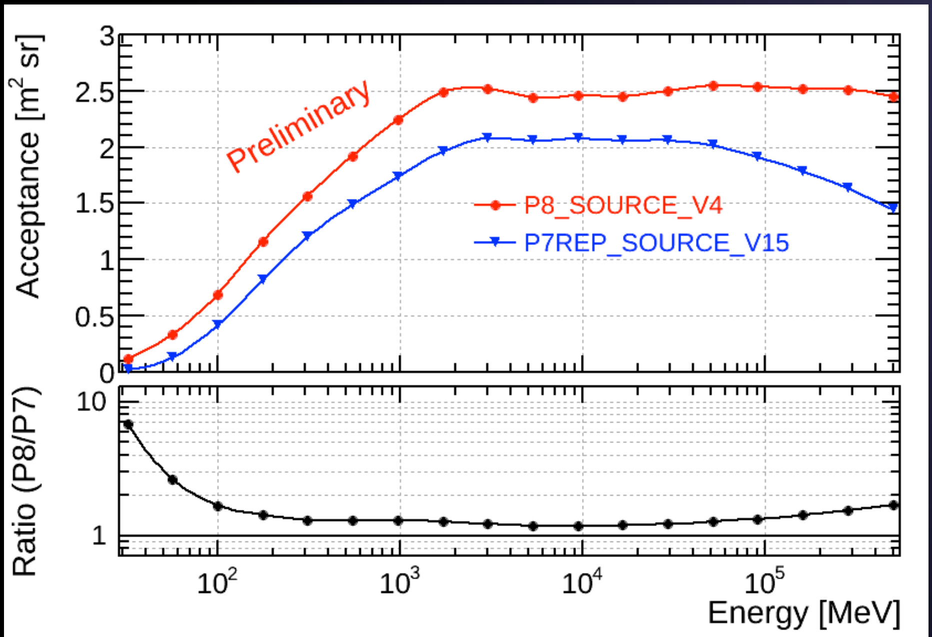


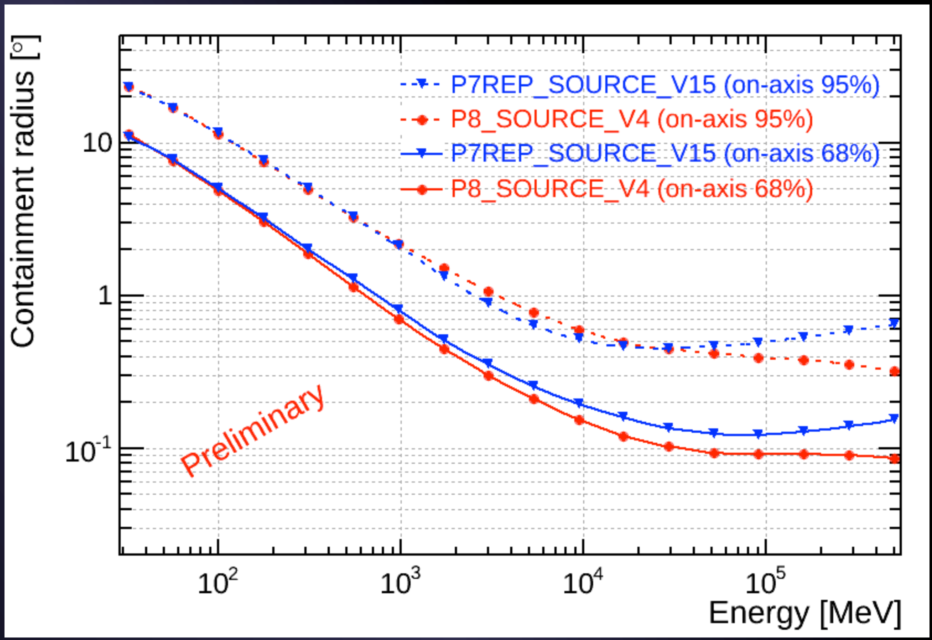


Point Spread Function



THE IMMINENT FUTURE: *Pass 8*
(a.k.a. improved LAT performance)





Impacts for ALP search:

- Increased energy range <==> explore new mass parameter space
- Increased effective area <==> increased flux sensitivity
- Better background rejection
- New event classes <==> check systematic effects in event selection

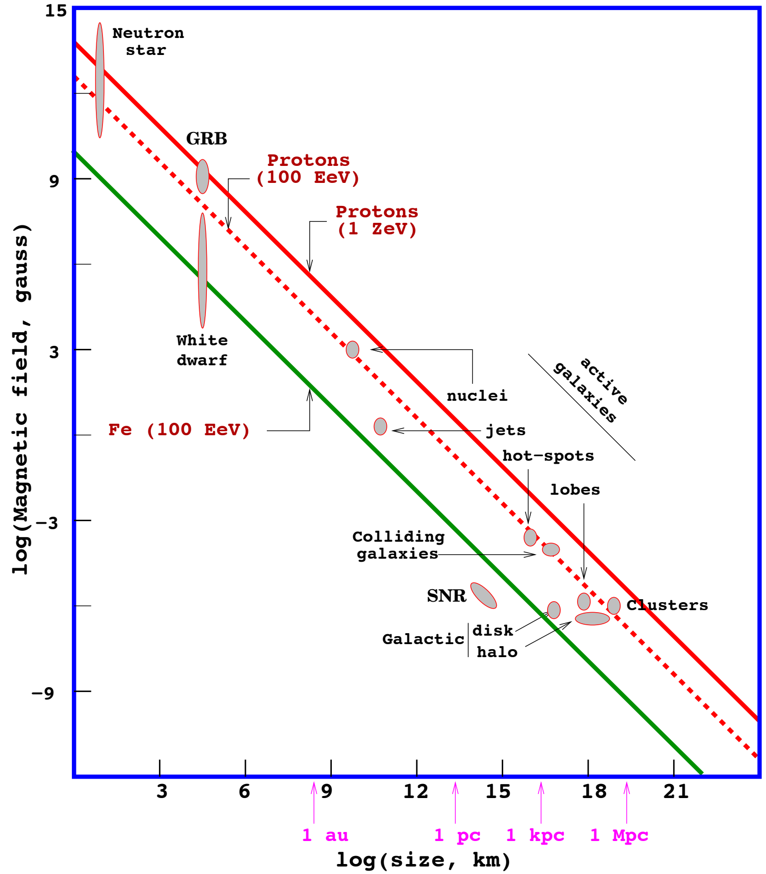


FIG. 2: Hillas diagram showing size and magnetic field strengths of astrophysical objects required to accelerate ultra-high energy cosmic rays (figure from Ref. [17] with permission). The Hillas condition is closely related to the condition for the efficient conversion of gamma rays into ALPs [see Eq. (7)].

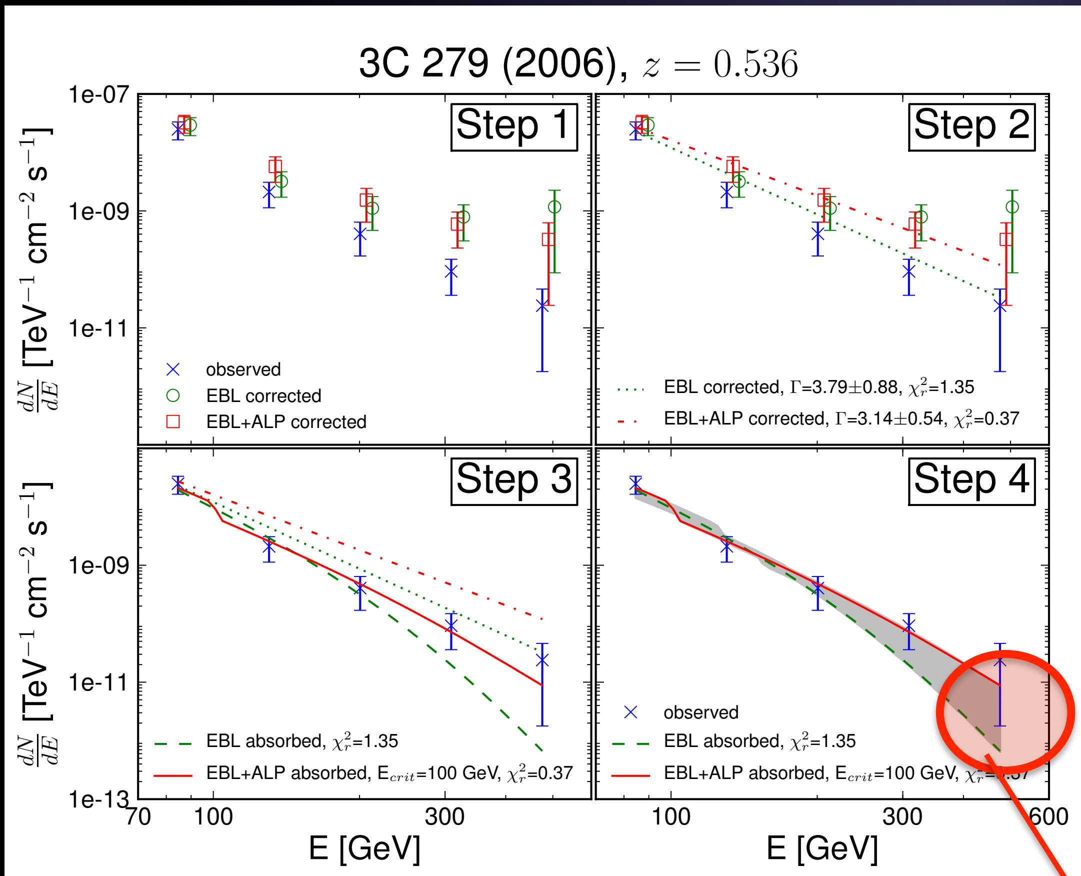
$B_G \cdot s_{pc}$ also determines the Emax to which sources can accelerate cosmic rays:

$E_{max} = 9.3 \cdot 10^{20} \cdot B_G \cdot s_{pc}$ eV (**Hillas criterion)**

We observe cosmic rays up to $3 \cdot 10^{20}$ eV -> $B_G \cdot s_{pc}$ up to 0.3 must exist!

Hooper & Serpico 07

ALP can alleviate the pile up problem



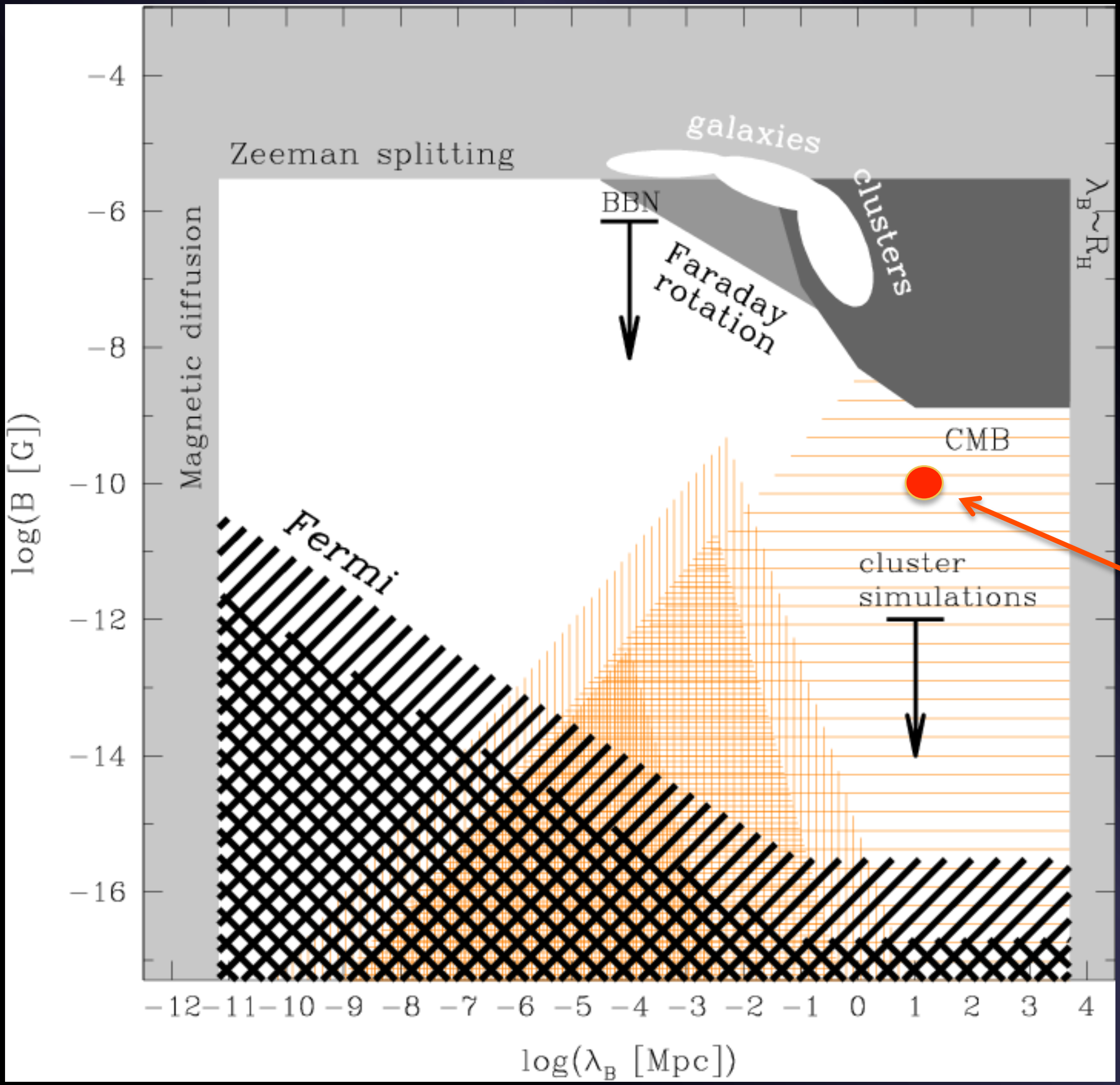
Domínguez, Sánchez-Conde and Prada, JCAP 11 (2011) 020

★ 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!



fiducial Model in MASC+09

Neronov+10, Science

GALACTIC MAGNETIC FIELD MODELS

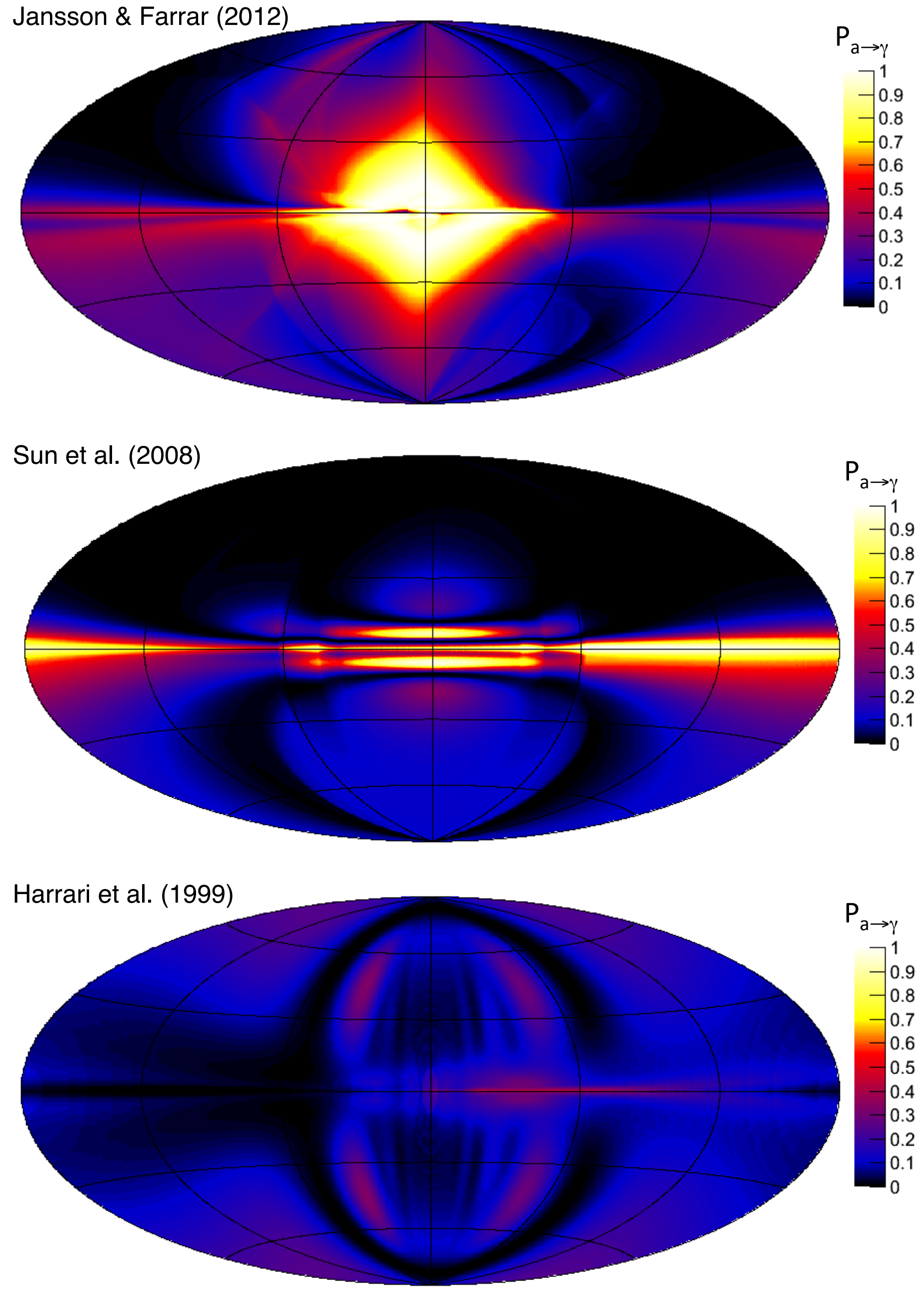
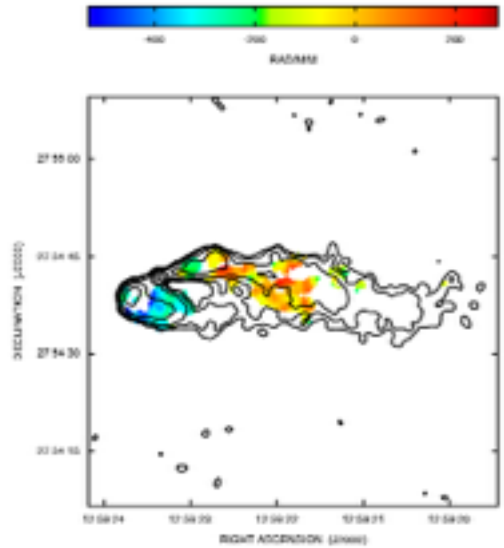


Figure 2. Maps of probability of conversion from ALPs to photons in the galactic magnetic fields for three different models, [65, 67, 68] from top to bottom, assuming $g_{\gamma a} = 5 \times 10^{-11}$ GeV^{-1}.

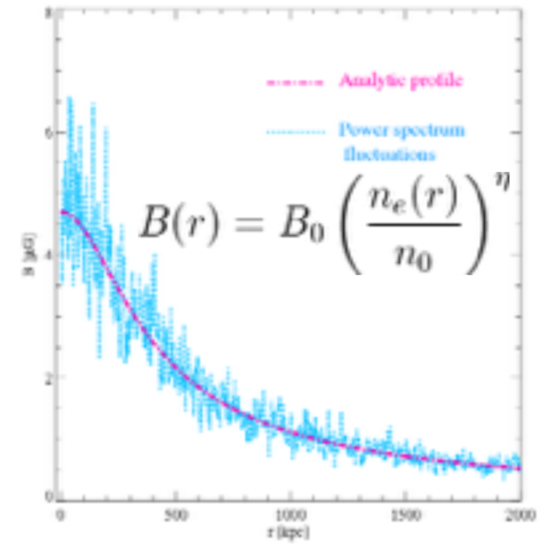
Intracluster magnetic fields

- Observational evidence:
  - **Non-thermal (synchrotron) emission** of intracluster medium
  - **Rotation measure** measurements
- Field strength between **0.1 and 10 μG**
- Extent: **up to few Mpc**
- Magnetic field **follows thermal electron distribution *$n_e(r)$***

[Figure from Bonafede et al., 2010; see, e.g., Feretti et al., 2012, for a review]



Rotation measure map with 5 GHz contours of galaxy NGC 4869 in the Coma cluster



Simulated B field (blue) and analytical profile (magenta) of the Coma cluster

$$\Delta\Psi = \Psi - \Psi_0 = \lambda^2(\mathrm{RM})$$

$$\mathrm{RM} = 812 \int_0^{L/\mathrm{kpc}} n_e B_{||}\, \mathrm{d}\ell \, (\mathrm{rad\,m^{-2}})$$

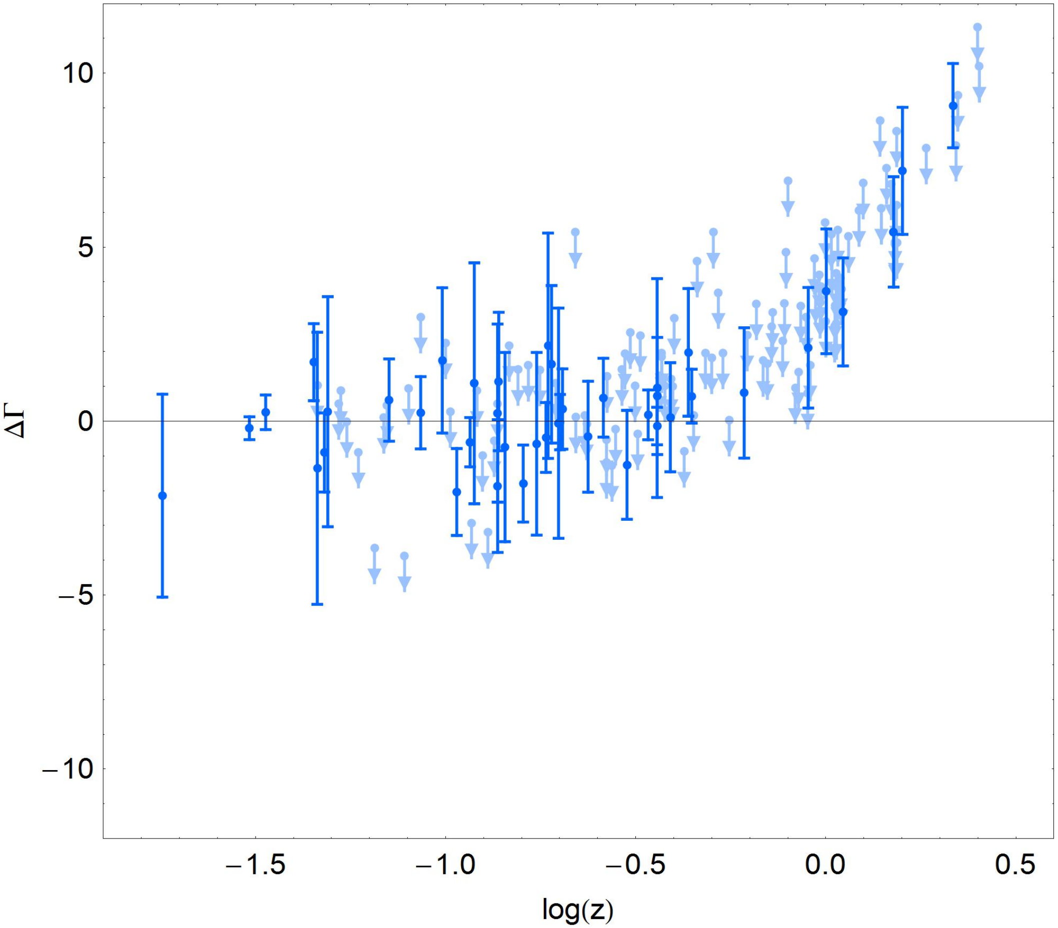
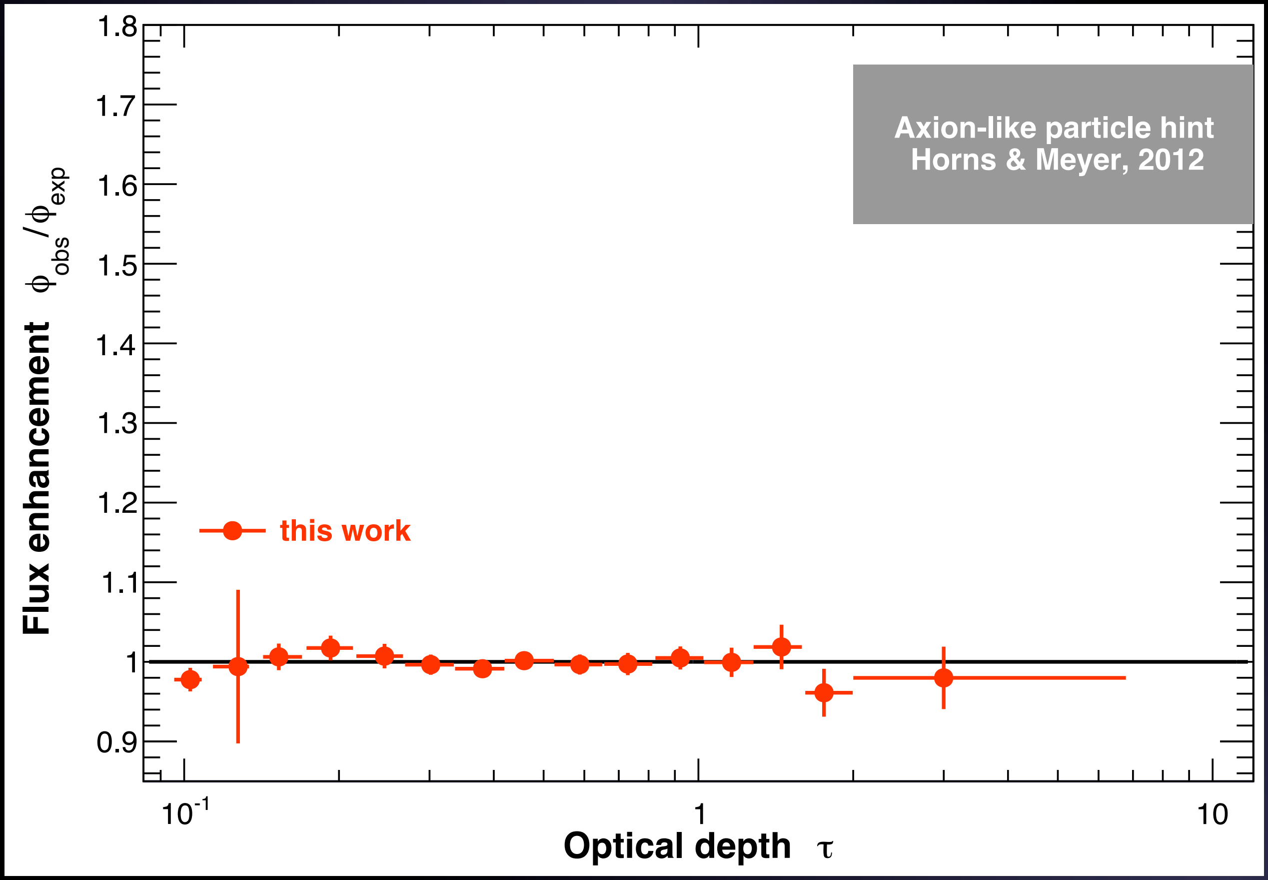


Figure 4: Same as in Fig. 3 but for the break assumed to happen at $E = 100$ GeV, for the extended sample of Fermi-LAT blazars described in the text. The breaks appear for distant objects only, for which $E_0 \sim 100$ GeV.

Rubtsov+14



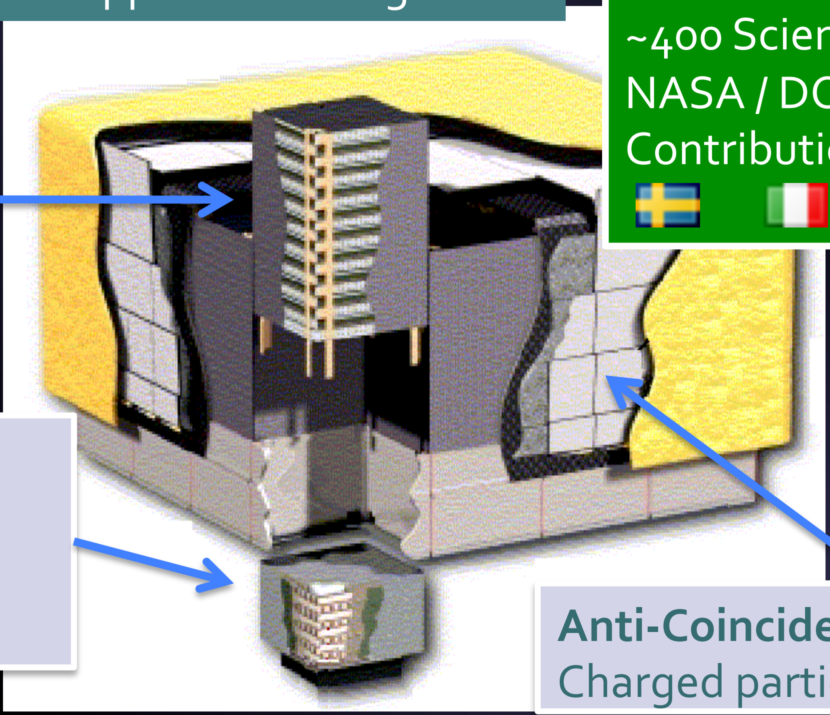
Biteau & Thompson 15

The Fermi Large Area Telescope

LAUNCHED IN JUNE 2008
Mission approved through 2016

Fermi LAT Collaboration:
~400 Scientific Members,
NASA / DOE & International
Contributions

Si-Strip Tracker:
convert $\gamma \to e^+e^-$
reconstruct γ direction
EM v. hadron separation



Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

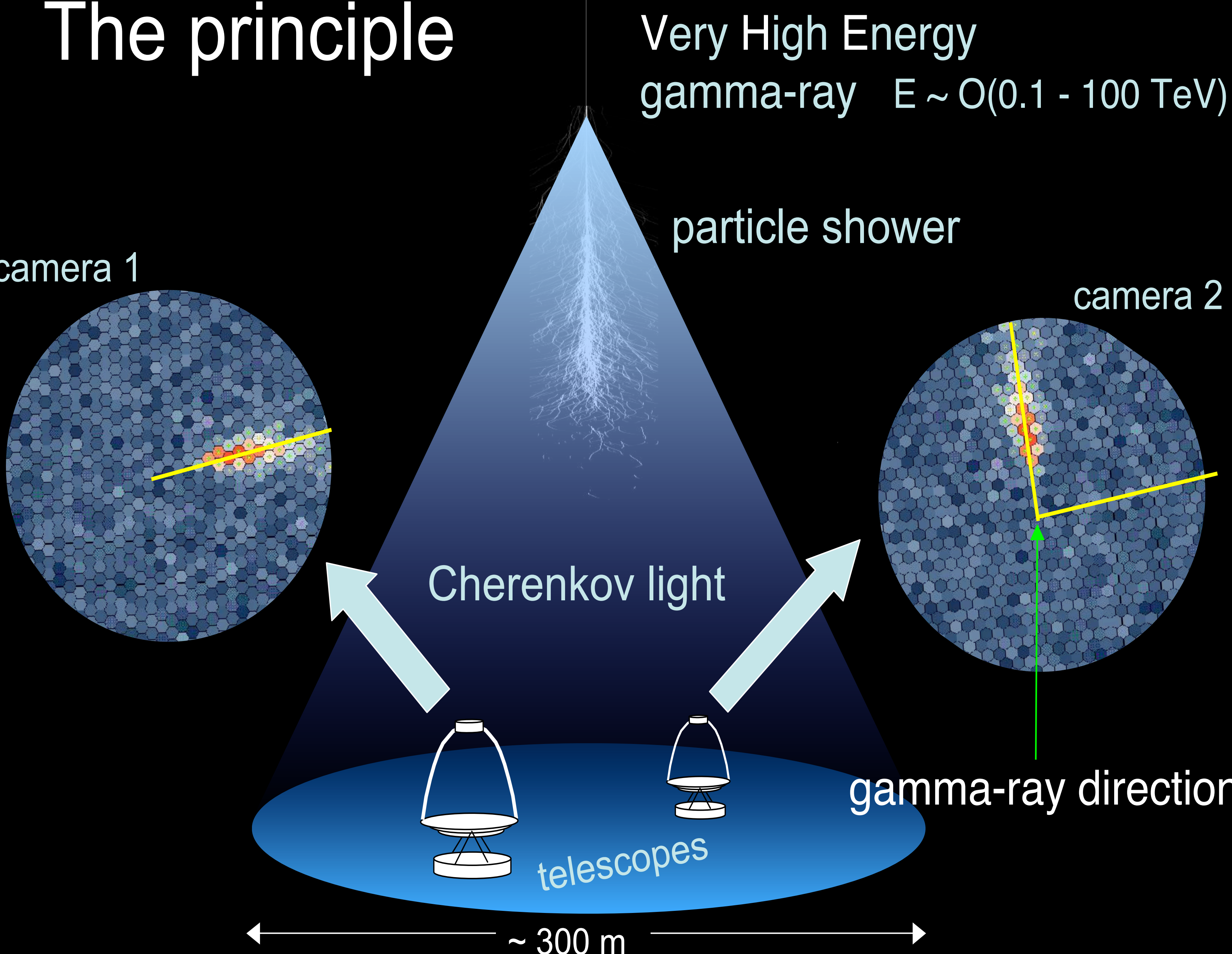
Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
2.5 sr field-of-view
whole sky every 3 hours

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

The principle



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 (12m)
+ HESS II (28m)