AXION-LIKE PARTICLES : THE TEV TRANSPARENCY ISSUE

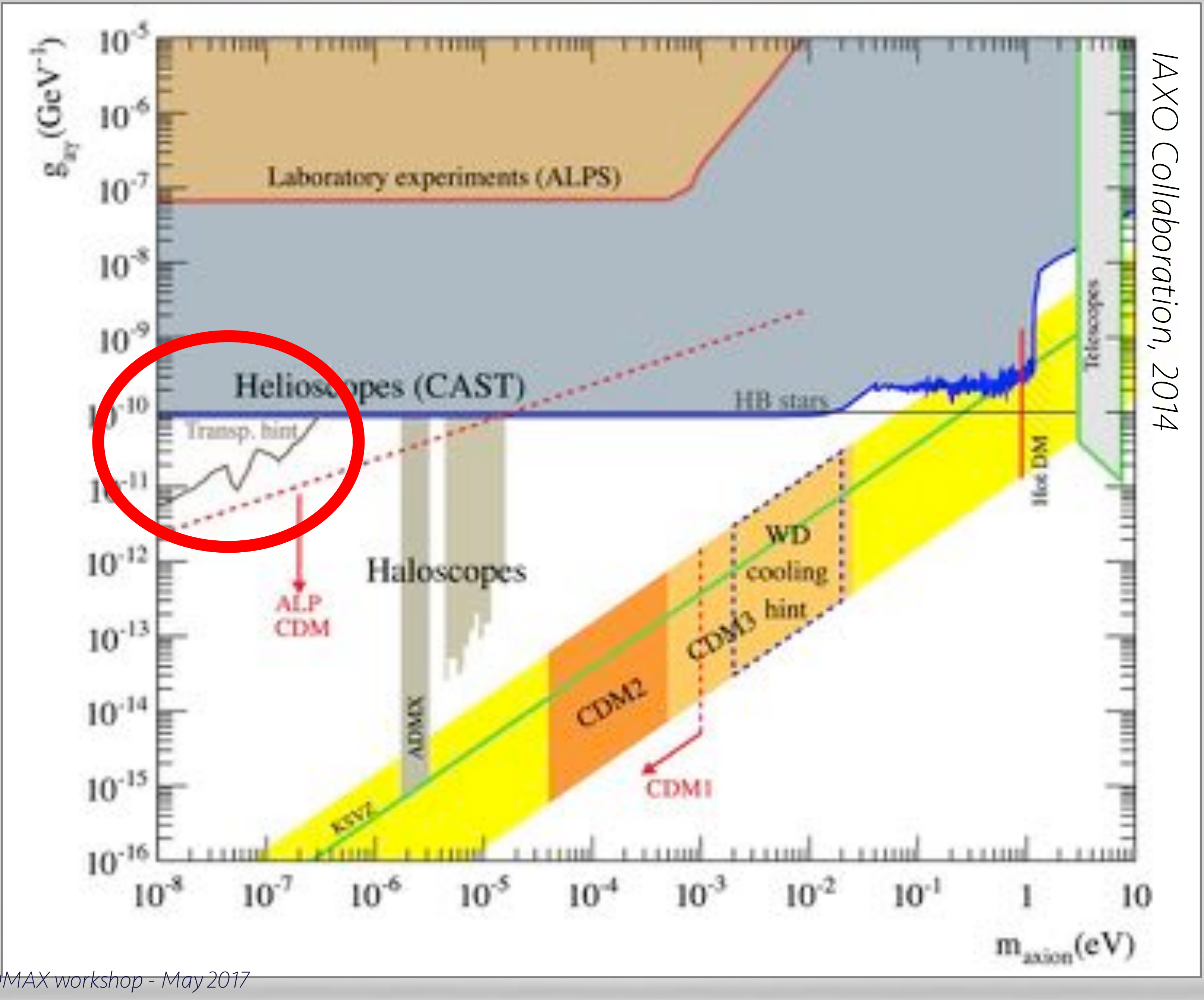
Pierre Brun – CEA Saclay
MADMAX Workshop
Paris – May 2017

OUTLINE

- ★ Photon-ALP mixing in astrophysical magnetic fields
- ★ Possible scenarios
  - → Mixing in intergalactic magnetic fields (IGMF)
  - → Mixing at the source and in the Milky Way
  - → Related theoretical predictions
- ★ Opacity anomaly
- ★ EBL measurements
- ★ Constraints

TeV photon propagation

CONSTRAINTS ON ALPS

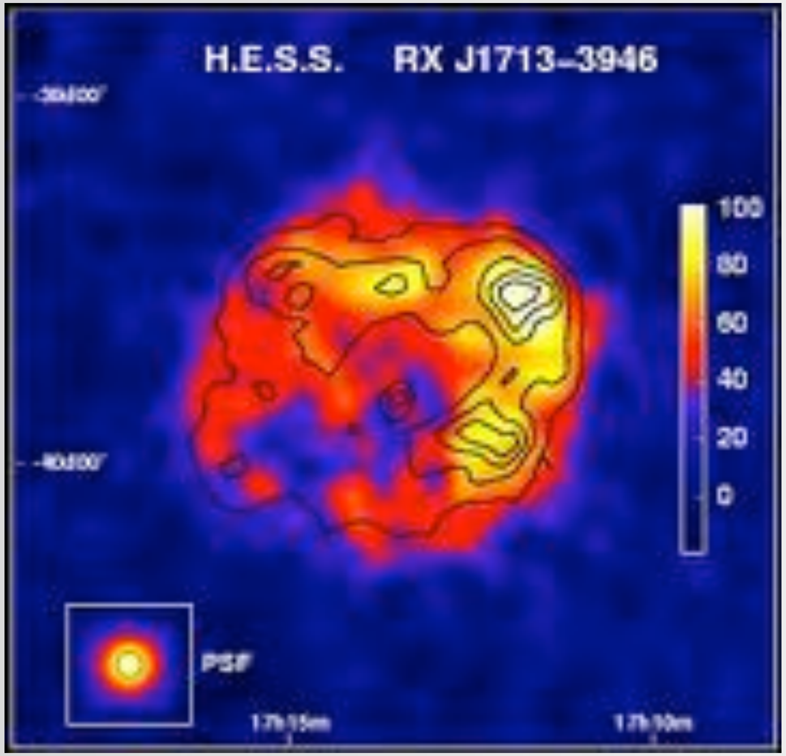


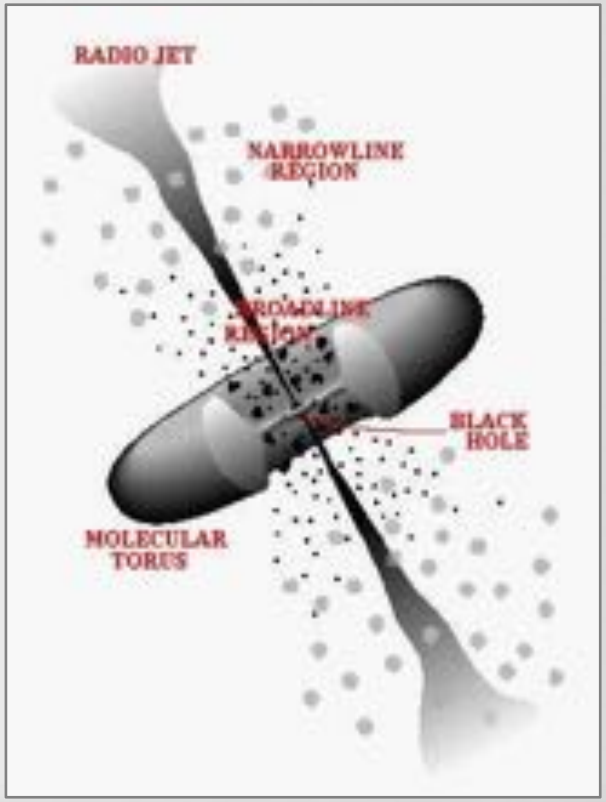
IAXO Collaboration, 2014

GAMMA-RAY SOURCES

A variety of sources is observed in gamma rays

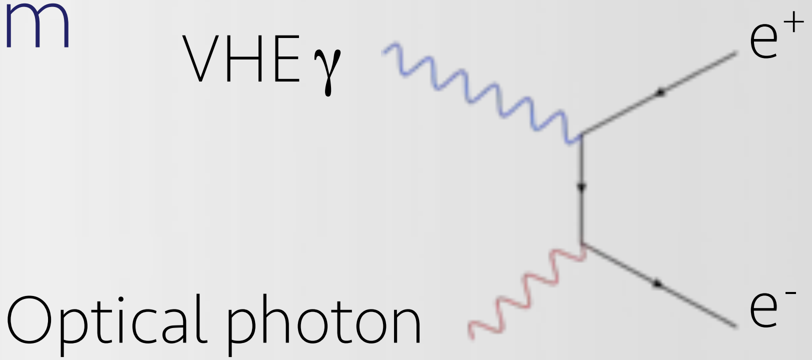
- → Galactic : supernova remnants, pulsar wind nebulae
- → Diffuse emission (induced by cosmic rays)
- → Extragalactic : blazars, starburst galaxies





GAMMA-RAY ABSORPTION

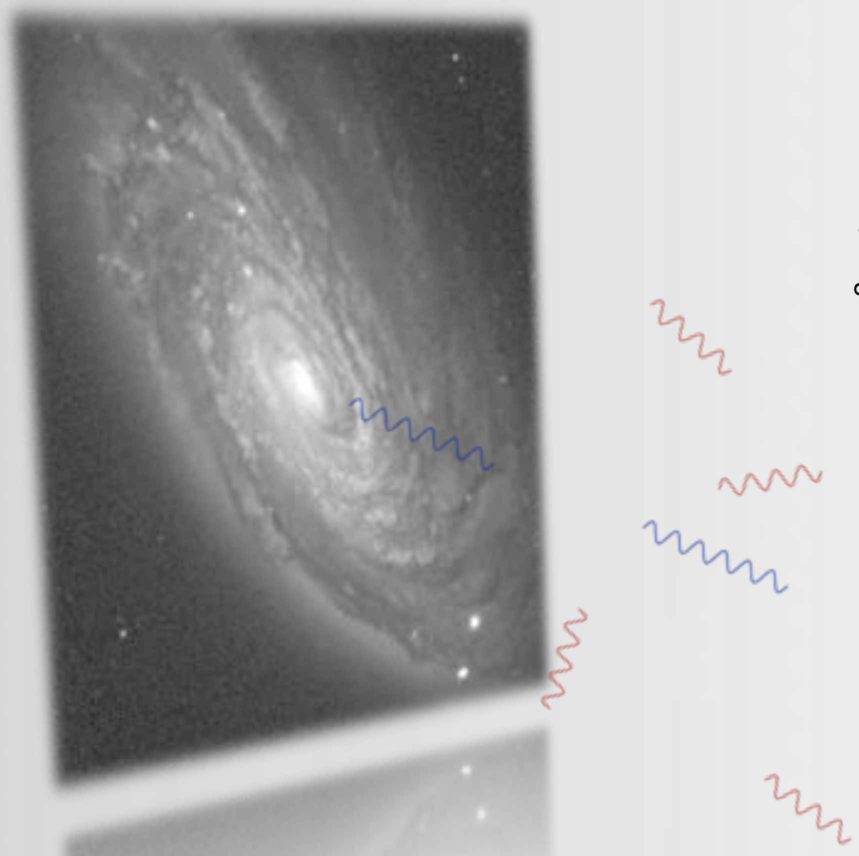
- ★ Gamma rays interact with IR-UV photons
- ★ Pair creation destroy them

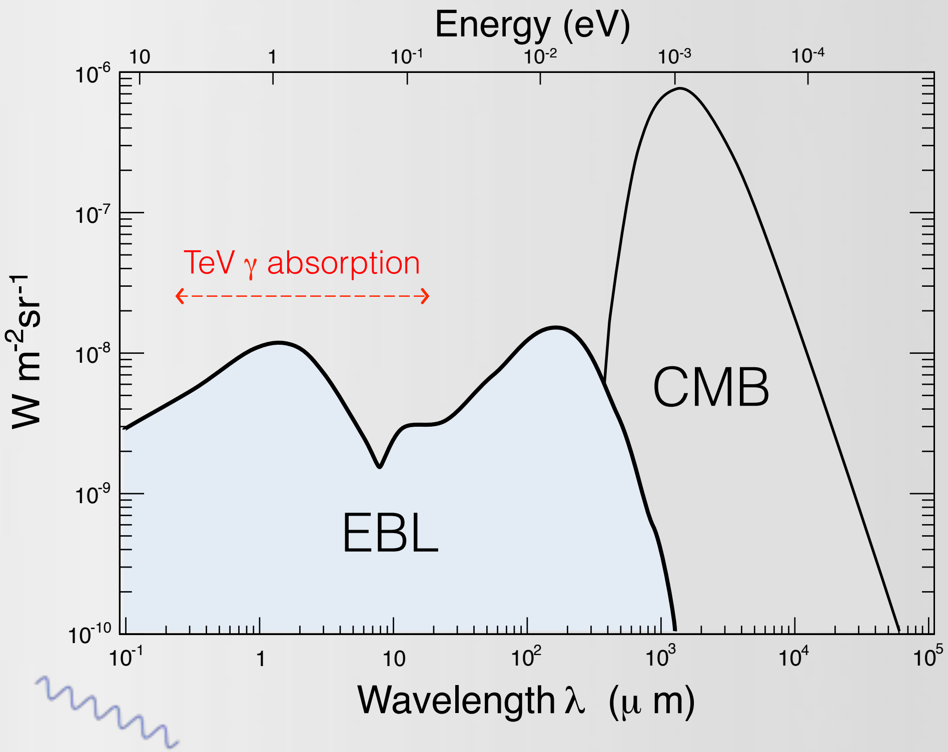


- ★ Two radiation fields can induce absorption
  - → Optical-IR photons near the source (broad line region)
  - → Extragalactic light

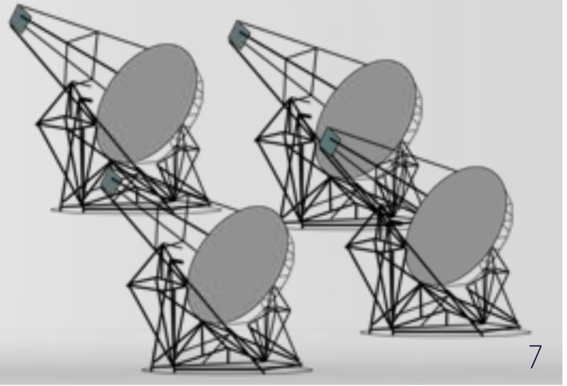
UNIVERSE OPACITY TO γ-RAYS

Background UV/IR photons

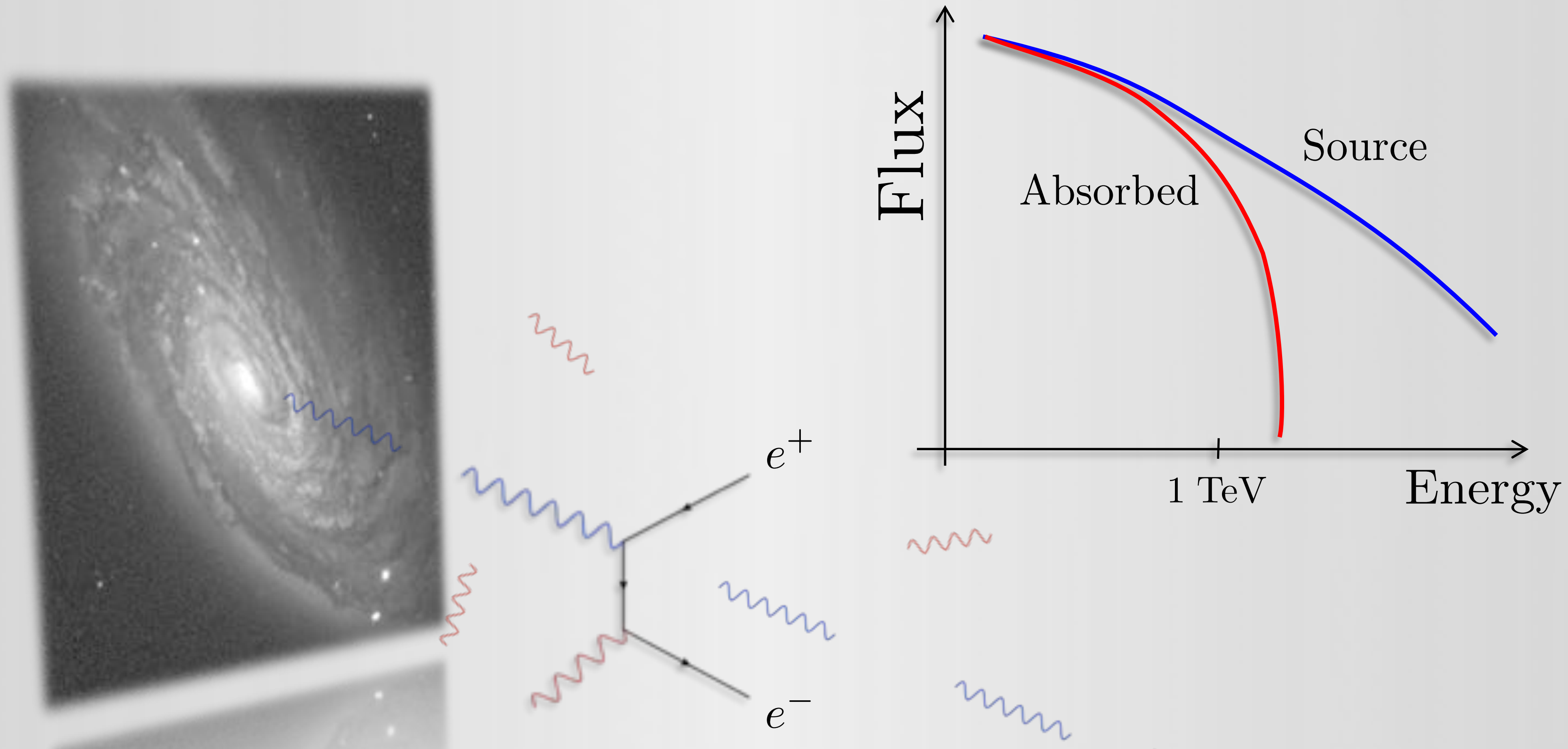


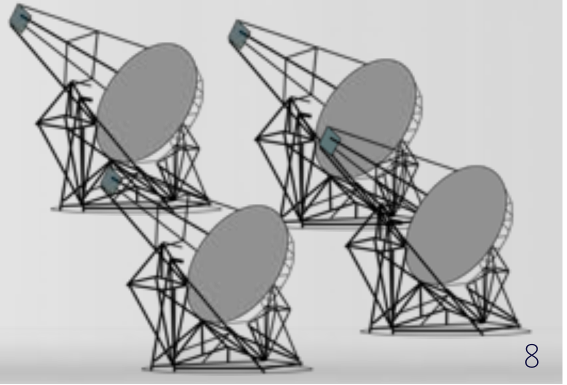


H. Dole et al., A&A, 2006



UNIVERSE OPACITY TO γ-RAYS

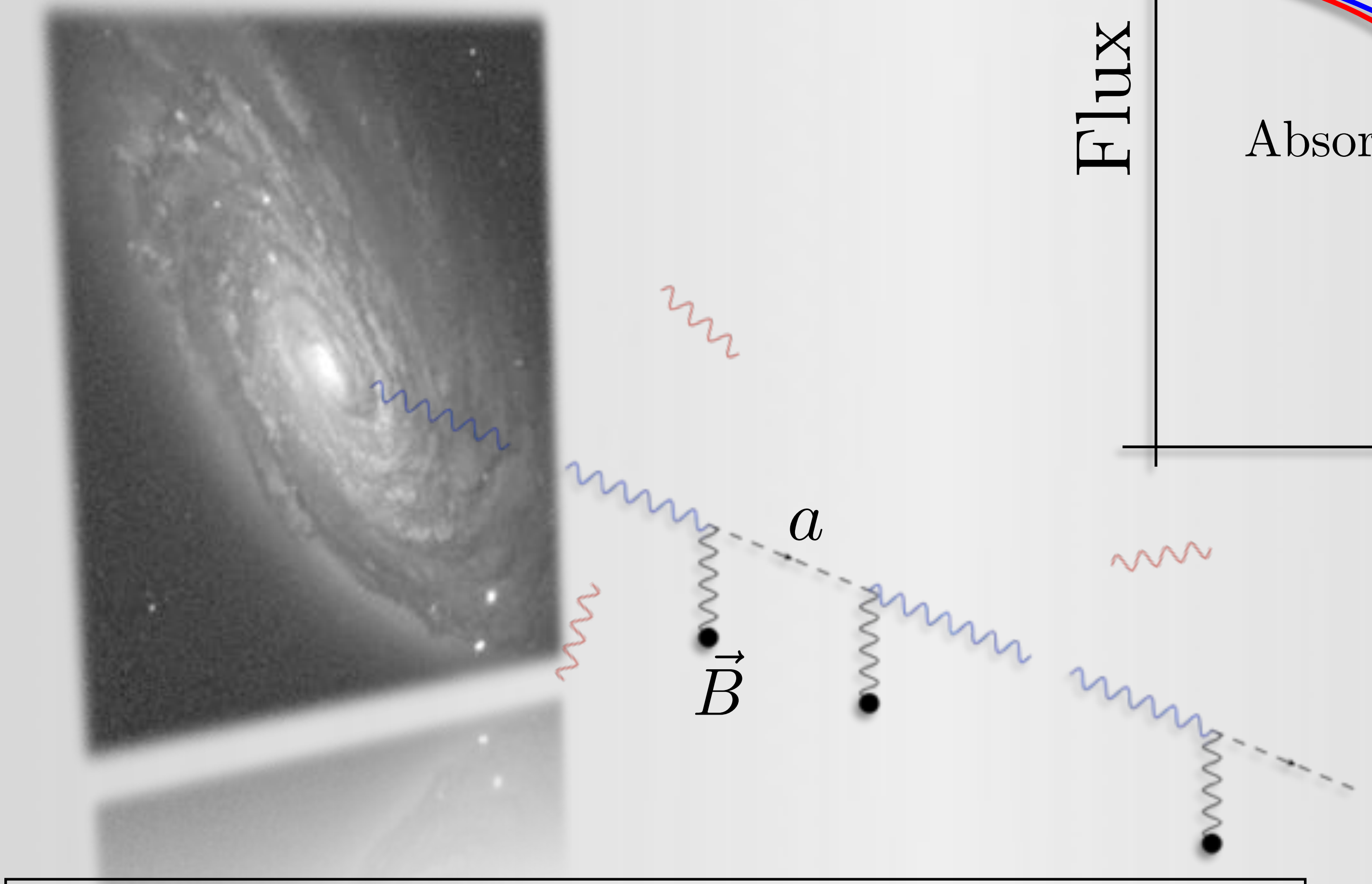


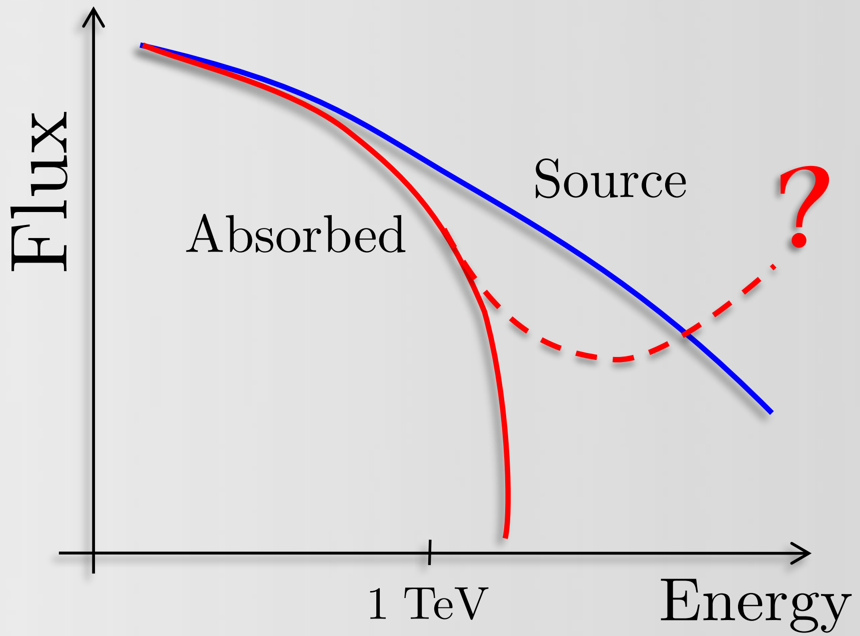


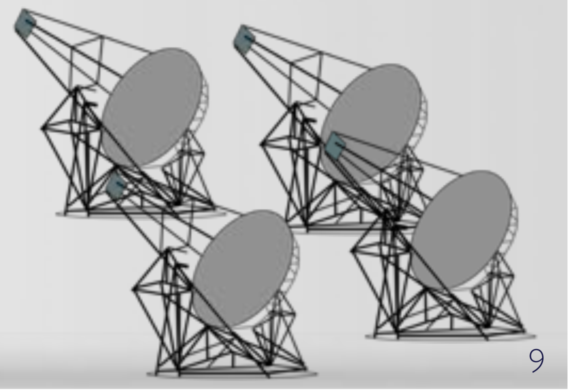
Pair production induces a gamma-ray horizon $z \simeq 0.1$ at 1 TeV

$$\phi_{\text{observed}} = \phi_{\text{source}} \times \exp(-\tau)$$

UNIVERSE OPACITY TO γ-RAYS







Light ALPs ($m \sim \mathrm{neV}$) with $\frac{g}{\mathrm{GeV}^{-1}} \sim 10^{-11}$
could modify this picture

WHY SUCH HE SCALES ?

- Photons mix with ALPs through

$$\mathcal{M} = \begin{pmatrix} 0 & \Delta_{\mathrm{B}} \\ \Delta_{\mathrm{B}} & \Delta_{\mathrm{a}} \end{pmatrix}$$

- Mixing angle in that case:

$$\tan 2\theta = -\frac{2\Delta_{\mathrm{B}}}{\Delta_{\mathrm{a}}}$$

- Probability of transition:

$$P_{\gamma\to a} = \frac{1}{1+\frac{\Delta_{\mathrm{a}}^2}{4\Delta_{\mathrm{B}}^2}} \sin^2\left(\frac{2\pi z}{\lambda(E)}\right)$$

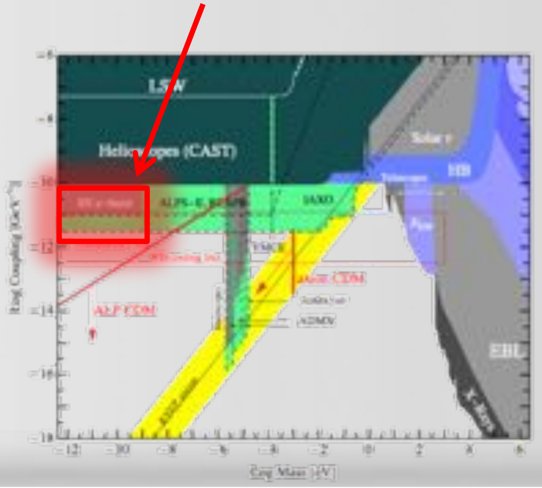
WHY SUCH HE SCALES ?

- ⋆ Amplitude of the oscillation $\frac{1}{1+\left(\frac{\Delta_\mathrm{a}}{2\Delta_\mathrm{B}}\right)^2} \equiv \frac{1}{1+\left(\frac{E_\mathrm{c}}{E}\right)^2}$
- ⋆ The relevant energy scale

$$\left.\begin{aligned}\Delta_\mathrm{B} &= \frac{gB_t}{2}\\ \Delta_\mathrm{a} &= \frac{m_\mathrm{a}^2}{2E}\end{aligned}\right\} \Rightarrow \boxed{E_\mathrm{c} = \frac{m_\mathrm{a}^2}{2gB_t}}$$

- ⋆ With cosmological magnetic fields of $B \sim 1\ \mathrm{nG}$

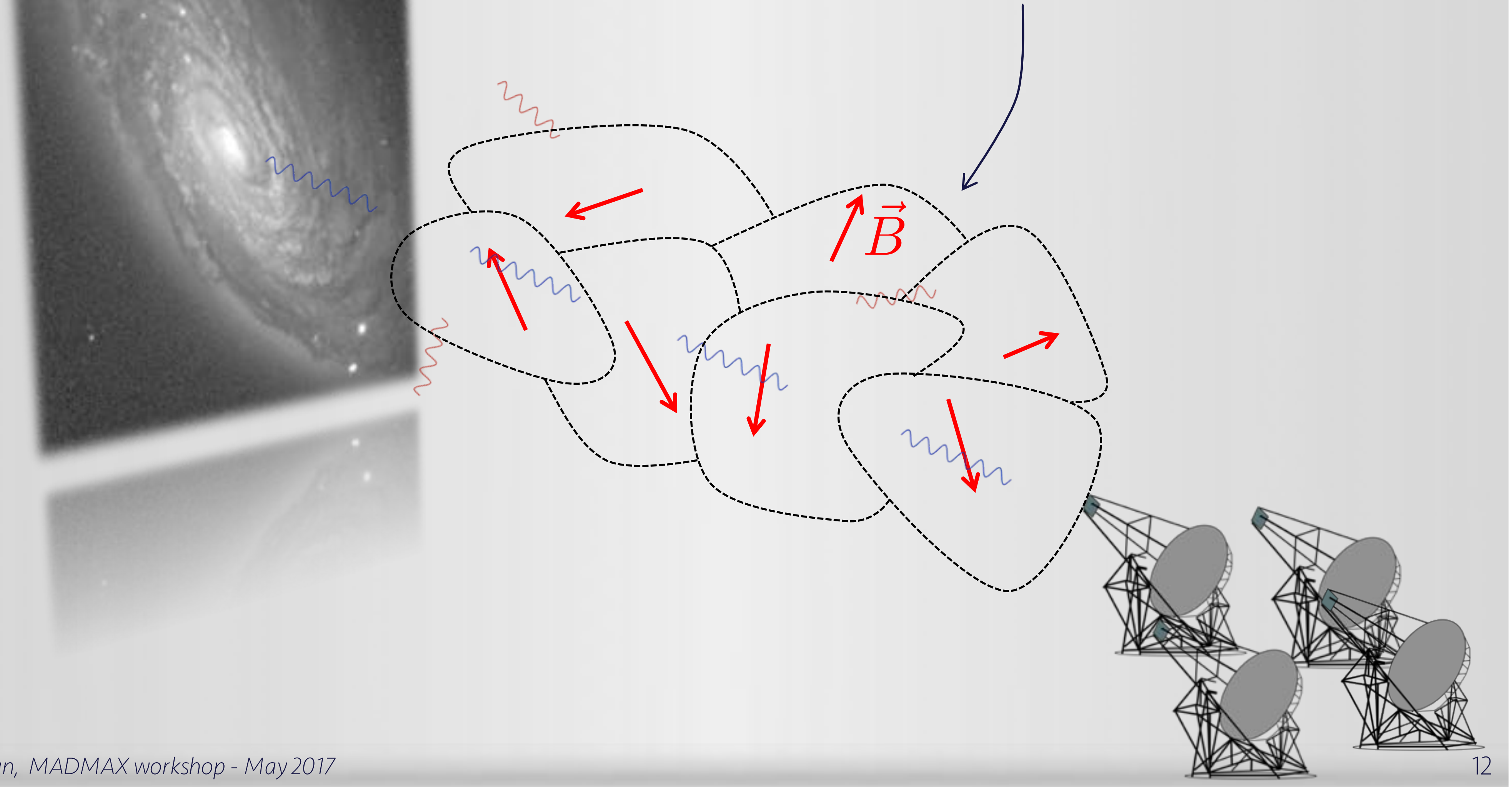
$$\left.\begin{aligned} m &\sim \mathrm{neV}\\ \frac{g}{\mathrm{GeV}^{-1}} &\sim 10^{-11}\end{aligned}\right\} E_\mathrm{c} = 2.5\ \mathrm{TeV}$$



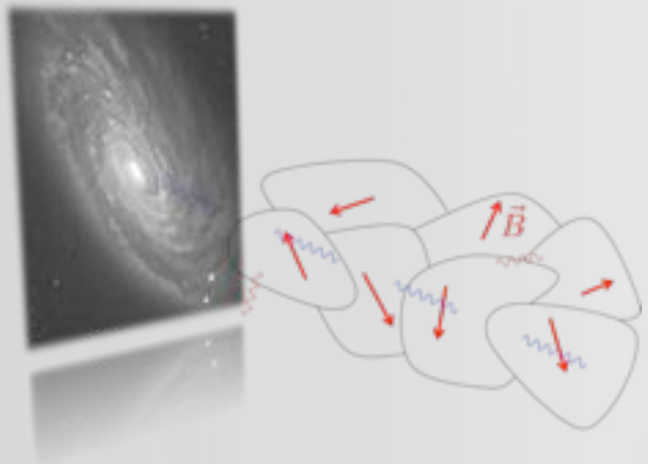
THEORETICAL PREDICTIONS

ASTROPHYSICAL MAGNETIC FIELDS

MF ~ patches of coherent domains
random orientations



CONVERSION WITHIN MULTIPLE DOMAINS



Effect could have been predictable after averaging over many domains

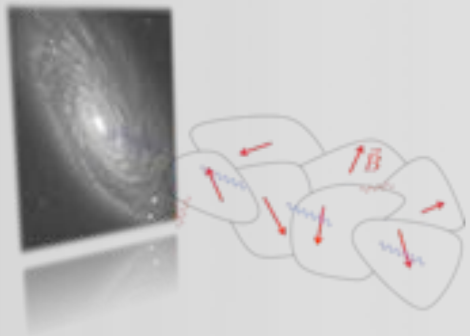
Additional ingredients:

- Absorption on the EBL:

$$\begin{pmatrix} E - i\partial_z \boxed{- i\frac{\tau}{2z}} & \Delta_{\rm B} \\ \Delta_{\rm B} & E - i\partial_z + \Delta_{\rm a} \end{pmatrix} \begin{pmatrix} A \\ a \end{pmatrix} = 0$$

- Account for photon polarizations: use a 3-state system

CONVERSION WITHIN MULTIPLE DOMAINS



$$P_{\gamma\to a} = \frac{1}{1+\left(\frac{E_c}{E}\right)^2}\sin^2\left(\frac{2\pi z}{\lambda(E)}\right)$$

with $\lambda(E) = \dfrac{4\pi}{gB_t\sqrt{1+\left(\frac{E_c}{E}\right)^2}}$

$$\boxed{E_c = \frac{m_a^2}{2gB_t}}$$

2 regimes:

→ $E \ll E_c$ no oscillations

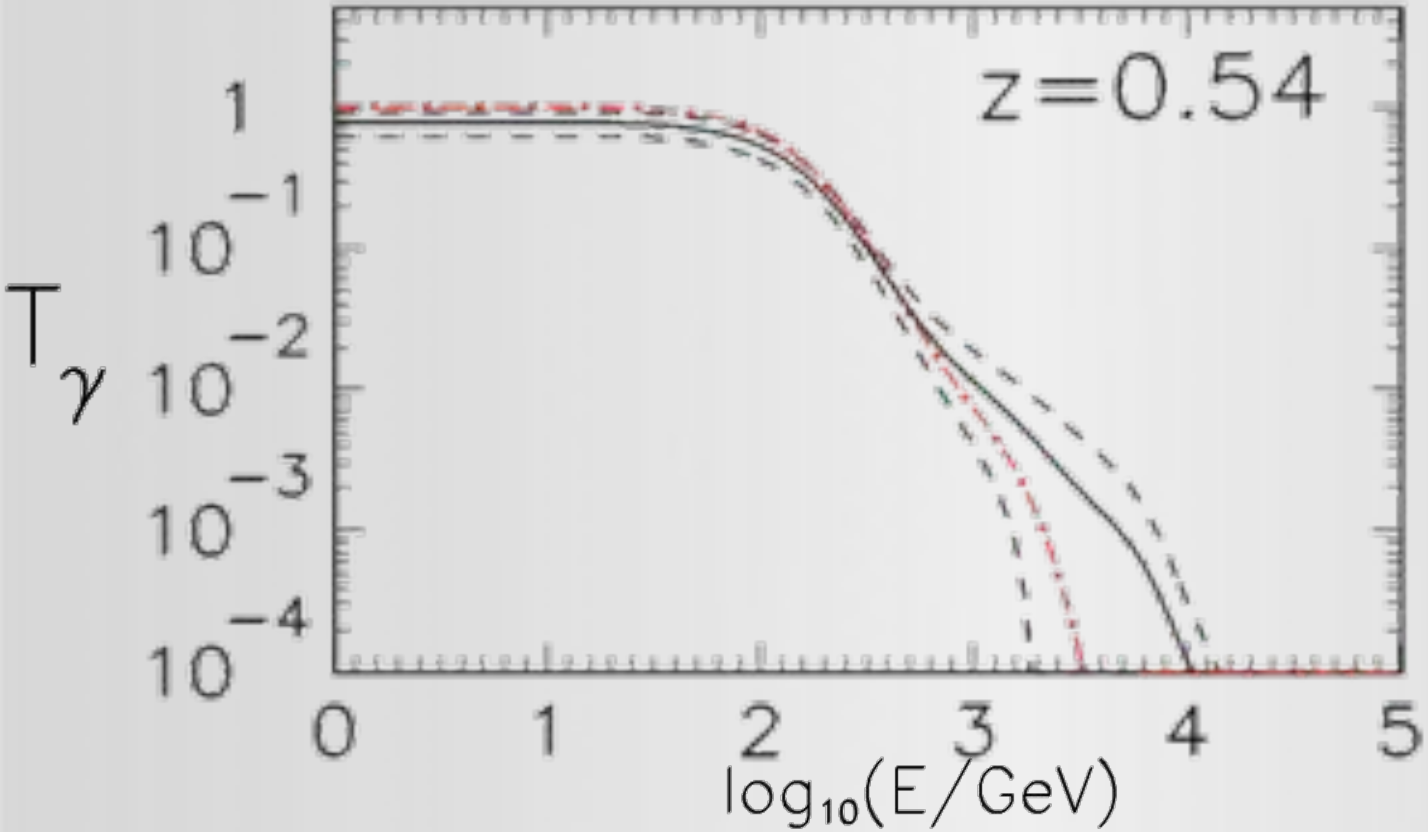
→ $E \gg E_c$ energy independent oscillations

If many (N) domains : $P_{\gamma\to a} = \dfrac{1}{3}\left(1-\exp\left(-\dfrac{3NP_0}{2}\right)\right)$

$P_{\gamma\to a} \to \dfrac{1}{3}$ for $NP_0 \gg 1$

INFLUENCE OF THE RANDOMNESS

- ★ Prediction has a large variance!



A. Mirizzi & D. Montanino, JCAP, 2009

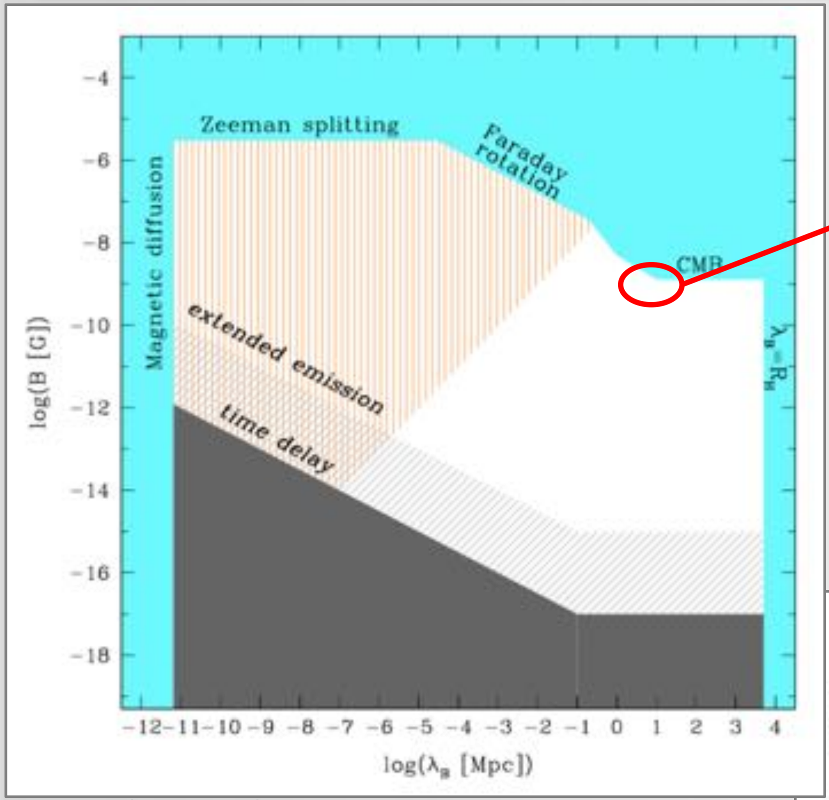
-·-·- Conventional opacity

— Average ALP prediction

- - - ALP prediction envelope

- ★ Not all realizations lead to a more transparent Universe
- ★ Effect useless to set constraints
- ★ Other problem is IGMF

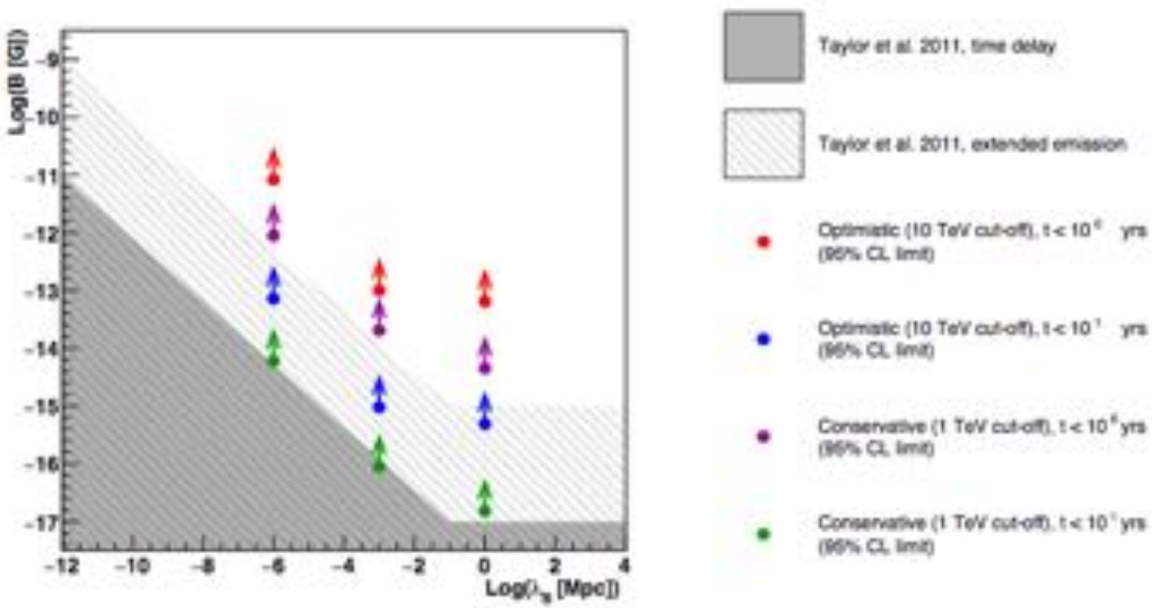
CONSTRAINTS ON IGMF



A. Taylor et al., A&A 2011

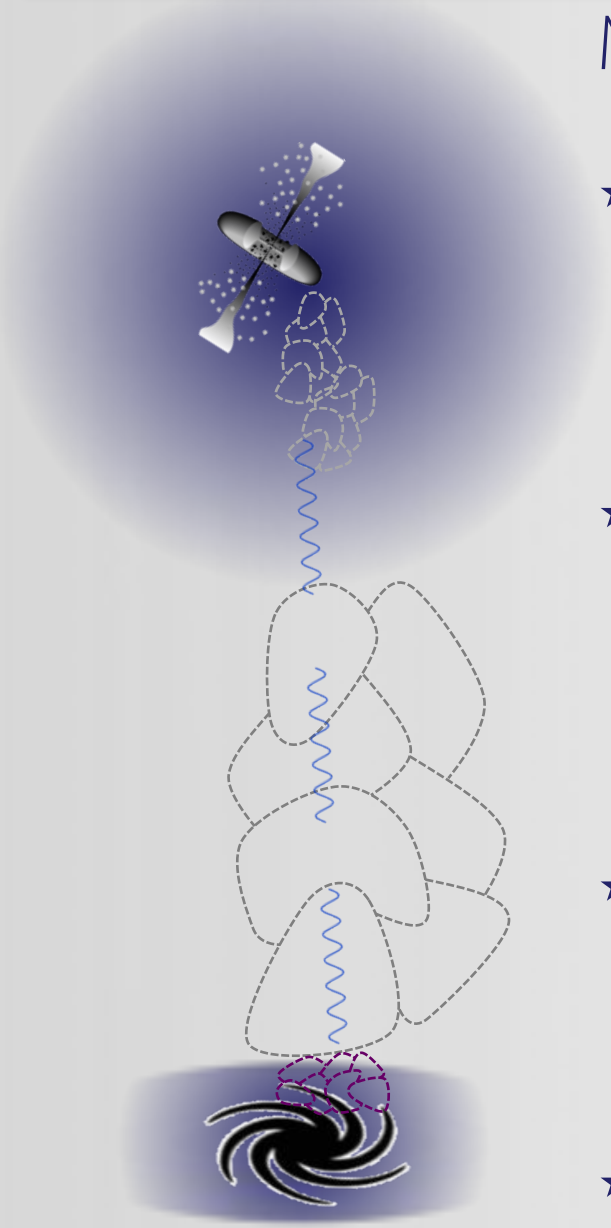
Required value
close to upper limit

IGMF probably ≠ 0
but much weaker



M. Lorentz, P.B., in prep.

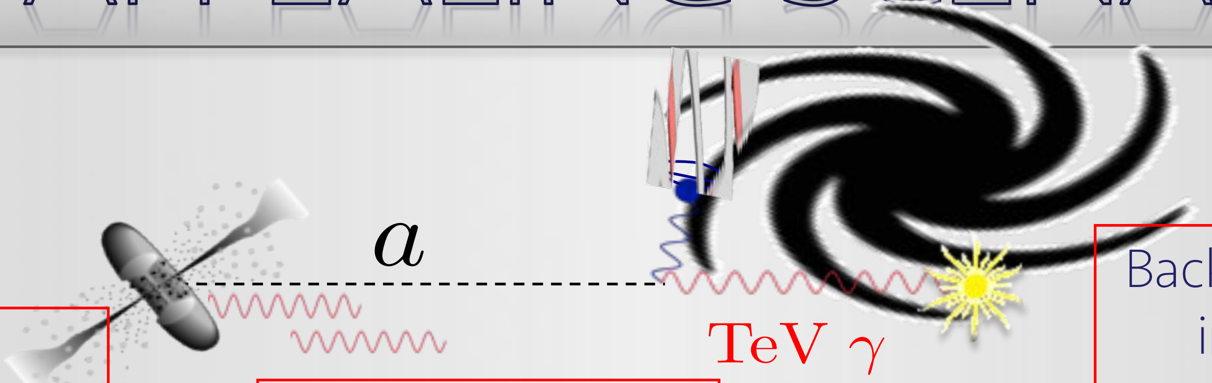
MIXING WITH MAGNETIC FIELDS



Mixing can occur :

- ⋆ Within the source (jet) $\begin{cases} B \sim 1\ \mathrm{G} \\ L \sim 0.1\ \mathrm{pc} \\ \lambda_a \sim 0.01\ \mathrm{pc} \end{cases}$
- ⋆ In the surrounding cluster $\begin{cases} B \sim \mu\mathrm{G} \\ L \sim 500\ \mathrm{kpc} \\ \lambda_a \sim 25\ \mathrm{kpc} \end{cases}$
- ⋆ In the inter-galactic medium $\begin{cases} B < 1\ \mathrm{nG} \\ L \sim 500\ \mathrm{Mpc} \\ \lambda_a \sim 25\ \mathrm{Mpc} \end{cases}$
- ⋆ In the Milky Way $\begin{cases} B \sim 5\ \mu\mathrm{G} \\ L \sim 10\ \mathrm{kpc} \\ \lambda_a \sim 5\ \mathrm{kpc} \end{cases}$

A APPEALING SCENARIO

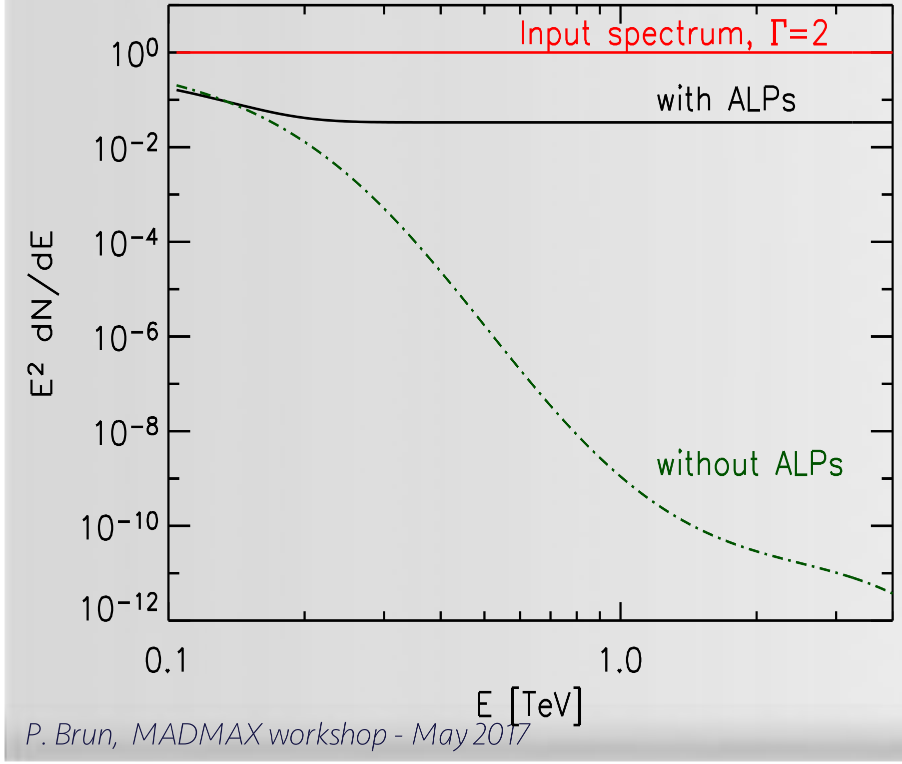


ALP – γ conversion in the source region

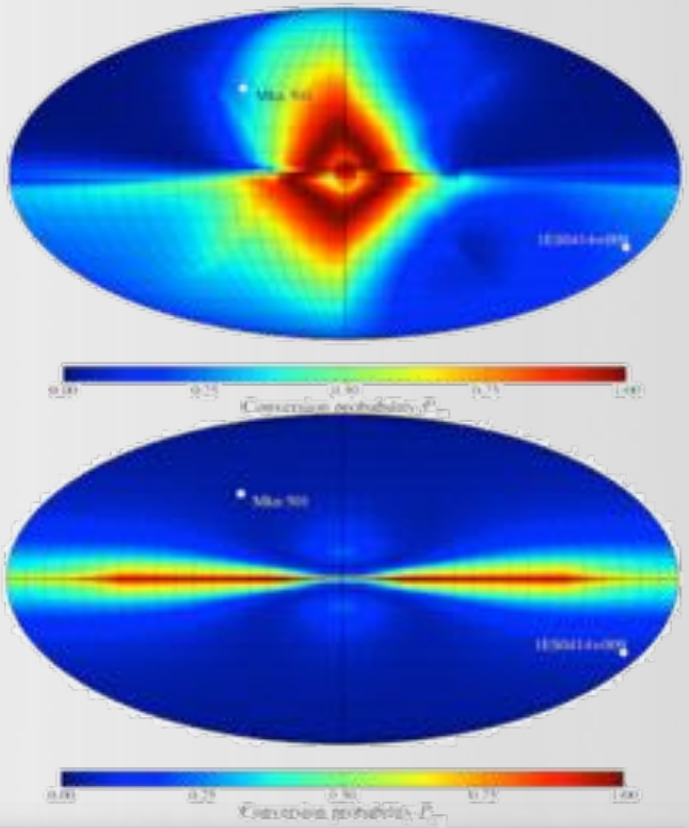
Propagation of the mixed beam

Attenuation of γ

Back-conversion of γ in the Galactic magnetic field



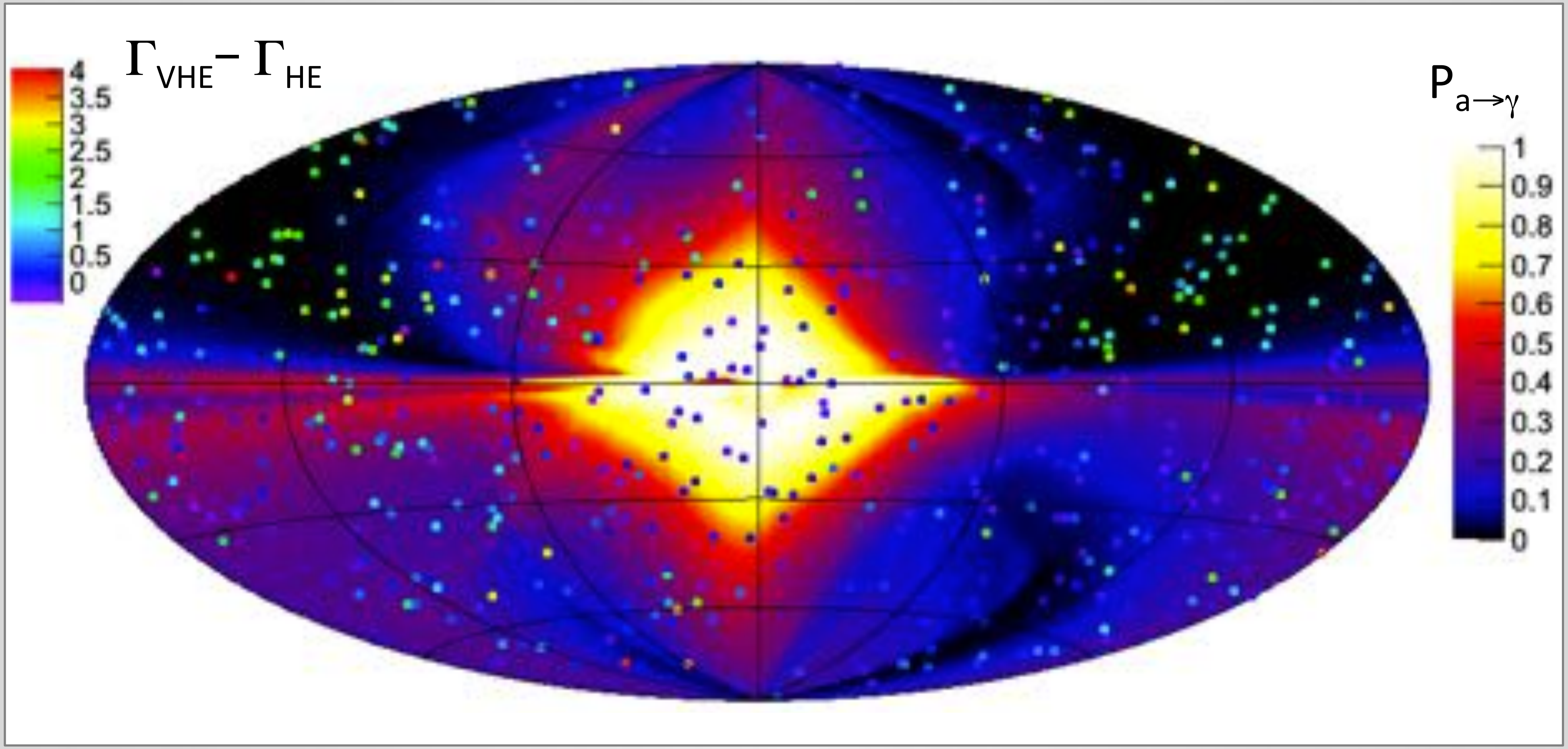
M. Simet, D. Hooper & P. Serpico, PRD, 2008



Horns, Maccione, Meyer, Mirizzi, Montanino, Roncadelli, PRD 2012

PREDICTION FOR MULTIPLE SOURCES

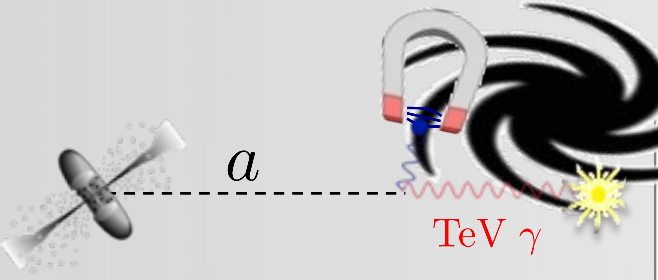
The opacity effect would depend on position

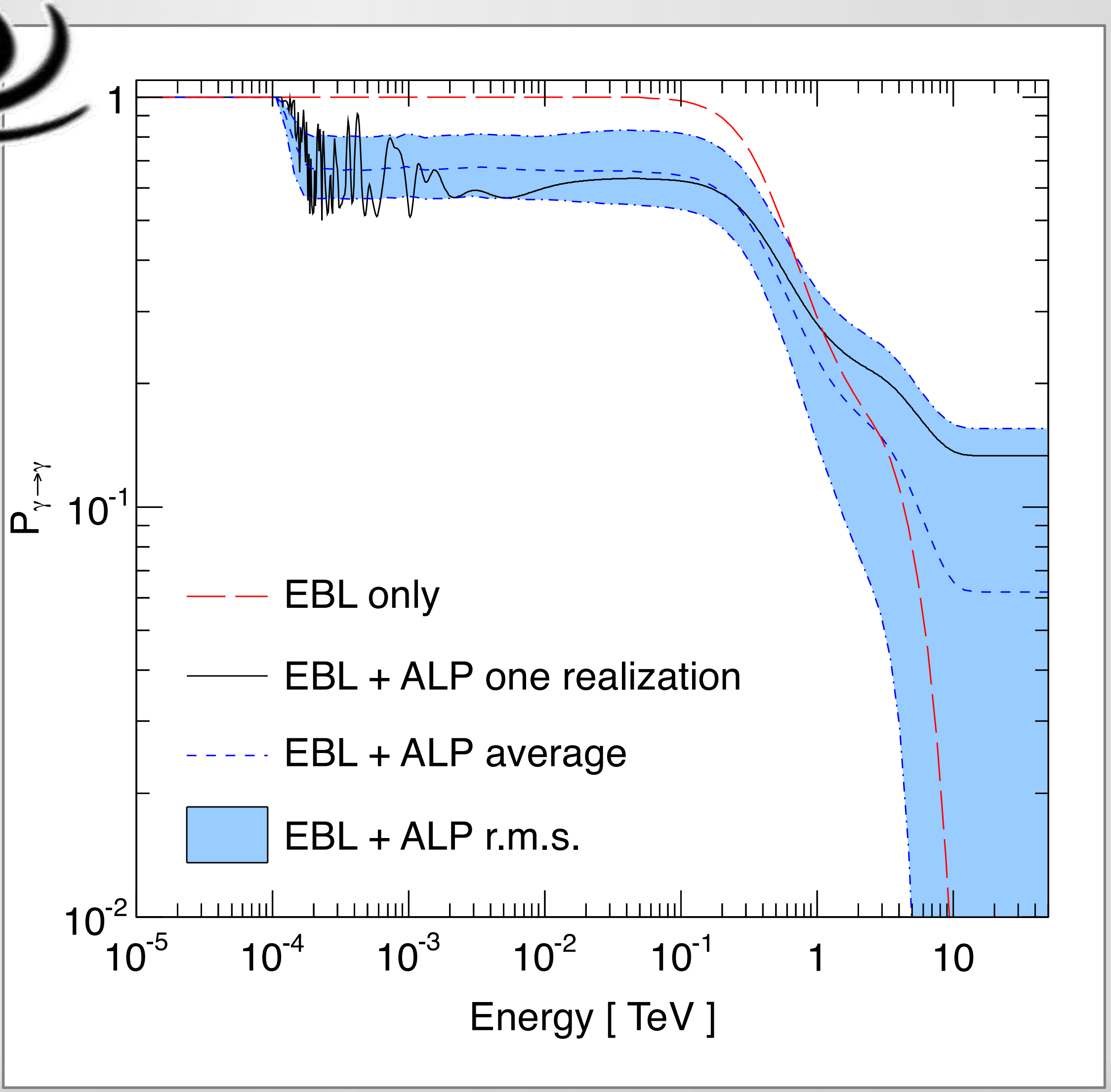


D. Wouters & P.B., JCAP 2014

SPECIFIC PREDICTIONS

Source magnetic field configuration unknown: variance of the prediction





D. Wouters & P.B., JCAP 2014

Opacity anomaly

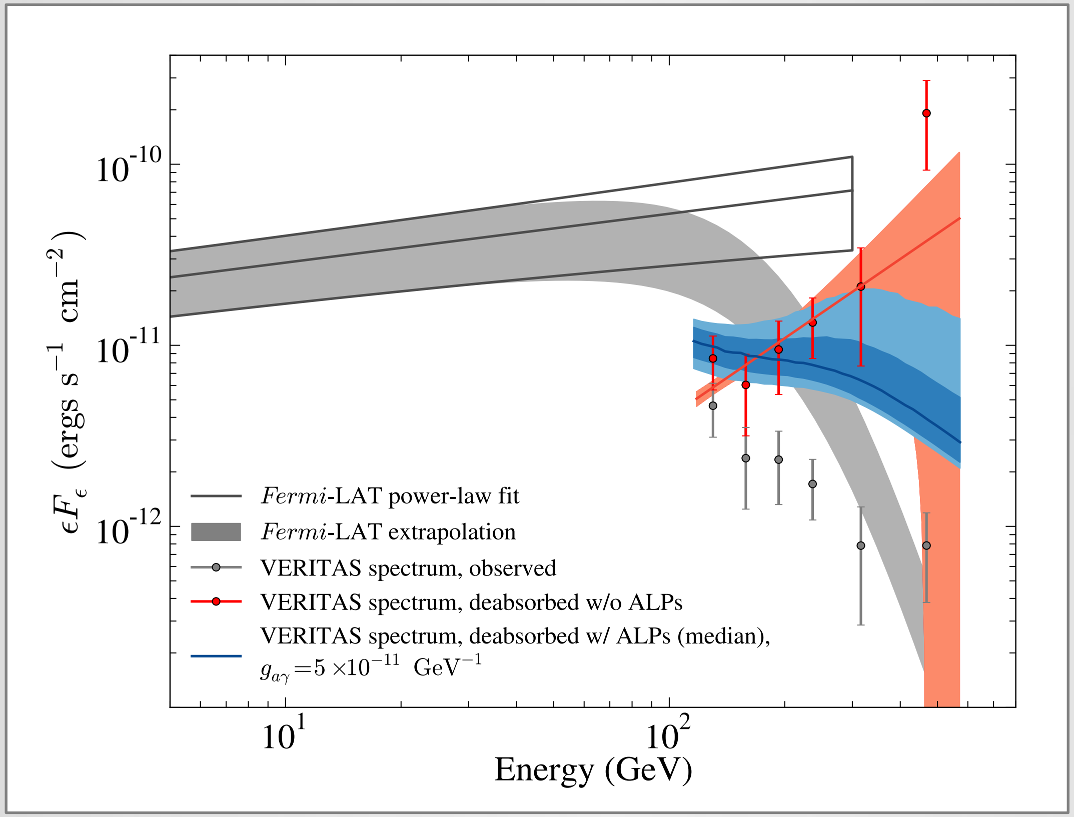
ABSORPTION WITHIN THE SOURCES

- ★ One class of AGN was not expected to shine in γ
  - → Flat-spectrum radio quasars (FSRQs)
  - → Important opacity due to IR-optical photons

- ★ At least 5 FSRQs discovered in the last few years
  - → Gamma rays observed above 100 GeV
  - → $z > 0.3$

PKS 1424-240

- ★ Another FSQR : axions allow to keep spectrum concave

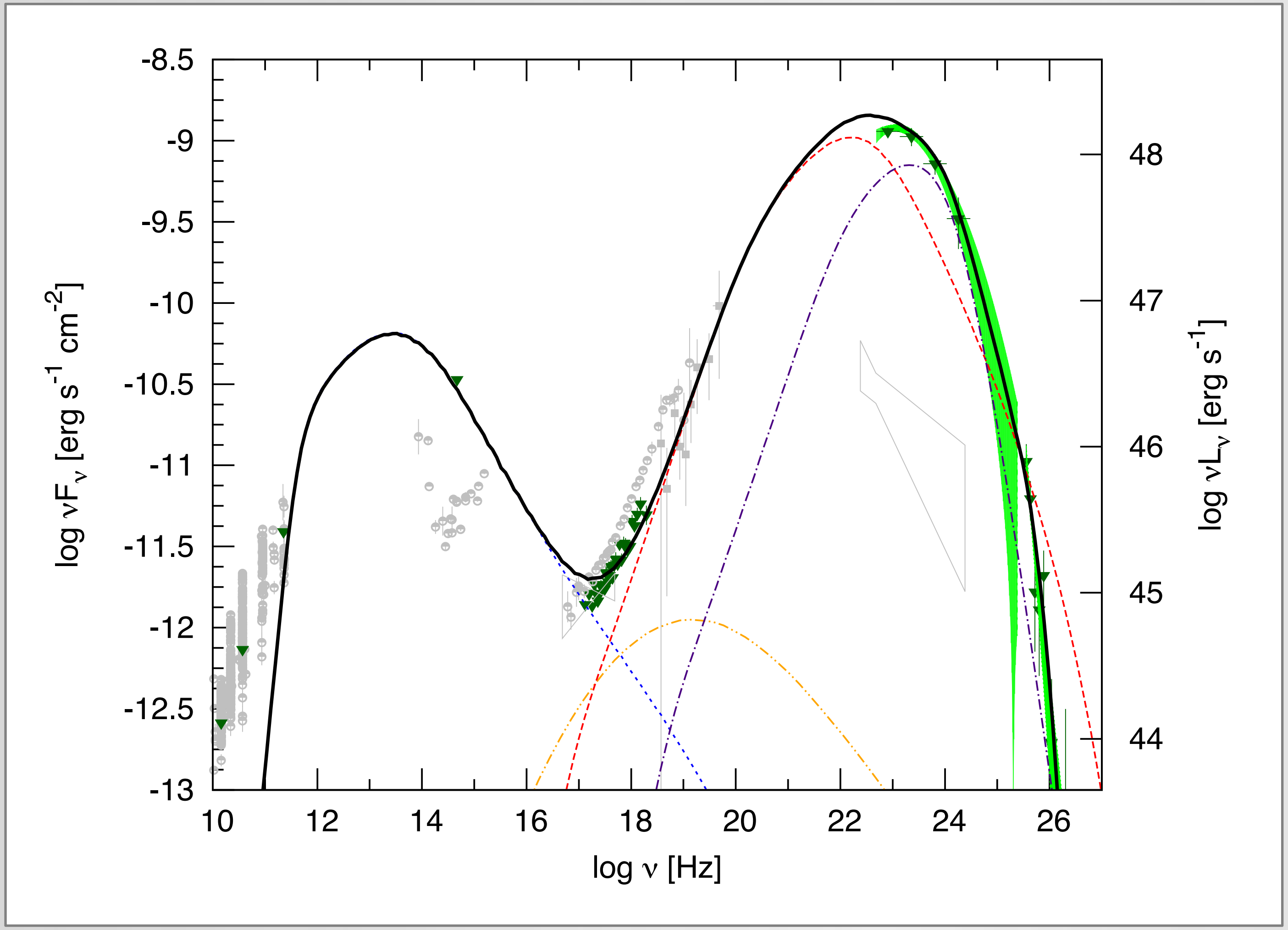


M. Meyer & D. Horns, 2013

- ★ Same for PKS 1222+216 *(F. Tavecchio et al., PRD 2012)*
- ★ Can be explained with non-minimal conventional models

PKS 1510-089

- ★ Example of a FSRQ with γ-ray emission

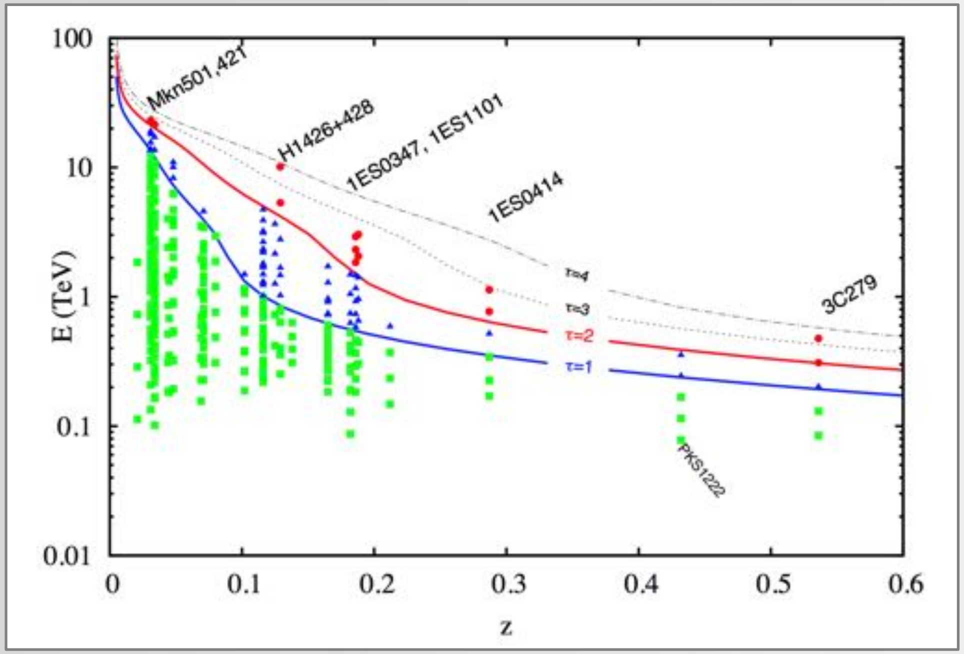


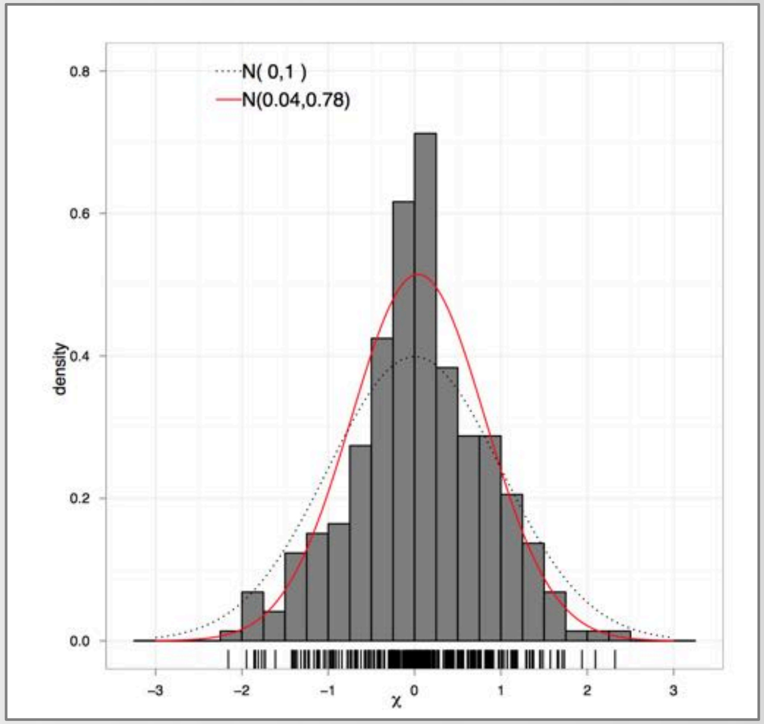
A. Barnacka, R. Moderski, B. Behera, P.B., S. Wagner, A&A 2014

Note the HE spectrum always concave

EXTRAGALACTIC TRANSPARENCY

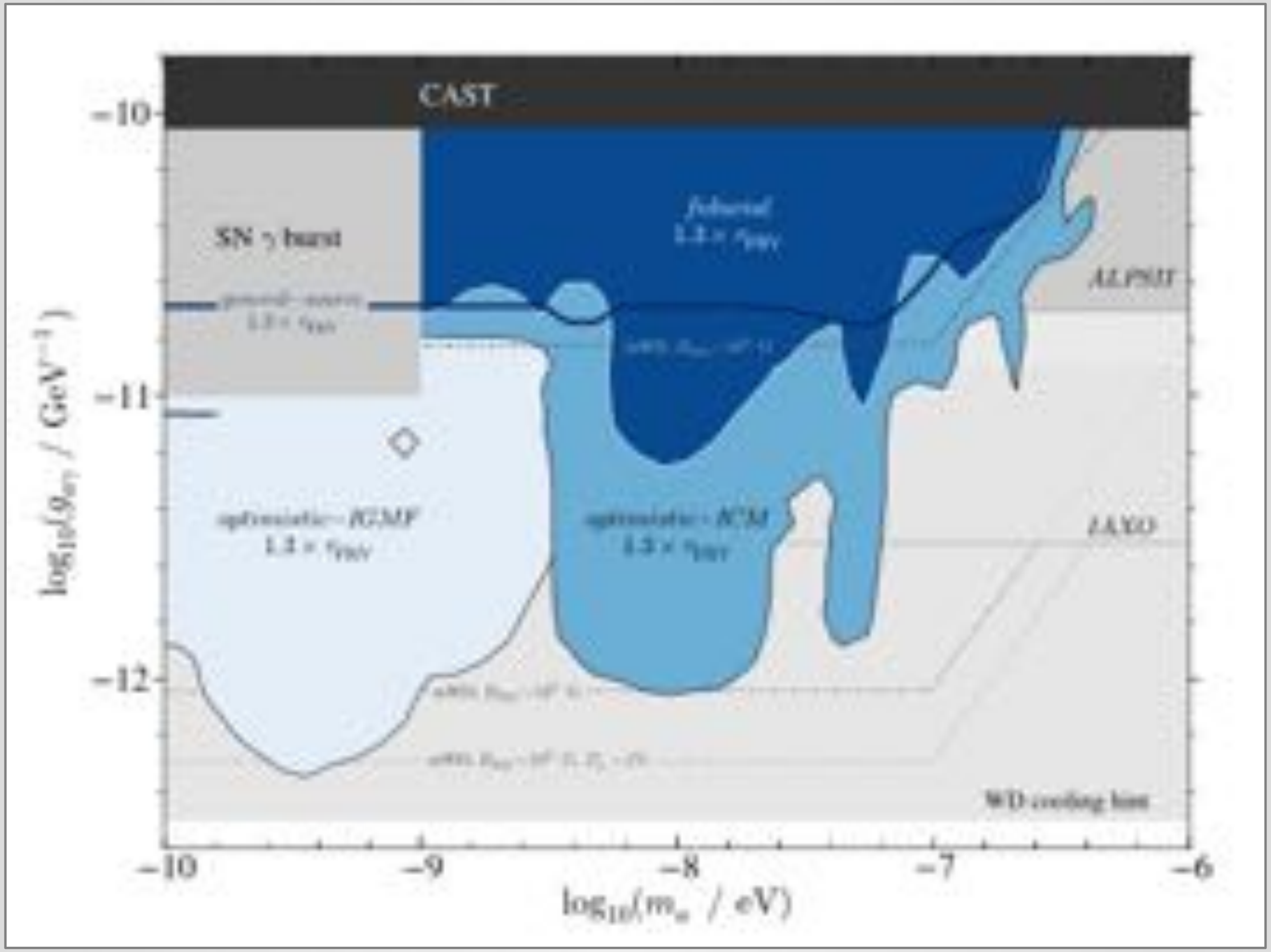
D. Horns, M. Meyer, JCAP 2012





D. Horns, M. Meyer, JCAP 2012

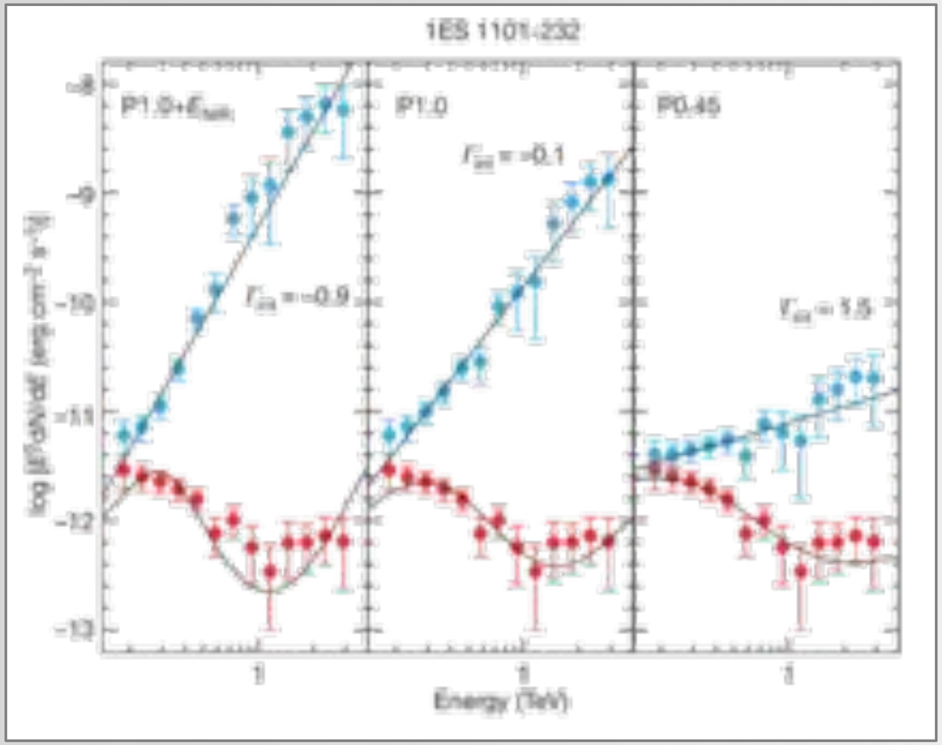
Extragalactic transparency



Measurements of EBL density

AN OPACITY ANOMALY ?

- ★ 2006 HESS observations of $z = 0.165$ and $z = 0.186$ AGNs



HESS Collaboration, Nature 2006

Observed spectra too hard

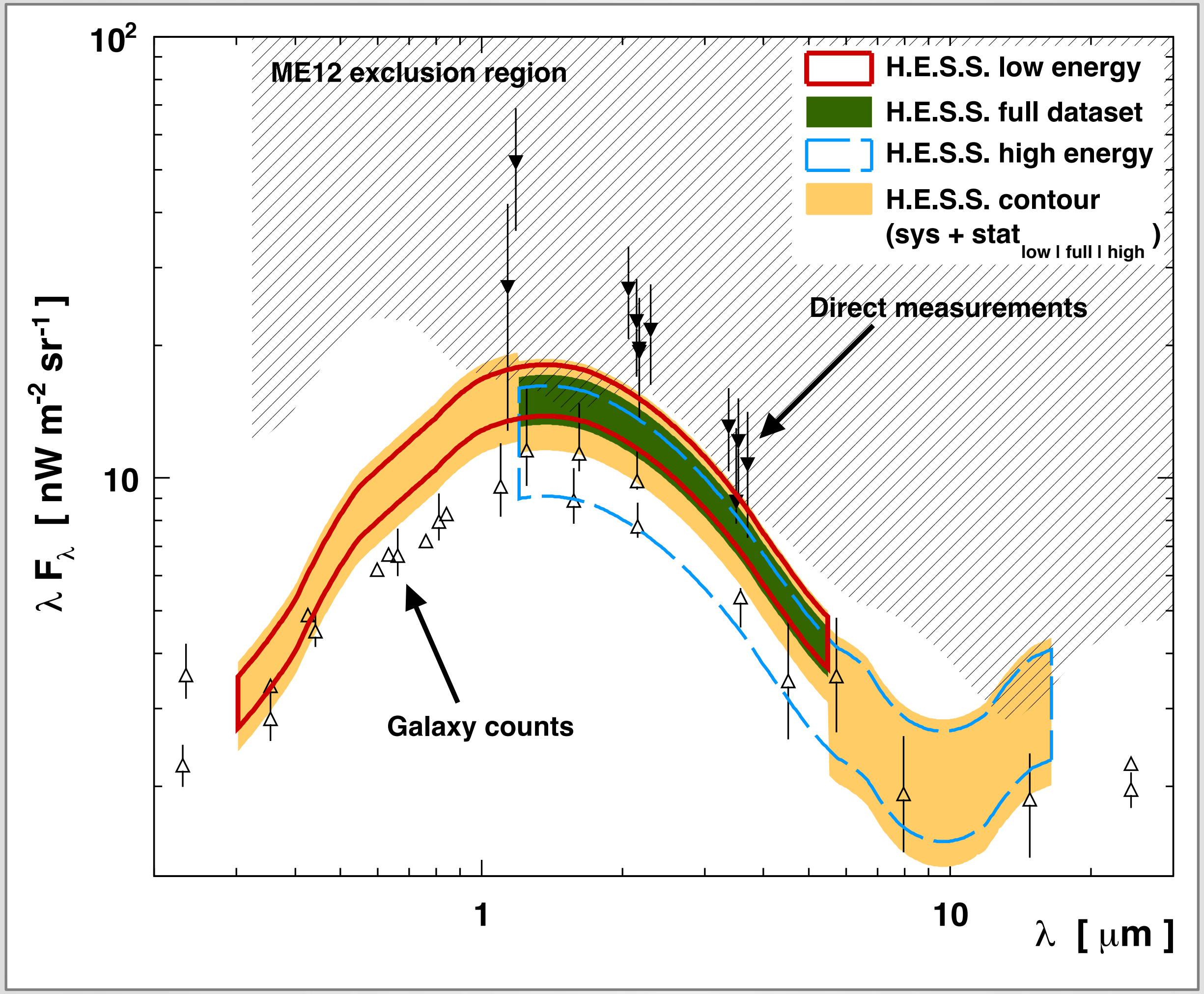
Not compatible with source models

- ★ 2008: $z = \mathbf{0.531}$ AGN (MAGIC), 2010: $z = \mathbf{0.61}$ (HESS)

Universe was bit more transparent than expected

FIT OF THE EBL DENSITY

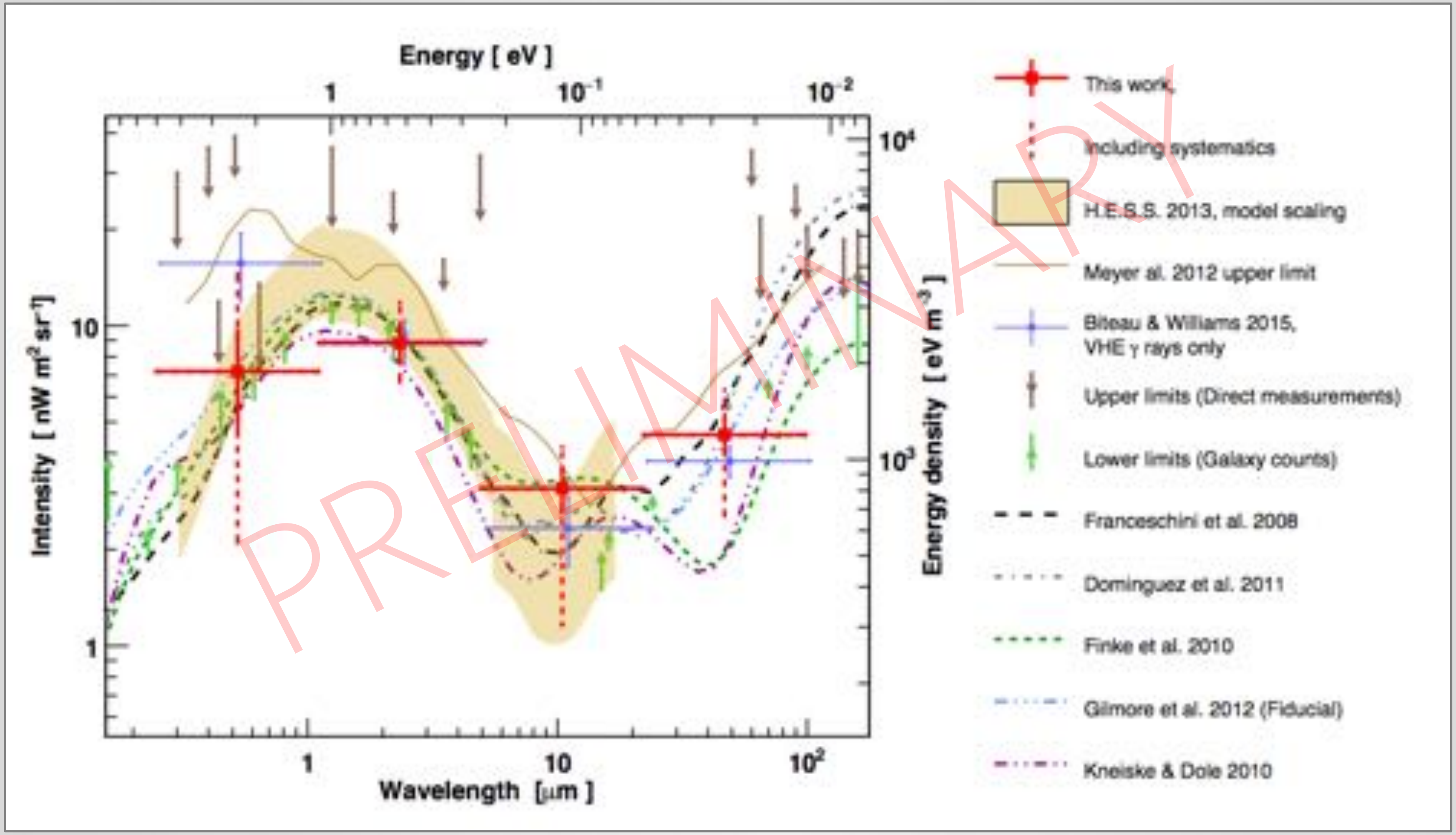
Normalization of the EBL model fitted on data



HESS Collaboration, A&A 2013

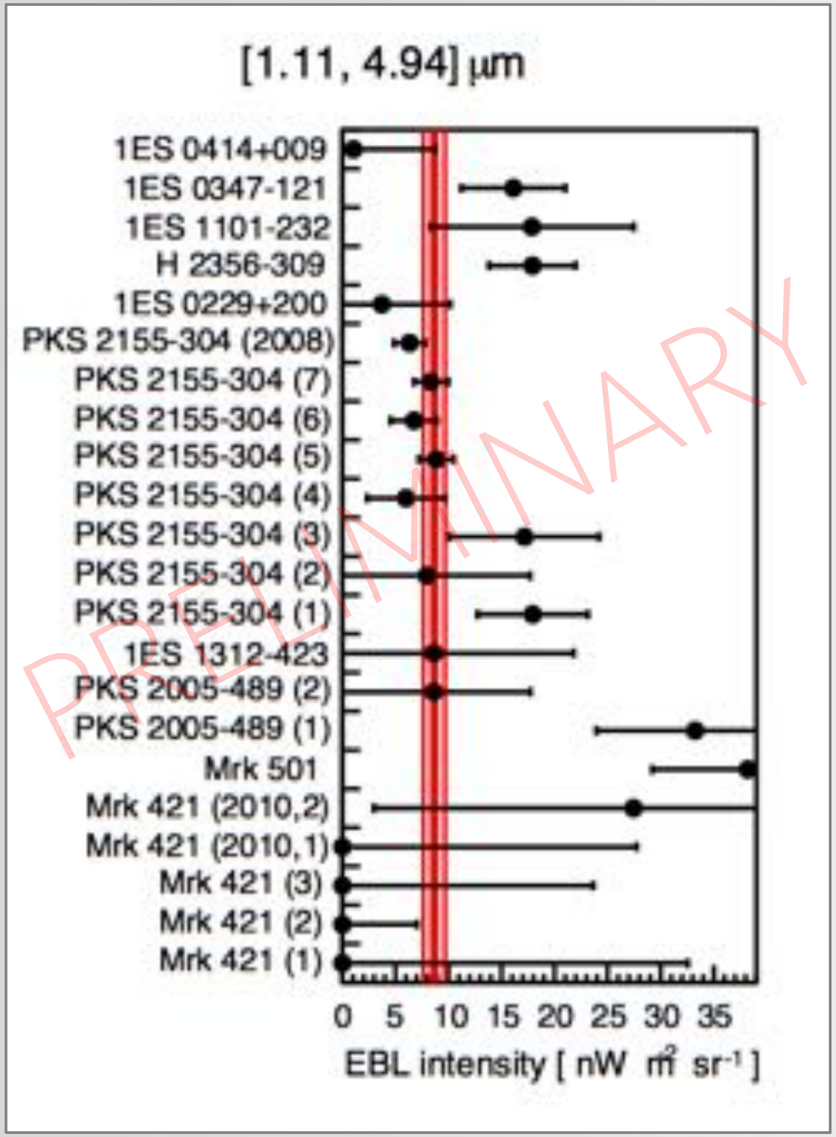
$$\alpha_0 = 1.27^{+0.18}_{-0.15\ \mathrm{stat}} \pm 0.25_{\mathrm{syst}}$$

RECENT UPDATE



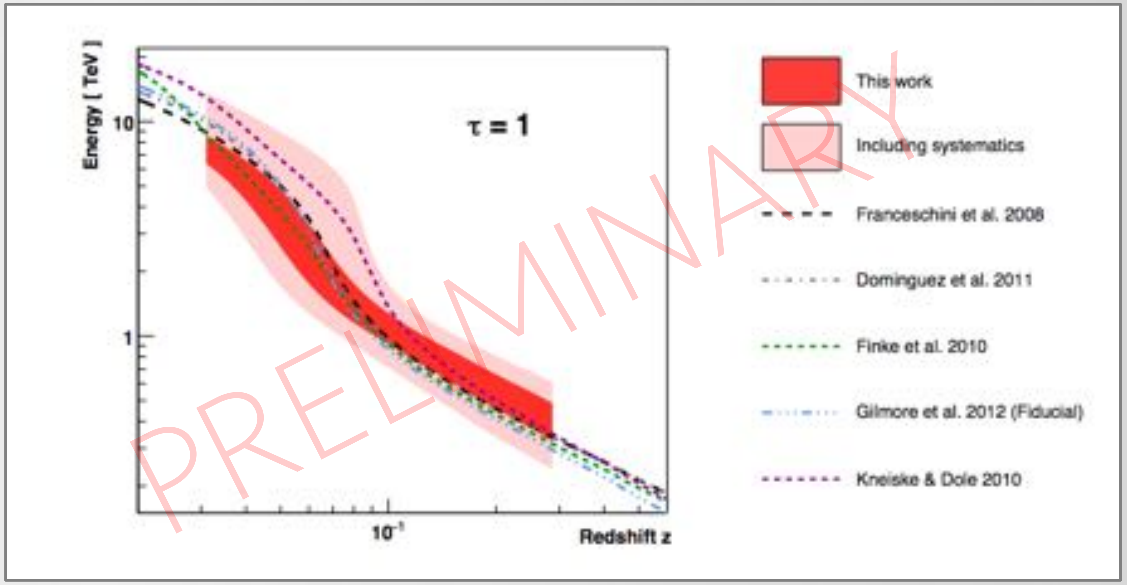
HESS Collaboration, M. Lorentz, P.B. , submitted

RECENT UPDATE



No significant deviation from any single source

Related horizon, no tension wrt models



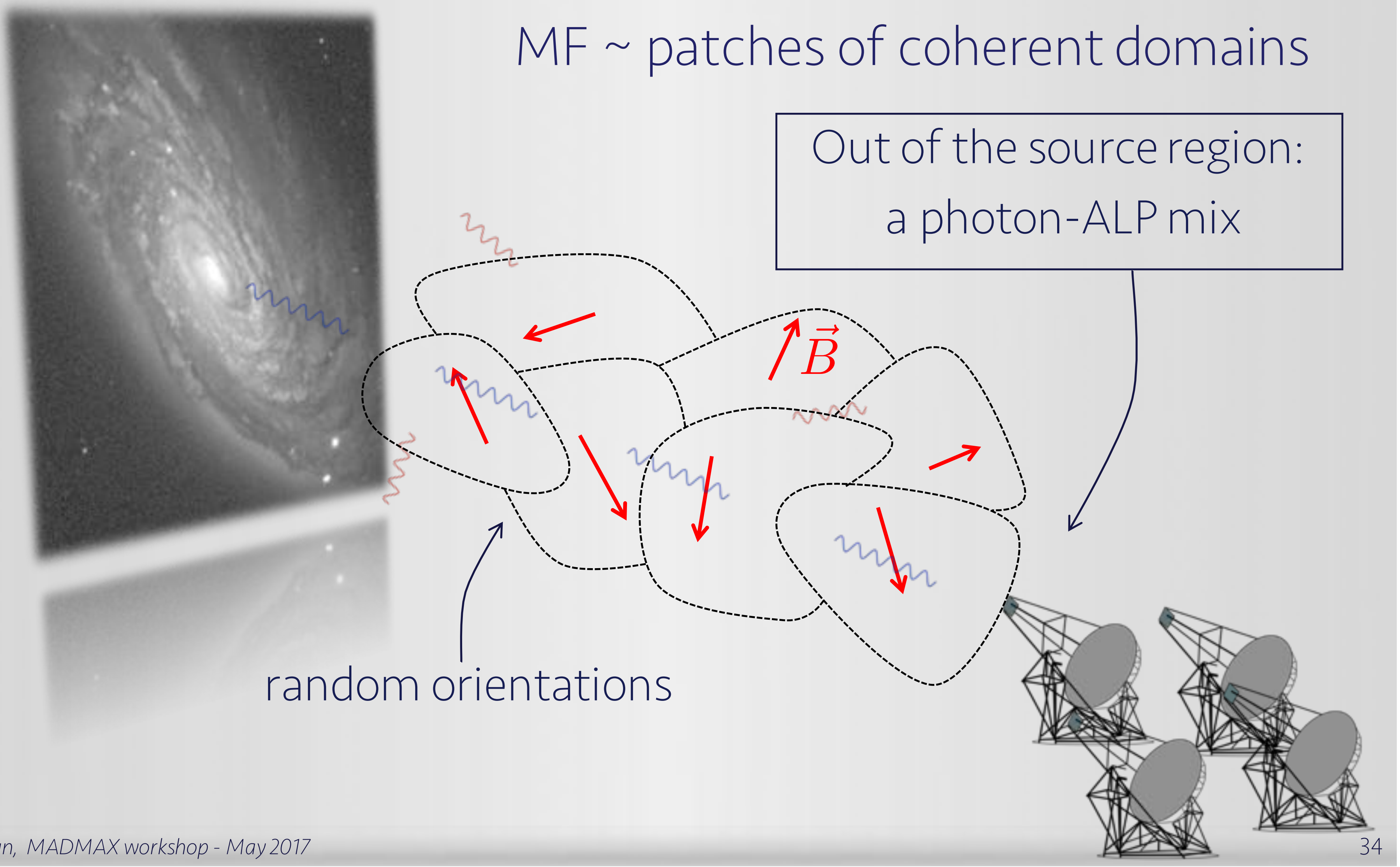
HESS Collaboration, M. Lorentz, P.B. , submitted

CONSTRAINTS ON THIS SCENARIO

ASTROPHYSICAL MAGNETIC FIELDS

Astrophysical MF = always turbulent

MF ~ patches of coherent domains



Out of the source region:
a photon-ALP mix

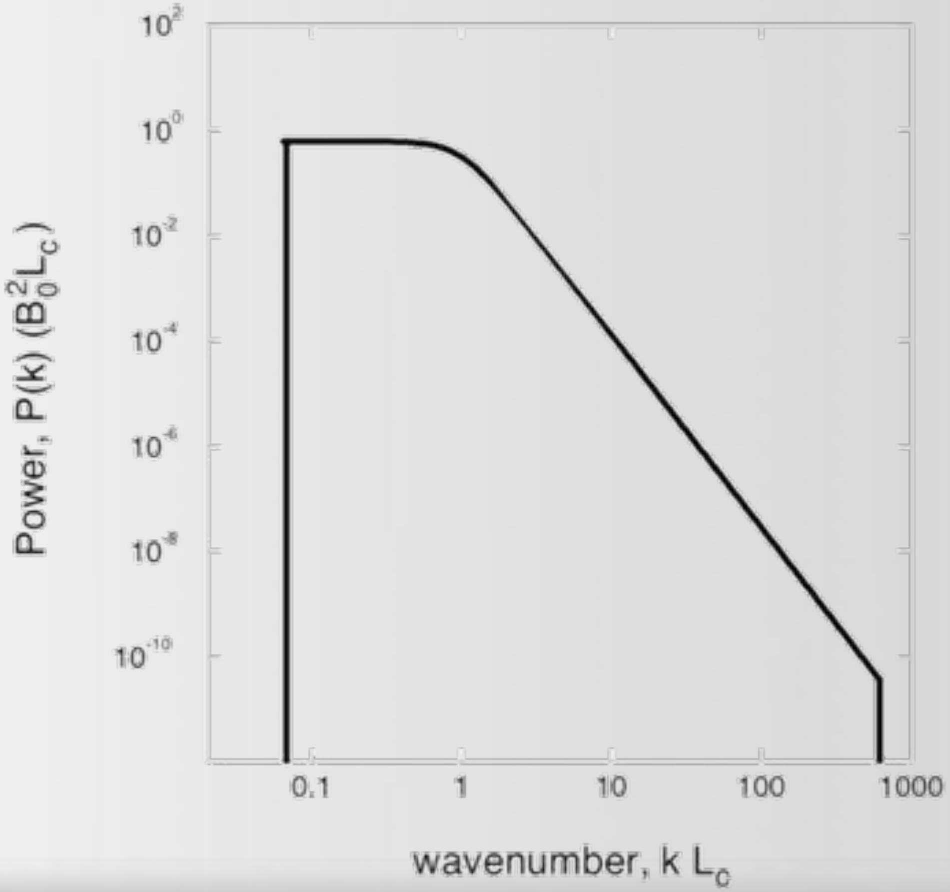
random orientations

CLUSTER MAGNETIC FIELDS

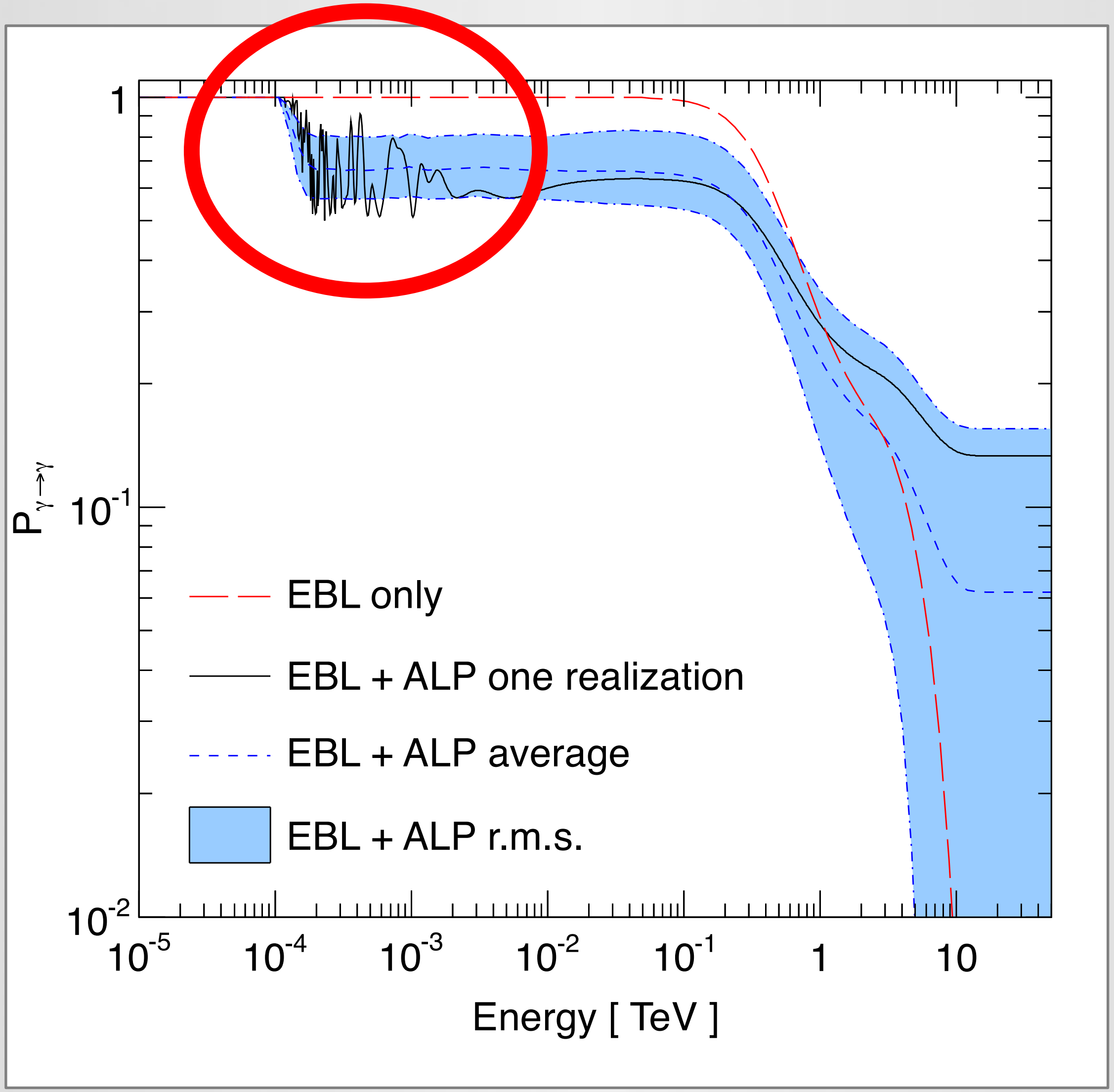
- ★ Smooth radio halos observed on scales of Mpc (100 x galaxy)
- ★ Equipartition assumption sets a minimal strength of 1 μG
- ★ Field is turbulent, described by its power spectrum

$$\vec{B} \;=\; \vec{B}_0 + \delta\vec{B}$$

$$(\delta B)^2 \propto \sigma^2 \frac{k^2}{1+(kL_\mathrm{c})^\gamma}$$



INDUCTION OF NOISE IN SPECTRA

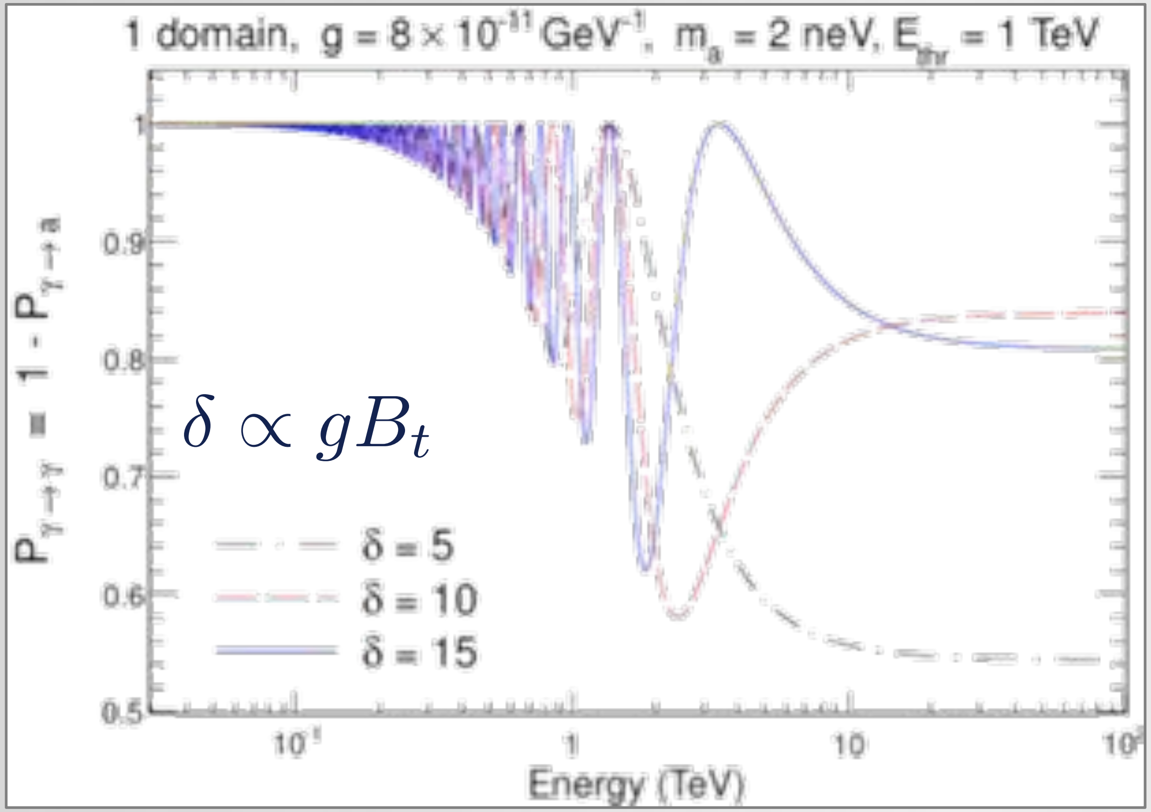


D. Wouters & P.B., JCAP 2014

γ SURVIVAL PROBABILITY IN 1 DOMAIN

Mixing induces spatial and ***spectral*** oscillations

$$P_{\gamma\rightarrow a} = \frac{1}{1+\left(\frac{E_c}{E}\right)^2}\sin^2\left(\frac{2\pi z}{\lambda(E)}\right)$$



$$\delta \propto gB_t$$

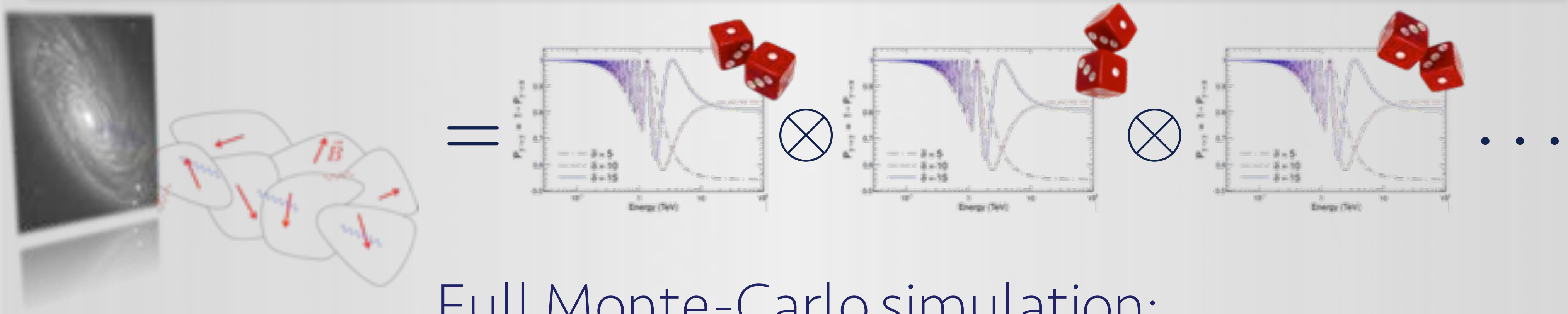
D. Wouters & P.B., PRD, 2012

Efficient around

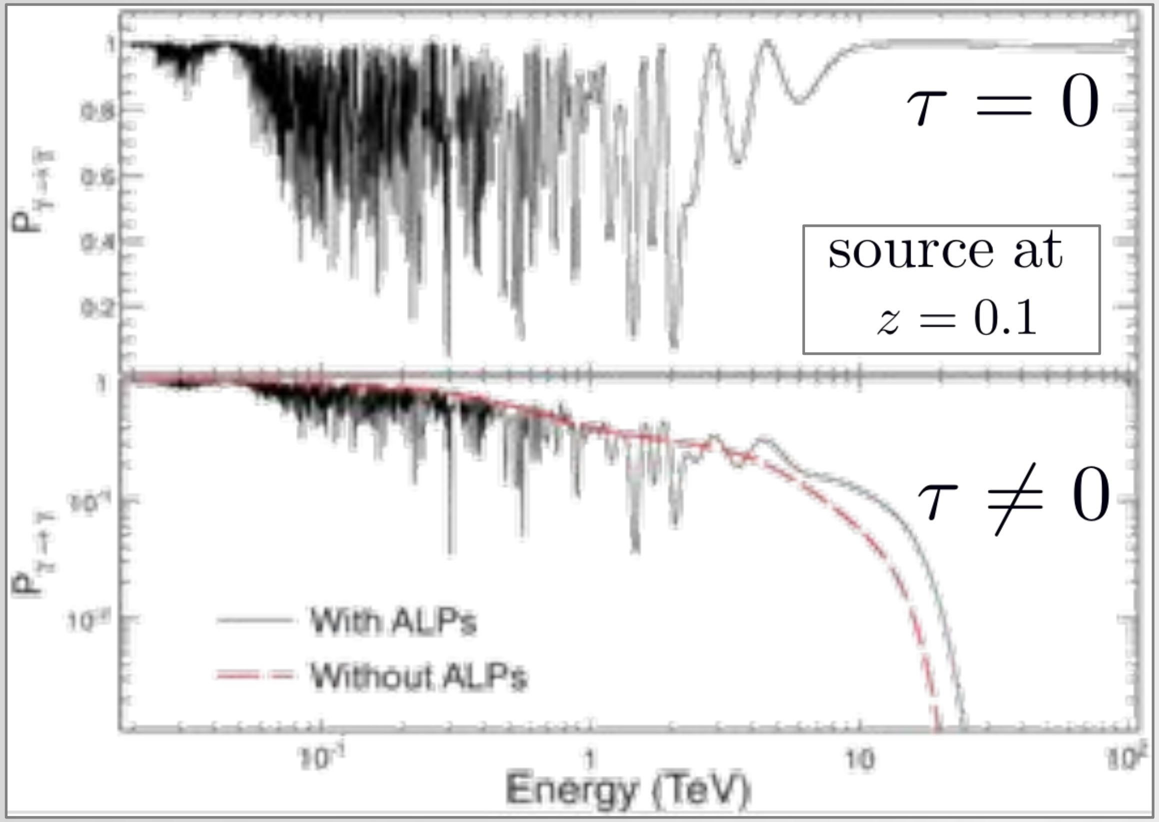
$$E_\mathrm{c} = \frac{m_\mathrm{a}^2}{2gB_t}$$

Oscillations will mix up from one cell to the next

RESULTS FOR SINGLE SOURCES



Full Monte-Carlo simulation:

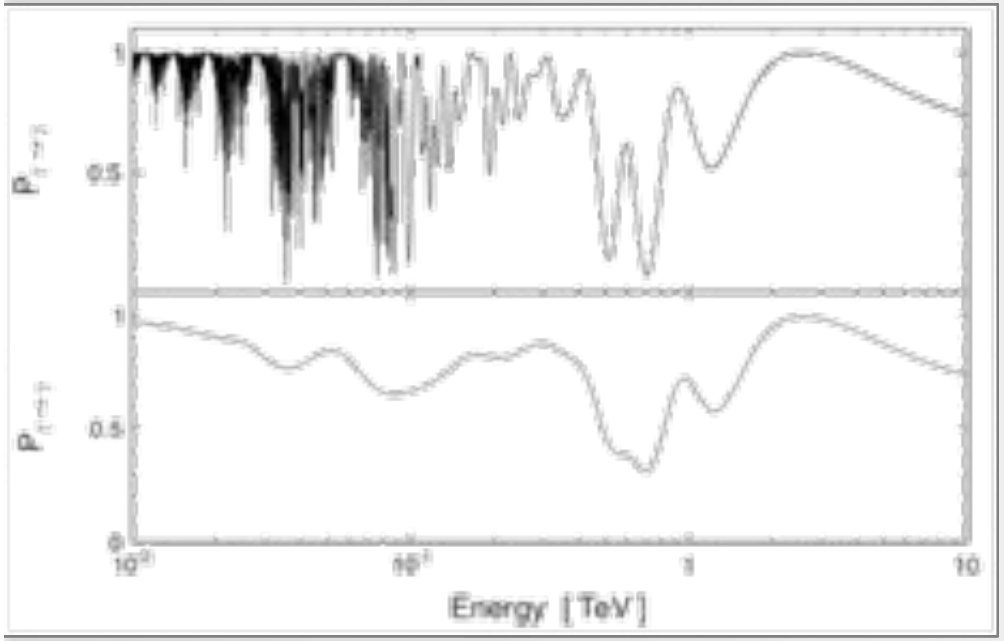


D. Wouters & P.B., PRD 2012

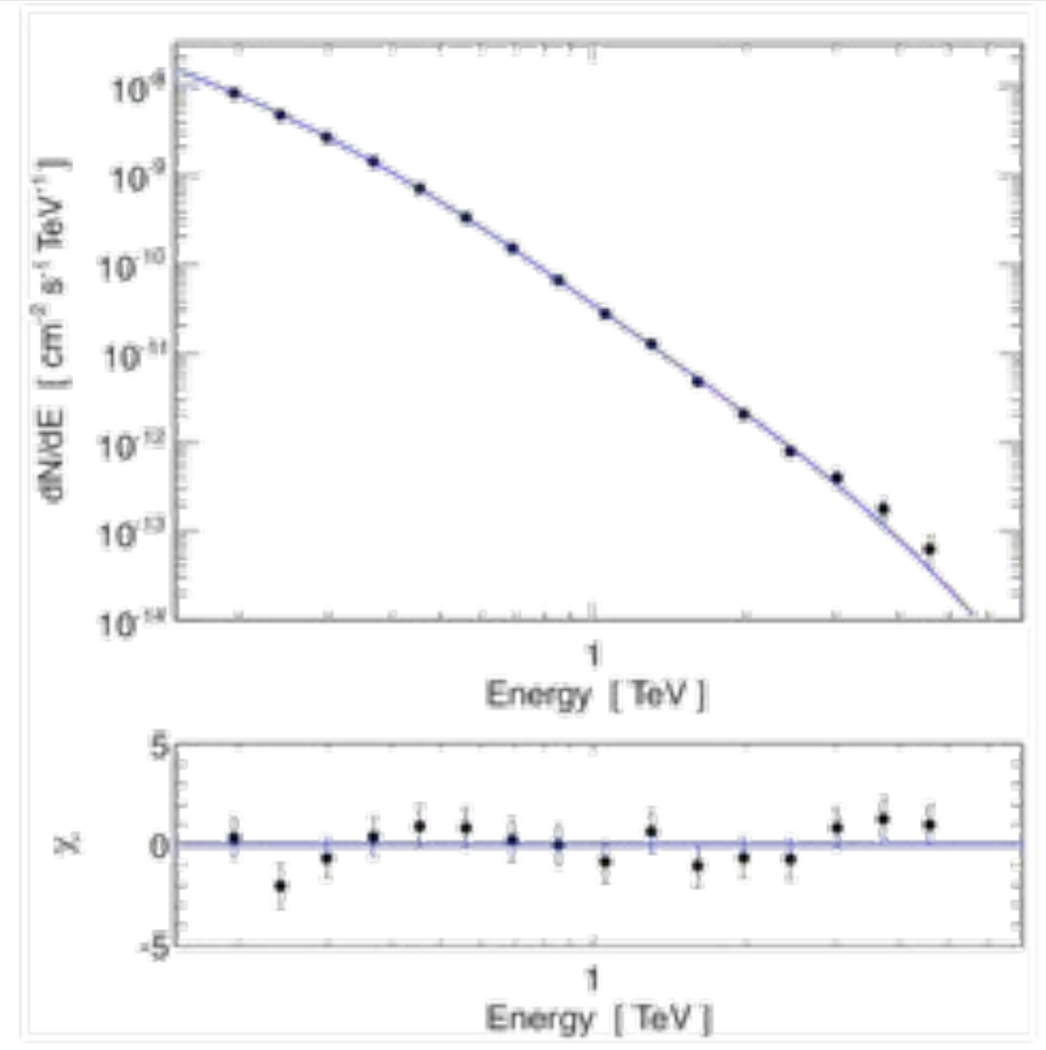
- ⋆ ALPs: noise around E_c
- ⋆ Noise level related to B field turbulence
- ⋆ New effect independent of opacity issue

ALPs in PKS 2155-304

Example of 1 realization as would be seen by HESS



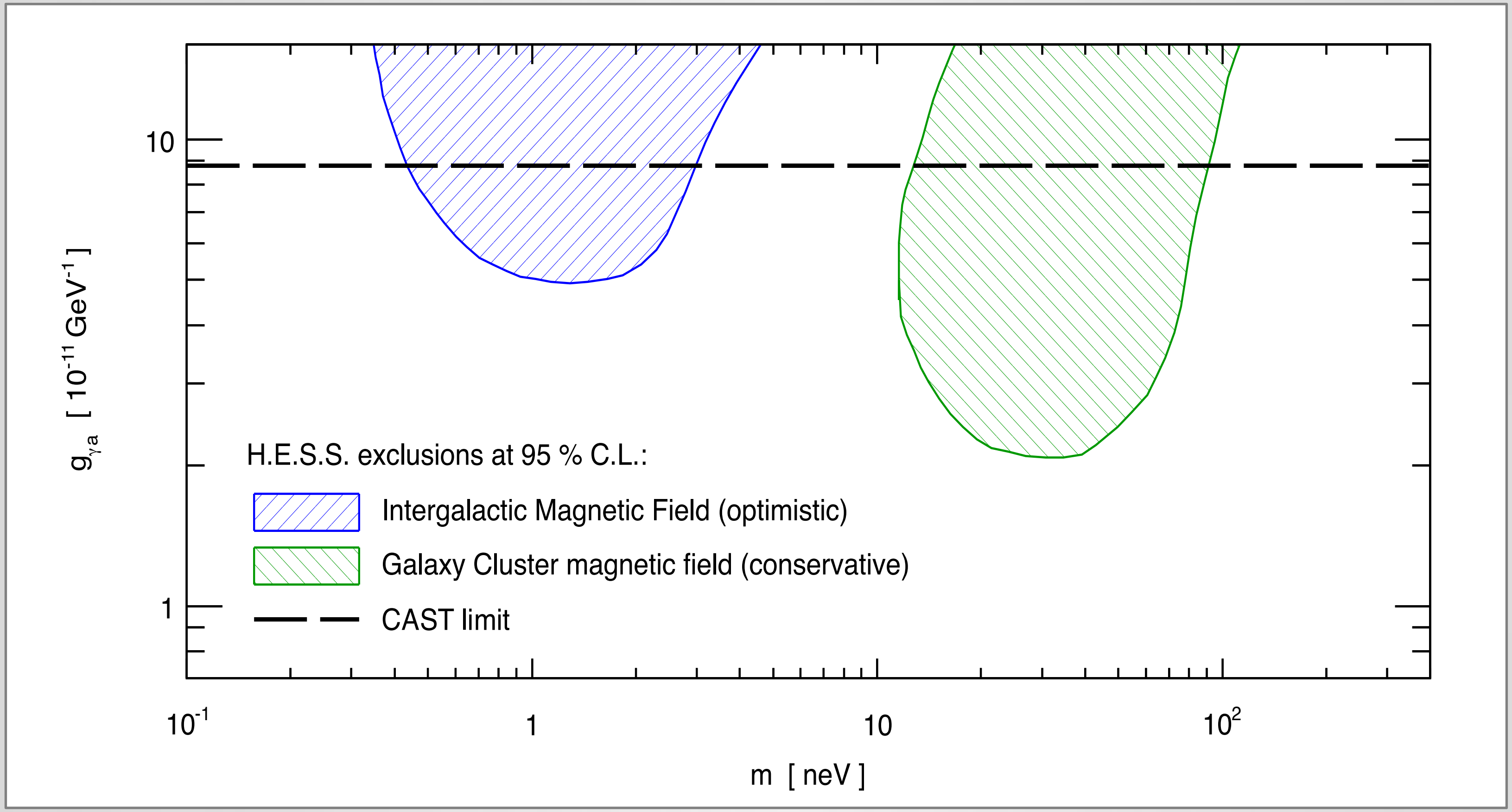
Energy spectrum from HESS observations



How much irregularities can be accomodated by the data?

HESS collaboration (D. Wouters, P.B.), PRD 2013

CONSTRAINTS FROM THE TEV SKY



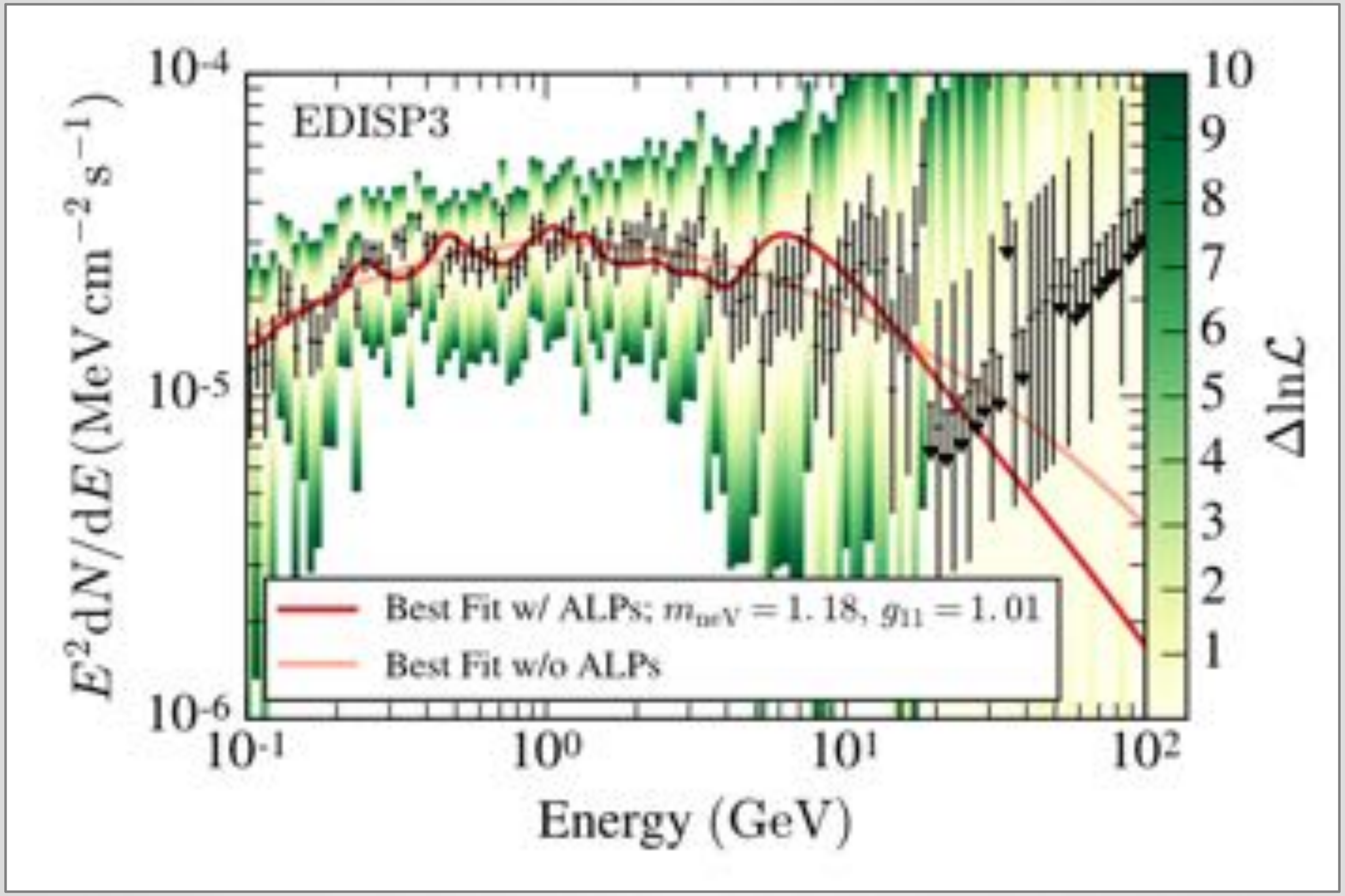
HESS collaboration (D. Wouters, P.B.), PRD 2013

Narrow region around 20 neV probed

Due to localized irregularities around E_c

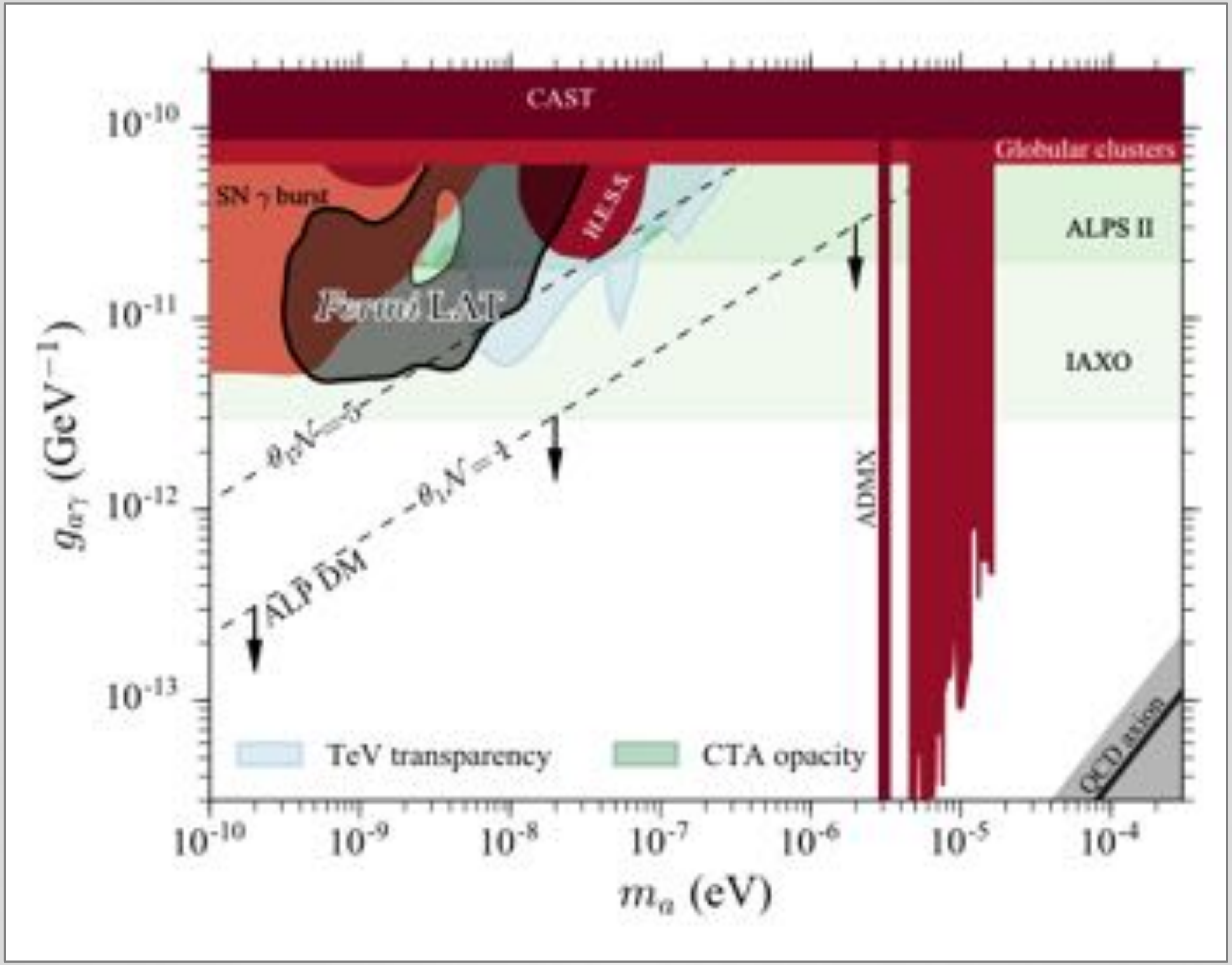
FERMI ANALYSIS

- ★ Same analysis conducted at lower energies
- ★ Data from NGC 1275 (Perseus cluster)



Ajello et al. (FERMI), PRL (2016)

REMAINING PARAMETER SPACE



Ajello et al. (FERMI), PRL (2016)

CONCLUSIONS

- ★ ALPs can influence gamma-ray observations
- ★ Opacity anomaly is subject to debate
  - → Specific cases can be explained with conventional
  - → Global fit might include unclear error combination
- ★ Most recent EBL measurements do not show issues
  - → Systematic uncertainties too large to be conclusive

Personal opinion:

Opacity is more a search channel than a hint