Search for axion-like particle signatures in gamma-ray spectra with H.E.S.S. II

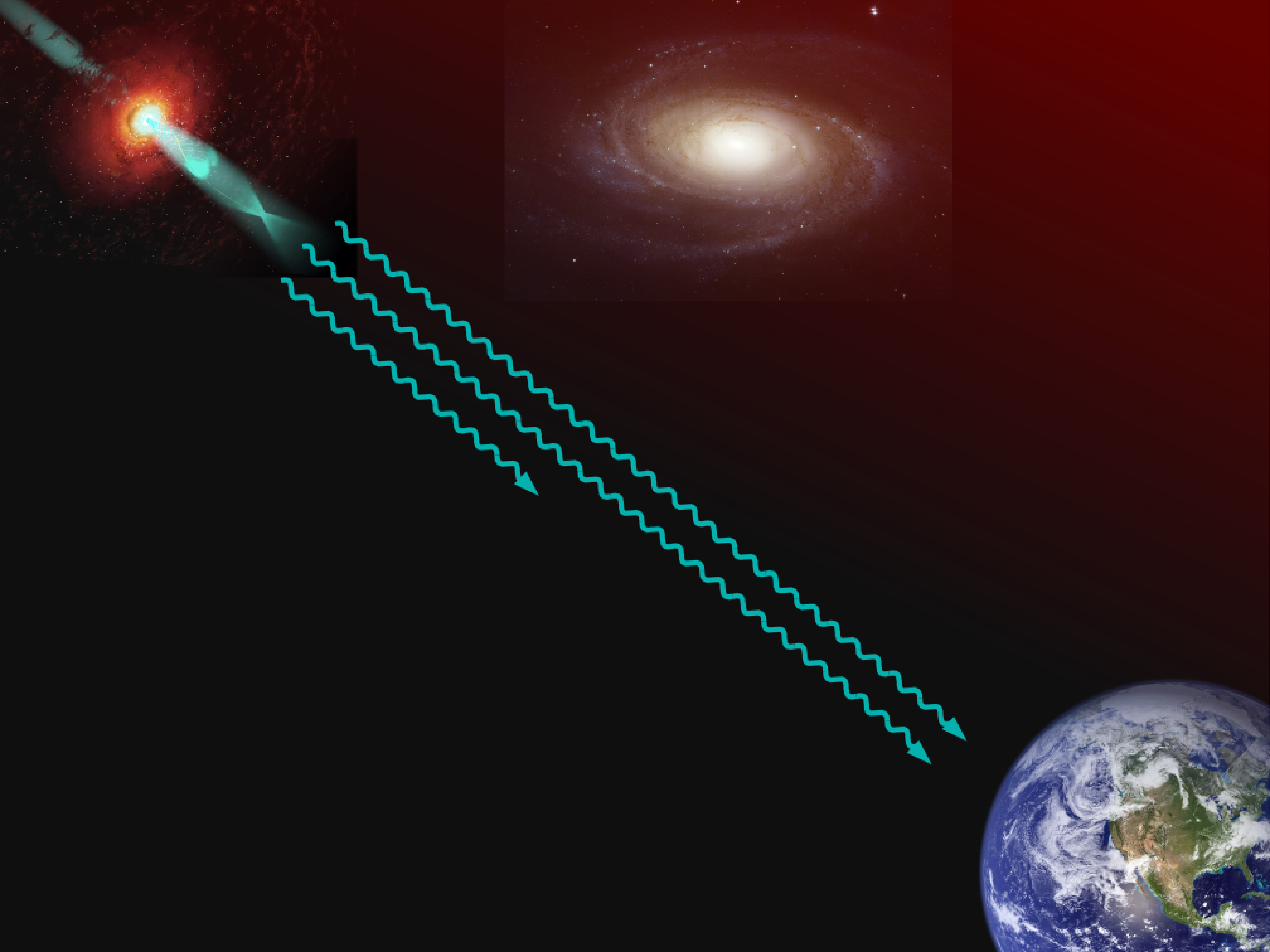
Manuel Meyer*

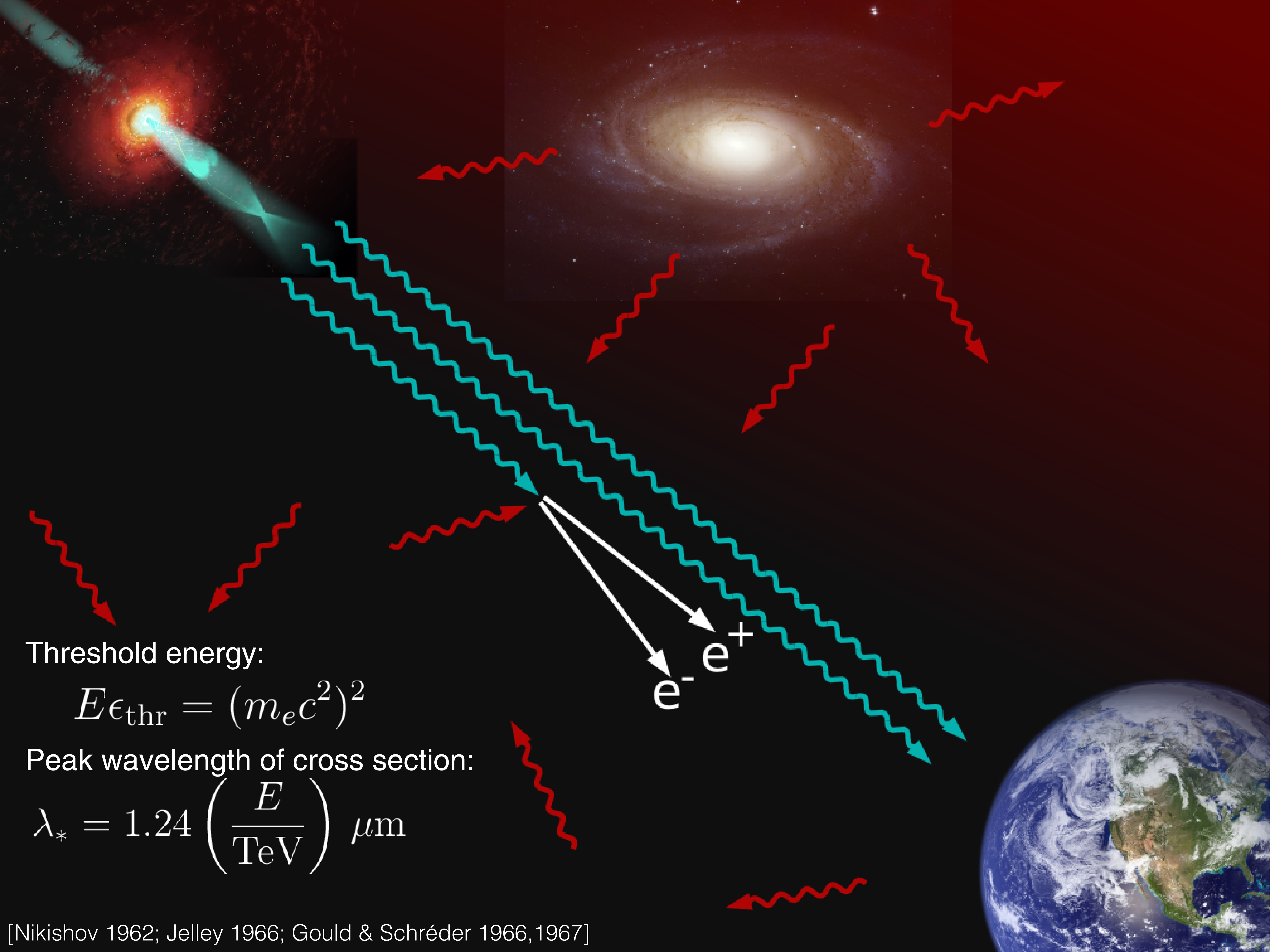
October 24, 2013
2nd OKC DIAS workshop: science with H.E.S.S. II

manuel.meyer@fysik.su.se
*Oskar Klein Centre, Stockholm University

Oskar Klein centre

Stockholm University





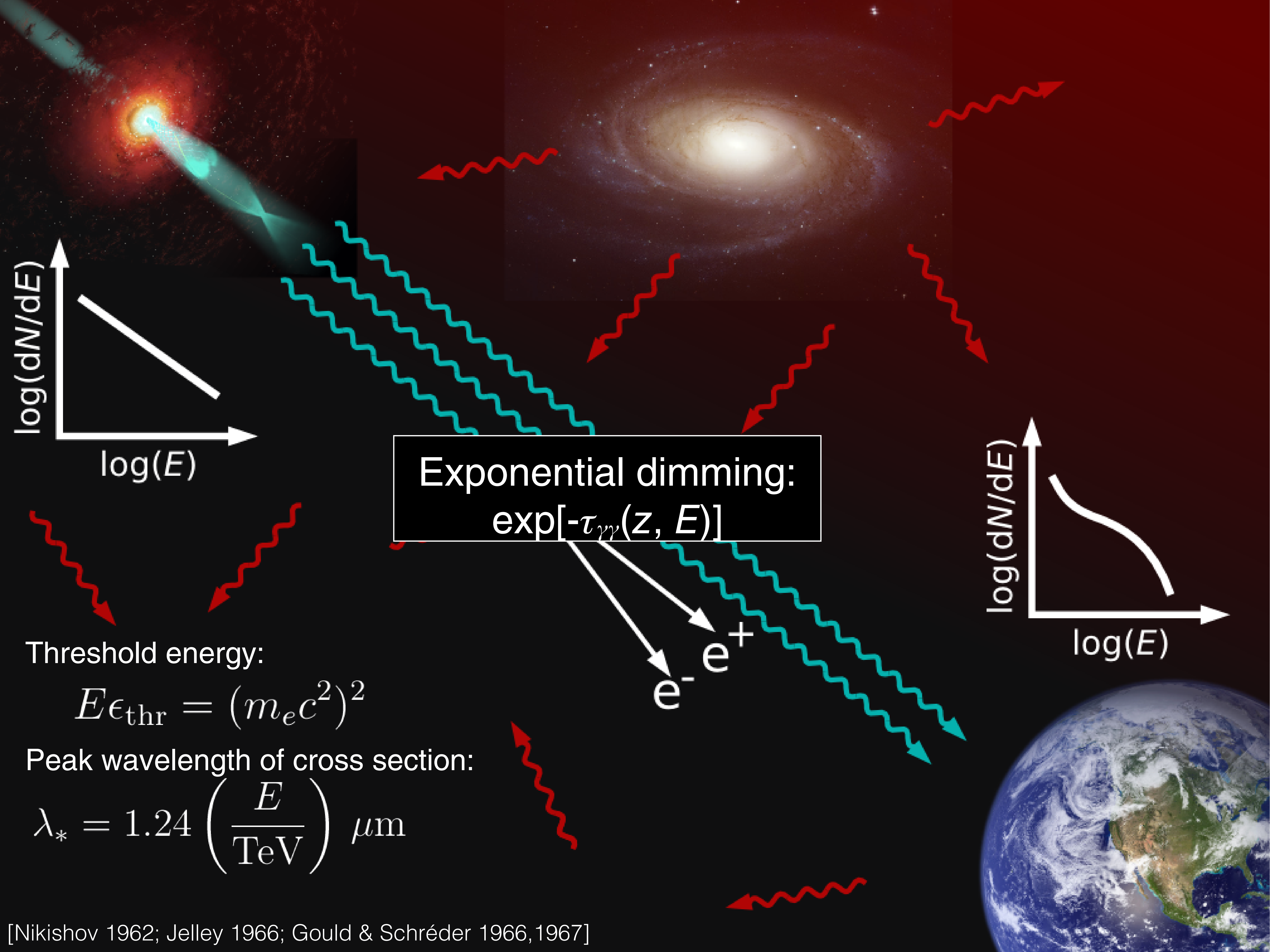
Threshold energy:

$$E\epsilon_{\rm thr} = (m_e c^2)^2$$

Peak wavelength of cross section:

$$\lambda_* = 1.24 \left(\frac{E}{\rm TeV}\right) \mu{\rm m}$$

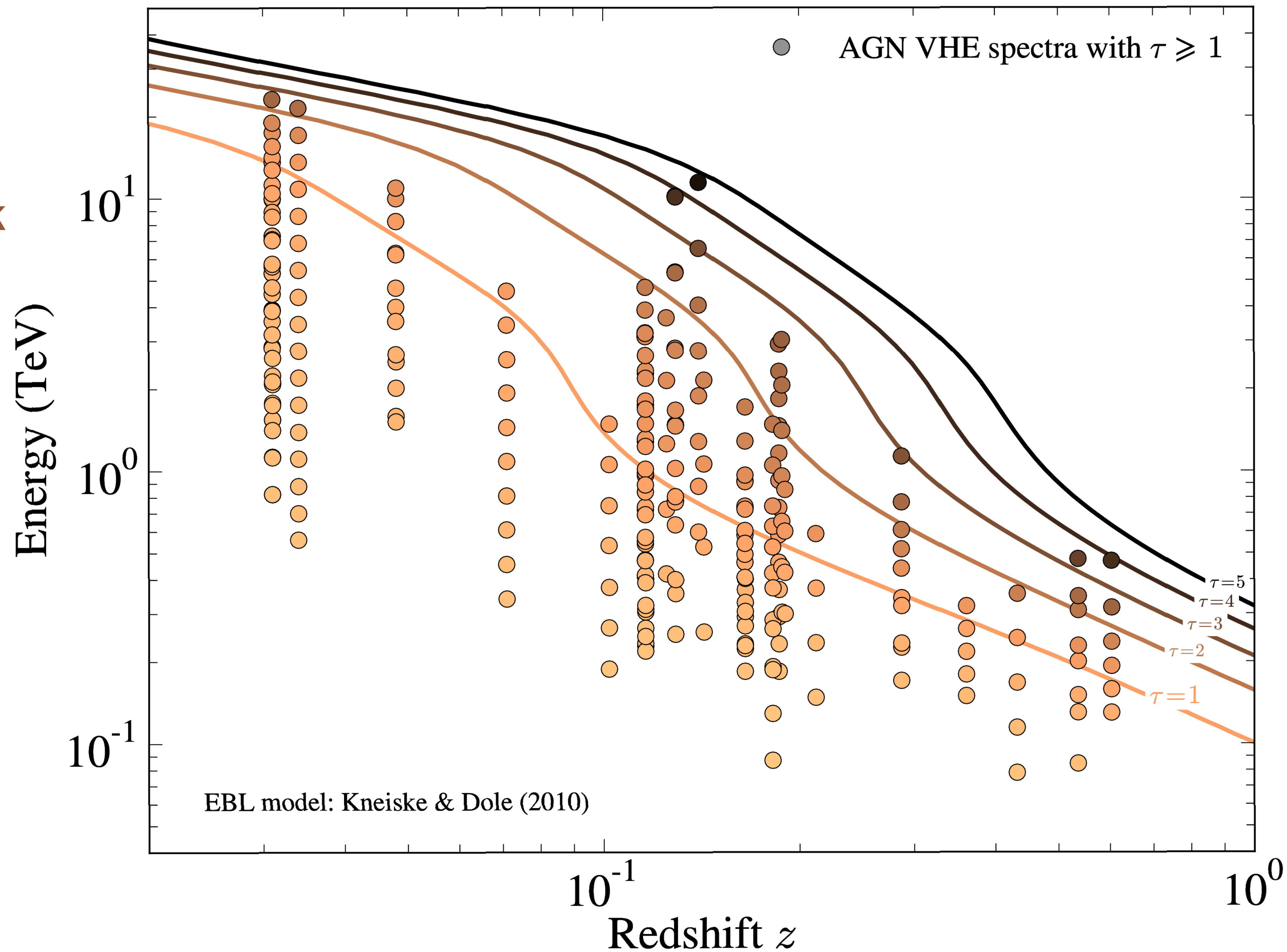
[Nikishov 1962; Jelley 1966; Gould & Schréder 1966,1967]



log(dN/dE)
log(E)
Exponential dimming:
$\exp[-\tau_{\gamma\gamma}(z, E)]$
e^-
e^+
log(dN/dE)
log(E)
Threshold energy:
$E\epsilon_{\rm thr} = (m_e c^2)^2$
Peak wavelength of cross section:
$\lambda_* = 1.24 \left(\frac{E}{\rm TeV}\right)\ \mu{\rm m}$
[Nikishov 1962; Jelley 1966; Gould & Schréder 1966,1967]

Investigate opacity of the Universe

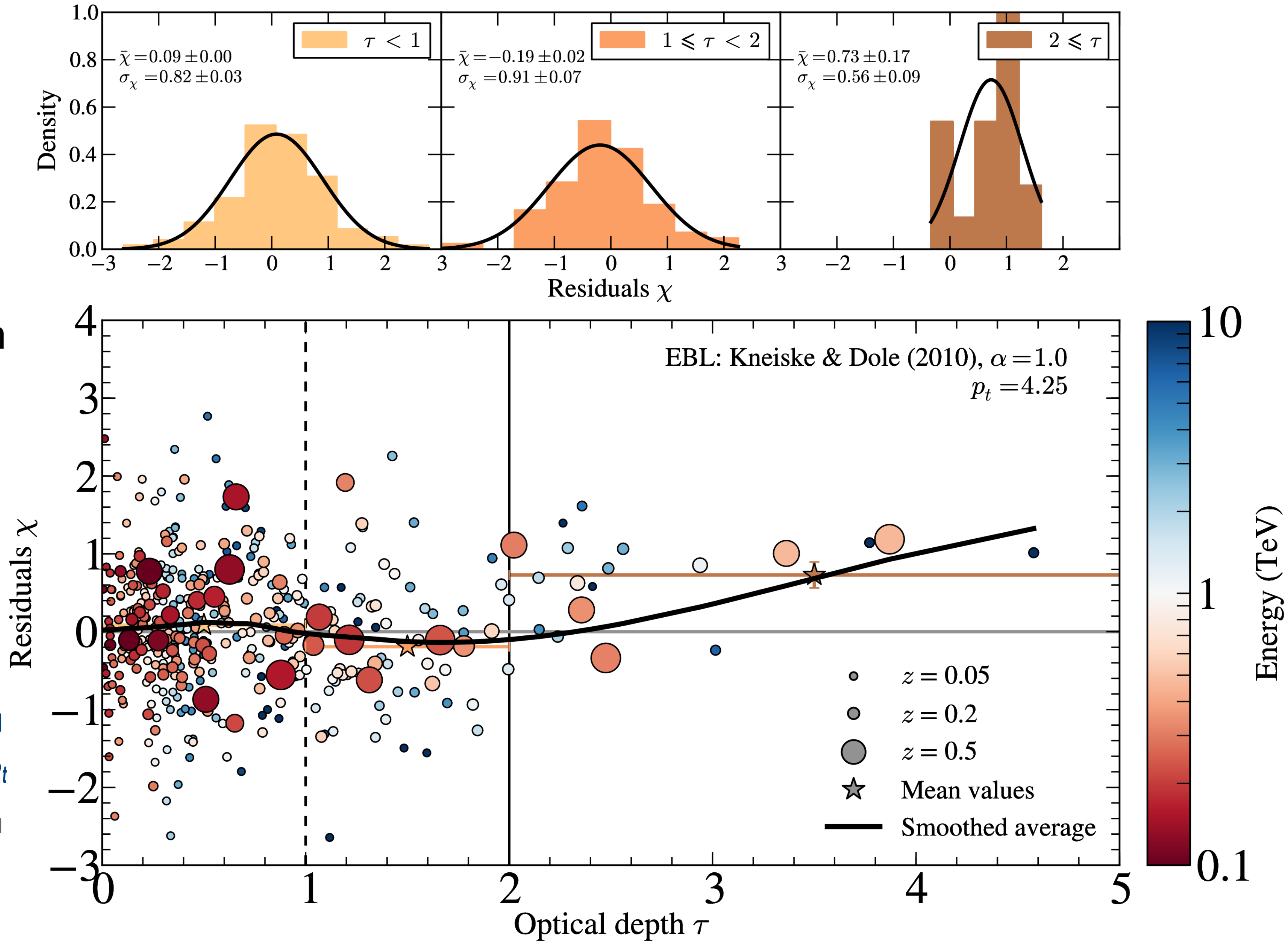
- Investigate *all* VHE spectra in **optical thick regime** (i.e., $\tau_{\gamma\gamma} \geq 2$)
- Use EBL model from Kneiske & Dole, 2010 (KD): predicts **minimal attenuation at TeV energies**



[Horns & **MM**, 2012]

Indication for pair-production anomaly

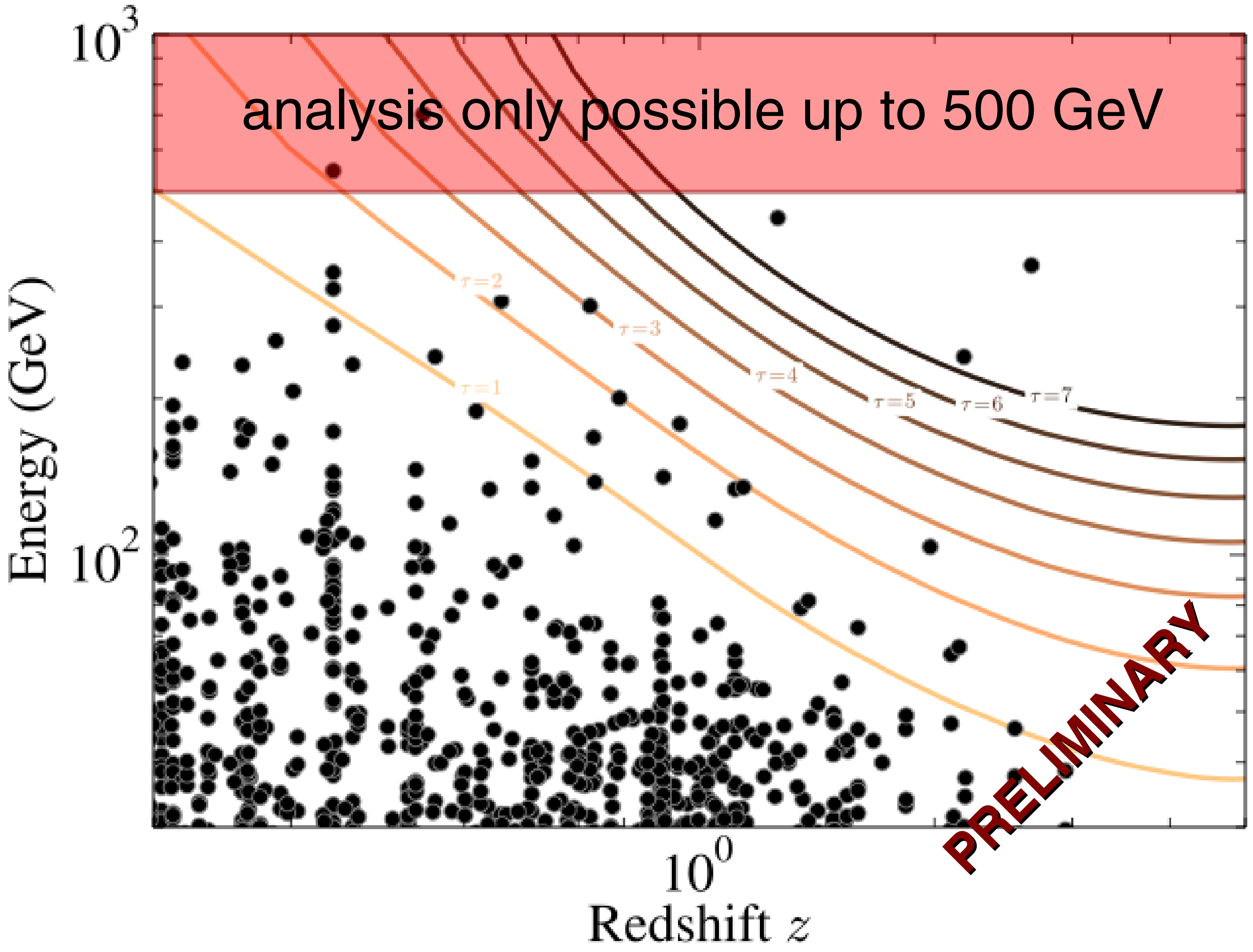
- Fit function to **absorption corrected spectra**
- Calculate **residuals** $\chi_i = (F_{meas,i} - F_{theo}(E_i)) / \sigma_i$
- **Expectation: mean of residuals $\langle \chi \rangle = 0$,** test with Student's t test
- Result: **p_t=4.3σ indication for overcorrection for τ > 2**
- Systematics: **energy calibration and resolution** strongest effect (**reduces p_t to 2σ**, however, no indication in mock data sample, energy cross calibration of the order of 5%; Meyer et al. 2010)



[Horns & **MM**, 2012]

Search for low opacity in *Fermi*-LAT data

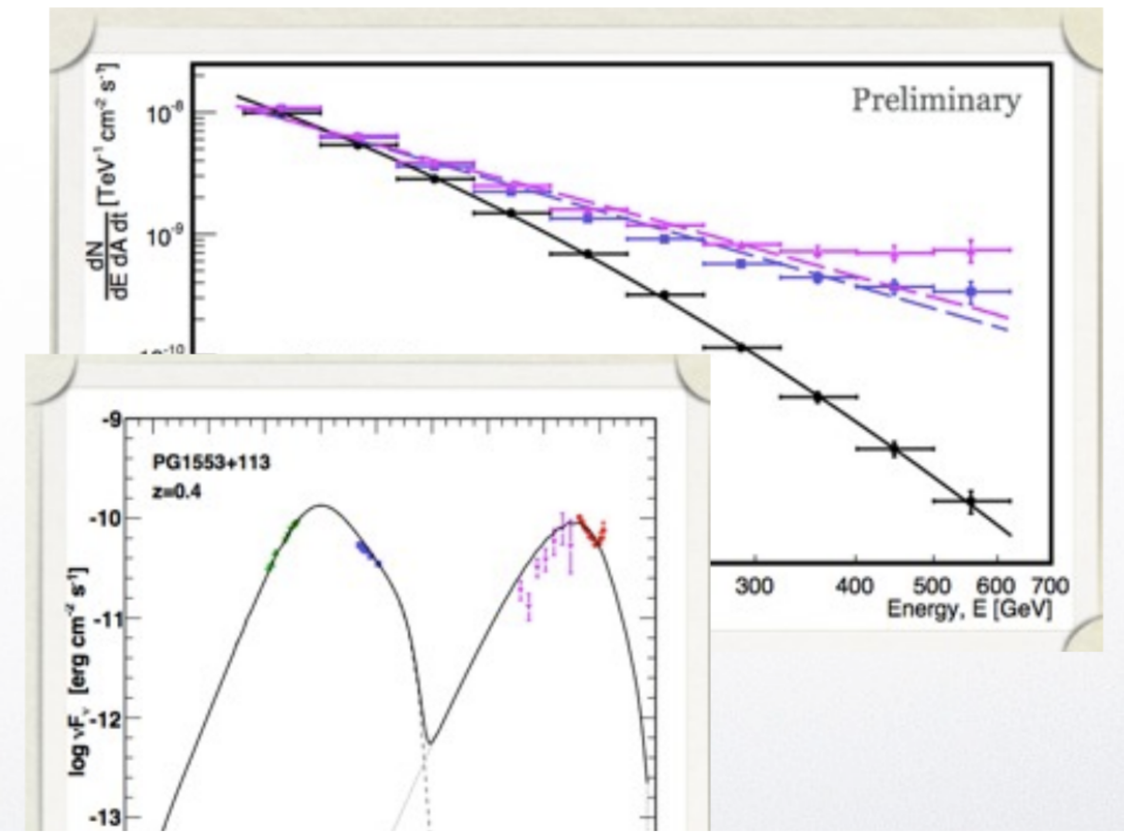
- **Associate photons with AGN** (listed in 2FGL, known redshift)
- For each photon, **calculate optical depth**
- From intrinsic spectrum: **calculate probability to observe detected photons**
- **Combining results from all sources** and correct for trials
- **Preliminary** results for *Pass 7*:
  - $P_{\text{post-trial}}(\tau_{\gamma\gamma} \geq 1) = 0.06$
  - $P_{\text{post-trial}}(\tau_{\gamma\gamma} \geq 2) = 1.2 \times 10^{-4}$
- Redo analysis with ***Pass 7 reprocessed*** and ***Pass 8***



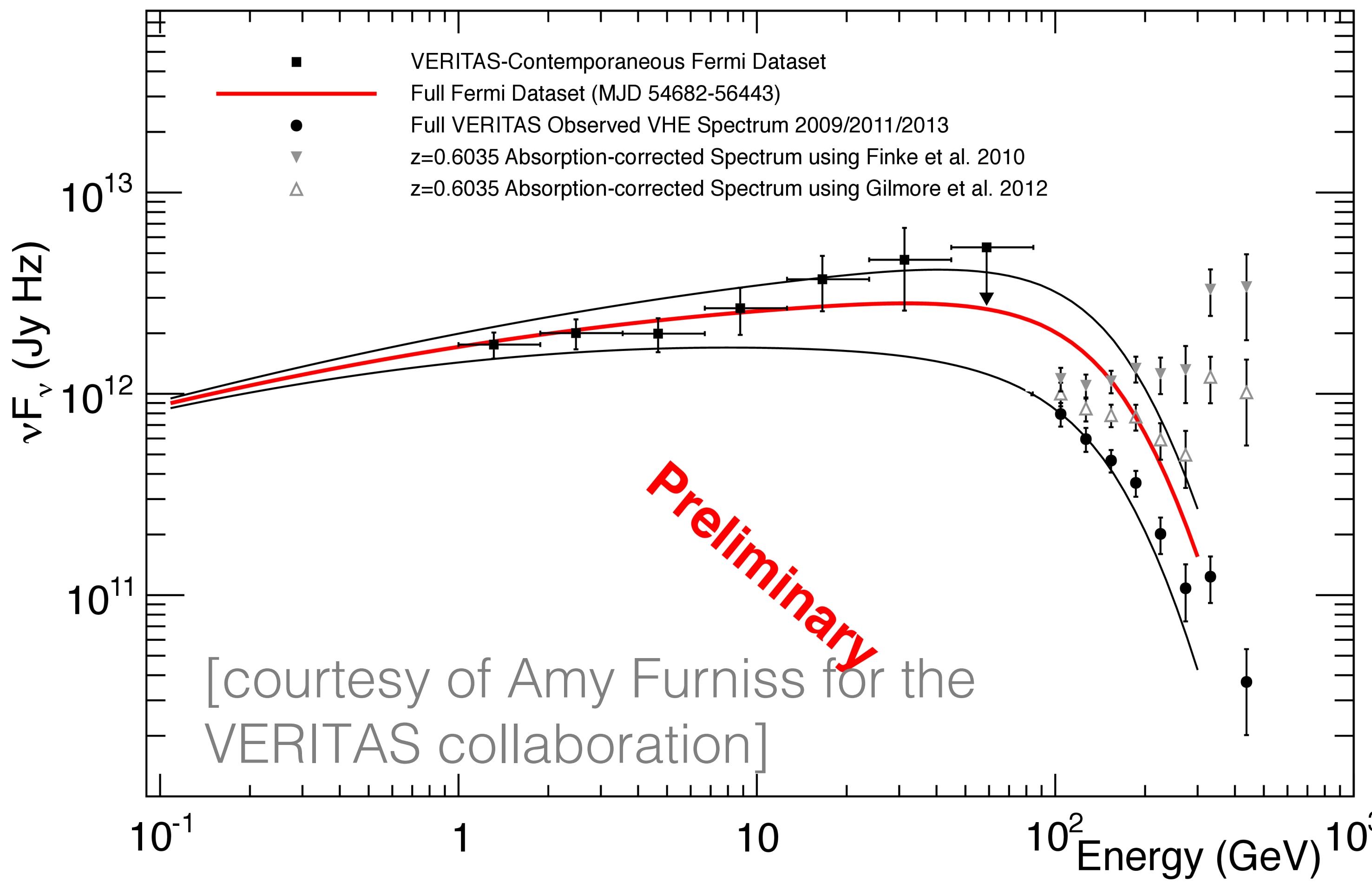
[Horns and MM 2013, see also MM, PhD thesis 2013 – Disclaimer: analysis conducted ***before*** joining the *Fermi* -LAT collaboration]

Observation of sources with $\tau > 4$

Pepa Becerra et al., MAGIC
PG1553+113,z>0.4

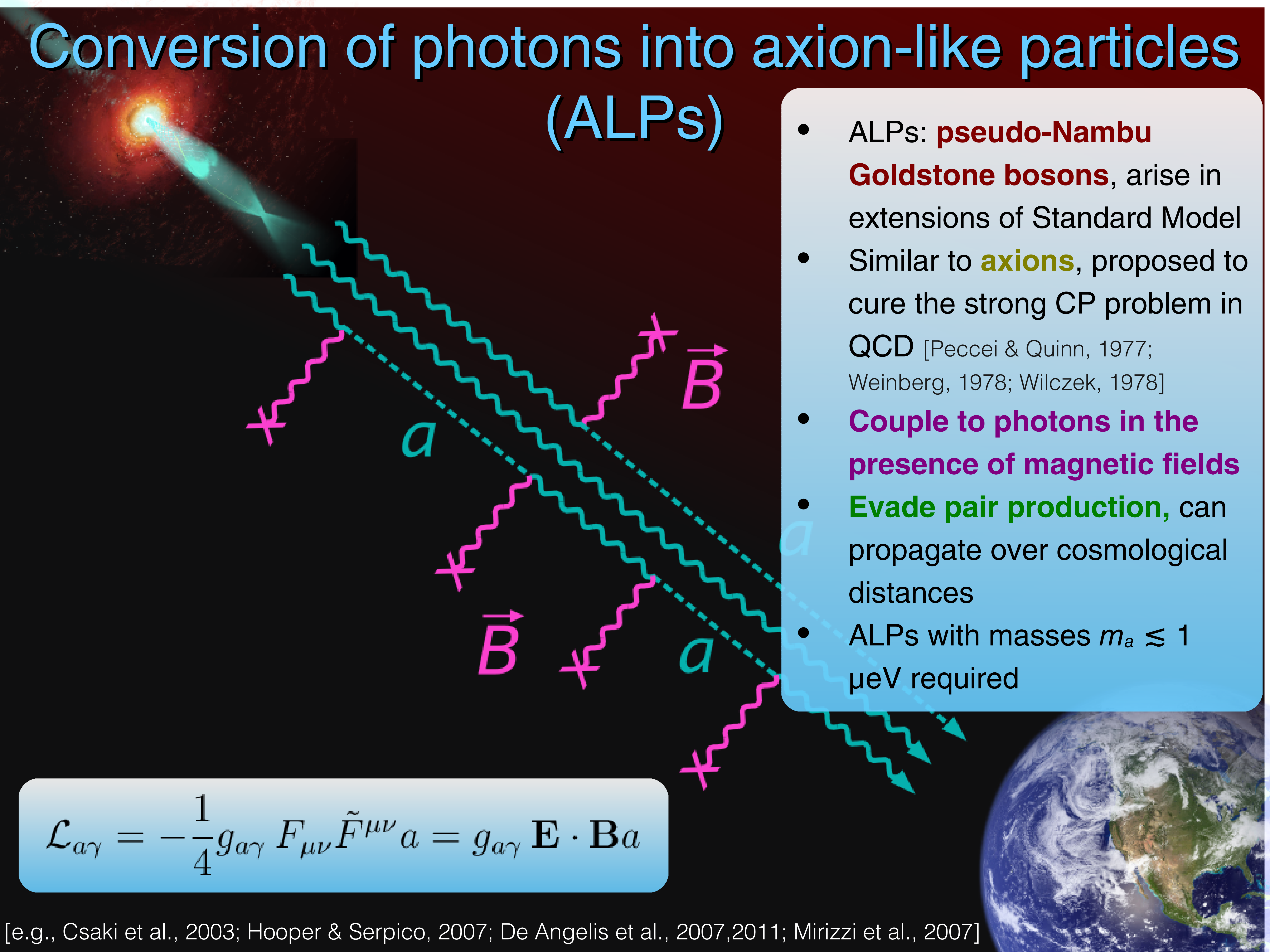


Gamma-ray SED Peak



- Recent observations of sources correspond to **high optical depth**
- **Spectral hardening** towards highest energies
- **PG 1553+113: z > 0.4** [Danforth et al., 2010]
- **PKS 1424+240, z > 0.6035** [Furniss et al., 2013]

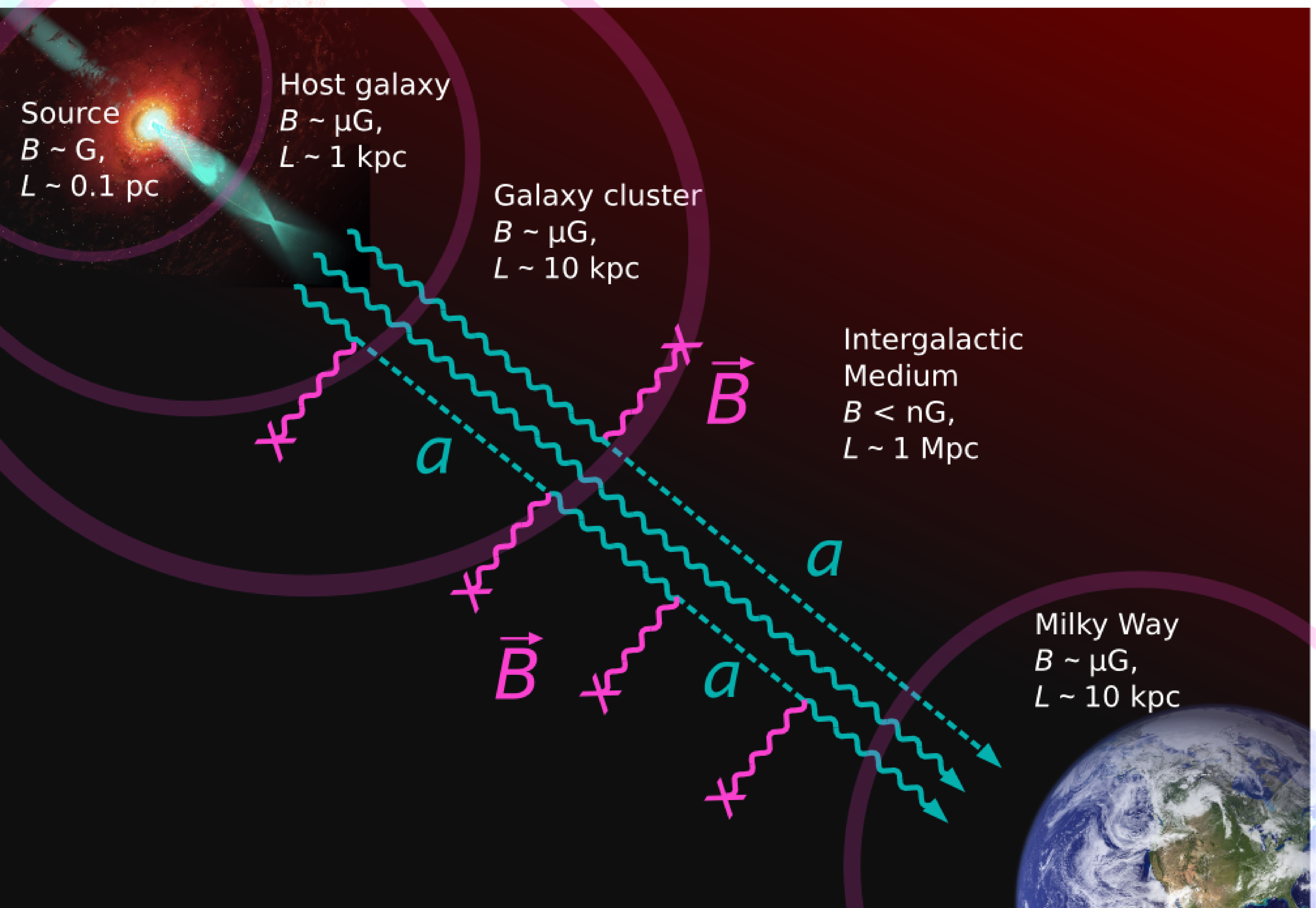
Conversion of photons into axion-like particles (ALPs)



- ALPs: **pseudo-Nambu Goldstone bosons**, arise in extensions of Standard Model
- Similar to **axions**, proposed to cure the strong CP problem in QCD [Peccei & Quinn, 1977; Weinberg, 1978; Wilczek, 1978]
- **Couple to photons in the presence of magnetic fields**
- **Evade pair production,** can propagate over cosmological distances
- ALPs with masses $m_a \lesssim 1$ μeV required

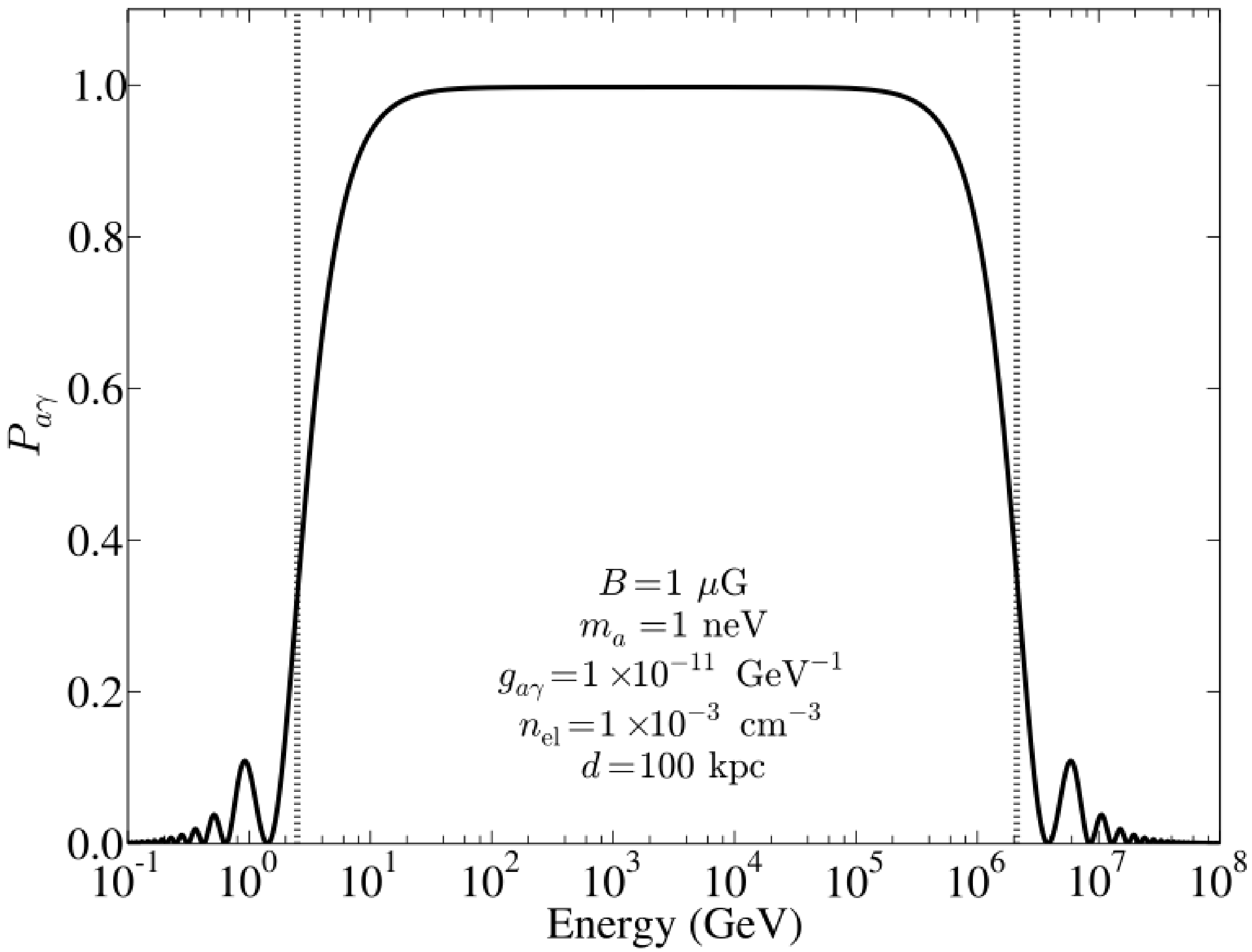
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma}\, F_{\mu\nu}\tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$$

[e.g., Csaki et al., 2003; Hooper & Serpico, 2007; De Angelis et al., 2007,2011; Mirizzi et al., 2007]



[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 mixing in coherent B field



- Mixing becomes maximal (**strong mixing regime**) above **critical energy E_{crit}**
- Above a maximum energy, **QED effects suppress mixing**

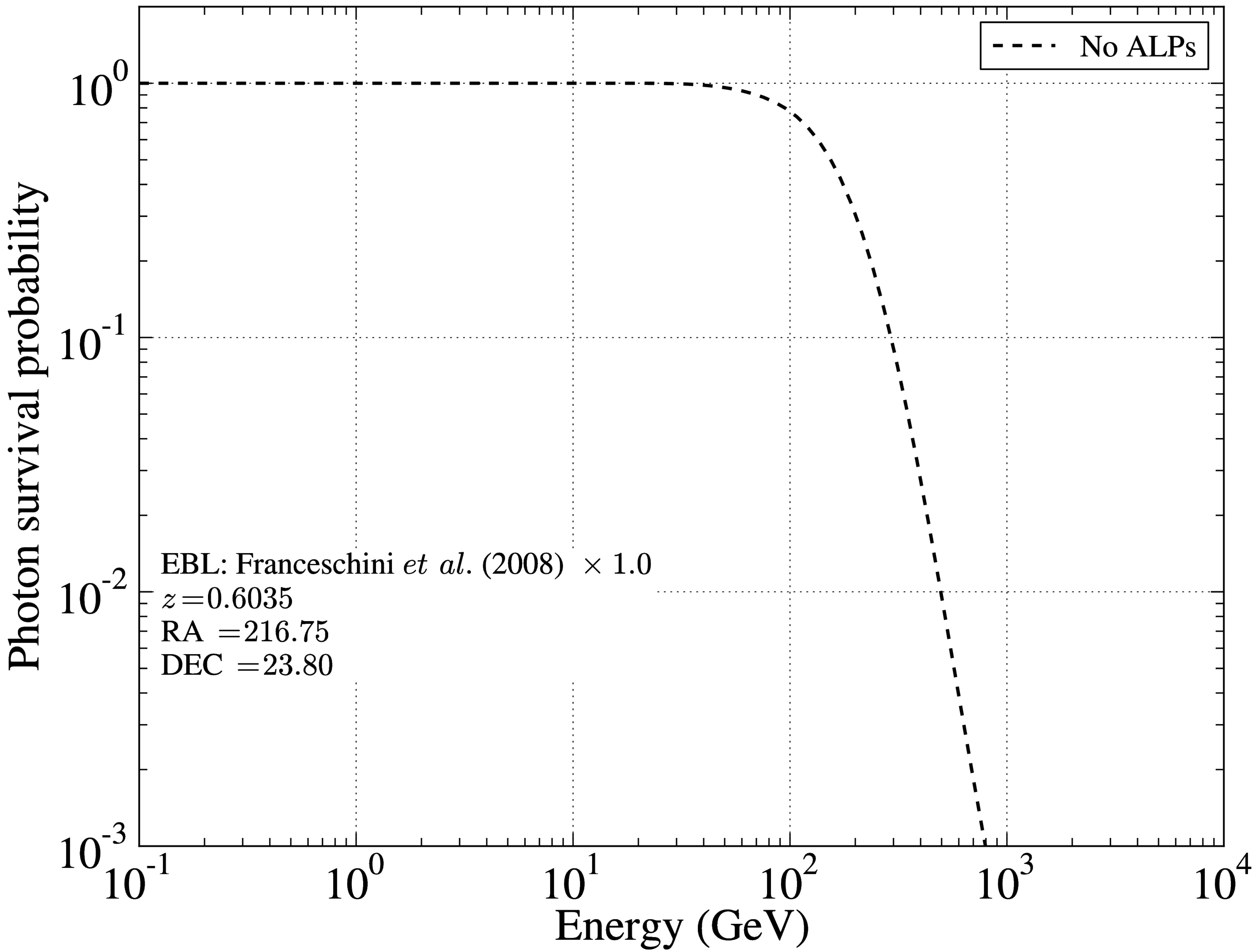
$$P_{a\gamma} = (\Delta_{a\gamma} d)^2 \frac{\sin^2(\Delta_{\rm osc} d/2)}{(\Delta_{\rm osc} d/2)^2}$$

$$\frac{E_{\rm crit}}{\rm GeV} = 2.5 \frac{|m_a^2 - \omega_{\rm pl}^2|}{\rm neV} \left(\frac{g_{a\gamma}}{10^{-11}\rm GeV^{-1}}\right)^{-1} \left(\frac{B_\perp}{\mu \rm G}\right)^{-1}$$

Δ terms are combinations of parameters B, m_a, $g_{a\gamma}$, n_{el}, and energy

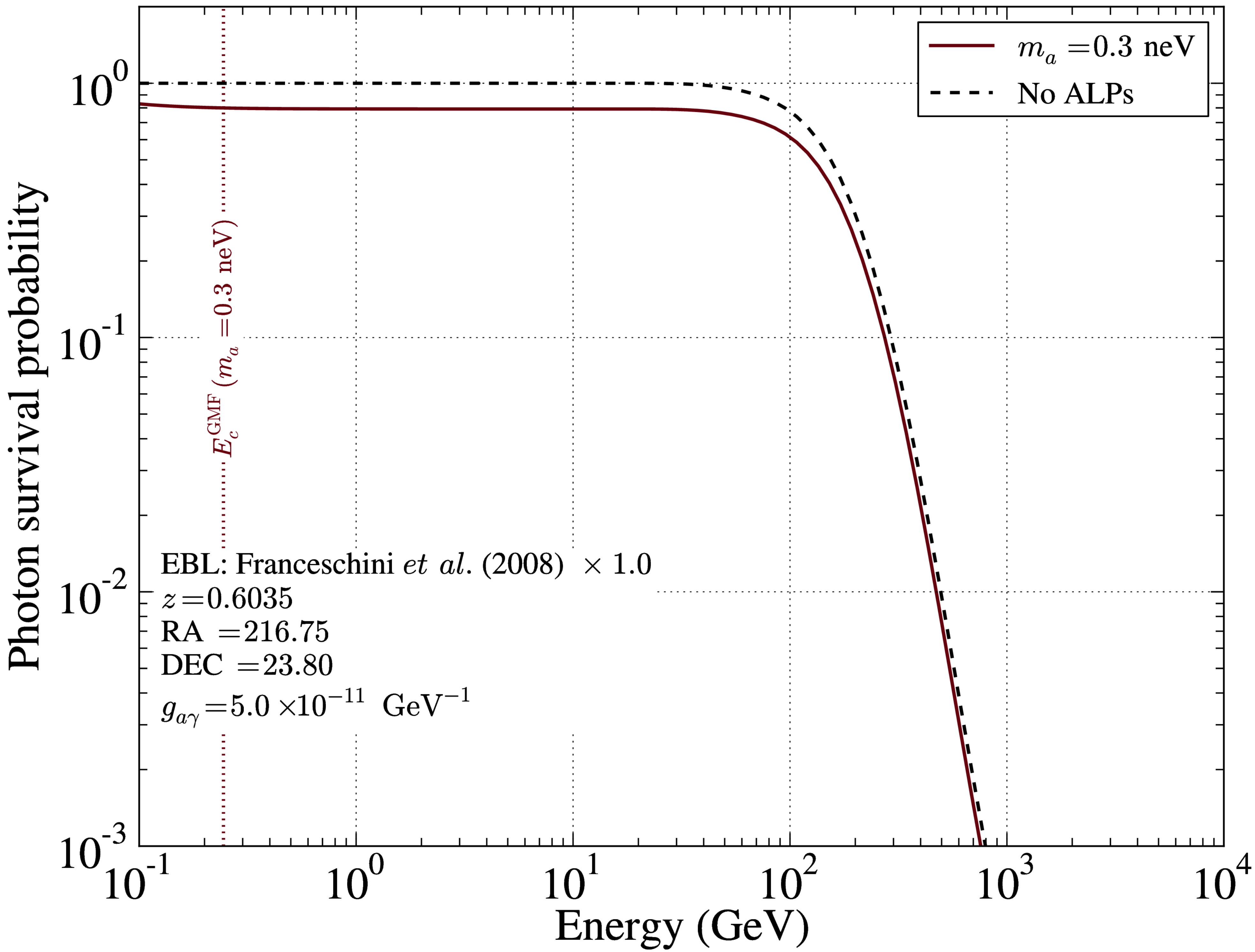
[e.g., Raffelt & Stodolsky 1988; Csaki et al., 2003; Hooper & Serpico 2007; De Angelis et al., 2007,2011; Mirizzi et al., 2007; Bassan & Roncadelli 2009]

Influence of ALP mixing on ɣ-ray attenuation



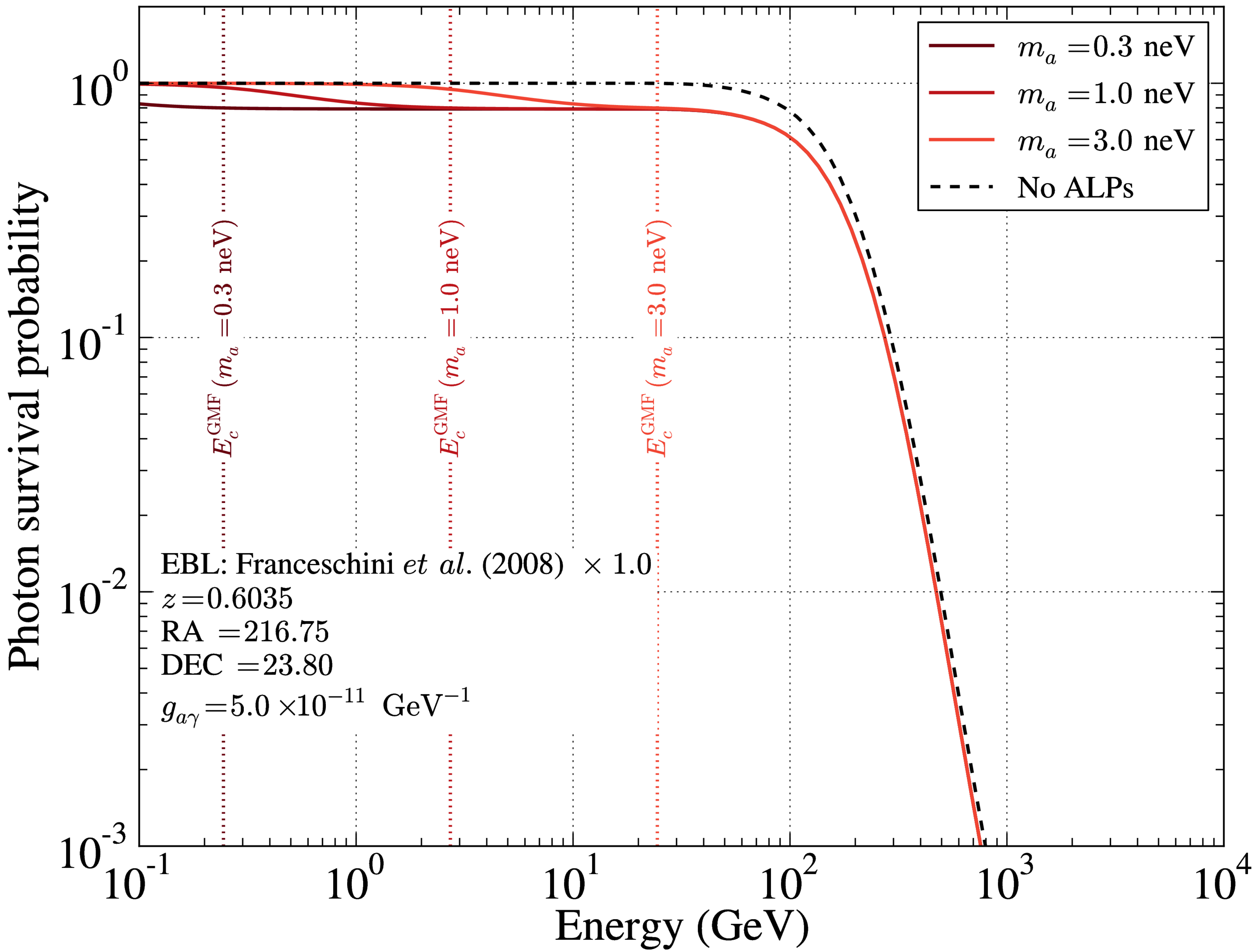
- **No mixing** with ALPs
- Source position coincident with **PKS 1424+240** (with lower limit on redshift)

Influence of ALP mixing on ɣ-ray attenuation



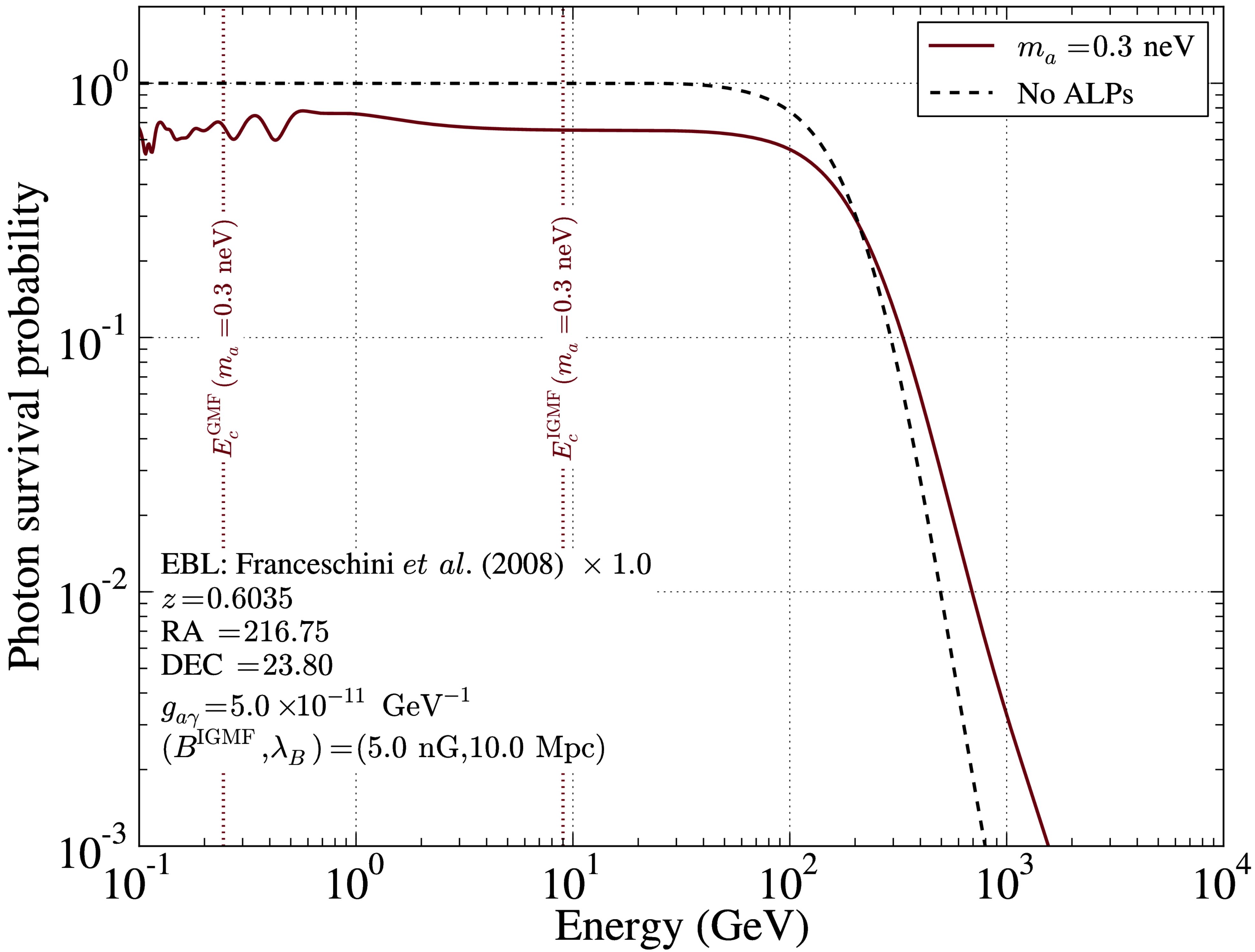
- Unpolarized **pure photon beam** entering the **Galactic magnetic field**
- GMF model: Jansson & Farrar, 2012

Influence of ALP mixing on ɣ-ray attenuation



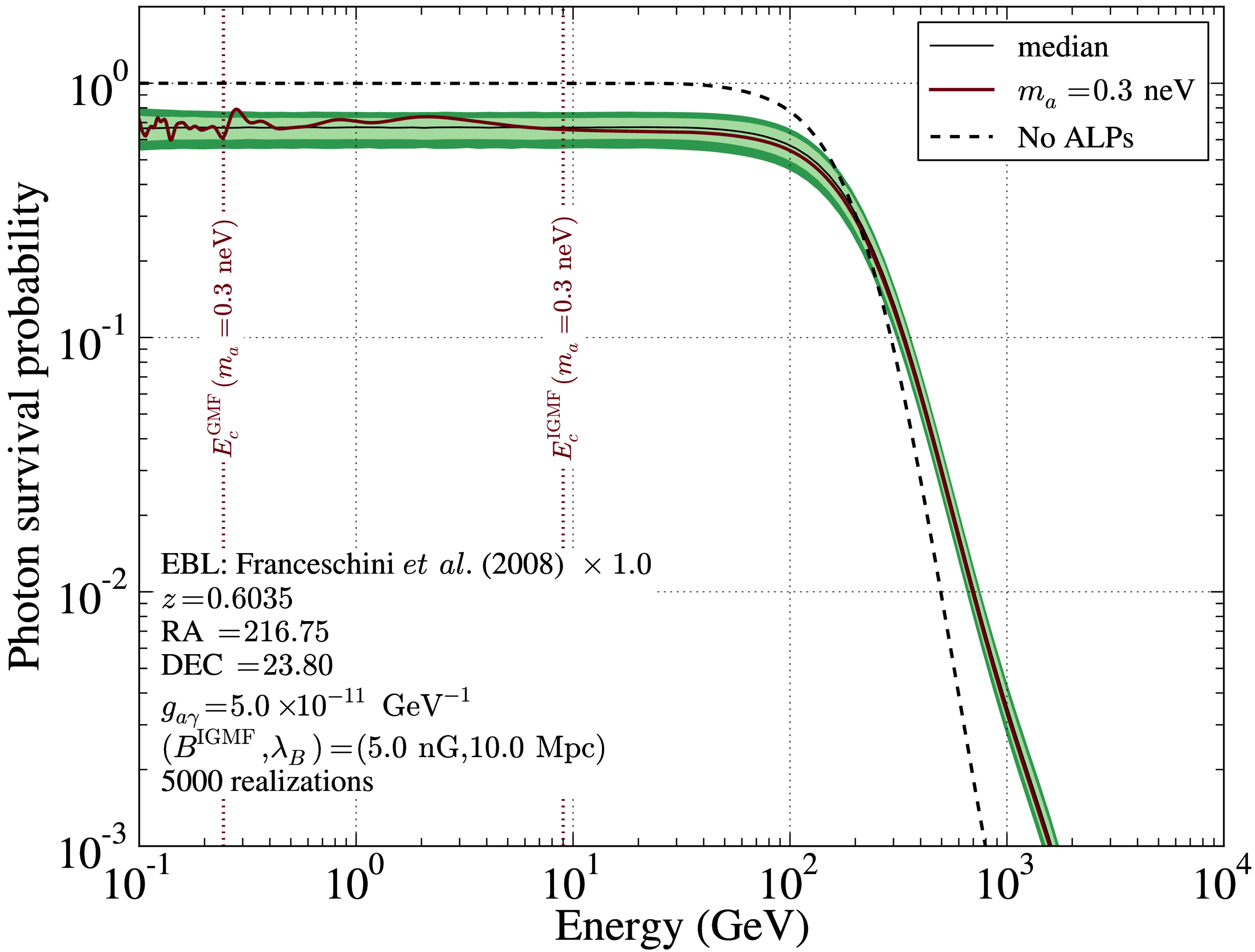
- Different **ALP masses** give different **critical energies**

Influence of ALP mixing on ɣ-ray attenuation



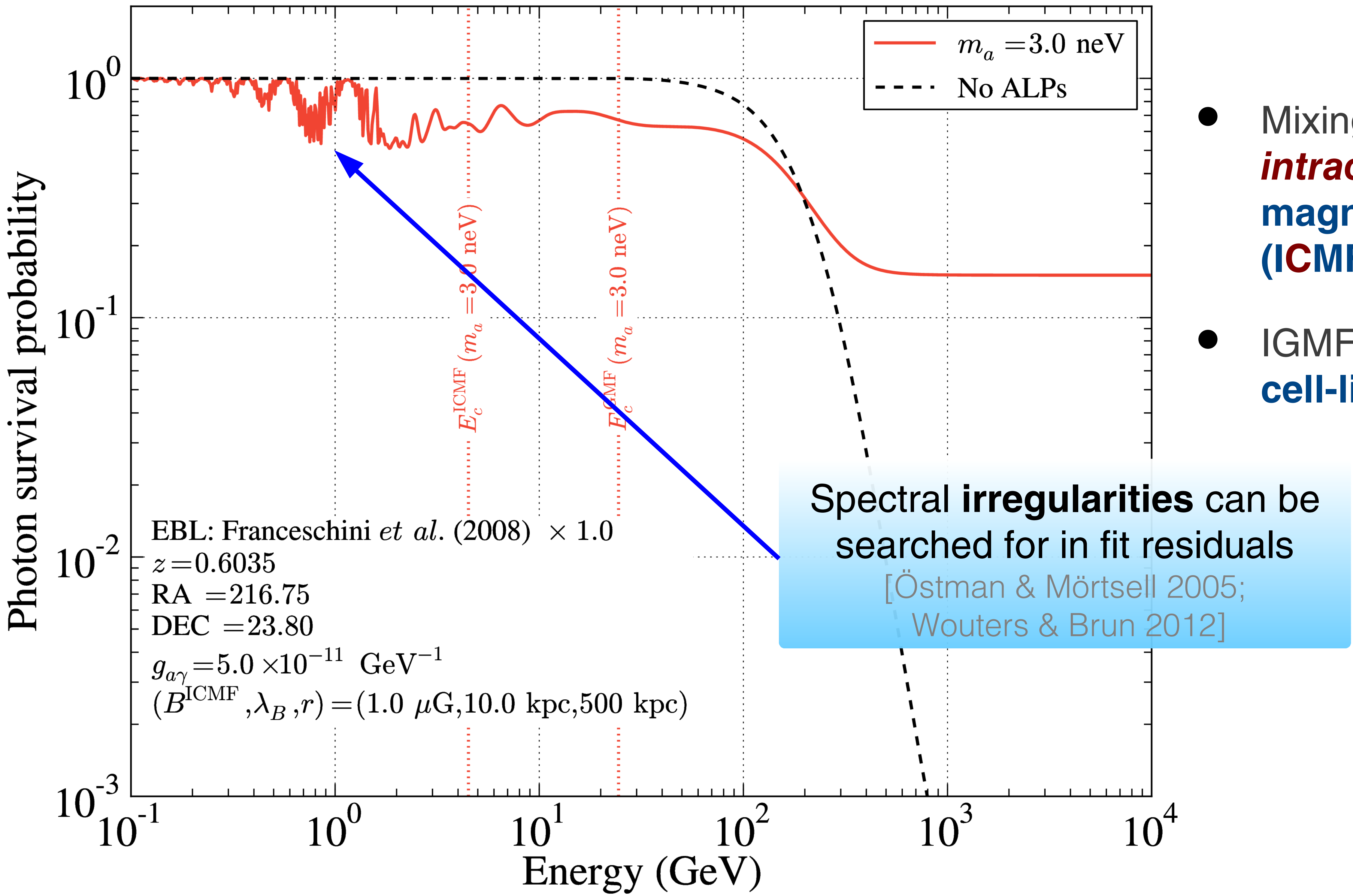
- Mixing in random **intergalactic magnetic field (IGMF)**
- IGMF morphology: **cell-like structure**

Influence of ALP mixing on ɣ-ray attenuation



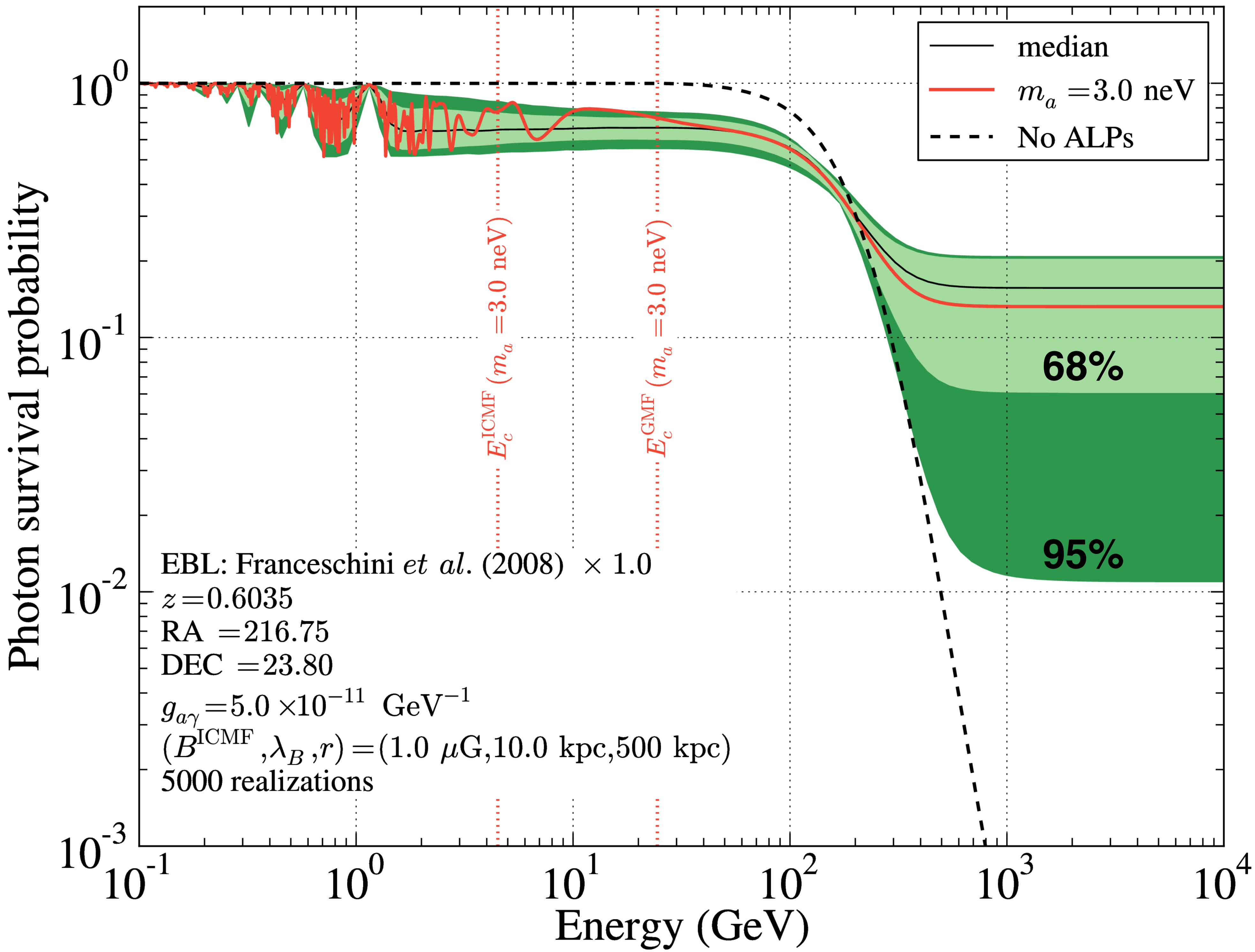
- Mixing in random **intergalactic magnetic field (IGMF)**
- IGMF morphology: **cell-like structure**

Influence of ALP mixing on ɣ-ray attenuation



- Mixing in random ***intracluster* magnetic field (ICMF) & GMF**
- IGMF morphology: **cell-like structure**

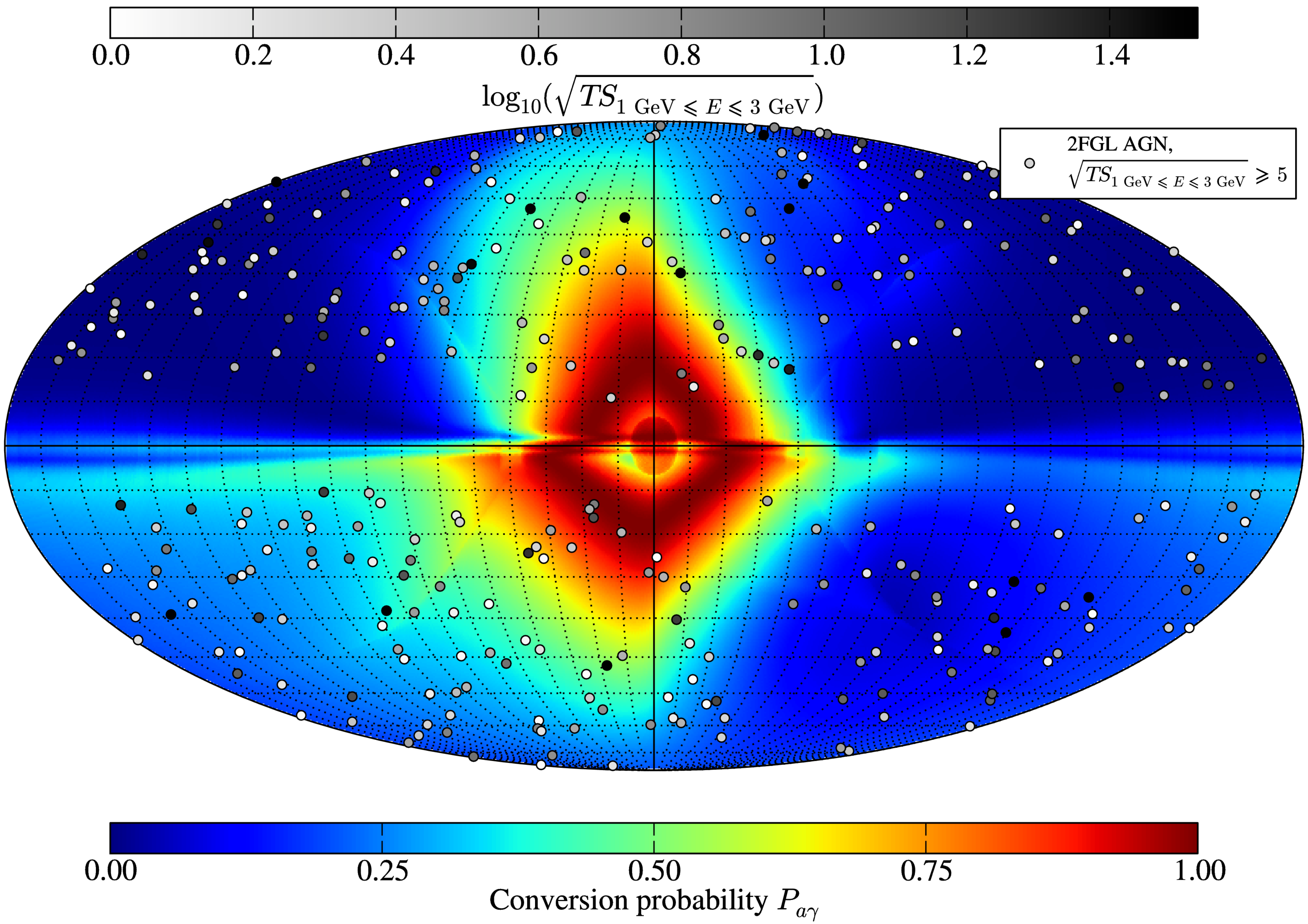
Influence of ALP mixing on ɣ-ray attenuation



- Mixing in random ***intracluster* magnetic field (ICMF) & GMF**
- IGMF morphology: **cell-like structure**

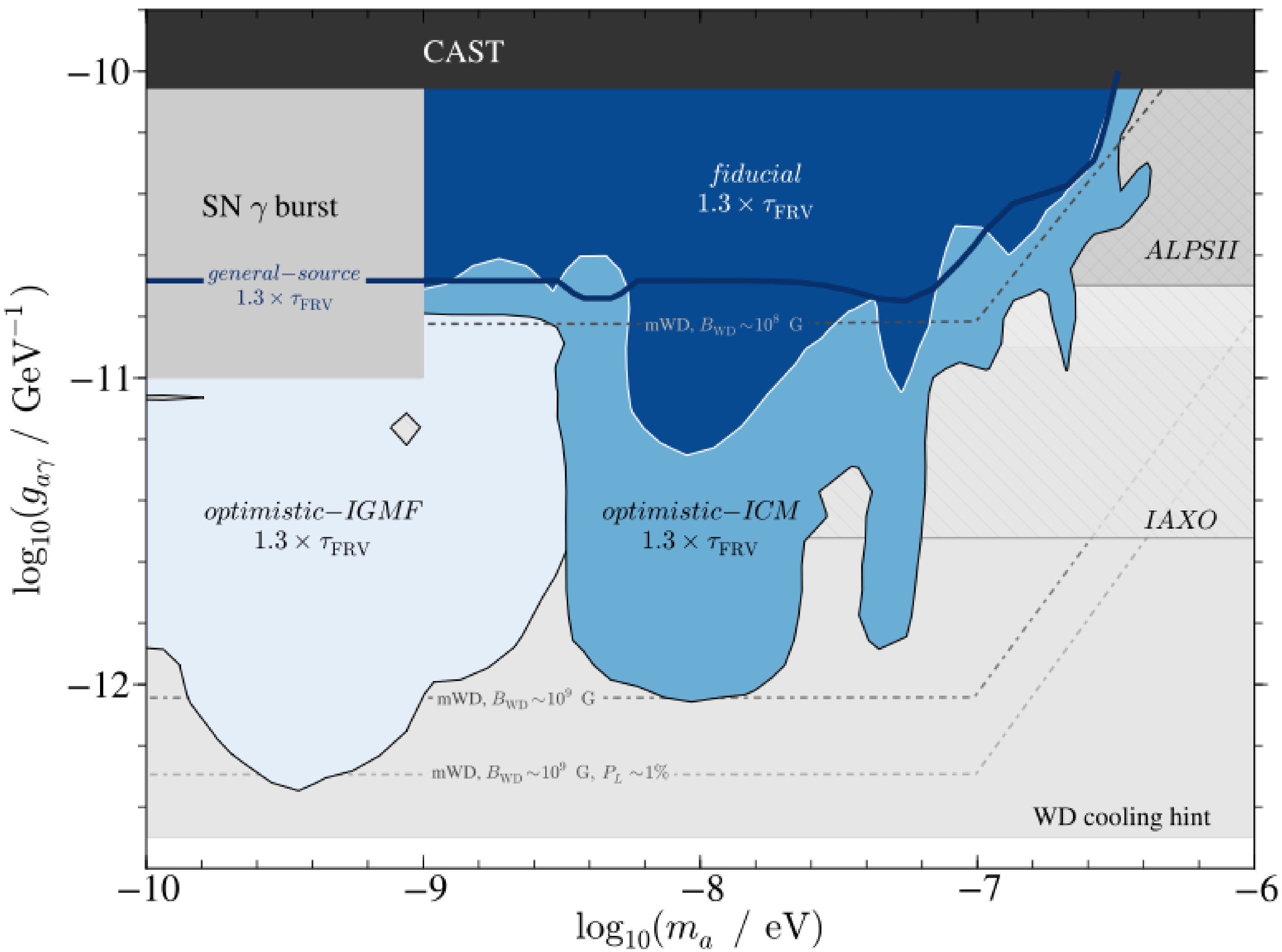
Conversion in Galactic magnetic field

pure ALP beam in strong mixing regime, with ALP mass m_a = 1 neV
GMF model (regular component) by Jansson & Farrar, (2012)



[Horns, Maccione, **MM**, Mirizzi, Roncadelli, 2012]

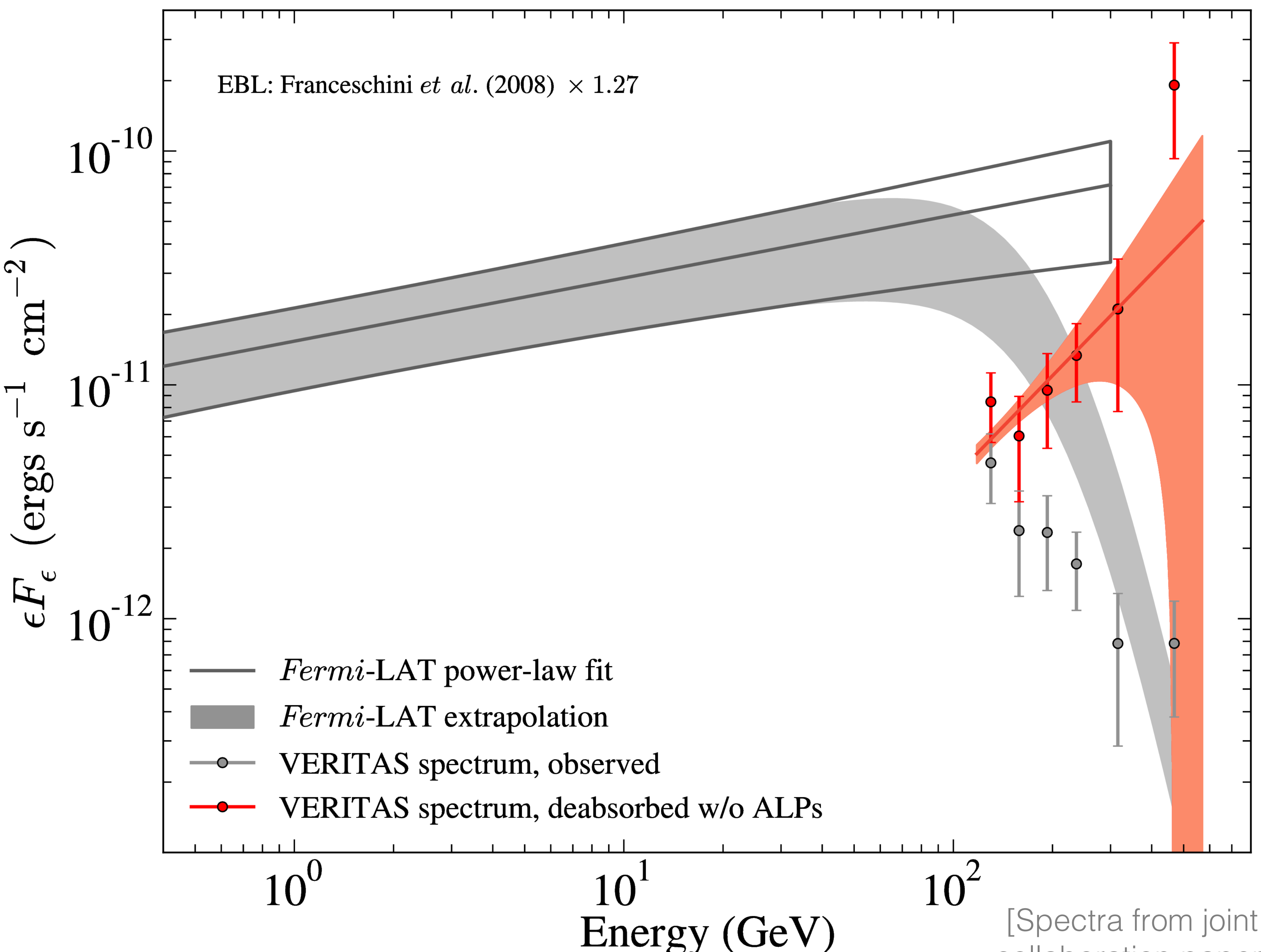
Coupling $g_{a\gamma}$ to explain opacity hint



- **Lower limits** on couplings to **explain reduced opacity** close to **upper imits from CAST** experiment [Andriamonje et al., 2007]
- In reach of **future dedicated ALP searches** such as ALPS II and IAXO
- Reach into region to **explain white dwarf cooling hint** [Isern et al., 2008]

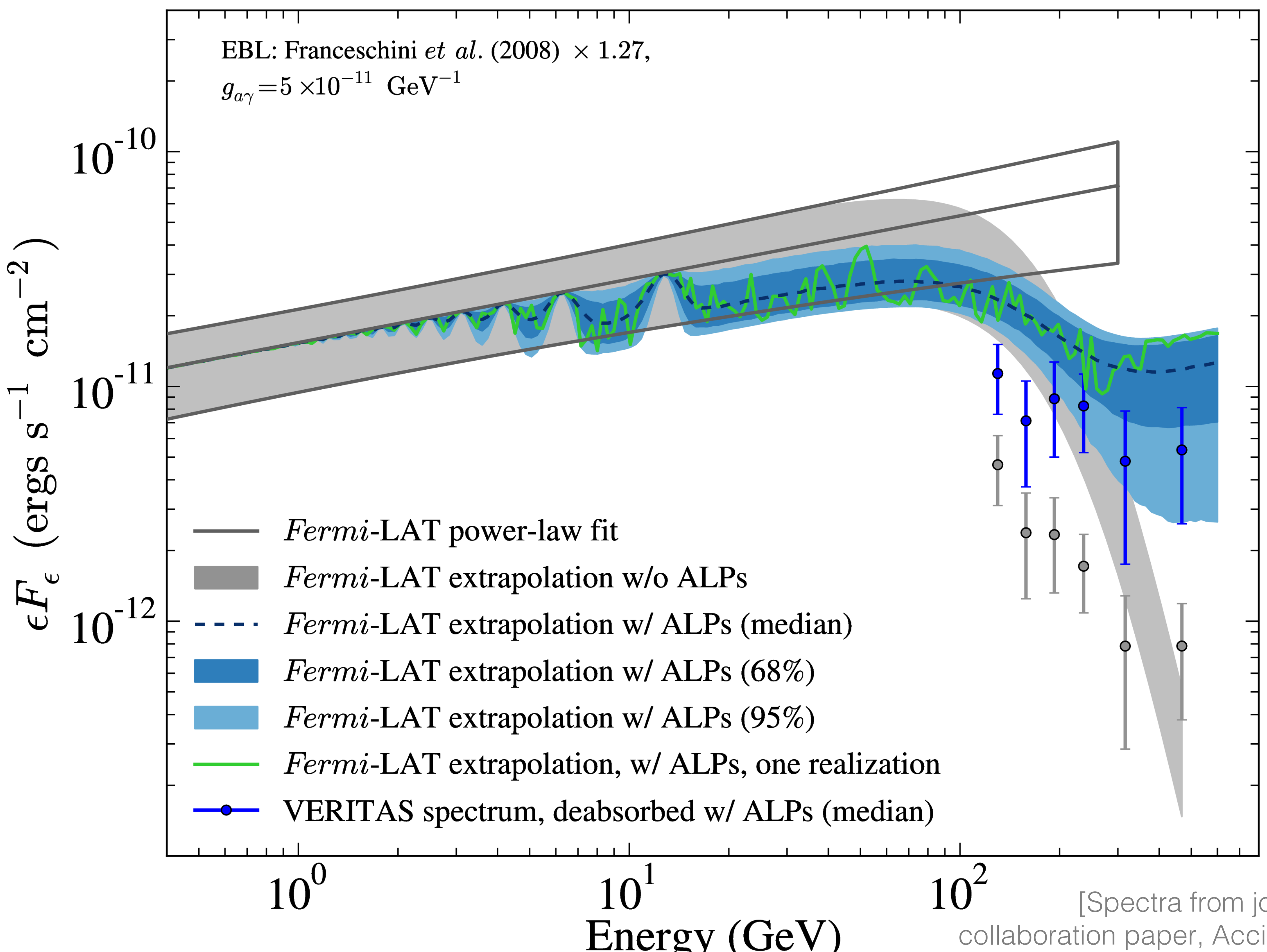
[**MM**, Horns, Raue 2013]

A closer look on PKS 1424+240



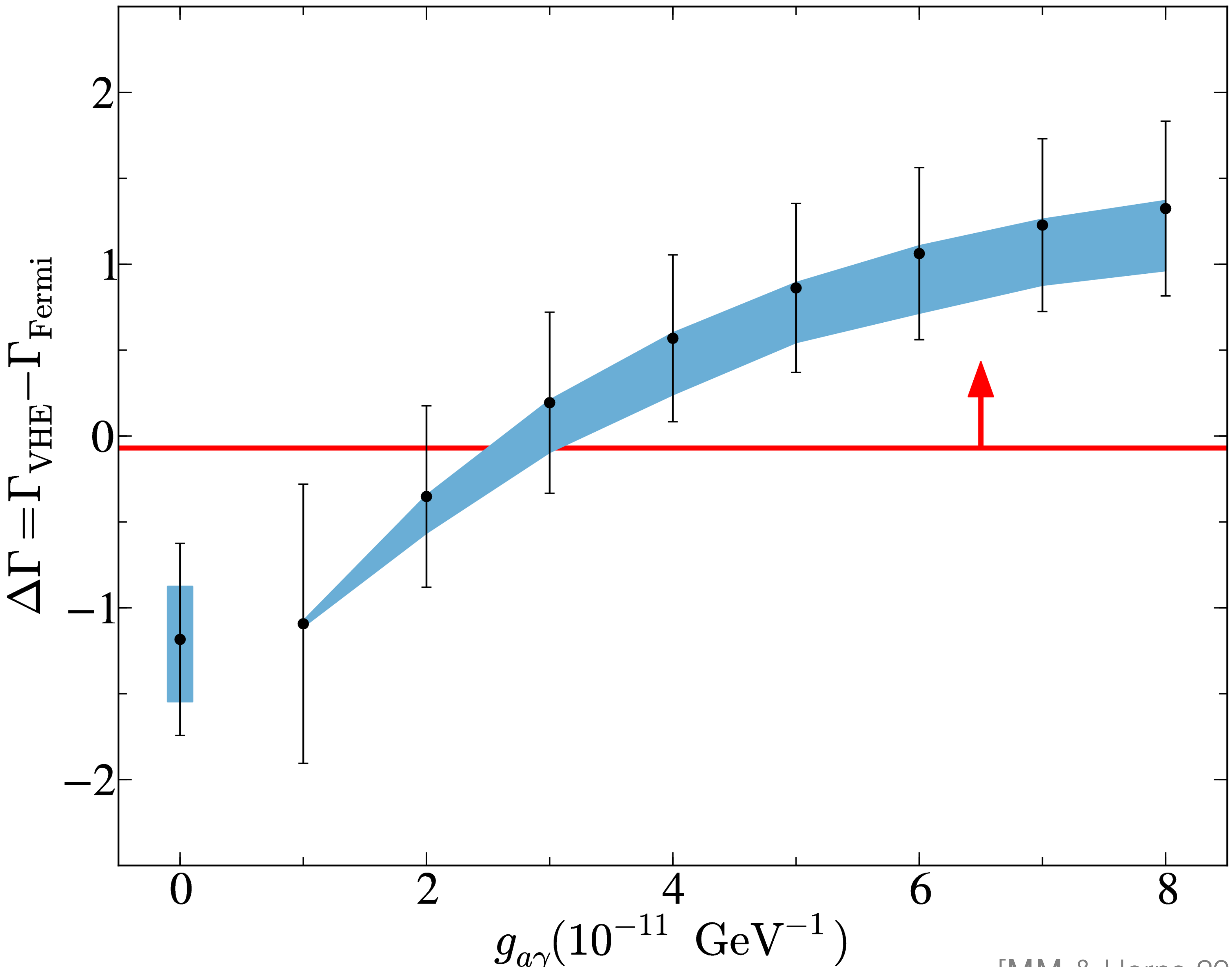
[Spectra from joint Fermi and VERITAS collaboration paper, Acciari et al. 2010]

A closer look on PKS 1424+240



[Spectra from joint Fermi and VERITAS collaboration paper, Acciari et al. 2010, see also **MM** & Horns 2013, and Domínguez et al., 2011]

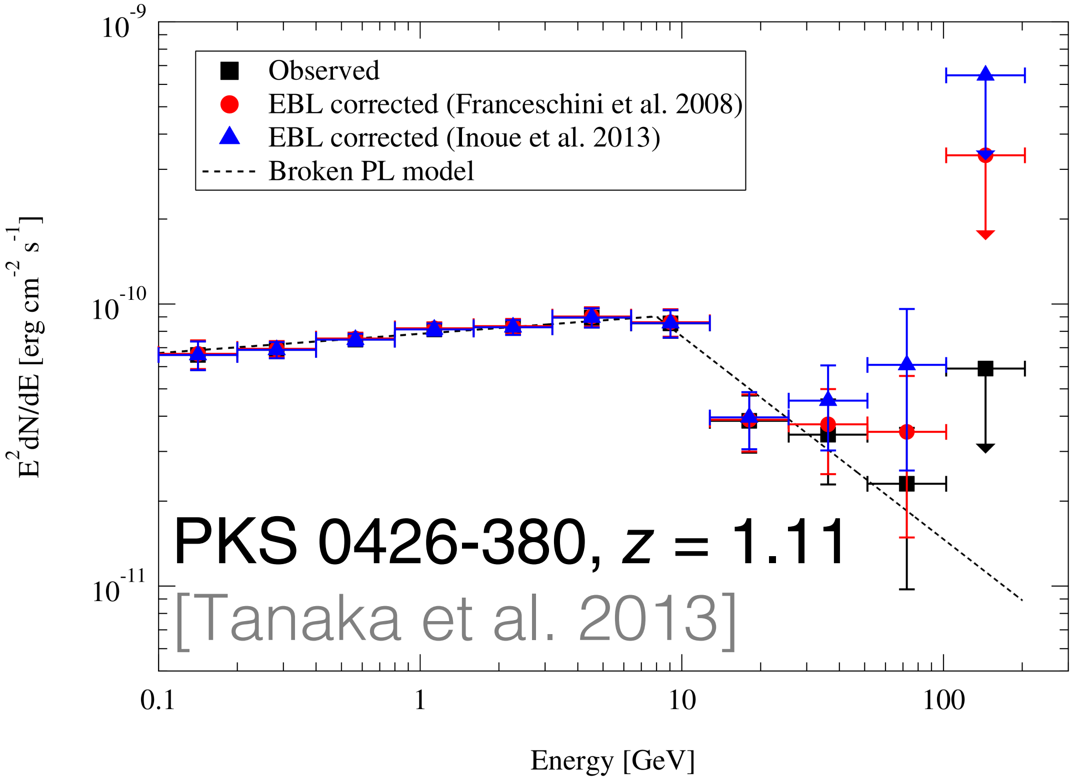
A closer look on PKS 1424+240

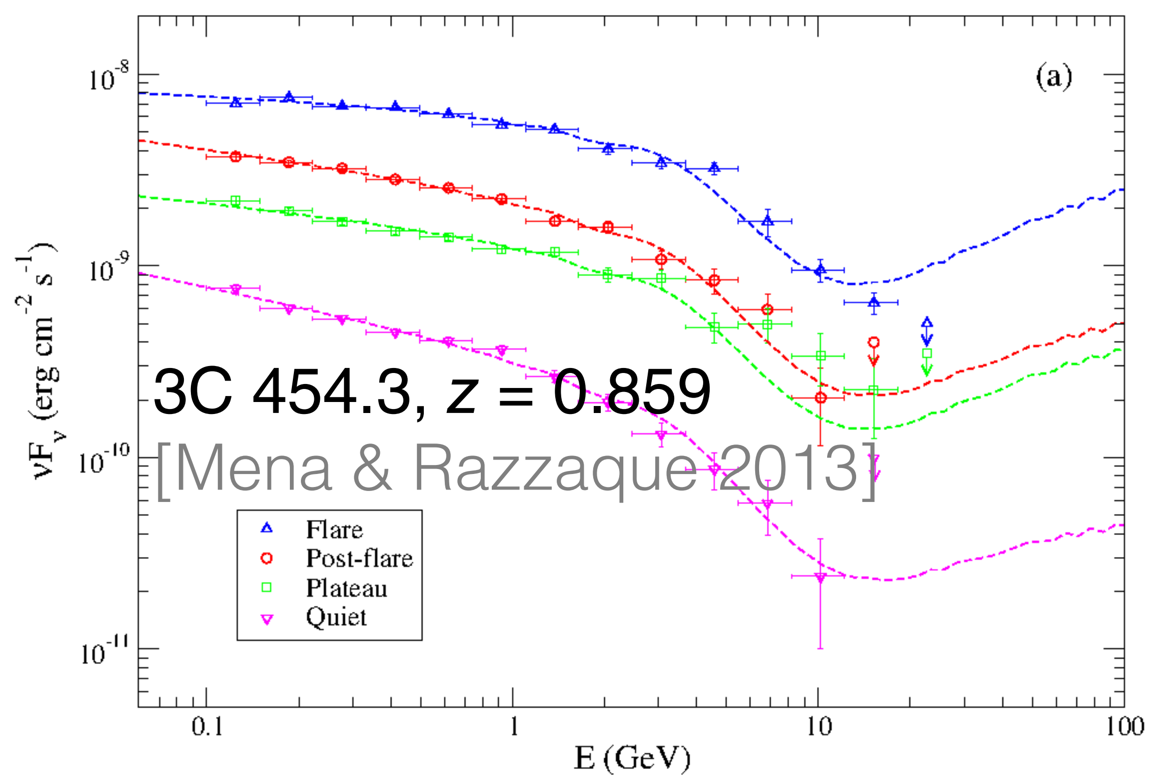


[MM & Horns 2013, arXiv:1310.2058]

Steps in spectra observed?

- **„Step" feature observed** in blazars with Fermi-LAT
- Explanations: absorption of gamma-rays in BLR? [Stern & Poutanen, 2011]
- Or: **Conversion into ALPs**? [Mena & Razzaque, 2013]





Conclusions

- **Indications for a reduced opacity** have been found in IACT and *Fermi*-LAT spectra (**preliminary!**) of blazars at a **~4σ confidence level** *and* growing **number of sources observed at high optical depths**

- **Spectral features** observed with *Fermi*-LAT

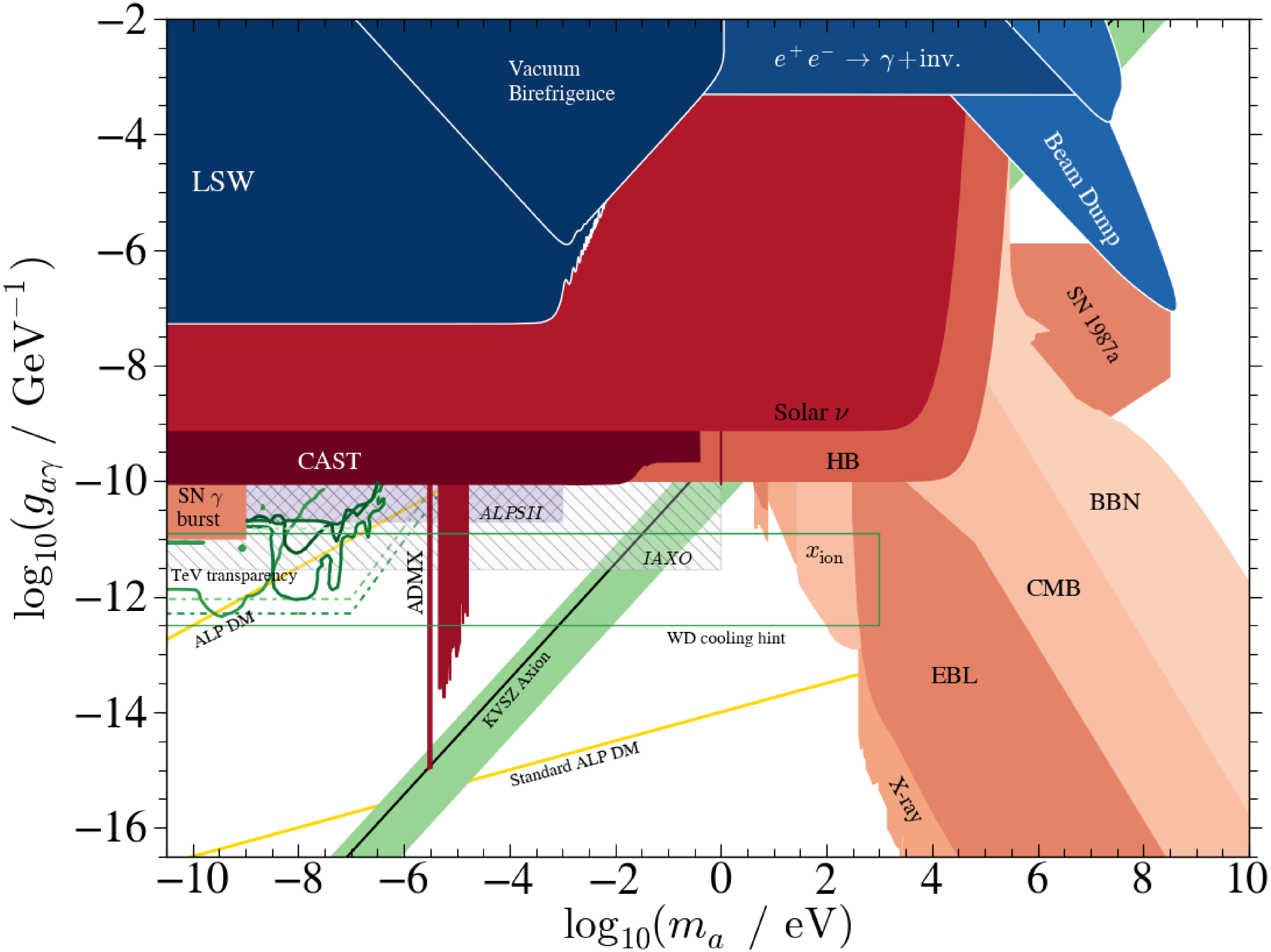
- **H.E.S.S. Phase II:**

  - Identify **promising sources at high redhshift** (e.g. PKS 0426-380 in flaring state), **GRBs**

  - **Increased energy range: lever arm for intrinsic blazar spectrum**

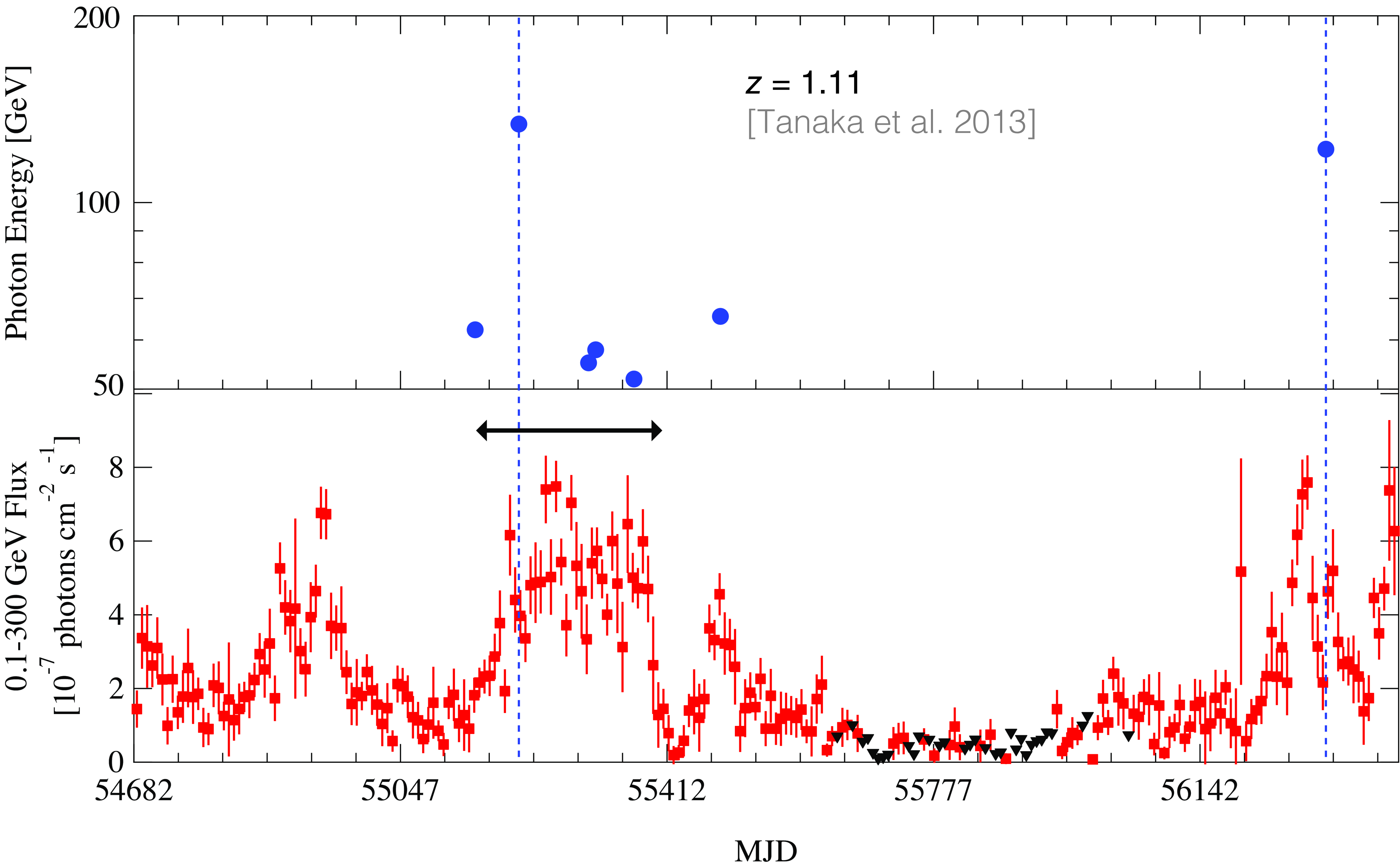
  - **high S/N observations** to search for **spectral features** (step near critical energy, irregularities) – also **galactic sources**!

ALP parameter space



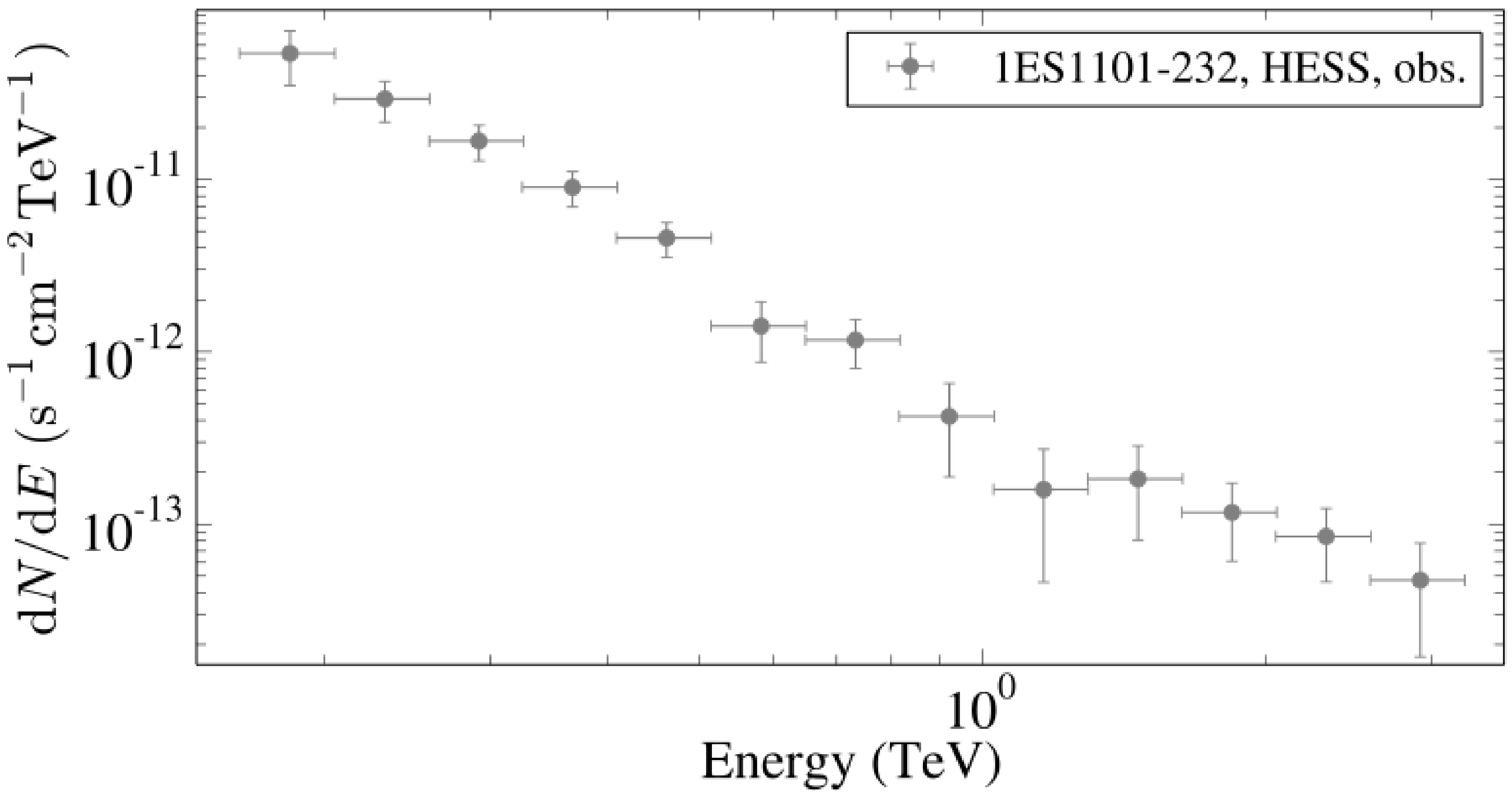
Backup slides

Light curve of PKS 0426-380



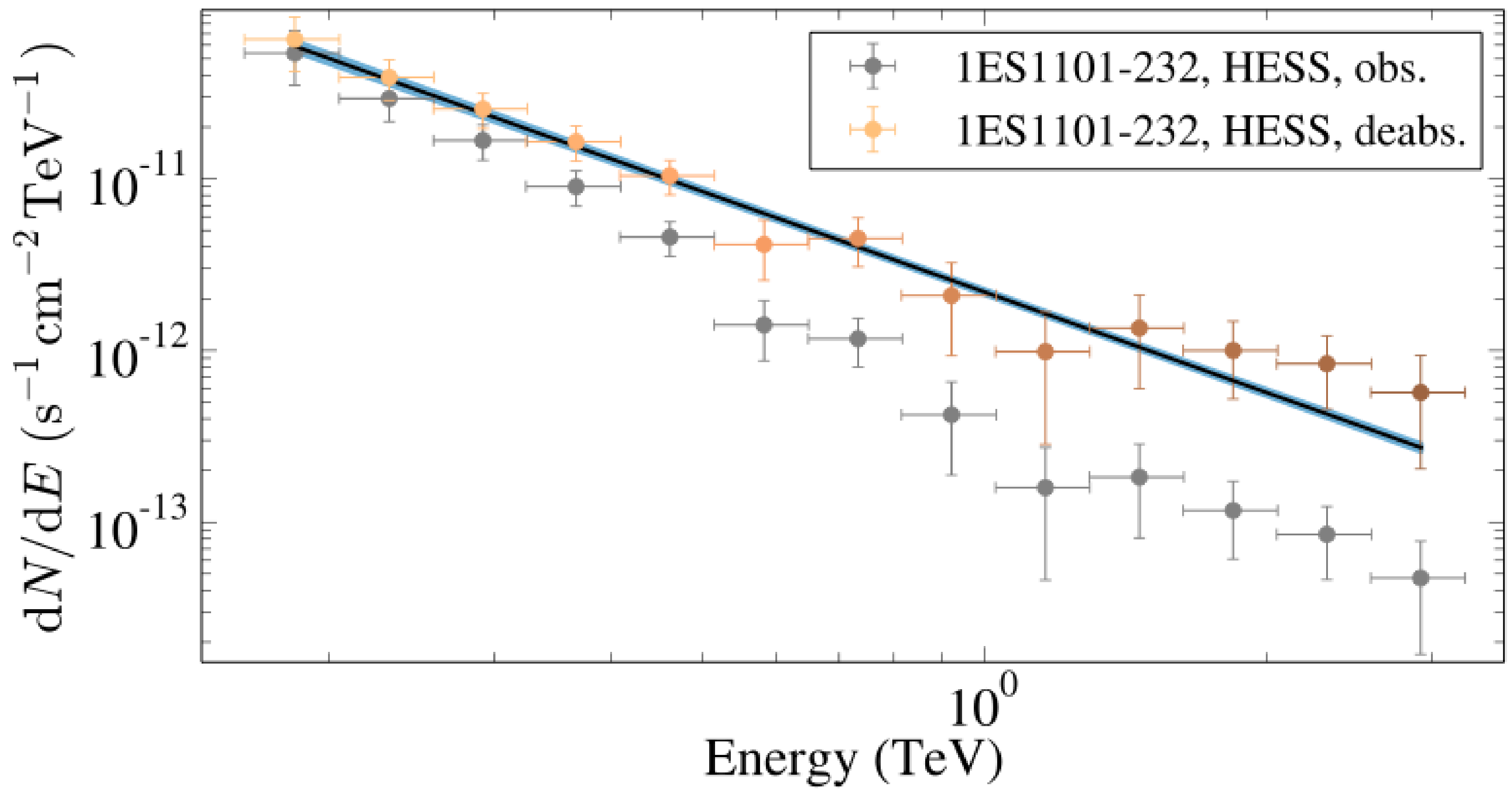
Method to search for low opacity

- apply **absorption-correction with KD model** to observed spectrum



Method to search for low opacity

- apply **absorption-correction with KD model** to observed spectrum
- **Fit corrected spectrum with analytical function** (either power law or log parabola)

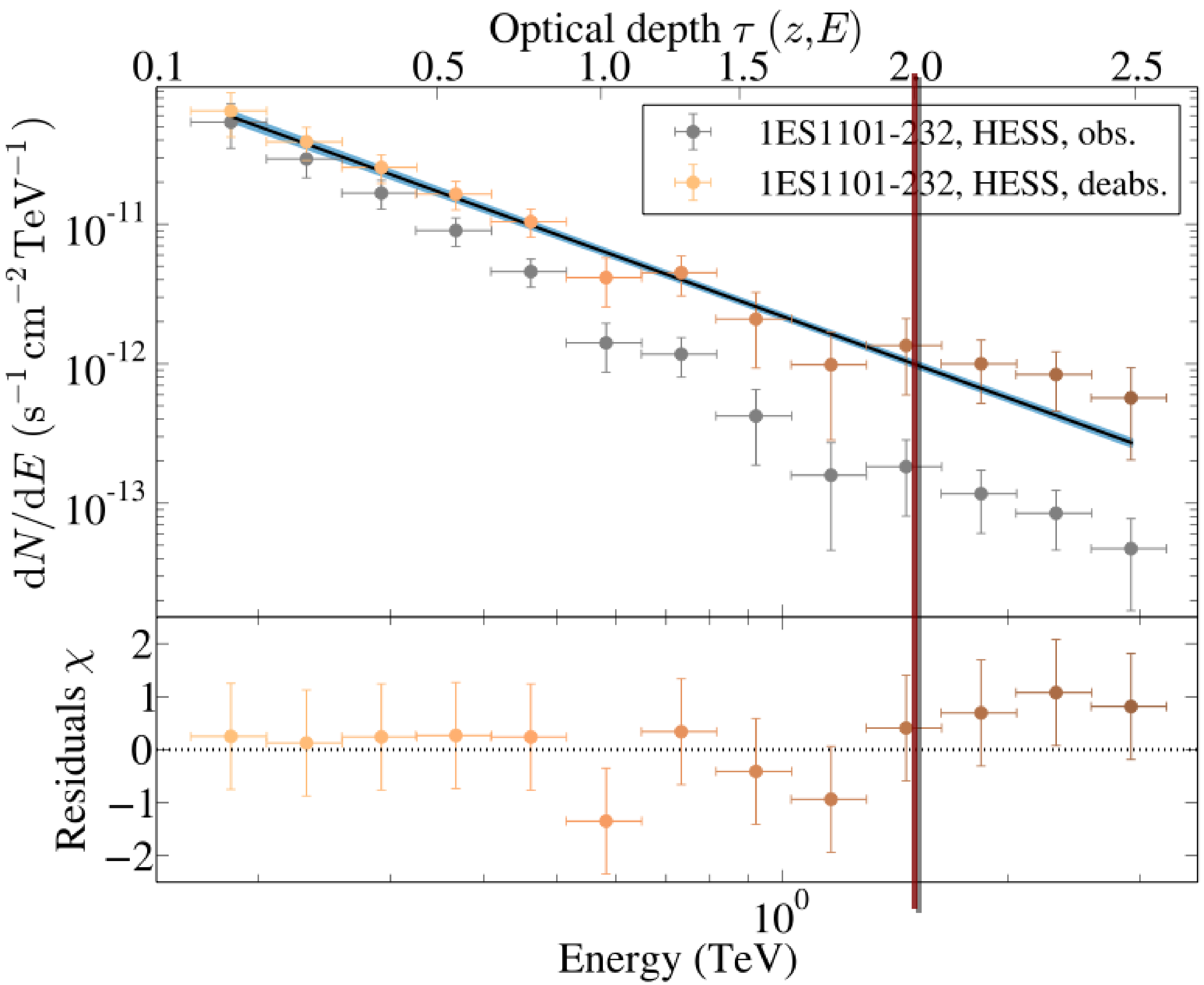


[Horns & **MM**, 2012]

Method to search for low opacity

- apply **absorption-correction with KD model** to observed spectrum
- **Fit corrected spectrum with analytical function** (either power law or log parabola)
- Fit **residuals should follow (0,1) normal distribution**, also for $\tau_{\gamma\gamma} \geq 2$
- If $\chi > 0$: **overcorrection**

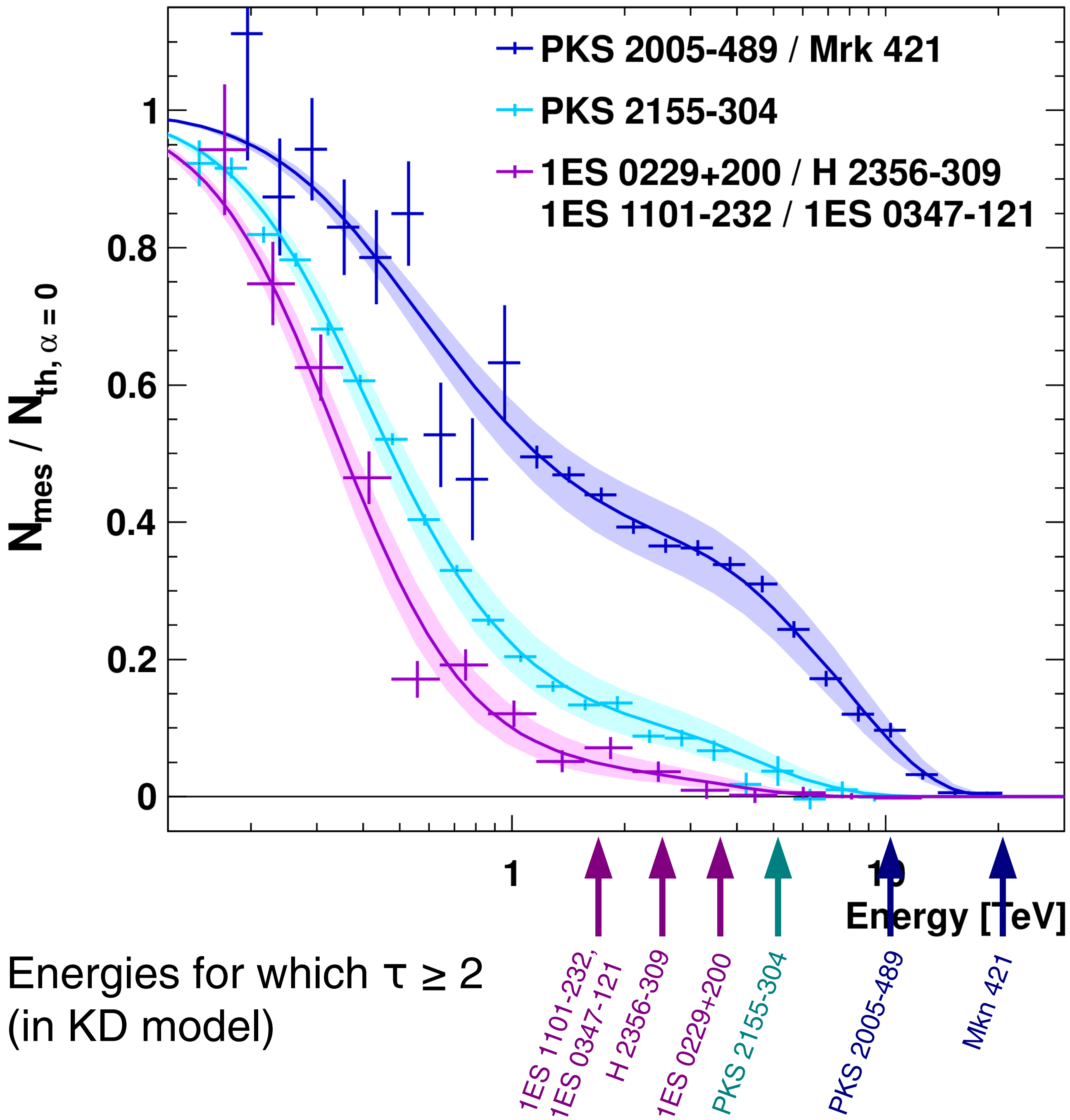
$$\chi_i = (F_{meas,\,i} - F_{theo}(E_i)) / \sigma_i$$



[Horns & **MM**, 2012]

No hint for low opacity from H.E.S.S. Data?

[Figure from H.E.S.S. Collaboration, 2013]

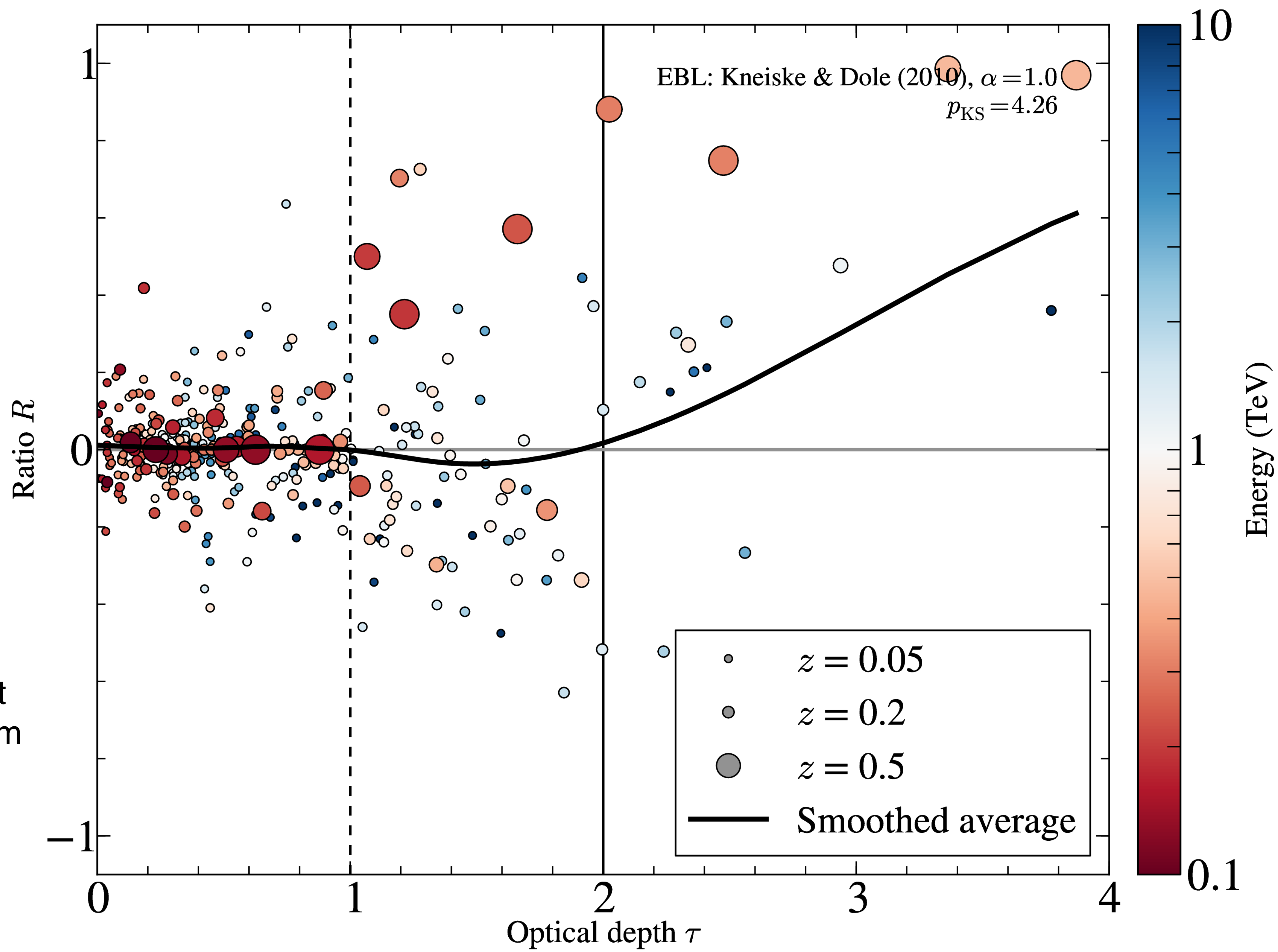


Energies for which τ ≥ 2
(in KD model)

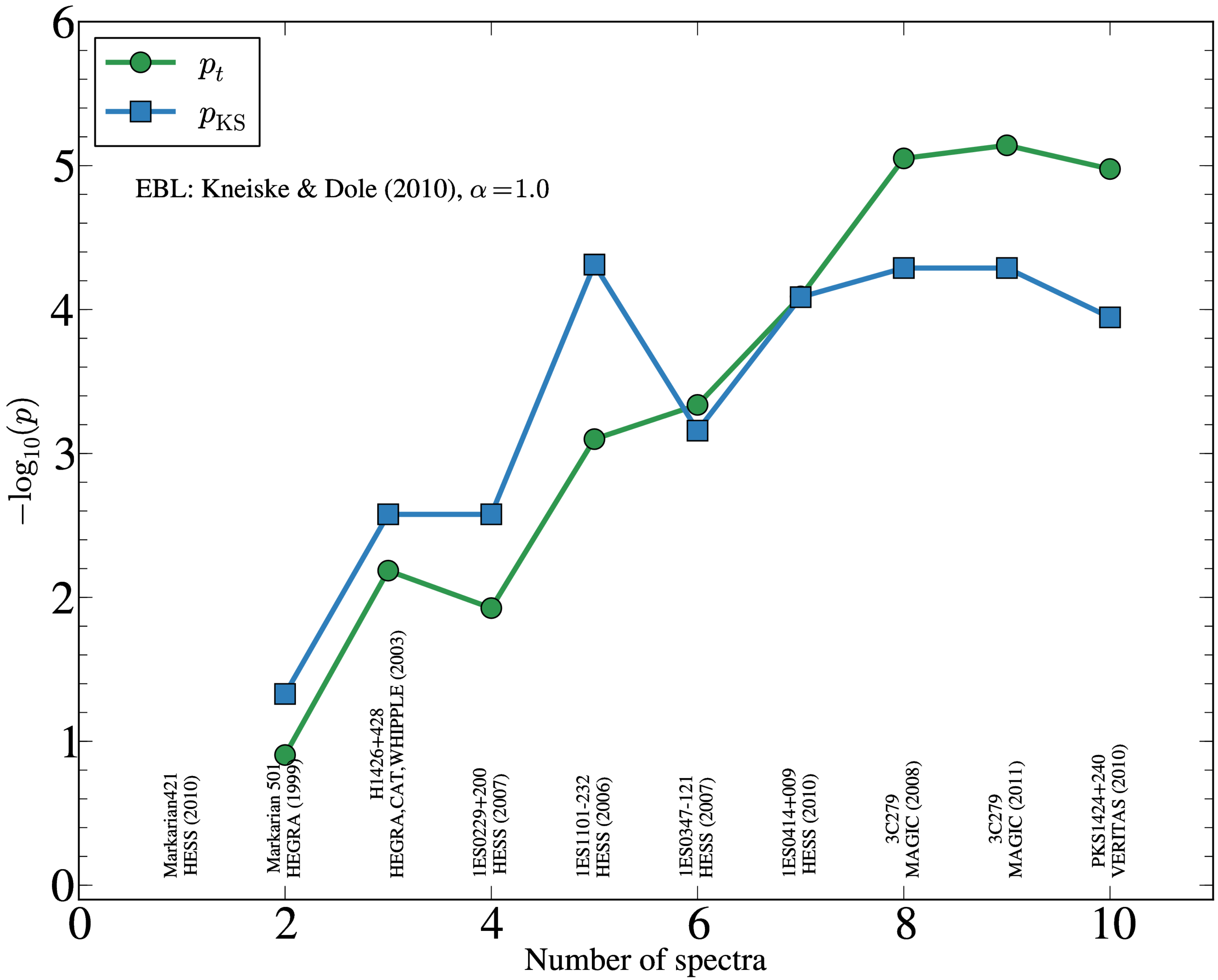
- Reduced opacity should become **visible in residuals** of recent H.E.S.S. analysis of EBL imprint in blazar spectra
- **No excess seen** (although hard to tell from the plot)
- Sources binned into 3 redshift bins, might **mask the effect**

Test opacity with KS test

- Fit VHE spectra in optical thin regime, i.e., $\tau_{\gamma\gamma} < 1$
- extrapolate to higher optical depths
- calculate ratio between extrapolation and absorption-corrected data points
- compare distributions of ratios for $1 < \tau_{\gamma\gamma} \leq 2$ and $\tau_{\gamma\gamma} \geq 2$ with Kolomogorov-Smirnov test
- Results in 4 σ significance that distributions are nor drawn from same underlying probability distribution function



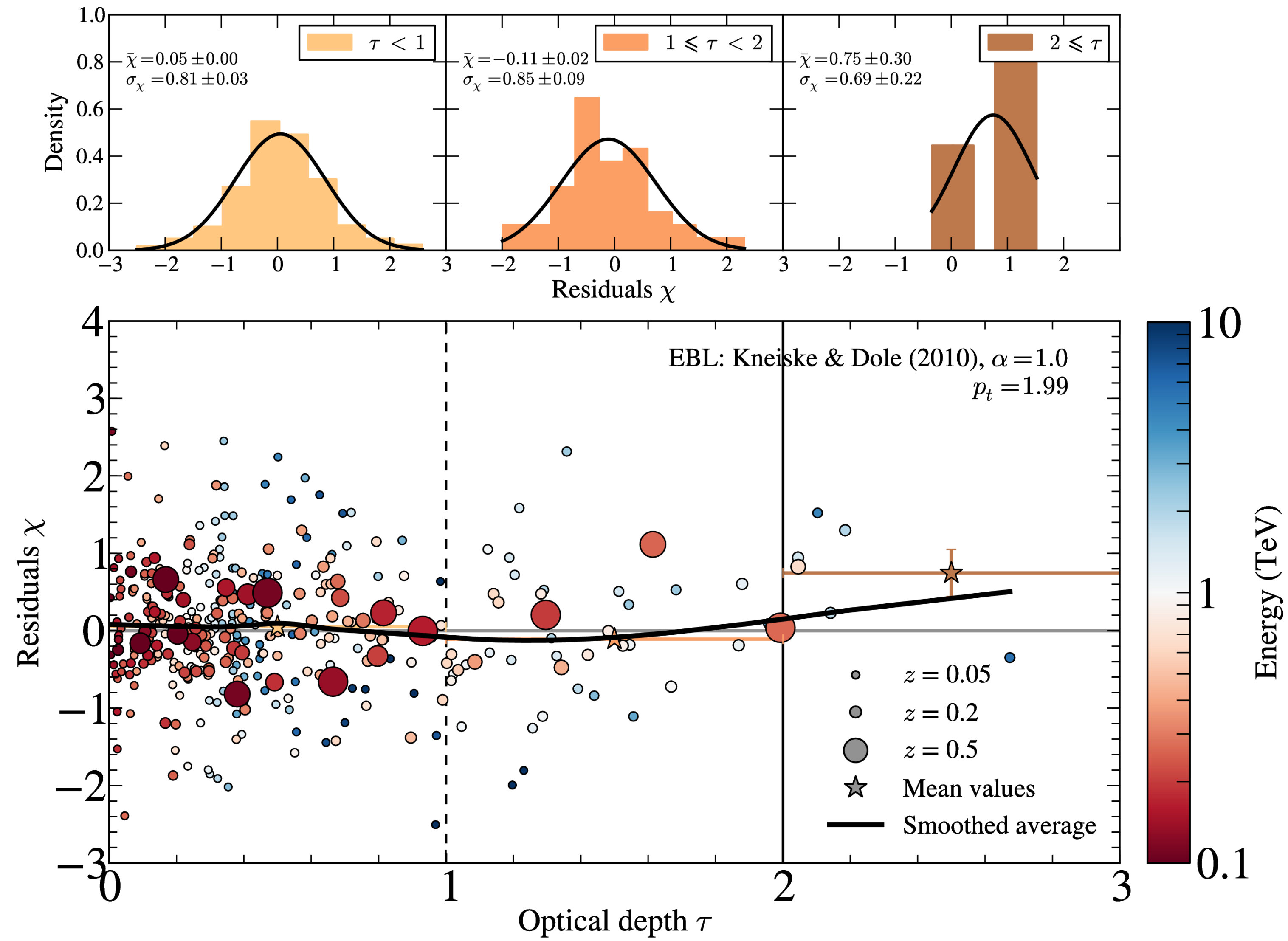
Cumulative significance of PPA for VHE analysis



[Horns & MM, 2012]

Study of systematic uncertainties: energy resolution and calibration

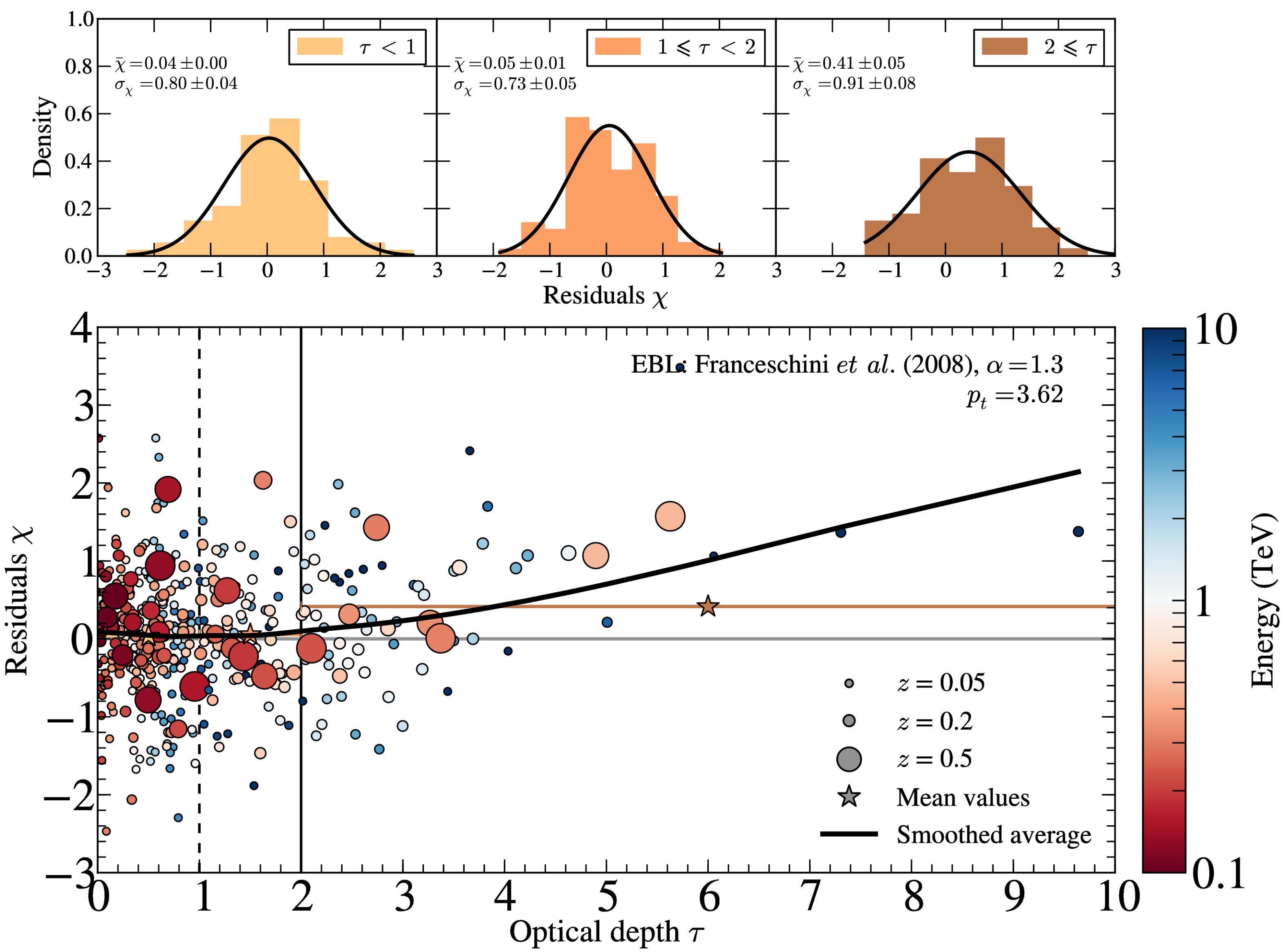
- Limited energy resolution might cause **spill-over effect**
- Energy **calibration (Δ*E*/*E* ~ 15%)** uncertain [however: Cross calibration with LAT ⇒ only energy shift of ~ 5% necessary, see Meyer et al., 2010]
- Test repeated with energy points scaled by -15% and last energy point removed ⇒ **significance reduced to 2 σ**
- However: **Mock data** sample with Galactic sources **does not show indication**
- **Further tests** conducted: source intrinsic effects (spectral hardening, selection bias), different EBL models



[Horns & **MM**, 2012]

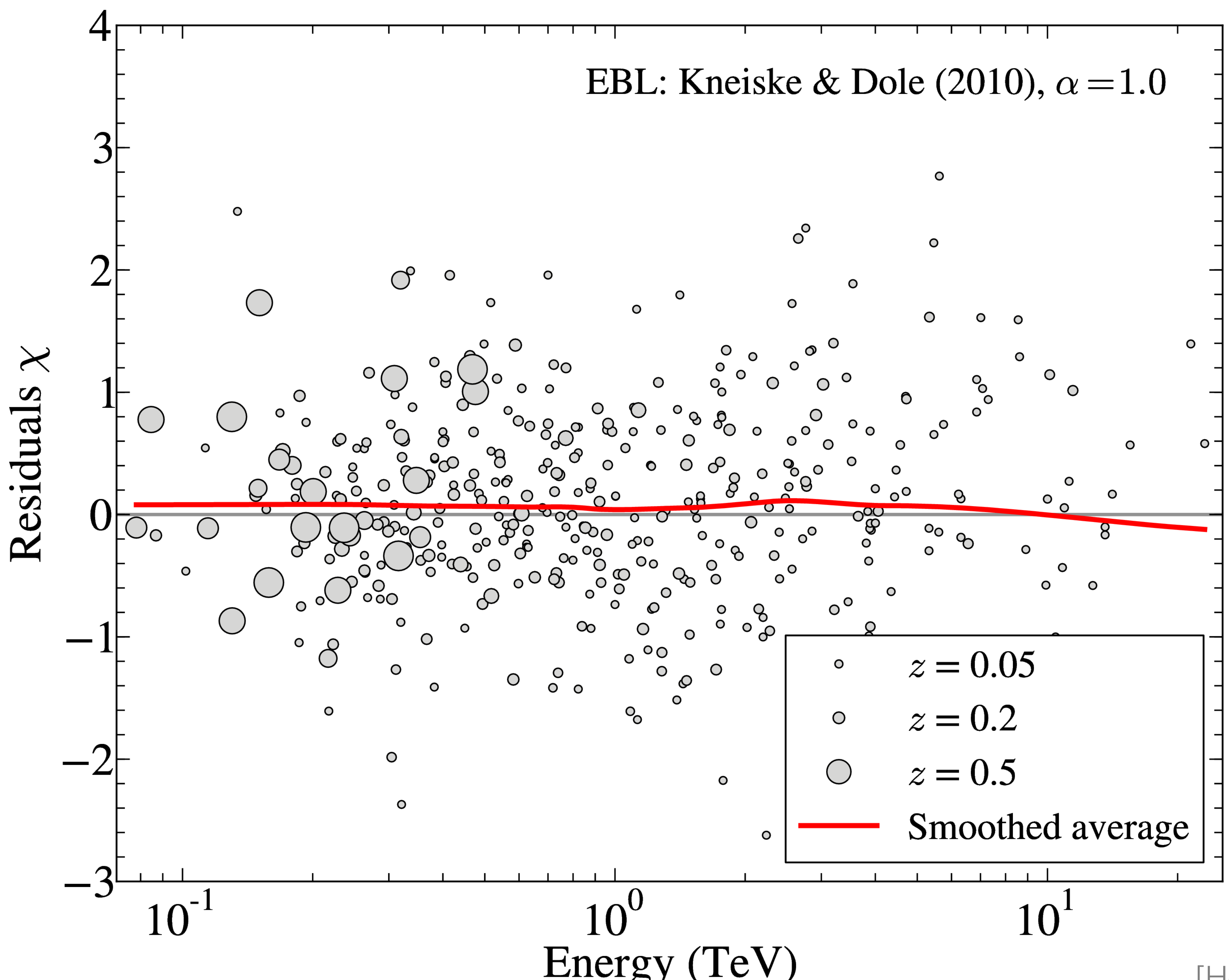
Study of systematic uncertainties II

- **Study of mock data sample:**
  - Redshift assigned to Galactic VHE spectra
  - No absorption correction applied
  - Test repeated, no indication found
- **Different EBL models:**
  - Repeated test with EBL model of Franceschini et al., 2008, additionally scaled optical depth by 1.3 [suggested by H.E.S.S. measurements, H.E.S.S. collaboration, 2013]
  - Indication less significant, but trend still present



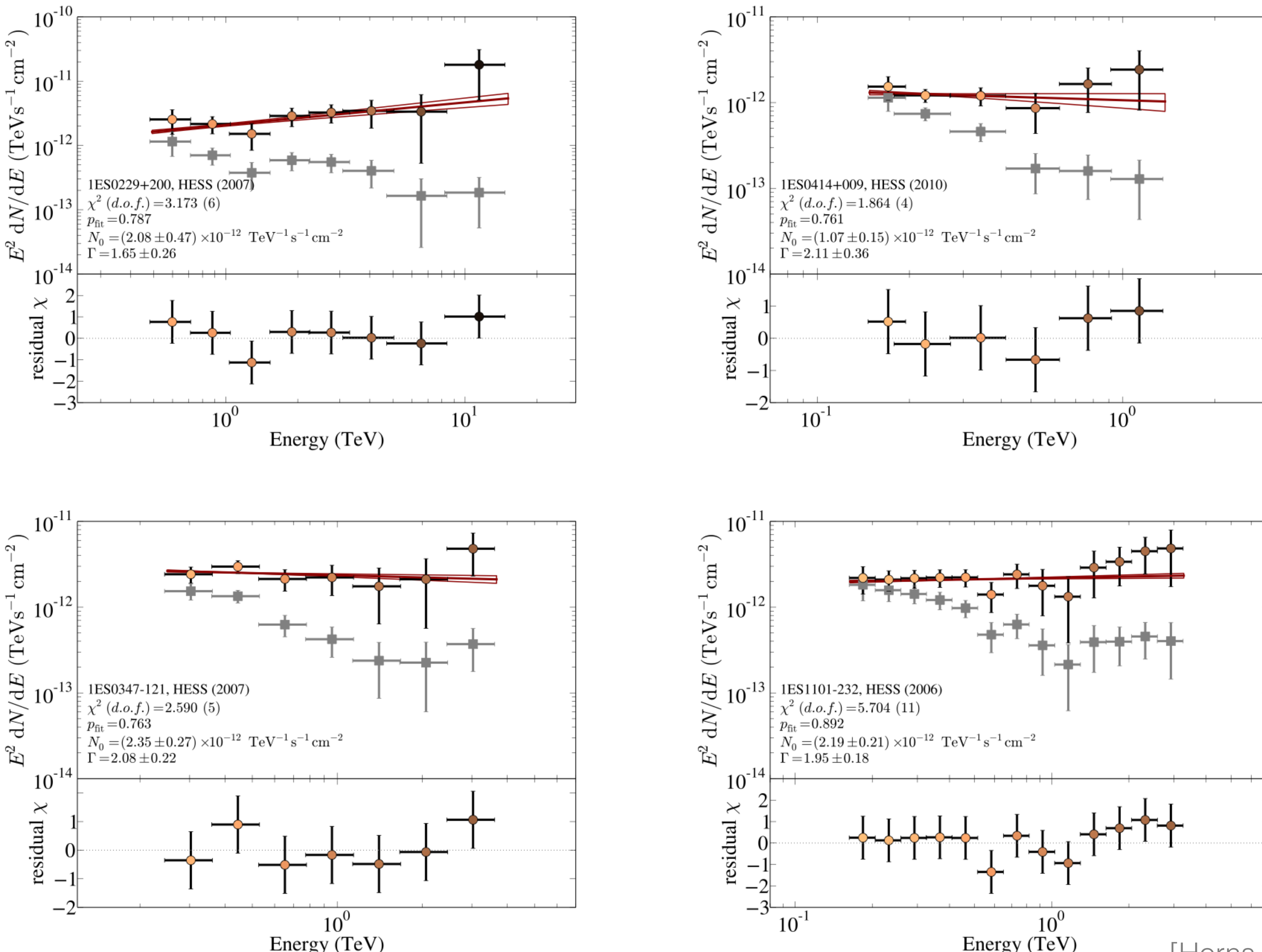
[Horns & MM, 2012]

No trend in energy seen



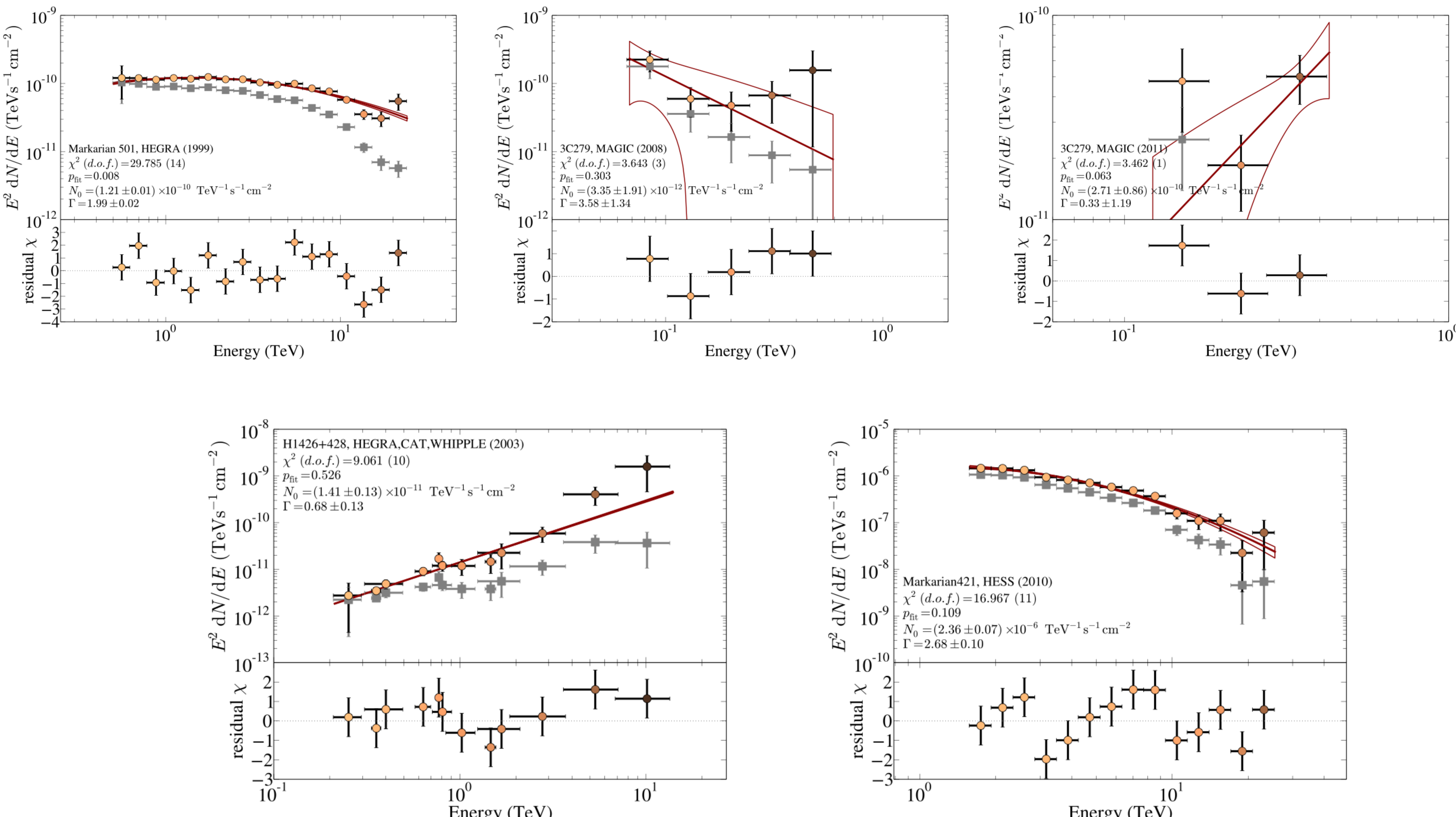
[Horns & **MM**, 2012]

Spectral fits I



[Horns & **MM**, 2012]

Spectral fits II



[Horns & **MM**, 2012]

Cross checks for VHE opacity analysis

Systematic check	Significance p_{KS}		Significance p_t	
-15 % energy scaling	2.93×10^{-4}	$3.44\,\sigma$	1.18×10^{-4}	$3.68\,\sigma$
Removed last energy point	1.02×10^{-3}	$3.09\,\sigma$	6.74×10^{-3}	$2.44\,\sigma$
Removed last energy point and -15 % energy scaling	6.74×10^{-3}	$2.44\,\sigma$	2.33×10^{-2}	$1.99\,\sigma$
FRV model	1.66×10^{-2}	$2.13\,\sigma$	4.61×10^{-3}	$2.60\,\sigma$
FRV model scaled by 1.3	0.17	$0.97\,\sigma$	2.33×10^{-4}	$3.50\,\sigma$
KD model scaled by 0.7	4.34×10^{-3}	$2.63\,\sigma$	4.23×10^{-2}	$1.73\,\sigma$
No absorption correction	0.32	$0.47\,\sigma$	3.37×10^{-2}	$1.83\,\sigma$

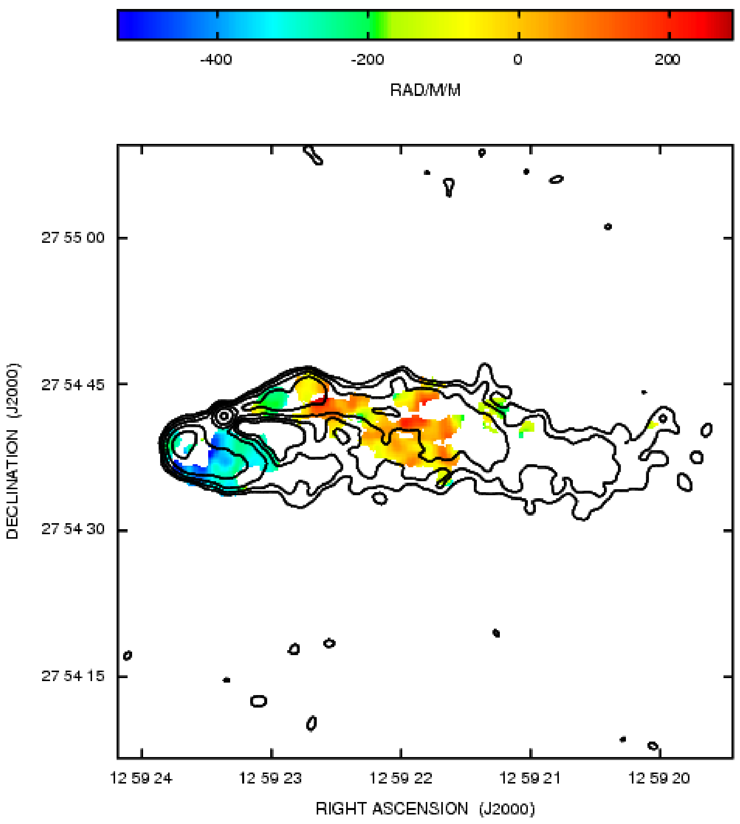
Note: PKS 1424+420 not included here

Backup: B-fields

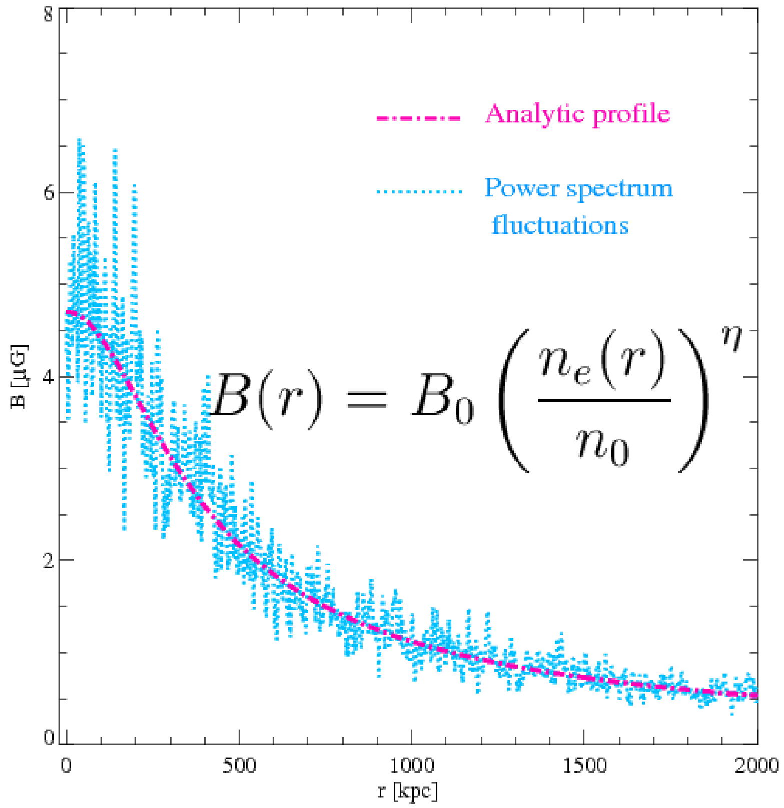
Intracluster magnetic fields

- 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



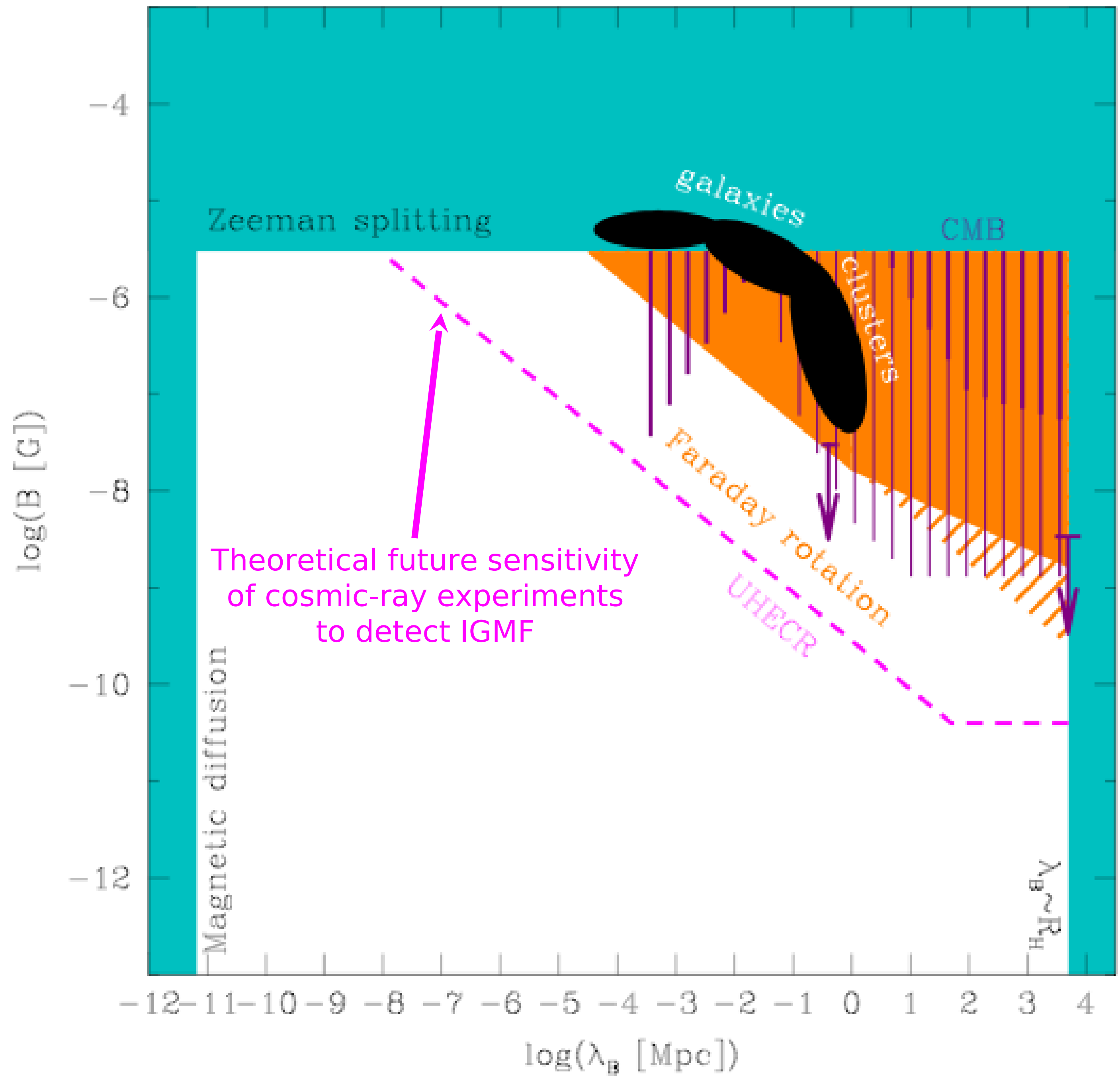
Simulated B field (blue) and analytical profile (magenta) of the Coma cluster

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

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

Intergalactic magnetic fields

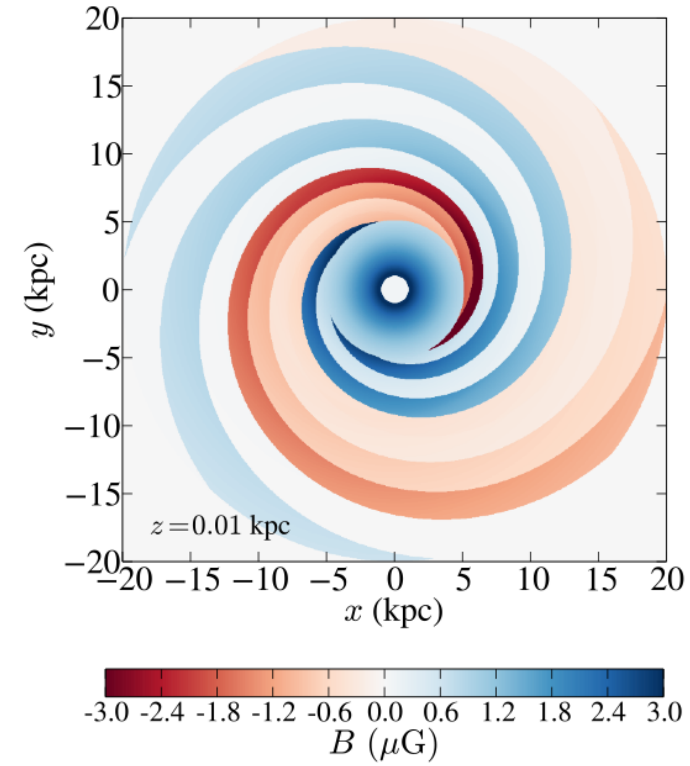
- **Zeeman splitting** of 21cm line of distant quasars in IGMF cannot be stronger than splitting due to galactic magnetic field
- **Faraday rotation** of polarized radio emission of distant quasars - depends on correlation length and assumed electron density in the IGM
- Theoretical limits from **simulations** of magnetic fields in **galaxies and galaxy clusters**

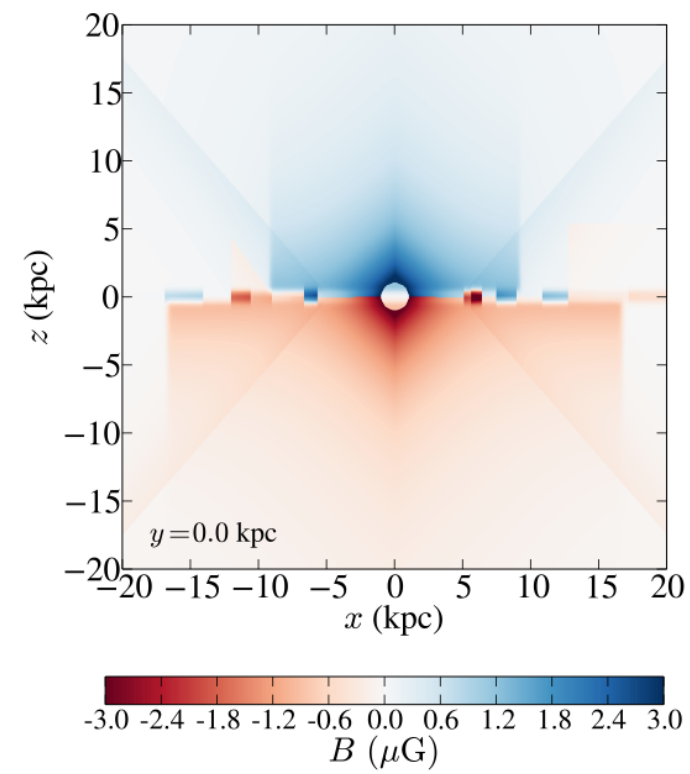


[see, e.g., Neronov & Vovk, 2009, for a review, Figure from same reference]

Galactic magnetic field model

- **Regular component** of Galactic magnetic field (GMF) model of Jansson & Farrar (2012)
- Consists of three components:
  1. **Disk**
  2. **Halo**
  3. **X**
- Derived from χ^2-fit to WMAP7 synchrotron emission maps and Faraday rotation measurements
- Additionally: purely **turbulent and striated component**





[Figures reproduced from regular component of the GMF model of Jansson & Farrar, 2012]

Axion and ALPs

The strong CP problem

- QCD allows for **CP violating term** in Lagrangian

$$\mathcal{L}_{\mathrm{CP}} = \frac{\alpha_S}{4\pi}\theta \,\mathrm{tr}\left[G_{\mu\nu}\tilde{G}^{\mu\nu}\right]$$

- Observable effect: **electric dipole moment of the neutron**, strength depends on θ, expected of order unity

- measurement gives rise to strong CP problem:

$$|\bar{\theta}| = |\theta + \arg\det\mathcal{M}_q| \lesssim 10^{-10}$$

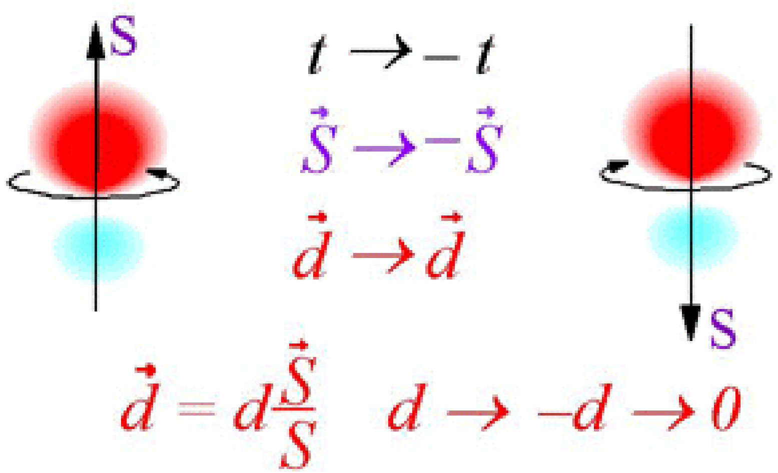
- Solution: introduce **new symmetry U(1)$_{\mathrm{PQ}}$**, spontaneously broken at scale f_a

- θ replaced by field *a*, associated with U(1)$_{\mathrm{PQ}}$, relaxes to zero $\langle a\rangle = 0$, solves strong CP problem

$$\theta \rightarrow a/f_a$$

- Symmetry breaking gives rise to **pseudo-Nambu-Goldstone boson, the axion**

$$m_a \sim 6\,\mathrm{meV}\frac{10^9\mathrm{GeV}}{f_a}$$



Electric dipole moment of neutron violates *T* symmetry (and thus *CP* symmetry, since *CPT* is conserved)
[Figure from http://oldwww.phys.washington.edu/users/wcgriff/romalis/EDM/imageA8M.gif]

[Peccei & Quinn, 1977; Weinberg, 1978; Wilczek, 1978]

Photon-ALPs Lagrangian

Propagation of photon in external magnetic field:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Photon propagator

$$+\frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 a^2\right)$$

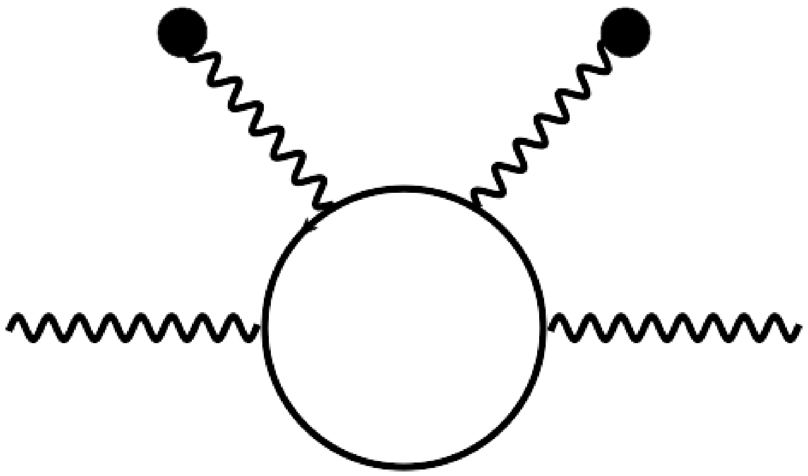
Kinetic and mass term for ALP

$$-\frac{1}{4}g_{a\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}a$$

Photon-ALP interaction

$$+\frac{\alpha^2}{90 m_e^4}\left[\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \frac{7}{4}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2\right]$$

Euler-Heisenberg effective Lagrangian



EoM of ALPs

- From Lagrangian, derive equation of motion:

$$\left[i\partial_{x_3} + E + \mathcal{M}_0\right]\psi(x_3) = 0$$

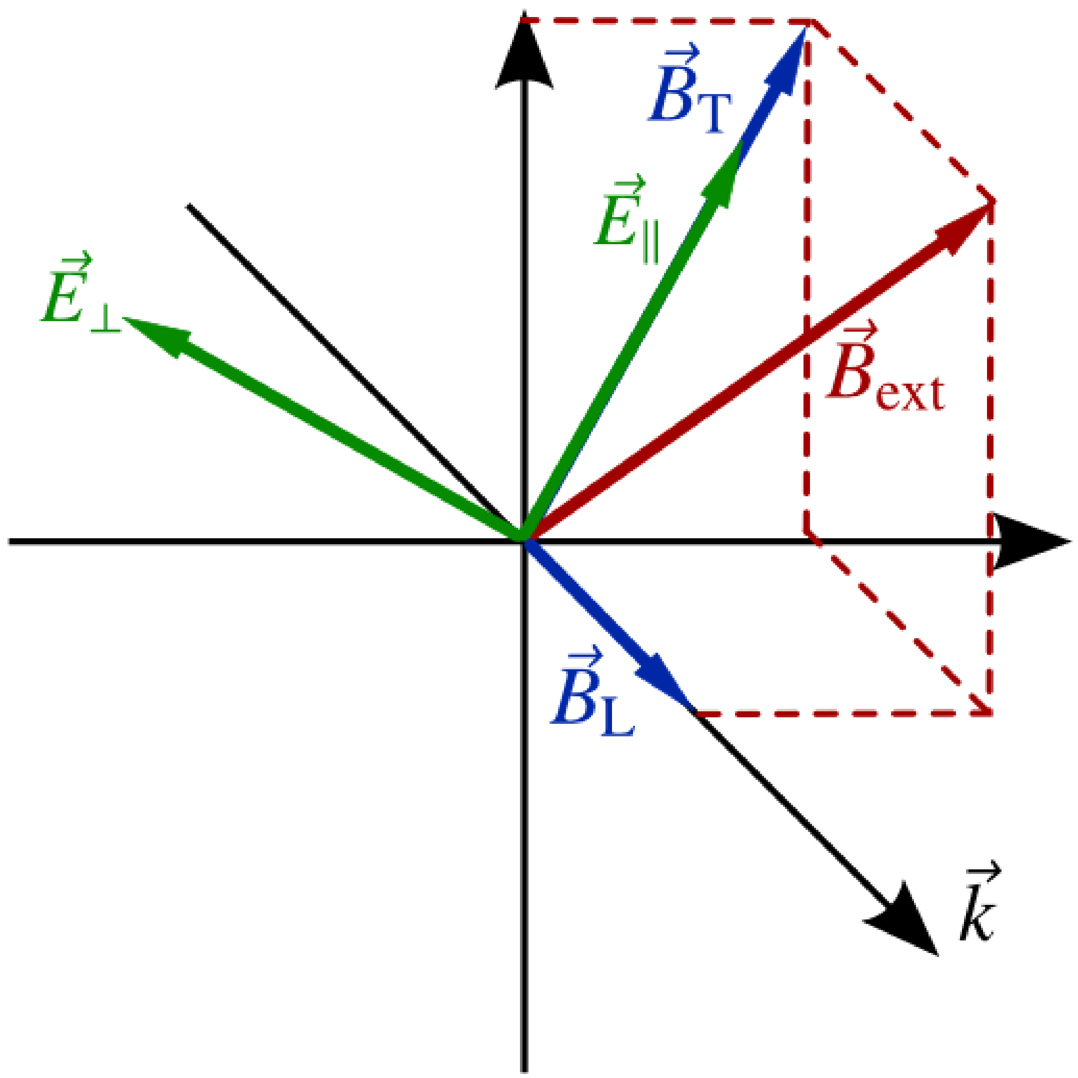
- ALPs only mix with $E_{\|}$
- Solve with Ansatz:

$$\psi(x_3) = (A_{\perp}(x_3), A_{||}(x_3), a(x_3))^T$$

$$\psi(x_3) = e^{iE(x_3 - x_{3,0})}\mathcal{T}(x_3, x_{3,0})\psi(x_{3,0})$$

- Diagonalize mixing matrix, transfer matrix given by:

$$\mathcal{T}(x_3, x_{3,0}) = \sum_{j=1}^{3} e^{i\lambda_j(x_3 - x_{3,0})}T_j$$



Photon-ALP mixing matrix

$$\mathcal{M}_0 = \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_{||} & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix}$$

$$\Delta_{\rm pl} = -1.1 \times 10^{-7} \left(\frac{n_{\rm el}}{10^{-3}{\rm cm}^{-3}}\right) \left(\frac{E}{\rm GeV}\right)^{-1} {\rm kpc}^{-1},$$

$$\Delta_{\rm QED} = 4.1 \times 10^{-9} \left(\frac{E}{\rm GeV}\right) \left(\frac{B_\perp}{\mu{\rm G}}\right)^2 {\rm kpc}^{-1},$$

$$\Delta_a = -7.8 \times 10^{-2} \left(\frac{m_a}{\rm neV}\right)^2 \left(\frac{E}{\rm GeV}\right)^{-1} {\rm kpc}^{-1},$$

$$\Delta_{a\gamma} = 1.52 \times 10^{-2} \left(\frac{g_{a\gamma}}{10^{-11}\,{\rm GeV}^{-1}}\right) \left(\frac{B_\perp}{\mu{\rm G}}\right) {\rm kpc}^{-1}$$

$$\Delta_{\rm pl} = -\omega^2/(2E)$$

$$\Delta_{||} = \Delta_{\rm pl} + 7/2\Delta_{\rm QED}$$

$$\Delta_\perp = \Delta_{\rm pl} + 2\Delta_{\rm QED}$$

- Neglected: Cotton-Mouton effect, i.e., assumed $\Delta_{\rm pl}^{||} = \Delta_{\rm pl}^{\perp} = \Delta_{\rm pl}$
- Neglected: Faraday rotation
- Both effects proportional to λ^2, small contributions at ɣ-ray energies

Density matrix formalism

- **Polarization of VHE -rays cannot be measured**, use **density matrix formalism** to describe photon-ALP conversions:

$$\rho(x_3) = \begin{pmatrix} A_1(x_3) \\ A_2(x_3) \\ a(x_3) \end{pmatrix} \otimes \begin{pmatrix} A_1(x_3) & A_2(x_3) & a(x_3) \end{pmatrix}^*$$

- **Evolution** of density matrix given by von-Neumann like equation:

$$i\frac{\mathrm{d}\rho}{\mathrm{d}x_3} = [\rho, \mathcal{M}_0]$$

- **Probability** to find photons in polarization final:

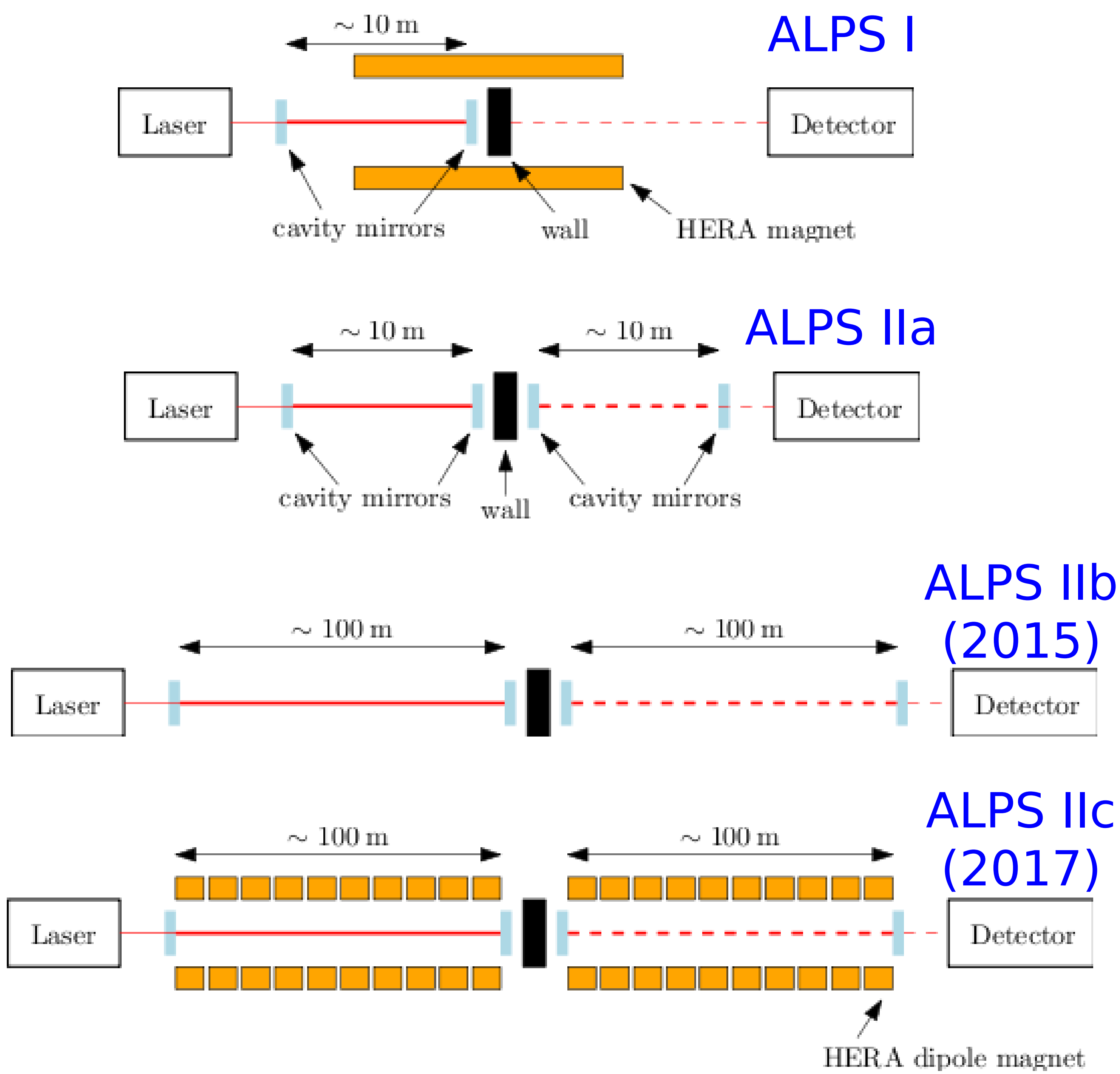
$$P_{\mathrm{final}} = \mathrm{Tr}(\rho_{\mathrm{final}}\mathcal{T}\rho_{\mathrm{init}}\mathcal{T}^\dagger)$$

- **Unpolarized** initial matrix:

$$\rho_{\mathrm{unpol}} = 1/2\ \mathrm{diag}(1,1,0)$$

Any Light Particle Search (ALPS) Phase II

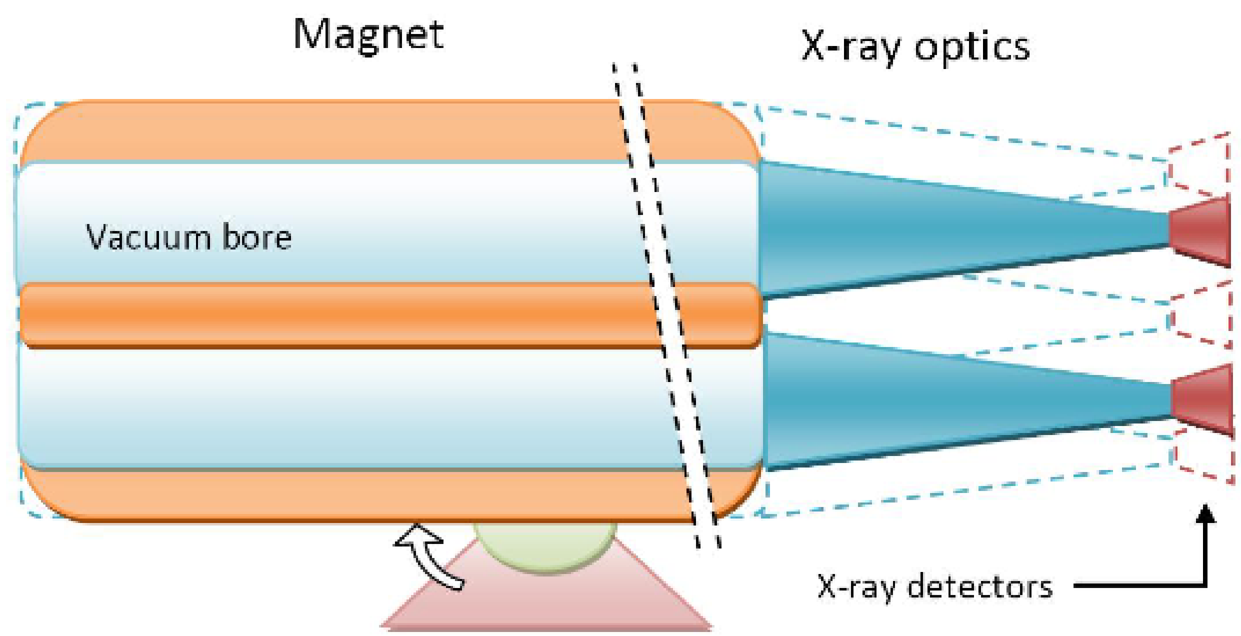
- Next generation **"Light shining through a wall"** experiment
- Several upgrades compared to ALPS I:
  - **Higher laser power** (using a 1064nm laser instead of 532nm)
  - **Transition Edge Sensor** instead of a CCD
  - **Regeneration** cavity
  - Maximizing ***B x L***: final stage with **20 straightened HERA dipole magnets**

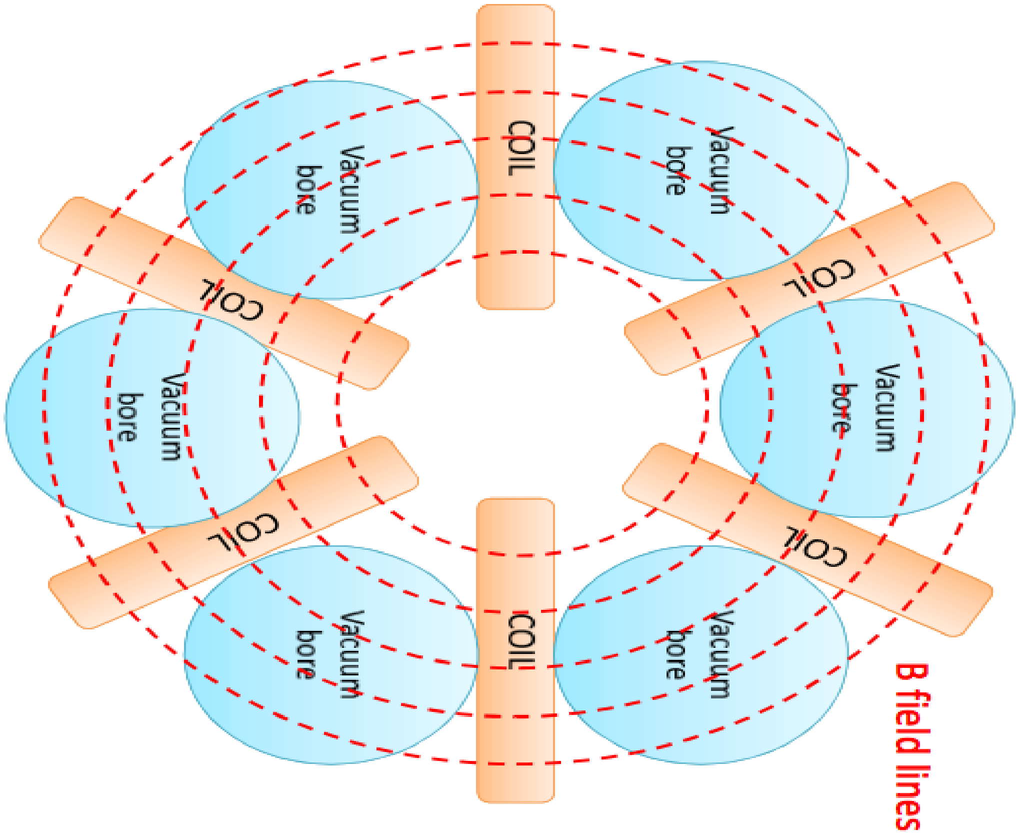


[ALPS II Technical design report, Bähre et al., 2013]

International Axion Observatory (IAXO)

- Next generation axion helioscope
- Toroidal magnetic field design (like ATLAS experiment) to increase geometrical cross section to several m^2
- X-ray optics as used in space missions (e.g. NuStar)
- State of the art X-ray detectors
- will probe couplings down to $g_{a\gamma} \gtrsim 10^{-12}$ GeV^{-1}

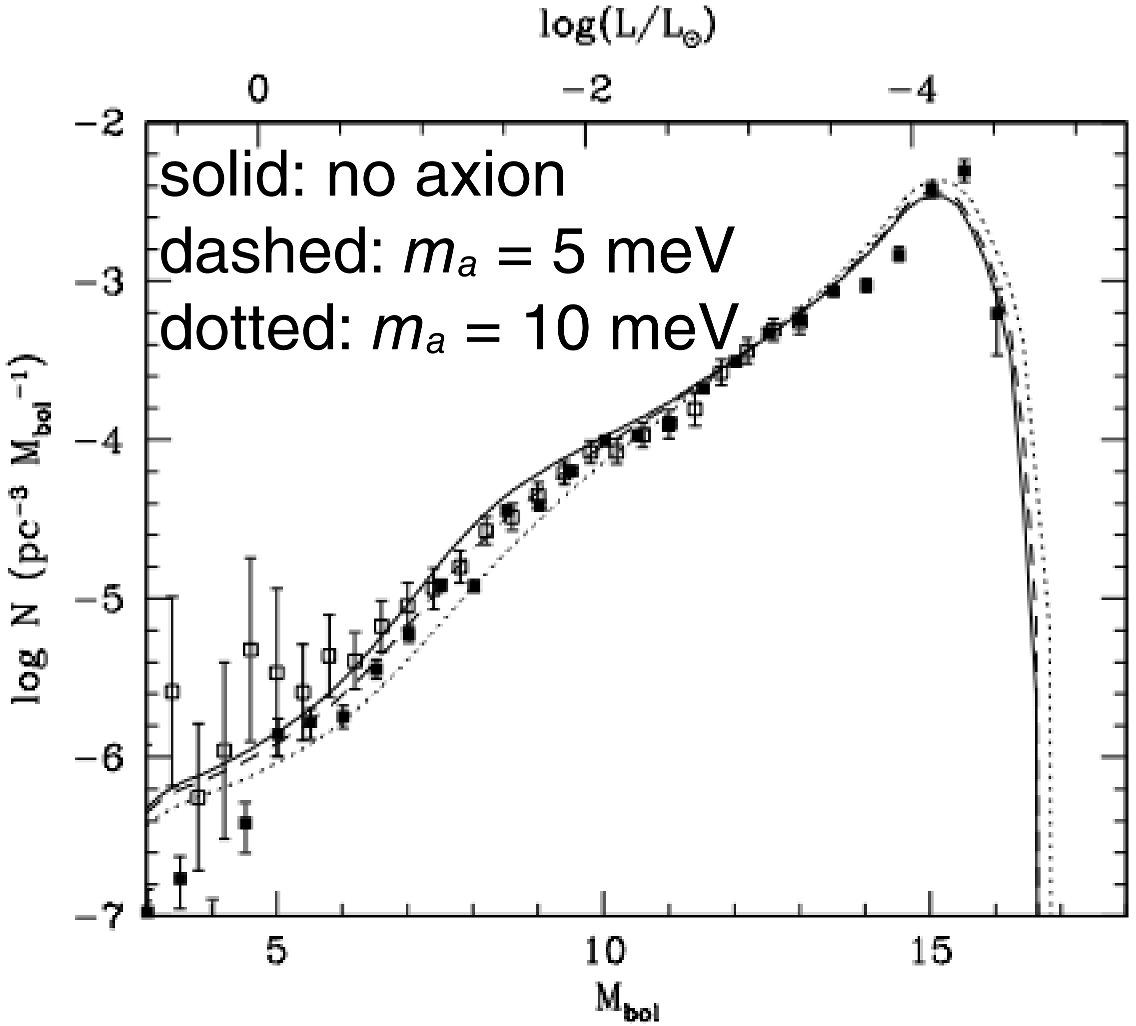


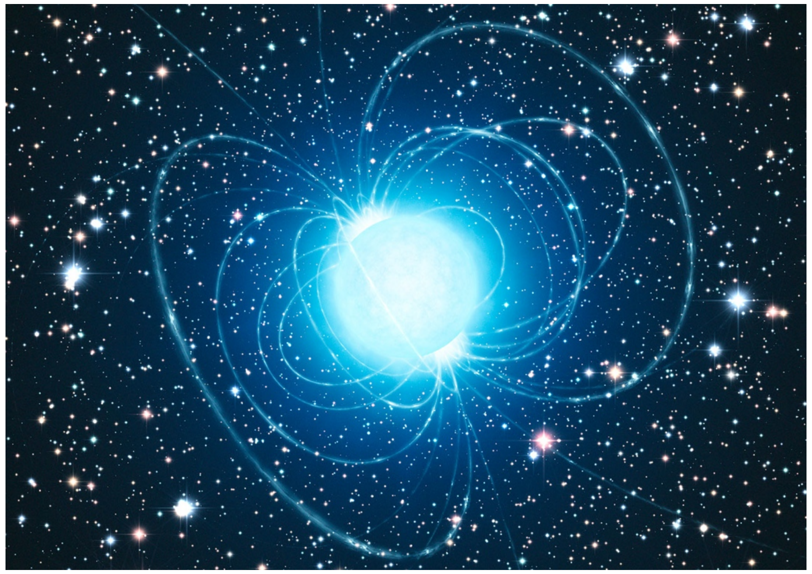


[Irastorza et al., 2011]

White dwarfs and ALPs

- Luminosity function of WD: **suggest extra cooling agent**
- **Including ALPs improves fit** to data
- Magnetic WD: **linear polarization of 5% observed**, none expected
- Derive limits on photon-ALP coupling: **ALPs should not overproduce polarization**
- On the other hand: **ALPs could also explain observed linear polarization**





[Isern et al., 2008; Gill & Heyl 2011]

[http://eso.org/public/archives/images/screen/eso1034a.jpg]

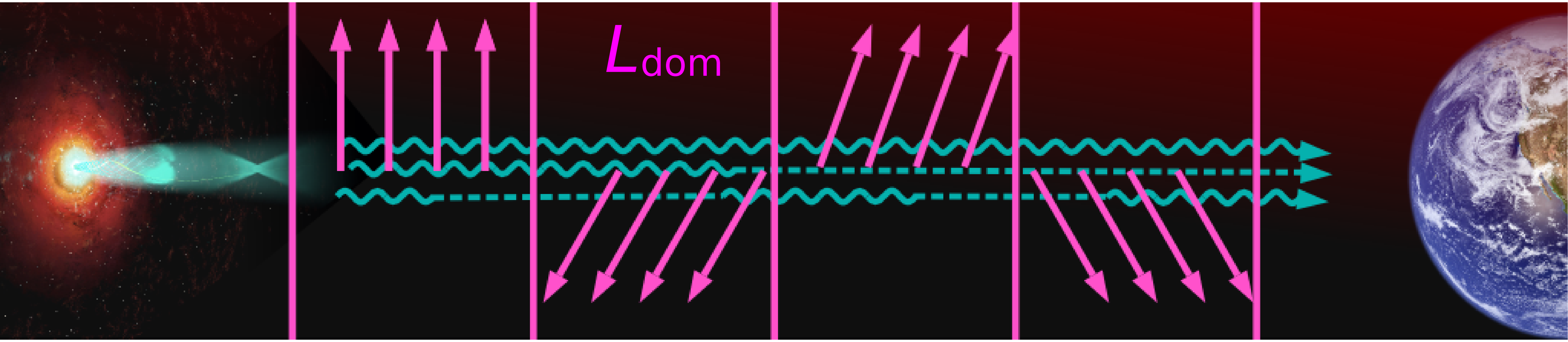
Lower limits on photon-ALP coupling

B-field scenarios

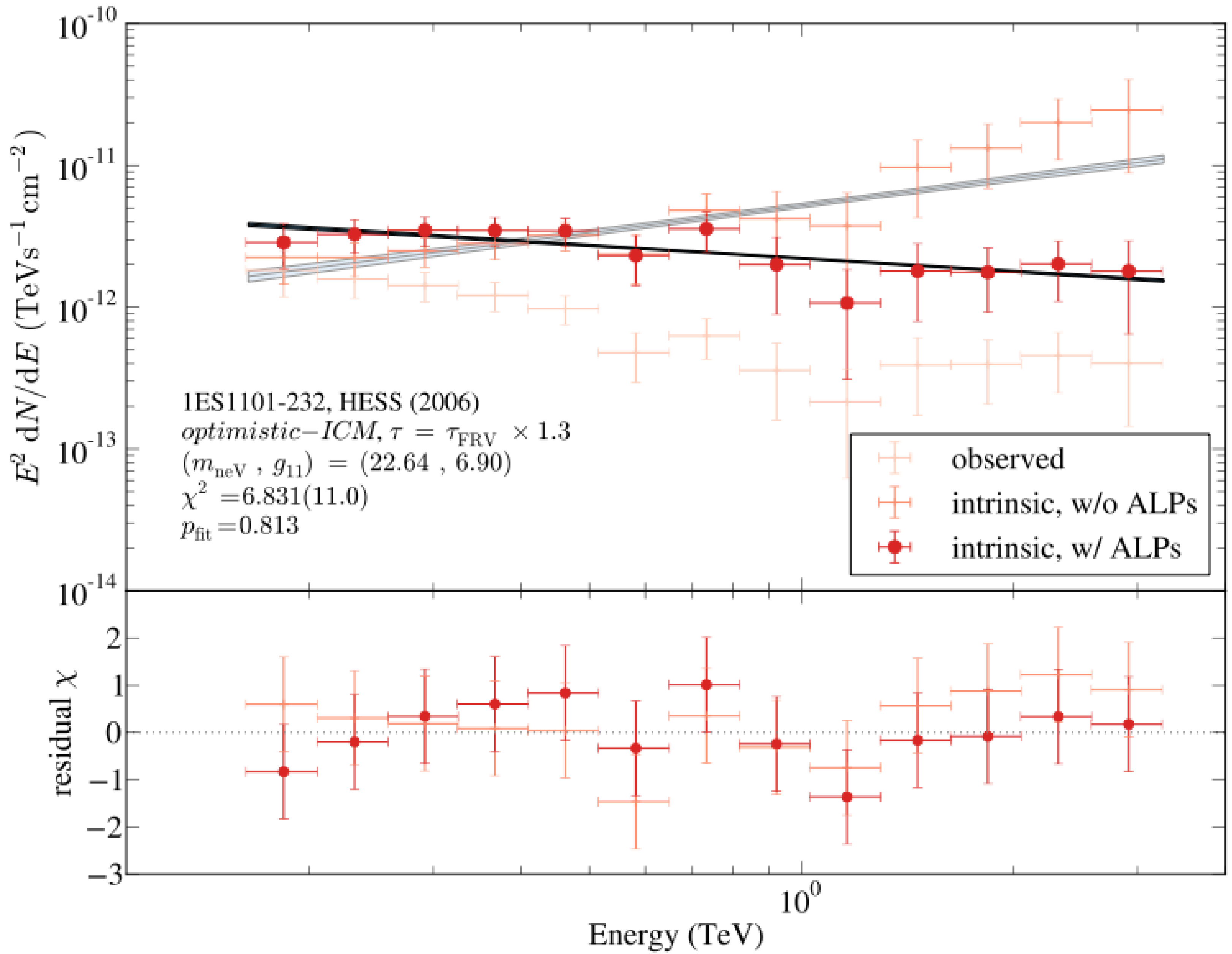
	B^0_{IGMF} (nG)	λ^c_{IGMF} (Mpc)	B^0_{ICMF} (µG)	λ^c_{ICMF} (kpc)	$r_{cluster}$ (Mpc)	GMF
Optimistic ICMF	-	-	10	10	1	✓
Optimistic IGMF	5	50	-	-	-	✓
Fiducial	0.01	10	1	10	2/3	✓

- Intracluster and intergalactic *B* fields: modeled with **domain like structure**: strength constant, **orientation changes randomly** from one cell to the next
- In *optimistic ICMF* scenario: **all AGN assumed to be located in clusters**, in *fiducial* scenario only if observational evidence exists

[MM, Horns, Raue 2013]



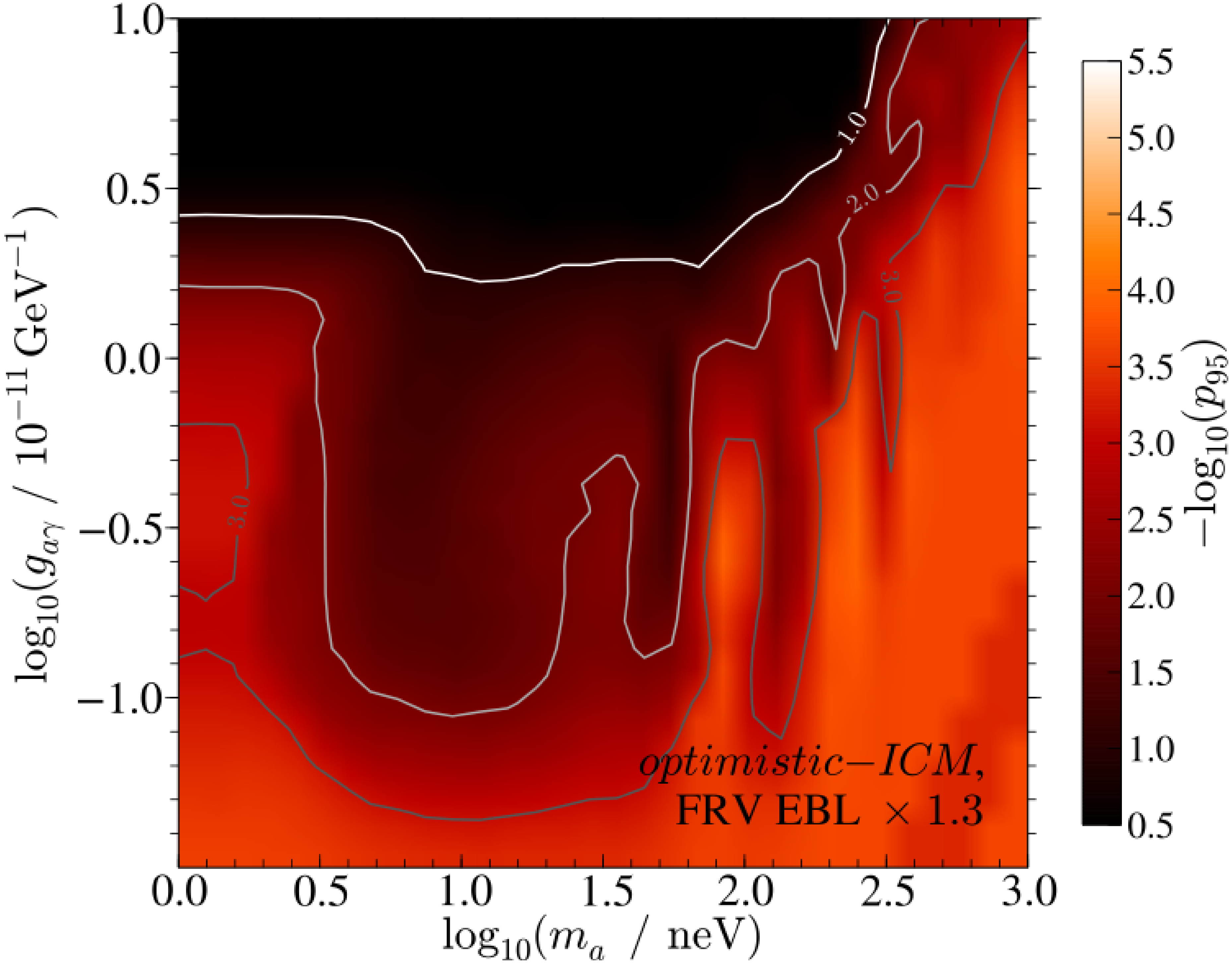
Effect on VHE spectra



- Compared to case w/o ALPs: **residuals close to zero**
- **No overcorrection** anymore
- Depends on **realization of random B field**

[**MM**, Horns, Raue 2013]

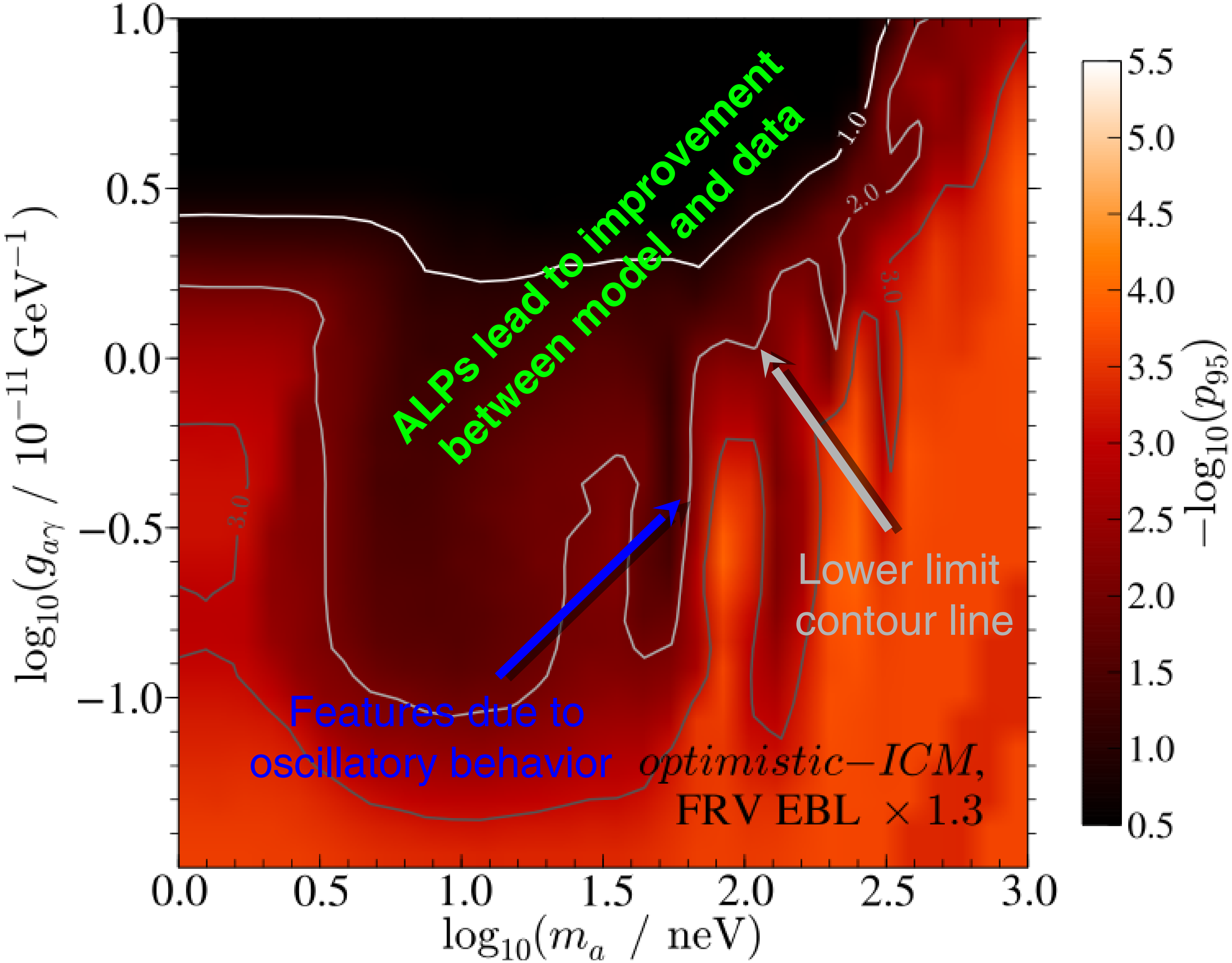
Lower limits for *optimistic ICMF* scenario



- 32 x 32 grid **in (m_a, $g_{a\gamma}$)**
- for each point: **5000 realizations simulated**
- **Lower limit on coupling:** at least 5 % of all simulated realizations need to describe data with probability > 1%

[**MM**, Horns, Raue 2013]

Lower limits for *optimistic ICMF* scenario

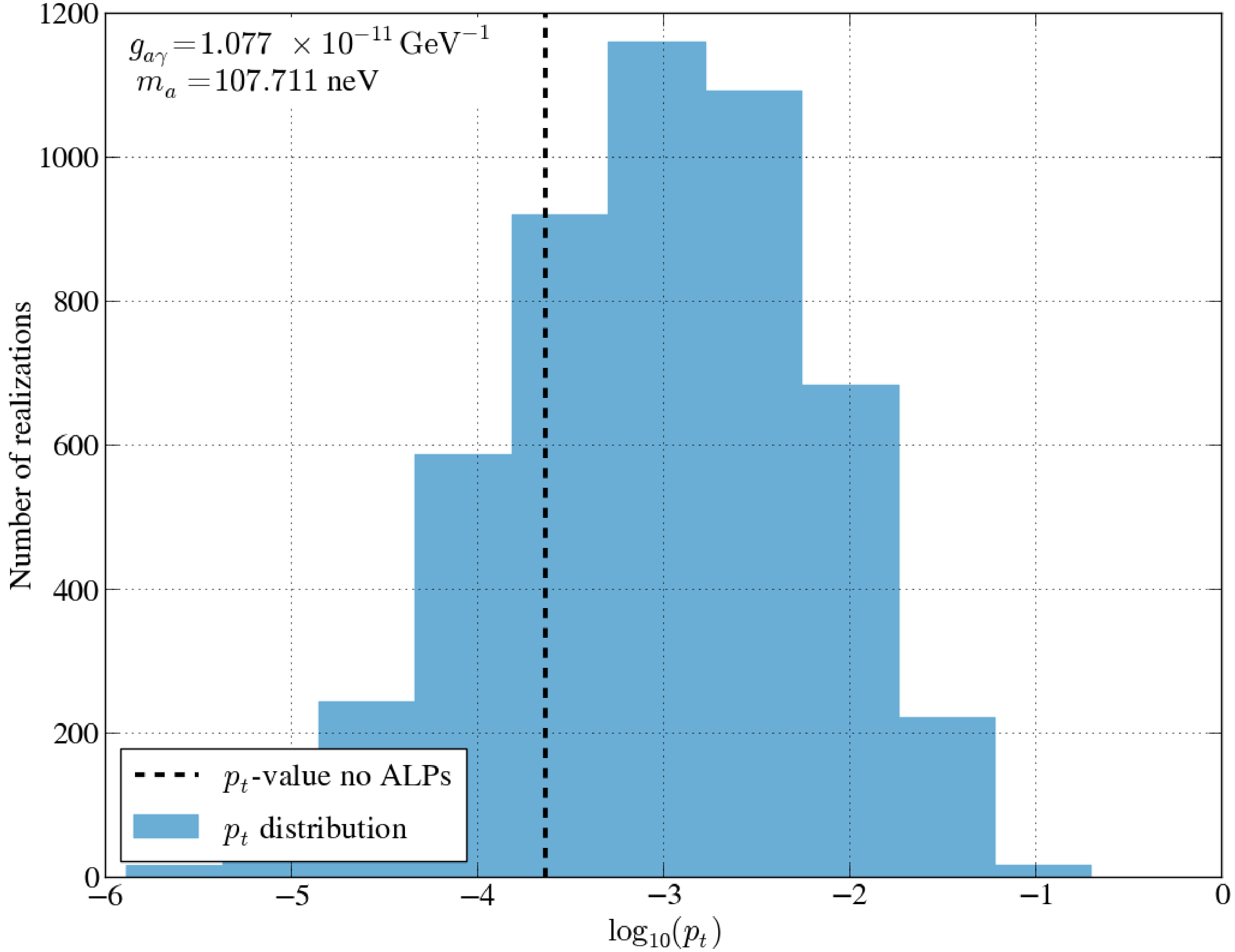


- 32 x 32 grid **in (m_a, $g_{a\gamma}$)**
- for each point: **5000 realizations simulated**
- **Lower limit on coupling:** at least 5 % of all simulated realizations need to describe data with probability > 1%

[**MM**, Horns, Raue 2013]

Definition of lower limit on $g_{a\gamma}$

- Example: calculate 5000 random *B*-field realizations in *optimistic ICMF* scenario for one (m_a, $g_{a\gamma}$) pair



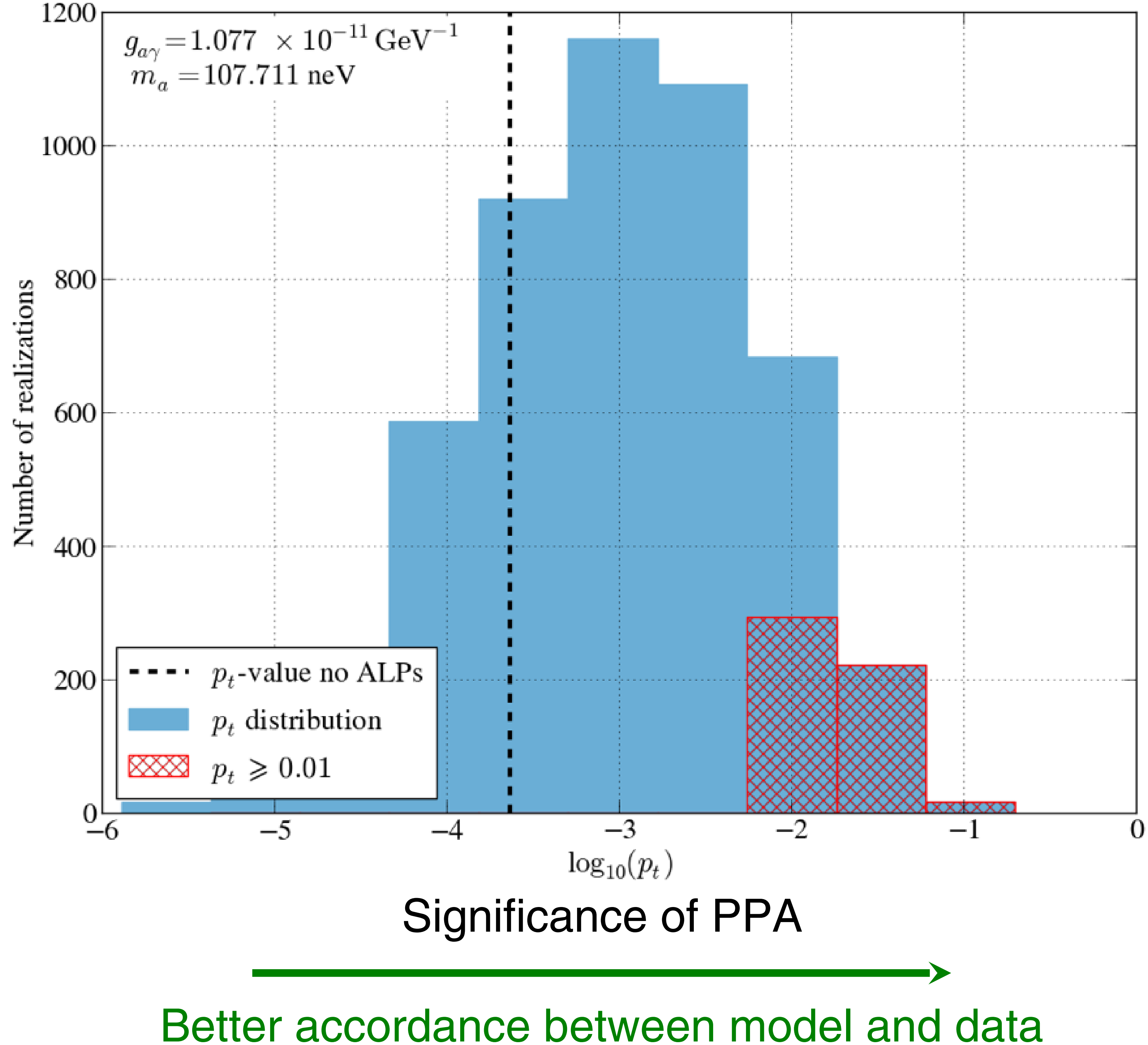
Significance of PPA

Better accordance between model and data

[MM, Horns, Raue 2013]

Definition of lower limit on $g_{a\gamma}$

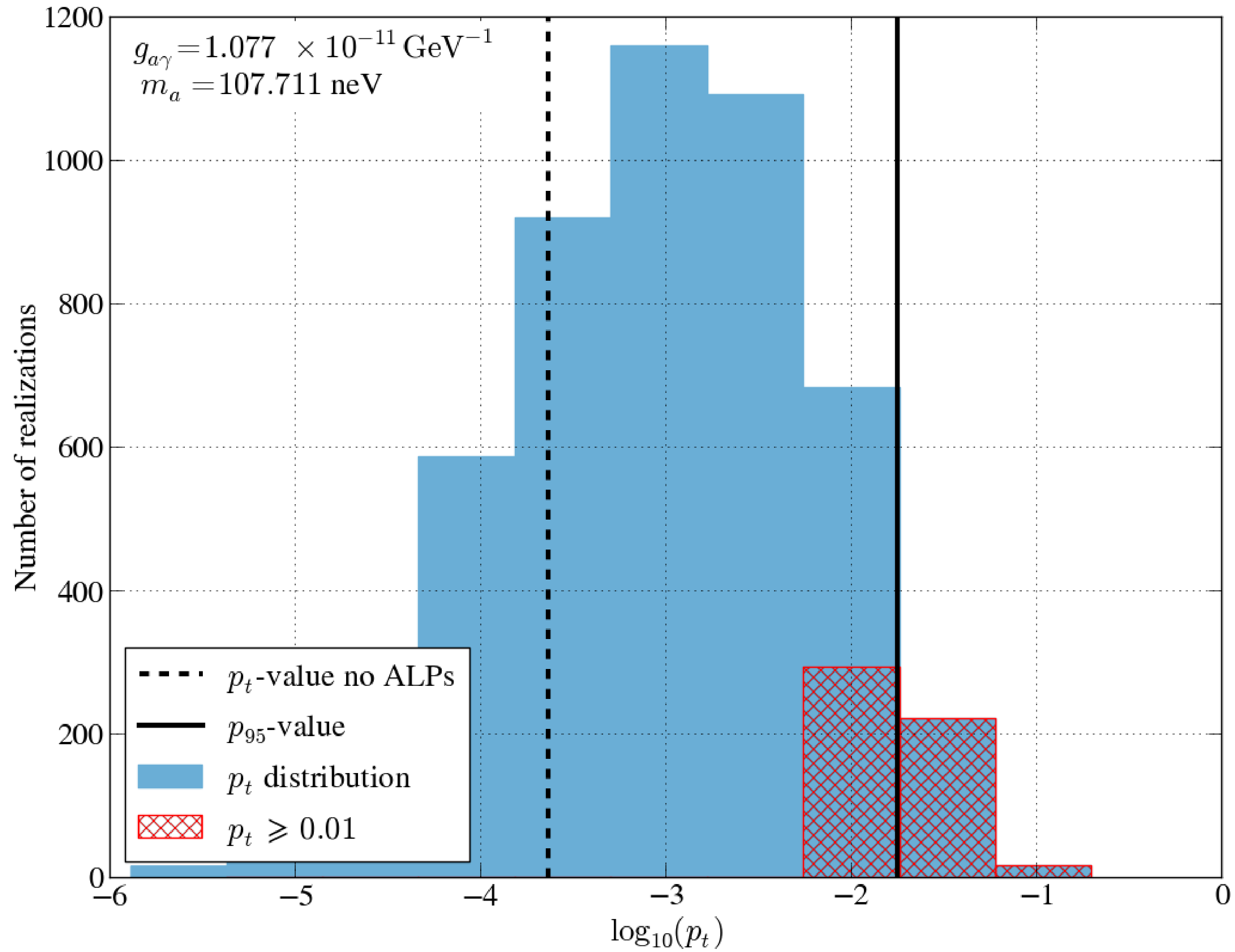
- Example: calculate 5000 random *B*-field realizations in *optimistic ICMF* scenario for one (m_a, $g_{a\gamma}$) pair
- Demand **accordance** between model and data of $p_t > 0.01$



[MM, Horns, Raue 2013]

Definition of lower limit on $g_{a\gamma}$

- Example: calculate 5000 random *B*-field realizations in *optimistic ICMF* scenario for one (m_a, $g_{a\gamma}$) pair
- Demand **accordance** between model and data of **$p_t > 0.01$**
- Demand that **at least 5% of all realizations result in $p_t > 0.01$ (p_{95}-value)**

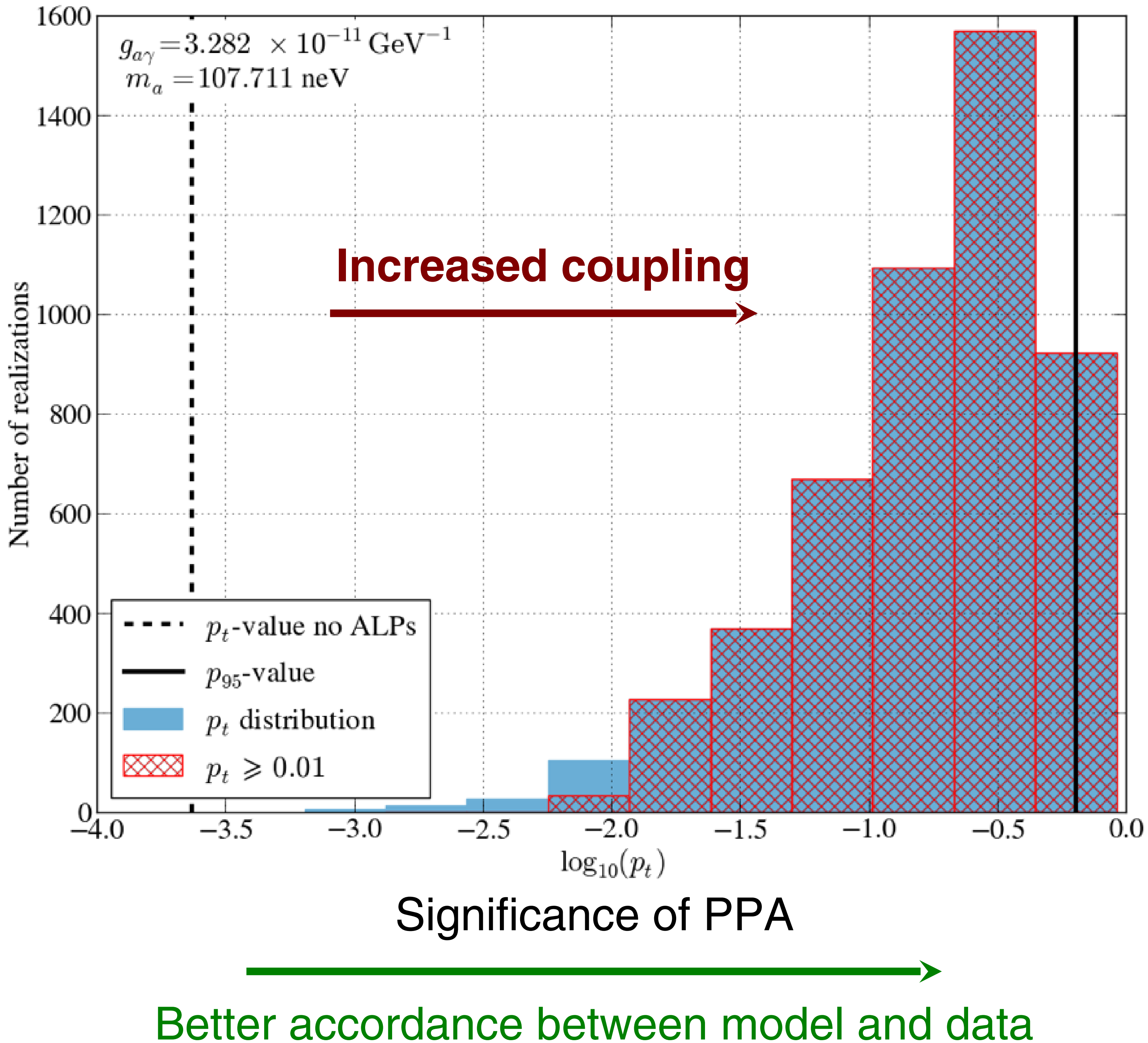


Significance of PPA

Better accordance between model and data

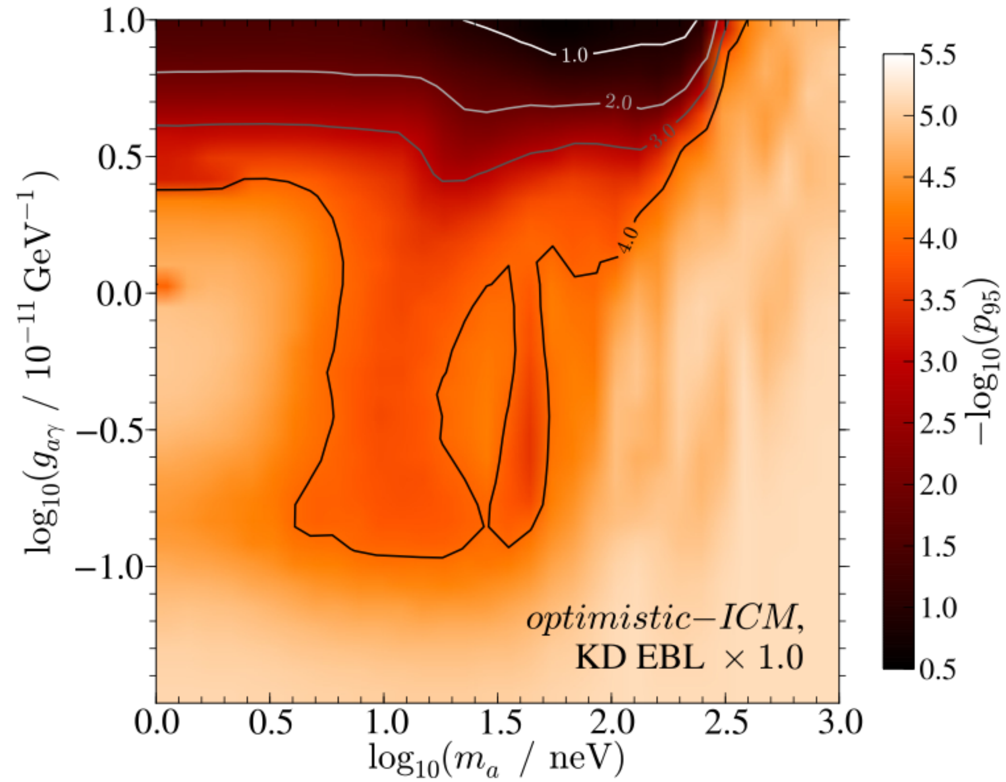
Definition of lower limit on $g_{a\gamma}$

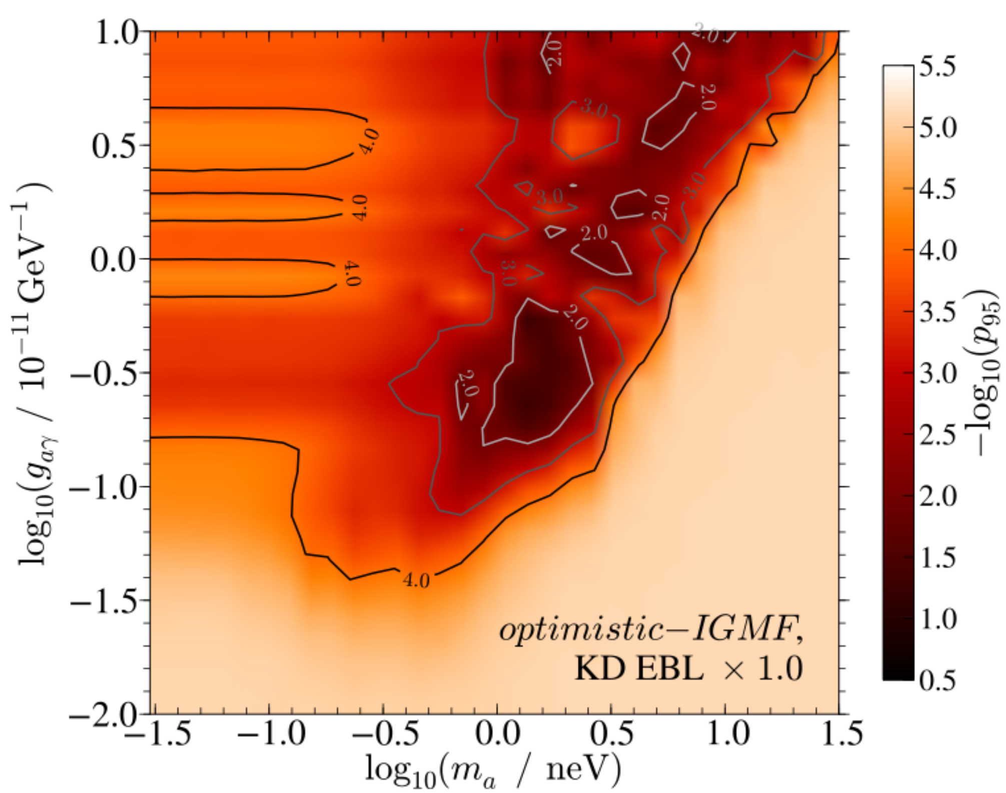
- Example: calculate 5000 random *B*-field realizations in *optimistic ICMF* scenario for one (m_a, $g_{a\gamma}$) pair
- Demand **accordance** between model and data of $p_t > 0.01$
- Demand that **at least 5% of all realizations result in $p_t > 0.01$ (p_{95}-value)**

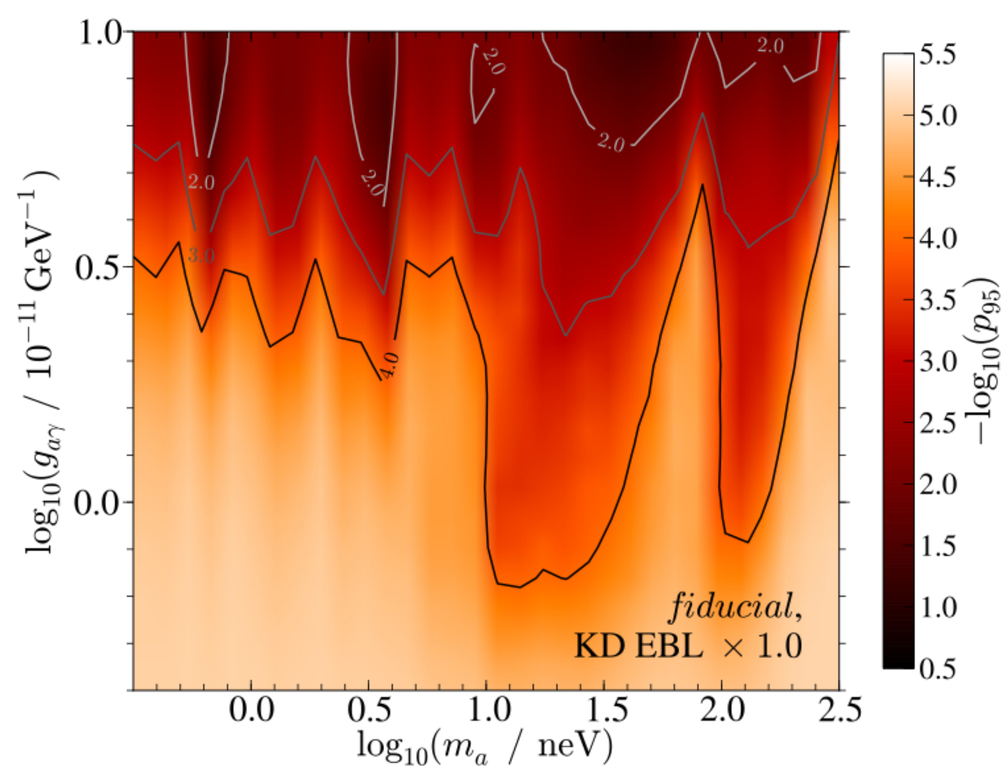


Lower limits on $g_{a\gamma}$ for EBL model of Kneiske & Dole (2010)

- Lower limits for KD model more stringent than in FRV case
- Reason: Significance of PPA higher w/o ALPs than in FRV case
- For same level of improvement as in FRV case: use 4.0 contour line

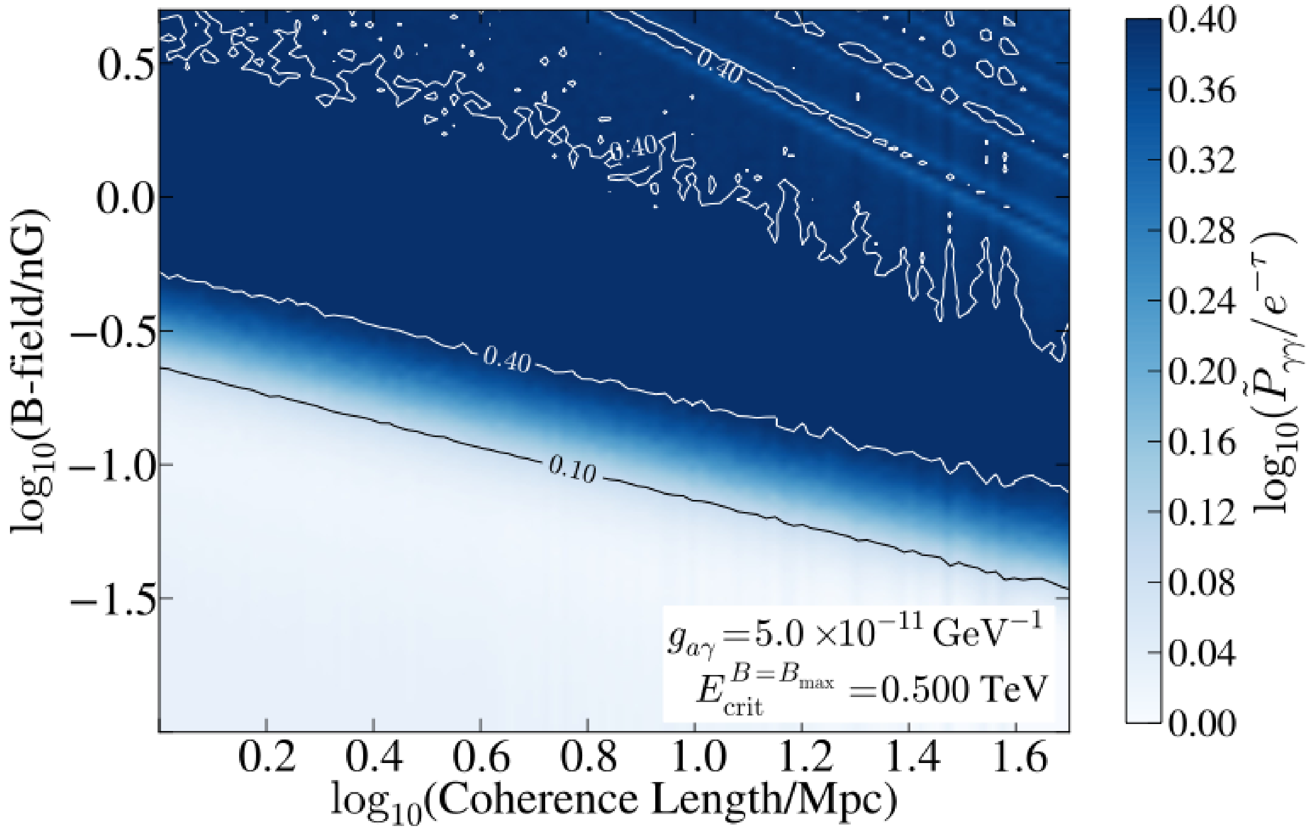


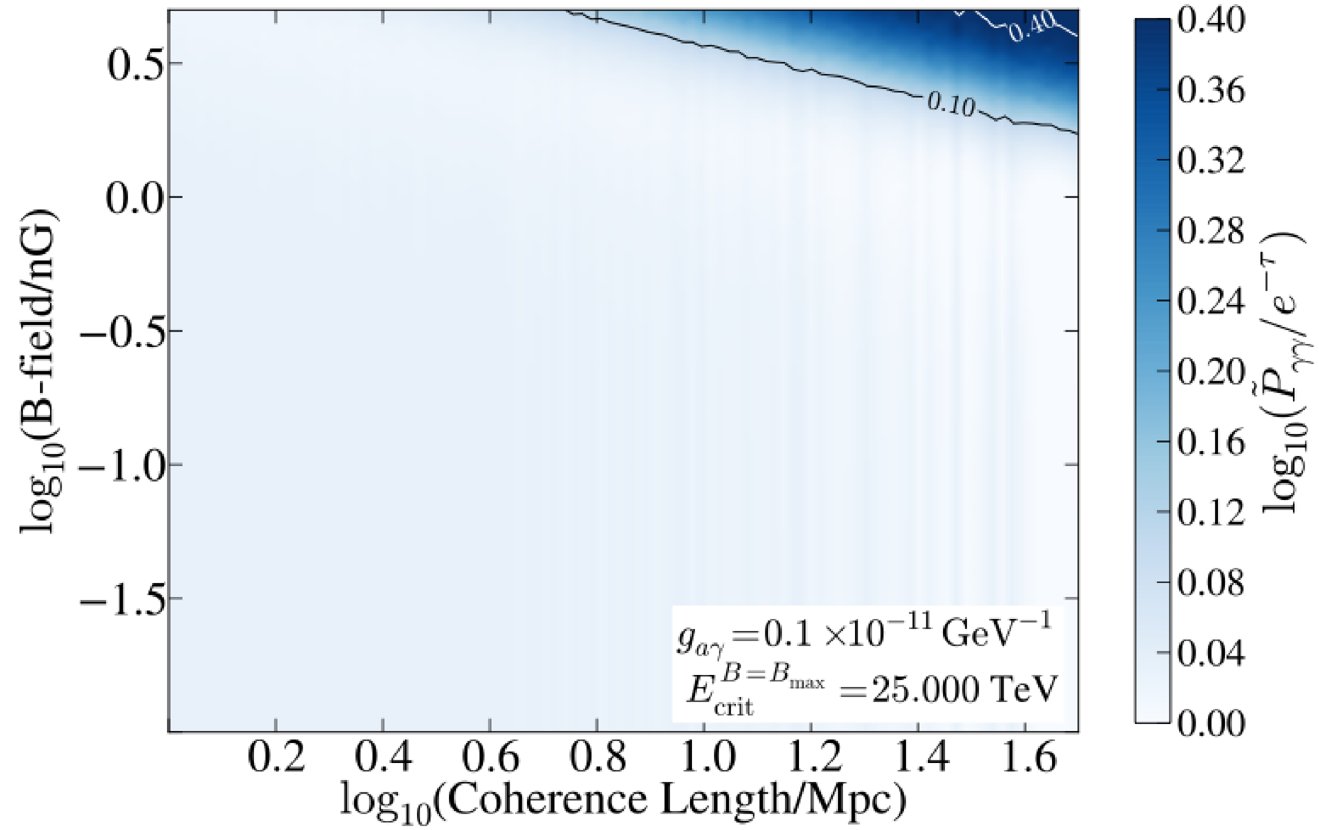




[MM, Horns, Raue 2013]

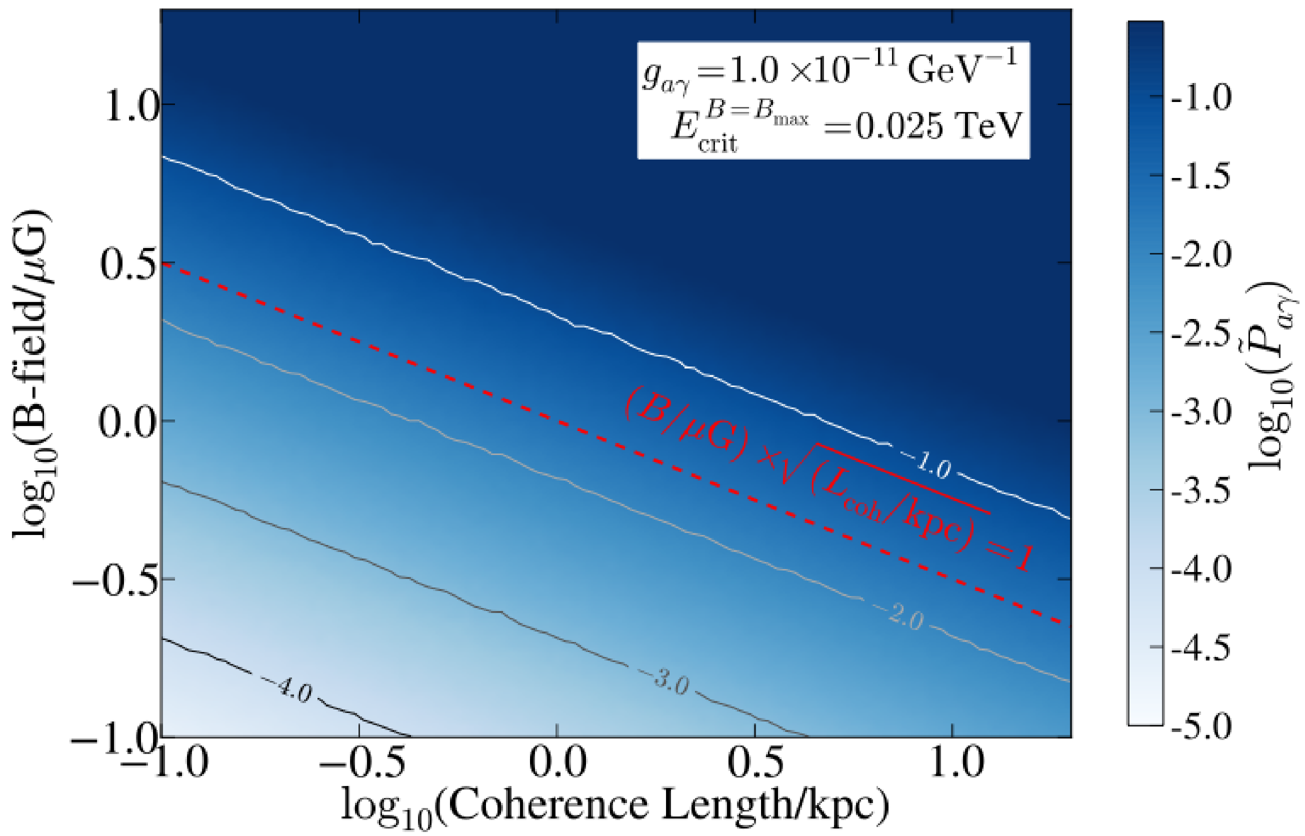
Determination of optimistic *B*-field values

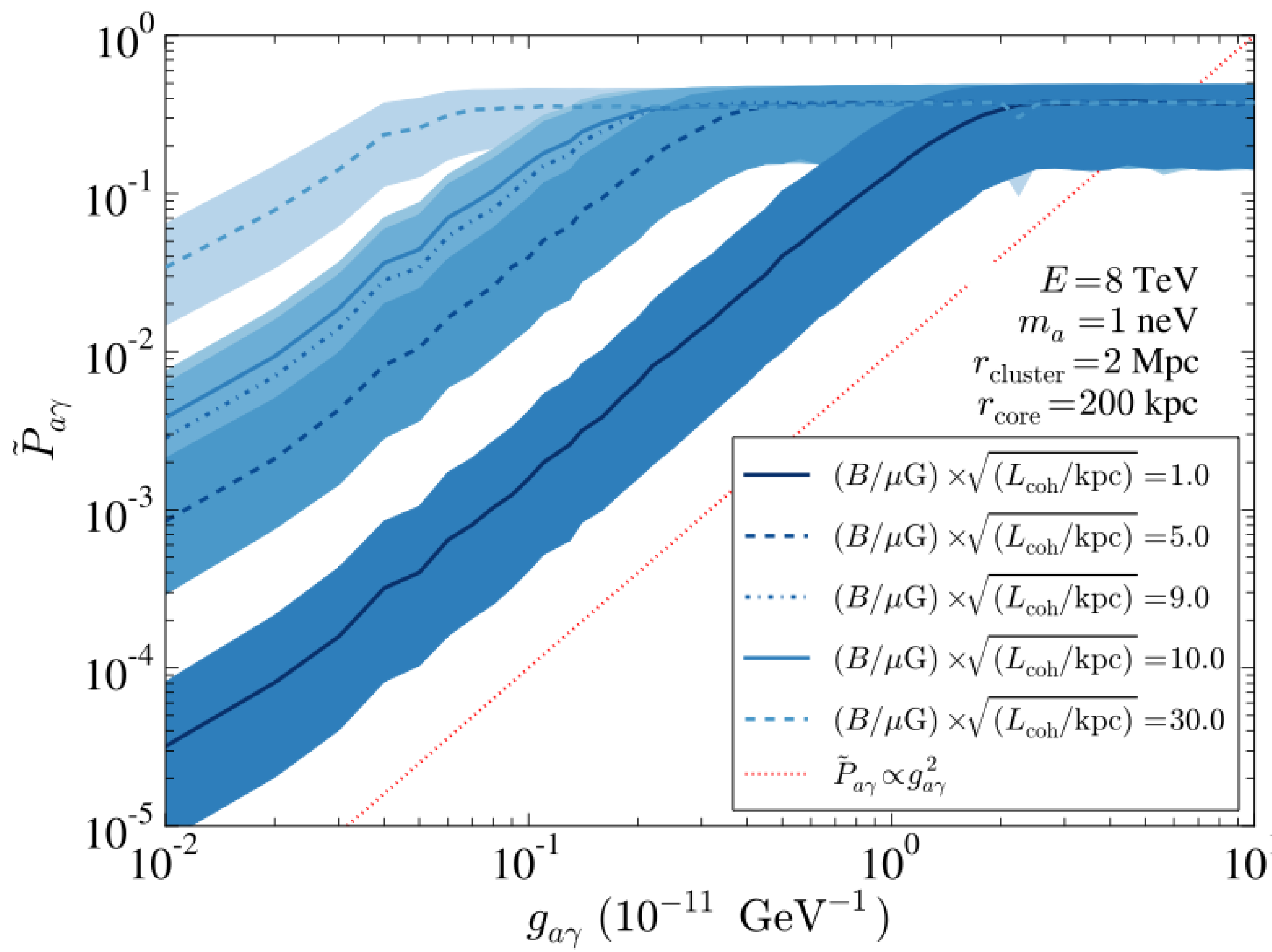




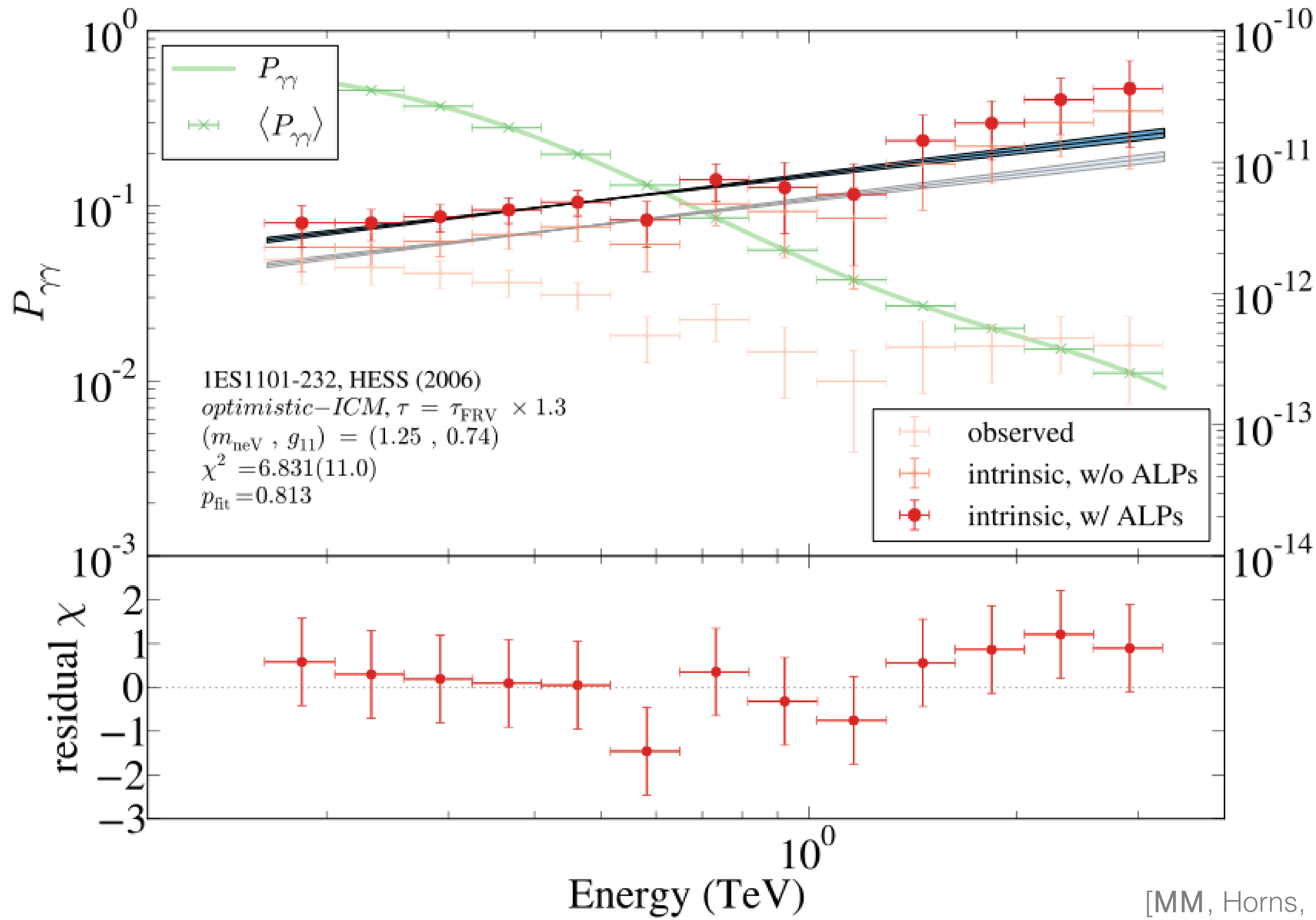
[**MM**, Horns, Raue 2013]

Determination of optimistic B-field values



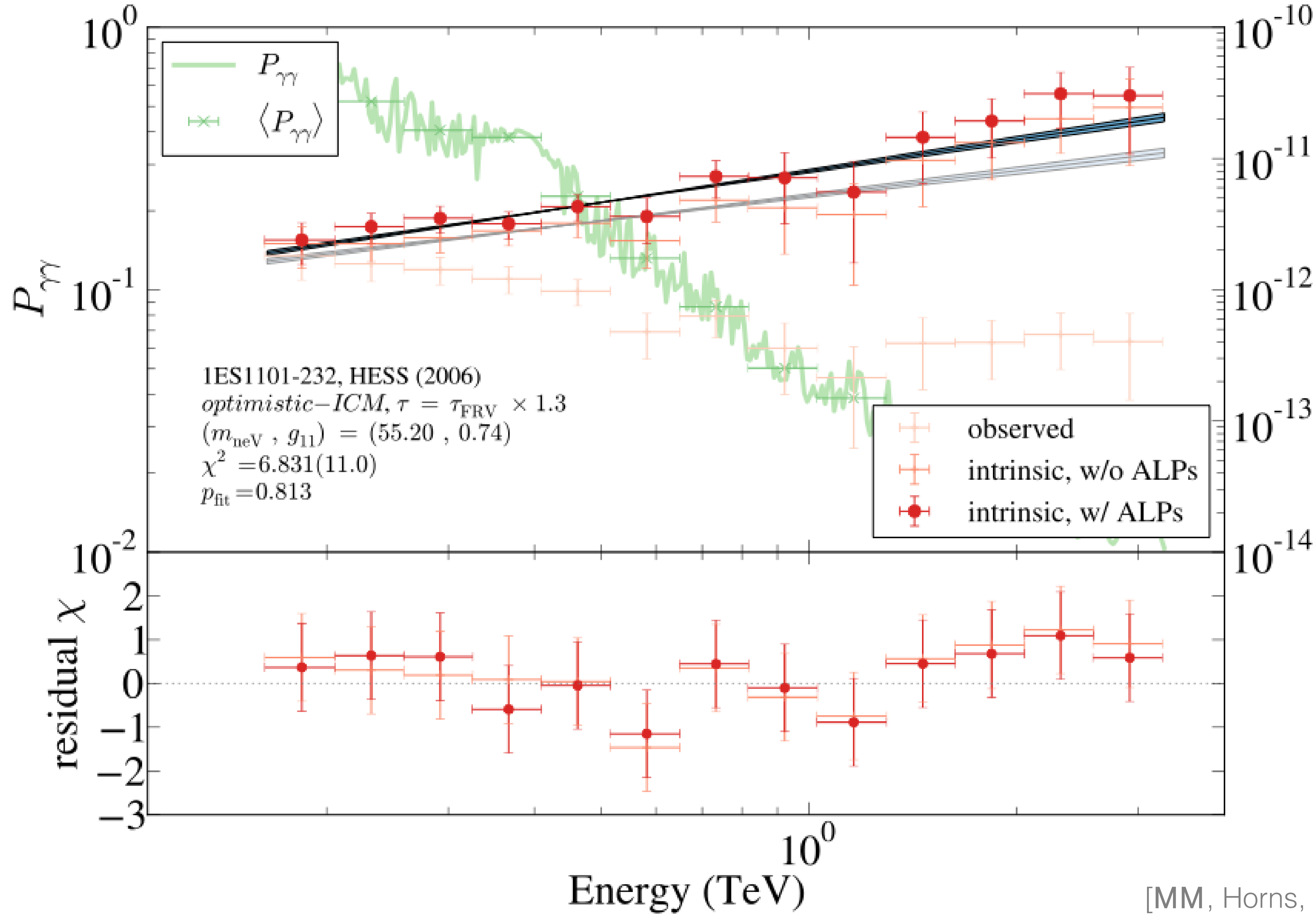


Features in lower limts on $g_{a\gamma}$



[MM, Horns, Raue 2013]

Features in lower limts on $g_{a\gamma}$



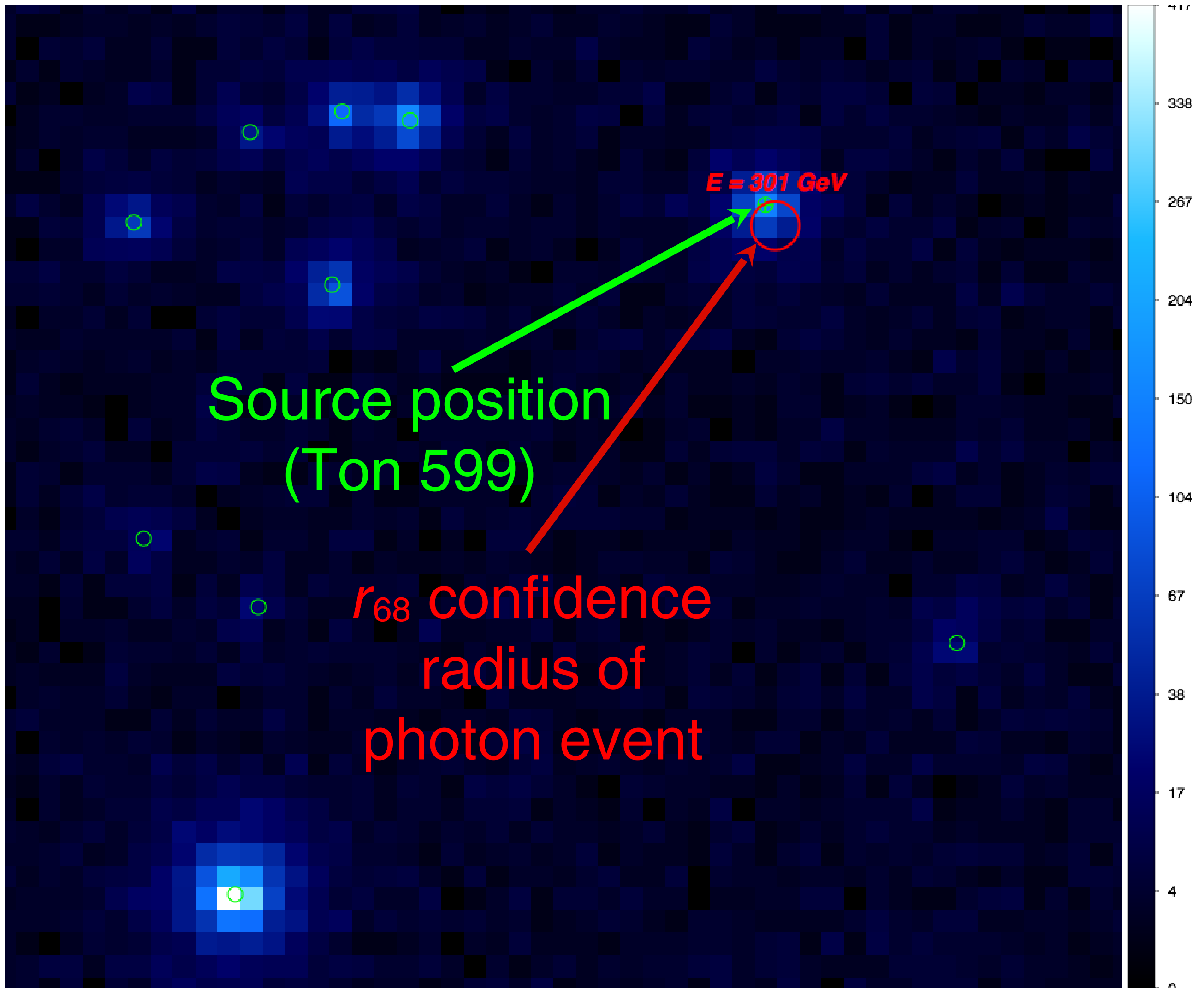
[MM, Horns, Raue 2013]

Indications for low opacity in Fermi-LAT data

Search for PPA in *Fermi*-LAT data

- **Associate photons** detected within first 4.3 years of *Fermi*-LAT **with AGN** listed in 2FGL with known redshift
- Photon associated if angular separation < 68% confidence radius of point spread function (r_{68})
- Consider only photons with E > 10 GeV outside galactic plane (b > 10°) from "ULTRACLEAN" sample
- For each associated photon, **calculate optical depth**

[Horns & **MM**, 2013; **MM**, PhD thesis 2013 – Disclaimer: analysis conducted ***before*** joining the *Fermi* -LAT collaboration]

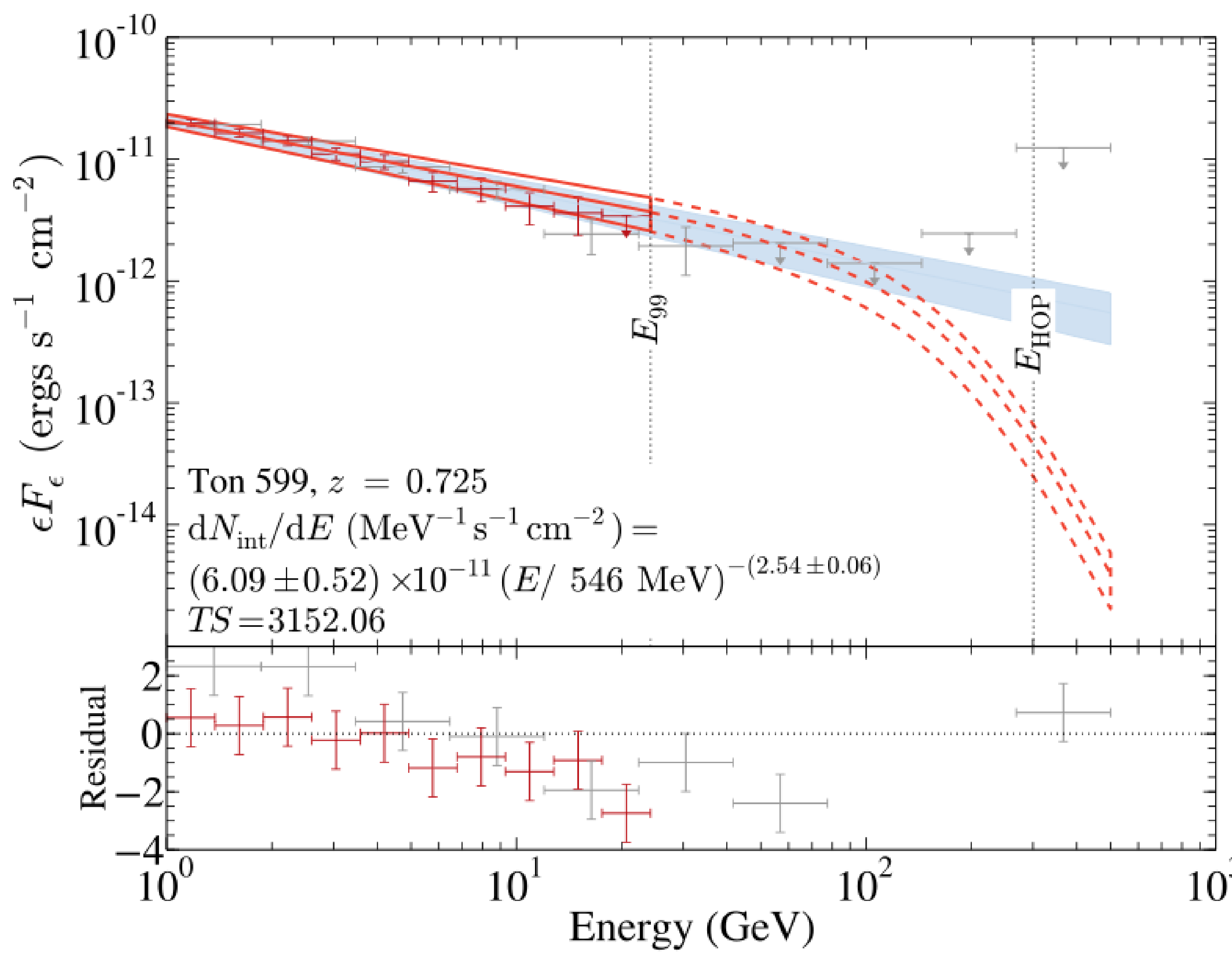


Fermi-LAT counts map with ***E* > 10 GeV** and **2FGL source positions**

Assess probability to observe the HOP

[Horns and **MM** 2013, see also **MM**, PhD thesis 2013 – Disclaimer: analysis conducted ***before*** joining the *Fermi* -LAT collaboration]

- For each associated photon, **fit power law to intrinsic spectrum**
- **Extrapolate spectrum, assume EBL model**
- Calculate **expected number** of **source** photons, λ_{pred}, and **background** photons λ_{bkg}
- **Probability** to observe at least number of detected photons $n_{0,i}$ of source *i*:

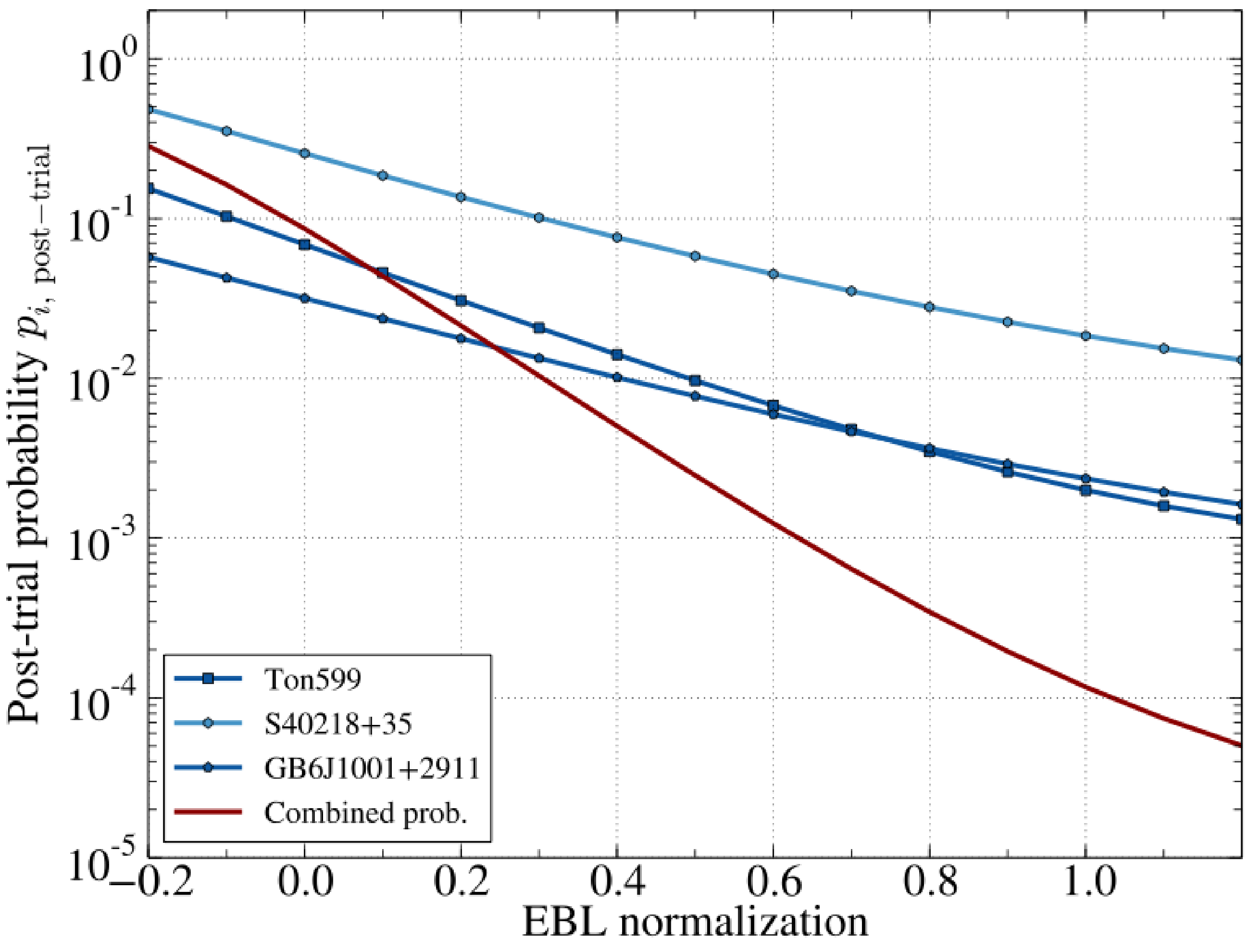


$$p_i \equiv p(n \geqslant n_{0,i}) = 1 - \sum_{k=0}^{n_{0,i}-1} \frac{\lambda_i^k}{k!} \exp(-\lambda_i)$$

$$\lambda_i = \lambda_{i,\mathrm{pred}} + \lambda_{i,\mathrm{bkg}}$$

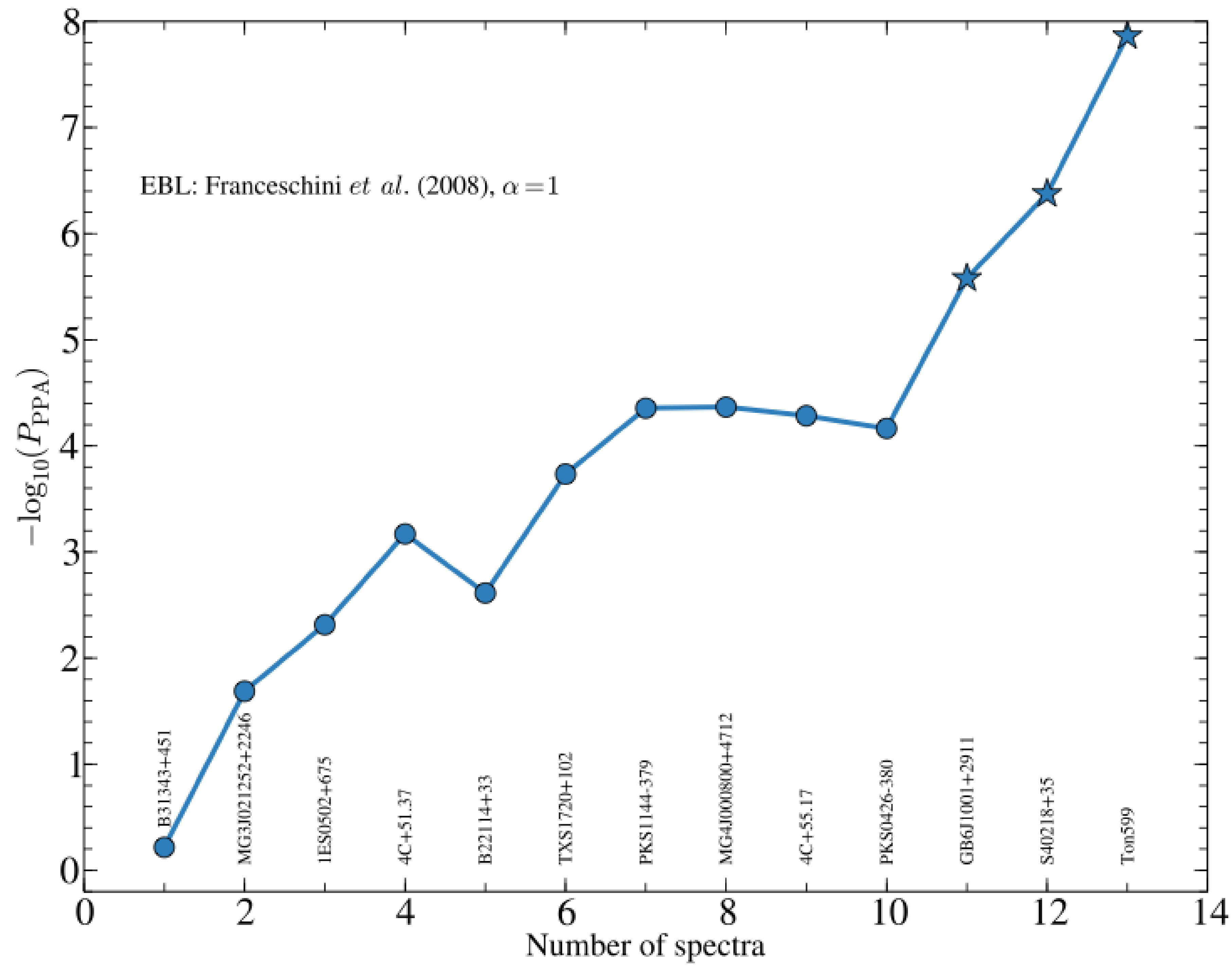
Combine probabilities from all AGN

- Each source: **independent hypothesis test**
- Include only sources for which **photon is associated with 90% confidence**
- combine probabilities using Fisher's method [Fisher, 1925]
- **Tested various systematics** (energy resolution, different intrinsic spectra, different background estimation, etc.)
- Account for **multi-trial factors**
- Result: **probability to observe detected photons for α = 1**:
  - $P_{\mathrm{PPA,\,post\text{-}trial}} = 0.06\ (\tau_{\gamma\gamma} \geq 1)$
  - $P_{\mathrm{PPA,\,post\text{-}trial}} = 1.2 \times 10^{-4}\ (\tau_{\gamma\gamma} \geq 2)$



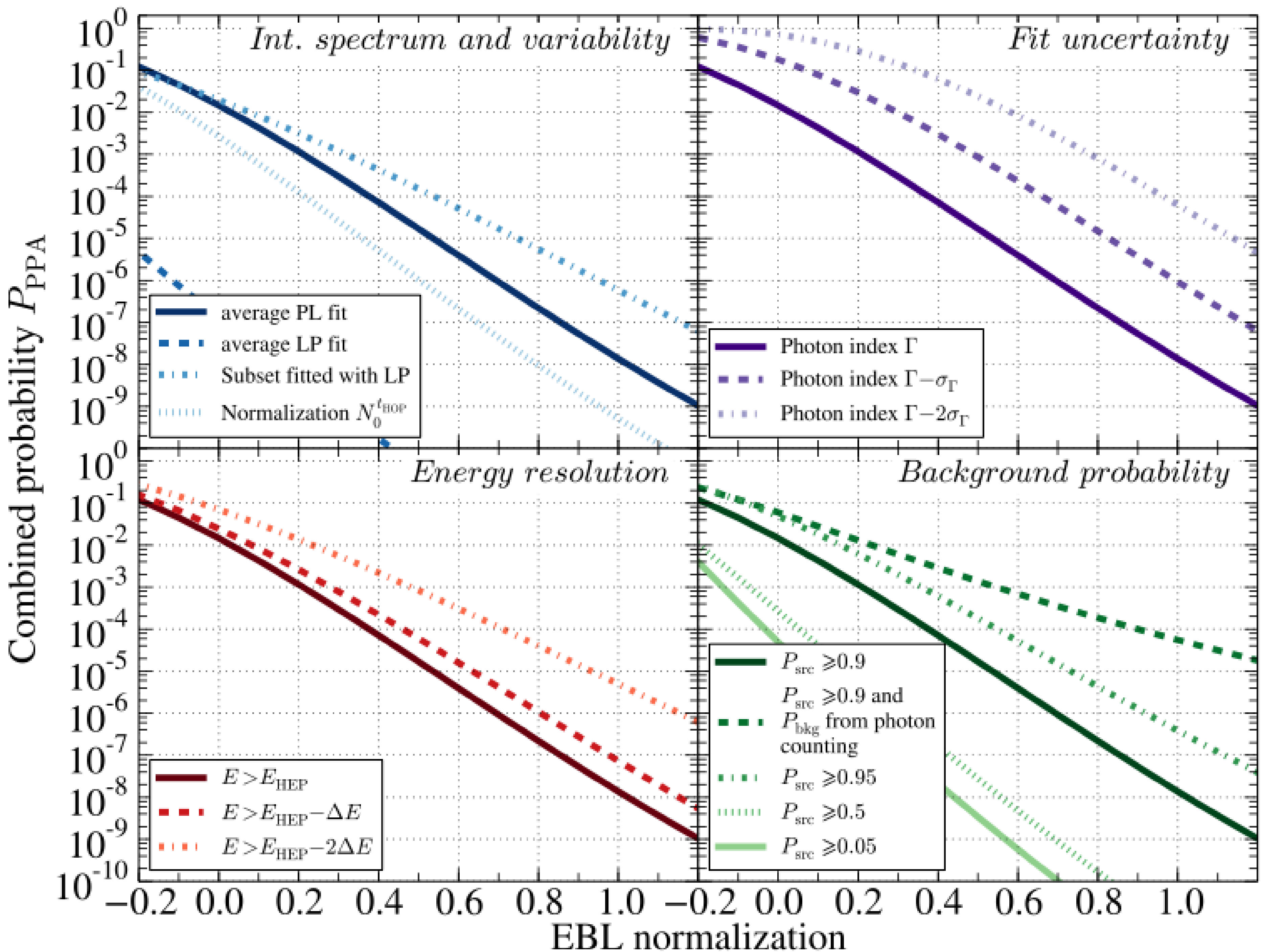
[Horns and MM 2013, see also MM, PhD thesis 2013 – Disclaimer: analysis conducted *before* joining the *Fermi* -LAT collaboration]

Cumulative significance for *Fermi*-LAT analysis



[**MM**, PhD thesis 2013 – Disclaimer: analysis conducted ***before*** joining the *Fermi* -LAT collaboration]

Cross check for *Fermi*-LAT analysis



[**MM**, PhD thesis 2013 – Disclaimer: analysis conducted ***before*** joining the *Fermi* -LAT collaboration]

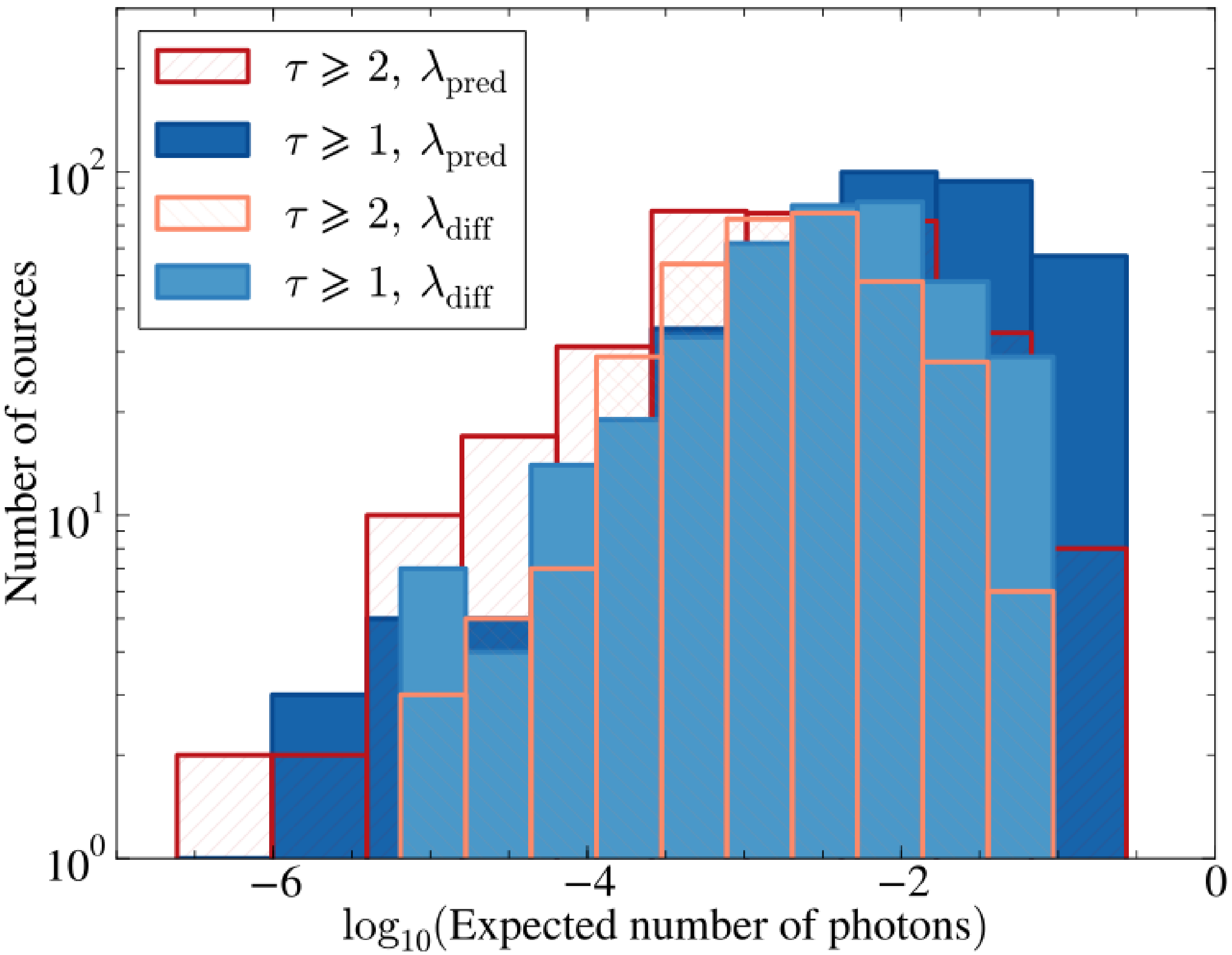
Cross check for *Fermi*-LAT analysis

Cross check	$P_{\text{PPA}}(\alpha = 1; \tau_{\gamma\gamma} \geqslant 1)$		$P_{\text{PPA}}(\alpha = 1; \tau_{\gamma\gamma} \geqslant 2)$	
fiducial[a]	1.37×10^{-8}	$5.56\,\sigma$	6.57×10^{-6}	$4.36\,\sigma$
Intrinsic spectrum and spectral hardening				
LP all spectra	5.30×10^{-14}	$7.43\,\sigma$	9.69×10^{-7}	$4.76\,\sigma$
LP for $TS_{\text{fit}} > 8$	5.12×10^{-10}	$6.12\,\sigma$	...	...
Intrinsic index $\Gamma - \sigma_\Gamma$	9.21×10^{-7}	$4.77\,\sigma$	1.85×10^{-5}	$4.16\,\sigma$
Intrinsic index $\Gamma - 2\sigma_\Gamma$	6.21×10^{-5}	$3.84\,\sigma$	6.08×10^{-5}	$3.84\,\sigma$
Normalization $N_0^{t_{\text{HOP}}}$	5.81×10^{-7}	$4.86\,\sigma$	5.15×10^{-6}	$4.41\,\sigma$
Energy resolution				
$E_{\text{HOP}} - \Delta E$	7.32×10^{-8}	$5.26\,\sigma$	3.34×10^{-5}	$3.99\,\sigma$
$E_{\text{HOP}} - 2\Delta E$	4.96×10^{-6}	$4.42\,\sigma$	1.91×10^{-4}	$3.55\,\sigma$
Source probability $P_{\text{src}}(\alpha = 0)$ and number of background photons				
$P_{\text{src}} = 0.95$	3.84×10^{-7}	$4.94\,\sigma$	2.62×10^{-4}	$3.47\,\sigma$
$P_{\text{src}} = 0.5$	7.50×10^{-12}	$6.75\,\sigma$	6.96×10^{-7}	$4.83\,\sigma$
$P_{\text{src}} = 0.05$	8.65×10^{-13}	$7.06\,\sigma$	7.69×10^{-8}	$5.24\,\sigma$
λ_{all}	5.54×10^{-5}	$3.87\,\sigma$	8.13×10^{-4}	$3.15\,\sigma$
EBL models				
KD model	5.06×10^{-9}	$5.73\,\sigma$	7.75×10^{-6}	$4.32\,\sigma$
Domínguez *et al*. (2011)	1.27×10^{-8}	$5.57\,\sigma$	5.90×10^{-6}	$4.38\,\sigma$
Inoue *et al*. (2012)	1.34×10^{-8}	$5.56\,\sigma$	2.41×10^{-5}	$4.06\,\sigma$
Trial factors				
Including trials	0.06	$1.57\,\sigma$	1.17×10^{-4}	$3.68\,\sigma$

[MM, PhD thesis 2013 – Disclaimer: analysis conducted **before** joining the *Fermi* -LAT collaboration]

Including all *Fermi*-LAT detected AGN in opacity analysis

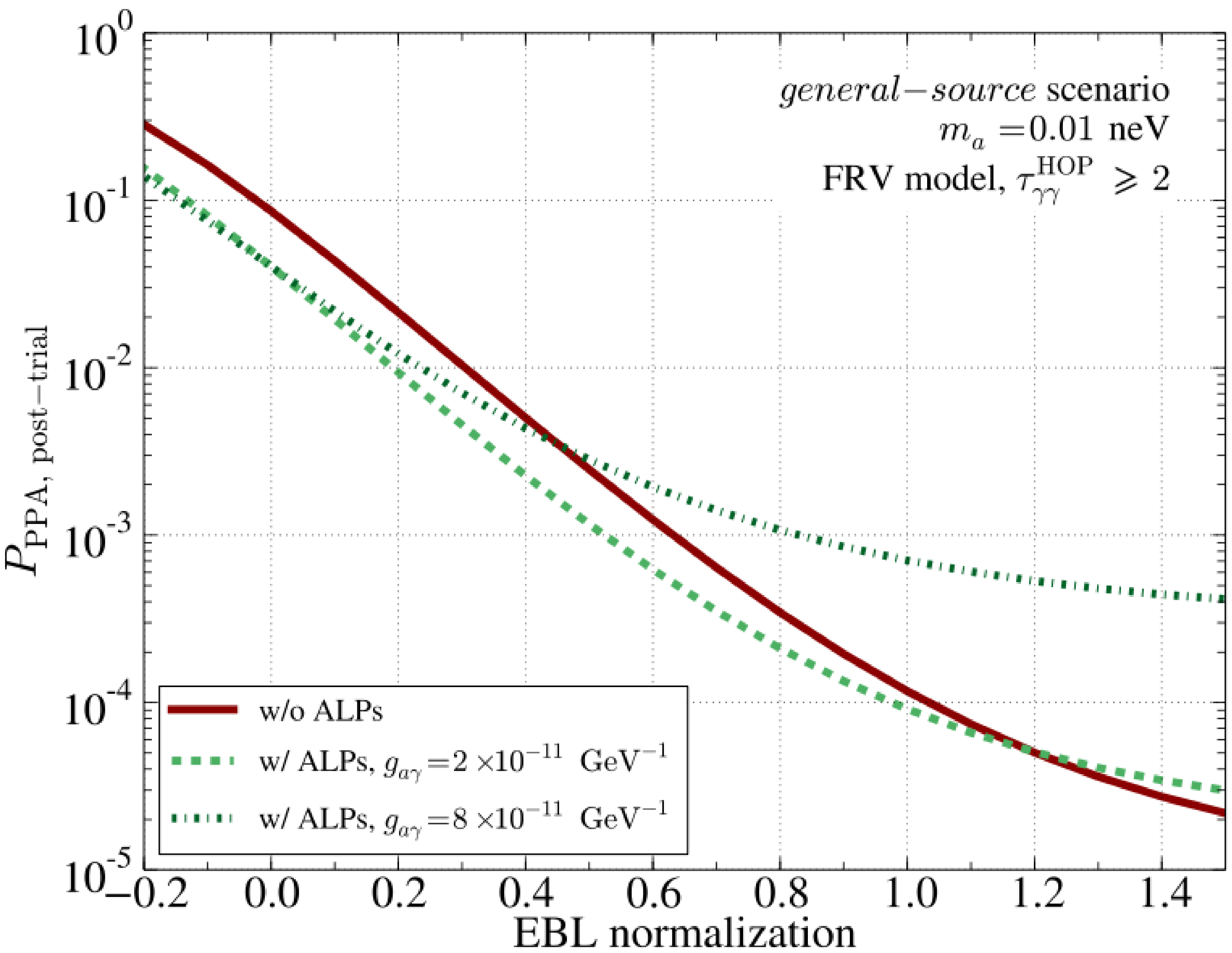
- Fermi-LAT: all-sky instrument, 2FGL lists ~400 AGN with sufficient redshift to potentially emit $\tau_{\gamma\gamma} \geq 1$ ($\tau_{\gamma\gamma} \geq 2$) photon
- If analysis is repeated with all sources that are firmly detected with Fermi-LAT, in total, 25 (3.5) photons are expected for $\tau_{\gamma\gamma} \geq 1$ ($\tau_{\gamma\gamma} \geq 2$) (*Fermi*-LAT not sensitive enough?)
- If instead of a power law, a log parabola is assumed as intrinsic spectrum, only 9 (1) photons are expected for $\tau_{\gamma\gamma} \geq 1$ ($\tau_{\gamma\gamma} \geq 2$)
- Numbers dominated by a few bright sources
- *Pass 8*: maybe more definite answer



[**MM**, PhD thesis 2013 – Disclaimer: analysis conducted ***before*** joining the *Fermi* -LAT collaboration]

Expected number of photons measured with *Fermi*-LAT including ALPs

- Calculate expected number of high optical depth photons including ALPs
- Compare with number of observed photons with *Fermi*-LAT
- ALPs improve situation



[**MM**, PhD thesis 2013 – Disclaimer: analysis conducted *before* joining the *Fermi* -LAT collaboration]