Pair-production opacity at high and very high energies

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Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

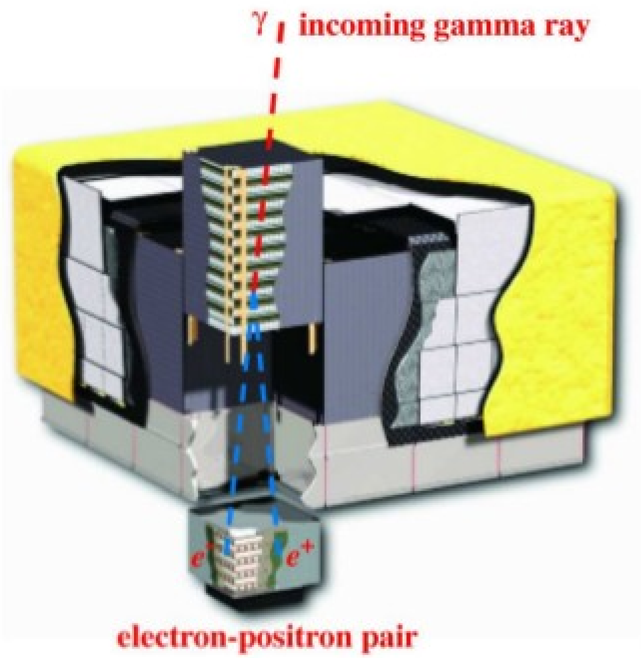
Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

High energy (HE): E>100 MeV

Meyer, M. [PhD thesis]

Very High energy (VHE): E>100 GeV

ArXiv: [1201.4711, 1207.0776, 1302.1208]



with Alessandro Mirizzi, Marco Roncadelli, Alessandro Montanino, Luca Maccione, Martin Raue, Tanja Kneiske

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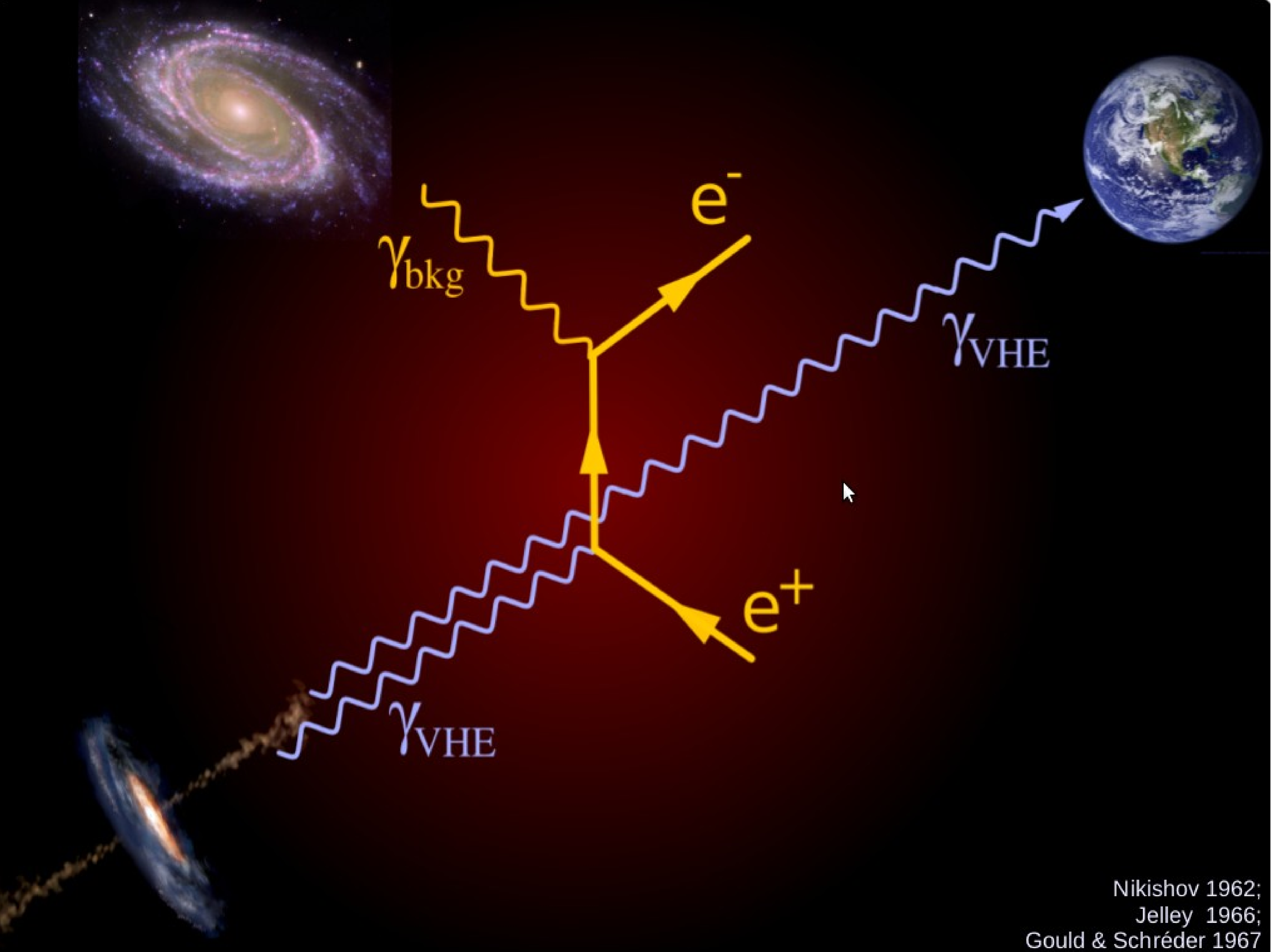


γbkg
e-
γVHE
e+
γVHE
Nikishov 1962;
Jelley 1966;
Gould & Schréder 1967

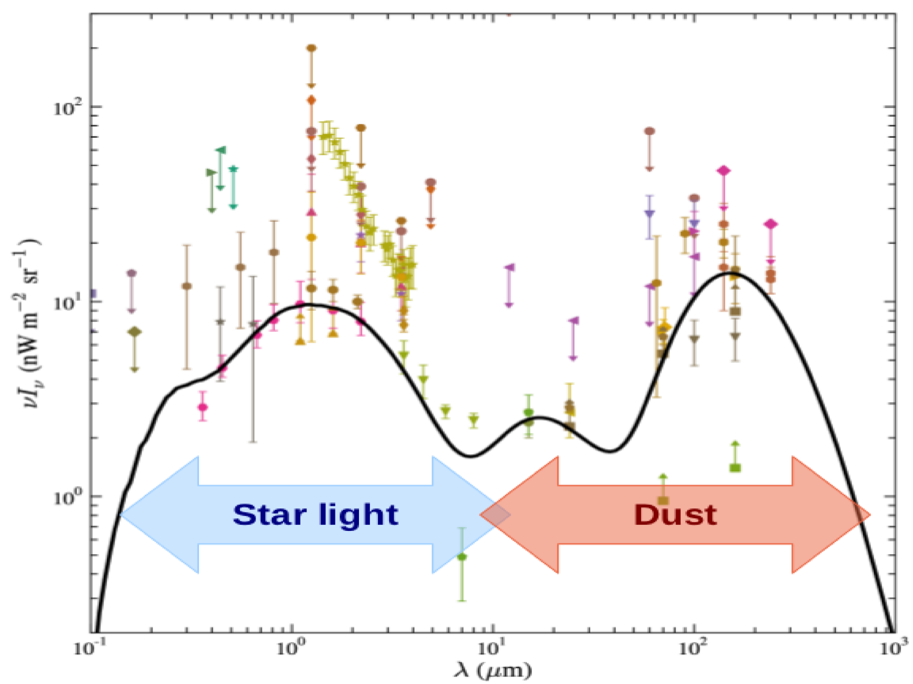
Pair-production → absorption+ reprocessing of gamma-rays

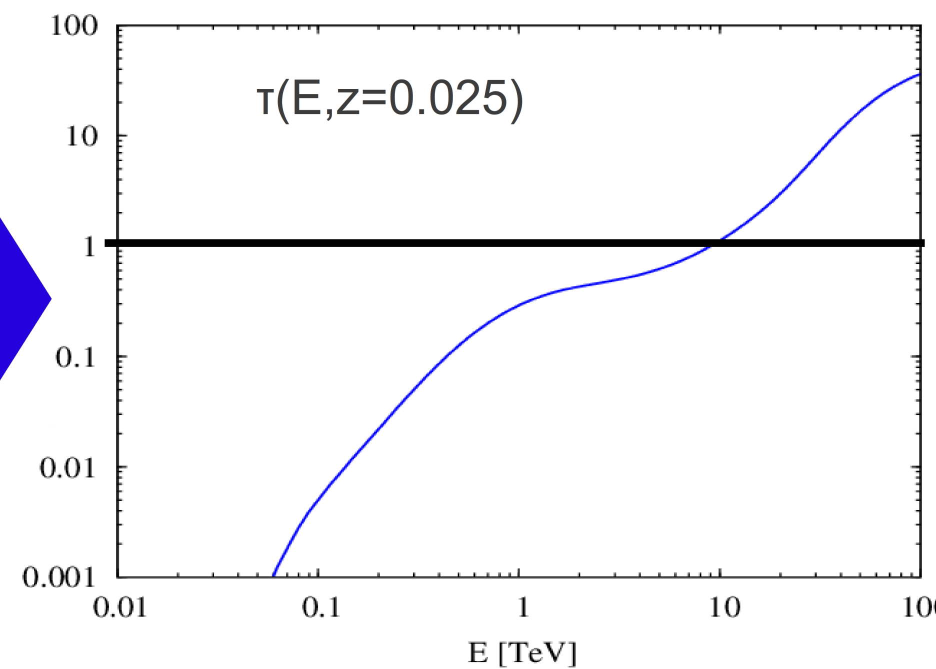
Photon density of EBL
εn(0.8eV,z=0)~10^{-2} cm^{-3}

$$\tau_\gamma(E, z_0) = \int_0^{z_0} d\ell(z) \int_{-1}^{+1} d\mu \frac{1-\mu}{2} \int_{\epsilon_{\rm thr}}^{\infty} d\epsilon' n_{\rm EBL}(\epsilon', z) \sigma_{\gamma\gamma}(E, \epsilon', \mu)$$

Pair production cross
Section peaks at
λ=1.2 μm (E/TeV)
~σ_T~6×10^{-25} cm^2

$$\frac{dN_{\rm obs}}{dE} = \frac{dN_{\rm int}}{dE} \times \exp\left[-\tau_\gamma(E, z_0)\right]$$





Pair-production → absorption+ reprocessing of gamma-rays

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$$\frac{dN_{obs}}{dE} = \frac{dN_{int}}{dE} \times \exp\left[-\tau_\gamma(E,z_0)\right]$$

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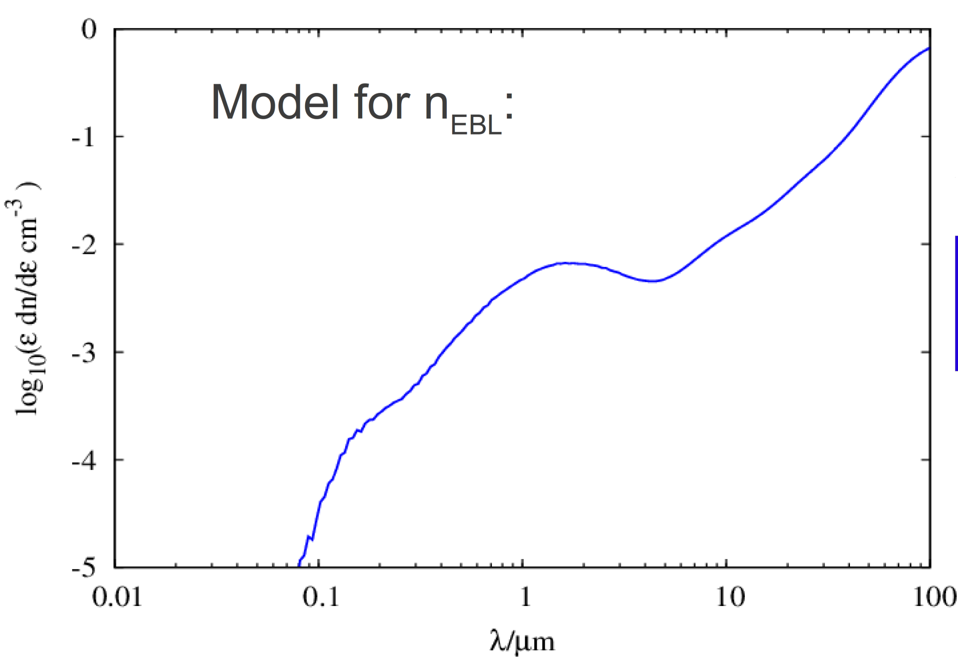
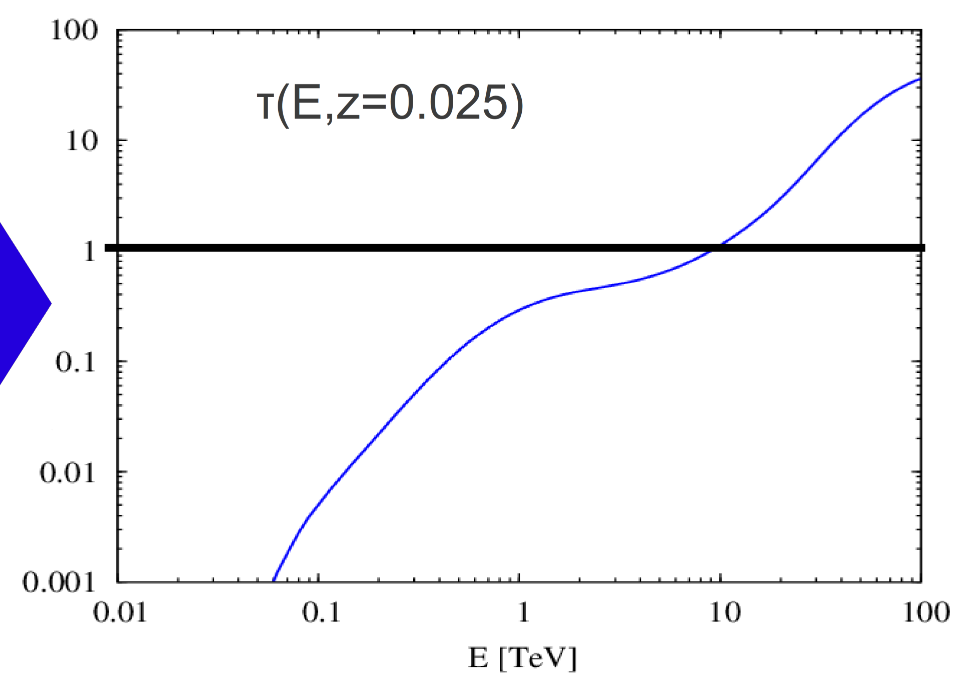


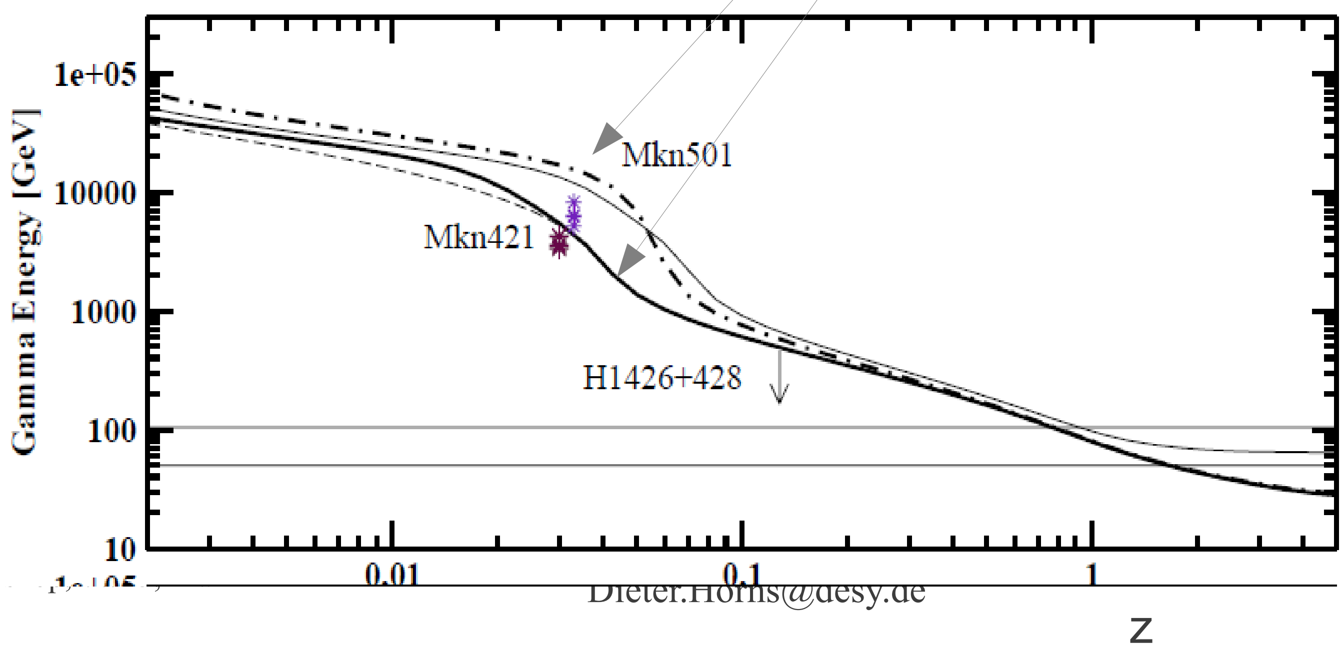


Gamma-ray opacity

- Pair production of gamma-rays with background photons: *“GZK”-like cut-off for photons* [Jelley 1966], [Gould & Schréder 1967]

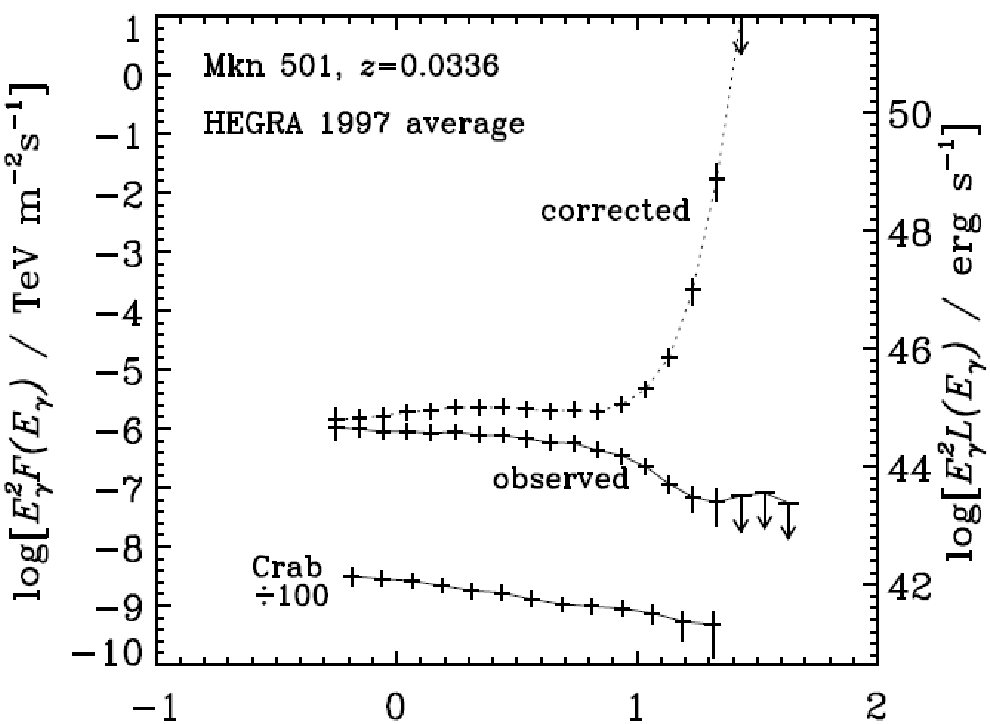
$$\tau_\gamma(E, z_0) = \int_0^{z_0} \mathrm{d}\ell(z) \int_{-1}^{+1} \mathrm{d}\mu \frac{1-\mu}{2} \int_{\epsilon'_{\mathrm{thr}}}^{\infty} \mathrm{d}\epsilon' \, n_{\mathrm{EBL}}(\epsilon', z) \sigma_{\gamma\gamma}(E', \epsilon', \mu).$$

- To first order: exponential cut-off at τ(E,z)=1 “Fazio-Stecker” relation [Fazio&Stecker 1970],[Kneiske et al. 2004]



1st TeV crisis in 2000: new physics?

- Observations of Mkn 501 (z=0.03) in a flaring state in 1997 – spectrum with cut-off at 5 TeV measured up to > 20 TeV
  [HEGRA coll. 1999]
- After correcting the observed spectrum $\frac{dN_{obs}}{dE} = \frac{dN_{int}}{dE} \times \exp\left[-\tau_\gamma(E, z_0)\right]$



[Protheroe&Meyer 2000]

suggested remedies:
a) lower the EBL
b) shift the energy scale of HEGRA
c) Bose-Einstein-Condensate of gamma-rays
d) Lorentz invariance violation

a) most likely
b) ruled out [Meyer, DH, Zechlin 2010]
c) is excluded from observations [DH 2000]
d) not entirely ruled out (→ D-branes of Ellis/Nanopoulos)

Extragalactic background light (EBL)

Excellent review in Dwek&Krennrich [arxiv:1209.4661]

- Direct measurements → overwhelming foreground
- Lower limits from galaxy counts → constrained to optical/near infrared
- Upper limits from VHE&HE spectroscopy
- New: Measurement of EBL-normalization of EBL-models from VHE & HE spectroscopy

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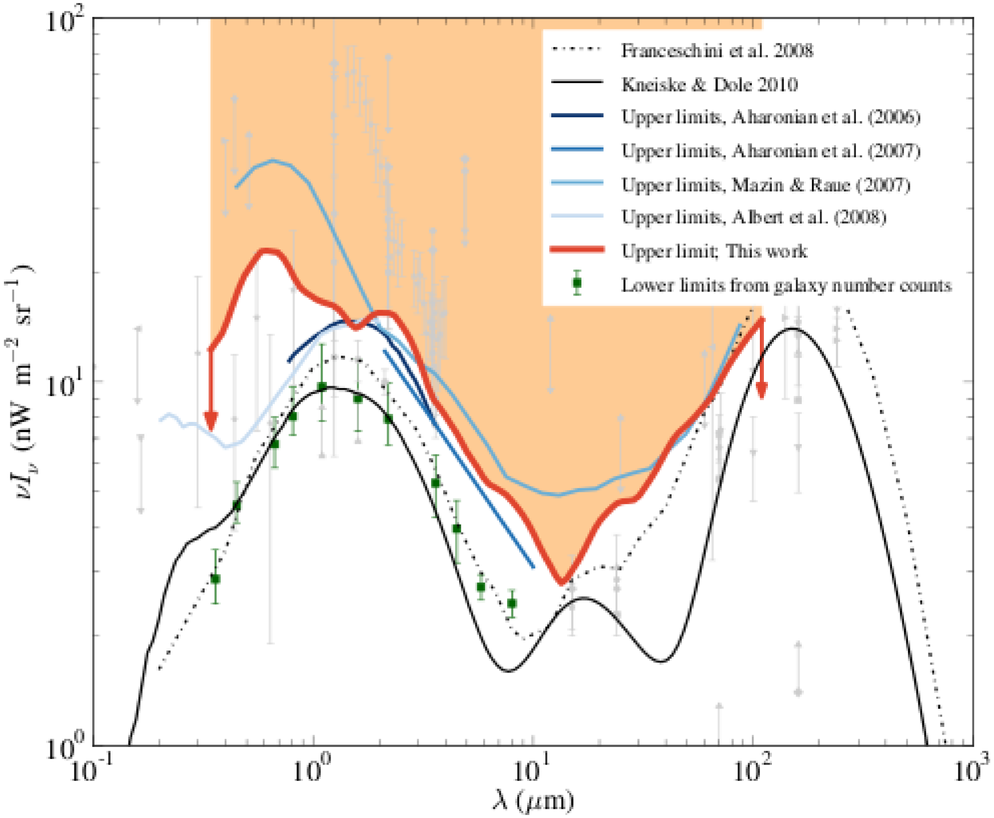
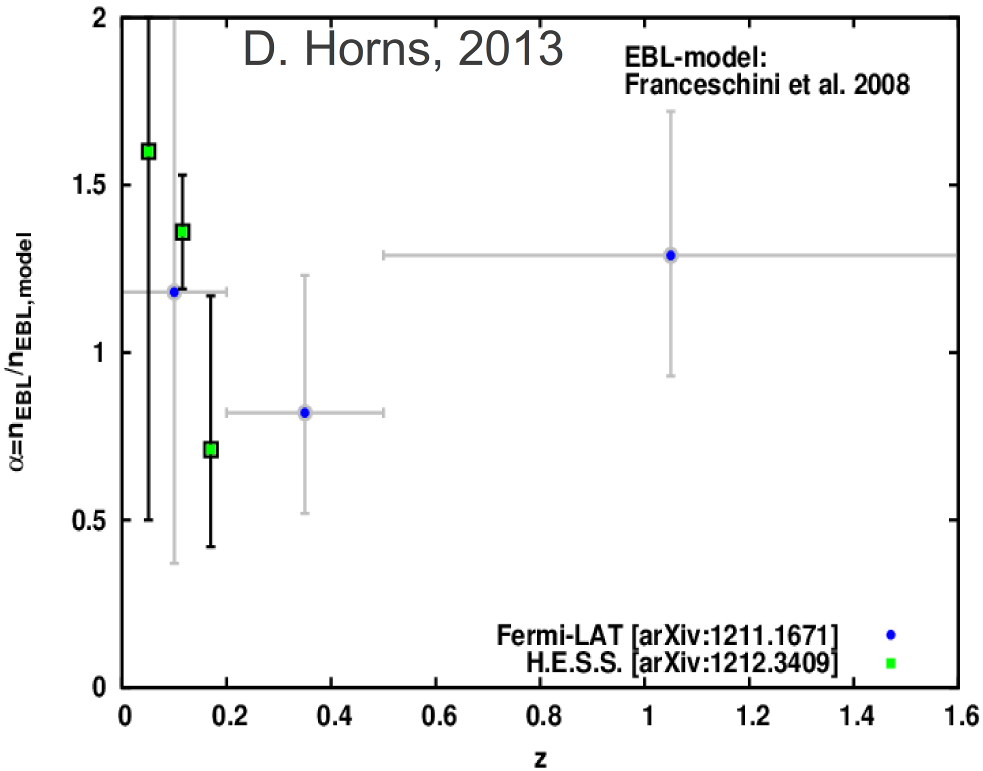
Constraining the EBL with VHE/HE spectroscopy

Meyer, Raue, Mazin & DH [arxiv:1202.2867]



Measuring a model-normalization with VHE/HE spectroscopy



What happens in the optically thick regime? (assuming a minimal EBL)

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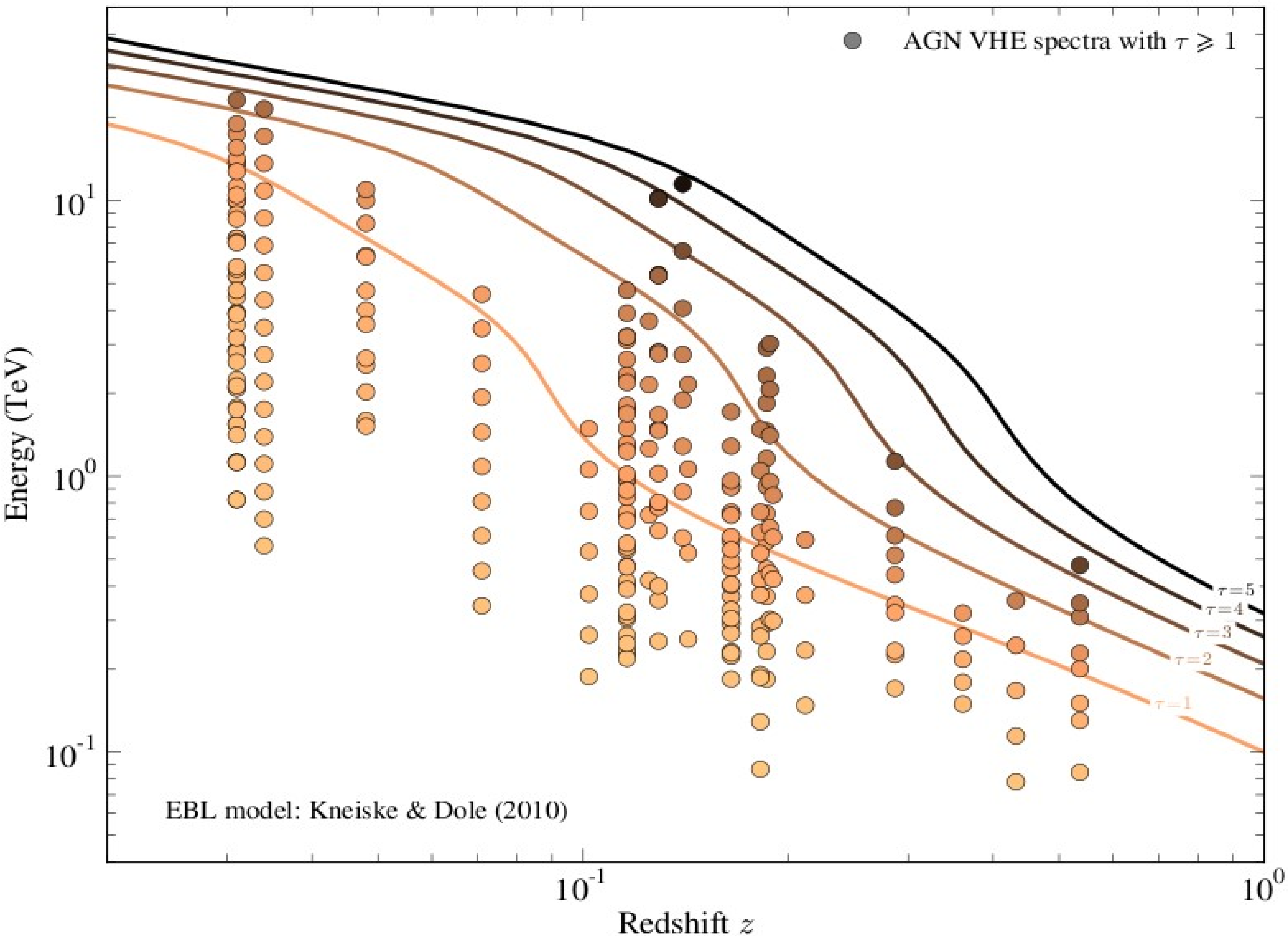
A coherent analysis of all VHE spectra from Blazars

DH & Meyer
[arXiv:1201.4711]



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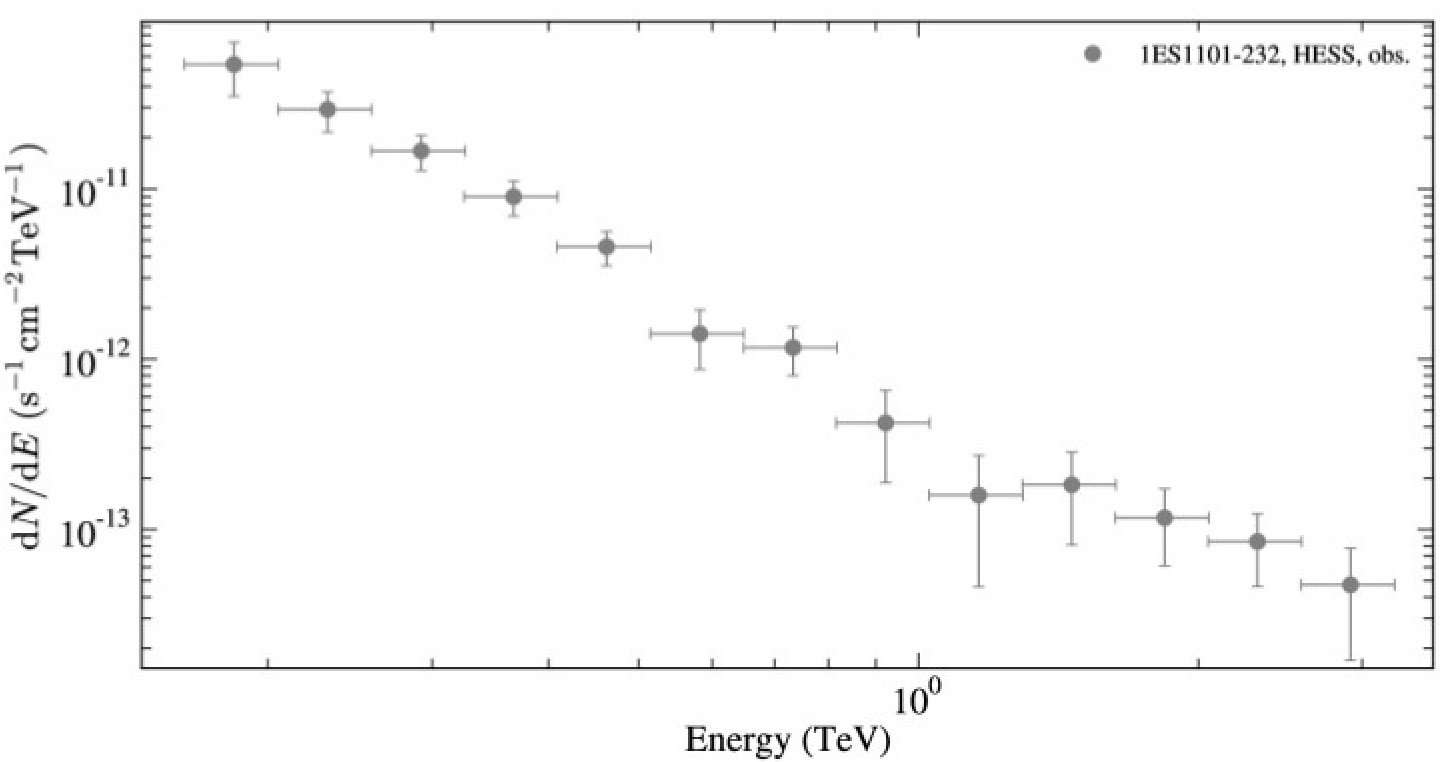
Method

- Correct observed spectra with lower limit EBL model



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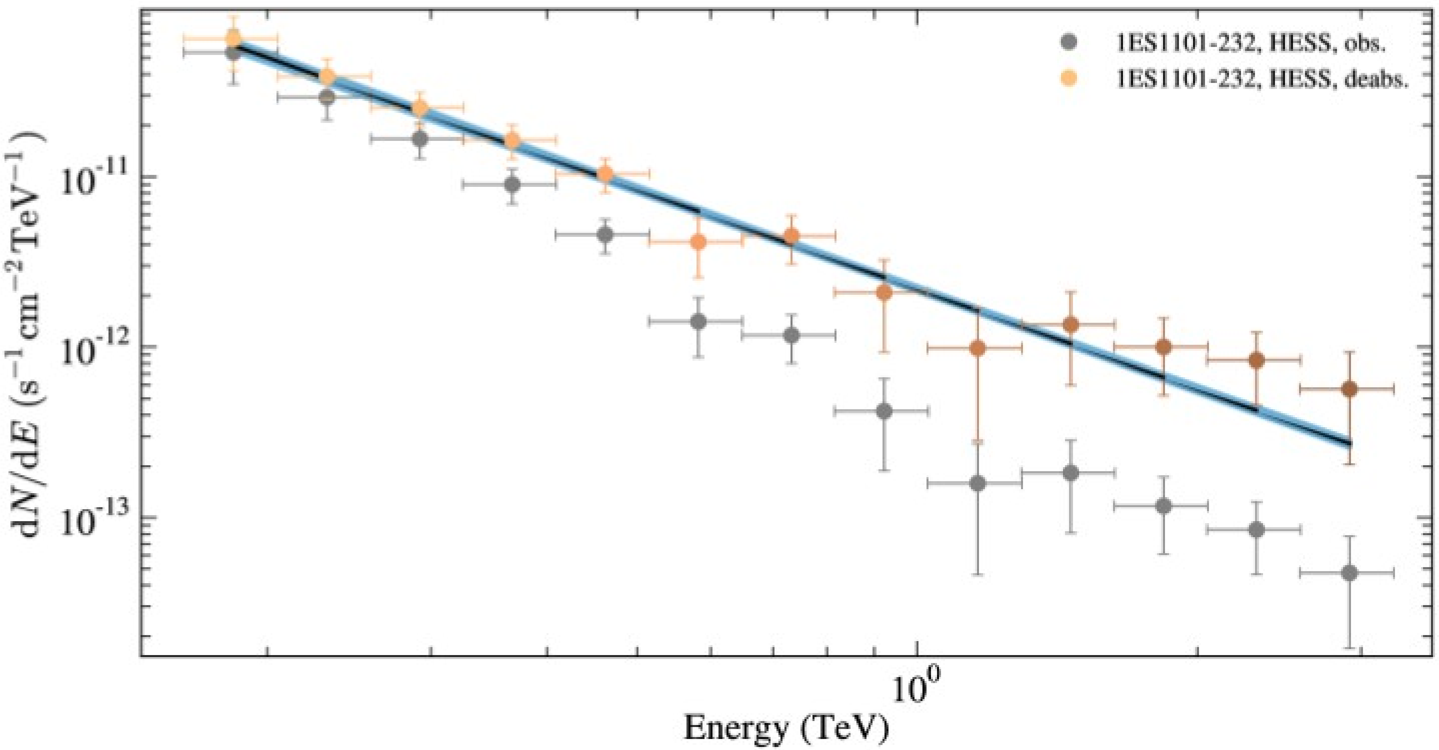
Method

- Correct observed spectra with lower limit EBL model
- Fit analytical function to intrinsic spectrum



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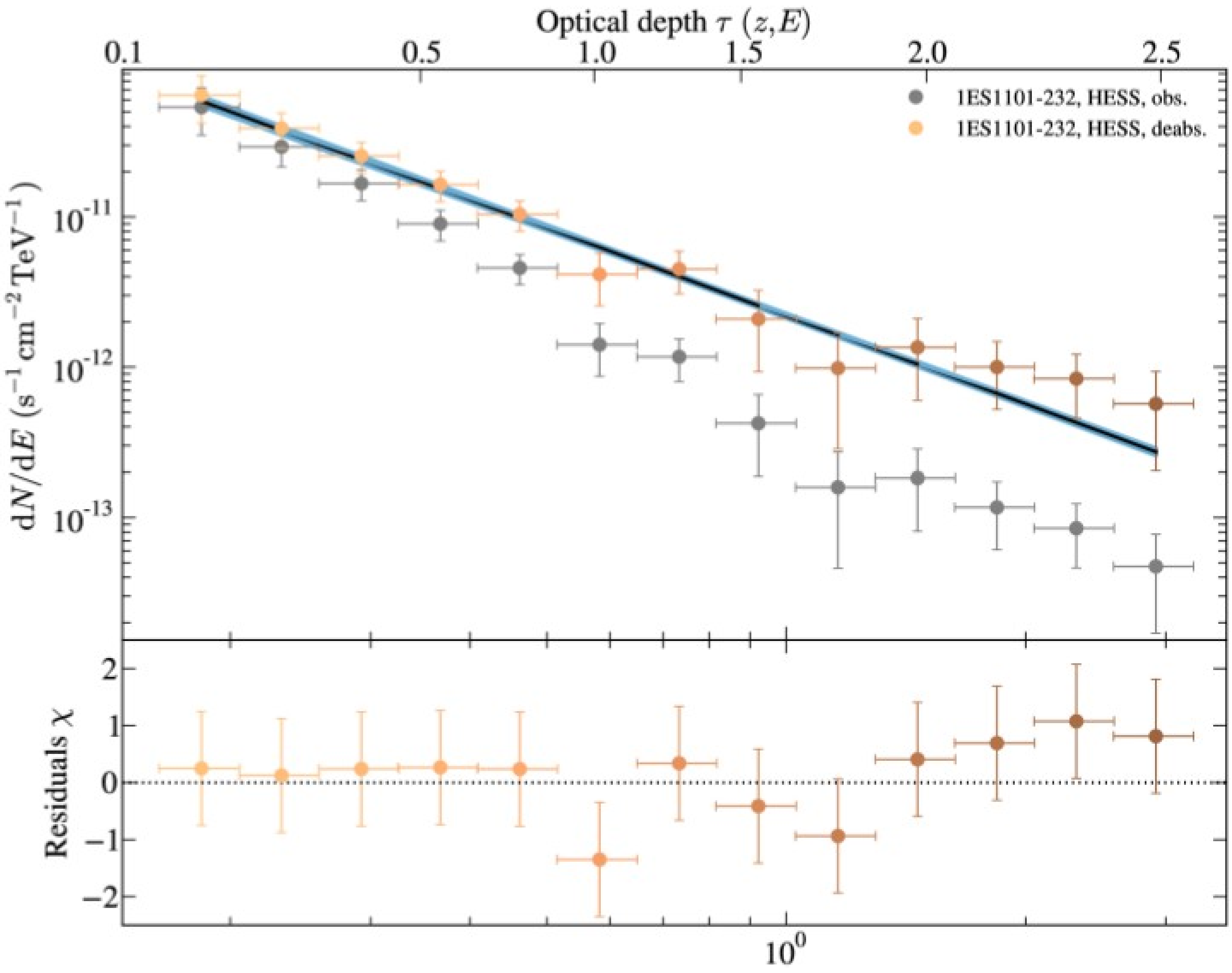
Method

- Correct observed spectra with lower limit EBL model
- Fit analytical function to intrinsic spectrum
- Calculate residuals, should scatter around 0



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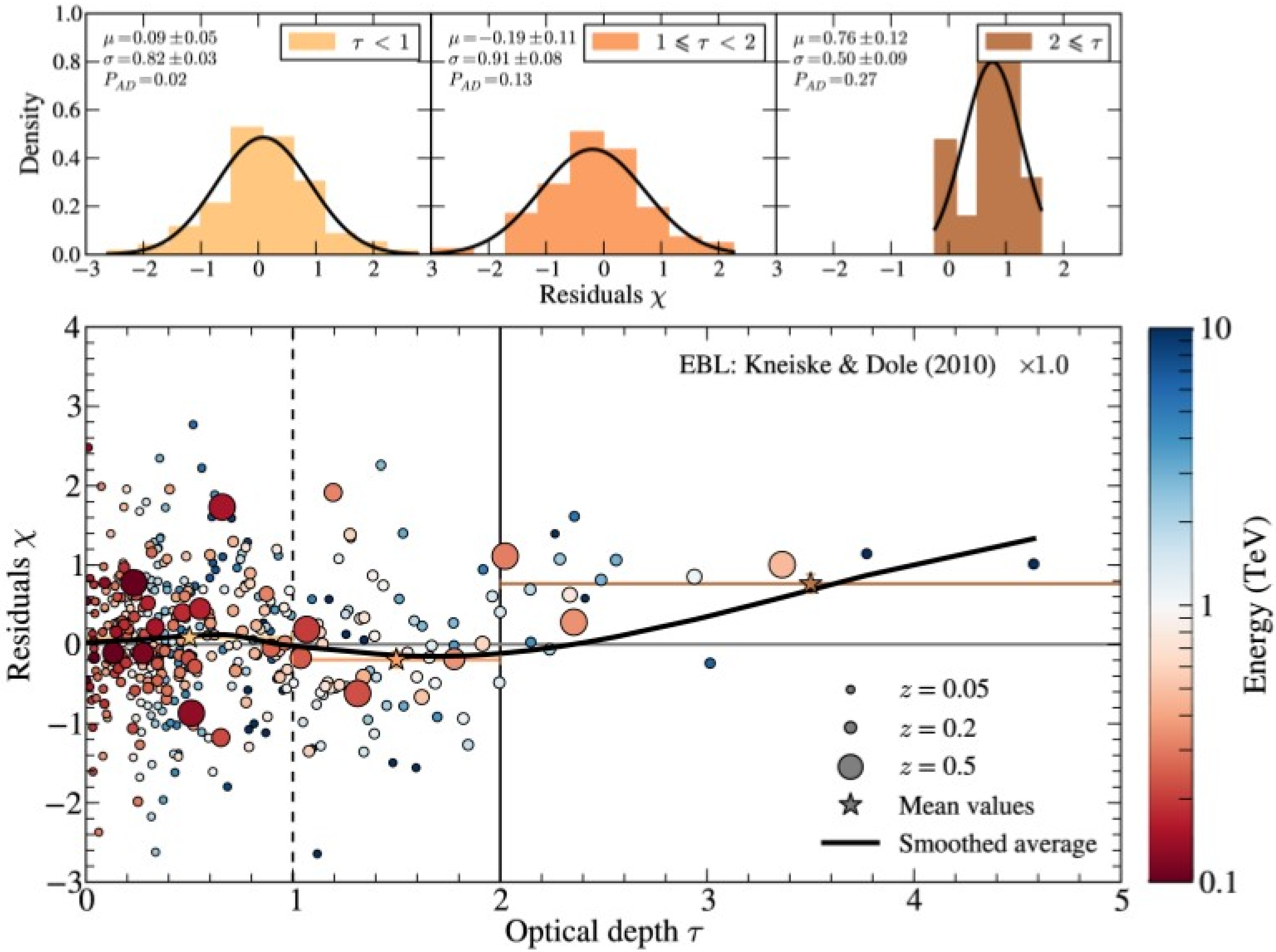
Method

[DH & M. Meyer arXiv: 1201.4711]

- **Residuals** in optical thick regime **do not scatter around 0**
- absorption corrected points **lie above the fit**
- ***Result (pair production anomaly) significant with 4.3σ***
- Systematic effects (energy resolution, spill over, single spectra, cross check with galactic sources…) cannot account for the effect
- **Can Axion-like particles reduce the tension?**



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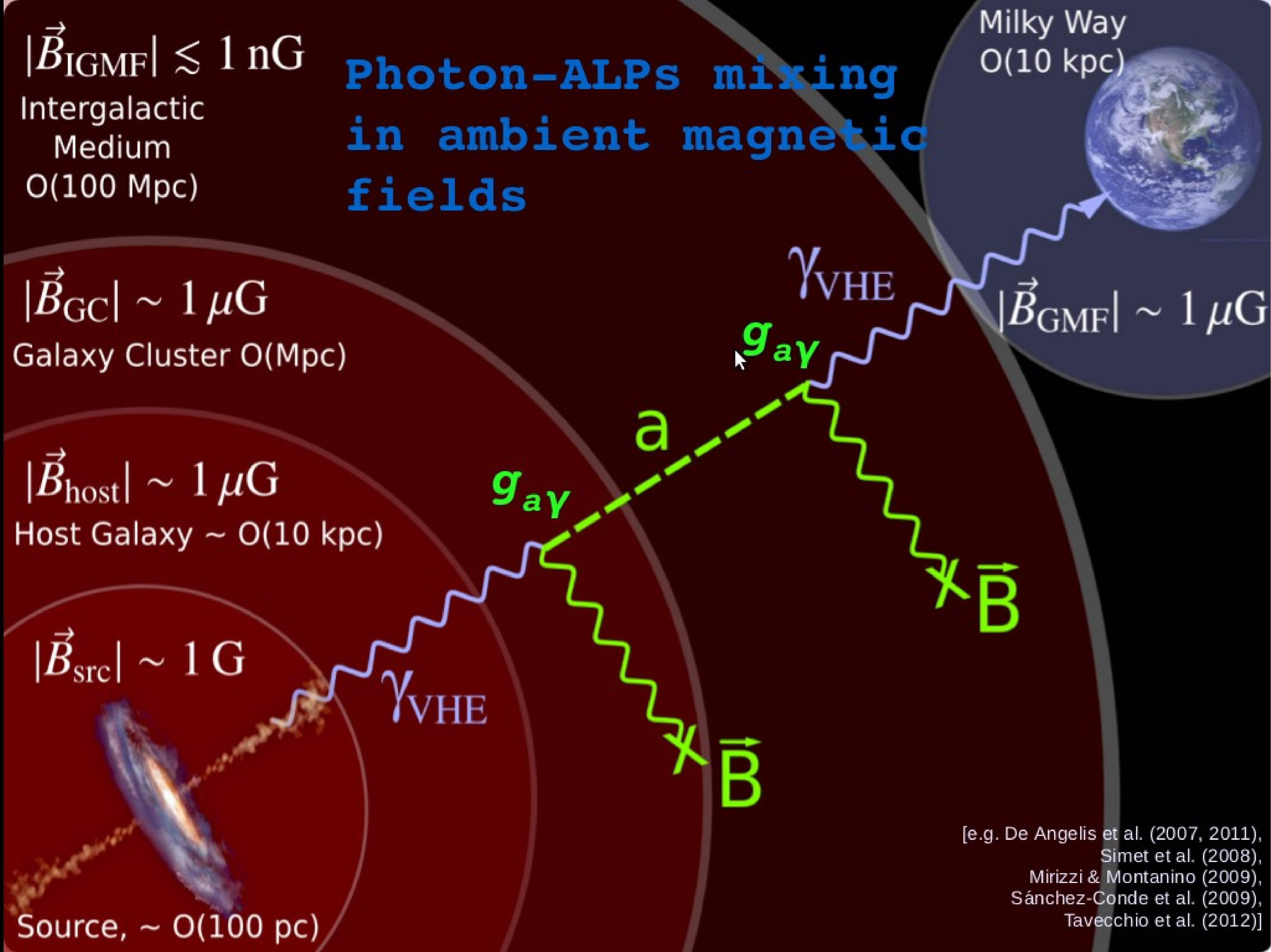
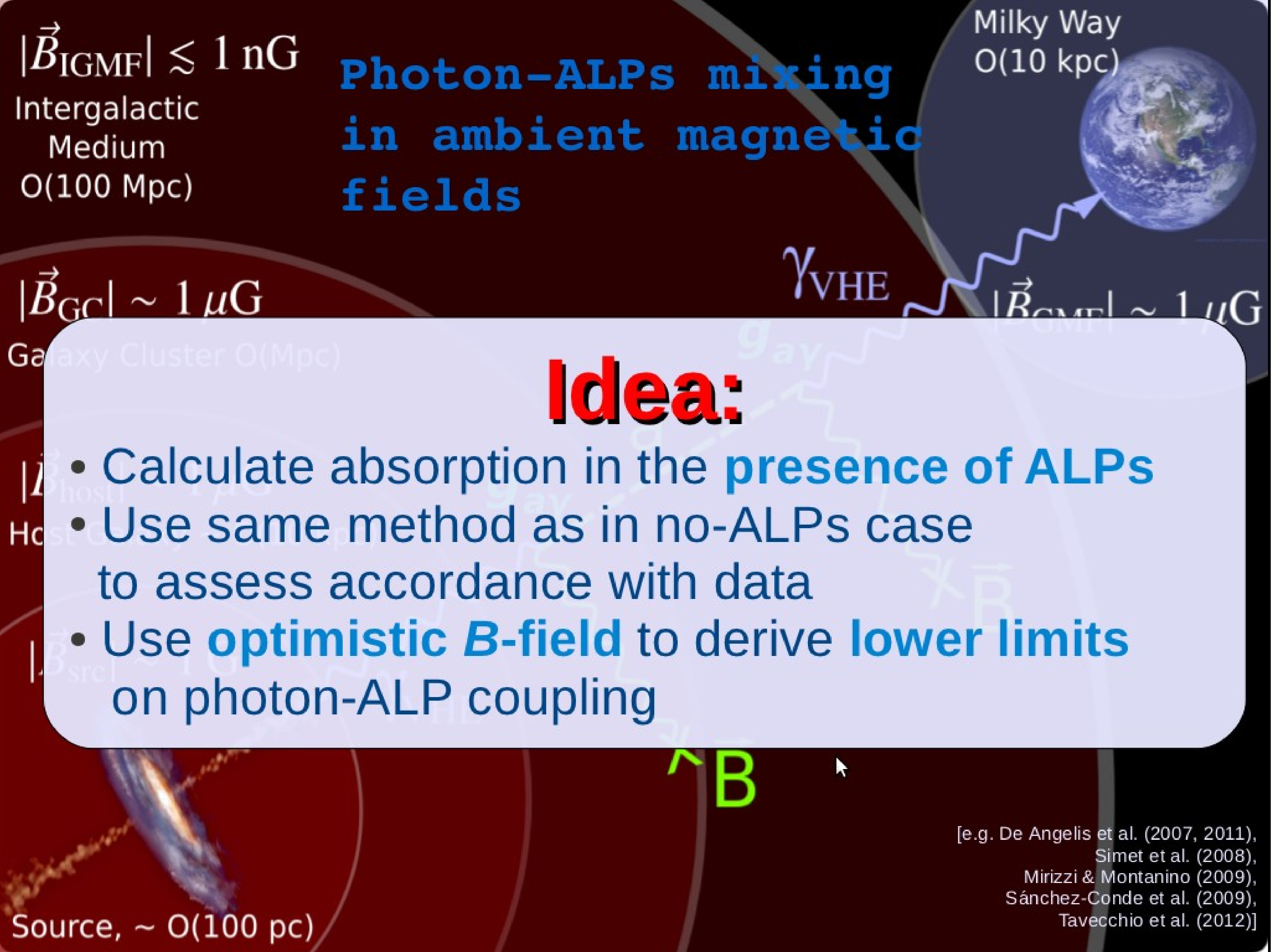


Photon-ALPs mixing in ambient magnetic fields
$|\vec{B}_{\rm IGMF}| \lesssim 1\,{\rm nG}$
Intergalactic Medium O(100 Mpc)
$|\vec{B}_{\rm GC}| \sim 1\,\mu{\rm G}$
Galaxy Cluster O(Mpc)
$|\vec{B}_{\rm host}| \sim 1\,\mu{\rm G}$
Host Galaxy ~ O(10 kpc)
$|\vec{B}_{\rm src}| \sim 1\,{\rm G}$
Source, ~ O(100 pc)
Milky Way O(10 kpc)
$|\vec{B}_{\rm GMF}| \sim 1\,\mu{\rm G}$
$\gamma_{\rm VHE}$
$g_{a\gamma}$
a
$g_{a\gamma}$
$\gamma_{\rm VHE}$
$\vec{B}$
$\vec{B}$
[e.g. De Angelis et al. (2007, 2011), Simet et al. (2008), Mirizzi & Montanino (2009), Sánchez-Conde et al. (2009), Tavecchio et al. (2012)]



Photon-ALPs mixing in ambient magnetic fields

Idea:

- Calculate absorption in the **presence of ALPs**
- Use same method as in no-ALPs case to assess accordance with data
- Use **optimistic *B*-field** to derive **lower limits** on photon-ALP coupling

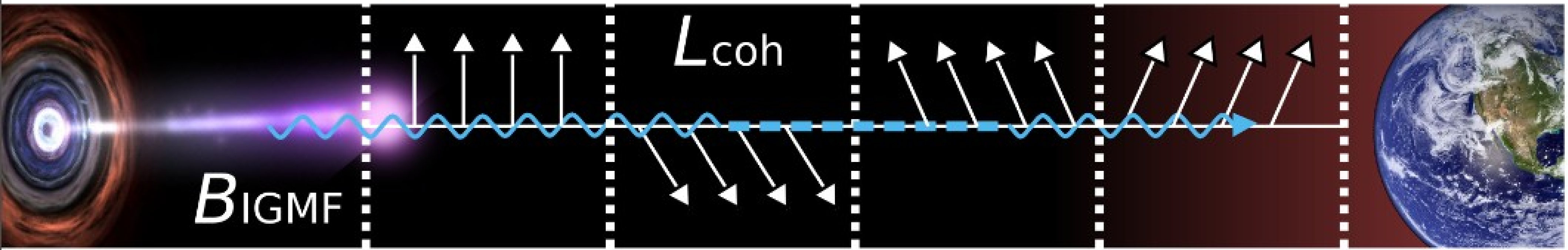
[e.g. De Angelis et al. (2007, 2011), Simet et al. (2008), Mirizzi & Montanino (2009), Sánchez-Conde et al. (2009), Tavecchio et al. (2012)]

Magnetic field scenarios for lower limits on $g_{a\gamma}$

Parameter	Scenarios		
	Optimistic IGMF	***Optimistic ICM****	***Fiducial*****
Intergalactic *B*-field (IGMF, nG)	5	–	0.01
Coherence length IGMF (Mpc)	50	–	10
Intra-cluster *B*-field (ICMF, μG)	–	10	1
Coherence length ICMF (kpc)	–	10	10
Cluster radius (Mpc)	–	2	2 / 3

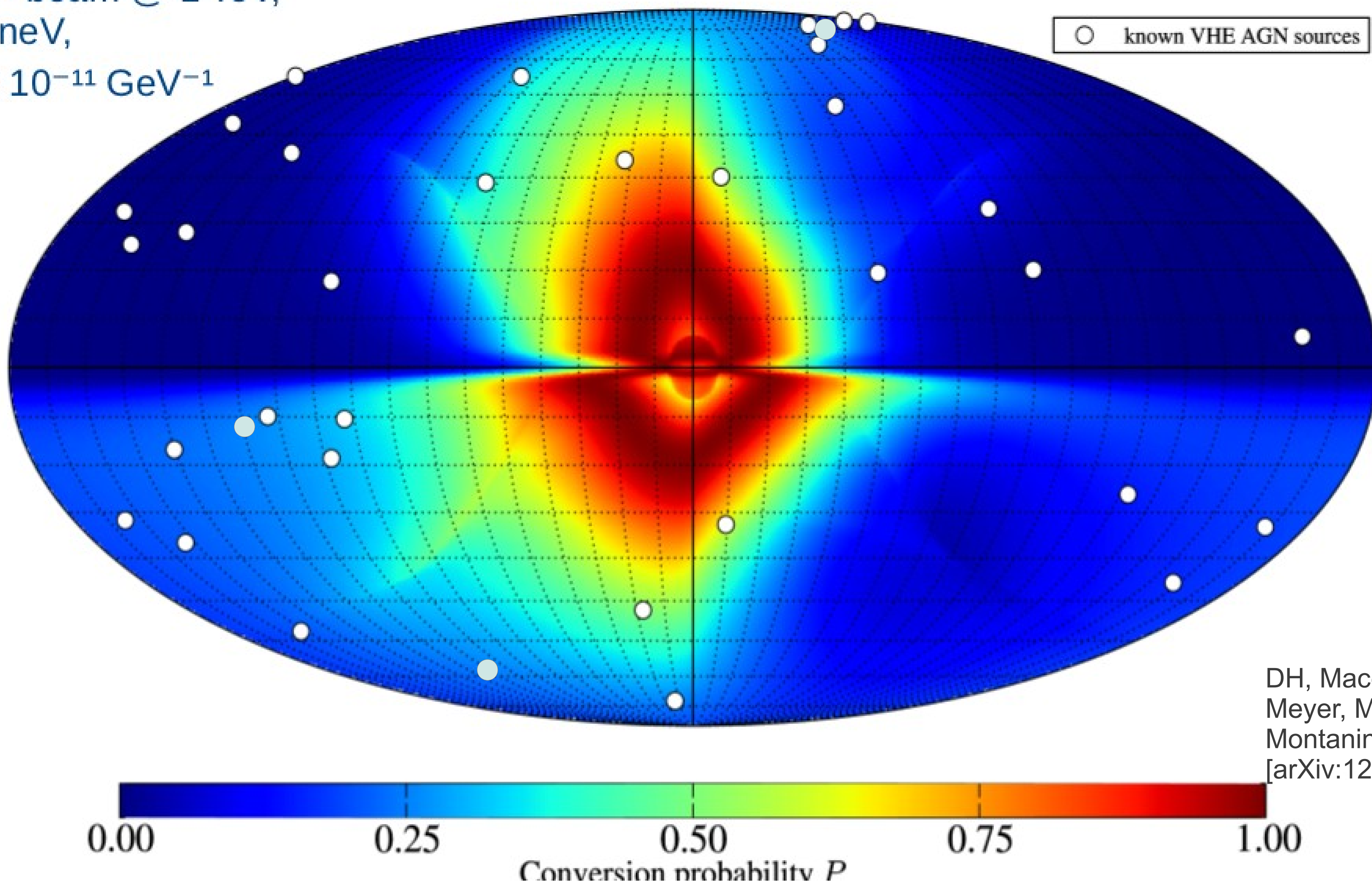
* All AGN are assumed to lie inside a Galaxy Cluster
** Only those AGN lie inside Galaxy cluster for which observational evidence exists

Random magnetic fields:



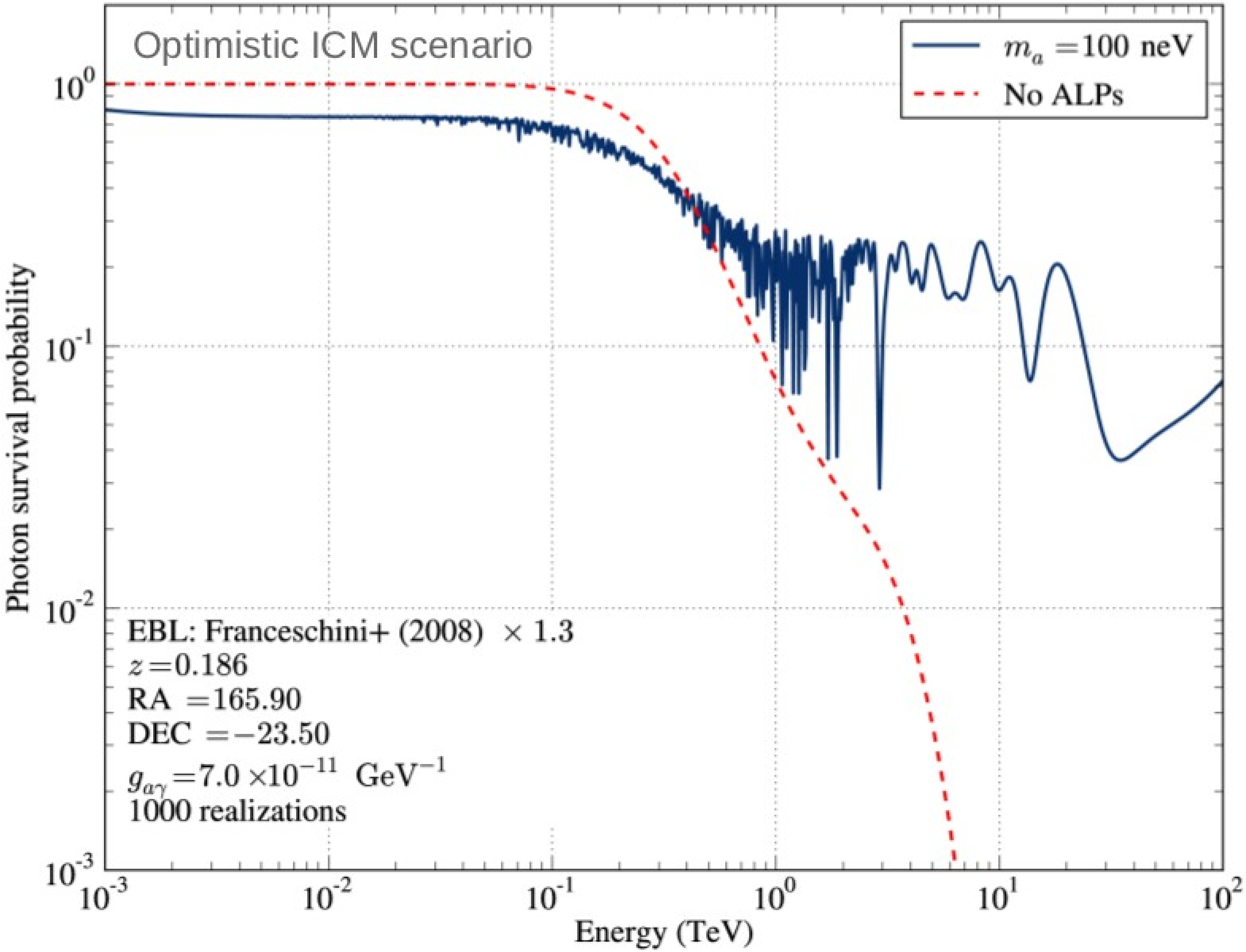
Reconversion in the Galactic B-field

B-field model of Jansson & Farrar (2012),
(only regular component)
Pure ALP beam @ 1 TeV,
m_a = 10 neV,
$g_{a\gamma}$ = 5 x 10^{-11} GeV^{-1}



DH, Maccione, Meyer, Mirizzi, Montanino [arXiv:1207.0776]

Effect of photon-ALPs mixing



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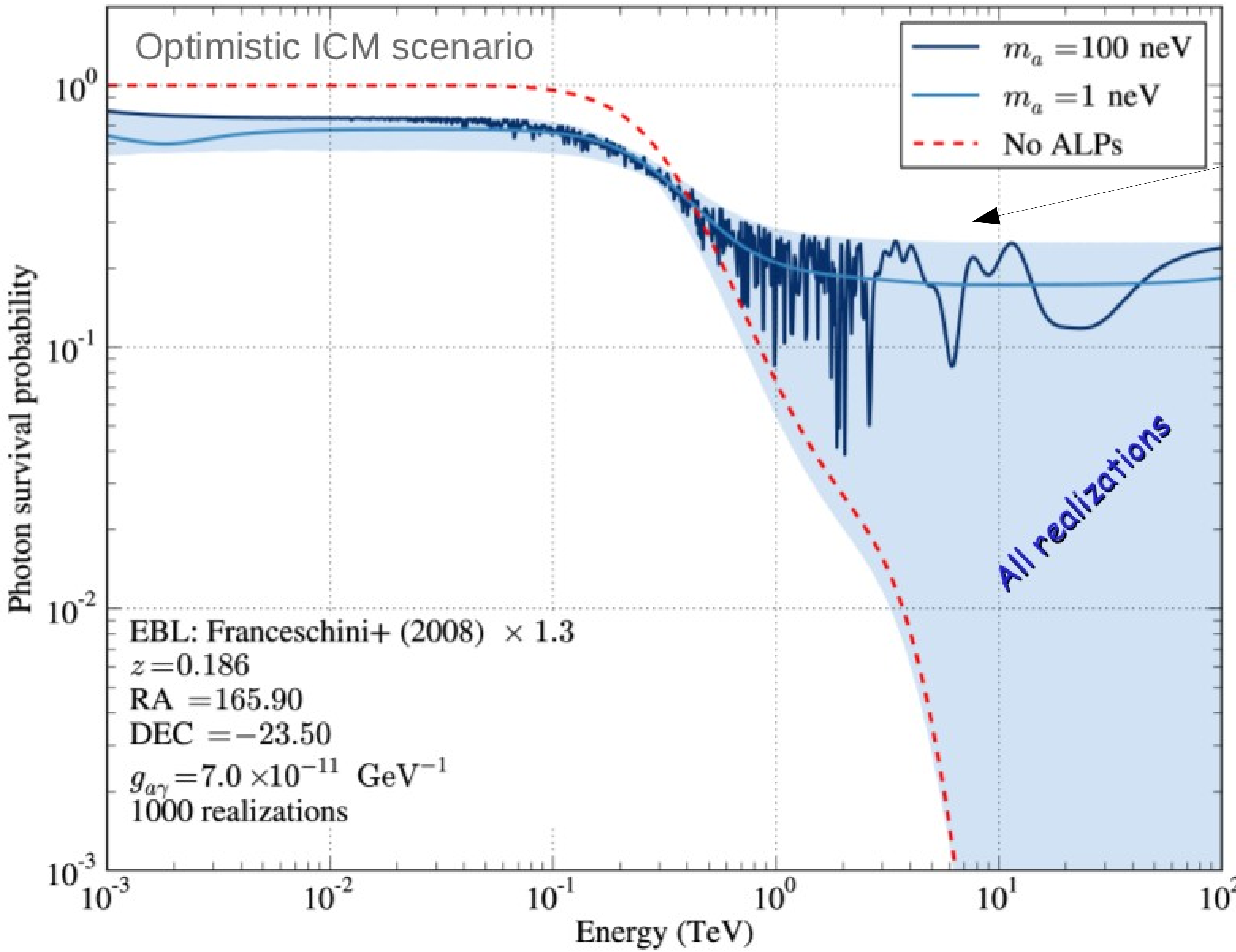
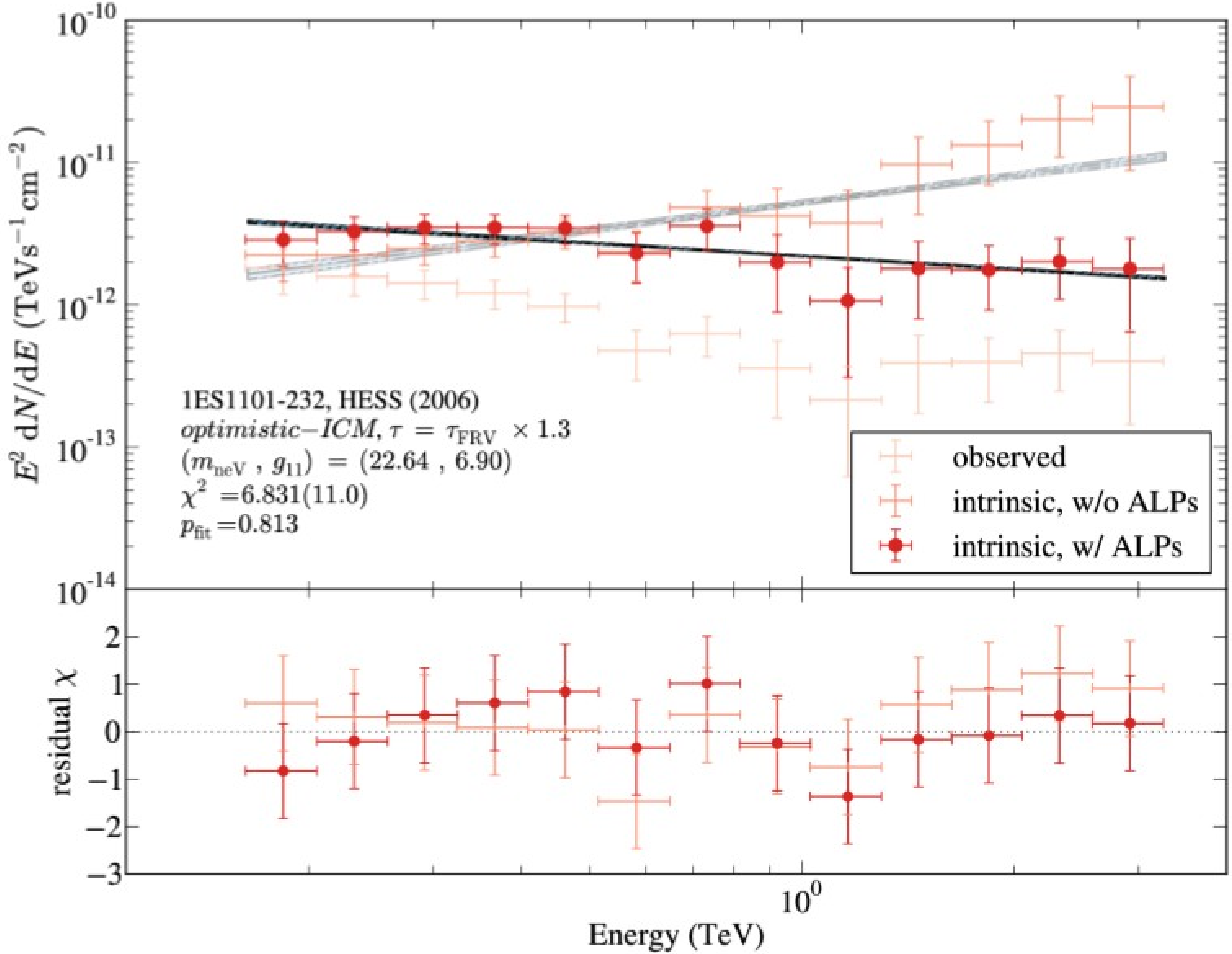
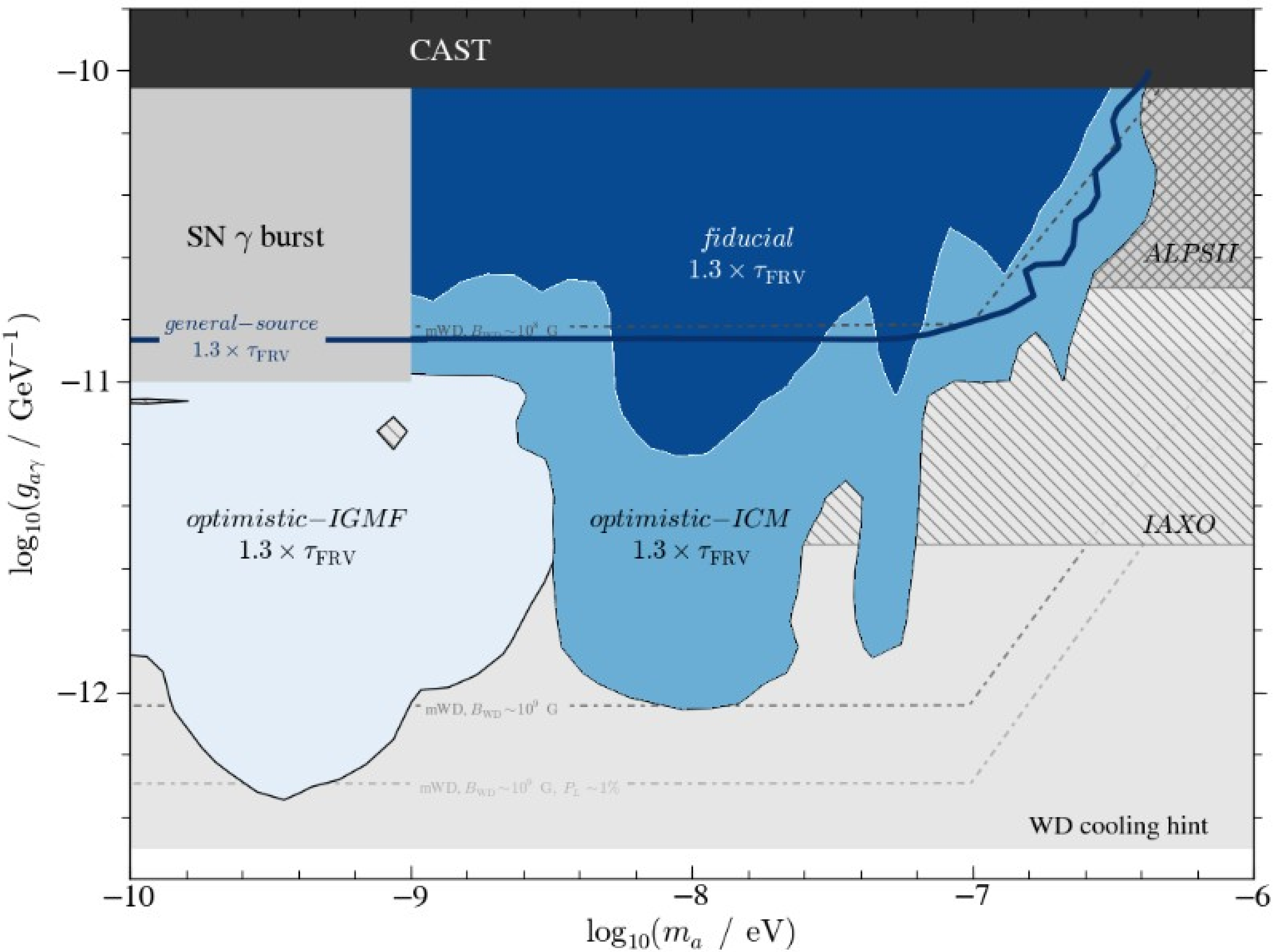


Oscillation →
Additional noise
(Östmann&Mörtsell
[astro-ph/0410501])
→ talk by Wouters)

Effect of photon-ALPs mixing

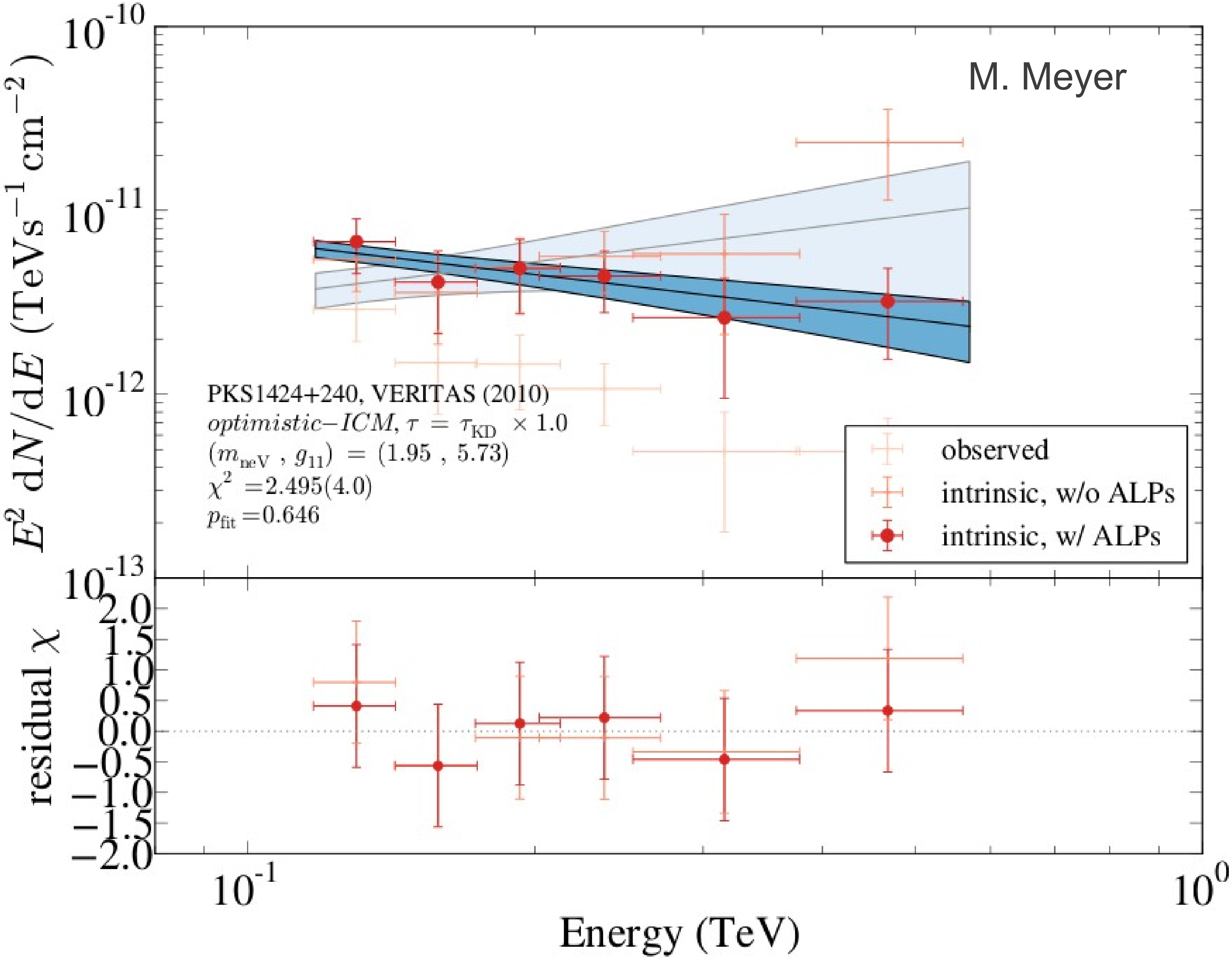


Resulting lower limits



New results: lower limit on z>0.6 for PKS1424+240

Furniss et al. ArXiv:1304.4859.



New result: Pair-production anomaly with Fermi-LAT

- Method:
  - Associate individual photons at E>10 GeV and high galactic latitude ($|b|>10^o$) to AGN with red-shift (AGN within $\Delta\Omega_{68}$)
  - Calculate optical depth for E_{hop}
  - Fit spectra to energy range up to E_{99} ($\exp(-\tau(E_{99}))=0.99$) → optical thin regime
  - Calculate the expected number of photons extrapolating and after absorption (λ_{pred})
  - Estimate background in $\Delta\Omega_{68}$ (gal., extra-gal.)

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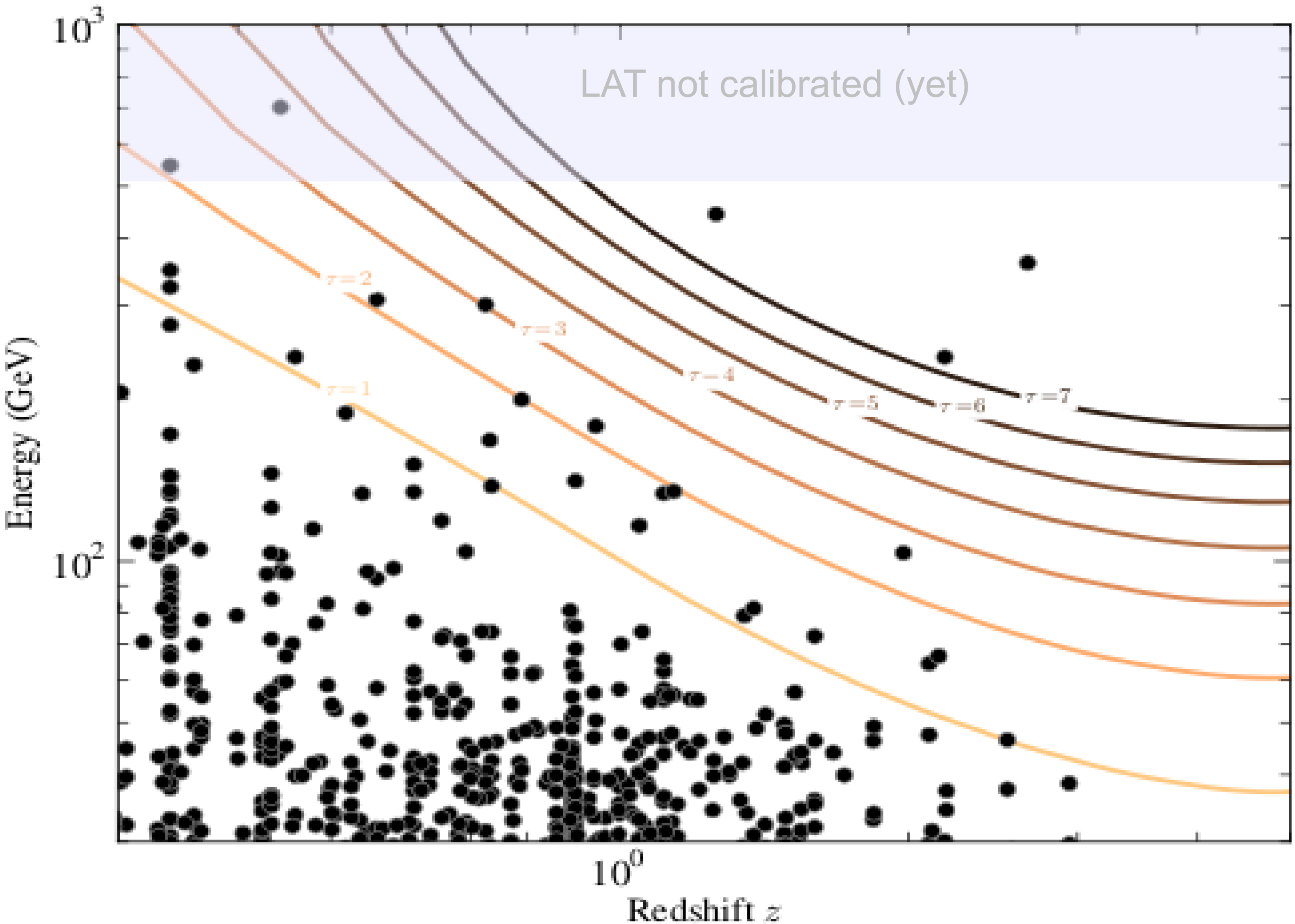
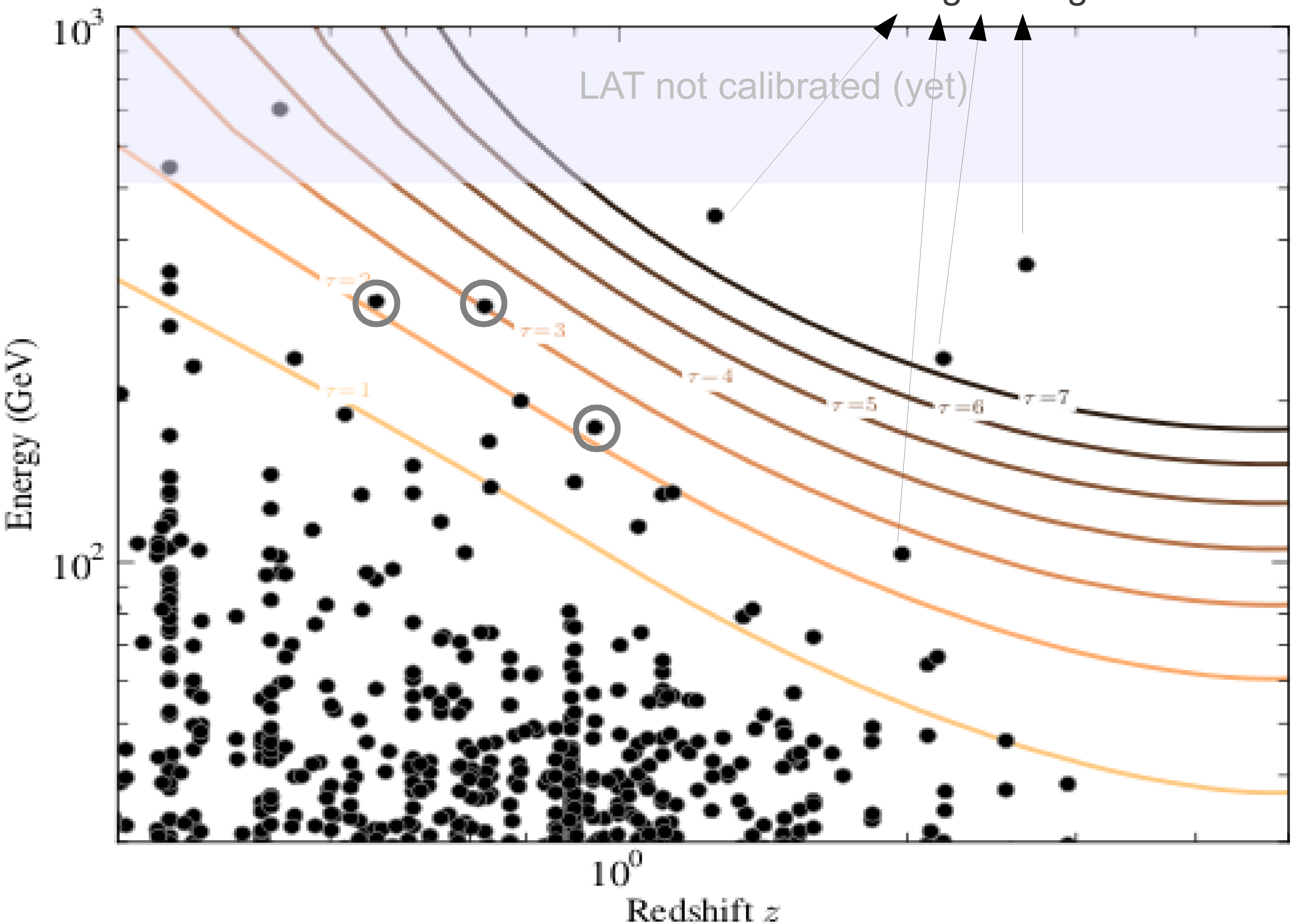
Photon sample from Fermi-LAT (until Nov. 2012)



Photon sample from Fermi-LAT

3 Photons with tau>2

Spill-over from
neighboring sources



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How significant is this?

- Poissonian probability for photon detection

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

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

- Typical values $\lambda_{pred} \sim \lambda_{bkg} \sim 10^{-3}$
- Combined (Fisher 1925)
  X^2 is $\chi^2(2N_{src})$ distributed → estimate P

$$X^2 = -2 \sum_{i=1}^{N_{\mathrm{src}}} \ln p_i$$

- Result for P(tau>2)=6.57×10^{-6}=4.36 σ
- Correcting for trials: p(tau>2)=3.68 σ

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Summary

- Indication for Pair-production anomaly (PPA) in VHE gamma-ray spectra persists (new sources are coming – PKS1424+24 (z>0.6) strengthens the case).
- Interpretation in ALPs-scenario: $8\text{x}10^{-11} > g_{agg}$ GeV$>10^{-12}$
- First study of the Fermi-LAT → 3 (+2) photons with tau>2 : post-trial S=3.68 σ. Completely independent confirmation of PPA.
- Outlook:
  - New Fermi-LAT data are coming (Pass 7 reprocessed, Pass 8) with TeV reach.
  - More Blazars with z-measurement will come...
  - HESS Phase II & Fermi-LAT → ideal instruments for this study

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Backup

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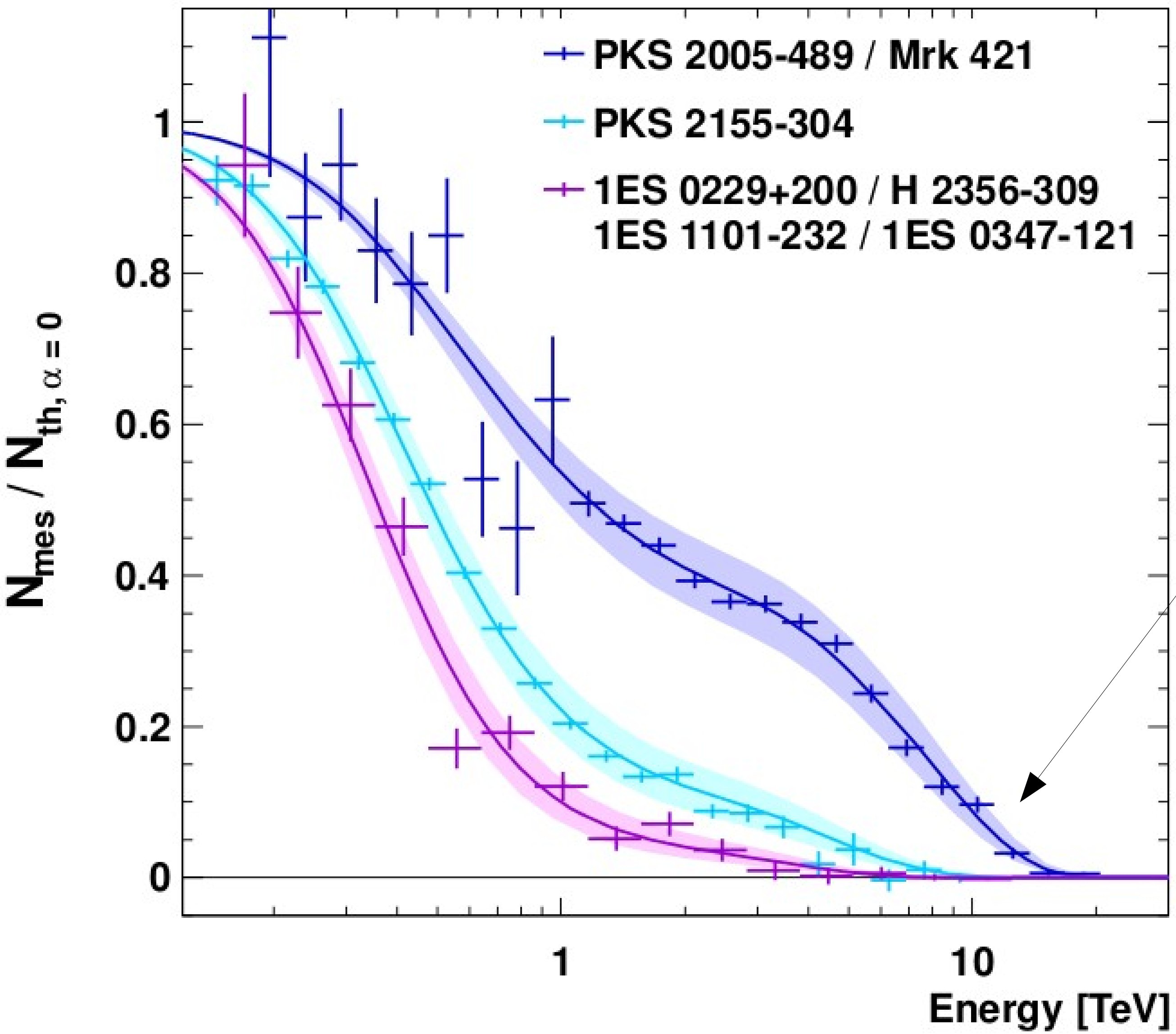
EBL measurement H.E.S.S.



No clear deviations evident.
Caveats:
Normalization of the optical depth changes by x2

Binning in z (combination of sources)

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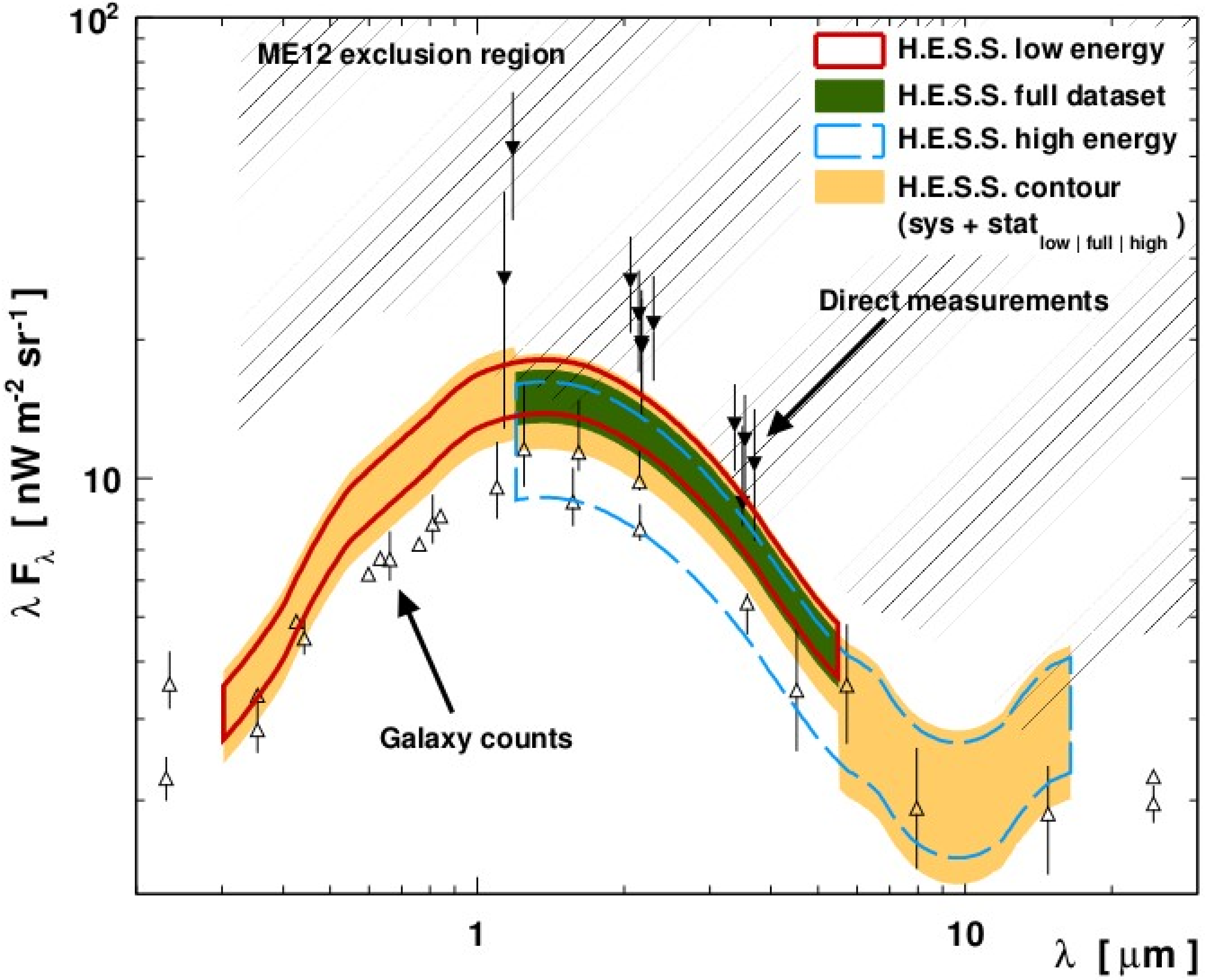
HESS normalization



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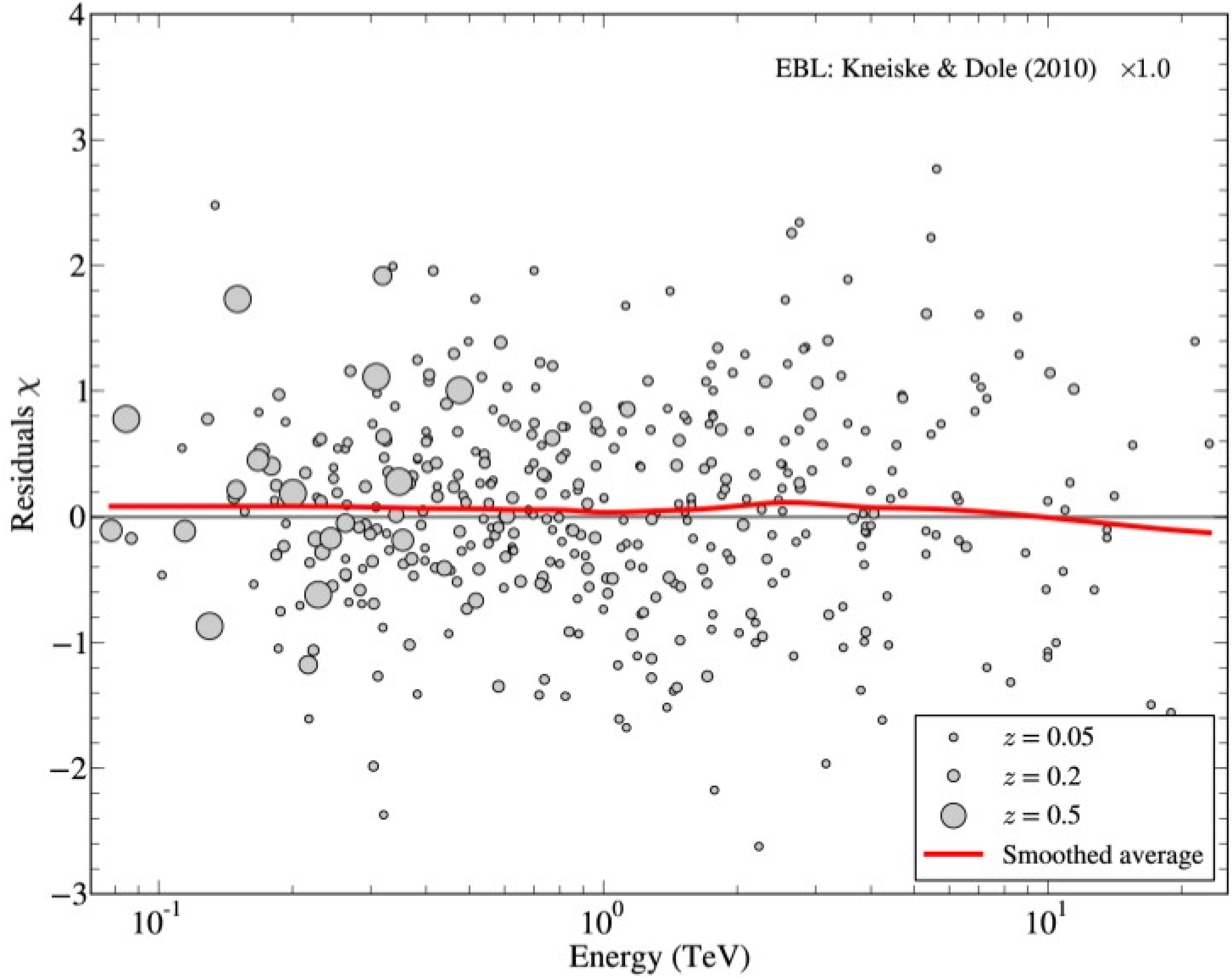
Systematic effects: Energy dependence



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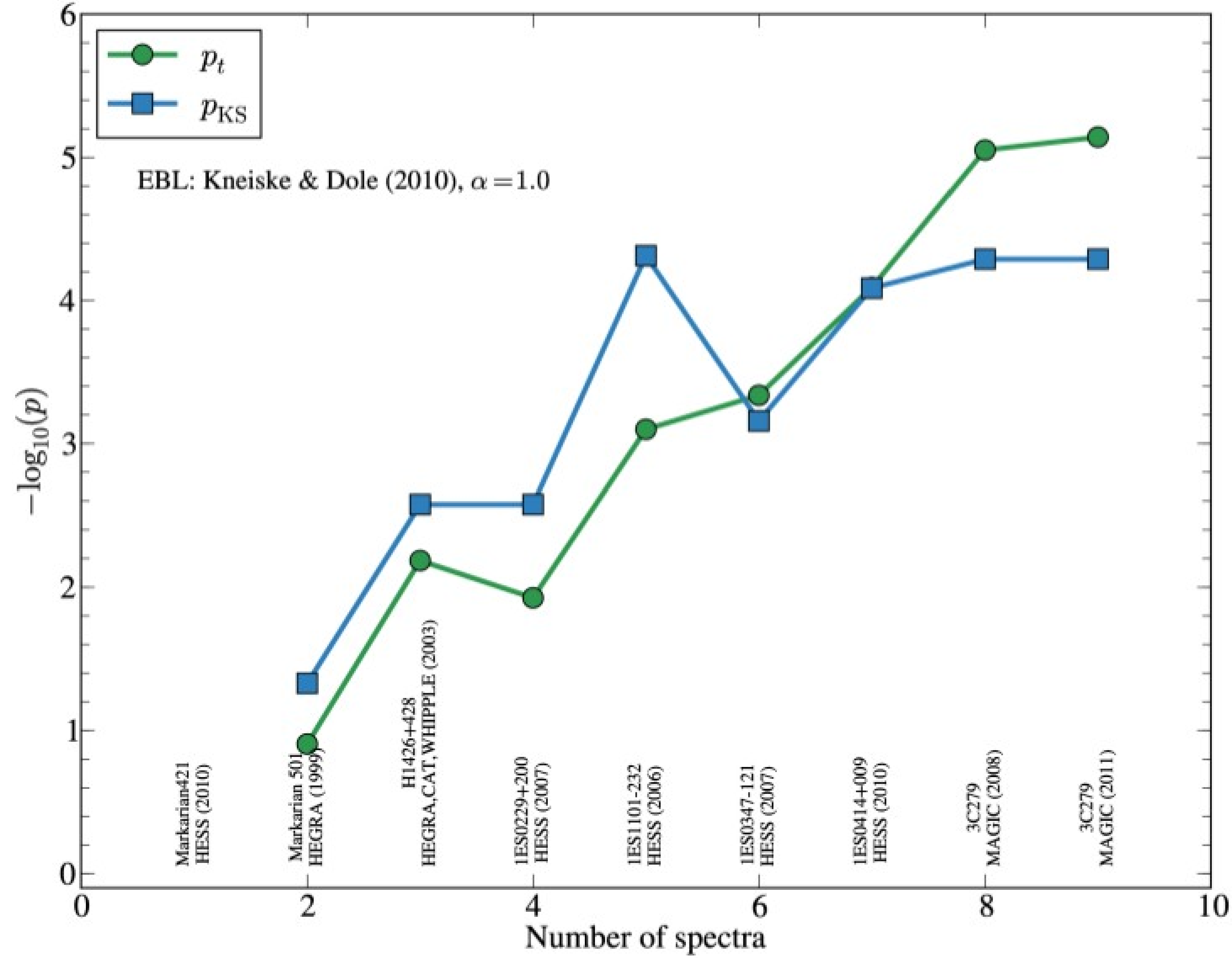
Systematic effects: Source contributions



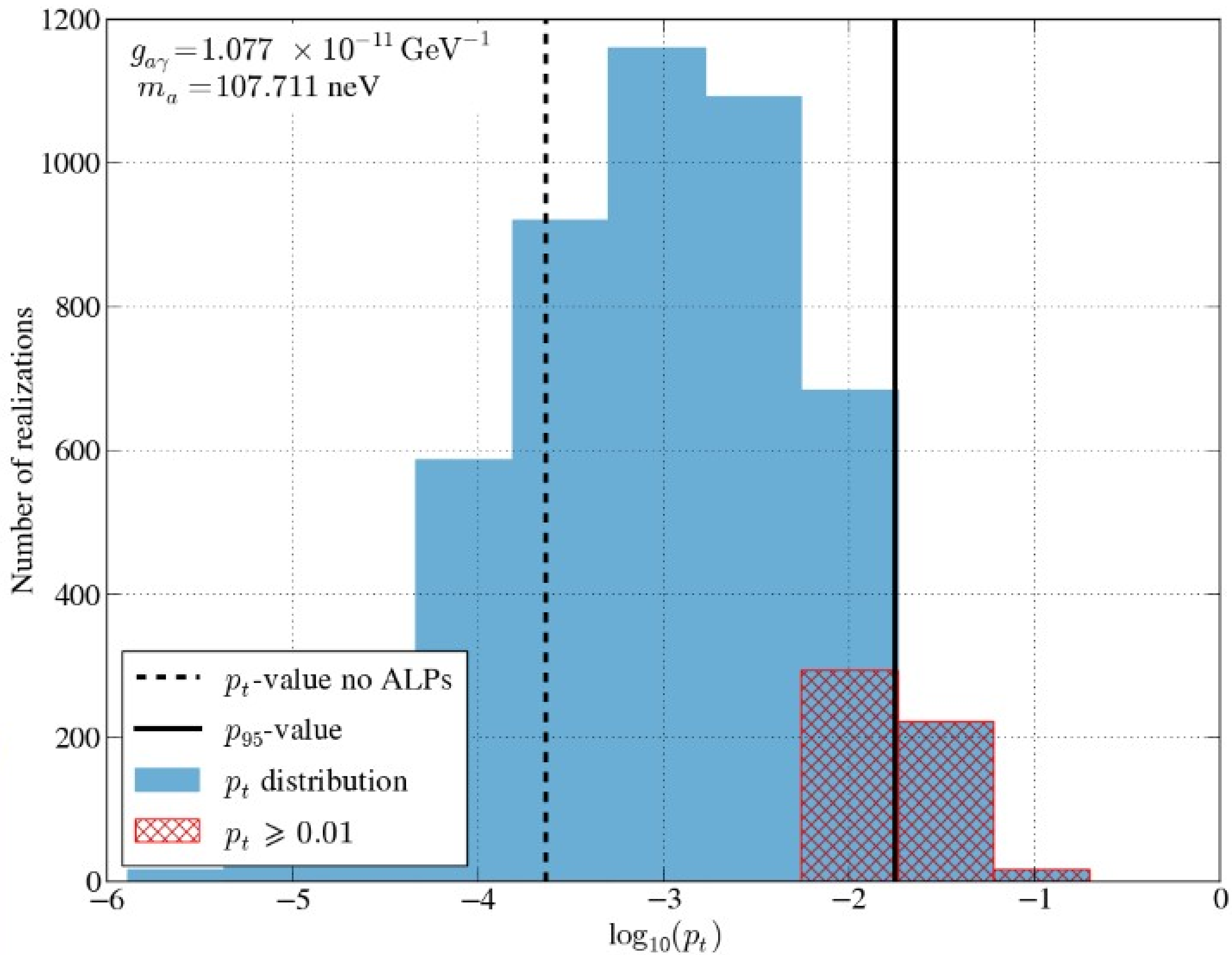
Systematic effects summary

Systematic check	Significance $p_{\rm KS}$		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}	$1.83\,\sigma$

How to make the limit

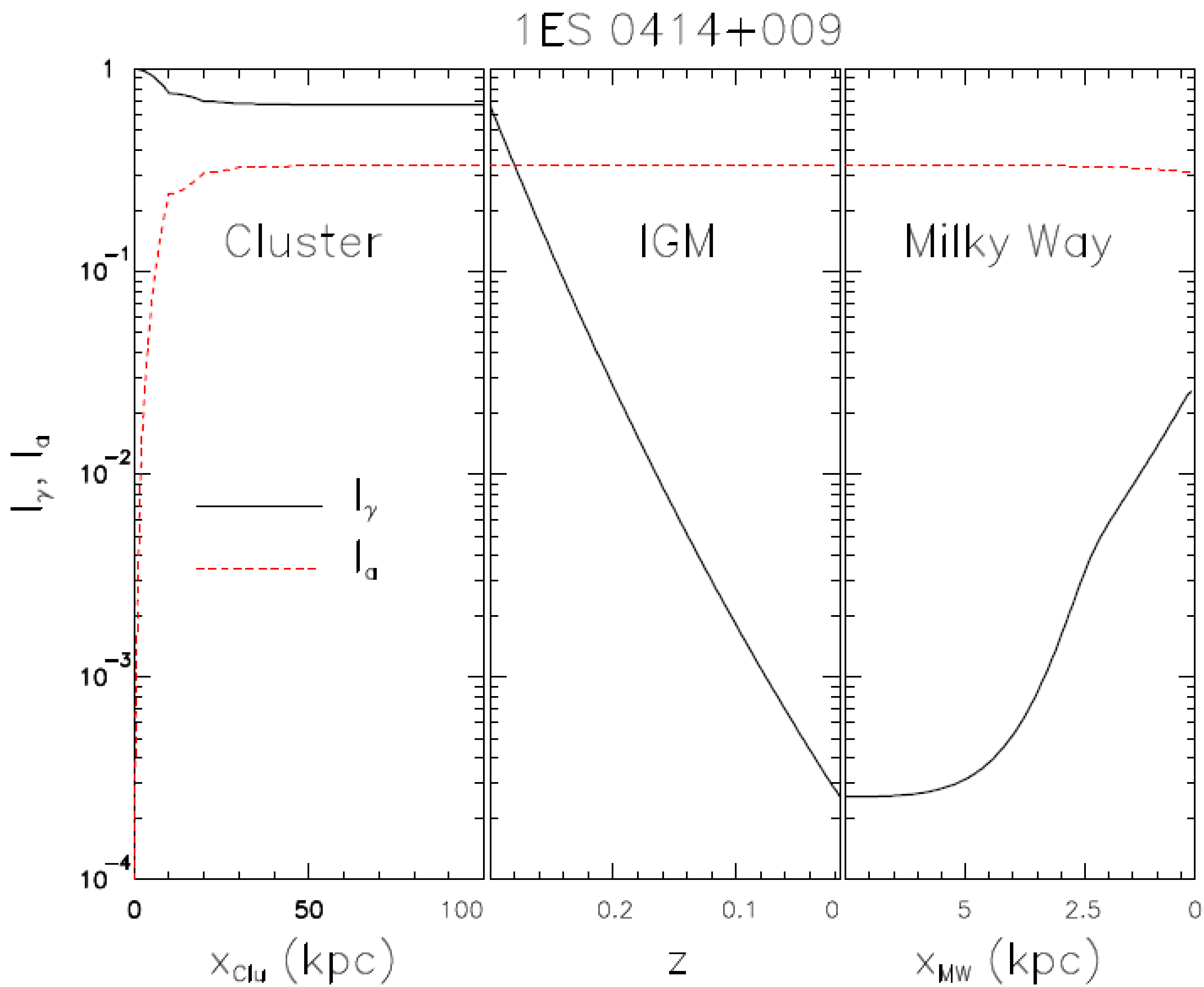
- For each (m_a,$g_{a\gamma}$)-pair: 5000 random *B*-field realizations
  ⇒ **5000 values for accordance between model and data** (p_t-values)
- **Which p_t-value for lower limit?**
- Choose **0.01** as confidence interval
- Demand that **at least 5%** (p_{95}-value) of all realizations give $p_t > 0.01$

Lower limit:
p_{95}-value ≥ 0.01,
i.e. at least 5%
of all realizations
give an accordance with
the data better than 1%



→ Better accordance between model and data

Conversion scheme



E=8 TeV

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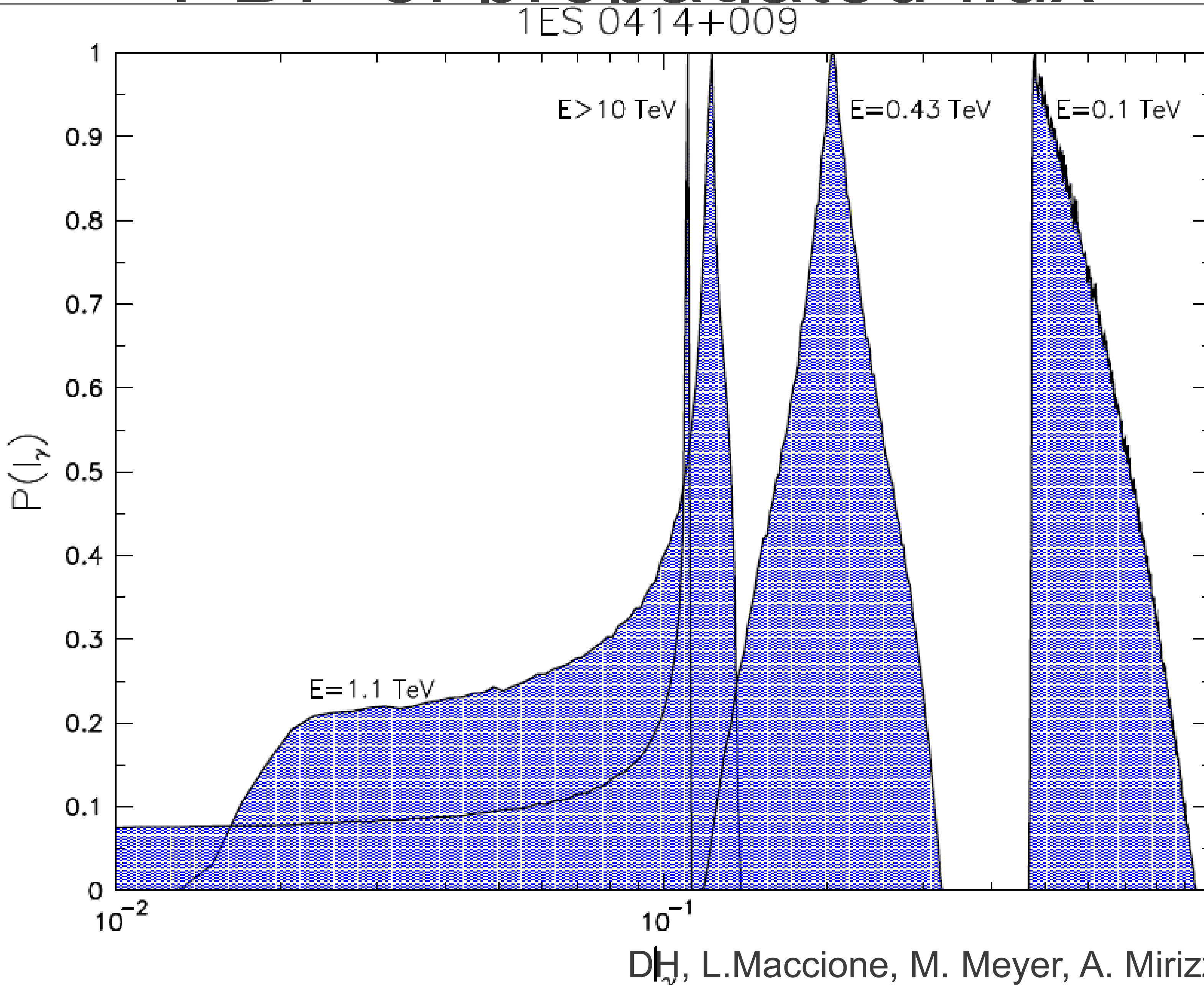
PDF of propagated flux



DH, L.Maccione, M. Meyer, A. Mirizzi, A. Montanino [arXiv:1207.0776]

Systematic checks Fermi-LAT

Cross check	$P_{\mathrm{PPA}}(\alpha = 1; \tau_{\gamma\gamma} \geqslant 2)$	
fiducial[a]	6.57×10^{-6}	$4.36\,\sigma$
Intrinsic spectra		
LP all spectra	9.69×10^{-7}	$4.76\,\sigma$
LP for $TS_{\mathrm{fit}} > 8$	...	...
Intrinsic index $\Gamma - \sigma_\Gamma$	1.85×10^{-5}	$4.16\,\sigma$
Intrinsic index $\Gamma - 2\sigma_\Gamma$	6.08×10^{-5}	$3.84\,\sigma$
Normalization $N_0^{t_{\mathrm{HOP}}}$	5.15×10^{-6}	$4.41\,\sigma$
Energy resolution		
$E_{\mathrm{HOP}} - \Delta E$	3.34×10^{-5}	$3.99\,\sigma$
$E_{\mathrm{HOP}} - 2\Delta E$	1.91×10^{-4}	$3.55\,\sigma$
Source probability		
$P_{\mathrm{src}} = 0.95$	2.62×10^{-4}	$3.47\,\sigma$
$P_{\mathrm{src}} = 0.5$	6.96×10^{-7}	$4.83\,\sigma$
$P_{\mathrm{src}} = 0.05$	7.69×10^{-8}	$5.24\,\sigma$
λ_{all}	8.13×10^{-4}	$3.15\,\sigma$
EBL model		
KD model	7.75×10^{-6}	$4.32\,\sigma$
Domínguez *et al.* (2011)	5.90×10^{-6}	$4.38\,\sigma$
Inoue *et al.* (2012)	2.41×10^{-5}	$4.06\,\sigma$
Including trials	1.17×10^{-4}	$3.68\,\sigma$

List of photons

i	Source	E_{HOP} (GeV)	z[a]	$\tau_{\gamma\gamma}$[b]	r_{68} (degrees)	d (degrees)	ΔE[c] (GeV)	λ_{pred}[d] ($\times 10^{-2}$)	p[e] ($\times 10^{-3}$)	λ_{diff}[f] ($\times 10^{-3}$)	λ_{all}[g] ($\times 10^{-2}$)	P_{src}[h]	Source type[j]	Variability index[k]
1	TXS 0907+230	360.09	2.661	11.64	0.27	0.19	30.52	2.1×10^{-6}	0.36	0.36	1.01	2.2×10^{-3}	FSRQ (LSP)	108.18
2	S5 1039+81	444.00	1.260	8.66	0.26	0.18	53.79	2.0×10^{-8}	0.14	0.14	1.07	1.1×10^{-2}	FSRQ (LSP)	51.87
3	PMN J2135-5006	240.30	2.181	7.53	0.27	0.23	29.99	5.1×10^{-7}	9.15	9.19	2.13	0.11	FSRQ (Unc.)	35.09
4	RBS 0405	702.21	0.443	3.70	0.26	0.21	107.87	...	...	...	...	...	BL Lac (HSP)	31.62
5	Ton 599	300.88	0.725	3.03	0.27	0.26	33.46	0.09	2.00	0.70	1.42	0.95	FSRQ (LSP)	406.93
6	PKS 0048-071	103.66	1.975	2.57	0.29	0.19	6.85	0.11	9.25	7.64	3.93	0.81	FSRQ (LSP)	192.85
7	S4 0218+35	178.65	0.944	2.22	0.28	0.15	21.46	0.91	18.4	4.92	3.37	0.98	FSRQ (Unc.)	157.51
8	1ES 0502+675	546.94	0.340	2.13	0.11	0.00	51.95	...	...	1.47	0.79	...	FSRQ (LSP)	41.46
9	...	348.99	0.340	1.25	0.27	0.02	40.83	...	...	1.47	1.49	1.00	BL Lac (HSP)	41.46
10	...	324.50	0.340	1.12	0.27	0.14	39.94	26.6	59.4	1.47	1.49	1.00	BL Lac (HSP)	41.46
11	GB6 J1001+2911	307.54	0.558	2.13	0.27	0.27	38.86	0.12	2.35	0.63	1.54	0.92	BL Lac (ISP)	109.00
12	B2 2234+28A	200.17	0.790	1.98	0.28	0.15	5.29	0.12	5.29	3.58	0.43	0.90	FSRQ (LSP)	379.91
13	PKS 0426-380	133.79	1.111	1.85	0.12	0.01	12.45	34.9	402	0.93	3.76	1.00	FSRQ (LSP)	920.63
14	PKS 1329-049	66.58	2.150	1.48	0.30	0.17	3.83	0.32	35.2	31.2	4.23	0.55	FSRQ (LSP)	322.35
15	4C +55.17	141.20	0.899	1.44	0.28	0.06	16.00	27.9	340	5.00	3.64	1.00	FSRQ (LSP)	23.41
16	MG4 J000800+4712	64.42	2.100	1.38	0.13	0.07	5.17	18.1	243	11.8	9.62	0.99	FSRQ (LSP)	19.32
17	PKS 1144-379	116.58	1.048	1.37	0.12	0.03	10.82	2.43	37.3	2.34	4.82	0.99	FSRQ (LSP)	52.88
18	TXS 1720+102	168.22	0.732	1.35	0.12	0.02	16.23	0.43	7.73	1.44	3.04	0.99	FSRQ (LSP)	91.68
19	B2 2114+33	72.54	1.596	1.21	0.13	0.07	3.18	331	992	22.4	6.49	1.00	FSRQ (LSP)	68.77
20	4C +51.37	81.69	1.379	1.19	0.13	0.03	7.03	1.08	19.4	3.70	6.63	0.98	FSRQ (LSP)	432.08
21	MG3 J021252+2246	240.37	0.459	1.11	0.27	0.12	21.27	0.30	6.38	1.97	1.78	0.95	BL Lac (HSP)	27.48
22	PKS 0302-623	79.09	1.348	1.10	0.29	0.22	7.01	0.93	27.5	14.3	5.66	0.73	FSRQ (LSP)	70.21
23	B3 1343+451	46.44	2.534	1.00	0.13	0.03	3.61	92.4	746	10.5	10.3	1.00	FSRQ (LSP)	392.94

[a] Redshift of the source.
[b] Optical depth of the HOPs in the KD model.
[c] Energy dispersion at 68 % confidence (see Section 3.2.4).
[d] Predicted number of γ-rays detected from the source for $\alpha = 1$ (see Section 3.2.4).
[e] Poissonian probability to observe at least the detected number of photons from the source at $\alpha = 1$ (see Section 3.2.4).
[f] Expected number of background photons determined from a fit to the intrinsic spectrum (see Section 3.2.3).
[g] Expected number of background photons determined from photon counting (see Section 3.2.3).
[h] Probability that the HOP originates from the source (evaluated with `gtsrcprob`, see Section 3.2.3).
[j] Taken from the 2 year Fermi AGN catalog (see `http://www.asdc.asi.it/fermi2lac` and Ackermann *et al.*, 2011). The abbreviations in brackets refer to the frequency of the synchrotron peak of the SED, see Section 1.1.2, *Unc.* stands for uncertain.
[k] Variability index taken from the 2FGL.

Alternative scenarios

- UHECR Cascade (Essay & Kusenko 2011)
- CMB IC from extended jets (Böttcher et al. 2008)
- LIV (Kifune 1999)

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Fermi-LAT spectra

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