Impact of axion-like particles on observations with IACTs

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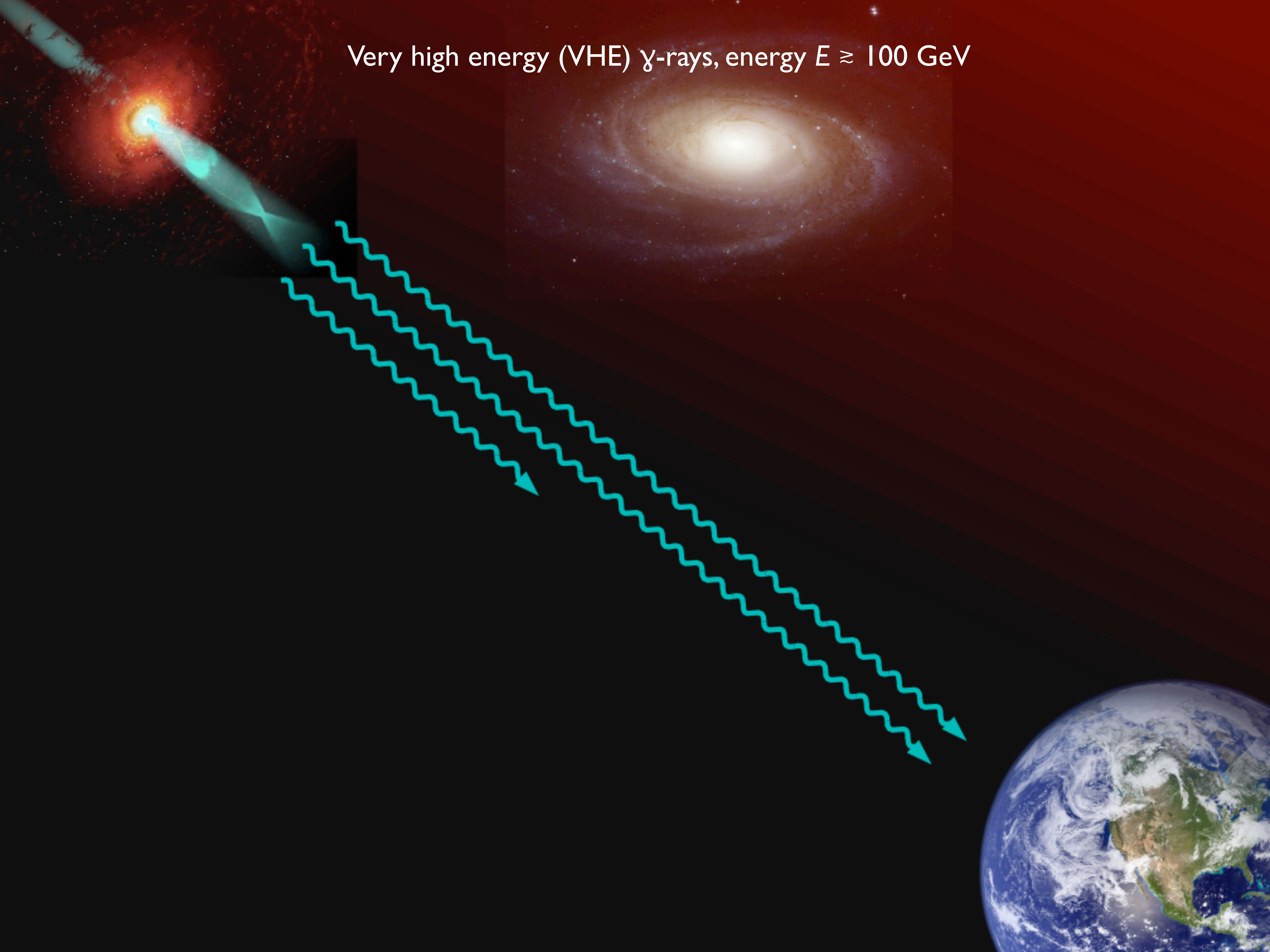
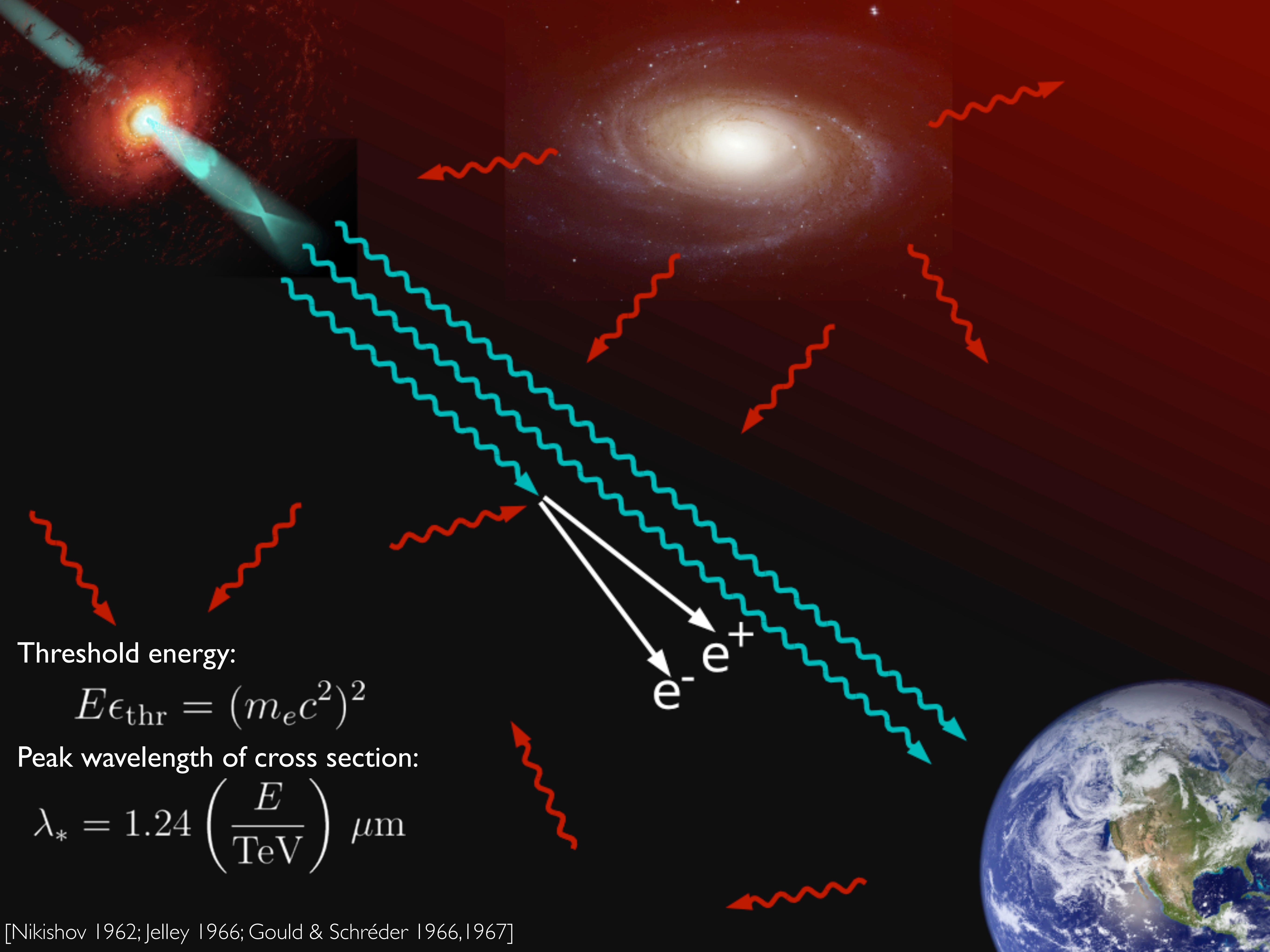
LEXI
LANDESEXZELLENZINITIATIVE
HAMBURG

UH
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Very high energy (VHE) γ-rays, energy $E \gtrsim 100$ GeV





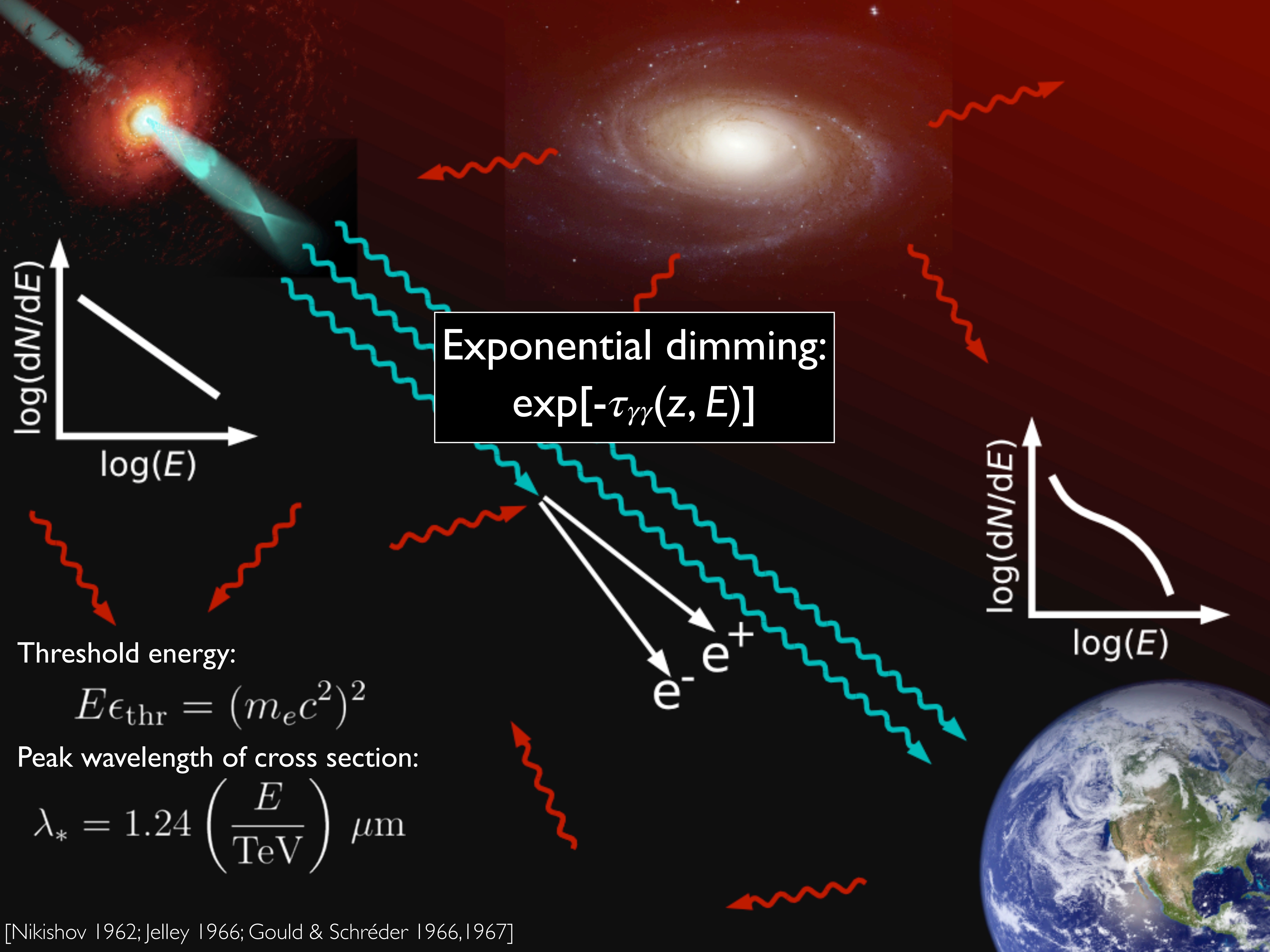
Threshold energy:

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

Peak wavelength of cross section:

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

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



Exponential dimming:
$\exp[-\tau_{\gamma\gamma}(z, E)]$

Threshold energy:

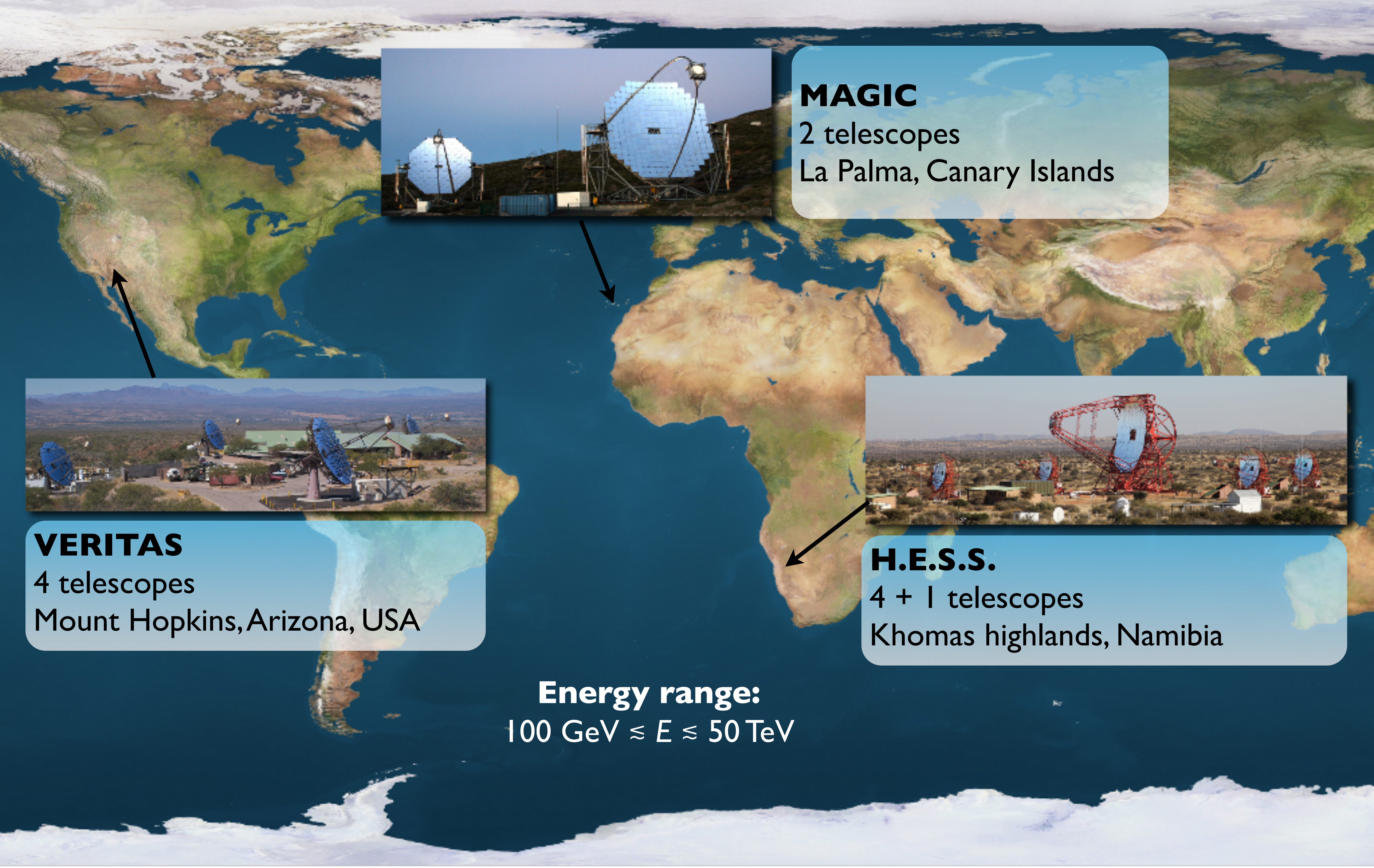
$$E\epsilon_{\mathrm{thr}} = (m_e c^2)^2$$

Peak wavelength of cross section:

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

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

Selection of currently operating IACTs



MAGIC
2 telescopes
La Palma, Canary Islands

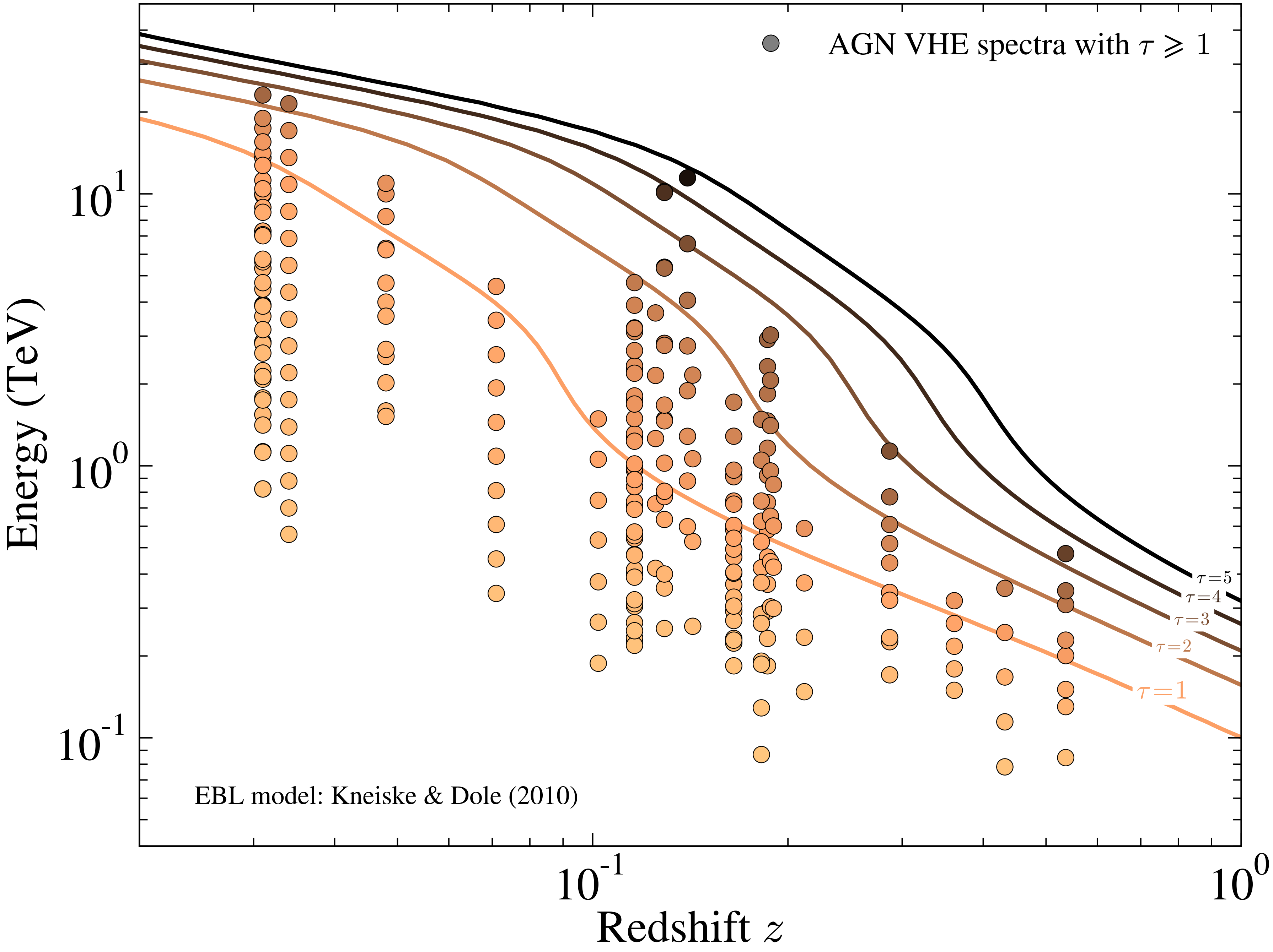
VERITAS
4 telescopes
Mount Hopkins, Arizona, USA

H.E.S.S.
4 + 1 telescopes
Khomas highlands, Namibia

Energy range:
$100\,\mathrm{GeV} \lesssim E \lesssim 50\,\mathrm{TeV}$

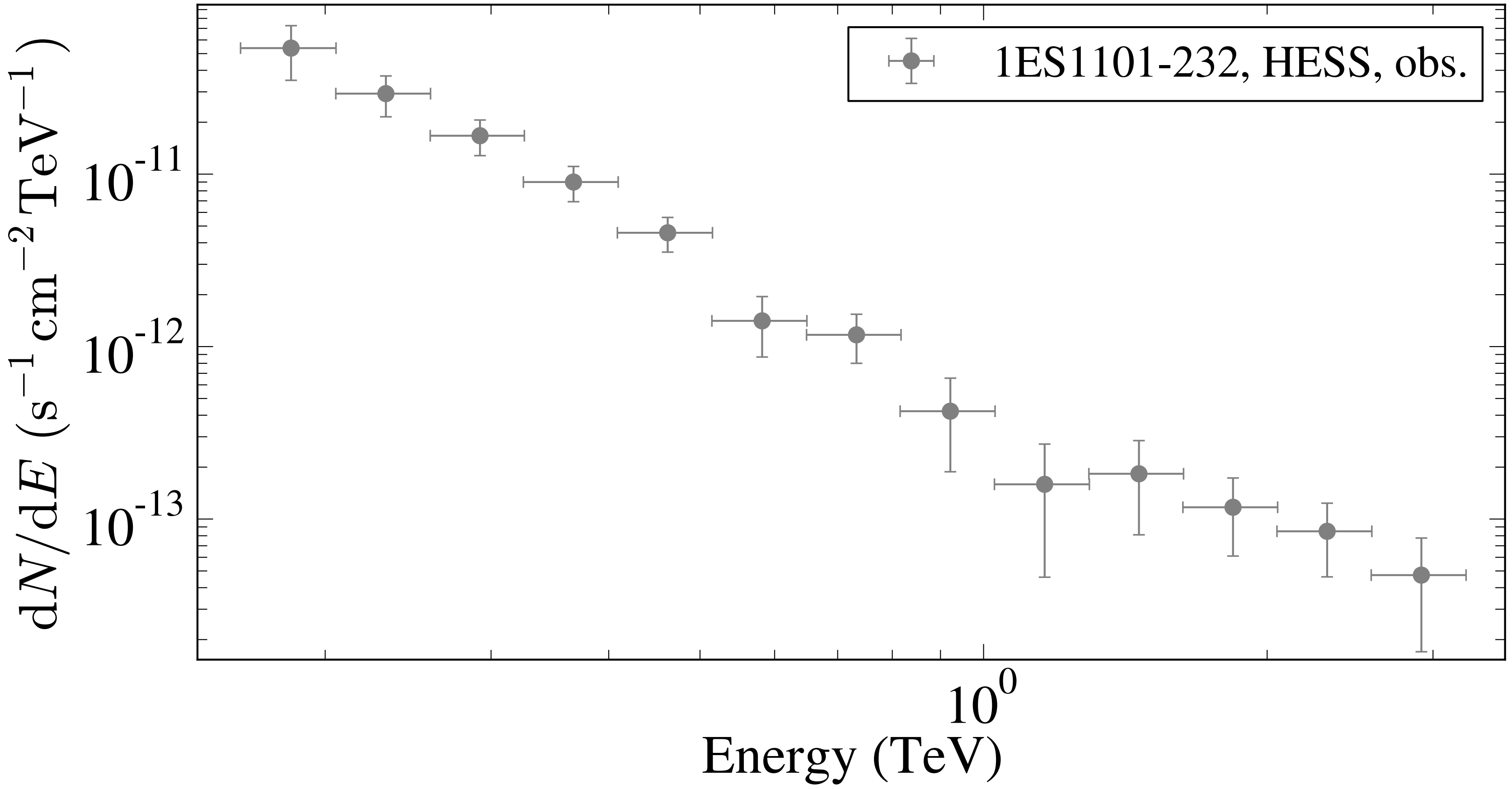
Investigate opacity of the Universe

- Upper limits assumed standard physics - are there **hints for a reduced 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**



Method to search for low opacity

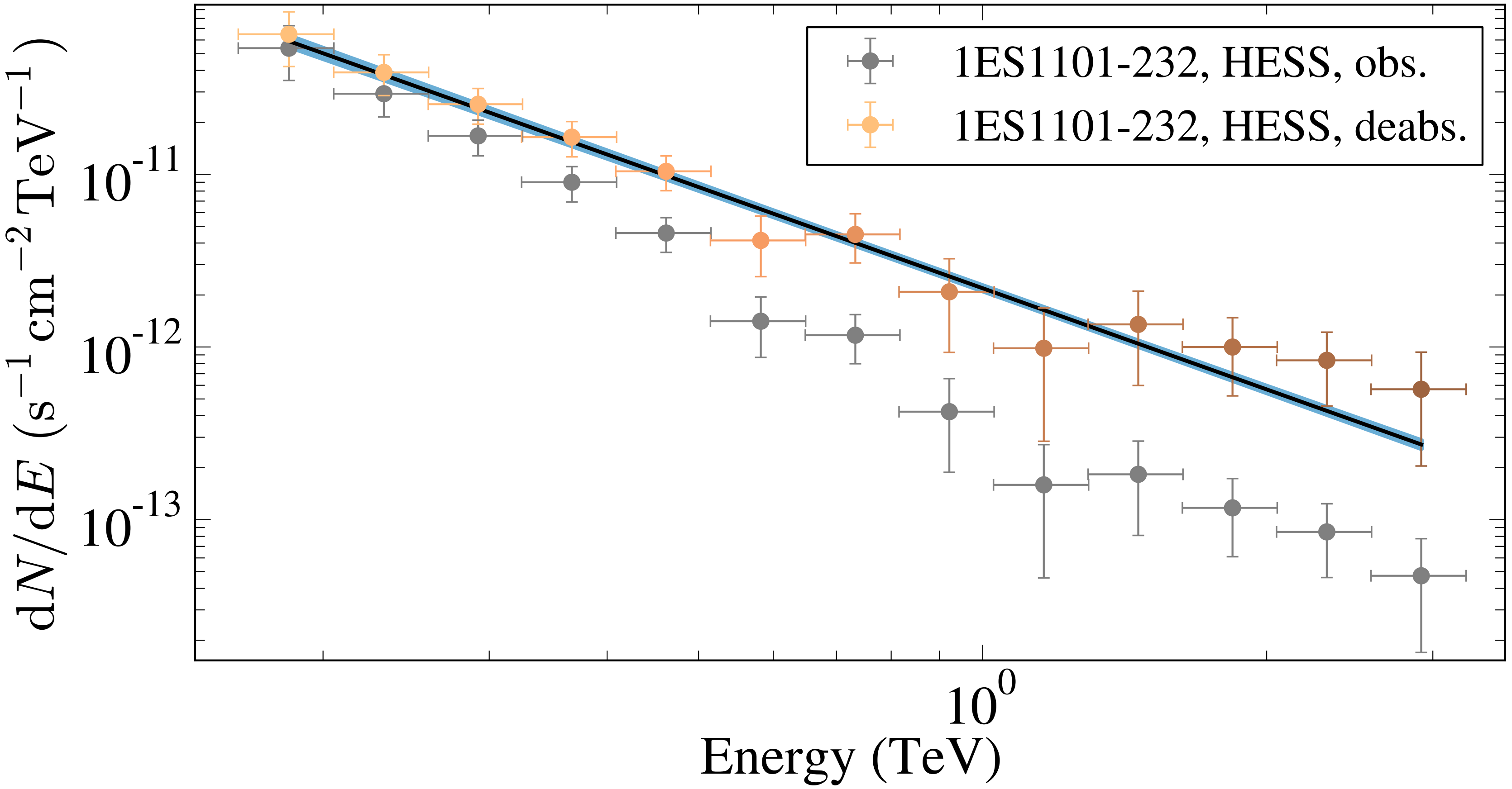
- apply **absorption-correction with KD model** to observed spectrum



Method to search for low opacity

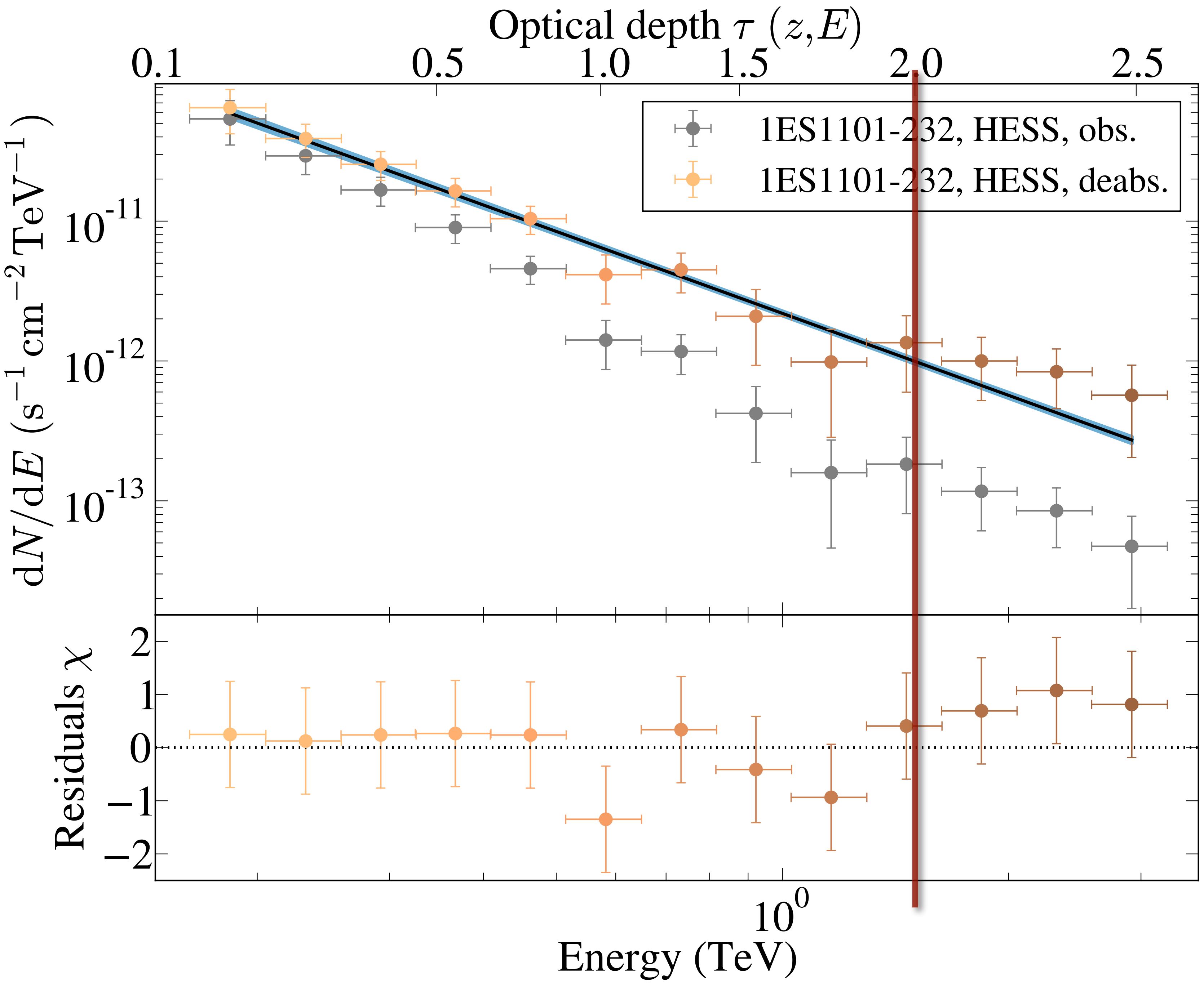
- apply **absorption-correction with KD model** to observed spectrum

- **Fit corrected spectrum with analytical function** (either power law or log parabola)



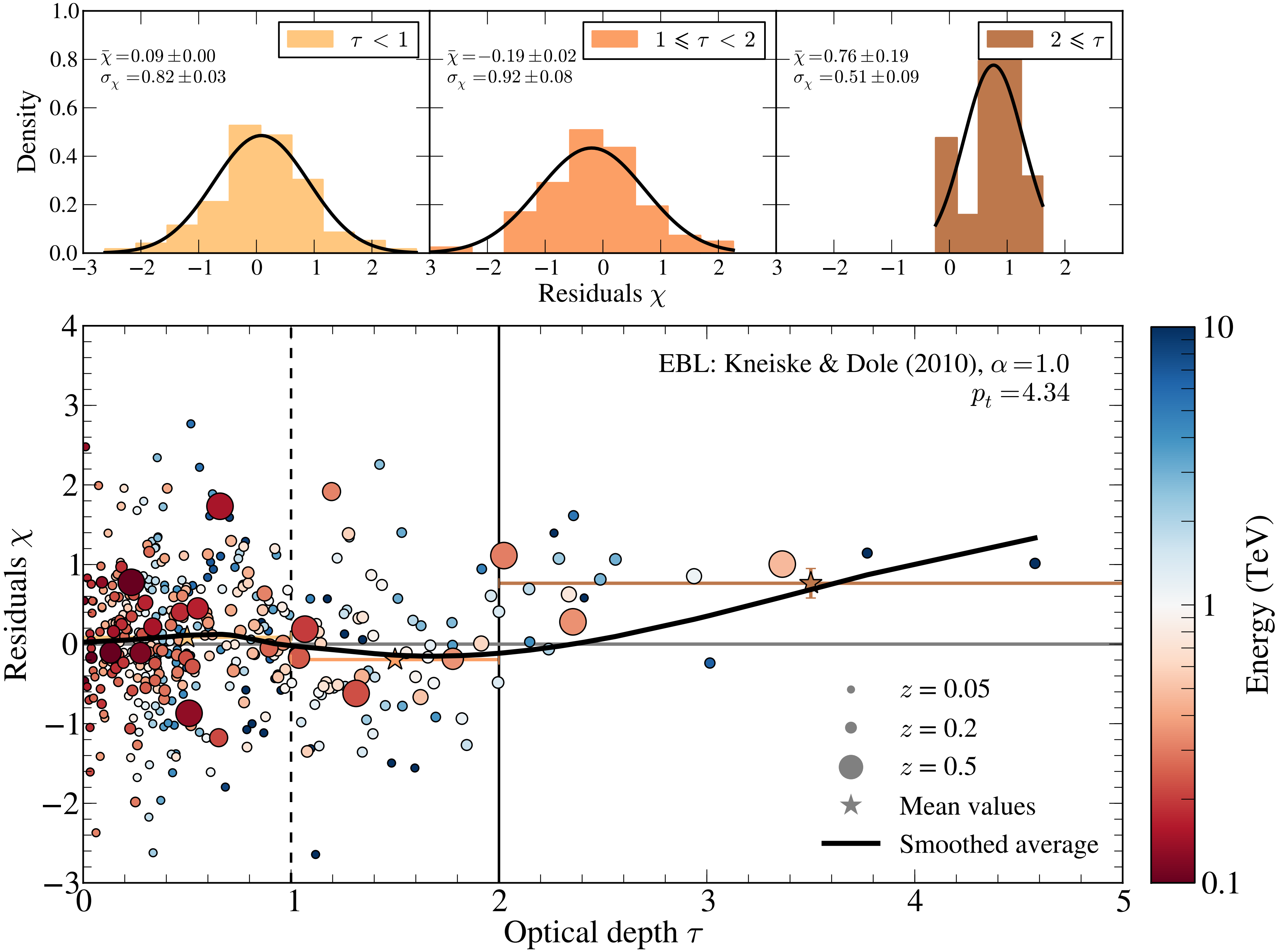
Method to search for low opacity

- 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 χ > 0: **overcorrection**



Indication for pair-production anomaly (PPA)

- Compare mean of residual distribution with **expectation $\langle \chi \rangle = 0$** with Student's t test
- Result: **$p_t = 4.3\sigma$ indication for overcorrection**
- **All spectra contribute** to significance
- 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)



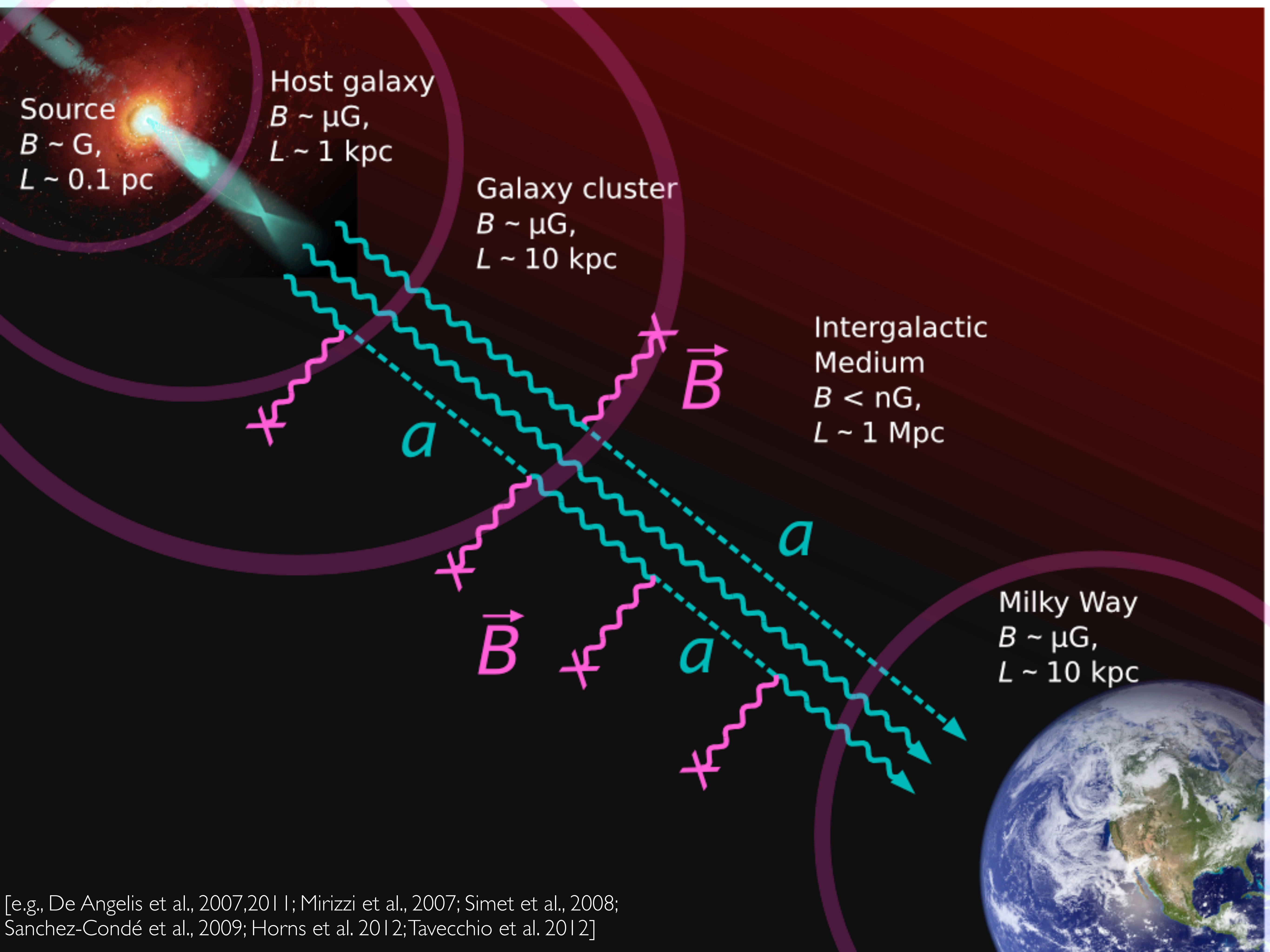
[Horns & Meyer, 2012, *JCAP* 02, id.033
Meyer et al., 2012, AIP Conf. Proc., Vol. 1505, pp. 598-601]

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 $m_a \lesssim 1\ \mu\text{eV}$ 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., De Angelis et al., 2007,2011; Mirizzi et al., 2007]



Source
$B \sim$ G,
$L \sim 0.1$ pc

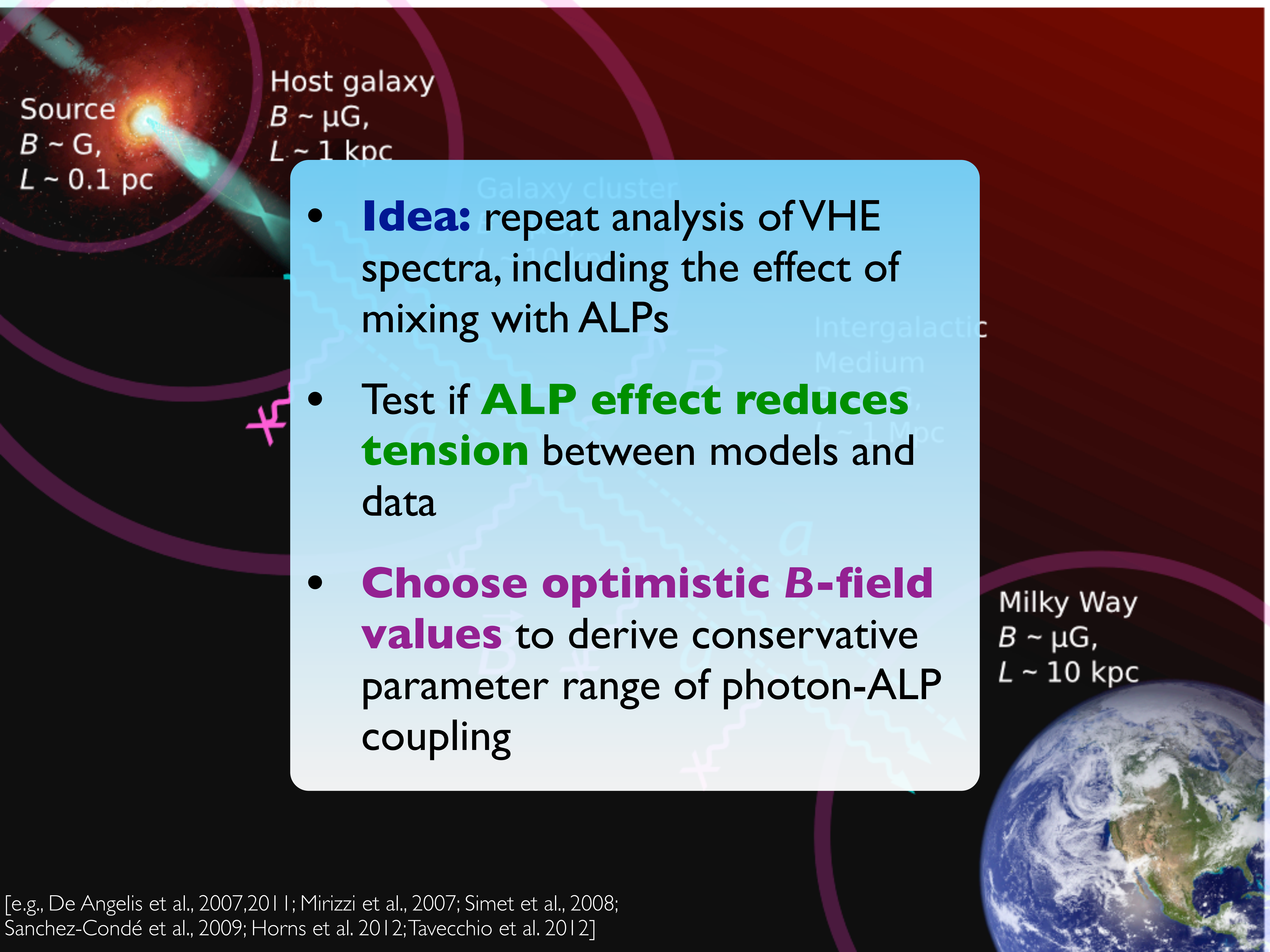
Host galaxy
$B \sim \mu$G,
$L \sim 1$ kpc

Galaxy cluster
$B \sim \mu$G,
$L \sim 10$ kpc

Intergalactic
Medium
$B <$ nG,
$L \sim 1$ Mpc

Milky Way
$B \sim \mu$G,
$L \sim 10$ kpc

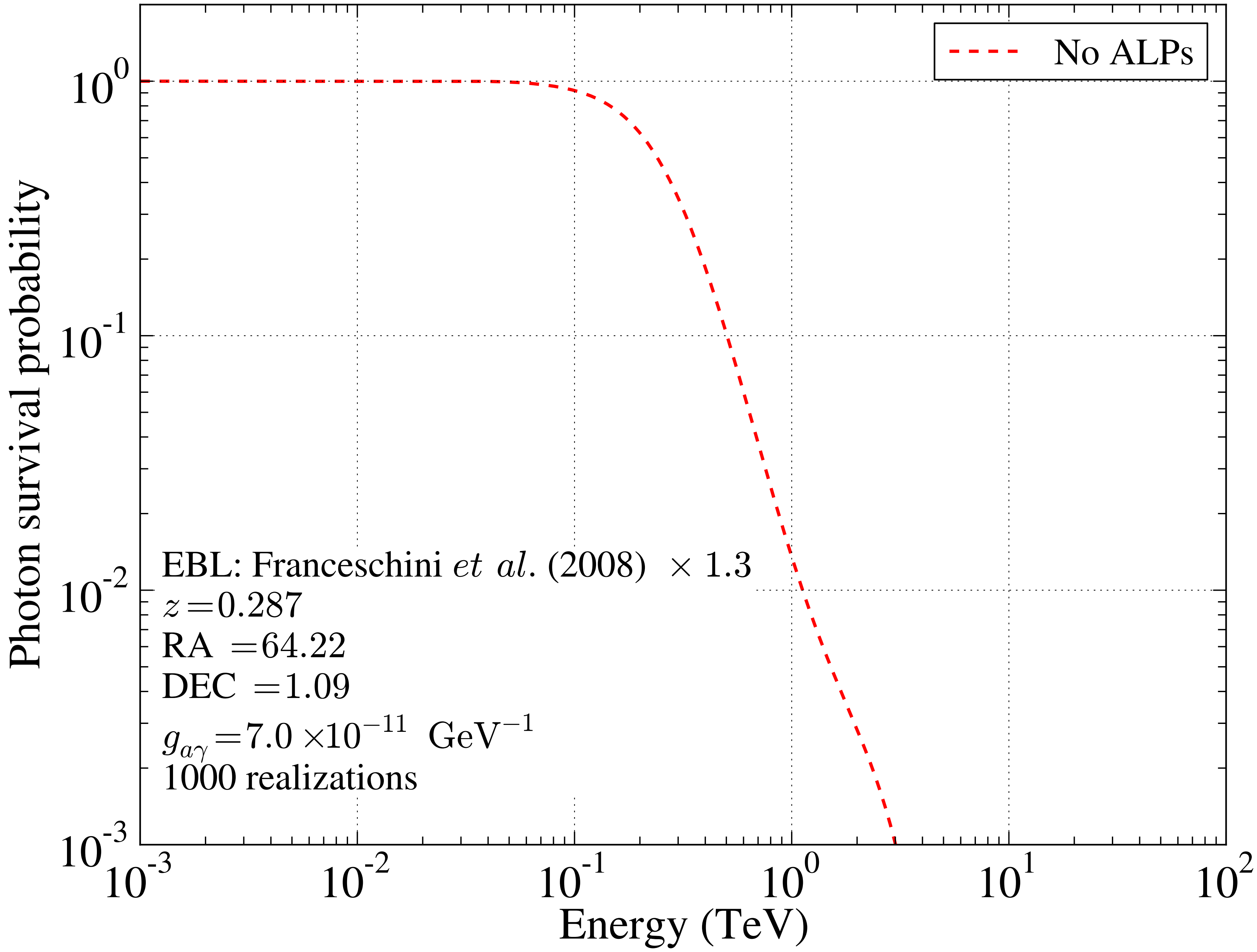
[e.g., De Angelis et al., 2007,2011; Mirizzi et al., 2007; Simet et al., 2008;
Sanchez-Condé et al., 2009; Horns et al. 2012; Tavecchio et al. 2012]



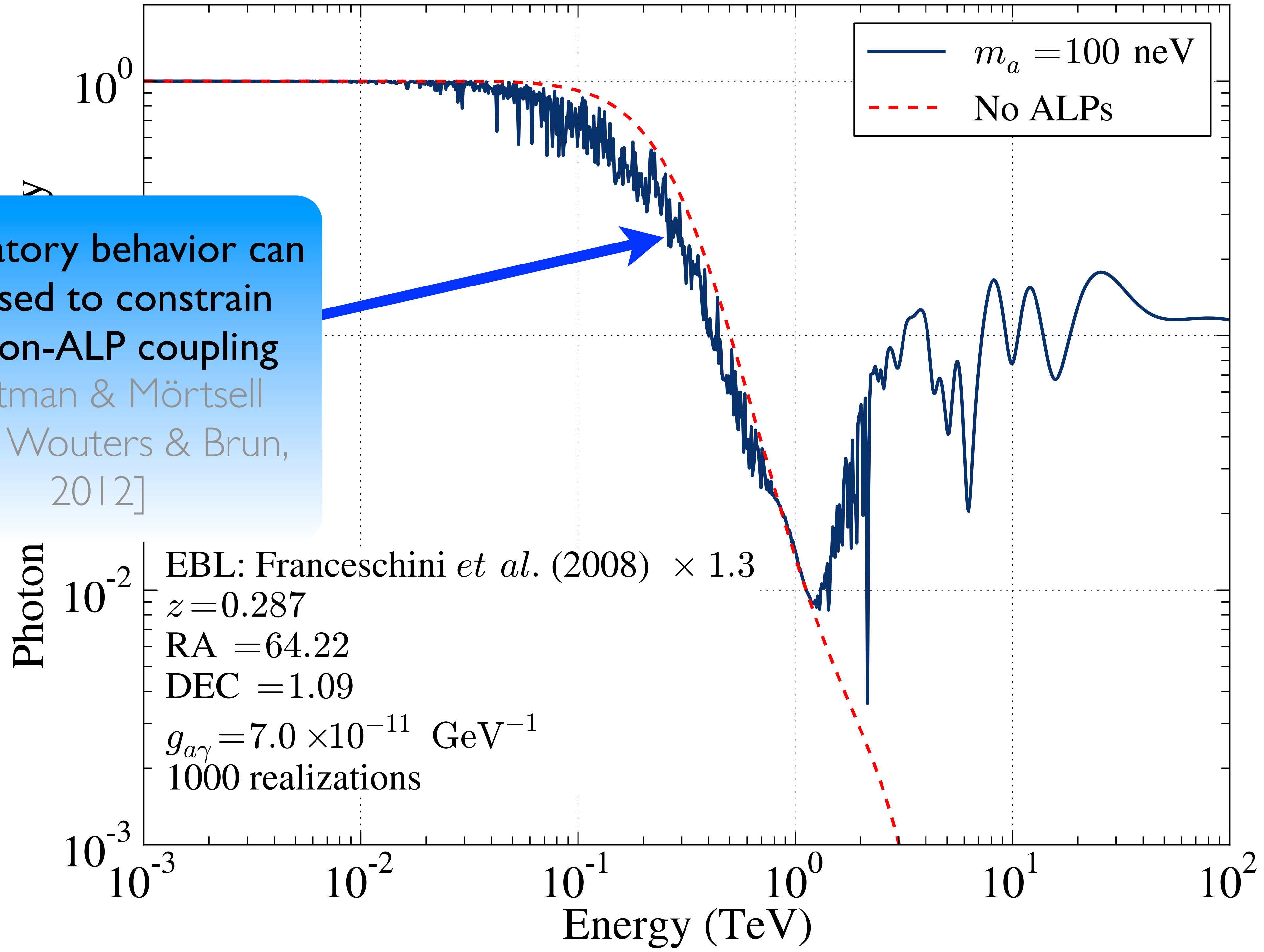
- **Idea:** repeat analysis of VHE spectra, including the effect of mixing with ALPs
- Test if **ALP effect reduces tension** between models and data
- **Choose optimistic *B*-field values** to derive conservative parameter range of photon-ALP coupling

[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]

Influence of ALP mixing on ɣ-ray attenuation

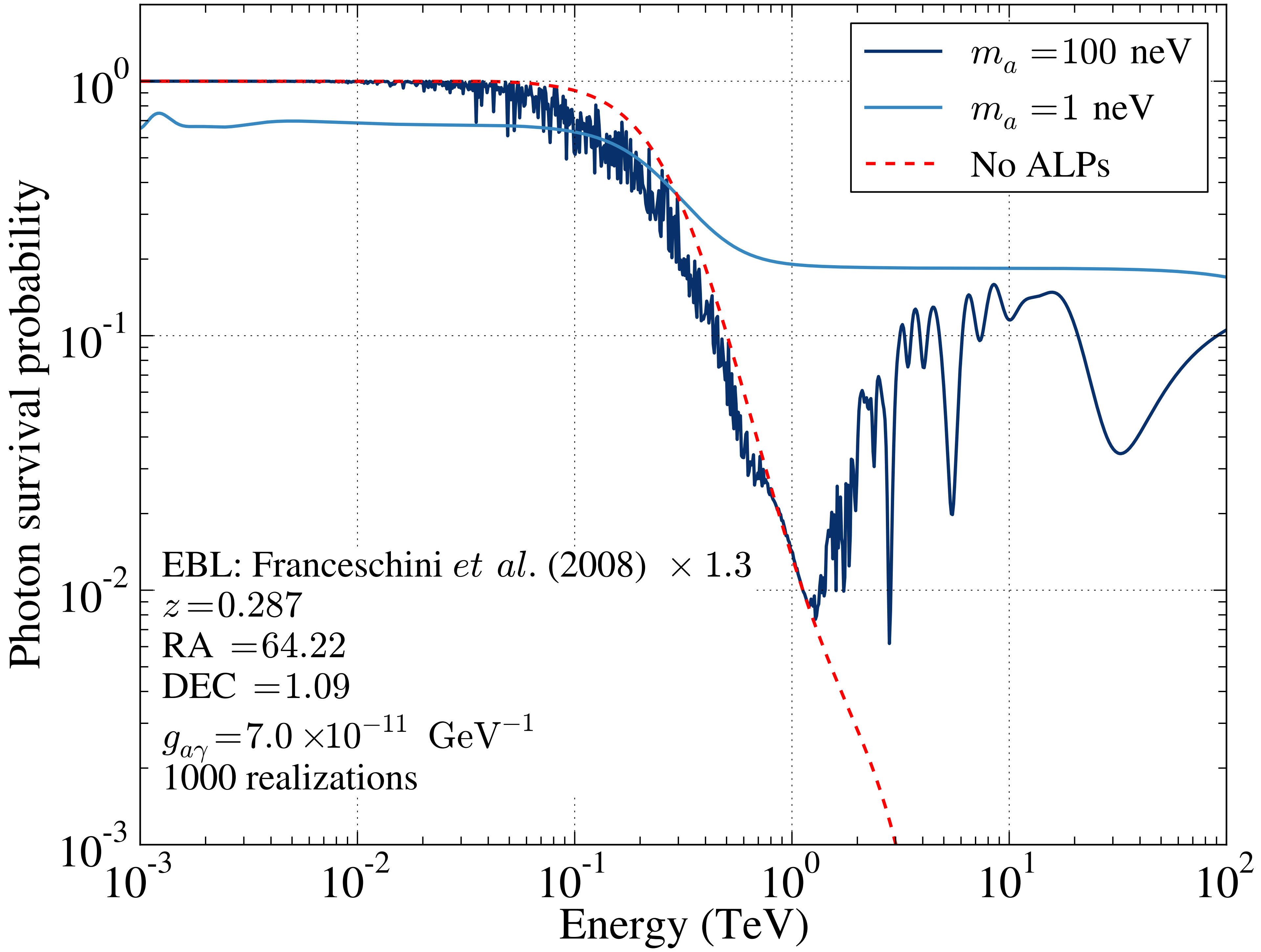


Influence of ALP mixing on γ-ray attenuation

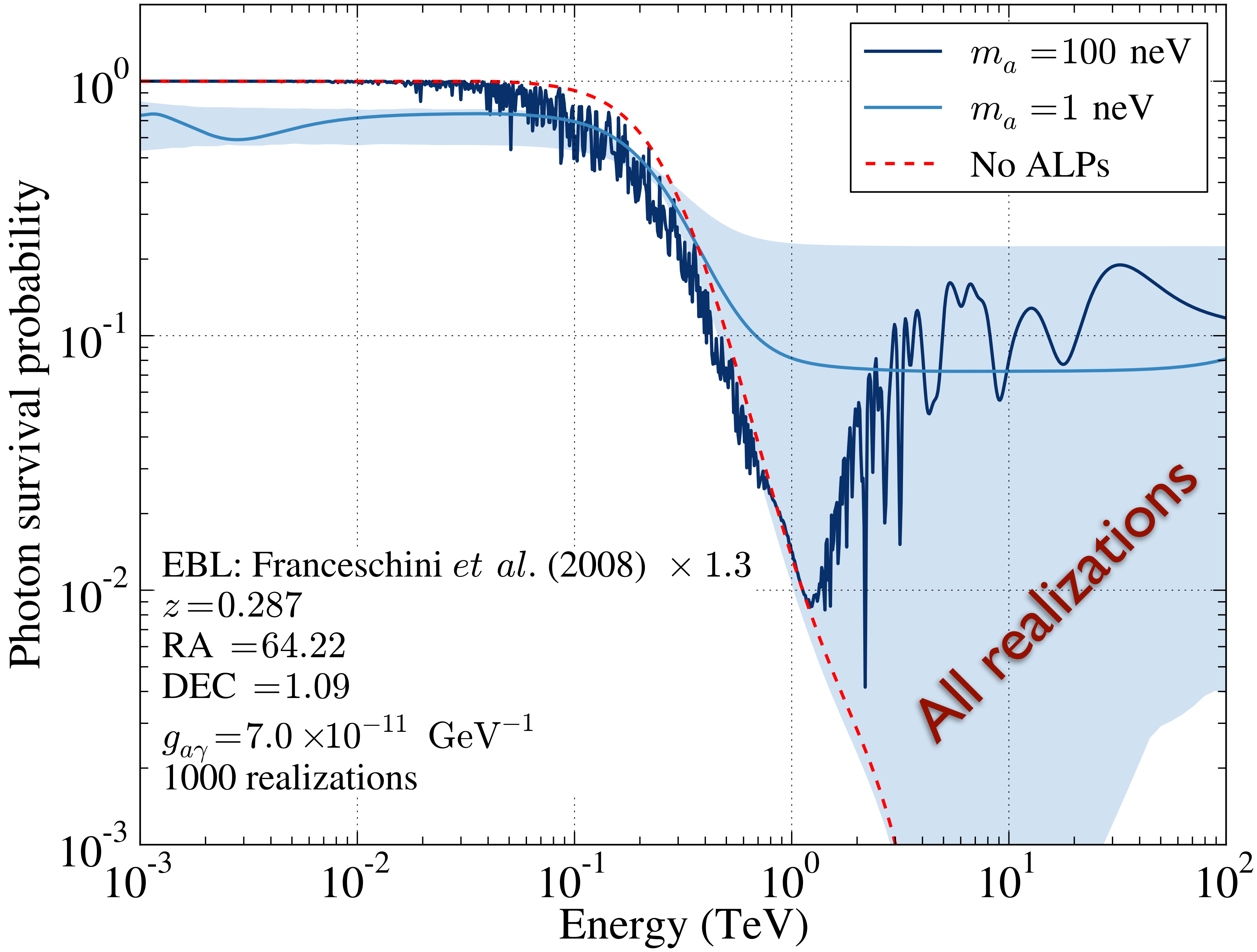


Oscillatory behavior can be used to constrain photon-ALP coupling [Östman & Mörtsell 2005; Wouters & Brun, 2012]

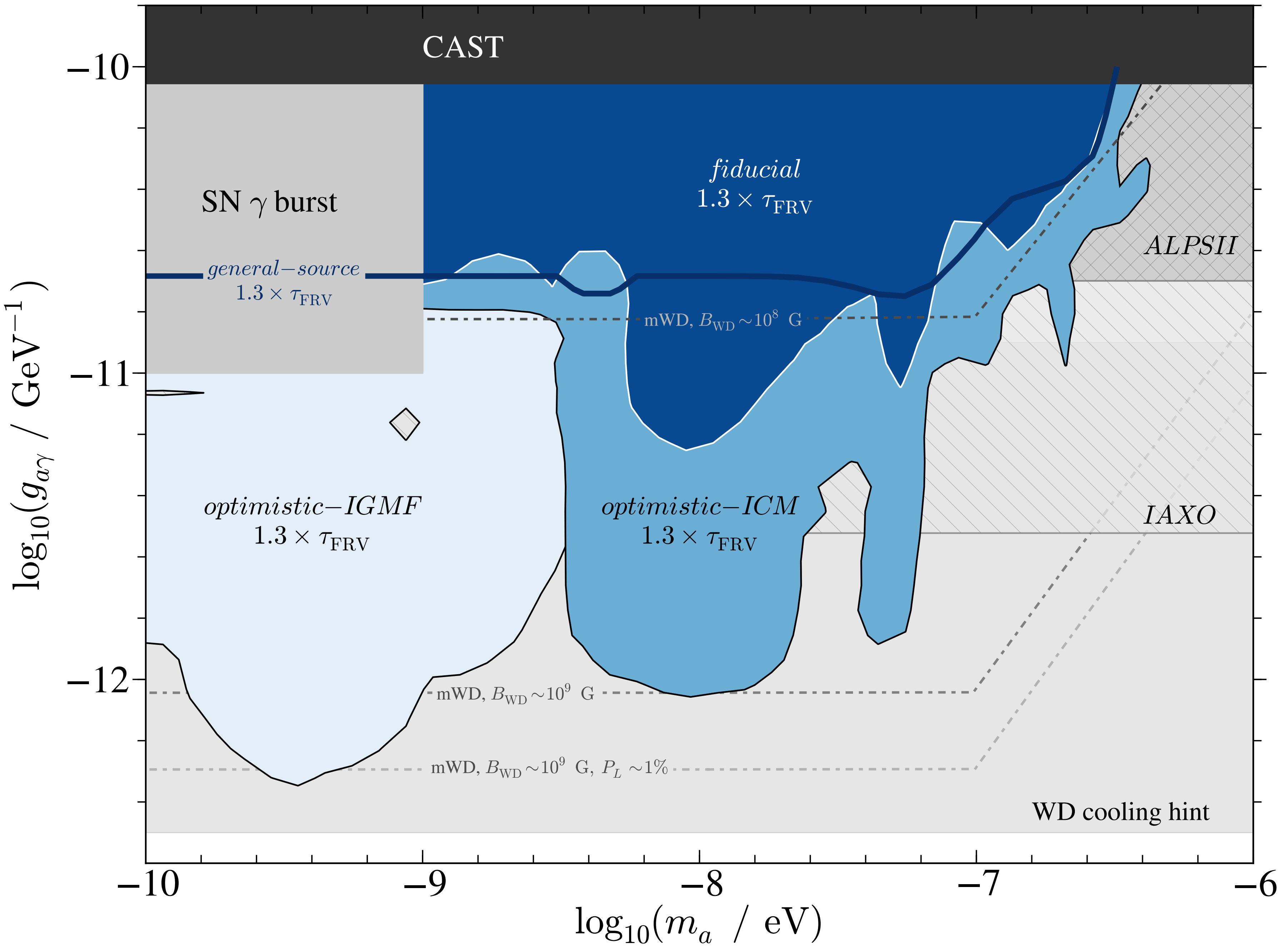
Influence of ALP mixing on γ-ray attenuation



Influence of ALP mixing on γ-ray attenuation



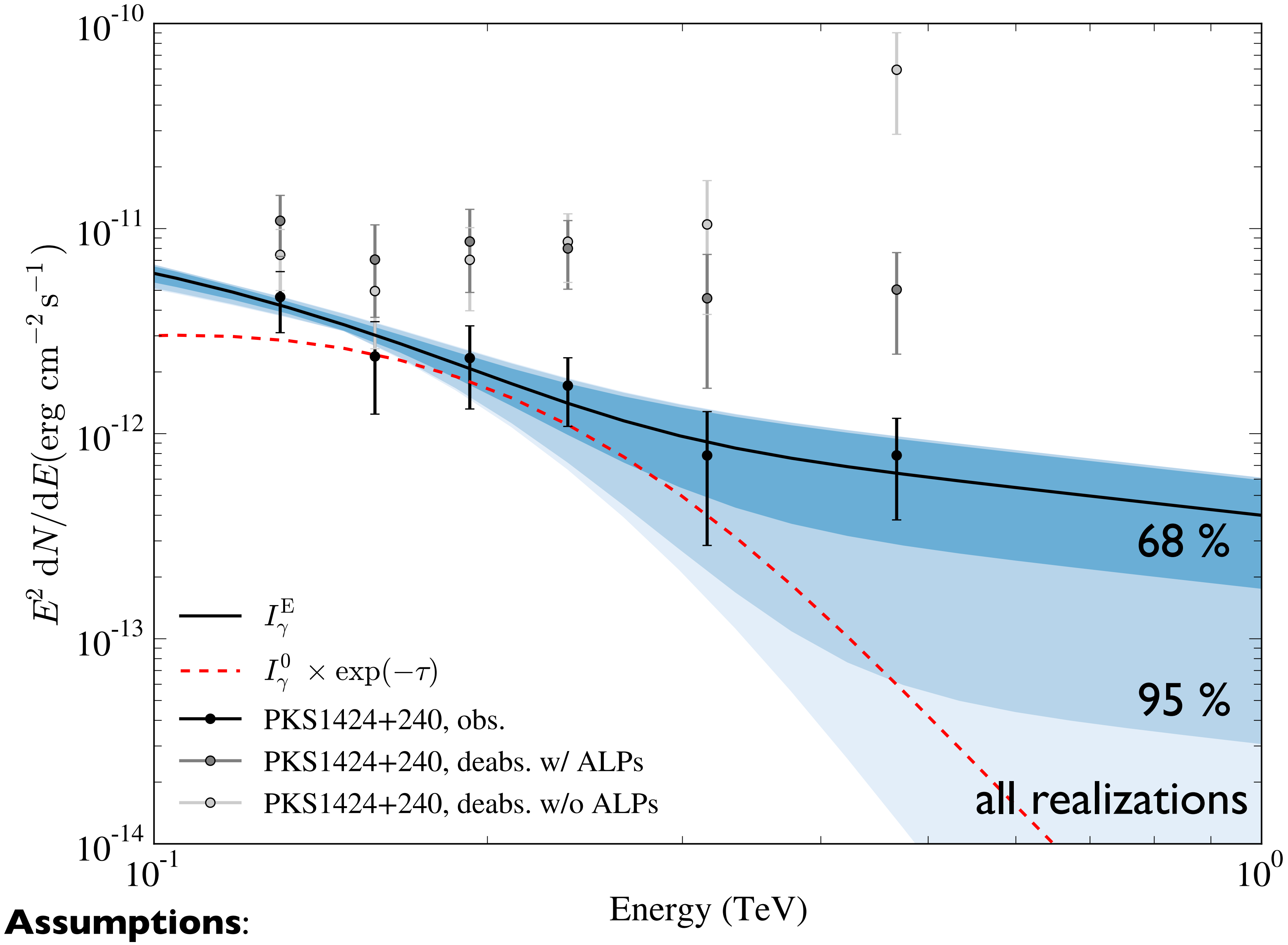
Limits on $g_{a\gamma}$



- Couplings to explain reduced opacity close to **limits 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]

[Meyer et al., 2013, Phys. Rev. D, vol 87, Issue 3]

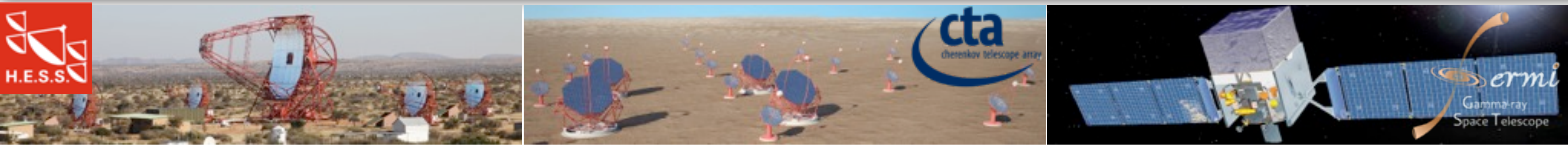
PKS 1424+240 at z > 0.6035



- Recently: **lower limit on redshift** found by Furniss et al., 2013
- Spectrum extends deep into **optical thick regime**
- **ALPs** might explain **flux regeneration**

Assumptions:
EBL: Franceschini et al. (2008) x 1.3
Photon-ALP mixing in GMF and galaxy cluster of size 500 kpc
with 1 μG field strength and 10 kpc coherence length
ALP mass: 1 neV
Coupling: 5 x 10^{-11} GeV^{-1}

Summary & Outlook



- Indications for a **reduced opacity** have been found in IACT of blazars at a **$\sim 4\sigma$ confidence level**
- If interpreted as evidence for physics beyond the standard model, **conversion of photons into ALPs** in ambient magnetic could explain anomaly
- **Further ALP signatures**: enhanced **dispersion** and **"step"** feature in transition from weak to strong mixing regime
- **H.E.S.S. Phase II** will be able to **measure intrinsic and absorbed blazar spectra simultaneously**
- **CTA: 10 times more sensitive** than currently operating IACT, energy range 10 GeV $\lesssim E \lesssim$ 100 TeV
- ***Fermi*-LAT**: search for **indication for low opacity**, wait for **Pass 8**
- In general: search for **ALPs** in **high $\tau_{\gamma\gamma}$-environments** where a **B field** is present

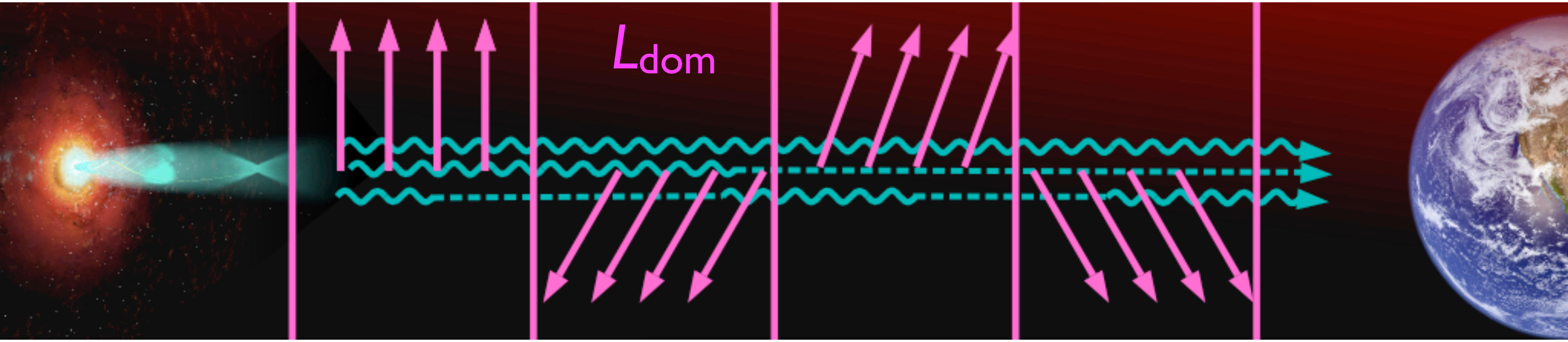
Backup slides

B-field scenarios

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

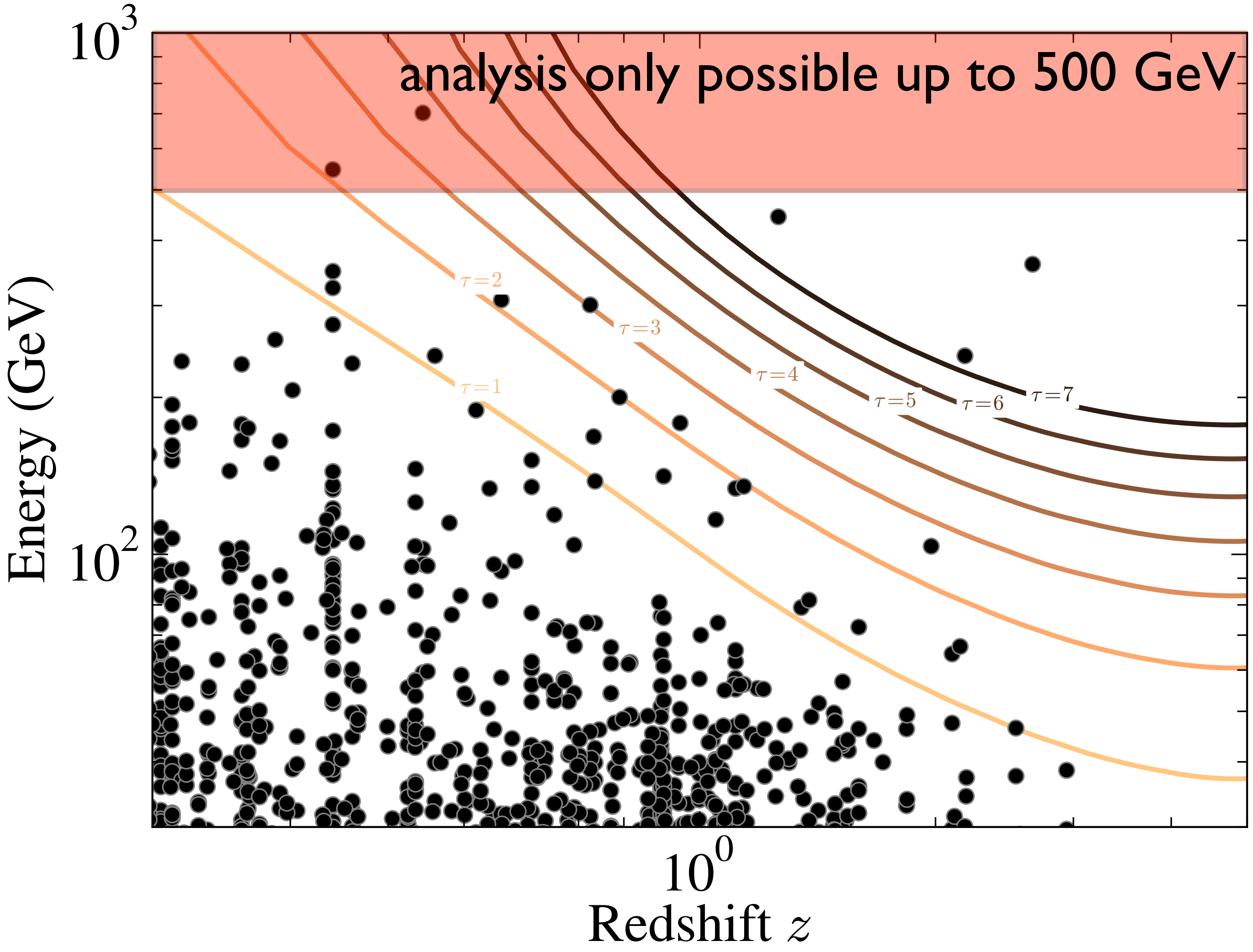
- Intracluster and intergalactic *B* fields: modeled with **domain like structure**: strength constant, **orientation changes randomly** from one cell to the next

- In *optimistic ICMF* scenario: **all AGN assumed to be located in clusters**, in *fiducial* scenario only if observational evidence exists



Search for low opacity in *Fermi*-LAT data

- **Associate photons** detected within first 4.3 years of *Fermi*-LAT **with AGN** listed in 2FGL with known redshift
- For each associated photon, **calculate optical depth**
- From intrinsic spectrum: **calculate probability to observe detected photons**
- **Combining results from all sources** and correcting for trials gives probability:
  - $P_{\text{post-trial}}(\tau_{\gamma\gamma} \geq 1) = 0.06$
  - $P_{\text{post-trial}}(\tau_{\gamma\gamma} \geq 2) = 1.2 \times 10^{-4}$

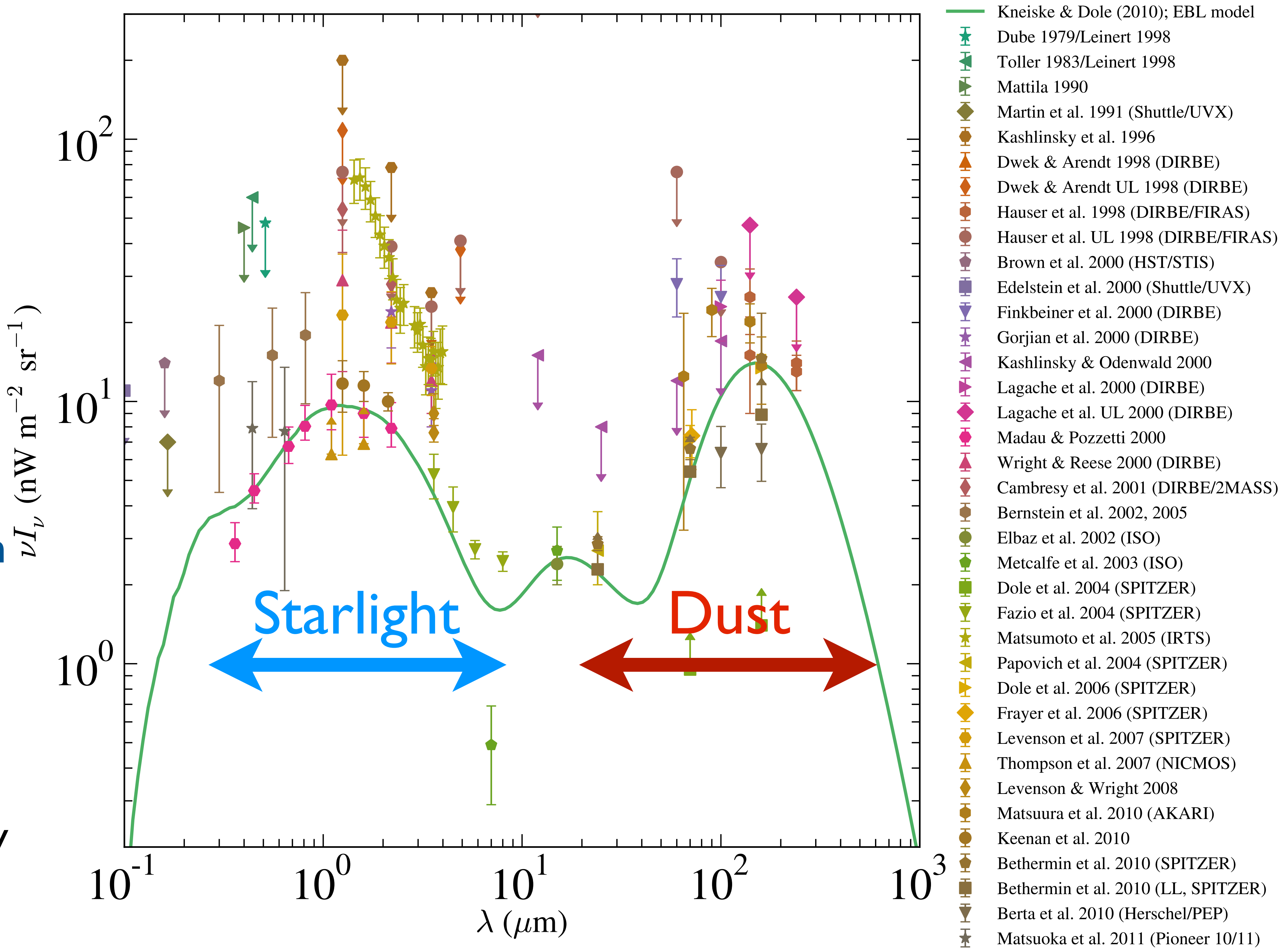


[Meyer et al., 2012, Gamma 2012 Proceedings, Meyer, 2013]

Extragalactic background light

[Figure and references adapted from Mazin & Raue, 2007,2011; see, e.g., Hauser & Dwek, 2001; Dwek & Krennrich, 2013, for reviews]

- Most important for **attenuation of γ-rays** due to cross section
- Main contributors: **integral starlight** and starlight reprocessed by **dust**
- Direct **detection difficult** due to foreground emission
- Firm **lower limits** from galaxy number counts



Attenuation of γ-rays

- Absorbed (observed) spectra given by

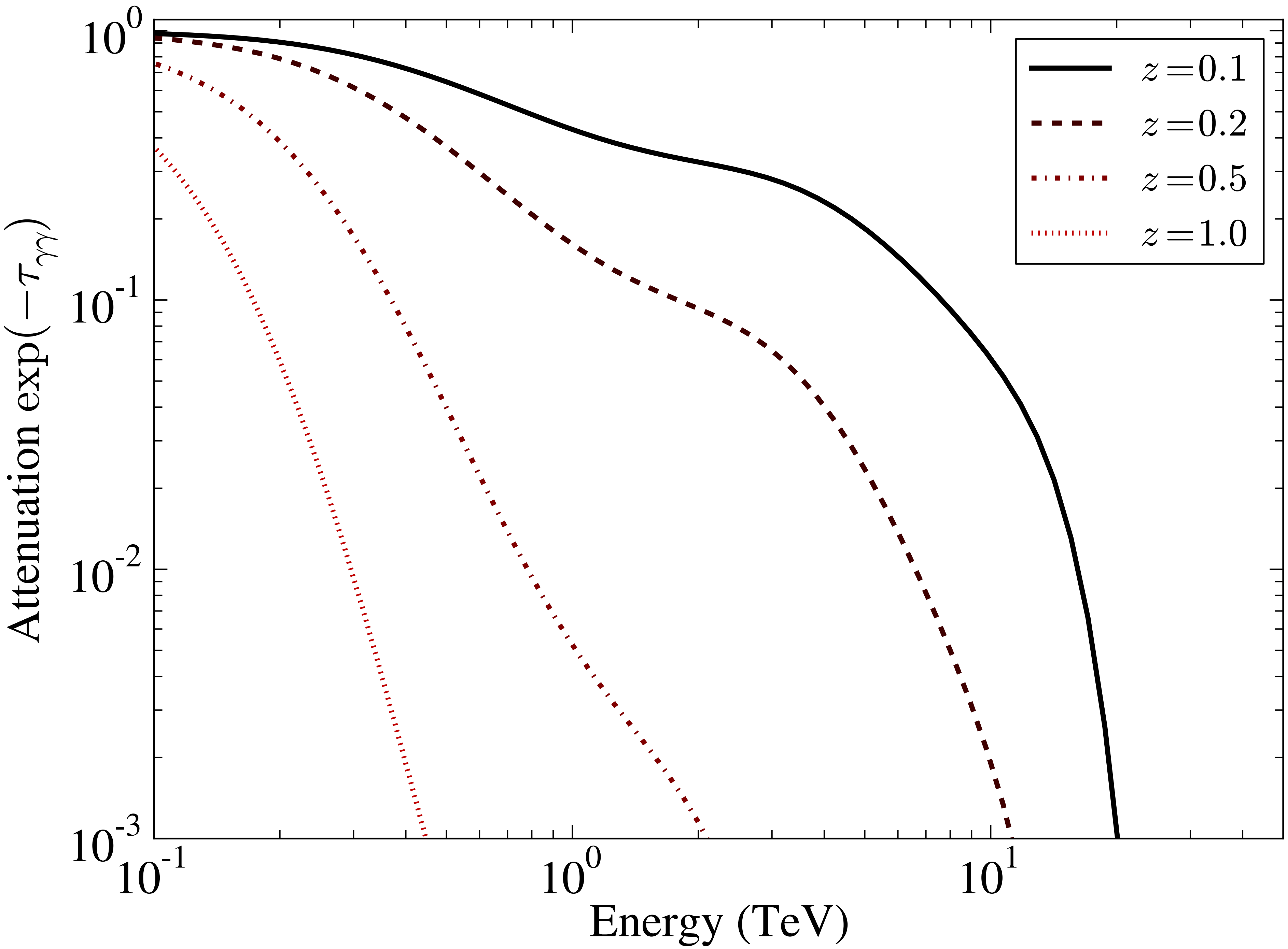
$$f_\nu = \exp[-\tau_{\gamma\gamma}(E, z)]F_\nu$$

- Strength of absorption determined by **optical depth**:

$$\tau_{\gamma\gamma}(E, z_0) = \underbrace{\int\limits_0^{z_0} \mathrm{d}\ell(z)}_{\text{l.o.s. integral}} \underbrace{\int\limits_{-1}^{+1} \mathrm{d}\mu \, \frac{1-\mu}{2}}_{\text{angle between photon momenta}} \int\limits_{\epsilon'_{\mathrm{thr}}}^{\infty} \mathrm{d}\epsilon' \underbrace{n_\epsilon(\epsilon', z)}_{\text{EBL photon density}} \underbrace{\sigma_{\gamma\gamma}(E', \epsilon', \mu)}_{\text{pair-production cross section}}$$

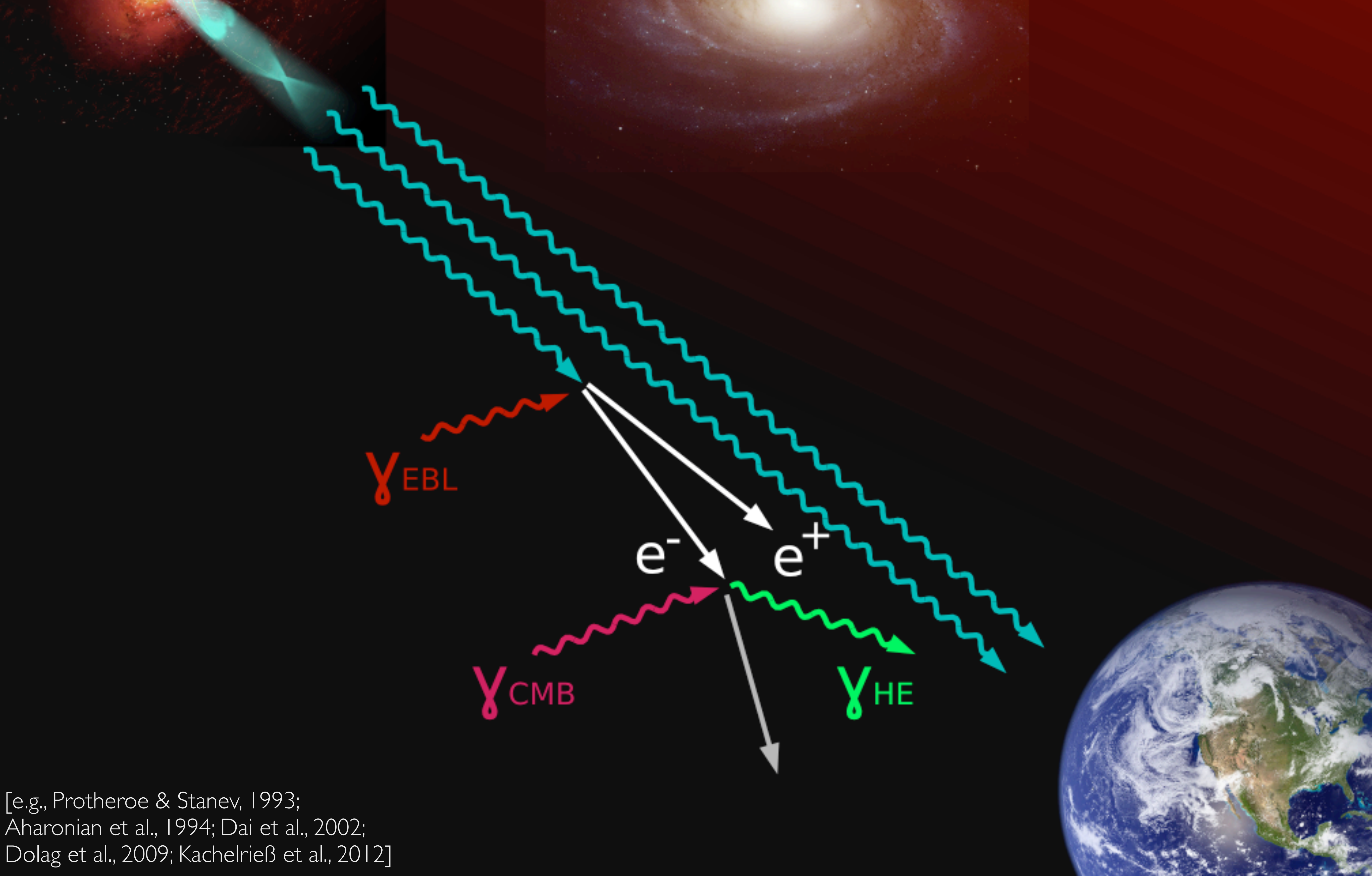
[e.g., Dwek & Krennrich, 2005]

Attenuation of γ-rays



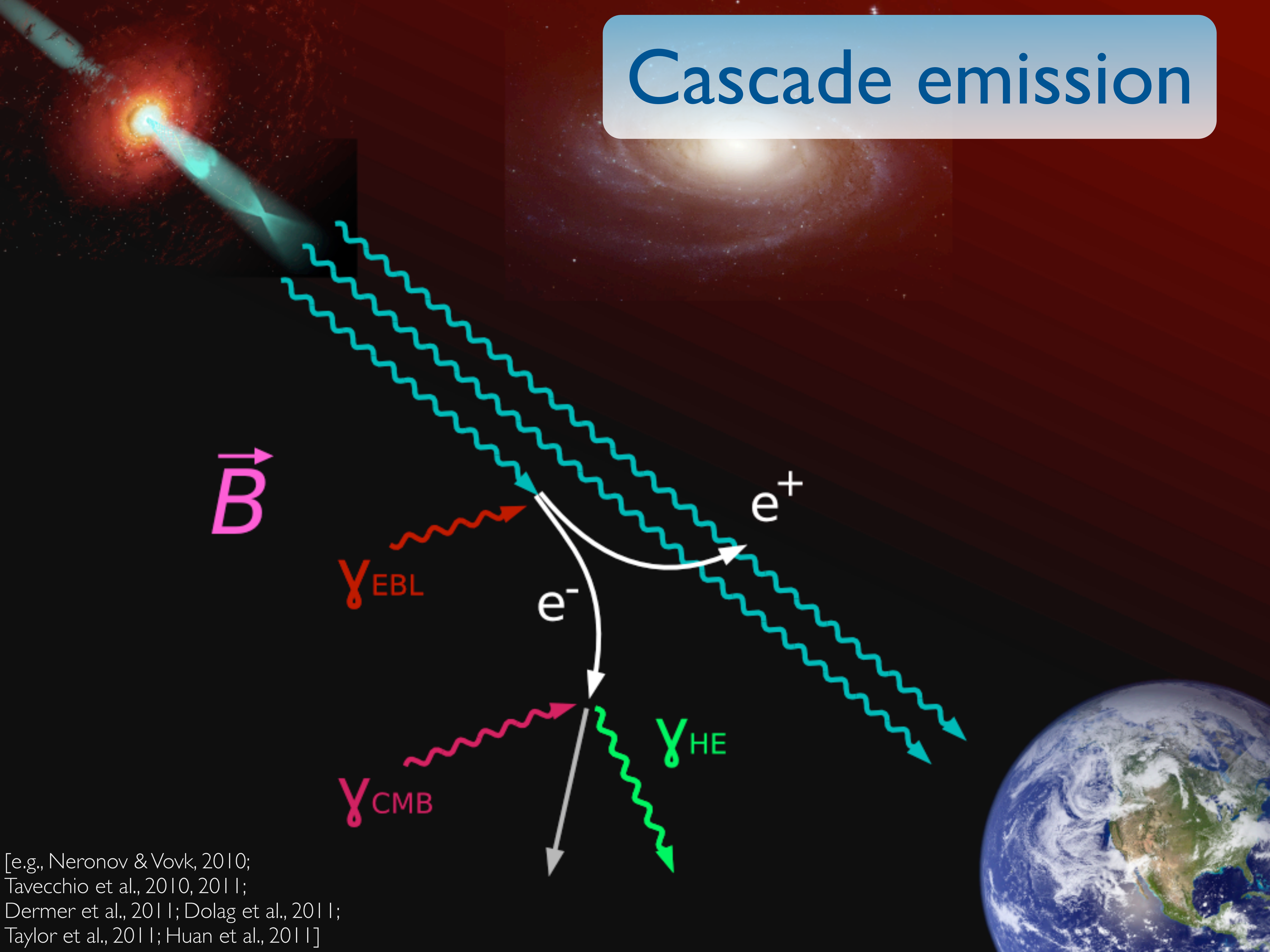
[Kneiske & Dole, 2010]

Cascade emission



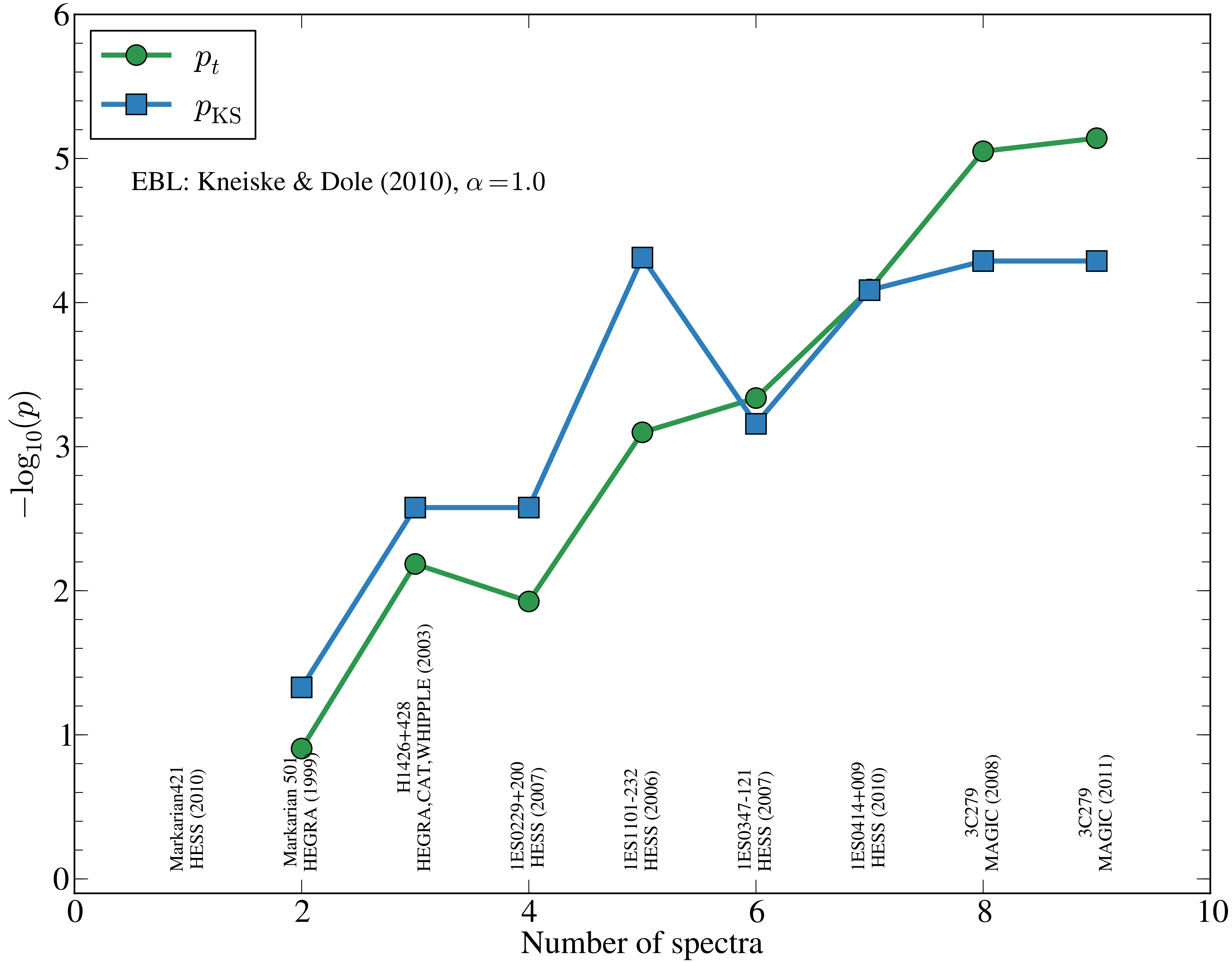
[e.g., Protheroe & Stanev, 1993;
Aharonian et al., 1994; Dai et al., 2002;
Dolag et al., 2009; Kachelrieß et al., 2012]

Cascade emission



[e.g., Neronov & Vovk, 2010;
Tavecchio et al., 2010, 2011;
Dermer et al., 2011; Dolag et al., 2011;
Taylor et al., 2011; Huan et al., 2011]

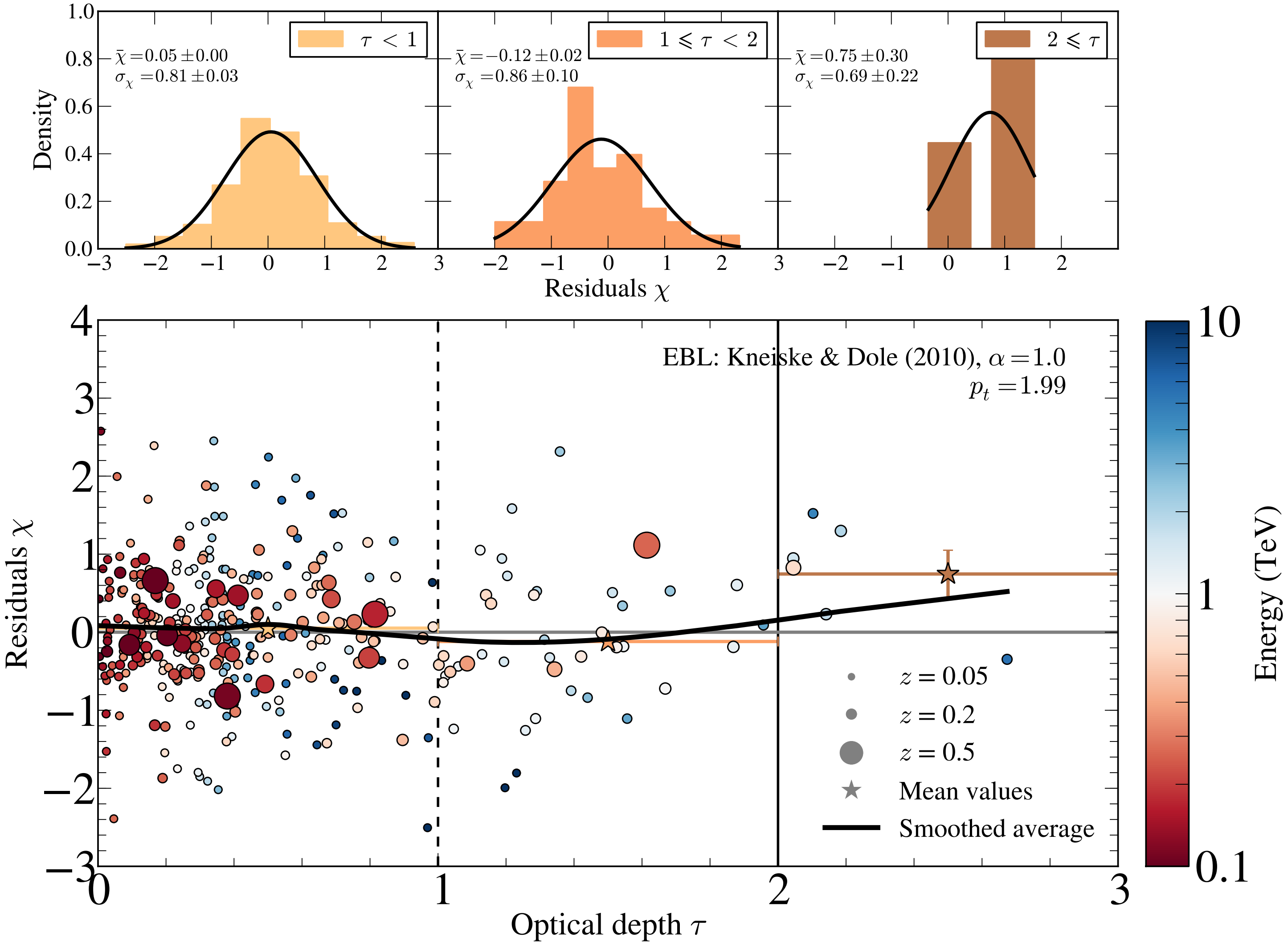
Cumulative significance of PPA for VHE analysis



[Meyer, 2013]

Study of systematic uncertainties: energy resolution and calibration

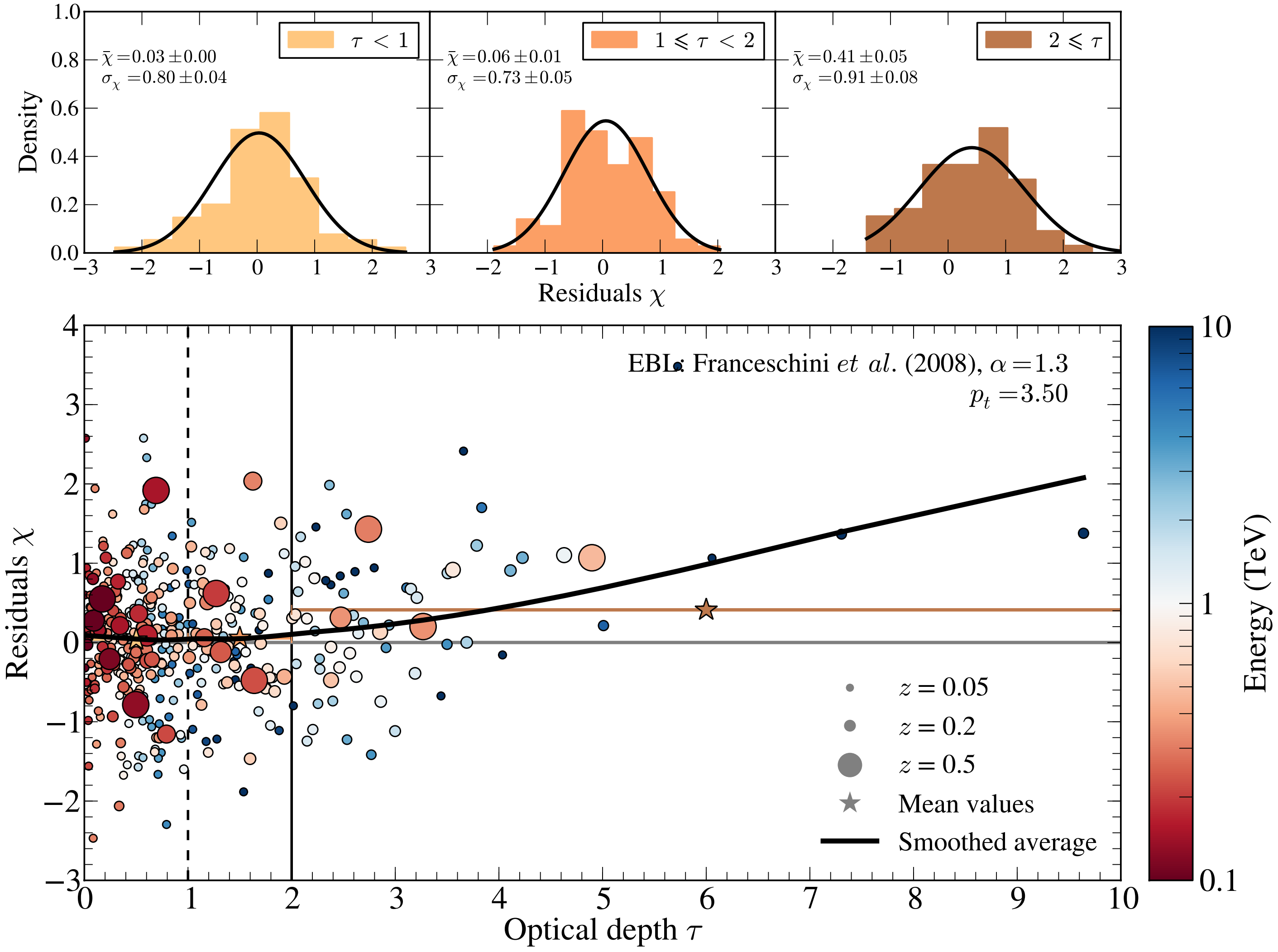
- Limited energy resolution might cause **spill-over effect**
- Energy **calibration (Δ*E*/*E* ~ 15%)** uncertain [however: Cross calibration with LAT ⇒ only energy shift of ~ 5% necessary, see Meyer et al., 2010]
- Test repeated with energy points scaled by -15% and last energy point removed ⇒ **significance 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



[Meyer, 2013]

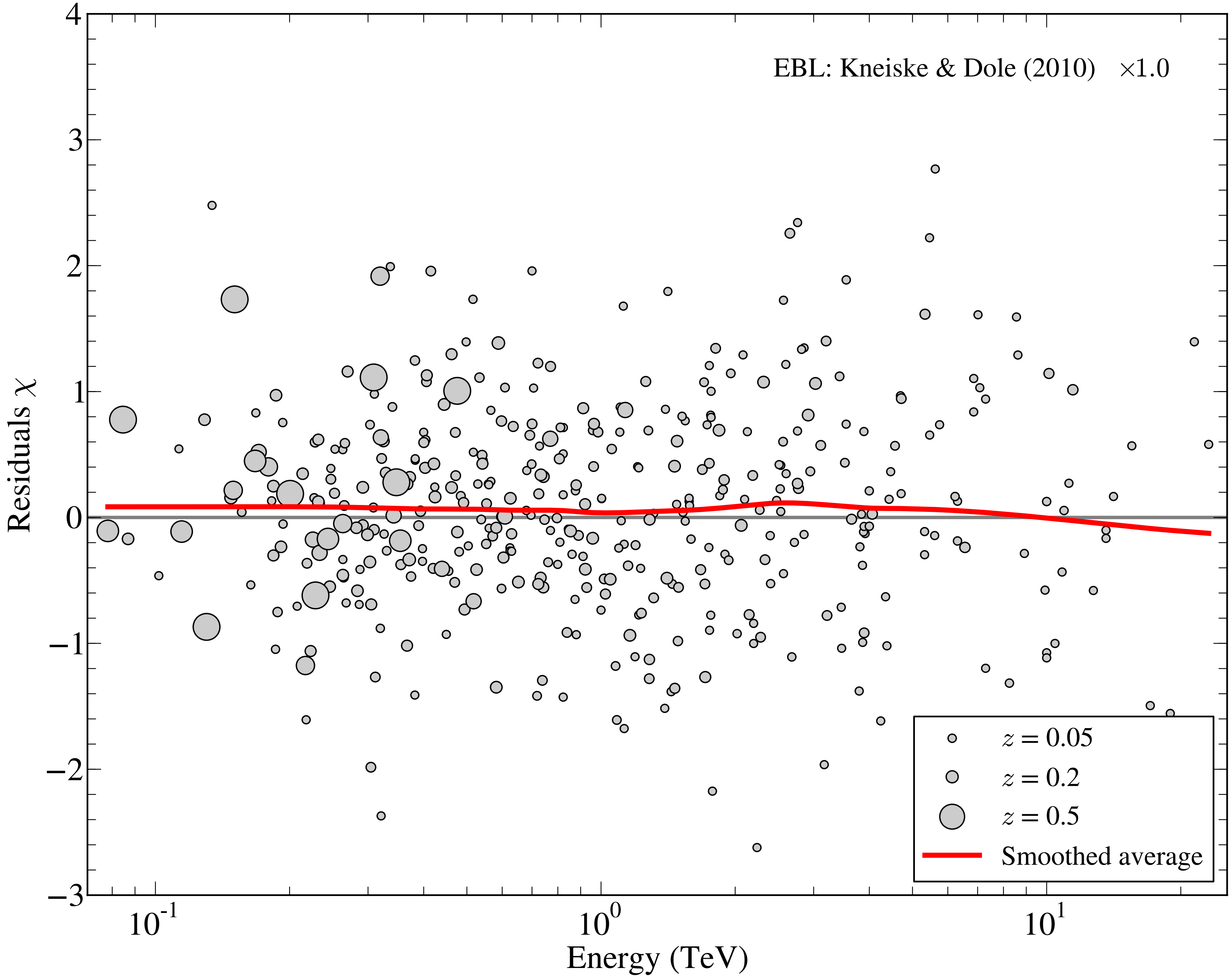
Study of systematic uncertainties II

- **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



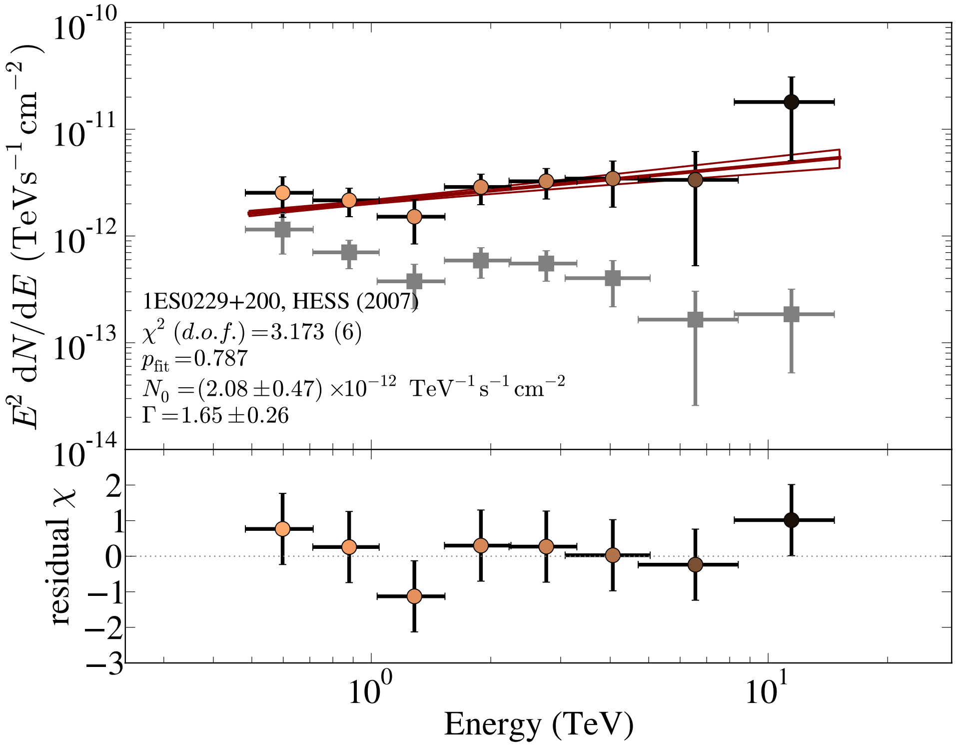
[Meyer, 2013]

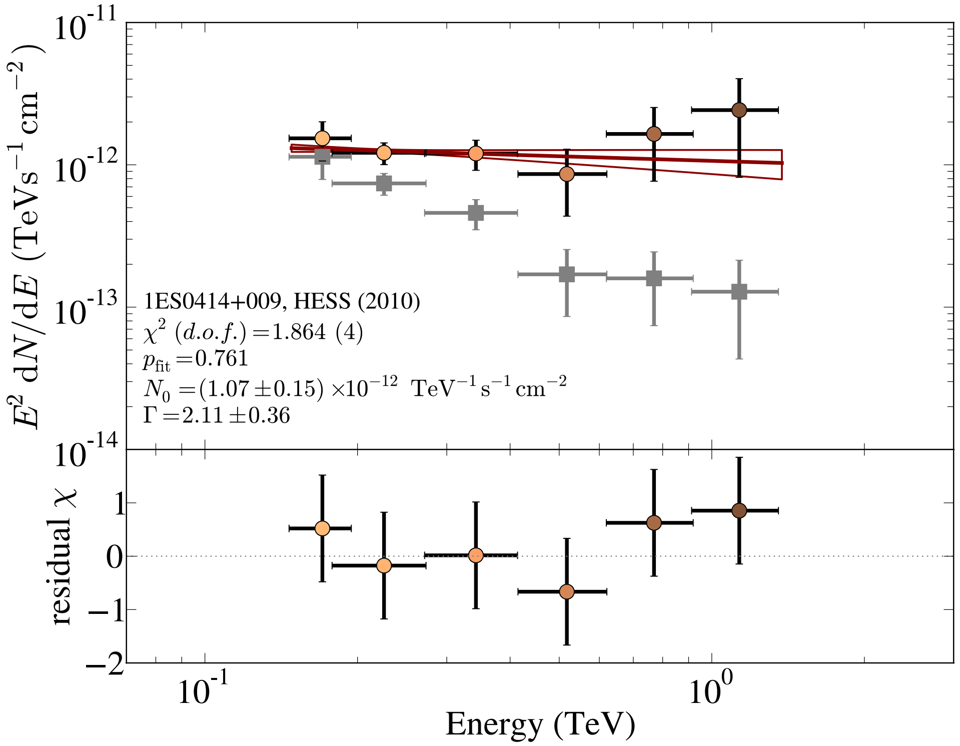
No trend in energy seen

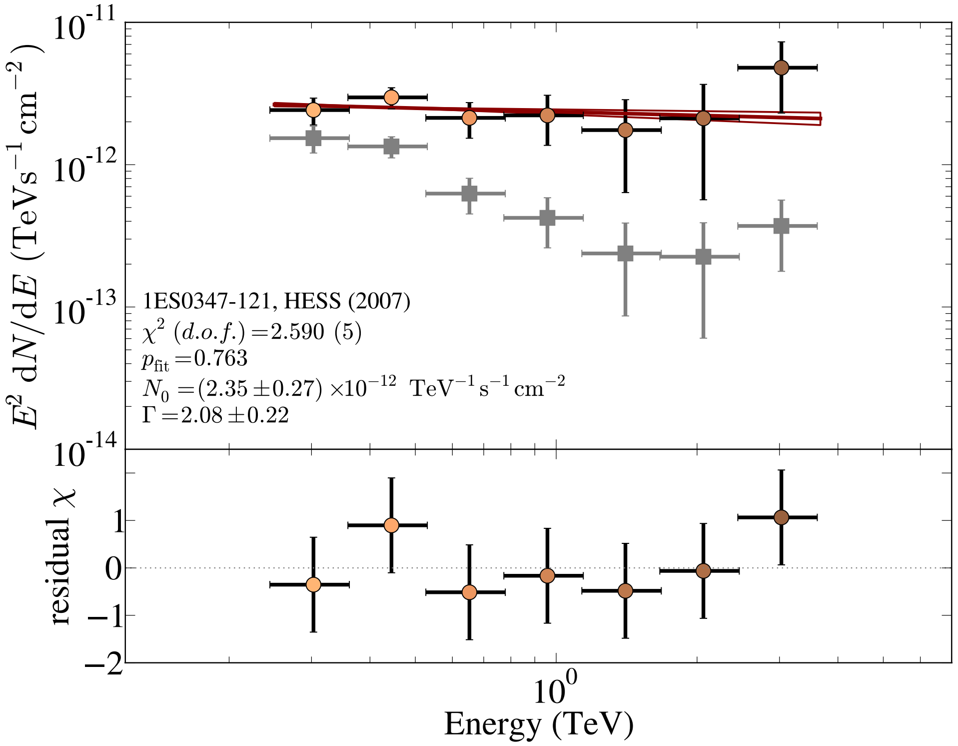


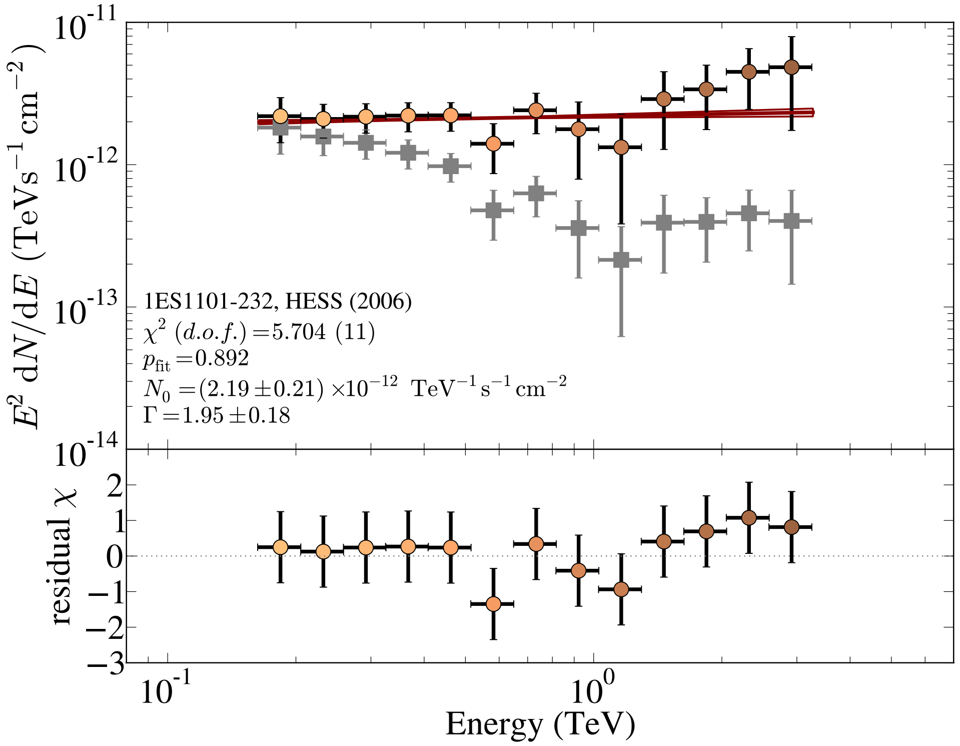
[Horns & Meyer, 2012; Meyer, 2013]

Spectral fits I



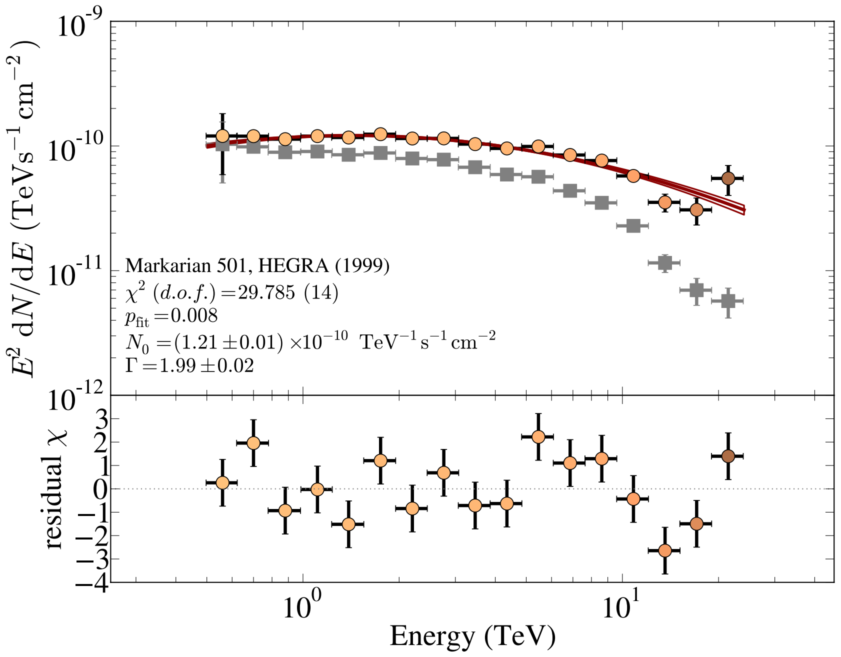


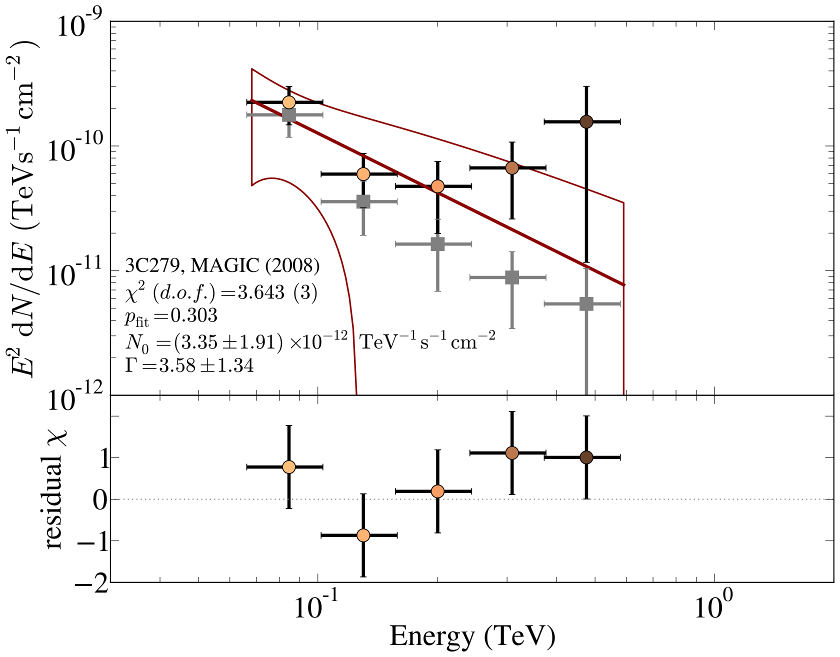


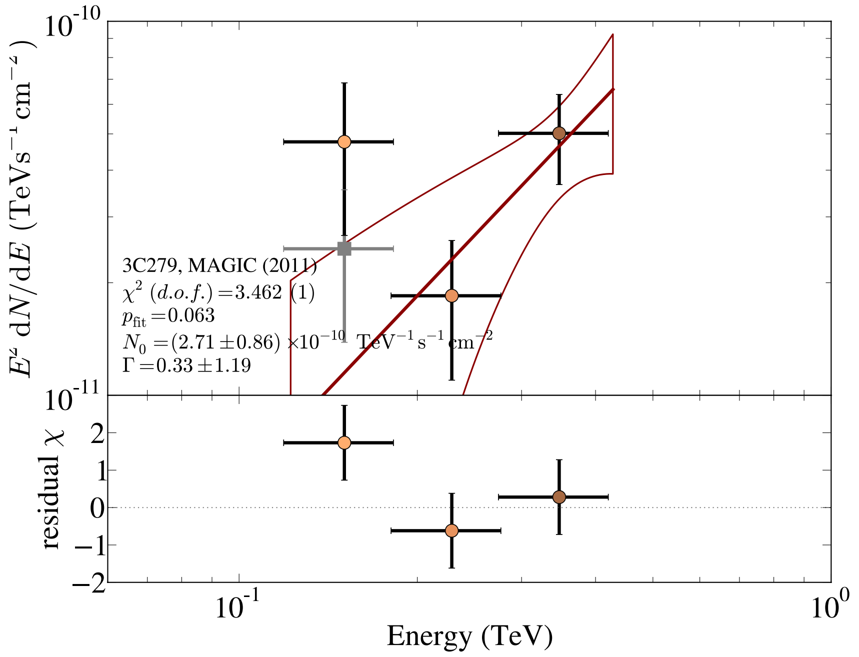


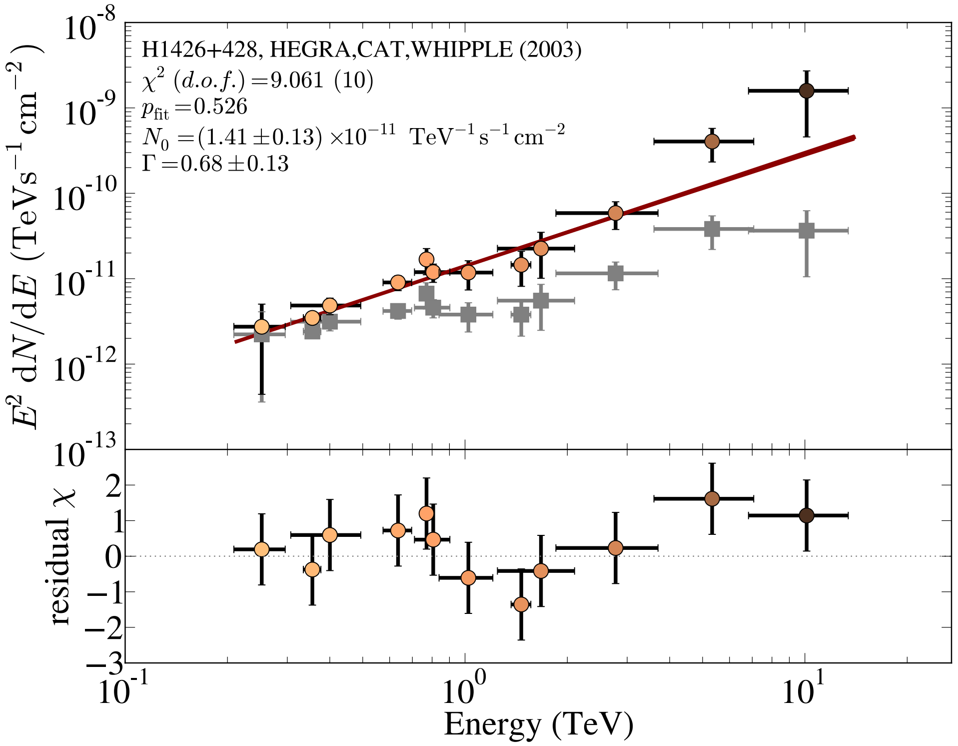
[Meyer, 2013]

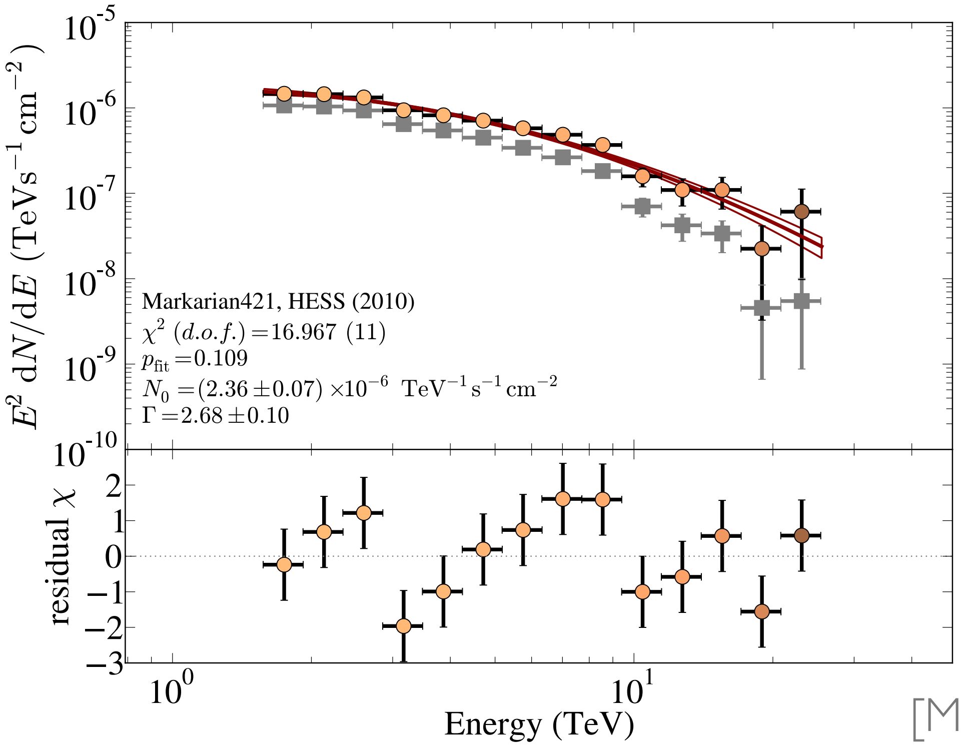
Spectral fits II





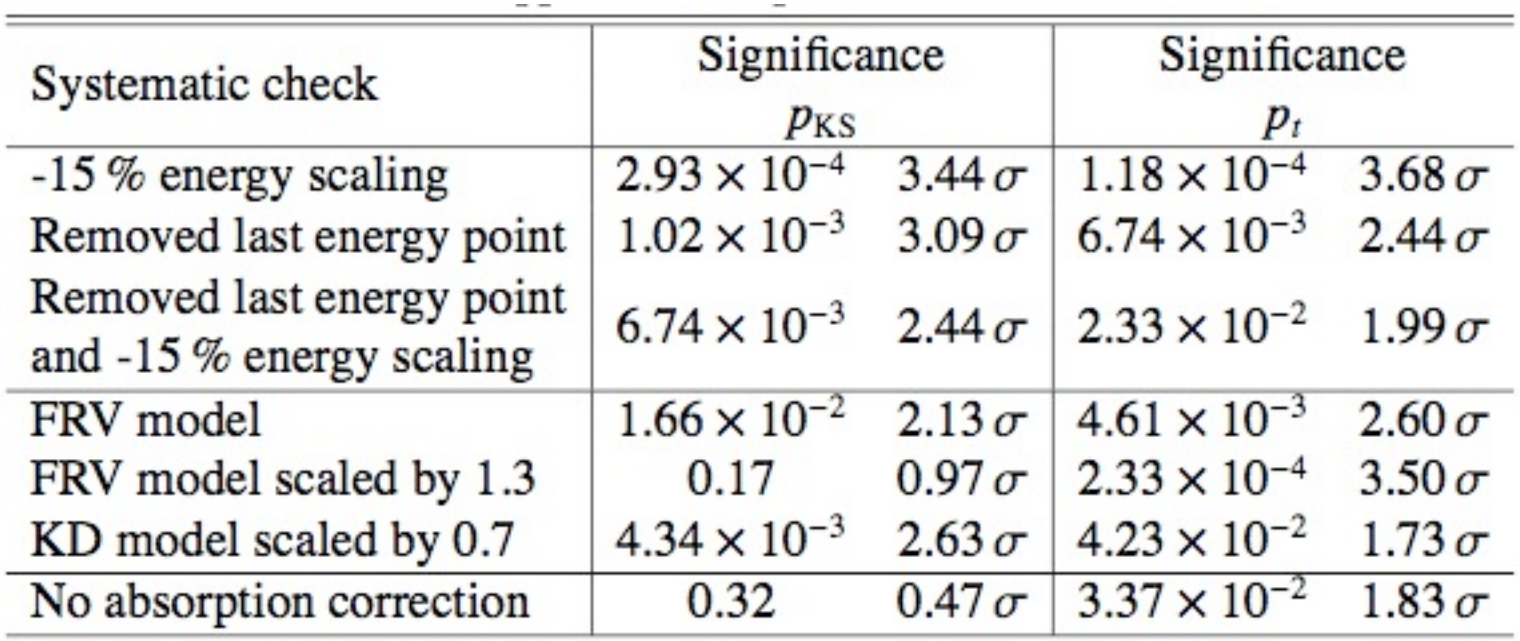






[Meyer, 2013]

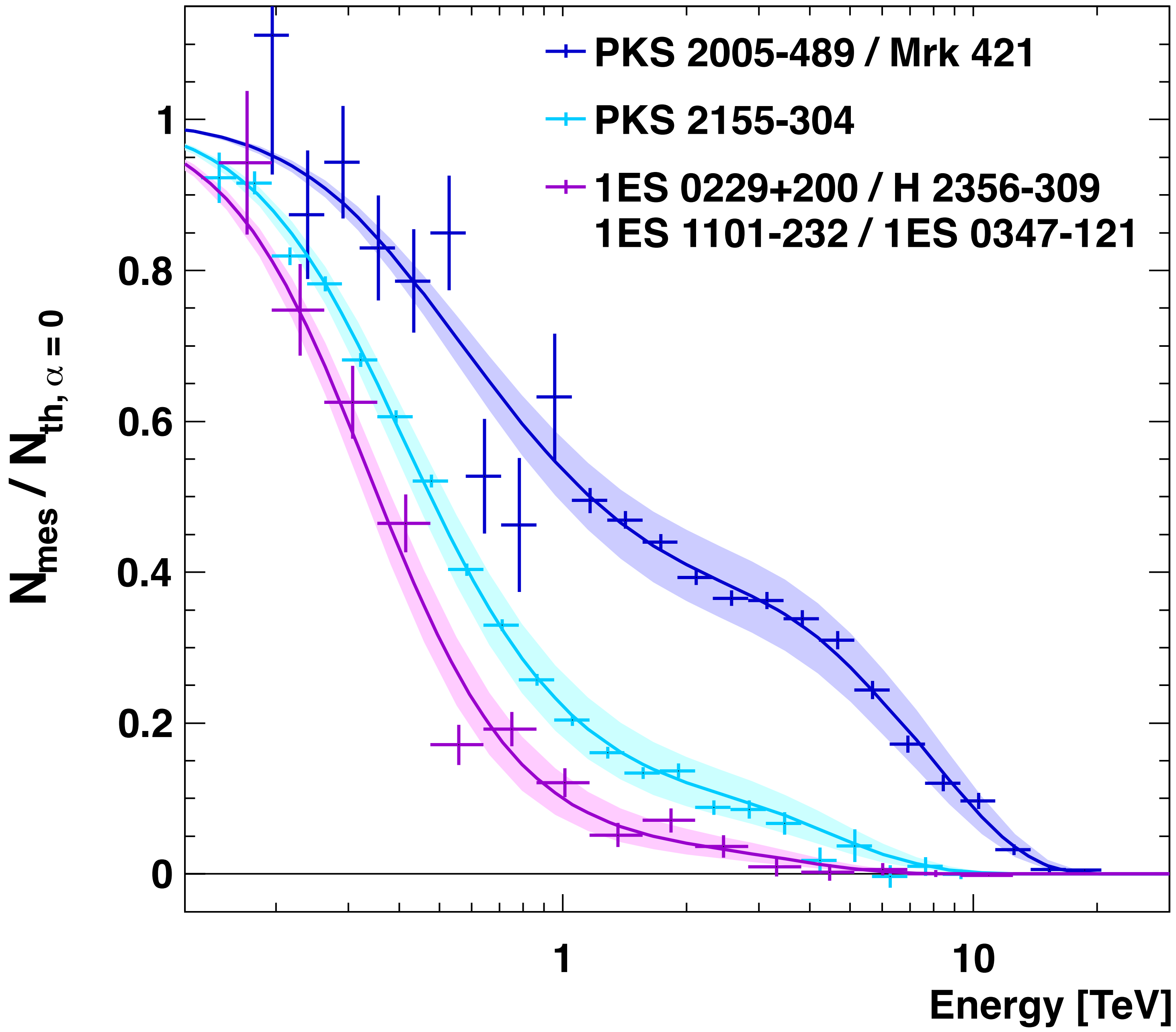
Cross checks for VHE opacity analysis



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}	$1.83\,\sigma$

[Meyer, 2013]

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



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

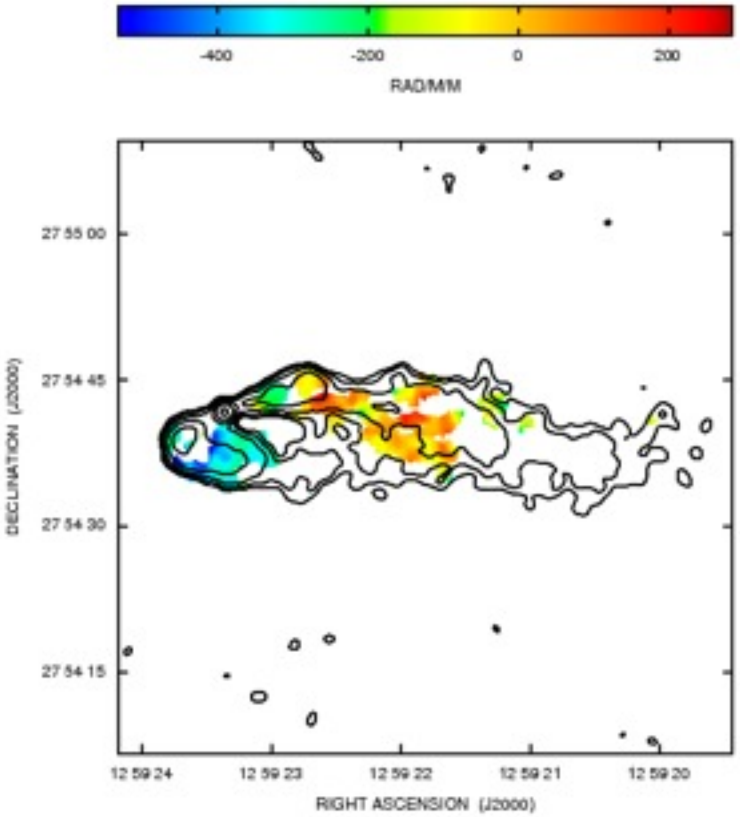
- Reduced opacity should become visible in residuals of recent H.E.S.S. analysis of EBL imprint in blazar spectra
- No excess seen (although hard to tell from the plot)
- Sources binned into 3 redshift bins, might mask the effect

Backup: B-fields

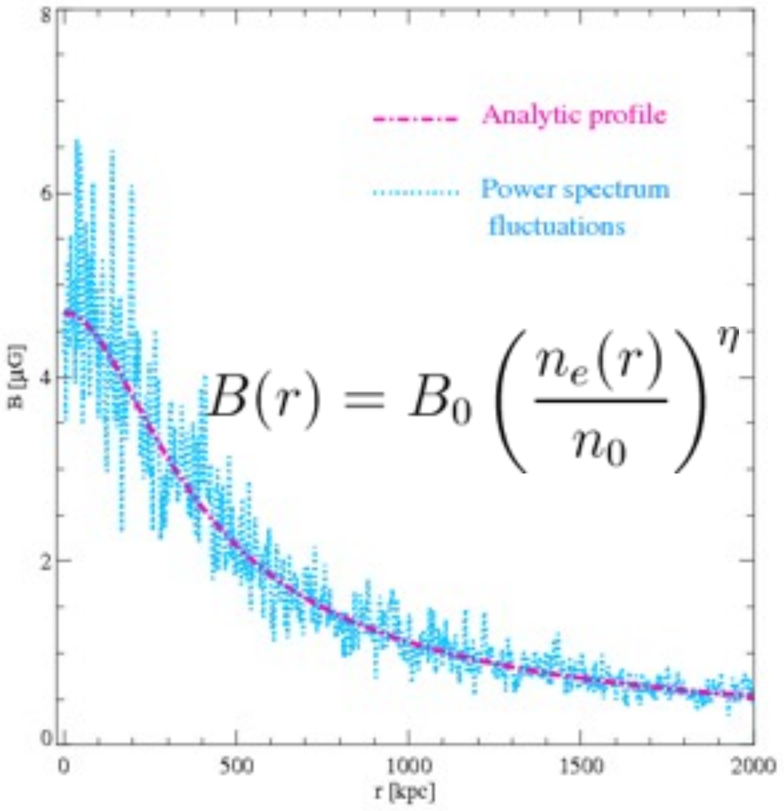
Intracluster magnetic fields

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

- 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)***



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



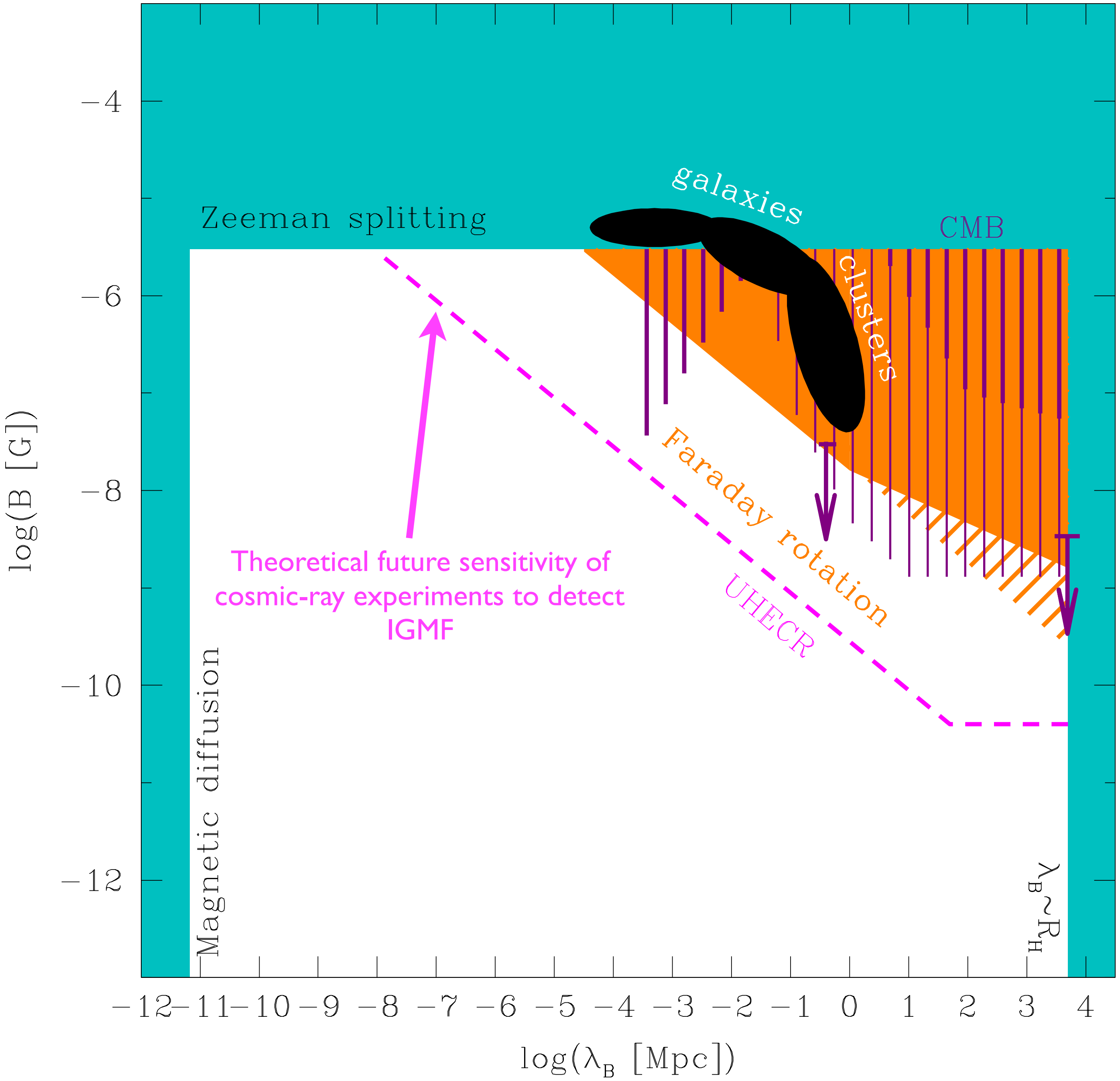
Simulated B field (blue) and analytical profile (magenta) of the Coma cluster

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

$$\mathrm{RM} = 812 \int\limits_0^{L/\mathrm{kpc}} n_e B_{||}\,\mathrm{d}\ell\,(\mathrm{rad\,m}^{-2})$$

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

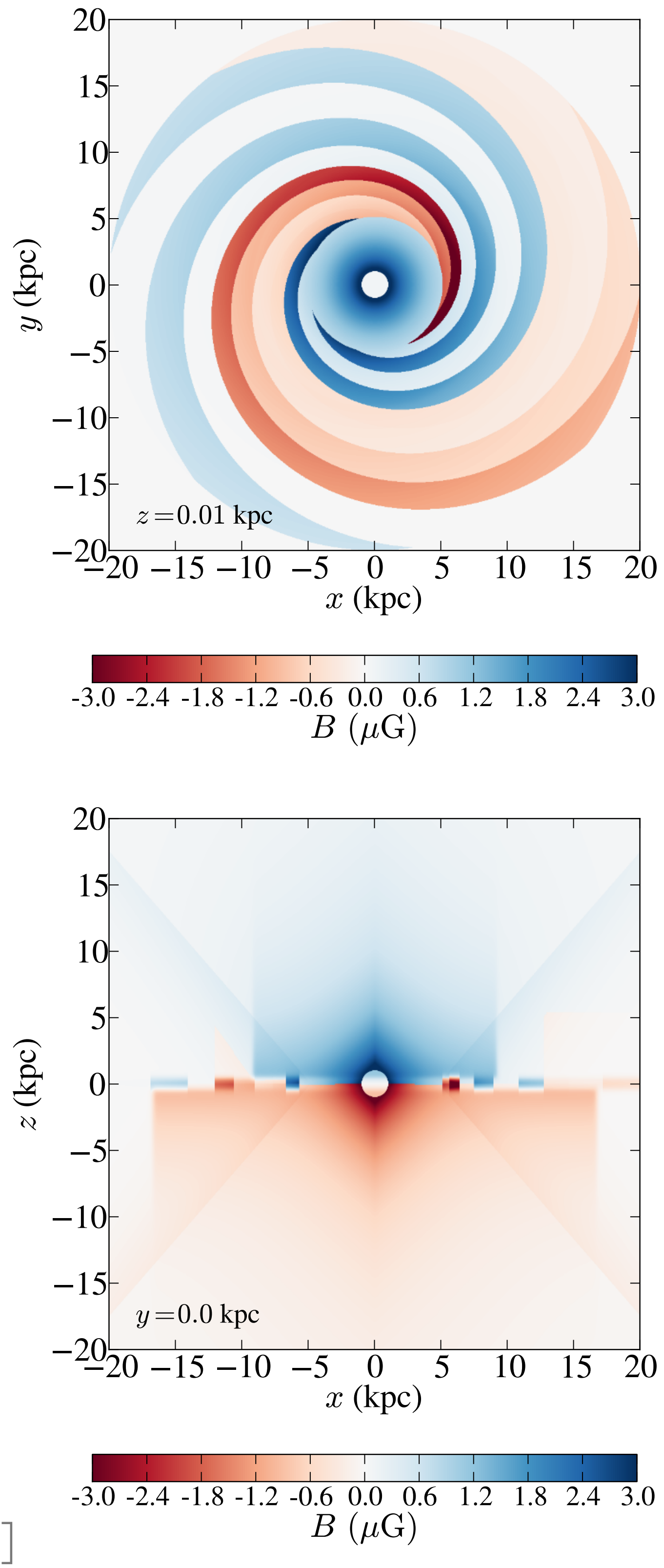
- **Regular component** of Galactic magnetic field (GMF) model of Jansson & Farrar (2012)

- 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**



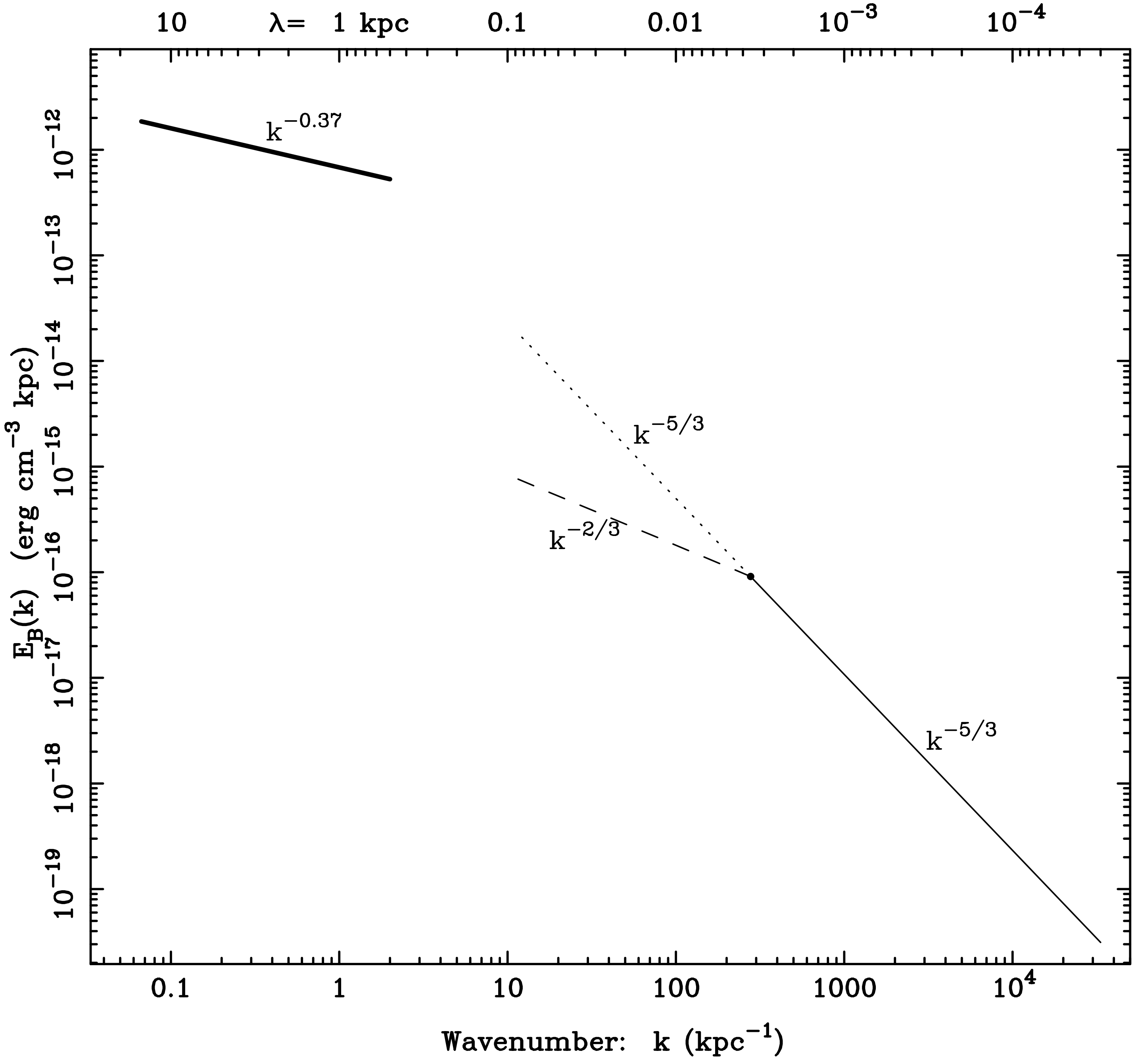
[Figures reproduced from regular component of the GMF model of Jansson & Farrar, 2012]

Kolmogorov turbulence spectrum

- Domain-like structure of B field is **simplification**
- B field likely **turbulent**, spectrum might instead follow a **power law**:

$$\langle |\mathbf{B}(\mathbf{x})|^2 \rangle_s = B_\mathrm{rms}^2 (s/s_\mathrm{max})^{\alpha-1}$$

- averaged over scales < s, and wavenumber $k = 2\pi / s$
- **Kolmogorov spectrum** for $\alpha = 5/3$
- Results for Photon-ALP conversion probability are almost unchanged [Wouters & Brun, 2012]



Spectrum for tangled component of the Galactic magnetic field [Han et al., 2004]

Backup: Axion and ALPs

The strong CP problem

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

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

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

- measurement gives rise to strong CP problem:

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

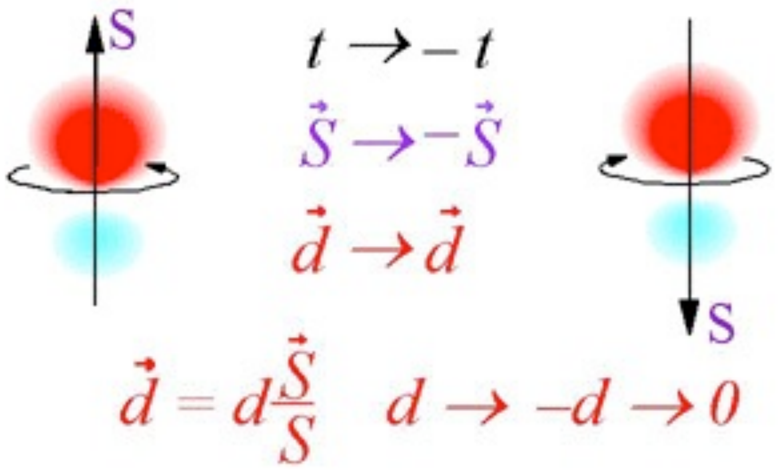
- Solution: introduce **new symmetry $U(1)_{PQ}$**, spontaneously broken at scale f_a

- θ replaced by field *a*, associated with $U(1)_{PQ}$, 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**

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



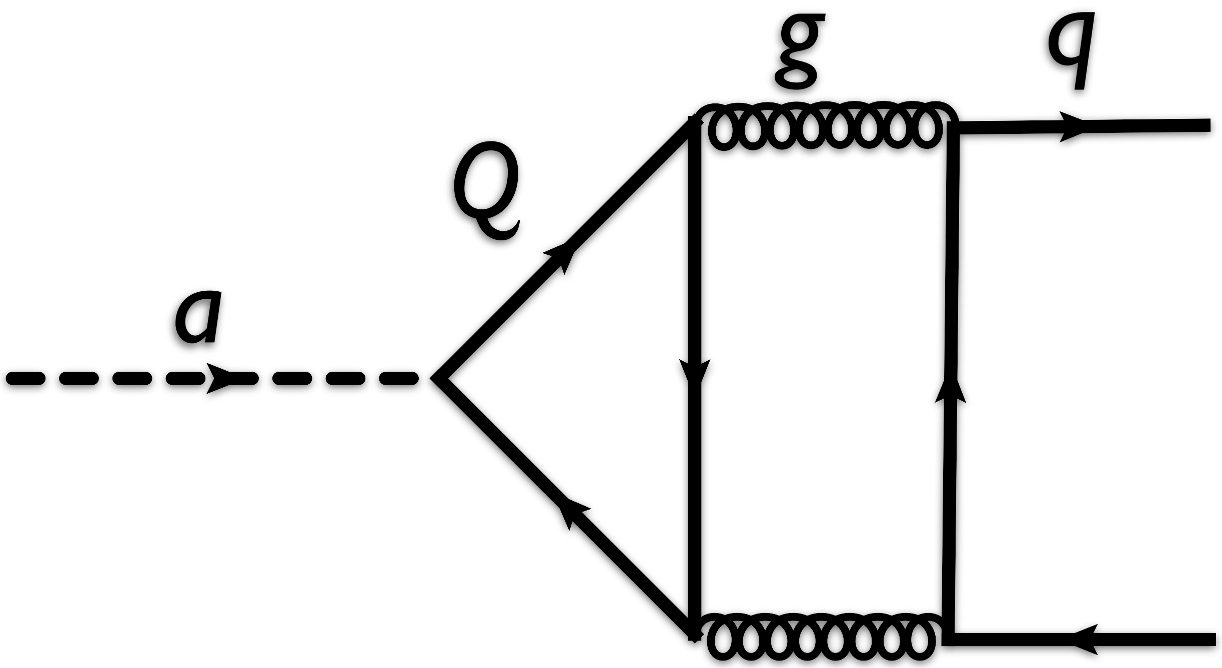
Electric dipole moment of neutron violates *T* symmetry (and thus *CP* symmetry, since *CPT* is conserved)

[Figure from http://oldwww.phys.washington.edu/users/wcgriff/romalis/EDM/imageA8M.gif]

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

Axion models

- **KVSZ model**:
    - Introduce new heavy quarks *Q* and complex scalar Higgs field σ
    - Additional *U(1)* symmetry, spontaneously broken by σ, axion as Goldstone boson
- **DFSZ model**:
    - additional complex scalar field ϕ (e.g. from GUT) and U(1) symmetry
    - ϕ potential spontaneously breaks *U(1)*
    - Axion primarily composed of field ϕ, decay constant $f_a \sim \langle \phi \rangle$
- **Axion acquires mass through mixing with light quarks**



$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_\gamma}{f_a}$$

$$C_\gamma \sim E/N - 1.92$$

$$m_a = \frac{m_u + m_d}{\sqrt{m_u m_d}}\frac{m_\pi f_\pi}{f_a}$$

[KVSZ model: Kim, 1979; Shifman et al., 1980;
DFSZ model: Dine et al., 1981; Zhitnitsky, 1980]

Photon-ALPs Lagrangian

Propagation of photon in external magnetic field:

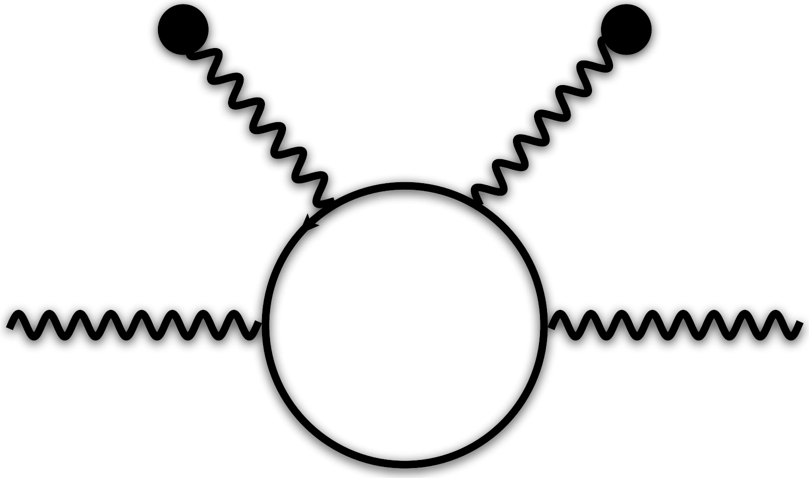
$$
\begin{aligned}
\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
&+ \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 a^2\right) \\
&- \frac{1}{4}g_{a\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}a \\
&+ \frac{\alpha^2}{90 m_e^4}\left[\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \frac{7}{4}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2\right]
\end{aligned}
$$

Photon propagator

Kinetic and mass term for ALP

Photon-ALP interaction

Euler-Heisenberg effective Lagrangian



EoM of ALPs

- From Lagrangian, derive equation of motion:

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

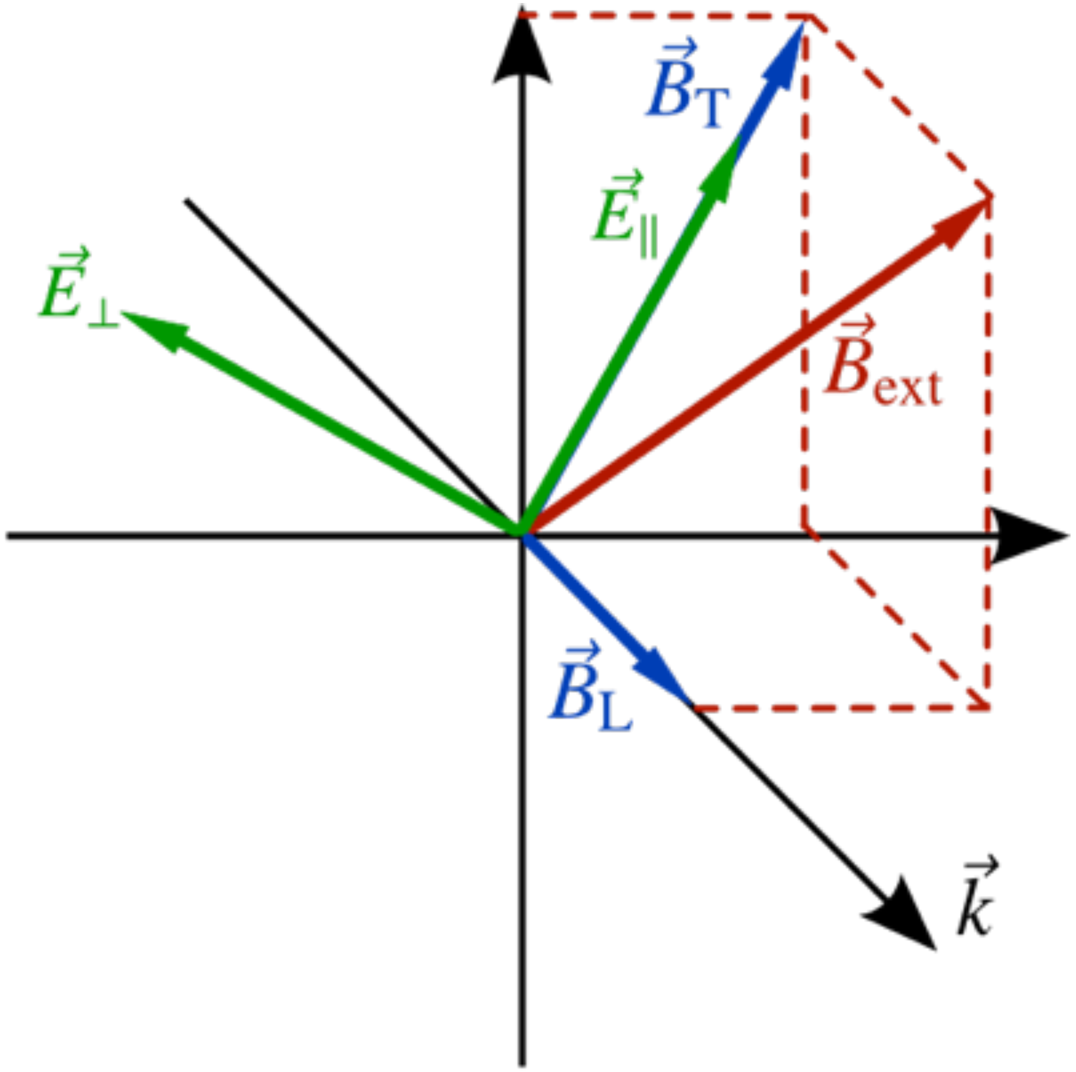
- ALPs only mix with $E_{||}$
- Solve with Ansatz:

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

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

- 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 γ-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:

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

Photon-ALP mixing

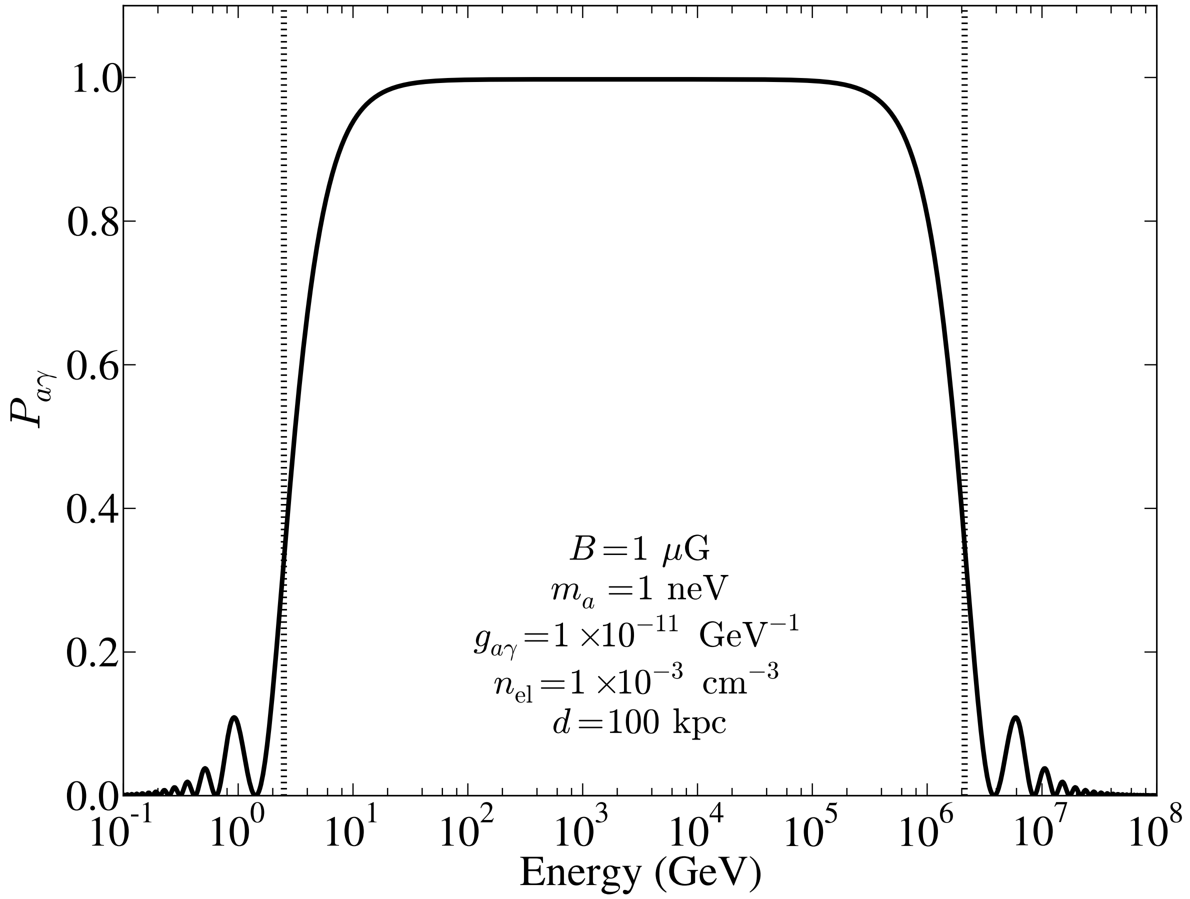
- **Lagrangian**:

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

- Mixing becomes maximal (**strong mixing regime**) above **critical energy**:

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

- Above a maximum energy, QED effects dominate and suppress mixing

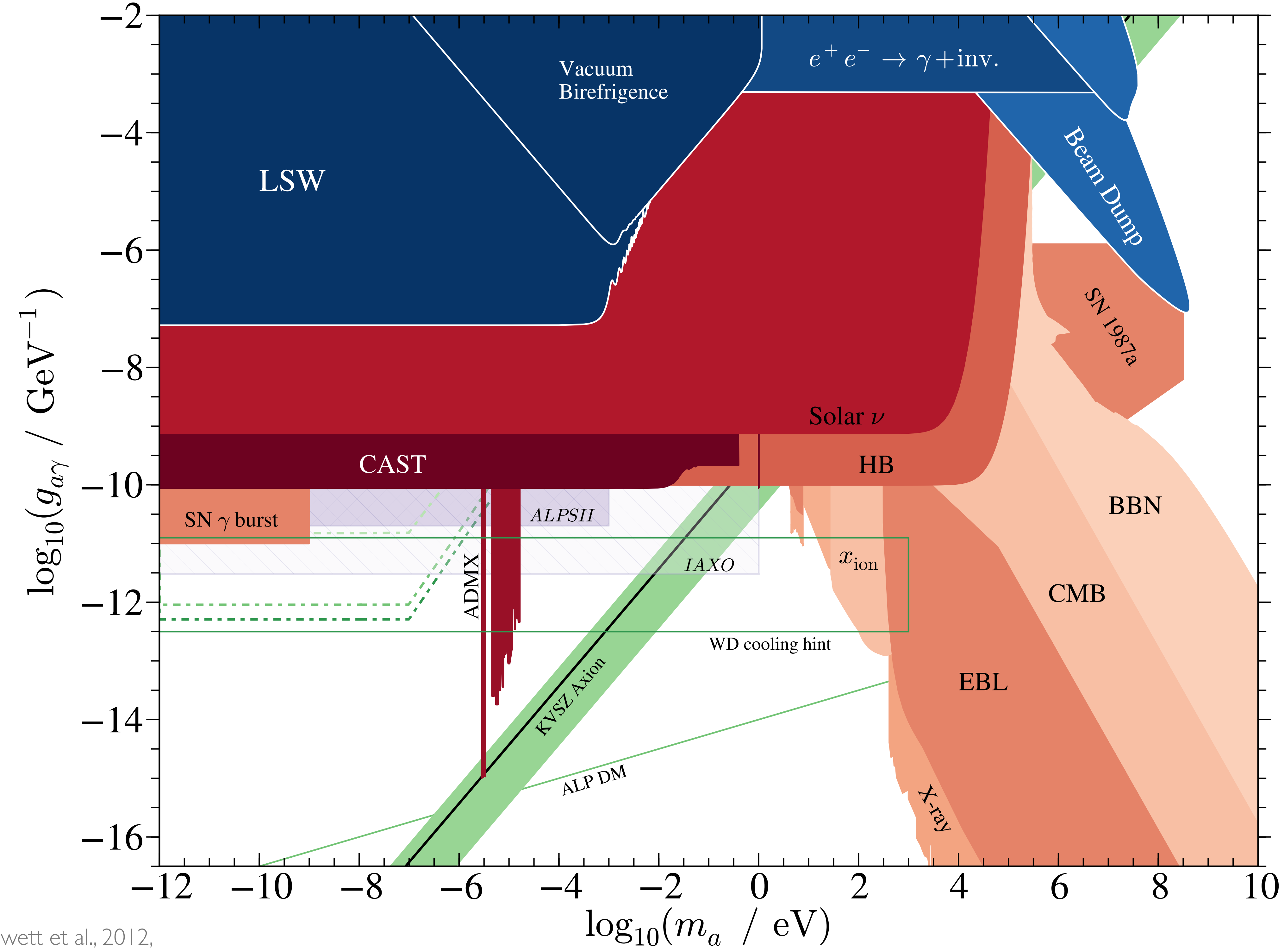


$$P_{a\gamma} = (\Delta_{a\gamma} d)^2 \frac{\sin^2(\Delta_\mathrm{osc} d/2)}{(\Delta_\mathrm{osc} d/2)^2}$$

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

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

Current limits on ALPs



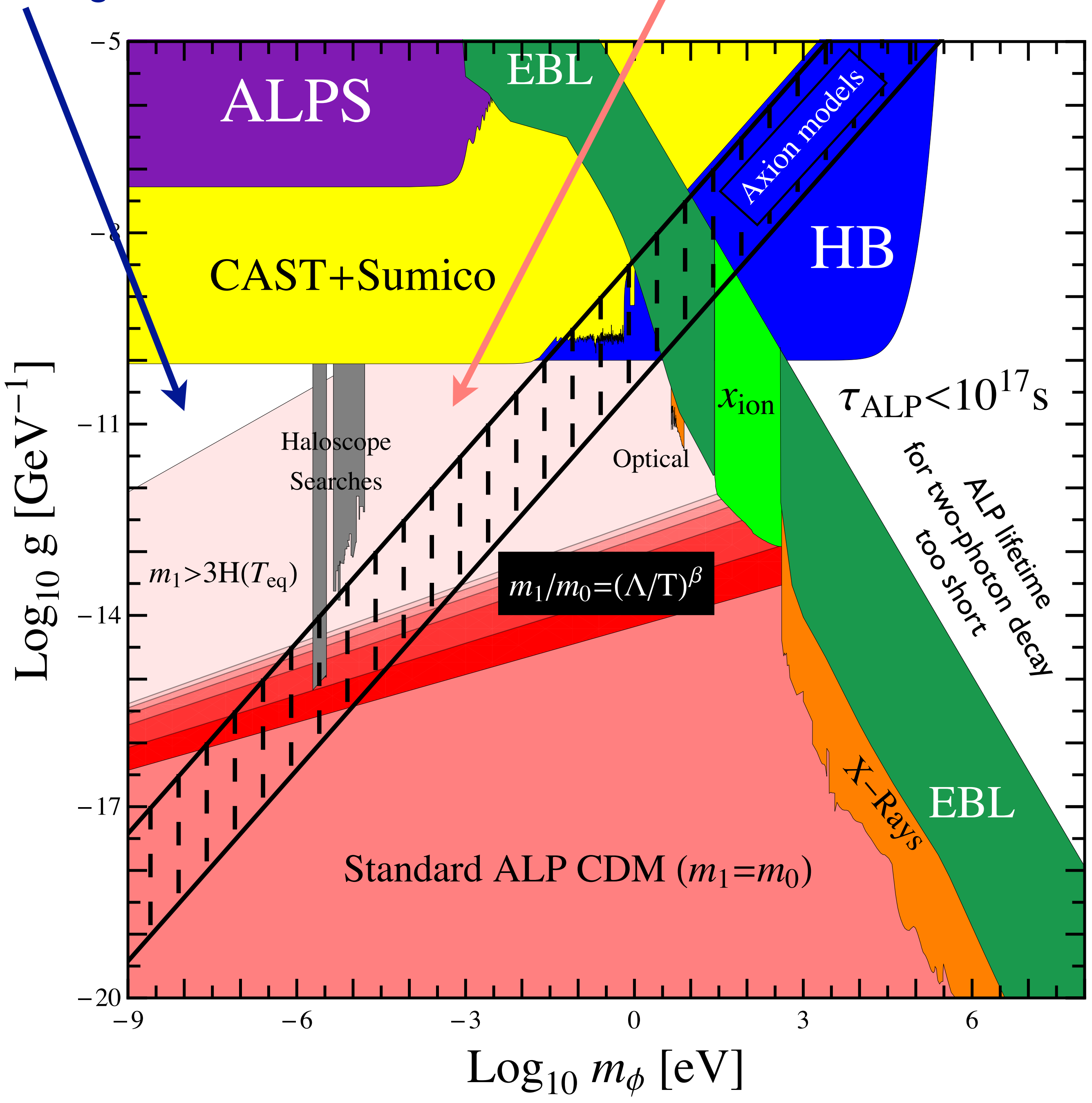
[adapted from Hewett et al., 2012,
with updates from J. Redondo, private communication]

ALP DM: misalignment mechanism

- If ALP produced thermally in early Universe: **hot Dark Matter** (DM; like neutrinos)
- Equation of motion of ALP field in expanding Universe:

$$\ddot{a} + 3H(t)\dot{a} + m_a^2(t)a = 0$$

- As long as $3H \gg m_a$, over-damped oscillator, frozen
- Later: $3H(t_1) = m_a(t_1)$, under-critical damping, field rolls down potential
- **oscillation of ALP field around minimum**: same equation of state as **cold DM**
- **Misalignment angle**: $\theta_1 = |\phi_1|/f_a$
- Mechanism depends when symmetry is broken (before, after, during inflation)



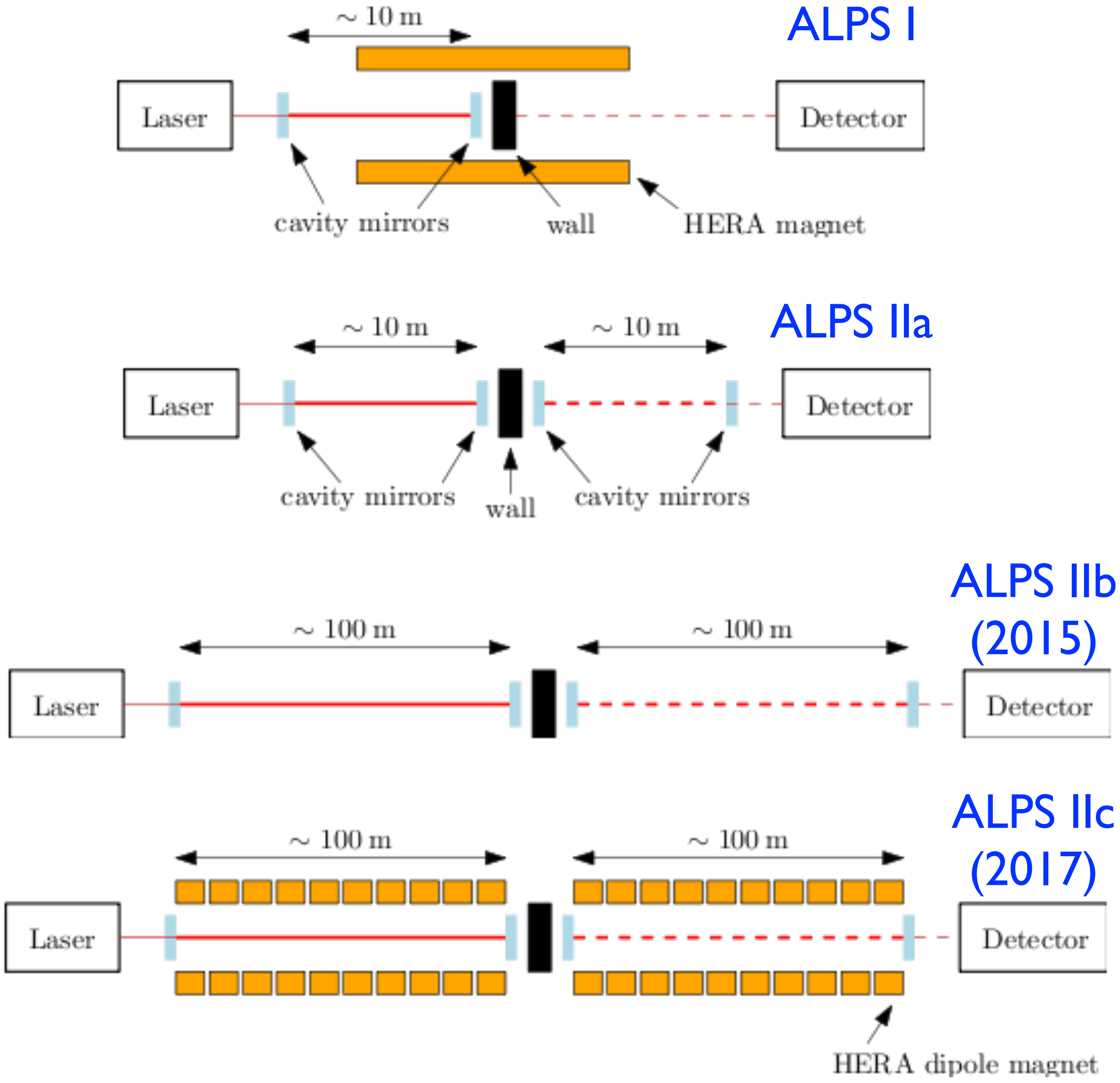
Possible if parameters like misalignment angle fine tuned

Field starts to oscillate at matter-radiation equality and mass remains constant, however, difficult to construct viable models

[Arias et al., 2012]

Any Light Particle Search (ALPS) Phase II

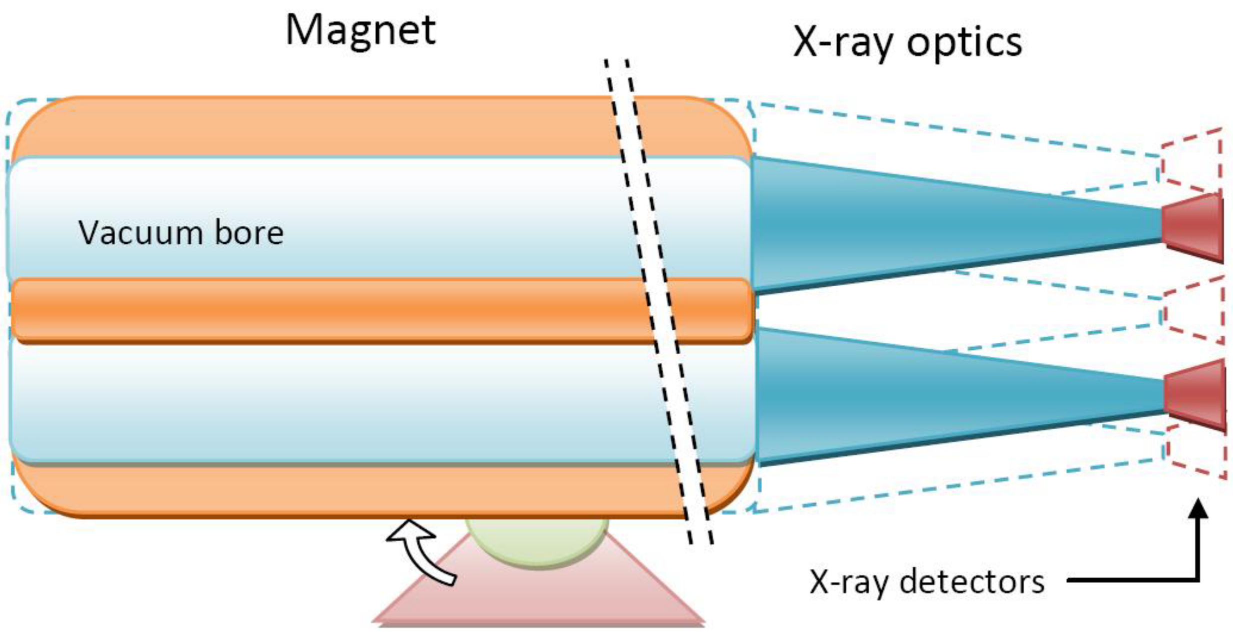
- Next generation **“Light shining through a wall”** experiment
- Several upgrades compared to ALPS I:
  - **Higher laser power** (using a 1064nm laser instead of 532nm)
  - **Transition Edge Sensor** instead of a CCD
  - **Regeneration** cavity
  - Maximizing ***B* x *L***: final stage with **20 straightened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

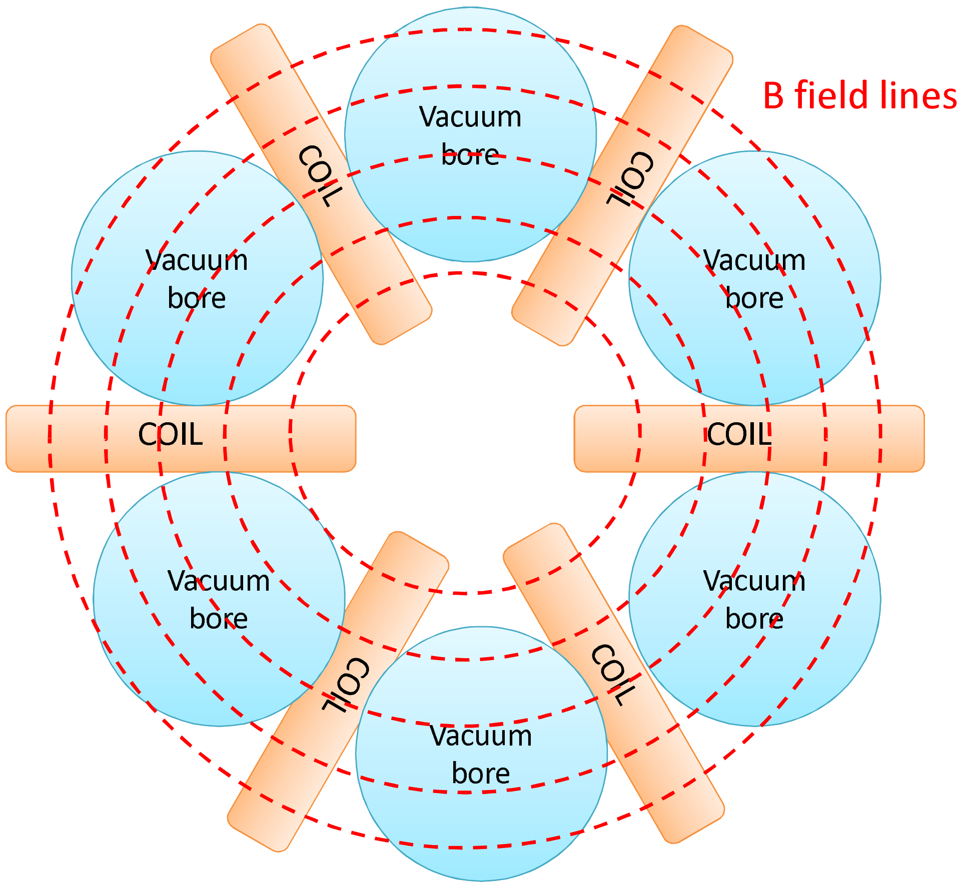


[ALPS II Technical design report, Bähre et al., 2013]

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}

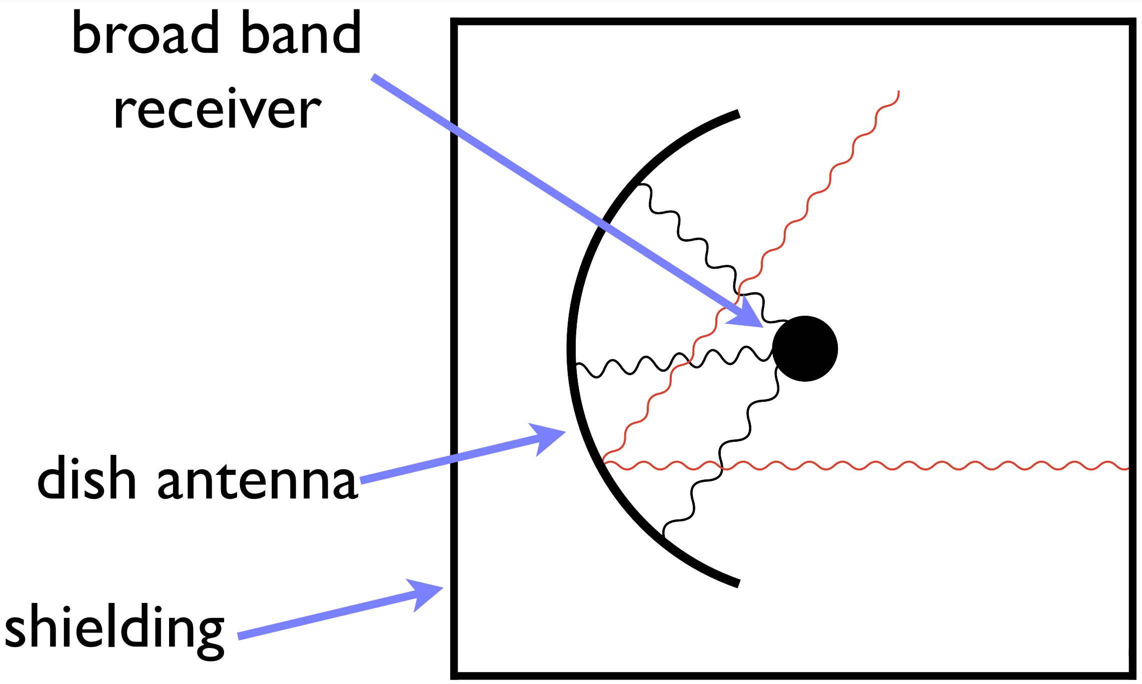




[Irastorza et al., 2011]

WISP searches with a dish antenna

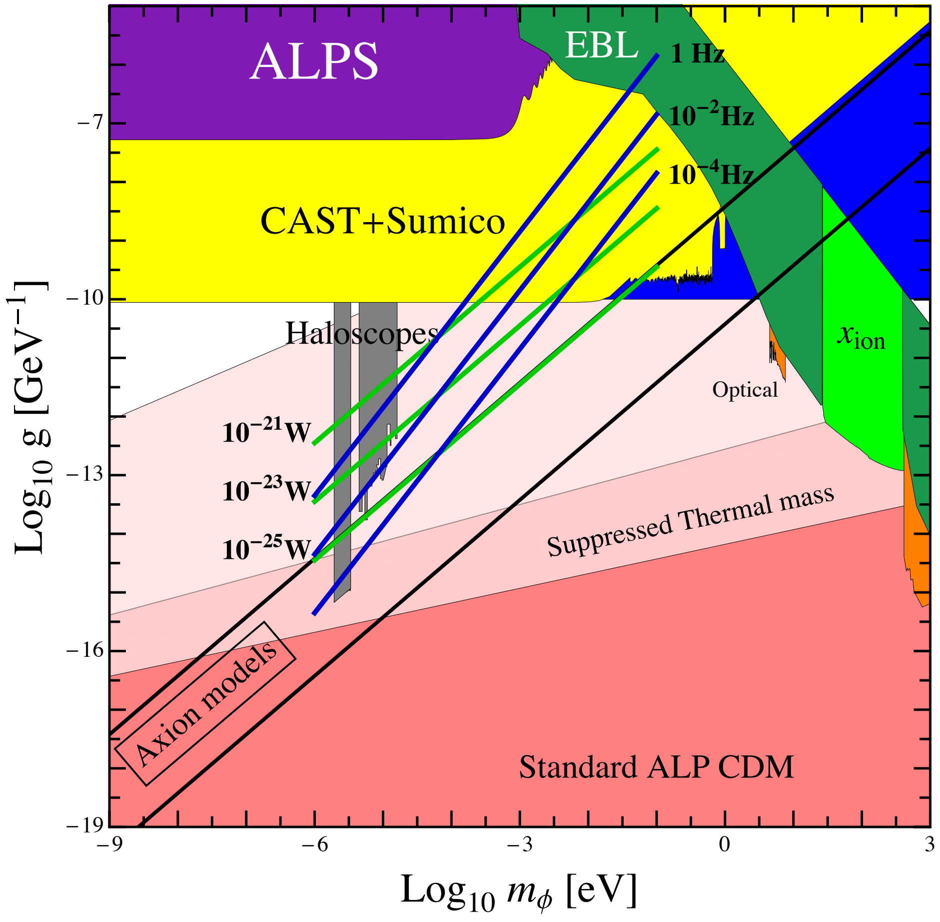
- Experiment to search for **WISP DM** (hidden photons and ALPs)
- Due to mixture of photons with WISP, small fraction of local DM energy density in form of **electric field**
- Electric field can cause **electrons in mirror (dish) to oscillate**
- This radiation is **collected** in **center of a spherical dish**
- **Broad band receiver**: sensitivity over large frequency (WISP mass) range



broad band receiver

dish antenna

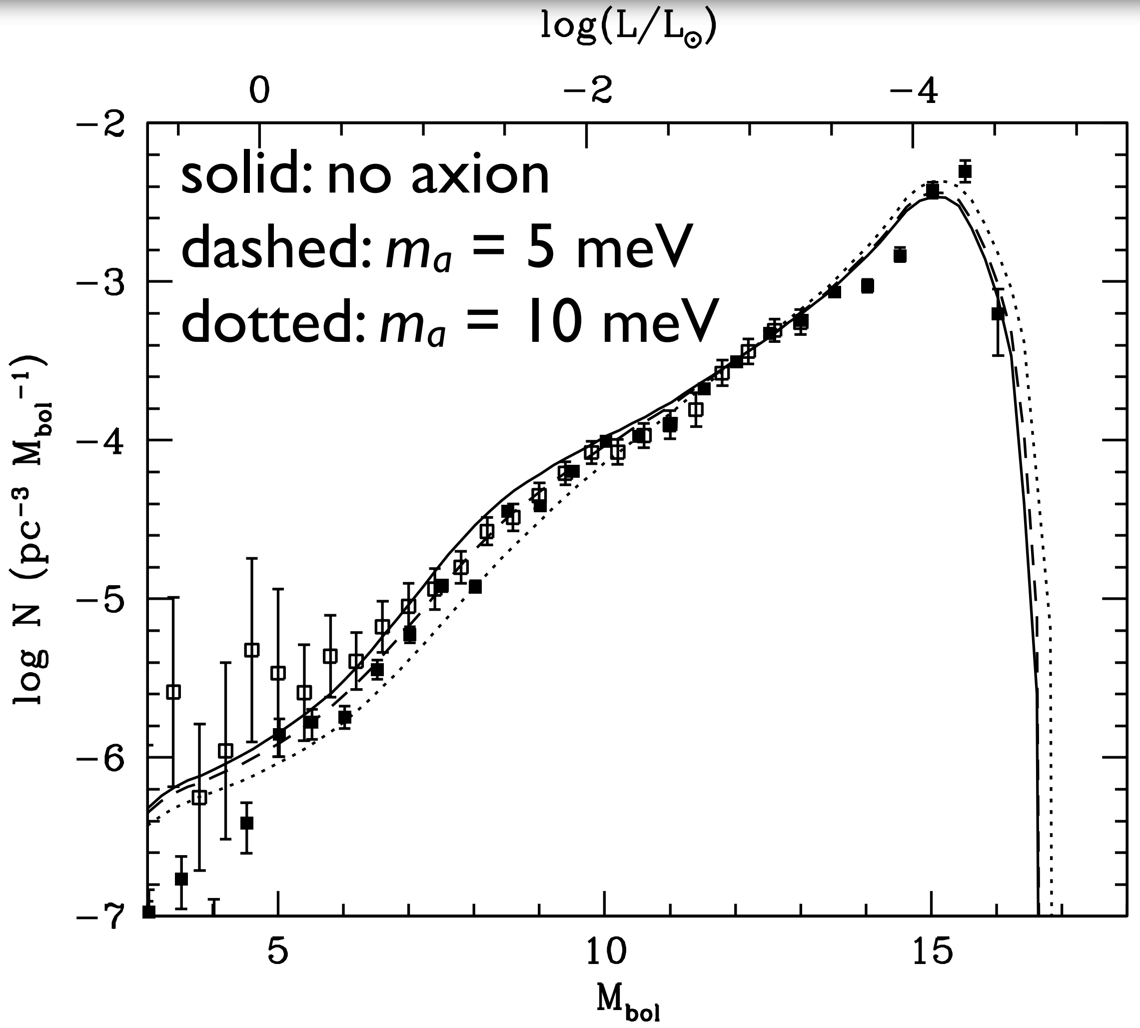
shielding



[Horns et al., 2013]

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**



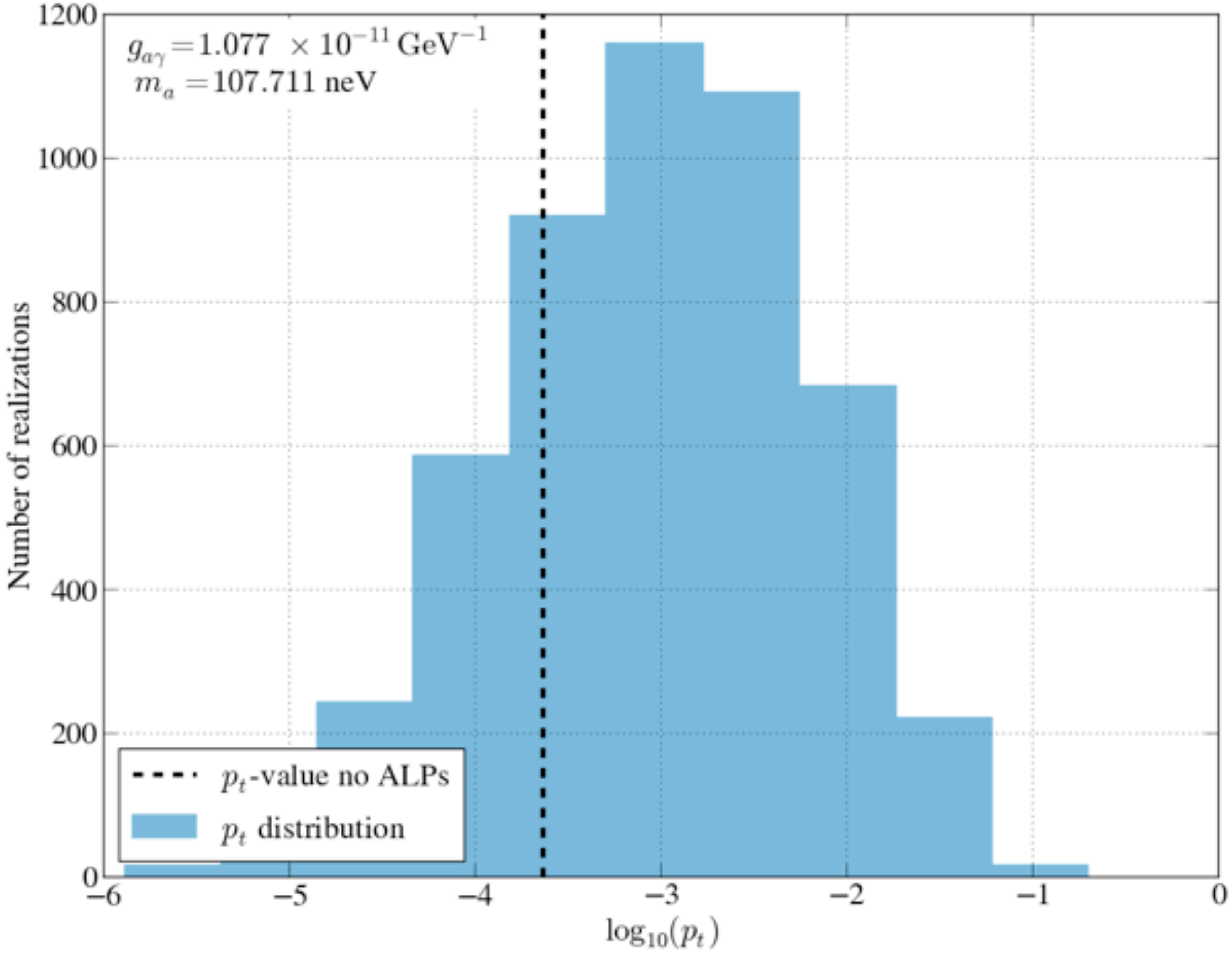
[Isern et al., 2008; Gill & Heyl 2011]

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

Backup: Lower limits on photon-ALP coupling

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



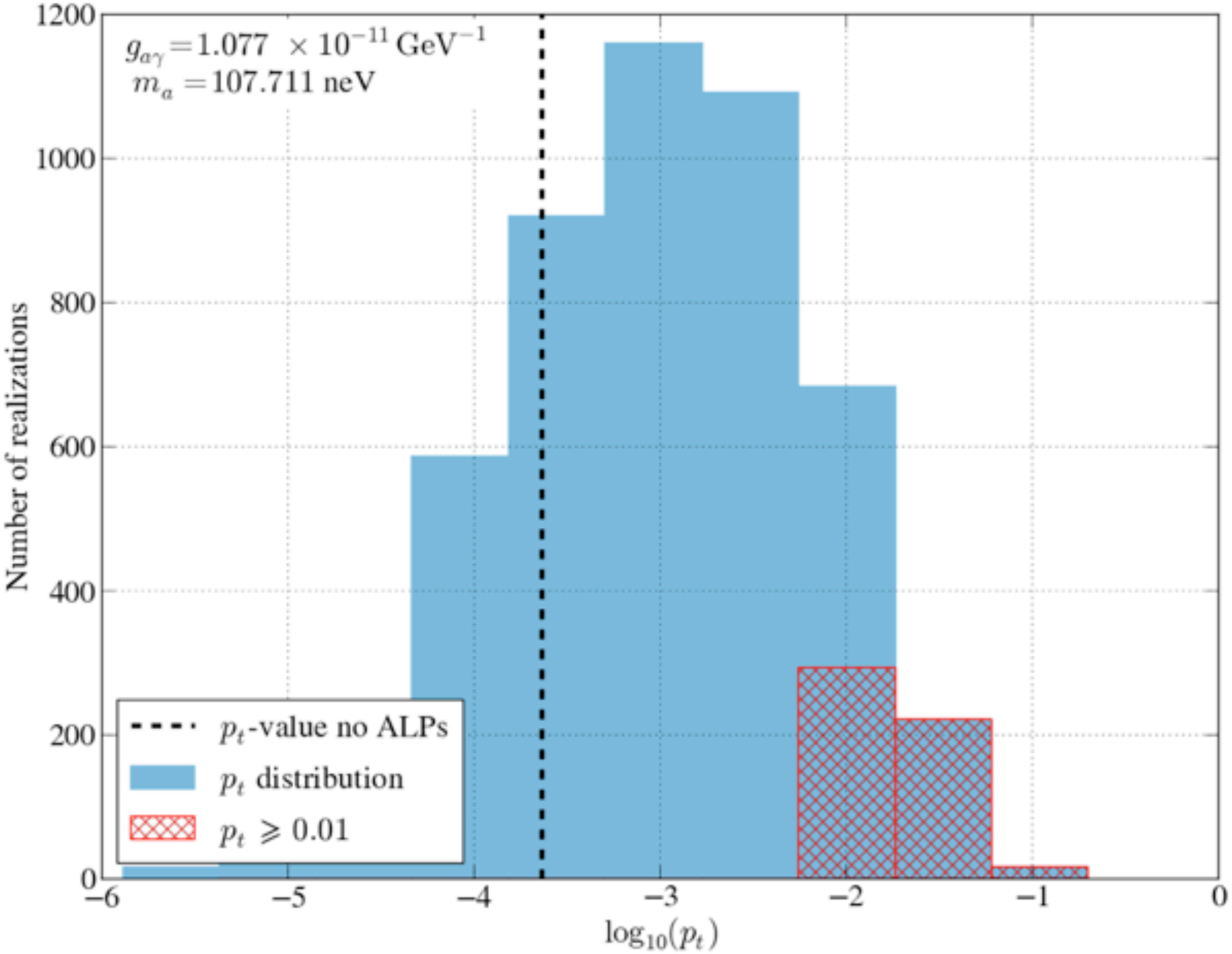
Significance of PPA

Better accordance between model and data

[Meyer et al., 2013, Phys. Rev. D, vol 87, Issue 3]

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 **$p_t > 0.01$**



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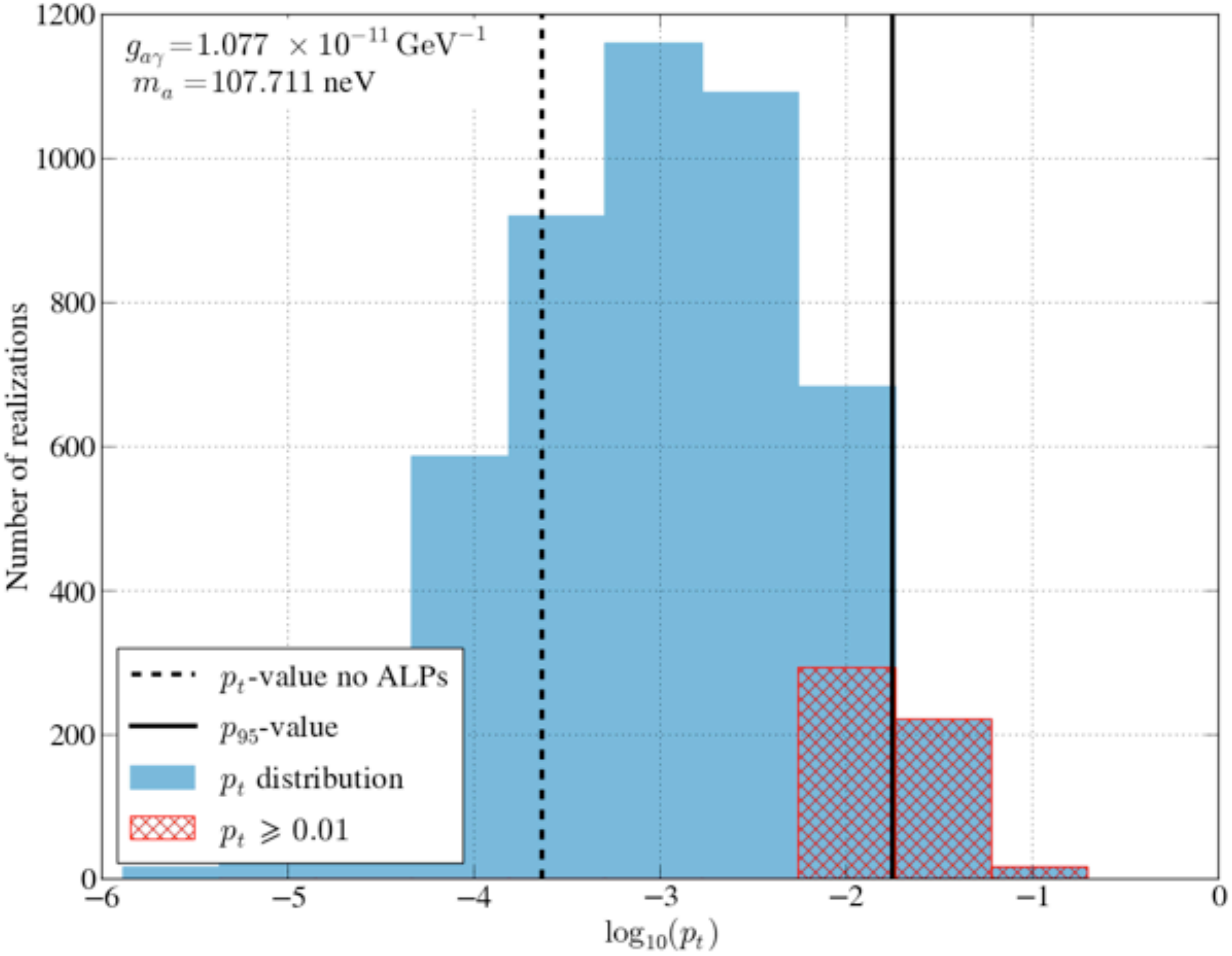
- Example: calculate 5000 random *B*-field realizations in *optimistic ICMF* scenario for one (m_a, $g_{a\gamma}$) pair
- Demand **accordance** between model and data of **$p_t > 0.01$**
- Demand that **at least 5% of all realizations result in $p_t > 0.01$ (p_{95}-value)**



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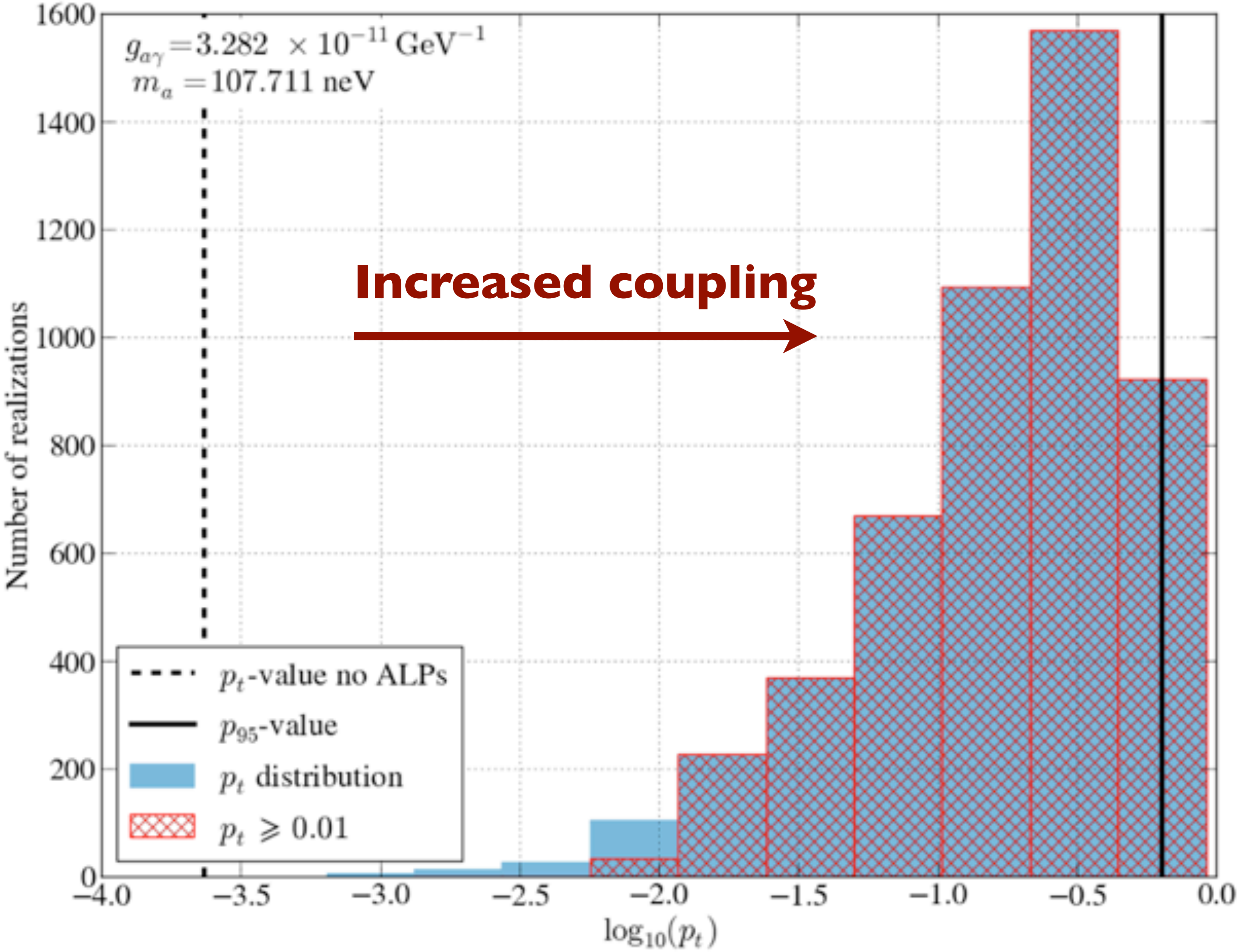
Definition of lower limit on $g_{a\gamma}$

- 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 $\boldsymbol{p_t > 0.01}$
- Demand that **at least 5% of all realizations result in $\boldsymbol{p_t > 0.01}$ ($\boldsymbol{p_{95}}$-value)**



Increased coupling →

Significance of PPA

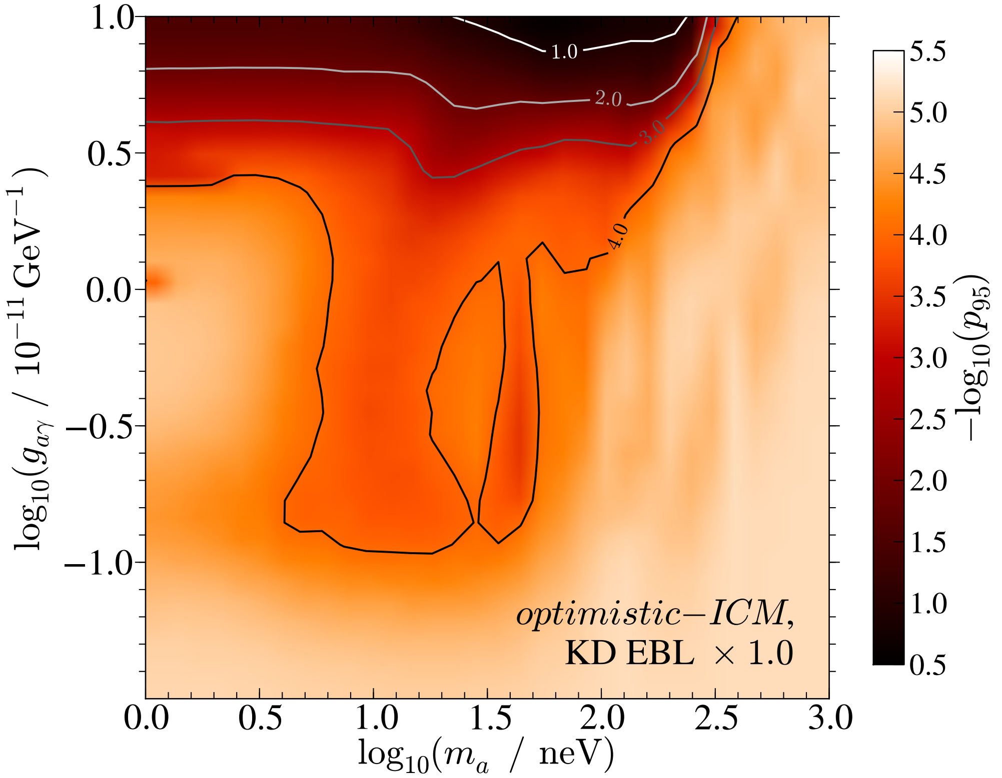
→

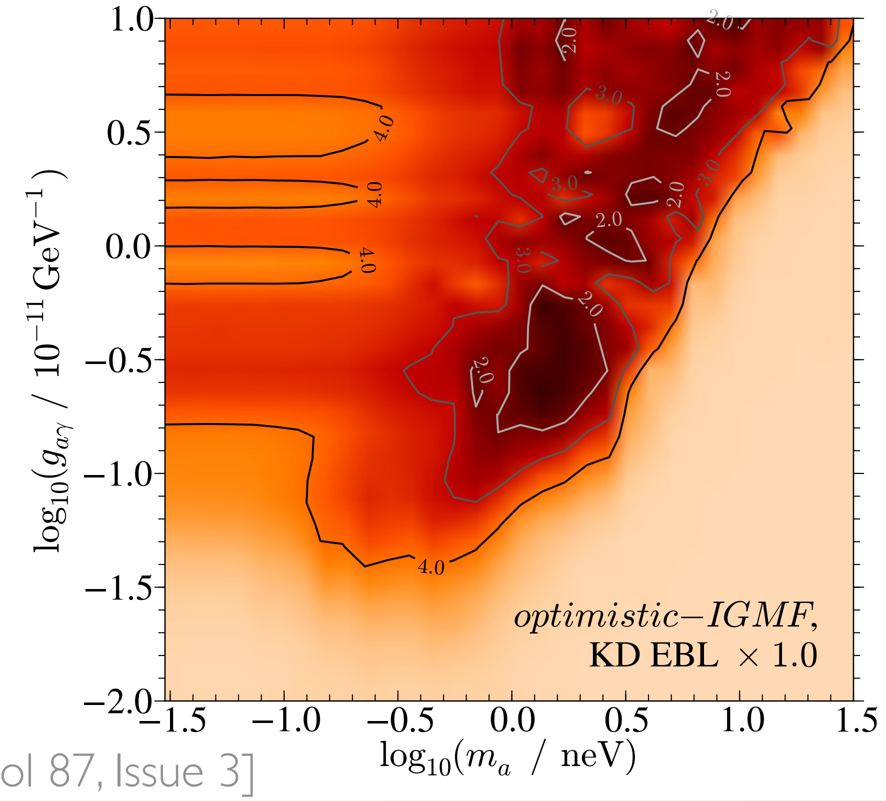
Better accordance between model and data

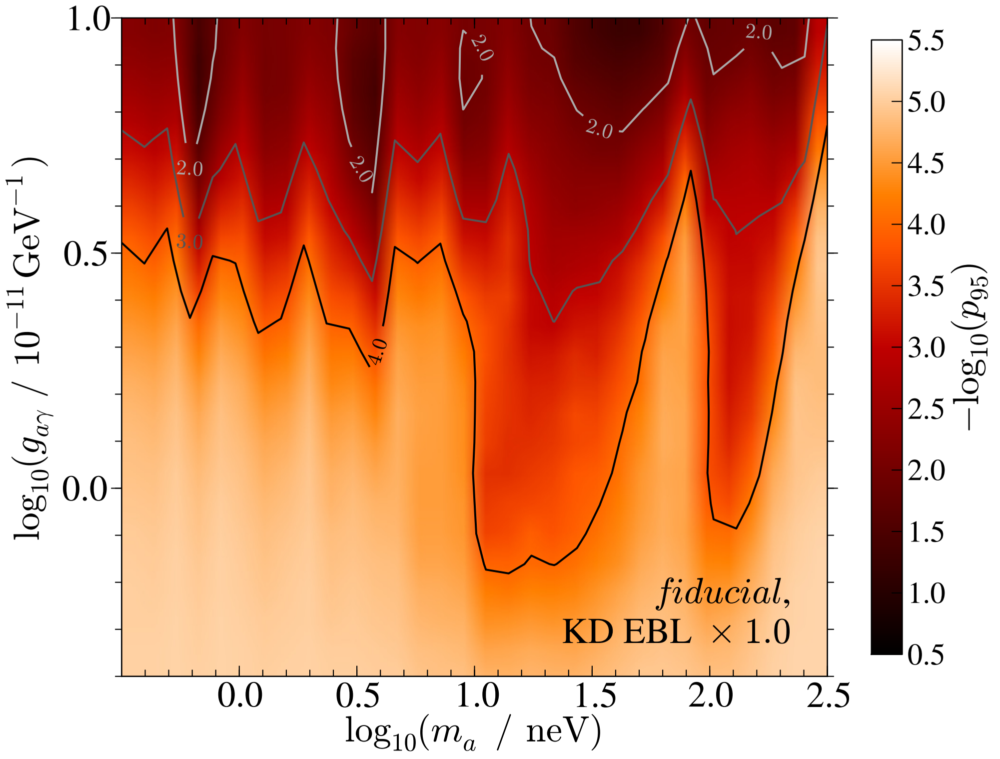
[Meyer et al., 2013, Phys. Rev. D, vol 87, Issue 3]

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

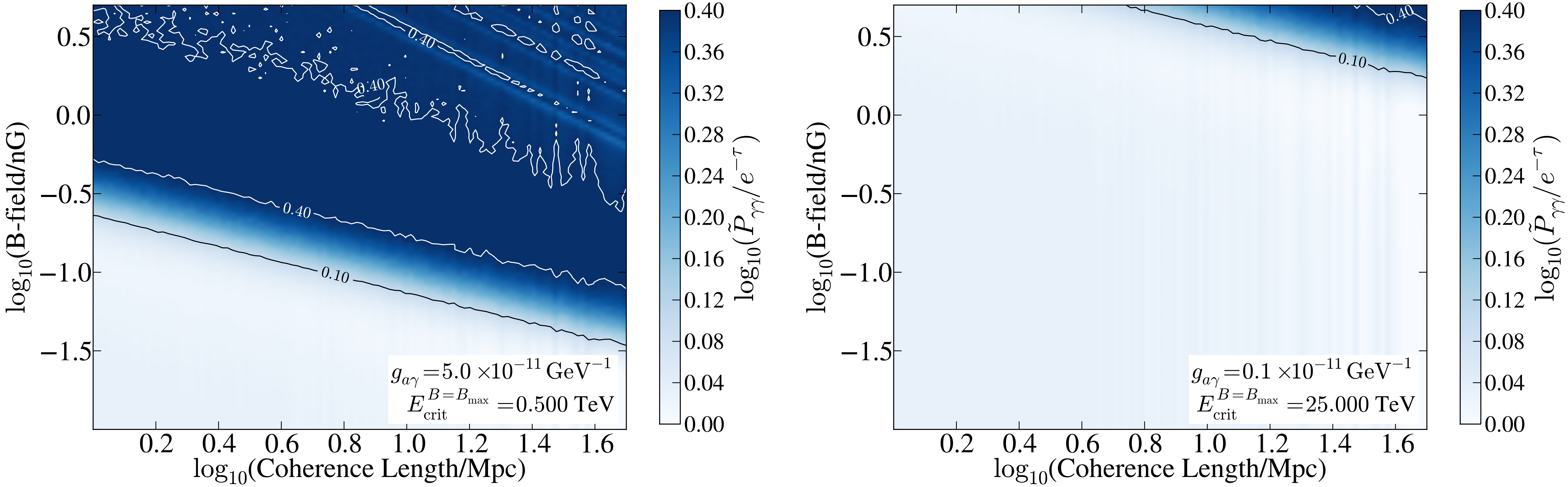






[Meyer et al., 2013, Phys. Rev. D, vol 87, Issue 3]

Determination of optimistic *B*-field values



[Meyer et al., 2013, Phys. Rev. D, vol 87, Issue 3]

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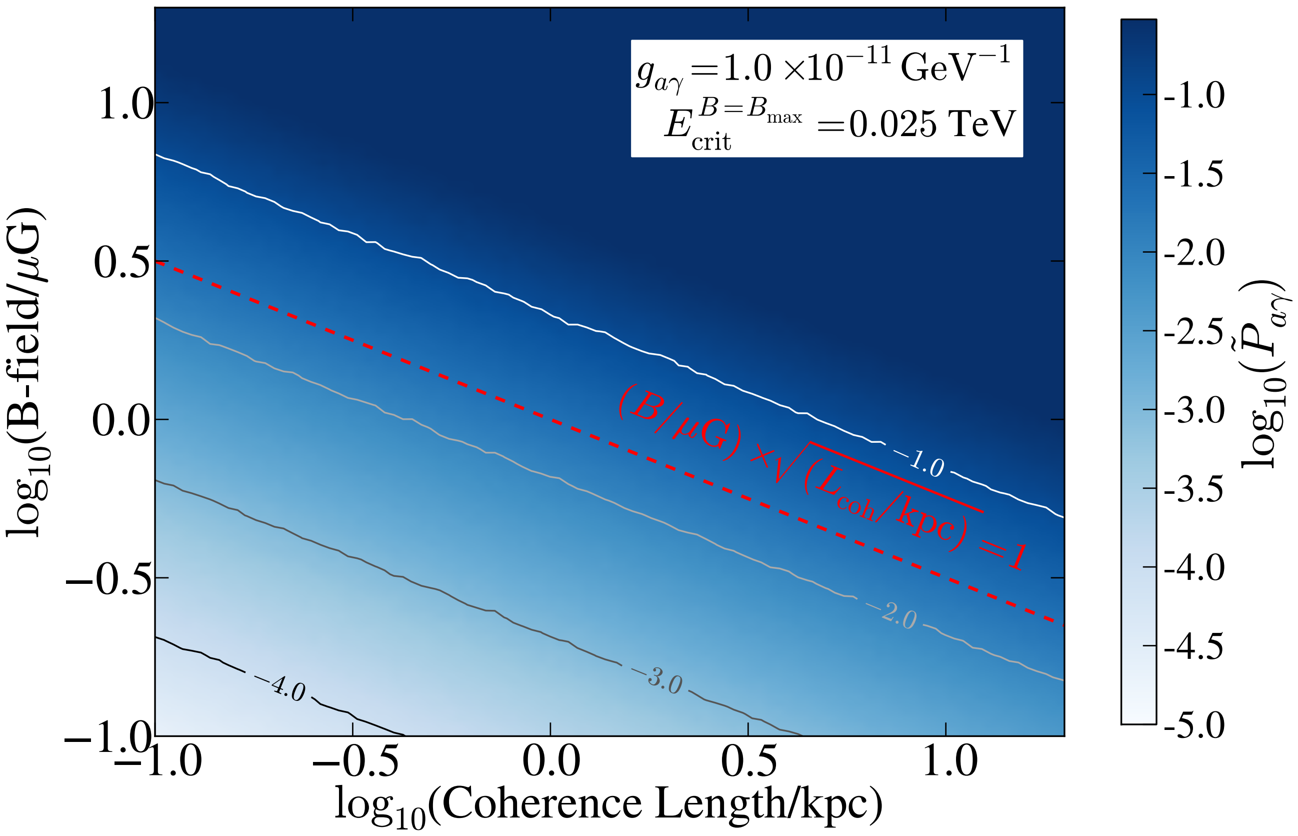
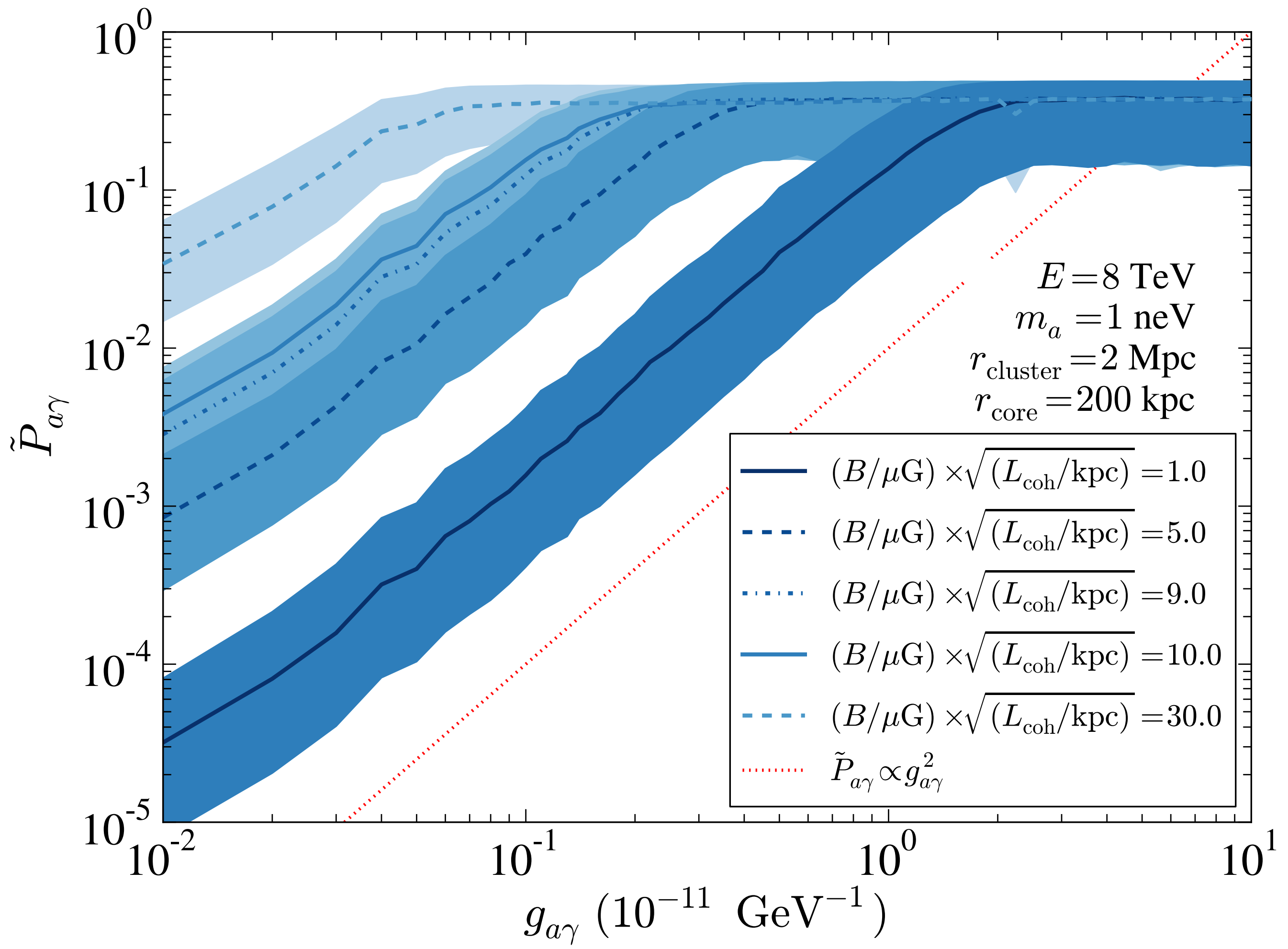
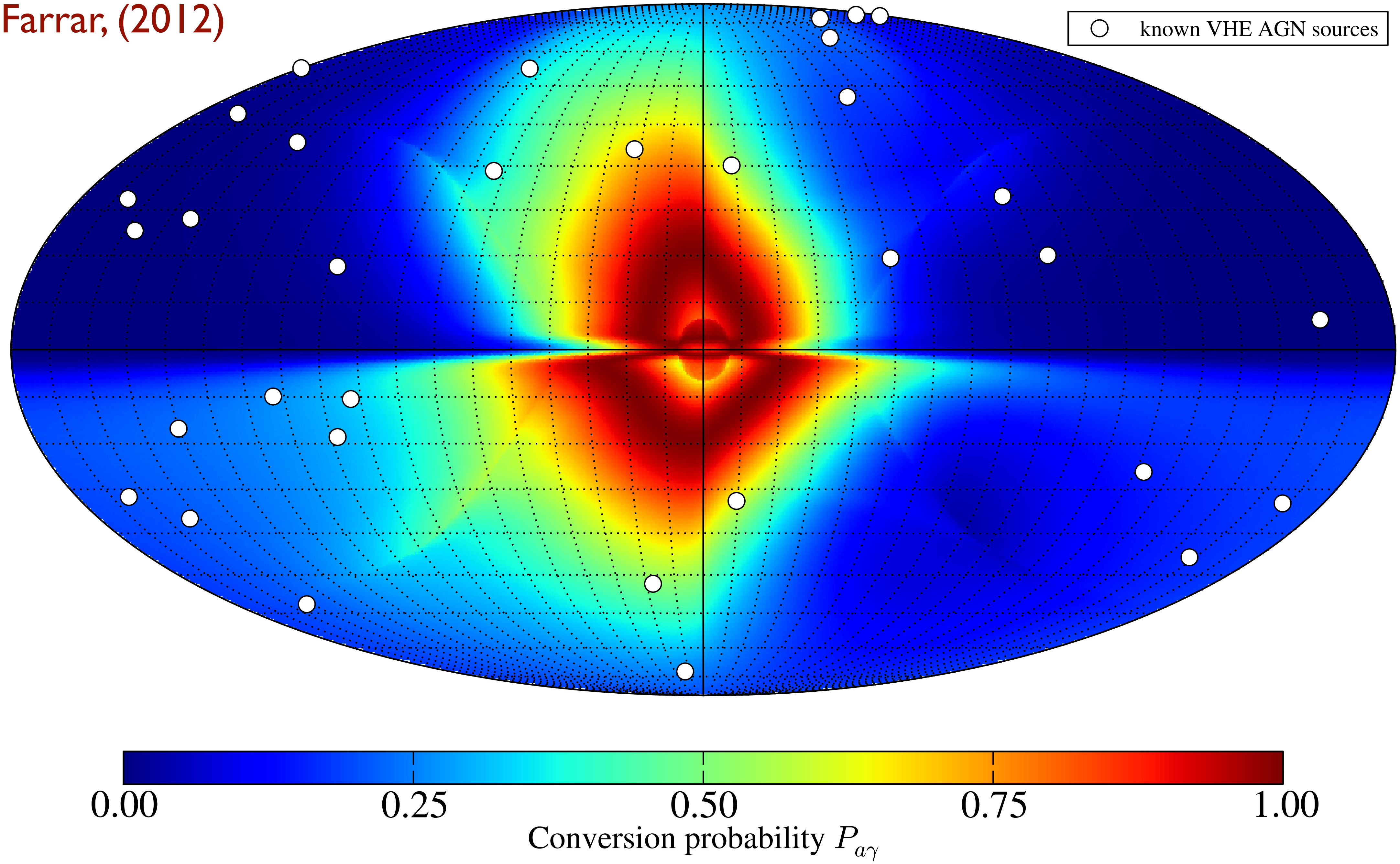




[Meyer et al., 2013, Phys. Rev. D, vol 87, Issue 3]

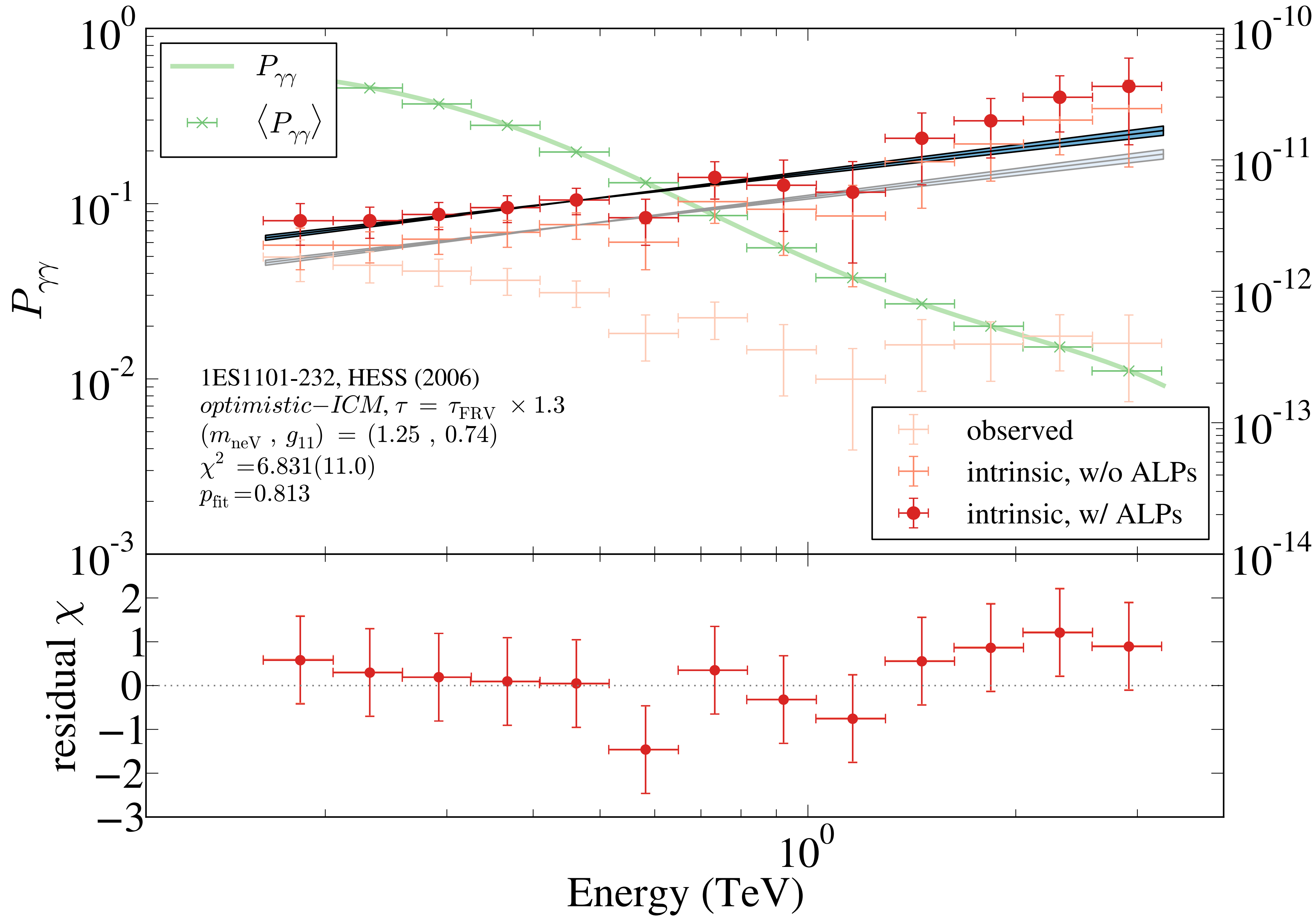
Galactic magnetic field

pure ALP beam @ 1 TeV
with ALP mass m_a = 1 neV
GMF model (regular component) by
Jansson & Farrar, (2012)

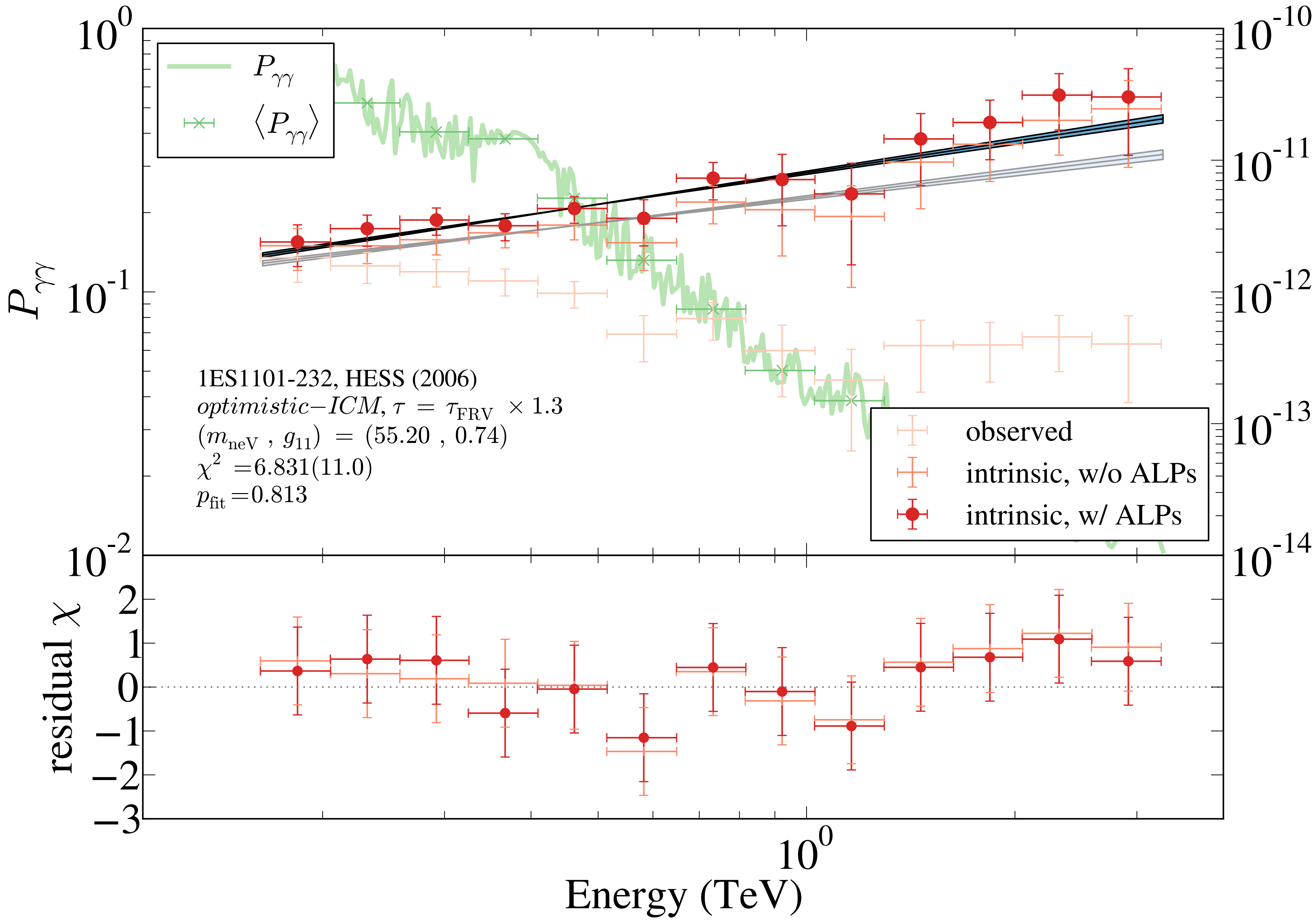


[Horns et al., 2012]

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

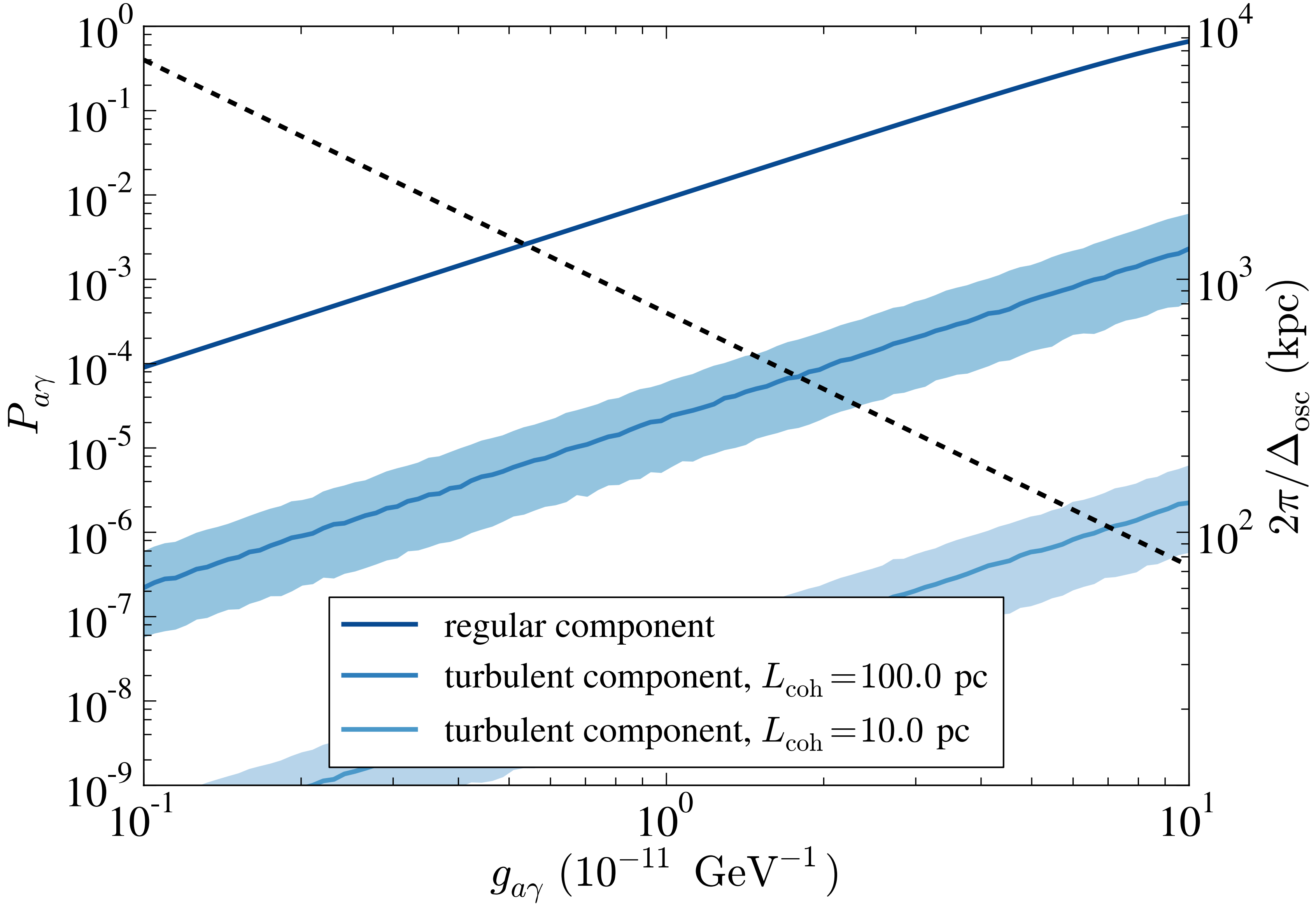


Features in lower limts on $g_{a\gamma}$



Conversion in turbulent GMF

- Conversion in GMF for blazar 1ES0414+009
- turbulent field modeled with **cell-like structure**
- Field strength determined from **Kolmogorov-type spectrum** with B_{rms} = 5 μG
- maximum scale = 1kpc



$$\langle|\mathbf{B}(\mathbf{x})|^2\rangle_s = B^2_{\mathrm{rms}}(s/s_{\mathrm{max}})^{\alpha-1}$$