Sensitivity of H.E.S.S. II and CTA to detect a reduced γ-ray opacity due to photon-axion-like-particle oscillations

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on behalf of the CTA consortium and the H.E.S.S. collaboration

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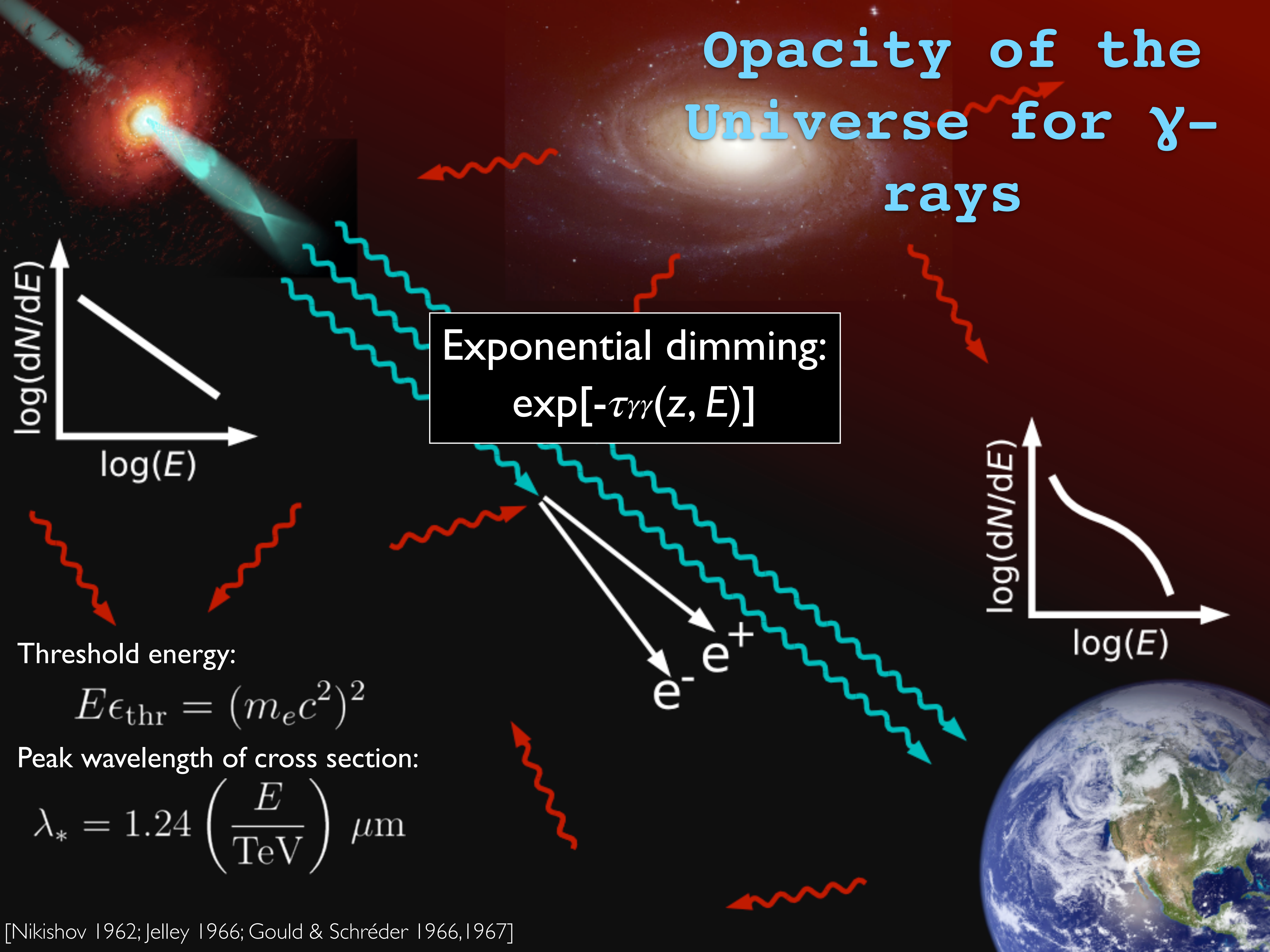
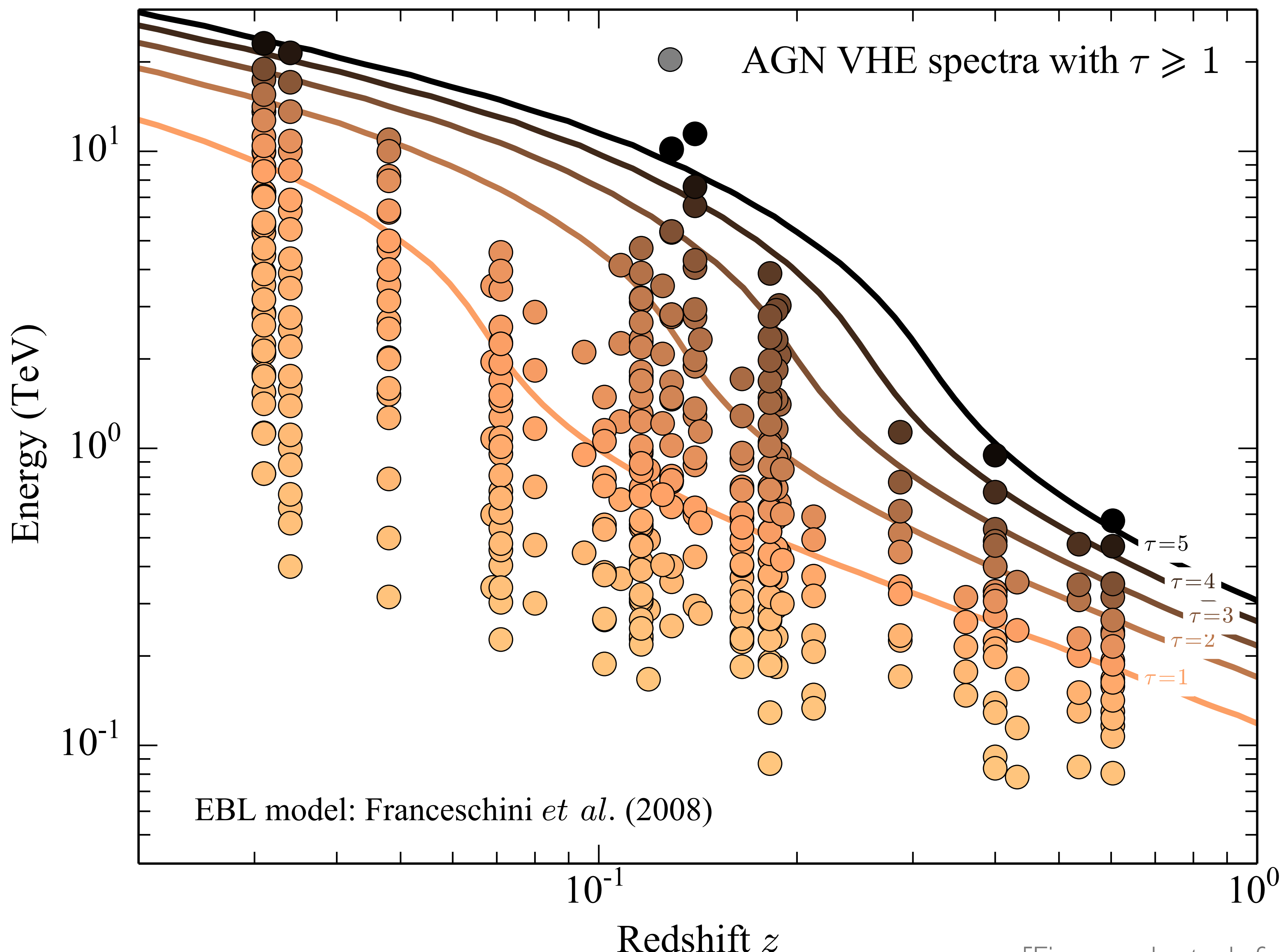


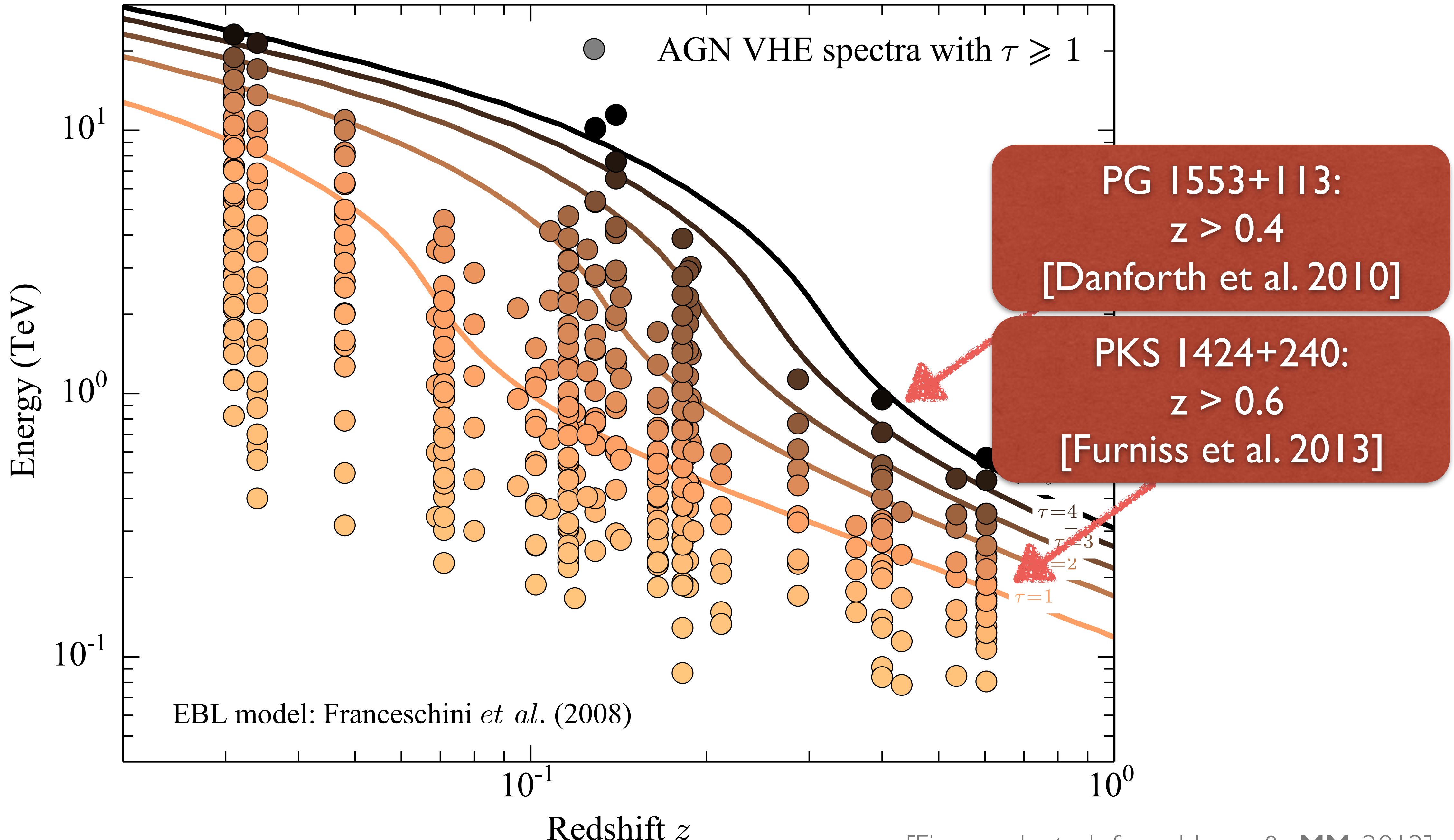
Opacity of the Universe for γ-rays
Exponential dimming:
$\exp[-\tau_{\gamma\gamma}(z, E)]$
log(dN/dE)
log(E)
log(dN/dE)
log(E)
e^+
e^-
Threshold energy:
$E\epsilon_{\rm thr} = (m_e c^2)^2$
Peak wavelength of cross section:
$\lambda_* = 1.24 \left(\frac{E}{\rm TeV}\right) \mu{\rm m}$
[Nikishov 1962; Jelley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

Increasing number of observations for high optical depths



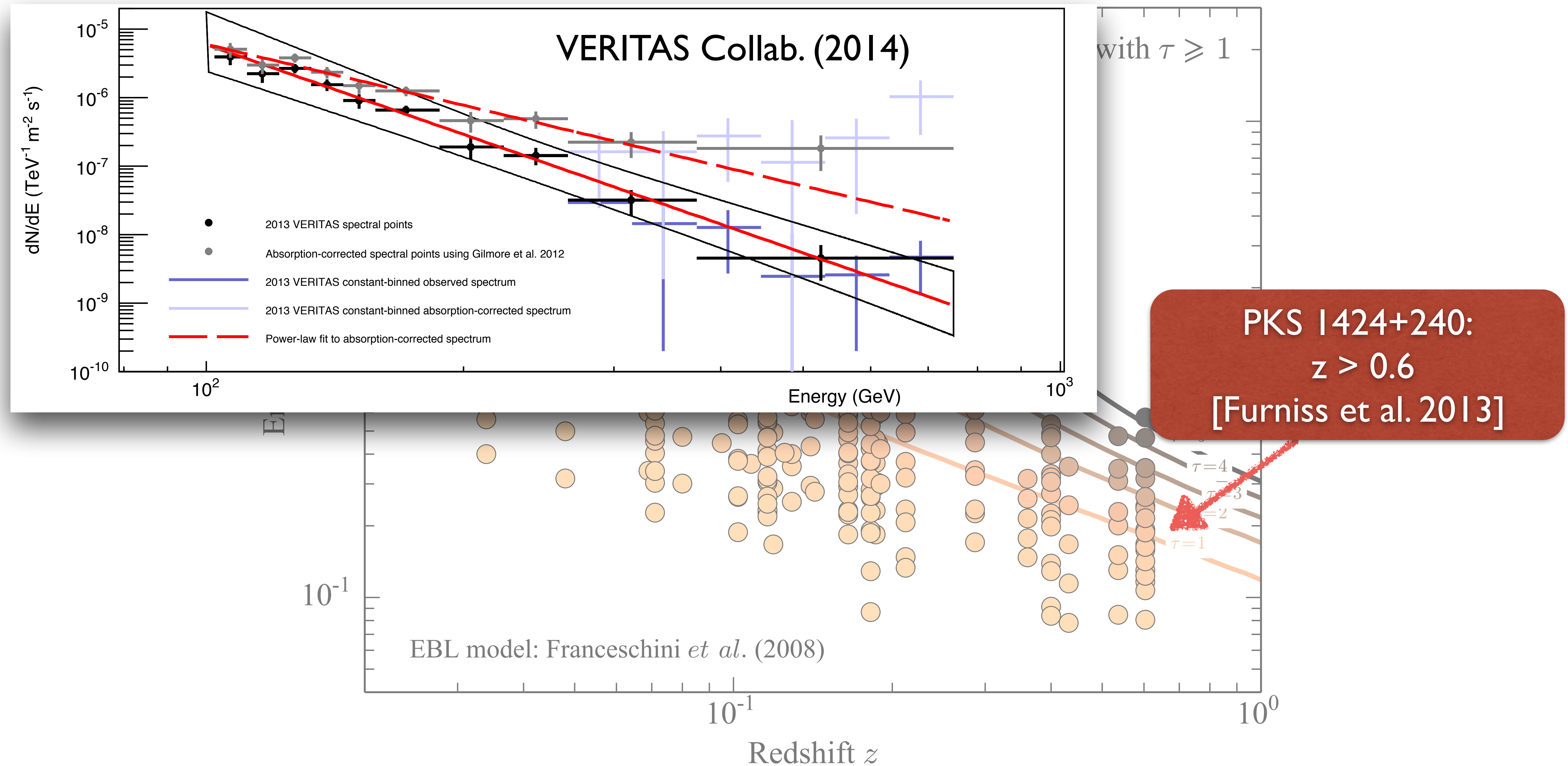
[Figure adapted from Horns & **MM**, 2012]

Recent observations at high optical depths / Redshift determinations

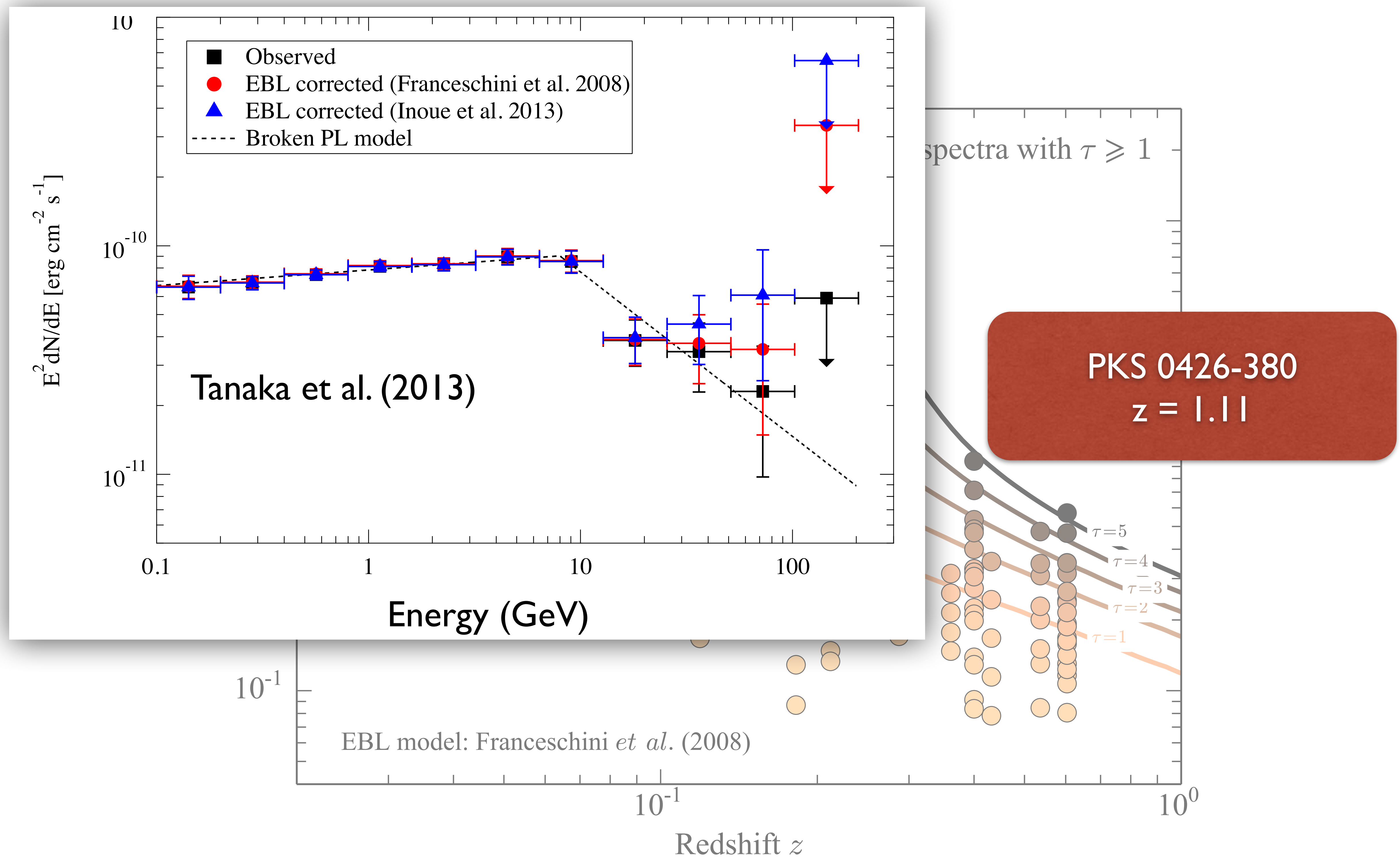


[Figure adapted from Horns & **MM**, 2012]

Spectral hardening at high optical depths?



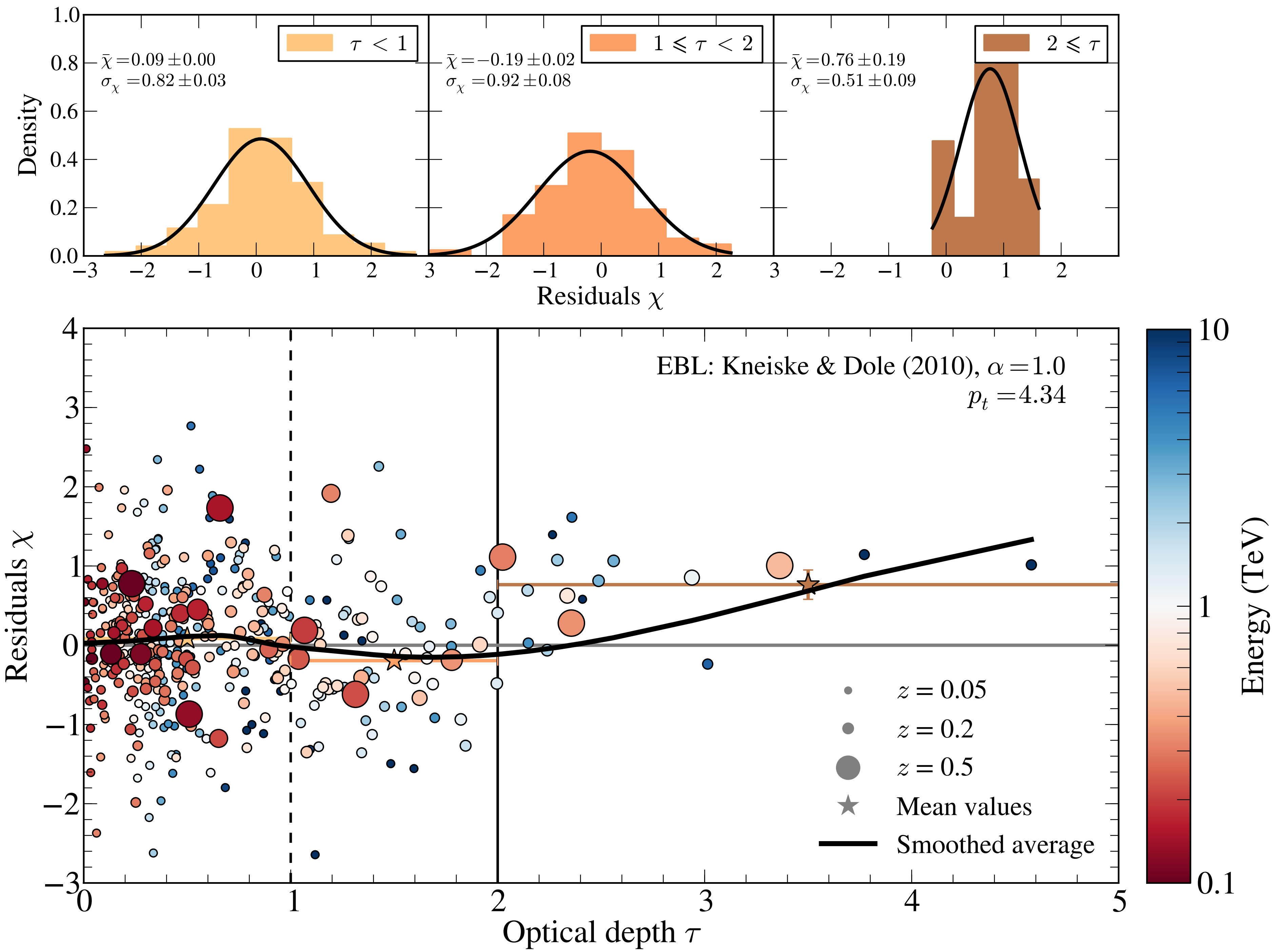
Spectral hardening at high optical depths?



Indications for modified opacity

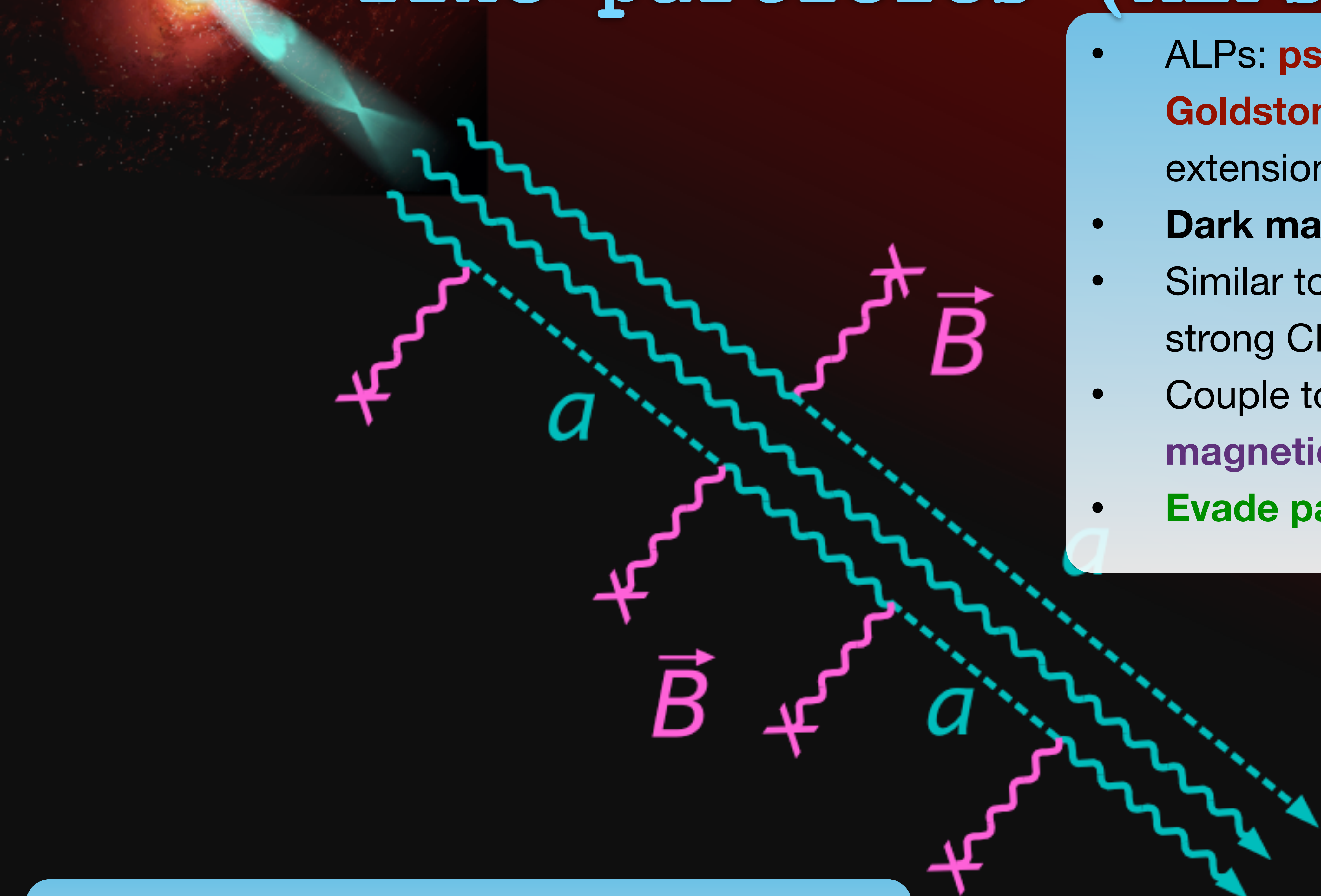
[Figure taken from **MM** & Horns, 2012]

- Increasing number of **AGN observed at high τ**
- Attenuation of VHE spectra too strong for τ > 2 at ~4σ [Horns & **MM**, 2012]
- Observed TeV spectra are too hard [De Angelis et al. 2009, 2011, 2013]
- Spectral breaks in intrinsic spectra? [arXiv1406.0239]
- **Hints for axion-like particles?**



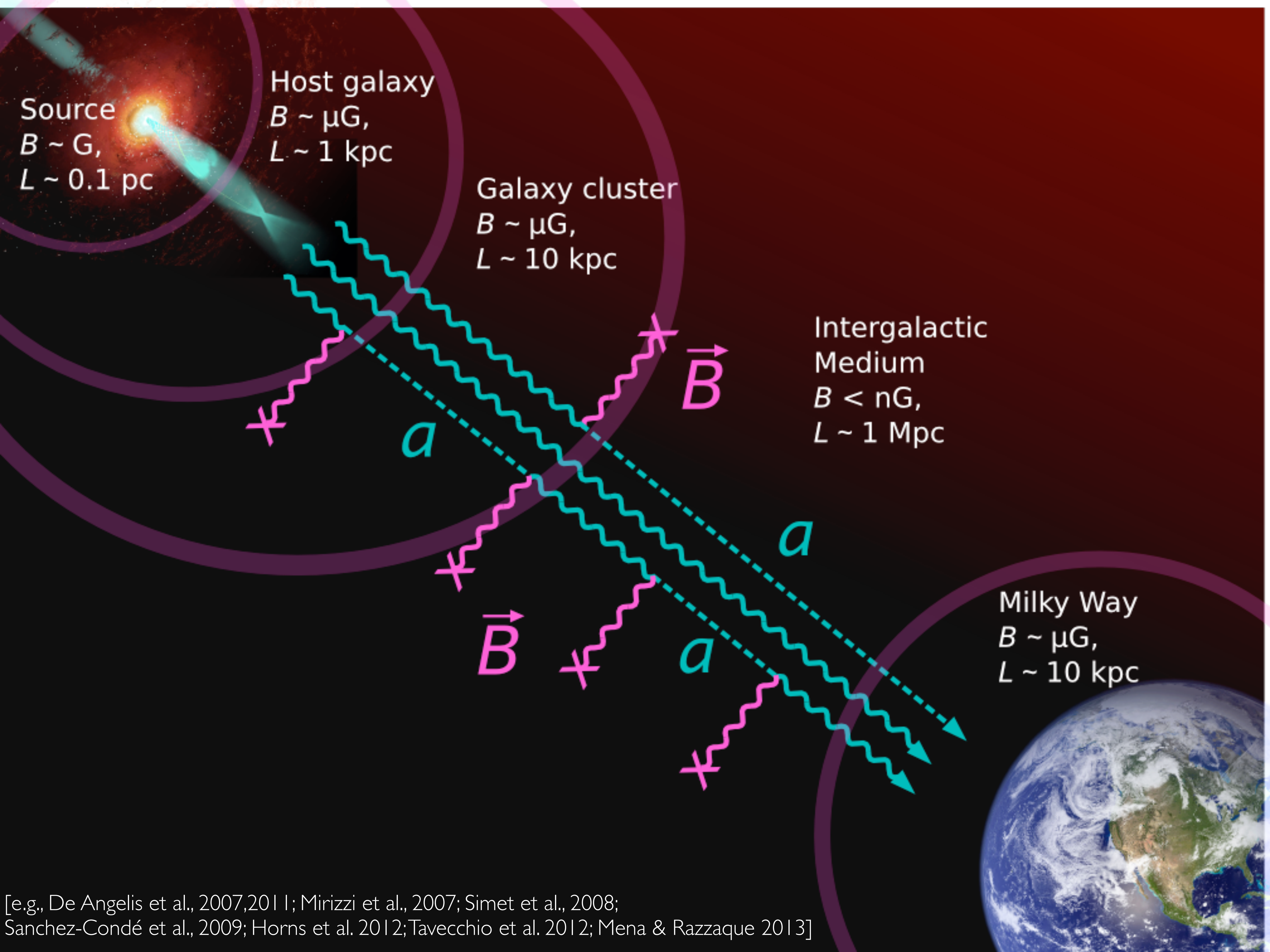
Conversion of photons into axion-like particles (ALPs)

- ALPs: **pseudo-Nambu Goldstone bosons**, arise in extensions of Standard Model
- **Dark matter candidate**
- Similar to **axions** that solve strong CP problem in QCD
- Couple to photons in **magnetic fields**
- **Evade pair production**



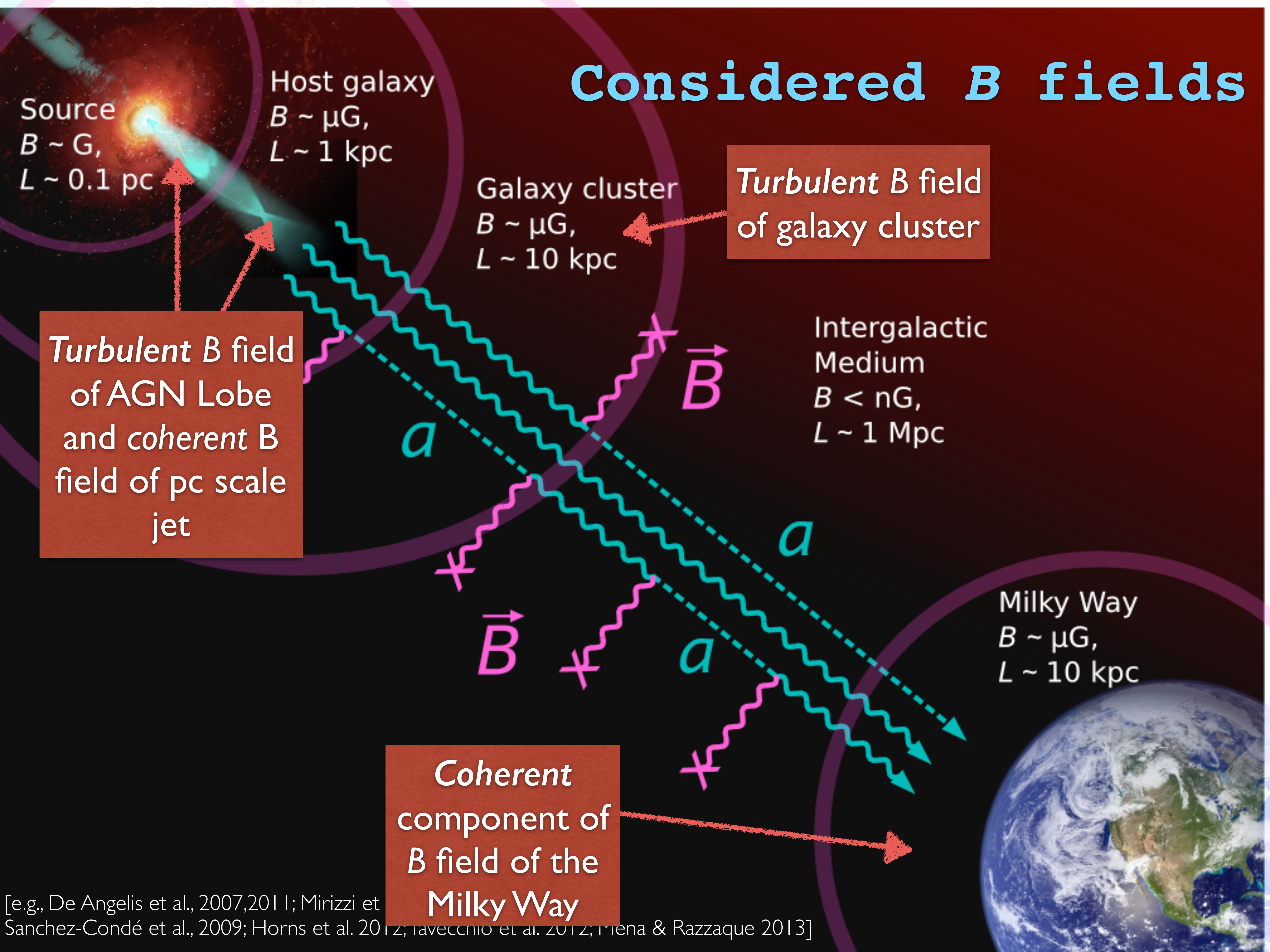
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B} a$$

[Peccei & Quinn, 1977; Weinberg, 1978; Wilczek, 1978;
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; Mena & Razzaque 2013]

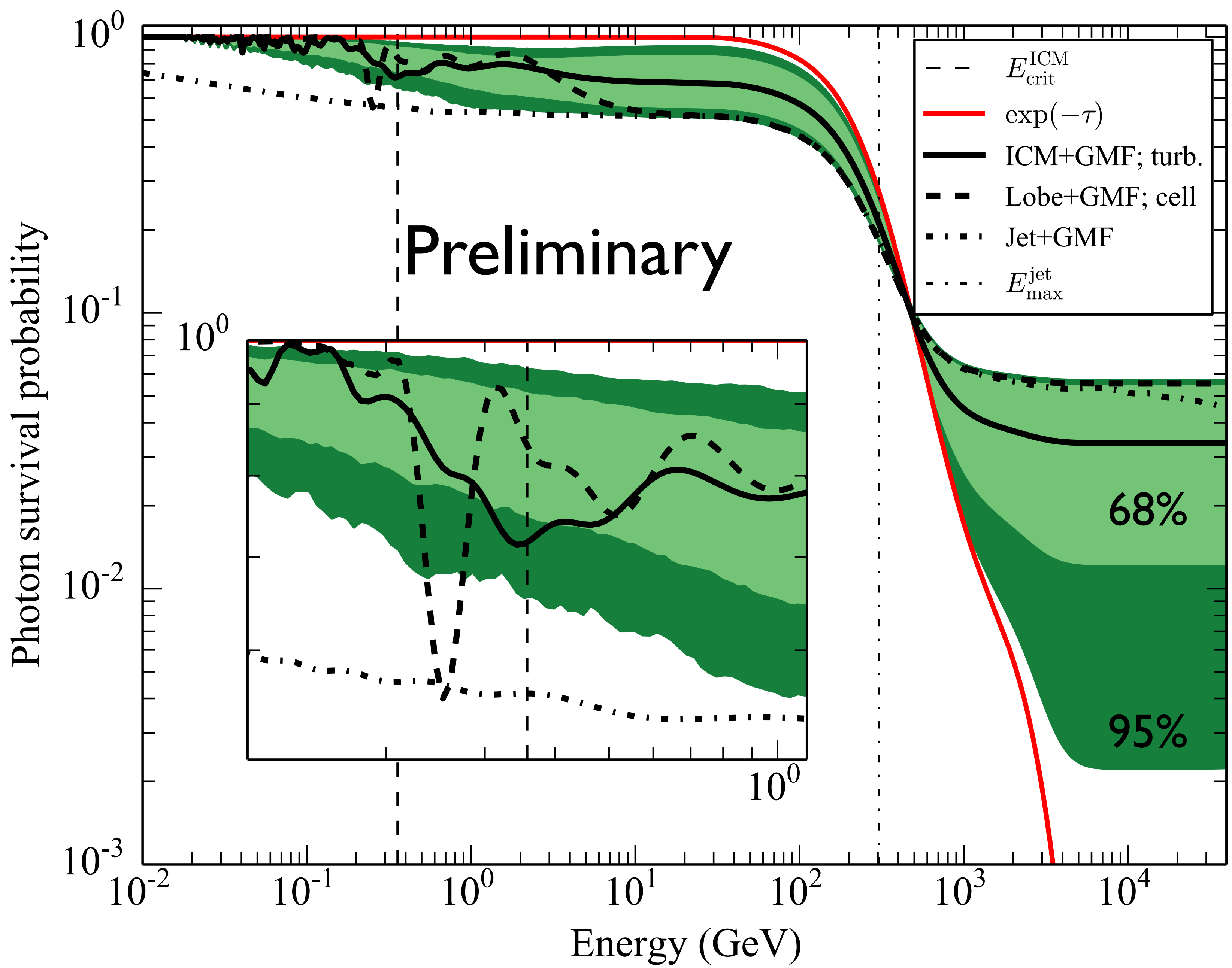
Considered *B* fields



[e.g., De Angelis et al., 2007,2011; Mirizzi et
Sanchez-Condé et al., 2009; Horns et al. 2012; Tavecchio et al. 2012; Mena & Razzaque 2013]

Reduced opacity in Photon-ALP conversion

PG 1553+113, z > 0.4

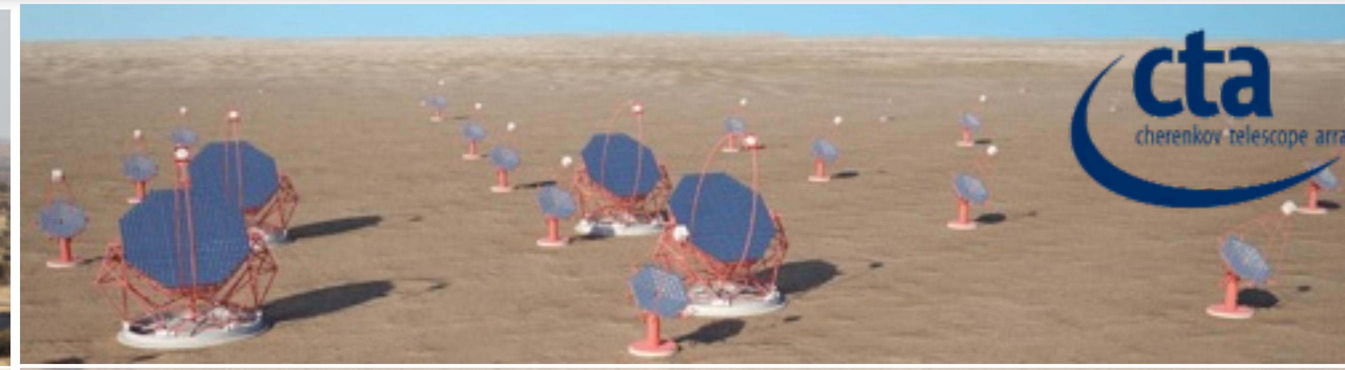


Parameter	Value
ALP mass	1 neV
photon-ALP coupling	2e-11 / GeV
Galactic *B* field (GMF)	Jansson & Farrar (2012)
EBL model	Kneiske & Dole (2010)

Conversion in galaxy cluster in magnetic field with gaussian turbulence and Kolmogorov power spectrum [**MM**; Conrad; Montanino, arXiv 1406.5972];

Galaxy cluster B-field values taken from Guidetti et al. (2010); see backup slides

H.E.S.S. II and CTA Concept



- H.E.S.S. I: 4 12m telescopes, energy threshold ~ 200 GeV
- H.E.S.S. II: additional 5th telescope, 28m diameter
- Lower energy threshold than phase I

- Northern and southern array for full sky coverage
- Southern array: multiple telescope designs, one (possible) set up:
  - 4 large (23m) telescopes, energy threshold ~30 GeV
  - 23 mid-size (12m) telescopes + U.S. Schwarzschild-Couder telescopes
  - Small (~6m) telescopes covering > 3 km^2, large collection area for E > 10 TeV

Assumed target AGN

Source	Redshift	Assumed observation time [hours]	Seen by	Comment
1ES 0229+200	0.139	41	H.E.S.S., VERITAS	Within ~700 kpc of cluster of Wen et al. (2012) catalog
PG 1553+113	> 0.4	20	H.E.S.S., MAGIC, VERITAS	Flare 2012, reaching 100% Crab [ATel 4069], within 1.5 Mpc of cluster of Hao et al. (2010) catalog
PKS 1424+240	> 0.6035	67	MAGIC, VERITAS	Observations beyond $\tau \gtrsim 5$, [VERITAS Collab. 2014], use mixing in BL Lac jet
PKS 0426-380	1.11	70	Fermi-LAT only	Long flaring period, two photons with E > 100 GeV [Tanaka+ 2013], use mixing in lobes

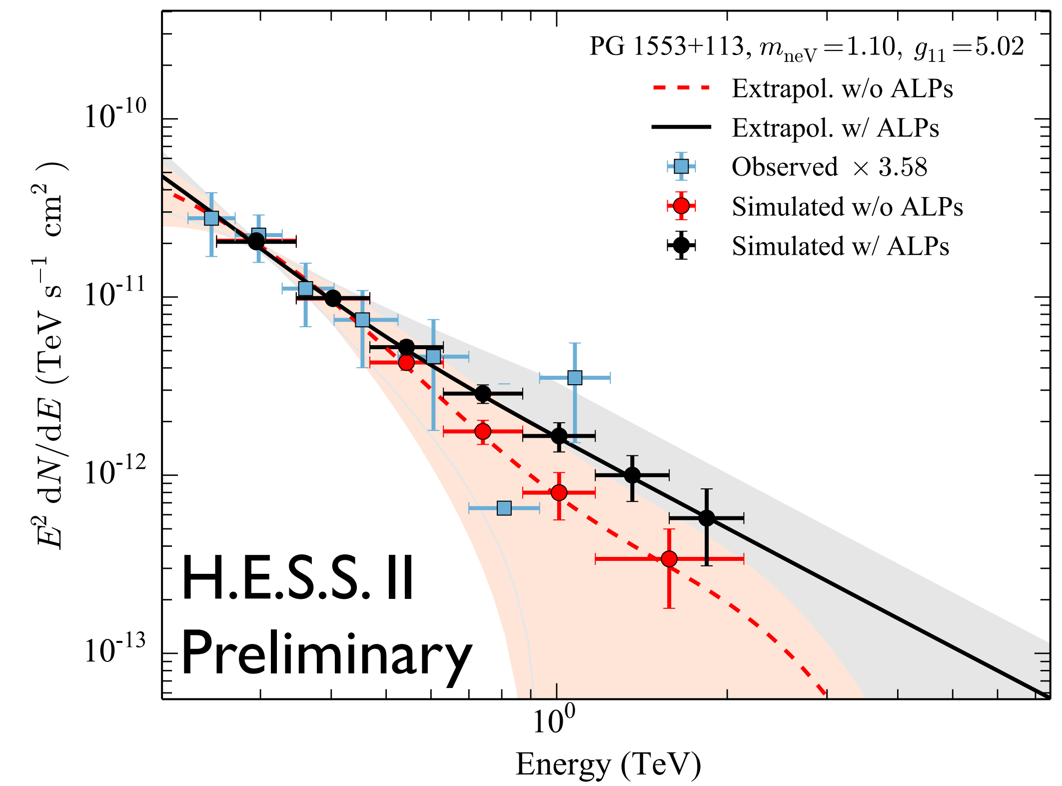
Instrumental response functions (IRFs, include point spread function, effective area and energy dispersion):

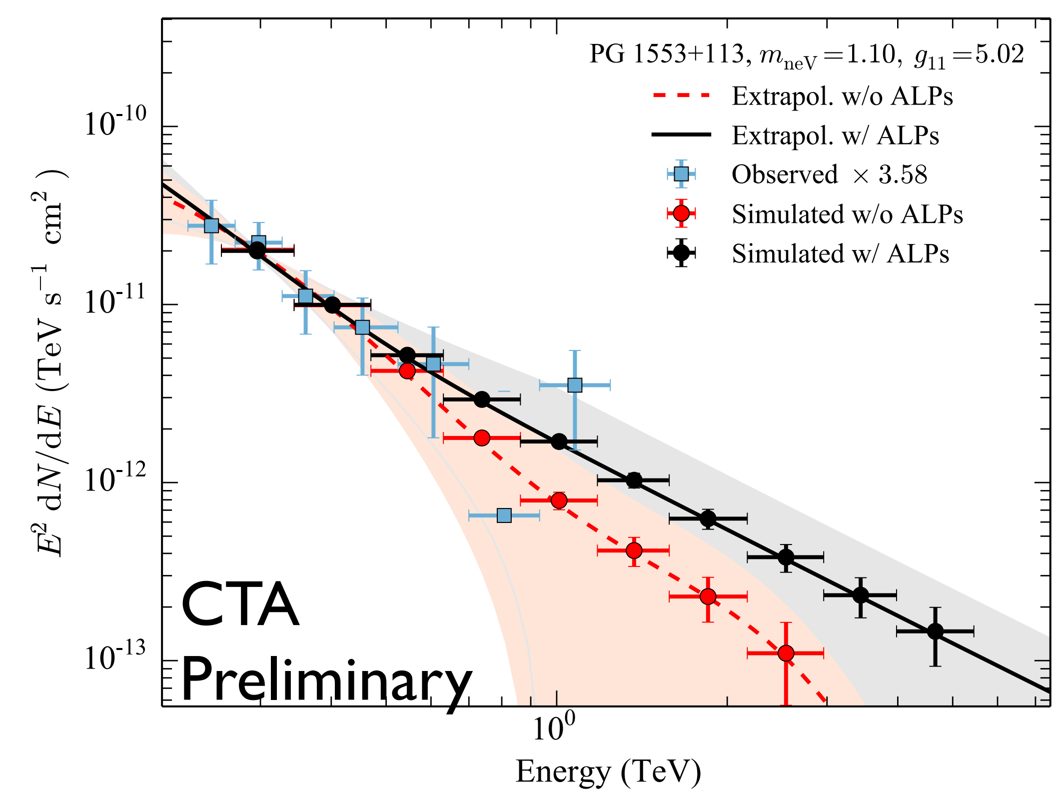
- CTA Array E configuration [Bernlöhr et al. 2013]
- H.E.S.S II preliminary hybrid IRF [Becherini et al. 2012], cuts at 5 TeV

Simulated spectra for H.E.S.S. II & CTA

- **1ES 0229+200, PG 1553+113, PKS 1424+240:**
  - First four data points (or $\tau < 1$) of VHE spectra de-absorbed w/ and w/o ALPs
- **PKS 0426-380:**
  - intrinsic index of 2.3 assumed (observed Fermi-LAT spectral index: 2.7)
- Intrinsic spectrum **extrapolated to energy for which τ = 12** (~ one order of magnitude in *E*)
- **Simulated** observed spectrum:

$$f_{\mathrm{obs}}(E) = N(E/E_0)^{-\Gamma} \times \begin{cases} P_{\gamma\gamma} & \text{w/ ALPs} \\ \exp(-\tau) & \text{w/o ALPs} \end{cases}$$





Sensitivity from likelihood ratio test

Expected counts w/o ALPs — Background counts that maximizes L for fixed μ

$$\lambda(\tilde{\boldsymbol{\mu}};\alpha|N_{\mathrm{ON}},N_{\mathrm{OFF}}) = \frac{\mathcal{L}(\tilde{\boldsymbol{\mu}},\widehat{\mathbf{b}}(\tilde{\boldsymbol{\mu}});\alpha|N_{\mathrm{ON}},N_{\mathrm{OFF}})}{\mathcal{L}(\widehat{\boldsymbol{\mu}},\widehat{\mathbf{b}};\alpha|N_{\mathrm{ON}},N_{\mathrm{OFF}})}$$

Expected counts w/ ALPs that maximizes L — Background counts that maximizes L

- Likelihood for high tau:

$$\mathcal{L}(\boldsymbol{\mu},\mathbf{b};\alpha|N_{\mathrm{ON}},N_{\mathrm{OFF}}) = \prod_{\substack{i \\ \tau(E_i,z)>2}} f(N_{i,\mathrm{ON}}|\mu_i+b_i)f(N_{i,\mathrm{OFF}}|b_i/\alpha).$$

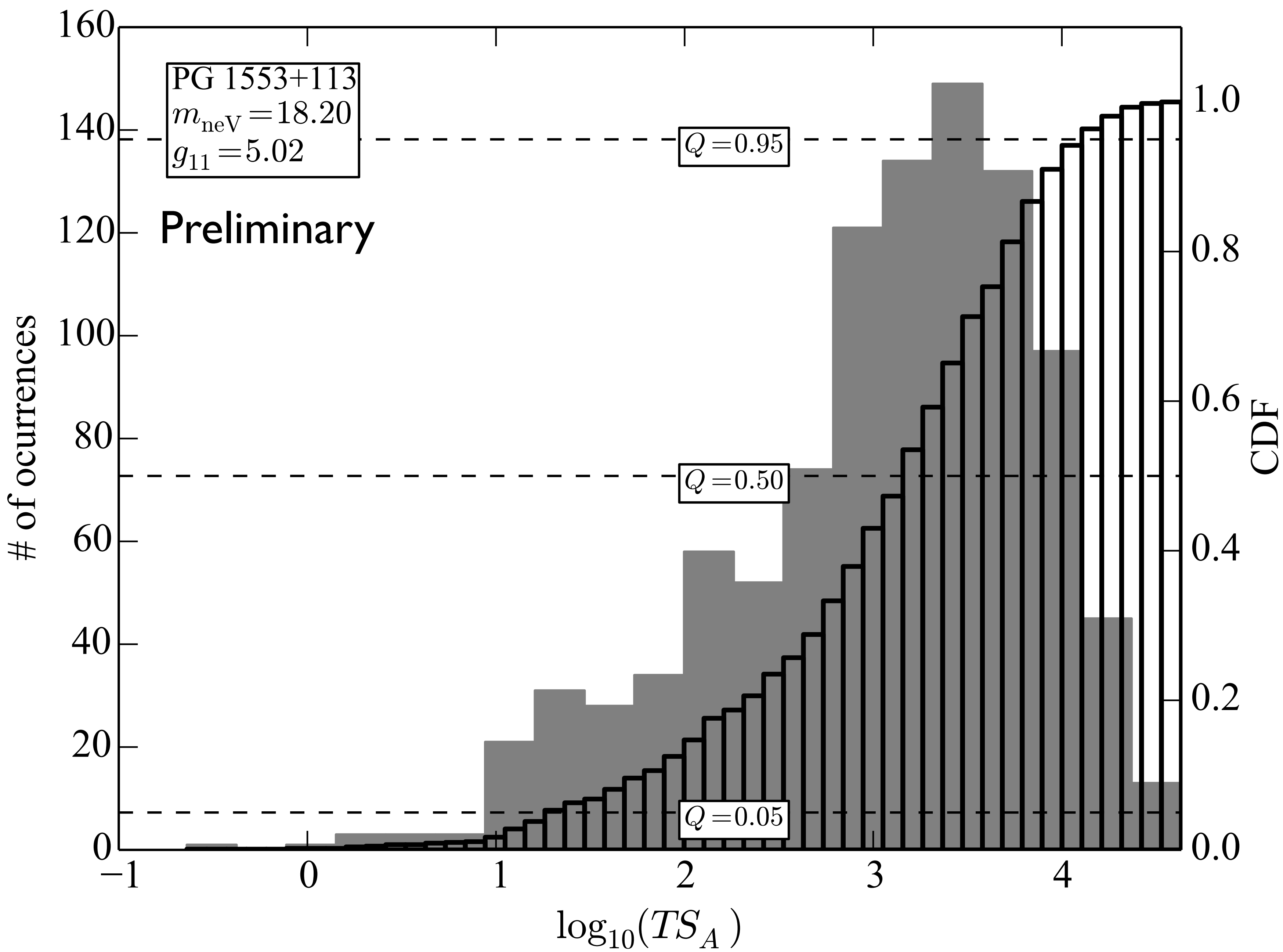
f: Poissonian probability mass function

- Test statistic ***TS* = -2 ln λ** follows χ^2 distribution with ~7 d.o.f. (determined from Monte-Carlo simulations)
- Use **Asimov data set** [Cowan et al. 2011]: $N_{\mathrm{ON}} = \mu + b$, $N_{\mathrm{OFF}} = b / \alpha$
- Only use bins detected with **$\tau > 2$ and significance > 2σ**

[**MM**, Conrad, Montanino, in preparation]

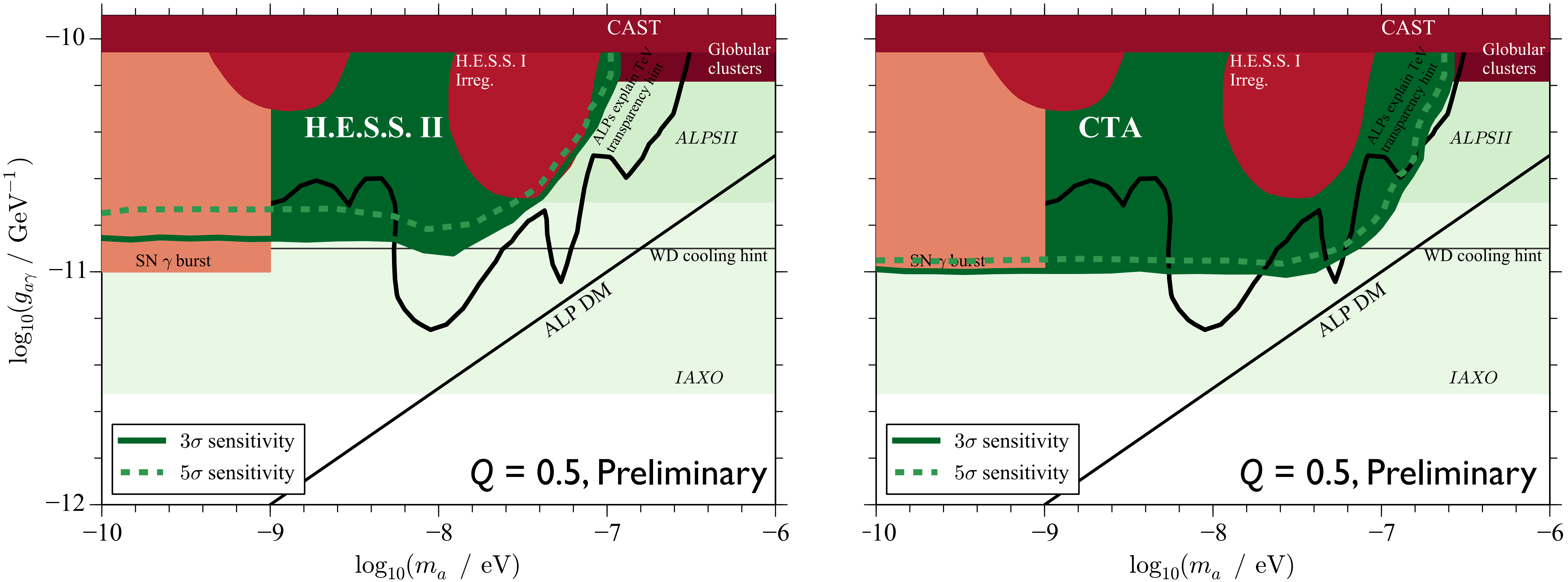
Test statistic for random magnetic fields

- In cluster scenario: ***B* fields random**
- Each realisation gives **different *TS* value**
- Define different **quantiles Q: CDF(*TS*) = Q**
- E.g. median: **Q = 0.5**



TS (CTA) distribution for **1000 random *B*-field** realisations in gaussian turbulent field,

Combined sensitivity and comparison to limits



- Spectrum of **PG 1553+113** results in highest sensitivity
- **Parameter range covered where ALPs could explain opacity hint** [**MM** et al., 2013]
- **CTA: ~2 times more sensitive than H.E.S.S. II** (ALP mixing in turbulent field scales as g^2)

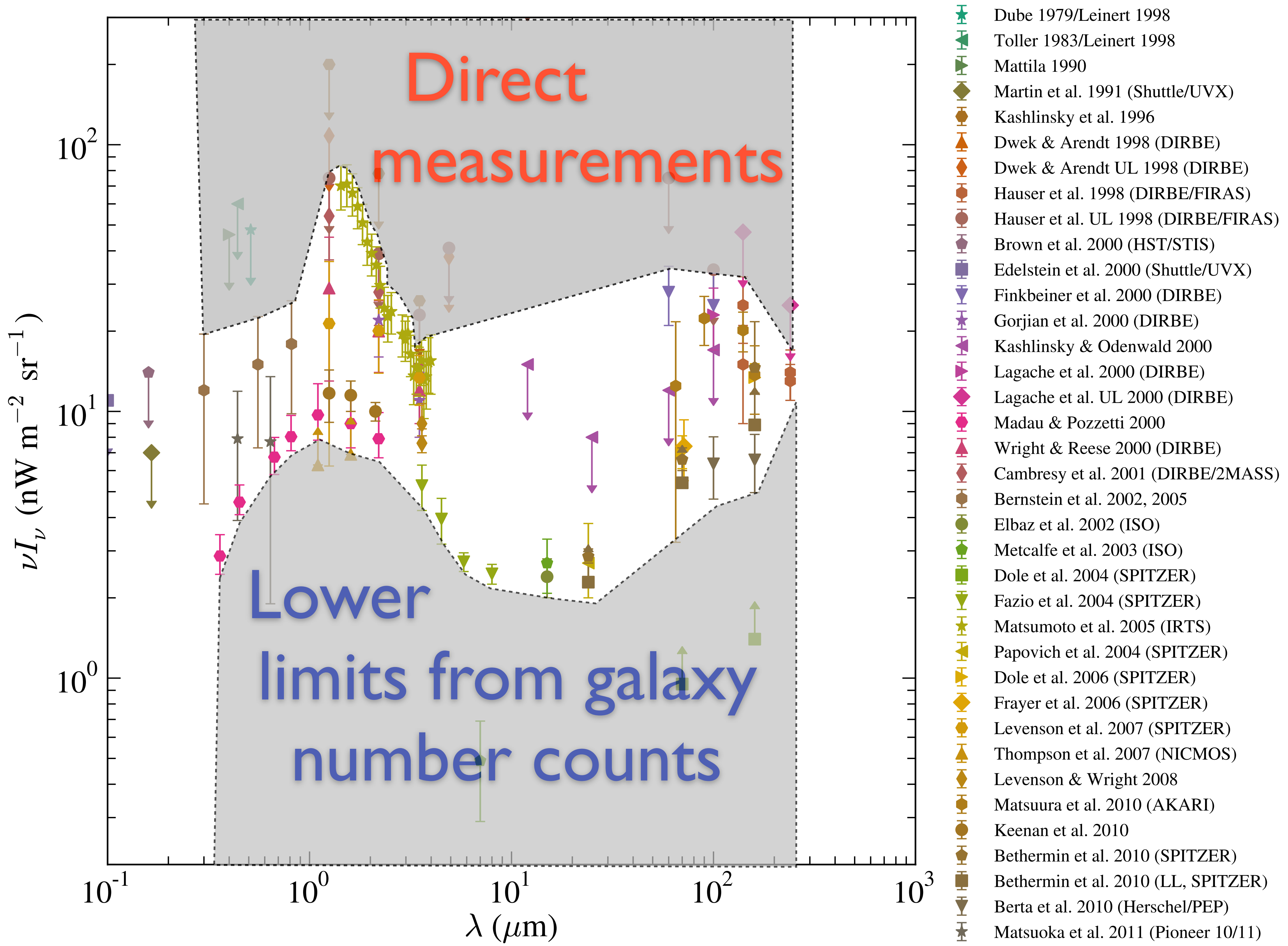
Summary & Conclusions

- Hints for **modified opacity at high optical depths** exist
- Possible explanation: **oscillation of photons into ALPs**
- **H.E.S.S. II and CTA can measure intrinsic (τ < 1) and absorbed spectrum (τ > 1) simultaneously**
- However: **Assumption about extrapolated spectrum necessary**
- Boost of γ-ray flux could be detected with **CTA (H.E.S.S. II) for photon-ALP coupling $\gtrsim 10^{-11}$ GeV^{-1} and ALP masses $\lesssim$ 100 neV** for conservative *B* fields
- **Flaring episodes of distant AGN** are suited best for ALP searches
- **Assumptions on *B* field necessary**, can be constrained from e.g. Faraday rotation measurements
- **Alternative scenarios to explain low opacity**: electromagnetic cascades induced by cosmic rays [e.g. Essey & Kusenko 2010,2011], Lorentz invariance violation [e.g. Jacob & Piran 2008]

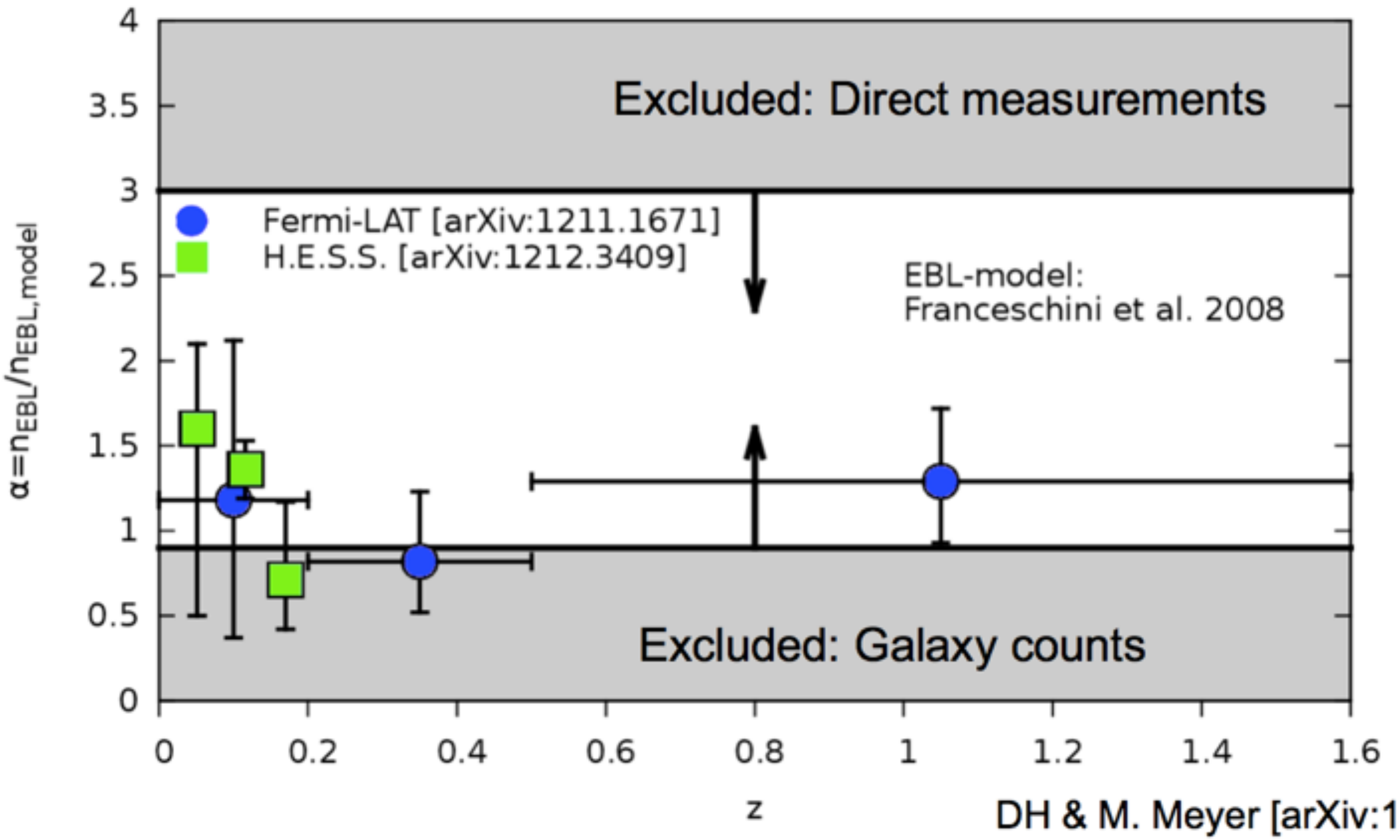
Backup slides

The extragalactic background light

- **Origin**:
  - **integrated starlight**
  - starlight **re-processed by dust**
- **Strong foreground emission** ⇒ direct observations difficult



Consistency of EBL measurements

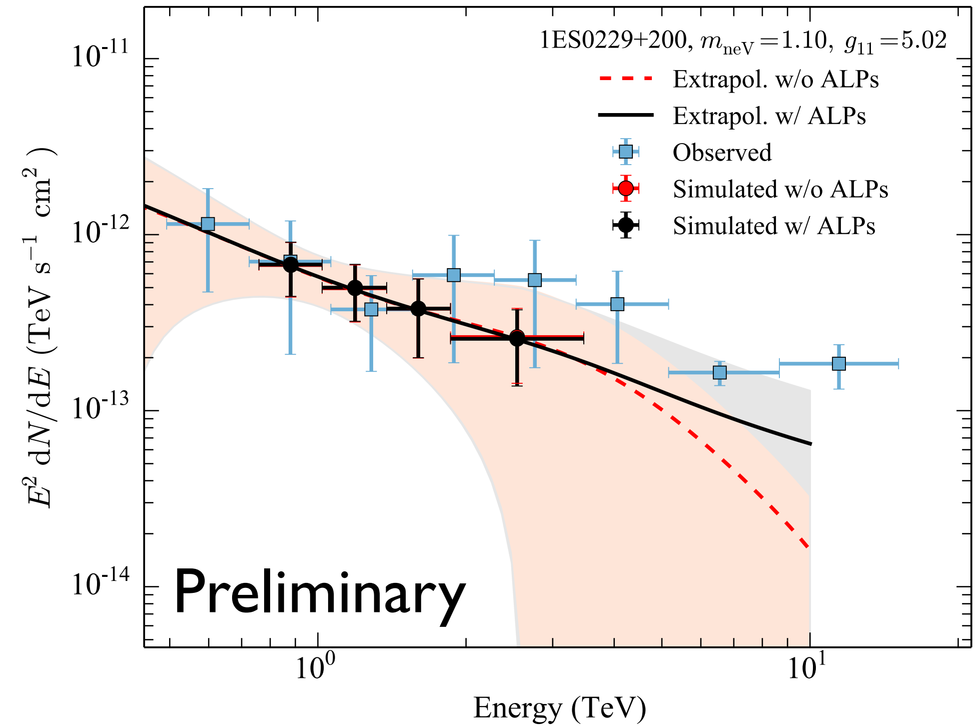


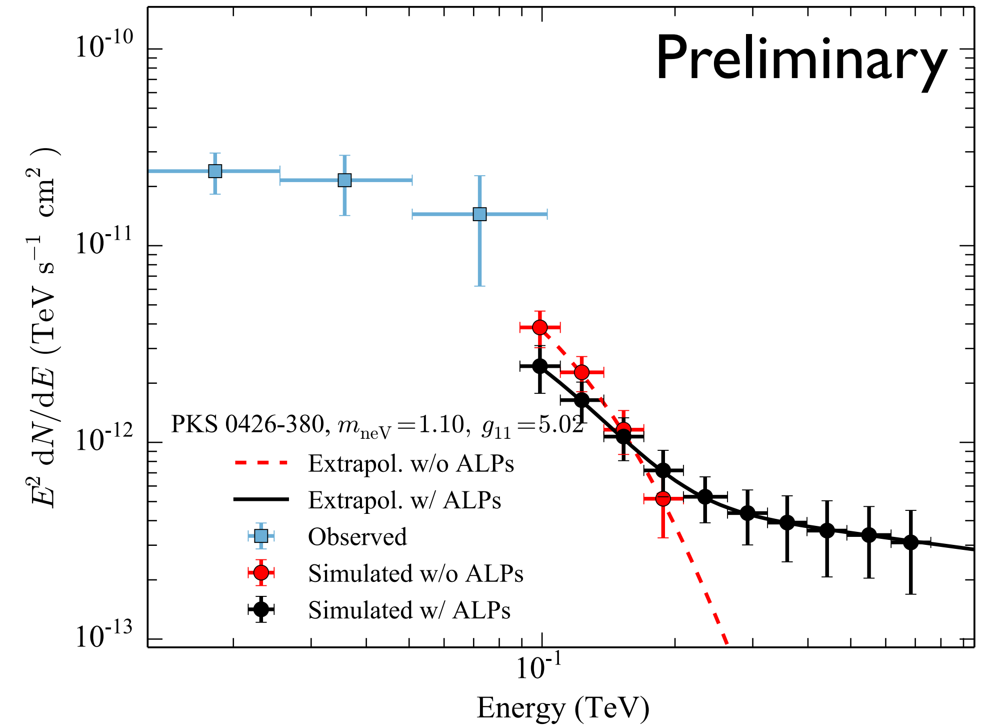
DH & M. Meyer [arXiv:1309.3846]

H.E.S.S. II and CTA simulated spectra

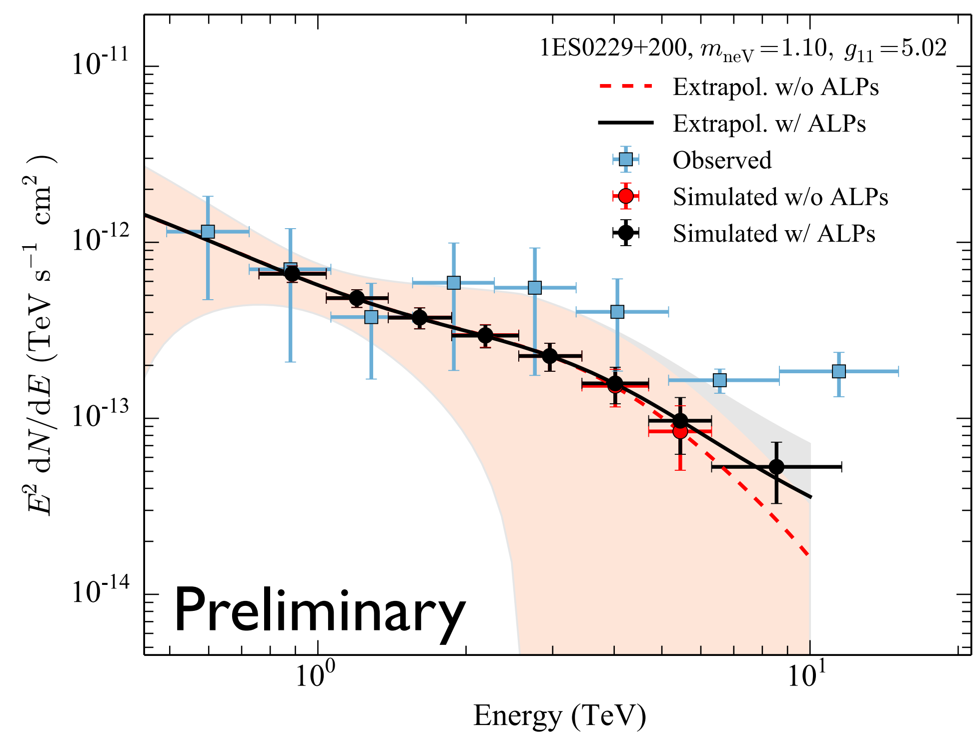
1ES 0229+200 | PKS 0426-380

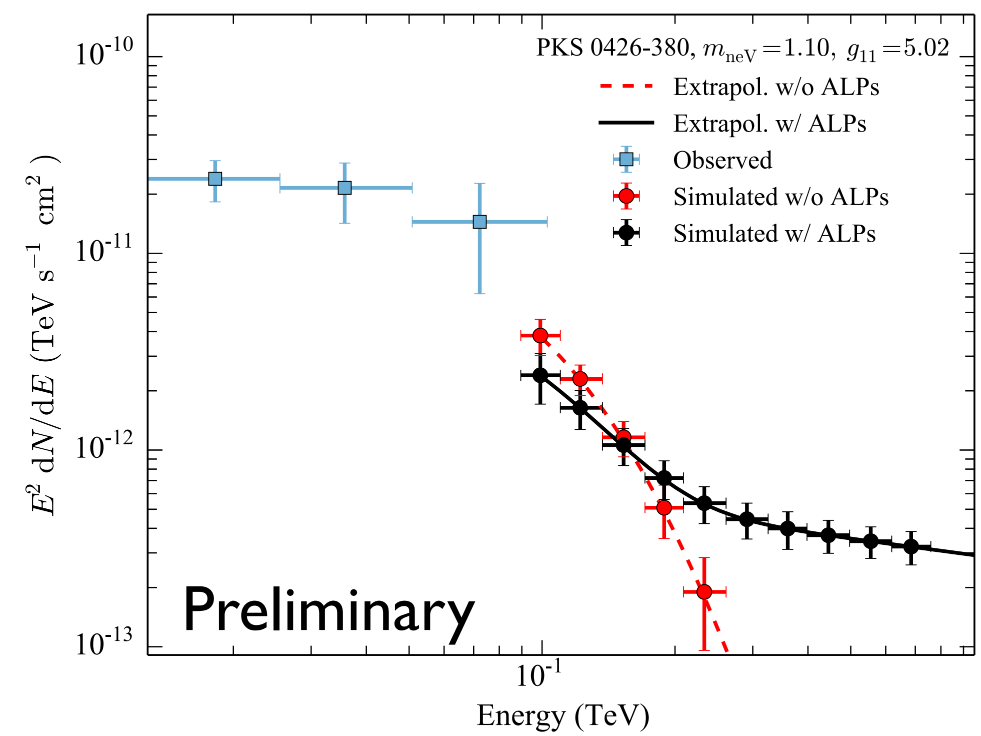
H.E.S.S. II



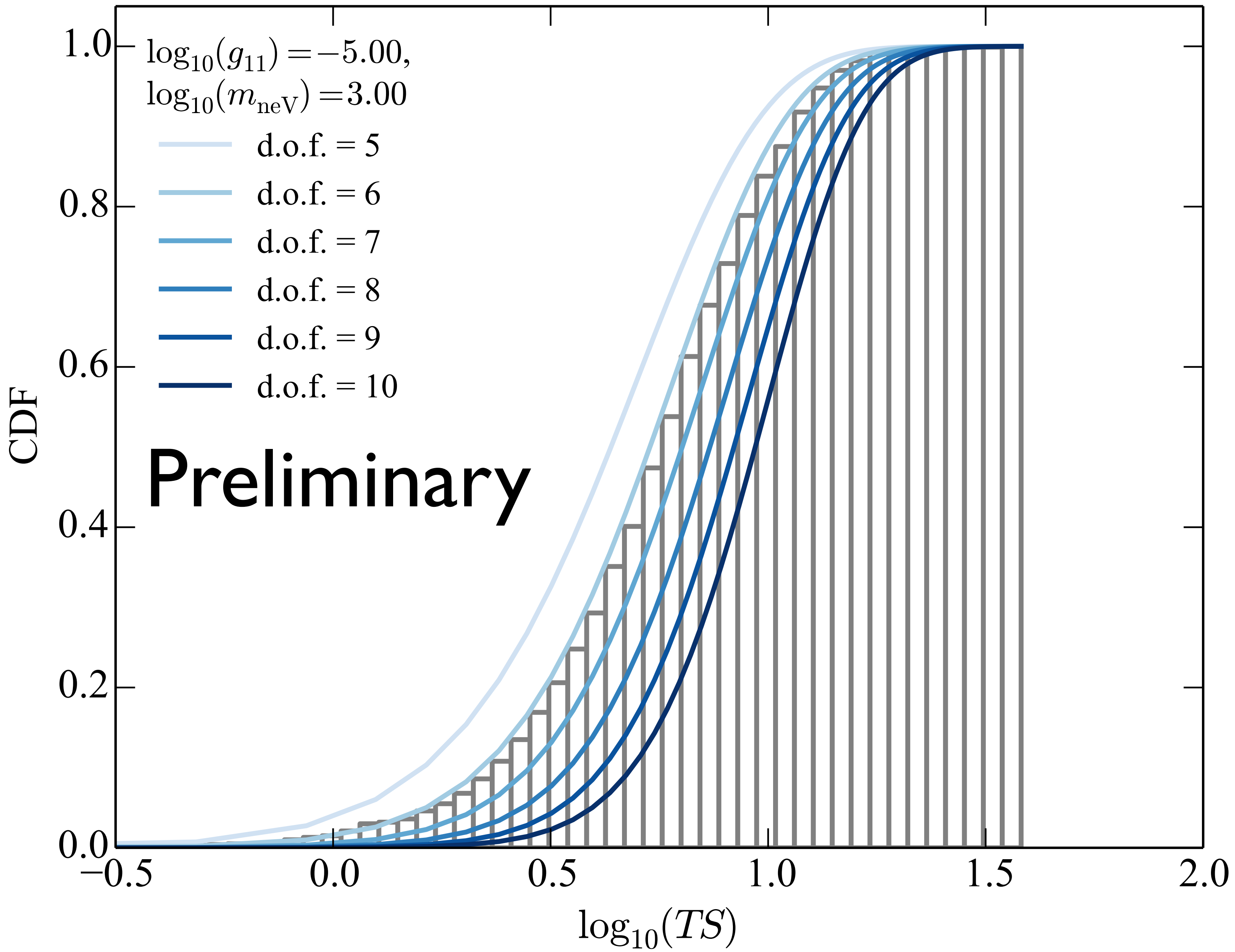


CTA





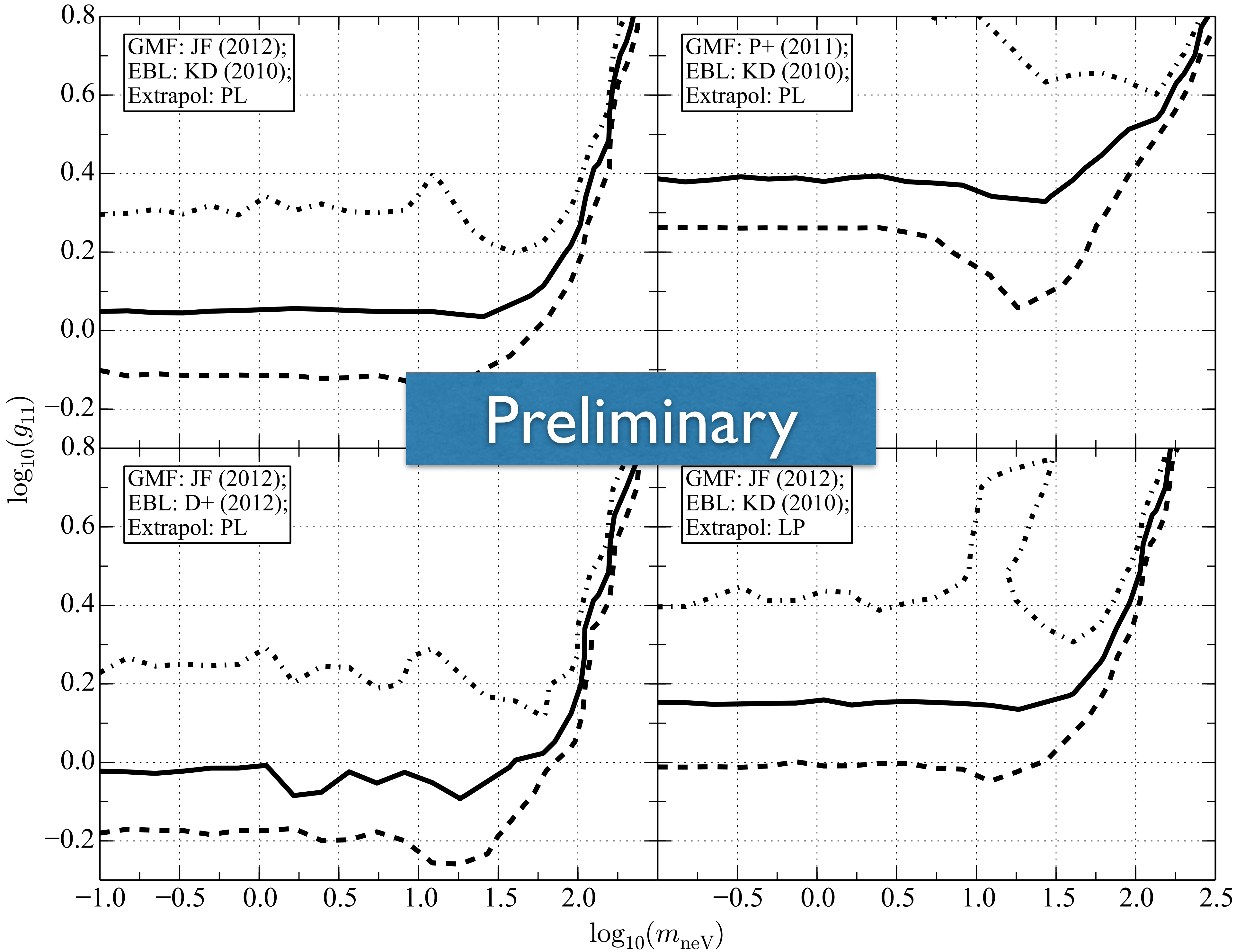
Null distribution of TS values



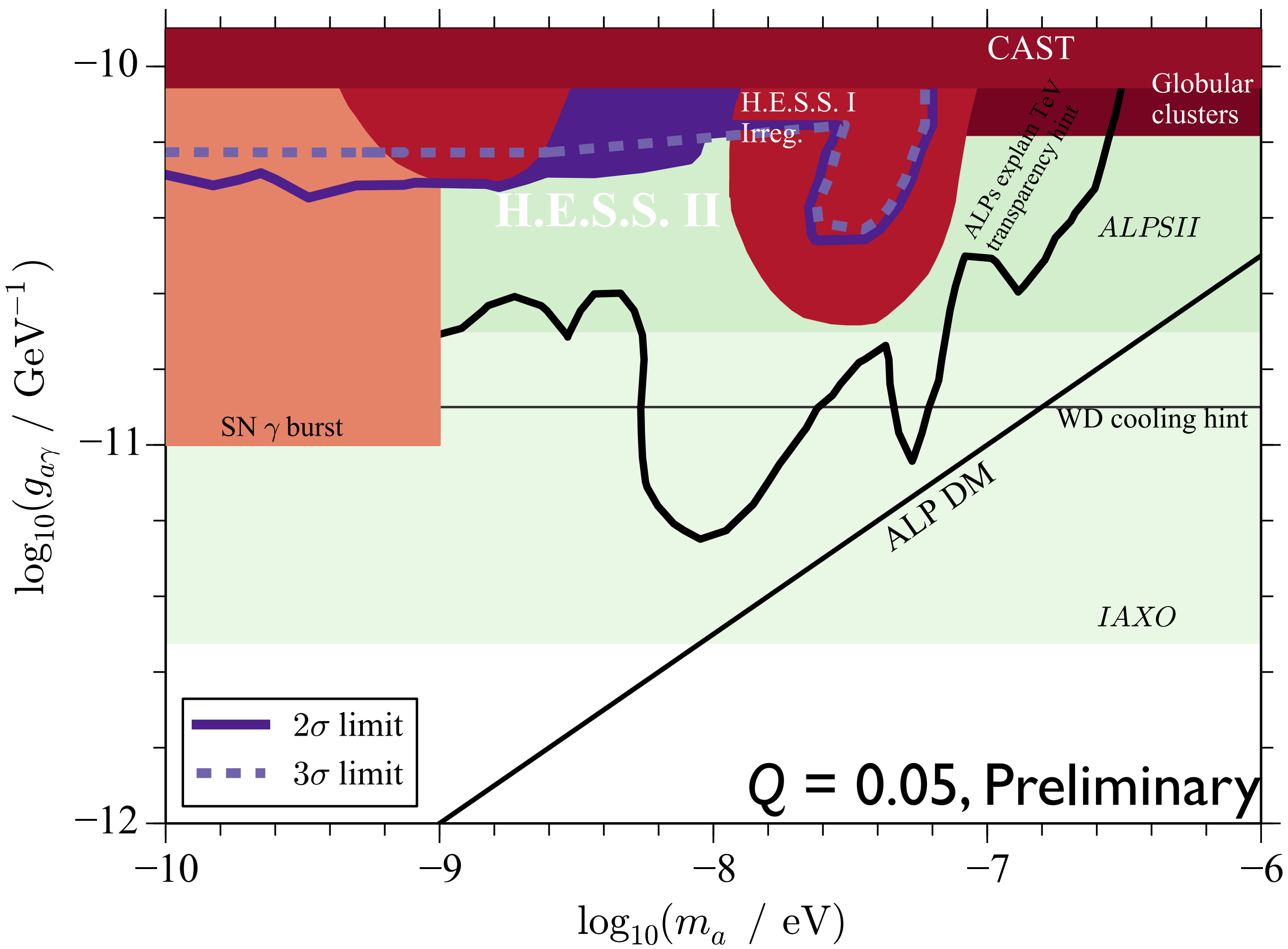
- Null distribution derived by considering ALP parameters where no effect is expected
- Simulate 10^6 observations

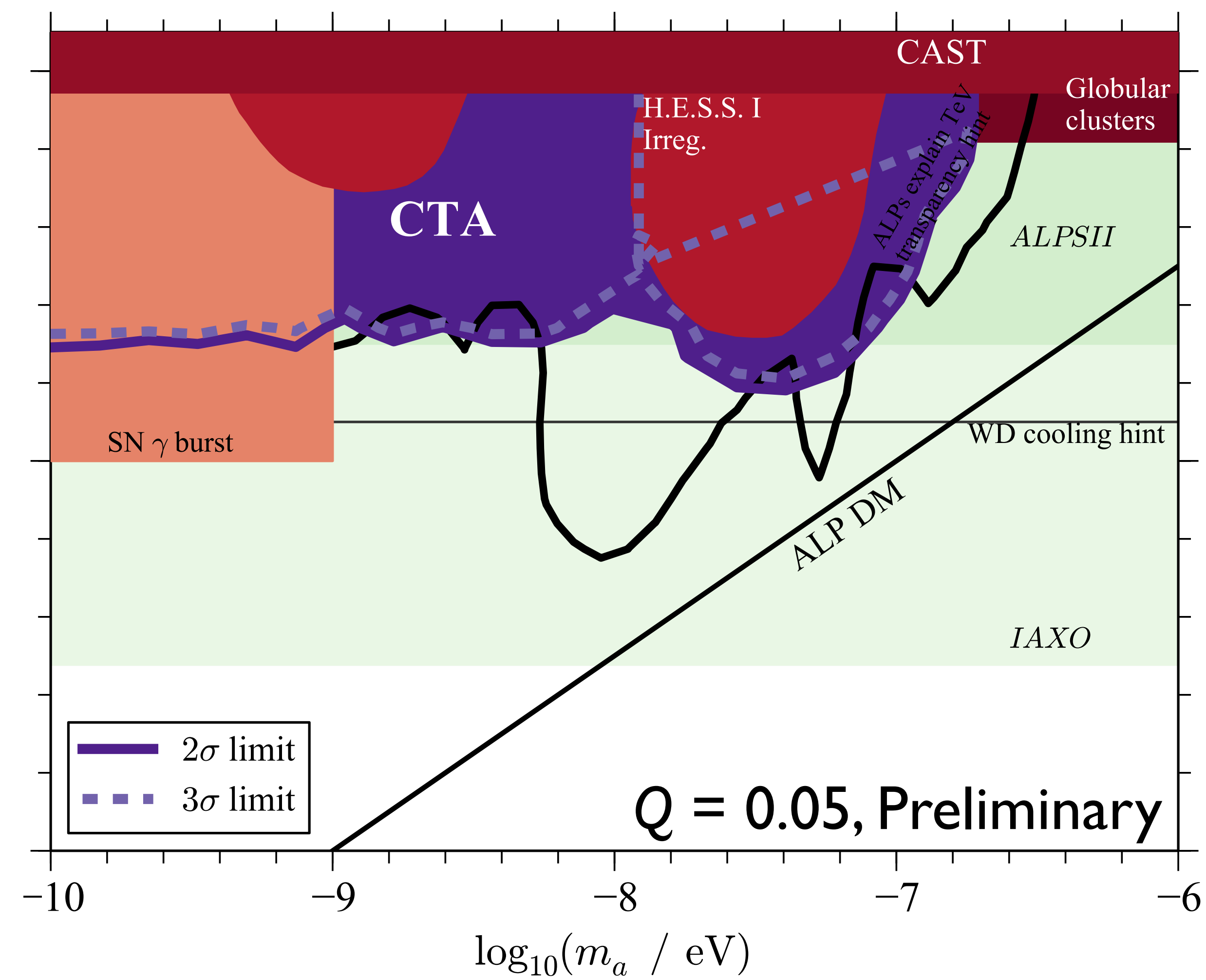
[**MM**; Conrad; Montanino, in preparation]

Dependence of sensitivity on model parameters



Possible limits





- Limits derived by **exchanging μ and $\tilde{\mu}$ in likelihood ratio test**
- Limits weaker than sensitivity due to **smaller statistics at high τ**
- At high masses: **Irregularities lead to exclusion**

Solving the EoM for ALPs

- From Lagrangian, derive equation of motion:

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

- ALPs only mix with $E_{||}$

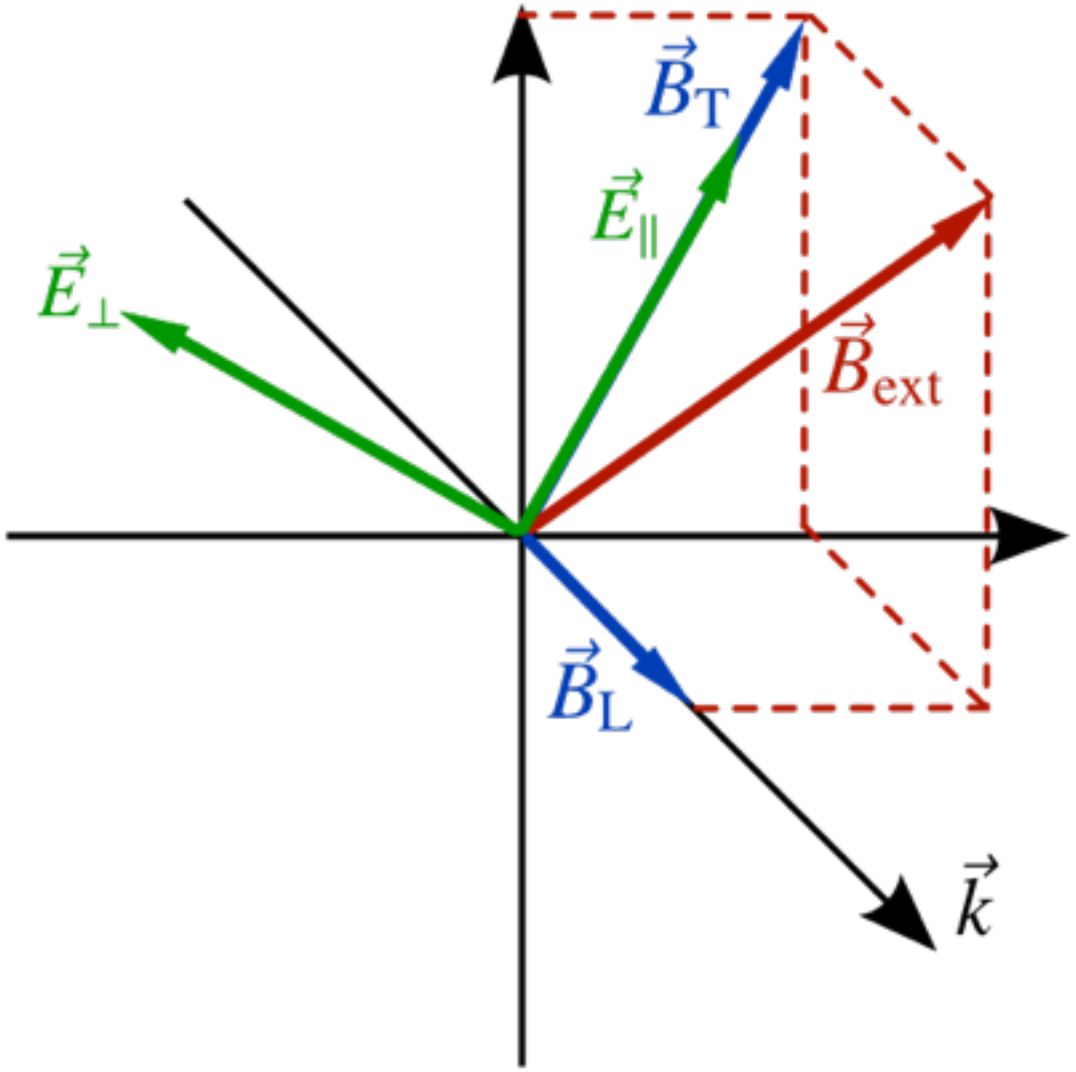
- Solve with Ansatz:

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

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

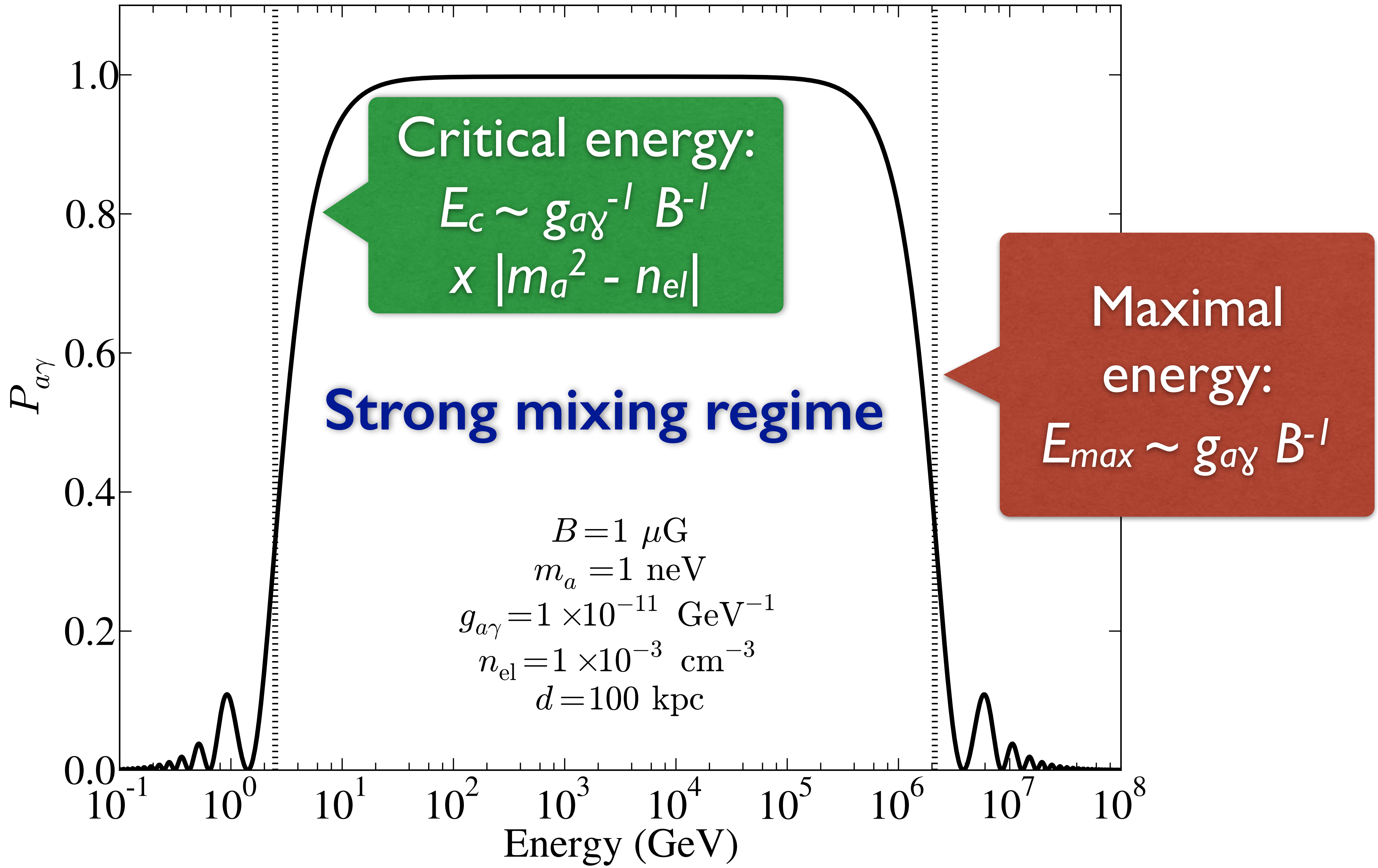
- Diagonalize mixing matrix, transfer matrix given by:

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



[e.g., Raffelt & Stodolsky; 1988; De Angelis et al. 2011]

Mixing in a homogeneous isotropic coherent B field

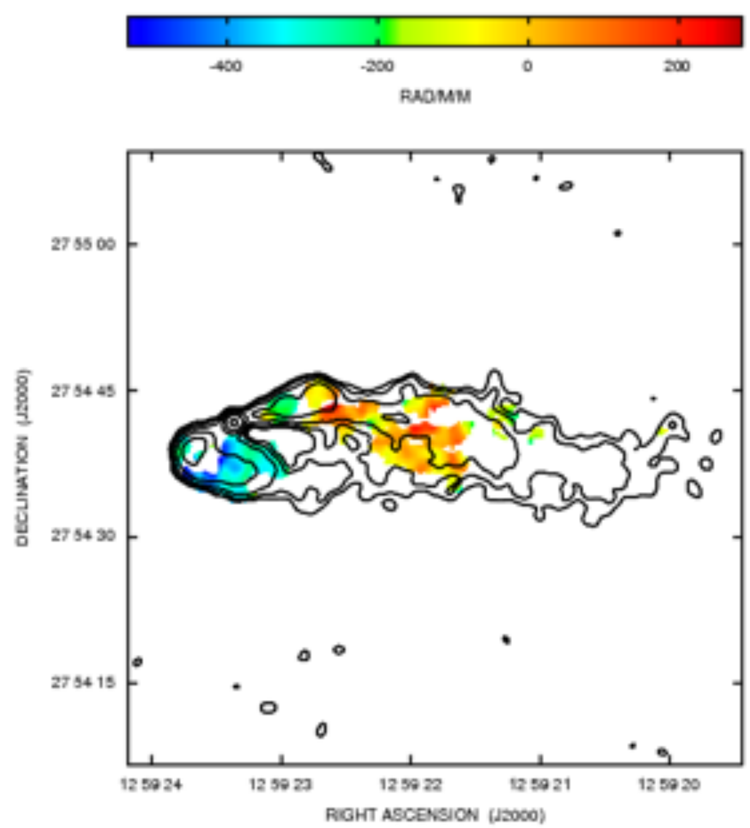


[e.g., Raffelt & Stodolsky; 1988]

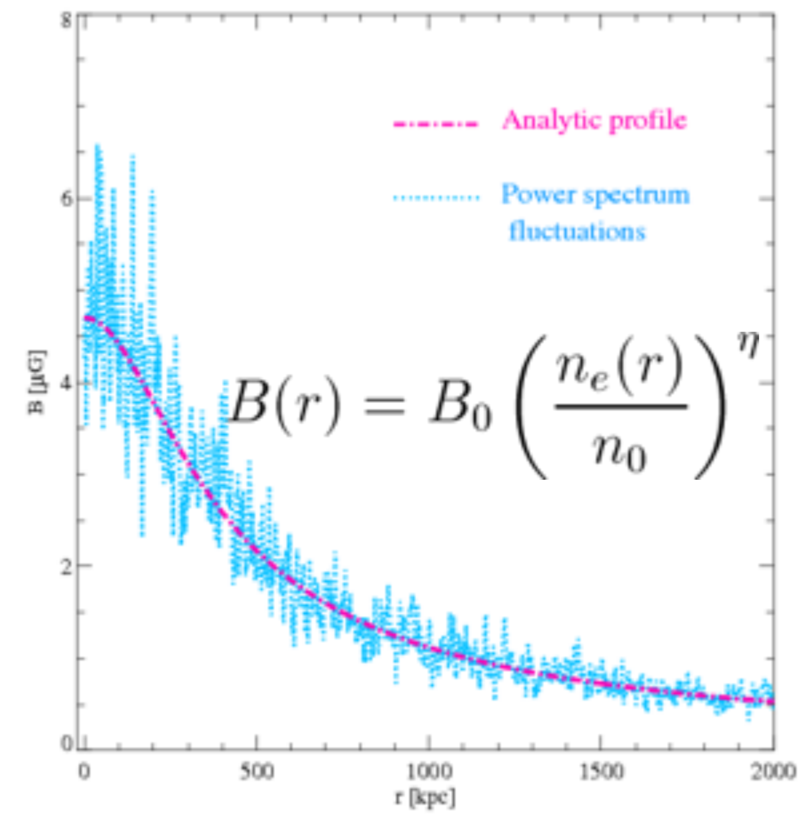
Observations of B fields in galaxy clusters

[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

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

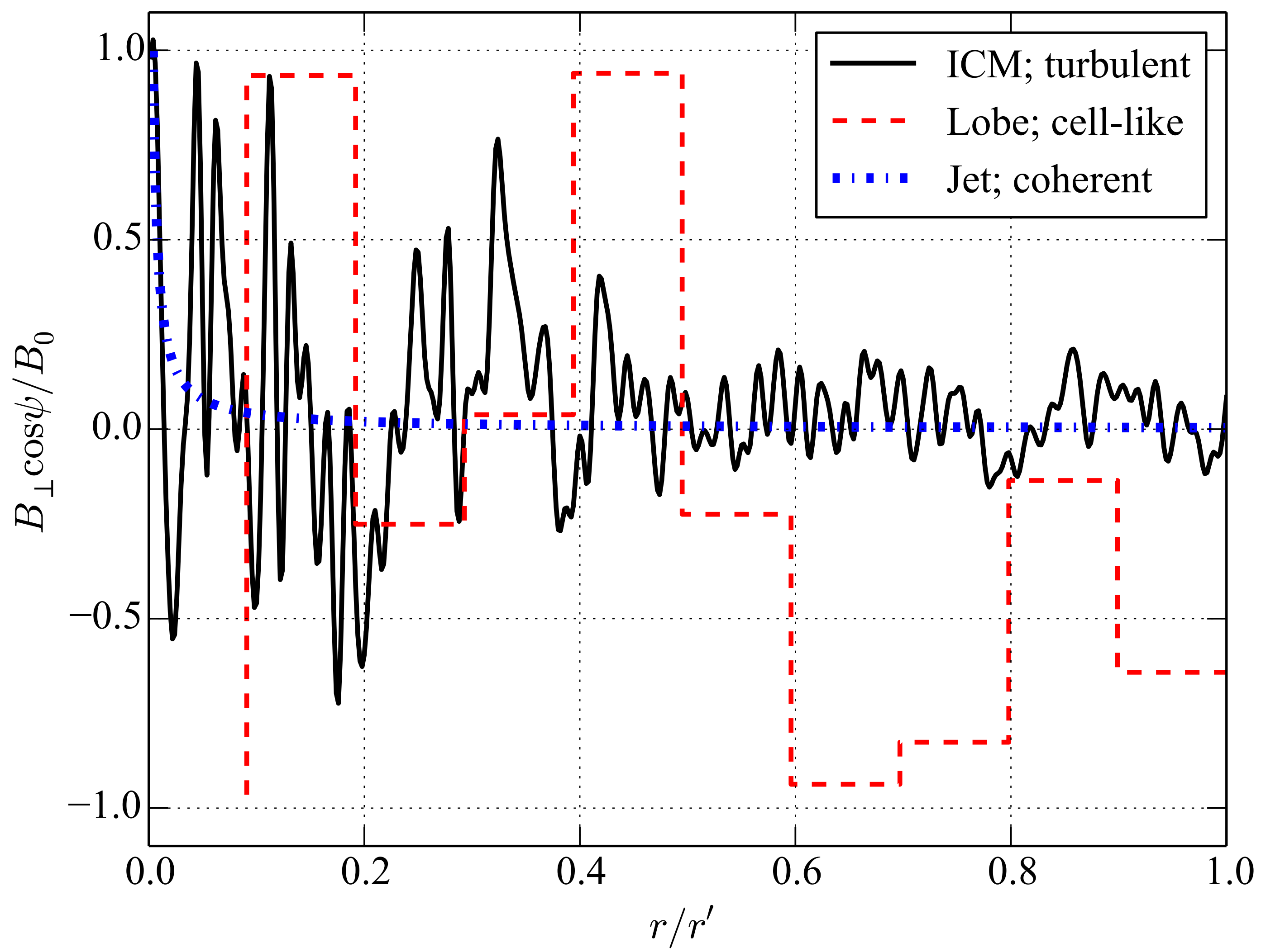
$$\mathrm{RM} = 812 \int_0^{L/\mathrm{kpc}} n_e B_{||} \, d\ell \; (\mathrm{rad\,m^{-2}})$$

Gaussian turbulent magnetic fields in galaxy clusters

- Homogeneous gaussian turbulent field with **zero mean and variance ~*B*²**
- Often applied to model cluster field [e.g. Kuchar & Enßlin 2011]
- **Turbulence spectrum:**

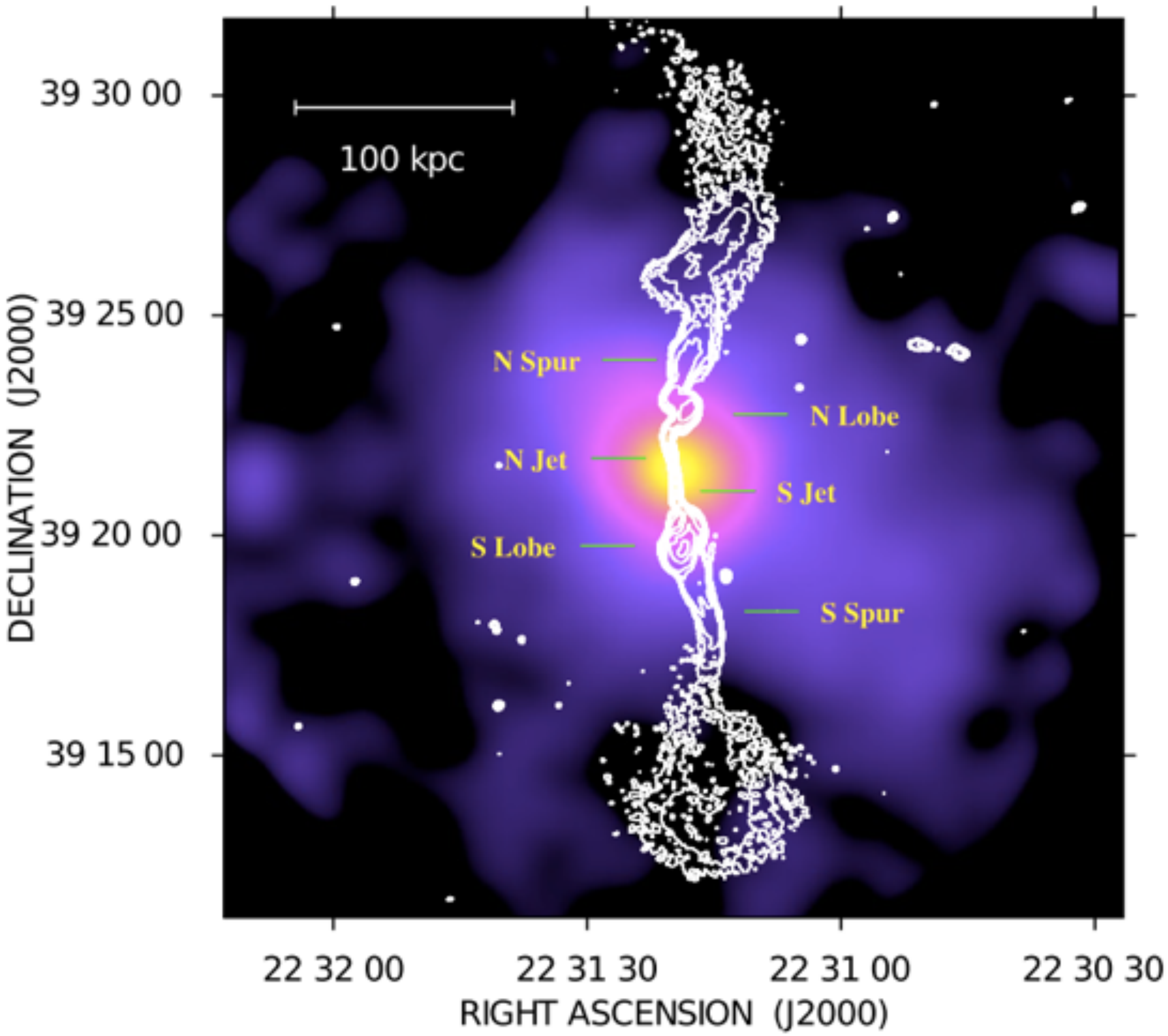
$$M(k) = Ak^q \quad \text{for}\, k_L \leqslant k \leqslant k_H$$

- **Kolmogorov turbulence**: q = -11/3, s.th. energy density follows power law with index -5/3



[**MM**; Conrad; Montanino, arXiv 1406.5972]

Turbulent magnetic field in over-dense regions in vicinity of FR I galaxy



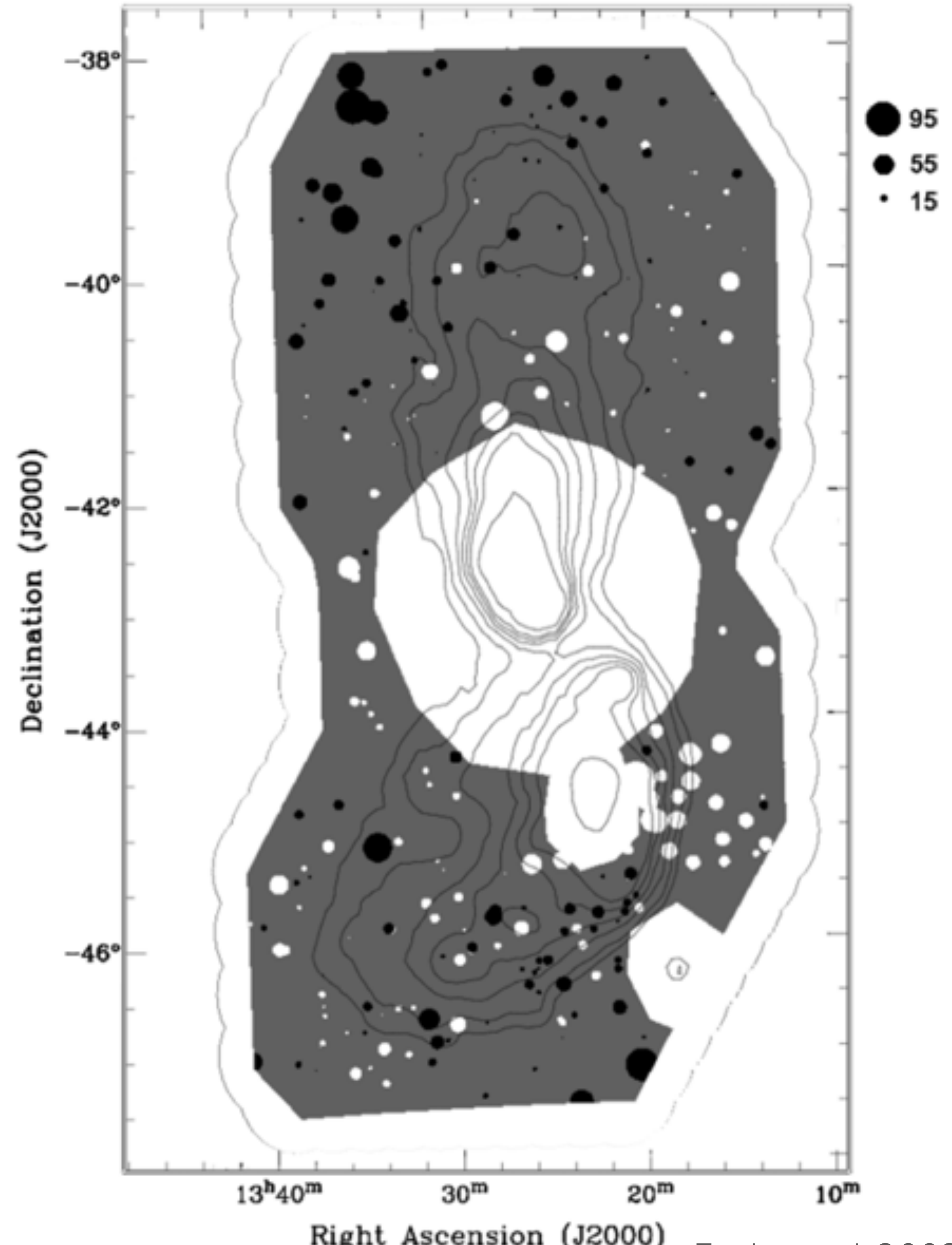
[Guidetti et al. 2010]

- 3C 449: FR I type galaxy located in **group of galaxies**
- Magnetic field from **rotation measure of background radio sources**
- **turbulent *B* field:**
  - ***B* = 3.5 μG**
  - **spectrum: power law** with index -2.98 and -2.07 at scales smaller and larger than 11 kpc
  - Fluctuation on **scales between 65 and 0.2 kpc**

Observations of magnetic field in AGN lobes

- **Rotation measure** of radio sources behind lobes of Cen A (misaligned BL Lac)
- **Turbulent component** (sheath?)
- Fit with **cell-like *B* field**:
  - $B \approx 0.8\ \mu G$
  - Cell size ≈ 20 kpc
  - Path length ≈ 180 kpc

Residuals of rotation measure



[Feain et al. 2009]

Mixing in BL Lac jet

- Modelling follows **Tavecchio et al. (2012,2014)** and **Mena & Razzaque (2013)**
- Environment modelled between VHE emission zone $r_{\rm VHE}$ to some outer radius $R_{\rm max}$
- **Magnetic field *(coherent)***, profile:

$$B(r) = B_0 \left(\frac{r}{r_{\rm VHE}}\right)^{-p}$$

- **p = 1** for toroidal field, p = 2 for poloidal field [Blandford et al., 1984; Rees, 1987; Lobanov 1998; O'Sullivan & Gabuzda, 2009]
- **Ambient electron density**:

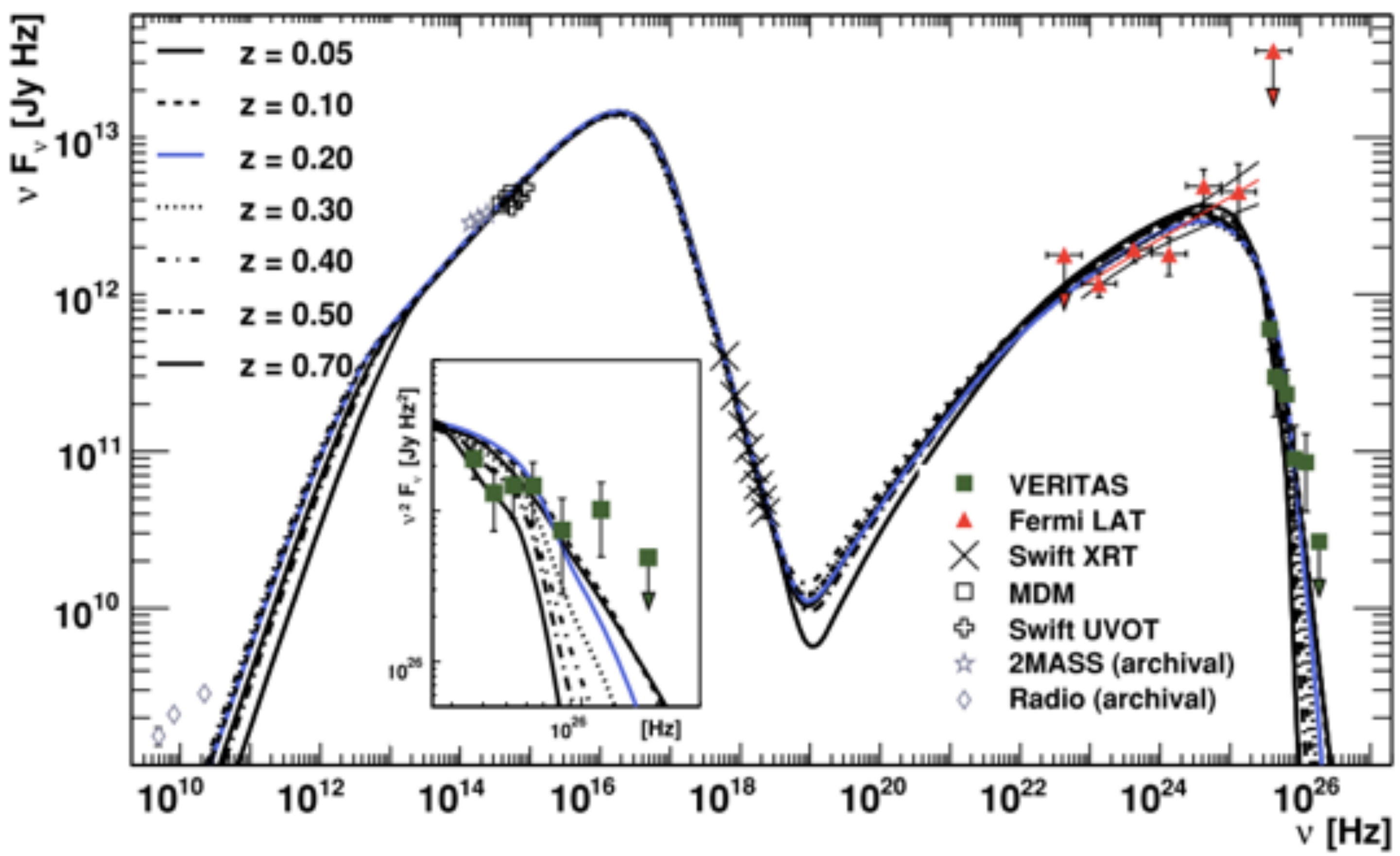
$$n(r) = n_0 \left(\frac{r}{r_{\rm VHE}}\right)^{-s}$$

- **s = 2** assuming equipartition [Lobanov 1998; O'Sullivan & Gabuzda, 2009, see also the review by Pudritz et al. 2012]
- **Values** for B and $r_{\rm VHE}$ from **SSC modelling**

Magnetic field values for mixing in BL Lac jet from SSC modelling

Parameter	Value
Redshift	0.7
B field	0.14 G
Doppler factor	60
Radius emission region	5e16 cm
Angle between jet and l.o.s.	1 degree
distance of VHE emitting zone to central BH	0.03 pc

SED models for PKS 1424+240

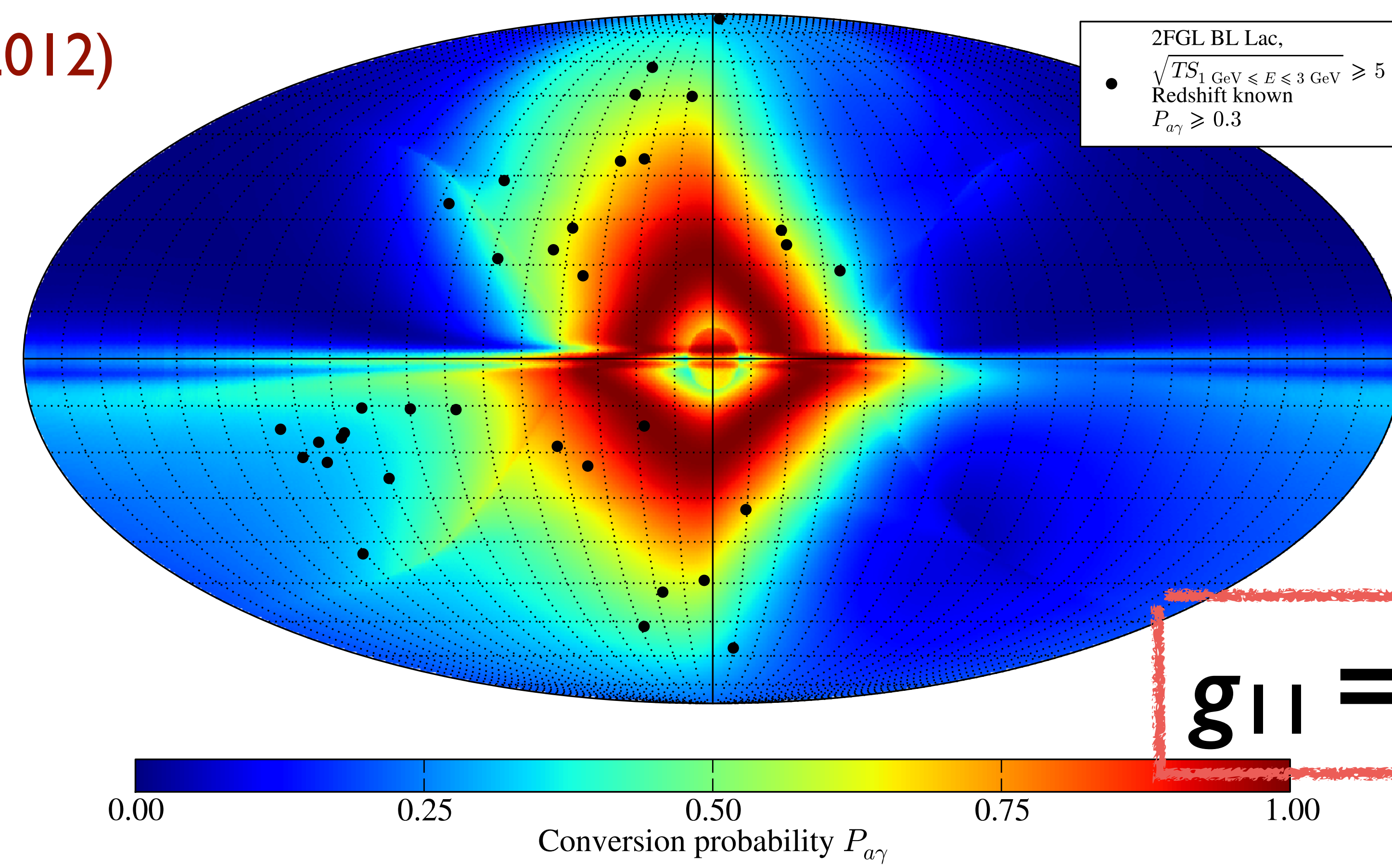


[Figure from Acciari et al. 2014]

Galactic magnetic field

Parameter	Value
Magnetic field *B*	~0.5 µG, given by Jansson & Farrar (2012) model
Electron density *n*	Given by NE2001 code

Jansson & Farrar (2012)



$g_{11} = 5$, $E > E_{crit}$

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