Indications for a low opacity Universe at high and very high energies

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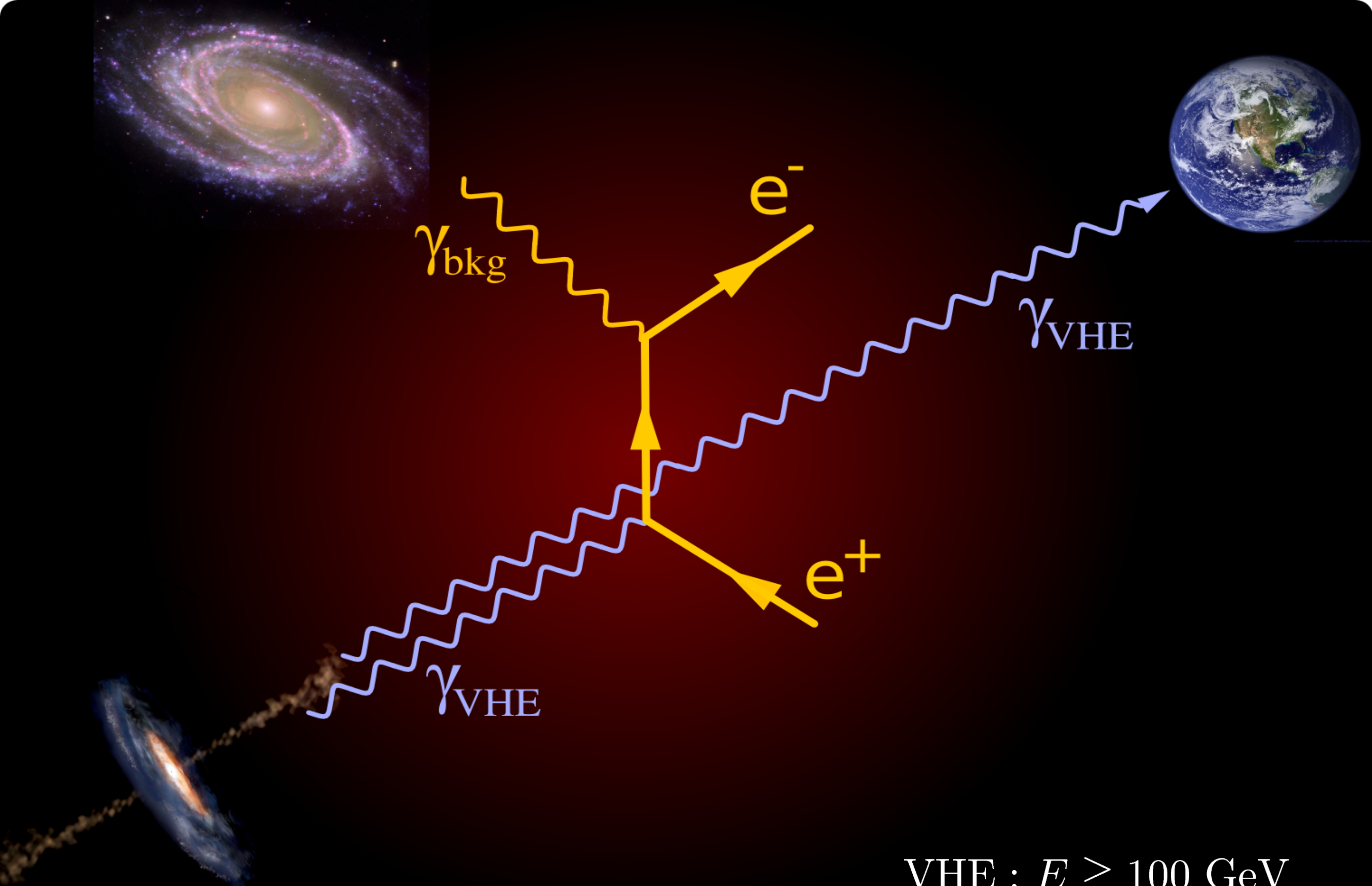
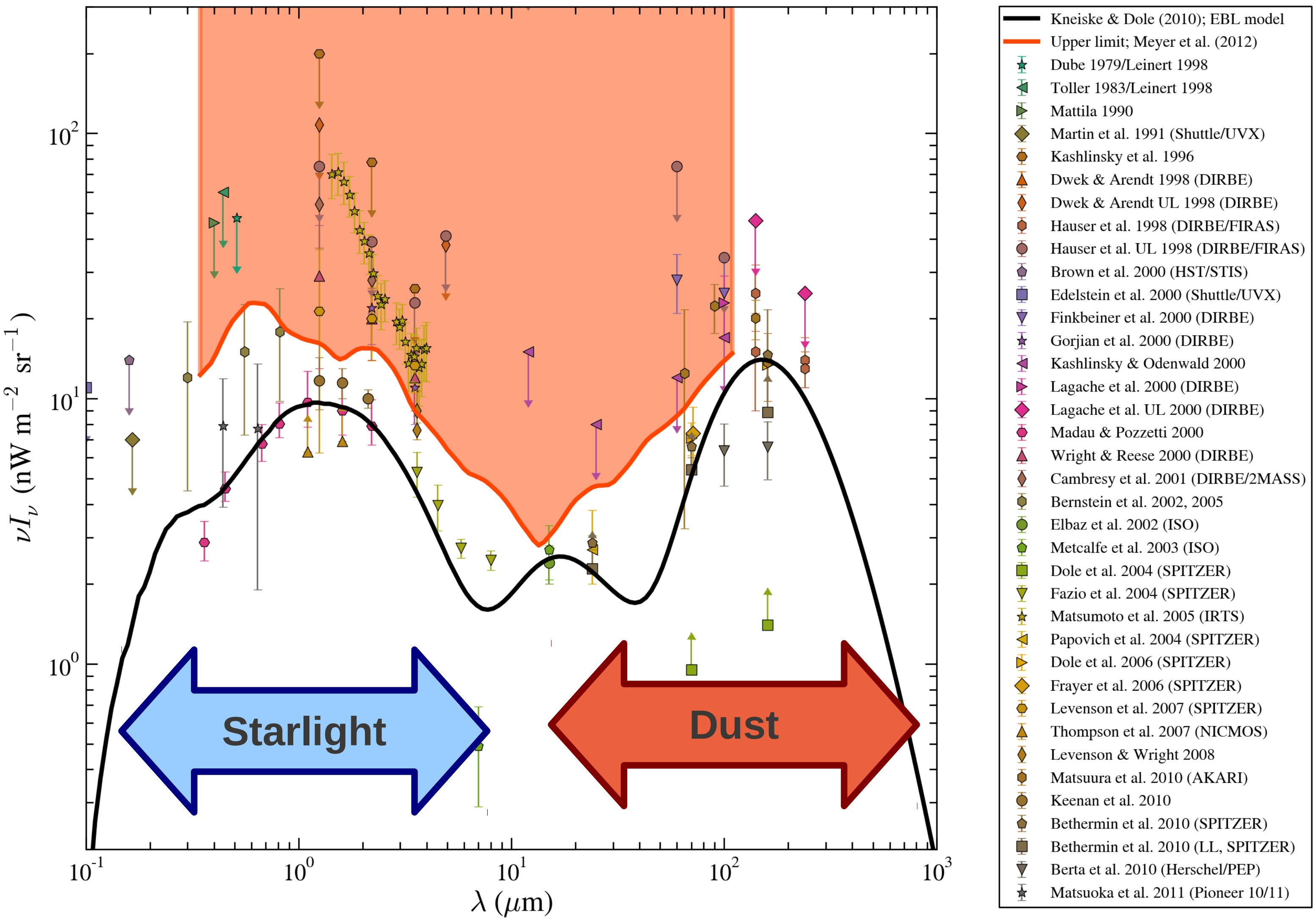


$$\mathrm{VHE}: E \gtrsim 100\ \mathrm{GeV}$$

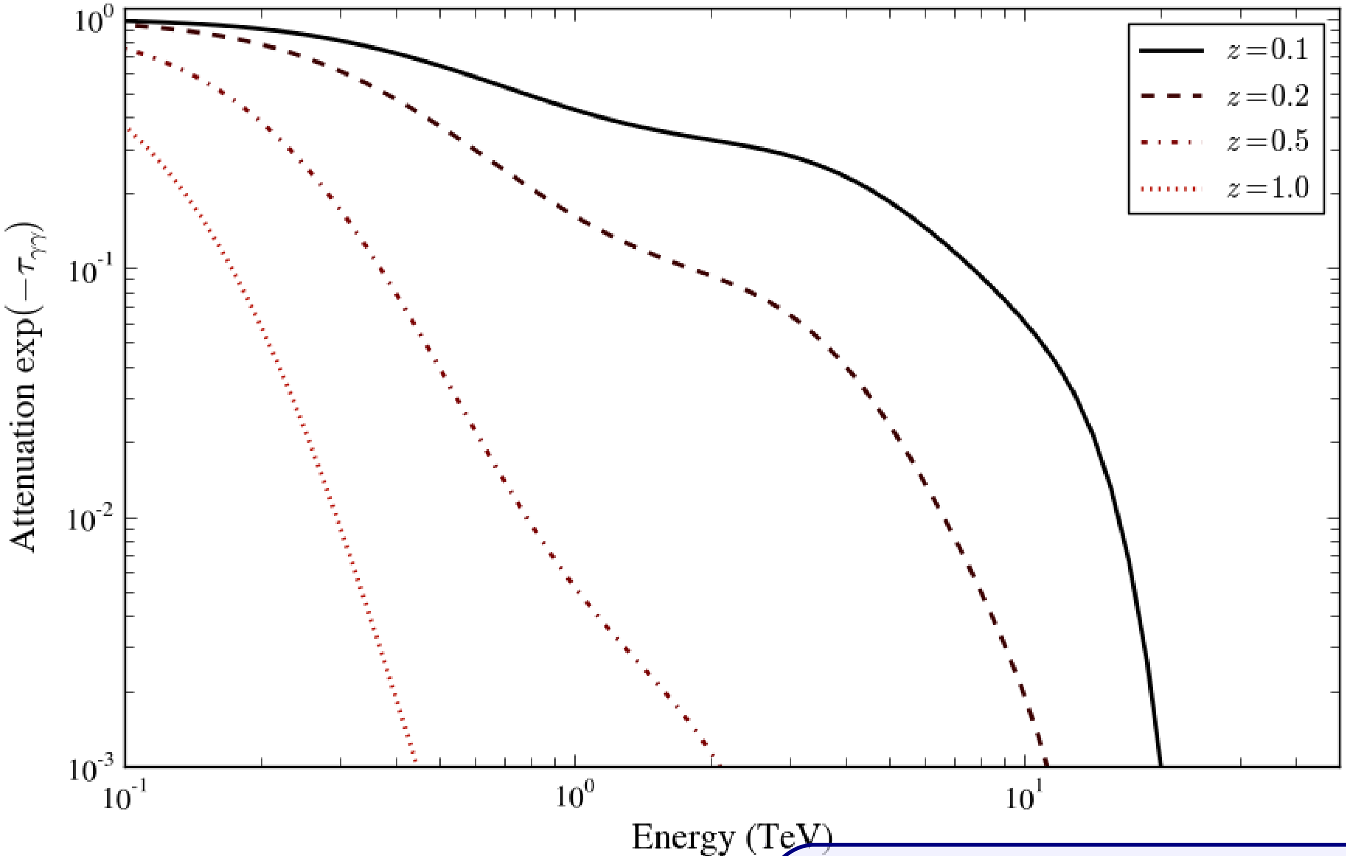
Extragalactic Background Light (EBL)

- Diffuse isotropic radiation field
- Originates from **starlight** integrated over all epochs and starlight **reprocessed by dust**
- Difficult to observe directly due to foreground contamination
- **EBL most important for attenuation of γ-rays** due to pair production cross section $\sigma_{\gamma\gamma}$
- For a γ-ray of energy E, $\sigma_{\gamma\gamma}$ peaks at a wavelength

$$\lambda_* \approx 1.24 \left(\frac{E}{\mathrm{TeV}} \right)$$



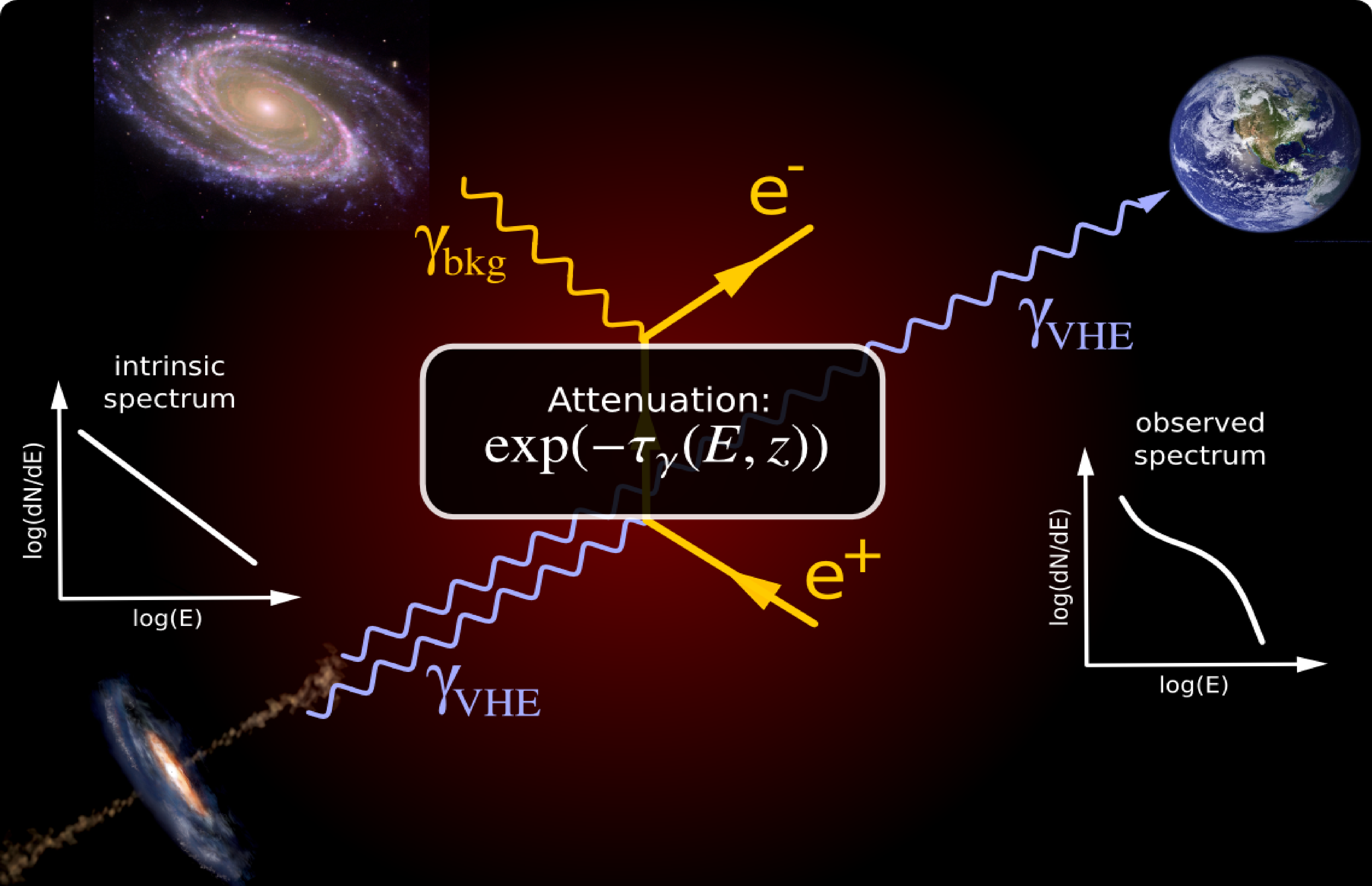
Attenuation of VHE gamma rays

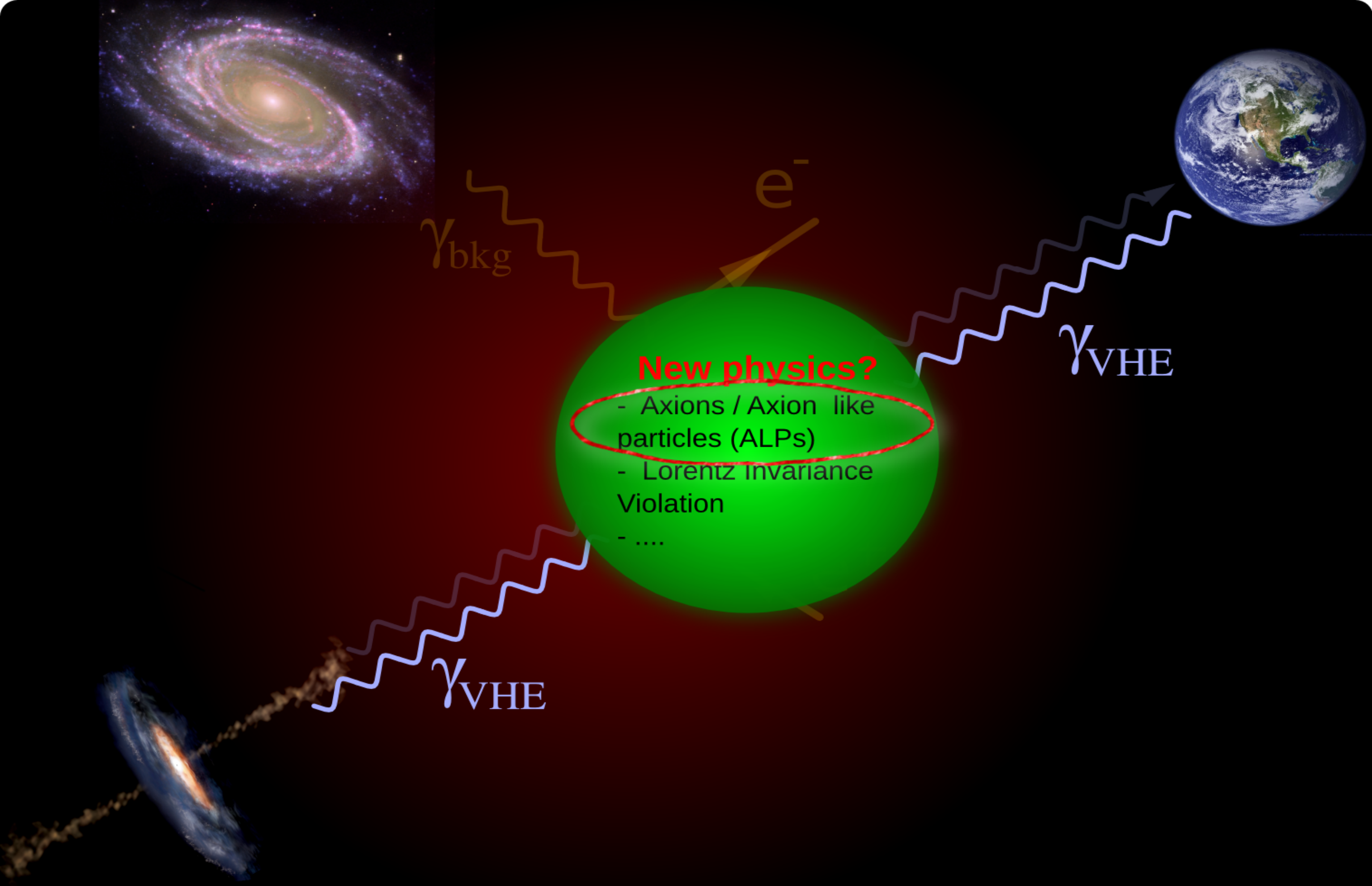


$$\frac{\mathrm{d}N_{\mathrm{obs}}}{\mathrm{d}E} = \frac{\mathrm{d}N_{\mathrm{int}}}{\mathrm{d}E} \times \exp\left[-\tau_{\gamma\gamma}(E, z)\right]$$

Observed spectrum — **Intrinsic spectrum** — **Attenuation due to interaction with EBL photons**

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

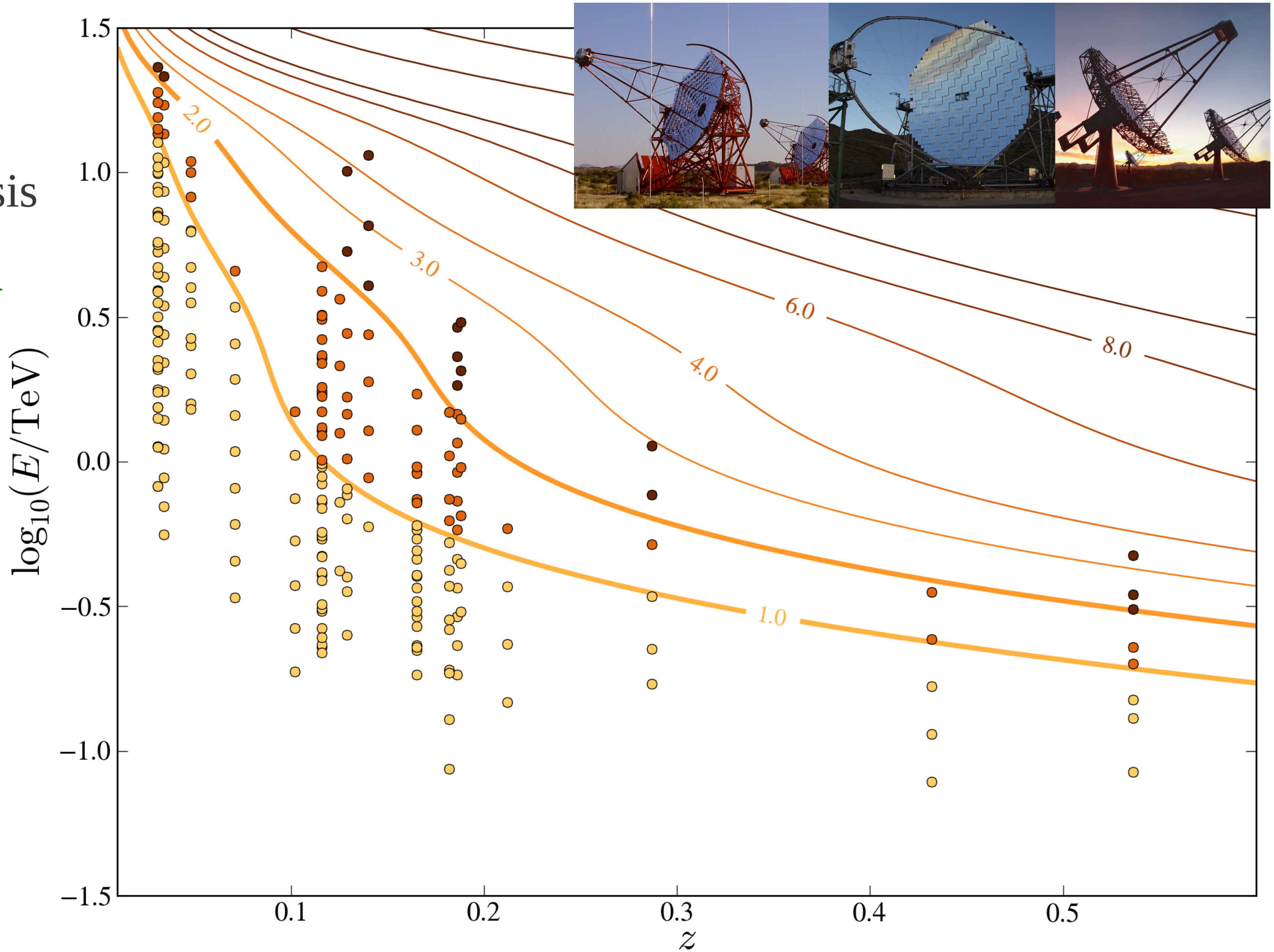

γ_{bkg}
e^-
γ_{VHE}
intrinsic spectrum
log(dN/dE)
log(E)
Attenuation:
$\exp(-\tau_\gamma(E,z))$
e^+
γ_{VHE}
observed spectrum
log(dN/dE)
log(E)



γ_{bkg}
e^-
New physics?
- Axions / Axion like particles (ALPs)
- Lorentz invariance Violation
- ....
γ_{VHE}
γ_{VHE}

Statistical analysis of VHE spectra

- Features expected to be small → statistical analysis
- In total: **50 AGN spectra**
- **28** spectra with **1 ≤ τ < 2** (*optically thin sample*)
- **9** spectra with **2 ≤ τ** (*optically thick sample*)



[Dieter Horns & MM, *JCAP* (2012), vol. 02 pp 33, arXiv: 1201.4711]

Compare distributions of ratios

- Fit data **up to τ < 1**
- Extrapolate fit
- Calculate ratio

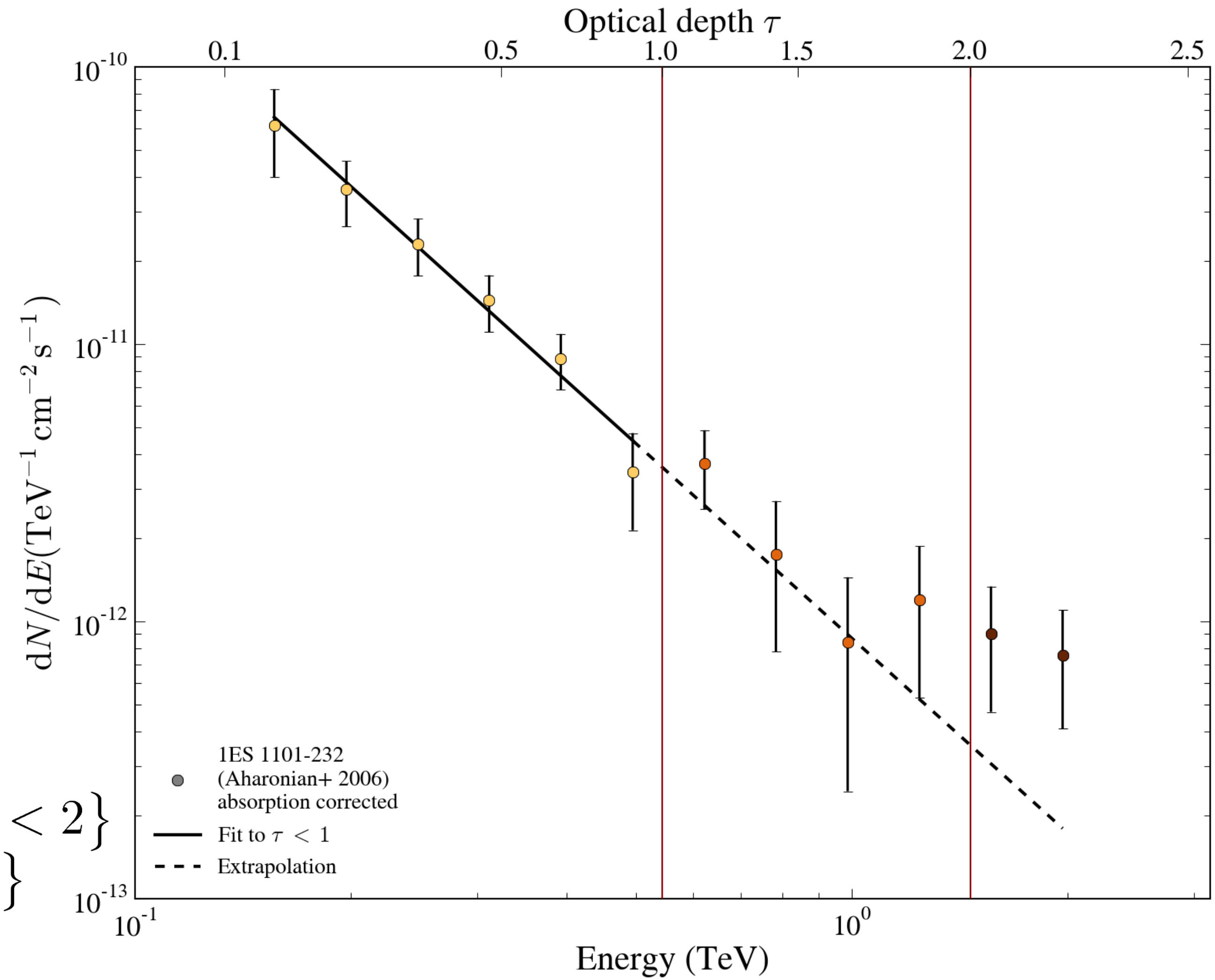
$$R_i = \frac{f_i^{\mathrm{int}} - f_i^{\mathrm{ext}}}{f_i^{\mathrm{int}} + f_i^{\mathrm{ext}}}$$

f_i^{int}: intrinsic flux

f_i^{ext}: extrapolated flux

- Compare distributions with **Kolmogorov-Smirnov** (KS) test

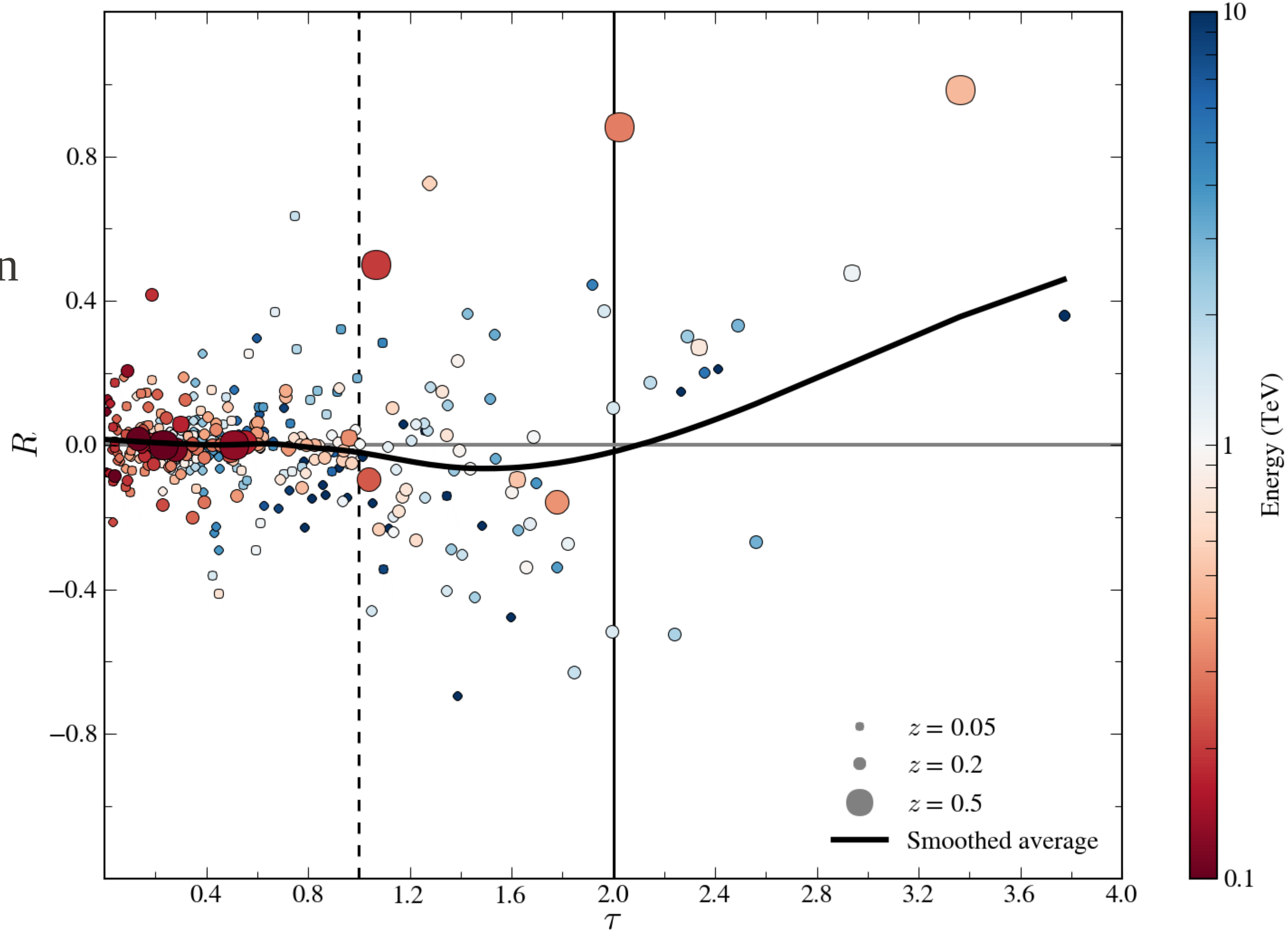
$$\mathcal{S}_{\mathrm{thin}} = \{R_i^{\mathrm{int}} | 1 \leq \tau_\gamma(E_i, z) < 2\}$$
$$\mathcal{S}_{\mathrm{thick}} = \{R_j^{\mathrm{int}} | 2 \leq \tau_\gamma(E_j, z)\}$$



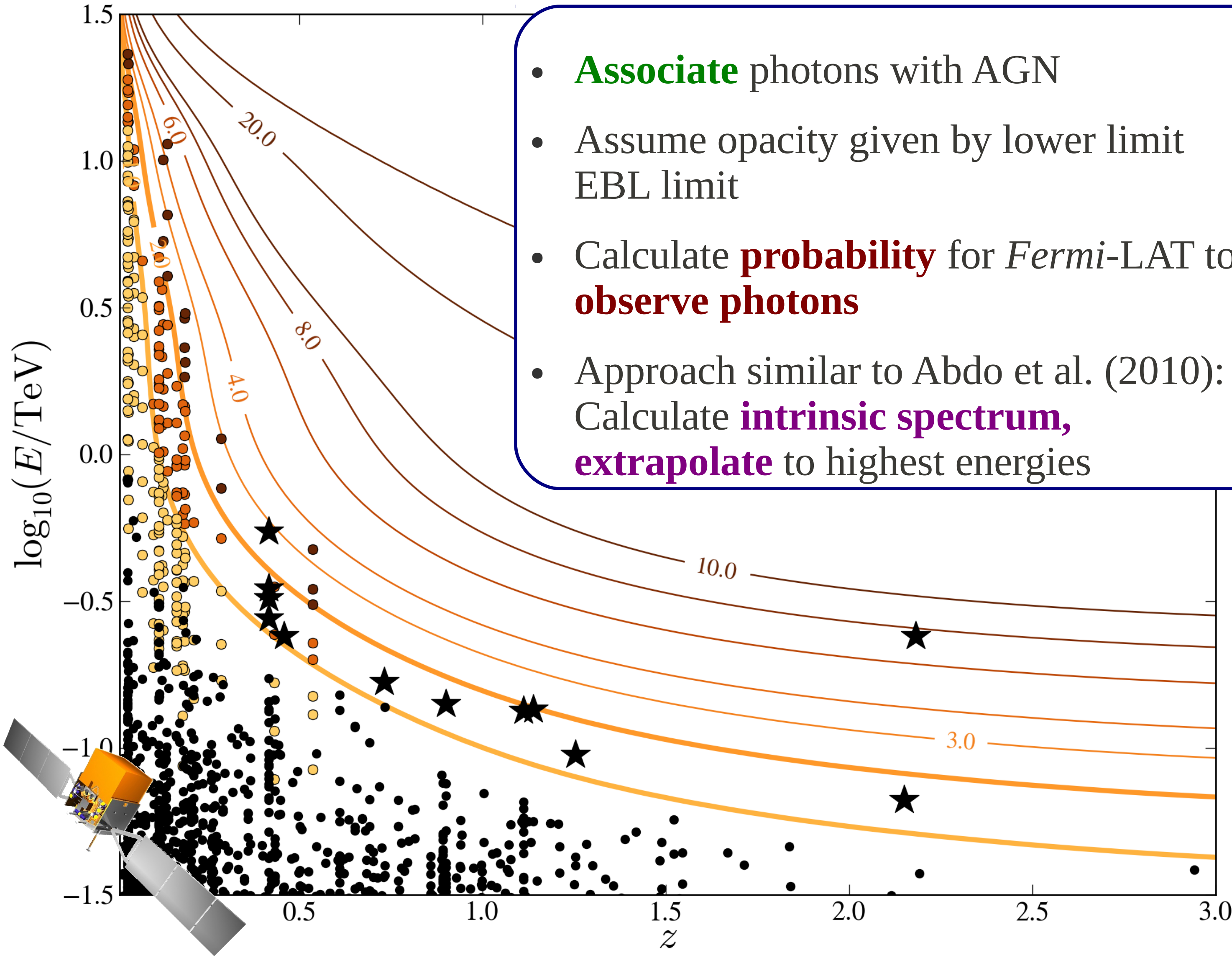
Compare distributions of ratios

- Samples **not drawn** from same underlying probability distribution files with probability ***P* = 4.2σ**
- Systematics checked:
  - excluded individual spectra
  - excluded highest energy spectral point
  - shift of 15% in energy

  cannot account for effect



Opacity with the *Fermi* - LAT



- **Associate** photons with AGN
- Assume opacity given by lower limit EBL limit
- Calculate **probability** for *Fermi*-LAT to **observe photons**
- Approach similar to Abdo et al. (2010): Calculate **intrinsic spectrum, extrapolate** to highest energies

Calculating the expected number of photons

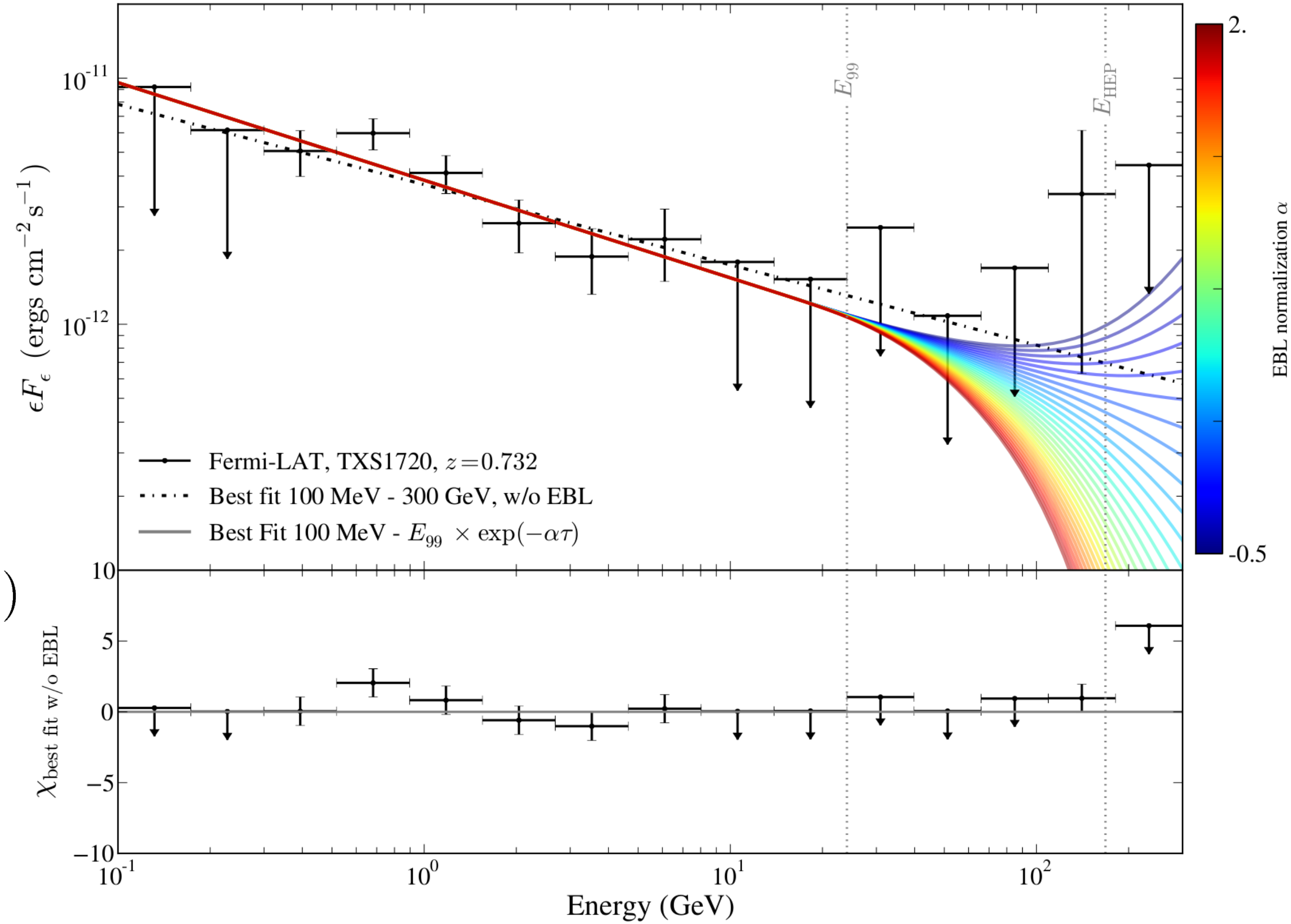
- **Fit analytical function to** spectrum up to energy E_{99}

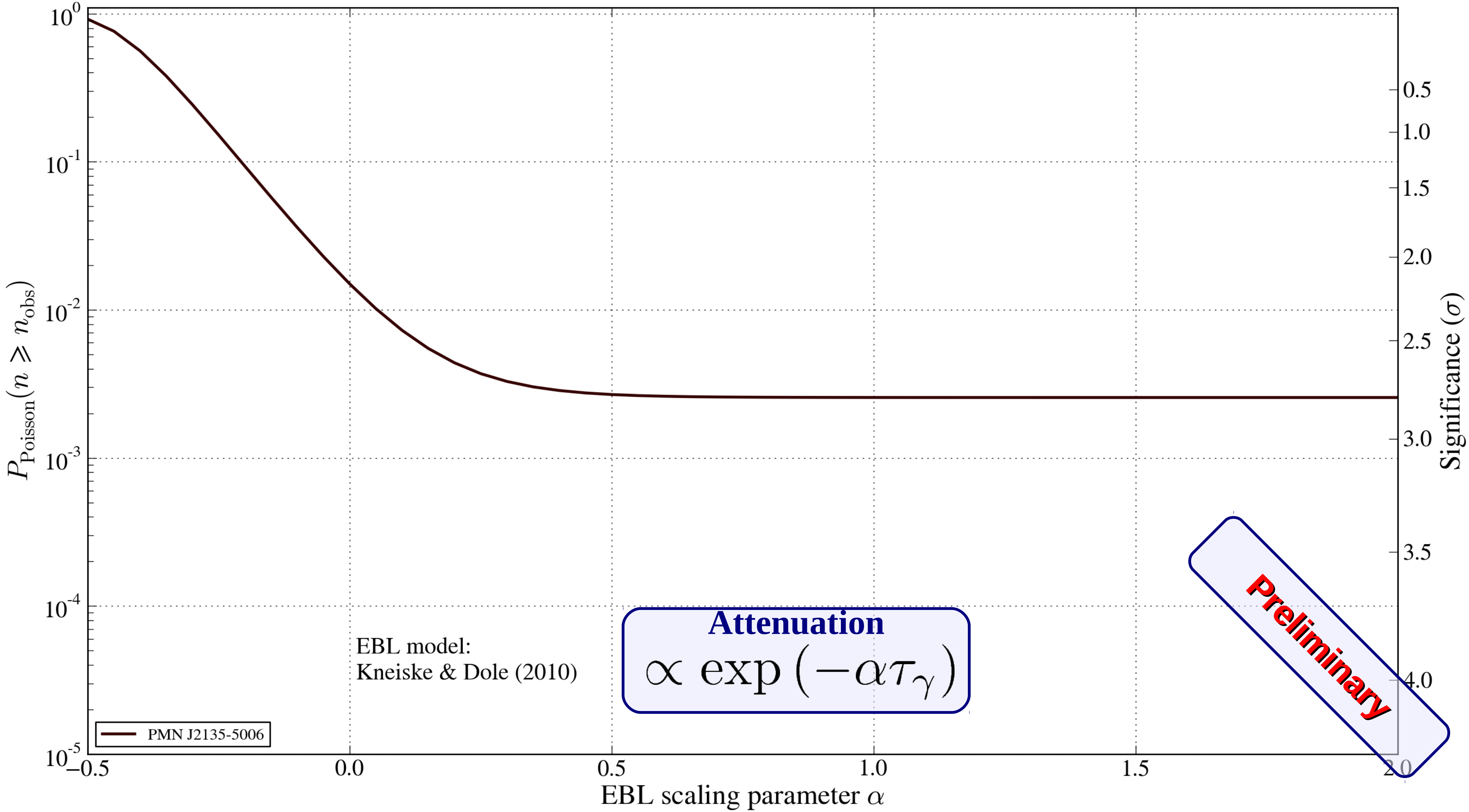
$$\exp\left(-\tau(z, E_{99})\right) = 0.99$$

- **Extrapolate spectrum to higher energies and multiply with absorption** as predicted by EBL models

$$f(E) = \exp\left(-\alpha\tau\right) \times f_{\rm int}(E)$$

- Calculate **expected number of photons** $\boldsymbol{\lambda_{\rm pred}}$ above $E_{\rm HEP}$

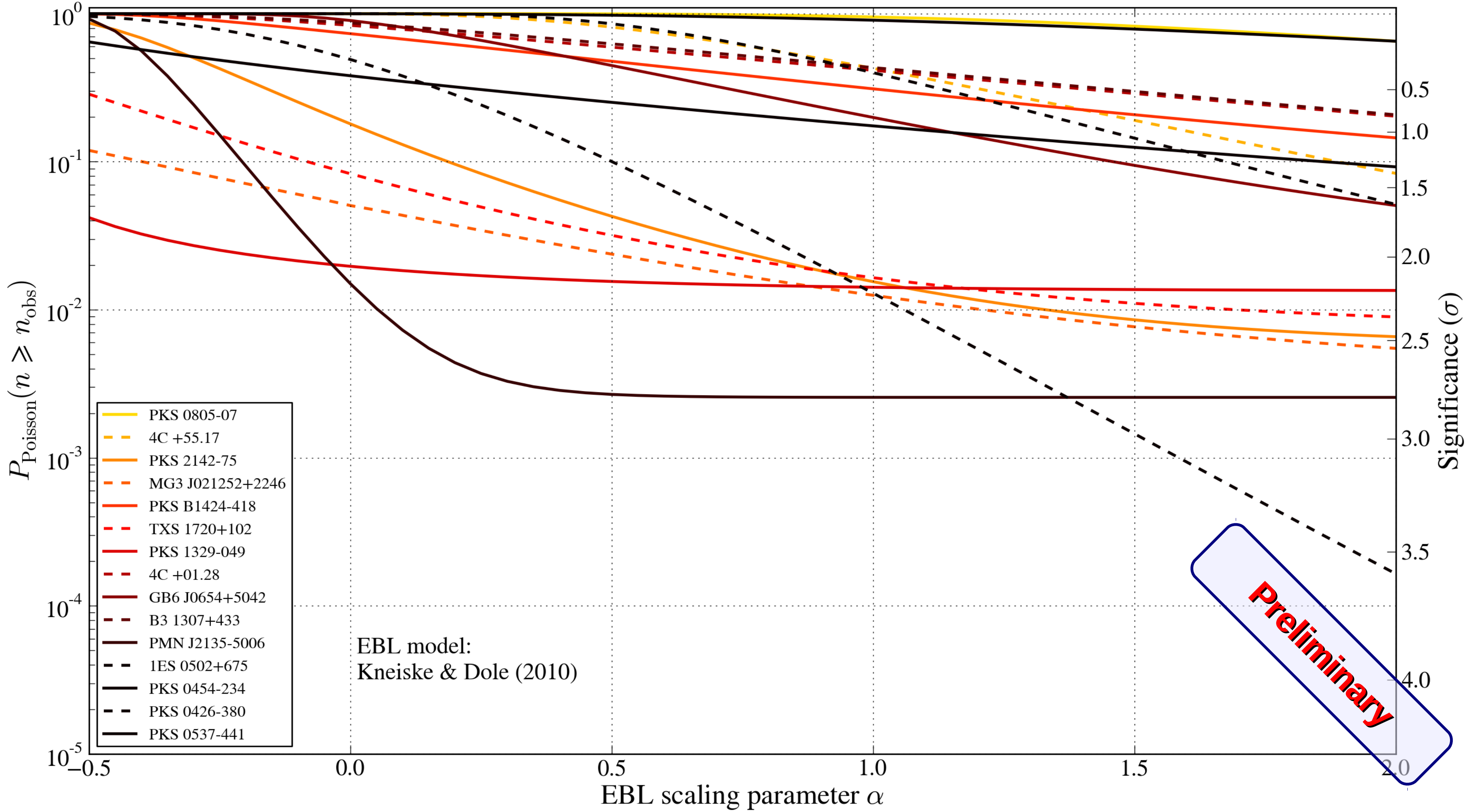




$$P_{\rm Poisson}(n \geqslant n_{\rm obs}) = \sum_{k=n_{\rm obs}}^{\infty} \frac{(\lambda_{\rm pred} + \lambda_{\rm bkg})^k}{k!} \exp\left(-(\lambda_{\rm pred} + \lambda_{\rm bkg})\right)$$

$\lambda_{\rm pred}$: Predicted # of source photons

$\lambda_{\rm bkg}$: Predicted # of bkg photons



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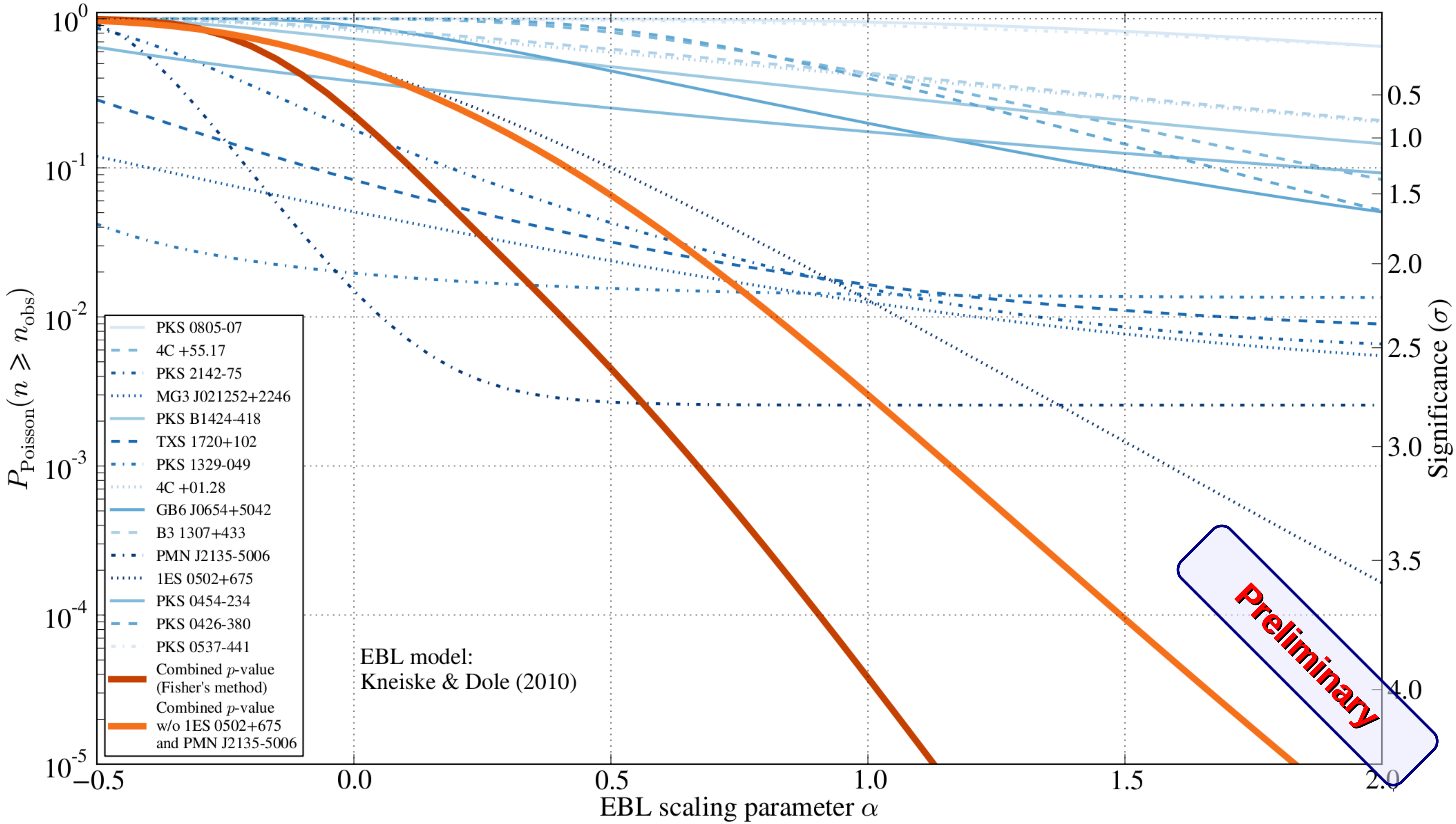

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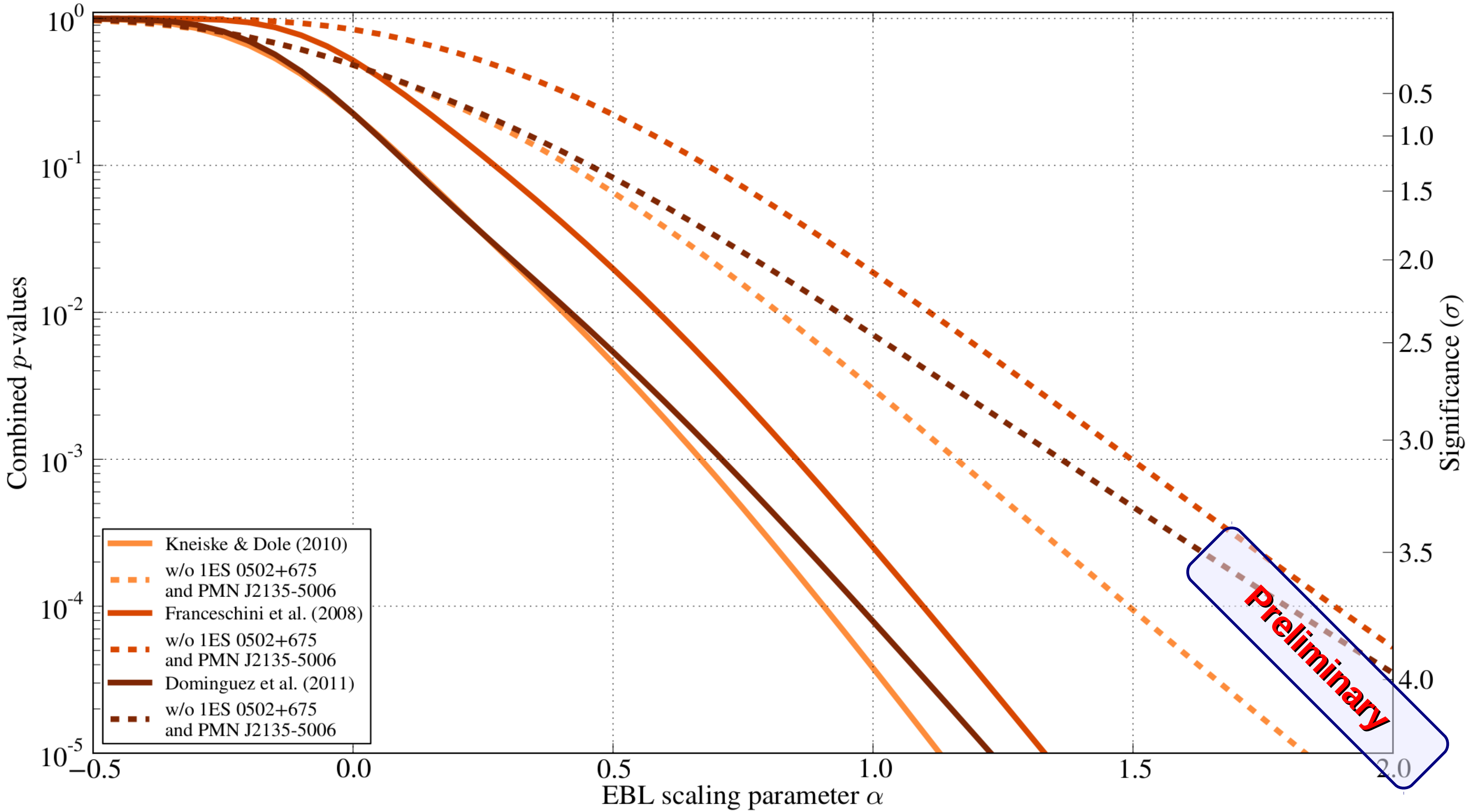

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Summary: Indications of a transparent Universe

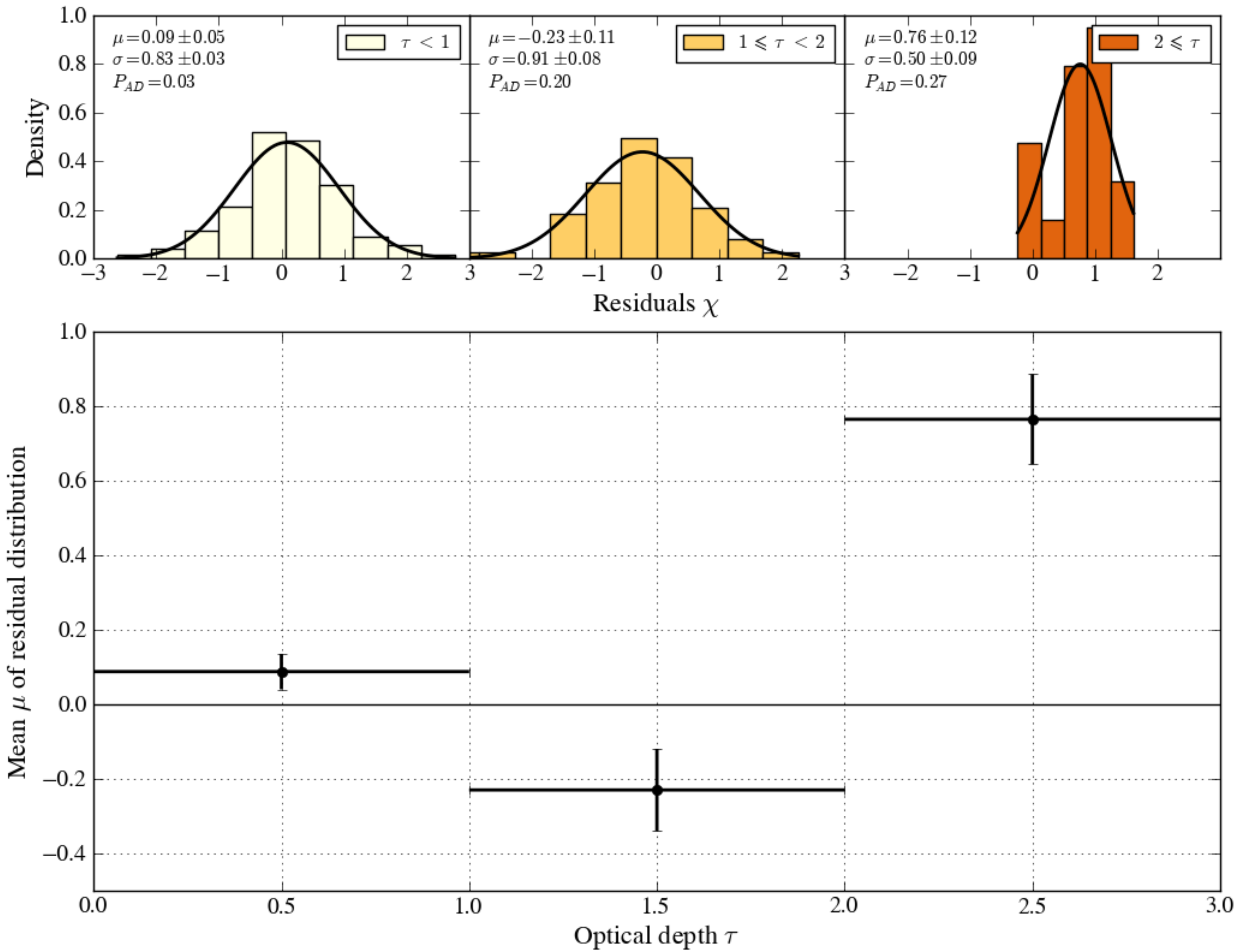
- Current VHE data indicate that lower limit EBL model leads to **over-correction of spectra for large values of τ** with more than **4σ**
- ***Fermi*-LAT data** show discrepancy between data and EBL models at ~ **3σ – 4σ level**
- More **high-τ observations necessary** (nearby sources at several tens of TeV, distant sources)
- Interpretation with ALP scenario? **ALPs would change opacity in a τ dependent way** (not the case for e.g. Lorentz Invariance violation)
- Other mechanism (e.g. formation of electro-magnetic cascade) can also affect the opacity [see e.g. Aharonian et al. (2012), arXiv:1206.6715]

Compare means of residual distributions

- **Fit entire data set** and calculate residuals

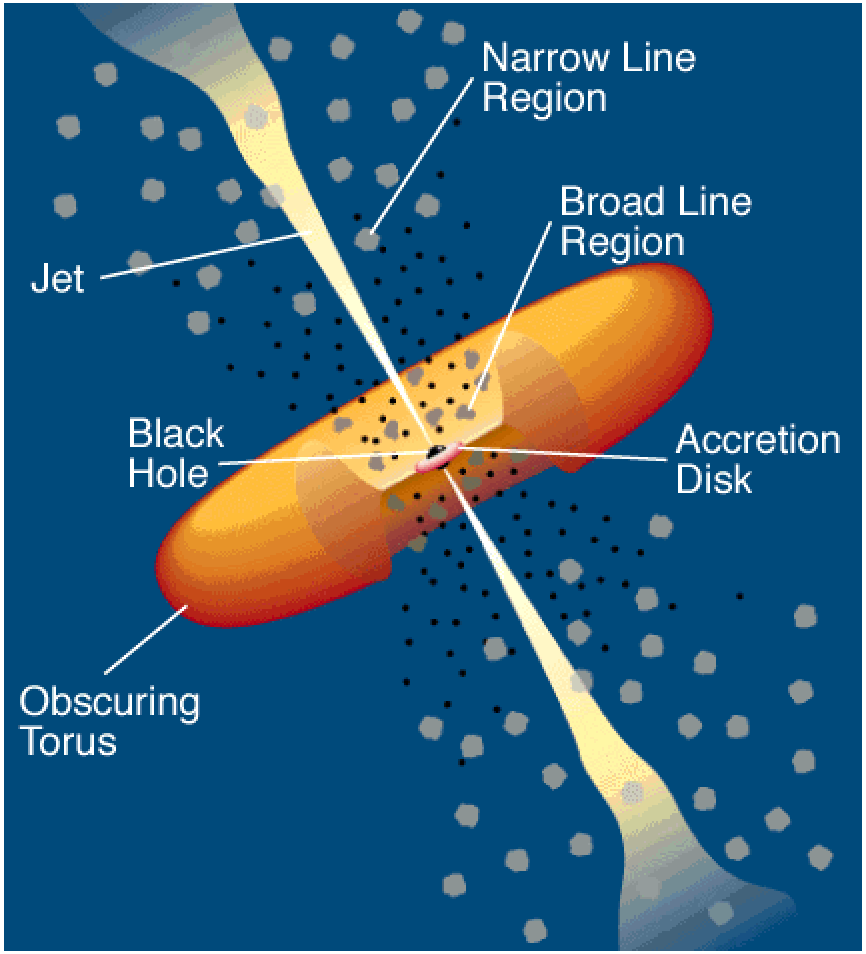
$$\chi_i = \frac{f_i^{\text{int}} - f^{\text{theo}}(E_i)}{\sigma_i}$$

- χ's **gaussian** distributed
- Mean value of (2 ≤ τ)-distribution **not compatible with 0 with more than 4σ**



Active galactic nuclei as γ-ray sources

- Center of active galactic nuclei (AGN): **super-massive black hole with accretion disk**
- γ-ray emission originates in **relativistic jets**
- ***Blazar*** := jet axis is aligned along l.o.s.



[Urry & Padovani (1995)]

Spectral energy distributions of blazars

- **Blazar sequence:** correlation between peak frequency and luminosity → observational bias
- Large scatter of measured photon indices
- **Selectional bias**: mostly high frequency synchrotron peaked blazars observed at VHE
- At VHE energies: due absorption **impossible to measure intrinsic spectrum** directly