The Extragalactic Background Light, Gamma-Ray Observations, and Cosmology

SCIPP
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with thanks to
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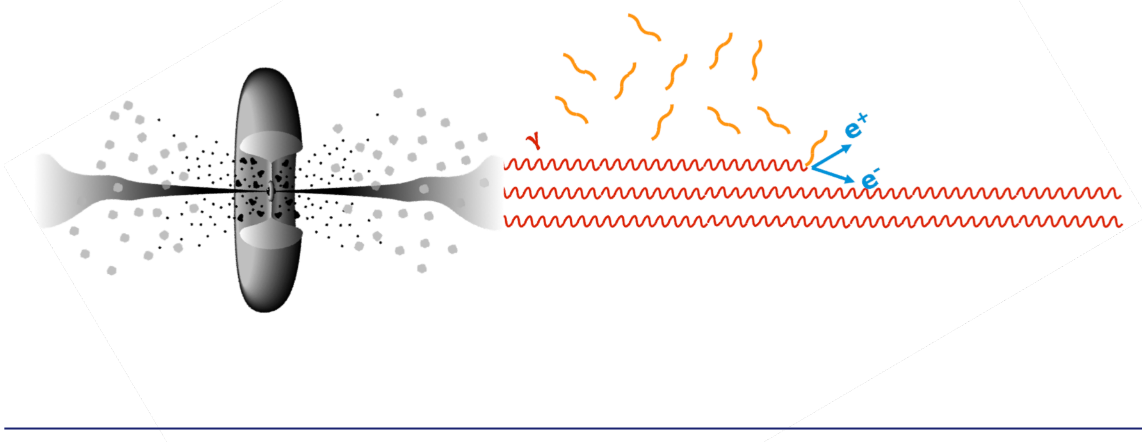
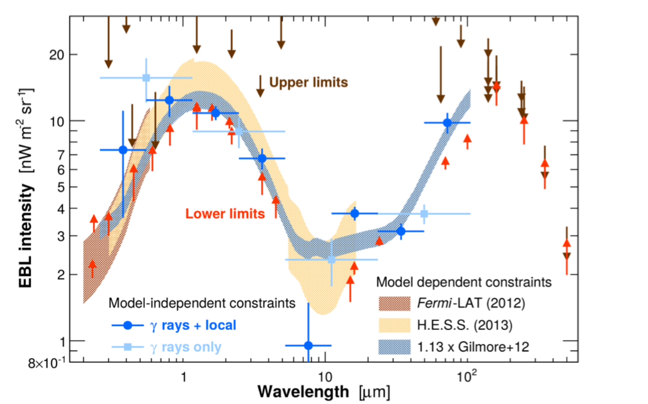
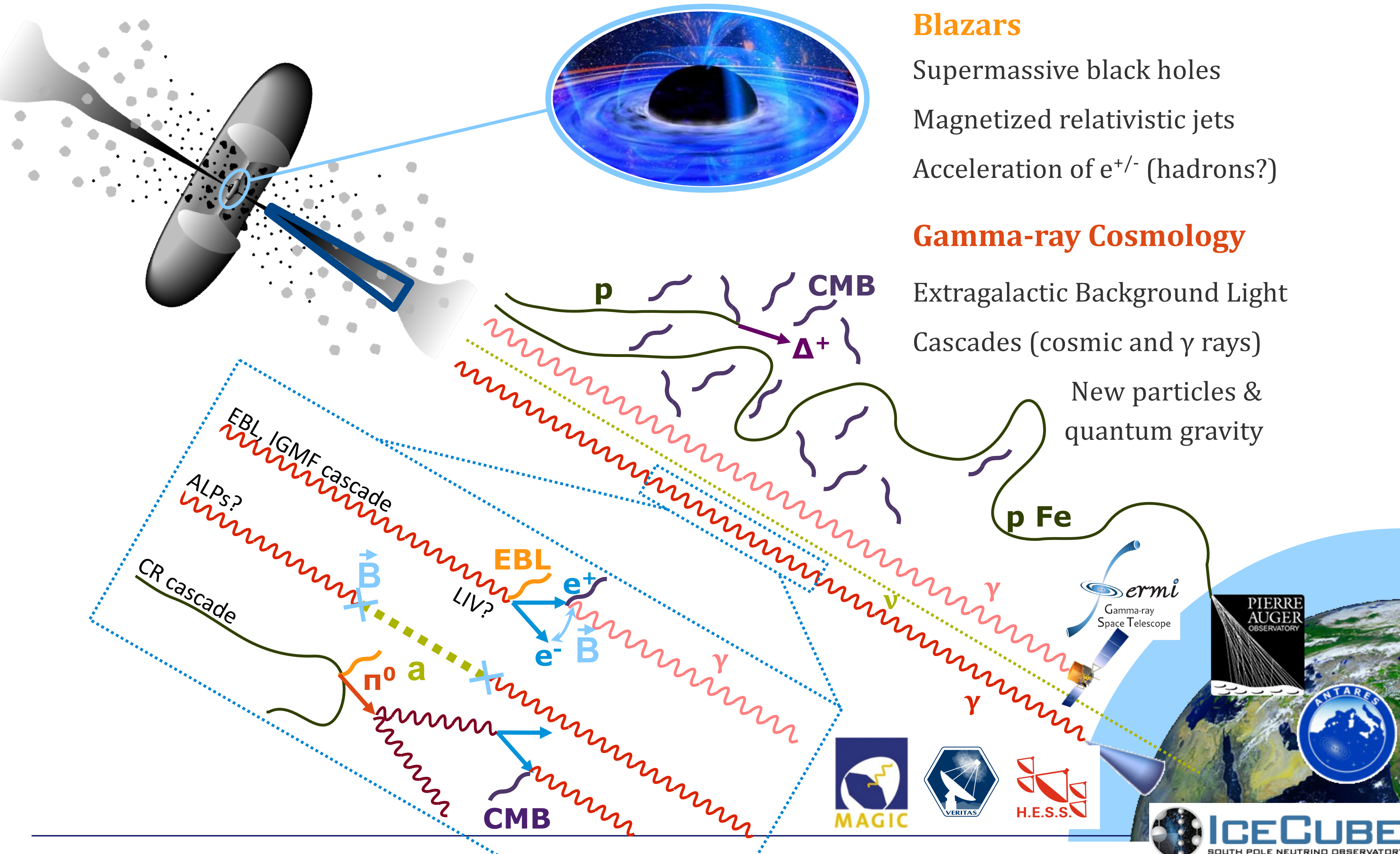




Observing the Extreme Universe with Blazars



Blazars

Supermassive black holes

Magnetized relativistic jets

Acceleration of $e^{+/-}$ (hadrons?)

Gamma-ray Cosmology

Extragalactic Background Light

Cascades (cosmic and γ rays)

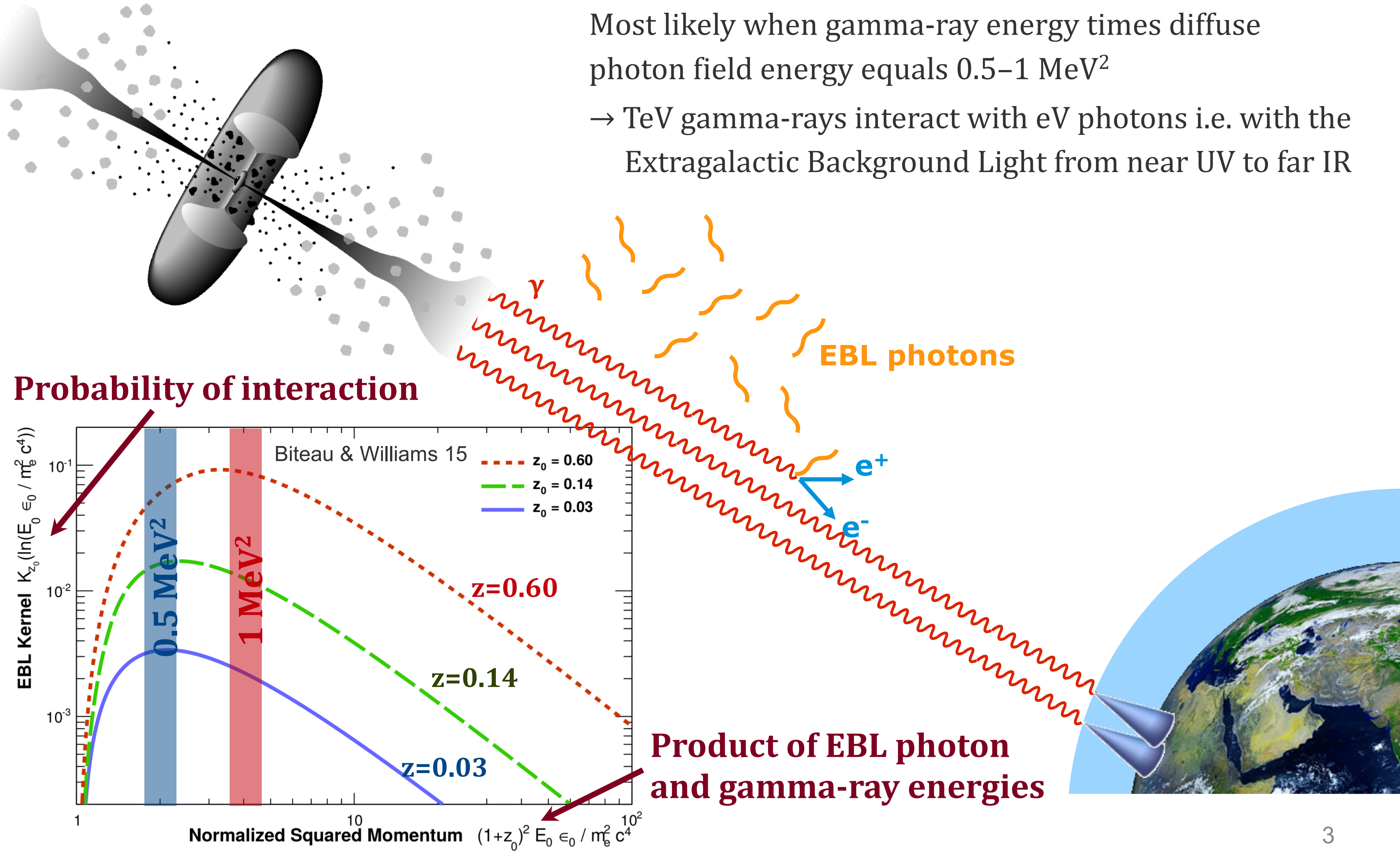
New particles & quantum gravity

Gamma-rays and the EBL

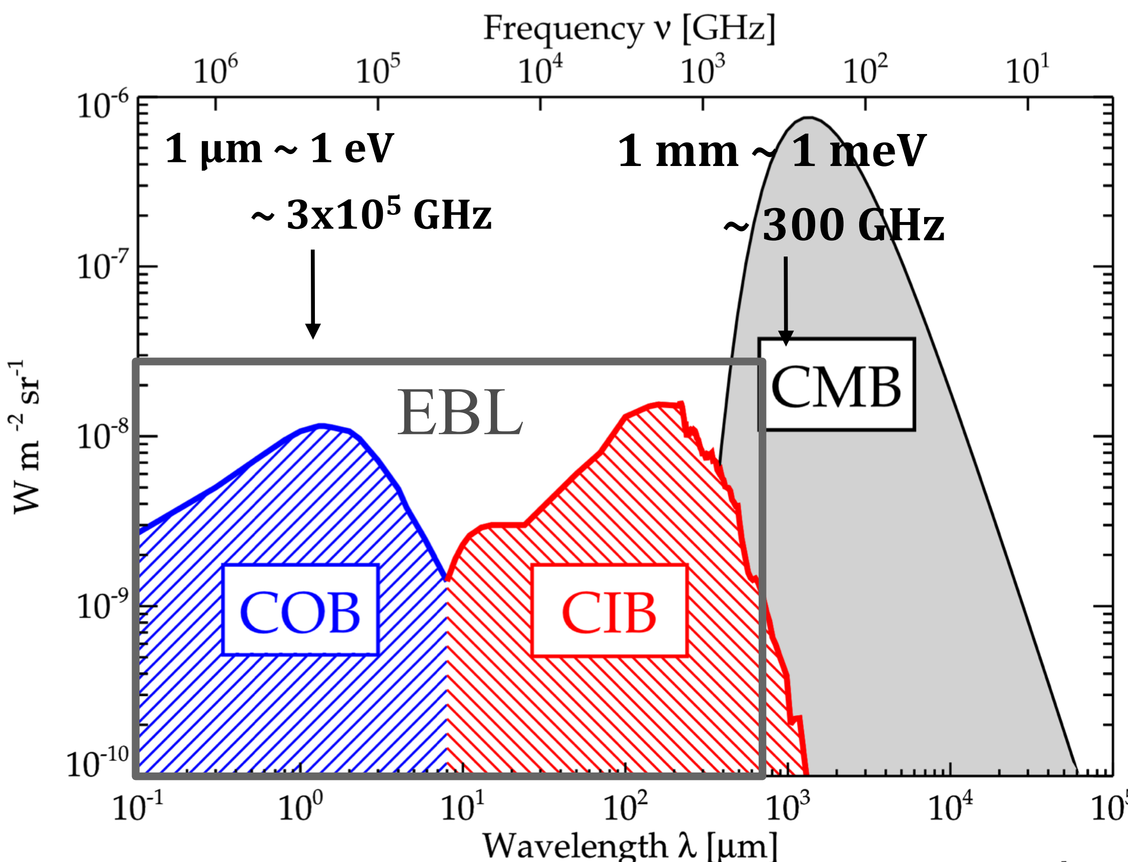
Pair creation along the line of sight

Most likely when gamma-ray energy times diffuse photon field energy equals 0.5–1 MeV^2

→ TeV gamma-rays interact with eV photons i.e. with the Extragalactic Background Light from near UV to far IR



The Extragalactic Background Light



Dole et al., A&A 451, 417 (2006)

Cosmic optical background (COB)

→ UV/O/NIR light from stars and galaxies

Cosmic infrared background (CIB)

→ UV/O light reprocessed by dust

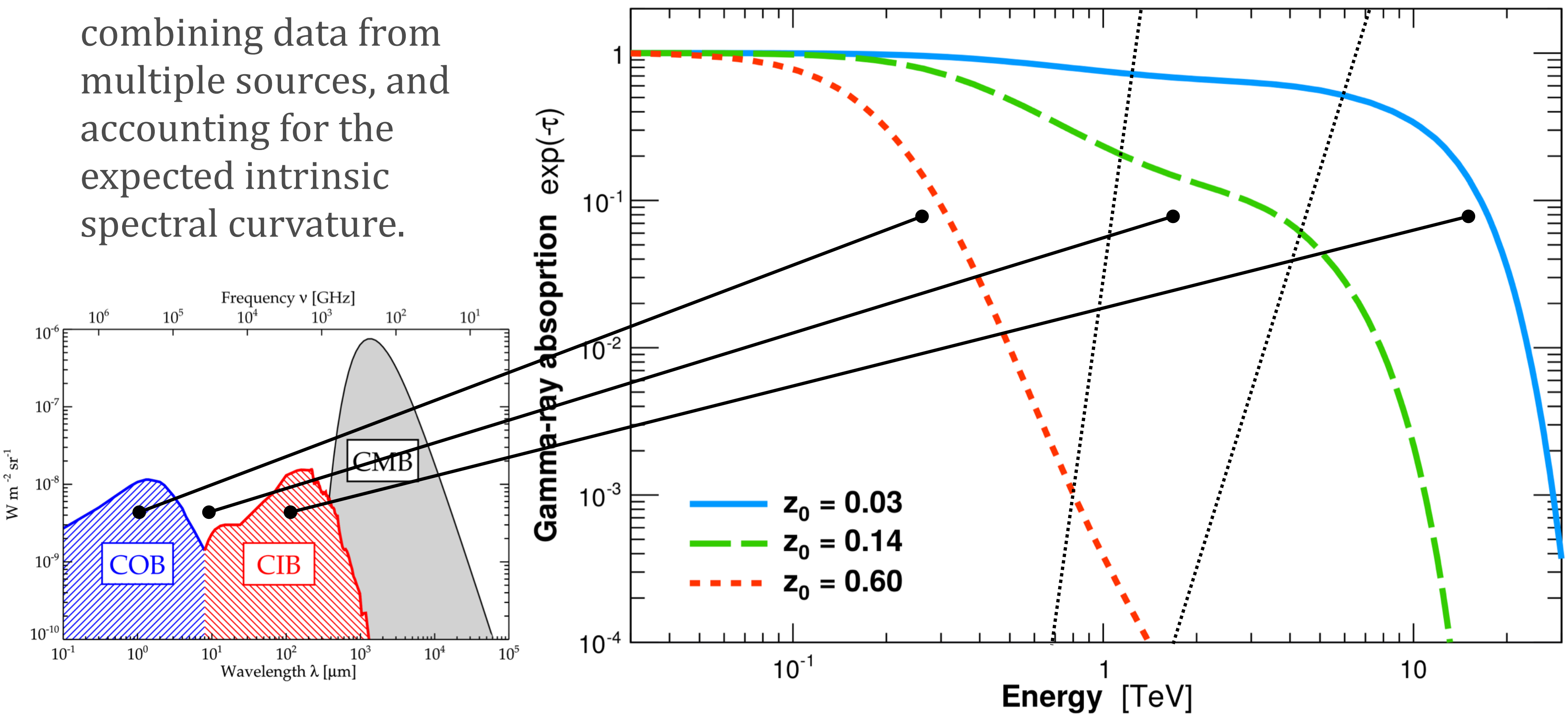
EBL Imprint on the γ-ray Spectrum

Gamma-ray disappearance imprints the spectra > 100 GeV

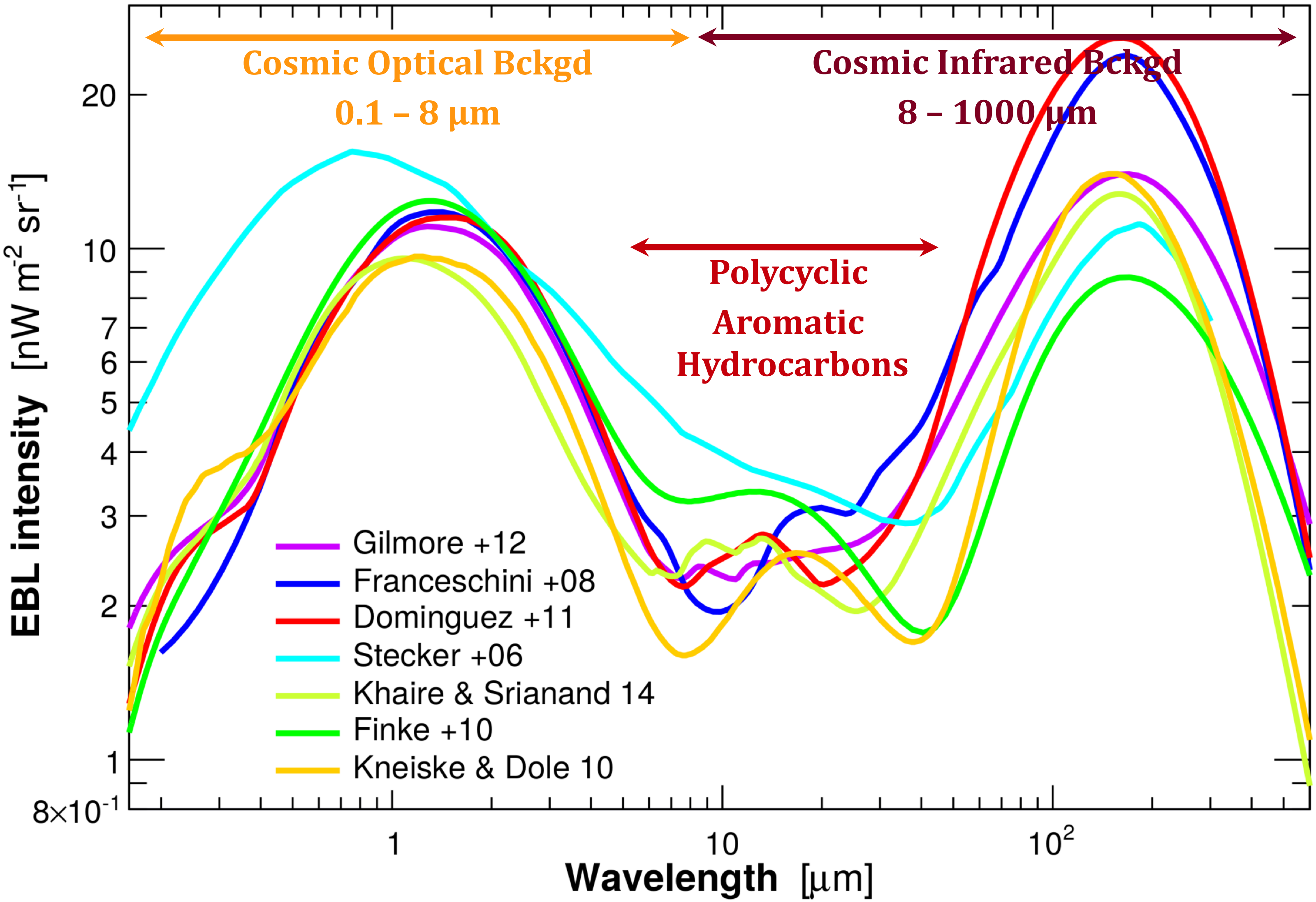
Near sources (z<0.05) mostly affected by the CIB

Far sources (z>0.3) mostly affected by the COB

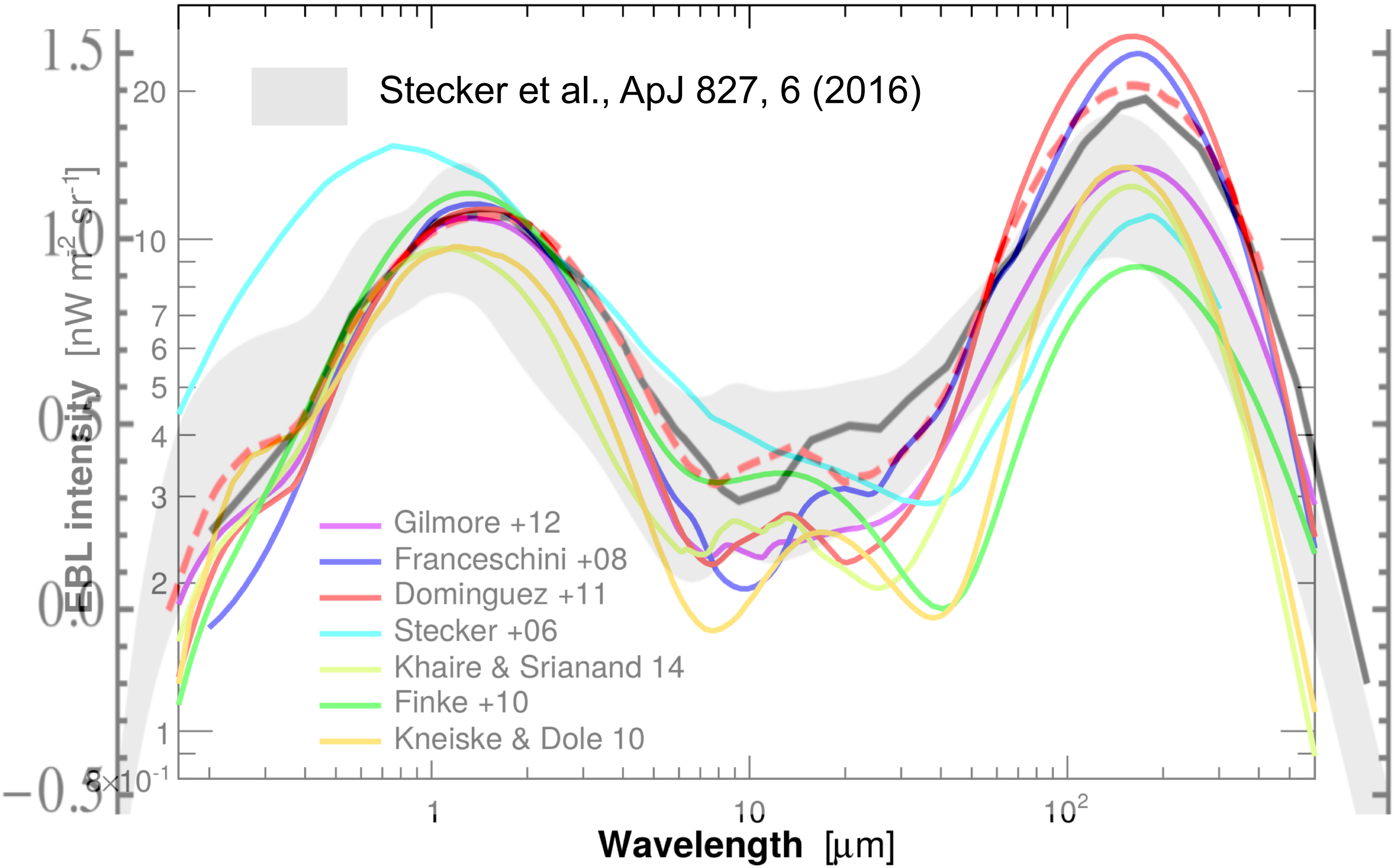
Specific imprint enabling a reconstruction of the EBL spectrum, combining data from multiple sources, and accounting for the expected intrinsic spectral curvature.



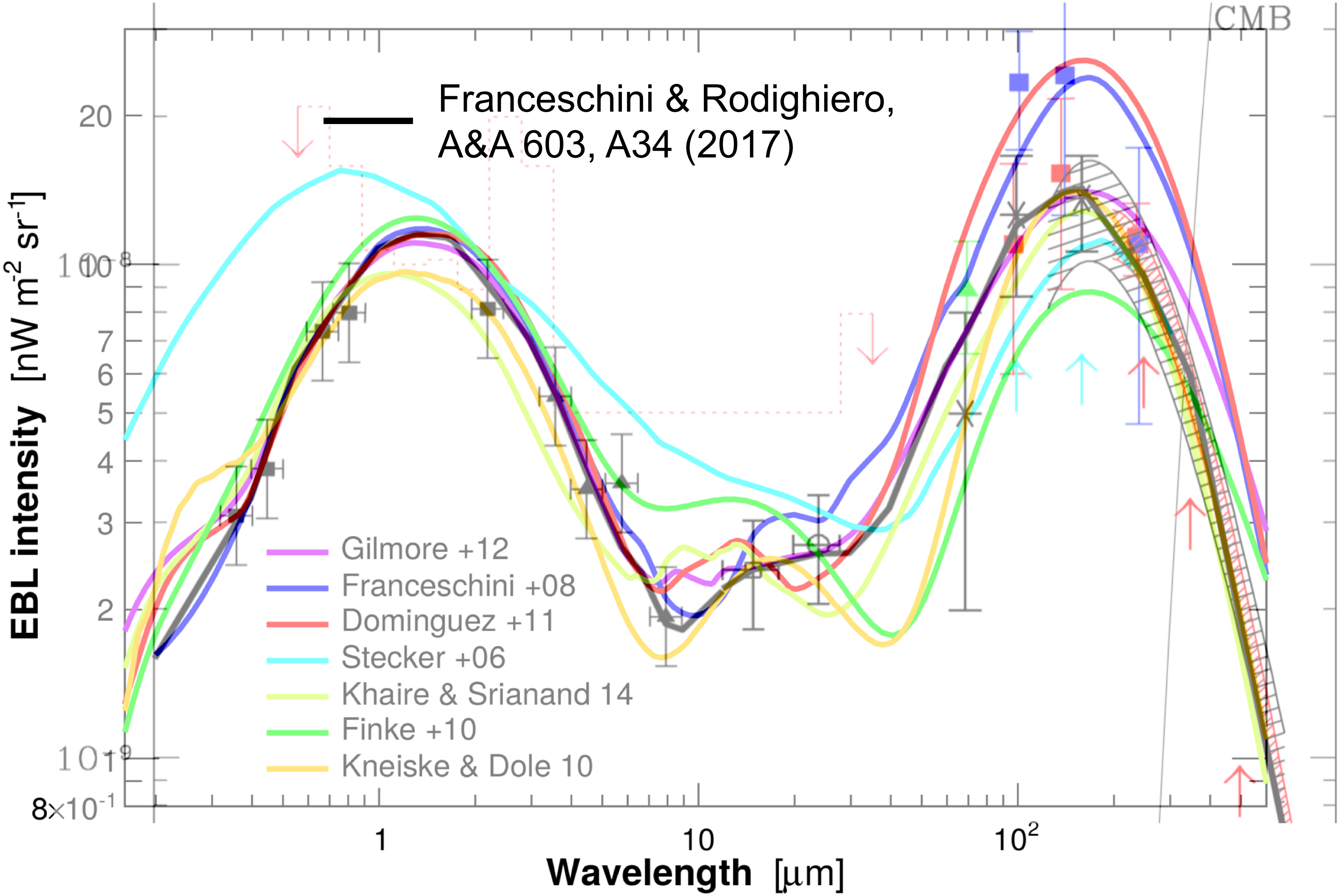
Models of the EBL



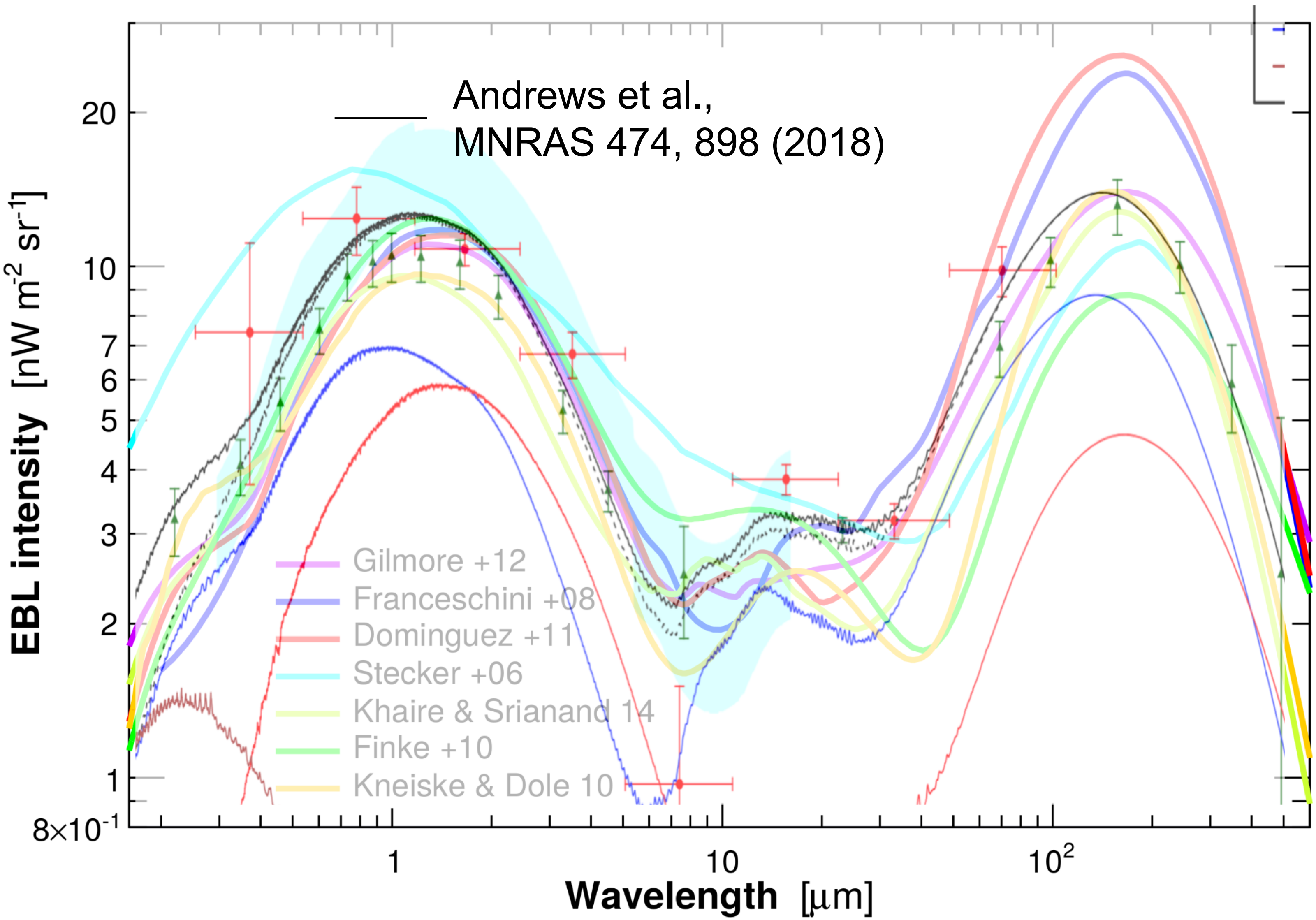
Models of the EBL – Stecker et al. Update



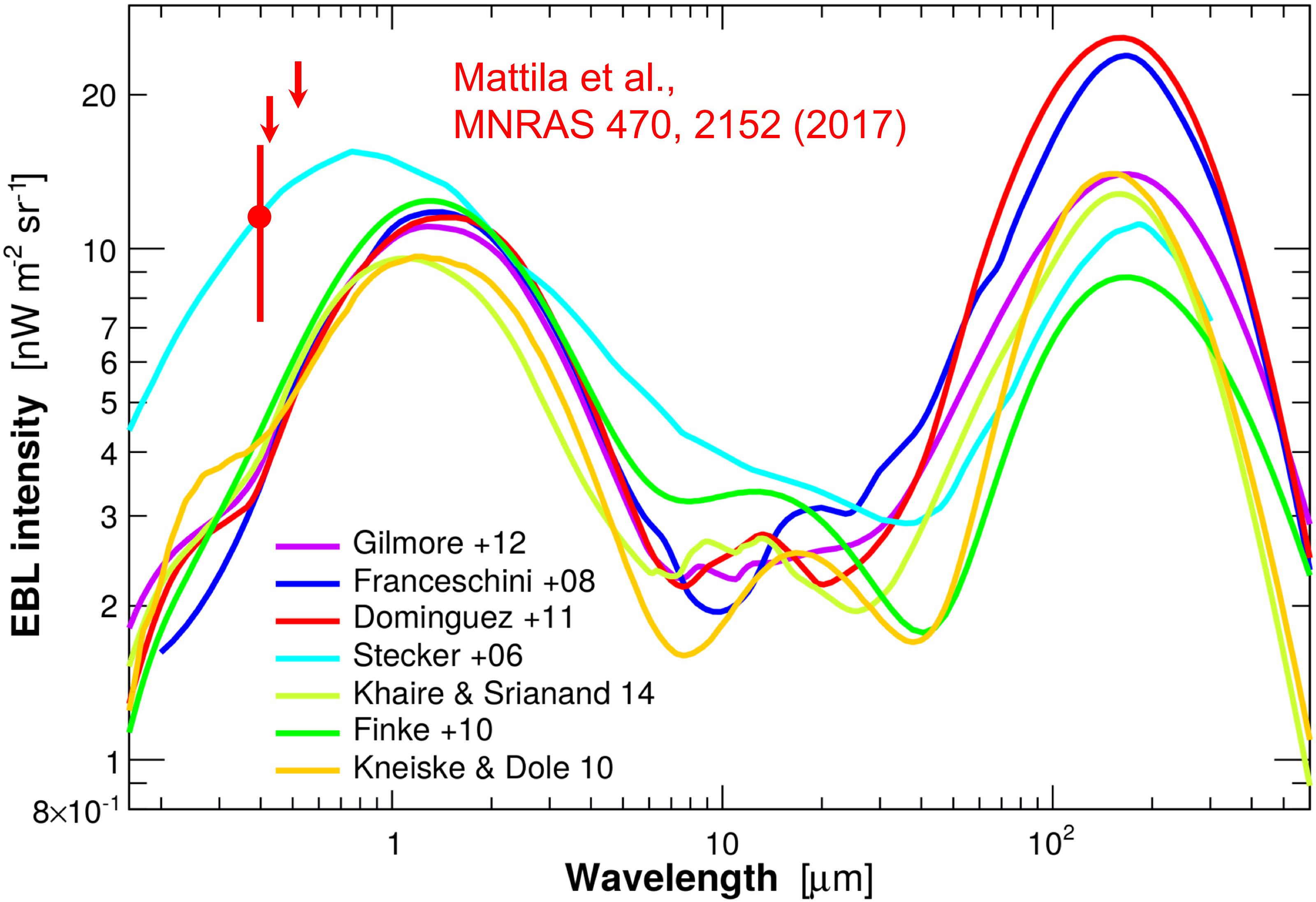
Models of the EBL – Franceschini et al. Update



Models of the EBL – New "forward-evolution" model



A New Direct EBL Measurement



Model Dependent Detection with VHE γ-rays

Gamma-ray constraints :

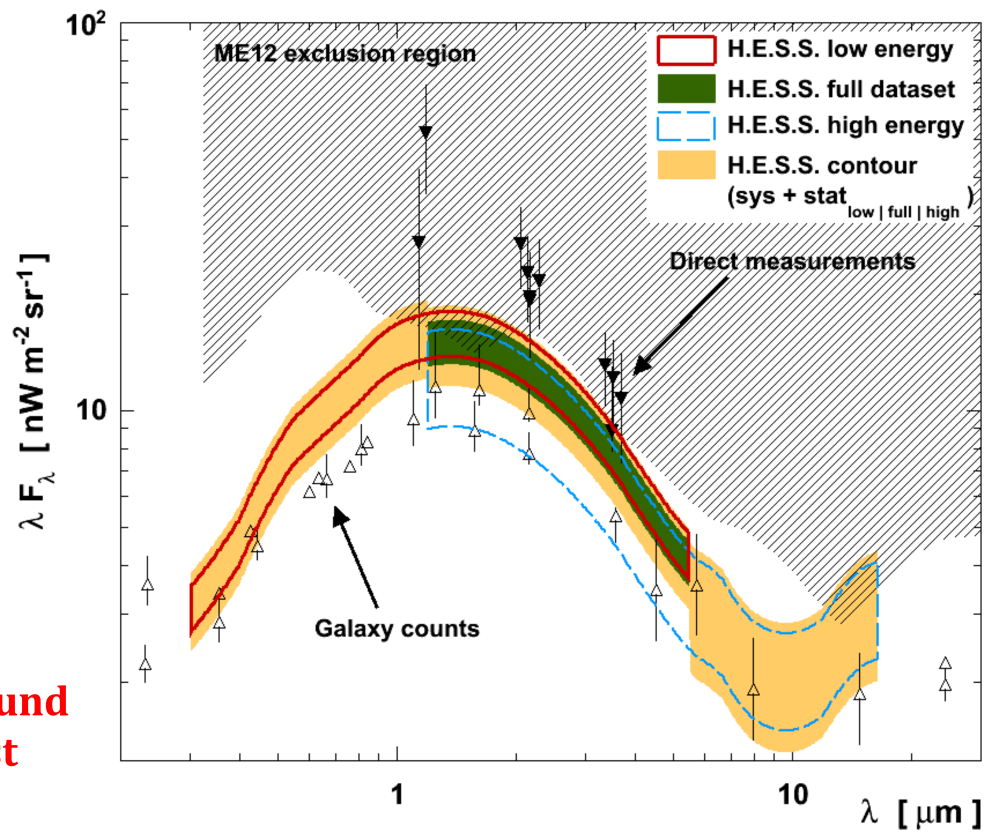
Prior to 2012 difficulty had been
disentangling intrinsic curvature from absorption by the EBL

By means of **hypothesis testing** and **accounting for intrinsic curvature**, model-dependent detections by Fermi-LAT (6σ) and **H.E.S.S. (9σ):**

Method:

Scale the optical depth (or EBL intensity) from a given model with a multiplicative factor + parametrize the intrinsic spectrum with a smooth concave function, as expected from radiative models.

Combine spectra from multiple sources

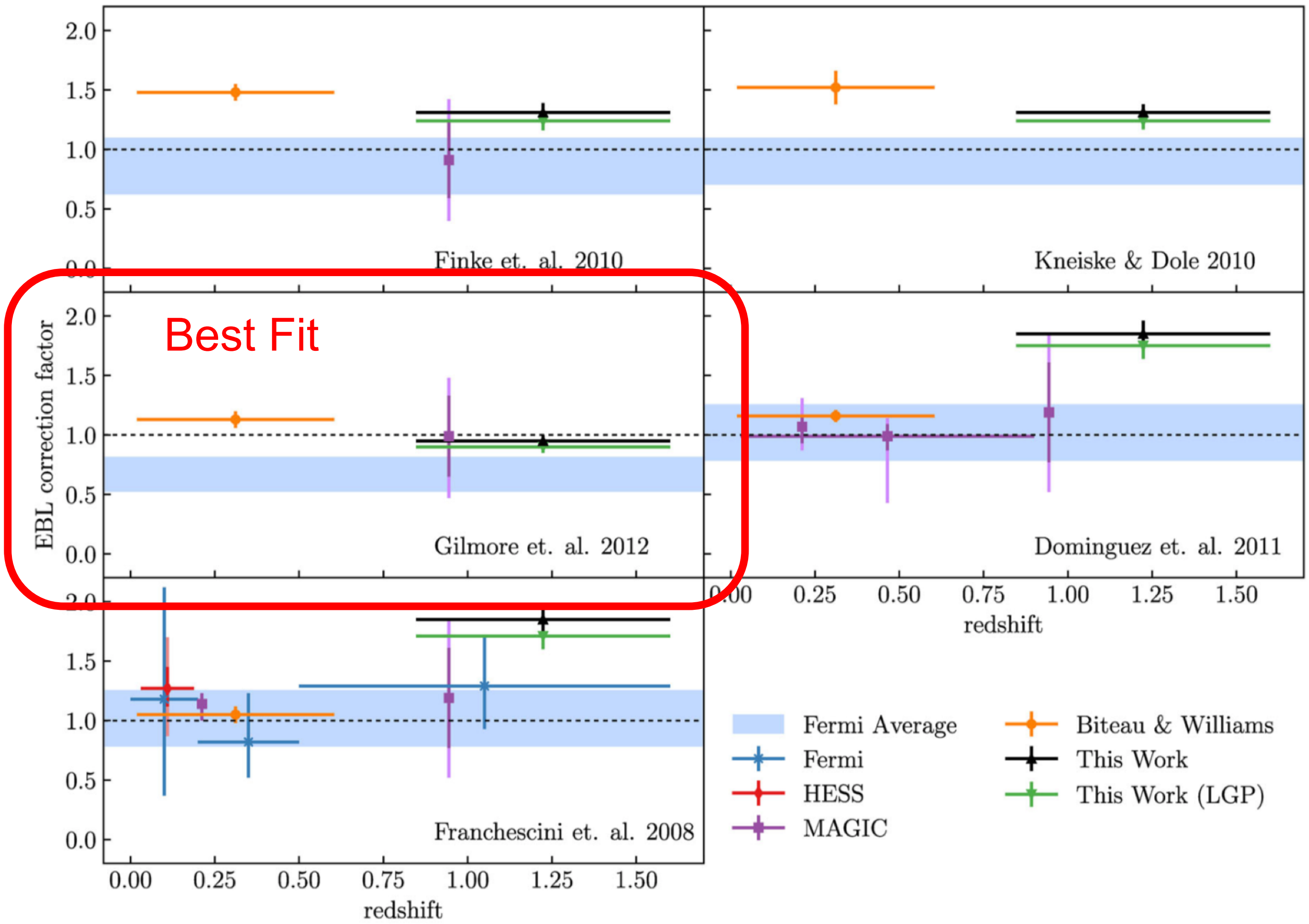


Measurement of the extragalactic background light imprint on the spectra of the brightest blazars observed with H.E.S.S.,
H.E.S.S., A&A 550, 4 (2013)

Model Dependent Detection with HE γ-rays

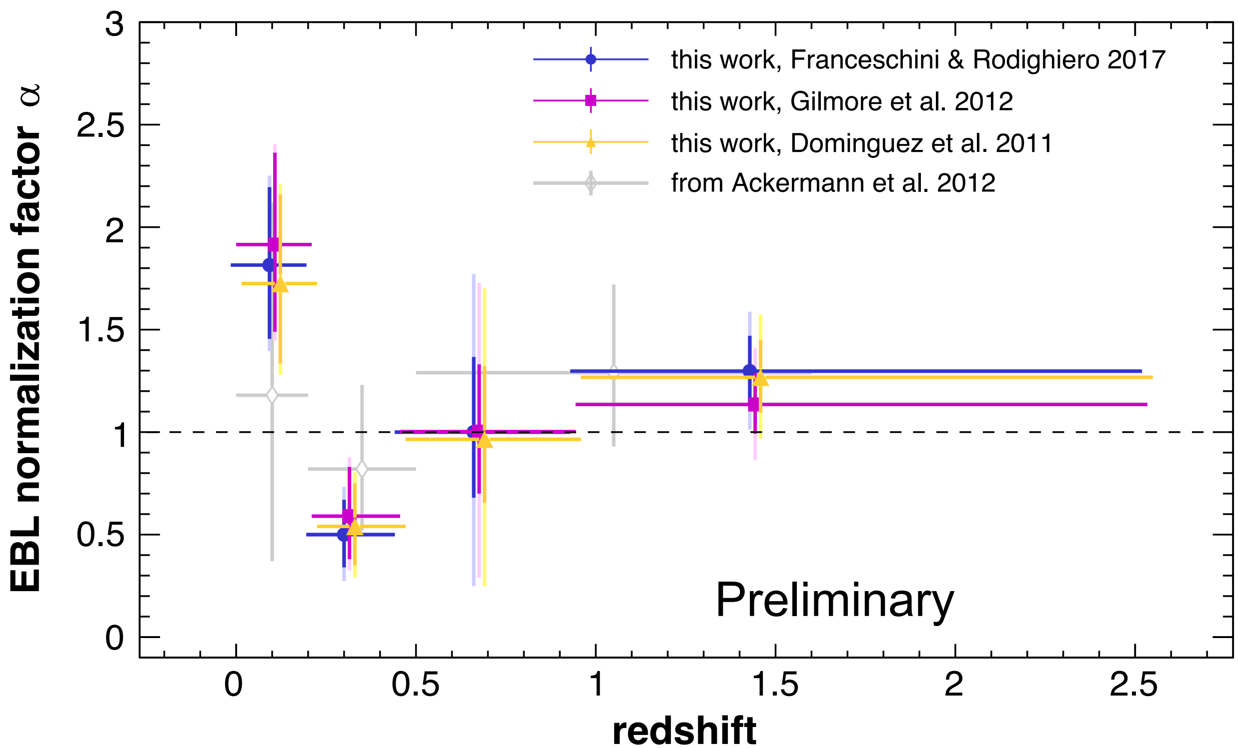
First result: **The Imprint of the Extragalactic Background Light in the Gamma-Ray Spectra of Blazars,** Ackermann et al., Science 338, 1190 (2012)

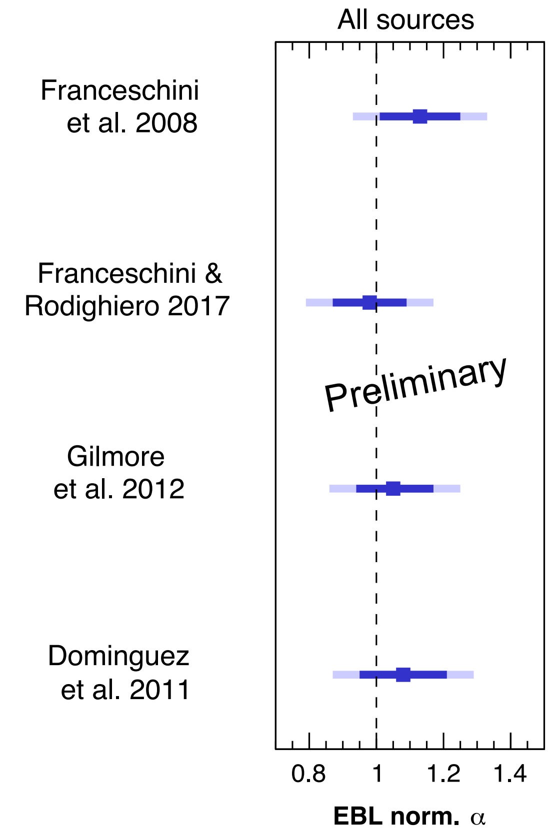
Armstrong et al., MNRAS 470, 4089 (2017) use a sample of 16 AGN with z > 0.89:



Model Dependent Detection with HE γ-rays

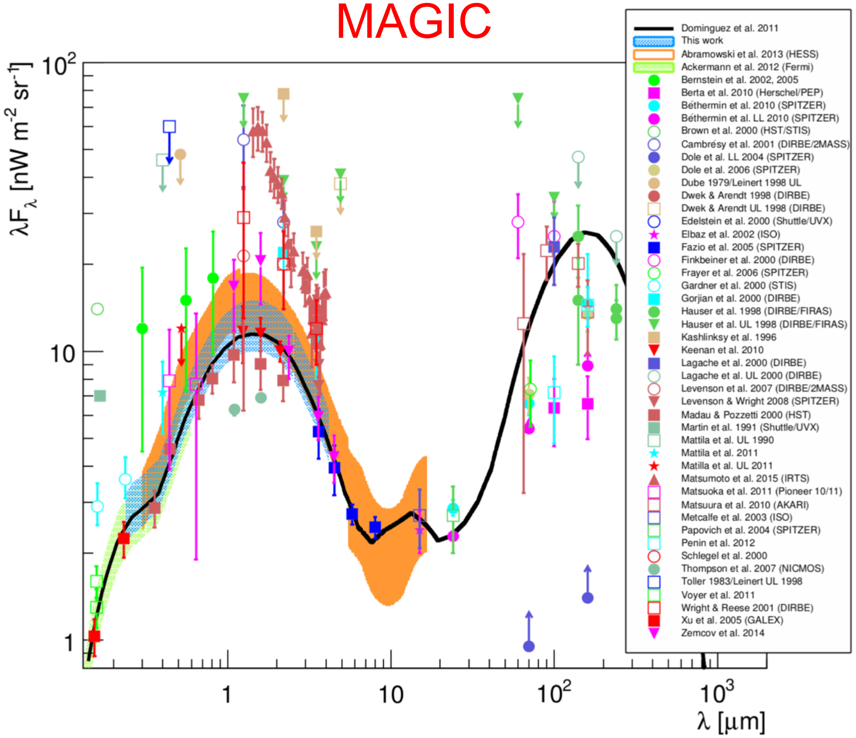
Biasuzzi et al., Proc. SF2A-2017 & in prep, use a sample of 490 AGN from 3FGL and 3FHL in four bins of redshift.
Consistent results with Ackermann et al. 2012, with smaller errors.





Strong Constraints from Single Sources

MAGIC

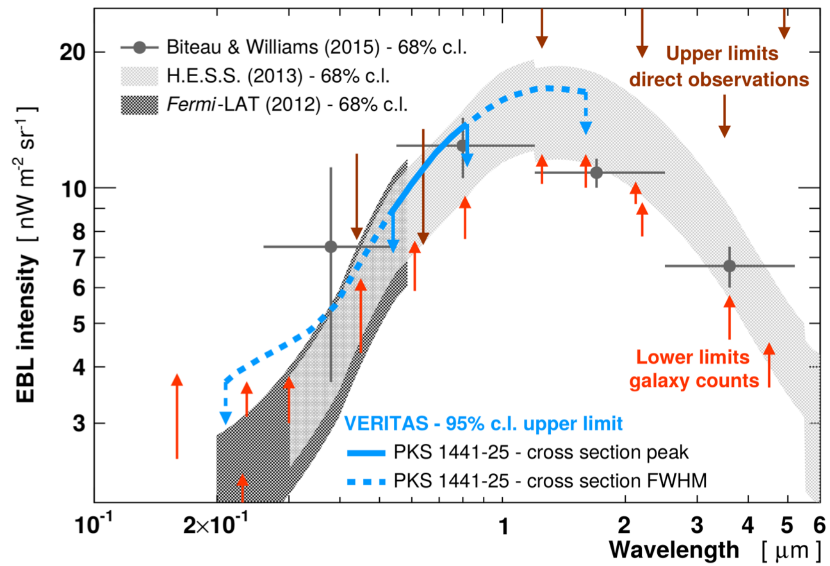


1ES 1011+496 : Excellent Spectrum from a Bright Flare

- z = 0.212
- Spectrum from 60 GeV to >3 TeV
- 4.6σ preference for non-zero EBL

A&A 590, A24 (2016)

VERITAS



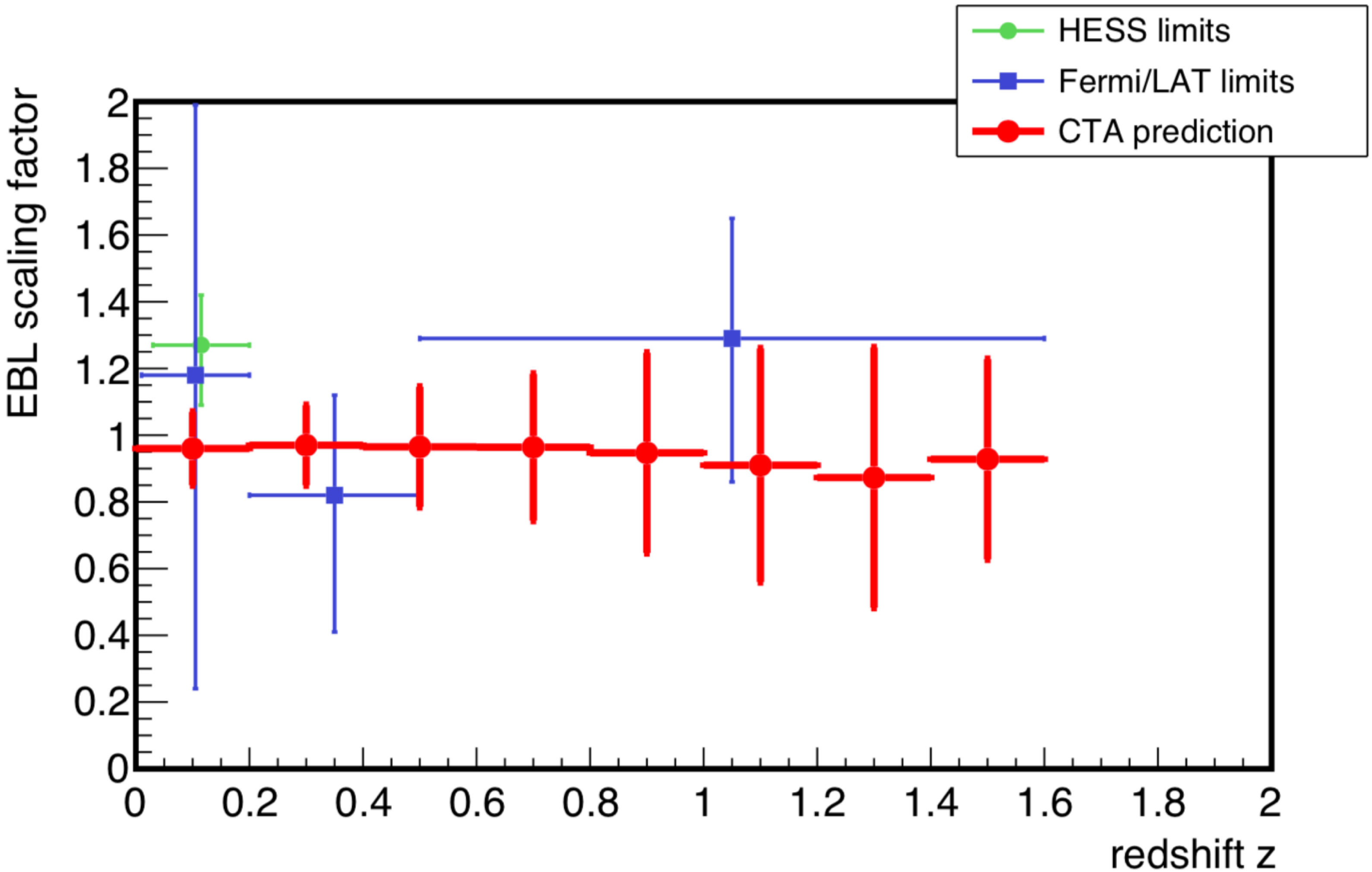
PKS 1441+25 : A Distant VHE Gamma-ray Quasar

- z = 0.94 ↔ light travel time of 7.5 Gyrs (more than half of the age of the universe!)
- 8σ detection by VERITAS above 80 GeV, following up on alerts by MAGIC & Fermi-LAT
- Gamma-rays detected up to 200 GeV (about 400 GeV in the source frame accounting for z)

ApJL 815, L22 (2015)
See also ApJL 815, L23 (2015)

Projection for CTA

Acharya et al., Science with the Cherenkov Telescope Array (2017), arXiv: 1709.07997



Model Independent Constraints from γ-rays

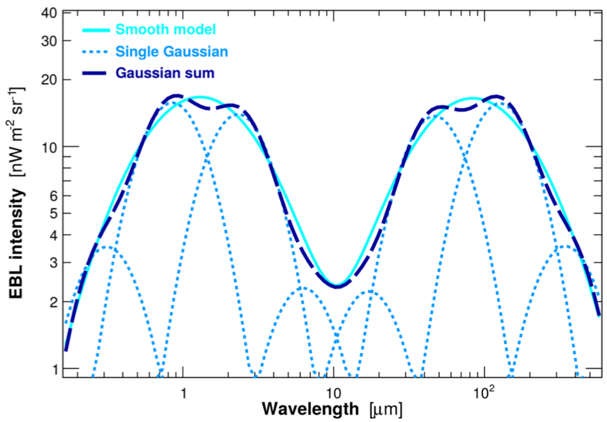
Optical depth: $\tau(E_0,z_0)$ = Target density x Distance x Cross section

→ 3D integral over: energy of target photons, redshift, gamma-to-target angle

→ 2D integral after analytical reduction of the integral over the angle

If Target density(ϵ_0,z_0) = Target density$(\epsilon_0,z_0=0)$ x Evolution(z_0), then

→ $\tau(E_0,z_0) = 3\pi\sigma_T/H_0 \times E_0/m^2c^4 \times$



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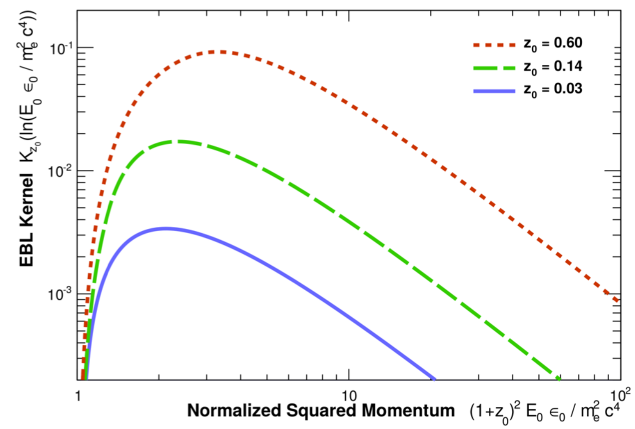


$\ln(E_0/mc^2)$

Evolution:

$evol(z) = (1+z)^{3-fevol}$

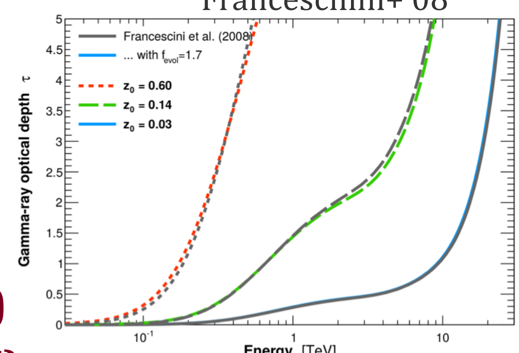
Decoupling hypothesis:

impact on τ of about ~2%

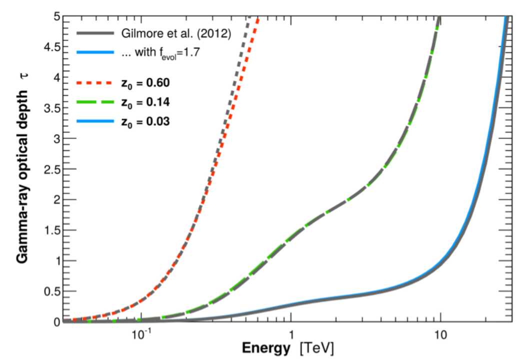
Biteau & Williams, ApJ 812, 60 (2015)

cf. Mazin & Raue, A&A 471, 439 (2007)

Franceschini+ 08



Gilmore+ 12

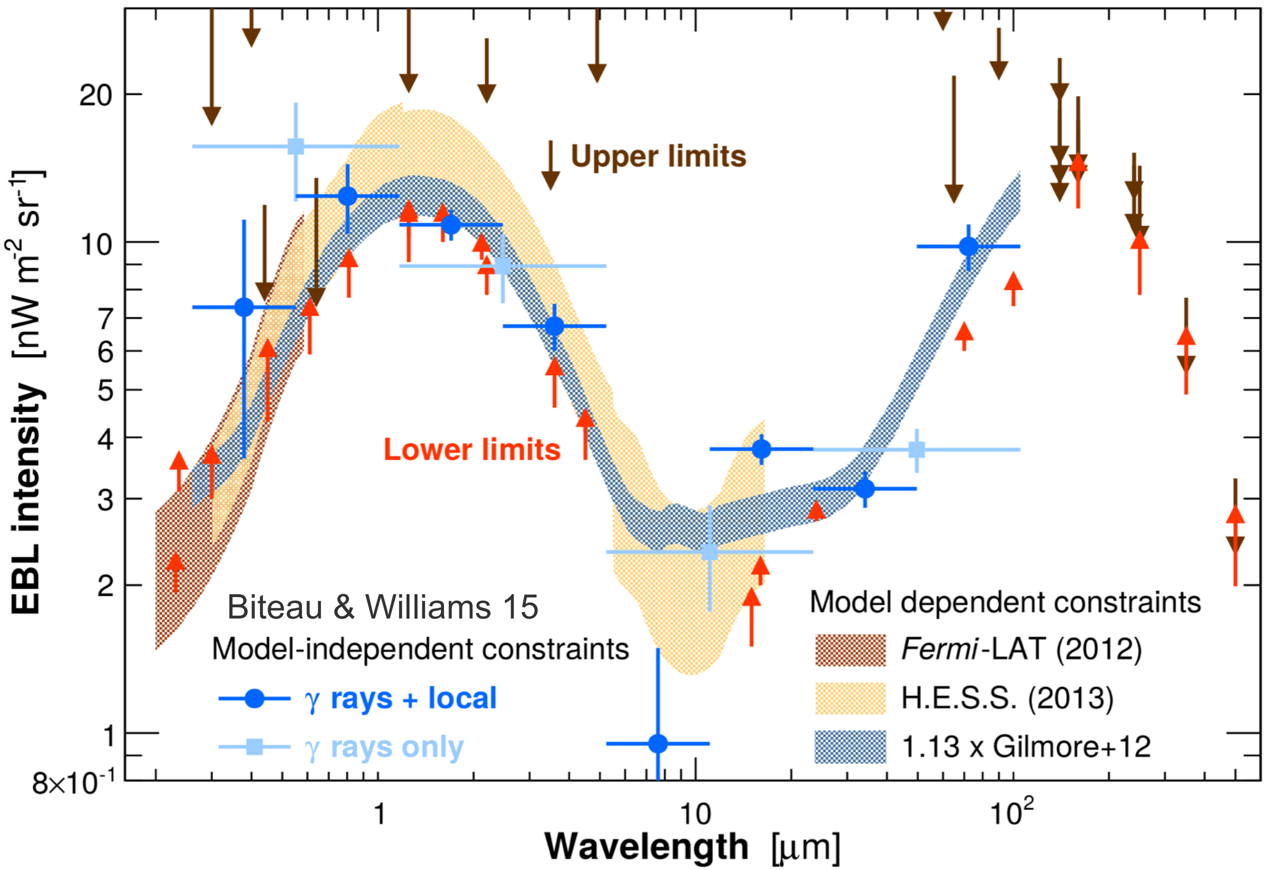


Model Independent Results

- 106 spectra from 38 sources
- Parametrization of EBL evolution up to z~0.8

Method: maximum likelihood

- TeV points, GeV-TeV hardness, (local EBL constraints)



Biteau & Williams, ApJ 812, 60 (2015)

Results

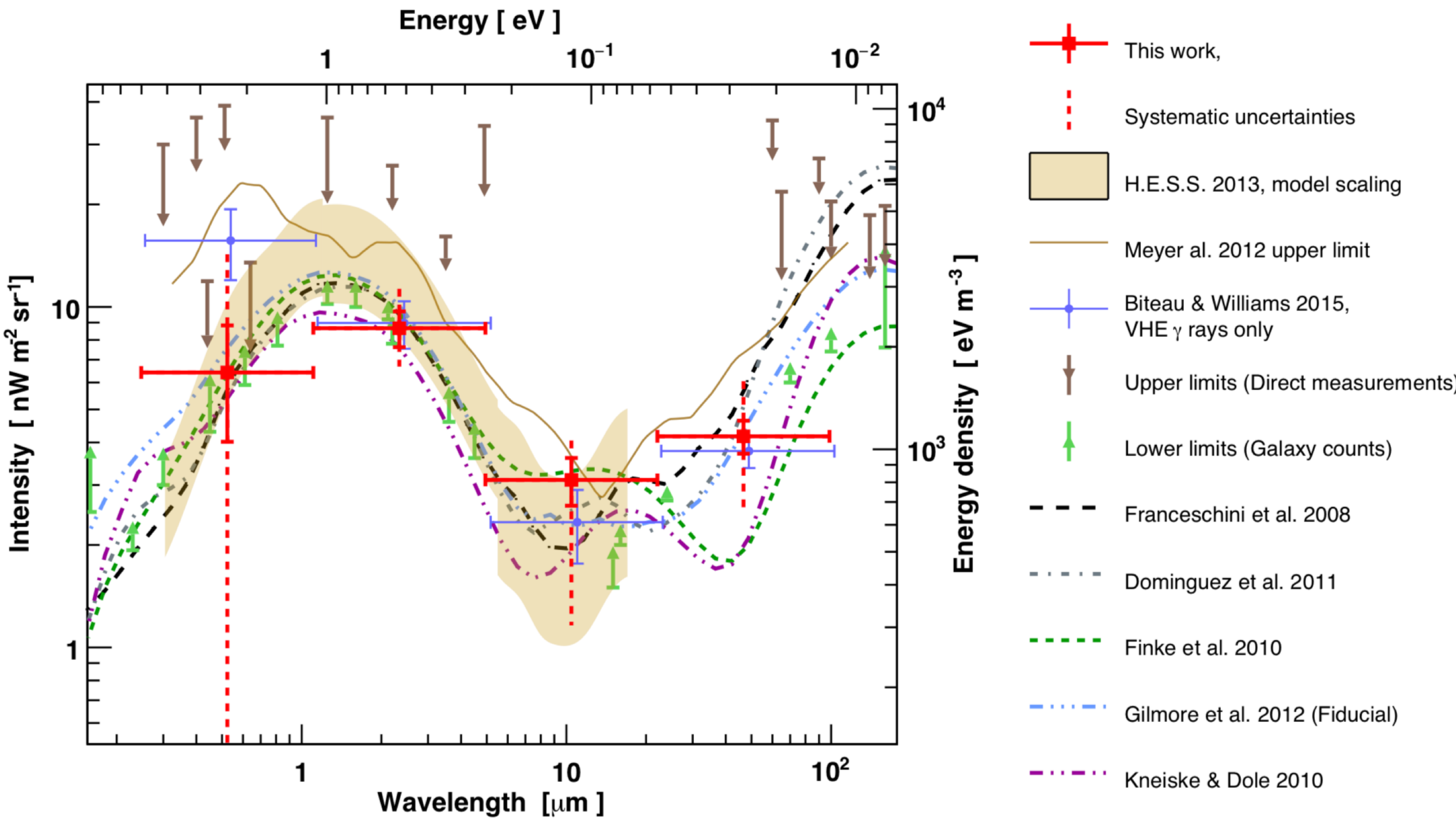
- 11σ detection for model-dependent & model-independent methods
- Study of 7 models:
  - ✓ 4 ruled out
  - ✓ 3 about as good as model-independent
- EBL (0.1–1000 μm): 62±12 nW m^{-2} sr^{-1} 6.5±1.2% of the CMB
- No significant tension with galaxy counts

Gamma-ray inferred EBL is *not* too low wrt expectations from UV-IR observations!

Model Independent Results – H.E.S.S. only

H.E.S.S. Collaboration, A&A 606, A59 (2017)

Using 21 spectra from 9 blazars



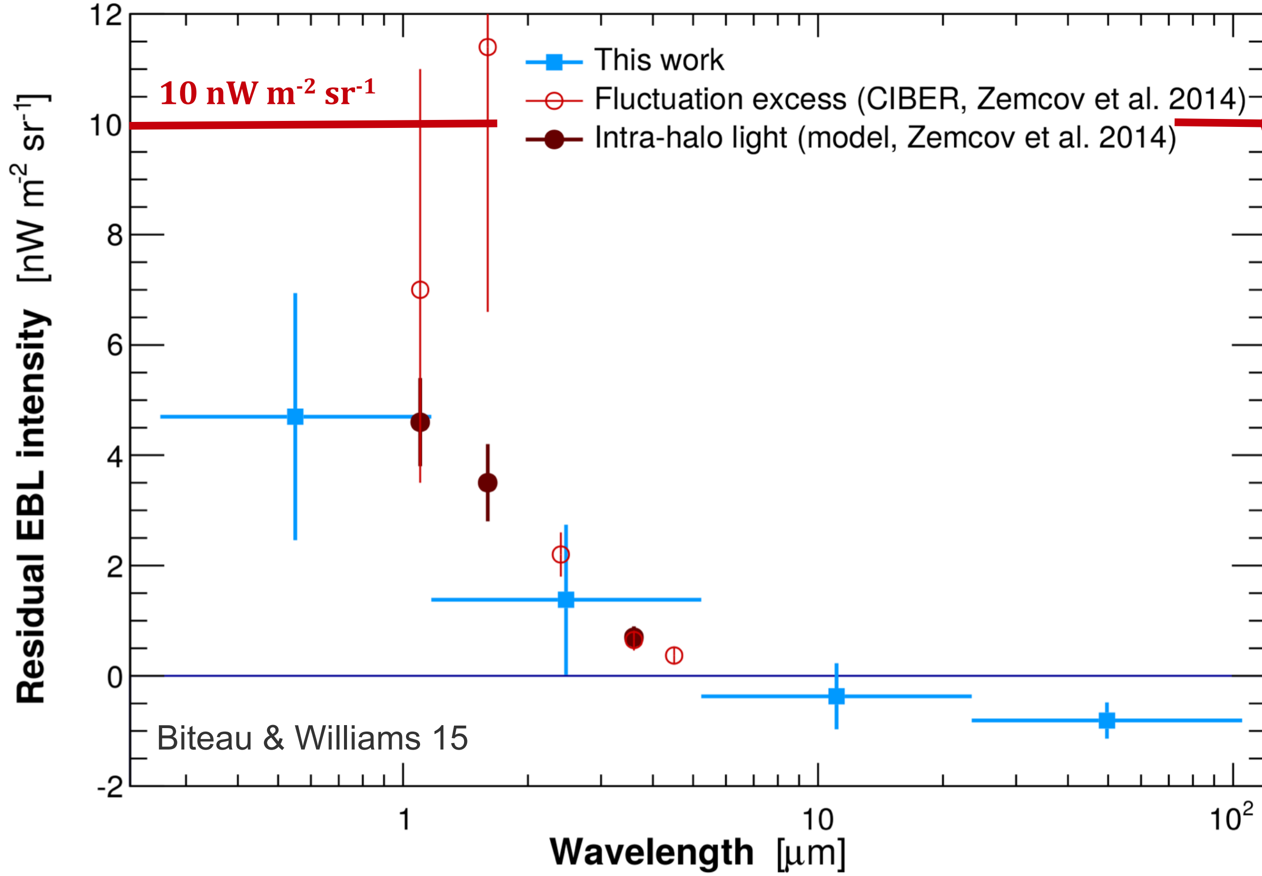
Unresolved Sources and Reionization

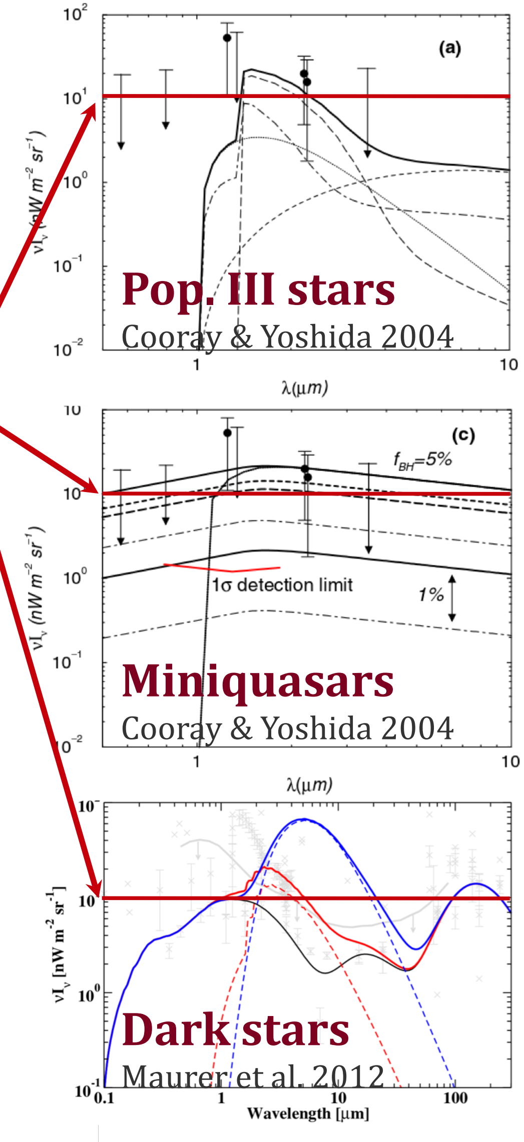
Method: gamma-ray inferred EBL – galaxy counts

- Using the EBL derived with gamma-ray data only

Results:

- Optimistic models of reionization rejected
- Good agreement, room left for intra-halo light (CIBER)



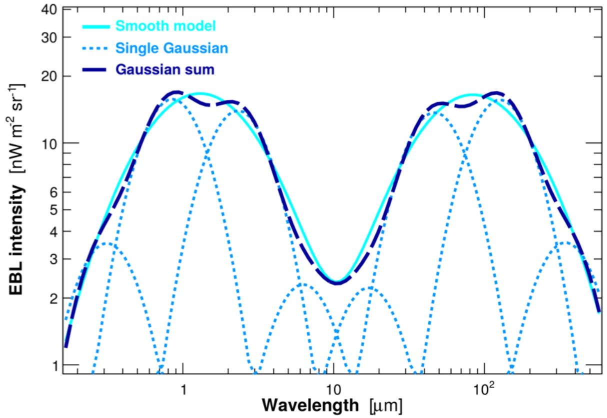


Measuring the Hubble Constant

Optical depth: $\tau(E_0,z_0)$ = Target density x Distance x Cross section

If Target density(ϵ_0,z_0) = Target density$(\epsilon_0,z_0=0)$ x Evolution(z_0), then

$\rightarrow \tau(E_0,z_0) = 3\pi\sigma_T/H_0 \times E_0/m^2c^4 \times$



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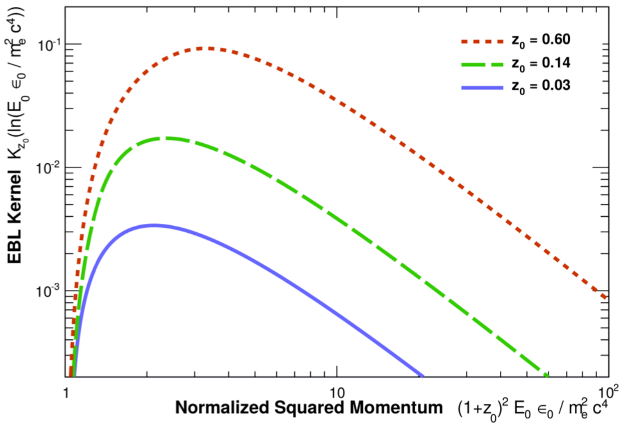

(E_0/mc^2)

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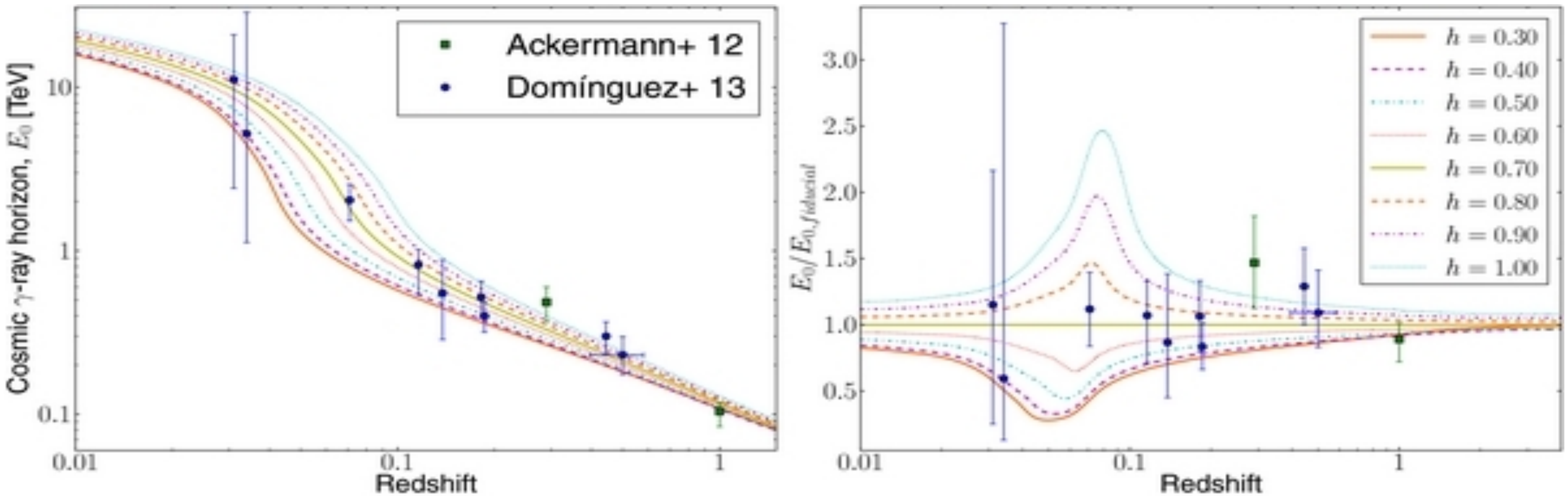

$H_0 = 71.8^{+4.6}_{-5.6}$ (stat) $^{+7.2}_{-13.8}$ (sys) km s^{-1} Mpc^{-1}

Dominguez & Prada, ApJL 771, L34 (2013)

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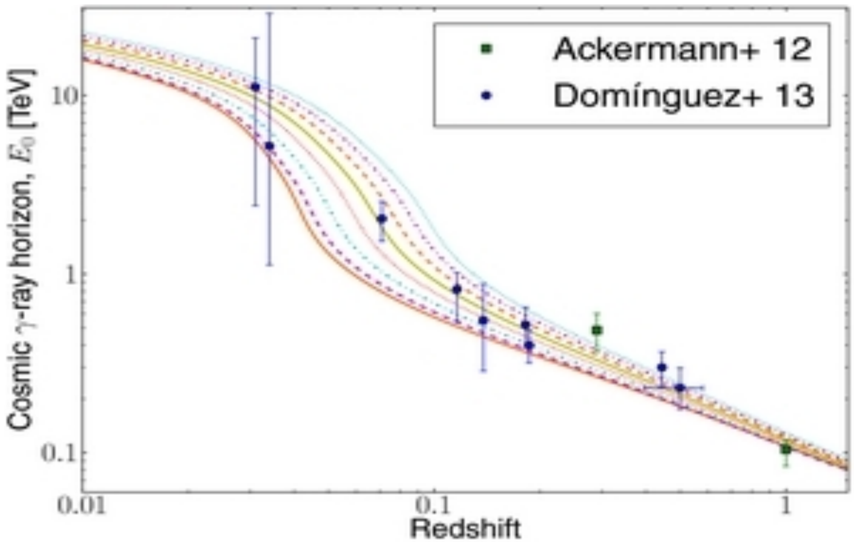

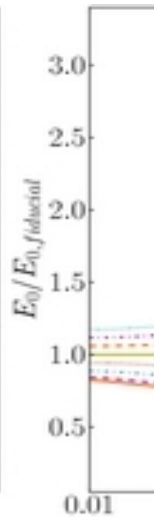

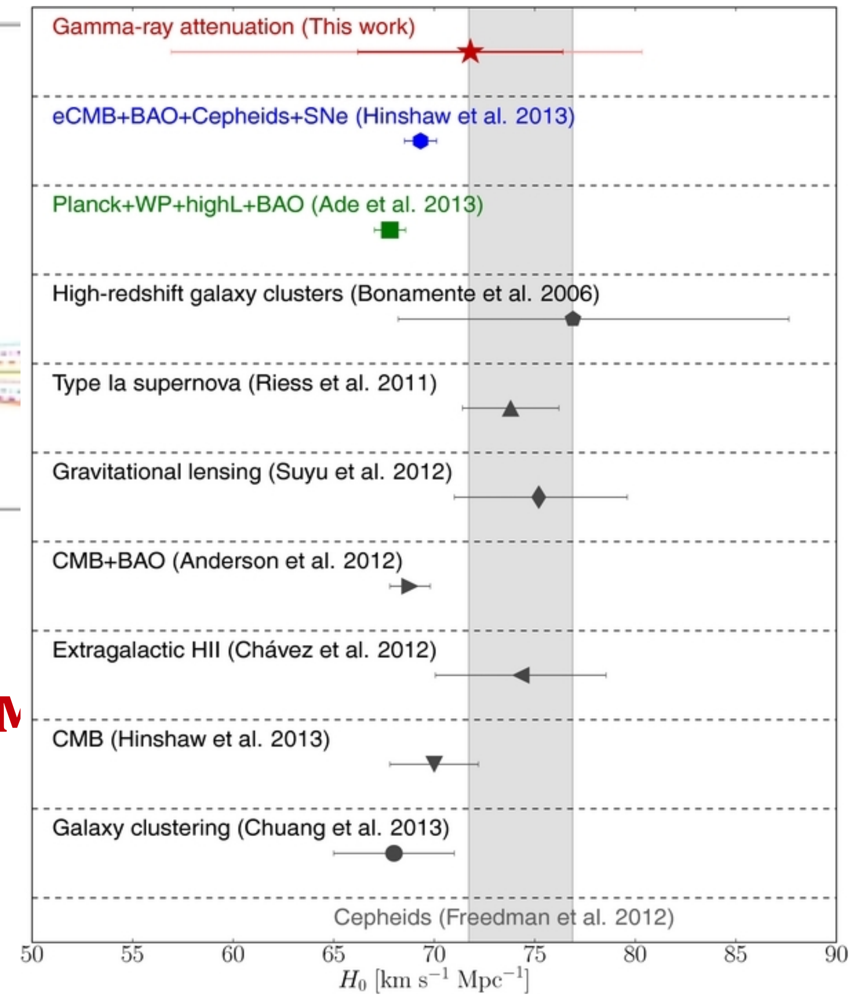

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Hints, Puzzles, Anomalies & Crises!

Recent examples:

- **Indications for a pair-production anomaly from the propagation of VHE gamma-rays — Horns & Meyer, JCAP 02, 033 (2012)**
- **A Firm Redshift Lower Limit of the Most Distant TeV-detected Blazar PKS 1424+240 — Furniss, Williams et al., ApJ 768, 31 (2013)**
- **Breaks in Gamma-Ray Spectra of Distant Blazars and the Transparency of the Universe — Rubtsov & Troitsky, JETP Letters 100, 355 (2014)**
- **Advantages of axion-like particles for the description of very-high-energy blazar spectra — Galanti et al., arXiv:1503.04436 (2015)**
- **The transparency of the universe for very high energy gamma-rays — Horns, Marcel Grossman Proc. 2014, arXiv:1602.07499 (2016)**

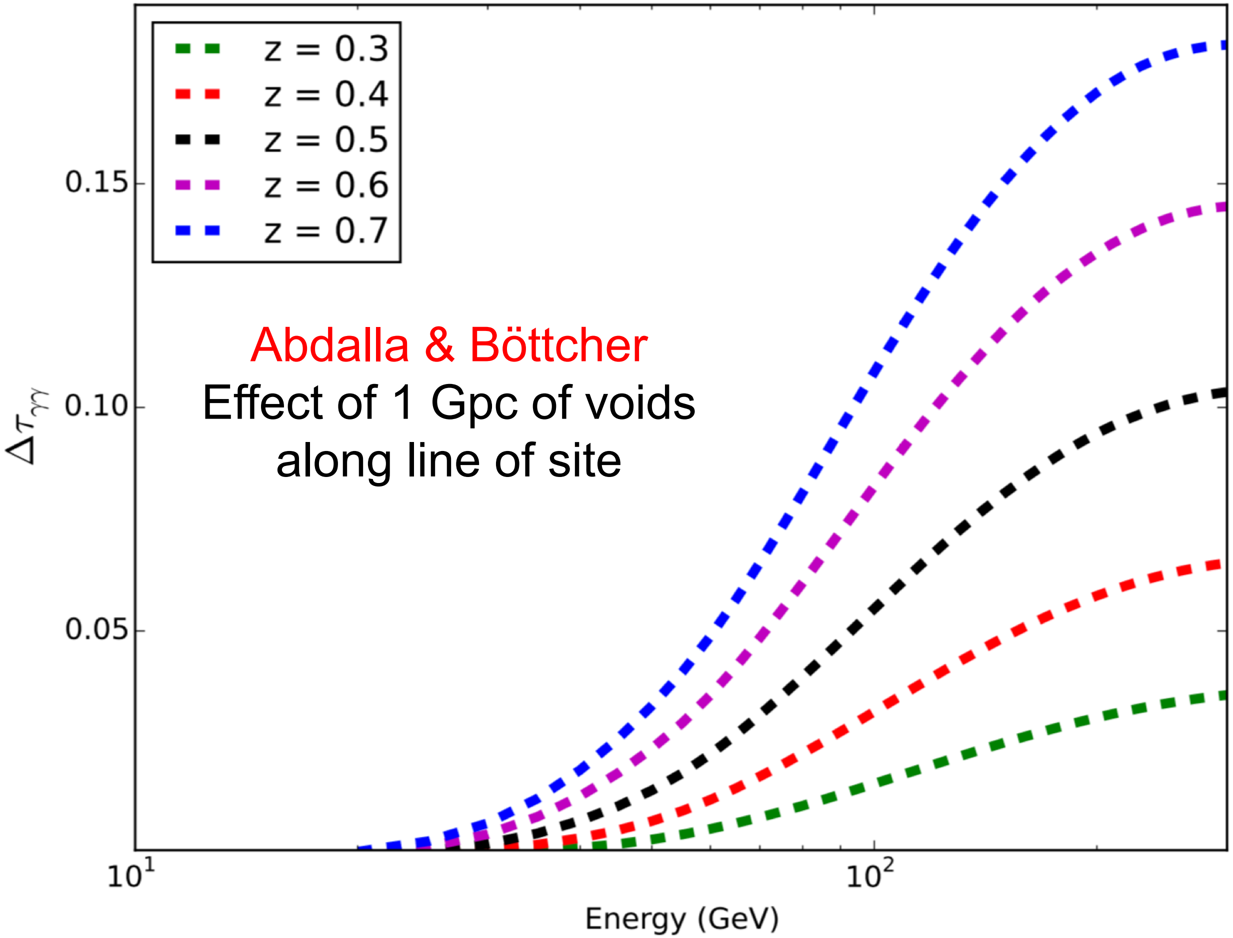
Possible explanations:

- Much Ado about Nothing
  - ✓ Biteau & Williams, ApJ 812, 60 (2015)
  - ✓ Franceschini & Rodighiero, A&A 603, 34 (2017)
  - ✓ H.E.S.S. Collaboration, A&A 606, A59 (2017)

EBL Inhomogeneity

Furniss et al., MNRAS 446, 2267 (2015)
Abdalla & Böttcher, ApJ 835, 237 (2017)
Kudoda & Faltenbacher, MNRAS 467, 2896 (2017)

- Effect of structure and fluctuations in star formation small
- ~few percent in local EBL density
- Can accumulate along photon trajectory
- Overall effect can be ~10%



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Possible explanations:

- Much Ado about Nothing
- Particle cascades along the line of sight
  - ✓ Essey & Kusenko, APh 31, 81 (2010)
  - ✓ Dzhatdoev et al., A&A 603, A59 (2017) — talk at this meeting

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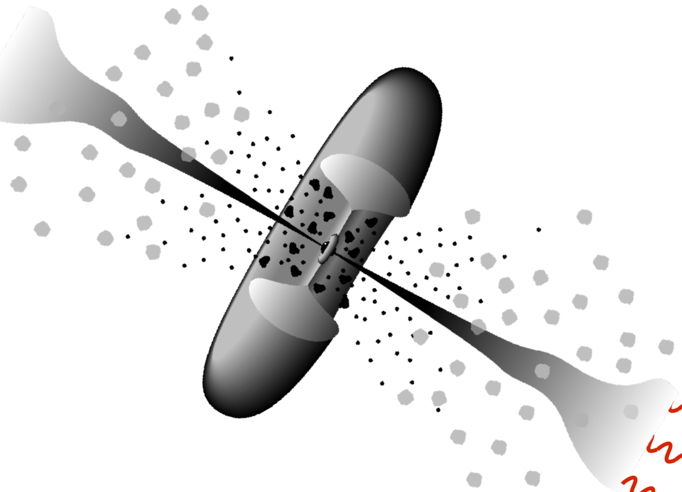
- Axion-like particles (ALPs)

Axion-like Particles

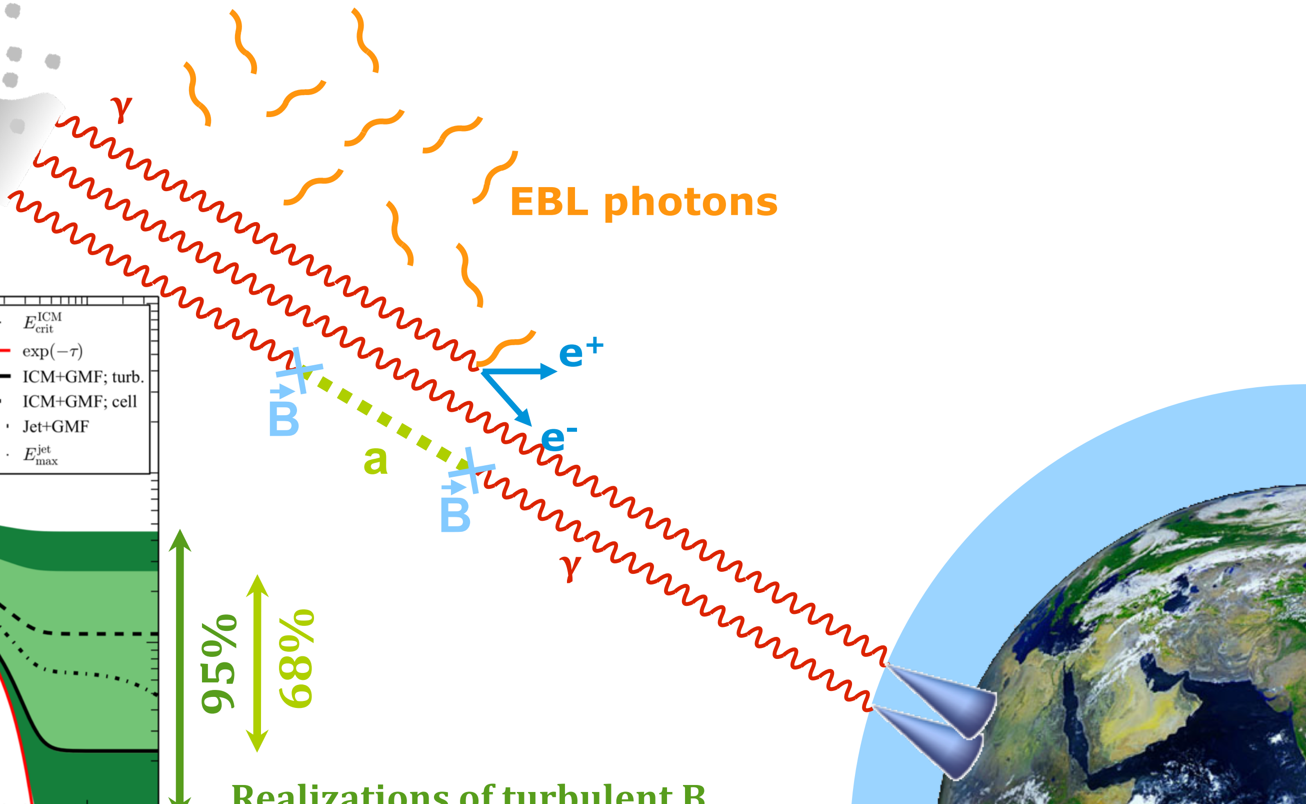


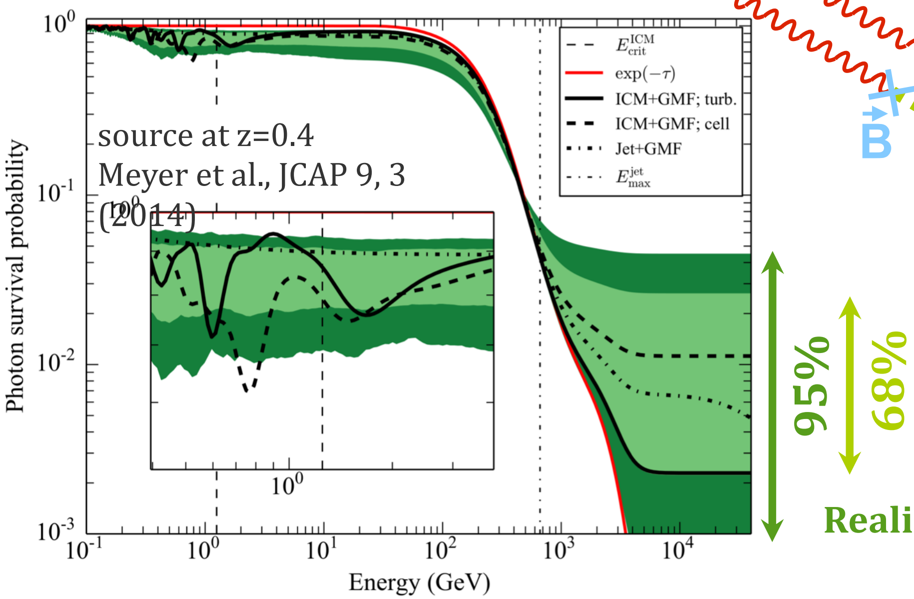
Hypothetical particles coupling with γ-rays: ALPs

- Inspired from QCD axion, but free mass and coupling

Impact on TeV spectra:

- Point-to-point fluctuations at low energies
- Reduction of absorption at large energies, or more specifically, flux enhancement at high optical depths





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Possible explanations:

- Much Ado about Nothing
- Particle cascades along the line of sight
- Axion-like particles (ALPs)
- Lorentz invariance violation (LIV)

Lorentz-invariance Violation

Principle:

- Modified dispersion relation around $E_{QG} \sim E_{Planck} \sim 10^{28}$ eV
- Modified threshold of pair creation, e.g. Jacob & Piran, PRD 78, 124010 (2008)
- Probe of the > 15–20 TeV energy range

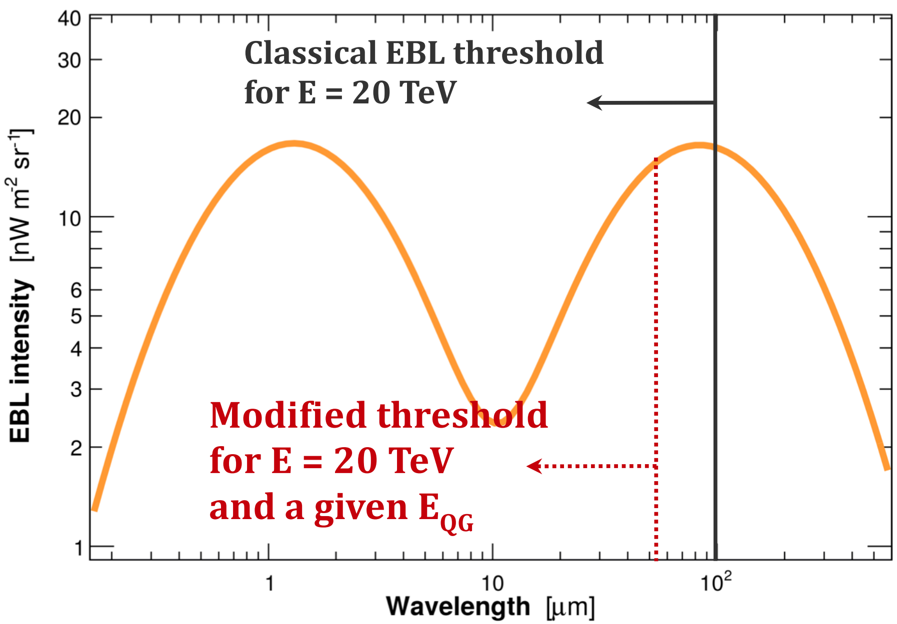
(1) $$E^2 = p^2 + m^2 - E^2 \times \frac{E}{E_{\rm QG}}$$

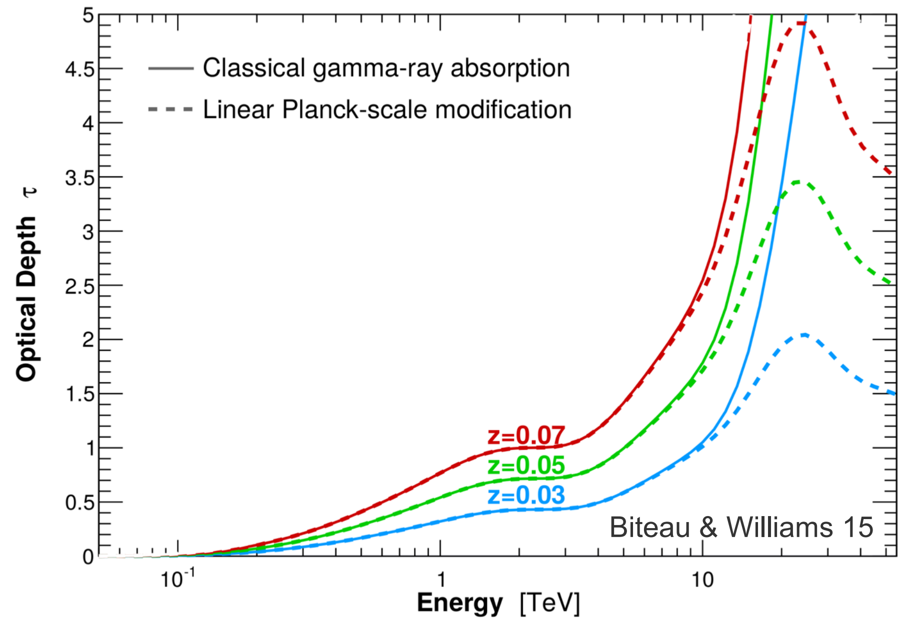
2a: 4-P conservation
2b: speed of light

(2a) $$\epsilon_{thr} = \frac{m_e^2}{E_\gamma} \times \left[1 + \left(\frac{E_\gamma}{E_{\gamma,\rm LIV}}\right)^3\right]$$

(2b) $$v = \frac{\partial E}{\partial p} = 1 - \frac{E_\gamma}{E_{\rm QG}}$$

(3a) $$E_{\gamma,\rm LIV} = \left(8 m_e^2 E_{\rm QG}\right)^{1/3} = 29.4\,\mathrm{TeV} \times \left(\frac{E_{\rm QG}}{E_{\rm Planck}}\right)^{1/3}$$





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1 $$E^2 = p^2 + m^2 - E^2 \times \left(\frac{E}{E_{\rm QG}}\right)^n$$

2a: 4-P conservation
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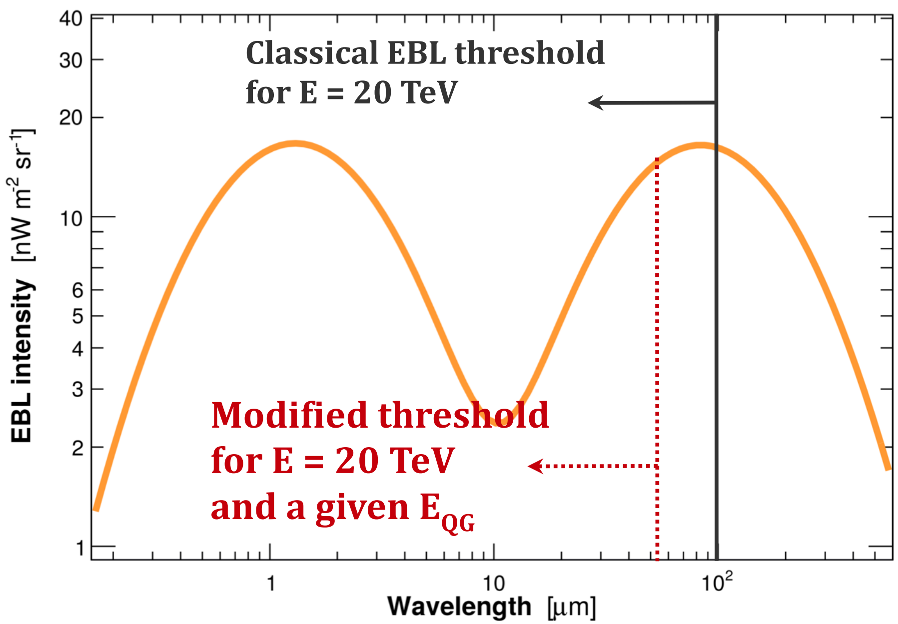
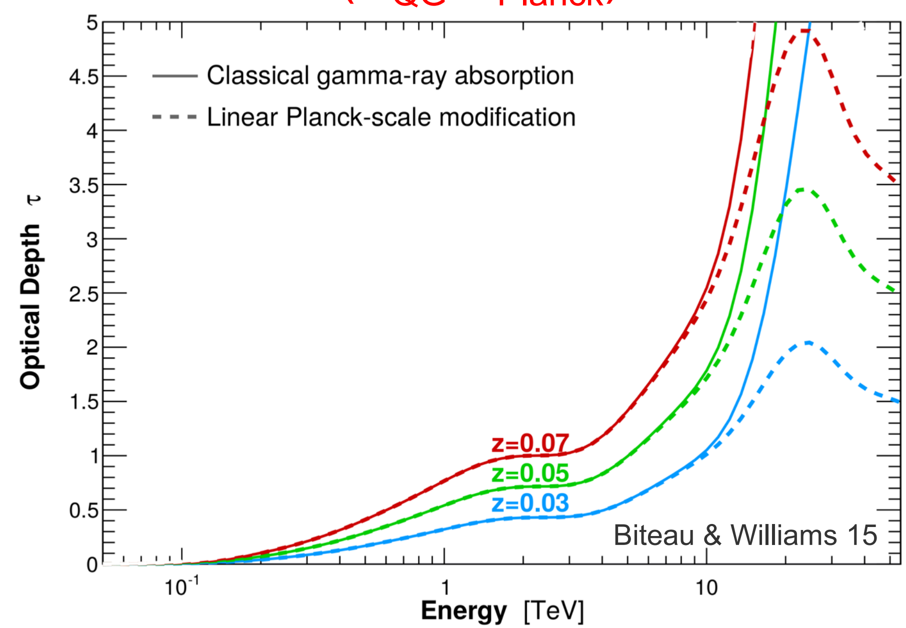
2a $$\epsilon_{thr} = \frac{m_e^2}{E_\gamma} \times \left[1 + \left(\frac{E_\gamma}{E_{\gamma,\rm LIV}}\right)^4\right]$$

2b $$v = \frac{\partial E}{\partial p} = 1 - \frac{E_\gamma}{E_{\rm QG}}$$

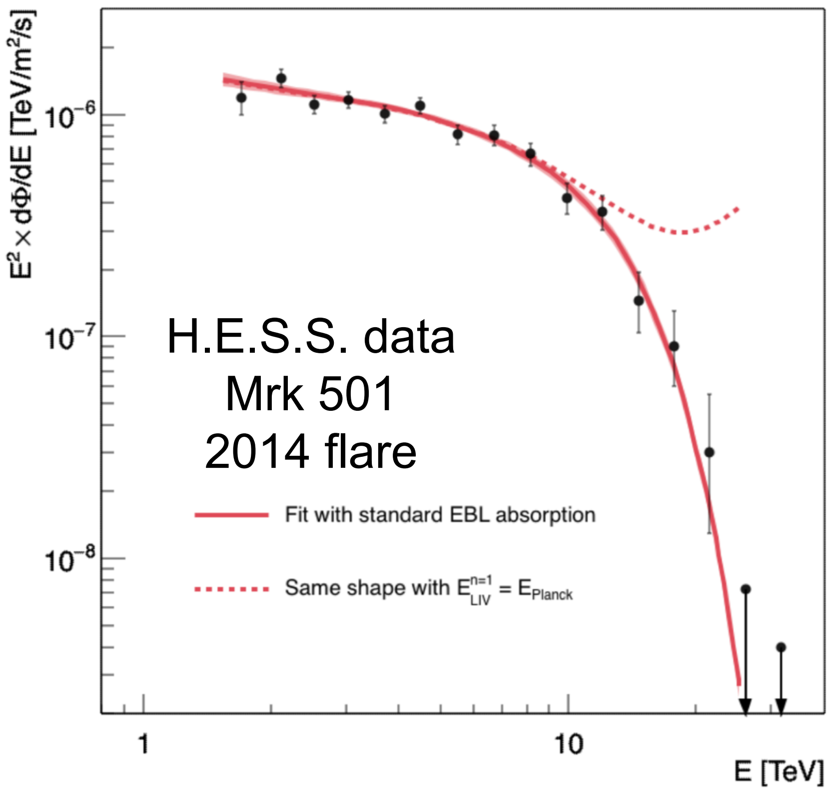
3a $$E_{\gamma,\rm LIV} = \left(8 m_e^2 E_{\rm QG}\right)^{1/3} = 29.4\,{\rm TeV} \times \left(\frac{E_{\rm QG}}{E_{\rm Planck}}\right)^{1/3}$$

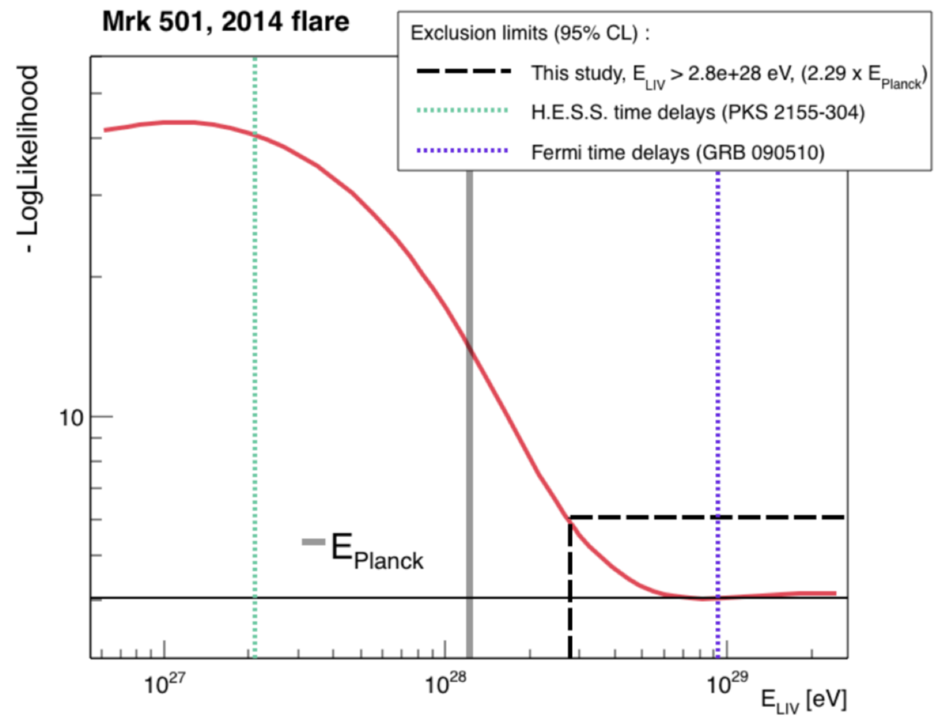
$= 120$ PeV x $(E_{QG}/E_{Planck})^{1/2}$ for $n = 2$





Limit on Lorentz-invariance Violation





	$2\,\sigma$	$3\,\sigma$	$5\,\sigma$
n=1	2.8×10^{28} eV ($2.29 \times E_{Planck}$)	1.9×10^{28} eV ($1.6 \times E_{Planck}$)	1.04×10^{28} eV ($0.86 \times E_{Planck}$)
n=2	7.5×10^{20} eV	6.4×10^{20} eV	4.7×10^{20} eV

Lorentz & Brun, Proc. RICAP16, EPJ Web of Conferences 136, 03018 (2017)

Hints, Puzzles, Anomalies & Crises!

Recent examples:

- **Indications for a pair-production anomaly from the propagation of VHE gamma-rays — Horns & Meyer, JCAP 02, 033 (2012)**
- **A Firm Redshift Lower Limit of the Most Distant TeV-detected Blazar PKS 1424+240 — Furniss, Williams et al., ApJ 768, 31 (20 3)**
- **Breaks in Gamma-Ray Spectra of Distant Blaz he Transparency of the Universe — Rubtsov & Troitsky, JE 355 (2014)**
- **Advantages of axion-like particles f ery-high-energy blazar spectra — Galanti et al**
- **The transparency of the rgy gamma-rays — Horns, Marcel Gros 02.07499 (2016)**

Possible e

- Much Ado ng
- Particle cas along the line of sight
- Axion-like particles (ALPs)
- Lorentz invariance violation (LIV)

Stay Tuned!

Conclusions

Theoretical models of the EBL are converging

- Direct measurements still challenging

EBL can be extracted from imprint on gamma-ray data

- Both the normalization *and* the spectrum
- Constraining models of additional contributions

EBL & gamma-ray observations test cosmology

- Test of star formation history
- Hubble constant

Anomalies (or lack thereof) test exotic physics

- Axion-like particles & Lorentz invariance violation
- Need to be sure all the astrophysics taken into account

More to come

- Better galaxy surveys
- Larger ensembles of gamma-ray sources
- More sophisticated methods