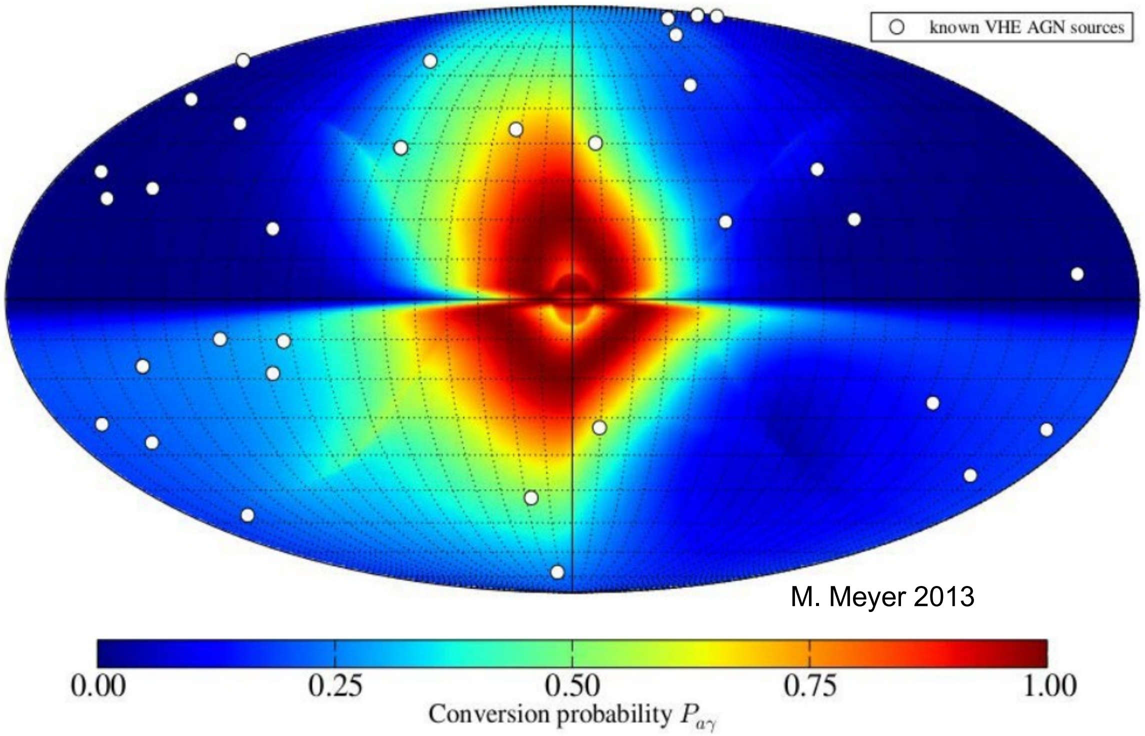
Opacity of the Universe to gamma-rays

Dieter Horns, University of Hamburg



M. Meyer 2013

Transparency of the Universe to gamma-rays

Astroparticle Physics

Propagation of
Extra-galactic
Gamma-rays

Astrophysics

Extra-galactic
Background light
(EBL)

Particle Physics

Peccei-Quinn symmetry
And axion-like particles

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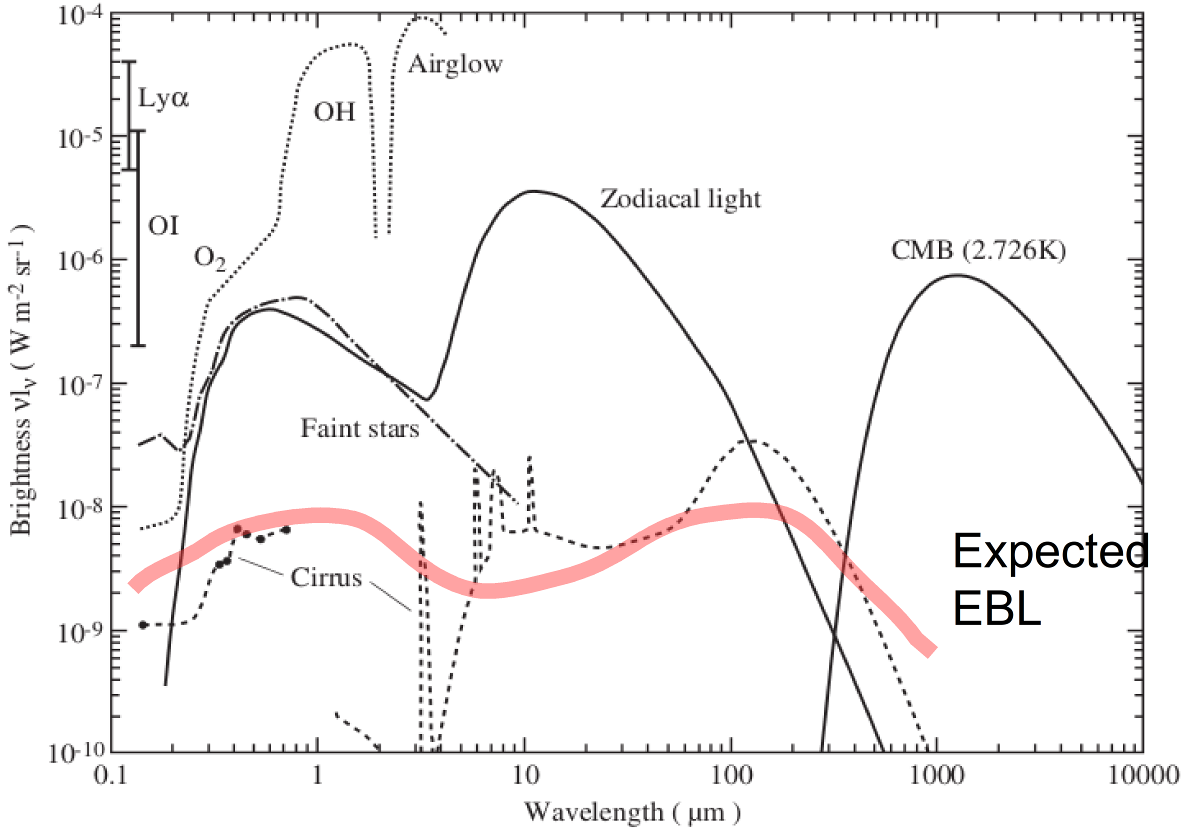
And axion-like particles


Daniel López
Observatorio del Teide, IAC

The sky is bright – the universe is not..

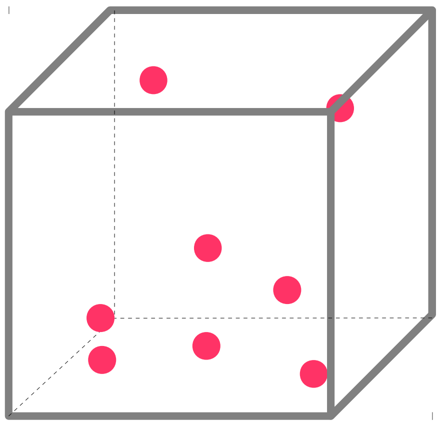


Leinert et al. 1998

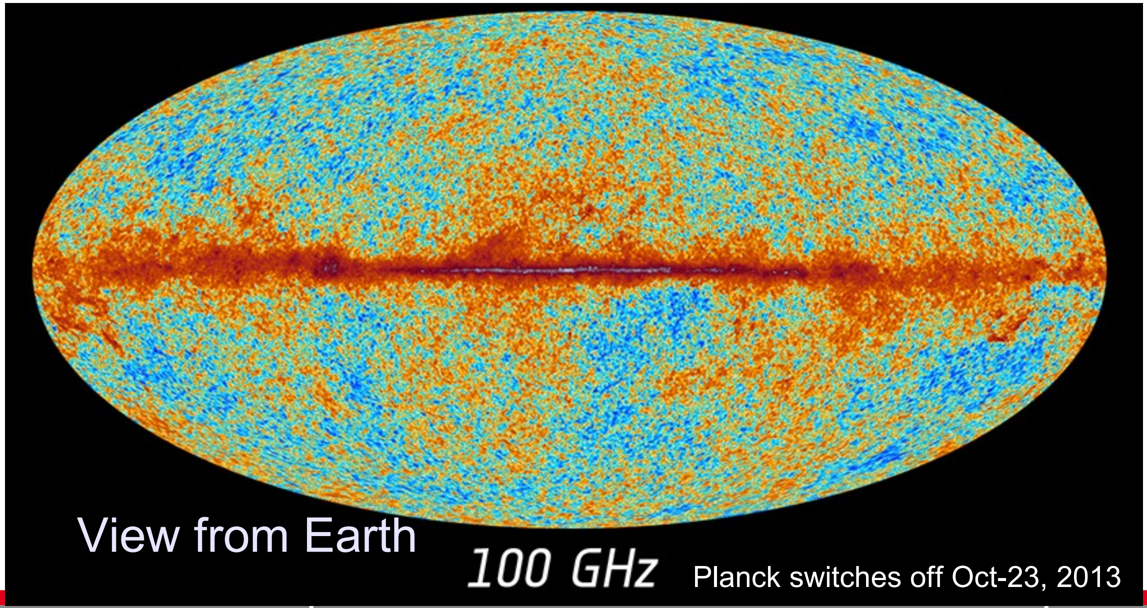
The Extra-galactic background light in a box

- Counting photons in a 1 m³ box:

4 x 10^8 Cosmic-microwave background photons



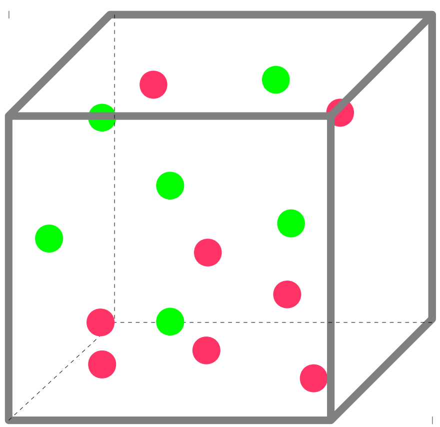
Somewhere in Extra-galactic space



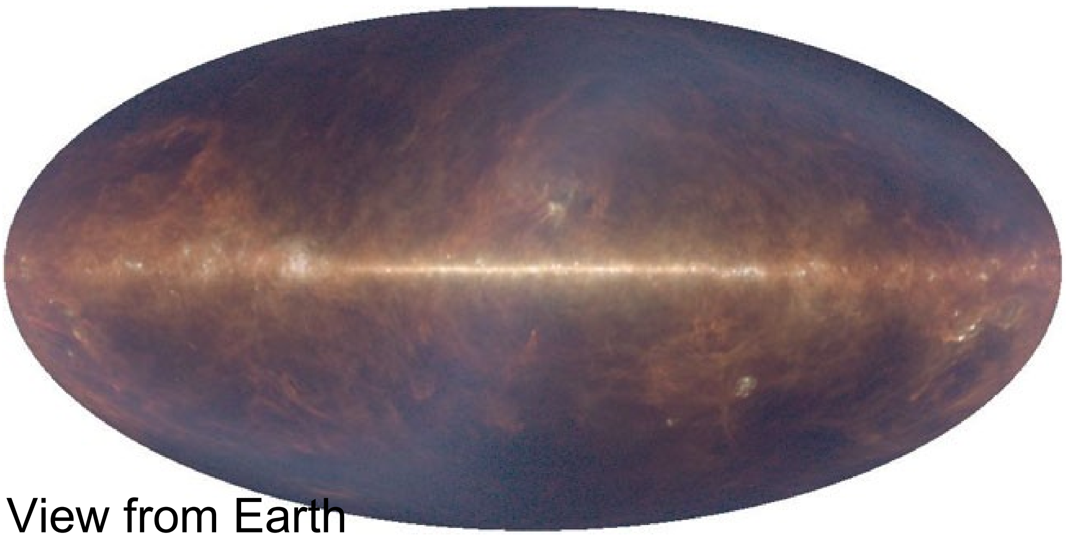
The Extra-galactic background light in a box

- Counting photons in a 1 m^3 box:

4 x 10^8 Cosmic microwave background photons
~10^6 Cosmic infra-red background photons



Somewhere in Extra-galactic space

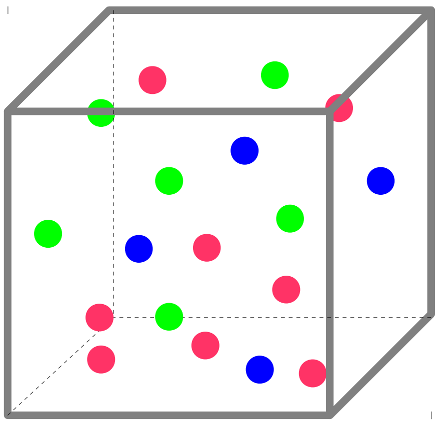


View from Earth

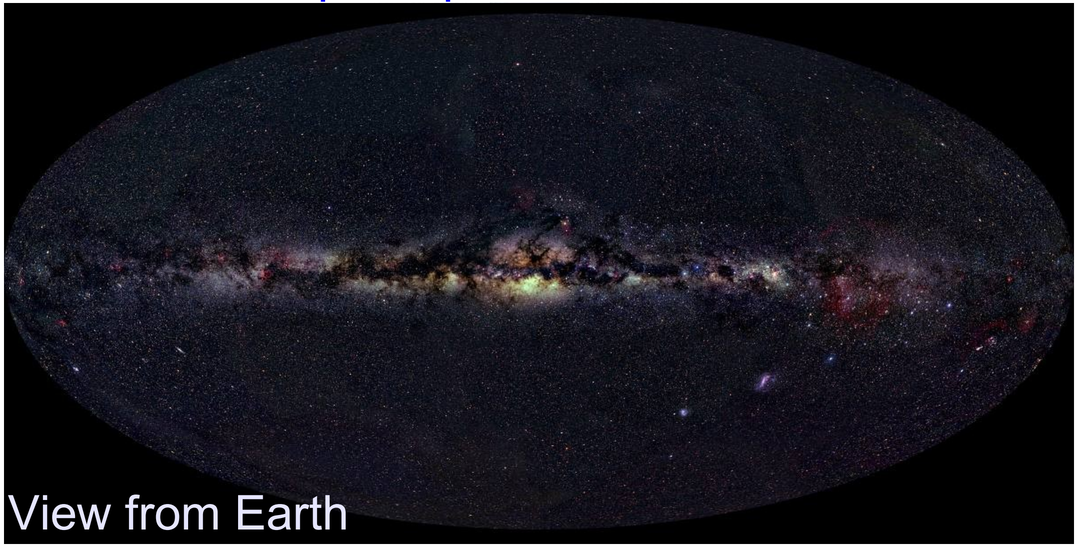
The Extra-galactic background light in a box

- Counting photons in a 1 m^3 box:

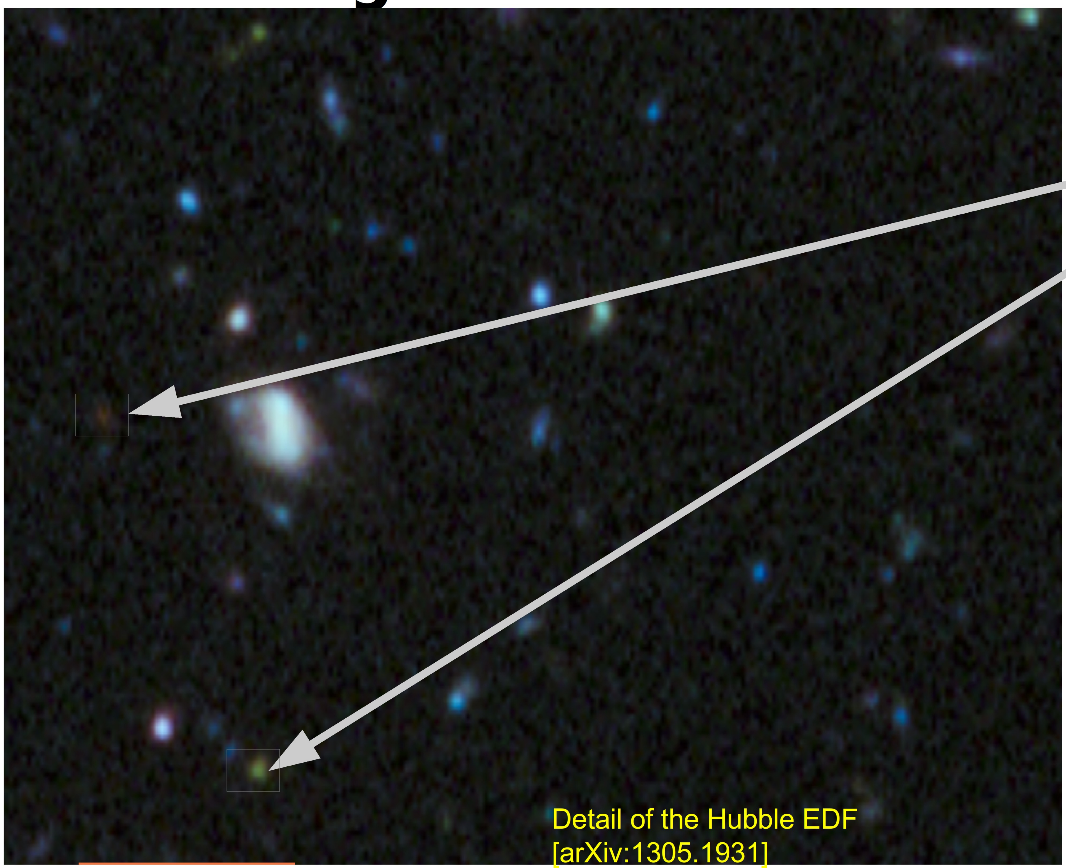
4 x 10^8 Cosmic microwave background photons
~10^6 Cosmic infra-red background photons
~10^4 Cosmic optical photons



Somewhere in Extra-galactic space



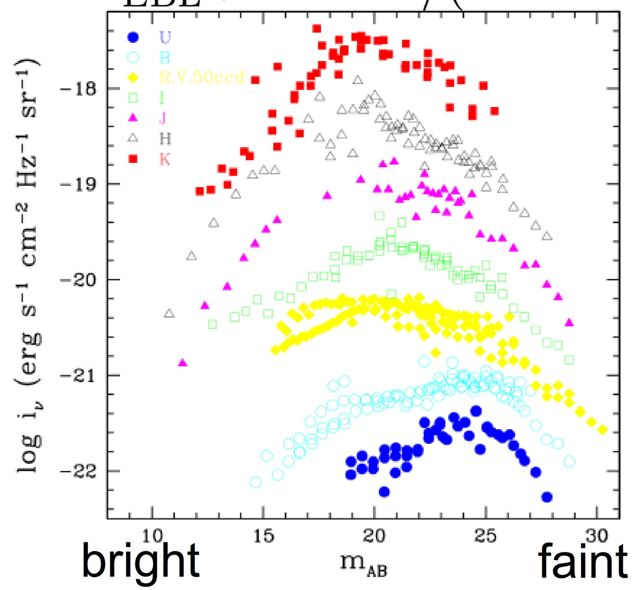
Dissecting the EBL with the Hubble telescope



Detail of the Hubble EDF
[arXiv:1305.1931]

Resolved Sources (galaxies):

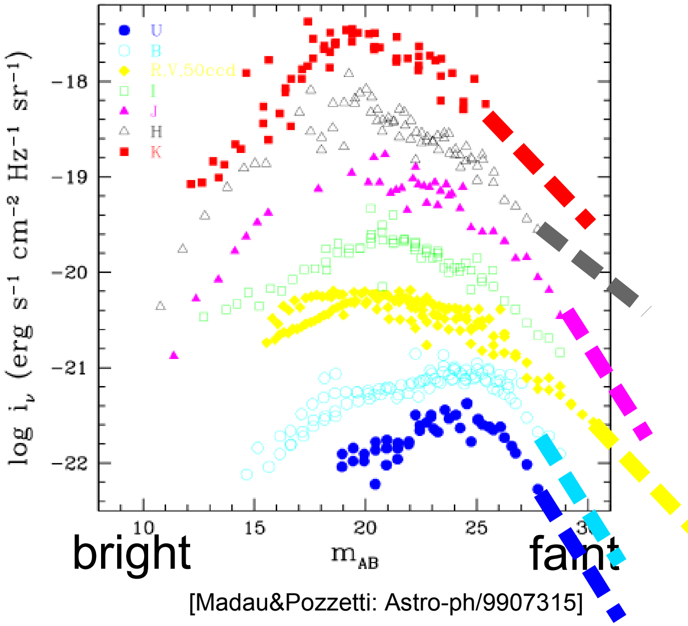
$$\nu I_{\rm EBL} > 10\ {\rm nW/(m^2\ srad)}$$



[Madau&Pozzetti: Astro-ph/9907315]

Dissecting the EBL with the Hubble telescope

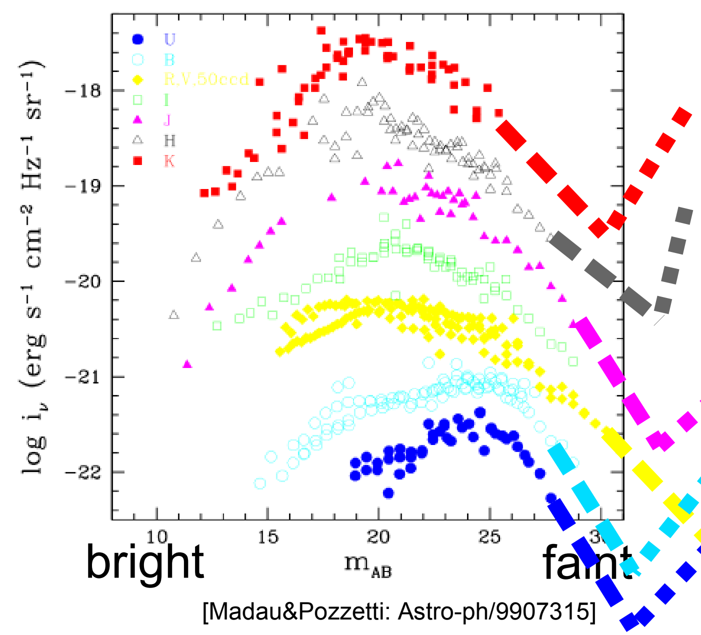
Detail of the Hubble EDF
[arXiv:1305.1931]



[Madau&Pozzetti: Astro-ph/9907315]

Dissecting the EBL with the Hubble telescope

Unresolved and *unknown* Sources (too faint)



[Madau&Pozzetti: Astro-ph/9907315]

Dissecting the EBL with the Hubble telescope

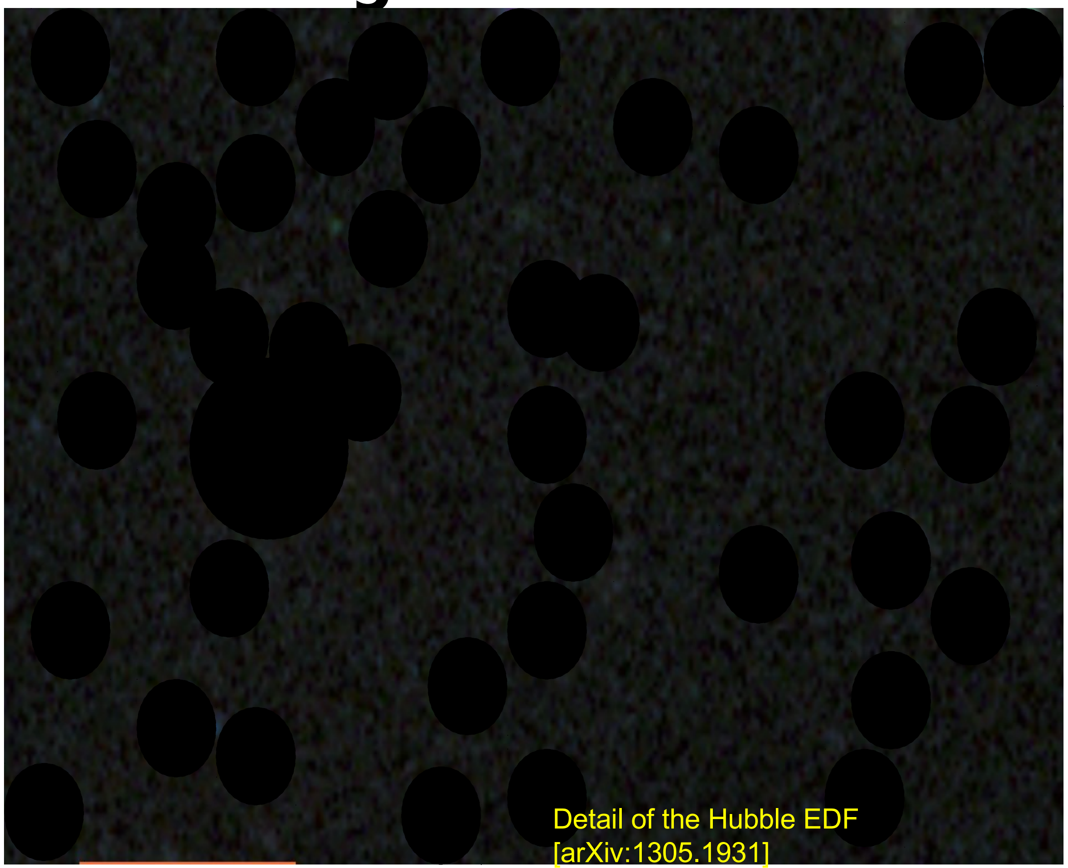
Detail of the Hubble EDF
[arXiv:1305.1931]

Additional contribution
(particle decays,...)

The Unknown
Unknowns....

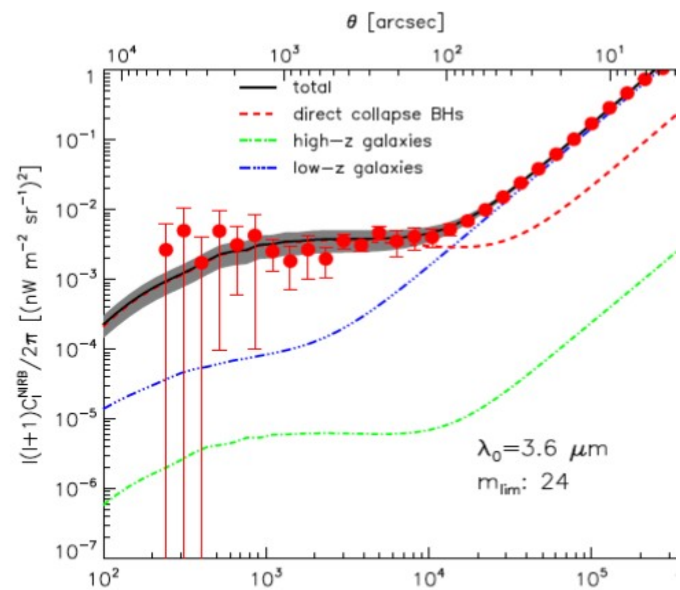
Cambresy et al. 2001
[astro-ph/0103078]

Dissecting the EBL with the Hubble telescope



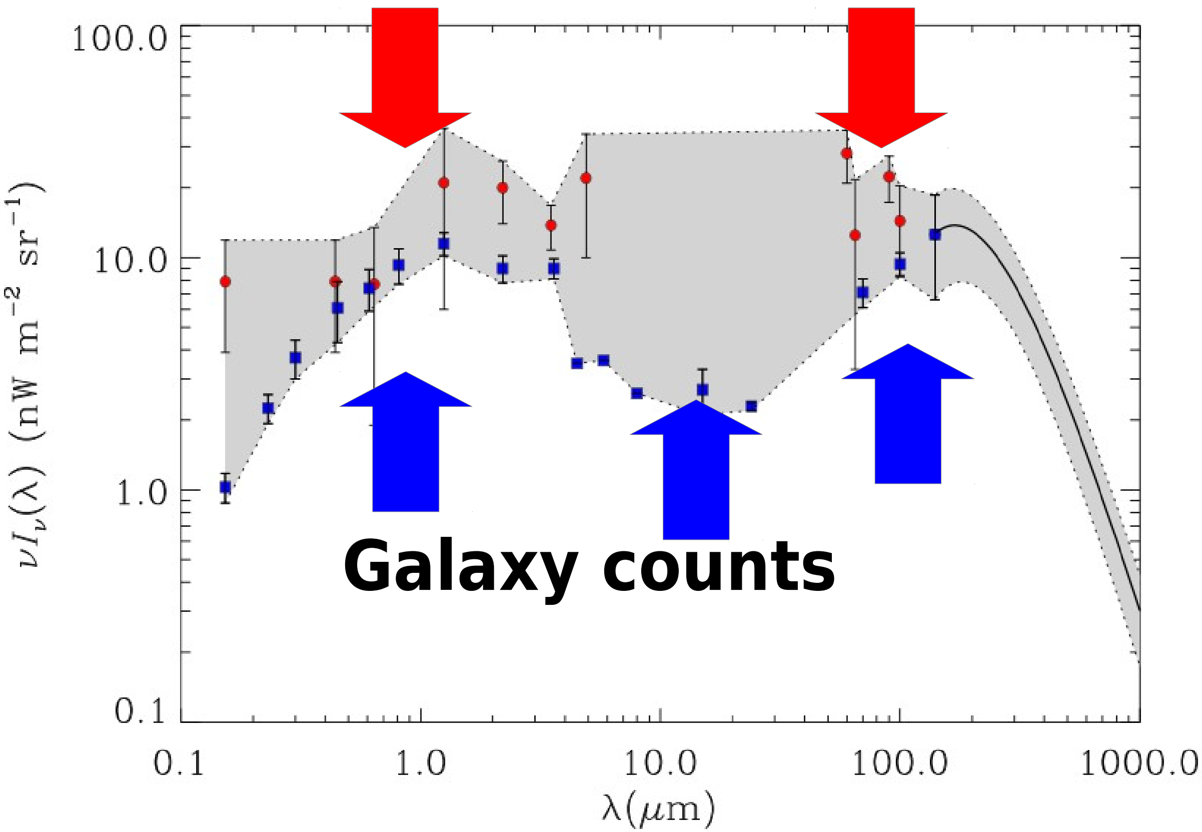
Detail of the Hubble EDF
[arXiv:1305.1931]

Background fluctuations
Unresolved contribution
~1 nW/(m²srad)



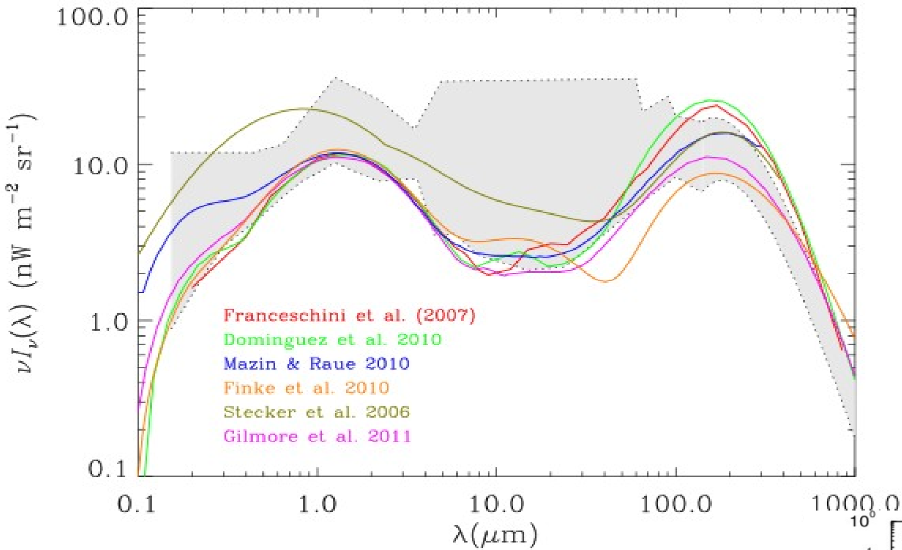
Yue et al. 2013 [arXiv:1305.5177]

Absolute Measurements of the EBL



Dwek & Krennrich
[arXiv:1209.4661]

Models (one slide only)



The simplest type of model (Dwek et al. 1998, Kneiske et al. 2002)

$$P_\nu(z) = \nu I_\nu(z) = \nu \frac{c}{4\pi} \int_z^{z_m} \mathcal{E}_{\nu'}(z') \left| \frac{dt'}{dz'} \right| dz'$$

EBL

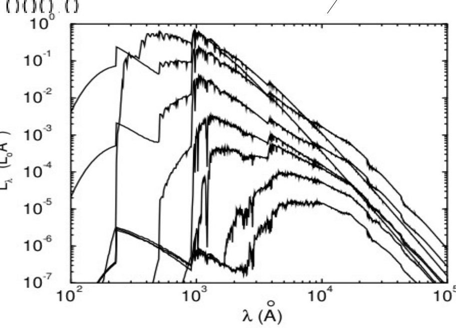
$$\mathcal{E}_\nu(z) = \int_z^{z_m} L_\nu(t(z) - t(z')) \dot{\rho}_*(z') \left| \frac{dt'}{dz'} \right| dz'$$

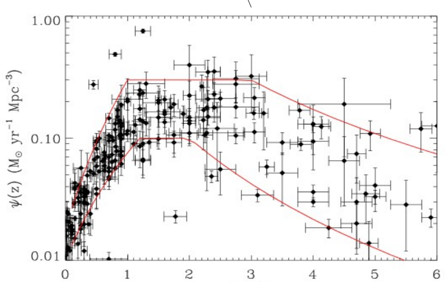
Emissivity

Stellar population spectra (SPS)

Star formation rate density (SFRD)

[Raue 2012]





Different models & different methods → Converging results!

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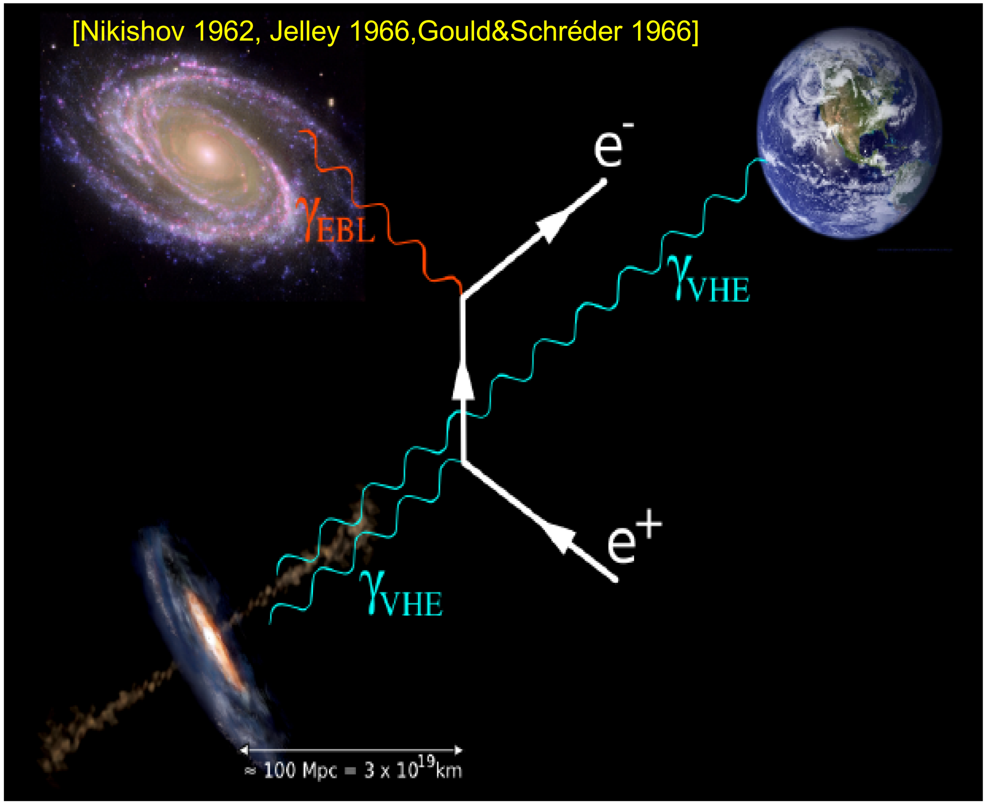
Very high energy gamma-ray observations

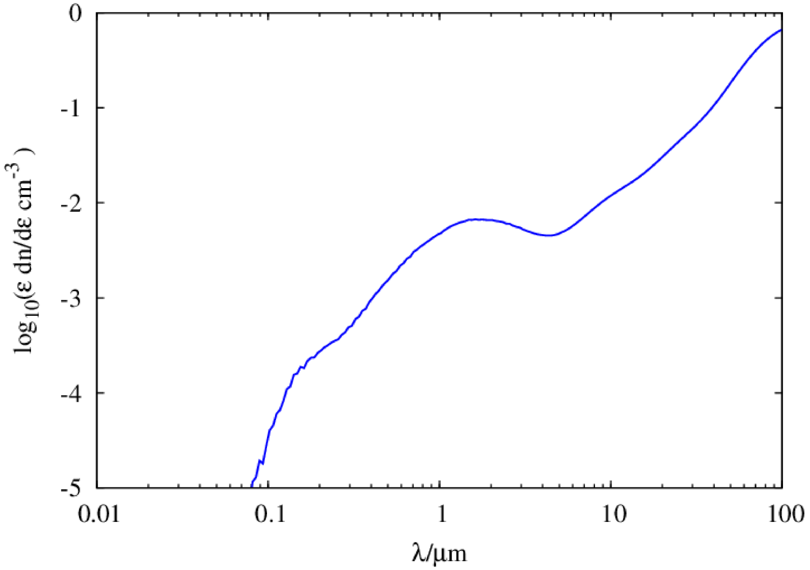
Excellent review: Hillas (2013)

Gamma-ray attenuation via pair-production

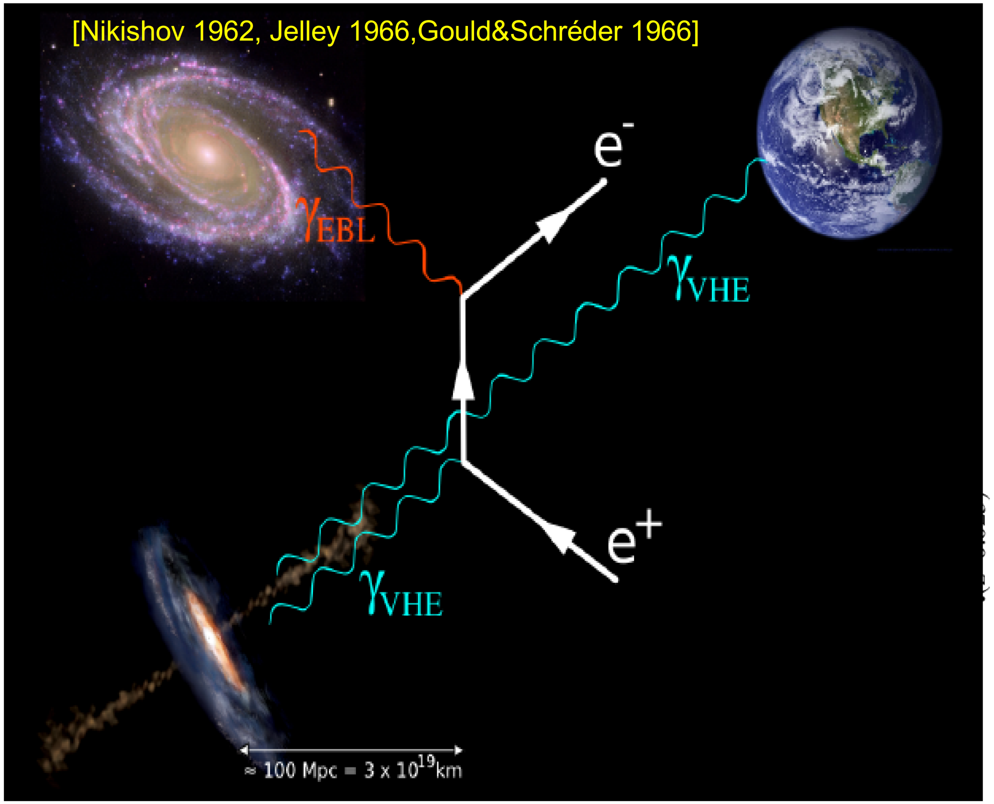


$$\tau_\gamma(E,z_0) = \int_0^{z_0} d\ell(z) \int_{-1}^{+1} d\mu \frac{1-\mu}{2} \int_{\epsilon_{\rm thr}}^{\infty} d\epsilon' n_{\rm EBL}(\epsilon',z)\sigma_{\gamma\gamma}(E,\epsilon',\mu)$$

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



Gamma-ray attenuation via pair-production



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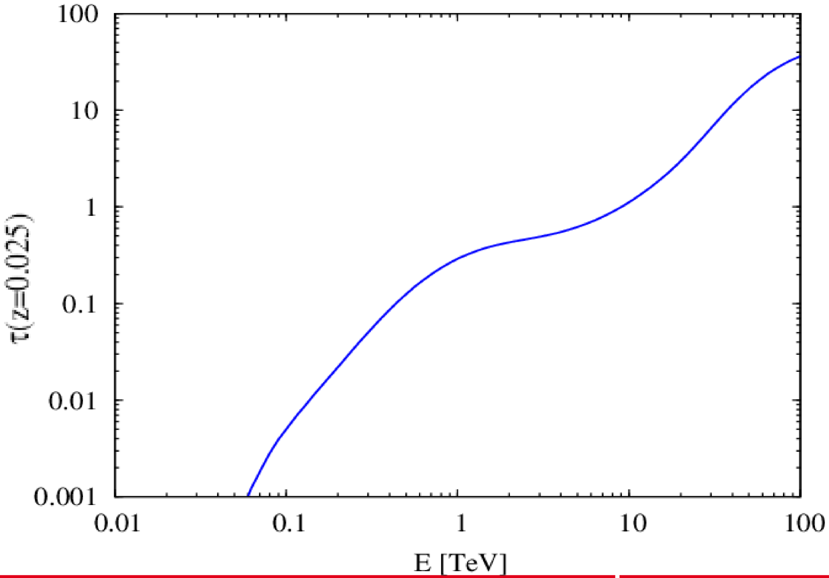

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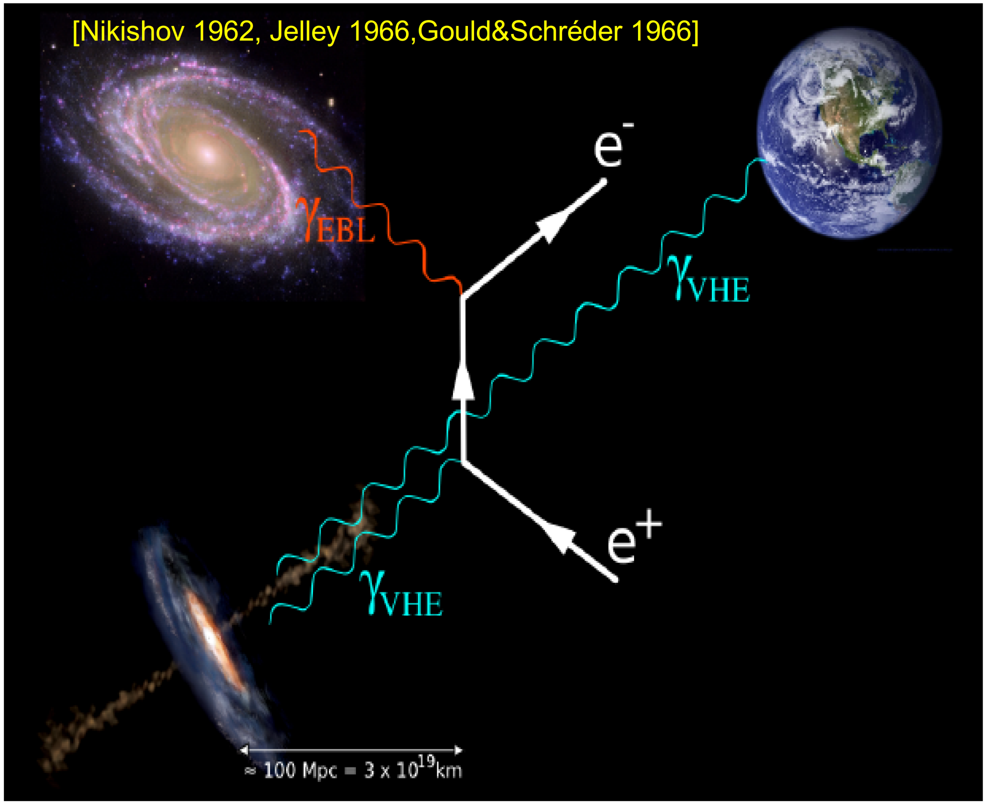

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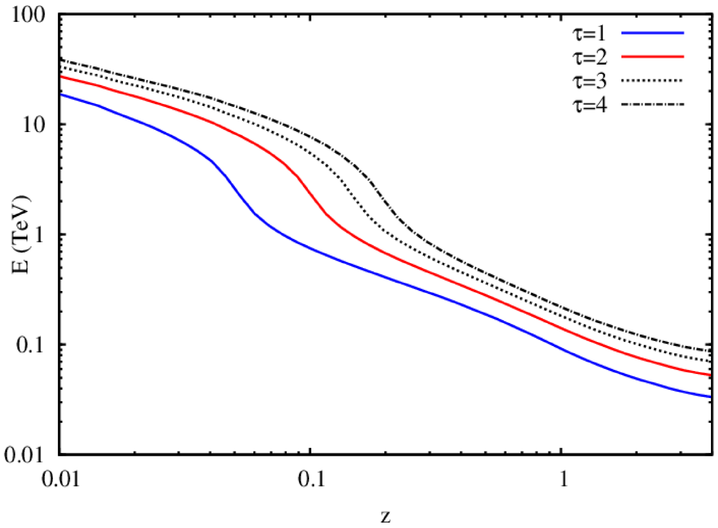
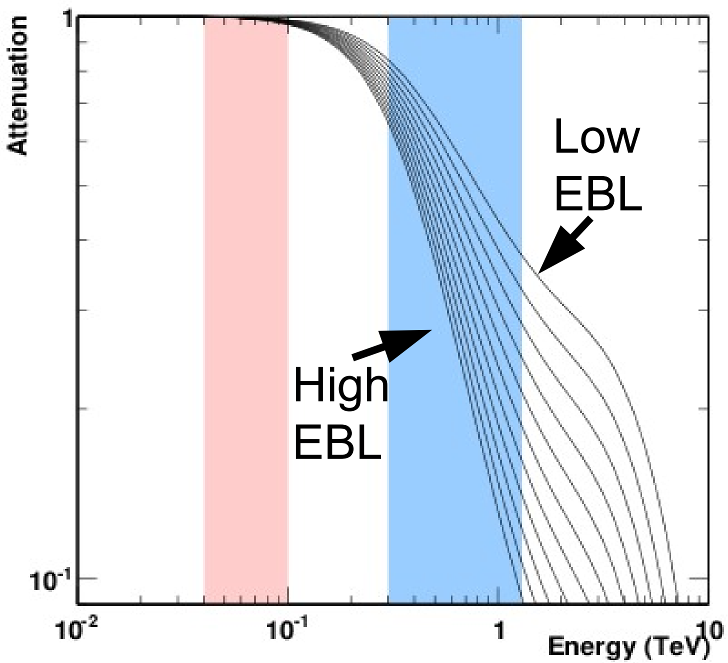
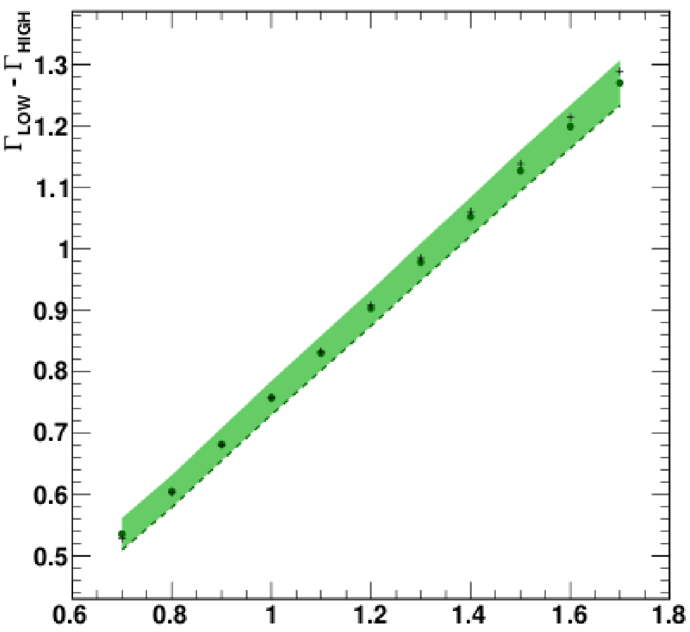


Measuring the EBL with VHE gamma-ray attenuation

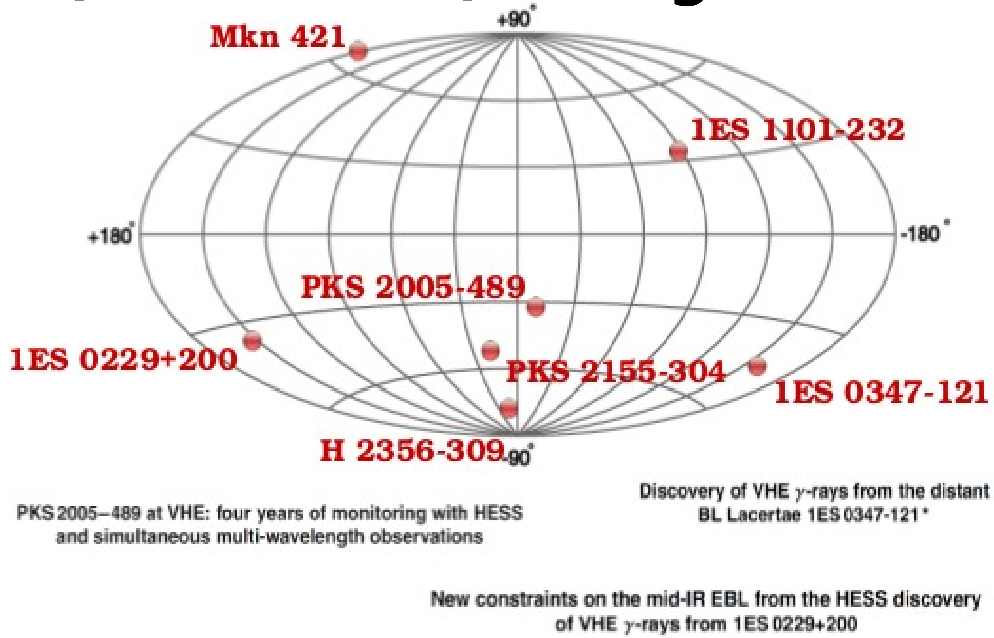
Raue & Mazin 2010
[arXiv:1005.1196]

z=0.116





First detection of the EBL (1-5 µm) at VHE (0.2-20 TeV) energies!!



Source	z	N_γ	$E_{\rm min} - E_{\rm max}$ [TeV]
Mrk 421 (*1*)	0.031	3381	0.95 – 41
Mrk 421 (*2*)	0.031	5548	0.95 – 37
Mrk 421 (*3*)	0.031	5156	0.95 – 45
PKS 2005-489 (*1*)	0.071	1540	0.16 – 37
PKS 2005-489 (*2*)	0.071	910	0.18 – 25
PKS 2155-304 (*2008*)	0.116	5279	0.13 – 19
PKS 2155-304 (*1*)	0.116	3499	0.13 – 5.7
PKS 2155-304 (*2*)	0.116	3470	0.13 – 9.3
PKS 2155-304 (*3*)	0.116	9555	0.13 – 14
PKS 2155-304 (*4*)	0.116	4606	0.18 – 4.6
PKS 2155-304 (*5*)	0.116	11901	0.13 – 5.7
PKS 2155-304 (*6*)	0.116	6494	0.15 – 5.7
PKS 2155-304 (*7*)	0.116	8253	0.20 – 7.6
1ES 0229+200	0.14	670	0.29 – 25
H 2356-309	0.165	1642	0.11 – 34
1ES 1101-232	0.186	1268	0.12 – 23
1ES 0347-121	0.188	604	0.13 – 11

Data sets on highly significant sources were divided and sorted by flux level

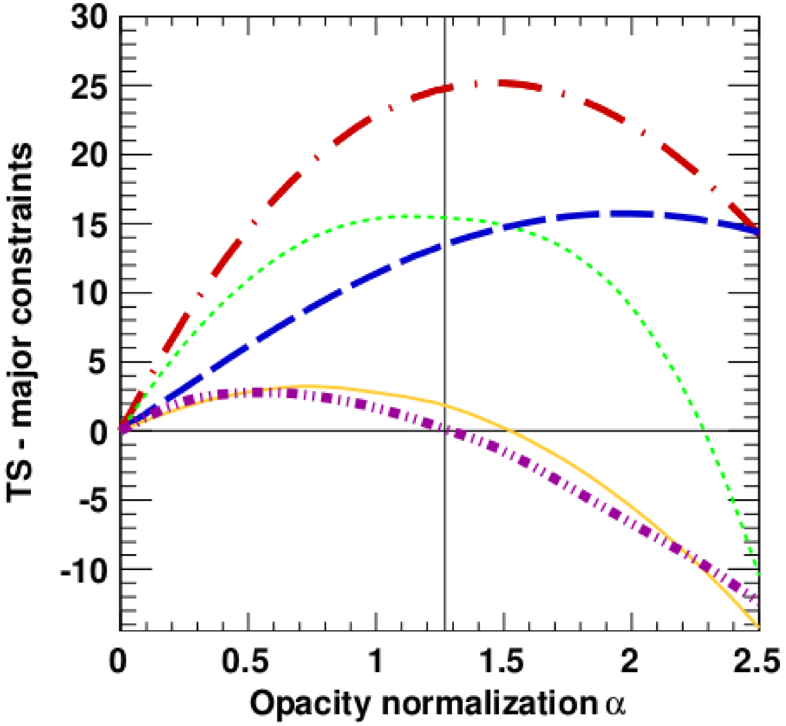
75 000 γ-rays from the seven brightest blazars, with 0.03 < z < 0.19, collected during 400 hours with H.E.S.S.

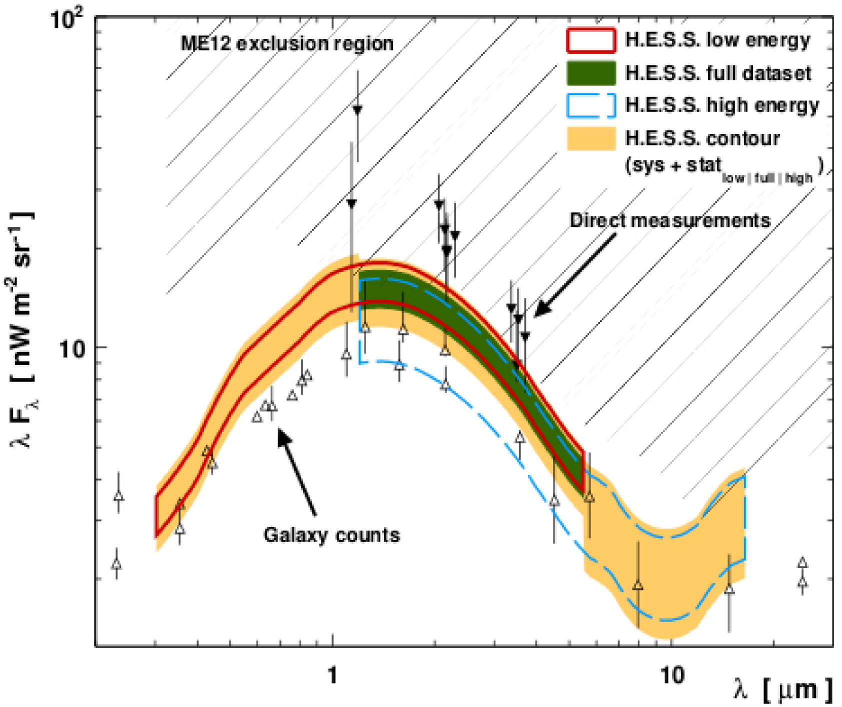
Biteau,
H.E.S.S coll. (2013)
[arXiv:1212.3459]

First detection of the EBL (1-5 μm) at VHE (0.2-20 TeV) energies!!

H.E.S.S coll. (2013) [arXiv:1212.3459]

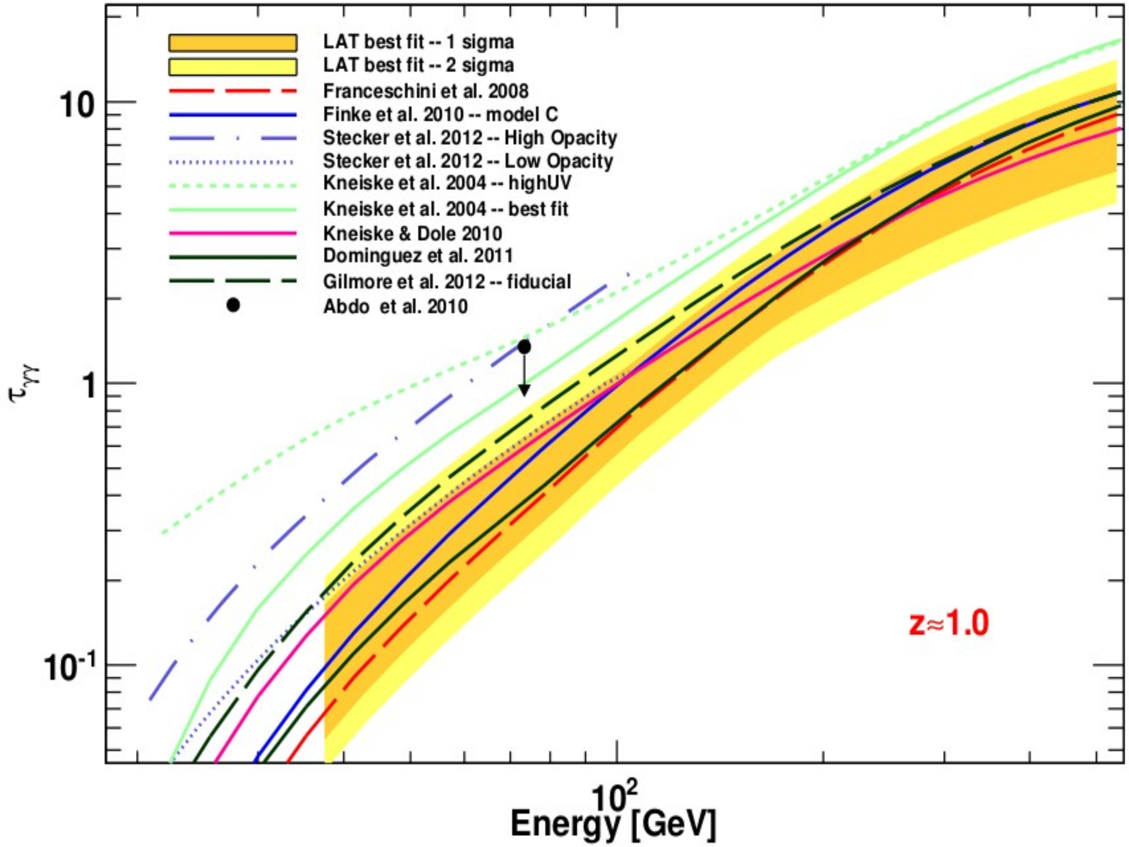
Fit of normalization: $$\phi(E,z) = \Phi(E)\cdot\exp(-\alpha\tau(E,z))$$



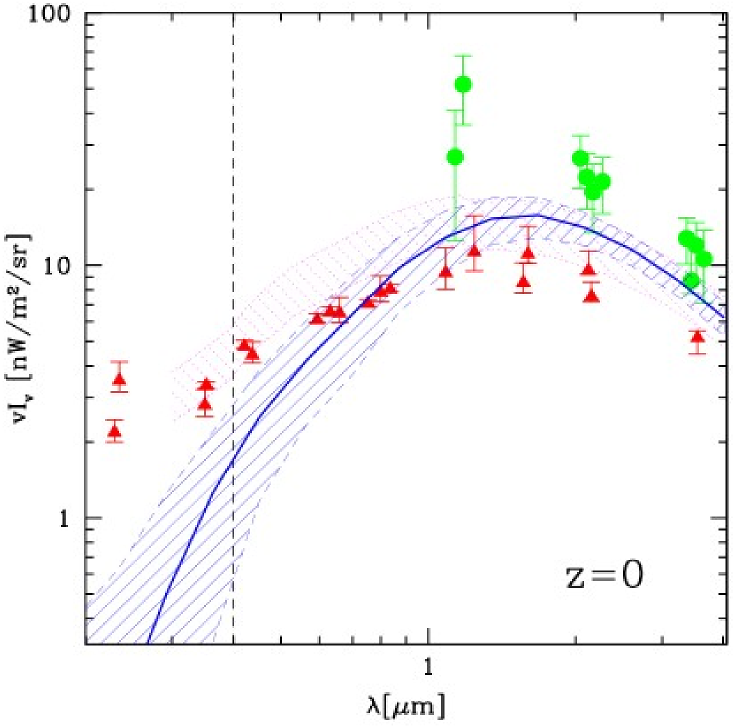


Detection of the EBL at high energies

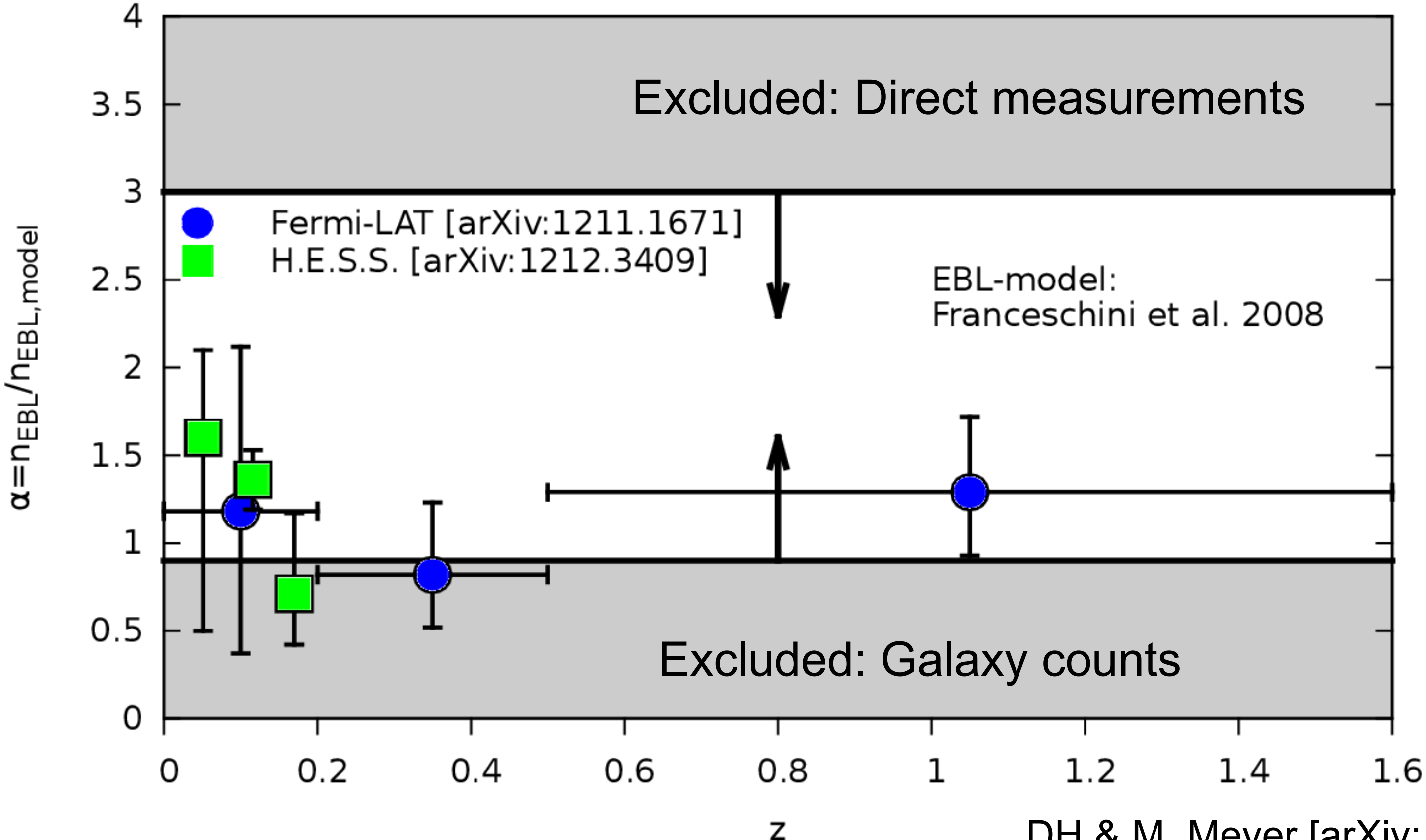
Fermi-LAT coll.Science 2012 [arXiv:1211.1671]



Similar results
Gong&Cooray [arXiv:1305.5249]



Consistency of the EBL-measurements



DH & M. Meyer [arXiv:1309.3846]

Hidden treasures?

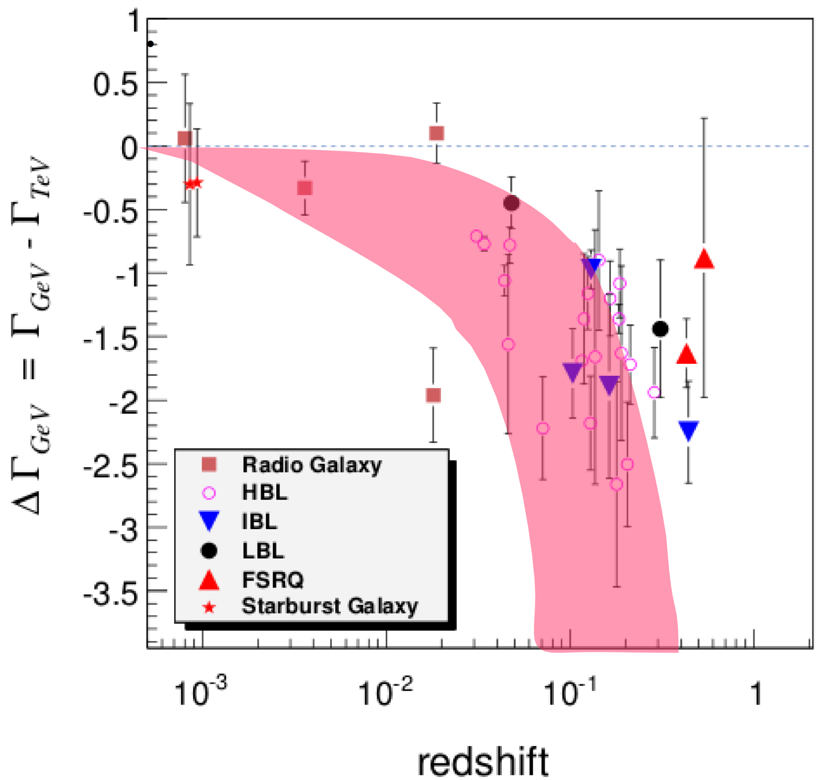
- EBL measurement leaves little room for additional components (QSO at UV, first stars, decaying dark matter, …)
- In fact, the measured EBL falls below the lower limit from Galaxy counts

Indications for modified optical depth

Adapted from Dwek&Krennrich 2012

- De Angelis et al. 2009, 2011, 2013:

  The observed TeV spectra are too hard.



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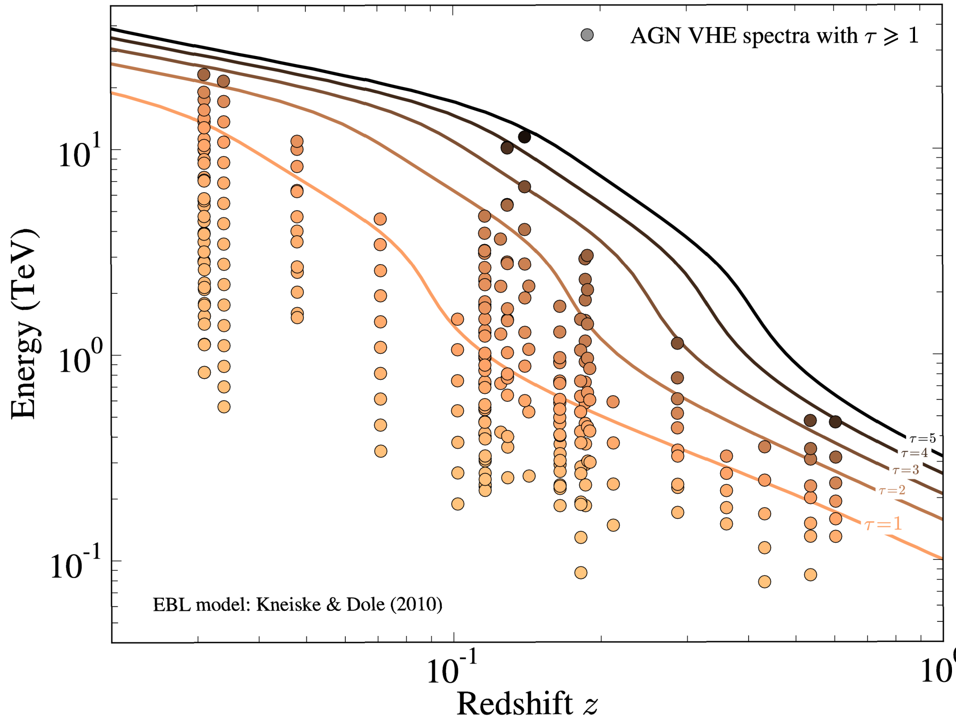
- DH and Meyer 2012 [arXiv:1201.4711]: The attenuation of VHE spectra at τ>2 is too small (at ~4 σ)



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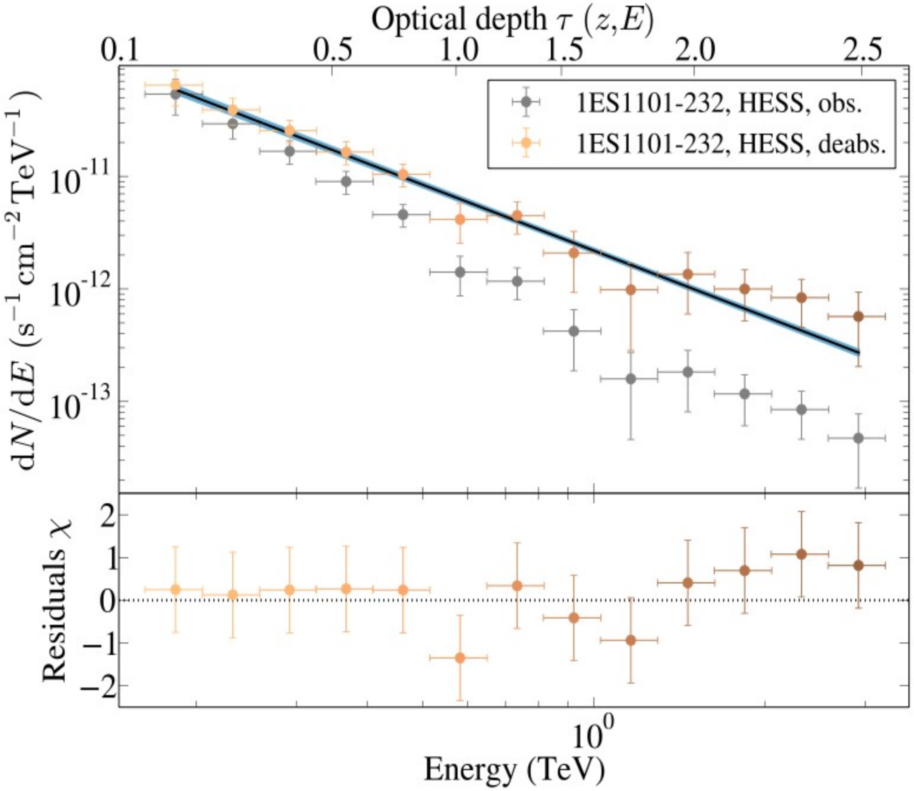

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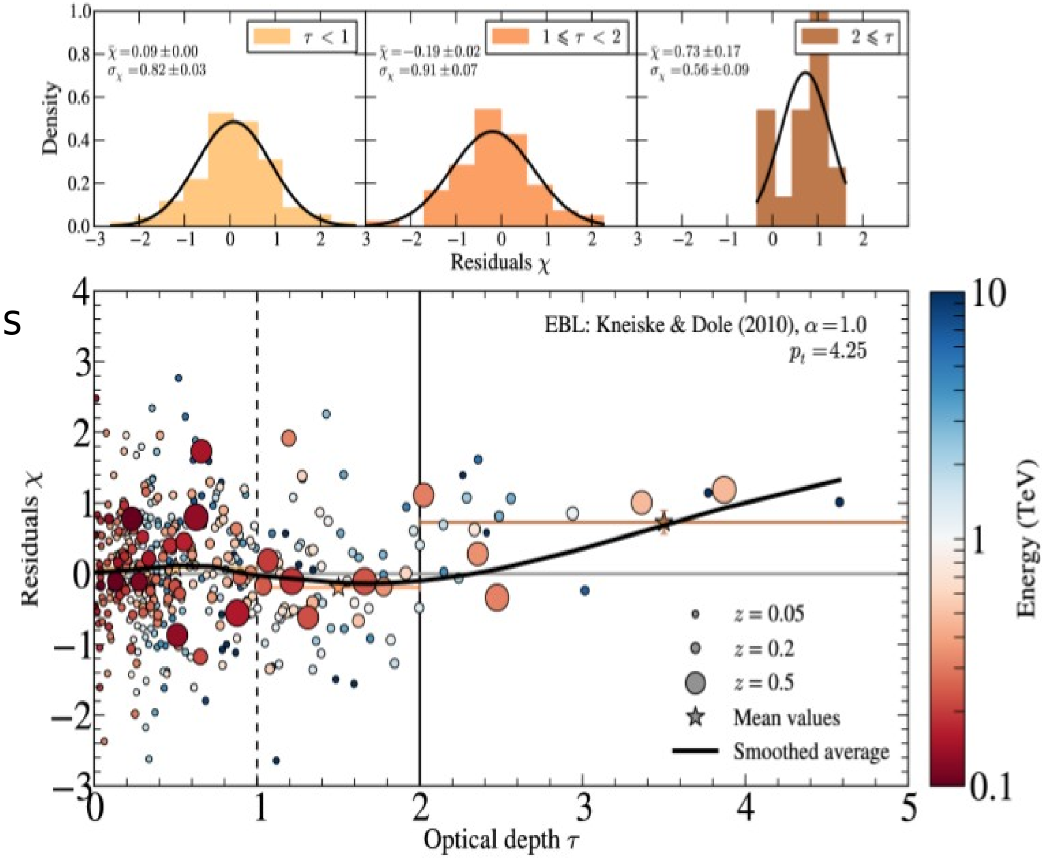
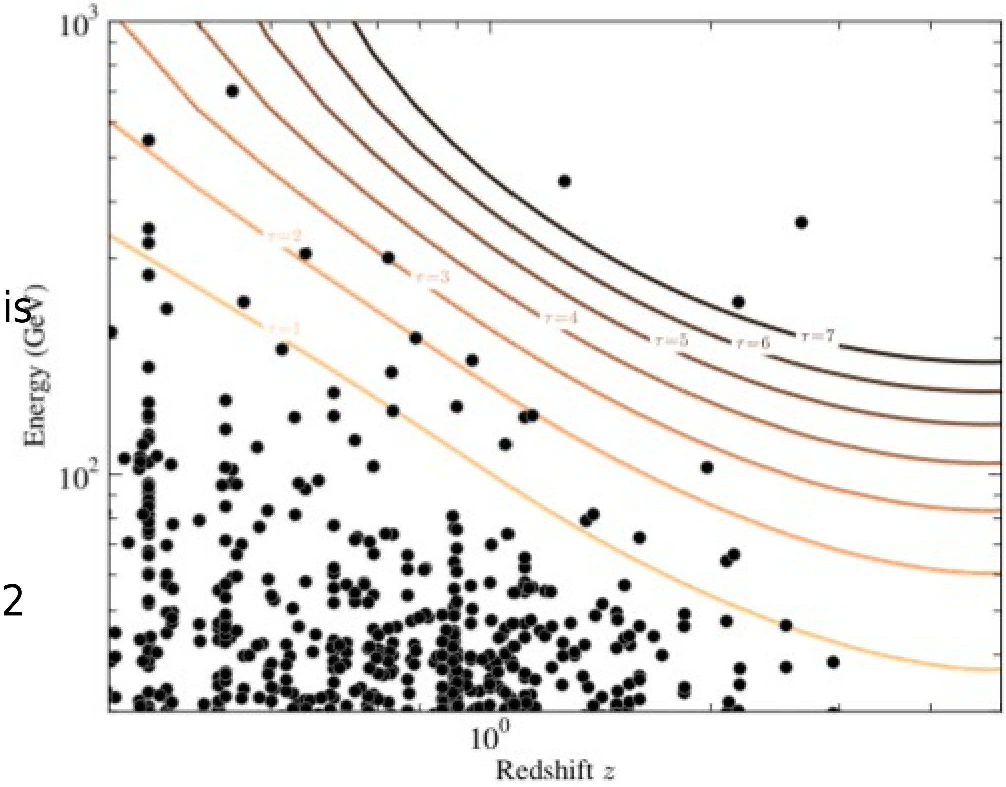


Indications for modified optical depth

- De Angelis et al. 2009, 2011, 2013:

  The observed TeV spectra are too hard.
- DH and Meyer 2012 [arXiv:1201.4711]: The attenuation of VHE spectra at $\tau>2$ is too small (at ~4 σ)
- Meyer 2013 (desy-thesis 2013-33), DH and Meyer 2013[arXiv:1309.3846]: Fermi-LAT photon (~3.5σ) excess at $\tau>2$



Proposed ways to explain the transparency anomaly:

- Gamma-ray/cosmic-ray induced cascades → TeV emission is secondary nature (e.g., Essay & Kusenko 2010)
- Lorentz invariance violation (e.g., Jacob&Piran 2008, Shao&Ma 2010)
- Oscillations into hidden photons (e.g., Jaeckel&Ringwald 2010; Jaeckel 2013 for reviews)
- Oscillations into axion-like particles (e.g., Jaeckel&Ringwald 2010, Carosi et al. 2013)

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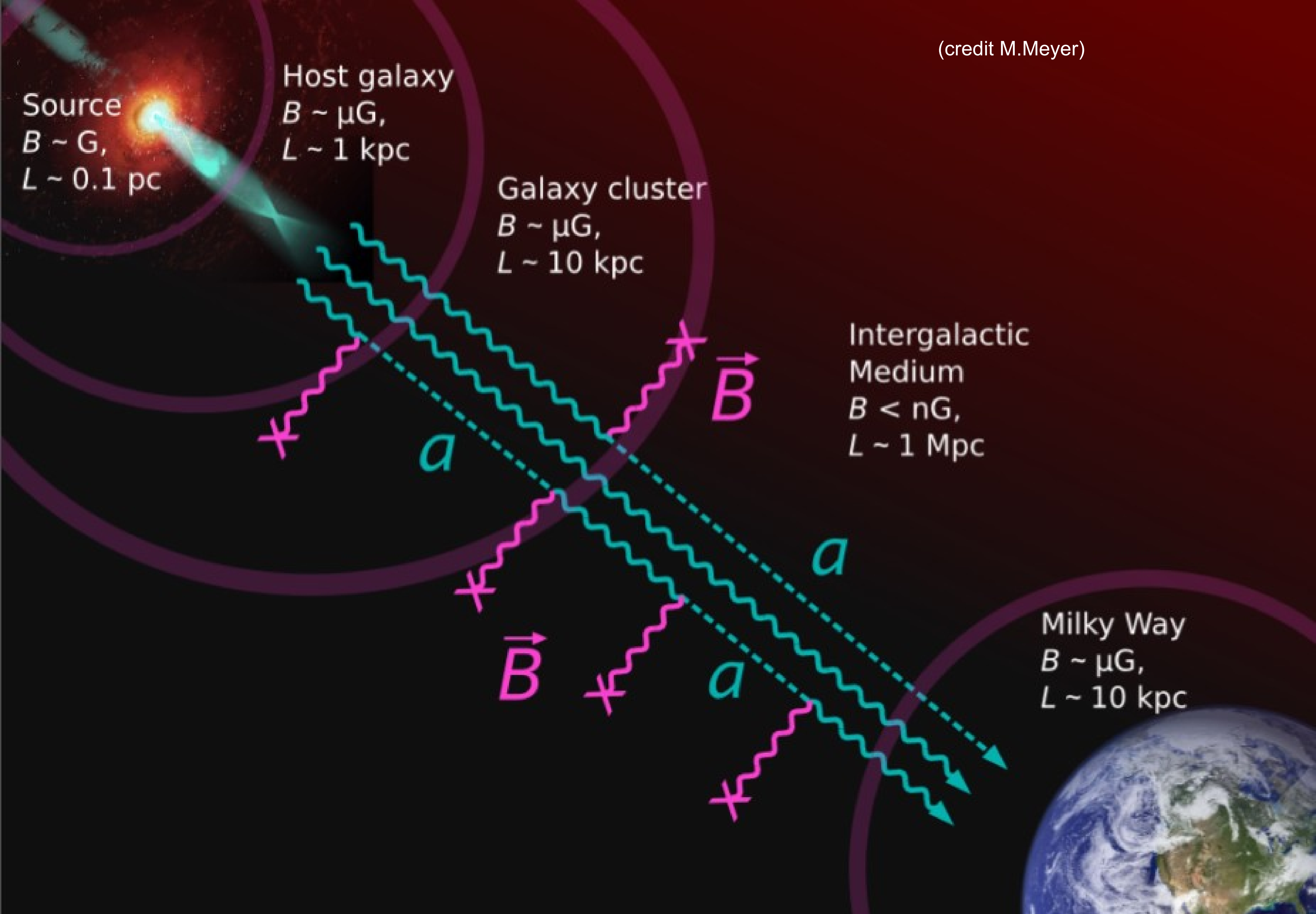
Peccei-Quinn symmetry
And axion-like particles

Peccei-Quinn symmetries ↔ Axion & ALPs

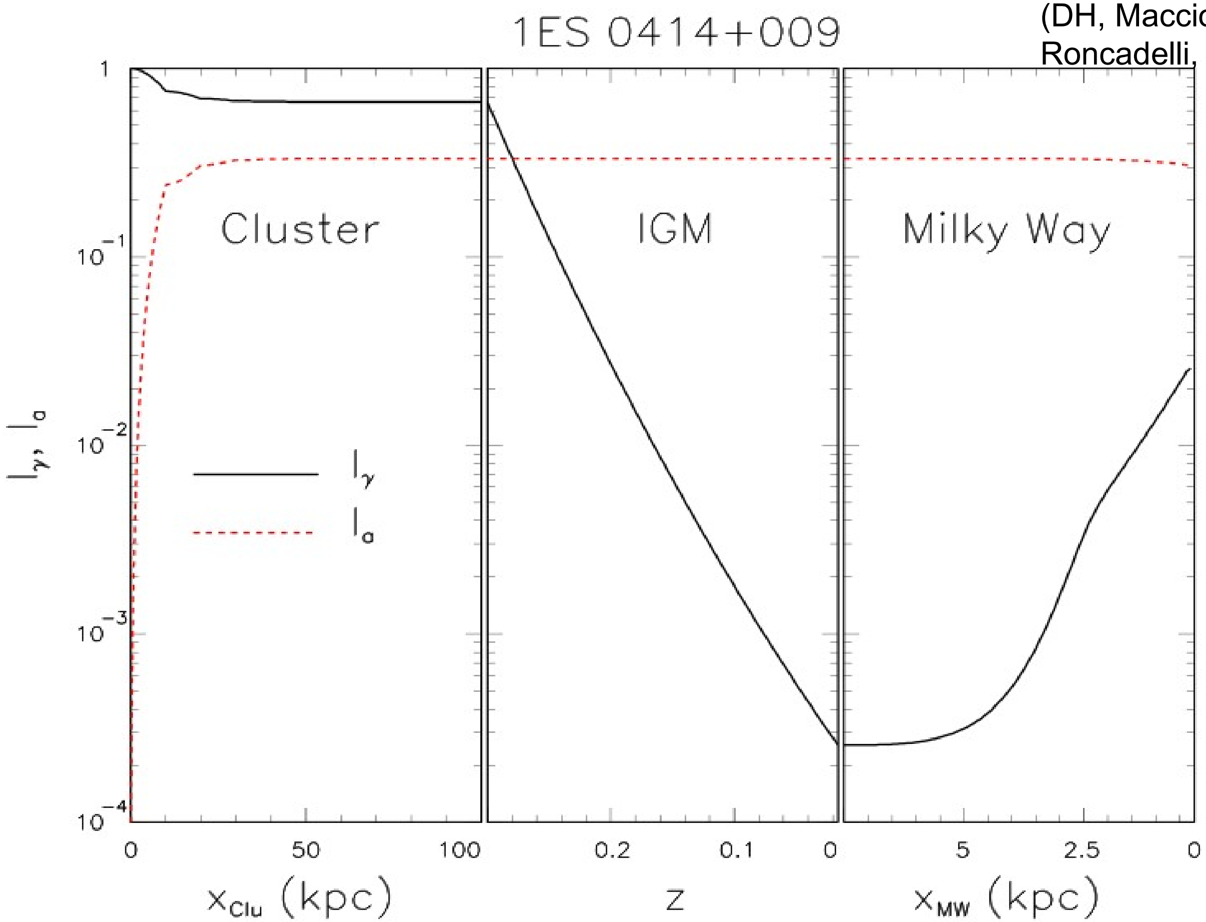
- Additional symmetry to cure strong CP problem (Peccei&Quinn 77), leading „axion“ particle (Weinberg 78, Wilczek 78) with non-vanishing coupling to photons
- Generic $U(1)_{PQ}$ → $\mathcal{L} \supset -\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
  - Motivated by string compactifications („top bottom“) → axiverse
  - Phenomenological solution to CP-Problem, Dark Matter, neutrino-masses, baryon asymmetry, stability of vacuum
- *Rich phenomenology through photon coupling of ALPs (Jaeckel&Ringwald 2010)*



[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]

Effect of gamma-ALPs mixing on propagation

(DH, Maccione, Meyer, Mirizzi, Montanino, Roncadelli, arXiv: 1207.0776)



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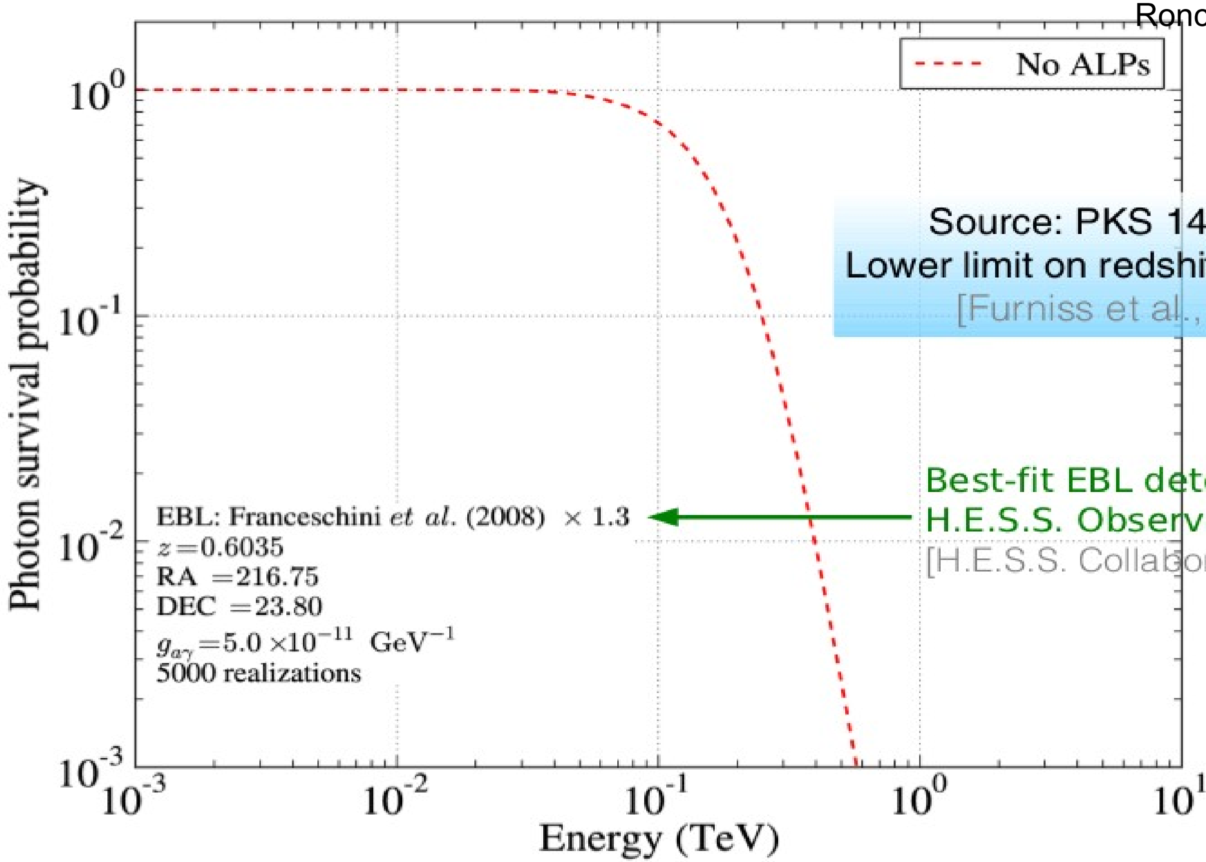
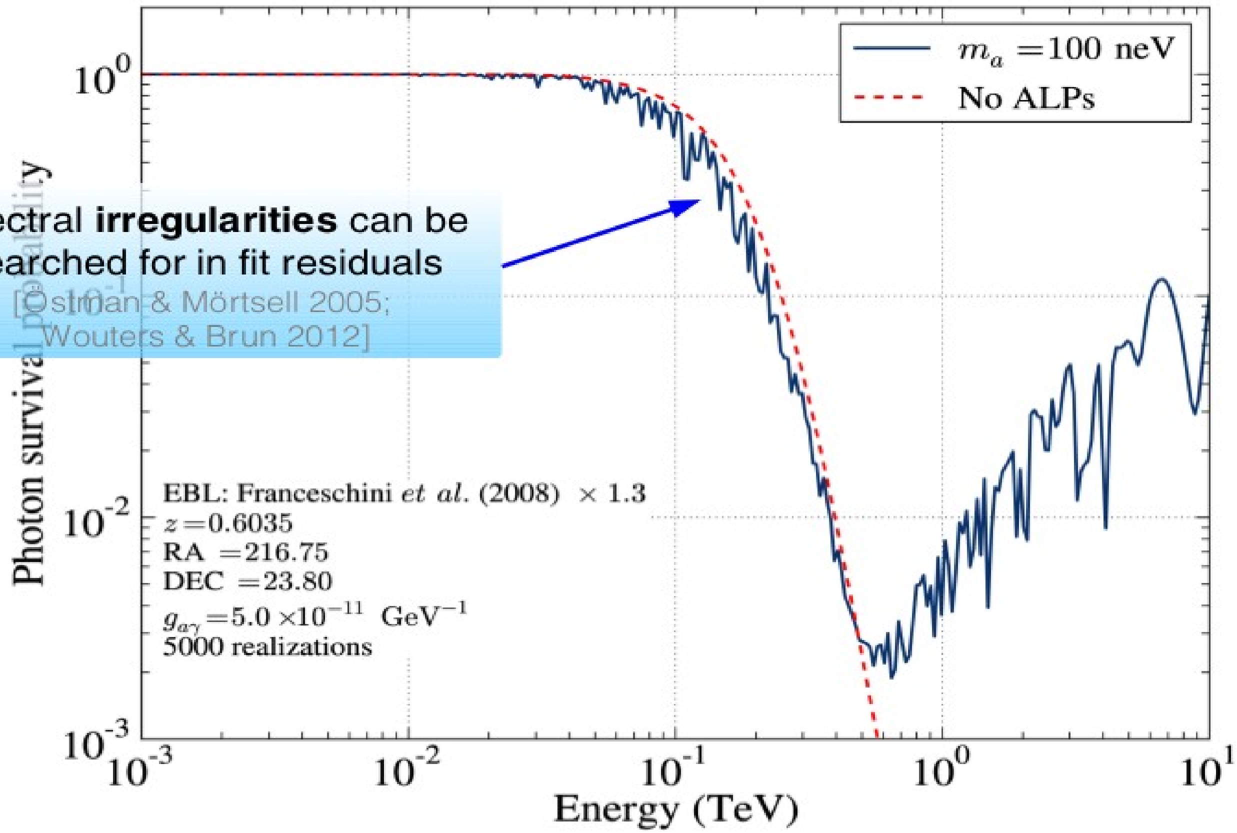


Source: PKS 1424+240
Lower limit on redshift z ≥ 0.6035
[Furniss et al., 2013]

Best-fit EBL determined with H.E.S.S. Observations
[H.E.S.S. Collaboration, 2013]

Effect of gamma-ALPs mixing on propagation

(DH, Maccione, Meyer, Mirizzi, Montanino, elli, arXiv: 1207.0776)



Spectral **irregularities** can be searched for in fit residuals
[Östman & Mörtsell 2005; Wouters & Brun 2012]

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Fachbereich
Physik

Effect of gamma-ALPs mixing on propagation

(DH, Maccione, Meyer, Mirizzi, Montanino,
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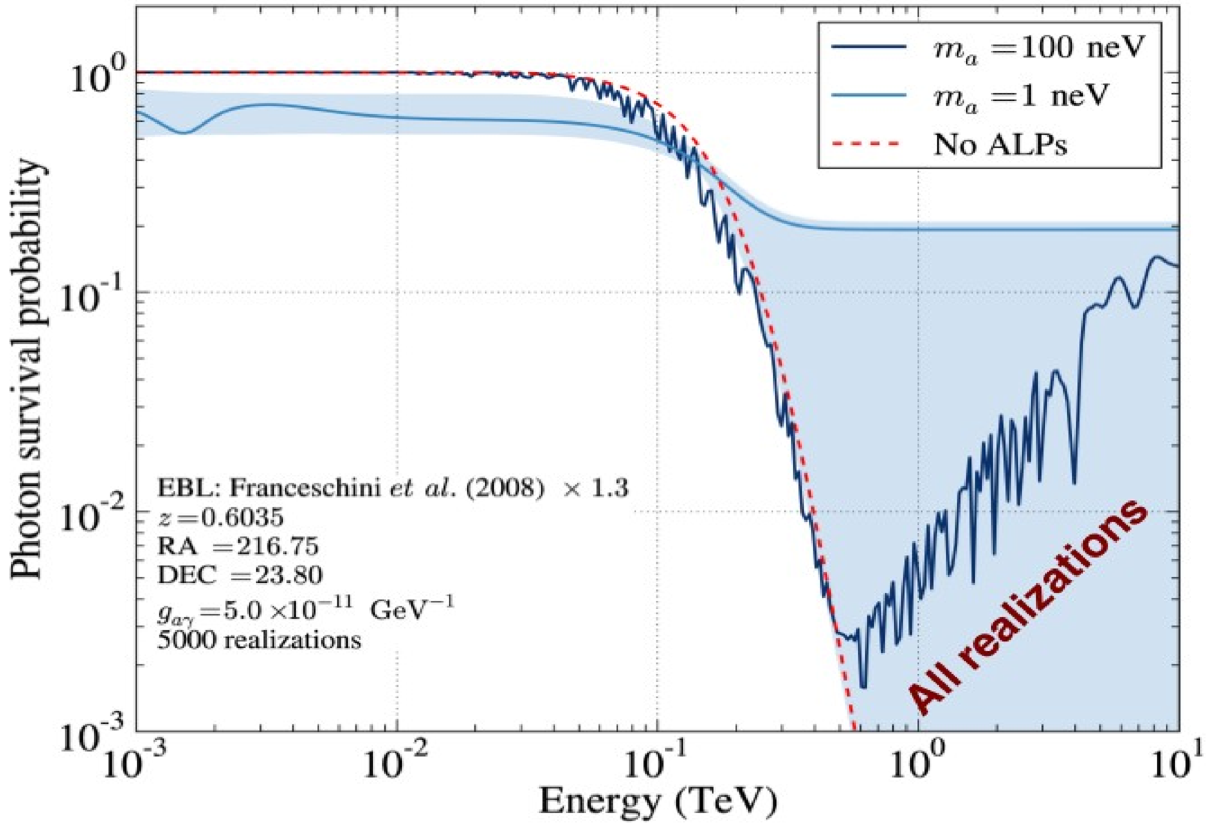

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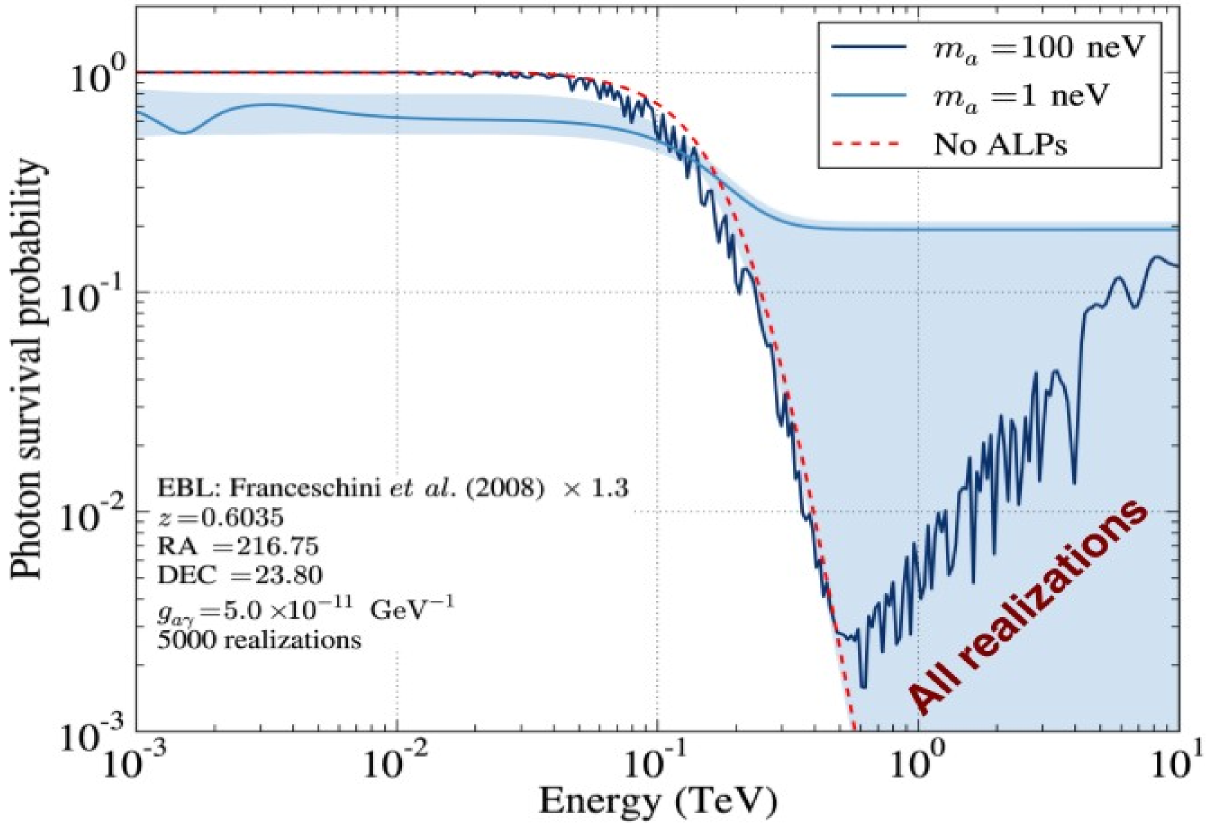

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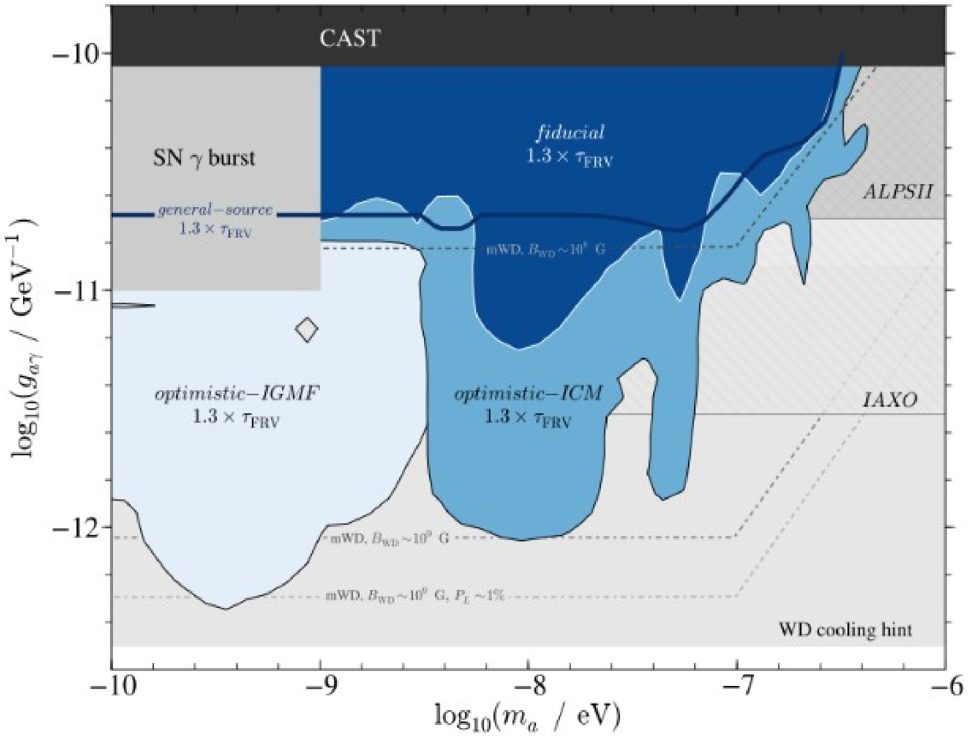
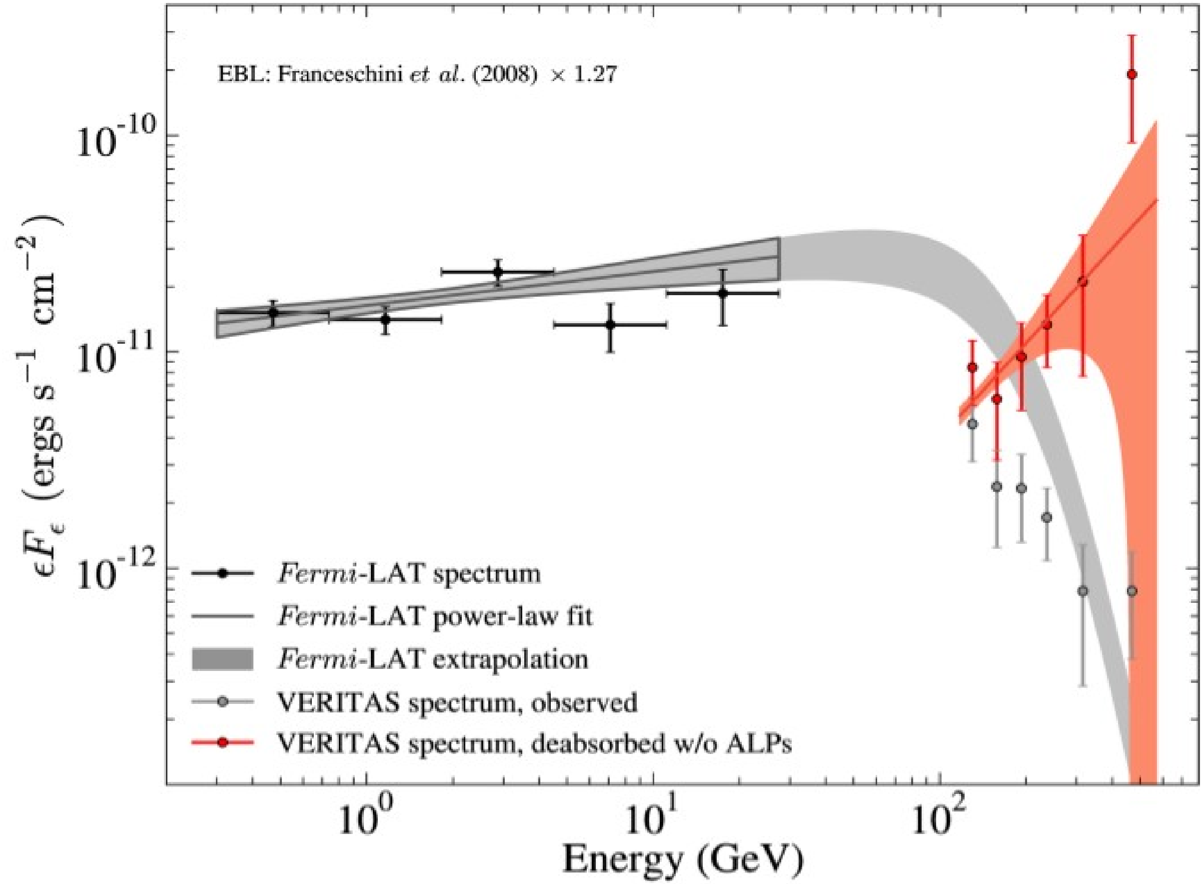
Physik

Lower limit on coupling $g_{a\gamma}$

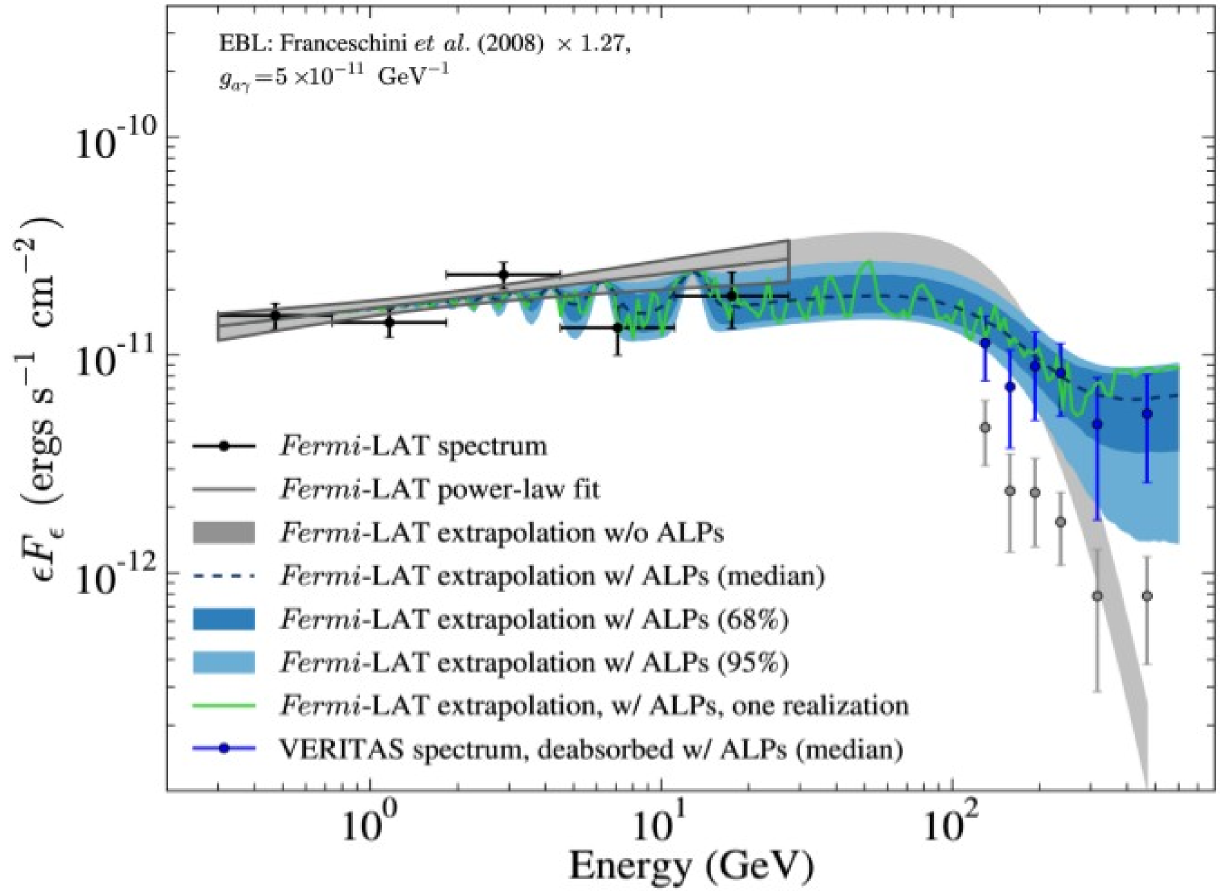


- Coupling within reach of future helioscope IAXO (Irastorza et al. 2013), light-shining-through the wall ALPS-II (Bähre et al. [arXiv:1302.5647])
- Coupling consistent with anomalous cooling of WD (Isern et al. 2008)

A closer look on PKS 1424+240



A closer look on PKS 1424+240



Summary

- Extra-galactic background light constrained by galaxy counts and direct measurements: 10..30 nW/(m^2 srad) in the optical/NIR
- Detection of absorption feature with Fermi-LAT and HESS at 8..18 nW/(m^2 srad) ↔ tension with galaxy counts
- Indications (4 σ) for excess transparency at large optical depth (both with Fermi-LAT and Cherenkov telescopes)
- Observations consistent with photon/ALPs mixing (m_a<100 neV, $g_{a\gamma}$>10^{-12} GeV^{-1}

Outlook

- New VHE spectra available since ICRC 2013 (confirms and strengthens previous finding)
- Improved Fermi-LAT calibration/background rejection, more exposure, higher energy reach (up to 3 TeV) soon
- HESS-II accumulates data
- CTA in preparation (>2017)
- ALPS-II ideal laboratory experiment to search for gamma-ALPs mixing