Characterizing Cosmological Fields with Blazar Observations: the EBL and IGMF

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eXtreme19
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
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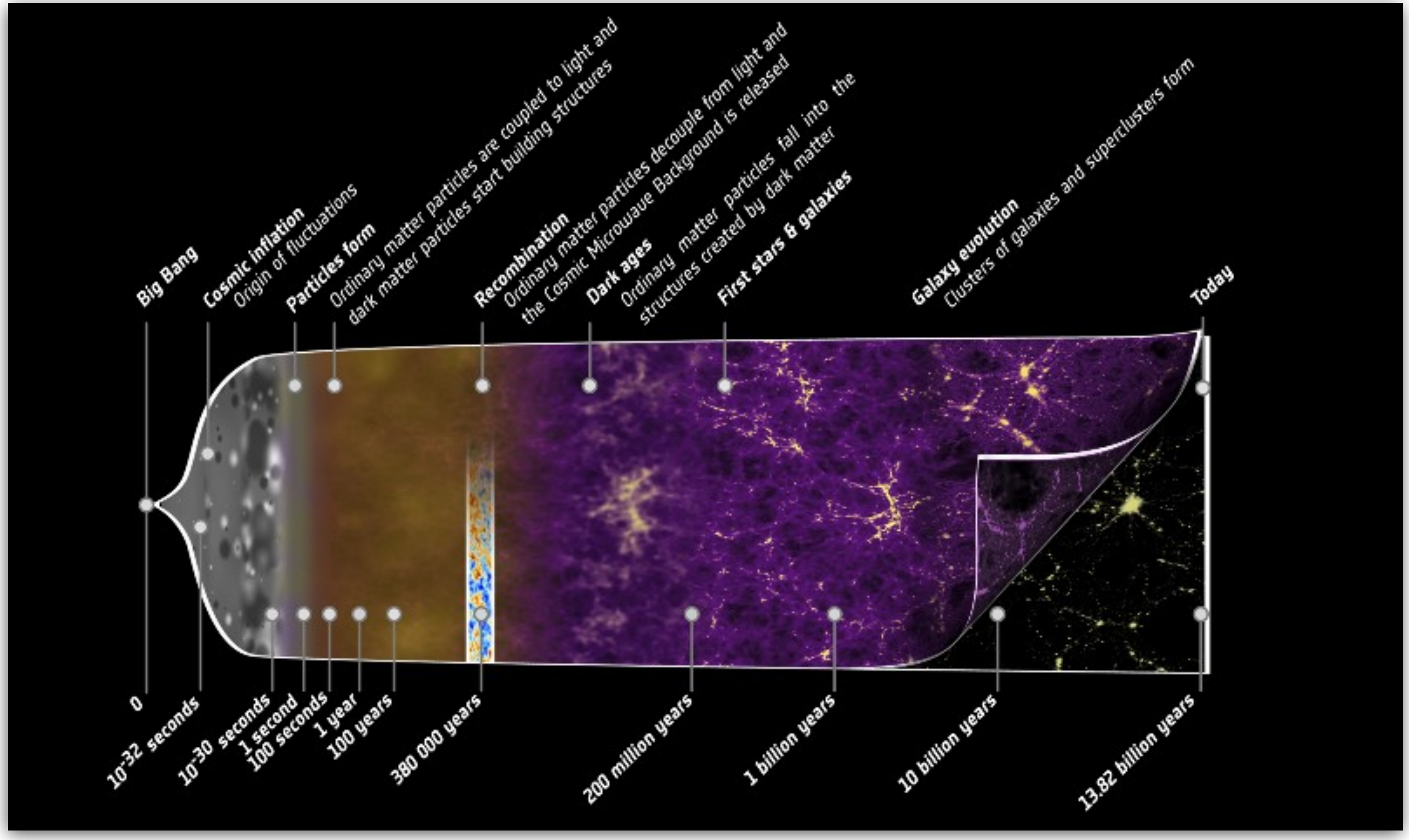
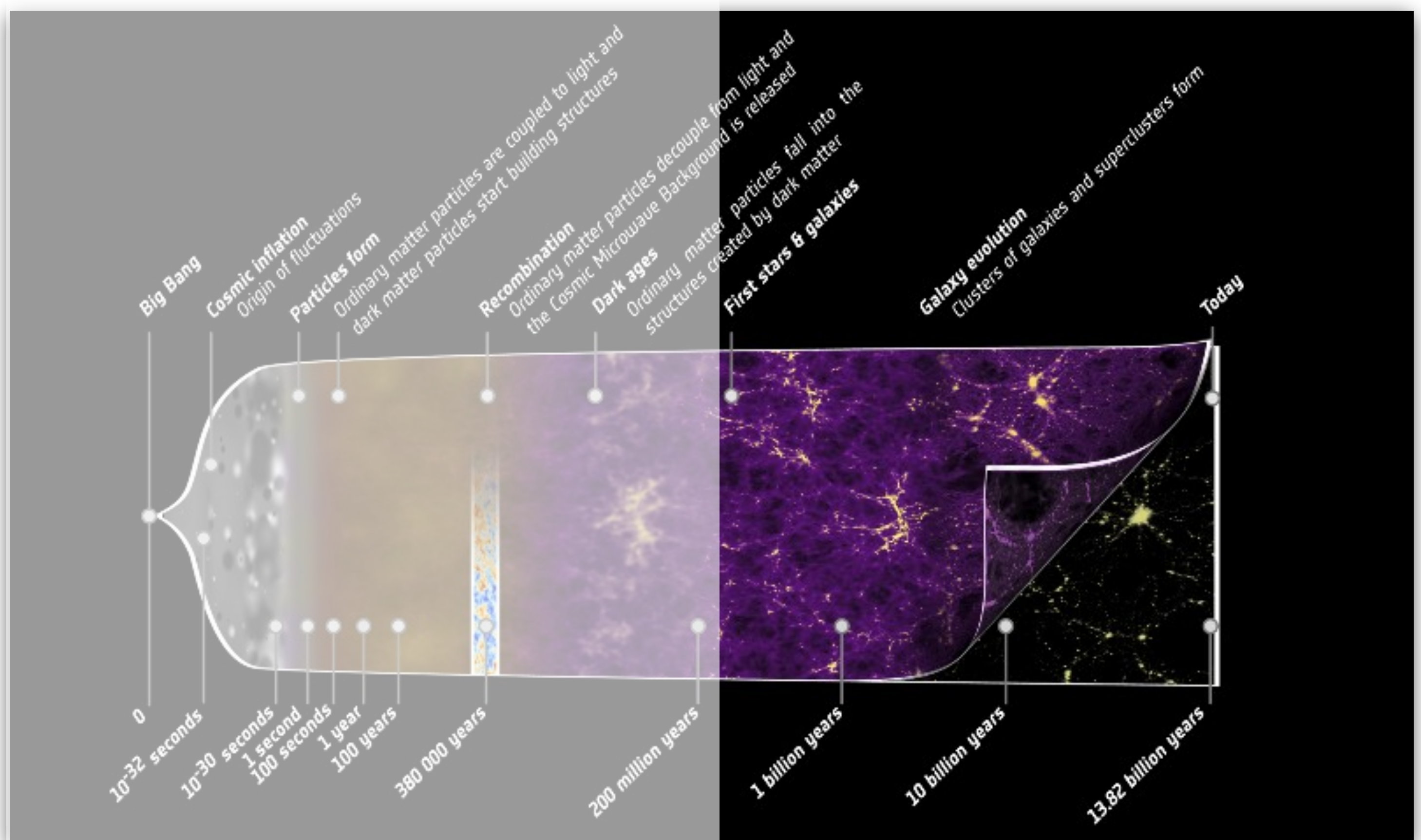
DESY.

The Big Picture: Cosmology



Many observables that reflect the universe's evolution
Including **diffuse light** and **magnetic fields**

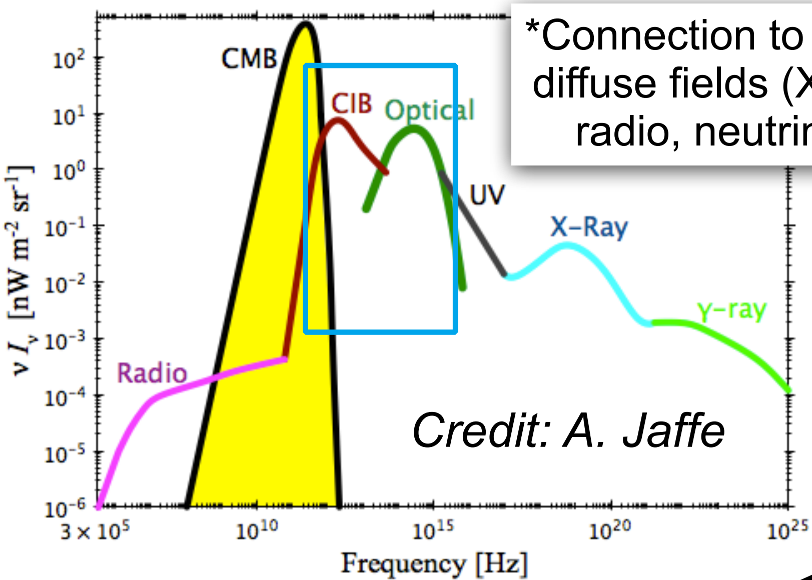
Extragalactic Background Light



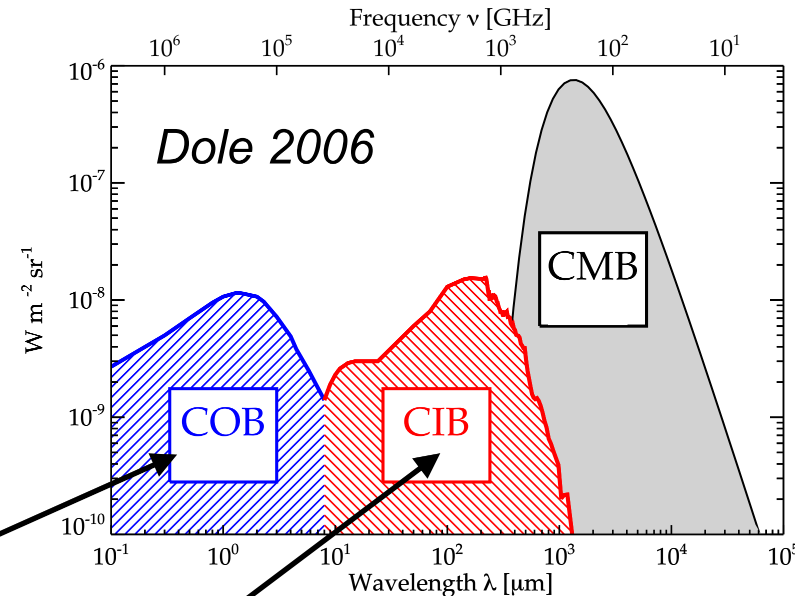
Imprint from reionization, star formation, galaxy evolution, emission by active galactic nuclei
Unresolved sources? Dark matter decay? Exotic physics?

Extragalactic Background Light

Refers to one part of the diffuse photon background



*Connection to other diffuse fields (X-ray, radio, neutrino)



- COB = **Cosmic optical** background
- Light from stars, galaxies, etc

- CIB = **Cosmic infrared** background
- Light reprocessed by dust

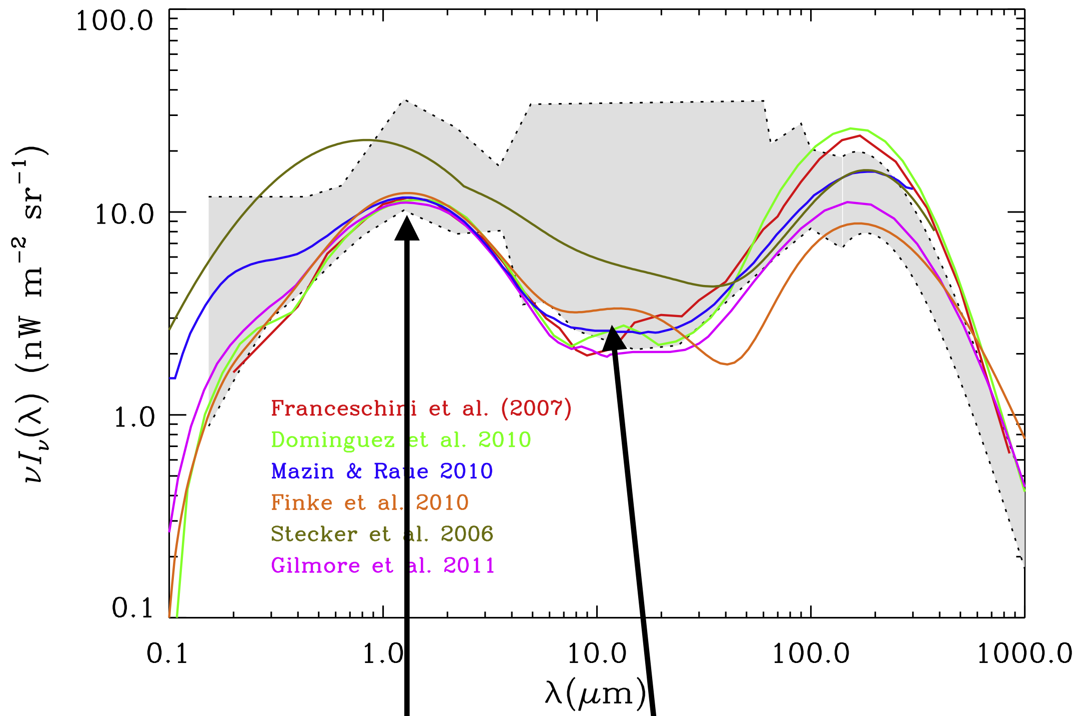
EBL density evolves with time/redshift

Modeling the Extragalactic Background Light

Multiple approaches to predict the EBL intensity & spectrum

- **Backward evolution** models
  - Start with local luminosity density + galaxy number counts
- **Forward evolution** models
  - Start with cosmic star formation rate, radiative transfer + population synthesis models
- **Semi-analytical** models
  - Start with ΛCDM universe
  - Account for dark matter, baryonic physics, feedback in galaxy evolution

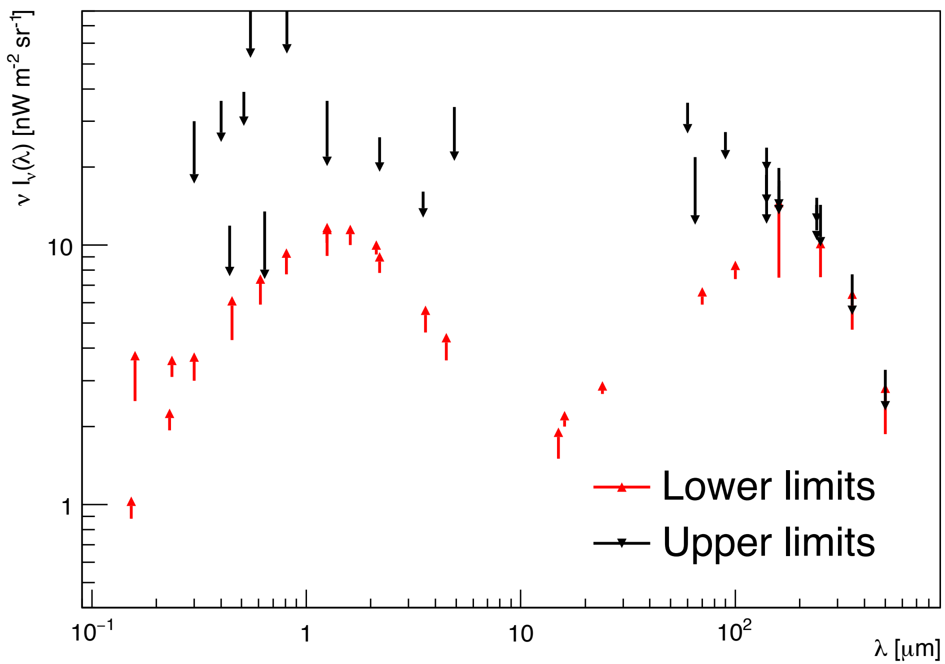
Dwek & Krennrich 2013



Good agreement

Models start to diverge

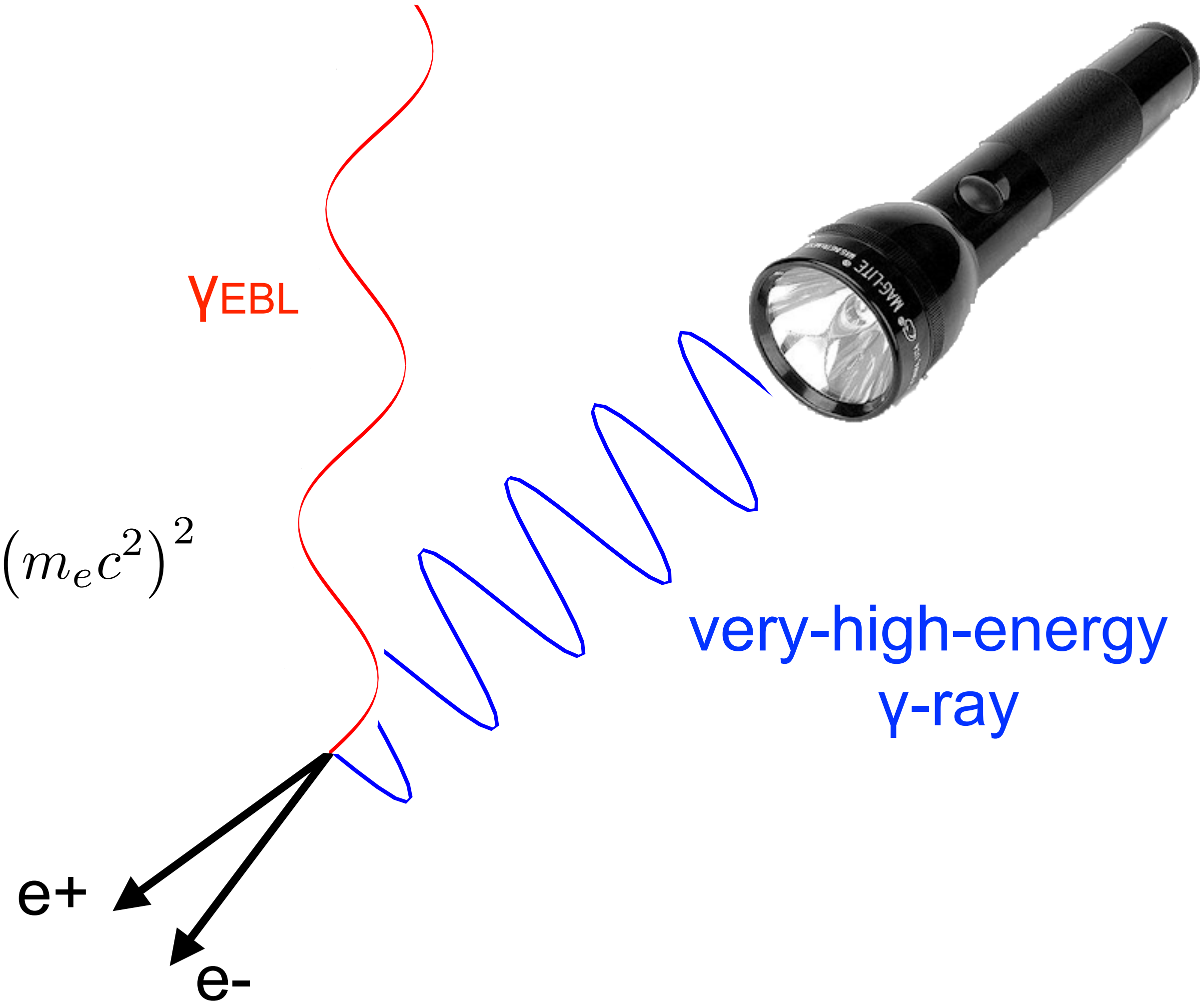
Measuring the Extragalactic Background Light



- **Direct measurements** of night sky background
  - Sensitive to foreground contamination
  - Treat as **upper limits**
- **Galaxy counts** in magnitude bands
- Stacking analysis
  - Not sensitive to diffuse/ unknown components
  - Treat as **lower limits**

Indirect Measurements of EBL with Gamma-ray Emitters

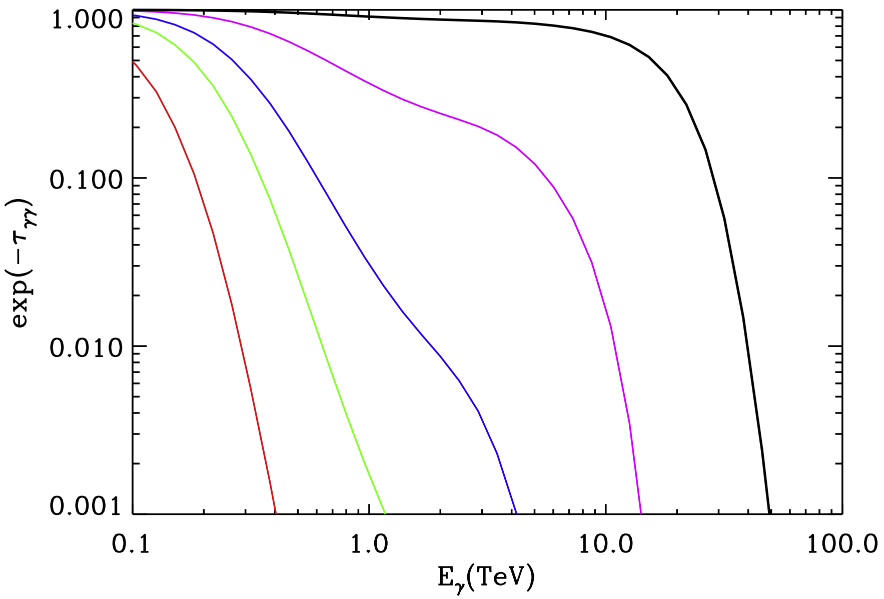
$$E'_\gamma \epsilon'_{\mathrm{EBL}} \geq \left(m_e c^2\right)^2$$

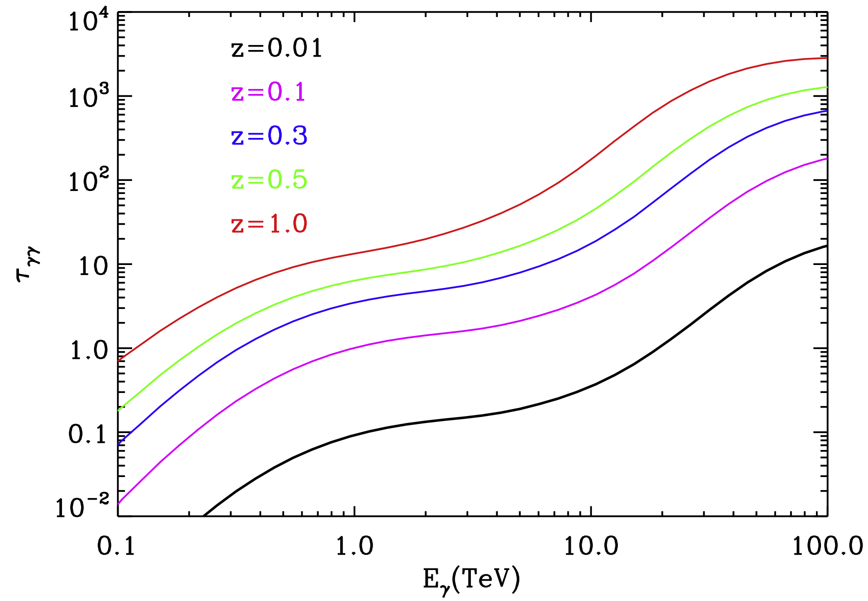


Photons from distant gamma-ray sources interact with **EBL photons** via **pair production**, VHE γ-ray flux attenuated

TeV Transparency

- Optical depth τ increases with **energy** and **redshift**
  - Depends on γγ interaction cross-section and number density of EBL photons (product integrated over distance, energy and angle)





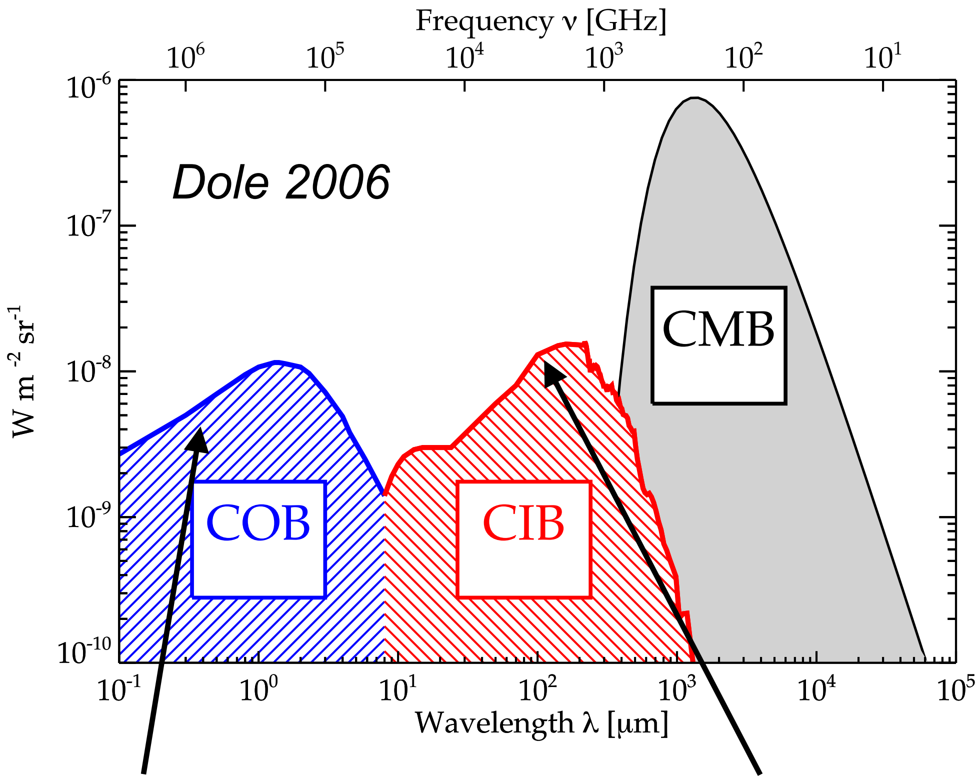
Dwek & Krennrich 2013

To probe full EBL spectrum, need gamma-ray sources emitting to **high energies**, located out to **large distances**

DESY.

Probing the EBL Spectrum

$$\lambda_{\mathrm{EBL}} \simeq 0.5 - 5\,\mu\mathrm{m} \times \left(\frac{E_\gamma}{1\,\mathrm{TeV}}\right) \times (1+z)^2$$

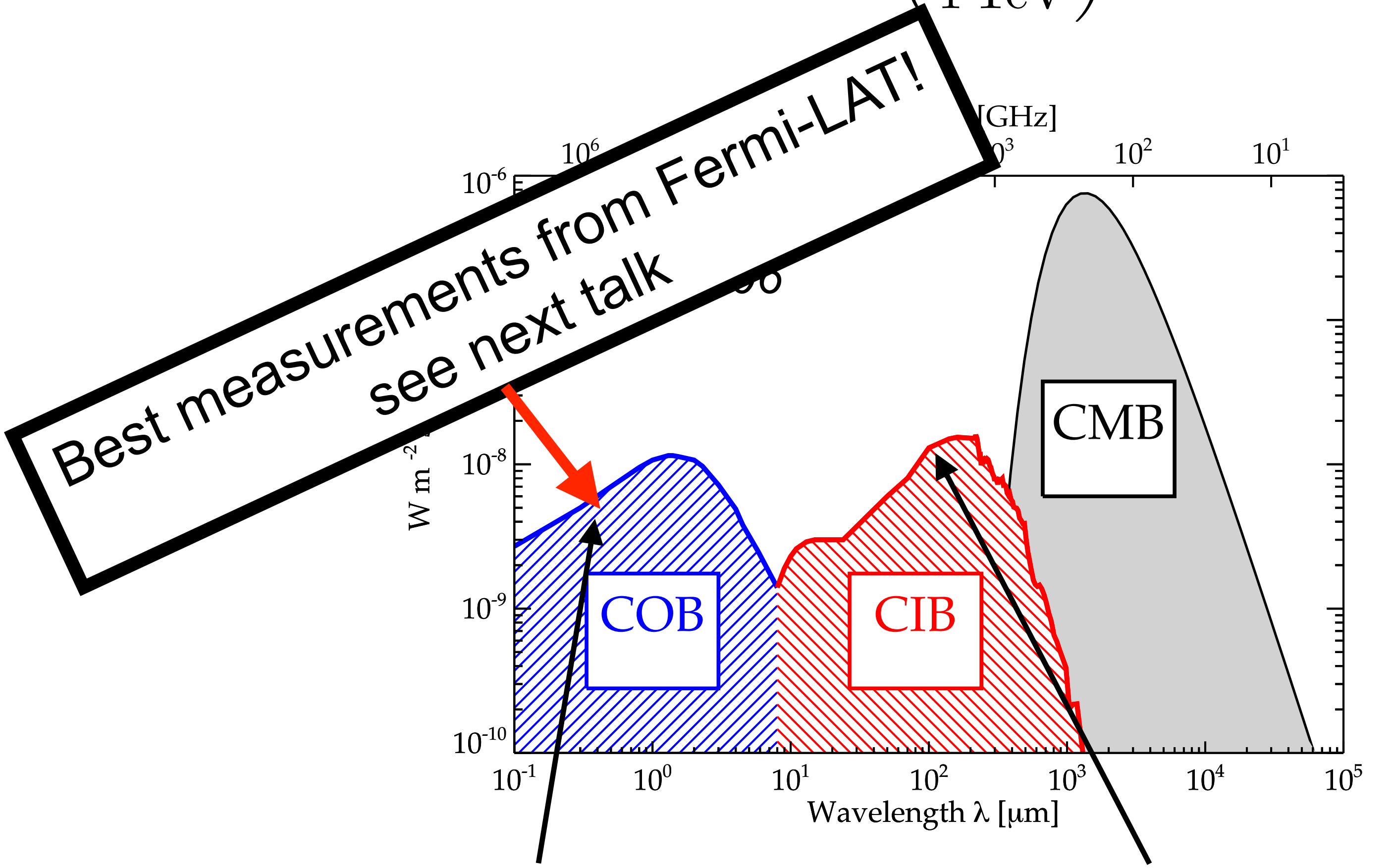


Dominated by distant sources

Dominated by (relatively) nearby and “extreme” sources

Probing the EBL Spectrum

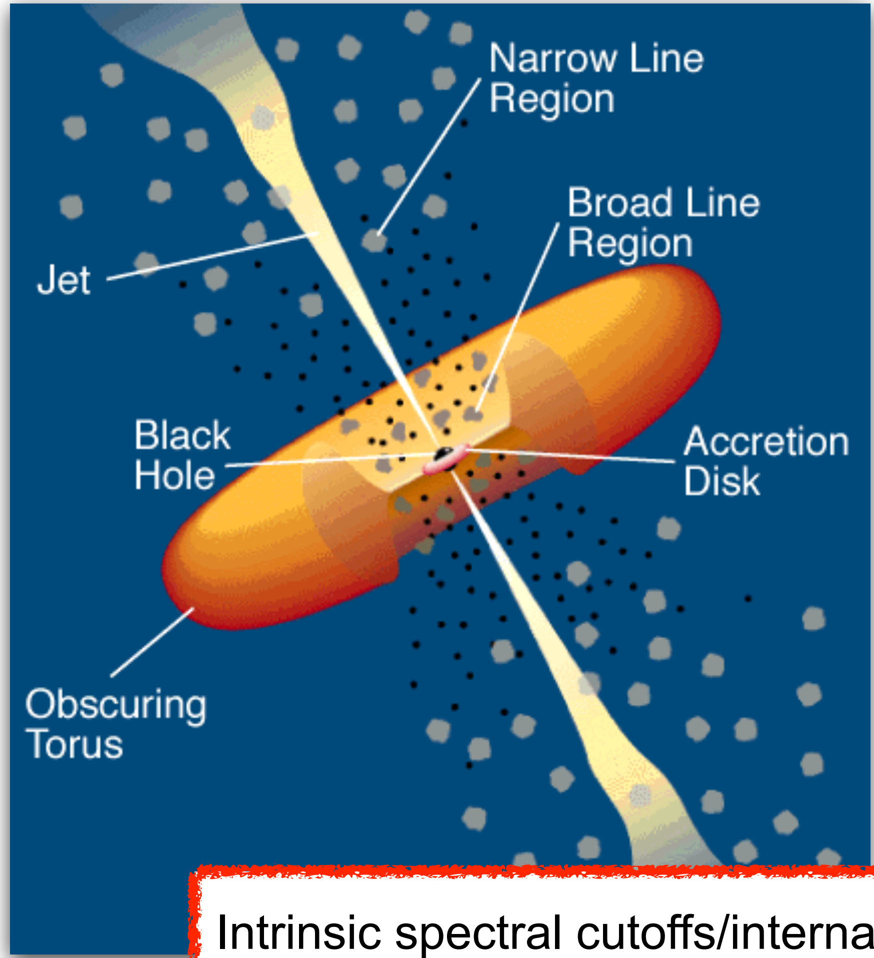
$$\lambda_{\rm EBL} \simeq 0.5 - 5\,\mu{\rm m} \times \left(\frac{E_\gamma}{1\,{\rm TeV}}\right) \times (1+z)^2$$



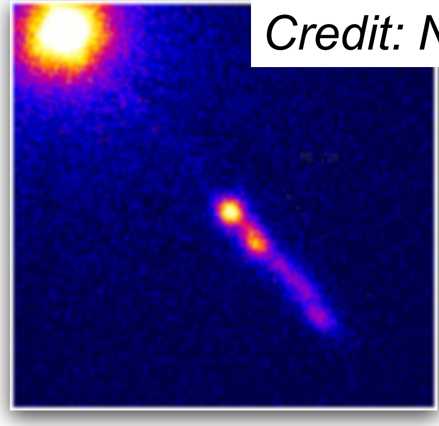
Dominated by distant sources

Dominated by (relatively) nearby and "extreme" sources

Blazars: A Convenient Probe



3C 273 as seen in X-ray



Credit: NASA

- Blazars detected to cosmological distances
  - z=3 at HE (<100 GeV)
  - z~1 at VHE (>100 GeV)

Intrinsic spectral cutoffs/internal absorption at high energy?

Spectral hardening/softening, extreme flux variability

Redshift/distance determination can be challenging

EBL Imprint on Blazar Spectra

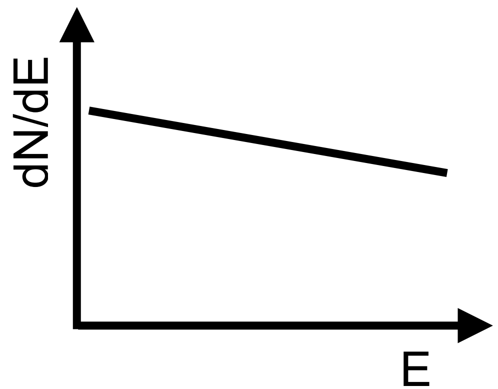
Use blazar observations to learn about EBL ↔ Need to understand EBL to understand blazar spectral properties!

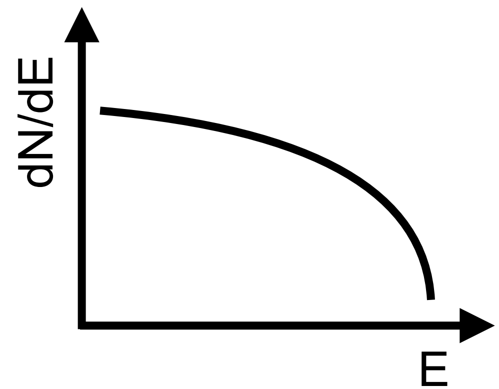
Intrinsic spectrum:

$$\frac{dN}{dE} \propto E^{-\Gamma}, \frac{dN}{dE} \propto E^{-\Gamma} \exp\left(-\frac{E}{E_C}\right), ...?$$

Observed spectrum:

$$\frac{dN}{dE} \propto \left(\frac{dN}{dE}_{int}\right) \exp(-\tau_{\gamma\gamma})$$





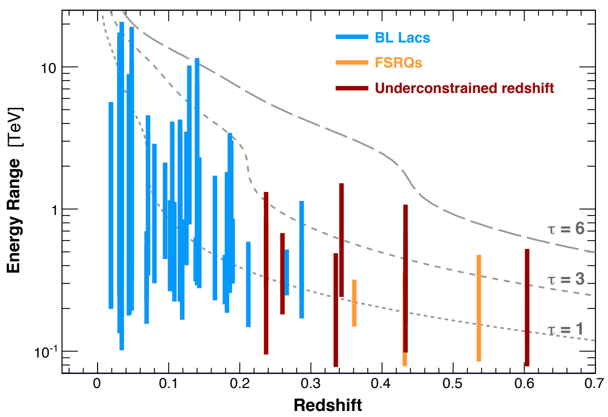
Joint fit of EBL parameters & spectral properties or

Minimal assumptions on intrinsic spectral properties + multiple sources

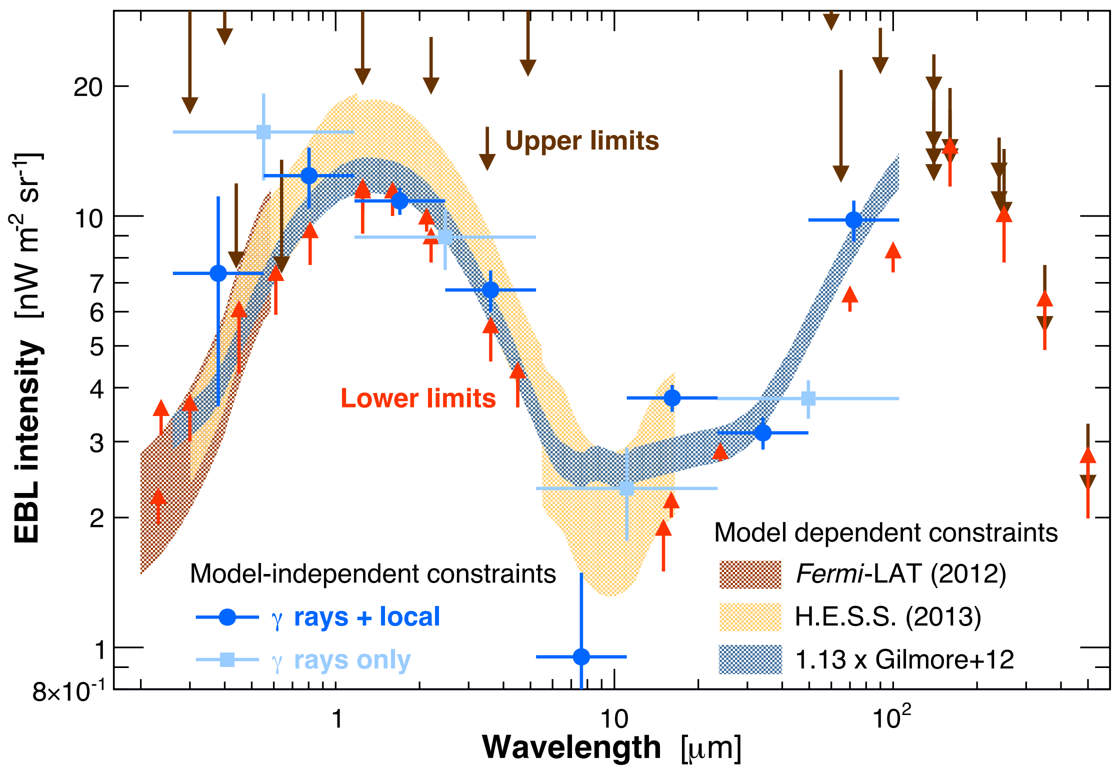
1. No convex spectral shapes 2. Extrapolate lower energy spectral measurements

EBL Measurement from Archival Spectra

- Archival dataset of 30 blazars, 86 spectra
- Independent of EBL shape assumption
- Use Fermi-LAT spectra
- 11σ EBL detection
    - Good agreement with 3 theoretical models



Biteau & Williams 2015



EBL Measurement with H.E.S.S.

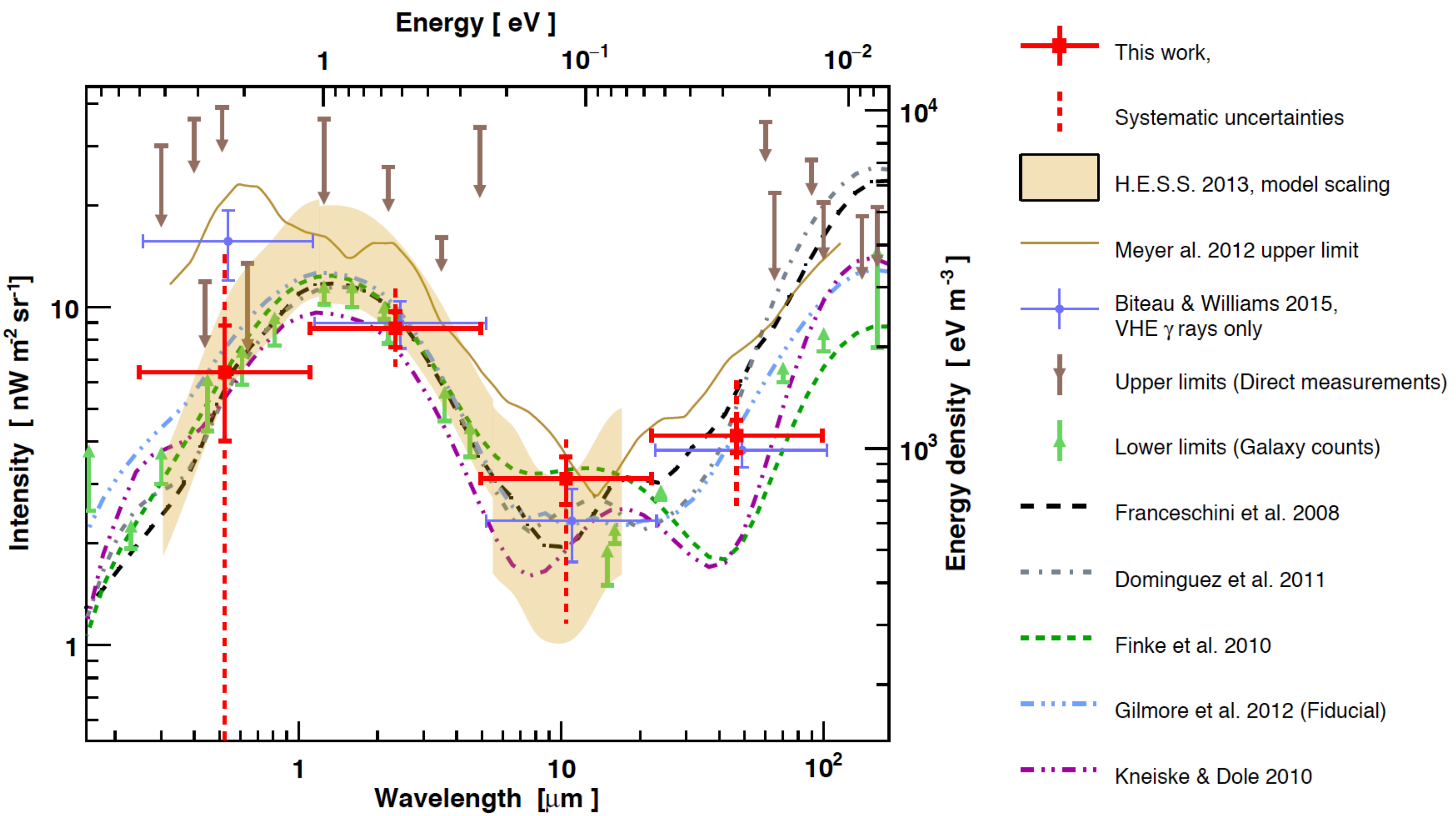
- 9 blazars, 21 spectra
- z = 0.031-0.287

H.E.S.S. collaboration 2017

Data set	Live time (hours)	σ	z	$E_{\rm min} - E_{\rm max}$ (TeV)
Mrk 421 (1)	4.9	89.6	0.031	1.41 – 14.9
Mrk 421 (2)	3.8	122	0.031	1.22 – 15.9
Mrk 421 (3)	2.9	123	0.031	1.19 – 19.5
Mrk 421 (4)	3.3	96.2	0.031	1.6 – 16.5
Mrk 421 (5)	1.6	46.0	0.031	1.5 – 15.2
Mrk 501	1.8	66.7	0.034	1.9 – 19.5
PKS 2005−489 (1)	71.2	28.8	0.071	0.29 – 1.6
PKS 2005−489 (2)	18.7	29.2	0.071	0.29 – 3.0
PKS 2155−304 (1)	7.4	94.8	0.116	0.24 – 4.6
PKS 2155−304 (2)	6.1	119	0.116	0.24 – 1.98
PKS 2155−304 (3)	5.5	187	0.116	0.24 – 3.7
PKS 2155−304 (4)	2.6	135	0.116	0.24 – 2.44
PKS 2155−304 (5)	3.5	227	0.116	0.24 – 4.6
PKS 2155−304 (6)	1.3	172	0.116	0.29 – 4.6
PKS 2155−304 (7)	1.3	200	0.116	0.29 – 3.6
PKS 2155−304 (8)	25.4	111	0.116	0.19 – 3.7
1ES 0229+200	57.7	11.6	0.14	0.4 – 2.8
H 2356−309	92.6	19.6	0.165	0.19 – 1.98
1ES 1101−232	58.2	16.8	0.186	0.19 – 1.98
1ES 0347−121	33.9	14.1	0.188	0.19 – 6.9
1ES 0414+009	73.7	9.6	0.287	0.19 – 0.69

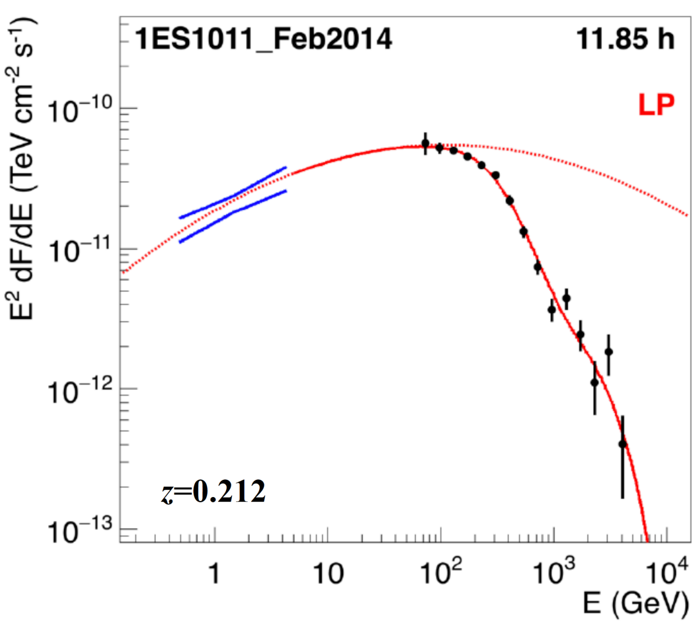
EBL Measurement with H.E.S.S.

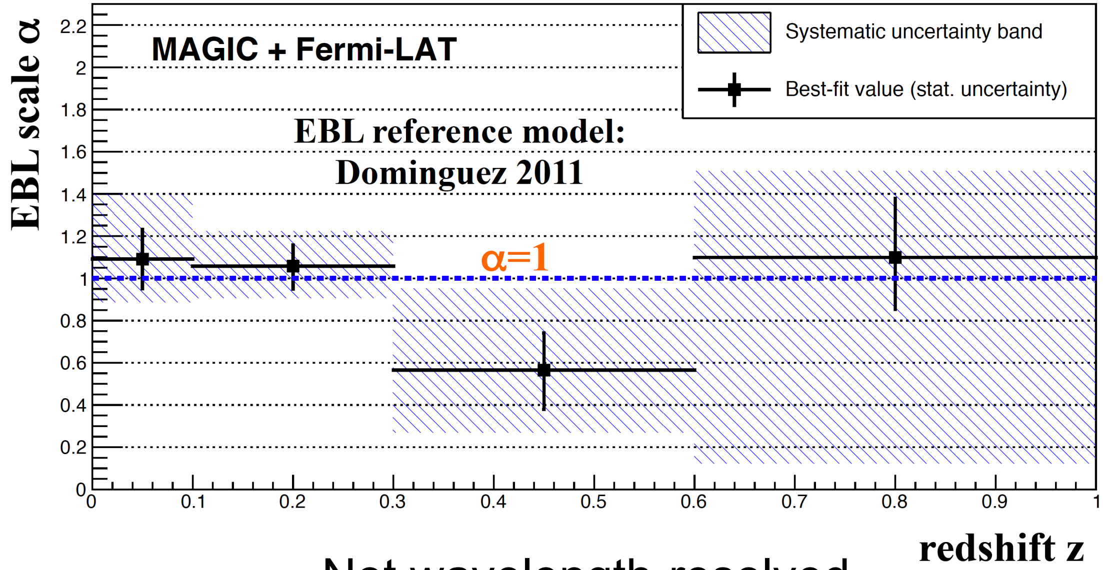
- Wavelength-resolved analysis
  - Joint fit to EBL intensity & spectral parameters
- 9.5σ EBL detection



EBL Measurement with MAGIC

- 12 blazars, 32 spectra
- z = 0.03-0.944
- Use contemporaneous Fermi-LAT spectra





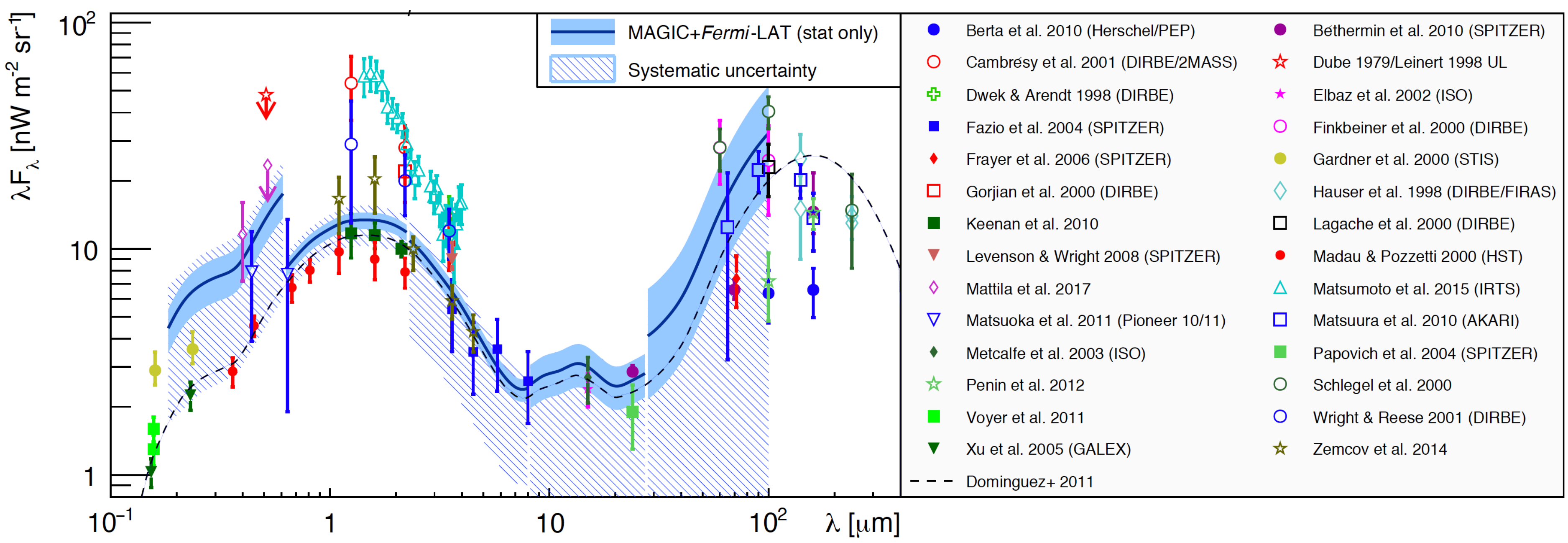
Not wavelength-resolved

$$\left(\frac{dN}{dE}\right)_{obs} = \left(\frac{dN}{dE}\right)_{int} \exp(-\alpha\tau_{\gamma\gamma})$$

EBL Measurement with MAGIC

- Wavelength-resolved analysis
  - EBL reference model Dominguez 2011

$$\left(\frac{dN}{dE}\right)_{obs} = \left(\frac{dN}{dE}\right)_{int} \exp(-\alpha_1\tau_1)...\exp(-\alpha_n\tau_n)$$



Summary: Extragalactic Background Light

- Gamma-ray measurements show good consistency with lower limits on EBL intensity from **galaxy counts**
  - No hint of diffuse component (but uncertainties large)

- Good consistency with several theoretical models

- Full treatment of systematic uncertainties → more robust results
  - Ignorance of **intrinsic spectral shape** major confounding factor
  - EBL evolution with redshift still guided by theoretical models for “model-independent” measurements

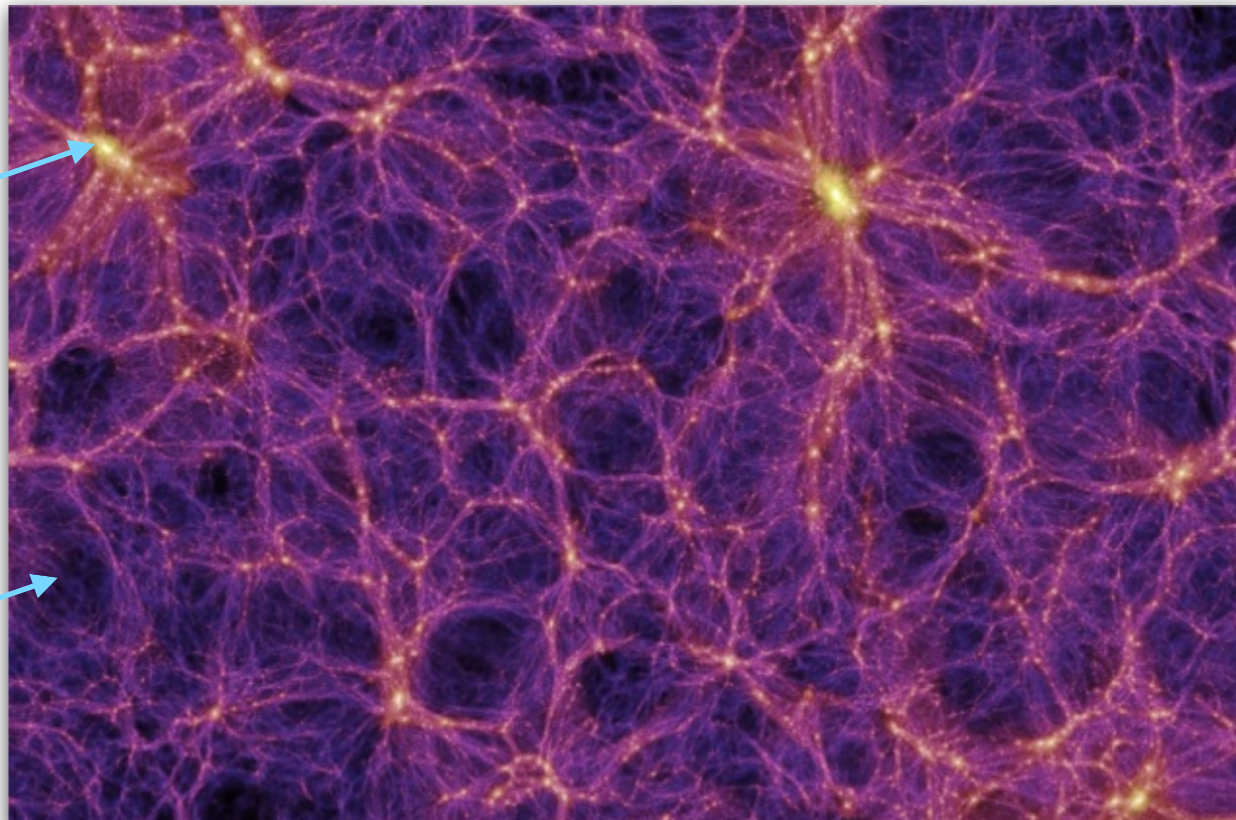
- **COB** well-resolved, **CIB** only partially resolved
  - Interesting region for testing models
  - Statistics limited & at edge of current IACT energy ranges

Magnetic fields in the universe

Important component in the universe's energy and evolution
How to produce strong B fields in galaxies/galaxy clusters?
→ Intergalactic magnetic field (IGMF) as **seed field**

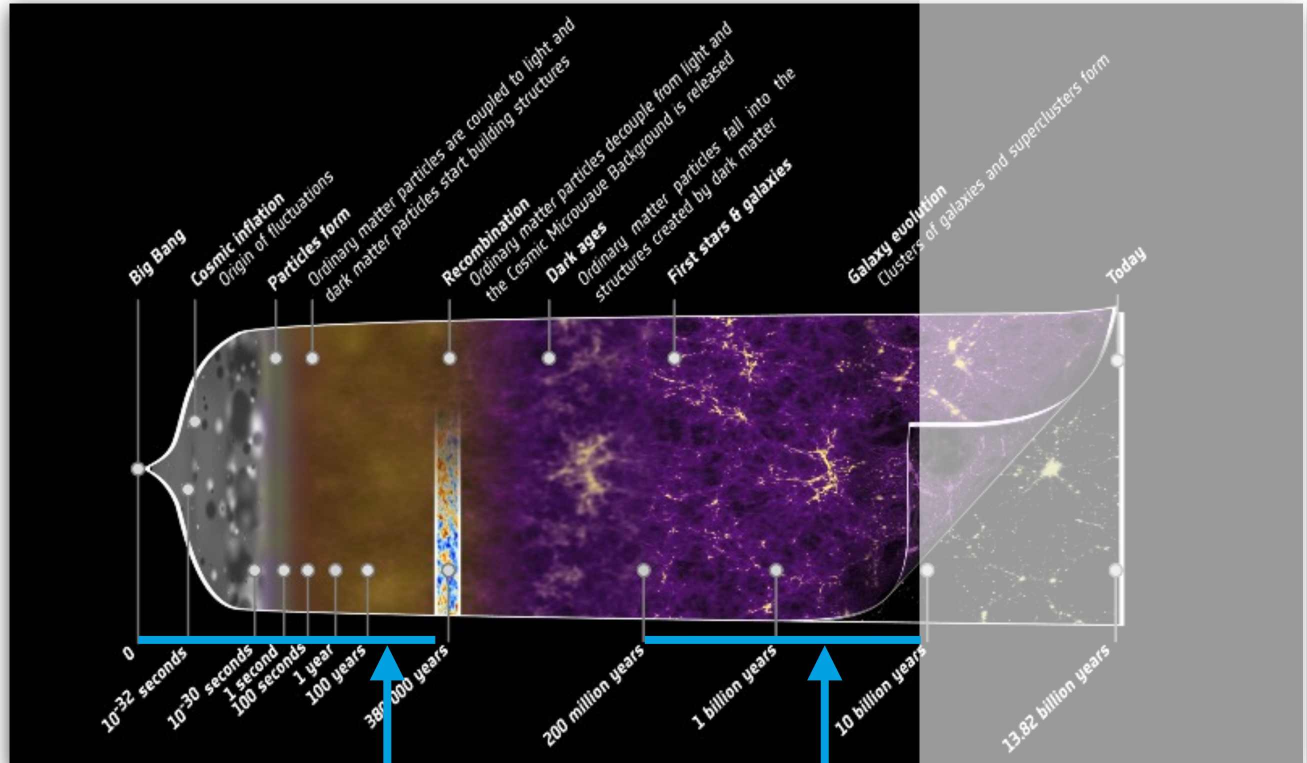
$B = 10^{-6}$ G

$B = ??$



Millennium simulation project

Primordial Generation/Astrophysical Generation



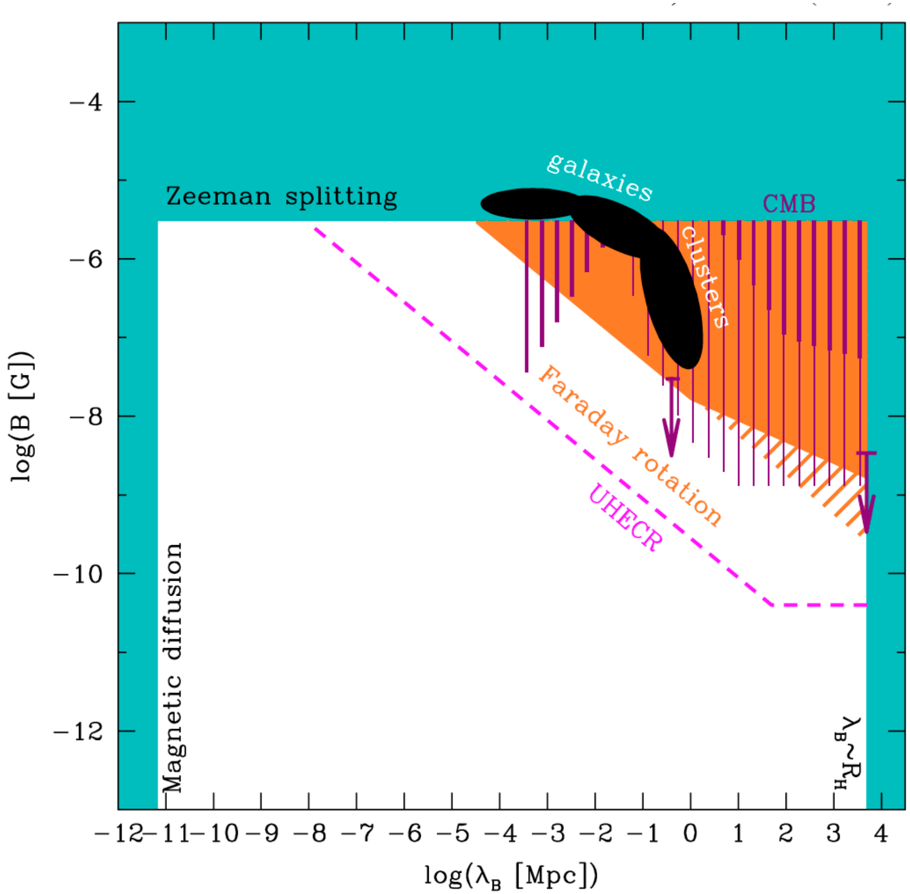
Charge separation in transitions in early universe

Injection of magnetized plasma into interstellar medium

Regardless of origin, insight from measuring **field in voids**

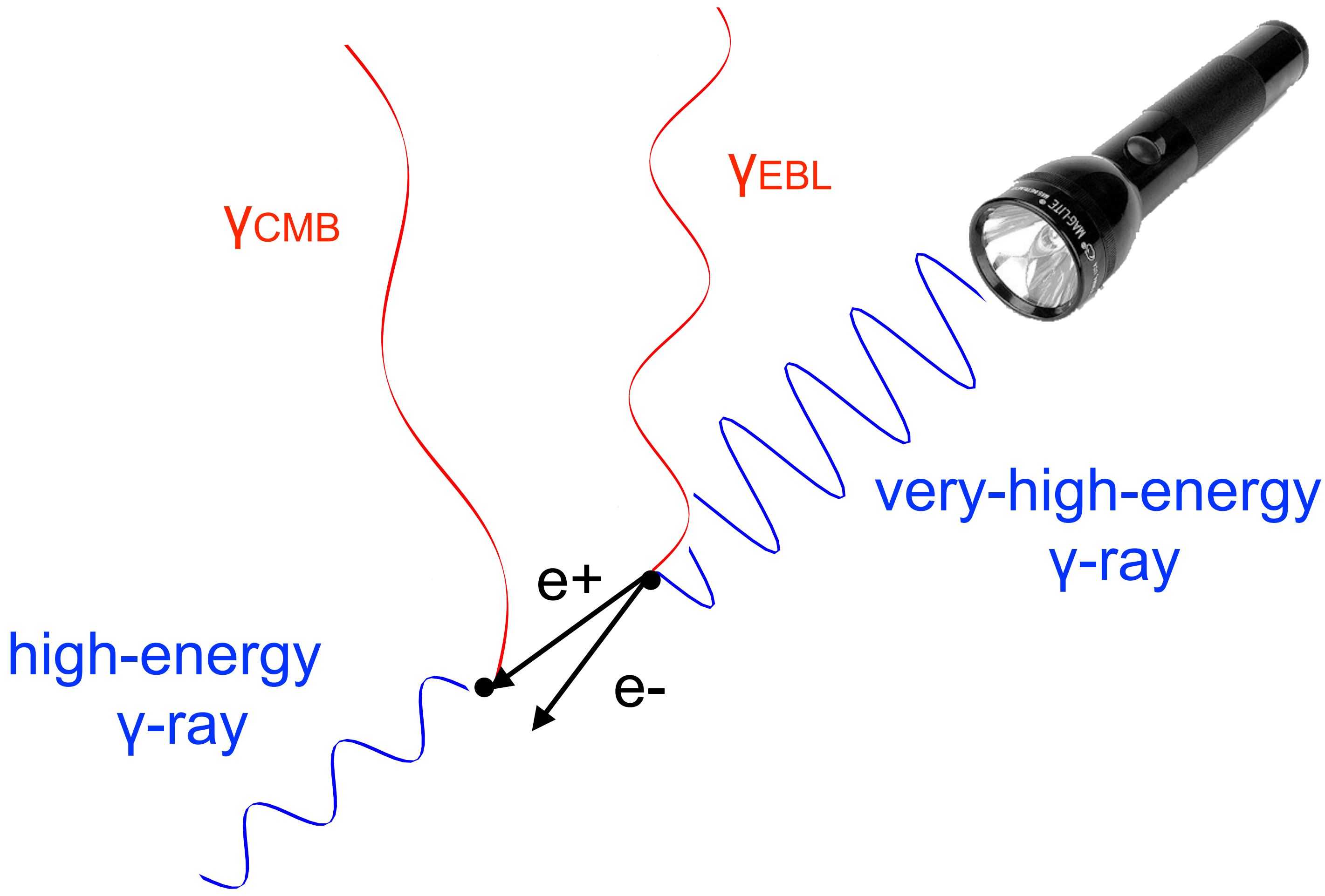
Existing Constraints on IGMF

- *NB: Ignoring constraints from gamma-rays*
- Large allowed phase space
  - Measure **strength** & **correlation length** to decipher generation scenario
  - Degeneracies



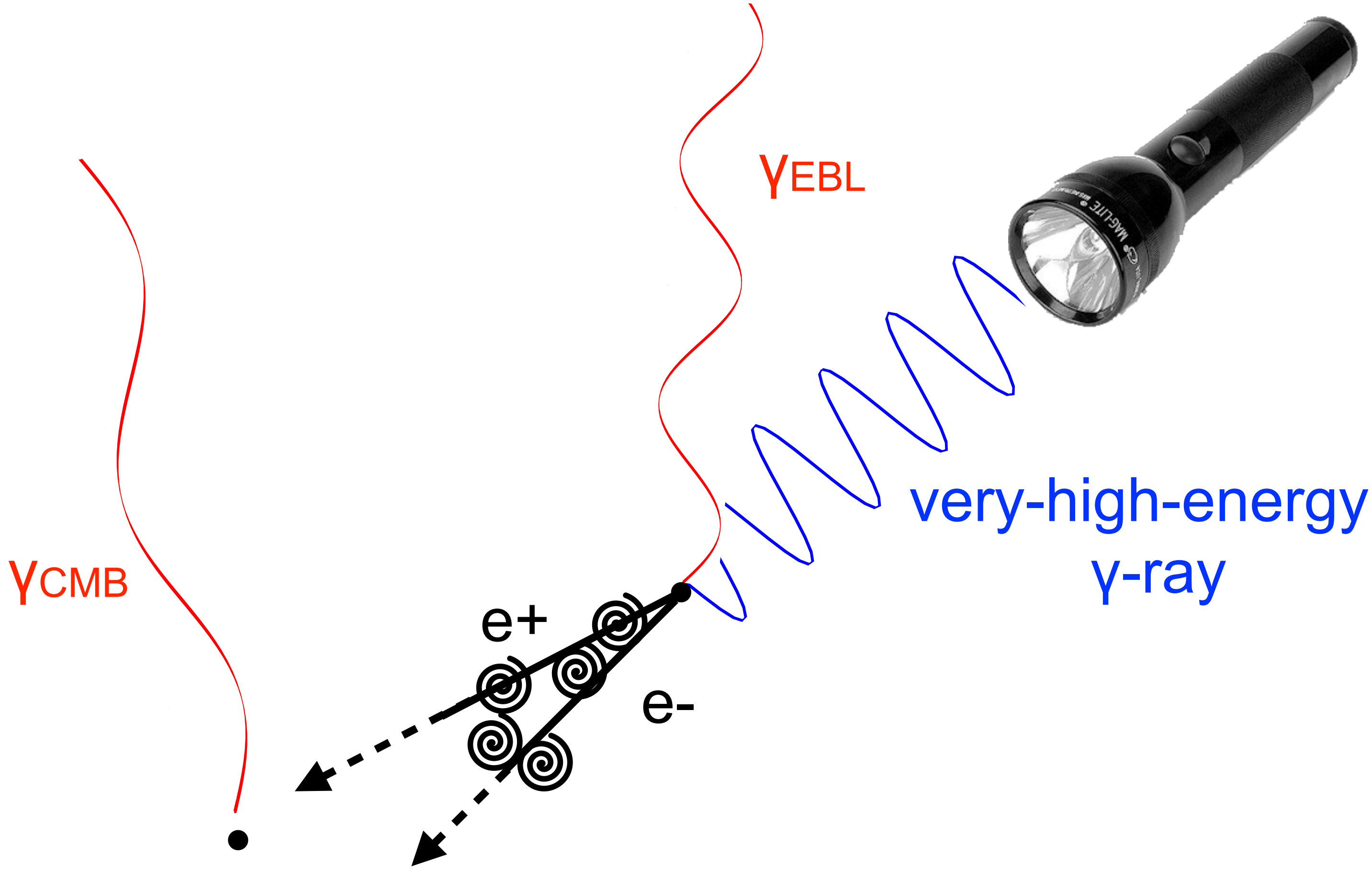
Neronov 2009

Electromagnetic Cascades



Photons from distant gamma-ray sources interact with **EBL photons** via **pair production**, e+e- pairs interact with **CMB photons** via **inverse-Compton scattering**

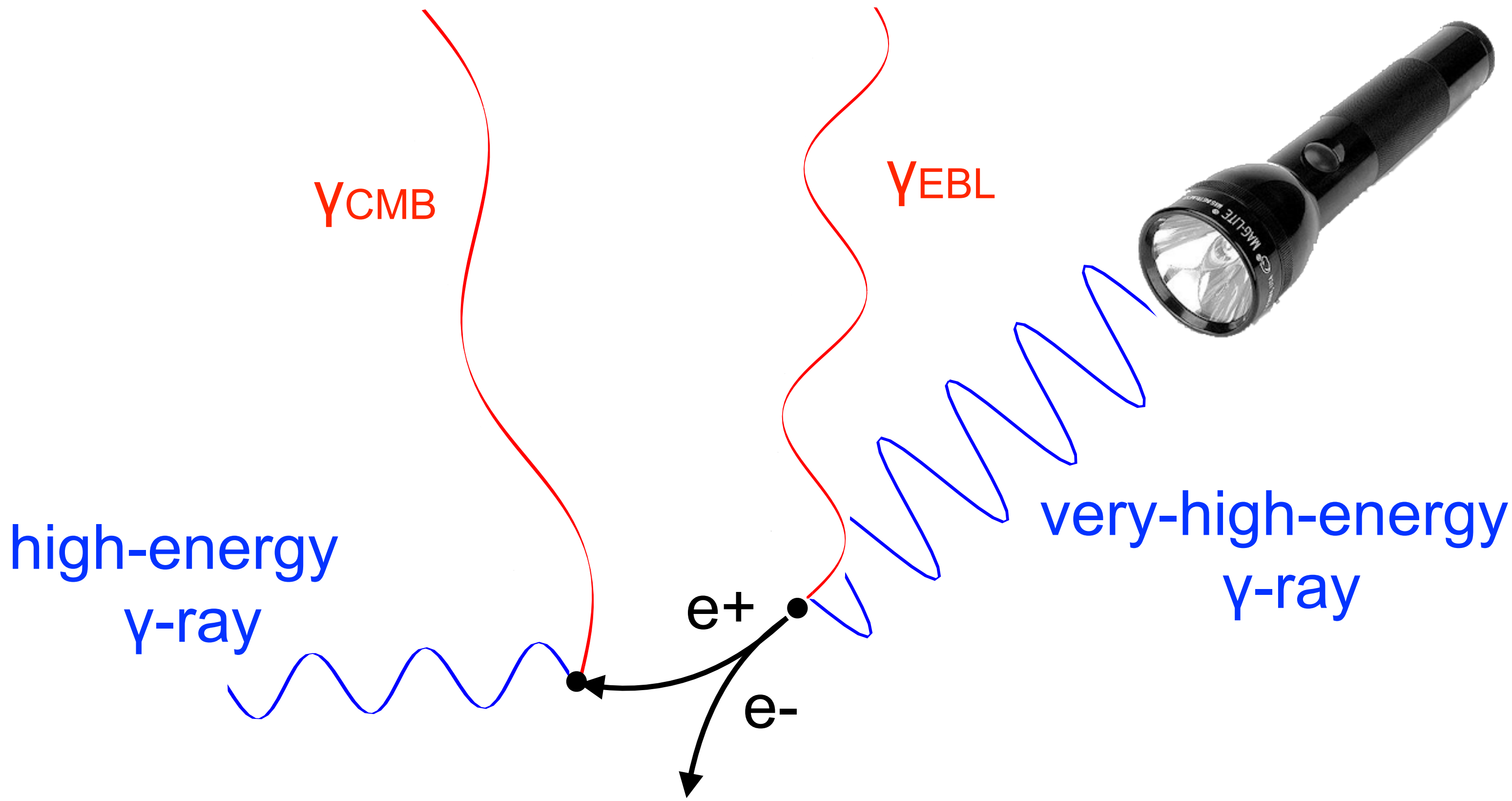
Plasma Beam Instabilities?



Energy loss of e+e- pairs due to plasma instabilities?
Relative cooling timescales determine cascade development

Following results assume inverse-Compton cooling to be dominant effect

Electromagnetic Cascades & IGMF



Magnetic field **deflects** e+e- pairs
Path length to observer **increases**

IGMF Strength Regimes

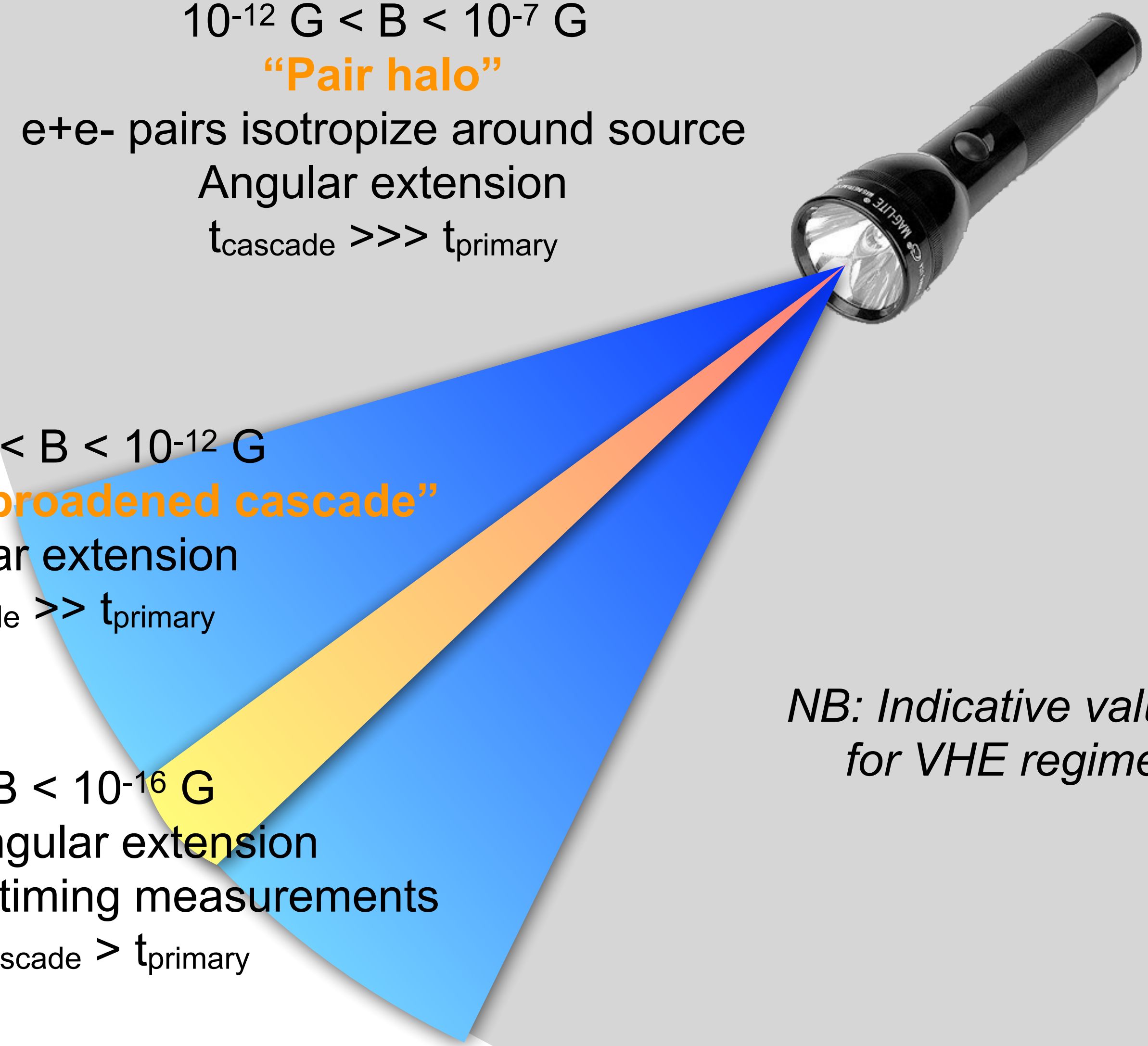
10^{-12} G < B < 10^{-7} G

"Pair halo"

e+e- pairs isotropize around source

Angular extension

$t_{cascade} >>> t_{primary}$



10^{-16} G < B < 10^{-12} G

"Magnetically broadened cascade"

Angular extension

$t_{cascade} >> t_{primary}$

B < 10^{-16} G

No angular extension

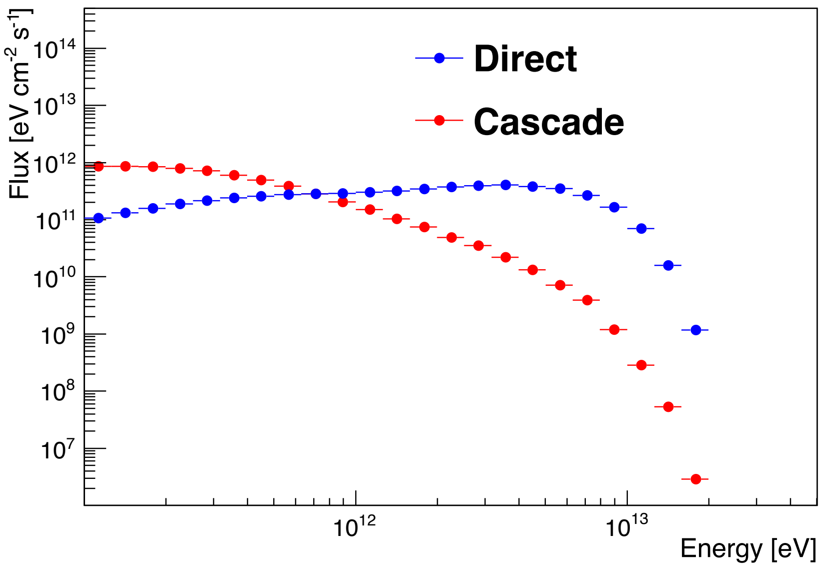
Spectral or timing measurements

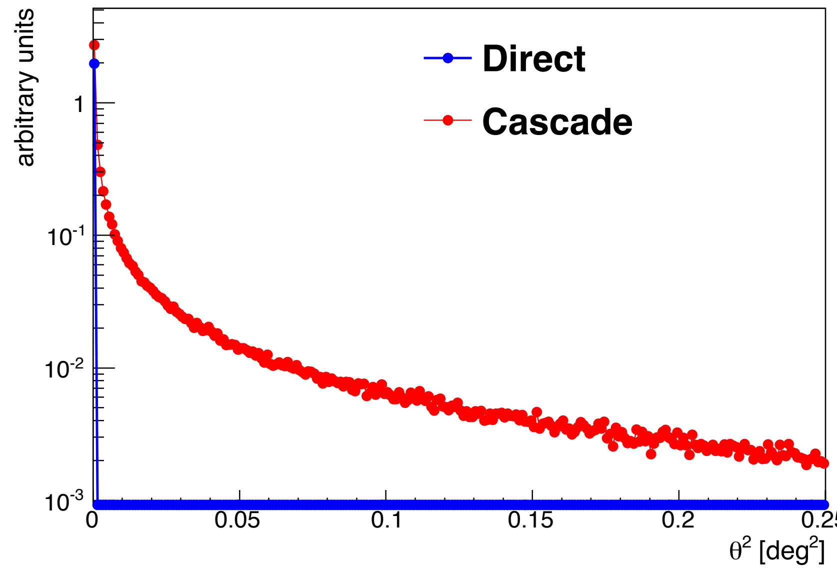
$t_{cascade} > t_{primary}$

NB: Indicative values for VHE regime

Predicted Energy/Angular Profiles

Cascade behavior predicted analytically or by simulations





Simulations by T. Weisgarber

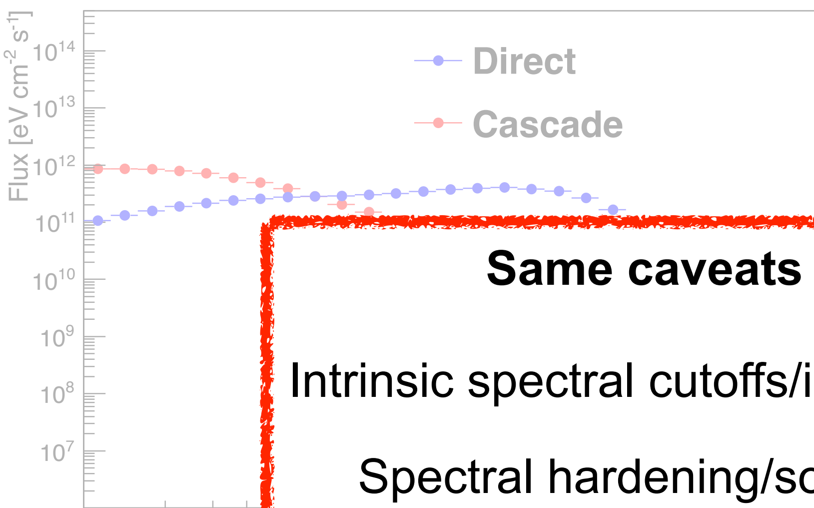
- Greatest cascade emission fraction → best chance of detection
  - Dependent on redshift (& energy)
  - Require emission to high energies

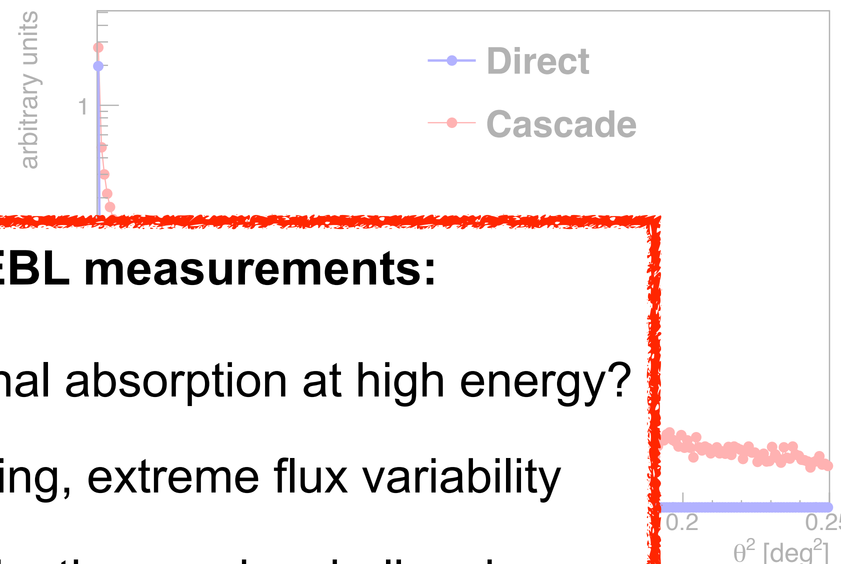
↓

(Extreme) **Blazars**

Predicted Energy/Angular Profiles

Cascade behavior predicted analytically or by simulations





Same caveats as EBL measurements:

Intrinsic spectral cutoffs/internal absorption at high energy?

Spectral hardening/softening, extreme flux variability

Redshift/distance determination can be challenging

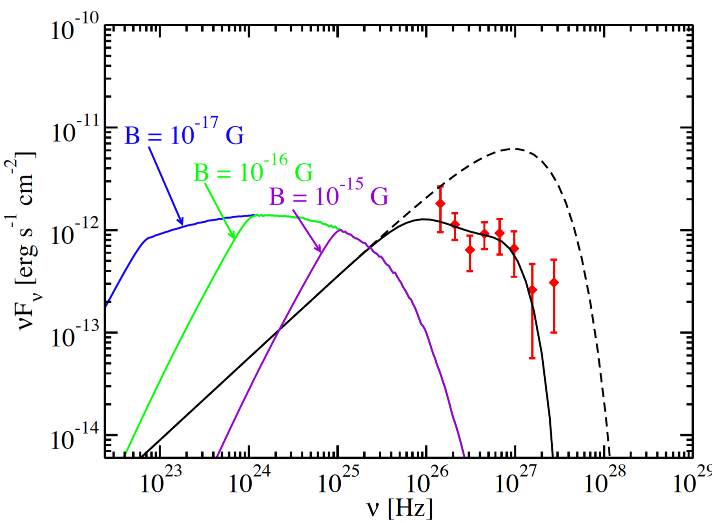
- Greatest cascade emission fraction → best chance of detection
  - Dependent on redshift (& energy)
  - Require emission to high energies

↓

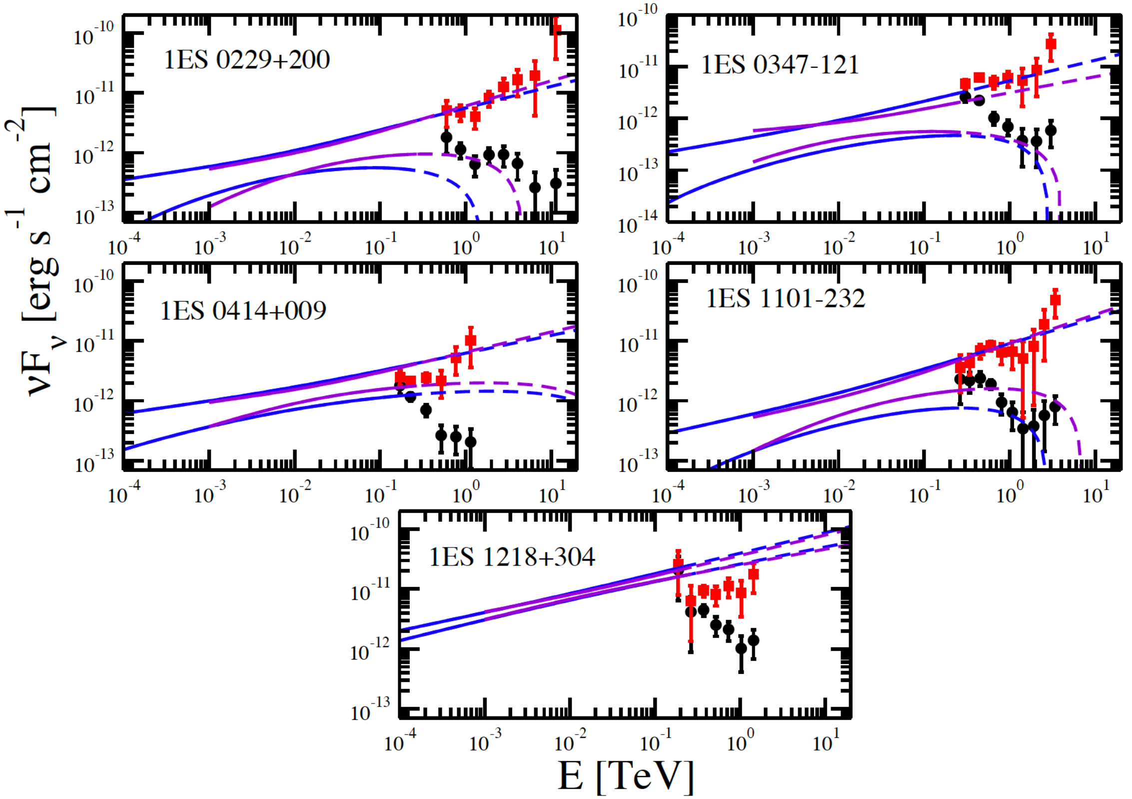
(Extreme) **Blazars**

IGMF Constraints from γ-ray SEDs

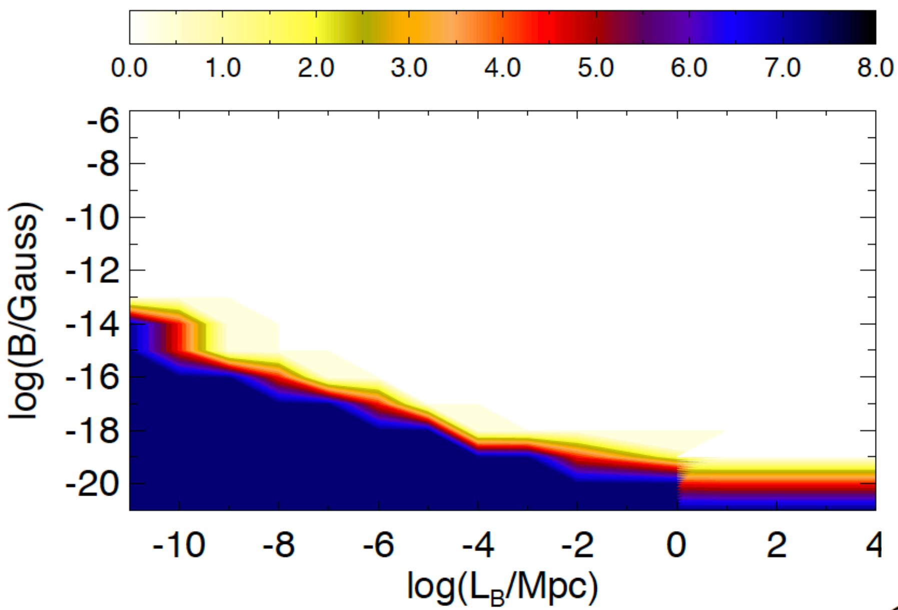
- Set IGMF constraints from GeV-TeV spectra
- Cascade component predicted (analytically) from VHE spectrum
    - Set **lower limits** on IGMF strength
    - Smaller IGMF → larger observed cascade flux



Finke et al. 2015

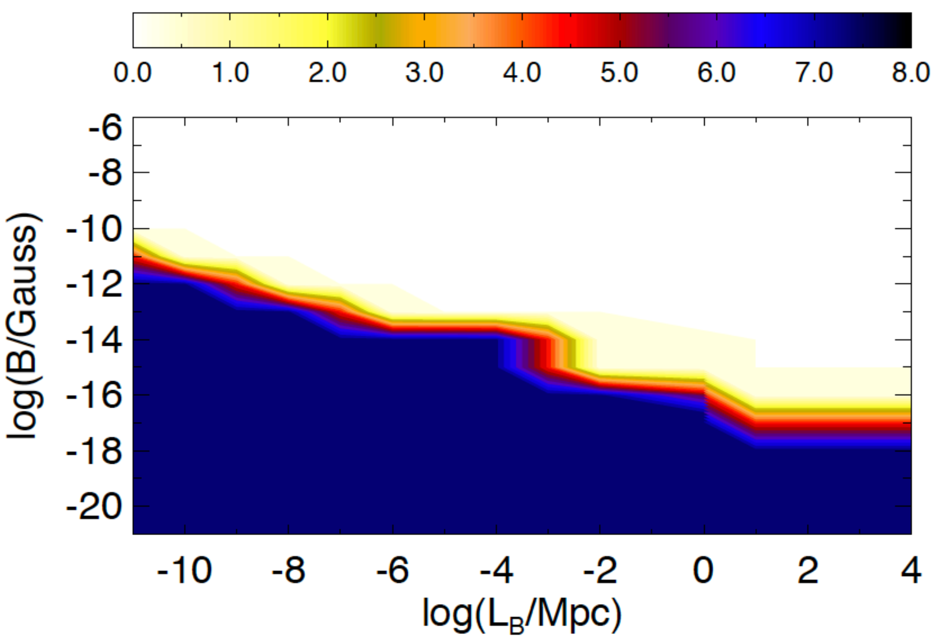


IGMF Constraints from γ-ray SEDs



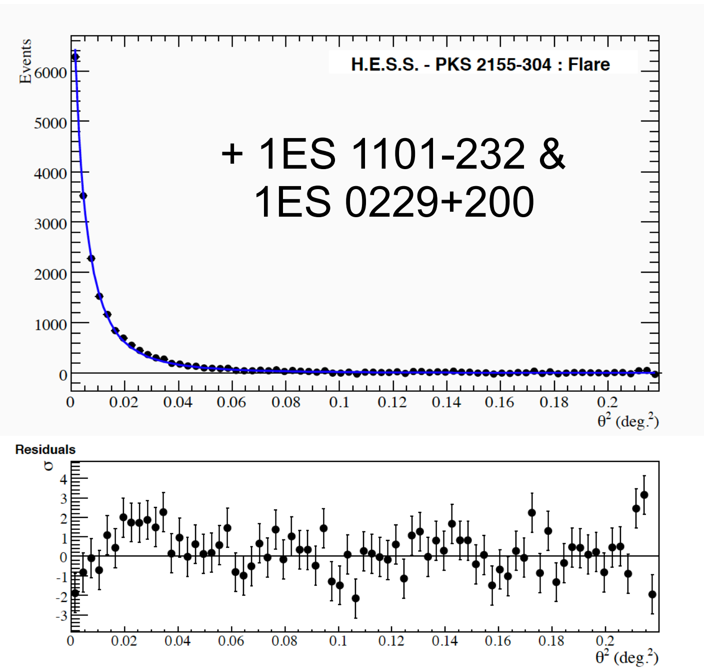
- Conservative assumptions
  - Blazar "on" for **3 years**
  - E_{max} = center of last VHE energy bin

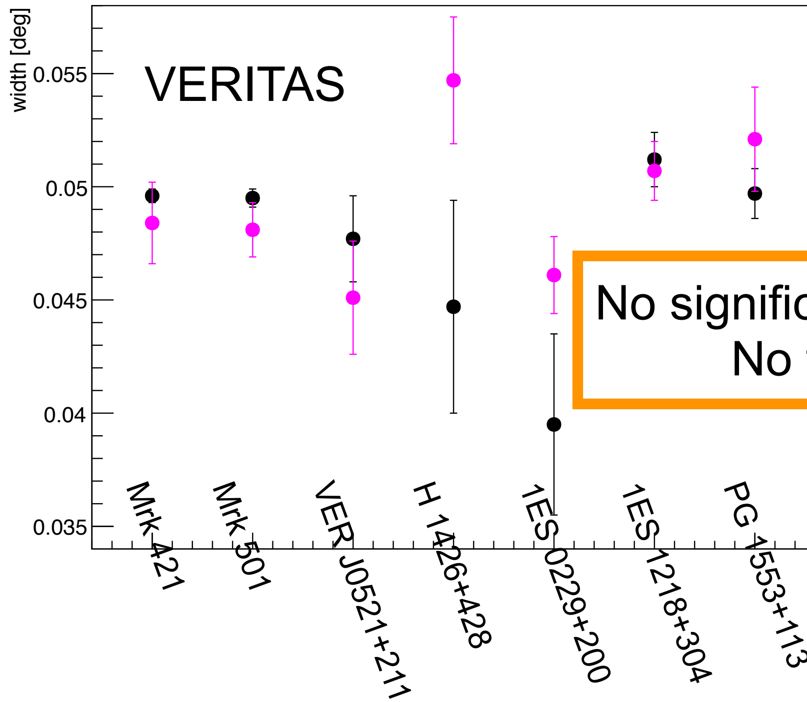
- Less-conservative assumptions
  - Blazar "on" for **age of universe**
  - E_{max} = end of VHE spectrum



Exclude B < 10^{-19} G (λ_B=1 Mpc) @ 5σ

IGMF Constraints from Angular Extension





No significant tension
No trend

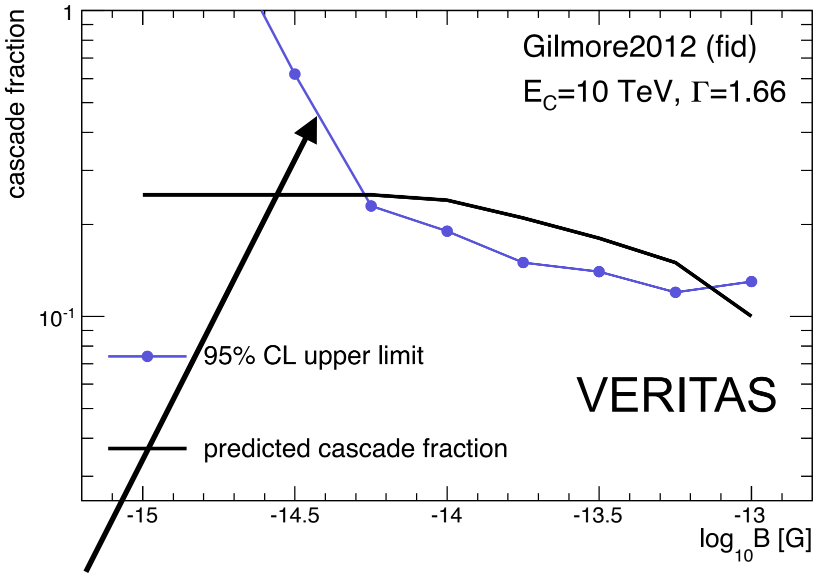
H.E.S.S. collaboration 2014
VERITAS collaboration 2017

Cascade fraction depends on:
EBL model
Intrinsic source spectrum
(spectral index & cutoff)

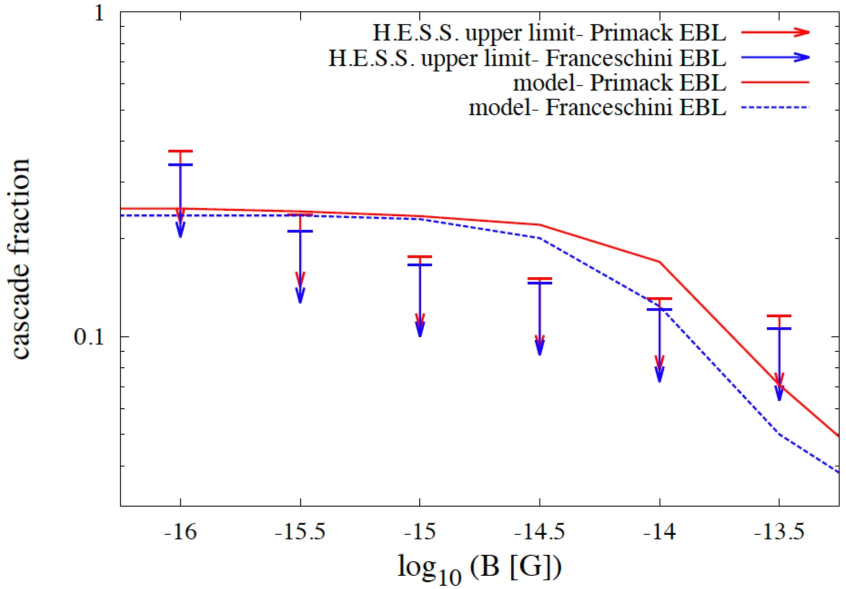
H.E.S.S. best source: **PKS 2155-304**
VERITAS best source: **1ES 1218+304**

IGMF Constraints from Angular Extension

Compare predicted cascade fraction with observed upper limits



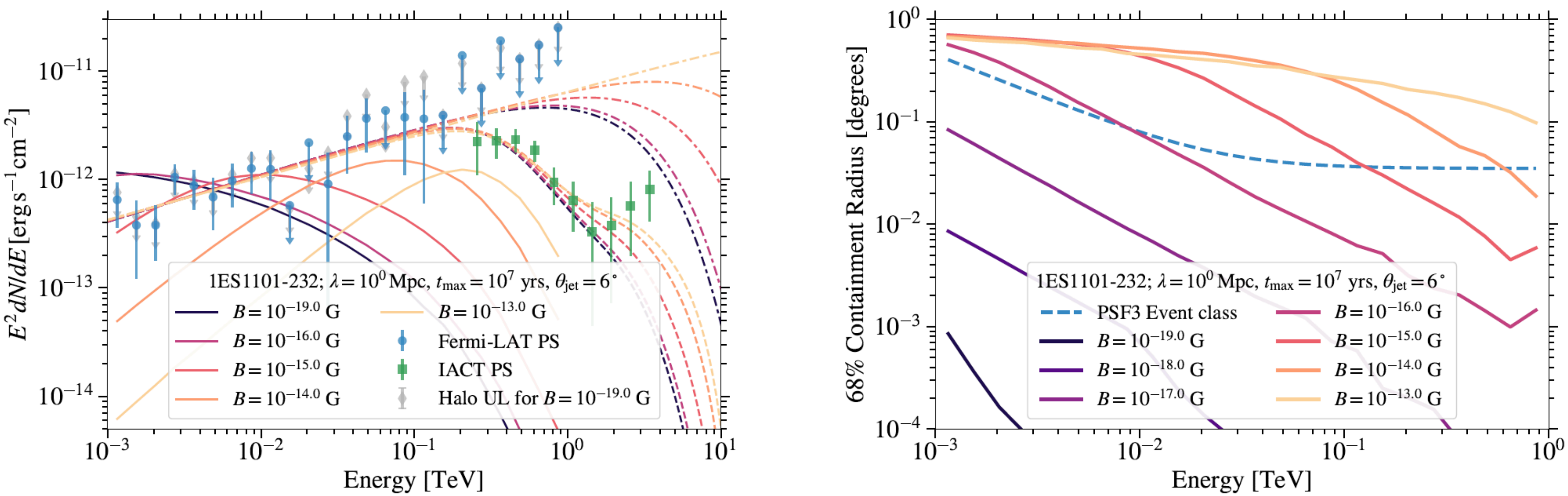
Lose sensitivity as angular extension becomes small



- Limits depend strongly on intrinsic spectrum assumption (weakly on EBL model)
- VERITAS, nominal assumptions: **exclude B ~ 10^{-14} G** at 95% C.L. (λ_B=1 Mpc)
- H.E.S.S., nominal assumptions: **exclude B = (0.3-3)x10^{-15} G** at 99% C.L. (λ_B=1 Mpc)

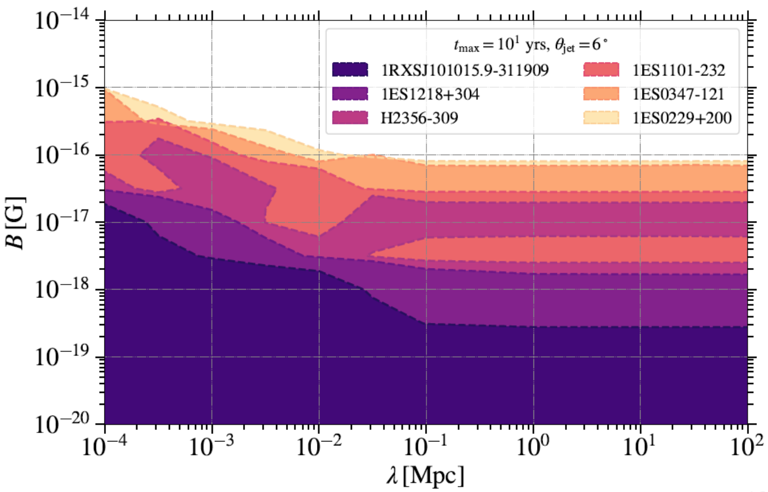
IGMF Constraints from Spectral/Angular Analysis

- Pass 8 LAT analysis with improved PSF
- Joint **spectral** & **angular** fit
  - Spectral information dominates sensitivity
- 9 HBLs included in analysis
  - Low variability, well-measured redshift, spectral points to τ>2



Fermi-LAT collaboration & J. Biteau 2018

IGMF Constraints from Spectral/Angular Analysis

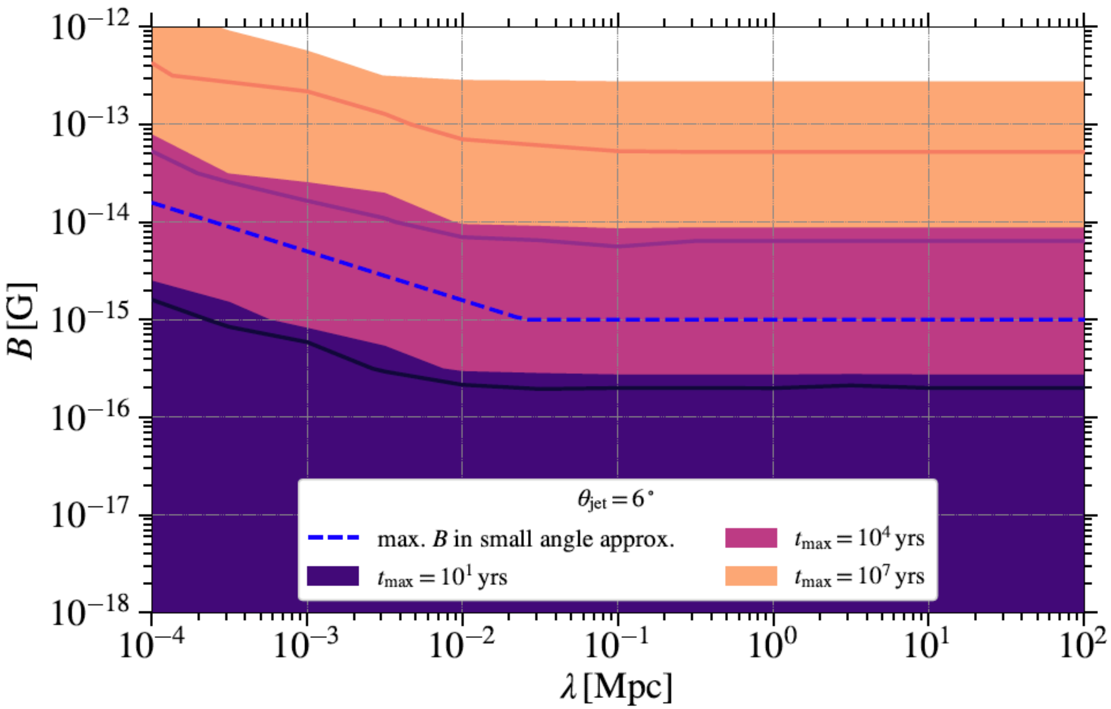


Individual source constraints for
6 best sources

(variability observed for
1ES 1218+308 & 1ES 0229+200)

Dependence of limits on time blazars are “on” / emit at present flux level

Strongest limits to date



IGMF Summary

- Recent studies disfavor zero/low IGMF strength
- Several factors **strongly** affect limits
  - **Timescale** of emission at current flux level
  - Assumed **intrinsic spectrum**
  - Cascade modeling

- Broderick 2018 (not covered) quote $B<10^{-15}$ G ($\lambda_B \geq 1$ Mpc)
  - Conflict with Fermi-LAT limits?

- Relative timescale of **inverse Compton cooling** versus cooling via **plasma instabilities** critical to interpretation of observations

Conclusions

- **Gamma-ray astronomy** has something to say about **cosmology**
- Access two important observables
  - **EBL** - imprint of stellar and galactic activity, energy transfer since the dark ages
  - **IGMF** - measuring fields in voids to understand evolution of magnetic fields in matter-dense regions
- Understanding blazar properties will feed into better cosmological understanding

Thank you!