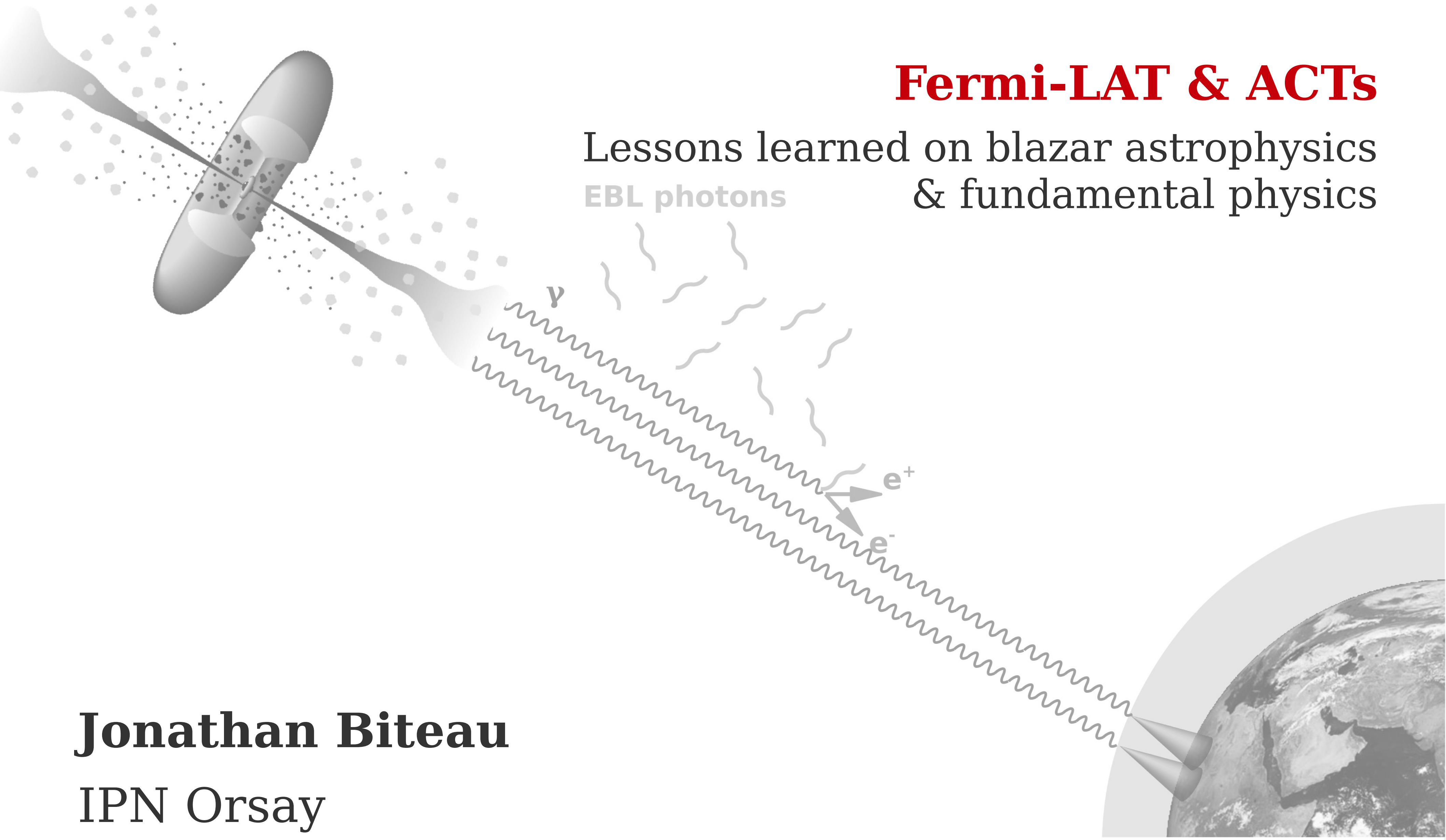
Fermi-LAT & ACTs

Lessons learned on blazar astrophysics & fundamental physics



Jonathan Biteau

IPN Orsay

Blazars: why do we care?

The Blazar class

Active Galactic Nuclei with jets pointed toward Earth (vs 'misaligned' AGNi)

Subclasses:
- BL Lacs: low L – high Emax
- FSRQs: high L – low Emax

Dominant in Number > 50 GeV

2FHL: unbiased sky view > 50 GeV

360 srcs: ~75 % blazars

~ 200 BL Lacs

~ 10 FSRQs

~ 60 Uncertain Blazars

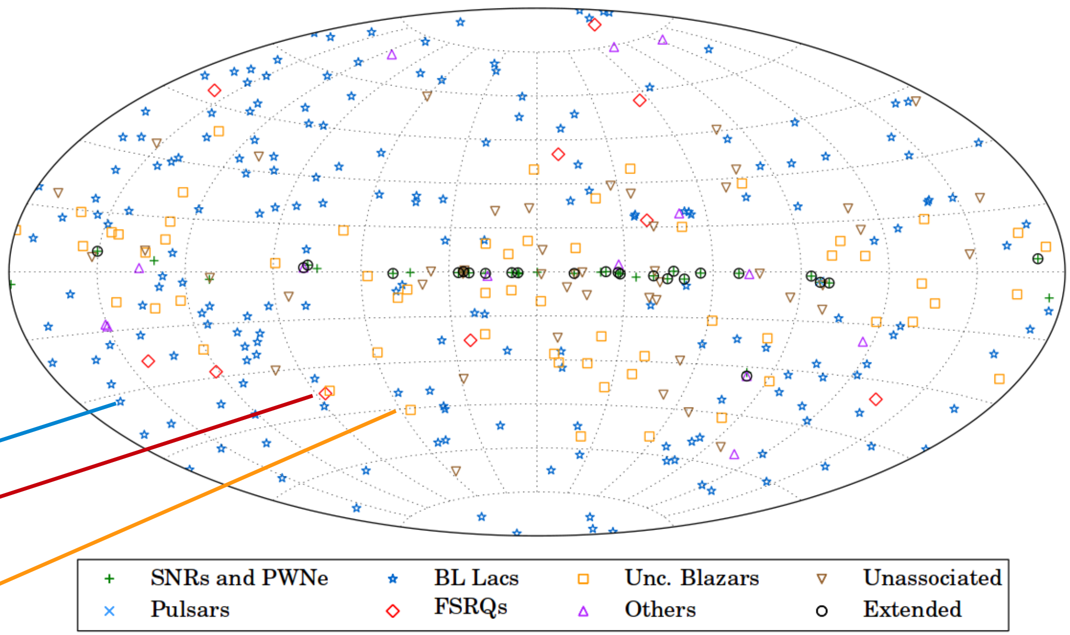
Dominant in Power > 50 GeV

Blazars – in particular BL Lacs – account for 86±15% of the EGB > 50 GeV
Fermi-LAT 15

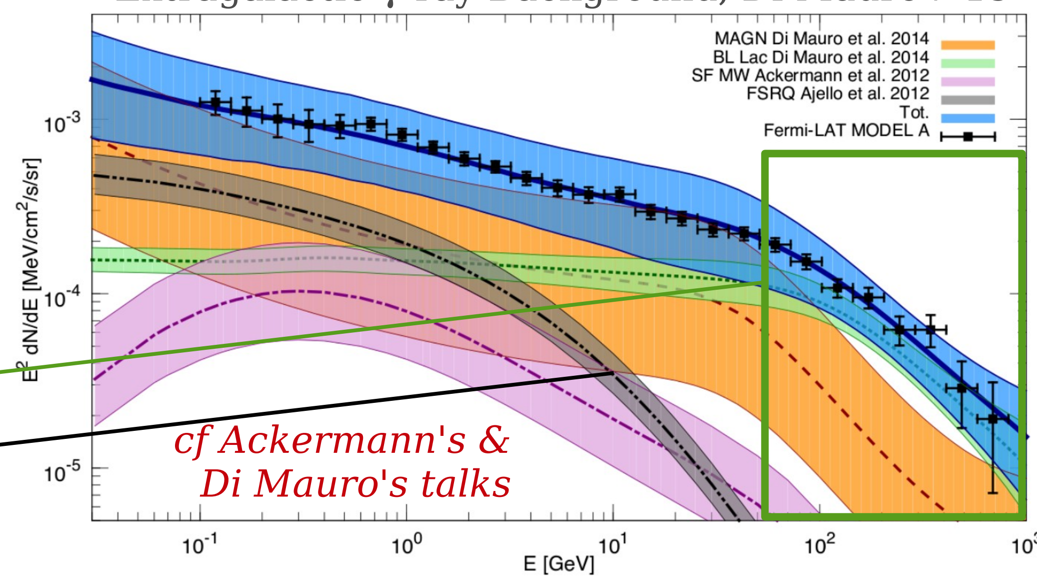
- BL Lacs

- FSRQs

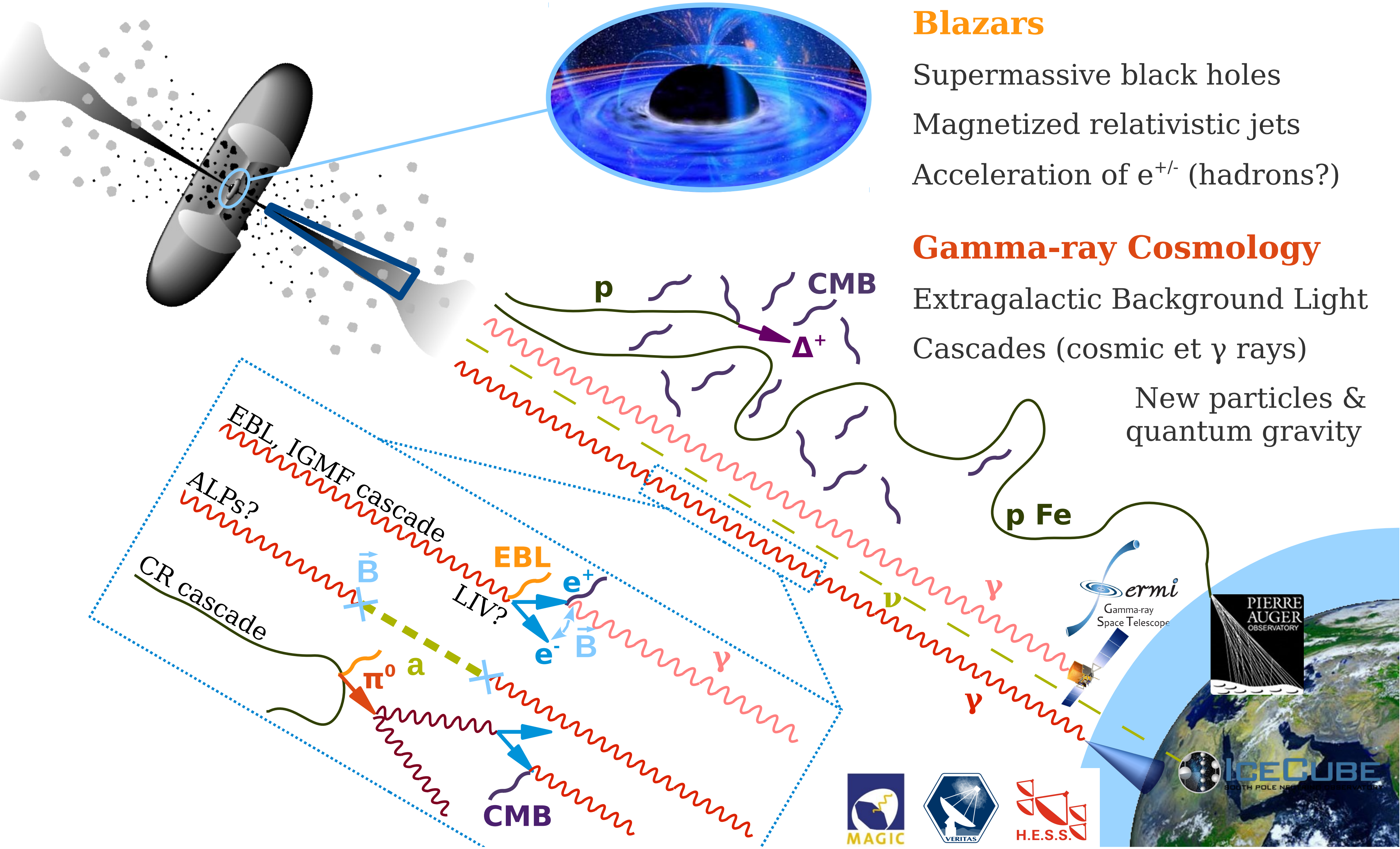
2FHL (>50 GeV), Fermi-LAT 15



Extragalactic γ-ray Background, Di Mauro+ 15



A probe of Astrophysics & Fundamental Physics



Blazars

Supermassive black holes

Magnetized relativistic jets

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

Gamma-ray Cosmology

Extragalactic Background Light

Cascades (cosmic et γ rays)

New particles & quantum gravity

Outline

1991-2006: Genesis

A Handful of Sources

Setting of the Phenomenology

2008-2018: The Glorious Decade of joint GeV – TeV Blazar Astronomy

Ground-base and Spaceborne Complementarity: a few examples

Gamma-ray Blazar Astrophysics: lessons learned (my biased view!)

Extragalactic Background Light & Anomalies: lessons learned (my biased view!)

The Near Future

Fermi-LAT and CTA Early Science

Open questions

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1991-2006: A Handful of Sources

Spaceborne γ-ray observations

COS-B: FSRQ 3C 273 < 1 GeV   Bignami+ 81

EGRET (1991-2001) 20 MeV – 30 GeV
- 66 high-confidence blazars   Hartman+ 99

BUT limited sensitivity → mostly access to flux averaged over long time periods

Ground-based γ-ray observations

Whipple 10-m telescope

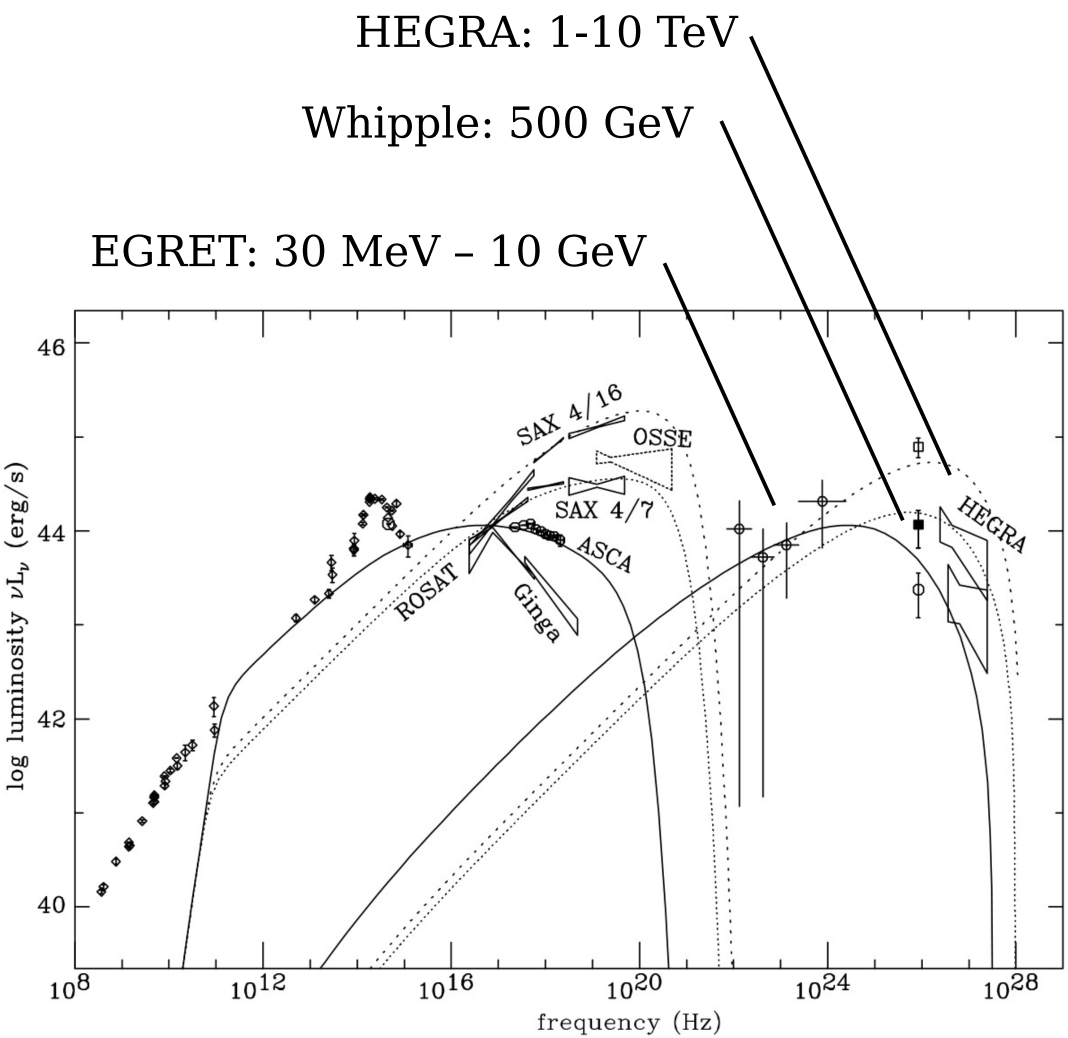
- BL Lac Mrk 421 > 500 GeV   Punch+ 92
+ 5-7 BL Lac detections in the next decade by multiple teams around the world

Low duty cycle → only and instantaneous picture of the source behavior

A few multi-wavelength campaigns

Radio and optical bands well covered
+ some X-ray coverage
→ low-energy bump constrained

Very rough gamma-ray coverage
→ high-energy bump poorly constrained



Mrk 501 1996 March 25-28, Kataoka+ 99

Setting of the phenomenology: Astrophysics

Tapping into the BH/Accretion Power

Magnetic fields anchored in the disk → energy of the accreted matter   Blandford & Payne 82

Black-hole magnetosphere → rotation energy of the black hole   Blandford & Znajek 77

Both can generate high luminosities close to the Eddington limit

Acceleration & Radiation Processes

Diffusive Shock Acceleration
Magnetic Reconnection   e.g. Lyutikov+ 03

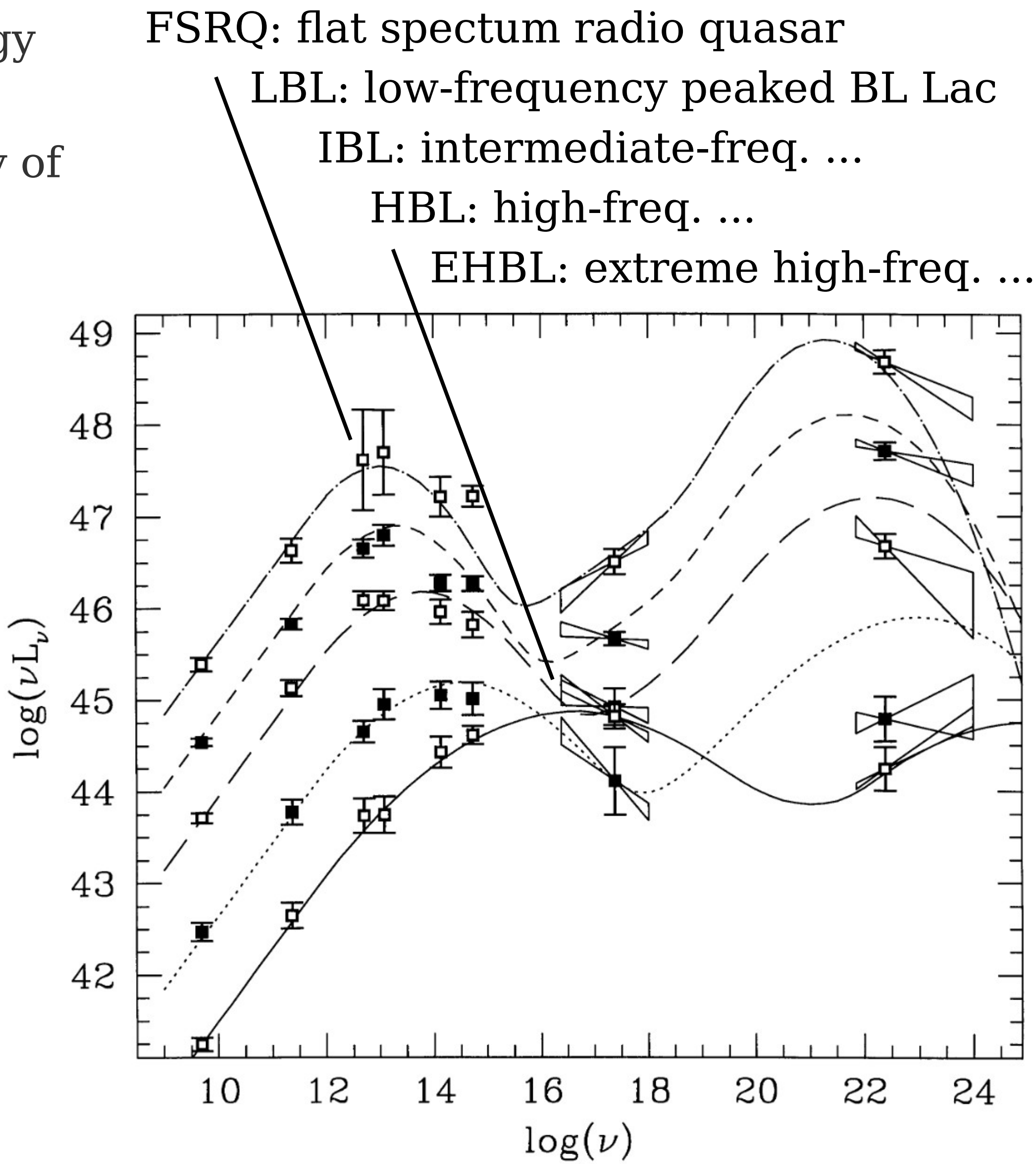
Radio-optical-(X-rays): e+e- synchrotron

(X-rays) – γ-rays:
- Inverse Compton on synchrotron field: SSC / external field: EC
- Hadronic?   Manheim+ 93, Aharonian+ 00

A Blazar Sequence?

Two-bump spectral energy distribution, with peak luminosity/frequency correlations

Possibly driven by the dominance of external photon fields



Blazar sequence, Fossati+ 98

Setting of the phenomenology: Line-of-sight physics

Extragalactic Background Light

Pair-production cross section maximum for Eγ ε ~ 1 MeV²

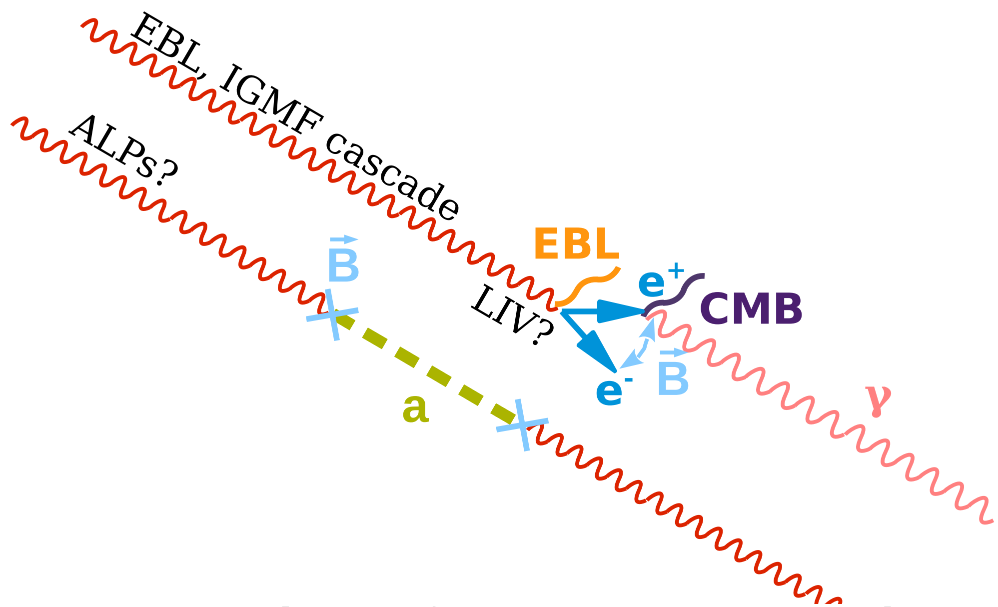
→ a TeV γ-ray produces 500 GeV e+e- when interacting with eV (μm) photons

→ absorption > 100 GeV probes the EBL: integrated UV-IR light output of stars

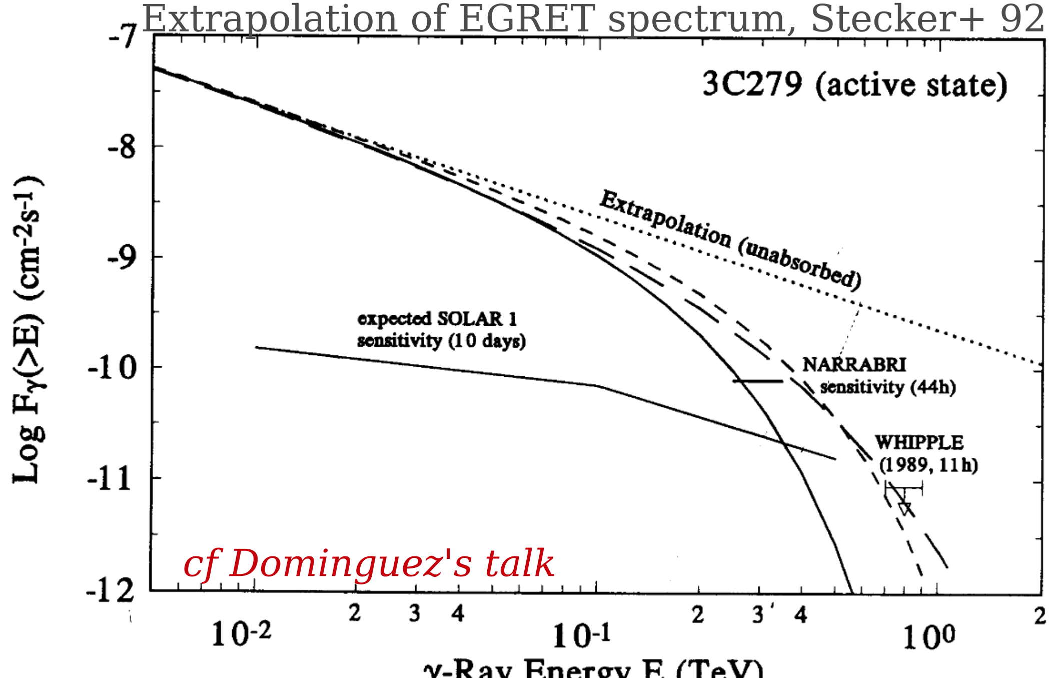
Gould & Schreder 1967

< 100 GeV: intrinsic / unabsorbed
> 100 GeV: absorption features

Stecker+ 92



Extrapolation of EGRET spectrum, Stecker+ 92



Intergalactic Magnetic Field

e+e- sensistive to B
inverse Compton off CMB with ε_{CMB} = 1 meV

Plaga+ 95

$E\gamma,f = (E\gamma,i/2m_e)^2\ \varepsilon_{CMB} = 1\ \mathrm{GeV}\ (E\gamma,i/1\mathrm{TeV})^2$

LIV and ALPs

Coupling with hypothetical ALPs

Csaki+ 03 (for super GZK photons though)

LIV modification of absorption >10 TeV

Kifune 99

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2006-2008: The GeV – TeV Revolution

Outstanding Instruments

Fermi-LAT launched in 2008

3rd generation Atmospheric Cherenkov Telescopes (ACTs), H.E.S.S. / MAGIC / VERITAS, first discoveries in 2005-08

Gain of 1-2 orders of magnitude in sensitivity wrt previous generation

Still some GeV – TeV differences due to the observing mode (all-sky / pointed, long / short exposures)

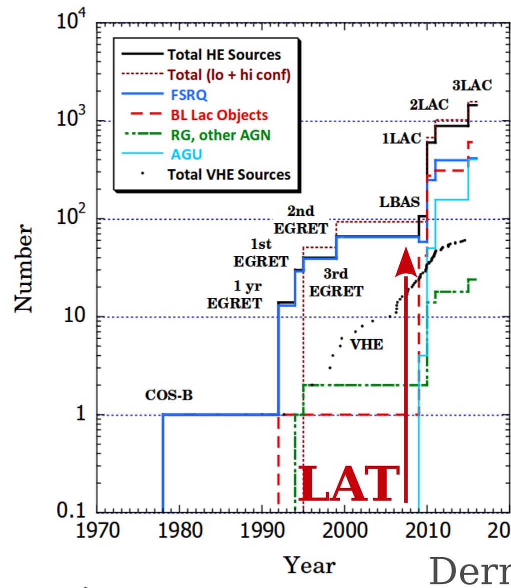
A Quantity Jump

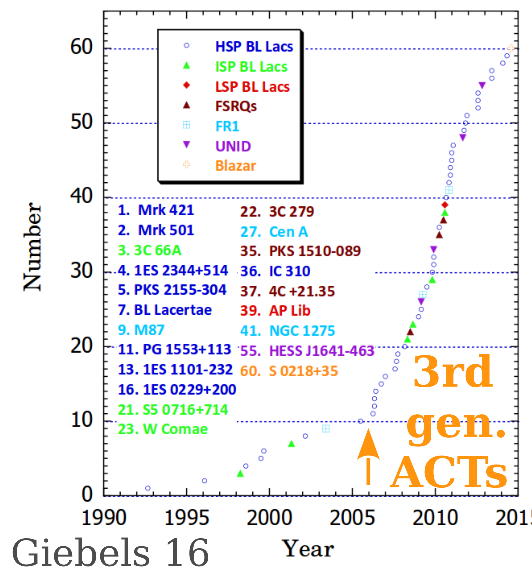
Number of blazars x 10!

0.1-300 GeV: ~1600 blazars (3LAC)
0.05 - 2 TeV: ~270 blazars (2FHL)
0.1 - 10 TeV: ~60 blazars (TeVCat)

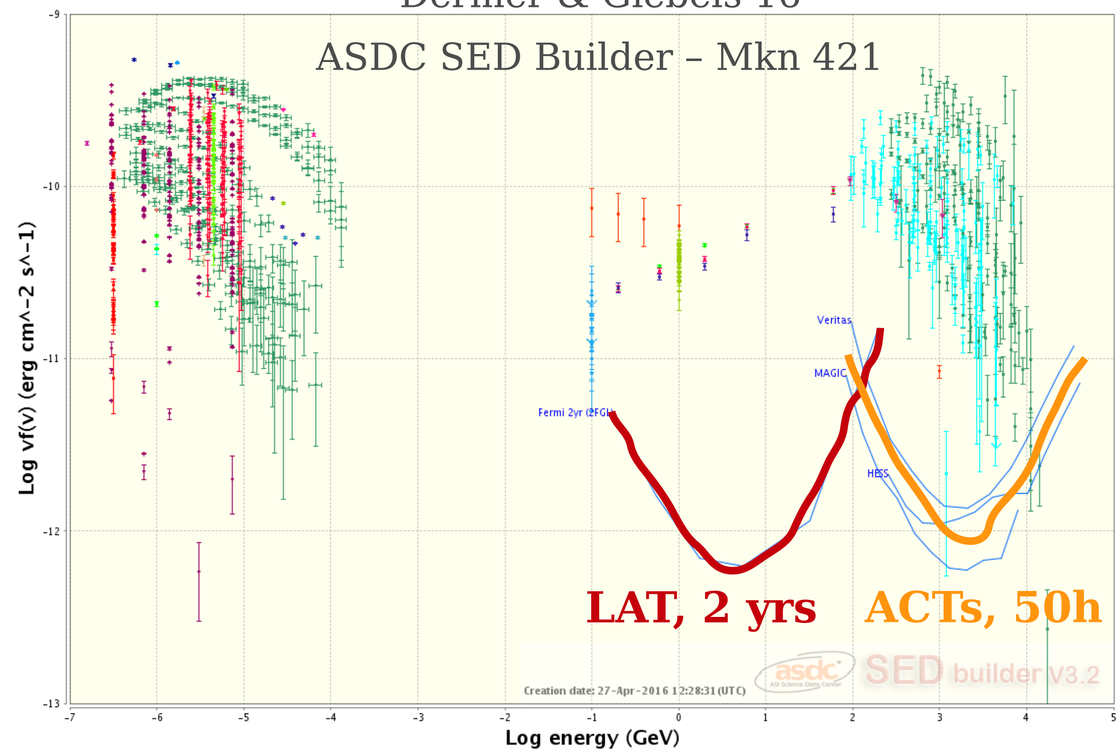
A Quality Jump

Diversity of spectral states probed by γ-ray instruments similar to X-rays!





Dermer & Giebels 16



Complementarity: Catching Sources

LAT triggers for ACTs

LAT long-term monitoring
+ flare advocates' work

→ high-flux triggers

→ hard-state triggers

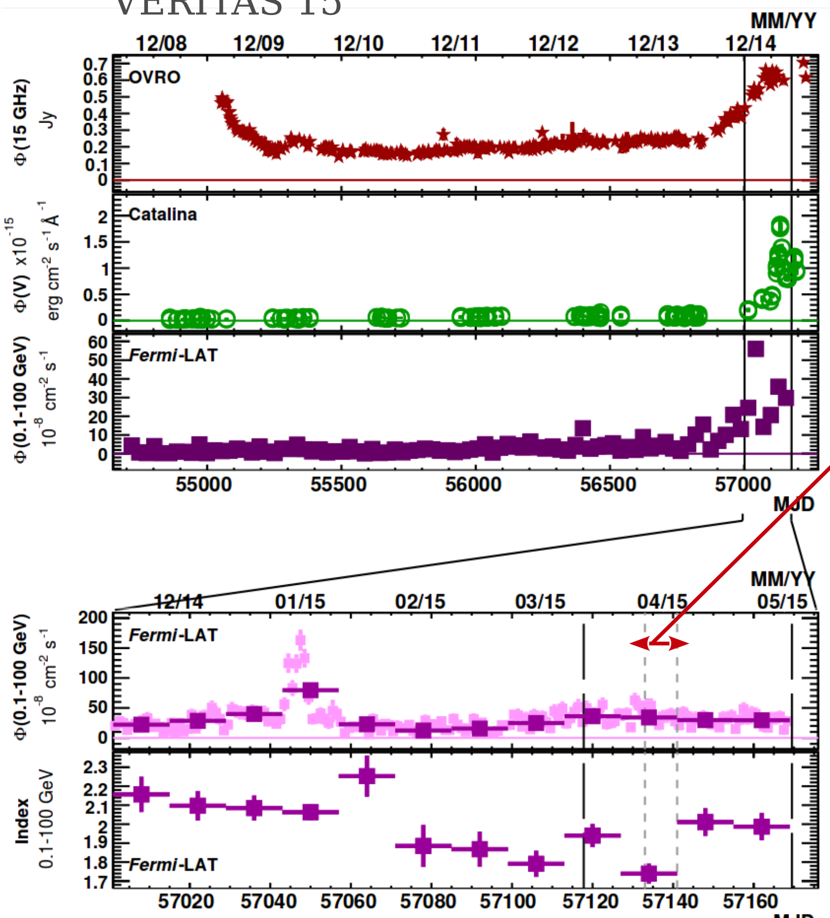
Example: FSRQ PKS 1441+25 (z=0.94)

LAT high & hard state trigger on the 2015-04-14

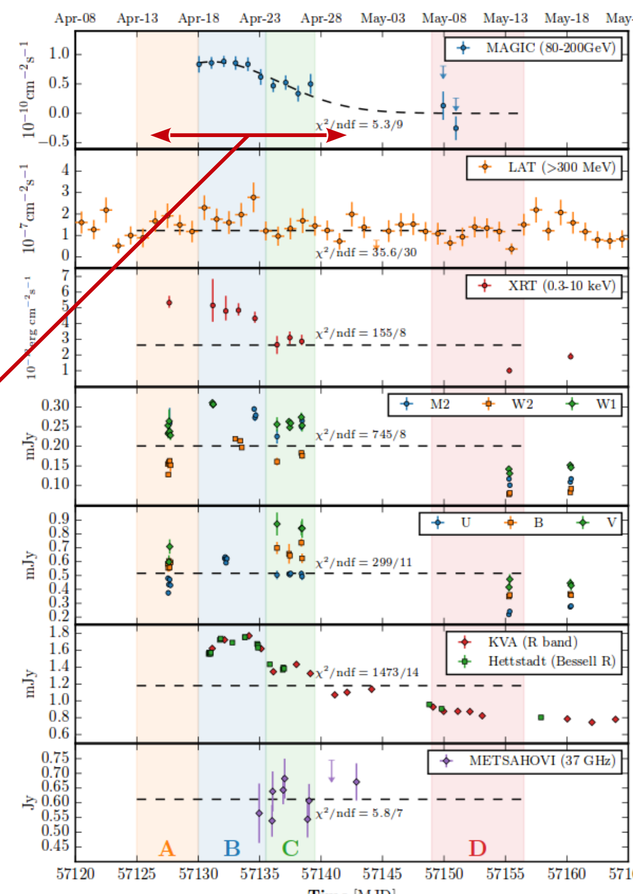
→ MAGIC discovery on 2015-04-18

→ VERITAS detection on 2015-04-21

VERITAS 15



MAGIC & Fermi-LAT 15



Outcome:

Detection of a 5th 'TeV' FSRQ

High-throughput multiwavelength campaign (radio, optical, polarimetry, UV, X-rays, γ-rays)

Insights on the emission location (pc scale)

Single-source EBL constraint with a probe at z~1

γ-ray insights: Astrophysics of HBLs

Steady-state 1-zone SSC model:

- Spherical region of size **R**
- Tangled magnetic field **B**
- Bulk motion with a Doppler factor **δ**

- Electron density $\mathbf{n_e}$
- Maximum electron energy $\boldsymbol{\gamma}_{\mathbf{max}}$
- Electron power-law index **p**

Band & Grindlay 85

Underconstrained w/o further assumption:
2 x (peak position / amplitude) + slope
→ 6 parameters for 5 observables

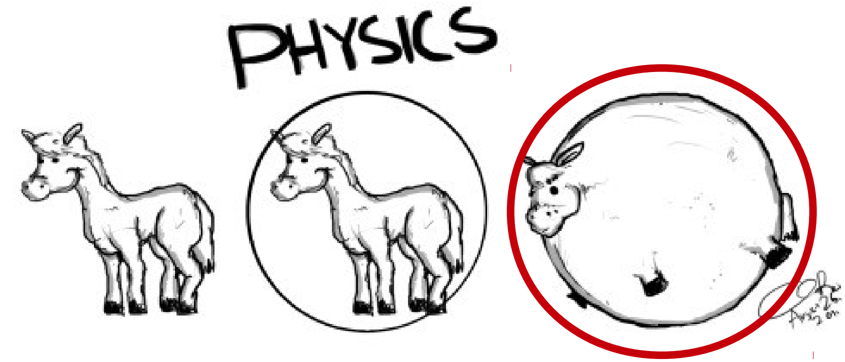
Usually, extra hypotheses on e.g. the maximum energy (cooloing vs escape), variability time-scale, or ratio U_e / U_B

OK for HBL snapshots

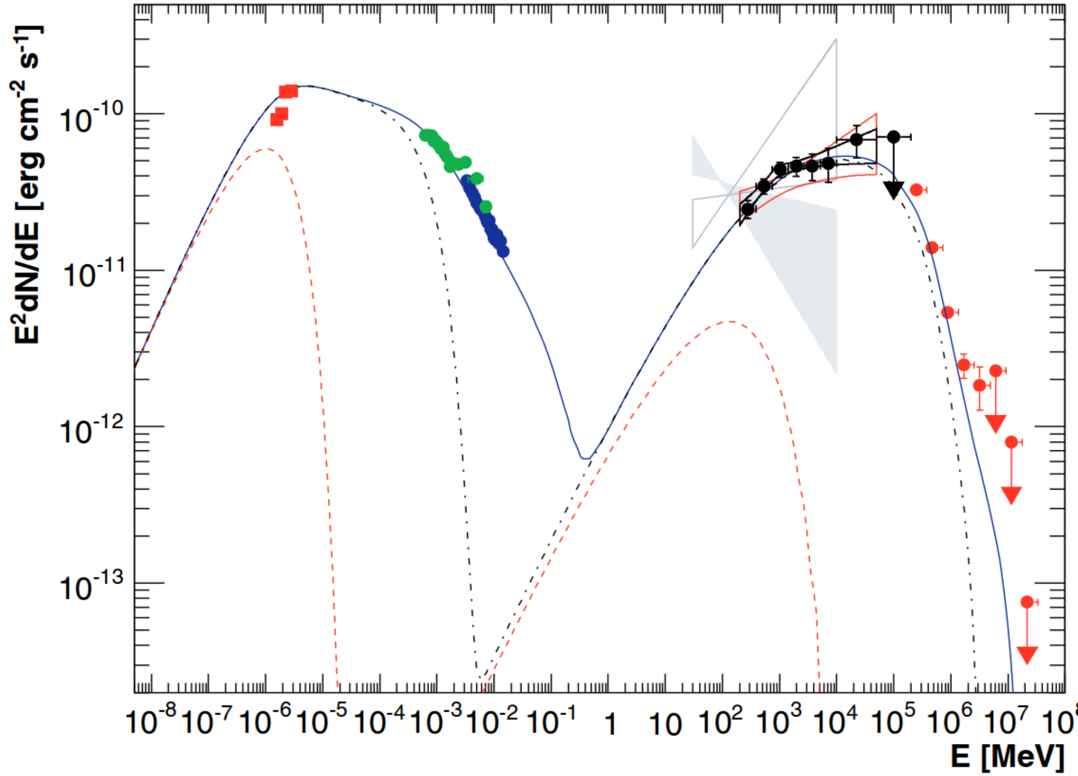
R: 1 mpc – 1 pc **B**: 1 mG – 1 G **δ:** 5-50

$\mathbf{U_e} >> U_B$ $\boldsymbol{\gamma}_{\mathbf{max}}$: $10^4 – 10^6$ **p**: 1.3 – 2.3

But does not work FSRQs / LBL / (IBL)
→ need external photon fields



HESS & Fermi-LAT 09
PKS 2155-304: low state 2008-08 campaign



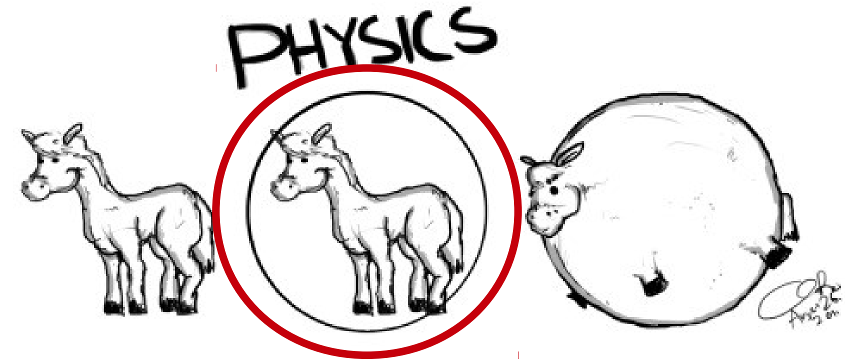
γ-ray (and MWL) insights: Astrophysics of Blazars

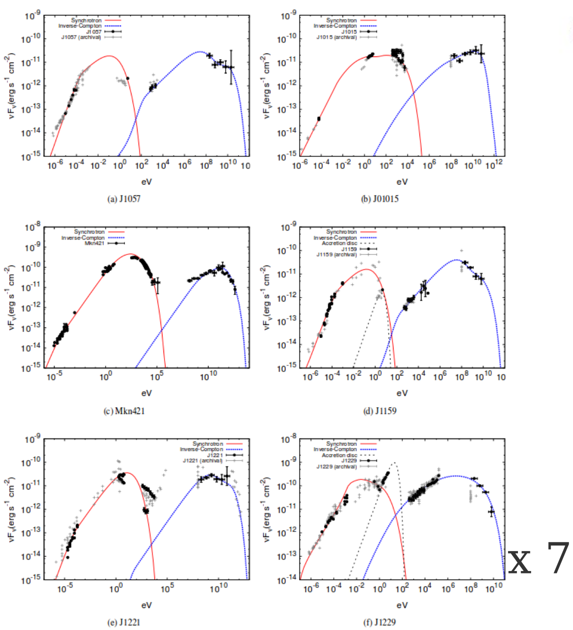
(One of the) most refined, steady-state model on the market:

→ Potter & Cotter 12, 13abc, 15:

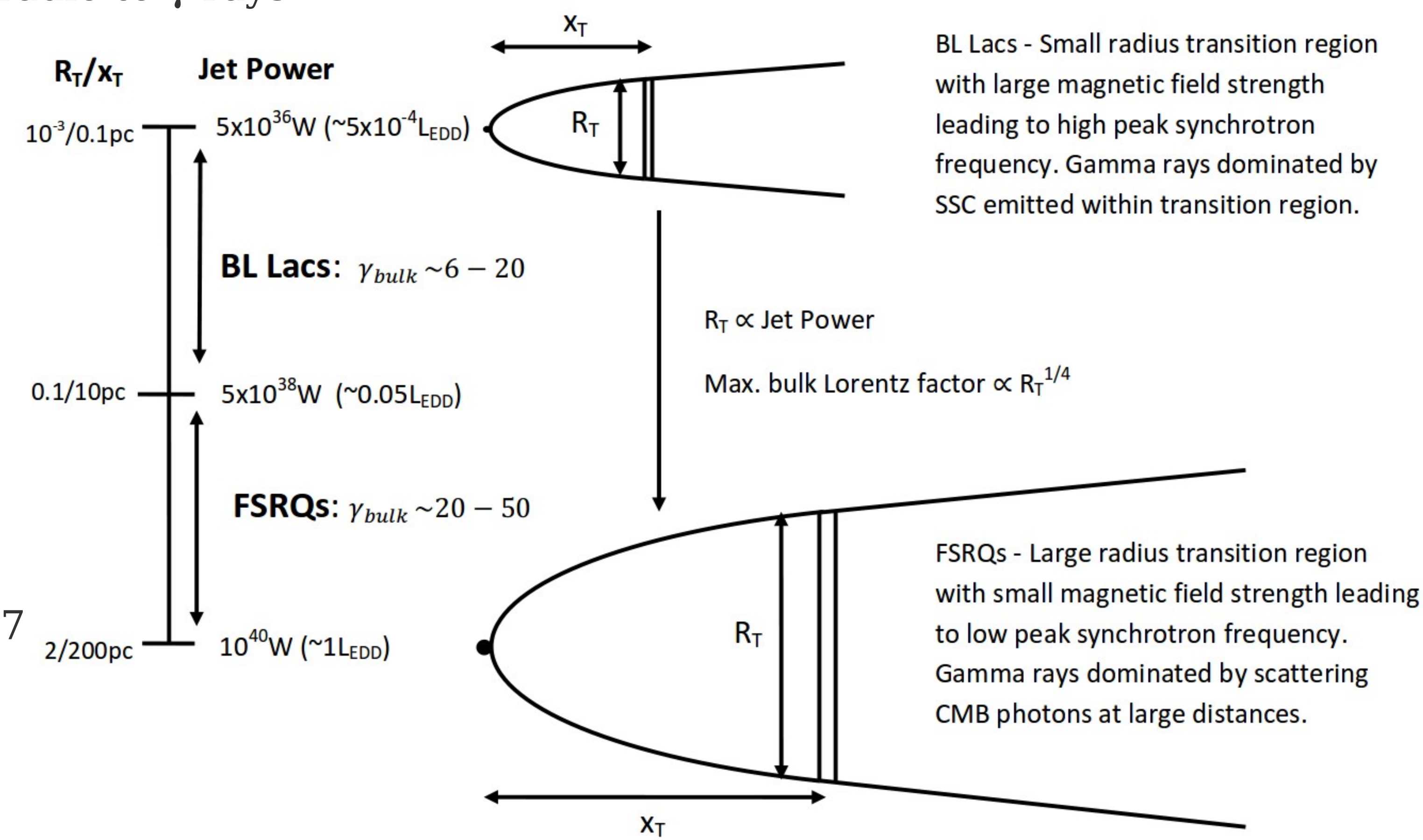
Relativistic fluid treatment of B, e+/e-, losses, scaling the jet geometry on M 87 observations.

Model of 42 SEDs from radio to γ rays





Potter & Cotter 15



γ-ray insights: Hadronic Models of Blazars

Models with significant hadronic radiative signature disfavored

- Hard to reproduce the short-time-scale (minute) variability observed in flares
- Require super-Eddington luminosities for most blazars Zdziarski & Böttcher 15

see also Böttcher's & Bonnoli's talks

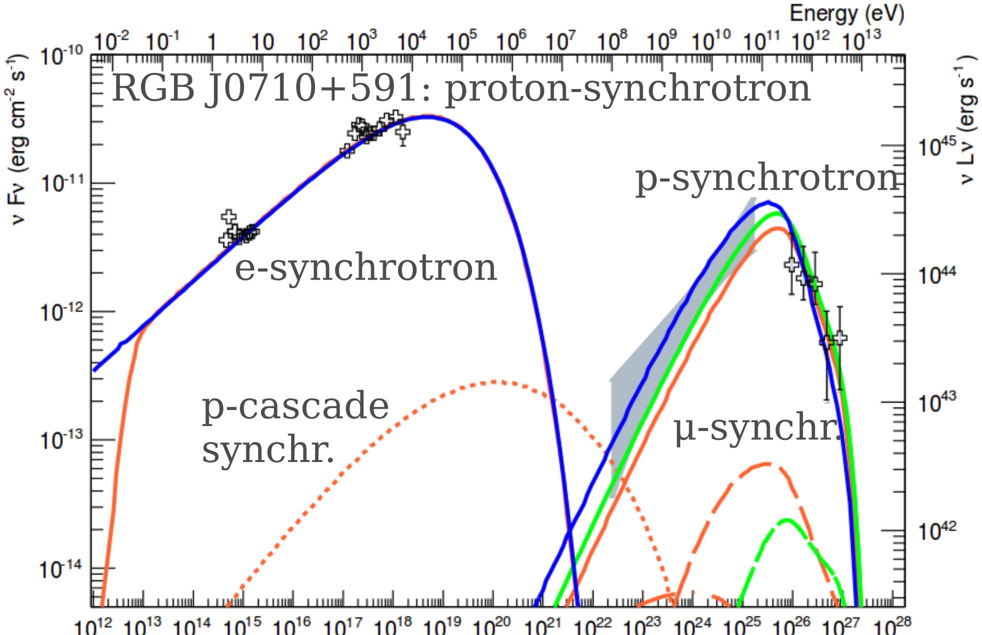
But interesting case of EHBLs:

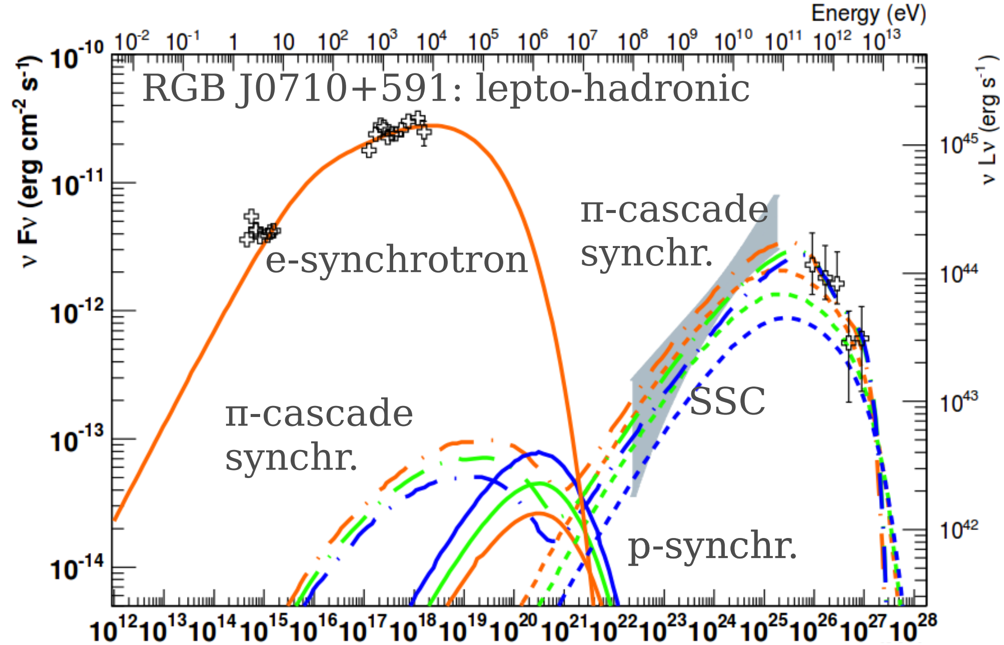
- 5 objects: 1ES 0229+200, 1ES 0347-121, RGB J0710+591, 1ES 1101-232, 1ES 1218+304
- No fast variability detected (truly an intrinsic property or limited by our sensitivity?)
- Simple leptonic models predict (too?) high Doppler factors ~50

Proton synchrotron & lepto-hadronic extensively explored

Cerruti+ 15

- Reasonable luminosities & parameters for EHBLs
- Max proton energy sligthly above the ankle



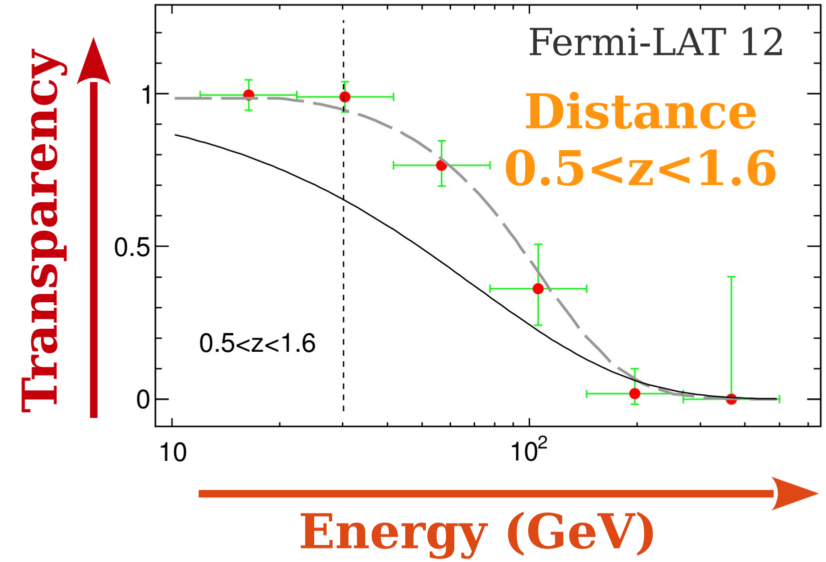


Cerruti+ 15

Complementarity: Nearby / Distant Universe

2012-13: Model-dependant discoveries of the EBL imprint by Fermi-LAT & HESS

Analyses of multi-sources sample, with a joint fit of the intrinsic curvature and of scaled EBL models (scaling significantly from zero → detection)

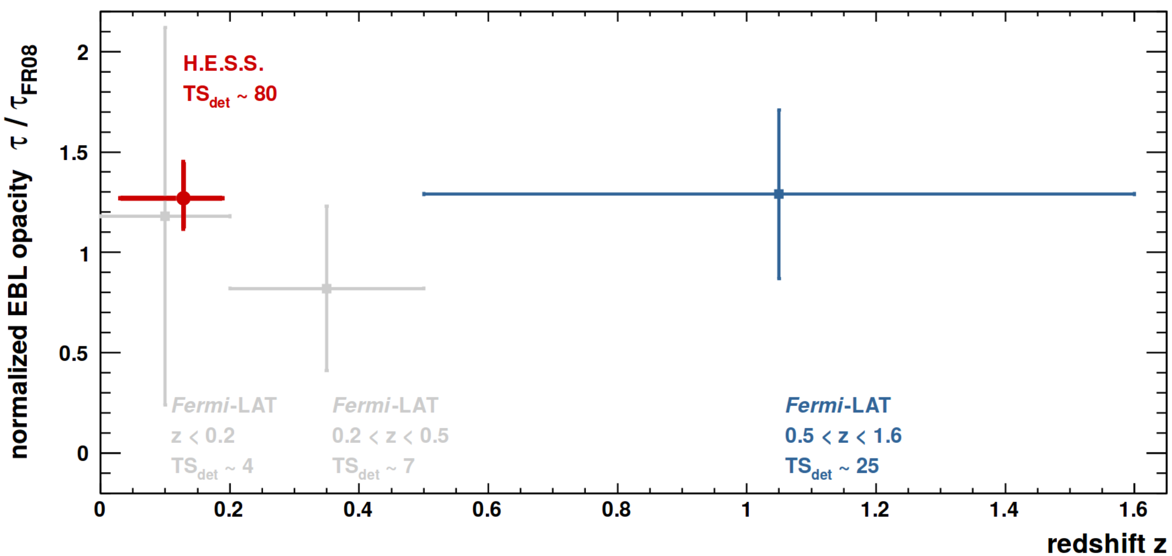


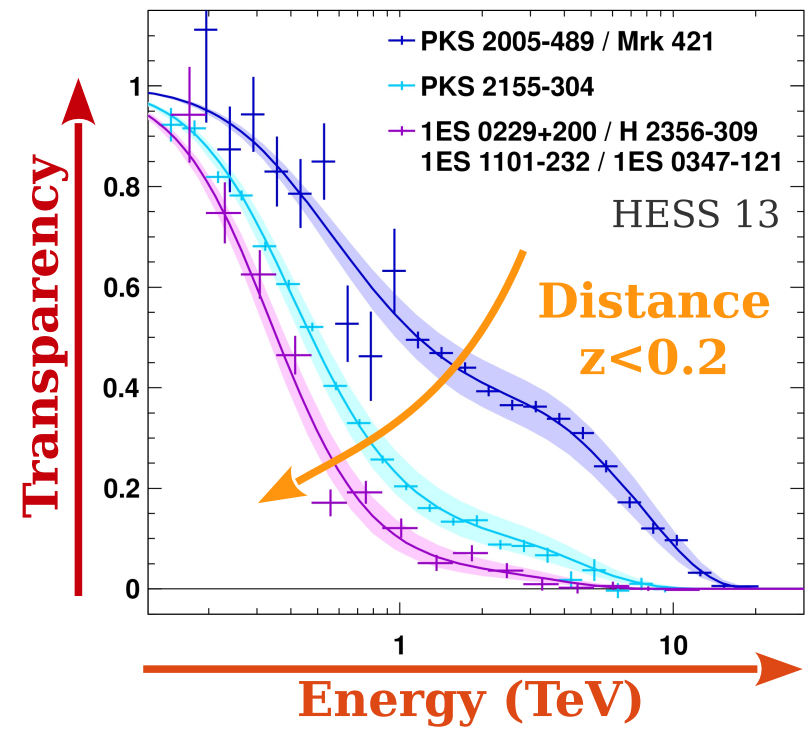
Fermi-LAT:

6σ detection, mostly from z ~ 1

H.E.S.S.:

9σ detection, mostly from z ~ 0.1





Biteau 12

γ-ray insights: Extragalactic Background Light

Complementarity of LAT / ACTs also on EBL wavelength coverage

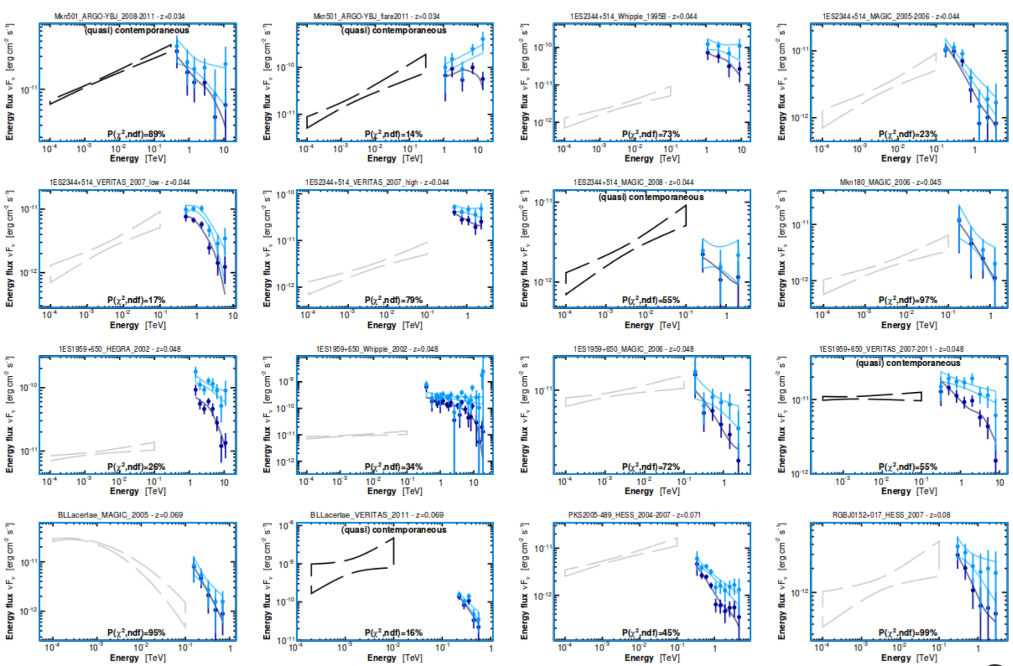
For a fixed evolution scenario, LAT probes UV-O, ACTs probe NUV-IR

Other complementarity: intrinsic (LAT) vs absorbed (ACTs)

Analysis of TeV spectra limiting the maximum hardness to that measured by LAT
→ Note: limited spectral variability observed in LAT (not true for flux variability!)

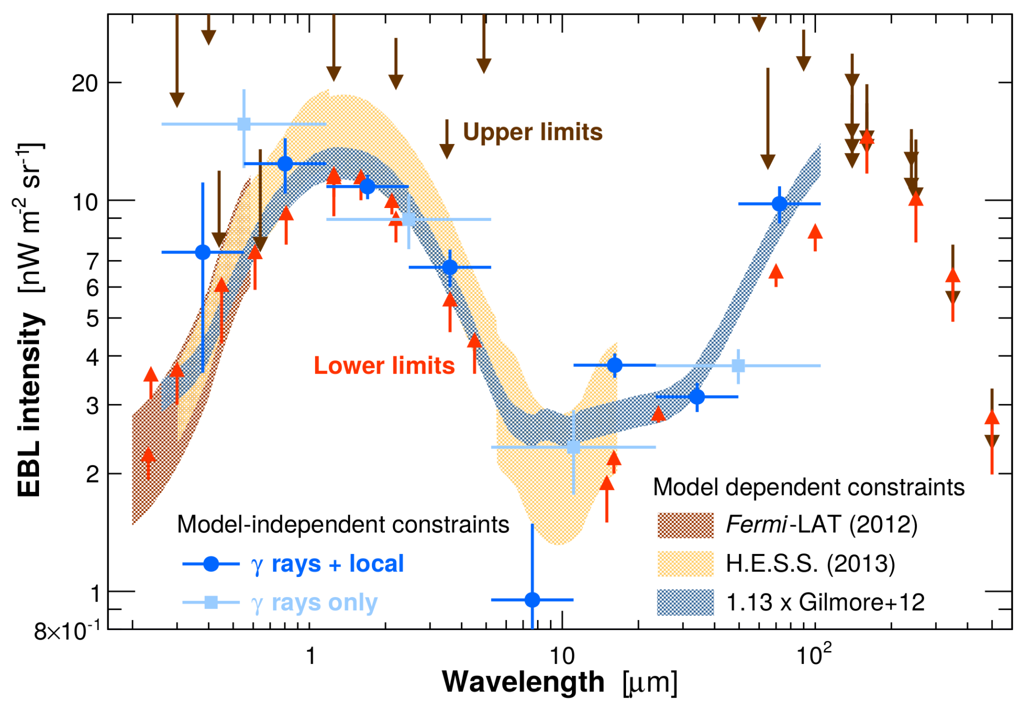
Results on the EBL   Biteau & Williams 15

Model-independant measurement from NUV to FIR → uncertainty down to 20 %
Only 3 models still on the market: Franceschini+ 08, Dominguez+ 11, Gilmore+ 12 (fixed)



x 6

Biteau & Williams 15



γ-ray insights: Search for Anomalies

"Gamma-ray constraints on the EBL are below galaxy counts"

WRONG! model-independent approach even shows a slight excess from gamma rays

"TeV intrinsic spectra are too hard"

WRONG! no tension with Fermi-LAT hardness for contemporaneous observations

"GeV extrapolation does not match TeV flux"

WRONG! good match for most, others easily explained GeV-TeV non simultaneity...

"Flux excess correlated with optical depth"

WRONG! see bottom right plot

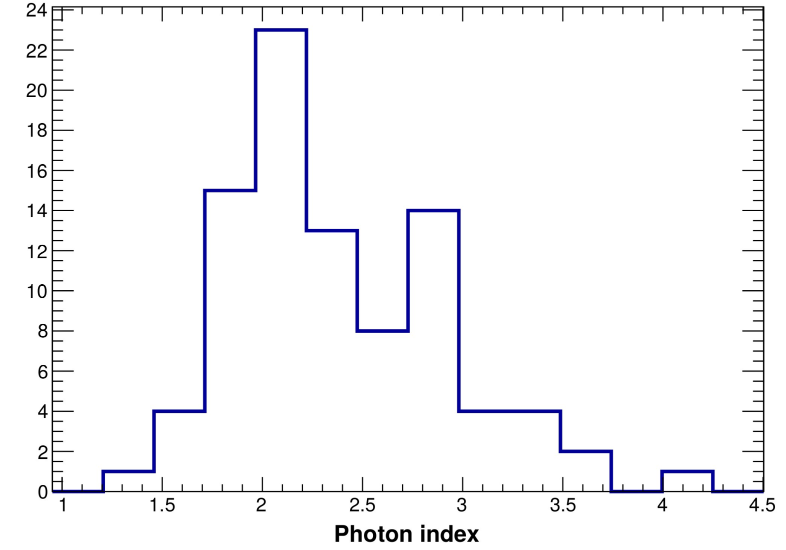
Status of alternative scenarios

ALPs: coupling < 2 x 10^{-11} GeV^{-1} between 15-60 neV
HESS 13

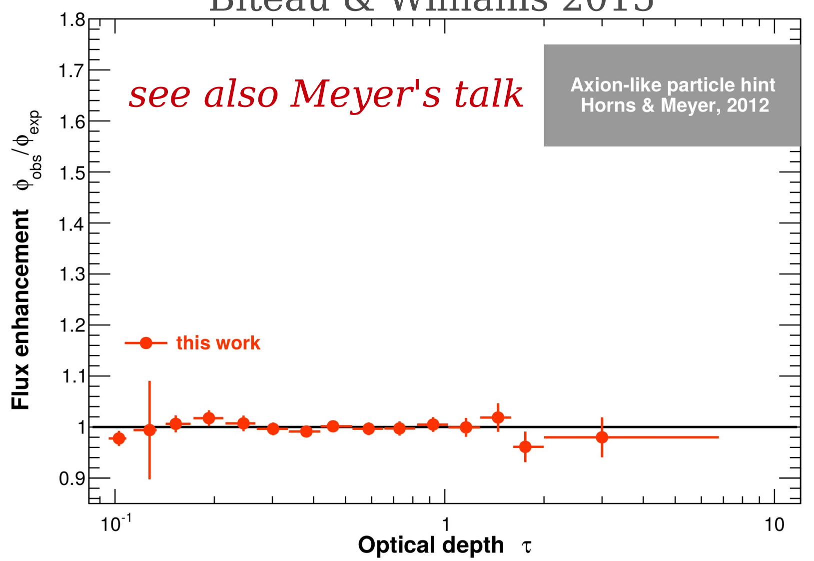
LIV: quantum gravity energy scale > 0.6 x E_{Planck}
Biteau & Williams 15

CR reprocessing: still needs to be quantified

Biteau & Williams 2015



Biteau & Williams 2015



γ-ray insights: Intergalactic Magnetic Fields

Gamma-ray based IGMF constraints

HBL and EHBL multi-TeV emission reprocessed at low energies: detectable?

Low-strength IGMF (sub fG)

Limit on the low-energy point-source flux

First constraints B > 10^{-16} G
Neronov and Vovk 10

Possibly relaxed releasing steady assumption B > 10^{-17} - 10^{-18} G
Taylor+ 11, Dermer 11, Arlen+ 12

Possible caveats from plasma physics not confirmed by PIC simulations
Sironi & Gianios 14

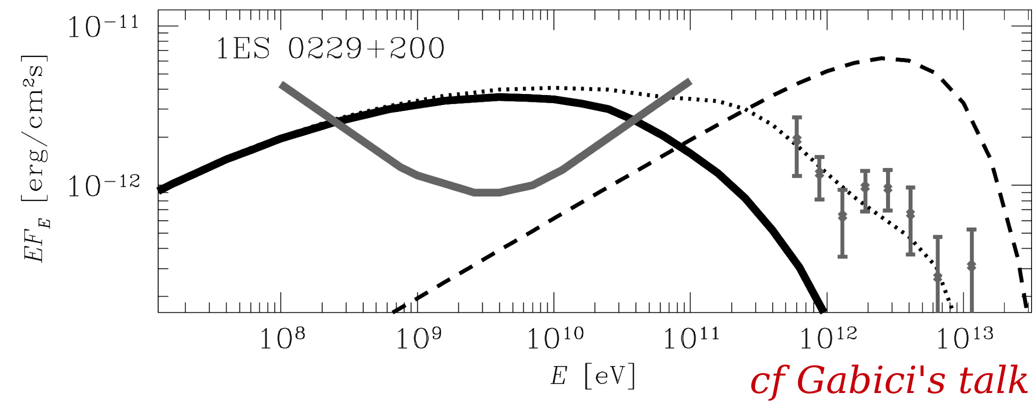
Mid-strength IGMF (fG-pG)

Limit on the low-energy source extension

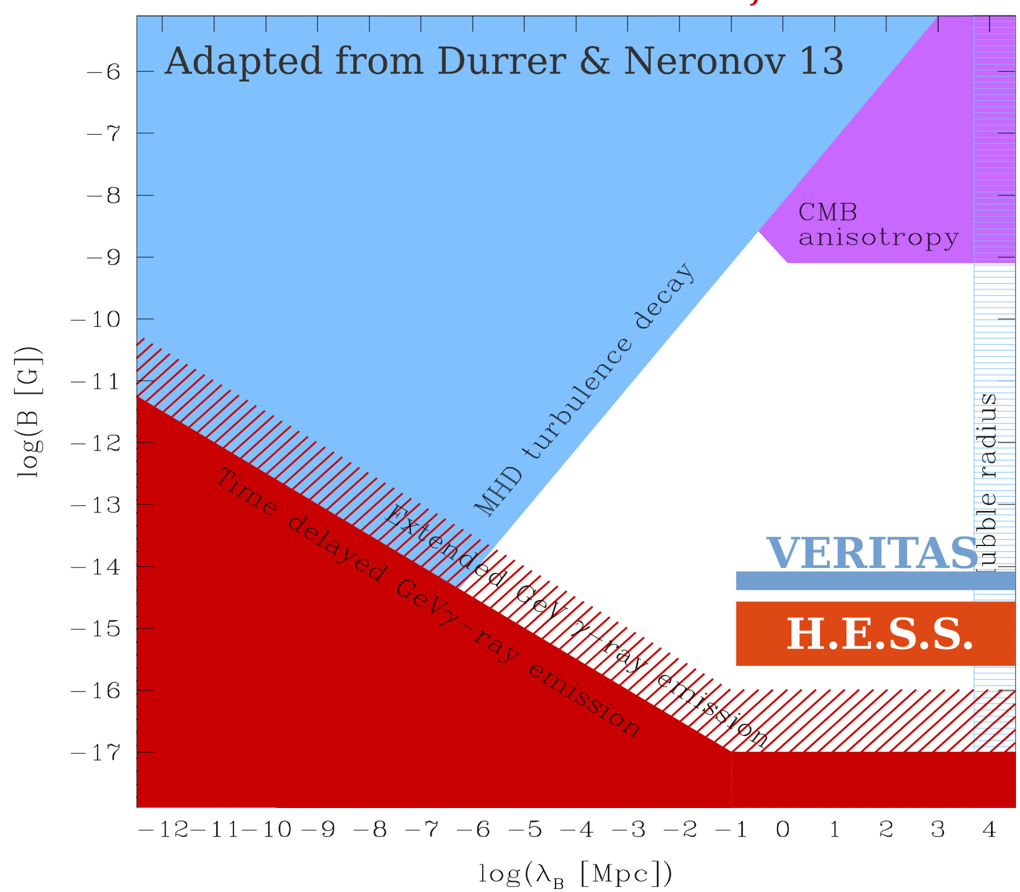
PKS 2155-304 by HESS → [0.3–3] x 10^{-15} G
HESS 14

1ES 0229+200 by VERITAS→ [5–10] x 10^{-15} G
VERITAS in prep, Pueschel, ICRC15

Neronov & Vovk 10



cf Gabici's talk



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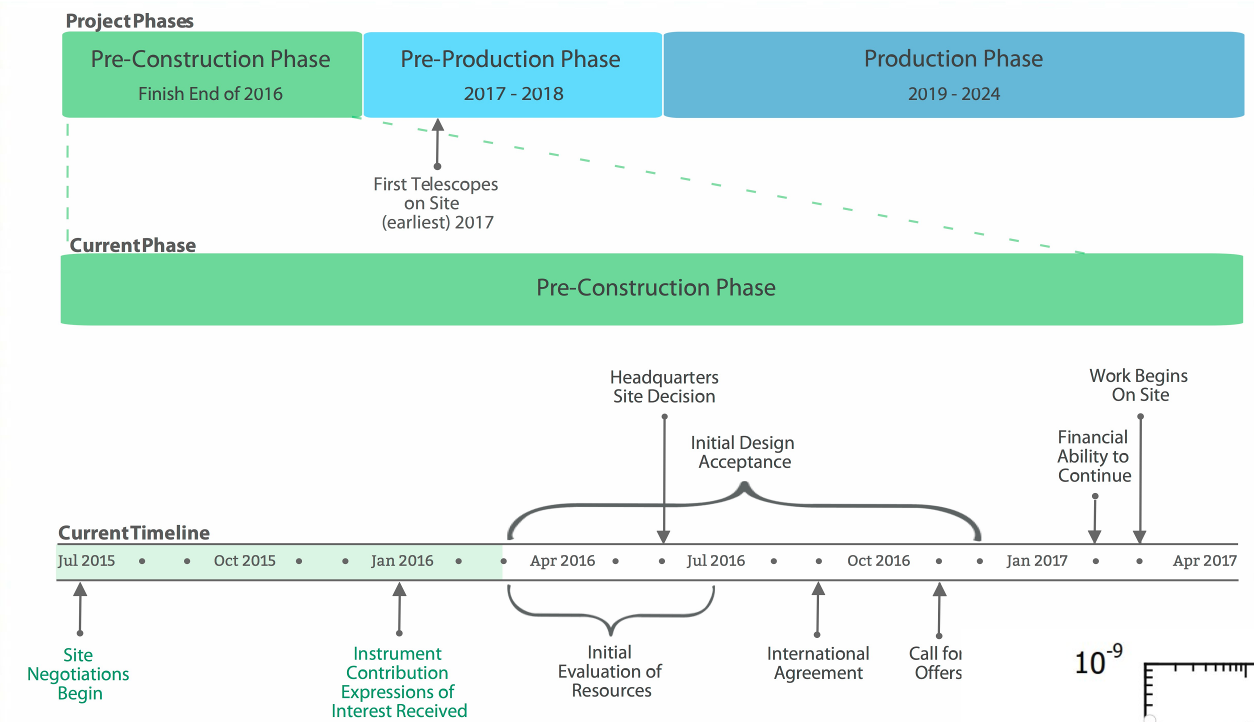
Fermi-LAT and CTA early science



Cherenkov Telescope Array official timeline
https://portal.cta-observatory.org/Pages/Preparatory-Phase.aspx

cf Sanchez's talk

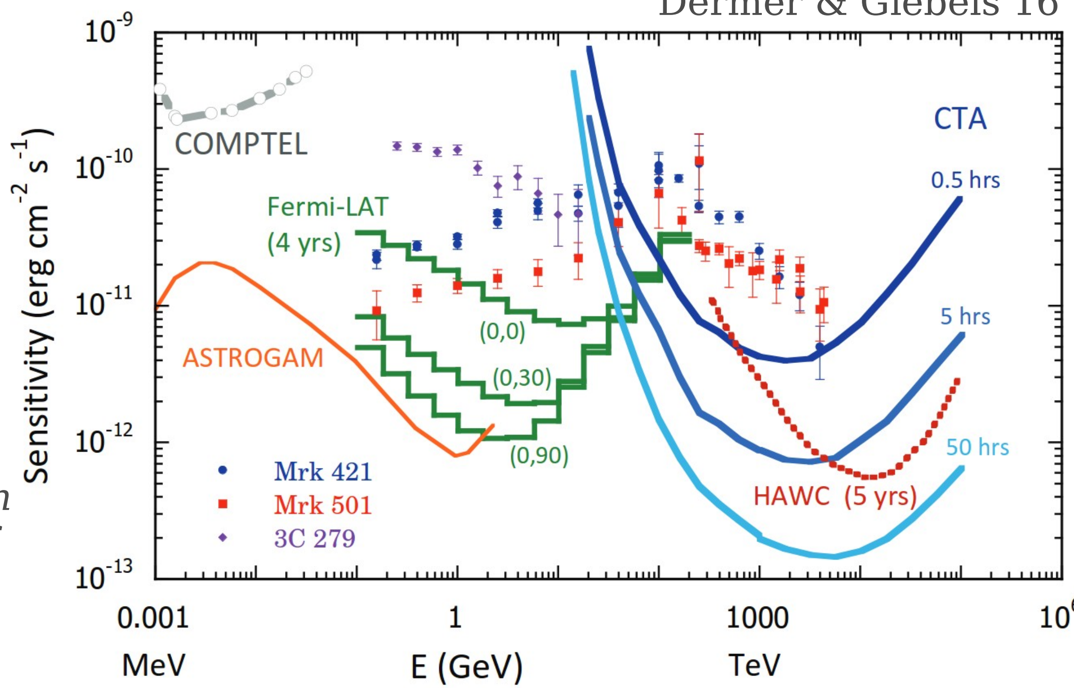
Fermi-LAT beyond 2018?

CTA-N and CTA-S will probably supersede current ACT by 2019/20

AGN Key Science Program:

Simultaneous observations with Fermi are of great interest for flaring AGN and should be given high priority during the first years of operation of CTA, as long as Fermi will be operational

Dermer & Giebels 16



Summary & Open questions

Blazars: lessons from Fermi, HESS, MAGIC, and VERITAS

Detailed view on the high-energy component of the blazar population, from FSRQs to EHBLs

Constraints on (leptonic) radiative models

Clues on the emitting-region location

Detection of the long-sought EBL imprint

Exclusion of part of the IGMF parameter space

Astrophysics: open questions

Origin and nature of variability

Hadronic fraction (cold? maximum energy?)

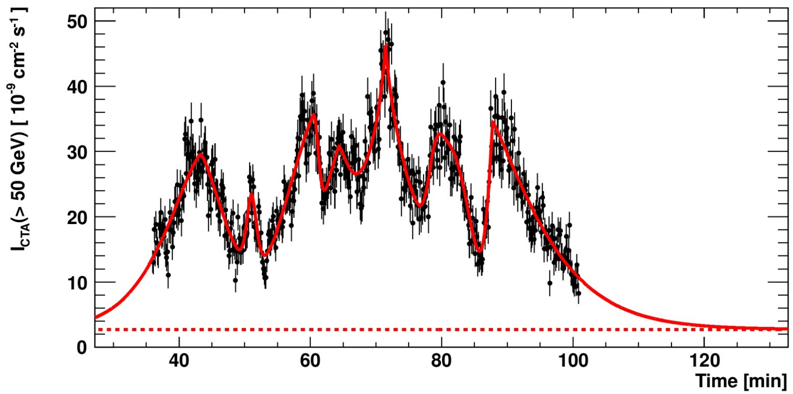
Links with UHECR and neutrinos

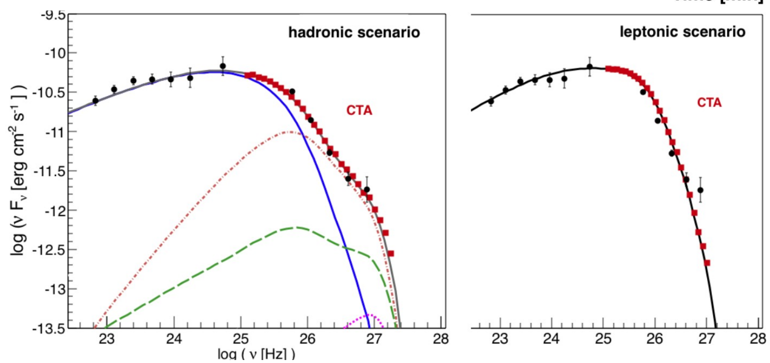
γ-ray cosmology: open questions

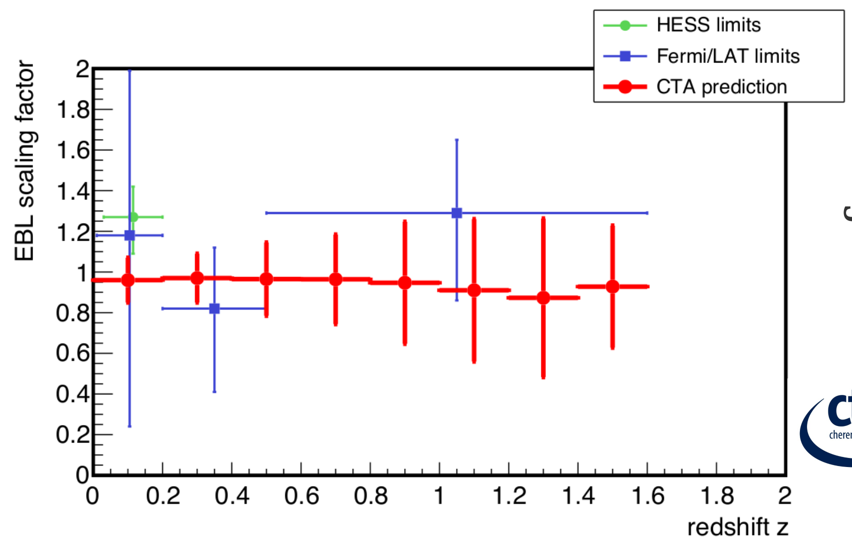
FUV background, EBL evolution

IGMF strength and coherence length

ALPs & LIV







CTA simulations, AGN Key Science Project

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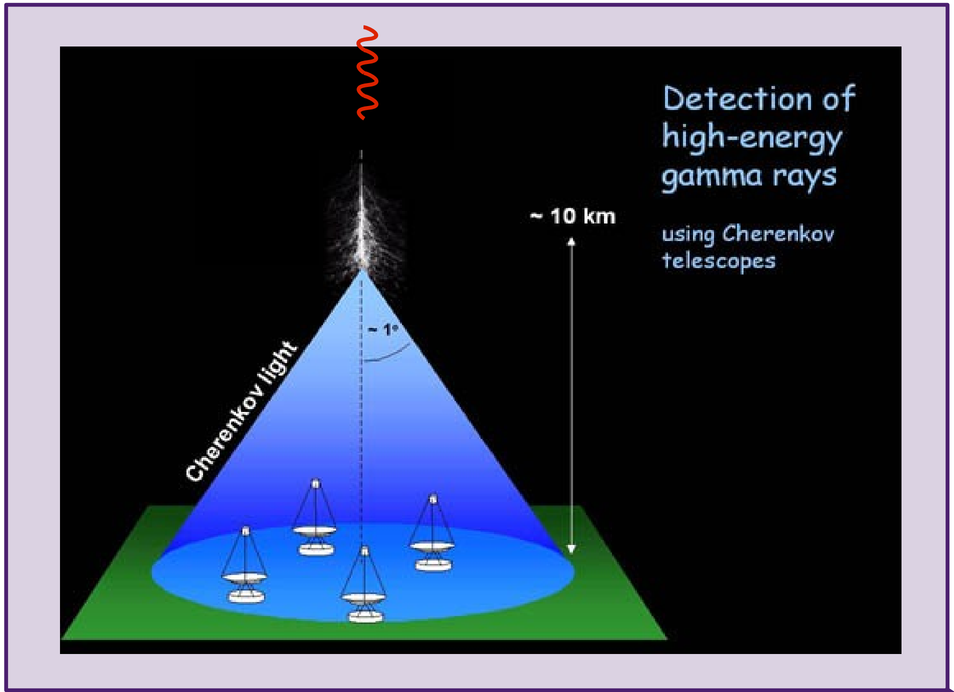
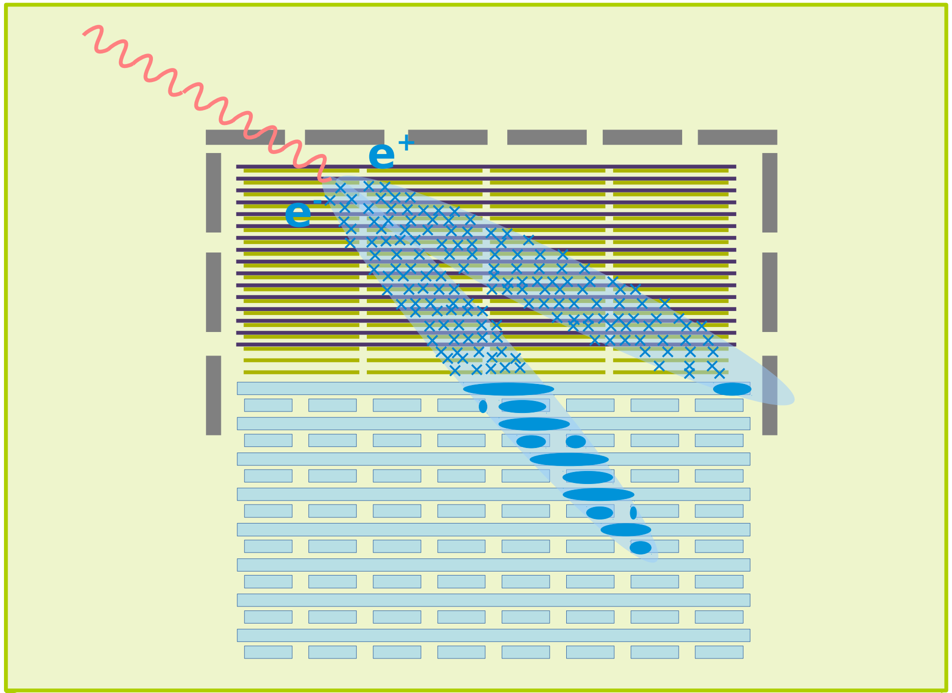
Kataoka 1999	http://adsabs.harvard.edu/abs/1999ApJ...514..138K
Khaire Srianand 2015	http://adsabs.harvard.edu/abs/2015ApJ...805...33K
Kifune 1999	http://adsabs.harvard.edu/abs/1999ApJ...518L..21K
Kneiske Dole 2010	http://adsabs.harvard.edu/abs/2010A%26A...515A..19K
Leinert 1998	http://adsabs.harvard.edu/abs/1998A%26AS..127....1L
Lyutikov 2003	http://adsabs.harvard.edu/abs/2003NewAR..47..513L
Madau Pozetti 2000	http://adsabs.harvard.edu/abs/2000MNRAS.312L...9M
MAGIC & Fermi-LAT 15	http://adsabs.harvard.edu/abs/2015ApJ...815L..23A
Mannheim 1993	http://adsabs.harvard.edu/abs/1993A%26A...269...67M
Meyer 2014	http://adsabs.harvard.edu/abs/2014JCAP...12..016M
Meyer Horns 2013	http://adsabs.harvard.edu/abs/2013PhRvD..87c5027M
Neronov Vovk 2010	http://adsabs.harvard.edu/abs/2010Sci...328...73N
Plaga 1995	http://adsabs.harvard.edu/abs/1995Natur.374..430P
Potter Cotter 2012	http://adsabs.harvard.edu/abs/2012MNRAS.423..756P
Potter Cotter 2013a	http://adsabs.harvard.edu/abs/2013MNRAS.429.1189P
Potter Cotter 2013b	http://adsabs.harvard.edu/abs/2013MNRAS.431.1840P
Potter Cotter 2013c	http://adsabs.harvard.edu/abs/2013MNRAS.436..304P
Potter Cotter 2015	http://adsabs.harvard.edu/abs/2015MNRAS.453.4070P
Pueschel 2015	http://adsabs.harvard.edu/abs/2015arXiv150805742P
Punch 1992	http://adsabs.harvard.edu/abs/1992Natur.358..477P
Sironi Giannios 2014	http://adsabs.harvard.edu/abs/2014ApJ...787...49S
Stecker 1992	http://adsabs.harvard.edu/abs/1992ApJ...390L..49S
Stecker 2006	http://adsabs.harvard.edu/abs/2006ApJ...652L...9S
Taylor 2011	http://adsabs.harvard.edu/abs/2011A%26A...529A.144T
VERITAS 2015	http://adsabs.harvard.edu/abs/2015ApJ...815L..22A
Viero 2013	http://adsabs.harvard.edu/abs/2013ApJ...779...32V
Zdziarski Boettcher 2015	http://adsabs.harvard.edu/abs/2015MNRAS.450L..21Z
Zemcov 2014	http://adsabs.harvard.edu/abs/2014Sci...346..732Z

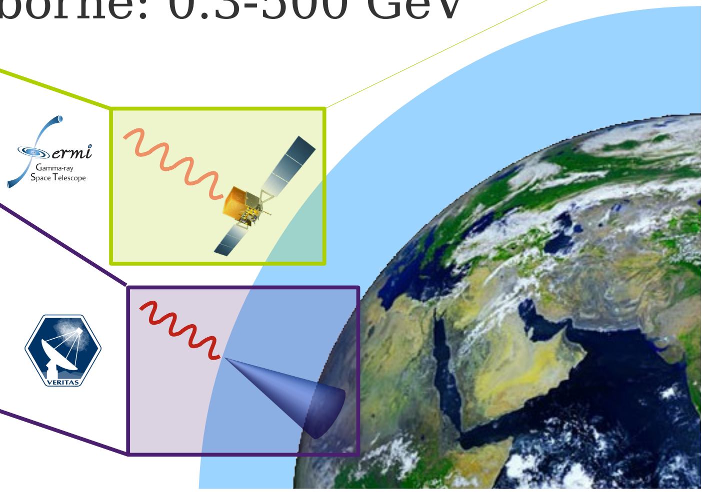
Detecting TeV and GeV gamma rays



Ground based: 0.1-30 TeV



Airborne: 0.3-500 GeV



→ **Angular resolution Δθ~0.1º**

→ **Calorimetric measurements ΔE~15%**

"Dark patches" observations

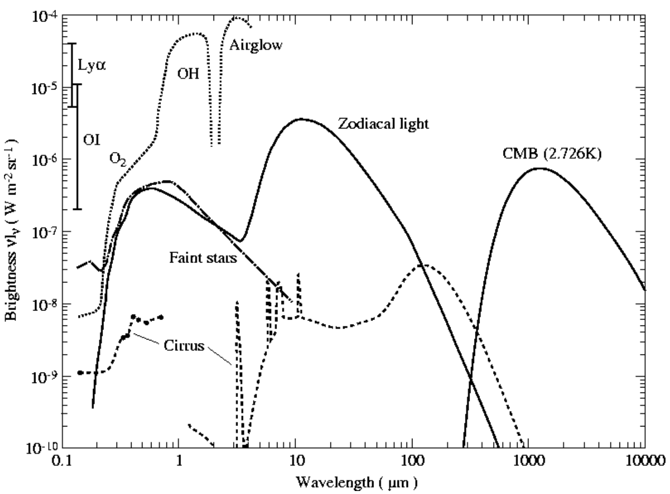
Direct measurement of the night-sky brightness

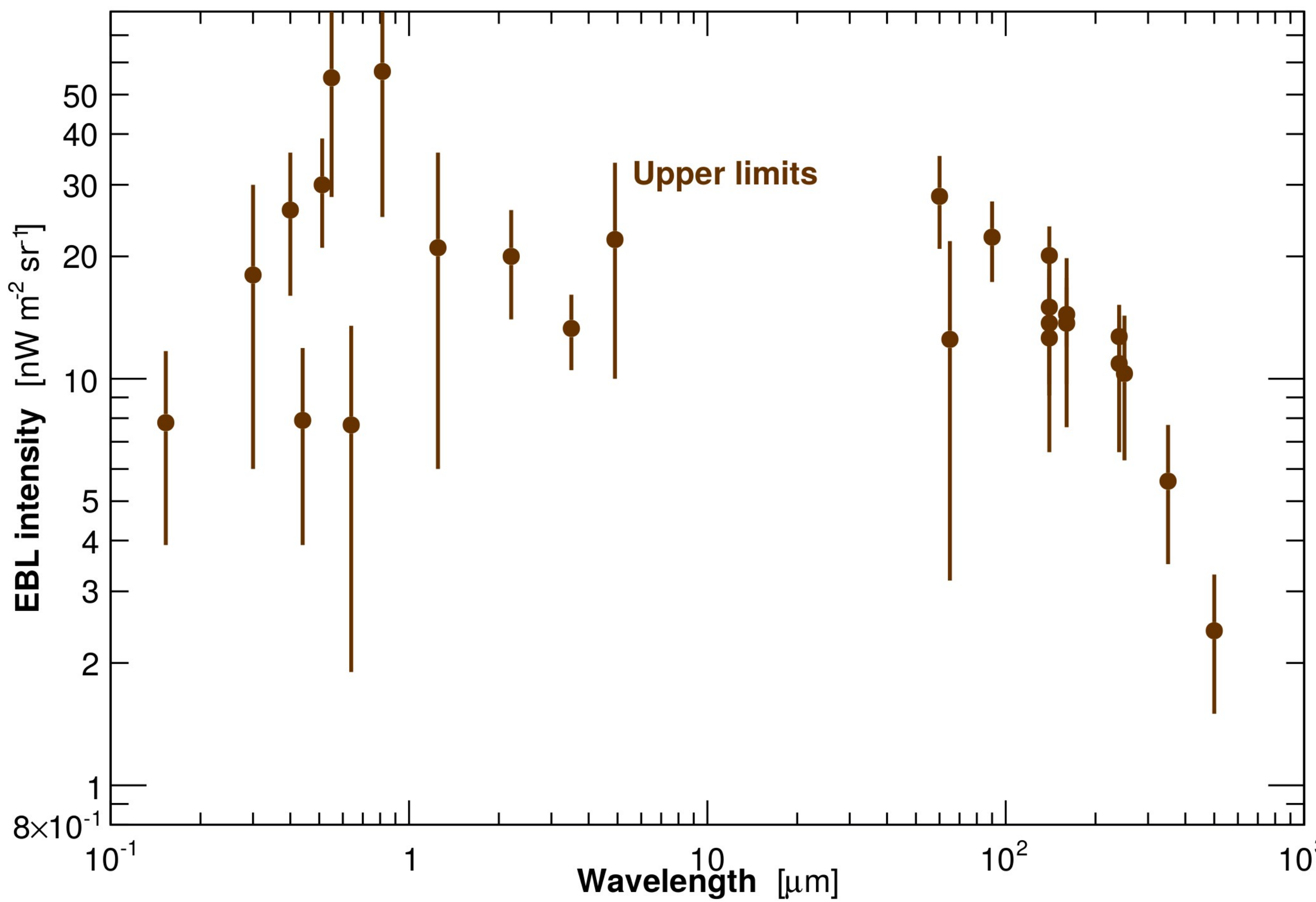
But bright local environment (e.g. zodiacal light) suggests foreground contamination, particularly for the COB → overestimation of the EBL.

> 100 μm: cleaner

COBE (FIRAS/DIRBE) measurements less prone to contamination

Leinert+ 1998

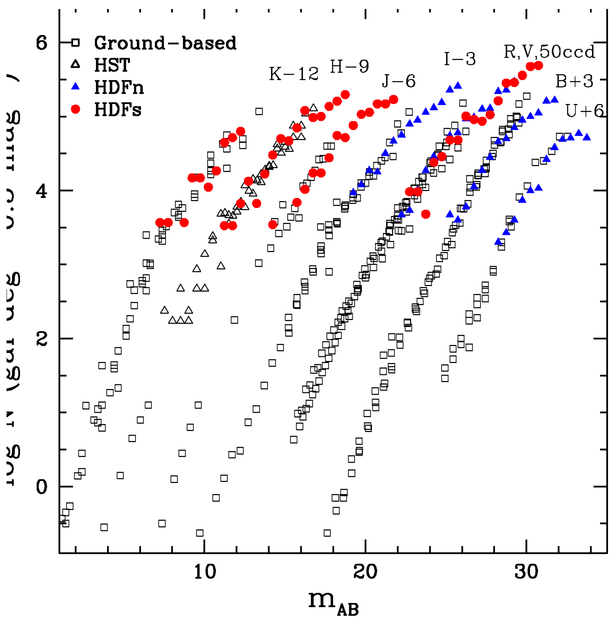




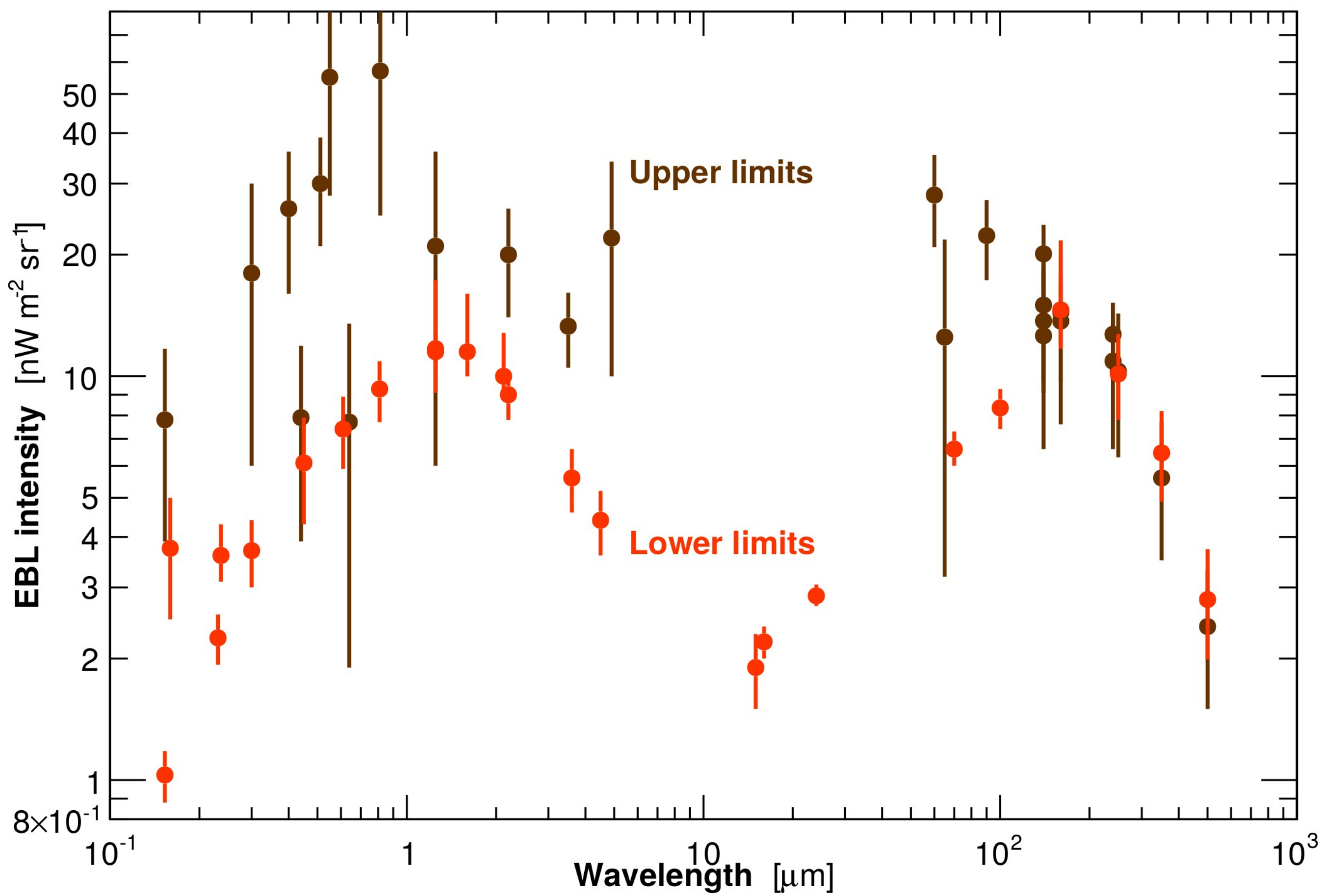
Galaxy Counts

Counting the number of objects per magnitude band

Faint end of the distribution function must drop below a given slope for the integral to converge (completeness). Does not account for unknown populations of sources or truly diffuse component → underestimation.



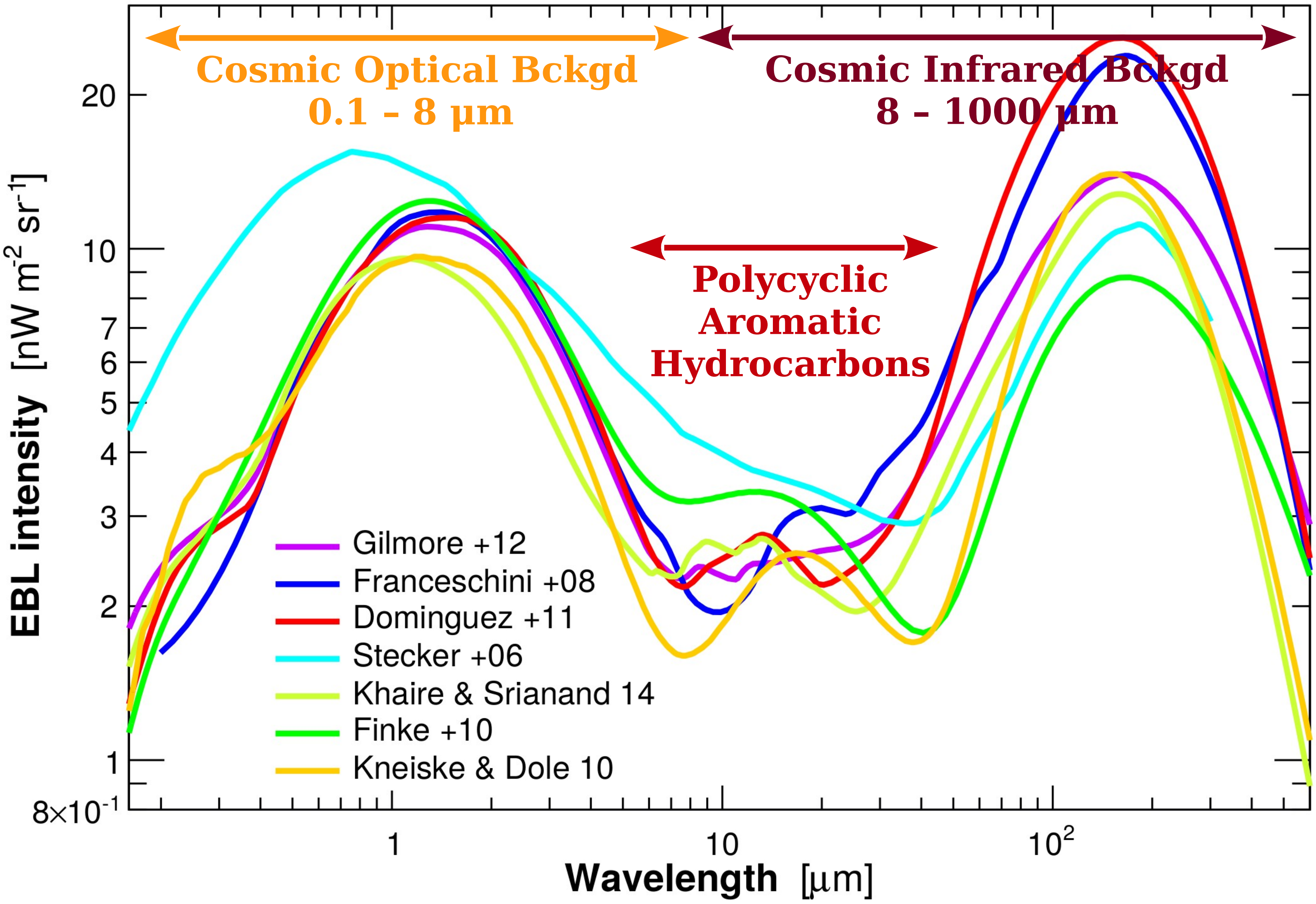
Madau & Pozetti 2000



+ stacking e.g. Viero +13

+ fluctuations
e.g. Zemcov +14

Models of the EBL



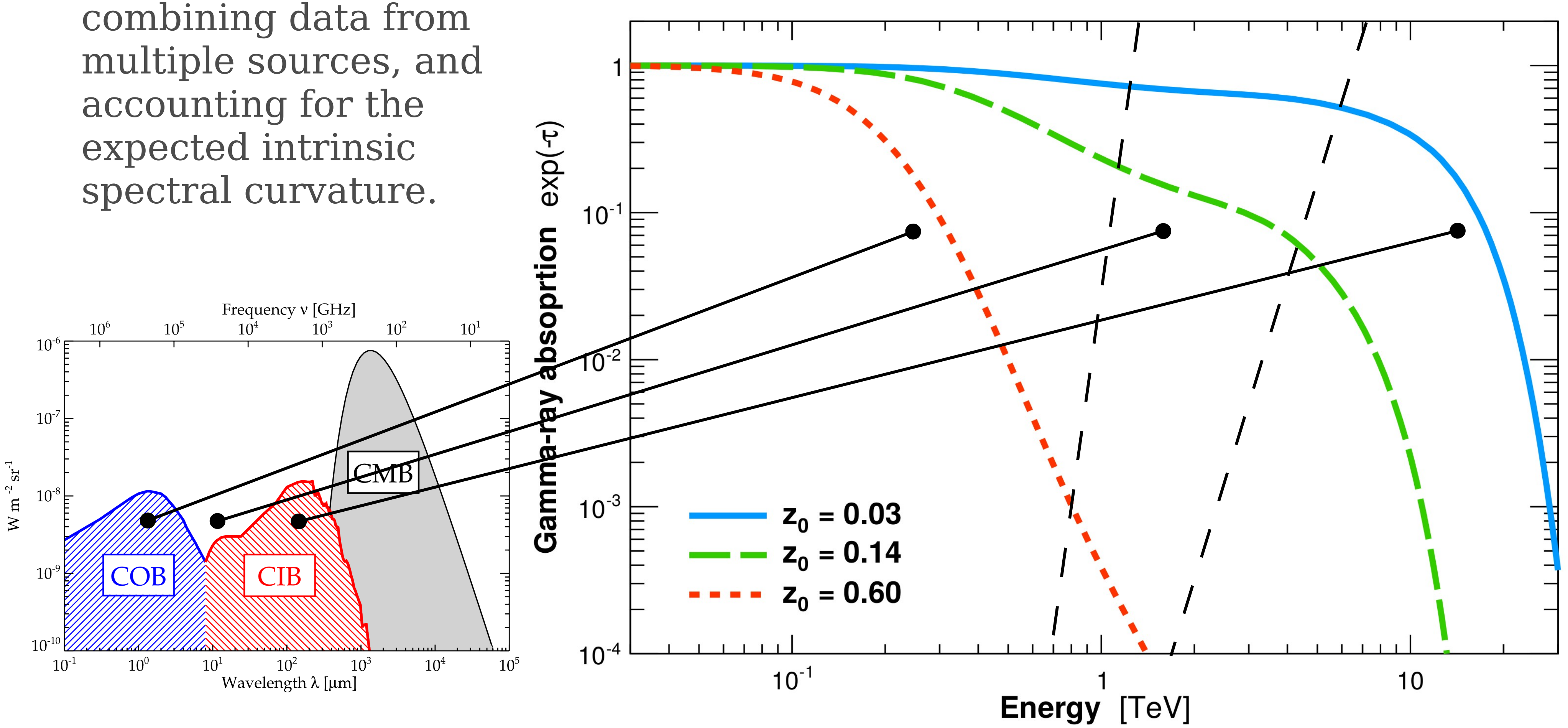
The EBL imprint on gamma-ray spectra

Gamma-ray disappearance imprints the spectra > 100 GeV

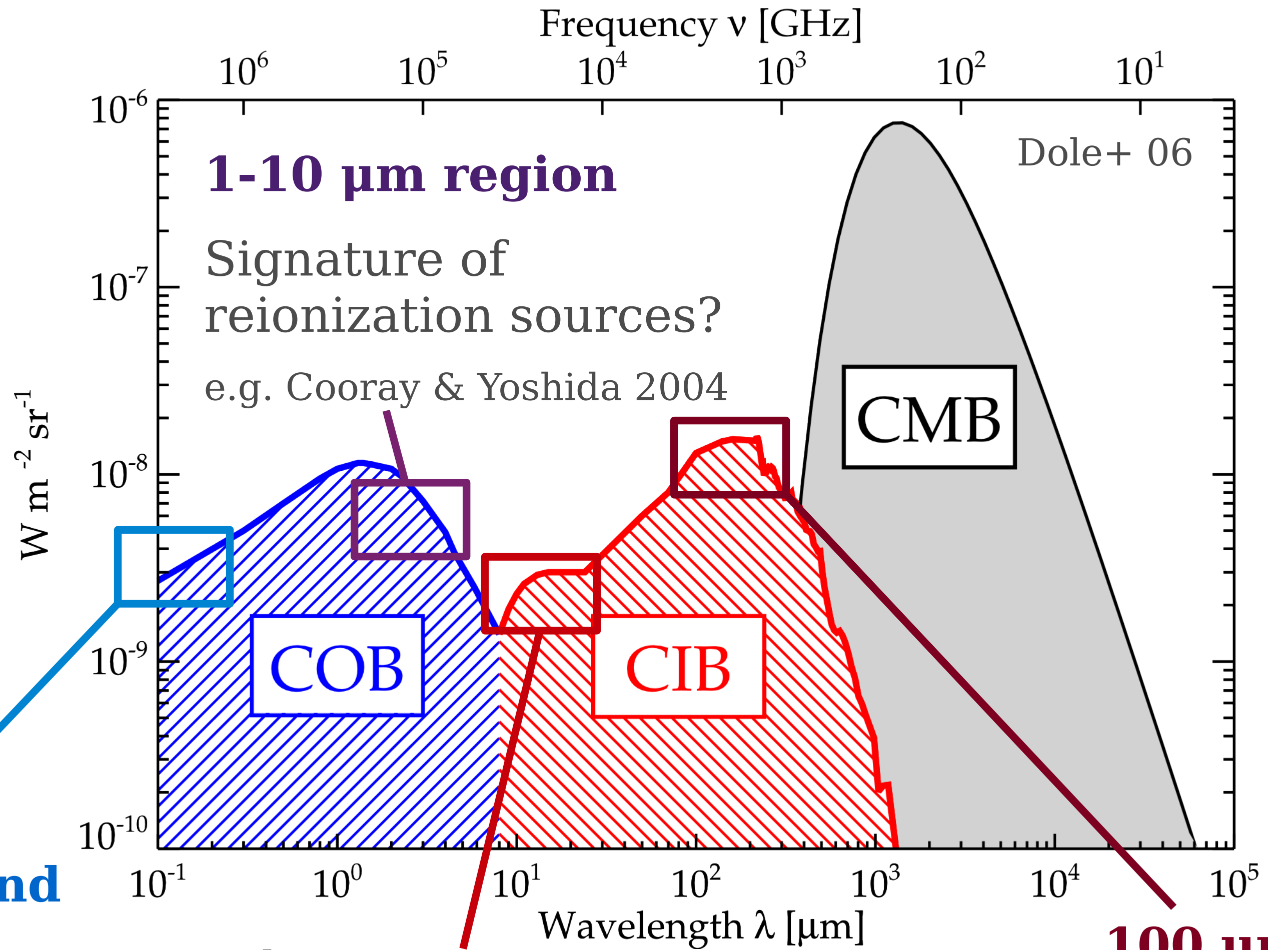
Near sources (z<0.05) mostly affected by the CIB

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.



EBL: what remains to be done?



1-10 μm region

Signature of reionization sources?

e.g. Cooray & Yoshida 2004

UV background

Largely underconstrained by theory and experiments

e.g. Haardt & Madau 2012

10-30 μm region

Amount of polycyclic aromatic hydrocarbons?

e.g. Dominguez+ 2011

100 μm region

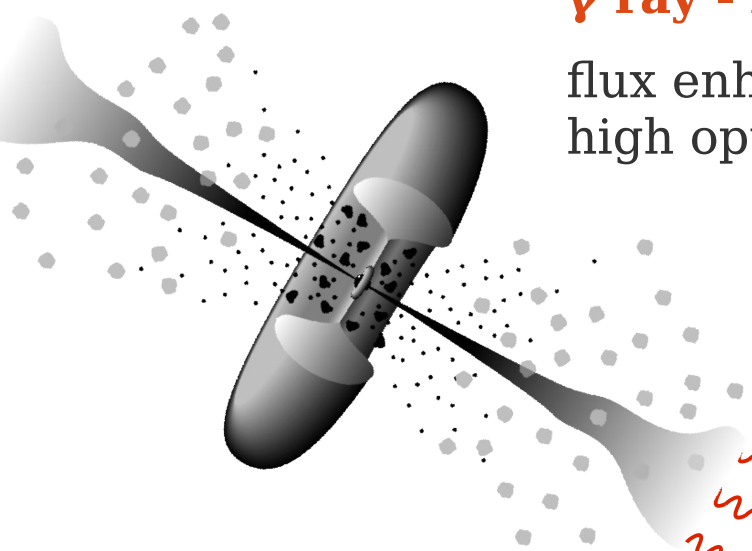
Probe of Lorentz Invariance Violation

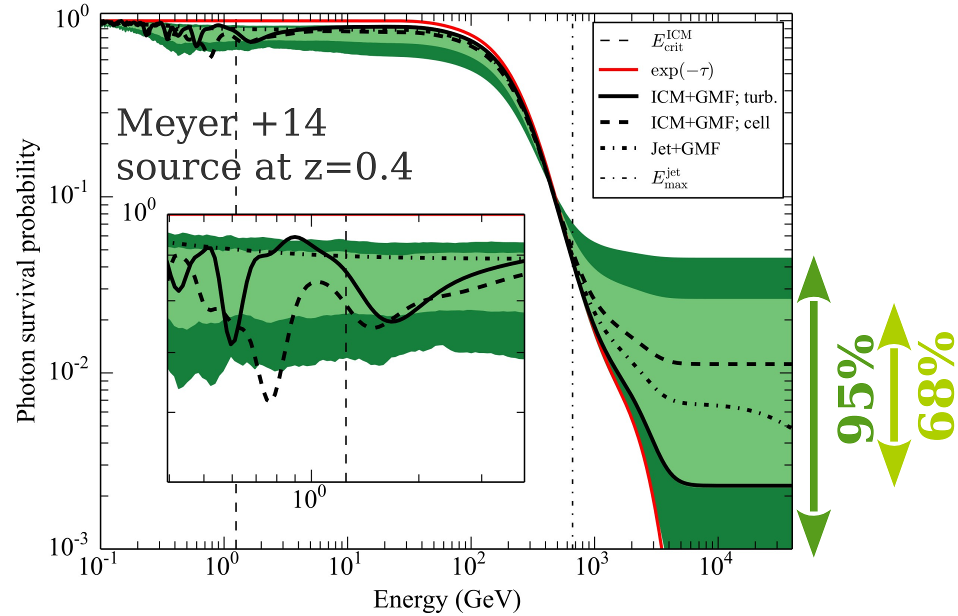
e.g. JB & Williams 2015

Axion-Like Particles

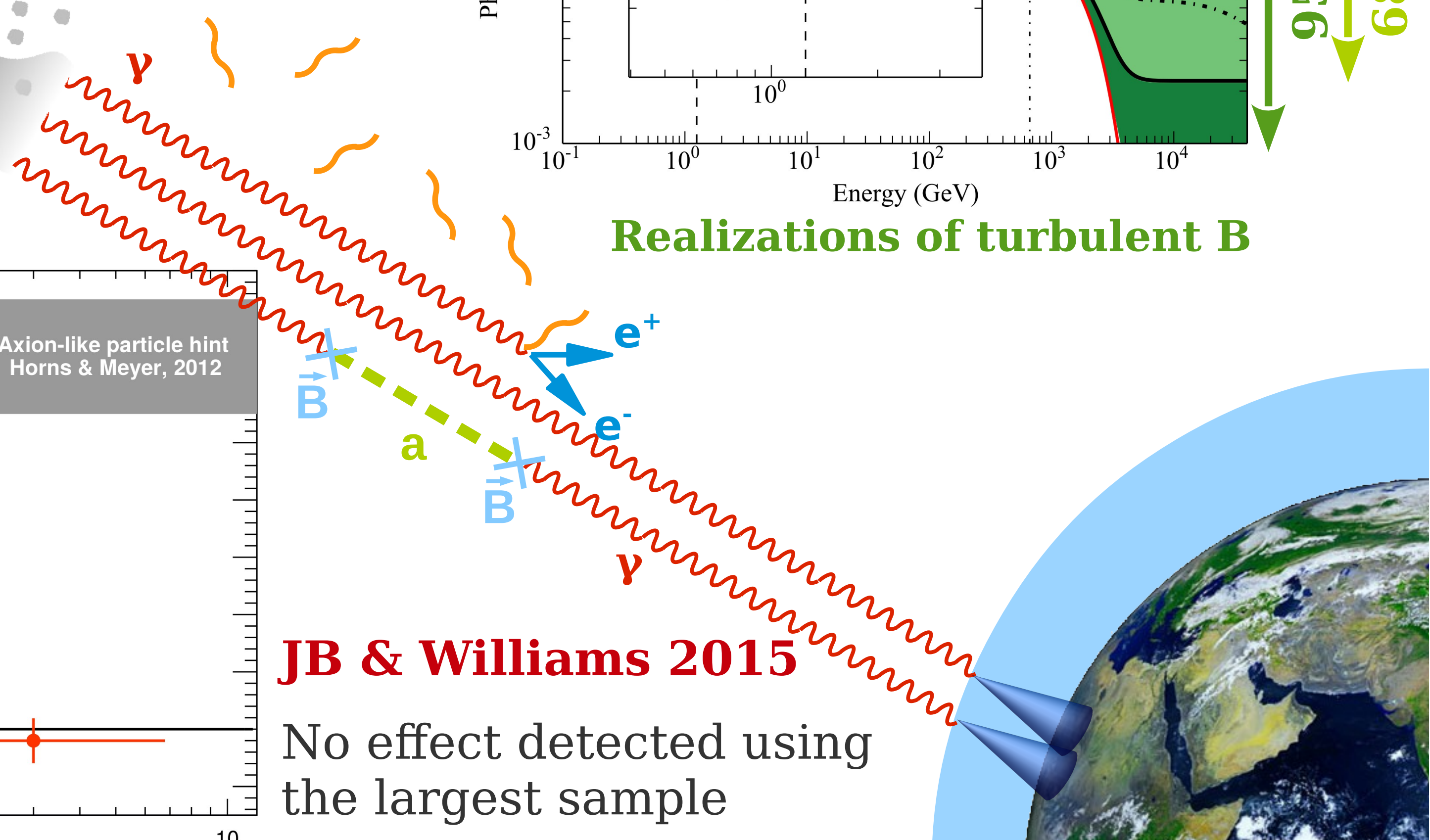
γ ray - ALP coupling

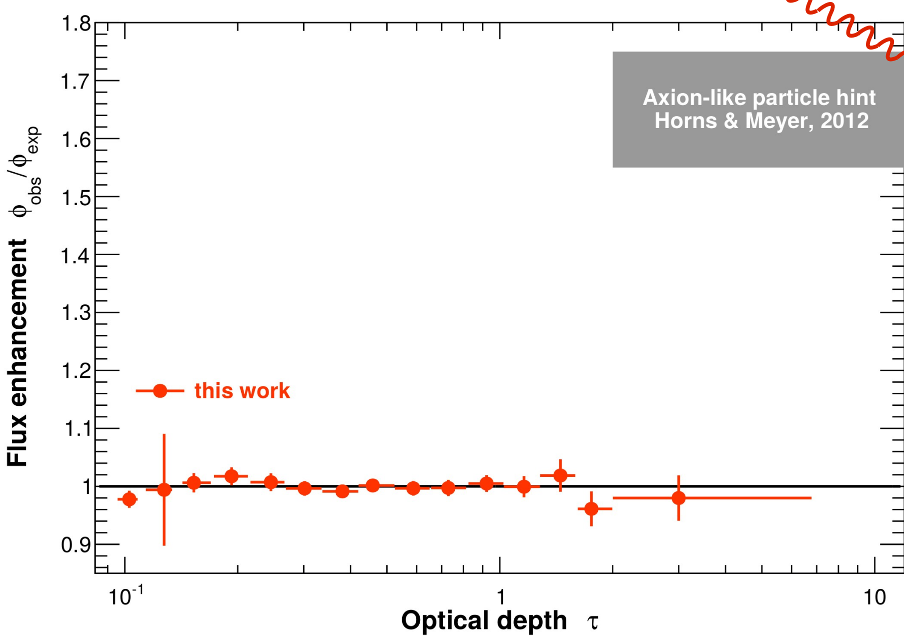
flux enhancement at
high optical depths??





Realizations of turbulent B





JB & Williams 2015

No effect detected using
the largest sample

Axion-Like Particles

An “anomaly” at large τ?

Study of the residuals to a fit including EBL absorption (although with obsolete model) for ~50 spectra.

Horns & Meyer 2012

Would correspond to a +70% flux enhancement with respect to classical absorption for τ>2

If “anomaly” due to ALP

→ Complex shaped dark pink “TeV transparency” region

Meyer and Horns 2013

Caveats

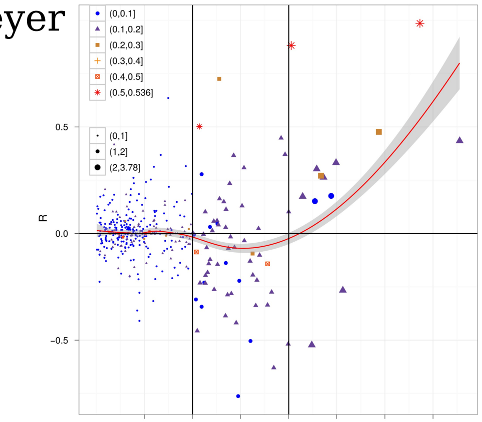
→ large fraction of the ALP parameter space excluded from H.E.S.S. observations of PKS 2155-304

Brun et al. 2013 (H.E.S.S. Collab.)

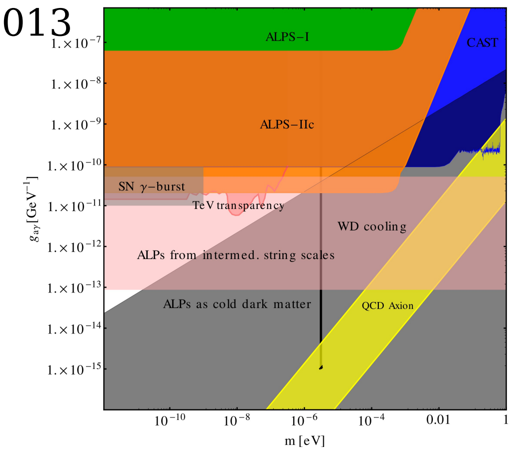
→ Treatment of uncertainties and correlation between points

e.g. discussion in Biteau 2013

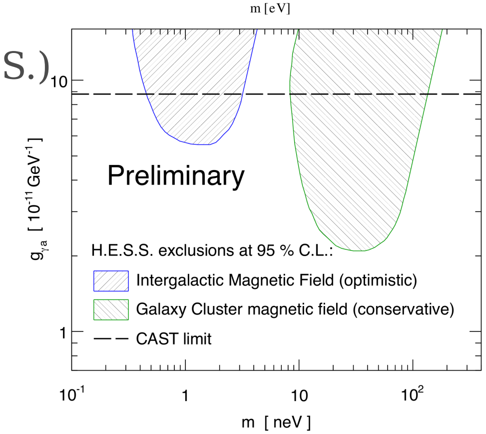
Horns & Meyer 2012



Bahre 2013



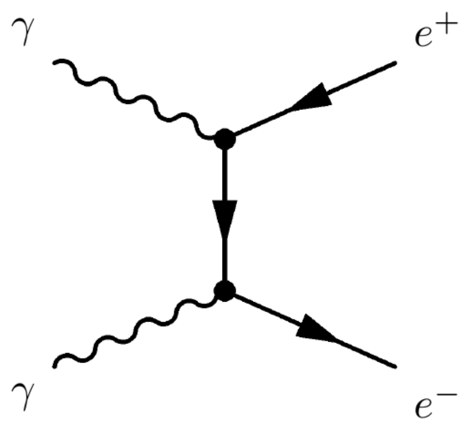
Brun et al. 2013 (H.E.S.S.)



Probing Lorentz Invariance Violation

Assume

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



Then

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

where

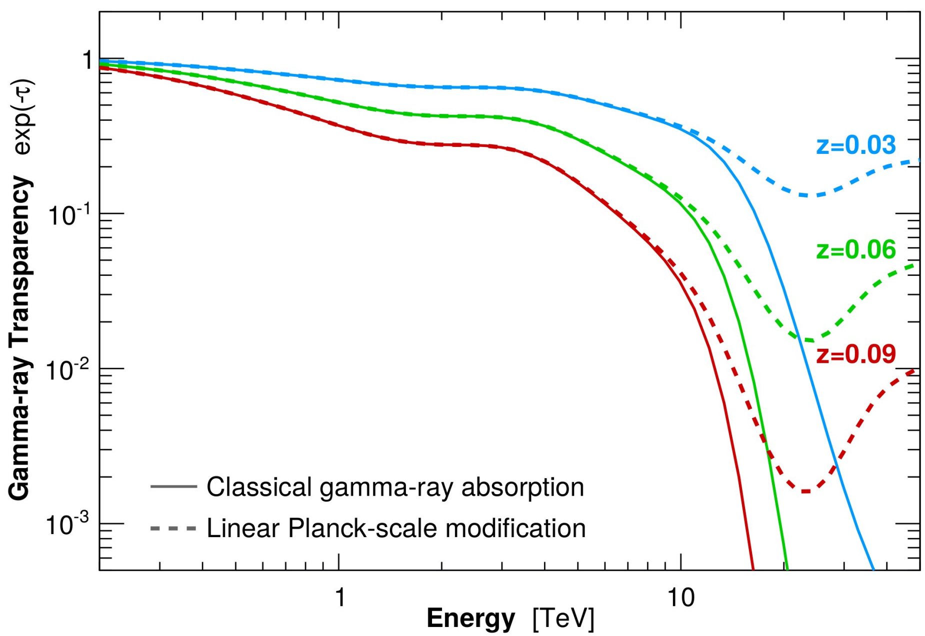
$$E_{\gamma,\rm LIV} = \left(8 m_e^2 E_{\rm QG}\right)^{1/3}$$

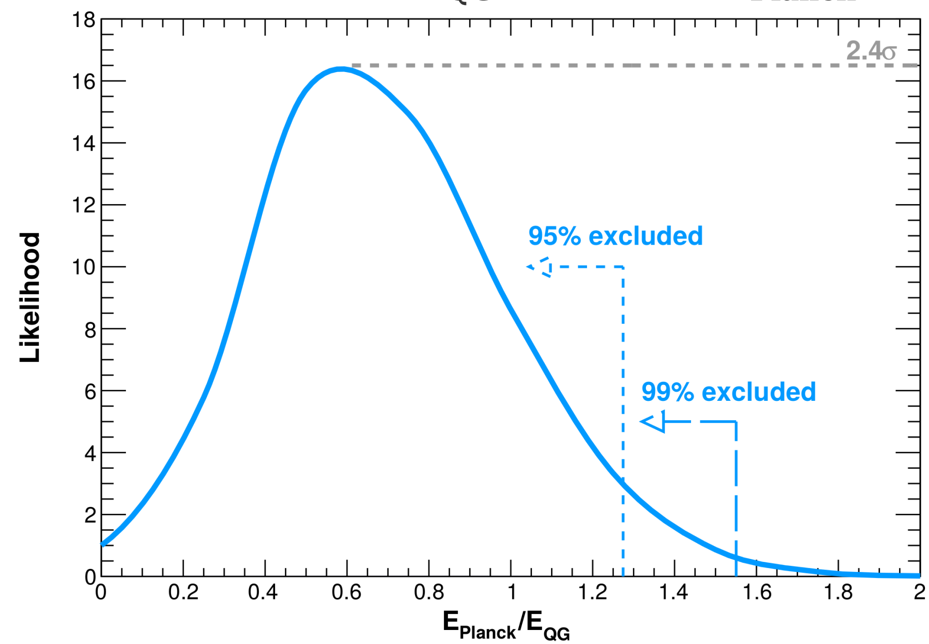
$$= 29.4\,\text{TeV} \times \left(\frac{E_{\rm QG}}{E_{\rm Planck}}\right)^{1/3}$$

Result

Fit leaving EBL & E_{QG} free

2.4σ prevents exclusion of Planck scale, 99% lower limit: $\mathbf{E_{QG} > 0.6 \times E_{Planck}}$





Unsignificant hint but pursue worth every penny!

→ Ongoing study of ideal CTA targets by a student at IPNO