# Cosmology with gamma-rays

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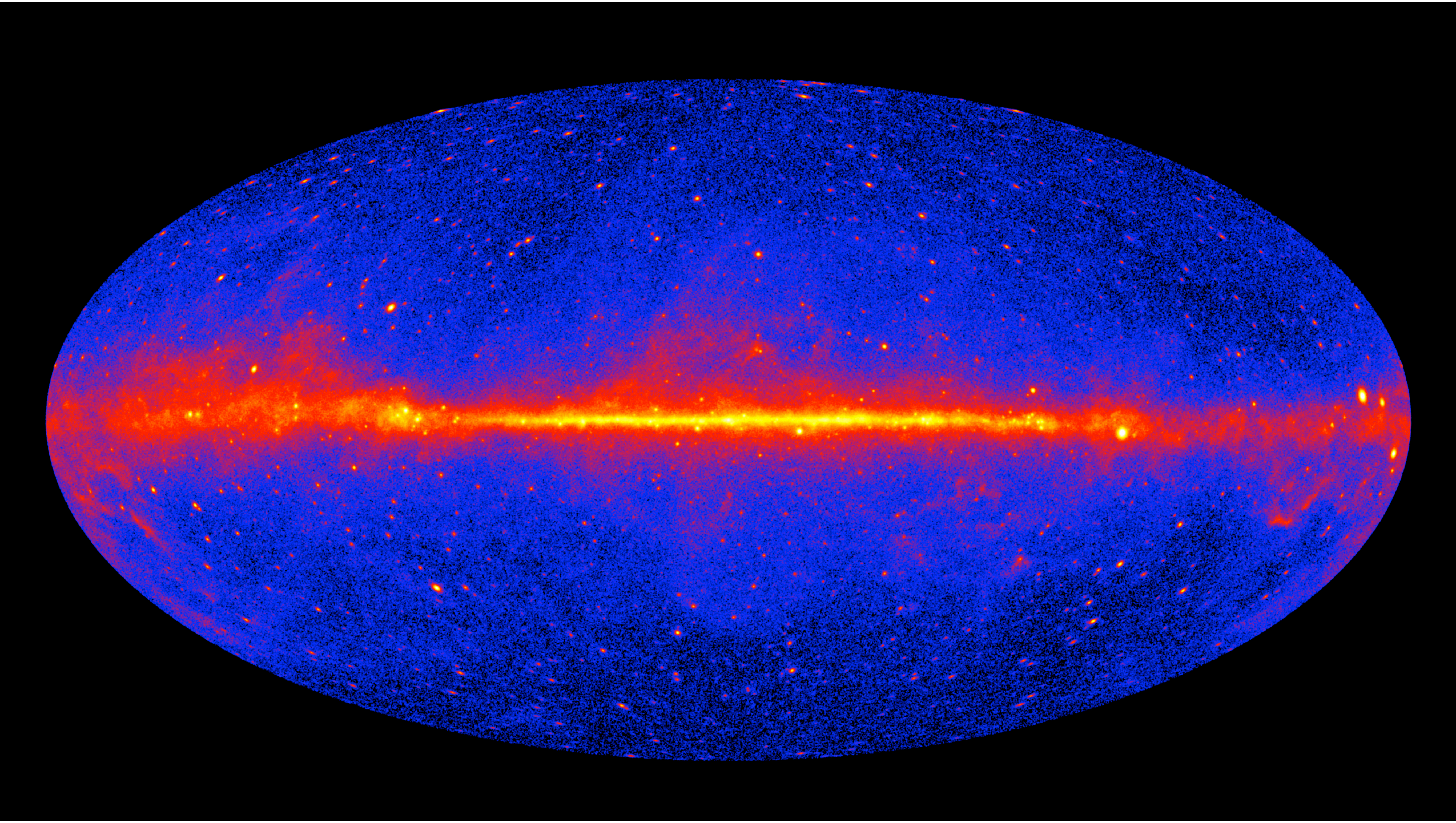
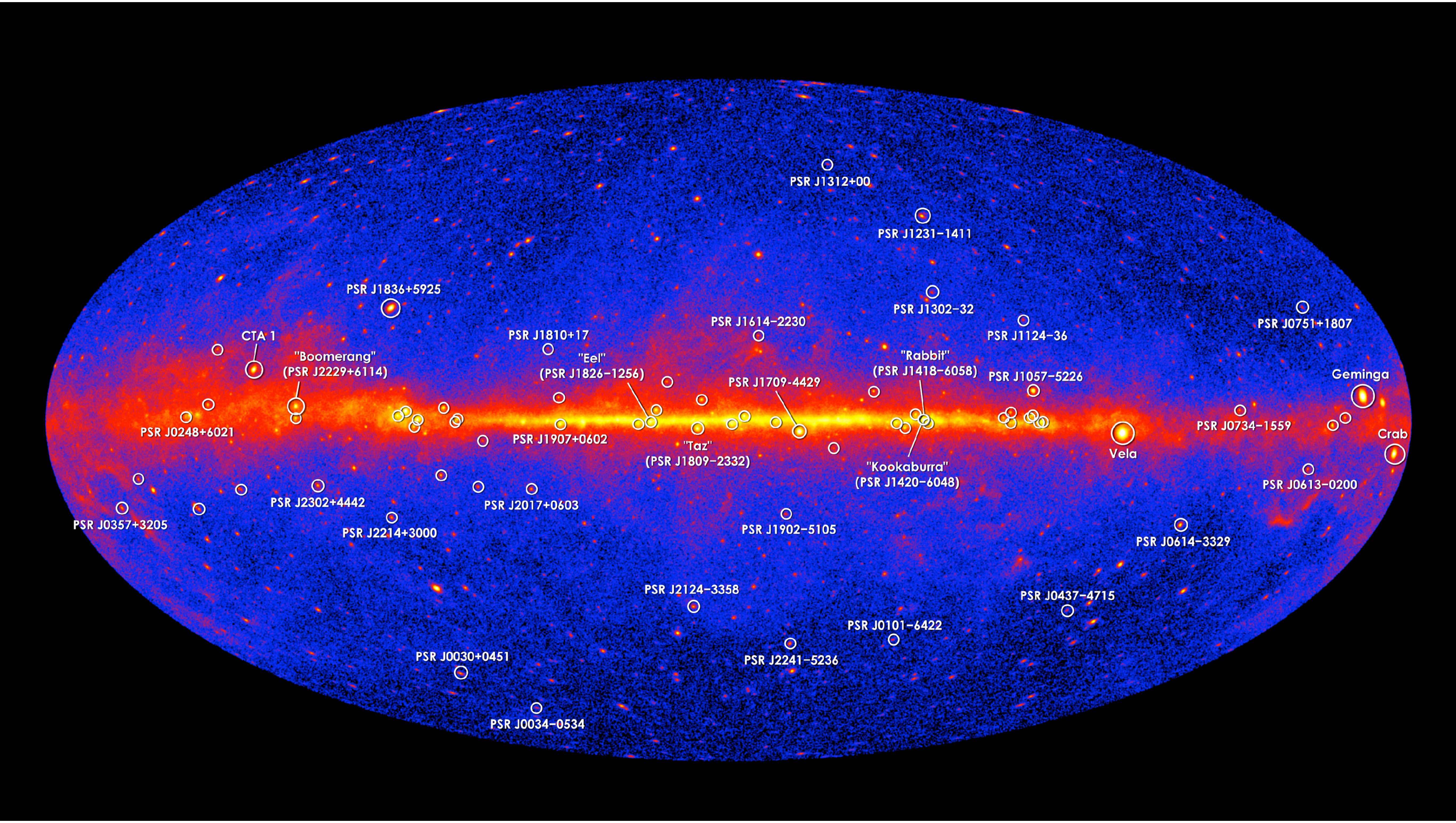
**High-energy astrophysics in the multi-messenger era, 8-12 May 2023, ECAP, Erlangen**

# Target sources

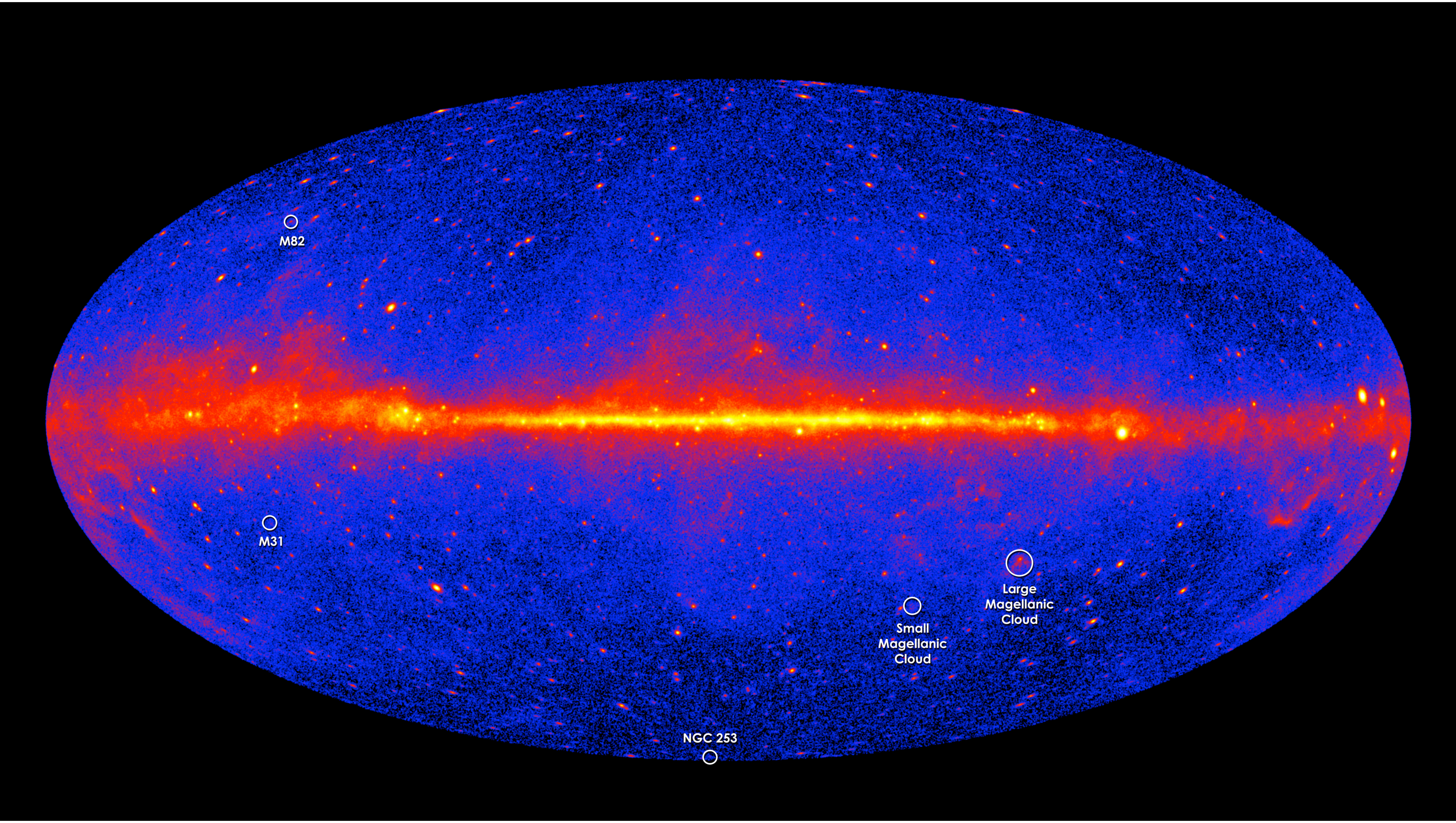
# Fermi-LAT all sky map



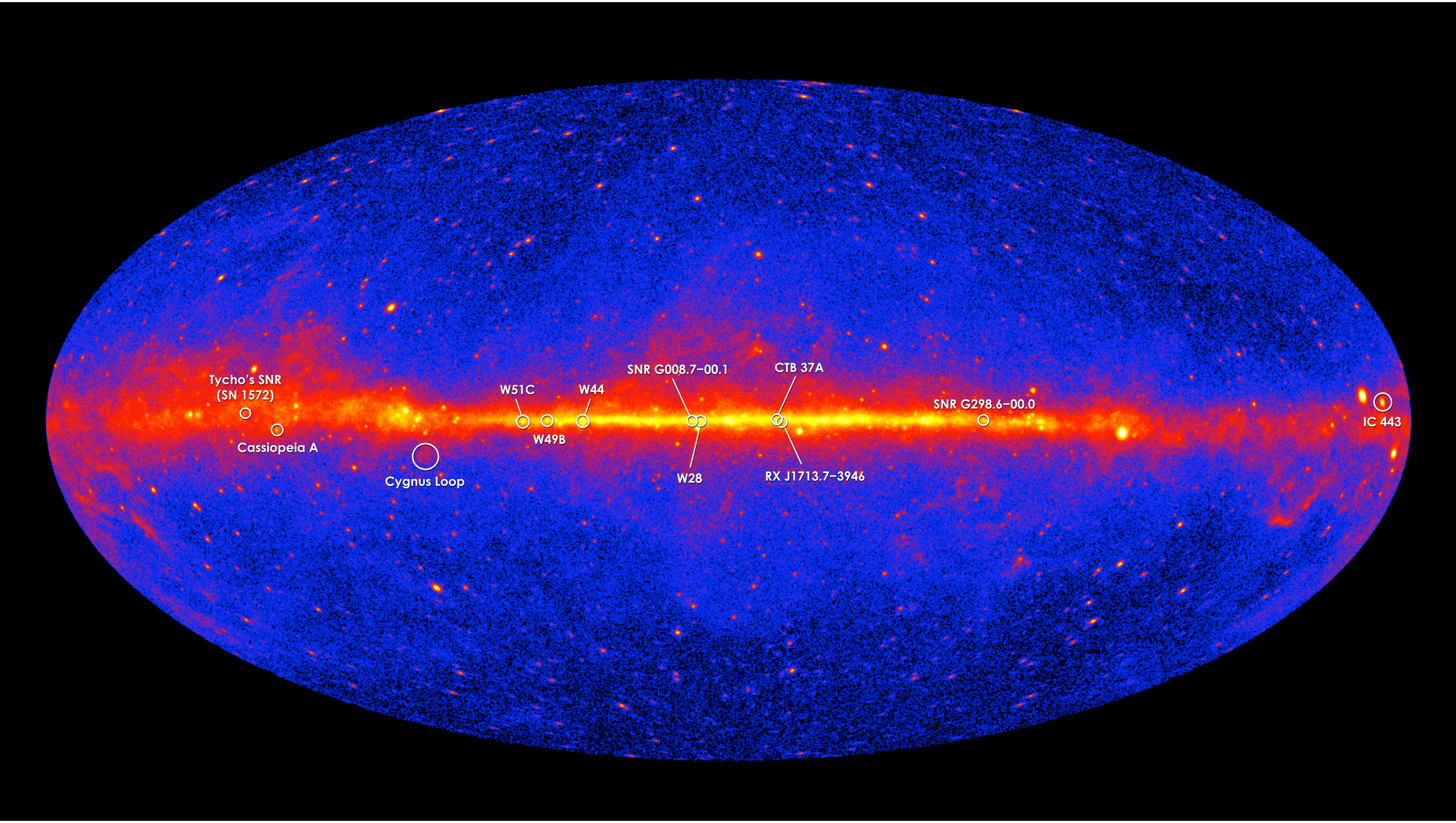
# Pulsars


PSR J1312+00
PSR J1231−1411
PSR J1836+5925
PSR J1302−32
PSR J0751+1807
PSR J1614−2230
PSR J1124−36
CTA 1
PSR J1810+17
"Boomerang"
(PSR J2229+6114)
"Eel"
(PSR J1826−1256)
"Rabbit"
(PSR J1418−6058)
PSR J1709-4429
PSR J1057−5226
Geminga
PSR J0248+6021
PSR J1907+0602
PSR J0734−1559
Crab
Vela
"Taz"
(PSR J1809−2332)
"Kookaburra"
(PSR J1420−6048)
PSR J0613−0200
PSR J2302+4442
PSR J2017+0603
PSR J0357+3205
PSR J2214+3000
PSR J1902−5105
PSR J0614−3329
PSR J2124−3358
PSR J0437−4715
PSR J0101−6422
PSR J2241−5236
PSR J0030+0451
PSR J0034−0534

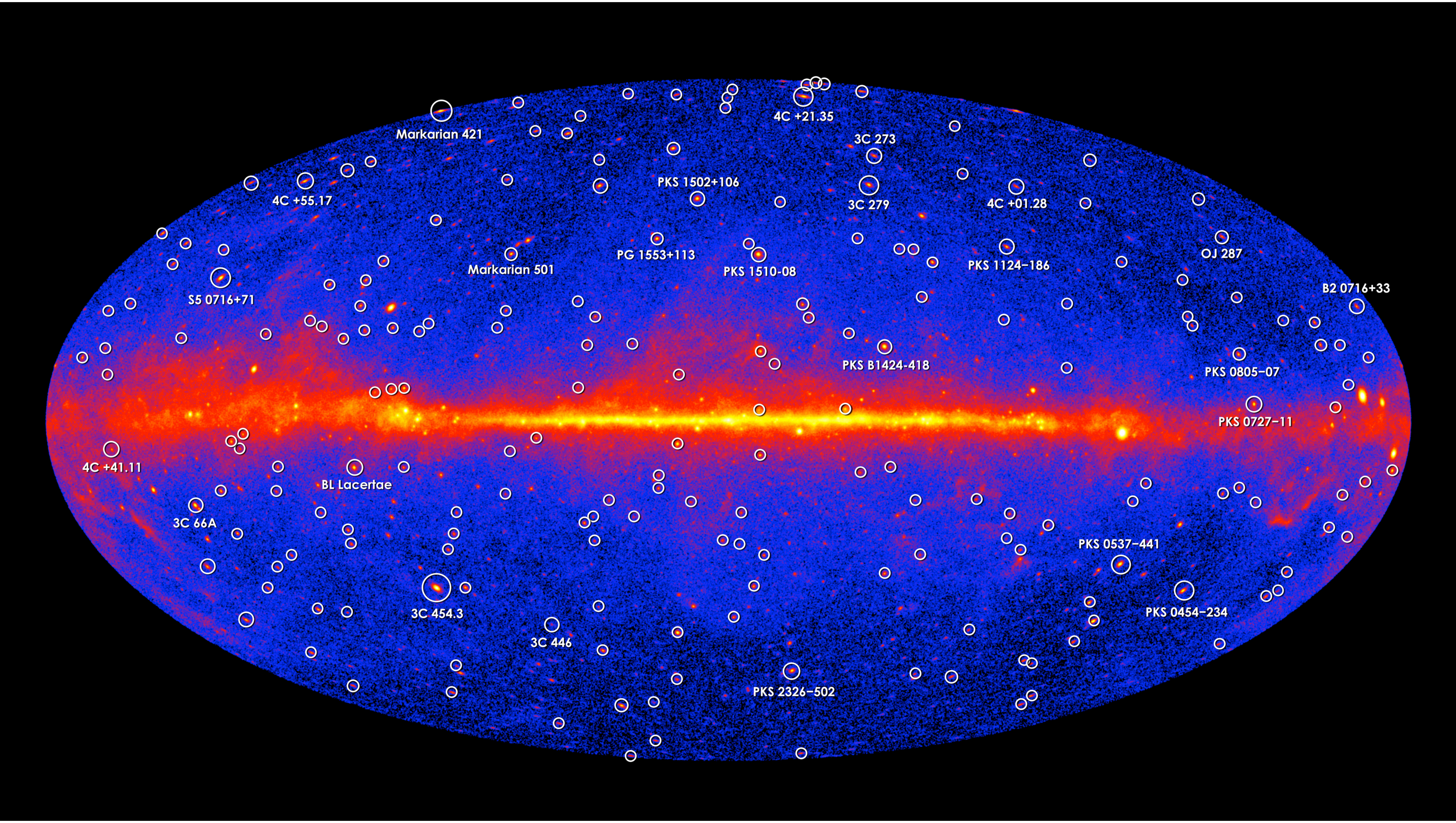
# Normal galaxies



# Supernova remnants



# Blazars



Markarian 421
4C +21.35
3C 273
4C +55.17
PKS 1502+106
3C 279
4C +01.28
PG 1553+113
Markarian 501
PKS 1510-08
PKS 1124-186
OJ 287
S5 0716+71
B2 0716+33
PKS B1424-418
PKS 0805-07
PKS 0727-11
4C +41.11
BL Lacertae
3C 66A
PKS 0537-441
3C 454.3
PKS 0454-234
3C 446
PKS 2326-502

# Normal galaxies

- The light of normal galaxies in the optical and near infrared part of the spectrum is dominated by stars, with small contributions by gas and dust.

- In the optical, a normal galaxy spectrum can, therefore, be approximated by a superposition of stellar spectrum.

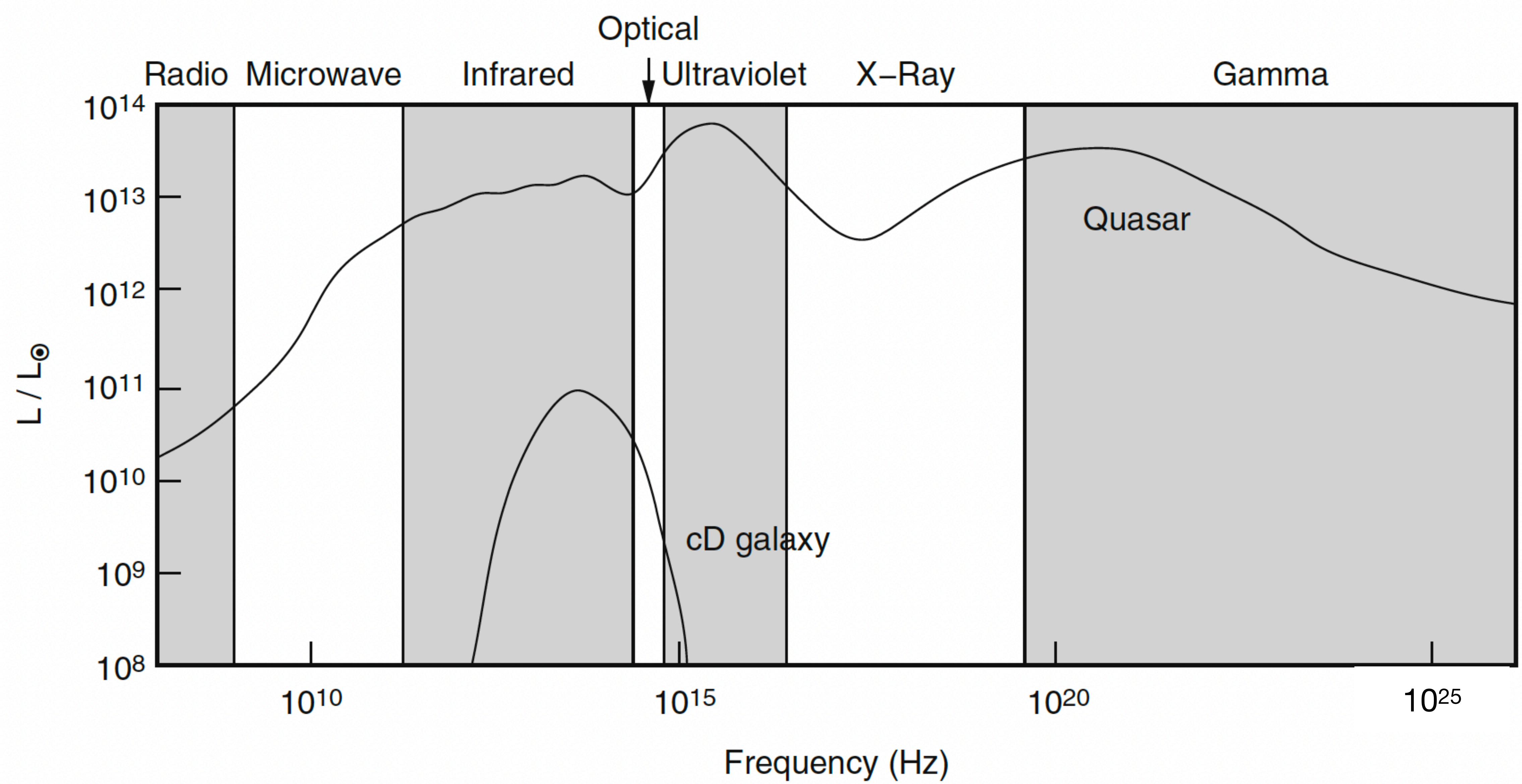
$$\Phi_{gal} \simeq \sum_i \Phi_{star}(T_i)$$

with stellar atmosphere temperatures typically in the range 3000 K < $T_i$ < 40000 K.

- If the stellar atmospheres are assumed to emit as blackbodies, the narrowness of the Planck distribution around its maximum ($h\nu \sim 3k_BT$), the superposition leads, in turn, to narrow galactic spectra in the range 4000 Å < λ < 20000 Å

# Active Galactic Nuclei (AGN)

- Some galaxies present a much broader spectrum, with significant emission essentially in the whole electromagnetic spectrum, from radio all the way to X-rays and even $\gamma$-rays.



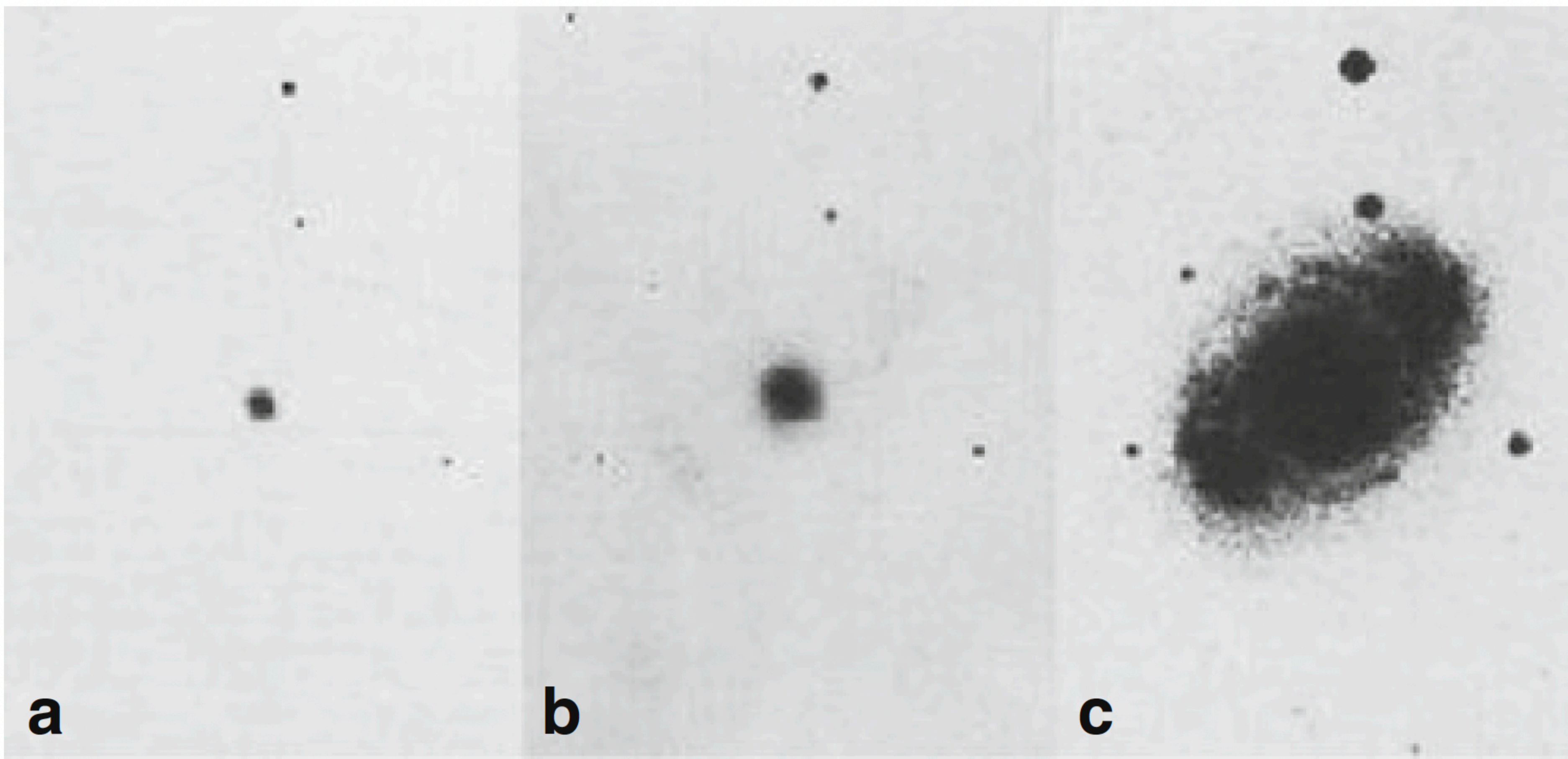

- Their luminosity is much higher than normal galaxies: $L_{AGN} \gtrsim 10^3 L_{gal}$
- From the shape of the spectrum, we can see that the emission process is mostly non-thermal.

Schneider, Extragalactic Astronomy and Cosmology, 2014

# Active Galactic Nuclei (AGN)

- We nowadays know that the emission in these galaxies comes from a very small region (<1 pc) at the center of the galaxy called the active galactic nucleus (AGN).

Seyfert galaxy NGC4151




Exposure time →

- At low exposure times, only the central part of the galaxy is detectable. Only at high exposure times, the rest of the galaxy becomes visible (emission is dominated by the nucleus!)

W.W. Morgan, *A Comparison of the Optical Forms of Certain Seyfert Galaxies with the N-Type Radio Galaxies*, ApJ 153, 27 (1968)

# Summarized properties

**Table 5.1** Overview of the classification of active galactic nuclei

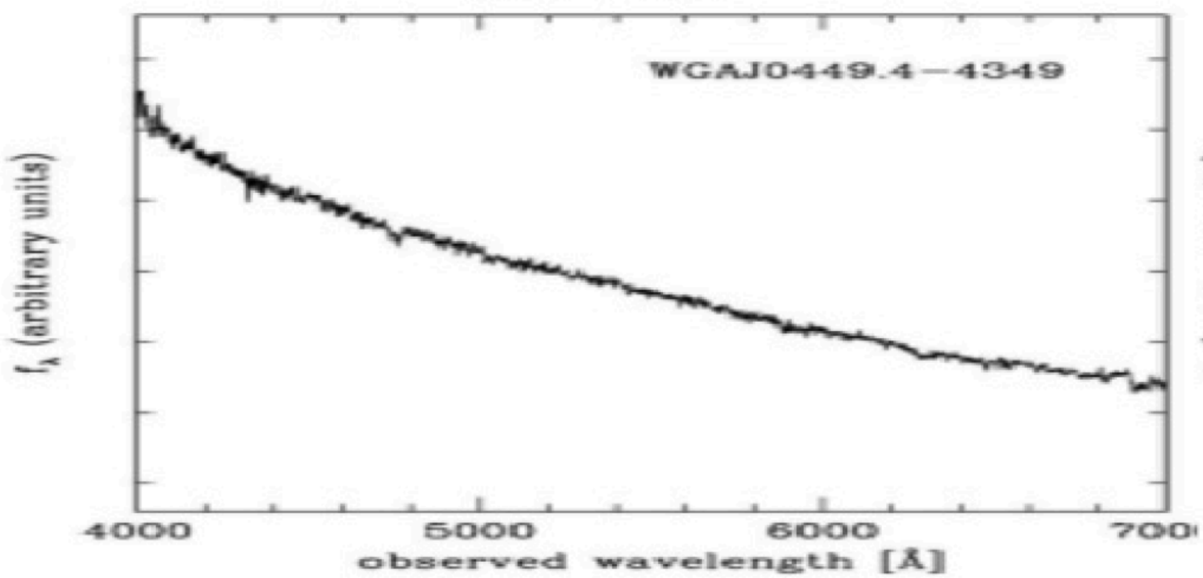
| | Normal galaxy | Radio galaxy | Seyfert galaxy | Quasar | Blazar |
|---|---|---|---|---|---|
| Example | Milky Way | M87, Cygnus A | NGC 4151 | 3C273 | BL Lac, 3C279 |
| Galaxy type | Spiral | Elliptical, Irregular | Spiral | Irregular | Elliptical? |
| $L_{AGN}/L_{\odot}$ | $< 10^4$ | $10^6$–$10^8$ | $10^8$–$10^{11}$ | $10^{11}$–$10^{14}$ | $10^{11}$–$10^{14}$ |
| $M_{BH}/M_{\odot}$ | $4 \times 10^6$ | $3 \times 10^9$ | $10^6$–$10^9$ | $10^6$–$10^9$ | $10^6$–$10^9$ |
| Radio emission | Weak | Core, jets, lobes | Only ≈5 % radio-loud | Only ≈5 % radio-loud | Strong, Short-time variable |
| X-ray emission | Weak | Strong | Strong | Strong | Strong |
| Gamma emission | Weak | Weak | Medium | Strong | Strong |



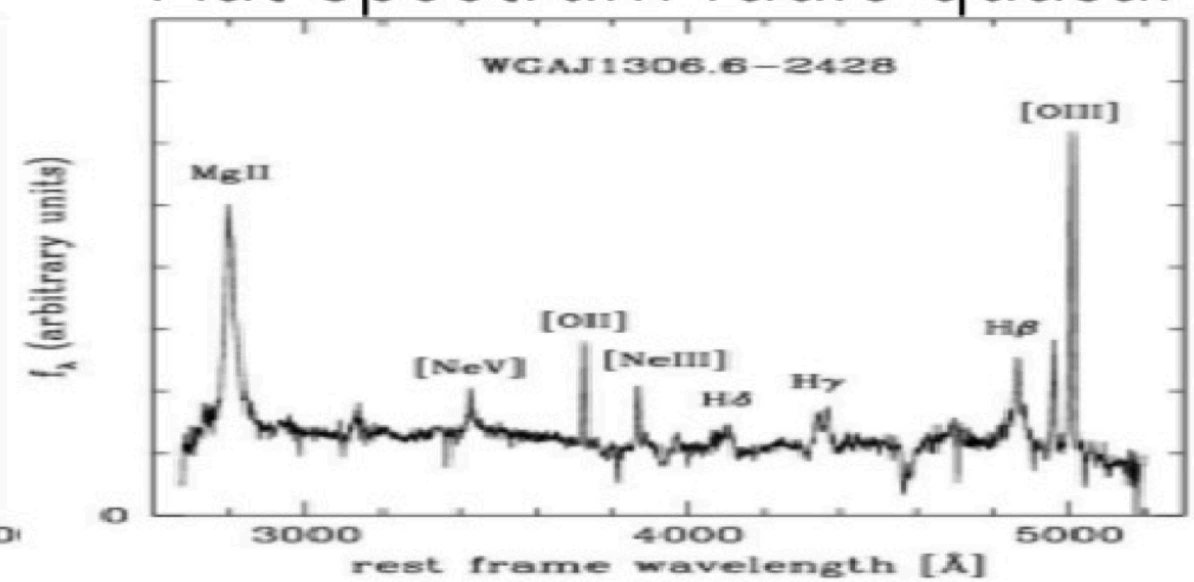
Schneider, Extragalactic Astronomy and Cosmology, 2014

# BL Lac and FSRQ in the optical

BL Lac

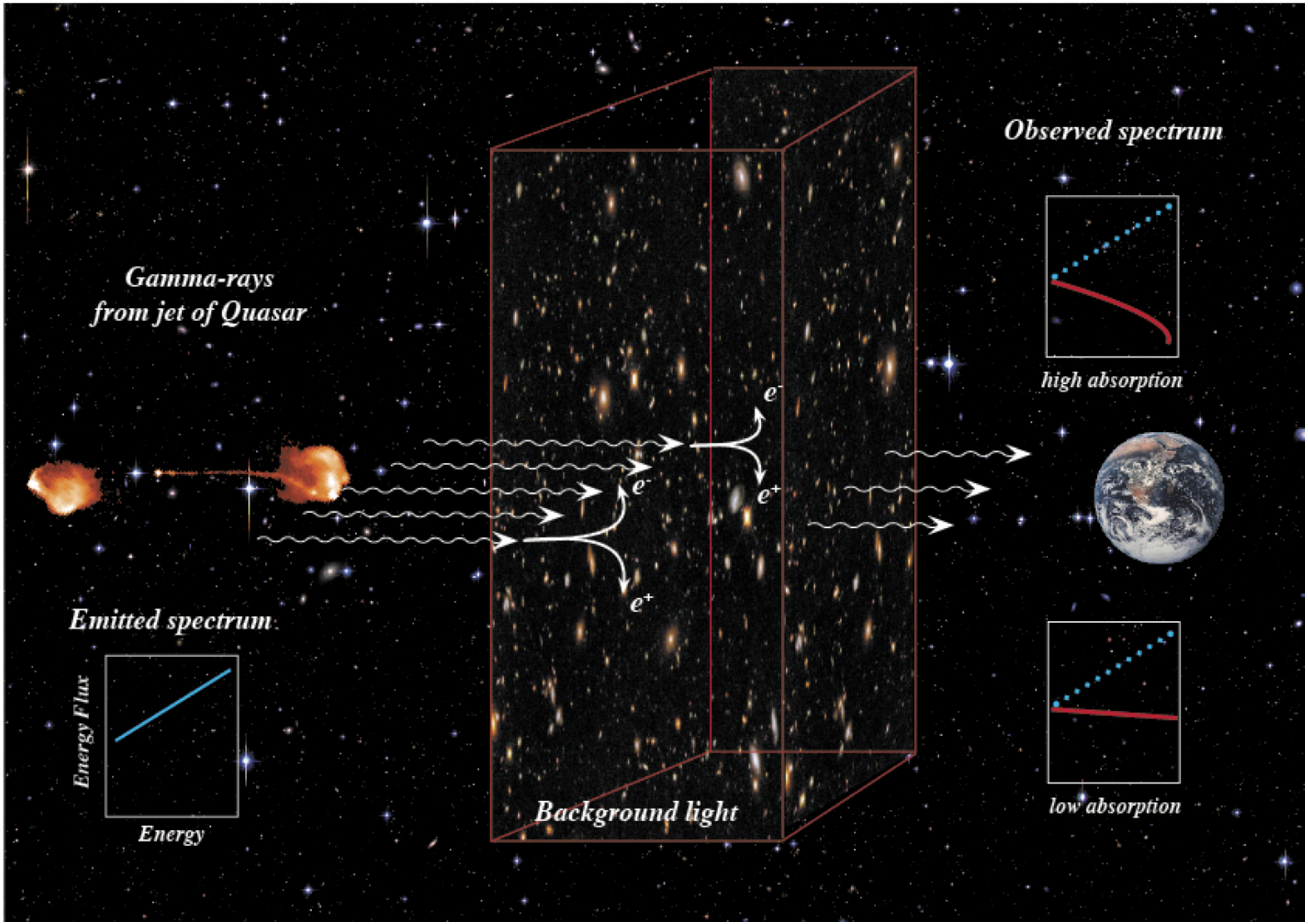



Flat spectrum radio quasar



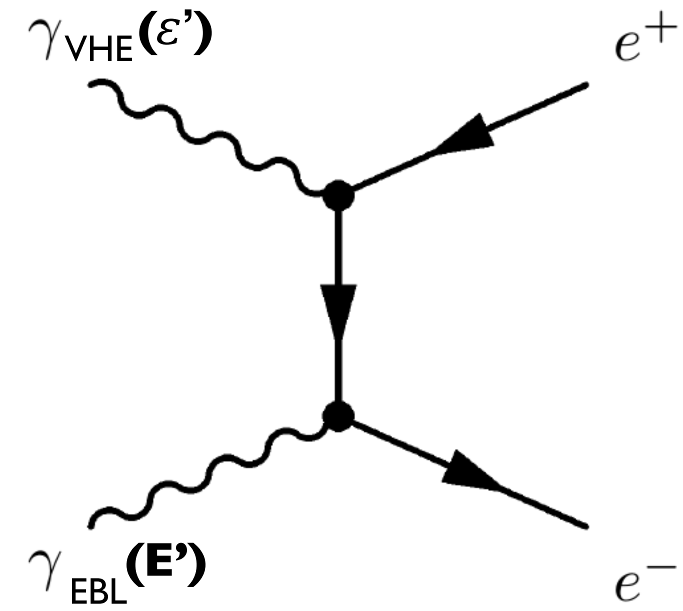
# Probing cosmology with gamma-ray absorption effects

# Universe's opacity to VHE photons



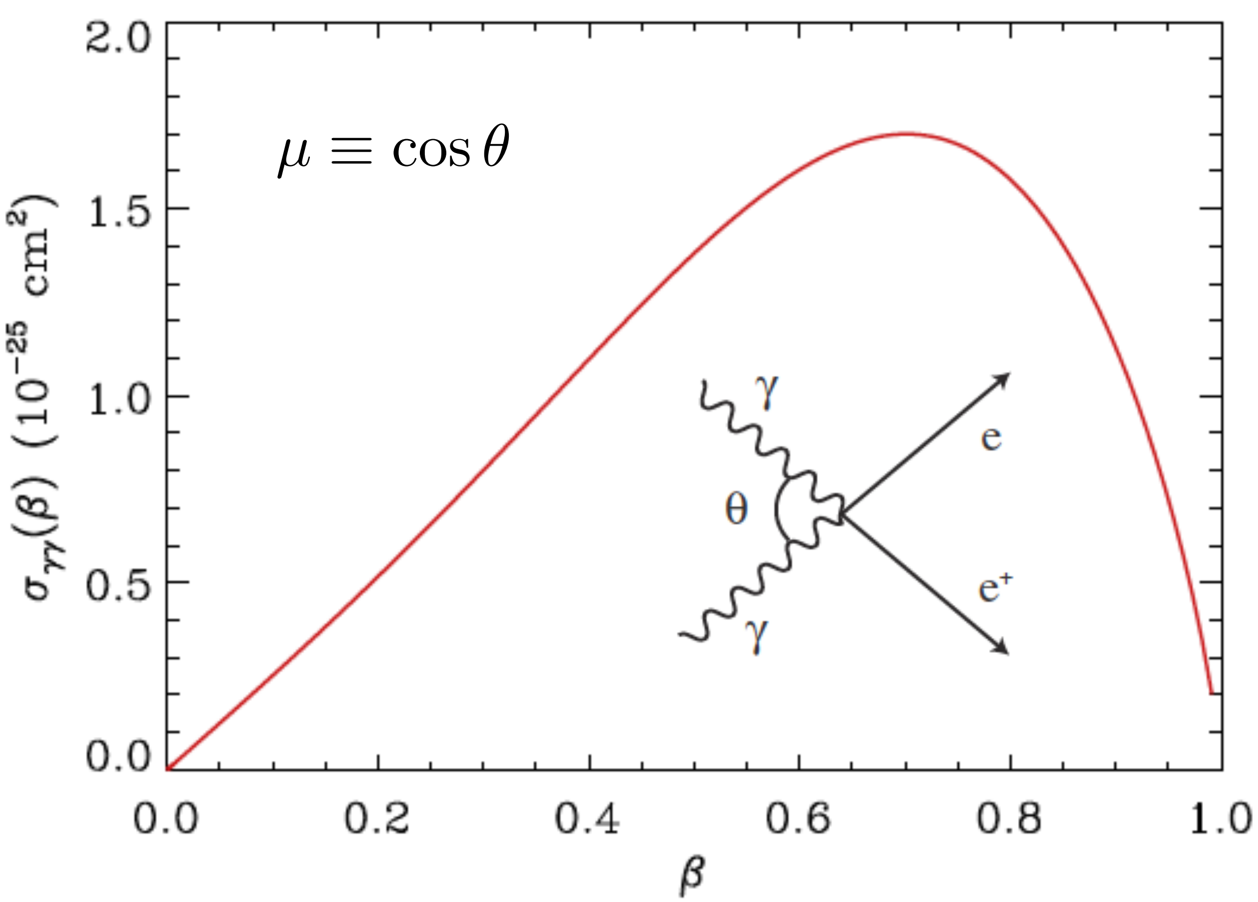
# Cross-section for gamma-gamma scattering

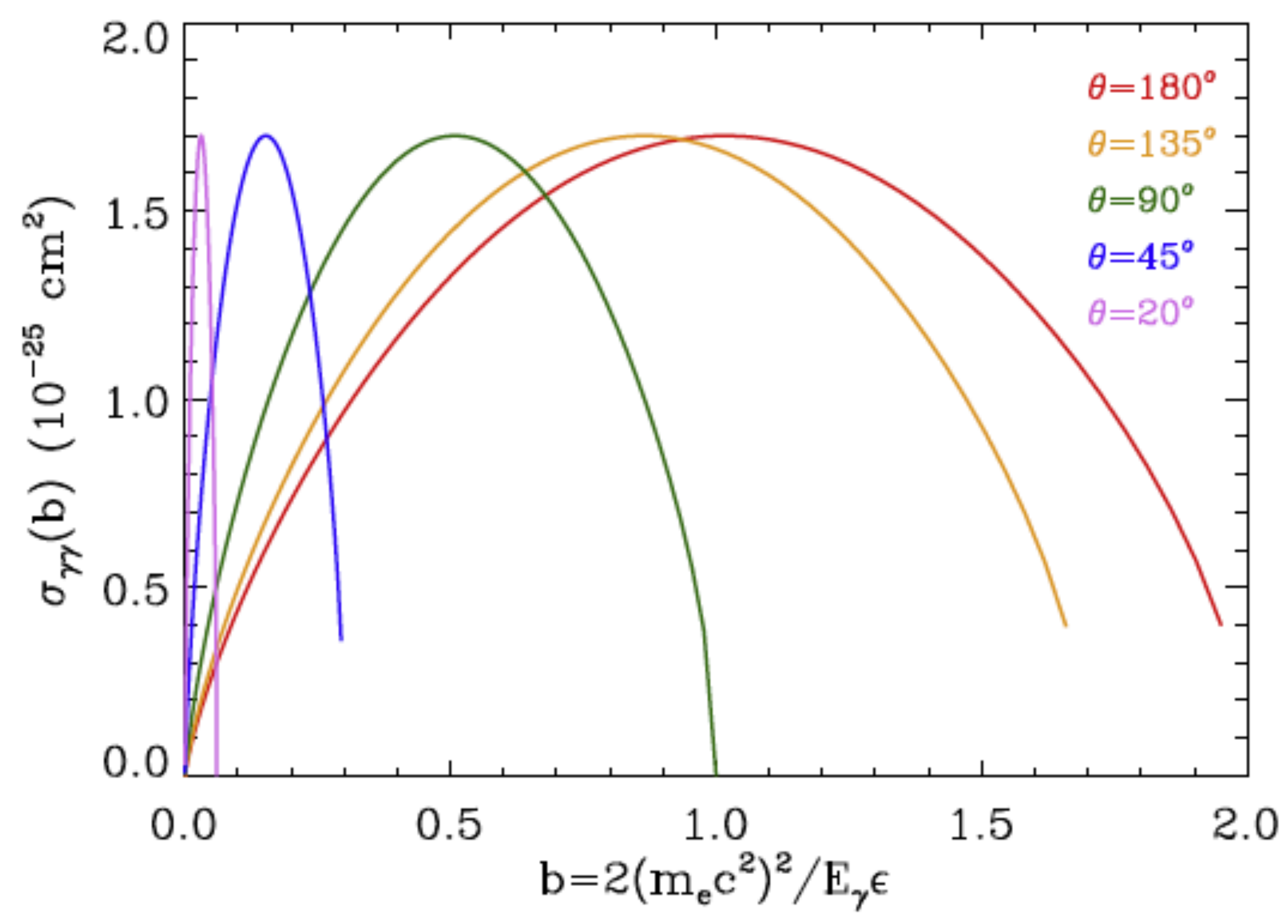
Well understood QED process:




$$\sigma(E',\varepsilon',\mu) = \frac{3\sigma_T}{16}(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$

$$\beta = \sqrt{1-\frac{2m_e^2c^4}{E'\varepsilon'(1-\mu)}} \qquad E'_{th} = \frac{2m_ec^2}{\epsilon'(1-\mu)}$$

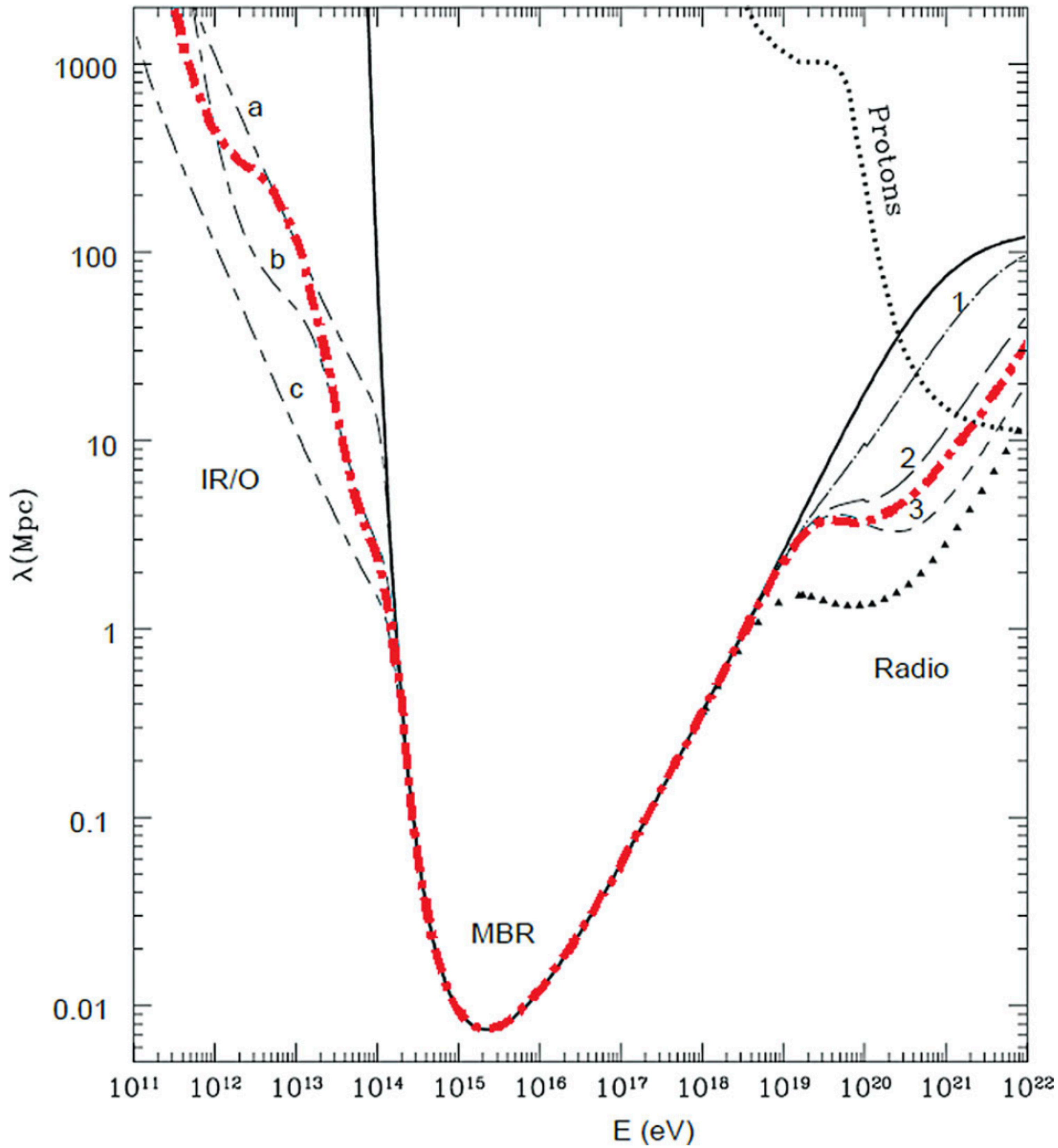





**Astrop. Phys. 43 112 (2013)**

# VHE photon mean free path




$$\lambda = \frac{1}{\int \sigma dn}$$

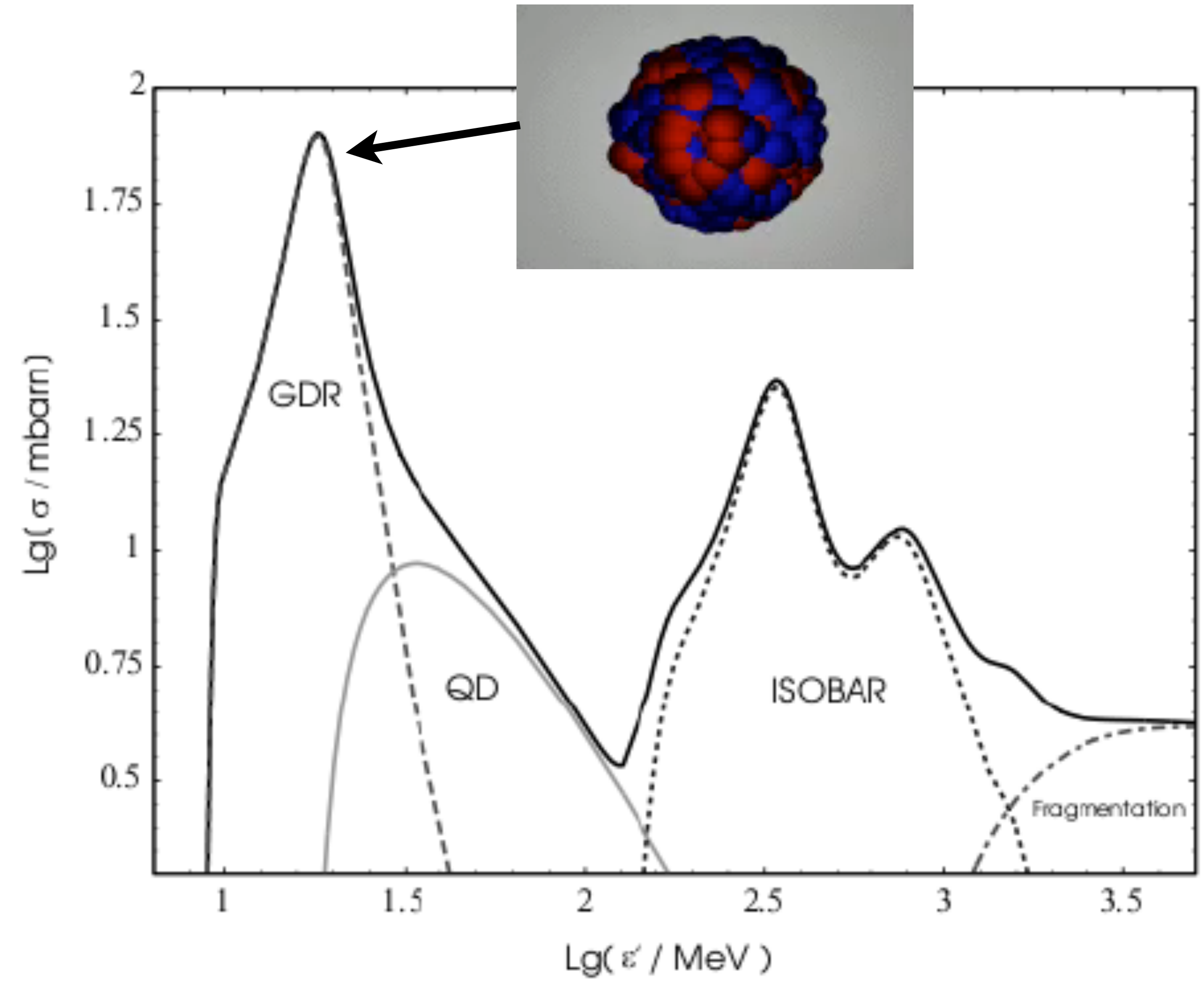
**A. De Angelis et al, MNRAS 432, 3245 (2013)**

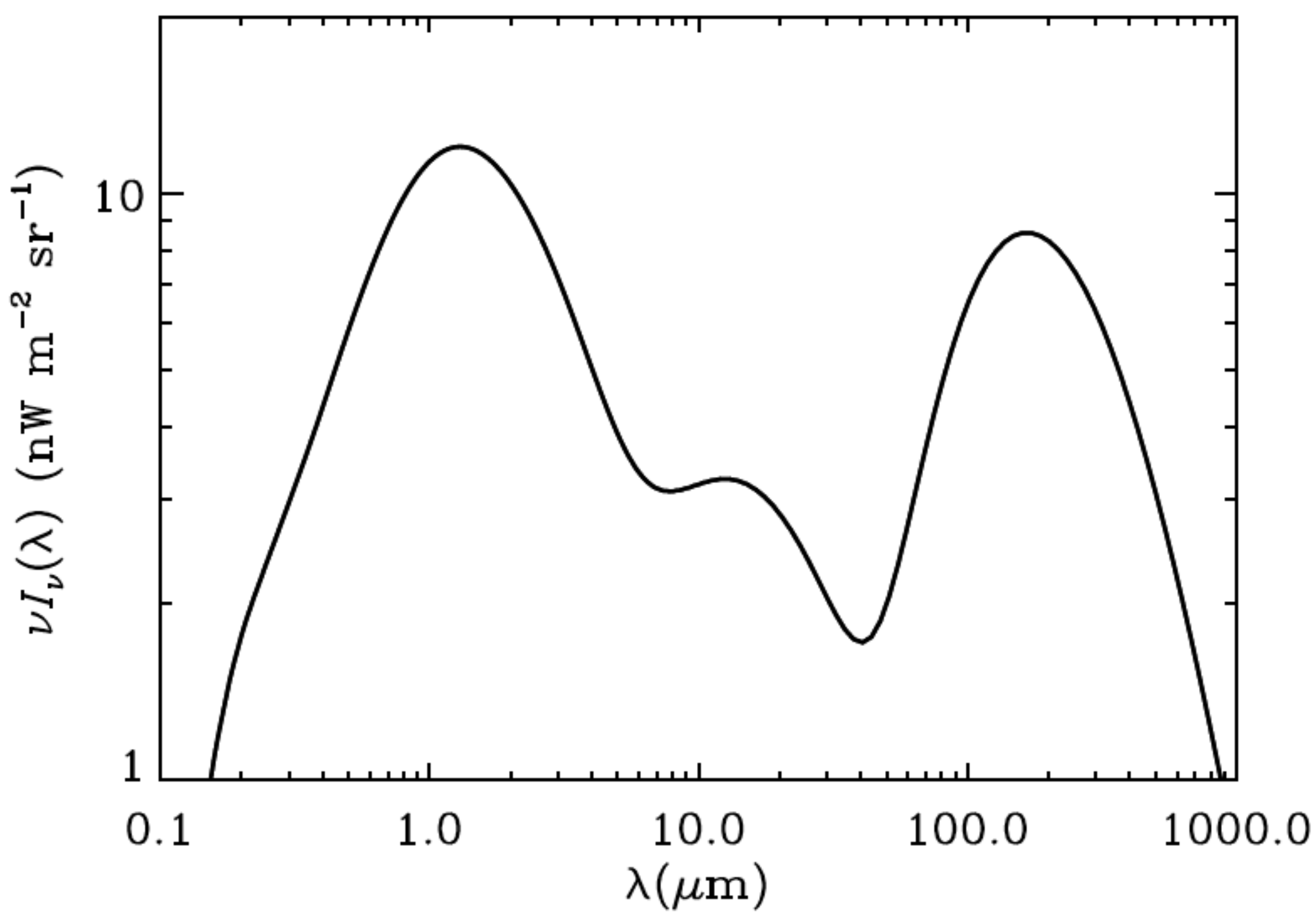
# EBL and UHECRs nuclei

**@ nucleus rest-frame:**

photon-nucleus cross-section at MeV energies dominated by **GDR (Giant Dipole Resonance)**

collective oscillation mode of the nucleus: protons against neutrons (induced dipole moment)



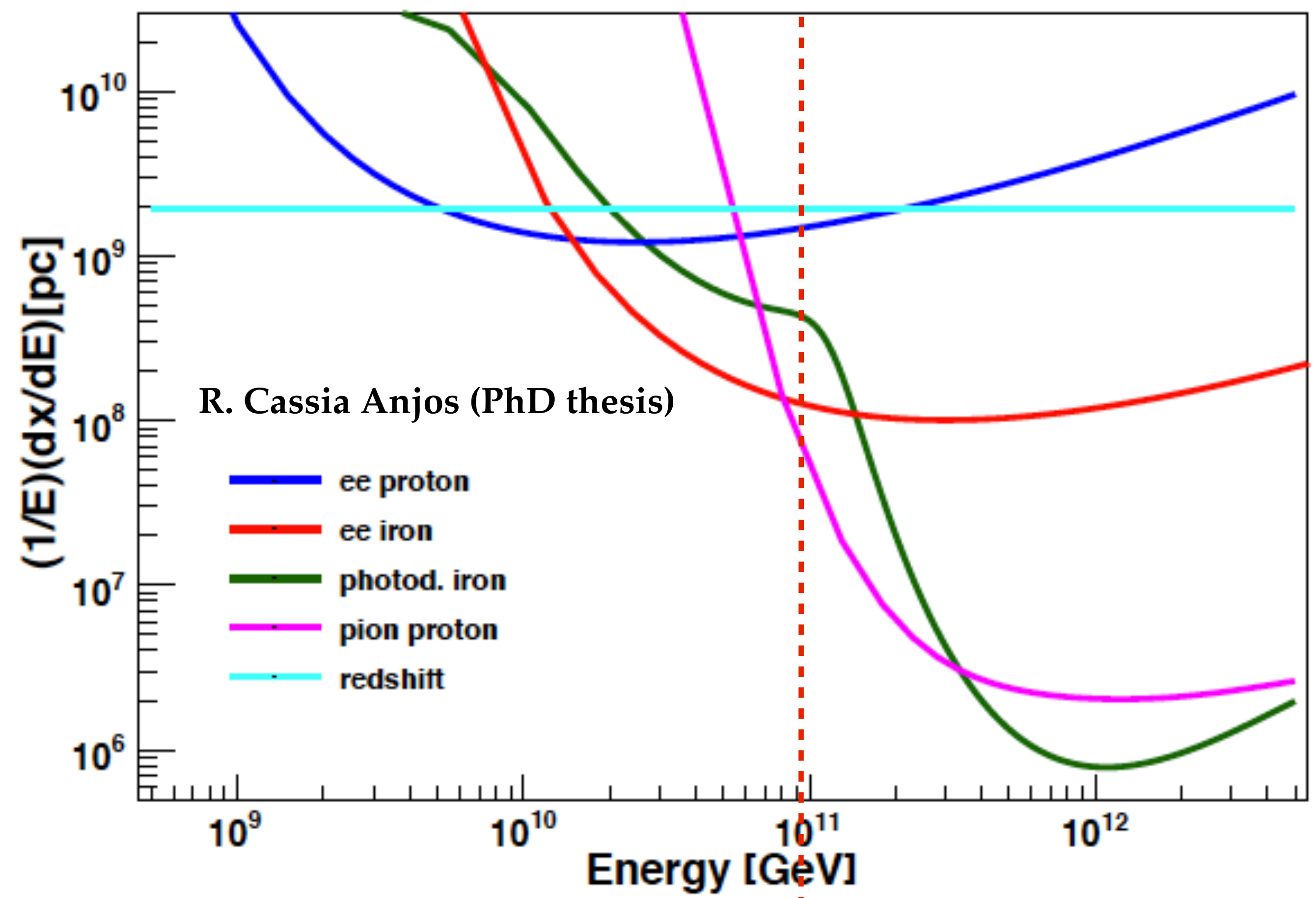

Infrared is important for nuclei

$$\epsilon_{\rm GDR} \simeq 80 A^{-1/3}\ \mathrm{MeV}$$

$$\frac{\epsilon_{\rm th1}}{\epsilon_{\rm th2}} \simeq \left(\frac{A_1}{A_2}\right)^{2/3}$$

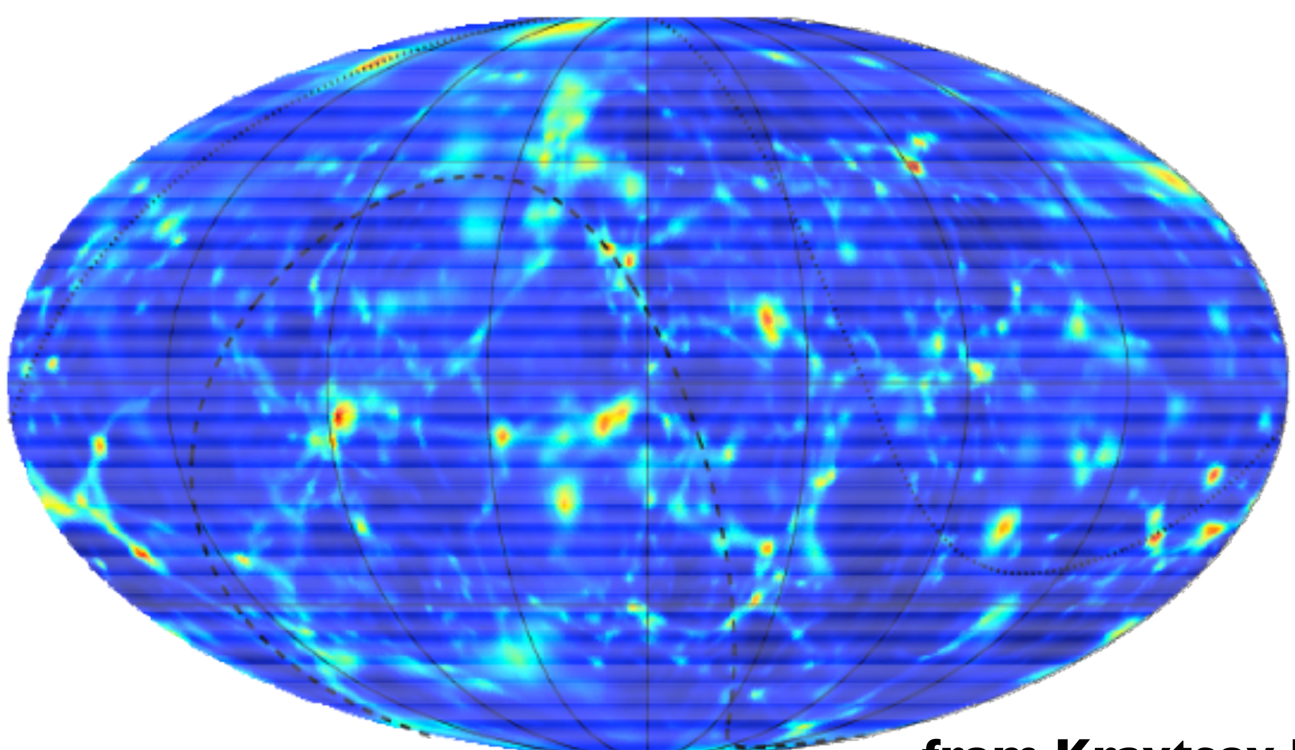
Light nuclei will disintegrate faster than heavy ones

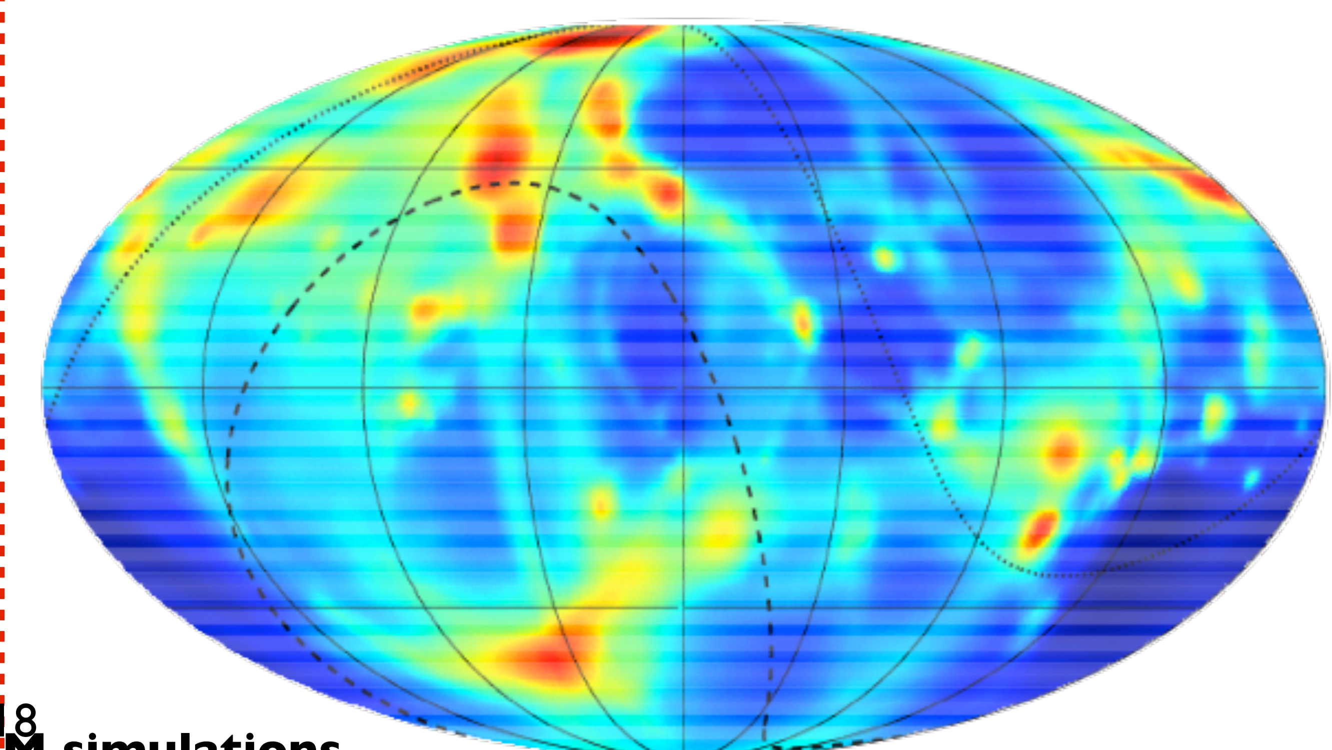
# EBL and UHECRs nuclei




Universe should be very isotropic at “low” energies...

...and become anisotropic above $10^{19.5}$ eV

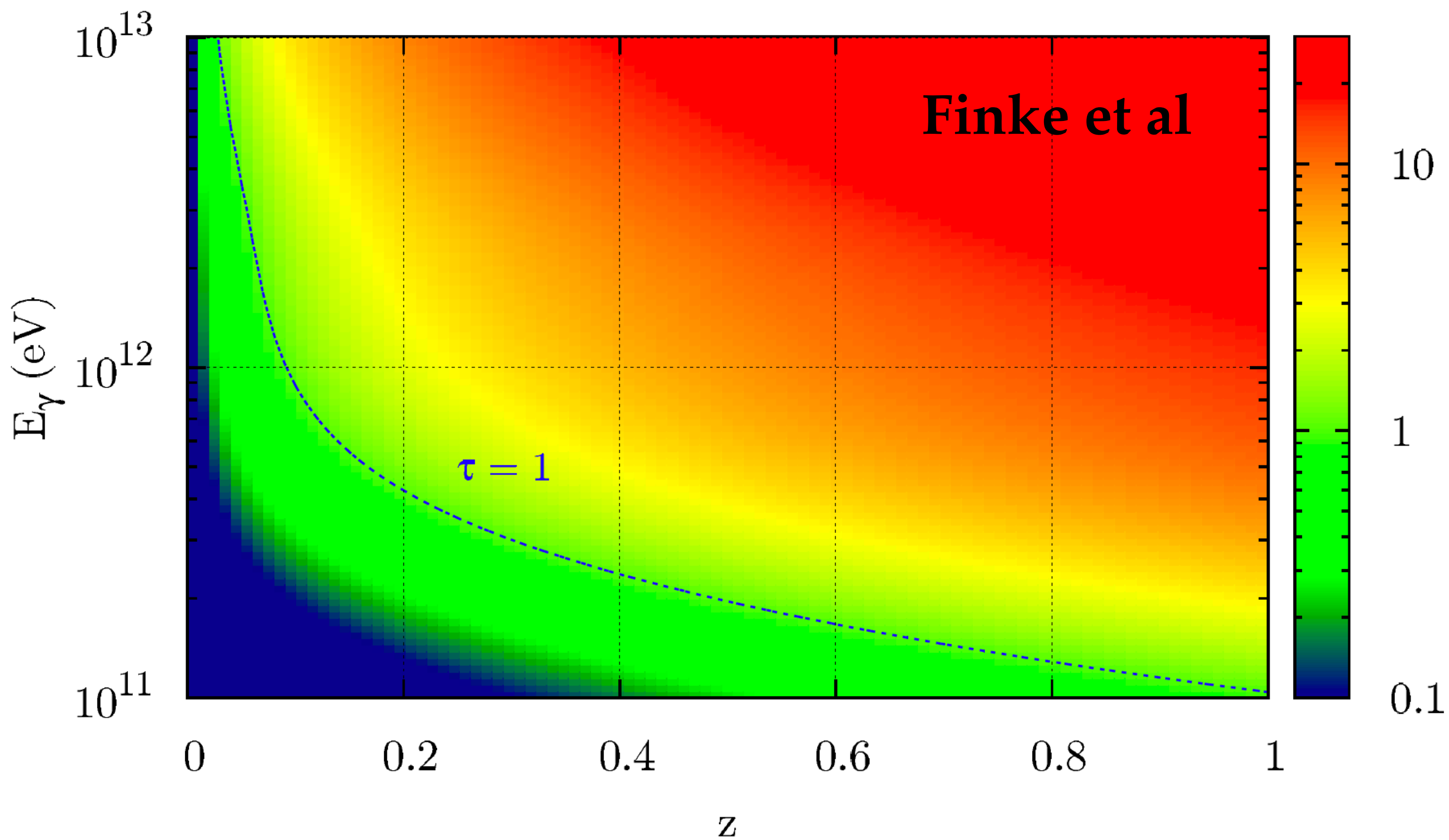




from Kravtsov DM simulations

# Optical depth

$$\tau_{\gamma\gamma}(\varepsilon, z) = c \int_0^z \frac{dt}{dz'} dz' \int_{-1}^{1} (1-\mu)\frac{d\mu}{2} \int_{E_{th}}^{\infty} \sigma(E', \varepsilon', \mu) n(E', z') dE'$$

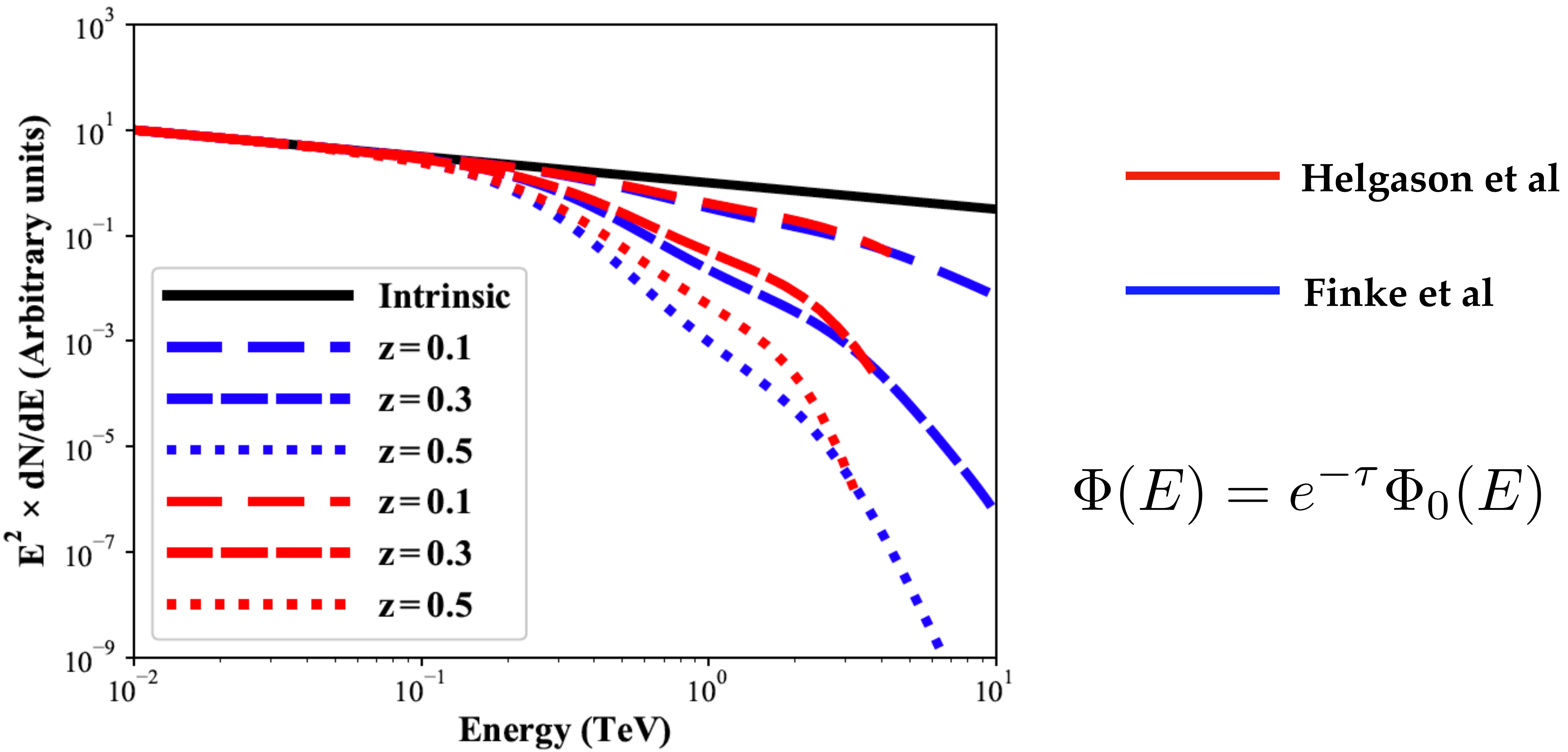



Cosmic gamma-ray horizon (CGRH): τ=1

Attenuation effects important for τ>1

**D.R.M. Pimentel, PhD thesis USP, (2019)**

# Fingerprints of attenuation

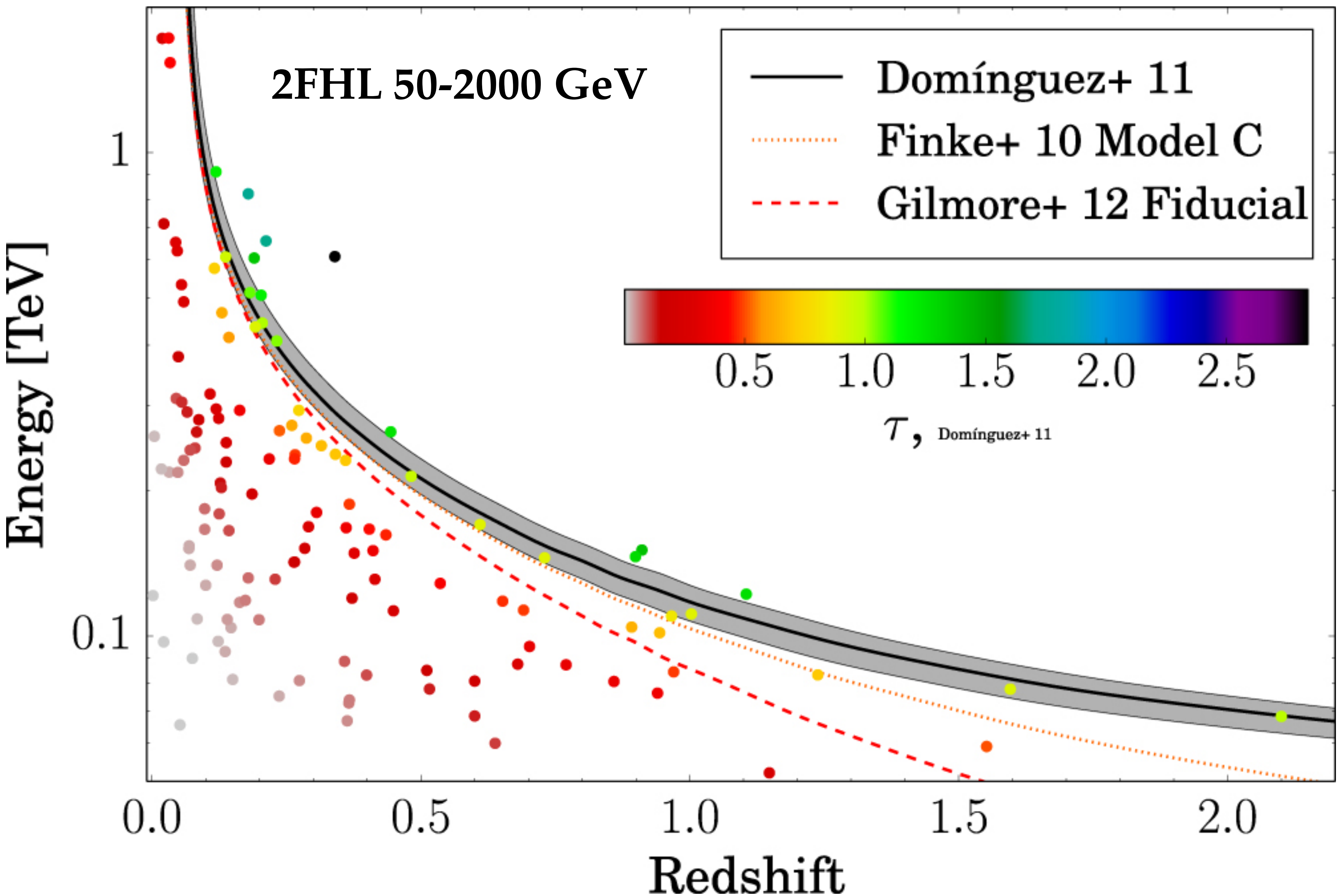



$$\Phi(E) = e^{-\tau}\Phi_0(E)$$

- Hypothetical source with intrinsic power-law spectrum $E^{-2.5}$
- Attenuation unimportant for energies below 100 GeV

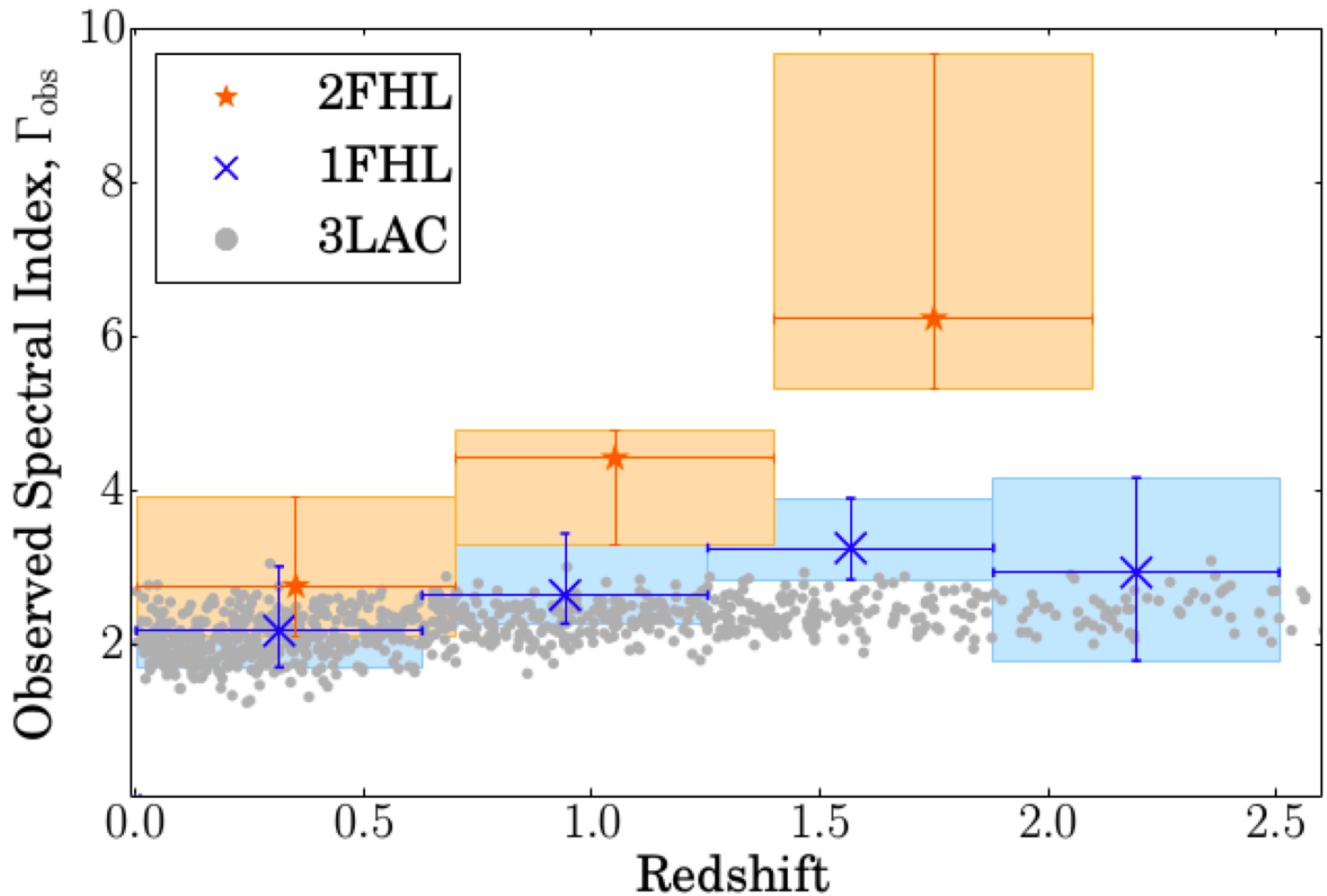
D.R.M. Pimentel, PhD thesis, USP, 2019.

# The cosmic gamma-ray horizon (CGRH)




ApJS 222(1), 5 (2016)

# Spectral index "running"




**2FHL: 50-2000 GeV**

**1FHL: 10-500 GeV**

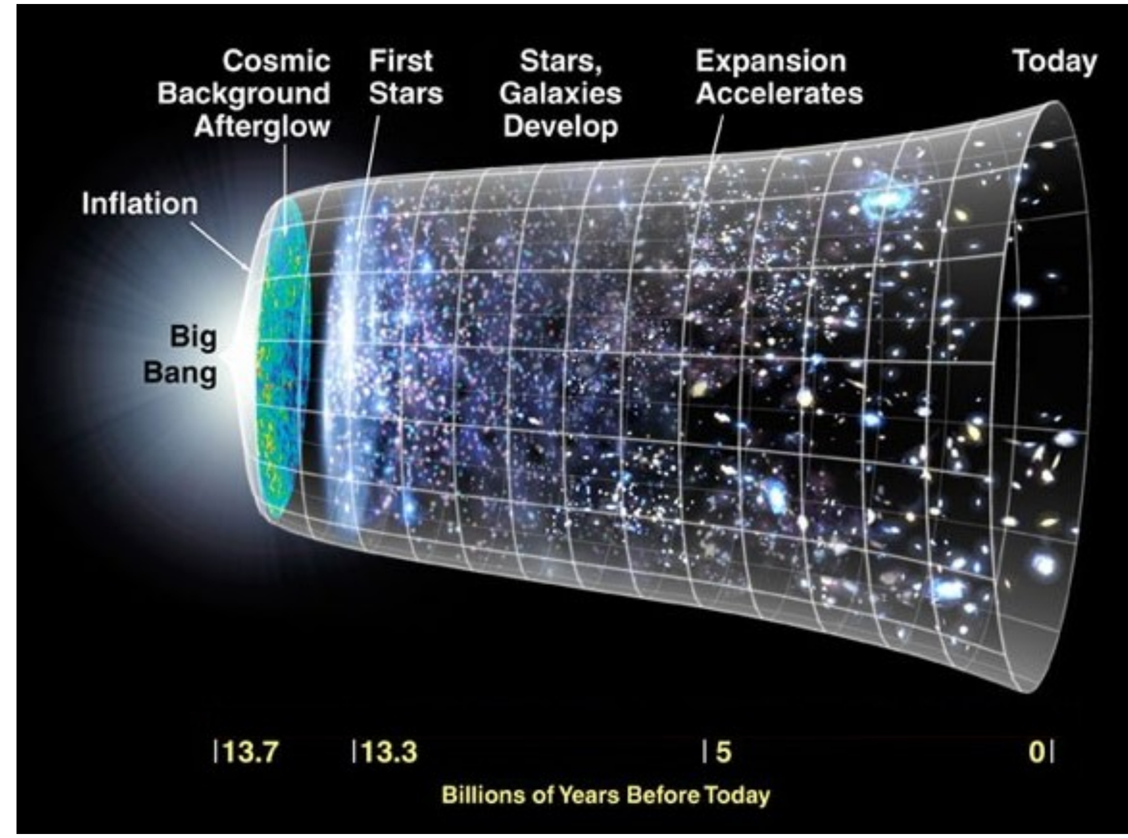
**3LAC: 0.1-100 GeV**

**ApJS 222(1), 5 (2016)**

# EBL and star formation rate (SFR)

Comoving volume emissivity:

$$\epsilon_\nu(z) = \int L_\nu \phi(L_\nu, z) dL_\nu$$




Integrate over the whole SFR history:

$$n(E', z) = (1+z)^3 \int_z^\infty \frac{\epsilon_{\nu'}/h}{h\nu'} \frac{dt}{dz'} dz'$$

- star light (UV/optical)
- dust emission (IR)
- AGN emission (accretion)
- First (pop III) and second (pop II) generation of stars (?)
- Exotic emissions (?)

For a $\Lambda$CDM model:

$$\left|\frac{dt}{dz}\right| = \frac{1}{H_0(1+z)\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}}$$

# Boltzmann equation for EBL

- **Time evolution for the brightness I in physical coordinates:**

**EBL brightness [W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$]** **Emissivity [L$\odot$ Mpc$^{-3}$ Hz$^{-1}$]**

$$\frac{dI(t,\lambda)}{dt} = \underbrace{-3\frac{\dot{a}}{a}I(t,\lambda)}_{\text{expansion}} + \underbrace{\frac{c}{4\pi}j(t,\lambda)}_{\text{source term}}$$

- **Formal solution:**

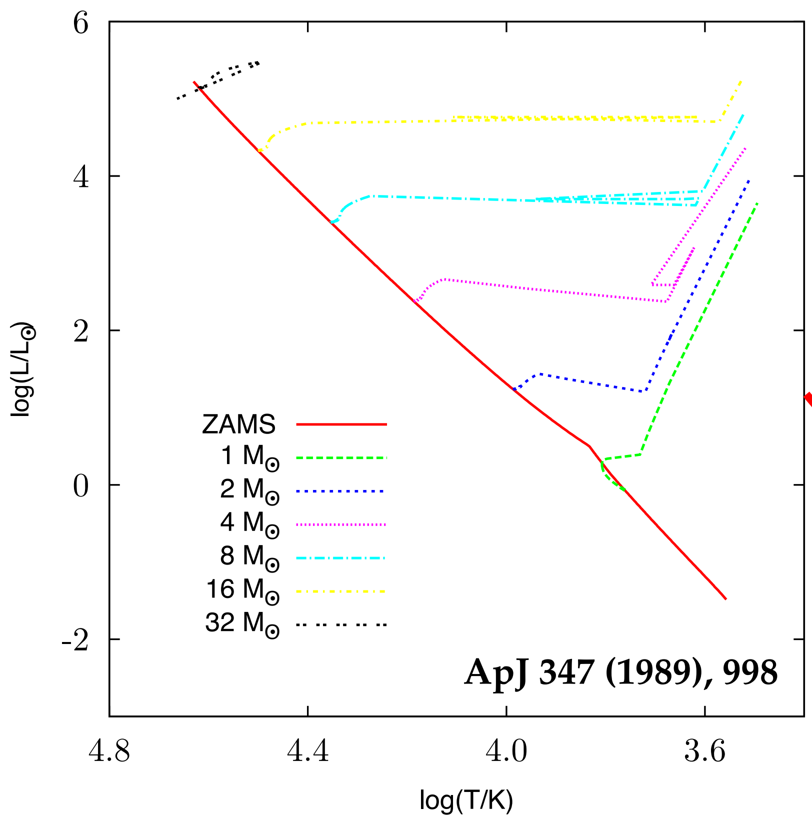
$$I(t,\lambda) = \frac{c}{4\pi}\int_0^t \frac{a^3(t')}{a^3(t)} j(t',\lambda')dt' = (1+z)^3\frac{c}{4\pi}\int_z^\infty j_c(z',\lambda')\left|\frac{dt'}{dz'}\right|dz'$$

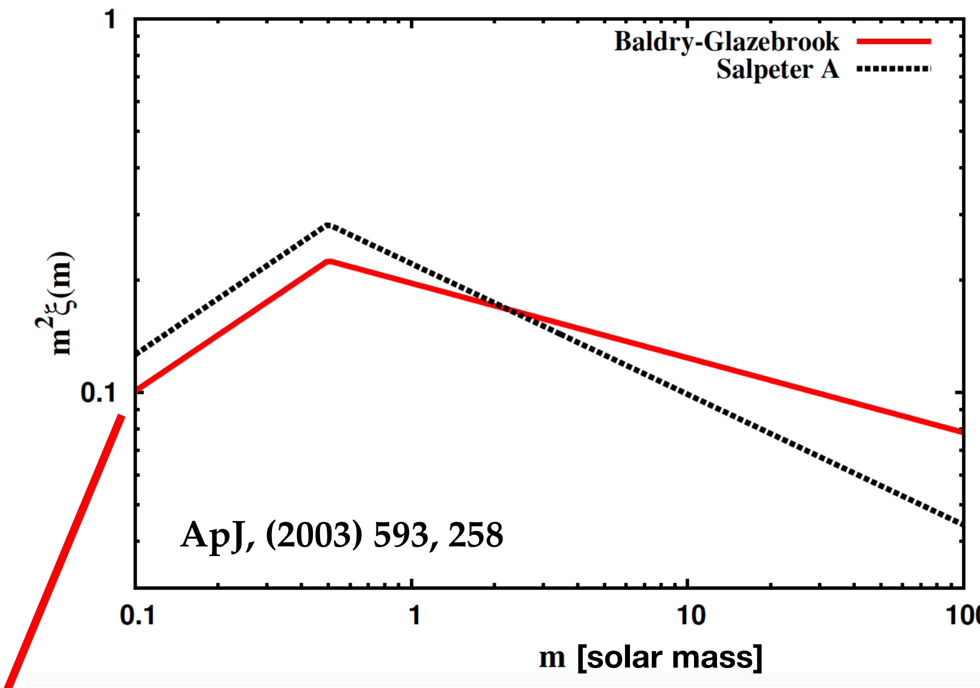
**Comoving emissivity**

- **Therefore, for a given cosmology, the EBL can be model by defining the coming emissivity $j_c(z,\lambda)$**

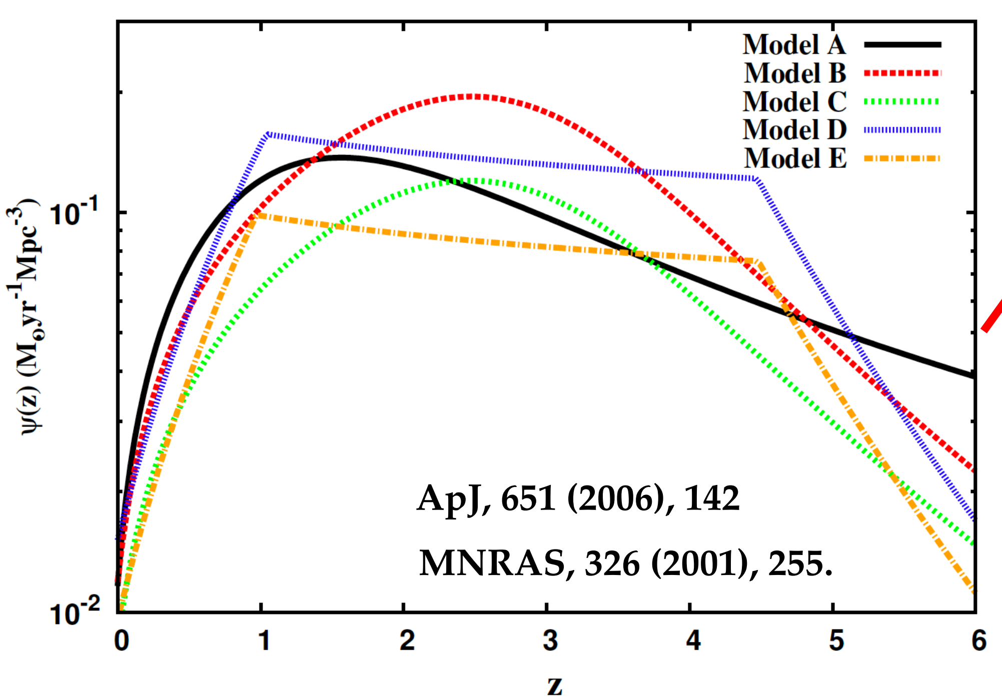
ApJ 712 (2010) 238:249

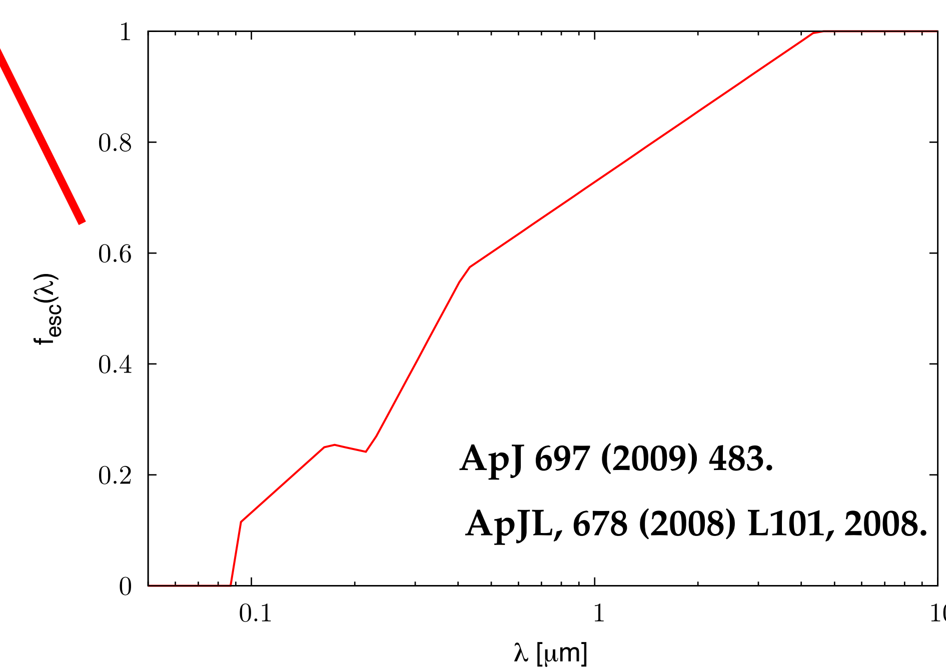
# EBL model based on star+dust (Finke et al.)



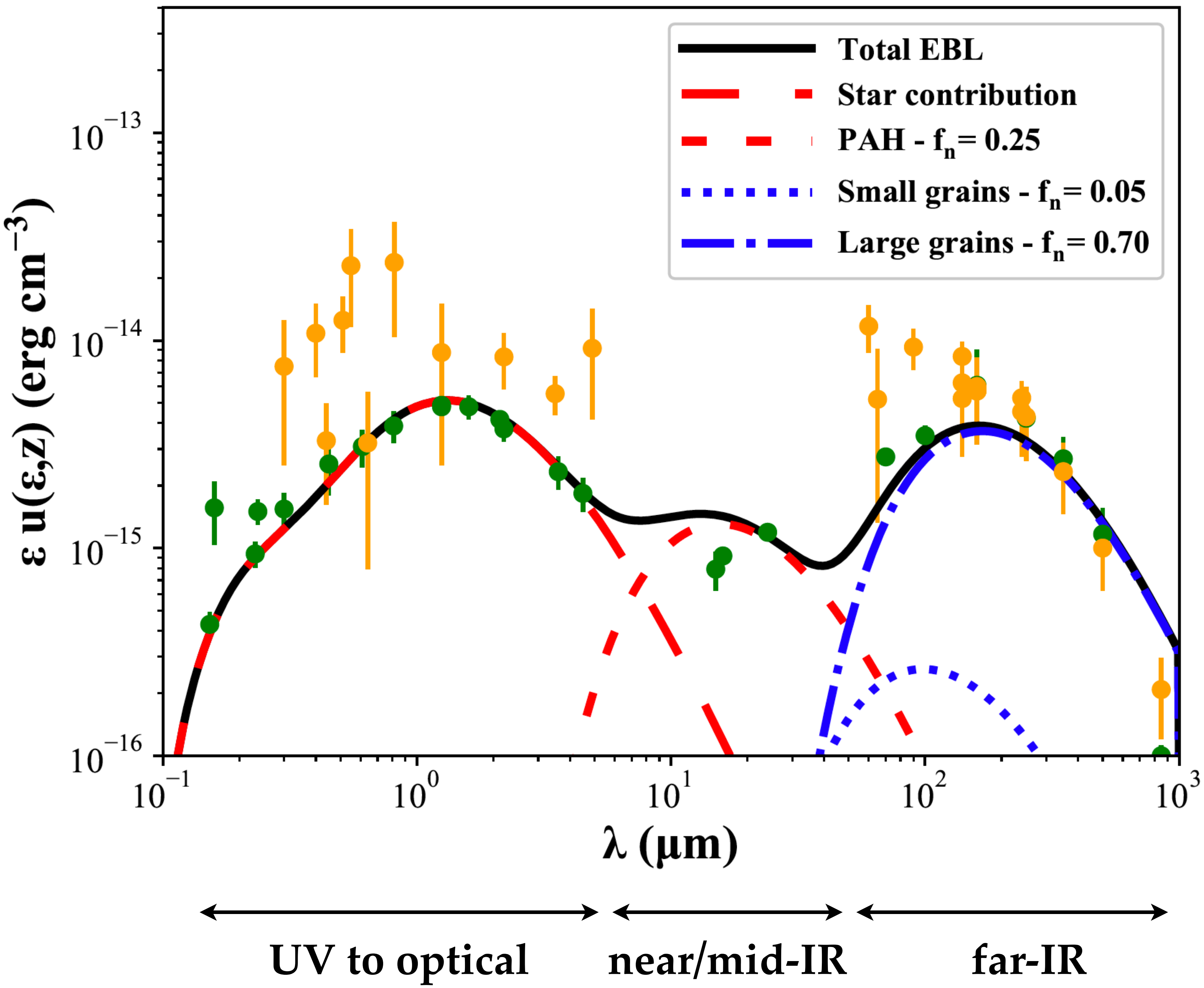




$$I(t,\lambda) = (1+z)^3 \frac{c}{4\pi} \int_z^\infty j_c(z',\lambda') \left| \frac{dt'}{dz'} \right| dz'$$



# Energy density @ z=0 (Finke et al.)




| Component | $I_{bol}$ (nW m$^{-2}$ sr$^{-1}$) |
|---|---|
| Star | 25.9 |
| PAH | 5.5 |
| Small grains | 1.1 |
| Large grains | 14.9 |
| Total | 47.4 |
| CMB | 1000.9 |

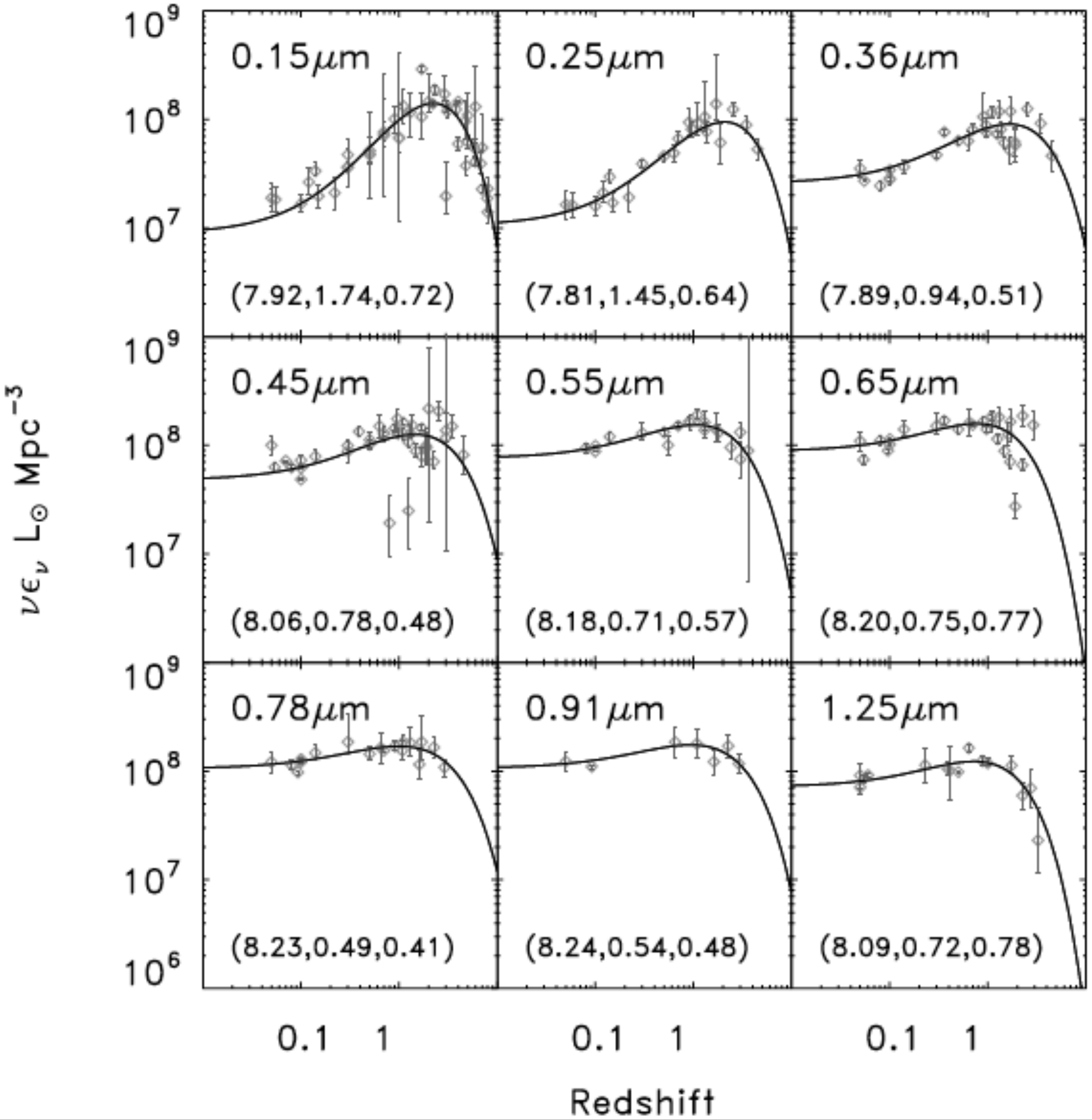
- **About 5% of the CMB energy density**

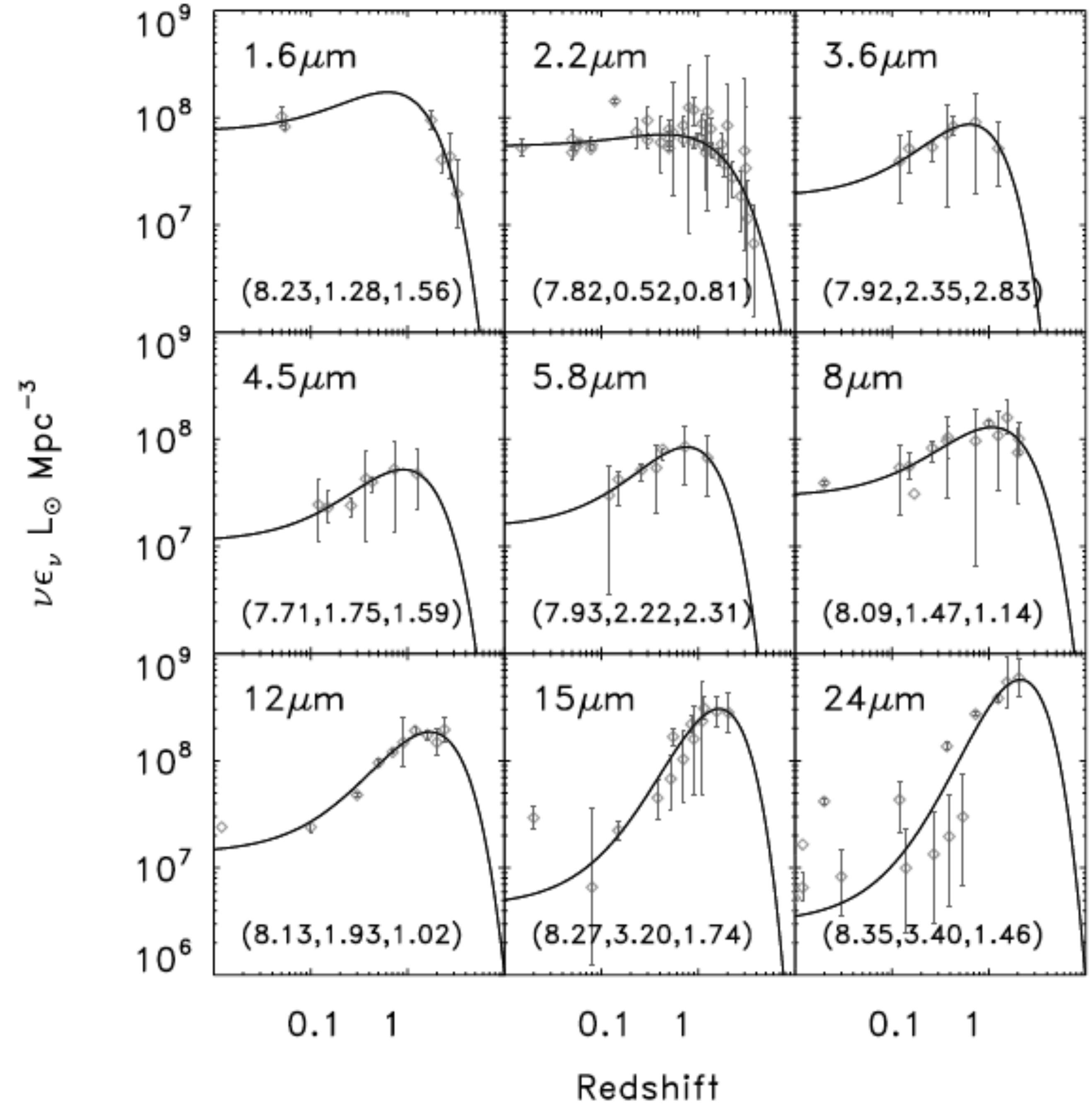
- **Energy density very close to lower bound from galaxy counts**

**D.R.M. Pimentel, EMS, JCAP 04 (2019) 043**

# Galaxy luminosity function and EBL

$$\nu j_c(z) = a_\nu (1 + (z - z_0))^{b_\nu} \exp\left(-c_\nu (z - z_0)\right)$$



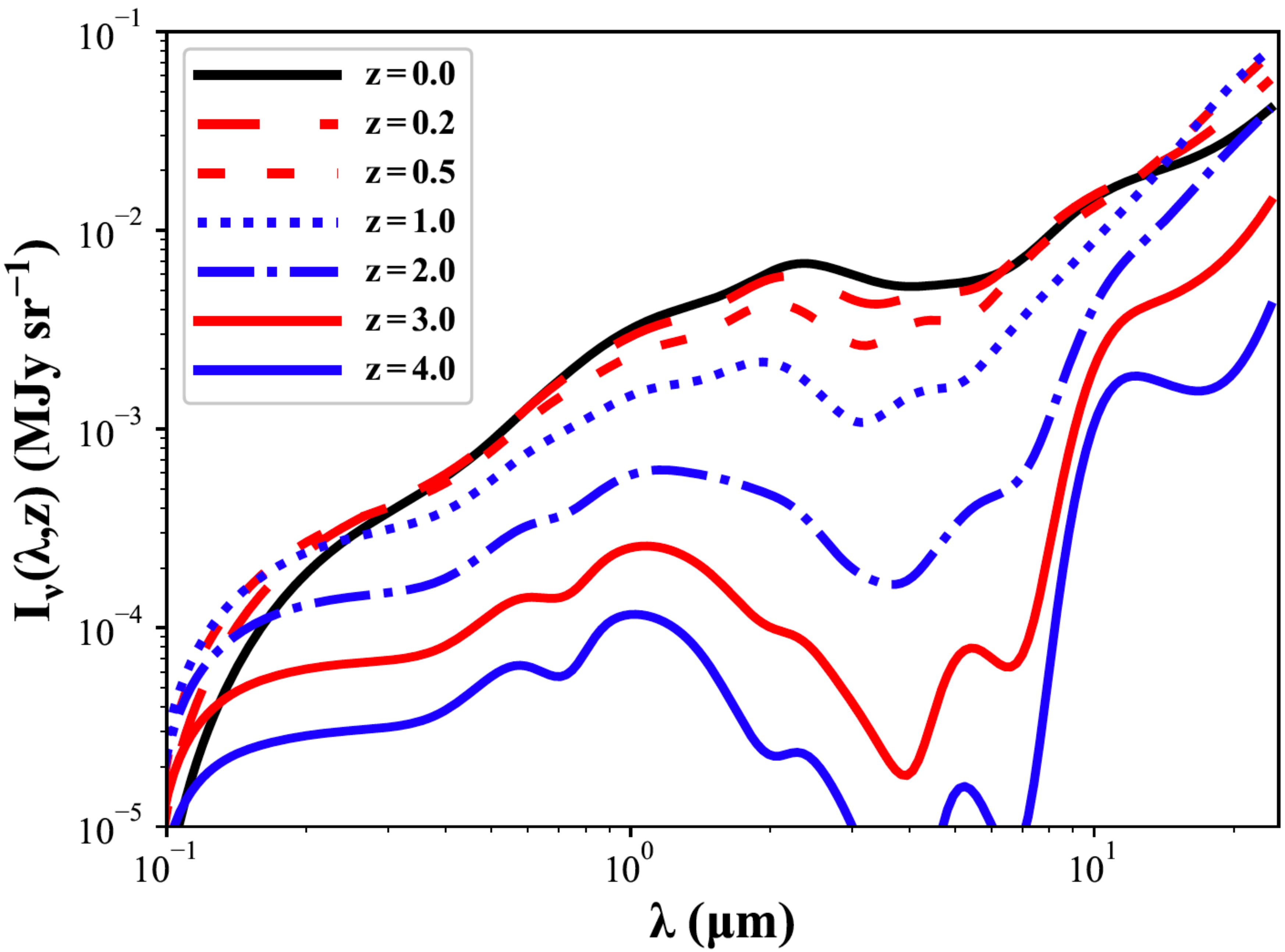

- Final library of 342 LF measurements
- Allow modeling of absorption across entire Fermi-LAT energy range for pair production

- Also part of the TeV region important for IACTs



ApJL 758 L13 (2012)

# An EBL model based on galaxy luminosity function

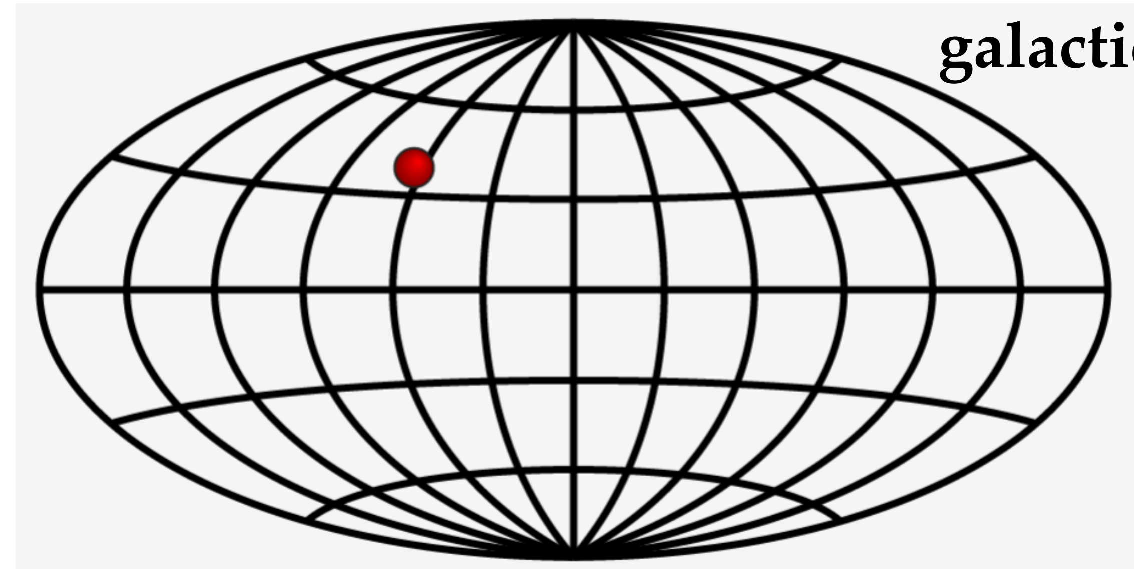


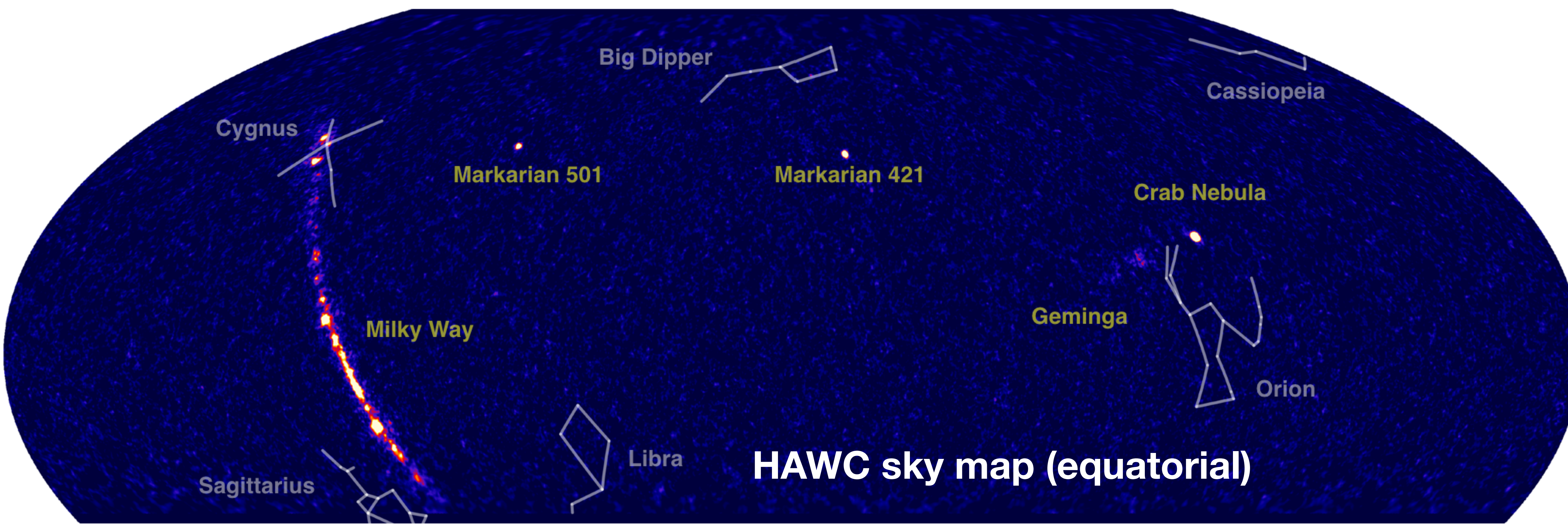

- Consistent with integrated galaxy counts
- Near and far-IR not covered by the model

ApJL 758 L13 (2012)

# Case study: Markarian 501

- Blazar
- BL Lac type AGN
- z=0.034 (~140 Mpc)
- $(L_{gal}, B_{gal})$ = (63.60, 38.86) deg
- High variability at TeV
- Violent flare seen by HEGRA in 1997

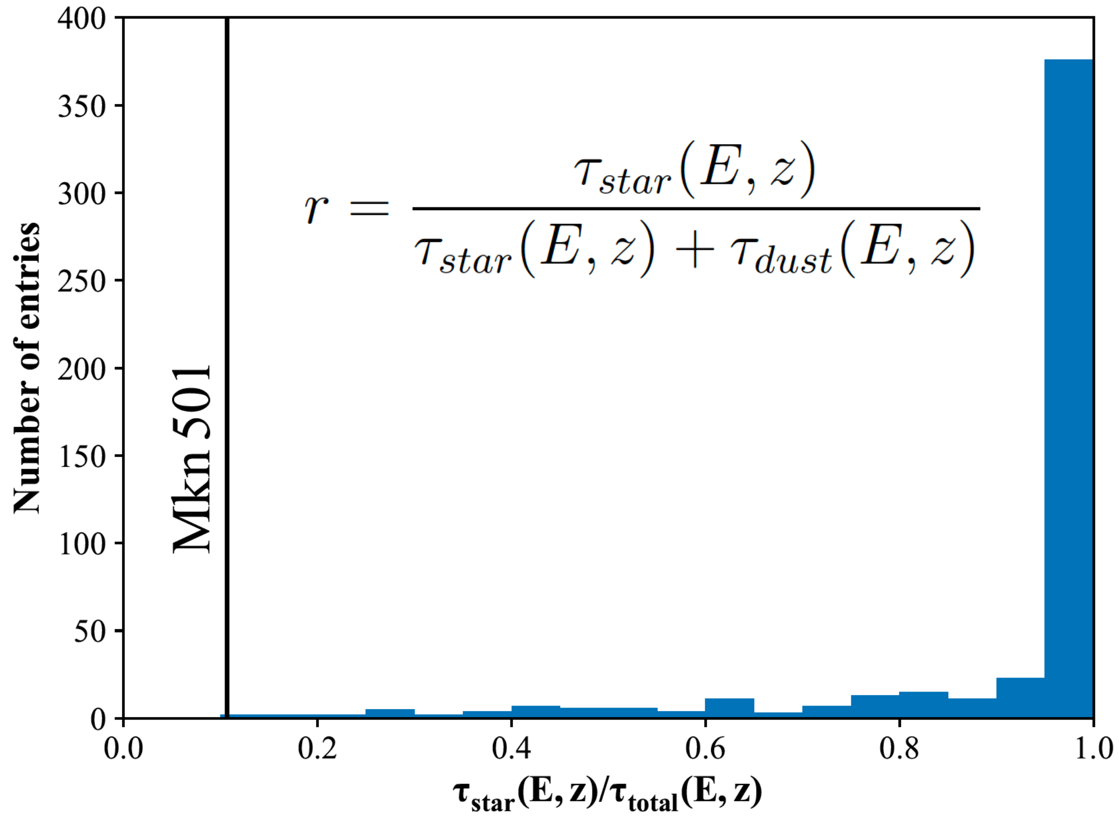


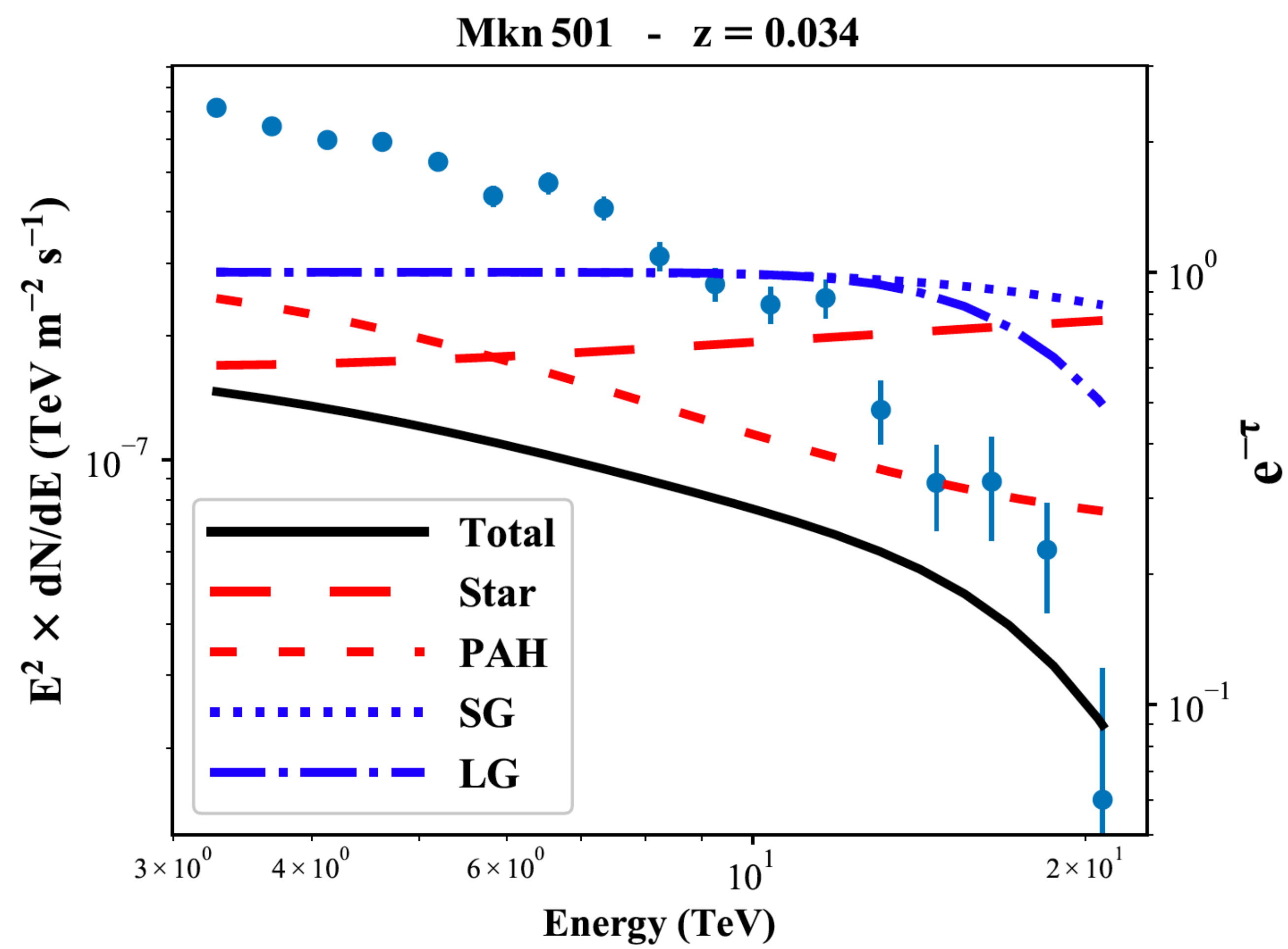



# Case study: Markarian 501

- **SED very well measured with emission extending up to 20 TeV**

- **High levels of attenuation predicted at the very end of Mkn 501 SED**




**Can we use the SED of Mkn 501 to constrain EBL model parameters?**

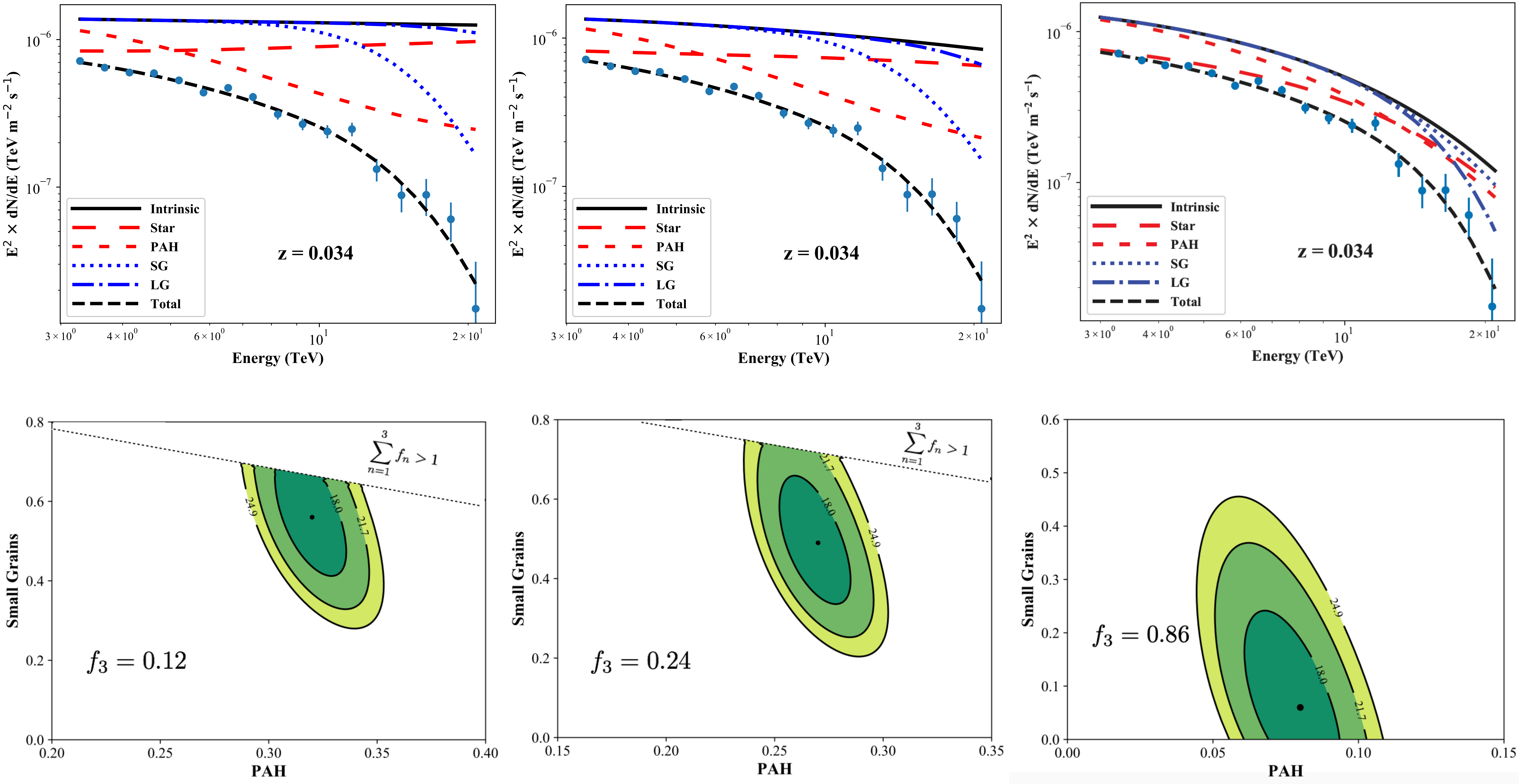
# Analysis strategy

- **Different flavors of intrinsic spectrum to assess this systematic uncertainty:**

$$\Phi_0(E) = \begin{cases} N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} & \text{(power-law)} \\ N_0 \left(\frac{E}{E_0}\right)^{-a-b\log(E/E_0)} & \text{(log-parabola)} \\ N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} e^{-\left(\frac{E}{E_{\rm cut}}\right)} & \text{(power-law with exponential cutoff)} \end{cases}$$

- **$E_0$ = 1 TeV fixed to minimize correlations between parameters**
- **An EBL model based on star+dust blackbody contributions (Finke et al)**
- **Temperature of dust grains fixed a priori**
- **Relative grain contributions varied together with intrinsic spectrum parameters.**
- **Grain fractions will be subject to normalization condition:** $\sum_i^3 f_n = 1$
- **Fits will be performed with either 4 (PL) or 5 (LP/PLC)**

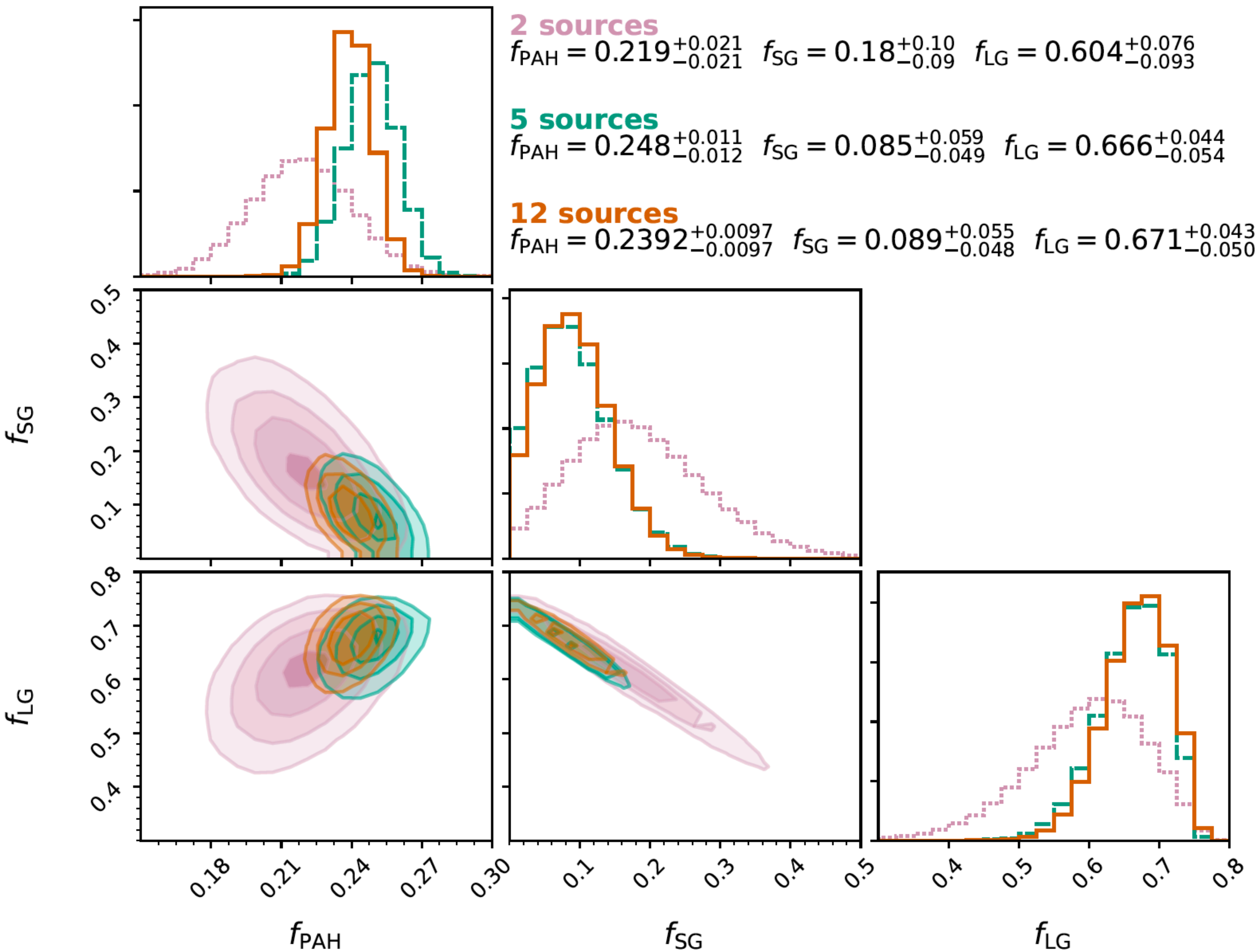
# Fit results




- Intrinsic spectrum parametrization is an important source of systematic uncertainty
- See, how important are PAHs to give the SED the correct inclination at low energies

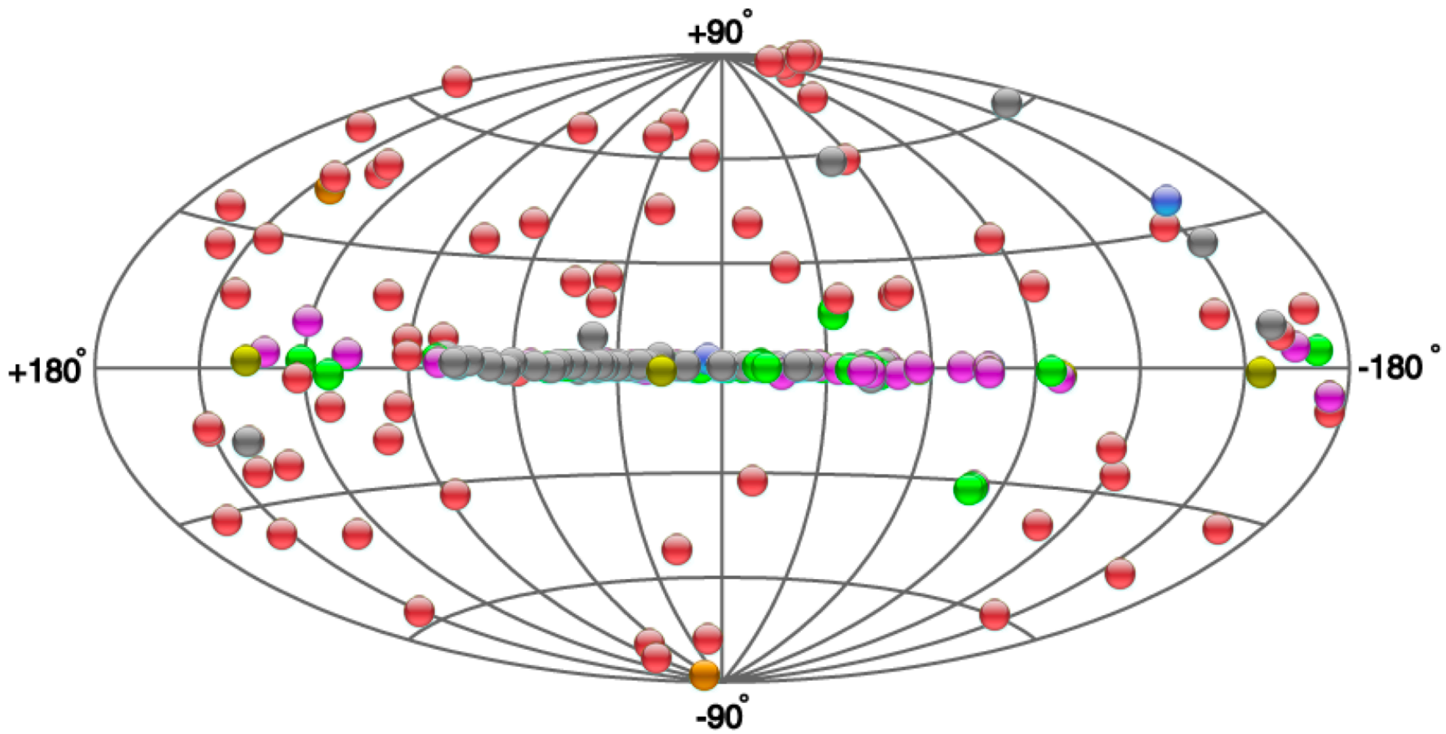
D.R.M. Pimentel, EMS, JCAP 04 (2019) 043

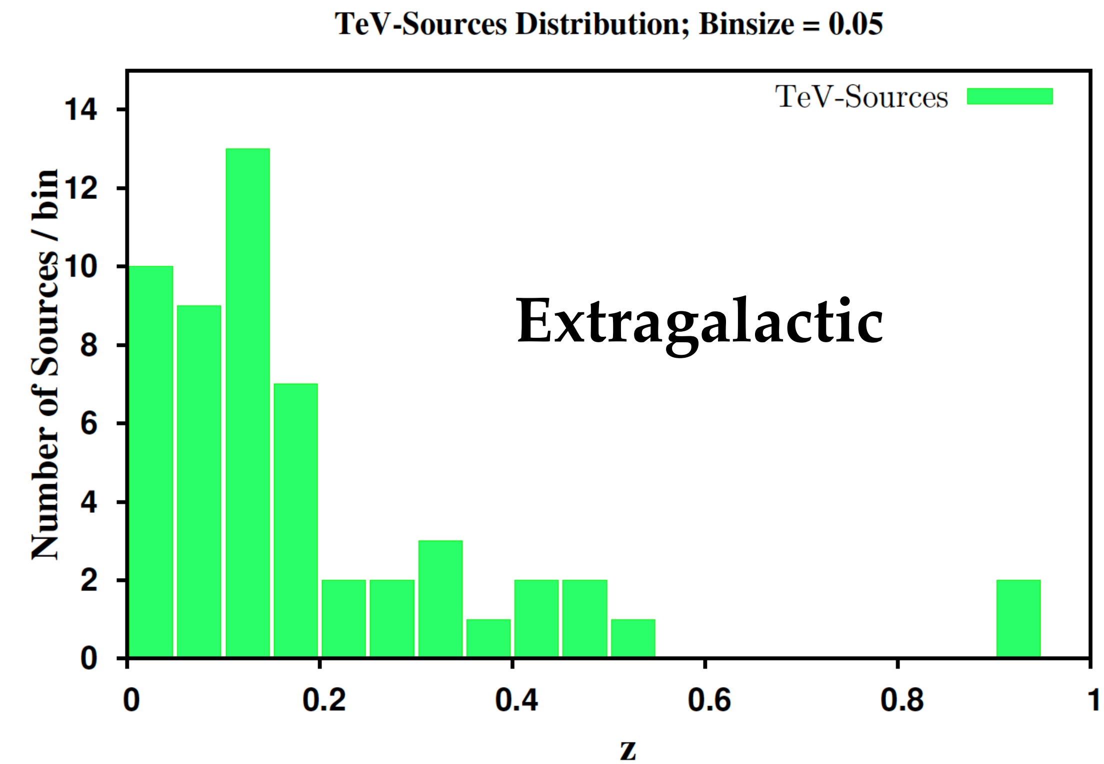
# Breaking degeneracies with a combined fit



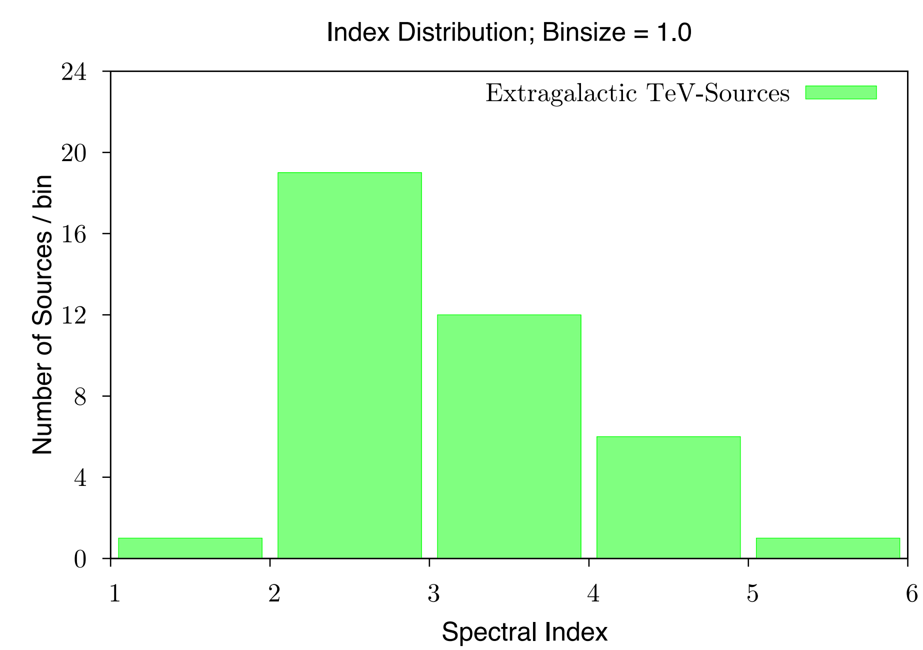

**M. G. Dantas Xavier et al, in preparation**

# What does the data tell us?



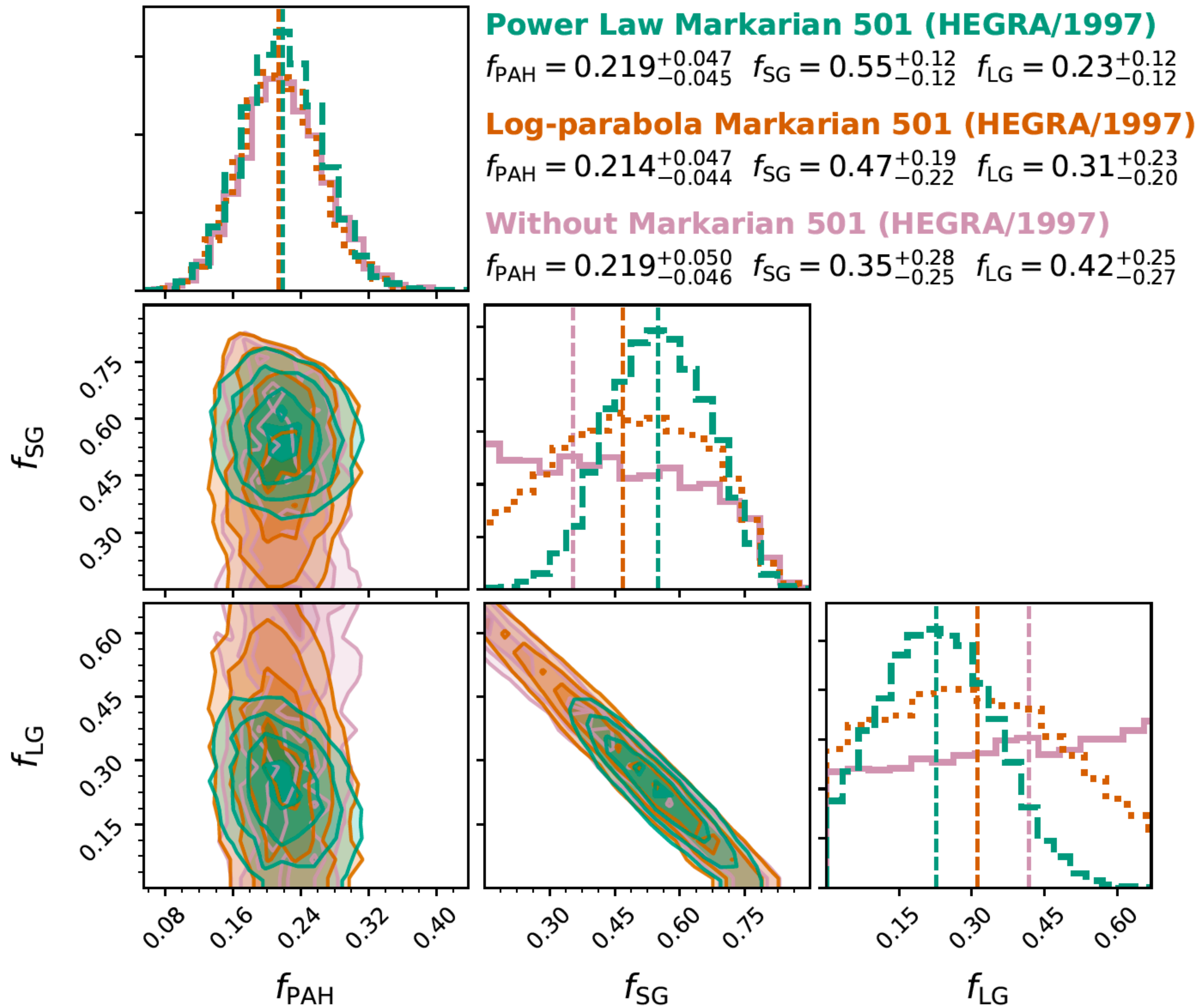




**http://tevcat2.uchicago.edu**




- **54 (6 FSRQ + 48 BL Lac) of these TeV emitters are extragalactic sources**

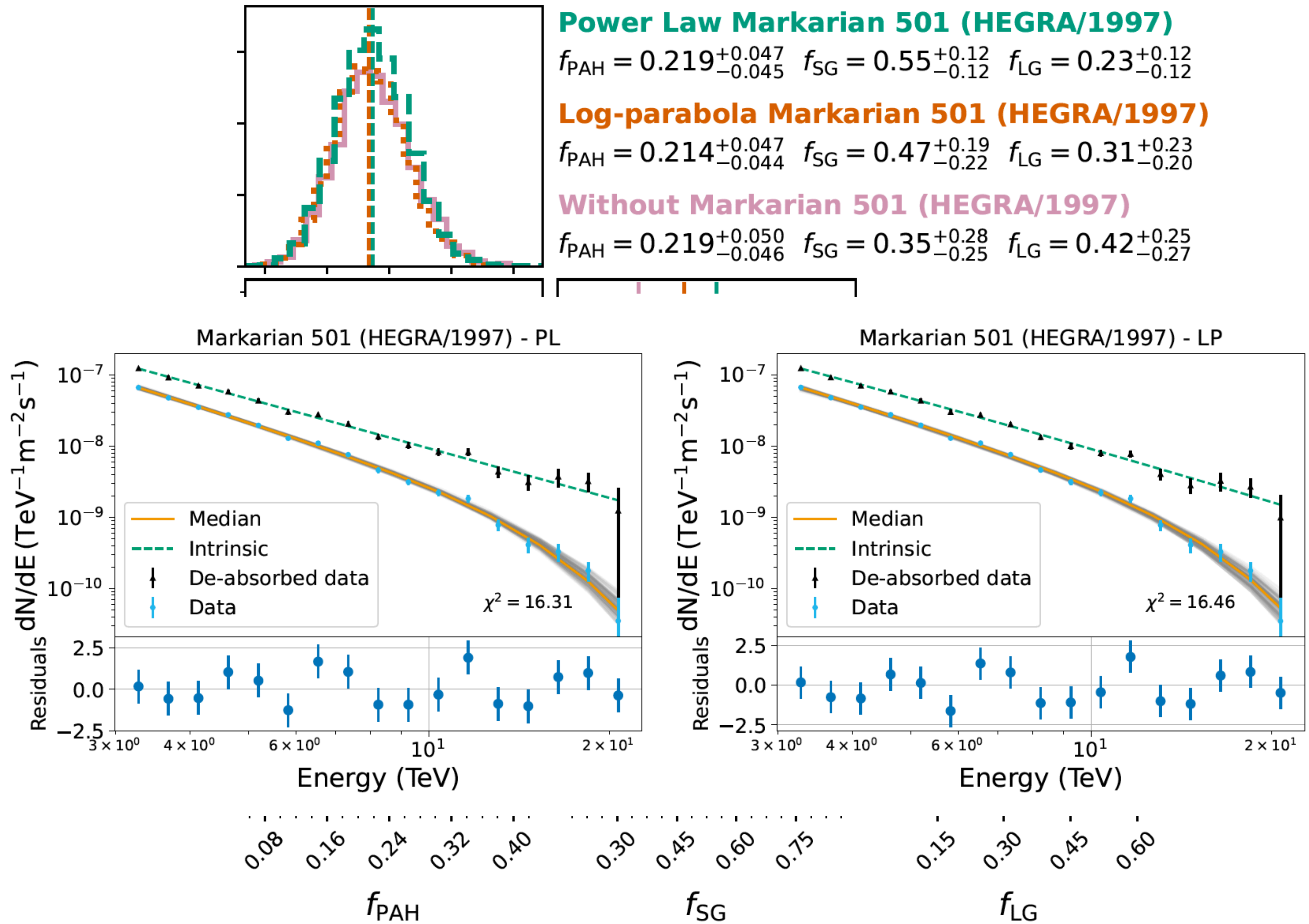
# Breaking degeneracies with a combined fit




- **Spectra of all 54 extragalactic TeVCat sources fitted simultaneously**

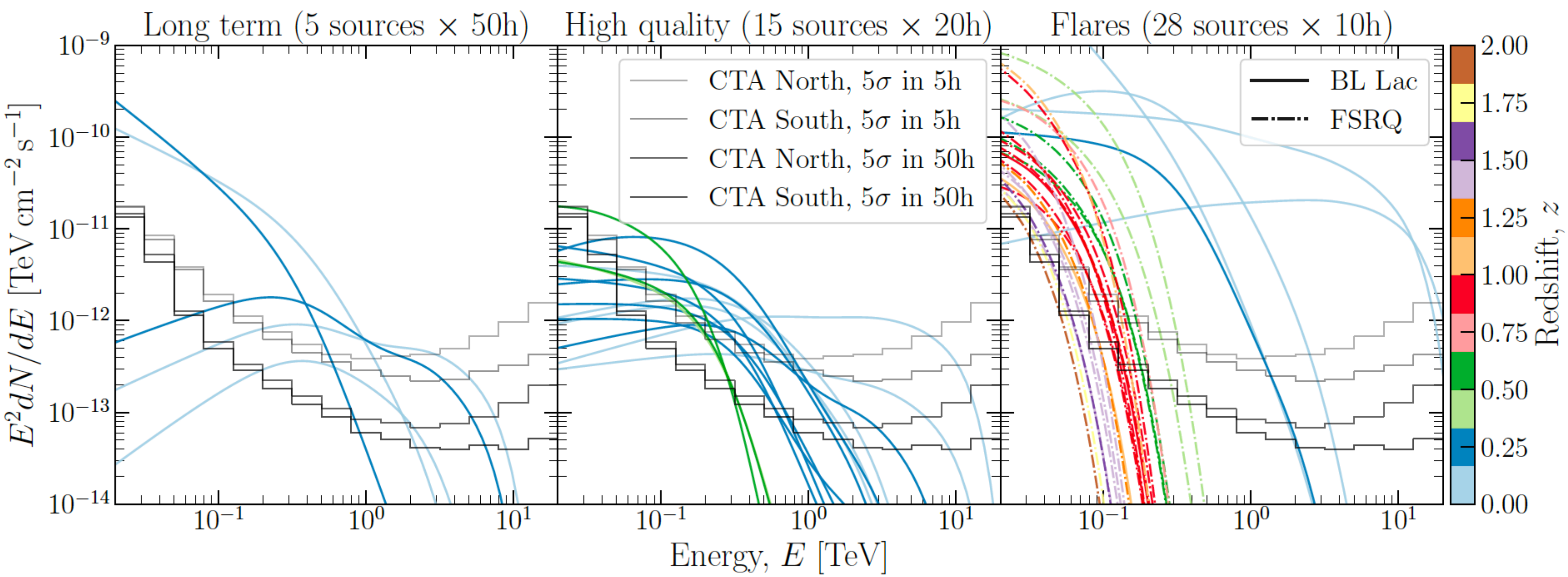
**M. G. Dantas Xavier et al, in preparation**

# Breaking degeneracies with a combined fit




M. G. Dantas Xavier et al, in preparation

# Constraining EBL with CTA

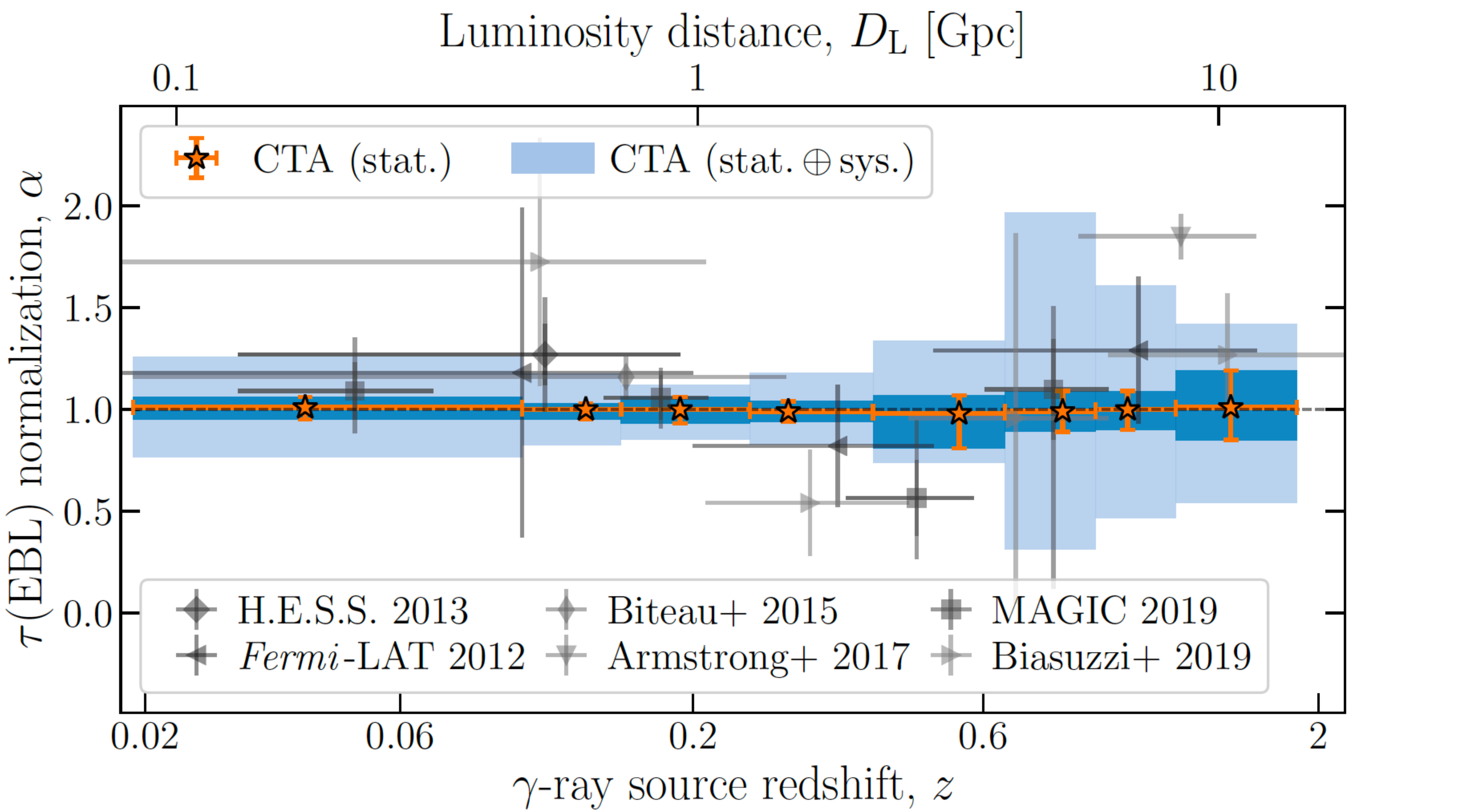



- TS > 25 for E(tau=1)
- Class dependent intrinsic cutoff at comoving energies: Ecut= 100 GeV (LSP/ ISP), Ecut= 1TeV (HSP), and Ecut= 10 TeV (EHSP).
- Only sources with well determined redshift (spectral lines, Ly$\alpha$)



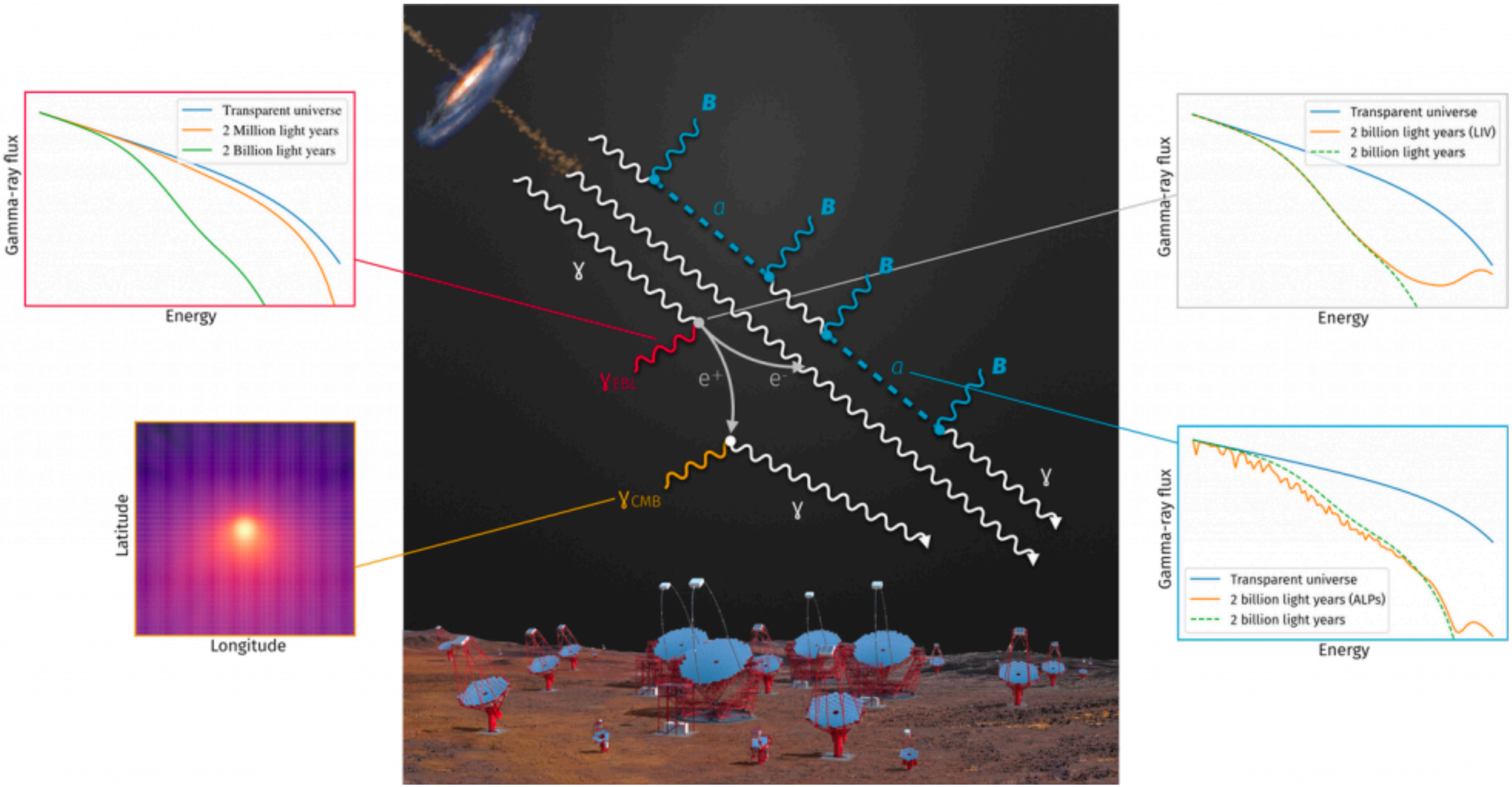
H. Abdalla et al JCAP02(2021)048

# Constraining EBL with CTA




**H. Abdalla et al JCAP02(2021)048**

# Probing the IGMF with CTA




Jonathan Biteau / Manuel Meyer

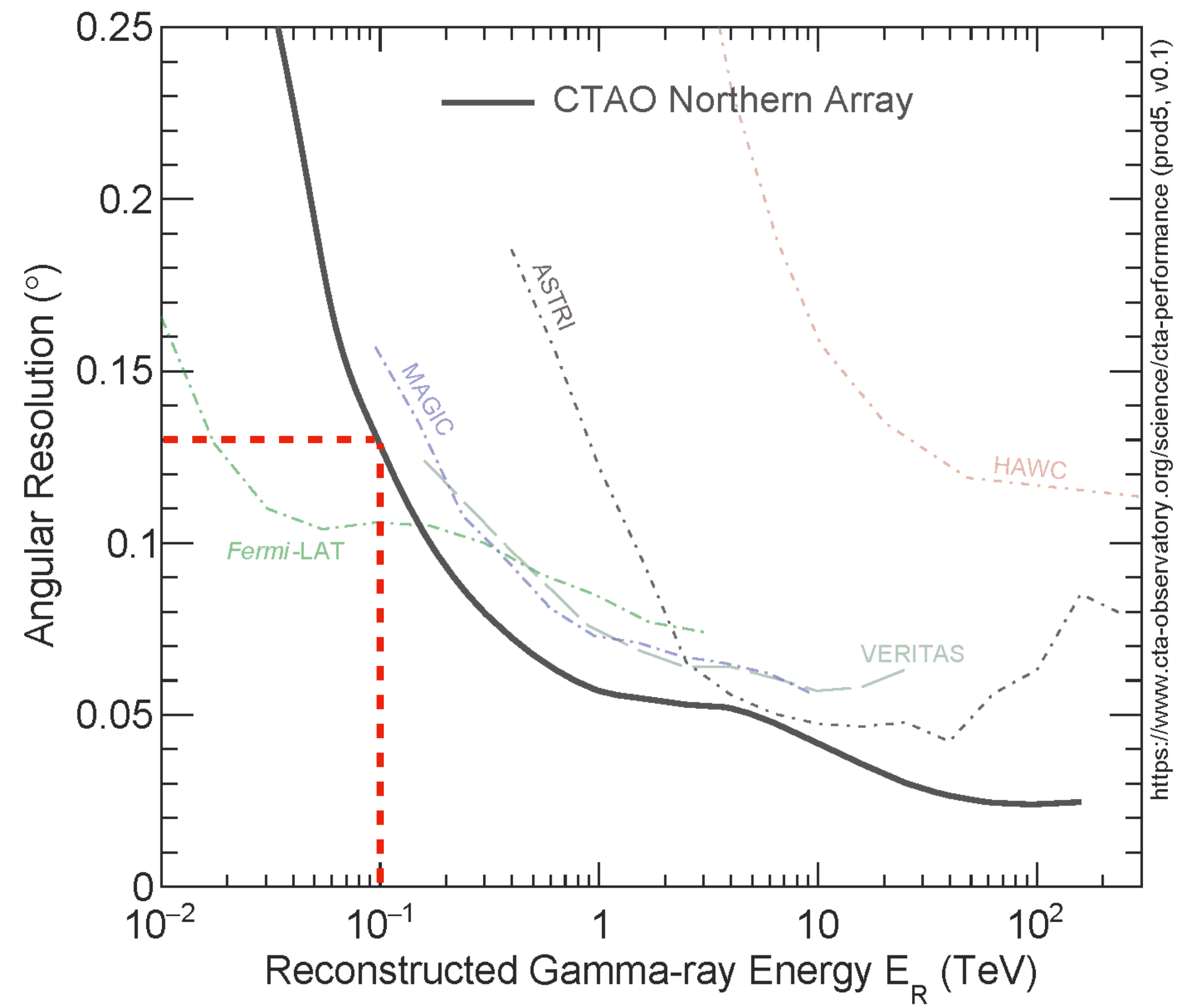
# Probing the IGMF with CTA

$$\theta(100\ \mathrm{GeV}) \simeq 0.5^\circ \times \left(\frac{B_{\mathrm{IGMF}}}{10^{-14}\ \mathrm{G}}\right)$$

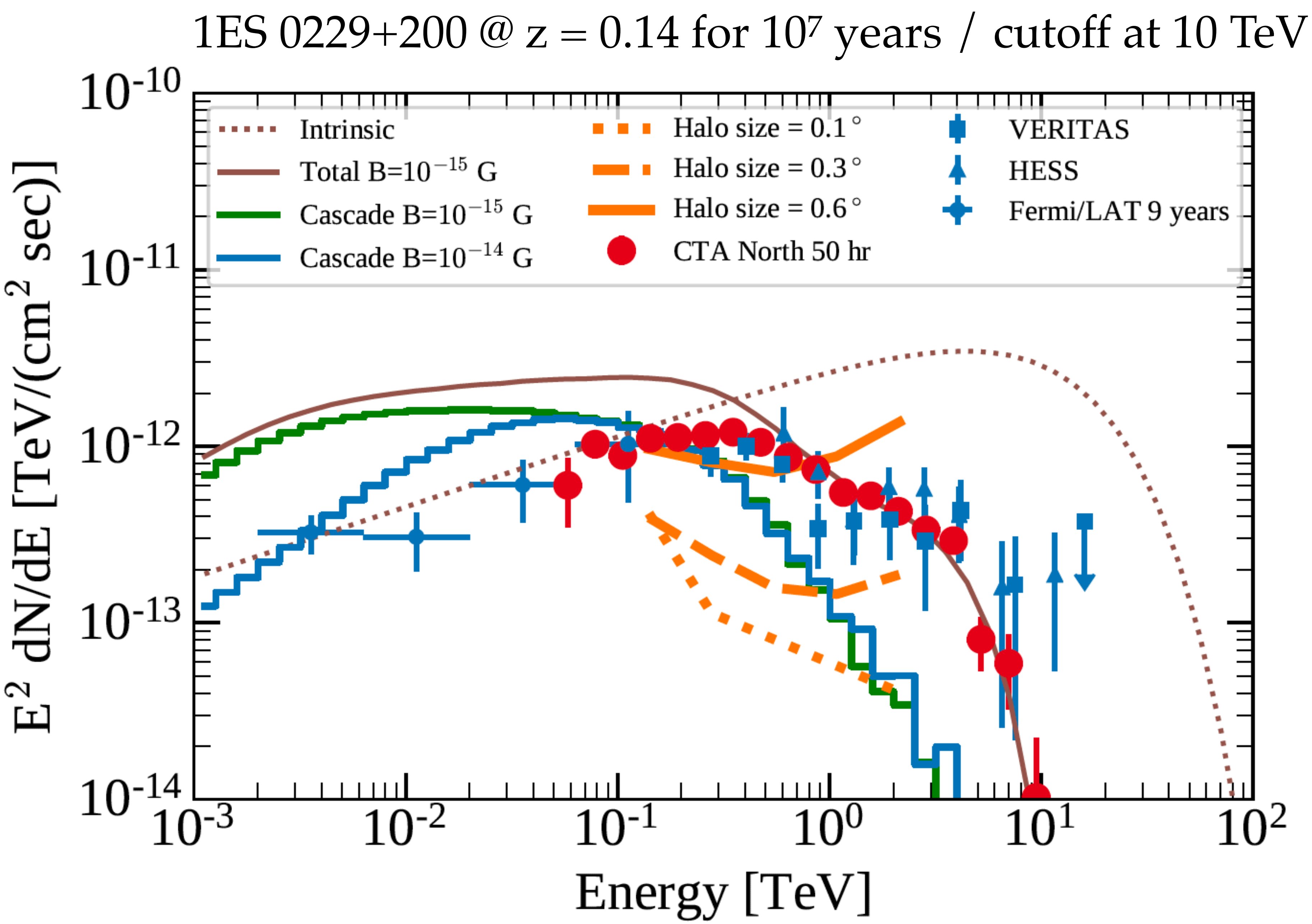
$$B_{\mathrm{IGMF}} \gtrsim 3 \times 10^{-15}\ \mathrm{G}$$

**+ CTA sensitivity**

$$B_{\mathrm{IGMF}} \lesssim 10^{-13} - 10^{-12}\ \mathrm{G}$$



# Probing the IGMF with CTA






H. Abdalla et al JCAP02(2021)048

# The blazar luminosity function

# Modeling the γ-ray AGN luminosity function (GLF)

- **Modification over the so called pure luminosity evolution GLF to better describe first year LAT data (LDDE):**

$$\Phi(L_\gamma, z, \Gamma) = \underbrace{\Phi(L_\gamma, z=0, \Gamma)}_{\text{GLF @ z=0}} \times \underbrace{e(z, L_\gamma)}_{\text{redshift and luminosity evolution}}$$

- **Local behavior:**

$$\mu(L_\gamma) = \mu^* + \beta[\log(L_\gamma) - 46]$$

$$\Phi(L_\gamma, z=0, \Gamma) = \frac{A}{\ln(10) L_\gamma}\left[\left(\frac{L_\gamma}{L_*}\right)^{\gamma_1} + \left(\frac{L_\gamma}{L_*}\right)^{\gamma_2}\right]^{-1} e^{-0.5[\Gamma - \mu(L_\gamma)]^2/\sigma^2}$$

- **Luminosity dependent redshift evolution:**

$$p_1(L_\gamma) = p_1^* + \tau(\log(L_\gamma) - 46)$$

$$p_2(L_\gamma) = p_2^* + \delta(\log(L_\gamma) - 46)$$

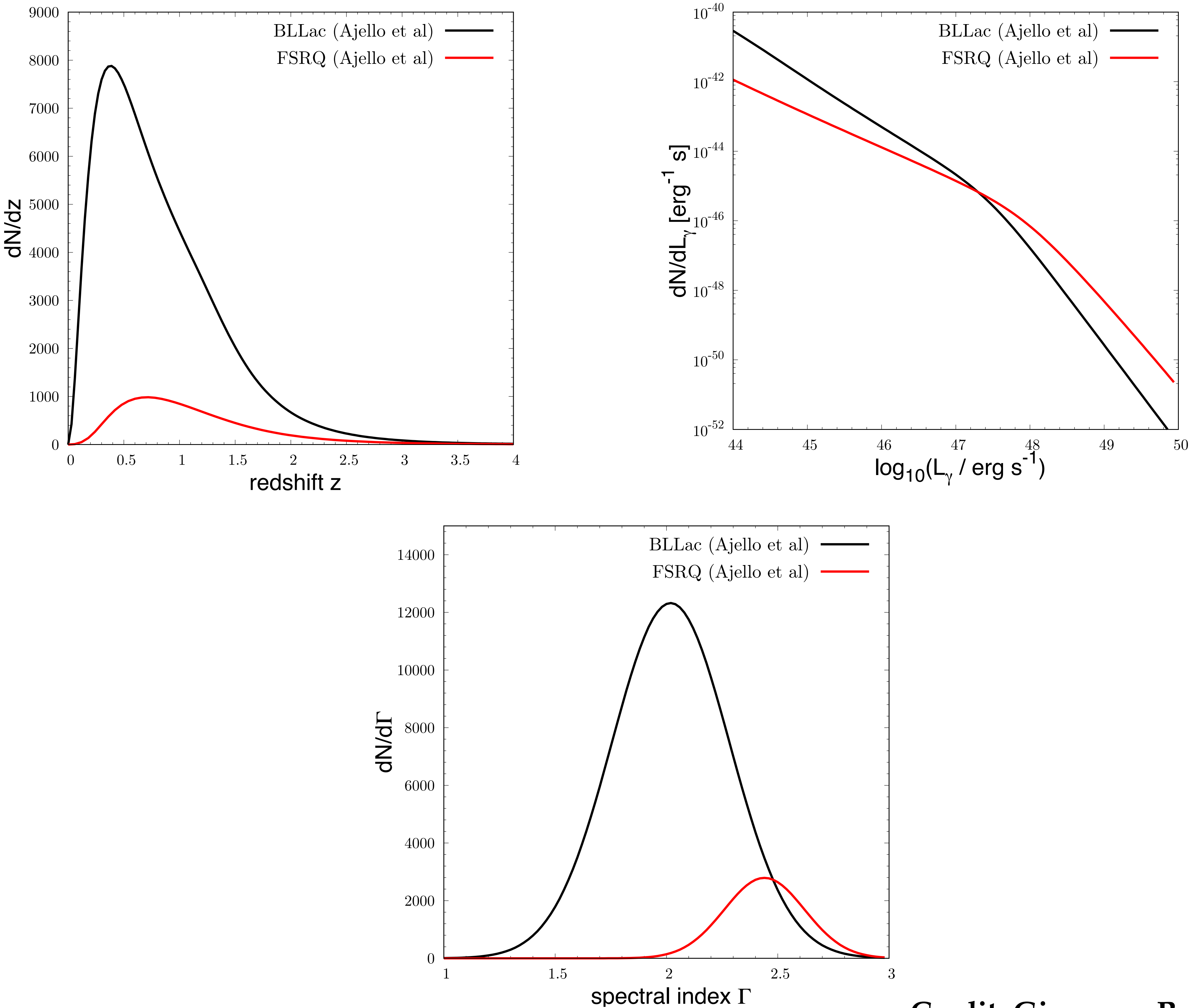
$$z_c(L_\gamma) = z_c^*(L_\gamma/10^{48})^\alpha$$

$$e(z, L_\gamma) = \left[\left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{-p_1(L_\gamma)} + \left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{-p_2(L_\gamma)}\right]^{-1}$$

| source | A [Gpc$^{-3}$] | $\gamma_1$ | $\gamma_2$ | $L_*$ [erg/s] | $p_1^*$ | $p_2^*$ | $\tau$ | $z_c^*$ | $\alpha$ | $\mu^*$ | $\beta$ | $\sigma$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BL Lac | 3.39 | 0.27 | 1.86 | $10^{47.4472}$ | 2.24 | -7.37 | 4.92 | 1.34 | 0.0453 | 2.10 | 0.0646 | 0.26 |
| FSRQ | 3.06 | 0.21 | 1.58 | $10^{47.9243}$ | 7.35 | -6.51 | 0.0 | 1.47 | 0.21 | 2.44 | 0.0 | 0.18 |



**Ajello M. et al., ApJ, 780 (2014) 73**




**Credit: Giovanna Rocha Cordeiro**

# A few questions

- What will likely to be extragalactic sky seem by CTA in the near future?
- What is the best (unbiased) way to probe parameters of the blazar GLF?
- How well will CTA determine parameters of blazar GLF?
- Can we go beyond phenomenological GLF parameterizations?

# Monte Carlo simulation strategy

- **Intrinsic spectrum parameterization: power-law**
- **Sources with redshifts, luminosities and spectral indices drawn from the Ajello's AGN luminosity function and extrapolated to the TeV range**
- **Observations following the extragalactic survey of the CTA KSP**
- **IRFs from prod3b-v1 (omega) and prod5 (alpha)**
- **Cosmic ray background rate after gamma/hadron separation cuts**
- **Detections threshold: TS>25 for a power-law spectrum**

# OMEGA CONFIGURATION (118 telescopes)

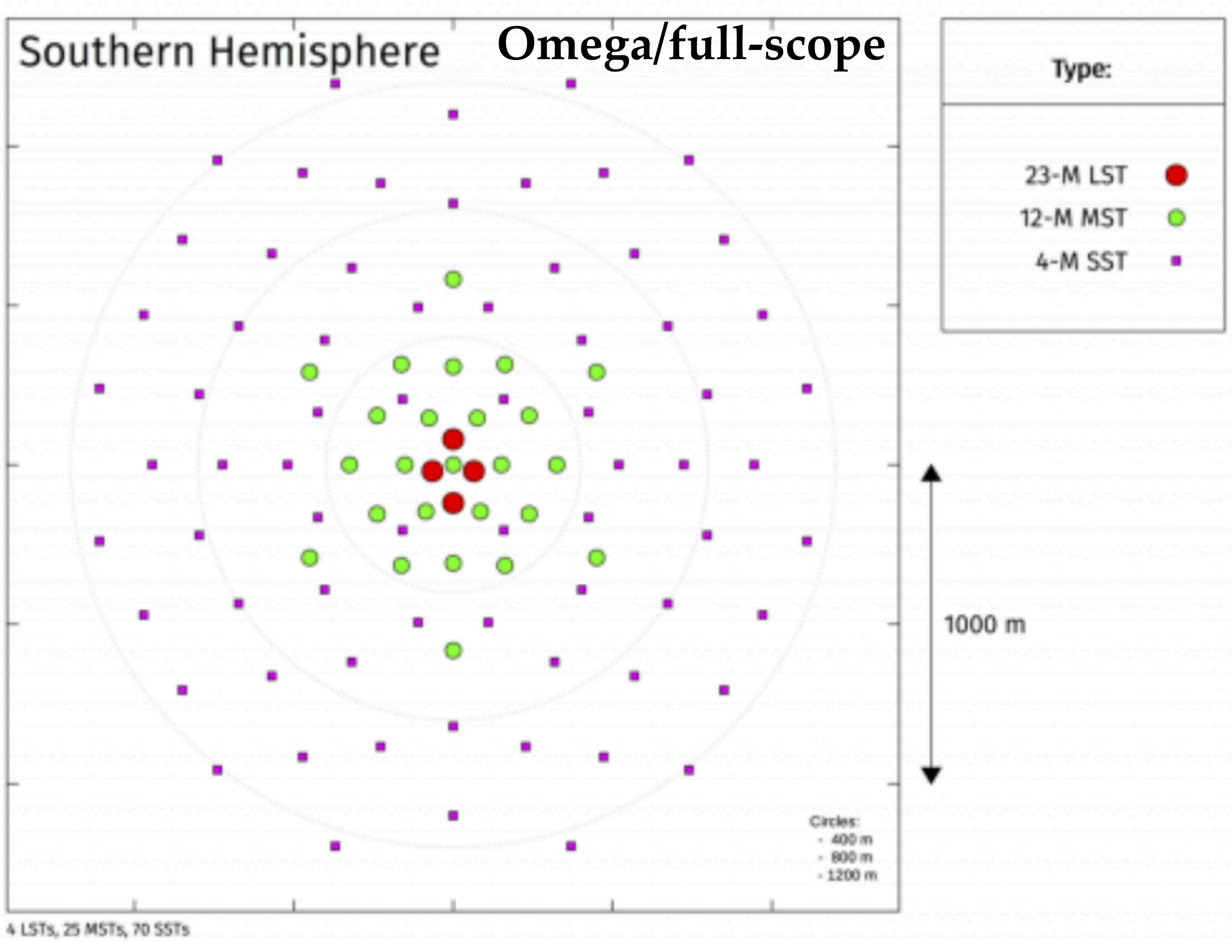
**Southern Hemisphere:** 4 LSTs, 25 MSTs, 70 SSTs (covered area: ~ 4 km²)

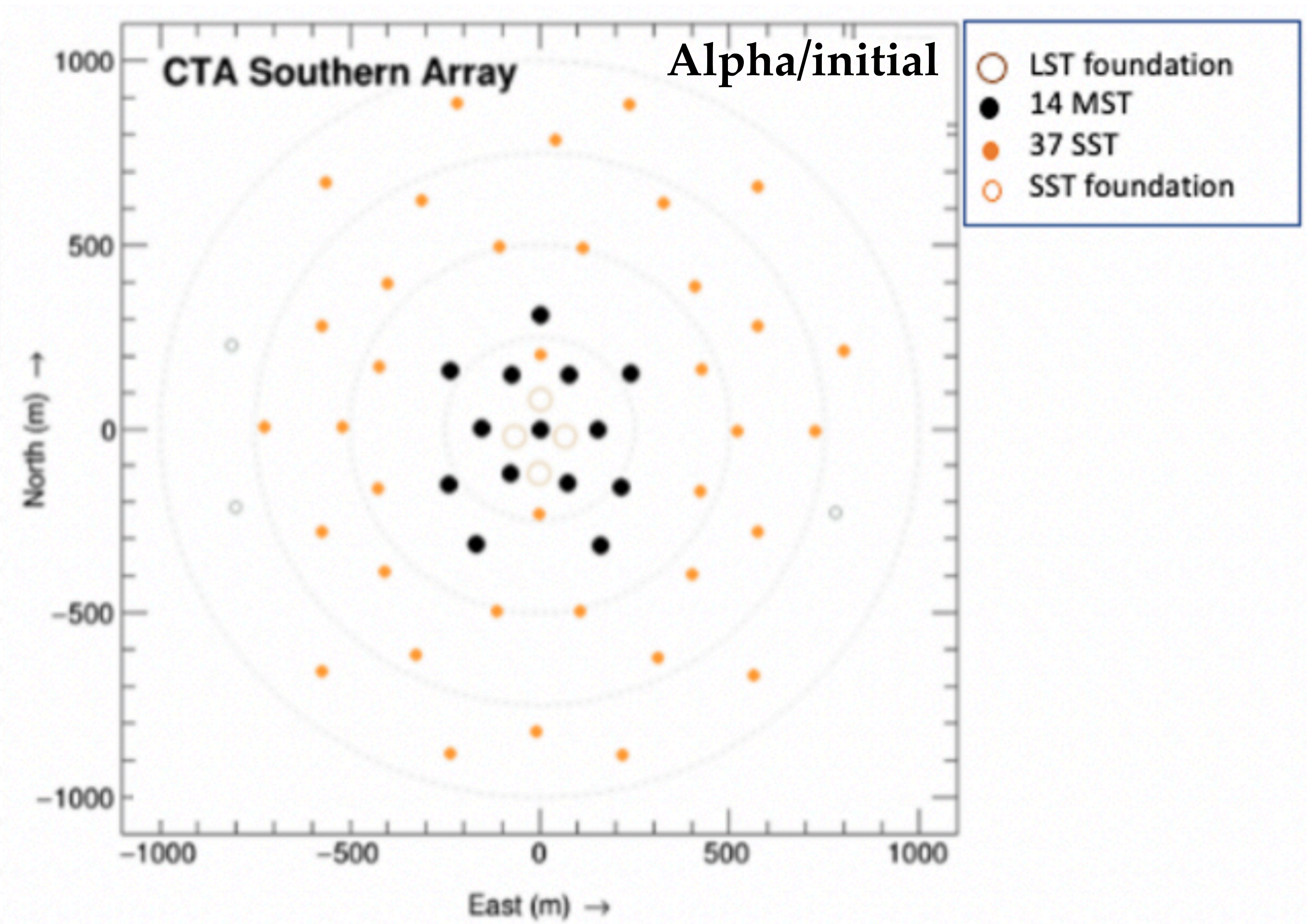
**Northern Hemisphere:** 4 LSTs, 15 MSTs (covered area: ~ 0.6 km²)

# ALPHA CONFIGURATION (64 telescopes)

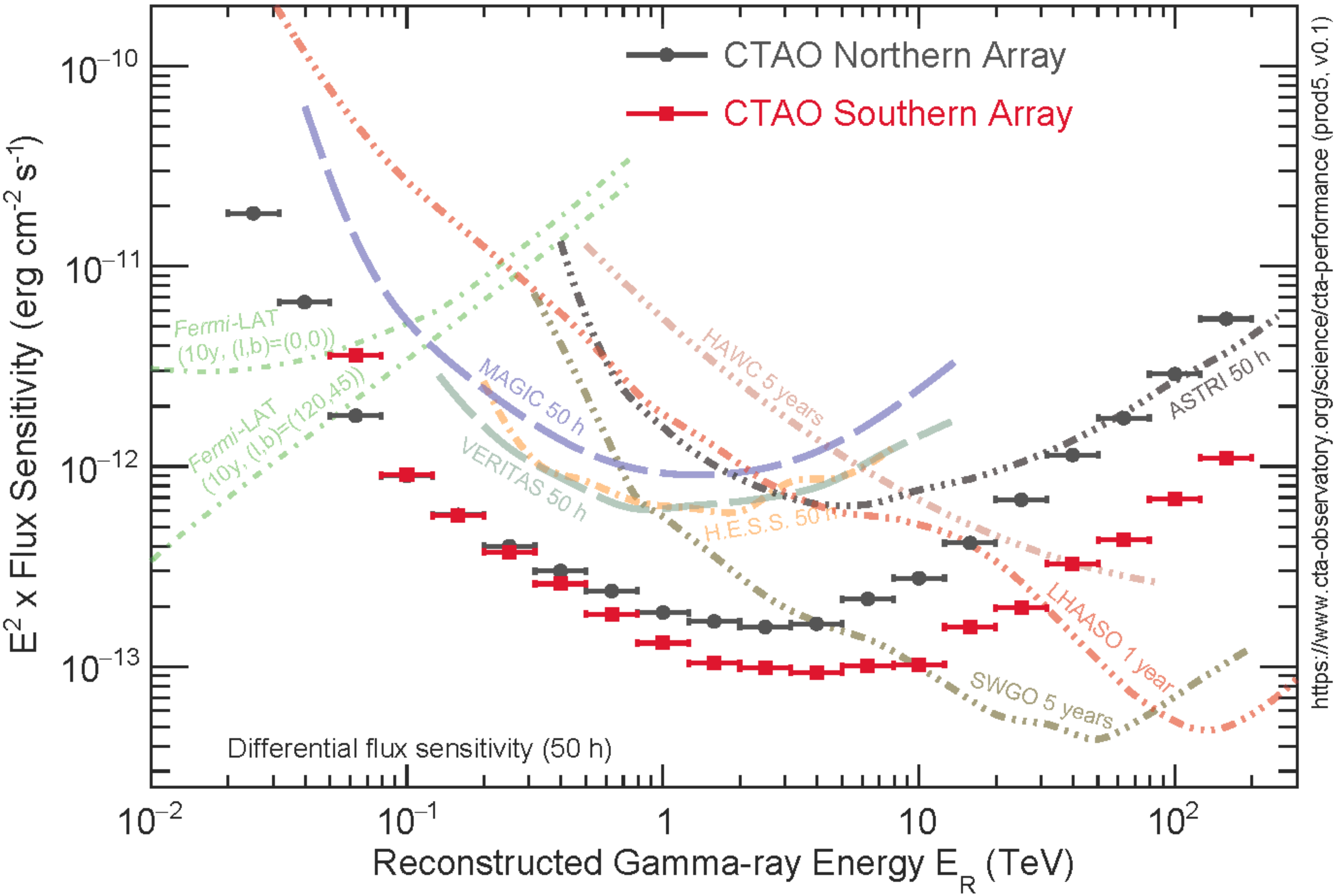
**Southern Hemisphere:** 14 MSTs, 37 SSTs (covered area: ~ 3 km²) (150 GeV - 300 TeV)

**Northern Hemisphere:** 4 LSTs, 9 MSTs (covered area: ~ 0.25 km²) (20 GeV - 5 TeV)

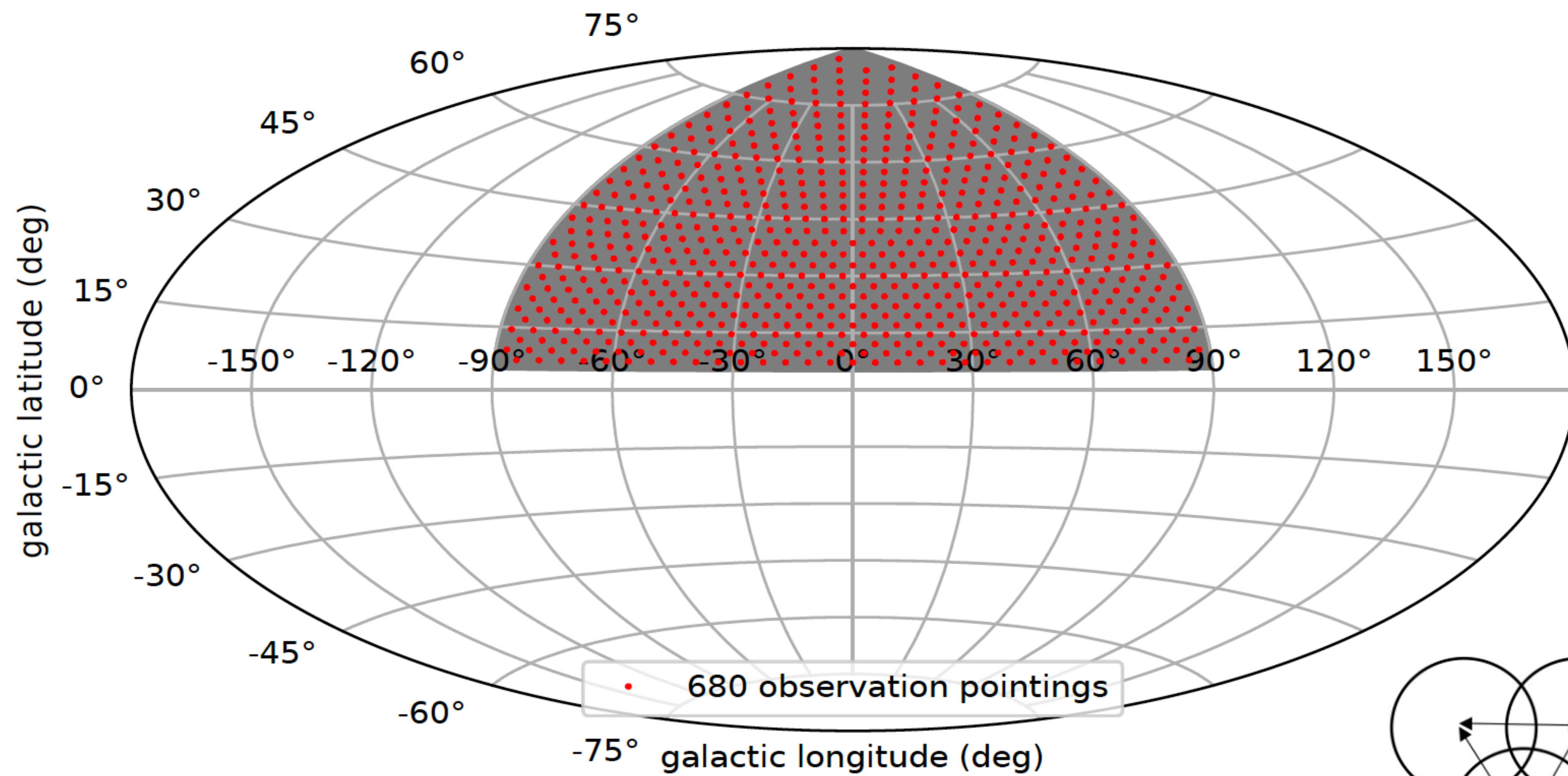


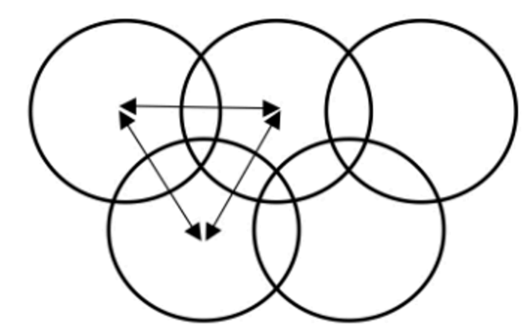



# Alpha configuration sensitivity



# EGAL survey observation strategy



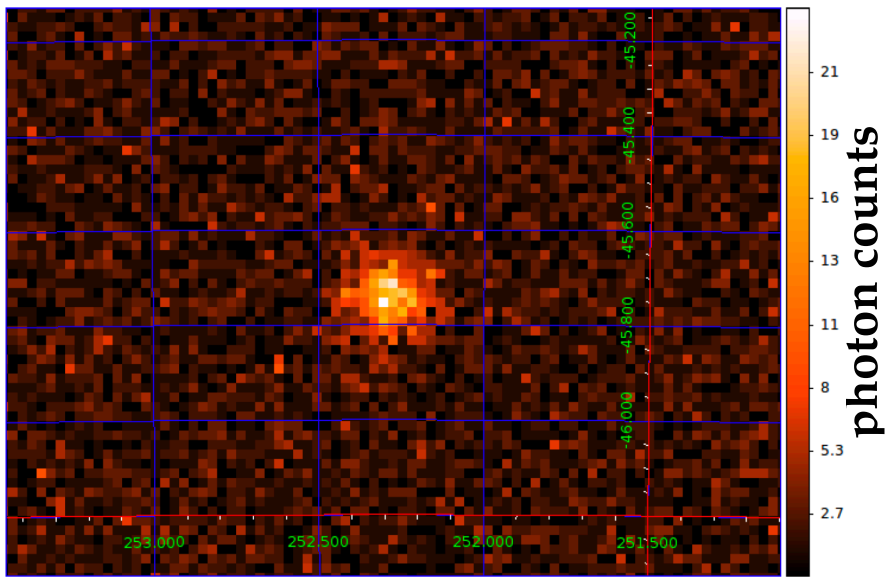
- One of the Key Science Projects (KSP)
- 25% of the sky (B>5deg -90<L<90)
- 1000 hours of observations (~400h [S] + ~600h [N])

**2.21 h / pointing [N]**

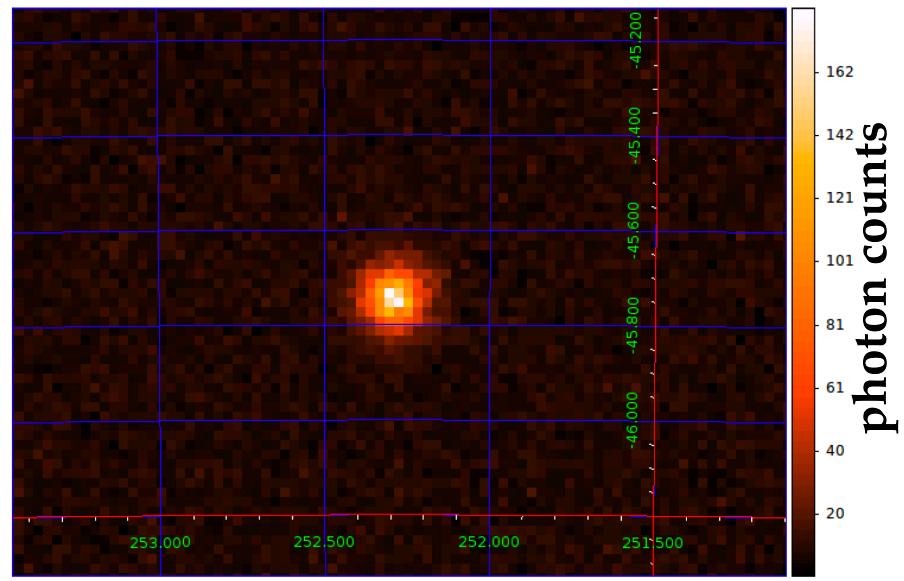
**0.98 h / pointing [S]**

## z=0.0982 | 421 Mpc | (RA, dec) = (252.29, -45.74)º | Γ=1.98

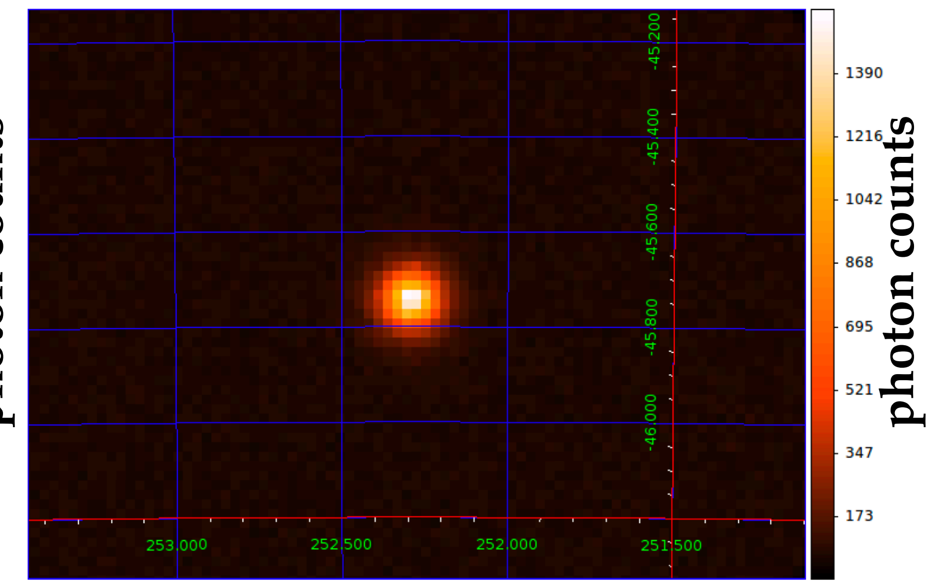
### 0.5 hour



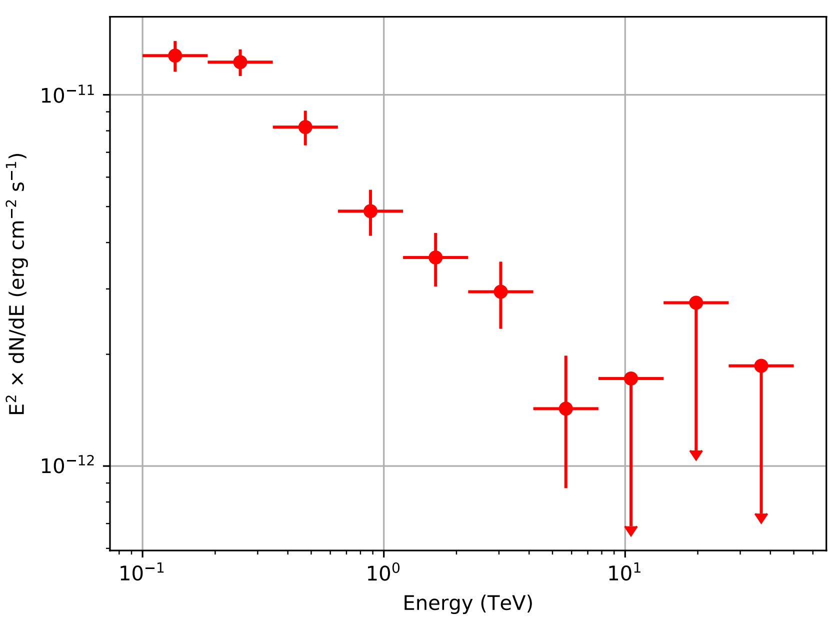

### 5 hours

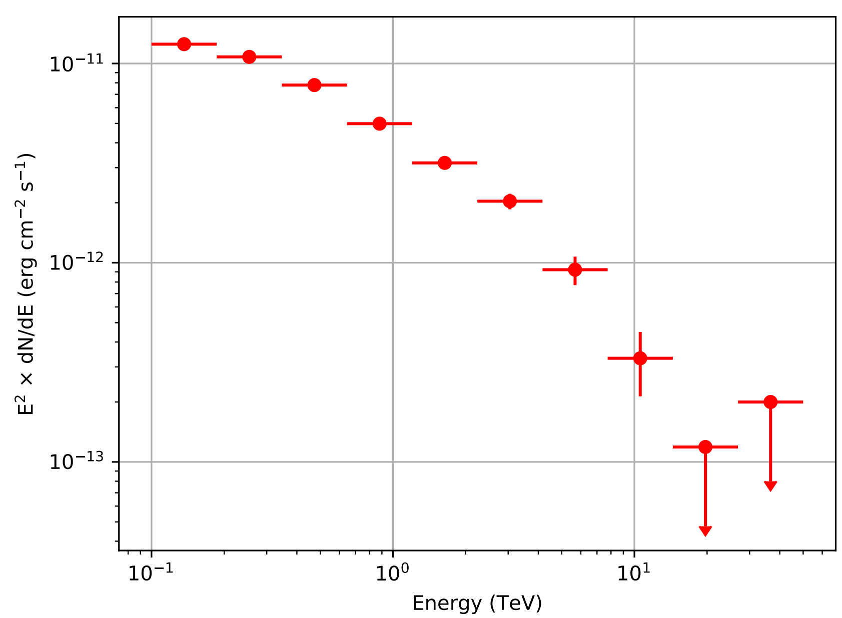


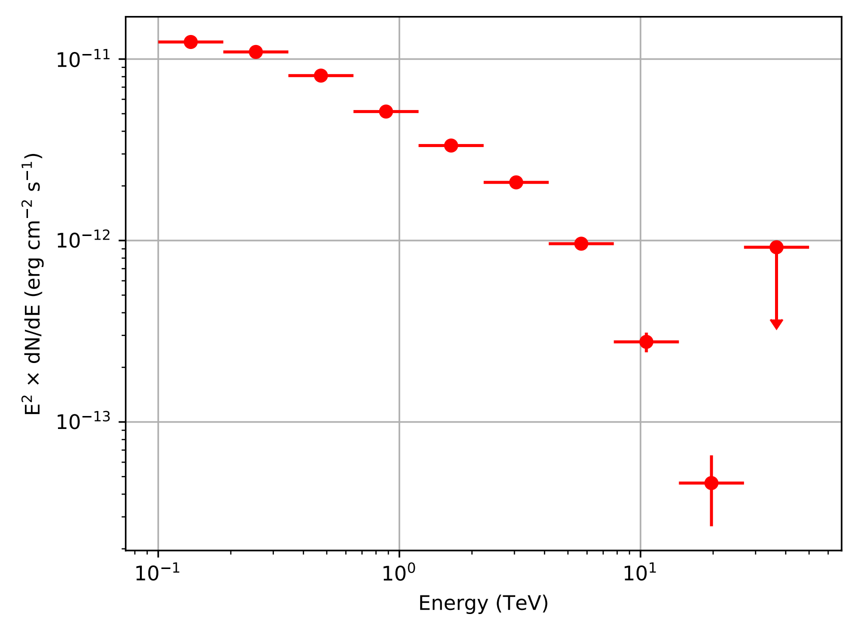

### 50 hours




## Omega configuration

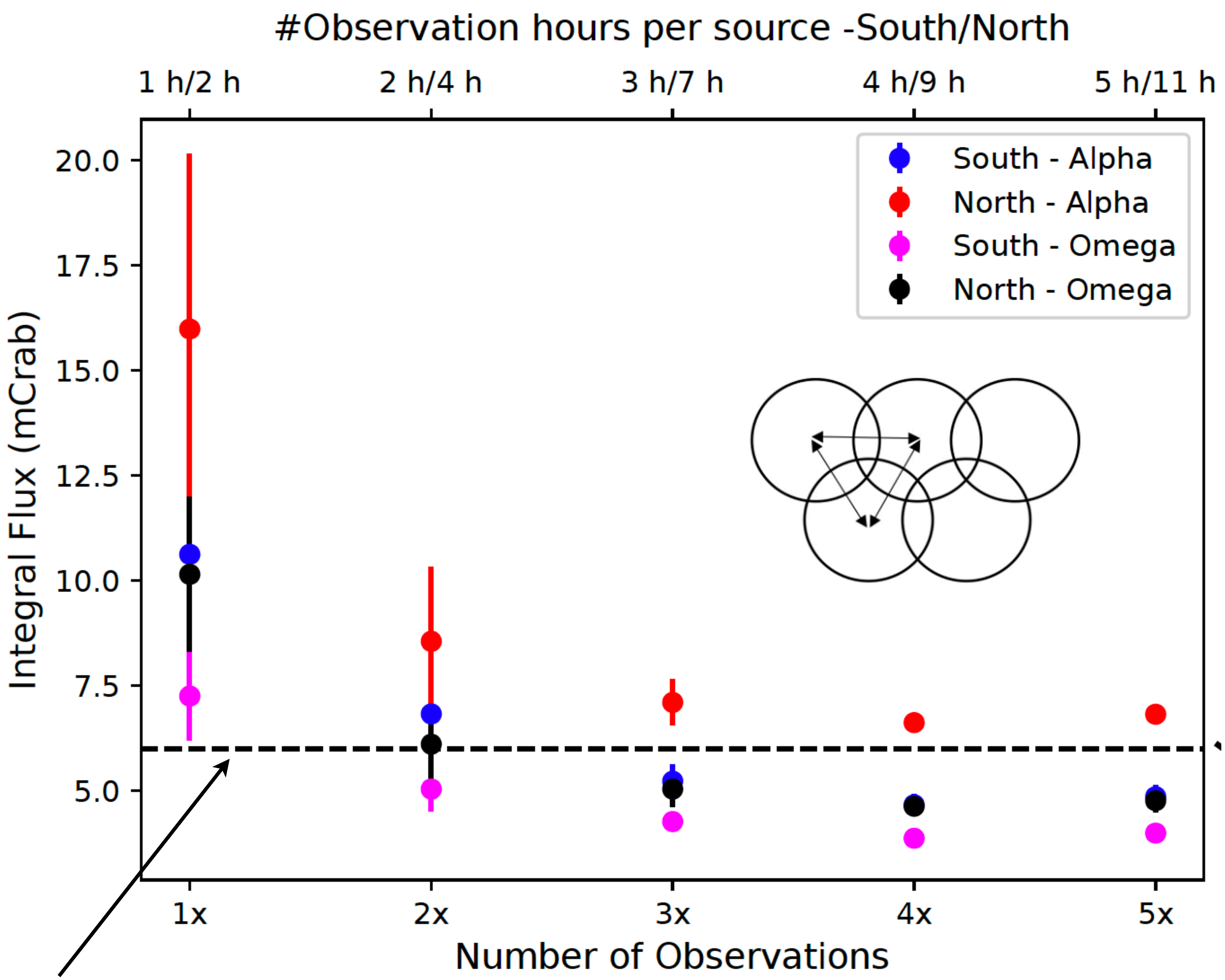



D.R.M. Pimentel, PhD thesis, USP, 2019.

# EGAL survey sensitivity (alpha)




**Target sensitivity**

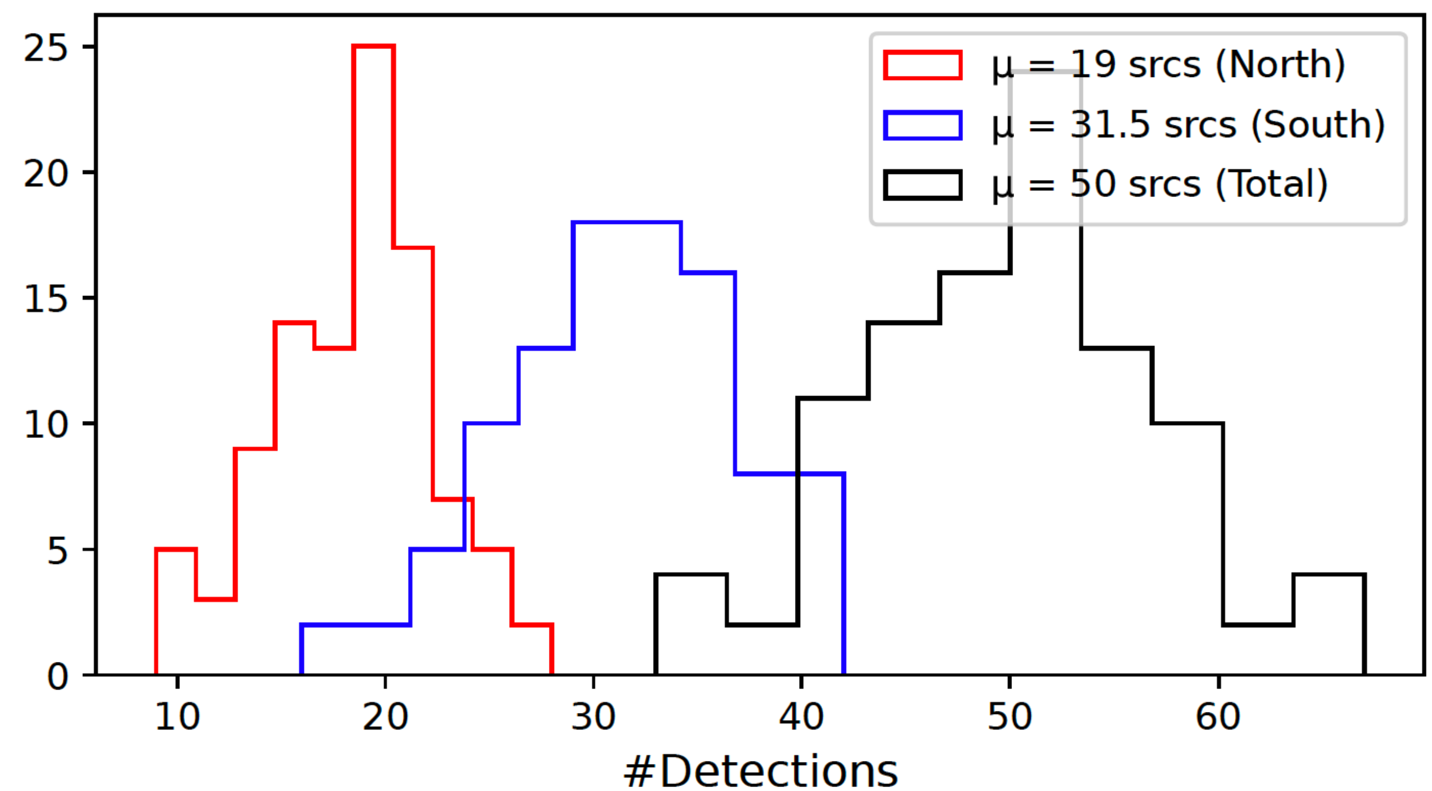


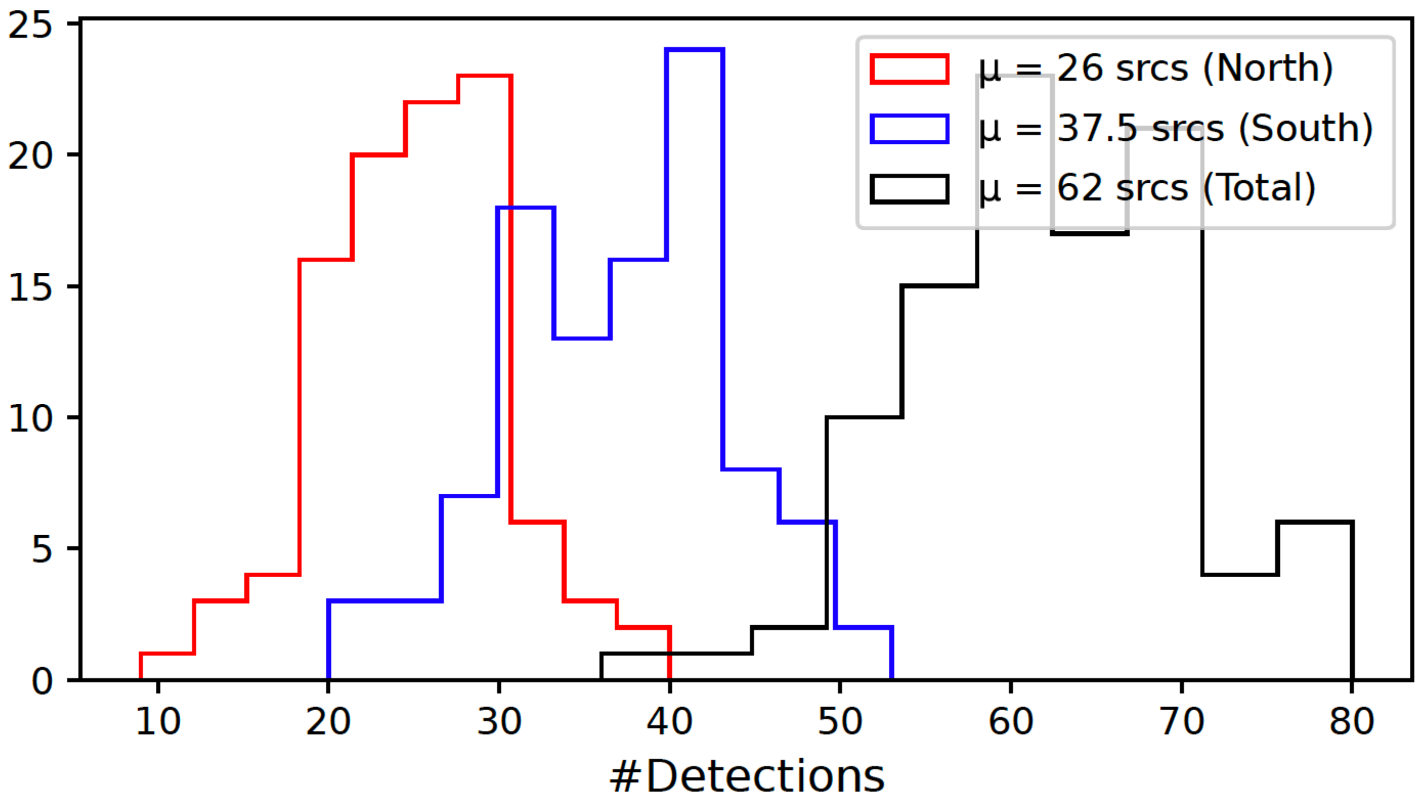
**Credit: Luiz Augusto Stuani**

# Expected number of new detections

**PRELIMINARY**

**ALPHA**




**OMEGA**



**Credit: Luiz Augusto Stuani**

# Summary

- Absorption effects are important tools for cosmological studies, showing sensitivity to IMF, SFR, IGMF, dust, etc.
- Results from IACTs in the last 20 years already indicated that our universe is more transparent than what we initially thought.
- CTA's peak sensitivity around 1 TeV will allow us to probe the EBL brightness at mid-IR, i.e., its dust-generated component.
- A resolution of ~5% ($z<0.4$) or 10-15% ($0.4<z<1.85$) on the EBL overall normalization can be expected to be achieved with CTA in the near future.
- CTA has AR and sensitivity to probe IGMFs in the range [$10^{-15}$ G, - $10^{-12}$ G] through the search of halos around blazars.
- The extragalactic survey is the ideal tool to assess the shape of the blazar LF.

# Obrigado!