Prospects for AGN populations studies with the CTA

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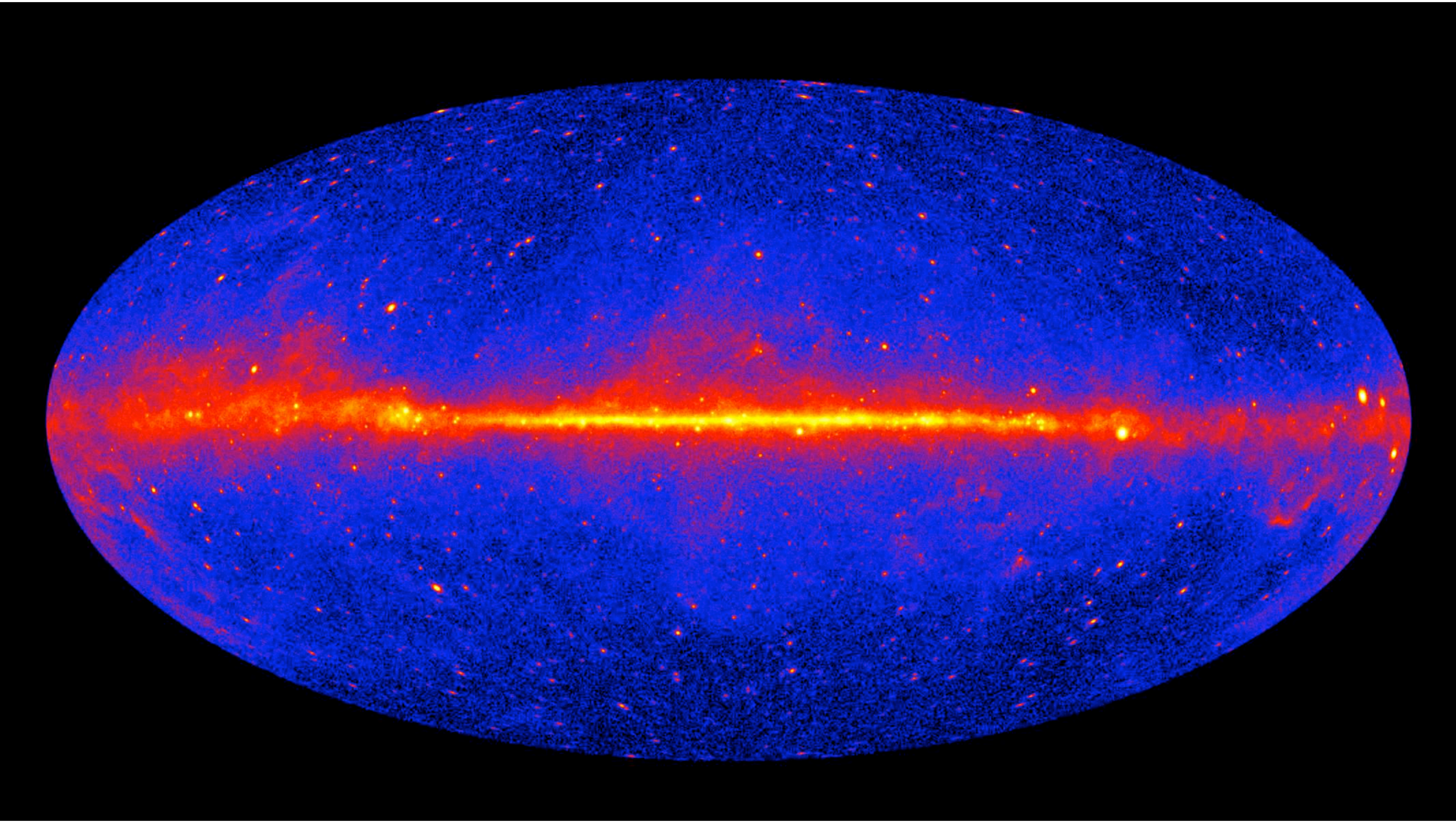
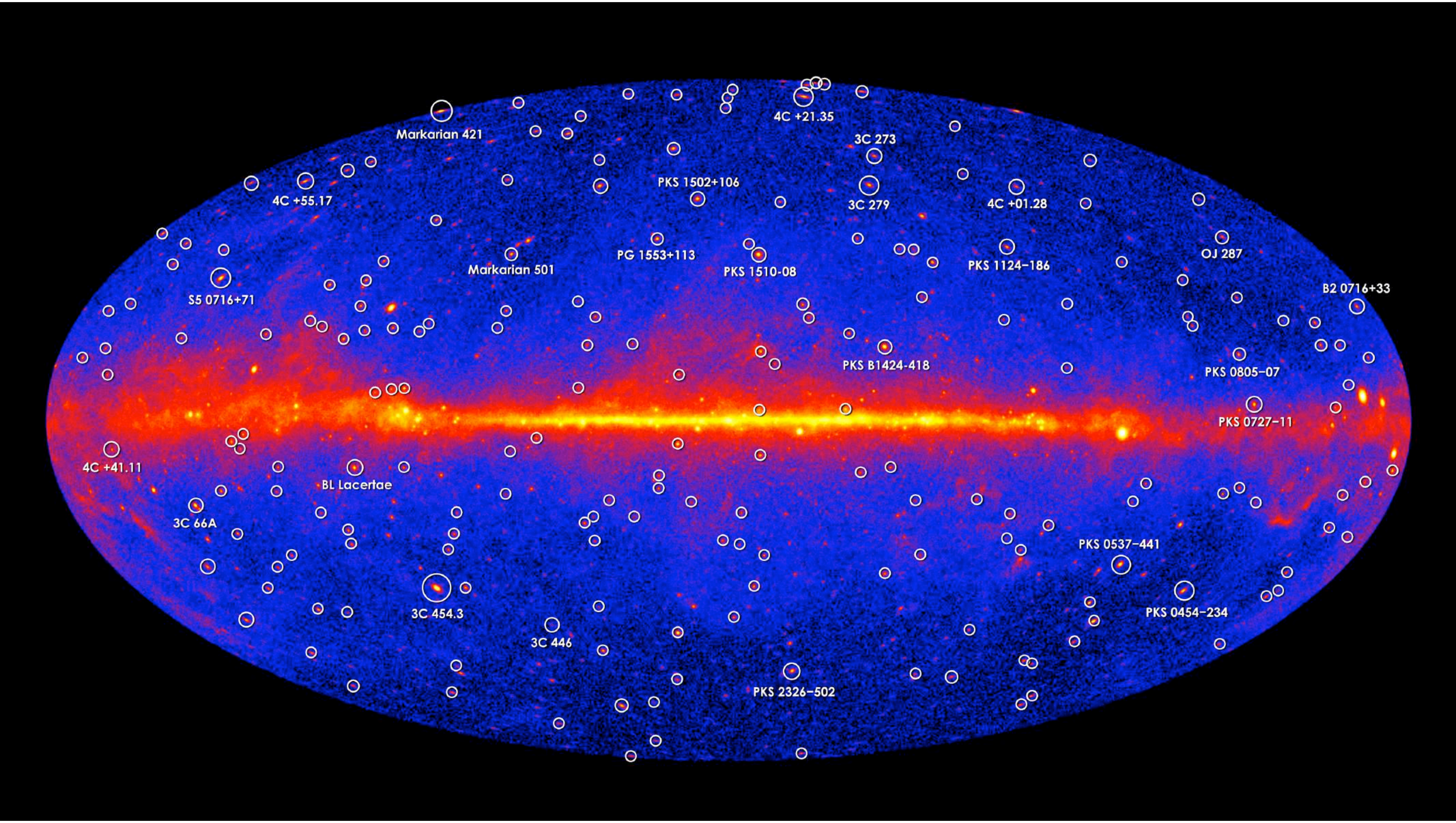
The gamma-ray sky

Fermi-LAT all sky map

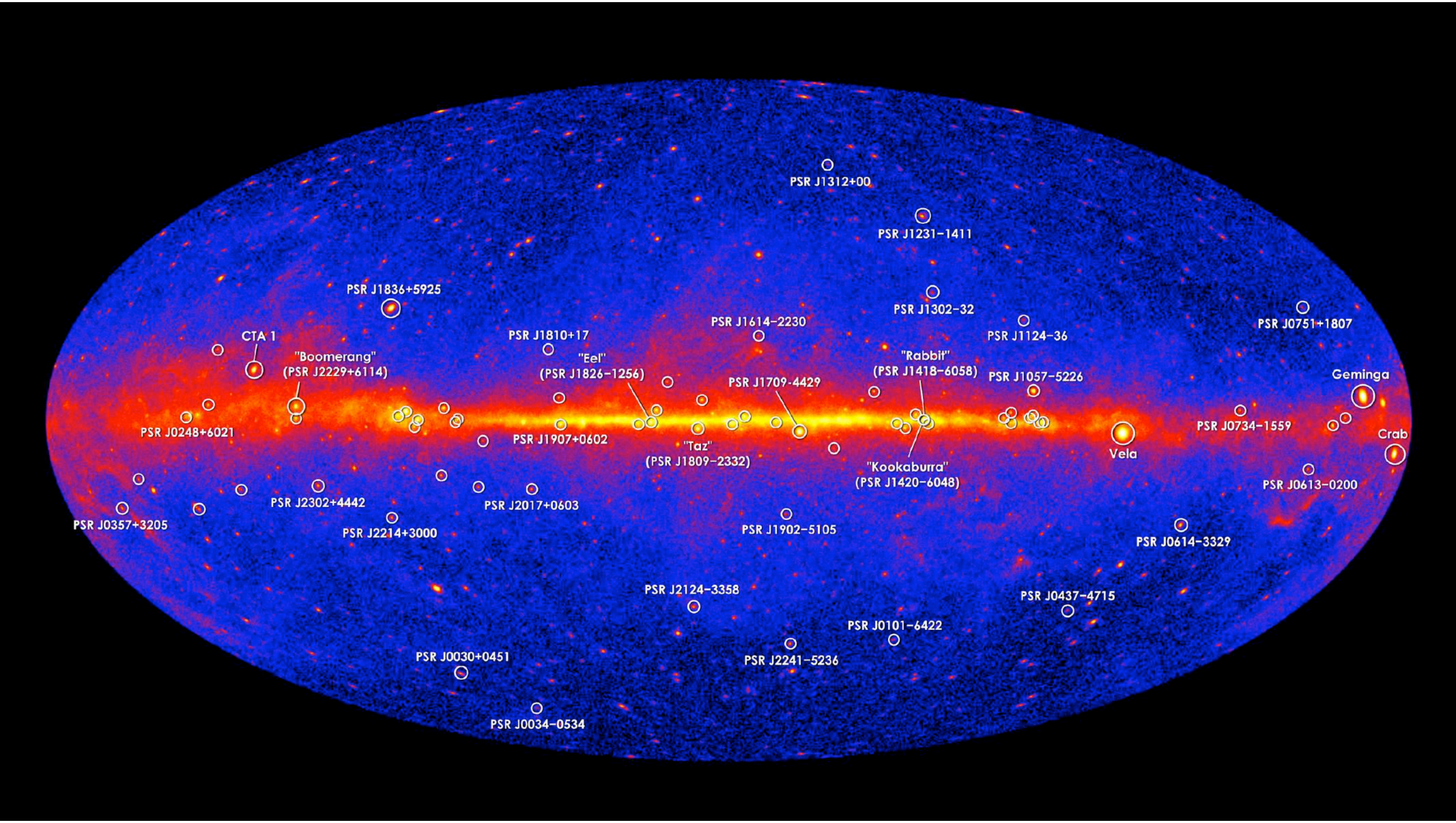


Blazars

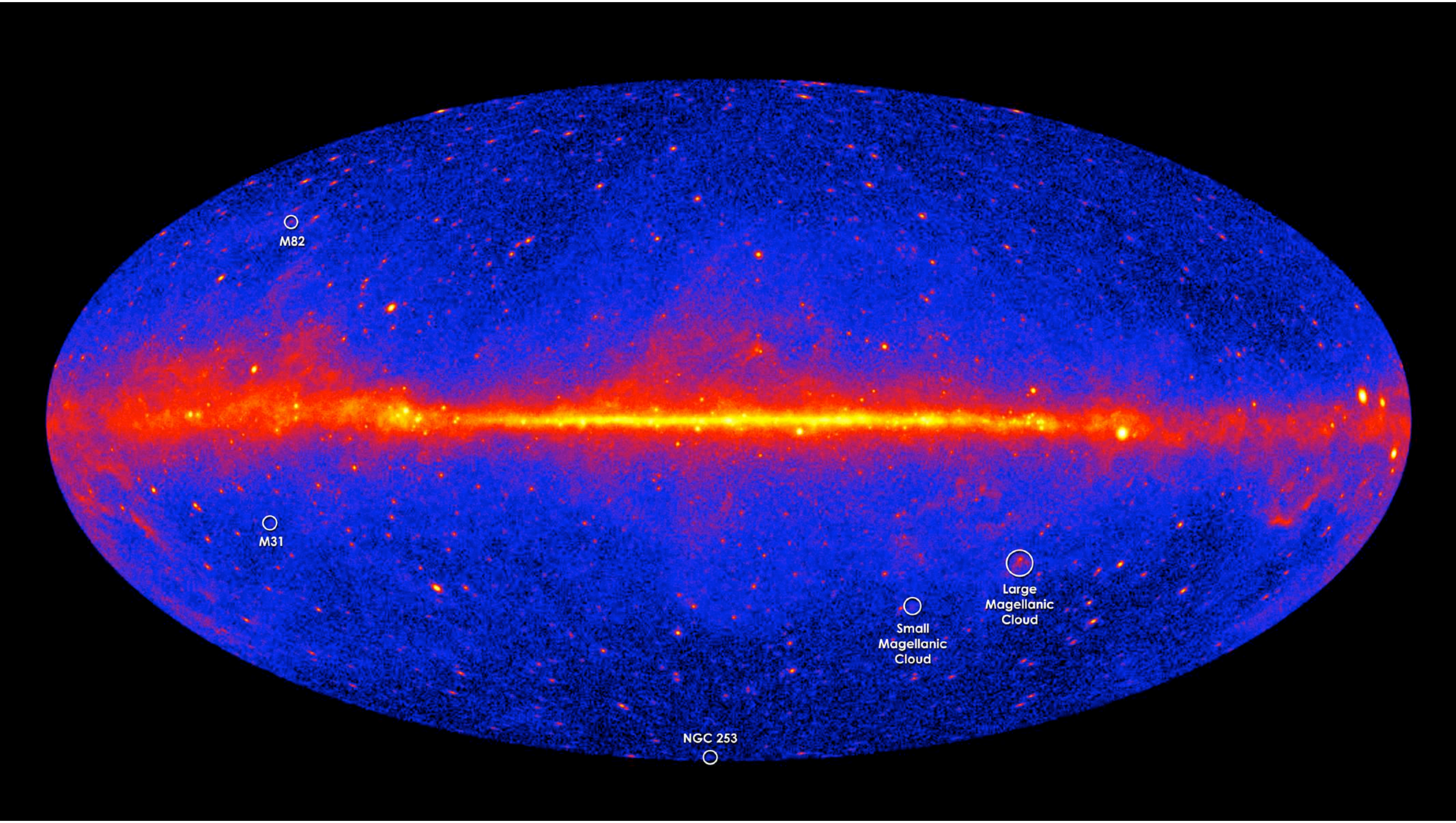


Markarian 421
4C +21.35
3C 273
4C +55.17
PKS 1502+106
3C 279
4C +01.28
Markarian 501
PG 1553+113
PKS 1510-08
PKS 1124-186
OJ 287
S5 0716+71
B2 0716+33
PKS B1424-418
PKS 0805-07
PKS 0727-11
4C +41.11
BL Lacertae
3C 66A
PKS 0537-441
3C 454.3
PKS 0454-234
3C 446
PKS 2326-502

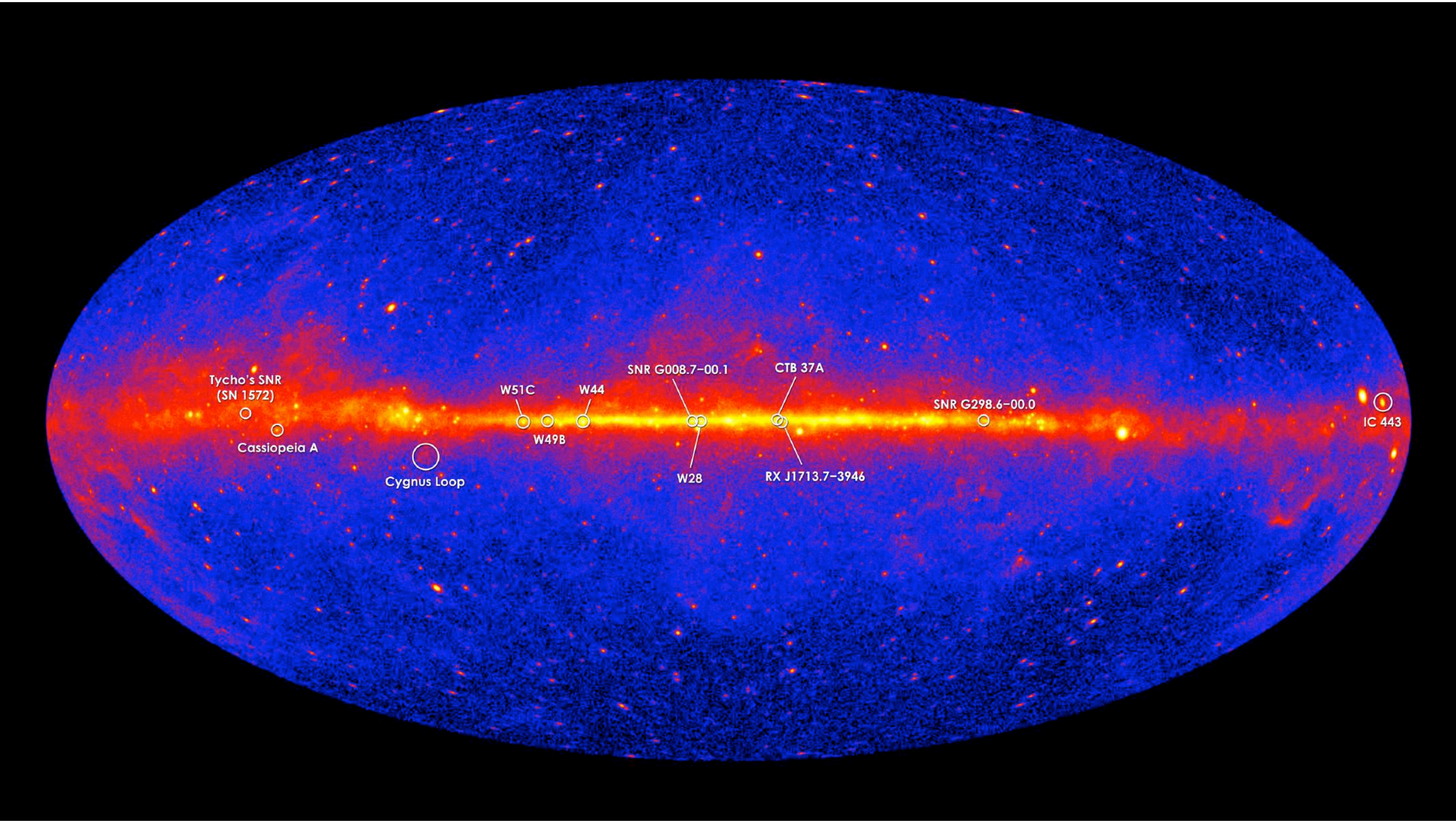
Pulsars


PSR J1312+00
PSR J1231−1411
PSR J1836+5925
PSR J1302−32
PSR J1614−2230
PSR J0751+1807
PSR J1124−36
CTA 1
PSR J1810+17
"Boomerang"
(PSR J2229+6114)
"Eel"
(PSR J1826−1256)
"Rabbit"
(PSR J1418−6058)
PSR J1057−5226
Geminga
PSR J1709-4429
PSR J0734−1559
PSR J0248+6021
PSR J1907+0602
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



Active Galactic Nuclei x Normal Galaxies

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.

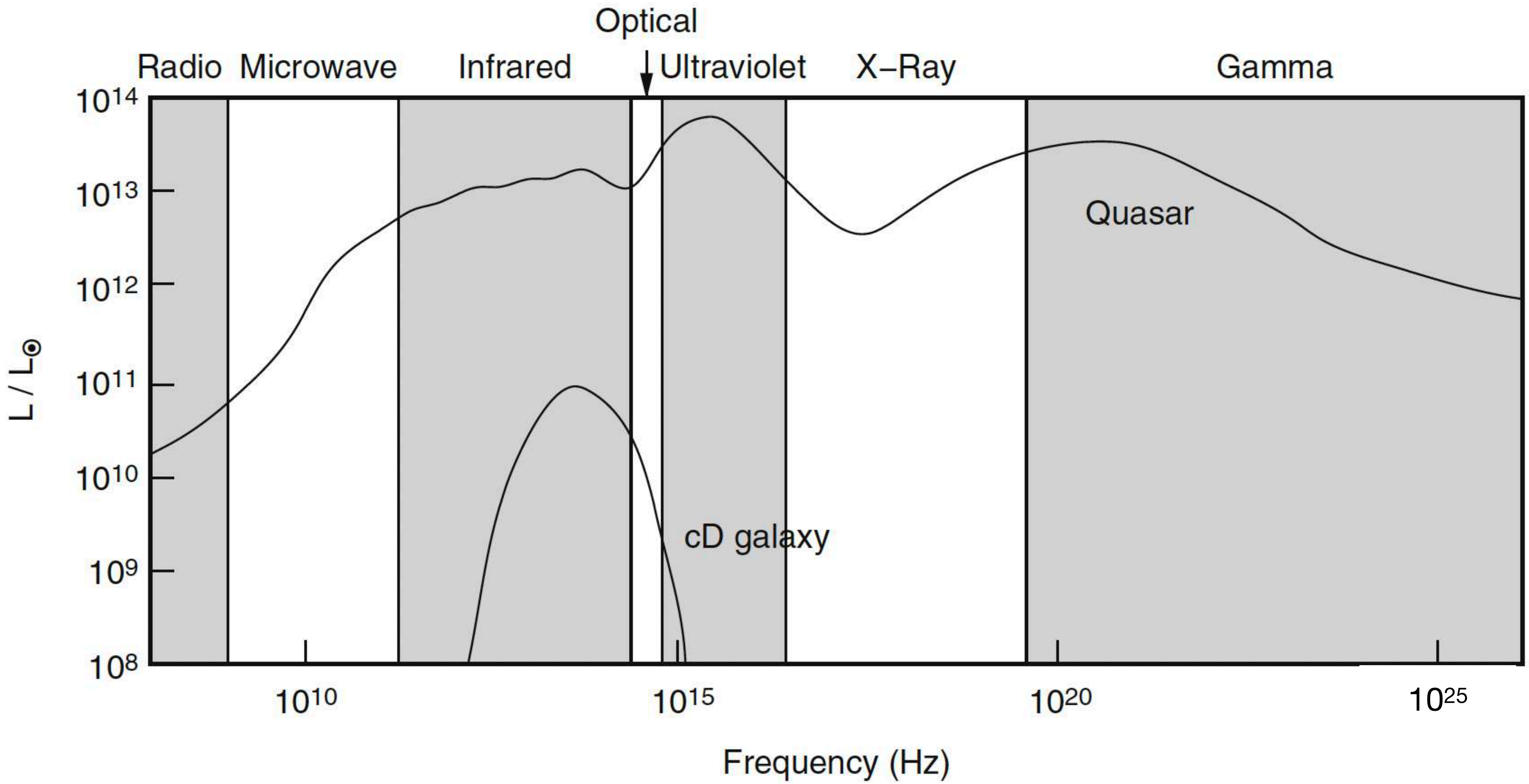
$$\Phi_{gal} \simeq \sum_i \Phi_{star}(T_i)$$

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 ($h\nu \sim 3k_B T$), 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 γ-rays.



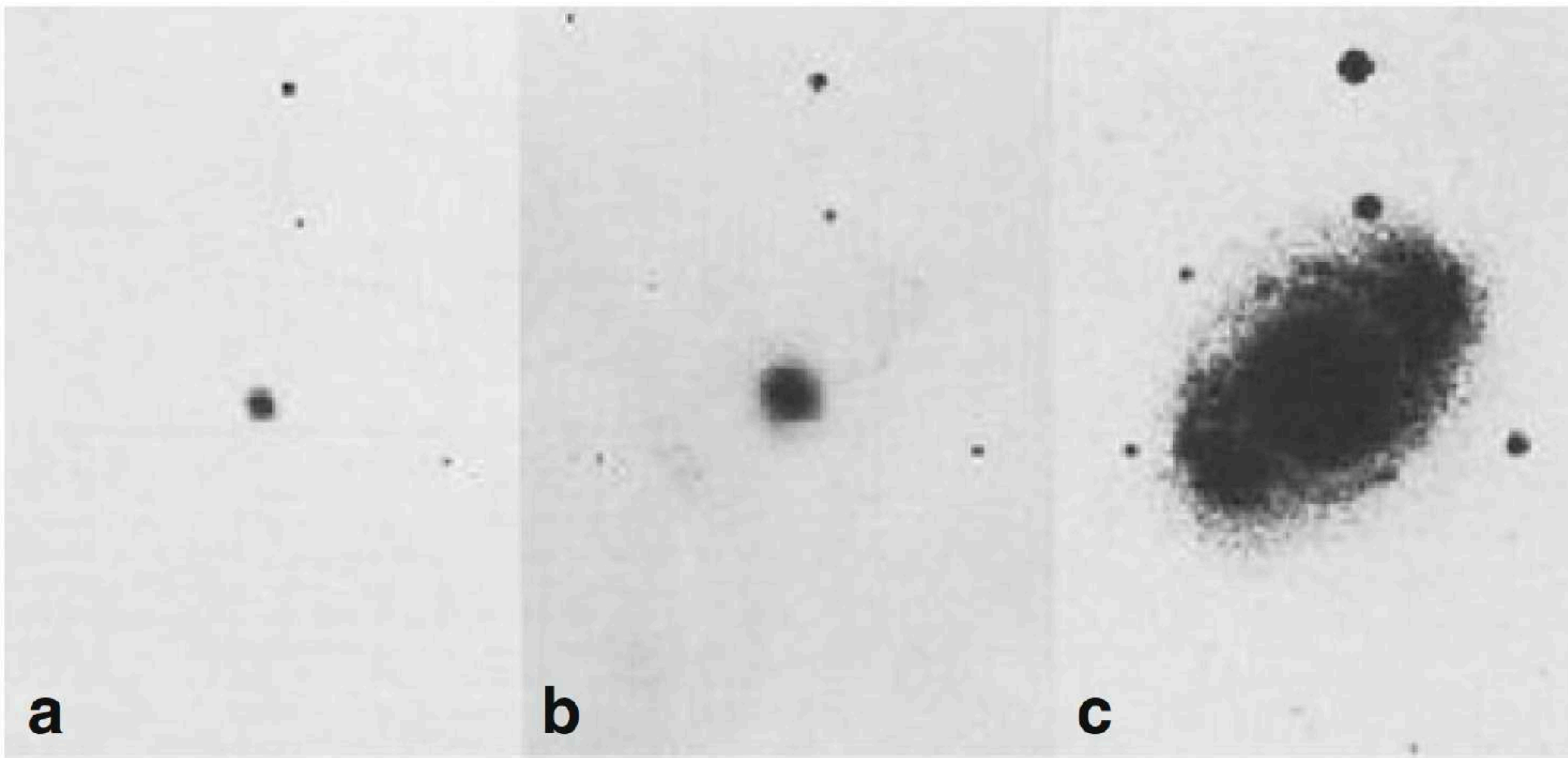
- Their luminosity is much higher than normal galaxies: $L_{AGN} \gtrsim 10^3 L_{gal}$
- From the shape of the spectrum, we can see that the emission process is mostly non-thermal.

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)

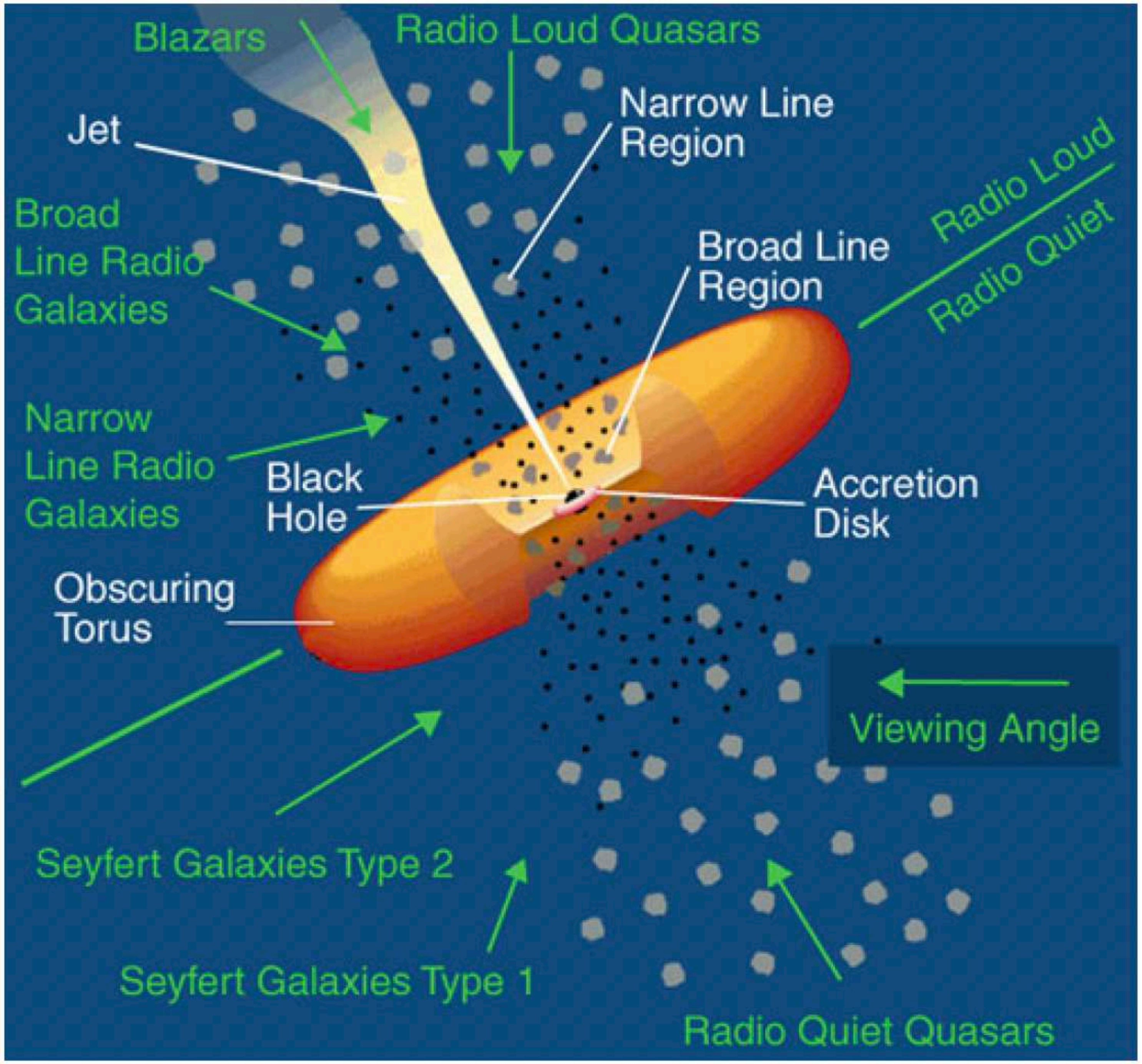
Summarized properties

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}
$M_{BH}/M_{\odot}$	4×10^6	3×10^9	10^6–10^9	10^6–10^9	10^6–10^9
Radio emission	Weak	Core, jets, lobes	Only $\approx$5 % radio-loud	Only $\approx$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

AGN unified model



See Walter Max-Moerbeck's lecture on SMBH physics tomorrow

NASA

AGN unified model

- Surrounding the central supermassive black hole is an accretion disk which emits the bulk part of the optical and UV continuum emission.

- Gas clouds above and below the accretion disk are responsible for the broad emission lines.

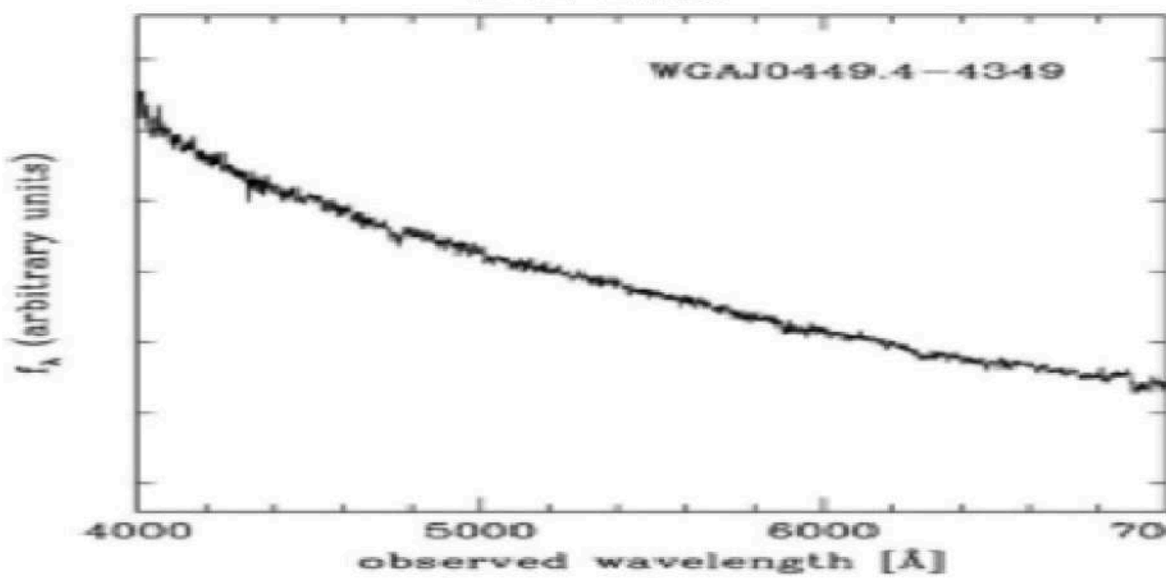
- In the plane of the disk, a distribution of gas and dust is present, which can absorb radiation from the inner region of the AGN; this obscuring material is sometimes depicted as a torus, though its geometry is probably more complicated.

- In contrast, the gas responsible for the narrow emission lines is located at much larger distances from the black hole, so that it cannot be fully hidden by the obscuring torus

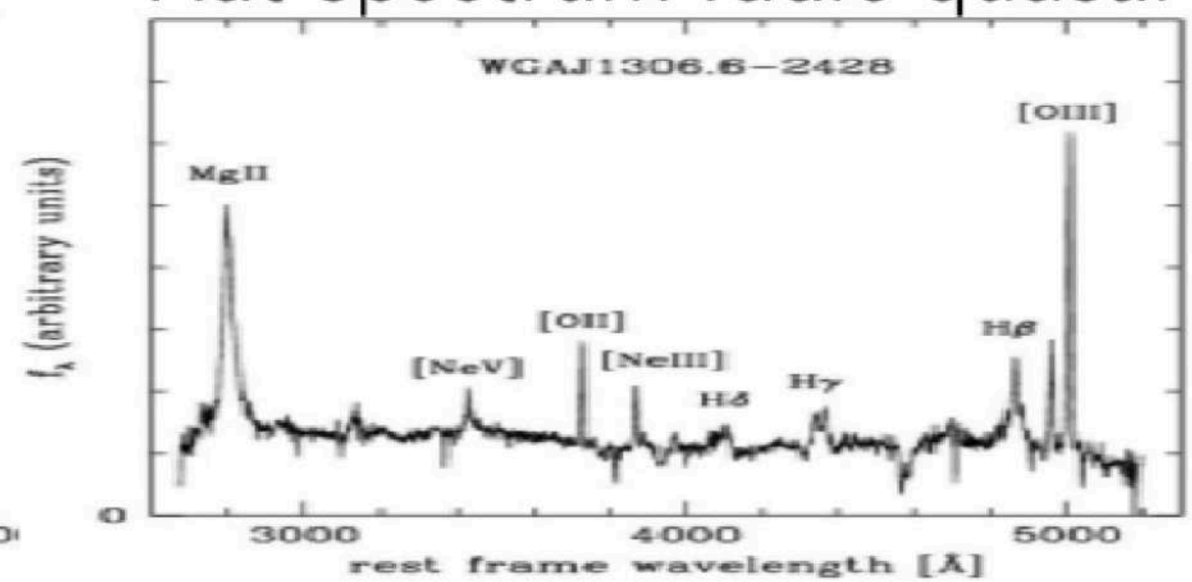
- The emission from the jets is highly anisotropic, because the velocity in the inner part of the jets is close to the speed of light; then, according to the theory of Special Relativity, the jet emission is strongly beamed in the direction of jet motion. This implies that the appearance of the jet depends on how close the line-of-sight to an observer is to the jet axis. If the jet points almost directly at the observer, the jet emission can outshine all the other radiation from the AGN.

BL Lac and FSRQ in the optical

BL Lac

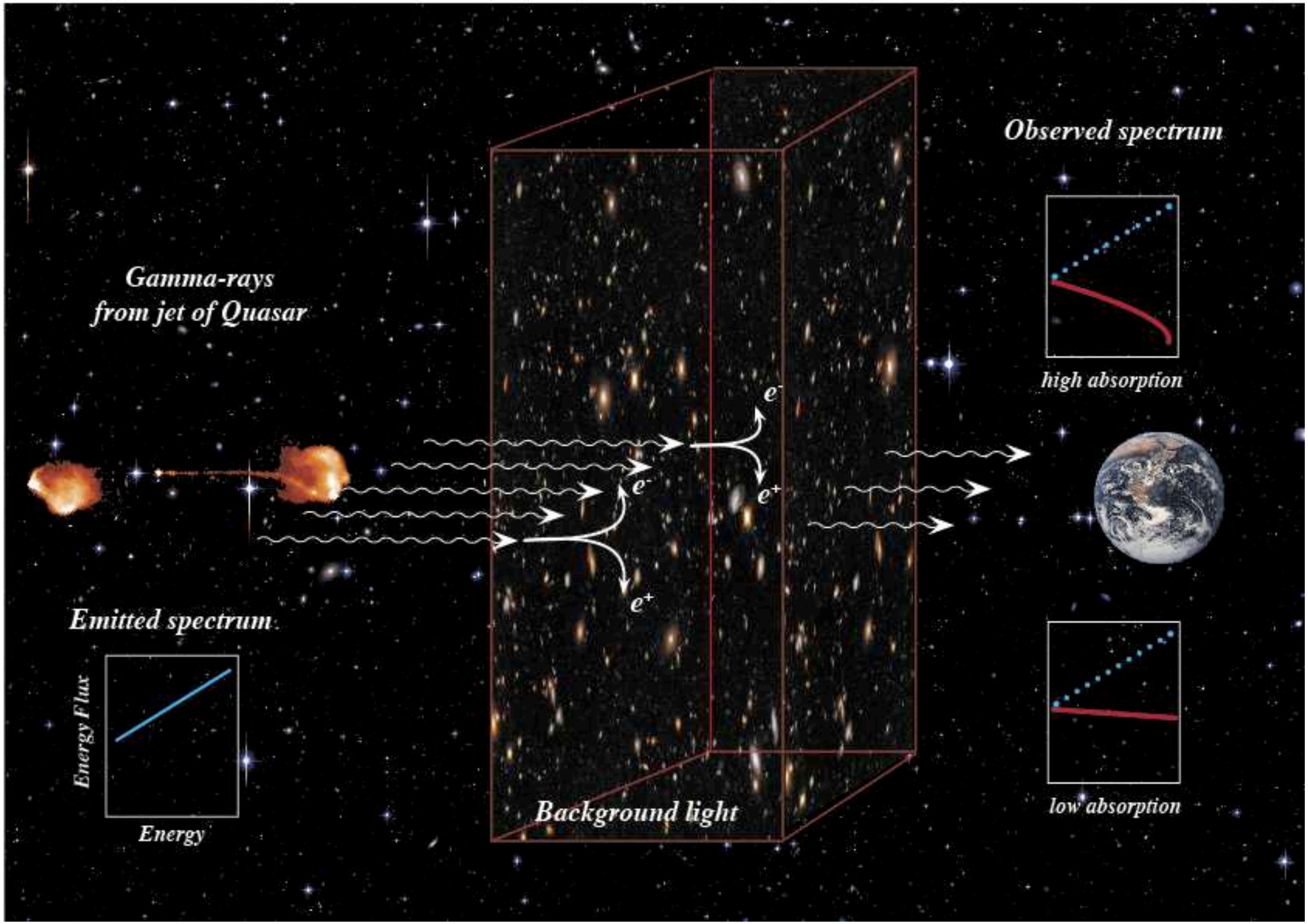


Flat spectrum radio quasar



How to properly assess blazar intrinsic properties in the presence of absorption in the extragalactic medium?

Universe’s opacity to VHE photons

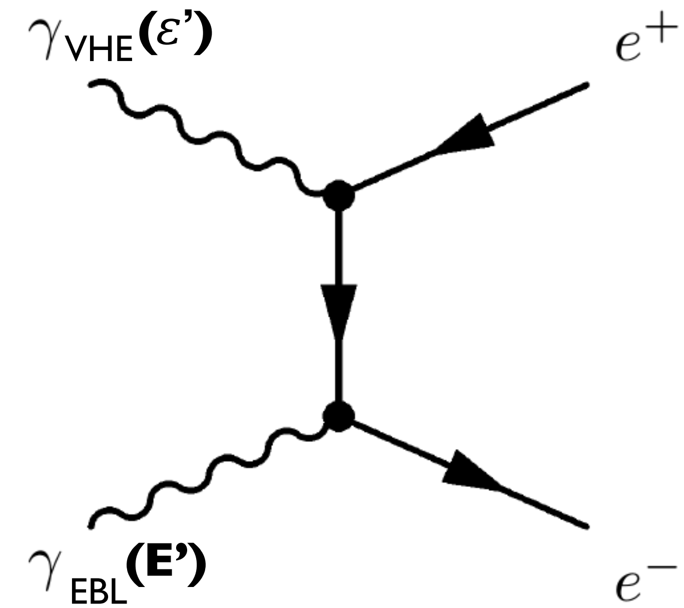


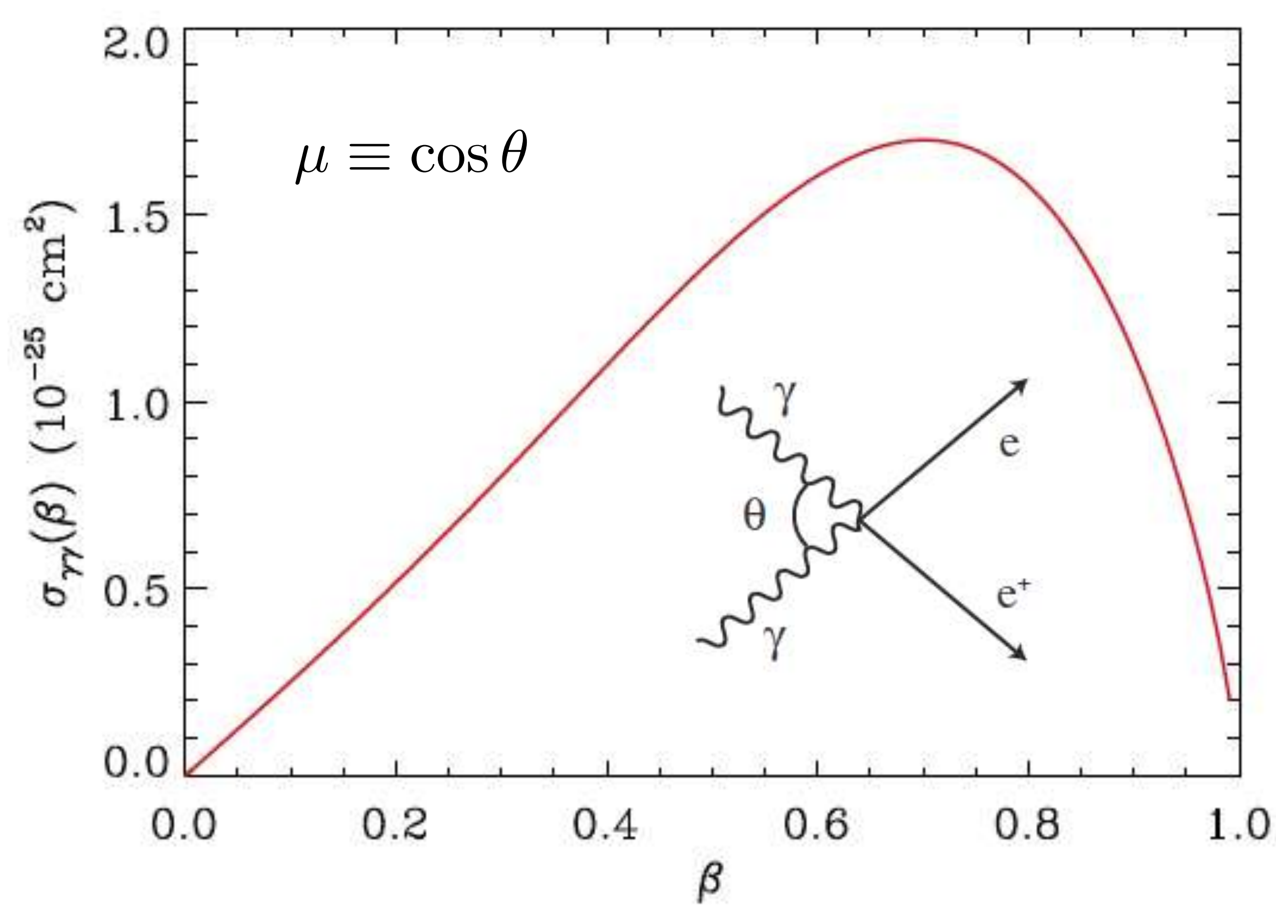
Cross-section for gamma-gamma scattering

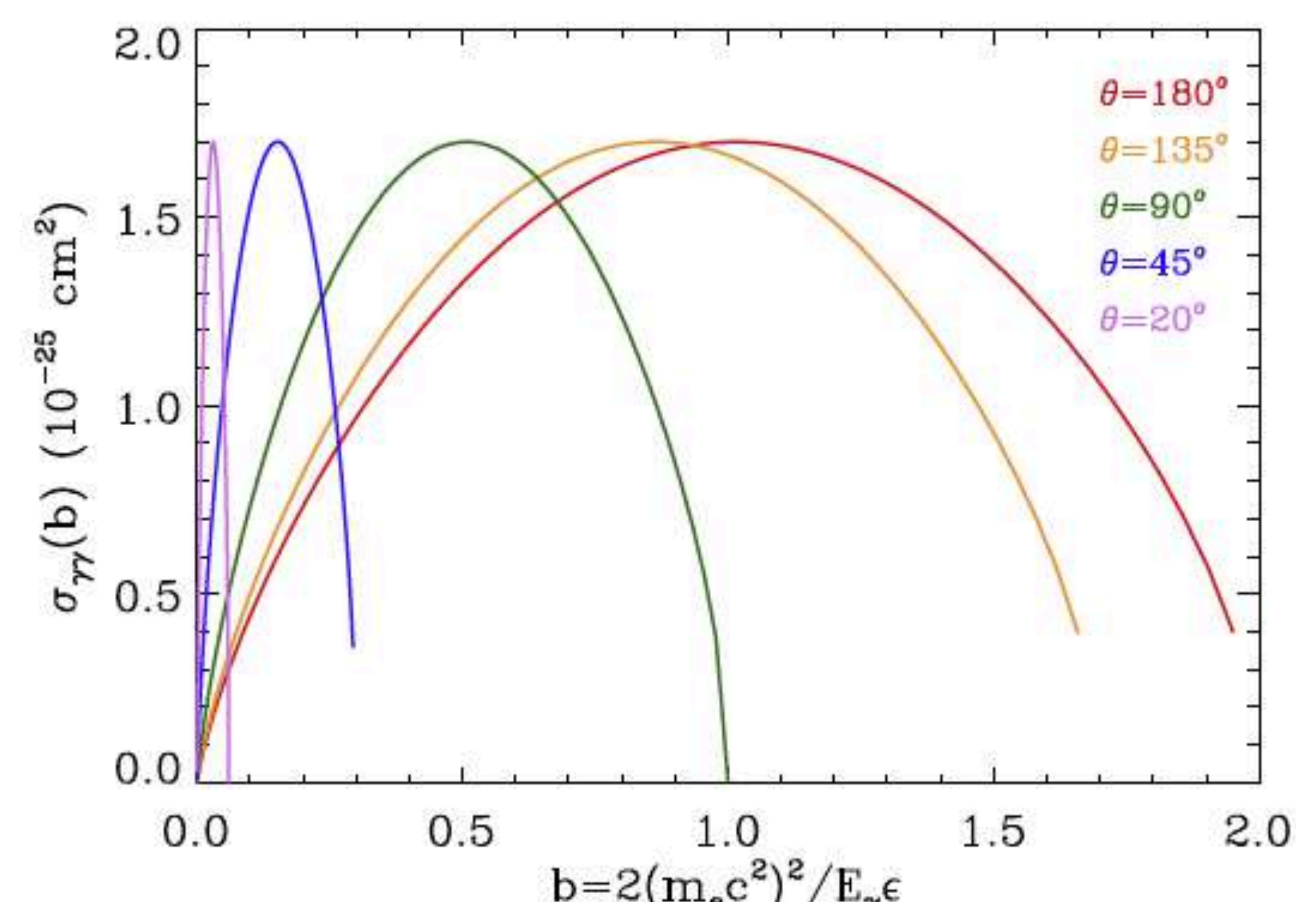
Well understood QED process:

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

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

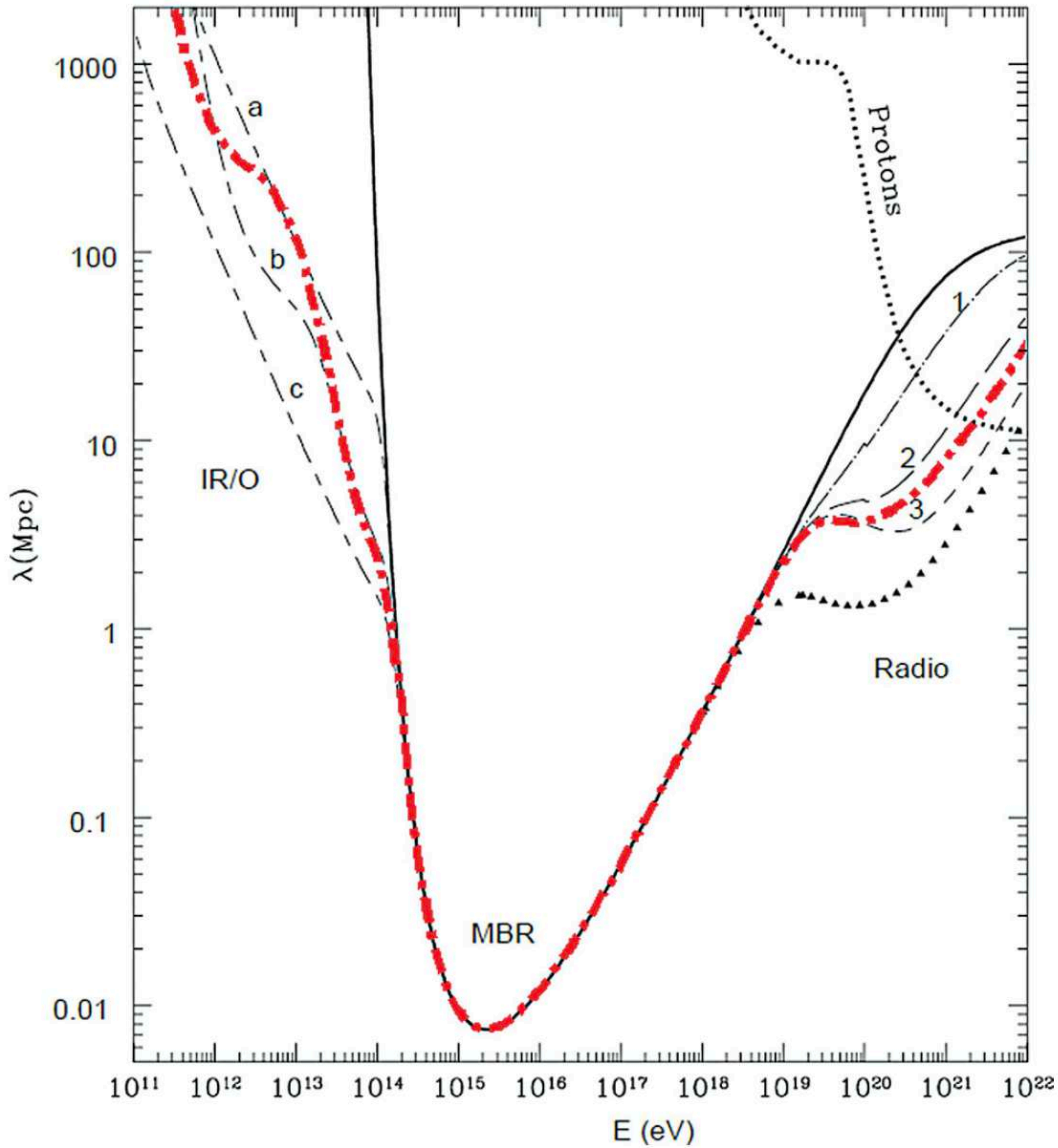






Astrop. Phys. 43 112 (2013)

VHE photon mean free path

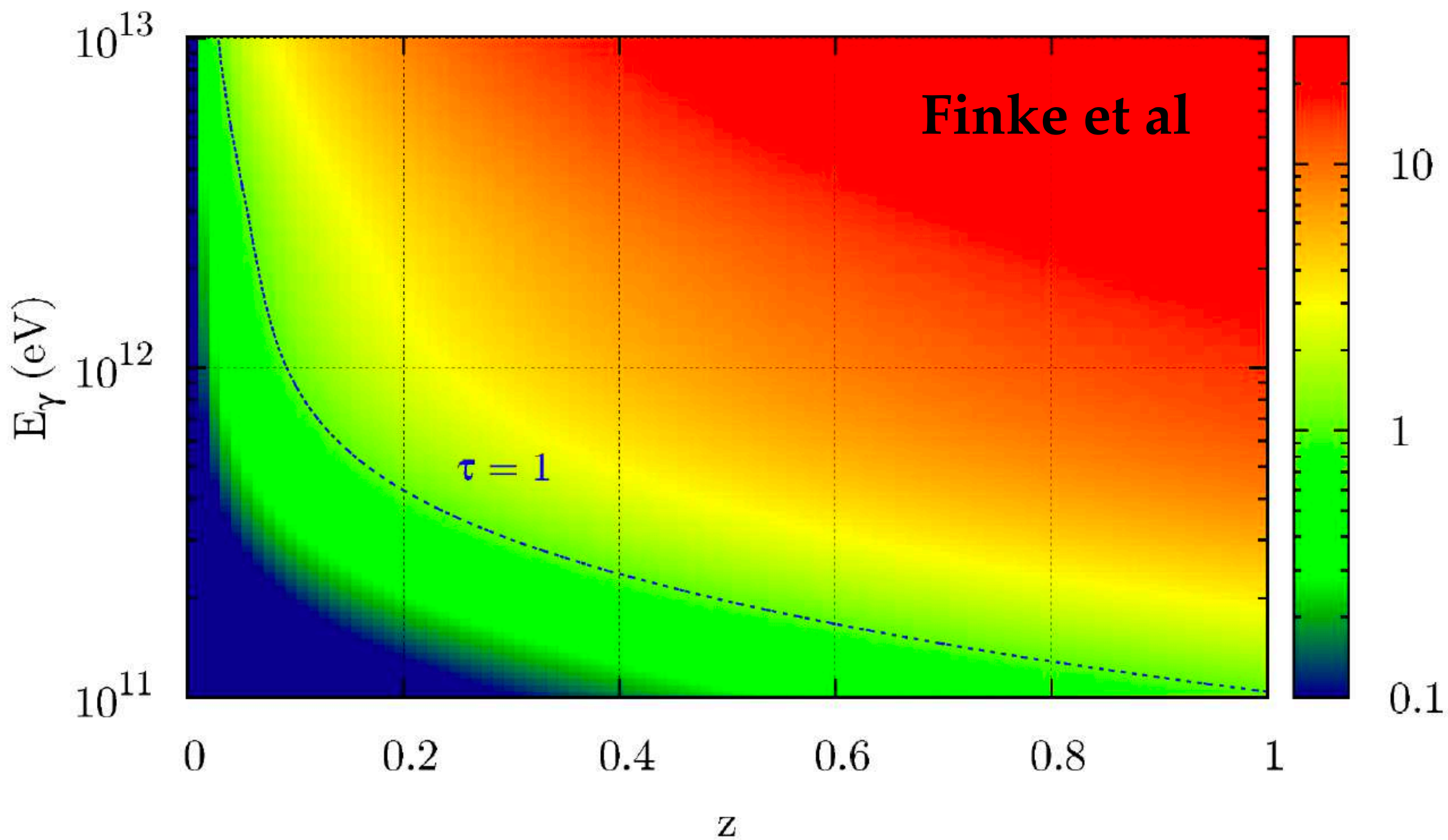


$$\lambda = \frac{1}{\int \sigma dn}$$

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

Optical depth

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

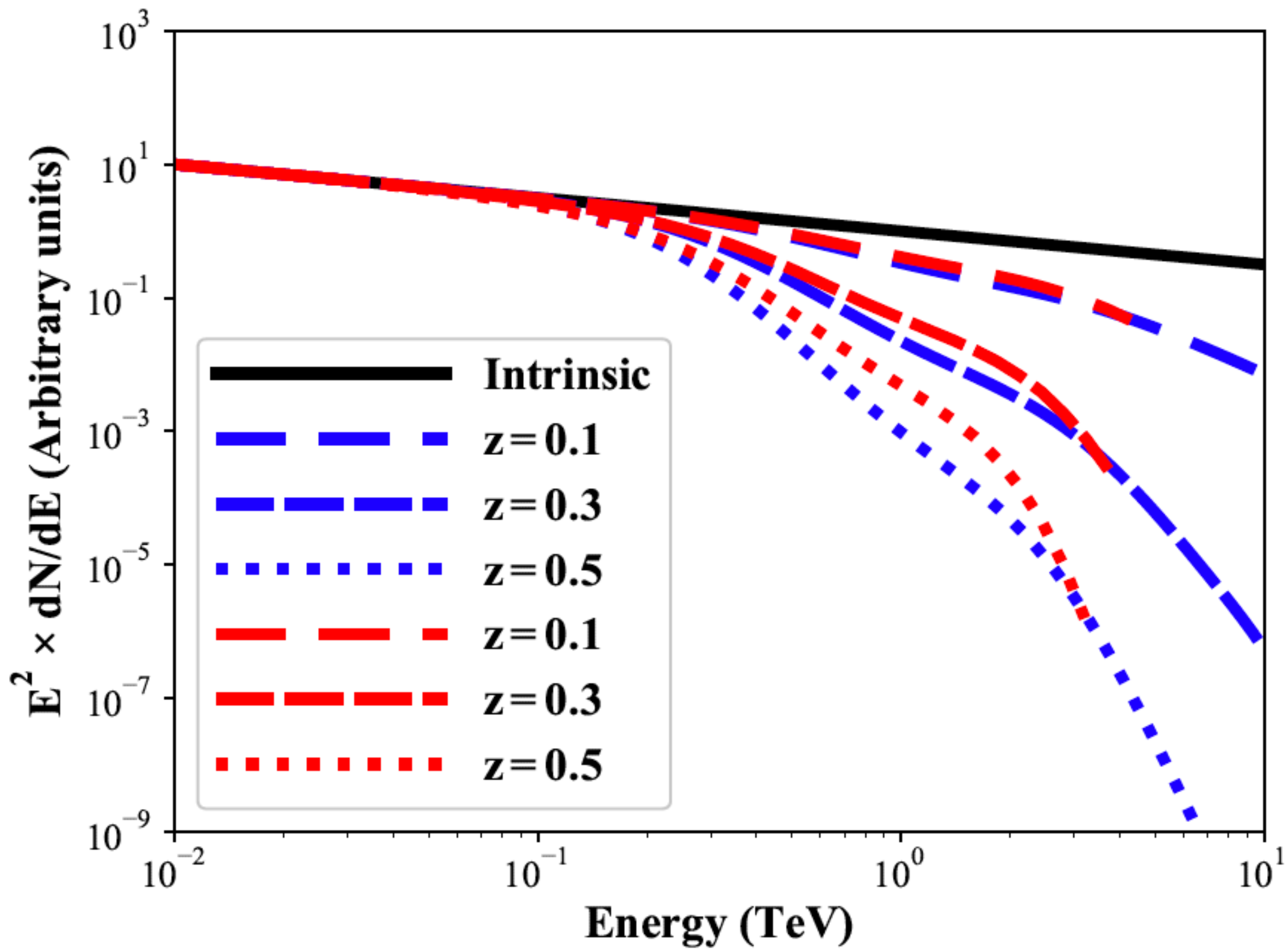


Cosmic gamma-ray horizon (CGRH): τ=1

Attenuation effects important for τ>1

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

Fingerprints of attenuation



Helgason et al

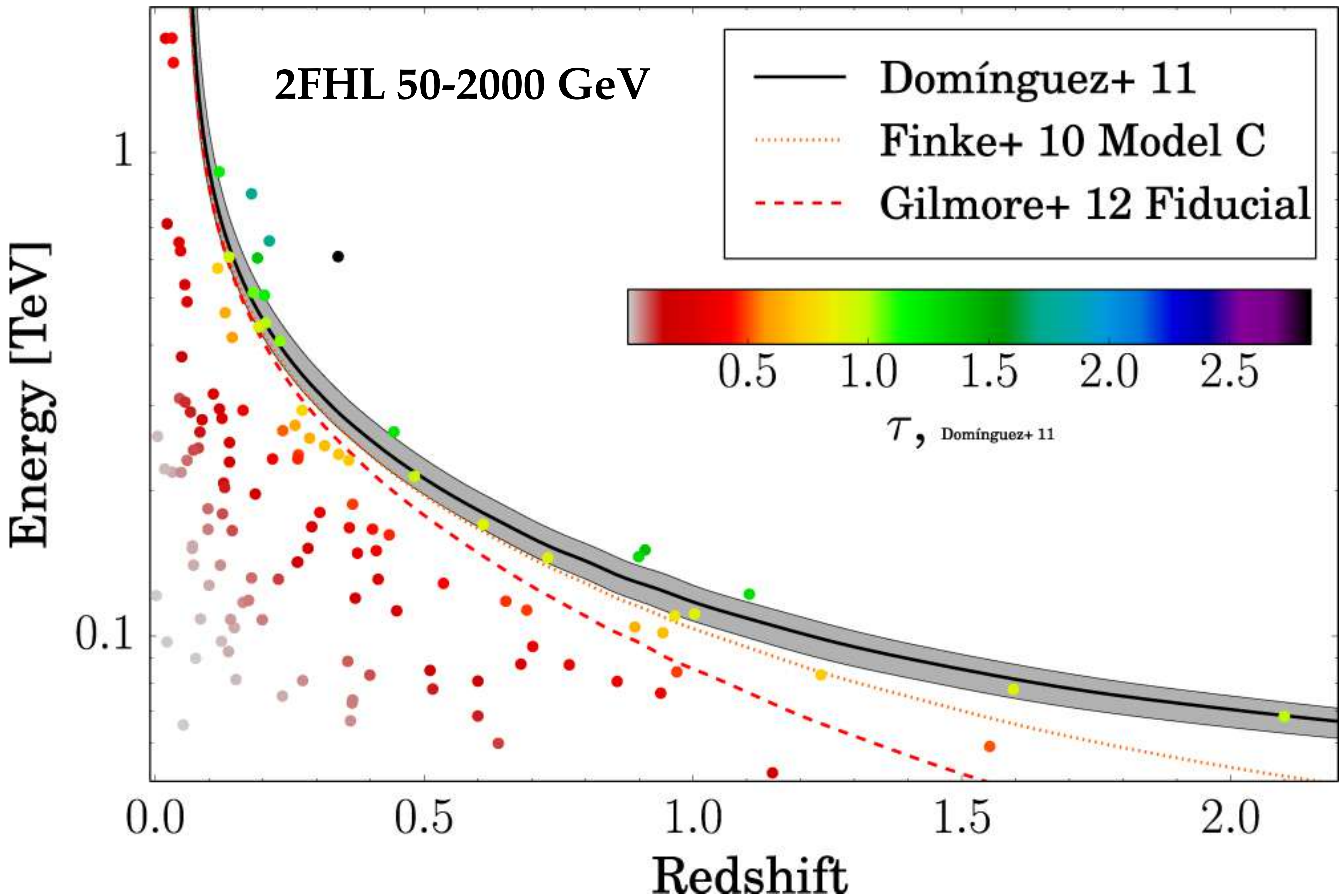
Finke et al

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

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

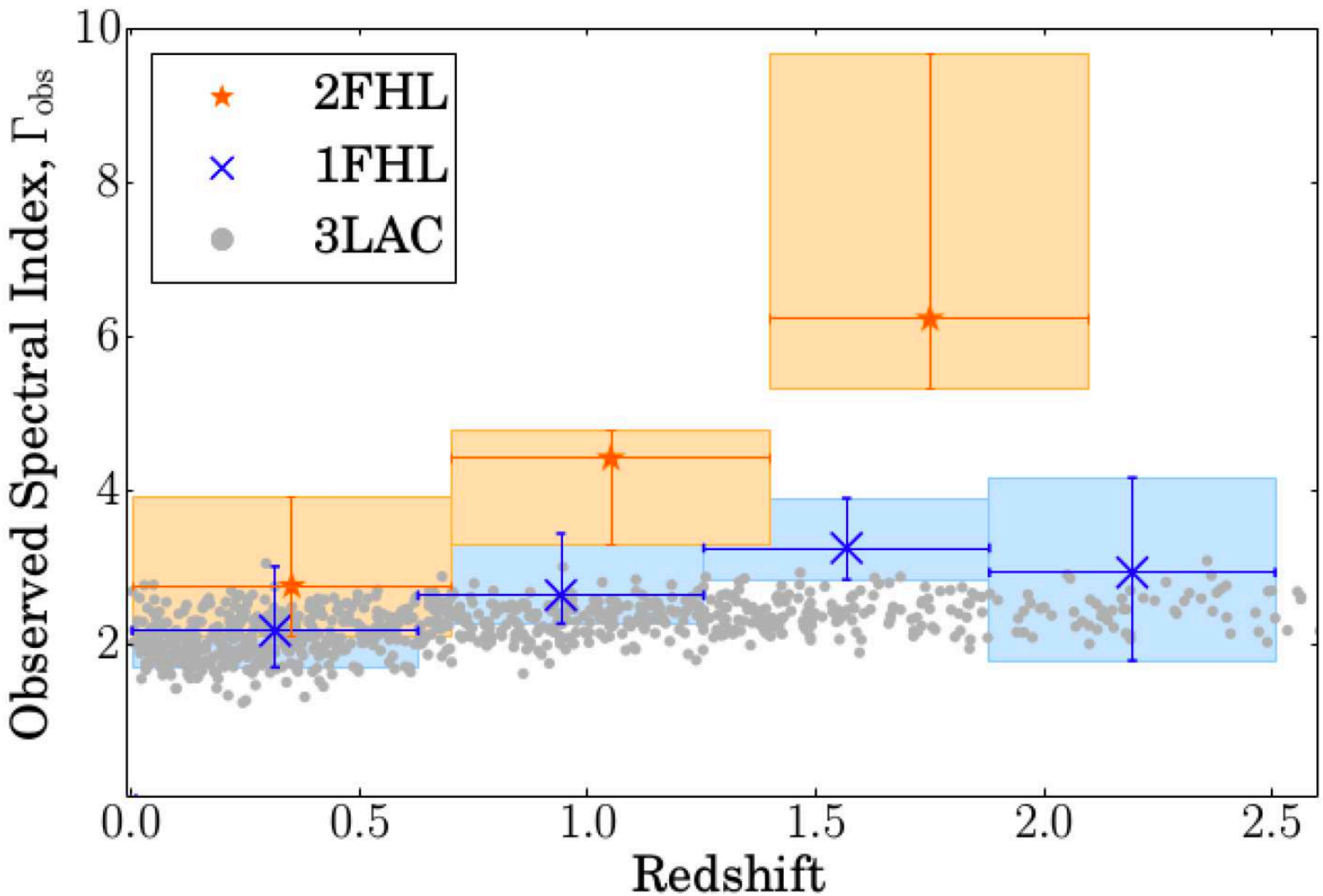
D.R.M. Pimentel, PhD thesis, USP, 2019.

The cosmic gamma-ray horizon (CGRH)



ApJS 222(1), 5 (2016)

Spectral index "running"



2FHL: 50-2000 GeV

1FHL: 10-500 GeV

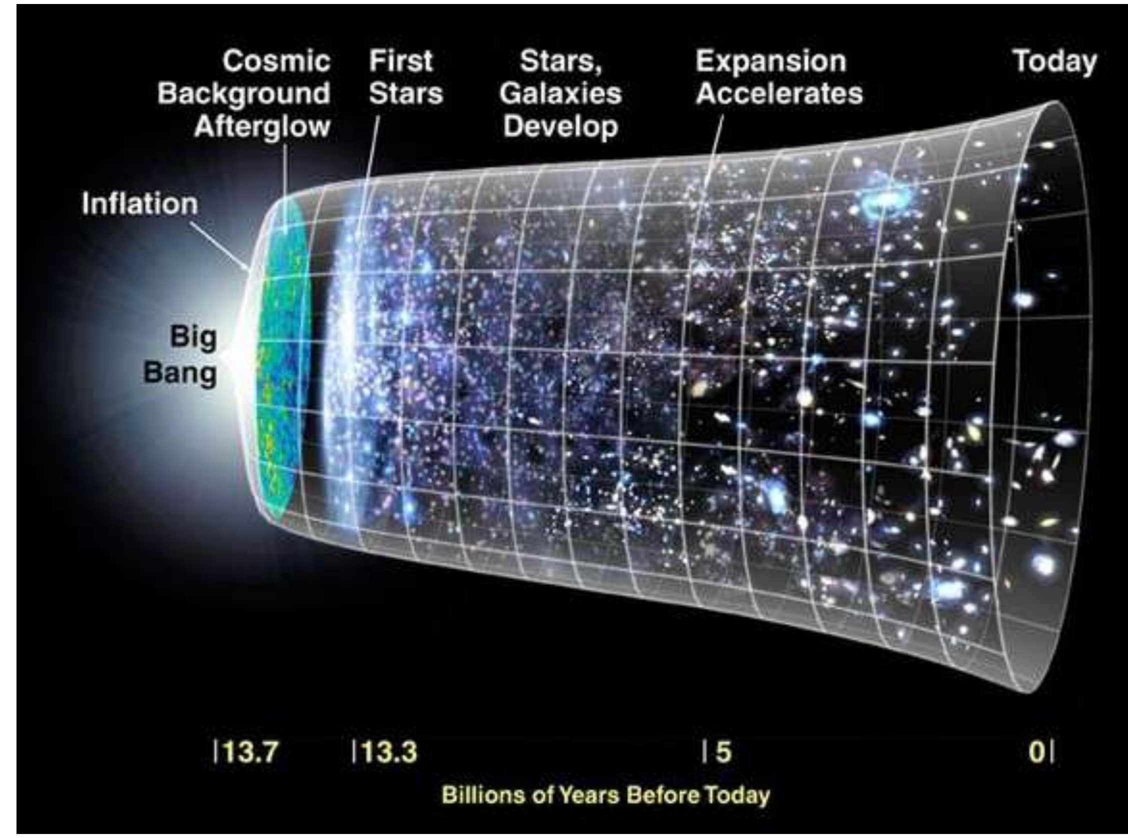
3LAC: 0.1-100 GeV

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
- First (pop III) and second (pop II) generation of stars (?)
- Exotic emissions (?)

For a ΛCDM 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}]

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

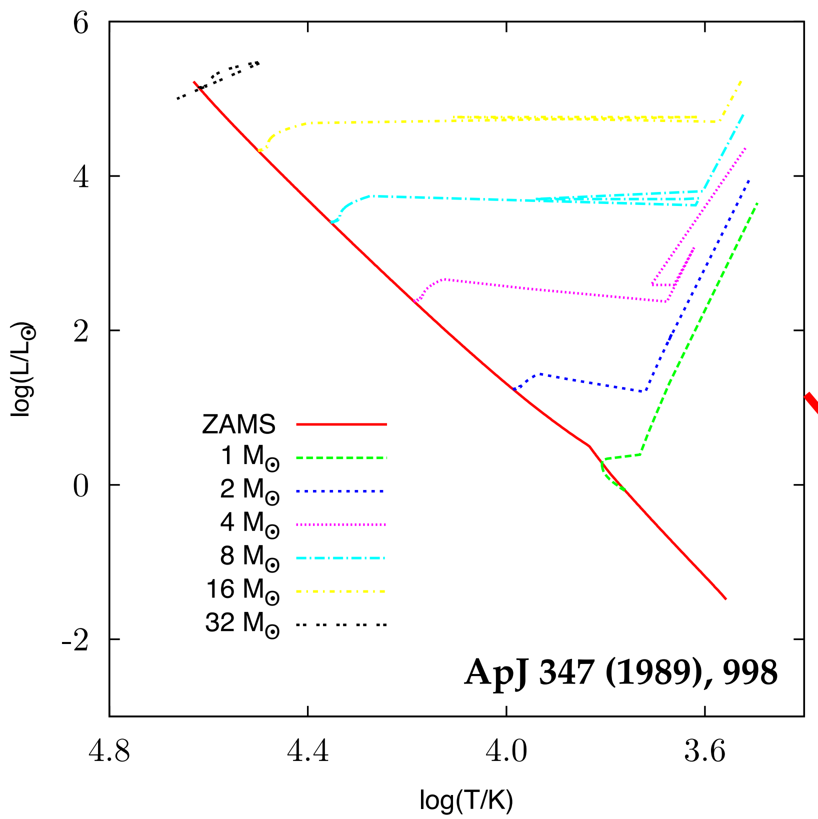
- **Formal solution:**

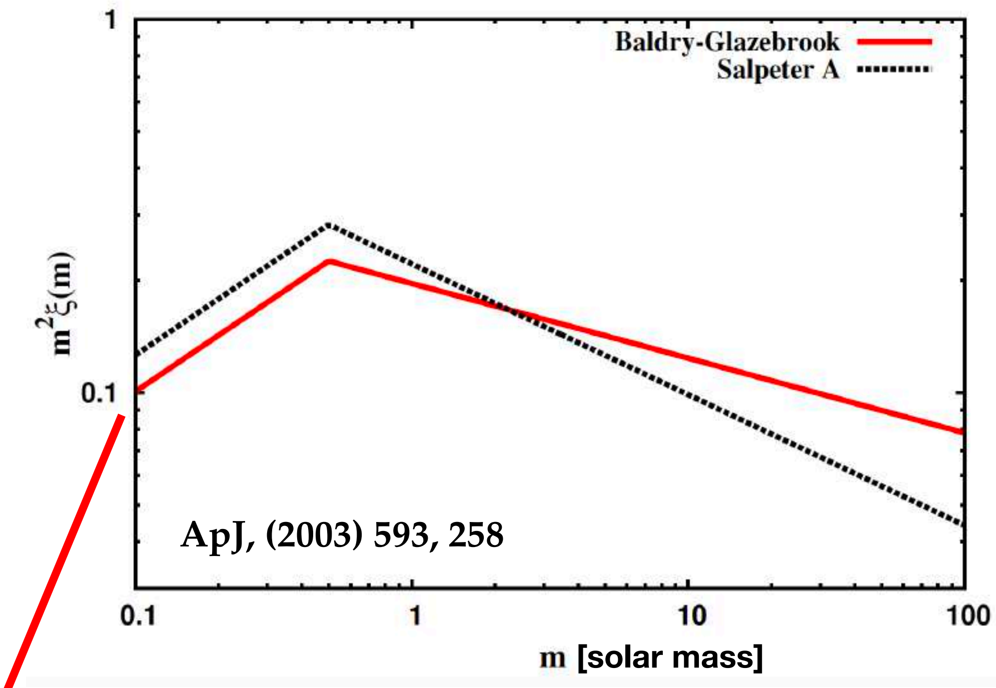
$$I(t,\lambda) = \frac{c}{4\pi}\int_0^t \frac{a^3(t')}{a^3(t)} j(t',\lambda')dt' = (1+z)^3\frac{c}{4\pi}\int_z^\infty j_c(z',\lambda')\left|\frac{dt'}{dz'}\right|dz'$$

Comoving emissivity

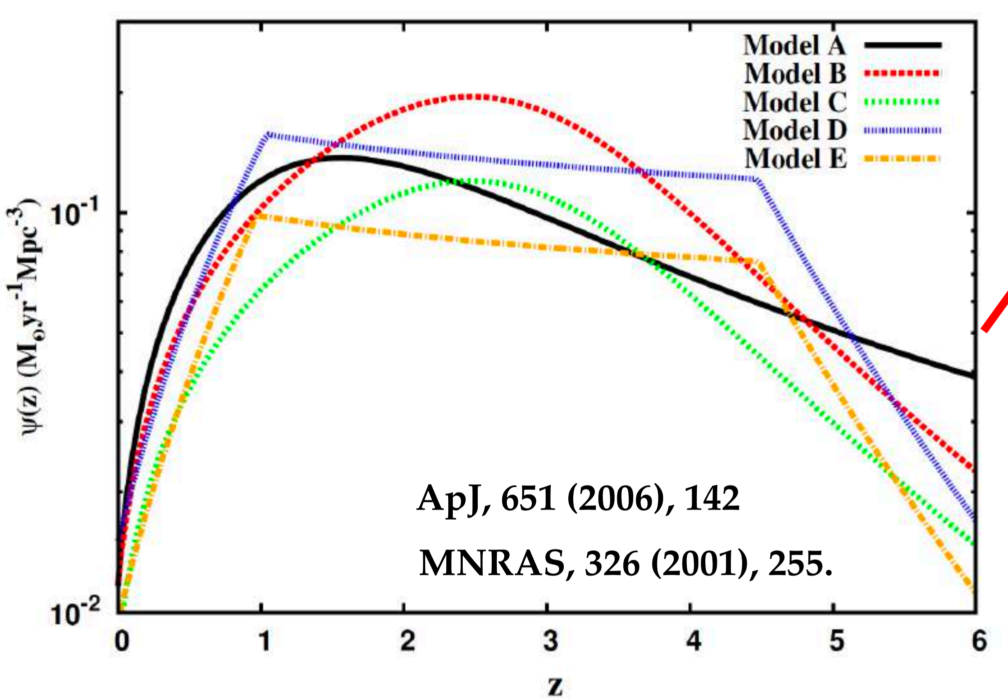
- **Therefore, for a given cosmology, the EBL can be model by defining the coming emissivity $j_c(z,\lambda)$**

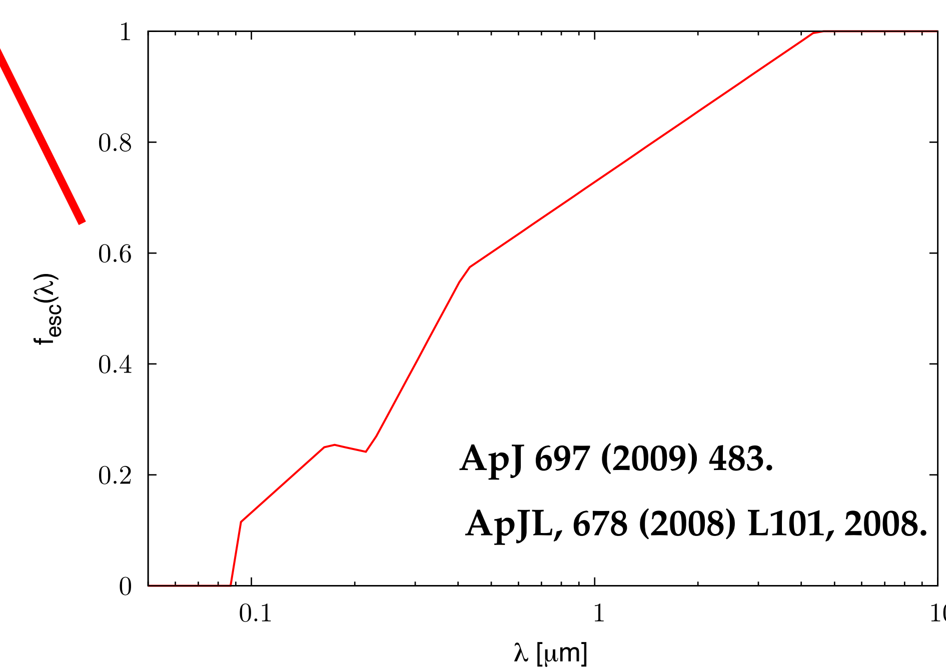
EBL model based on star+dust (Finke et al.)



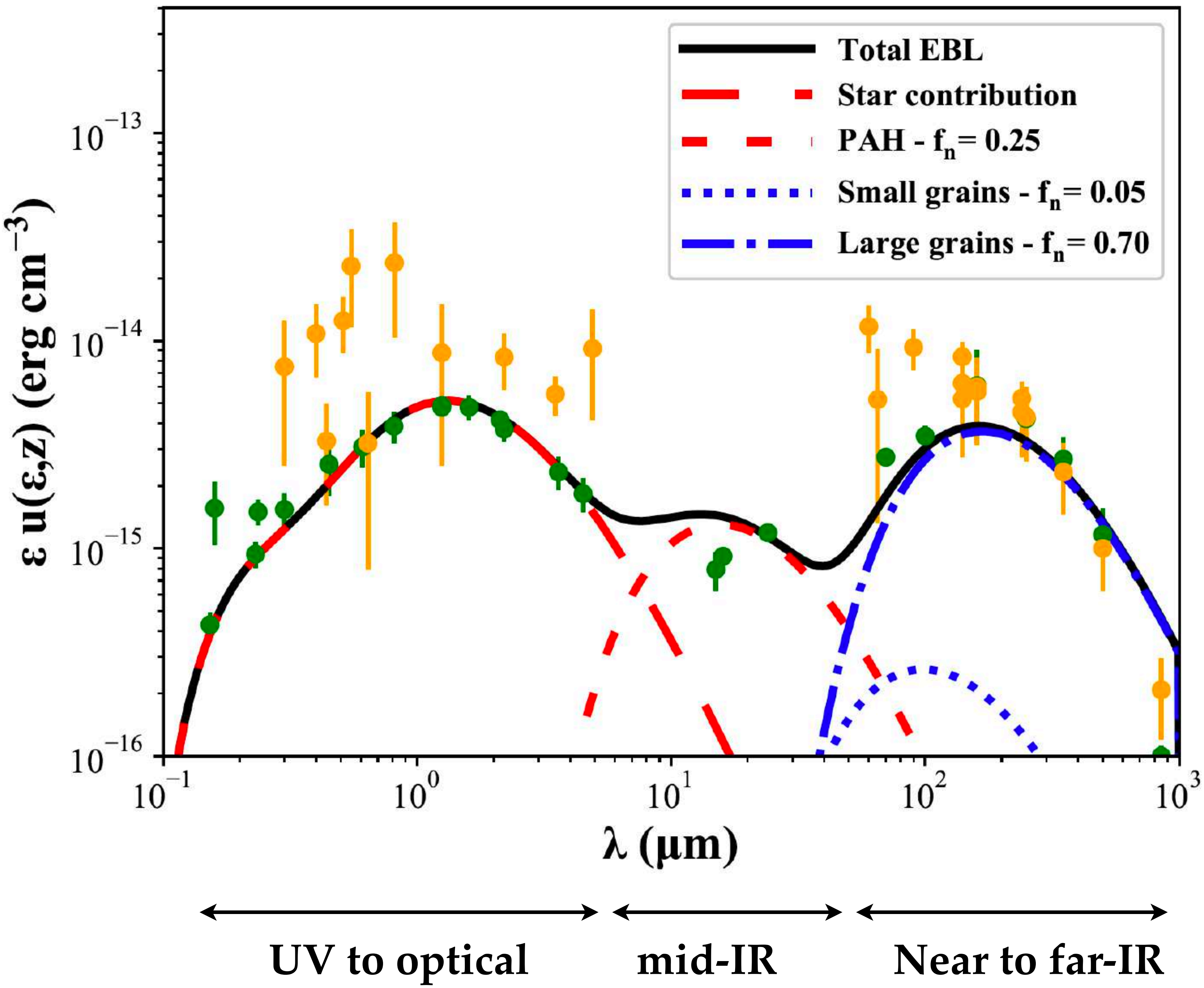


$$I(t,\lambda) = (1+z)^3 \frac{c}{4\pi} \int_z^{\infty} j_c(z',\lambda') \left| \frac{dt'}{dz'} \right| dz'$$





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

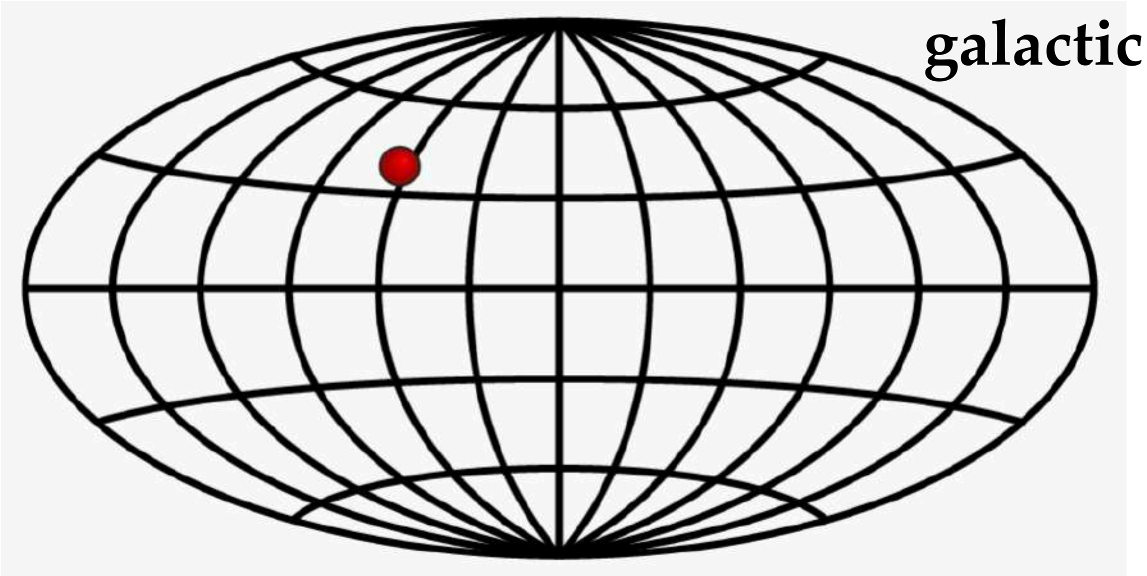
- About 5% of the CMB energy density

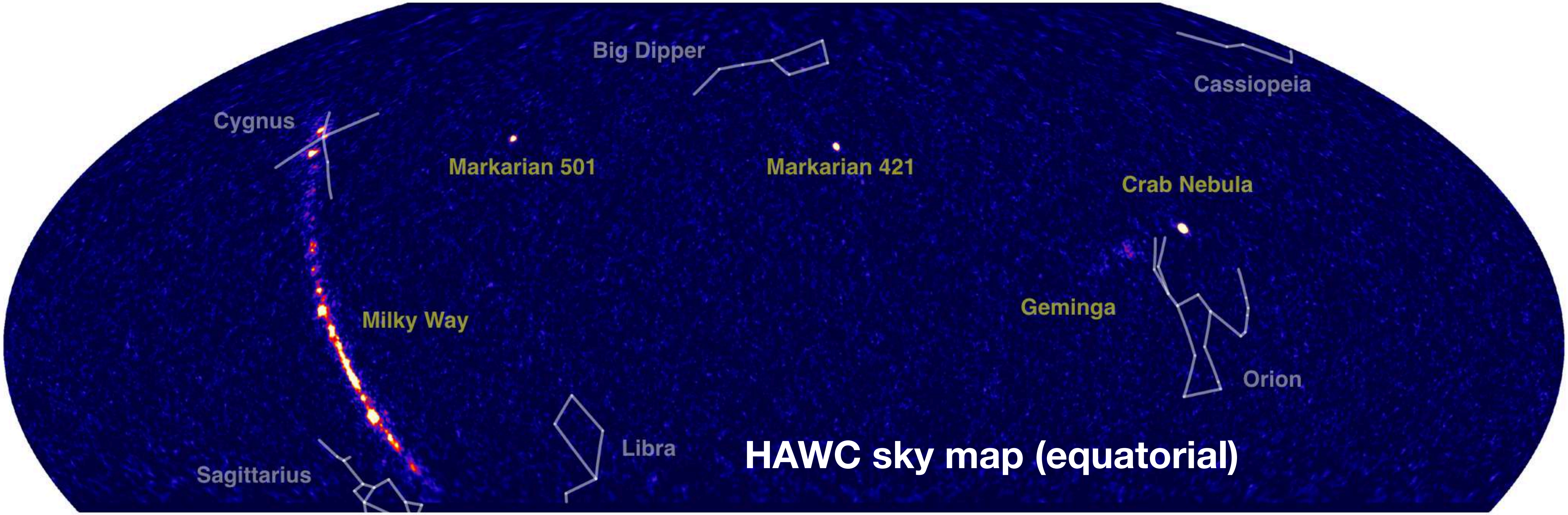
- Energy density very close to lower bound from galaxy counts

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

Case study: Markarian 501

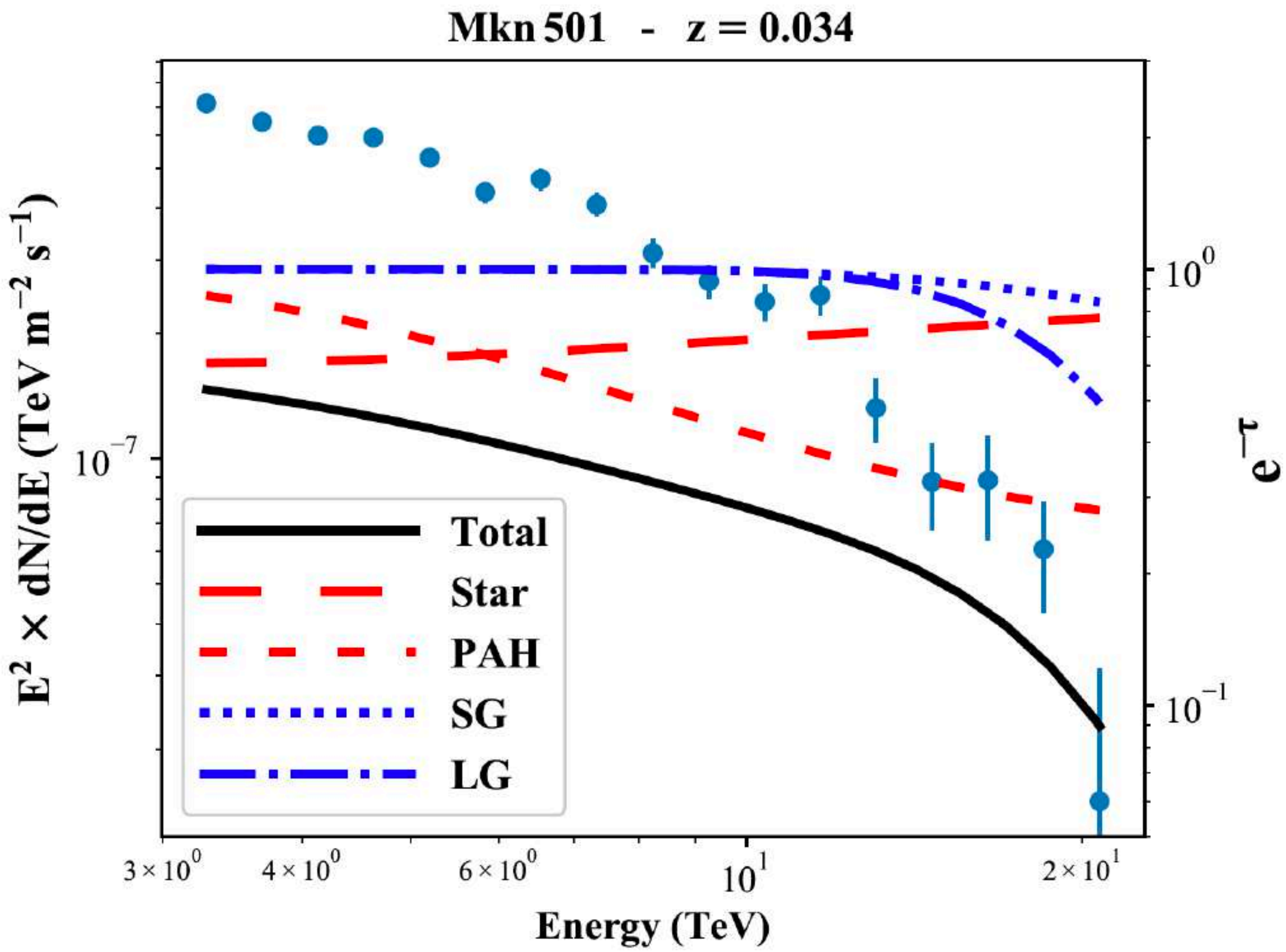
- Blazar
- BL Lac type AGN
- z=0.034 (~140 Mpc)
- (L_{gal}, B_{gal}) = (63.60, 38.86) deg
- High variability at TeV
- Violent flare seen by HEGRA in 1997

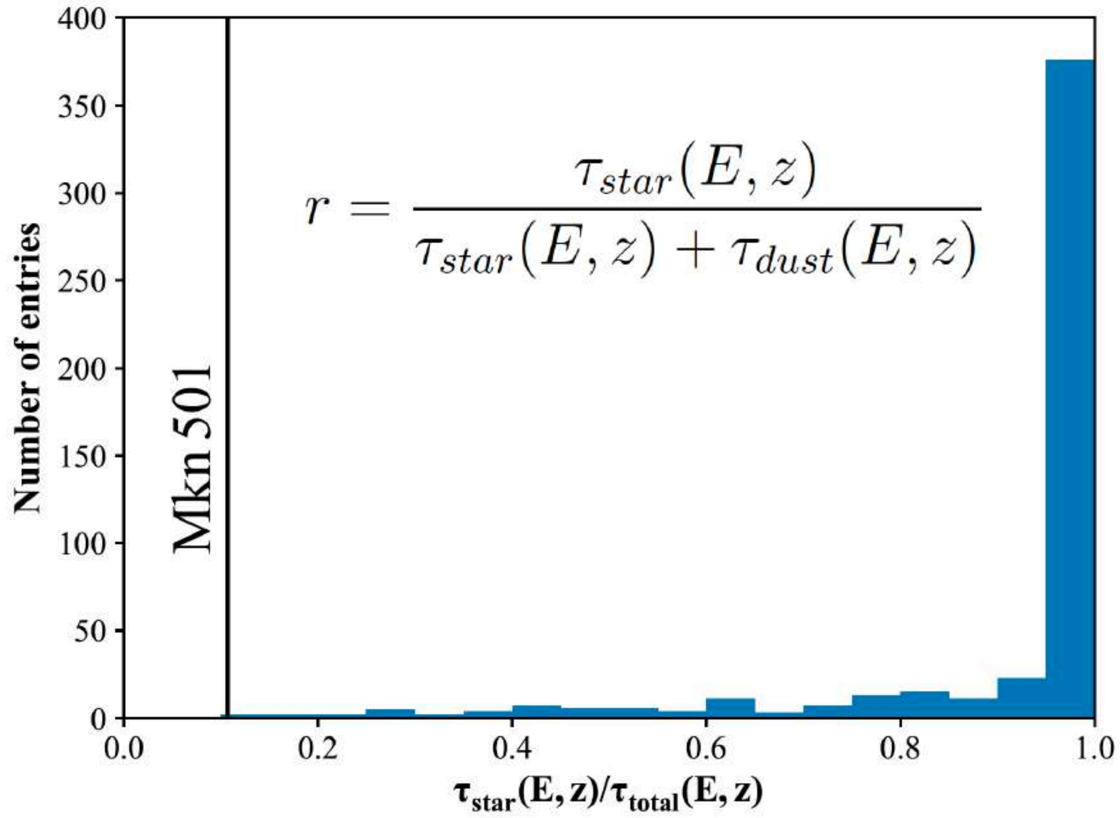




Case study: Markarian 501

- **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?

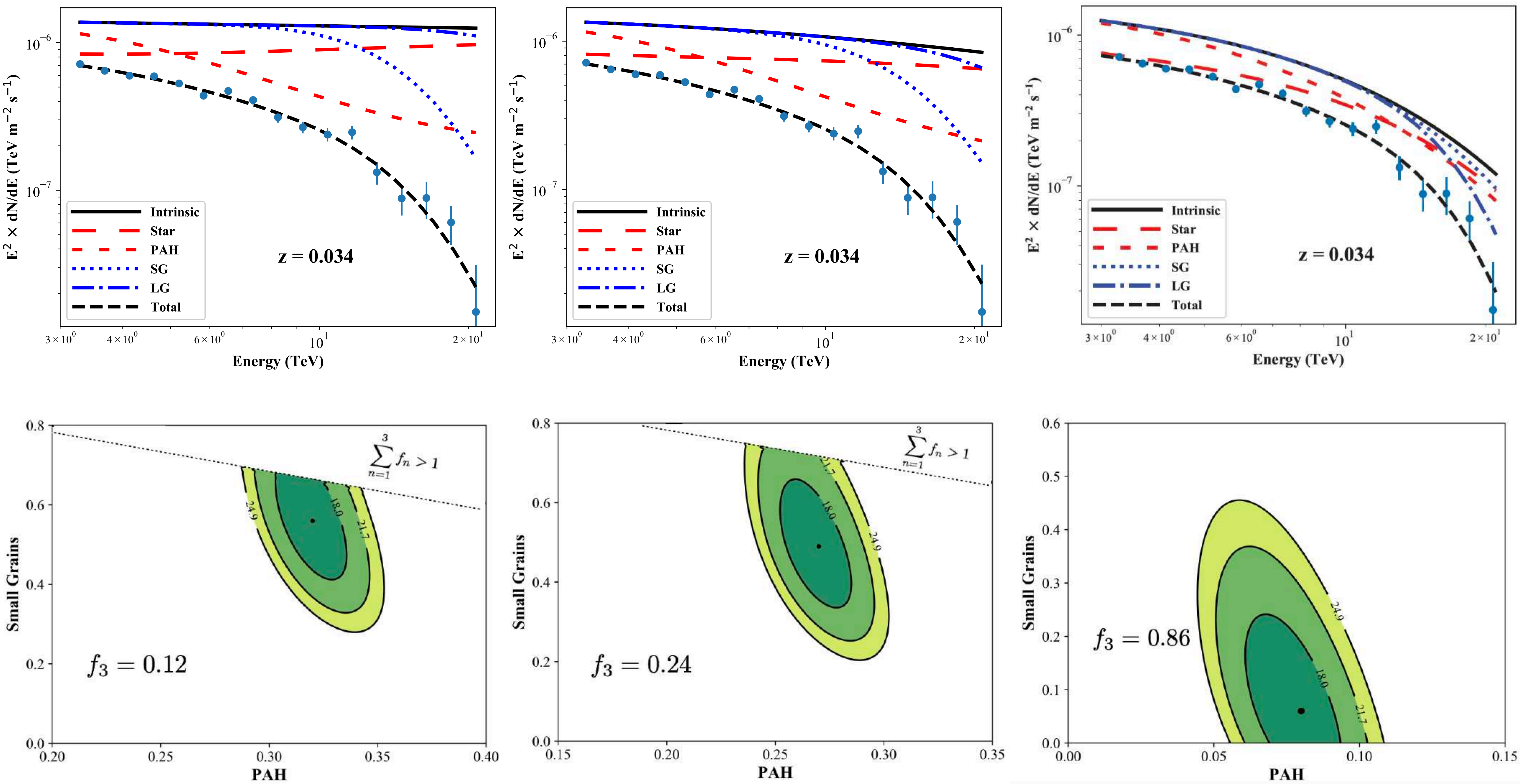
Analysis strategy

- **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)**

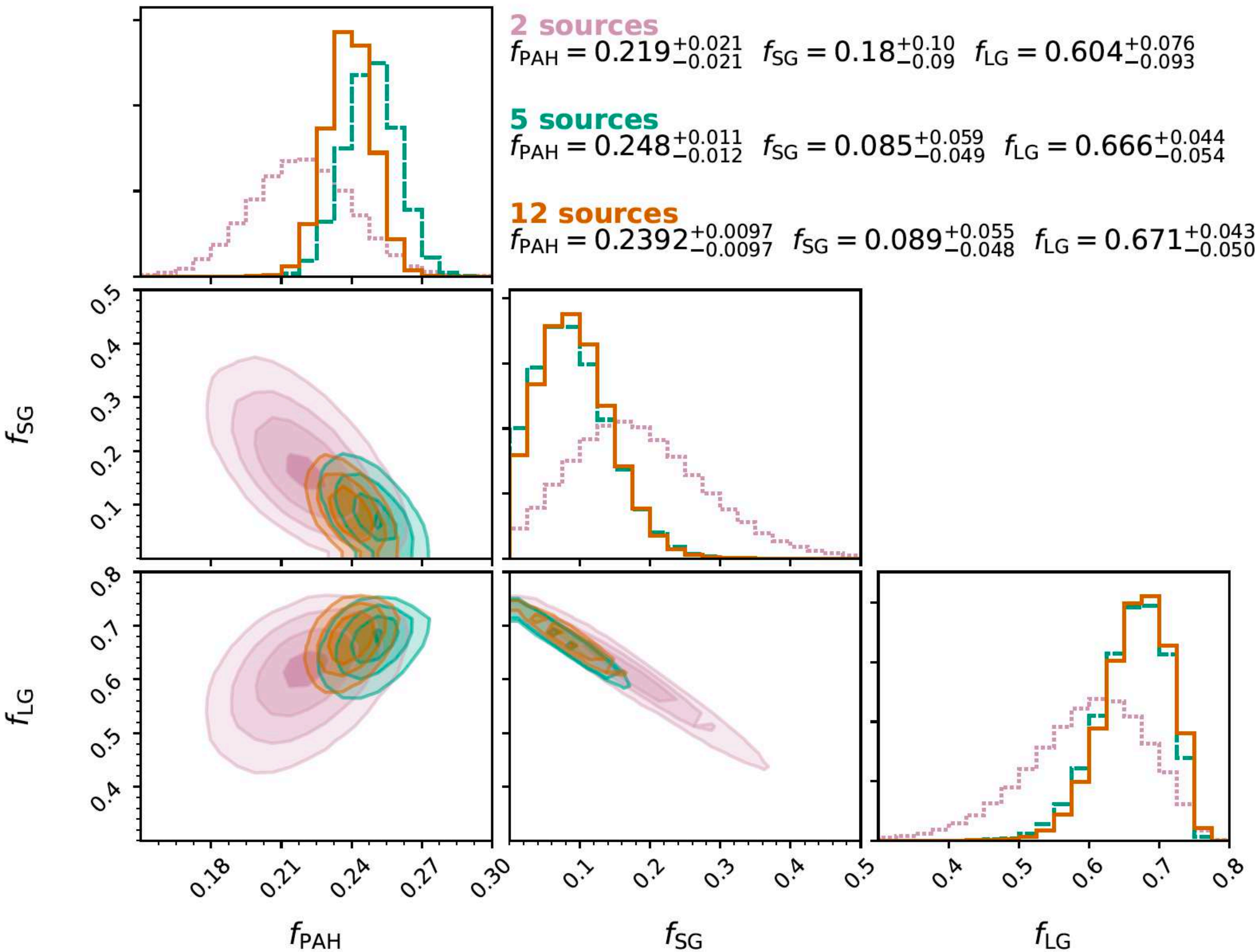
Fit results



- **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**

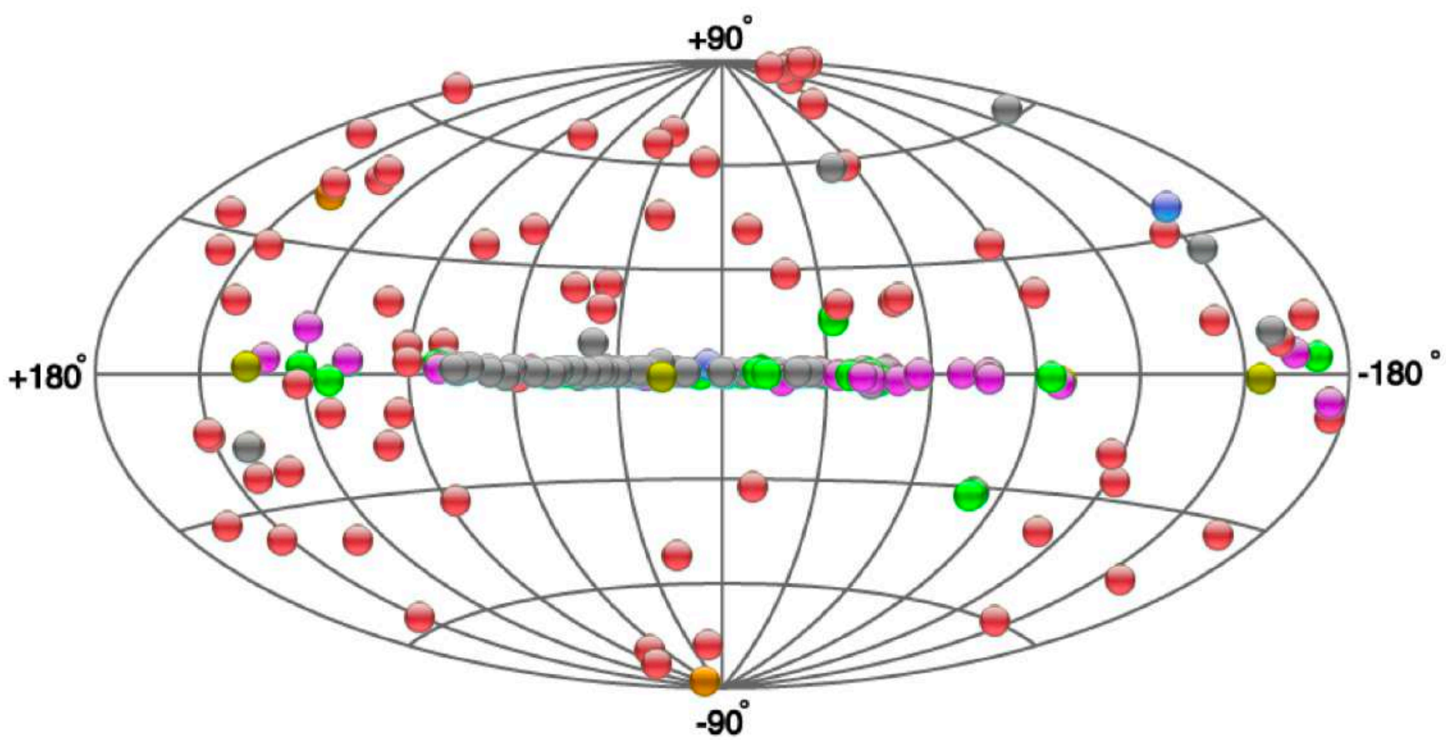
D.R.M. Pimentel, EMS, JCAP 04 (2019) 043

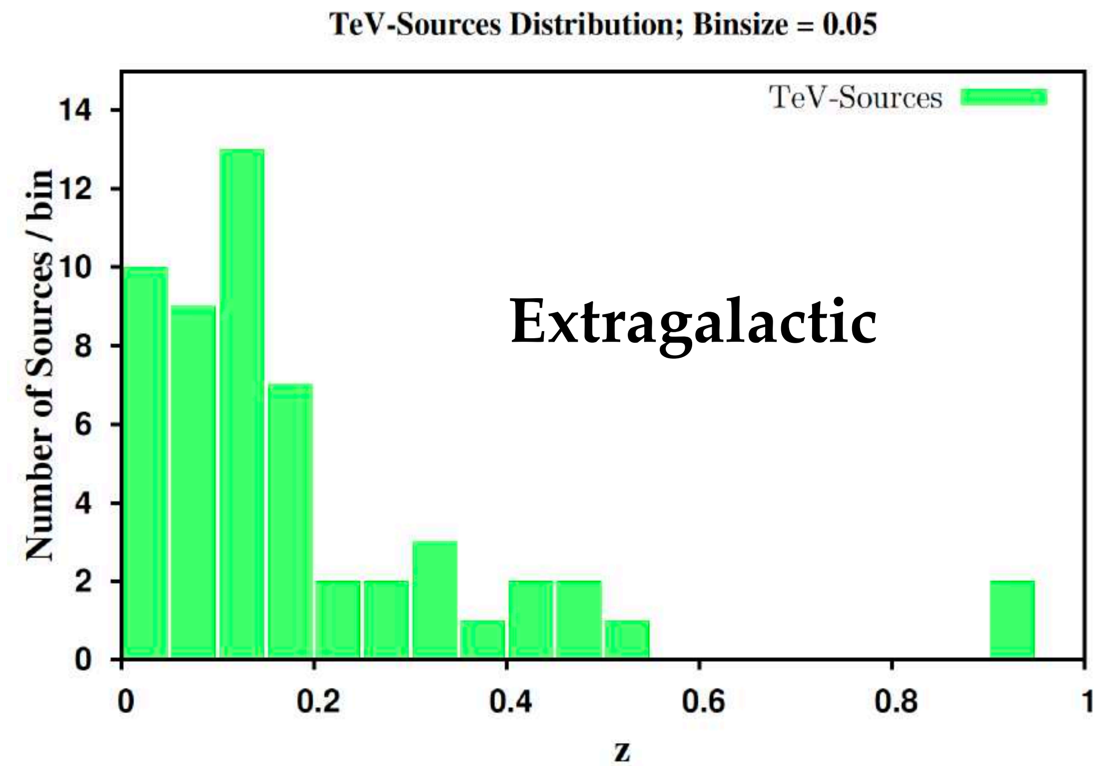
Breaking degeneracies with a combined fit



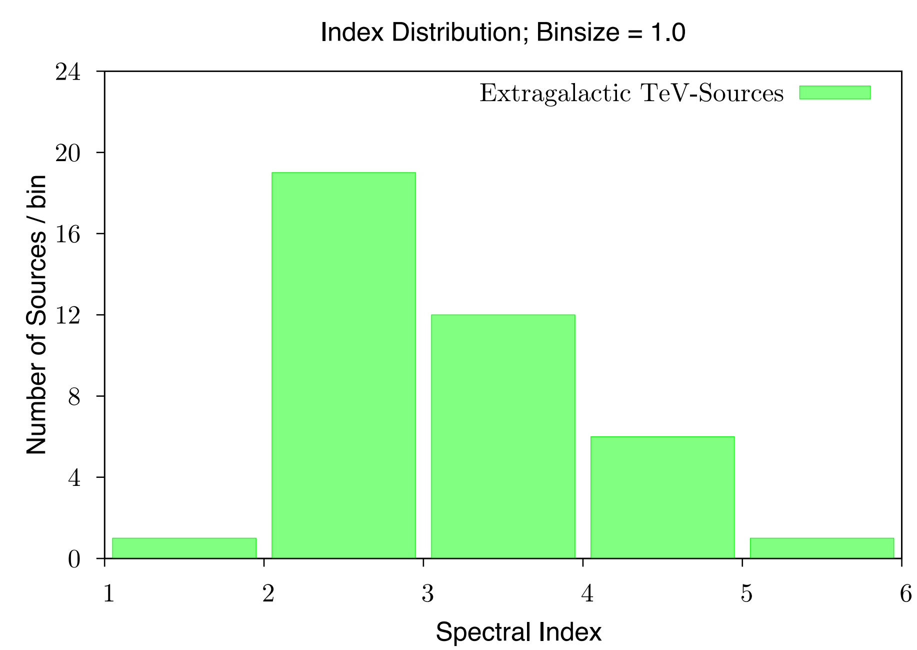
M. G. Dantas Xavier et al, in preparation

What does the data tell us?



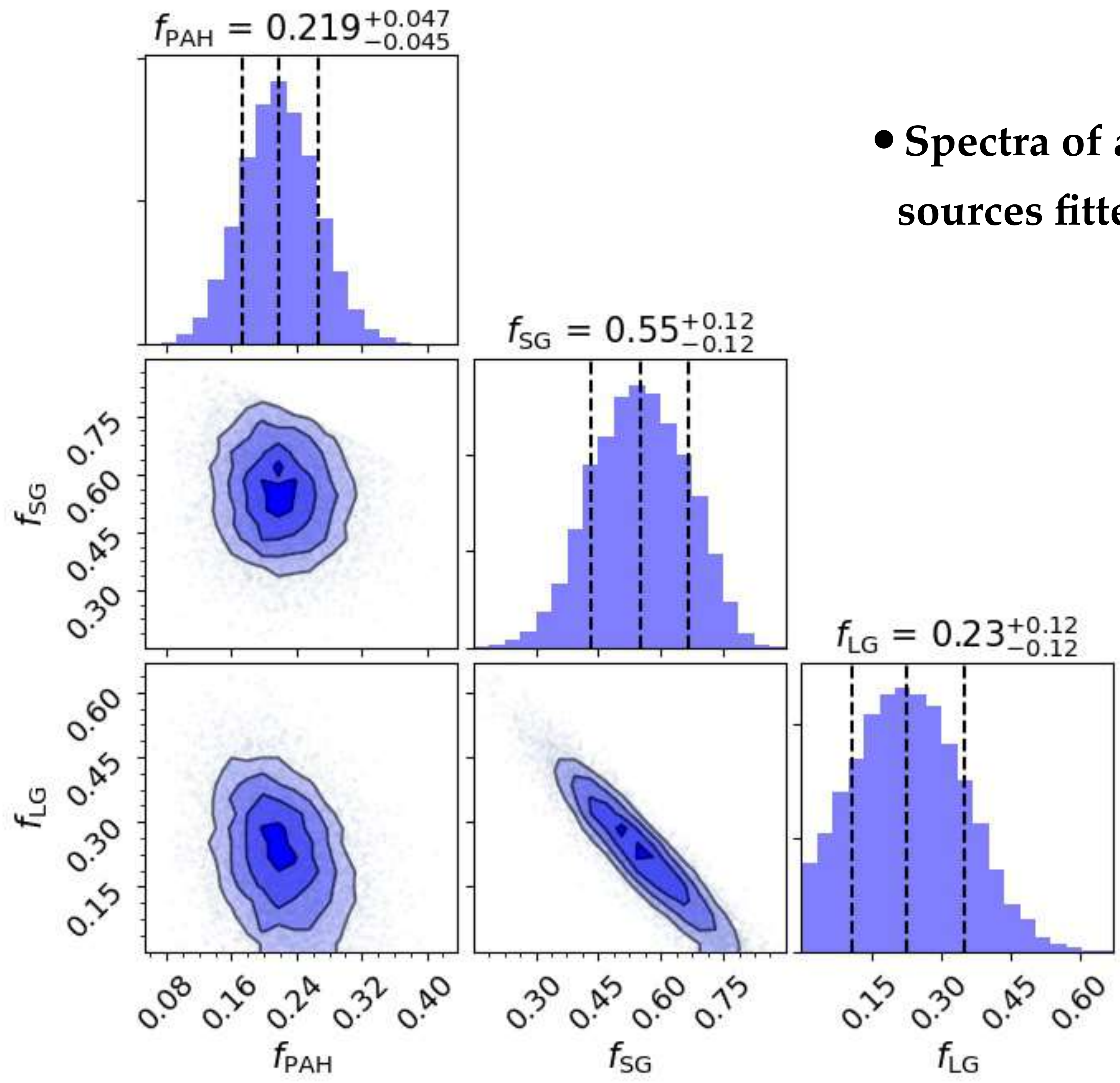


http://tevcat2.uchicago.edu



- **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

Blazar population studies with CTA

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):**

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

- **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:**

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

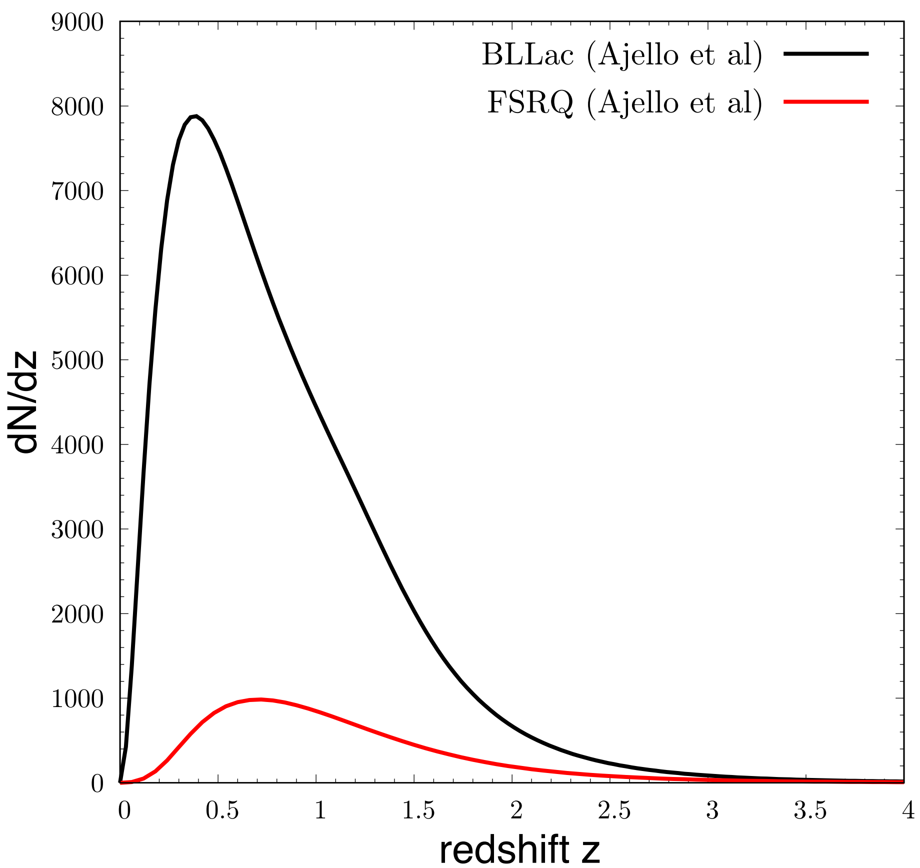
$$p_2(L_\gamma) = p_2^* + \delta(\log(L_\gamma) - 46)$$

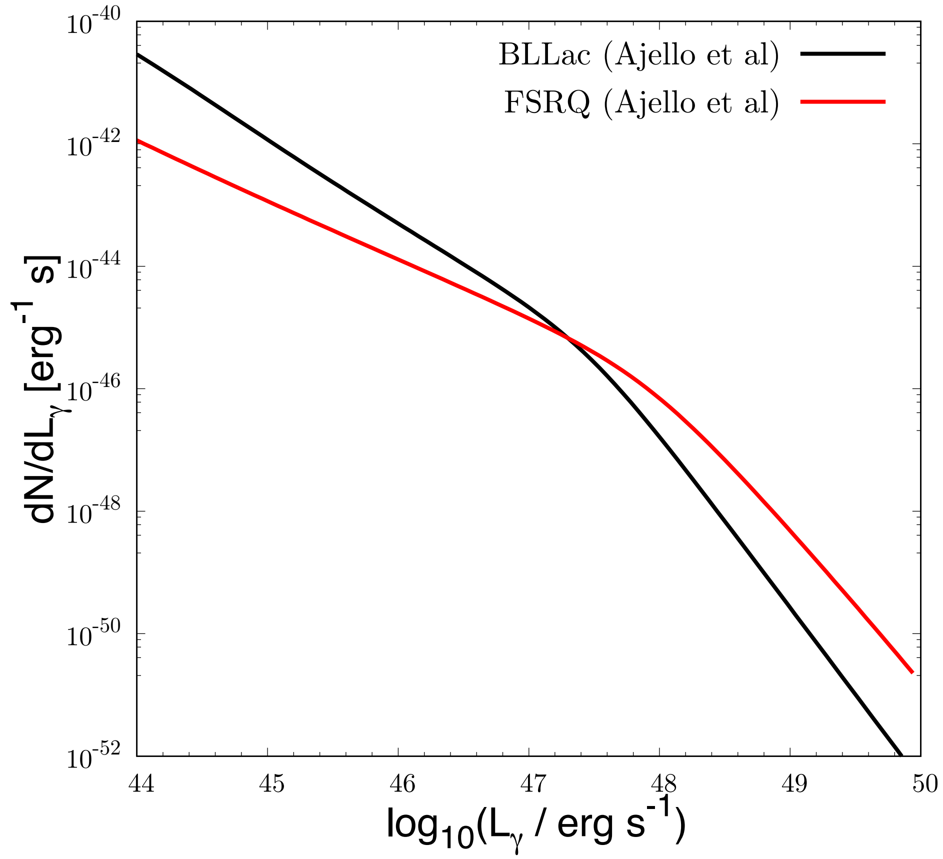
$$z_c(L_\gamma) = z_c^*(L_\gamma/10^{48})^\alpha$$

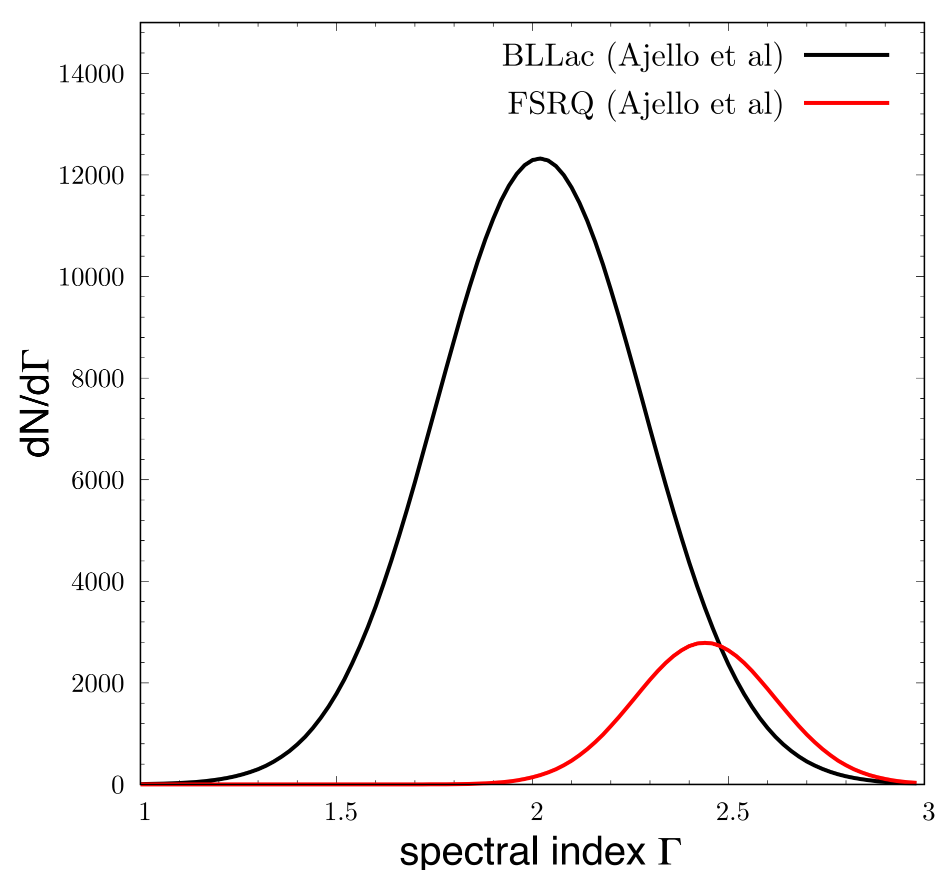
$$e(z, L_\gamma) = \left[\left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{-p_1(L_\gamma)} + \left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{-p_2(L_\gamma)}\right]^{-1}$$

source	A [Gpc^{-3}]	γ_1	γ_2	L_* [erg/s]	p_1^*	p_2^*	τ	z_c^*	α	μ^*	β	σ
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)

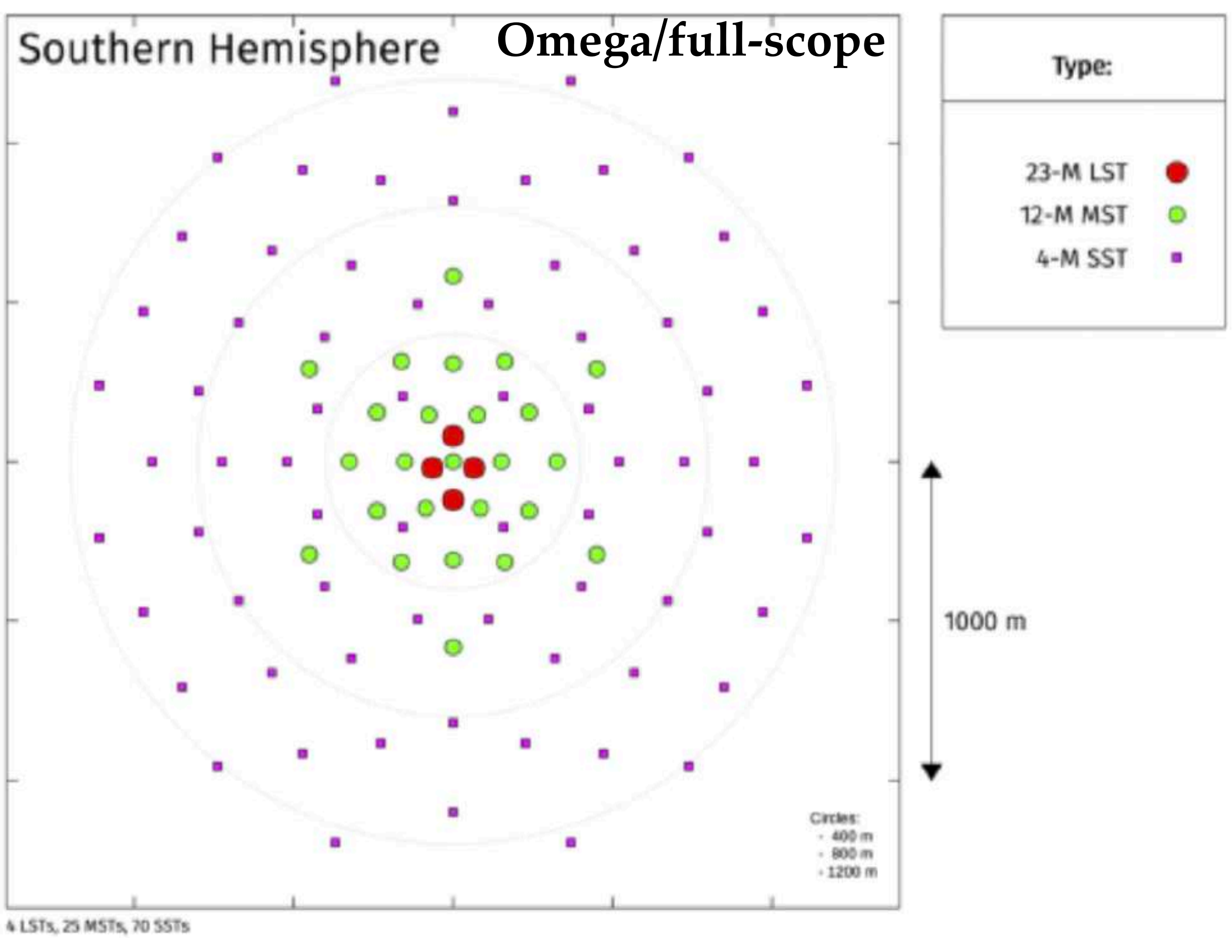
Southern Hemisphere: 4 LSTs, 25 MSTs, 70 SSTs (covered area: ~ 4 km^2)

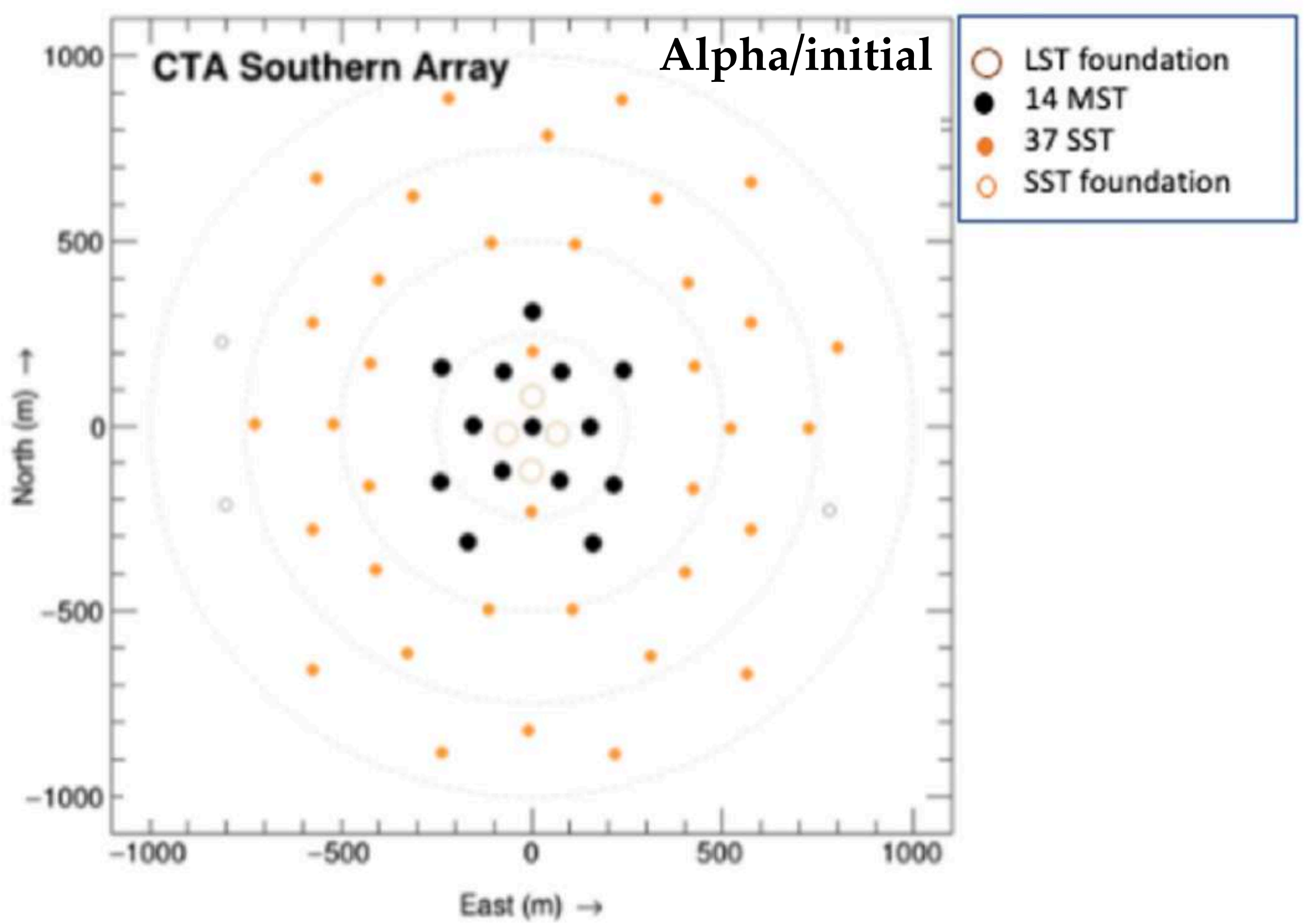
Northern Hemisphere: 4 LSTs, 15 MSTs (covered area: ~ 0.6 km^2)

ALPHA CONFIGURATION (64 telescopes)

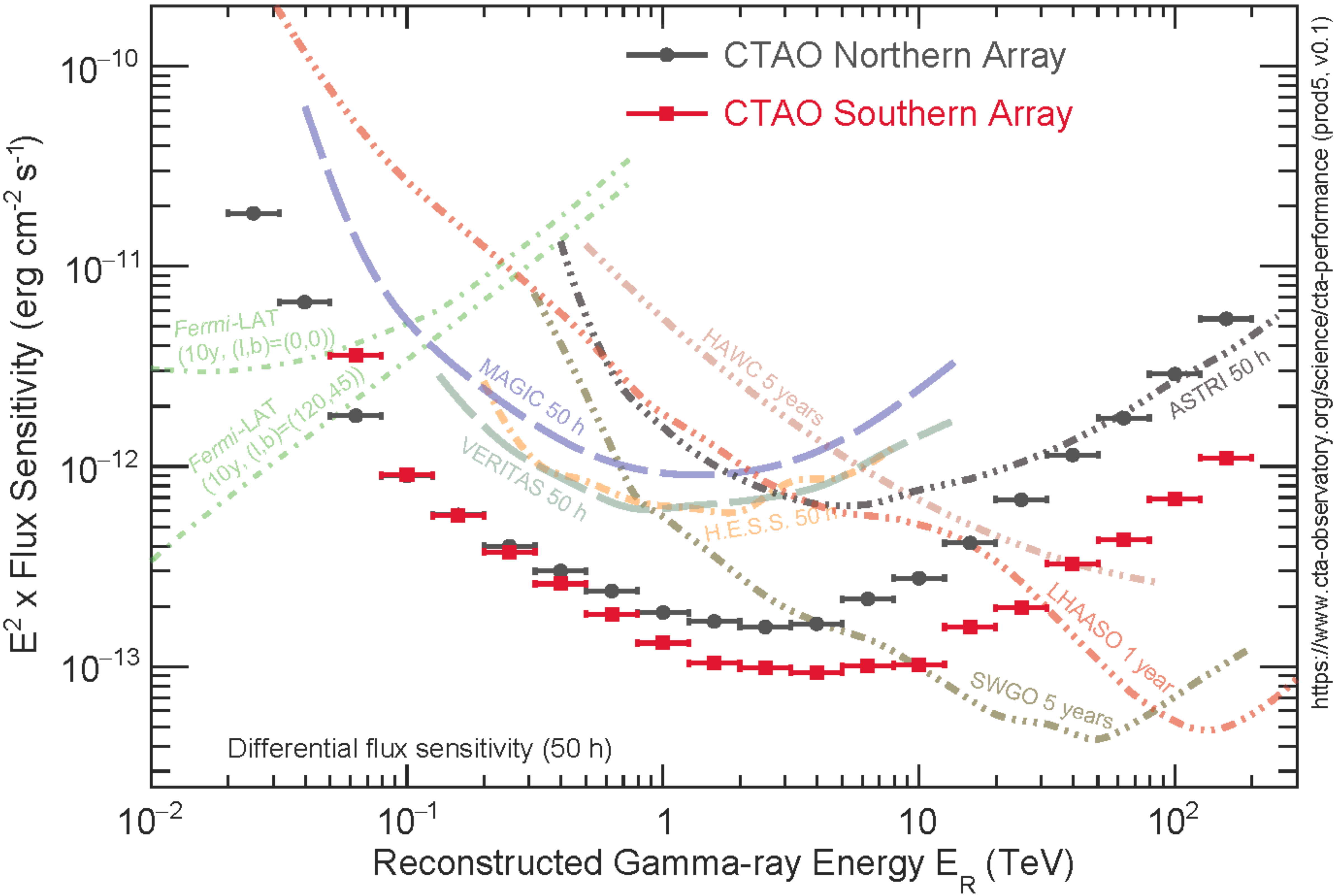
Southern Hemisphere: 14 MSTs, 37 SSTs (covered area: ~ 3 km^2) (150 GeV - 300 TeV)

Northern Hemisphere: 4 LSTs, 9 MSTs (covered area: ~ 0.25 km^2) (20 GeV - 5 TeV)

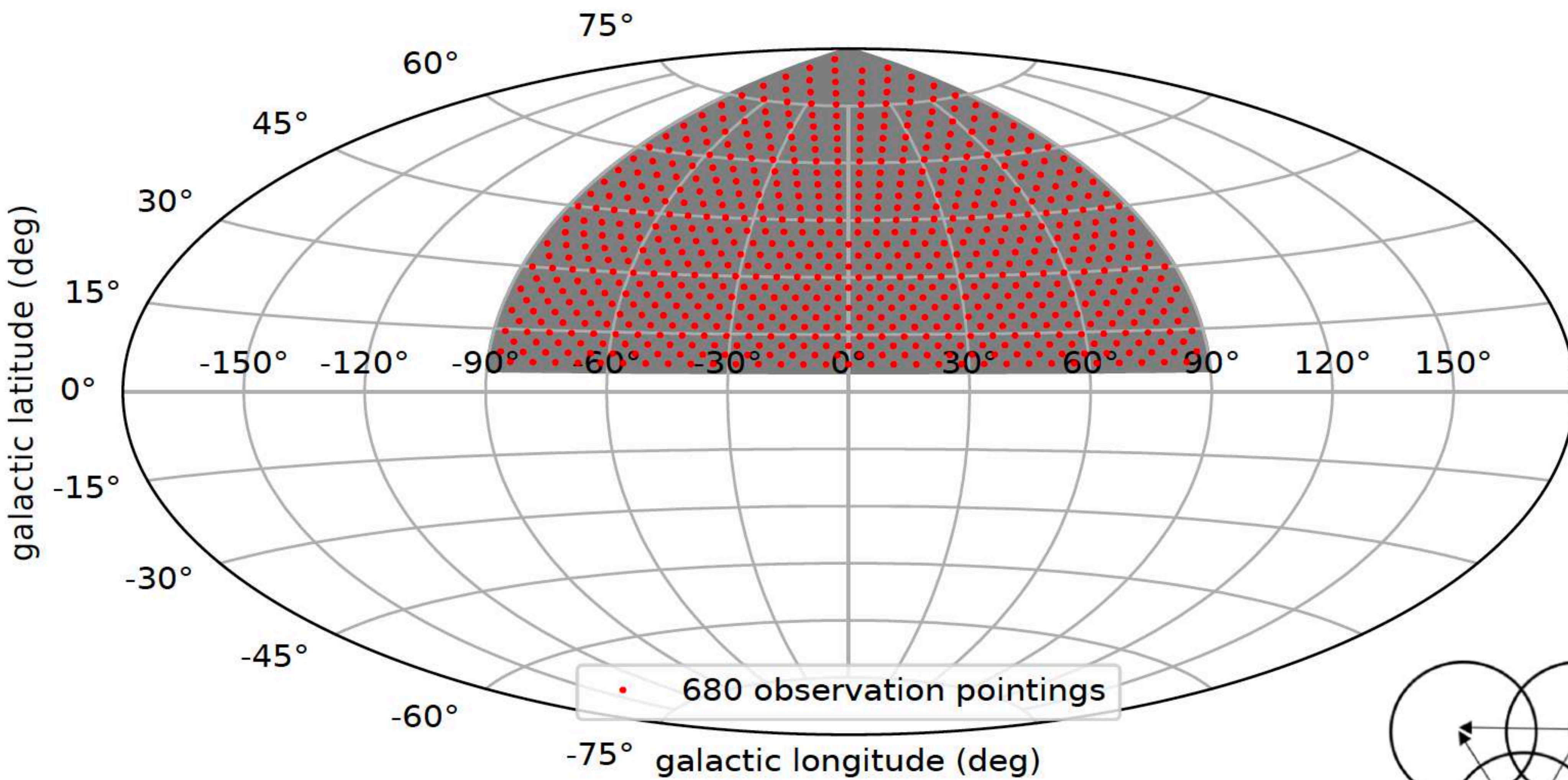


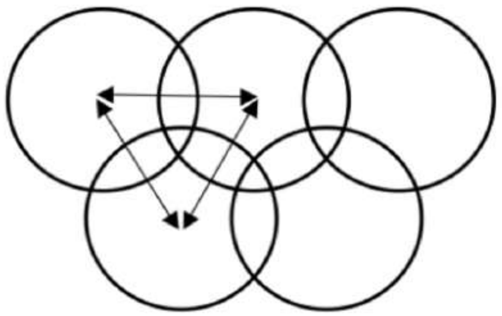


Alpha configuration sensitivity



EGAL survey observation strategy





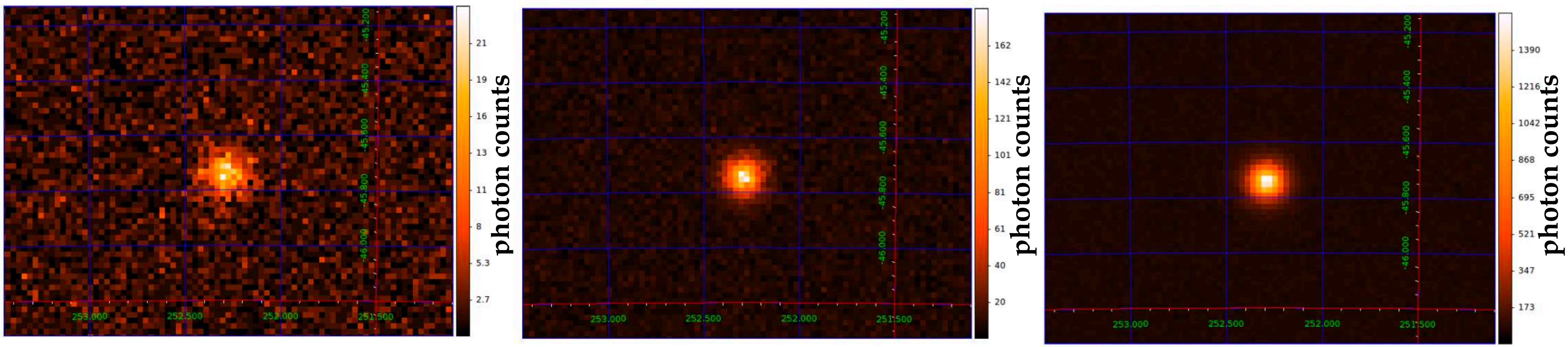
- One of the Key Science Projects (KSP)
- 25% of the sky (B>5deg -90<L<90)
- 1000 hours of observations (~400h [S] + ~600h [N])

2.21 h / pointing [N]

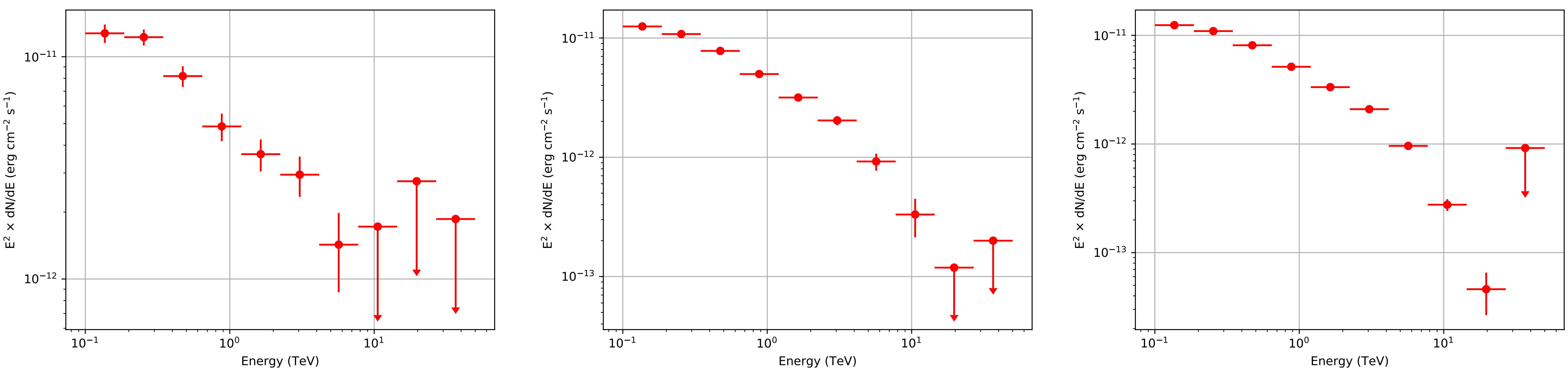
0.98 h / pointing [S]

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

0.5 hour | 5 hours | 50 hours

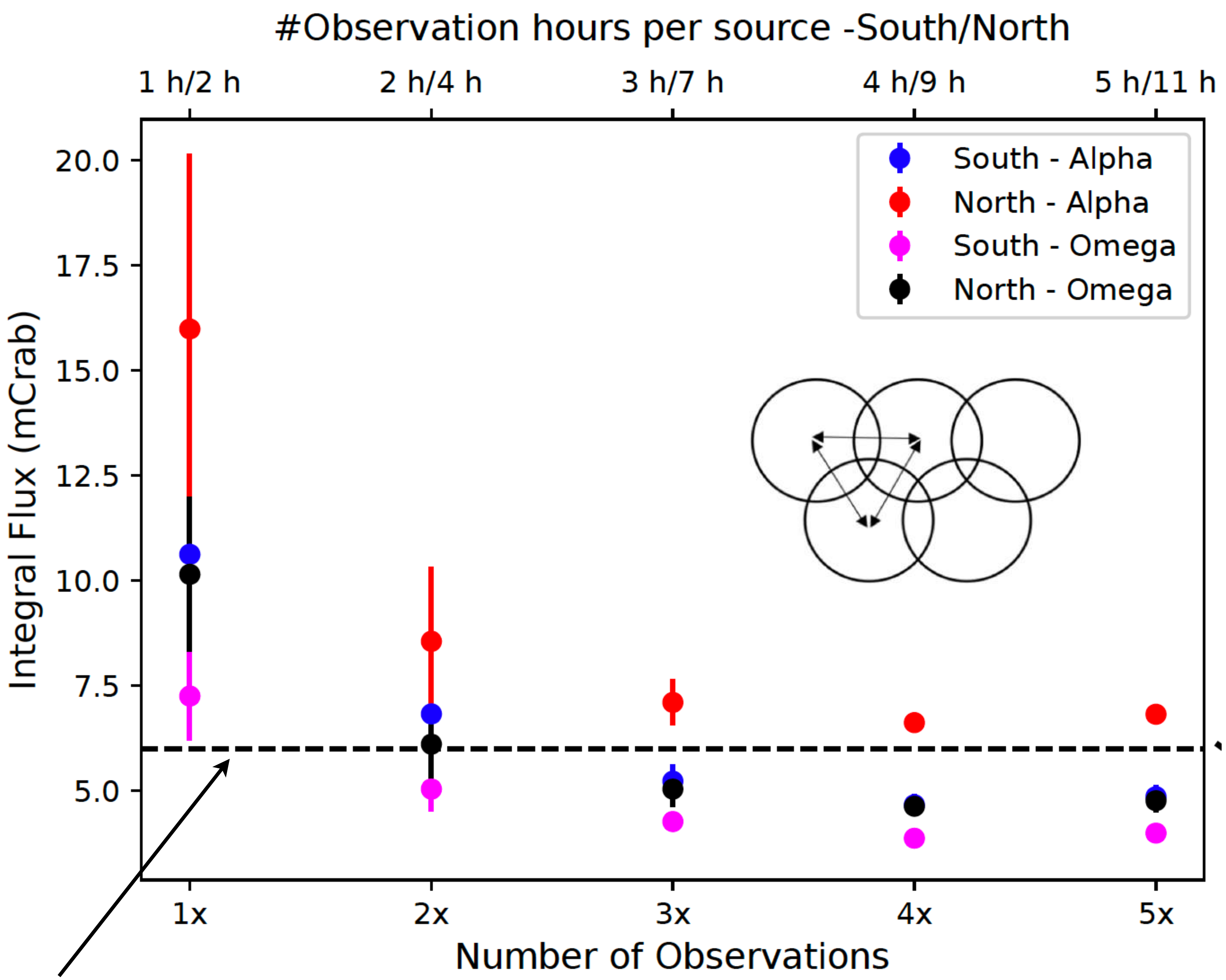


Omega configuration



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

EGAL survey sensitivity (alpha)



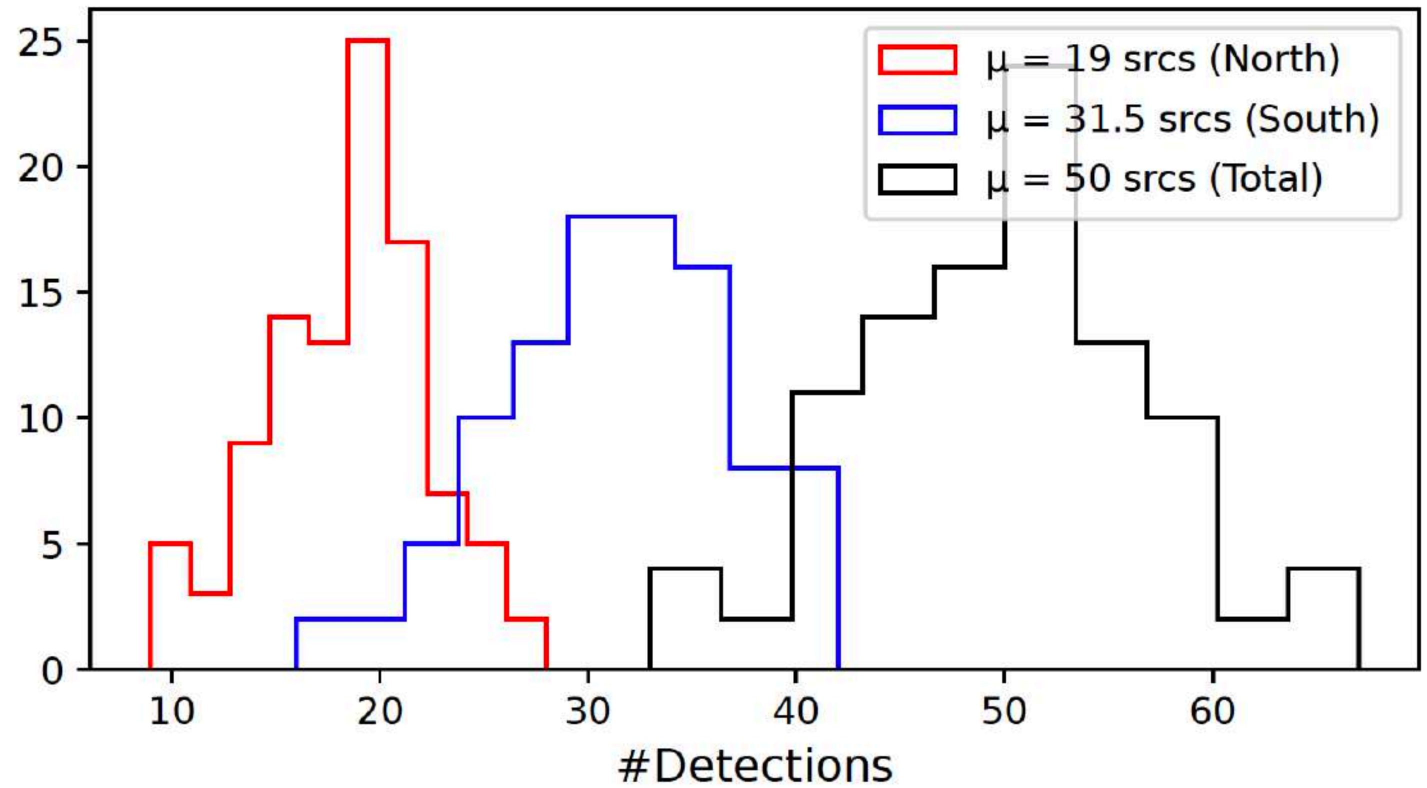
Target sensitivity

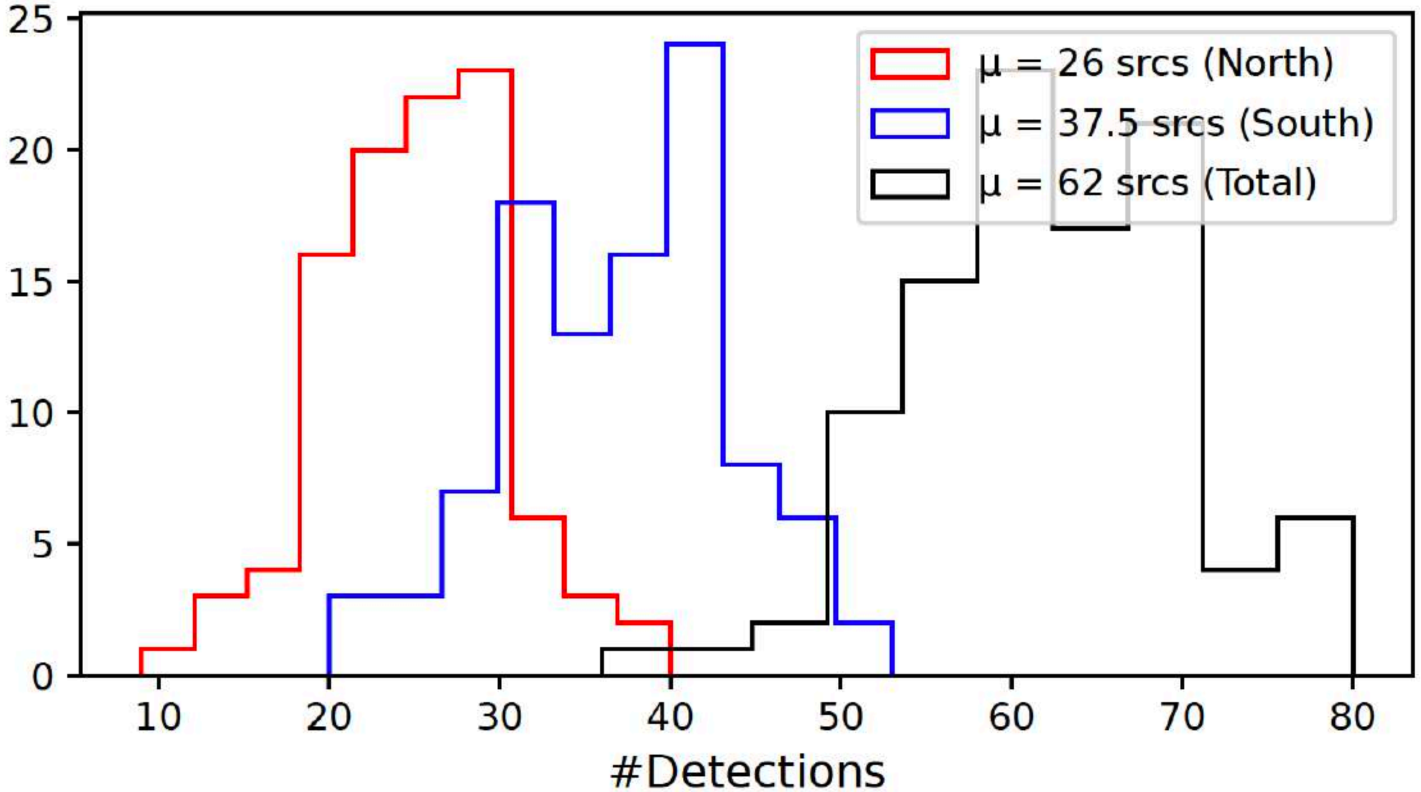
Credit: Luiz Augusto Stuani

Expected number of new detections

PRELIMINARY

ALPHA





OMEGA

Credit: Luiz Augusto Stuani

Summary

- There is robust evidences for EBL attenuation at TeV energies
- Any AGN population study at TeV energies need to properly account for EBL attenuation to assess AGN intrinsic properties
- Precisely measured SED are sensitive to both EBL and intrinsic AGN parameters
- Potential of an observatory like CTA is evident for this type of study
- The extragalactic survey is a CTA KSP and ideal for probing the AGN LF at the GeV-TeV energy range