Gamma-ray measurement of the cosmic optical and infrared backgrounds

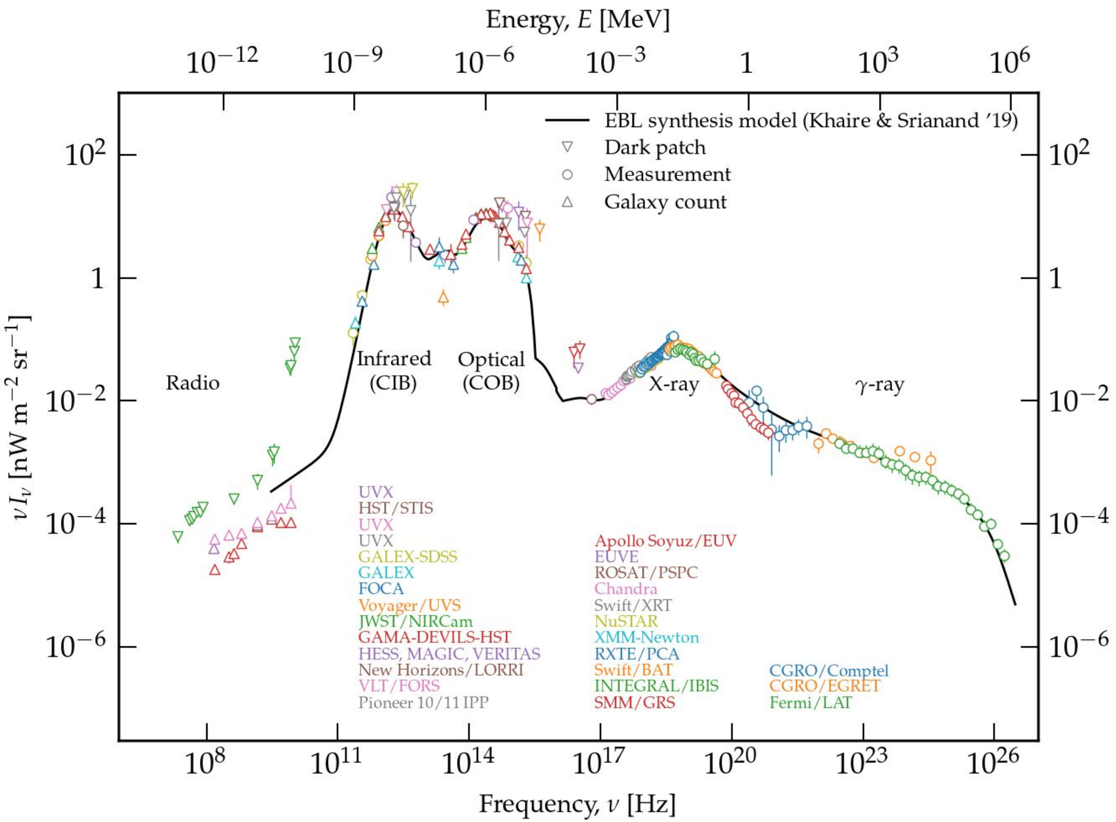
Lucas Gréaux, J. Biteau, M. Nievas-Rosillo

AstroParticle Symposium – 13.11.24

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

RUHR UNIVERSITÄT BOCHUM RUB

The panchromatic EBL: ~2023



Specific intensity:

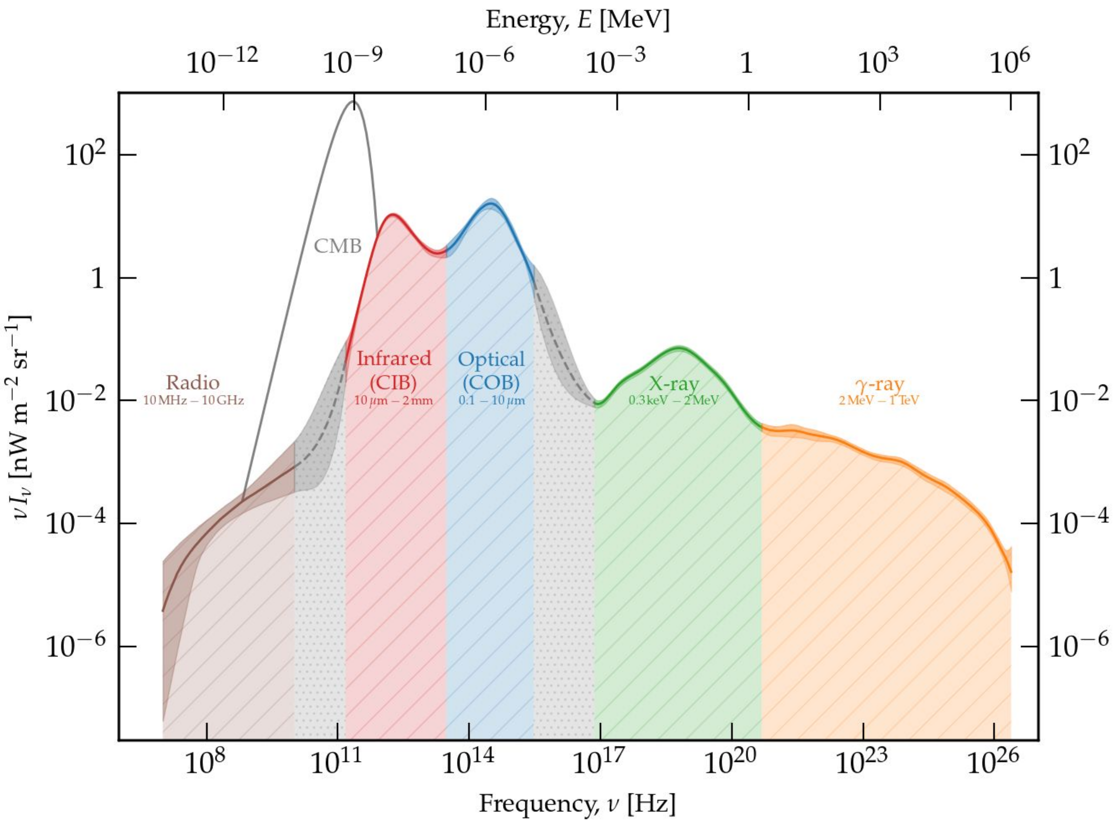
$$\nu I_\nu = \frac{c}{4\pi}\,\epsilon^2\,\frac{\partial n}{\partial \epsilon}$$

Dominated by the **cosmic optical background (COB)** and the **cosmic infrared background (CIB)**

Extragalactic Background Light, EBL

J. Biteau, 10.5281/zenodo.7842239

The extragalactic spectrum of the Universe



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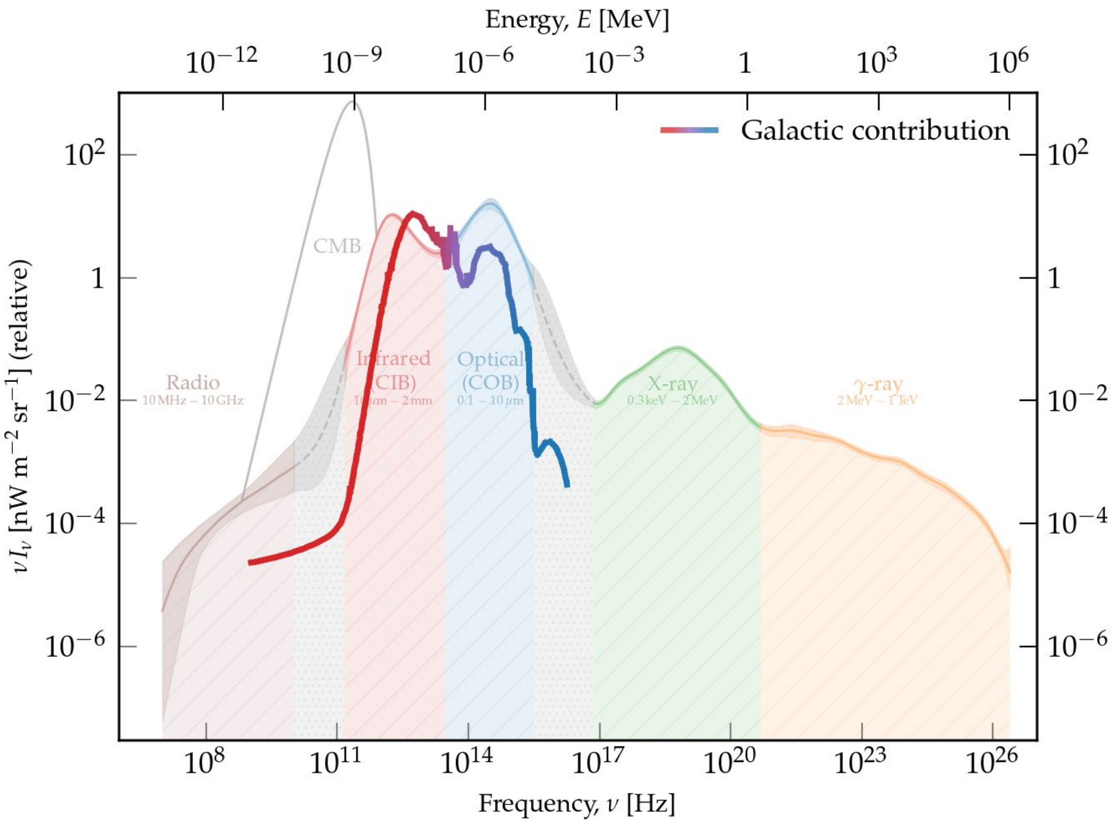
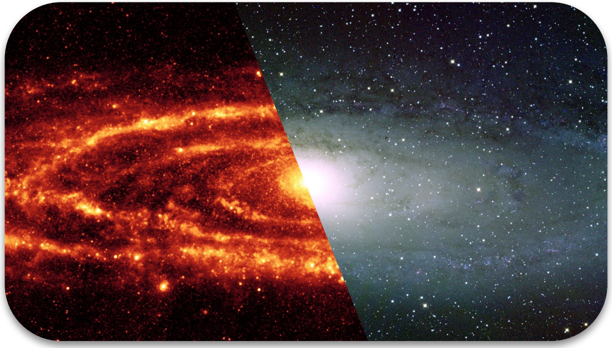
Contribution from stars in galaxies





Light from stars:

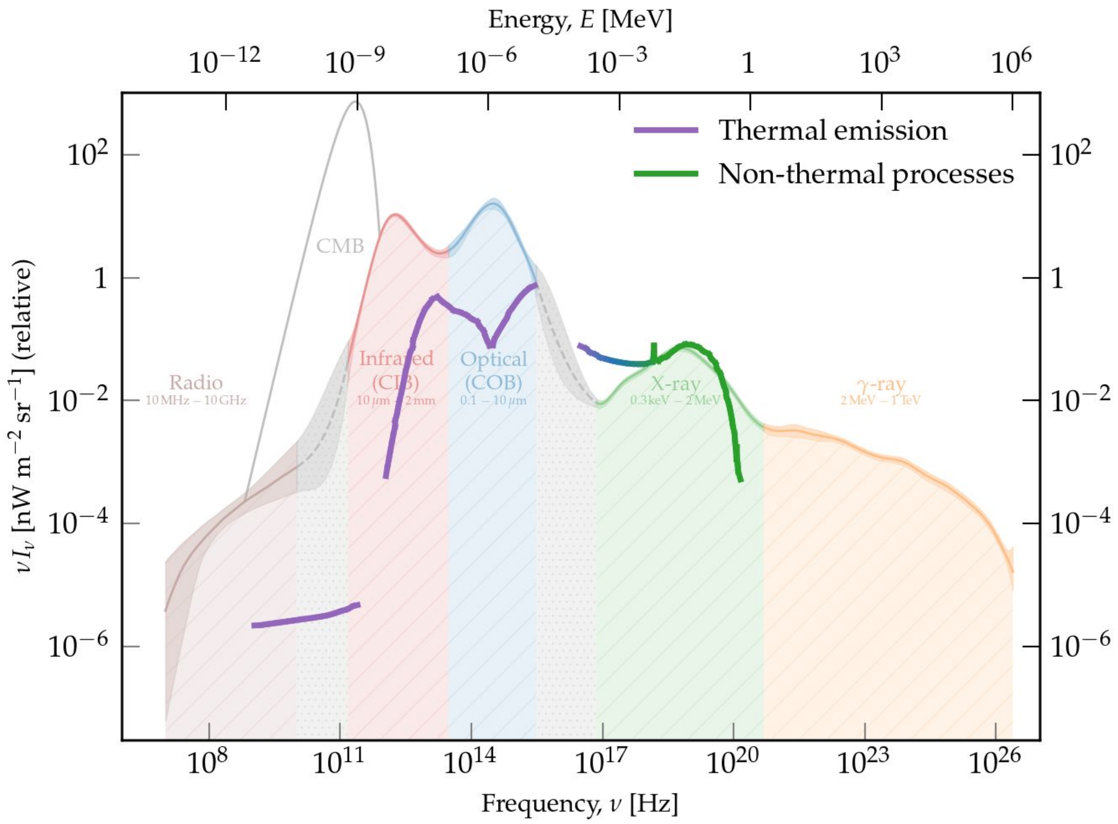
⇨ **Escaping the host**, optical contribution

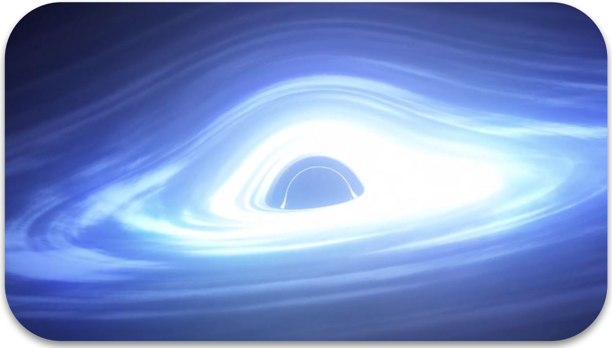
⇨ **Absorbed by dust**, reemitted in infrared

Adapted from J. Biteau, 10.5281/zenodo.7842239 and C. Harrison, 10.1007/978-3-319-28454-5

Credit: NOAO, AURA/NSF (optical) NASA, JPL-Caltech, K. Gordon (infrared)

Contribution from accretion on supermassive black holes





Active galactic nucleus, AGN

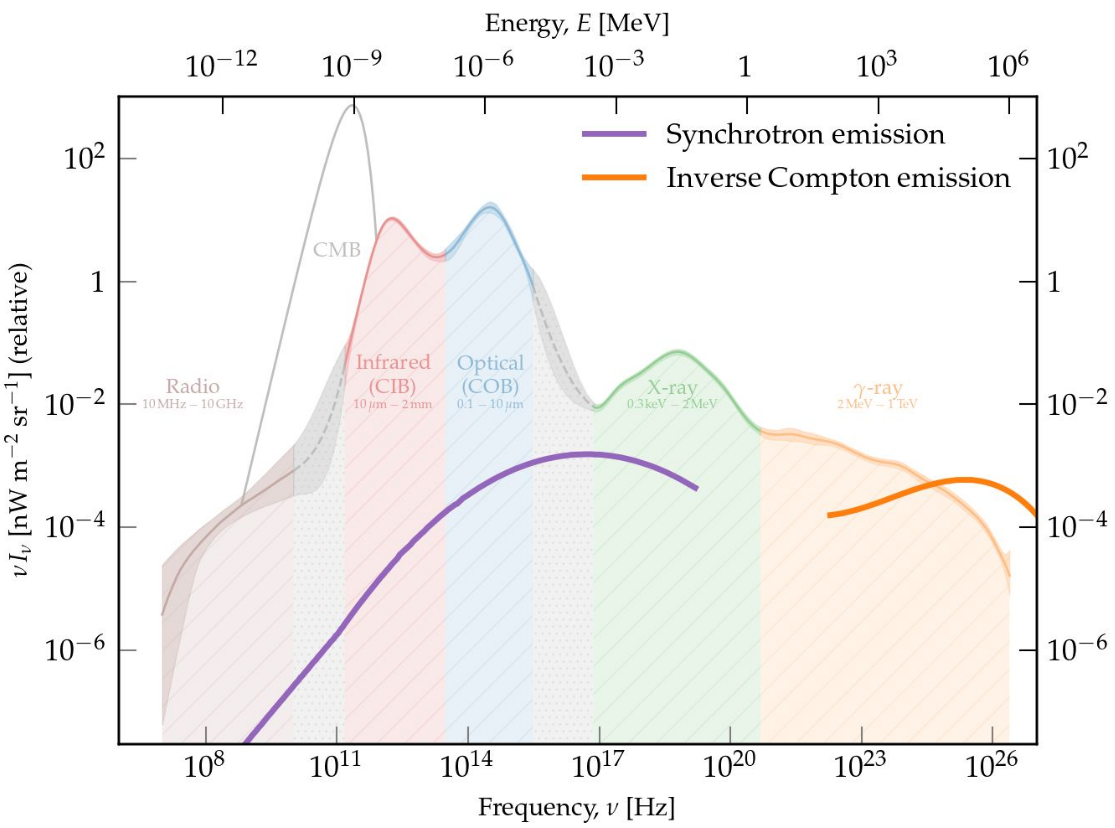
Compact region at galaxy center **outshining the host**

Thermal emission from **accretion disk**, **X-rays** from **non-thermal** processes

Adapted from J. Biteau, 10.5281/zenodo.7842239
and C. Harrison, 10.1007/978-3-319-28454-5

Credit: A. Roussel

Contribution from relativistic jets



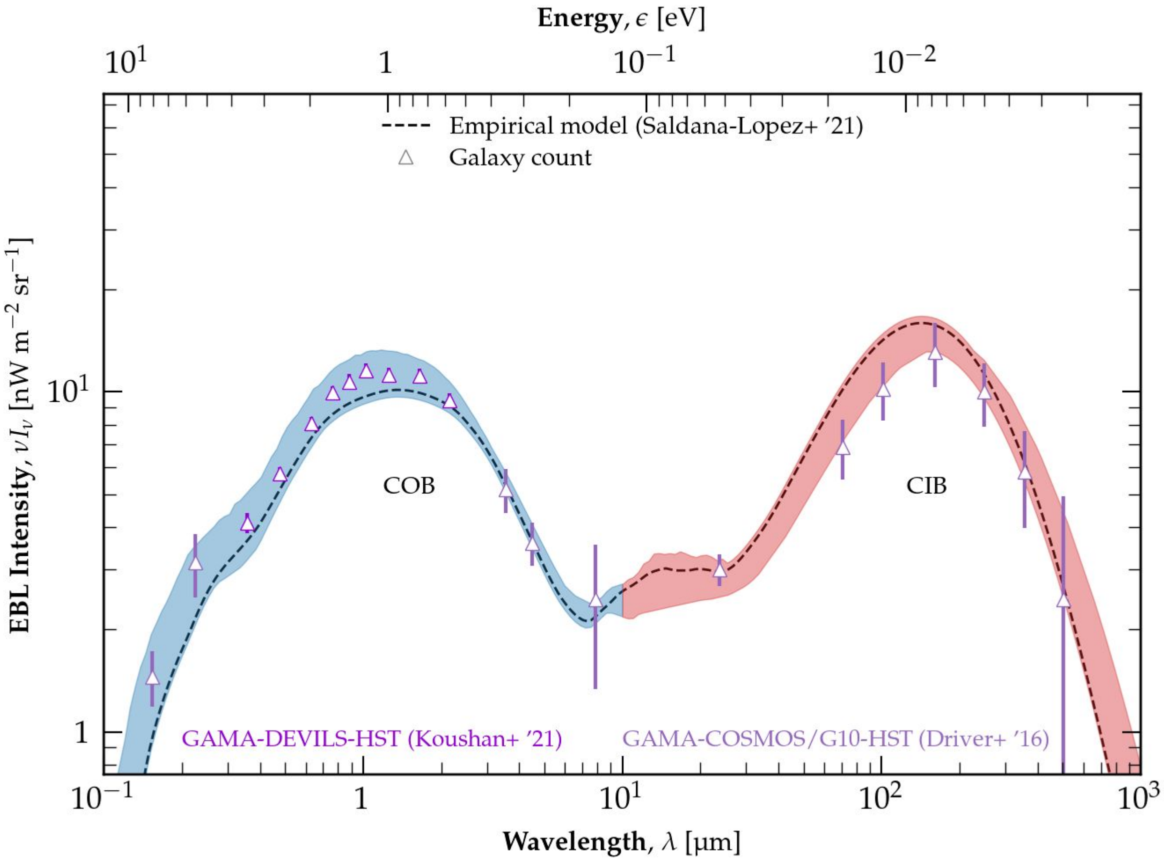
Some AGNs harbor **relativistic jets**

Typical jet spectrum show **two components**, **synchrotron** component at **low energies**, **inverse Compton** component in **γ-rays**

Adapted from J. Biteau, 10.5281/zenodo.7842239
and C. Harrison, 10.1007/978-3-319-28454-5

Credit: unknown author (from H.E.S.S. Collaboration)

EBL measurements from galaxy counts



Main EBL component: IGL, integrated galactic light

Measured from deep field **galaxy counts**

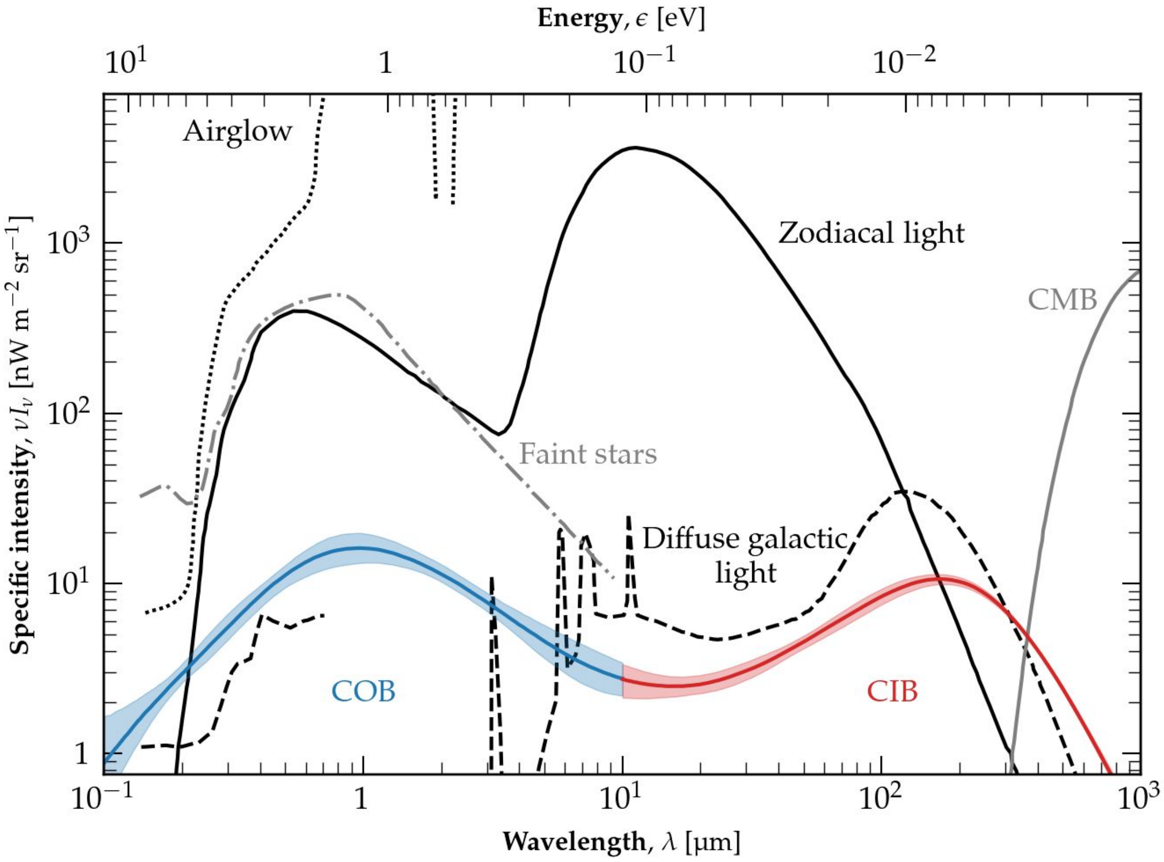
✕ Only **resolved galaxies**

⇨ Potential **diffuse**, **non-IGL components?**

- **Intra-halo light** (5-30% of EBL)
- Sources of **reionization** (0.1 - 0.8 nW m^{-2} sr^{-1})
- Low surface brightness galaxies
- Exotic processes

$$\nu I_\nu^{\mathrm{EBL}} = \nu I_\nu^{\mathrm{IGL}} \times (1 + f_{\mathrm{diff}})$$

The problem of foregrounds



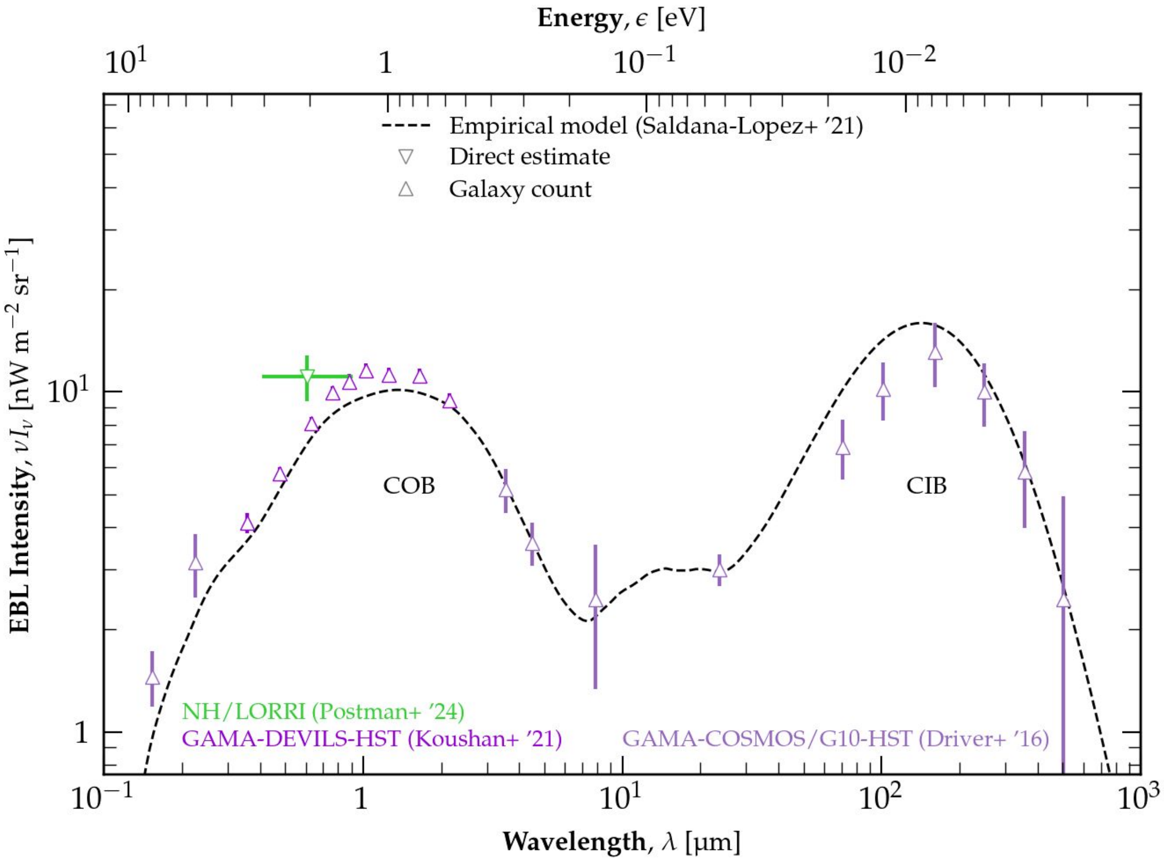
Direct measurements: EBL from remaining light after **subtraction of foregrounds**

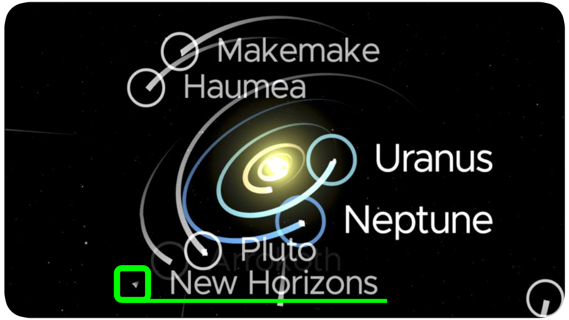
Zodiacal light:
Sunlight scattered on Solar System dust

- ✕ **Outshines the EBL** by more than an order of magnitude

Adapted from C. Leinert, 10.1038/128704a0 and J. Biteau, 10.5281/zenodo.7842239

EBL measurement from New Horizons





New Horizons probe:
Direct EBL measurement from **beyond Pluto's orbit**

- ✓ Agreement with **IGL** (**galaxy counts**)
- ✗ Only at **600nm** (400-900nm)

Outline of the presentation

01 Principles of γ-ray astronomy and γ-ray cosmology

The γ-ray sky and its interaction with the EBL

02 A new EBL measurements from γ-ray cosmology

From an era of discovery to an era of precision

03 Perspectives for the Cherenkov Telescope Array Observatory

What could future results look like?

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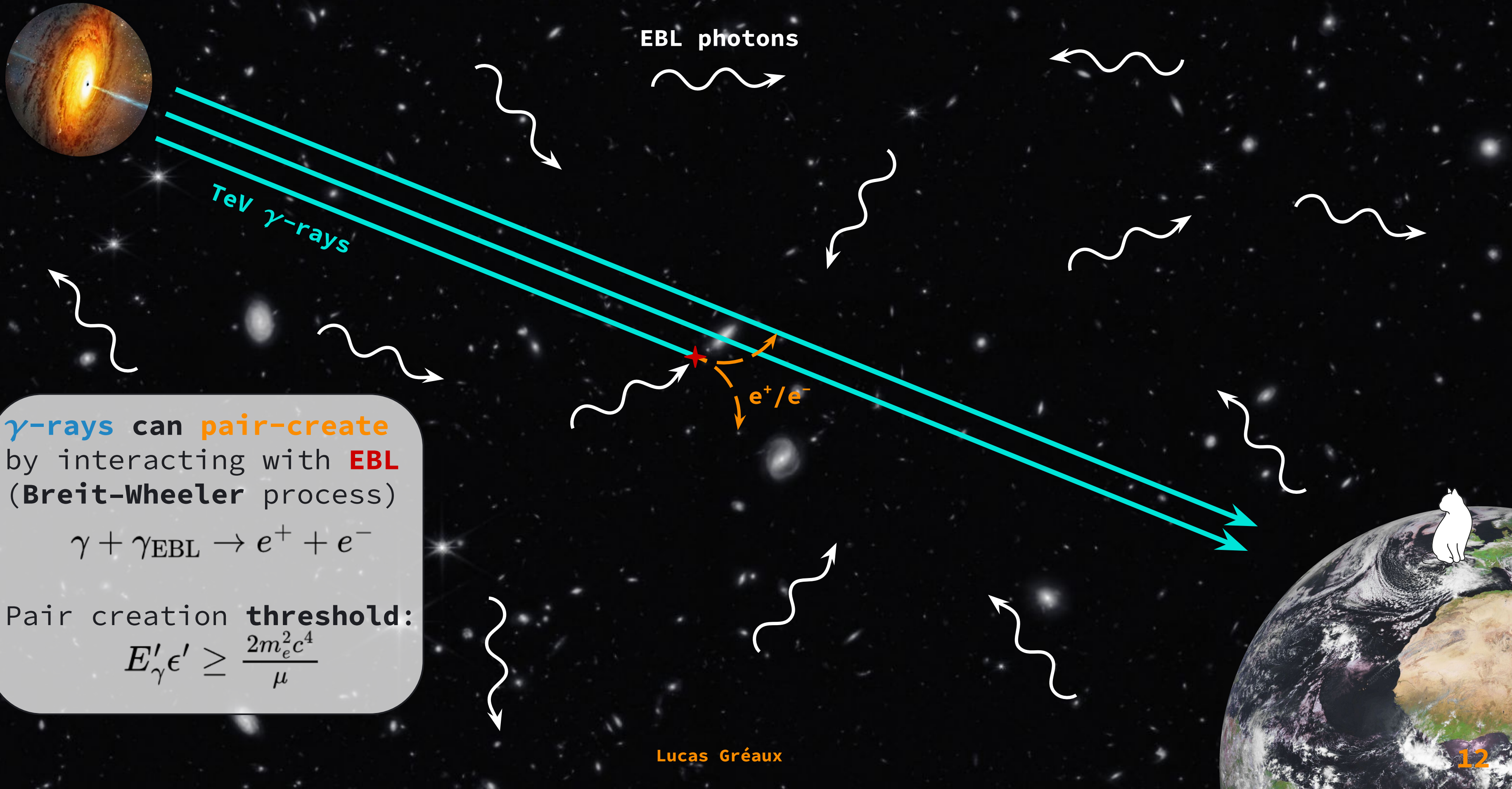
Gamma-ray propagation



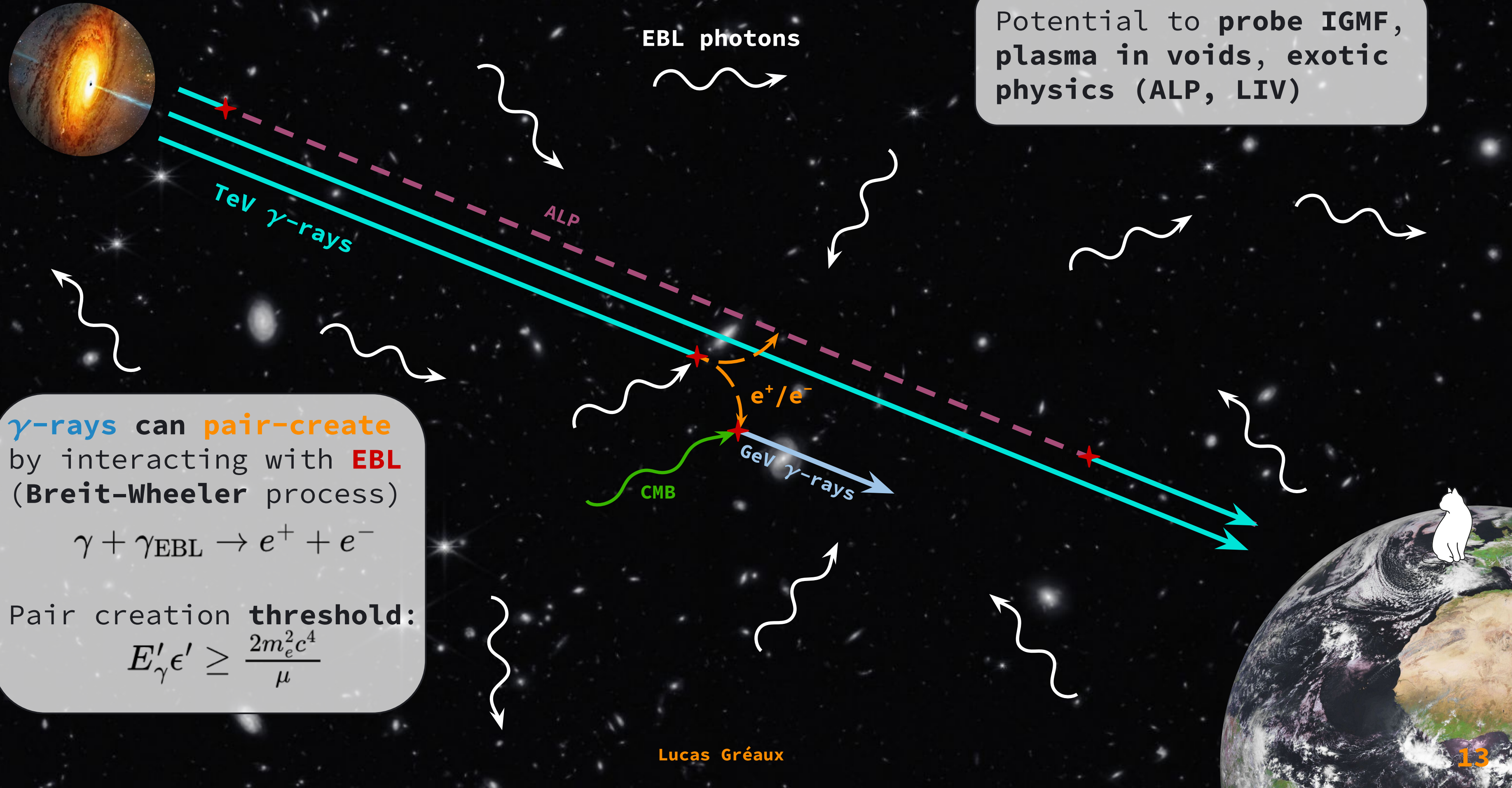
γ-rays can pair-create by interacting with **EBL** (**Breit-Wheeler** process)

$$\gamma + \gamma_{\mathrm{EBL}} \rightarrow e^+ + e^-$$

Pair creation **threshold:**

$$E'_\gamma \epsilon' \geq \frac{2 m_e^2 c^4}{\mu}$$

Gamma-ray propagation



Potential to **probe IGMF, plasma in voids, exotic physics (ALP, LIV)**

γ**-rays can pair-create** by interacting with **EBL** (**Breit-Wheeler** process)

$$\gamma + \gamma_{\mathrm{EBL}} \rightarrow e^+ + e^-$$

Pair creation **threshold:**

$$E'_\gamma \epsilon' \geq \frac{2m_e^2c^4}{\mu}$$

Gamma-ray cosmology

Optical depth τ, with **EBL transparency** $e^{-\tau}$

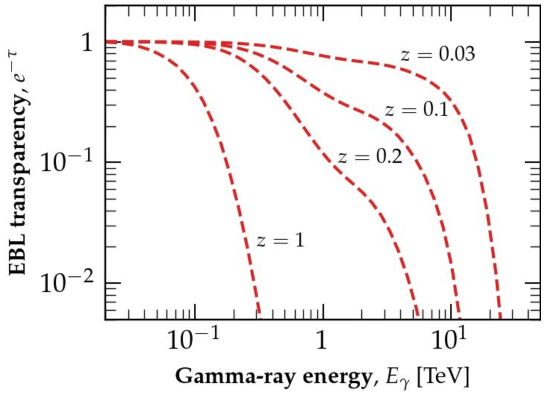
seen by γ-rays — $\propto 1/H_0$ — EBL density

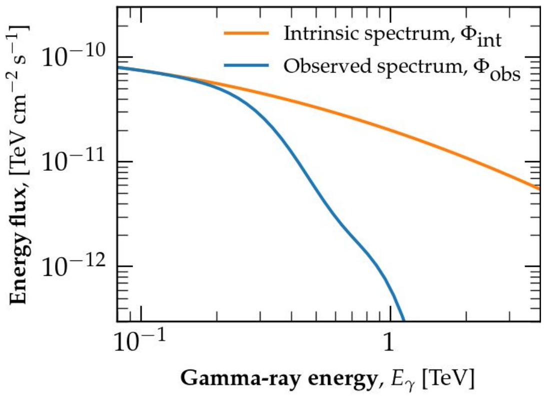
$$\tau(E_\gamma, z_0) = \int_0^{z_0} dz \frac{\partial L}{\partial z}(z) \int_0^{\infty} d\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) \int_{-1}^{1} d\mu \frac{1-\mu}{2} \sigma_{\gamma\gamma}(E_\gamma(1+z), \epsilon, \mu)$$

$\gamma\gamma$ cross-section

TeV γ**-ray suppression:** $\Phi_{obs} = \Phi_{int} \times e^{-\tau}$

observed — emitted





Source at z=0.2, EBL model: Saldana-Lopez+ ‘21

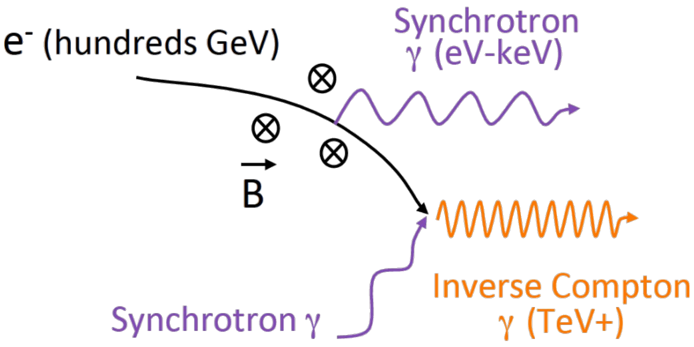
Simplified emissions from relativistic jets

Synchrotron radiation

- ⇨ Ultrarelativistic **electrons** ($\gamma \geq 10^3$) in **magnetic field**
- ⇨ Peaking in UV / X-rays, E_{sp}
- ⇨ **Power-law** spectrum at 1st order

Inverse Compton (leptonic scenario)

- ⇨ Ultrarelativistic **electrons** upscattering synchrotron photon, **Synchrotron self-Compton**
- ⇨ Peaking in **γ-rays**, E_{cp}
- ⇨ **Power-law** spectrum at 1st order



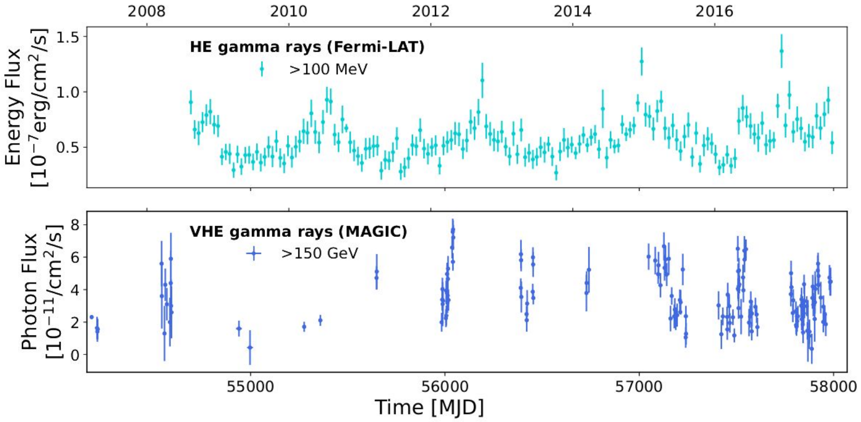
A. De Angelis, M. Pimenta, 10.1007/978-3-319-78181-5

Observed extragalactic sources of γ-rays

Blazars: AGNs with **jets** aligned with the **line of sight**

⇨ **Relativistic beaming**, boosted bolometric luminosity, very bright objects

⇨ **Highly variable** (down to minute)



High energy (HE): 0.1 - 300 **GeV**

⇨ Satellite (*Fermi*-LAT)

⇨ Regular, full sky observations

Very-high energy (VHE): 0.1 - 300 **TeV**

⇨ Ground based telescopes

⇨ Pointed observations

MAGIC Collaboration, 10.1093/mnras/stae649

Gamma-ray astronomy at VHE

Charged particles with $v > c/n$ induce emission of coherent **Cherenkov light**

⇨ Observed with **Imaging Atmospheric Cherenkov Telescopes (IACTs)**

Pair creation:

$$\gamma + X \rightarrow e^{+} + e^{-} + X$$

Bremsstrahlung:

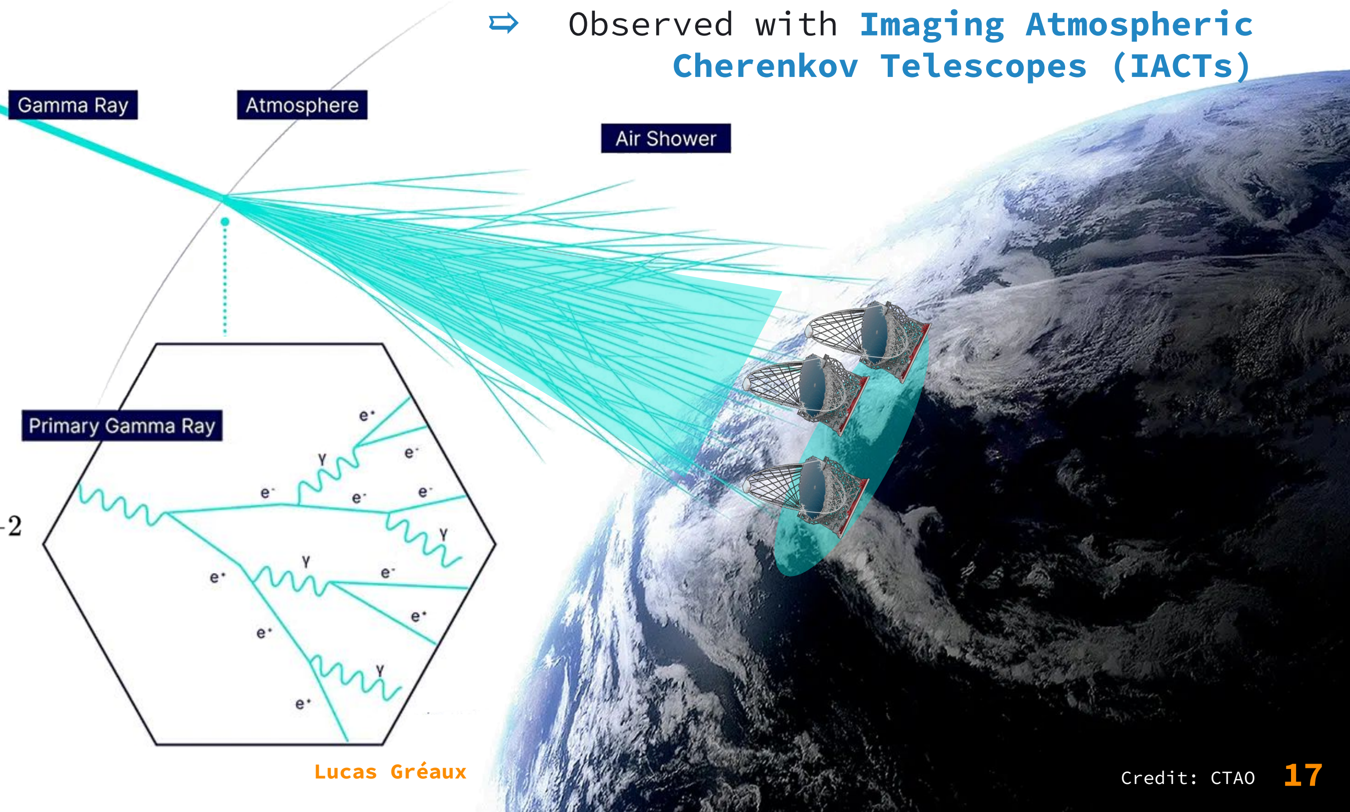
$$e^{\pm} + \mathrm{X} \rightarrow e^{\pm} + \mathrm{X} + \gamma$$

Radiation length:

$$X_0 \approx 40\,\mathrm{g\,cm}^{-2}$$

Atmosphere: $\sim 1000\,\mathrm{g\,cm}^{-2}$

⇨ Fully developed **electromagnetic cascade**

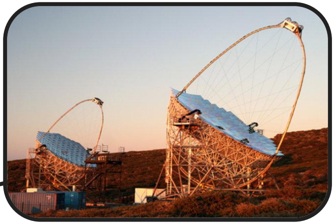


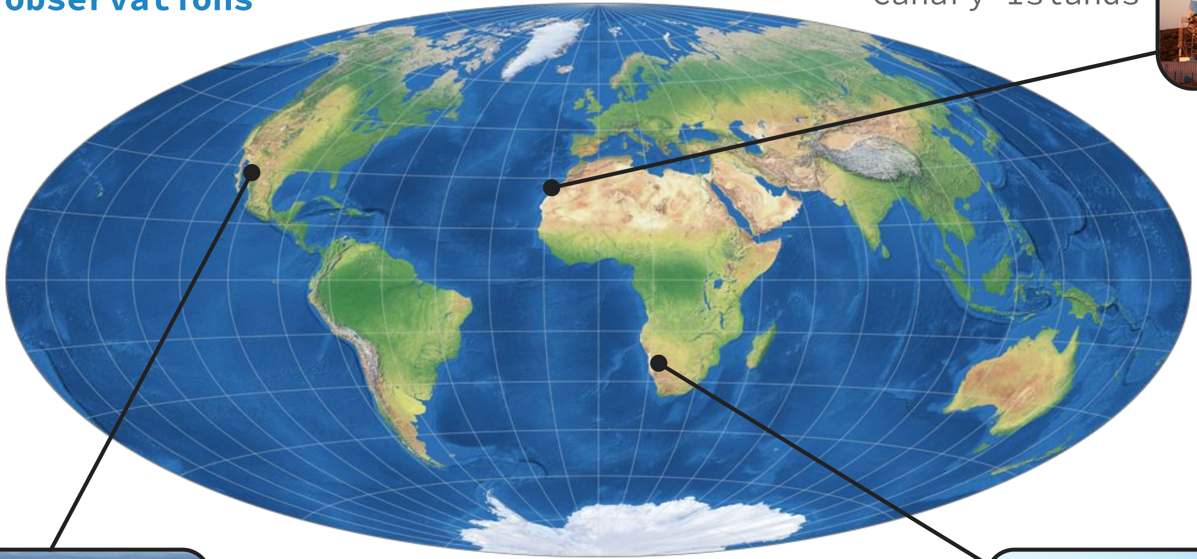
Credit: CTAO

The current generation of IACTs

Three **independent collaborations** operating IACTs performing **stereoscopic observations**

MAGIC (2004)
Roque de los Muchachos
Canary Islands

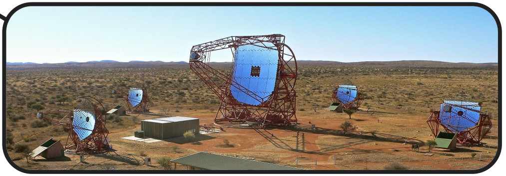




Catalog of sources:
⇨ **TeVCat**

VERITAS (2008)
Mount Hopkins
Arizona

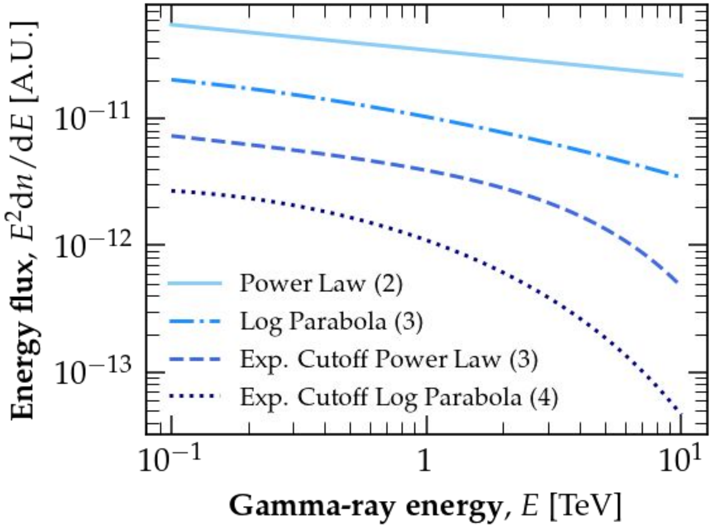
H.E.S.S. (2002)
Khomas Highland
Namibia



Credit: H.E.S.S., MAGIC, VERITAS Collaborations

Frequentist modelling of intrinsic spectra

Expected spectral shape
Power law, with or without **curvature**, with or without exponential **cutoff**



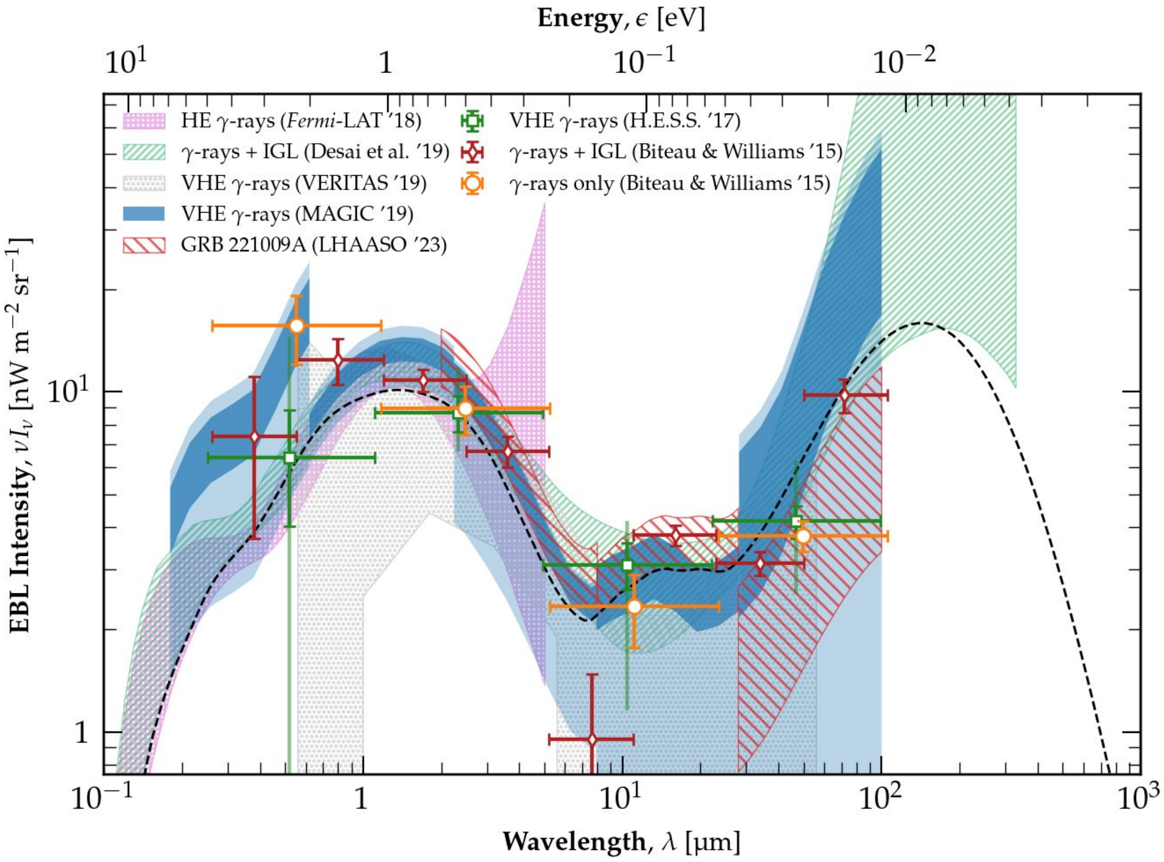
Frequentist framework

1. With **fixed EBL** parameters, **find** best set of **spectral shapes**
2. With **given spectral shapes**, **find best EBL** parameters
3. **Repeat** until **convergence**

✗ **Arbitrary** model selection **criterion** for the spectral shapes (e.g. $\geq 2\sigma$)

✗ **Uncertainties** on spectral shape **are not propagated** on EBL uncertainties

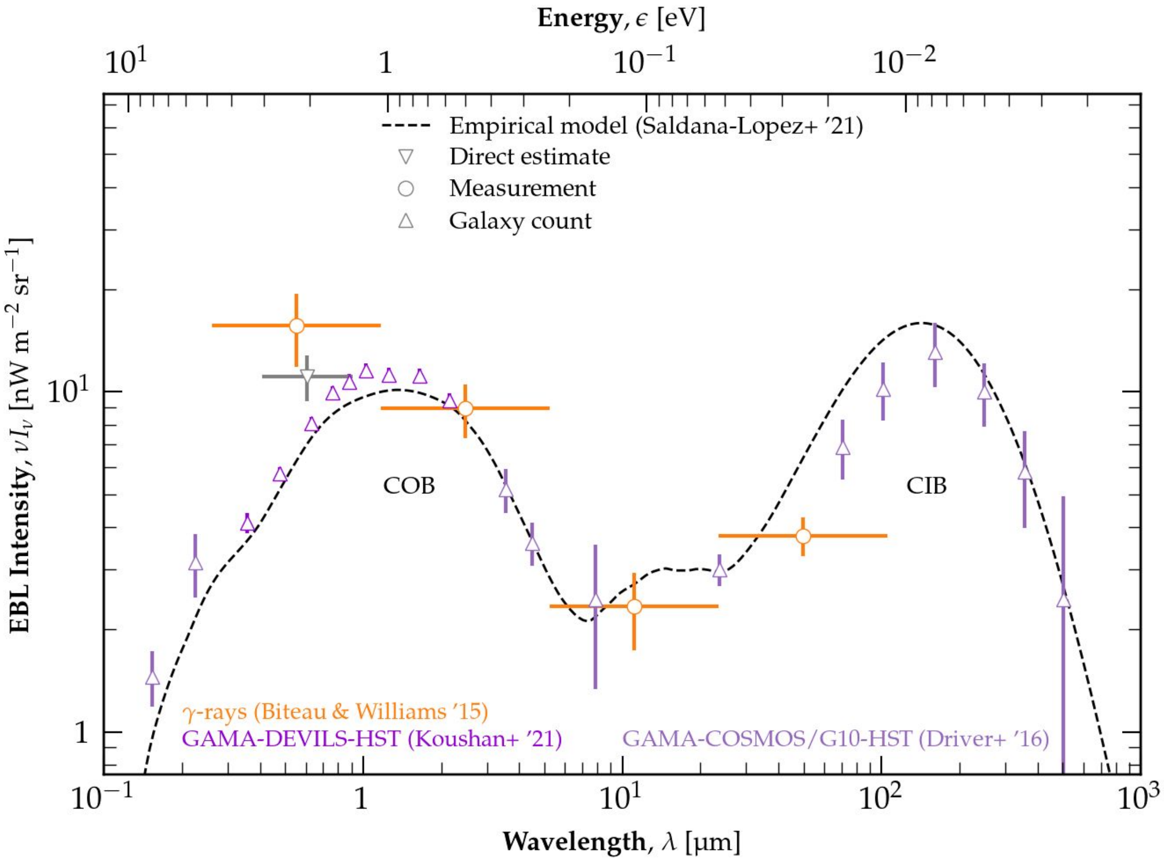
EBL measurements from gamma-ray cosmology



γ-ray cosmology:
Reconstruct EBL using the **absorption imprint** on TeV spectra

$$\Phi_{\rm obs} = \Phi_{\rm int} \times e^{-\tau}$$

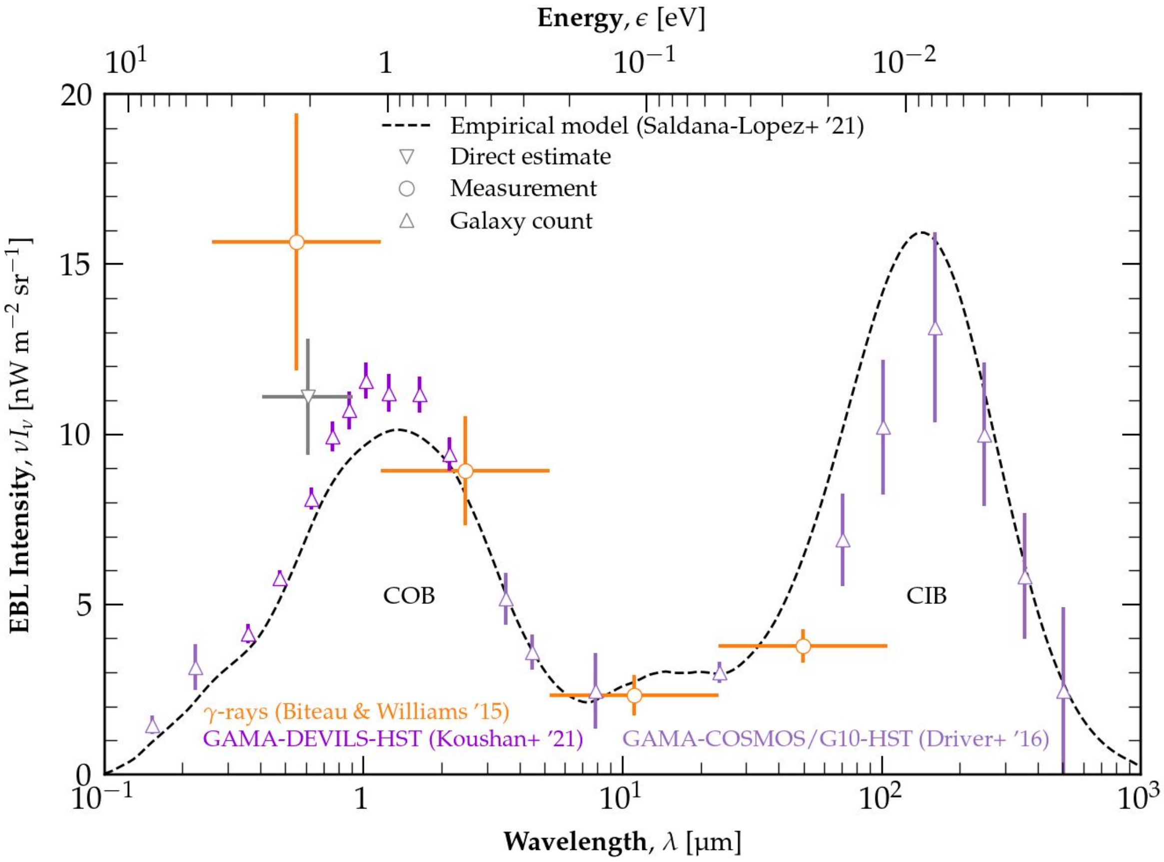
EBL measurements from gamma-ray cosmology



γ-ray cosmology:
Reconstruct EBL using the **absorption imprint** on TeV spectra

✓ Agreement with **IGL**

EBL measurements from gamma-ray cosmology



γ-ray cosmology:
Reconstruct EBL using the **absorption imprint** on TeV spectra

- ✓ Agreement with **IGL**
- ✗ Lacking **precision**

Non-IGL contributions to the EBL not sufficiently constrained

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What could future results look like?

STeVECat, the Spectral TeV Extragalactic Catalog

Most comprehensive catalog to date of **archival spectra** published by **current IACTs**

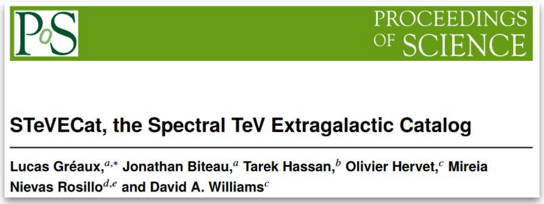
⇨ **403 spectra** from **78 sources**

International work

⇨ France (IJCLab)
⇨ Spain (CIEMAT, IAC)
⇨ USA (UCSC)

Publicly accessible from [Zenodo repository]()

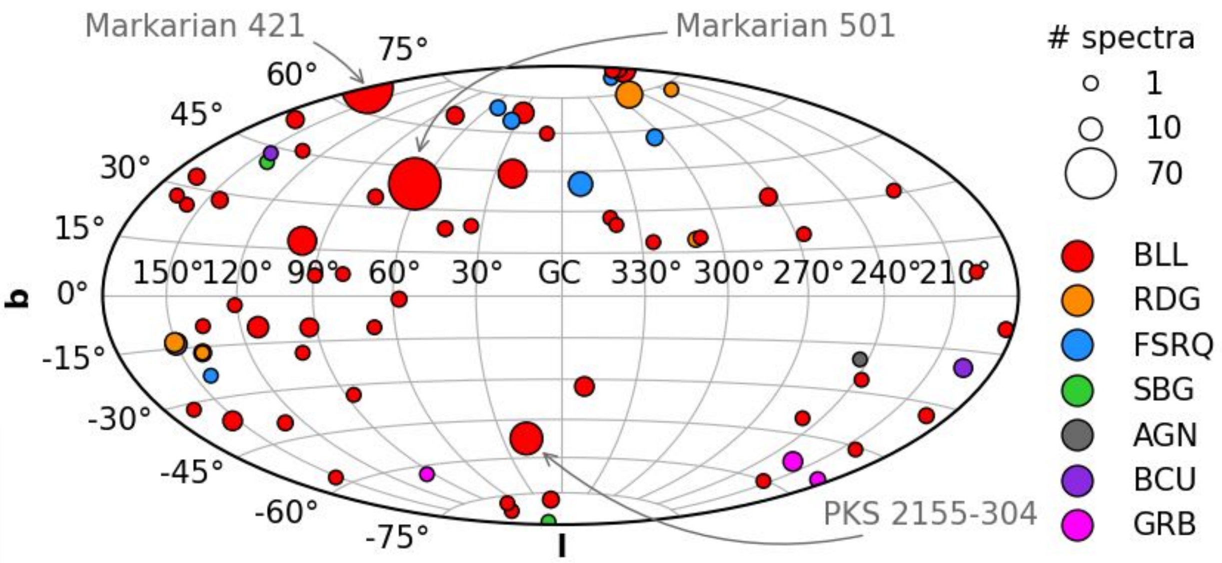
Reference: **ICRC 2023**



PROCEEDINGS OF SCIENCE

STeVECat, the Spectral TeV Extragalactic Catalog

Lucas Gréaux,[a,*] Jonathan Biteau,[a] Tarek Hassan,[b] Olivier Hervet,[c] Mireia Nievas Rosillo[d,e] and David A. Williams[c]



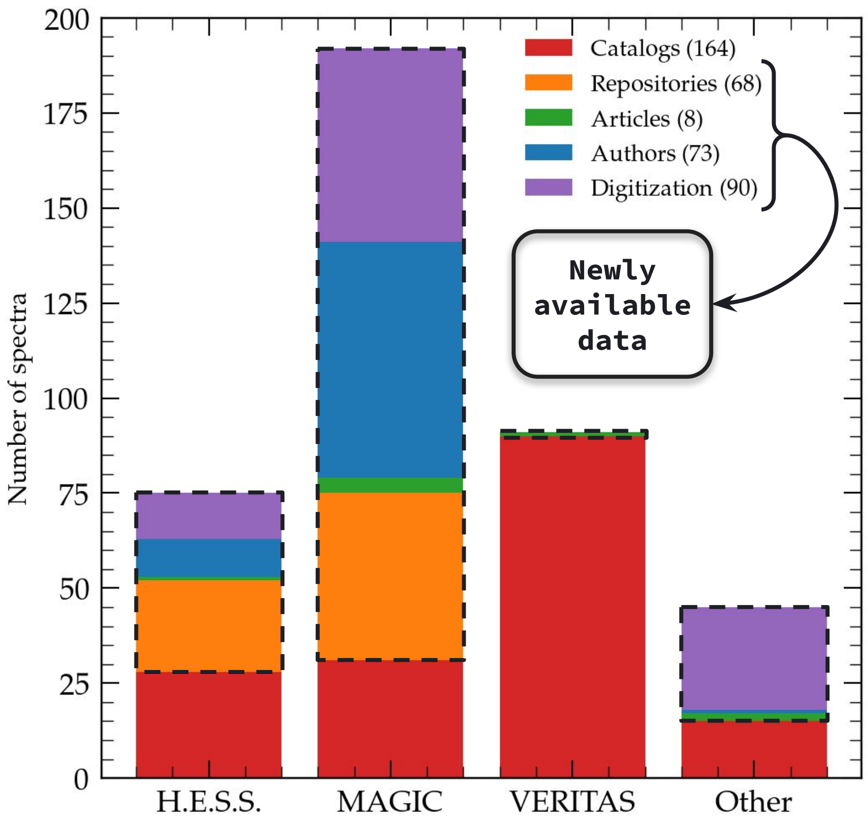
Collecting data for STeVECat

List of **extragalactic spectra** from **articles appearing in TeVCat**

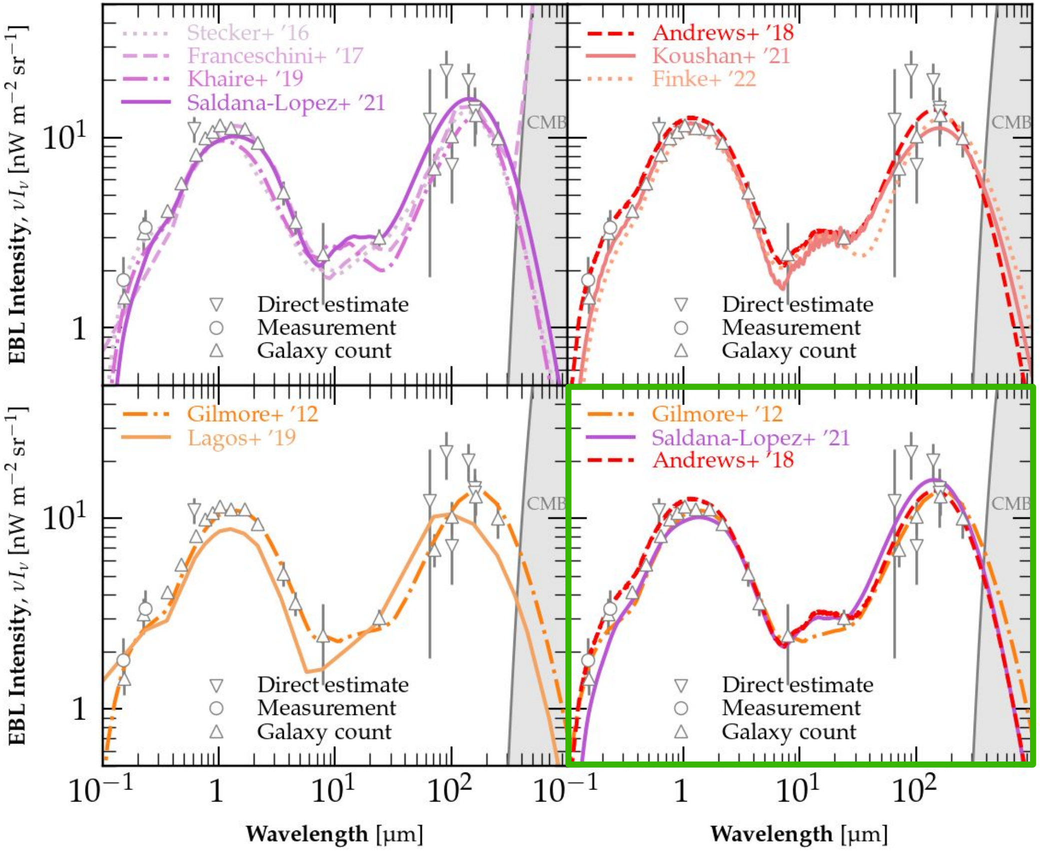
Extracted corresponding spectra from:

- ⇨ **Existing catalogs**: GammaCat, VTSCat
- ⇨ **Public repositories** of IACTs
- ⇨ Data from **journal articles**
- ⇨ Emails with **corresponding authors**
- ⇨ **Digitization** of the figures

Literature completeness checked with analysis of articles' **number of authors**



TeV appraisal of EBL models at z < 1



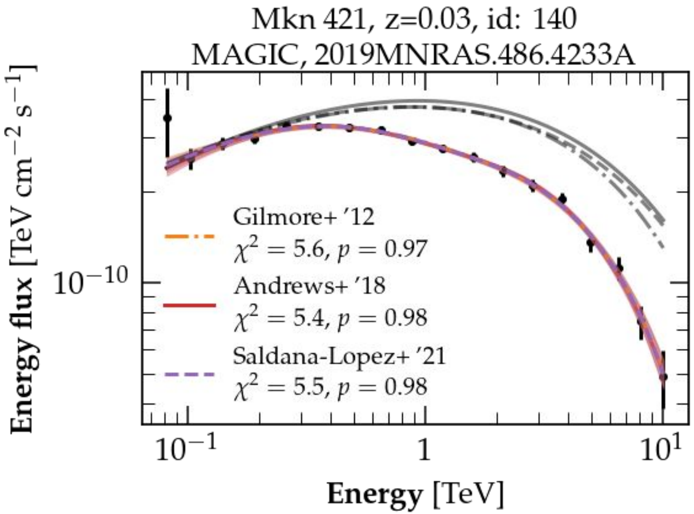
Empirical models:
Galaxy-counts, redshift distributions, luminosity functions

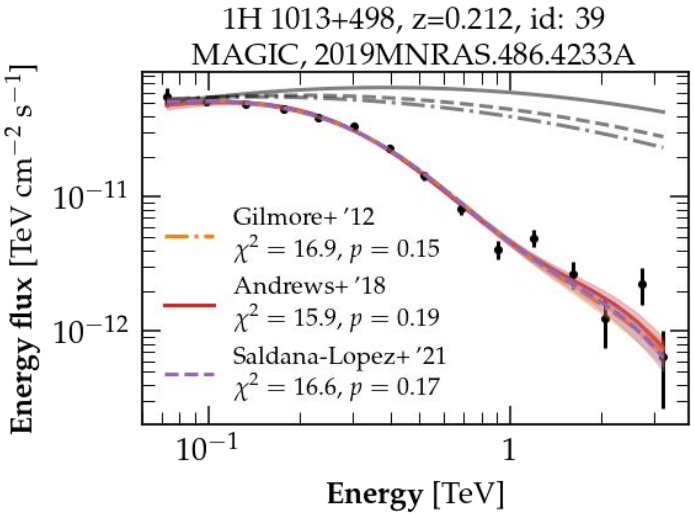
Phenomenological models:
History of star formation, stellar evolution

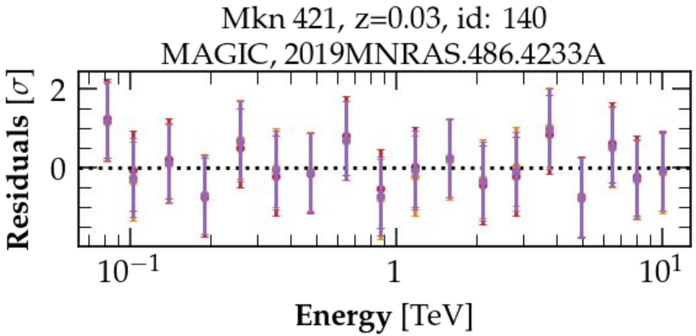
***A priori* models**:
N-bodies / hydrodynamical simulations of universe evolution

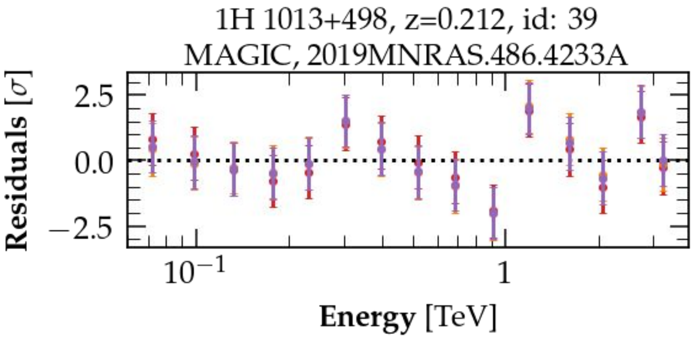
Best match with direct & IGL:
⇨ Saldana-Lopez+ '21
⇨ Gilmore+ '12
⇨ Andrews+ '18

Impact on reconstructed TeV spectra









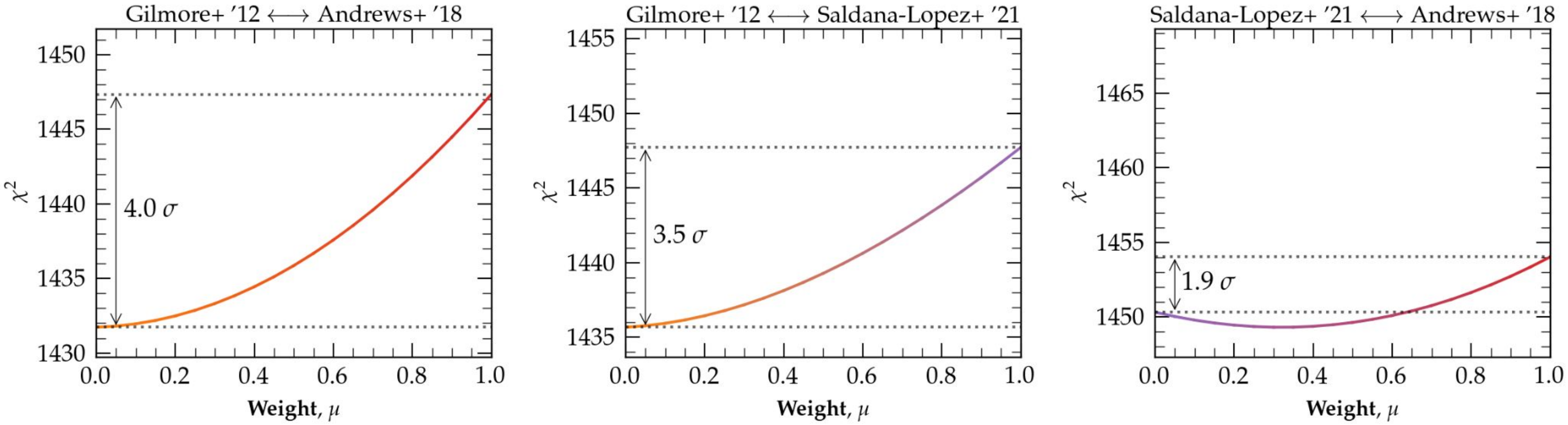
Comparison between the EBL models

Work with **linear combination** between the models of interest:

⇨ **Weight parameter μ:**
$\tau_\mu = (1-\mu)*\tau_1 + \mu*\tau_2$

Gilmore+ '12 favored at **more than 3σ** by gamma-ray observations wrt **Andrews+ '18** & **Saldana-Lopez+ '21**

⇨ **Paper in preparation** (see Antonio's talk)



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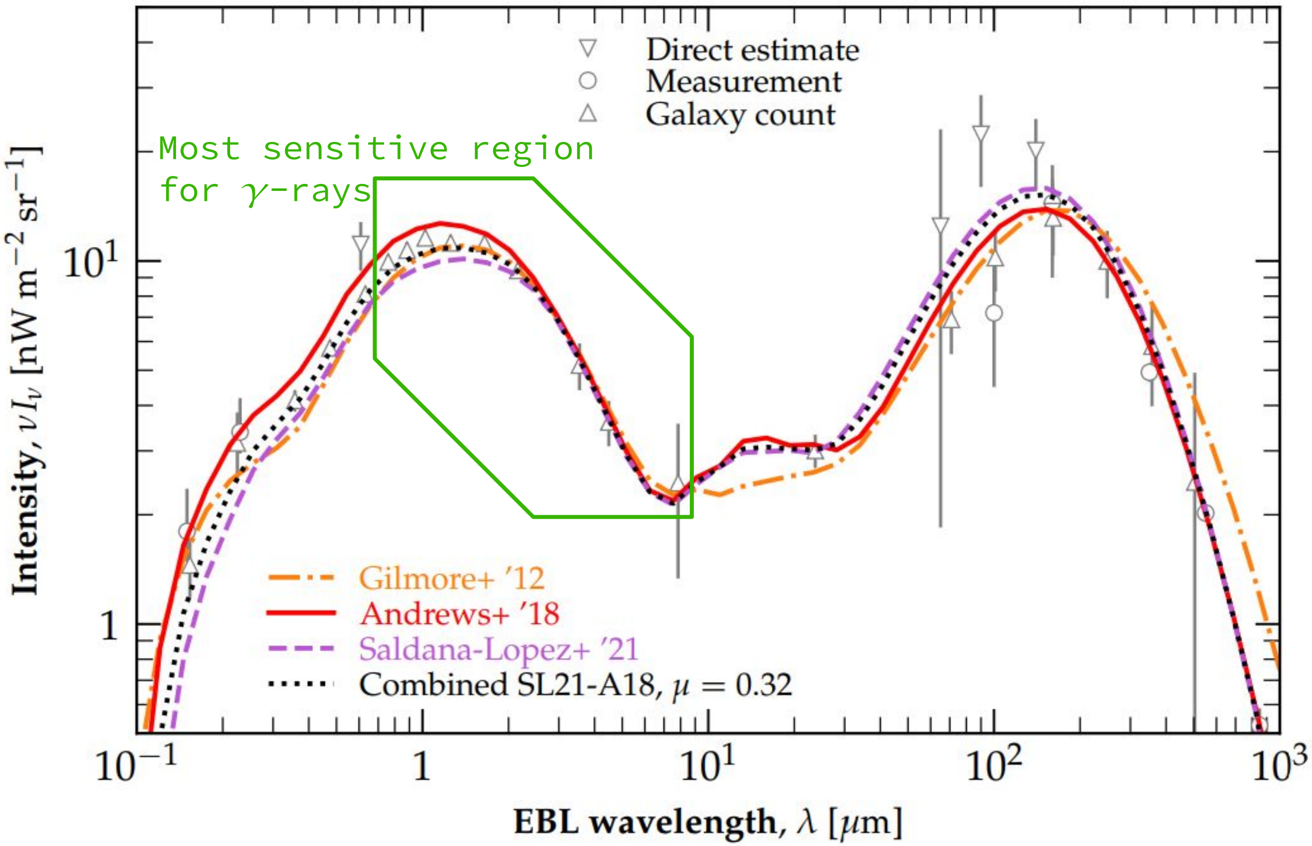


1st improvement - Updated data sample

TeV data from **STeVECat**:

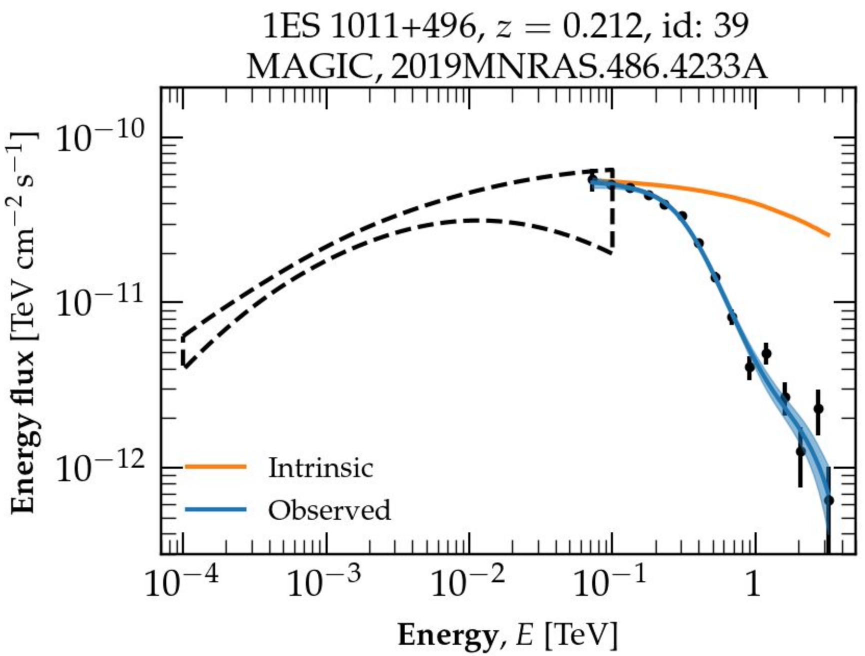
- At least **4 points**
- Sources with known **redshift > 0.01**

⇨ **268 spectra** (**86 for B&W'15**), z < 1

GeV data from ***Fermi*-LAT**

- **Contemporaneous** to TeV
- Analysis assuming **curvature**
- **Used as priors** for spectral index and curvature

⇨ **64 spectra** with GeV counterpart



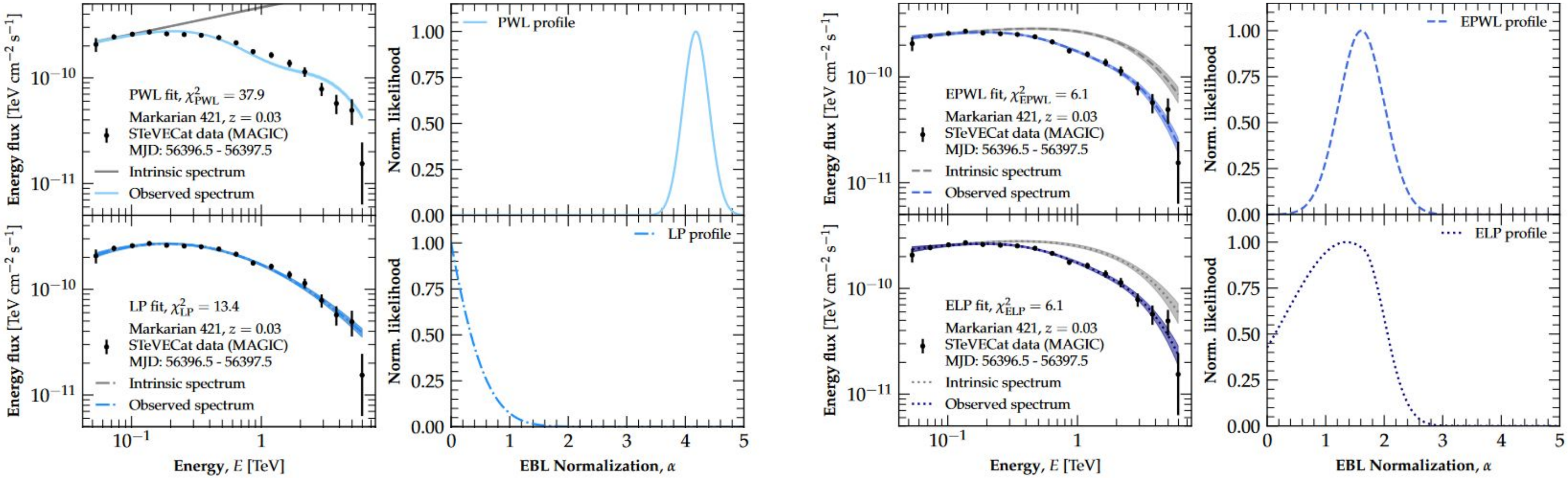
Shortcomings of the frequentist analysis

Expected spectral shape

Chosen between **power law**, with/without **curvature**, with/without exp. **cutoff**

❌ **Arbitrary** model selection **criterion**

❌ **Uncertainties** on spectral shape **are not propagated** on EBL uncertainties



Scaled EBL model: $\tau(E, z, a) = a \times \tau_{\mathrm{ref}}(E, z)$

2^{nd} improvement - The Bayesian Framework as an answer

Expected spectral shape

All spectra modeled with **log parabola with exponential cutoff** (ELP)

Parameters: a EBL, Θ spectral

$$\phi_{\mathrm{ELP}}(E,\Theta) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\log\left(\frac{E}{E_0}\right)} e^{-\lambda E}$$

$$\phi_{\mathrm{m}}(E,z,\Theta,a) = \phi_{\mathrm{ELP}}(E,\Theta) \times e^{-\tau_{\mathrm{m}}(E,z,a)}$$

Bayesian framework

$$\underbrace{\mathbf{Pr}(a|\mathcal{D})}_{\text{Posterior}} = \frac{\overbrace{\mathbf{Pr}(\mathcal{D}|a)}^{\text{Likelihood}}\,\underbrace{\mathbf{Pr}(a)}_{\text{Prior}}}{\int \mathrm{d}a\,\mathbf{Pr}(\mathcal{D}|a)\mathbf{Pr}(a)}$$

Marginalization:

$$\mathbf{Pr}(a|\mathcal{D}) = \int \mathrm{d}\Theta\,\mathbf{Pr}(a,\Theta|\mathcal{D})$$

Compute the **full probability distribution** and **marginalize** over spectral parameters

- ✓ **Removed** arbitrary **selection criterion**
- ✓ Inclusion of **nuisance parameters: energy-scale** bias, **ε**

2^{nd} improvement - Implementing the framework

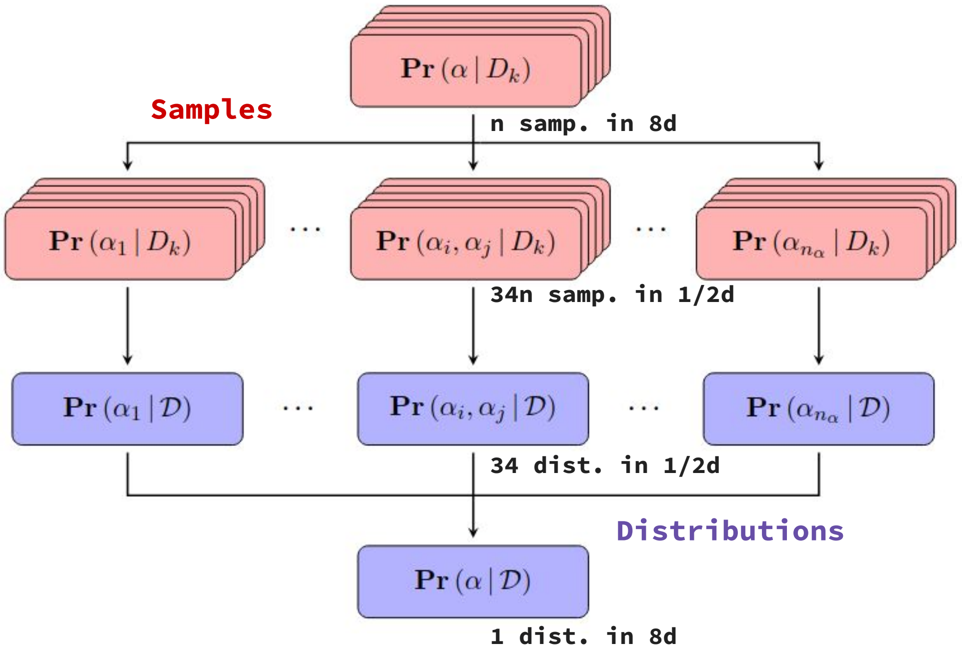
Sample the posterior distribution using **Markov chains Monte Carlo** using **uninformative priors**

✕ **Heavy computation time**, **$O(n^3)$**

Reworked the problem to analytically and numerically **decrease complexity**

✓ **Computation time** in **$O(n)$**

Reduction by **factor ~70 000**
(n = 268 spectra)



Spectrum and evolution decoupling

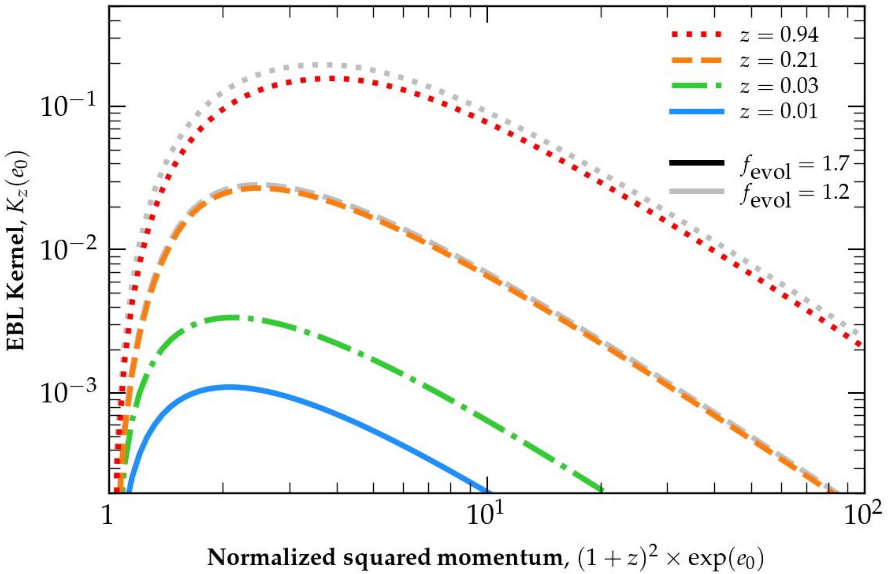
Assume **decoupling** between **EBL spectrum** and **EBL evolution**

$$\mathrm{d}\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) = \mathrm{d}\epsilon_0 \frac{\partial n}{\partial \epsilon_0}(\epsilon_0, 0) \times evol(z)$$

$$evol(z) = (1+z)^{3-f_{\mathrm{evol}}}$$

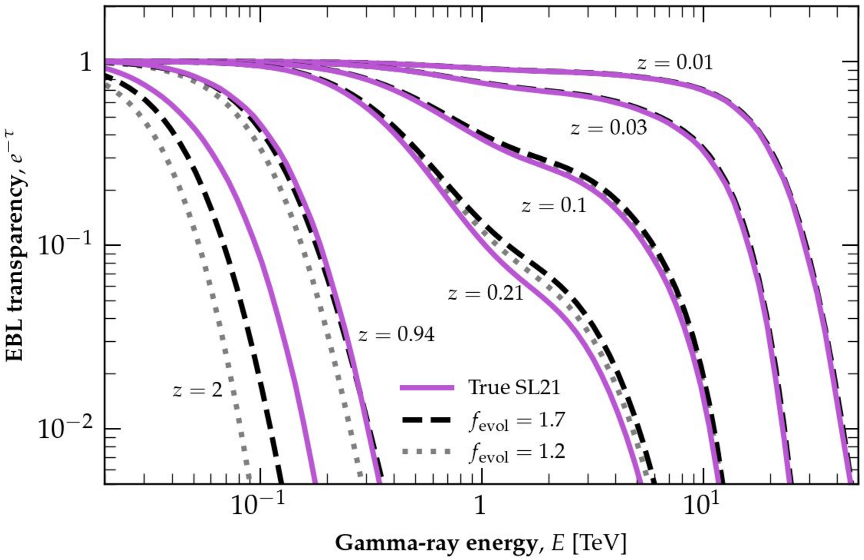
Optical depth computed as **convolution of specific intensity and EBL kernel**

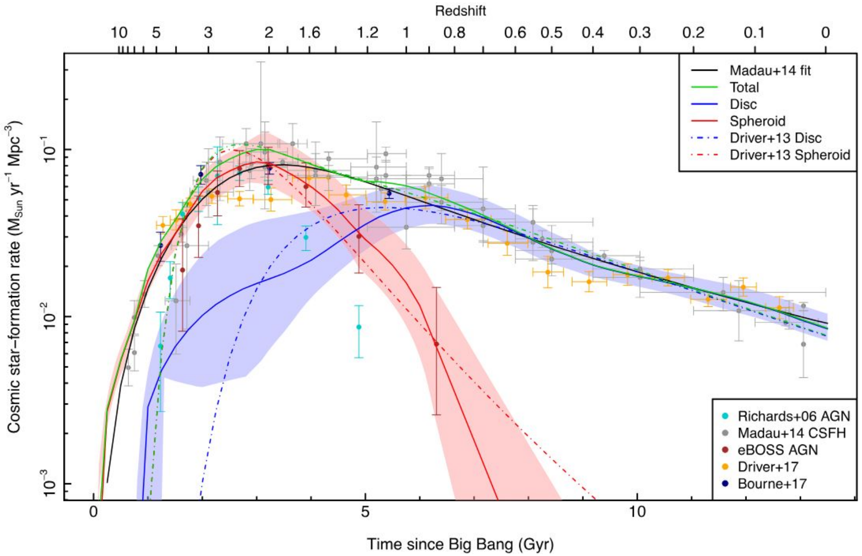
$$\tau(E, z) = \frac{3\pi\sigma_T}{H_0} \times \frac{E}{m_e^2 c^4} \times \nu I_\nu \otimes K_z\left(\ln \frac{E}{m_e c^2}\right)$$



With $e_0 = \ln(E\epsilon_0/m_e^2 c^4)$

Impact on the EBL transparency





S. K. Andrews, 10.1093/mnras/stx2843

3rd improvement - Model independent EBL parametrization

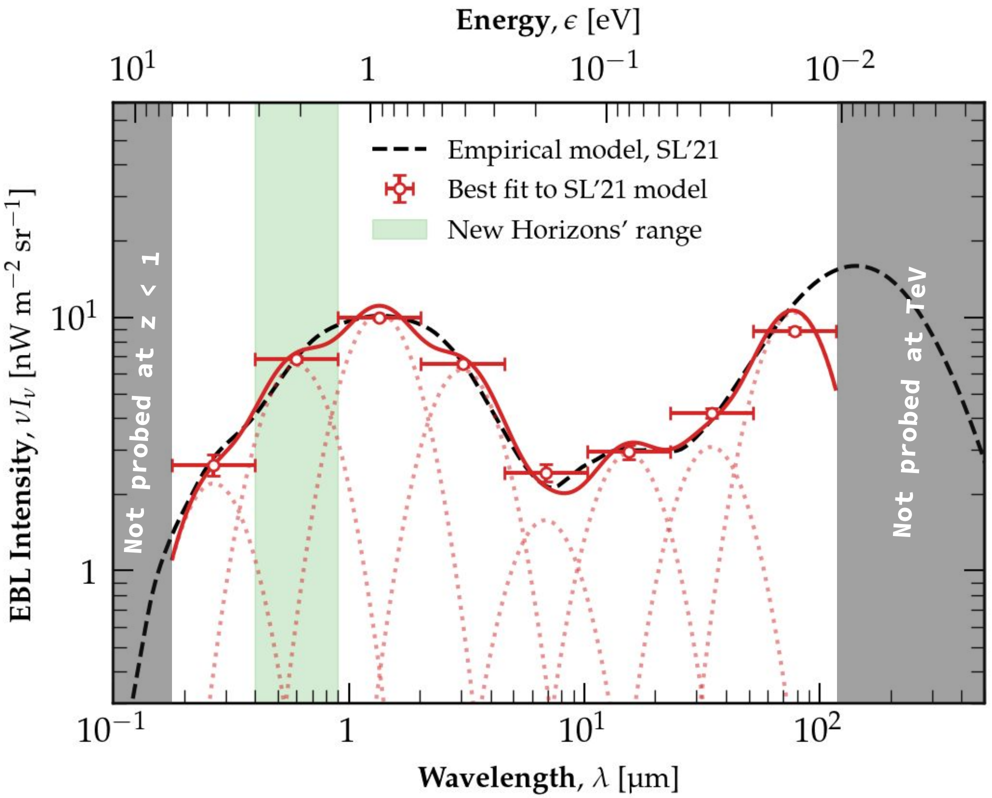
Parametric **EBL model**:

$$\nu I_\nu(l, z, a) = \sum_{i=1}^{8} a_i \, \nu I_\nu^i \times (1+z)^{4-f_{\rm evol}}$$

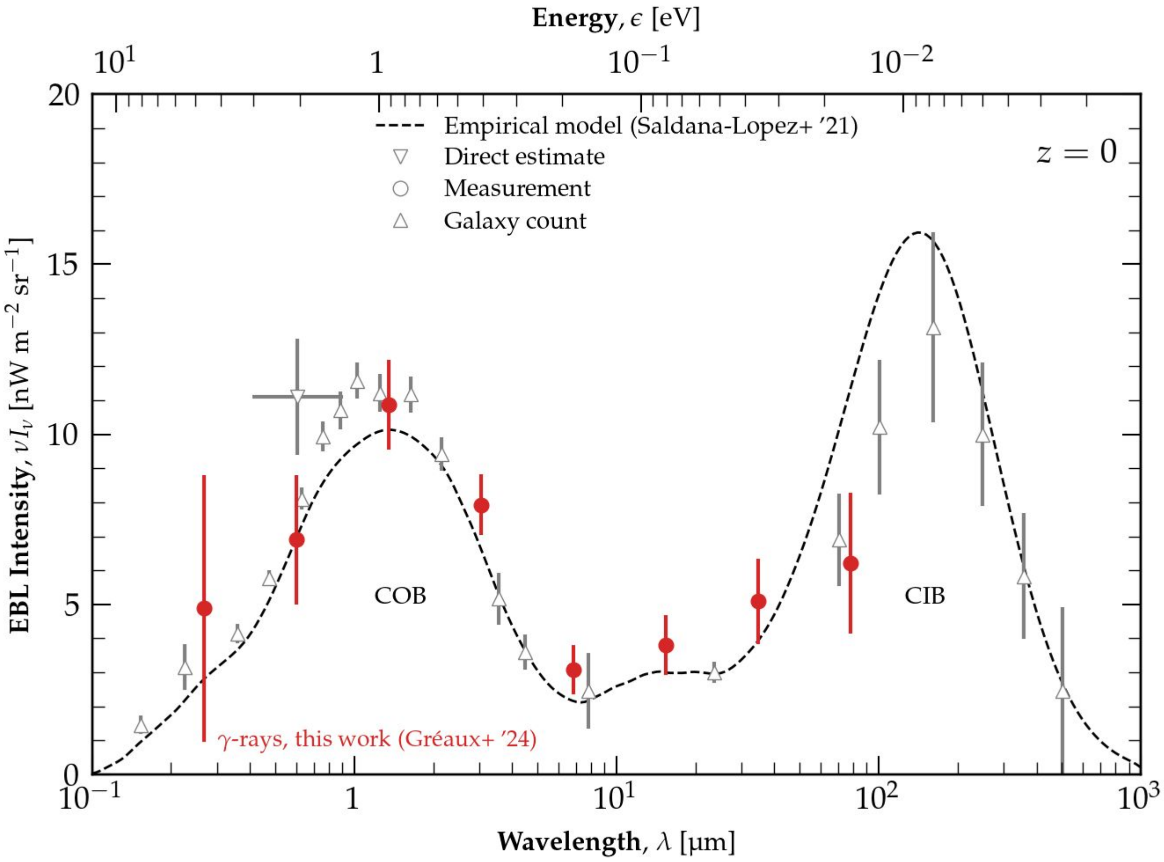
⇨ Sum of 8 Gaussians:
fixed widths & positions,
free amplitudes a_i

⇨ **Redshift evolution** with
free nuisance parameter $f_{\rm evol}$

First fully model-independent γ-ray reconstruction of the EBL



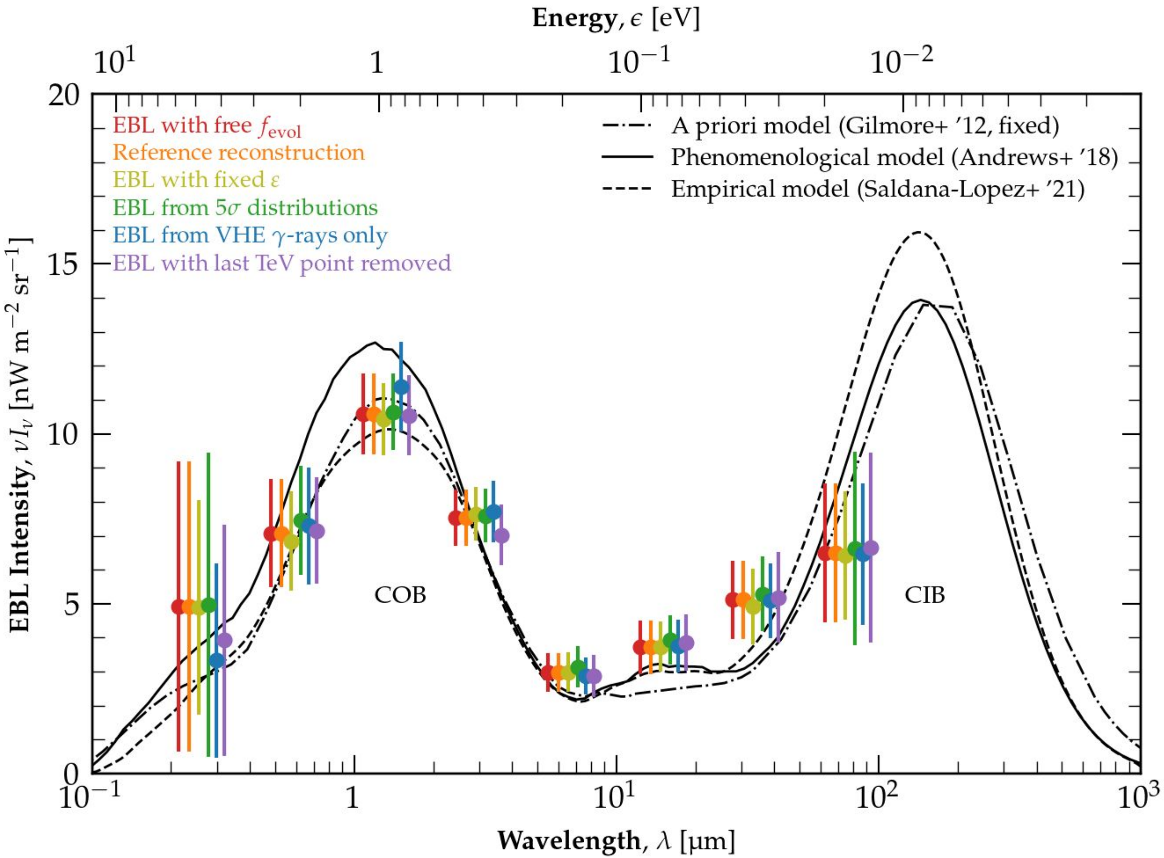
A new Bayesian measurement of the EBL



γ-ray cosmo measurement obtained from

- ⇨ **Improved TeV data sample**, STeVECat
- ⇨ **Updated analysis** paradigm, Bayesian
- ⇨ **Model independent** parameterization
- ⇨ Gréaux+ '24

Reliability of the reconstruction

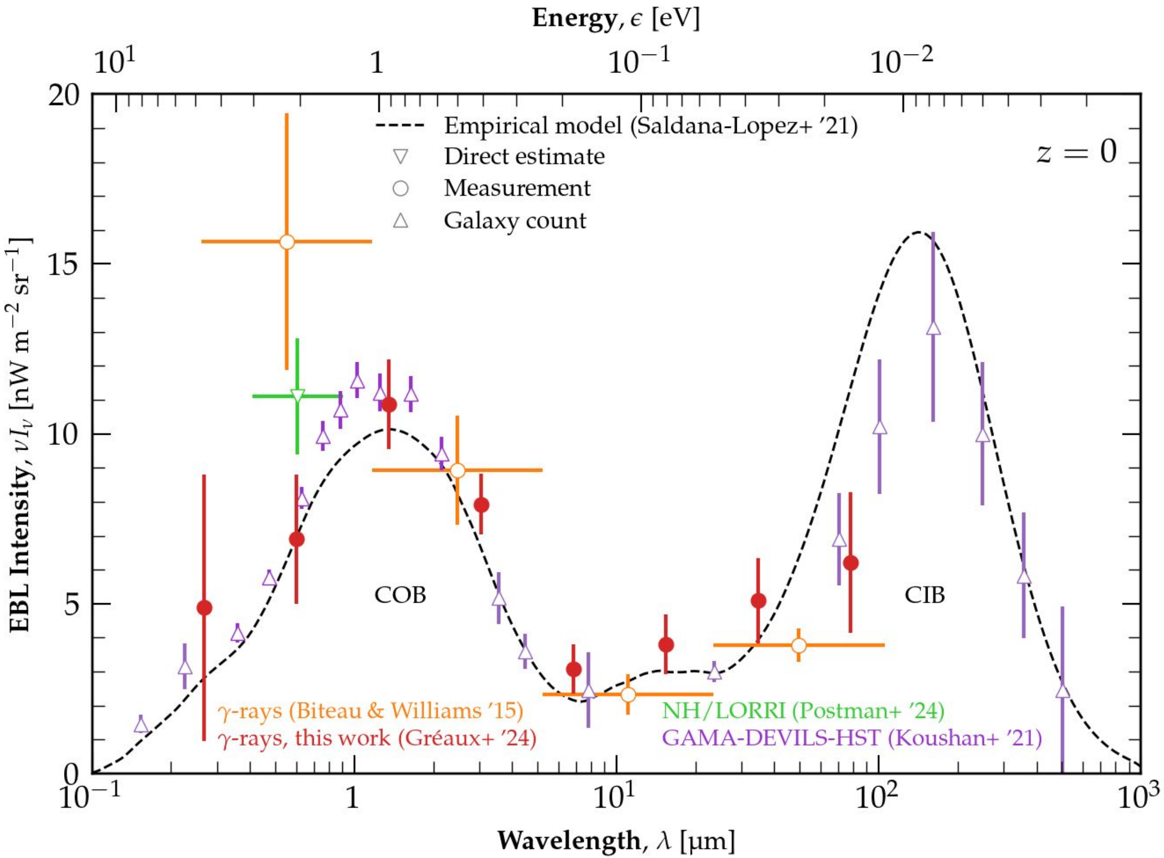


Reliability **cross-checks:**

- Parameterized EBL **redshift evolution**
- Nuisance parameter on **energy scale**
- **Variation** of the reconstruction **method**
- Assumption on **GeV-TeV spectral correlation**
- Bias from **highest energy flux point**

✓ **Negligible impact**

A new Bayesian measurement of the EBL



γ-ray cosmo measurement

⇨ Between 1 and 50µm: **±1.3 nW m^{-2} sr^{-1}**

✓ **Agreement** with **B&W'15**

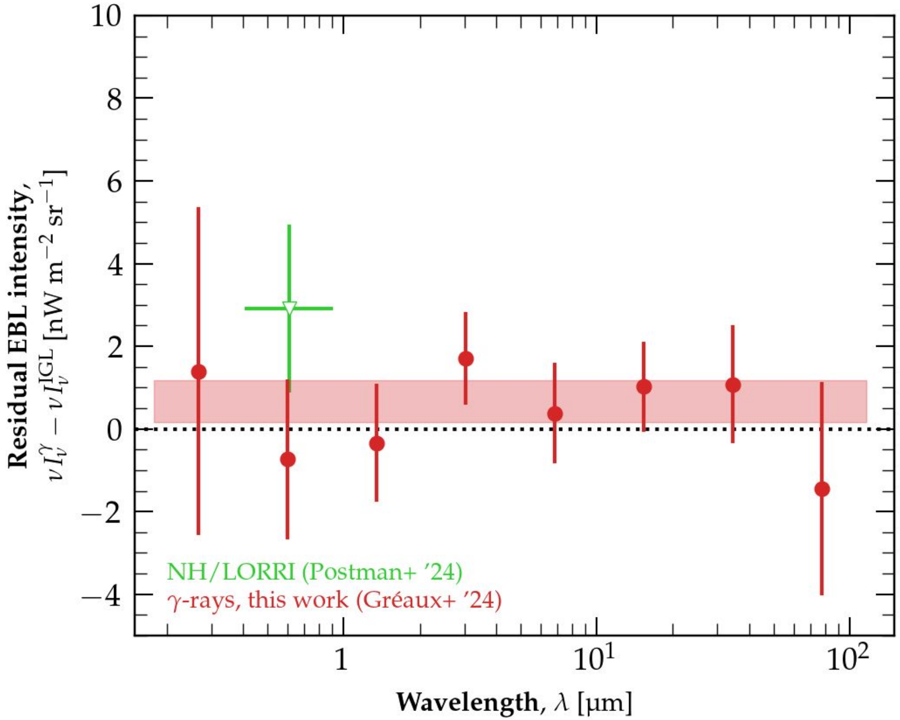
✓ **Reduced uncertainties**

⇨ **Syst. uncertainties underestimated** by **previous analyses**

✓ **Agreement** with **NH**

✓ **Indistinguishable** from **galaxy counts**

The cosmological optical convergence



Residual intensity wrt **galaxy counts**

⇨ Over whole range:
0.7 ± 0.5 nW m^{-2} sr^{-1}

$$\nu I_\nu^{\rm EBL} = \nu I_\nu^{\rm IGL} \times (1 + f_{\rm diff})$$

⇨ **Exclusion** of **diffuse components**
f_{diff} **≤ 20%** at 95% C.L.

Constraints on **diffuse contributions**

✓ **Intra-halo light**, 5-30% of IGL

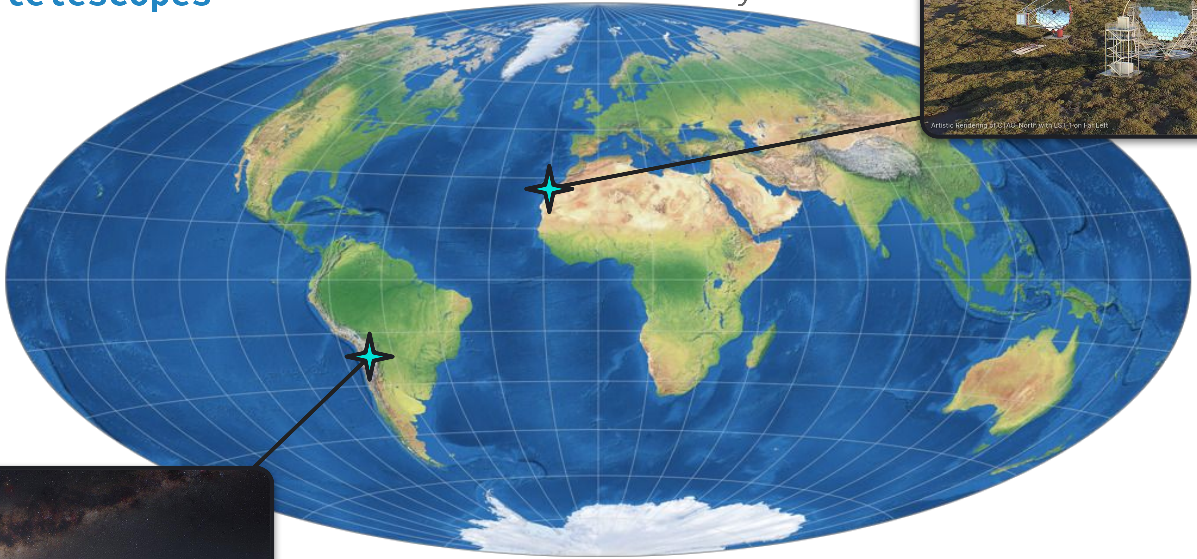
✕ **Reionization** contribution,
~ 0.1-1 nW m^{-2} sr^{-1} at 1.1 μm

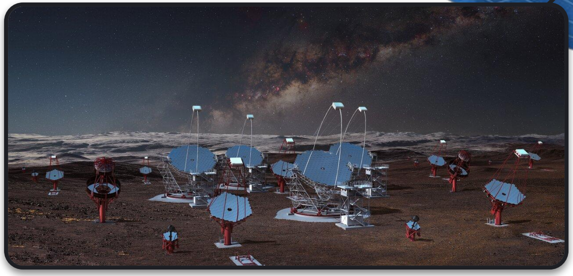
Outline of the presentation

CTAO, the future generation of instruments

One collaboration observing **both hemispheres** with arrays of **13 and 51 telescopes**

CTAO – North
Roque de los Muchachos
Canary Islands





CTAO – South
Atacama Desert
Chile

CTAO

Credit: CTAO, rendering

Simulating STeVECat seen by CTAO

Sensitivity increased by factor **~10**

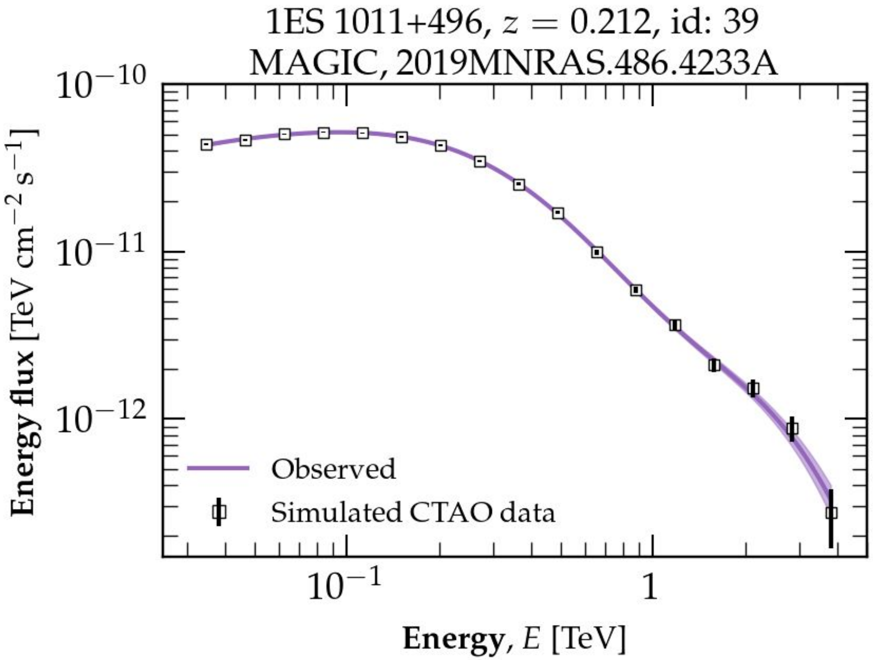
⇨ **What could CTAO have seen instead of H.E.S.S., MAGIC, VERITAS?**

Simulate **STeVECat** observations with **CTAO's instrument response functions** (prod5 IRFs, α-configuration)

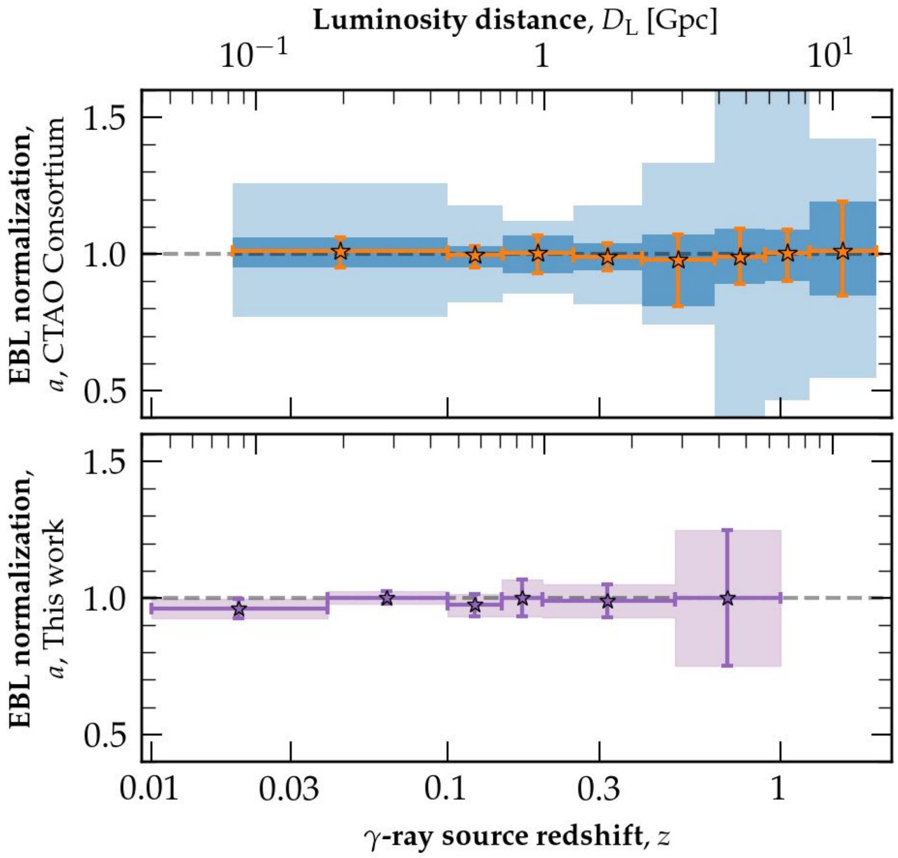
⇨ **228 spectra** (current IACTs)

⇨ ~ **3000 h** of simulated livetime

✓ **Compatible** with currently planned **CTAO observation program**



Redshift evolution of the reconstruction



EBL model: $\tau(E, z, a) = a \times \tau_{\text{ref}}(E, z)$

Published work by **CTAO Consortium**

- ✗ Dominated by **systematics**

Using the **Bayesian framework**:

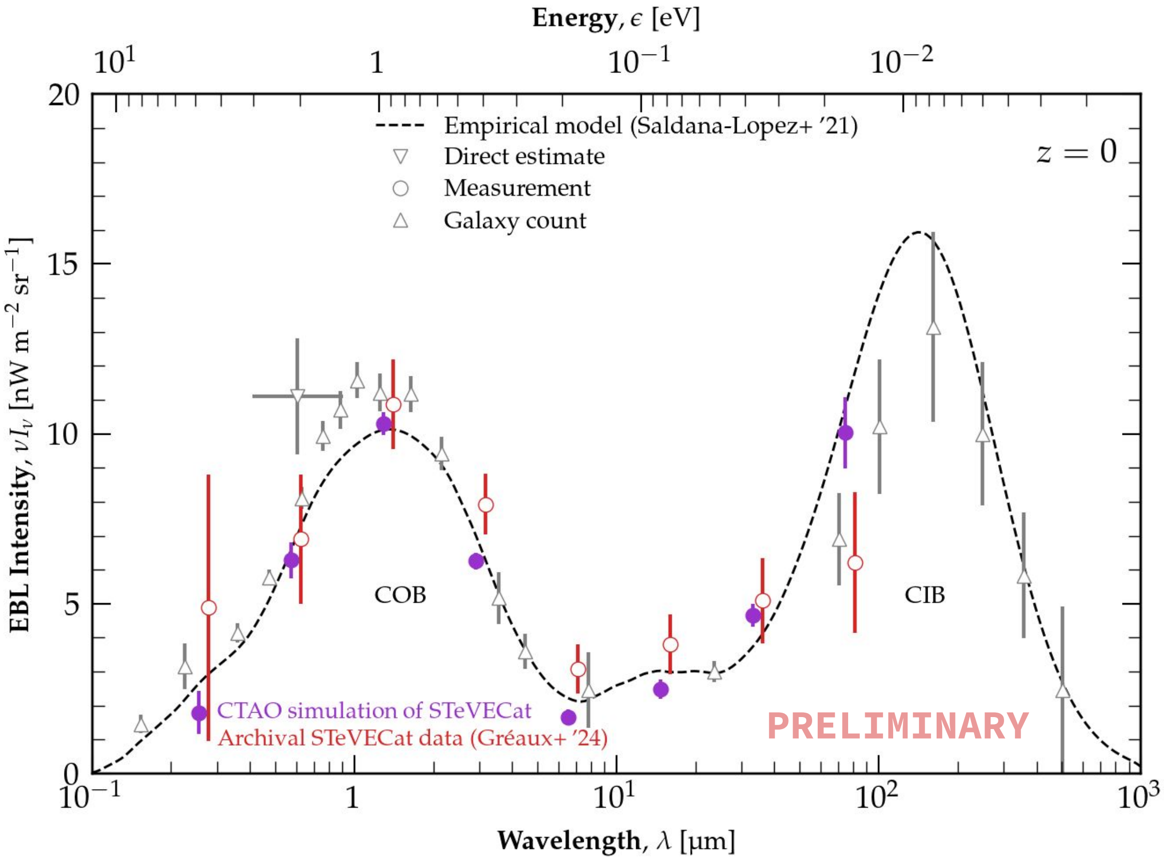
- ✓ **a = 0.99 ± 0.02** with bias 0.2% ± 0.7% (10 realisations)
- ✓ Same errors as **CTAO Consortium** below z < 0.4, ~5%

Improvements:

- ⇨ **Systematics** can be included (here, **energy scale**)
- ⇨ **Fast** and scalable, working with **spectra** instead of event lists

Adapted from CTAO Consortium, 10.1088/1475-7516/2021/02/048

Expectations on EBL seen by CTAO



Application to parametric **Gaussian EBL model**

⇨ Between 1 and 50μm: **±1.3 nW m^{-2} sr^{-1}**

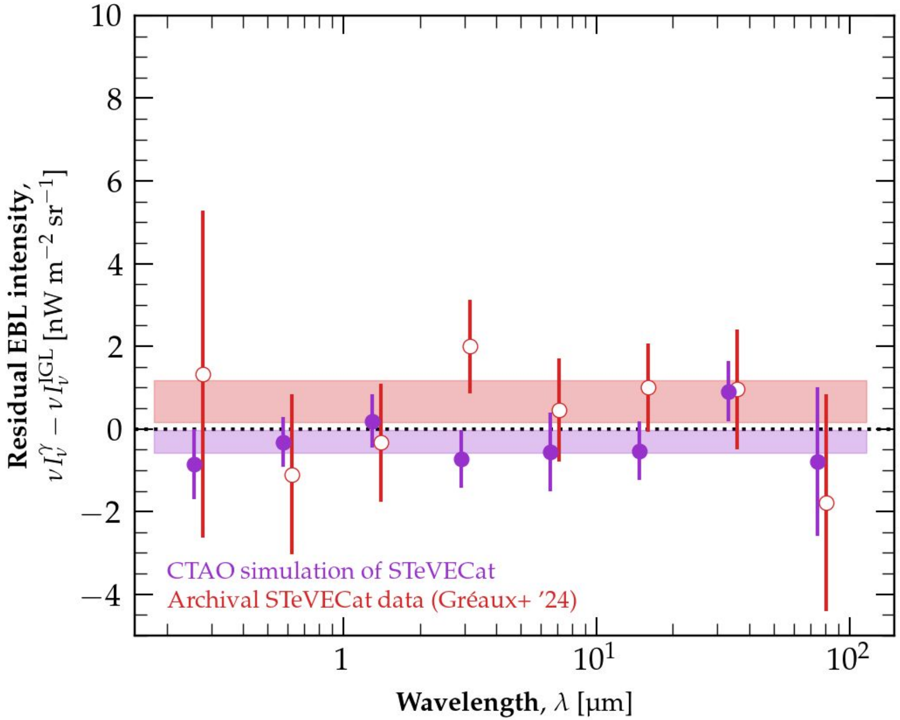
Using **CTAO simulations**

✓ Between 1 and 50μm: **±0.3 nW m^{-2} sr^{-1}** (without **HE priors**)

Reionization contribution: ~ 0.1-0.8 nW m^{-2} sr^{-1}

⇨ **Constrain emissions from sources of reionization?**

Expectations on EBL seen by CTAO



Residual intensity with respect to **IGL** / **reference EBL**

Overall bias on the reconstruction:
-0.27 ± 0.12 nW m^{-2} sr^{-1}

✓ **Compatible with SL21** (injected EBL model)

✓ Validation of the bias on **archival data**

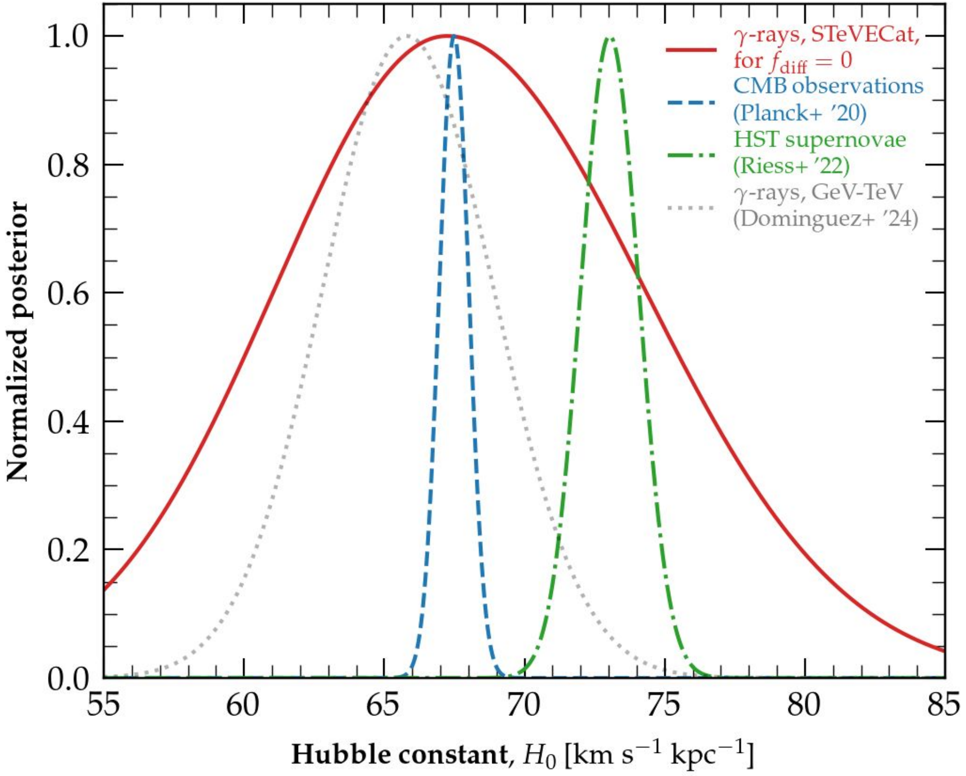
Hubble constant measurement

γ-ray data ∝ $1/H_0$ IGL intensity

$$\tau(E_\gamma, z_0) = \int_0^{z_0} dz \frac{\partial L}{\partial z}(z) \int_0^{\infty} d\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) \int_{-1}^{1} d\mu \frac{1-\mu}{2} \sigma_{\gamma\gamma}(E_\gamma(1+z), \epsilon, \mu)$$

Use the **γ-ray** & **IGL** to **measure H_0** independently from **CMB**, **cosmic distance ladder**, and GWs

H_0 = 67 ± 7 km s^{-1} Mpc^{-1} x $(1 + f_{diff})$



Hubble constant measurement

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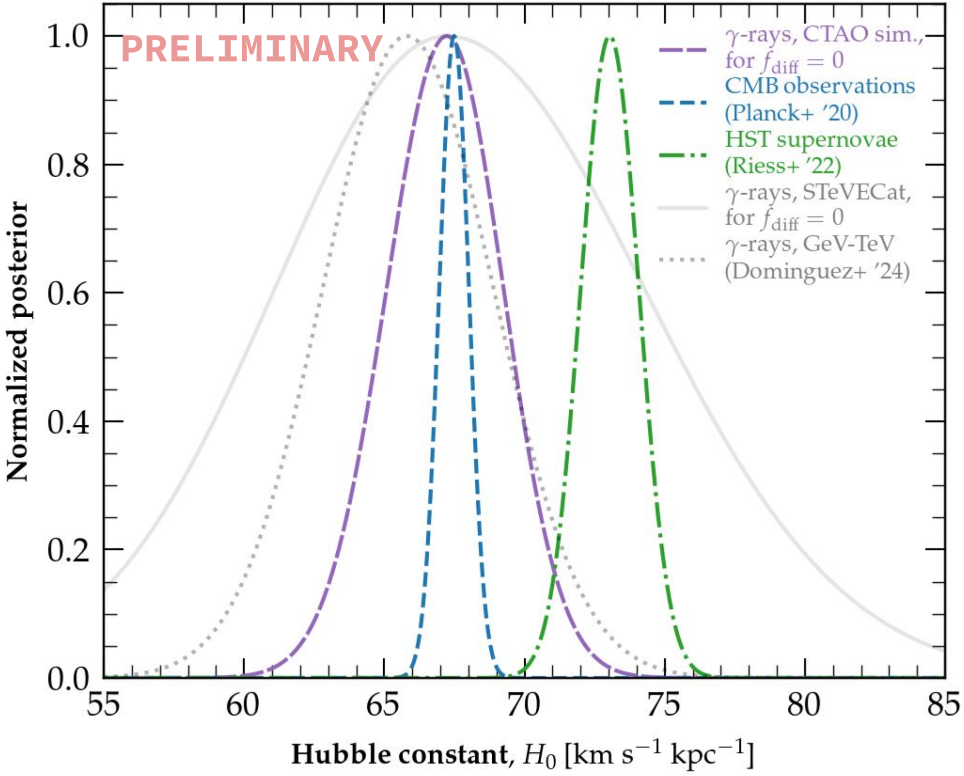
Use the **γ-ray** & **IGL** to **measure H_0** independently from **CMB**, **cosmic distance ladder**, and GWs

Expected **IGL precision of ~1%** from Euclid, JWST, LSST

⇨ **CTAO measurement of H_0: precision of ~3%**?



Conclusion

γ-ray cosmology: study the EBL through its **interaction with γ-ray**

New EBL measurement: Gréaux+ ‘24

⇨ **Bayesian** framework
- ➢ Marginalize over spectral/nuisance parameters

⇨ New data corpus, **STeVECat**
- ➢ Sample size ~tripled wrt previous

⇨ **Independent** from IGL, direct meas., and reference models
- ➢ Only use γ-ray observations

⇨ **Reduced uncertainties** with respect to **previous γ-ray studies**

⇨ EBL from **γ-rays** **indistinguishable from IGL**: **cosmological optical convergence**

⇨ Constraint on **diffuse components**: f_{diff} **≤ 20%** at 95% C.L.

⇨ $H_0 = 67 \pm 7$ km s^{-1} Mpc^{-1} x $(1 + f_{diff})$

IGL precision of ~1% expected for **LSST, Euclid, JWST**

Reionization contribution expected at ~0.1–0.8 nW m^{-2} sr^{-1} (~0.1–0.8% of EBL)

★ **Next generation** of γ instruments, **CTAO**, with exceptional sensitivity

★ **Exciting results** expected from **γ-ray cosmology**!