Gamma-Ray Cosmology

Probing the extragalactic background light, axion-like particles, and the Hubble constant

Lucas Gréaux

LPNHE – March 24th

RUHR UNIVERSITÄT BOCHUM

The night sky puzzle: Olbers' paradox

Credit: LG

Two and a half facts

When I began research in radio astronomy as a research student in 1963, my supervisor Dr Peter Scheuer gave me a copy of Sir Hermann Bondi's classic text *Cosmology* to absorb and warned me that

There are only $2\frac{1}{2}$ facts in cosmology.

Fact 1. The sky is dark at night

This is the well-known observation which leads to what is known as *Olbers' paradox* although the paradox was well known to earlier cosmologists. Sir Hermann in his text *Cosmology* gives a thought-provoking discussion of the meaning of the paradox (Bondi 1952). The fact that the sky is not as bright as the surface of the Sun provides us with some very general information about the Universe. Probably the most general way of expressing the significance of this observation is that the Universe must, in some sense, be far from equilibrium although in what way it is in disequilibrium cannot be deduced from this very simple observation.

Modern Cosmology - a Critical Assessment
M. S. Longair

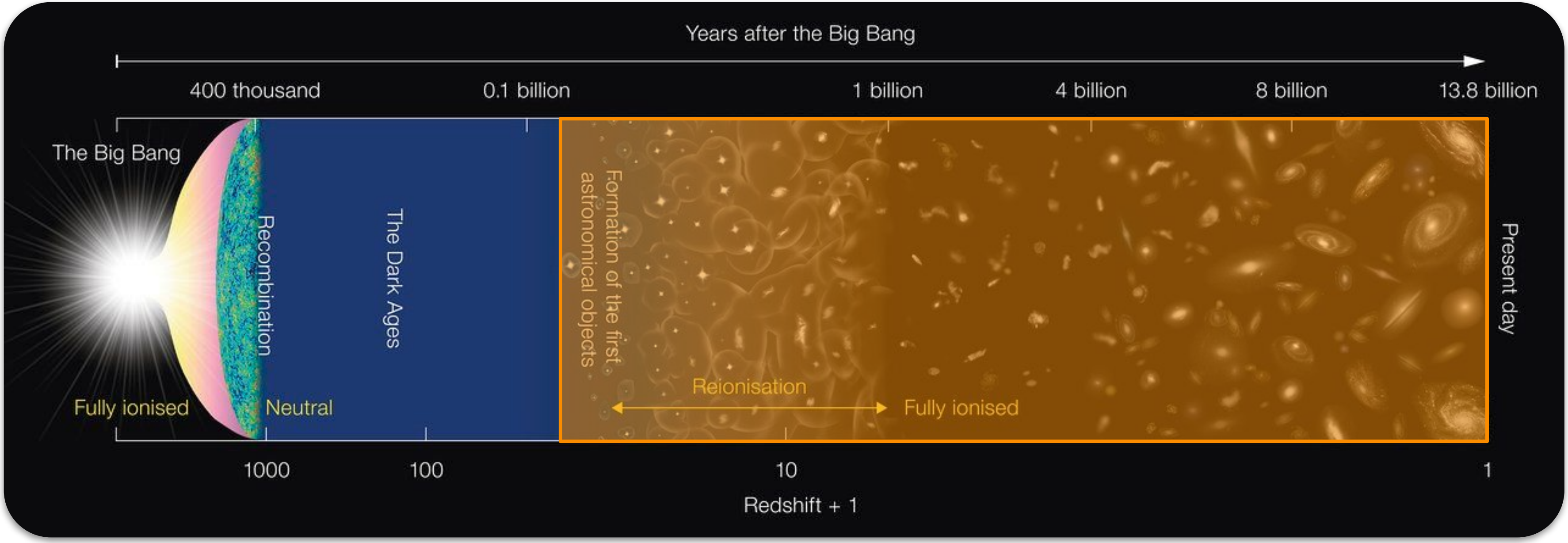
Fact 2. The galaxies are receding from each other as expected in a uniform expansion

This was Hubble's great discovery of 1929 and I will say much more about it in a moment. The $2\frac{1}{2}$th fact was as follows:

Fact $2\frac{1}{2}$. The contents of the Universe have probably changed as the Universe grows older

The reason for the ambiguous status of this fact was that the evidence for the evolution of extragalactic radio sources as the Universe grows older was then a matter of considerable controversy, particularly with the proponents of Steady-State cosmology. I was plunged straight into this debate as soon as I began my research programme with Martin Ryle and Peter Scheuer. As we will see, this is no longer a controversial issue – there is no question at all

A brief history of the Universe



Credit: NAOJ/ESO

Outline of the presentation

01 The extragalactic background light, EBL

How much light is there in the universe?

02 Principles of γ-ray cosmology

What can we extract from the propagation of γ-rays?

03 Measurement of the Hubble constant

How fast is the Universe expanding?

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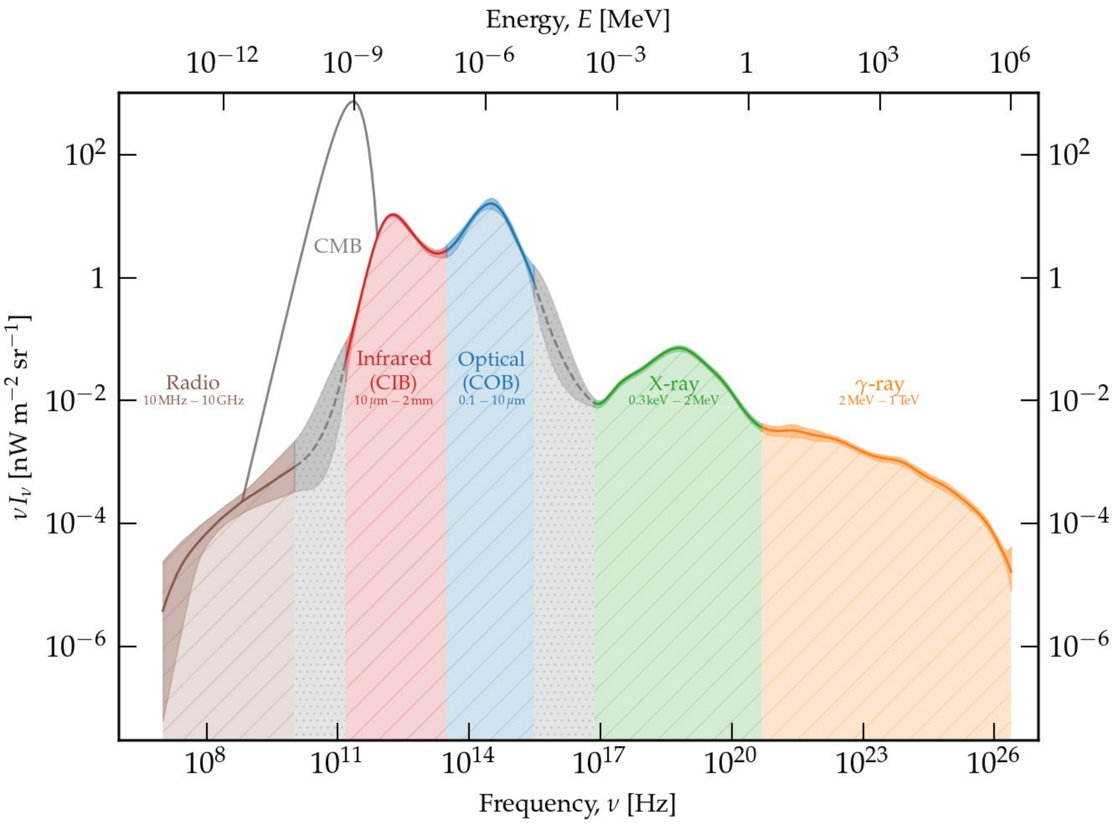
The extragalactic spectrum of the Universe



Specific intensity:

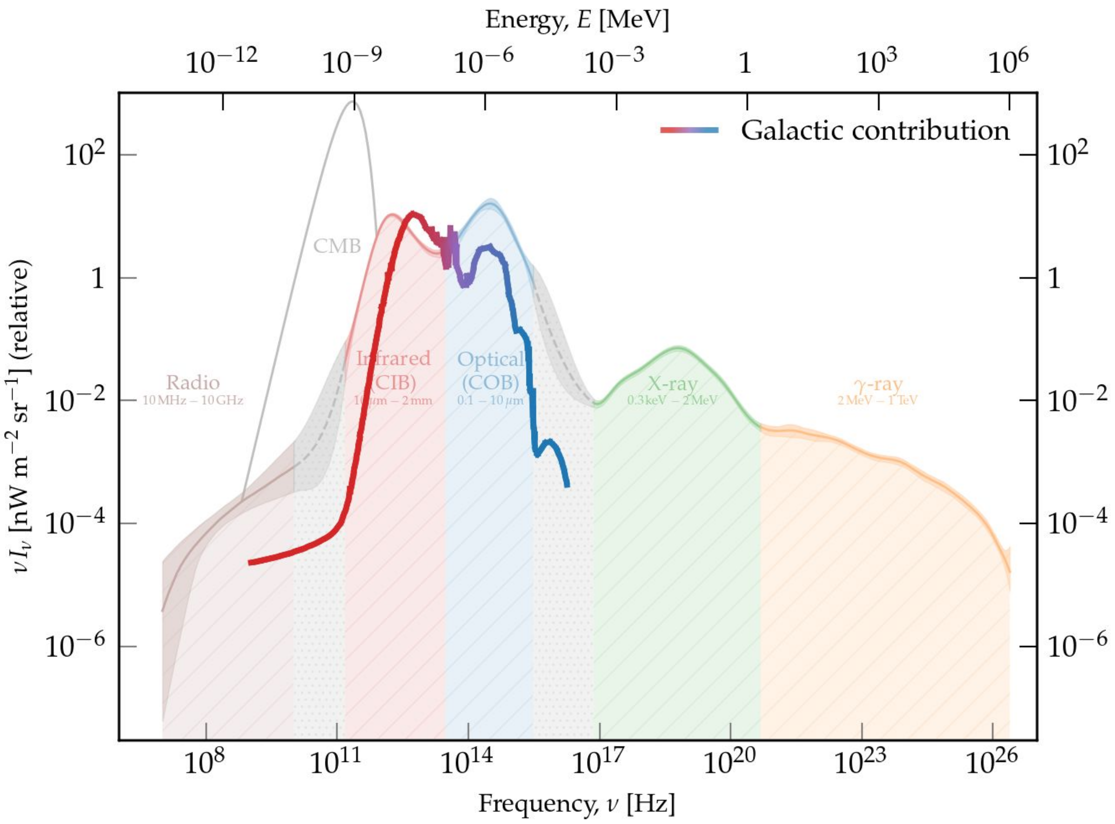
$$\nu I_\nu = \frac{c}{4\pi} \epsilon^2 \frac{\partial n}{\partial \epsilon}$$

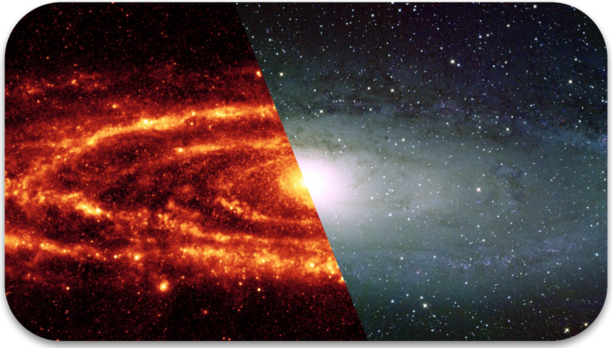
Dominated by the **cosmic optical background (COB)** and the **cosmic infrared background (CIB)**

Extragalactic Background Light, EBL

J. Biteau, 10.5281/zenodo.7842239

Contribution from stars in galaxies





Light from stars:

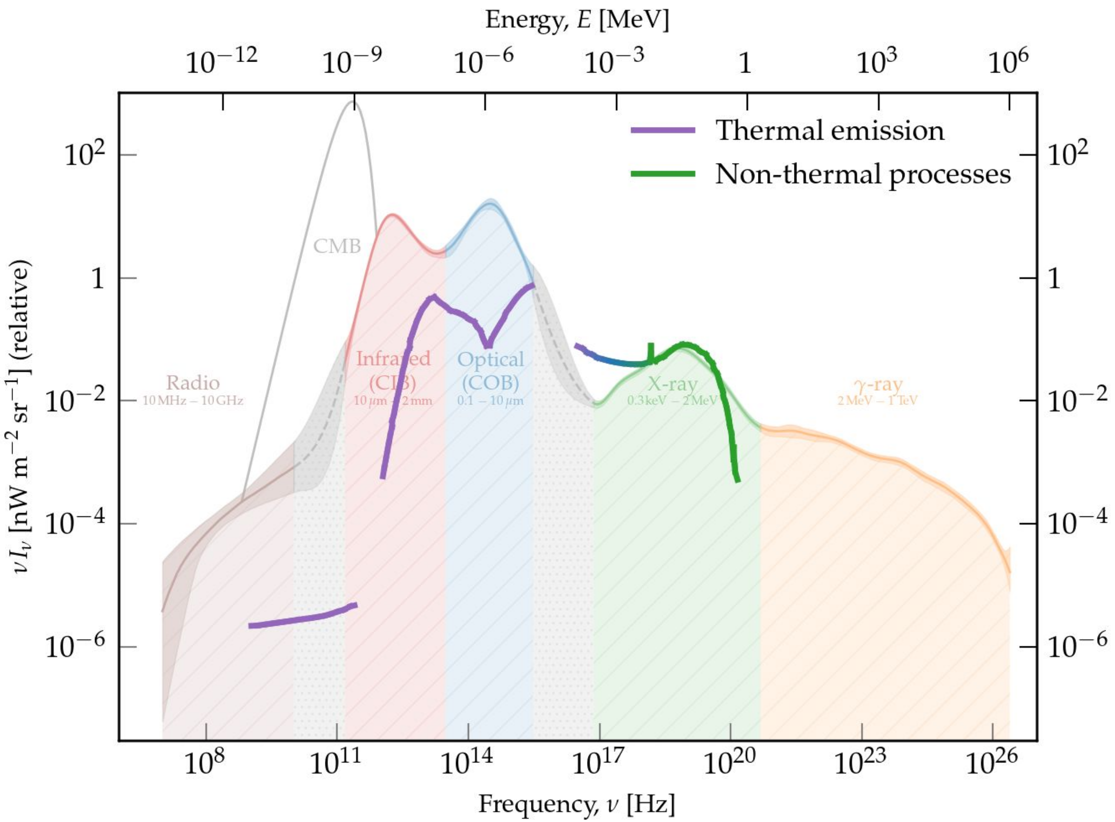
⇨ **Escaping the host**, optical contribution

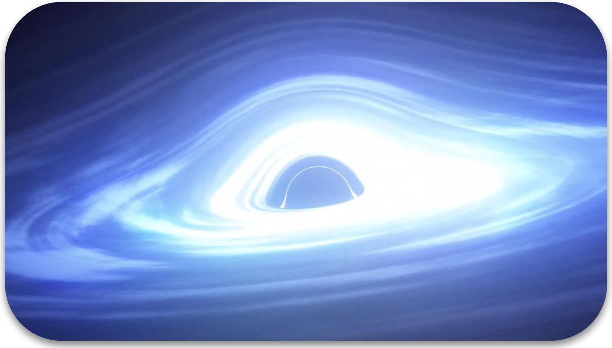
⇨ **Absorbed by dust**, reemitted in infrared

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

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

Contribution from accretion on supermassive black holes





Active galactic nucleus, AGN

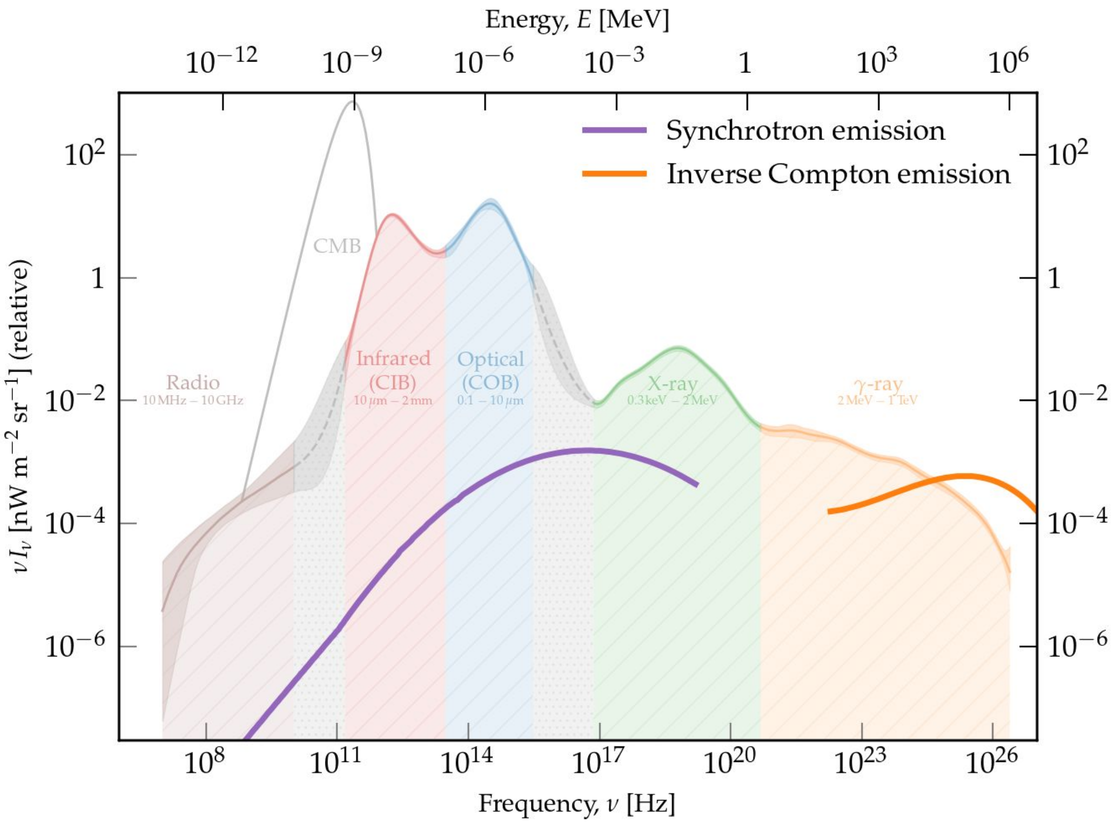
Compact region at galaxy center **outshining the host**

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



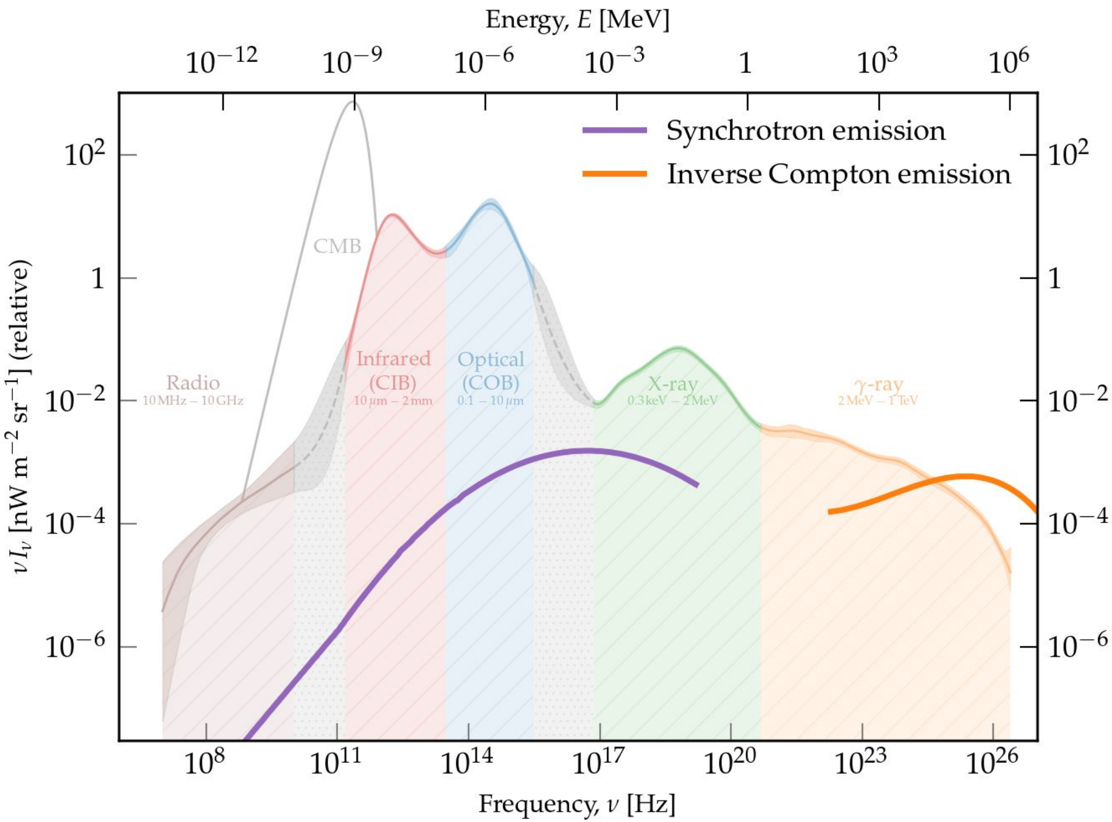
Some AGNs harbor **relativistic jets**

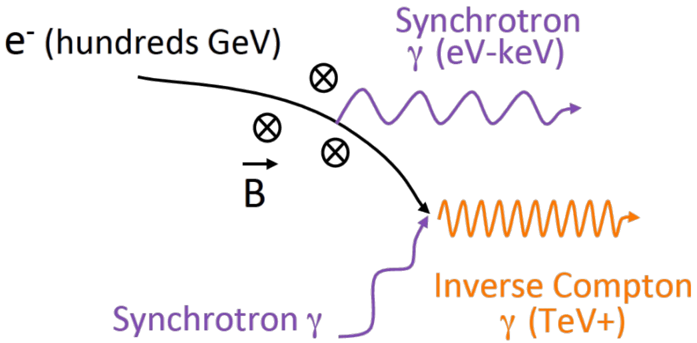
Typical jet spectrum show **two components**, **synchrotron** component at **low energies**, **inverse Compton** component in **γ-rays**

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)

Contribution from relativistic jets





Synchrotron radiation

⇨ Ultrarelativ. **electrons** in **magnetic field**

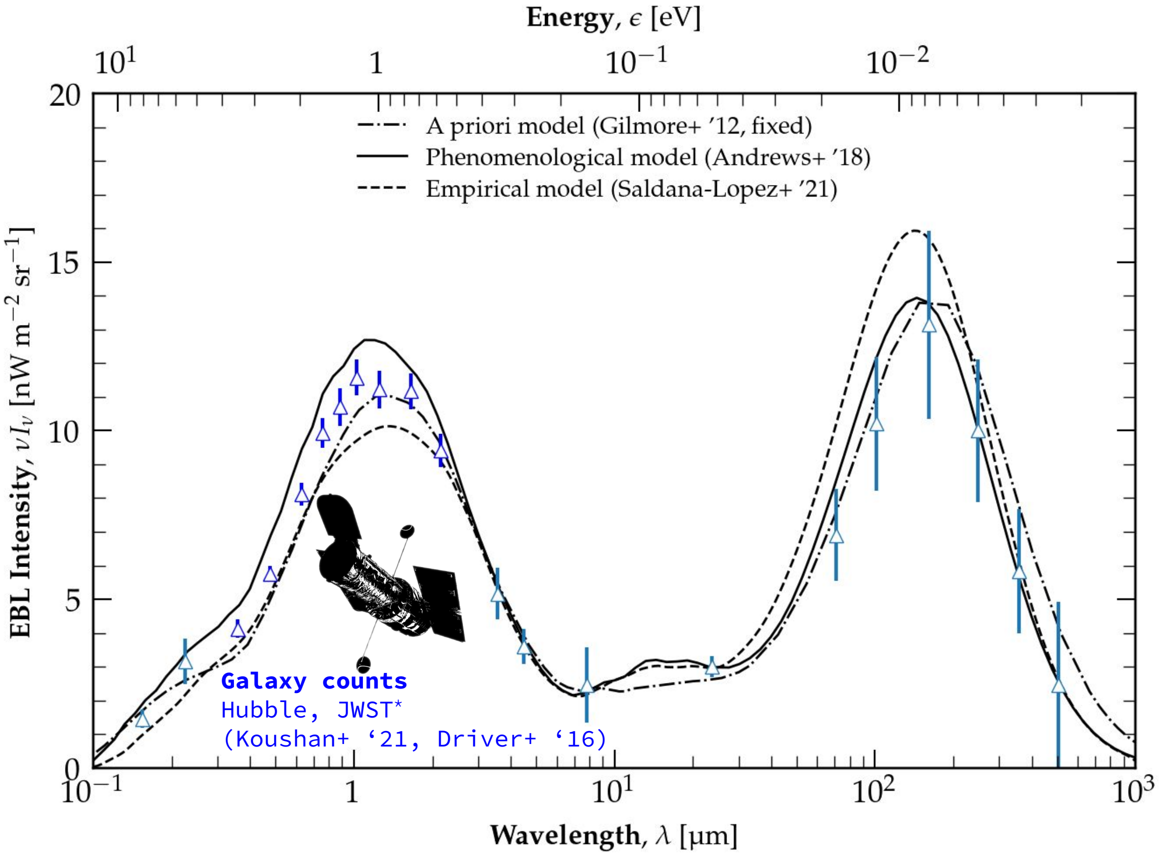
Inverse Compton (leptonic)

⇨ Synchrotron photons **upscattered** by electrons, **synchrotron self-Compton**

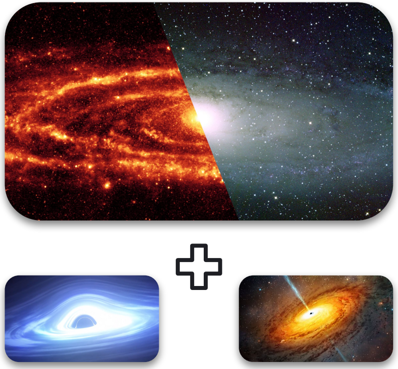
Adapted from J. Biteau, 10.5281/zenodo.7842239 and C. Harrison, 10.1007/978-3-319-28454-5

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

Measurements from galaxy counts



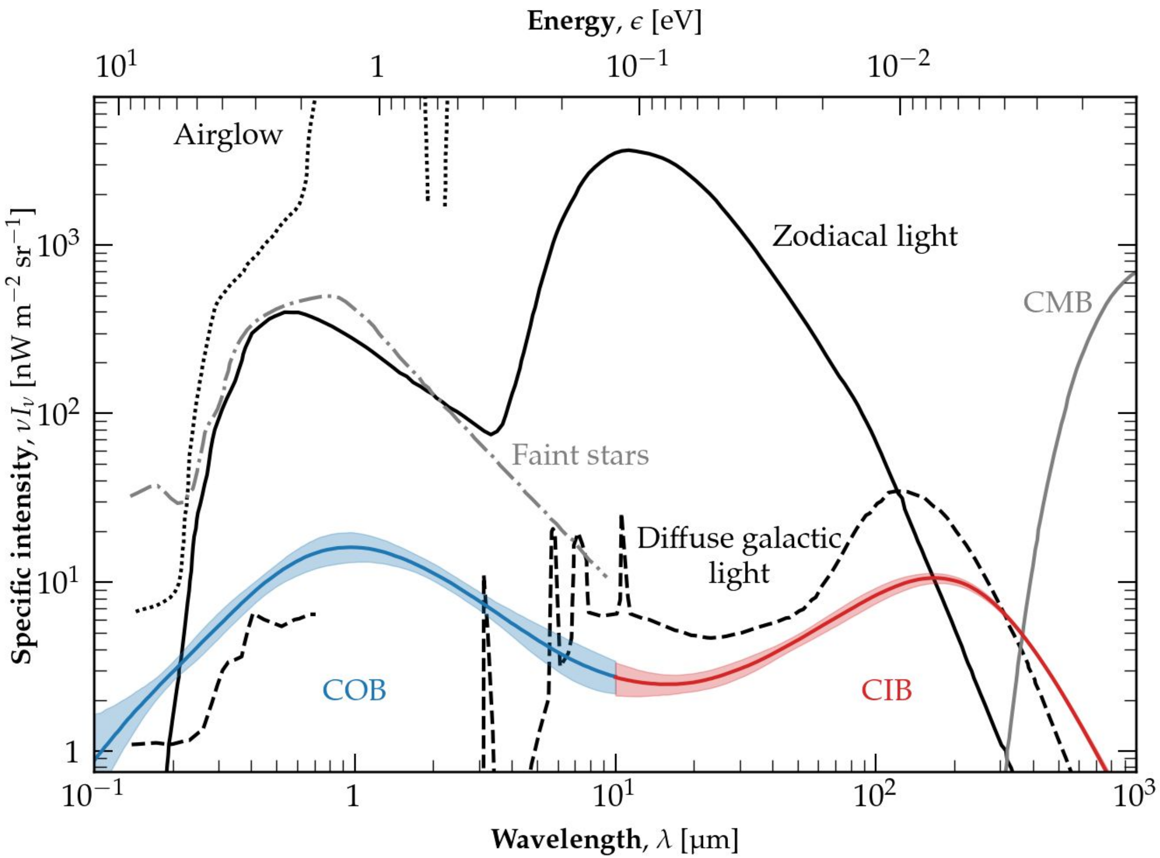
Main EBL component: IGL, integrated galactic light, deep field **galaxy counts**



✕ Only **resolved galaxies**

⇨ Proportion of **diffuse**, **non-IGL components?**

The problem of foregrounds



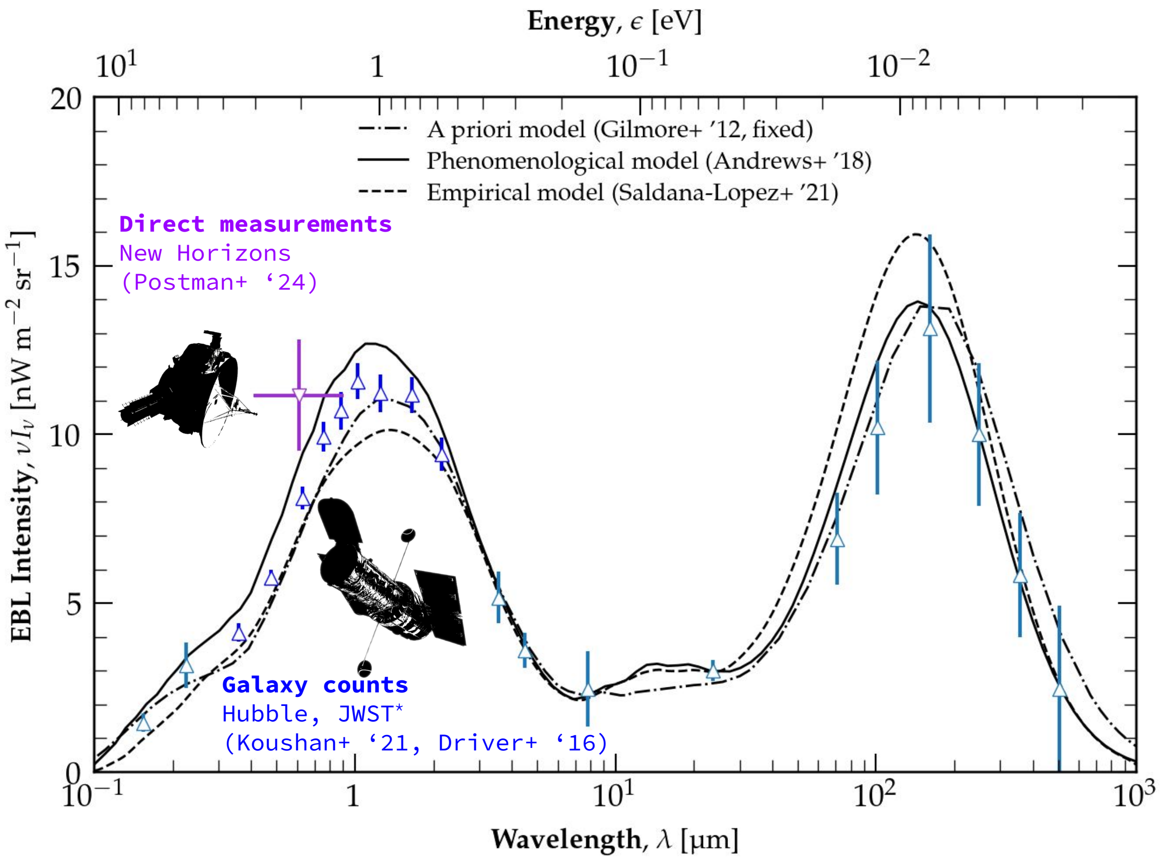
Direct measurements: EBL from remaining light after **subtraction of foregrounds**

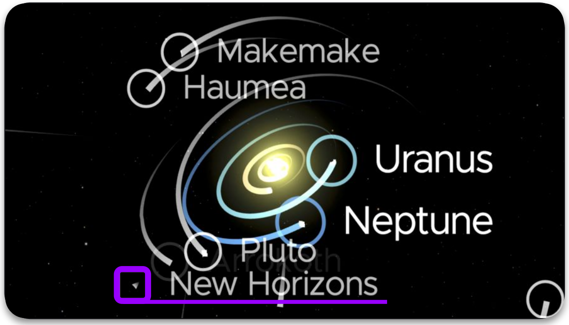
✕ **Foregrounds outshine the EBL** by more than an **order of magnitude**

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

Credit: S. Keys

Measurements from direct observations





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

✓ Agreement with **IGL** (**galaxy counts**)

✗ Only **one measurement** at **600nm** (400-900nm)

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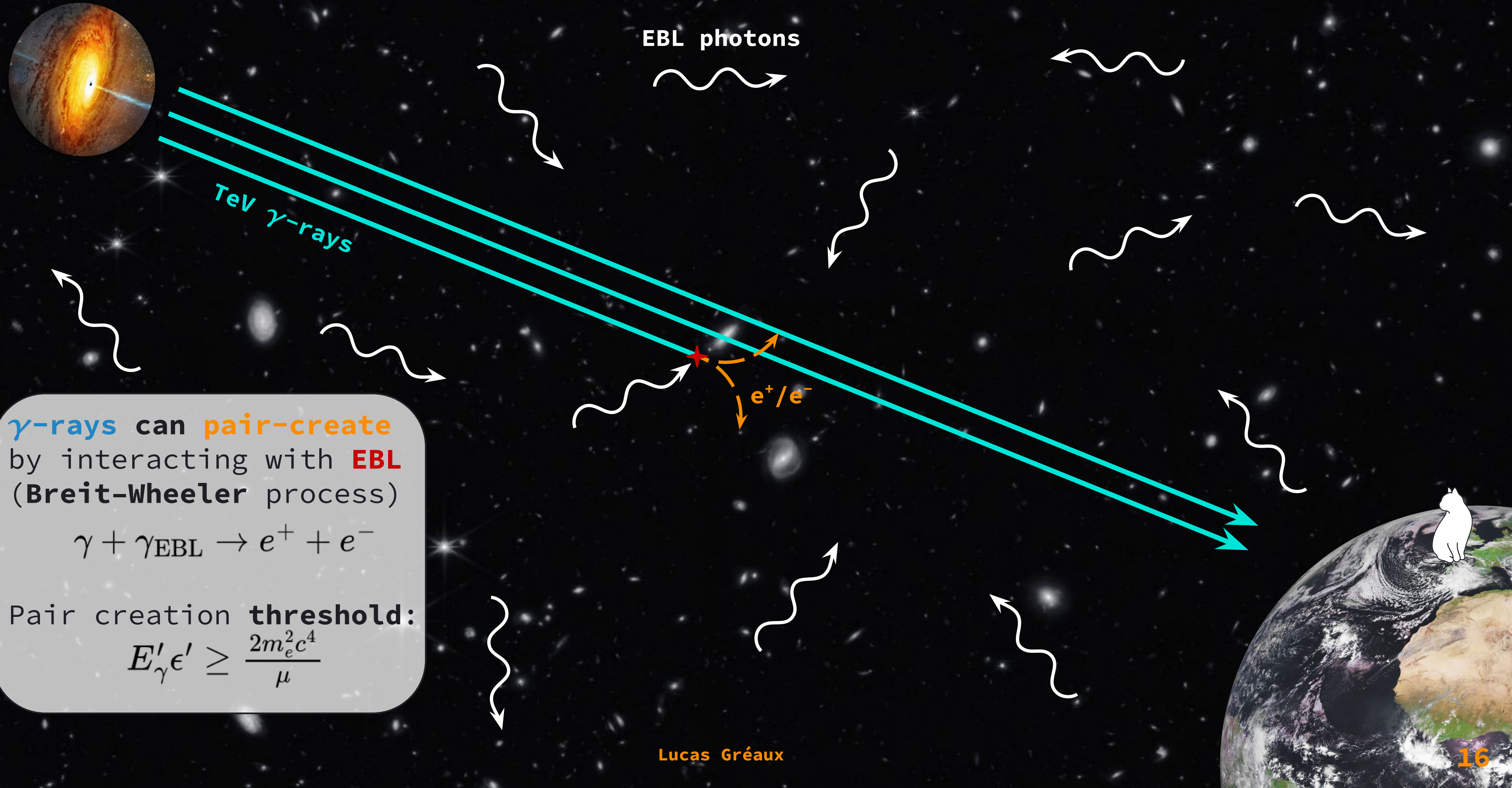
Gamma-ray propagation



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

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

Pair creation **threshold**:

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

Optical depth of the EBL

Interaction **characterized by** **optical depth** $\tau \propto l \times \sigma \times \rho$

Distance to the source — **Cross section for the pair creation process** — **Density of the EBL**

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

Cosmology — Particle physics — Astrophysics

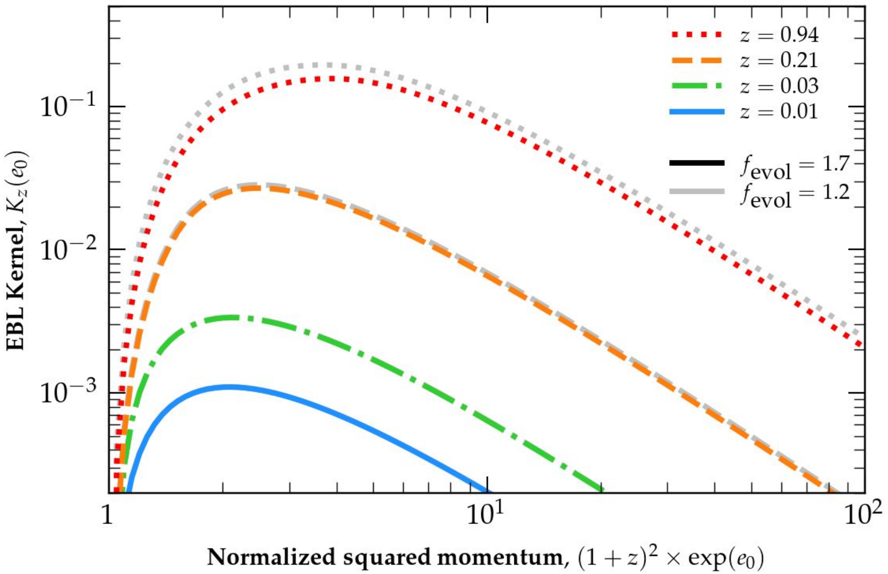
Spectrum and evolution decoupling

Assuming **decoupling** between **EBL spectrum** and **EBL evolution**,

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

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

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

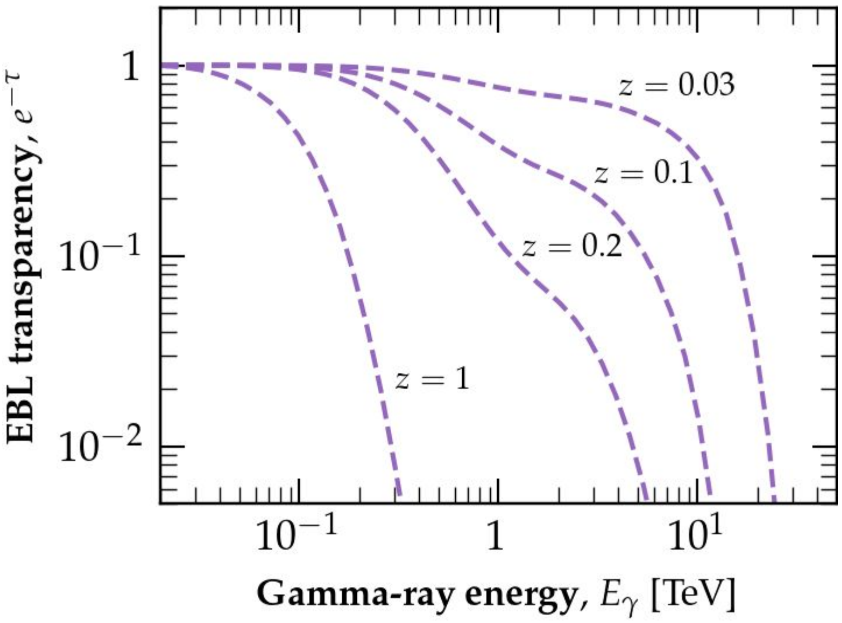


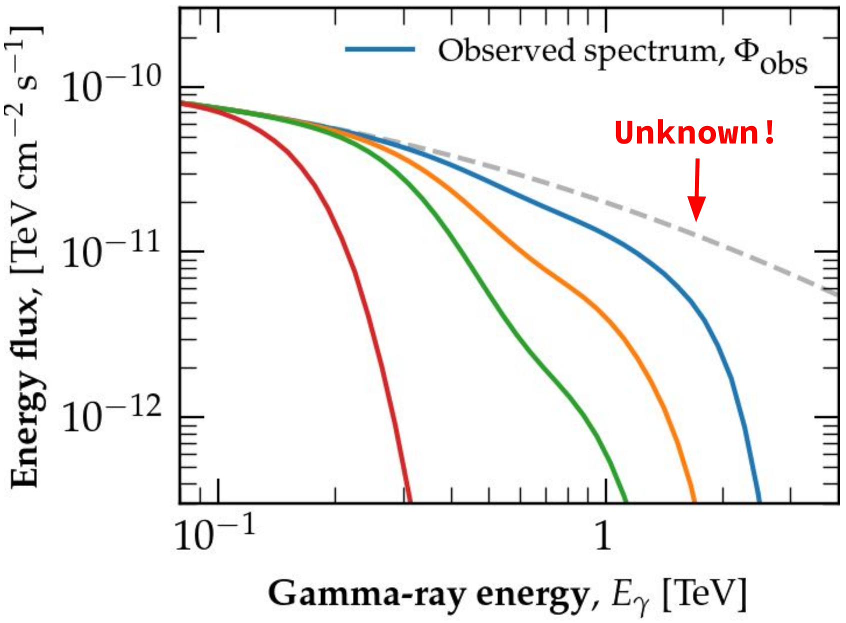
With $e_0 = \ln(E\epsilon_0/m_e^2c^4)$

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

Gamma-ray attenuation

EBL transparency: $e^{-\tau}$ **γ-ray attenuation**: $\Phi_{\rm int} \times e^{-\tau} = \Phi_{\rm obs}$





The Bayesian Framework as an analysis tool

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**

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:

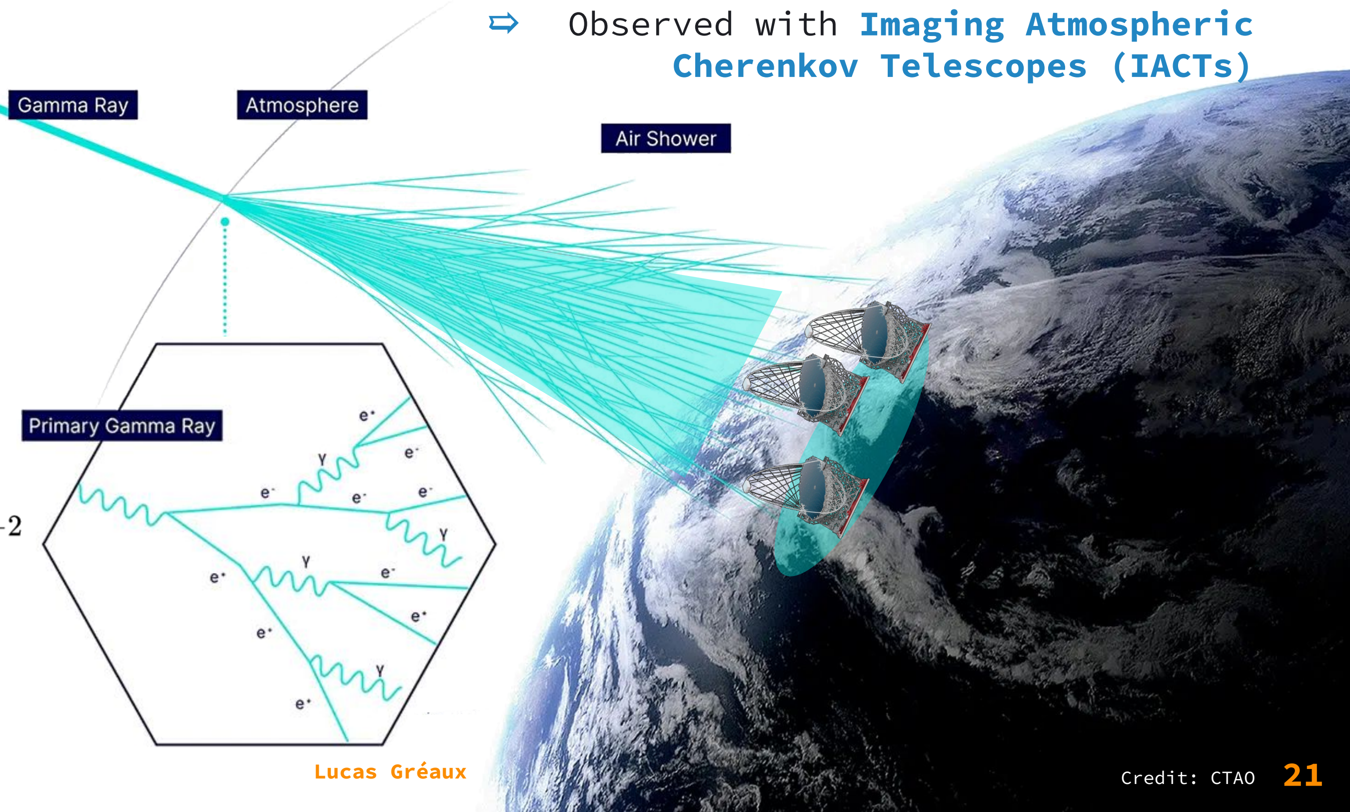
$$e^{\pm} + \mathrm{X} \rightarrow e^{\pm} + \mathrm{X} + \gamma$$

Radiation length:

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

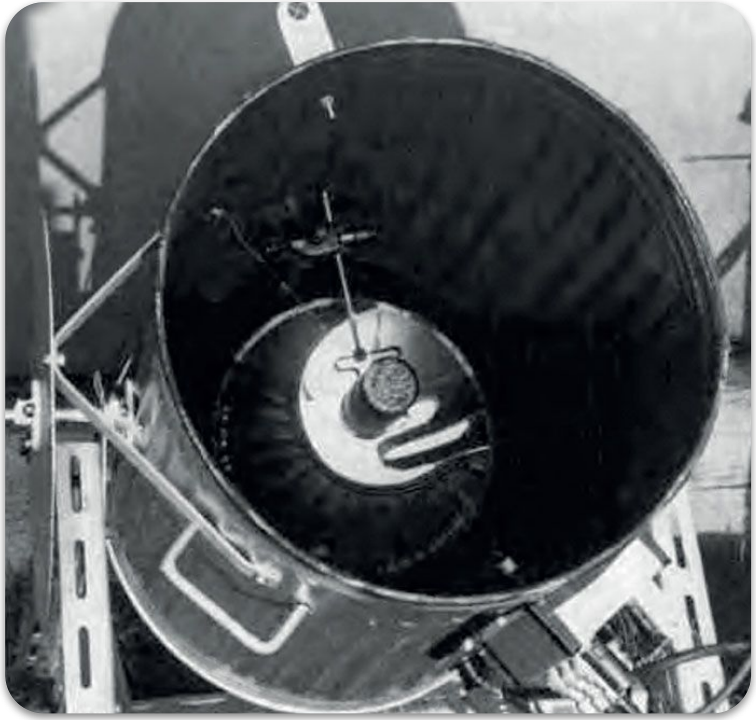
Atmosphere: $\sim 1000\,\mathrm{g\,cm^{-2}}$

⇨ Fully developed **electromagnetic cascade**



Credit: CTAO

The first IACT



Simple apparatus in 1952 by William Galbraith and John Jelley

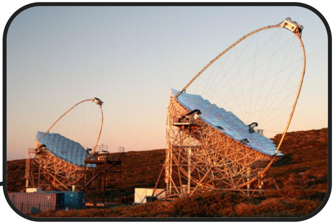
- Photomultiplier tube
- World war II mirror
- Standard-issue dustbin

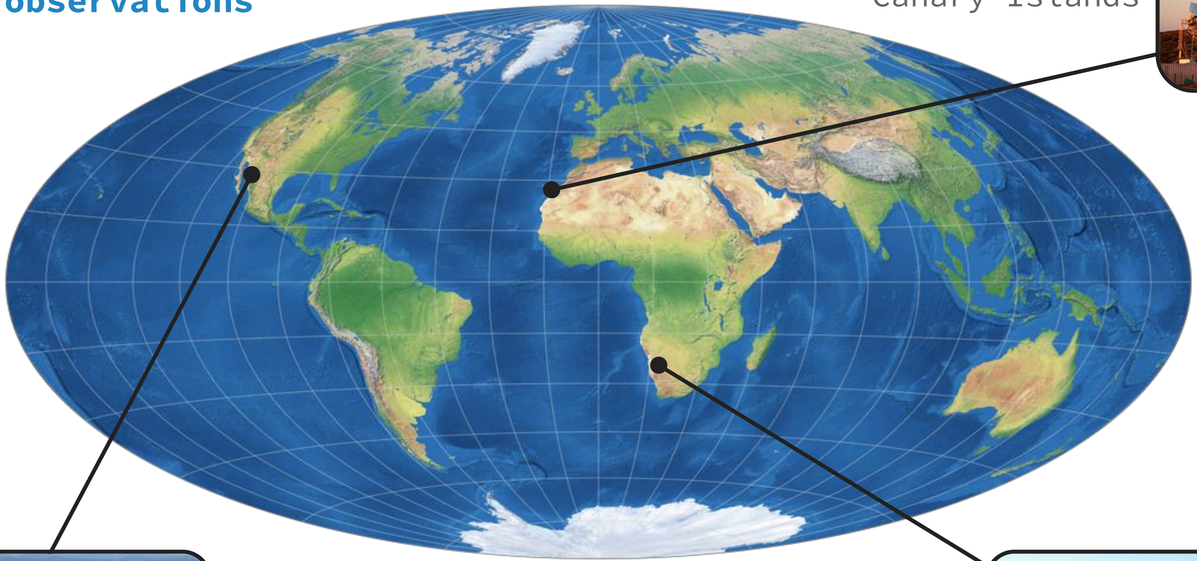
Credit: G. Hallewell

The current generation of IACTs

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

MAGIC (2004)
Roque de los Muchachos
Canary Islands

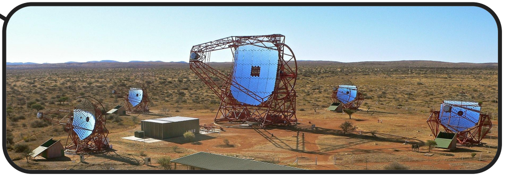




Catalog of sources:
⇨ **TeVCat**

VERITAS (2008)
Mount Hopkins
Arizona

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



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

STeVECat, the Spectral TeV Extragalactic Catalog

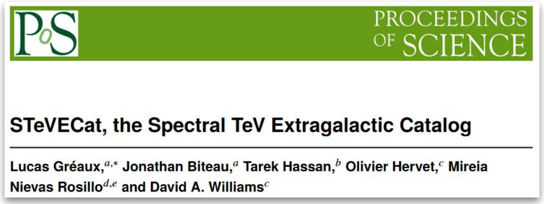
Most comprehensive catalog to date of **archival spectra** published by **current IACTs**

⇨ **403 spectra** from **78 sources**

International work
- ⇨ France (IJCLab)
- ⇨ Spain (CIEMAT, IAC)
- ⇨ USA (UCSC)

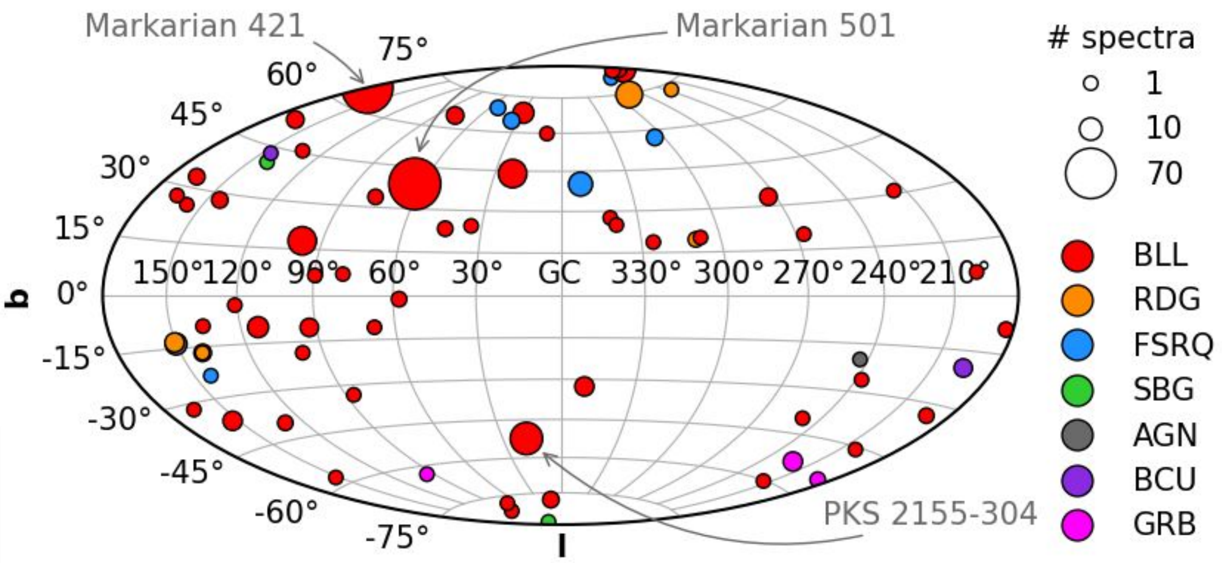
Publicly accessible from [Zenodo repository]

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]



Model independent EBL parametrization

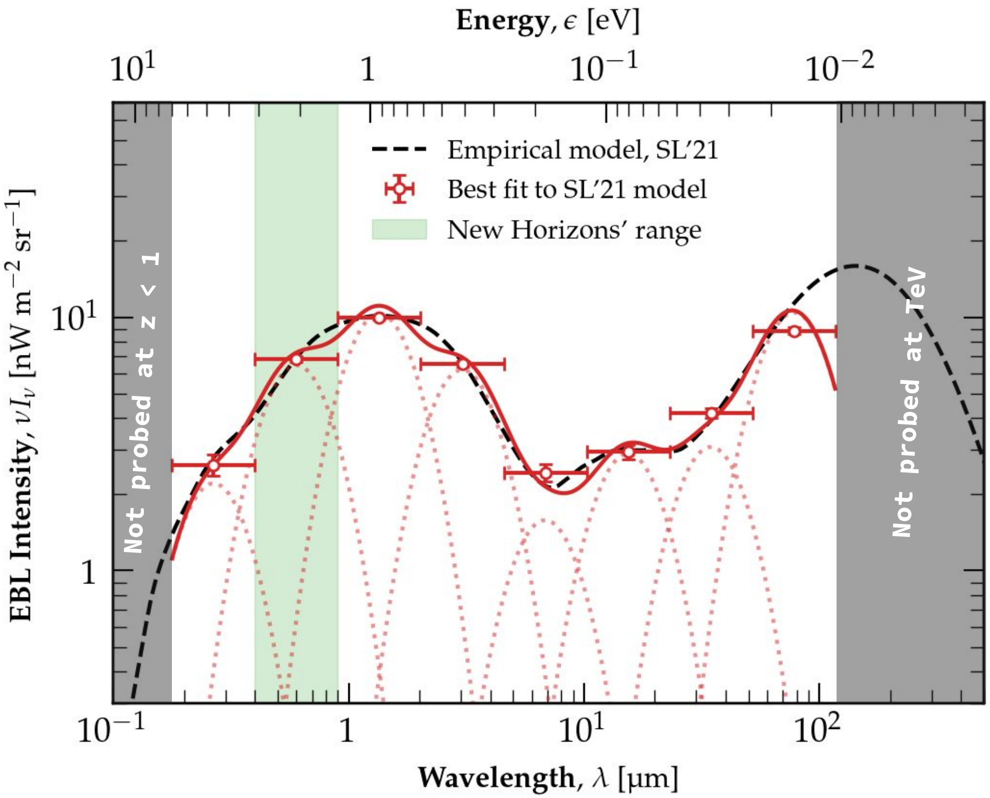
Parametric **EBL model**:

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

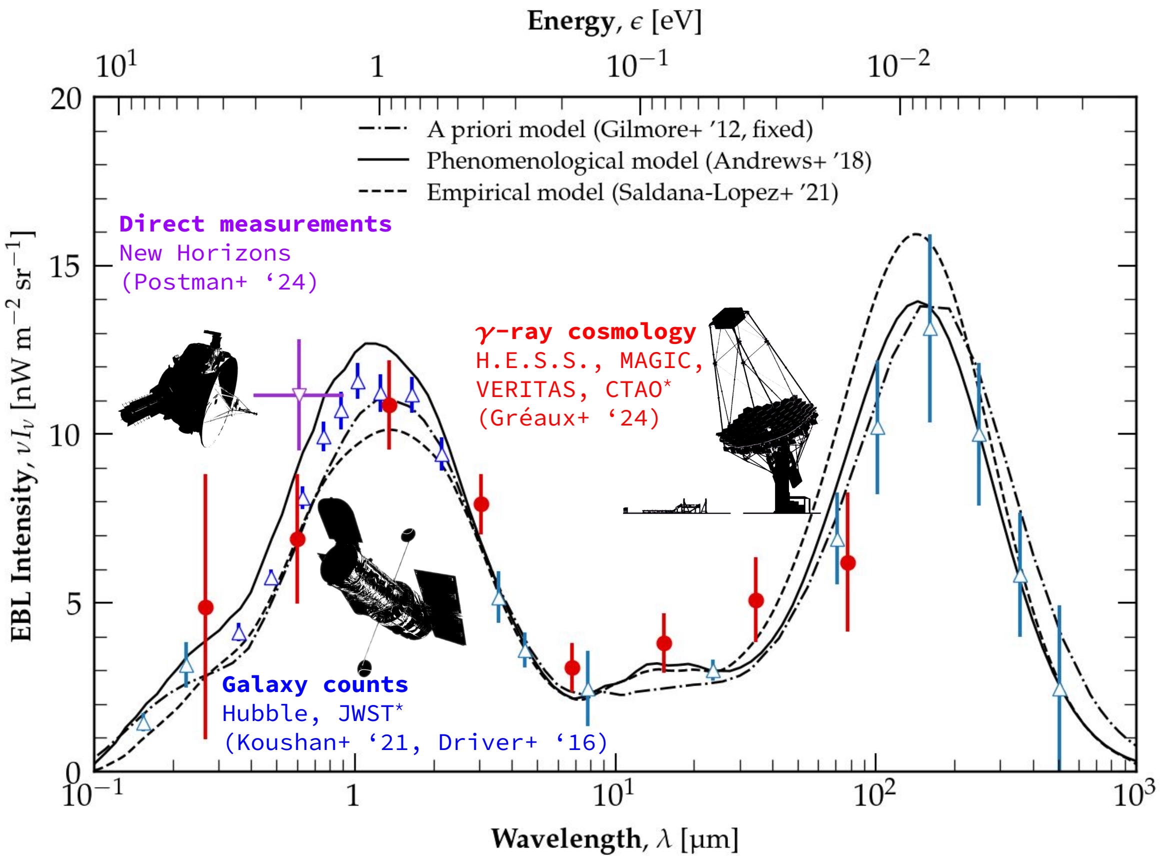
⇨ Sum of 8 Gaussians: fixed widths & positions, **free amplitudes a_i**

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

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



The cosmological optical convergence



***γ*-ray cosmology**: measure the EBL with **γ-rays from extragalactic sources**

First agreement in optical between **IGL**, **direct**, and ***γ*-ray** measurements

⇨ **IGL** gives **accurate view** of the EBL

⇨ Little room for other contribution from **diffuse components**

LG, 10.3847/2041-8213/ad85c9

Constraints on diffuse components

Assuming diffuse components with **same spectral shape** as the IGL:

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

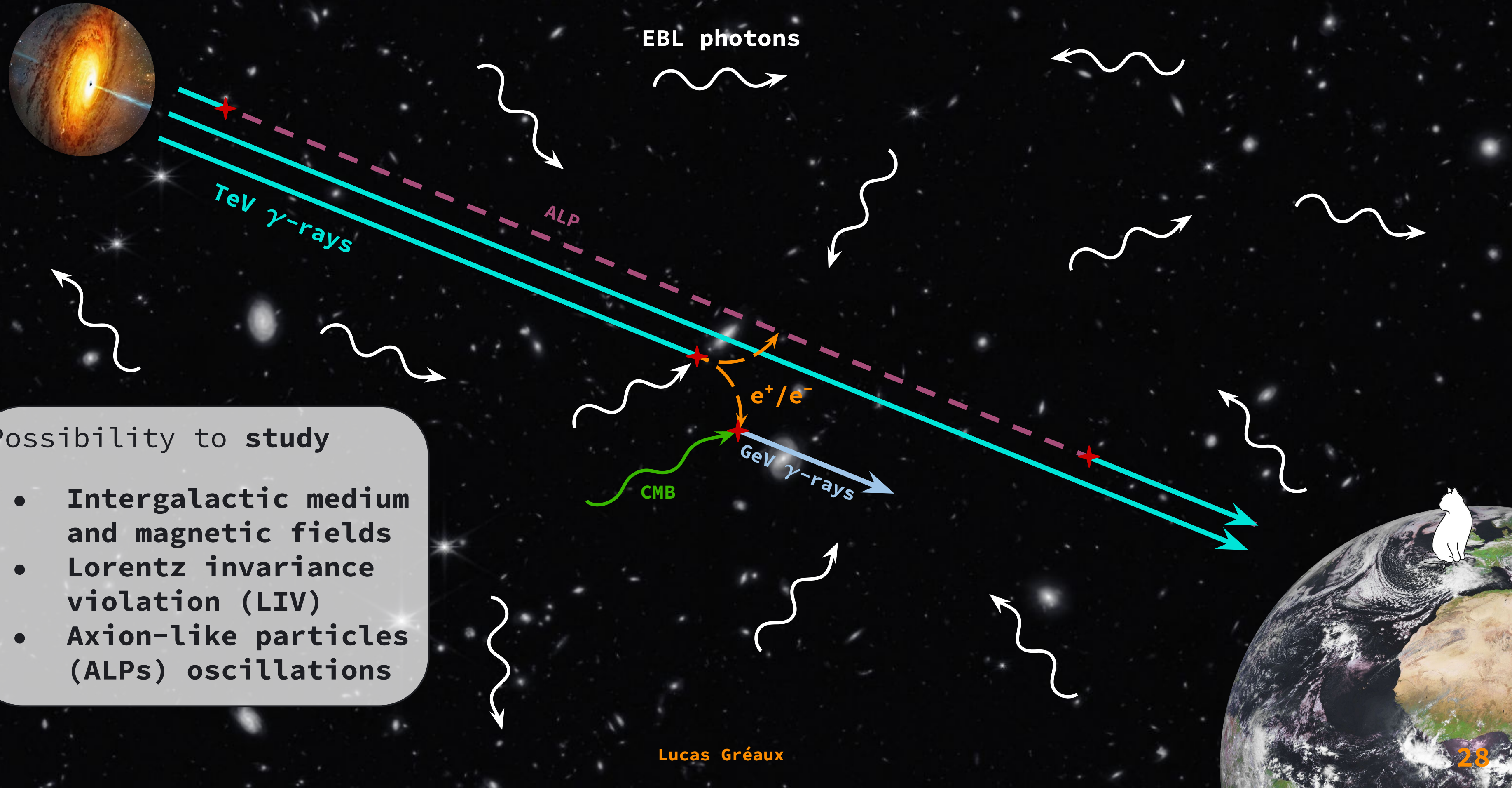
⇨ **Excluded values**:

f_{diff} **≤ 20%** (at 95% C.L.)

Intral halo light, clouds of stars tidally stripped from galaxies

NGC 5907. Credit: R. J. Gabany

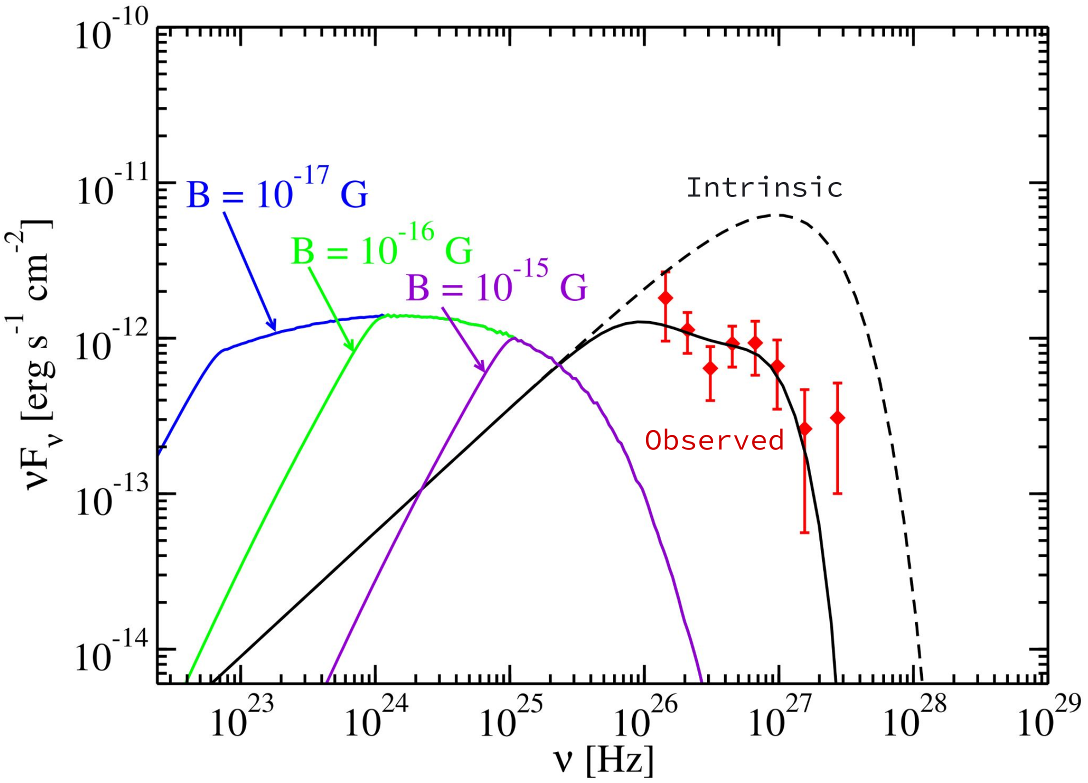
Gamma-ray propagation - other interactions



Possibility to **study**

- **Intergalactic medium and magnetic fields**
- **Lorentz invariance violation (LIV)**
- **Axion-like particles (ALPs) oscillations**

Secondary emissions from pairs



e^+/e^- pairs can **upscatter CMB photons**

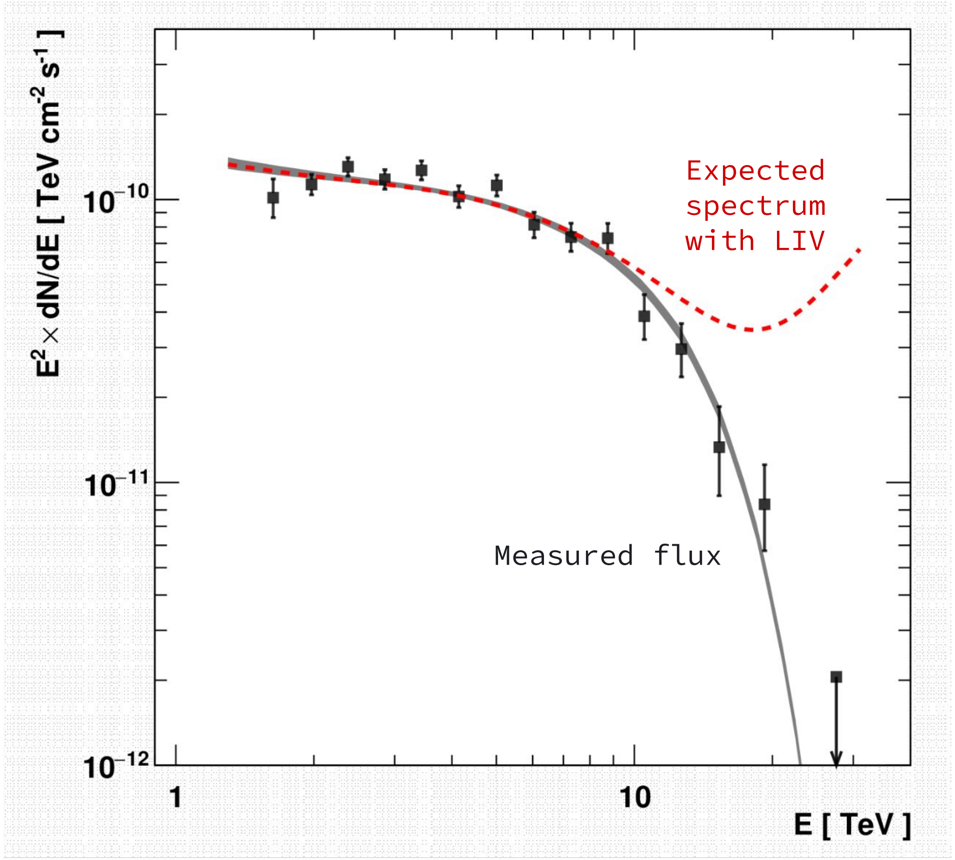
⇨ Expected **excess** at lower energies

⇨ Constrain the strength of the **intergalactic magnetic fields**

B < 10^{-19} G ruled out

J. D. Finke, 10.1088/0004-637X/814/1/20

Signatures of Lorentz invariance violation



Two channels to test Lorentz invariance violation

Temporal approach

⇨ Spread of the arrival time of γ-rays

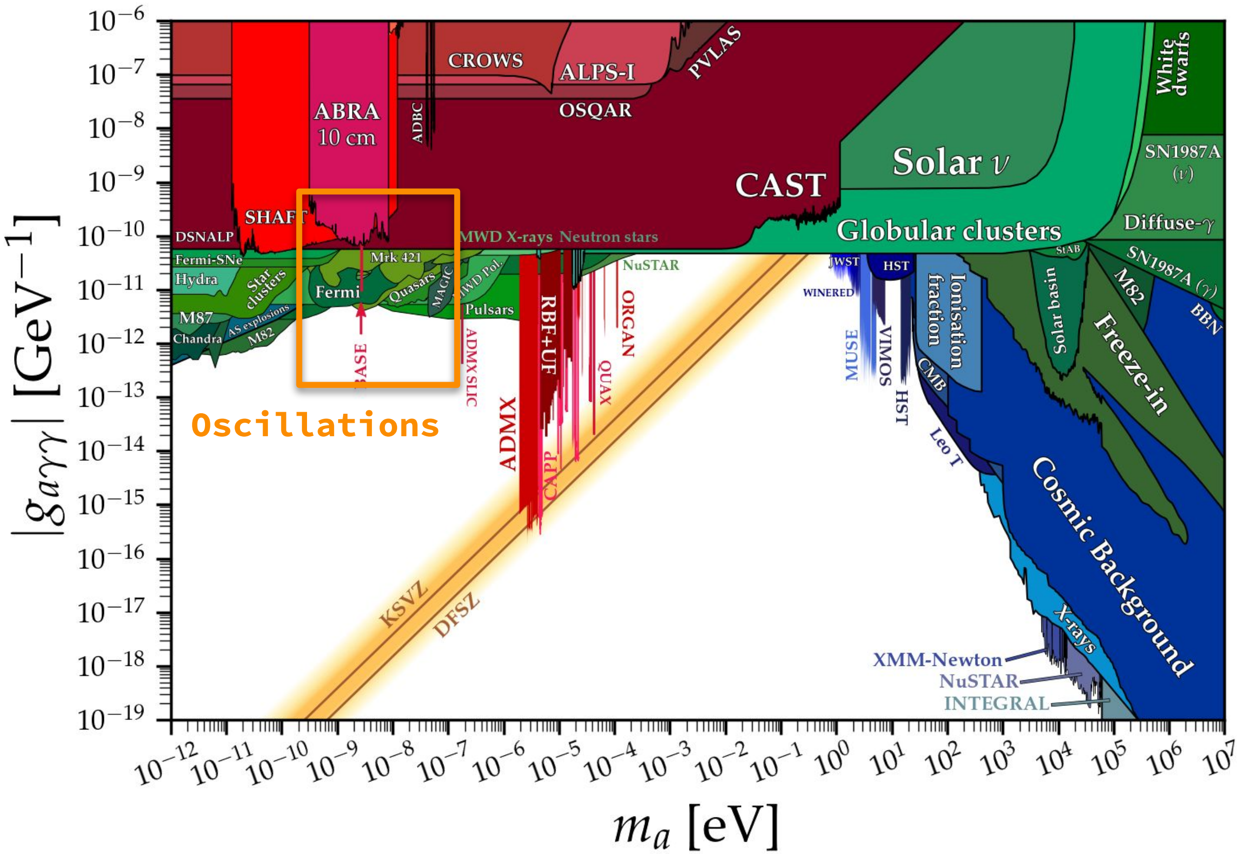
Spectral approach

⇨ **Modification** of the EBL interaction **cross-section**

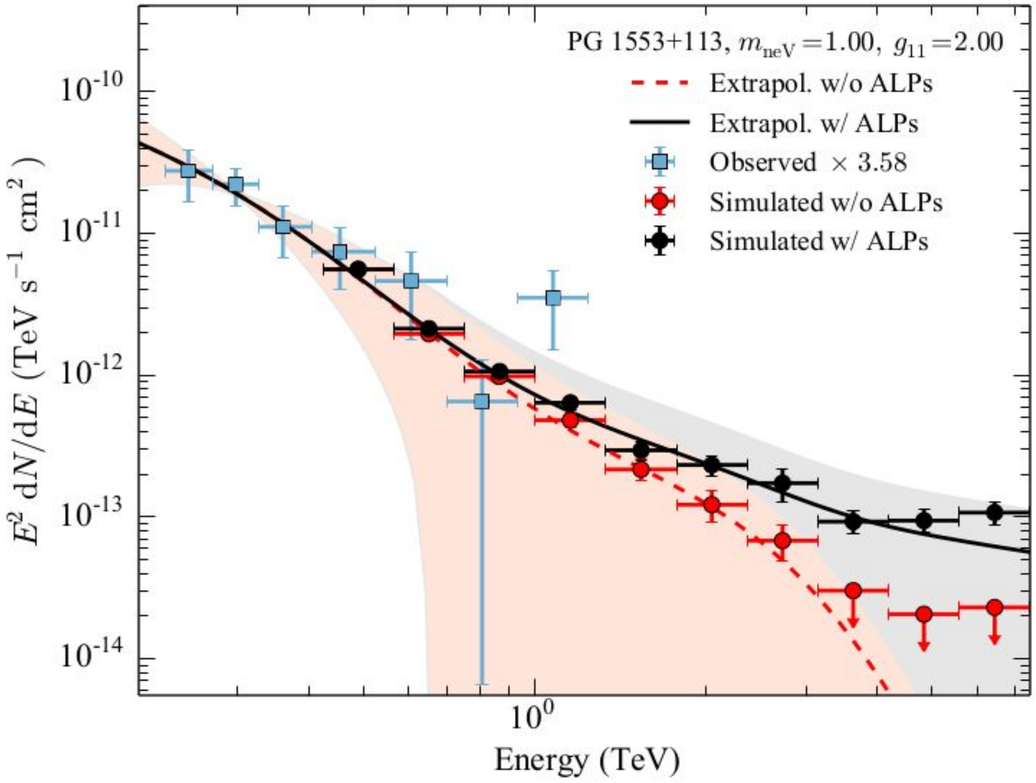
Axion-like particles (ALPs)

QCD axion:
hypothetical boson introduced to solve strong-CP violation

Axion-like particles:
dark-matter candidate, arising in extensions of the standard model



Oscillations of ALPs



γ-rays convert to ALPs in host galaxy, **travel** without seeing the EBL, **convert to γ-rays** into the Milky Way

⇨ Could lead to observable **γ-ray flux enhancement**

M. Meyer, 10.1088/1475-7516/2014/09/003

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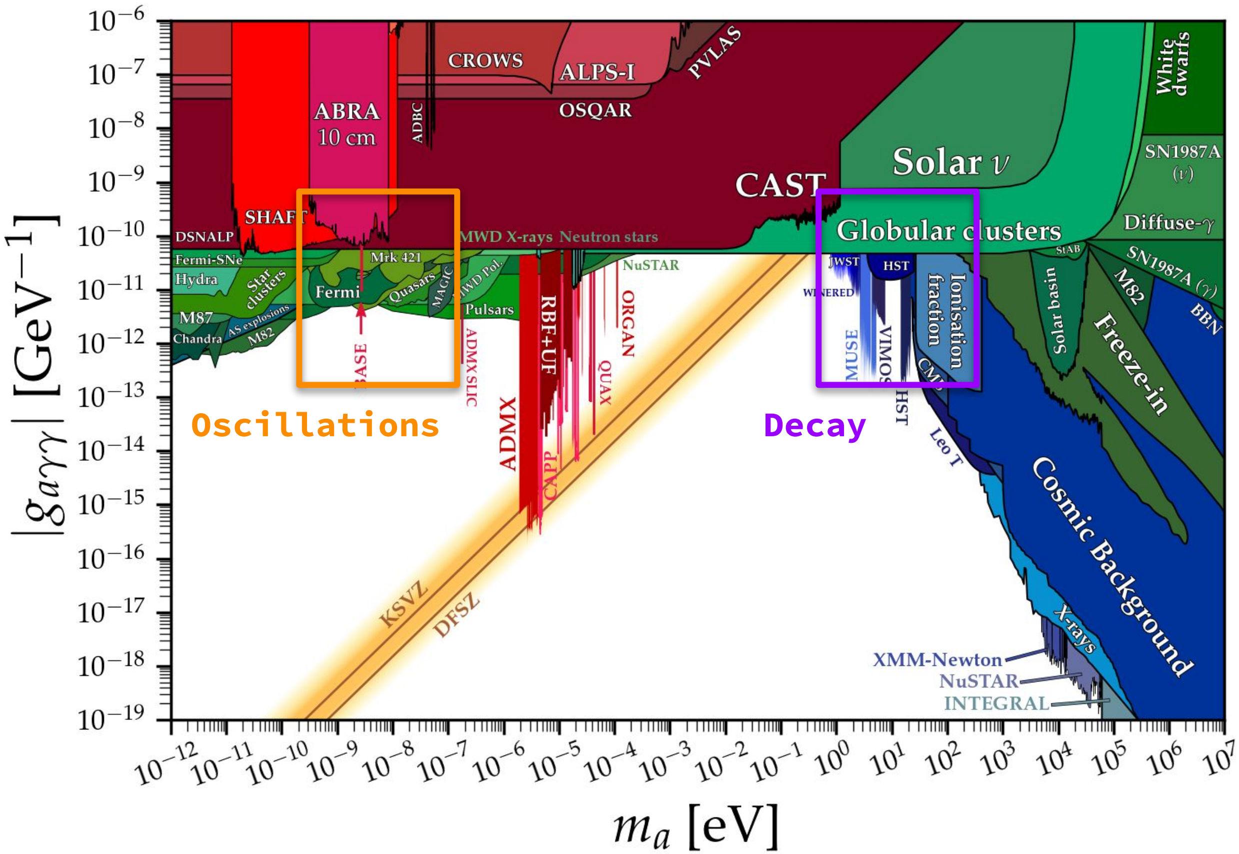
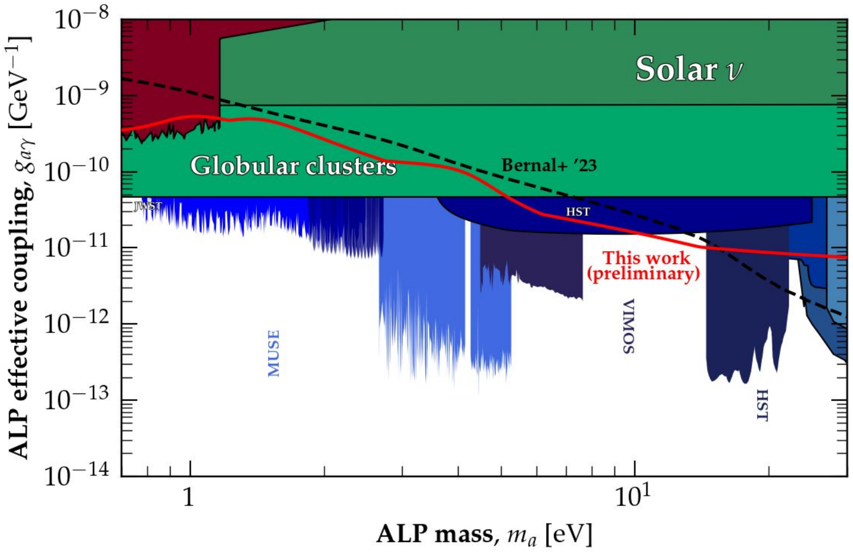


Decay of ALPs

ALPs decay into optical / infrared photons, potentially contributing to integrated **EBL intensity**

⇨ **Agreement between γ-rays and galaxy counts** limit the allowed parameter space for ALPs



Adapted from PDG 2024,
J. L. Bernal, 10.1103/PhysRevD.107.103046

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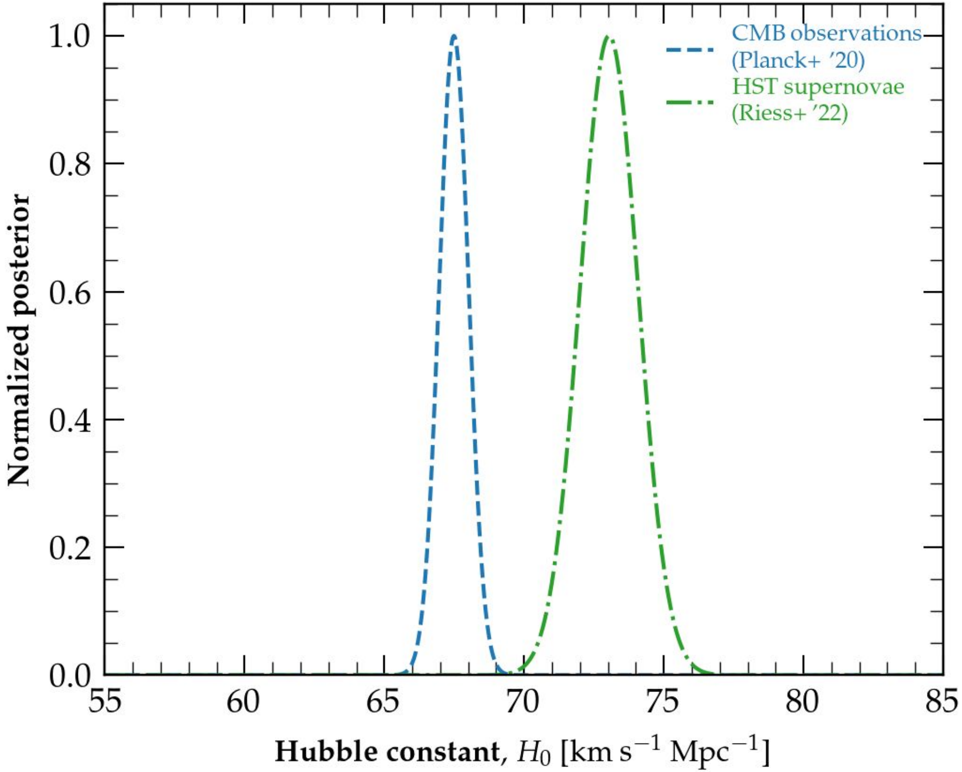
How fast is the Universe expanding?

The Hubble constant

The (local) **Hubble constant H_0**

- ⇨ **Fundamental quantity**
- ⇨ **Expansion rate** of the Universe
- ⇨ **Hubble law:** $v = H_0 \times D$

Disagreement between measurements from **fluctuations in the CMB** and **recession speed of galaxies**



Measuring H_0 with gamma rays

$\propto 1/H_0$

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

EBL intensity derived from **galaxy counts does not depend on H_0**

(successive scalings cancel out)

⇨ **Use the EBL** to **measure H_0**

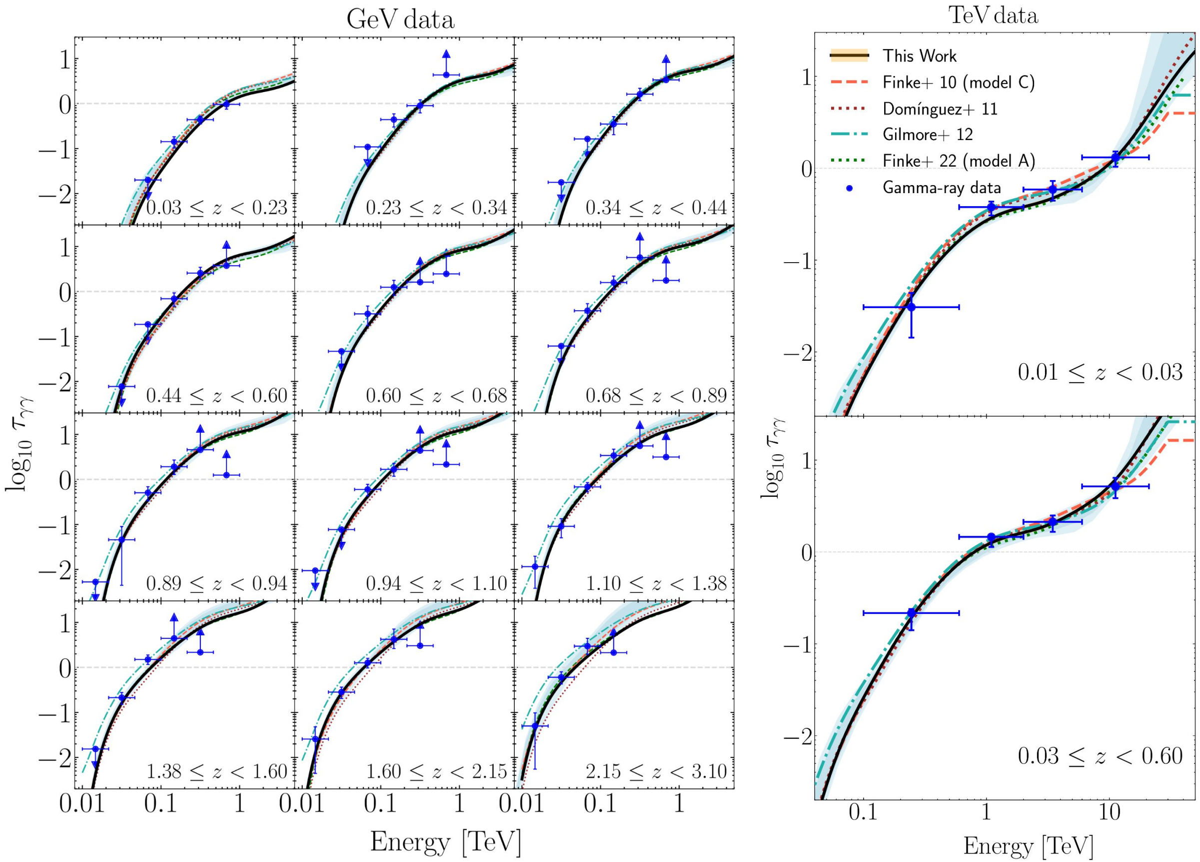
Two possible approaches

⇨ Use the **evolution of the EBL** (model dependent)

⇨ Use the **EBL spectrum** at $z = 0$ (model independent)

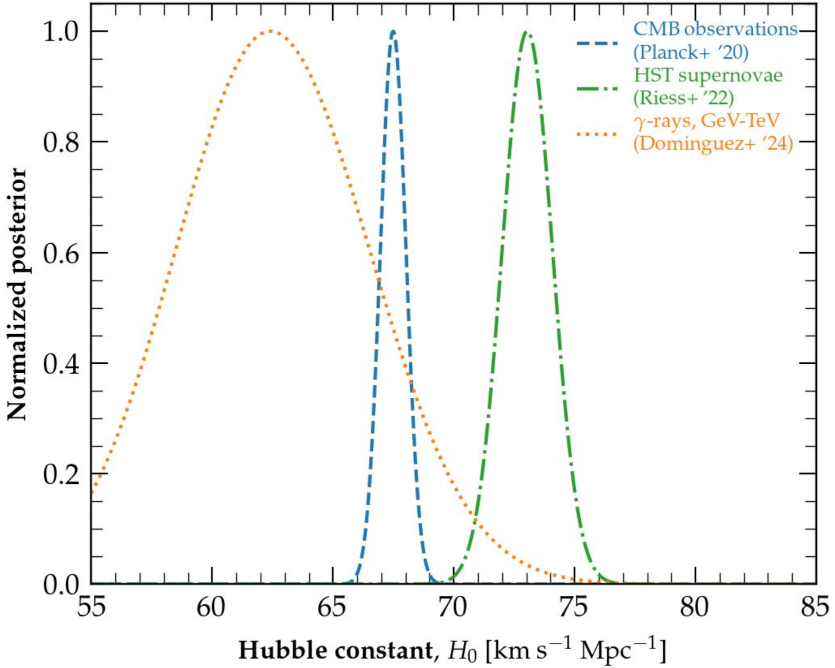
From the evolution - method

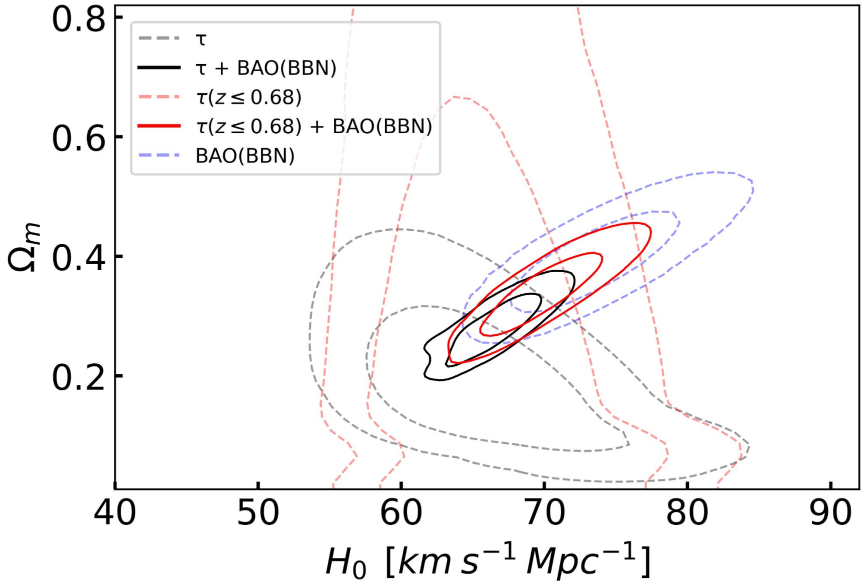
Match the optical depths derived from **GeV and TeV observations** to **galaxy counts measurements**



A. Domínguez, 10.1093/mnras/stad3425

Hubble constant from EBL evolution





H_0 = 62 ± 4 km s^{-1} Mpc^{-1} (fixed Ω_m)

H_0 = 65 ± 6 km s^{-1} Mpc^{-1}, Ω_m = 0.2 ± 0.1

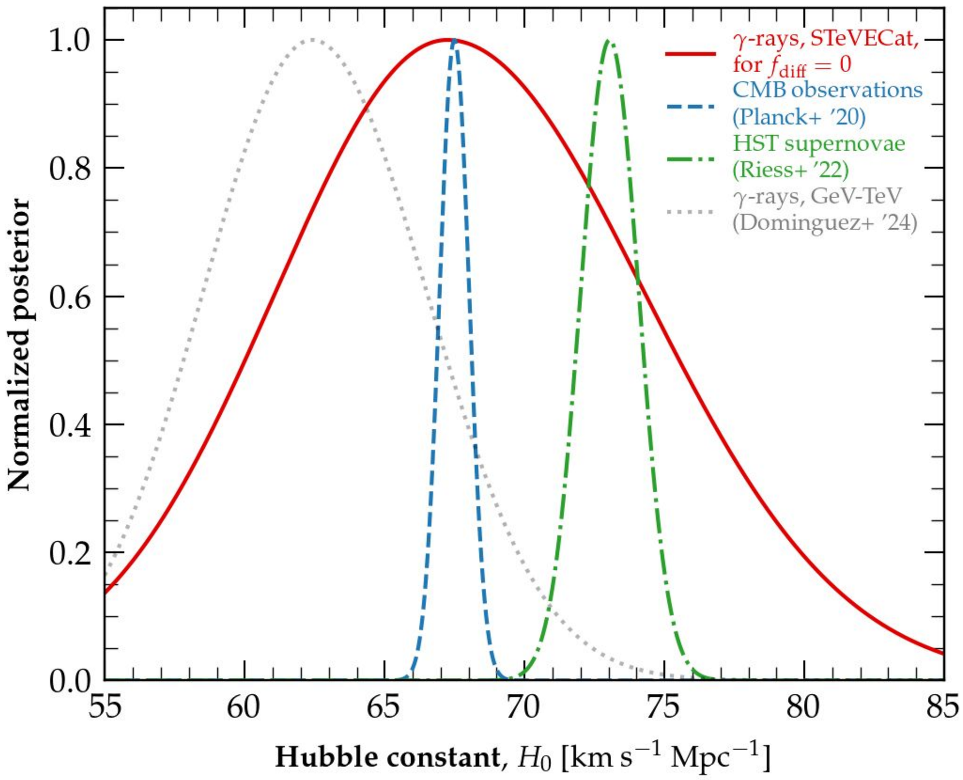
Hubble constant from EBL spectrum

EBL spectrum previously obtained assuming H_0 = 70 km s^{-1} Mpc^{-1}

Ratio of EBL intensity from γ-rays and galaxy counts **gives**

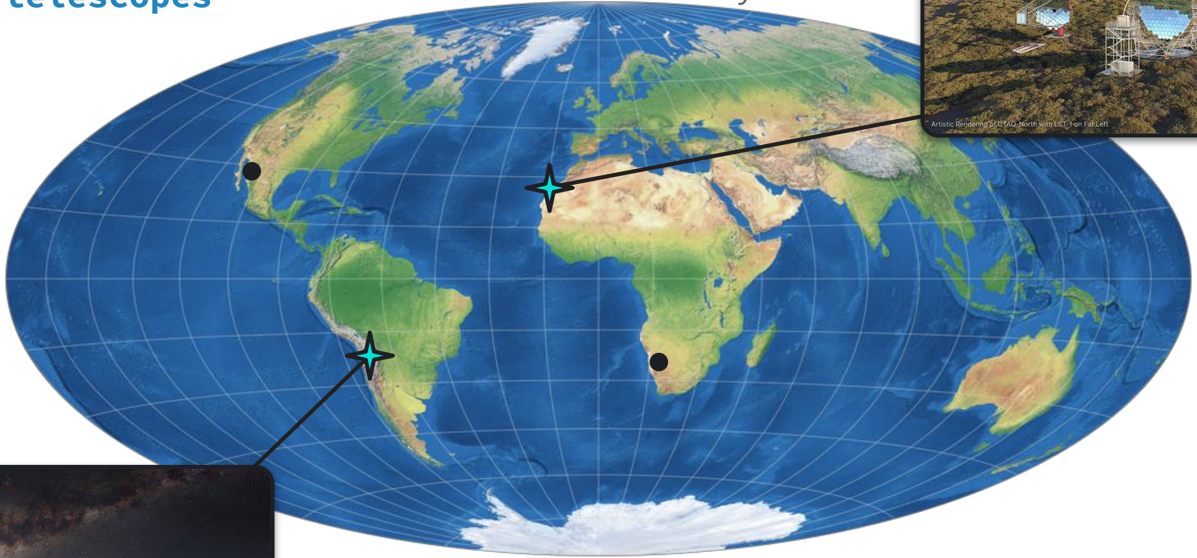
$$\frac{\nu I_\nu^\gamma}{\nu I_\nu^{\mathrm{IGL}}} = \frac{1 + f_{\mathrm{diff}}}{h_{70}}$$

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

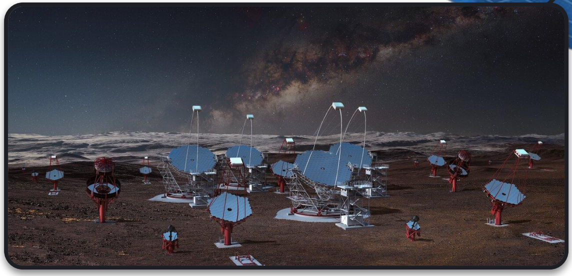


CTAO, the future generation of instruments

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

Credit: CTAO, rendering

Simulating STeVECat seen by CTAO

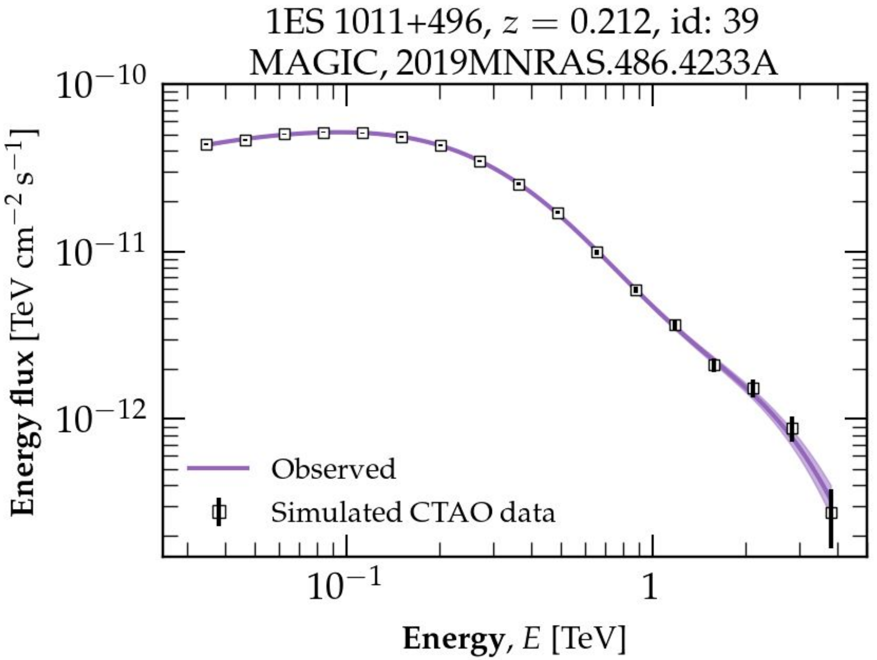
Sensitivity increased by factor **~10**

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

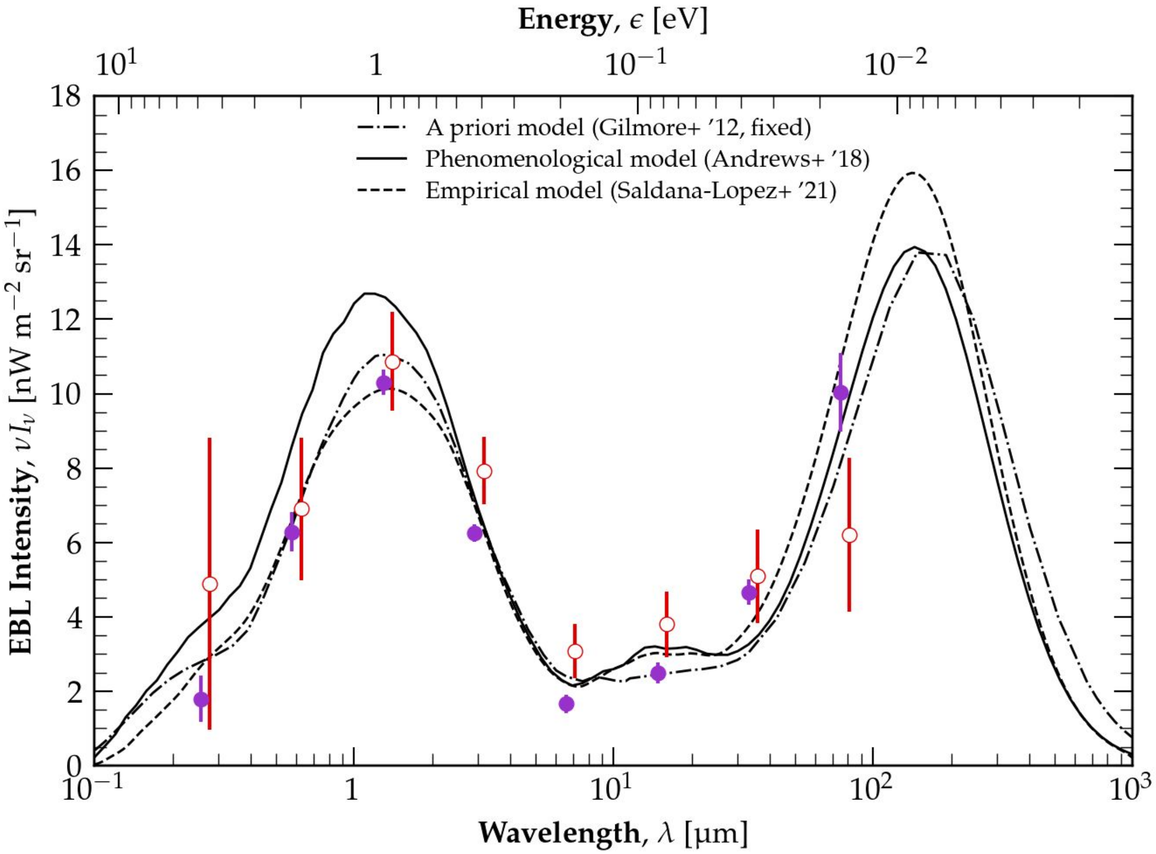
Simulate **STeVECat** observations with **CTAO's instrument response functions**

⇨ ~ **3000 h** of simulated livetime

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



The cosmological optical convergence



Precision on EBL spectrum should be greatly enhanced by **next generation**, **CTAO**

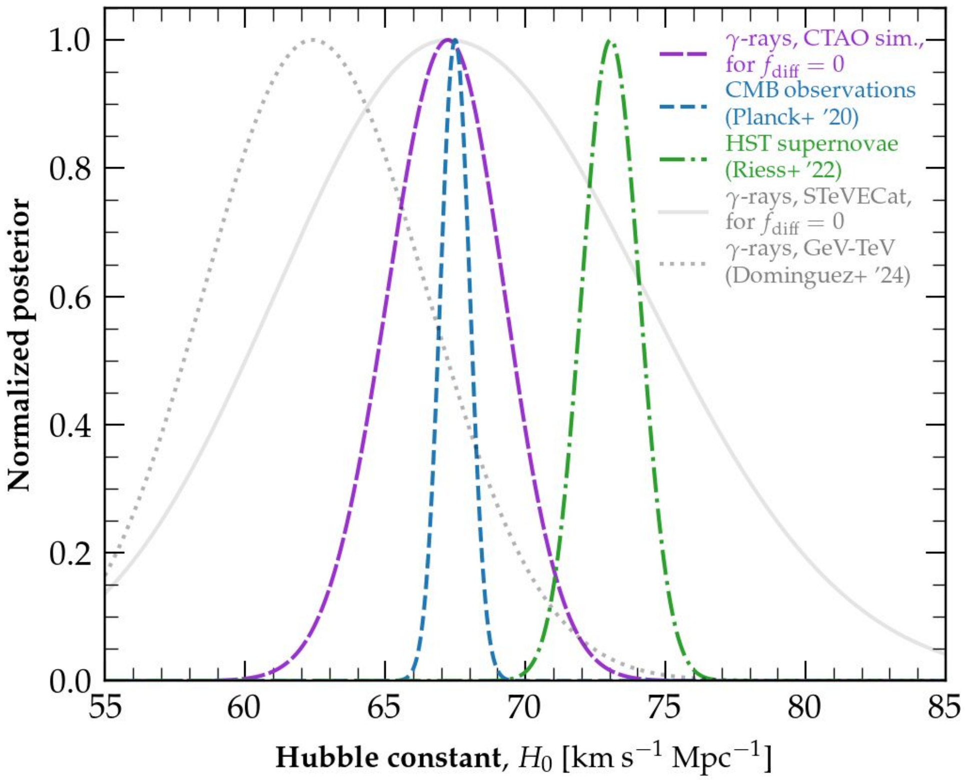
Hubble constant measurement — the future?

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

CTAO measurement of H_0:

⇨ **precision of ~3%**?

Pessimistic or realistic?



Conclusion

Extragalactic background light (EBL), sum of **all light** emitted in the Universe (following the CMB)

- ⇨ Fundamental observable, signature of all photon production pathways
- ⇨ Well described by **galaxy counts**
- ⇨ Hard to measure directly

Interaction between EBL and γ-rays: **γ-ray cosmology**

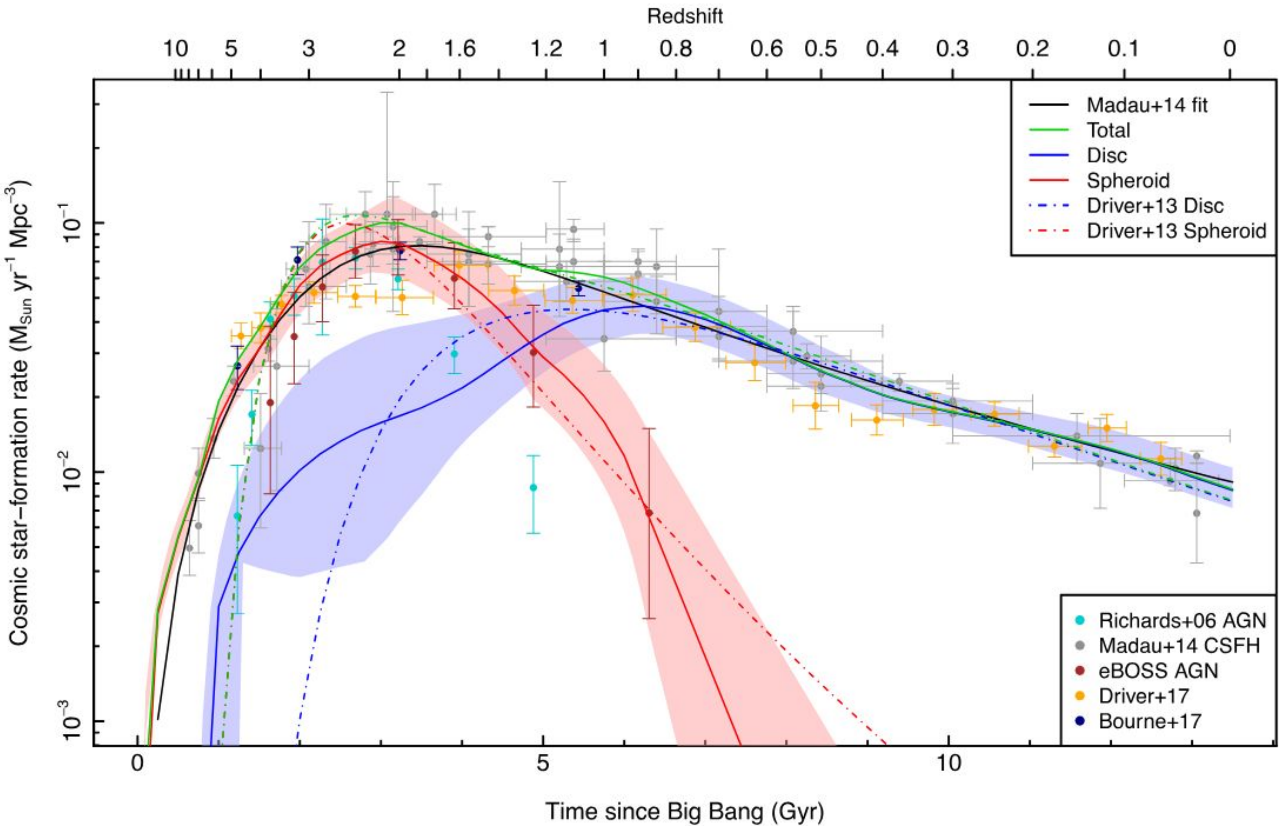
- ⇨ Measurement of the **EBL**
- ⇨ Limits on **fundamental physics**
- ⇨ Measurement of the **Hubble constant**

Next generation of instruments should lead to **precise measurement of H_0**

- ⇨ Will require great understanding of **systematic effects**
- ⇨ Updates on the **observation program of CTAO?**

Thank you for your attention

Cosmic star formation rate



S. K. Andrews, 10.1093/mnras/stx2843

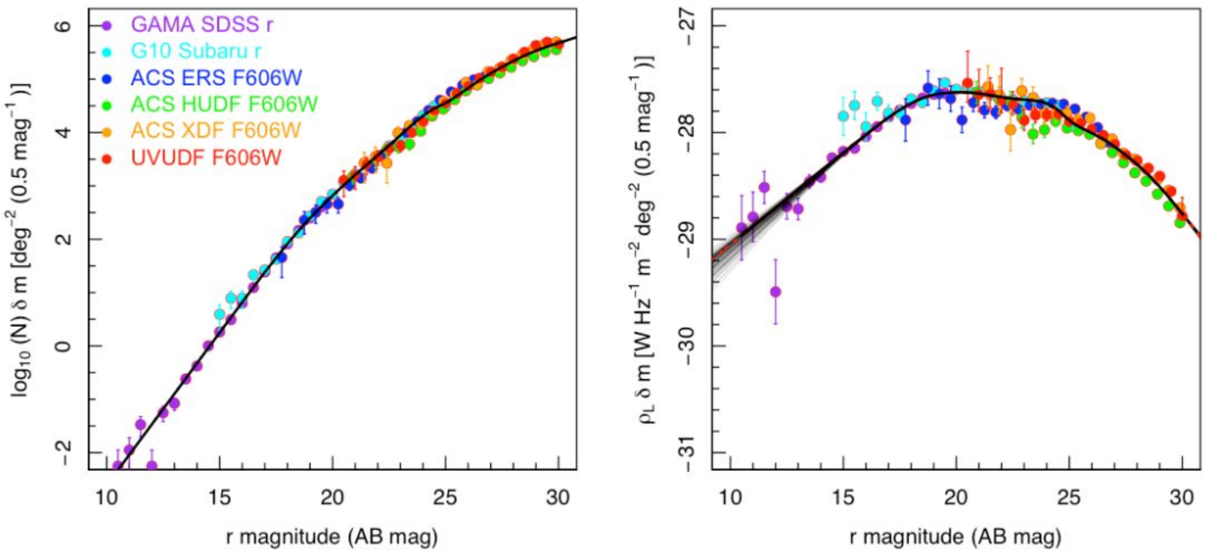
IGL measurements

IGL: integrated galactic light, emission from **resolved galaxies**

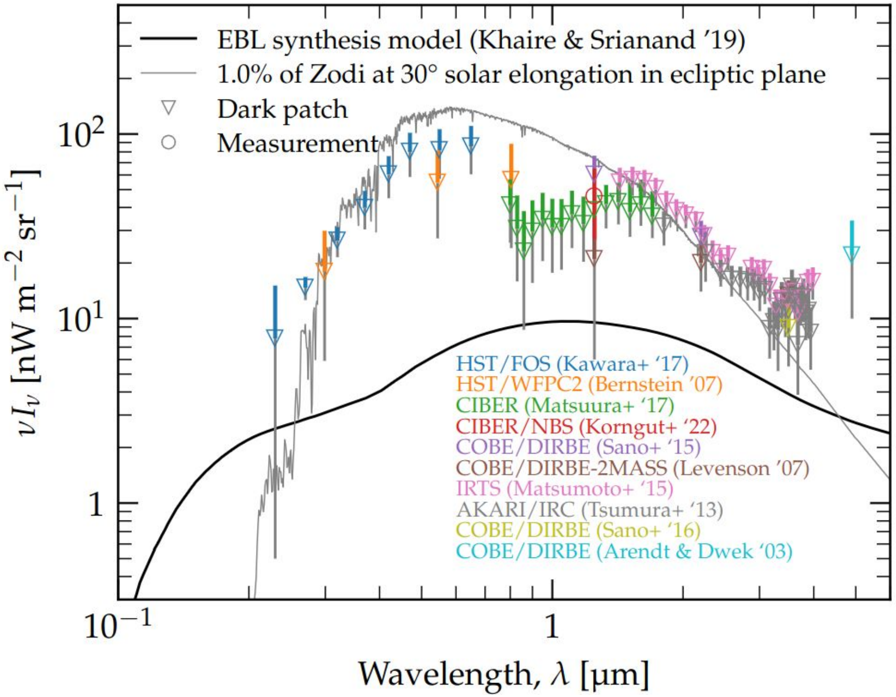
⇨ Expected as **main EBL contribution**

Measured from deep field **galaxy surveys**

⇨ Contribution mainly derived from **intermediate-magnitude galaxies**



Direct measurements at 1µm



J. Biteau, 10.5281/zenodo.7842239