Cosmic inventory of the background fields of relativistic particles in the Universe

with an emphasis on the cosmic optical and infrared backgrounds
→ incl. results by Lucas Gréaux (ED PHENIICS PhD prize ’24, see thesis here)

2025.12.03, DE / GDR CoPhy Webinar

Jonathan Biteau

Intro

The dark night sky

Overview of the measurements

From radio to ultra-high energies,
from the ‘70s to today

Focus: cosmic optical background

2024: convergence of the 3 techniques!

Outro

Light from baryons as a tool
for precision cosmology?

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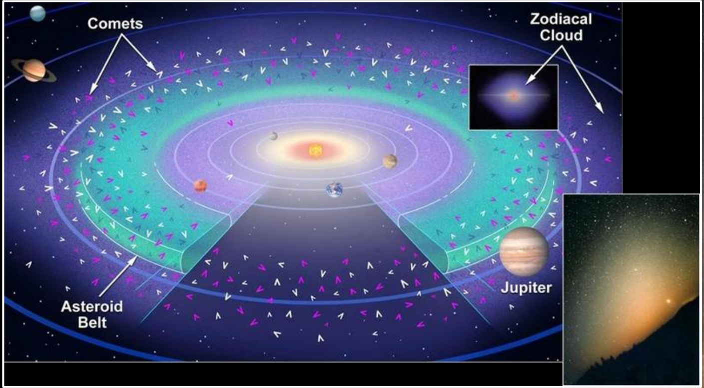
The dark night sky

Aoraki National Park, New Zealand.
Credits: chaka160, [reddit/itookapicture]

The dark night sky

You said dark?

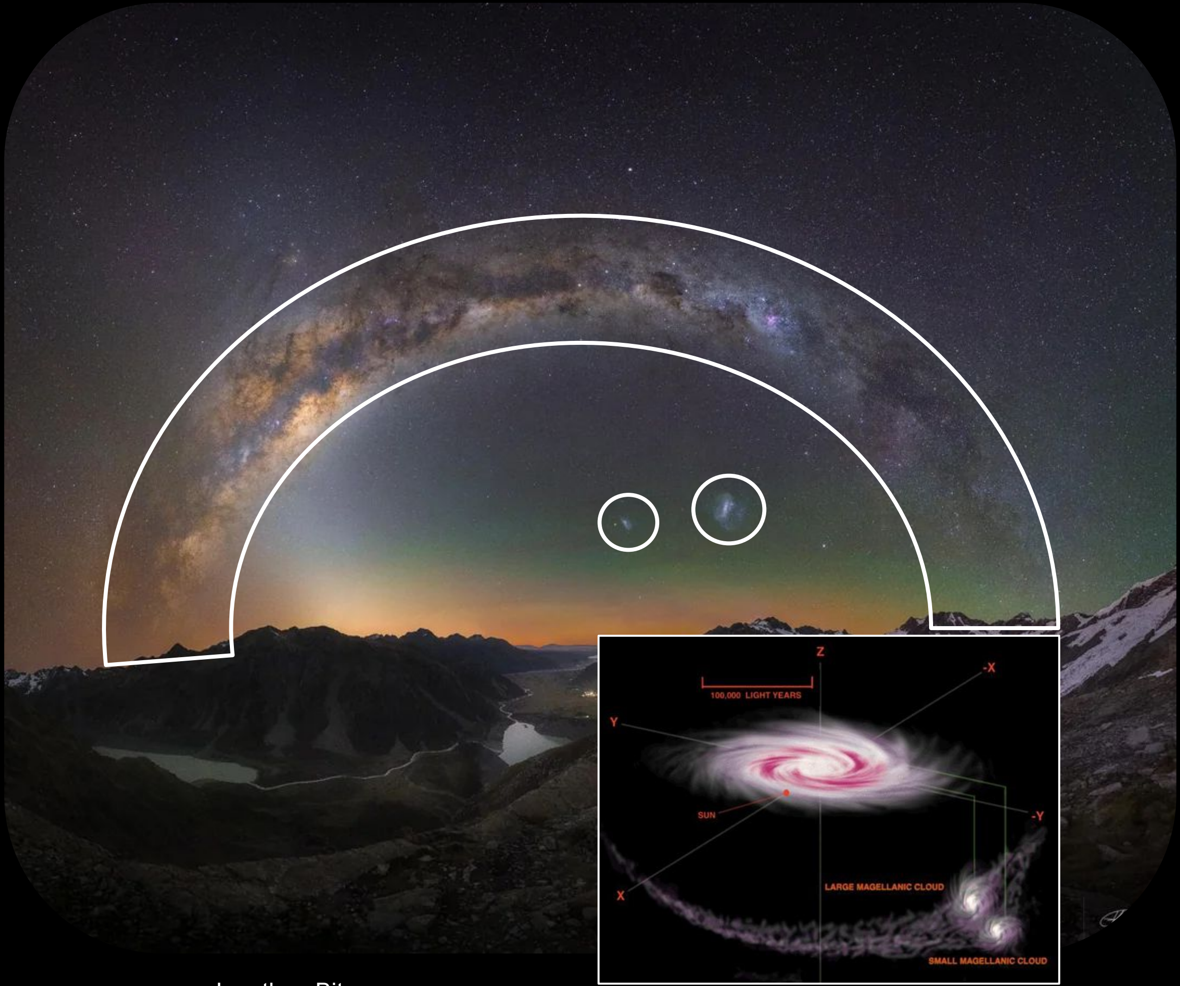
The dark night sky



You said dark?

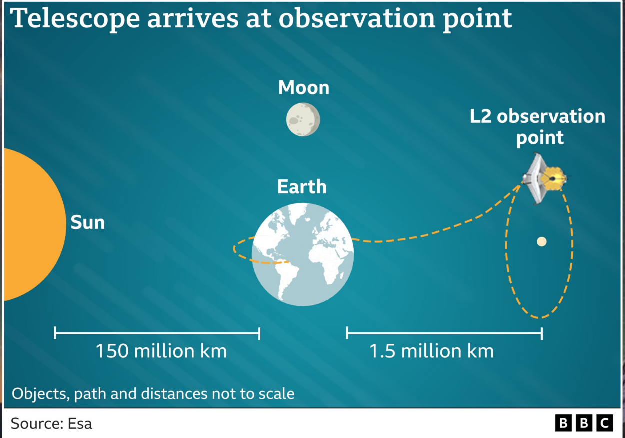
The dark night sky

You said dark?



The dark night sky

Crédit : ESA/Webb, NASA & CSA, A. Martel.



The de Chéseaux - Olbers paradox

see The Conversation article at this link

Why is the sky not covered by stars / galaxies ?

“Infinity of the sphere of stars” (Halley, 1721) at this link

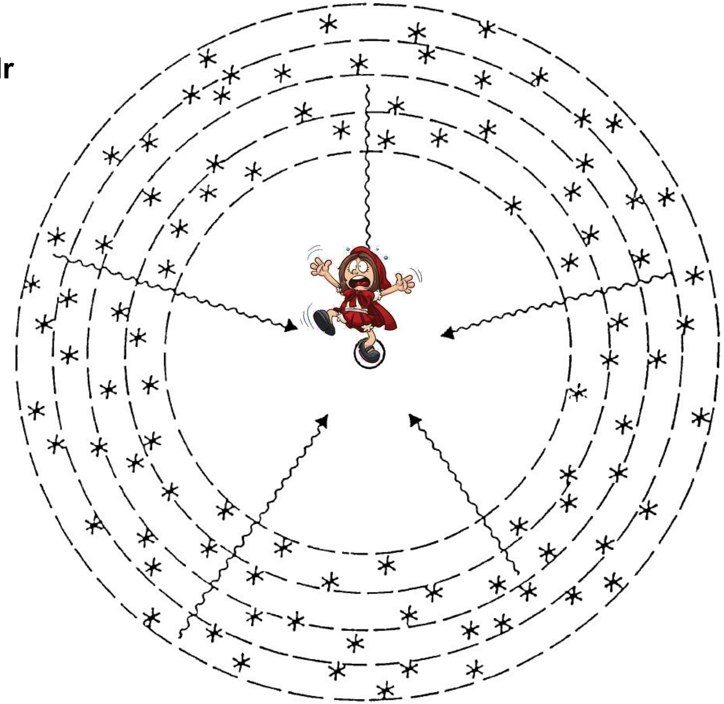
Riddle from Digges (1576) in his translation of Copernicus’ *De revolutionibus*

Formulation by de Chéseaux (1744), **Olbers** (1823):

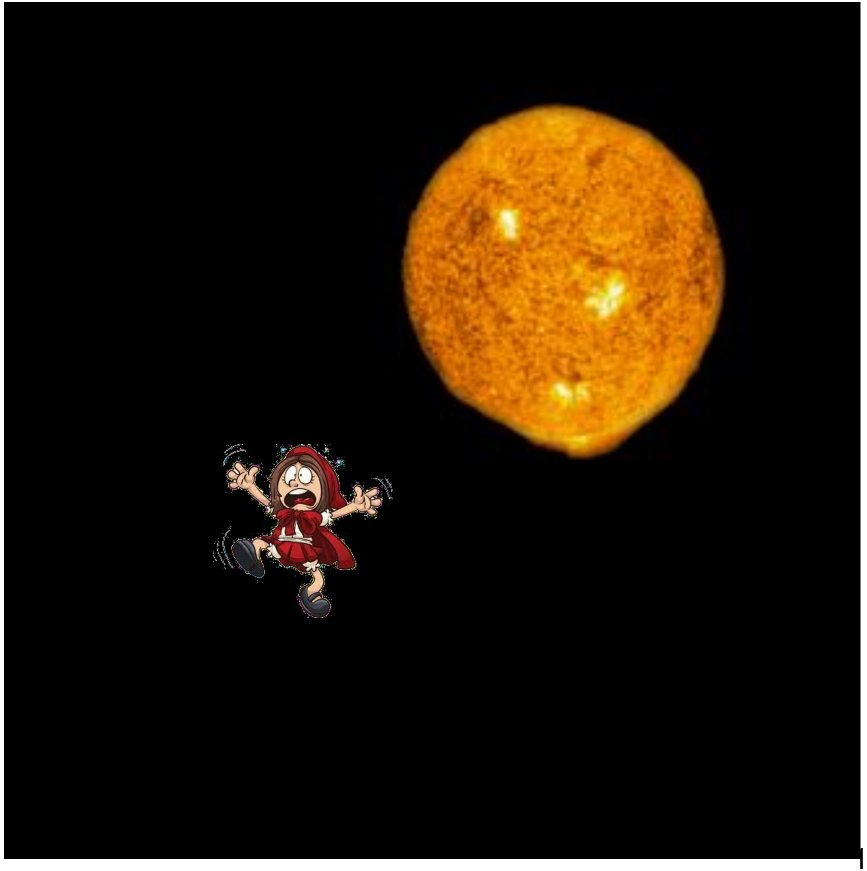
$\Phi_{total} = \int dr\ \Phi_{star} \times N_{star}(r; r+dr)$, with $\Phi_{star} \propto 1 / 4\pi r^2$ and $N_{star}(r; r+dr) \propto 4\pi r^2\, dr$

$\Phi_{total} \rightarrow \infty$ in a static unbounded universe (Descartes, Newton)

Credits: Harrison ‘90



Paradox: why is the night sky dark?



Olbers' paradox: a founding pillar of cosmology

Quoting Malcolm Longair:

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.

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

Modern Cosmology - a Critical Assessment,
M. S. Longair 1993

The solution by a poet, an old lord and a particle physicist

Unsatisfactory solutions

- ❏ Stoic universe (Huggins, Herschel, Proctor)
- ❏ Fractal arrangement of stars, galaxies, etc (Kant, Fournier d'Albe, Charlier)

Solution: the history of the universe (E. Harrison, "Olbers' Paradox", *Nature* 1964)

- ❏ Account for finite speed of light (cf. delay in Io/Jupiter eclipses, Rømer 1676)

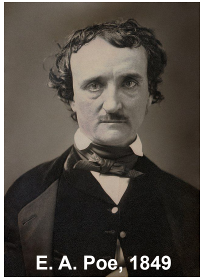
"The only mode, therefore, in which [...] we could comprehend the voids which our telescopes find in innumerable directions, would be by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all."

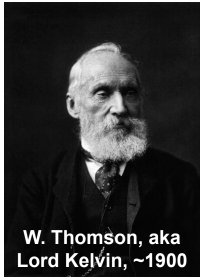
Edgar Allan Poe's *Eureka* (1848)

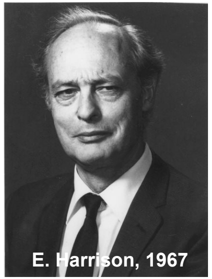
- ❏ Account for the finite lifetime of stars and show that the fraction of the sky covered by stars in a static universe is ~10^{-13}

Lord Kelvin in Baltimore Lectures, Lecture XVI (1904)

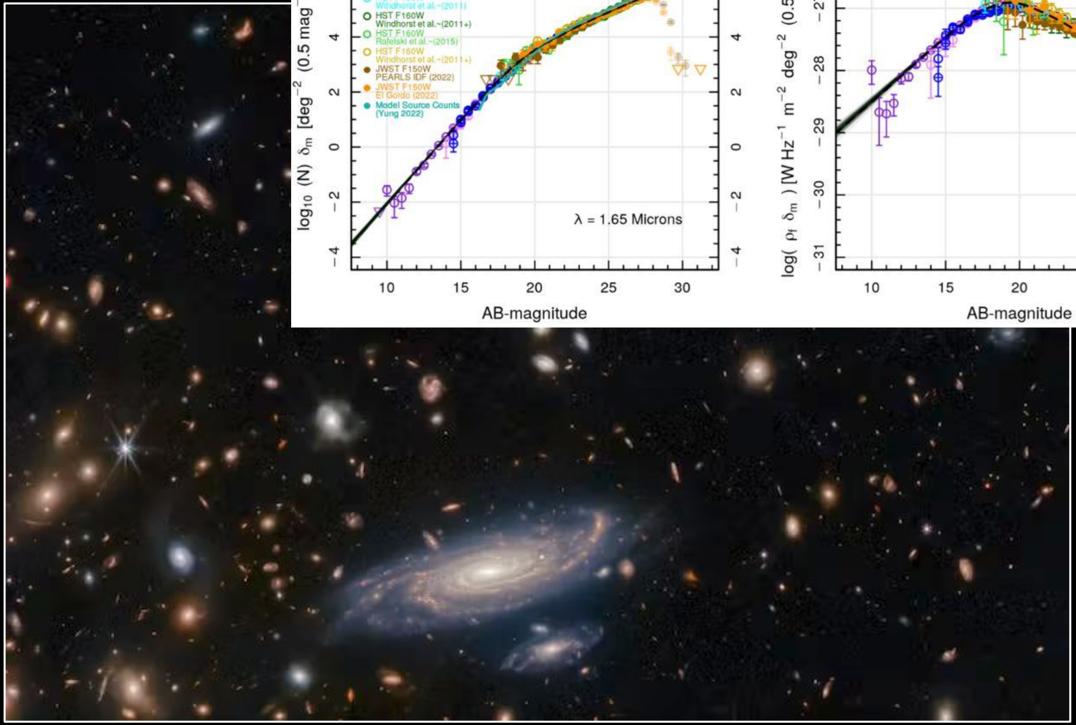
The history of the universe indeed governs the brightness of the sky, but only accepted a century after (late 1980s)... **when cosmology had matured!**

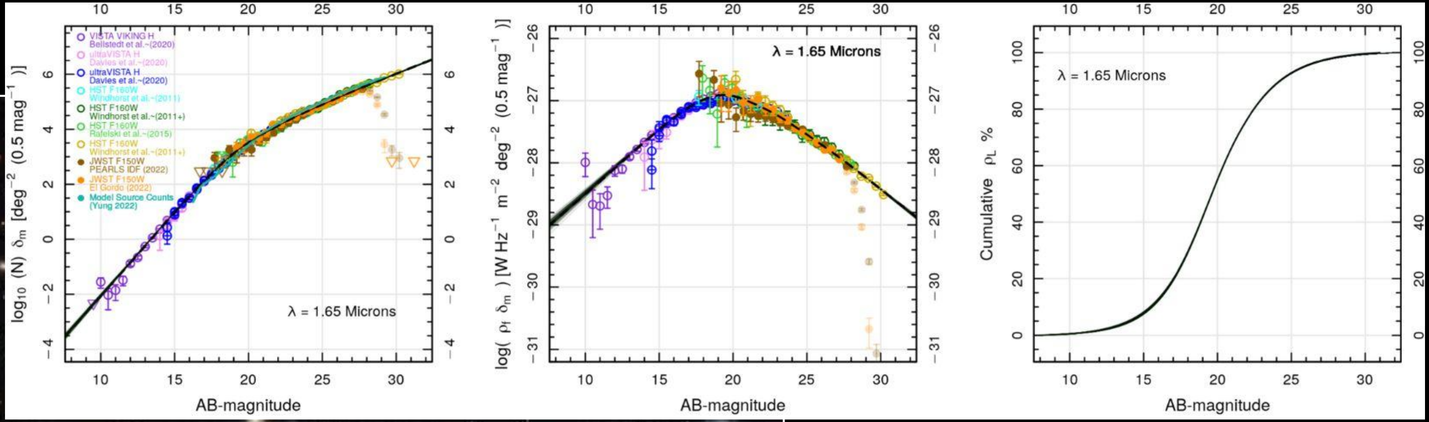






Integrated galaxy light (galaxy counts)





Windhorst+ ‘23

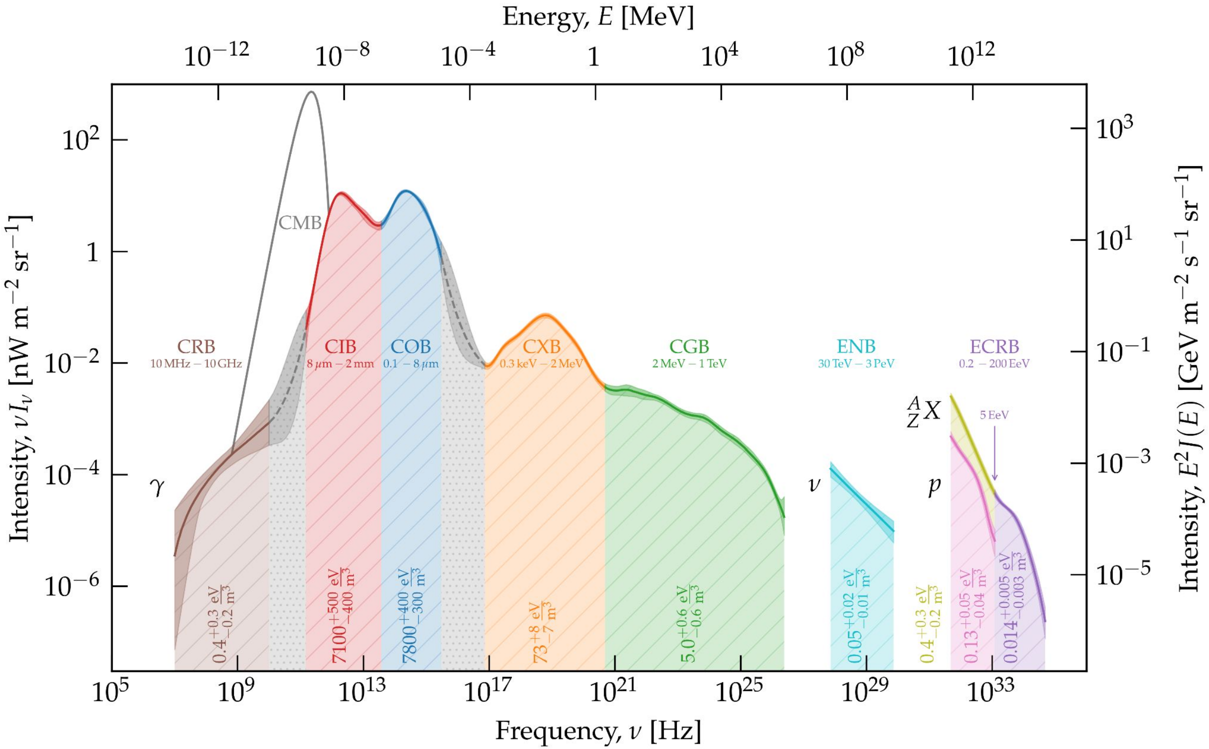
Seminal work with HST data by P. Madau & L. Pozzeti ‘00
→ galaxy counts converge

From Olbers’ paradox to precision measurement of the darkness level.

Crédit : ESA/Webb, NASA & CSA, A. Martel.

How Dark? *The multi-messenger spectrum of the universe*

More energy per photon / particle



More intense background = more power

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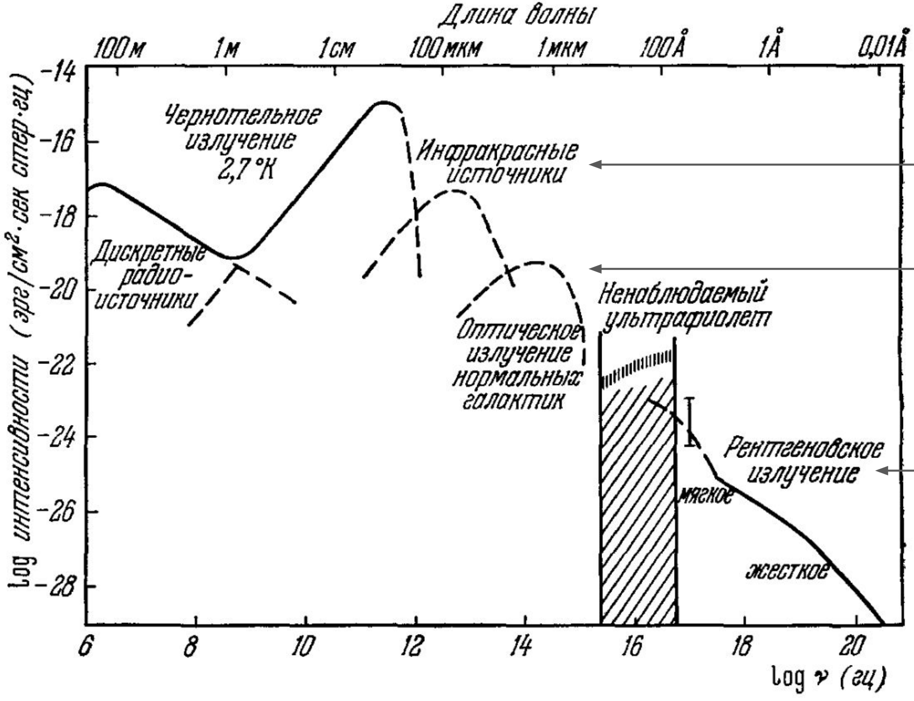
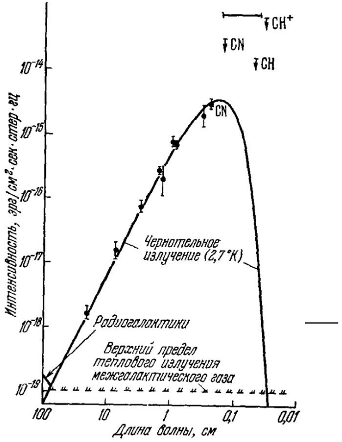
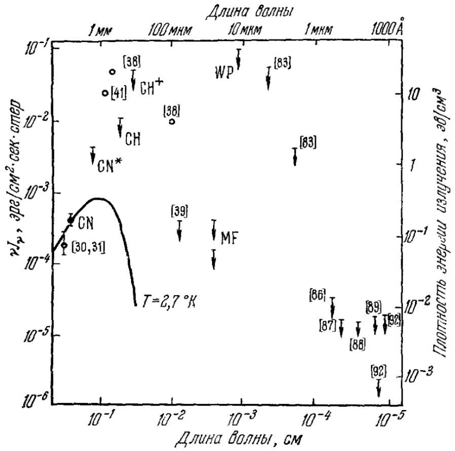
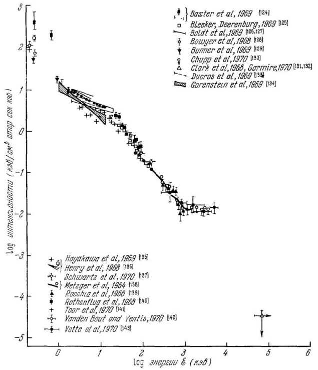
From the 1970s to the 2010s



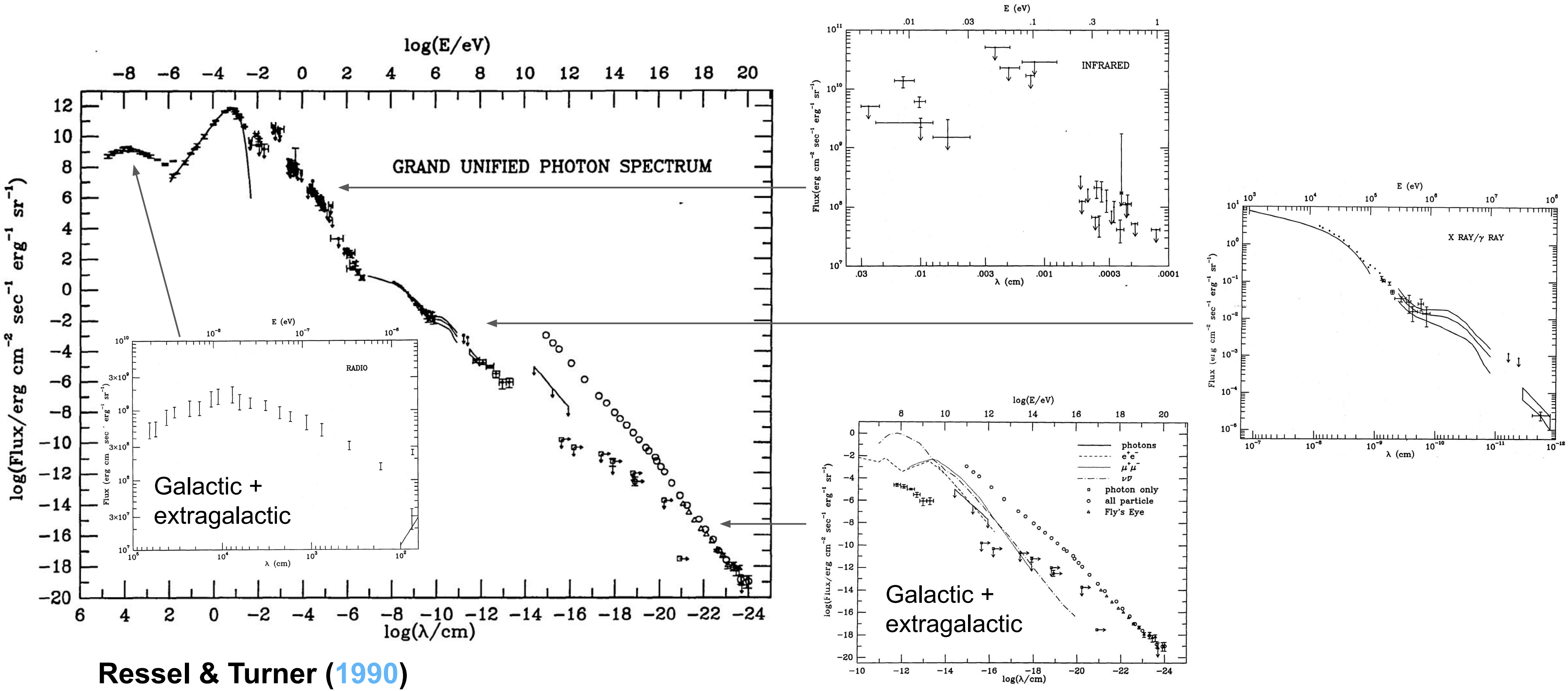






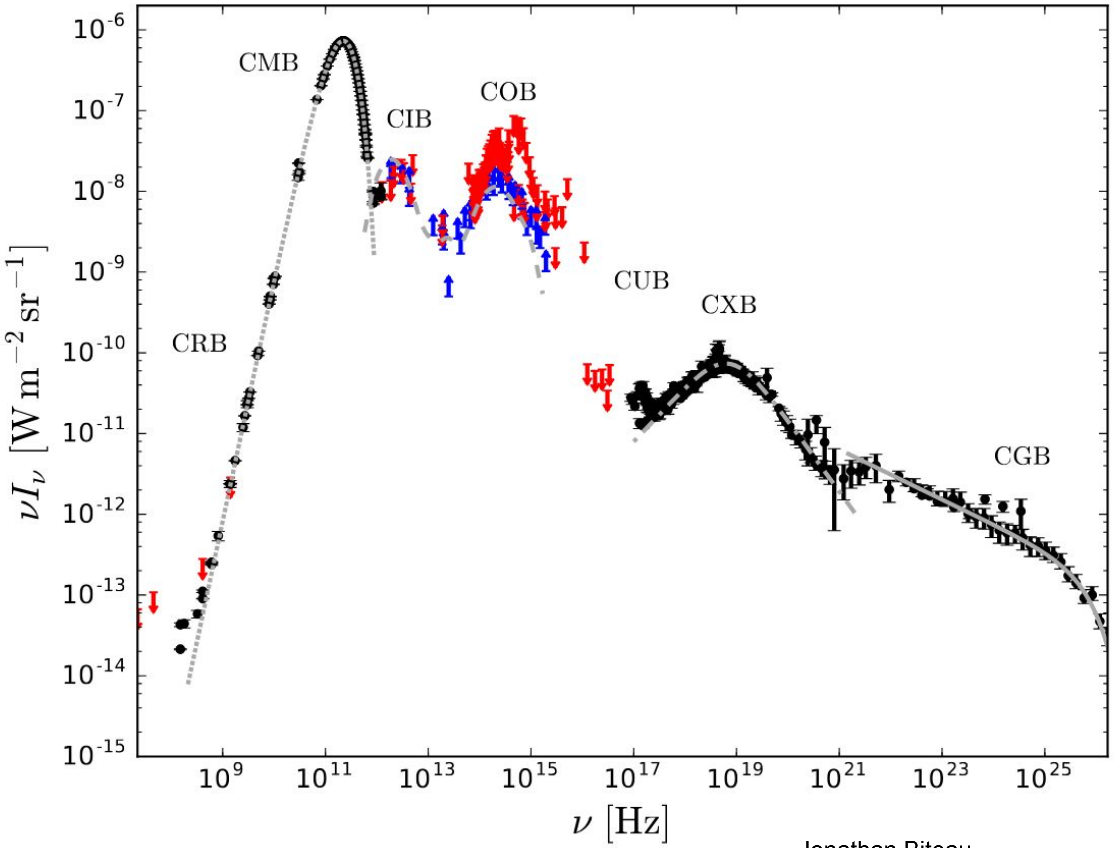
M. Longair & R. Sunyaev (Sov. Phys. Usp, 1971)

From the 1970s to the 2010s



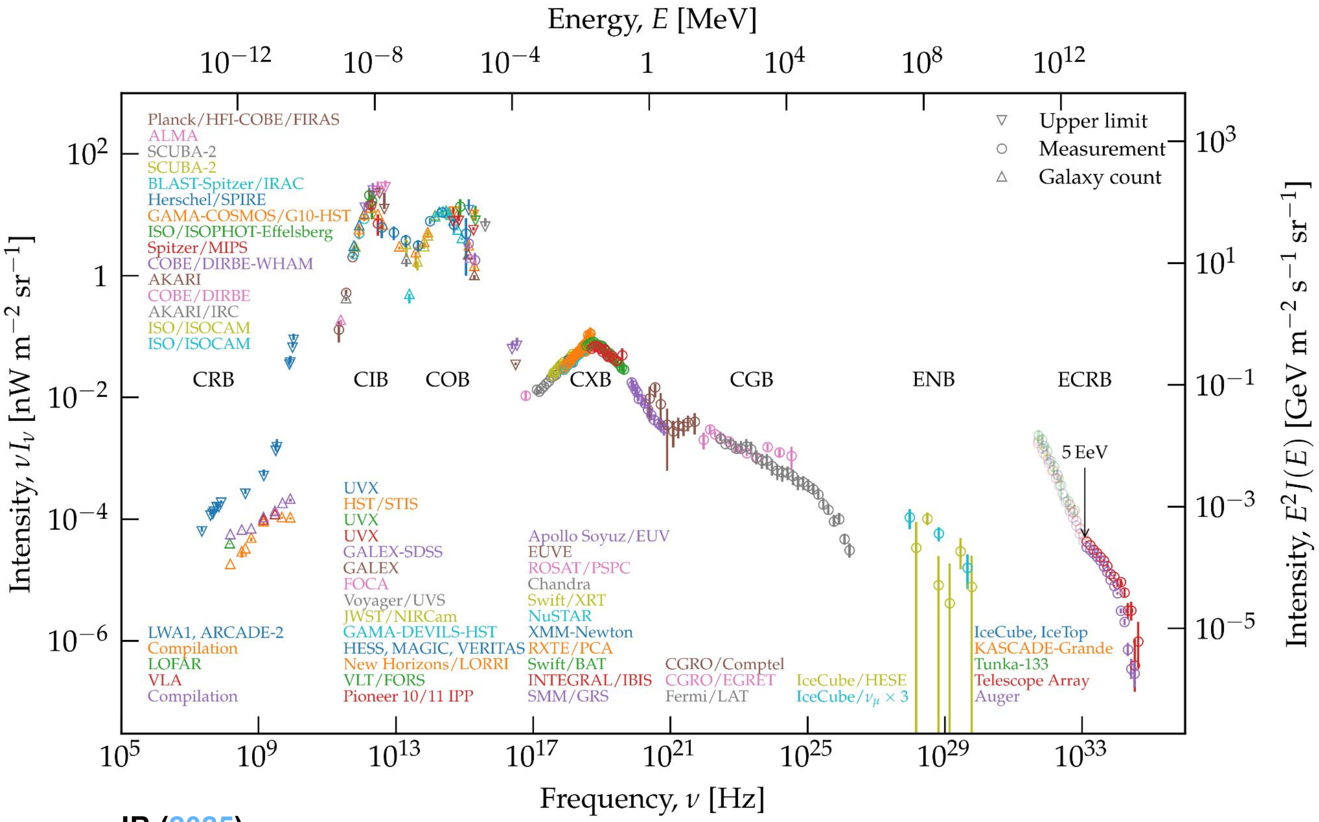
Ressel & Turner (1990)

From the 1970s to the 2010s



Hill, Masui & Scott (2018)

Overview of current measurements



JB (2025)

JB's habilitation (2023): collected non-redundant spectra, aiming at exhaustivity

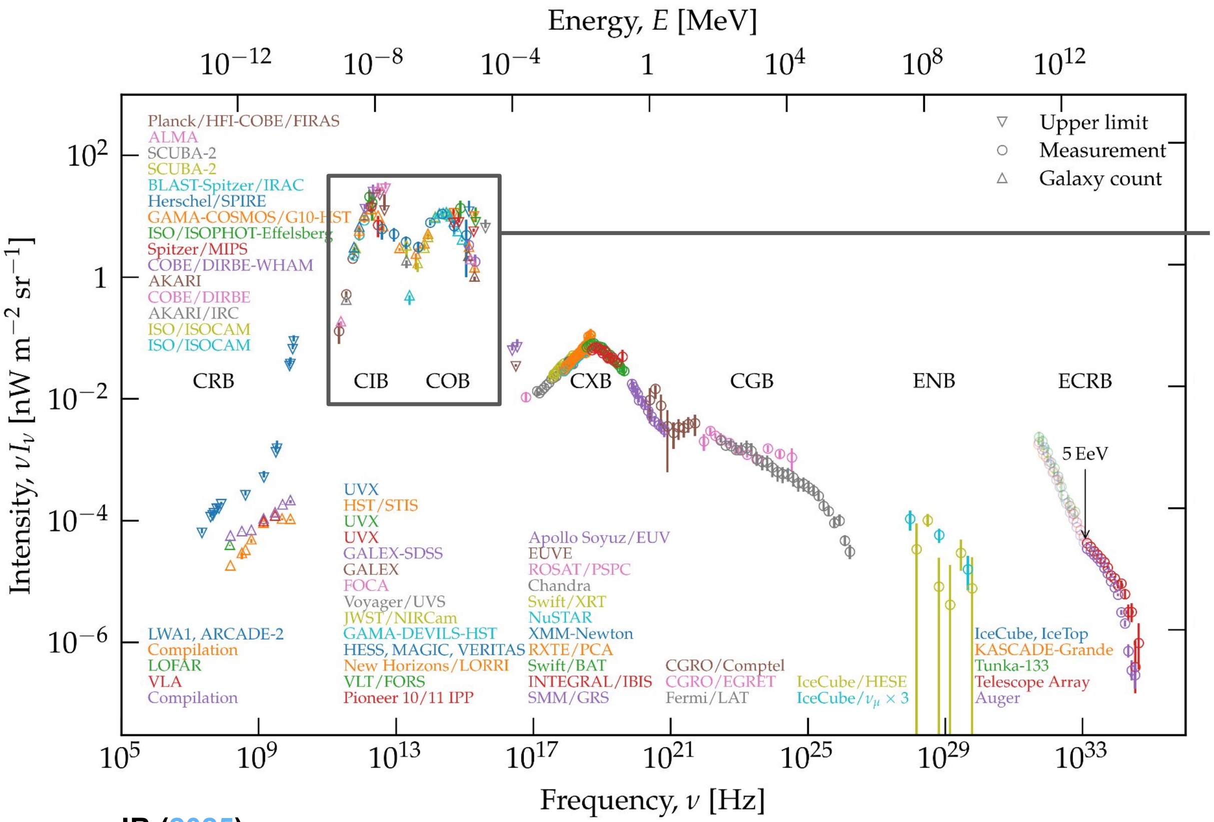
Dataset: 70 spectra, including 33 from Hill+ '18

Code: adapted from Evoli '21

Everything available on gitlab and Zenodo (check the proceedings here)

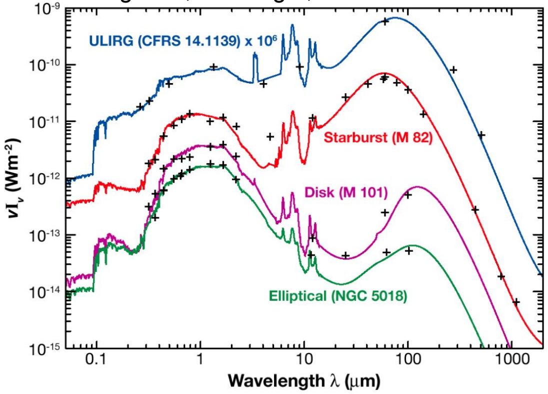
See also reviews from Cooray '16, Driver '21

Overview of current measurements



JB (2025)

G. Lagache, J.L. Puget, H. Dole 2005



Focus in the next slides:

Cosmic Optical & IR Backgrounds

→ accumulated light from all starforming galaxies (+ AGN ~10%)

→ important sanity check of all the light emitted since the EoR

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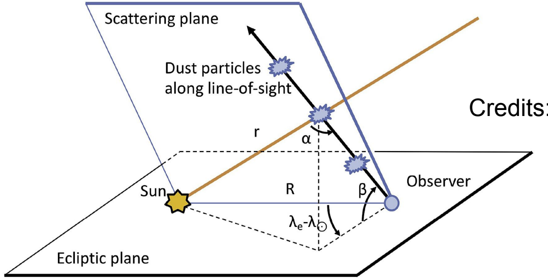
Contaminants in the O/IR

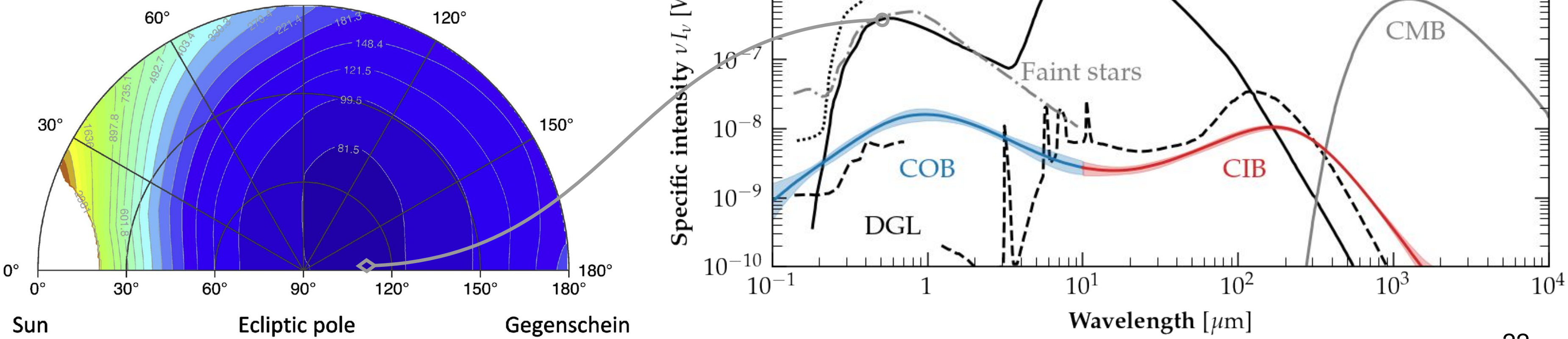
Zodiacal light, integrated star light, diffuse galactic light (cirrus)



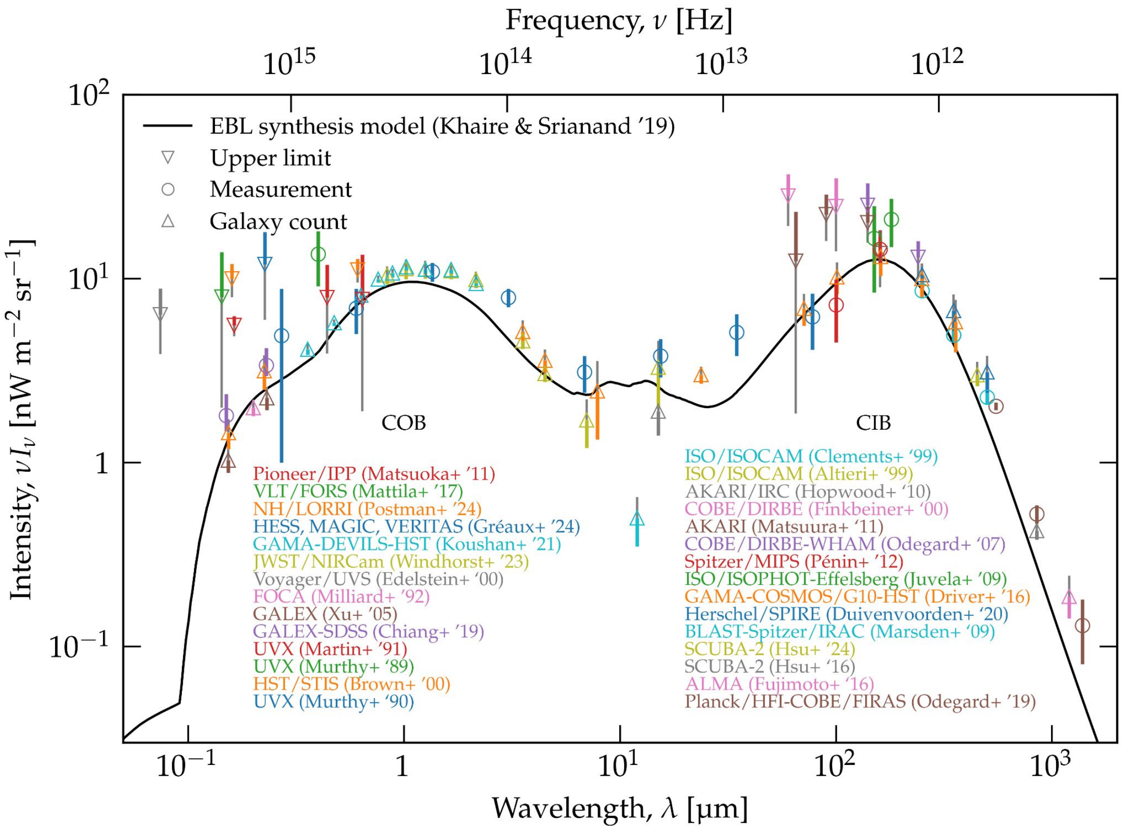
Credits: Lasue 2020

Credits: L. Gréaux
Adapted from Leinert '97 & JB '23

@ 0.55 µm



The light that remains once foregrounds are removed



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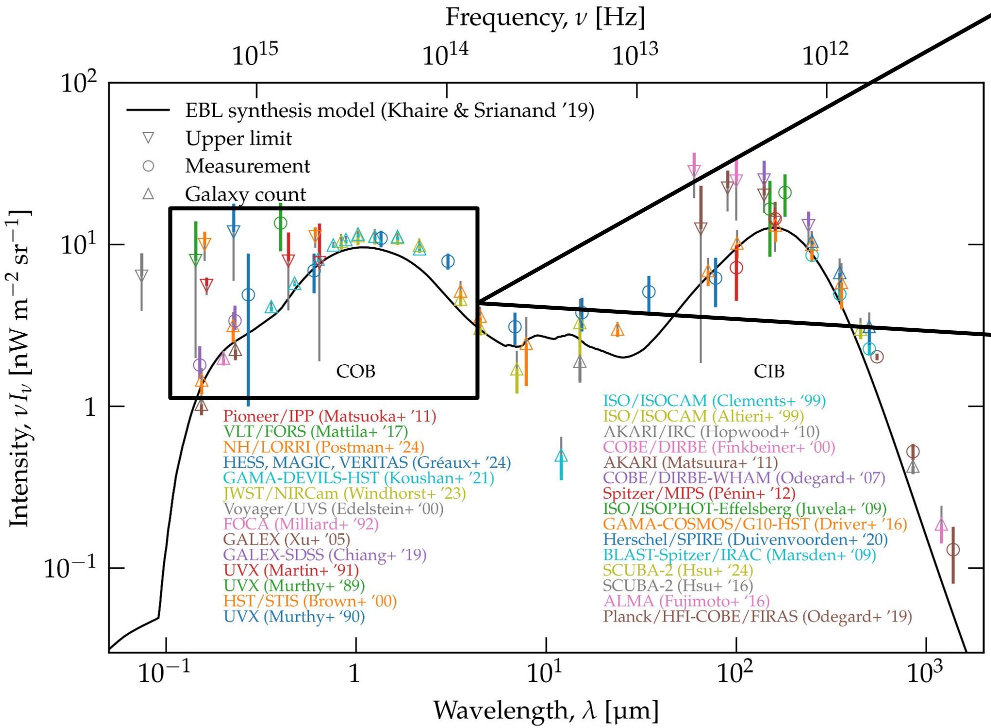
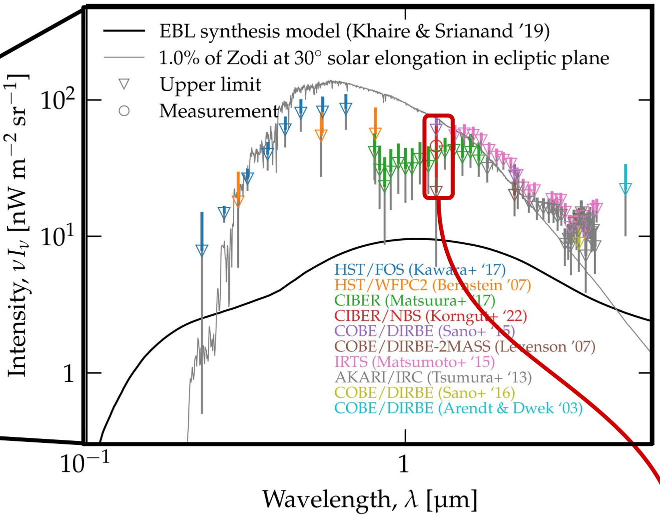
The light that remains once (all?) foregrounds are removed

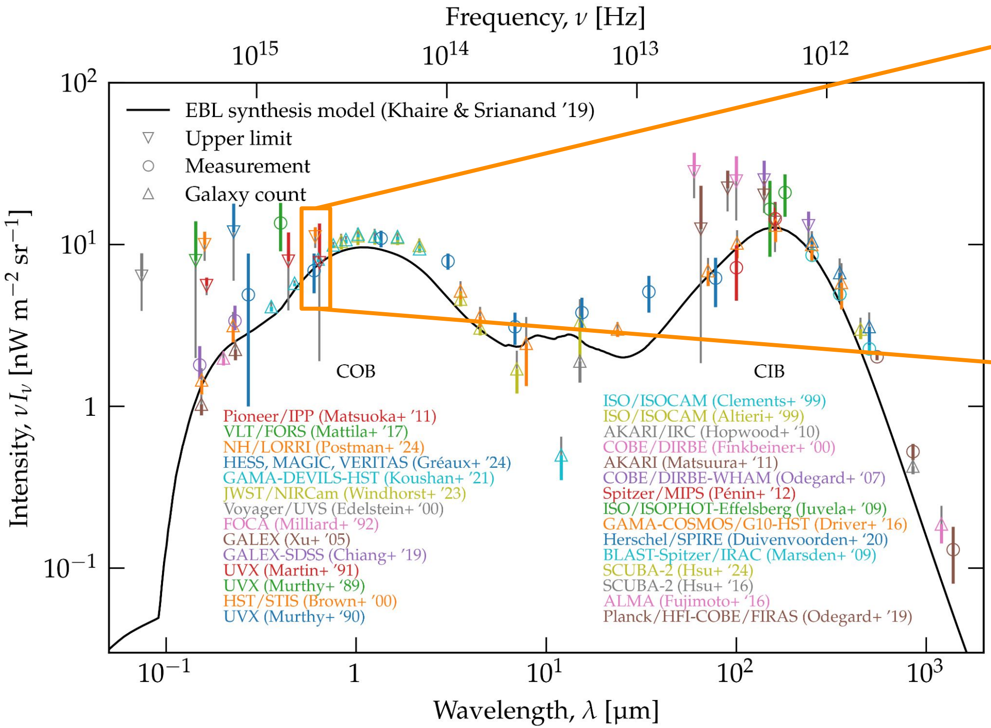




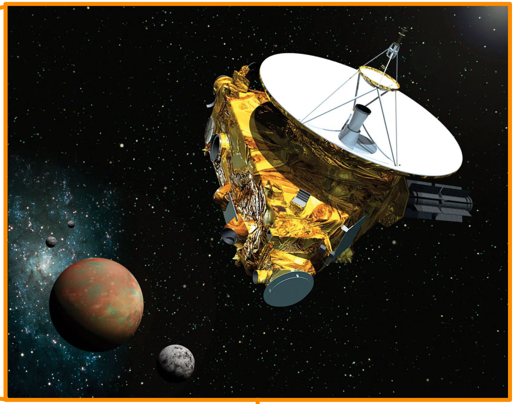
Ca-II absorption lines by CIBER
→ faint spherical component unaccounted
for by main Zodi model (Kelsall+ '98)

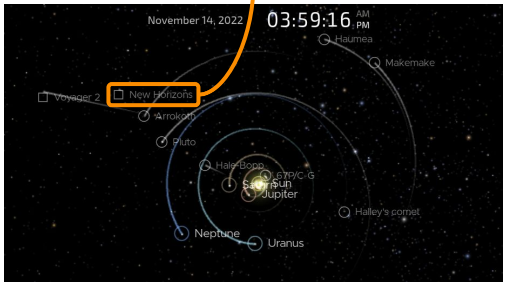
Next step for dark-patch measurements: SPHEREx
(NASA M-class launched in 2025-03)

The light that remains once Zodi foreground is removed



NASA / New Horizons





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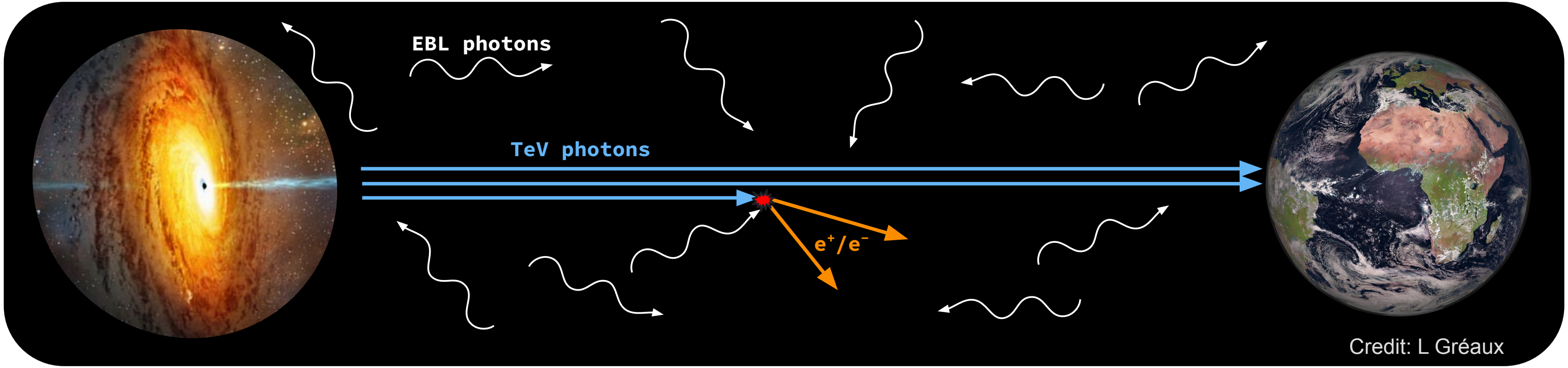
An absorption technique to probe the COB & CIB

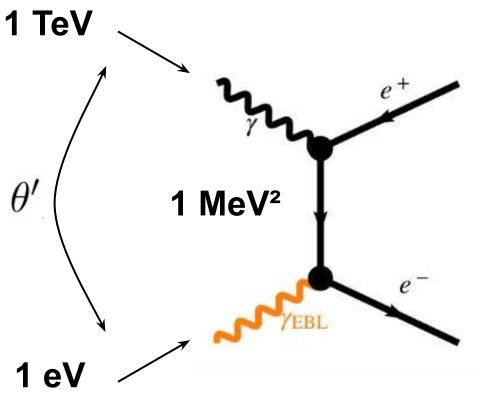


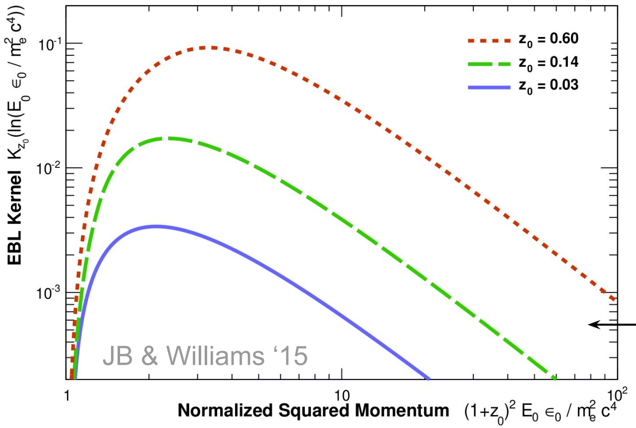
TeV gamma-ray suppression $$\Phi_{\rm obs}(E,z) = \Phi_{\rm int}(E) \times e^{-\tau(E,z)}$$

where the **optical depth τ** is the integral of the interaction rate **(inverse mean free path Γ)** over light travel time **(light travel distance *L*)**:

$$\tau(E,z) = \int_0^z {\rm d}z' \, \frac{\partial L}{\partial z'} \Gamma_{\gamma\gamma}^{-1}(E(1+z'),z')$$

Pair production on COB/CIB photons





Cross-section integrated over the line of sight

Optical depth $\tau(E, z) = \int_0^z \mathrm{d}z' \, \frac{\partial L}{\partial z'} \Gamma_{\gamma\gamma}^{-1}(E(1+z'), z')$

Light travel distance (ΛCDM)

$$\frac{\partial L}{\partial z} = \frac{c}{H_0} \frac{1}{1+z} \frac{1}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}$$

Mean free path (photon density, Breit-Wheeler cross section)

$$\Gamma_{\gamma\gamma}^{-1}(E', z) = \int_0^{+\infty} \mathrm{d}\epsilon \, \frac{\partial n}{\partial \epsilon} \int_{-1}^{1} \mathrm{d}\mu \, \frac{1-\mu}{2} \sigma_{\gamma\gamma}\left[E', \epsilon, \mu\right]$$

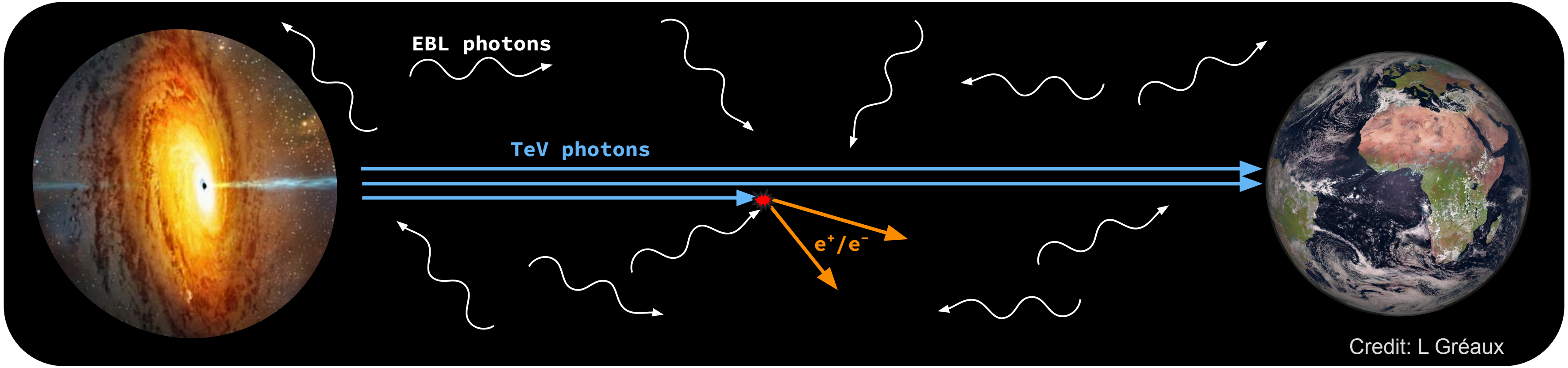
where $\mu = 1 - \cos\theta'$

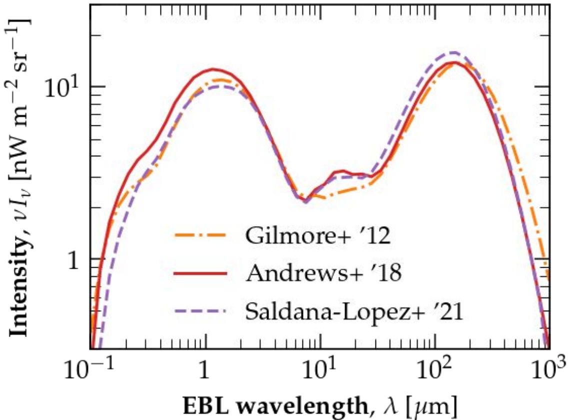
$$\rightarrow \Gamma_{\gamma\gamma}(1\,\mathrm{TeV}, z = 0.2) \approx 250\,\mathrm{Mpc}$$

Relevant targets for gamma-rays:

***E* ~ 1 TeV** ↔ ϵ ~ 1 eV (O bckgd)

TeV ɣ-ray flux suppression



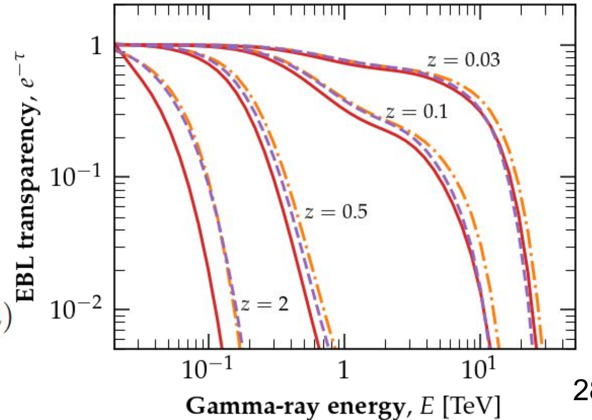


TeV gamma-ray suppression

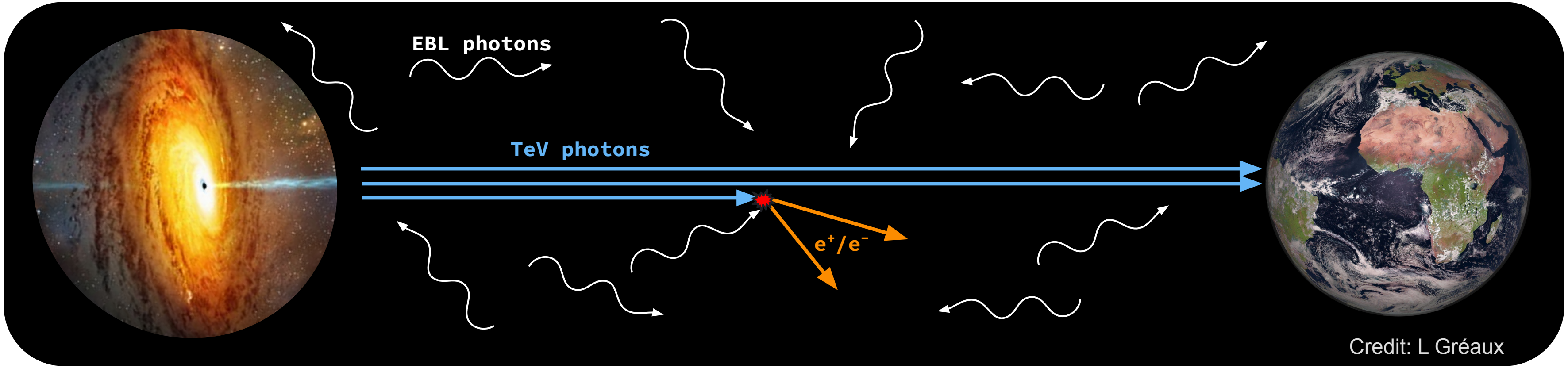
$$\Phi_{\rm obs} = \Phi_{\rm int} \times e^{-\tau}$$

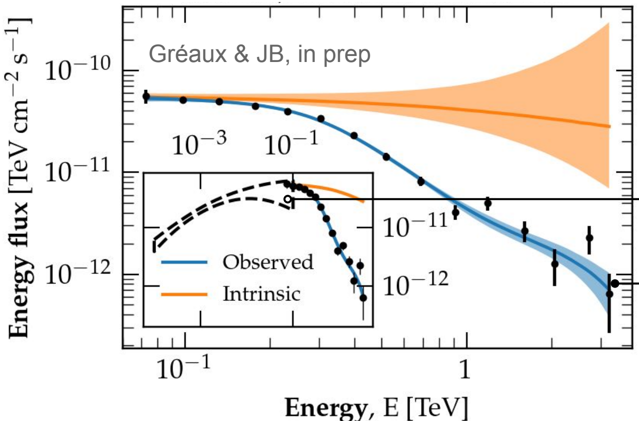
with

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



TeV ɣ-ray flux suppression

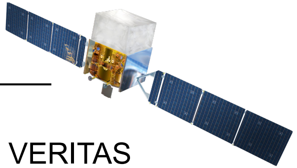




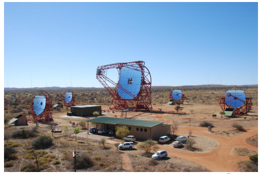
TeV gamma-ray suppression

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

with *Fermi*-LAT (GeV range)

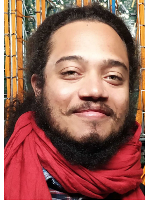


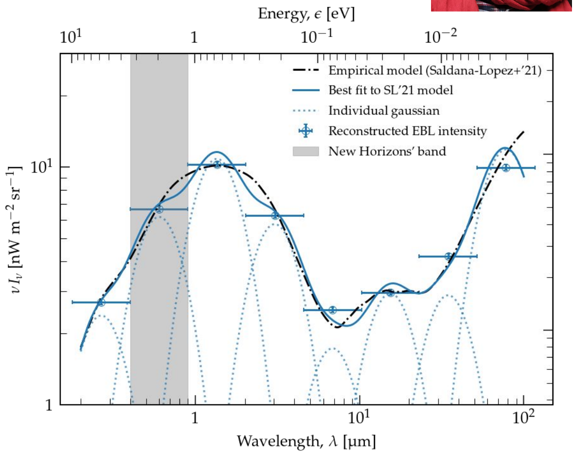
HESS, MAGIC, VERITAS (TeV range)



New ɣ-ray reconstruction of the EBL

Credits: Lucas Gréaux





Model-independent parametrization of the COB and CIB

Spectrum 8 Gaussians(λ) of free amplitude from 0.2-100 μm
with fixed width and central λ → 2nd Gaussian matches New Horizons

Evolution marginalisation over all possible histories out to *z* ~ 1

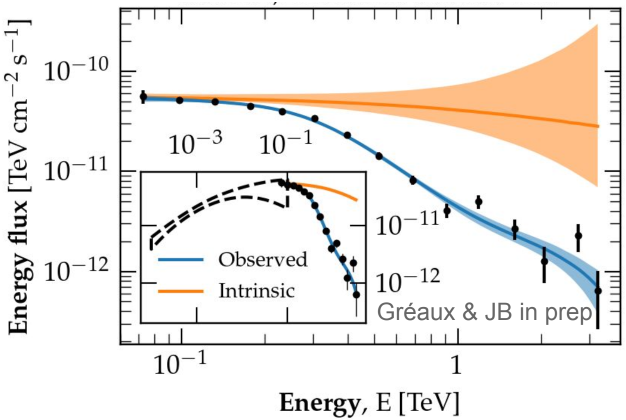
First fully model-independent ɣ-ray reconstruction of the EBL

Dataset: 3× larger than best archival dataset used so far

STeVECat Spectral TeV Extragalactic Catalog (Gréaux+ '23), see this link

268 TeV spectra from 56 sources with spectro. *z* + 95 contemporaneous GeV spectra

vs 86 spectra from 38 sources in previous reference study (JB & Williams '15)



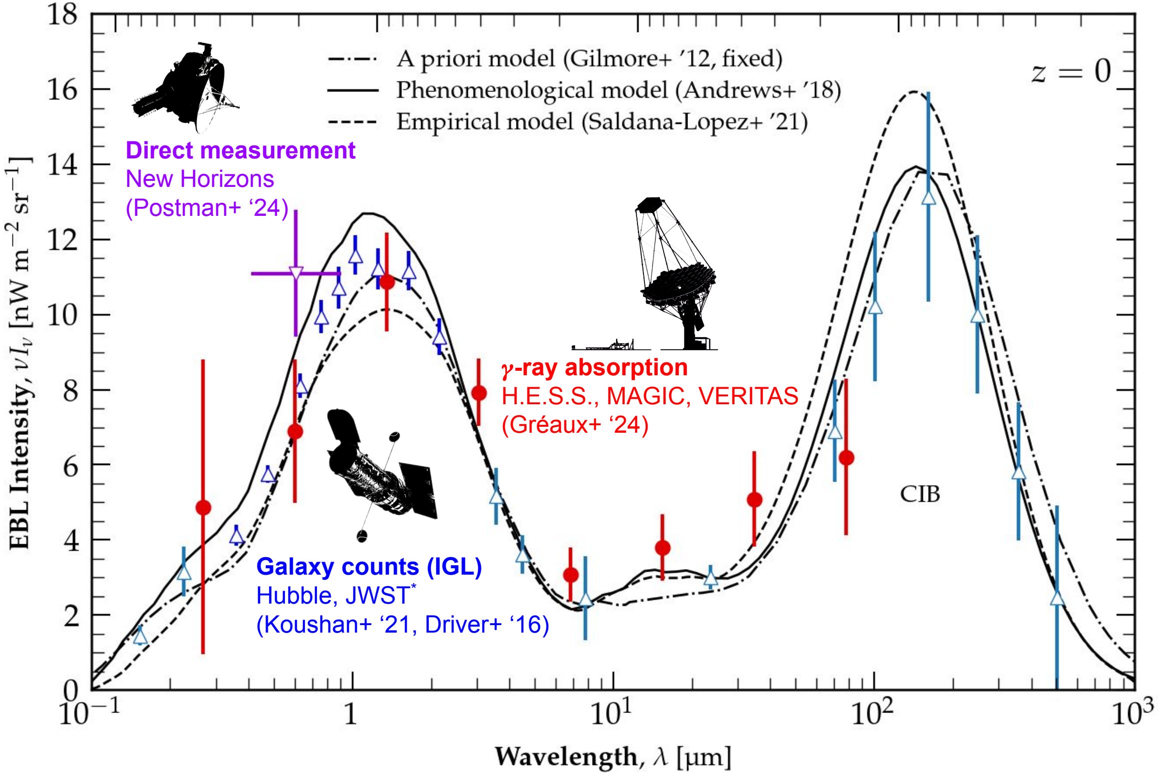
Analysis method

Each of 268 spectra: log-parabola with exponential cut-off/rise

i.e. 268 × 4 = 1072 intrinsic nuisance parameters (both + and - values allowed)

Fully Bayesian, including marginalisation over TeV *E*-scale uncertainty

The cosmological optical convergence



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

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

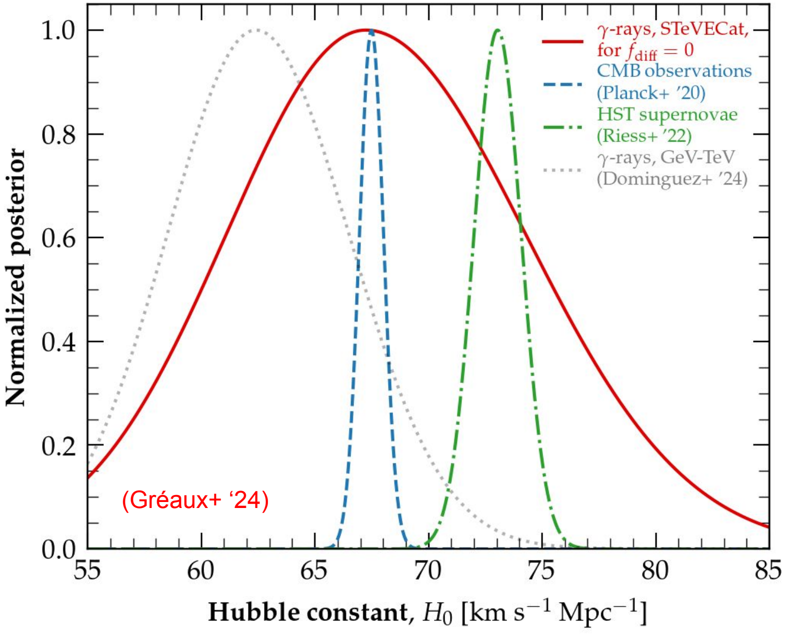
Note: γ-ray results obtained assuming std flat ΛCDM with $H_0 = 70$ km s^{-1} Mpc^{-1}

If EBL = IGL, measuring the optical depth can put constraints on the distance element ∝ c/H_0

Salamon+ '94, Barrau+ '08, Blanch+ '05, Dominguez+ '13 '15 '24, JB+ '15, Gréaux, JB+ '24

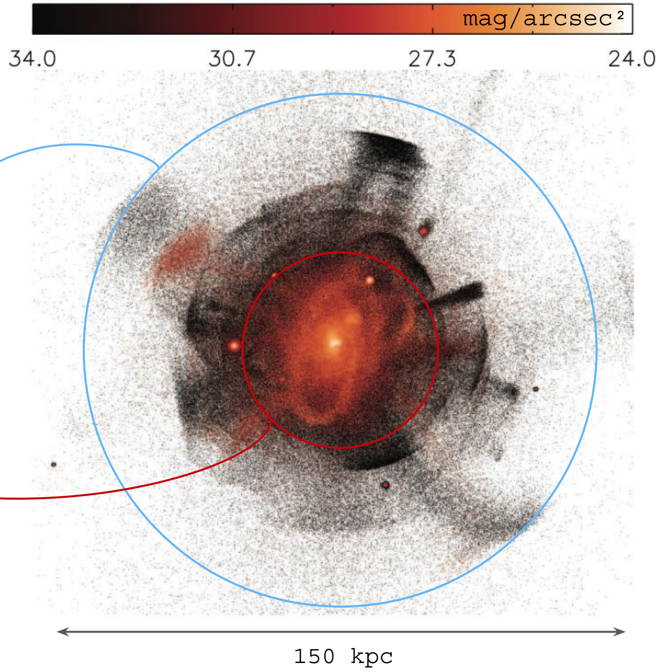
Hubble constant from γ-ray absorption

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



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

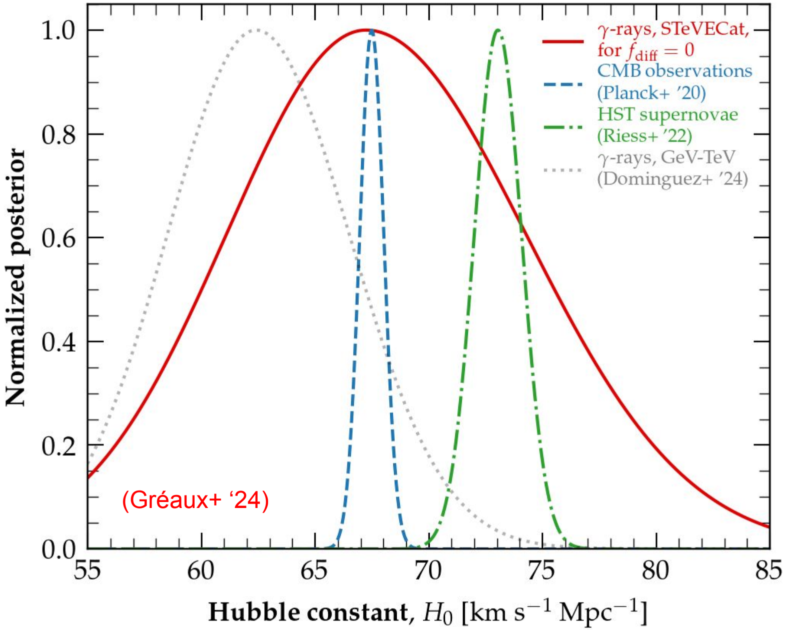
Caveat: low-surface brightness universe



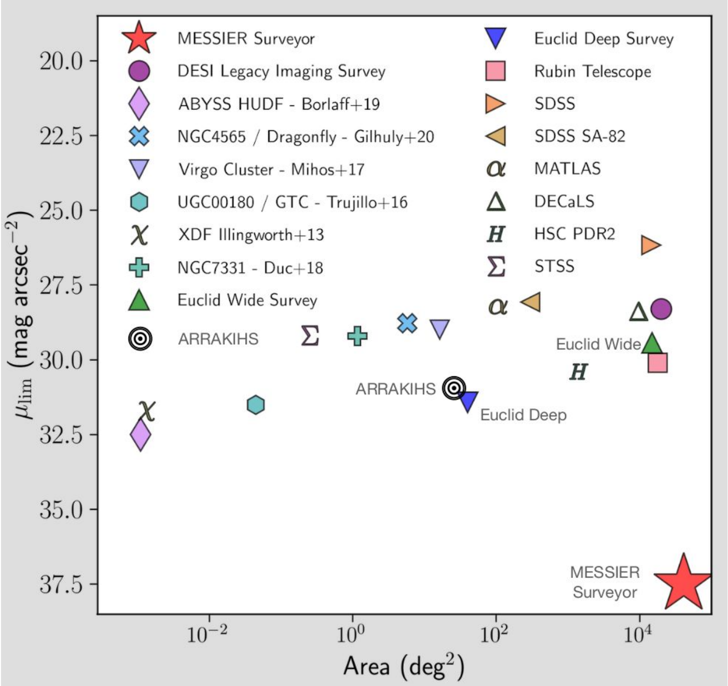
Simulation of M31 stellar halo
(Font+ '08)

Hubble constant from γ-ray absorption

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



How to: ARRAKIHS (launch planned in 2030)
<u>MESSIER</u> (in the running for 2030+)



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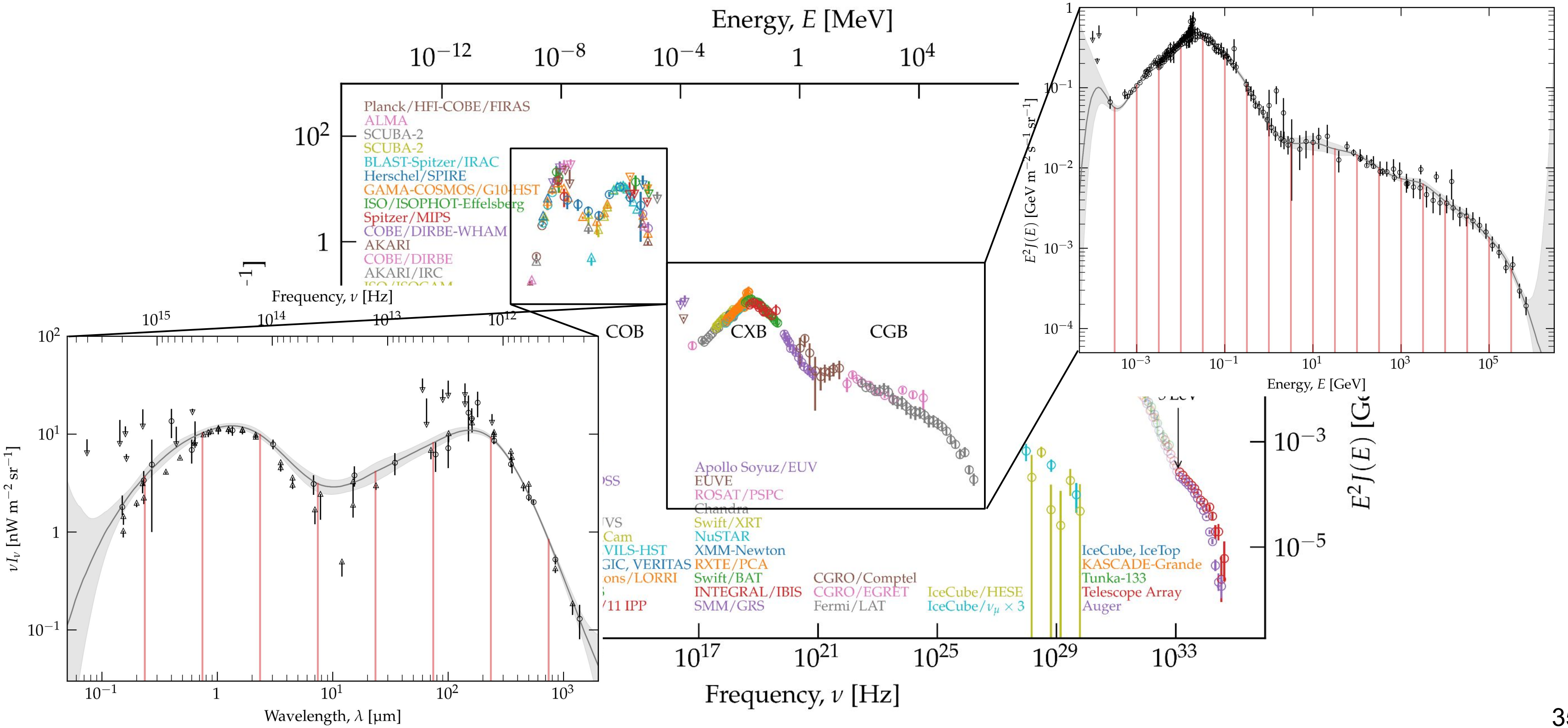
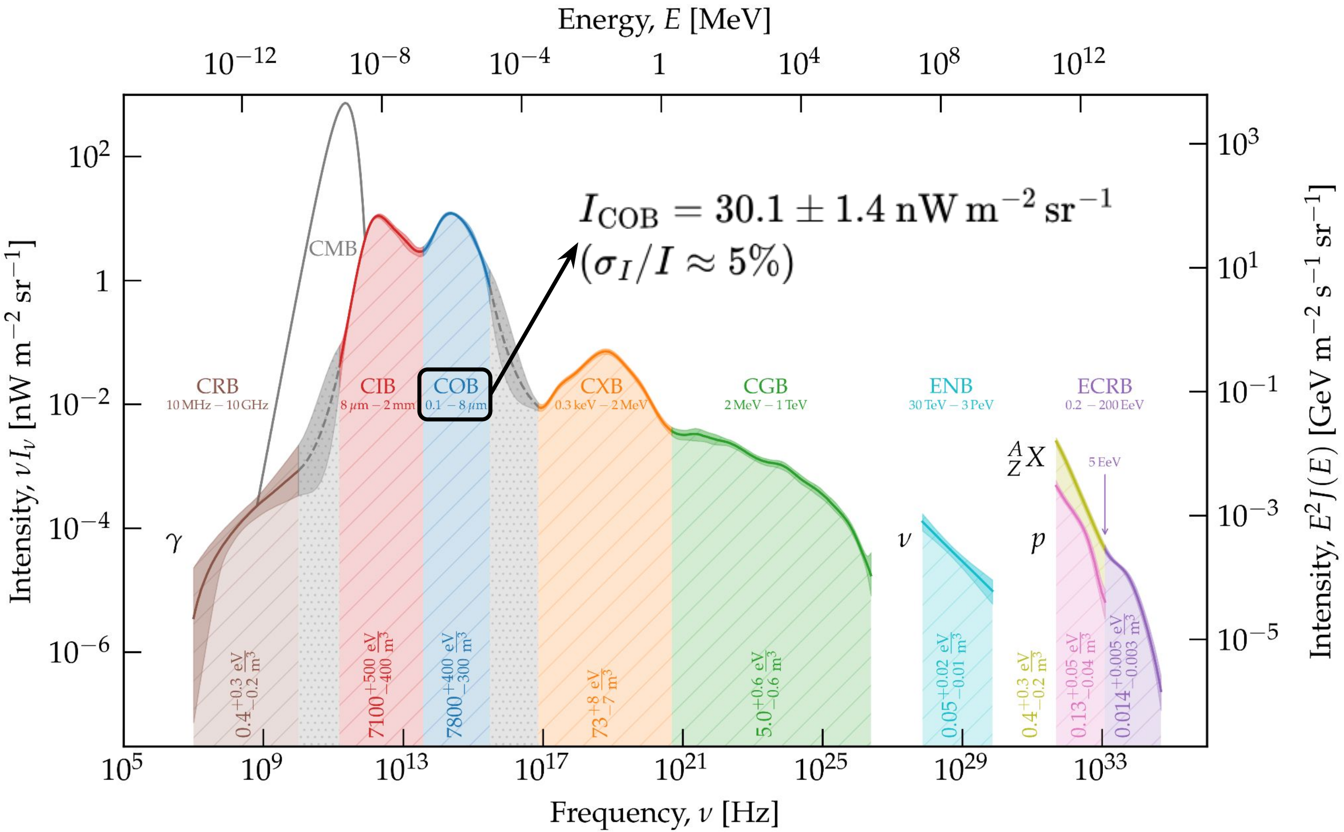
for precision cosmology?

Spline fit of the multi-messenger extragalactic spectrum

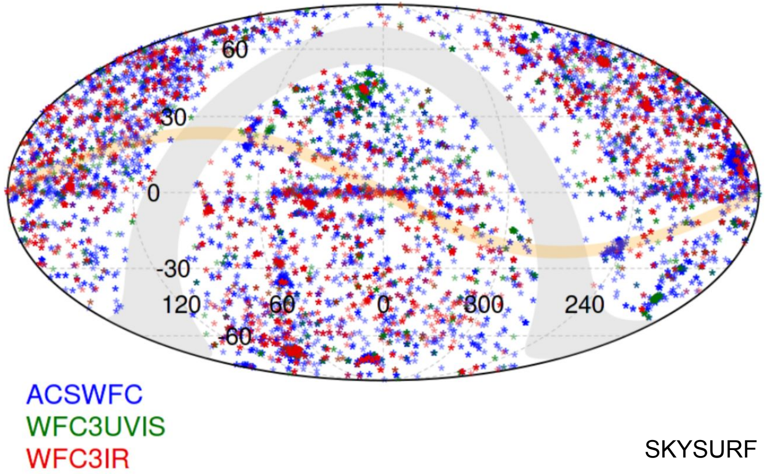


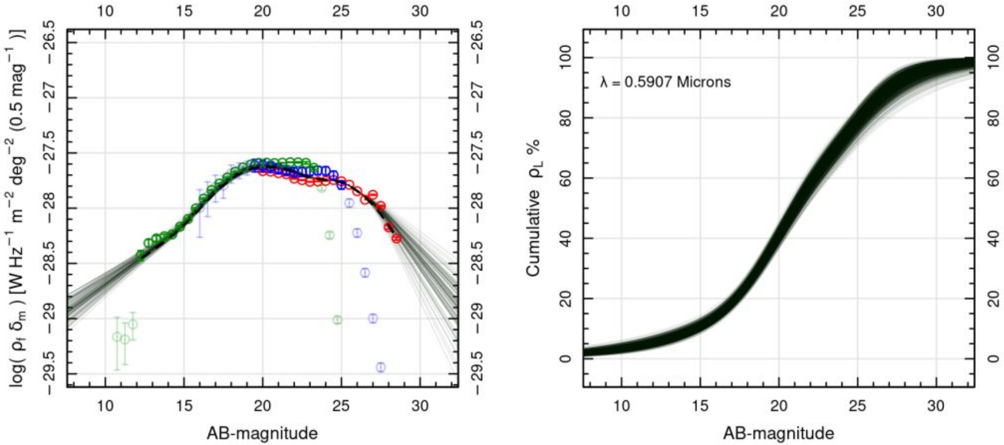
What is known about the extragalactic background



Jonathan Biteau

What is known about the integrated galaxy light



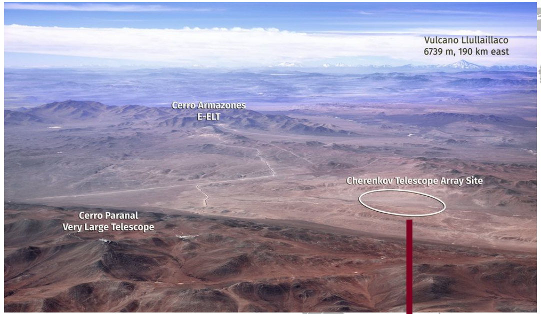


SKYSURF IX, Tompkins+ ‘25

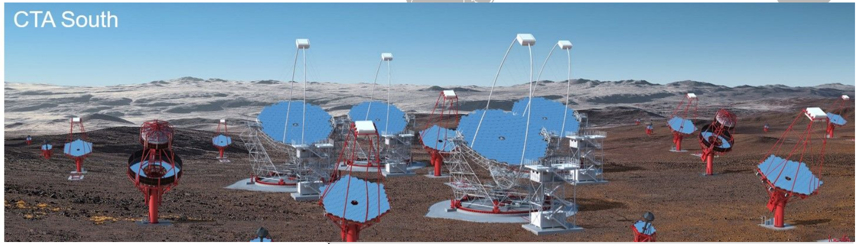
$$I_{\mathrm{IGL,\,COB}} = 25.5 \pm 0.5\ \mathrm{nW\,m^{-2}\,sr^{-1}} \quad (\sigma_I/I \approx 2\%)$$

Goal in this field: reach 1% precision, using HST+JWST+Euclid+LSST+Roman

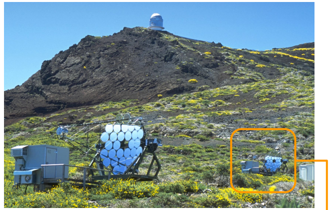
ɣ-rays: The Cherenkov Telescope Array Observatory (CTAO)



CTAO-S (‘20s-‘40s)



HEGRA (‘90s)



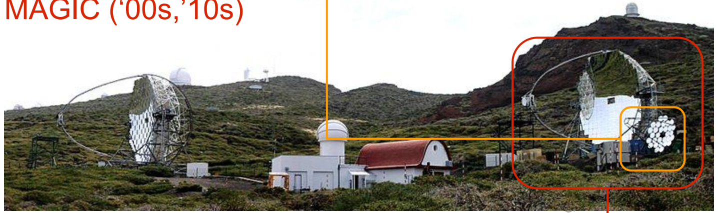
2 sites to access the entire sky w/ breakthrough performance

Sensitivity: 5-10× better than current

E-range: 0.02-200 TeV (vs 0.1-10 TeV)

E-resolution: <10% (vs <17%) >0.2 TeV

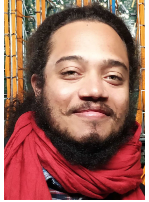
MAGIC (‘00s,’10s)



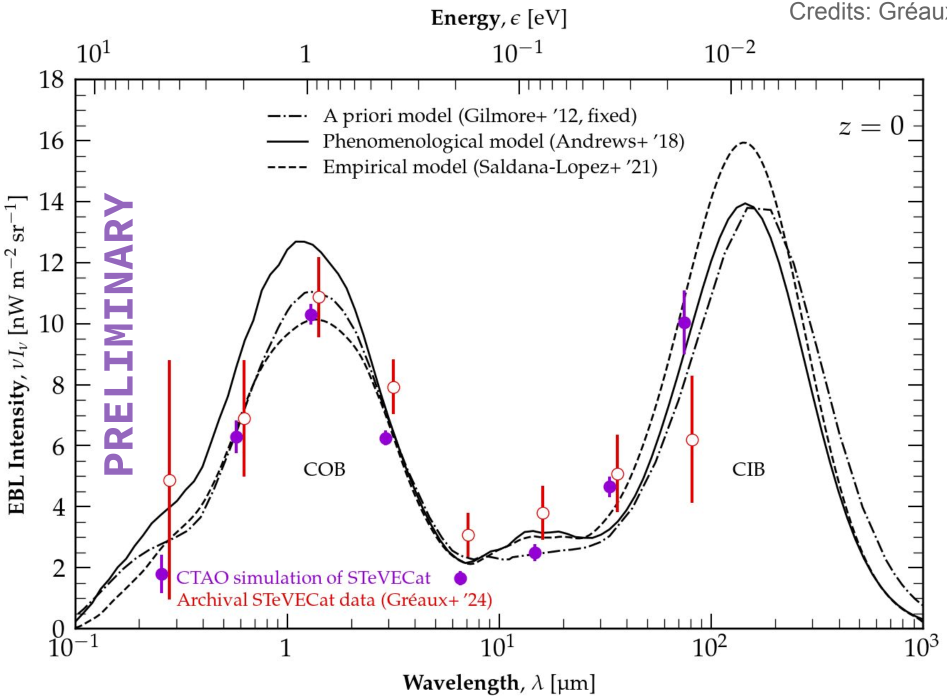
CTAO-N (‘20s-‘40s)

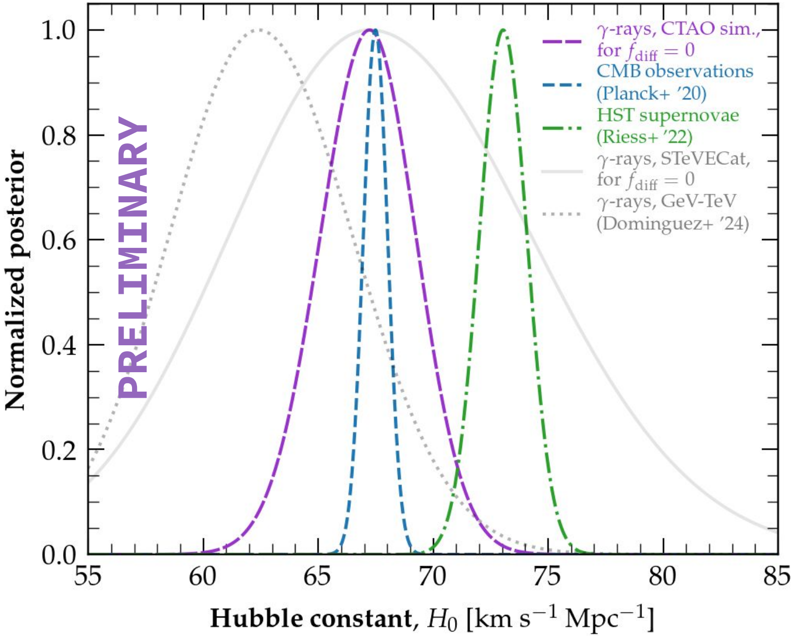
Expected COB and CIB with CTAO

Credits: Lucas Gréaux



Credits: Gréaux+, in prep





Simulations of ~3000h of CTAO observations (in-line with CTAO key science projects)

Assume 1% precision on `IGL x (1 + f_diff)` → **3% precision on H_0**

Conclusion

A long story started in 1576

Solution proposed in the early 20th, accepted in the '80s:

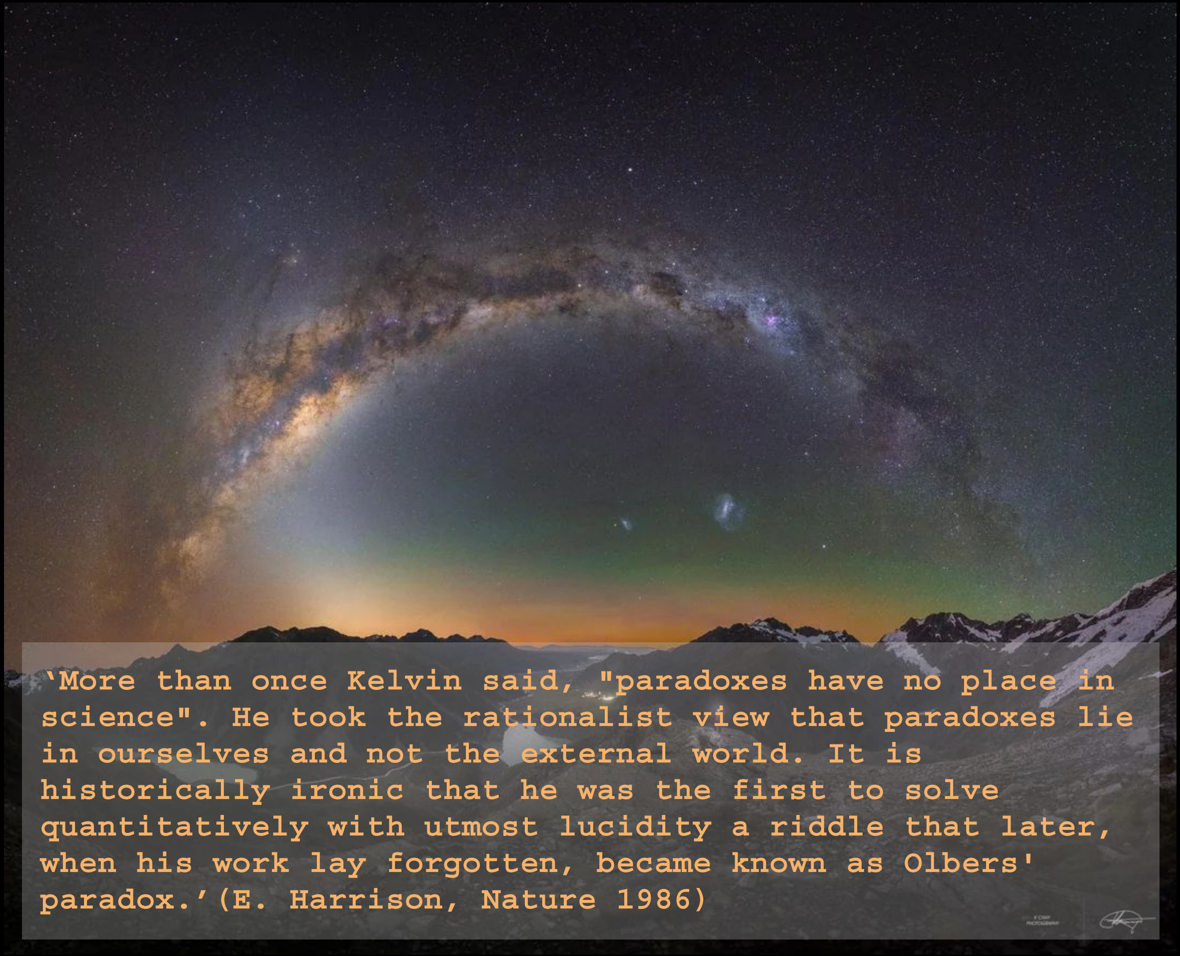
The history of emission of light by baryons is finite

First convincing measurements of the IGL in the early 2000s

First ɣ-ray absorption measurements in the early 2010s

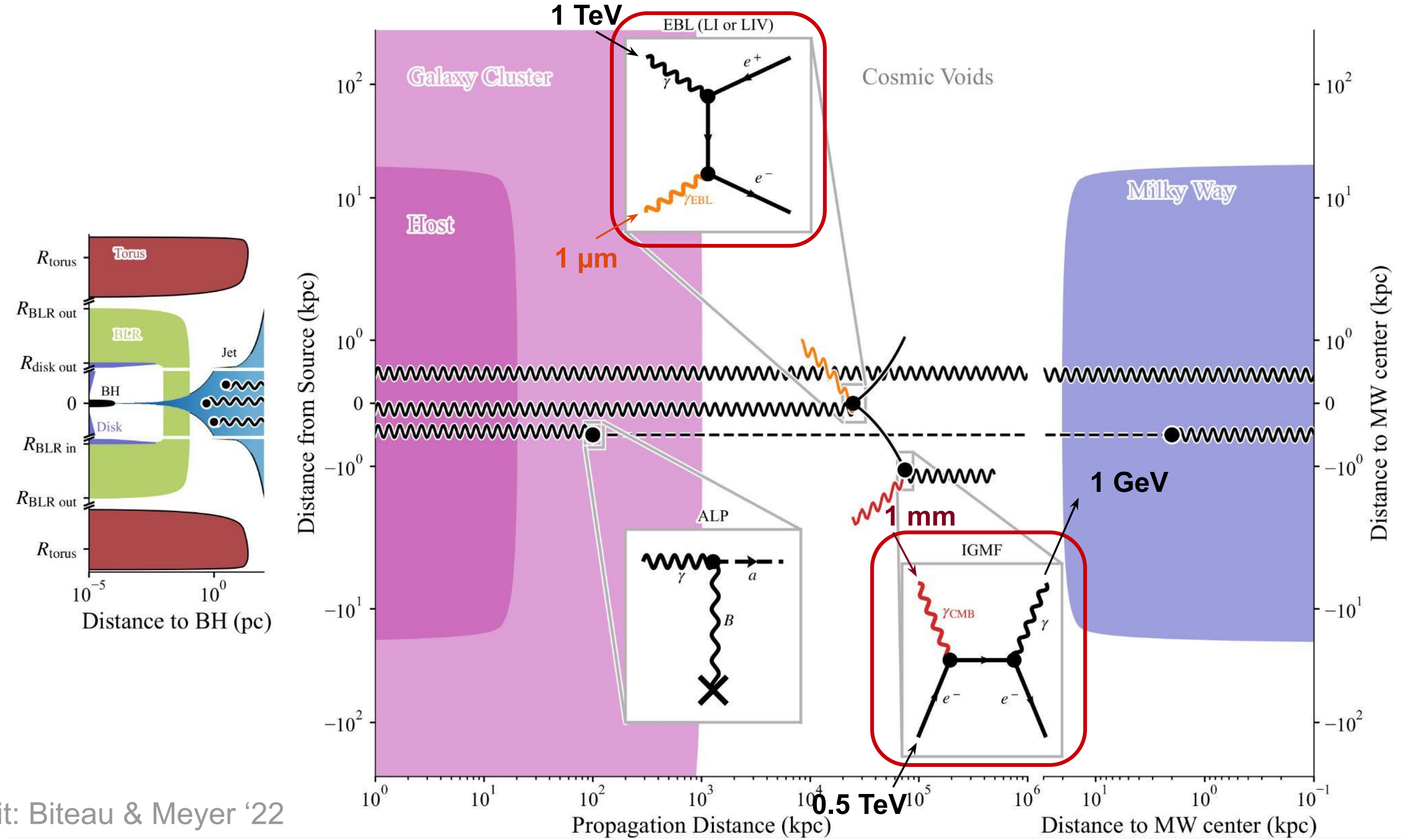
First Zodi-free direct measurement in the early 2020s

Now trying to catch up with precision cosmology!



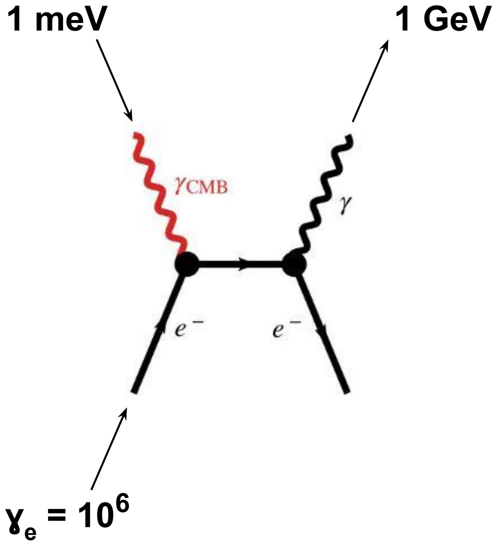
Backup

ɣ-ray propagation from sources down to Earth



Credit: Biteau & Meyer '22

Radiative losses of $e^+ e^-$: inverse Compton on CMB



Generation 1: TeV gamma-ray

$$\Gamma_{\gamma\gamma}(1\,\mathrm{TeV}, z=0.2) \approx 250\,\mathrm{Mpc}$$

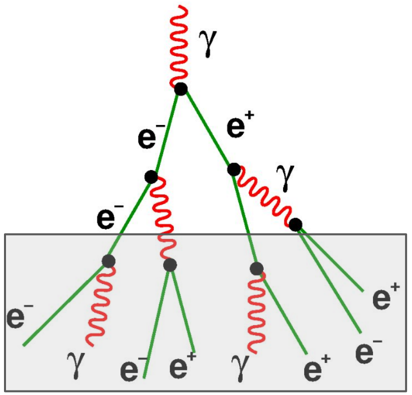
Generation 2: pair $e^+ e^-$

- Diffuse in $\langle B^2 \rangle$
  $$r_\mathrm{L}(\gamma_e = 10^6) \approx 0.5\,\mathrm{Mpc}(B_{IGM}/10^{-15}\,\mathrm{G})^{-1}$$
- Excite electrostatic instability of beam (~ 10^{-22} cm^{-3}) / intergalactic plasma (~ 10^{-7} cm^{-3})
  - ➔ Inefficient *E*-loss mechanism due to
    - ◆ background MeV e^- (Yang+ *ApJ* '24)
    - ◆ non-linear feedback (Alawashra & Pohl *ApJ* '24)
    - ◆ $B > 10^{-17}$ G $(\lambda_B/1\text{ pc})^{-1/2}$ (Alawashra & Pohl *ApJ* '22)
- Inverse Compton on CMB photons
  $$\Gamma_{e\gamma}(\gamma_e = 10^6) \approx 0.75\,\mathrm{Mpc}$$

Generation 3: GeV gamma-ray → stop

$$E_1 = \frac{4}{3}\gamma_e^2 \epsilon_\mathrm{CMB} \approx 1\,\mathrm{GeV}\left(\frac{E_0}{1\,\mathrm{TeV}}\right)^2$$

em cascade

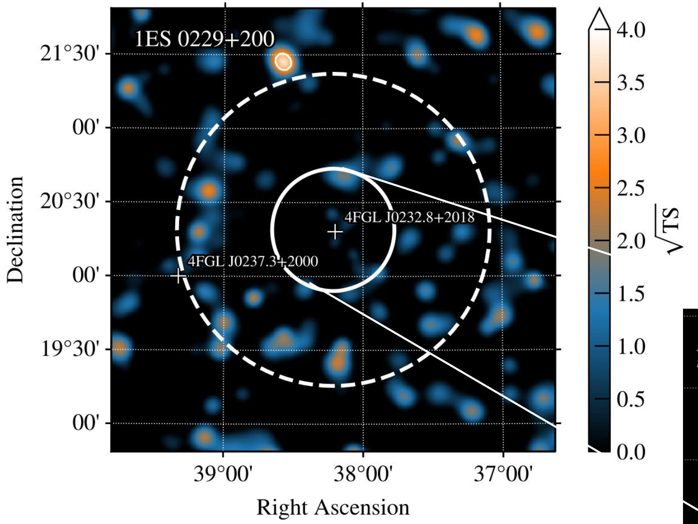


4th generation if
E_0 ~ 10 TeV (plausible)

5th generation if
E_0 ~ 100 TeV
→ unobserved &
Klein-Nishina suppressed

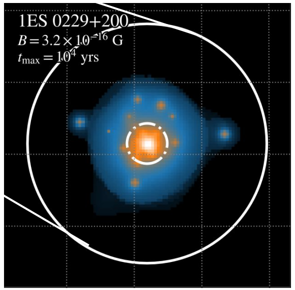
Search for the $e^+ e^-$ reprocessed energy

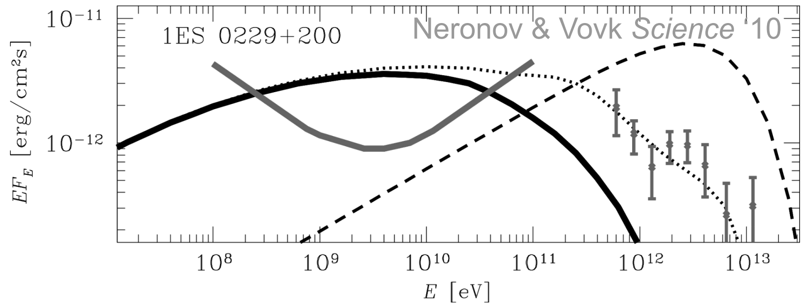
Observed

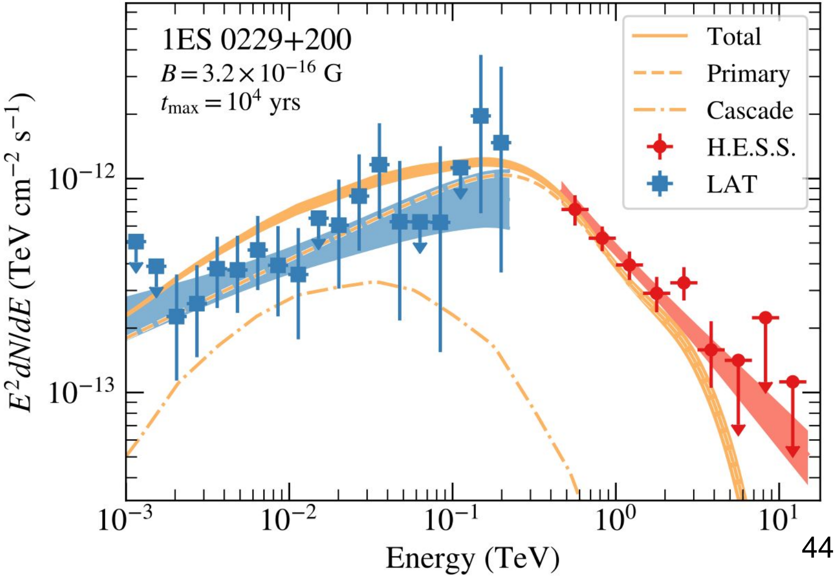


H.E.S.S. *ApJL* '23

Expected for
B **~ 3 × 10^-16^ G**





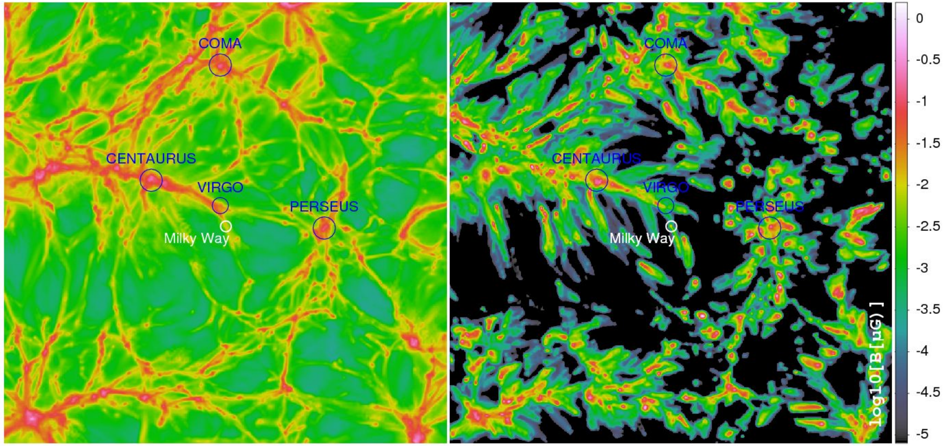


Magnetic fields in voids

Status and expectations

Current-generation (GeV+TeV - TeV extension): B > 10-100 fG

5σ CTA-discovery potential up to 300 fG



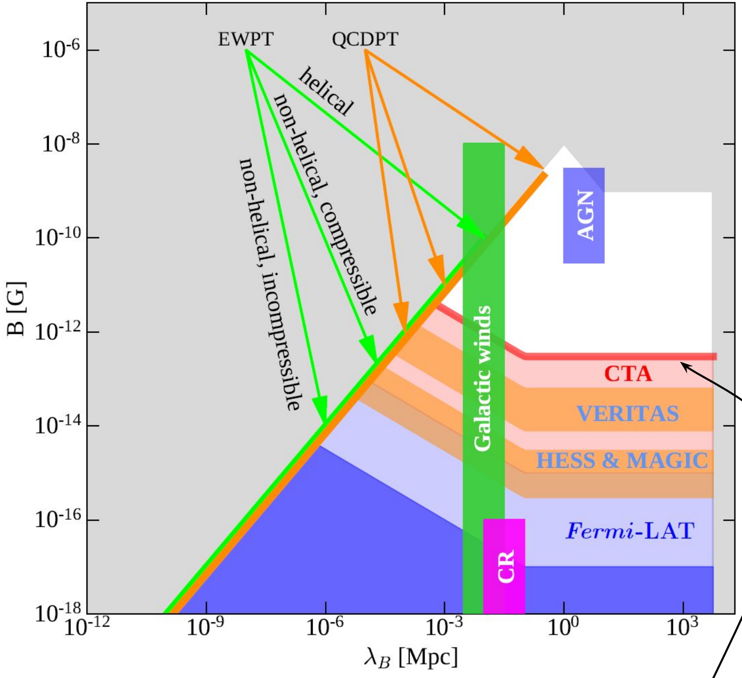
Credit: Hackstein+ 2018

Primordial origin simulation
B(void) < 1 nG

Astrophysical origin simulation
B(void) < 1 pG

In practice… largely unknown!

Credit: CTA Consortium 2021



1ES 0229+200 (z=0.14) up to E_{cut} = 10 TeV,
50h of CTAO-North to reach 5σ

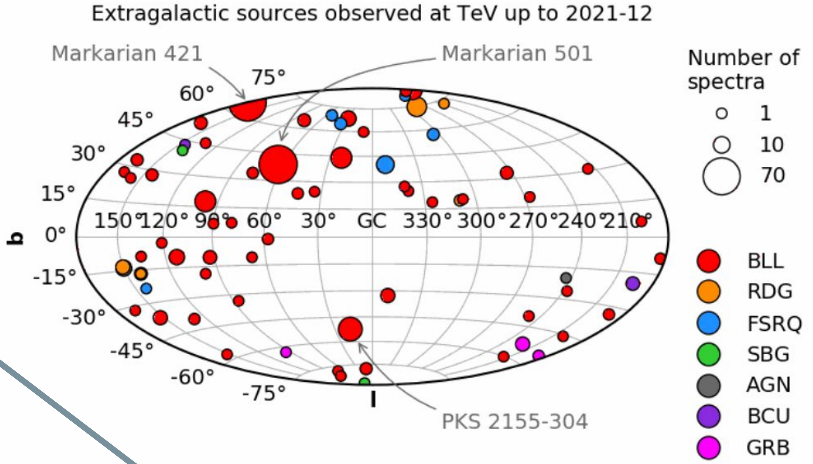
Data sample

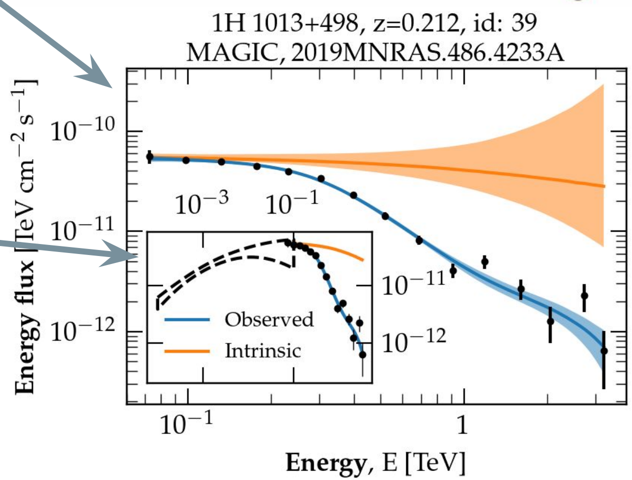
TeV data: STeVECat, [10.5281/zenodo.8152245](https://doi.org/10.5281/zenodo.8152245)
Spectral TeV Extragalactic Catalog

Archival spectra published by IACTs (H.E.S.S, MAGIC, VERITAS and other)

Selected spectra: **at least 4 points**, sources with solid **redshift > 0.01**

➢ **268 spectra** (**86 for B&W'15**)





GeV data: *Fermi*-LAT

Contemporaneous *Fermi*-LAT observations used as **priors** for spectral index and curvature

➢ **95** contemporaneous spectra

Shortcomings of the Frequentist analysis

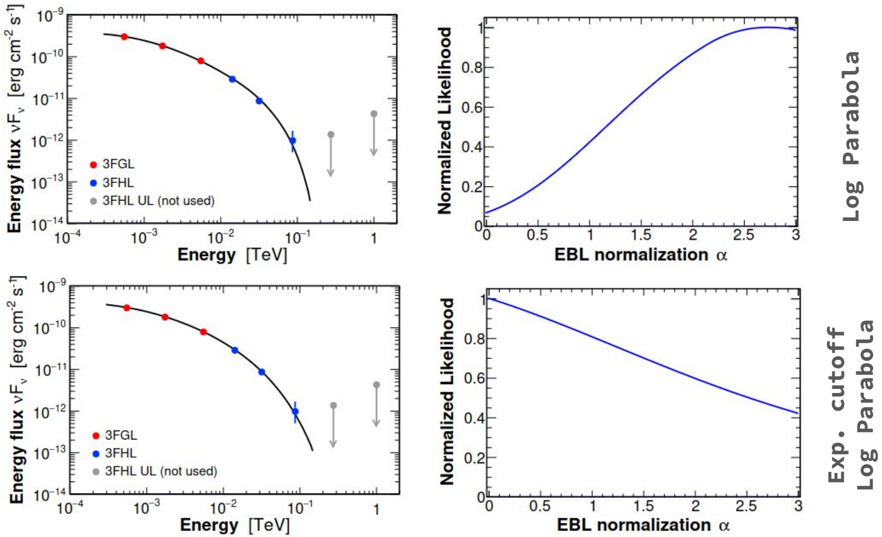
a EBL parameters
Θ spectral parameters

$$\phi_{\text{model}}(E, z, a, \Theta) = \phi_{\text{ELP}}(E, \Theta) \times e^{-\tau(E,z,a)}$$

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

With $\mathcal{D}$ observed **data**, **Likelihood**:

$$\begin{aligned} \mathbf{Pr}\left(\mathcal{D} \mid a\right) &= \max_{\Theta}\left\{\mathbf{Pr}\left(\mathcal{D} \mid a, \Theta\right)\right\} \\ &= \max_{\Theta}\left\{\prod_{k} \mathbf{Pr}\left(D_k \mid a, \theta_k\right)\right\} \end{aligned}$$



- Find best parameters **a** for a set of spectral models (**minimization**)
- **Update** the set of spectral models
- **Repeat** until convergence

B. Biasuzzi+, arXiv:1906.07653

The Bayesian Framework as an answer

α EBL parameters
Θ spectral parameters

$$\phi_{\text{model}}(E, z, a, \Theta) = \phi_{\text{ELP}}(E, \Theta) \times e^{-\tau(E,z,a)}$$

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

With $\mathcal{D}$ observed **data**, **Likelihood**:

$$\begin{aligned} \mathbf{Pr}(\mathcal{D} \mid a) &= \int \mathrm{d}\Theta \, \mathbf{Pr}(\mathcal{D} \mid a, \Theta) \\ &= \int \mathrm{d}\Theta \prod_k \mathbf{Pr}(D_k \mid a, \theta_k) \end{aligned}$$

$$\mathbf{Pr}(a \mid \mathcal{D}) = \frac{\mathbf{Pr}(\mathcal{D} \mid a)\, \mathbf{Pr}(a)}{\mathbf{Pr}(\mathcal{D})}$$

Compute the **full probability distribution** and **marginalize** over non-EBL parameters

- ⇨ **Sampling** with MCMC
- ⇨ **Uninformative priors**
- ⇨ All spectra as **log-parabola with exponential cutoff**
- ⇨ **Nuisance parameters**

Bias on the **energy scale**, **ε**

$$\phi_{\varepsilon-\text{model}}(E, z, a, \Theta, \varepsilon) = \phi_{\text{model}}\left(\frac{E}{1+\varepsilon}, z, a, \Theta\right) \times \frac{1}{1+\varepsilon}$$

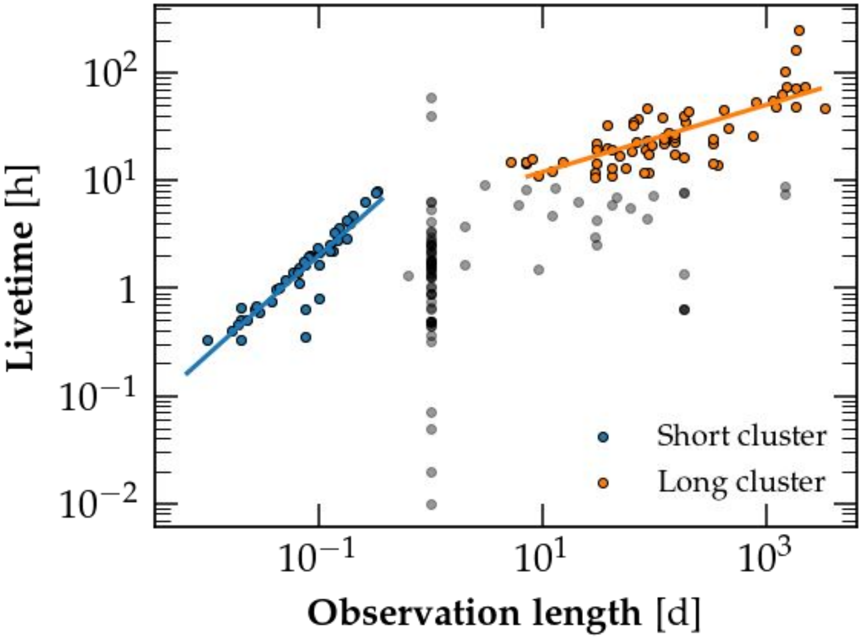
Simulated livetimes

Livetime estimation

228 spectra (H.E.S.S., MAGIC, VERITAS)
38 spectra without livetime

T = mjd_stop - mjd_max

- T < 0.5d : use short cluster fit
- T > 1d : use long cluster fit
- Middle : livetime = 2h

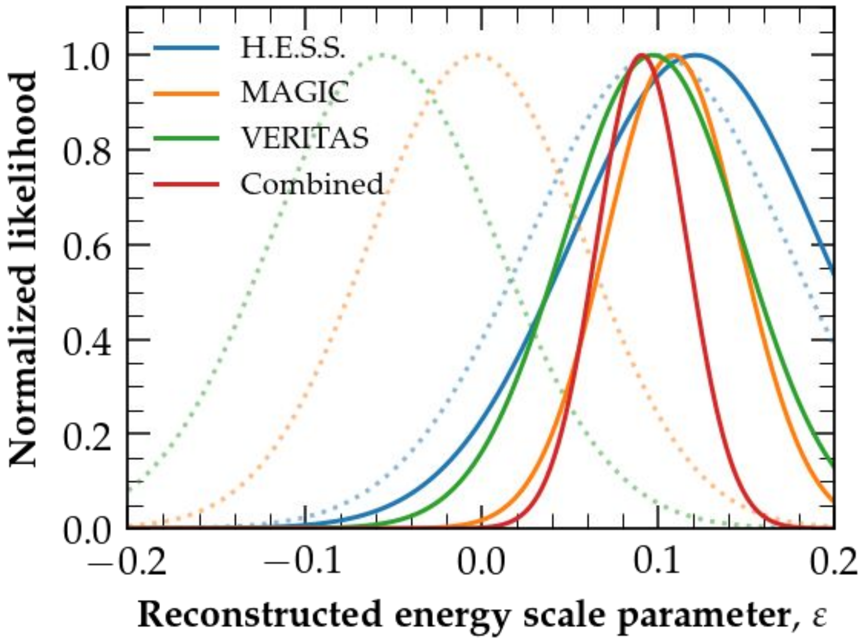


Total livetime

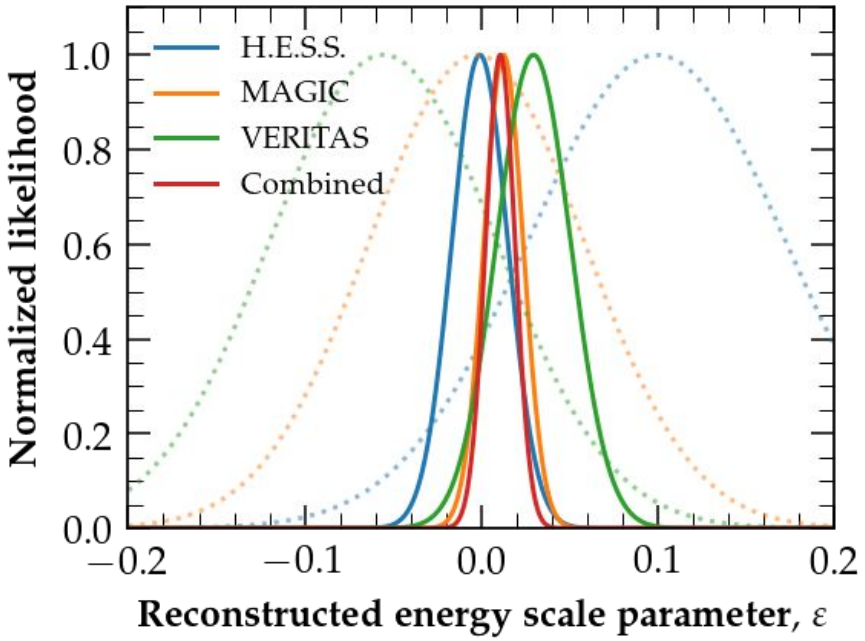
- 2907h (2629h from STeVECat)

Reconstructed energy scale nuisance parameter

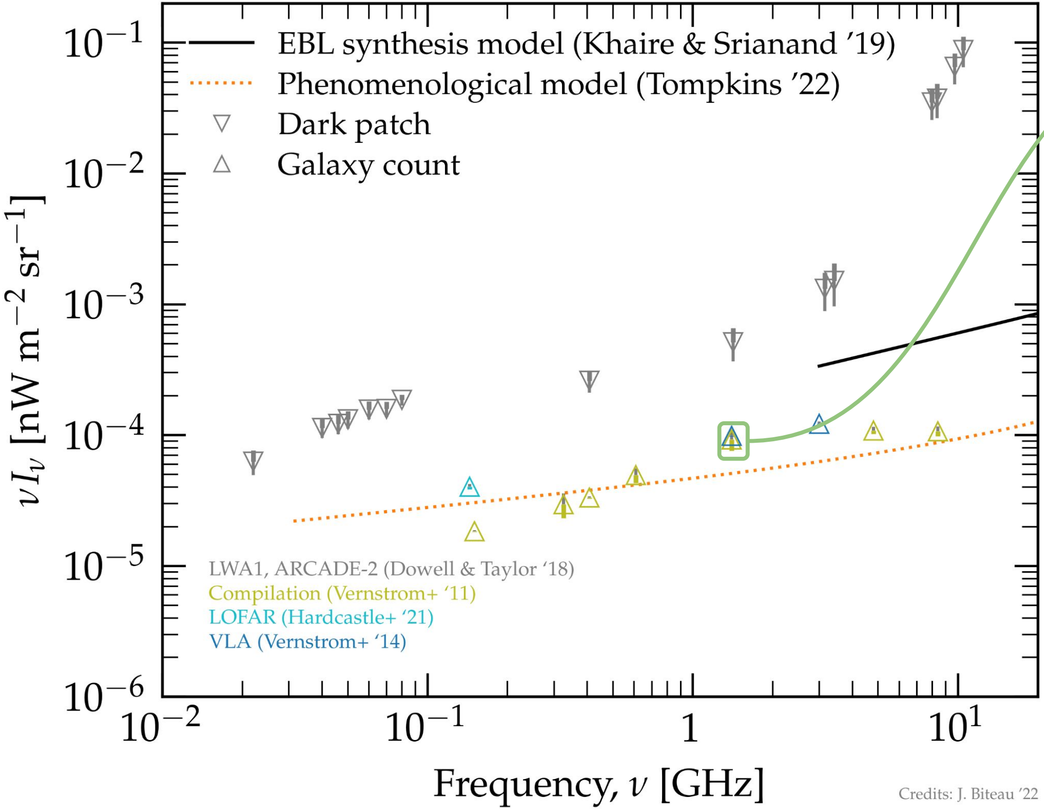
Fitting SL21 with **STeVECat** data



Fitting SL21 with **CTAO simulated** data



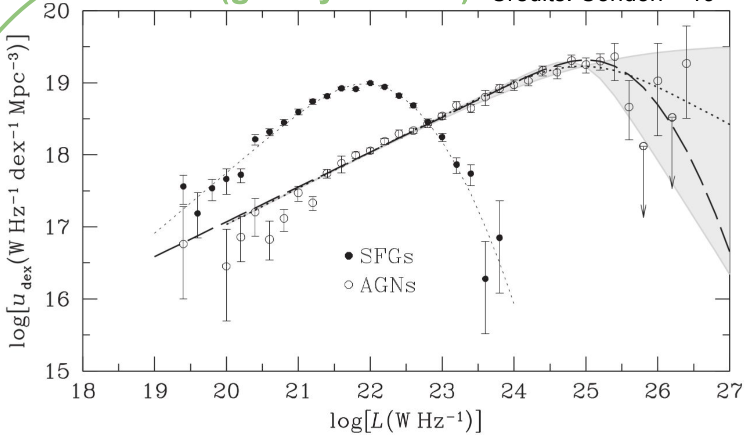
The Cosmic Radio Background



Credits: J. Biteau '22

Integrated galaxy light (galaxy counts)

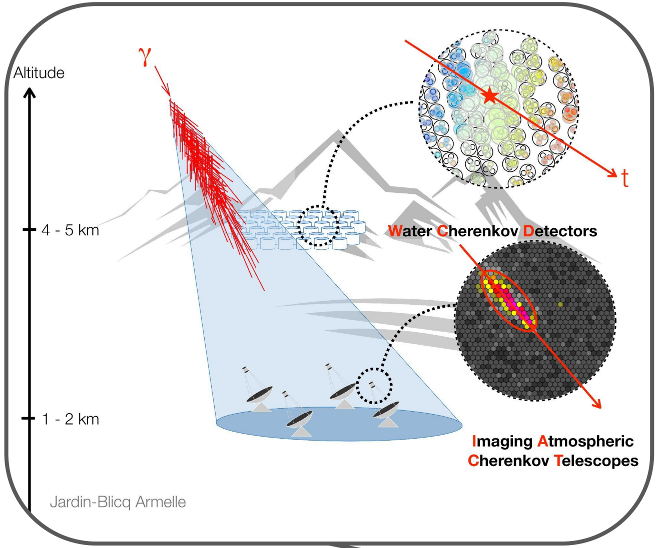
Credits: Condon+ '19



Tension with direct estimates (see Singal+ 2018)**:**

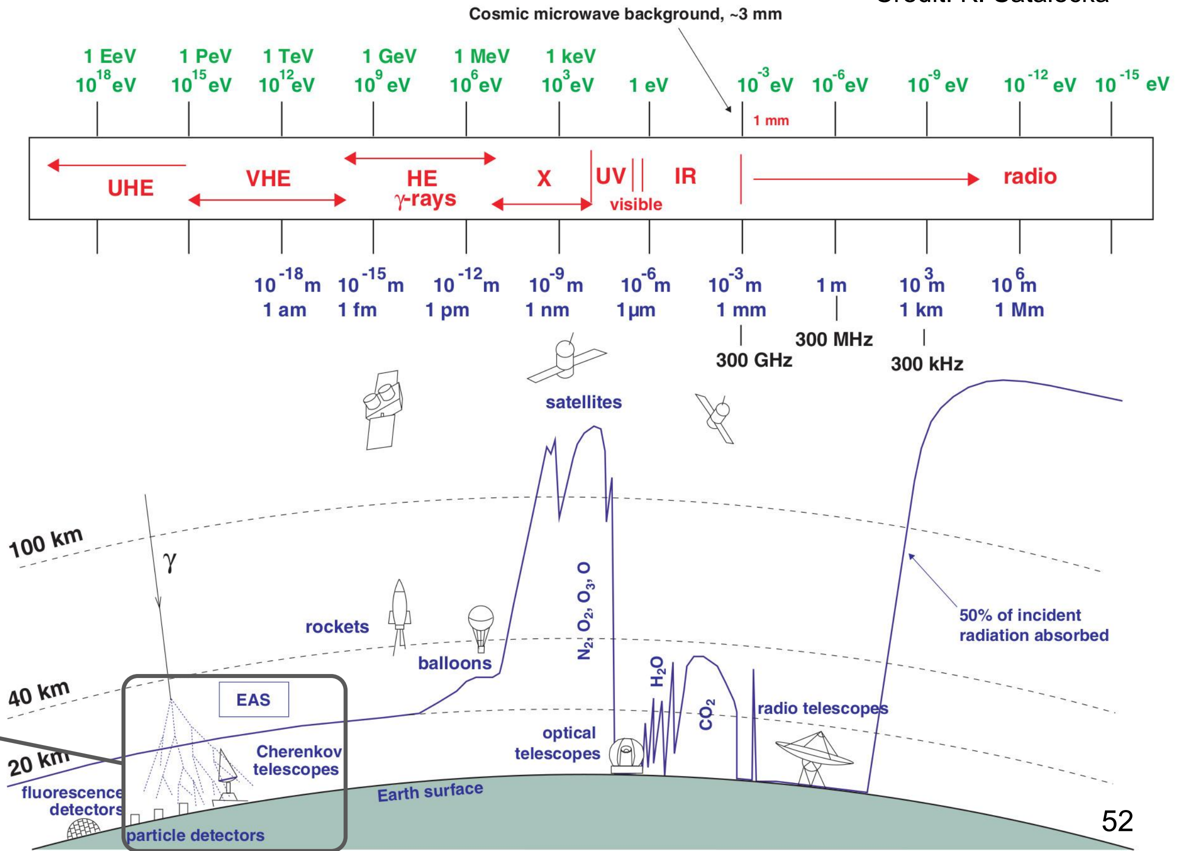
- Small sky coverage / Zero point?
- Galactic halo (X-ray IC counterpart)?
- Extragalactic unknown pop.?

Current and new generation ɣ-ray observatories



Credit: A. Jardin-Blicq

Credit: K. Satalecka



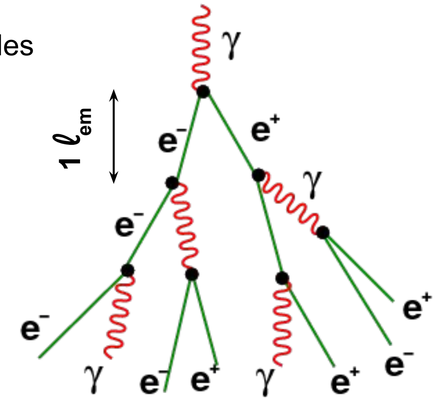
Detection of ɣ-rays near Earth

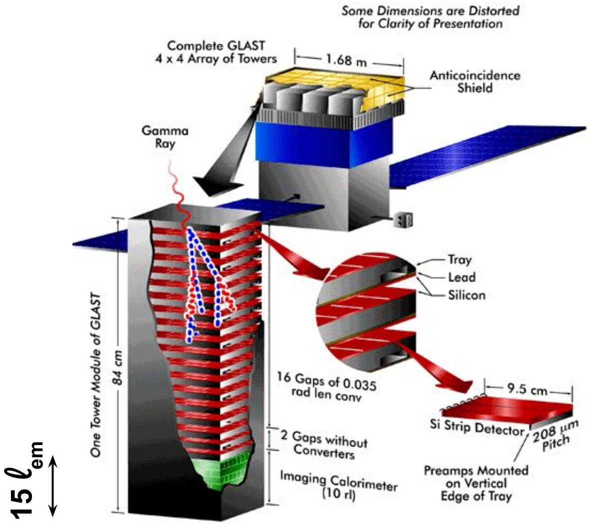
Satellite-based: 100 MeV - 1 TeV

O(100%) duty cycle, ~ 550 km altitude

Tracker with SSDs, CsI(TI) with photodiodes

Lead experiment: *Fermi*-LAT





Performance > 10 GeV

energy resolution ~10-20%

angular resolution ~0.1°

Telescope-based: 100 GeV - 100 TeV

O(10%) duty cycle, ~ 2 km above sea level

Cameras with O(1000) PMTs and ns sampling

Lead experiments: HESS, MAGIC, VERITAS