Reading the Universe's Light: Measuring the Extragalactic Background Light Through Gamma-Ray Attenuation

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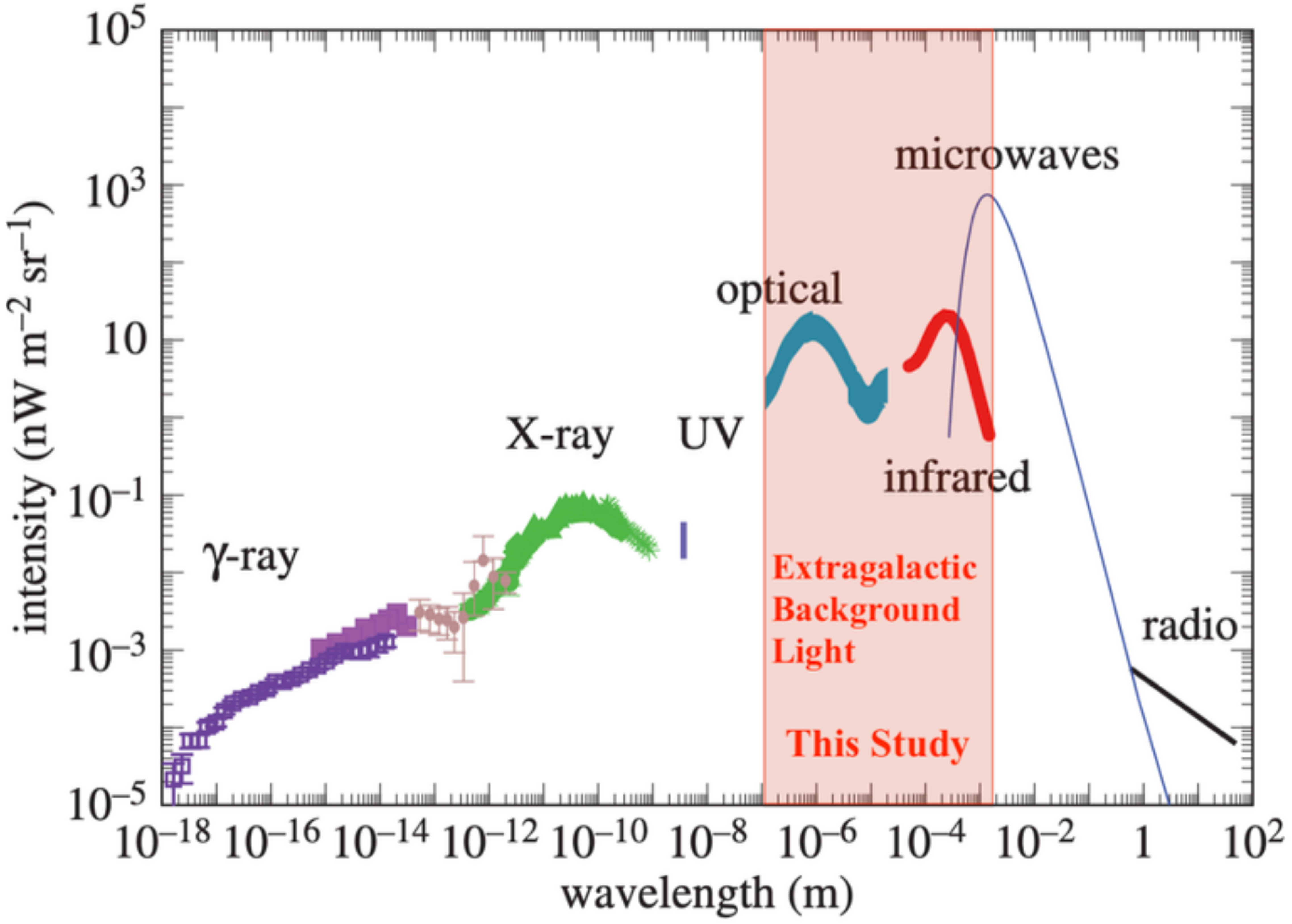
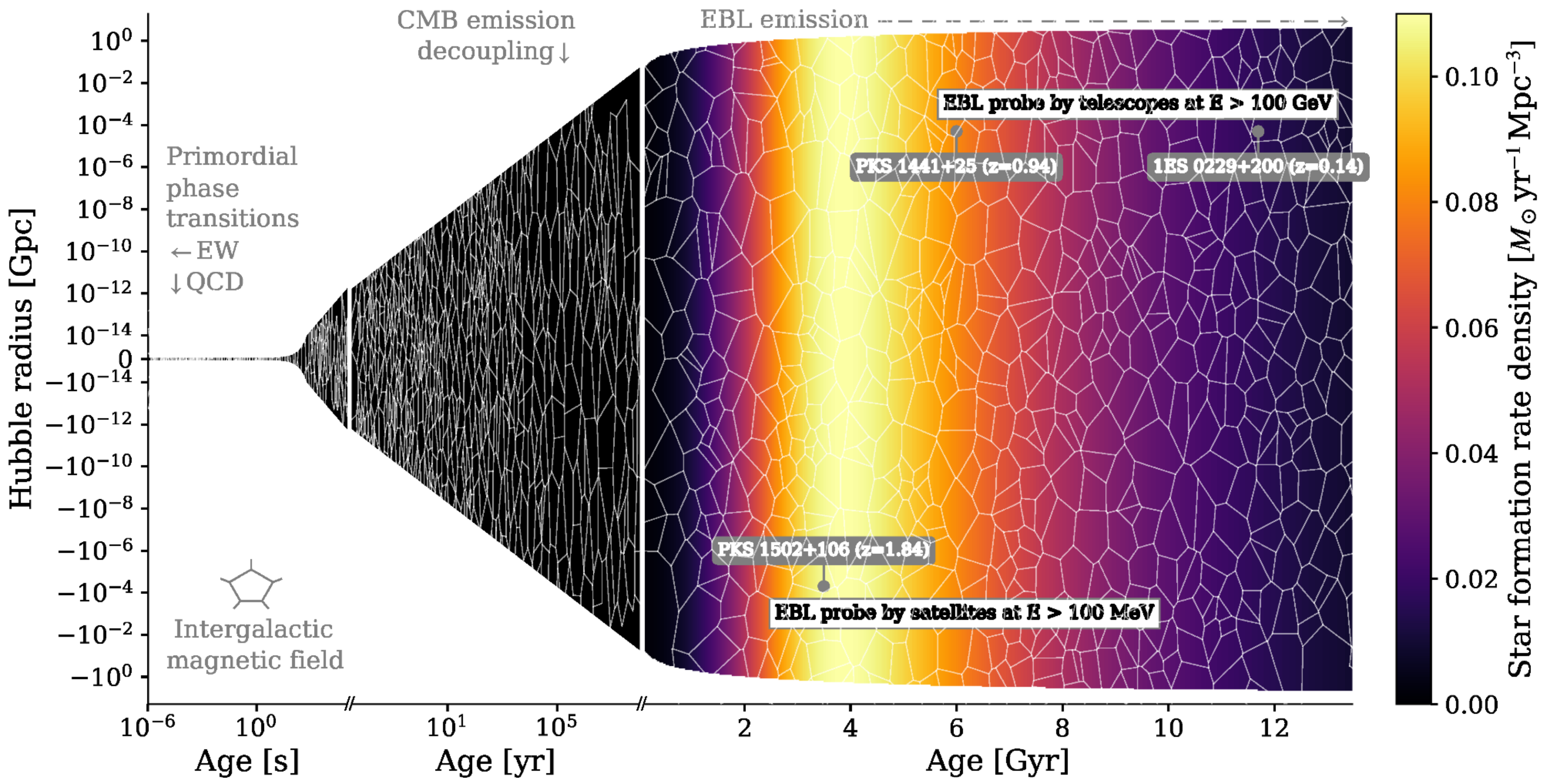
Extragalactic Background Light

- Accumulated **UV through infrared** light radiated by galaxies, stars, and dust across all cosmic epochs
- Measuring and modeling the EBL is important for **tracing star formation history and galaxy evolution**

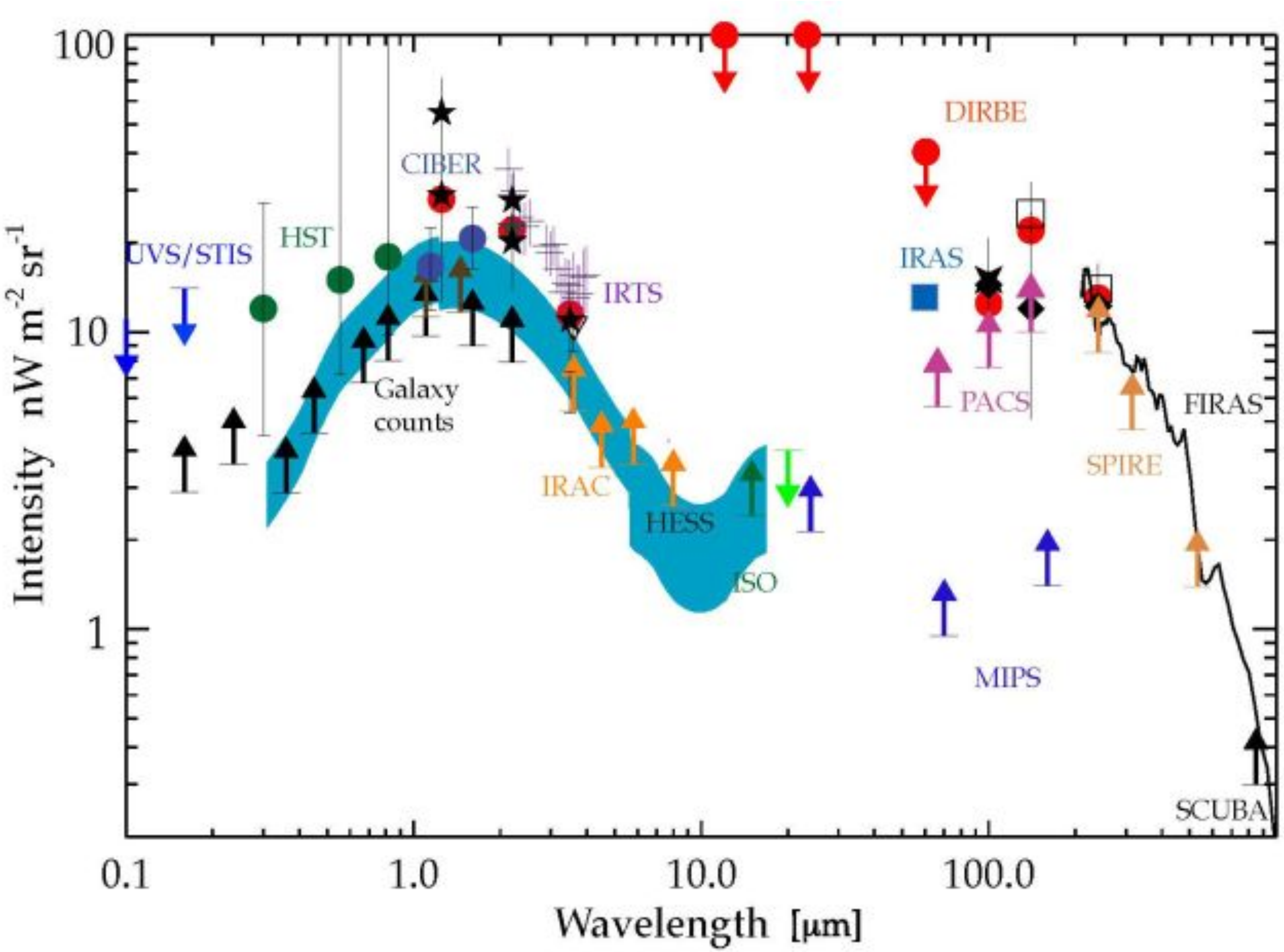


Cooray, A. (2016), "Extragalactic Background Light: Measurements and Applications", arXiv:1602.03512



Biteau, J.; Meyer, M. Gamma-Ray Cosmology and Tests of Fundamental Physics. *Galaxies* **2022**, *10*, 39. https://doi.org/10.3390/galaxies10020039

How do we measure the EBL



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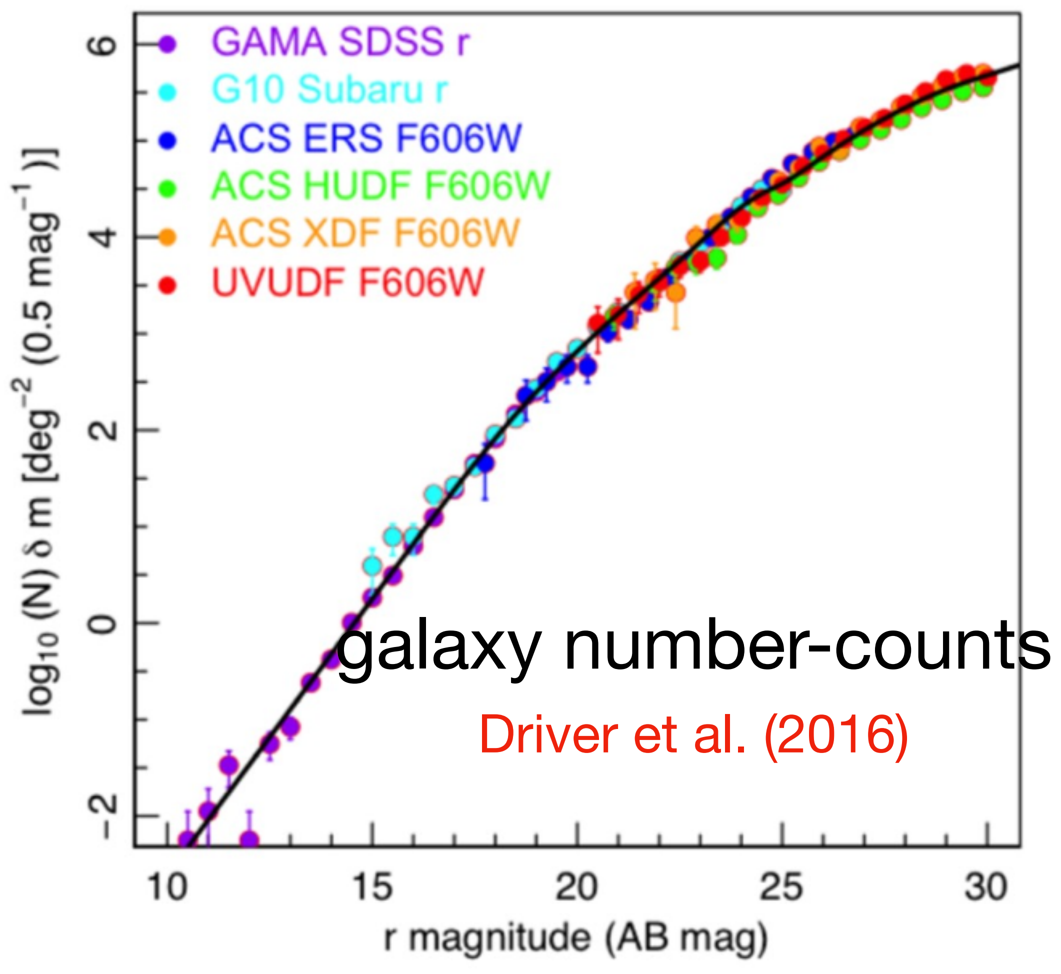
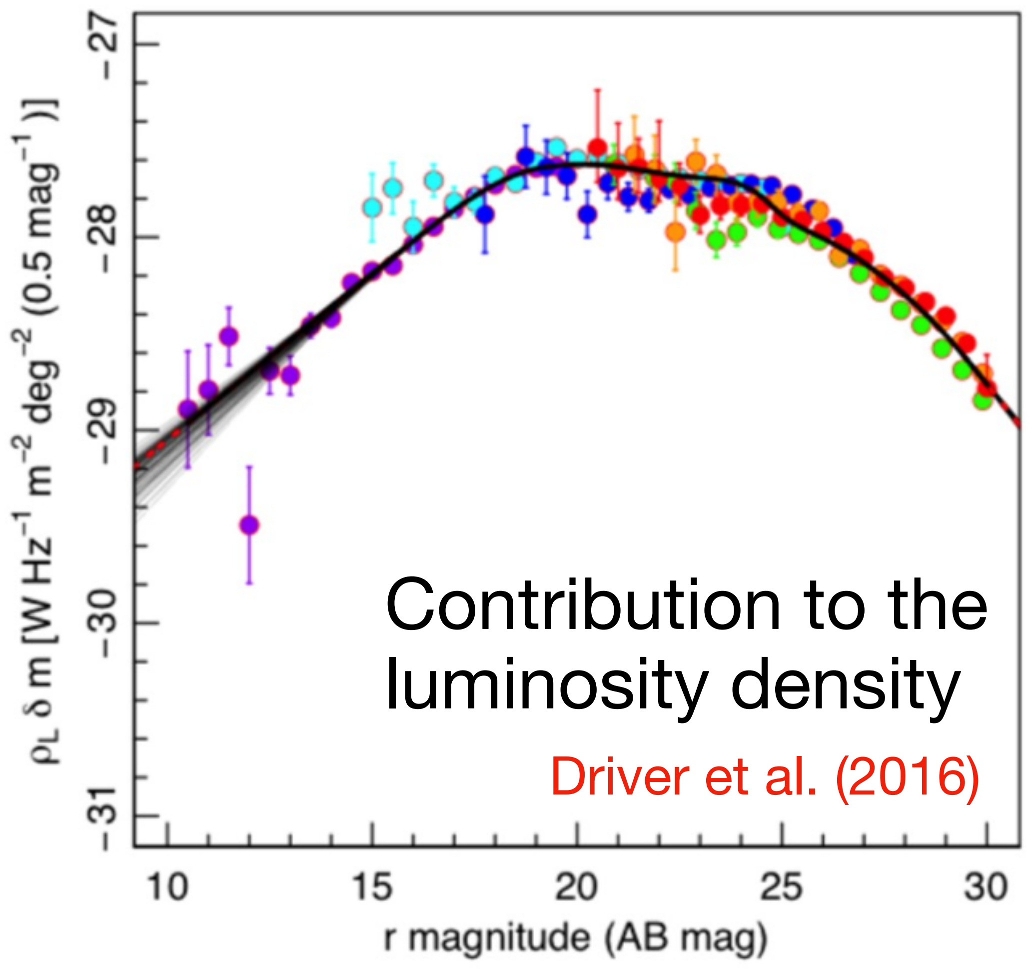
How do we measure the EBL

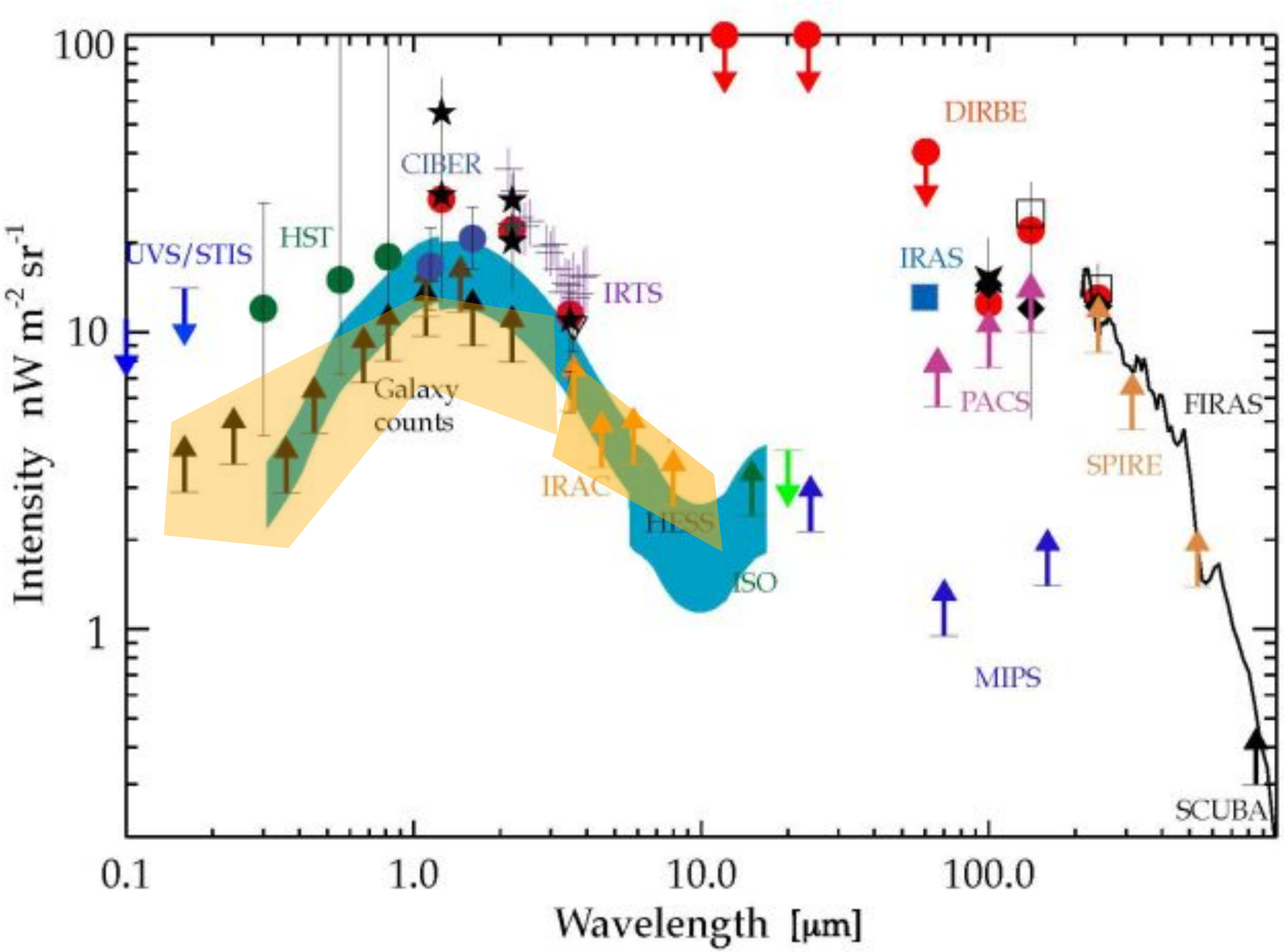
1. Integrated Galaxy Light (IGL)

⭕ A robust and direct measurement

✖ unresolved light is missed
→ Gives a lower limit by nature







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How do we measure the EBL

1. Integrated Galaxy Light (IGL)

2. Direct photometric observations

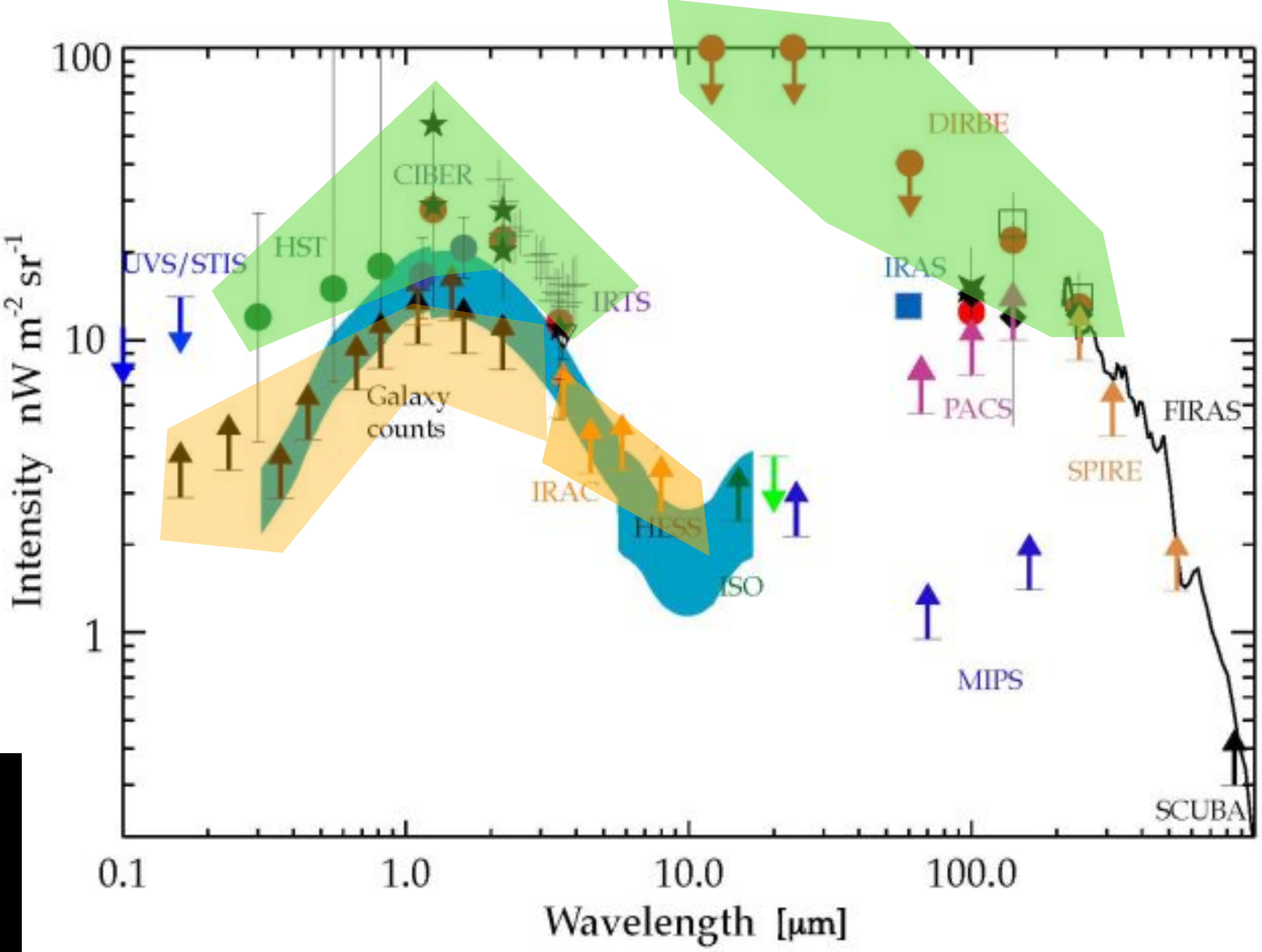
⭕ Sensitive to all light

✖ Limited to the local universe (z = 0)

✖ Very bright foreground
→ large systematic errors

Cosmic Infrared Background Experiment (CIBER)

HST



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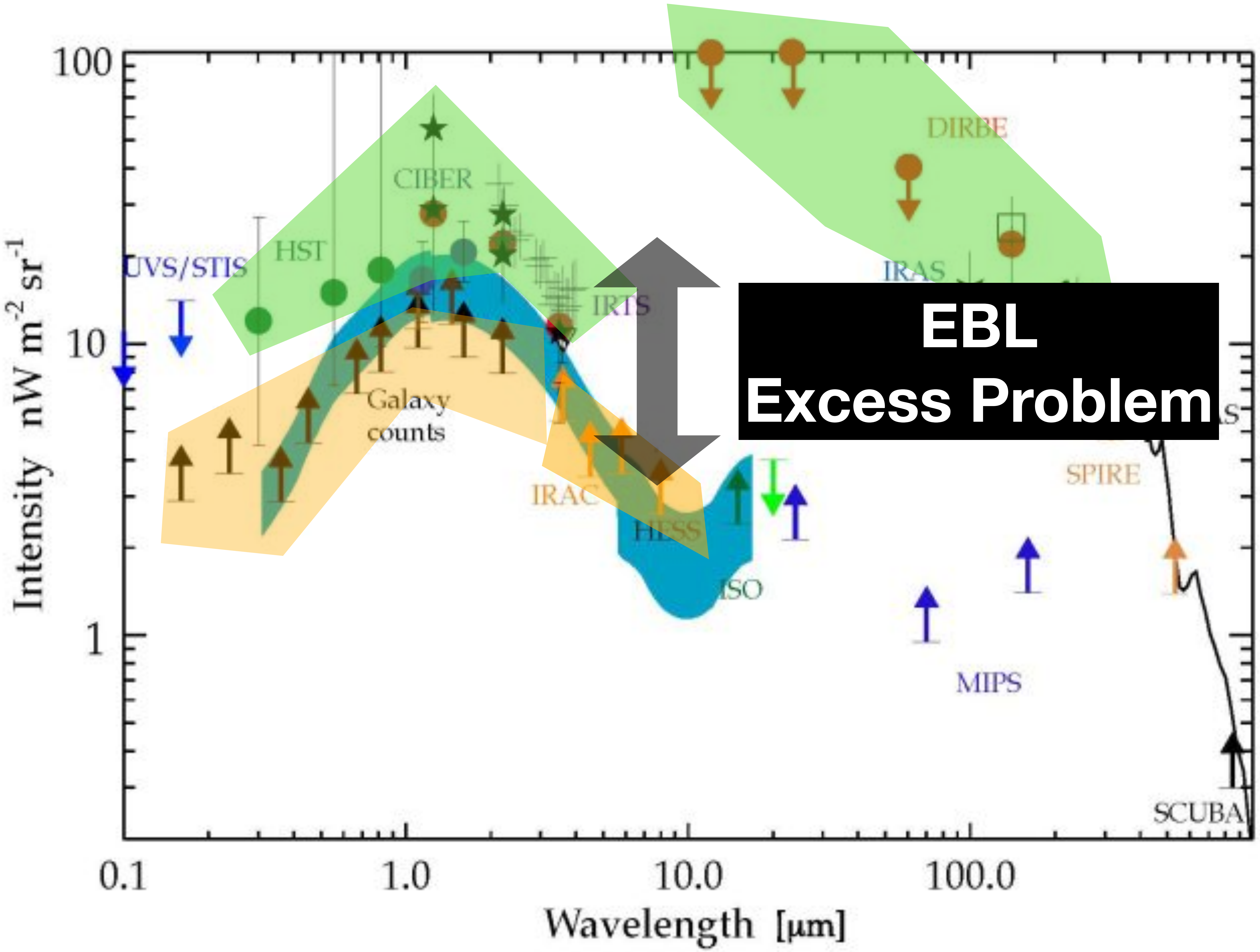

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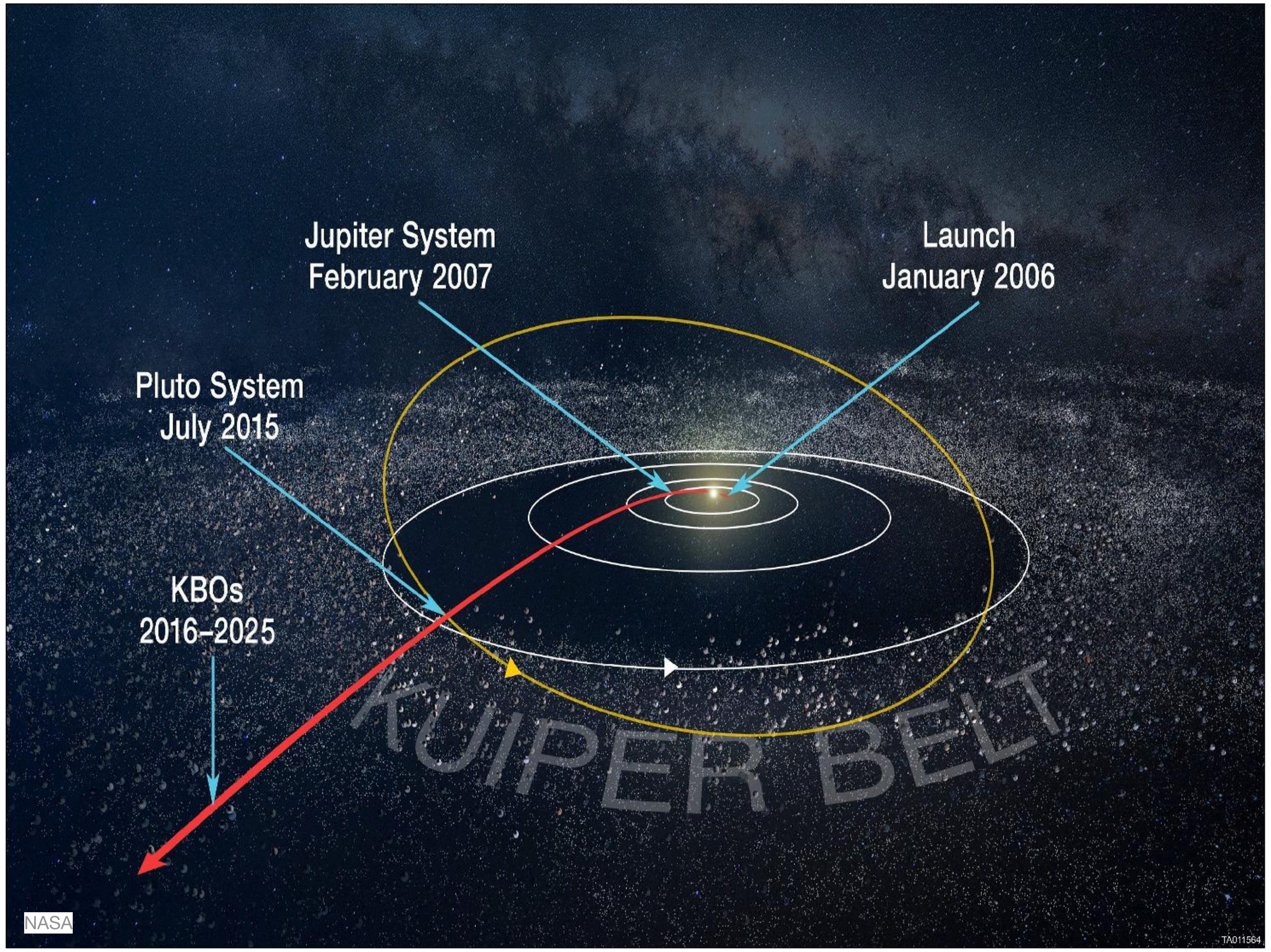
Why is there a discrepancy in EBL measurements? Three hypotheses

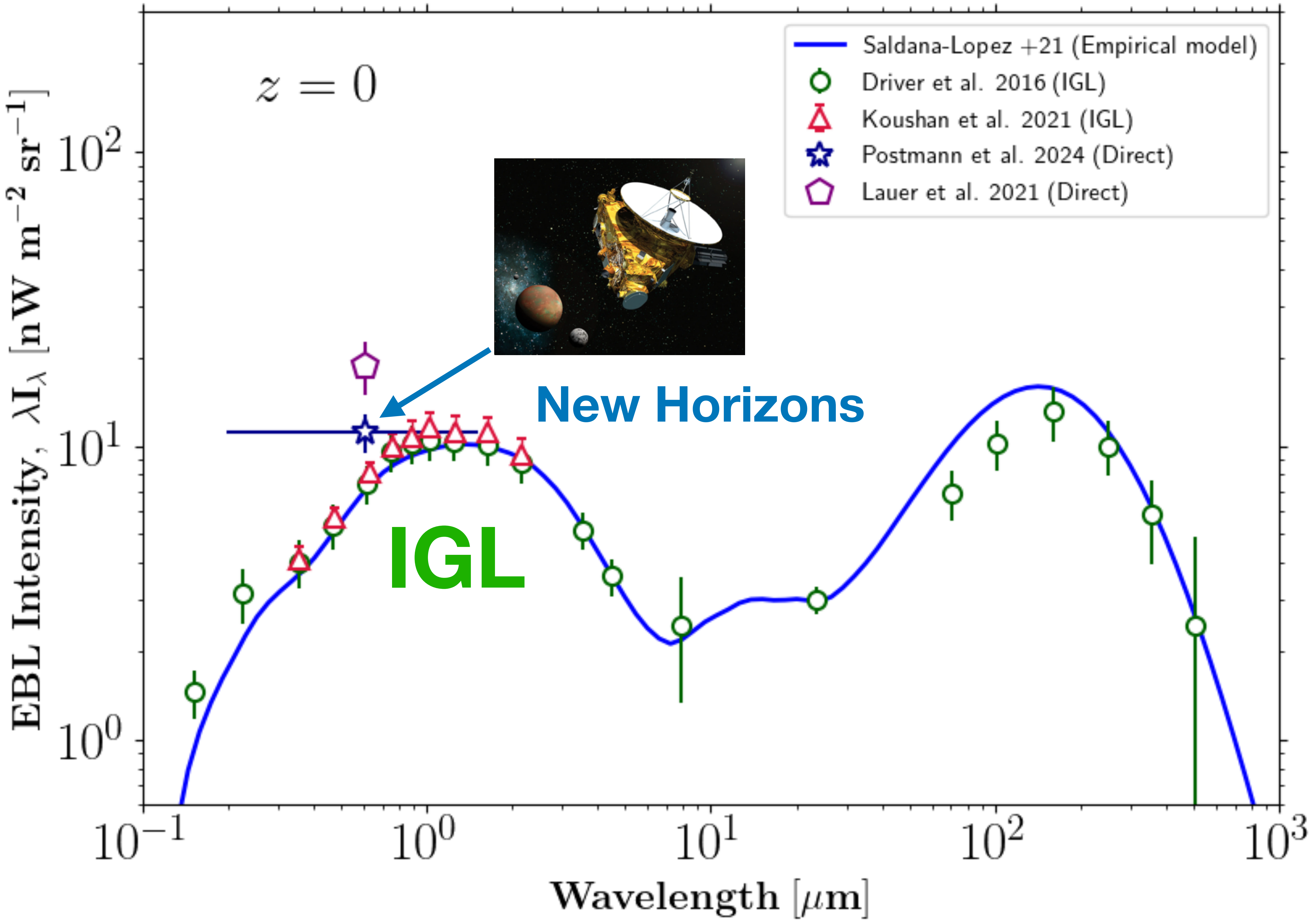
1. **On systematic errors in direct measurements:**
   - Direct photometric methods rely heavily on modeling the foreground emission
     → inadequate treatment of zodiacal light or diffuse galactic light introduces large uncertainties
2. **On the incompleteness of galaxy counts (IGL):**
   - Since IGL only includes light from resolvable galaxies, it can miss the following components:
     - Faint/low surface brightness galaxies
     - Intra-halo light (IHL) from stars stripped out of galaxies during mergers
     - More diffuse background light originating from the reionization era
3. **Possibility of new physics:**
   - The decay of axion-like particles (ALPs) could be supplying light, etc.

Latest direct EBL measurements

- New Horizons has traveled beyond 50 au from the Sun, **where zodiacal light drops off dramatically**, allowing EBL to be measured in a much cleaner environment (New Horizons / LORRI, Postman et al. 2024)

- The results are consistent with IGL at roughly the 2σ level, suggesting that conventional direct measurements may have been affected by significant systematic errors

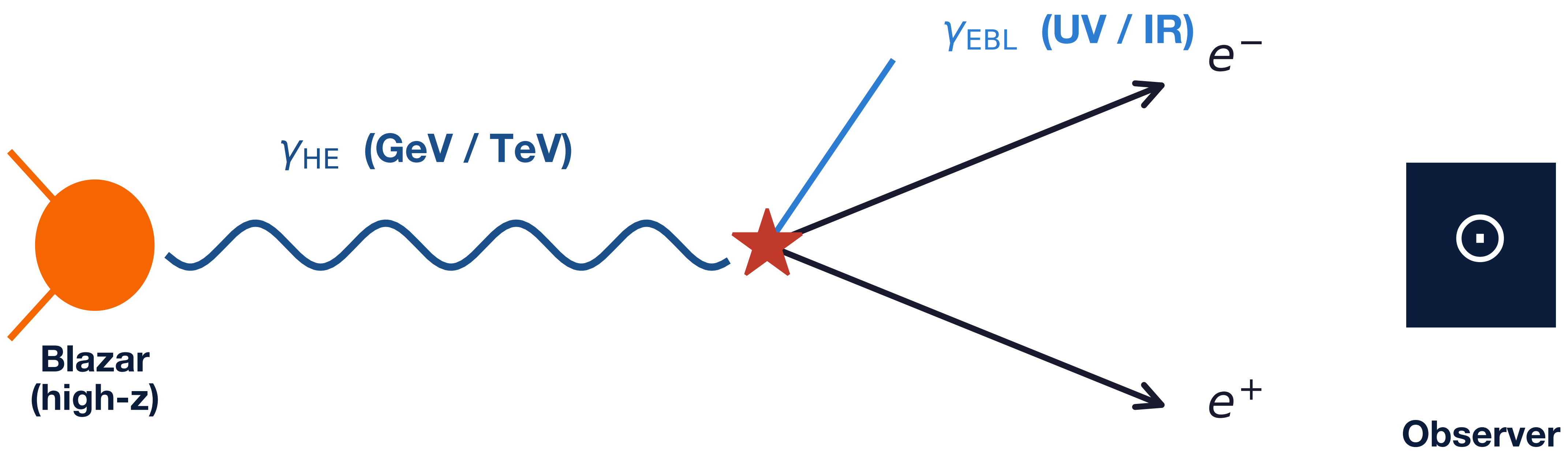




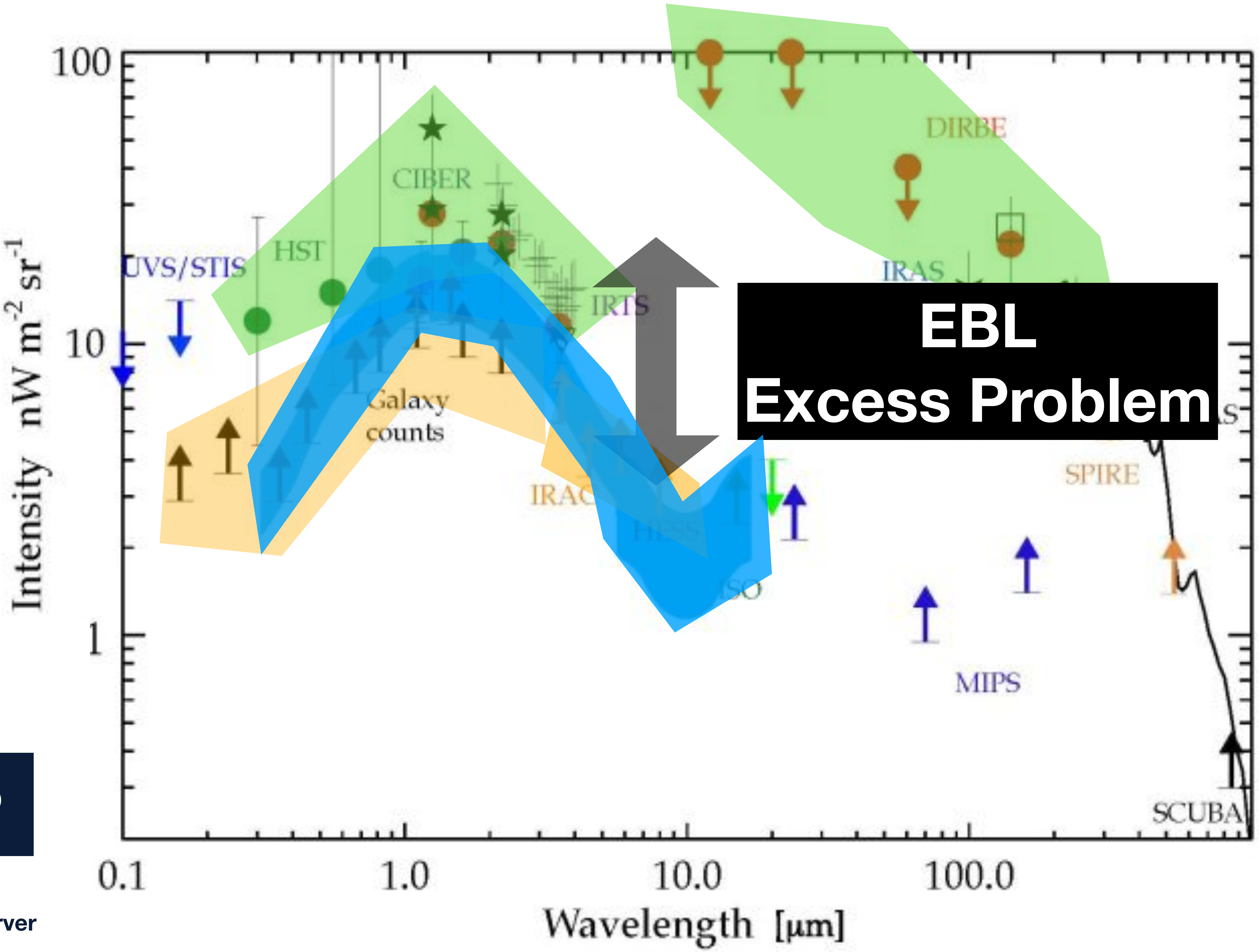
Indirect EBL measurements through gamma-ray observations

1. Integrated Galaxy Light (IGL)
2. Direct photometric observations
3. Using Gamma rays

   Using the interaction between γ rays and EBL photons, we can measure the EBL indirectly!



$\gamma_{HE} + \gamma_{EBL} \to e^+ e^-$ (Breit–Wheeler)



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Two complementary γ-ray analyses

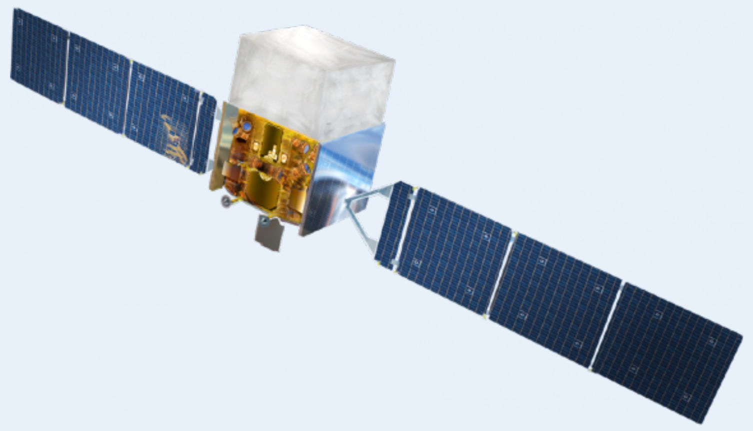
Combining Fermi-LAT GeV and Cherenkov-telescope TeV data to anchor both evolution and local EBL.

Two complementary γ-ray measurements of the EBL

Paper I — GeV (Banerjee+ 2026)

Fermi-LAT, 15 yr, 1–1000 GeV

- 1574 blazars (822 BL Lacs + 752 FSRQs)
- 19 redshift bins, $0 < z < 4.3$
- Detection ≈ 23σ (TS ≈ 540)
- Probes EBL evolution → SFH out to $z \approx 5$
- Samples UV / optical EBL (~0.2–2 μm)



https://arxiv.org/abs/2604.09139

Paper II — TeV (Baxter+ 2026)

STeVECat, H.E.S.S. / MAGIC / VERITAS

- 268 VHE spectra from 45 sources
- 4 redshift bins, up to $z \approx 0.94$
- 7 EBL models tested (all within 10 %)
- Anchors local ($z = 0$) EBL intensity
- Samples optical / near-IR (~0.5–30 μm)

https://arxiv.org/abs/2604.09397

Methodology

GeV: 15 yr of Fermi-LAT and 1574 blazars. TeV: 268 VHE spectra from STeVECat.

GeV (Paper I)

- Fit intrinsic Φ up to $E_{max}(z)$ where $\tau < 0.1$
- Log-parabola / power-law + cutoff
- Joint-likelihood over 1574 blazars → TS_EBL

TeV (Paper II)

- 4 intrinsic forms (PL / LP / PL-cut / LP-cut)
- Scan α (≡ b) from STeVECat flux points
- Template-marginalize over 4 EBL models

Common framework

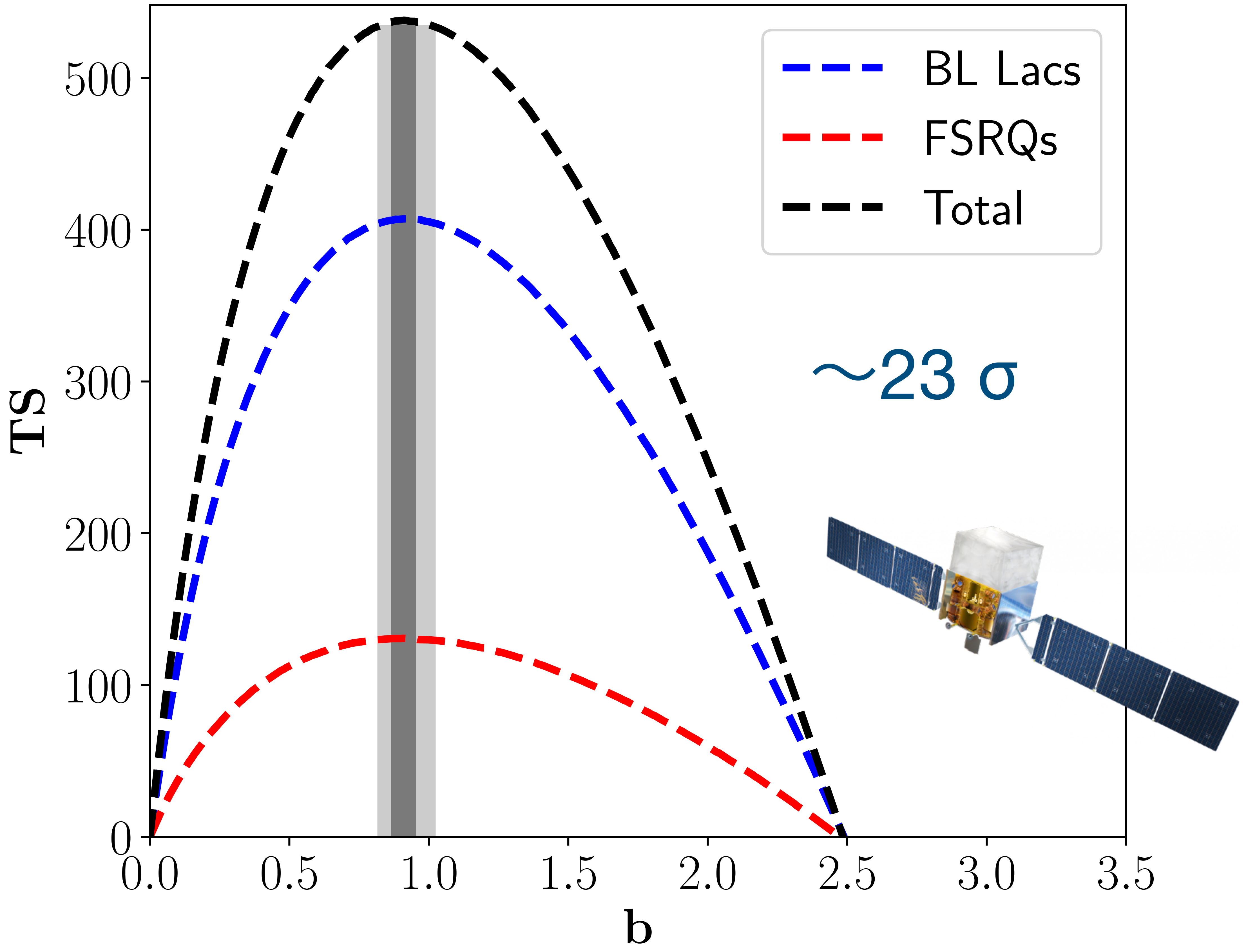
$$\Phi_{obs}(E) = \Phi_{int}(E)\, e^{-b\, \tau_{model}(E,\, z)}$$

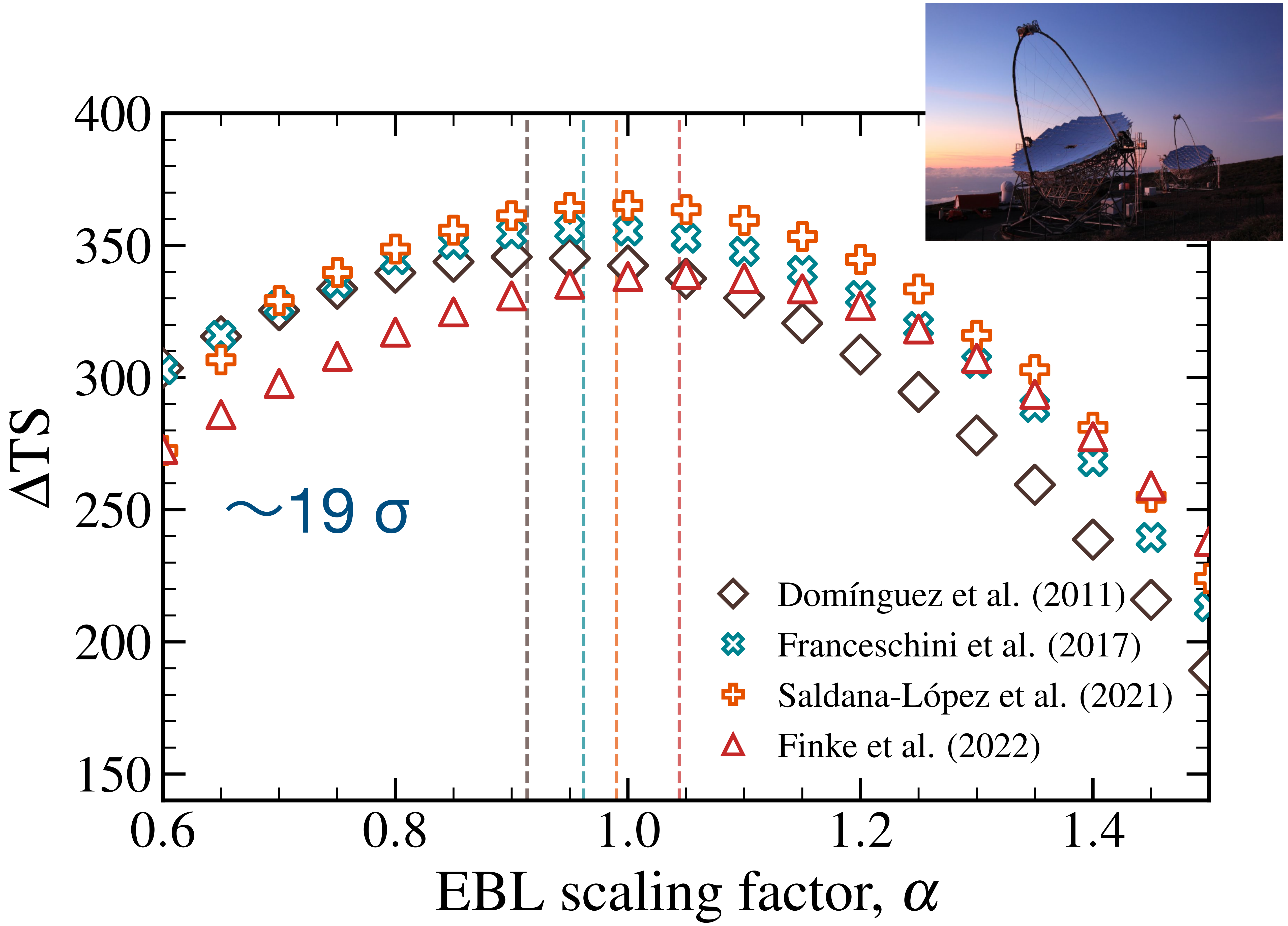
Output

$b\,(\alpha)$ best-fit → $\tau(E, z)$ → EBL intensity & SFH

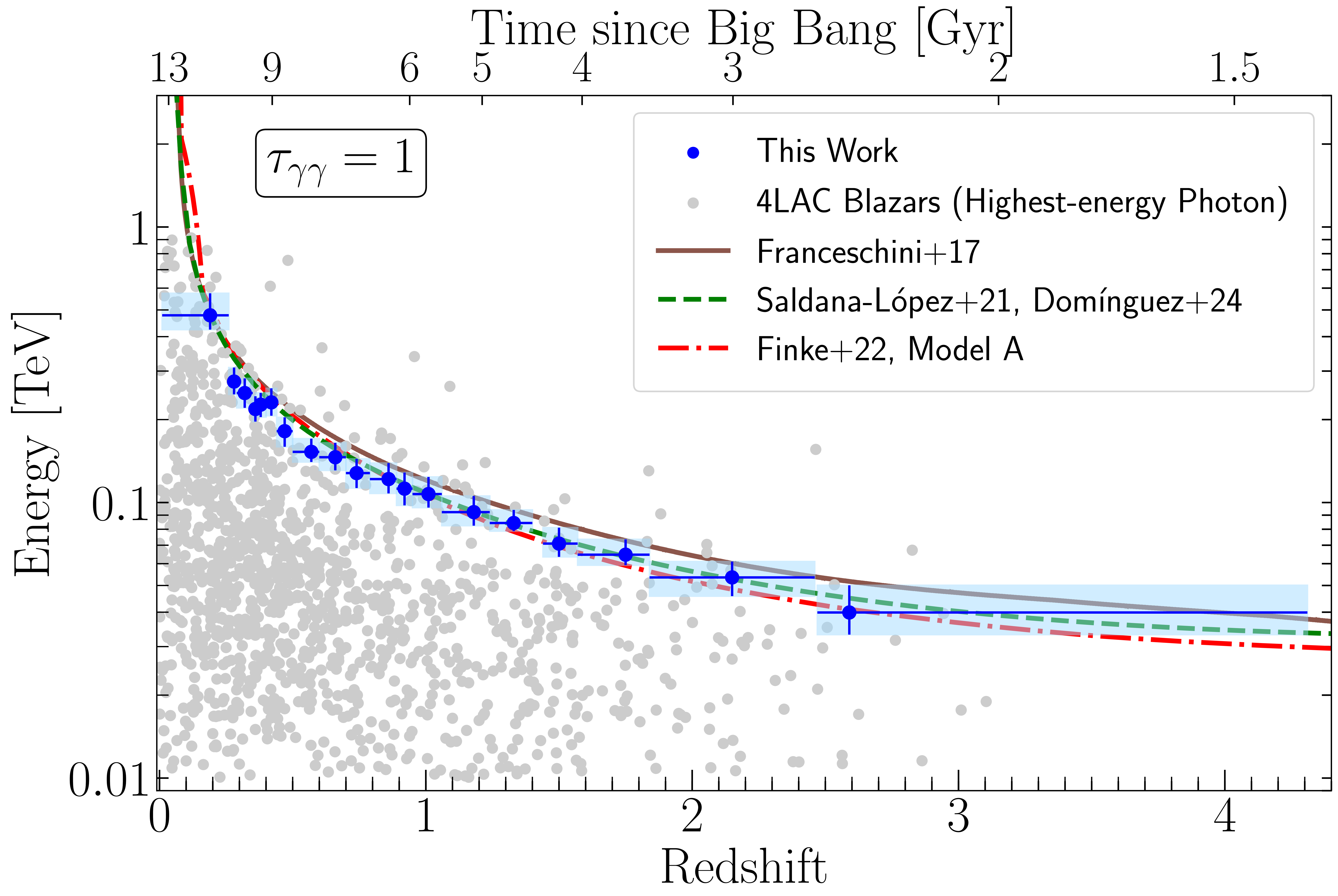
EBL Detection

Joint-likelihood profiles peak ~1 for all recent EBL models



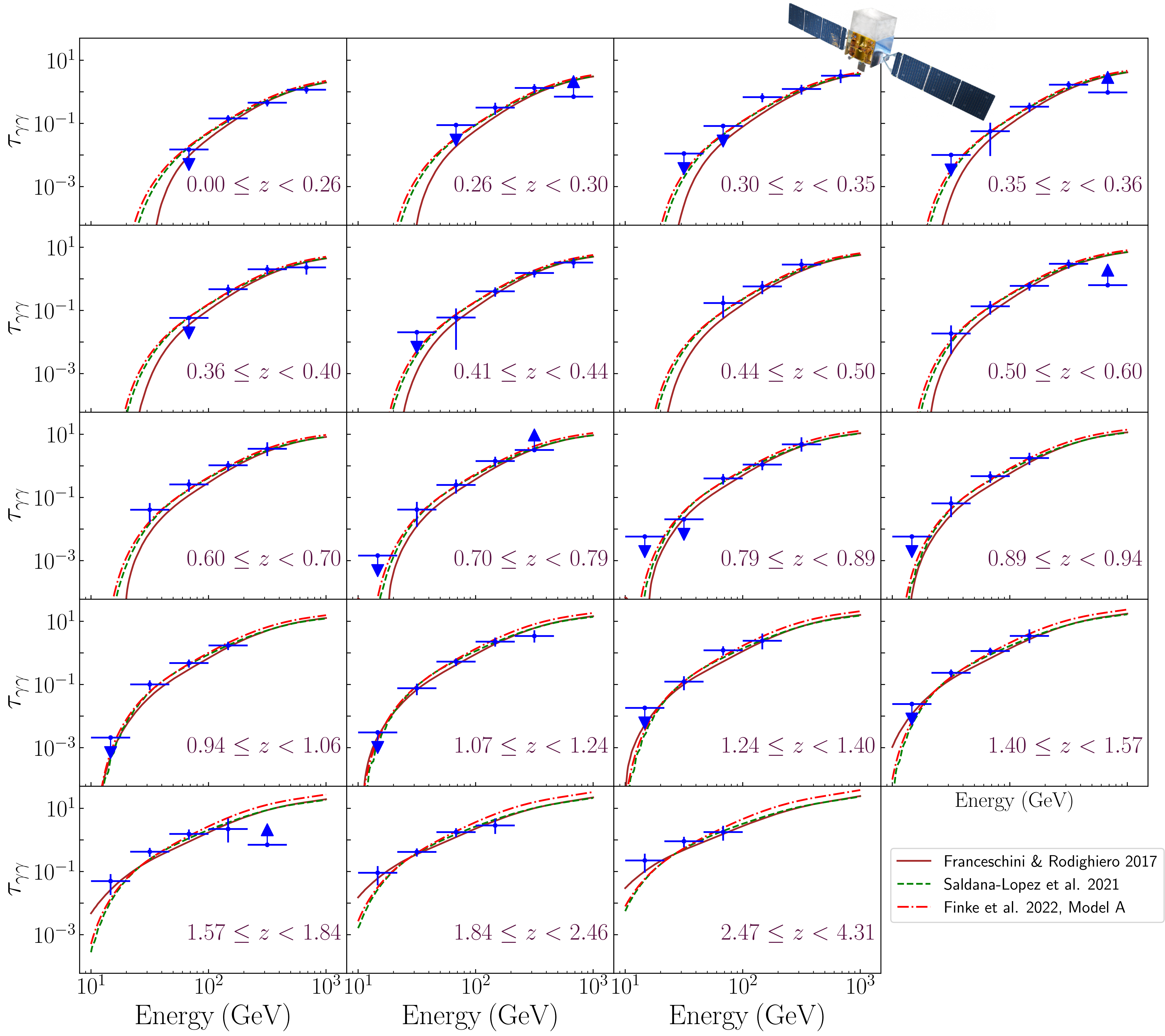


Gamma-ray Horizon

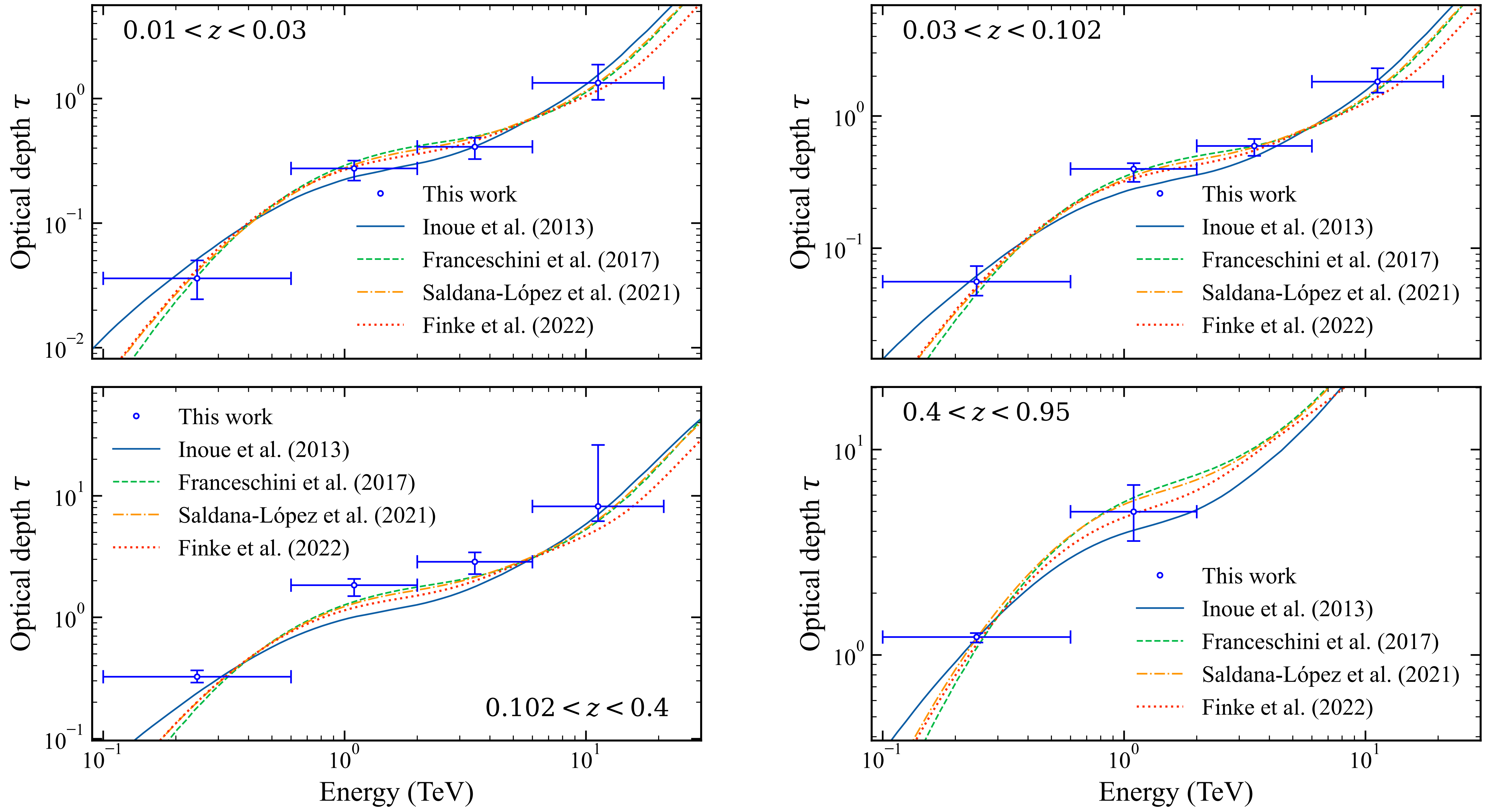


Optical Depth τ

GeV: 19 redshift bins up to z ≈ 4.3



TeV: 4 bins up to z ≈ 0.94



EBL intensity reconstruction upon optical depths

$$\tau_{\gamma\gamma}(E_\gamma, z_s) = c \int_0^{z_s} \left|\frac{dt}{dz}\right| dz \int_{-1}^{1} (1-\mu)\frac{d\mu}{2} \int_{2m_e^2c^4/\epsilon_\gamma(1-\mu)}^{\infty} \sigma(\epsilon_{\mathrm{EBL}}, \epsilon_\gamma, \mu) n_{\mathrm{EBL}}(\epsilon, z) d\epsilon_{\mathrm{EBL}}$$

Now we have this

$$n_{\mathrm{EBL}}(\epsilon, z) = (1+z)^3 \int_z^{\infty} \frac{j(\epsilon, z)}{\epsilon} \left|\frac{dt}{dz'}\right| dz'$$

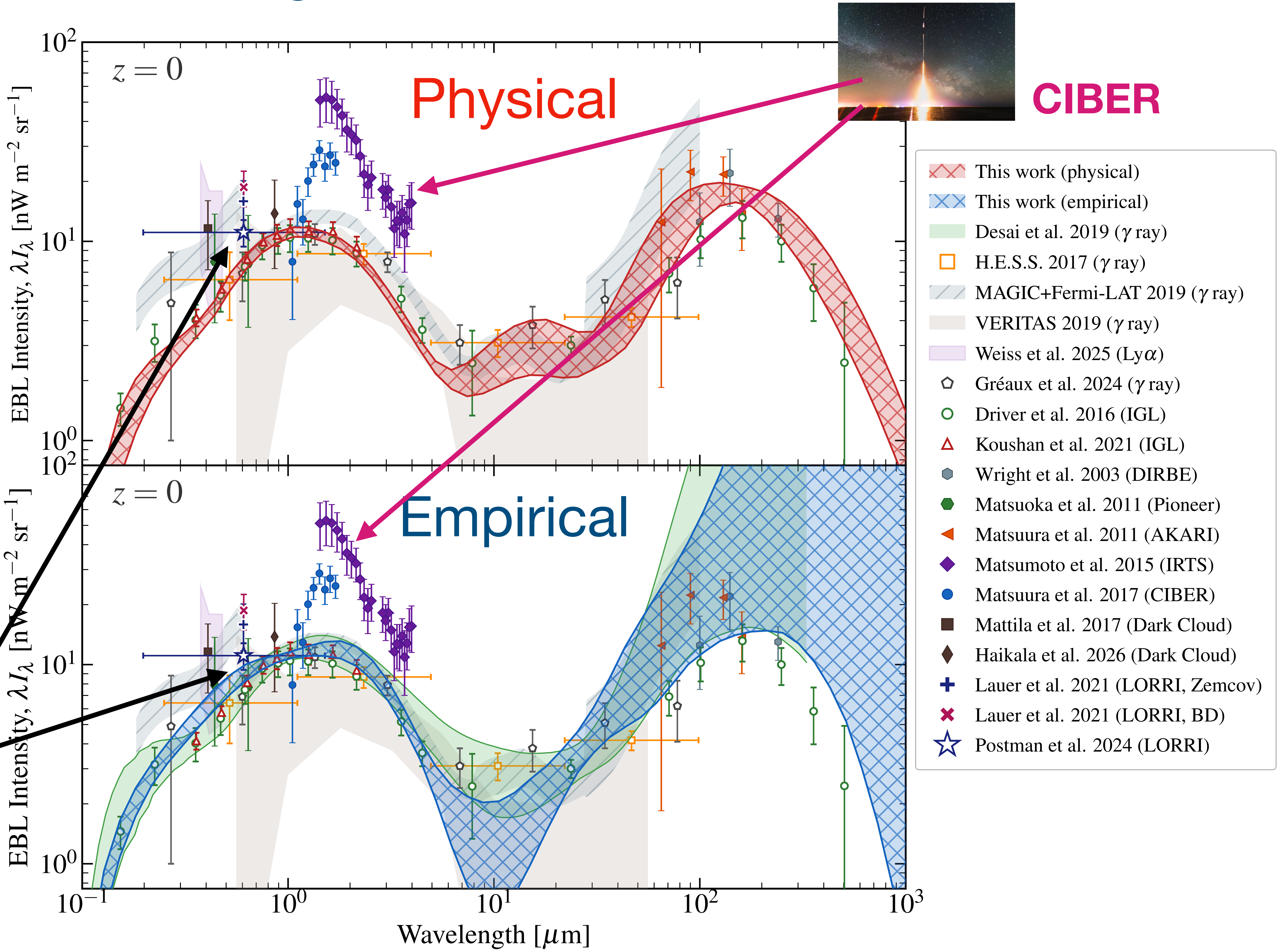
But we want this

- Two methods, both fitted via MCMC to GeV+TeV optical depth data
  - *Method 1-empirical*: model j(e,z) has sum of log-normal distributions that can evolve independently
  - *Method 2-physical*: use stellar population models and optimize the parameters of the Cosmic Star Formation History
    - We minimize the following $\chi^2 = \sum_{i=1}^{N} \sum_{j=1}^{M} \frac{\left[\tau_{\mathrm{data}}\left(E_i, z_j\right) - \tau_{\mathrm{model}}\left(\vec{\theta} \mid E_i, z_j\right)\right]^2}{\sigma_{i,j}^2}$

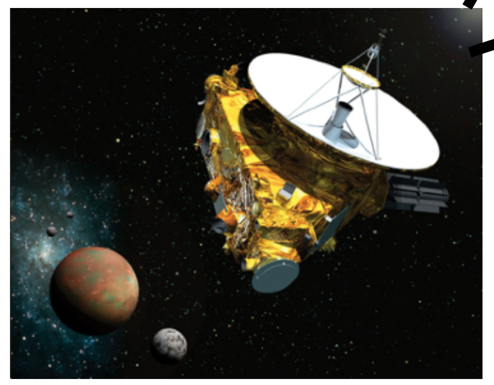
Local EBL intensity at z = 0

Empirical/physical reconstructions combining GeV + TeV τ : consistent with IGL

- Two independent reconstructions agree within uncertainties
- Follow IGL (Driver+2016; Koushan+2021) to 2–3 nW m^{-2} sr^{-1} (< 25 %) over 0.5–30 μm
- GeV τ constrains UV / optical EBL; TeV τ anchors the near- and mid-IR peak

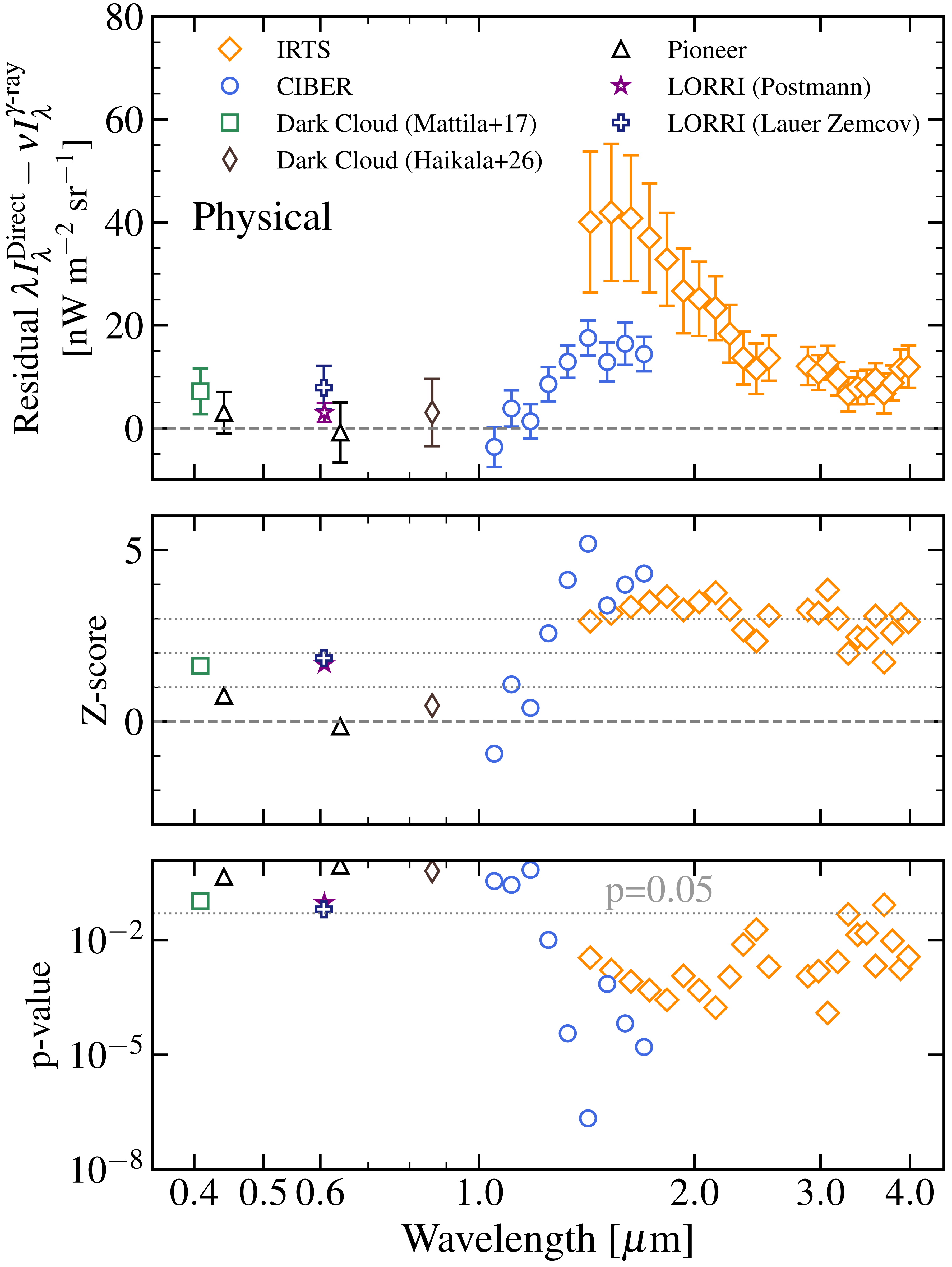


CIBER



New Horizons

Comparison with direct measurements



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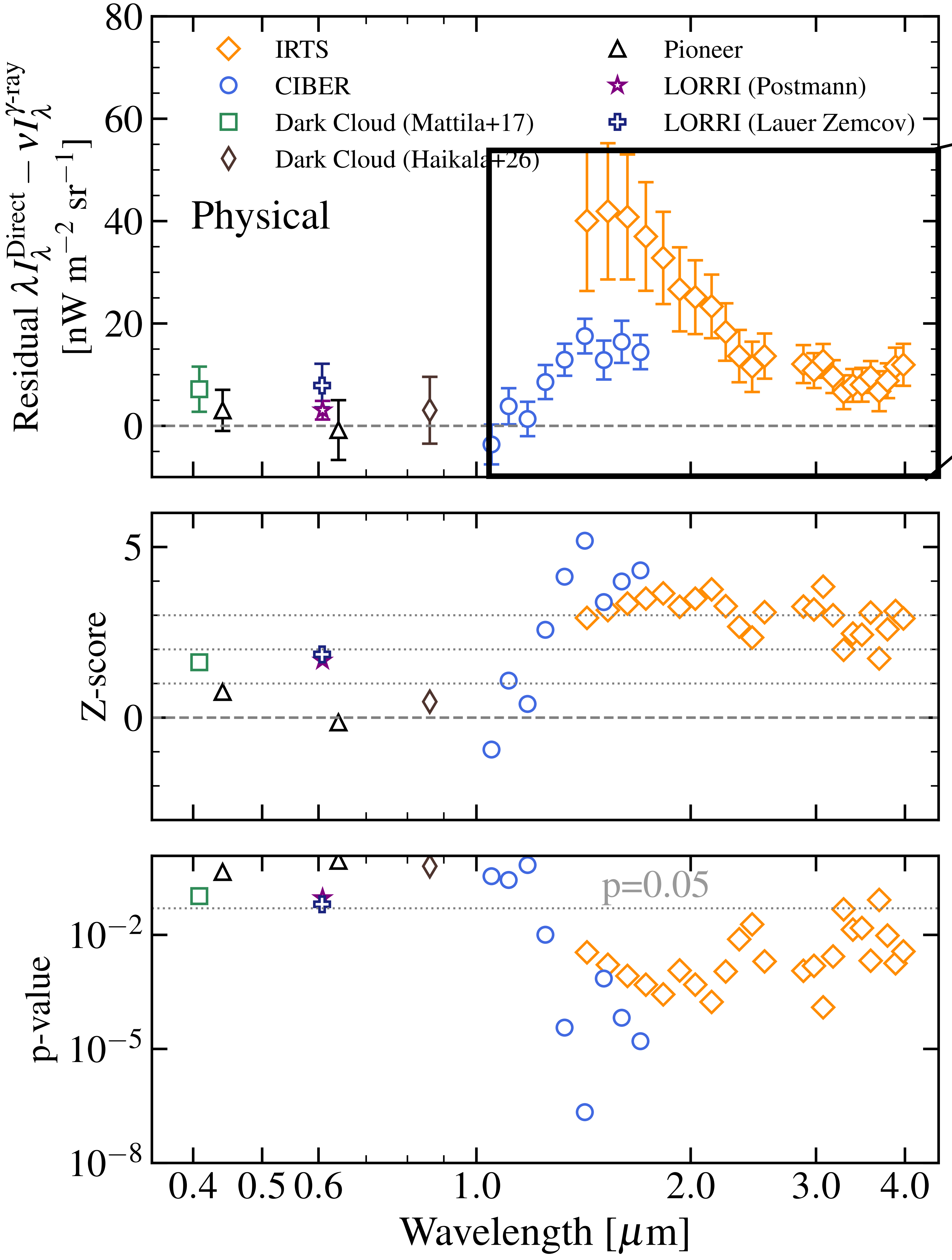
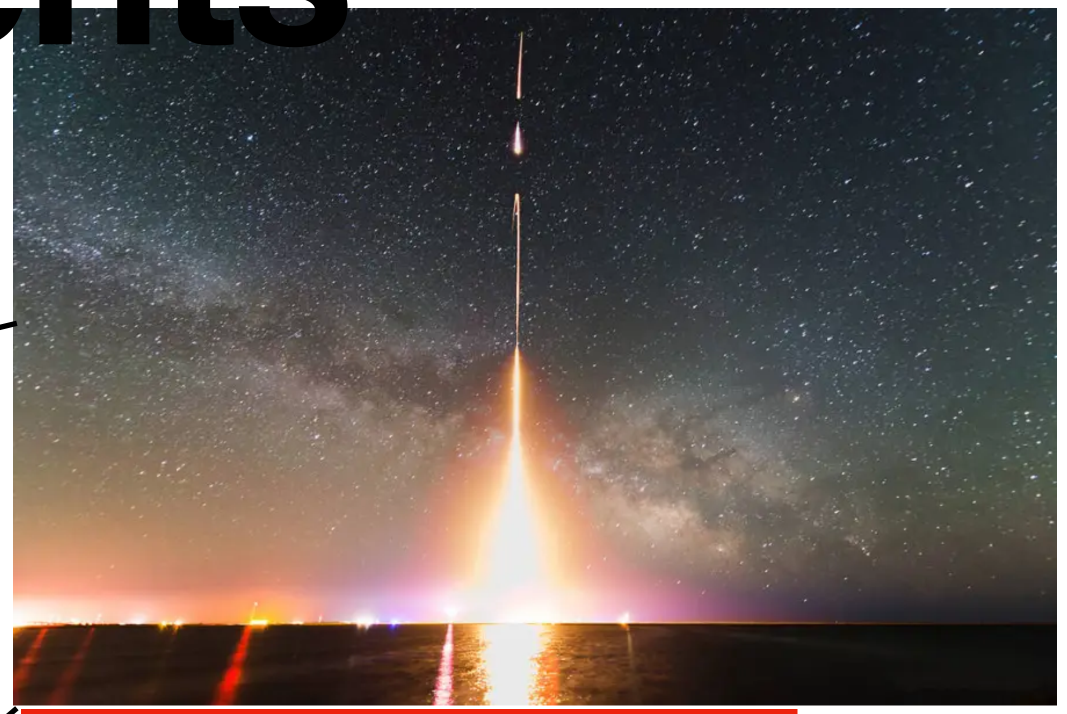
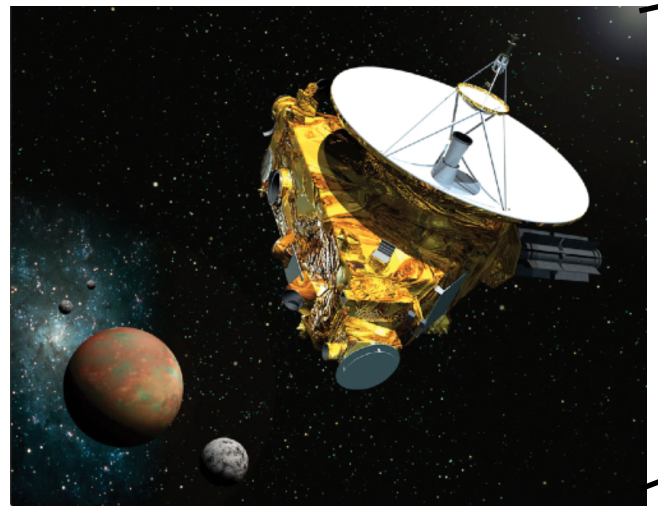




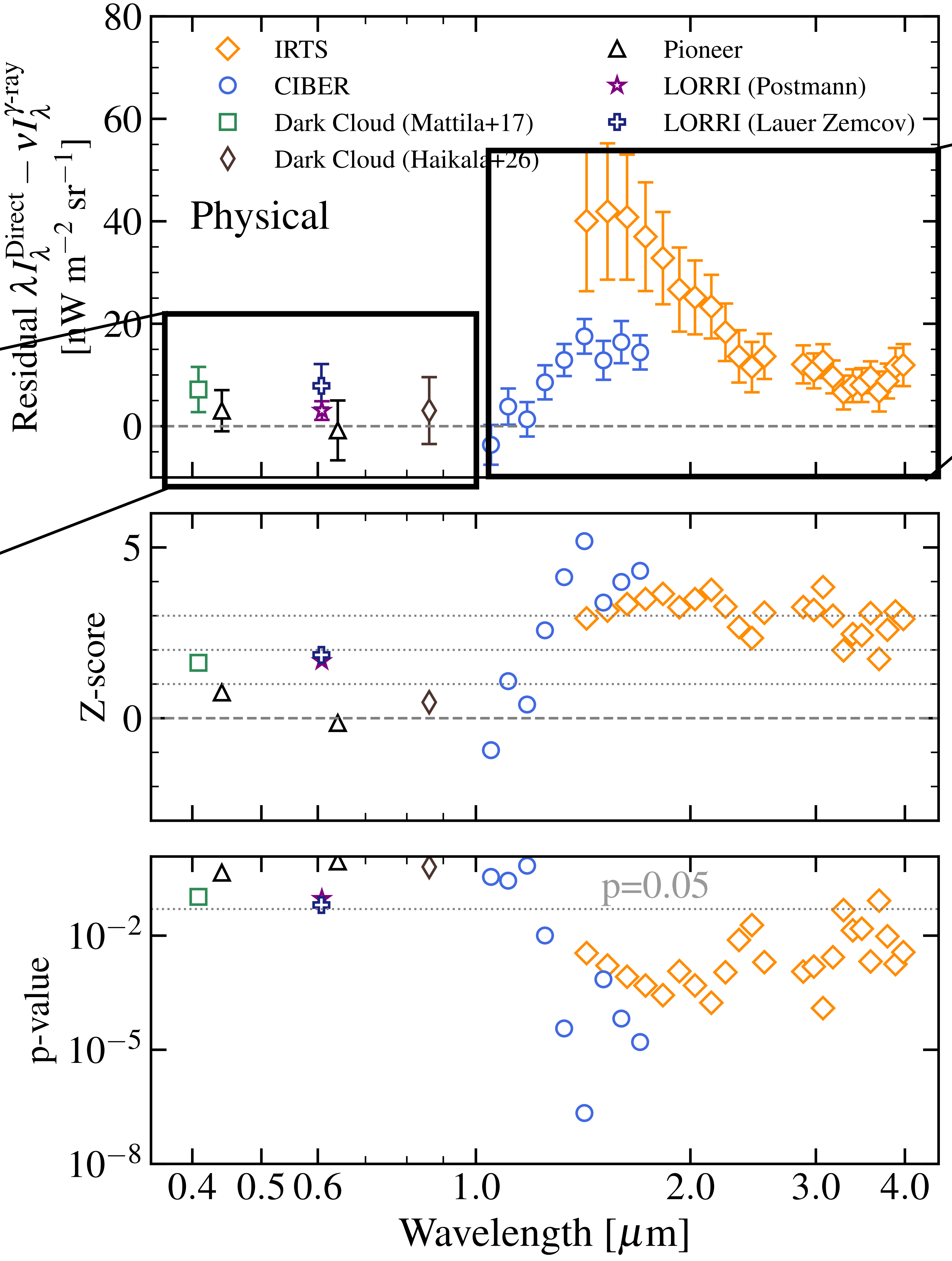
Rocket Experiment

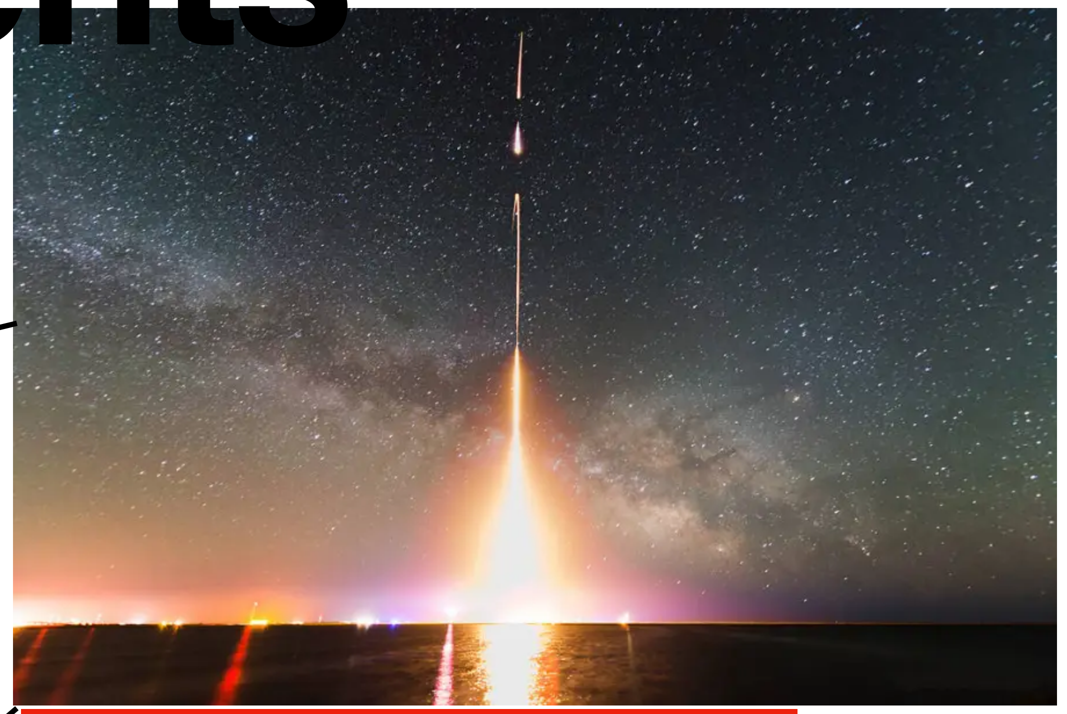
- CIBER, IRTS
- Large Systematics due to bright foreground

Comparison with direct measurements



- Reduced contamination from zodiacal light
- Potentially leading to smaller systematic errors





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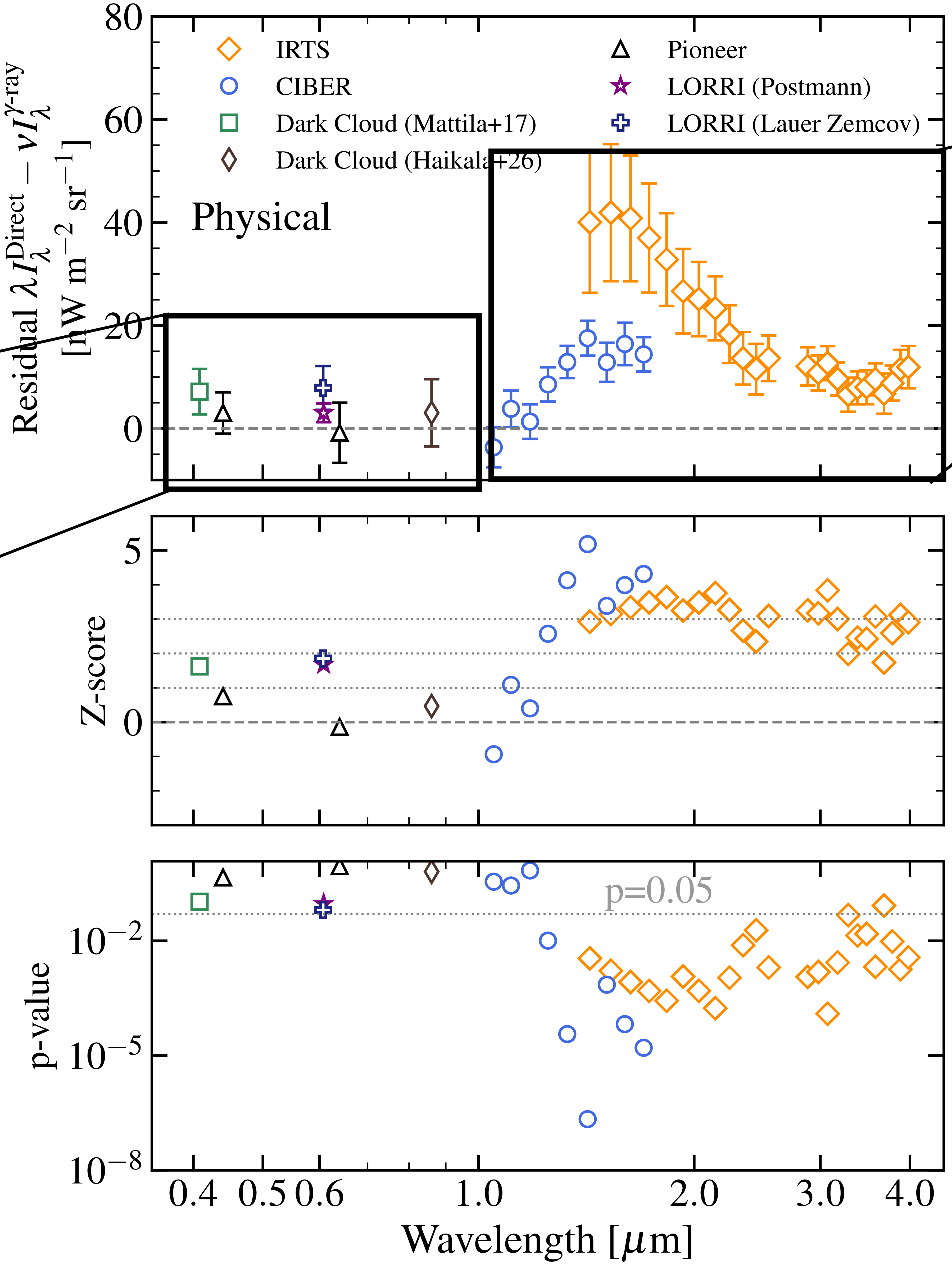

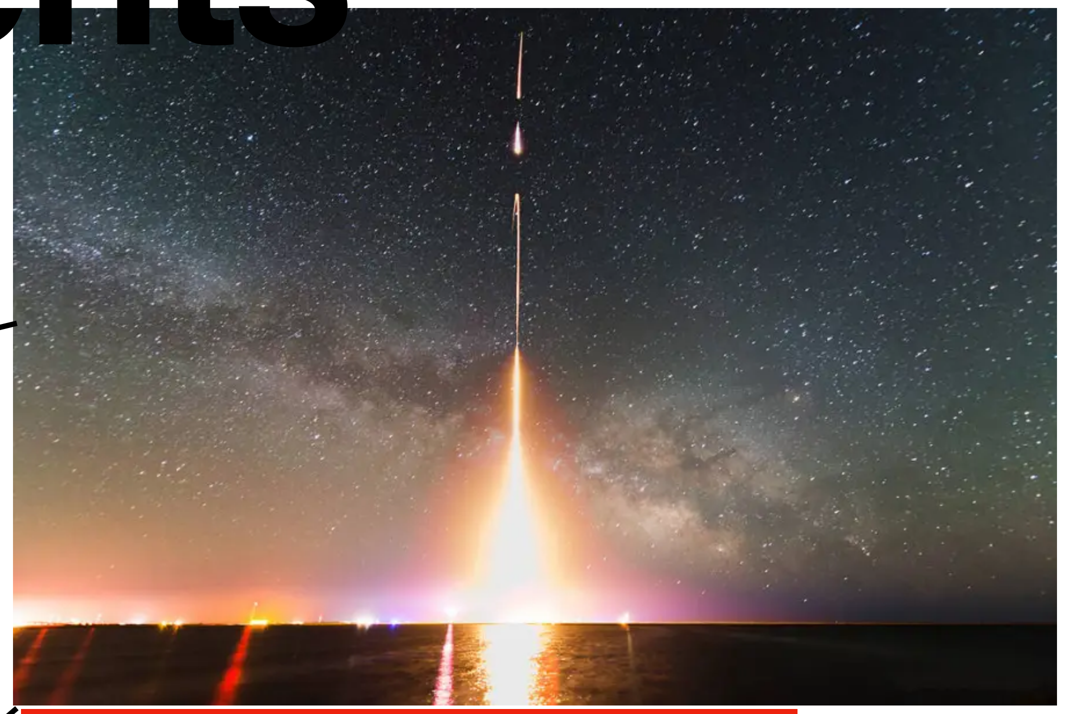

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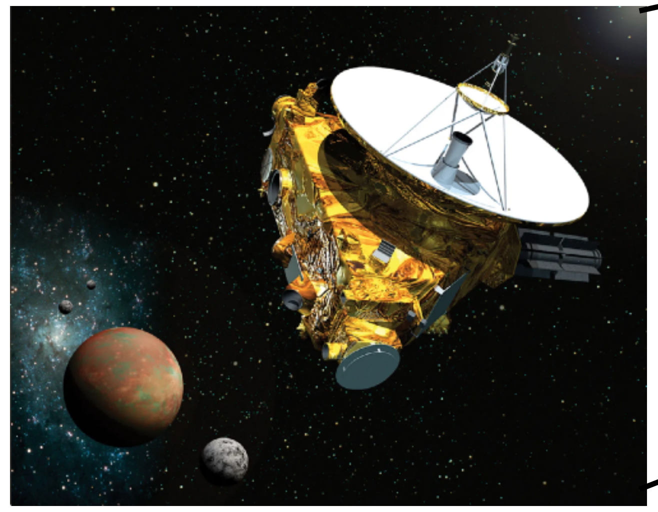


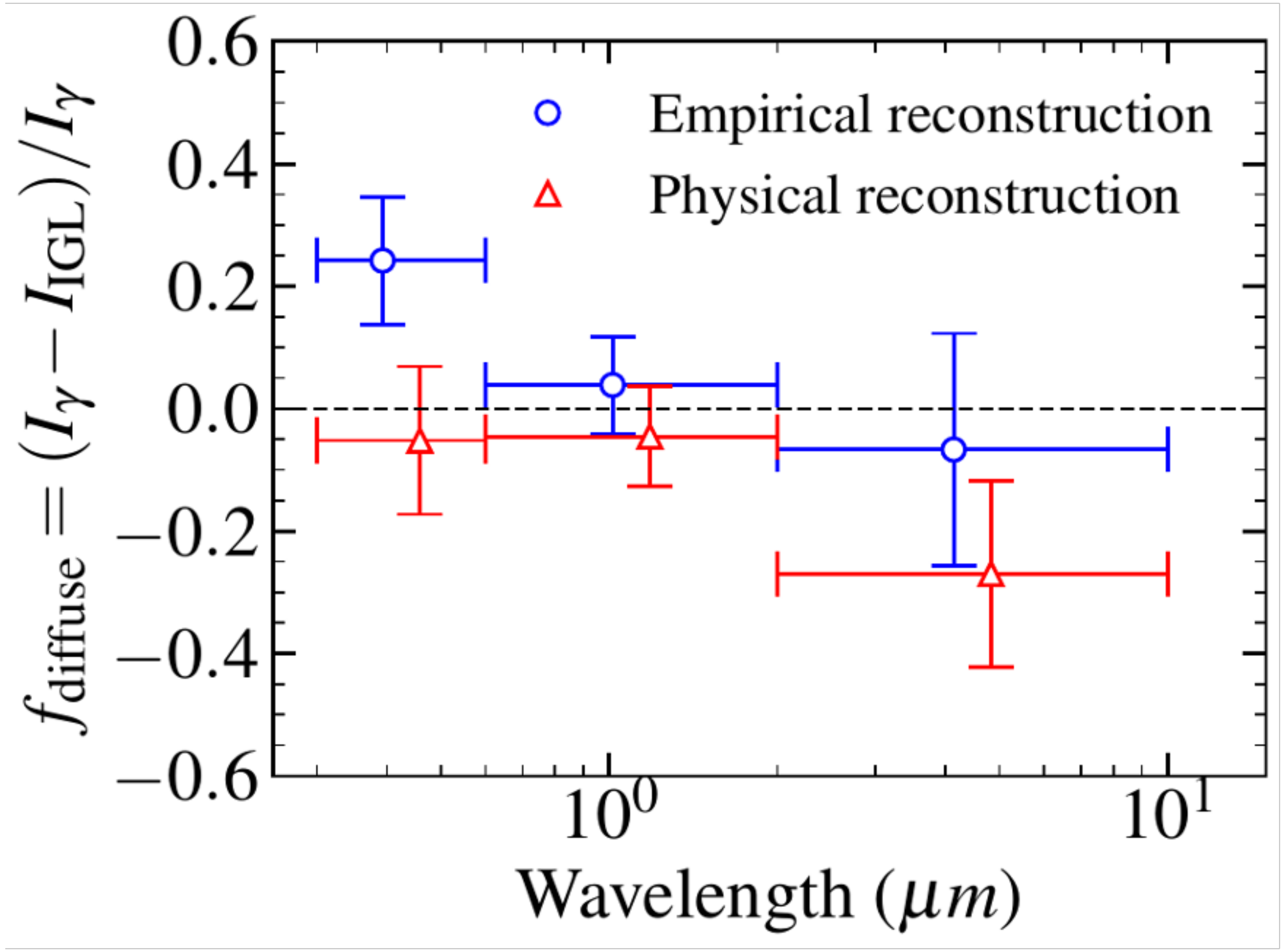
New Horizons

- Reduced contamination from zodiacal light
- Potentially leading to smaller systematic errors

- The gamma-ray results favor measurements from missions less affected by foreground light

How much diffuse light can hide beyond galaxies?

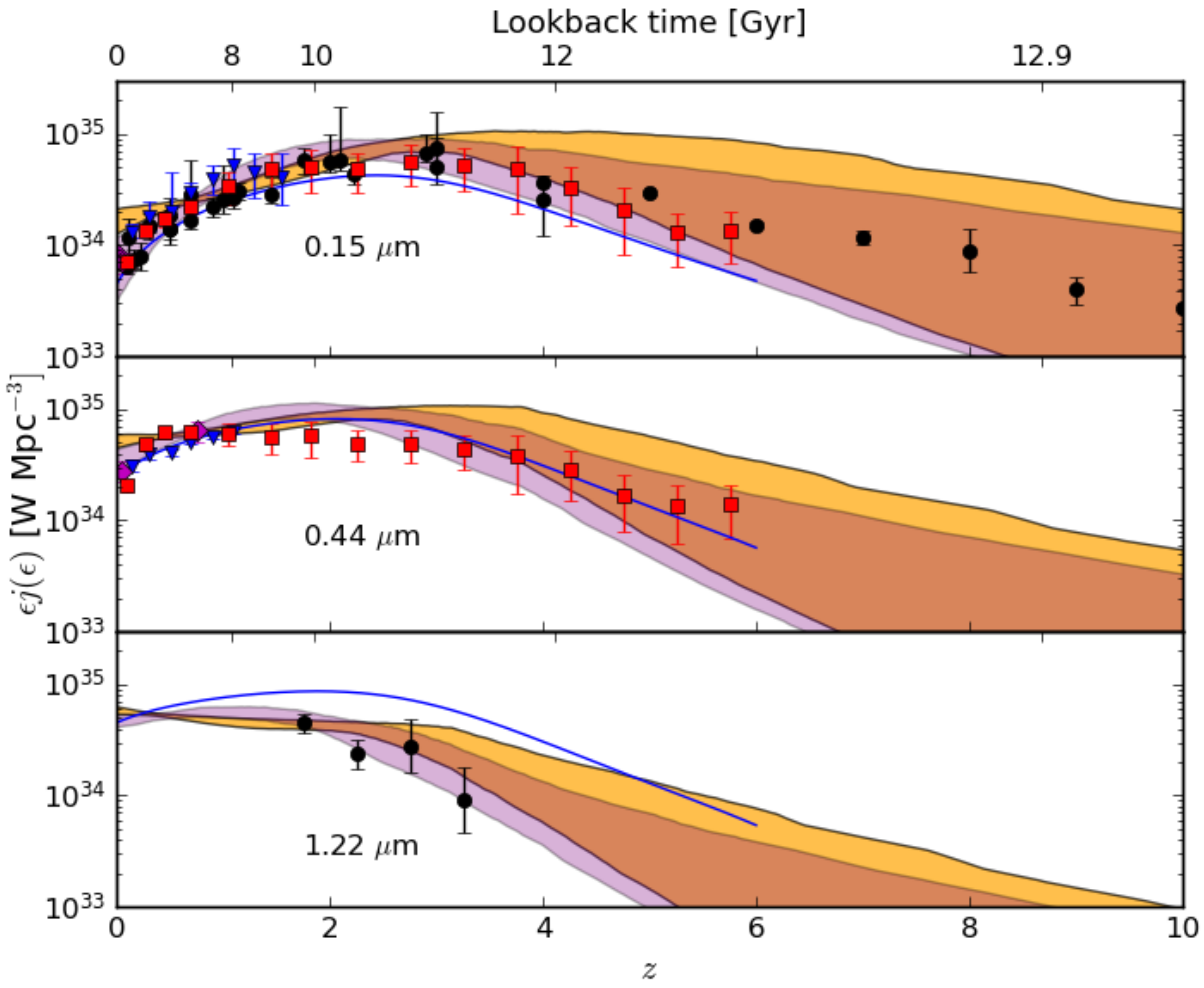
Constrain any additional diffuse EBL component to a small fraction of the IGL

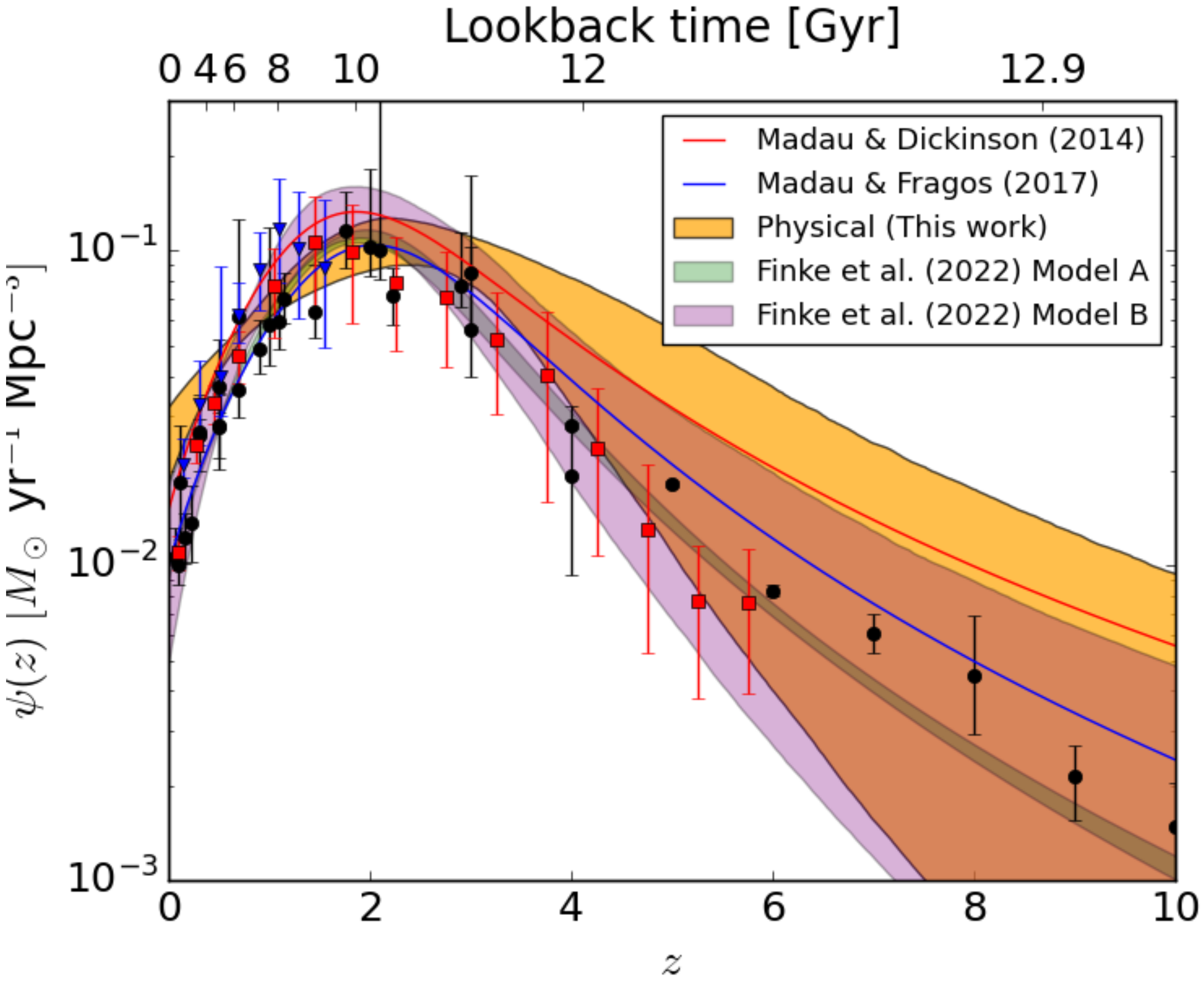


- IGL: integrated SEDs of known galaxies
- Gamma rays: sensitive to the total EBL
- The IGL vs. gamma-ray difference constrains the unresolved diffuse EBL component
- Assuming the diffuse light originates from intrahalo light, we constrain this component to **~23%**

More in the Paper...

- This talk focused on the local EBL, but the paper also covers the redshift evolution of the EBL, star formation rate measurements, and more, so check it out! (2604.09139, 2604.09397)





Summary

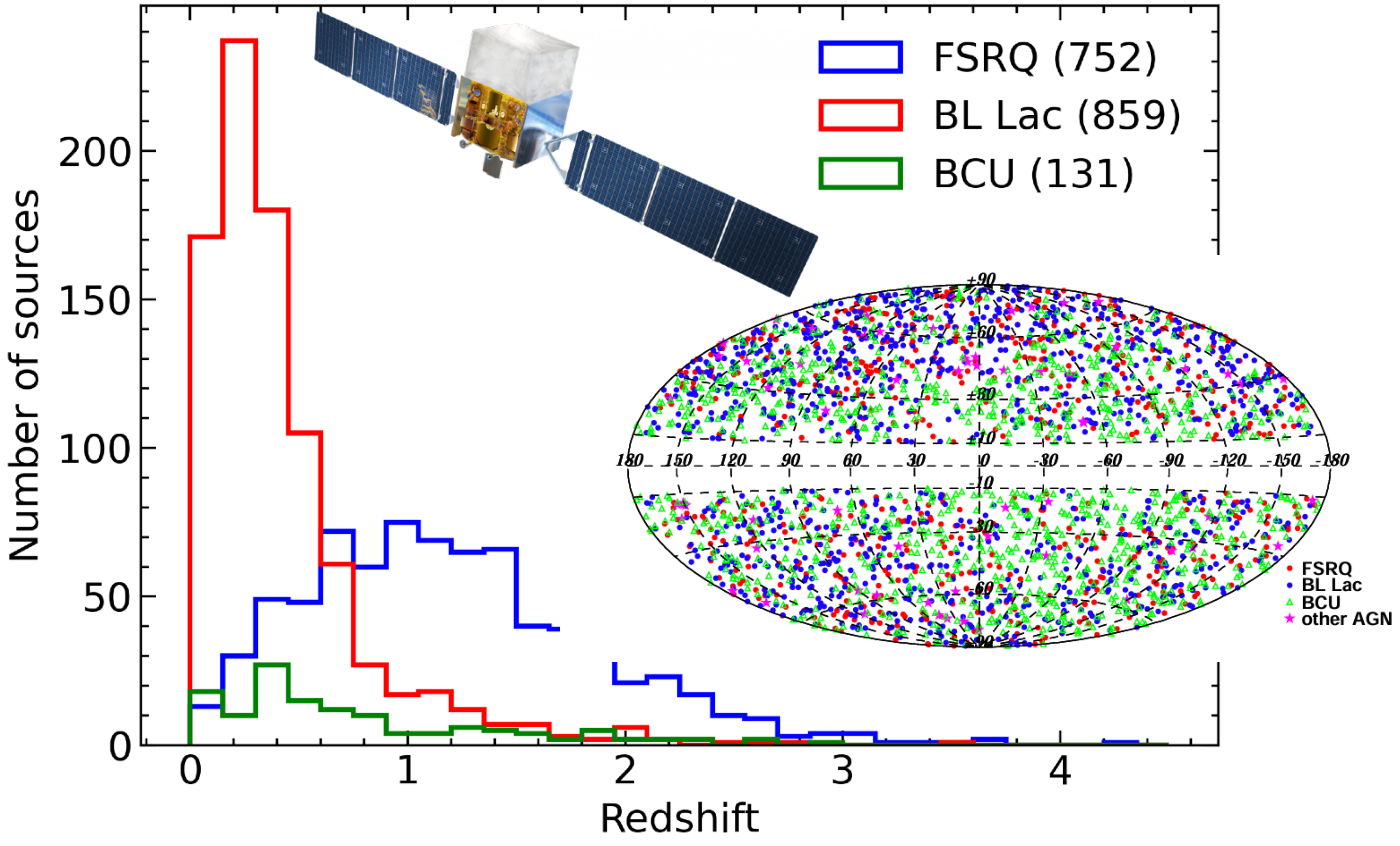
- EBL is the accumulated UV through infrared light radiated by galaxies, stars, and dust across all cosmic epochs
    - Measuring and modeling the EBL is important for tracing star formation history and galaxy evolution
- Three main techniques exist for measuring the EBL, but a long-standing discrepancy has been reported between IGL estimates and direct measurements
- To resolve this discrepancy, we analyzed 15 years of Fermi-LAT observations combined with three decades of Cherenkov telescope data
- Our results favor measurements from missions **with low foreground contamination**, indicating that **earlier measurements like CIBER and IRTS likely suffer from systematic errors that have not yet been accounted for**
    - In other words, there may be no need to invoke exotic physics (unfortunately)

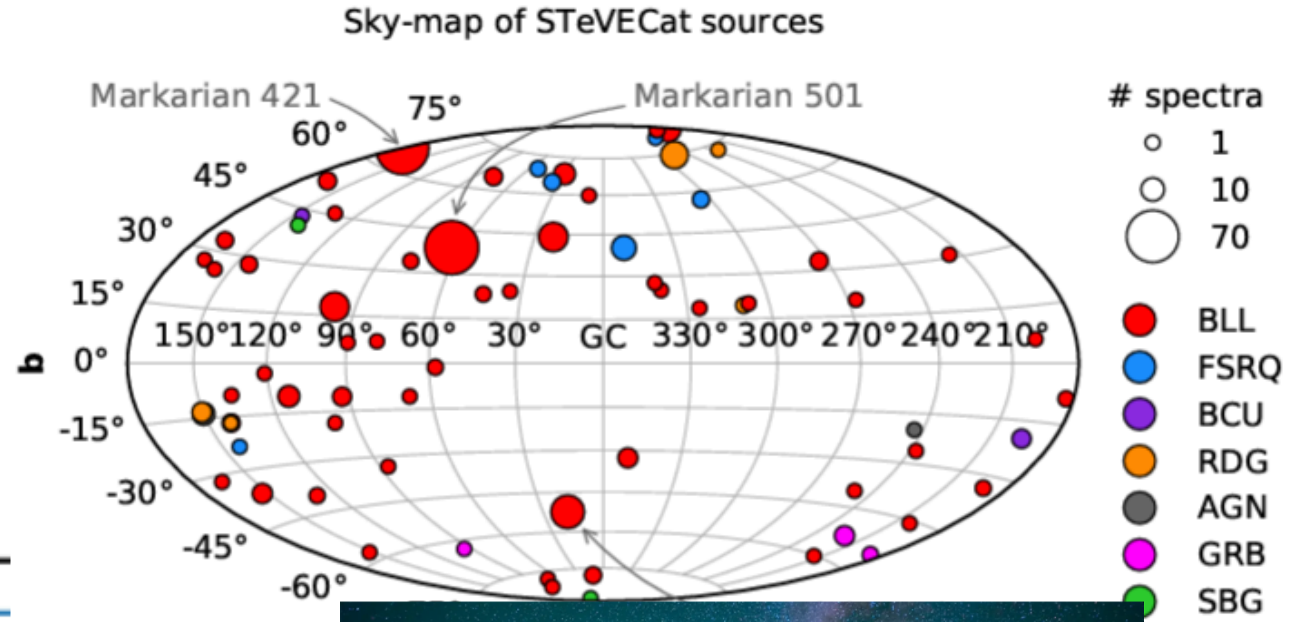
Backup

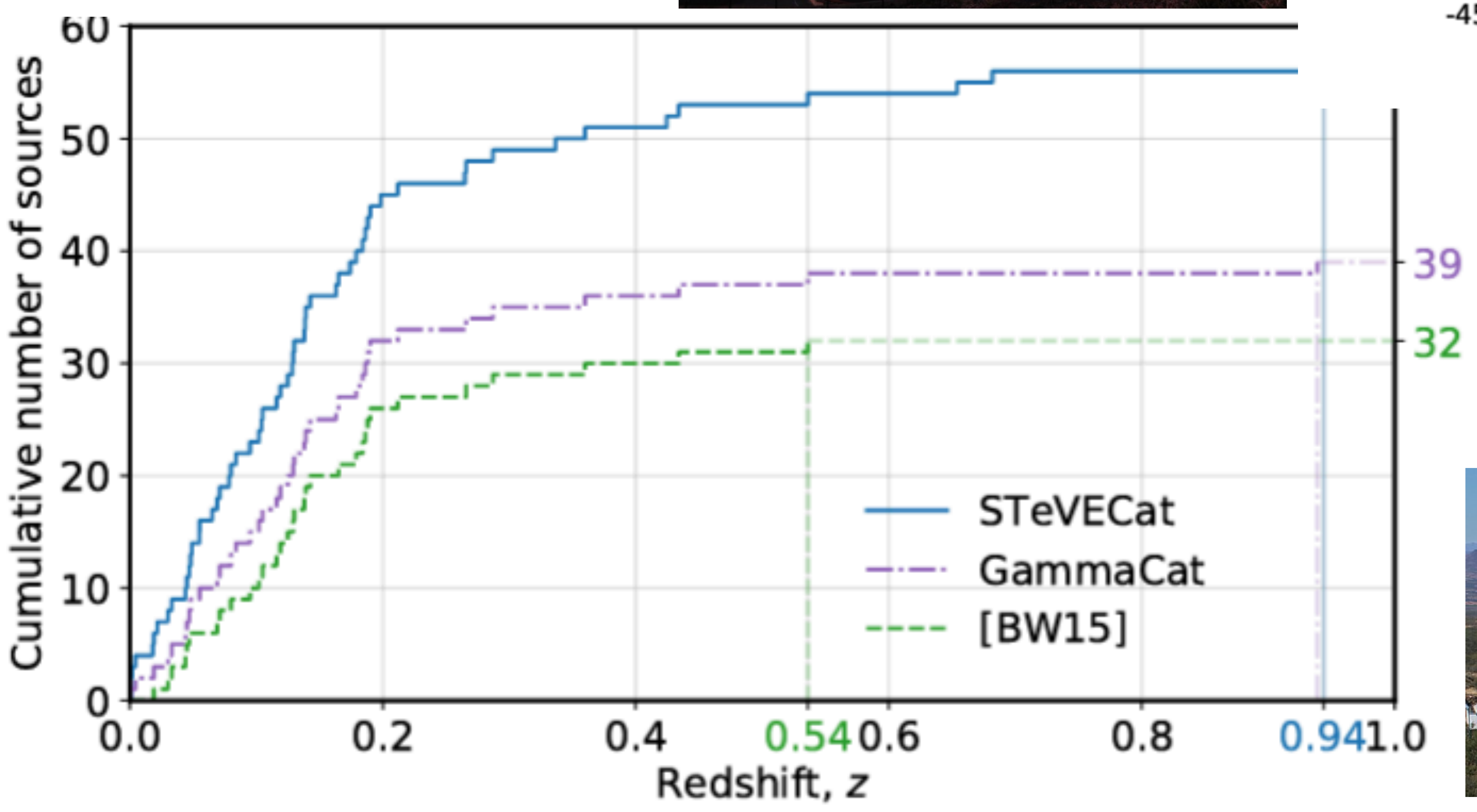
Samples

GeV: 15 yr of Fermi-LAT and 1574 blazars. TeV: 268 VHE spectra from STeVECat.

- New Horizons has traveled beyond 50 au from the Sun, where zodiacal light drops off dramatically, allowing EBL to be measured in a much cleaner environment (New Horizons / LORRI, Postman et al. 2024)
- The results are consistent with IGL at roughly the 2σ level, suggesting that conventional direct measurements may have been affected by significant systematic errors

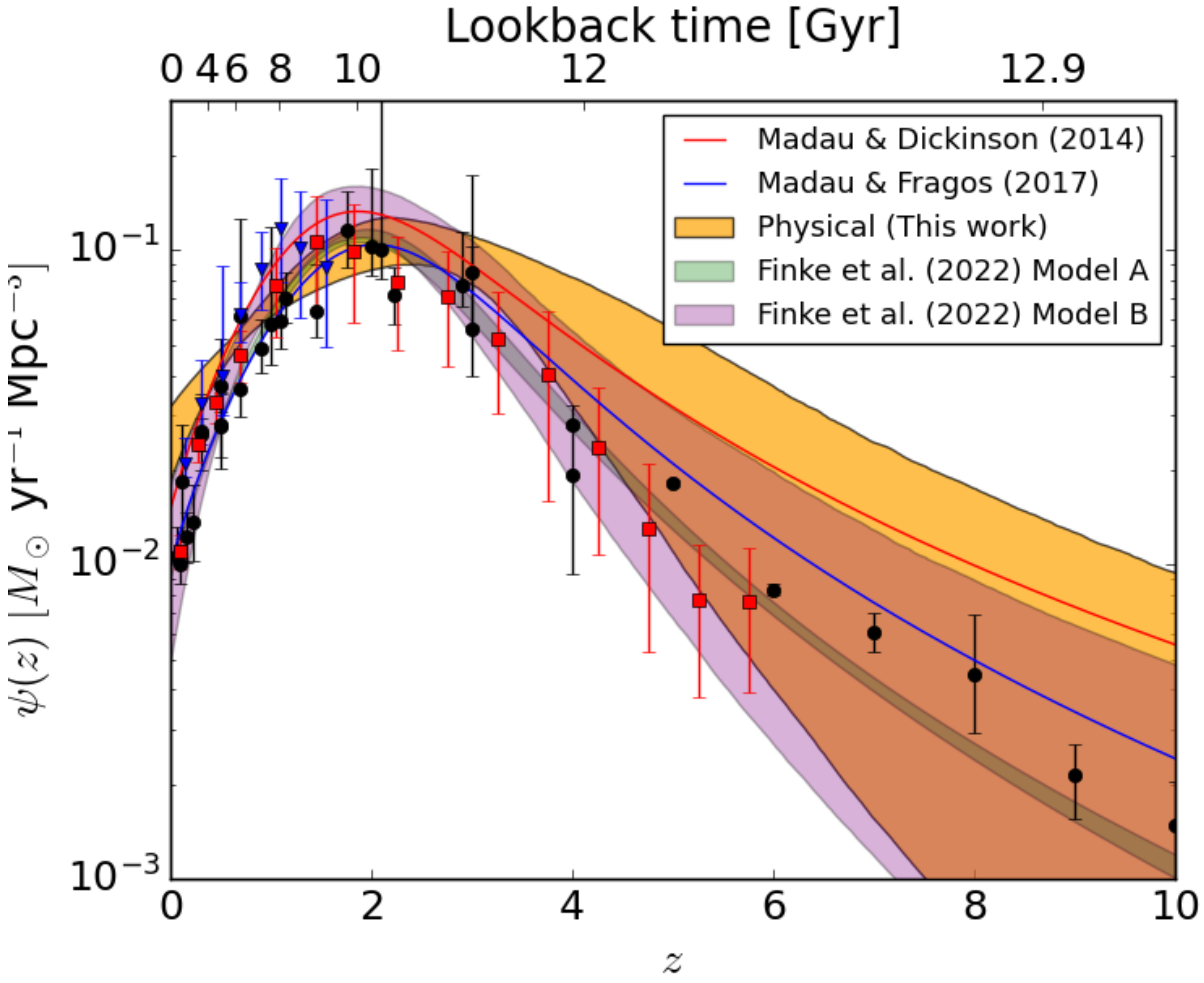






Cosmic star formation history out to z ≈ 5

Physical reconstruction of Paper I traces the SFR density from the γ-ray EBL



- Physical model: PEGASE spectra + Madau-type SFH + dust reprocessing.
- Only 6 free parameters (4 for SFR, 2 for dust fractions).
- SFR density recovered out to z ≈ 5 from γ rays alone.
- Consistent with Madau & Dickinson 2014 and direct UV surveys.
- Uncertainties grow at z ≳ 5 — needs high-z blazars / GRBs.