Cosmological Aspects of High Energy Astrophysics ~ Day 3 ~

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大阪大学 OSAKA UNIVERSITY
OU TAP Osaka University Theoretical Astrophysics
RIKEN iTHEMS
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Lecture Schedule

Be careful! It may change!

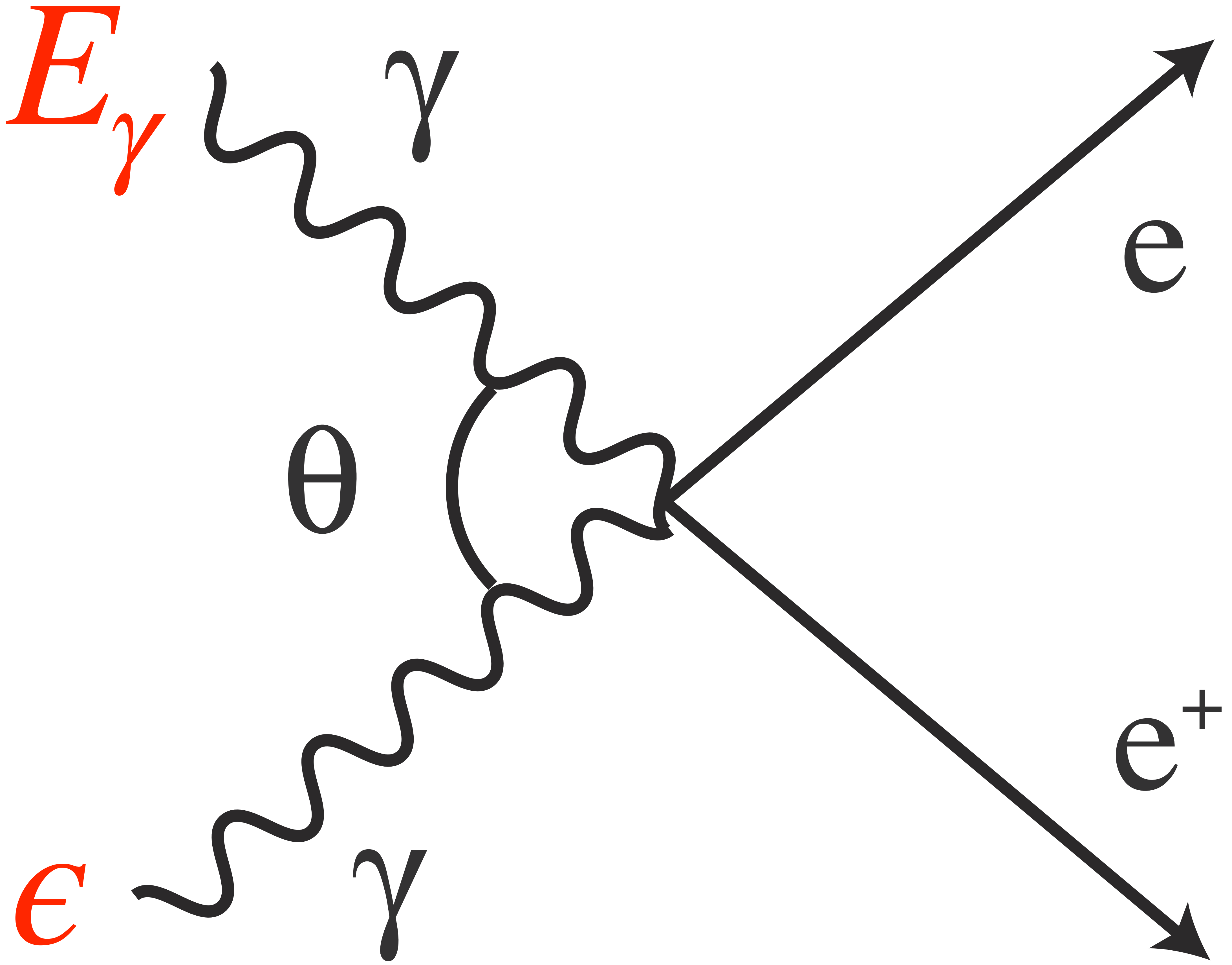
- ~~Day 1:~~
  - ~~Cosmological Evolution of Gamma-ray Emitting Objects~~
  - ~~Cosmic GeV Gamma-ray Background Radiation Spectrum~~
- ~~Day 2:~~
  - ~~Cosmic MeV Gamma-ray Background Radiation Spectrum~~
  - ~~Cosmic Gamma-ray Background Radiation Anisotropy~~
- **Day 3:**
  - **Gamma-ray Propagation in the Universe**
  - **Probing Extragalactic Background Light with Gamma-ray Observations**
- Day 4:
  - Intergalactic Magnetic Field and Gamma-ray Observations
  - Cosmic Expansion and Gamma-ray Horizon (if possible)

Gamma-ray Propagation in the Universe

Gamma-ray attenuation

Pair creation process: $\gamma + \gamma \to e^+ + e^-$

$\tau_{\gamma\gamma} \sim n_{ph} \cdot \sigma_{\gamma\gamma} \cdot l$



Dwek & Krennrich '13

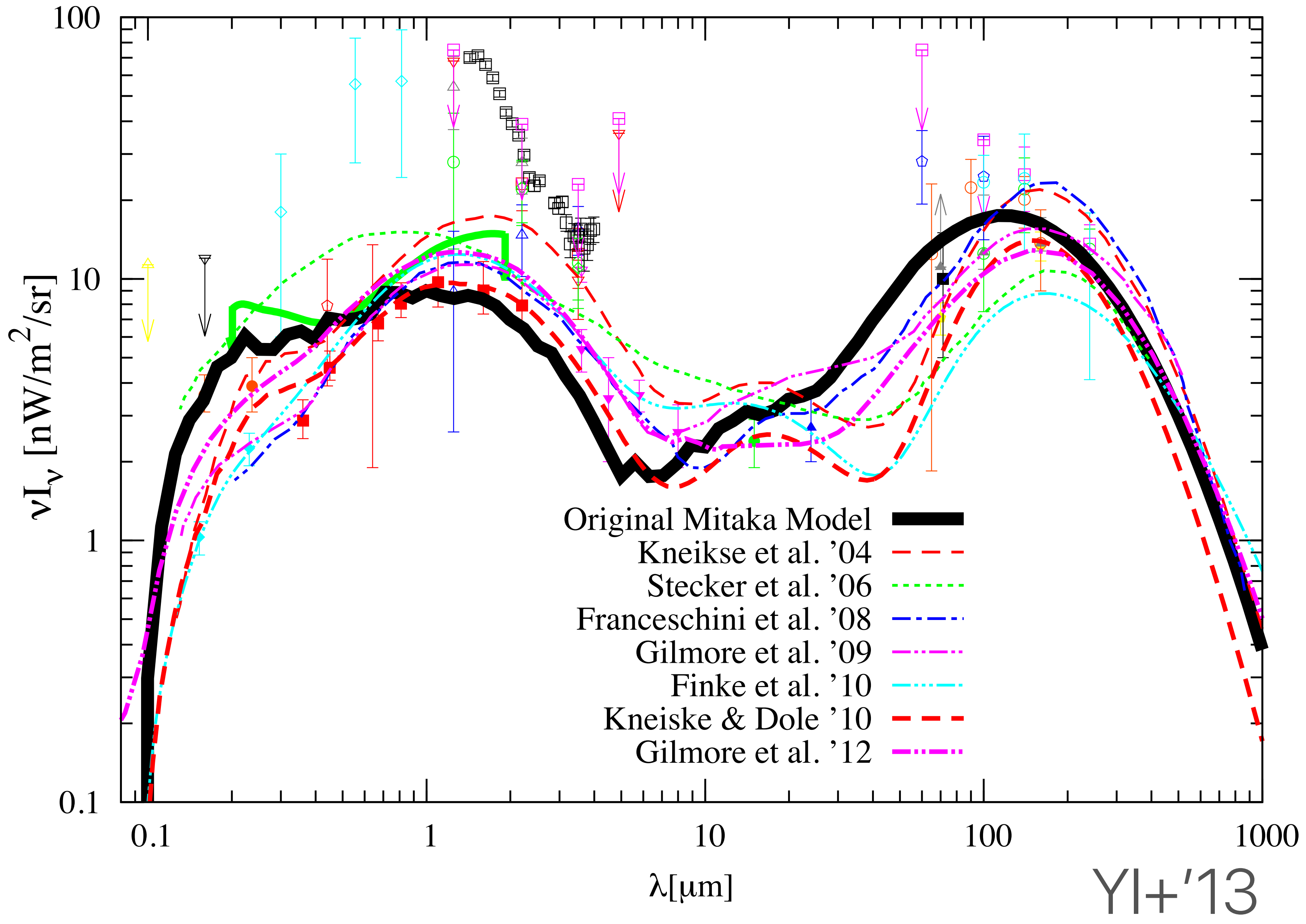
- Threshold: $E_\gamma \epsilon_{th}(1 - \cos\theta) > 2(m_e c^2)^2$
- Cross section:
$$\sigma_{\gamma\gamma} = \frac{3\sigma_T}{16}(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right],$$
where $\beta = \sqrt{1 - \epsilon_{th}/\epsilon}$
- Peak : $\sigma_{\gamma\gamma} \approx 0.2\sigma_T \sim 10^{-25}\ \mathrm{cm}^2$
@ $\epsilon \approx 1.0(E_\gamma/1\ \mathrm{TeV})^{-1}\ \mathrm{eV}$

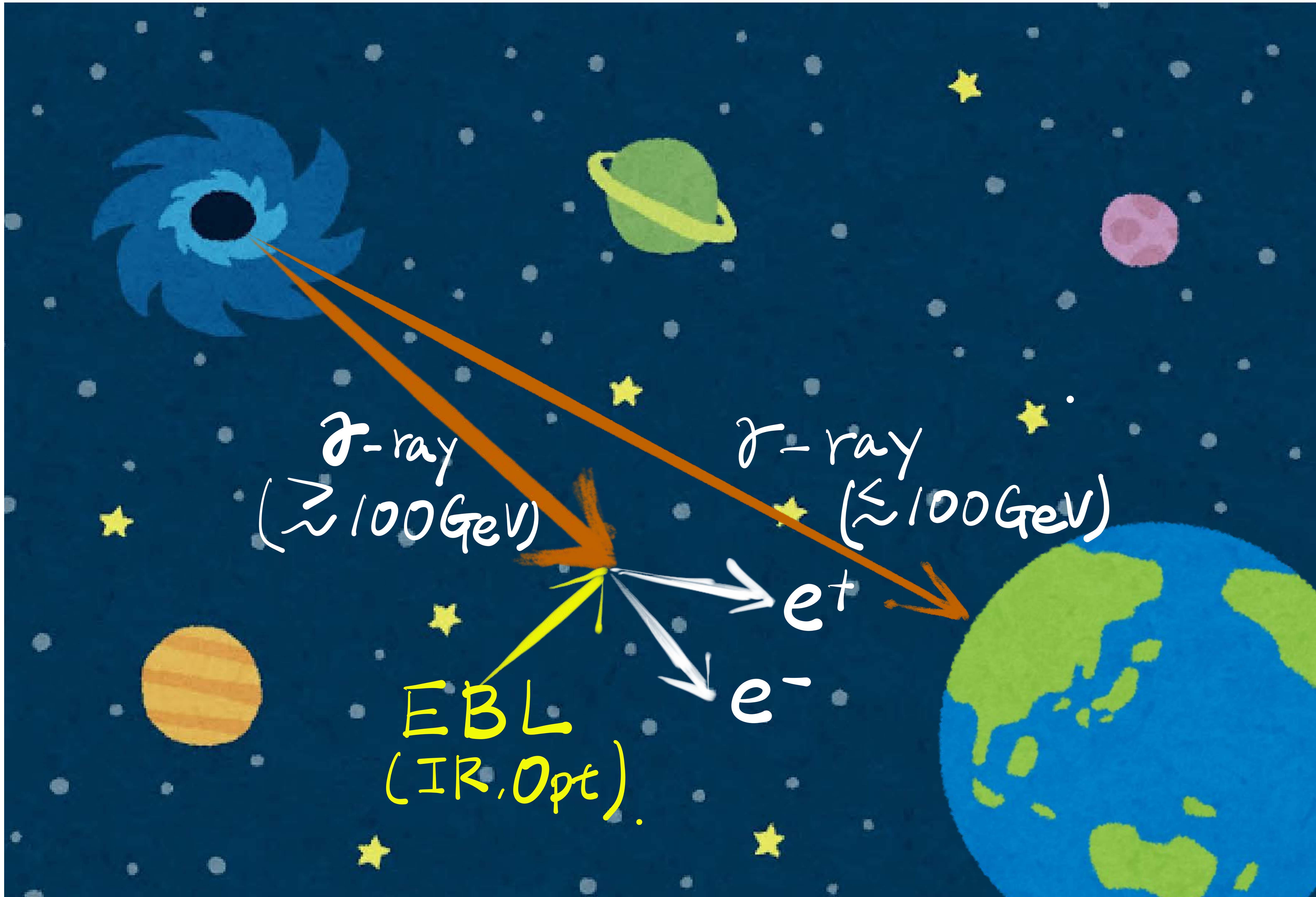
See talk by Ellis Owen

Gamma-ray attenuation during the propagation

$\gamma_{\gtrsim 100\ \mathrm{GeV}} + \gamma_{\mathrm{EBL}} \rightarrow e^{+} + e^{-}$

- Extragalactic Background (EBL)
  - Integration history of cosmic star formation activity.

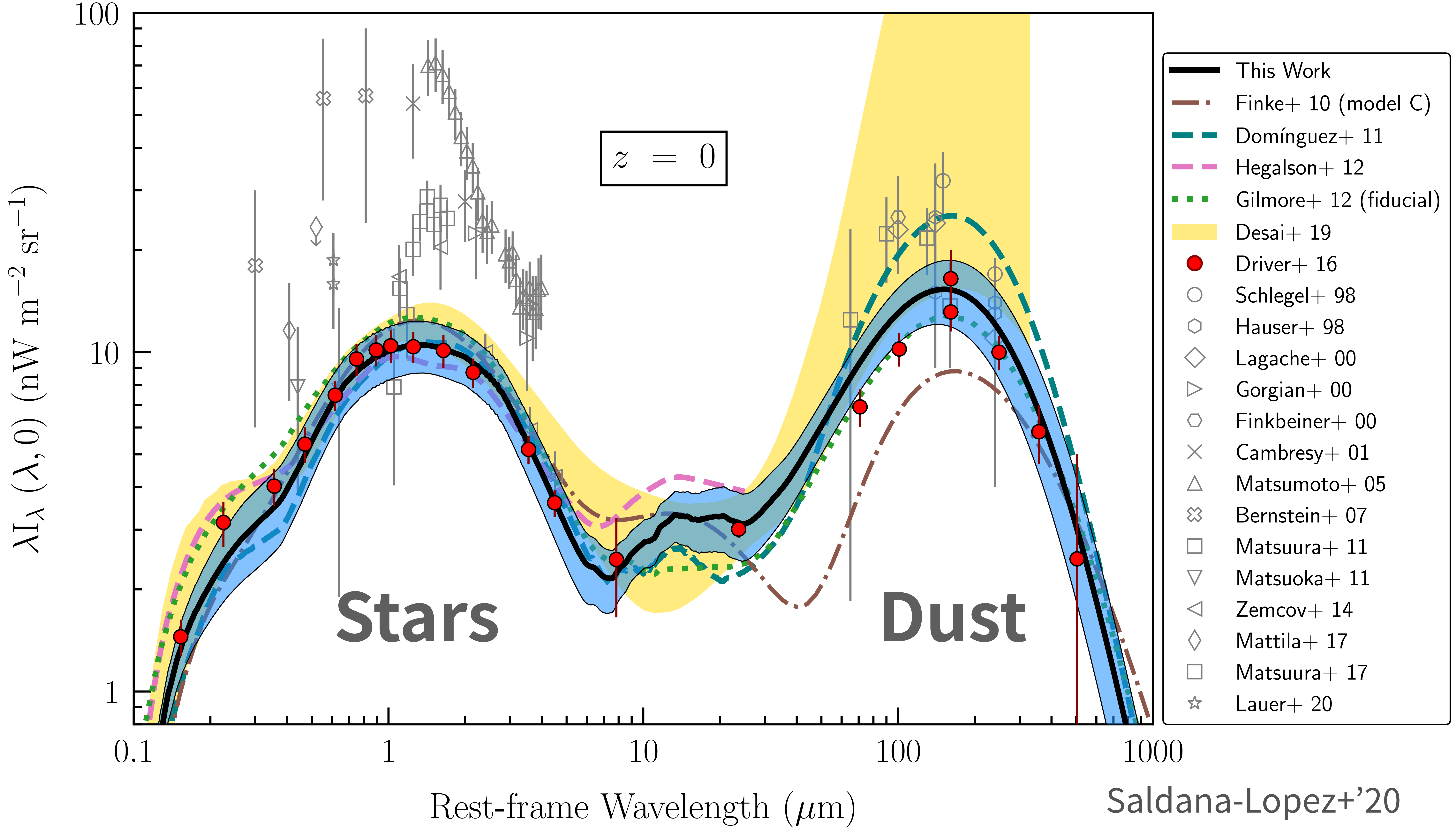




Extragalactic Background Light

Extragalactic Background Light (EBL)

Integrated Emission from Galaxies in the entire cosmic history

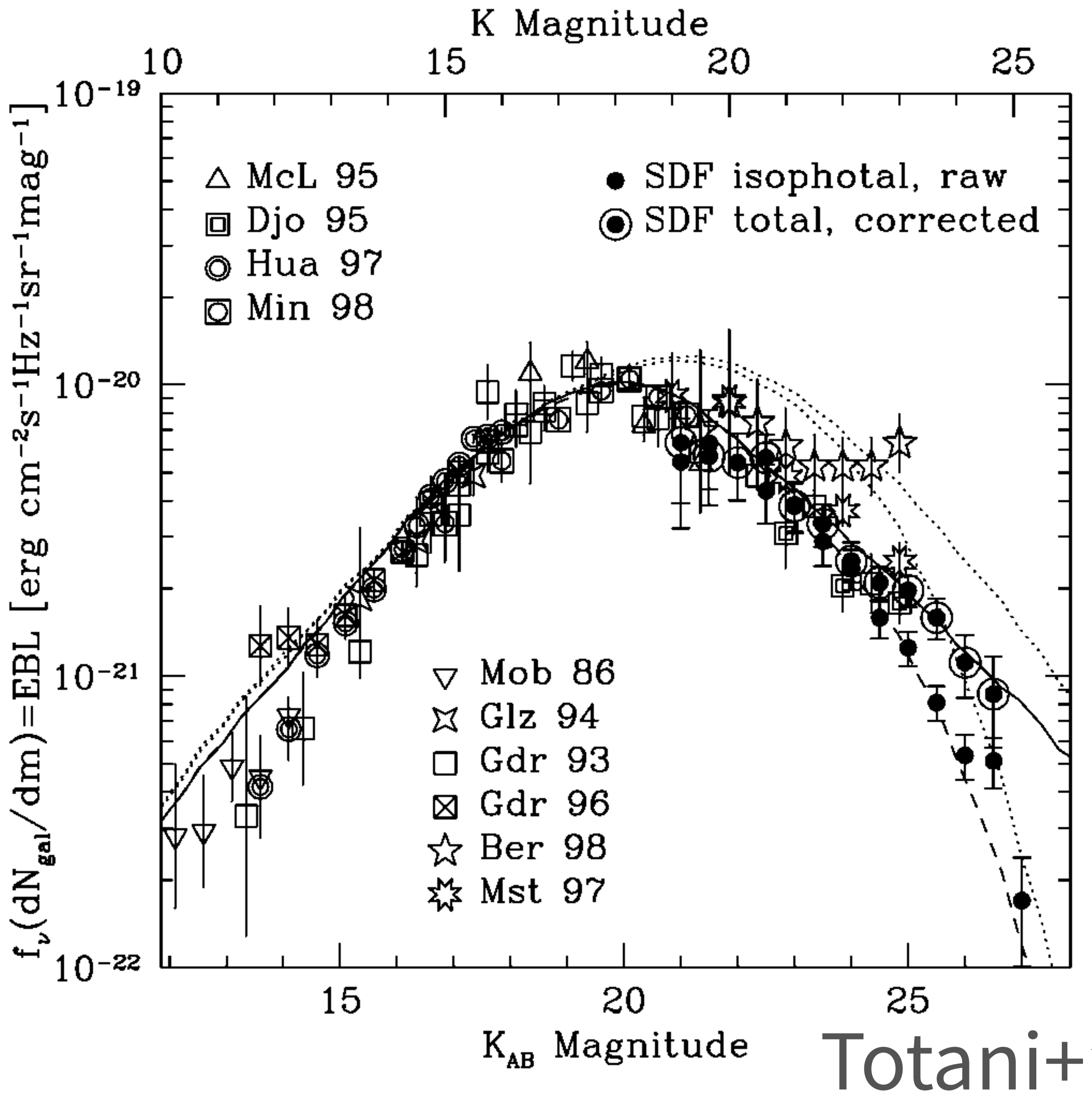


Saldana-Lopez+'20

Counting Galaxies

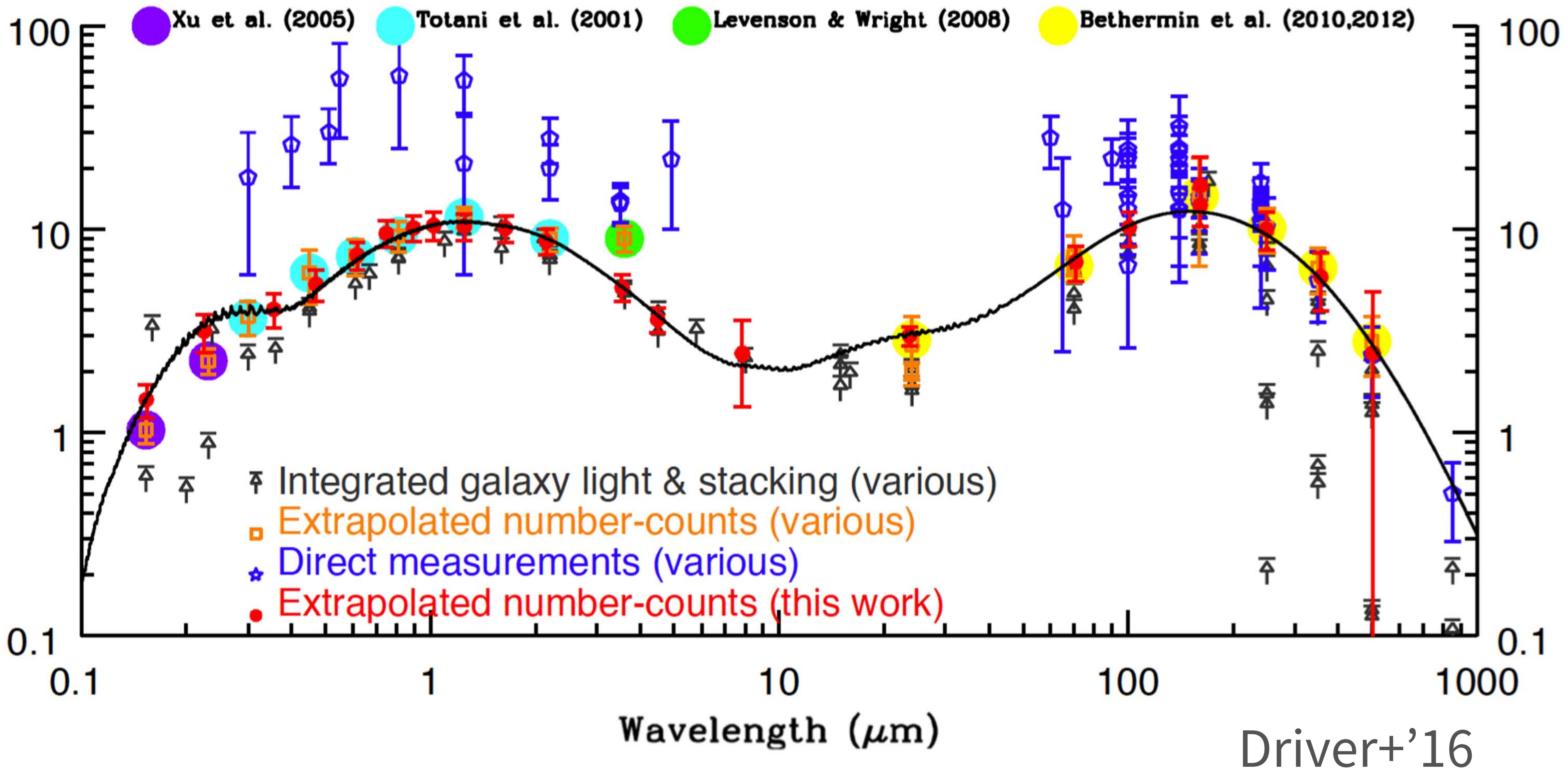
Lower bounds on the EBL

Credit:NASA, ESA, H. Teplitz and M. Rafelski (IPAC/ Caltech), A. Koekemoer (STScI), R. Windhorst (Arizona State University), and Z. Levay (STScI)



Totani+'01

- Current telescopes already resolve faint galaxies.
- Galaxy contribution is observationally well understood.



Driver+'16

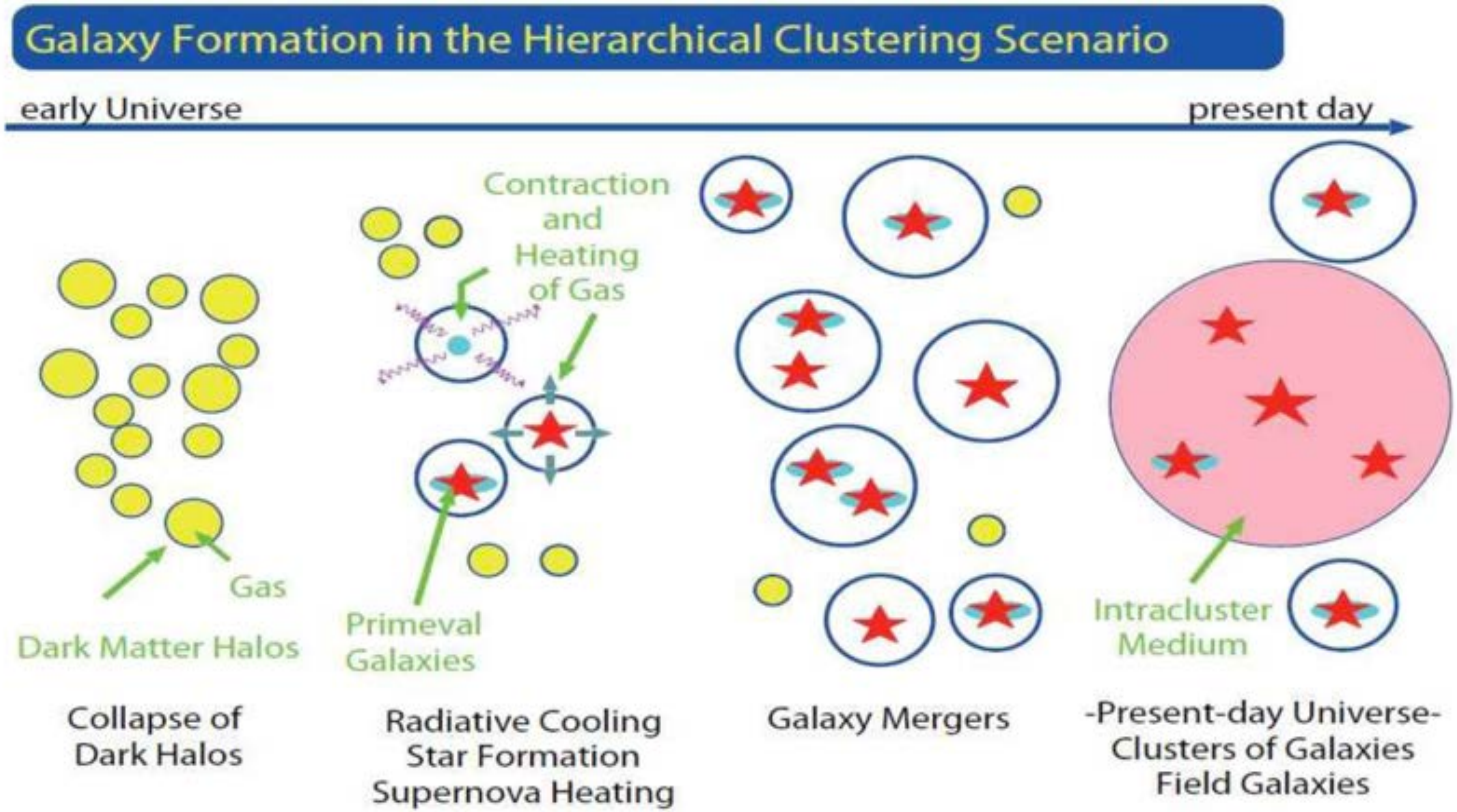
Modeling the extragalactic background light

theoretically? empirically? observationally?

Model	Evolution	Emission	Pros 😀	Cons 😫	Refernces
Theoretical	Semi-analytical	Stellar Population Synthesis	Applicable to any redshifts	Parameter uncertainty	Somerville+'12; Gilmore+'12; YI+'13
Empirical	Cosmic Star Formation History	Stellar Population Synthesis	Follow the global trend	Comparison to galaxy data	Kneiske+'04; Finke+'10
Observational	Galaxy Luminosity Function	Photometry of galaxies	Robust in the observed universe	Extrapolation to no data regions	Stecker+'92; Franceschini+'08; Dominguez+'11; Saldana-Lopez+'20

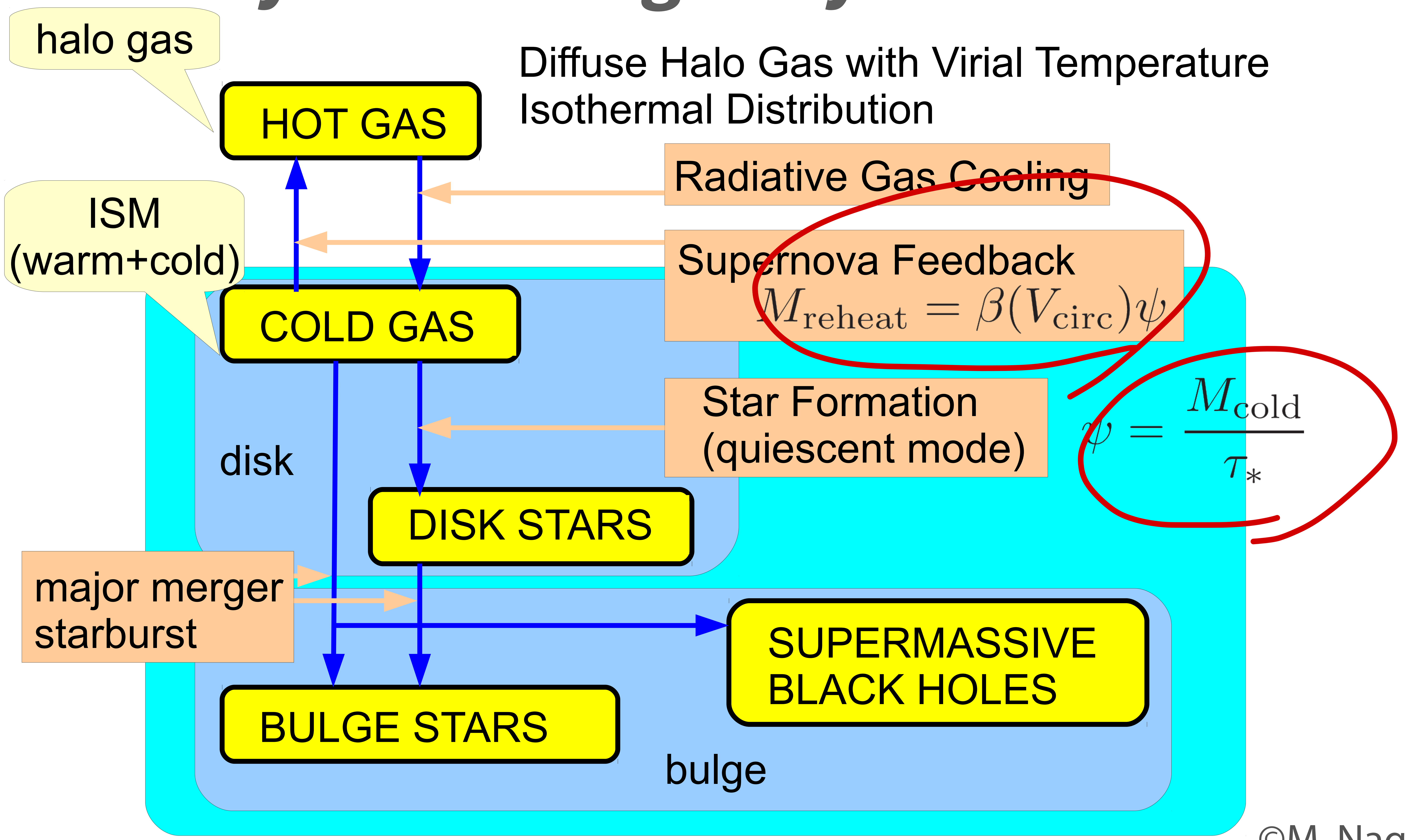
Hierarchical Galaxy Formation

Semi-analytical EBL Models



M. Nagashima

Cycle of Baryons in the galaxy formation



Galaxy Formation

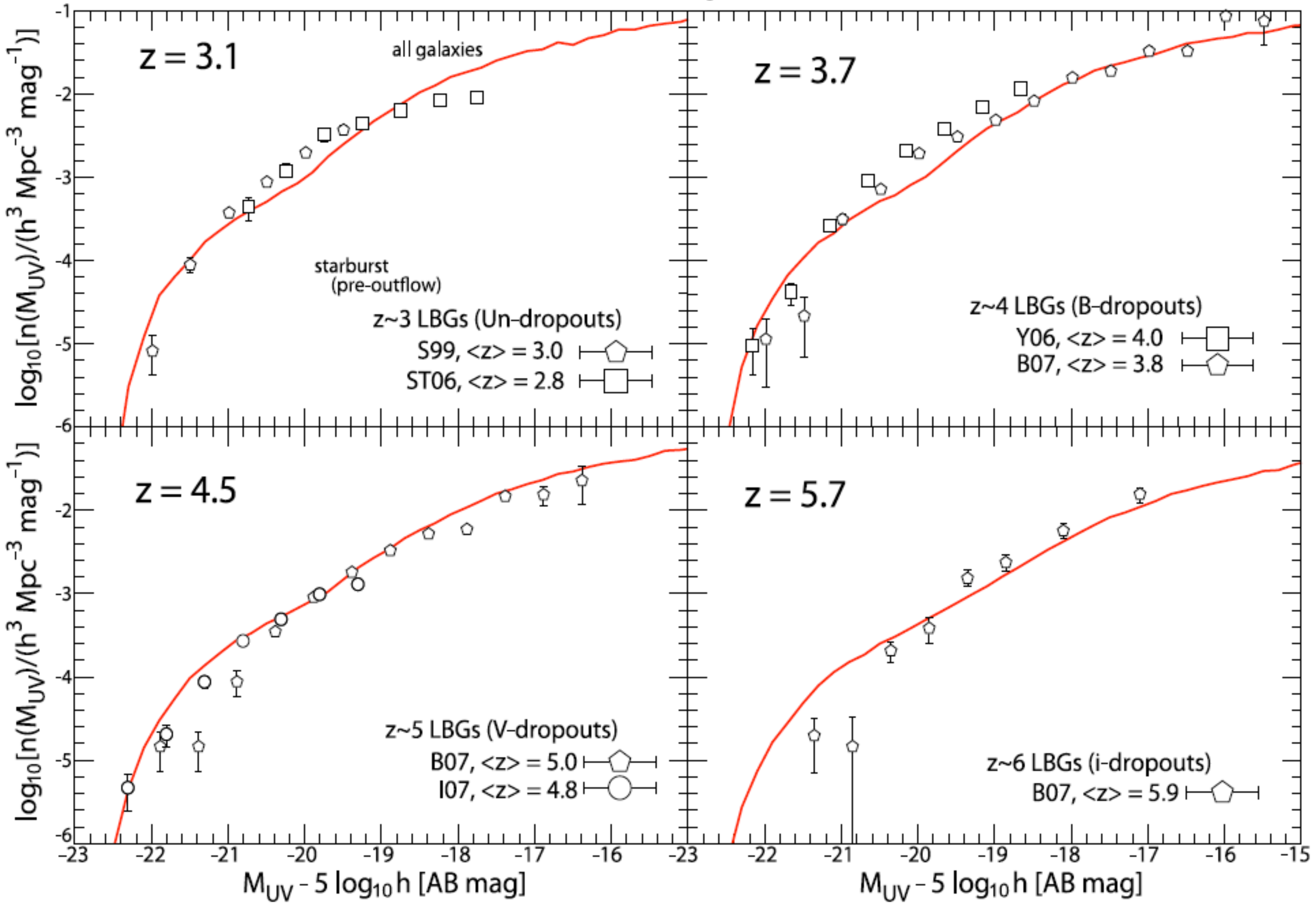
Integration of Non-linear physics

- Formation of Dark matter halo
- Contraction & heating of gas
- Star formation
- Supernova/AGN feedback
- Mergers
- ,,,,

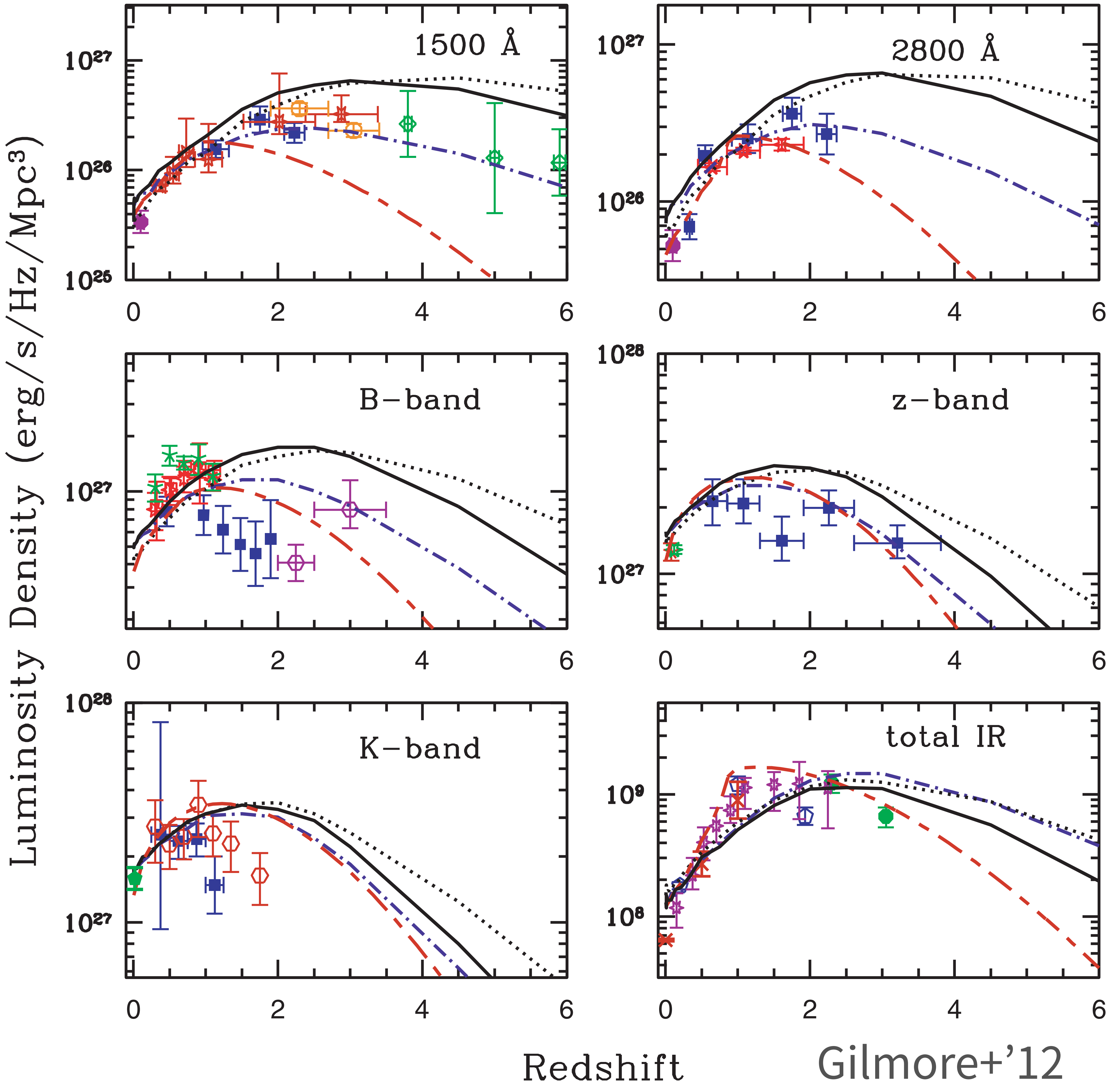
Can the model reproduce the galaxy evolution?

Galaxy Luminosity Functions & Luminosity Densities

UV Luminosity Function



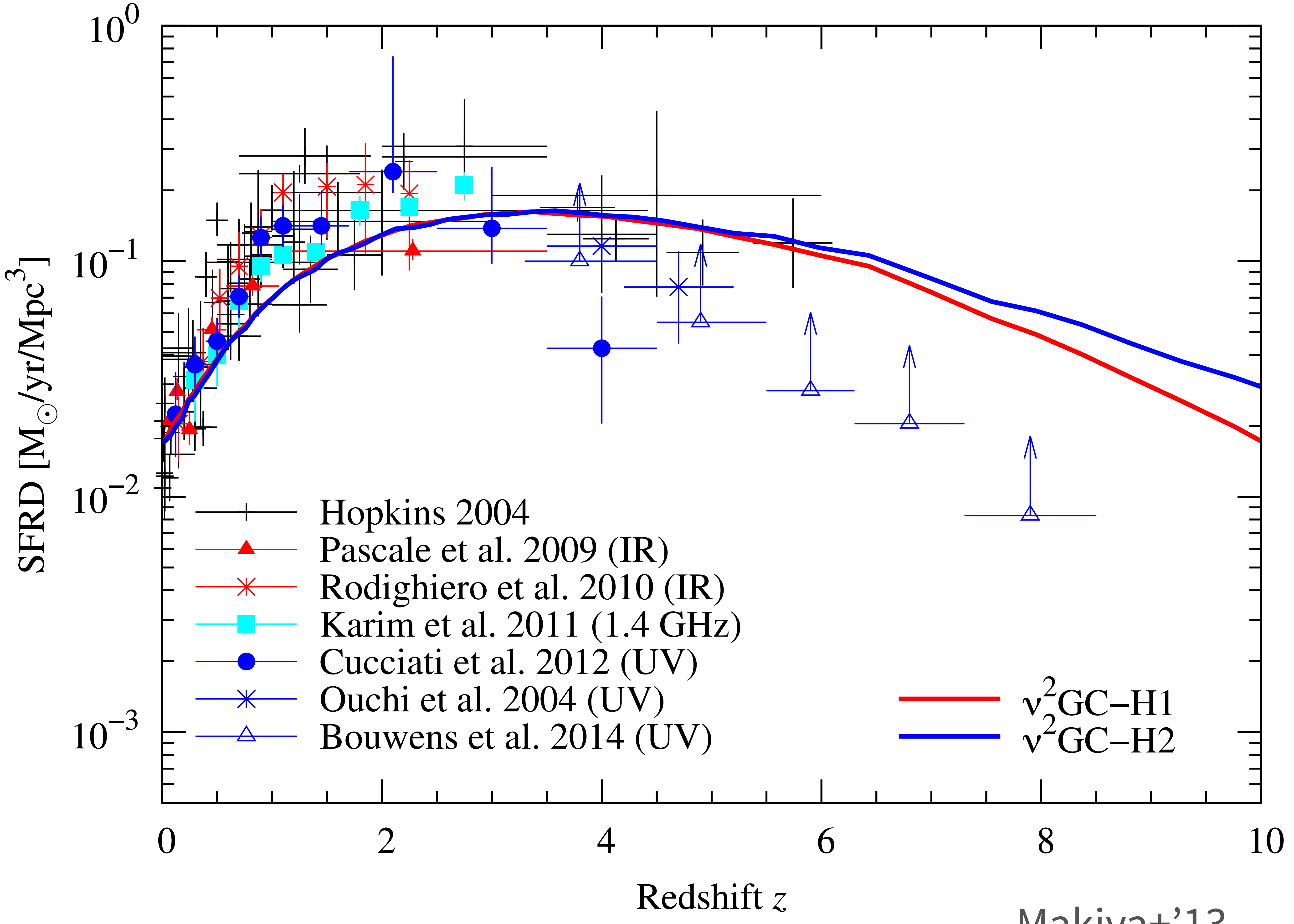
Kobayashi+'10



Gilmore+'12

Can the model reproduce the galaxy evolution?

Cosmic Star Formation History

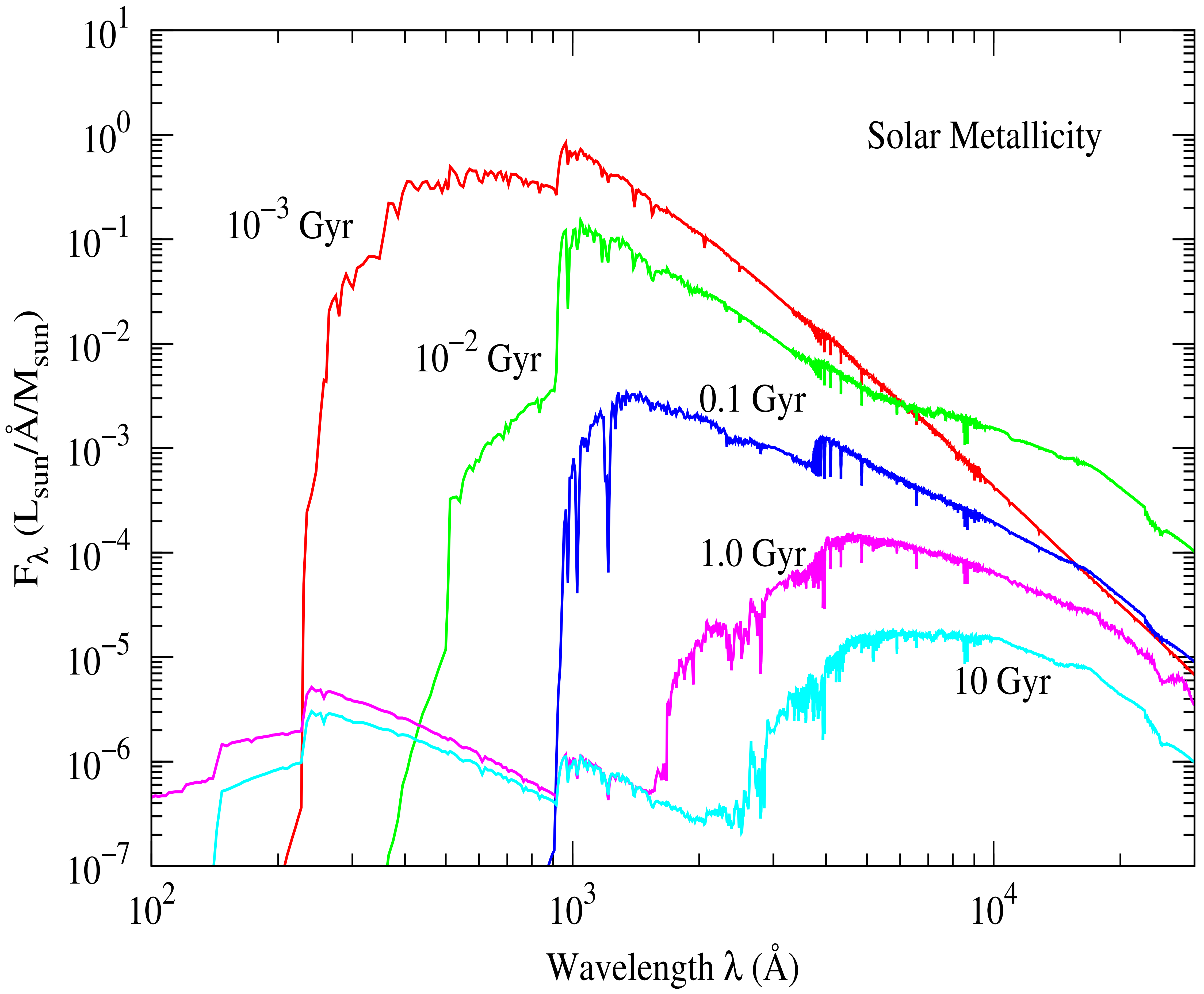


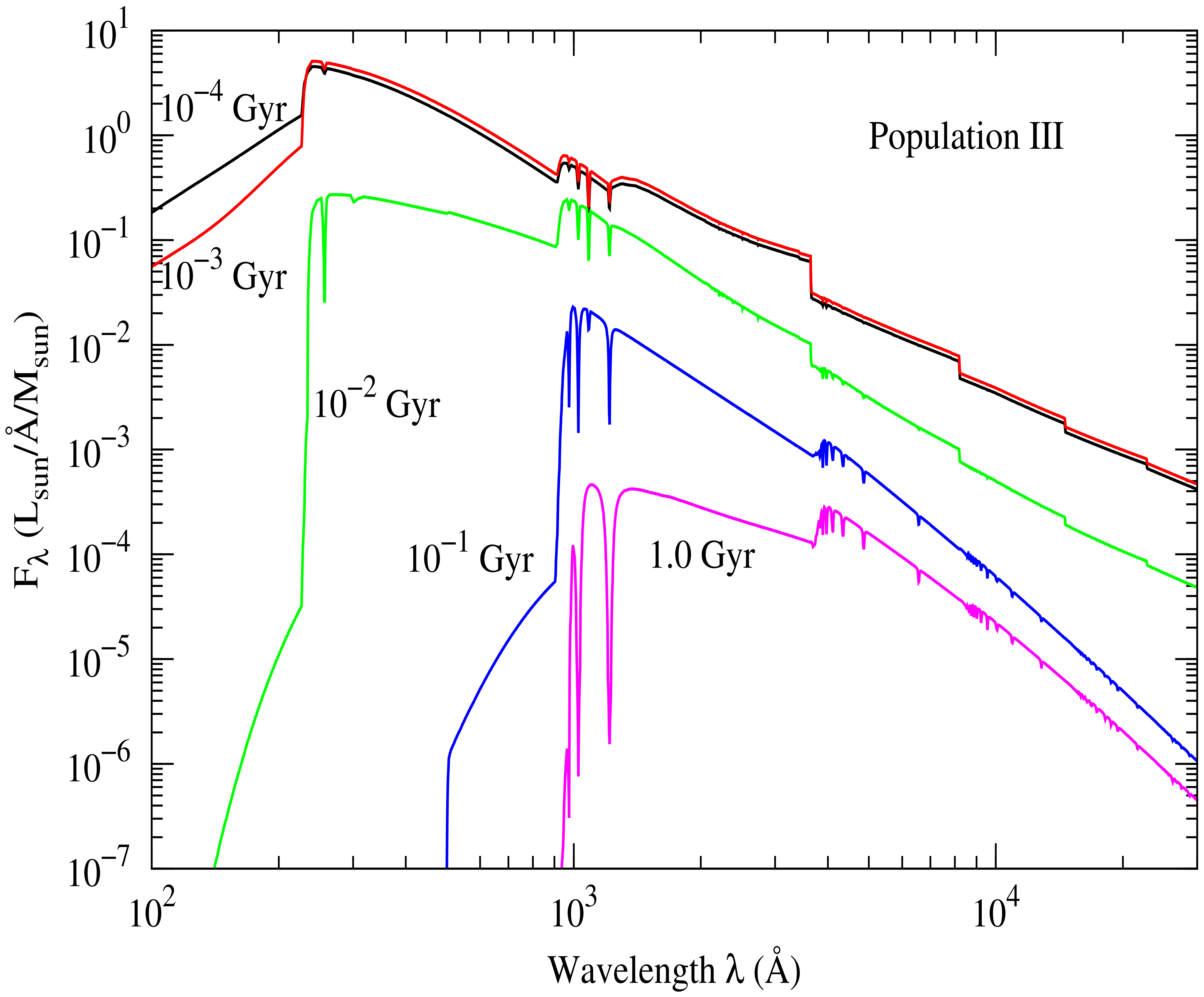
Makiya+'13

- Semi-analytical galaxy formation model can reproduce various observables.
  - Because parameters are determined to reproduce various observables.

Spectral energy distribution of Galaxies

Stellar population synthesis model (Bruzual & Charlot +’03; Schaerer’03,,,)

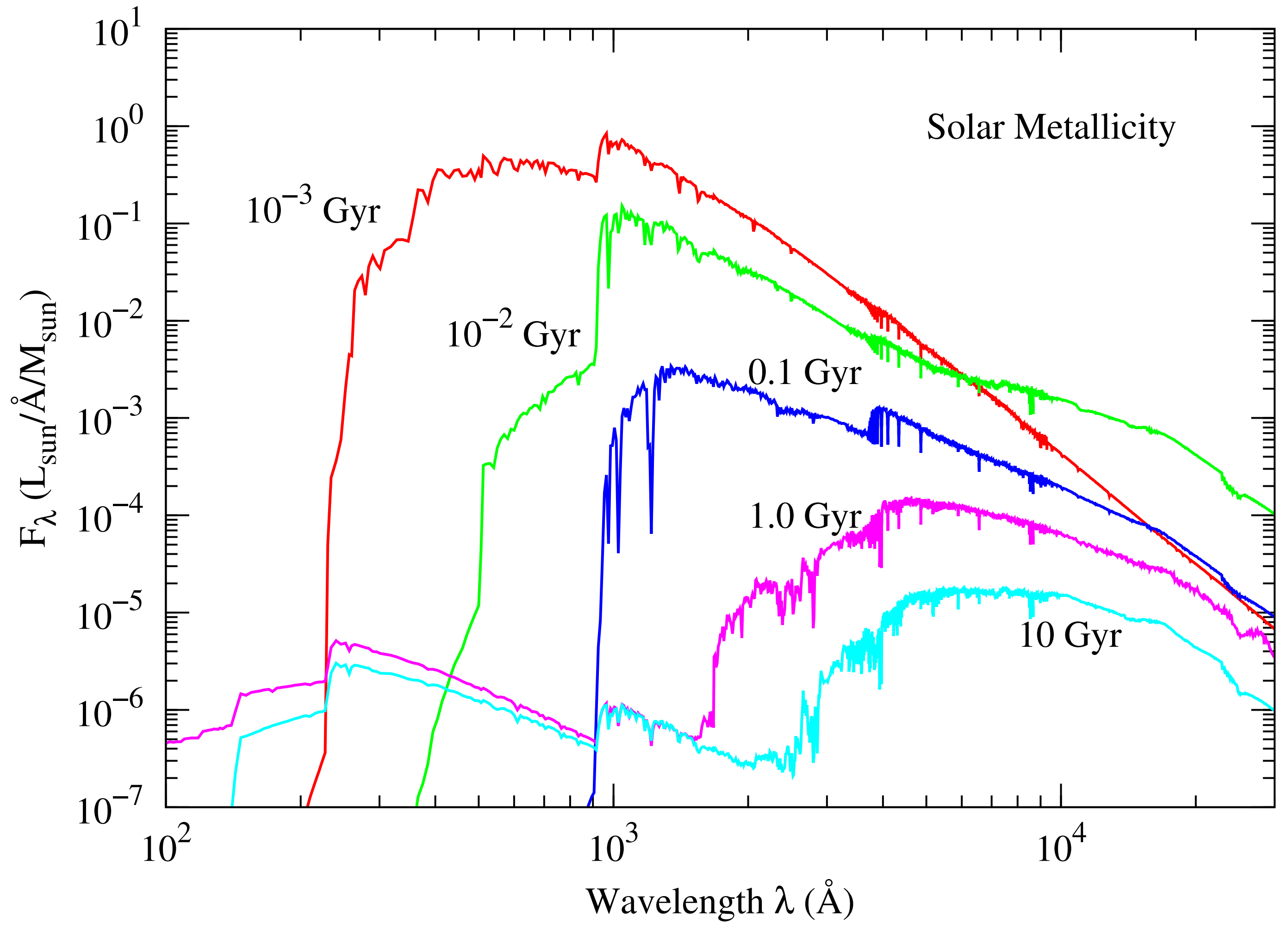




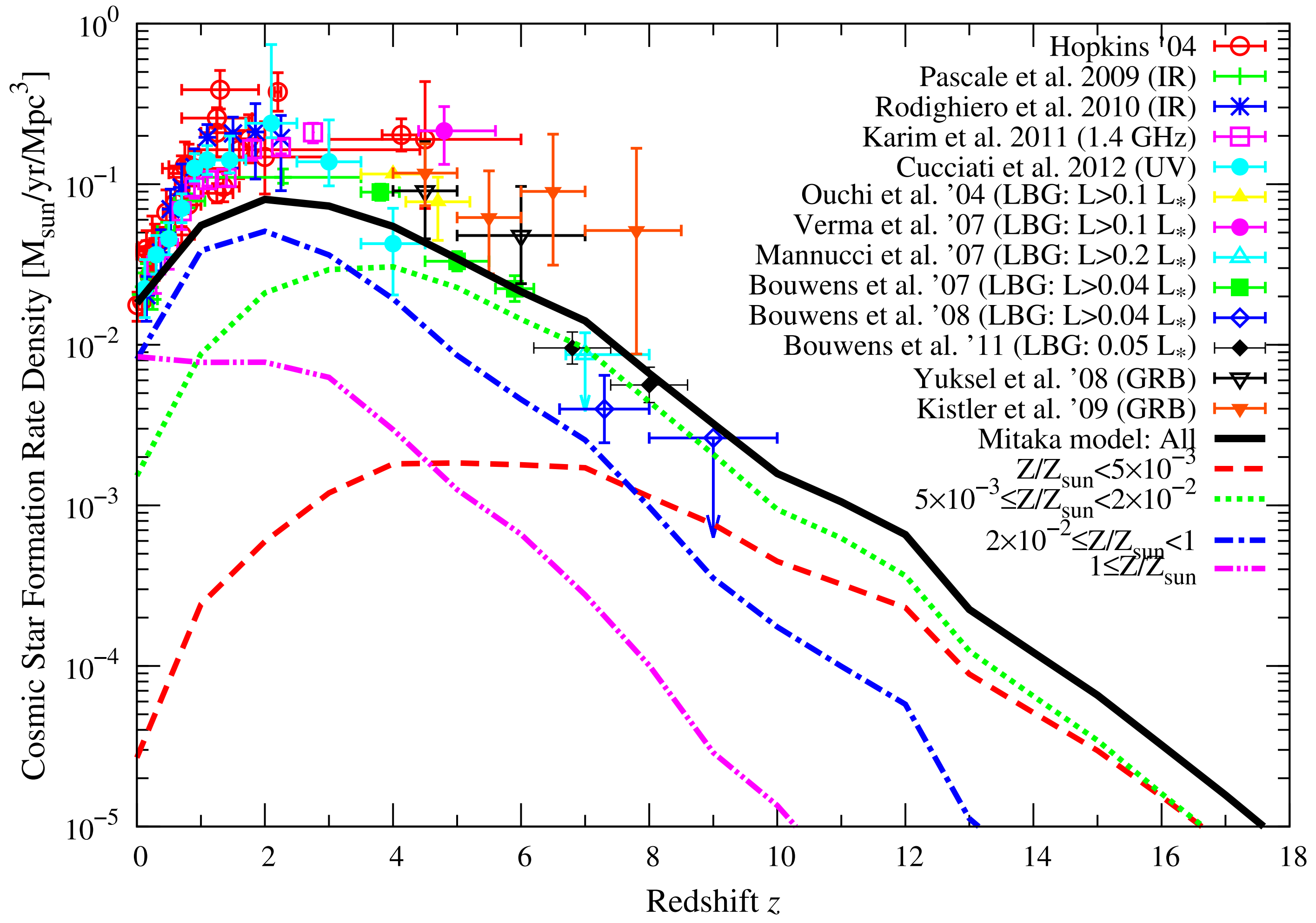
Extragalactic Background Light Spectrum

From Semi-analytical model

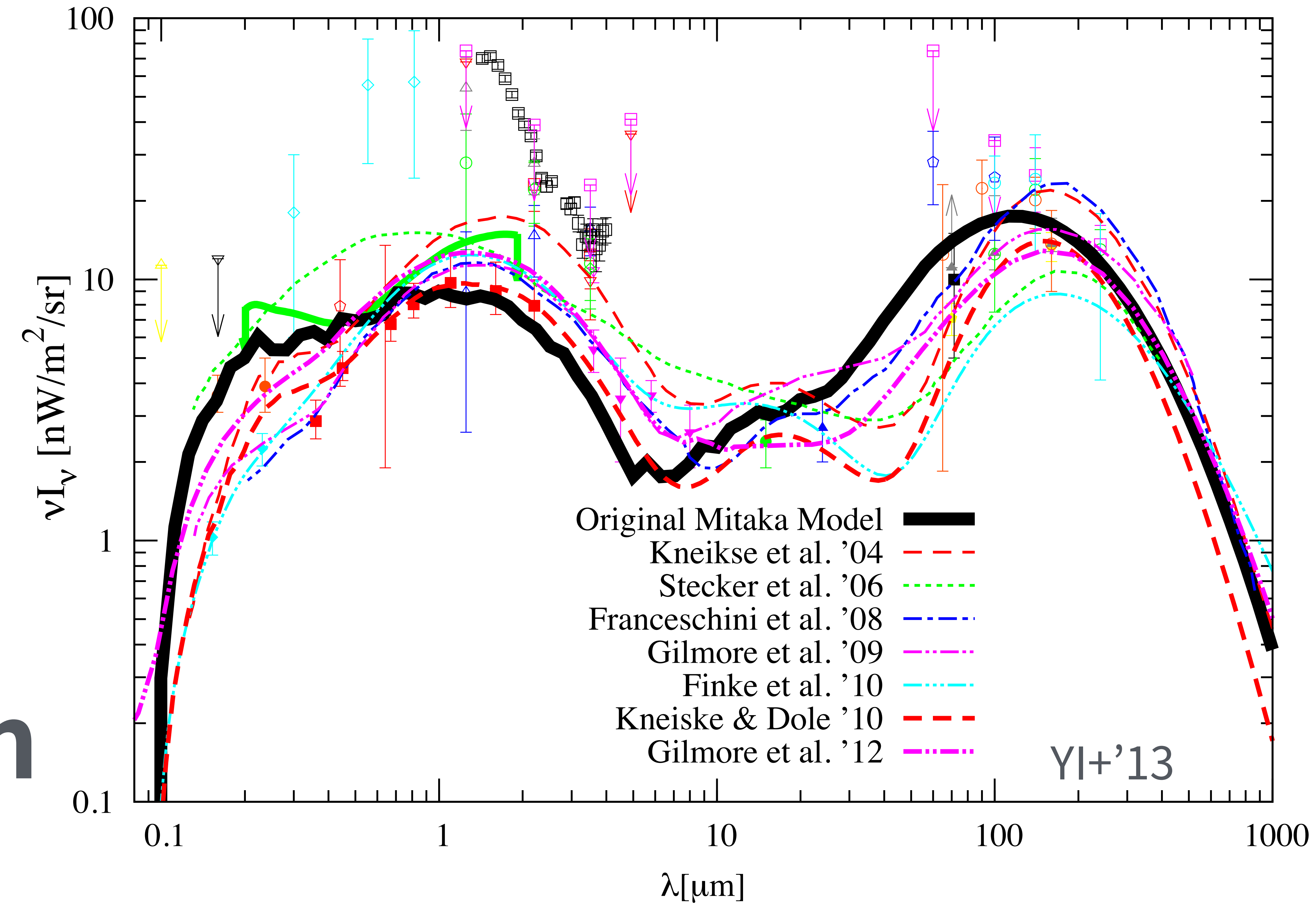
- Semi-analytical model can reproduce the EBL data.
  - Consistent with galaxy counts.



SED



Evolution



Blazar

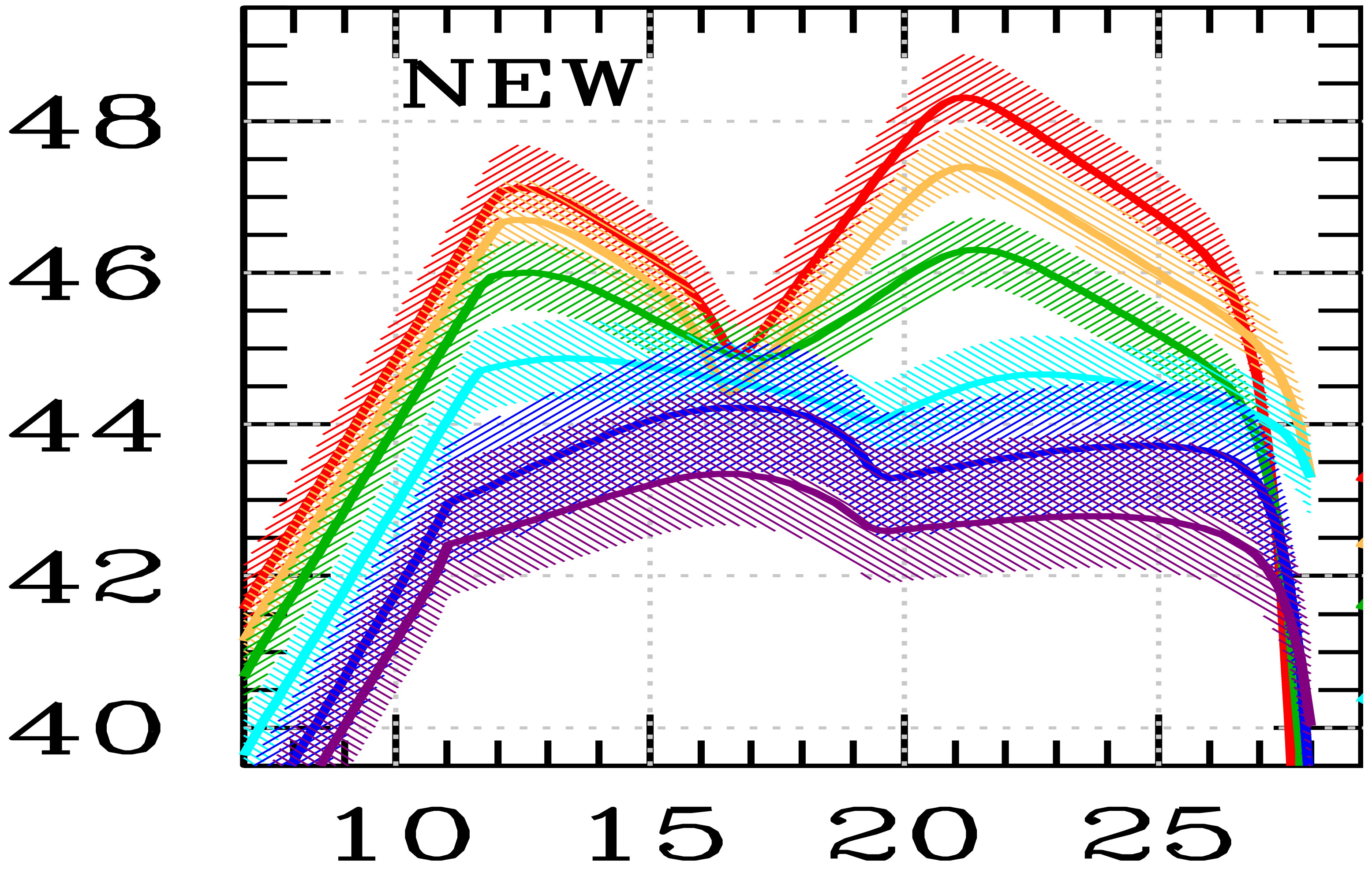
~50% of known gamma-ray objects

Day 1

- Blazars have been discussed as the origin for a long time.

Padovani+'93; Stecker+'93; Salamon & Stecker '94; Chiang + '95; Stecker & Salamon '96; Chiang & Mukherjee '98; Mukherjee & Chiang '99; Muecke & Pohl '00; Narumoto & Totani '06; Giommi +'06; Dermer '07; Pavlidou & Venters '08; Kneiske & Mannheim '08; Bhattacharya +'09; YI & Totani '09; Abdo+'10; Stecker & Venters '10; Cavadini+'11, Abazajian+'11, Zeng+'12, Ajello+'12, Broderick+'12, Singal+'12, Harding & Abazajian '12, Di Mauro+'14, Ajello+'14, Singal+'14, Ajello, YI, +'15,,,,

- Now, it turns out ~50%.



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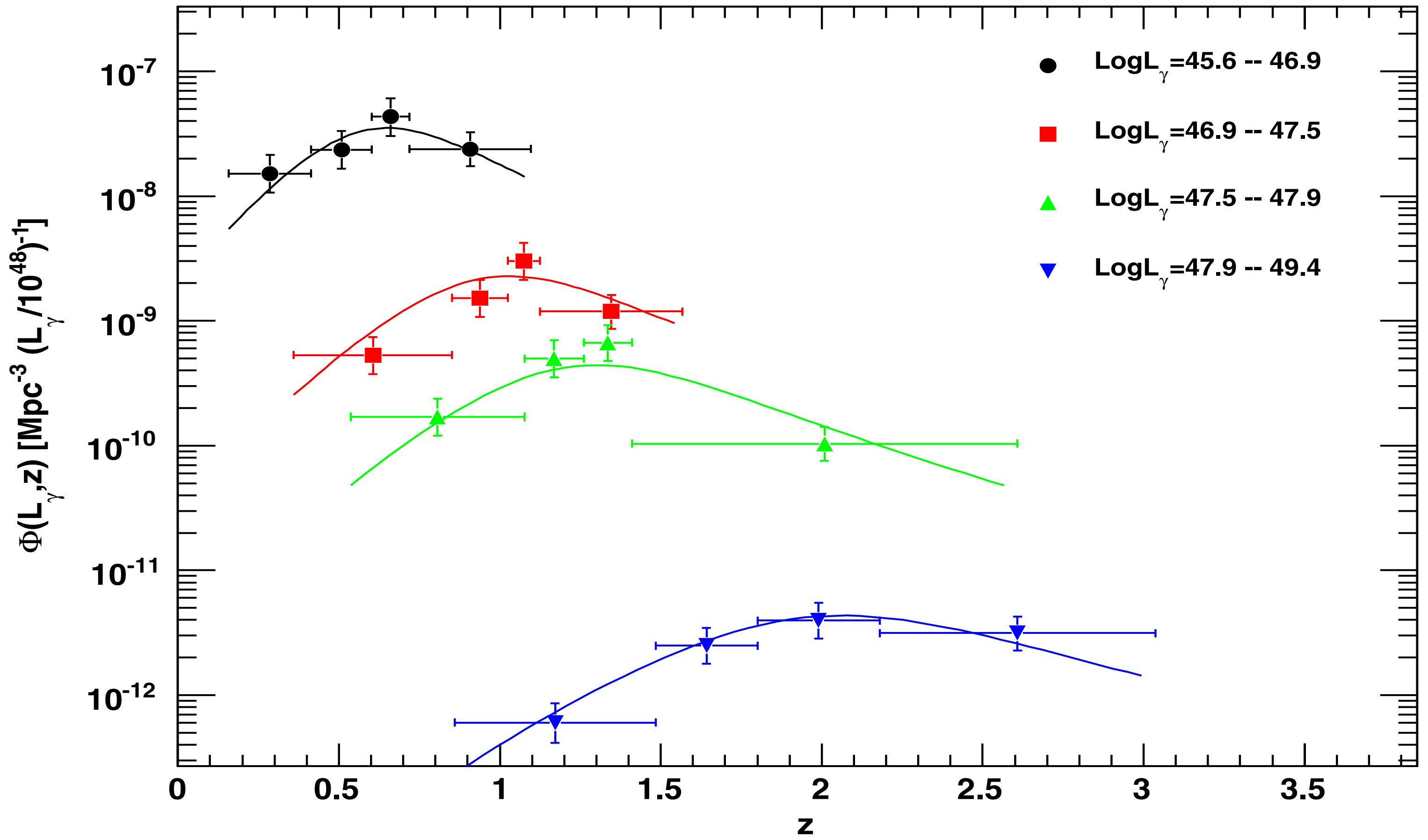
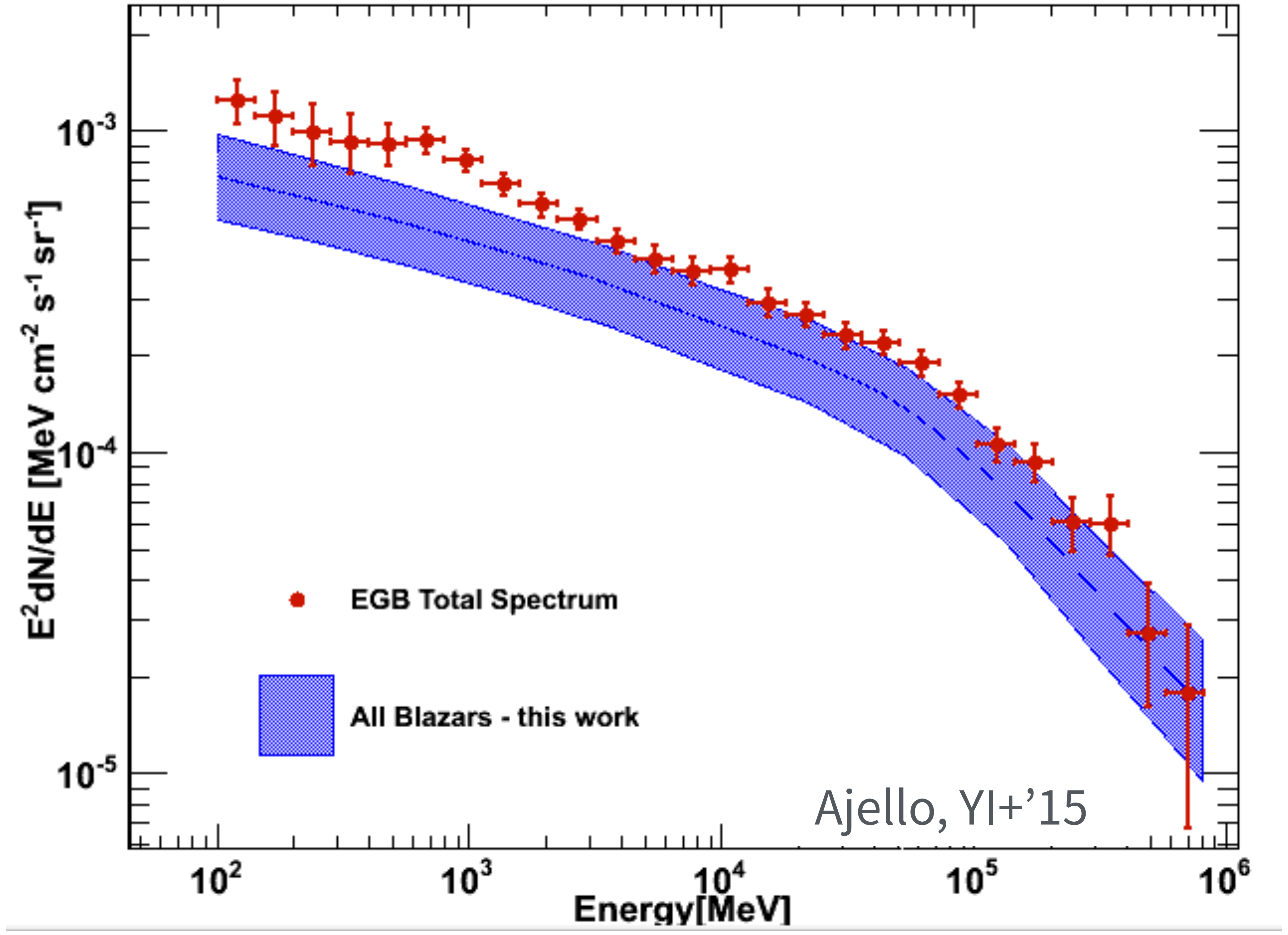


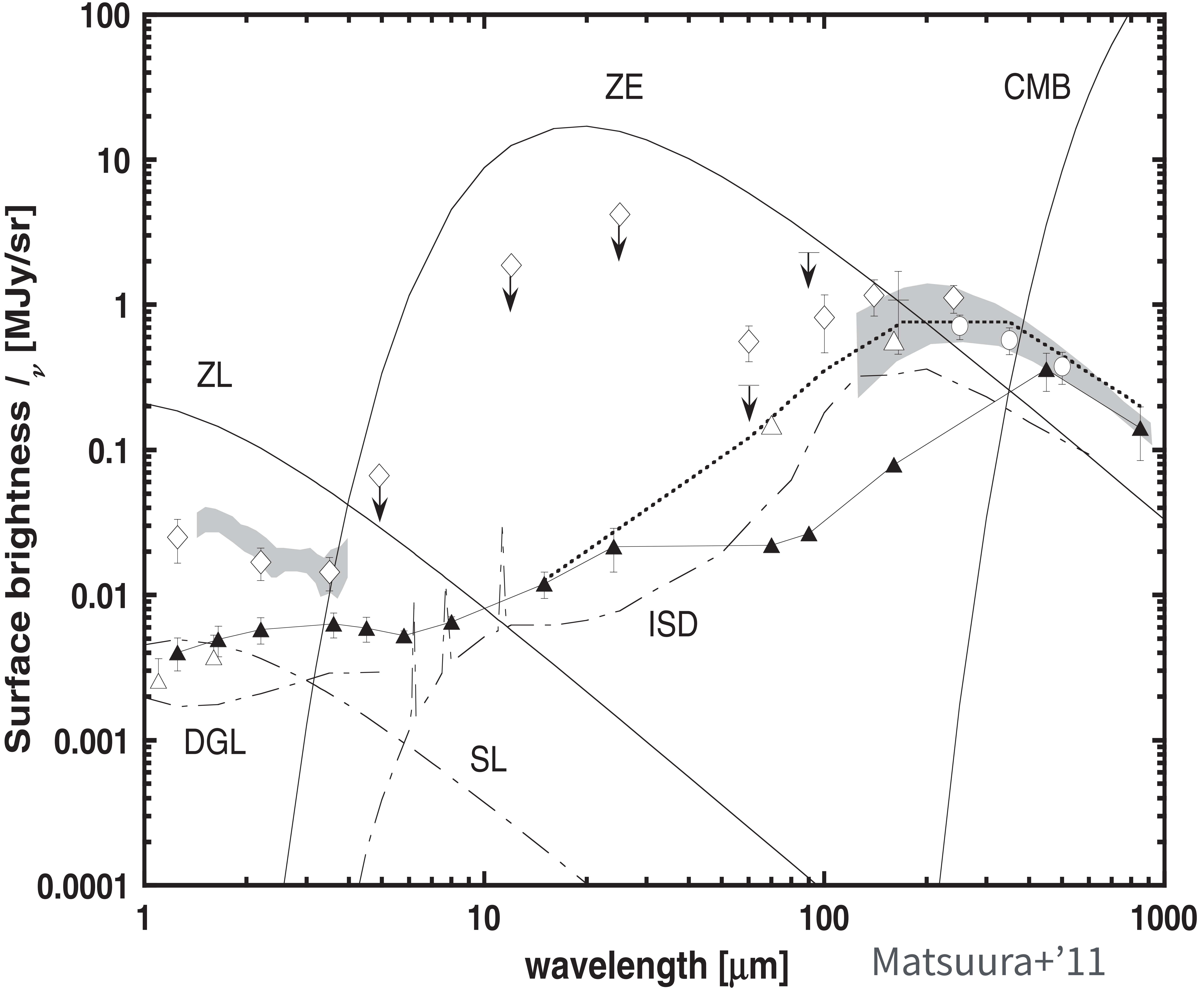
Evolution



Measuring EBL

Can we measure the EBL?

- Zodiacal light (ZL) is a factor of 100 higher than EBL intensity.
- Diffuse galactic light, Starlight makes comparable intensity.

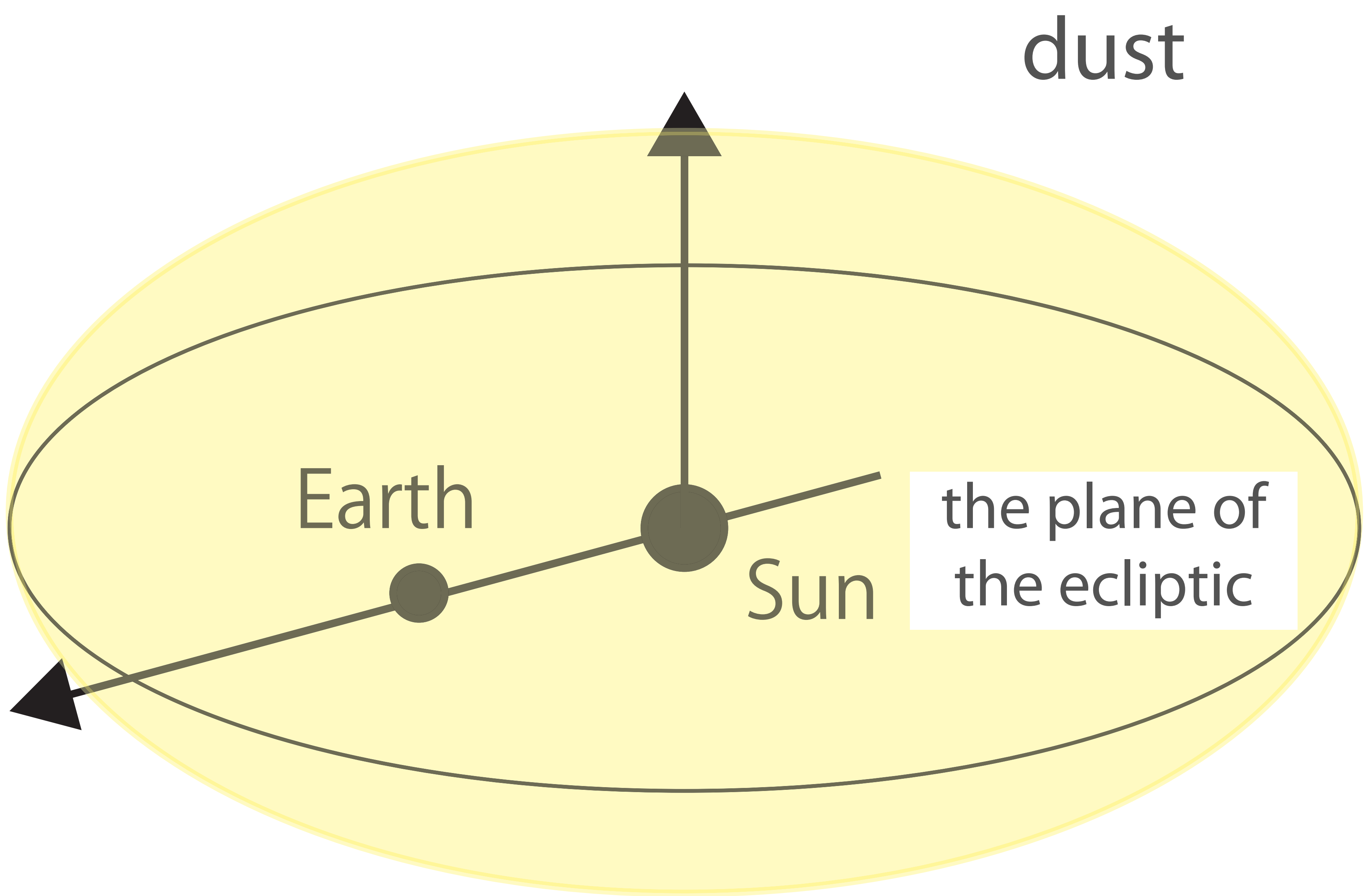


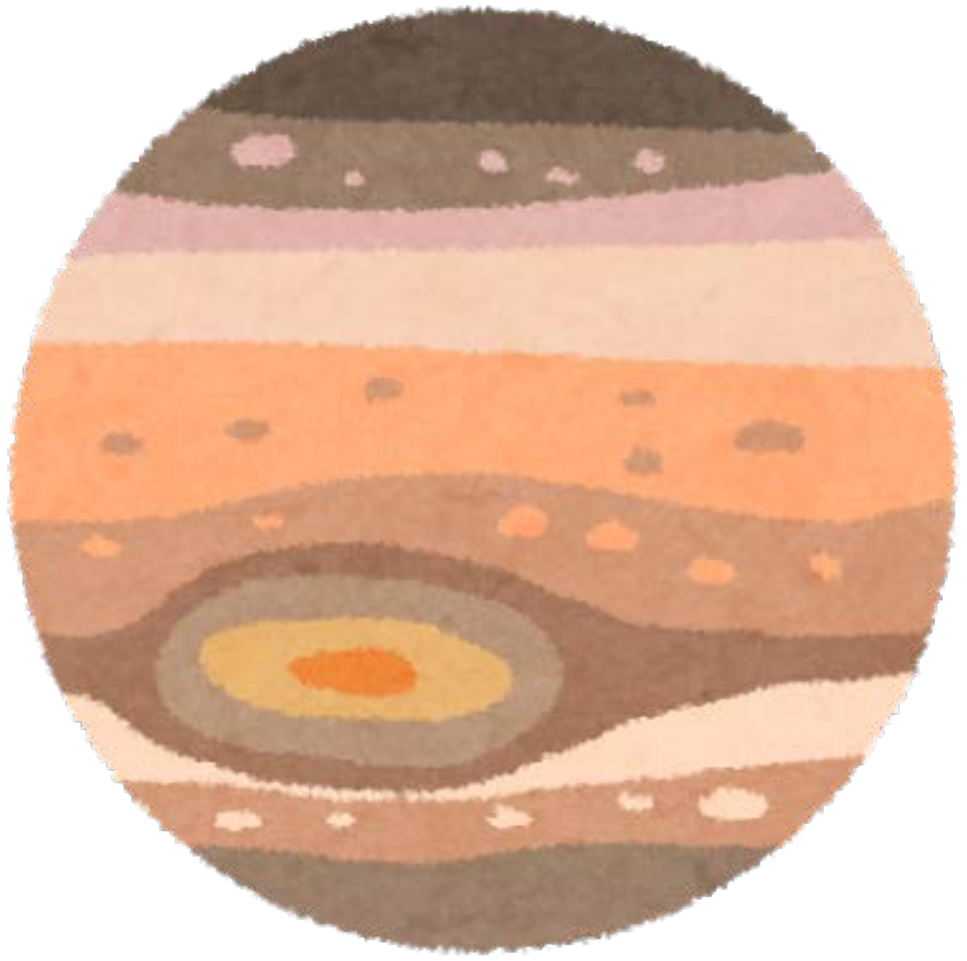
Matsuura+'11

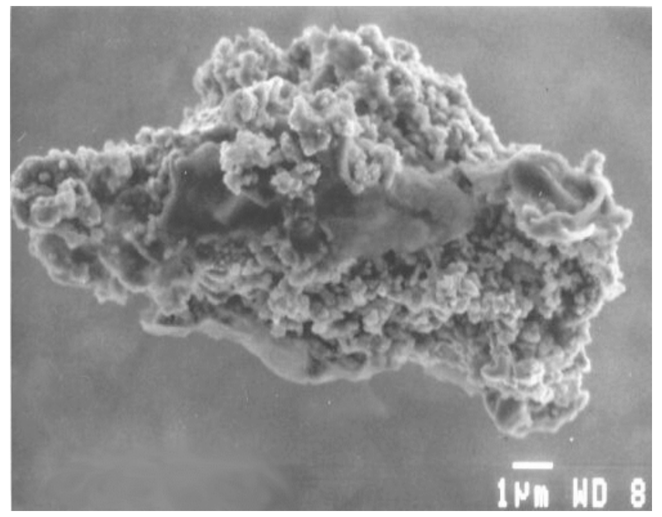
Zodiacal Light

Scattered solar emission by dust

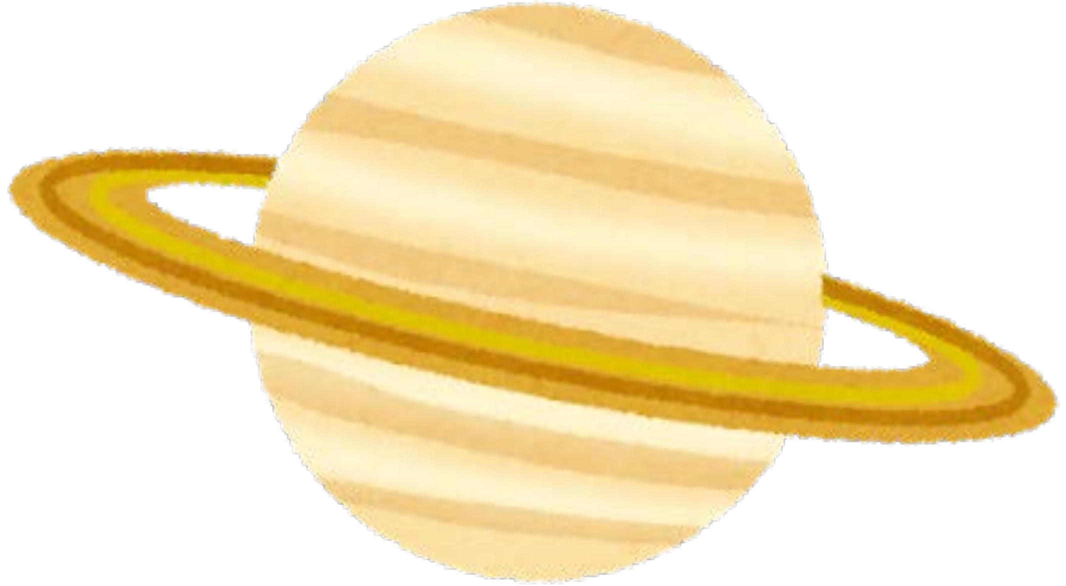
- interplanetary dust between Jupiter and Saturn
- Distribute around the plane of the ecliptic
- Brightest foreground for the EBL measurement

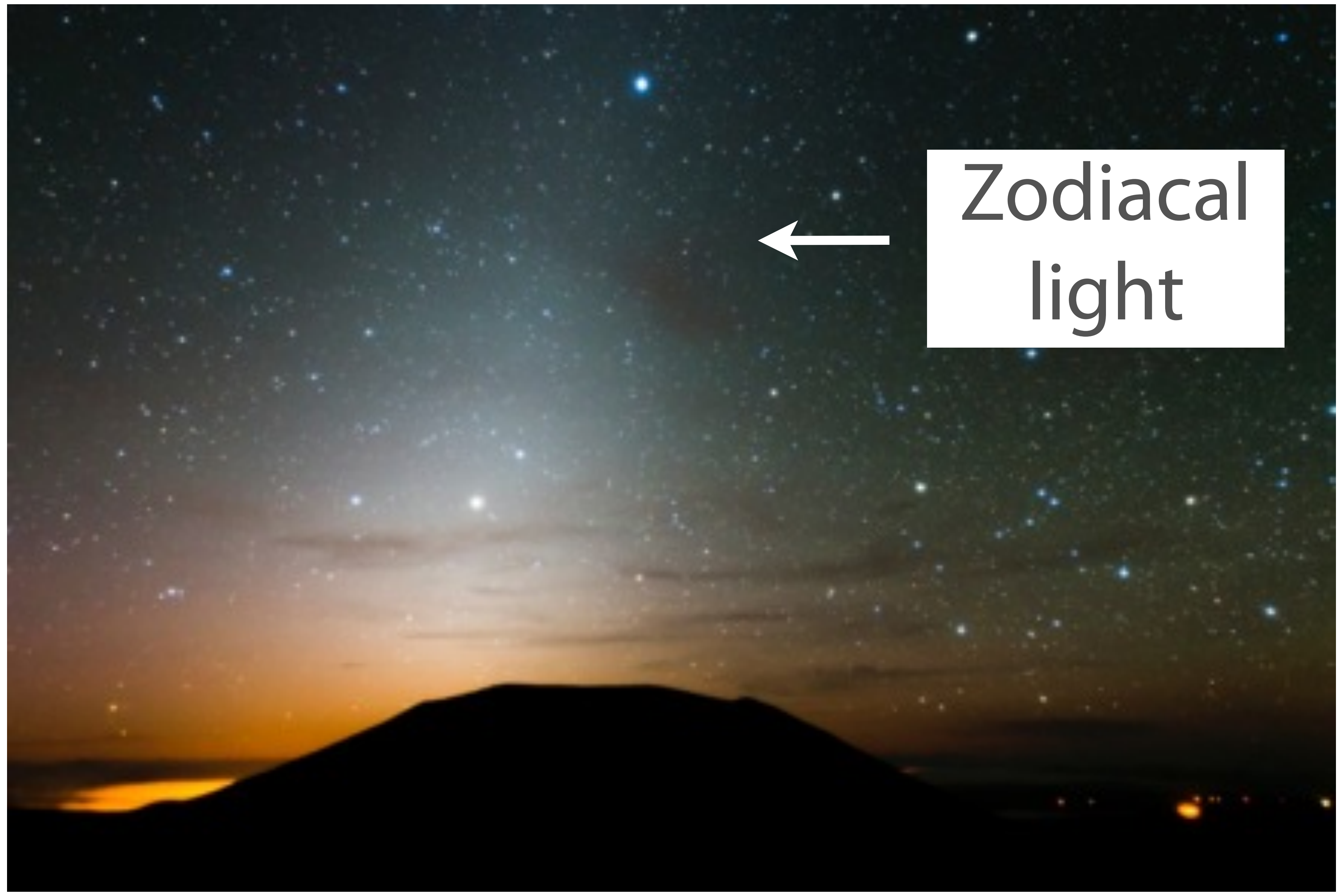






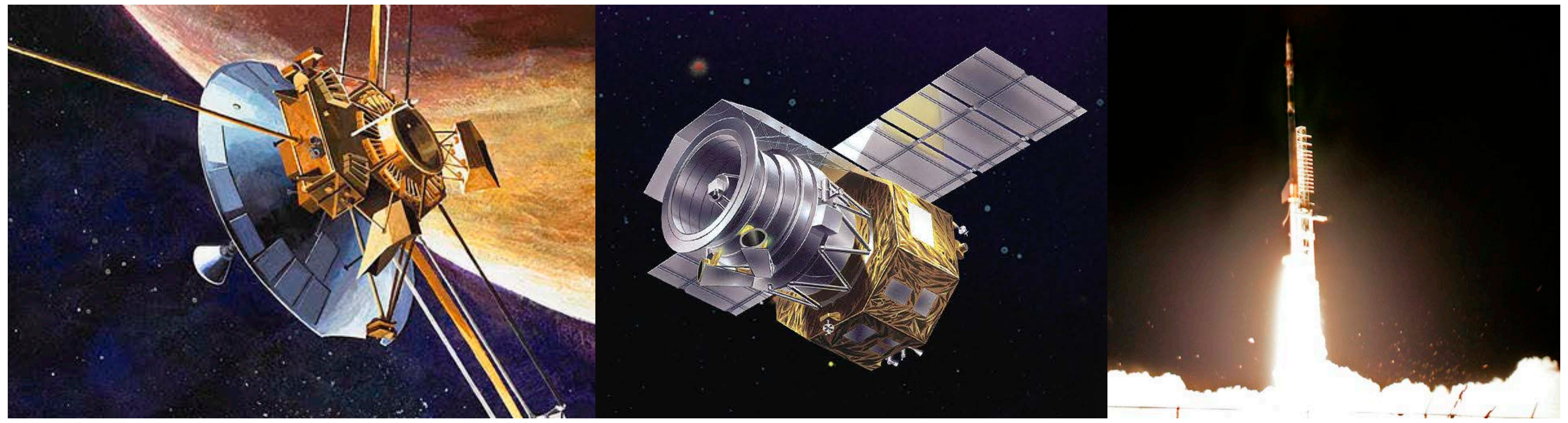
http://spiff.rit.edu/classes/phys230/lectures/ism_dust/ism_dust.html

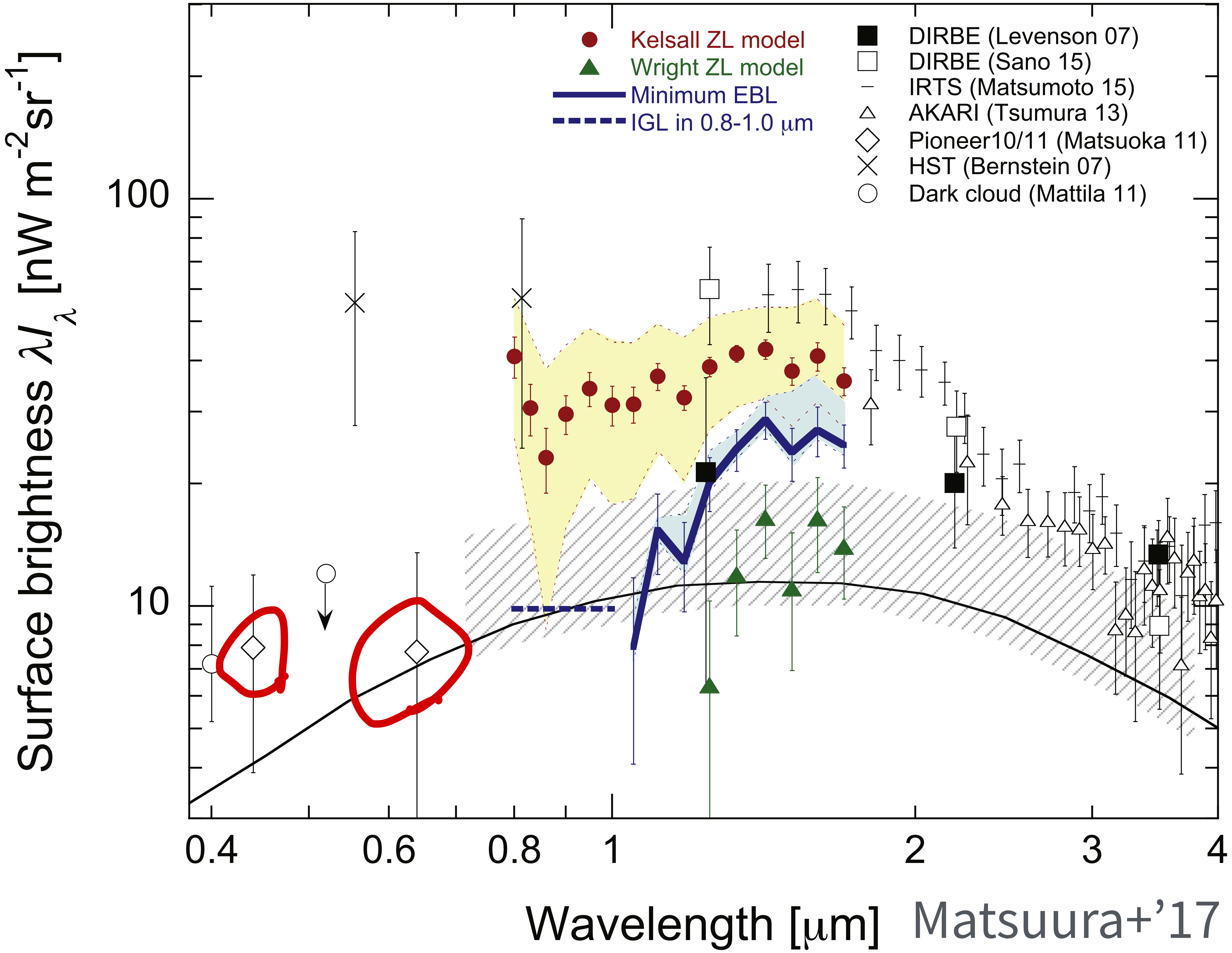




Direct Measurements of EBL

A excess in NIR



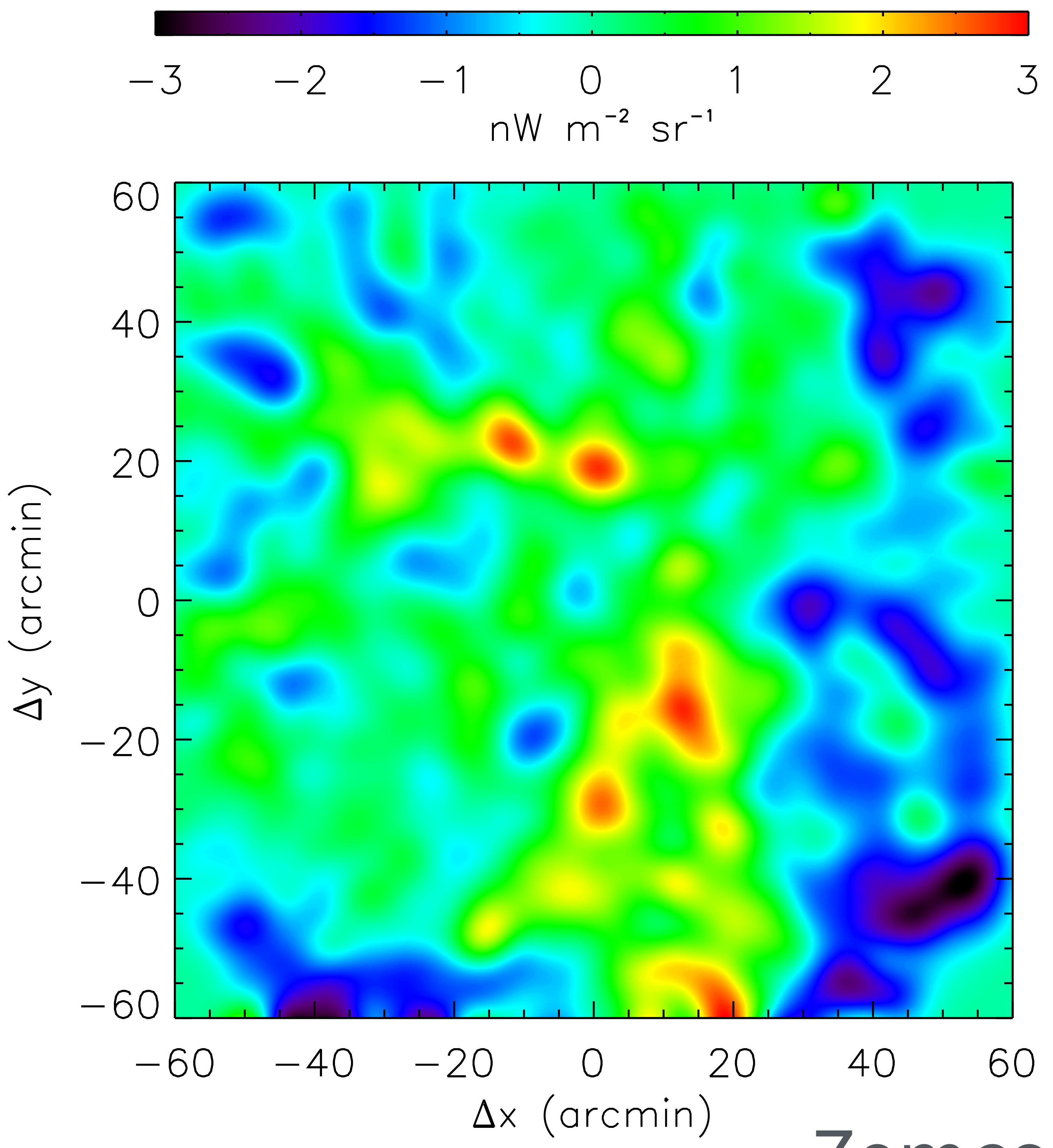


Matsuura+'17

- Pioneer 10/11 measurements are consistent with the galaxy count lower limit.
- IRTS, AKARI, & CIBER see the excess in NIR.
- Origin?
    - Cosmological? Nearby?

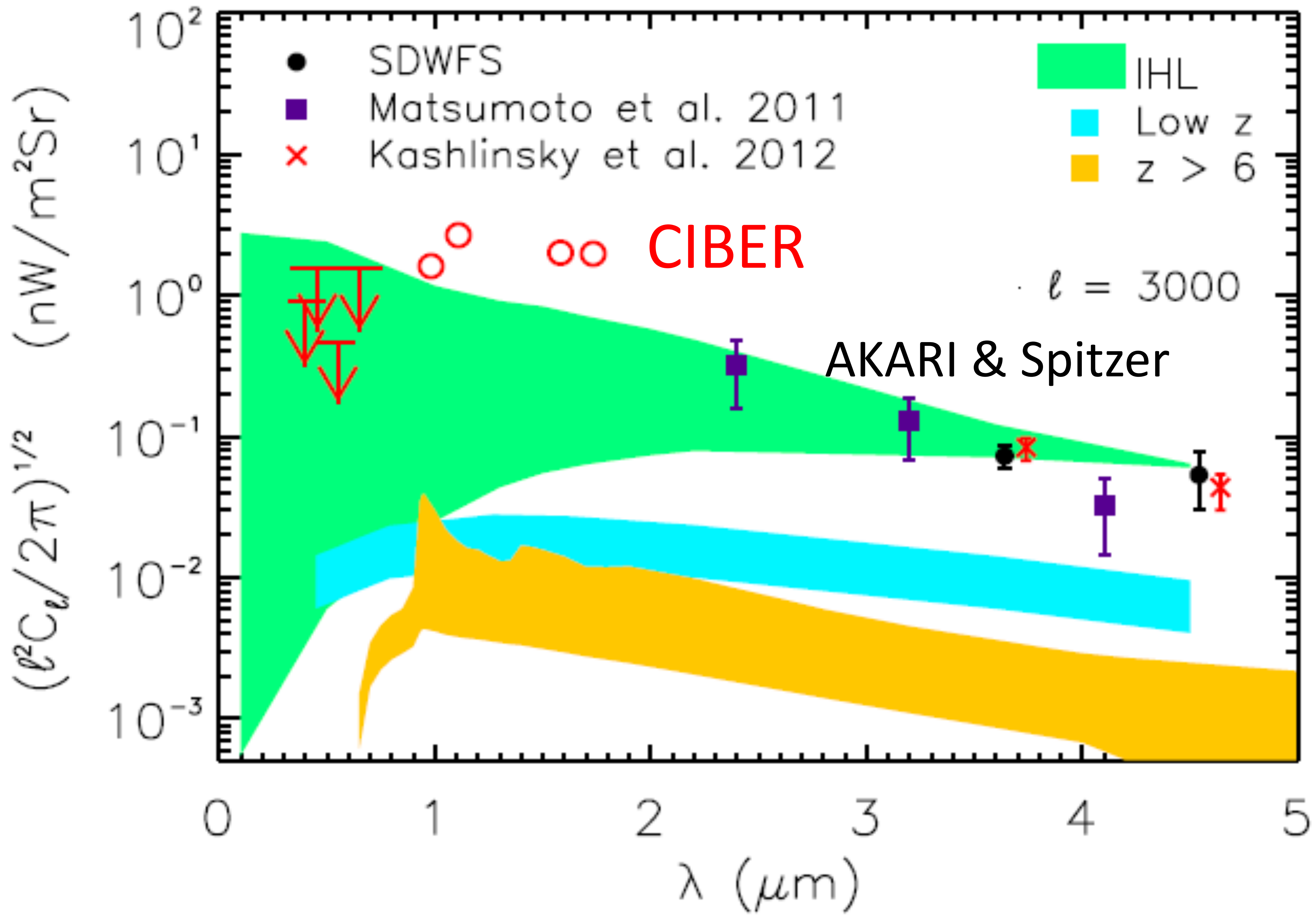
Is the NIR excess in EBL real?

Excess also in the angular power spectrum



Zemcov+'14

Cooray et al. *Nature*, 2012

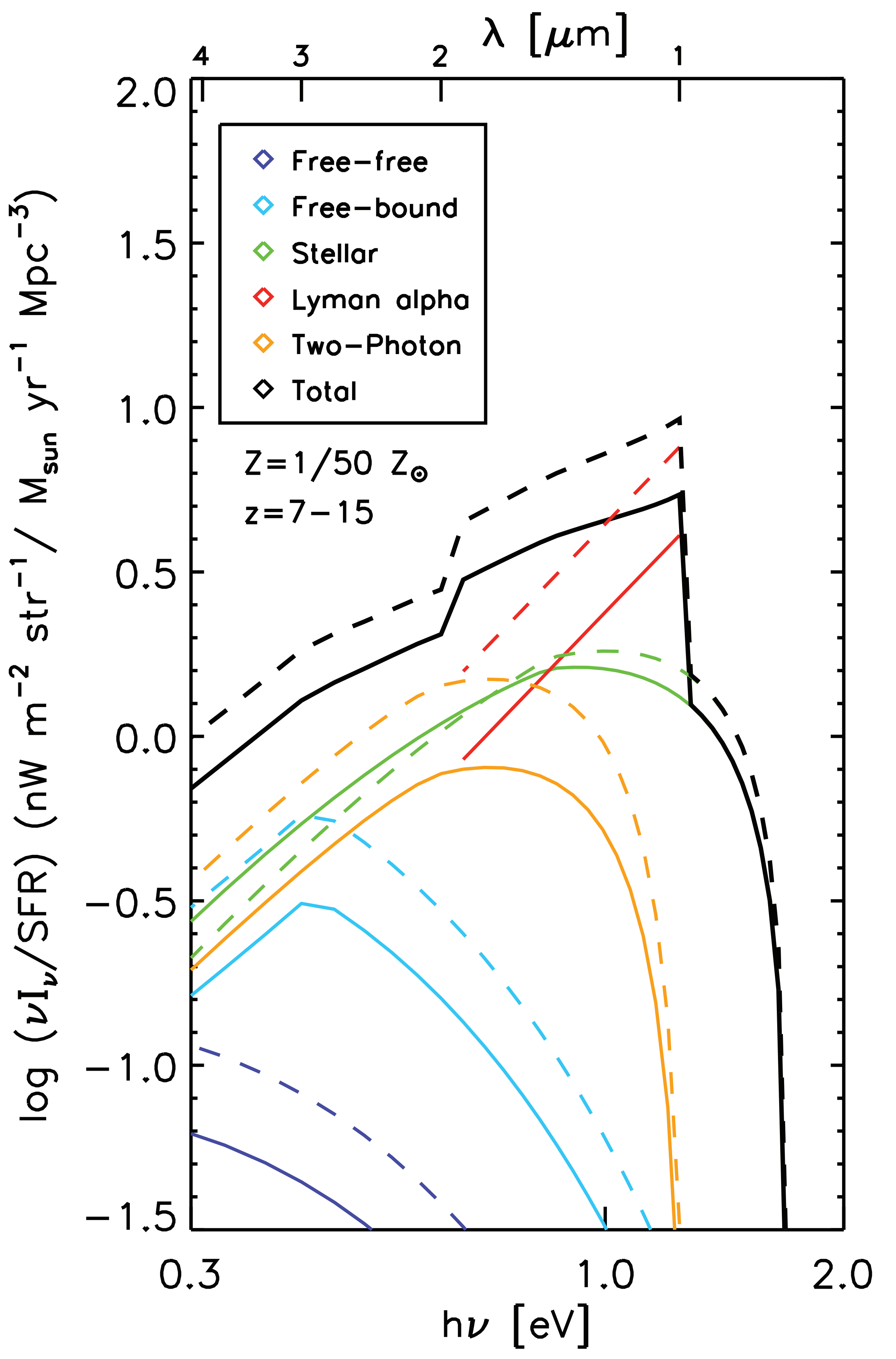


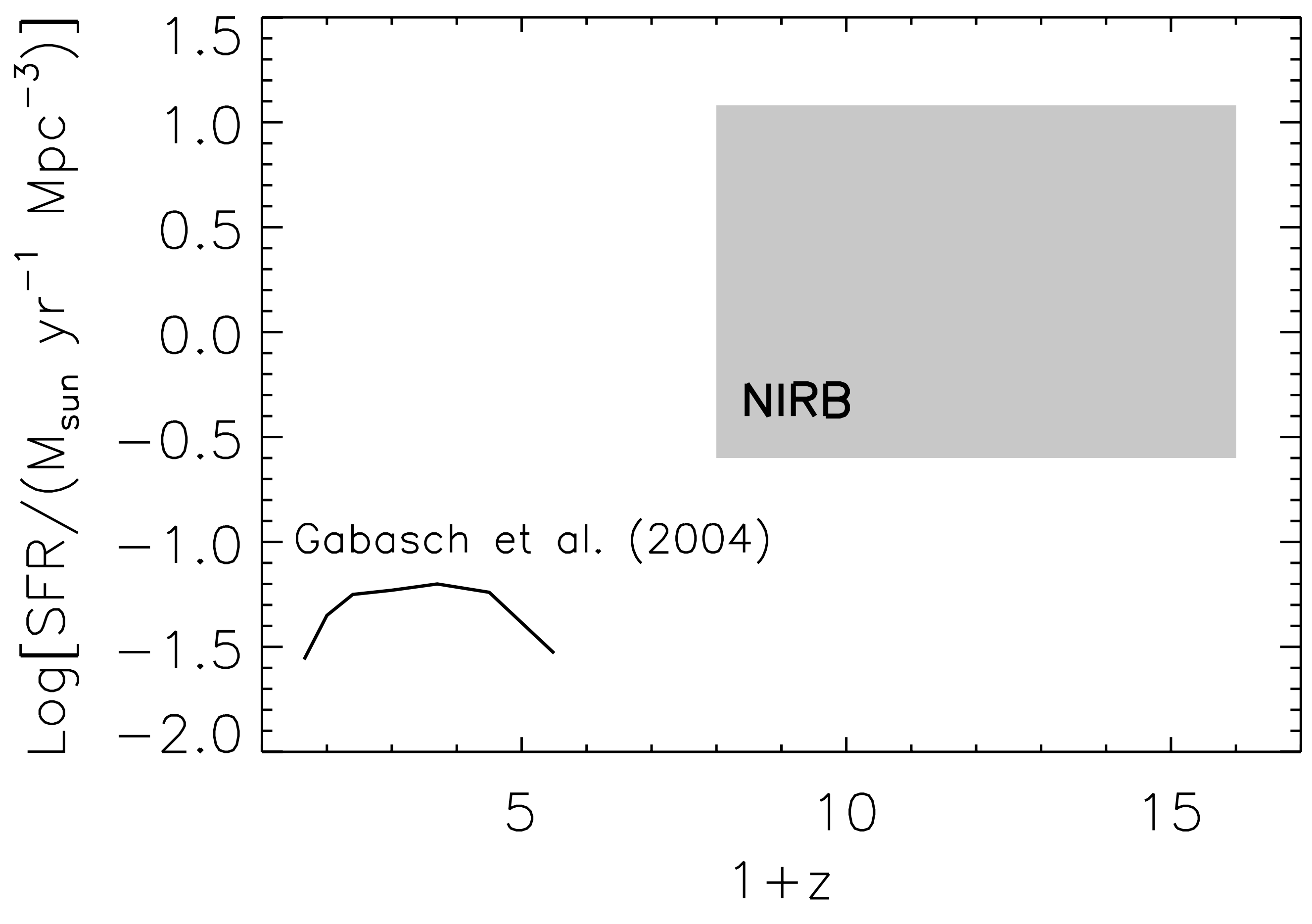
- A large scale fluctuation in the NIR sky (Kashlinsky+'05, '07, '12, Matsumoto+'11, Cooray+'12, zemcov+'15).
- Galaxies can not explain this excess.
  - Intrahalo stars (Cooray+'12)?

What makes the NIR excess in EBL?

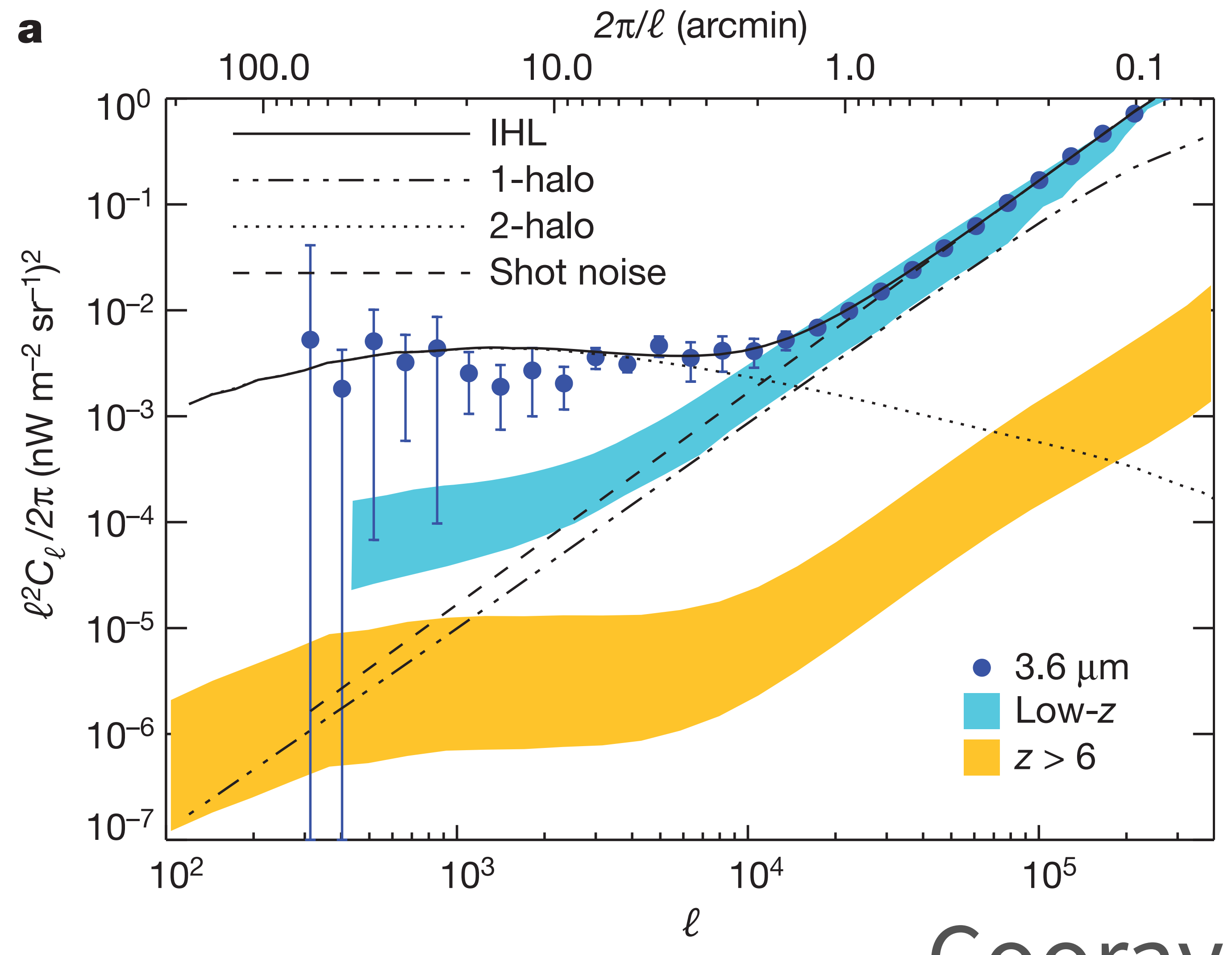
First Stars? Intra-Halo Stars?

- Lyman alpha photons from z~10 will redshifted to ~1 um.
  - But, we need very high first star formation rate density.
- Intra-Halo Stars
  - Stars stripped from host galaxies by major mergers.





Fernandez & Komatsu '06

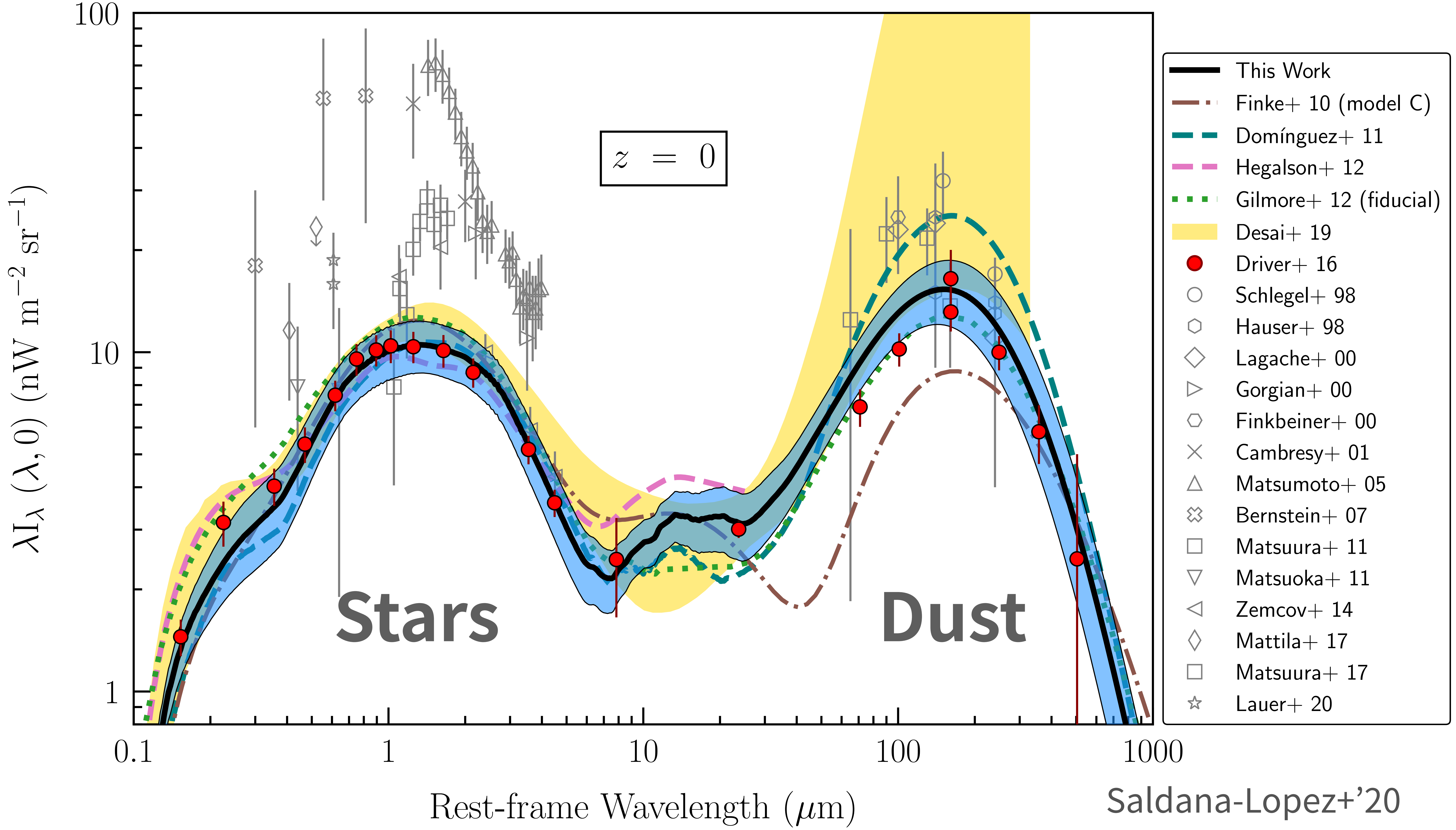


Cooray+'12

Probing Extragalactic Background Light with Gamma-ray Observations

Extragalactic Background Light (EBL)

Integrated Emission from Galaxies in the entire cosmic history



Saldana-Lopez+'20

Gamma-ray Opacity of the universe

Based on EBL models

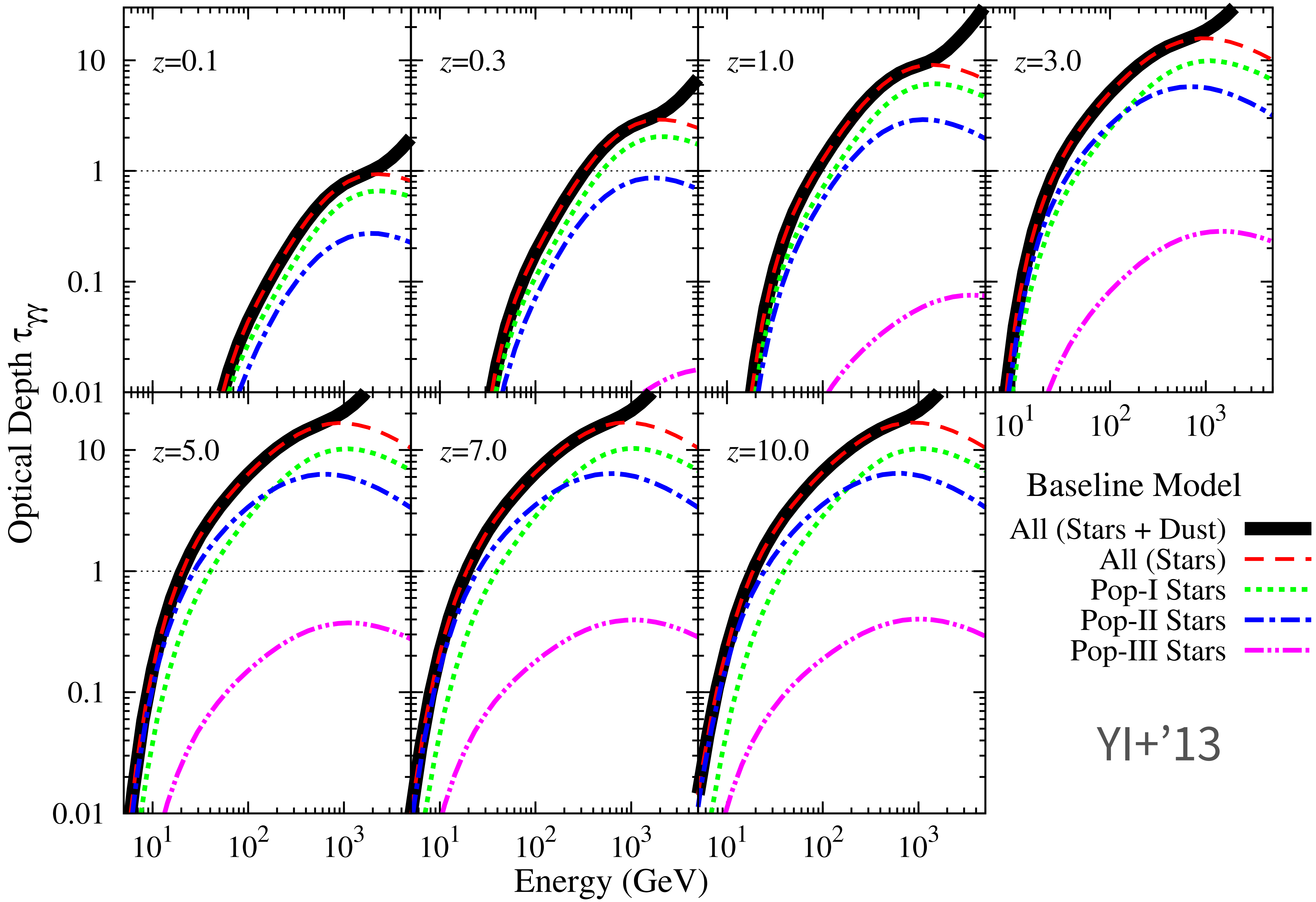
- The opacity is given as

$$\tau_{\gamma\gamma}(E_\gamma, z_s) = \int_0^{z_s} dz \int_{-1}^{1} d\mu \int_{\epsilon_{\rm th}}^{\infty} d\epsilon \frac{dl}{dz} \frac{1-\mu}{2} \frac{dn_{\rm EBL}}{d\epsilon} \sigma_{\gamma\gamma}$$

- The absorbed spectrum is

$$F_{\rm abs}(E_\gamma) = F_{\rm int}(E_\gamma)\exp(-\tau_{\gamma\gamma})$$

- Beyond z~0.1, TeV photons will be completely absorbed.



YI+'13

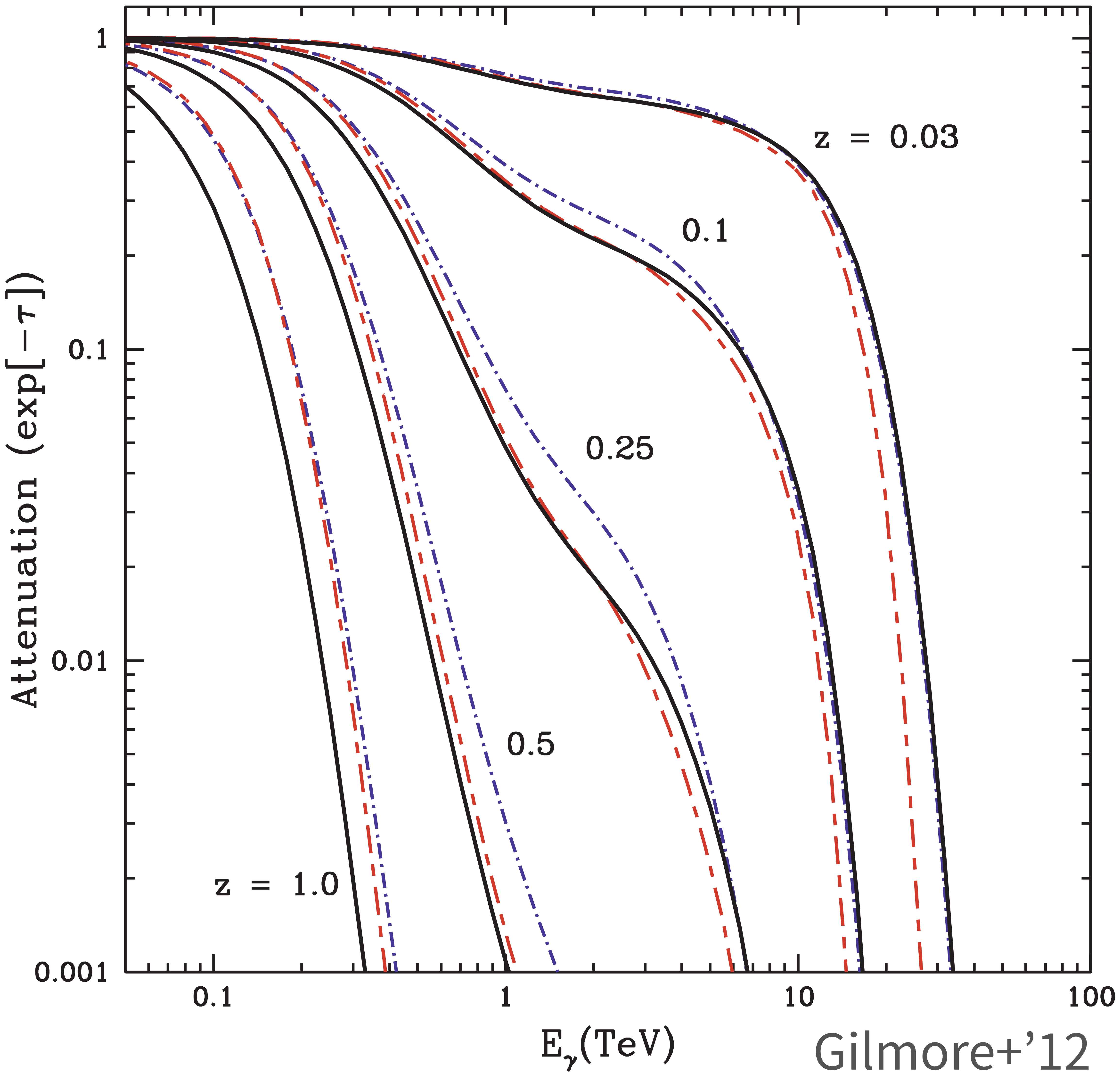
Expected attenuation features

Exponential cutoff in the VHE band

- The radiation transfer equation becomes: $\frac{dI_\nu}{d\tau_{\gamma\gamma}} = - I_\nu$

  ➡ $I_\nu(\tau_{\gamma\gamma}) = I_\nu(0)e^{-\tau_{\gamma\gamma}}$

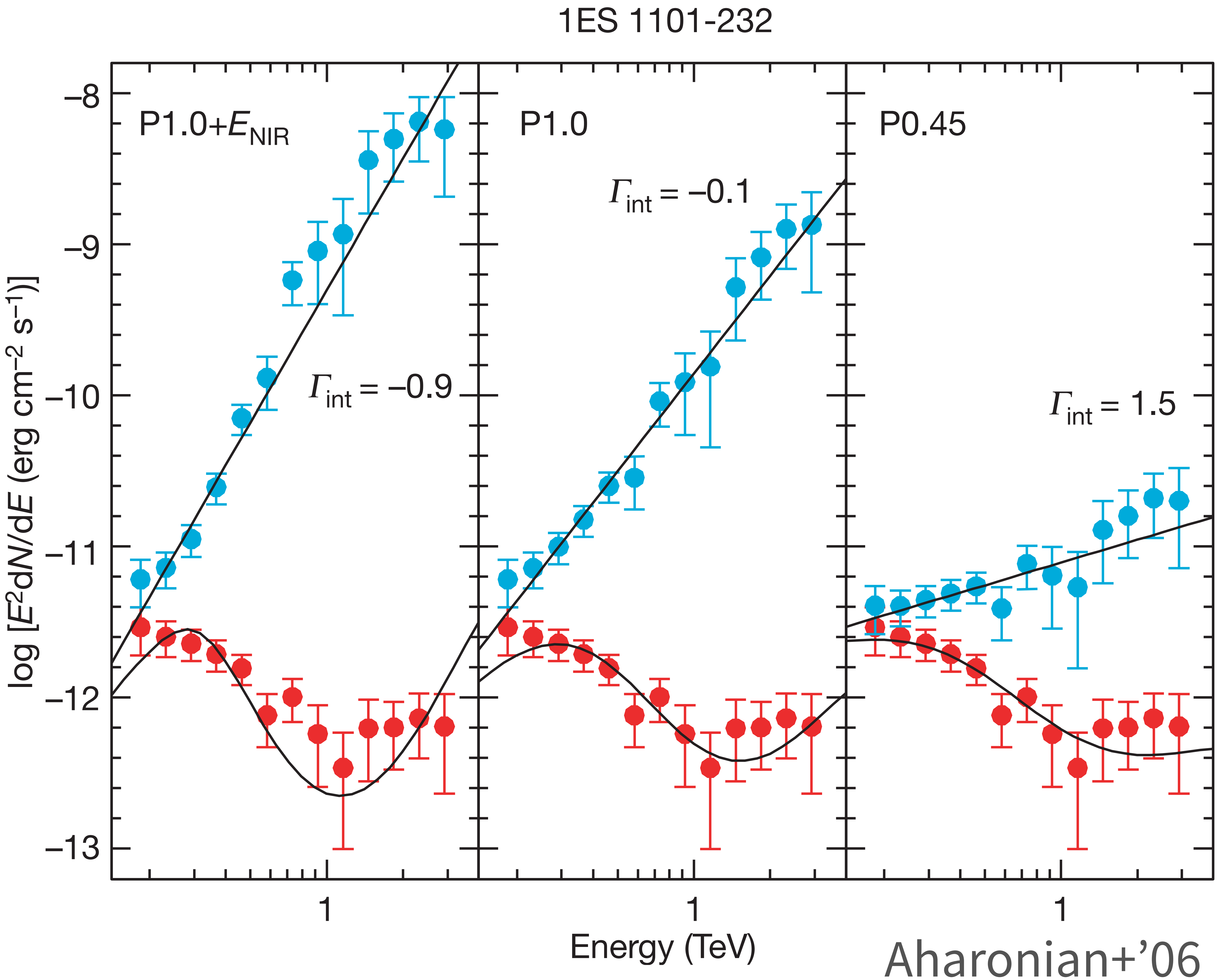
- Energy $\nearrow + z \nearrow \Rightarrow \tau_{\gamma\gamma} \nearrow \Rightarrow$ Flux $\searrow$



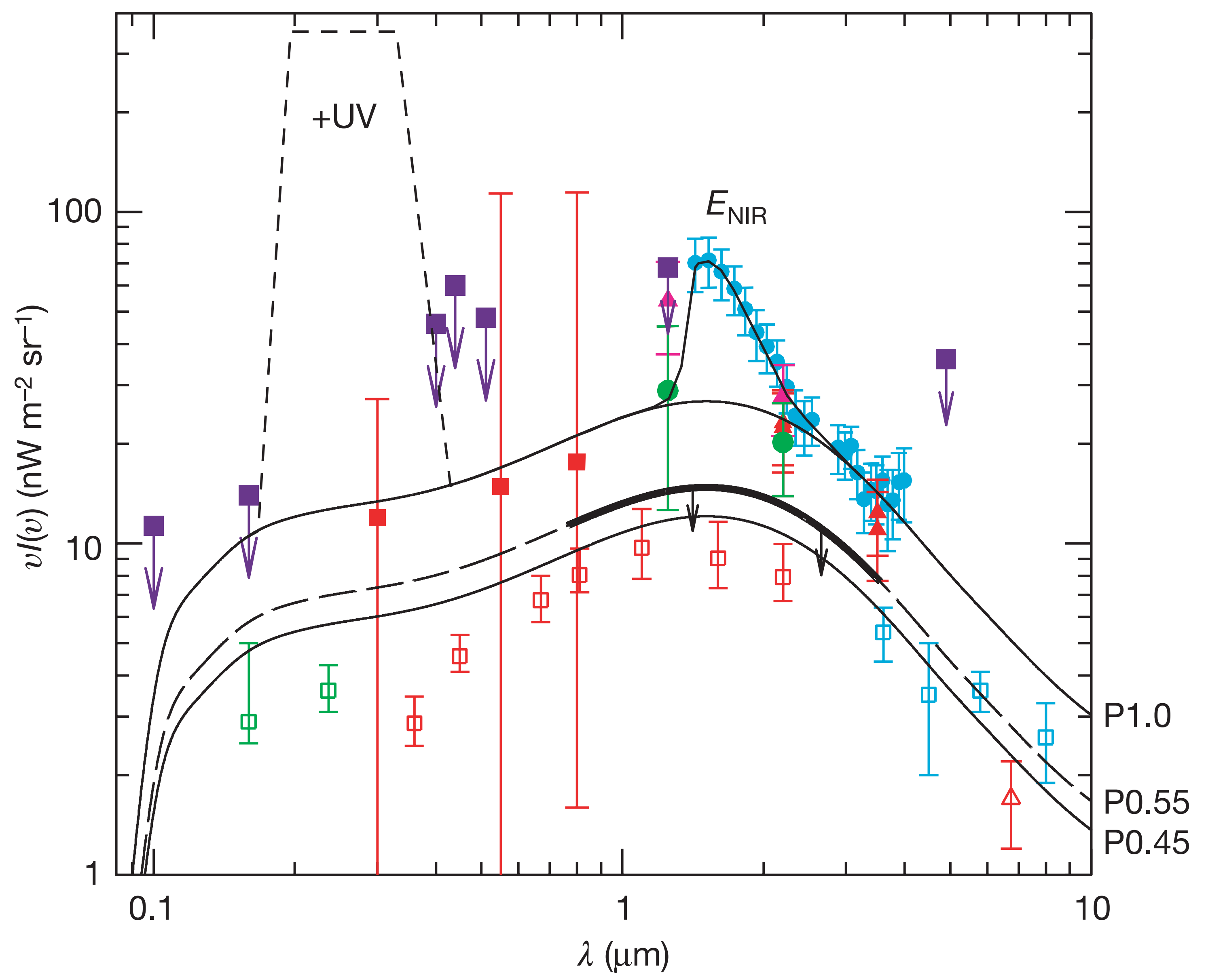
Gilmore+'12

Reconstruction of EBL using gamma-ray blazars

Let's assume the intrinsic spectral shape



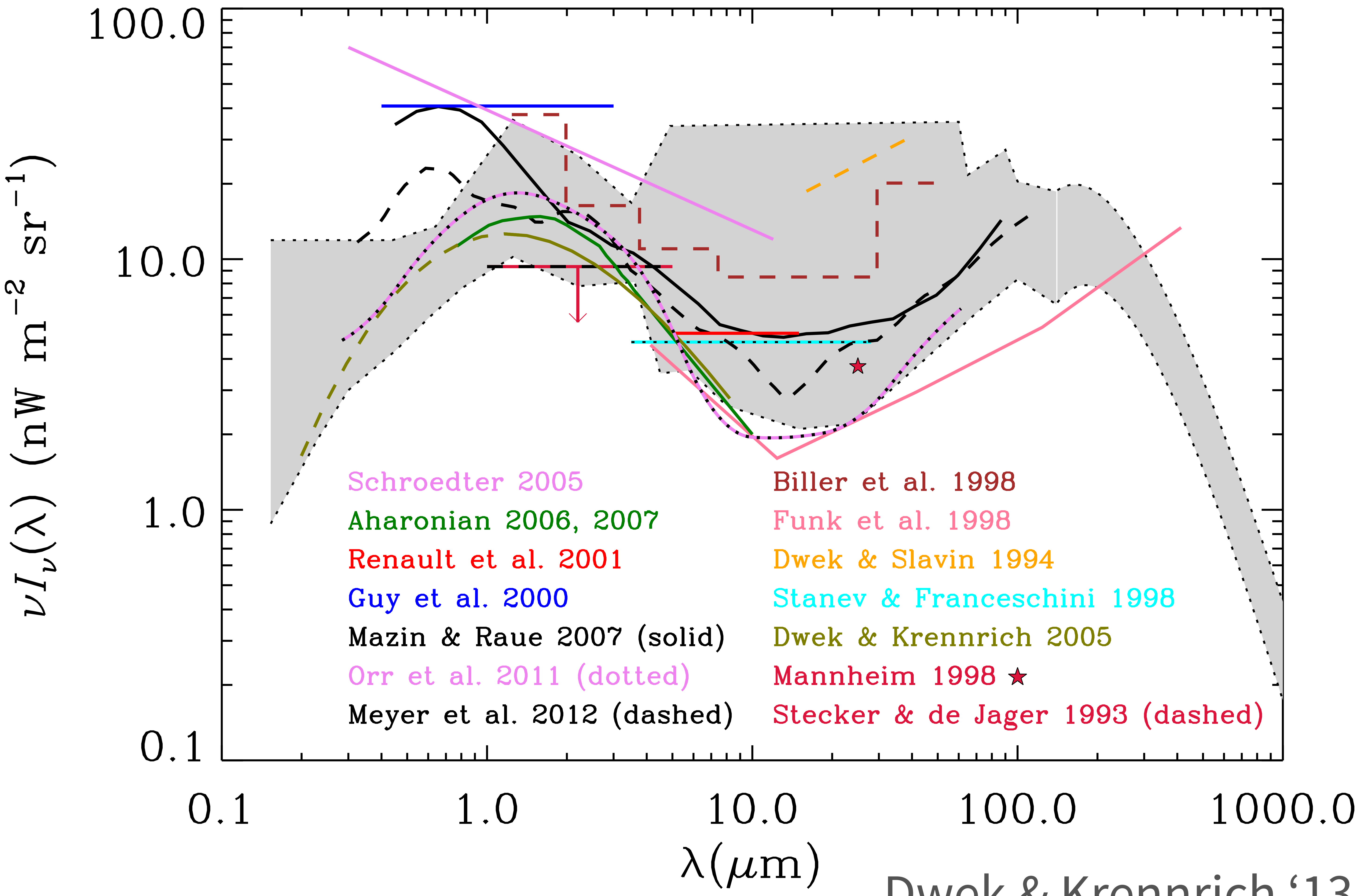
Aharonian+'06



- 😀 Upper limit on the EBL
- ☹️ no GeV data was available
- ☹️ only a few objects were used

EBL Determination Before 2012

Ruling out the cosmological origin for the NIR excess



Dwek & Krennrich '13

- about a factor of 10 uncertainties.
- NIR excess should not be cosmological.