# Cosmological Aspects of High Energy Astrophysics ~ Day 4 ~

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NTHU Astronomy Winter School @ Online, 2021-01-18-22

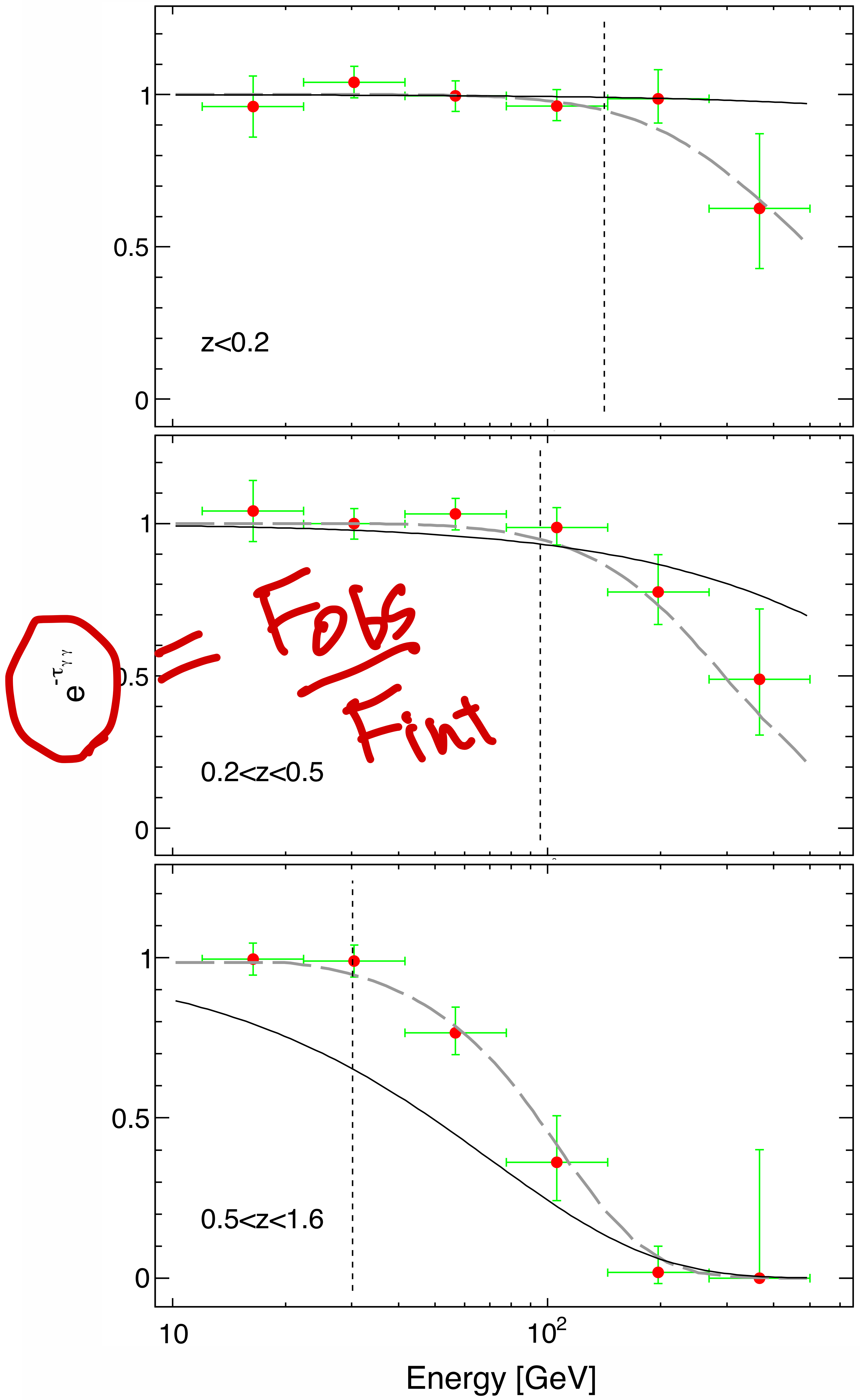
# Lecture Schedule

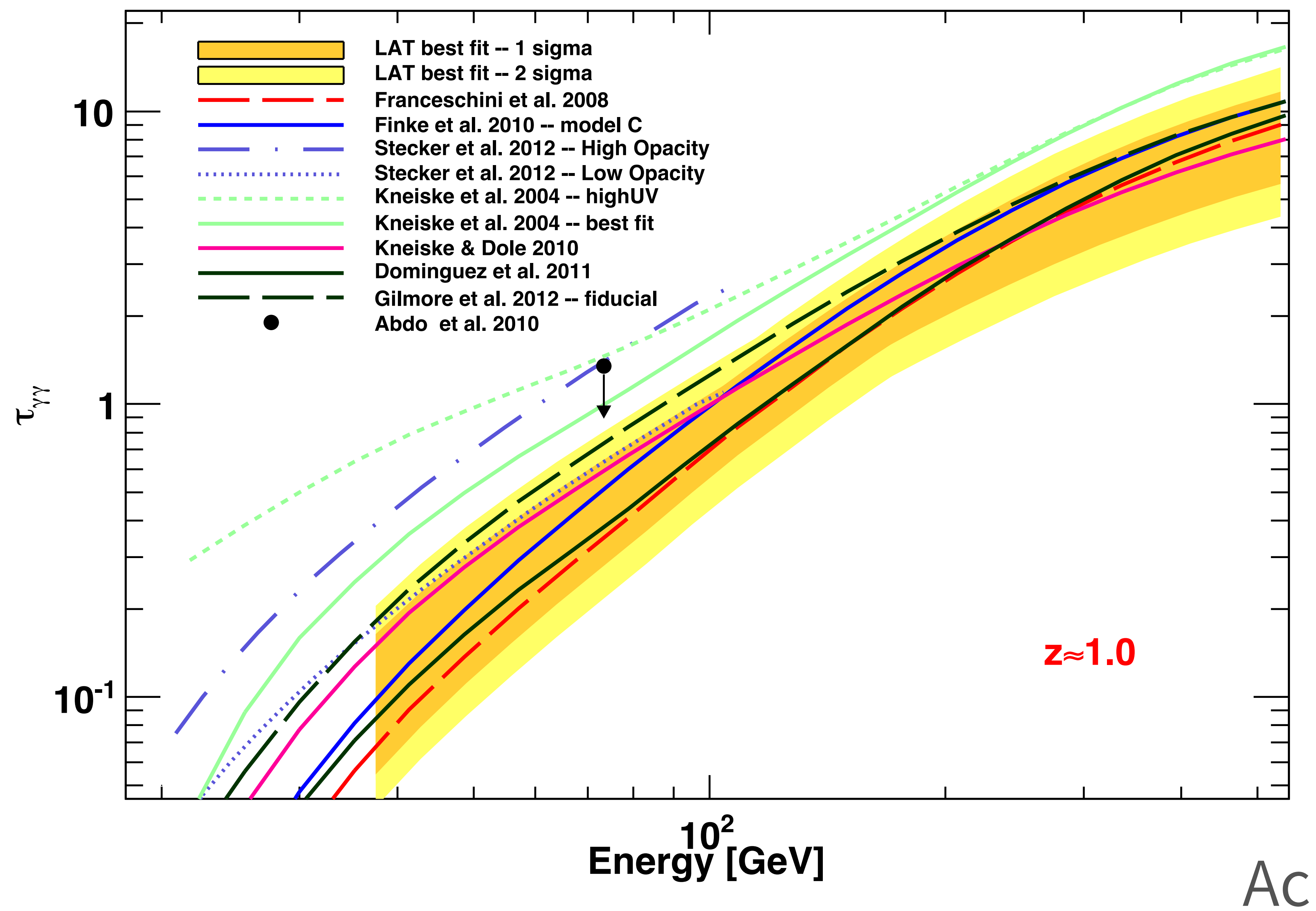
## Be careful! It may change!

- ~~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~~
- **Day 4:**
  - **Probing Extragalactic Background Light with Gamma-ray Observations**
  - **Intergalactic Magnetic Field and Gamma-ray Observations**
  - **Cosmic Expansion and Gamma-ray Horizon (if possible)**

# “Detection” of the EBL attenuation

## 150 Fermi blazars using ~4 yr Fermi survey data



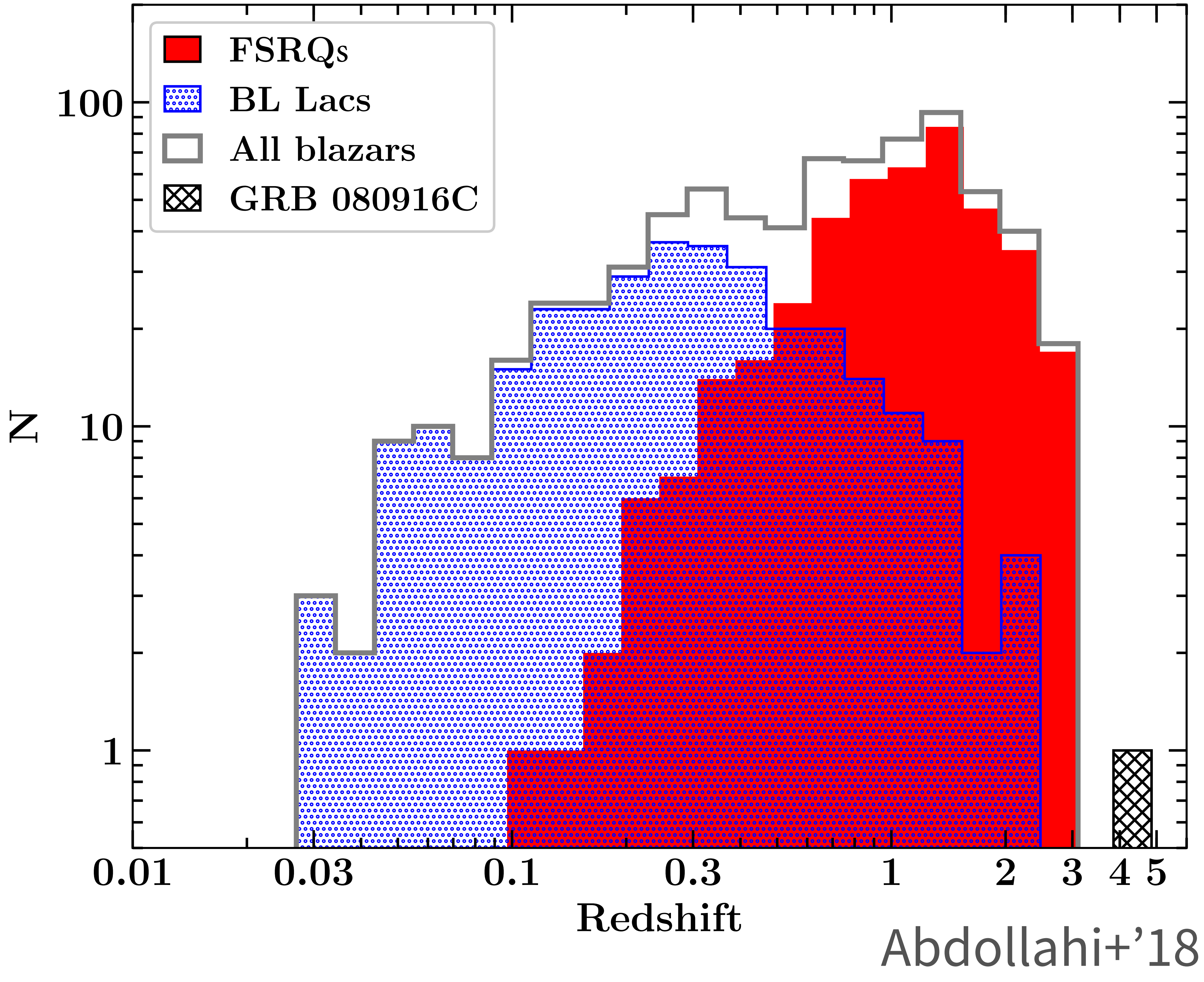



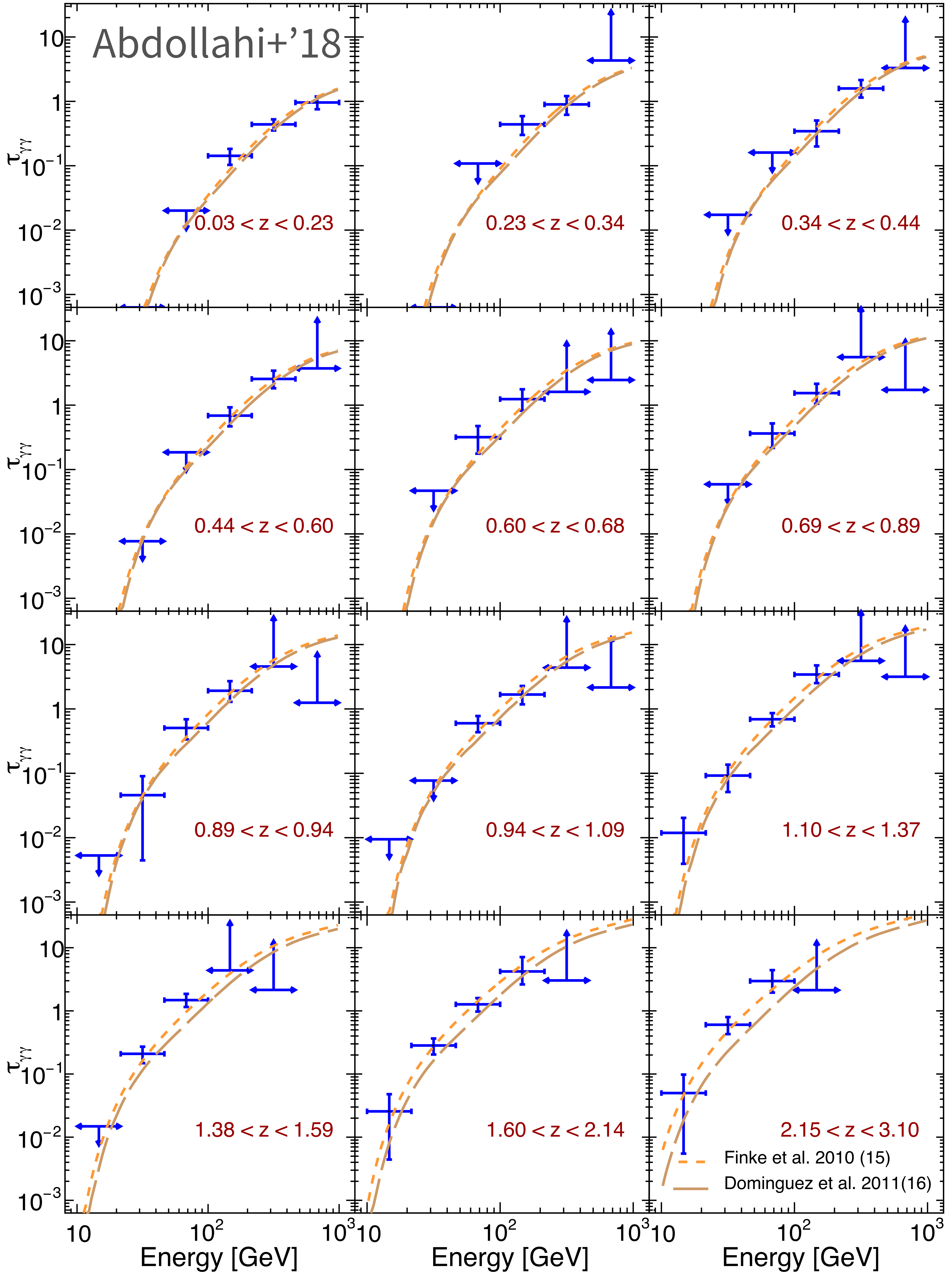

Ackermann+’12

- Fermi can cover the SED from 0.1 GeV to > 300 GeV
- Exponential attenuation feature is seen.

# “Characterization” of the EBL attenuation

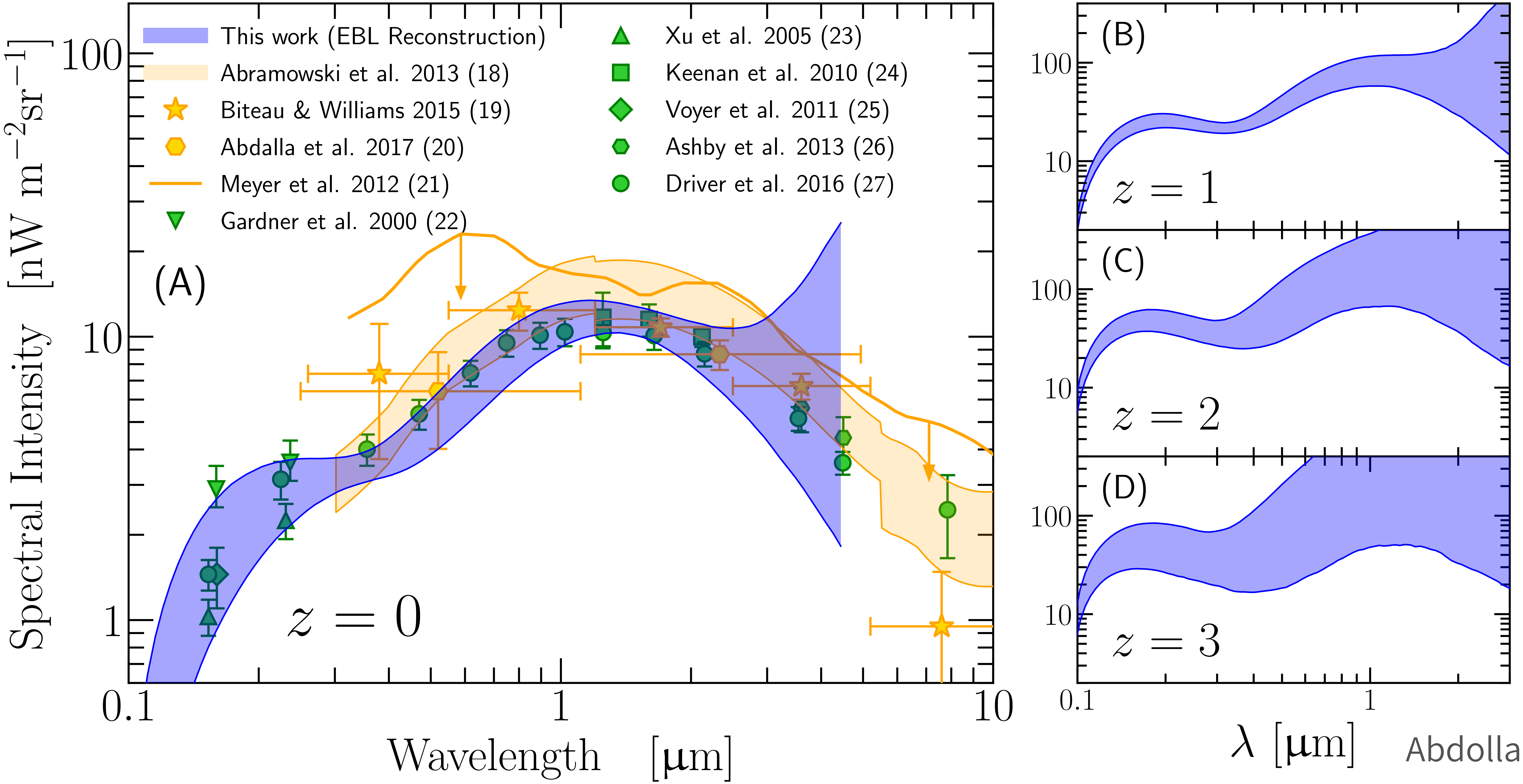
## 739 Fermi blazars + 1 Fermi GRB w/ 9-yr data



# EBL and its Evolution by Gamma-ray Observations

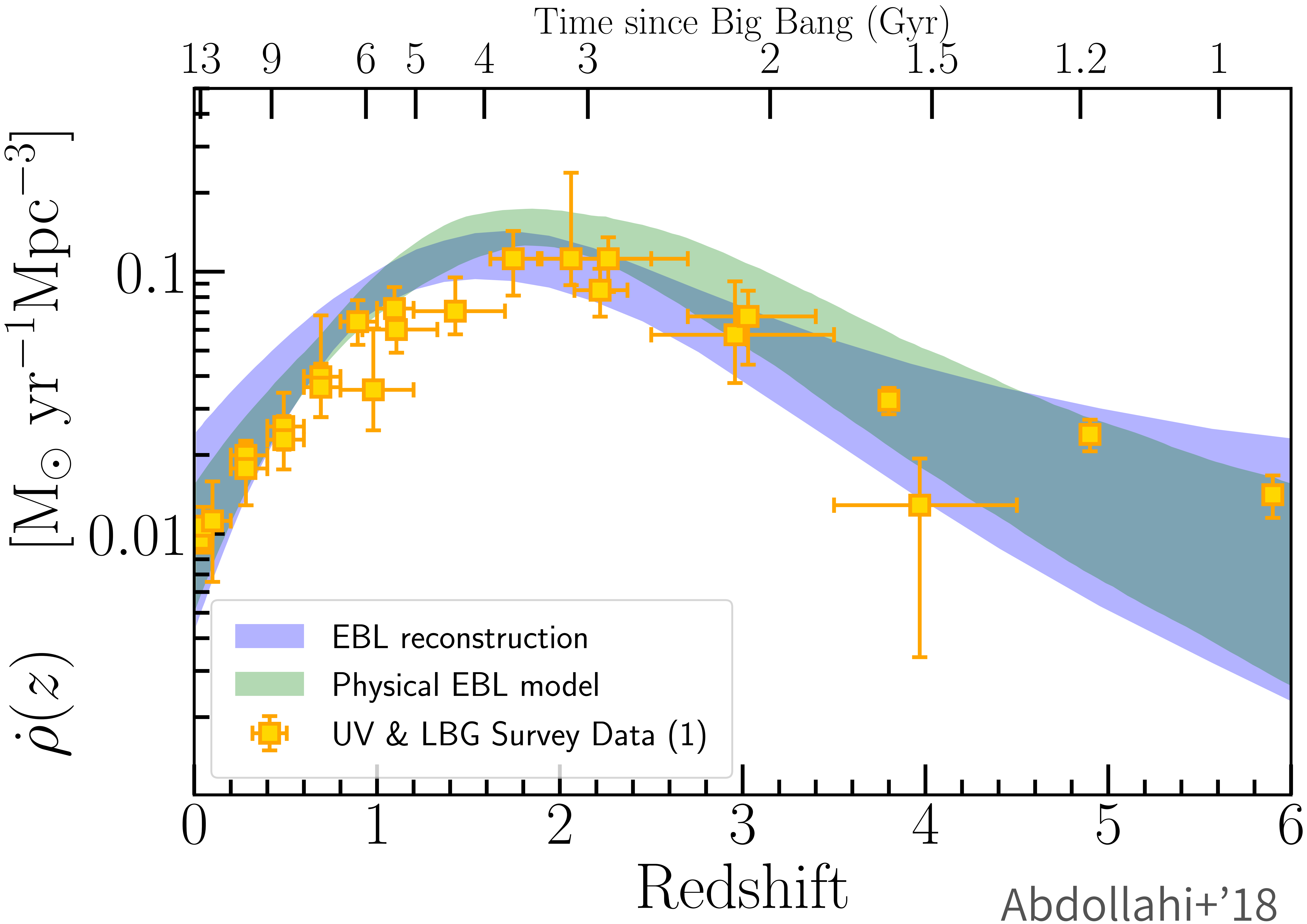
## Good agreement with galaxy counts




Abdollahi+'18

# Determination of the Cosmic Star Formation History

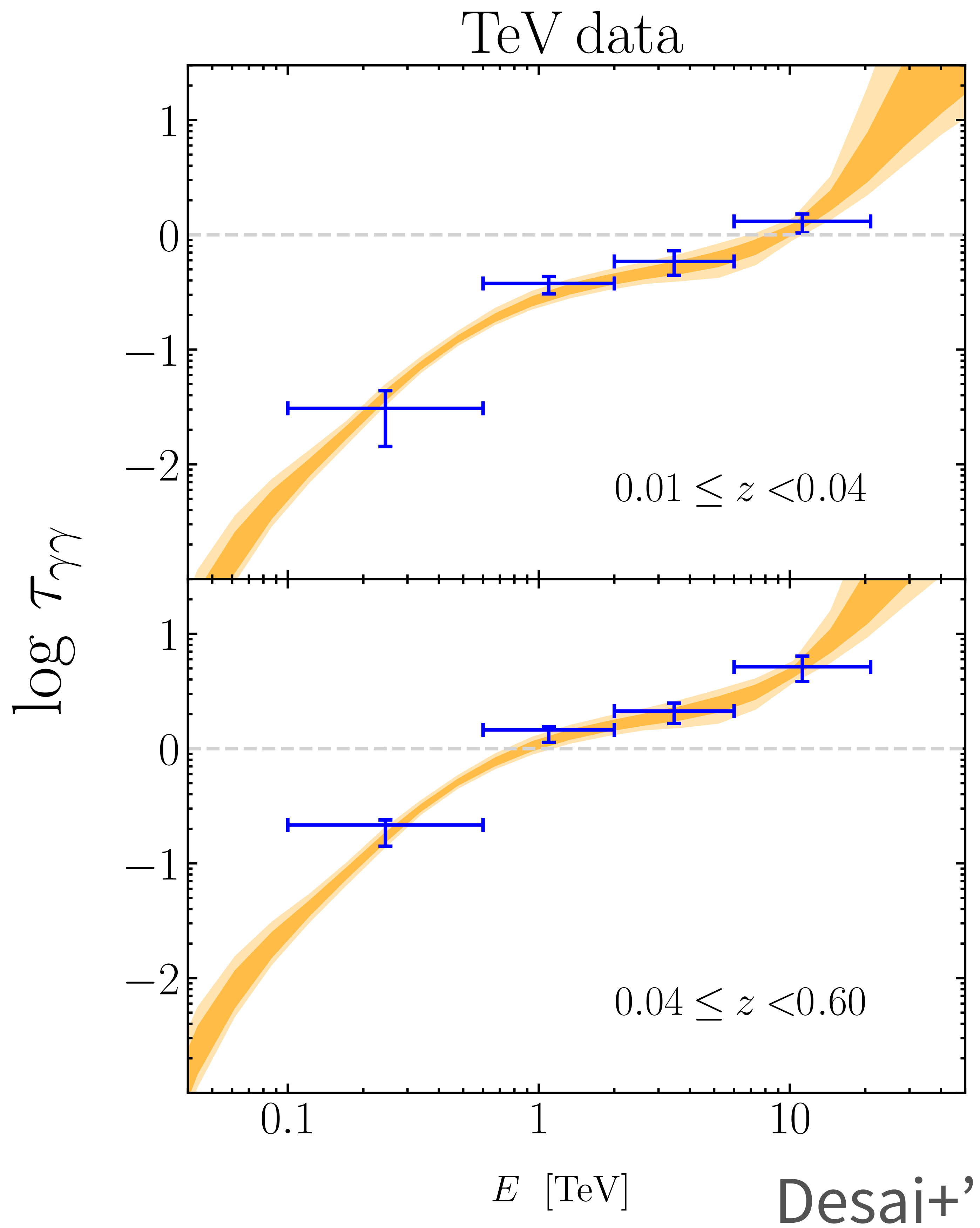
- Consistent with galaxy survey data.
    - Assume the EBL shape.
- We may need
    - Empirical EBL modeling based on the latest galaxy survey data
    - EBL model based on cosmological simulation



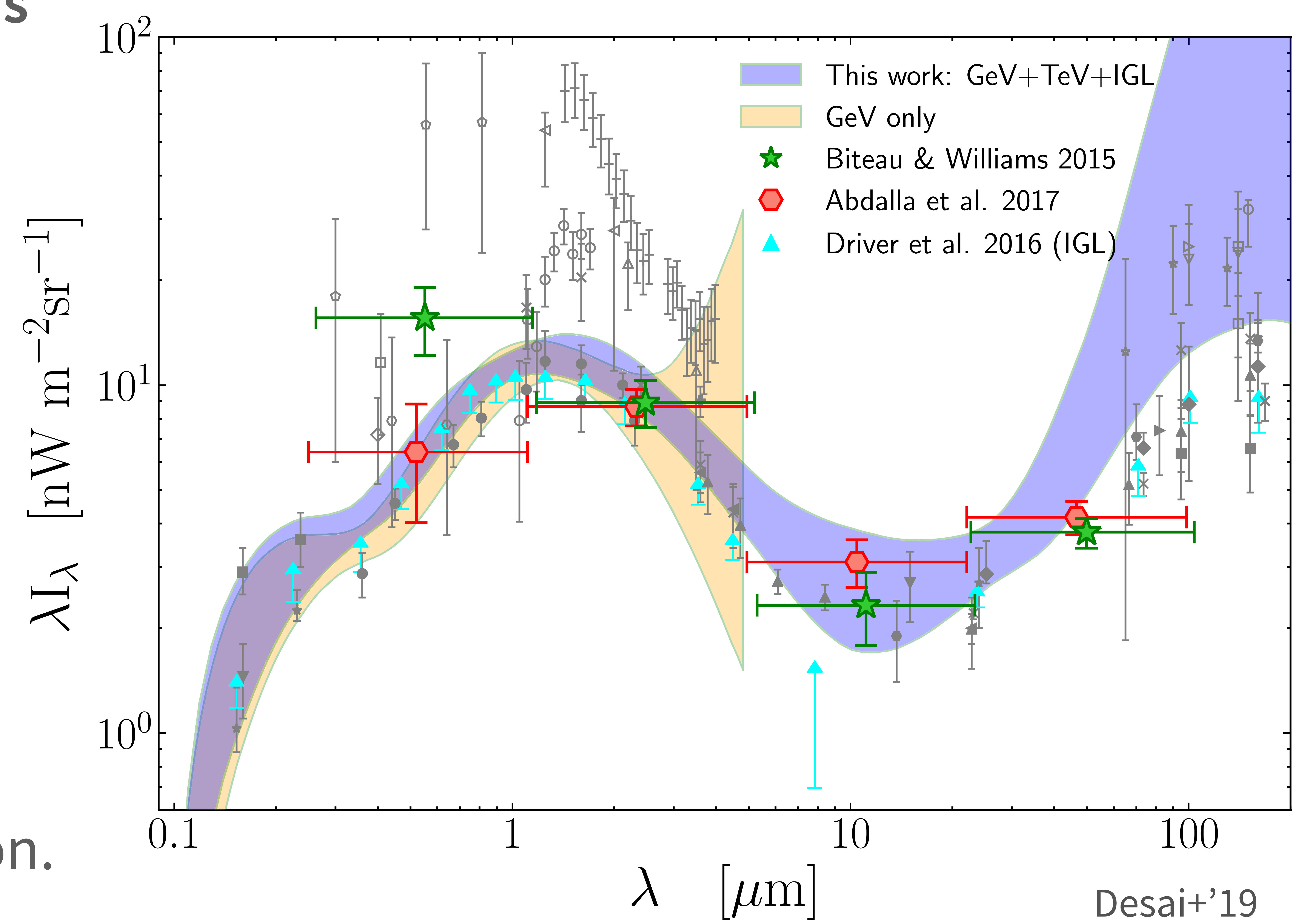

Abdollahi+'18

# EBL Determination with GeV-TeV data

## 38 GeV-TeV detected blazars




Desai+'19



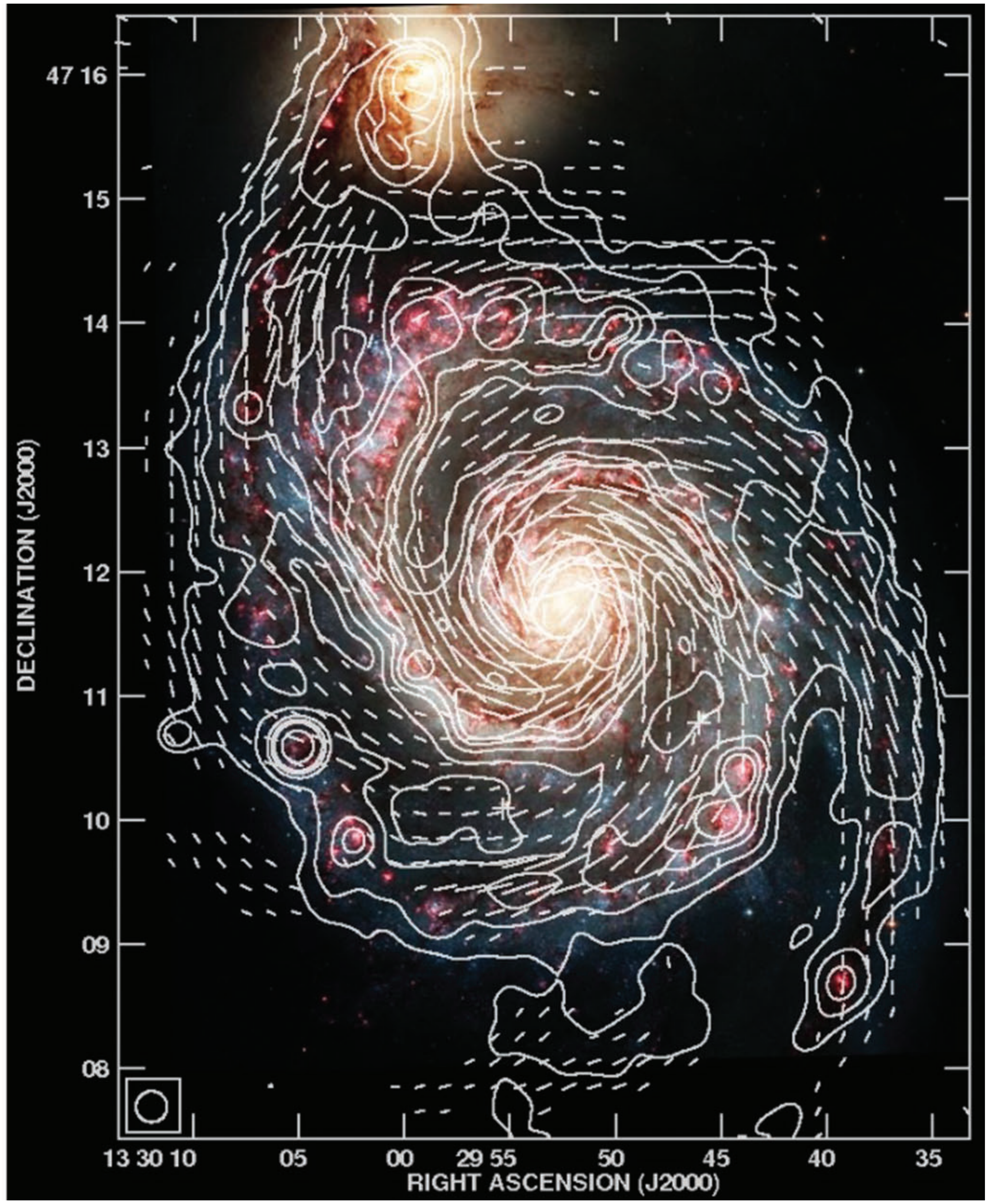

Desai+'19

- We can go to the IR region.

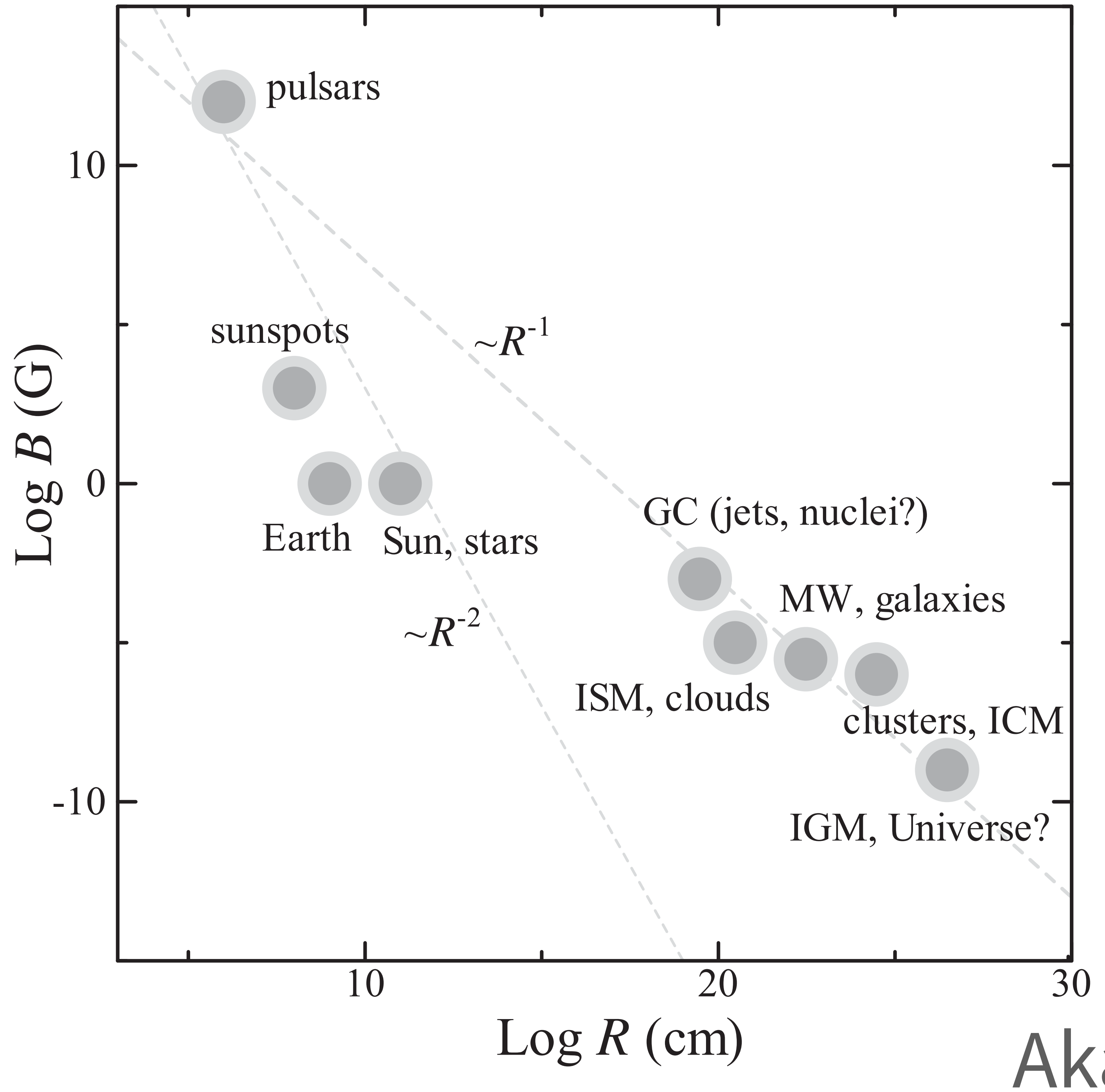
# Intergalactic Magnetic Field and Gamma-ray Observations

# Magnetic Fields in the Universe

## How strong is the cosmic magnetic field?




Fletcher+'11



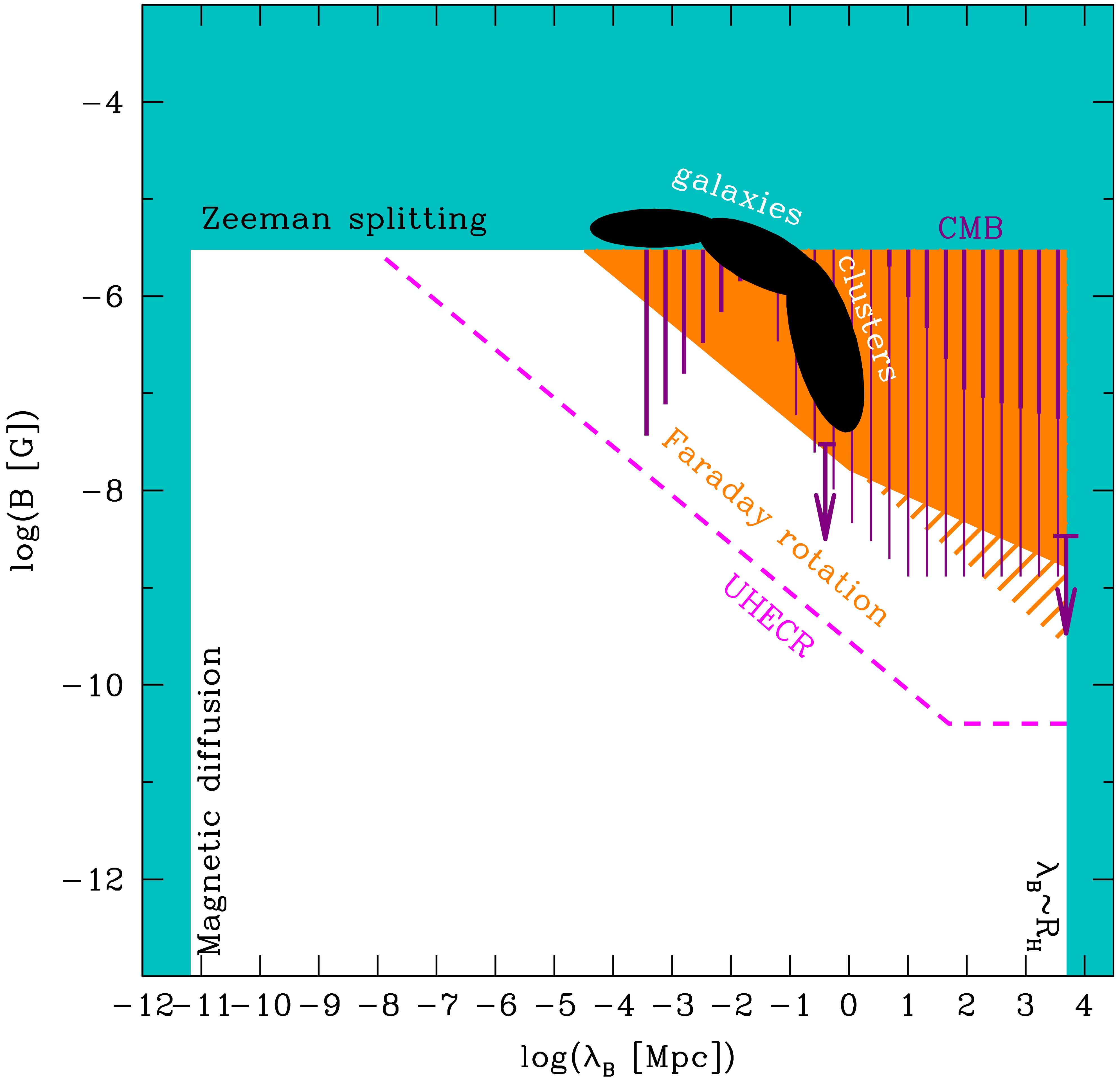

Akahori+'18

- Celestial objects are magnetized.
- Common presence of charged particles form high conductivity plasma in the universe.

# InterGalactic Magnetic Fields (IGMF)

## Toward the understanding of the seed of the cosmic magnetic fields

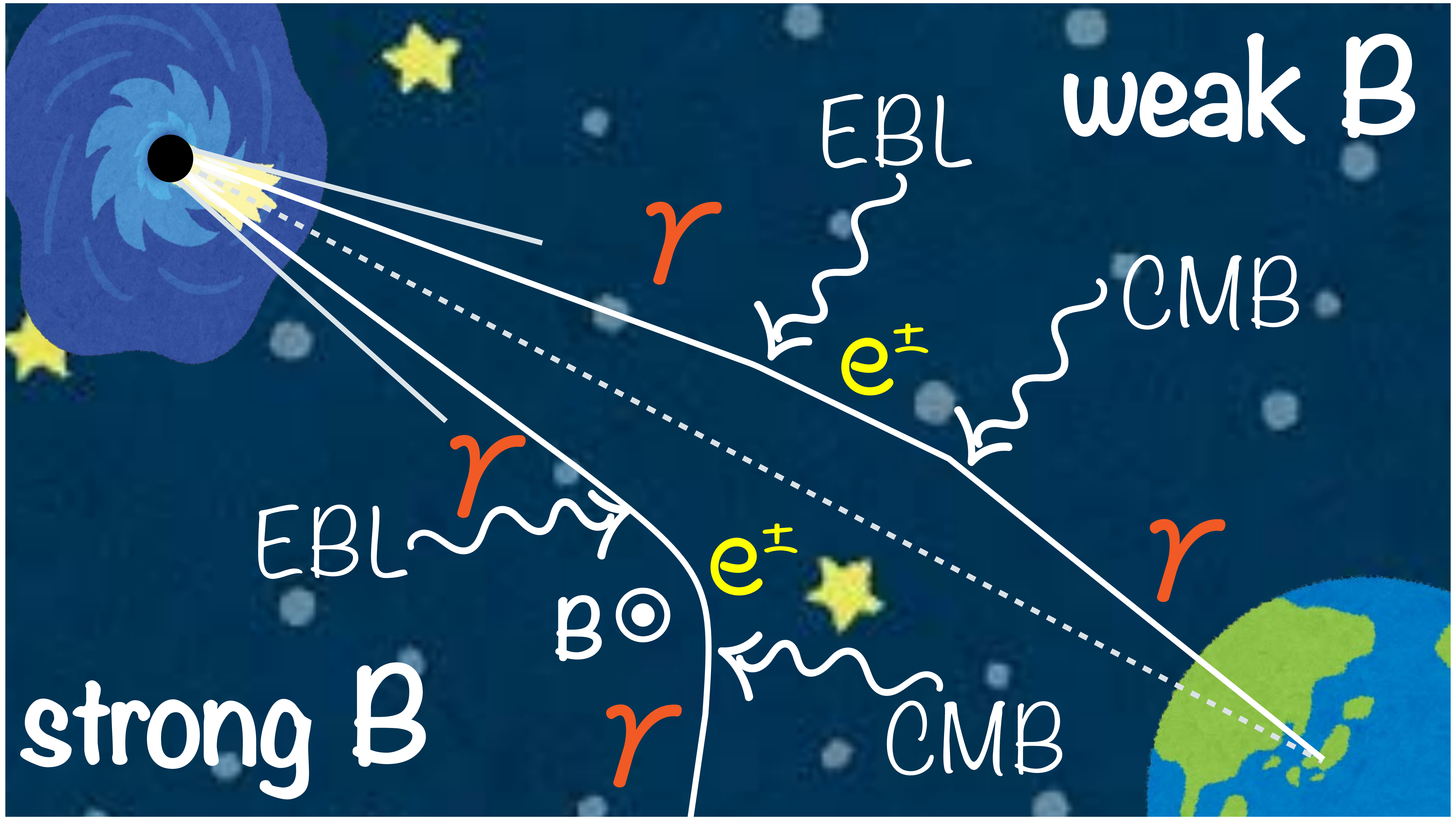
- Magnetic diffusion: $\lambda_{\rm coh} \geq \lambda_{\rm diff} = \sqrt{\frac{t_H}{4\pi\sigma}} \simeq 10^{13}$ cm
- Hubble radius: $\lambda_{\rm coh} \leq R_H$
- Zeeman splitting of 21 cm absorption line in quasar spectra (Heiles & Troland '04).
- Faraday rotation in quasars $\mathrm{RM} \leq \Delta\chi/\Delta\lambda^2 \propto B_{\rm IGMF} n_e$ (Kronberg & Simard-Normandin '76; Blasi+'99).
- Deflection of UHECRs (Lee+'95).
- Distortion on the CMB measurements (e.g., Jedamzik+'00; Barrow+'97;…)




Neronov & Semikoz '09

# Gamma-ray measurements can constrain IGMF

## Pairs Generate Cascade Emission



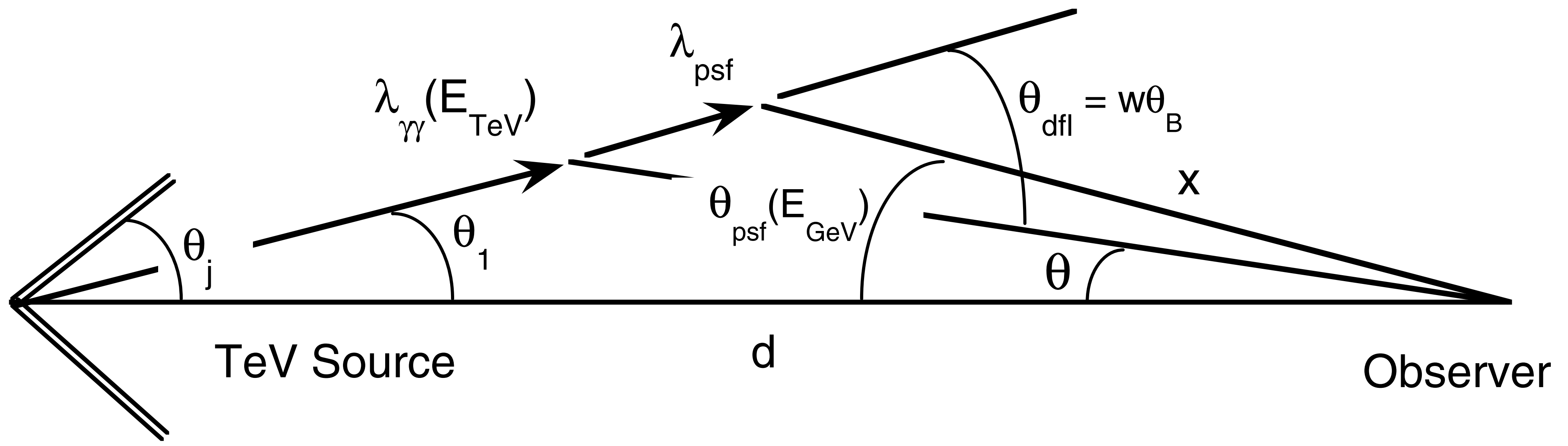

- Primary γ-rays are attenuated by EBL: $\gamma_{\mathrm{TeV}} + \gamma_{\mathrm{EBL}} \rightarrow e^+ + e^-$
- Pairs scatters CMBs as secondary γ-rays: $e^\pm + \gamma_{\mathrm{CMB}} \rightarrow e^\pm + \gamma_{\mathrm{GeV}}$
  - Energy is

$$E_{\mathrm{2nd}} \simeq \frac{4}{3}\gamma_e^2 E_{\mathrm{CMB}} \simeq 0.8 \left(\frac{E_{\mathrm{1st}}}{1\mathrm{TeV}}\right)^2 \mathrm{GeV}$$

- Magnetic field can deflect the trajectory of pairs.
  - Secondary signals strongly depends on IGMF (e.g., Plaga '95).

# Time Delay of Secondarys

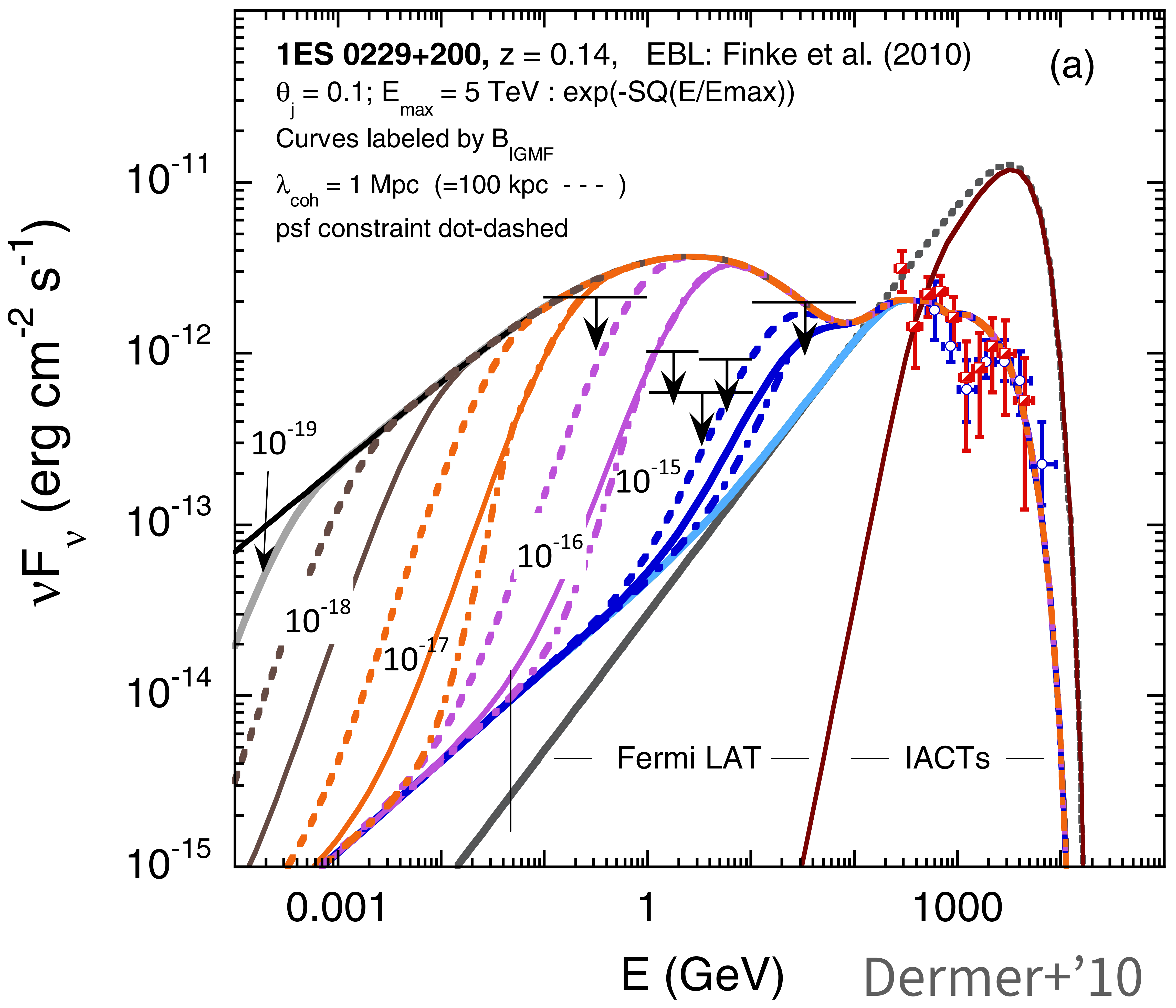
**Dai+'02; Fan+'04; Murase+'08,,,,**




- Activity Timescale
  - $\Delta t_{\rm flare} \simeq \text{min} - \text{Myr}$
- Angular Spreading
  - $\Delta t_{\rm Ang} \simeq \frac{\lambda_{\gamma\gamma}}{2\gamma_e^2 c} \simeq 10^3 \left(\frac{\gamma_e}{10^6}\right)^{-2} \left(\frac{n_{\rm EBL}}{0.1\ \text{cm}^{-3}}\right)^{-1}\ \text{s}$
- IC Cooling
  - $\Delta t_{\rm IC} \simeq \frac{\lambda_{\rm IC}}{2\gamma_e^2 c} \simeq 40 \left(\frac{\gamma_e}{10^6}\right)^{-3}\ \text{s}$
- Magnetic Deflection
  - $\Delta t_{\rm B} \simeq \frac{\lambda_{\rm IC}}{c}\theta_{\rm B}^2 \simeq 6 \times 10^3 \left(\frac{\gamma_e}{10^6}\right)^{-5} \left(\frac{B_{\rm IGMF}}{10^{-20}\ \text{G}}\right)^2\ \text{s}$
  - Deflection Angle
    $\theta_{\rm B} \simeq \max\left[\frac{\lambda_{\rm IC}}{R_{\rm L}}, \frac{(\lambda_{\rm IC}\lambda_{\rm coh})^{1/2}}{R_{\rm L}}\right]$
    - $\lambda_{\rm coh}$ is the coherent length of IGMF.
- Delay Timescale:
  $\Delta t = \max[\Delta t_{\rm flare}, \Delta t_{\rm Ang}, \Delta t_{\rm IC}, \Delta t_B]$

# Gamma-ray Spectrum of Secondary Emission

## Significant dependence on IGMF

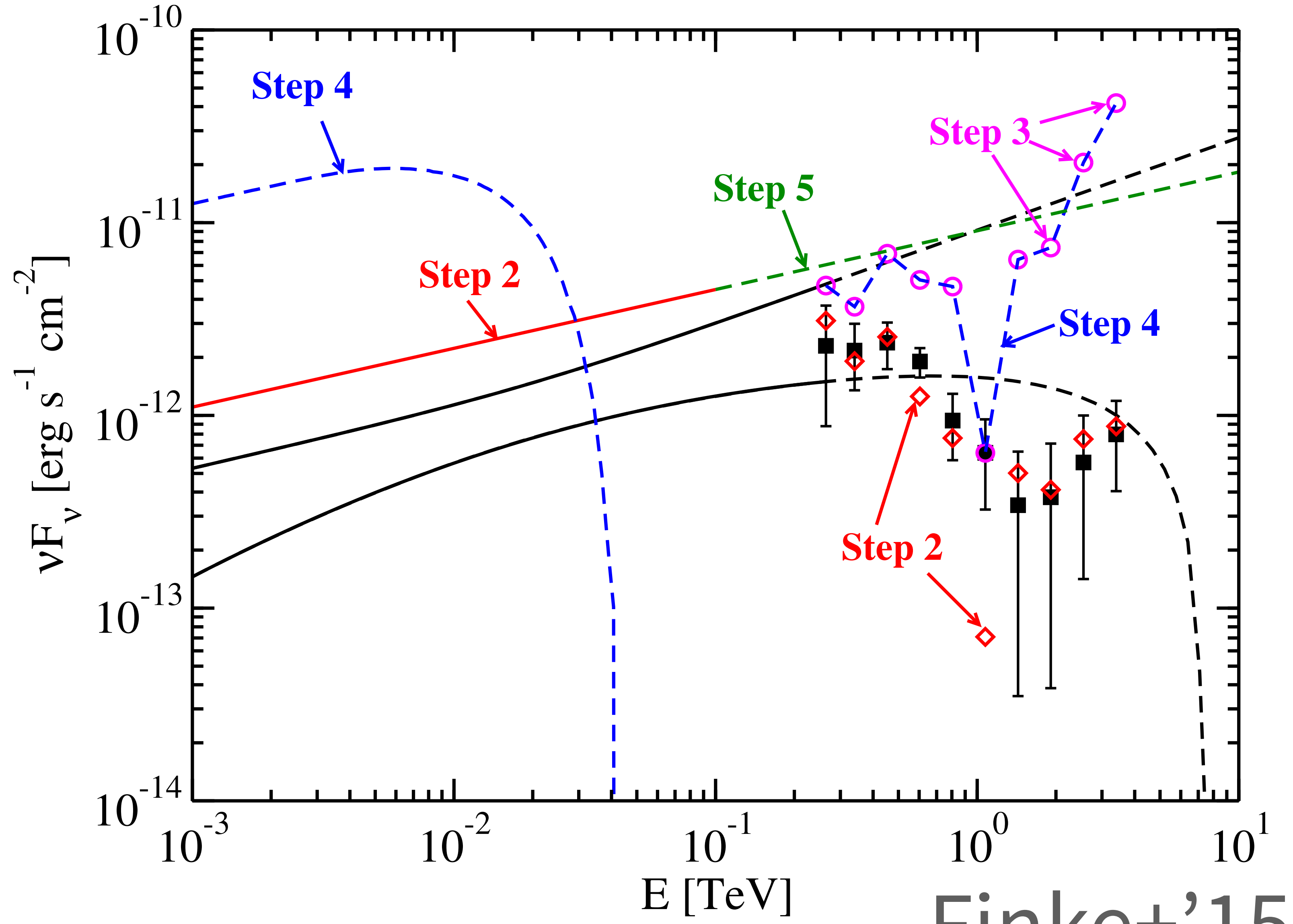



Dermer+’10

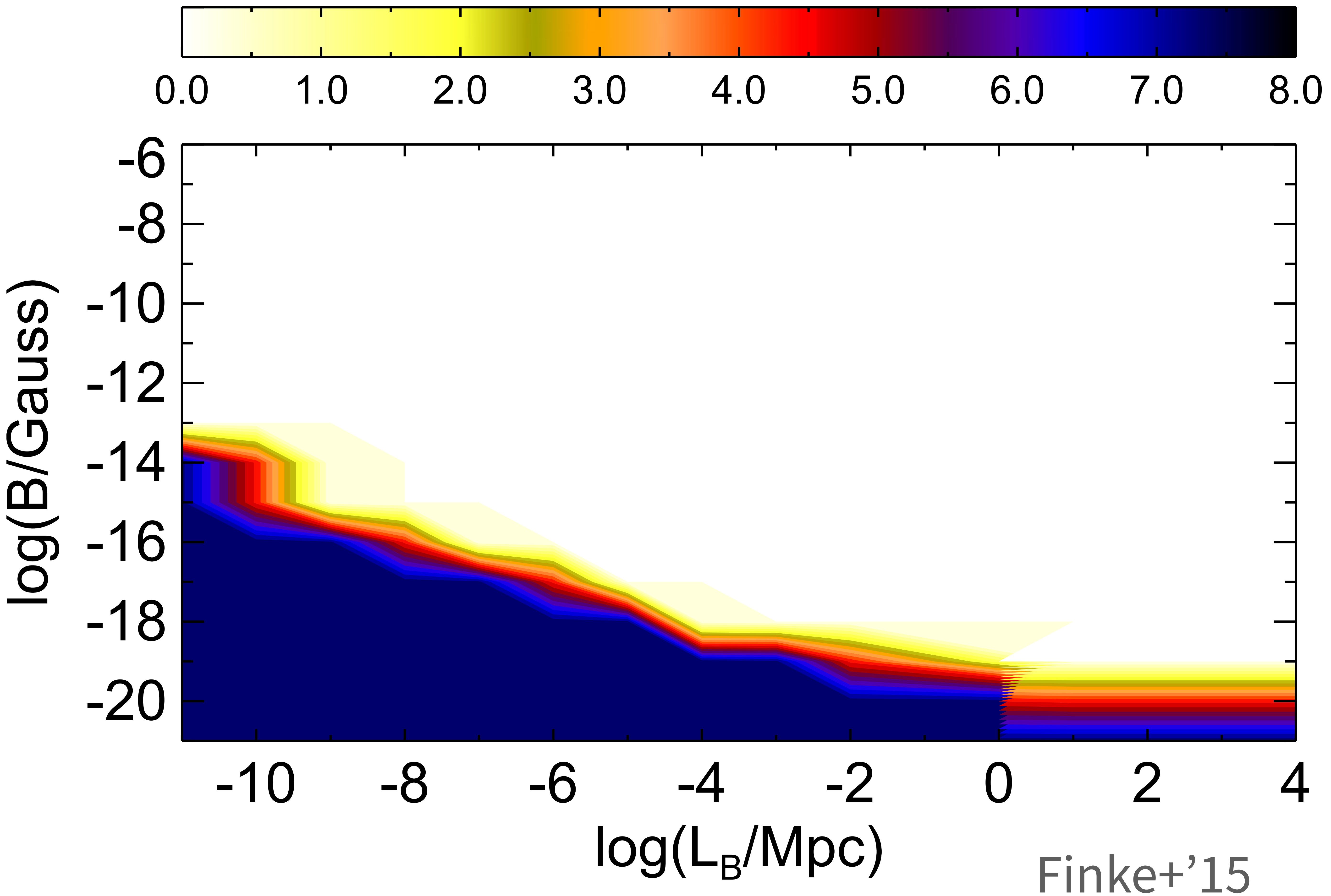
- IGMF dependence appears in the GeV band.
- But, be careful. It also depends on
  - Intrinsic spectrum
  - EBL model
  - Source activity timescale: $\Delta t_{\rm flare}$
  - Coherent length: $\lambda_{\rm coh}$
  - Jet opening angle: $\theta_{\rm jet}$

# Current bounds on the IGMF

## from the secondary spectrum




Finke+'15

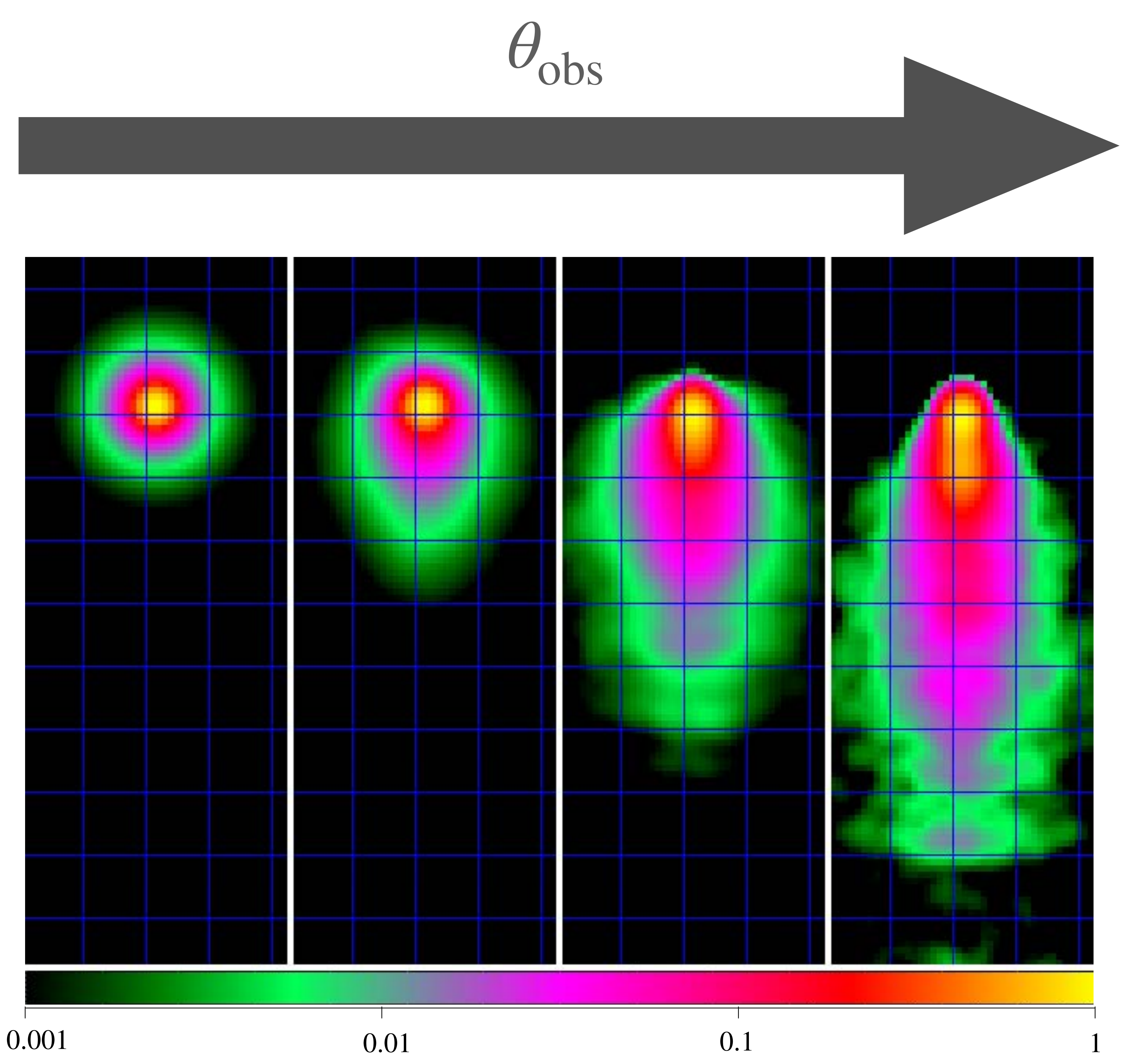



Finke+'15

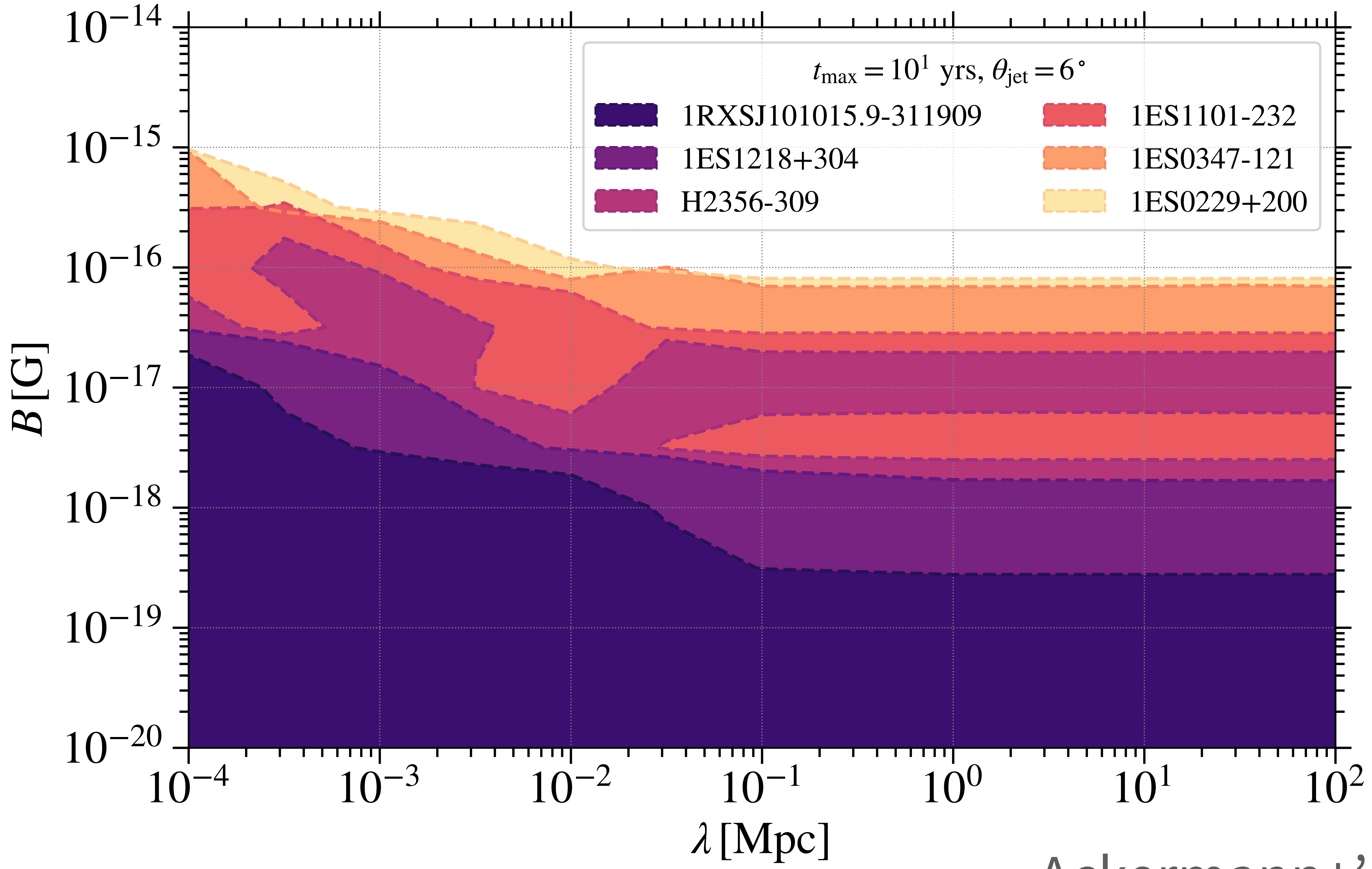
- $B_{\rm IGMF} \geq 10^{-19}$ G for $\lambda_{\rm coh} \geq 1$ Mpc with $\Delta t_{\rm flare} = 3$ yr
  - at >5σ confidence level

# Extended Pair Halo

## Secondary is spatially extended




Neronov+'10



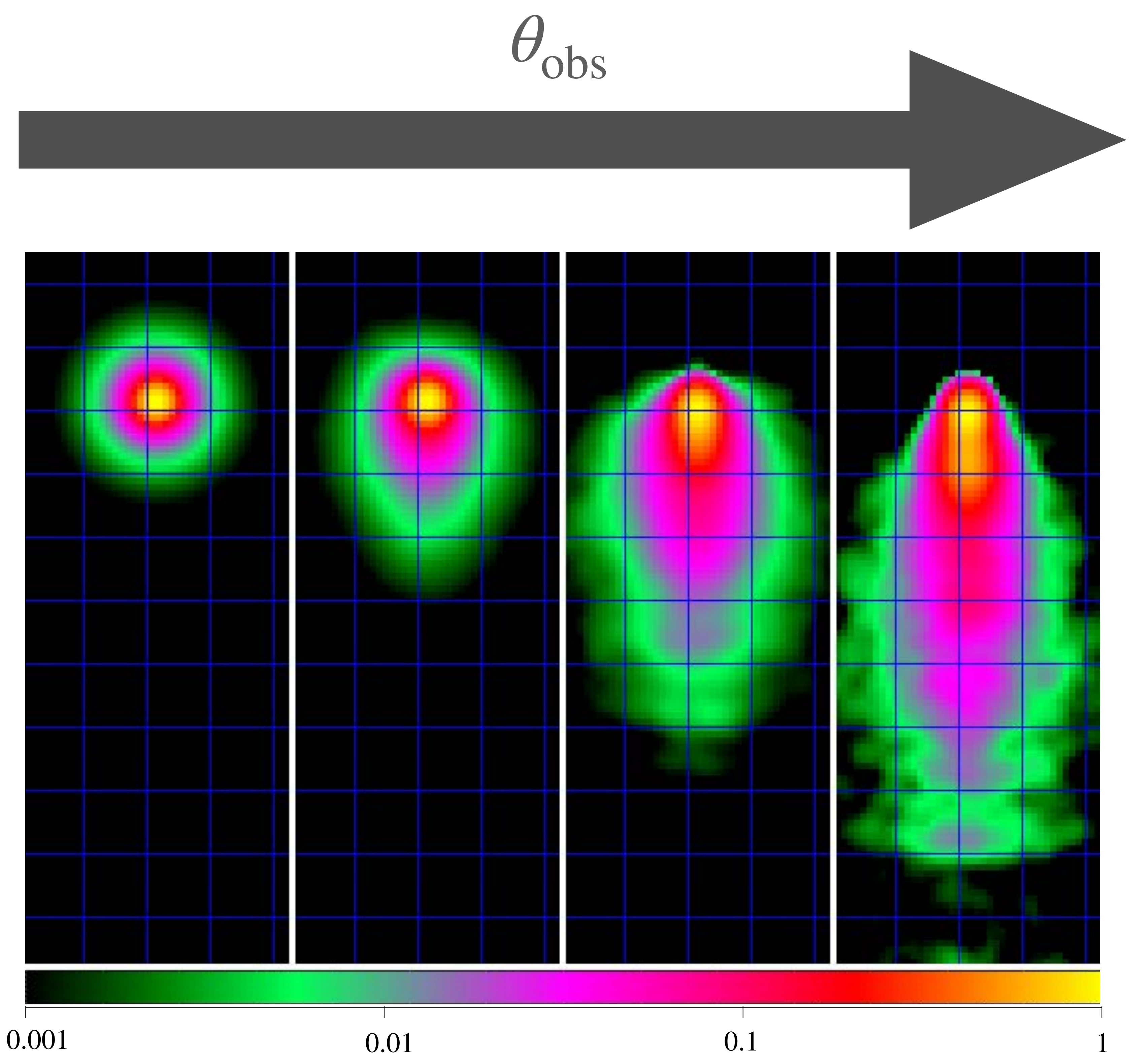

Ackermann+'18

- Currently no spatial extension is seen by Fermi.
- Combining with spectral constraints, we have
  - $B_{\rm IGMF} \geq 10^{-16}$ G for $\lambda_{\rm coh} \geq 1$ Mpc with $\Delta t_{\rm flare} = 10$ yr

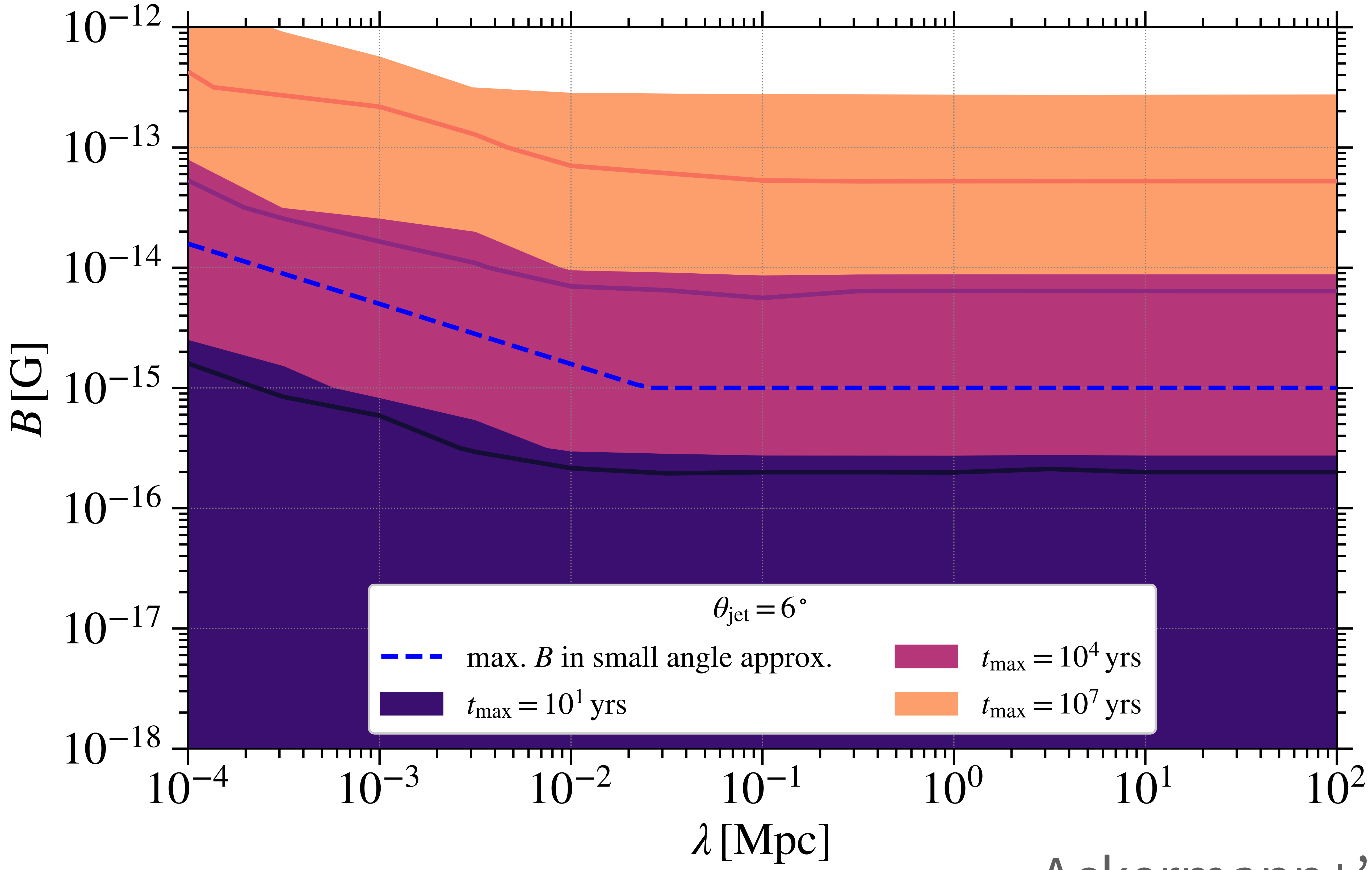
$$\tau = n\sigma l \Rightarrow l = \frac{1}{n\sigma_{\gamma\gamma}}$$

# Extended Pair Halo

## Secondary is spatially extended




Neronov+'10



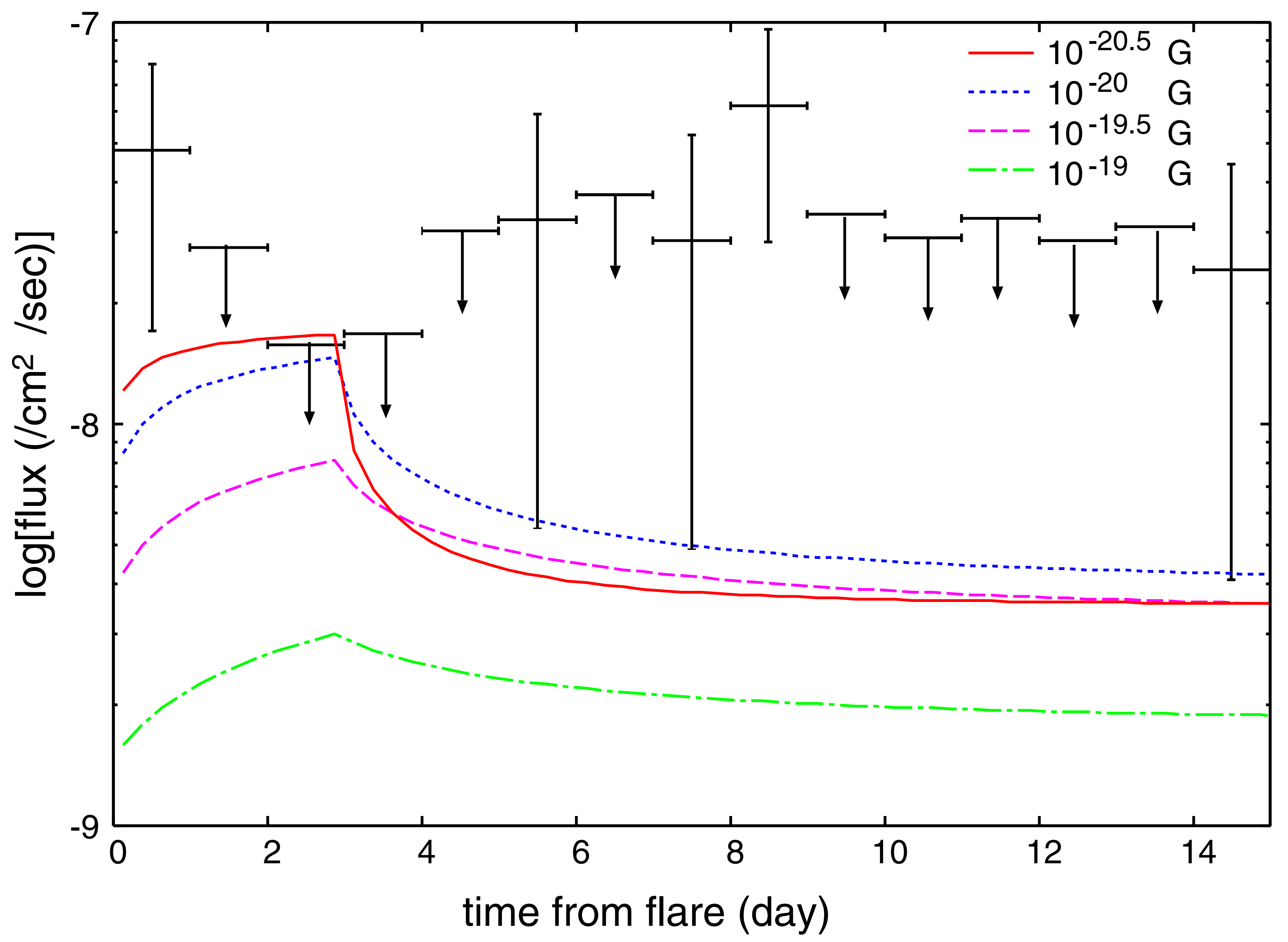

Ackermann+'18

- Currently no spatial extension is seen by Fermi.
- Combining with spectral constraints, we have
  - $B_{IGMF} \geq 10^{-16}$ G for $\lambda_{coh} \geq 1$ Mpc with $\Delta t_{flare} = 10$ yr

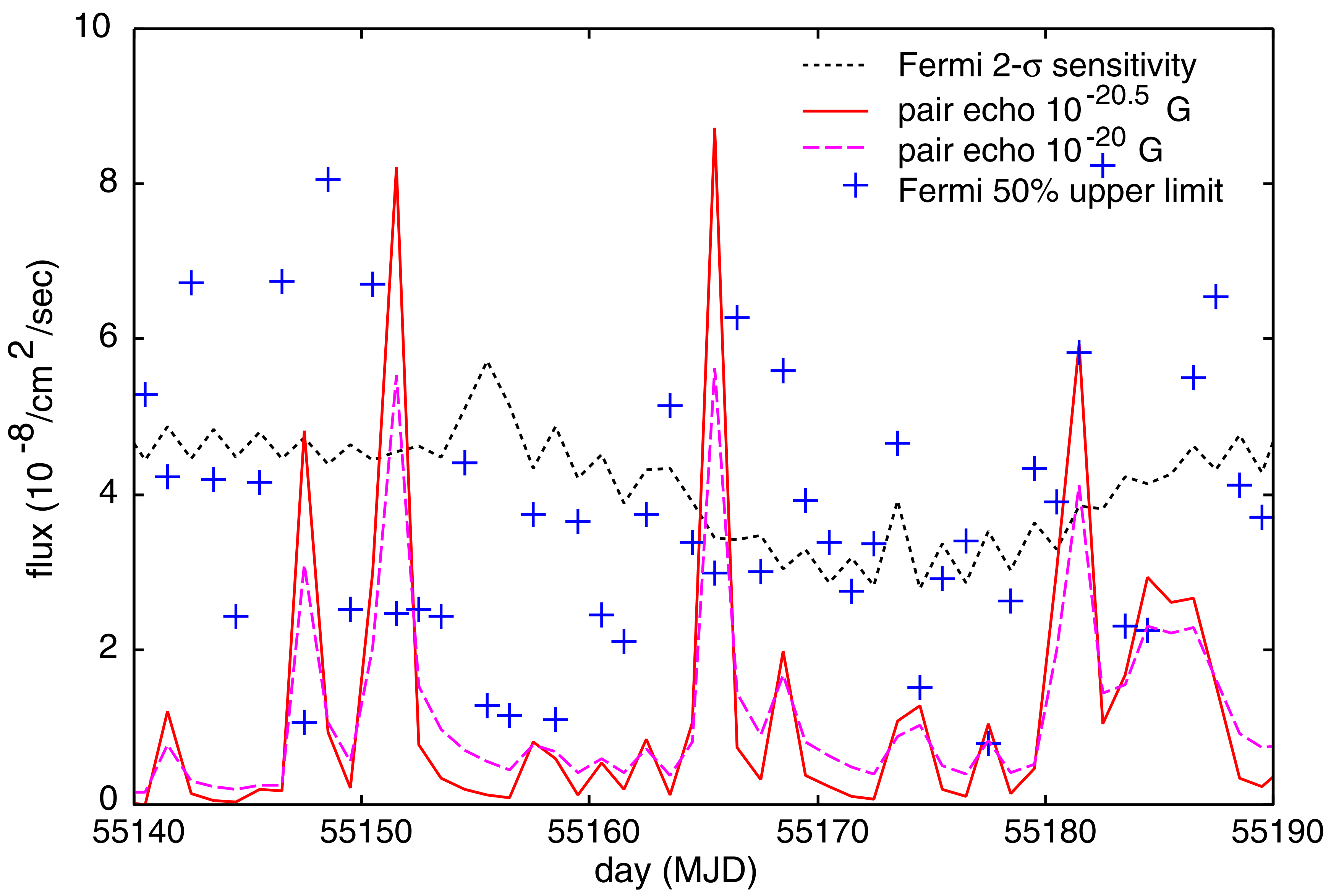
# Time delay

## Delayed flare in GeV band?

- $\Delta t_{\mathrm{B}} \simeq \frac{\lambda_{\mathrm{IC}}}{c}\theta_{\mathrm{B}}^2 \simeq 6 \times 10^3 \left(\frac{\gamma_e}{10^6}\right)^{-5} \left(\frac{B_{\mathrm{IGMF}}}{10^{-20}\ \mathrm{G}}\right)^2\ \mathrm{s}$
  - $B_{\mathrm{IGMF}} \geq 10^{-20}$ G for $\lambda_{\mathrm{coh}} \geq 1$ kpc
- Future simultaneous GeV-TeV observations will be useful.



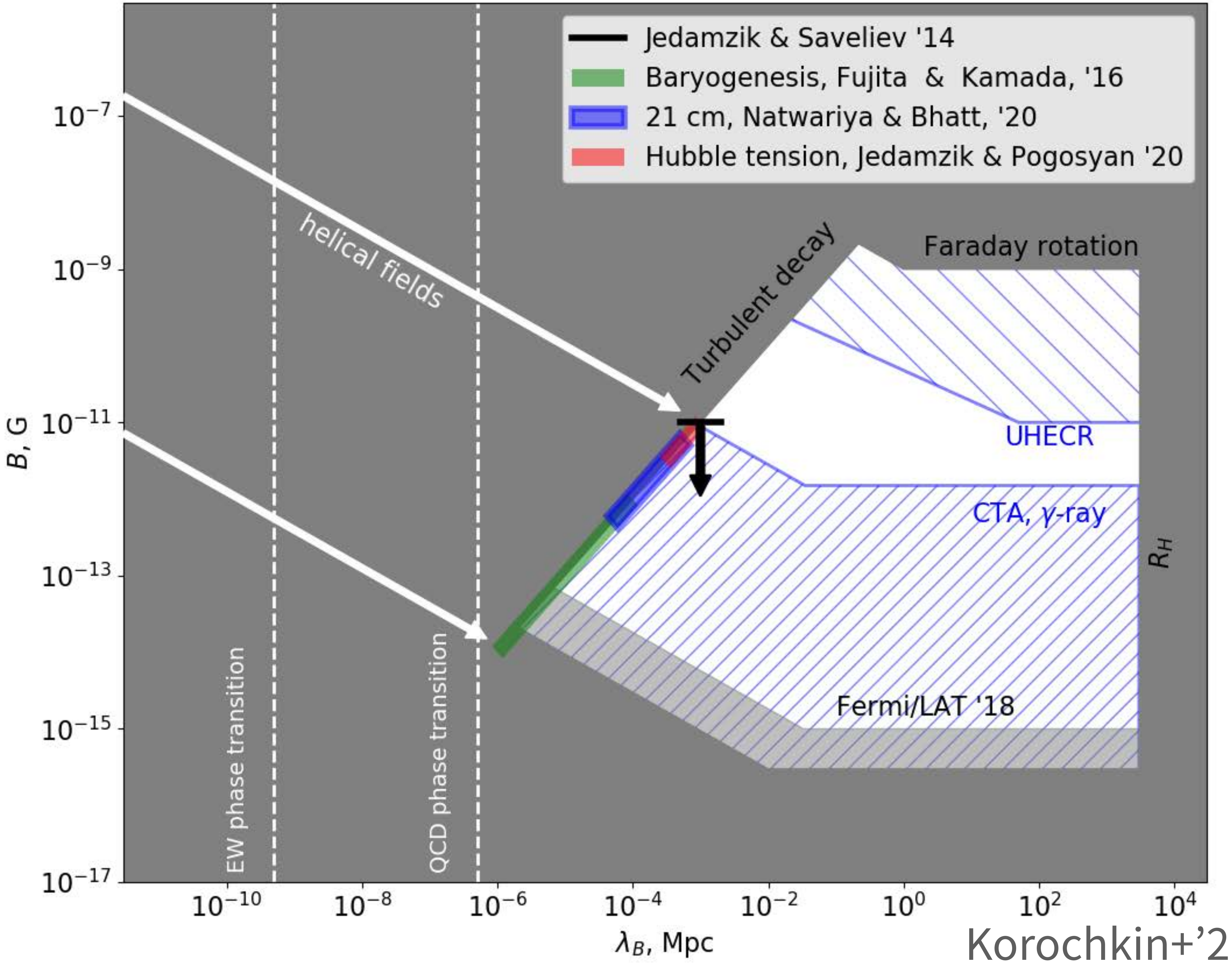

Takahashi+’12




Takahashi+’13

# Bounds on the IGMF

- IGMF parameter region is constrained by various methods.
- Future CTA observations will shrink the allowed region.

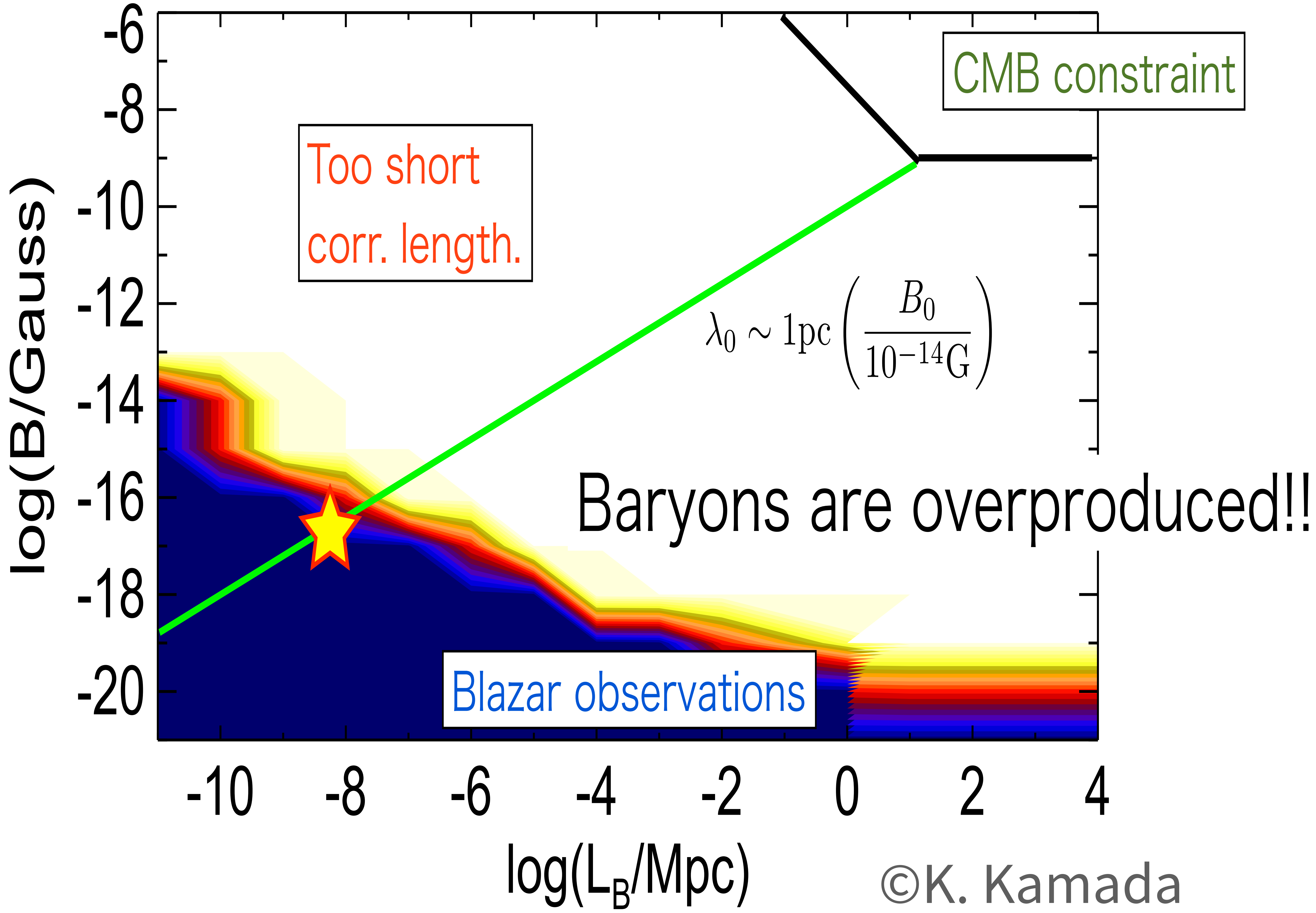



Korochkin+'20

# Baryogenesis?

## Please refer to Kamada & Fujita for details…

- Baryon asymmetry may generated through the magnetic activity in the early universe (Givannini & Shaposhnikov ’98, Kamada & Fujita ’16).
- The required values for the explanation of baryon asymmetry is
  - $B_{\rm IGMF} \simeq 10^{-17} - 10^{-16}$ G for $\lambda_{\rm coh} \simeq 10^{-2} - 10^{3}$ pc (Kamada & Long ’16)

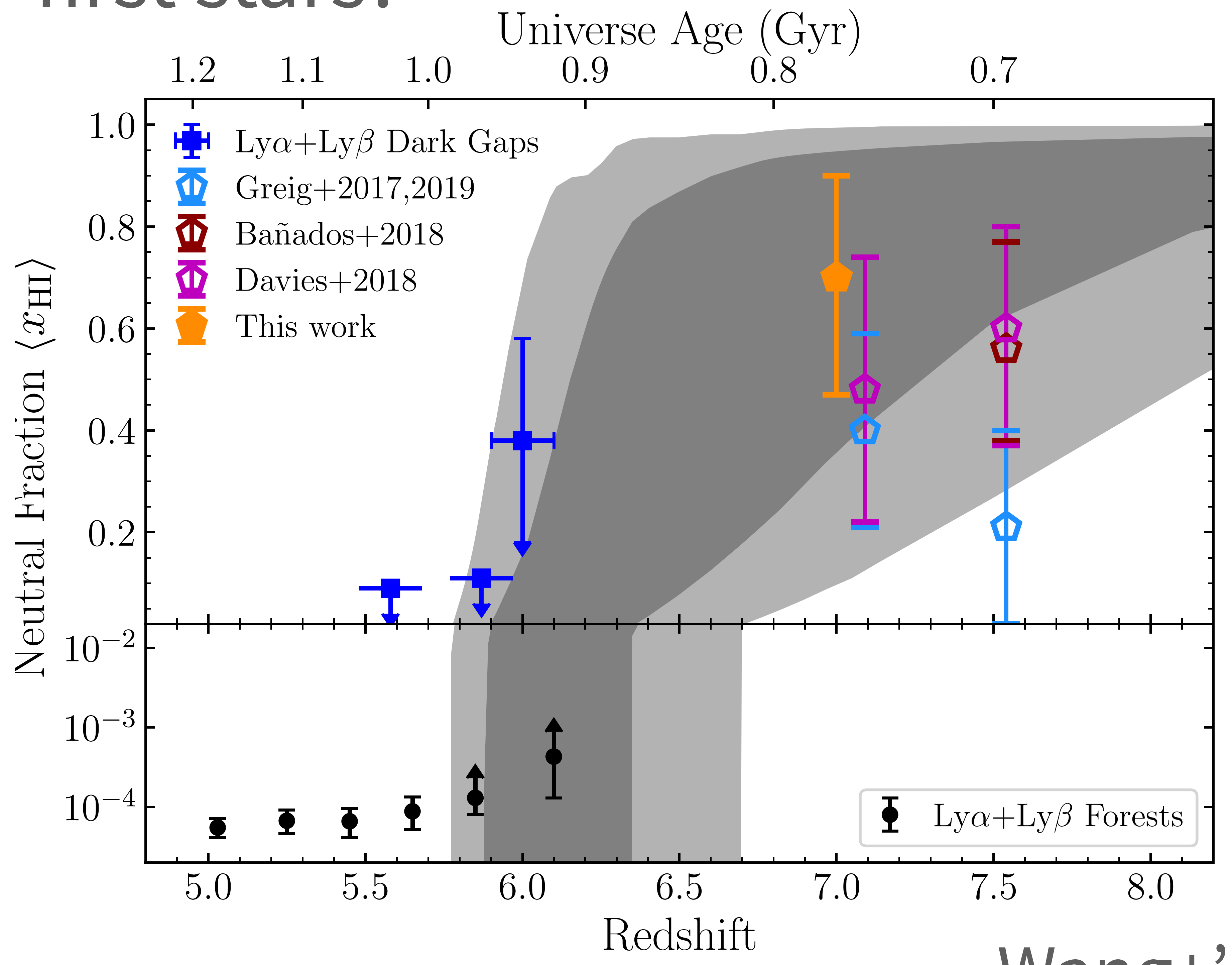


# Reionization and Cosmic Expansion

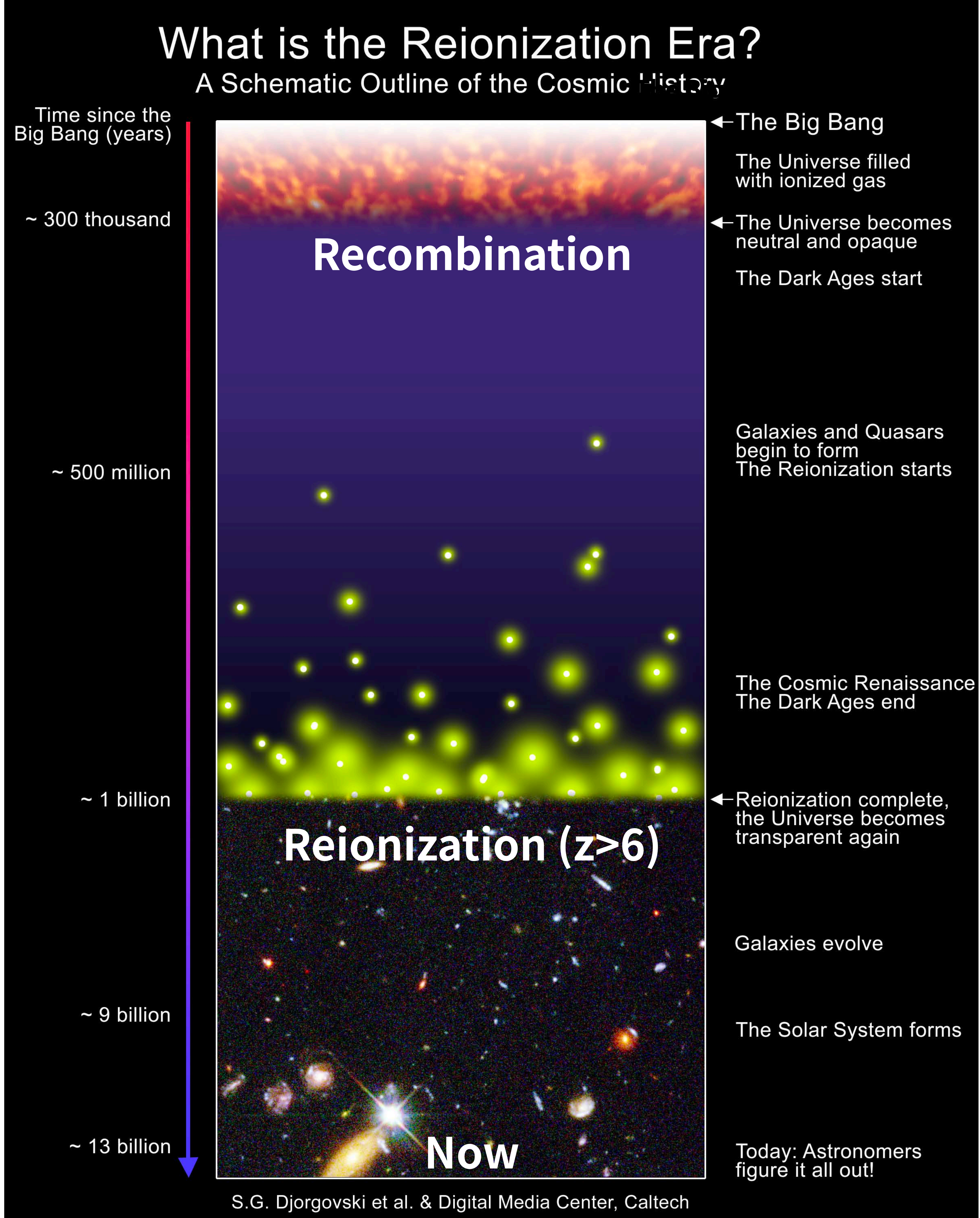
# Cosmic Reionization

## when was the universe ionized again?

- What was the cosmic star formation history in the early universe?
  - first stars?

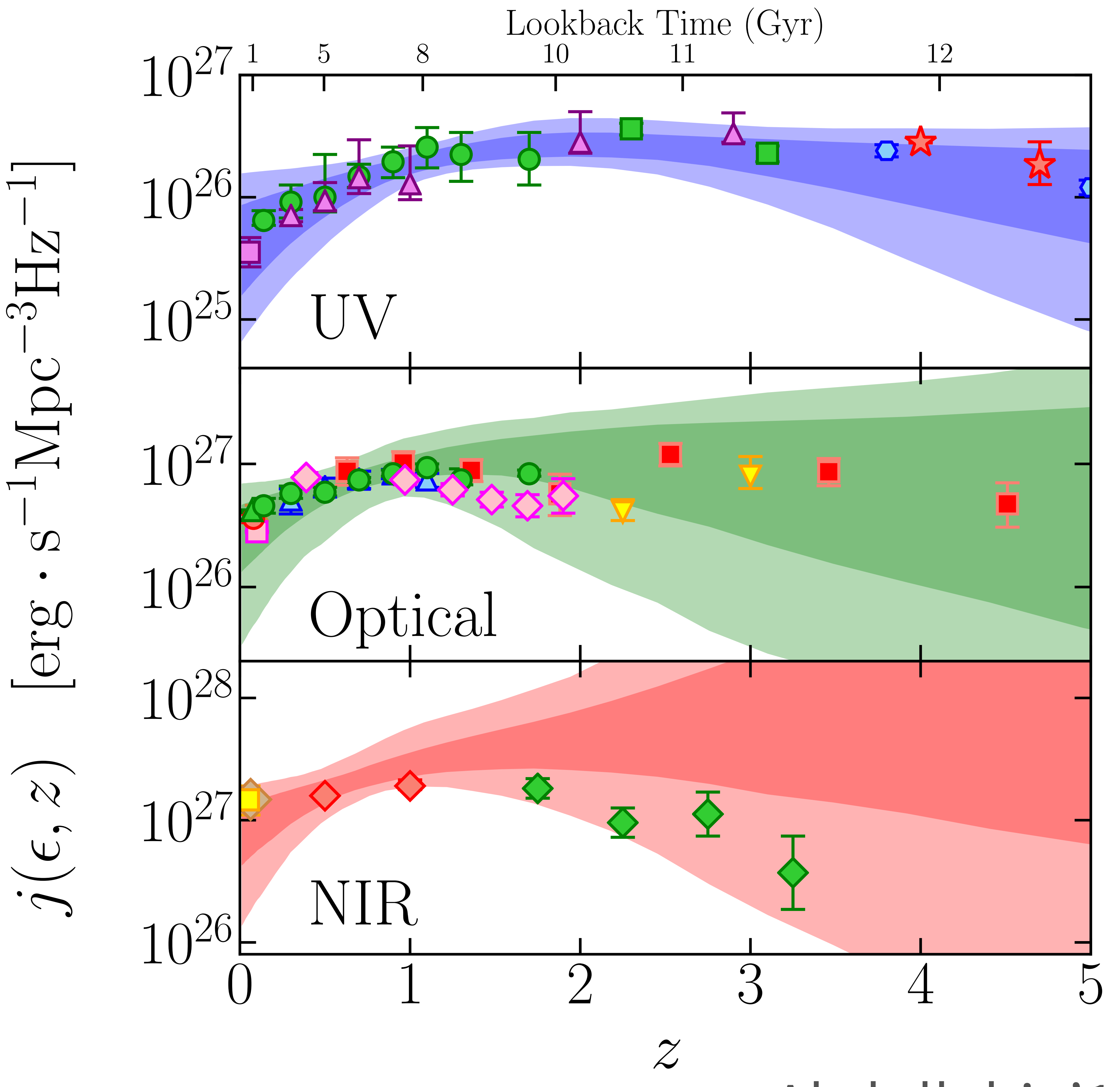



Wang+'20

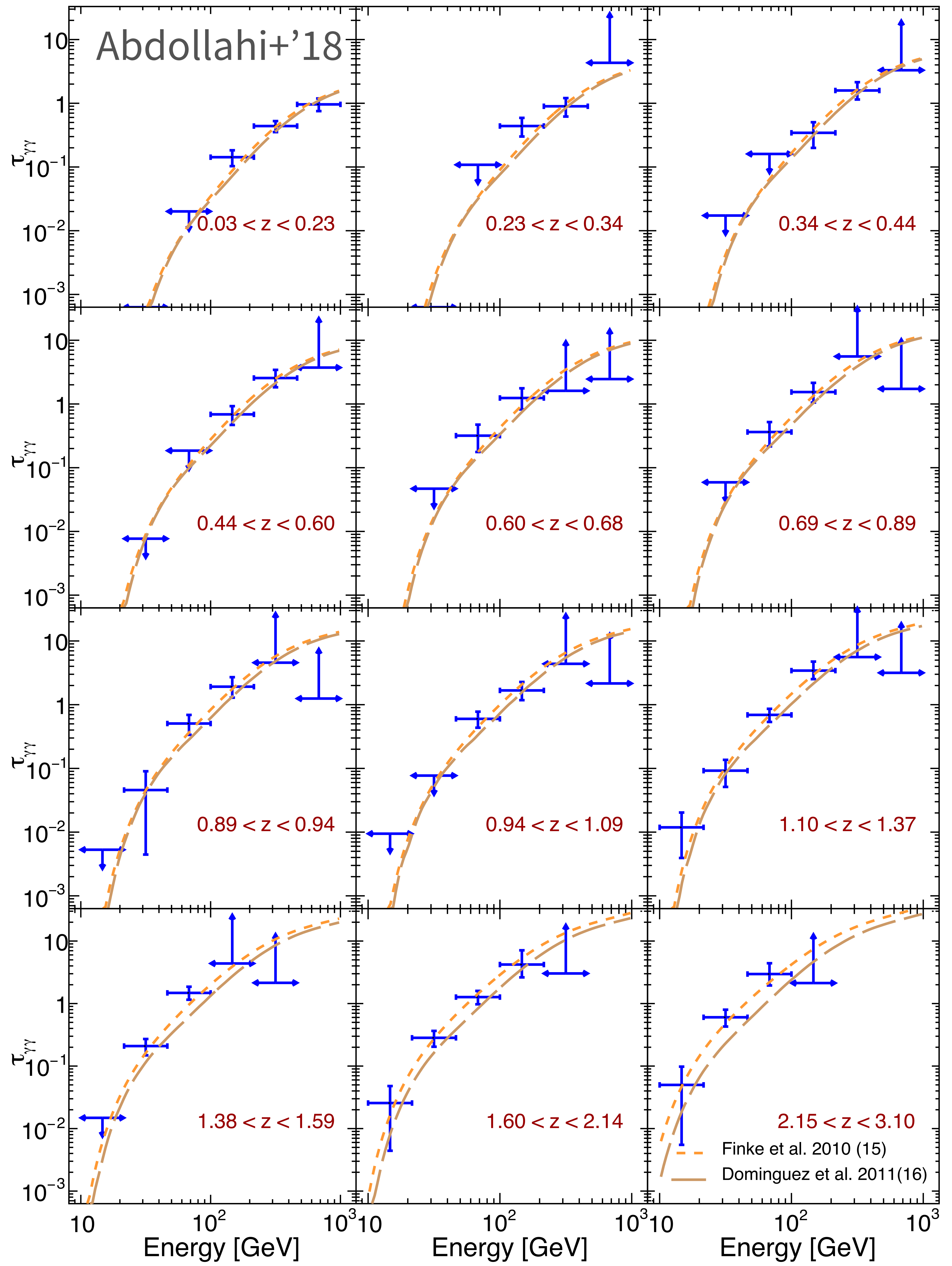


# Cosmic luminosity density

## Estimation from gamma-ray opacity



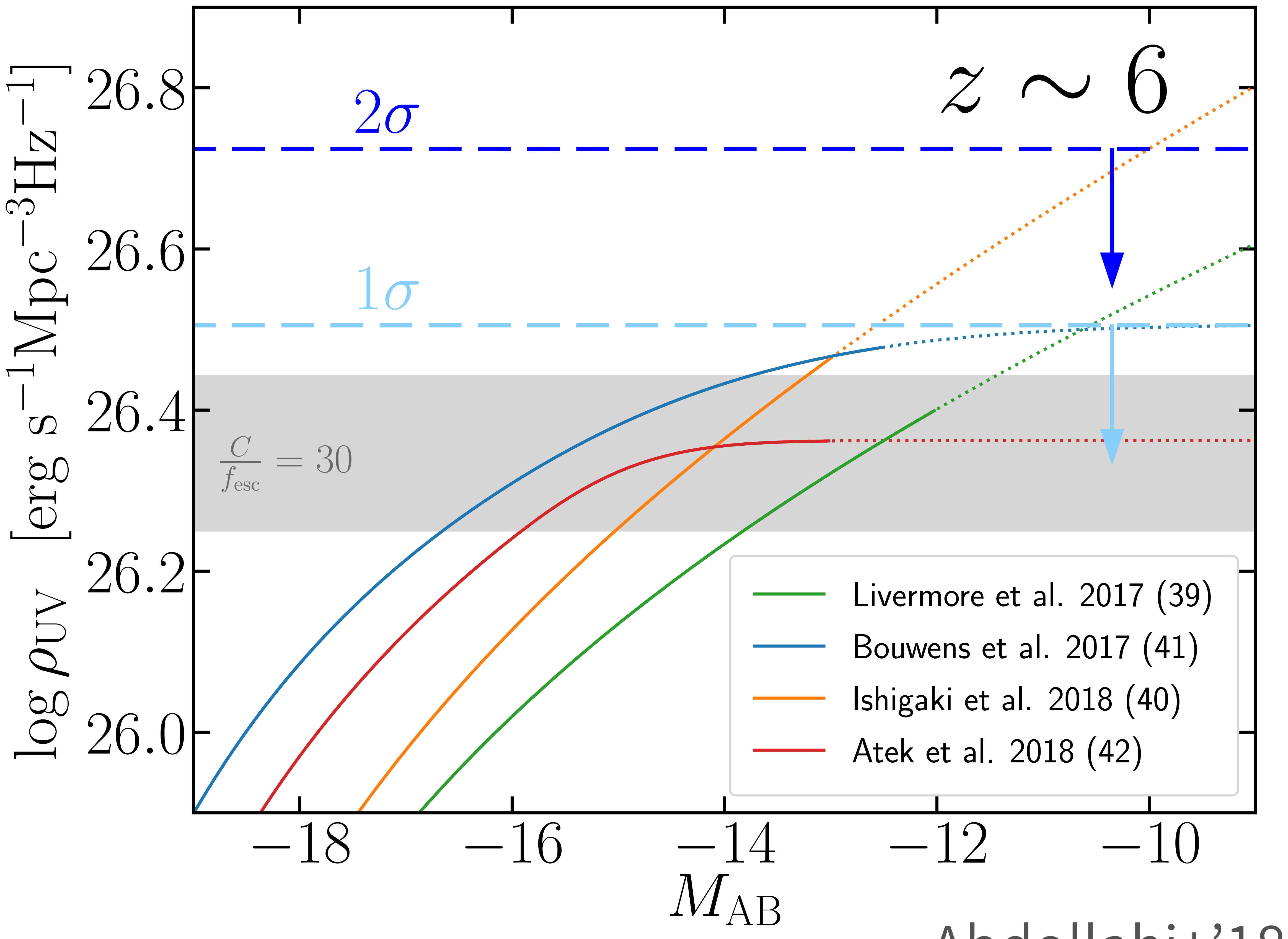

Abdollahi+'18



# Constraints on the reioniztion history

## Constraining galaxy luminosity functions

- Faint-end slope of galaxy luminosity function at high redshift is highly uncertain.
- Current gamma-ray observations constraints some available models.

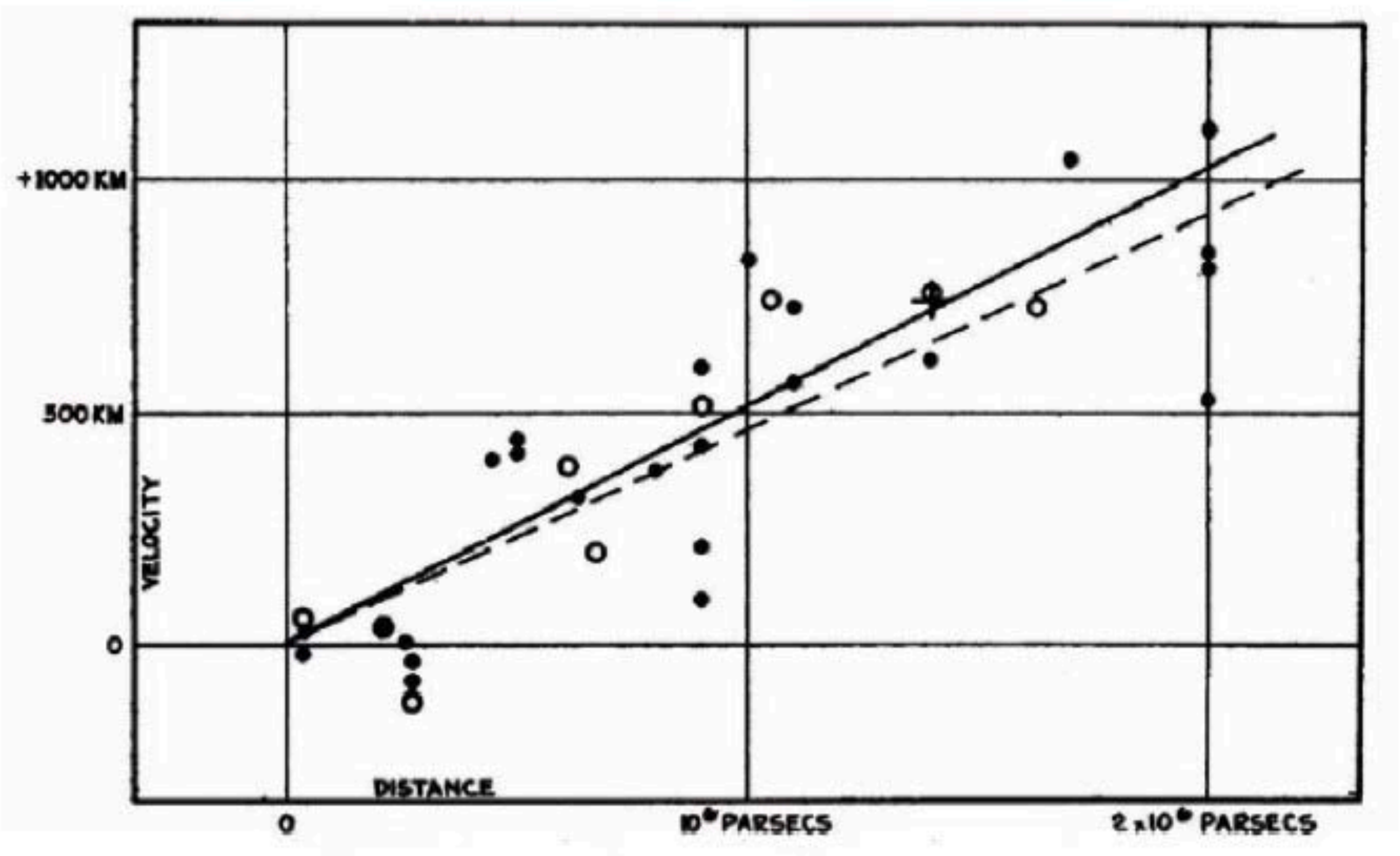



Abdollahi+'18

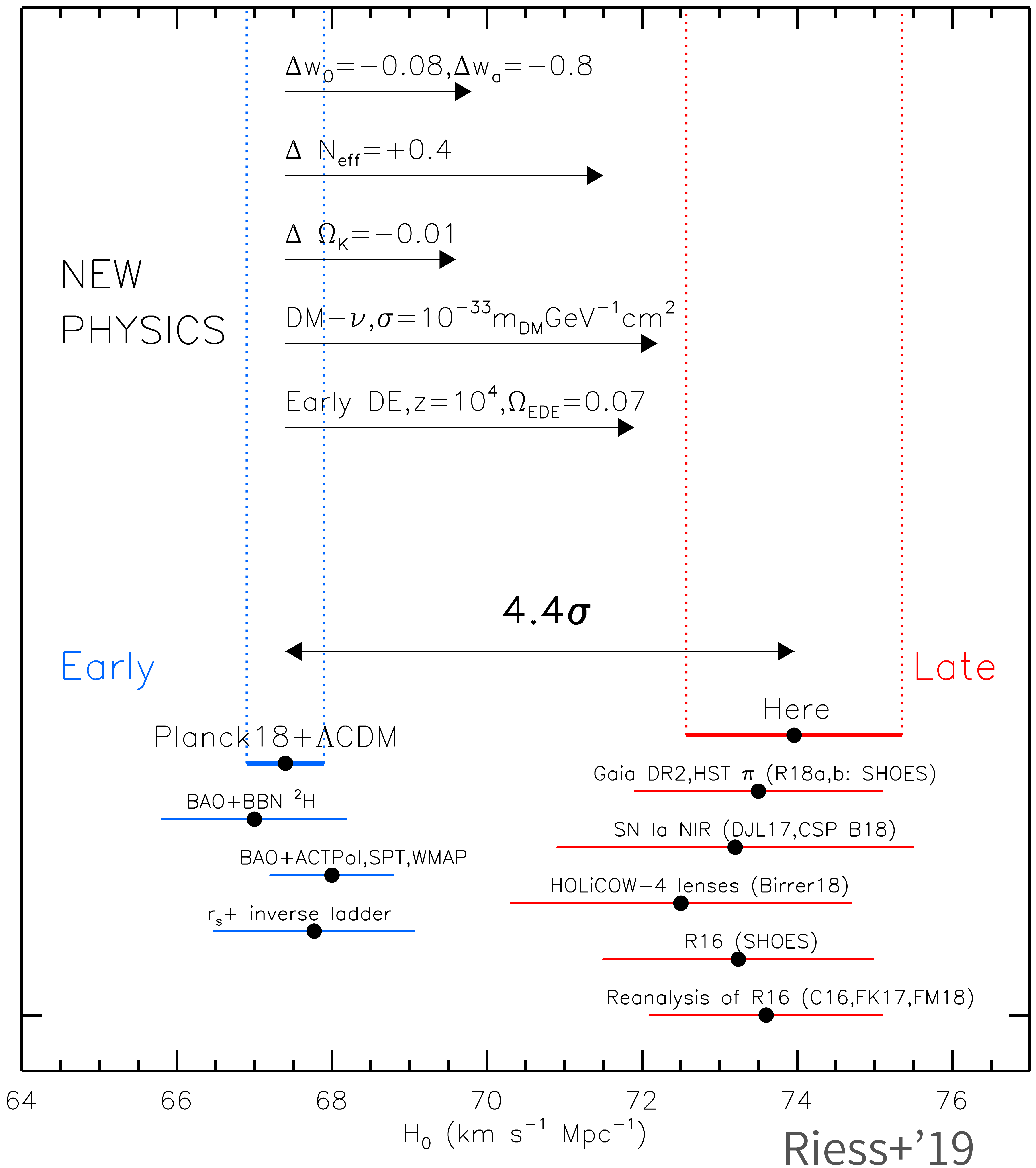
# Hubble–Lemaître law

## Tension in the $H_0$

- $H_0$ characterize the expansion of the universe.



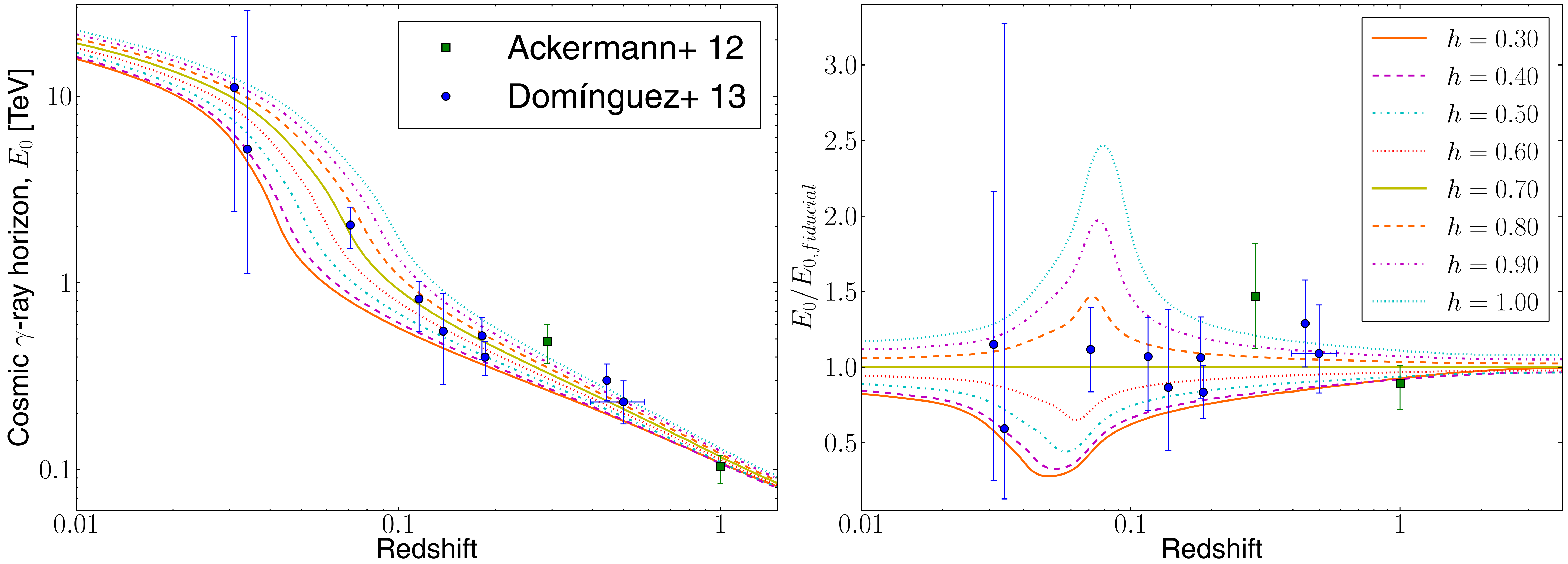

Hubble 1929



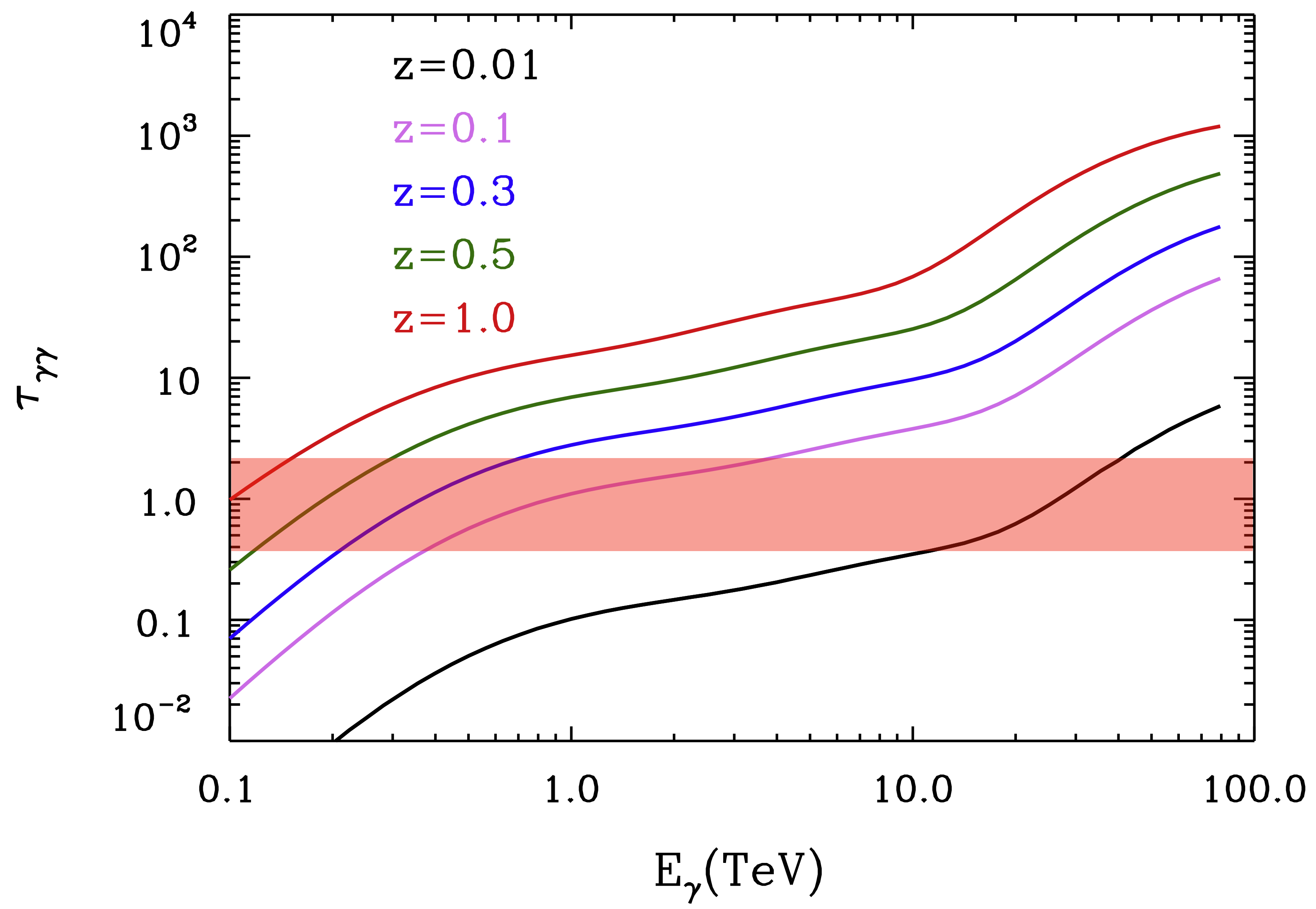

Riess+'19

# Cosmic gamma-ray horizon & Hubble Constant

**where** $\tau_{\gamma\gamma} = 1$




Dominguez+'13



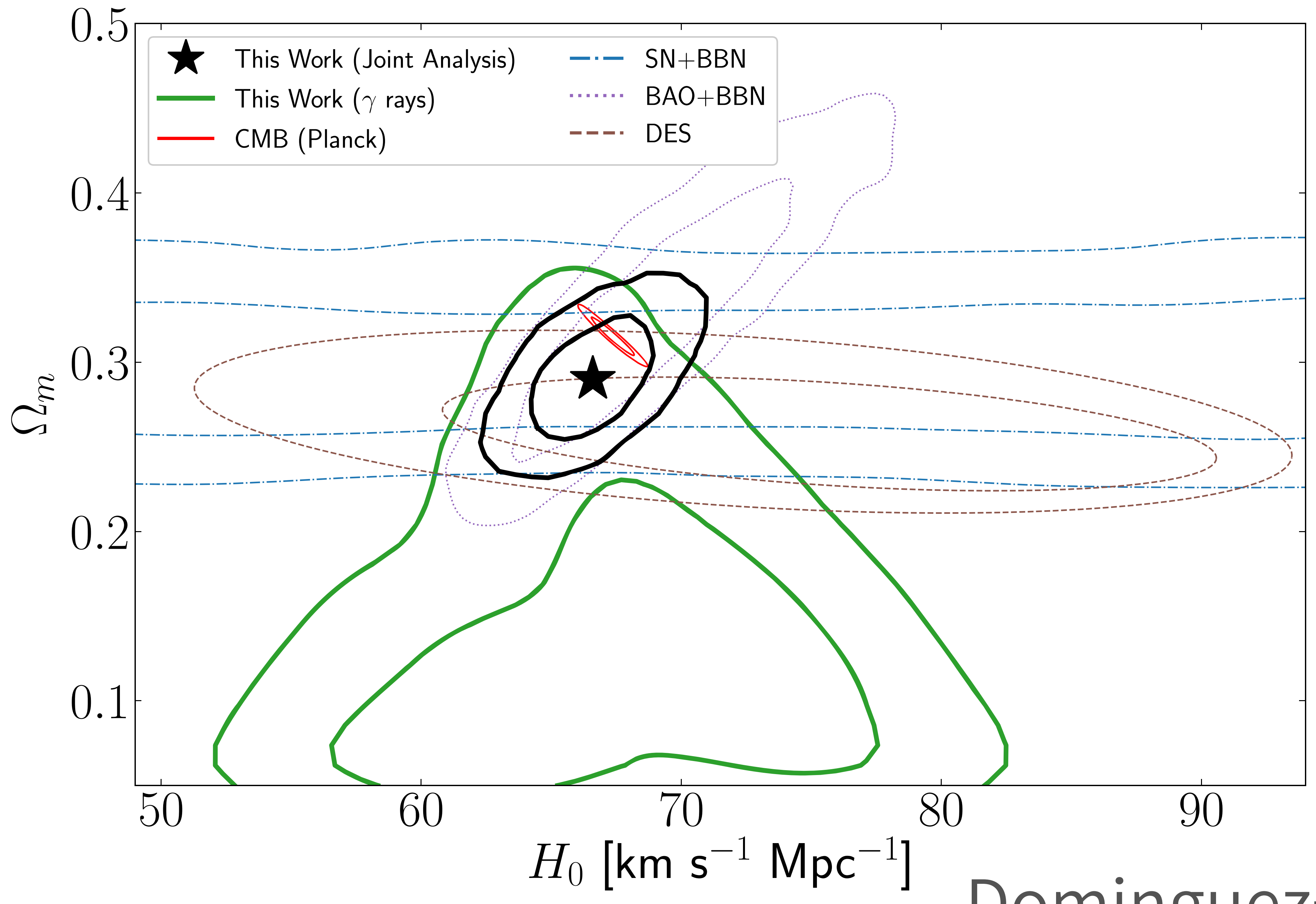

Dwek & Krennrich '13

- Cosmic gamma-ray horizon also depends on $H_0$.
- $0.04 < z < 0.1$ is important ($\tau_{\gamma\gamma} = 1$ region significantly changes).

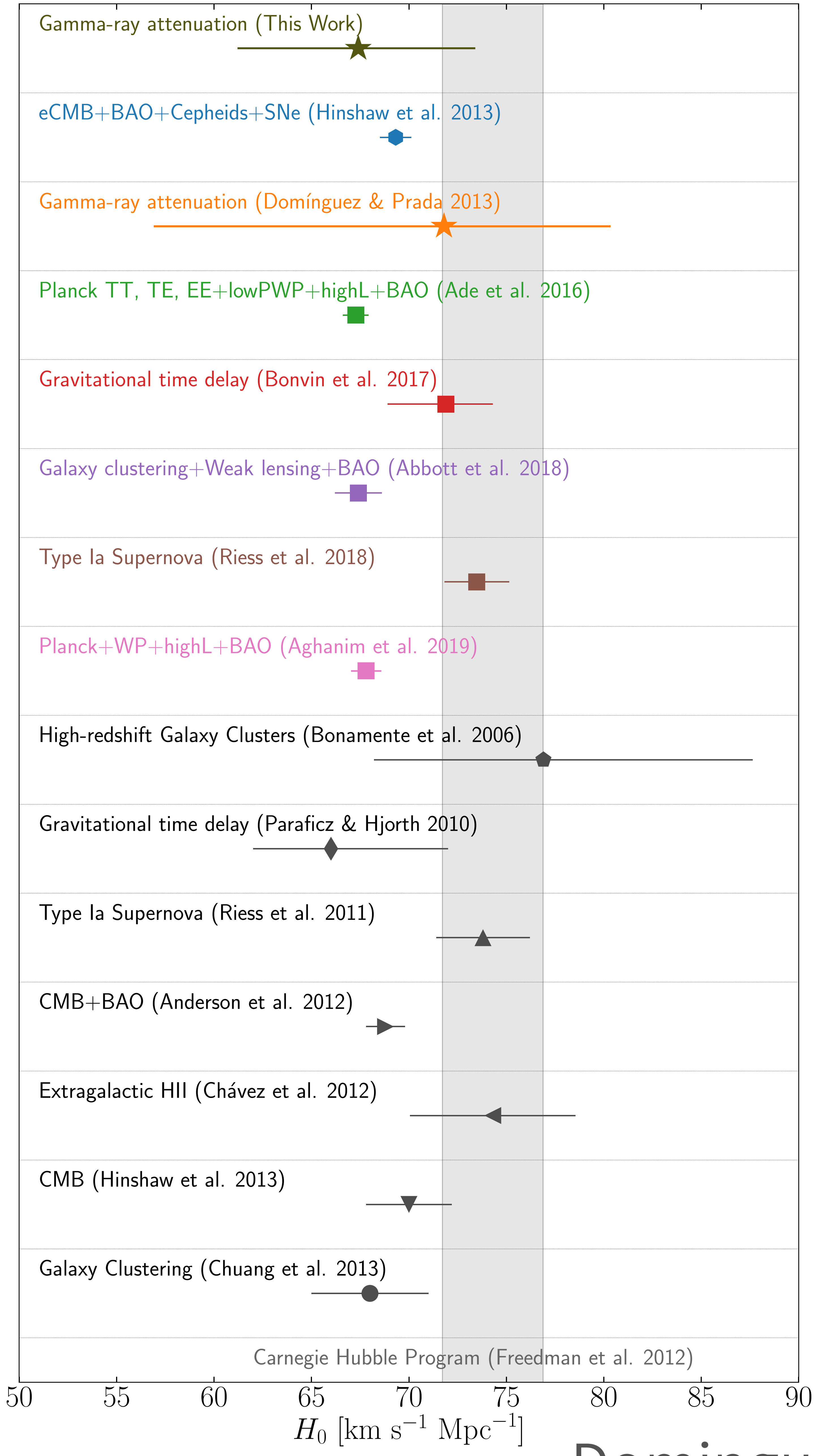
# Constraint on $H_0$

$$H_0 = 67.5 \pm 2.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

- Note: you need to assume the EBL shape.



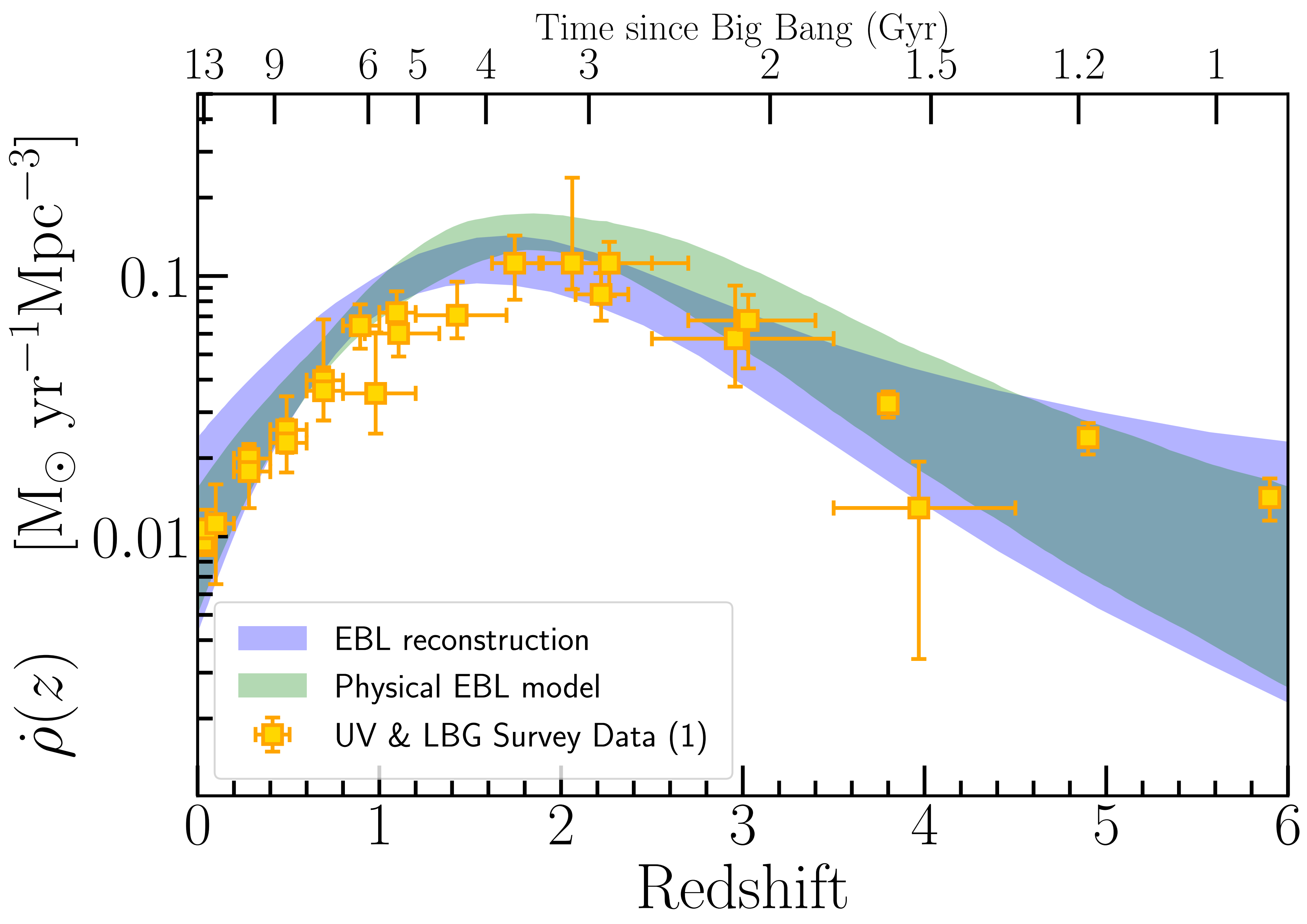

Dominguez+'19

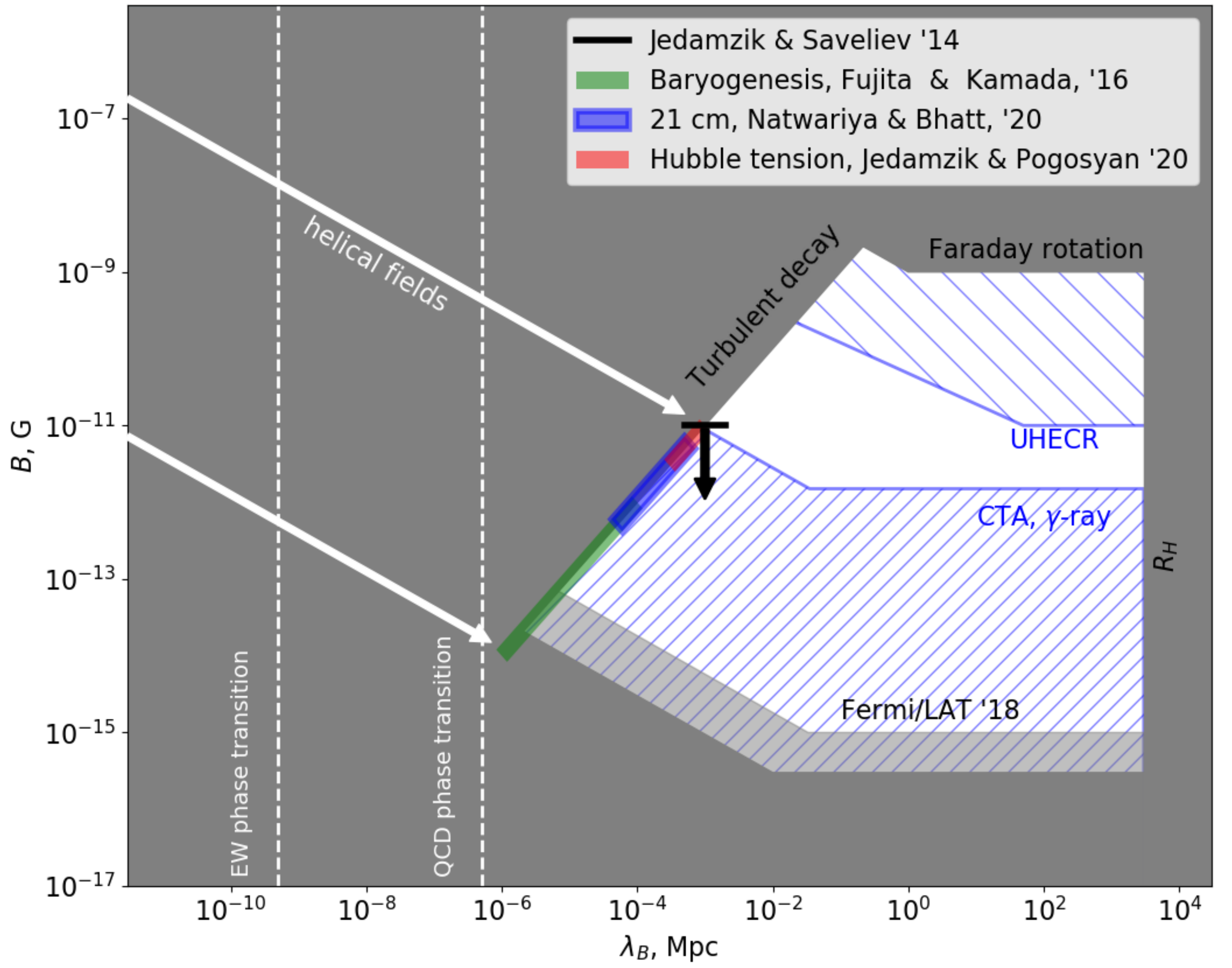



Dominguez+'19

# Day 4 Summary

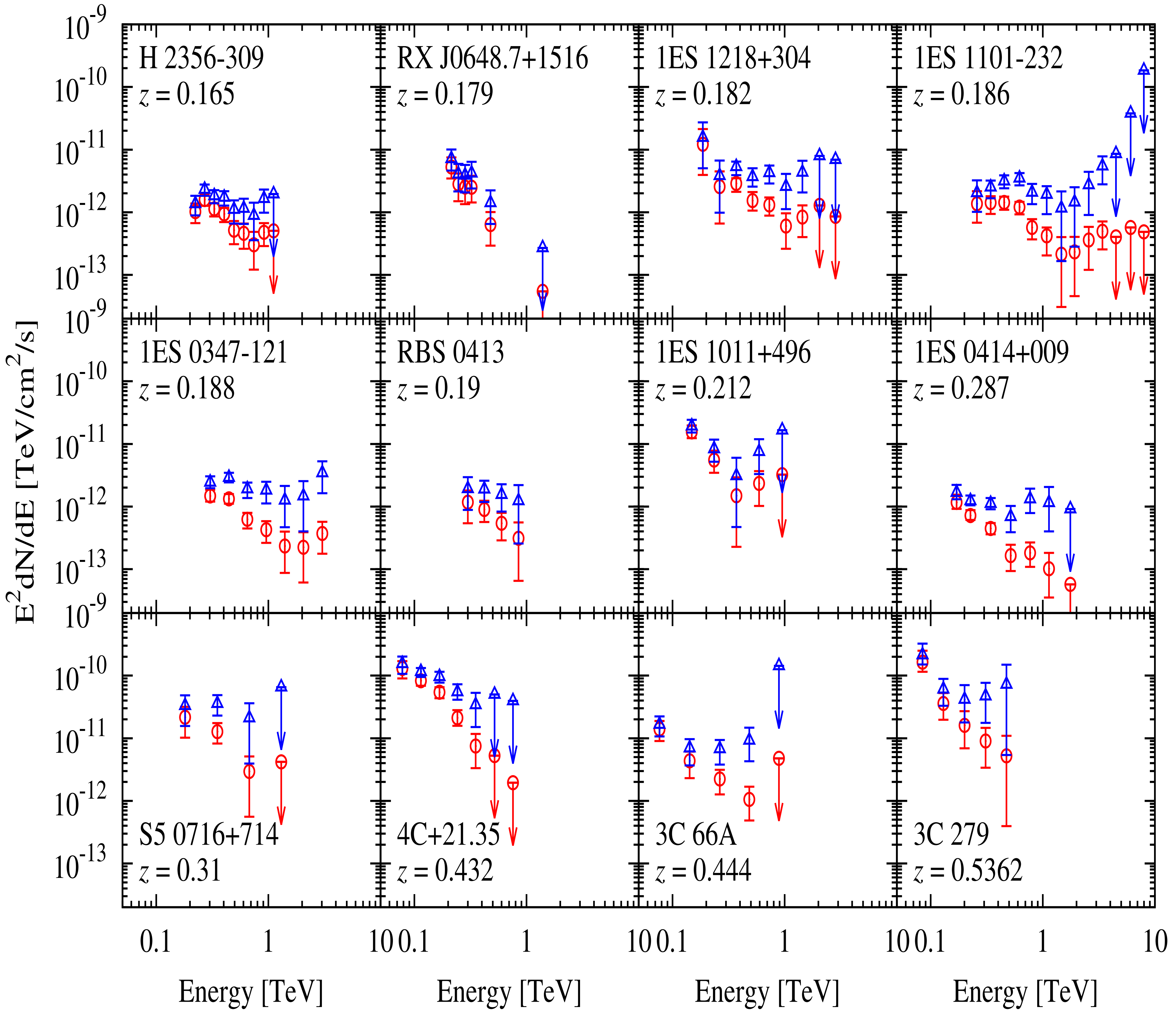
- Gamma-ray observations can measure the EBL & Cosmic Star Formation History.
- Gamma-ray observations can constrain IGMF.
  - Spectrum, Halo, & Time delay
  - $B_{\mathrm{IGMF}} \geq 10^{-16}$ G for $\lambda_{\mathrm{coh}} \geq 1$ Mpc with $\Delta t_{\mathrm{flare}} = 10$ yr
- Gamma-ray EBL measurements rules out some of galaxy evolution models from reionization data.
  - It also tells that $H_0 = 67.5 \pm 2.1\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$.



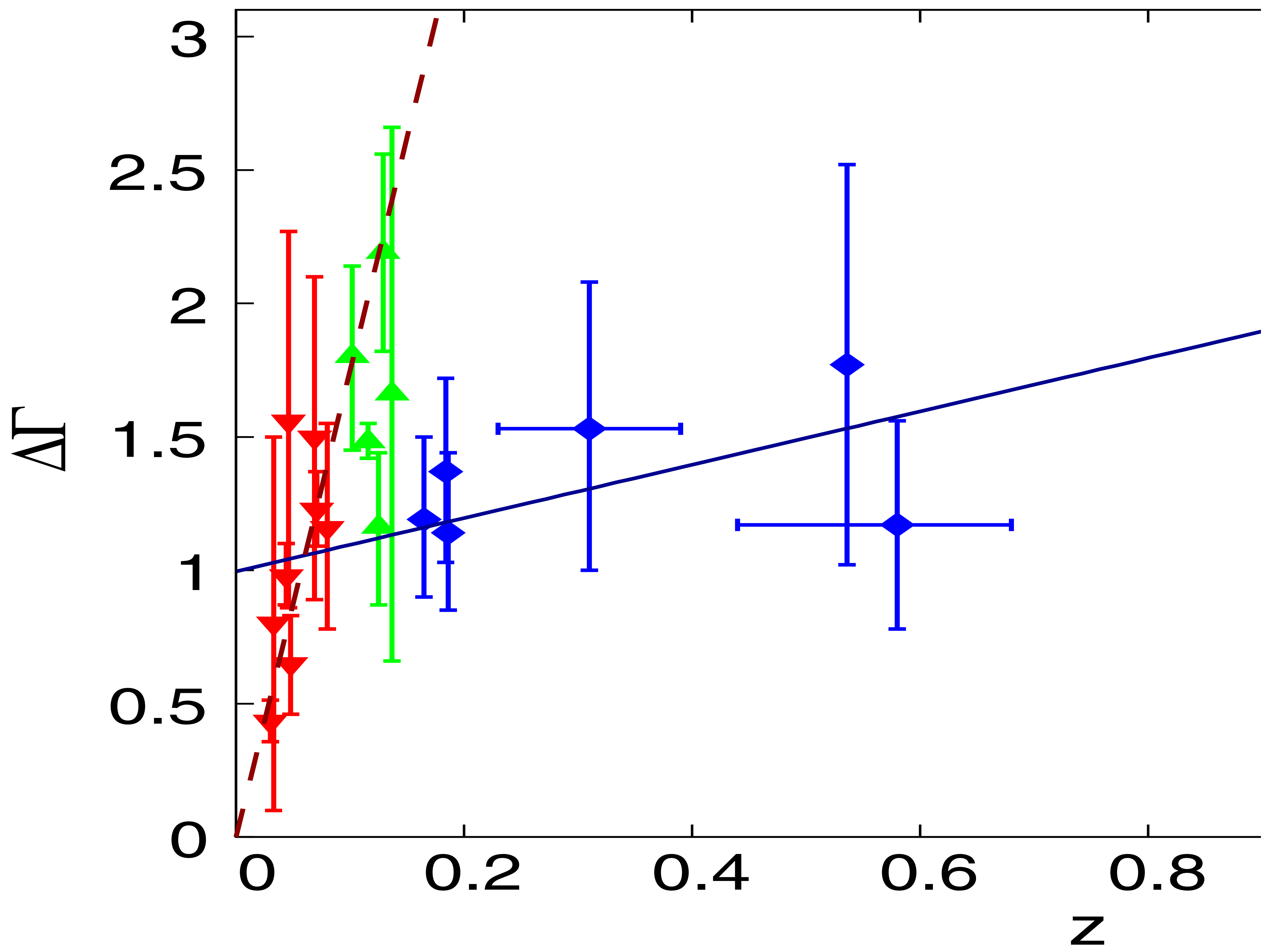



# VHE Spectral Hardening in Blazars

## Inconsistent with typically assumed SED




YI & Tanaka '16



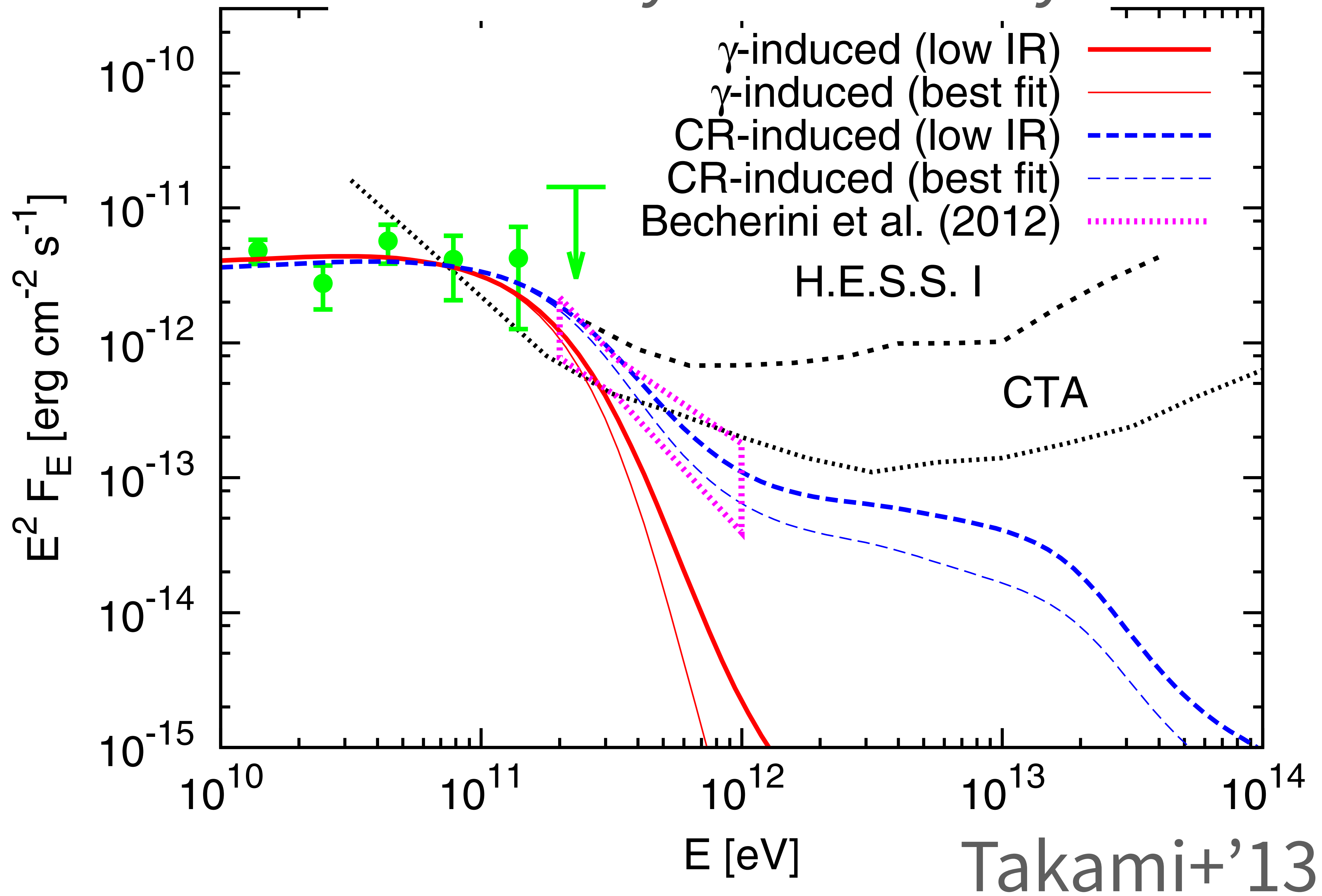

Essey & Kusenko '10

- Some blazars show spectral hardening after the EBL correction.

# Secondary Gamma Rays? Stochastic Acceleration?

KUV 00311-1938 (z=0.61)

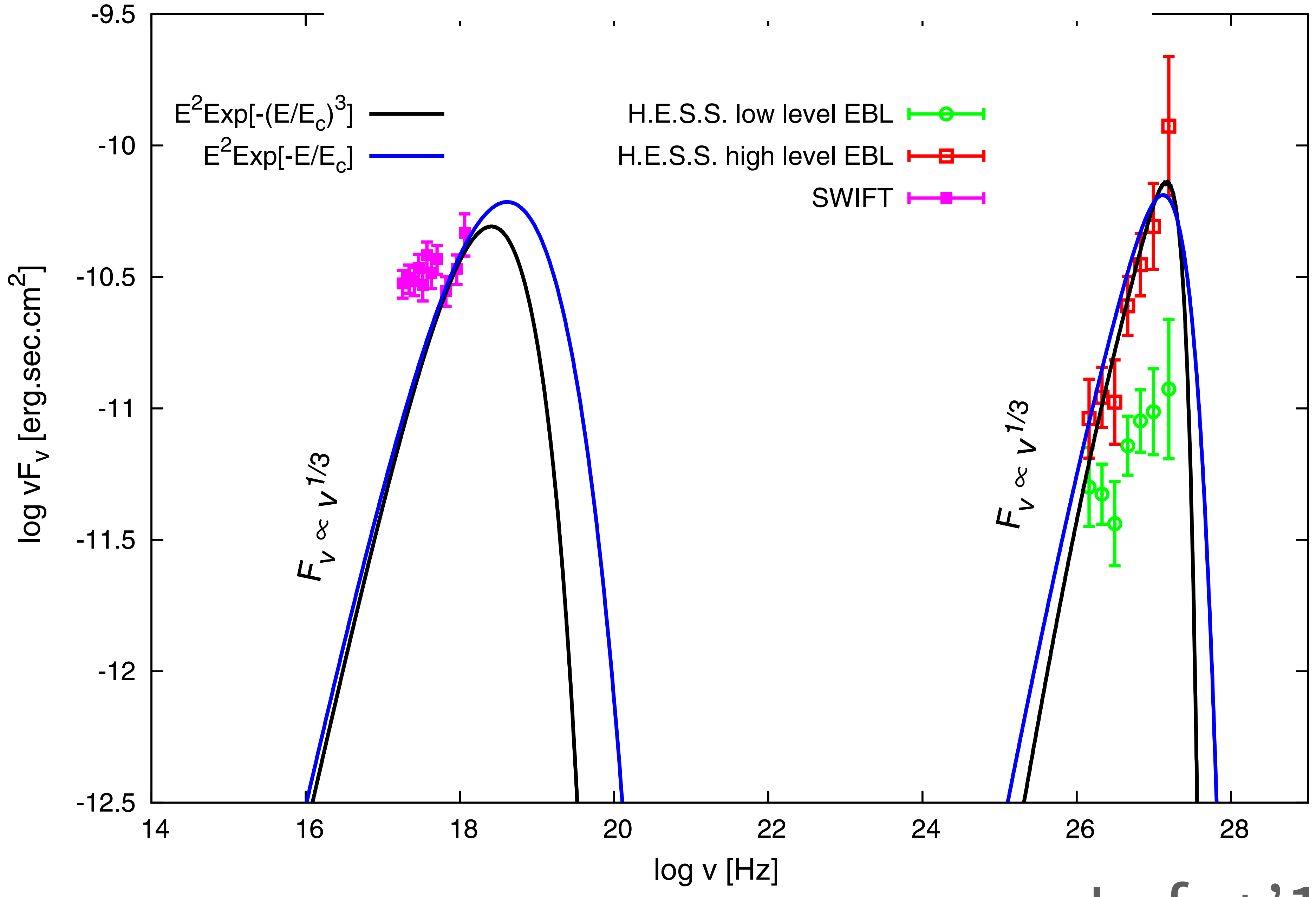
Secondary Gamma Rays




Takami+'13

1ES 0229+200 (z=0.1396)

Stochastic Acc.




Lefa+'11

- Secondary gamma rays from cosmic rays along line of sight
  (Essey & Kusenko '10, Essey+'10, '11; Murase+'12; Takami+'13).

- Stochastic (2nd-order Fermi) acceleration
  (Stawarz & Petrosian '08; Lefa+'11; Asano+'14).