Cosmological Aspects of High Energy Astrophysics ~ Day 1 ~

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

High Energy Astrophysics

Astrophysics

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

~13.8 Glyr

~10^{23} km

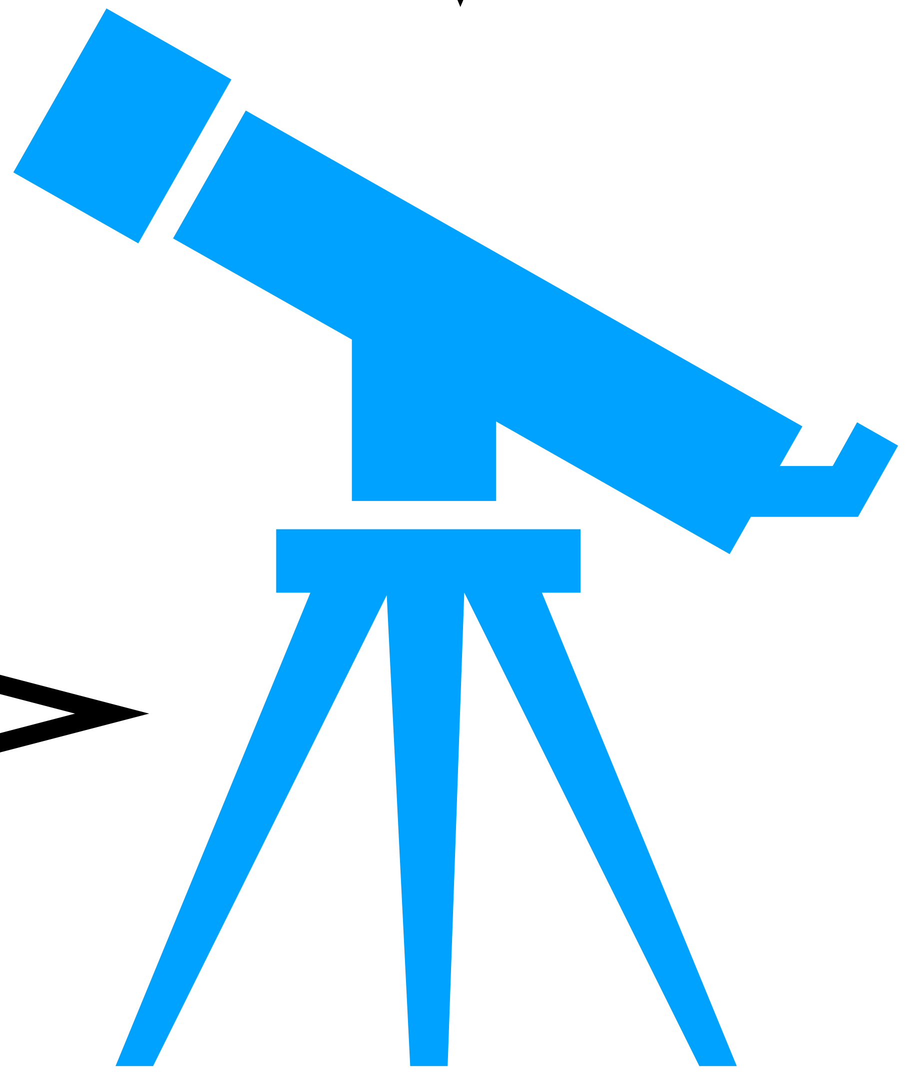
Very Very Far

Electromagnetic waves

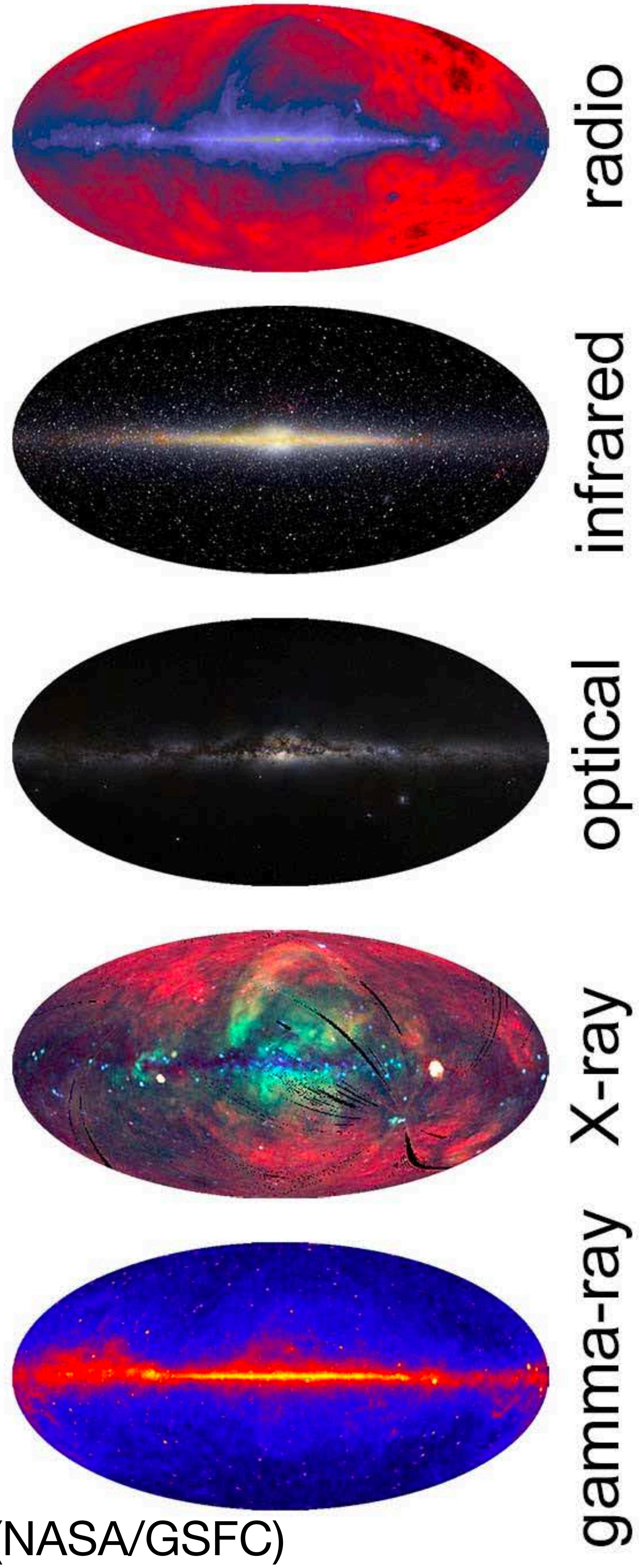
Cosmic rays

Gravitational waves

Image
Position
Flux
Variability

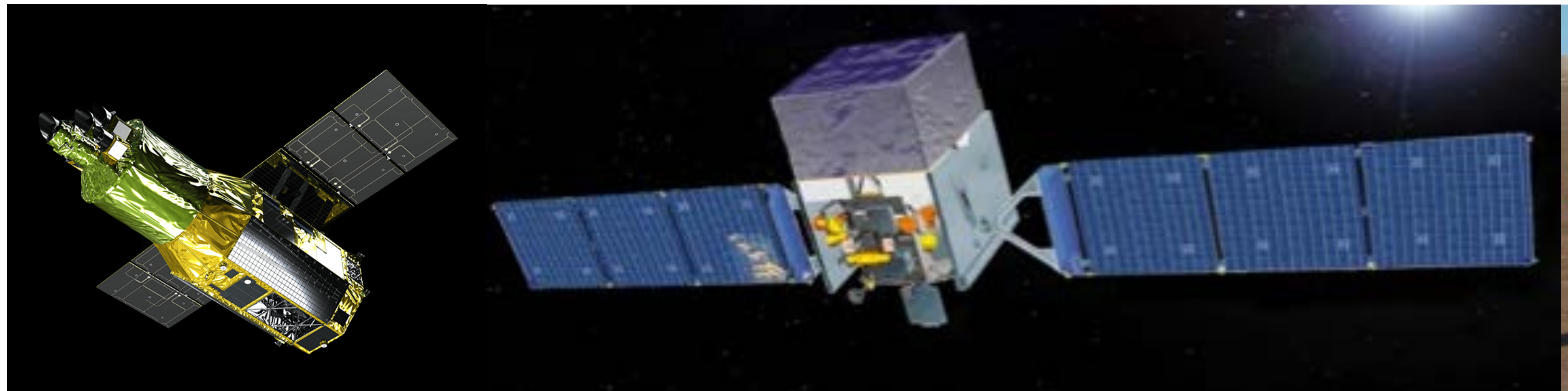


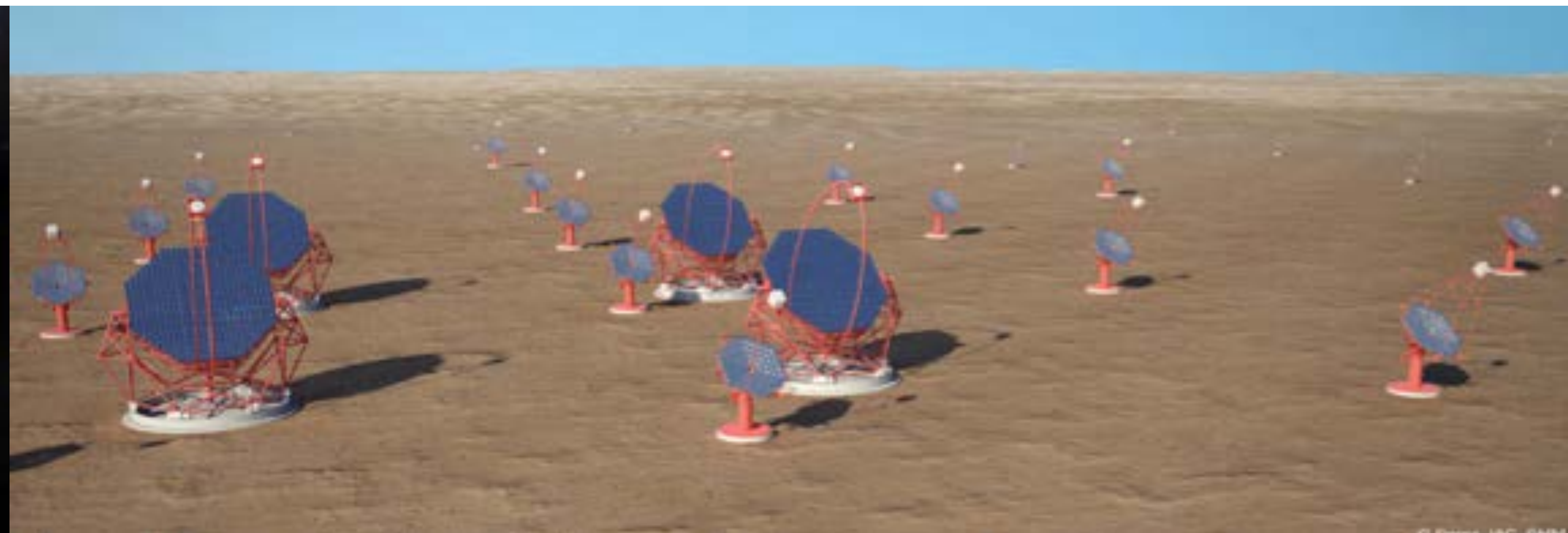
+ Physics =
Understand the universe
Prediction
New science



High Energy Astrophysics

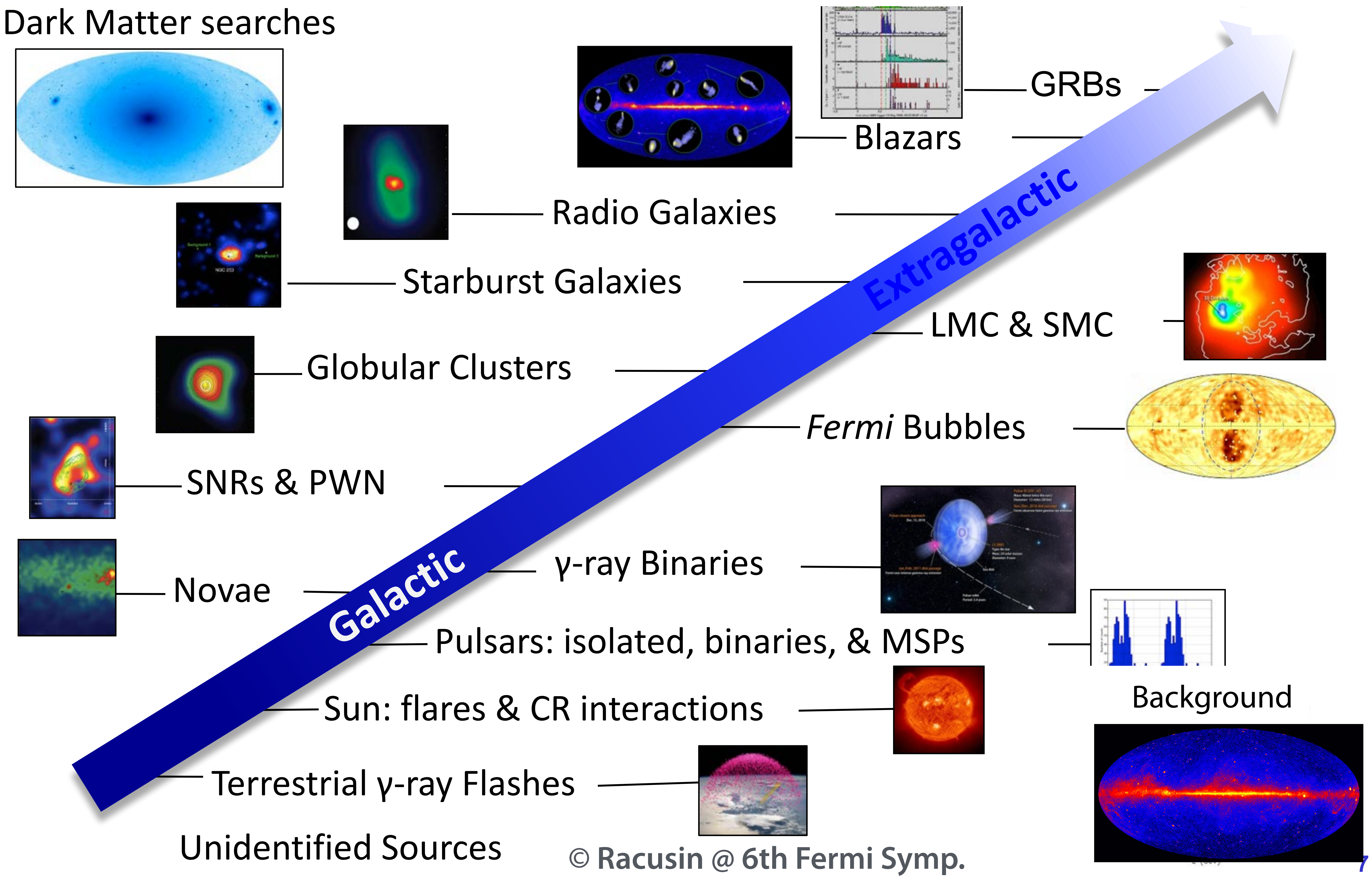
- Different wavelength tells different properties.
- High Energy Astrophysics?
  - “<u>**Energetic**</u>” universe
  - X-ray, Gamma-ray, TeV-PeV neutrinos (Multi-messenger)
  - New telescopes: XRISM, IXPE, ATHENA, Fermi, MAGIC, HESS, VERITAS, CTA, LHAASO, IceCube,,





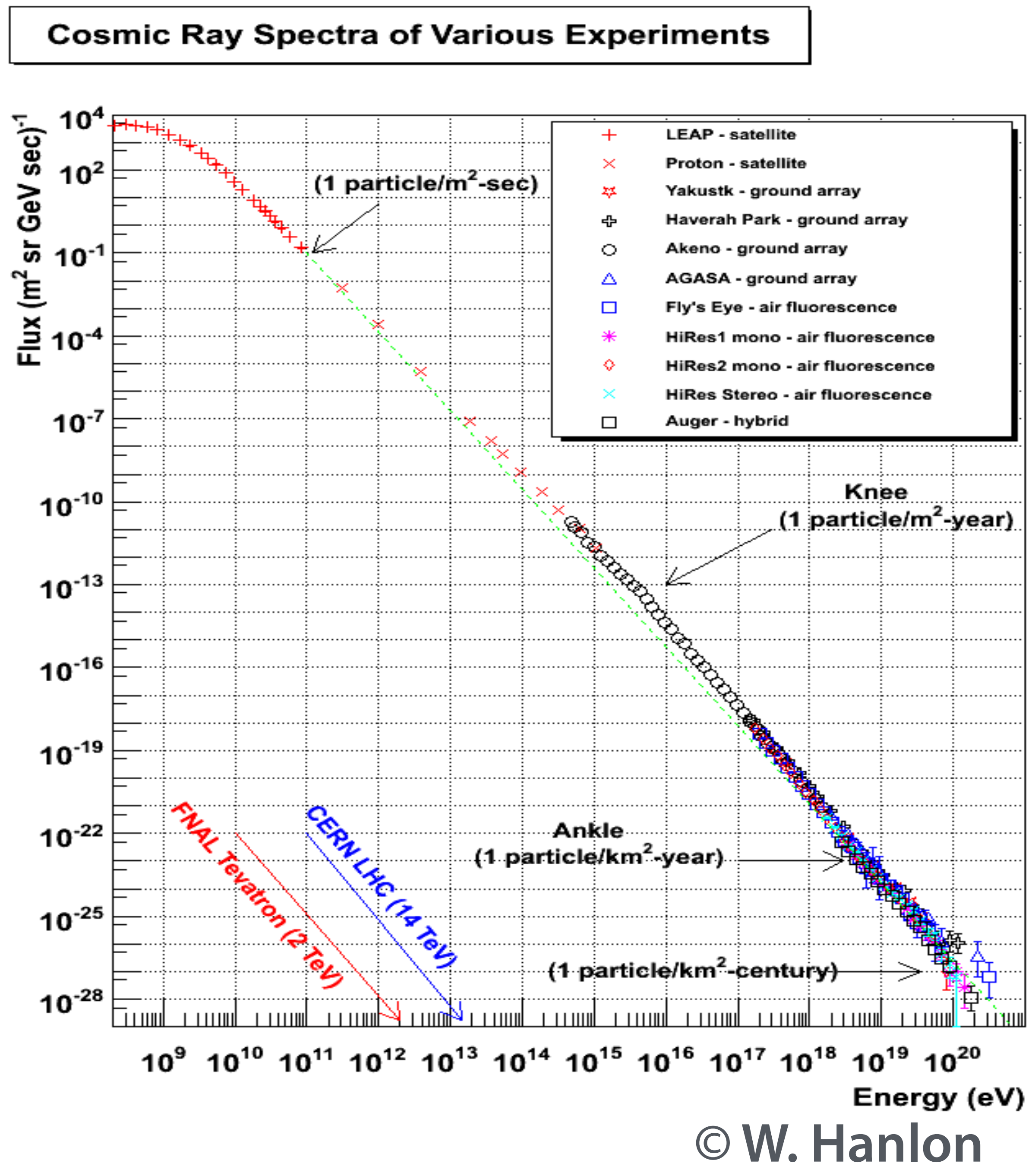
rowave
Infrared
Optical
450-750 nm
6,000 K
axy
SOLAR STARS: Optical light comes from stars around the size of the Sun.
VISIBLE LIGHT

High Energy Astrophysical Objects

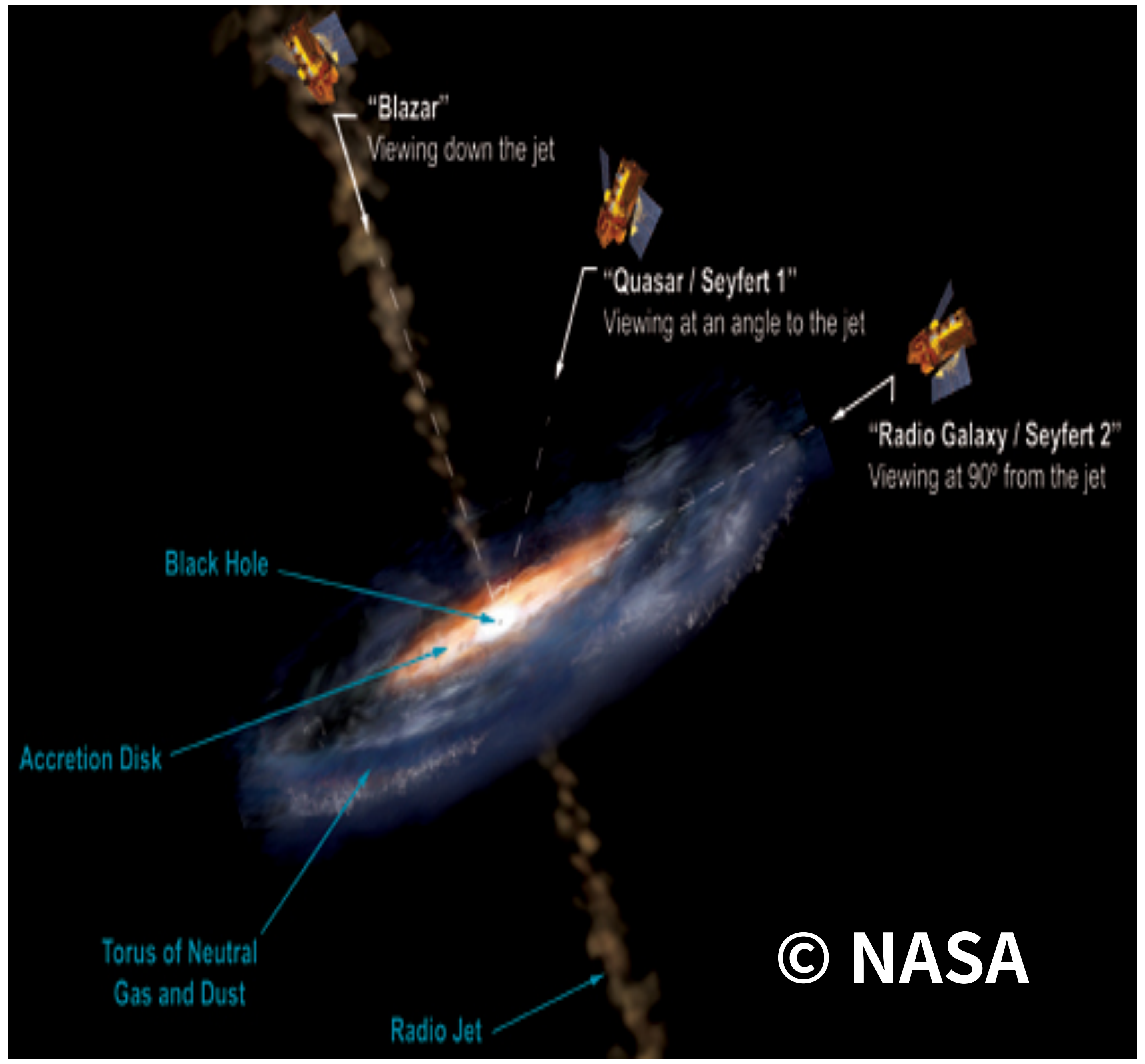


Why High Energy Astrophysics?

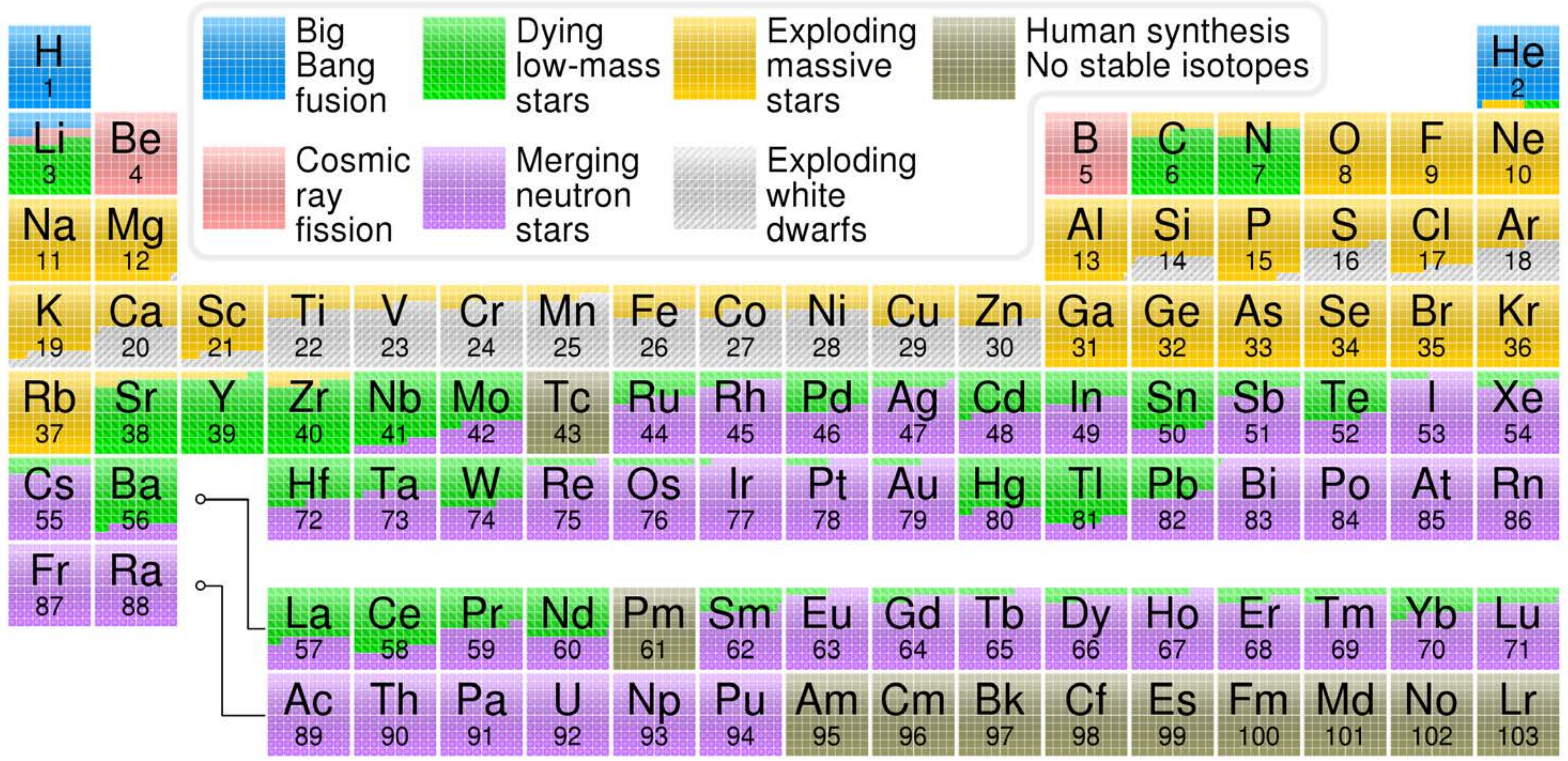
Origin of Cosmic Rays

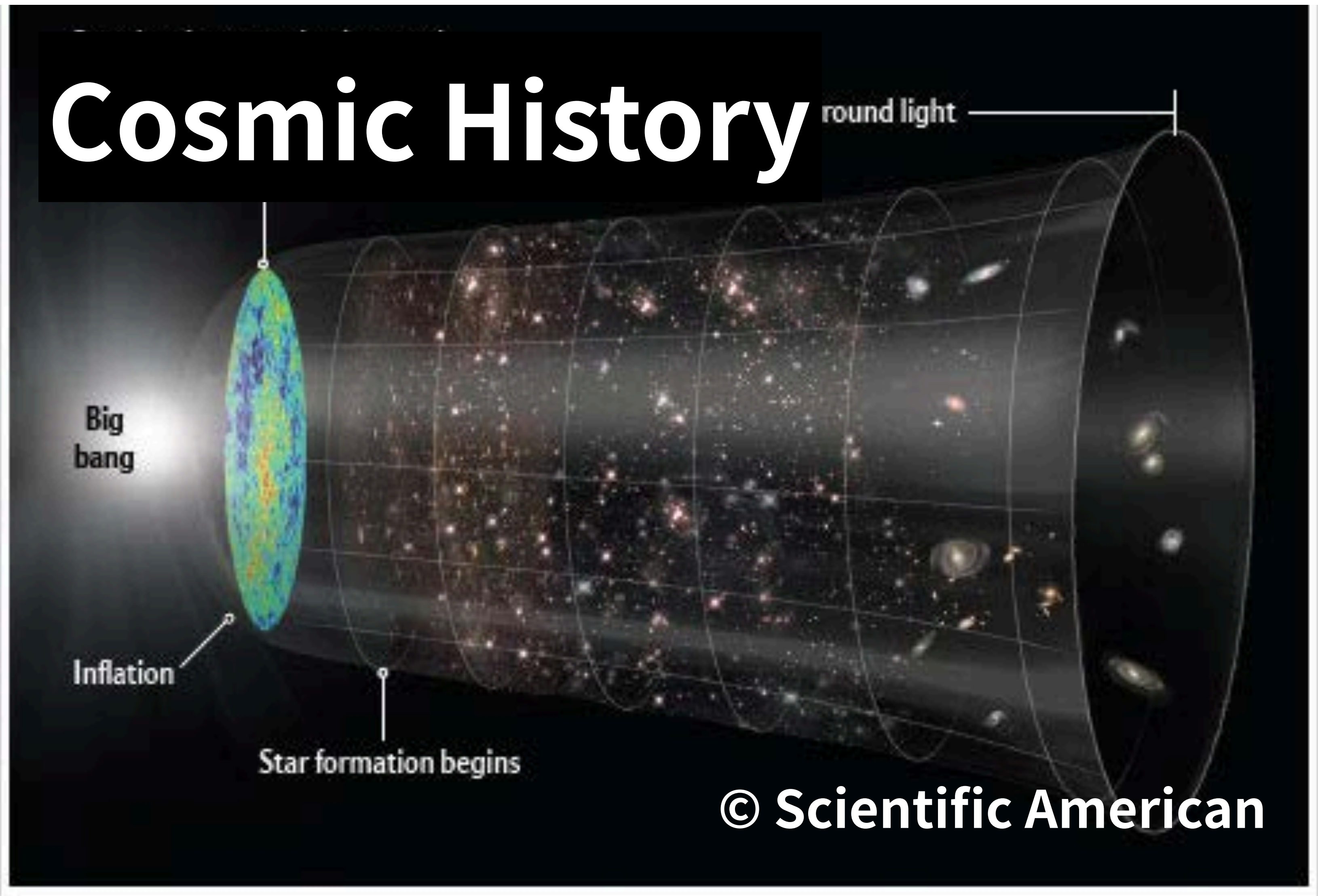


Relativistic Jets



Origin of Matter

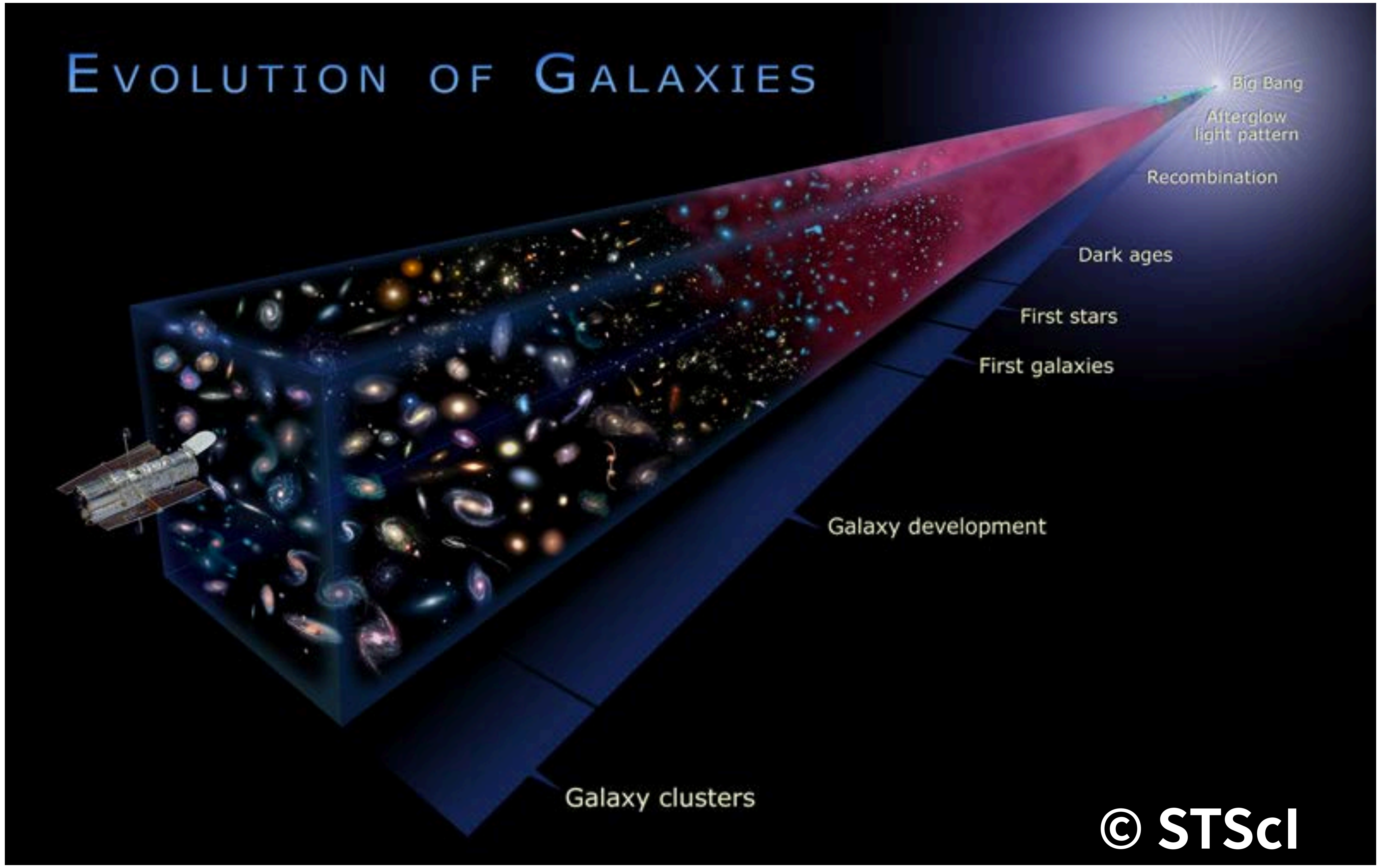




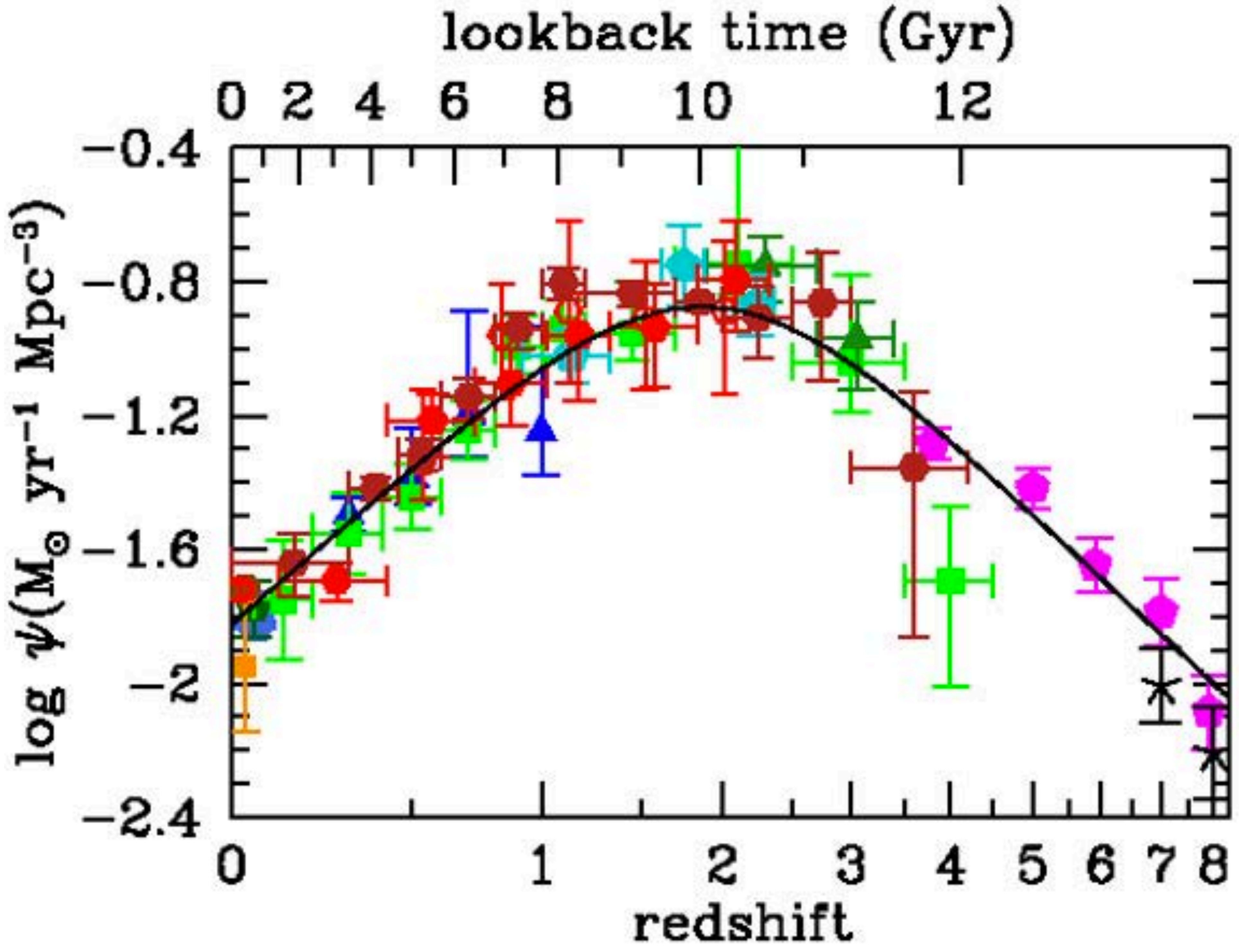
Cosmological Evolution of Gamma-ray Emitting Objects

Cosmological Evolution?

Probe the Cosmic History



Cosmic Star Formation History

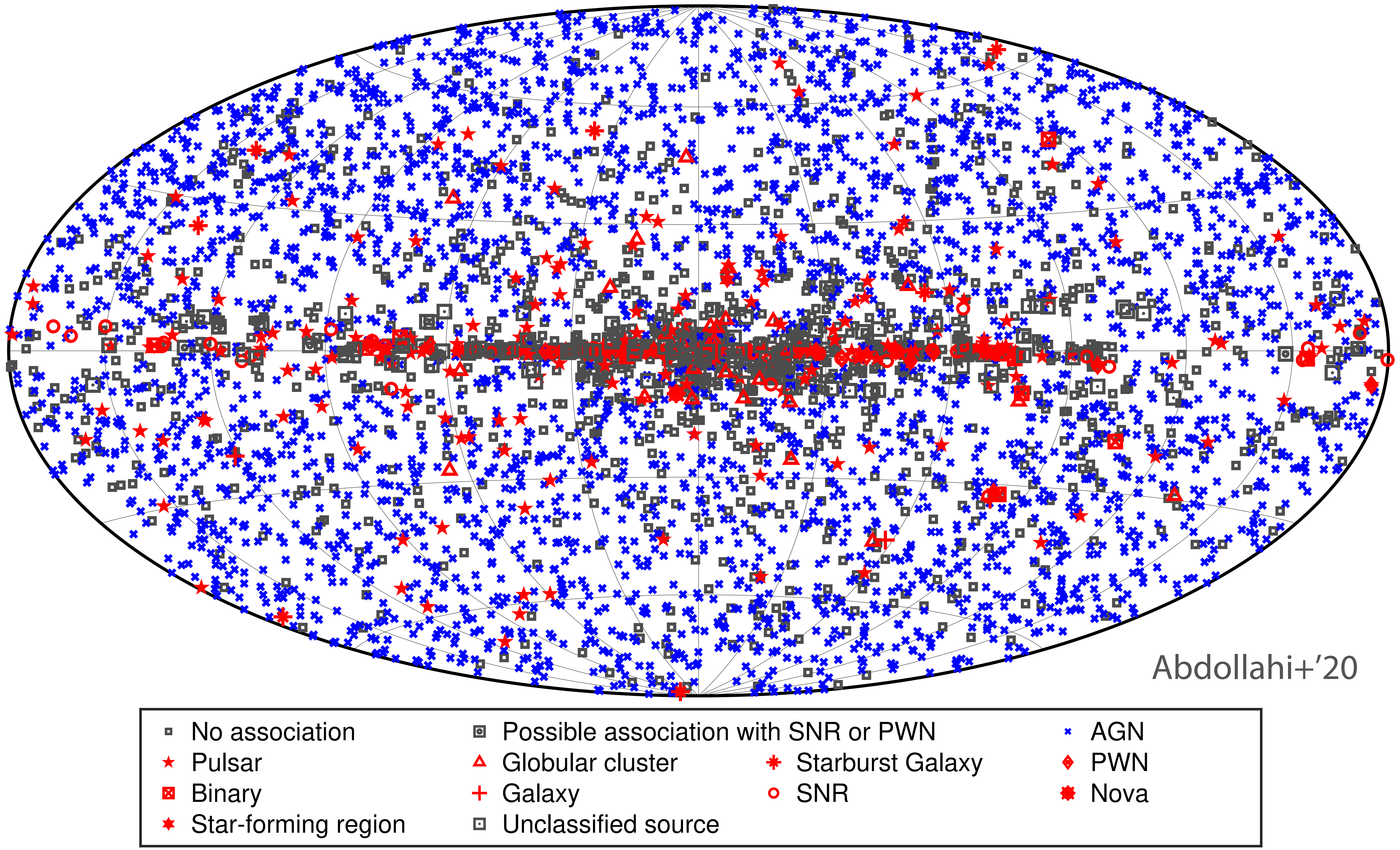


Madau & Dickinson +'14

- Understand the history.
  - how many in the past?
  - when they were active?

Which object class can we study the evolution?

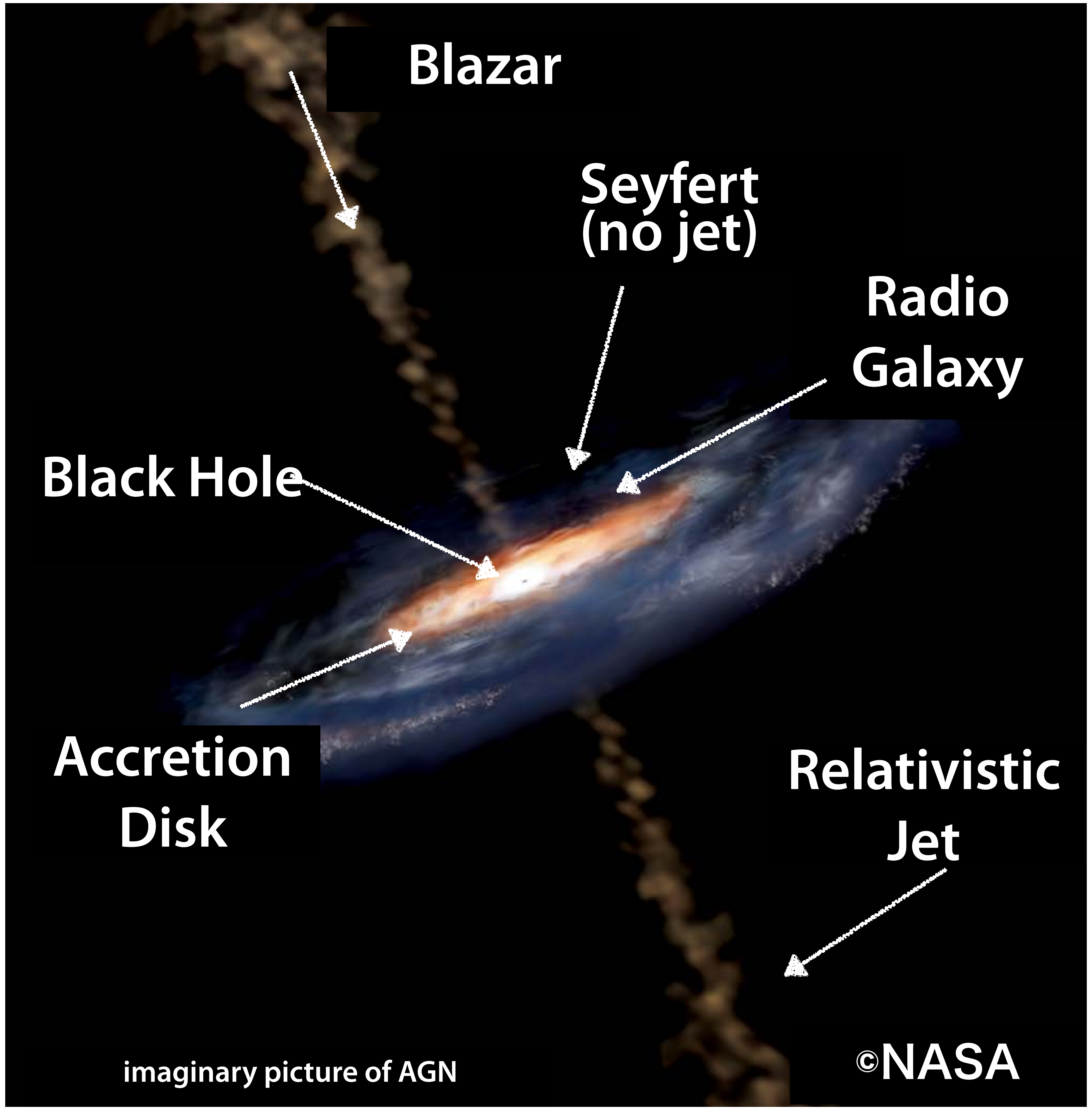
Yes. Many many samples are required.



Abdollahi+'20

- 4FGL Catalog
  - Fermi 8-year
- 5064 objects
  - **3137 blazars**
- We can study the blazar evolution w/ Fermi.

Active Galactic Nuclei (AGNs)



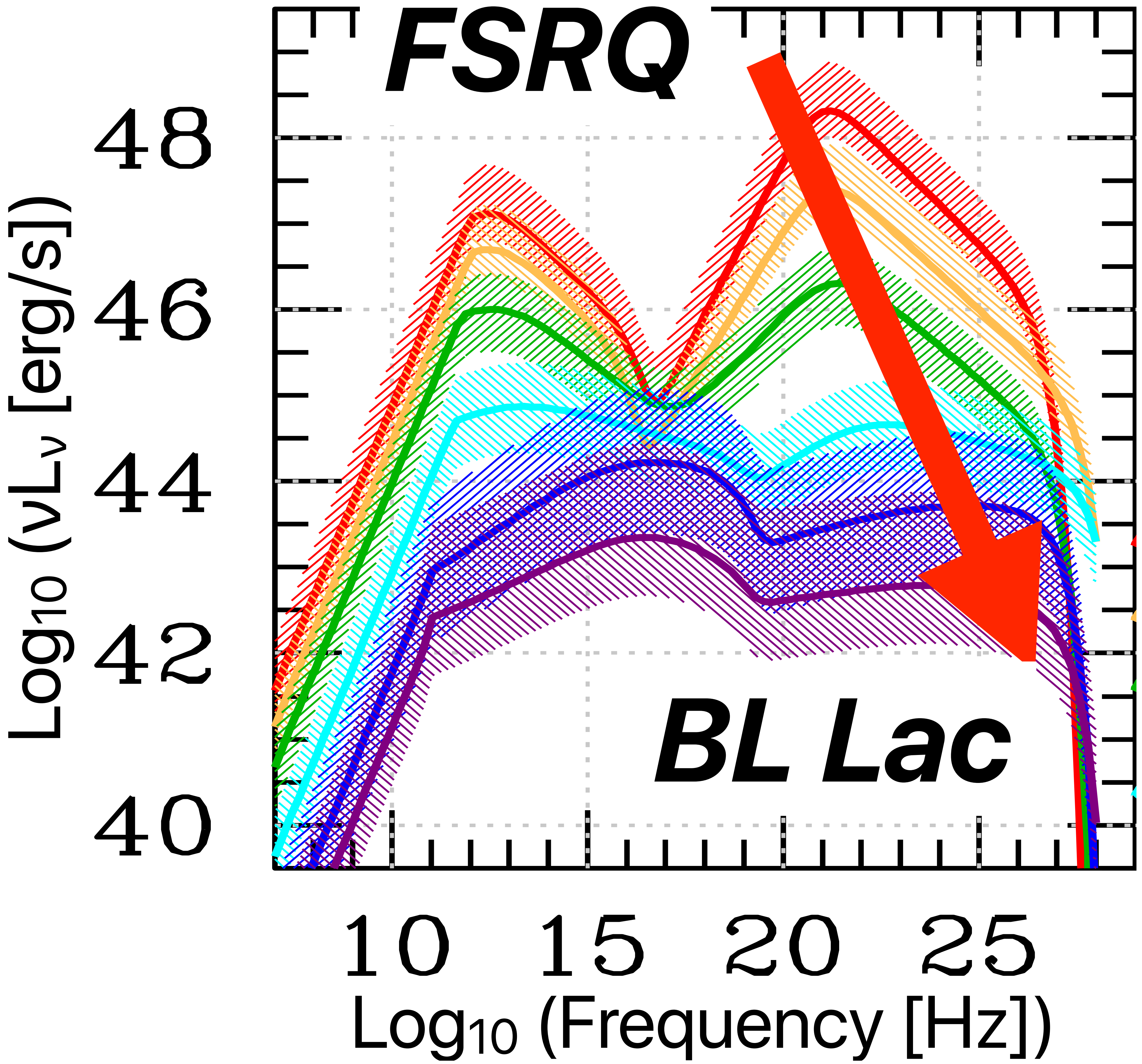
- Gas accretion on to SMBHs

  ➡brighter than the galaxy

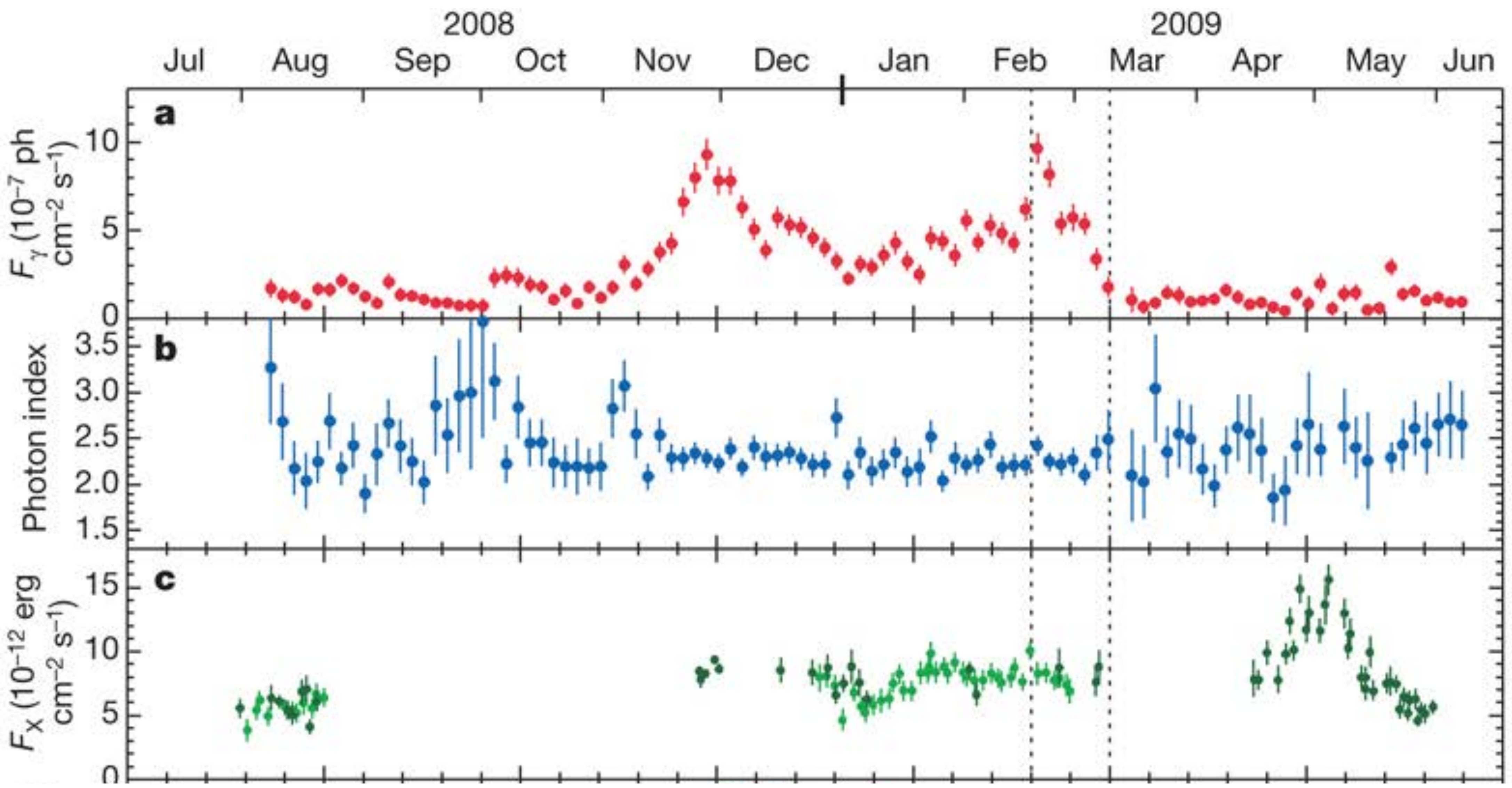
  - Active Galactic Nuclei: AGNs
- Various population
  - Blazar, Radio Galaxy, Seyfert,,,
  - Relativistic jet
    - Feedback / Cosmic rays / Neutrinos

Blazars

Jet pointing toward the Earth



Ghisellini+'17

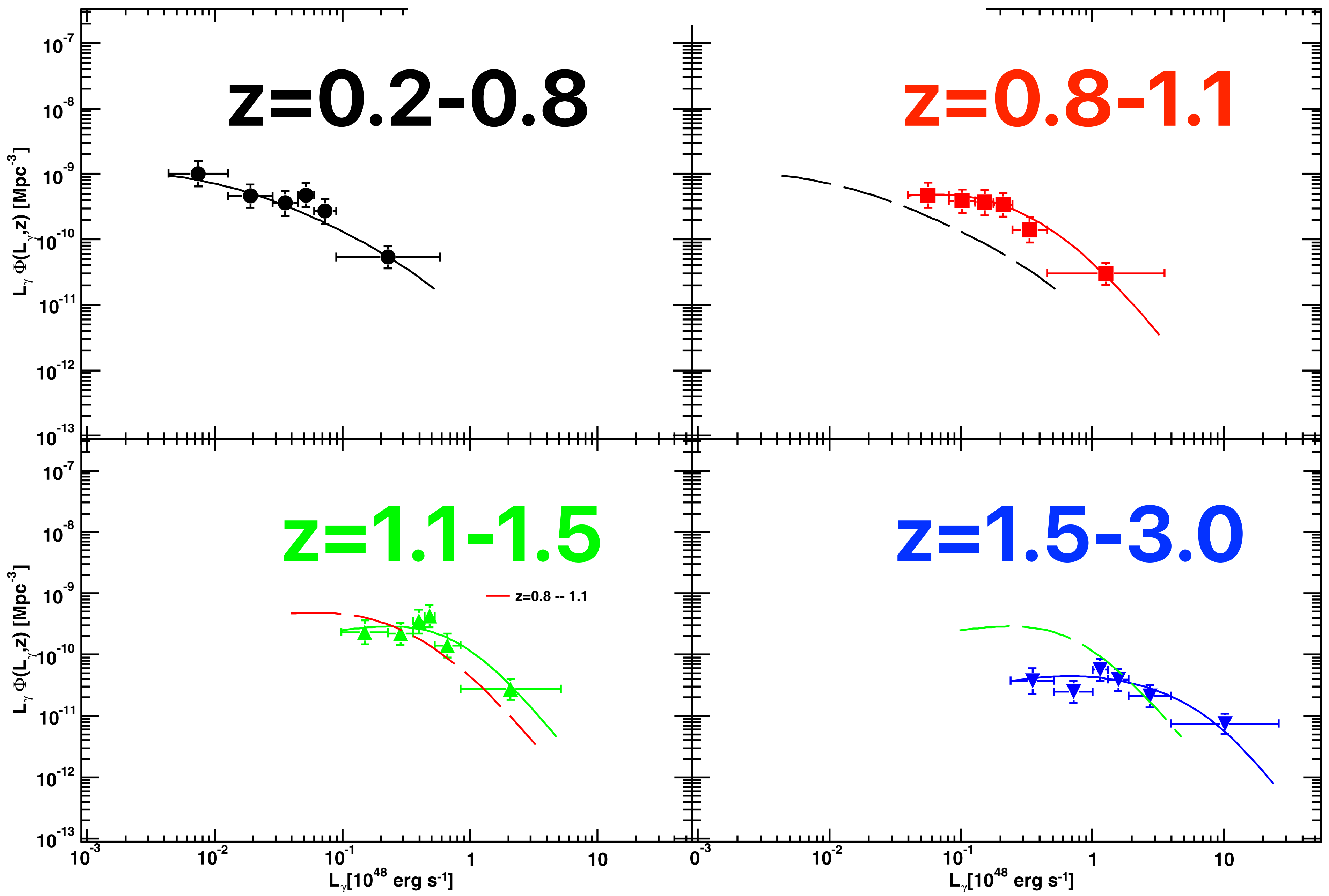


Abdo+'10

- Highly variable $\Delta t \sim 1$ day
- Non-thermal emission from radio to gamma-ray
- Two peaks
  - Synchrotron & Inverse Compton
    - Hadronic?
- Luminous blazars (Flat Spectrum Radio Quasars: FSRQs) tend to have lower peak energies (Fossati+'98, Kubo+'98; Ghisellini+'17)

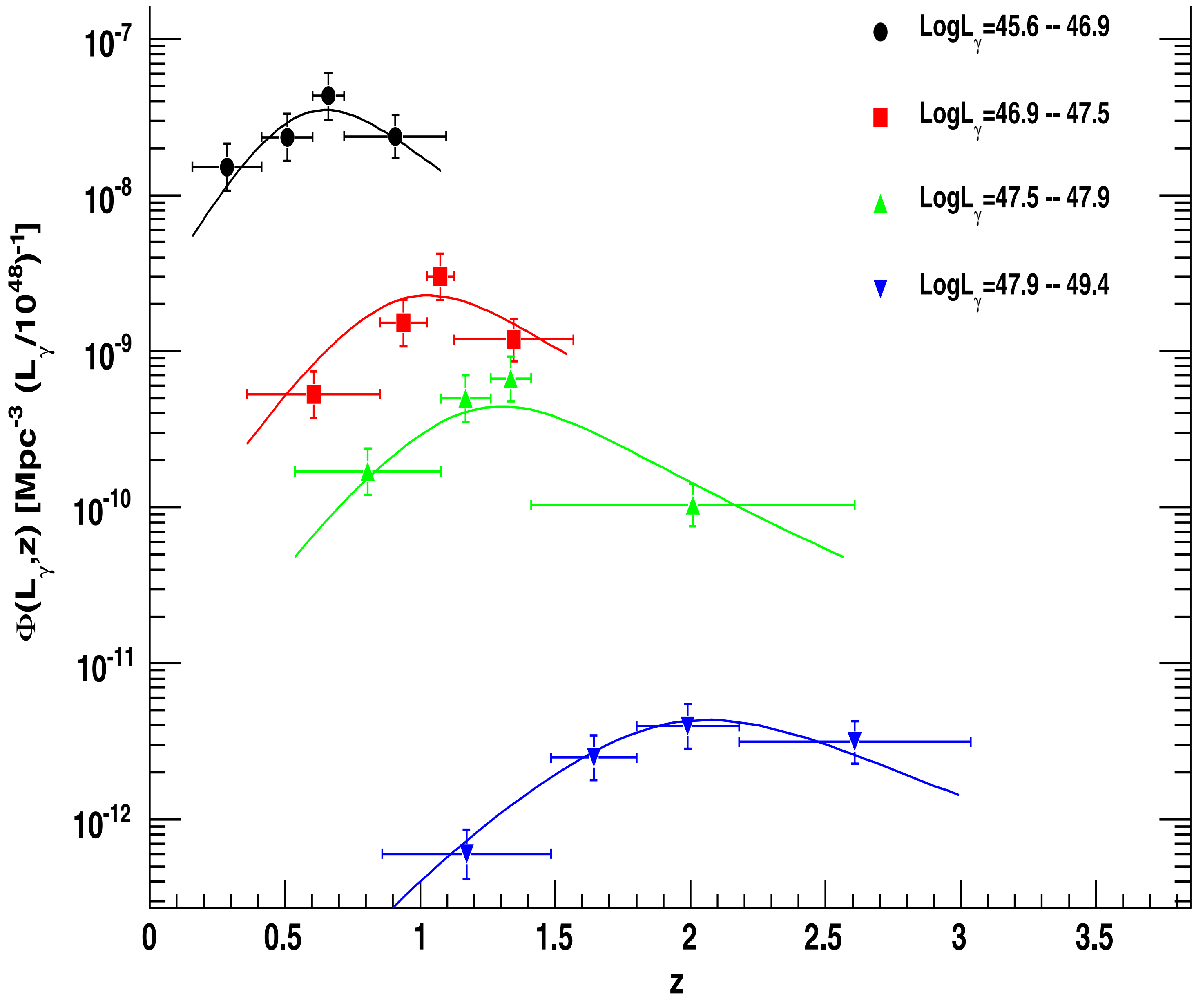
Cosmological Evolution of Blazars

$d^2N/dLdz$



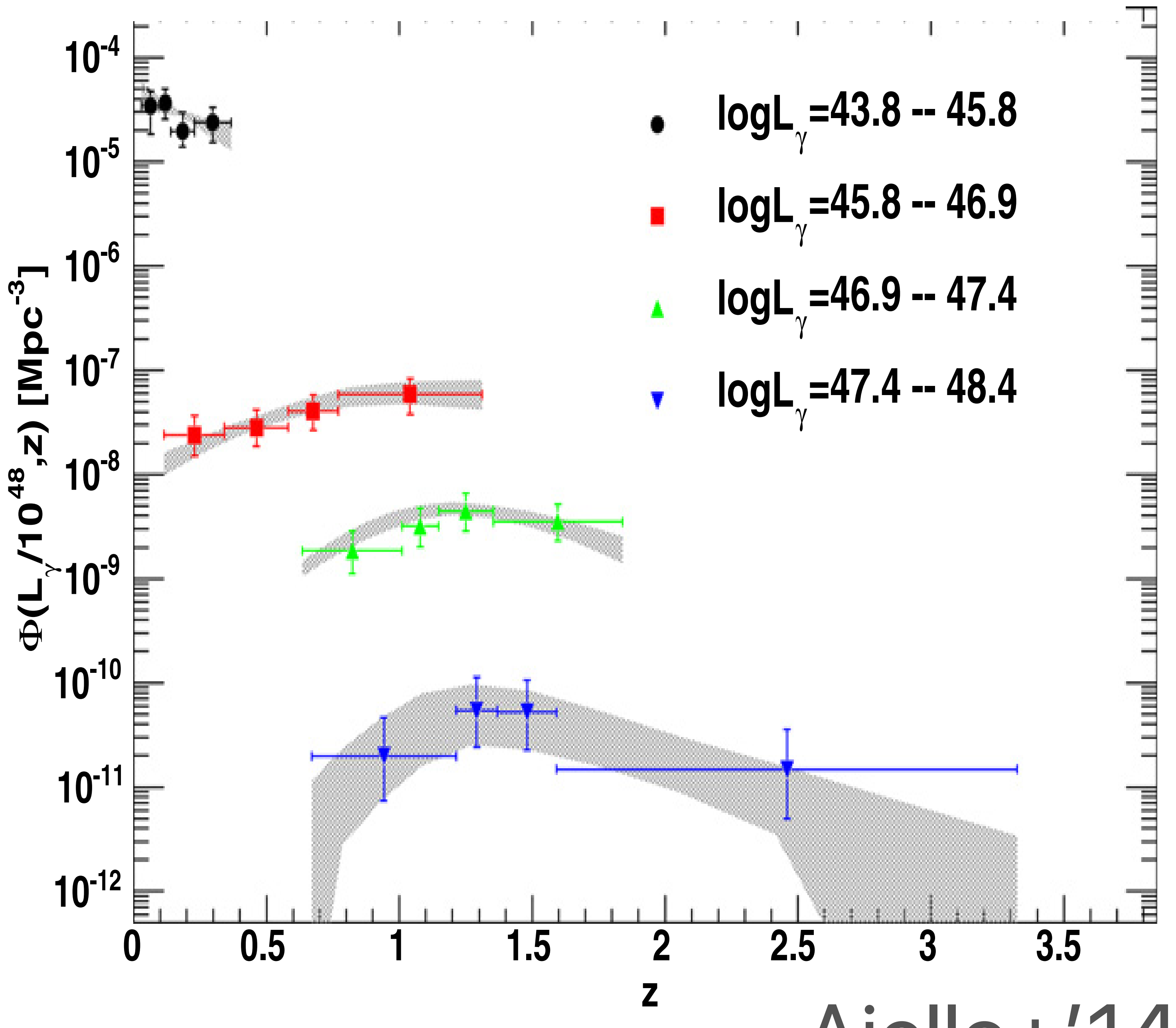
Ajello+'12

dN/dz **(FSRQs)**



Ajello+'12

dN/dz **(BL Lacs)**



Ajello+'14

- Luminosity-dependent density evolution
  (e.g., Narumoto & Totani '06; YI & Totani '09; Ajello+'12,,,)

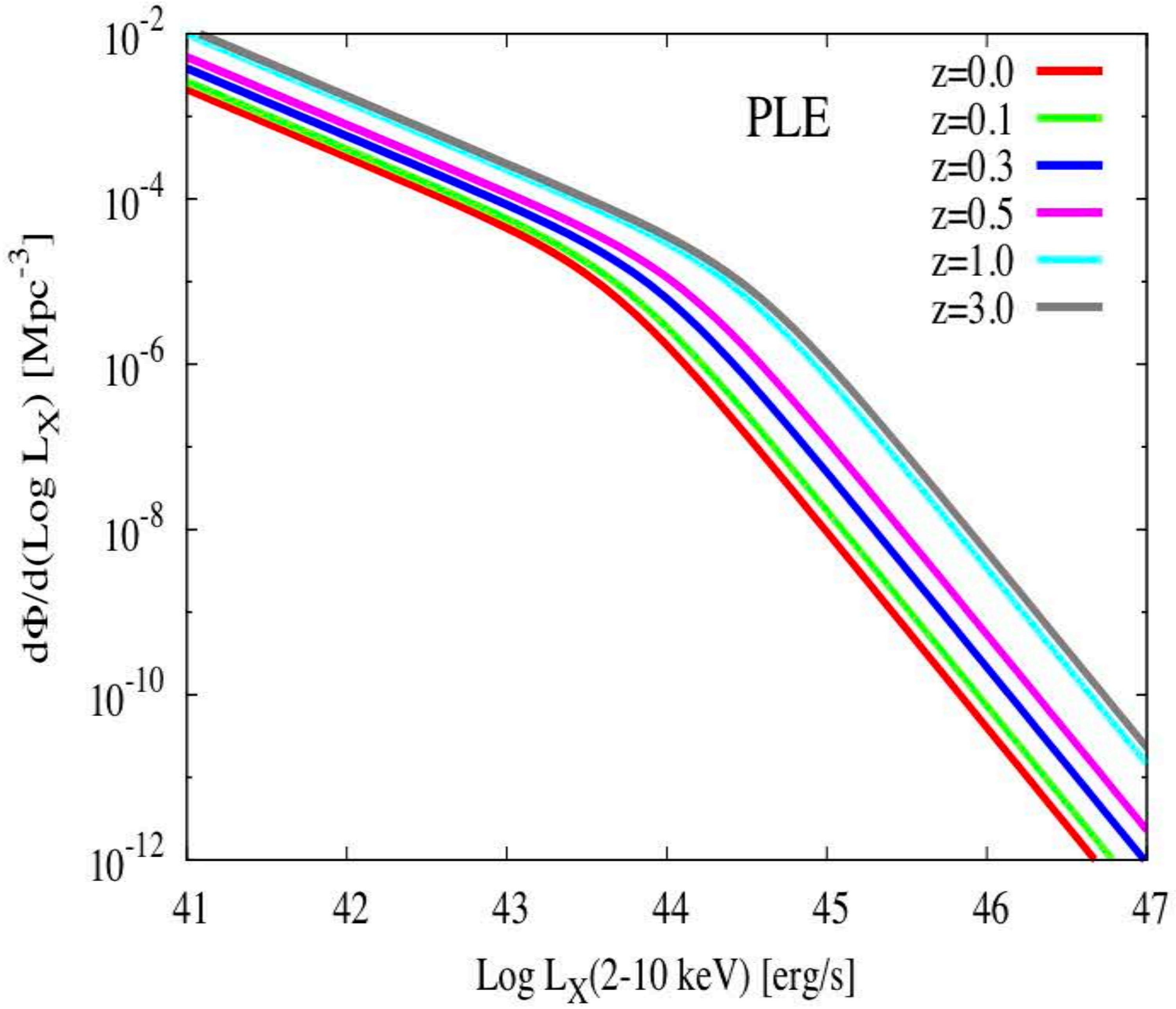
- Positive evolution.

- But, low-luminosity BL Lacs show negative evolution.

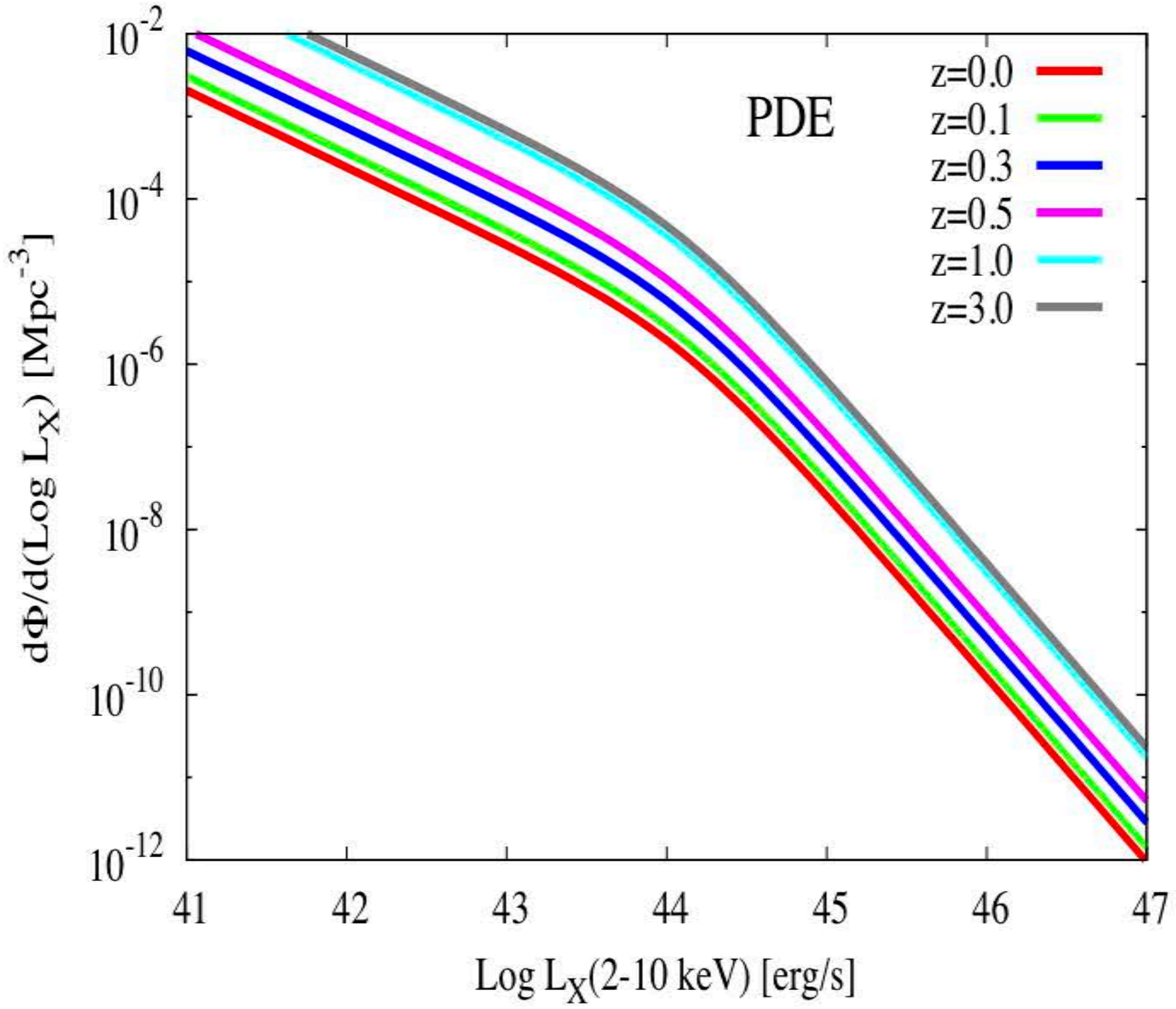
Luminosity function

Comoving density as a function of L and z

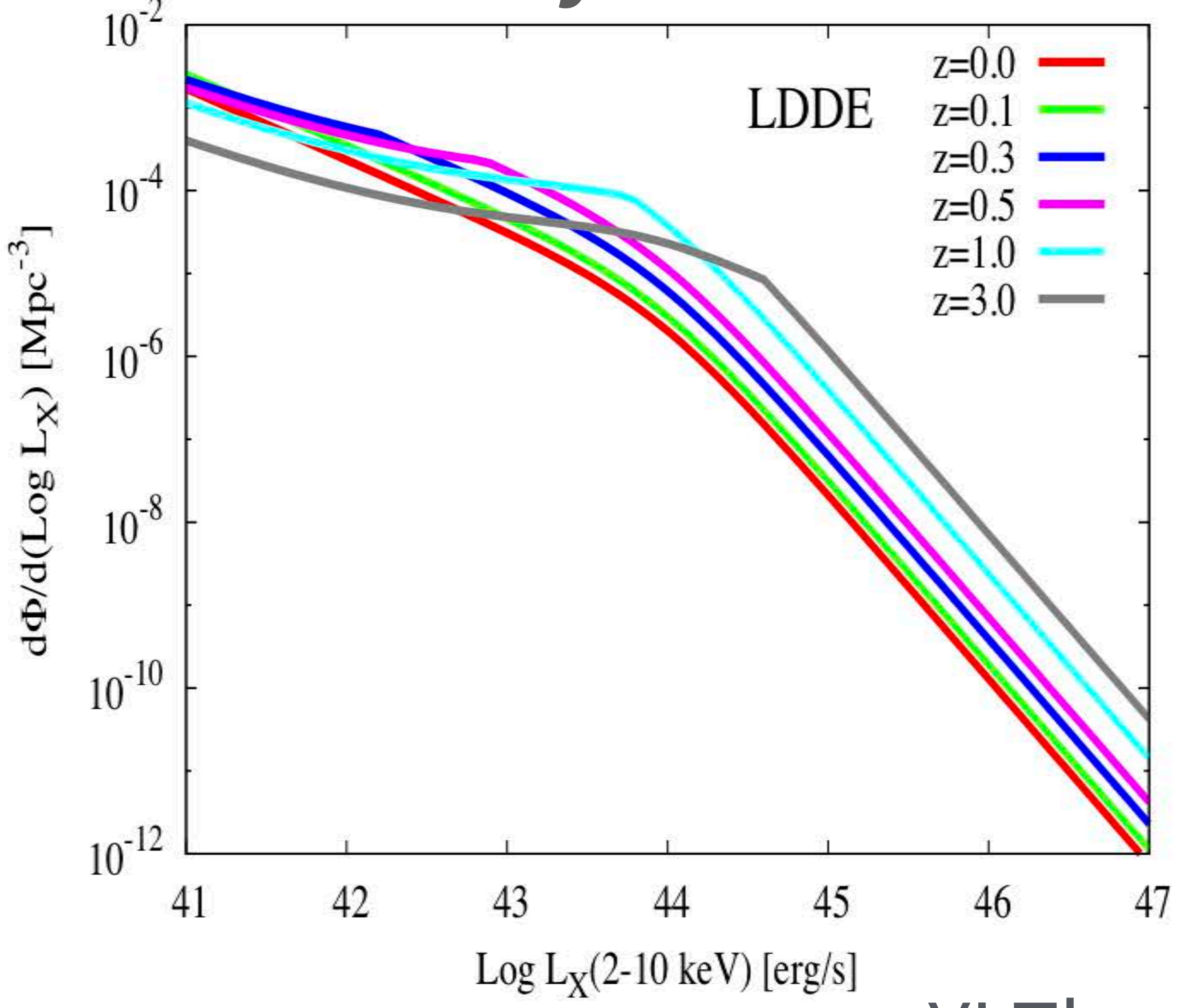
Pure Luminosity Evolution



Pure Density Evolution



Luminosity Dependent Density Evolution

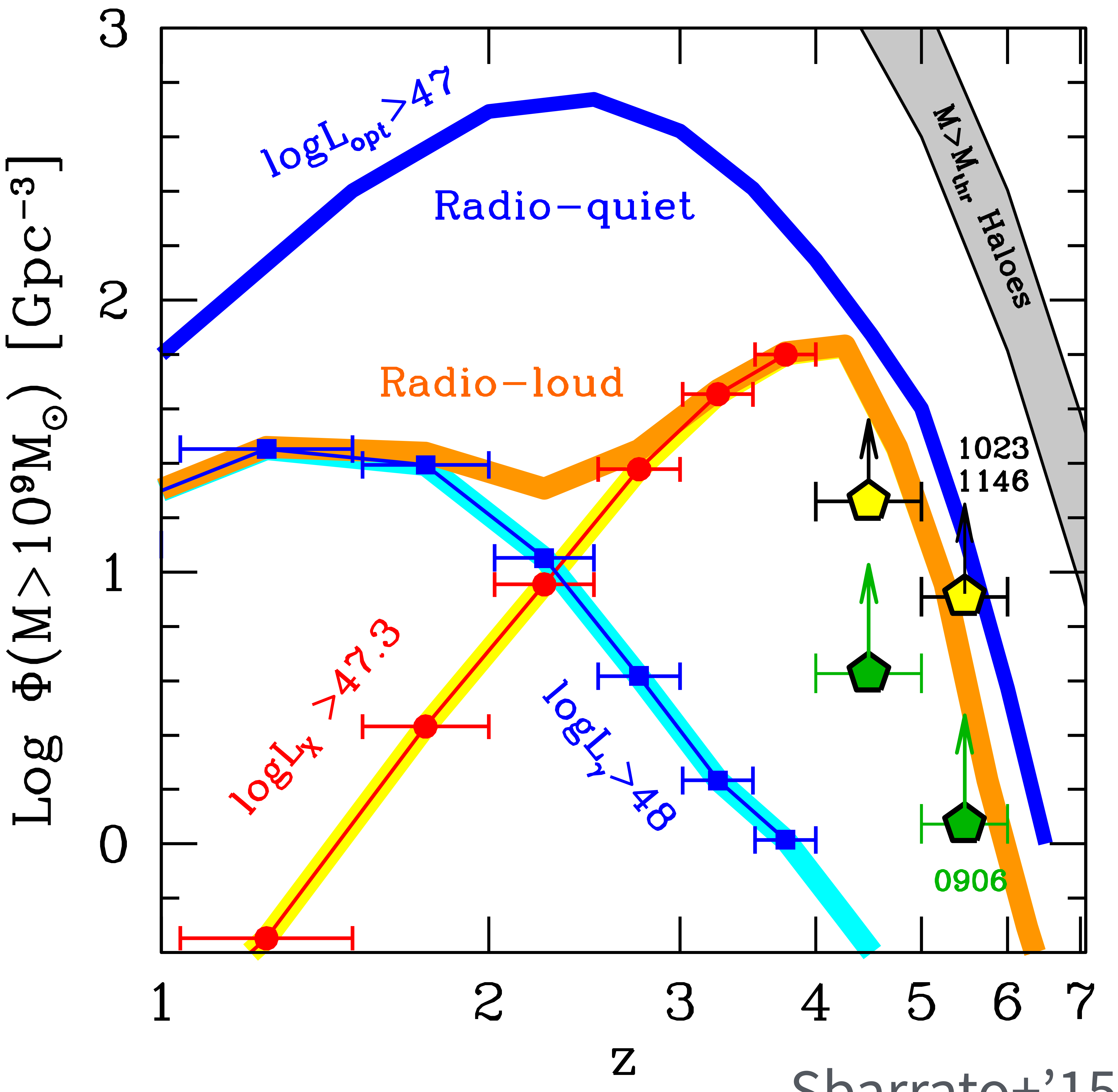


YI Thesis

- AGNs favor luminosity dependent density evolution (e.g., Ueda+’03,’14, YI&Totani’09; Ajello+’12; Ajello+’14; Ajello+’15,,,)

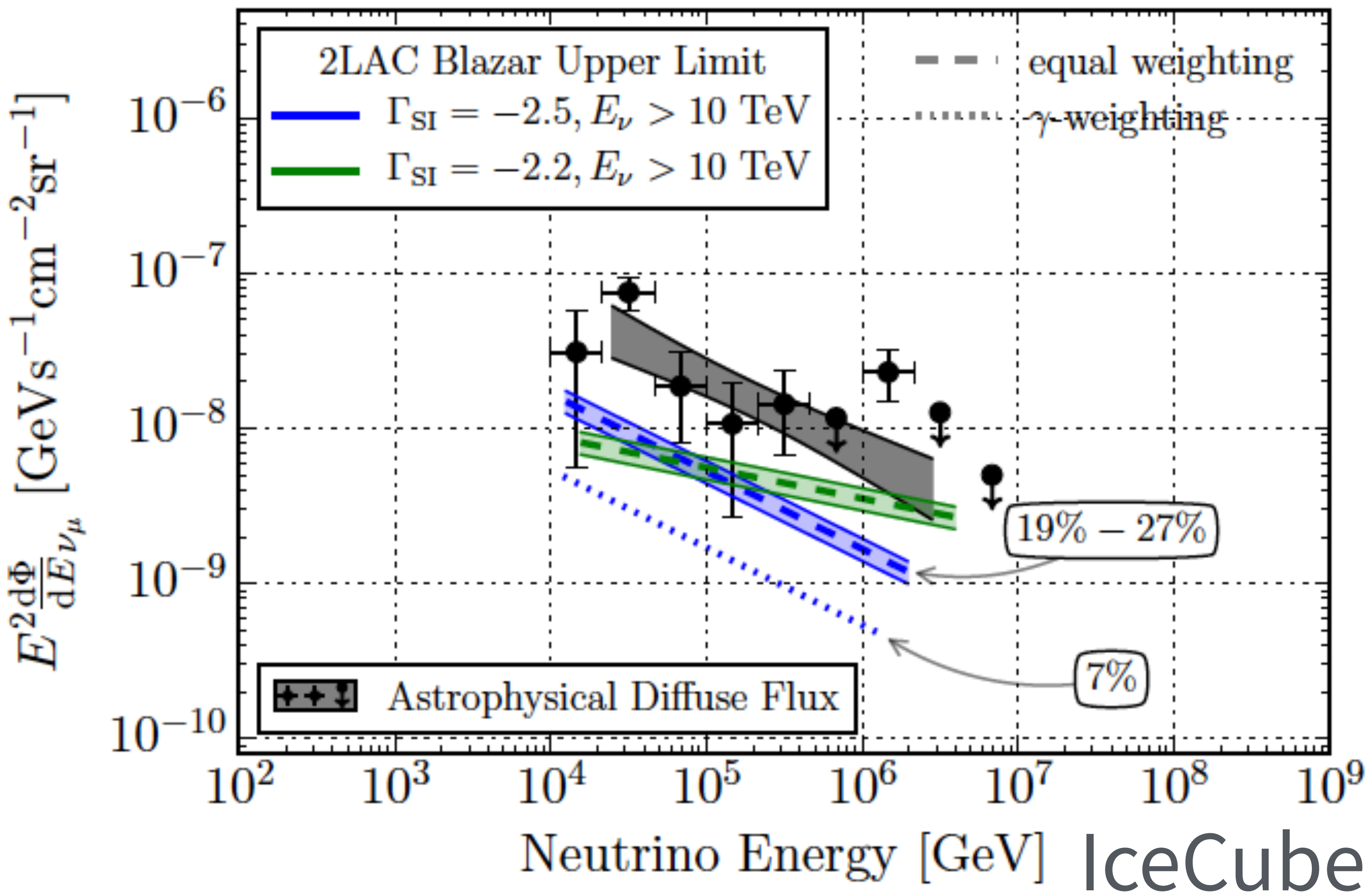
Do we understand the blazar evolution?

Maybe, Not Yet,,,



Sbarrato+'15

- Gamma-ray blazars show evolutionary peak at z~1-2 (e.g., YI & Totani'09; Ajello,YI+'15)
  - But, it is at z~3-4 for X-ray blazars (Ajello+'09, see also Toda, Fukazawa, YI'20).
- Important for high energy neutrinos.



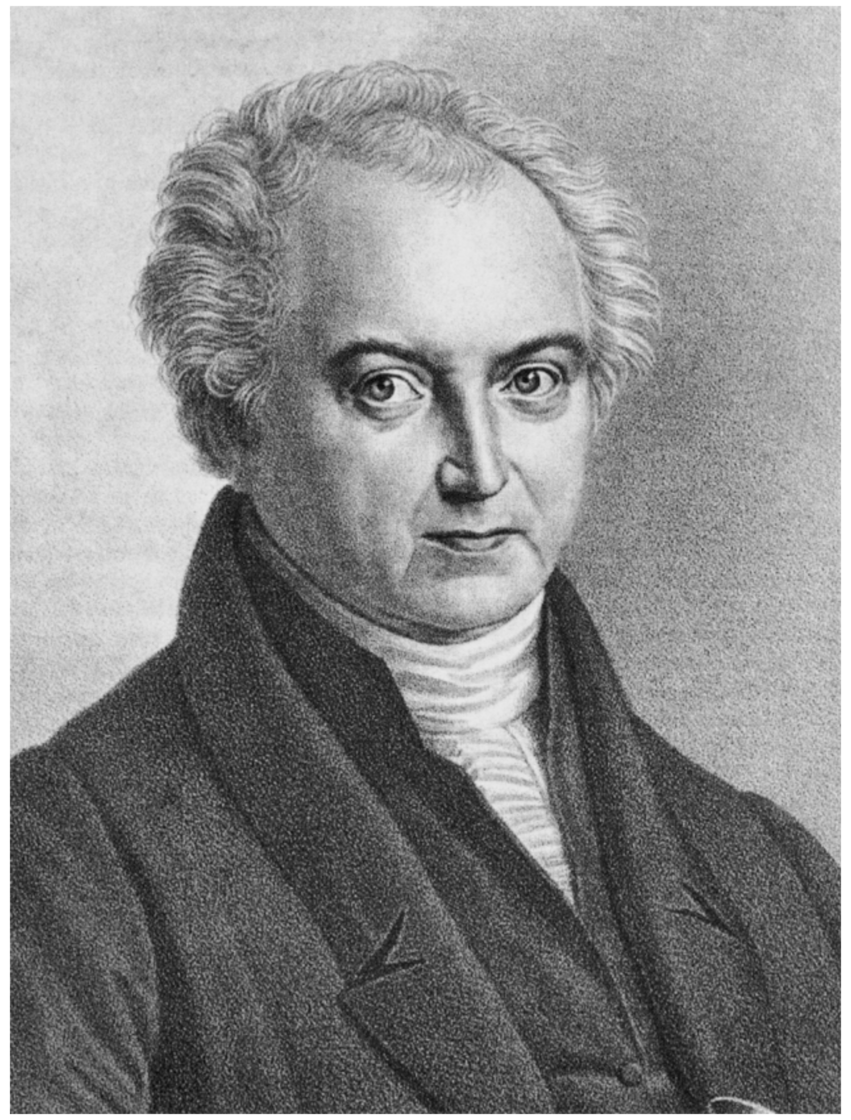
IceCube '17

Cosmic GeV Gamma-ray Background Radiation Spectrum

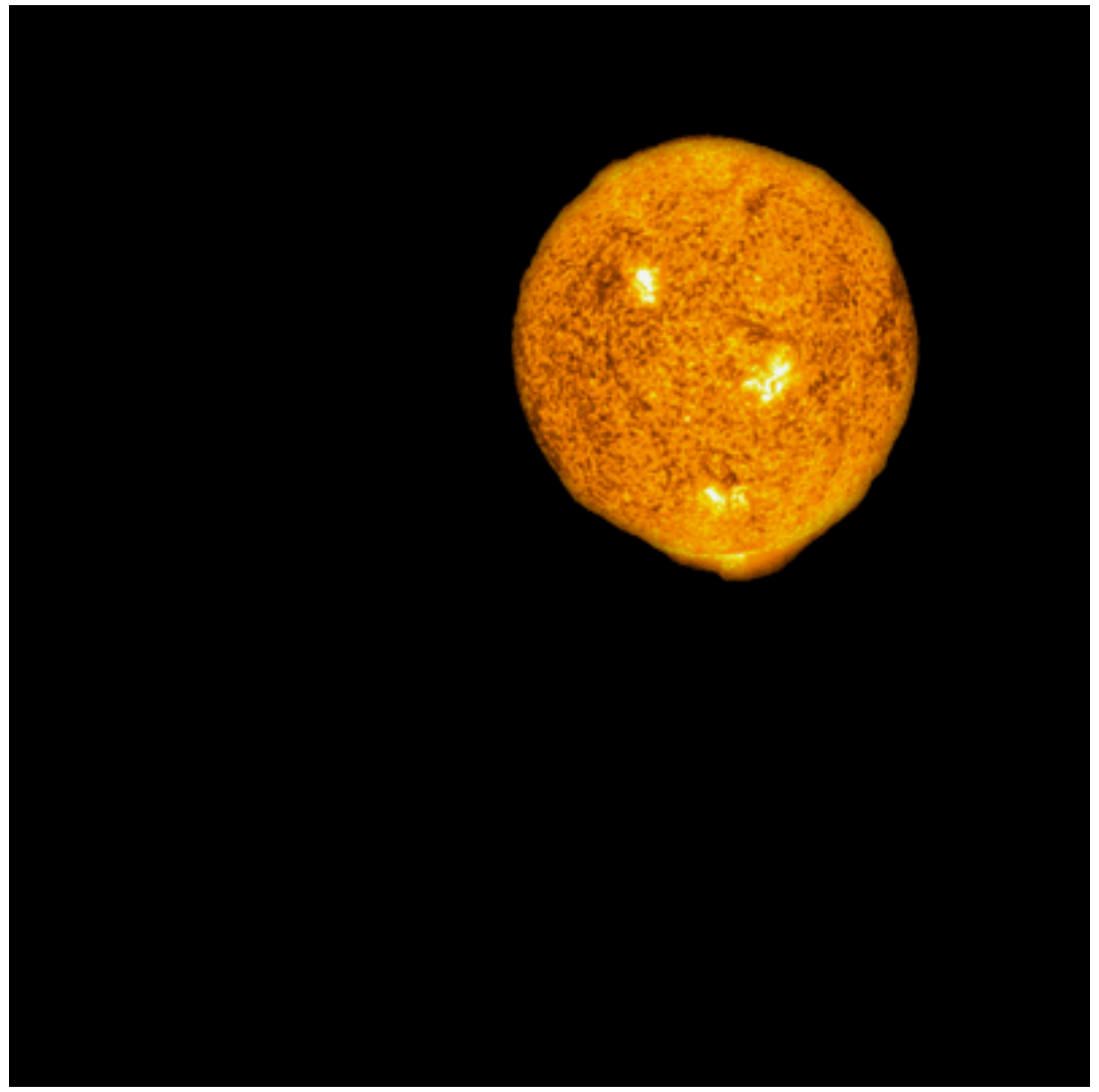
Why is the sky dark at night?

Olber's Paradox

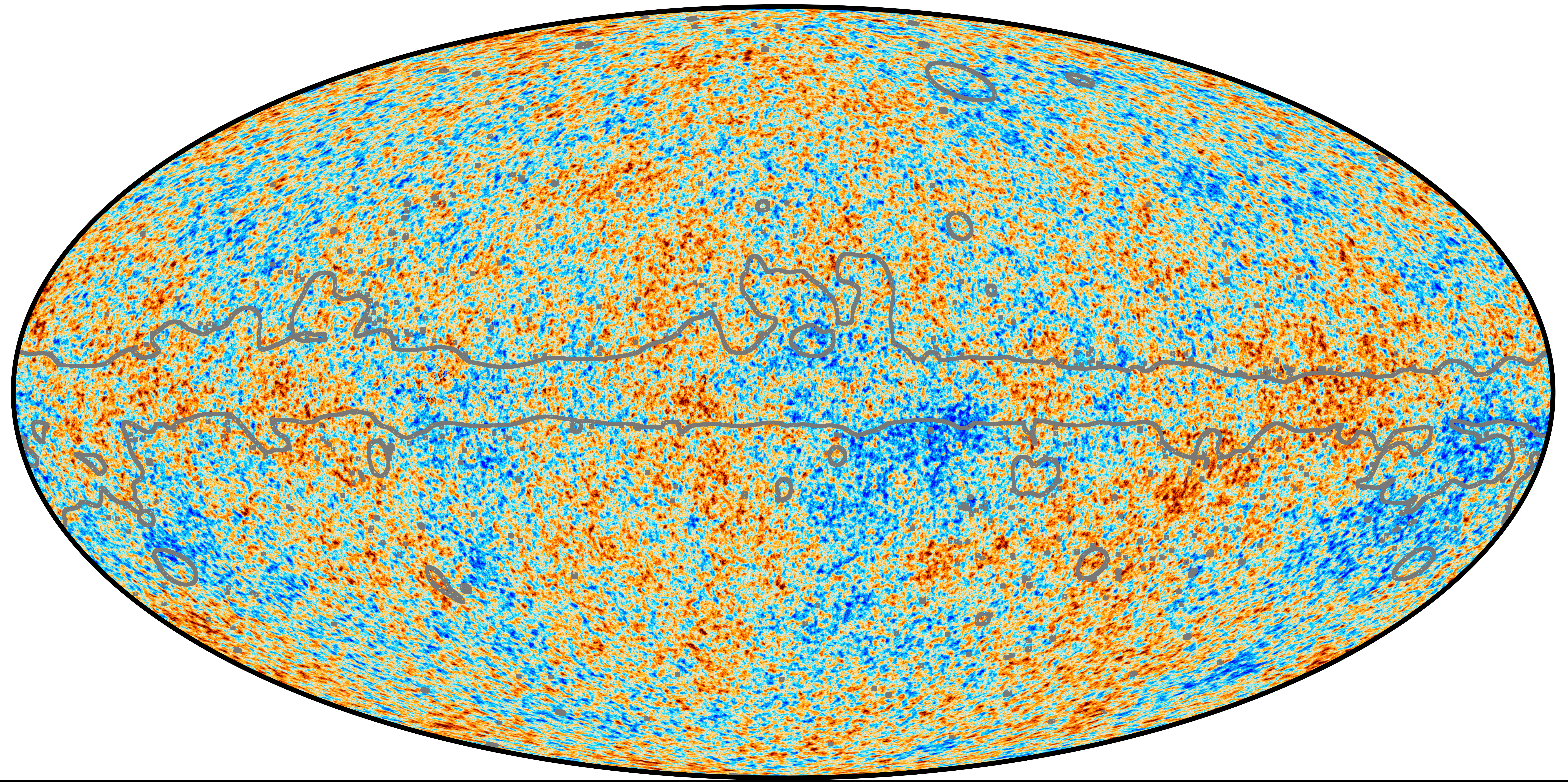
- If the Universe is infinite and has infinitely many stars, the sky should be as bright as the surface of the Sun.
- Answer: the Universe is **not** infinite.
- **Is the sky truly dark? No.**
  - There is faint but almost isotropic emission in the entire sky.
- "Cosmic Background Radiation"
  - Cumulative emission of the universe in its entire history.



Heinrich Wilhelm Matthias Olbers (1758-1840)

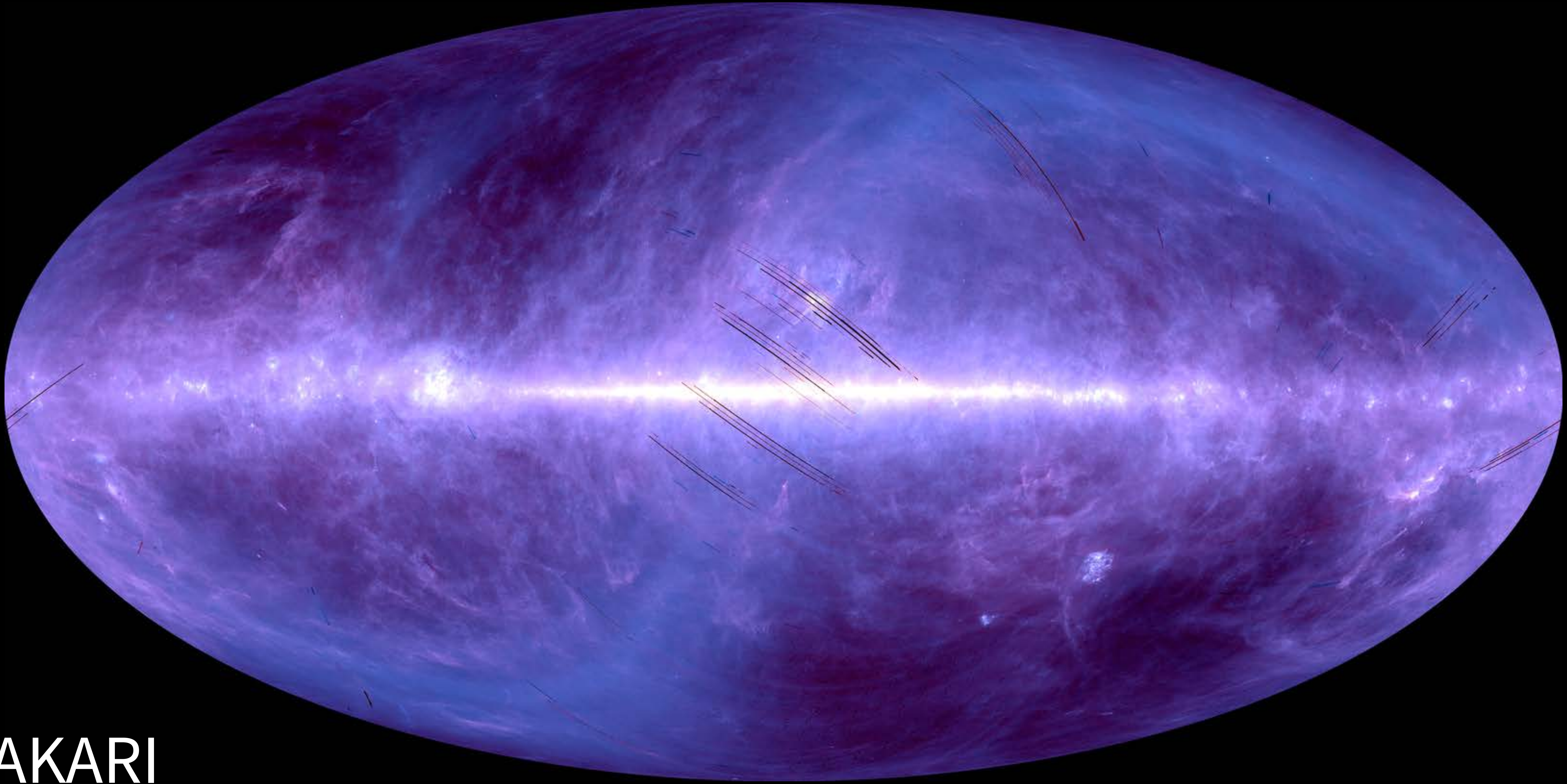


Microwave Sky



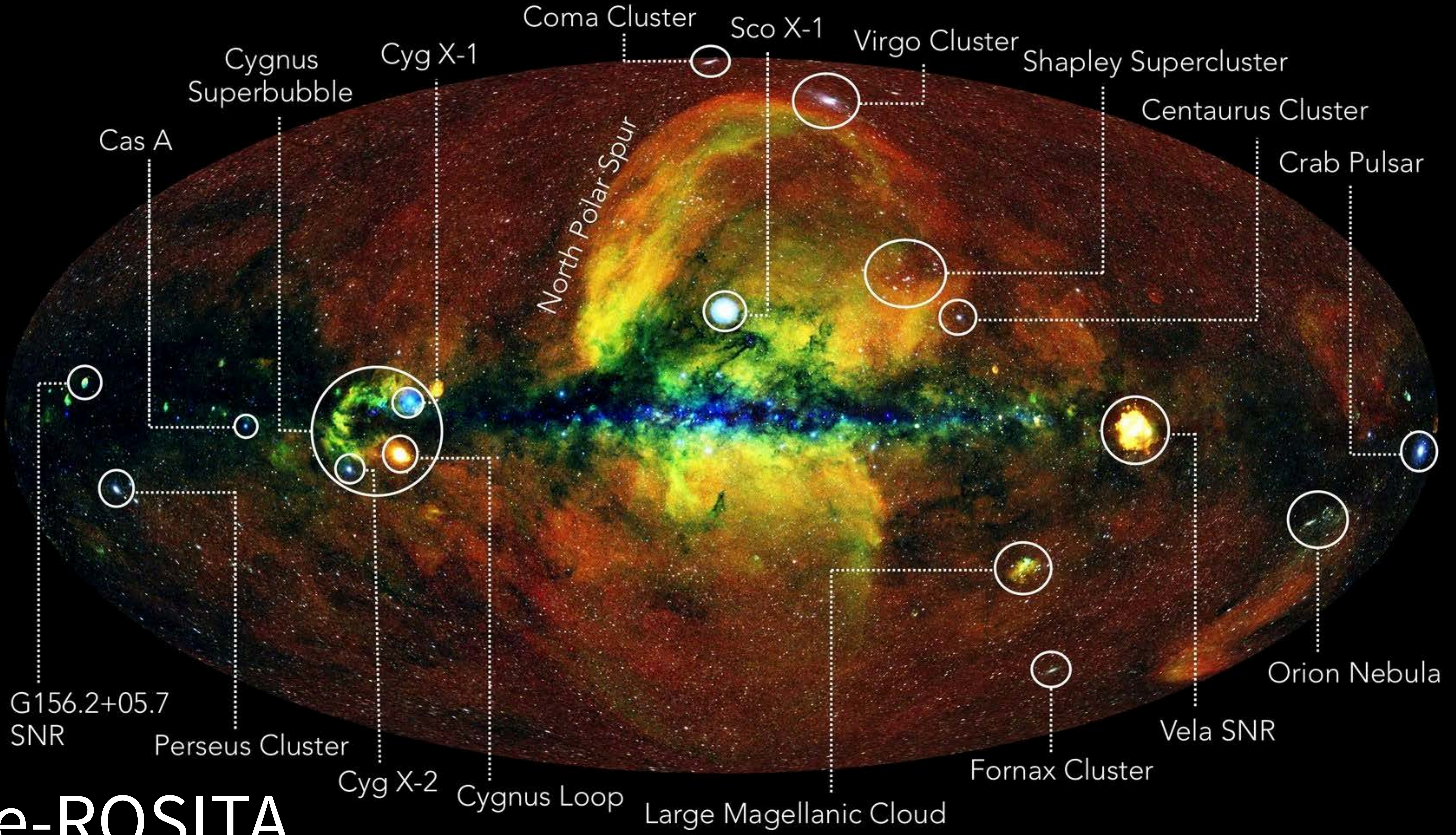
Planck

Far Infrared Sky



AKARI

Soft X-ray Sky (0.3-2.3 keV)

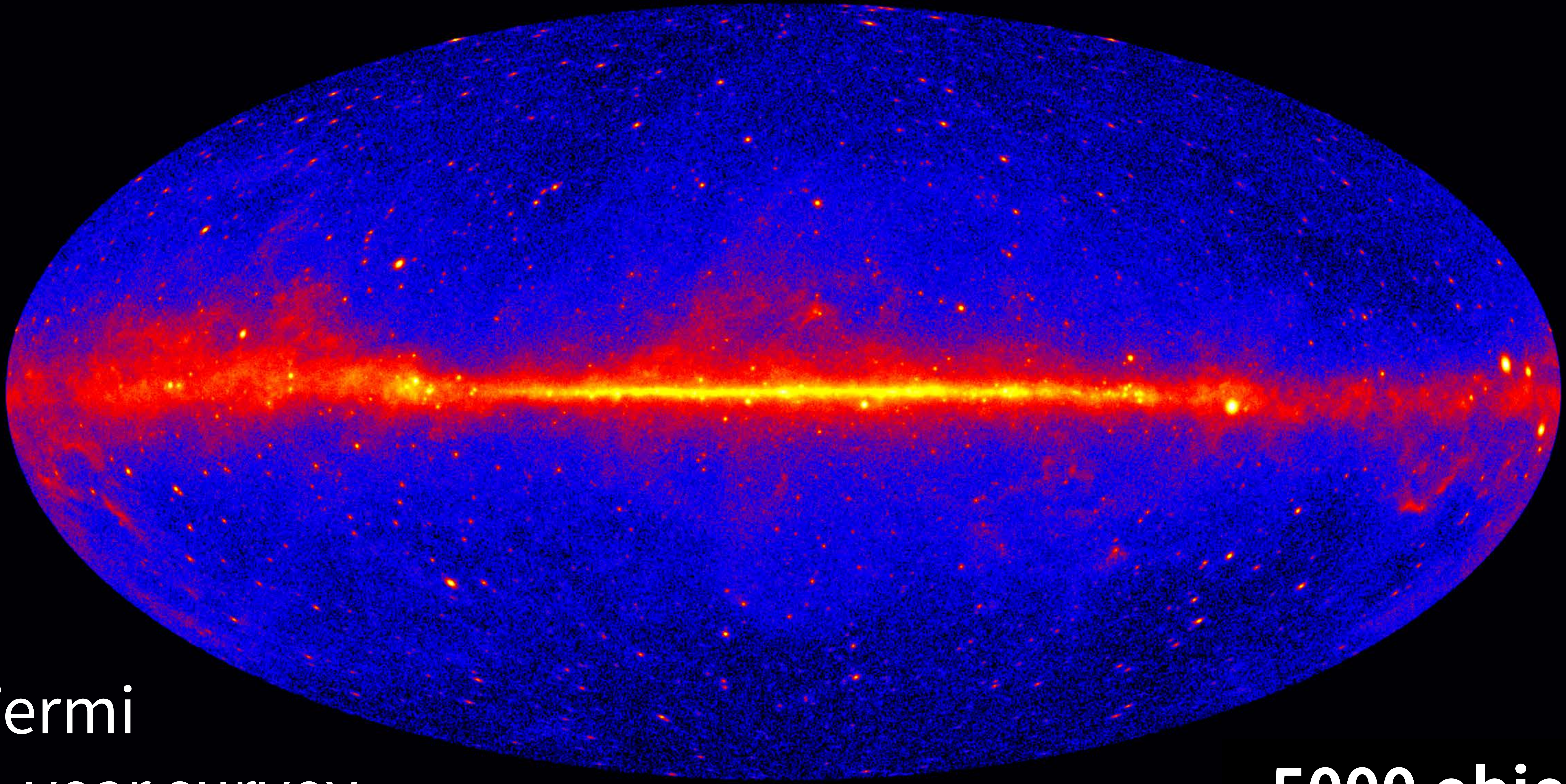


SRG/e-ROSITA
1-year survey

$> 1 \times 10^{-14}$ erg/cm²/s

~10^6 objects

GeV Gamma-ray Sky (0.1-100 GeV)

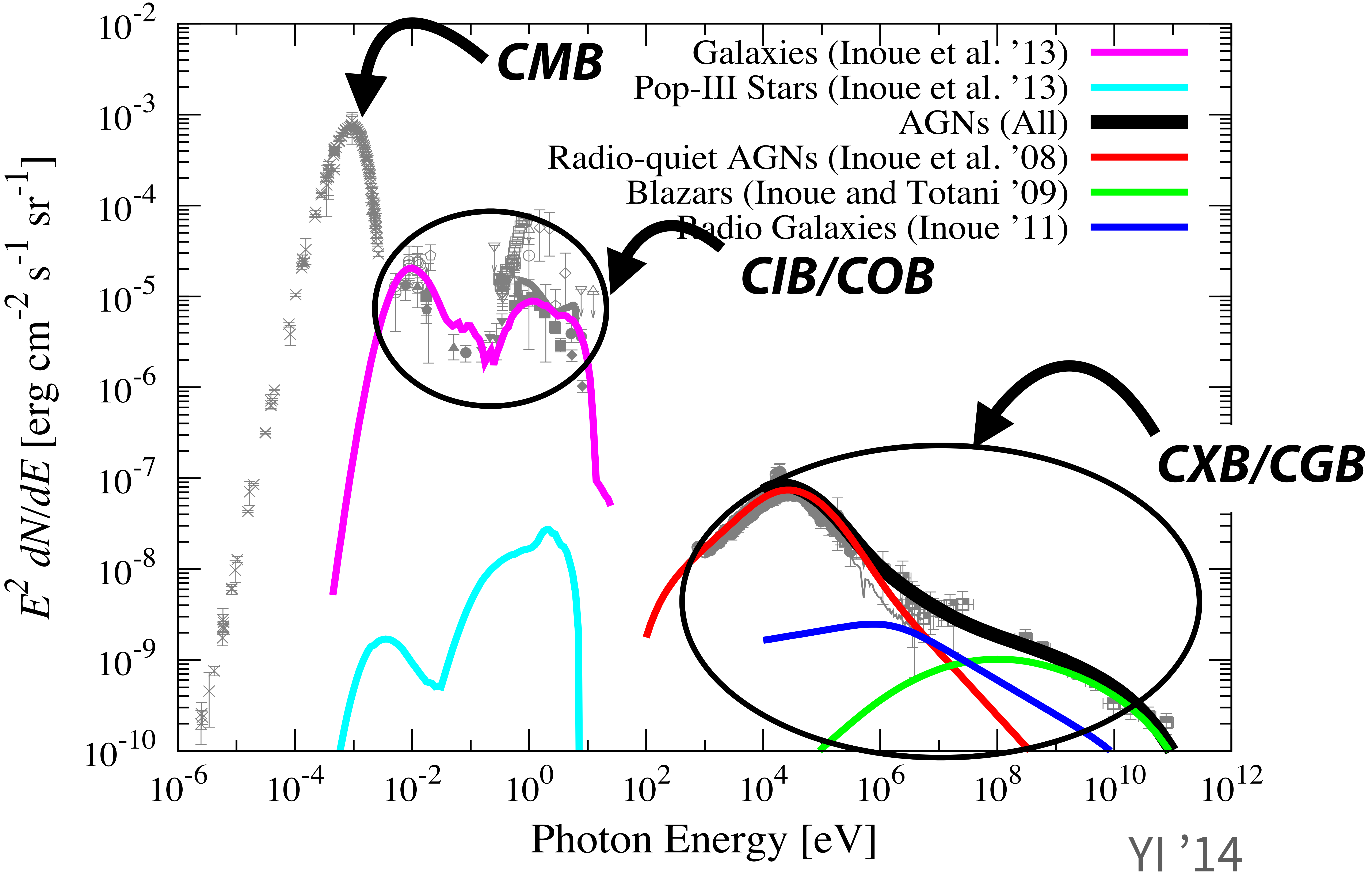


Fermi
5-year survey

~5000 objects

Cosmic Background Radiation Spectrum

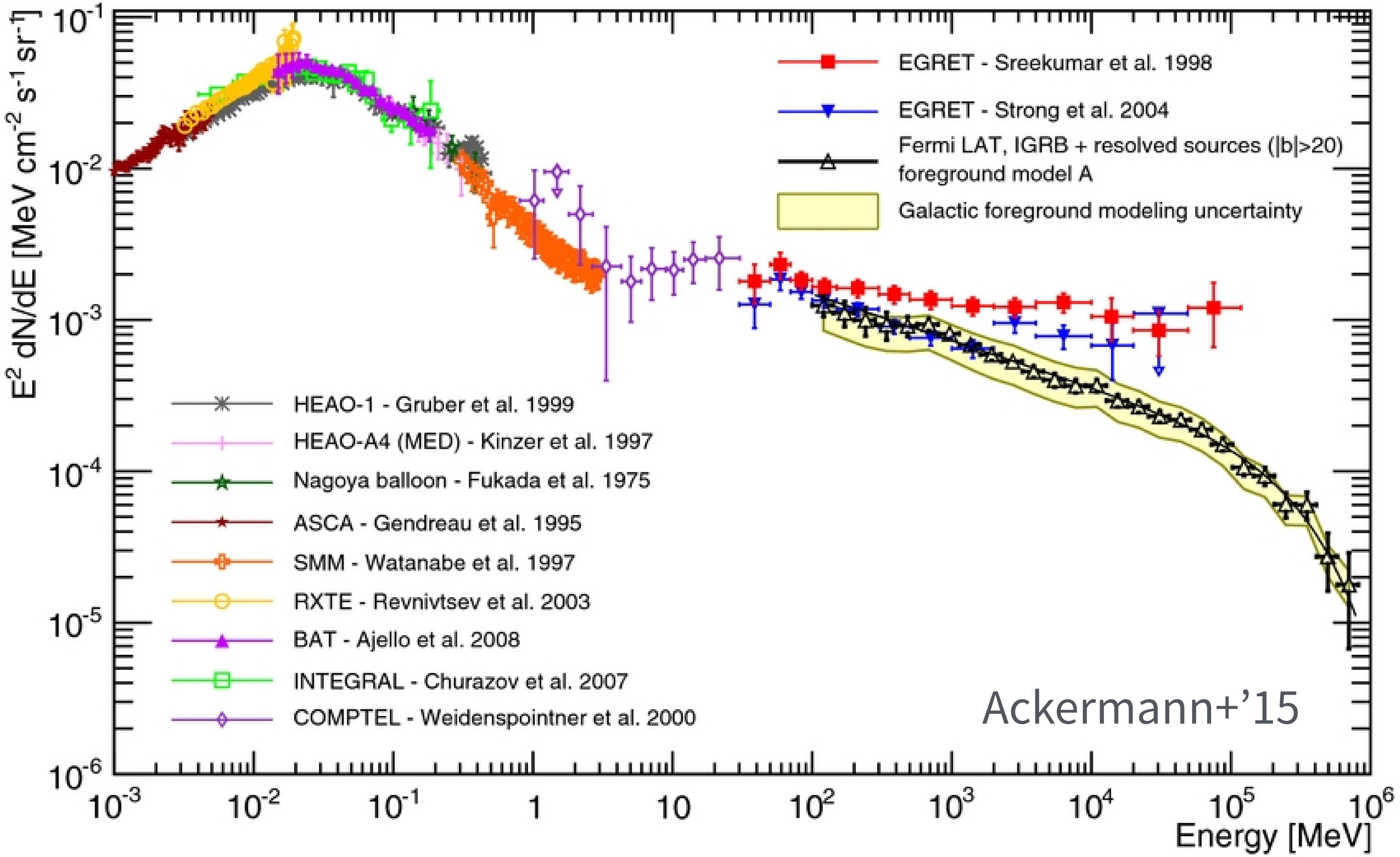
From Radio To Gamma-ray



YI '14

Cosmic X-ray & Gamma-ray Background Spectrum

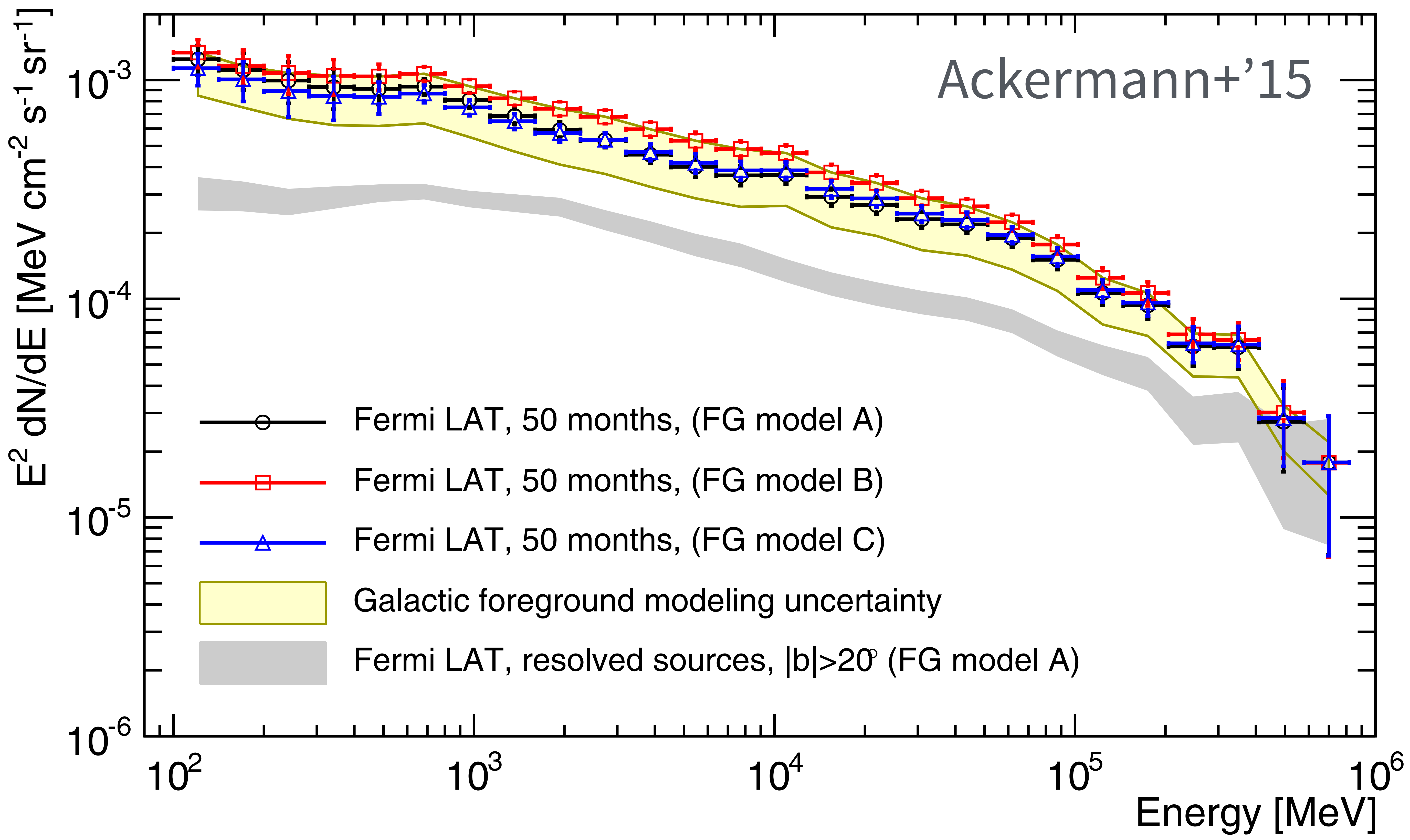
From X-ray to TeV Gamma-ray

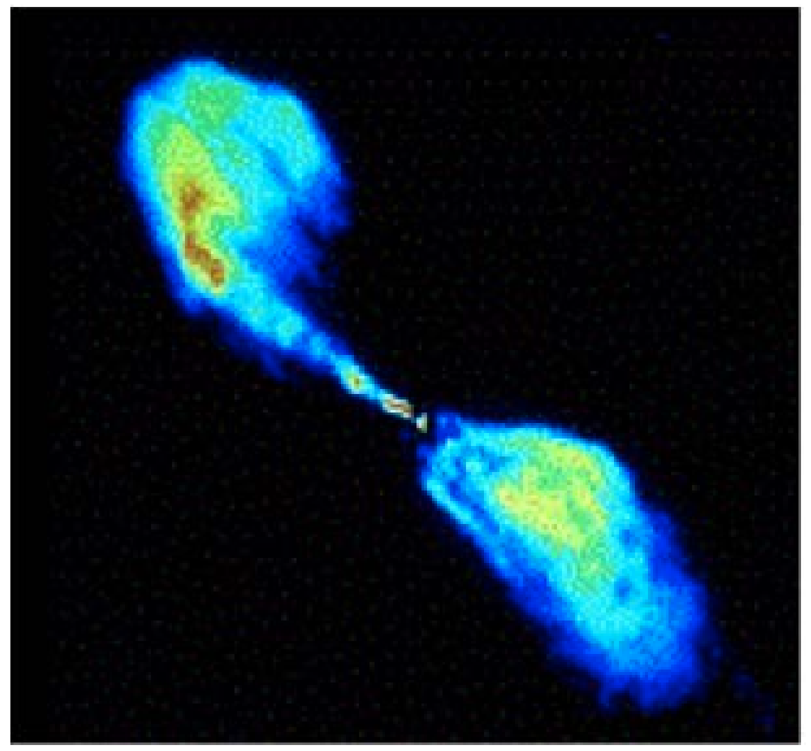


- X-ray background is well explained by Seyferts (e.g., Ueda+'03)
- MeV background is under debate (Day 2).
- GeV background is now understood by Fermi.

GeV Gamma-ray Background Radiation

- Single power-law spectrum
  - + cutoff @ ~sub TeV?
- 30% of CGB is resolved at ~1GeV.
  - Resolved more at higher energies.
- What are the origins?

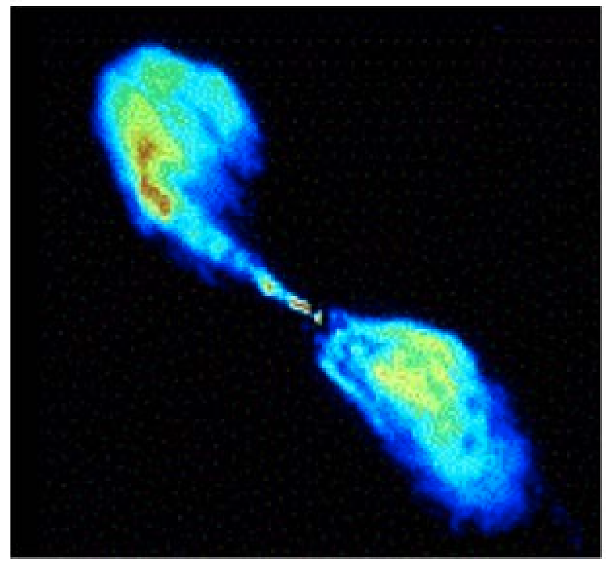




Origin of Cosmic Gamma-ray Background Radiation

- Blazars are discussed as the origin until ~2010
  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,,,,

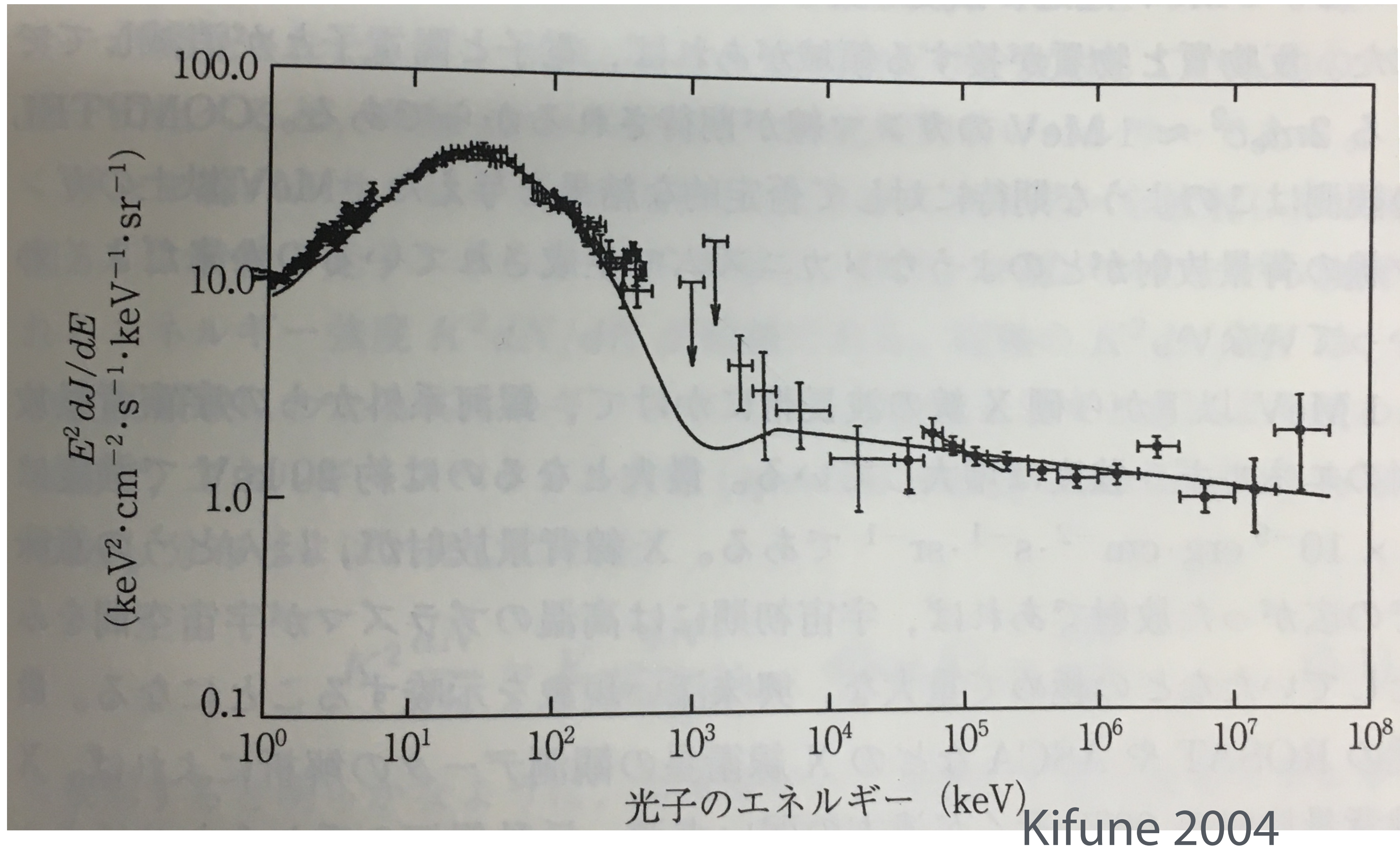
  - But, it turns out ~50%.



- Radio galaxy ~ 20%.
  YI '11; Di Mauro+'13; Zhou & Wang '13; Linden'16

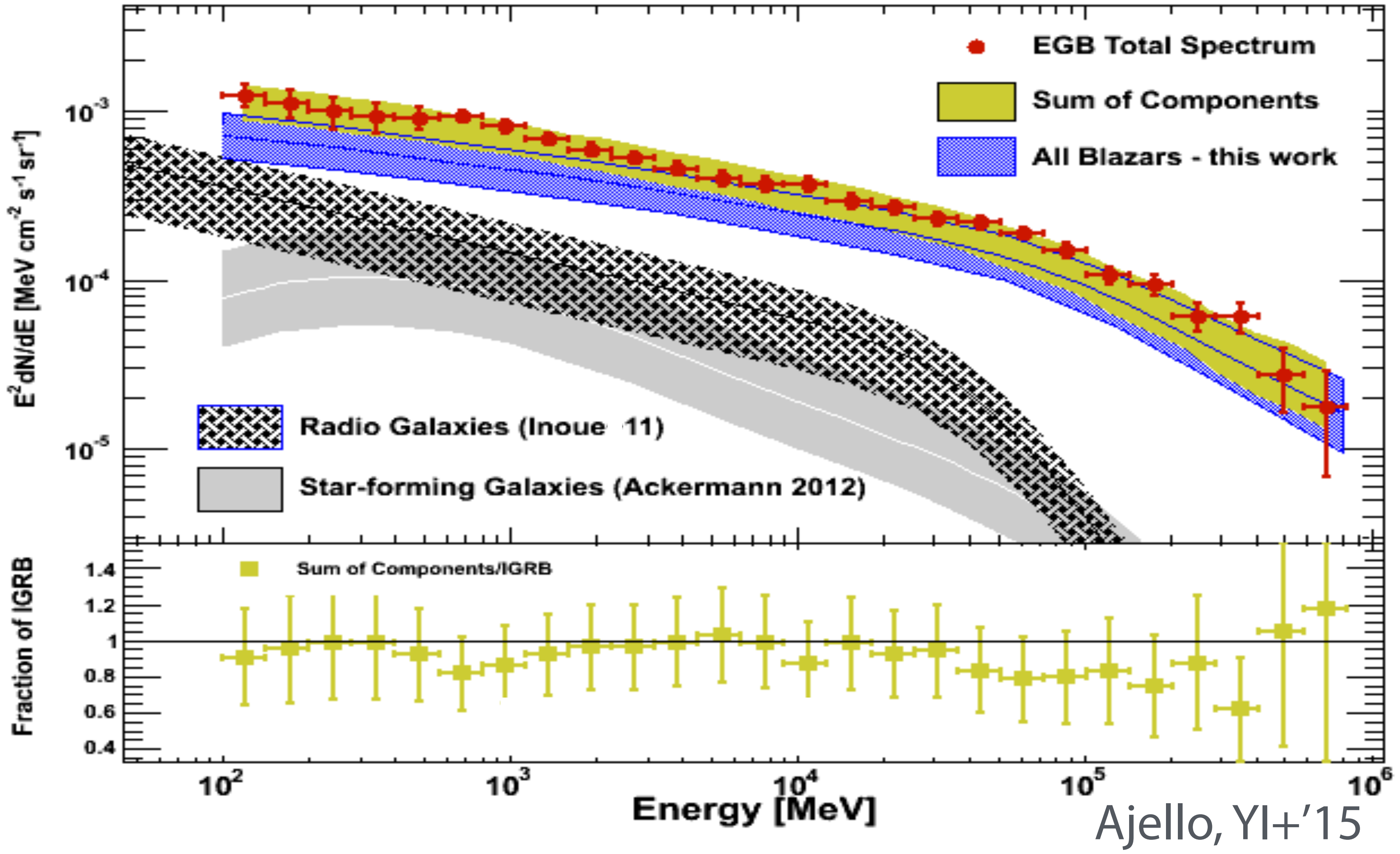
- Star-forming galaxy ~10-30%
  Soltan '99; Pavlidou & Fields '02; Thompson +'07; Bhattacharya & Sreekumar 2009; Fields et al. 2010; Makiya et al. 2011; Stecker & Venters 2011; Lien+'12, Ackermann+'12; Lacki+'12; Chakraborty & Fields '13; Tamborra+'14

Until ~2010



Kifune 2004
(Textbook in Japanese)

Now



Ajello, YI+'15

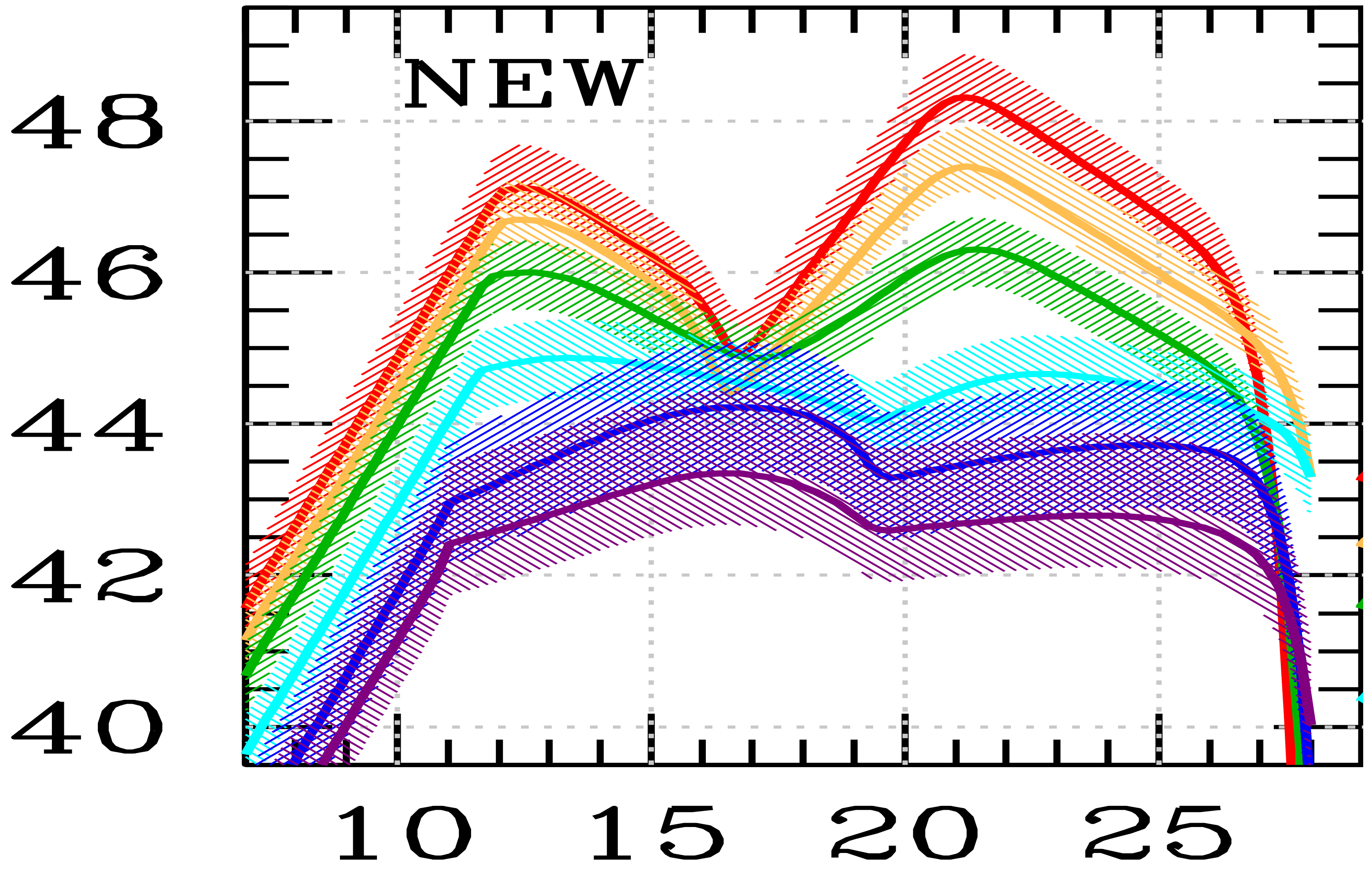
Blazar

~50% of known gamma-ray objects

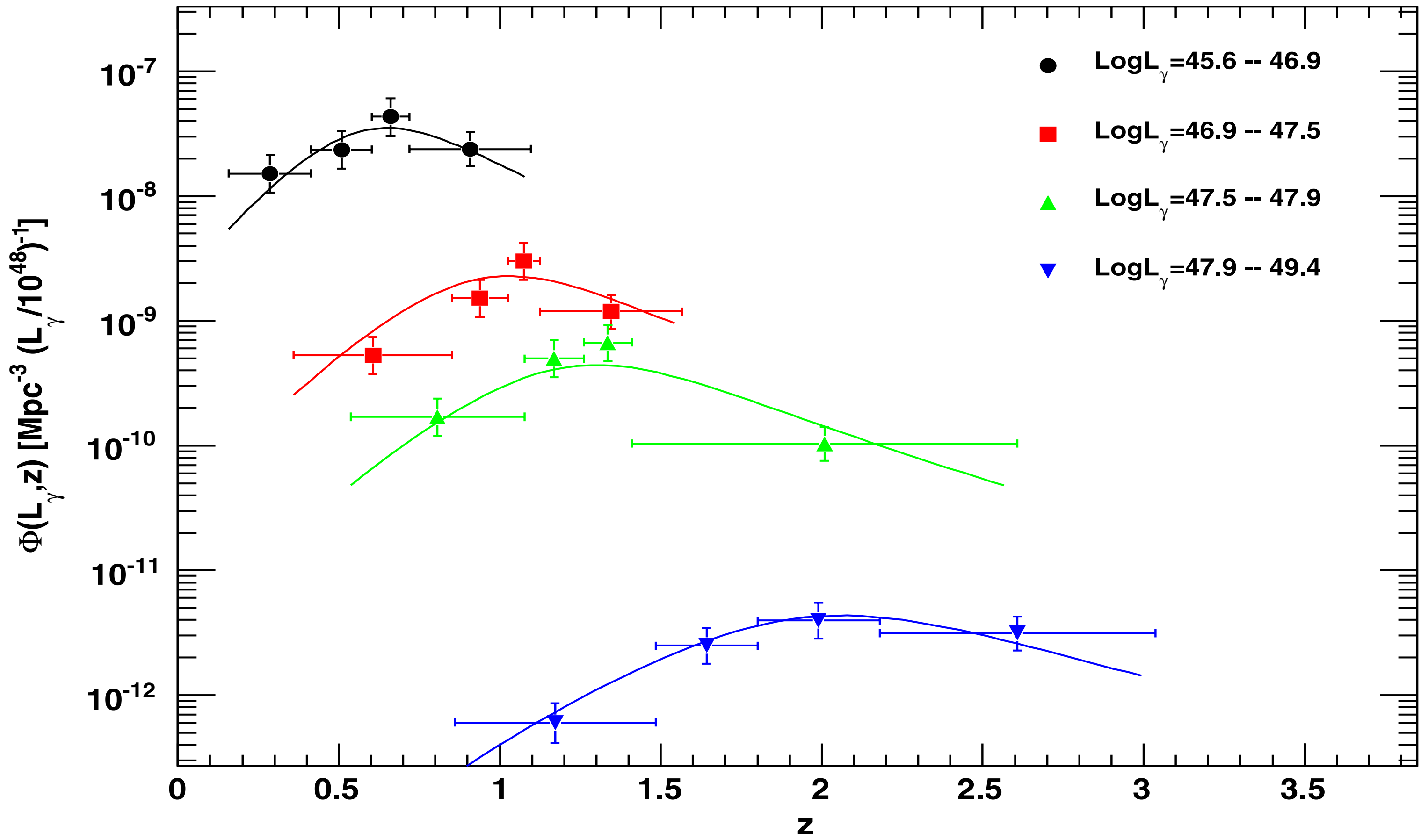
- Blazars have been discussed as the origin for a long time.

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,,,,

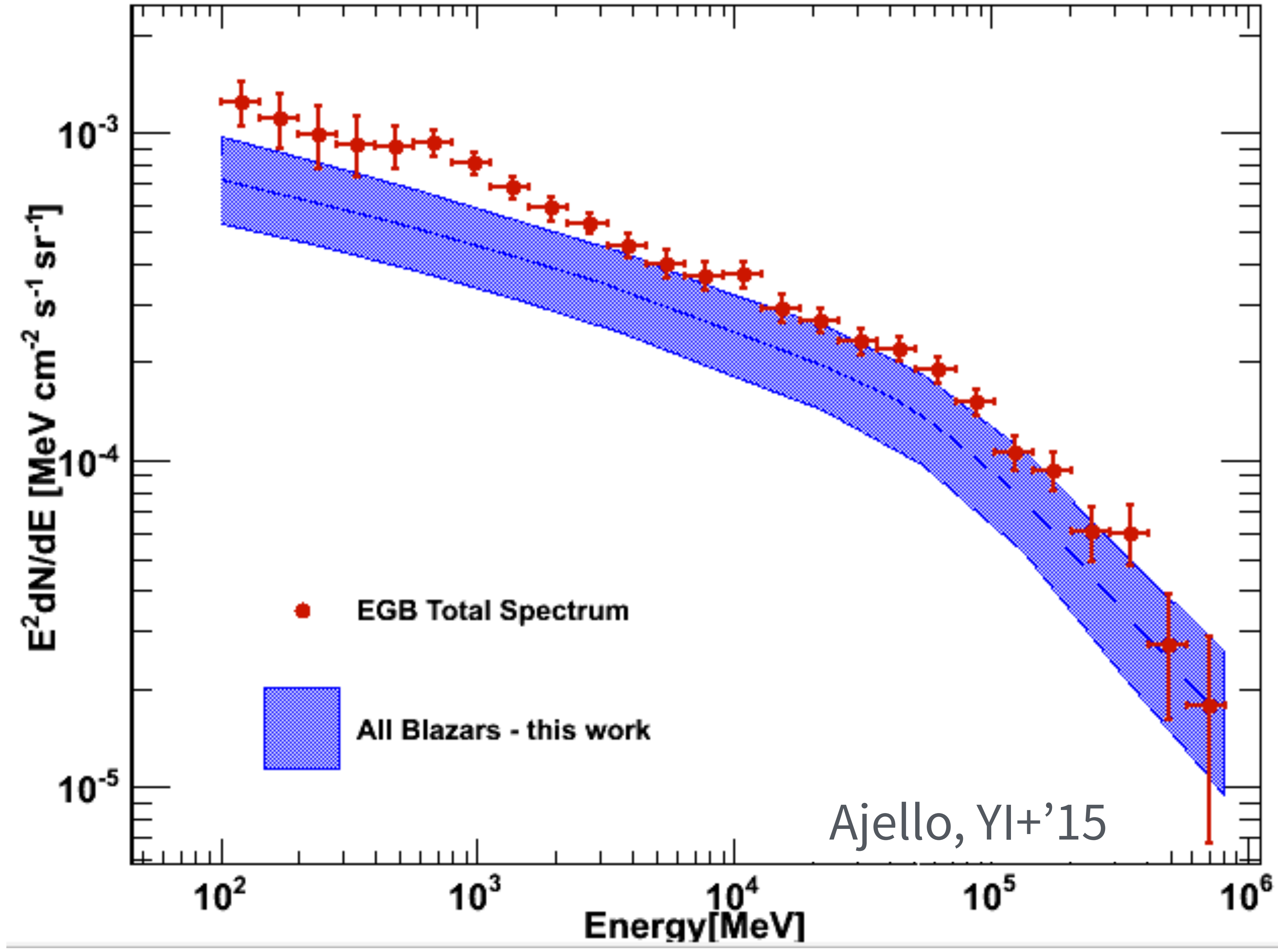
- Now, it turns out ~50%.



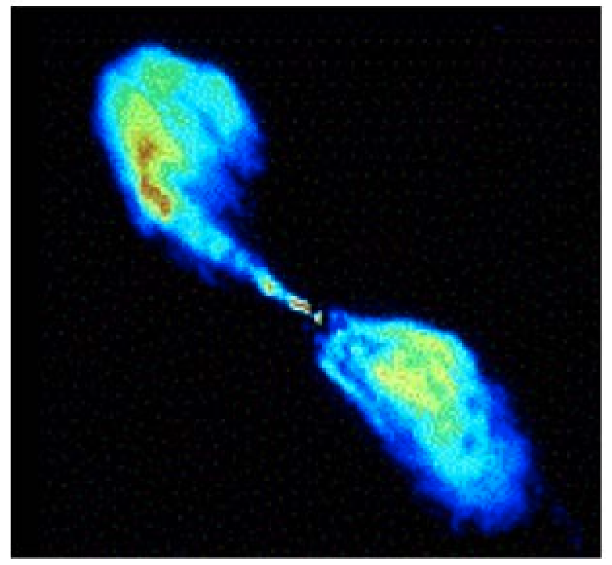
SED



Evolution



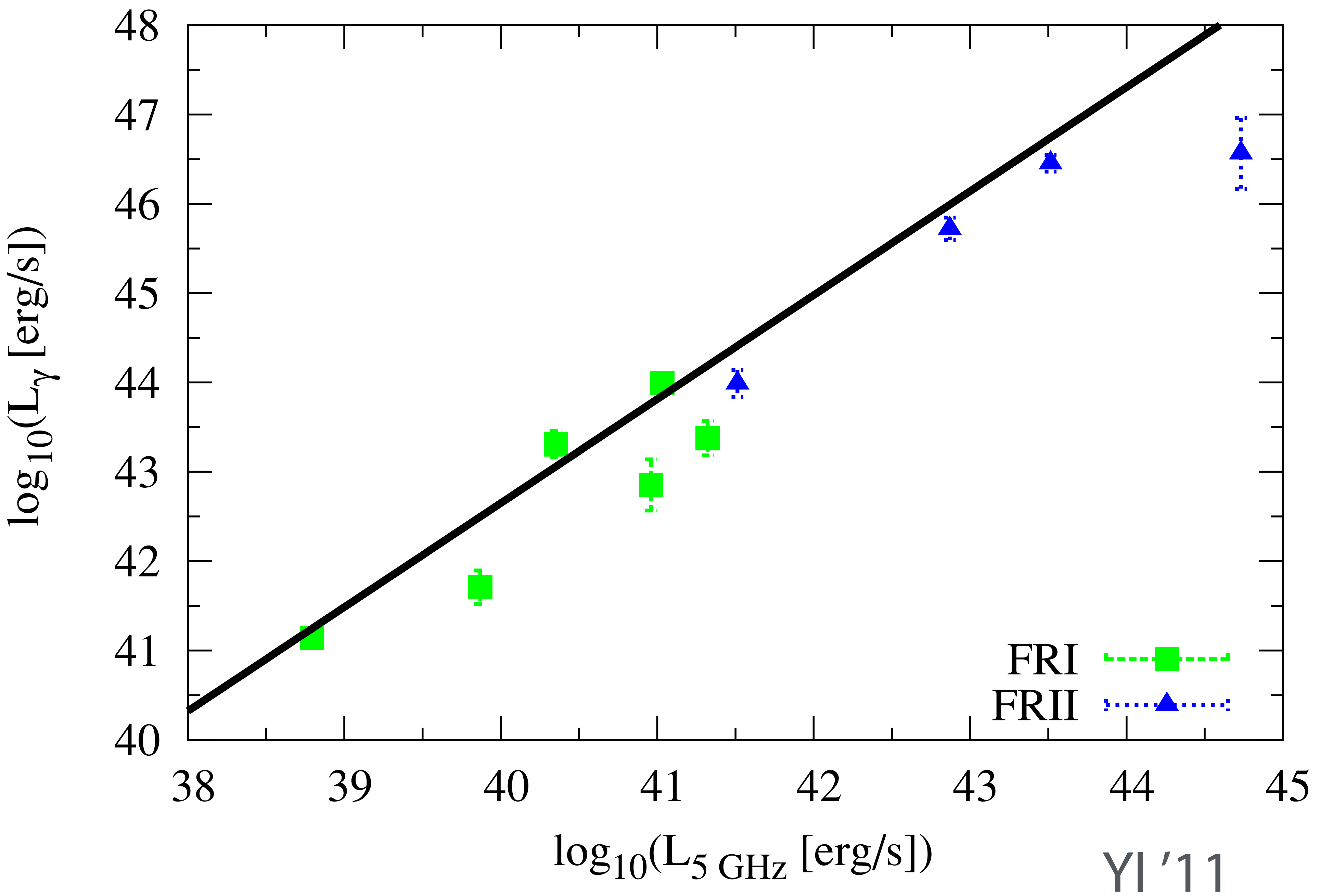
Ajello, YI+'15



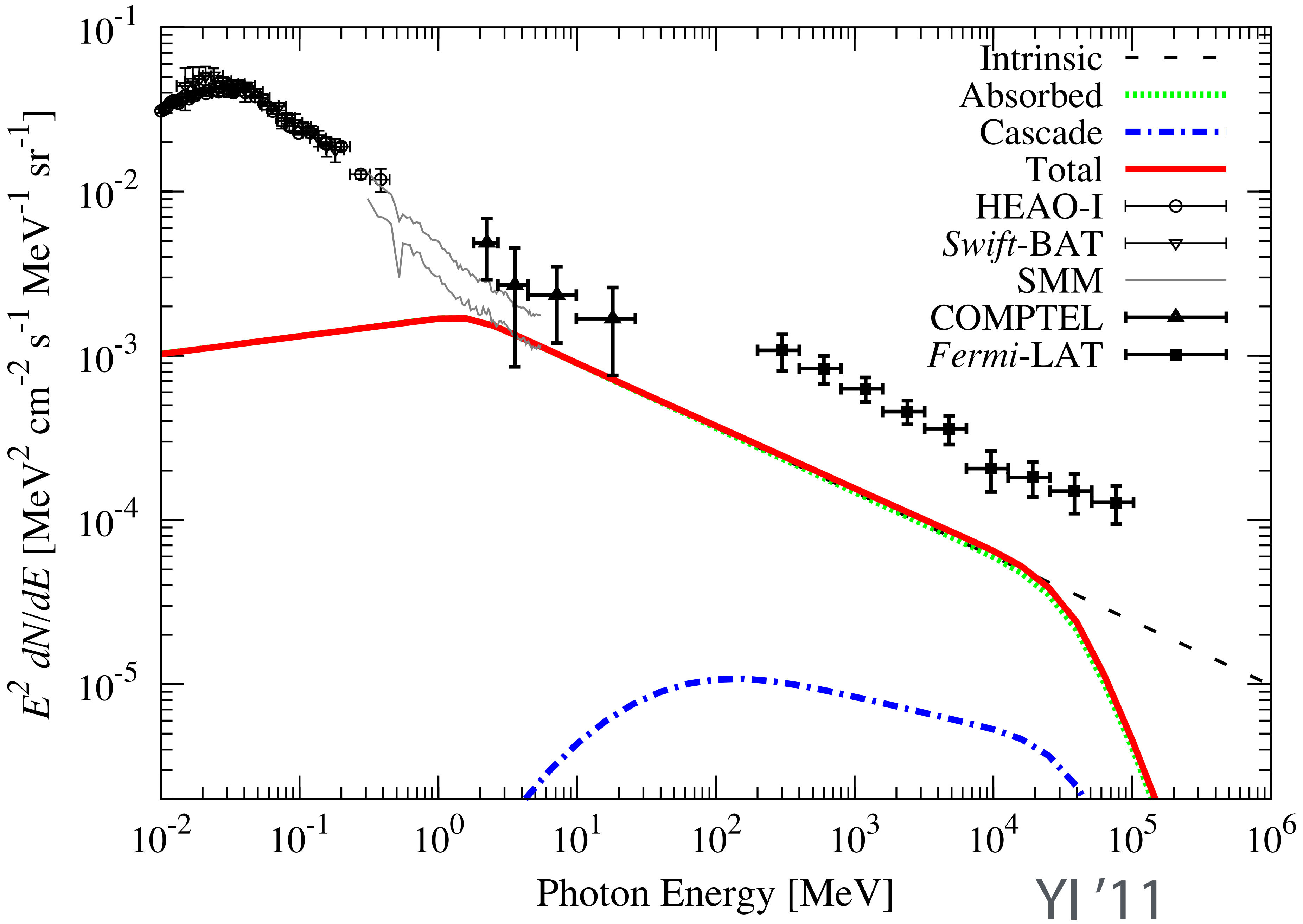
Radio Galaxy

Off-axis blazars

- Blazars can not explain the entire cosmic gamma-ray background.
- Use gamma-ray and radio luminosity correlation.
- ~20% of CGB at 0.1-100 GeV.
  (YI '11; Di Mauro+'13; Zhou & Wang '13; Linden'16)
- Only ~10 sources were reported by Fermi.
  - Now ~40.



YI '11

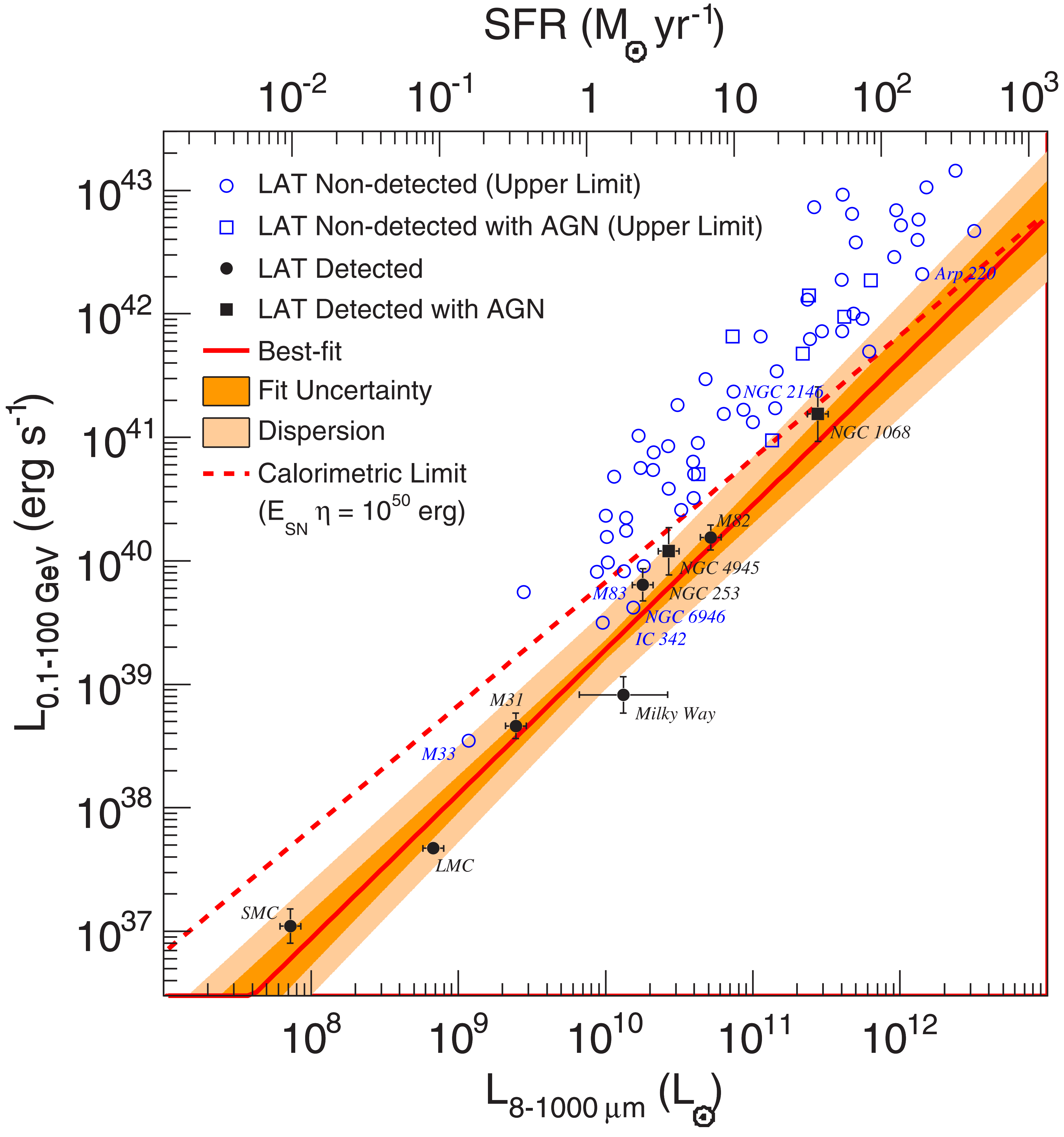


YI '11

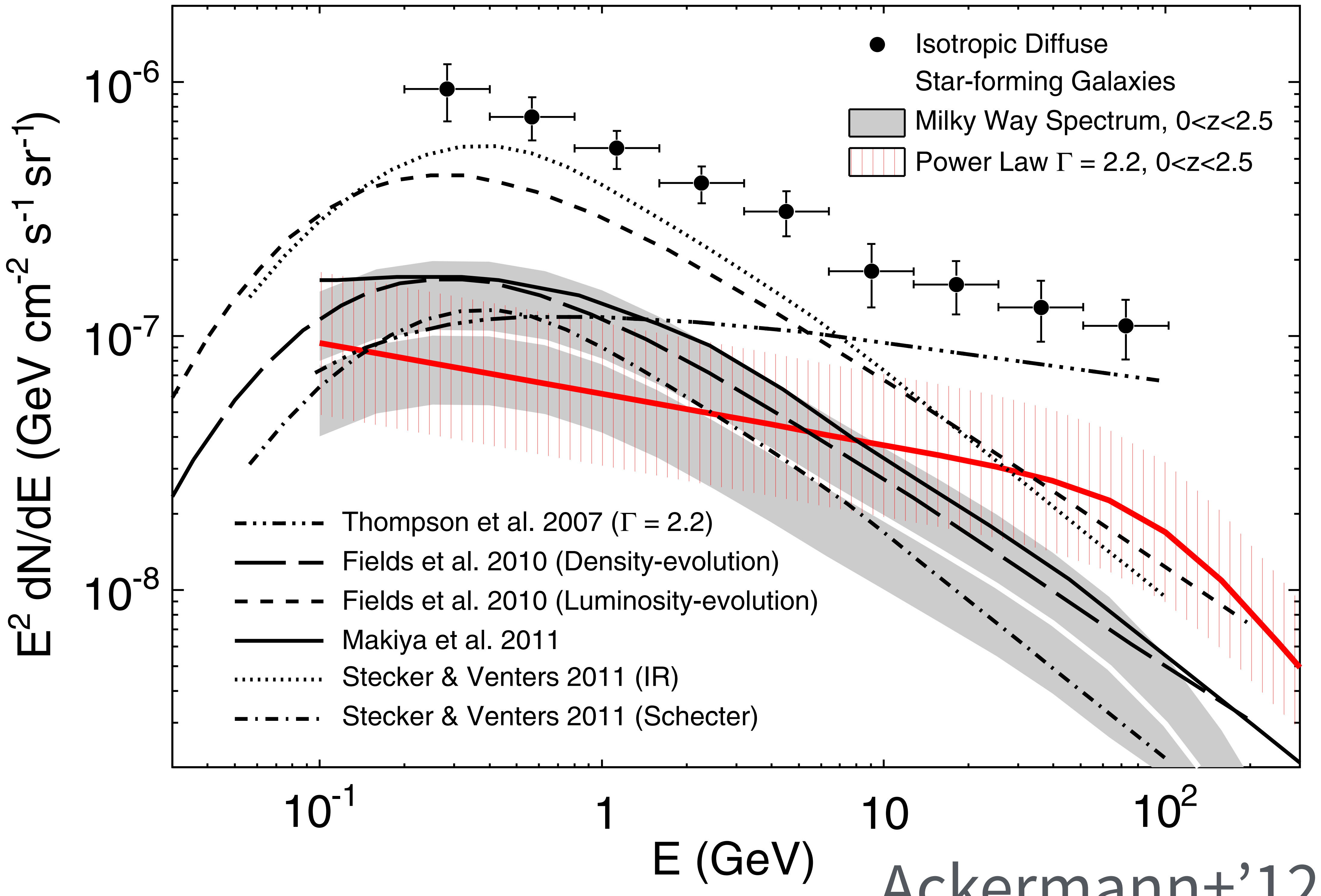
See talk by Ellis Owen

Star-forming Galaxy

like Milky way



Ackermann+'12

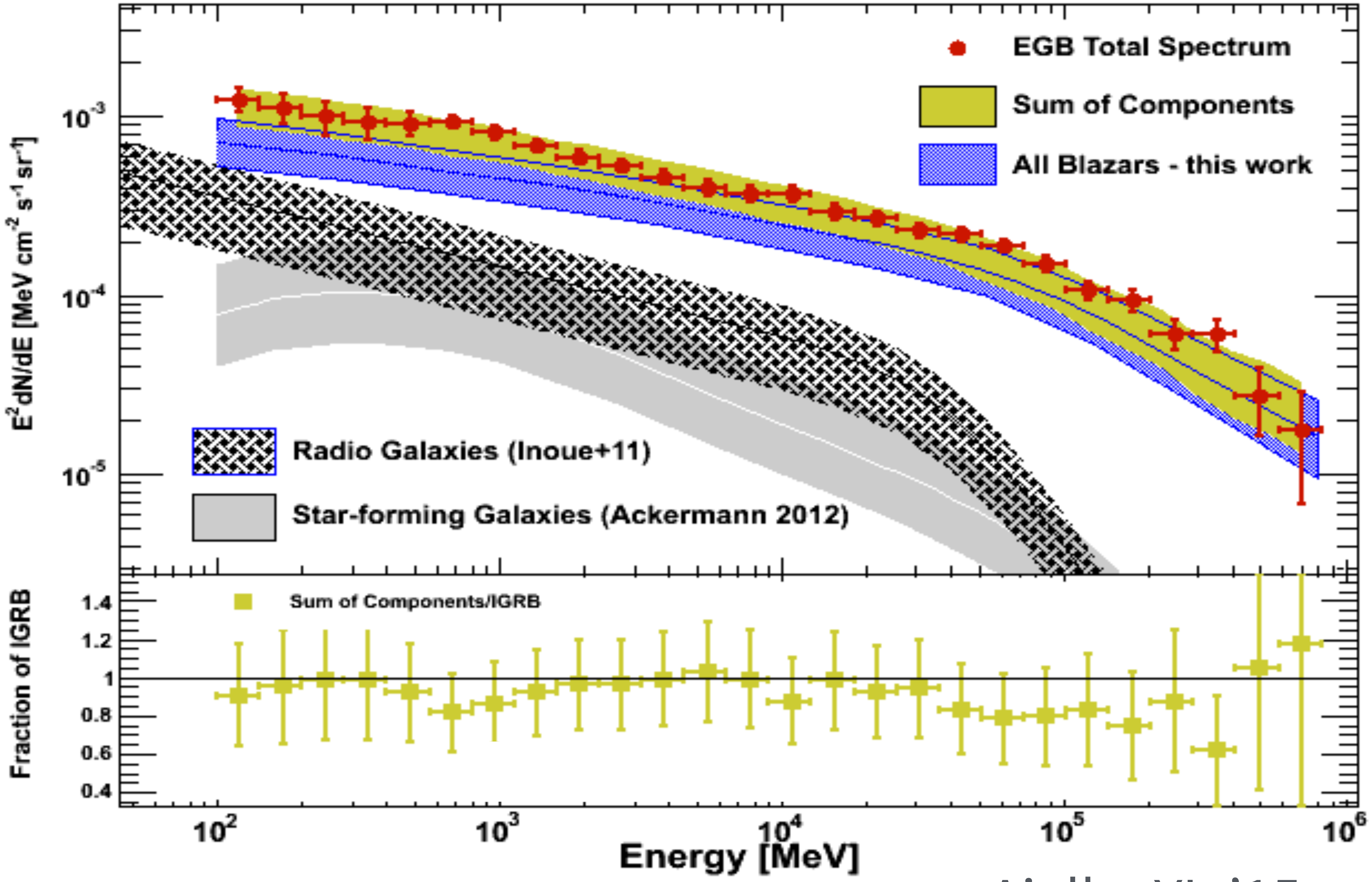


Ackermann+'12

- It has been discussed for a long time.
  (Soltan '99; Pavlidou & Fields '02; Thompson +'07; Bhattacharya & Sreekumar 2009; Fields et al. 2010; Makiya et al. 2011; Stecker & Venters 2011; Lien+'12, Ackermann+'12; Lacki+'12; Chakraborty & Fields '13; Tamborra+'14)
- Use gamma-ray and infrared luminosity correlation
- ~10-30% of CGB at 0.1-100 GeV.
- But, still only ~10 sources are detected by Fermi.

Components of Cosmic Gamma-ray Background

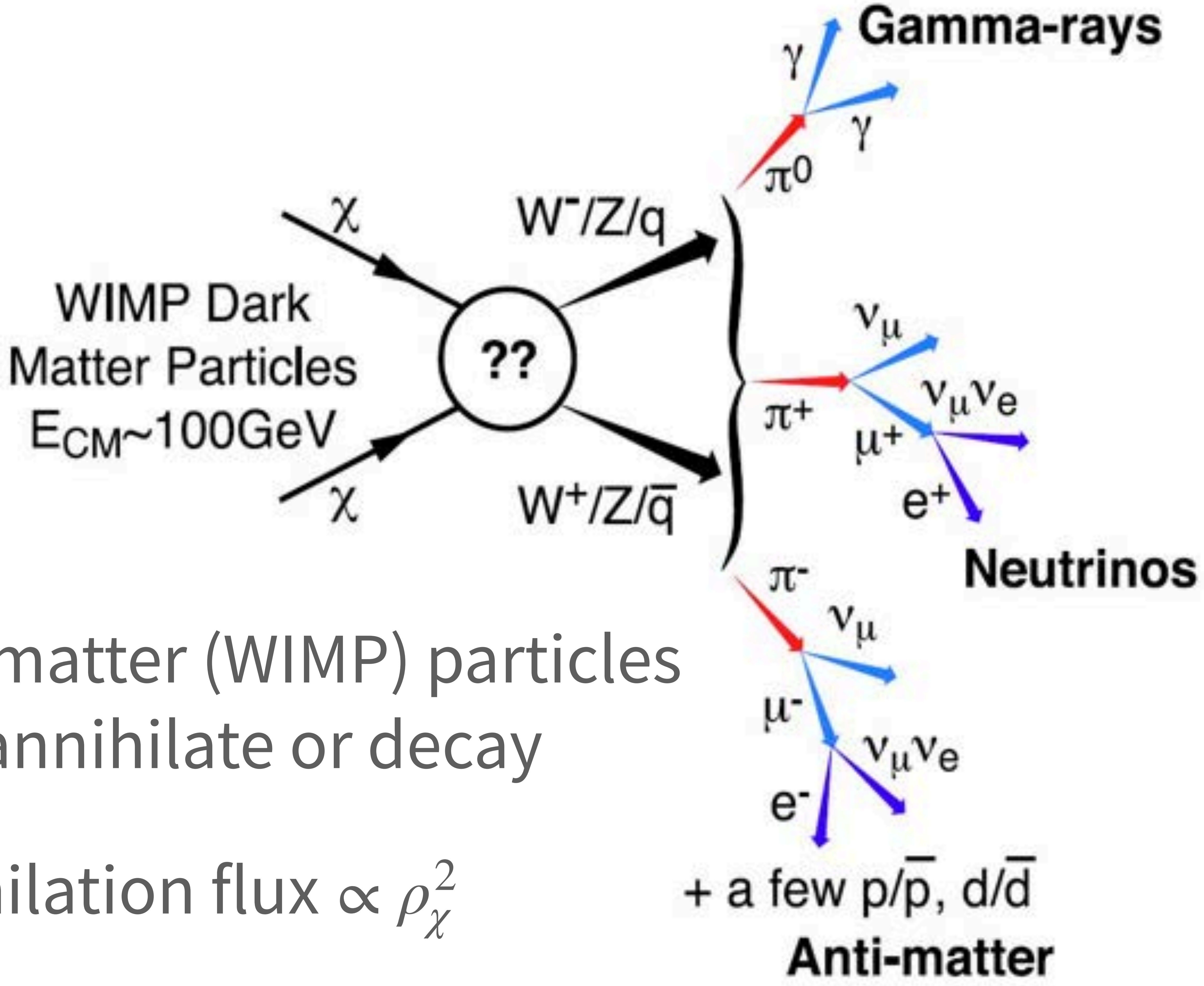
Blazars, Radio galaxies, & Star-forming galaxies



Ajello, YI+'15

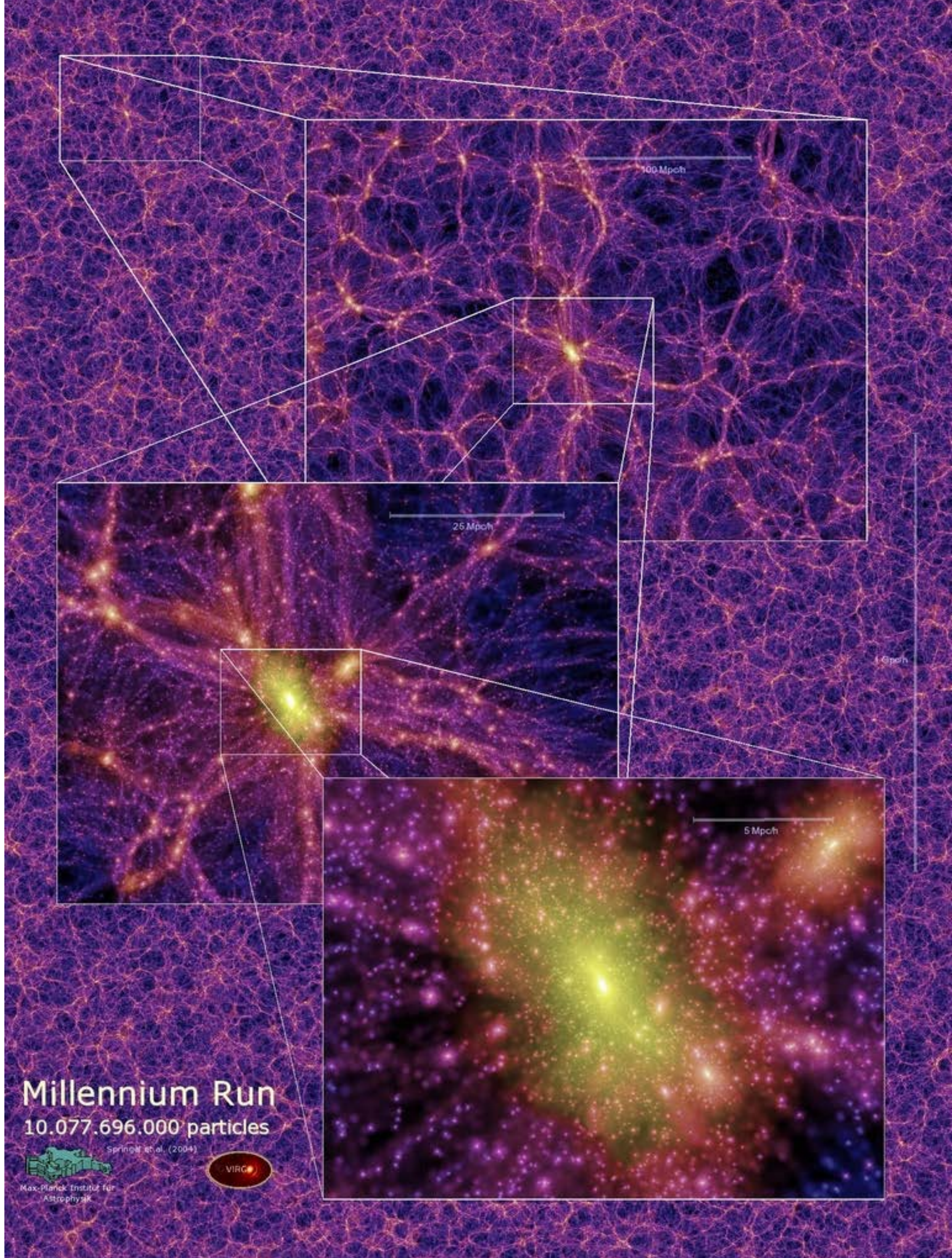
- Blazars: FSRQs (Ajello+'12)
- Blazars: BL Lacs (Ajello+'14)
- Radio galaxies (YI'11)
- Star-forming galaxies (Ackermann+'12)
  - make almost 100% of CGB from 0.1-1000 GeV.

Dark Matter Annihilation / Decay



- Dark matter (WIMP) particles may annihilate or decay
- Annihilation flux $\propto \rho_\chi^2$
- Decay flux $\propto \rho_\chi$

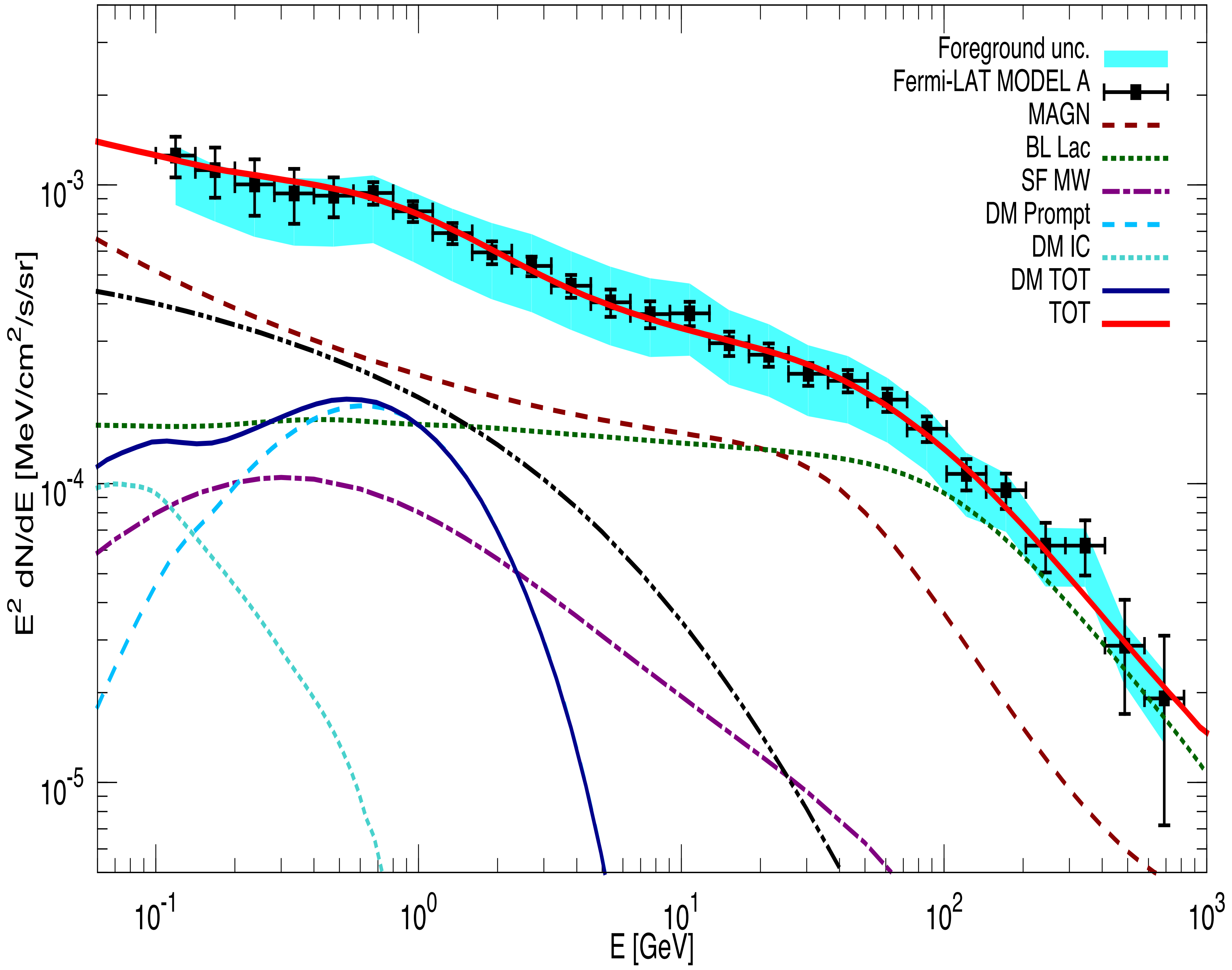
© Fermi



Dark Matter Contribution to the Cosmic Gamma-ray Background

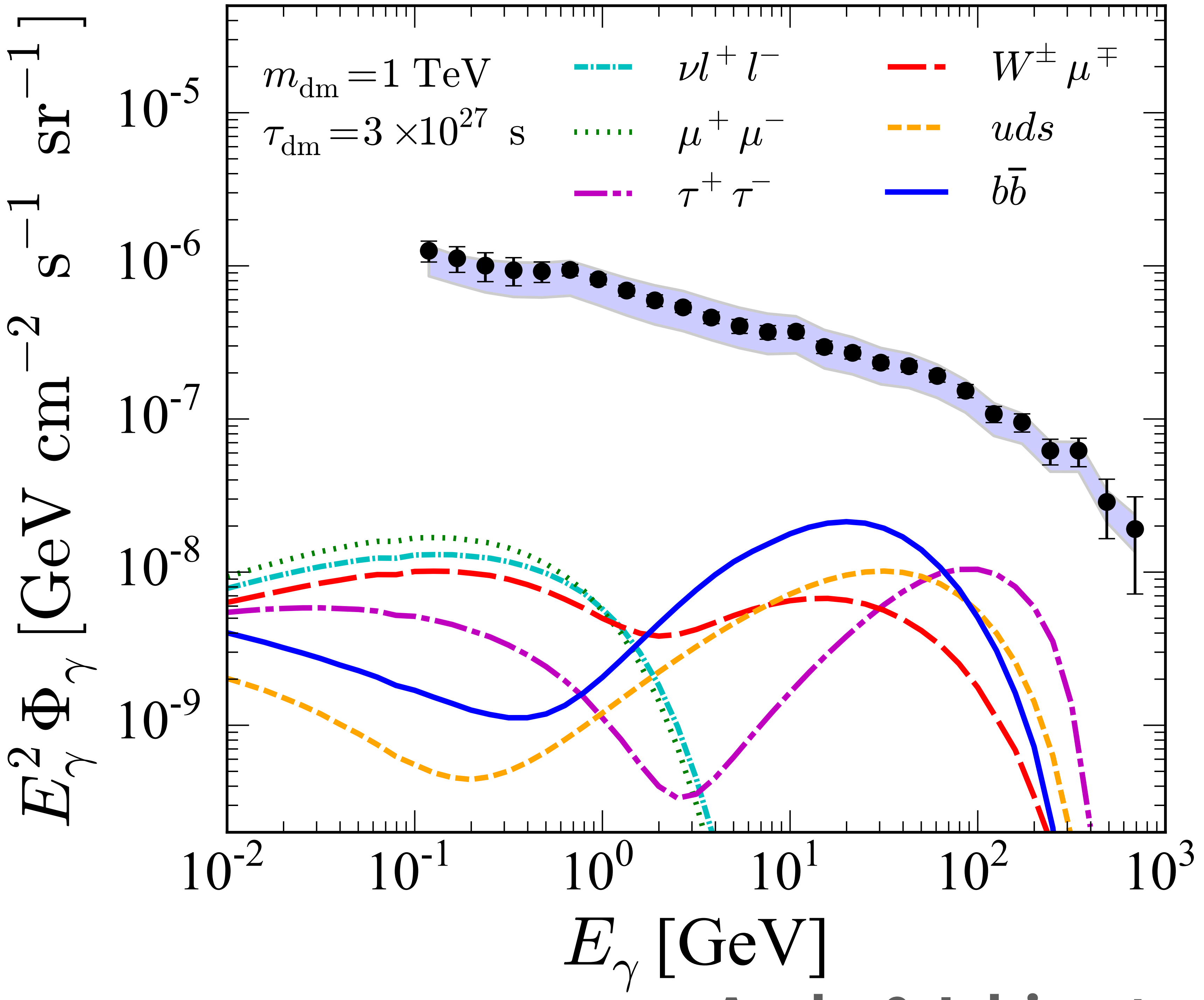
Spectrum

Annihilation



Di Mauro+'15

Decay

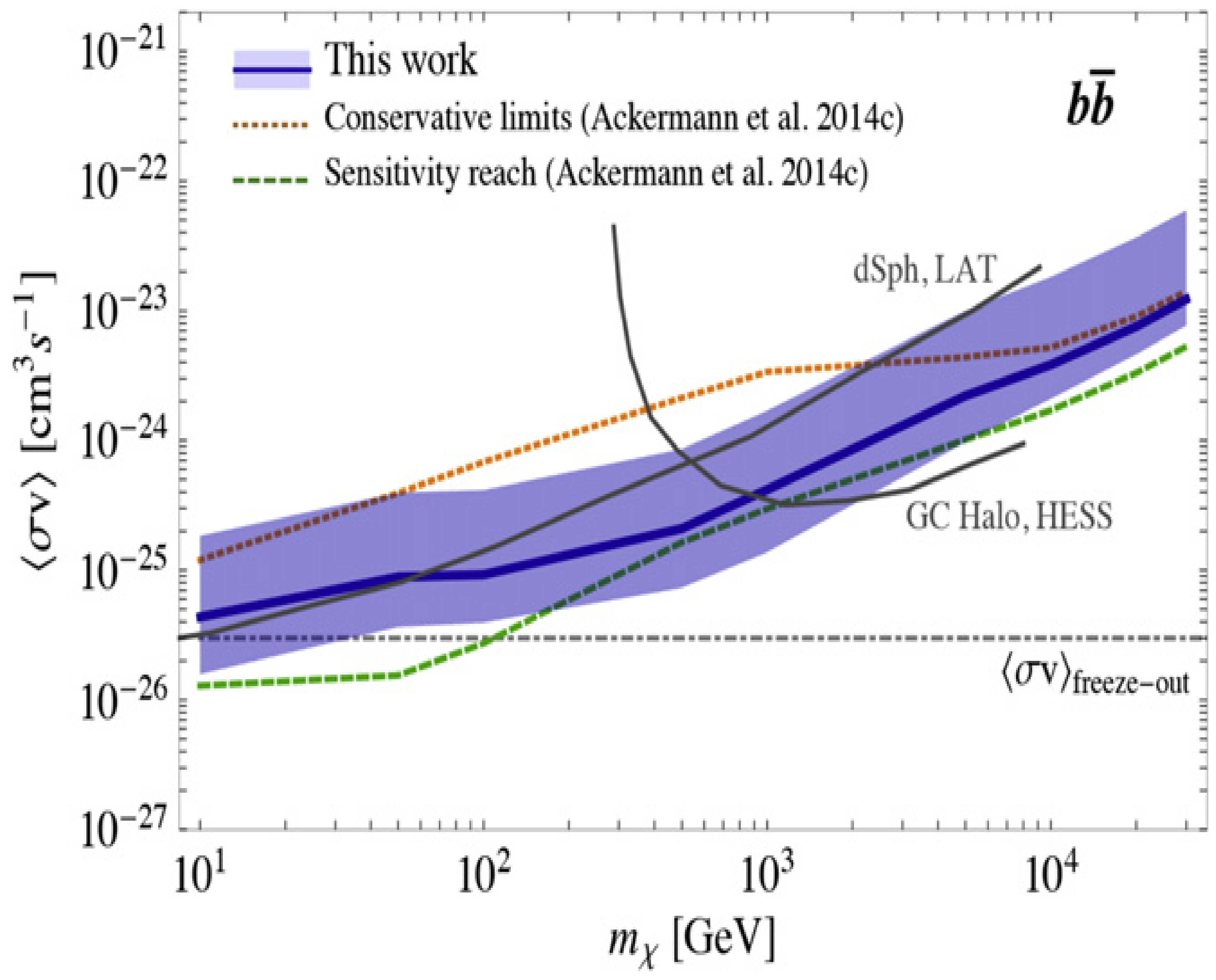


Ando & Ishiwata '15

- DM annihilation / decay create
  - a spectral feature in the spectrum
- Spectral shape of the gamma-ray background is important.

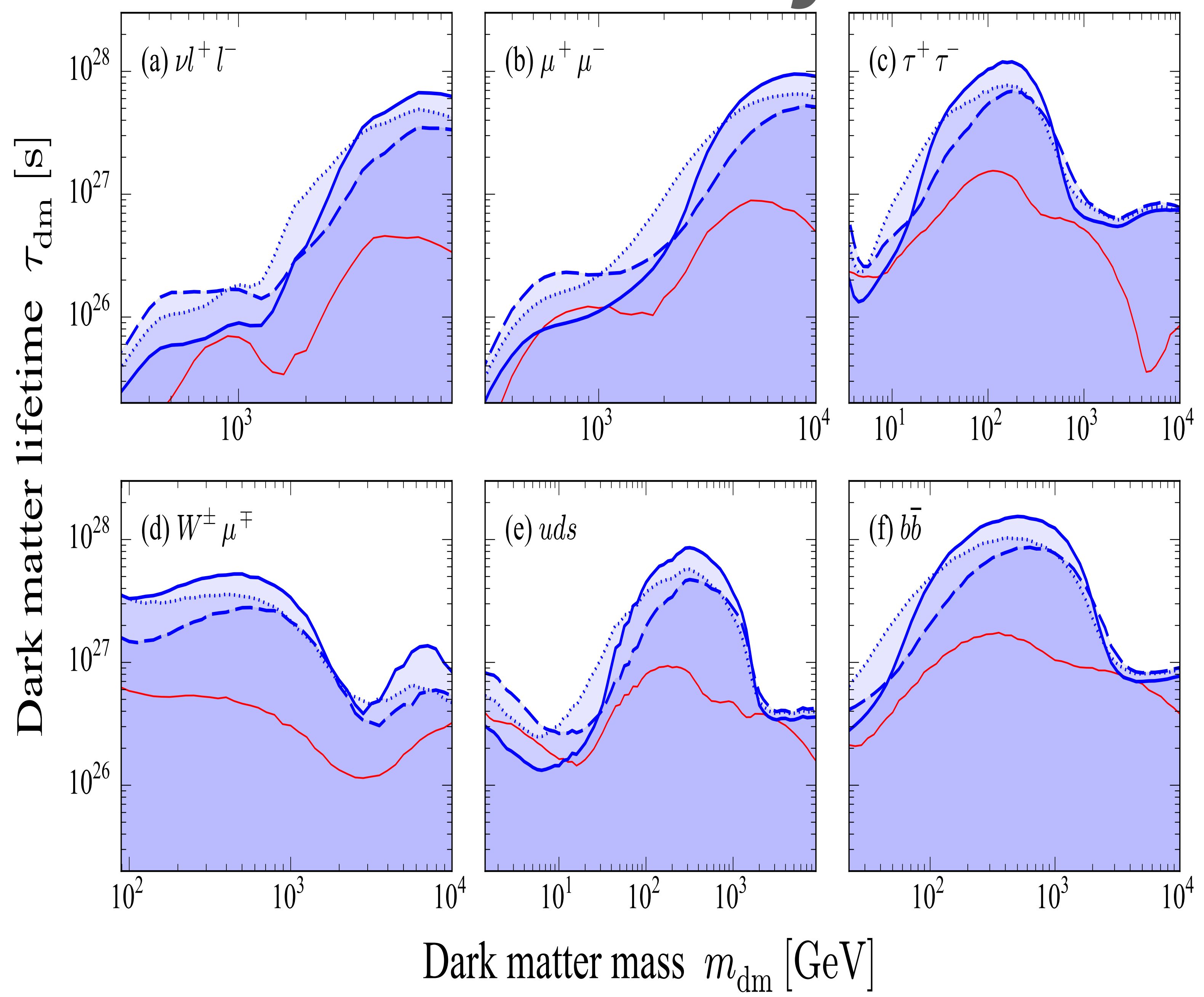
Constraints on Dark Matter Parameters

Annihilation



Ajello, YI+'15

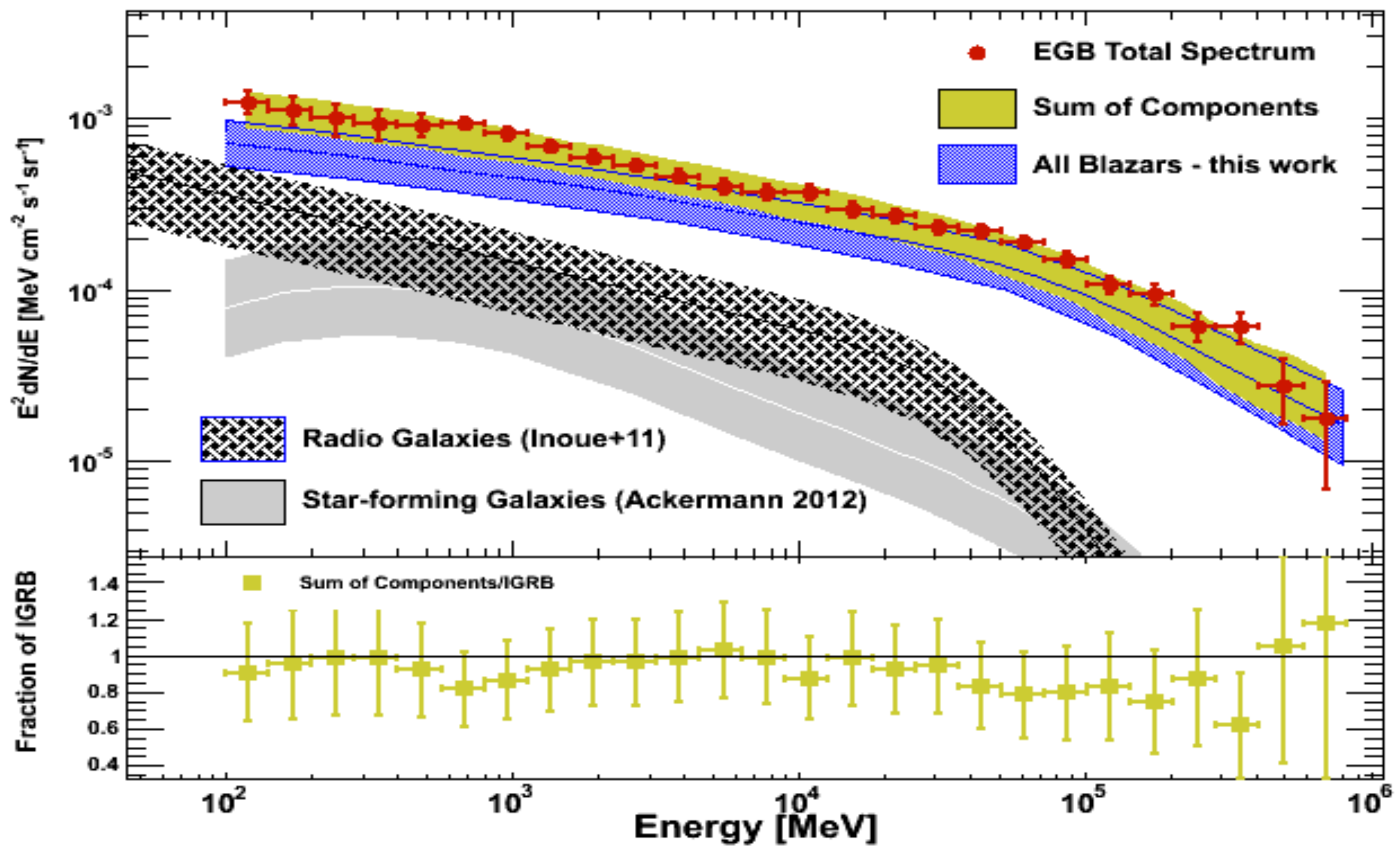
Decay



Ando & Ishiwata '15

- comparable to constraints from dwarf galaxies
- Decay timescale is >10^{27} s ($2\text{x}10^9$ t_H)

Day 1 Summary



- Cosmological evolution of blazars
  - Blazars show luminosity-dependent density evolution
  - Evolution in gamma-ray and X-ray is contradicting.
- Cosmic gamma-ray background radiation
  - = Blazars + Radio galaxies + Star-forming galaxies
  - But, contribution of radio galaxies and star-forming galaxies is uncertain
  - dark matter particles may also contribute.

Cosmological Aspects of High Energy Astrophysics ~ Day 2 ~

Yoshiyuki Inoue

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

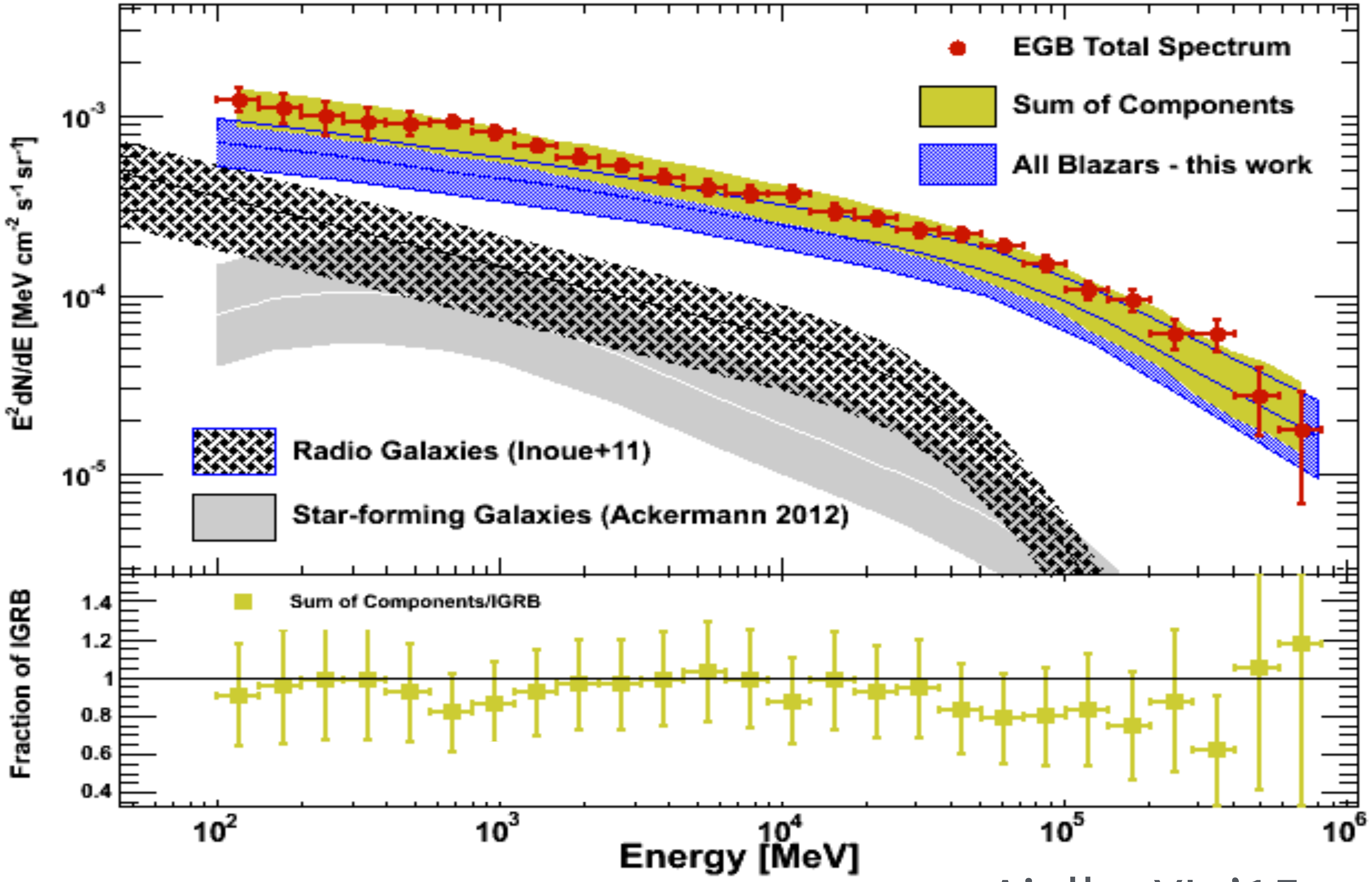
Lecture Schedule

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
  - 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)

Components of Cosmic Gamma-ray Background

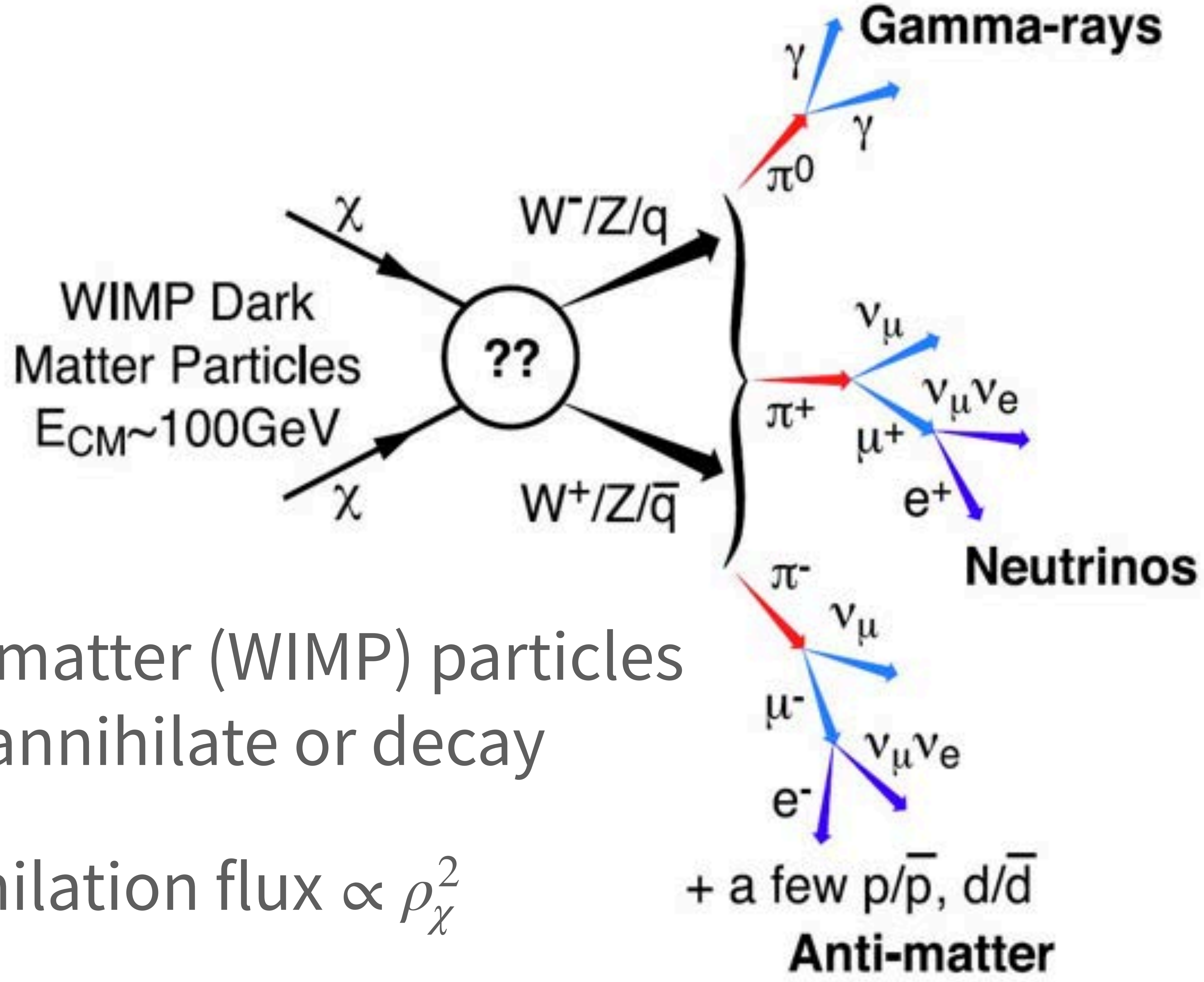
Blazars, Radio galaxies, & Star-forming galaxies



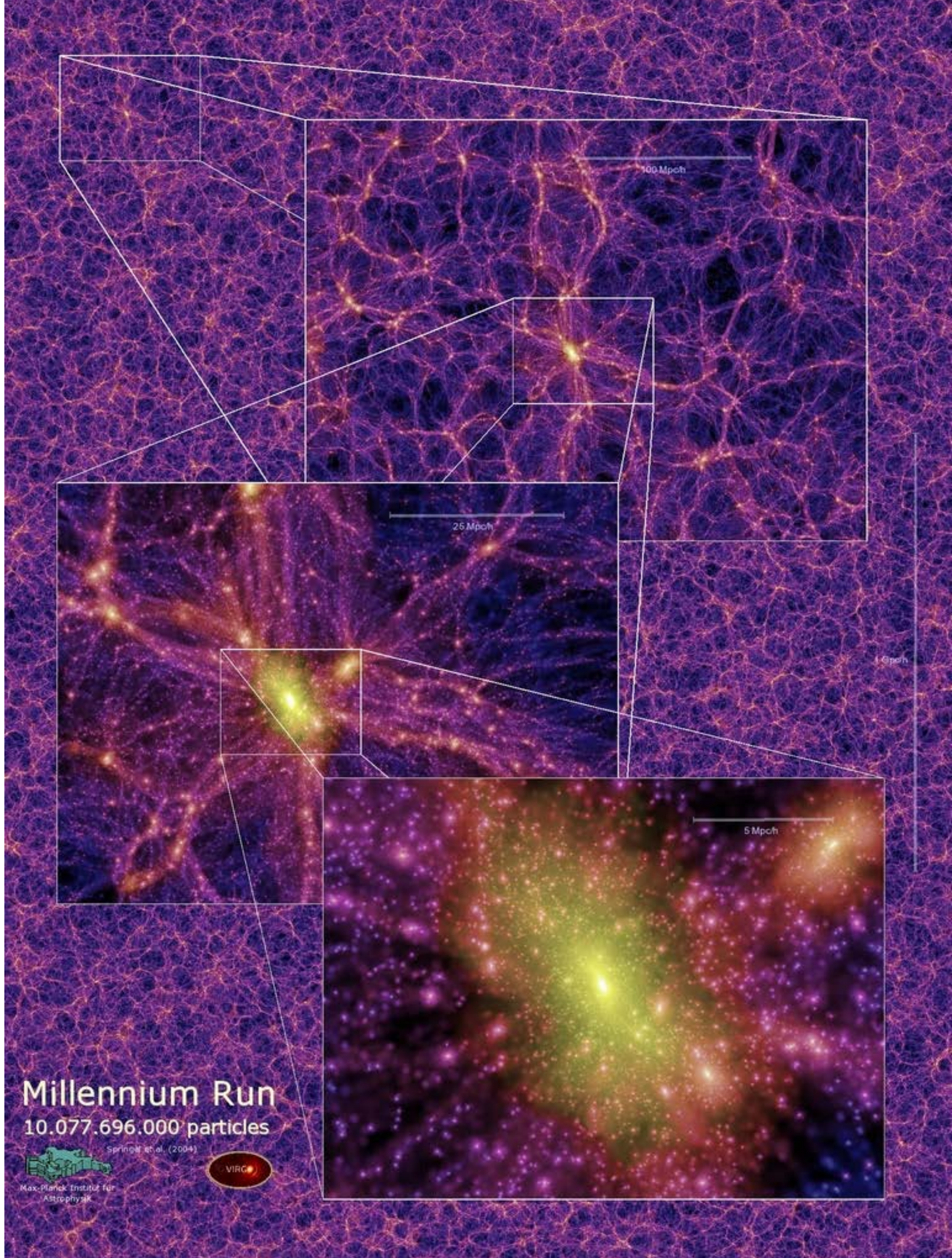
Ajello, YI+'15

- Blazars: FSRQs (Ajello+'12)
- Blazars: BL Lacs (Ajello+'14)
- Radio galaxies (YI'11)
- Star-forming galaxies (Ackermann+'12)
    - make almost 100% of CGB from 0.1-1000 GeV.

Dark Matter Annihilation / Decay



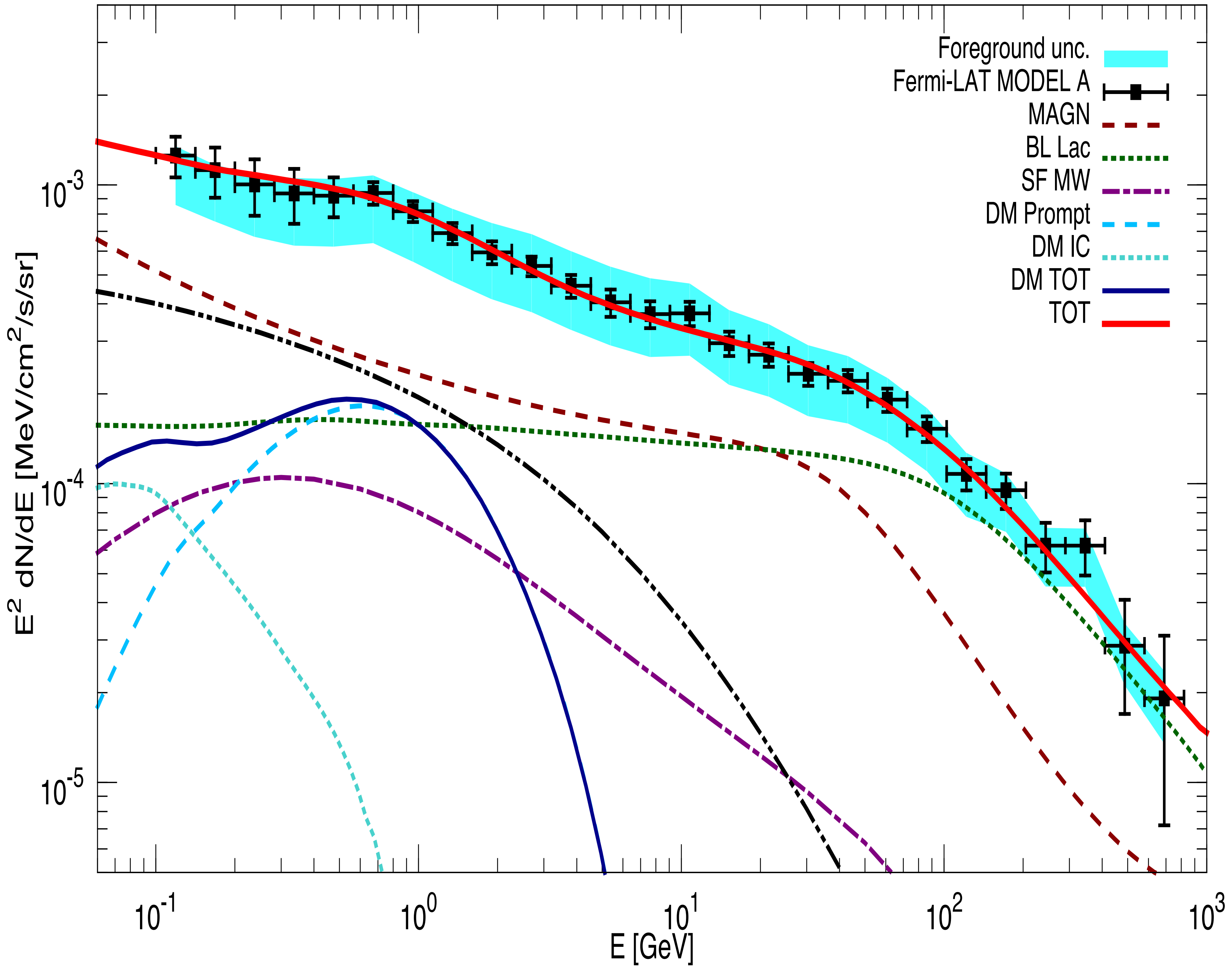
- Dark matter (WIMP) particles may annihilate or decay
- Annihilation flux $\propto \rho_\chi^2$
- Decay flux $\propto \rho_\chi$



Dark Matter Contribution to the Cosmic Gamma-ray Background

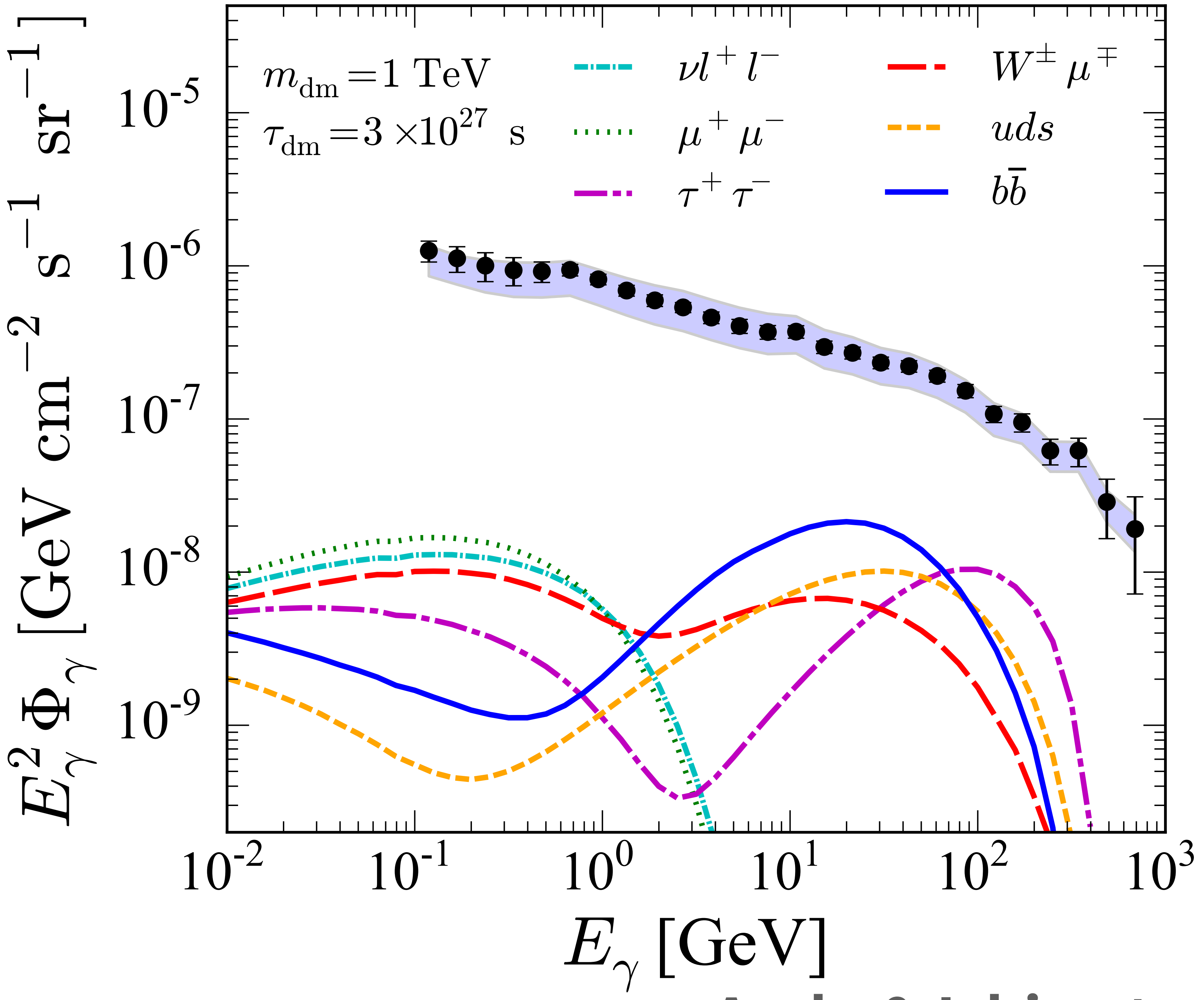
Spectrum

Annihilation



Di Mauro+'15

Decay

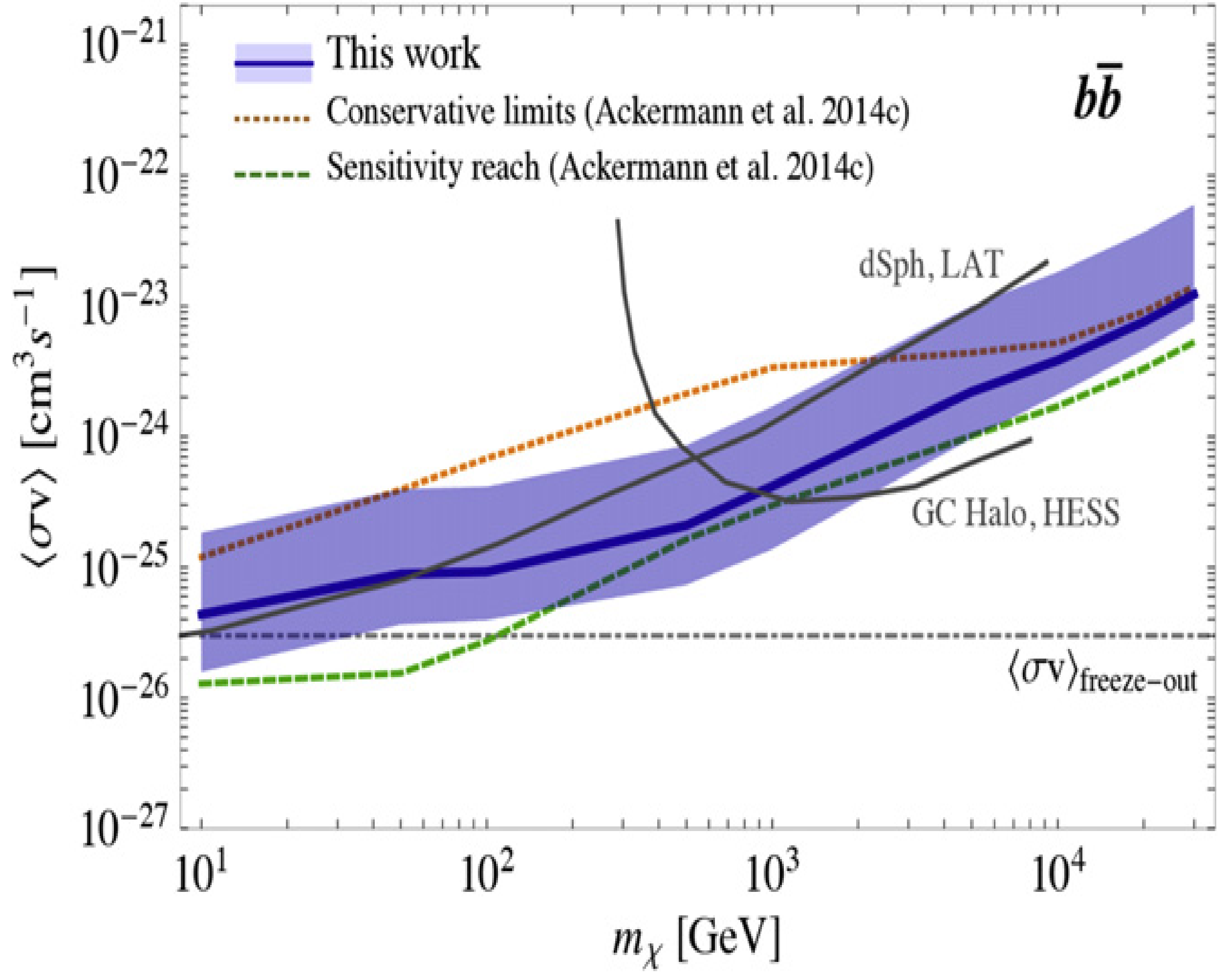


Ando & Ishiwata '15

- DM annihilation / decay create
  - a spectral feature in the spectrum
- Spectral shape of the gamma-ray background is important.

Constraints on Dark Matter Parameters

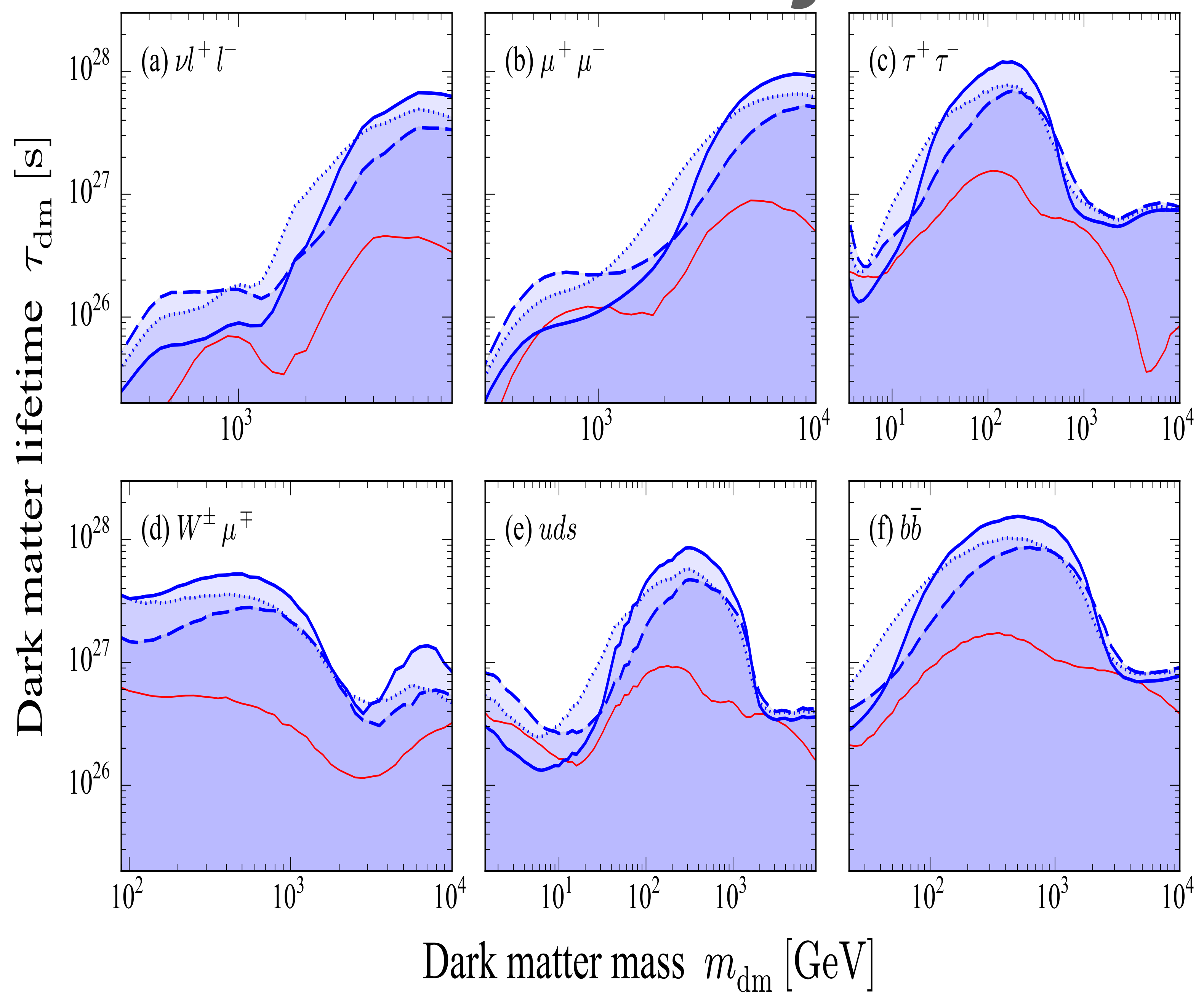
Annihilation



Ajello, YI+'15

- comparable to constraints from dwarf galaxies

Decay

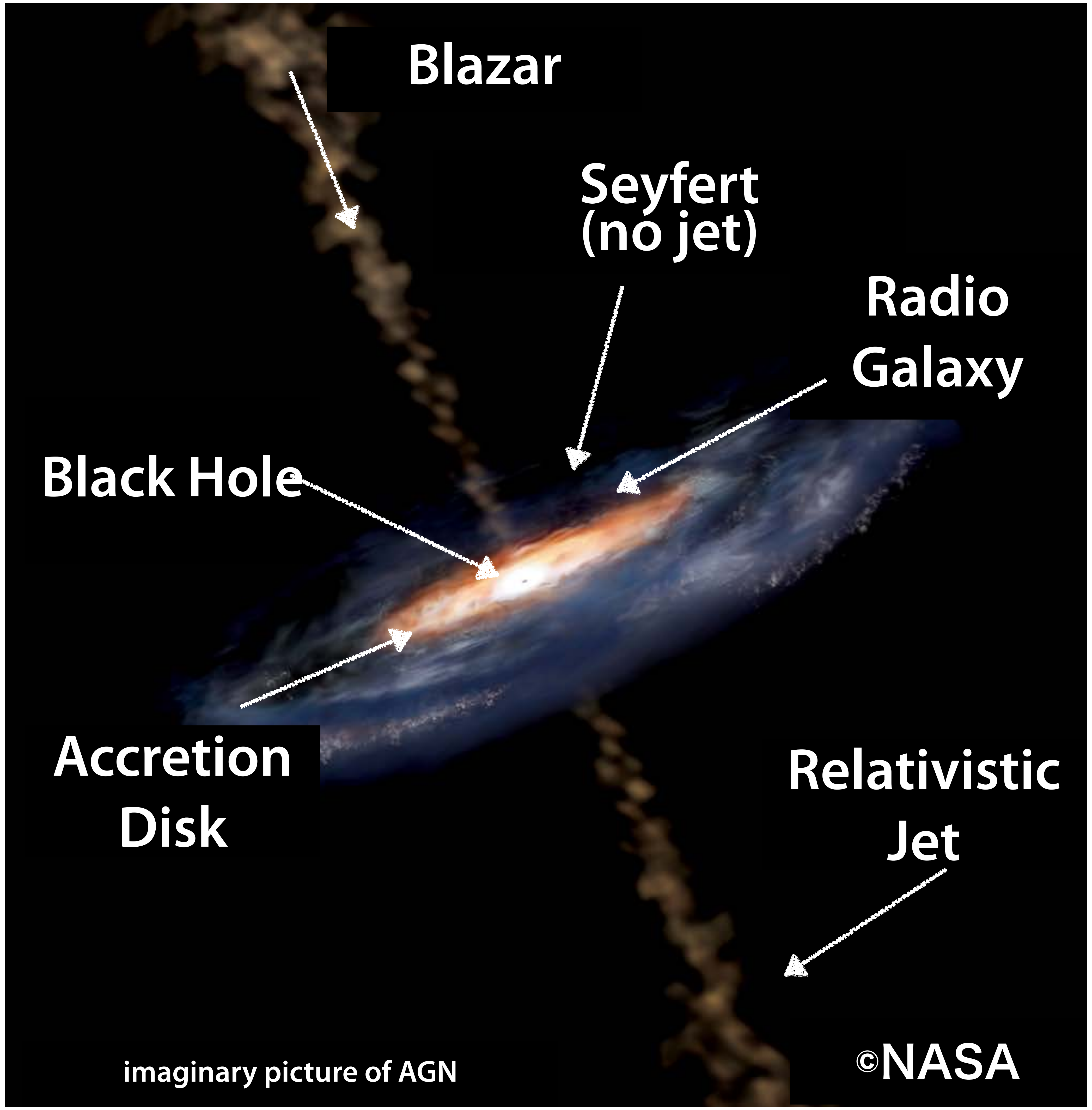


Ando & Ishiwata '15

- Decay timescale is >10^{27} s ($2\text{x}10^9$ t_H)

Cosmic MeV Gamma-ray Background Radiation Spectrum

Active Galactic Nuclei (AGNs)



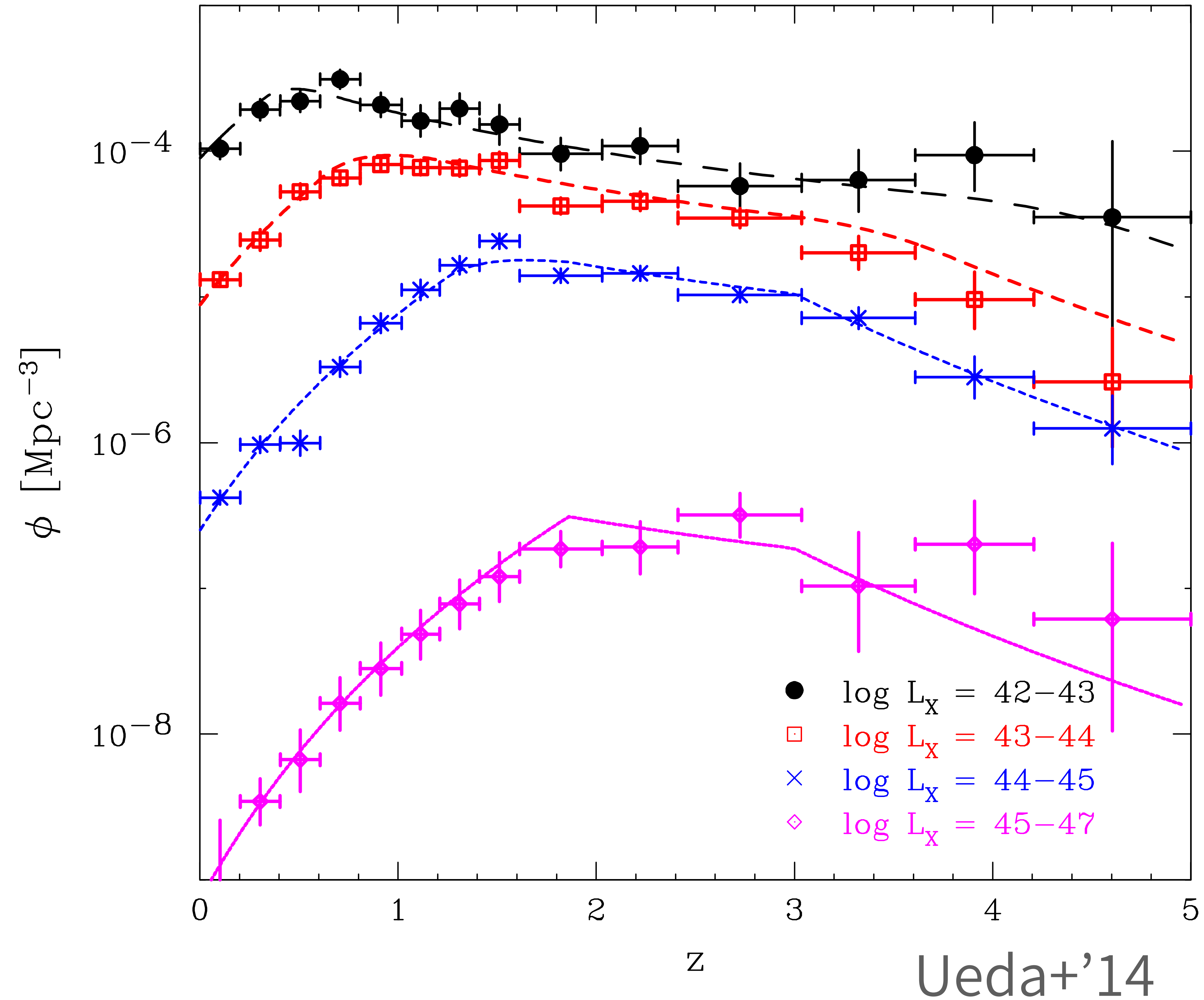
- Gas accretion on to SMBHs

  ➡brighter than the galaxy

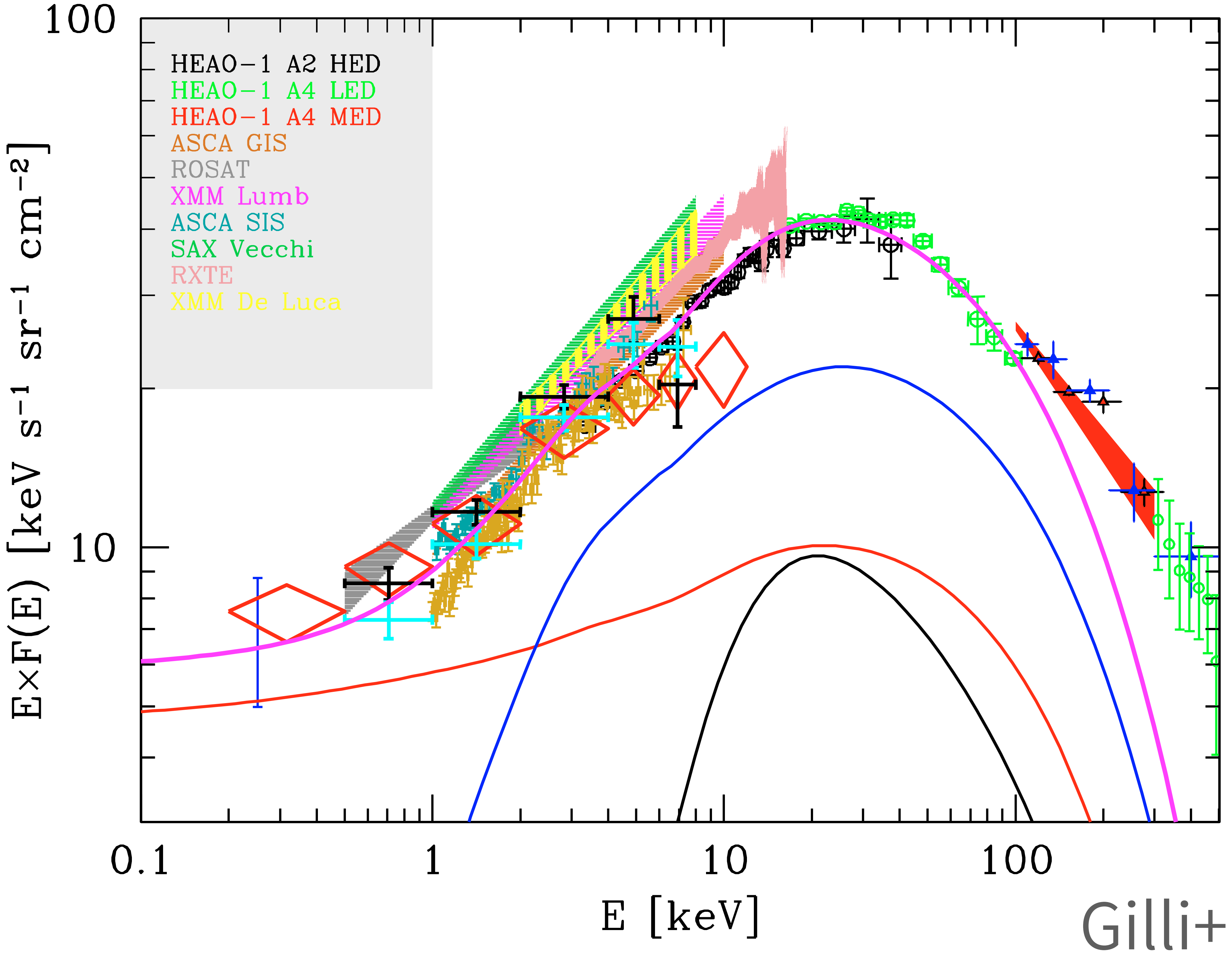
  - Active Galactic Nuclei: AGNs
- Various population
  - Blazar, Radio Galaxy, Seyfert,,,
  - Relativistic jet
    - Feedback / Cosmic rays / Neutrinos

Cosmic X-ray Background Radiation

X-ray emission from AGN disks



Ueda+'14

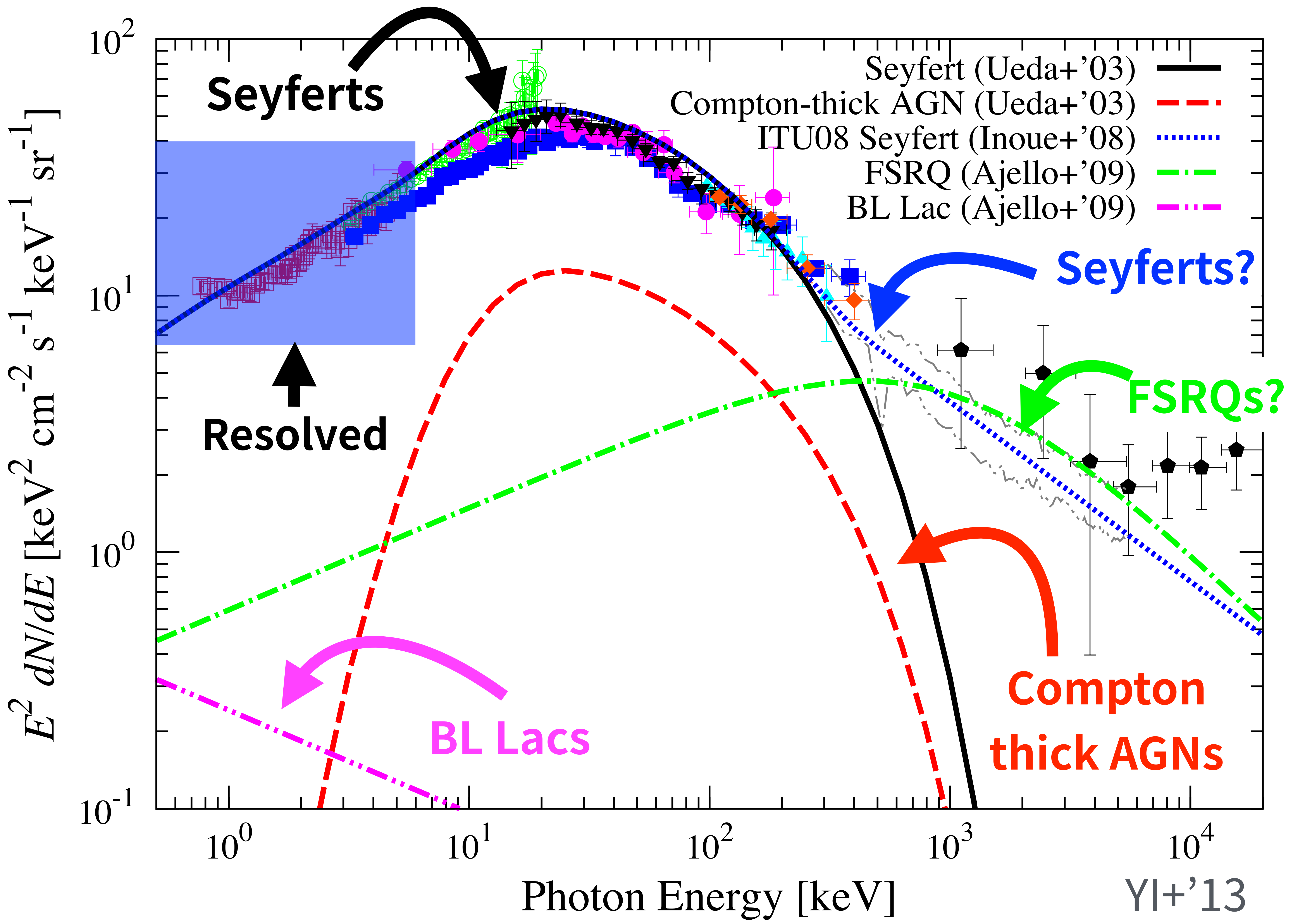


Gilli+'07

- The origin of the X-ray background is AGN disk emission.
  - >90% of CXB at 0.5-10 keV is resolved.

Cosmic MeV Gamma-ray Background Radiation

Huge discovery space behind it?



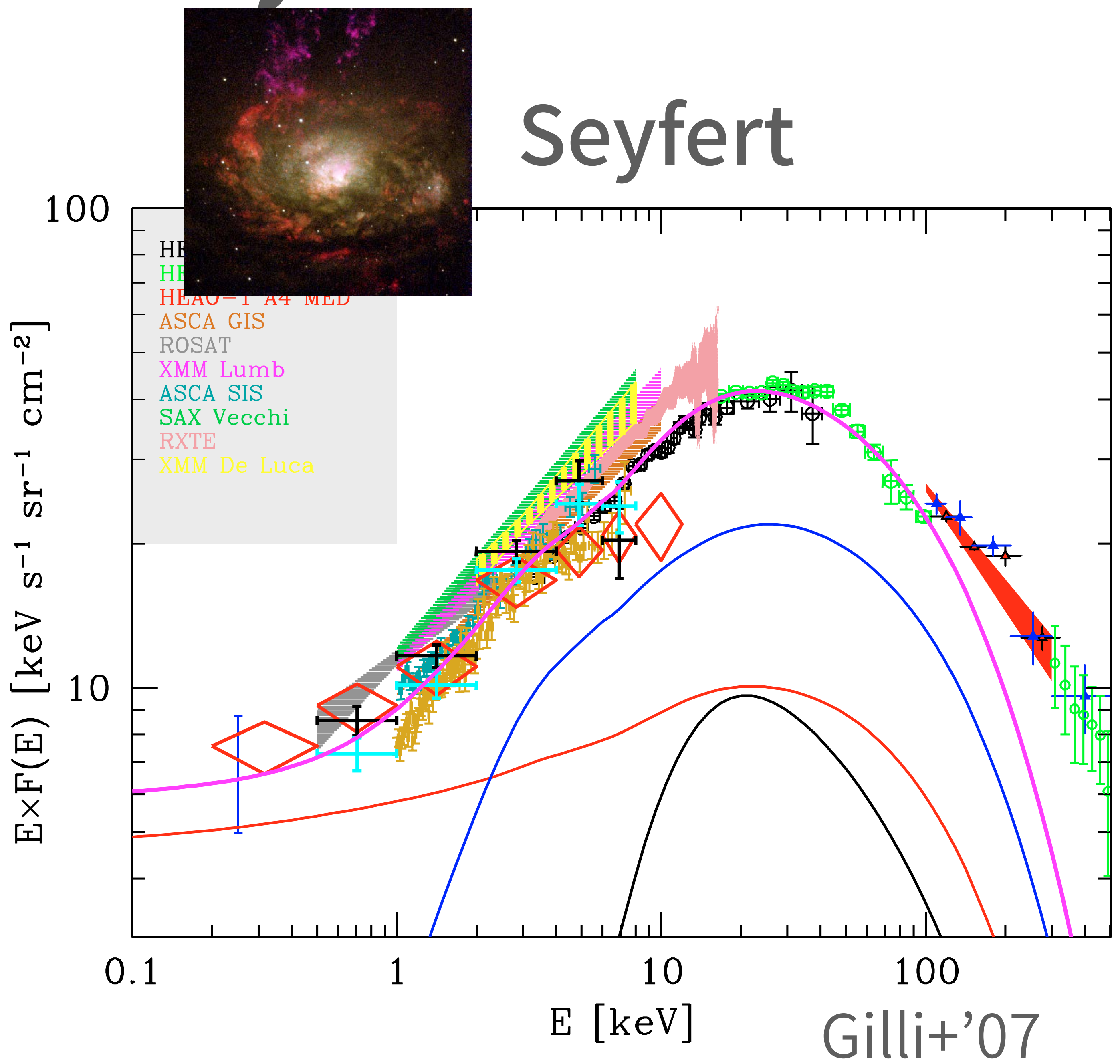
YI+'13

- X-ray background
    - AGN Disk
- GeV background
    - AGN jets + Galaxies
- What about MeV?

What is the origin of the MeV background?

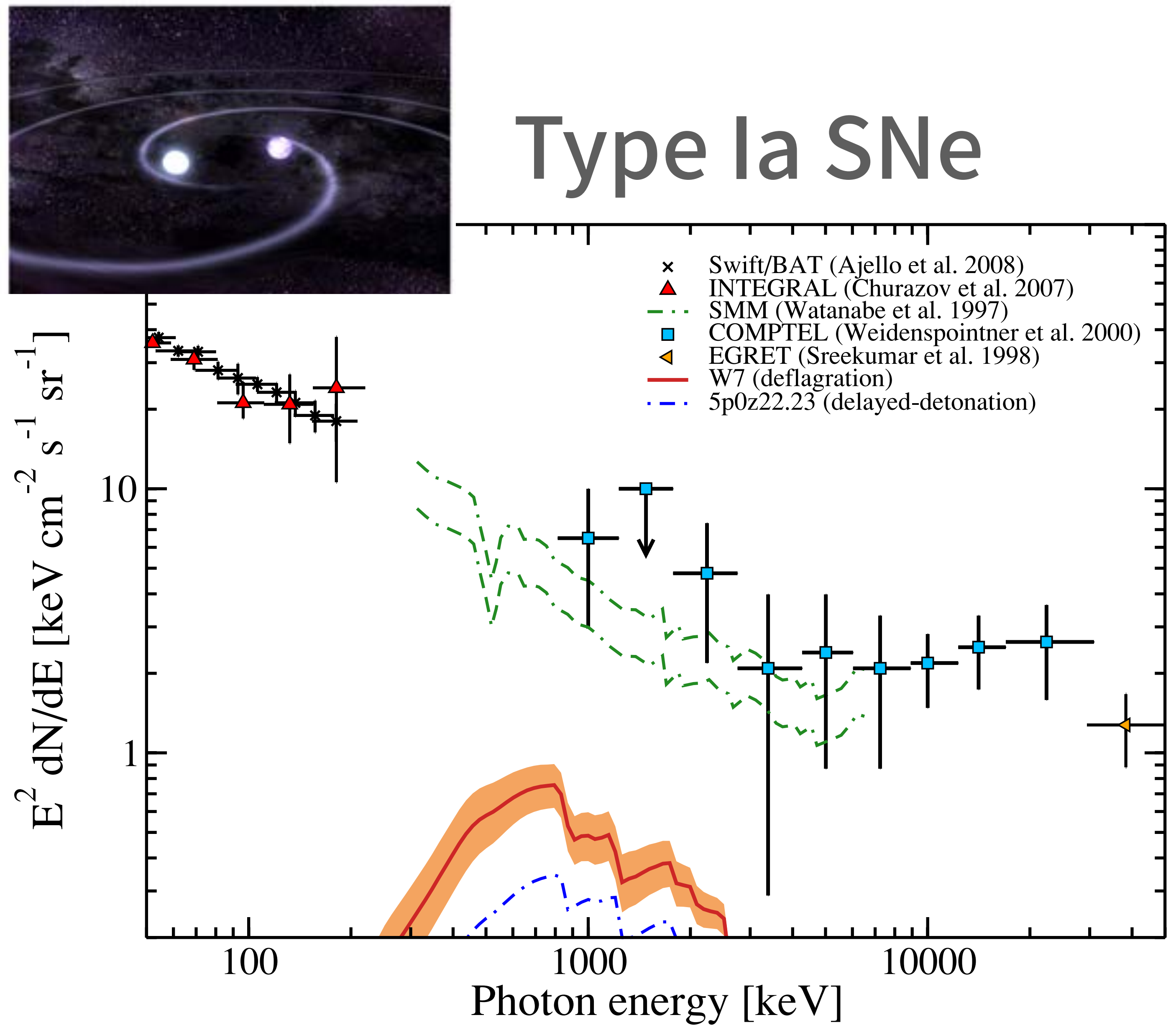
Many candidates = No conclusion…

Seyfert



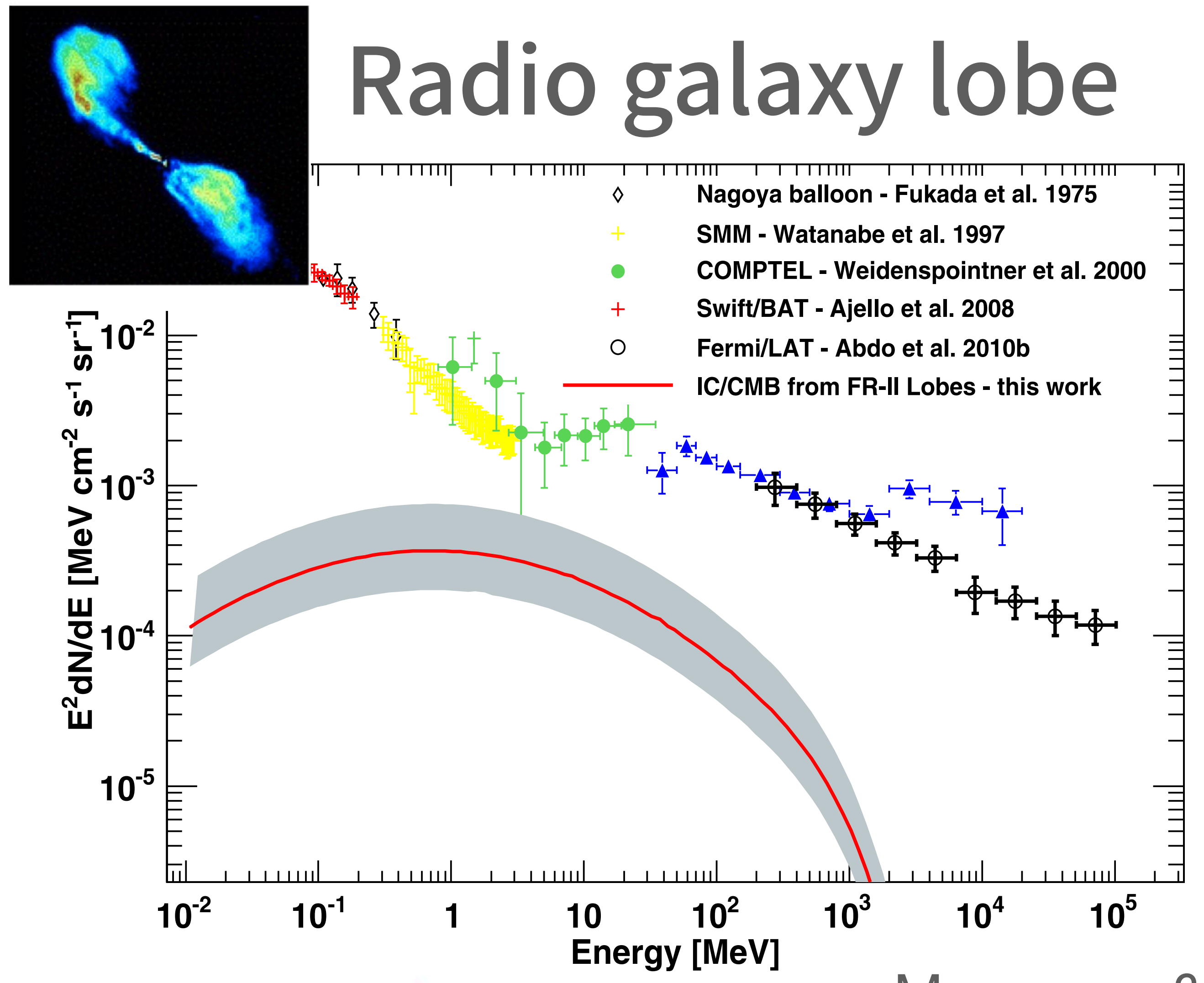
Gilli+'07

Type Ia SNe



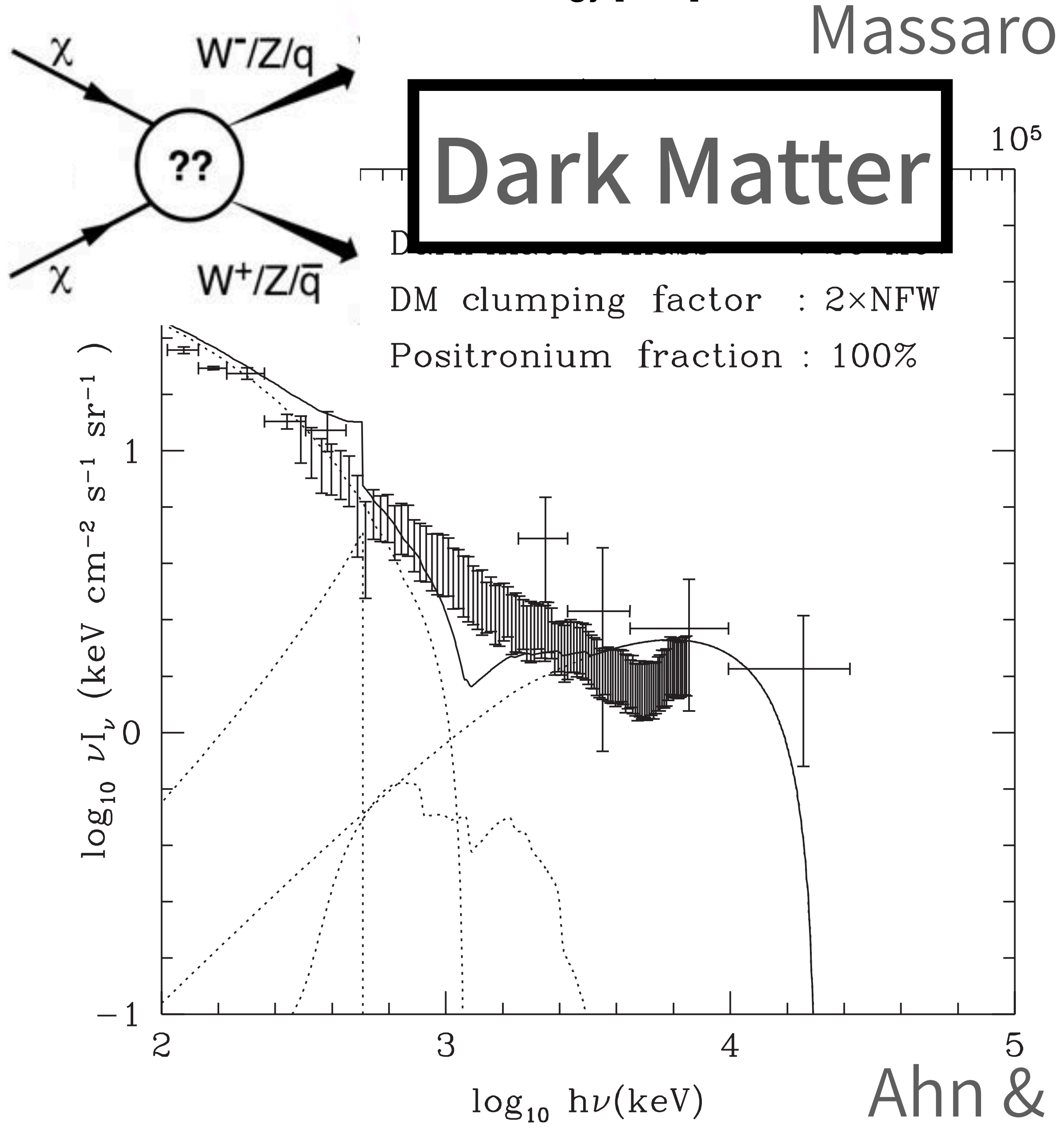
Horiuchi & Beacom +'10

Radio galaxy lobe



Massaro & Ajello '11

Dark Matter



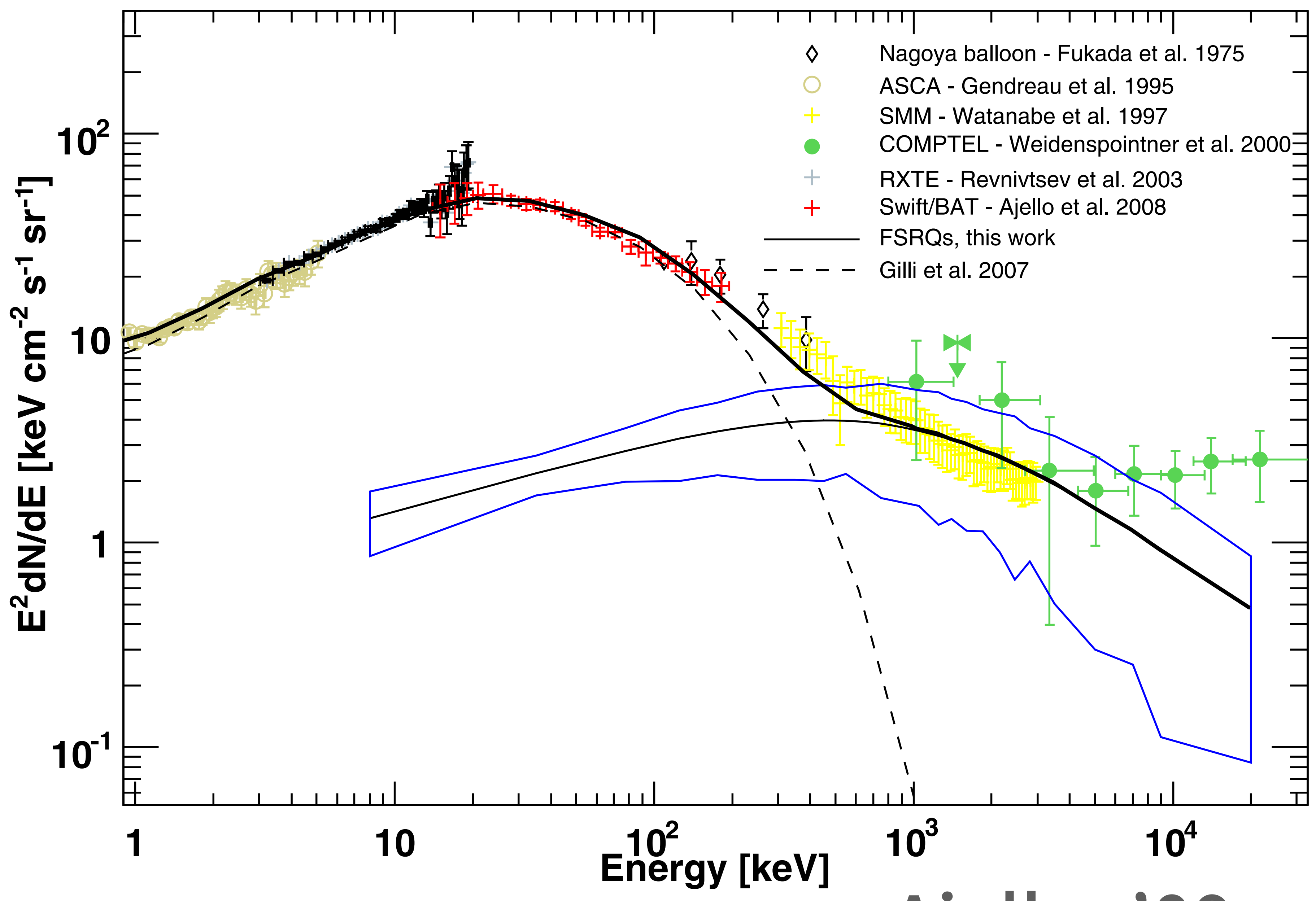
Ahn & Komatsu '05

- Smooth extension from the CXB is not well explained in literature.

FSRQs and the MeV Background

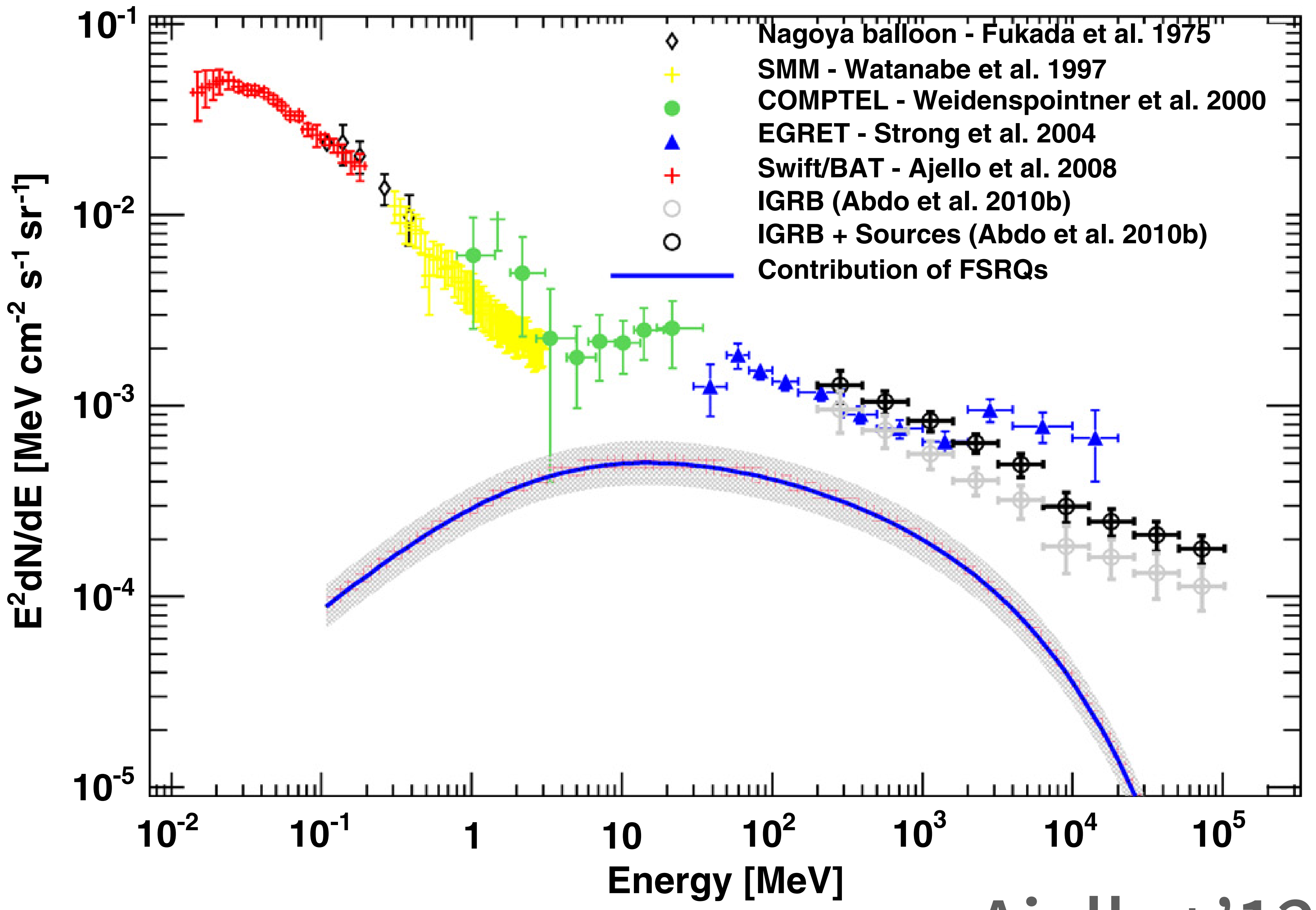
What happens between X-ray and GeV?

Based on Swift-BAT



Ajello+'09

Based on Fermi-LAT



Ajello+'12

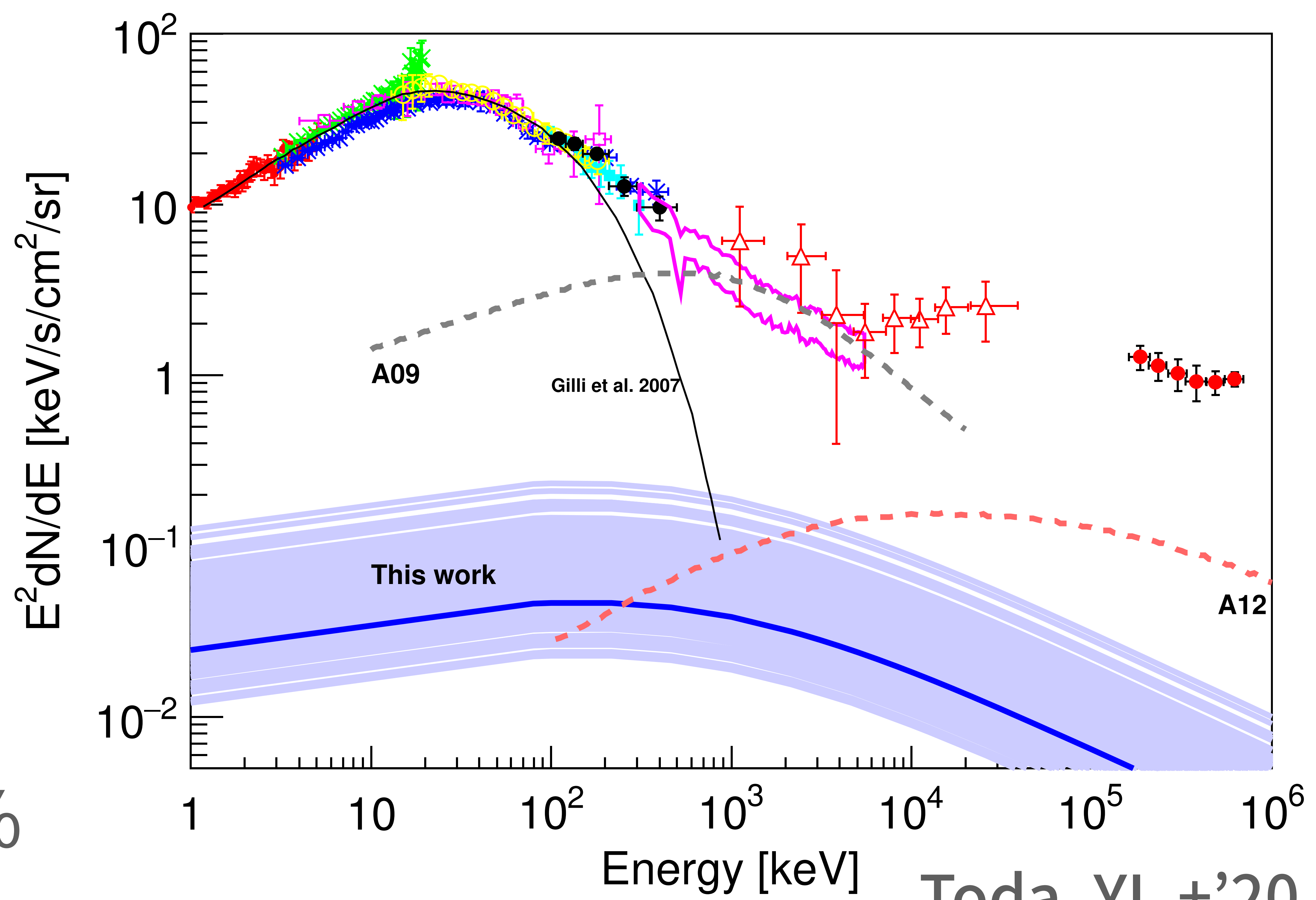
- FSRQs can explain the whole MeV background

FSRQs contribute to the GeV background with a peak at ~100 MeV

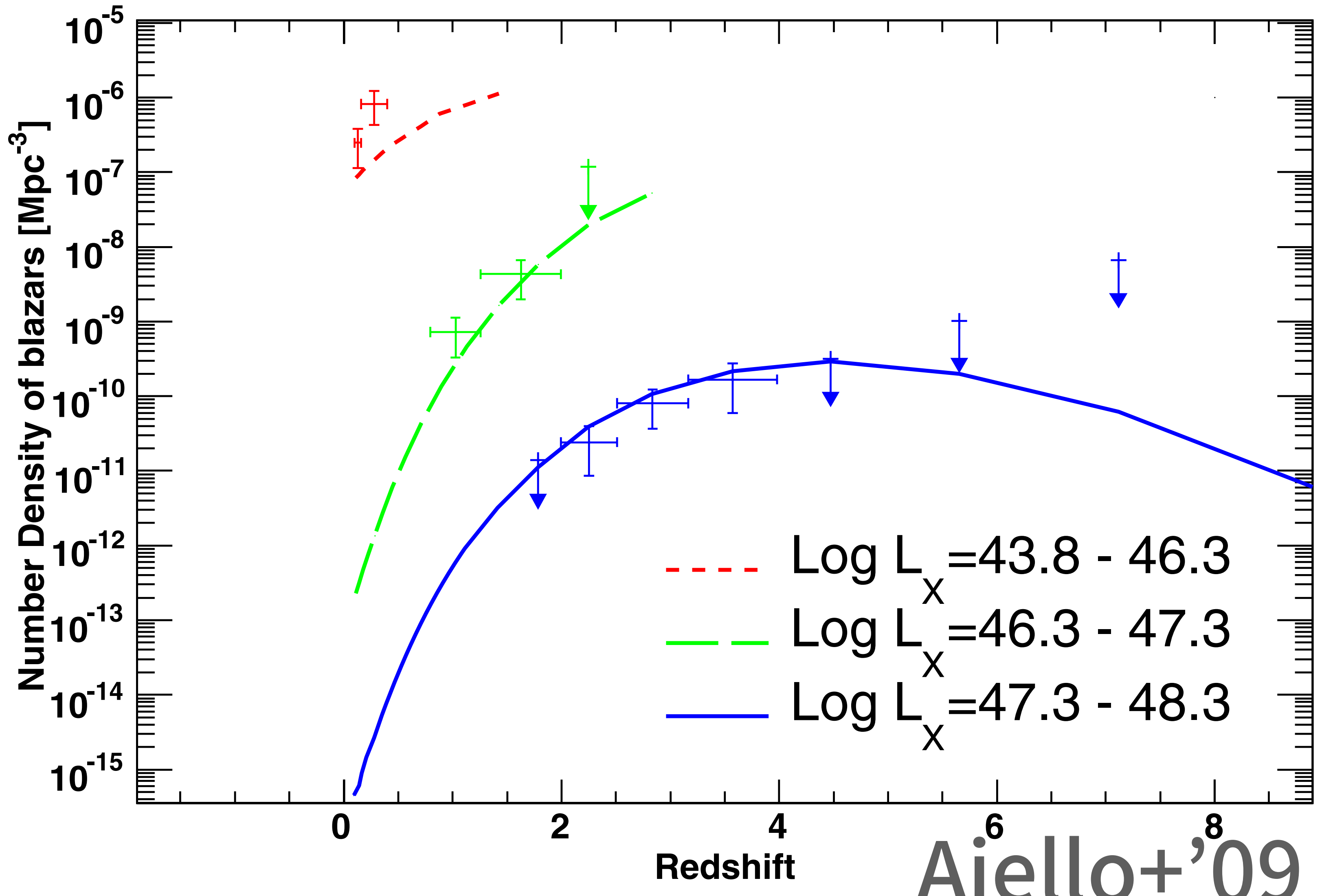
Revisiting FSRQ Evolution

Based on 105-month BAT catalog (Oh+’18)

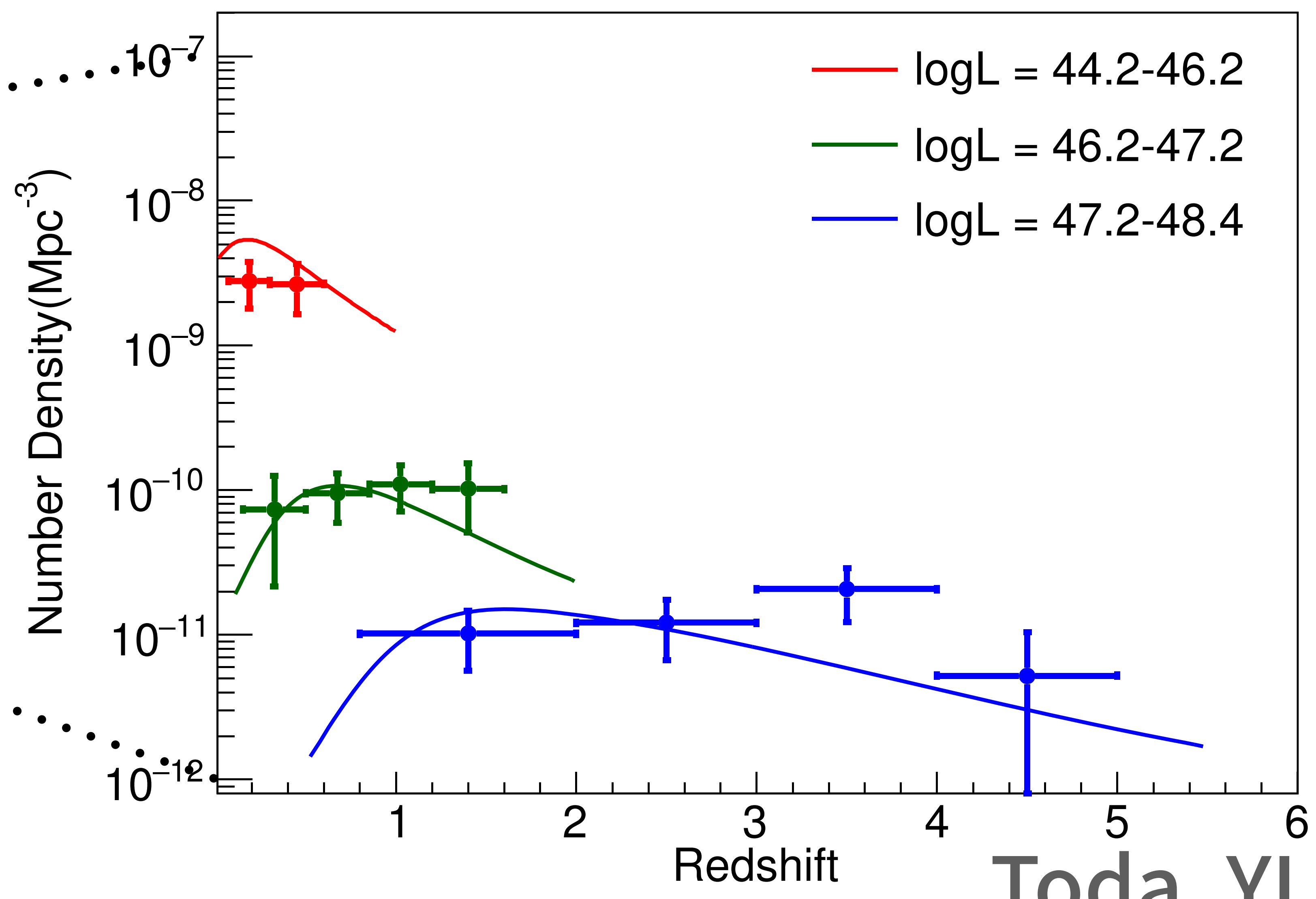
- 26 (Ajello+’09) → 53 FSRQs (Toda+’20)
- $z_{\mathrm{peak}} \sim 4 \rightarrow \sim 2$
- MeV background contribution: 100% → 3%



Toda, YI, +’20



Ajello+’09

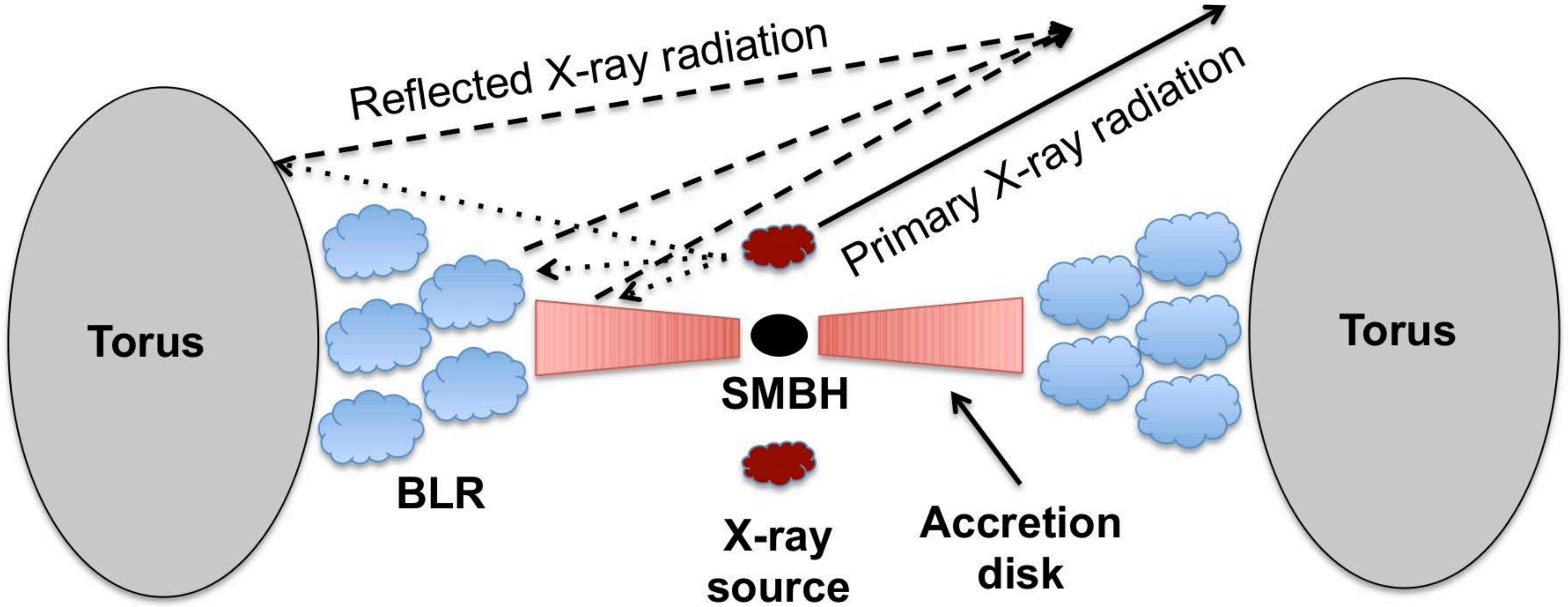


Toda, YI, +’20

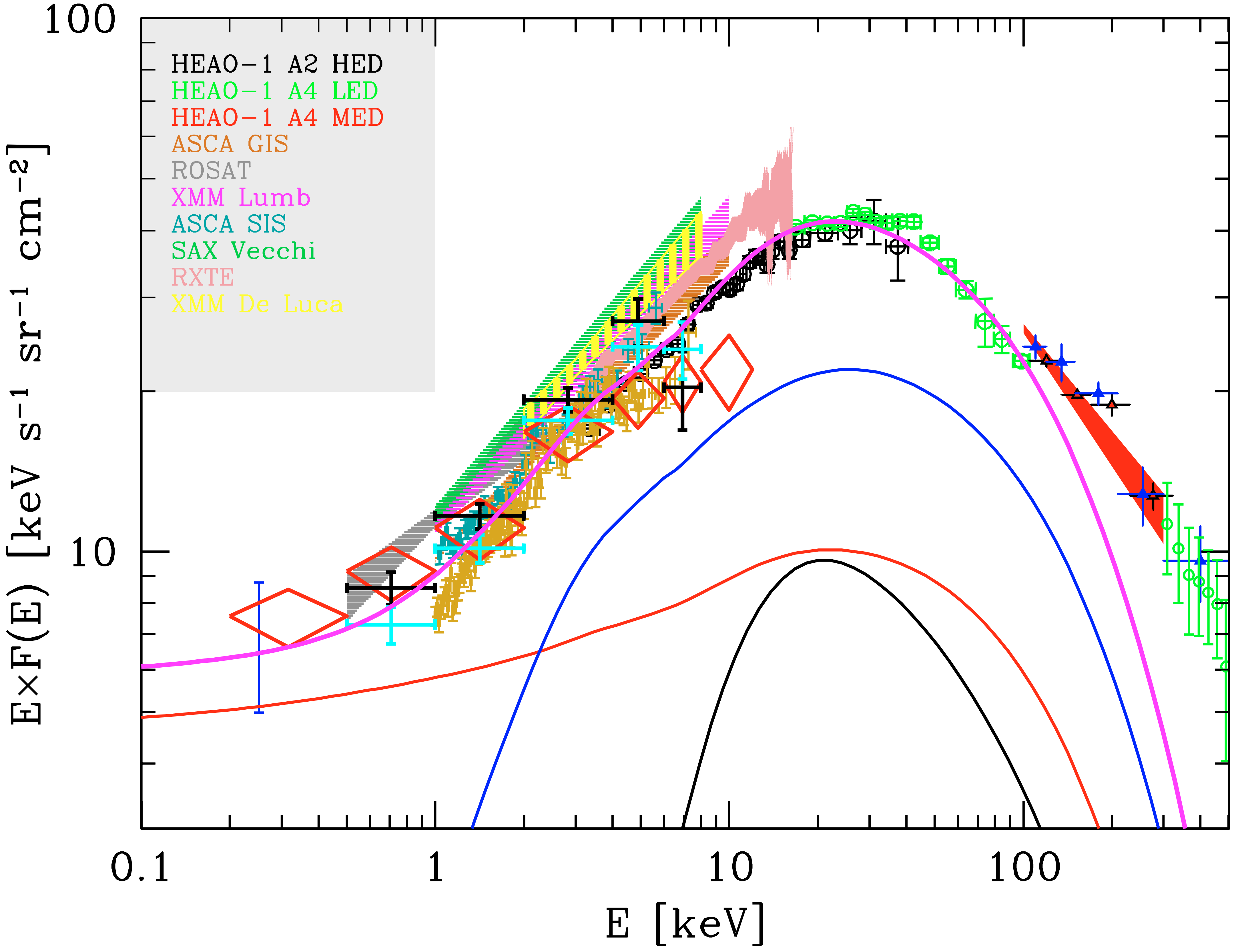
Seyferts and the MeV Background

Extension from X-ray background?

- X-ray emission of Seyferts comes from **thermal** hot disk corona
- If there are **non-thermal** particles, we can have a power-law tail from the X-ray background.

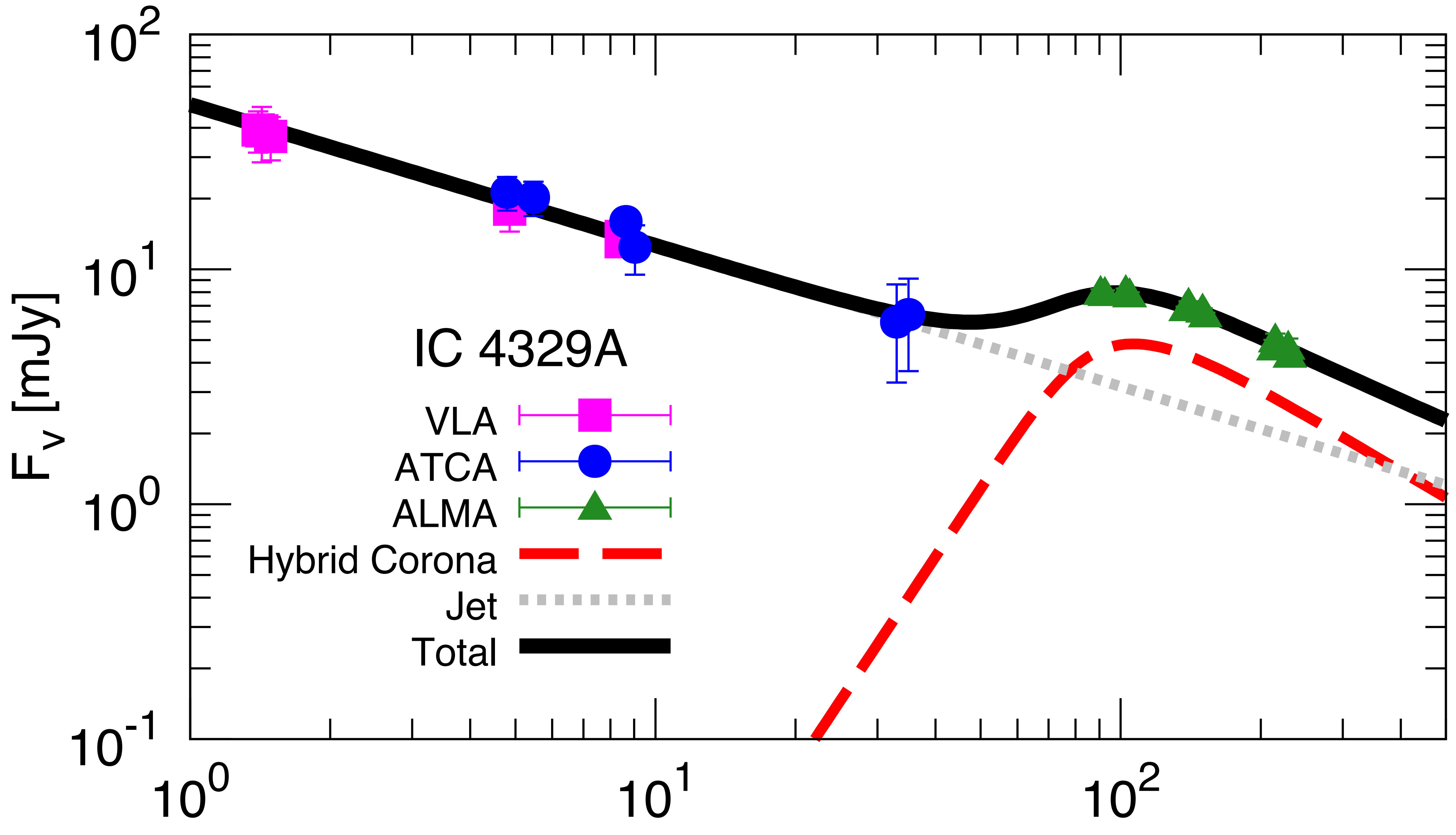


©Ricci

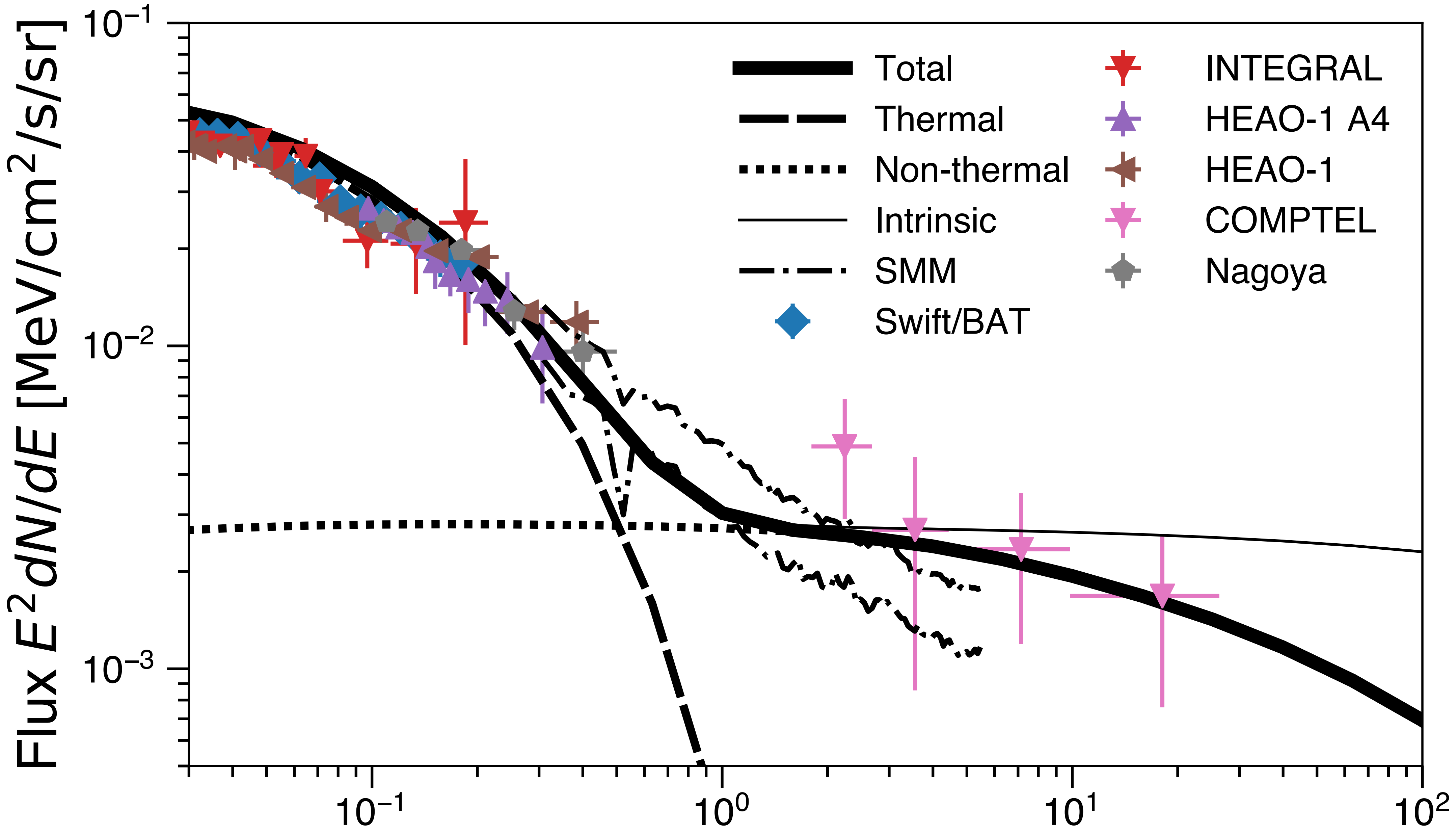


Gilli+'07

Non-thermal electrons exist in the coronae



YI & Doi '18

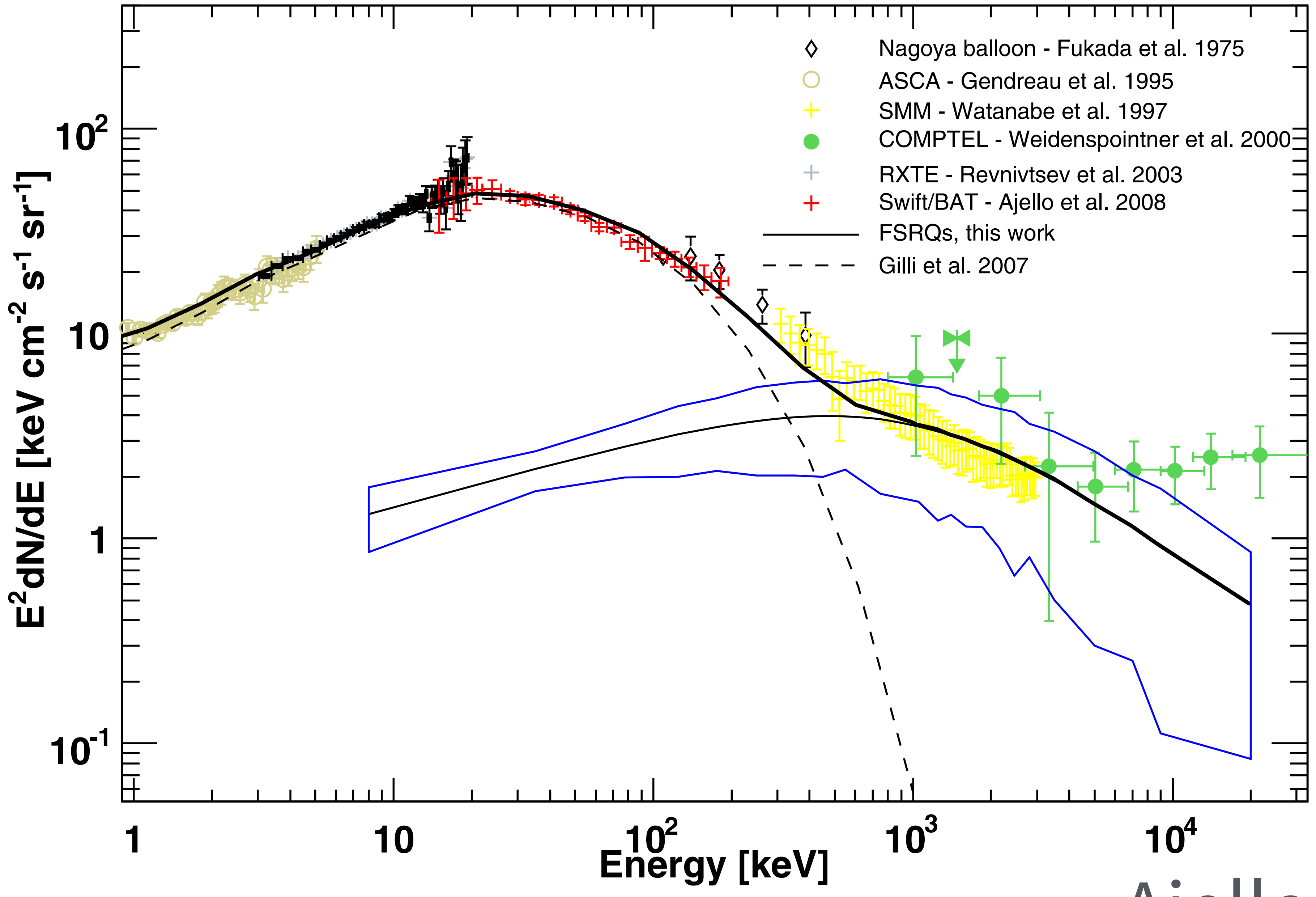


YI + '19

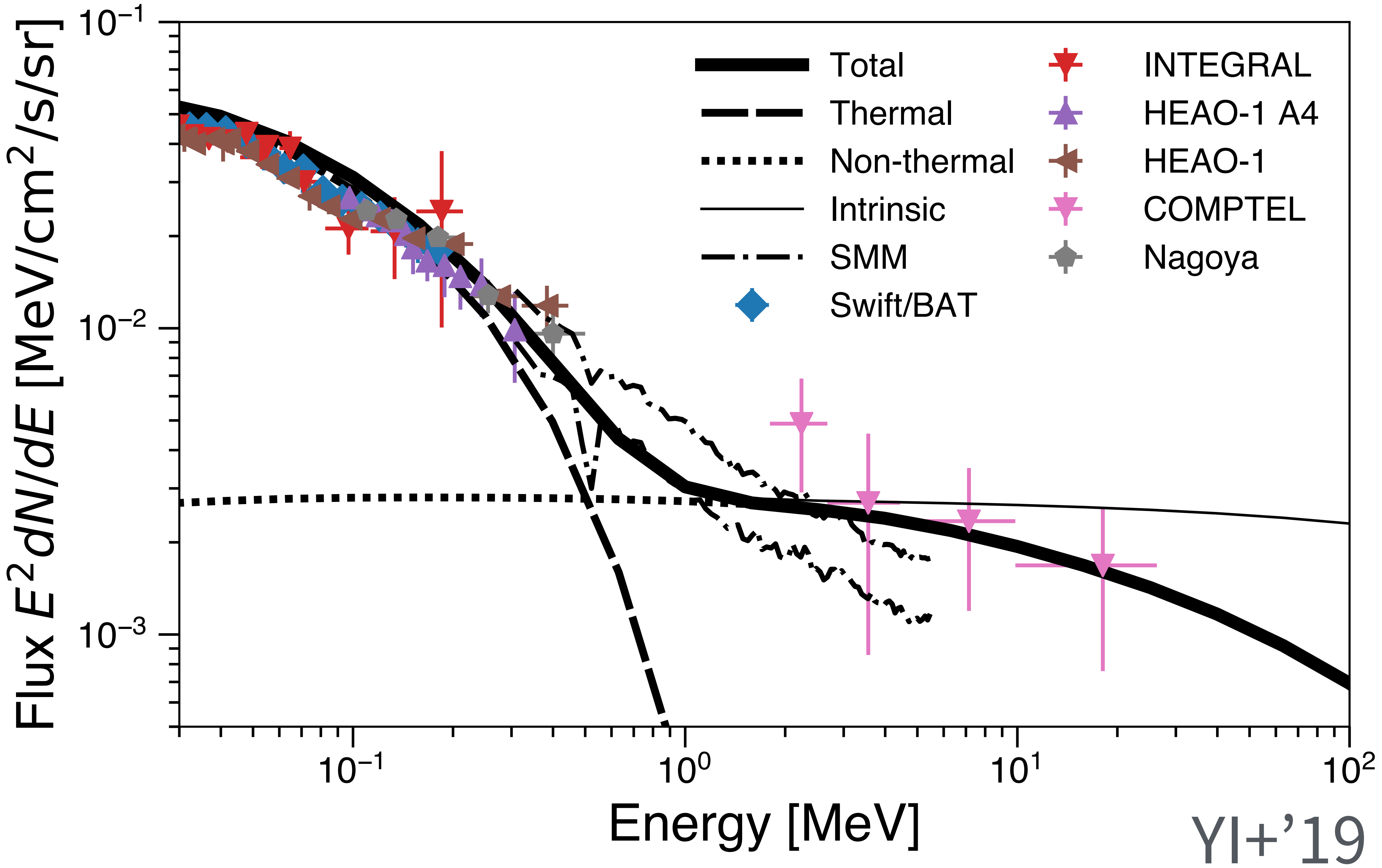
- Coronal synchrotron emission is found by ALMA (YI+'18)
- Non-thermal MeV tail in Seyferts can explain the MeV background radiation (YI+'08; YI+'19)

(Possible) Origins of the MeV Background

FSRQs (jet) ? Seyferts (disk)?



Ajello+'09



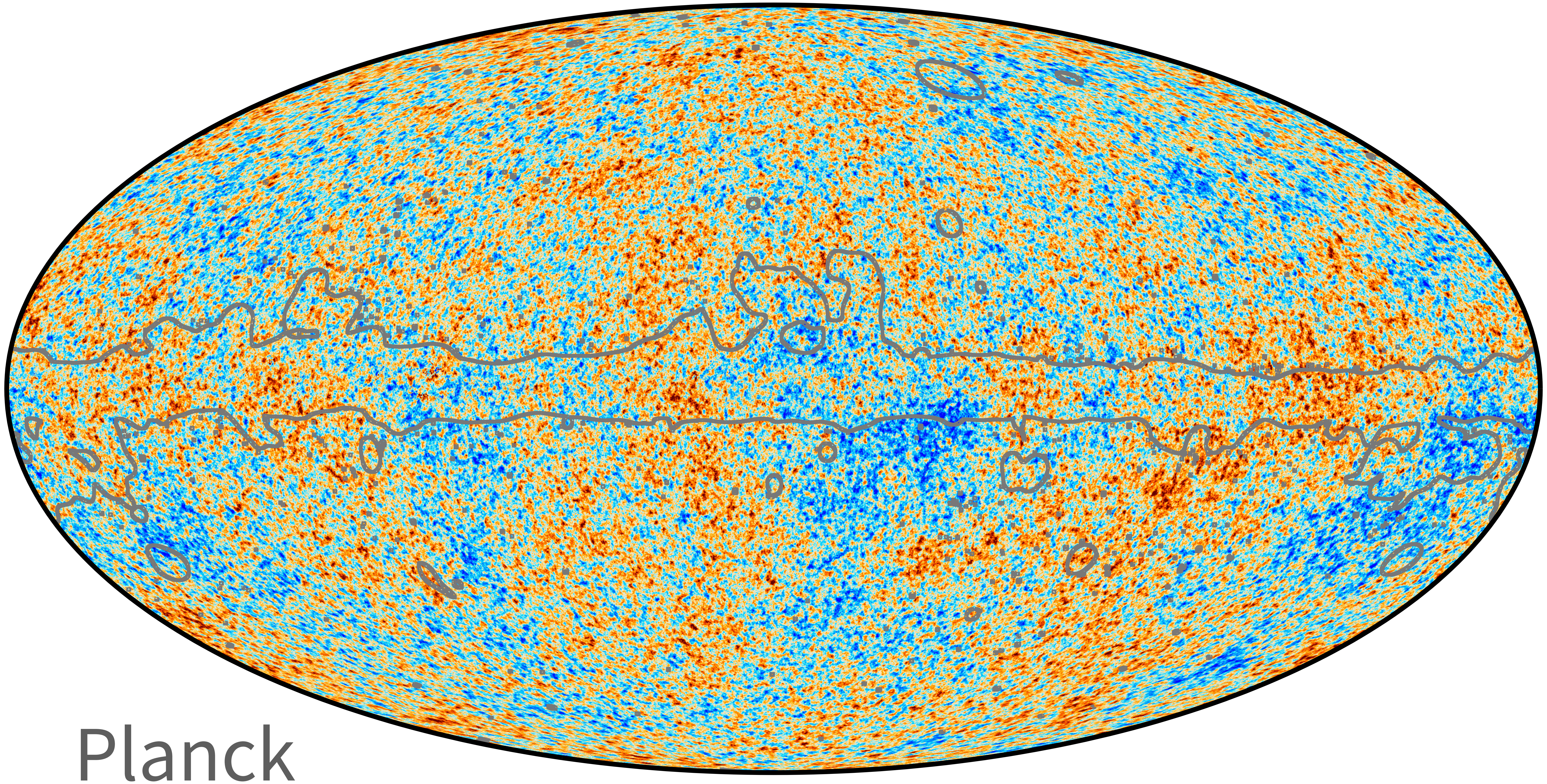
YI+'19

- FSRQs may explain (Ajello+'09)
  - Contradicts with evolution seen in GeV
  - Recent FSRQ XLF shows it is ~3%
- Seyferts may explain (YI+'08; YI+'19)
  - No MeV emission has been detected from Seyferts.
  - Synchrotron counterpart is detected by ALMA

Cosmic Gamma-ray Background Radiation Anisotropy

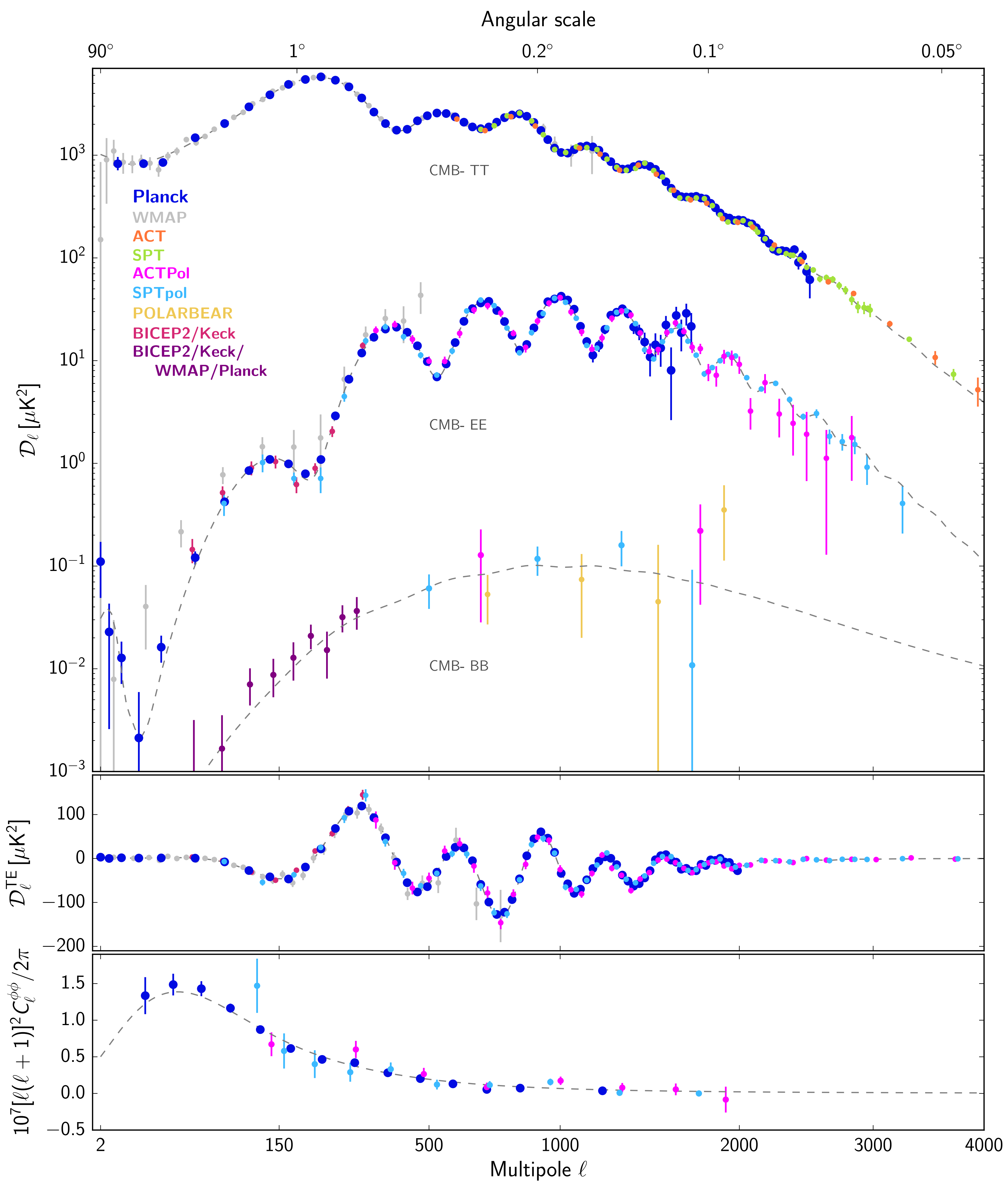
Anisotropy of the Cosmic Microwave Background

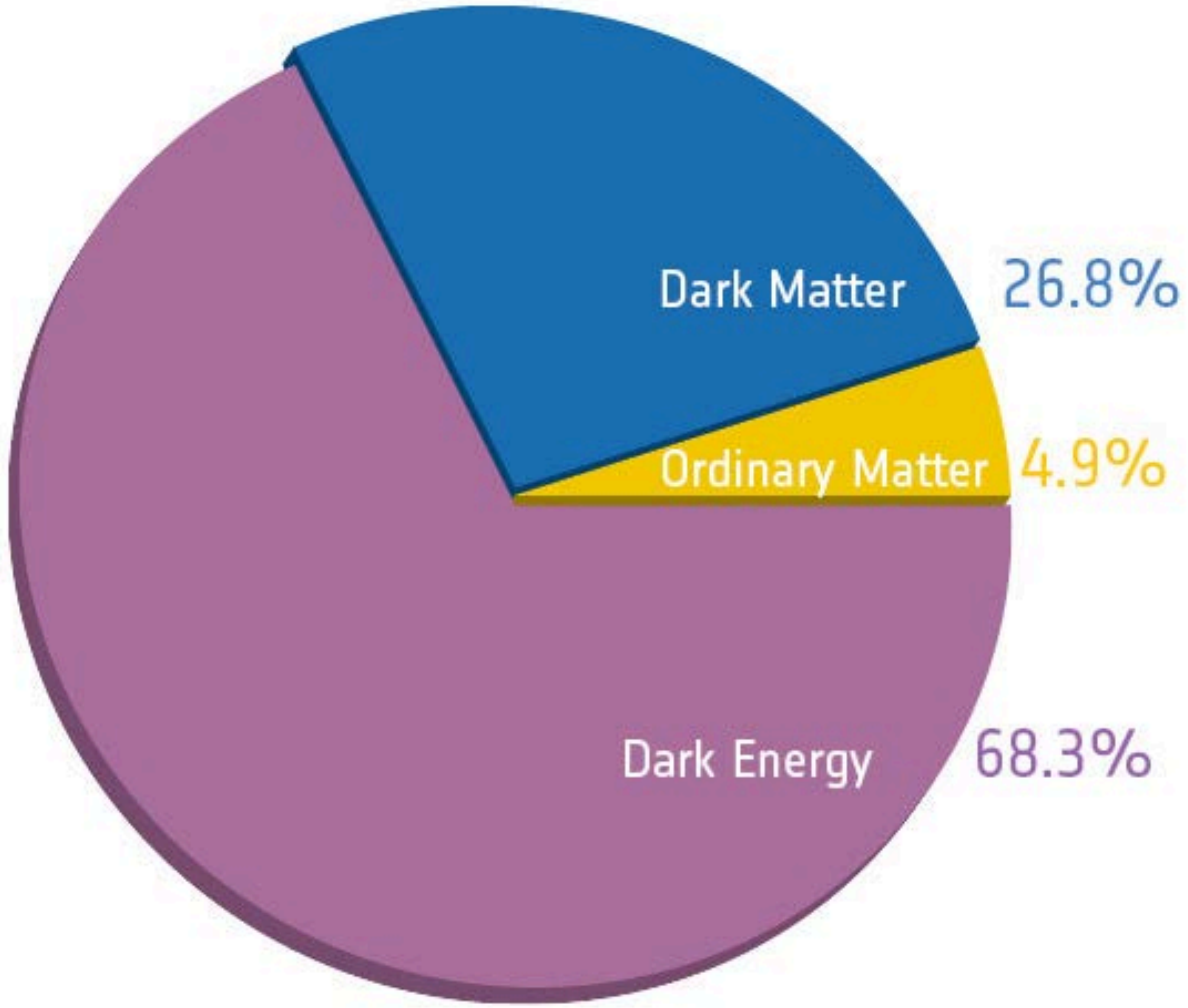
Clues for Big Bang Cosmology.



Anisotropy of the Cosmic Microwave Background

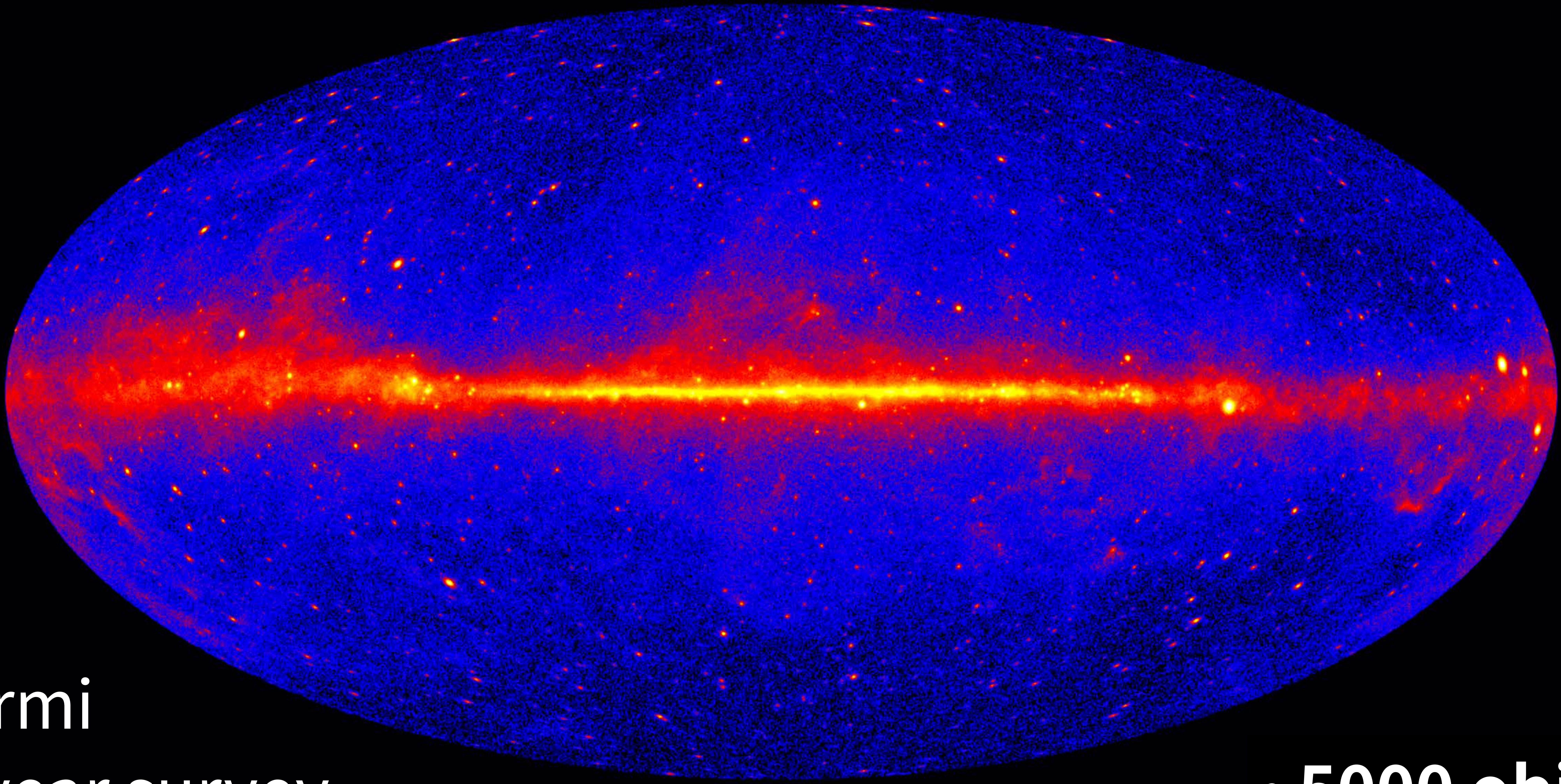
Converting the map to the angular power spectrum





Anisotropy of the sky

Trace the matter distribution in the universe

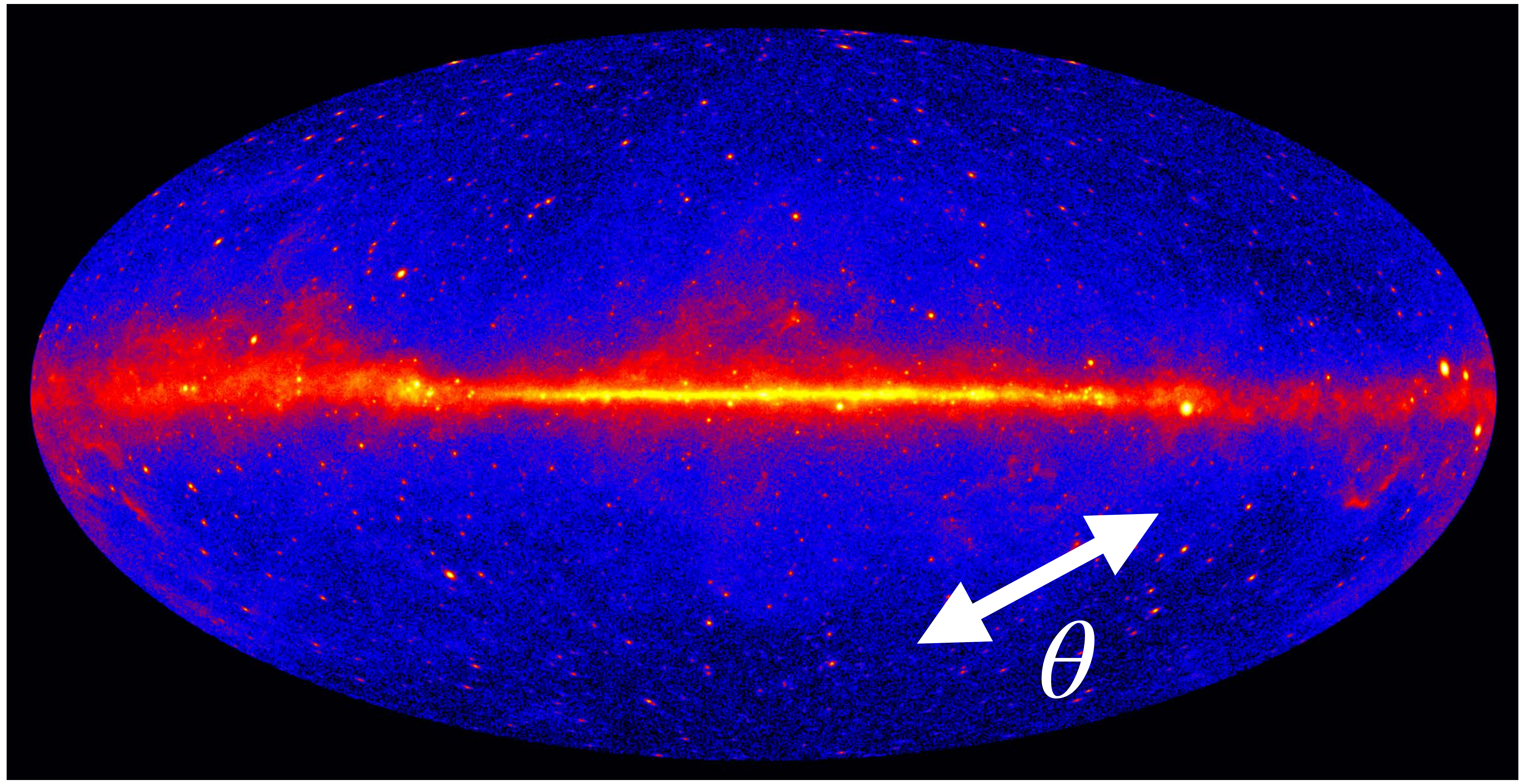


Fermi
5-year survey

~5000 objects

Anisotropy of the CGB

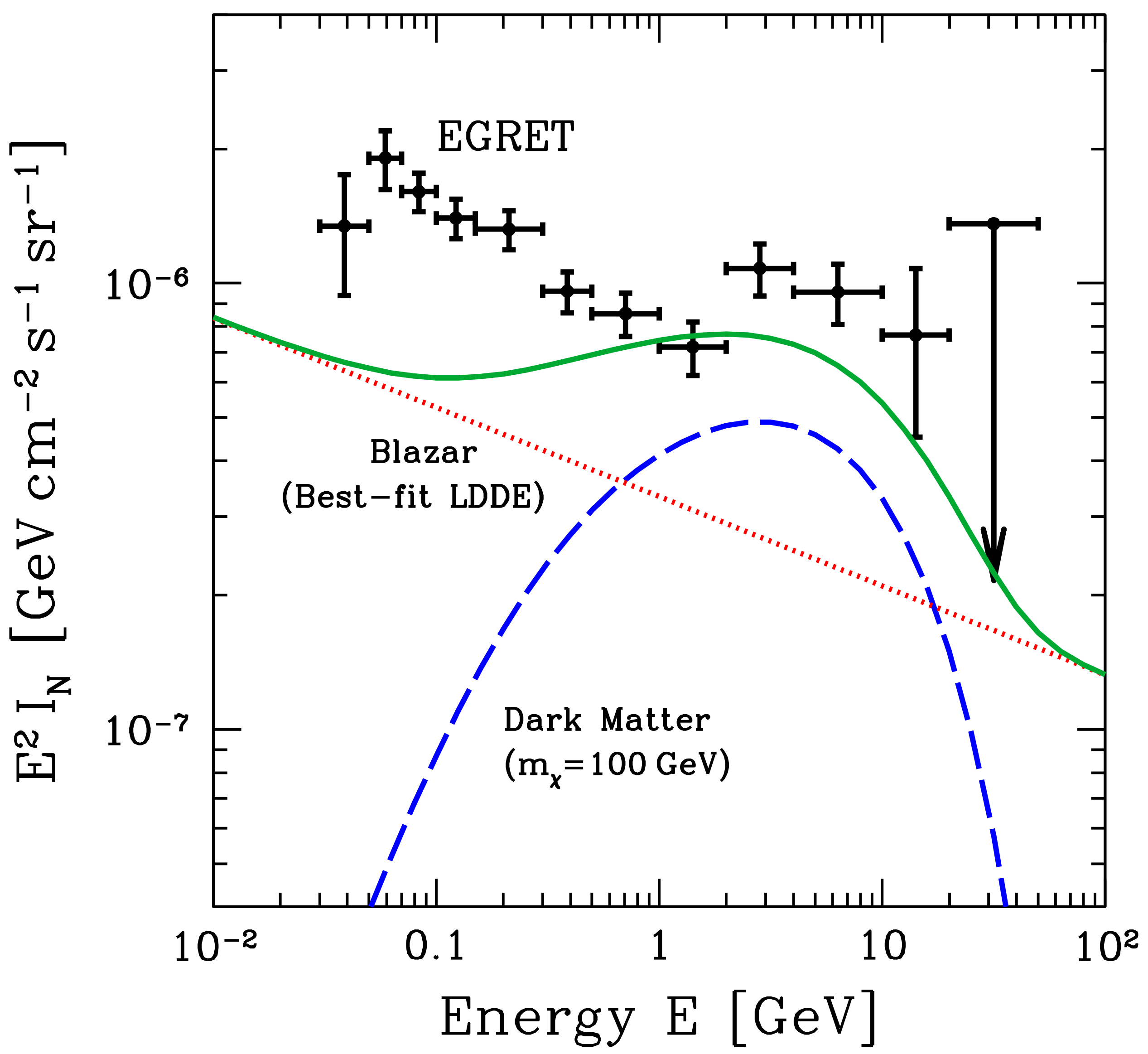
Proposed by Ando & Komatsu 2006

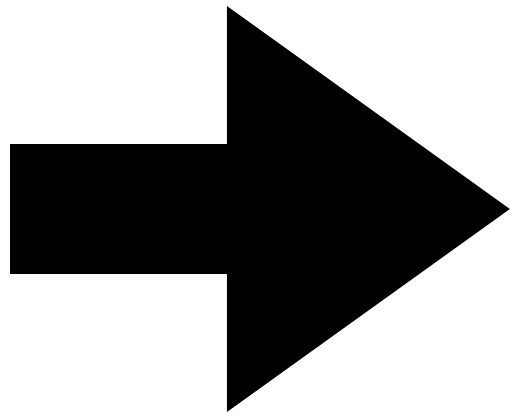


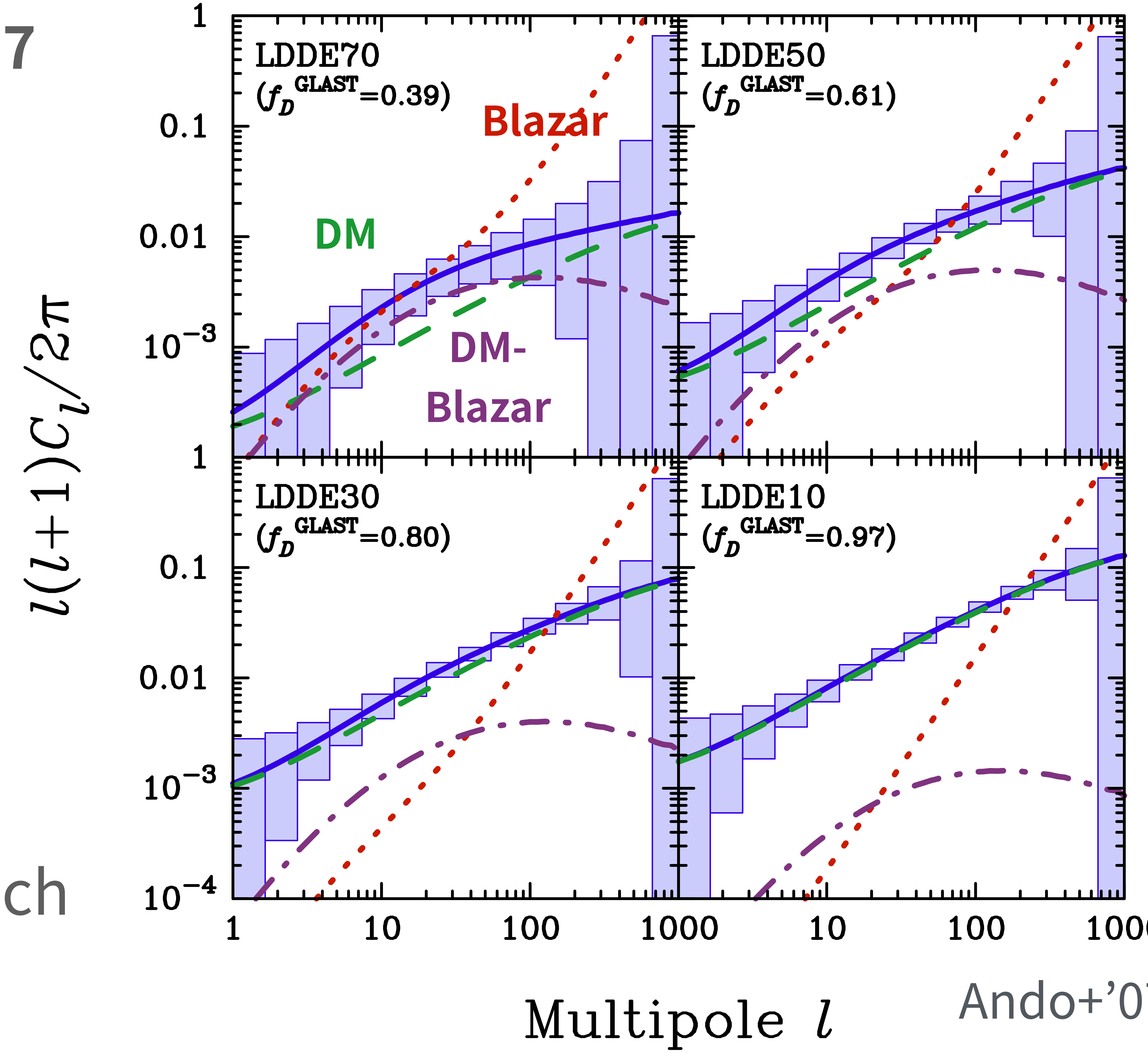
- Angular power spectrum: $C(\theta) = \langle \delta I(\hat{r}_1)\delta I(\hat{r}_2)\rangle$
  - Poisson term: $C_l^P \equiv C(\theta = 0)$
    - i.e., Shot noise $C_l^P = \int_0^{S_0} dS\ S^2 \frac{dN}{dS}$
  - Correlation term: $C_l^C \equiv \int_{\theta\neq 0} d^2\theta e^{-il\cdot\theta} C(\theta)$
    - includes structure information.
  - Note: multipole $l \simeq 180/\theta$

Angular Power Spectrum of the CGB

Ando & Komatsu 2006; Ando et al. 2007





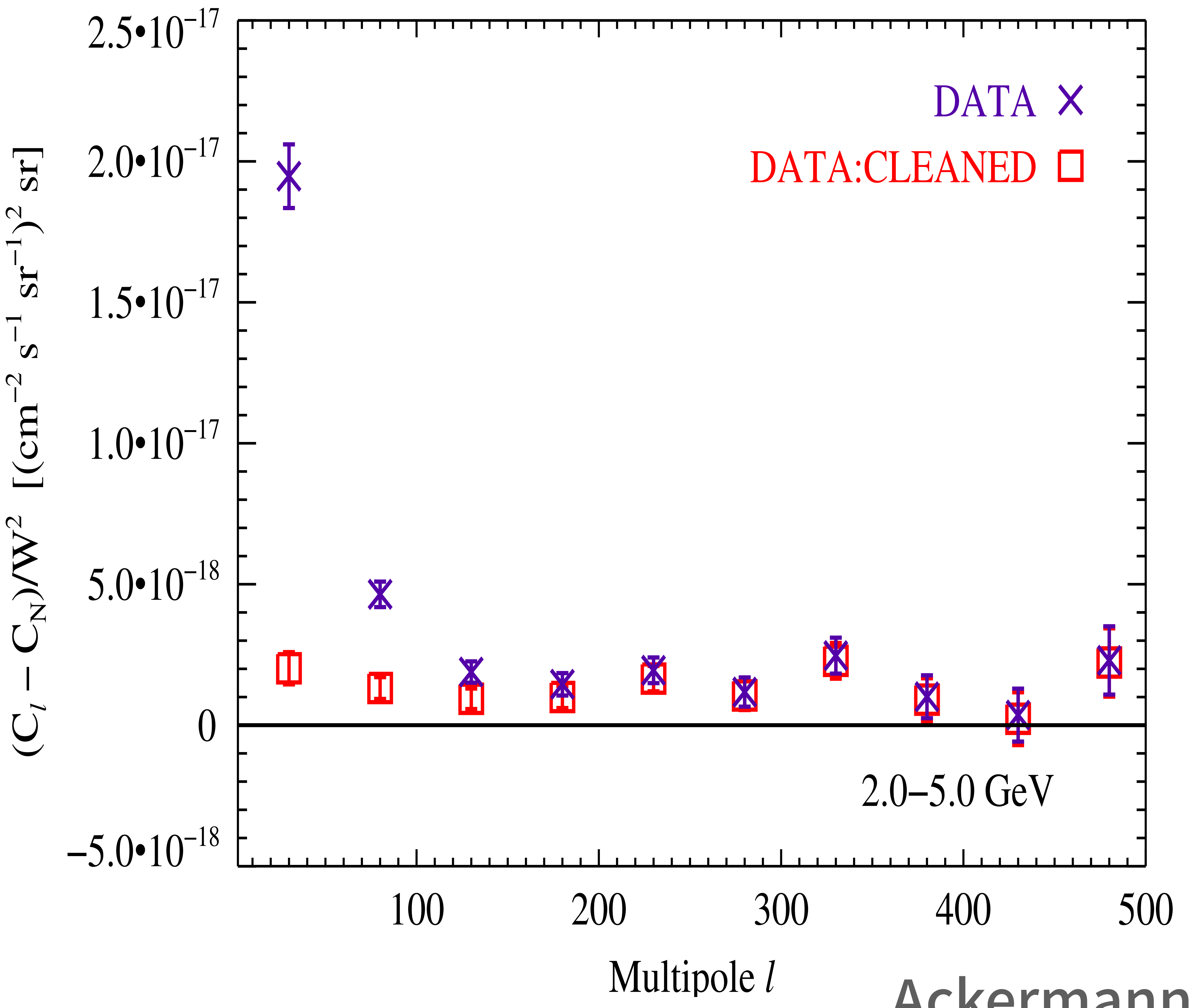


Ando+'07

- Note: this work was before the launch of Fermi.

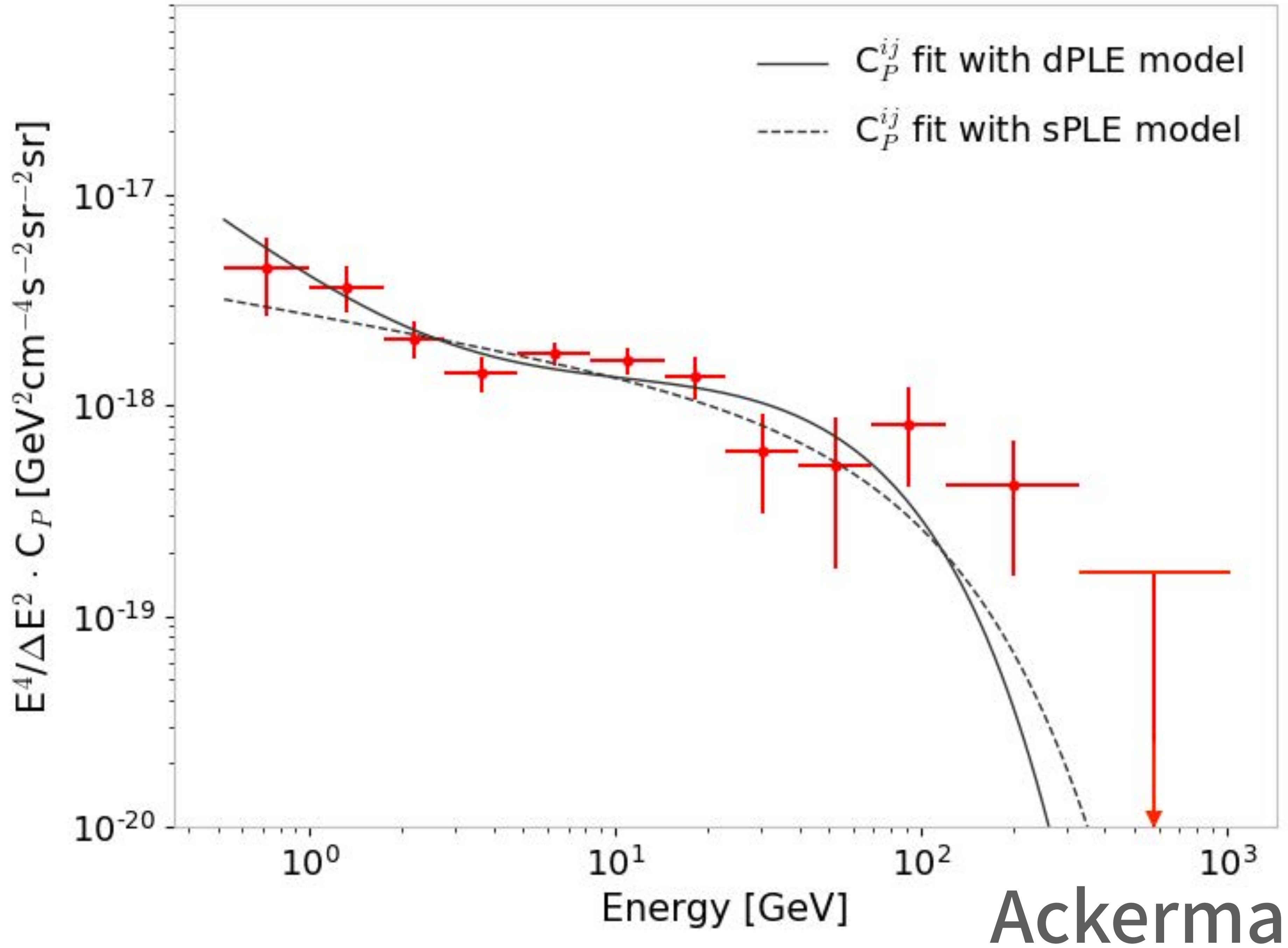
Anisotropy Measurement of the CGB

Fermi measured it.



Ackermann+'12

- Constant excess at 100 < l < 500
  - Poisson term
- >1 populations are required.

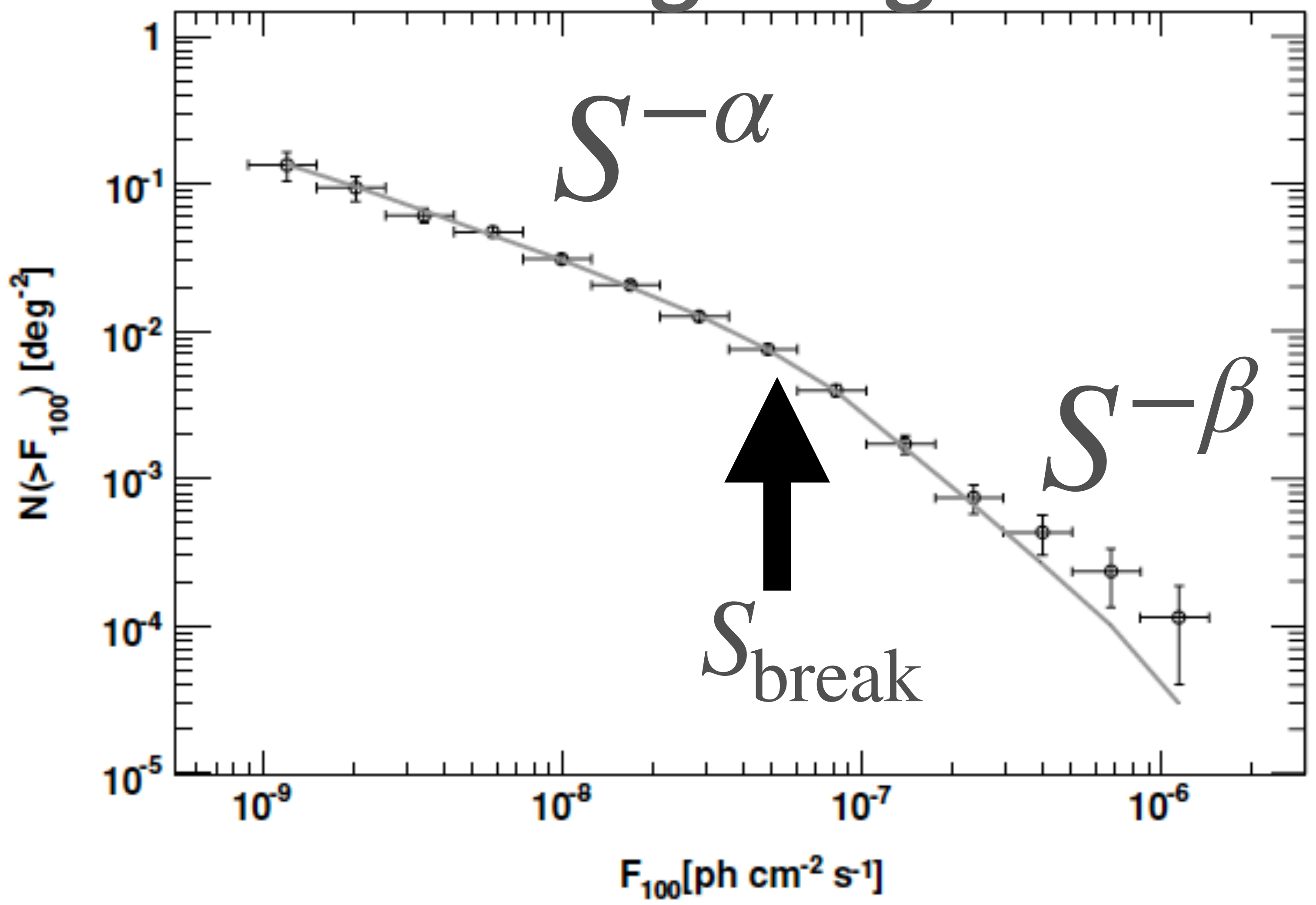


Ackermann+'19

Anisotropy Constraints on Blazar models

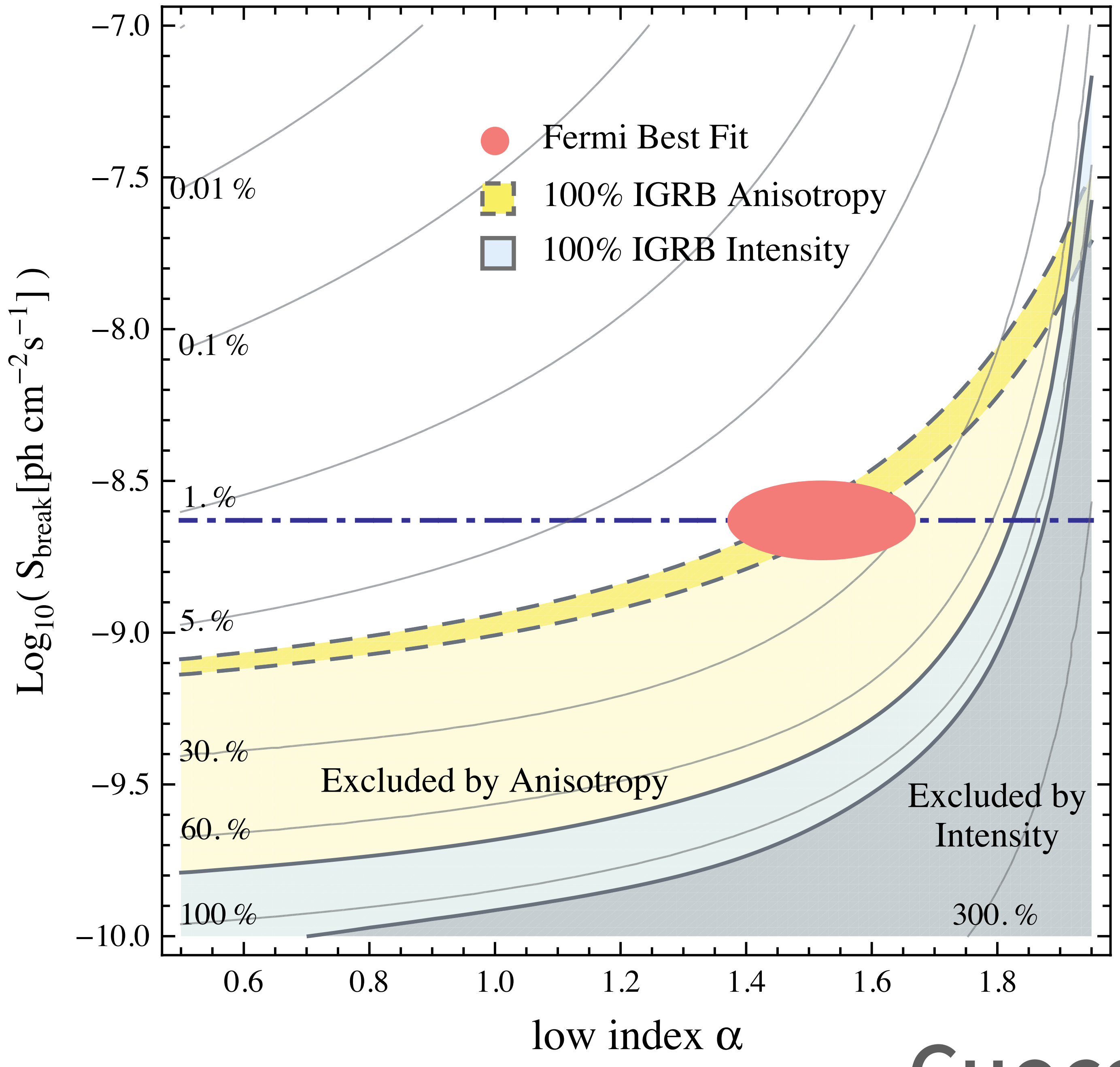
Independent test of blazar evolution

logN-logS



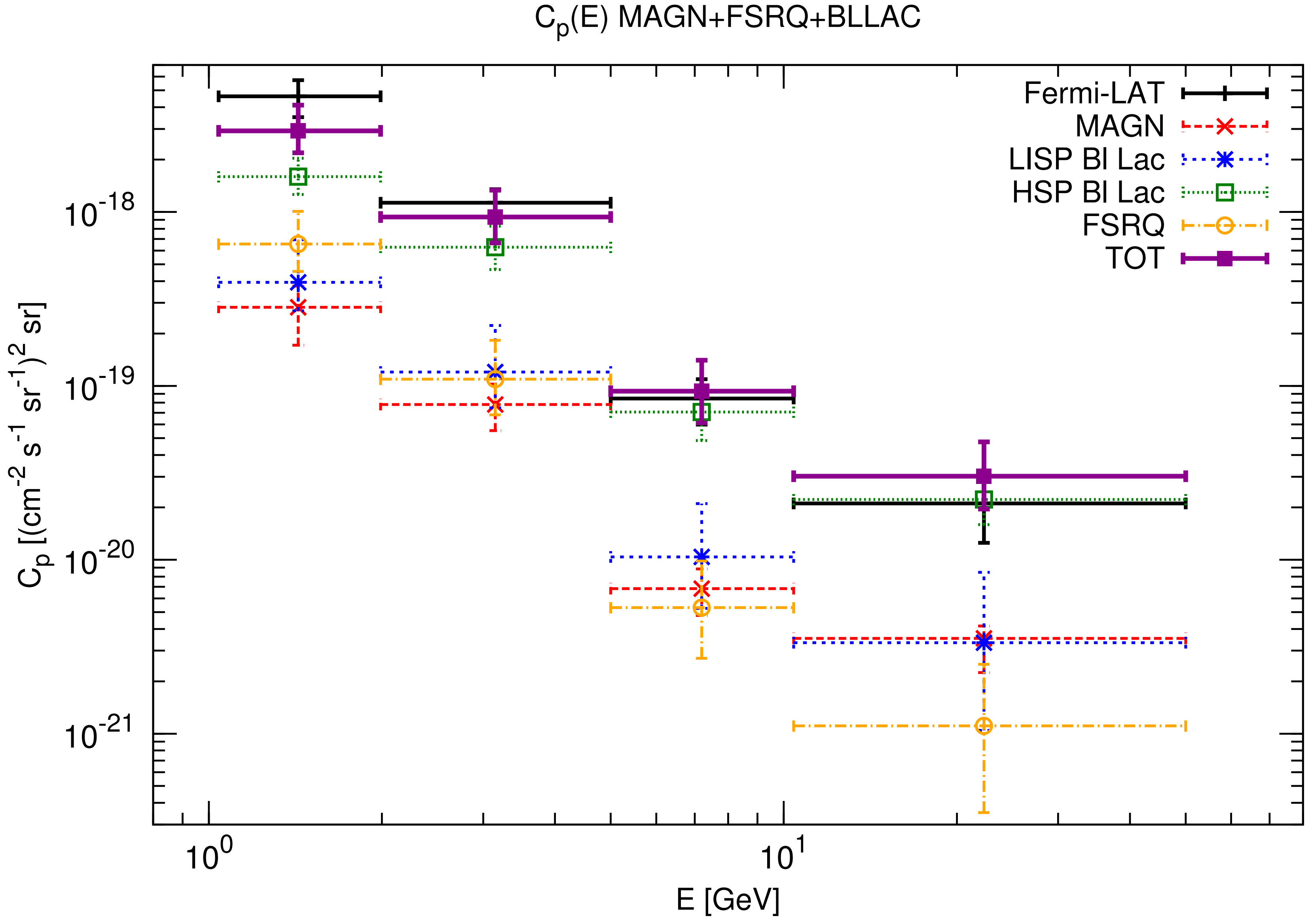
Abdo+'10

Joint constraint



Cuoco+'12

Energy dependent C_l^P

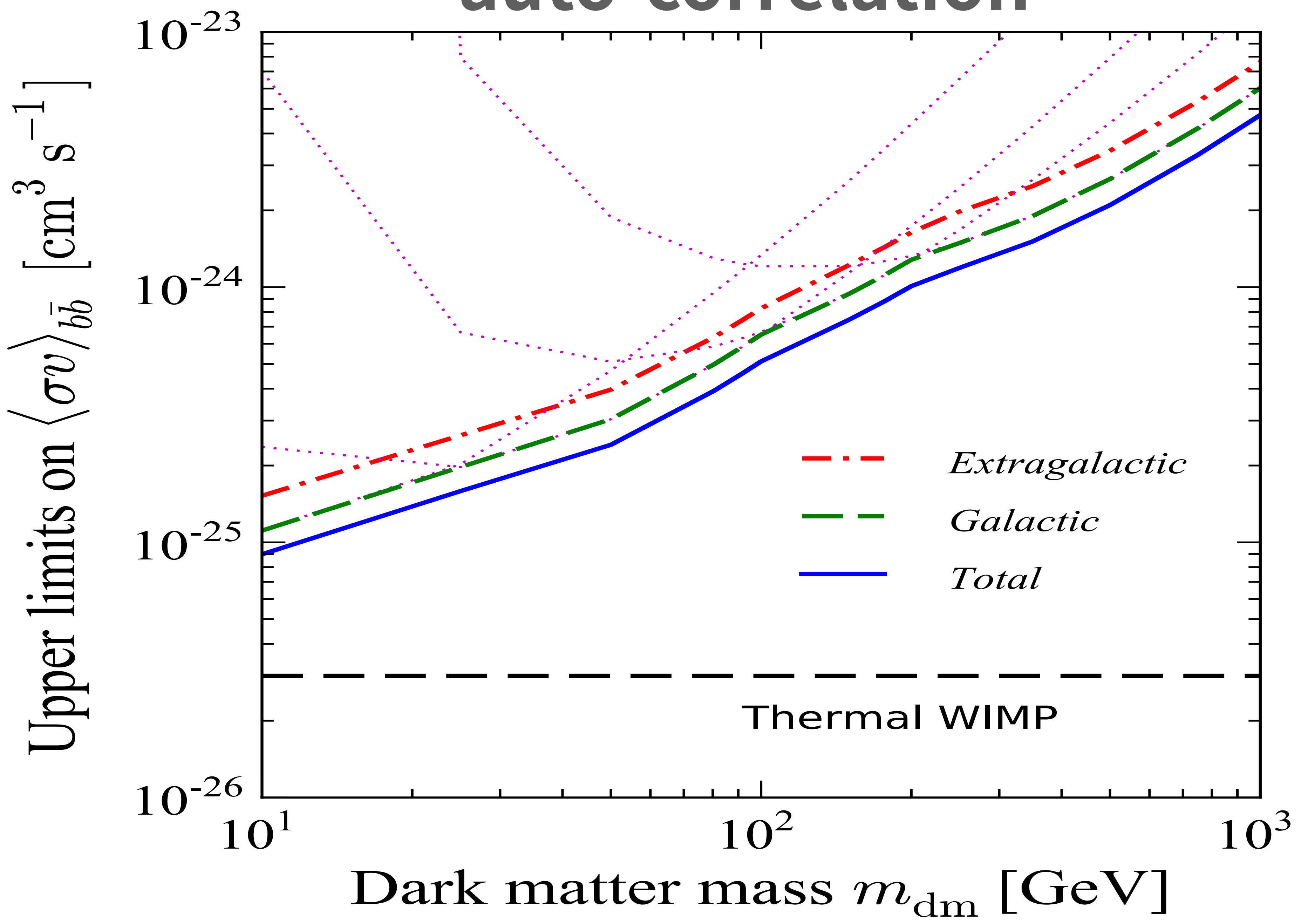


Di Mauro+'14

- We can estimate C_l^P
  - Anisotory & source count constrain the evolution models (Cuoco+'12; Harding & Abazajian '13)
- Anisotropy is well explained by blazars and radio galaxies (Di Mauro+'14)

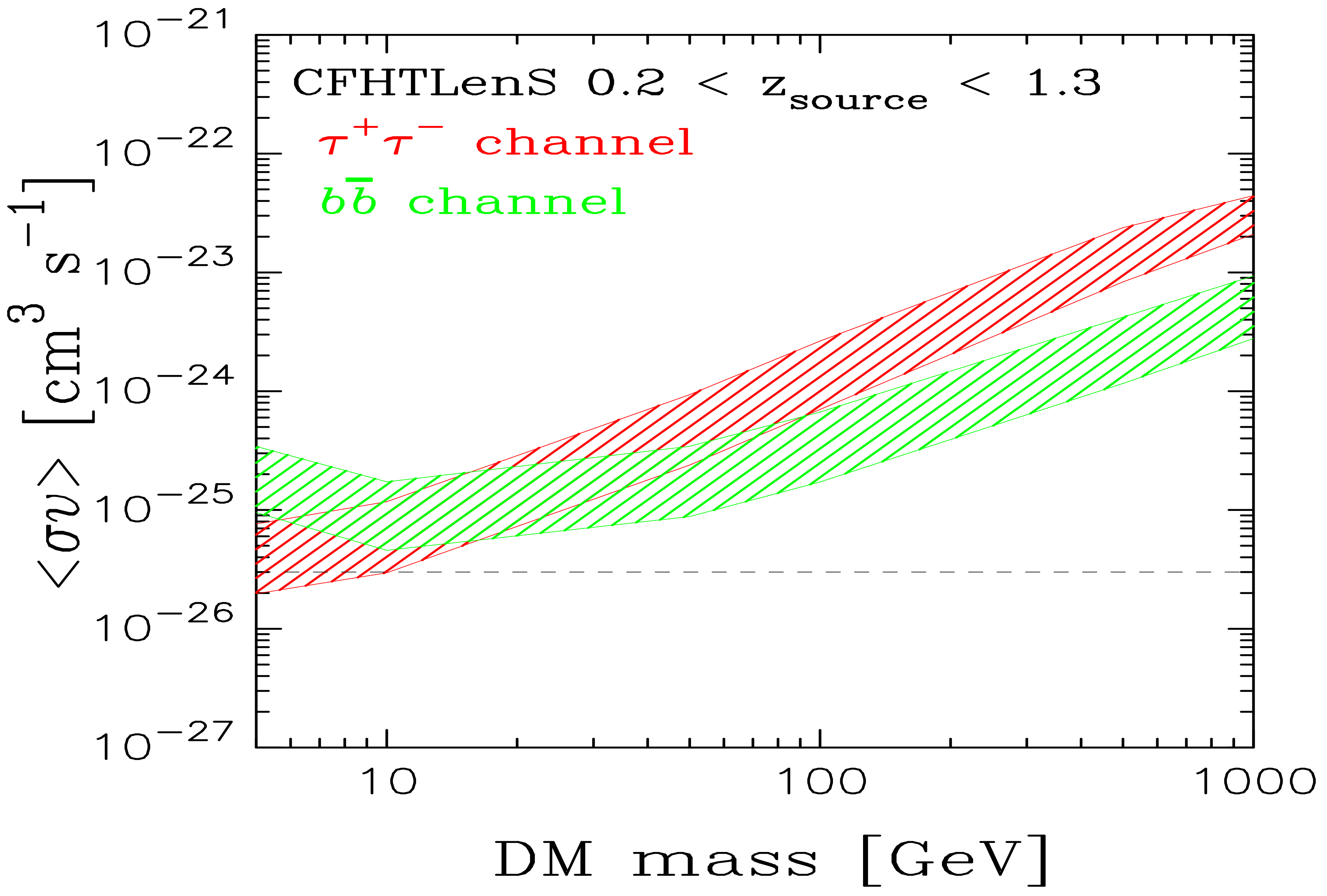
Anisotropy Constraints on Dark Matter Parameters

auto-correlation



Ando&Komatsu '13

cross-correlation

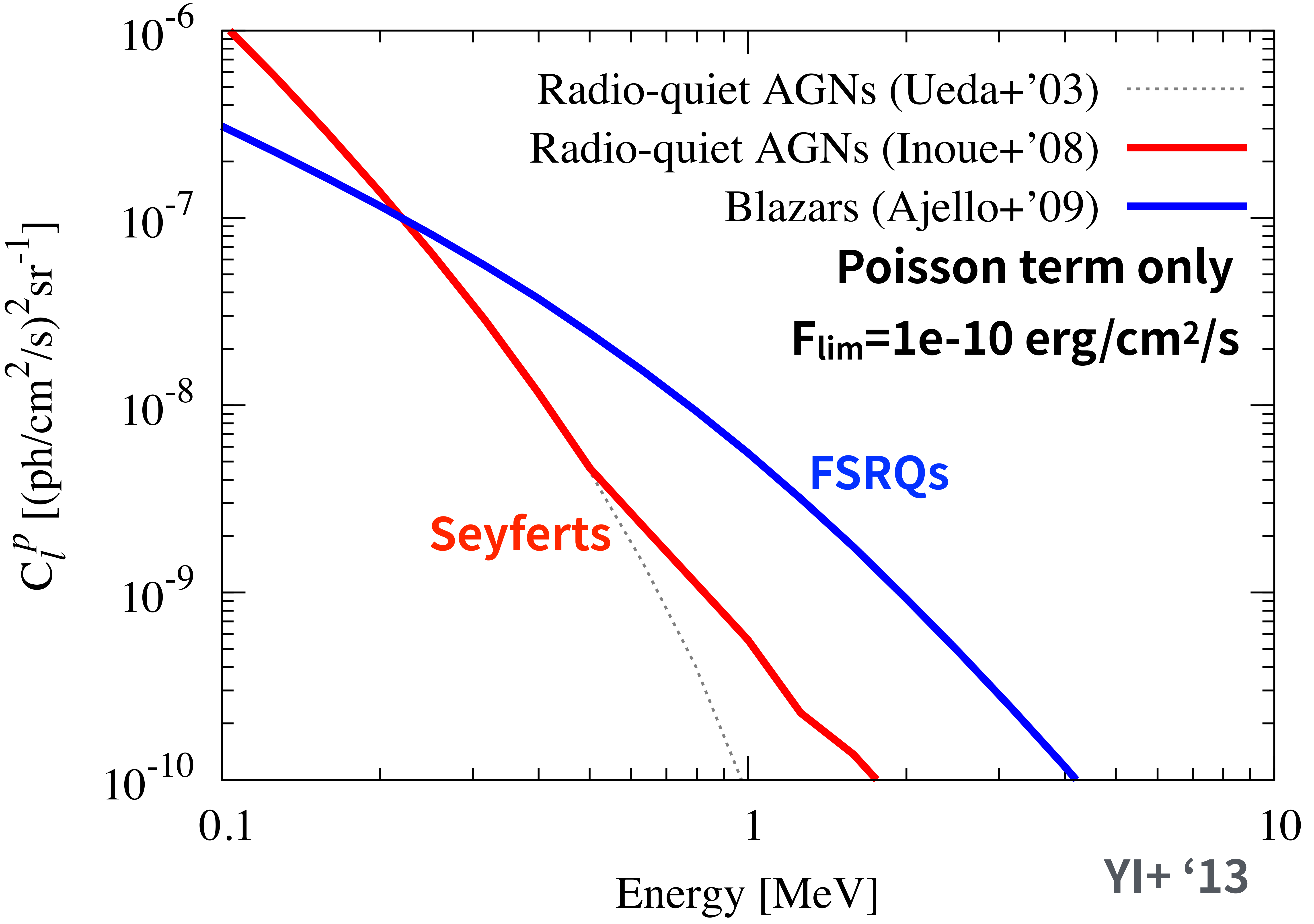


Shirasaki+'14

- Angular power spectra of CGB is a powerful tool to constrain the DM properties (e.g. Ando & Komatsu '06, '13).
- Cross-correlation between cosmic shear and CGB will be a new powerful tool (e.g. Camera+'13, Shirasaki+'14).

Anisotropy of the MeV Background

Can be achieved by coming balloon missions



- FSRQs are bright but rare

  ➡High C_l^P

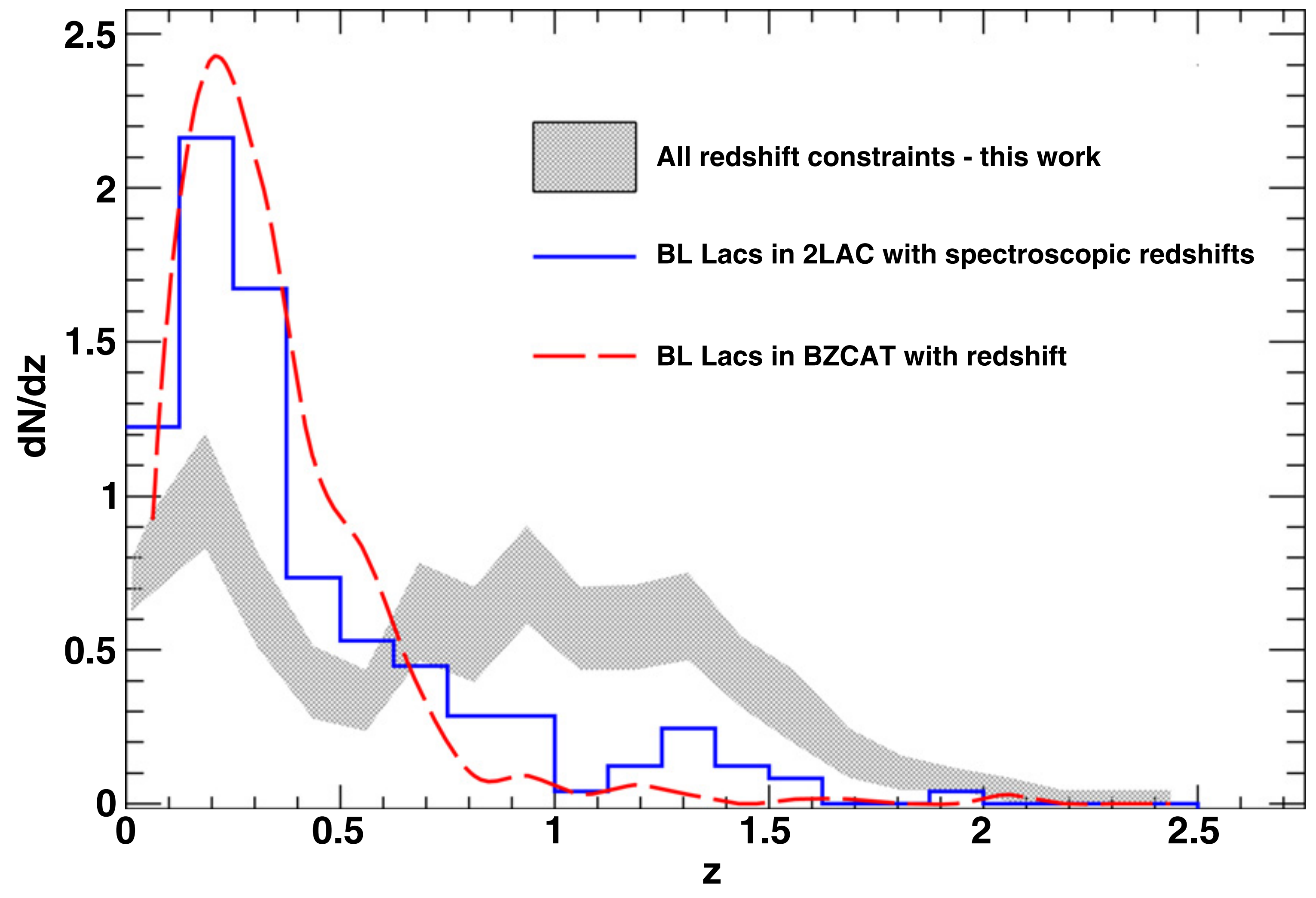
- Seyferts are faint but numerous

  ➡Low C_l^P

- Future missions can unveil the MeV background through anisotropy.

More topics in cosmic evolution studies

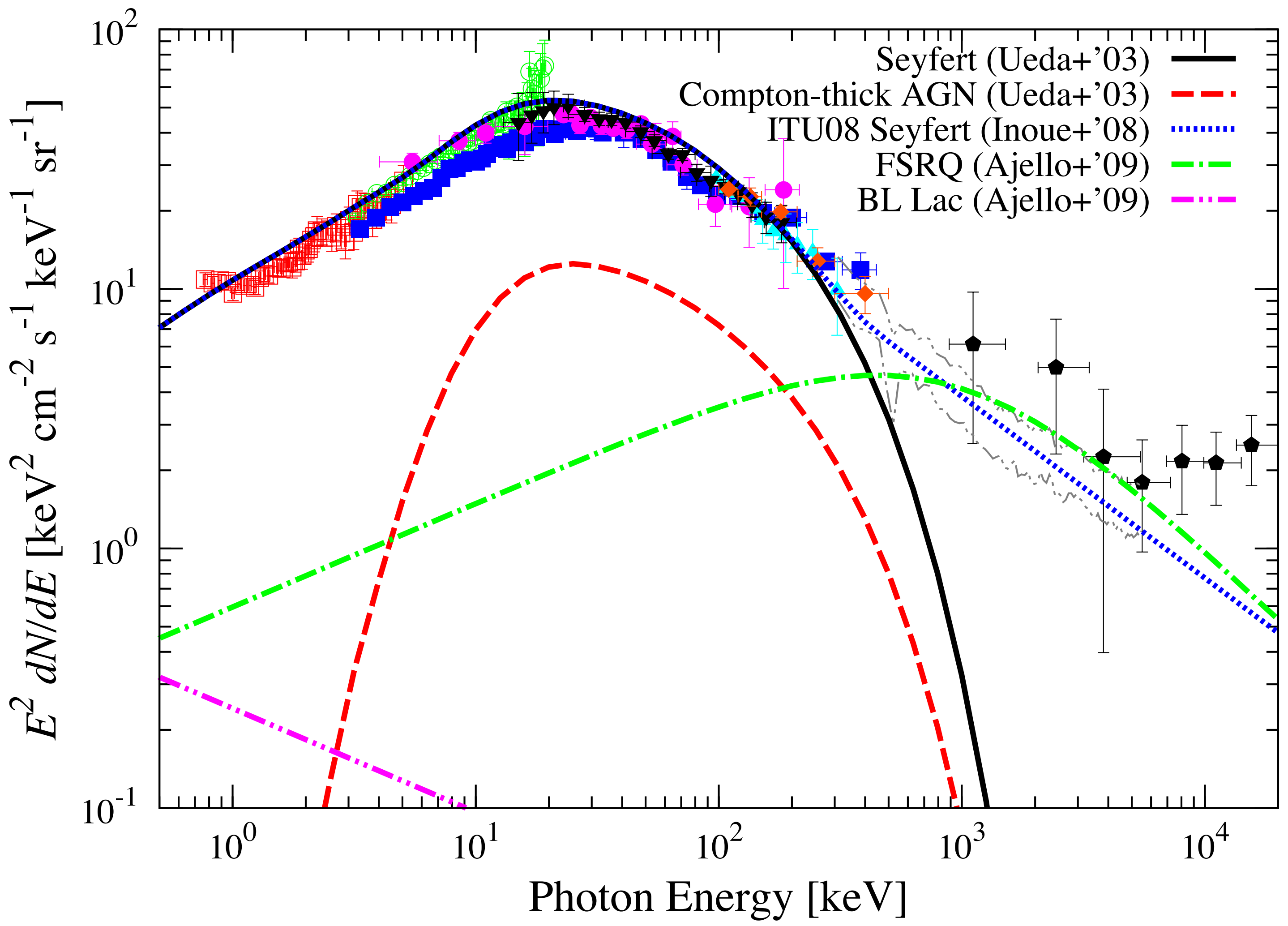
- Connection to Neutrinos & Cosmic-ray backgrounds
- Evolution of blazars
  - Redshift measurements of BL Lacs
- TeV background radiation

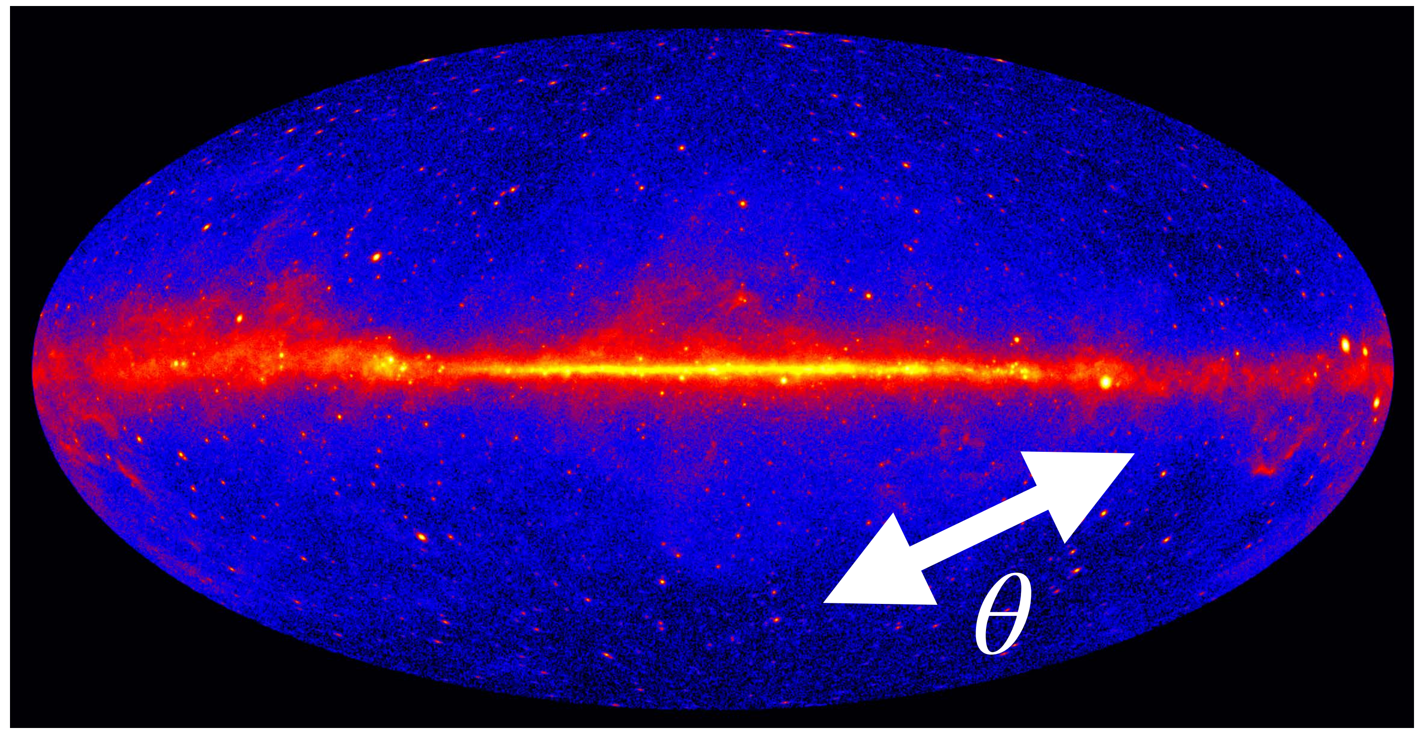


Ajello+'14

Day 2 Summary

- Origin of the cosmic MeV gamma-ray background is still under debate.
    - Seyferts?
        - But, no MeV emission is confirmed.
    - FSRQs?
        - But, evolution is inconsistent with GeV data.
- Anisotropy of the cosmic gamma-ray background is a powerful tool.
    - Fermi has measured the Poisson term.
    - >1 populations are required for the GeV background.





Cosmological Aspects of High Energy Astrophysics ~ Day 3 ~

Yoshiyuki Inoue

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

Lecture Schedule

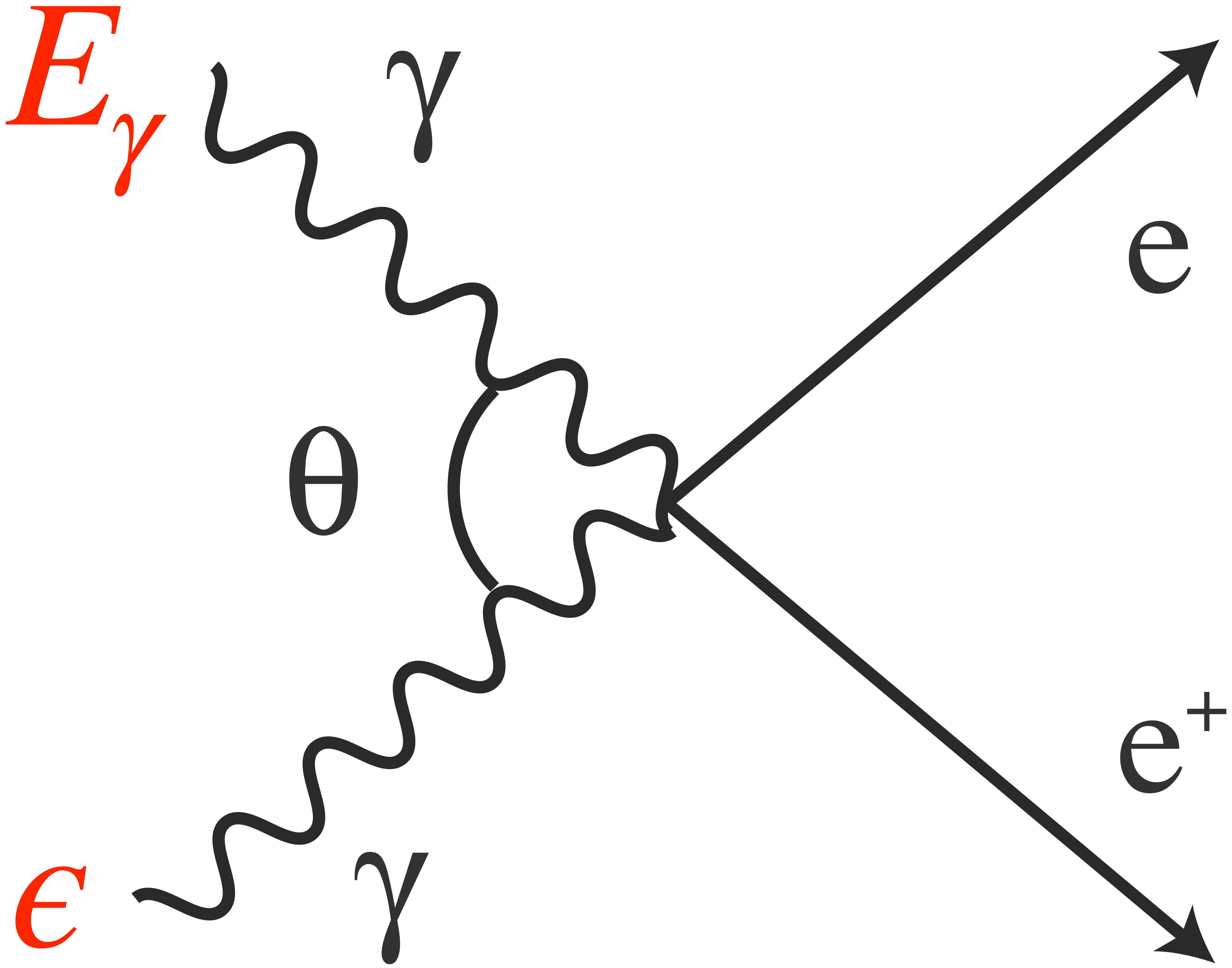
Be careful! It may change!

- ~~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**
  - **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: $\gamma + \gamma \rightarrow e^+ + e^-$



Dwek & Krennrich ‘13

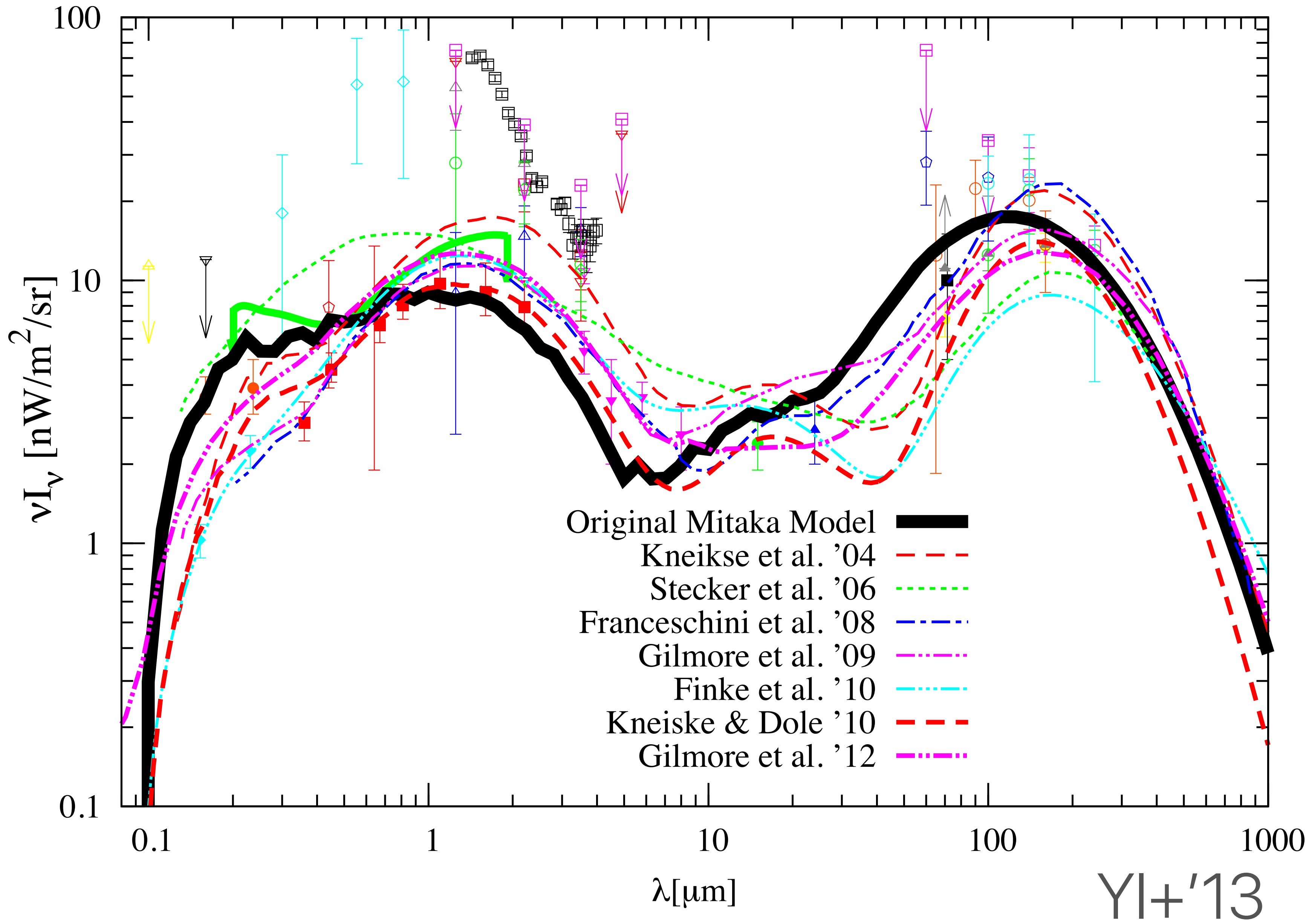
- Threshold: $E_\gamma \epsilon_{\rm th}(1 - \cos\theta) > 2(m_e c^2)^2$
- Cross section:
  $\sigma_{\gamma\gamma} = \frac{3\sigma_T}{16}(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right],$
  where $\beta = \sqrt{1 - \epsilon_{\rm th}/\epsilon}$
- Peak : $\sigma_{\gamma\gamma}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

See talk by Ellis Owen

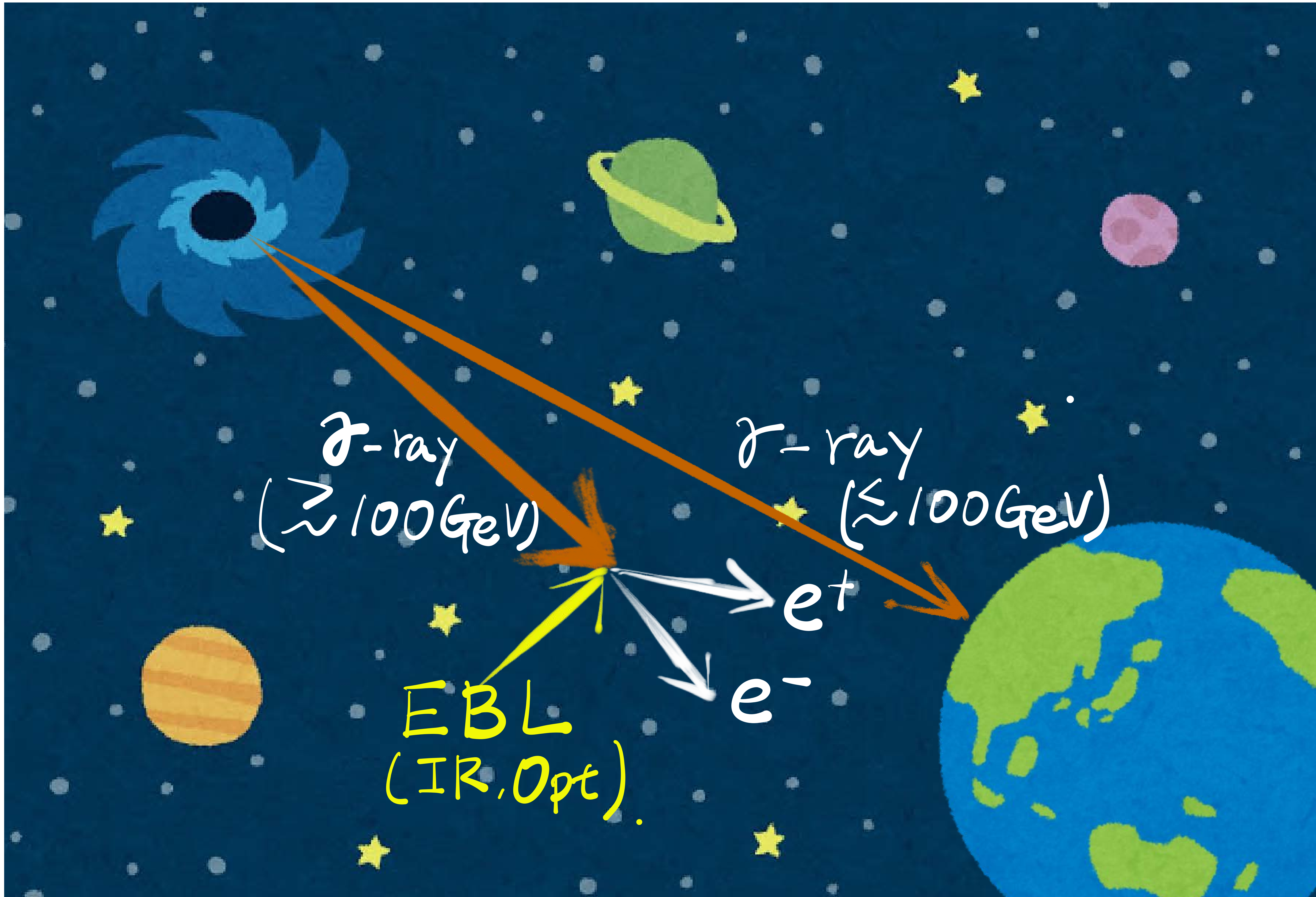
Gamma-ray attenuation during the propagation

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

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



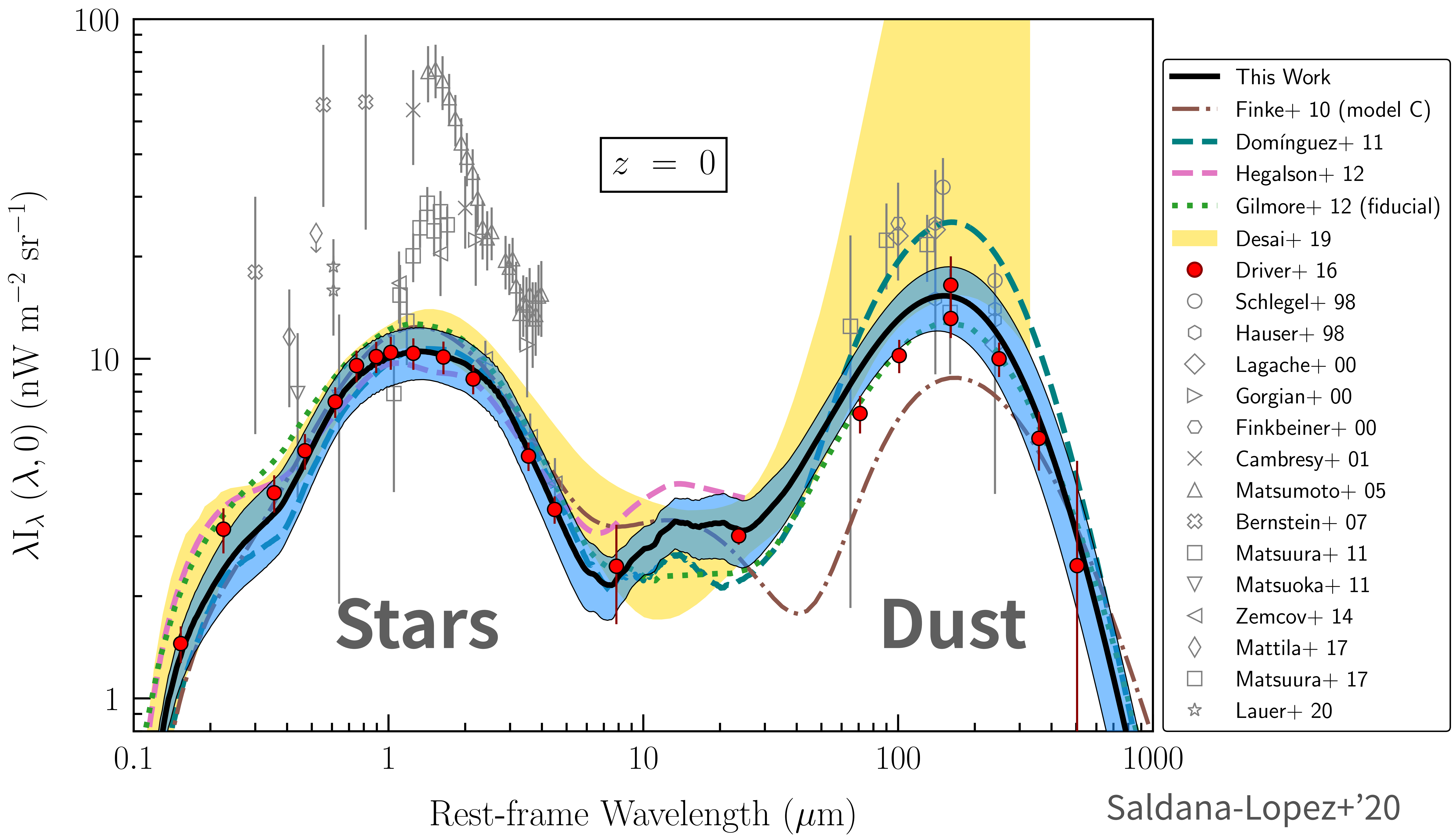
YI+'13



Extragalactic Background Light

Extragalactic Background Light (EBL)

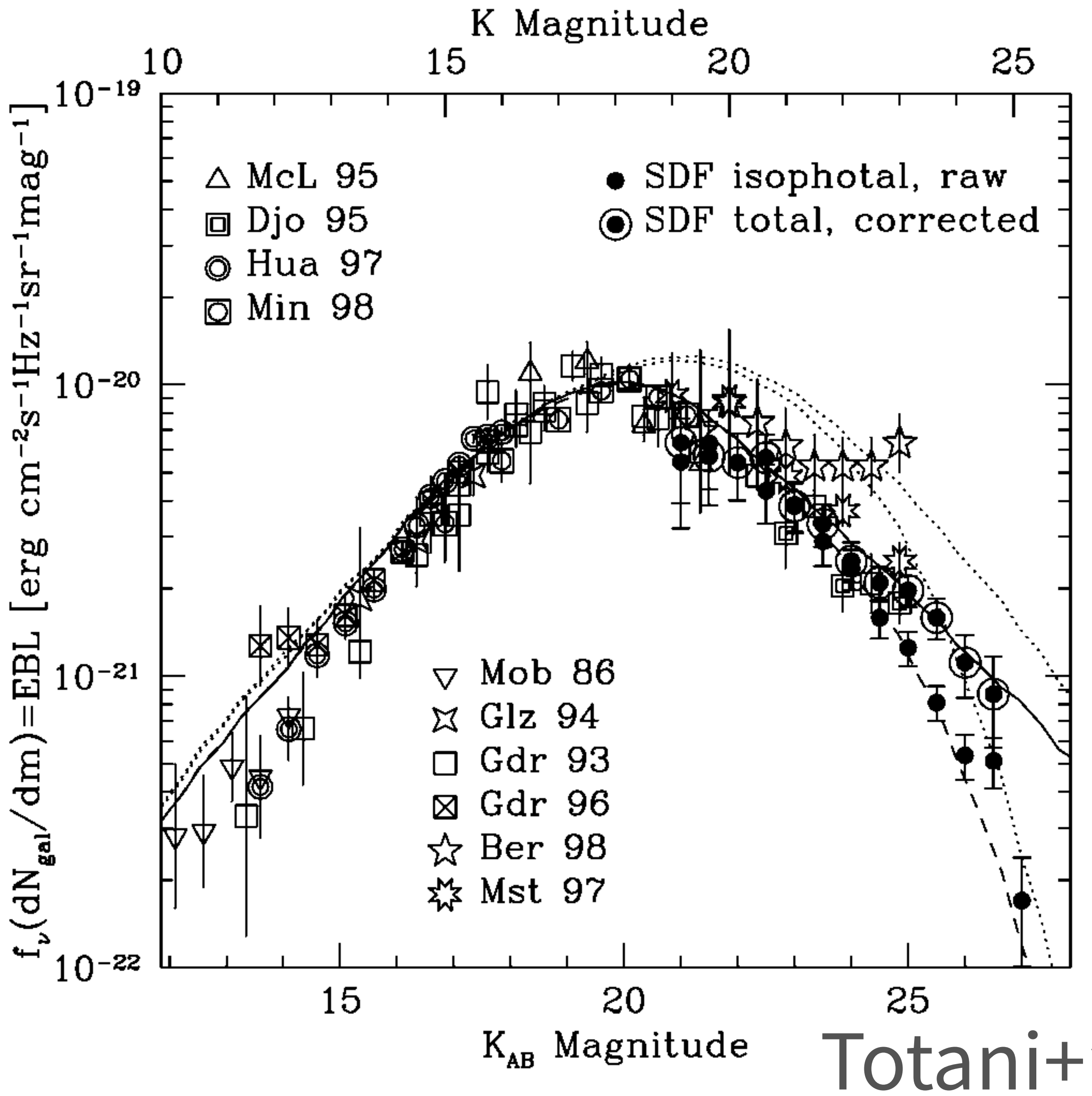
Integrated Emission from Galaxies in the entire cosmic history



Saldana-Lopez+'20

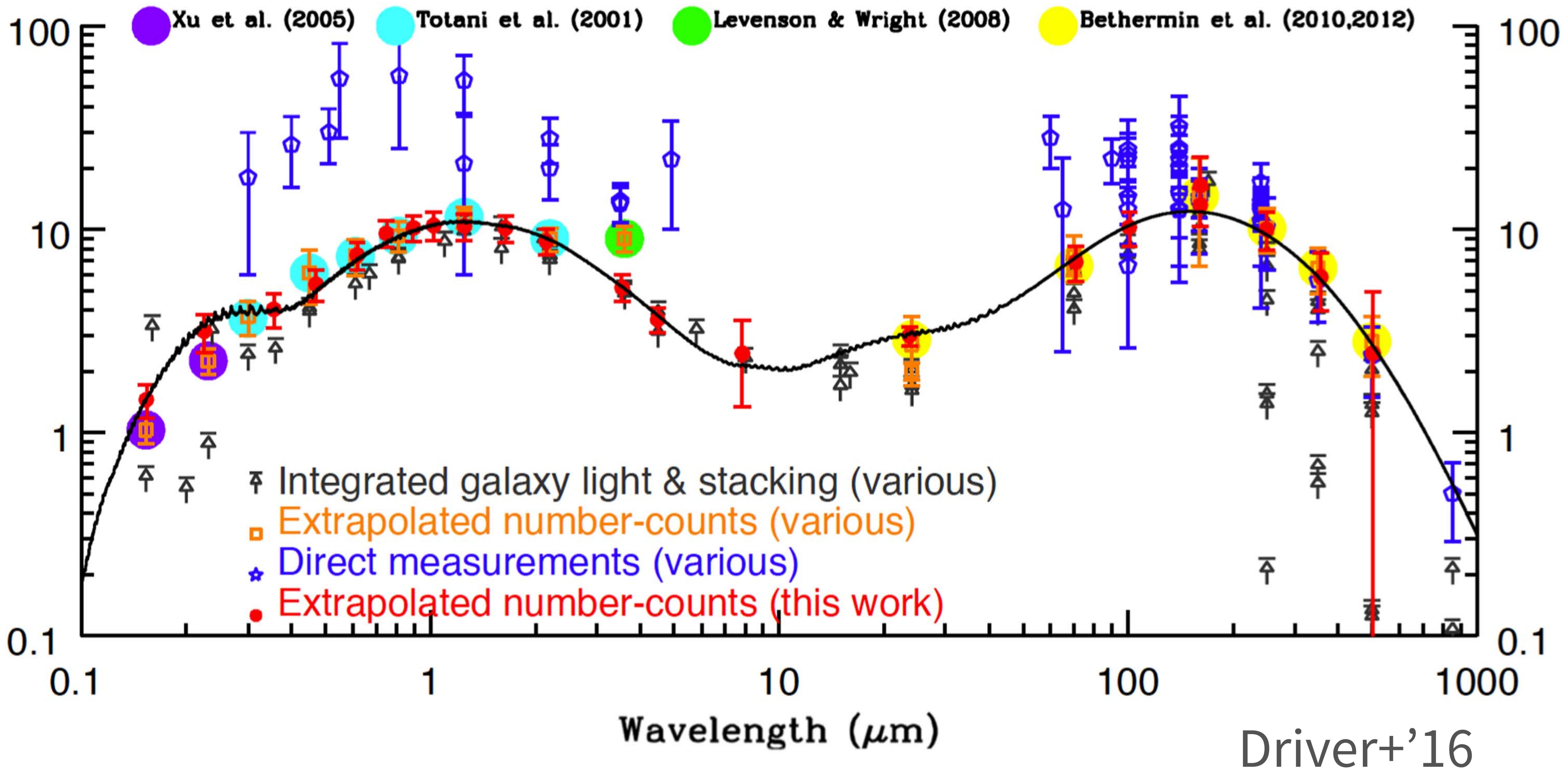
Counting Galaxies

Lower bounds on the EBL



Totani+'01

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



Driver+'16

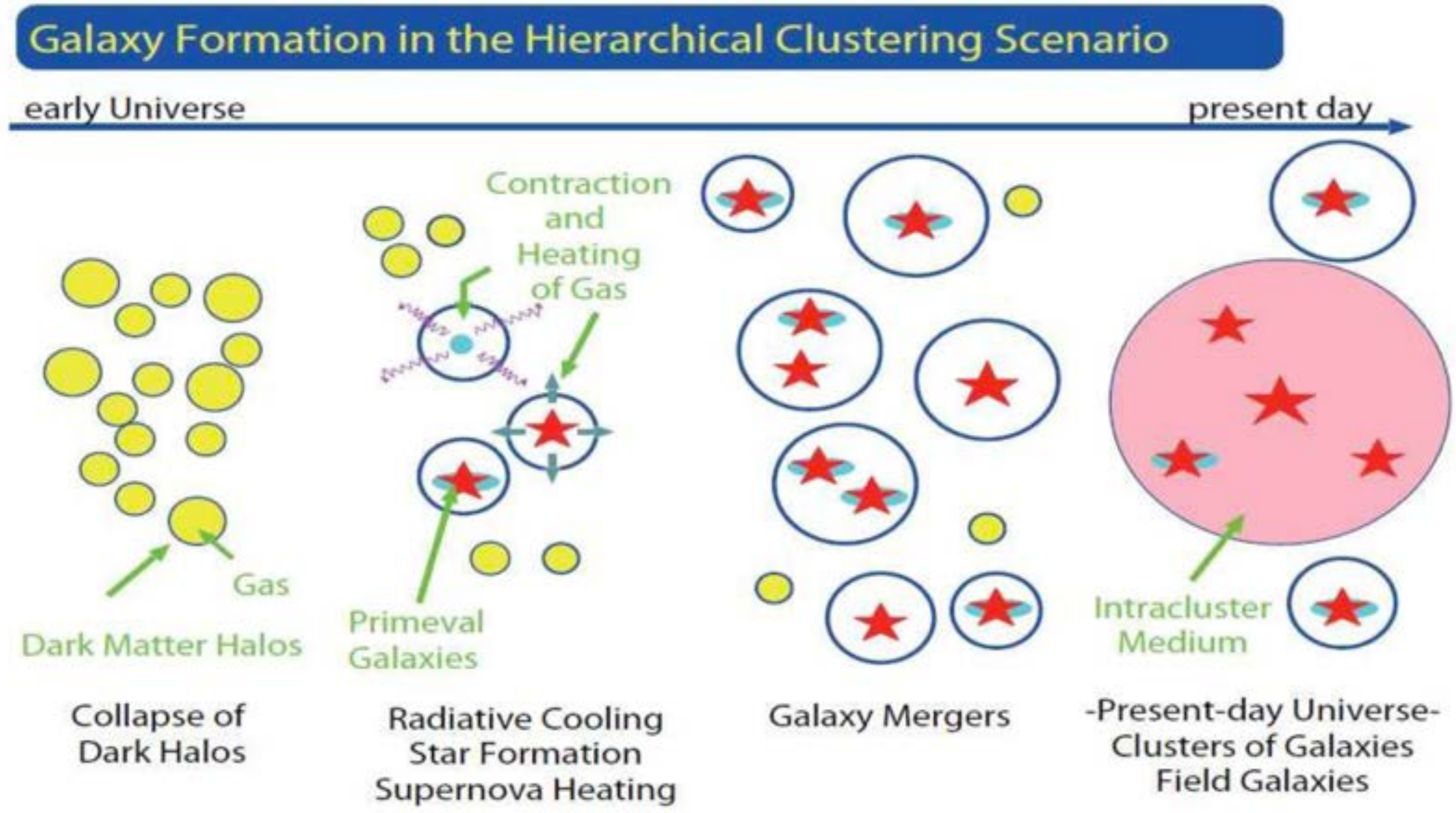
Modeling the extragalactic background light

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; Yl+'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

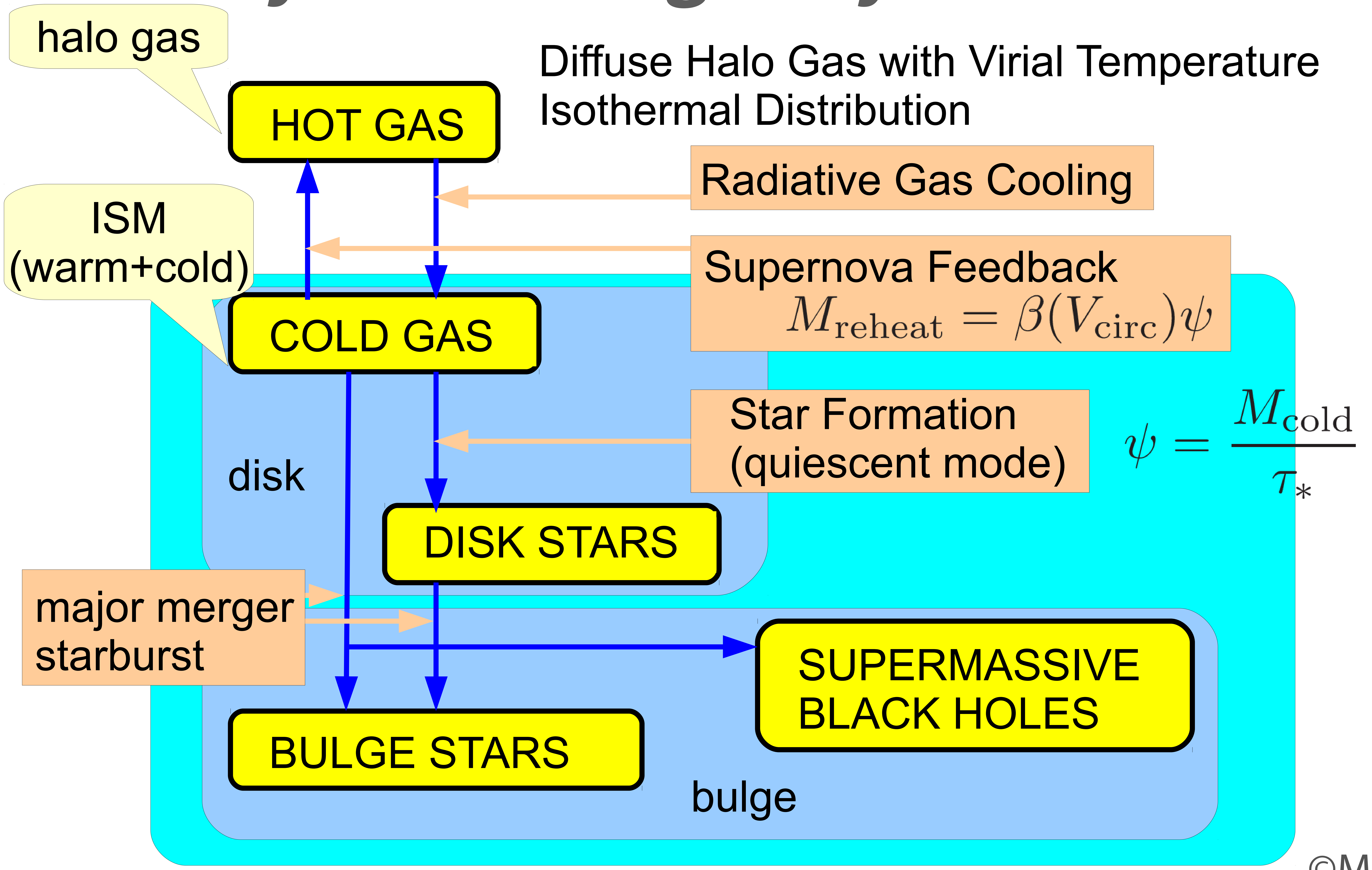
Hierarchical Galaxy Formation

Semi-analytical EBL Models



M. Nagashima

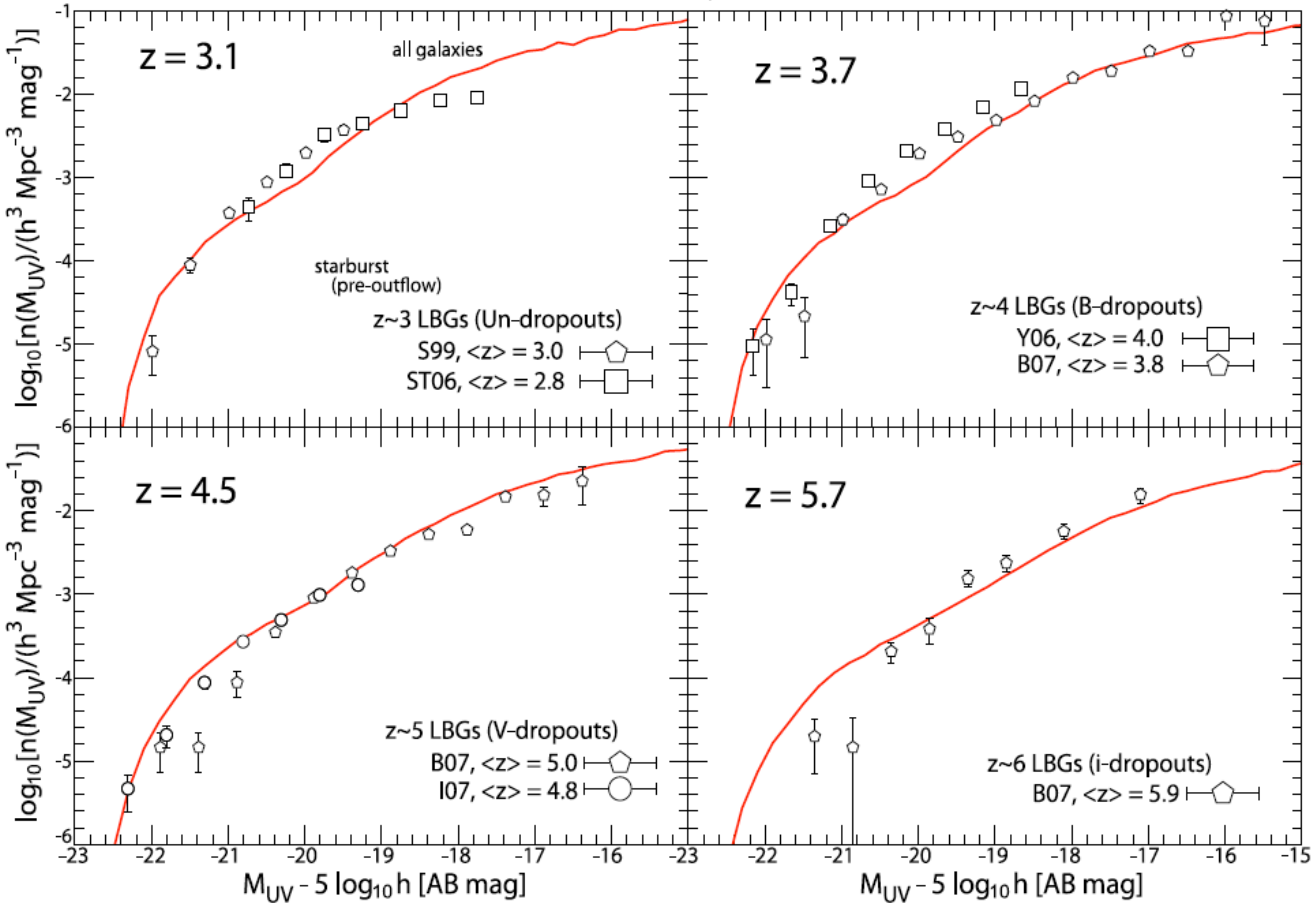
Cycle of Baryons in the galaxy formation



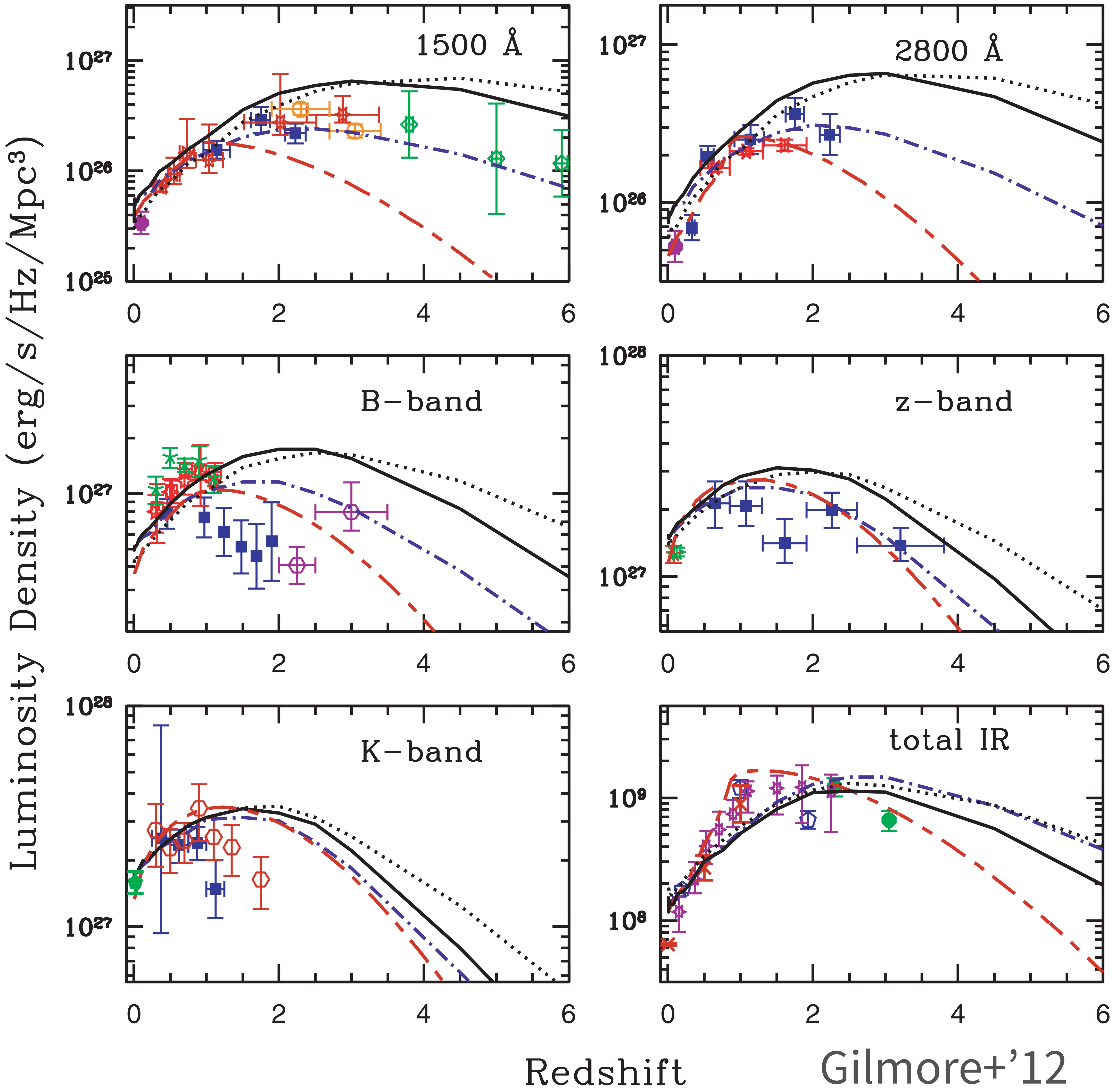
Can the model reproduce the galaxy evolution?

Galaxy Luminosity Functions & Luminosity Densities

UV Luminosity Function



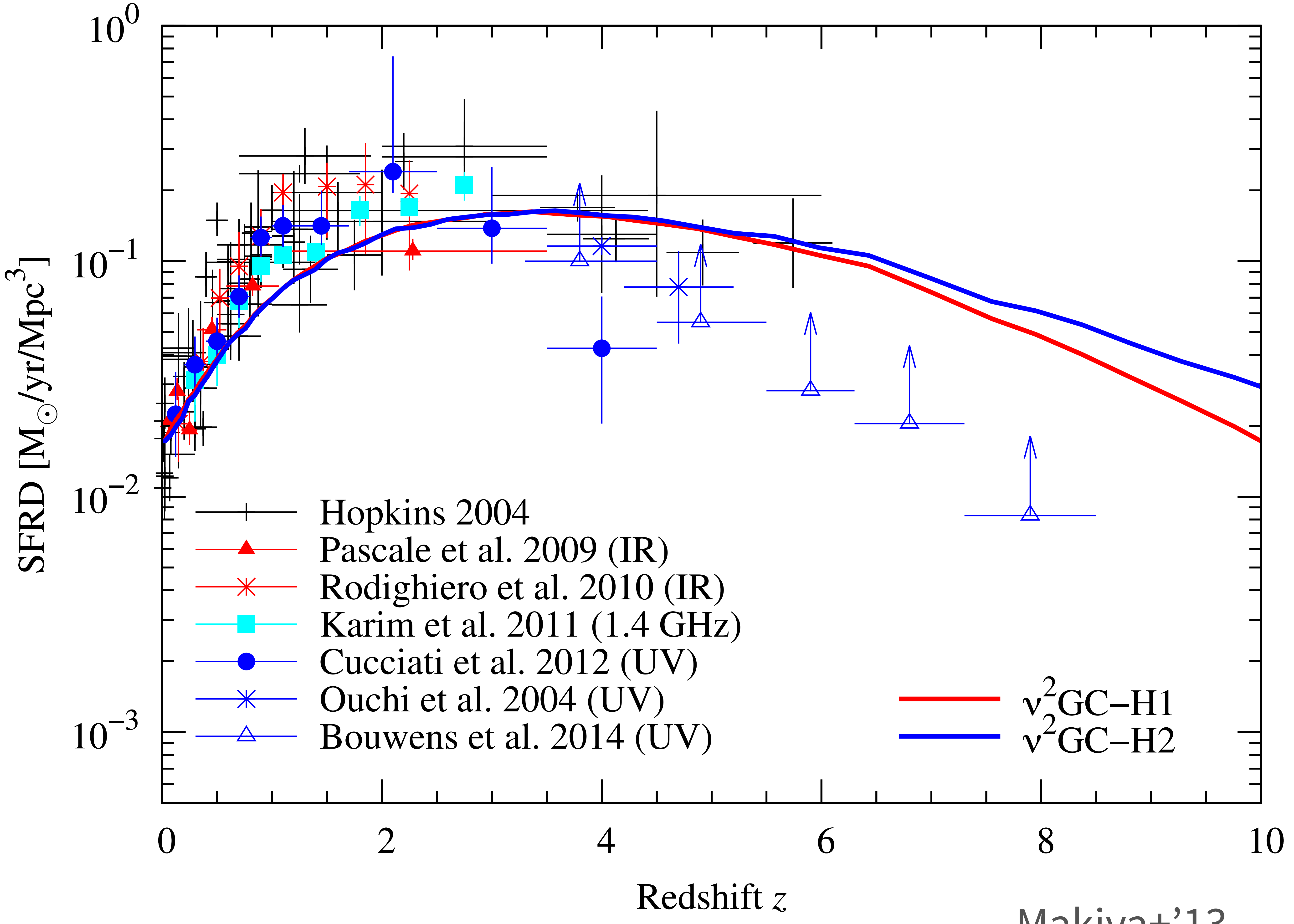
Kobayashi+’10



Gilmore+’12

Can the model reproduce the galaxy evolution?

Cosmic Star Formation History

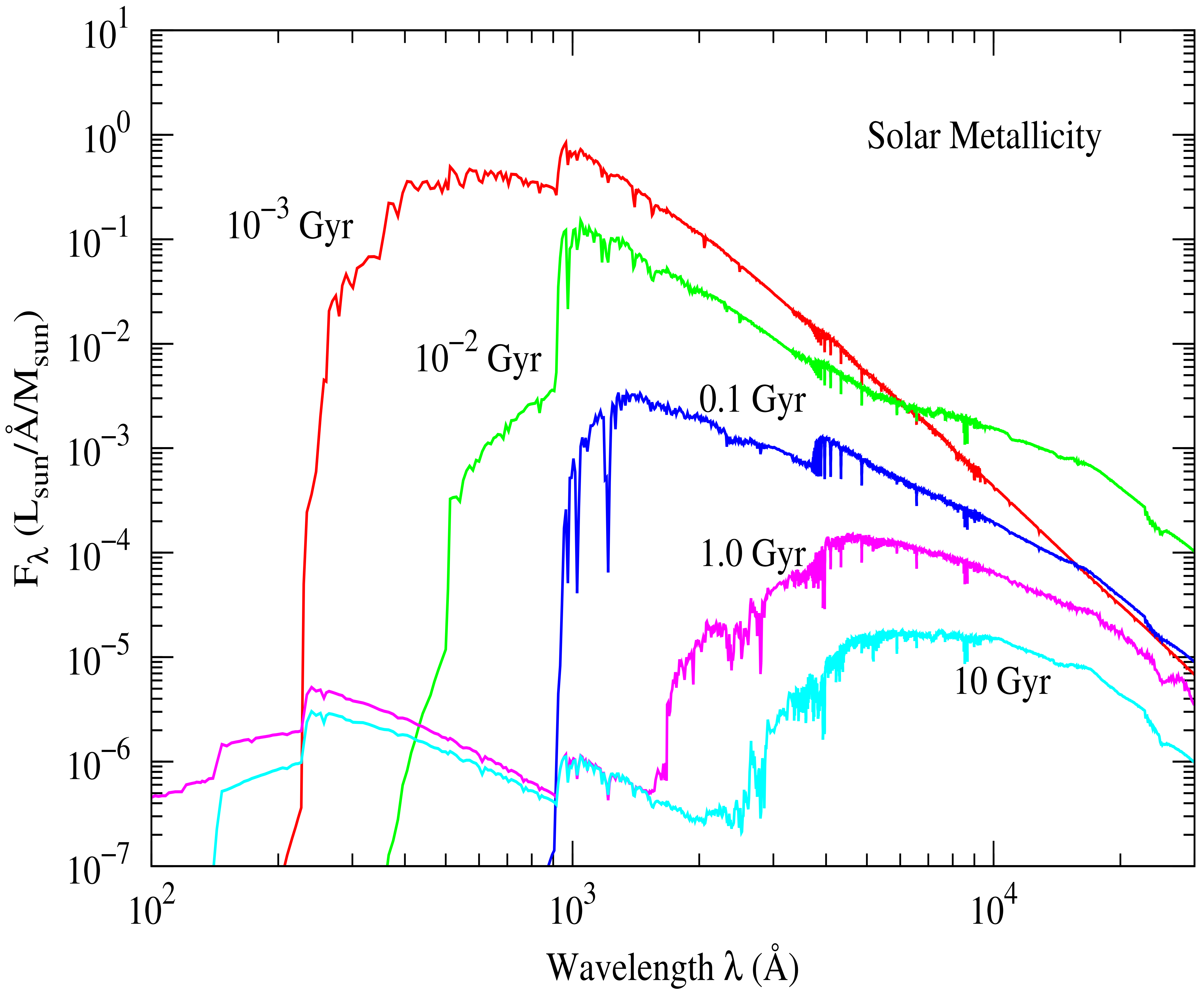


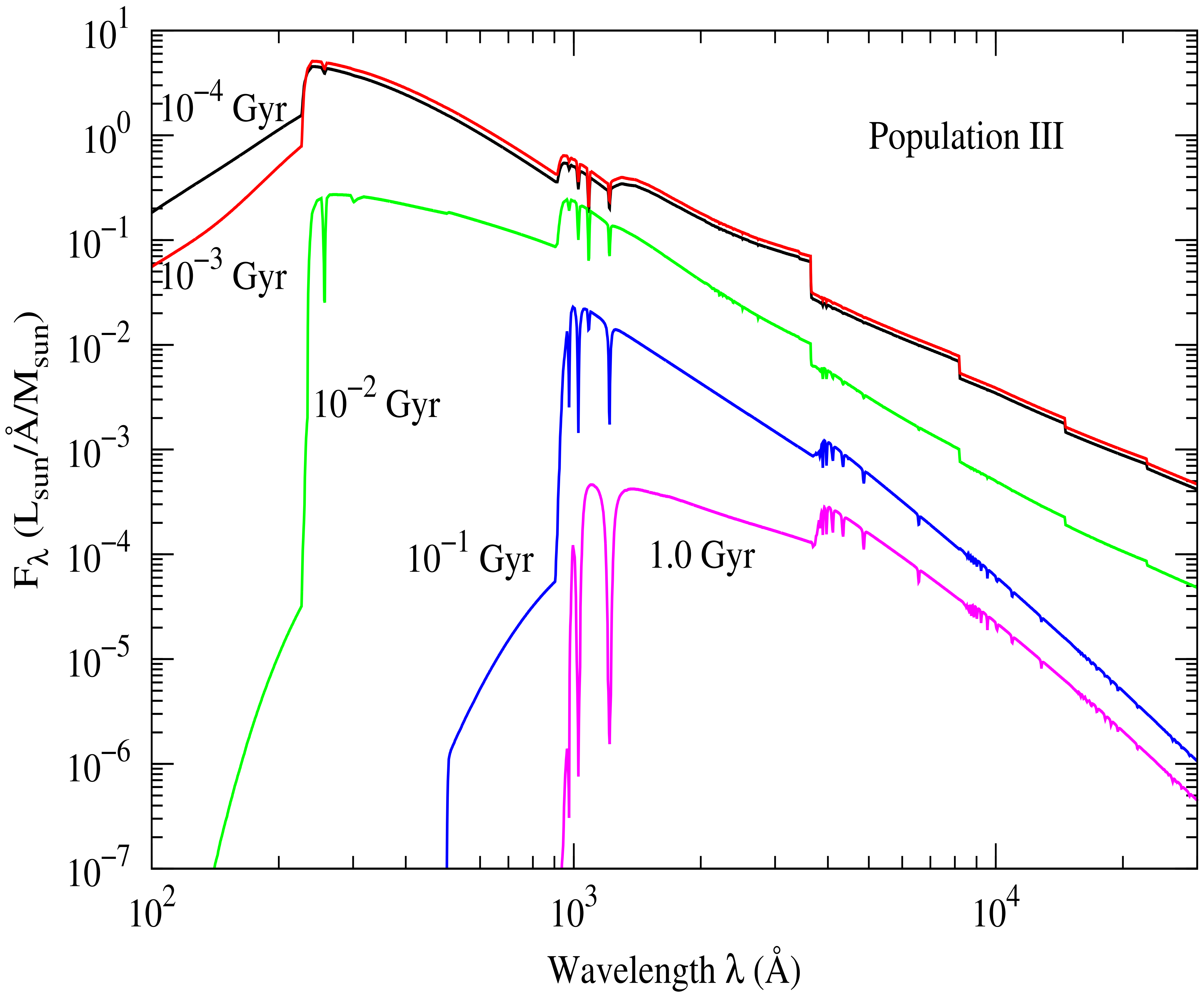
Makiya+'13

- 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,,,)

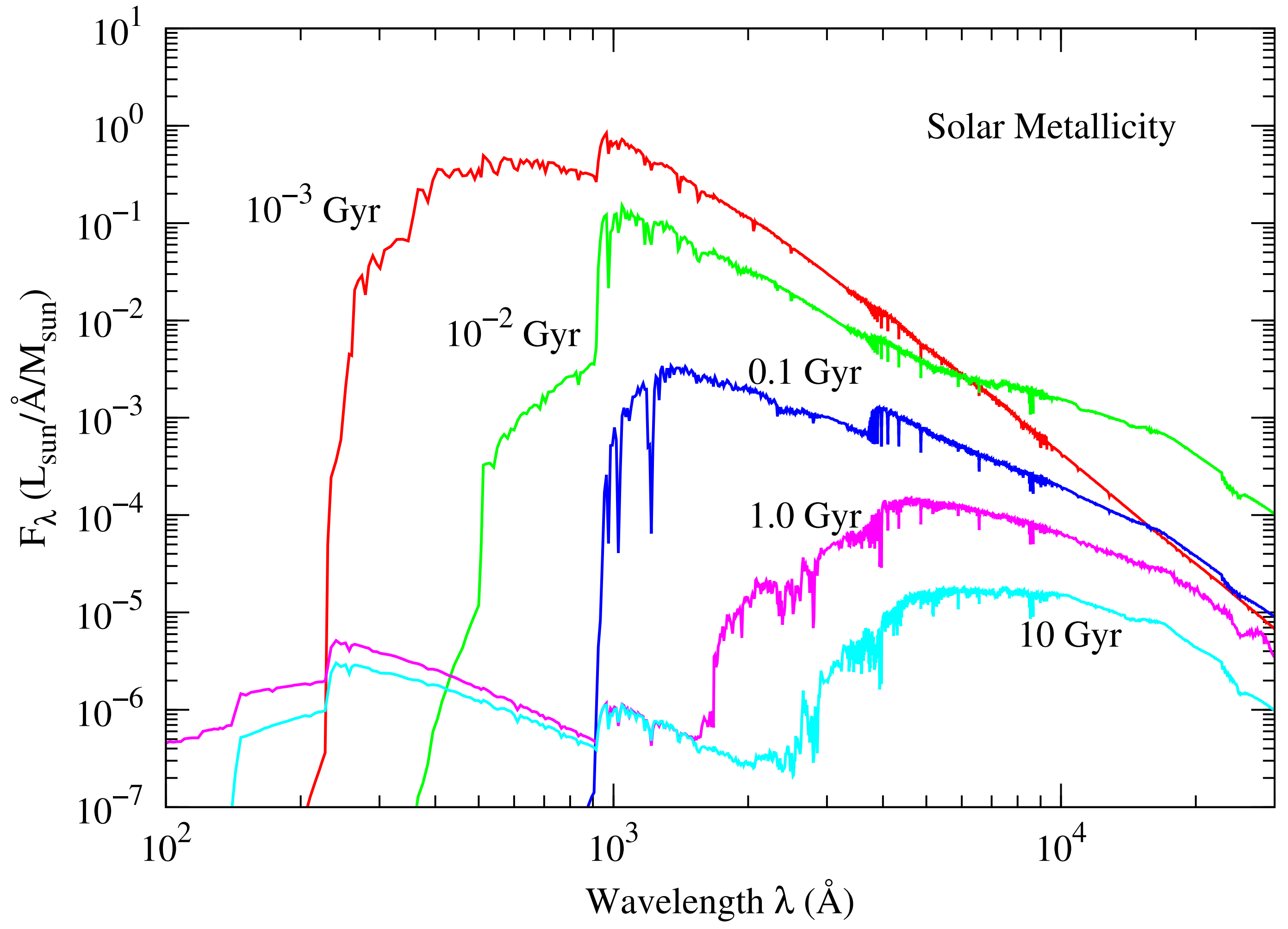


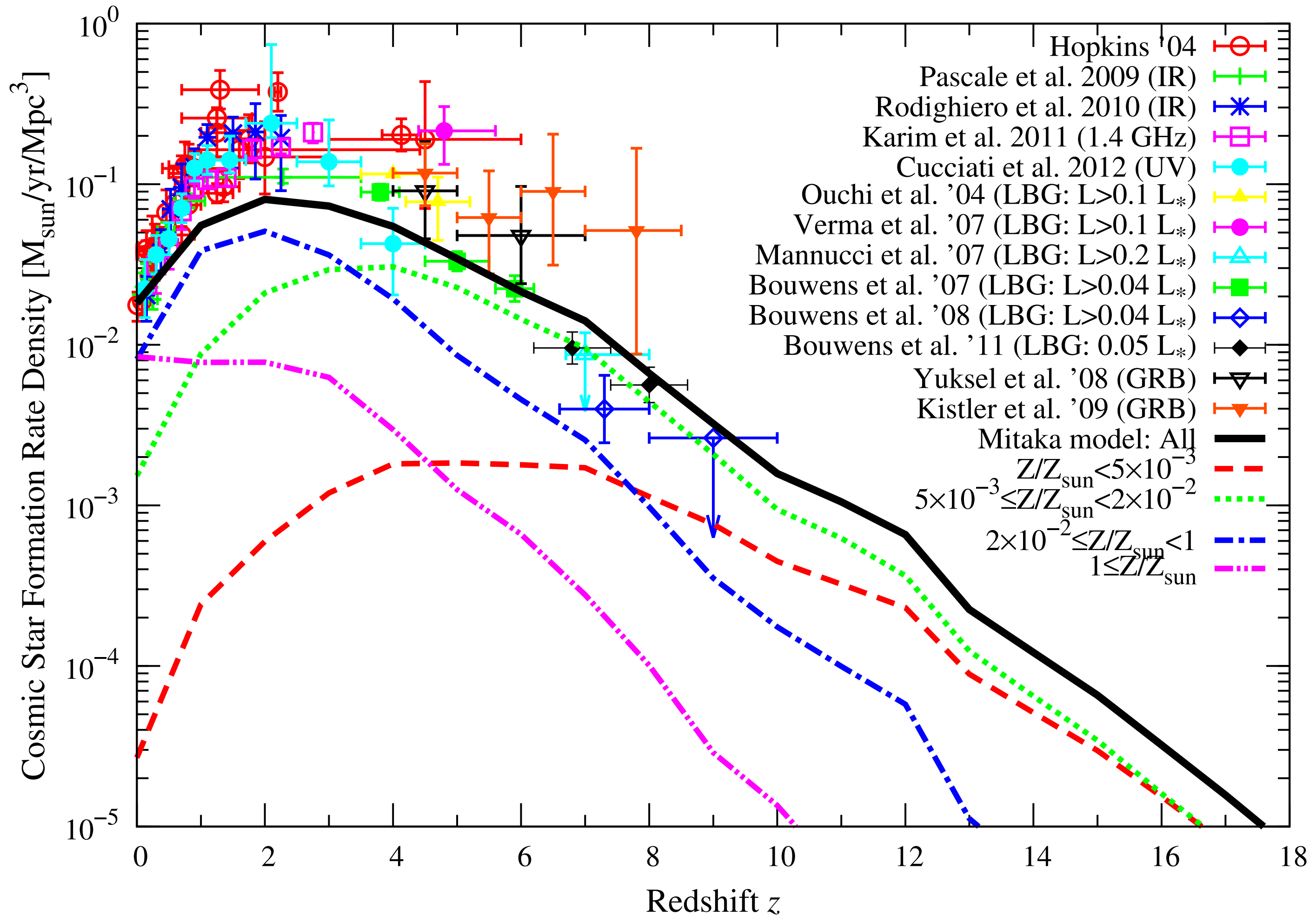


Extragalactic Background Light Spectrum

From Semi-analytical model

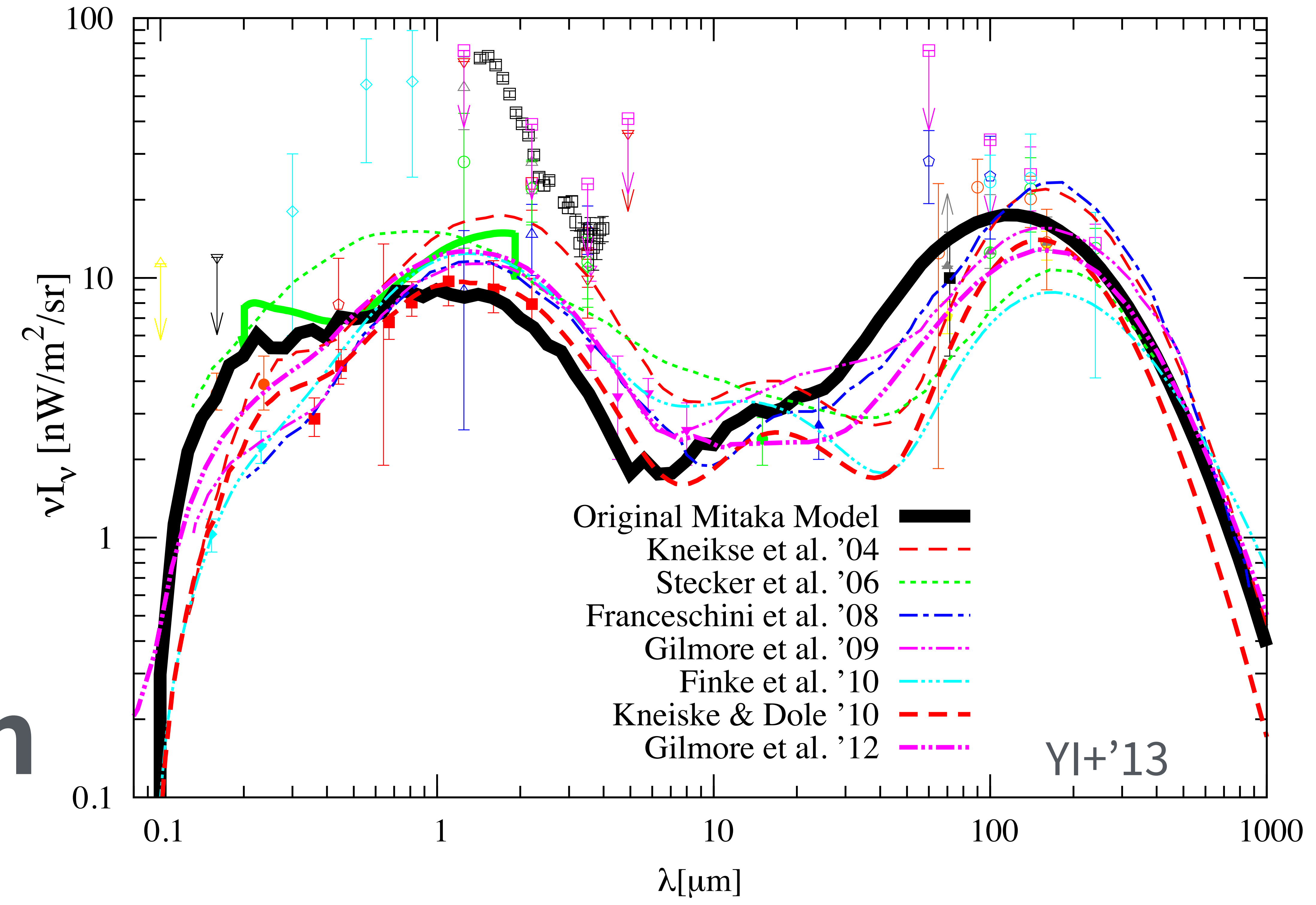
- Semi-analytical model can reproduce the EBL data.
  - Consistent with galaxy counts.





SED

Evolution



Blazar

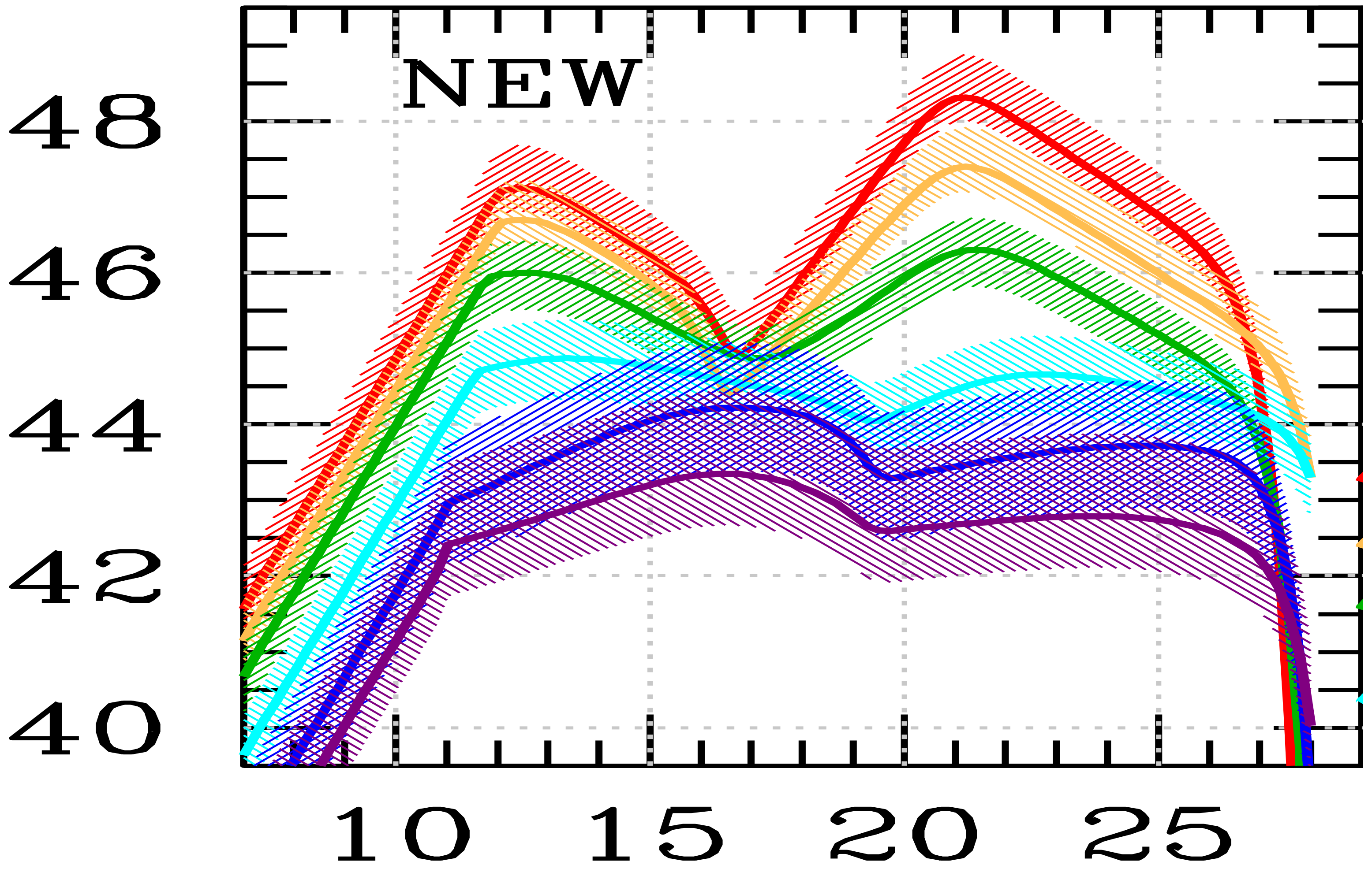
Day 1

~50% of known gamma-ray objects

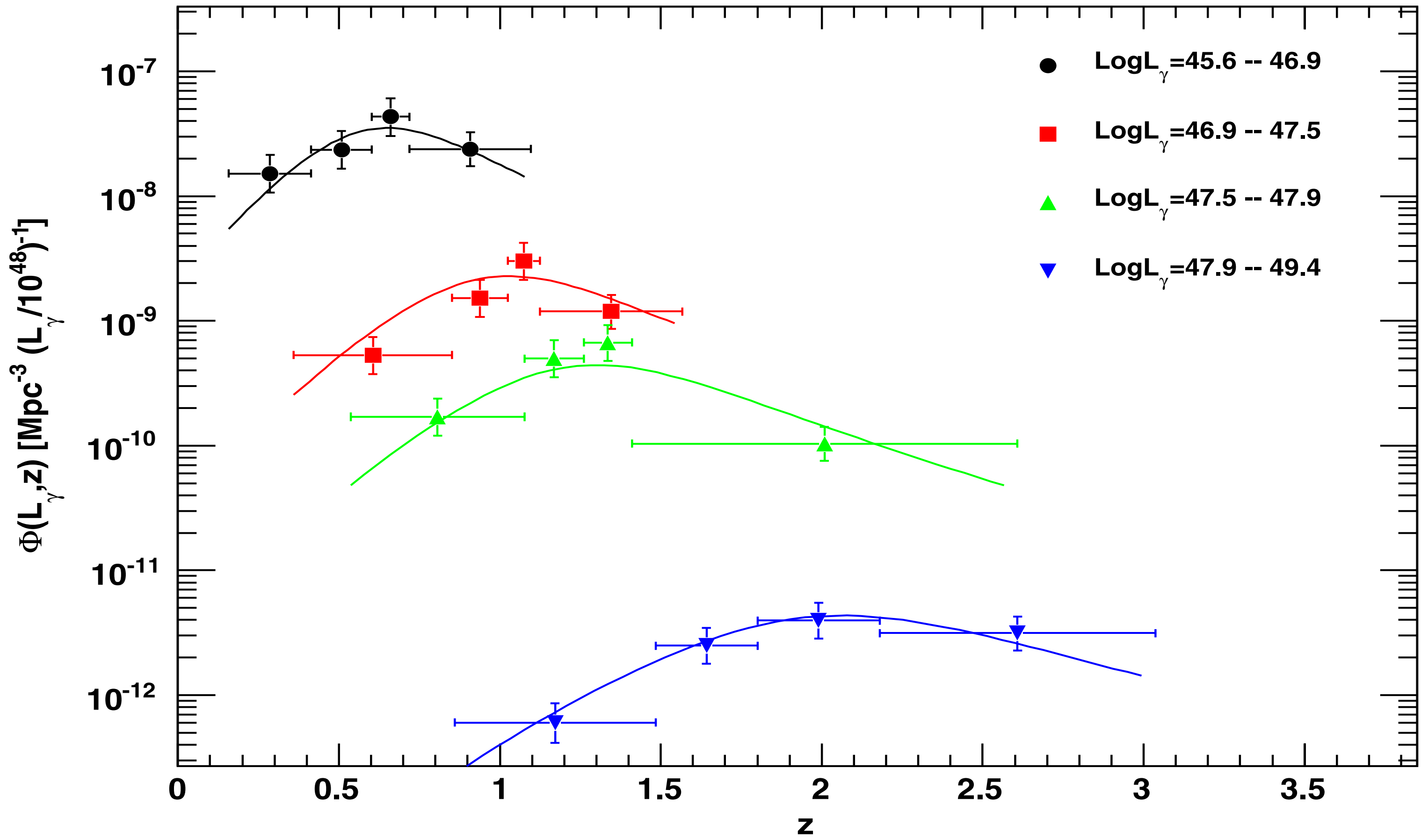
- Blazars have been discussed as the origin for a long time.

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,,,,

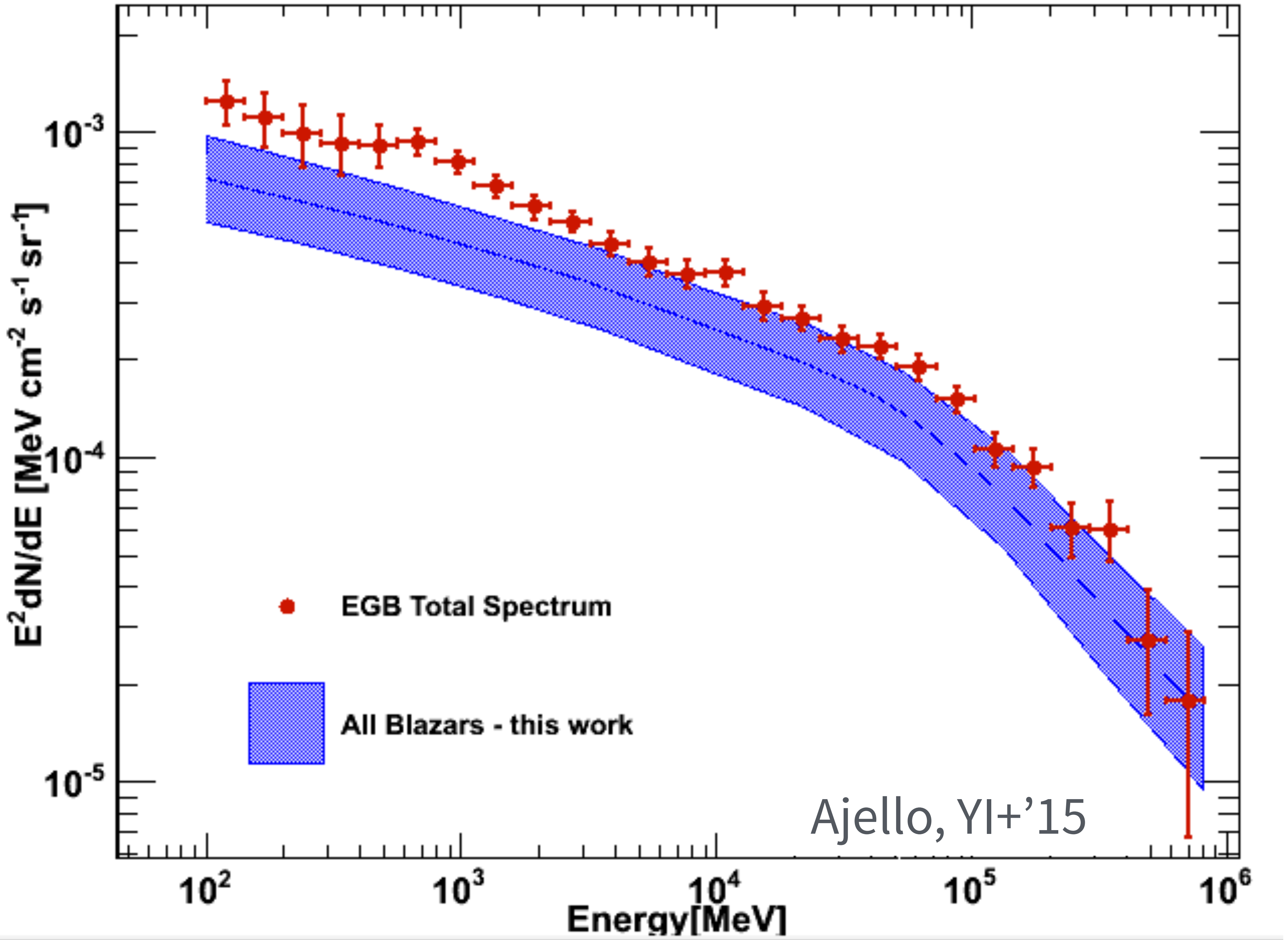
- Now, it turns out ~50%.



SED



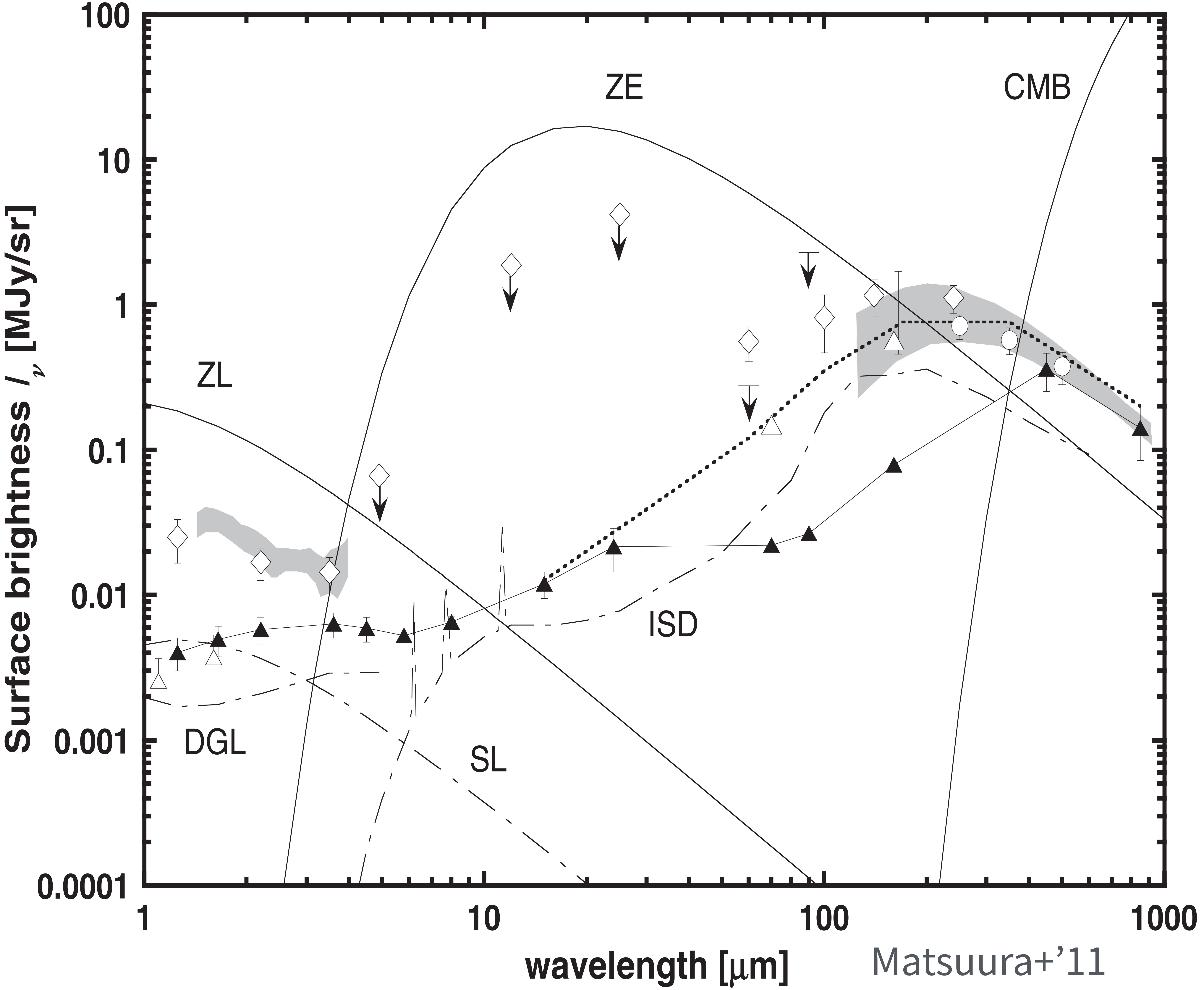
Evolution



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.

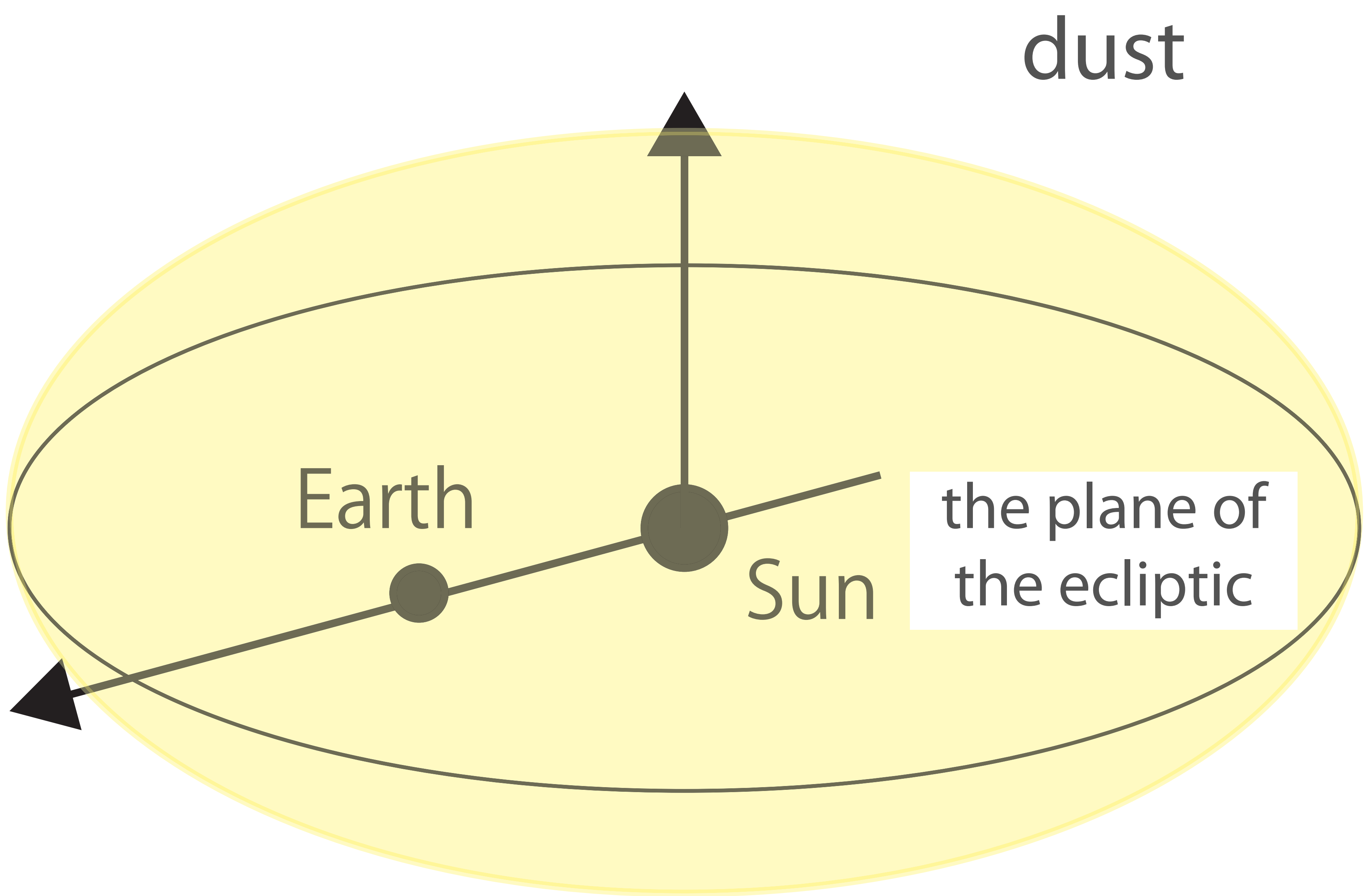


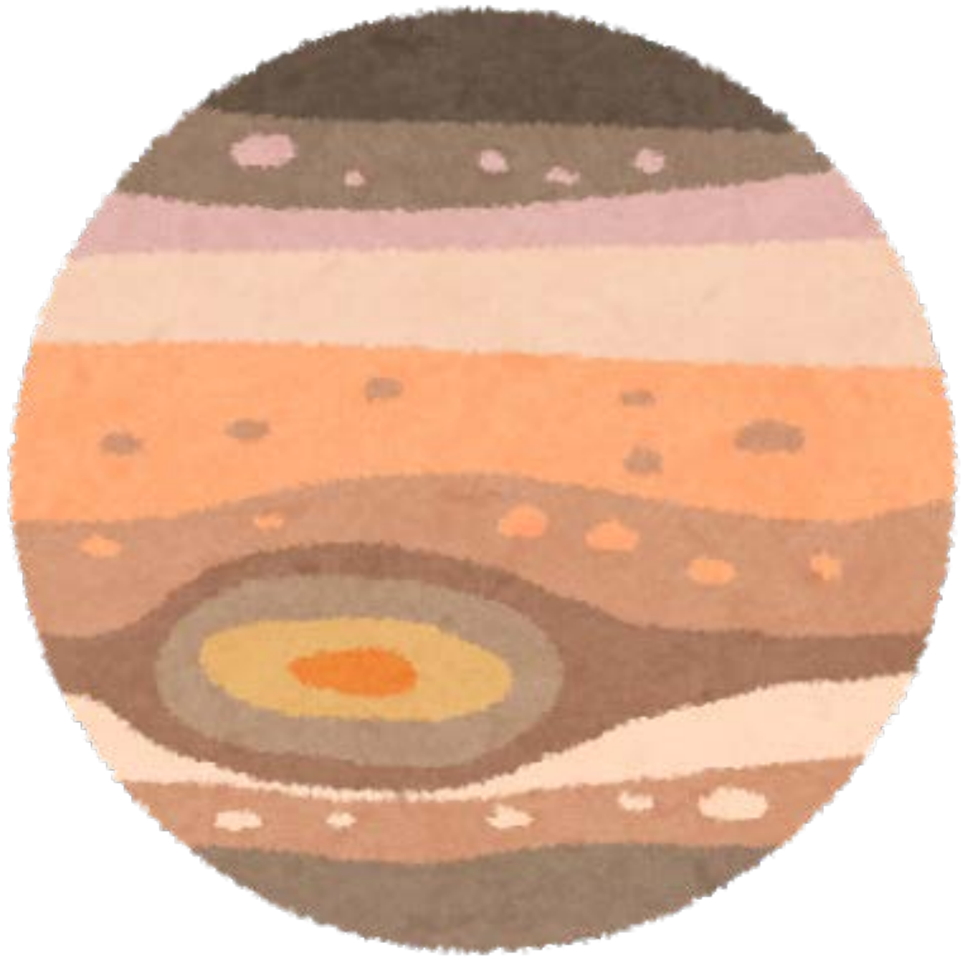
Matsuura+'11

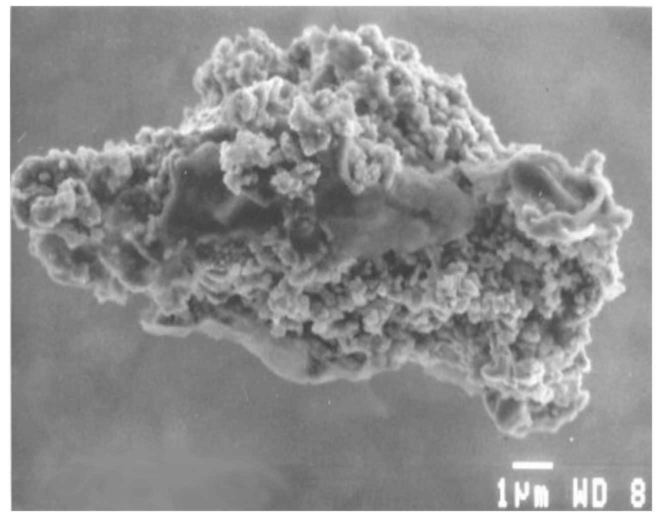
Zodiacal Light

Scattered solar emission by dust

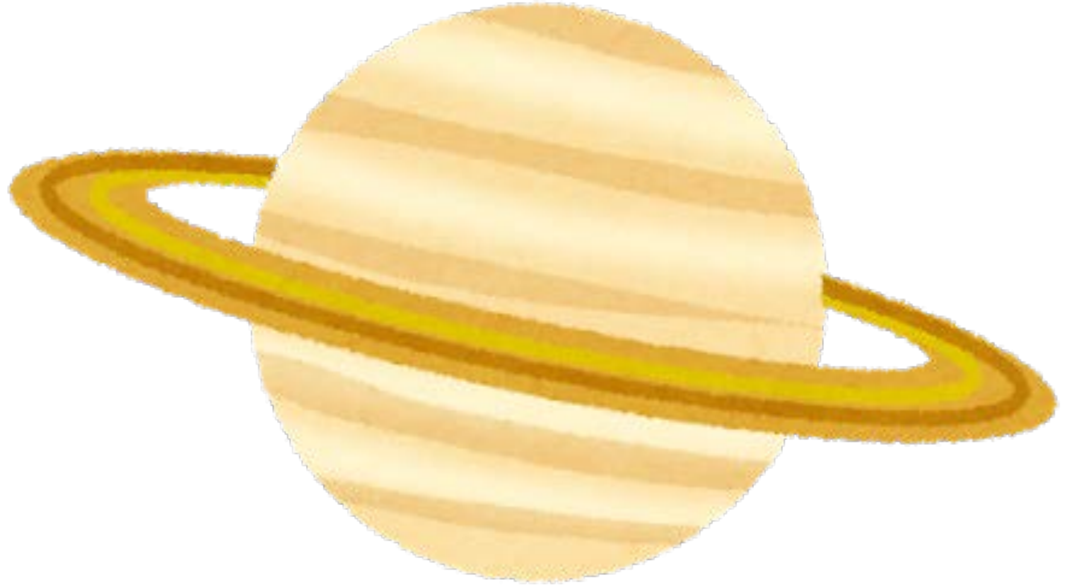
- interplanetary dust between Jupiter and Saturn
- Distribute around the plane of the ecliptic
- Brightest foreground for the EBL measurement

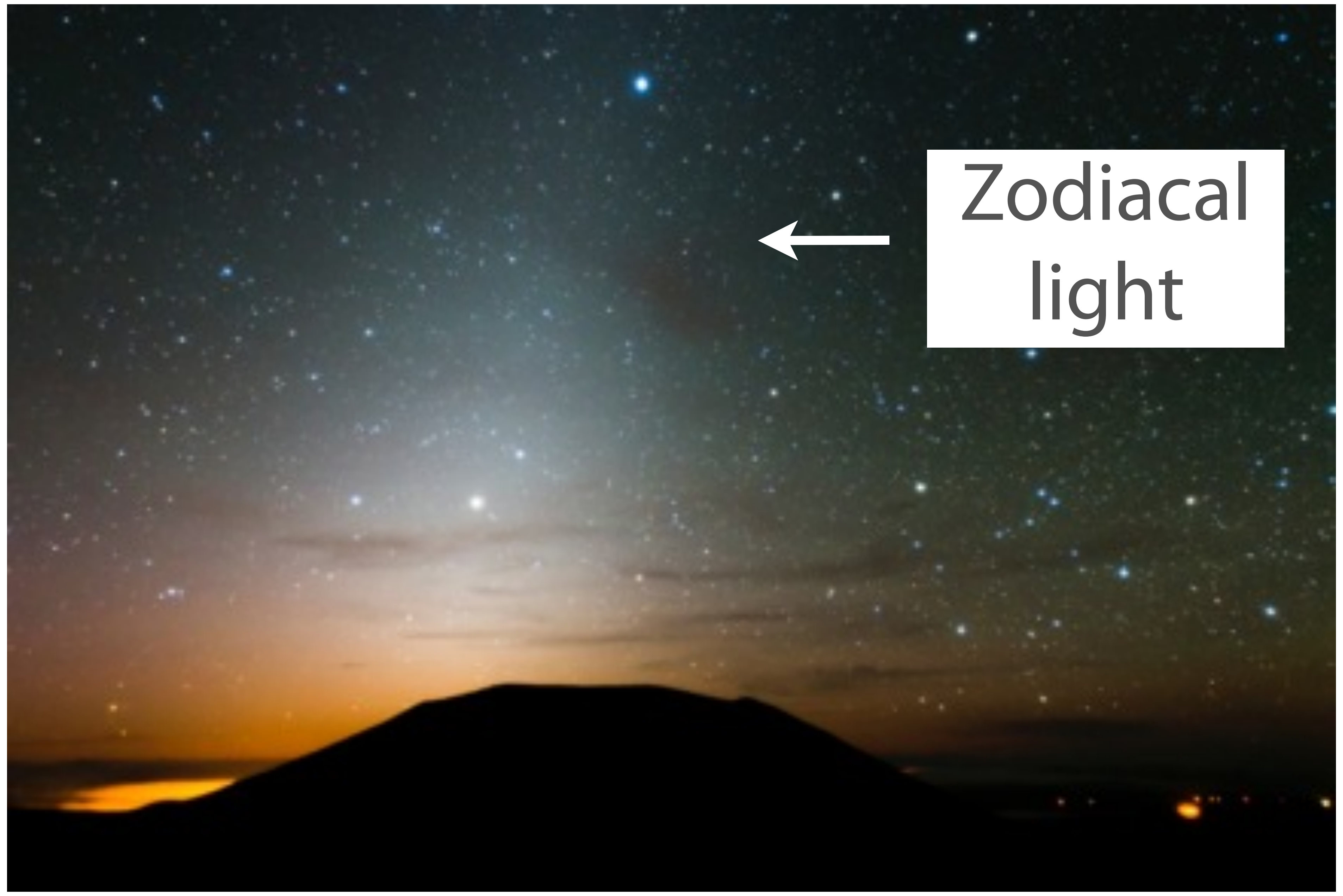






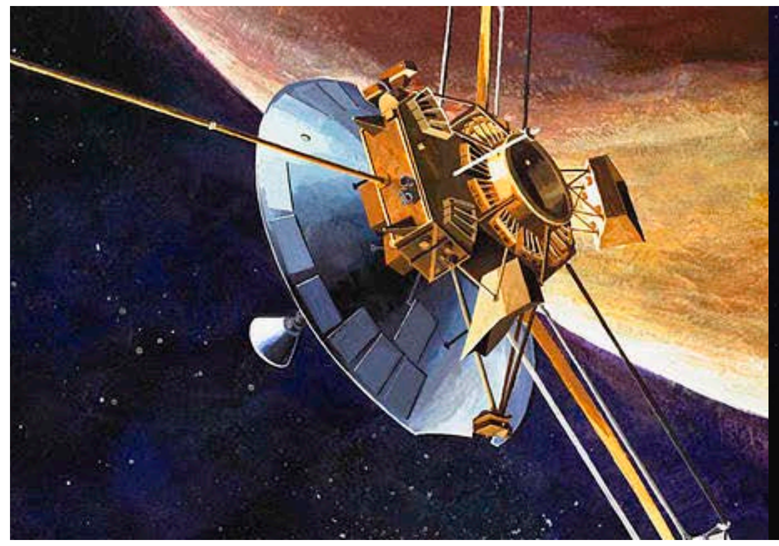
http://spiff.rit.edu/classes/phys230/lectures/ism_dust/ism_dust.html

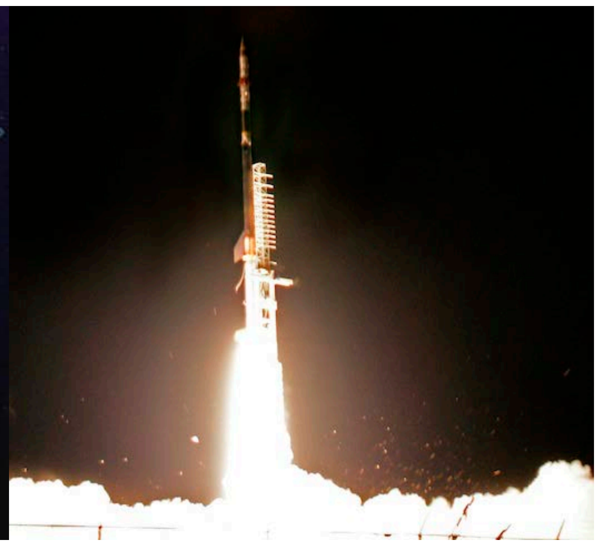


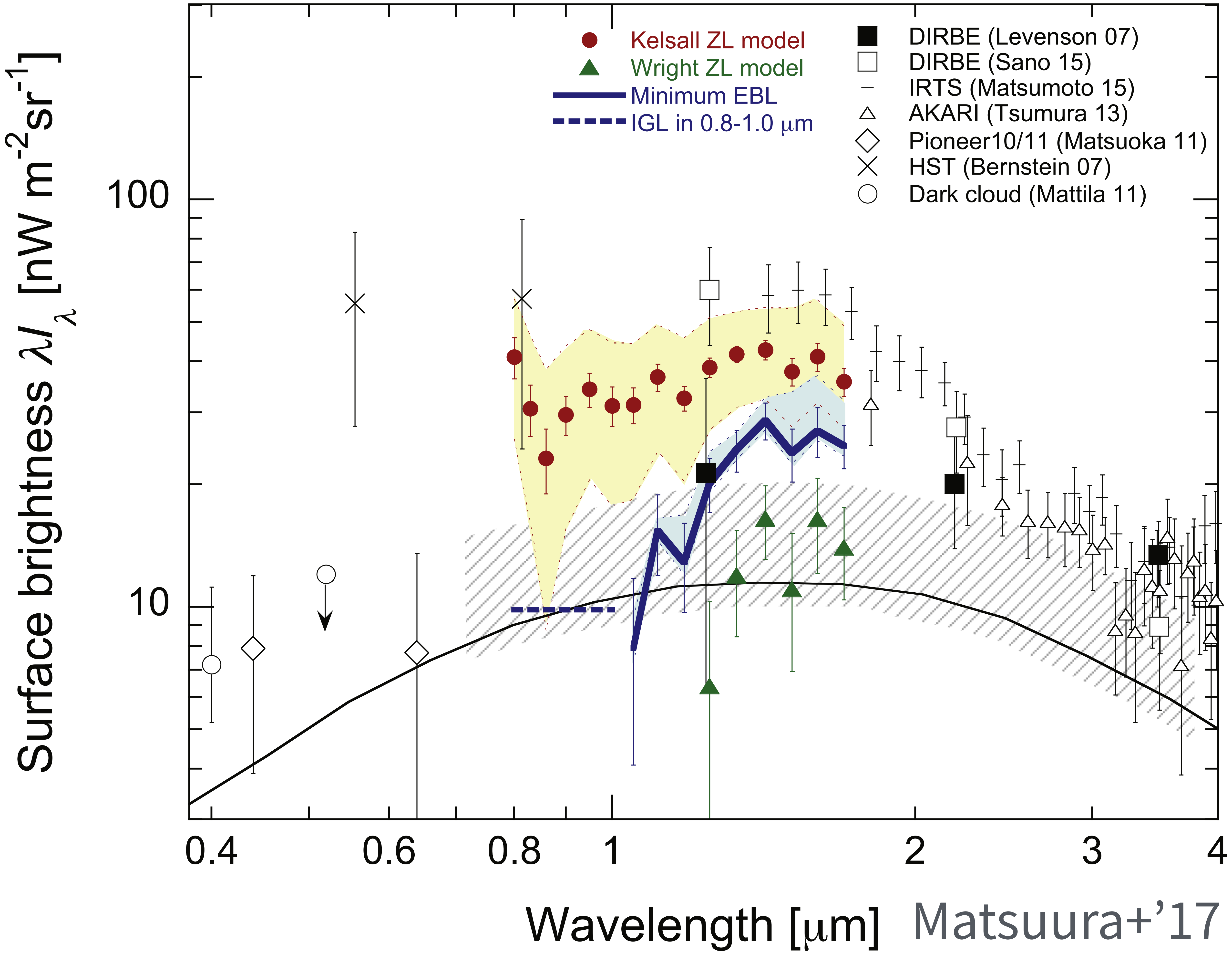


Direct Measurements of EBL

A excess in NIR





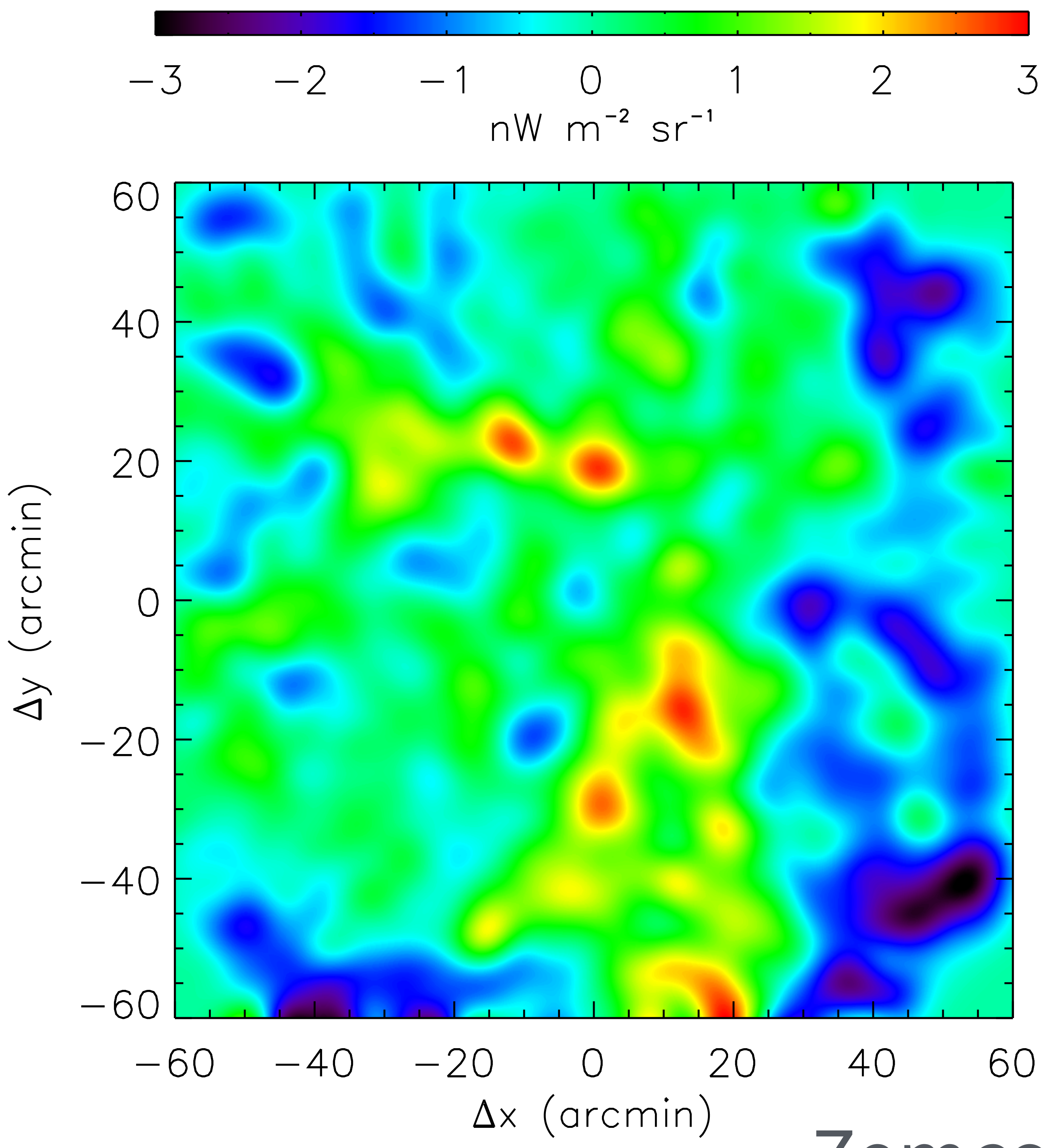


Matsuura+'17

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

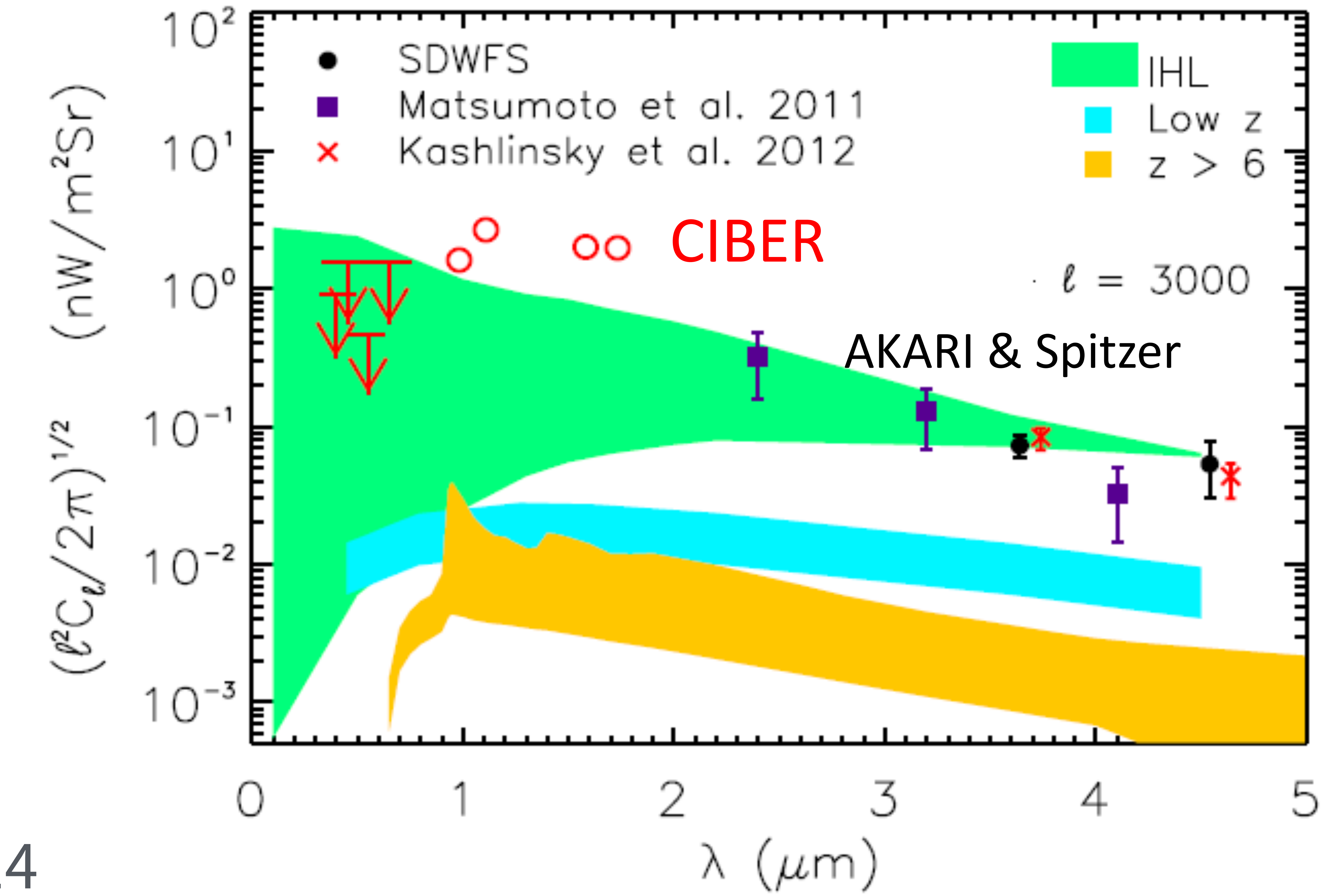
Is the NIR excess in EBL real?

Excess also in the angular power spectrum



Zemcov+’14

Cooray et al. *Nature*, 2012

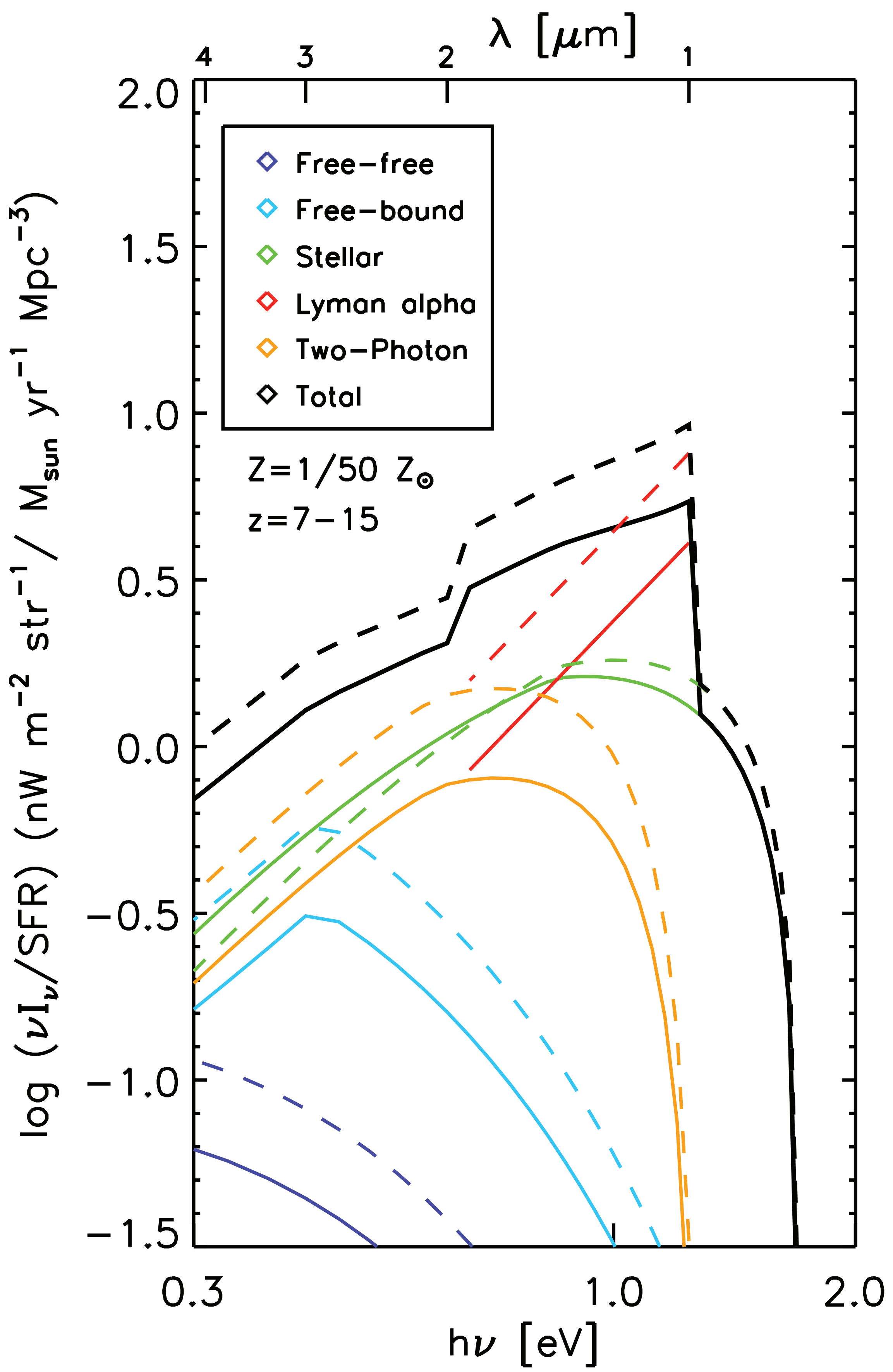


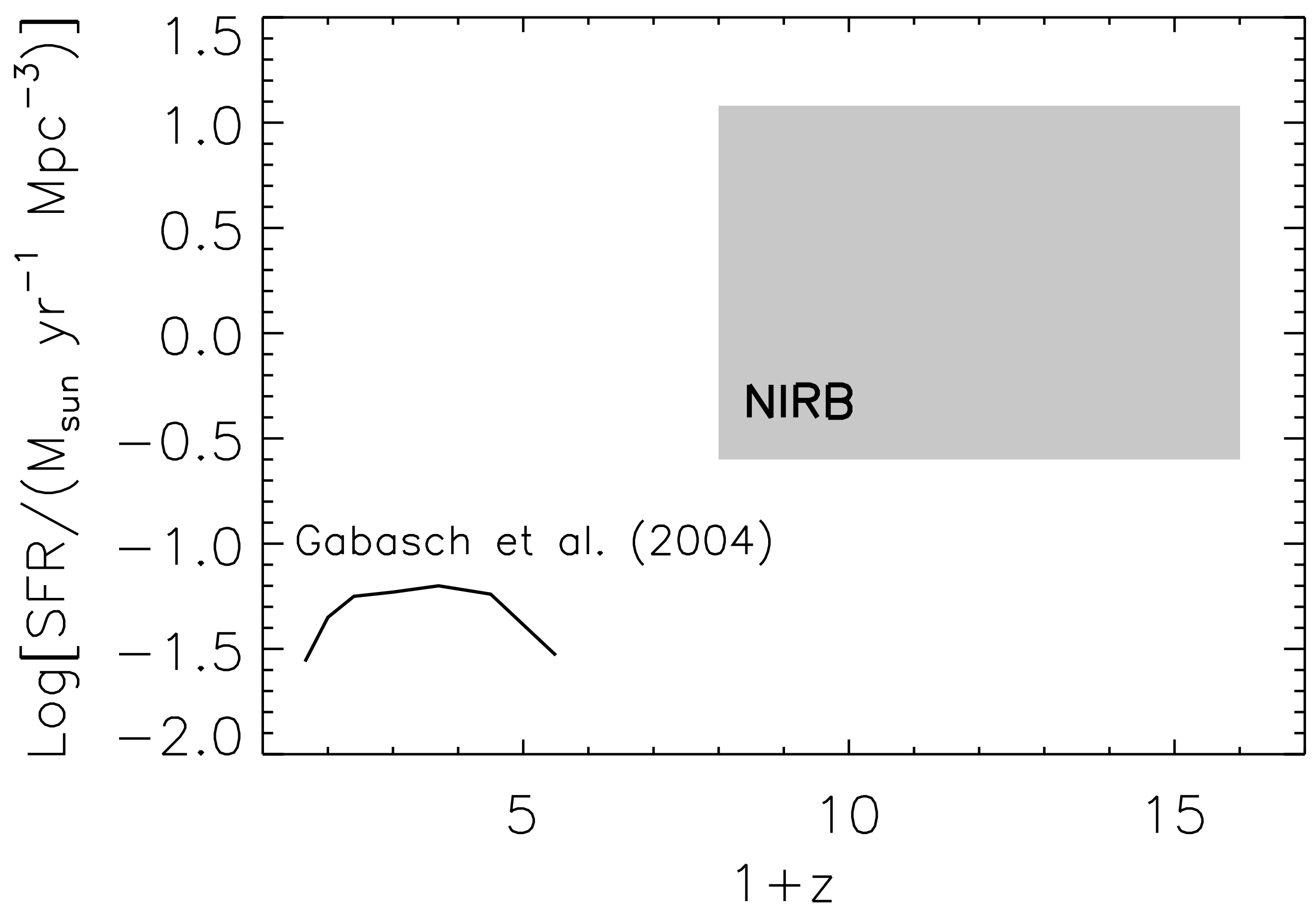
- A large scale fluctuation in the NIR sky (Kashlinsky+’05, ’07, ’12, Matsumoto+’11, Cooray+’12, zemcov+’15).
- Galaxies can not explain this excess.
  - Intrahalo stars (Cooray+’12)?

What makes the NIR excess in EBL?

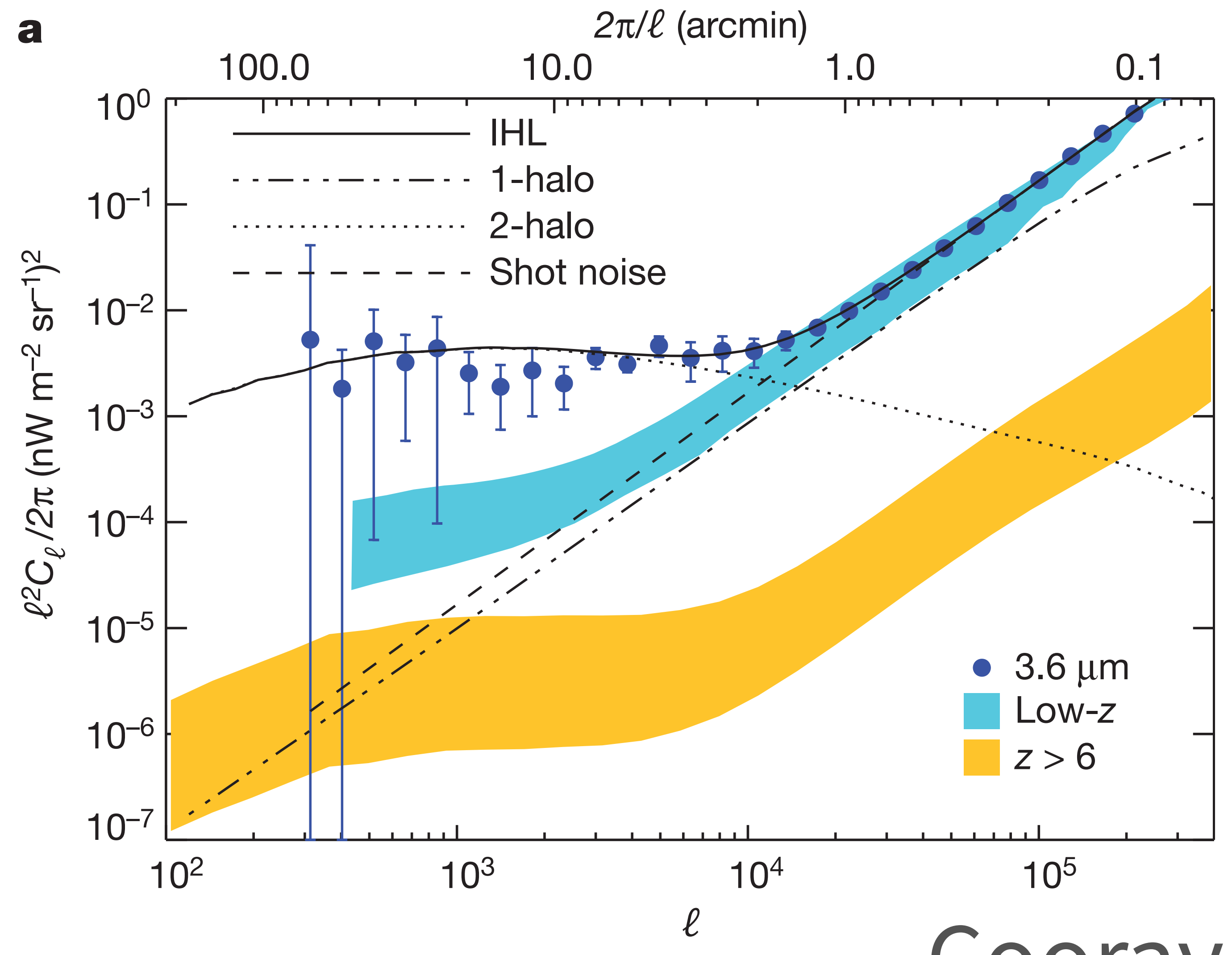
First Stars? Intra-Halo Stars?

- 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

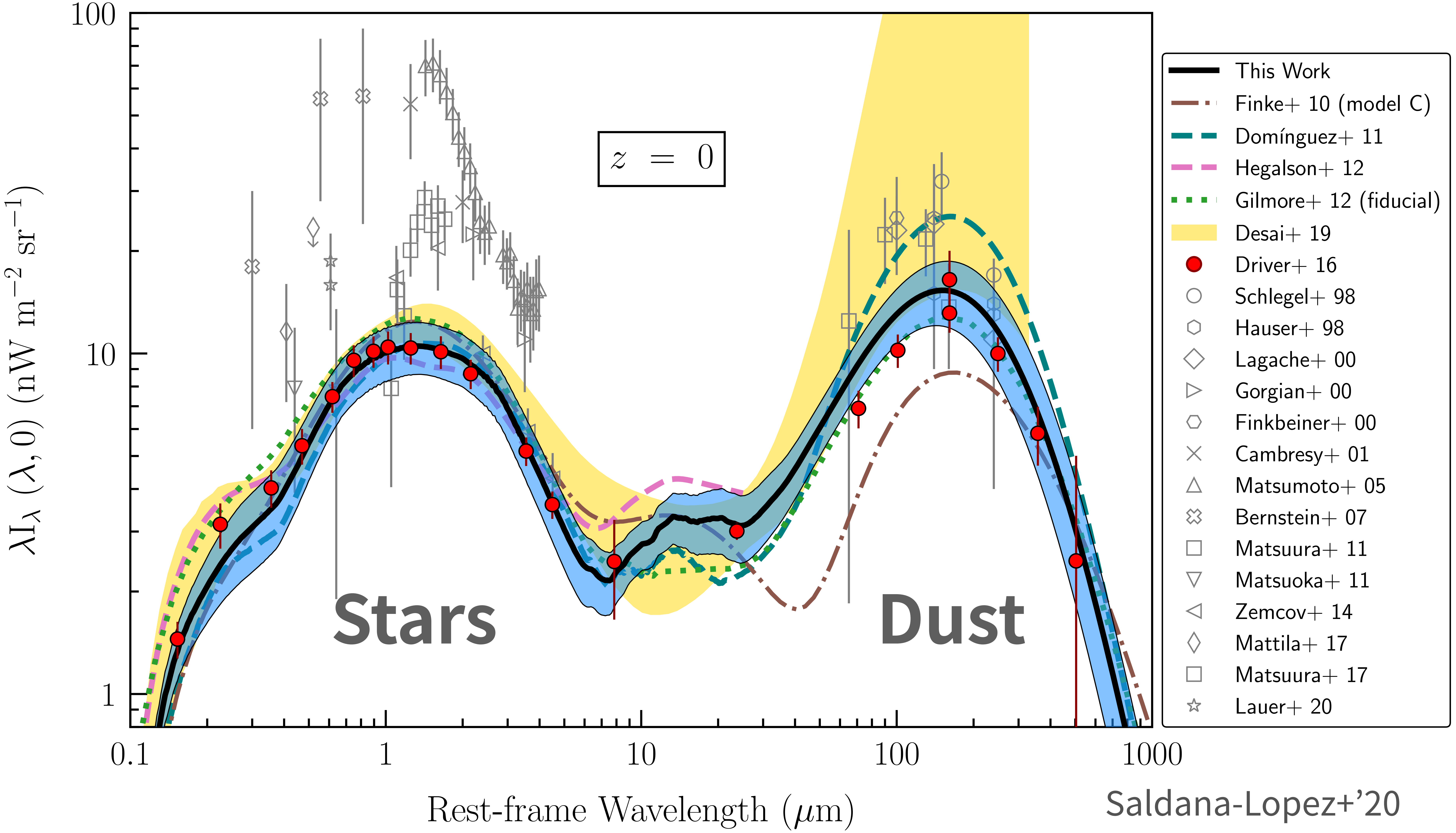


Cooray+'12

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

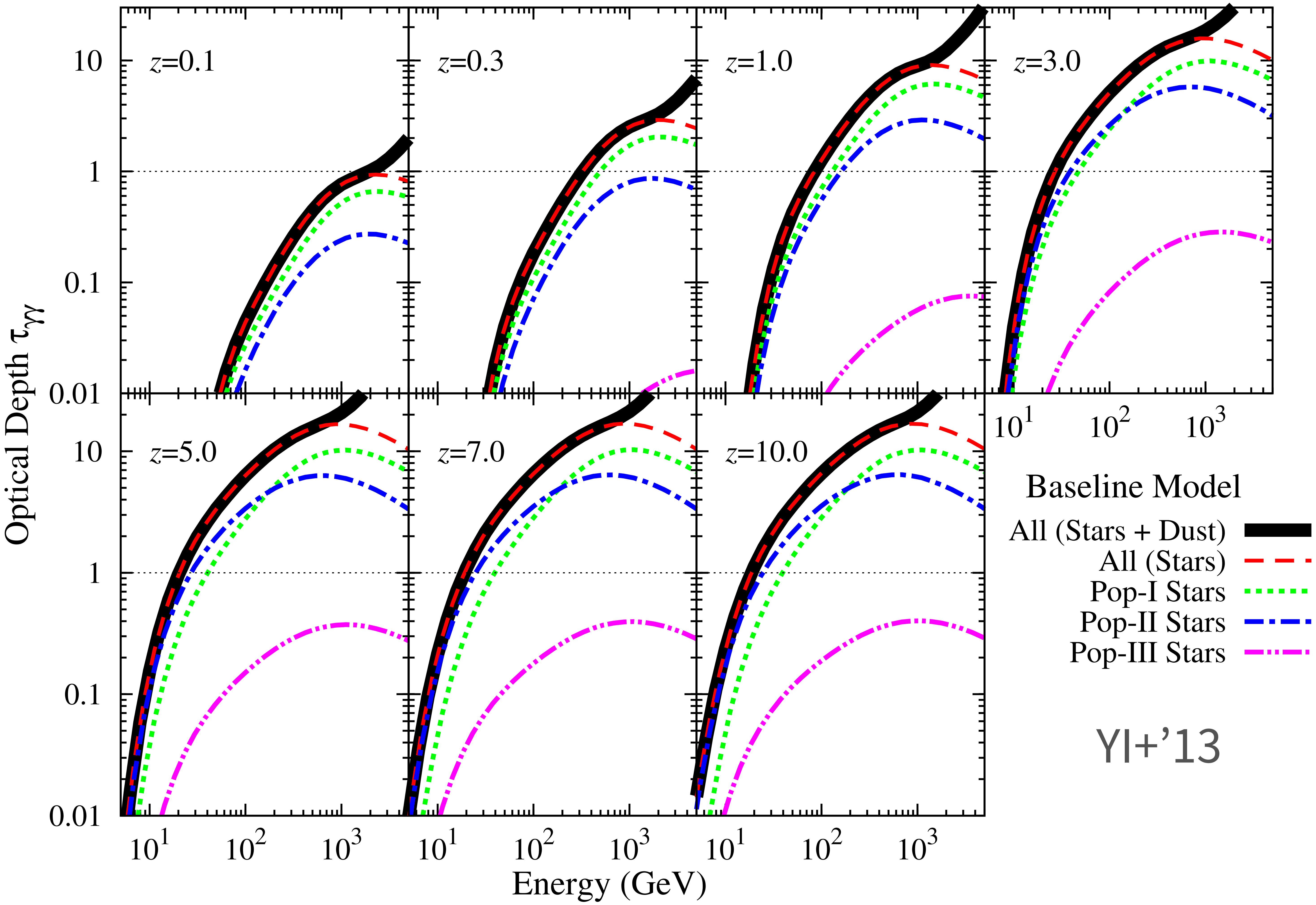
- The opacity is given as

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

- 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

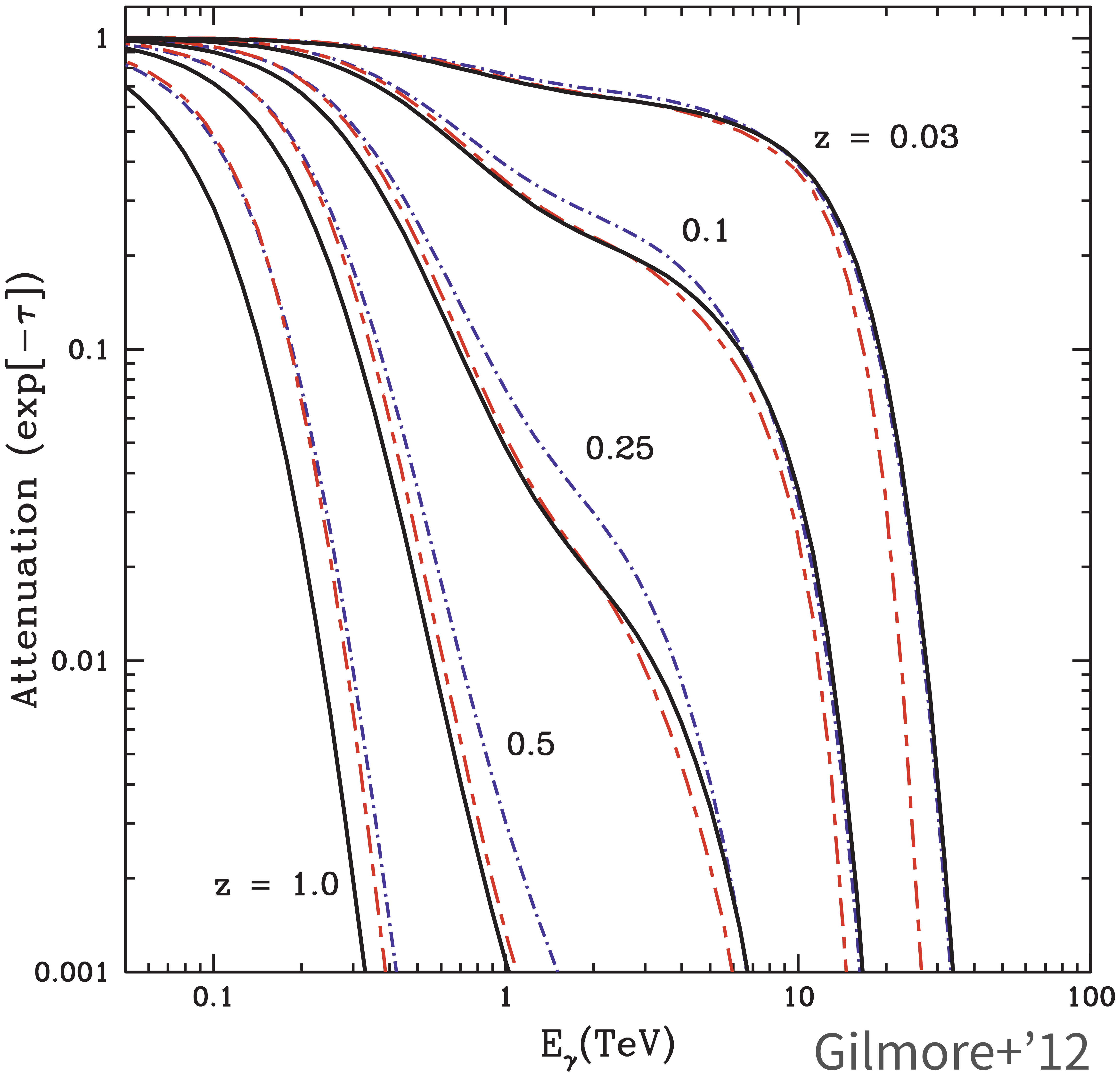
Expected attenuation features

Exponential cutoff in the VHE band

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

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

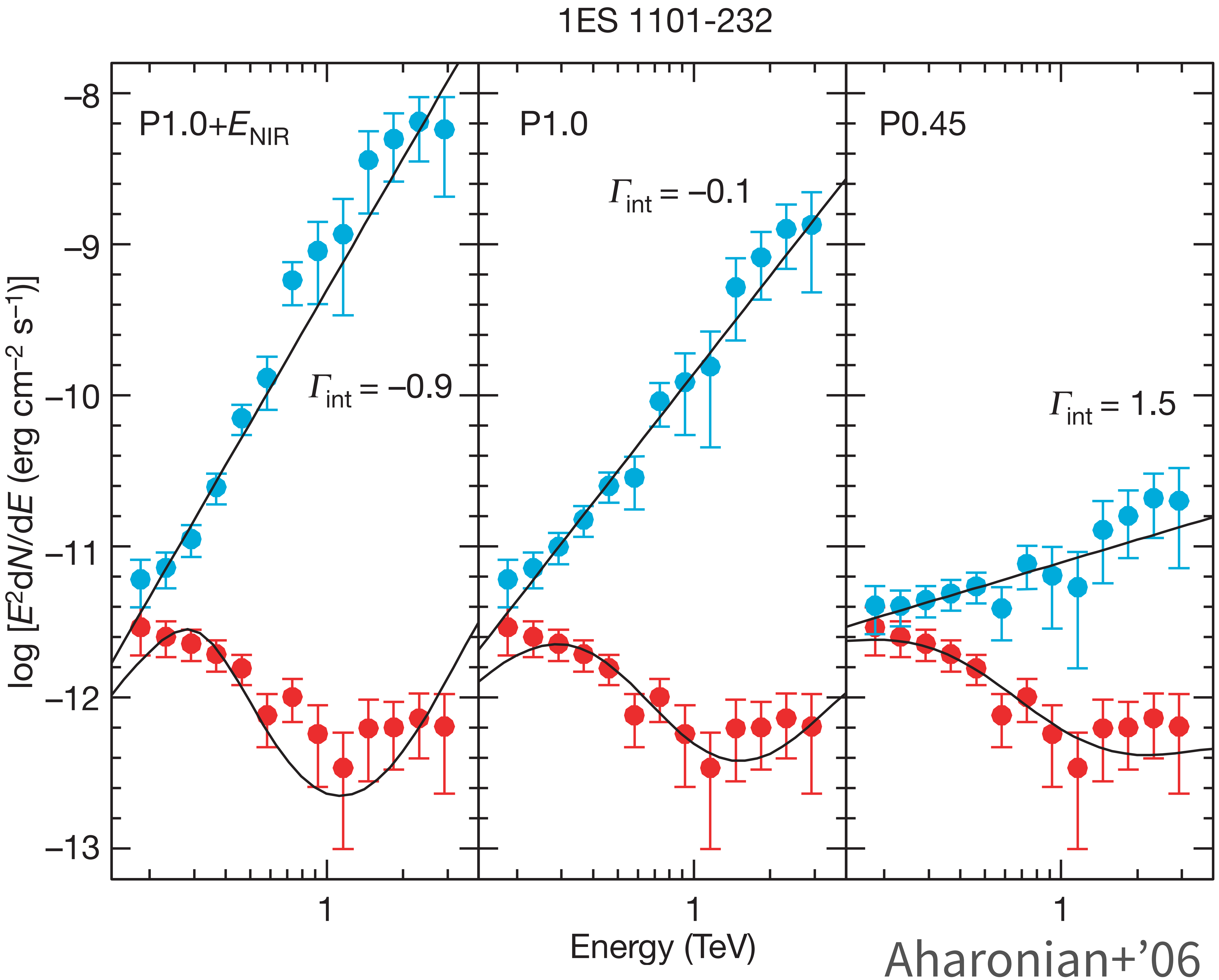
- Energy $\nearrow$ + $z \nearrow \Rightarrow \tau_{\gamma\gamma} \nearrow \Rightarrow$ Flux $\searrow$



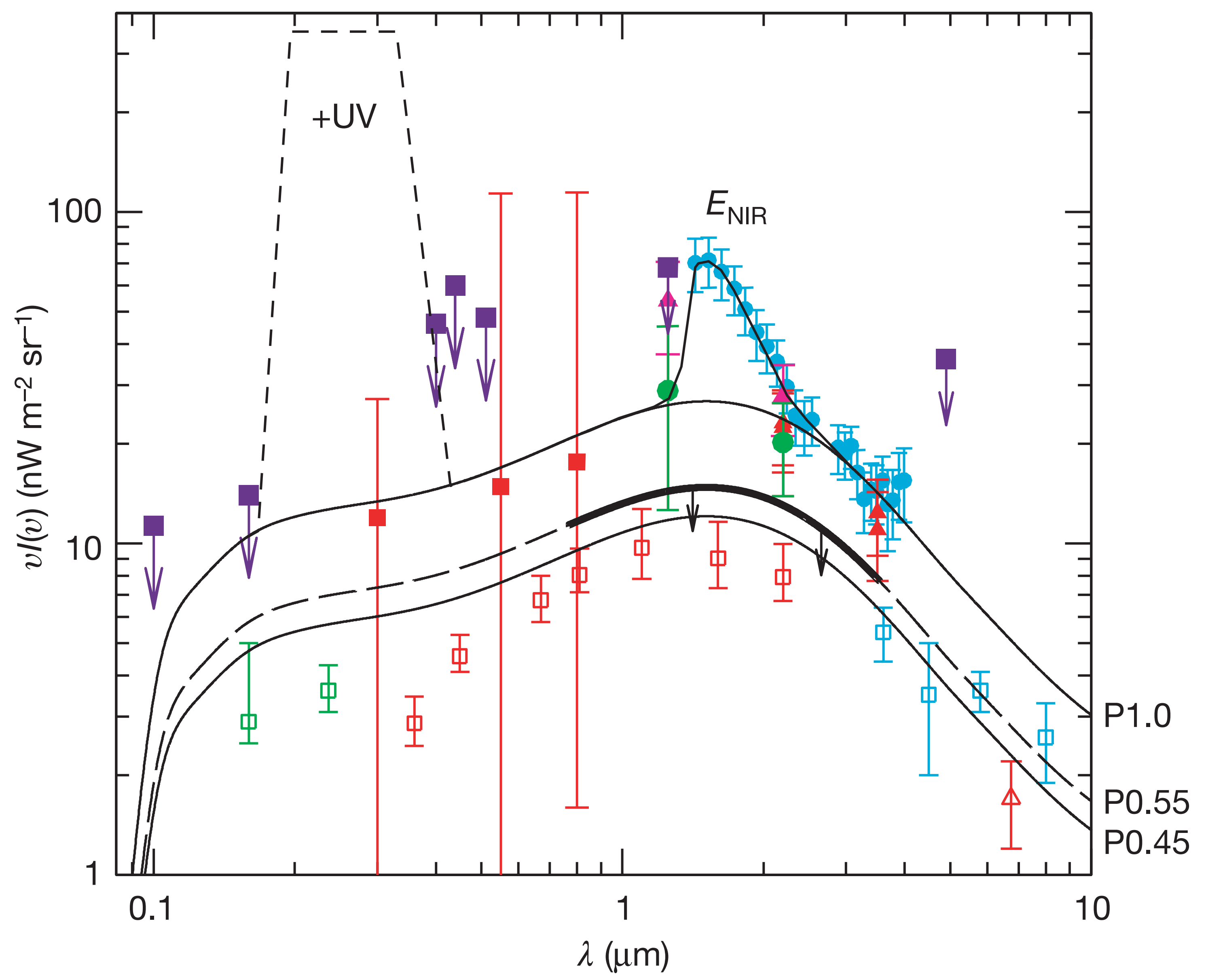
Gilmore+'12

Reconstruction of EBL using gamma-ray blazars

Let's assume the intrinsic spectral shape



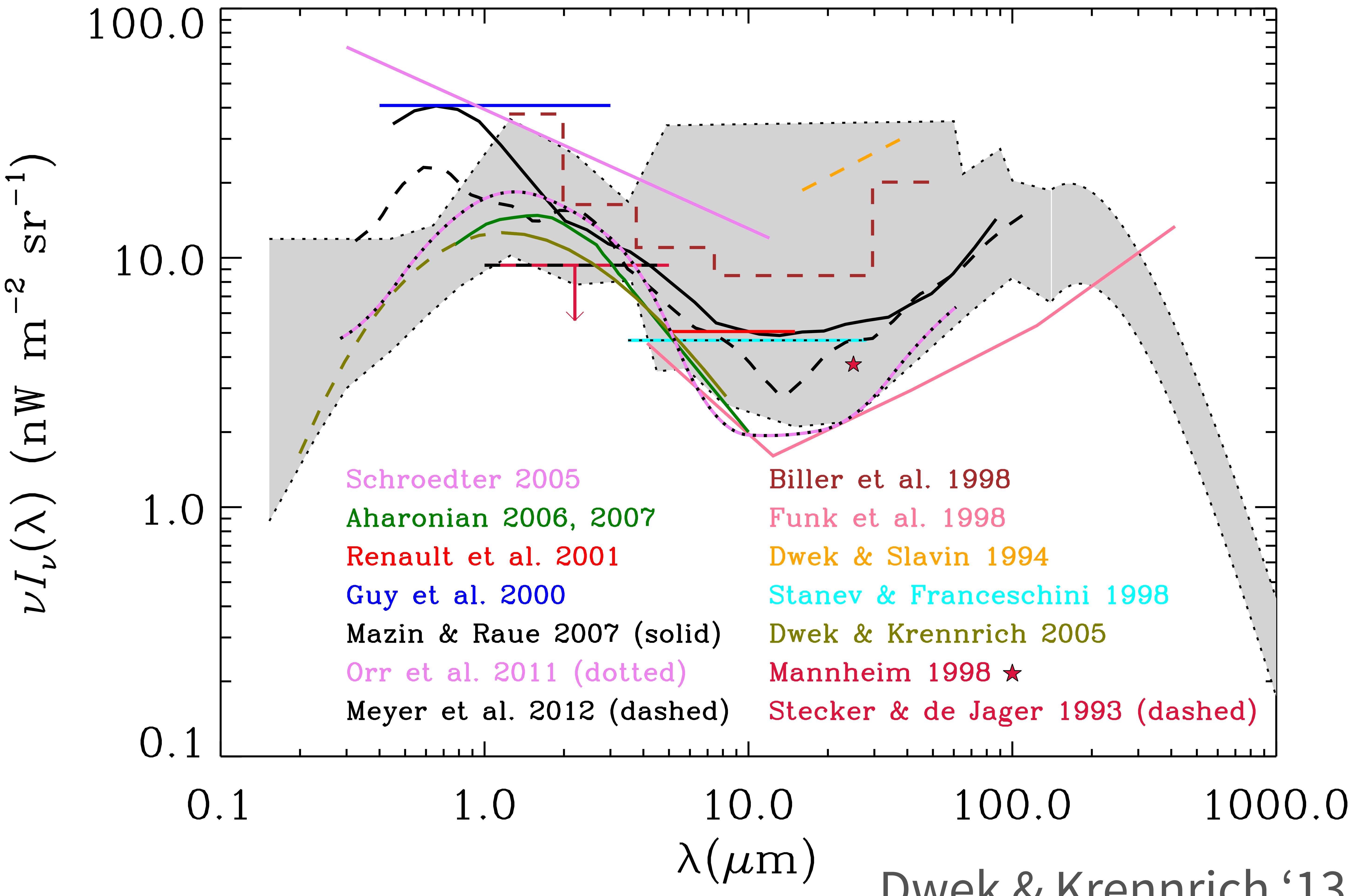
Aharonian+'06



- 😀 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.

Cosmological Aspects of High Energy Astrophysics ~ Day 4 ~

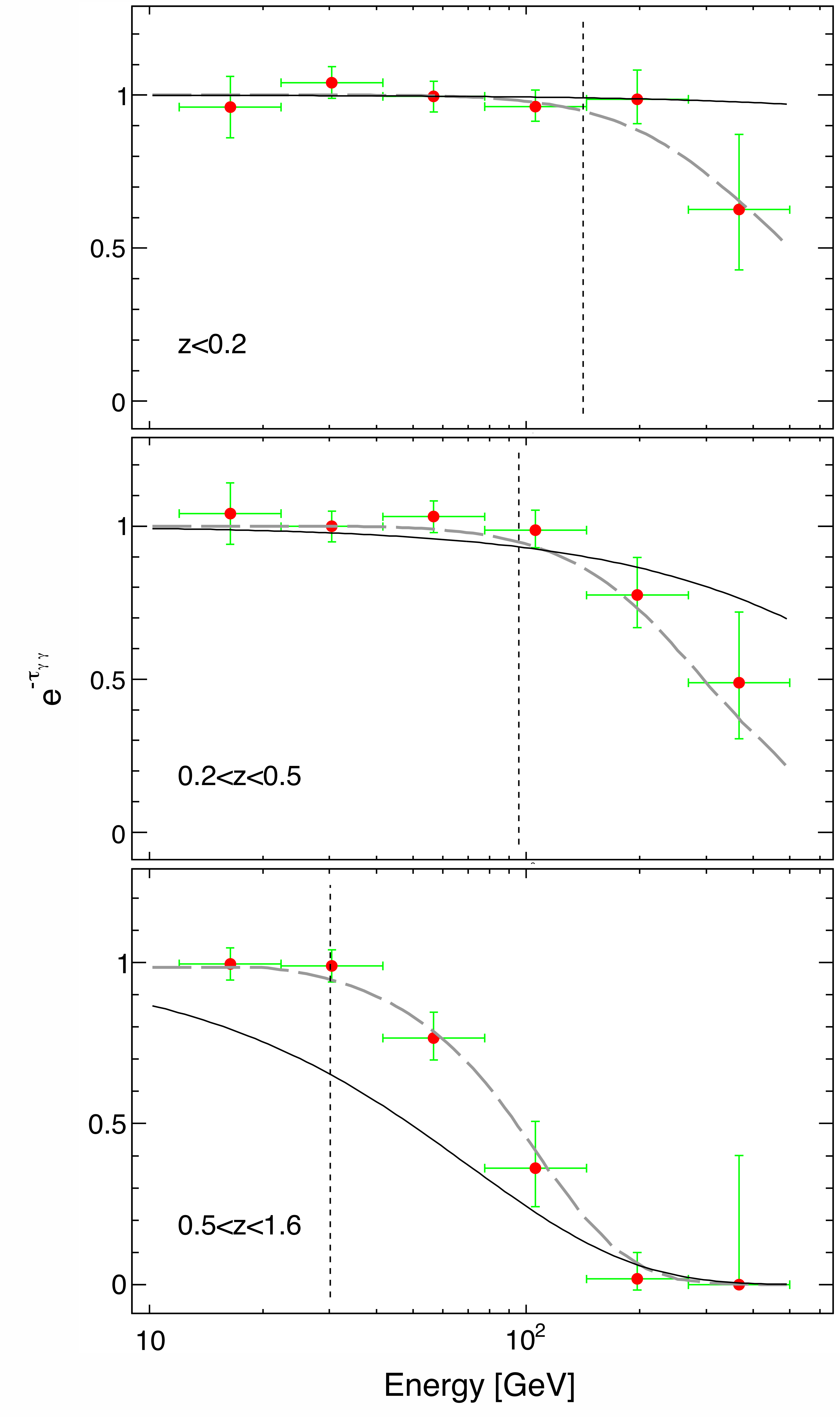
Yoshiyuki Inoue

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

Lecture Schedule

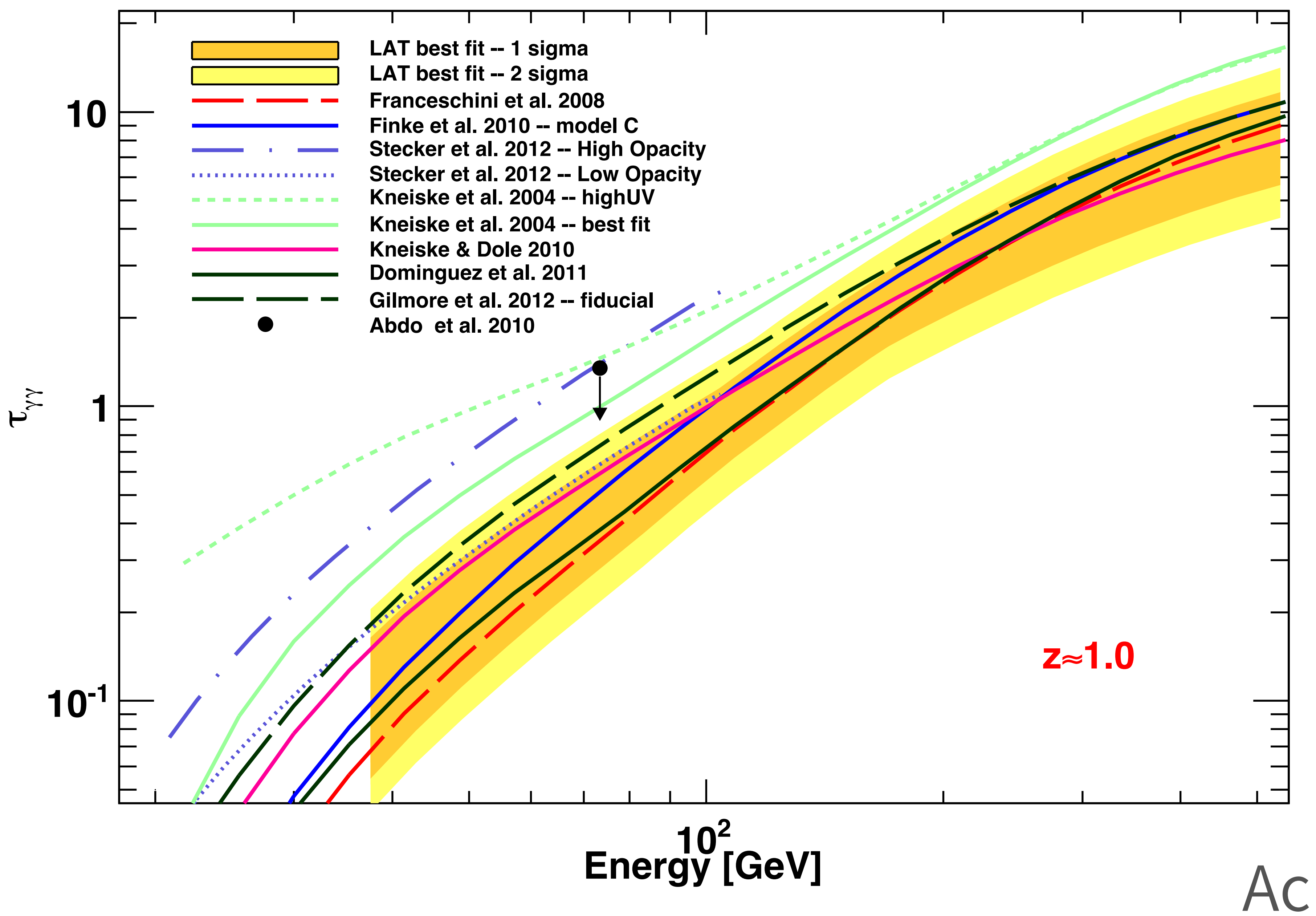
Be careful! It may change!

- ~~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

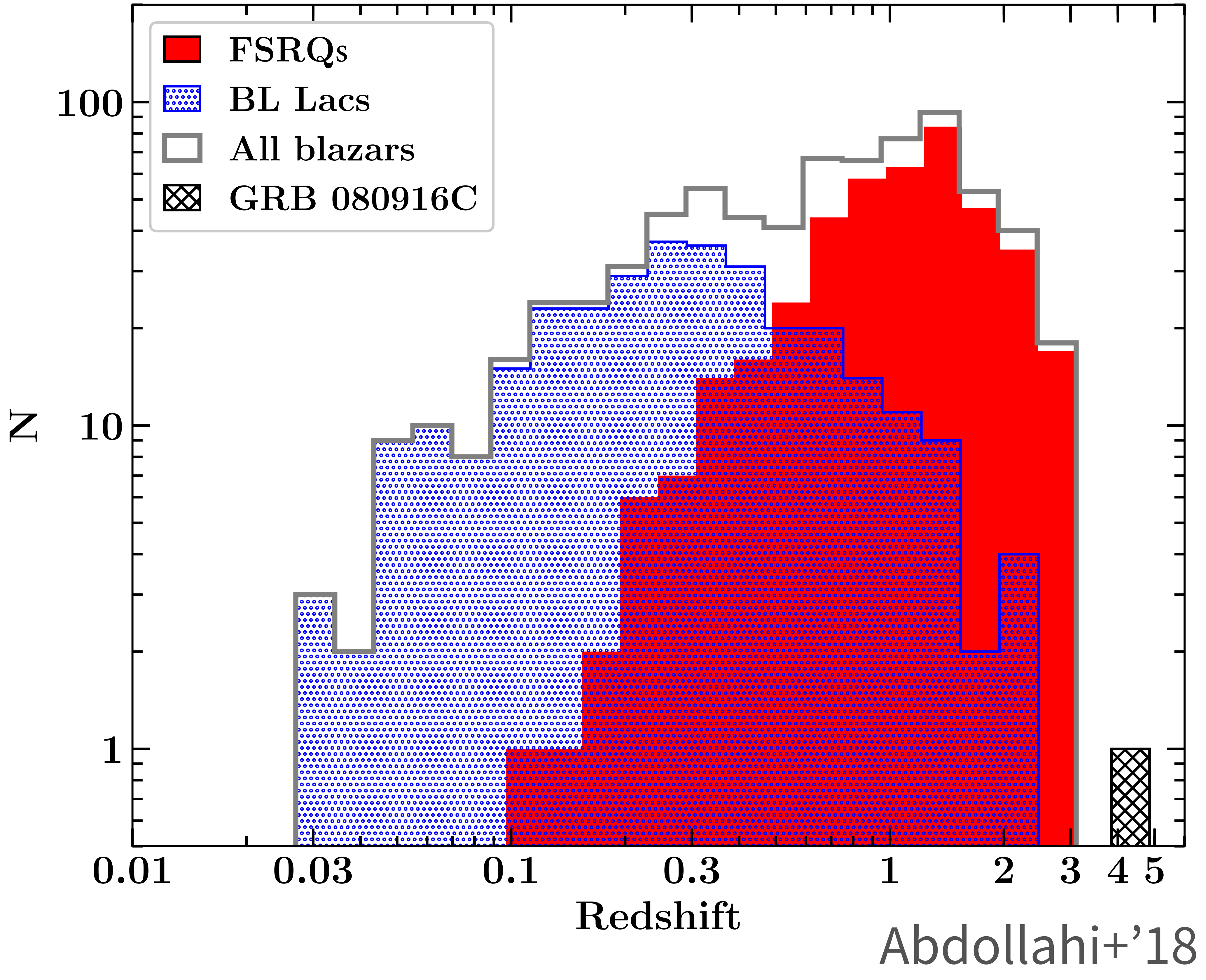


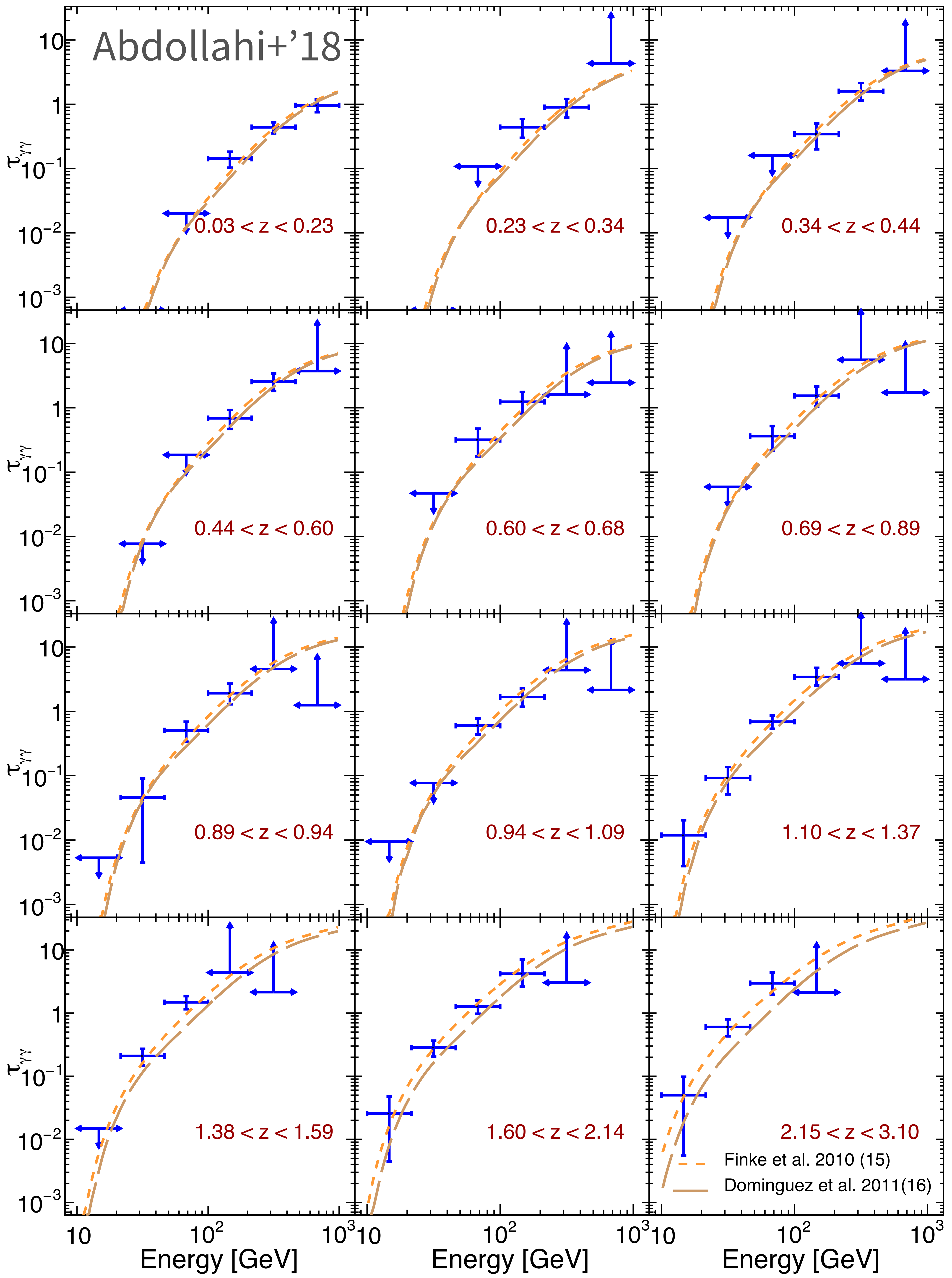
Ackermann+'12

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

"Characterization" of the EBL attenuation

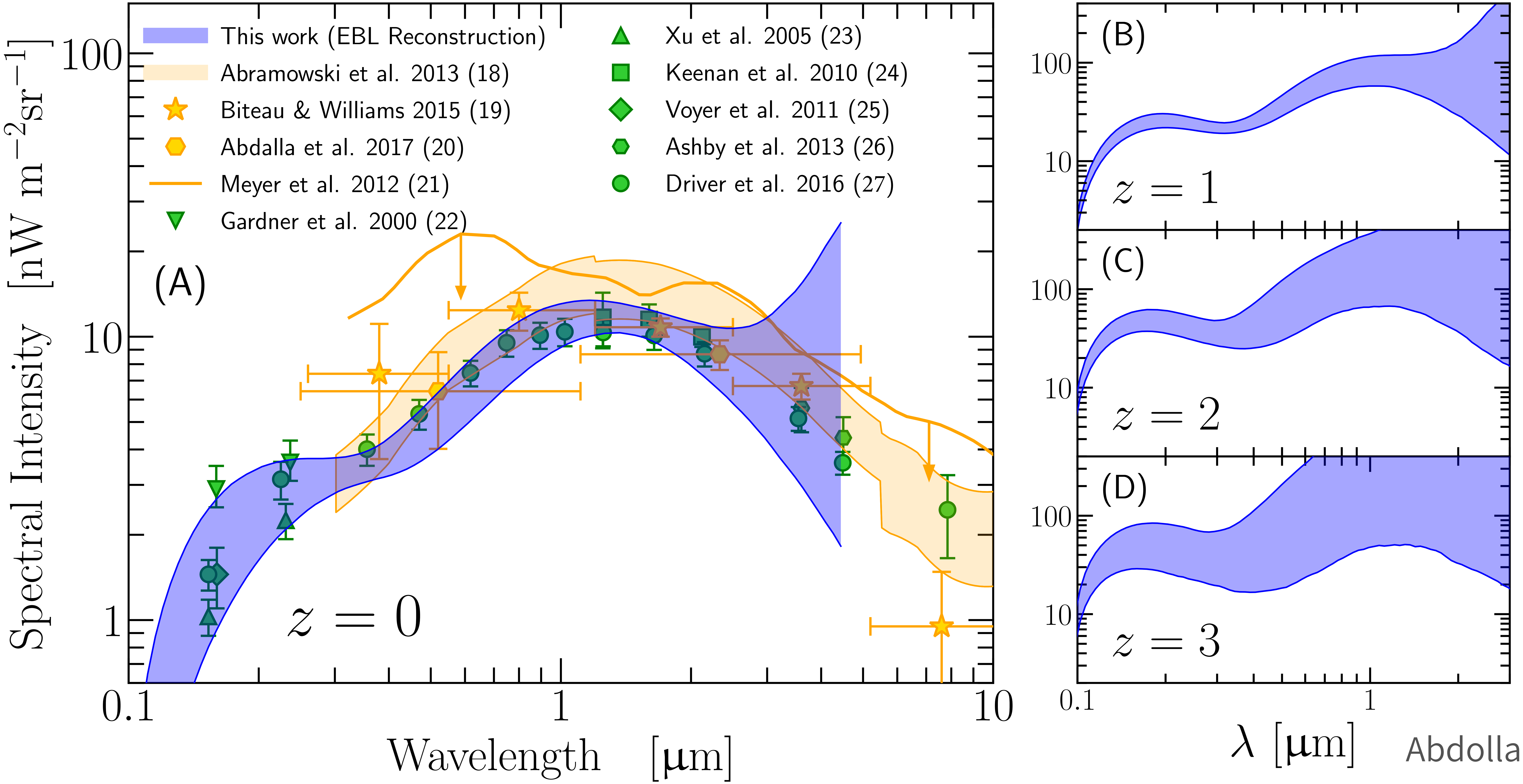
739 Fermi blazars + 1 Fermi GRB w/ 9-yr data





EBL and its Evolution by Gamma-ray Observations

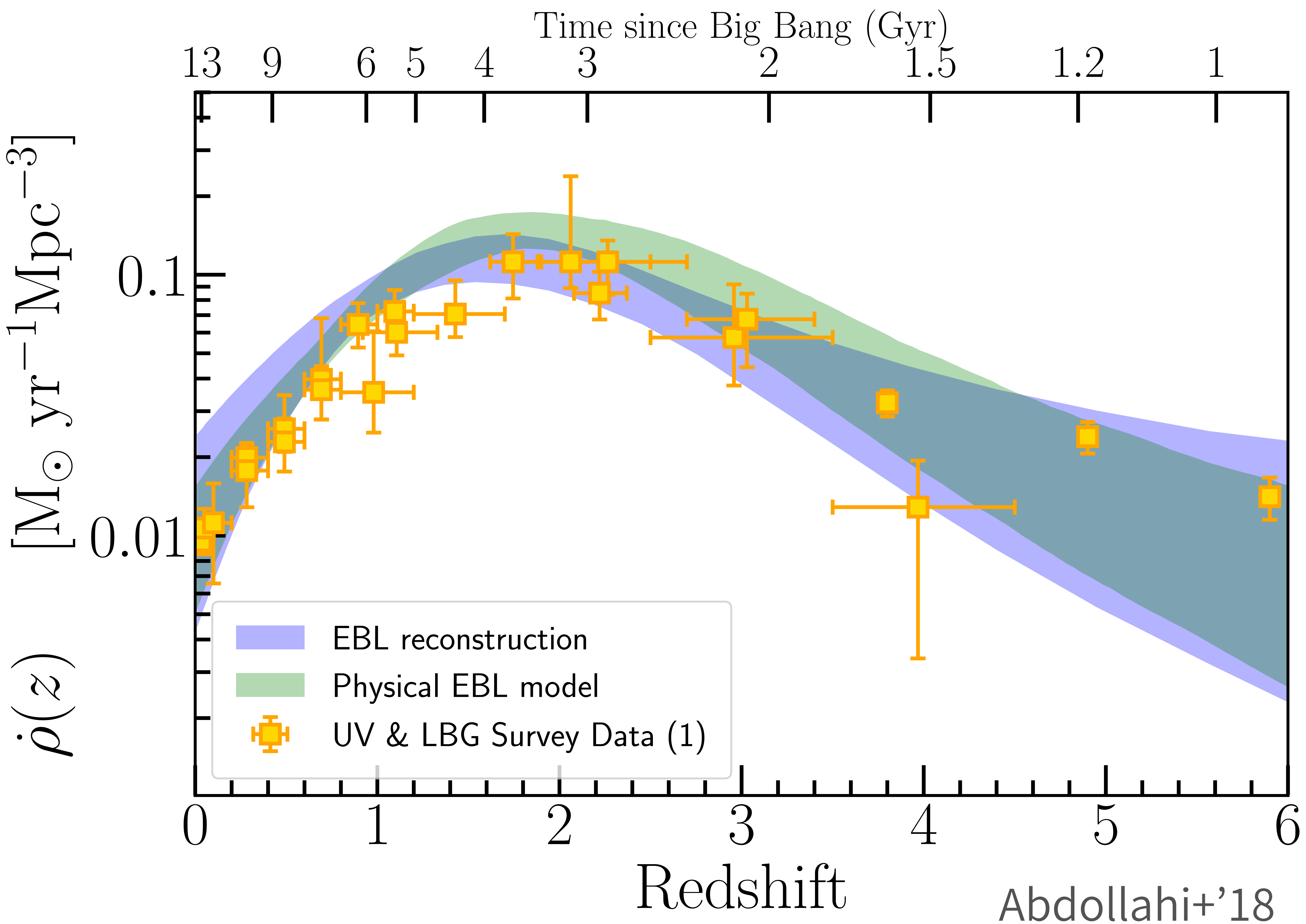
Good agreement with galaxy counts



Abdollahi+'18

Determination of the Cosmic Star Formation History

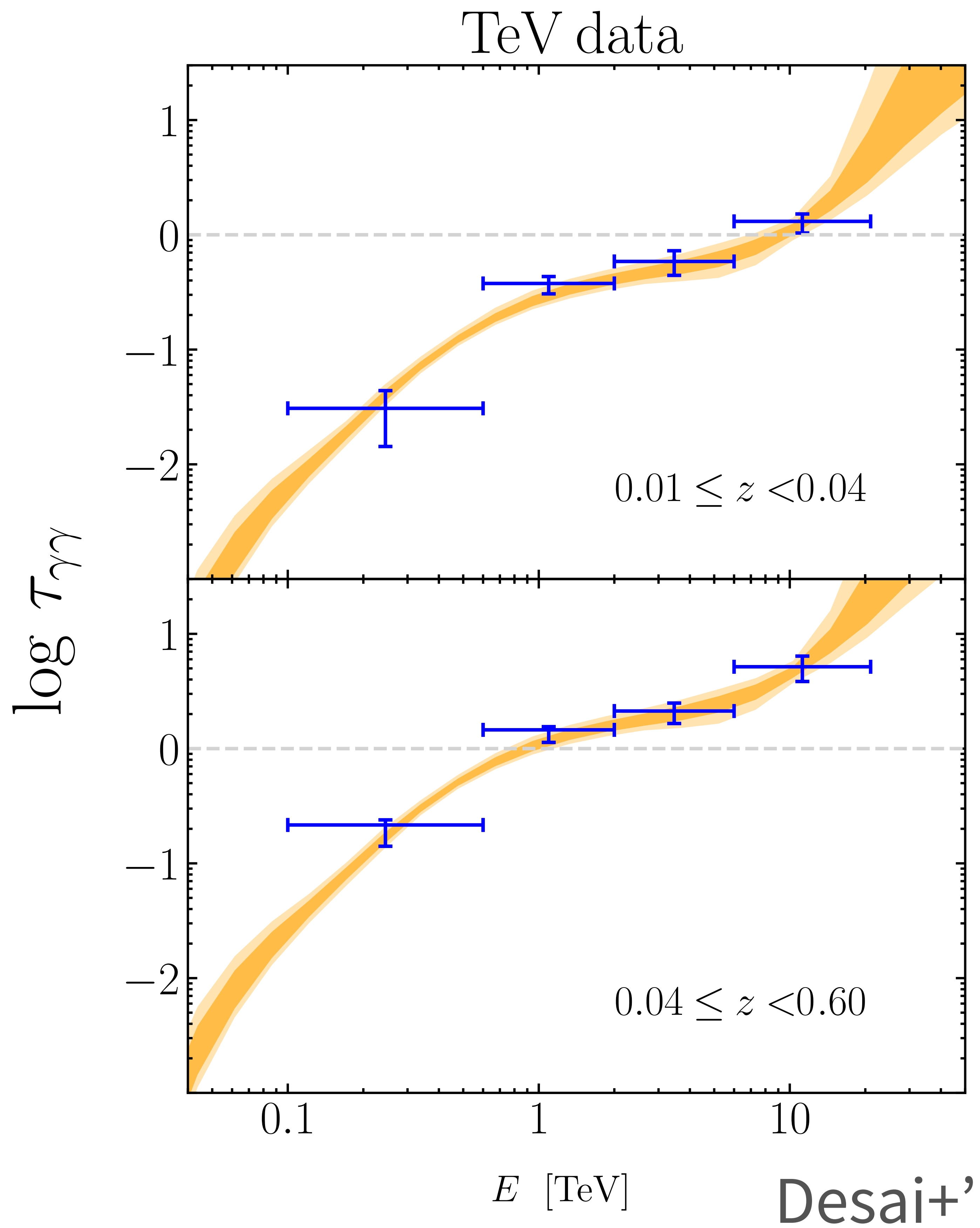
- Consistent with galaxy survey data.
    - Assume the EBL shape.
- We may need
    - Empirical EBL modeling based on the latest galaxy survey data
    - EBL model based on cosmological simulation



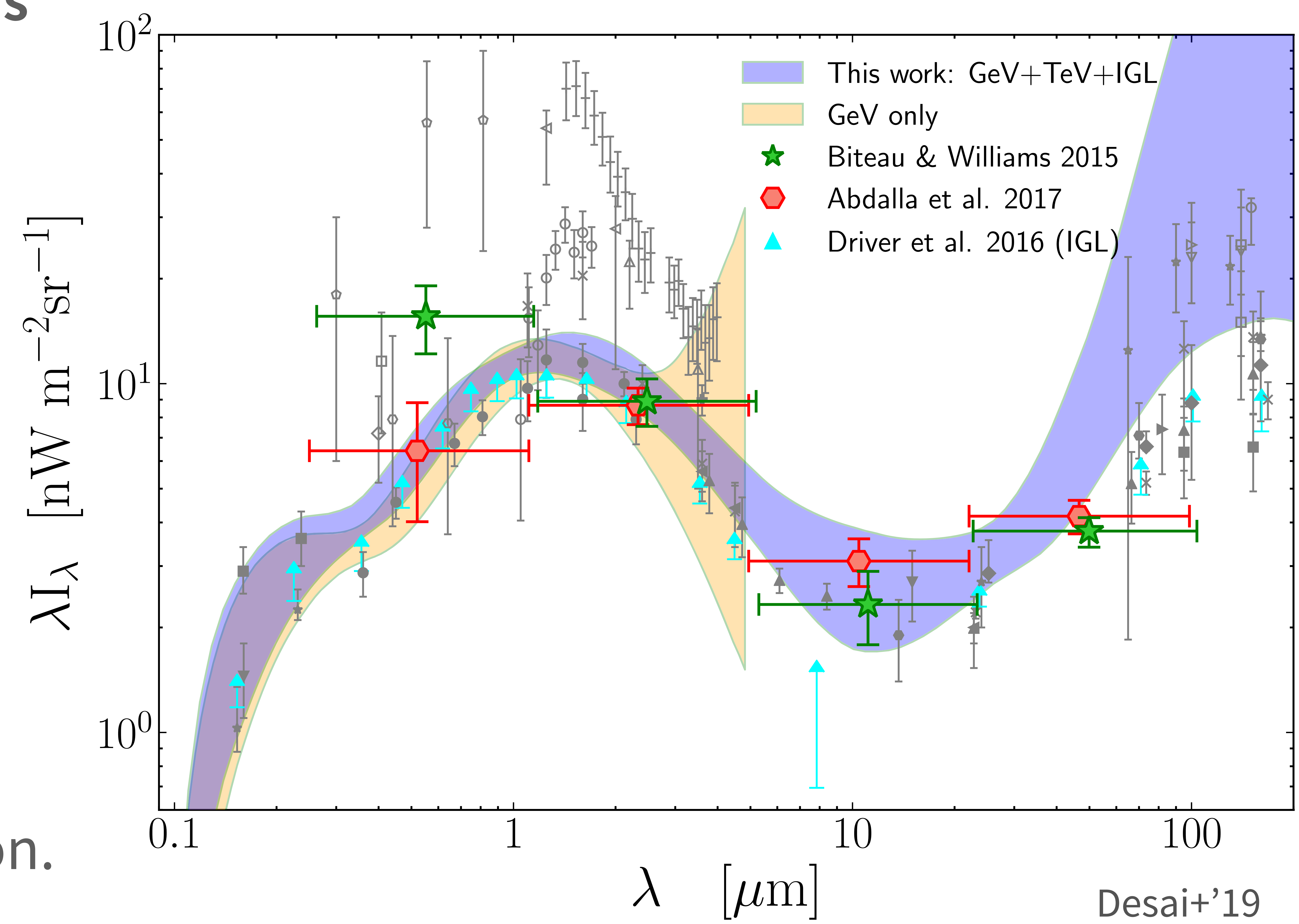
Abdollahi+'18

EBL Determination with GeV-TeV data

38 GeV-TeV detected blazars



Desai+'19

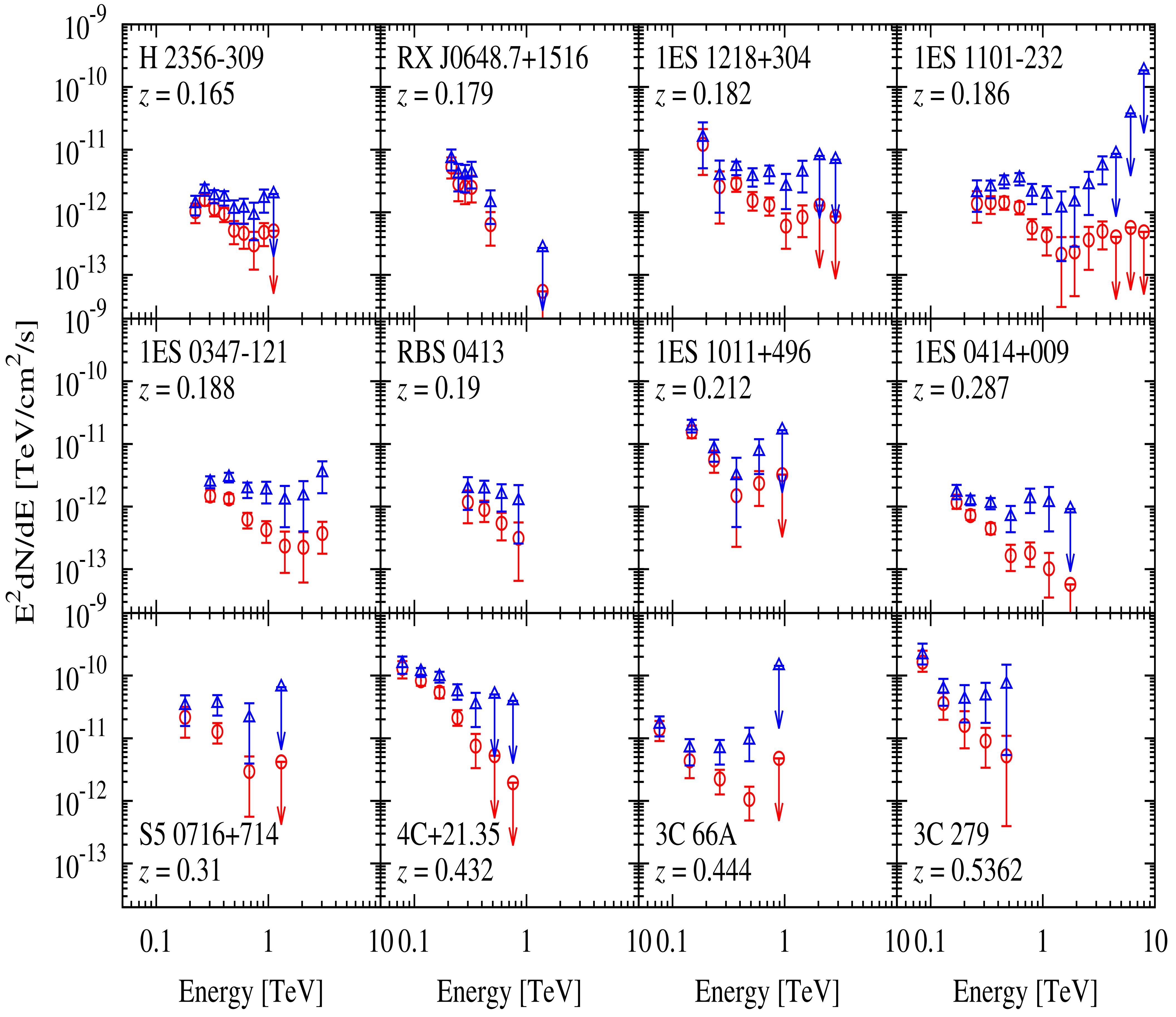


Desai+'19

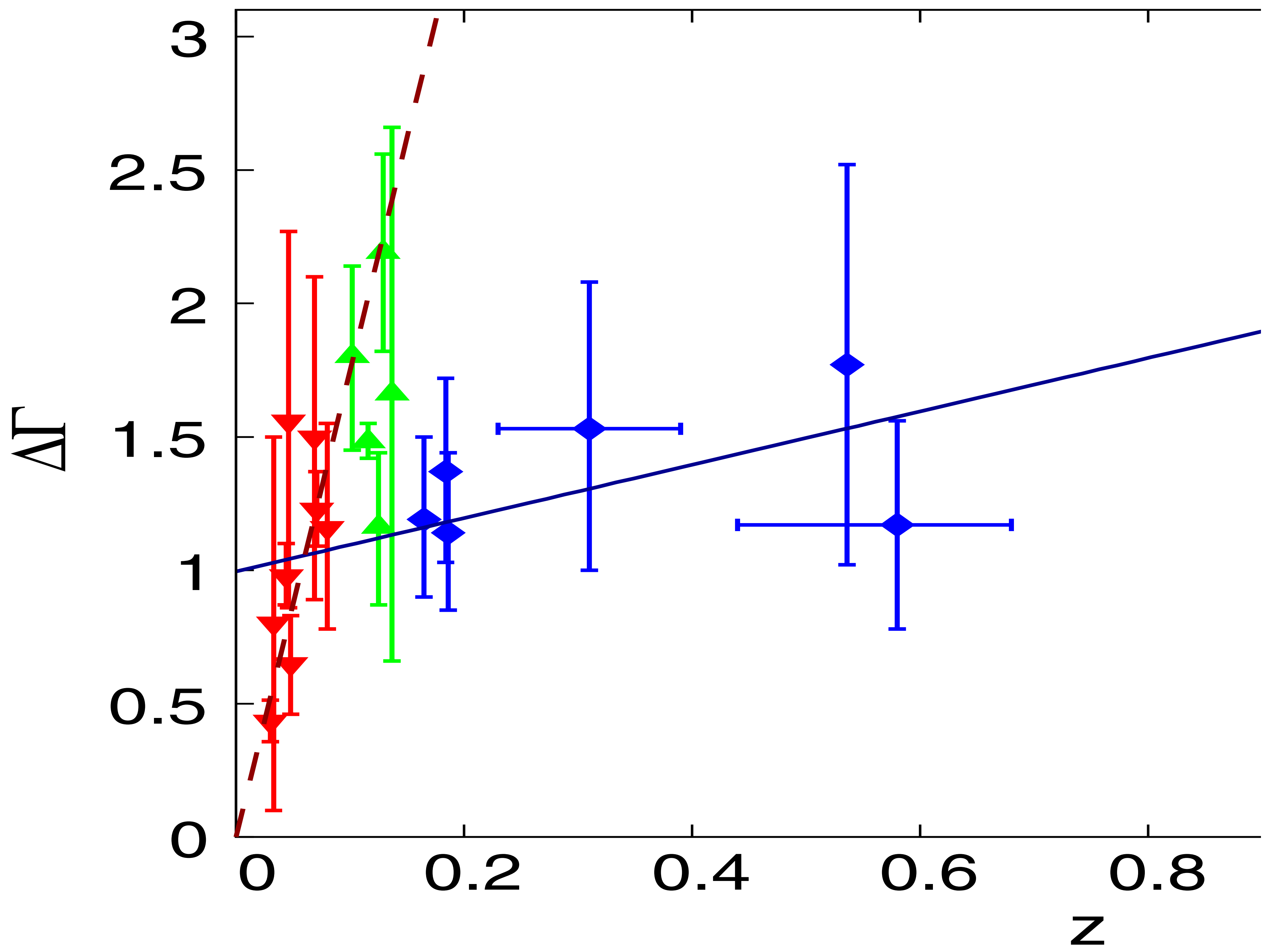
- We can go to the IR region.

VHE Spectral Hardening in Blazars

Inconsistent with typically assumed SED



YI & Tanaka '16



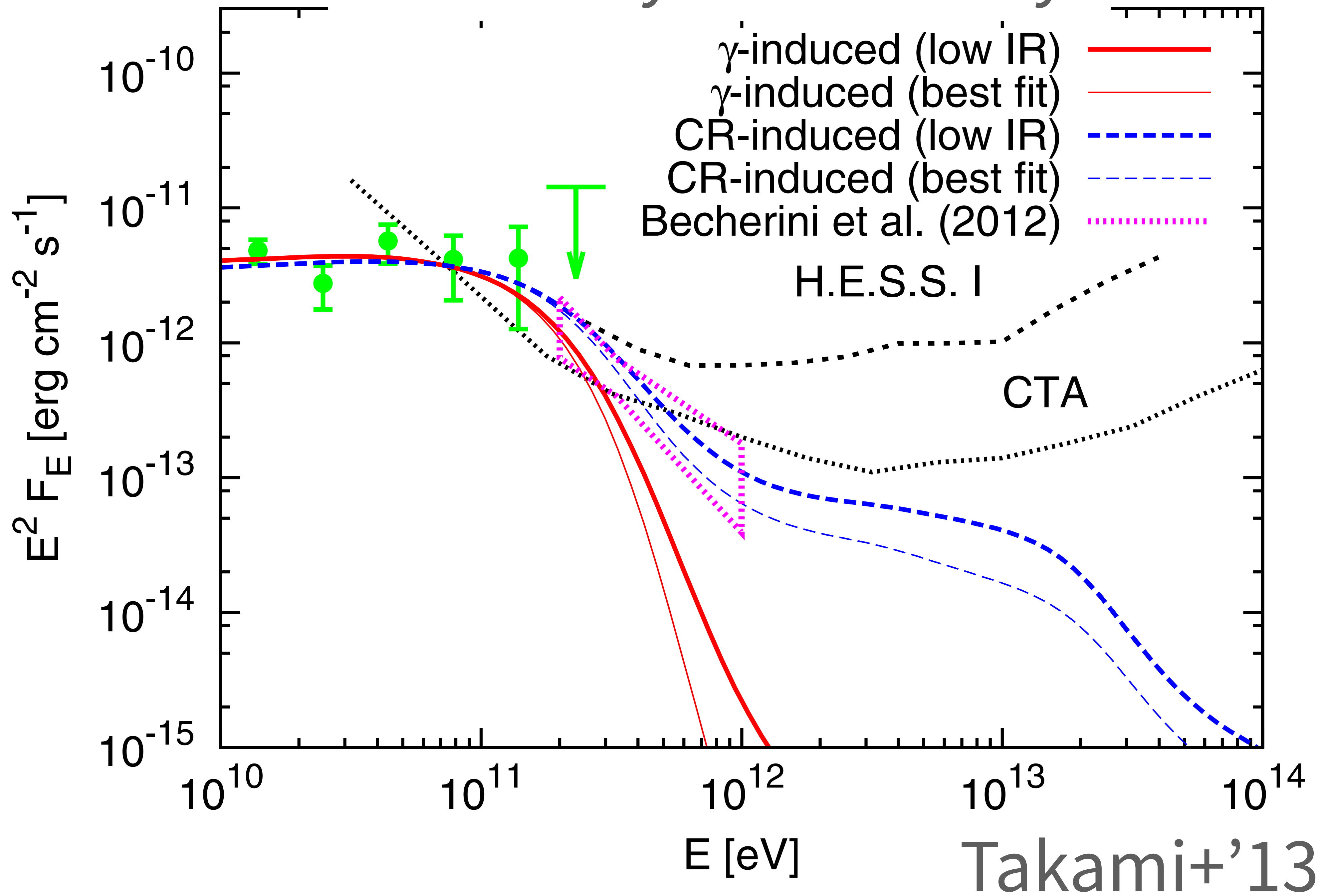
Essey & Kusenko '10

- Some blazars show spectral hardening after the EBL correction.

Secondary Gamma Rays? Stochastic Acceleration?

KUV 00311-1938 (z=0.61)

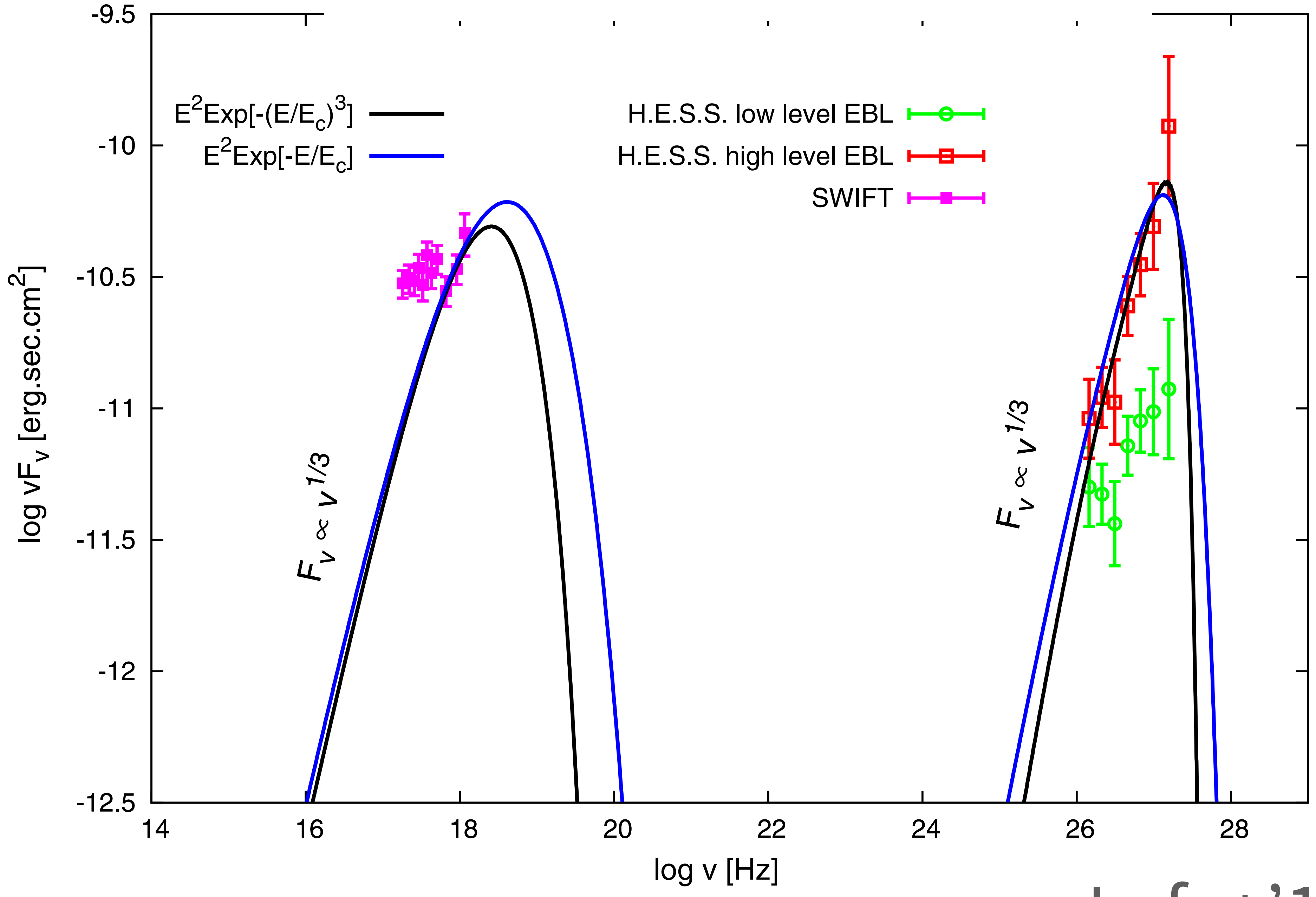
Secondary Gamma Rays



Takami+'13

1ES 0229+200 (z=0.1396)

Stochastic Acc.



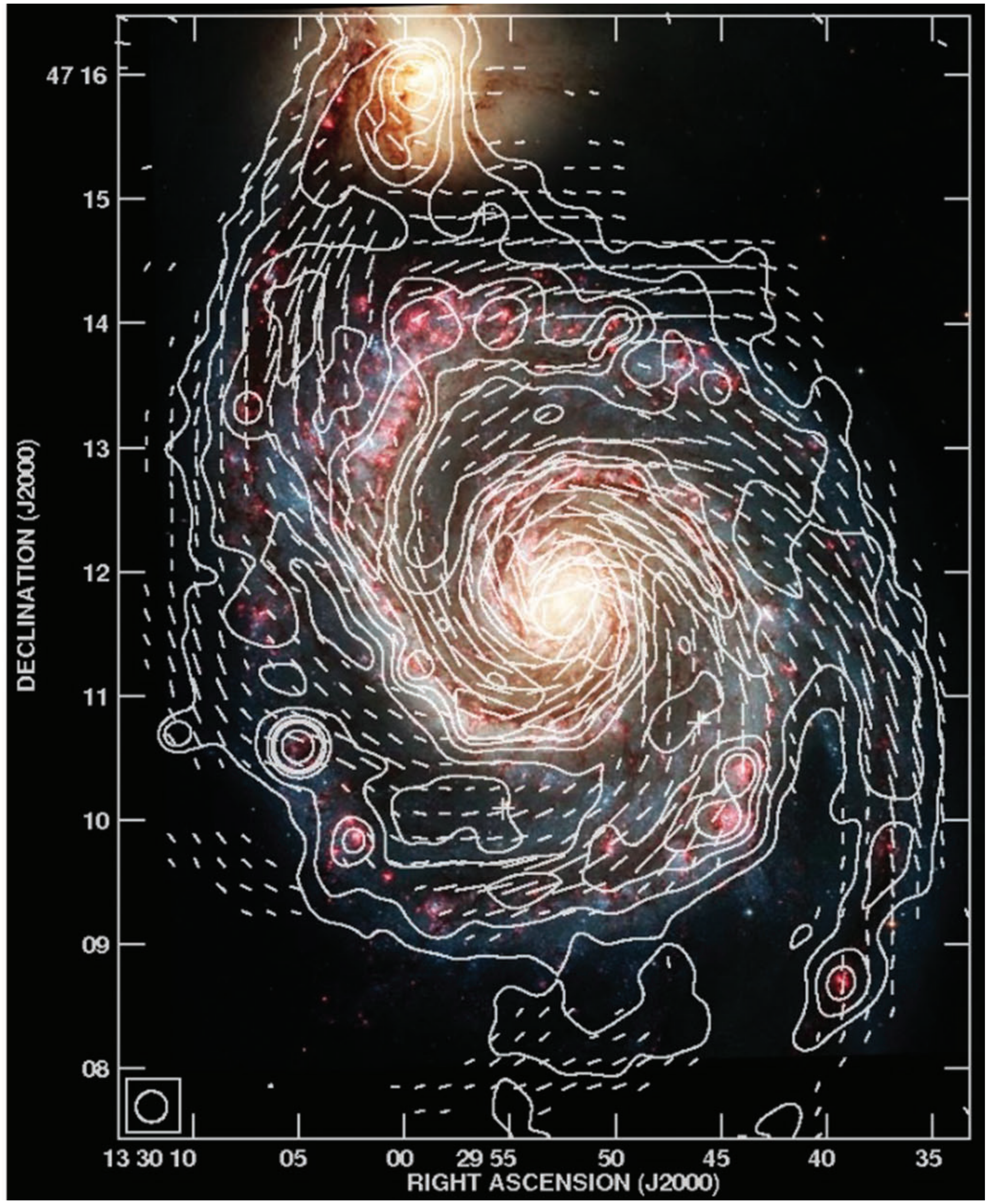
Lefa+'11

- 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).

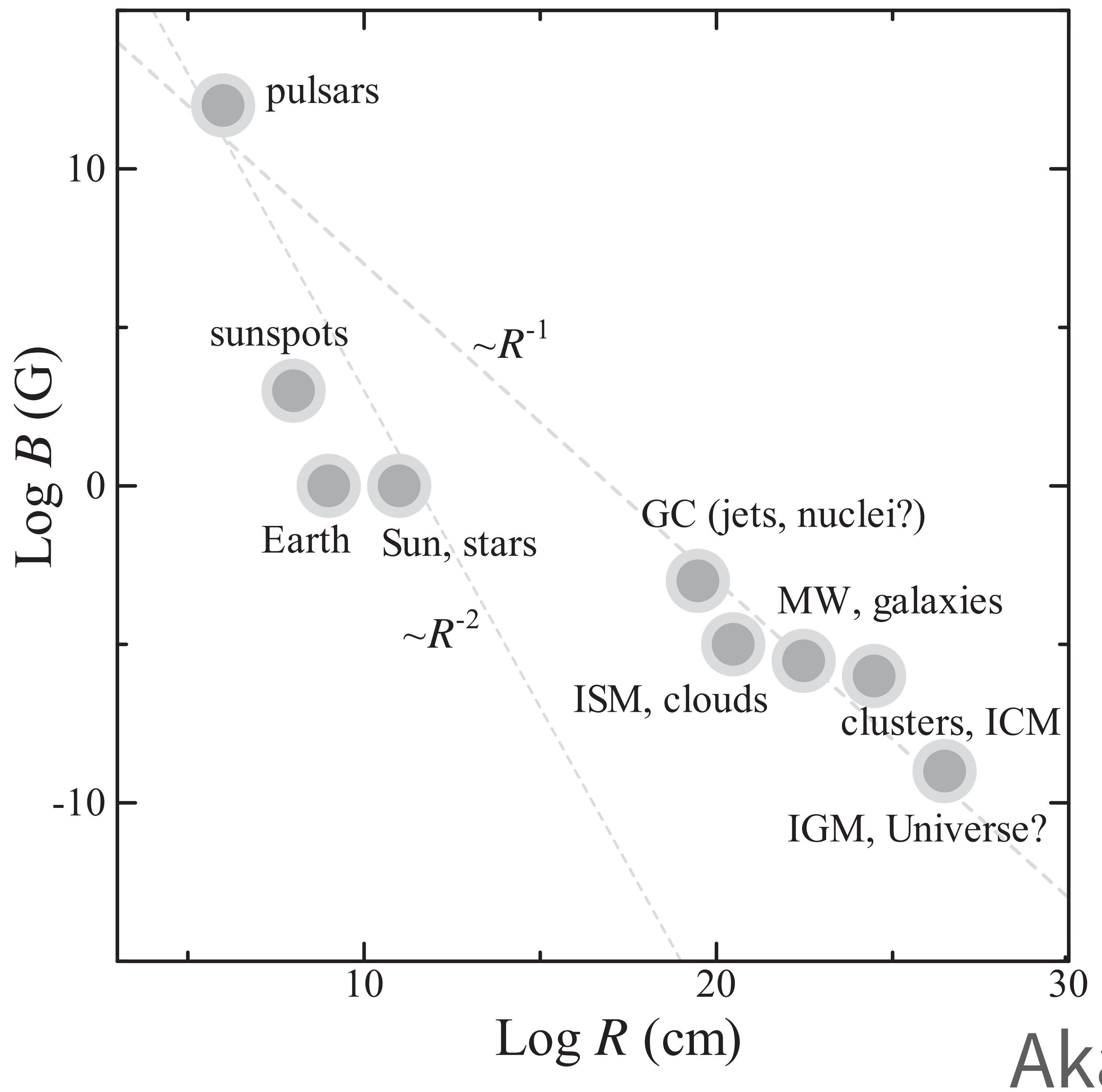
Intergalactic Magnetic Field and Gamma-ray Observations

Magnetic Fields in the Universe

How strong is the cosmic magnetic field?



Fletcher+'11



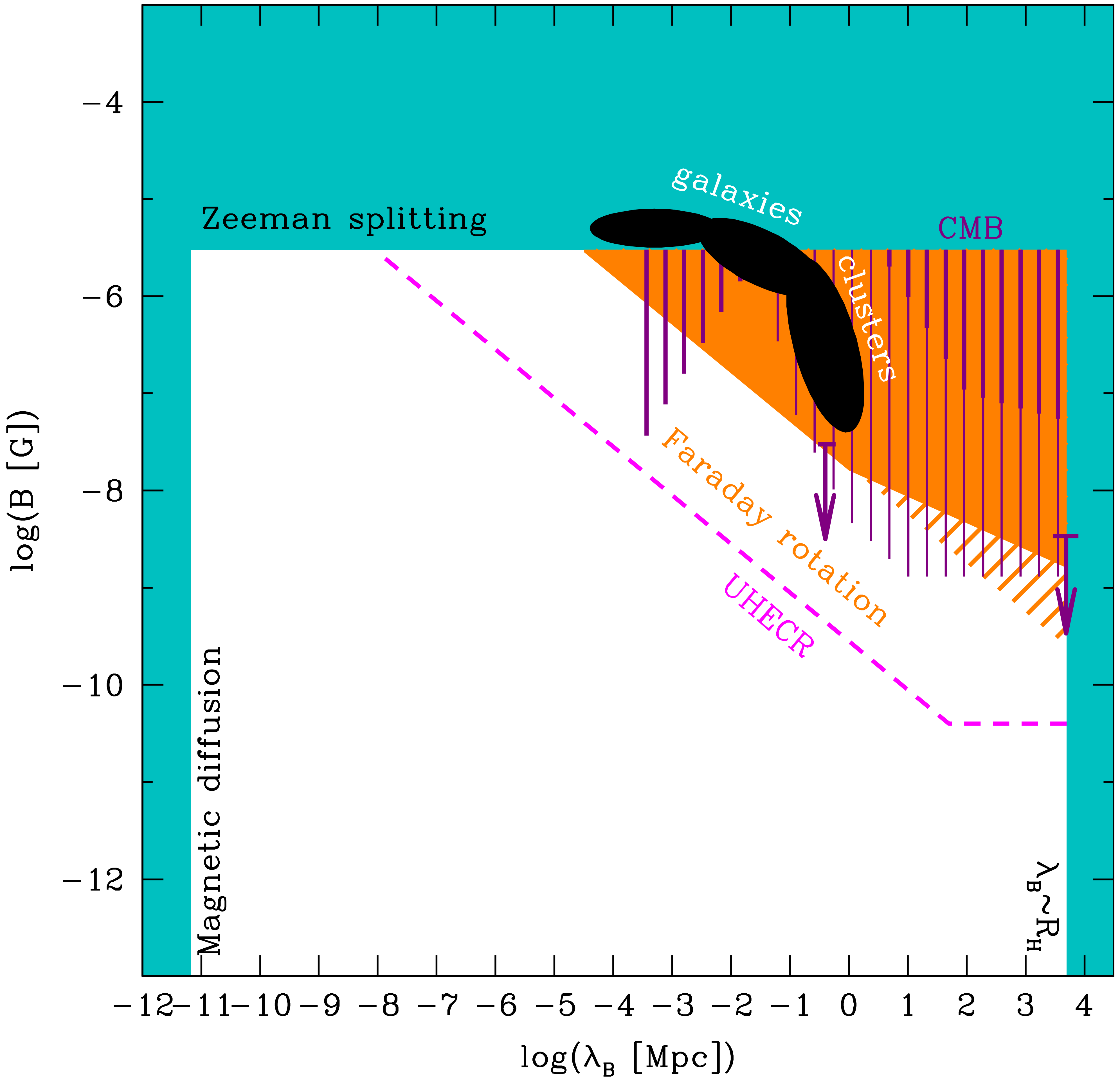
Akahori+'18

- 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

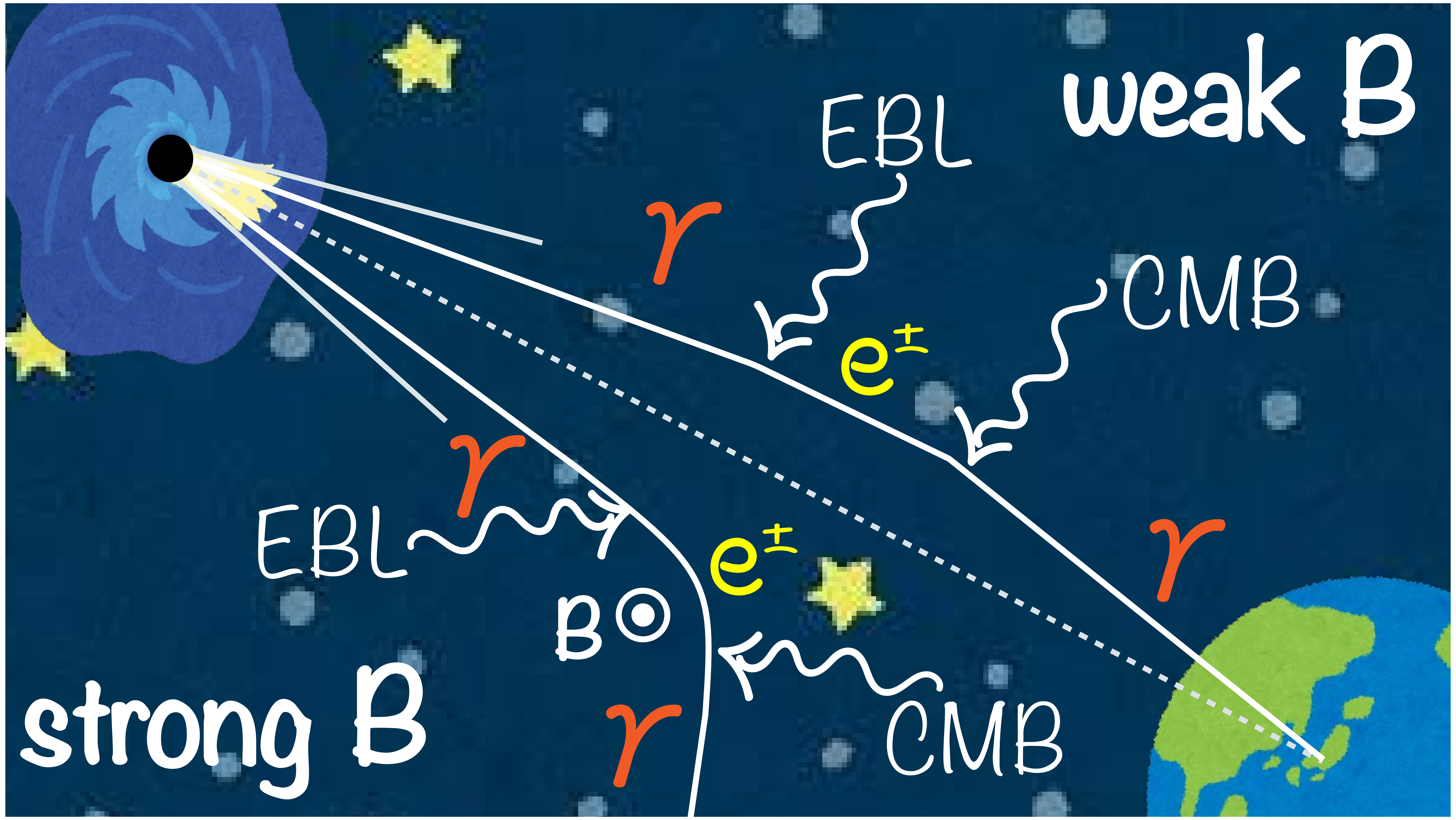
- Magnetic diffusion: $\lambda_{\mathrm{coh}} \geq \lambda_{\mathrm{diff}} = \sqrt{\frac{t_H}{4\pi\sigma}} \simeq 10^{13}$ cm
- Hubble radius: $\lambda_{\mathrm{coh}} \leq R_H$
- Zeeman splitting of 21 cm absorption line in quasar spectra (Heiles & Troland '04).
- Faraday rotation in quasars $\mathrm{RM} \leq \Delta\chi/\Delta\lambda^2 \propto B_{\mathrm{IGMF}} n_e$ (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

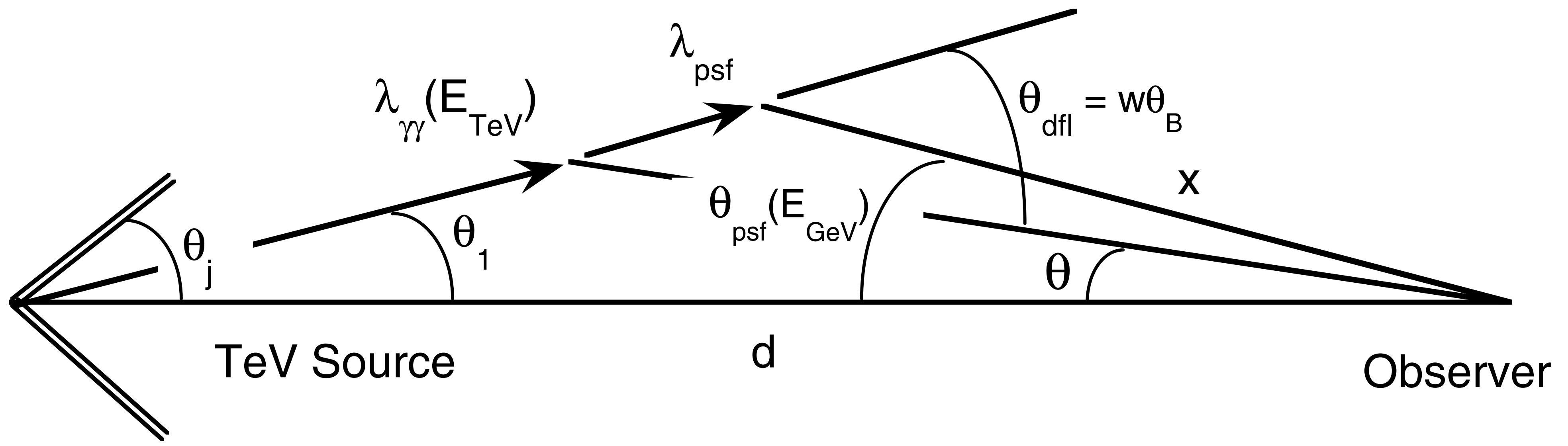
Pairs Generate Cascade Emission



- Primary γ-rays are attenuated by EBL: $\gamma_{\rm TeV} + \gamma_{\rm EBL} \to e^+ + e^-$
- Pairs scatters CMBs as secondary γ-rays: $e^\pm + \gamma_{\rm CMB} \to e^\pm + \gamma_{\rm GeV}$
  - Energy is
    $$E_{\rm 2nd} \simeq \frac{4}{3}\gamma_e^2 E_{\rm CMB} \simeq 0.8 \left(\frac{E_{\rm 1st}}{1{\rm TeV}}\right)^2 \ {\rm GeV}$$
- Magnetic field can deflect the trajectory of pairs.
  - Secondary signals strongly depends on IGMF (e.g., Plaga ‘95).

Time Delay of Secondarys

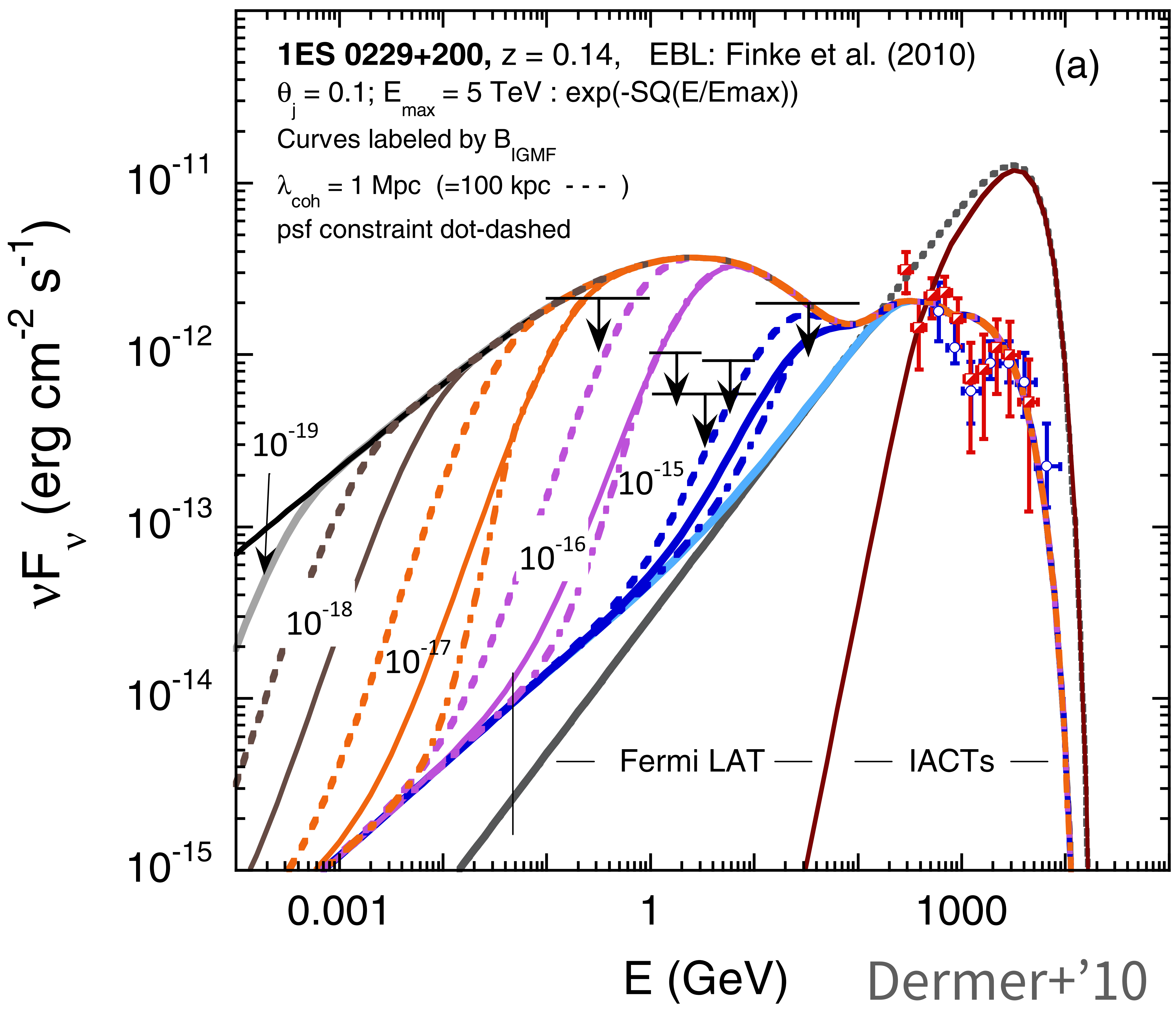
Dai+'02; Fan+'04; Murase+'08,,,,



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

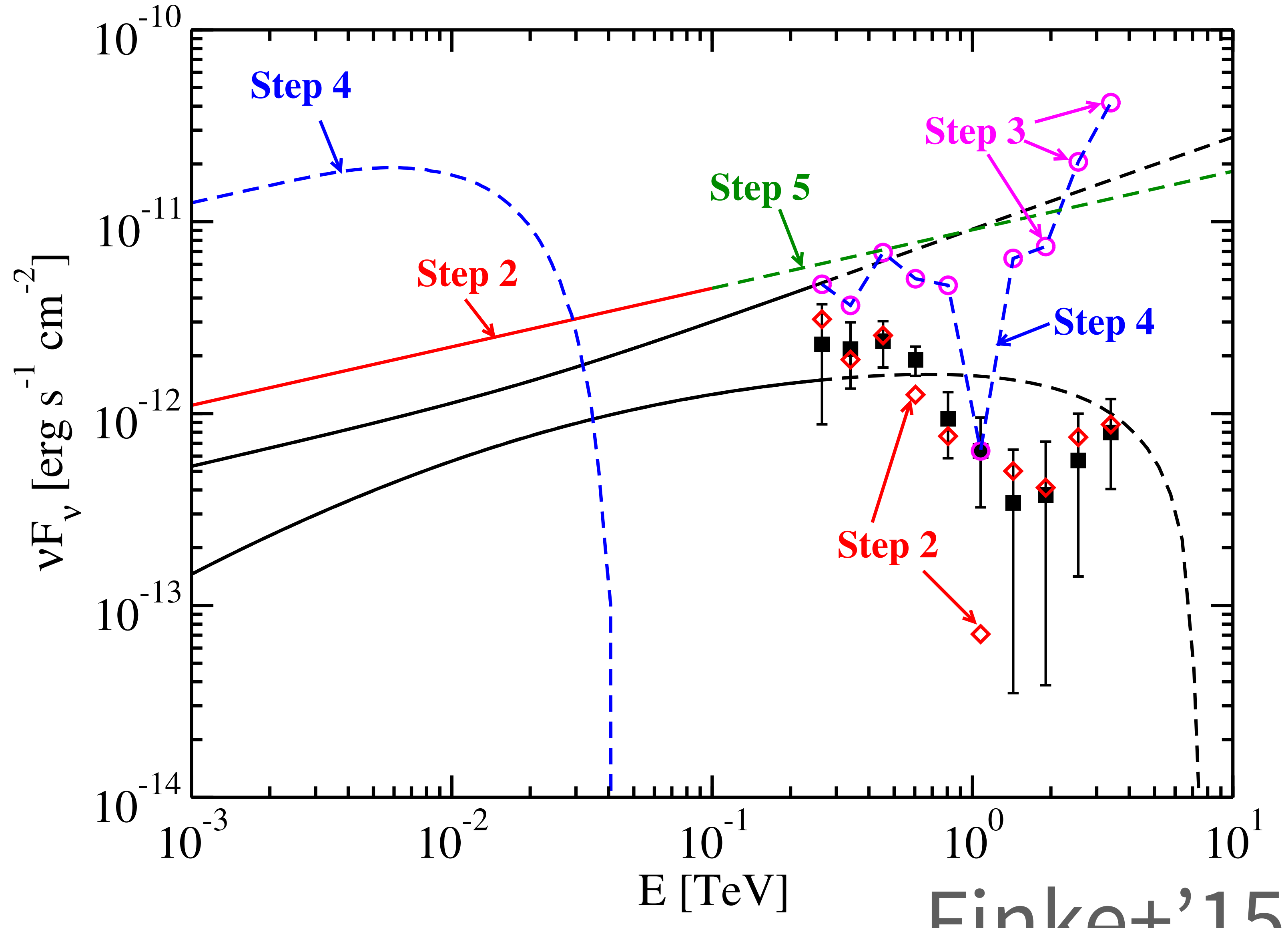


Dermer+'10

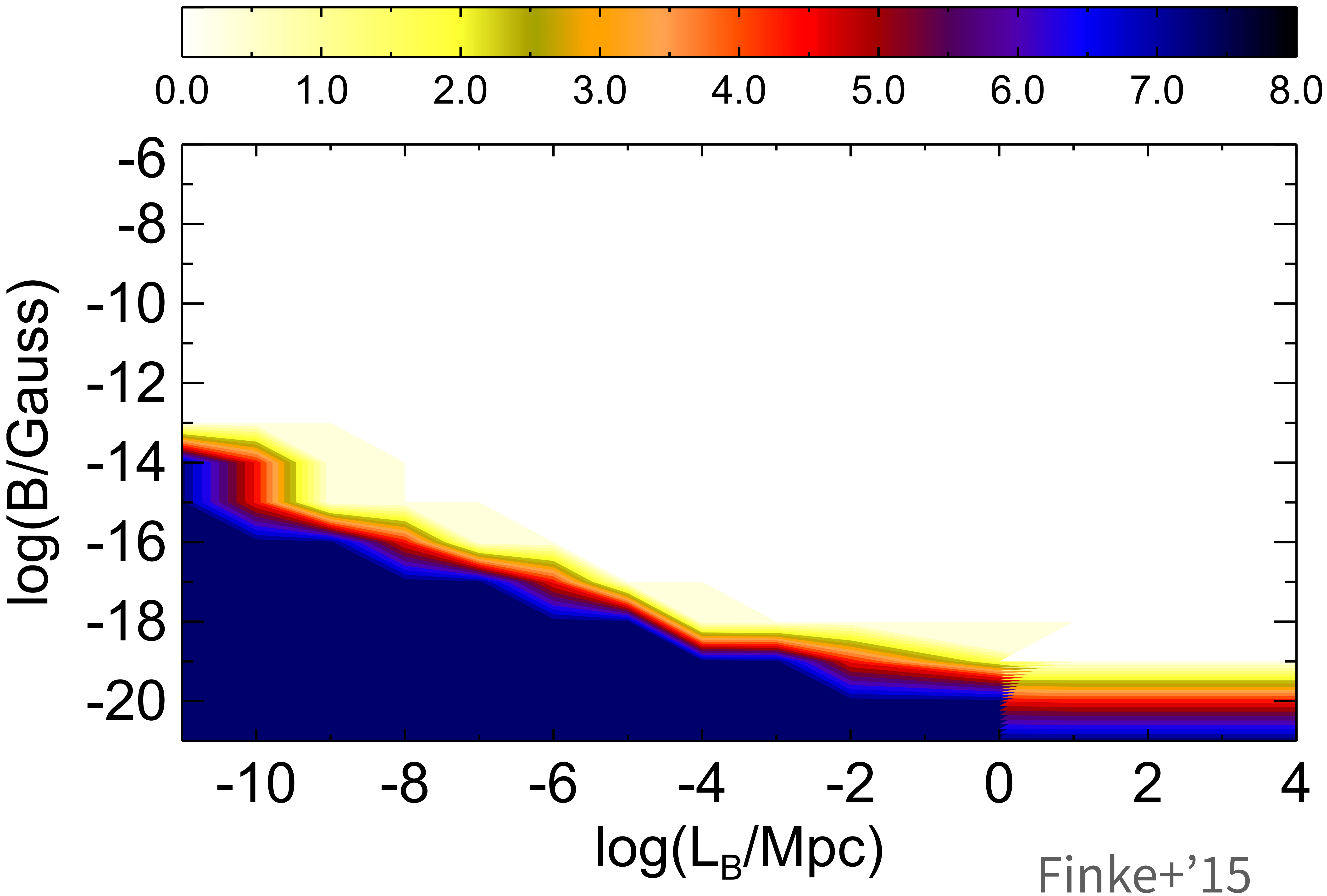
- IGMF dependence appears in the GeV band.
- But, be careful. It also depends on
  - Intrinsic spectrum
  - EBL model
  - Source activity timescale: $\Delta t_{\rm flare}$
  - Coherent length: $\lambda_{\rm coh}$
  - Jet opening angle: $\theta_{\rm jet}$

Current bounds on the IGMF

from the secondary spectrum



Finke+’15

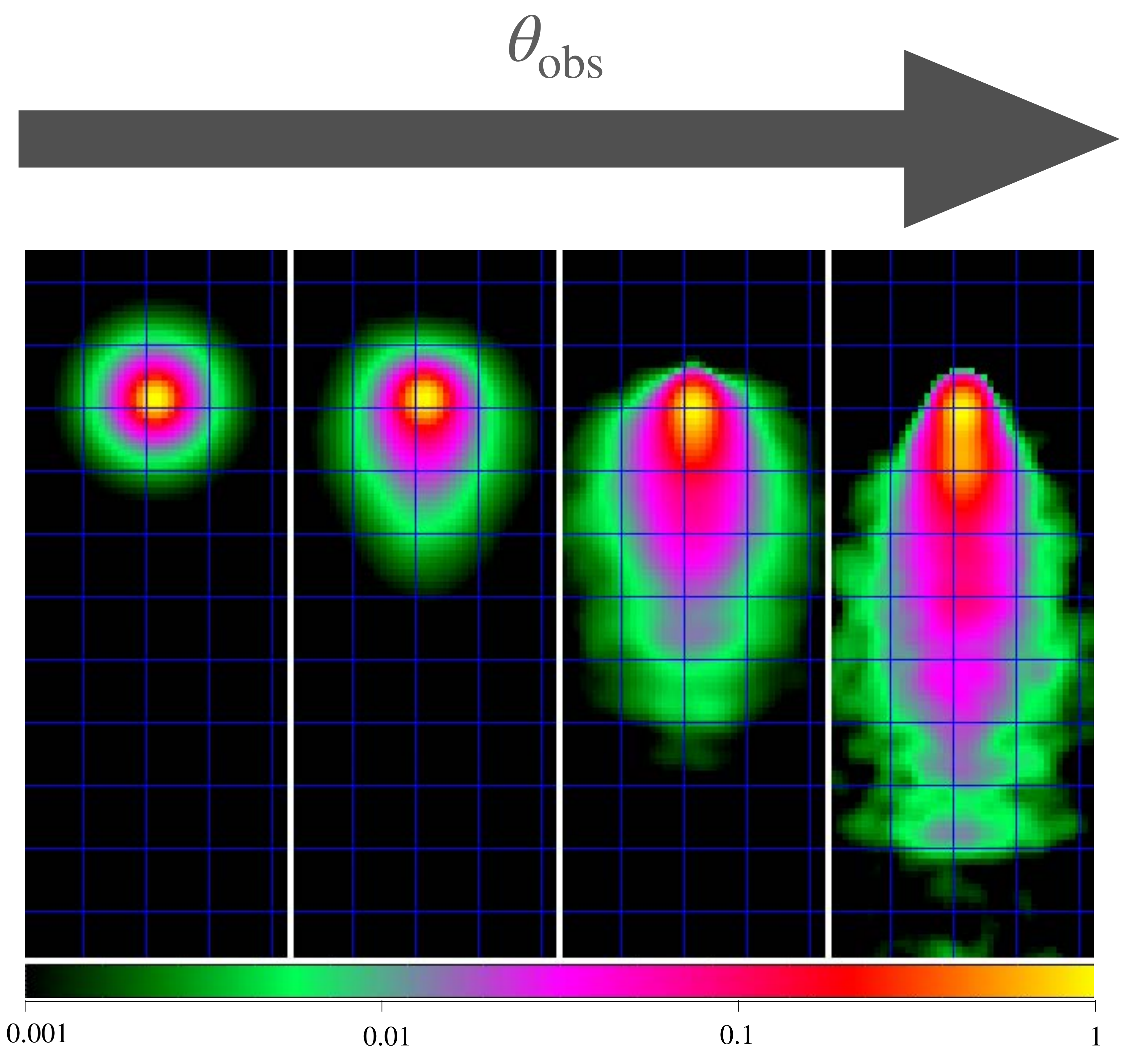


Finke+’15

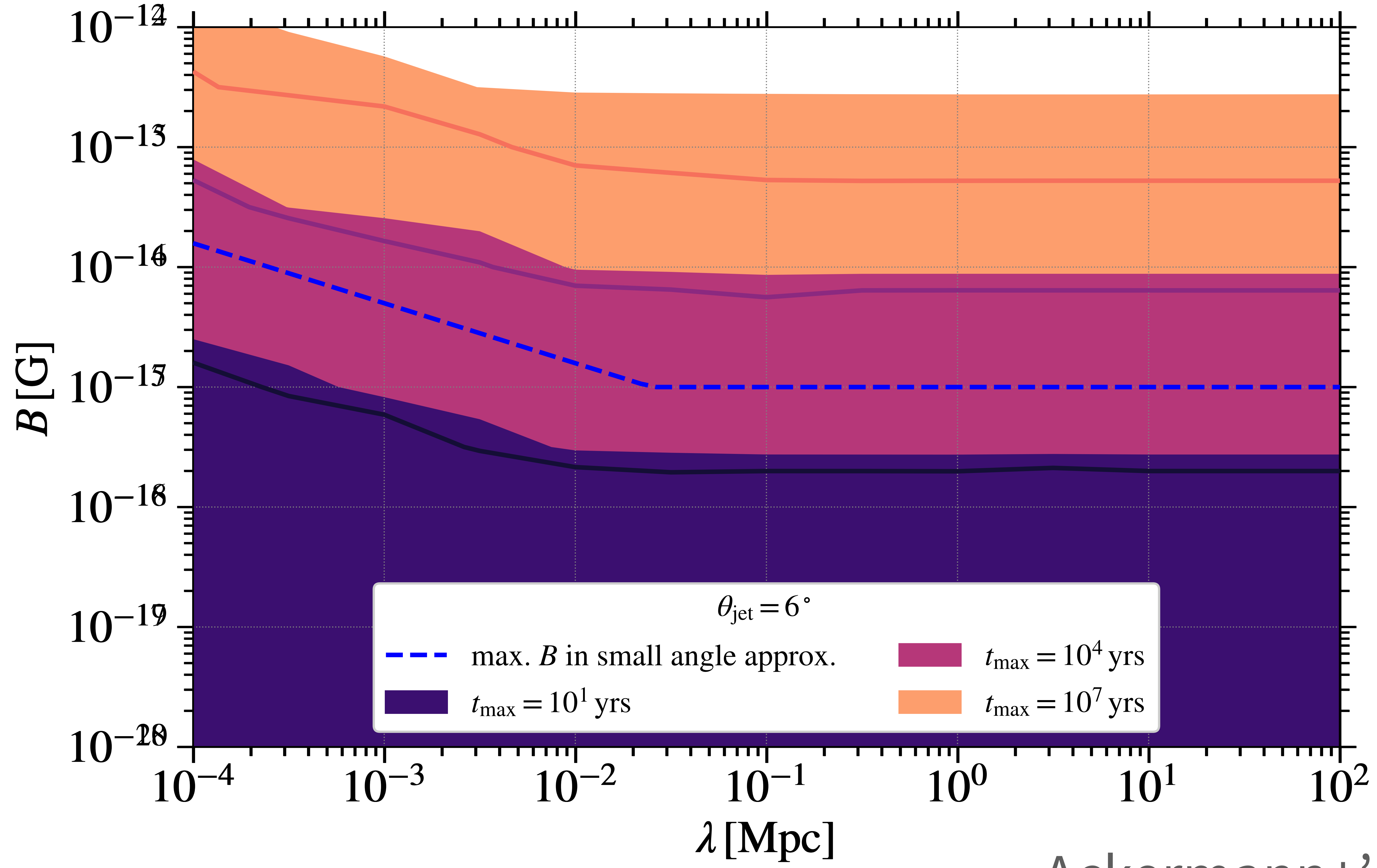
- $B_{\mathrm{IGMF}} \geq 10^{-19}$ G for $\lambda_{\mathrm{coh}} \geq 1$ Mpc with $\Delta t_{\mathrm{flare}} = 3$ yr
  - at >5σ confidence level

Extended Pair Halo

Secondary is spatially extended



Neronov+'10



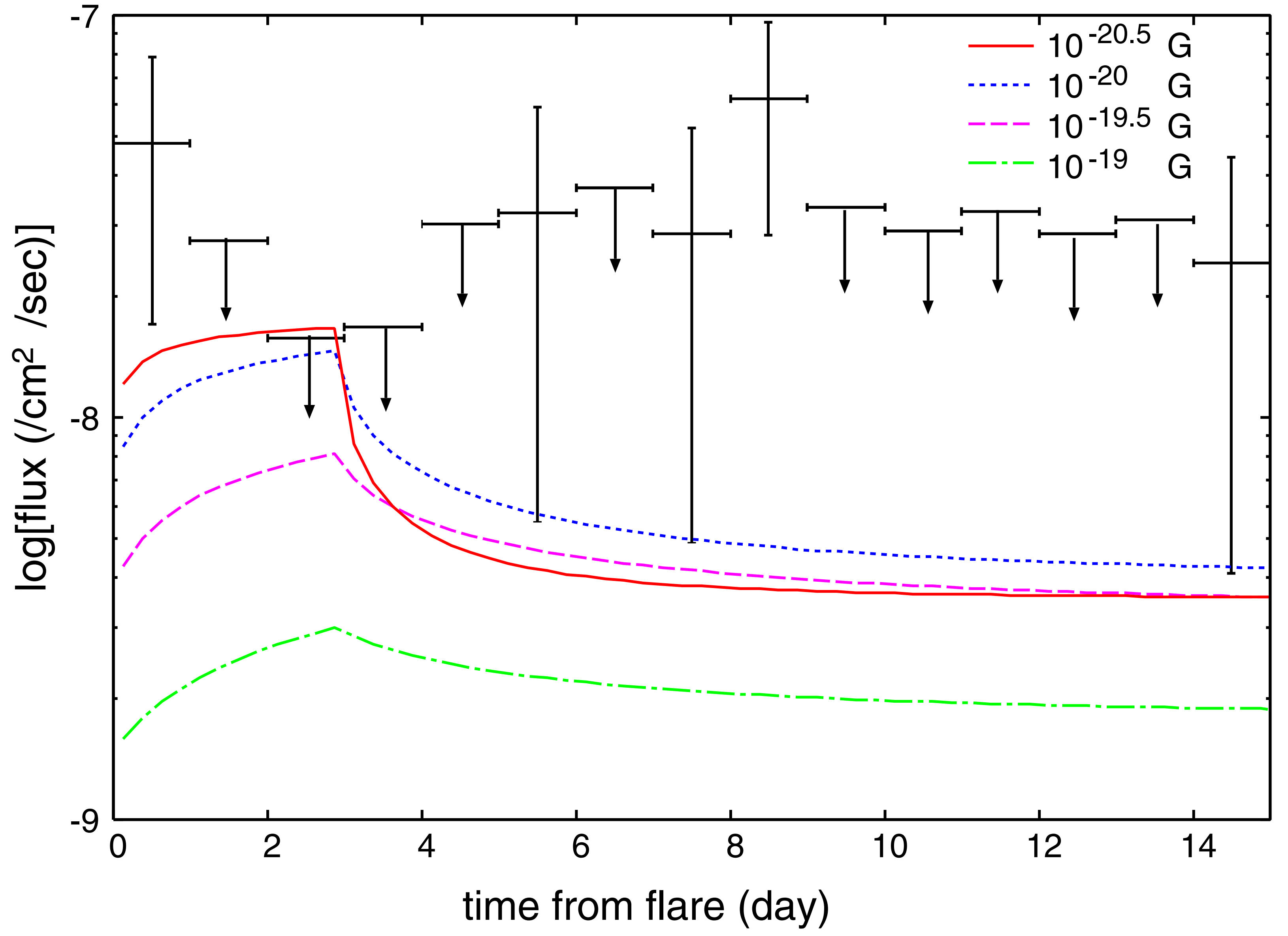
Ackermann+'18

- 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

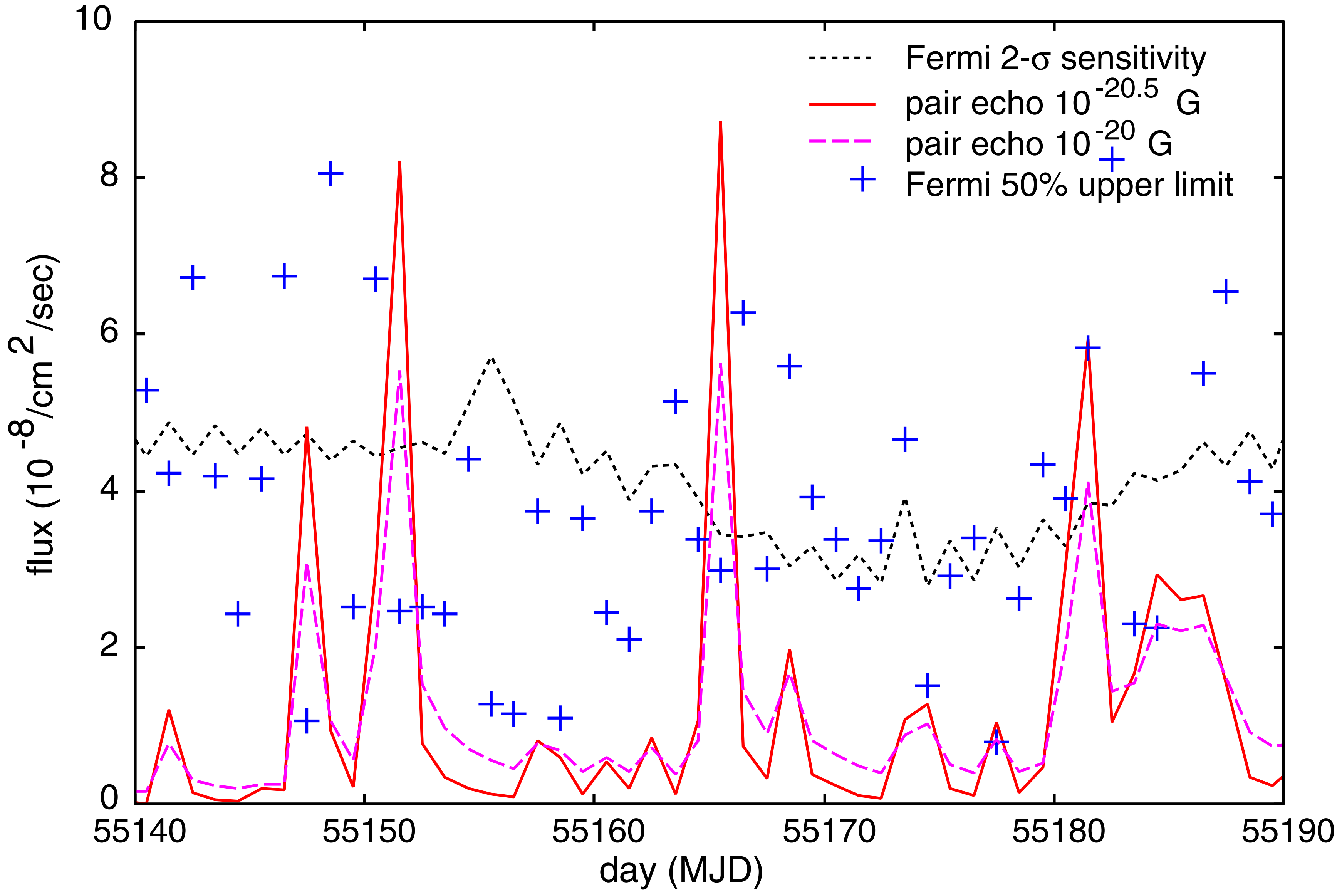
Time delay

Delayed flare in GeV band?

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



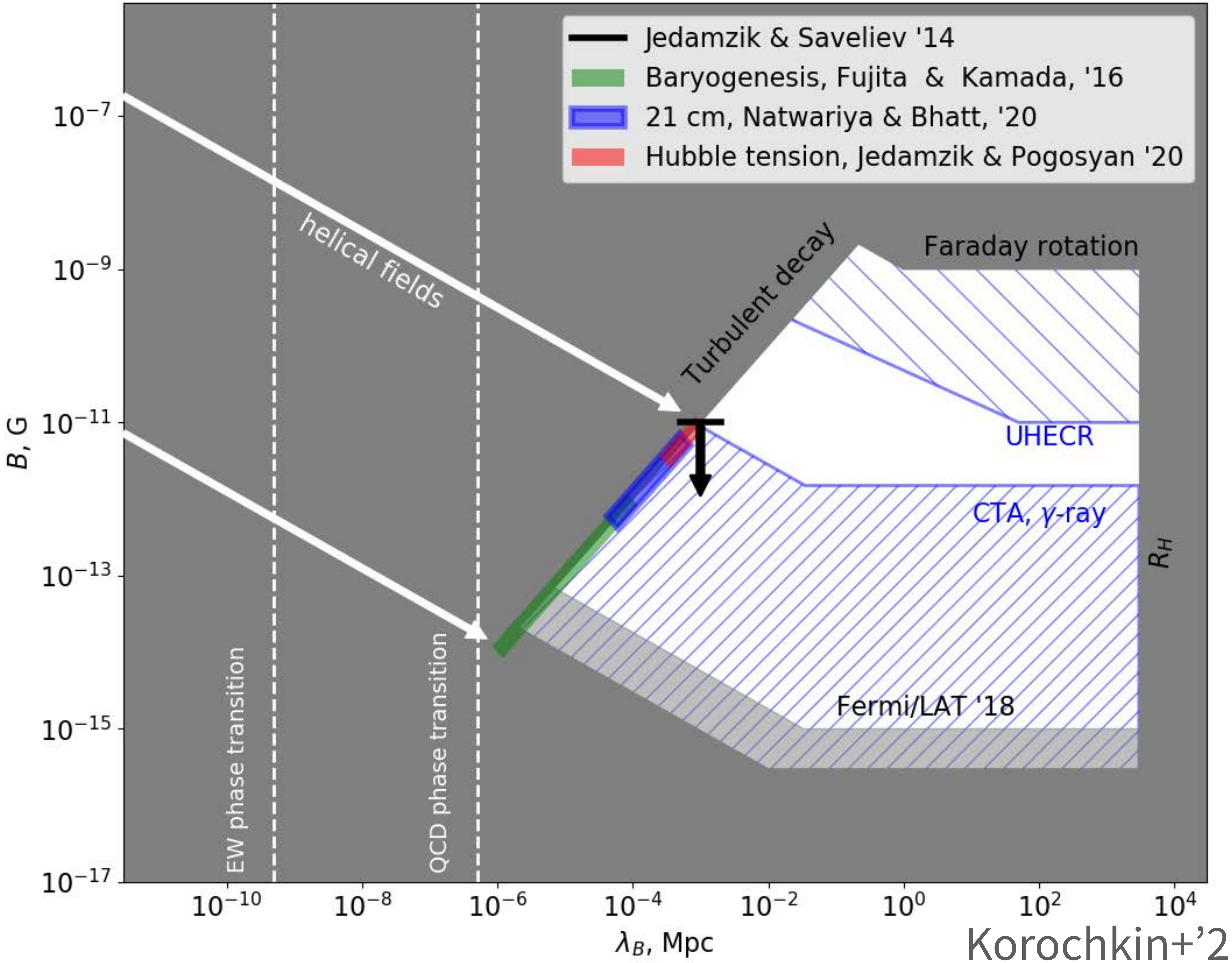
Takahashi+'12



Takahashi+'13

Bounds on the IGMF

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



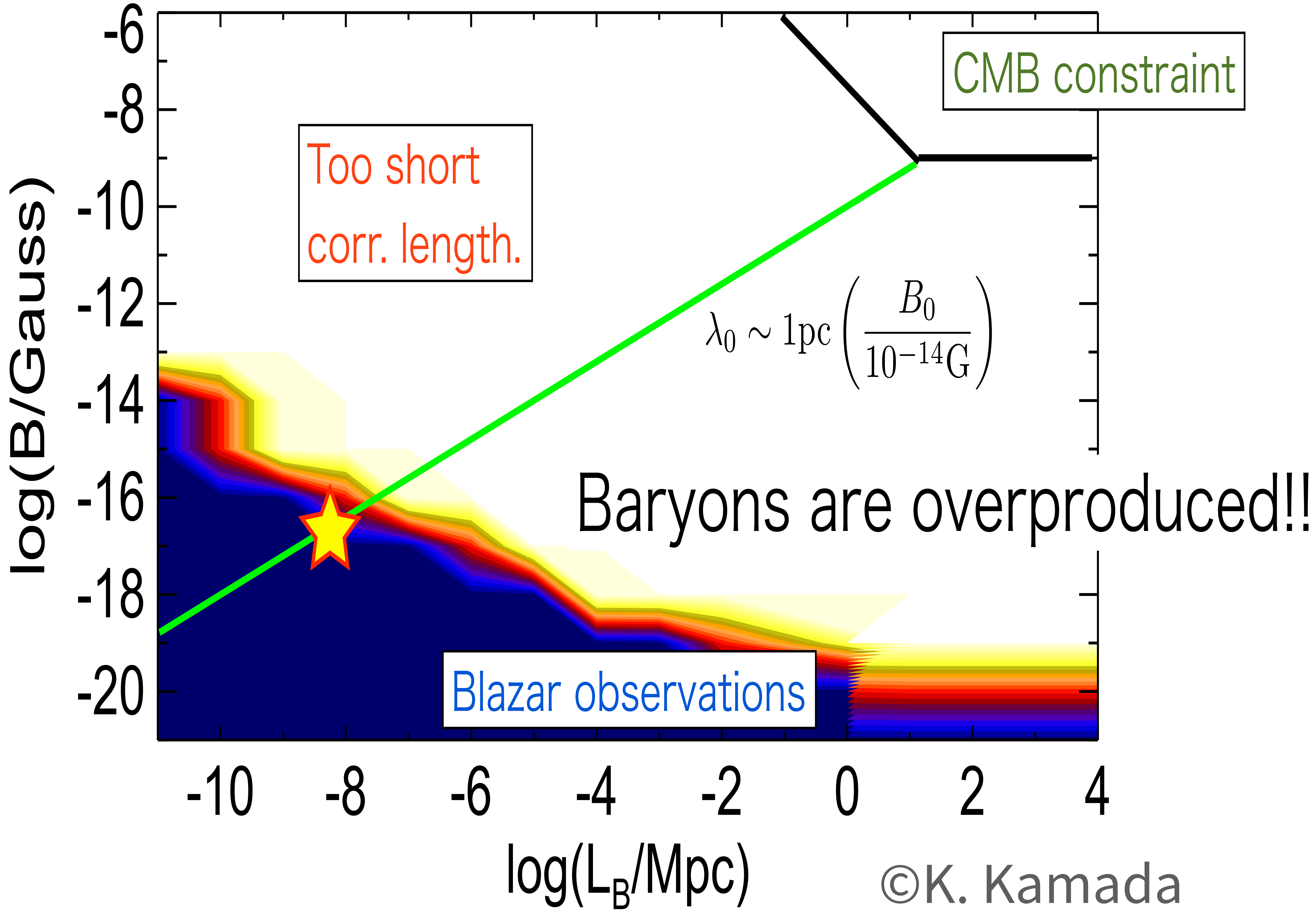
Korochkin+'20

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)



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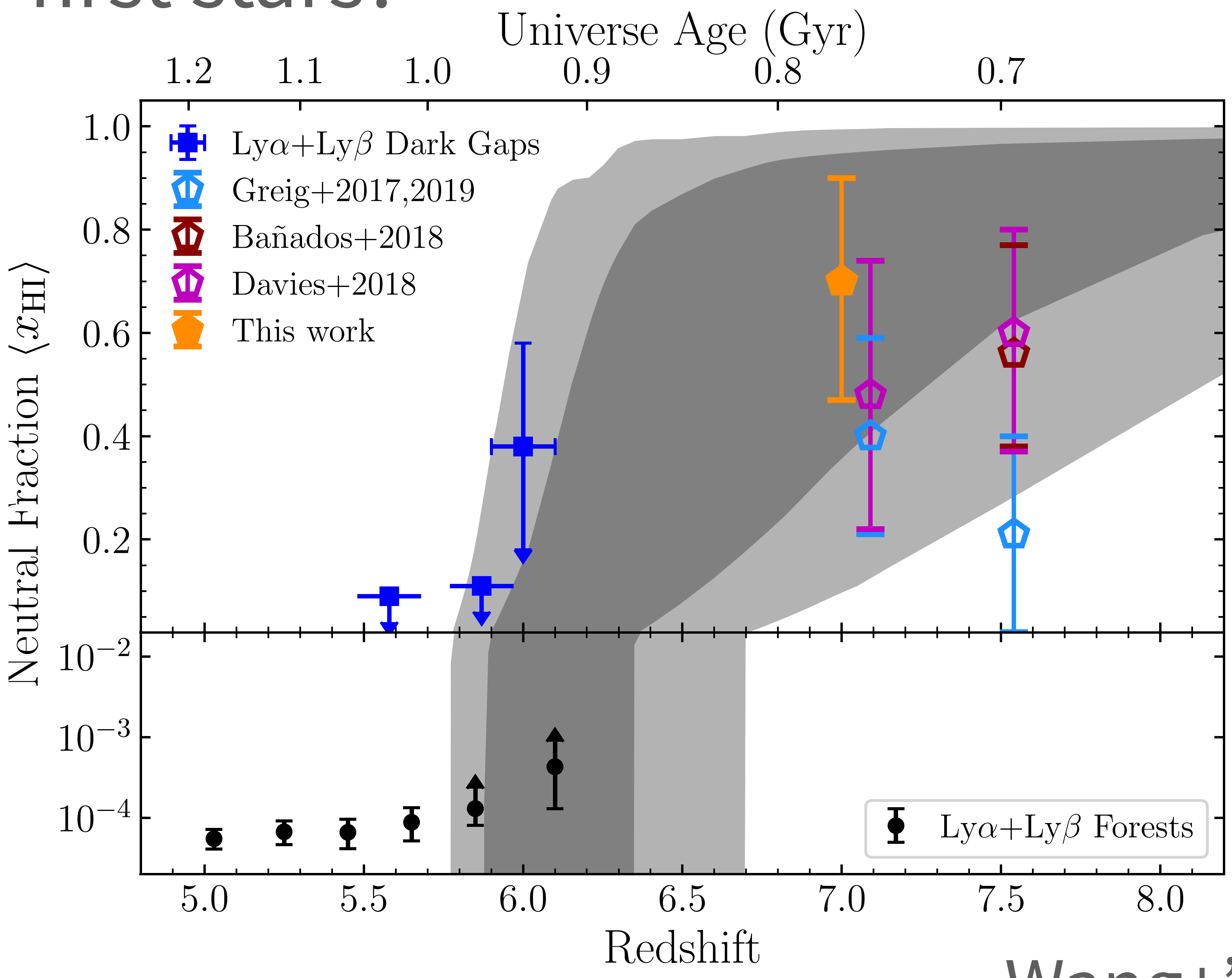
Reionization and Cosmic Expansion

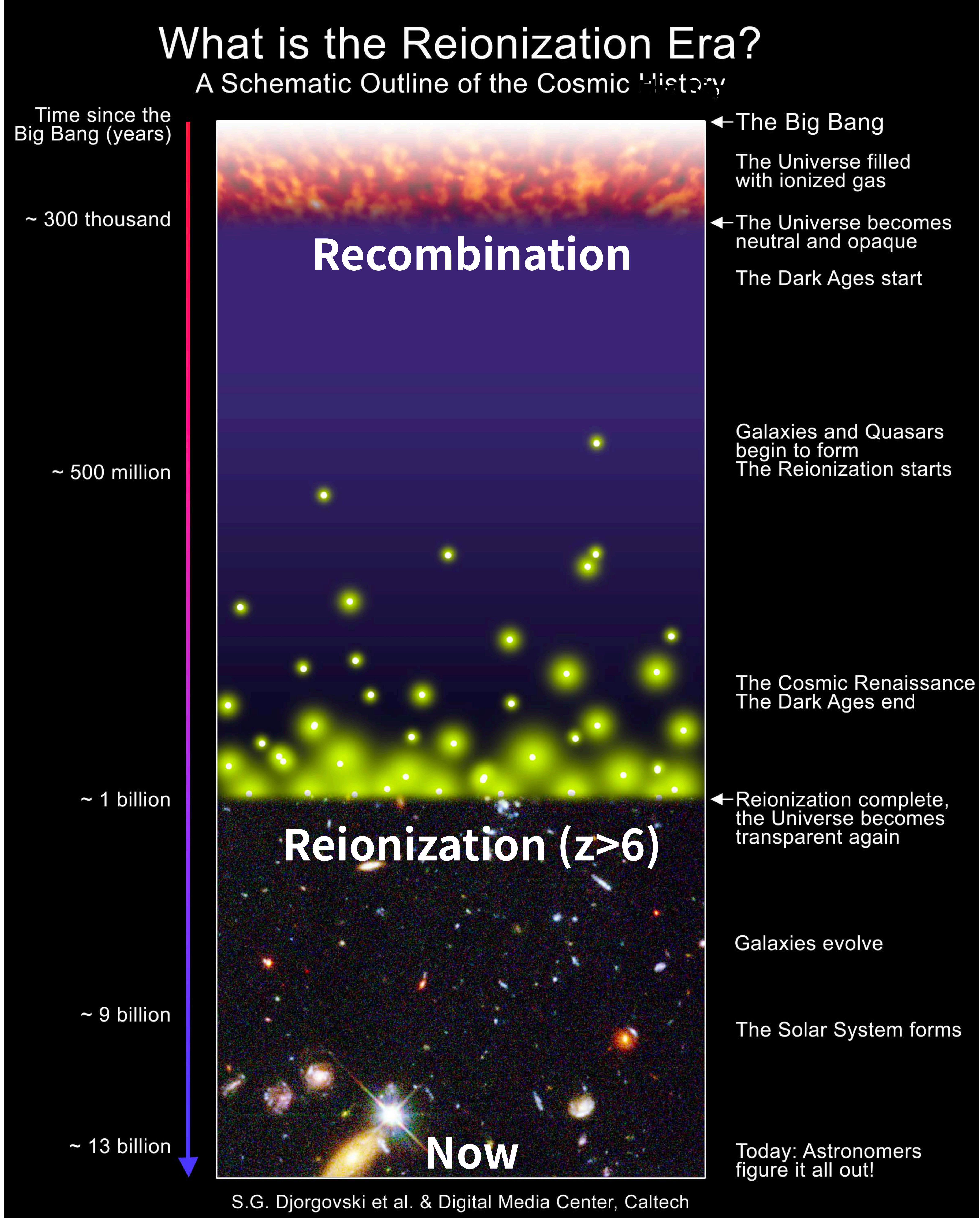
Cosmic Reionization

when was the universe ionized again?

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

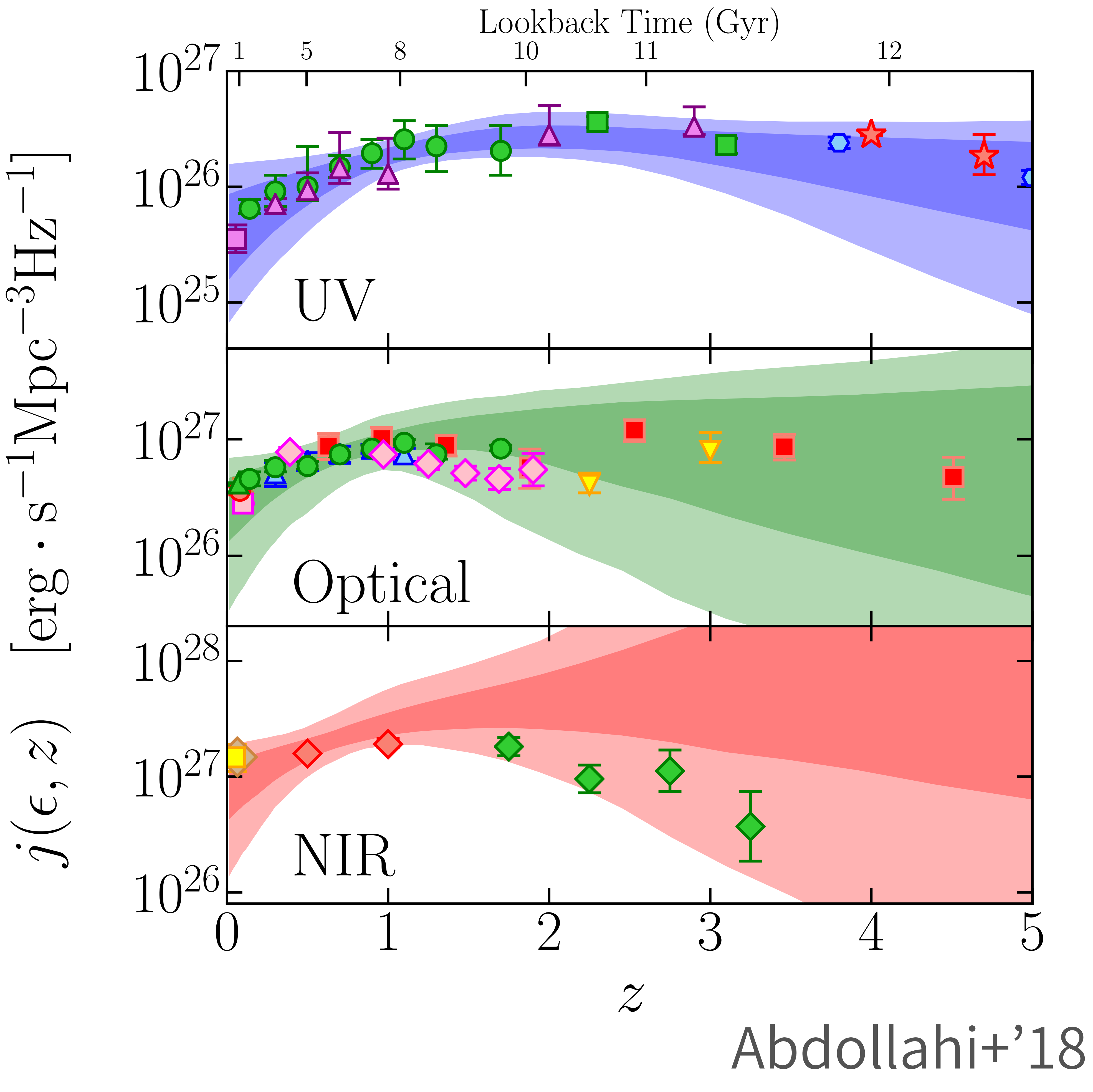


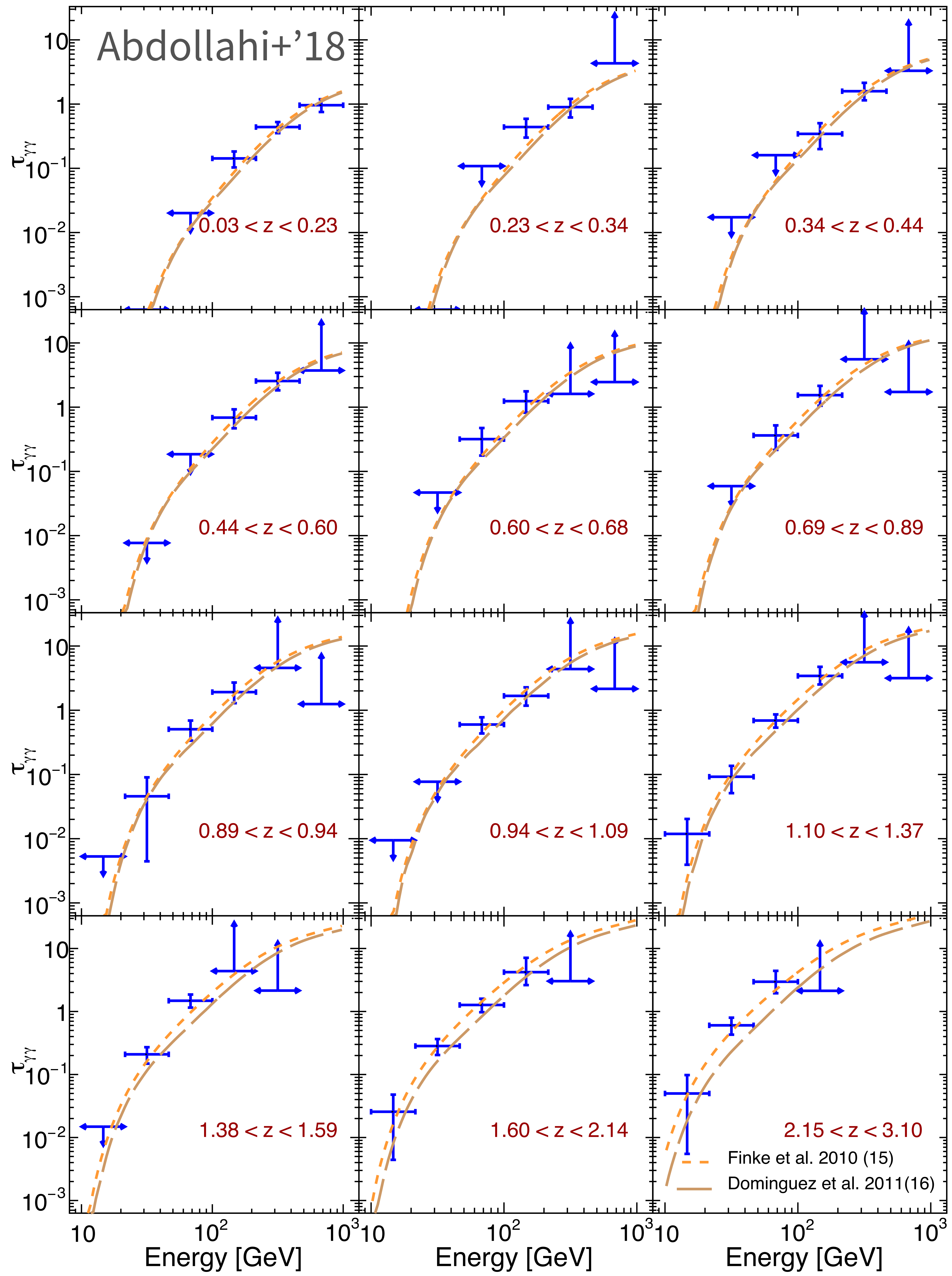
Wang+’20



Cosmic luminosity density

Estimation from gamma-ray opacity

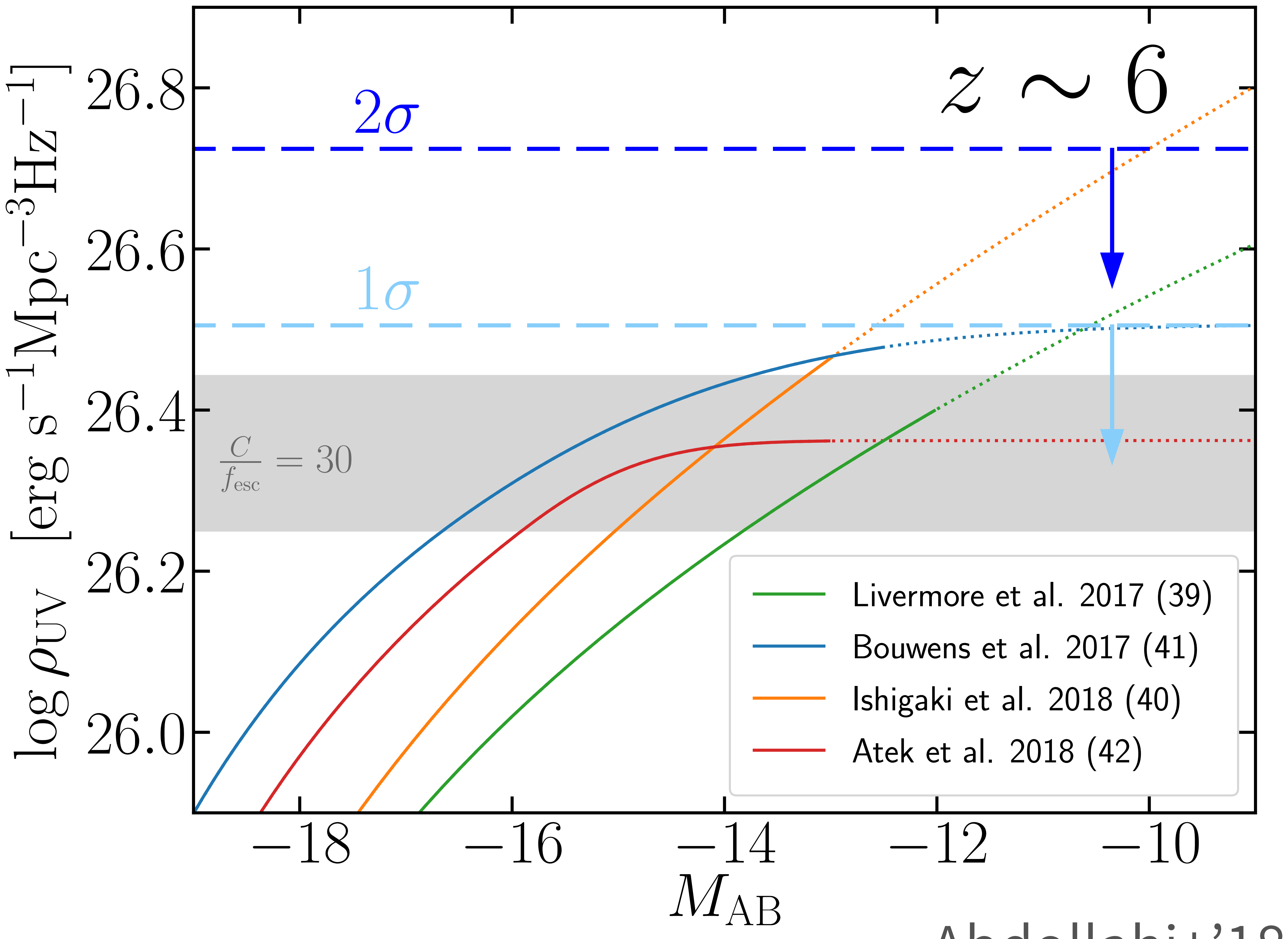




Constraints on the reioniztion history

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.

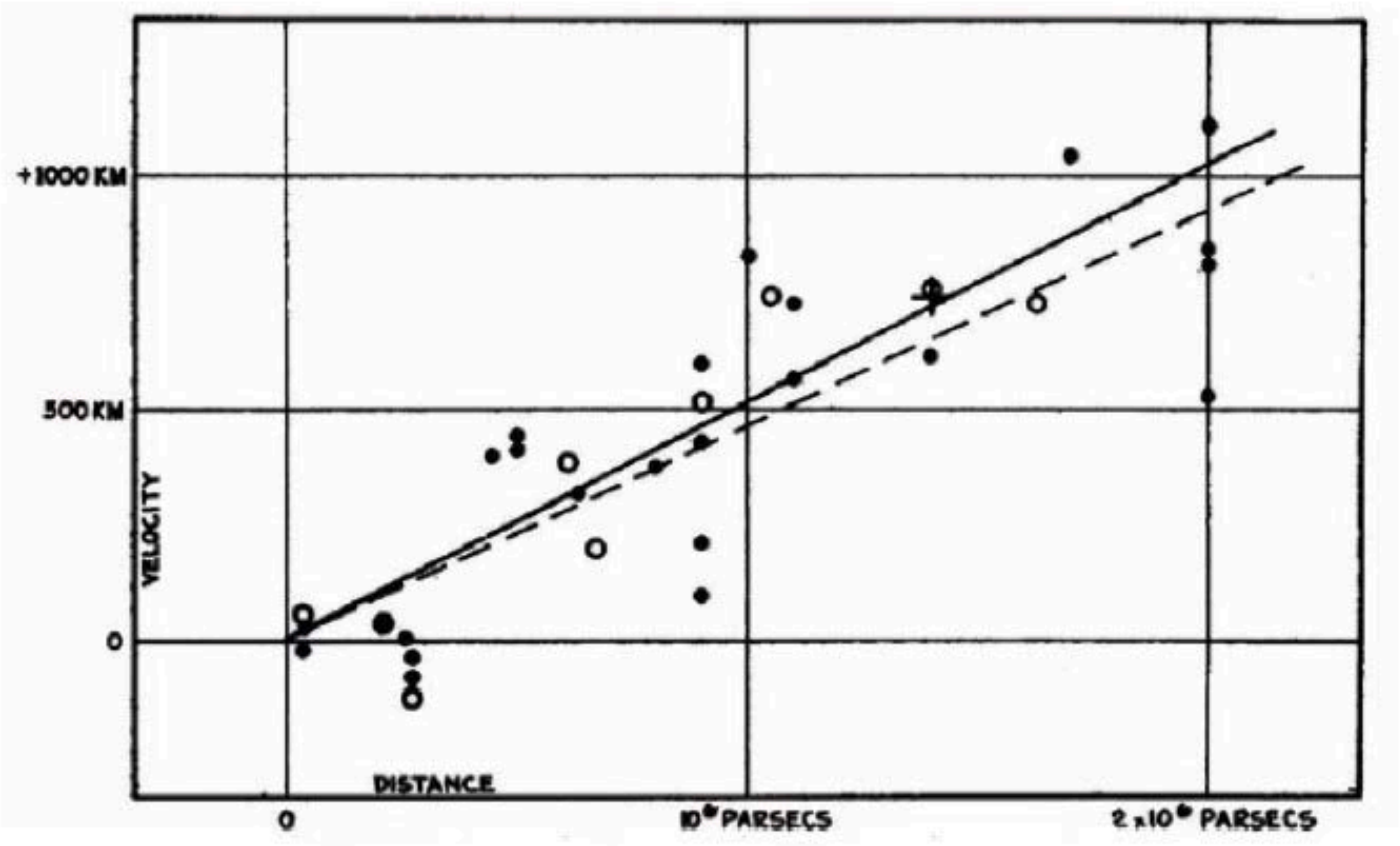


Abdollahi+'18

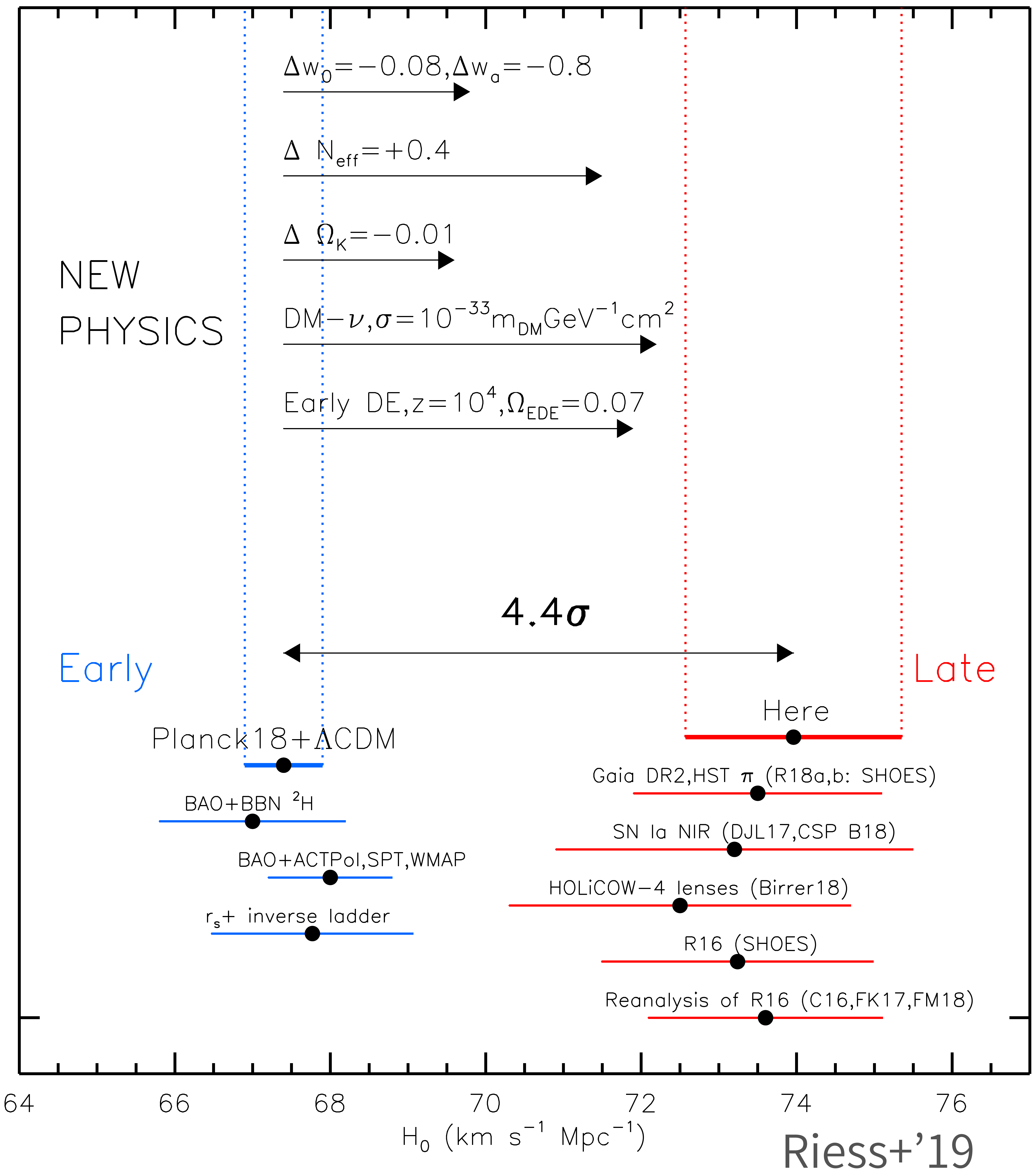
Hubble–Lemaître law

Tension in the H_0

- H_0 characterize the expansion of the universe.



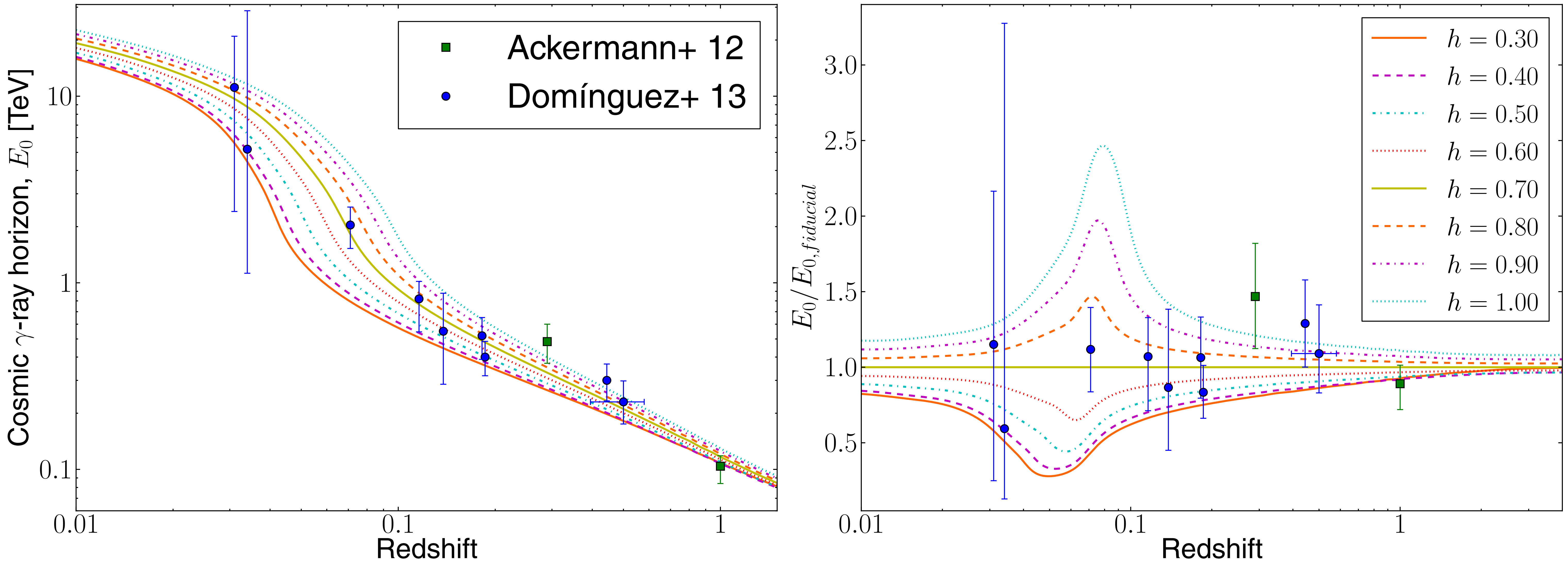
Hubble 1929



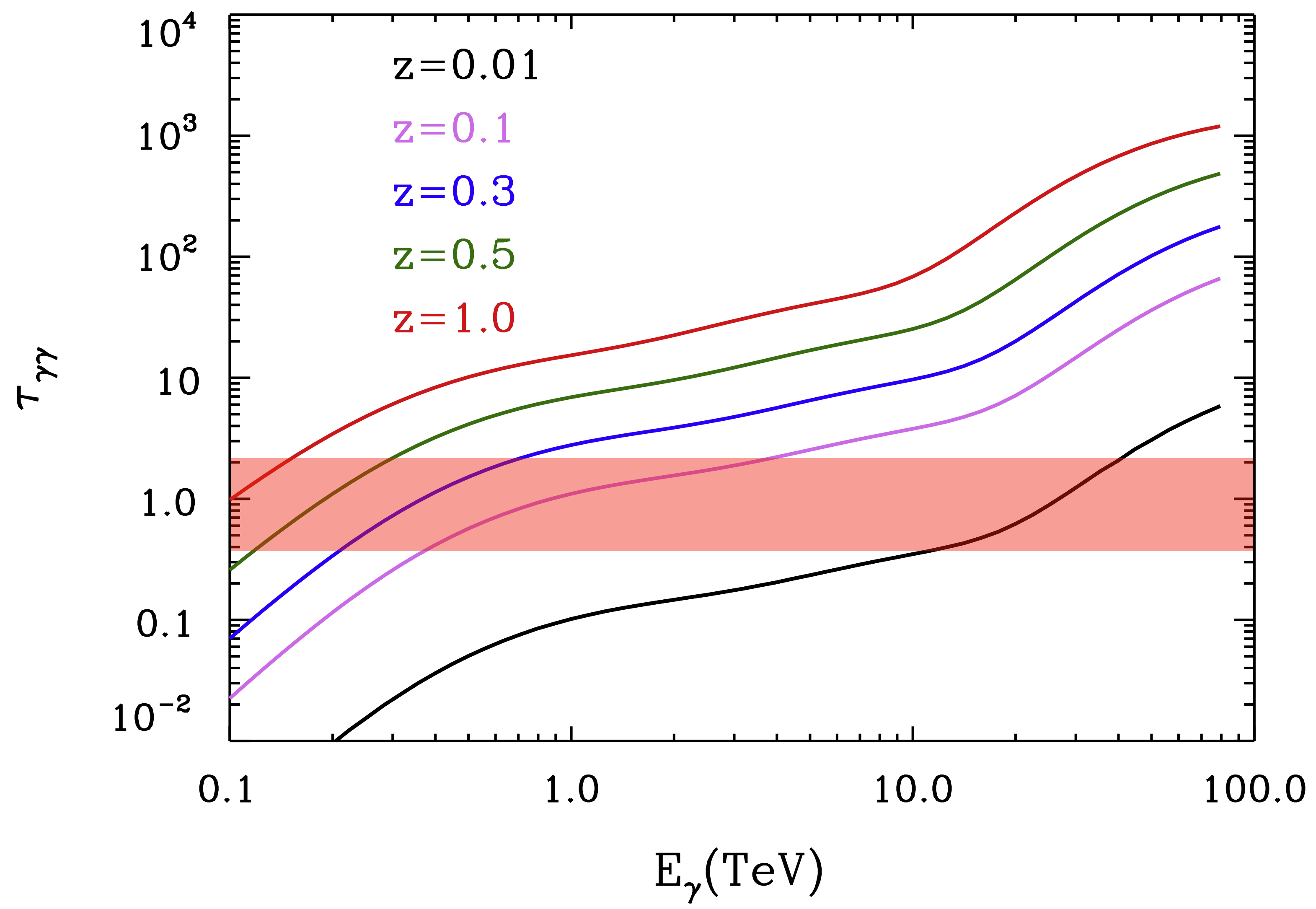
Riess+’19

Cosmic gamma-ray horizon & Hubble Constant

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



Dominguez+'13



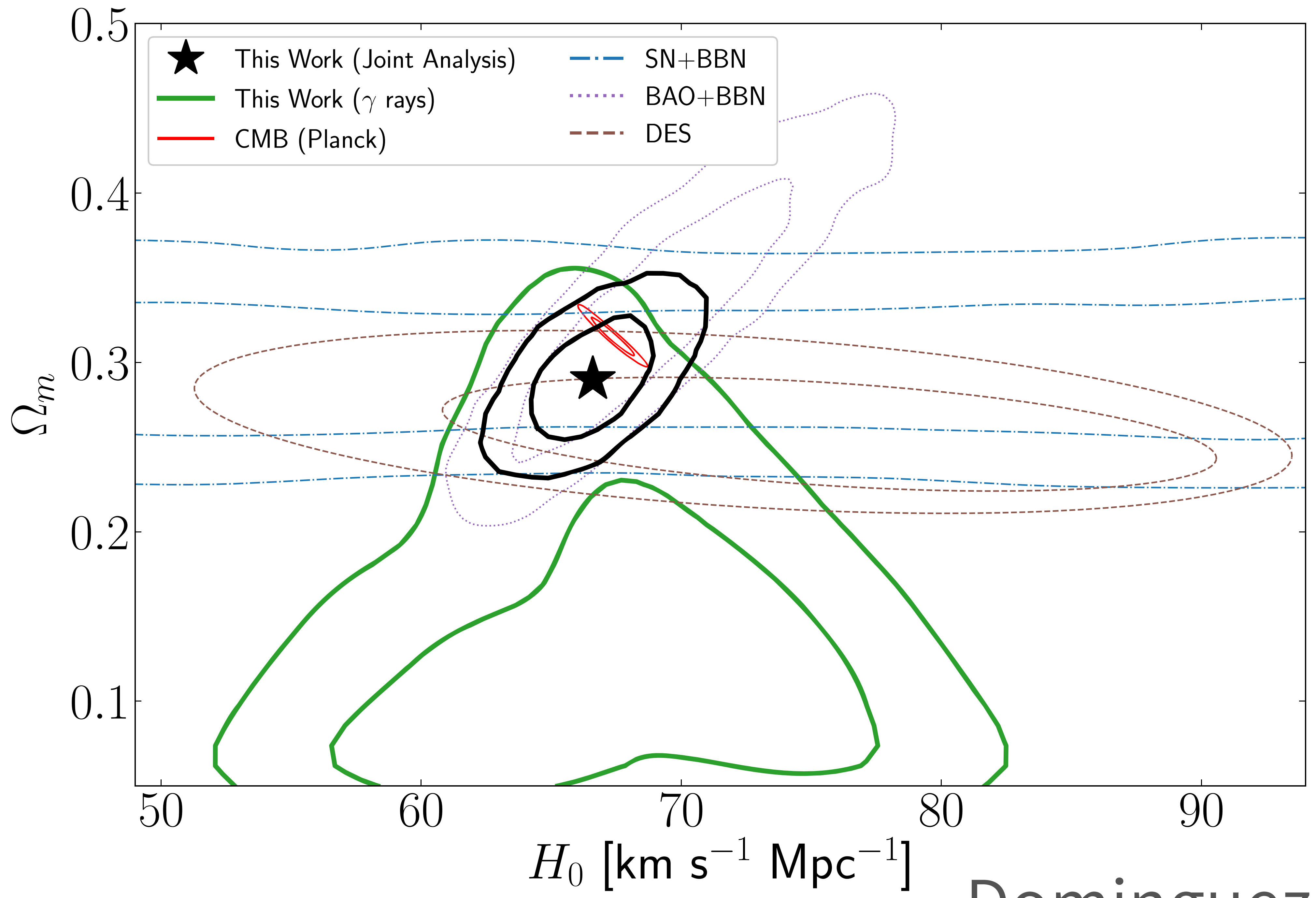
Dwek & Krennrich '13

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

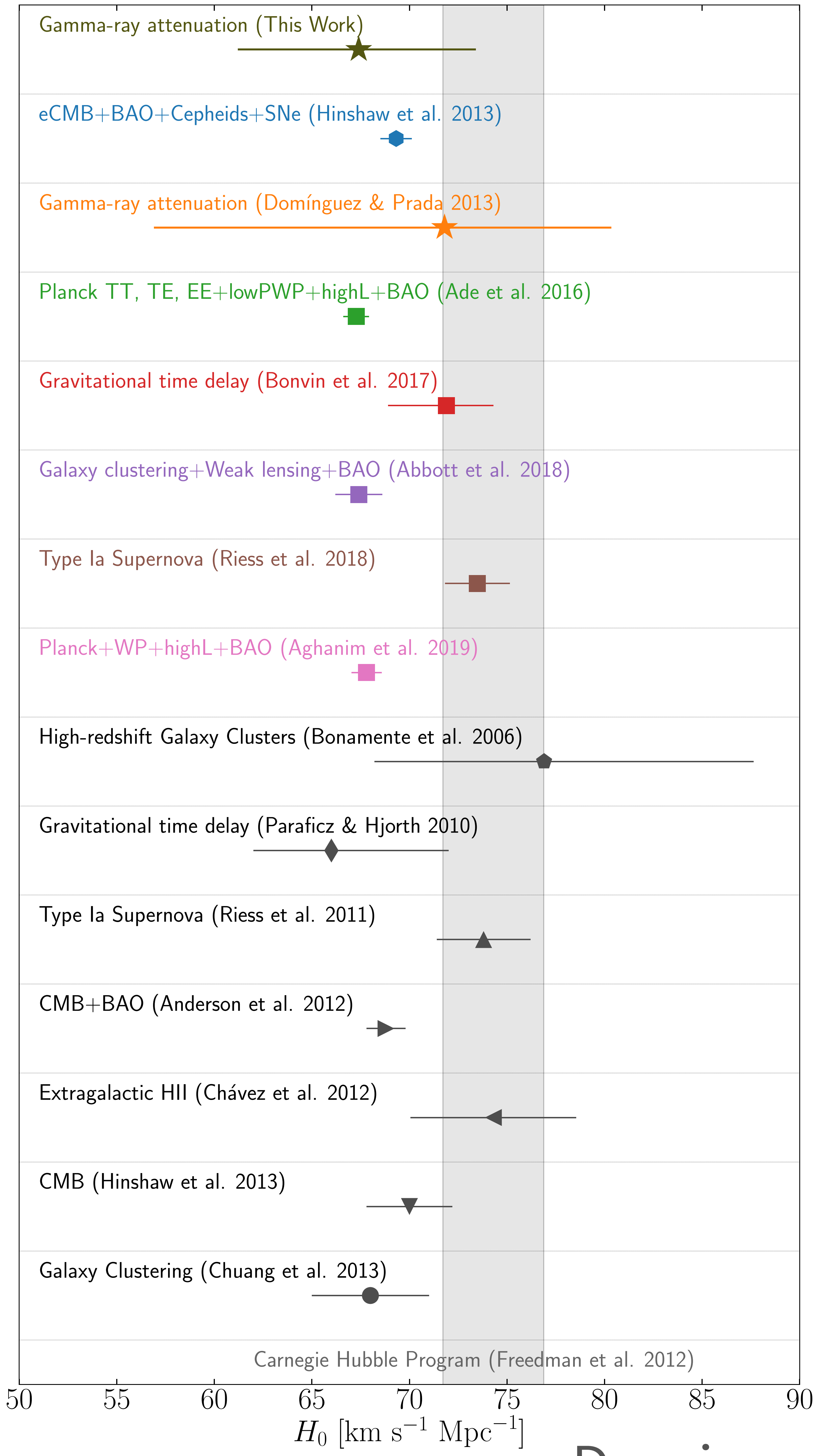
Constraint on H_0

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

- 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
  - $B_{\rm IGMF} \geq 10^{-16}$ G for $\lambda_{\rm coh} \geq 1$ Mpc with $\Delta t_{\rm flare} = 10$ yr
- Gamma-ray EBL measurements rules out some of galaxy evolution models from reionization data.
  - It also tells that $H_0 = 67.5 \pm 2.1$ km s^{-1} Mpc^{-1}.