Neutrino Emission from Blazars

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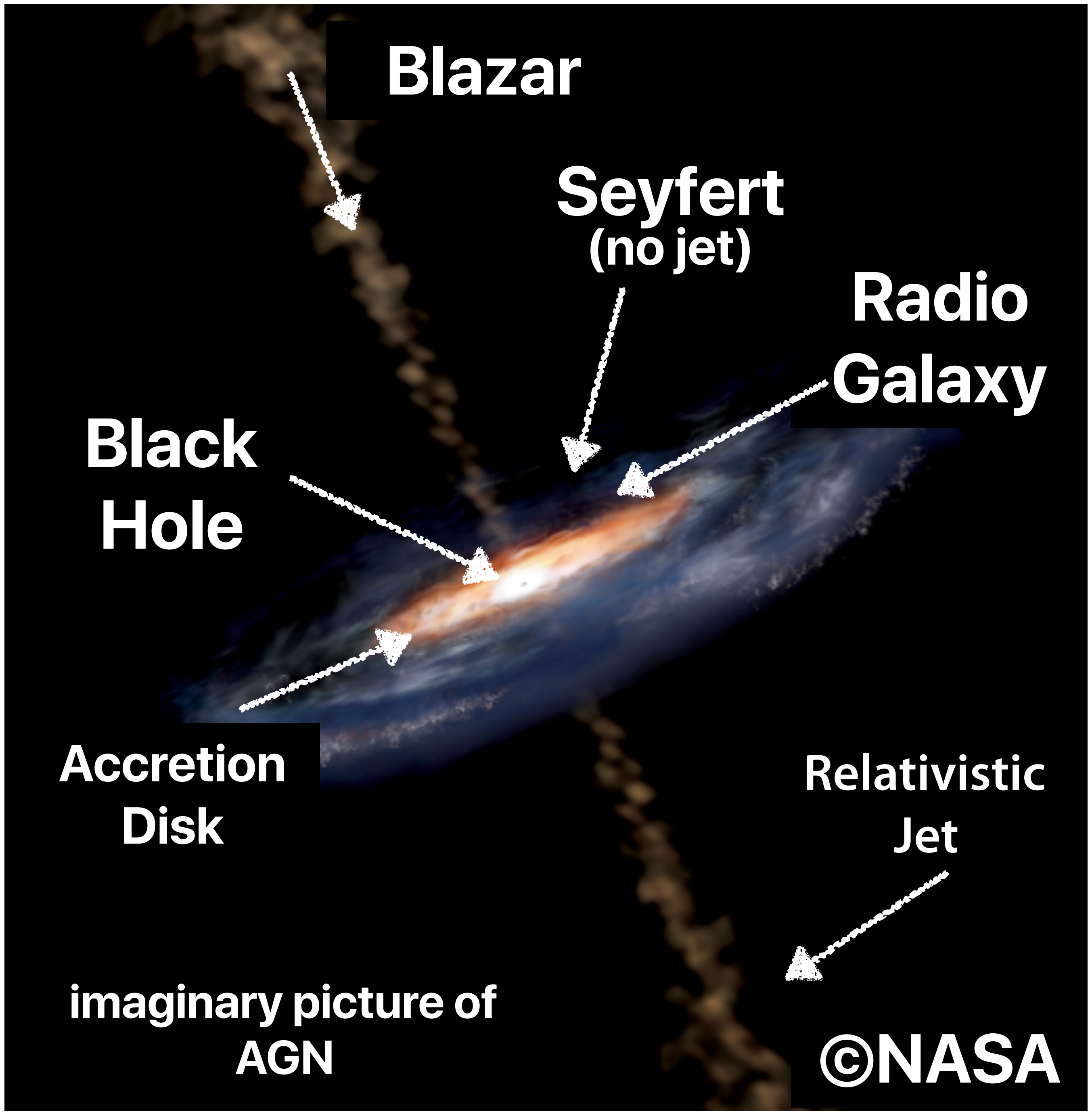
Multi-Messenger WS @ Chiba Univ., 2018-03-26

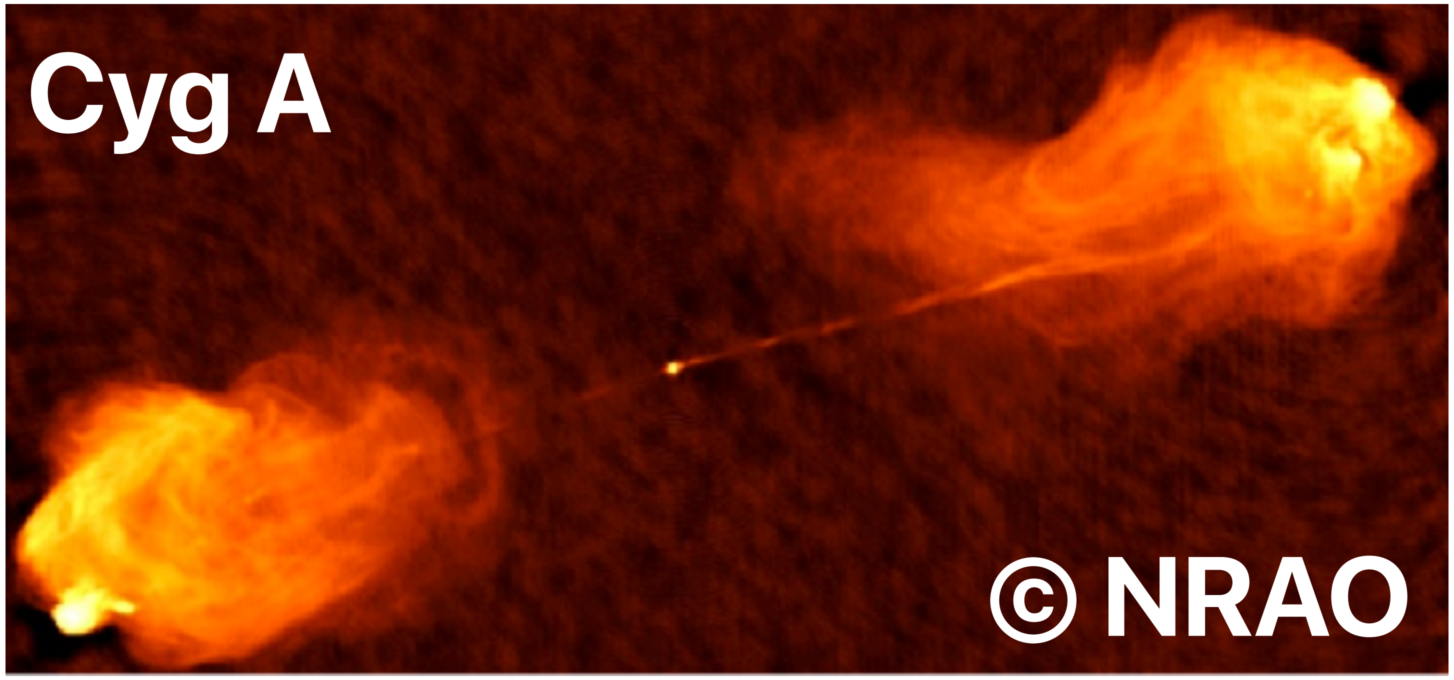
Contents

Active Galactic Nuclei (AGNs)

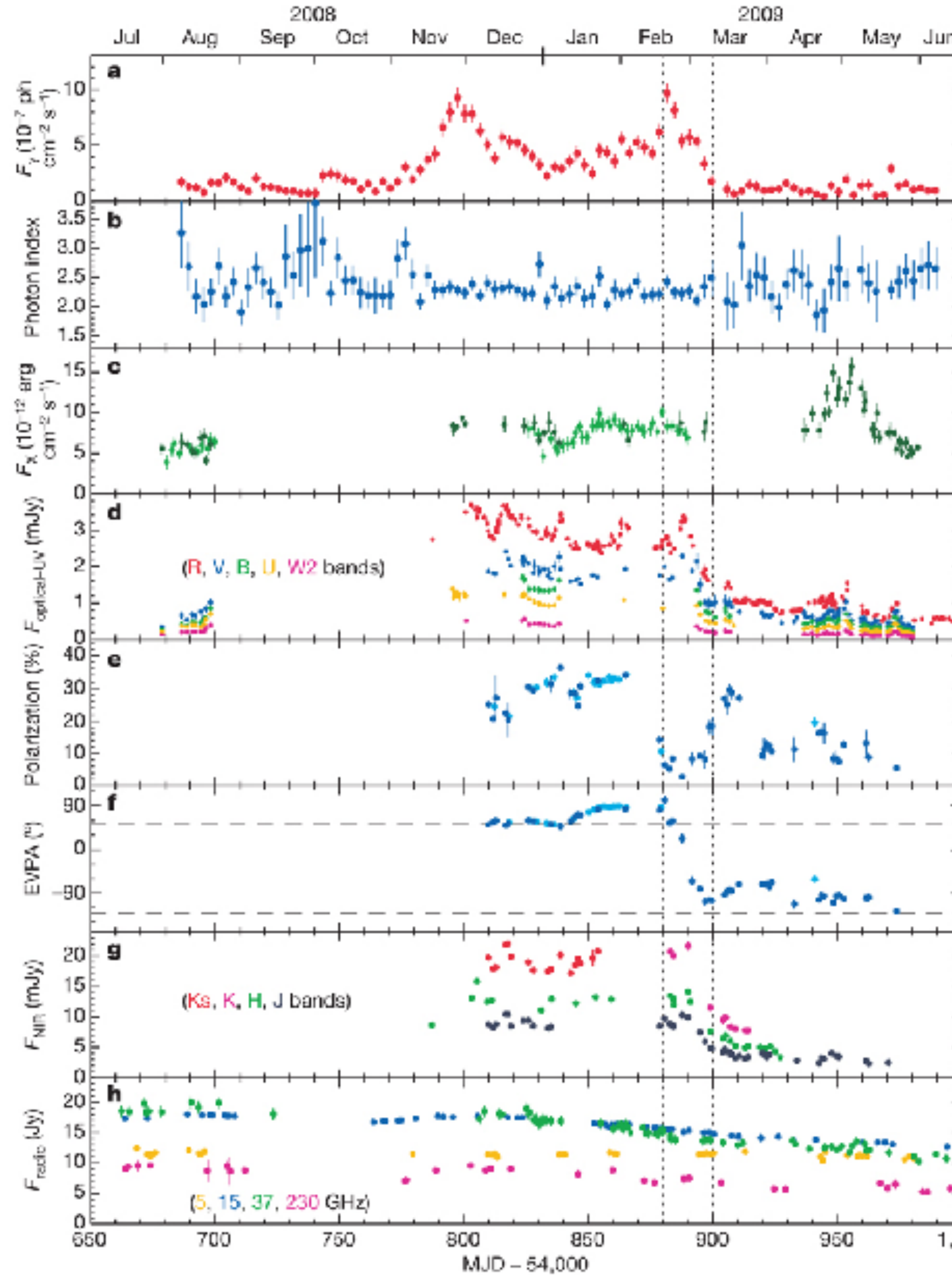


- $>10^6$ solar mass @ galactic center
    - Correlate with various physical parameters of host galaxies
- Gas accretion -> brighter than the galaxy (active galactic nuclei: AGNs)
    - Various population
    - Relativistic jet
        - Ultra-high-energy cosmic rays / high-energy neutrinos (?)
    - The SMBH of our galaxy does not show strong activities

Blazars



- AGNs whose relativistic jets pointing at us.
- Variable (⊿t ~ 1 day)
- ~10% polarization

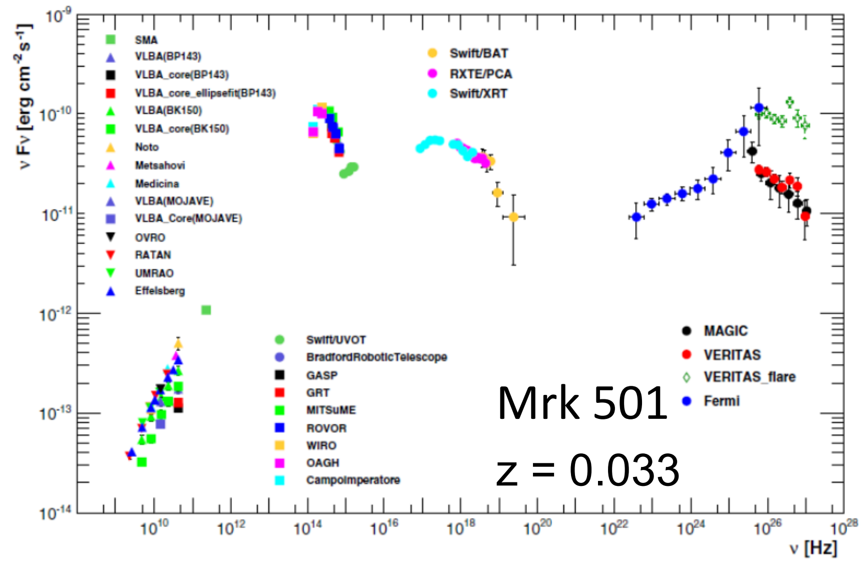


Abdo+'10

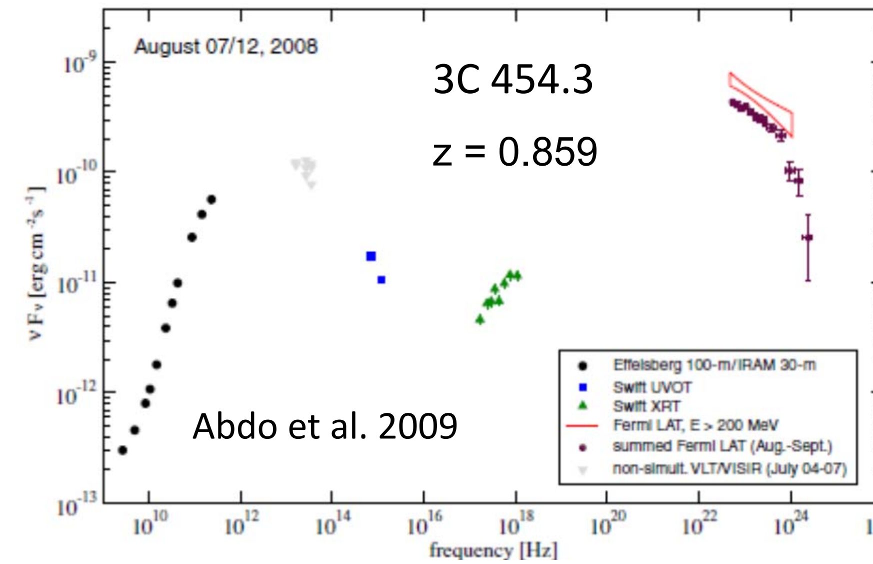
Individual Blazar Spectra

BL Lacs:
emission to VHE/TeV energies

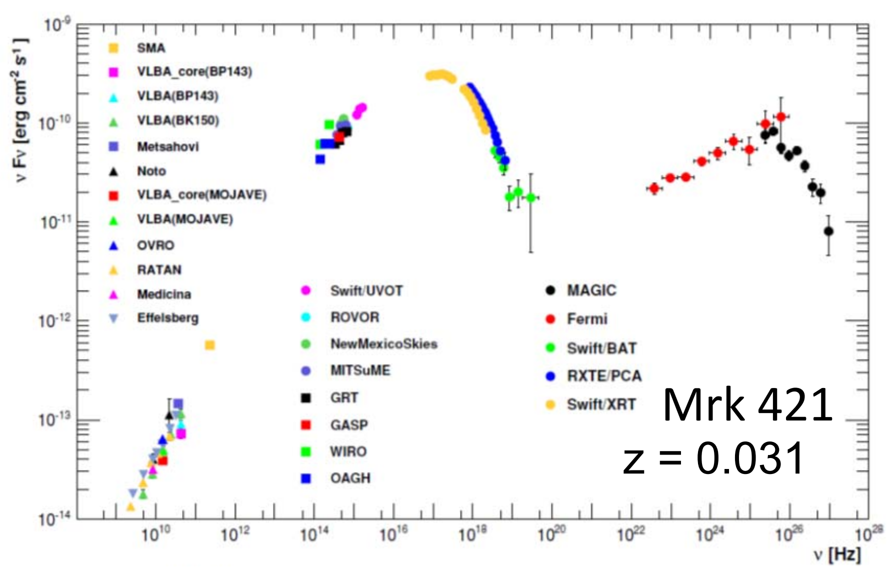
Flat-Spectrum Radio Quasars (FSRQs):
spectrum cutoff at GeV



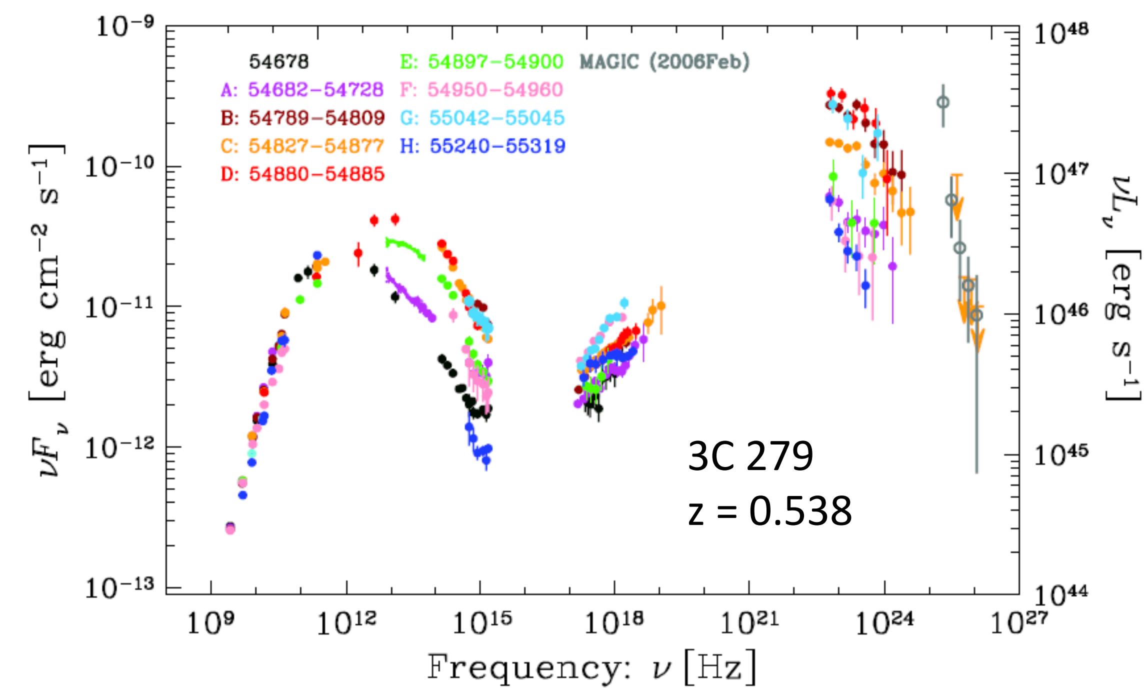
Abdo et al. 2011a



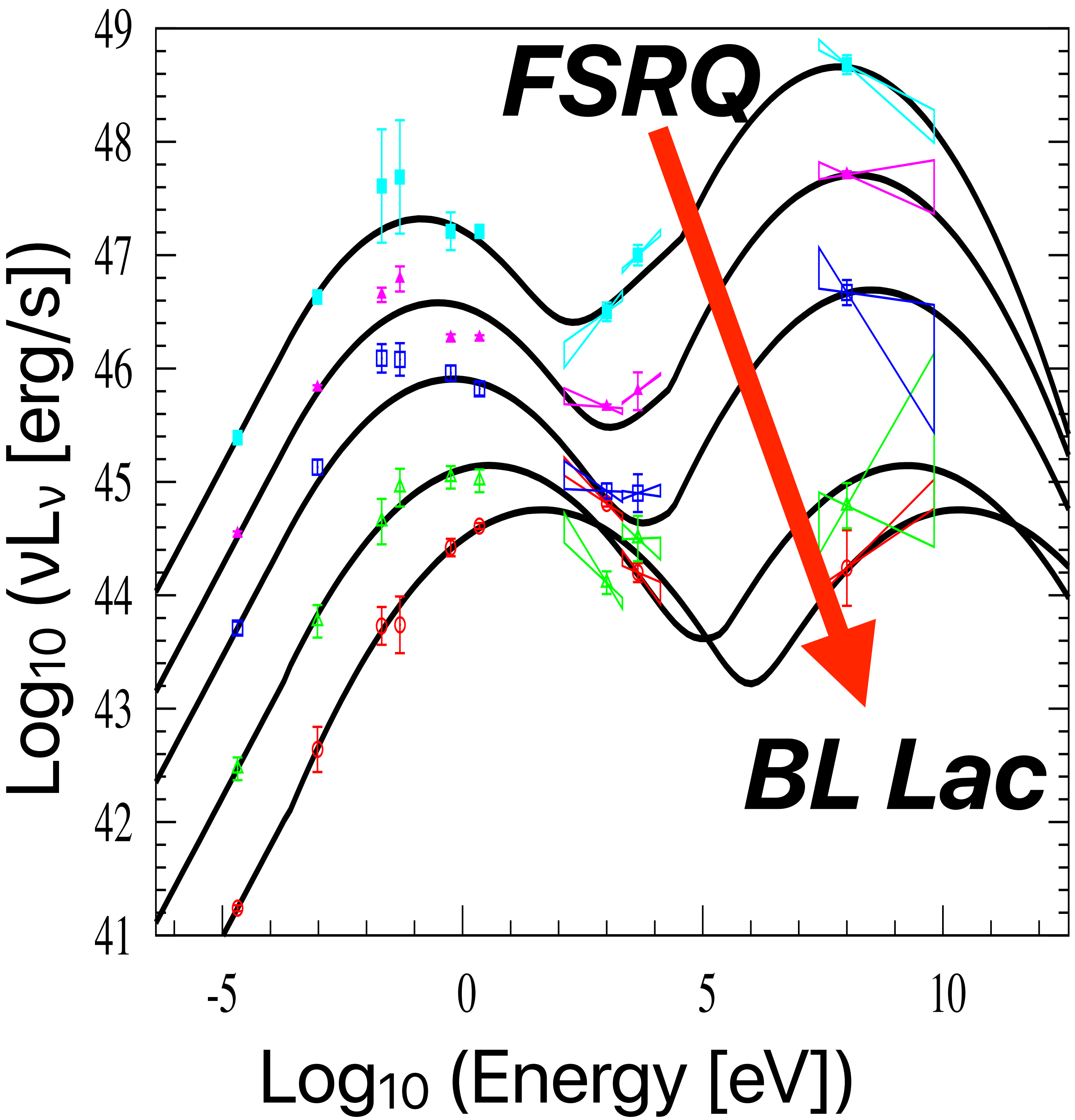
Abdo et al. 2011b



νF_ν [erg cm^{-2} s^{-1}]



Typical Spectra of Blazars



Fossati+'98, Donato+'01, YI & Totani '09

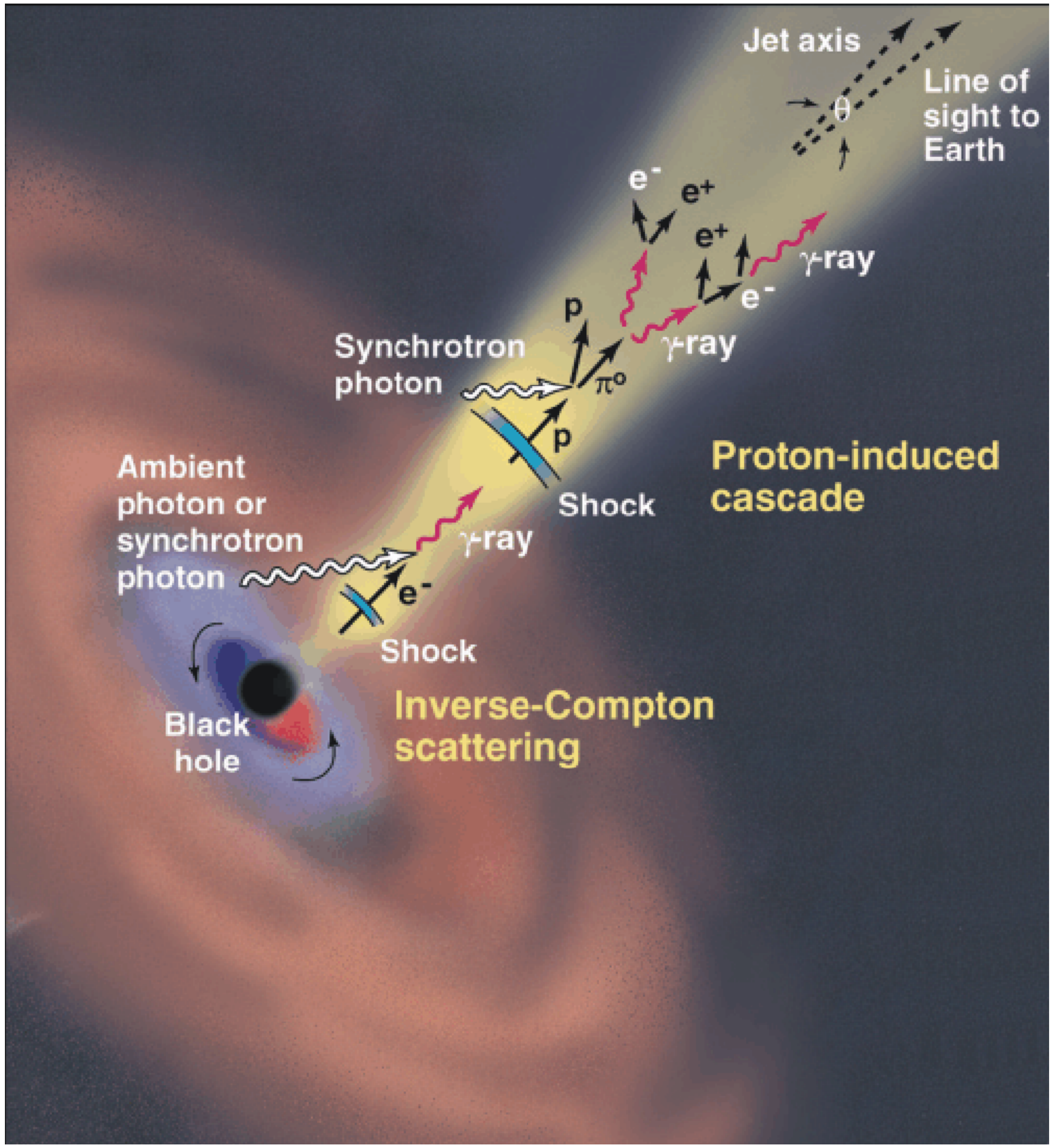
- Non-thermal emission from radio to gamma-ray
  - Two spectral humps

  ➡relativistic particles and intense photon fields

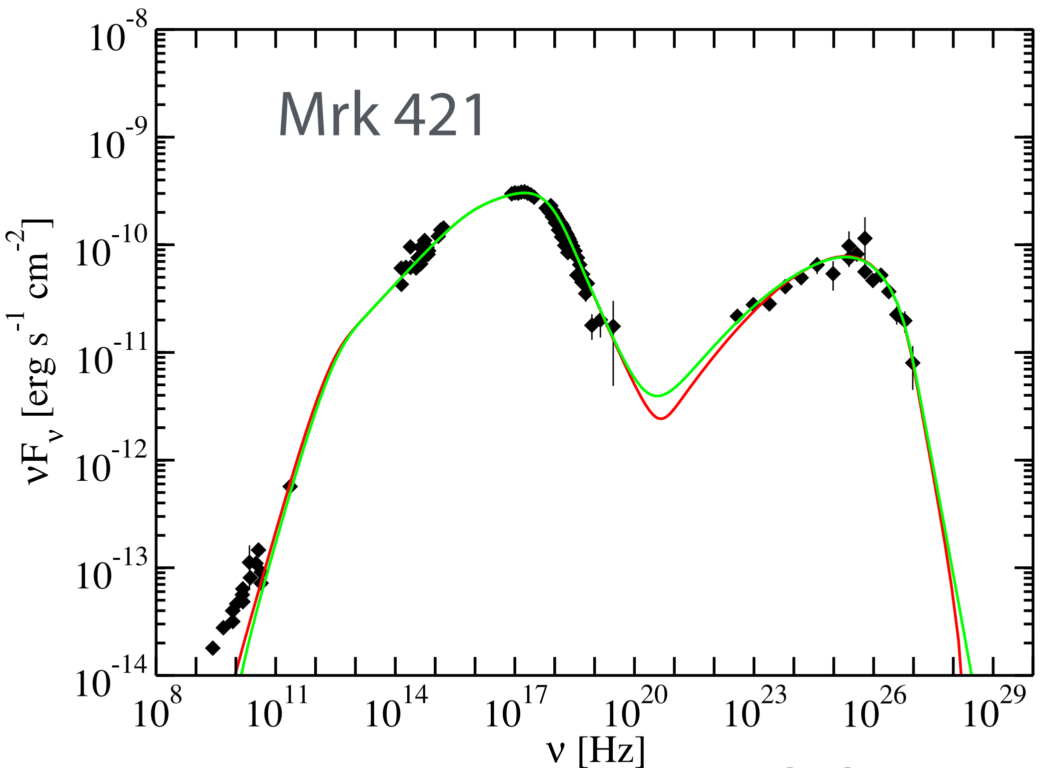
- Luminous blazars (FSRQs) tend to have lower peak energies (Fossati+'98;Kubo+'98;Donato+'01;Ghisellini+'17)

Blazar Emission Mechanism

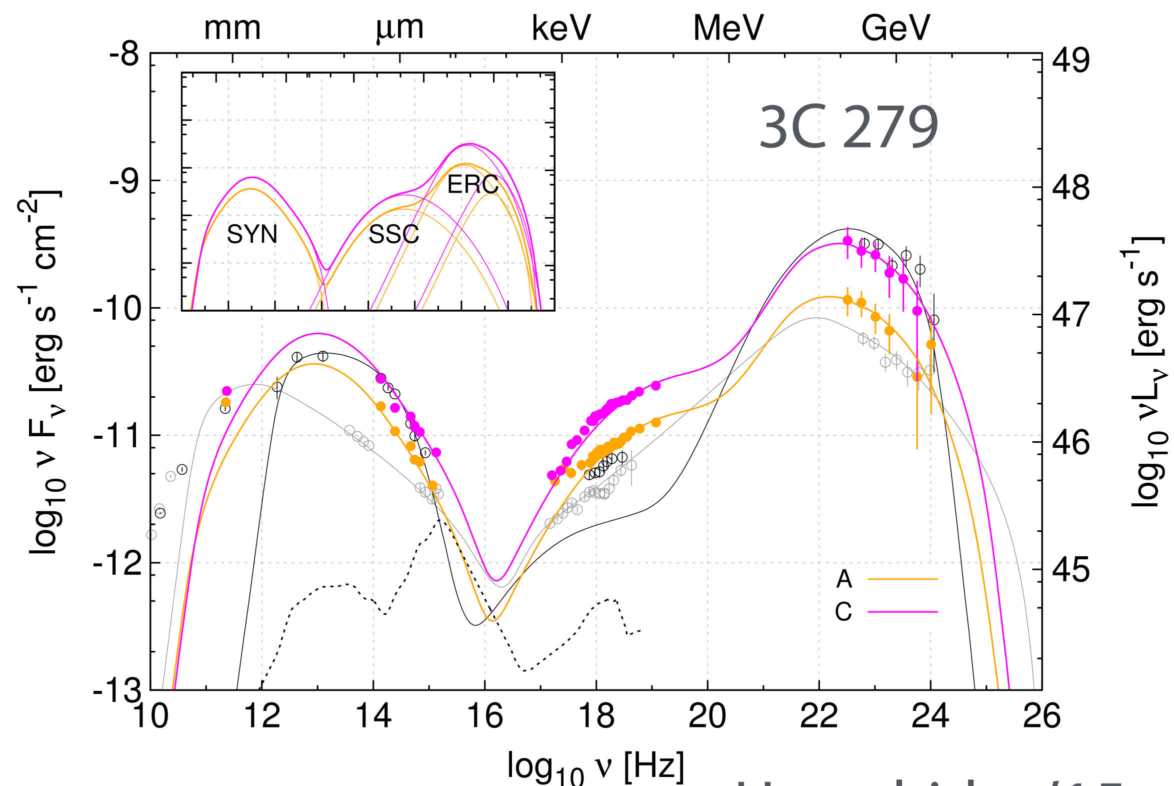
- **Leptonic model**
  - 1st hump: non-thermal e⁻ synchrotron
  - 2nd hump:
    - Synchrotron-Self-Compton (SSC)
    - External Inverse Compton (EIC)
- **Lepto-Hadronic model**
  - 1st hump: non-thermal e⁻ synchrotron
  - 2nd hump:
    - proton (ion) synchrotron
    - photomeson production (cascade)



Leptonic Scenario



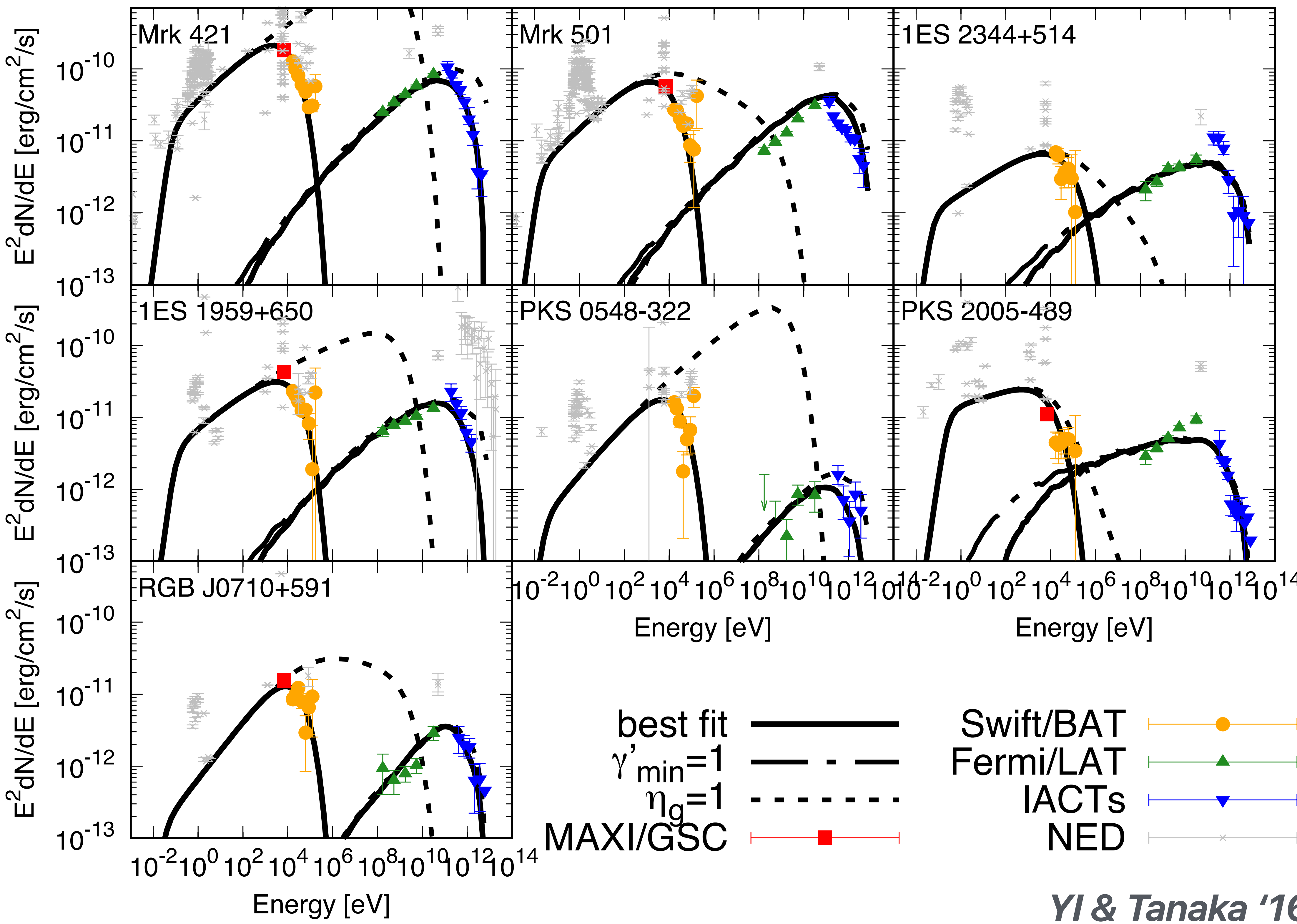
Abdo+’11



Hayashida+’15

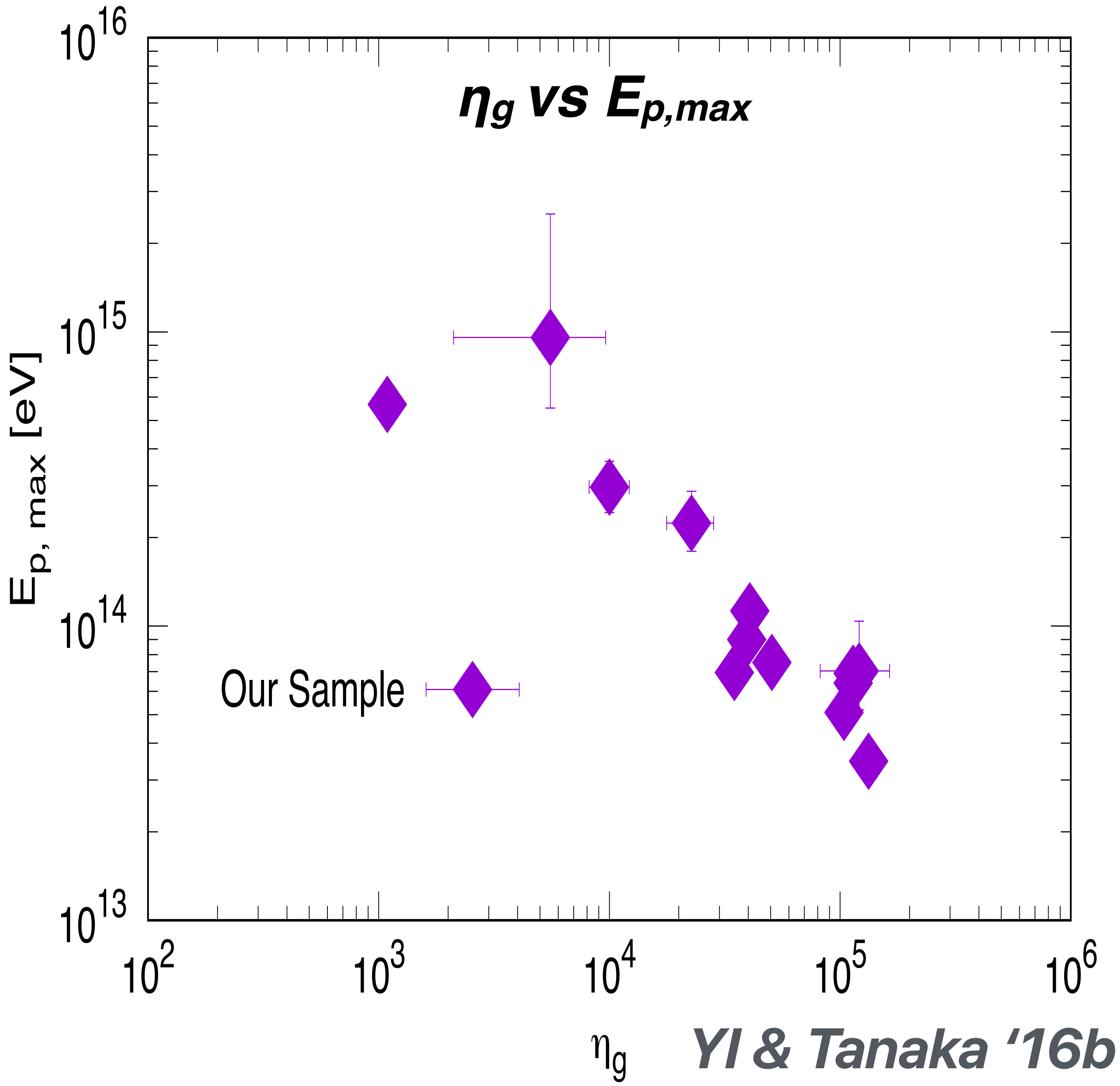
- Radiation from accelerated electrons in inner jets
    - shock? turbulence? reconnection? shear?
- One (multi)-zone synchrotron/SSC/EIC
- target photon: synchrotron, broad line regions (BLRs), dust torus, accretion disk

Spectral Fitting w/ a Leptonic Model



YI & Tanaka '16b

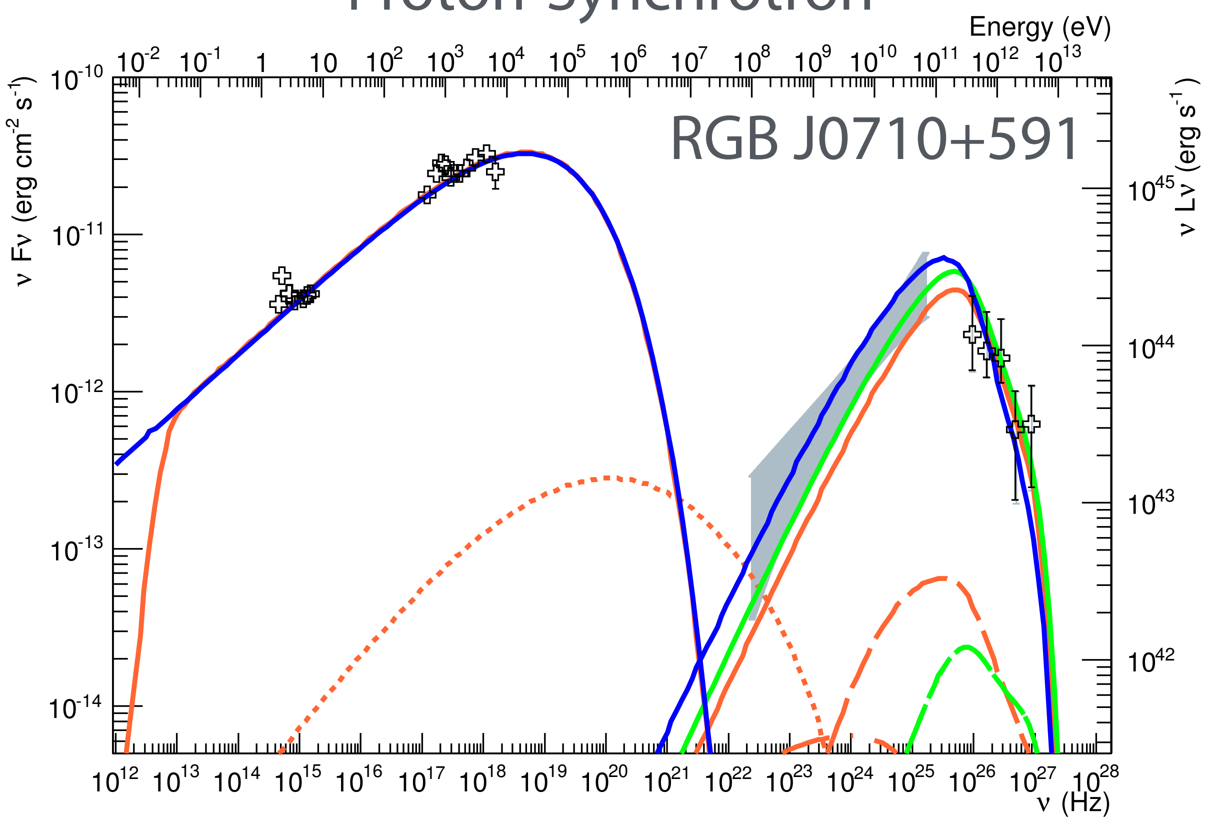
Maximum Proton Energy from HBLs



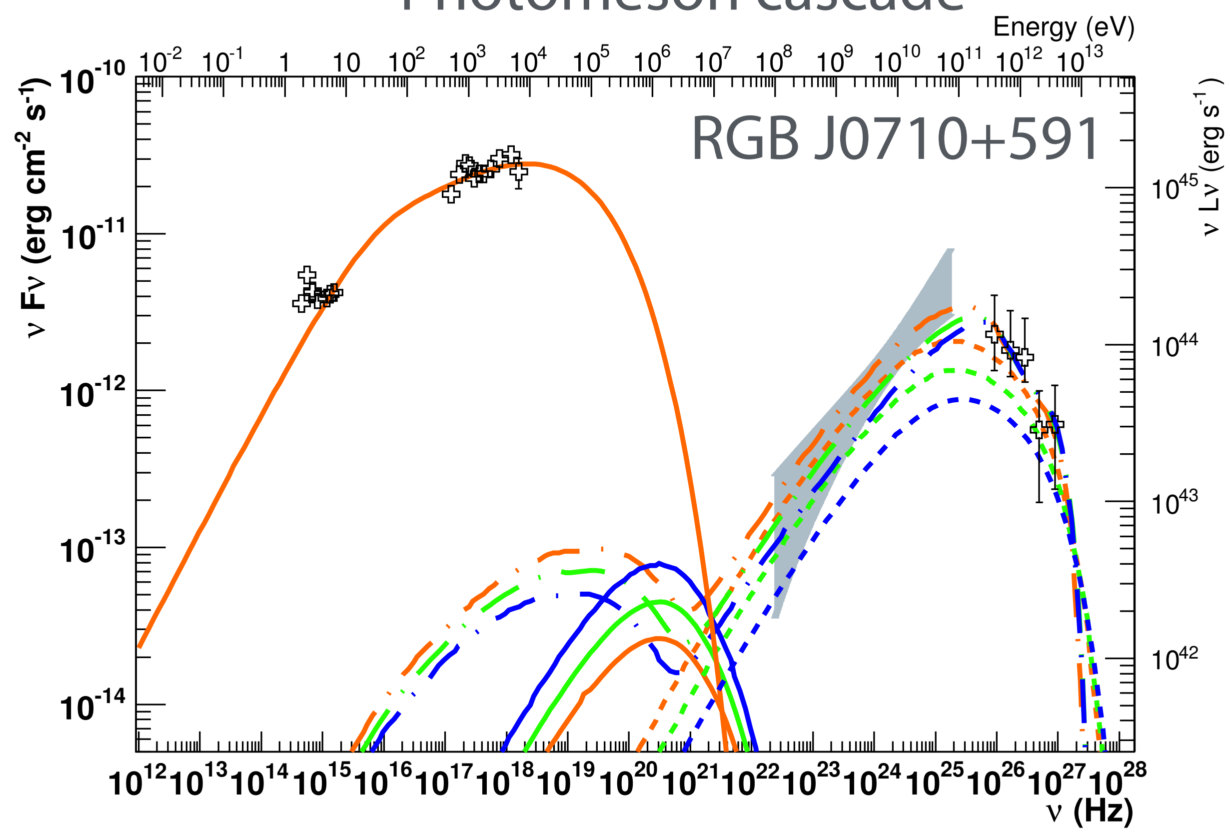
- HBLs are not efficient accelerators having $\eta_g \sim 5 \times 10^4$.
    - consistent with previous individual source studies (Inoue & Takahara '96, Sato+'08, Finke+'08)
- the maximum proton energy from low-luminosity HBLs is $<10^{15}$ eV.

Lepto-Hadronic Scenario

Proton-Synchrotron



Photomeson cascade

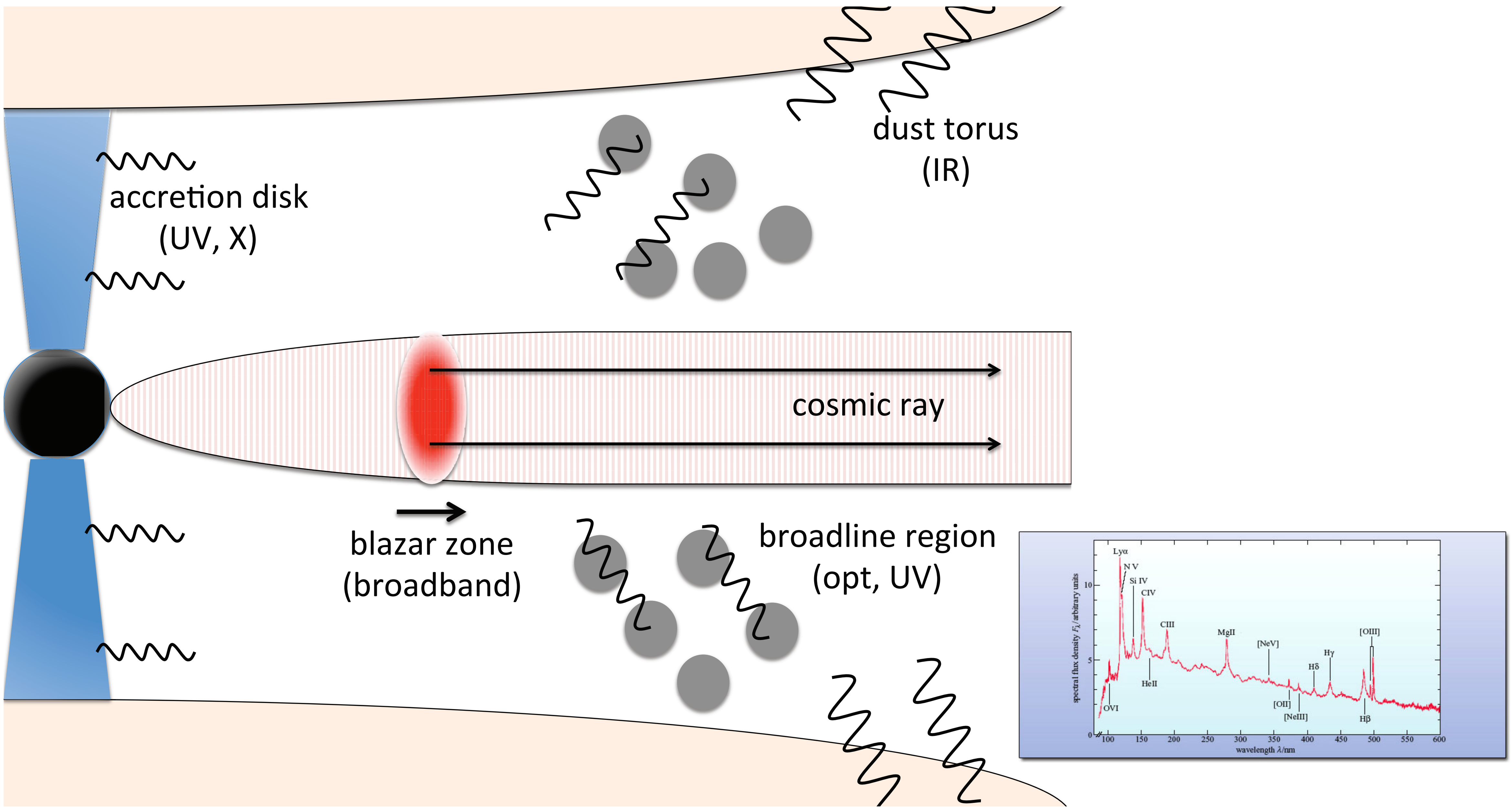


Cerutti+'14

- Proton (Ion) Synchrotron
  - p + B -> p + γ
- Photomeson interaction (cascade)
  - p+γ -> p/n, π -> p/n, ν, γ, e
- But, requires super-Eddington jet P_{jet} ~100 L_{Edd} ? (Sikora+'09, Zdziarski & Bottcher '15)

Photomeson Production in Blazars

Murase, YI, & Dermer '14



$$E'^{b}_{\nu} \approx 0.05 E'^{b}_{p} \simeq 80 \text{ PeV } \Gamma_1^2 (E'_s/10 \text{ eV})^{-1}$$ **inner jet photons**

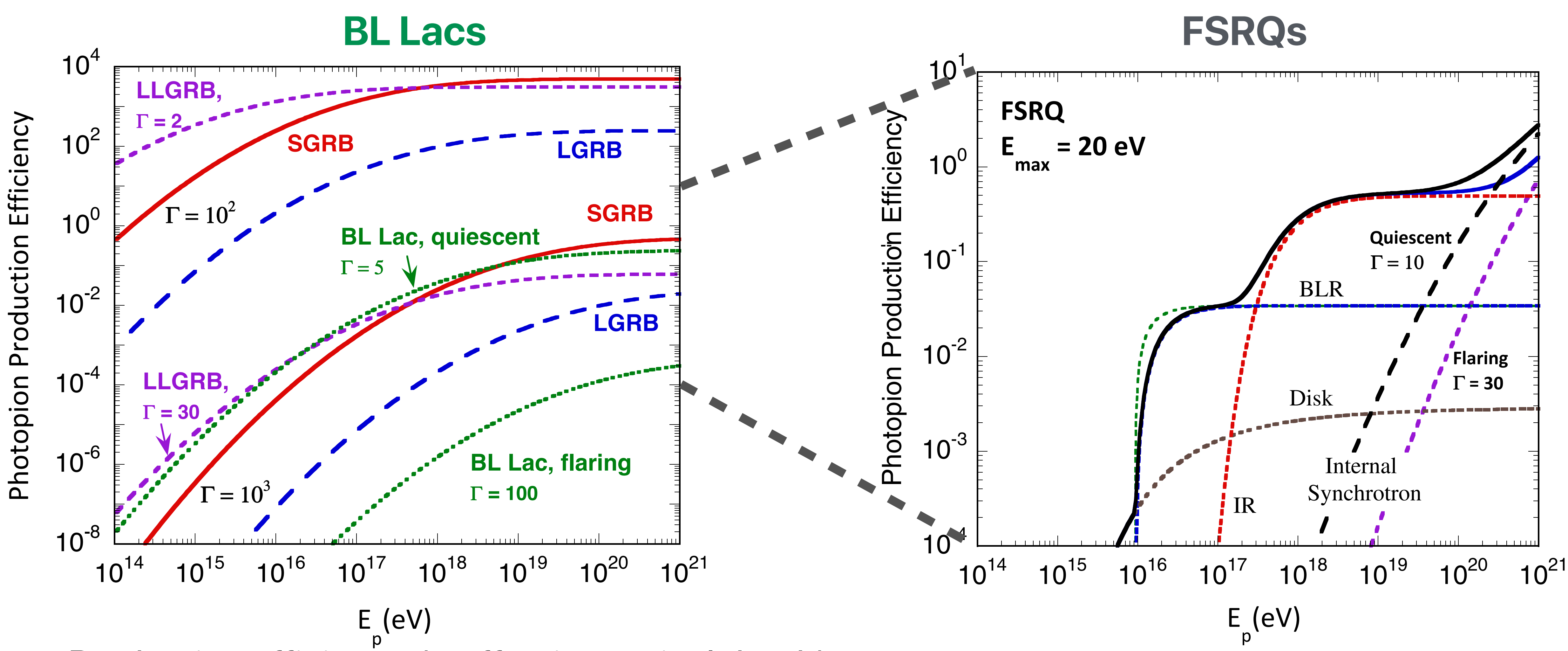
p$\gamma \rightarrow \Delta^+ \rightarrow \pi$ + N

$$E'^{b}_{\nu} \approx 0.05 (0.5 m_p c^2 \bar{\varepsilon}_\Delta / E'_{\rm BL}) \simeq 0.78 \text{ PeV}$$ **BLR photons**

$$E'^{b}_{\nu} \simeq 0.066 \text{ EeV} (T_{\rm IR}/500 \text{ K})^{-1}$$ **IR dust photons**

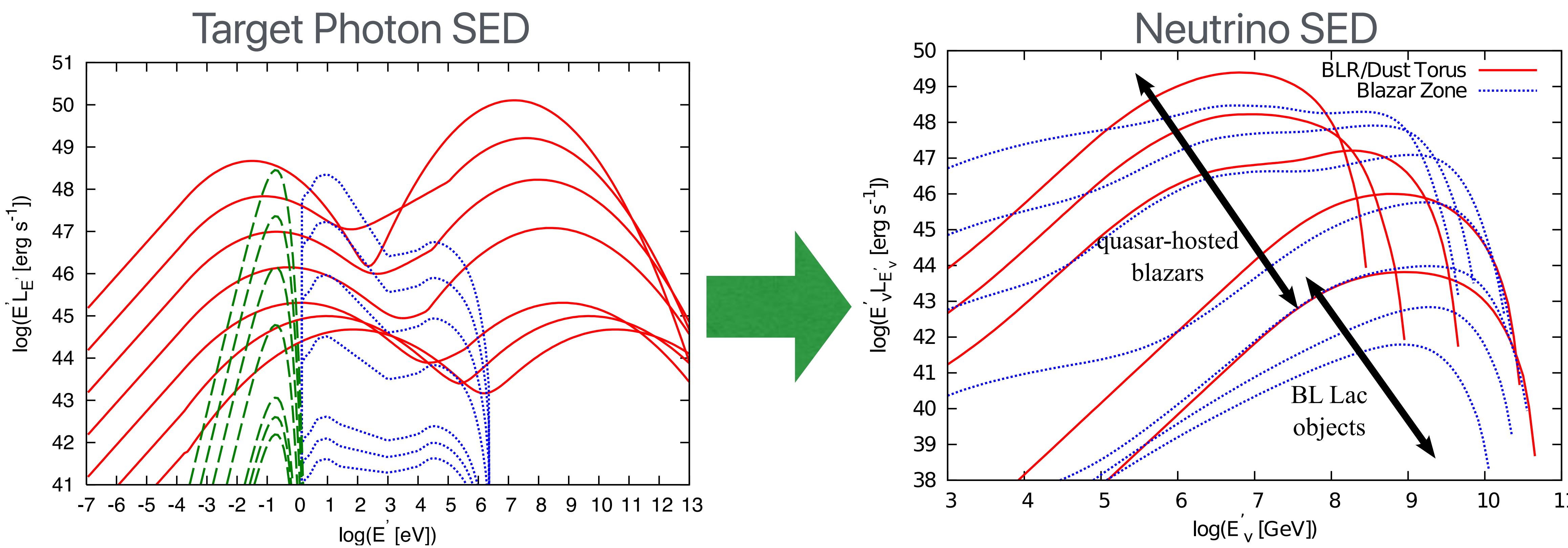
Photomeson Production Efficiency

Dermer, Murase, & YI '14



- Production efficiency (= effective optical depth)
  - $f_{p\gamma} \sim n_\gamma \kappa_p \sigma_{p\gamma} r$
- BL Lacs are inefficient neutrino factories, but UHECRs can survive
- FSRQs are more efficient due to external photon field
  - have a ν spectral peak at ~PeV due to BLR photons

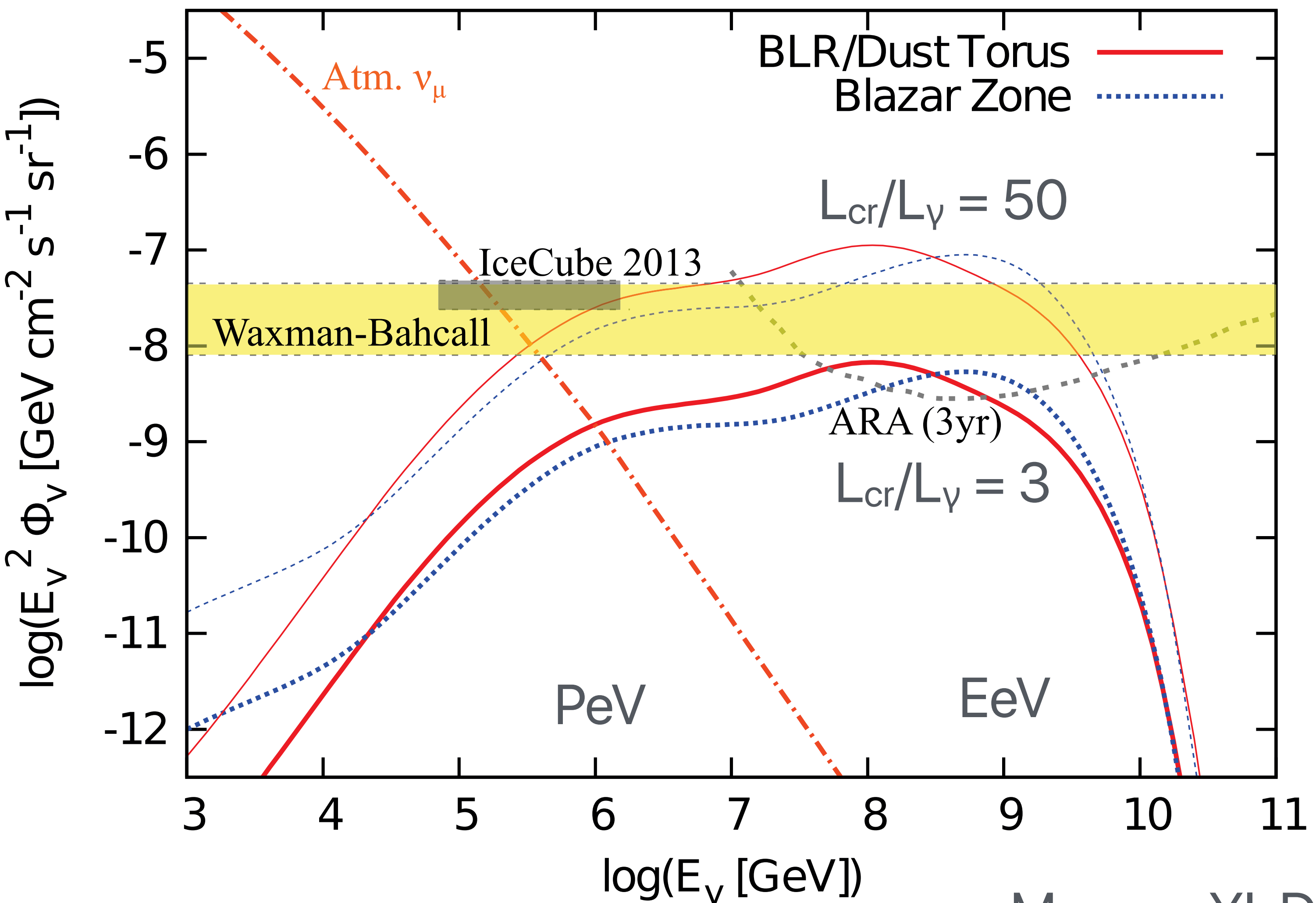
Neutrino SEDs



Murase, YI, Dermer '14

- Luminous blazars are brighter in ν
- pγ with internal rad. field: $f_{p\gamma} \propto L_{\rm ph,int} \Rightarrow L_\nu \propto L_\gamma^2$
- pγ with external rad. field: $f_{p\gamma} \propto L_{\rm ph,ext}^{0.5} \Rightarrow L_\nu \propto L_\gamma^{1.5}$
  - because $r_{\rm ext} \propto L_{\rm disk}^{0.5}$

Cosmic TeV-PeV Neutrino Background

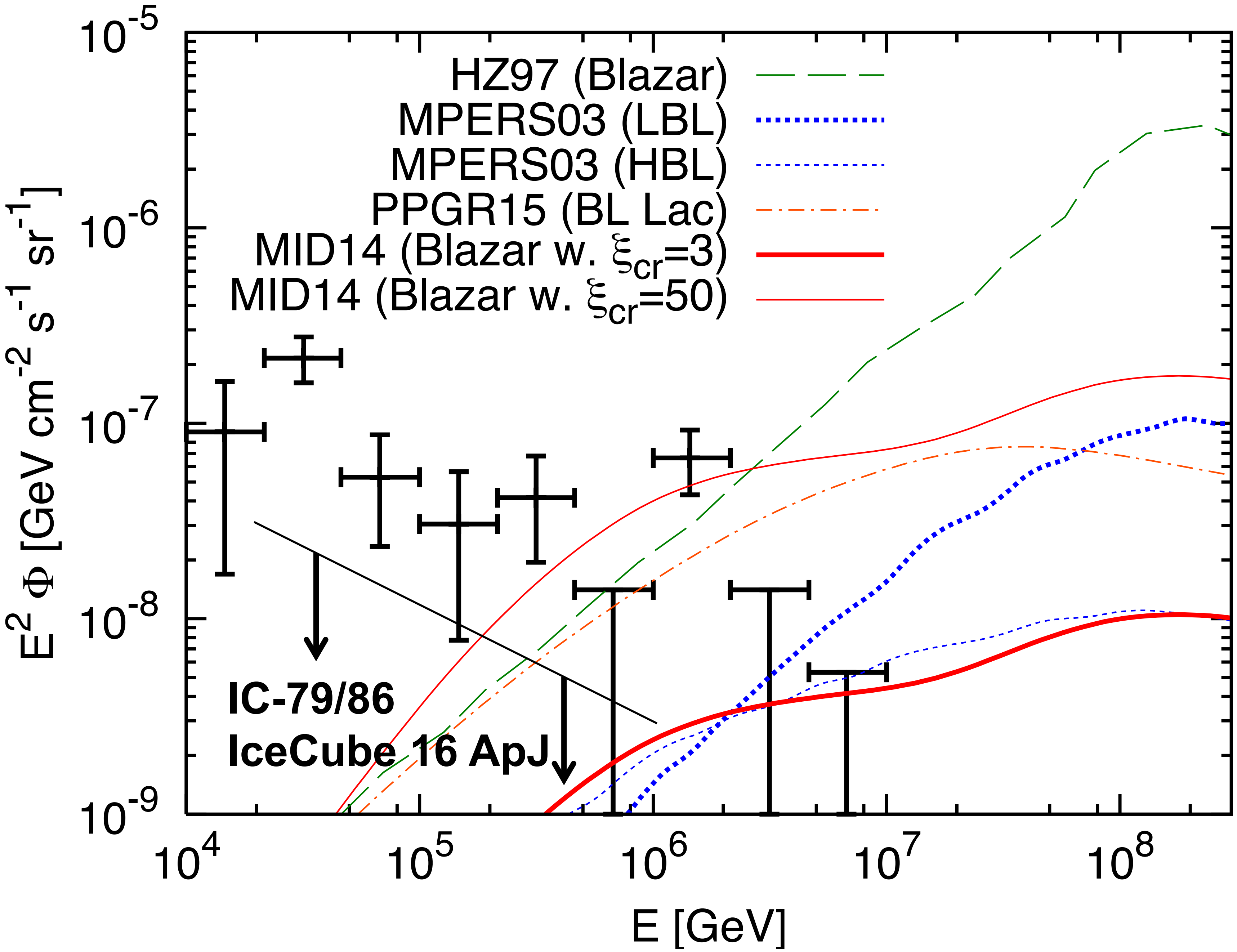


Murase, YI, Dermer '14

- Difficult to explain IceCube results only by blazars
- Spectral structure by BLR & Dust Torus emission
- Normalized by UHECRs ⇒ EeV ν detectable in future

Blazar Models vs. Data

Standard simplest jet models as the cosmic ν origin: many constraints…
- Blazars: power-law CR spectra & known SEDs→ hard spectral shape



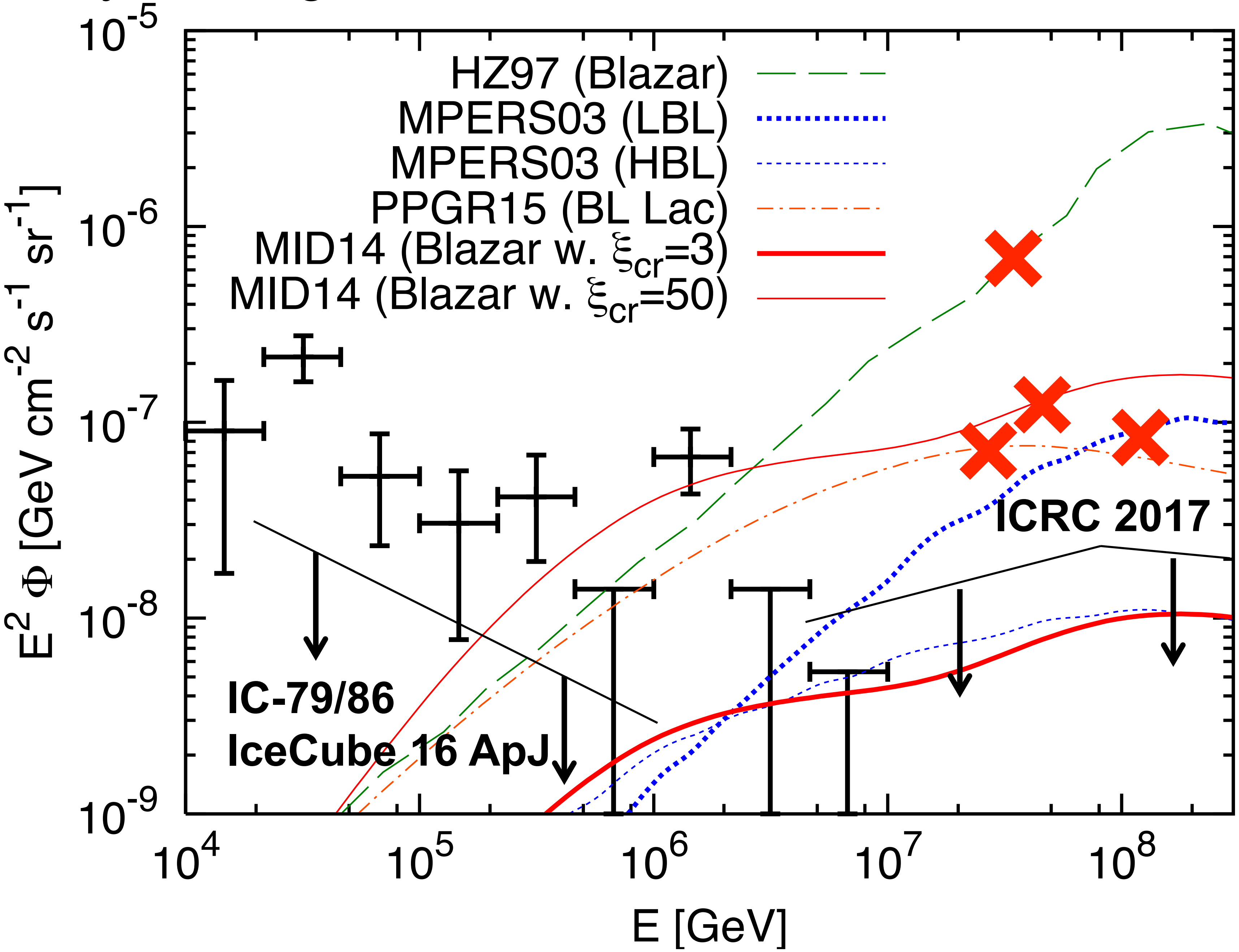
various diffuse ν predictions

leptonic
BL Lacs + FSRQ
(enhanced by BLR/IR photons)
lepto-hadronic norm.
BL Lacs (w.o. external fields)

leptonic w. UHECR norm.
BL Lacs + FSRQ

Blazar Models vs. Data

Standard simplest jet models as the cosmic ν origin: many constraints…
- Blazars: power-law CR spectra & known SEDs→ hard spectral shape
  IceCube 9-yr EHE analyses give a limit of $<10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} at 10 PeV
  many existing models have been constrained



various diffuse ν predictions

leptonic
BL Lacs + FSRQ
(enhanced by BLR/IR photons)
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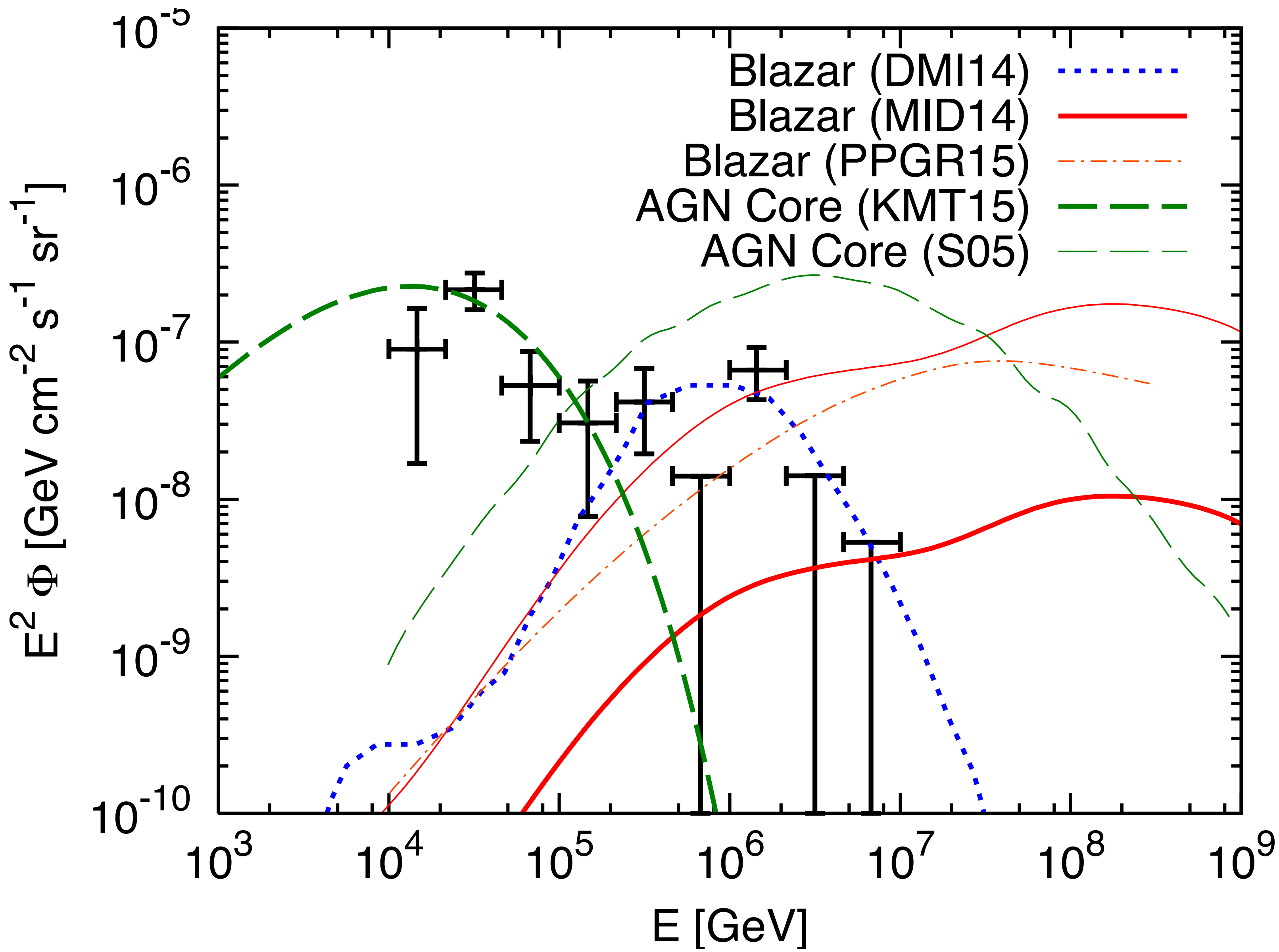
BL Lacs (w.o. external fields)

leptonic w. UHECR norm.
BL Lacs + FSRQ

Can Blazars Explain the IceCube Data?

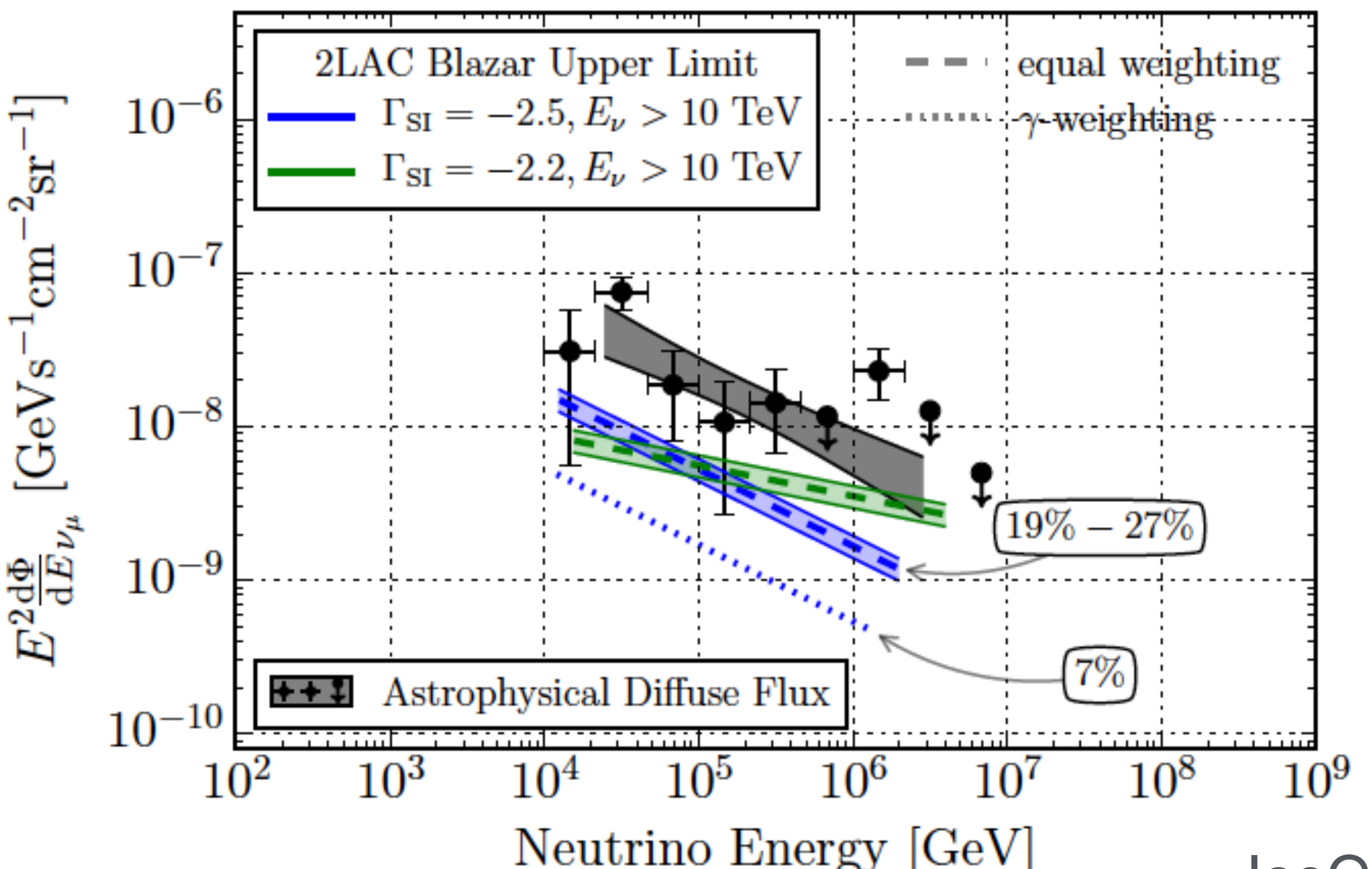


from KM 2015

Can blazars dominantly explain the IceCube data? – challenging
- Need a cutoff or steepening around a few PeV (ex. stochastic acceleration)
- Medium-energy (<100 TeV) data cannot be explained by proposed models

Can blazars dominantly explain the UHECR data? – maybe
- But the simultaneous explanation for the IceCube data is challenging

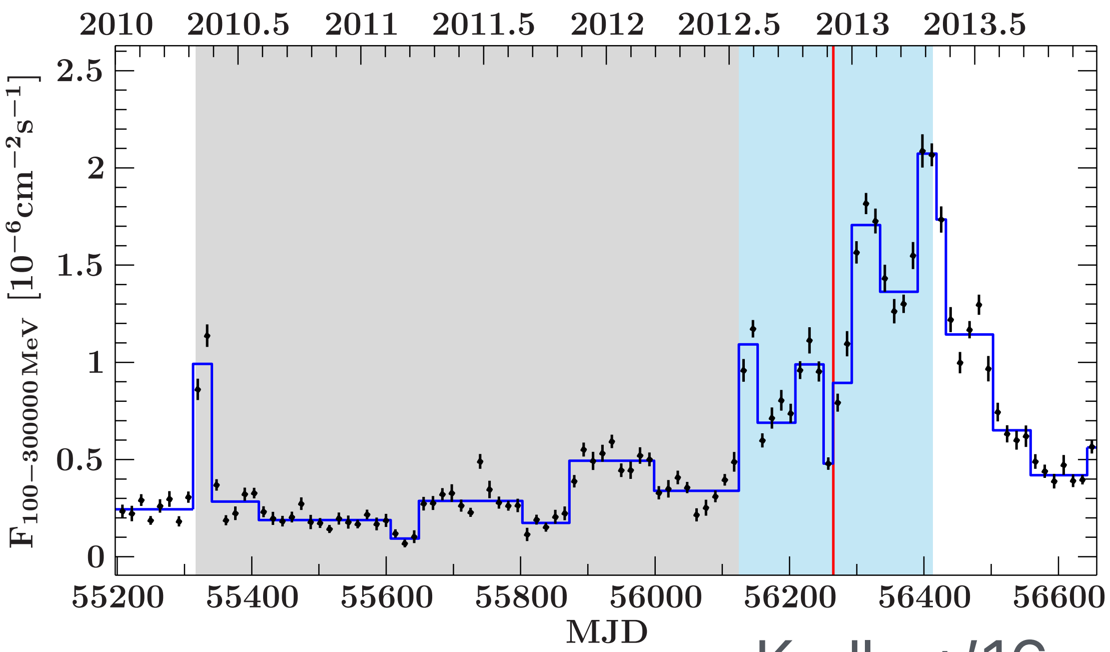
Fermi Blazars Contribution



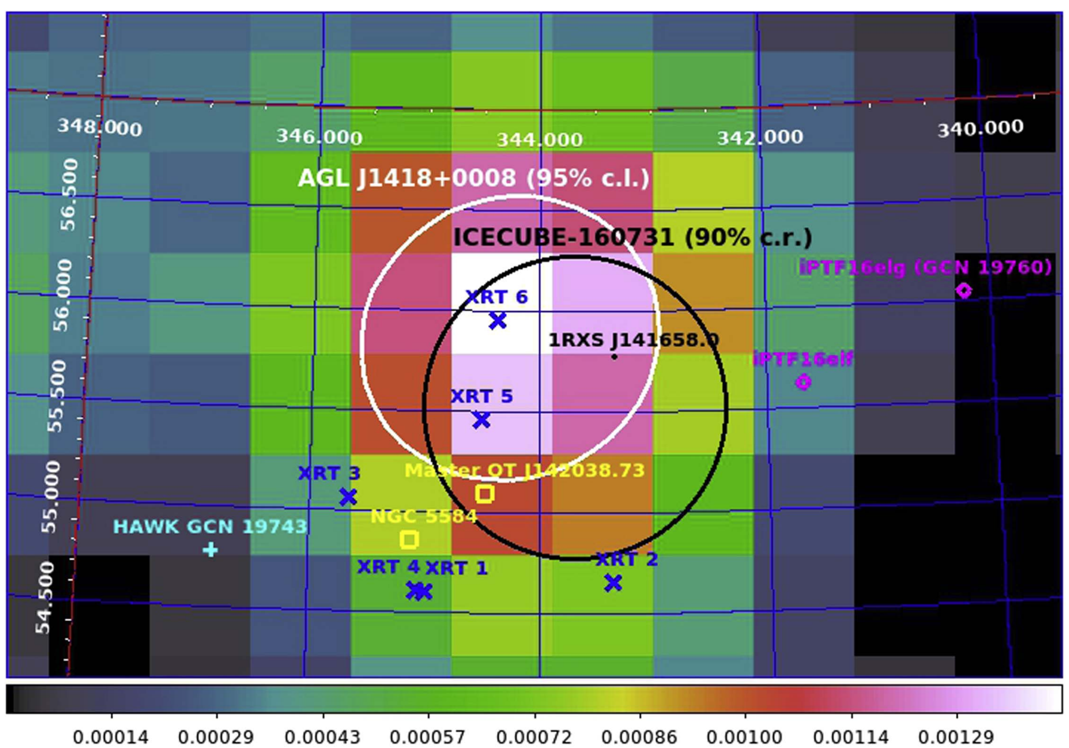
IceCube '17

- Blazars are rare (~1-10 deg^{-2})
- Fermi/LAT blazars can explain <7-27 % of the IceCube flux
  - Note: Fermi/LAT is not sensitive to MeV blazars (most powerful blazars) and extreme HBLs (highest energy blazars)

Neutrinos From Flaring Blazars



Kadler+'16



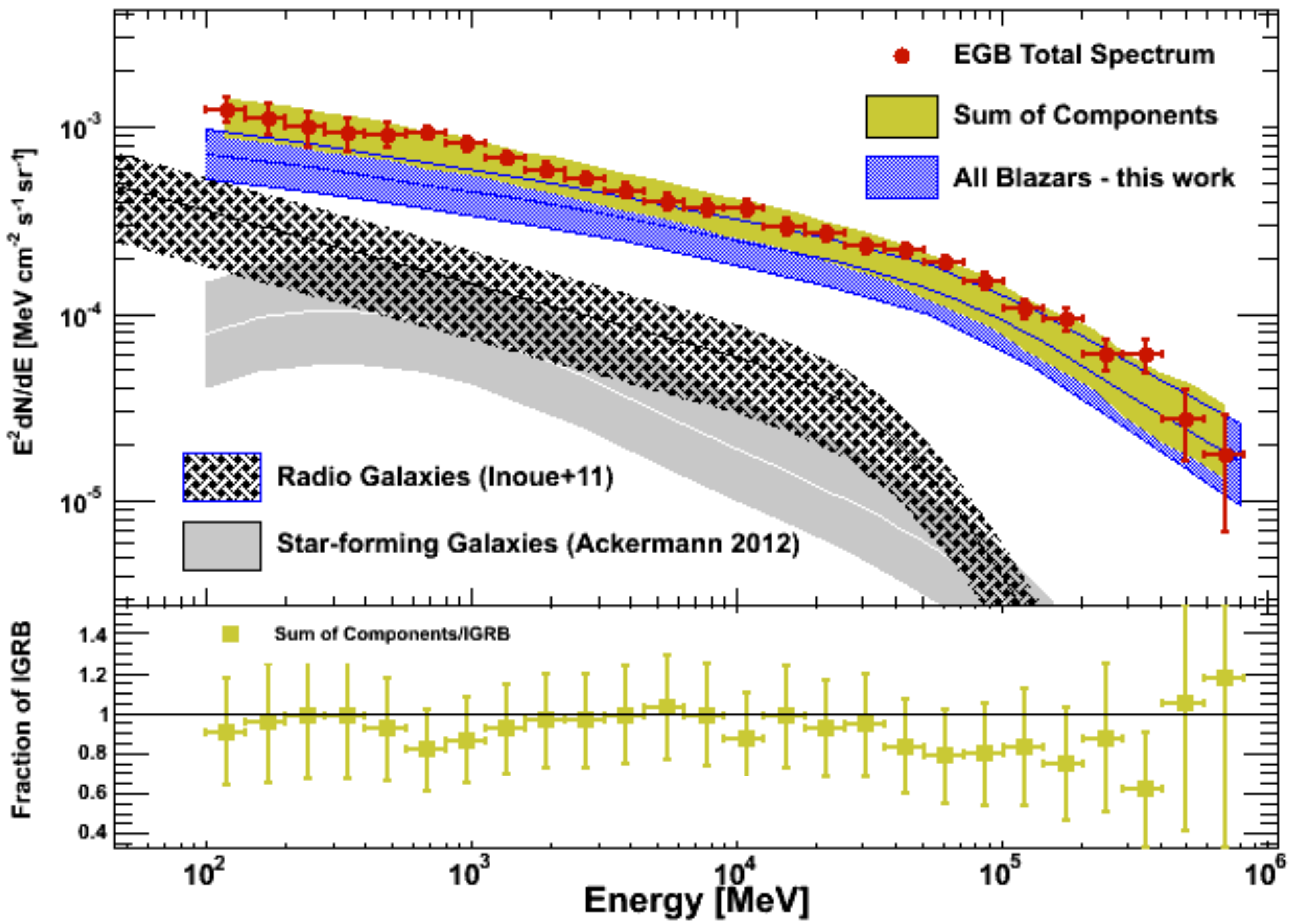
Lucarelli+'17

- Kadler+'16
  - IceCube: HESE-35 (2 PeV)
  - PKS B1424-418 (z=1.52)
  - Association level: ~2σ
- Lucarelli+'17
  - ICECUBE-160731 (several hundred TeV?)
  - 1RXS J141658.0-001449
  - Association level: ~4σ

IceCube 170922A

- Initial alert by AMON
    - E_ν ~ 300 TeV
- Flare of TXS 0506+056, located inside the error region
    - Fermi ATel #10791 (Tanaka+)
    - MAGIC ATel #10817 (Mirzoyan+)
    - Swift GCN #21930, ATel #10942 (Keivani+)
    - NuSTAR ATel #10861 (Fox+)
    - Kanata, Subaru, and so on,,,
- ?? True association ??

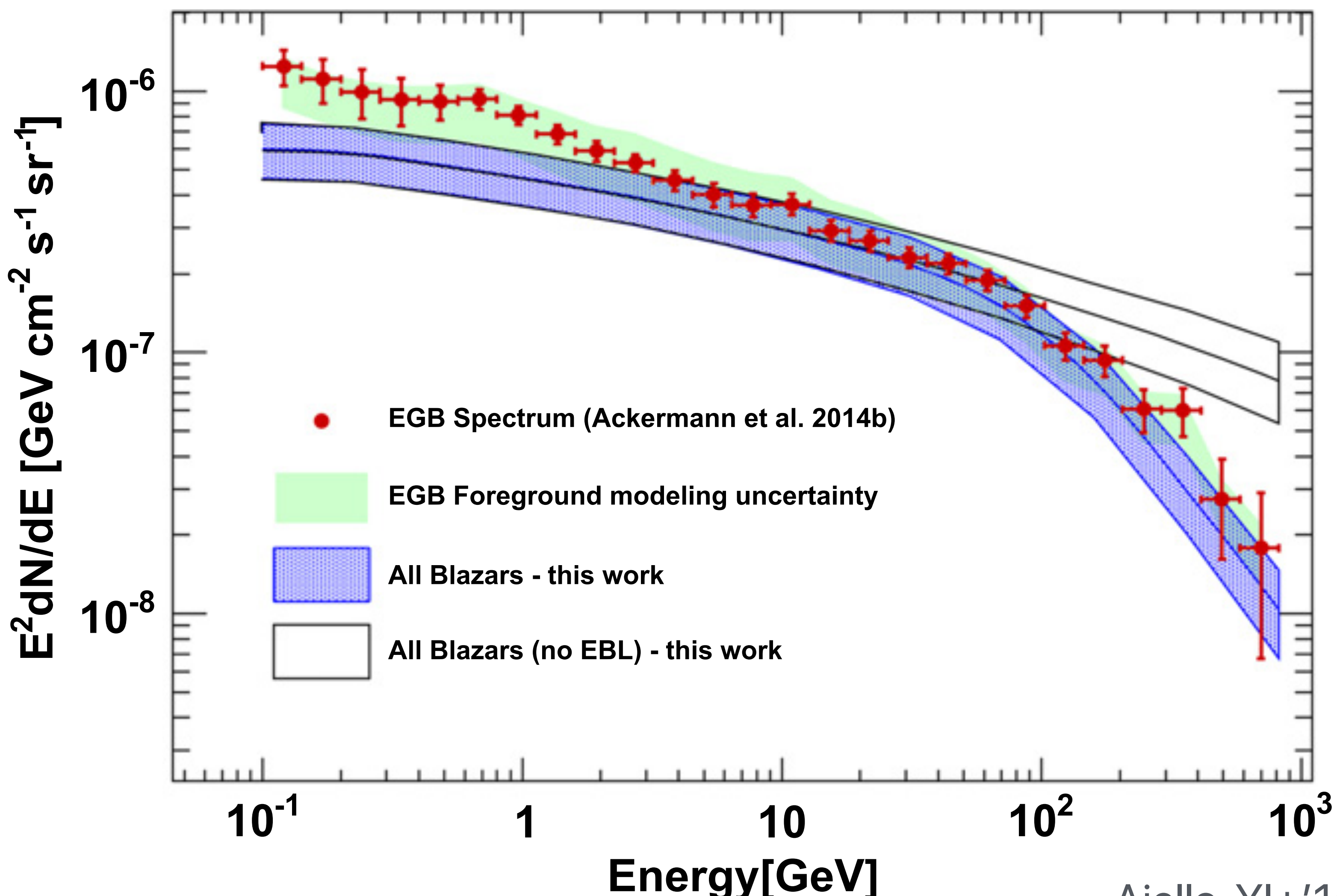
Components of Cosmic Gamma-ray Background



Ajello, YI +'15

- FSRQs (Ajello+'12), BL Lacs (Ajello+'14), Radio gals. (YI'11), & Star-forming gals. (Ackermann+'12) makes almost 100% of CGB from 0.1-1000 GeV.

Blazars in the Cosmic Gamma-ray Background

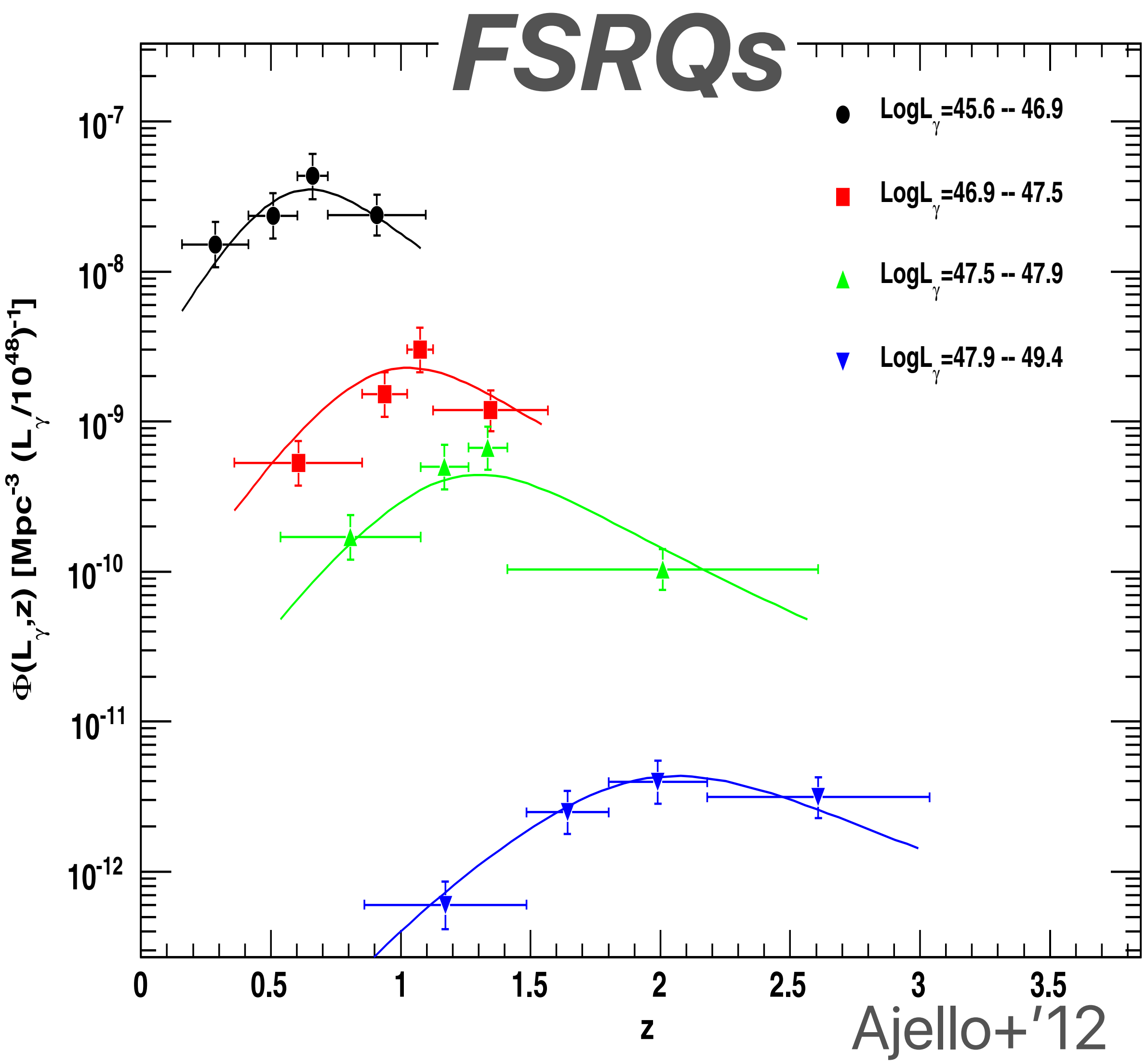


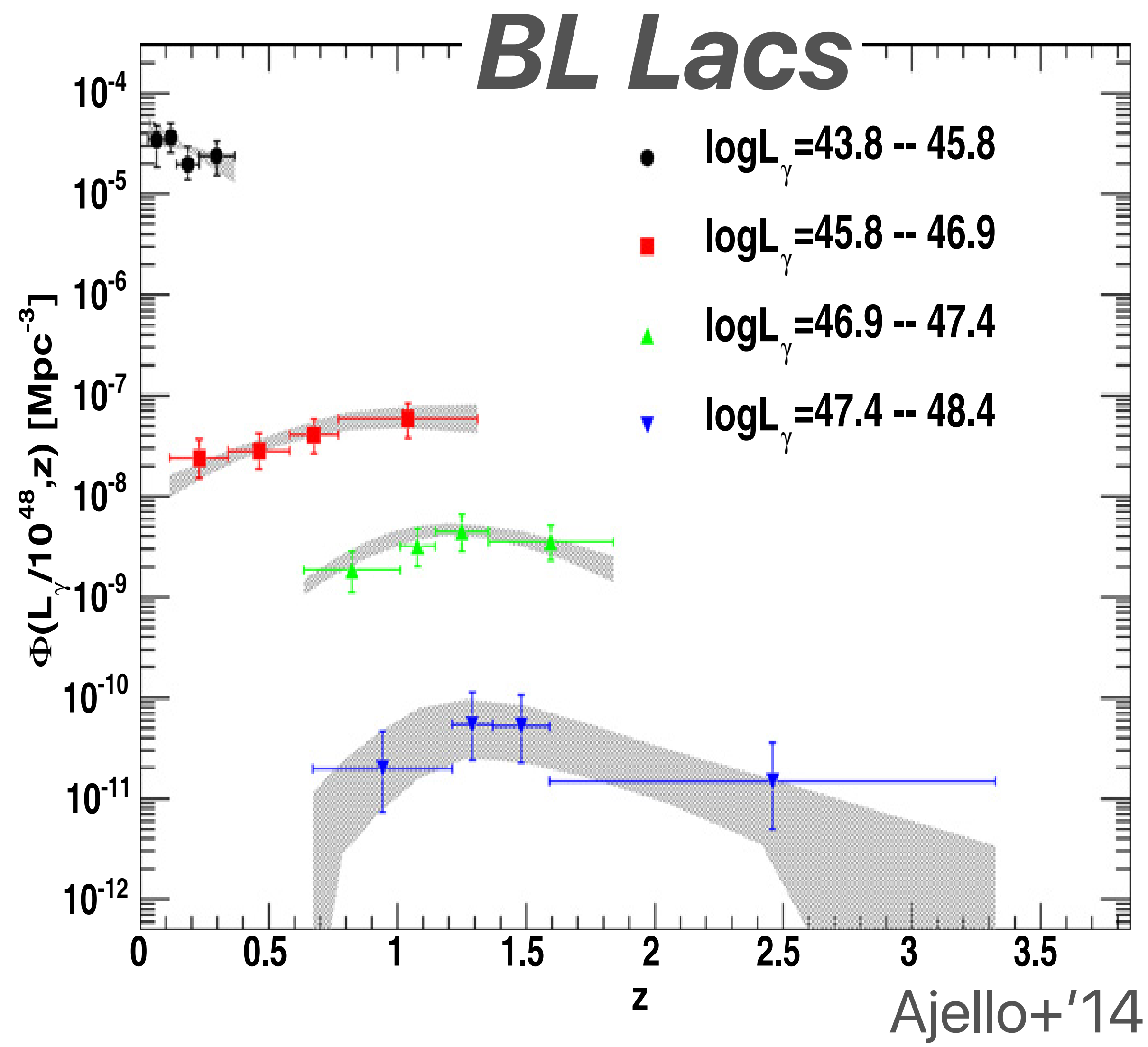
Ajello, YI+'15

- 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,

- Blazars explain ~50% of CGB at 0.1-100 GeV.
  - explain ~100% of CGB at >100 GeV.

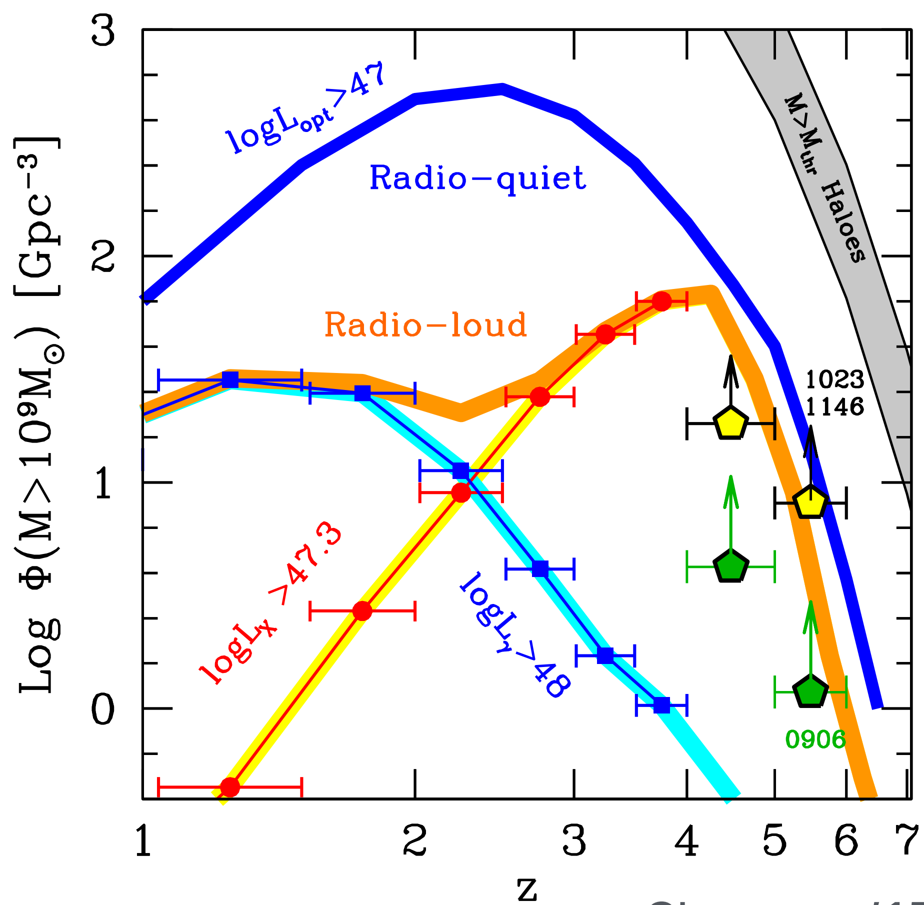
Cosmological Evolution of Blazars



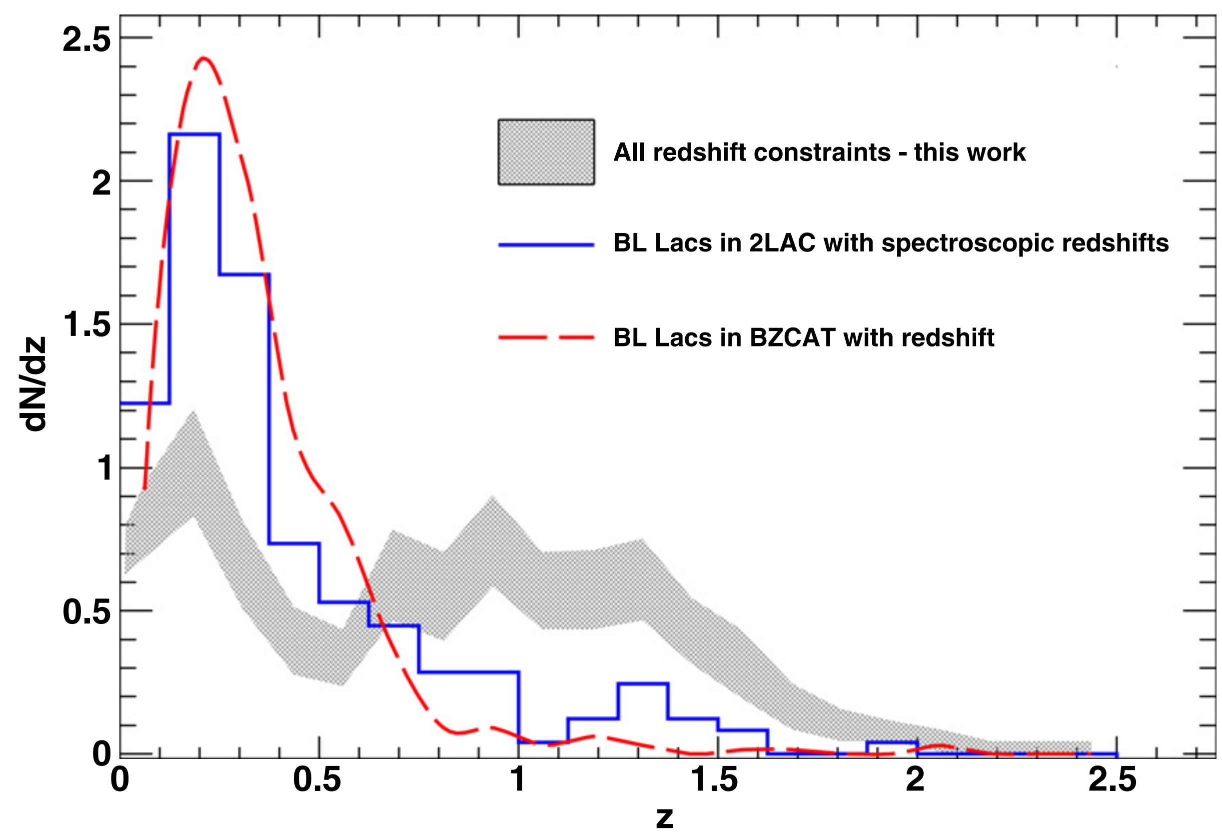


- FSRQs, luminous BL Lacs show positive evolution.
- low-luminosity BL Lacs show negative evolution unlike other AGNs.

Blazar evolution?



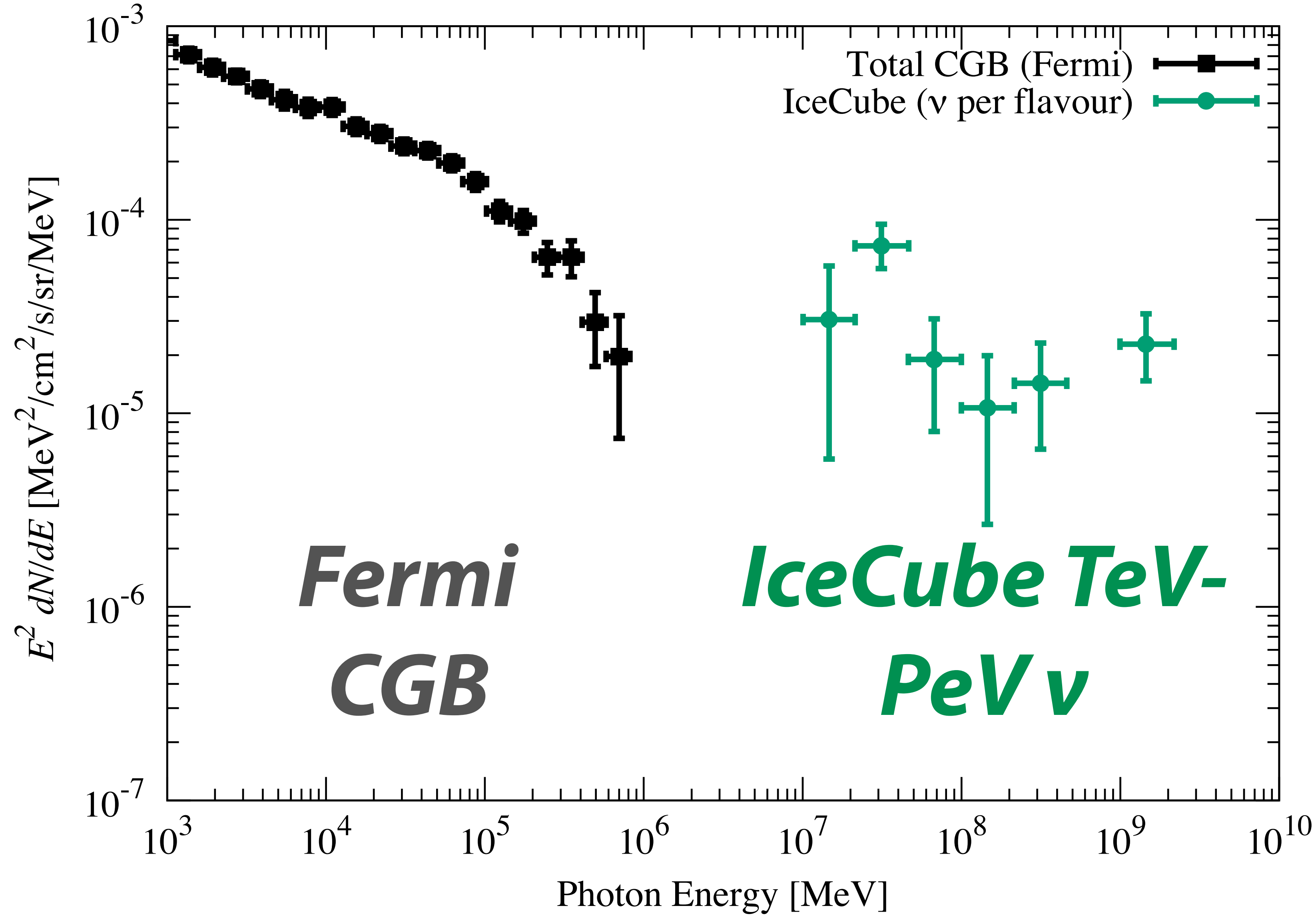
Sbarrato+'15



Ajello+'14

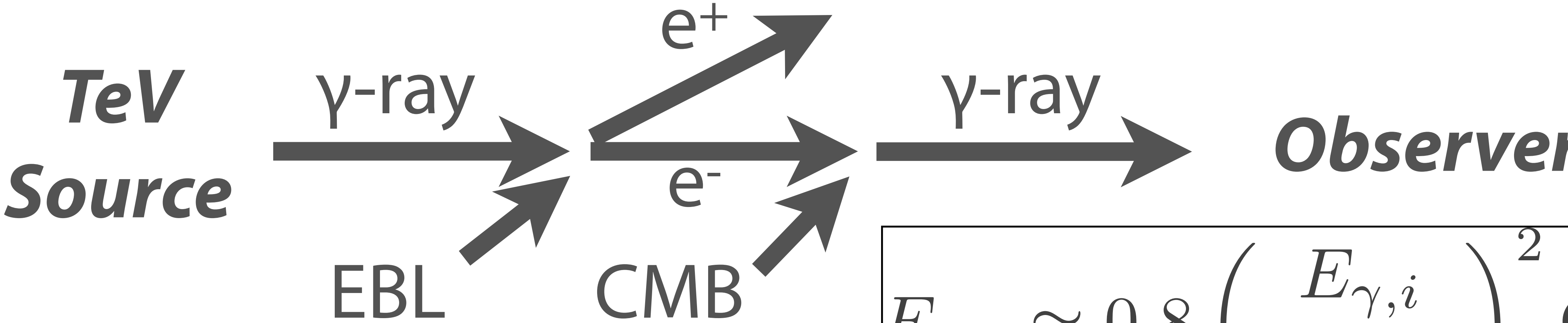
- Stronger evolution in X-ray selected blazars?
- Redshifts of 50% of Fermi BL Lacs are unknown.
  - ~10 hr exposure w/ 10-m telescope for TXS 0506+056

Cosmic TeV Gamma-ray Background



- Above 1 TeV, there is no gamma-ray data, though it is important for neutrino studies.

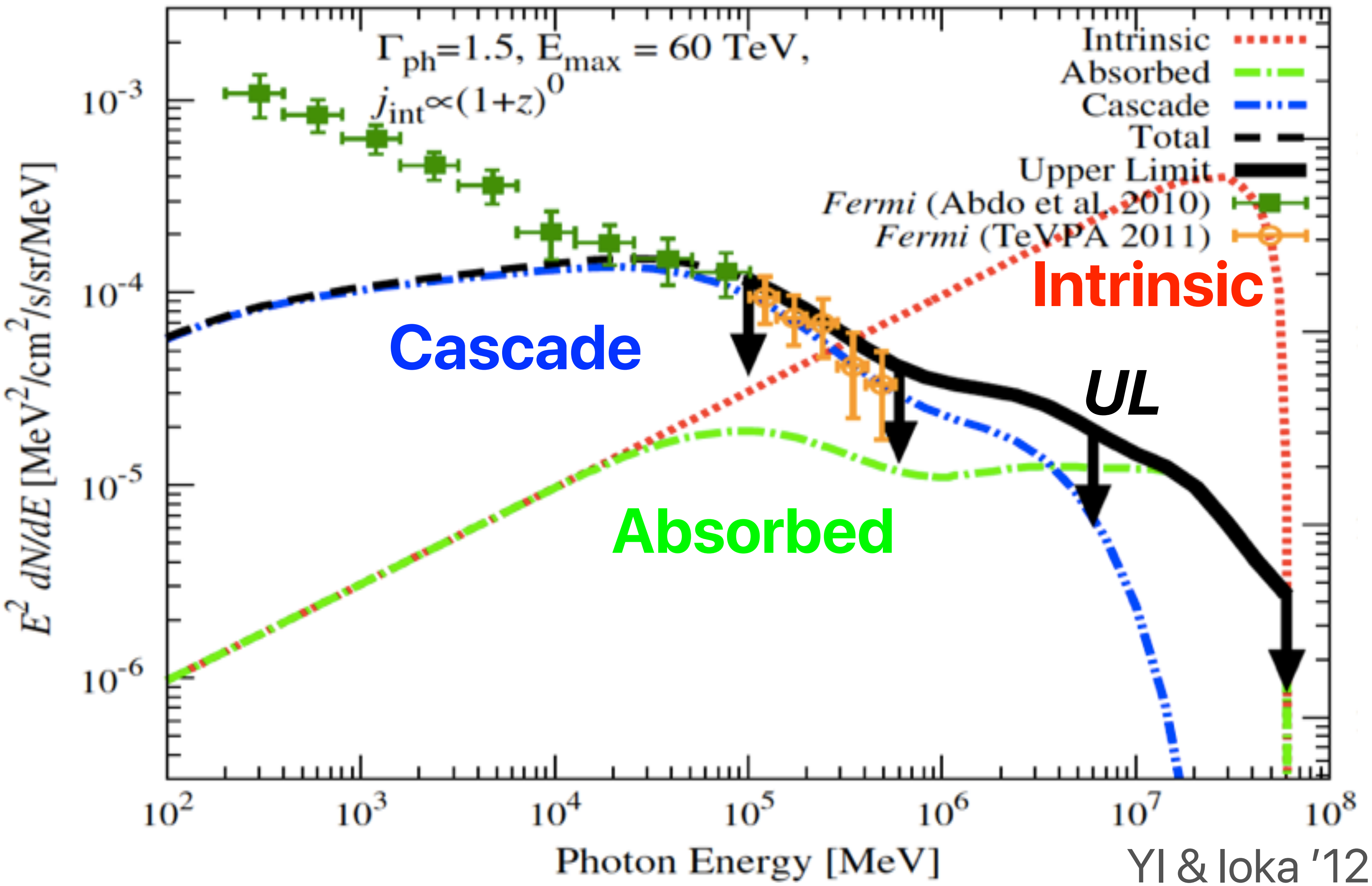
GeV-TeV Gamma-ray Connection: Cascade



$$E_{\gamma,c} \approx 0.8 \left(\frac{E_{\gamma,i}}{1\ \mathrm{TeV}} \right)^2 \mathrm{GeV}$$

- TeV gamma-ray photons are absorbed by EBL
- electron-positron pairs are created
- pairs scatter CMB via inverse-Compton process
    - 1 TeV (primary) -> ~1 GeV (secondary)
- Note: plasma instability may suppress the cascade
  (Broderick+’12, but see also Sironi & Giannios ‘14)

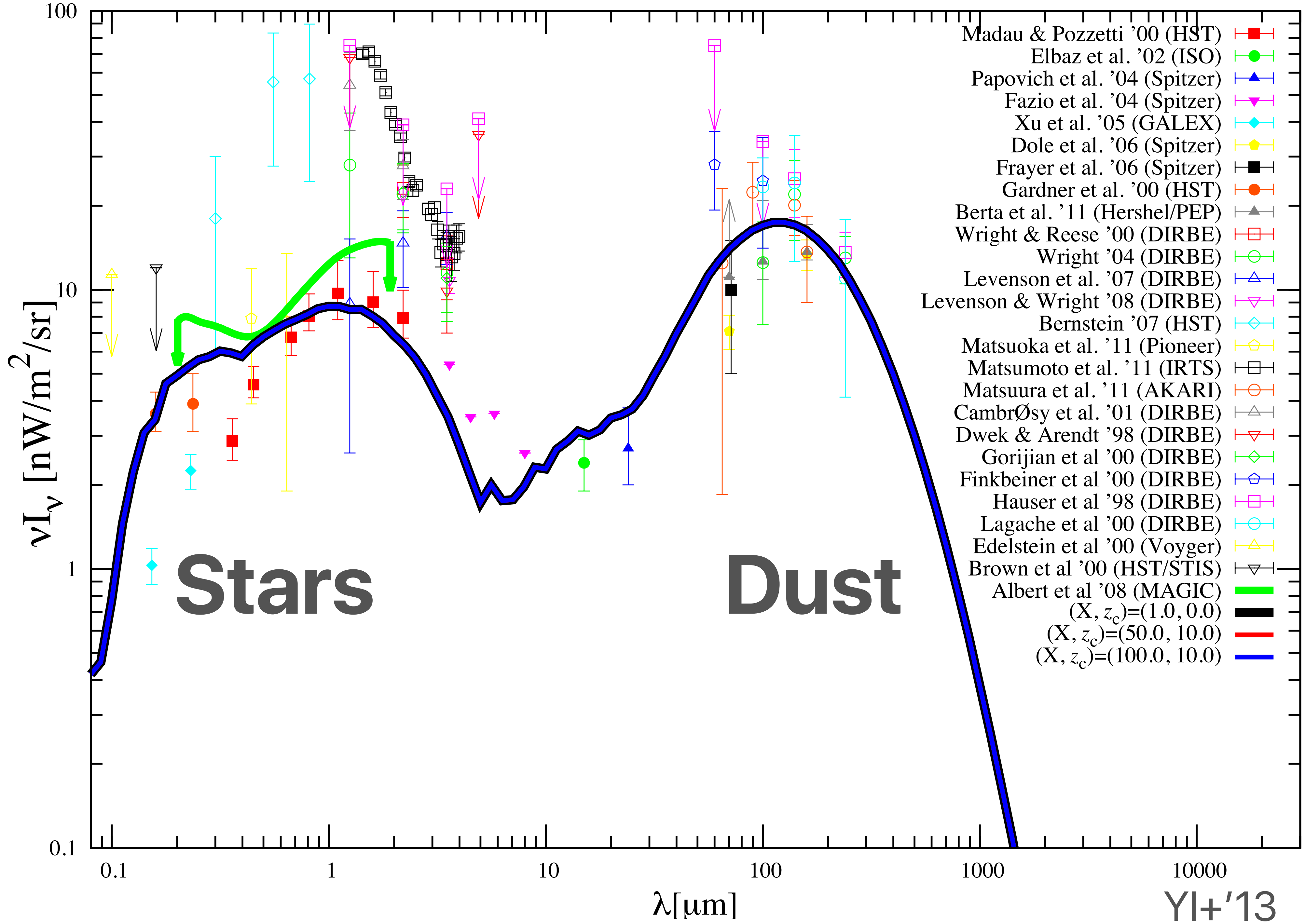
Upper Bound on the Cosmic Gamma-ray Background



YI & Ioka '12

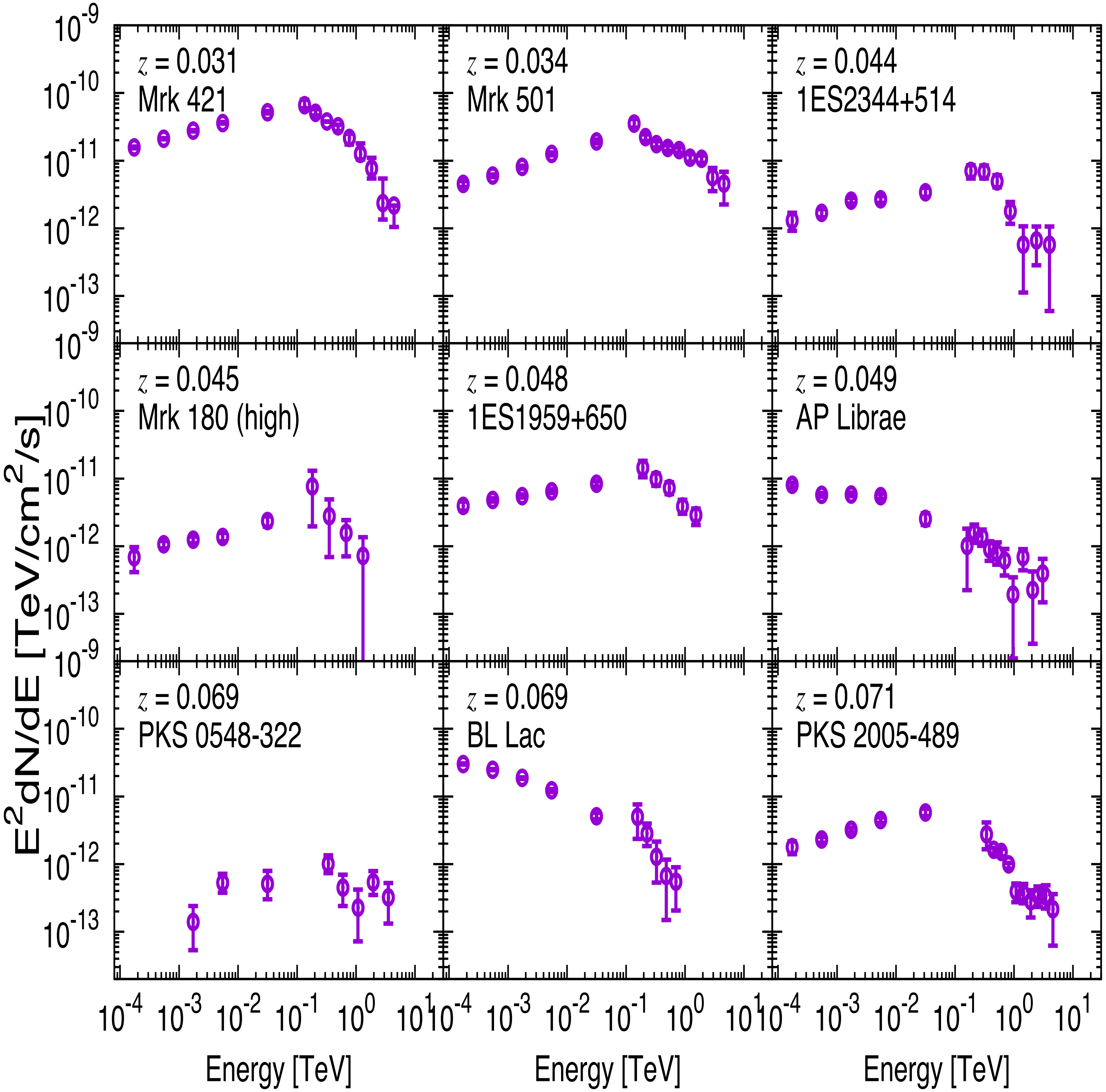
- Cascade component from the TeV background can not exceed the Fermi data (Coppi & Aharonian '97, YI & Ioka '12, Murase+'12, Ackermann+'14).
  - No or negative evolution is required -> low-luminosity BL Lacs show negative evolution (Ajello+'14).

Galaxy Counts: Lower Bound on the Cosmic Optical/Infrared Background



YI+'13

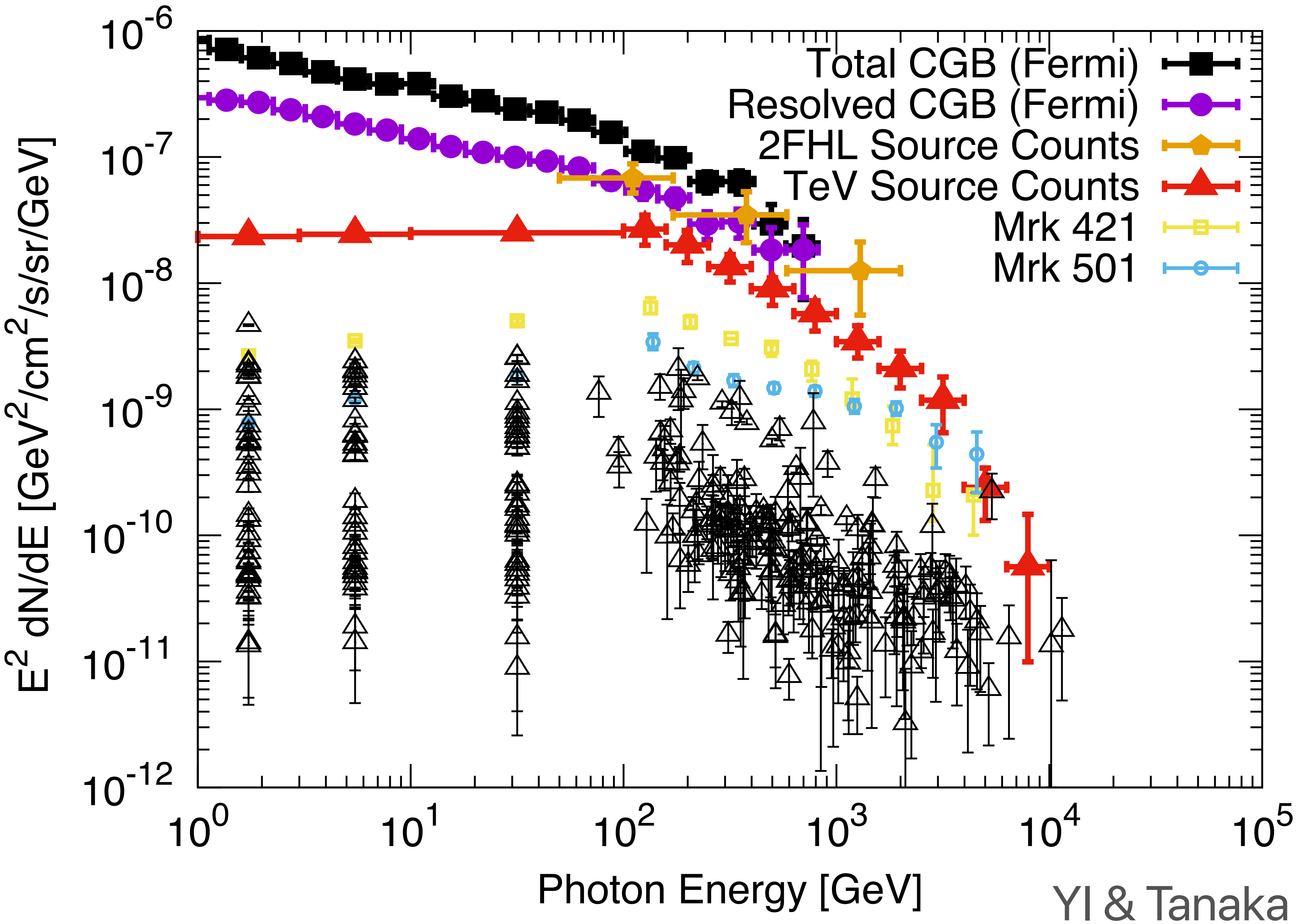
Known TeV sources



YI & Tanaka '16

- Select 35 known TeV sources at |b|>10 deg from the default TeVcat catalog.
  - low-state data only
  - 30 are blazars, 3 are radio galaxies, 2 are starbursts
- 3FGL SED data for the GeV data.

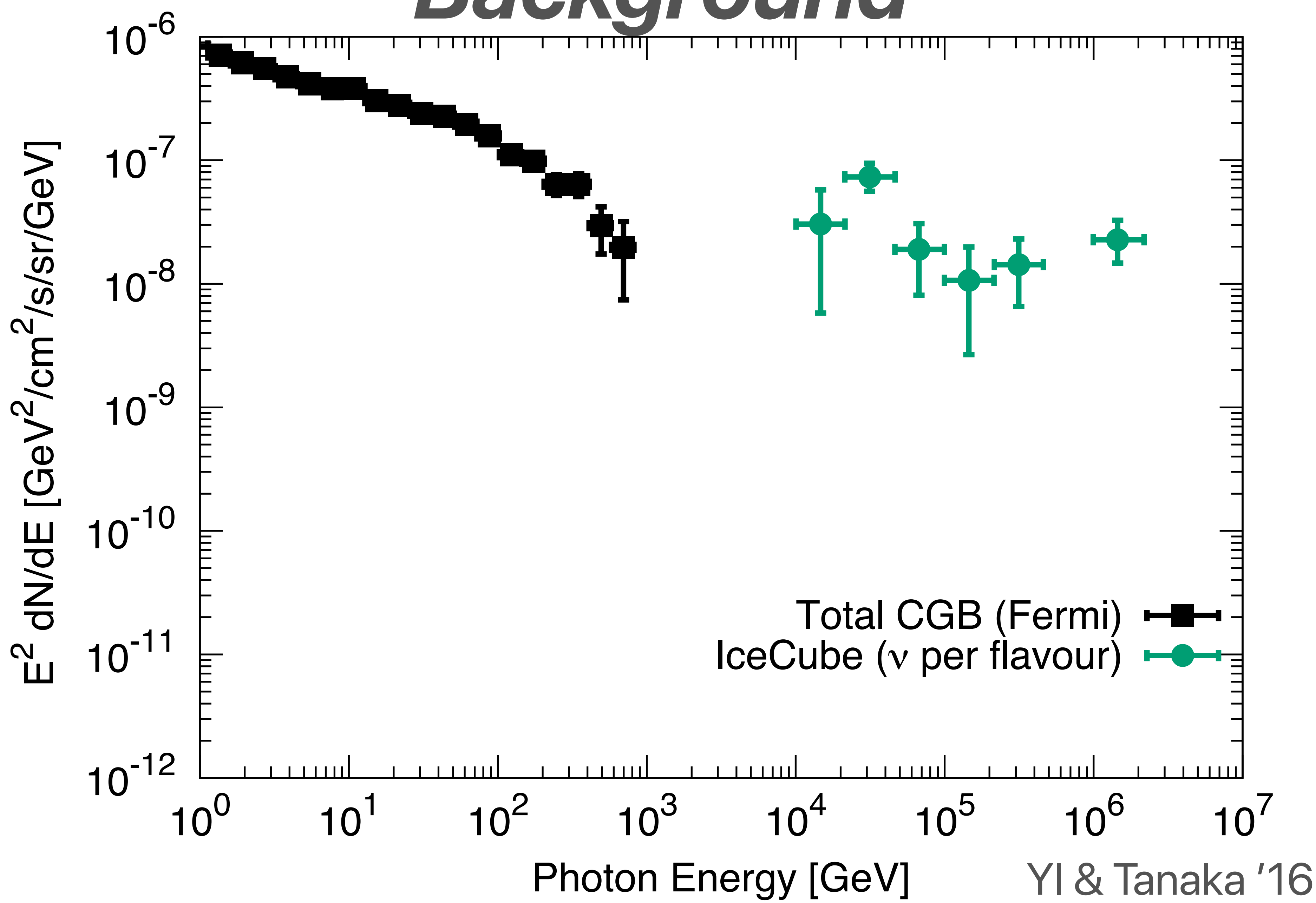
Lower Bound on the Cosmic Gamma-ray Background



YI & Tanaka '16

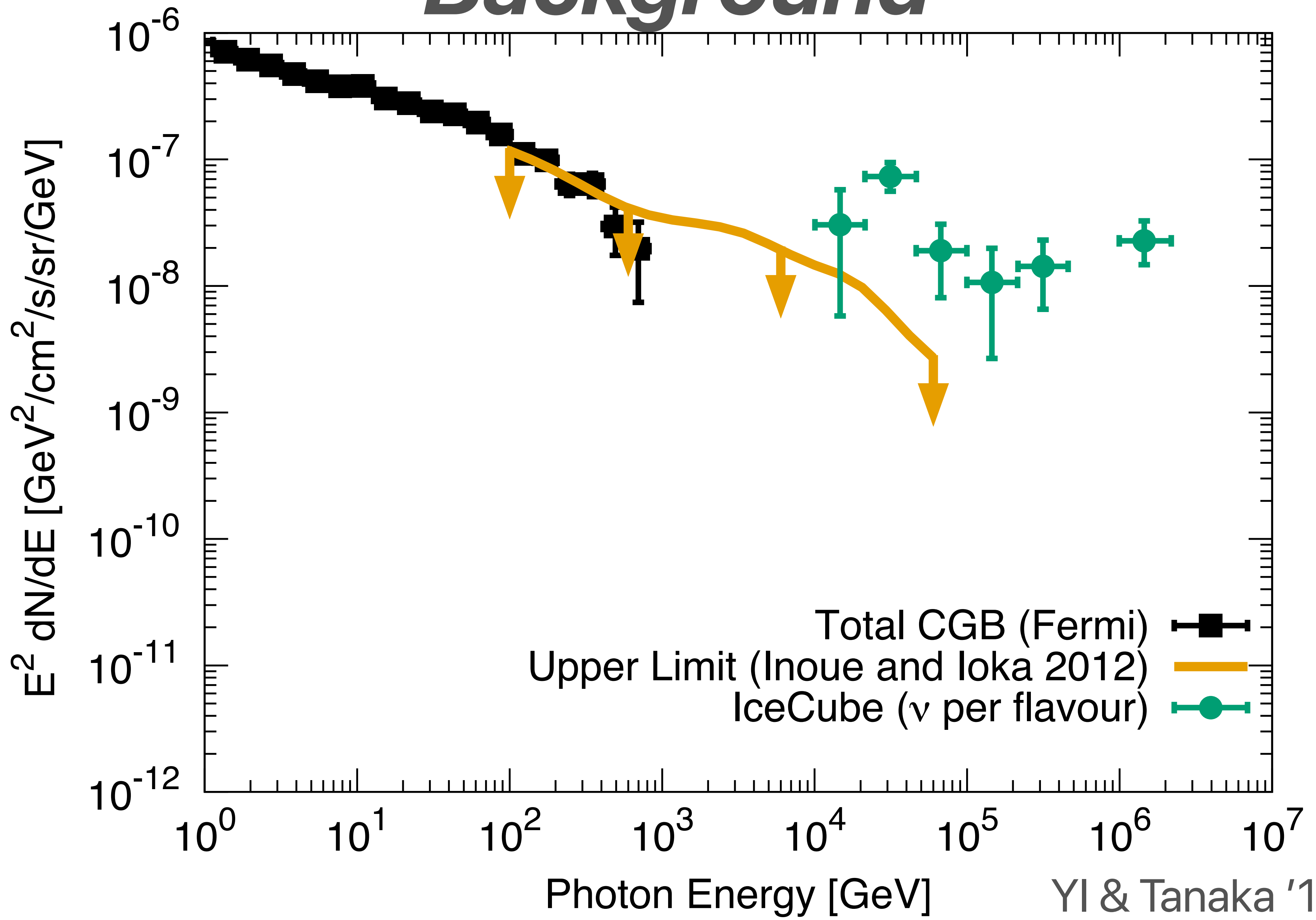
- TeV source counts give lower limit on to the cosmic gamma-ray background.
- Fermi has resolved more portion of the TeV sky than IACTs do.
    - CTA survey will be important (YI, Totani, & Mori 10; Dubus, YI, +'13; De Franco, YI,+'17)

Bounds on the Cosmic TeV Gamma-ray Background



- Current limit at 0.3-10 TeV is
  - 3×10^{-8} (E/0.1 TeV)$^{-0.8}$ exp(-E/2 TeV) < E^{2}dN/dE < 1×10^{-7} (E/0.1 TeV)$^{-0.5}$ [GeV/cm^2/s/sr]

Bounds on the Cosmic TeV Gamma-ray Background



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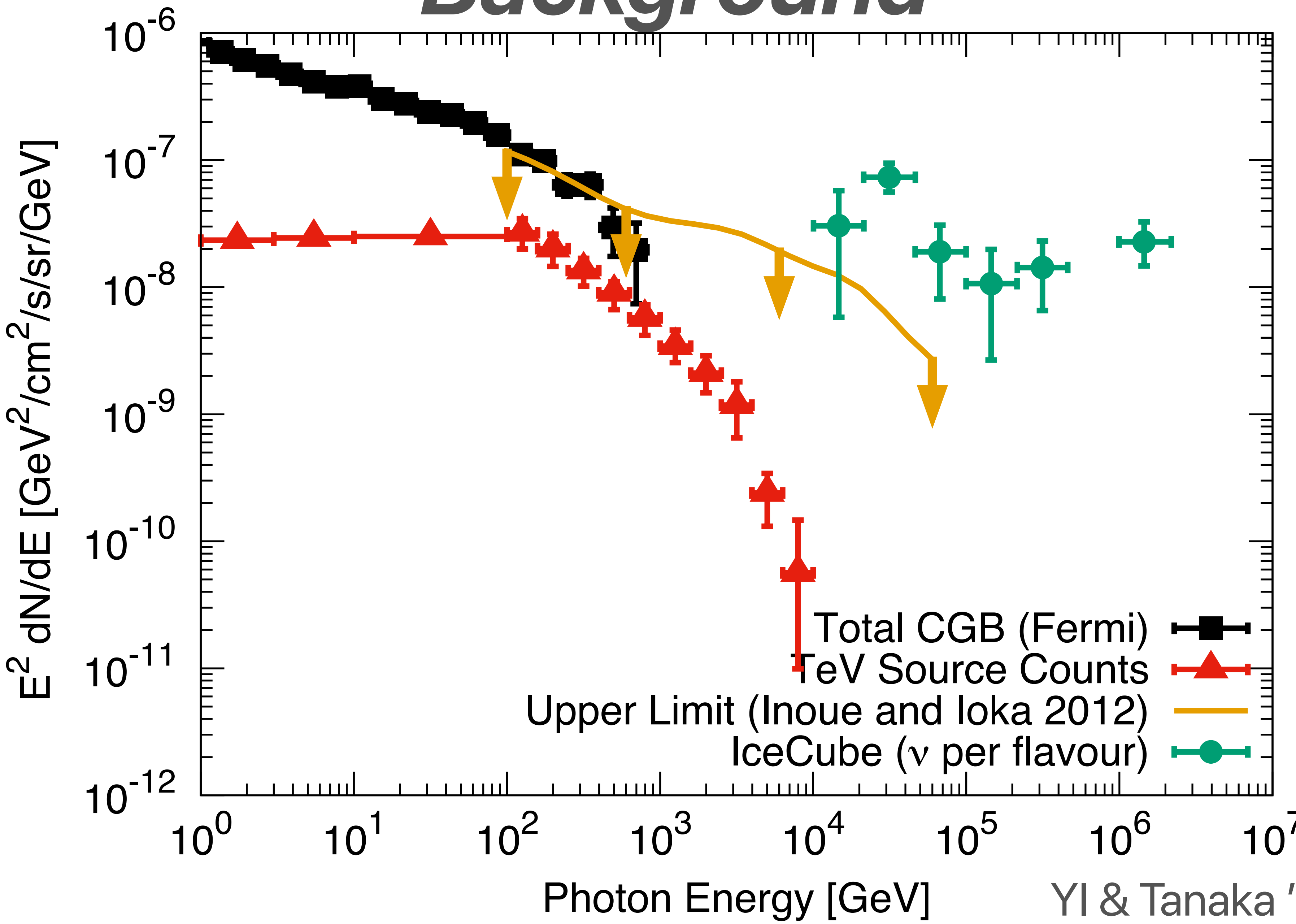

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Summary

- Blazar emission mechanism
  - Leptonic? Lepto-Hadronic?
- Even if blazars are neutrino emitters,
  - blazars can not explain the whole IceCube data
- Currently, association w/ blazars is still uncertain.
  - More events & more follow-ups
- We still do not understand evolution history of blazars
- Can CTA/HAWC measure the TeV background?