Introduction to Gamma-ray Astrophysics - Active Galactic Nuclei & Cosmic Gamma-ray Background -

Yoshiyuki Inoue

ISAS, JAXA international top young fellow

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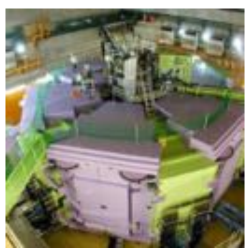
理化学研究所数理創造プログラム (iTHEMS) 上級・卓越研究員

極限宇宙セルリーダー from 2017/11/1

2nd YMAP Meeting @ Kashiwa, 2017-10-15

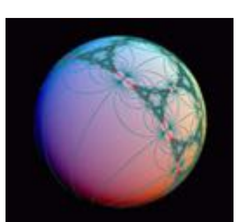
極限宇宙セル（極限宇宙現象とそれらを支配する時空と物質の起源の解明）

物理学・計算科学・数学の協働により、時空の起源と物質の起源を解明する。特に京コンピュータ及びその後継機を用いた素粒子原子核の大規模シミュレーションを推進するとともに、その超新星爆発・ガンマ線バーストの大規模数値計算の融合を達成し、国内外の加速器実験データ・宇宙観測データと併せて物質の起源を解明する。更に、現代数学と素粒子物理学及び宇宙物理学の融合を図り、ブラックホール時空創成や宇宙初期時空創成の謎の挑戦する。



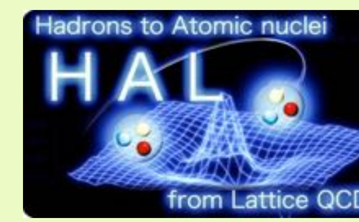
加速器実験データ・宇宙観測データによる極限天体中の元素合成計算の精度向上。

素粒子・原子核・極限天体の大規模かつ高精度シミュレーション。



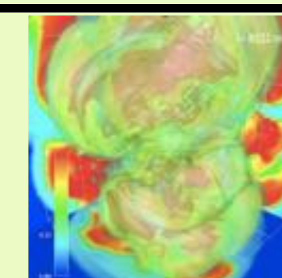
現代数学との協働によるブラックホール時空時空の解明。

極限物質



-2体核力の起源、3体力・4体力の起源を素粒子計算により解明。
-素粒子原子核計算に立脚した最先端の高密度状態方程式を構築。
-高密度状態方程式に基づく中性子星の構造の理解。

極限天体



-超新星・ガンマ線バーストの爆発機構を大規模数値計算で解明。
-極限天体で起こる元素合成過程計算の高精度予言。
-極限天体で発生する重力波・ニュートリノの高精度予言。

極限宇宙

-極限天体で形成される古典的ブラックホールの活動性解明。
-数学と素粒子論の協働による量子的ブラックホールの理解。
-宇宙時空構造創成の原理解明。

$$G^{\mu}{}_{\mu} = 8\pi G \langle T^{\mu}{}_{\mu} \rangle = \gamma \mathcal{F} - \alpha \mathcal{G} + \frac{2}{3} \beta \Box R$$

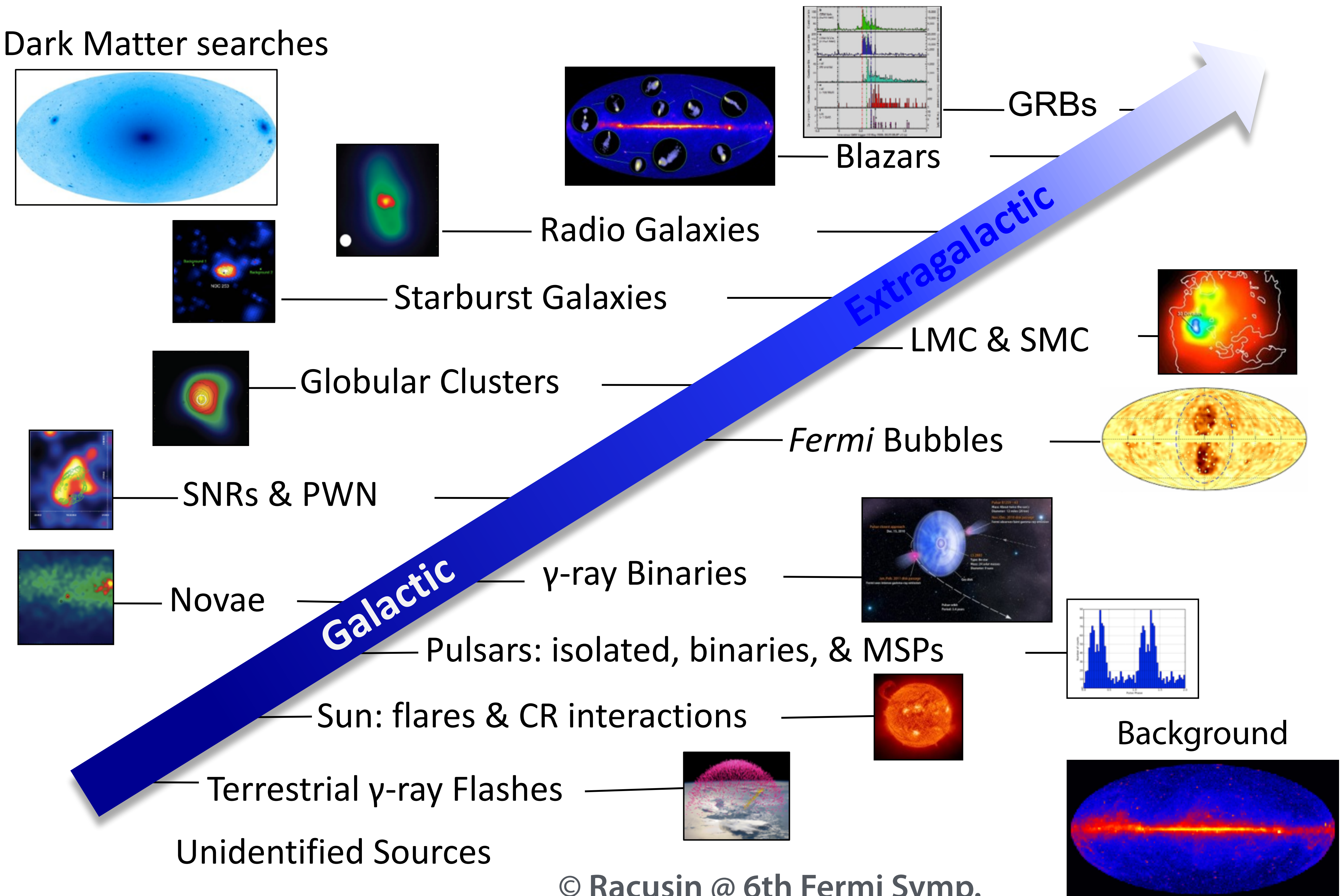
時空と物質の起源解明

Contents

- Introduction
- Active Galactic Nuclei
- Cosmic Gamma-ray Background
- Future Gamma-ray Astronomy
- Summary

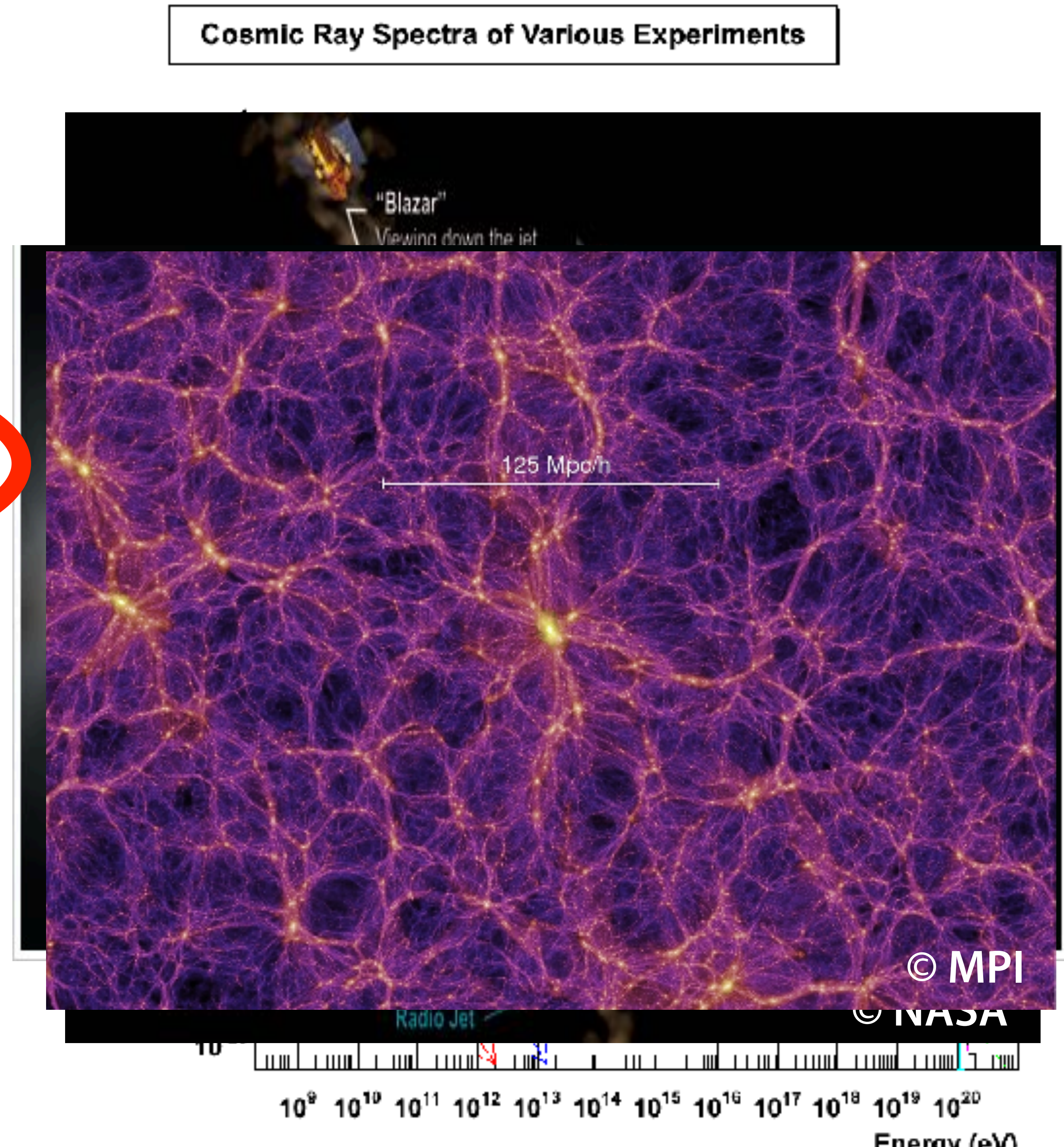
Introduction

Gamma-ray Objects



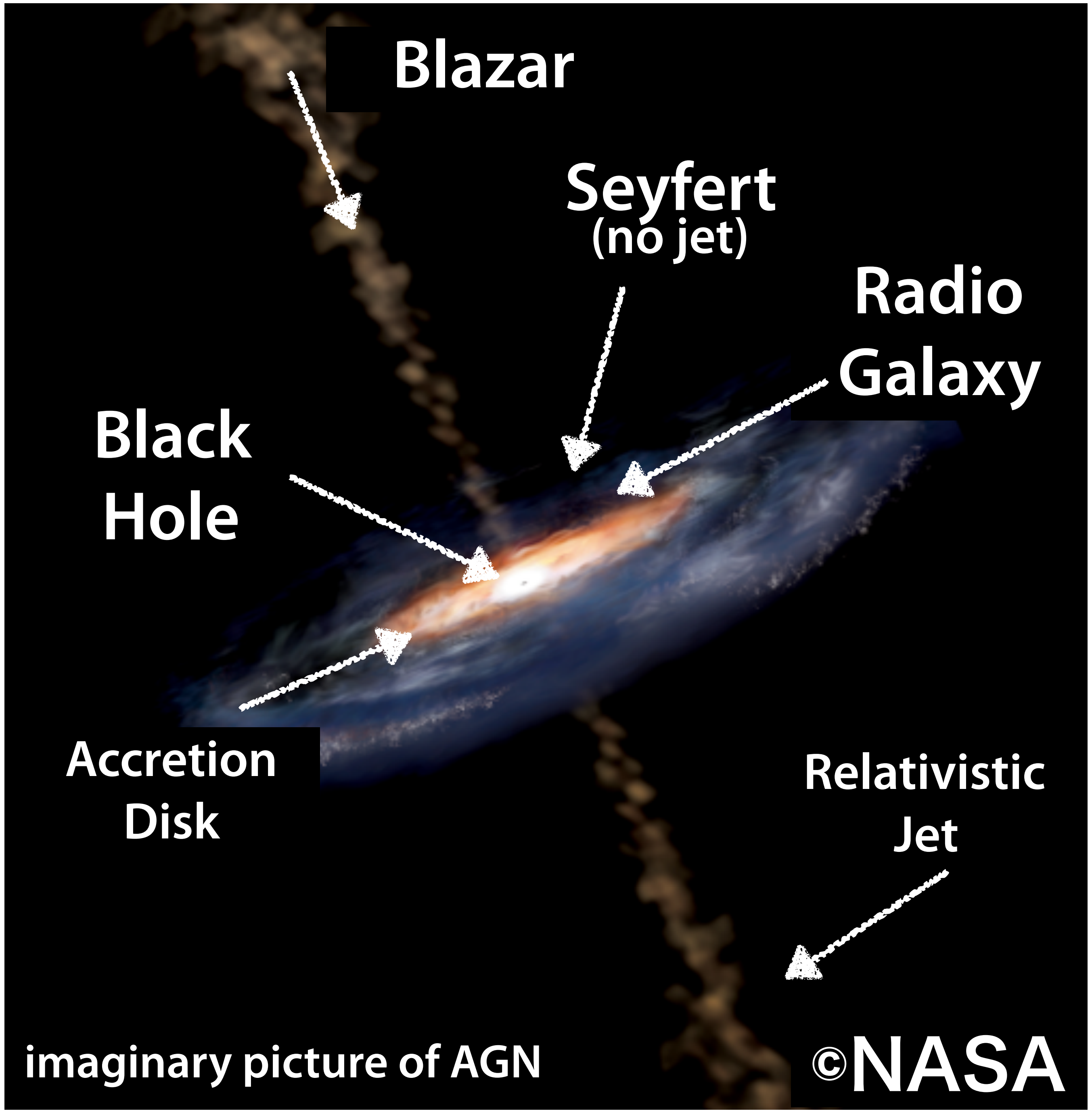
Why Gamma-ray Astrophysics?

- Probe the origin of cosmic rays
- Understand relativistic jets
- Measure intergalactic photon/magnetic fields
- Hunt dark matter signals



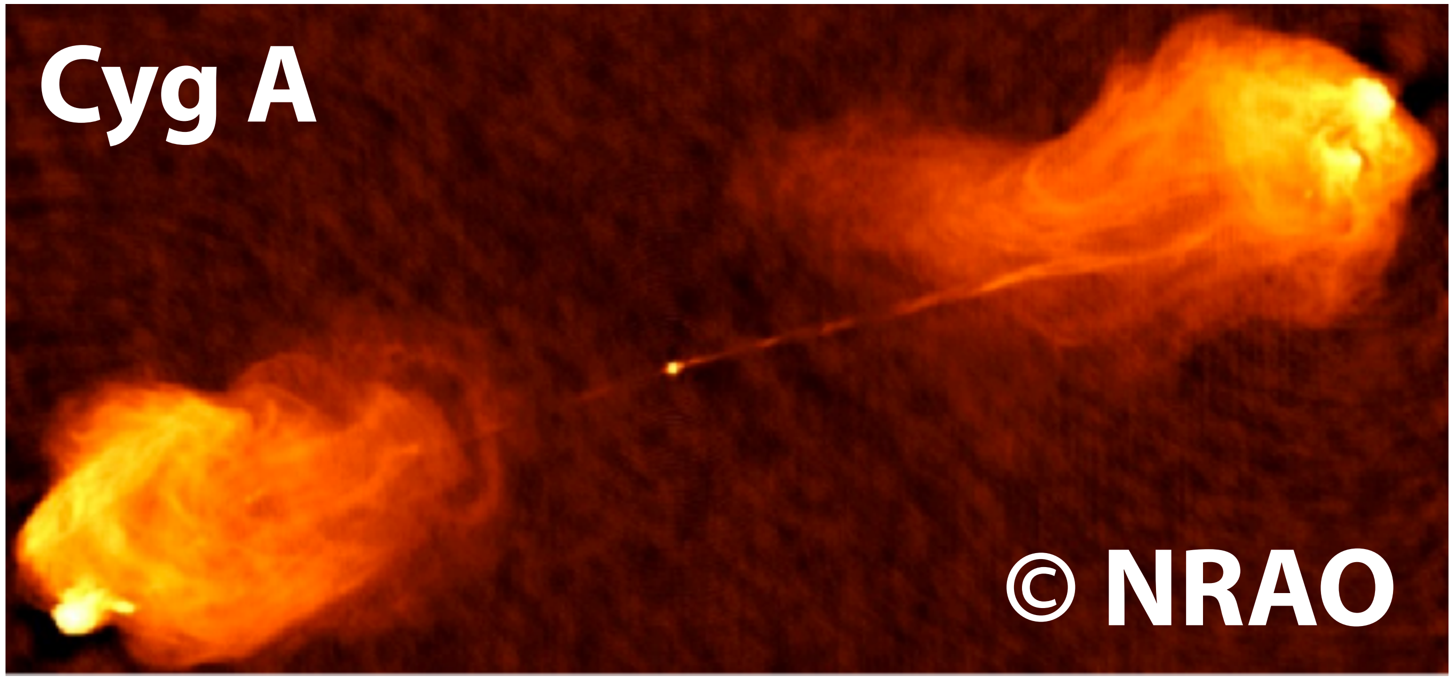
Active Galactic Nuclei

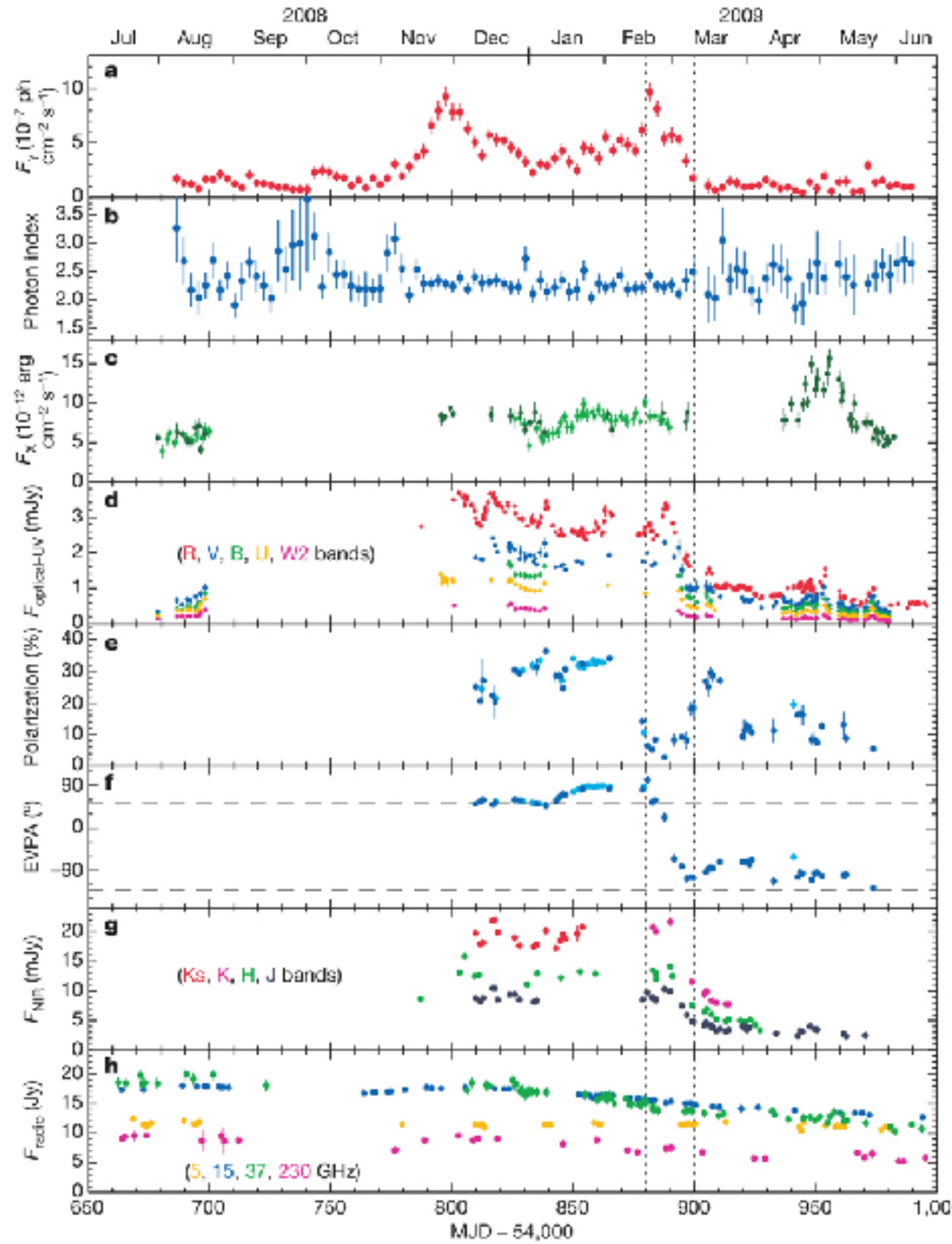
Active Galactic Nuclei (AGNs)



- >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



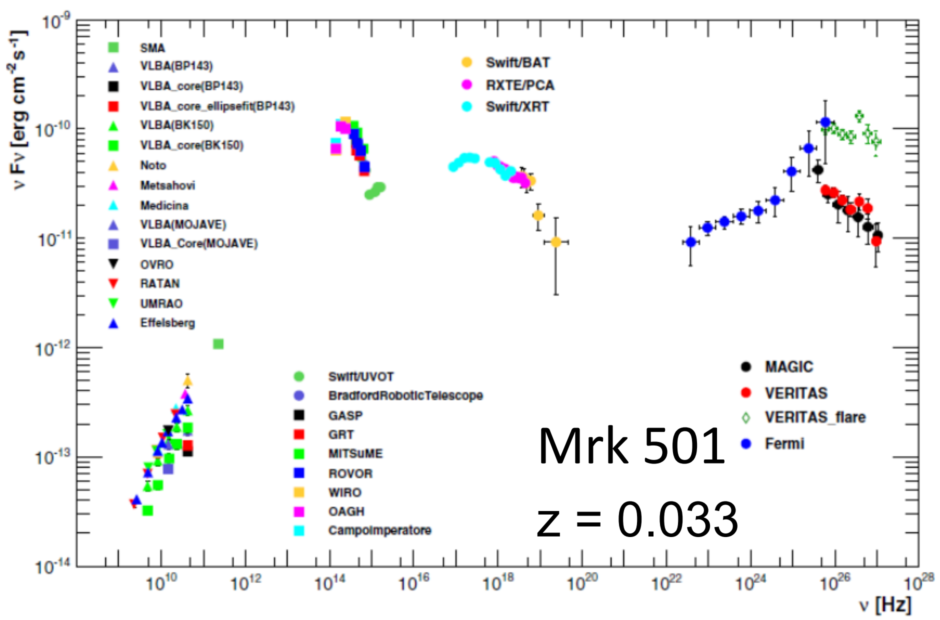


Abdo+'10

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

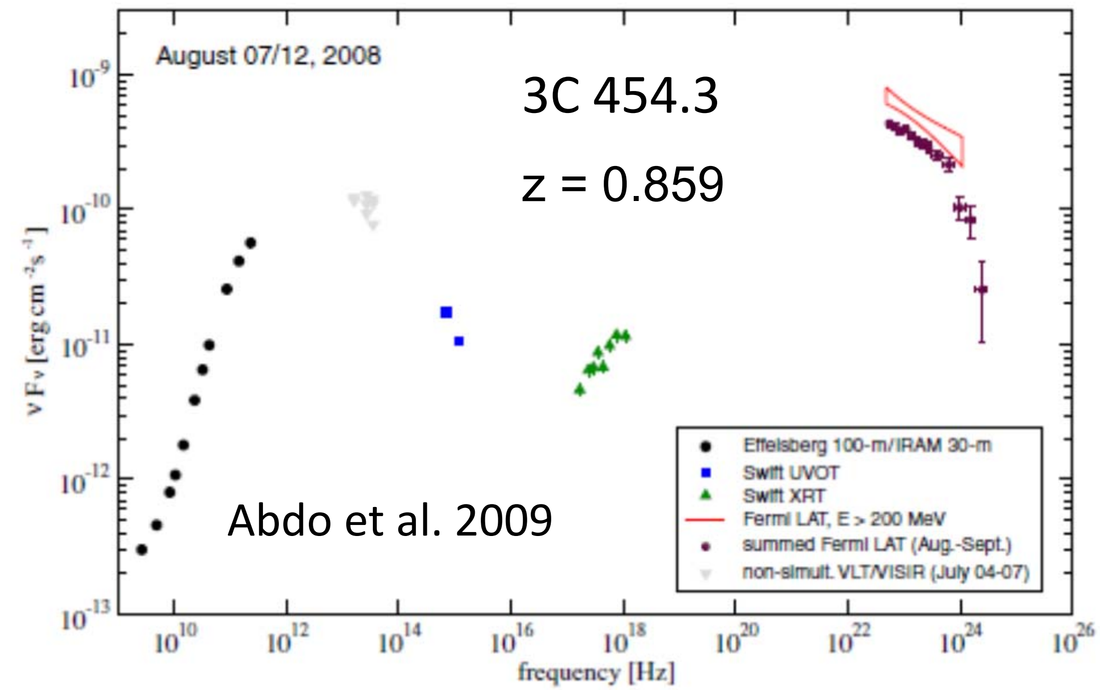
Blazar Spectra

BL Lacs: emission to VHE/TeV energies

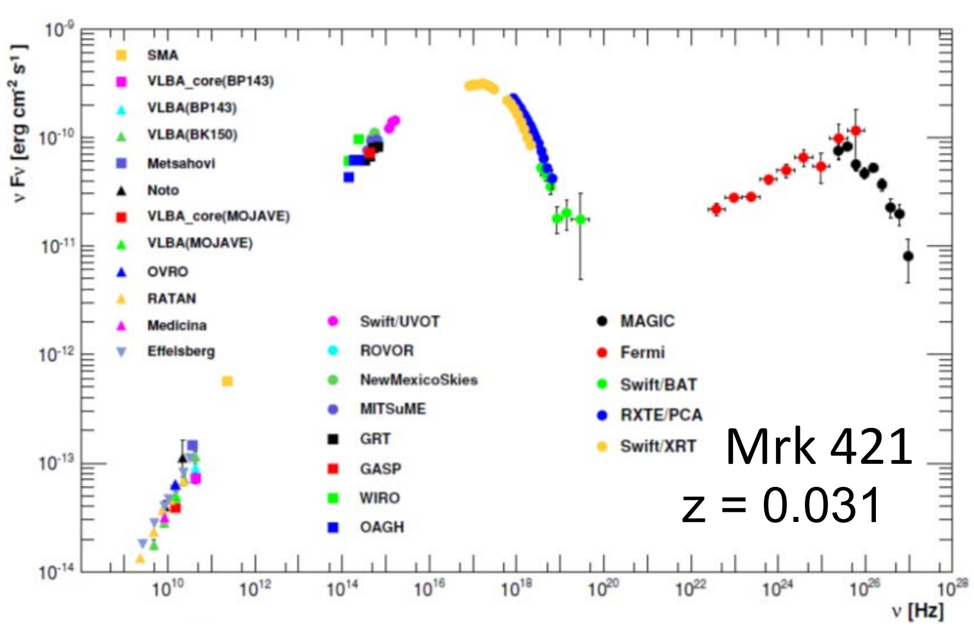


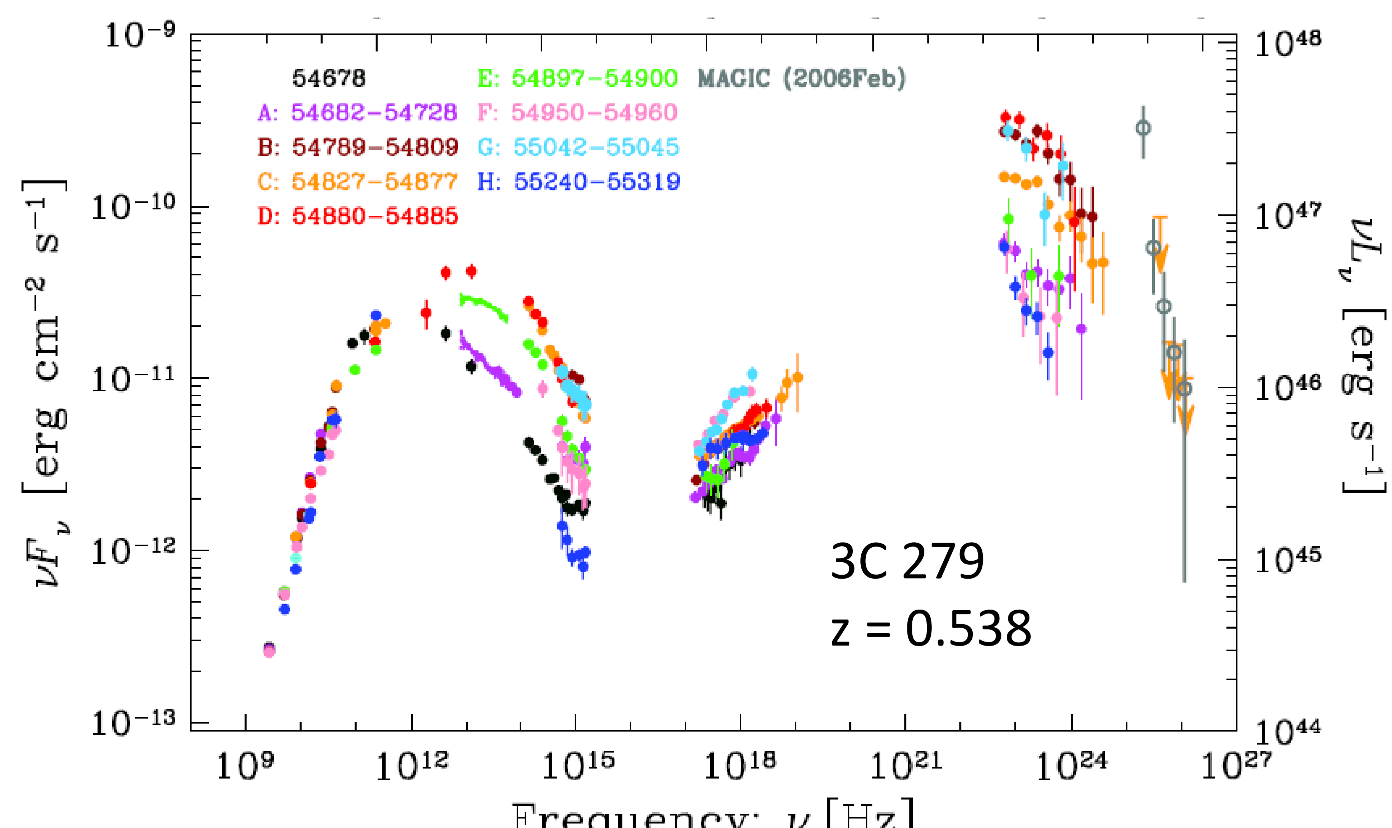
Abdo et al. 2011a

FSRQs: cutoffs at GeV with VHE episodes



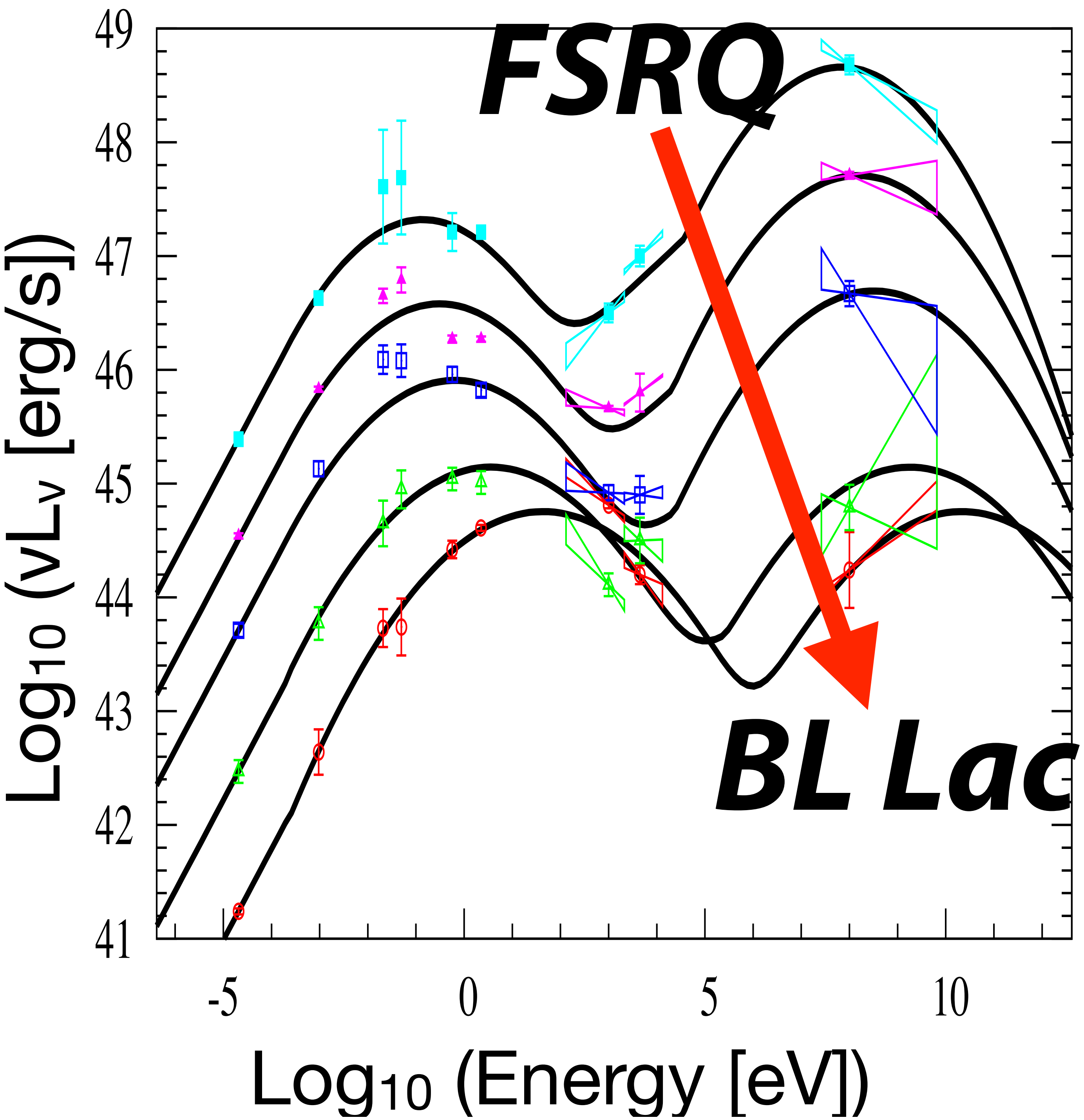
Abdo et al. 2011b





VHE (> 100 GeV)

Typical Spectra of Blazars

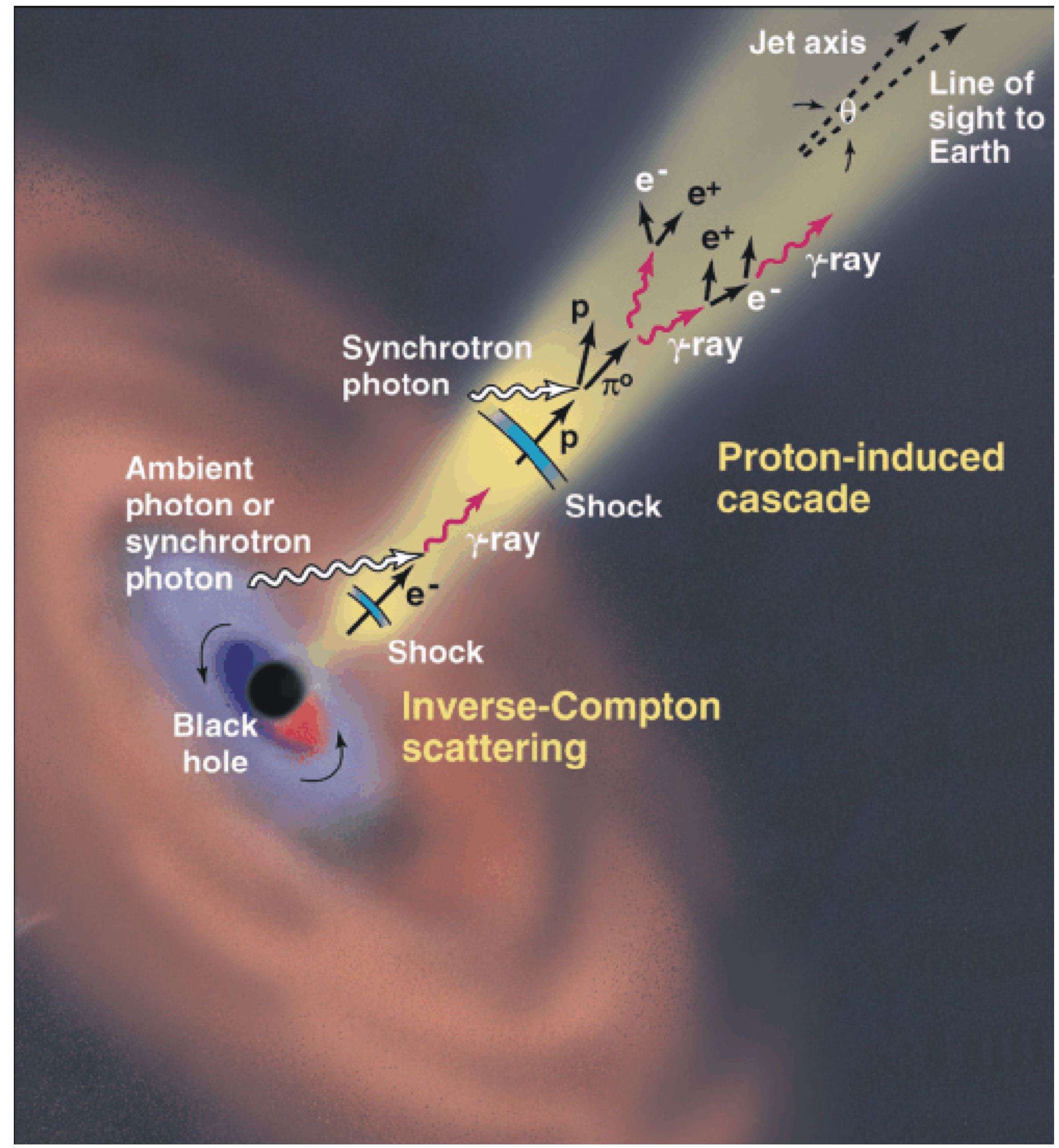


Fossati+'98, Kubo+'98,
YI & Totani '09

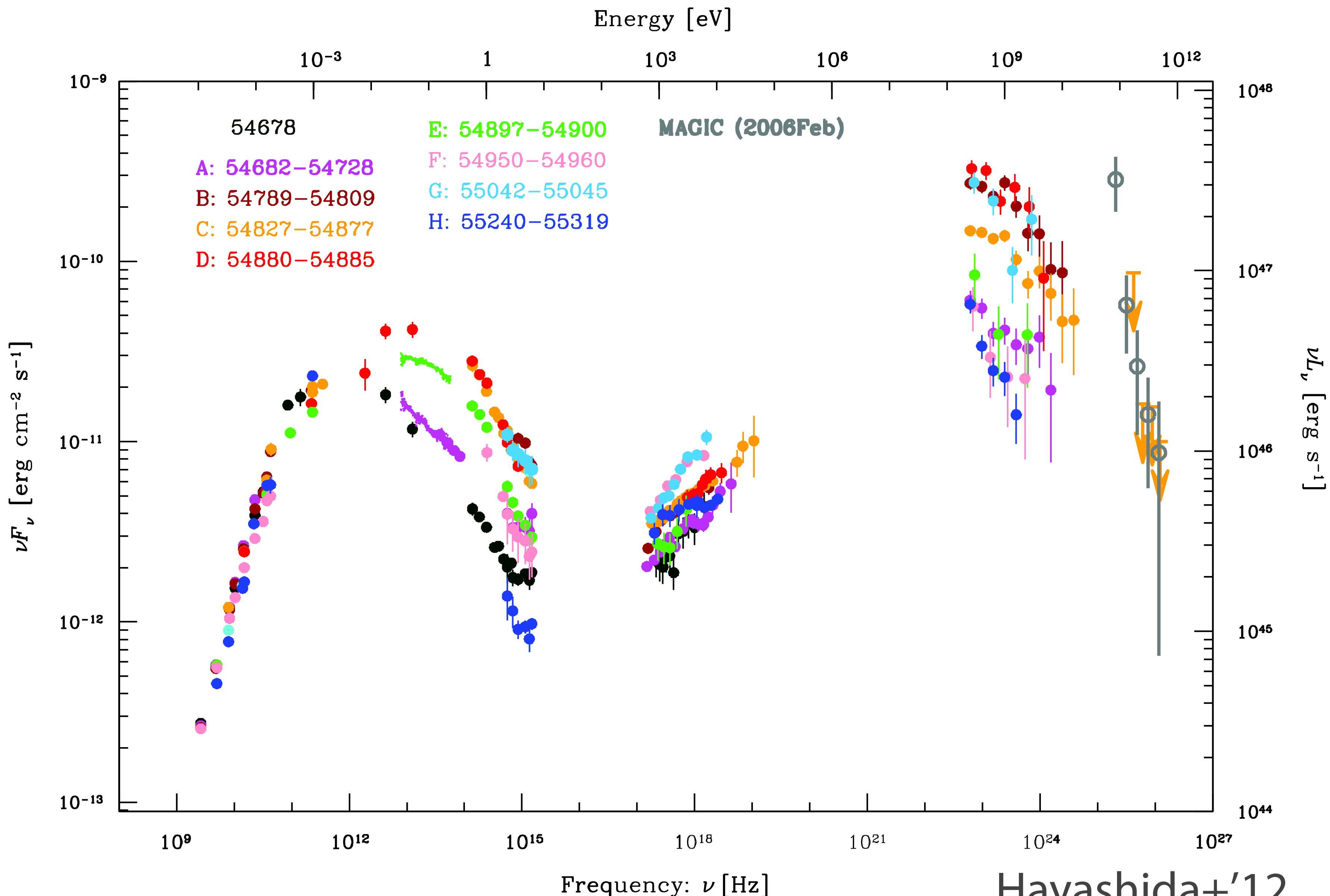
- Non-thermal emission from radio to gamma-ray
- Two peaks
  - Synchrotron
  - Inverse Compton
    - Hadronic?
- Luminous blazars (Flat Spectrum Radio Quasars: FSRQs) tend to have lower peak energies (Fossati+'98, Kubo+'98)

Blazar Emission Mechanism

- Non-thermal gamma rays
  - relativistic particles and intense photon fields
- **Leptonic model**
  - non-thermal synchrotron associated w/ Synchrotron-Self-Compton (SSC) or External Compton (EC) components
- **Hadronic model**
  - secondary nuclear production, proton synchrotron, photomeson production
  - But, requires super-Eddington jet P_{jet} ~100 L_{Edd} ? (Sikora+'09, Zdziarski & Bottcher '15)



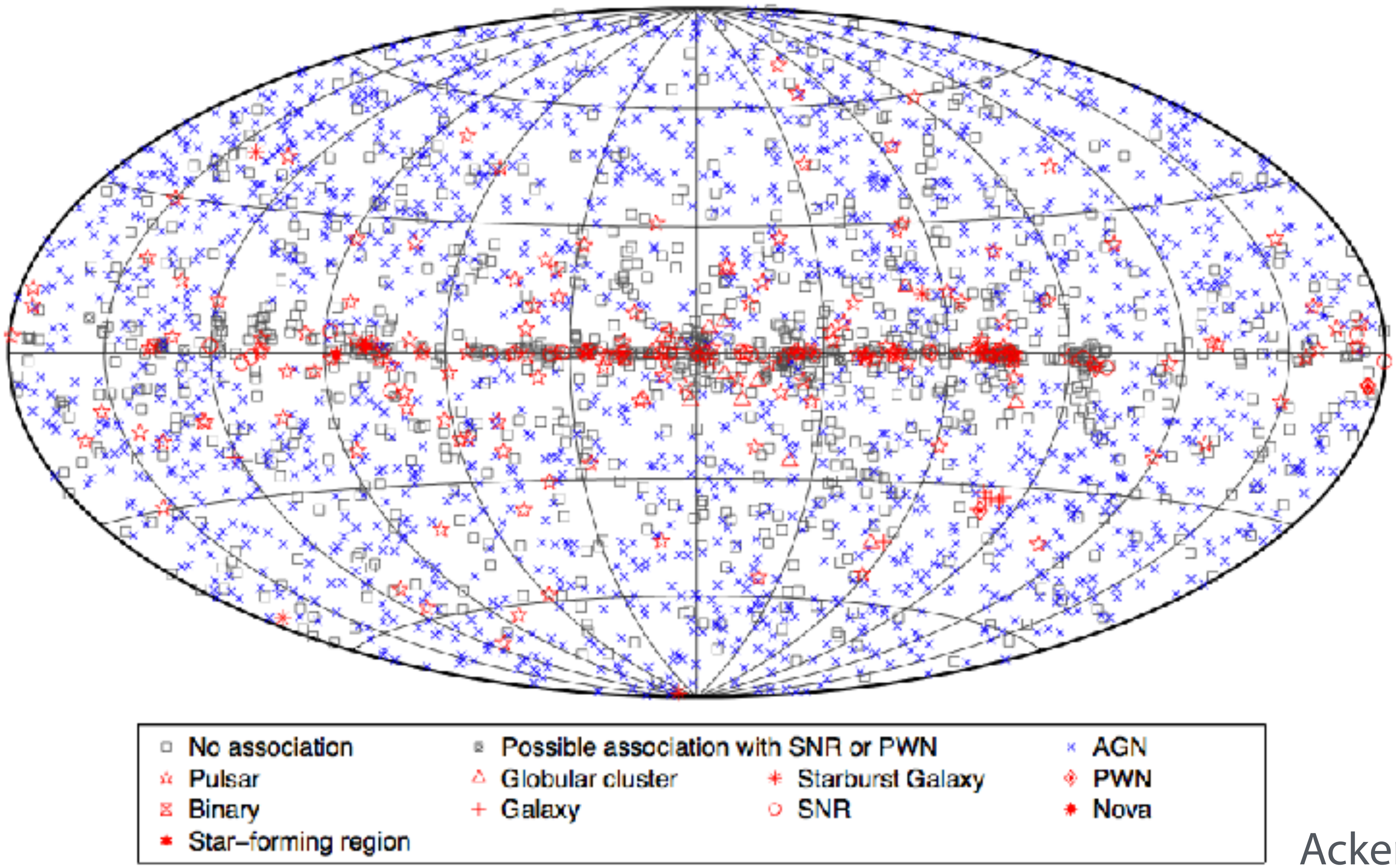
Why Gamma-ray for Blazars?



Hayashida+'12

- Spectral energy distribution (SED) of a blazar 3C279
- Jet radiative power is dominated by gamma-ray.

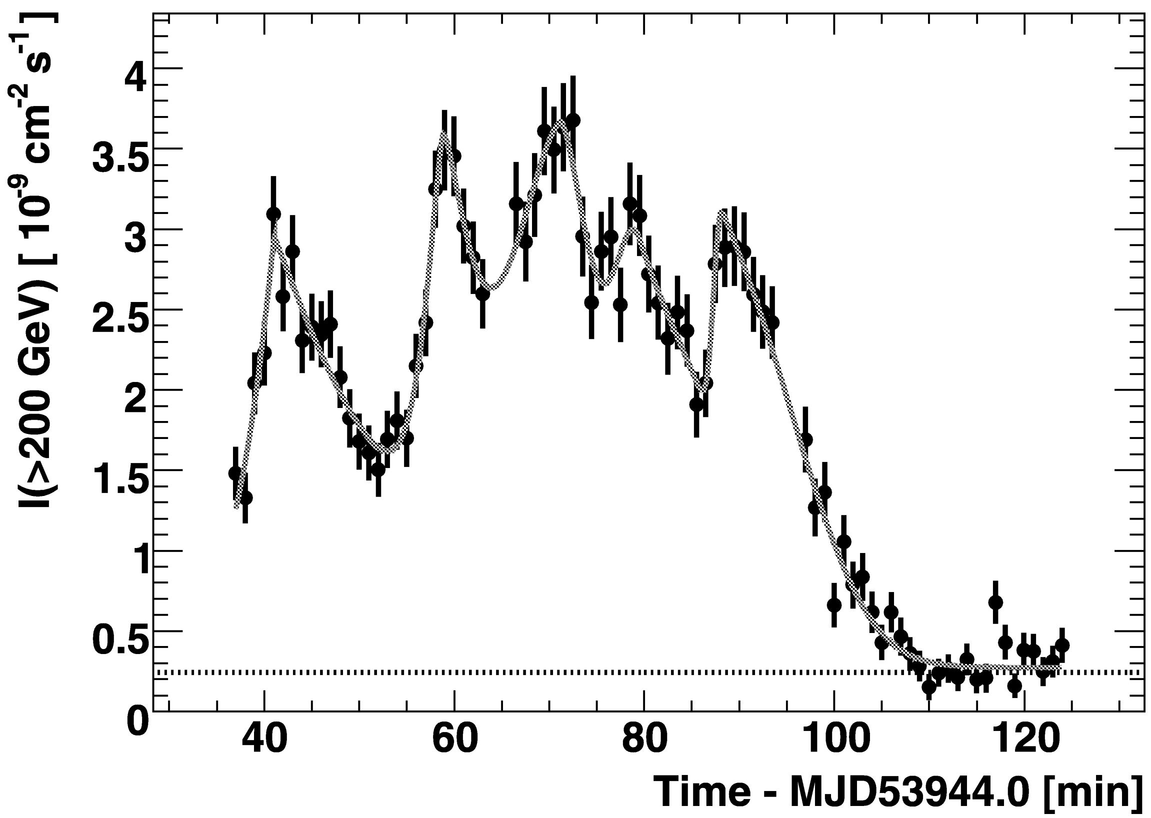
Golden Era for Blazar Studies



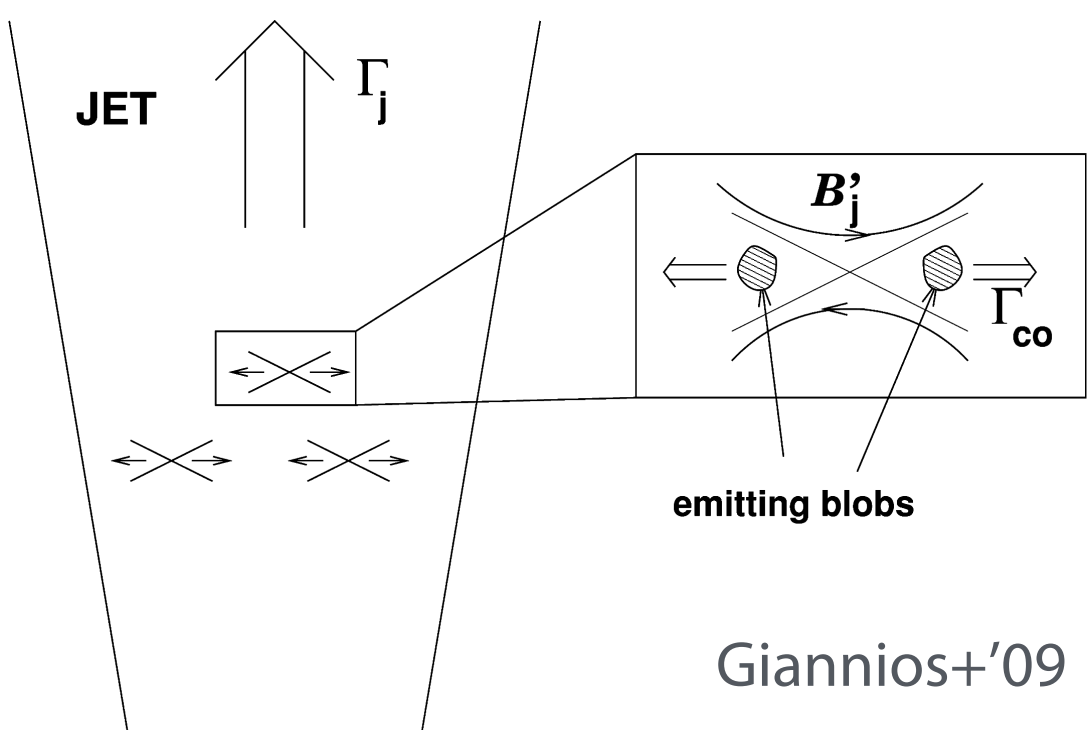
Ackerman+'15

- Fermi has detected 3033 sources in its 4-year survey.
  - 1591 AGN samples (467 FSRQs and 632 BL Lacs)
  - But, do we understand blazar physics?

Short time Variability



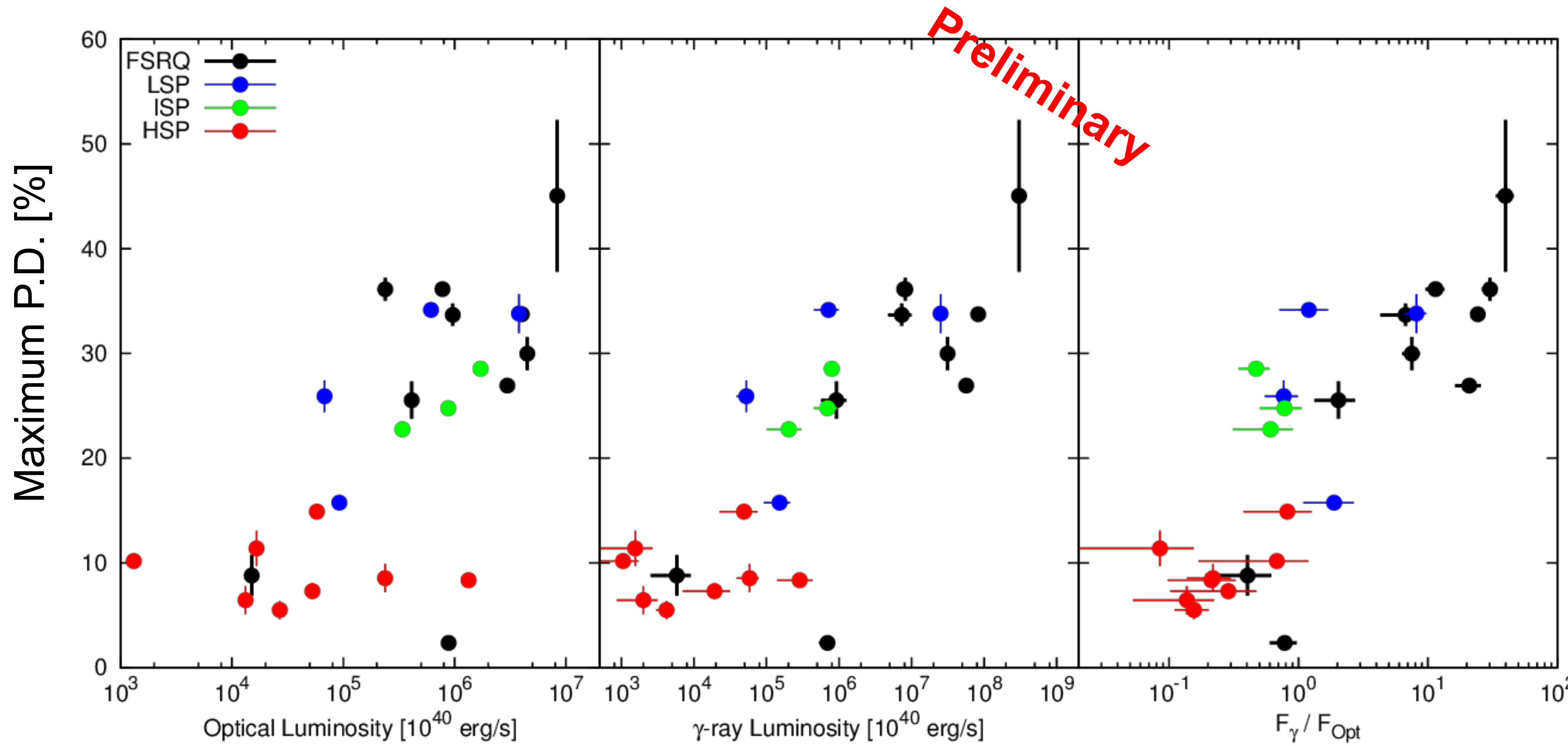
Aharonian+'07



Giannios+'09

- Fast variabilities ~200 s (Aharonian+'07, Albert+'08)
- requires very compact emitting region with Γ~100
- Jet-in-Jet (Giannios+'09) ?
  - But, anisotropic distribution required (Aharonian+'17)

Polarization



Itoh+'16

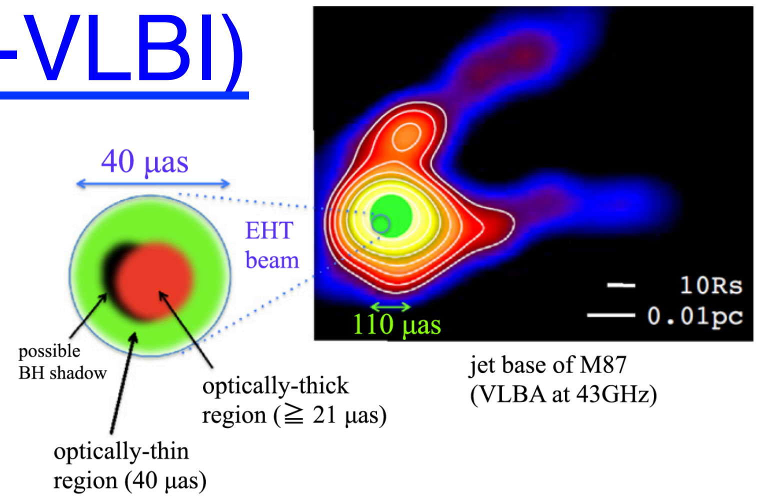
- Polarization tells the magnetic field environment in jets
- Gamma-ray luminous blazars tend to show higher maximum polarization degrees.
- Superposition of multiple emission regions in spine-sheath jet (Itoh+'16)?

Jet Energetics

radio (mm-VLBI)

(Kino+15,16)

poynting dominated @a few-10Rs



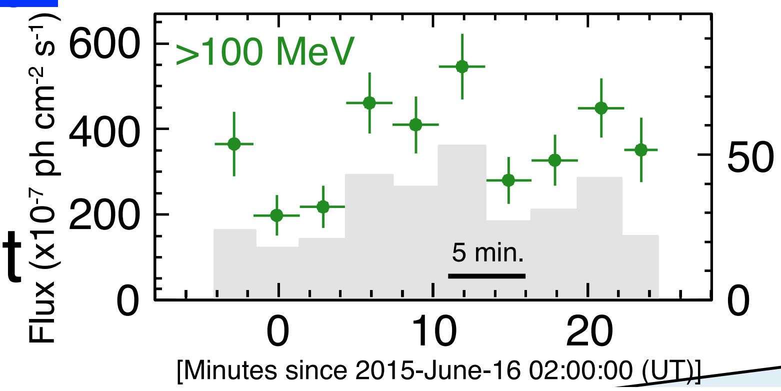
Gamma-ray

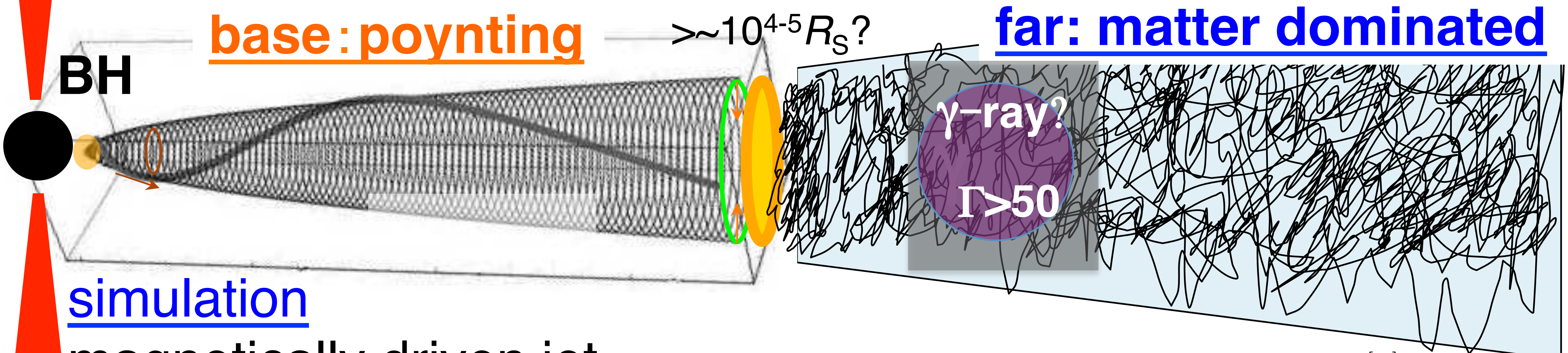
(LAT collab.16, MH+16)

minute-scale variability

→ very compact

→ high Γ(>50)

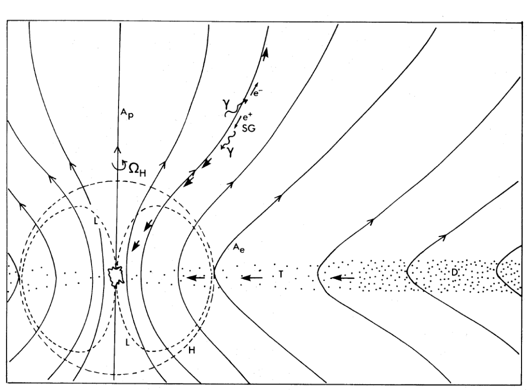


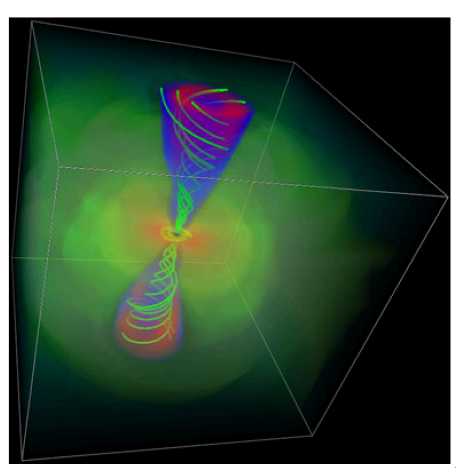


simulation

magnetically driven jet

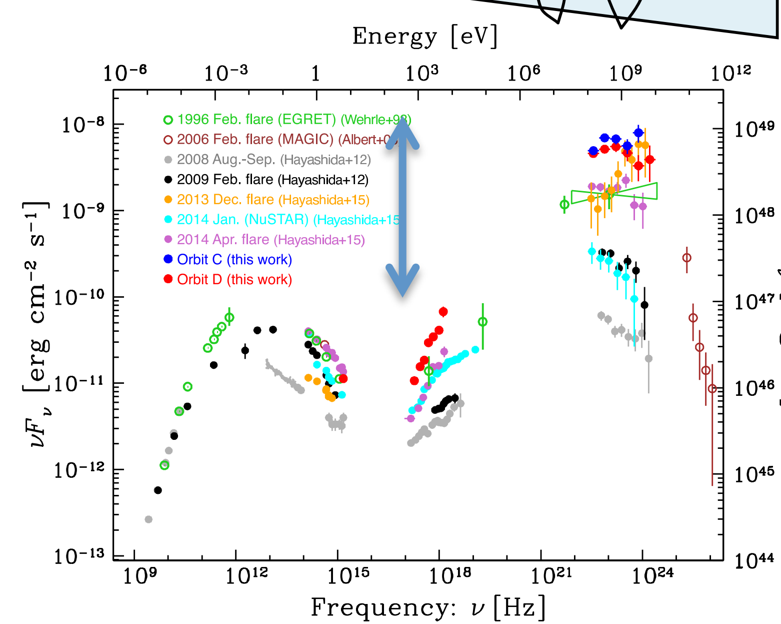
(e.g., BZ mechanism)



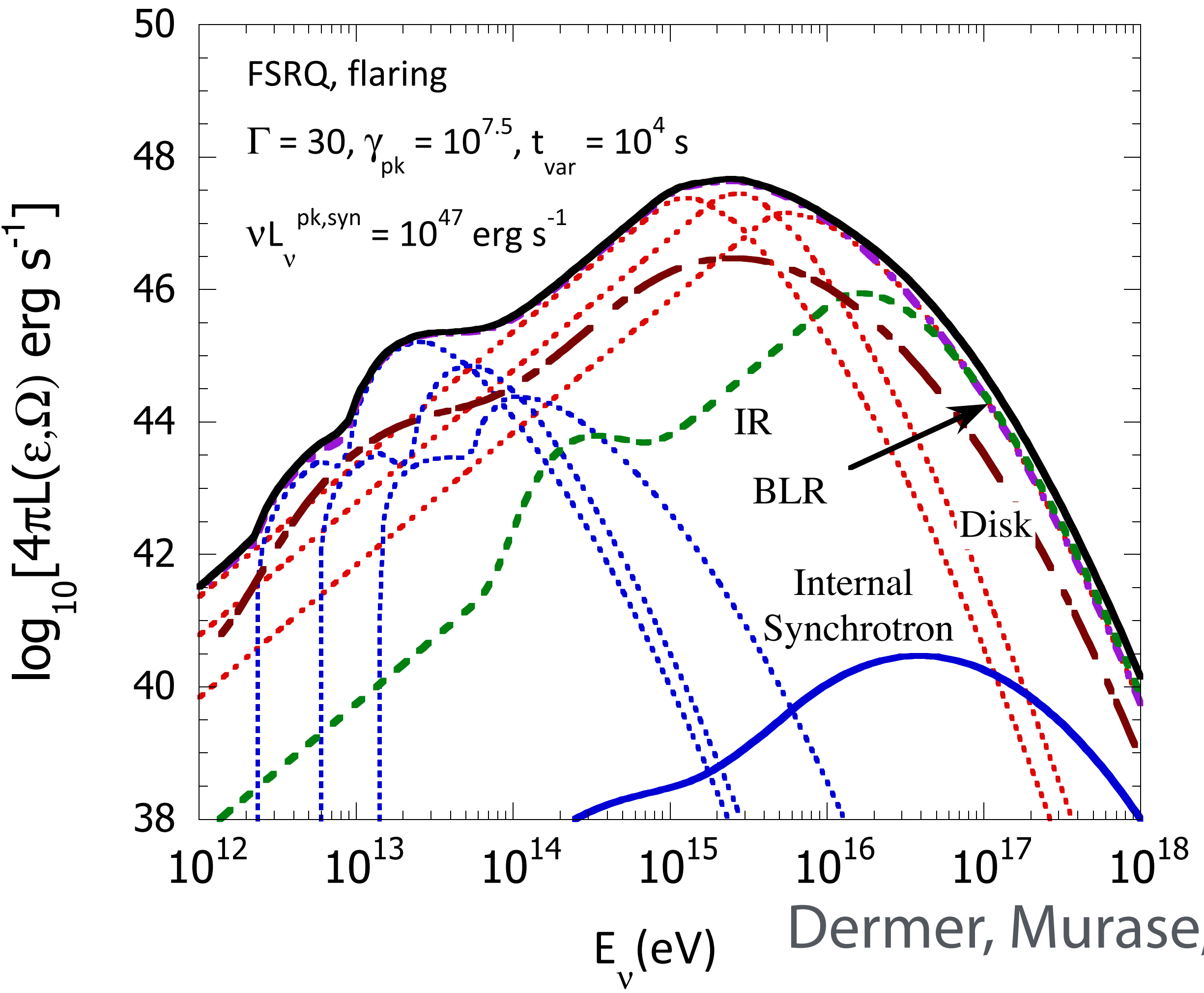


high-Compton dominance

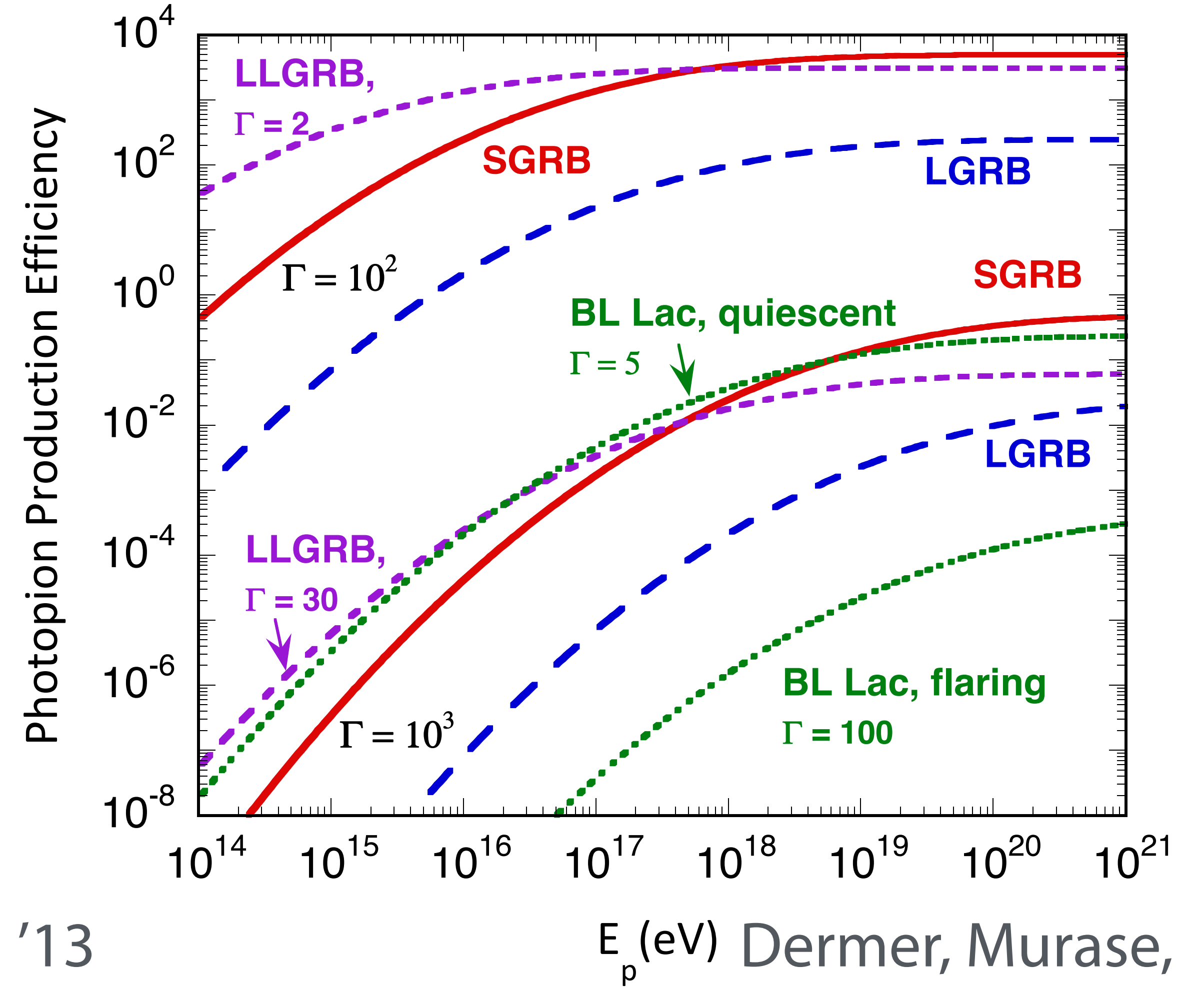
→ matter dominated jet



Neutrinos



Dermer, Murase, & YI '13



Dermer, Murase, & YI '13

- FSRQs would have a peak at ~PeV due to BLR photons

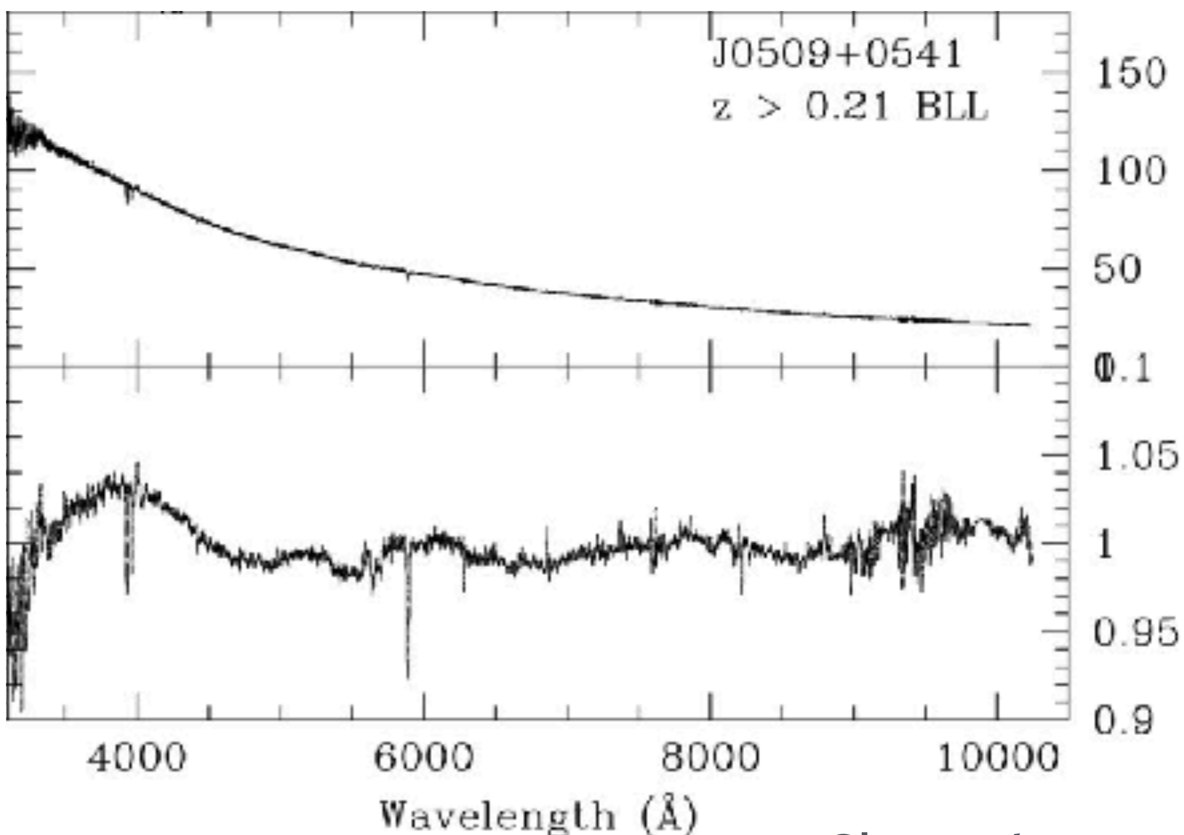
  (e.g. Dermer, Murase, & YI '13; Murase, Dermer, & YI '13)

- BL Lacs are inefficient neutrino factories

  (e.g. Dermer, Murase, & YI '13; Murase, Dermer, & YI '13)

Yoshida-san's talk

Do we know distances to blazars?

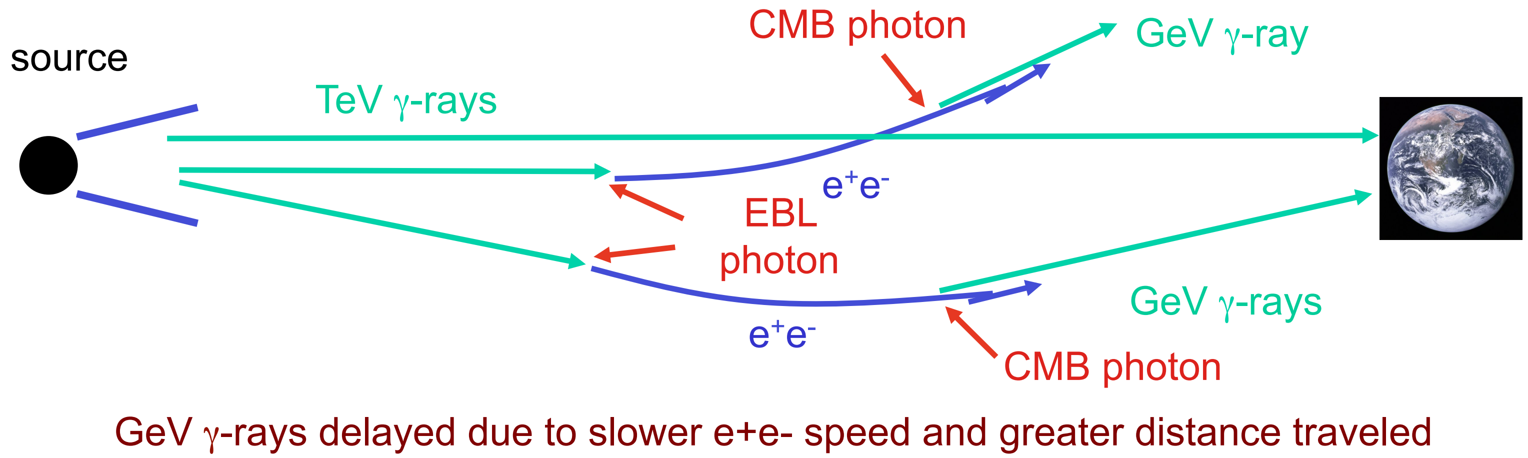


Shaw+'13

- Definition of BL Lacs: EW of emission lines < 5Å
  - weak emission lines
  - ~50% of Fermi BL Lacs do not have spectroscopic redshifts

- One example:
- Fermi/MAGIC detected gamma-ray flare events from TXS 0506+056 (ATel #10791, 10817)
  - 6 arcmin from IceCube-170922A (GCN #21916)
  - But, redshift is not determined,,,

Probing Intergalactic Magnetic Fields?



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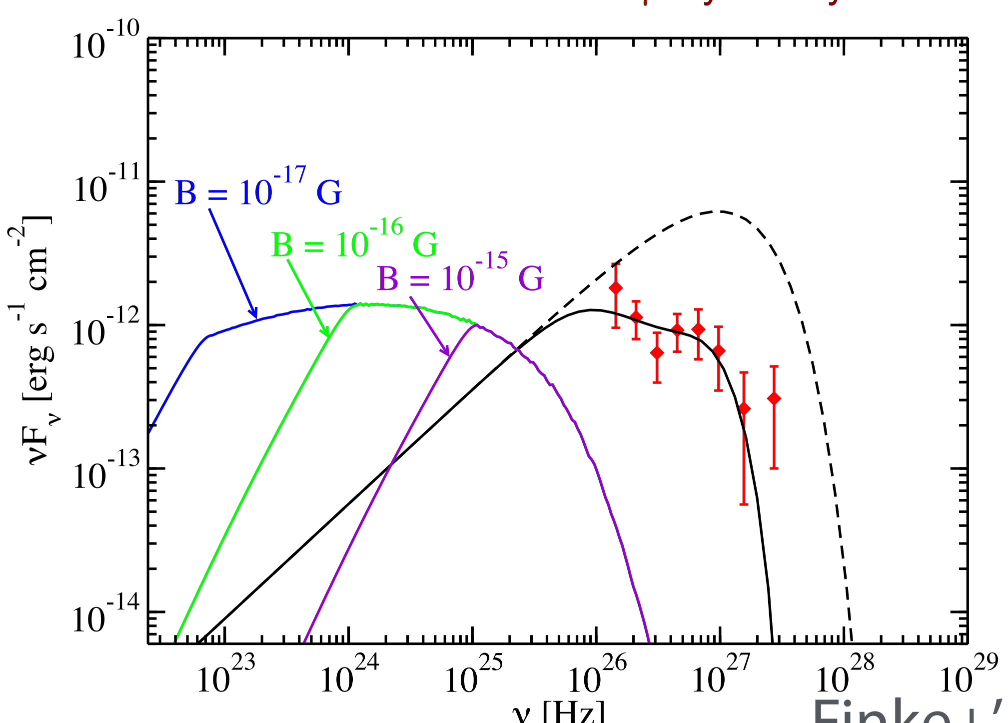
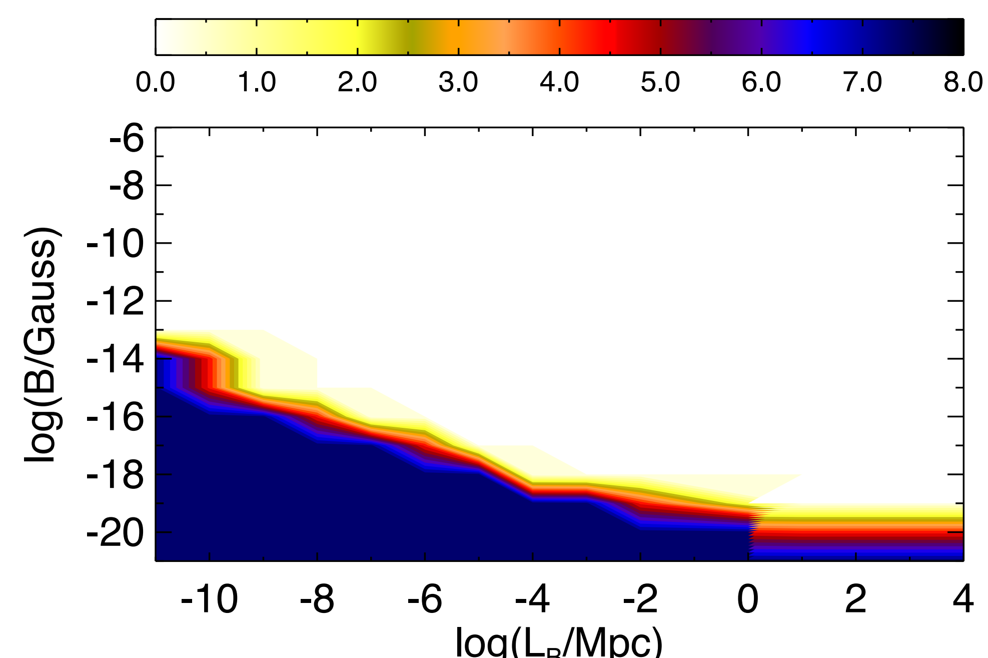


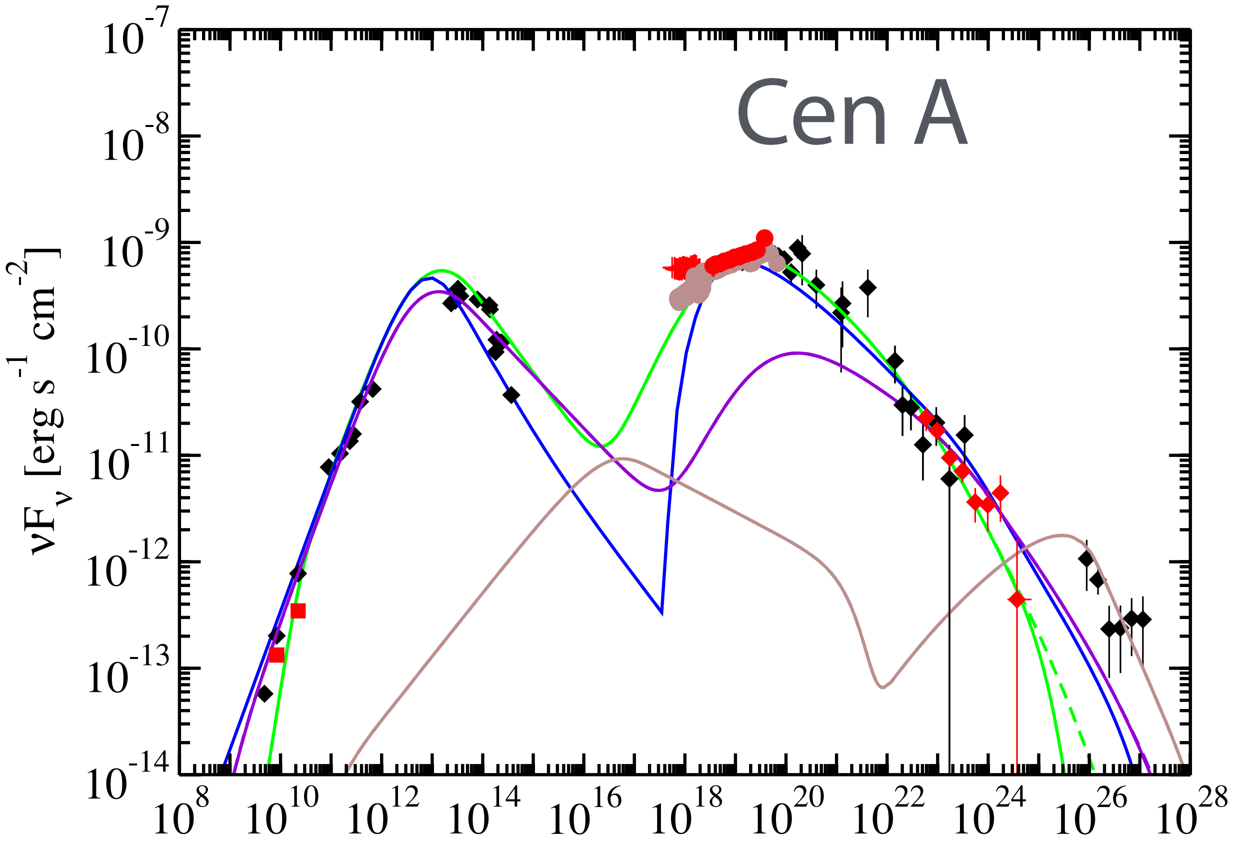
Finke+'15



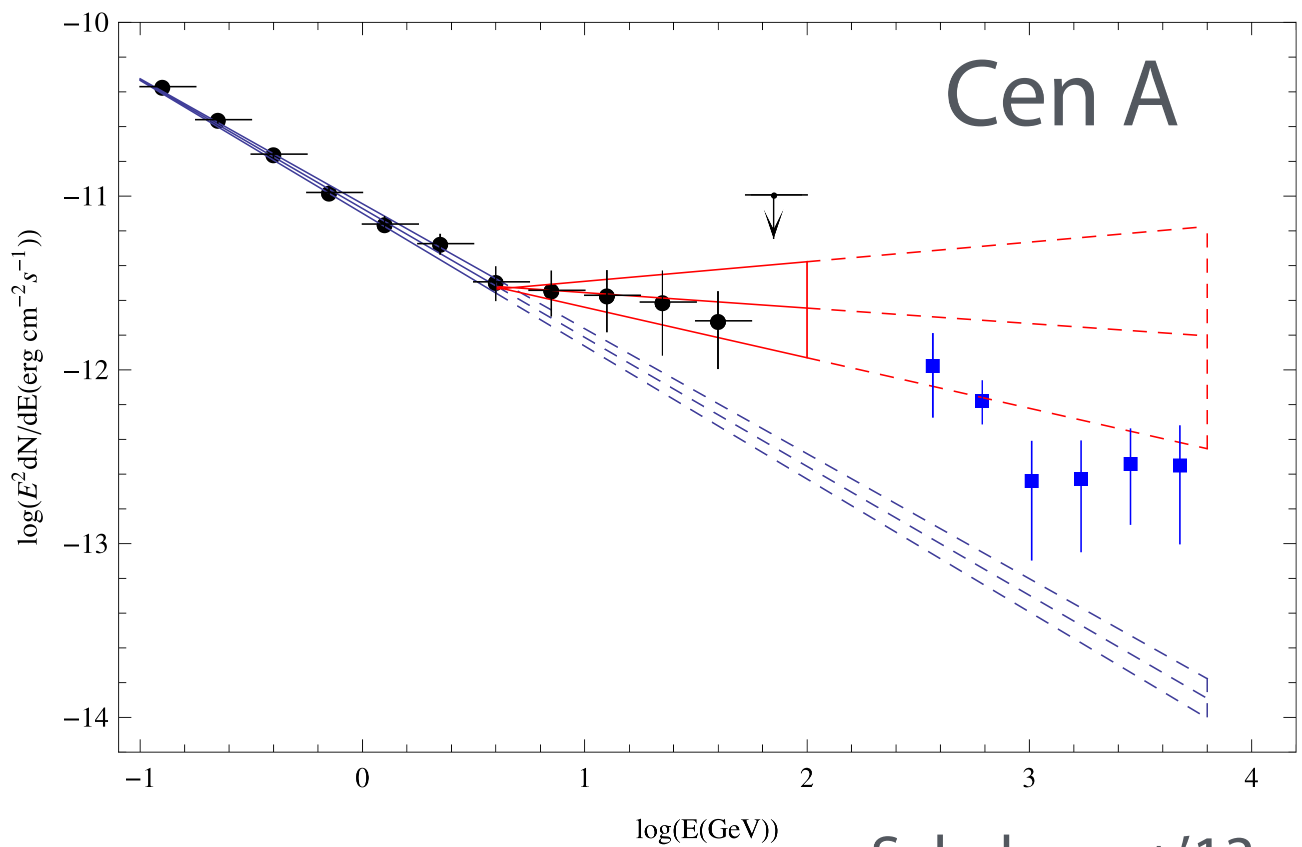
Finke+'15

- Delayed cascade emission and pair halos are probes of intergalactic magnetic fields (Plaga'95, Neronov & Semikoz '07, Ichiki+'08,….)
- Current constraint rules out low B values, $B<10^{-19}$ G for $L_B > 1$ Mpc (Finke+'15).
- Can we see pair halos? delayed emission?

Radio galaxy



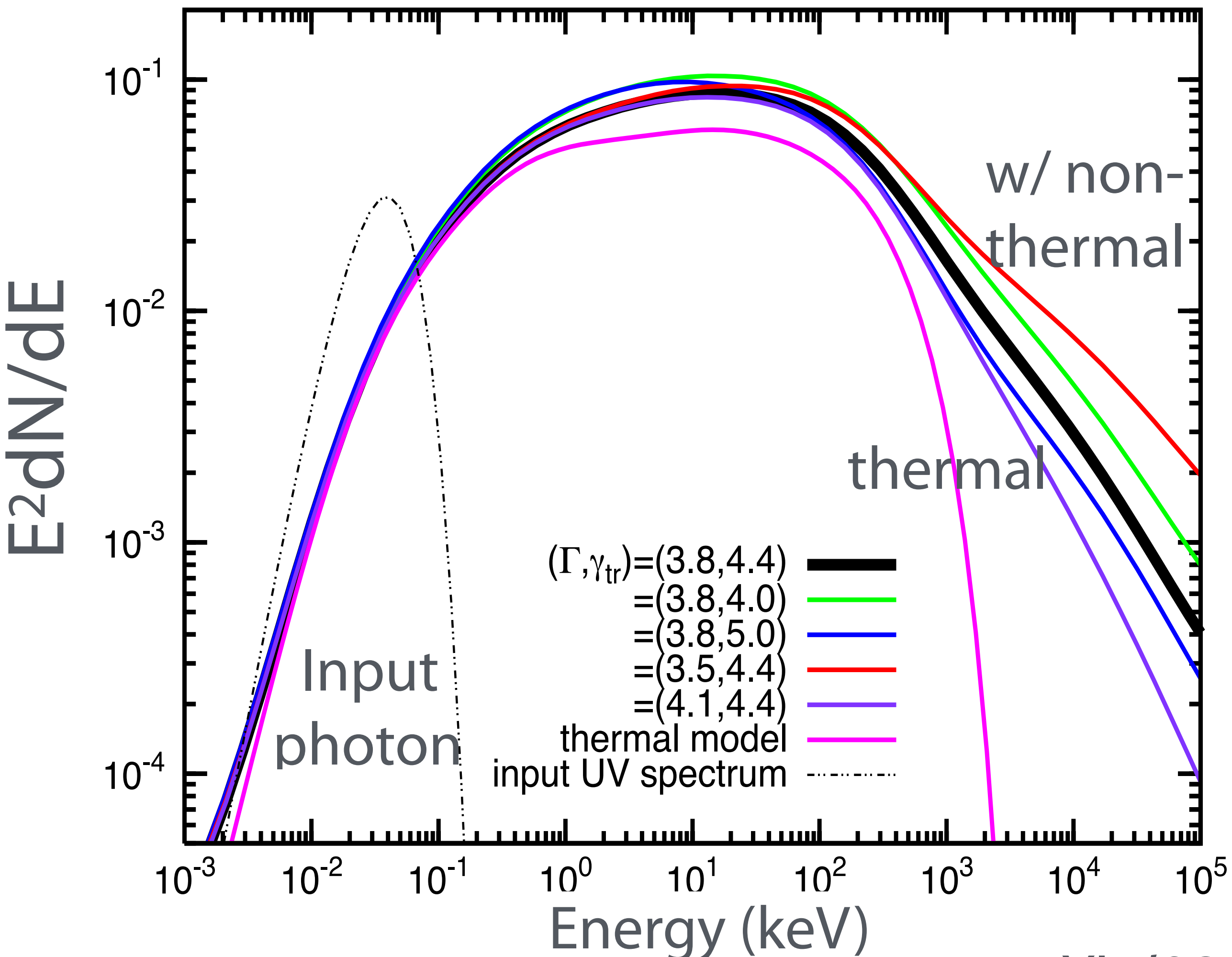
Abdo+’10



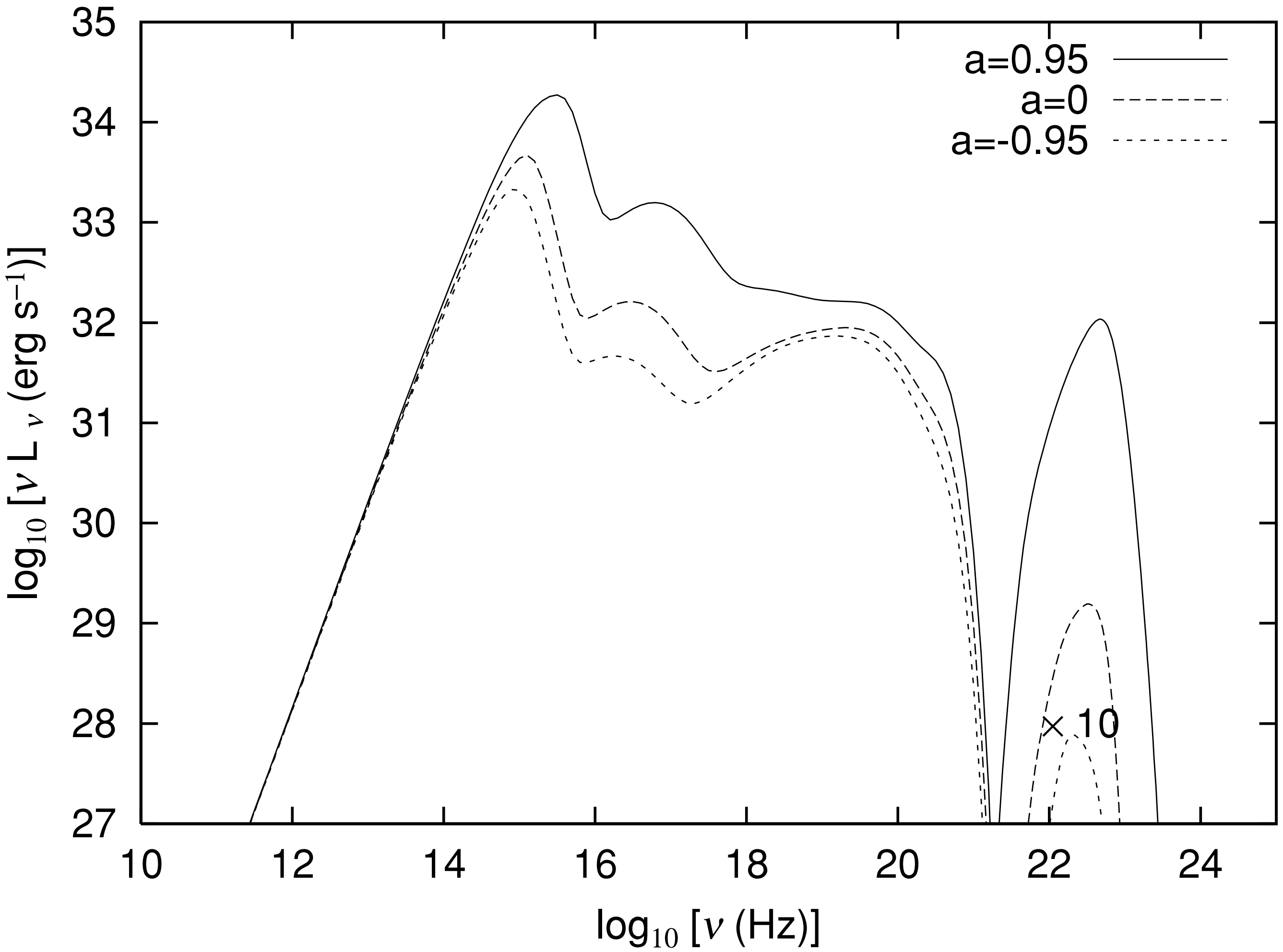
Sahakyan +’13

- Spectral hardening from ~4 GeV (Sahakyan+’13).
  - BH magnetosphere? multi components? hadronic? knots? cascade in torus? IC of host galaxy starlight?

Seyfert & low-luminosity AGNs



YI+'08



Oka & Manmoto '03

- Non-thermal tail from corona (YI+'08)?
- pp/pγ interaction in RIAF (Oka & Manmoto '03, Niedźwiecki+'13, Kimura+'15)?
- No clear detection yet (Teng+'11, Hayashida+'12)

Other problems

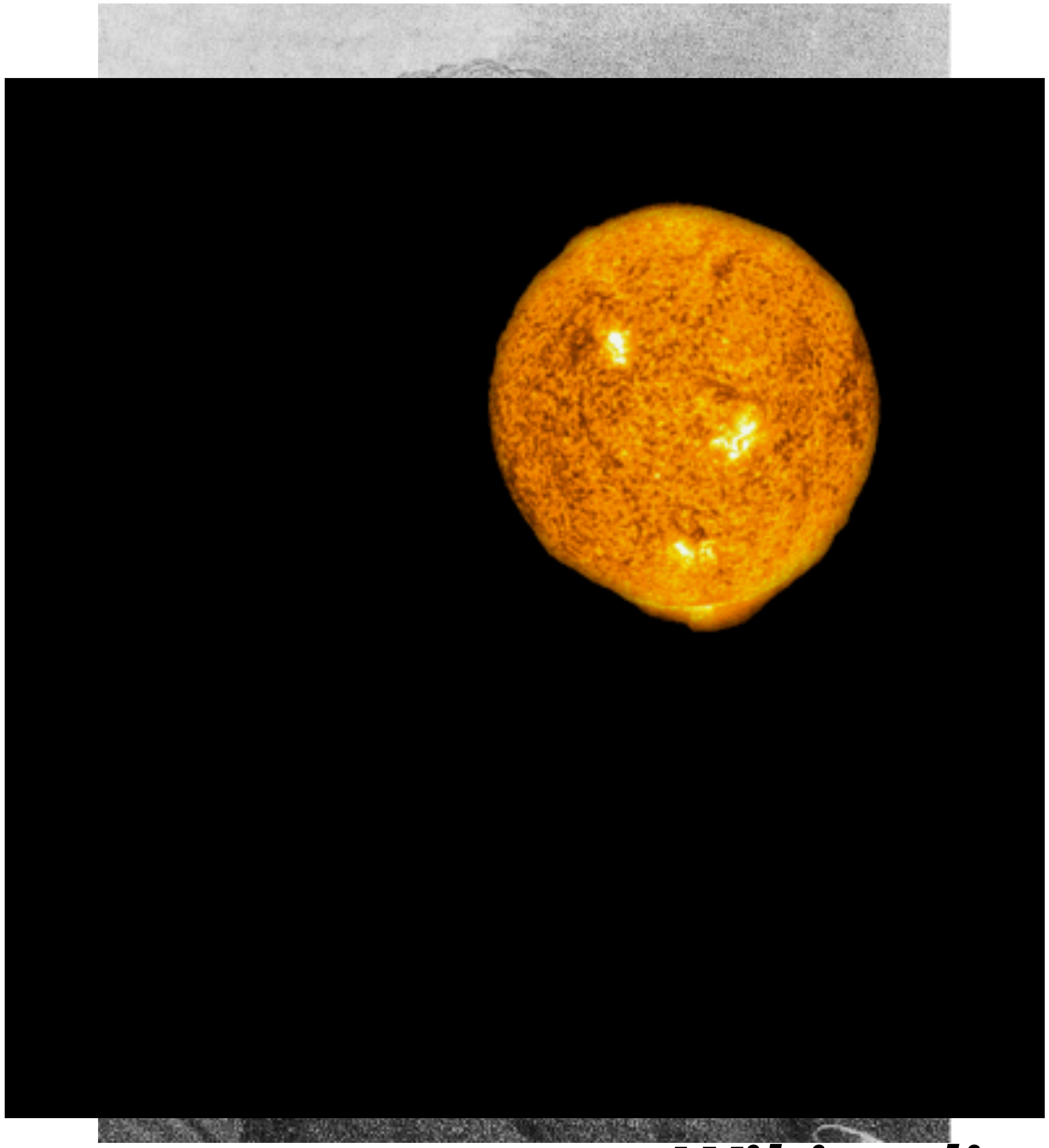
- Particle acceleration
  - diffusive shock acceleration? turbulence? reconnection?
  - ultra-high energy cosmic rays?
- Jet composition
  - proton? pairs?
- constraining intergalactic radiation field
  - EBL evolution? extrapolation OK?
- connection between radio and gamma-ray
- and so on,,,

Break

Cosmic Gamma-ray Background

Olbers' Paradox

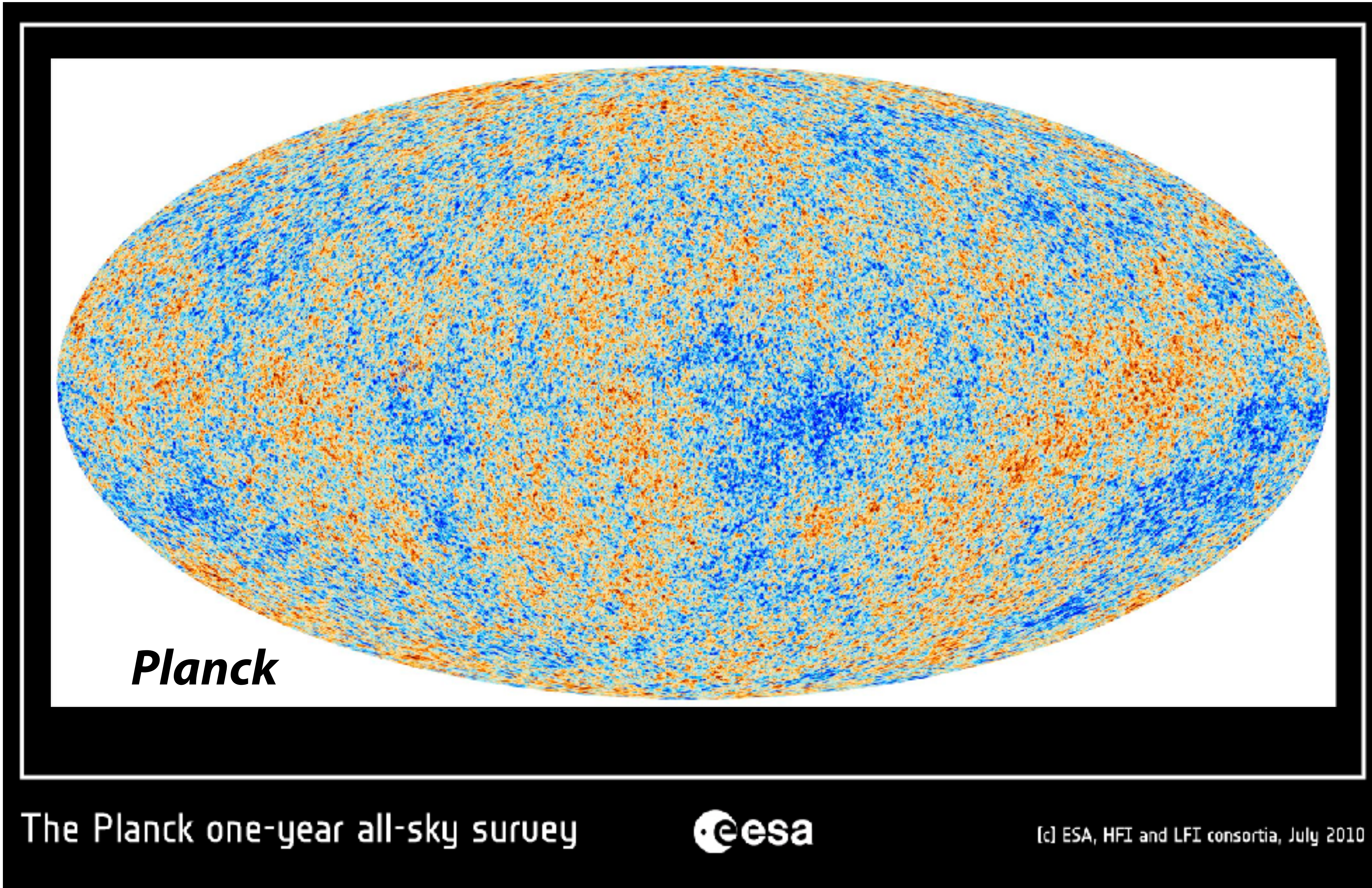
- Heinrich Wilhelm Matthias Olbers (1758-1840)
- "***Why is the sky dark at night?***"
- If the Universe is infinite and has infinitely many stars, the sky should be as bright as the surface of the Sun.
- Answer: the Universe is ***not*** infinite.



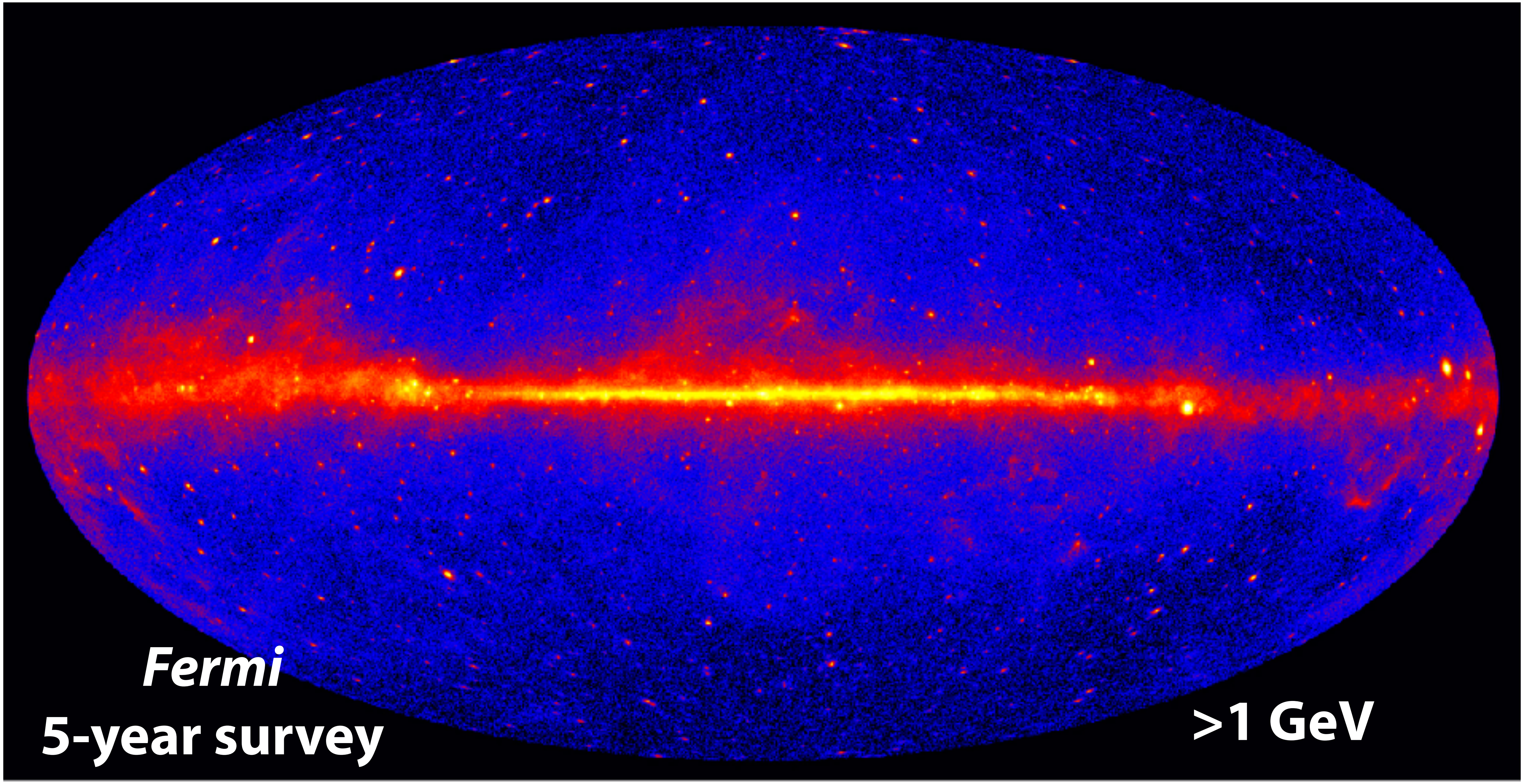
Is the sky truly dark?

- No.
- There is faint but almost isotropic emission in the entire sky.
- “Cosmic Background Radiation”.
    - cumulative emission of the universe in its entire history.

Sky in Microwave

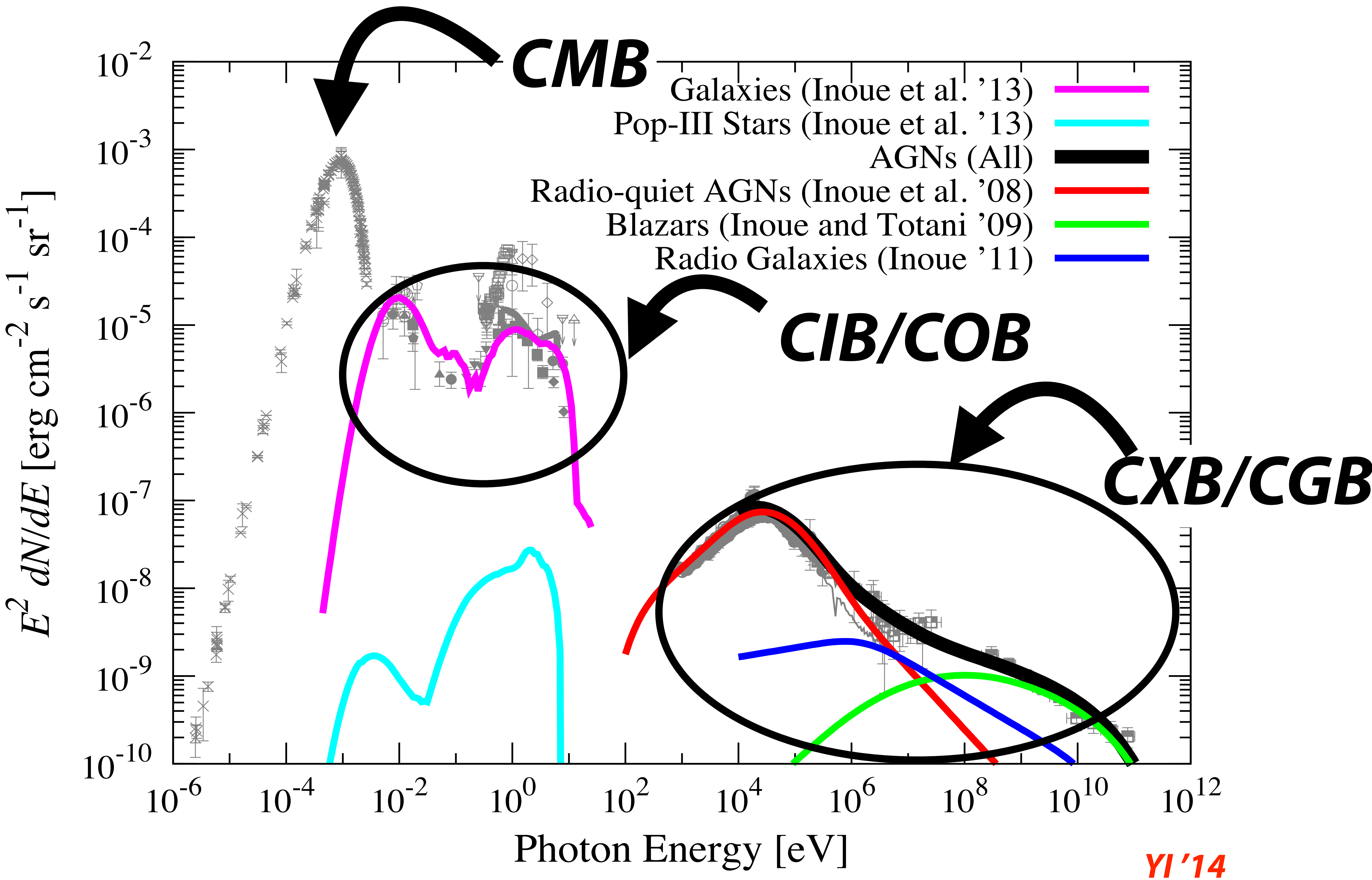


Sky in GeV Gamma rays

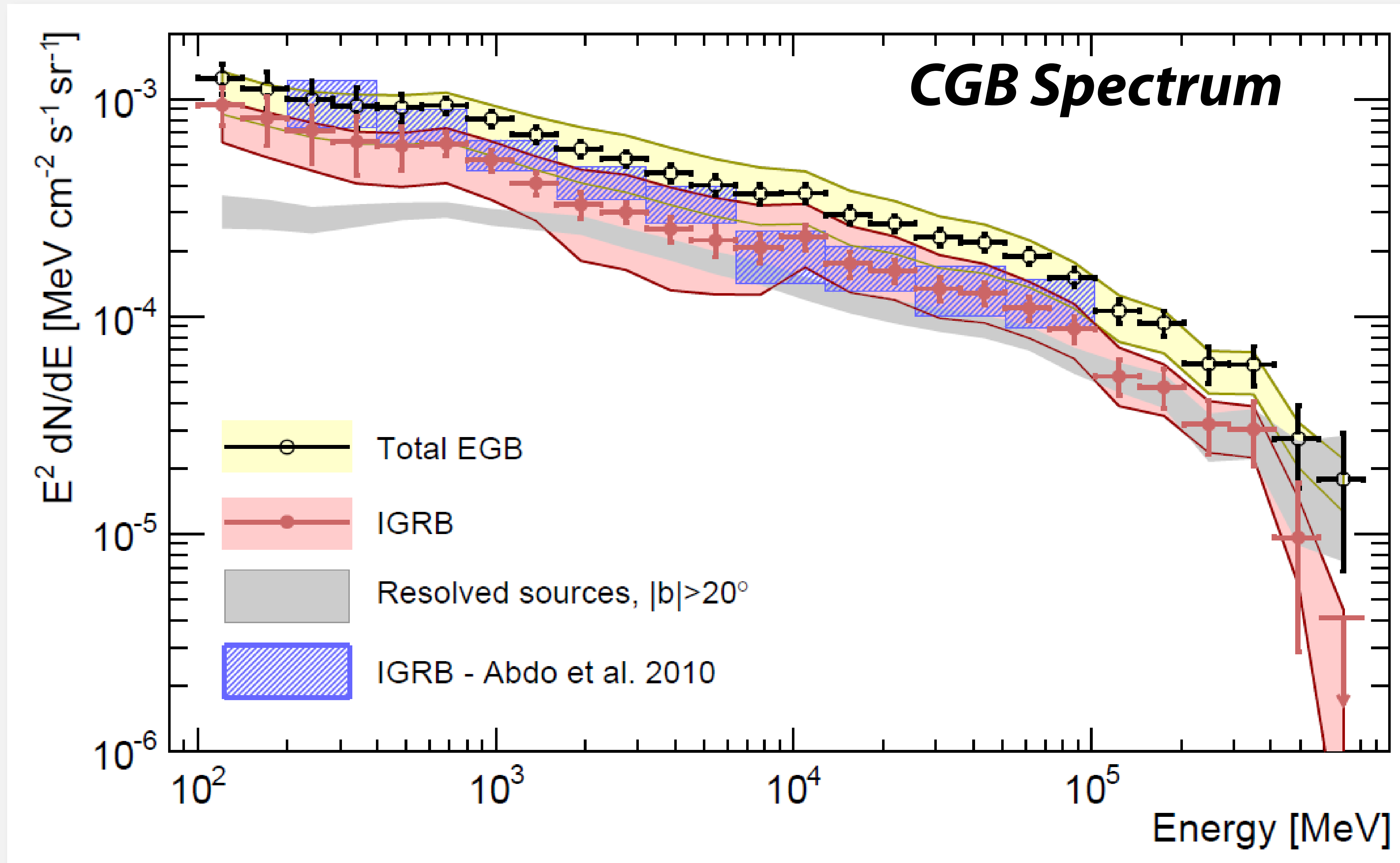


- Numerous sources are buried in the cosmic gamma-ray background (CGB).

Cosmic Background Radiation Spectrum



Cosmic Gamma-ray Background Spectrum at >0.1 GeV

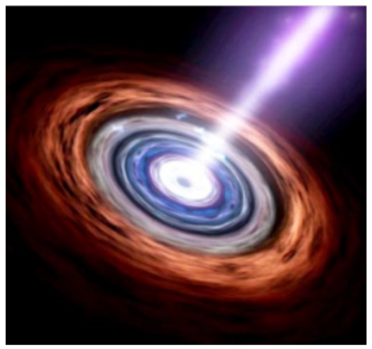


Ackerman+'15

- Fermi has resolved 30% of the CGB at ~1 GeV and more at higher energies.

Possible Origins of CGB at GeV

Unresolved sources



Blazars

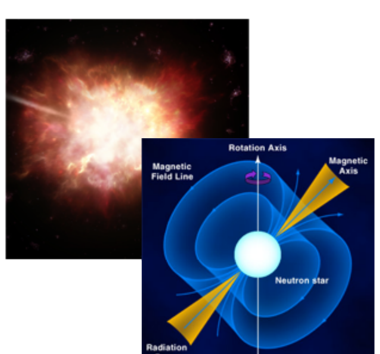
Dominant class of LAT extra-galactic sources. Many estimates in literature. EGB contribution ranging from 20% - 100%

Non-blazar active galaxies

27 sources resolved in 2FGL ~ 25% contribution of radio galaxies to EGB expected. (Inoue 2011)

Star-forming galaxies

Several galaxies outside the local group resolved by LAT. Significant contribution to EGB expected. (e.g. Pavlidou & Fields, 2002)



GRBs

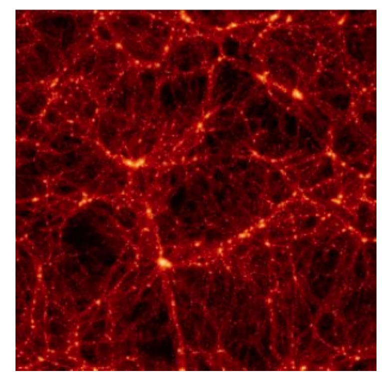
High-latitude pulsars

small contributions expected. (e.g. Dermer 2007, Siegal-Gaskins et al. 2010)

Diffuse processes

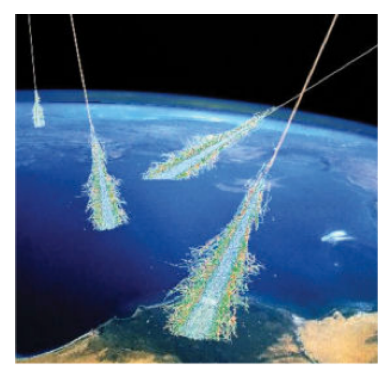
Intergalactic shocks

widely varying predictions of EGB contribution ranging from 1% to 100% (e.g. Loeb & Waxman 2000, Gabici & Blasi 2003)



Dark matter annihilation

Potential signal dependent on nature of DM, cross-section and structure of DM distribution (e.g. Ullio et al. 2002)



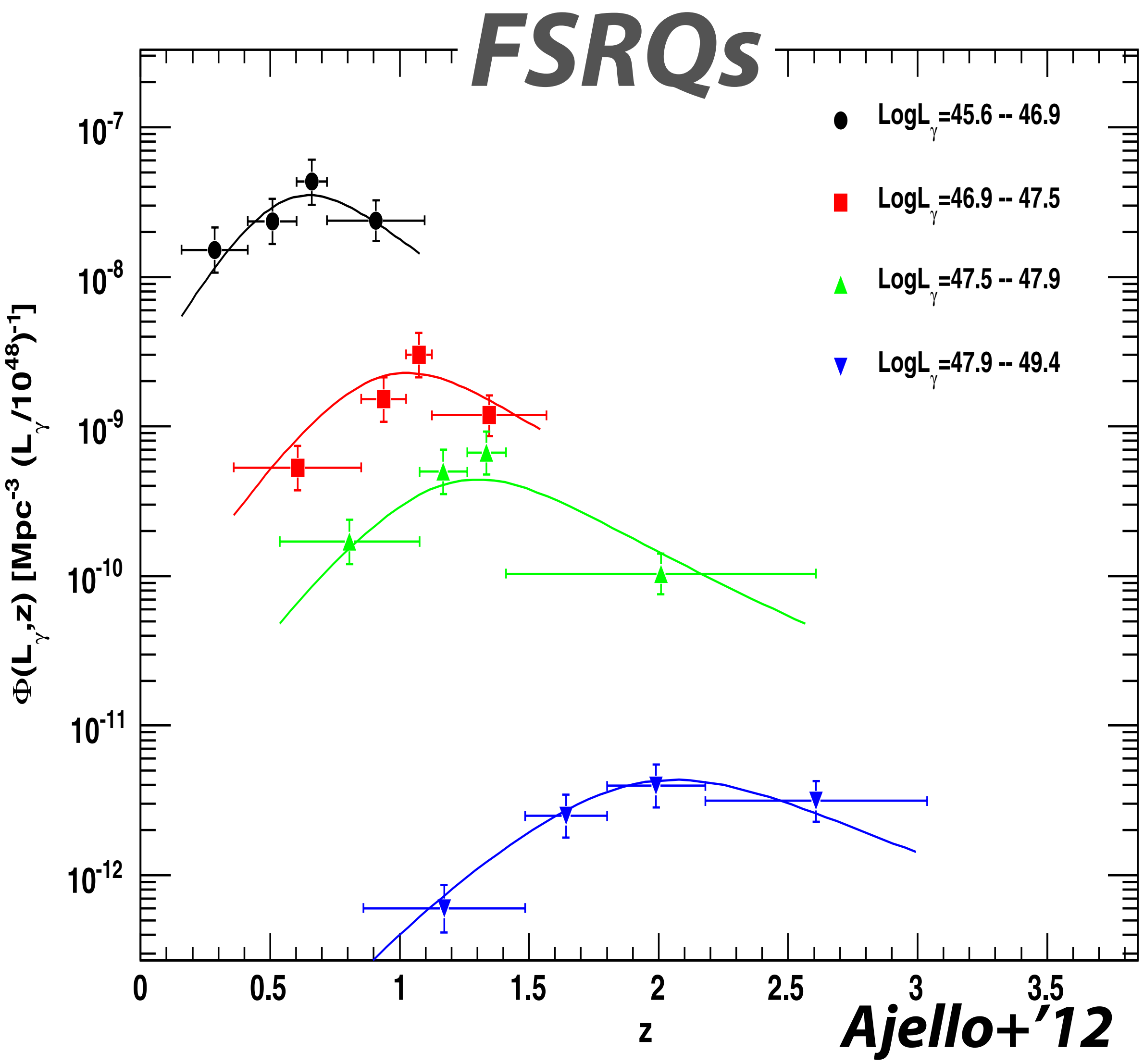
Interactions of UHE cosmic rays with the EBL

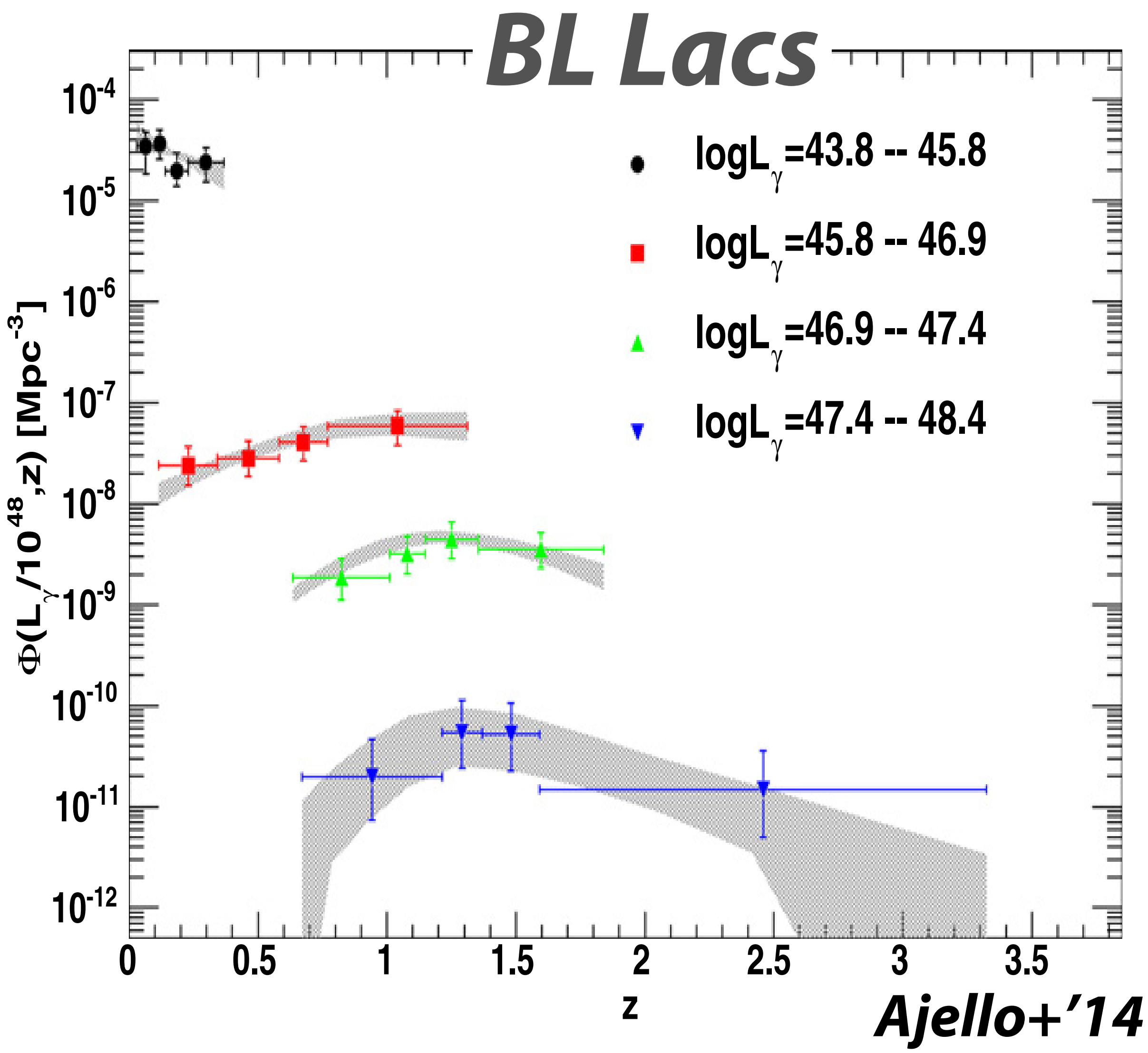
dependent on evolution of CR sources, predictions varying from 1% to 100 % (e.g. Kalashev et al. 2009)

Extremely large galactic electron halo (Keshet et al. 2004)

CR interaction in small solar system bodys (Moskalenko & Porter 2009)

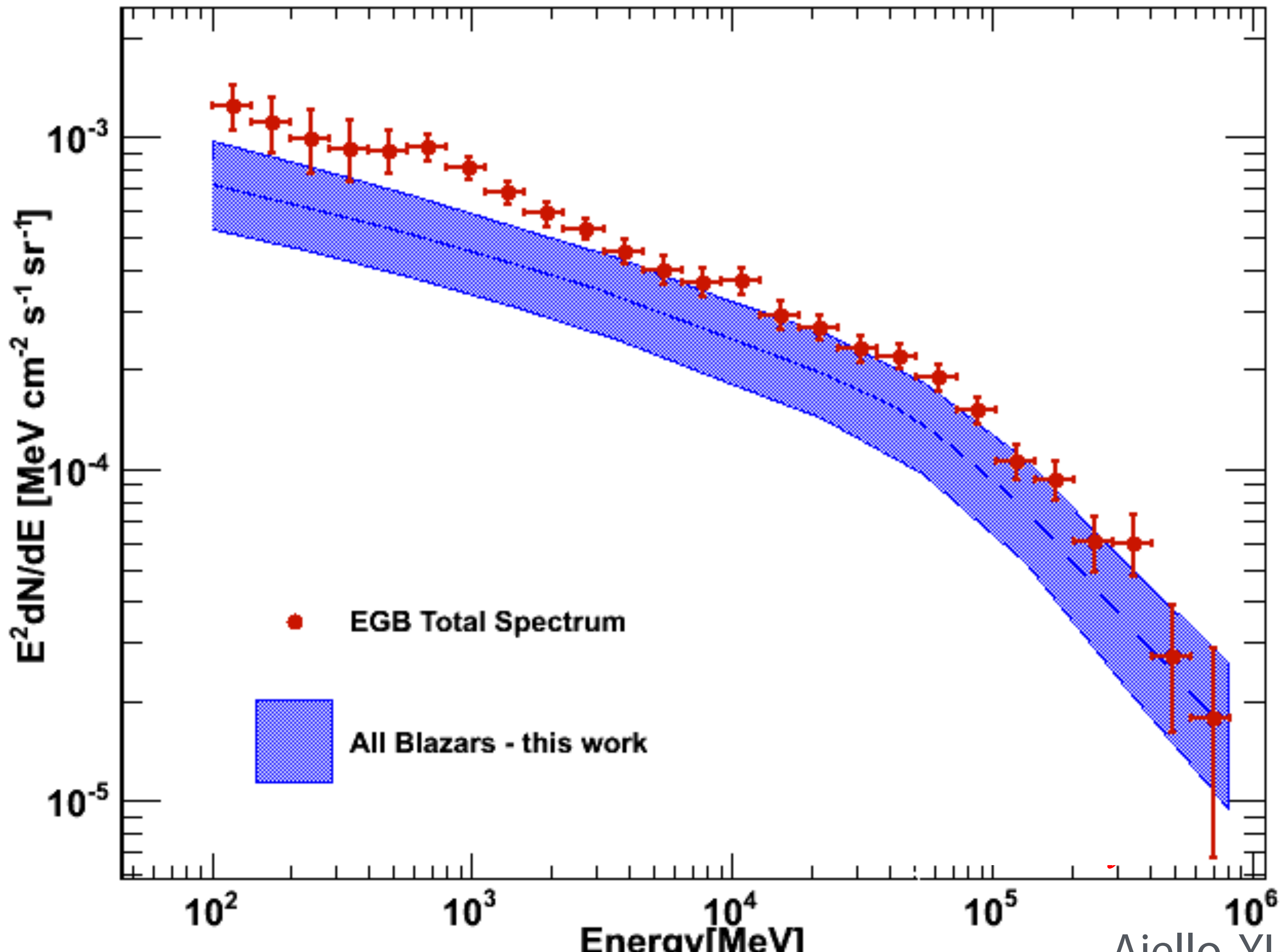
Cosmological Evolution of Blazars





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

Blazar contribution to CGB

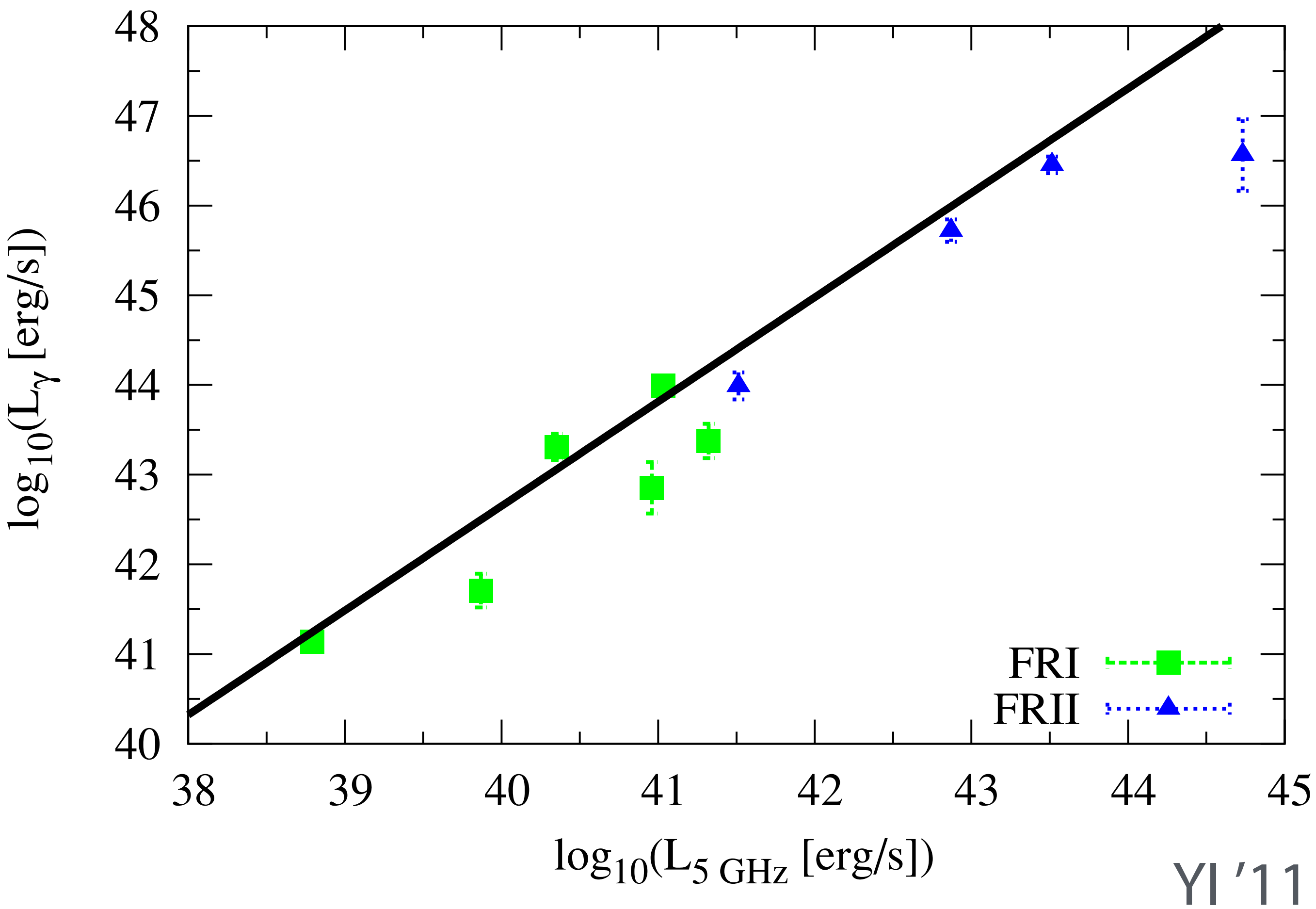


Ajello, YI+'15

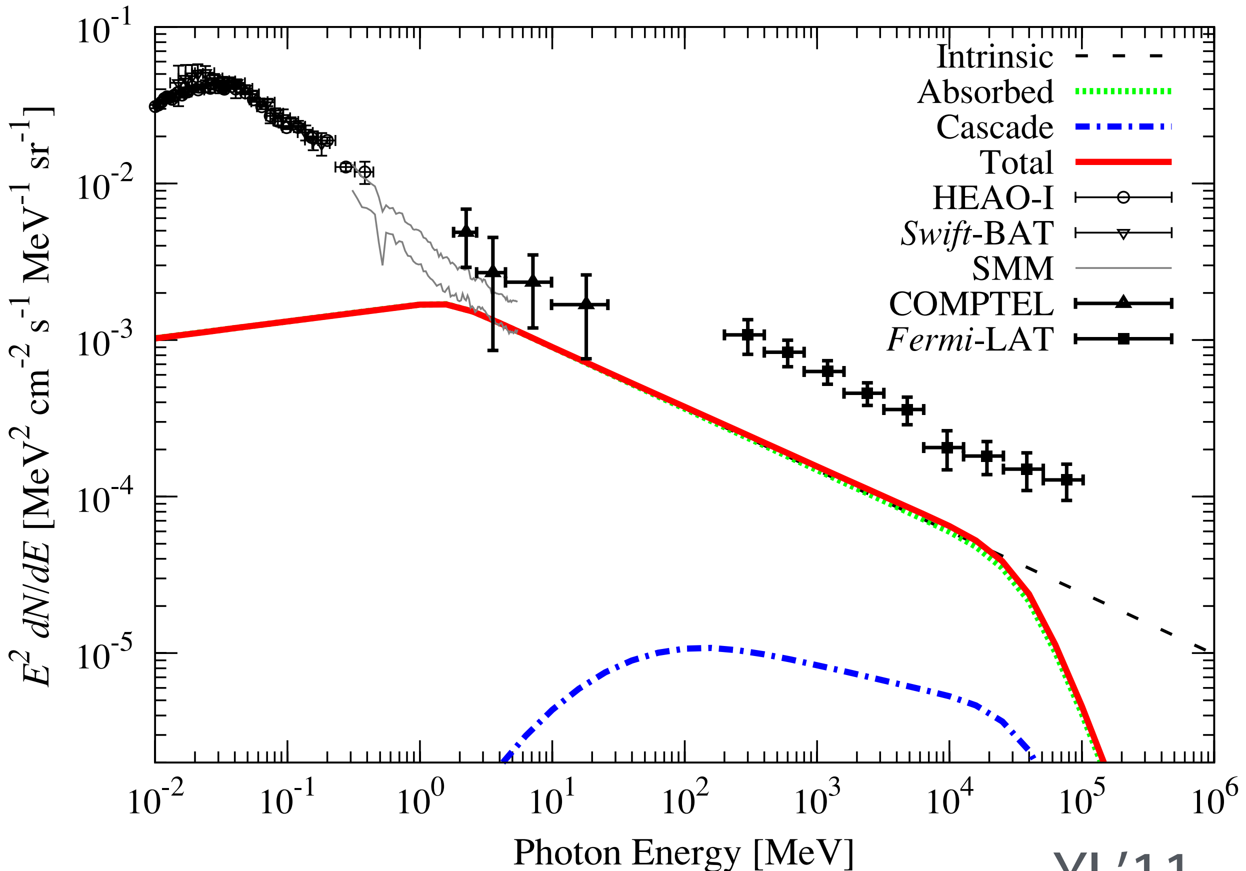
- Padovani+'93; Stecker+'93; Salamon & Stecker '94; Chiang + '95; Stecker & Salamon '96; Chiang & Mukherjee '98; Mukherjee & Chiang '99; Muecke & Pohl '00; Narumoto & Totani '06; Giommi +'06; Dermer '07; Pavlidou & Venters '08; Kneiske & Mannheim '08; Bhattacharya +'09; ***YI & Totani '09***; Abdo+'10; 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.

Radio Galaxies



YI '11

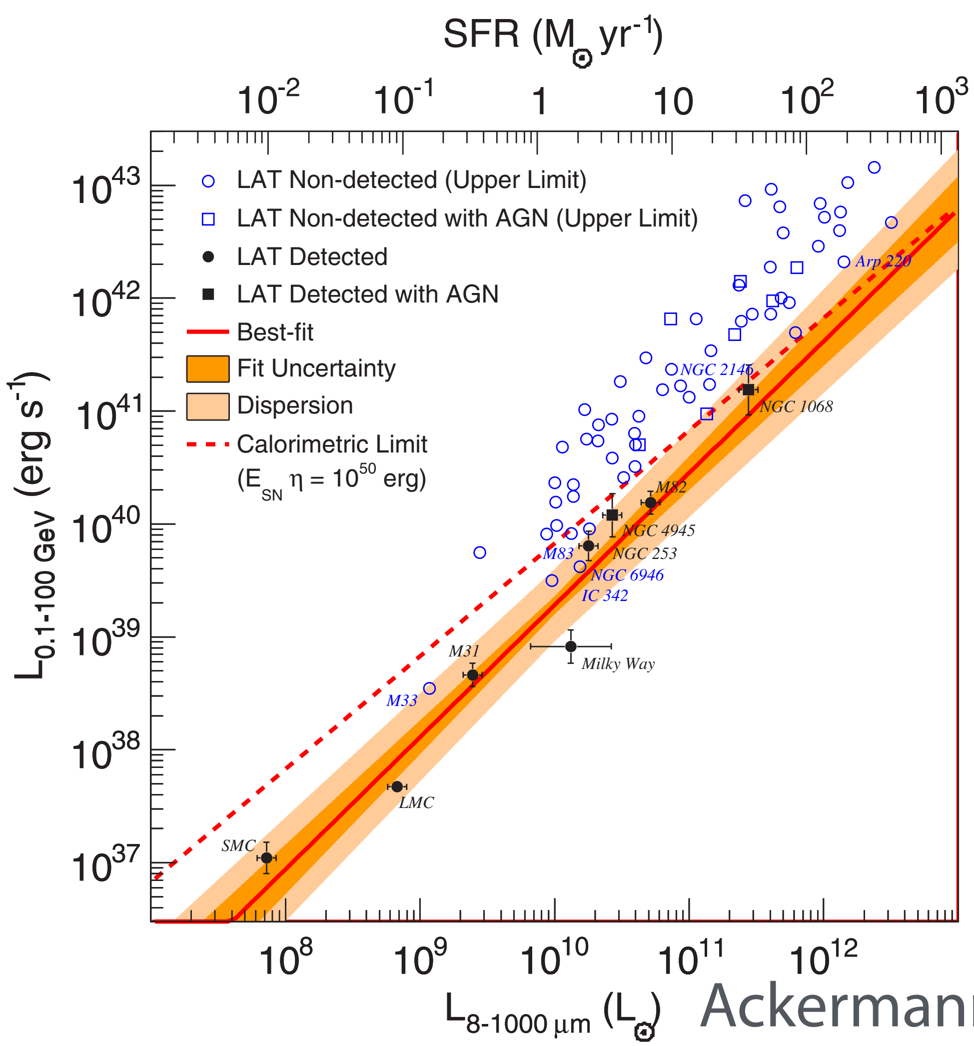


YI '11

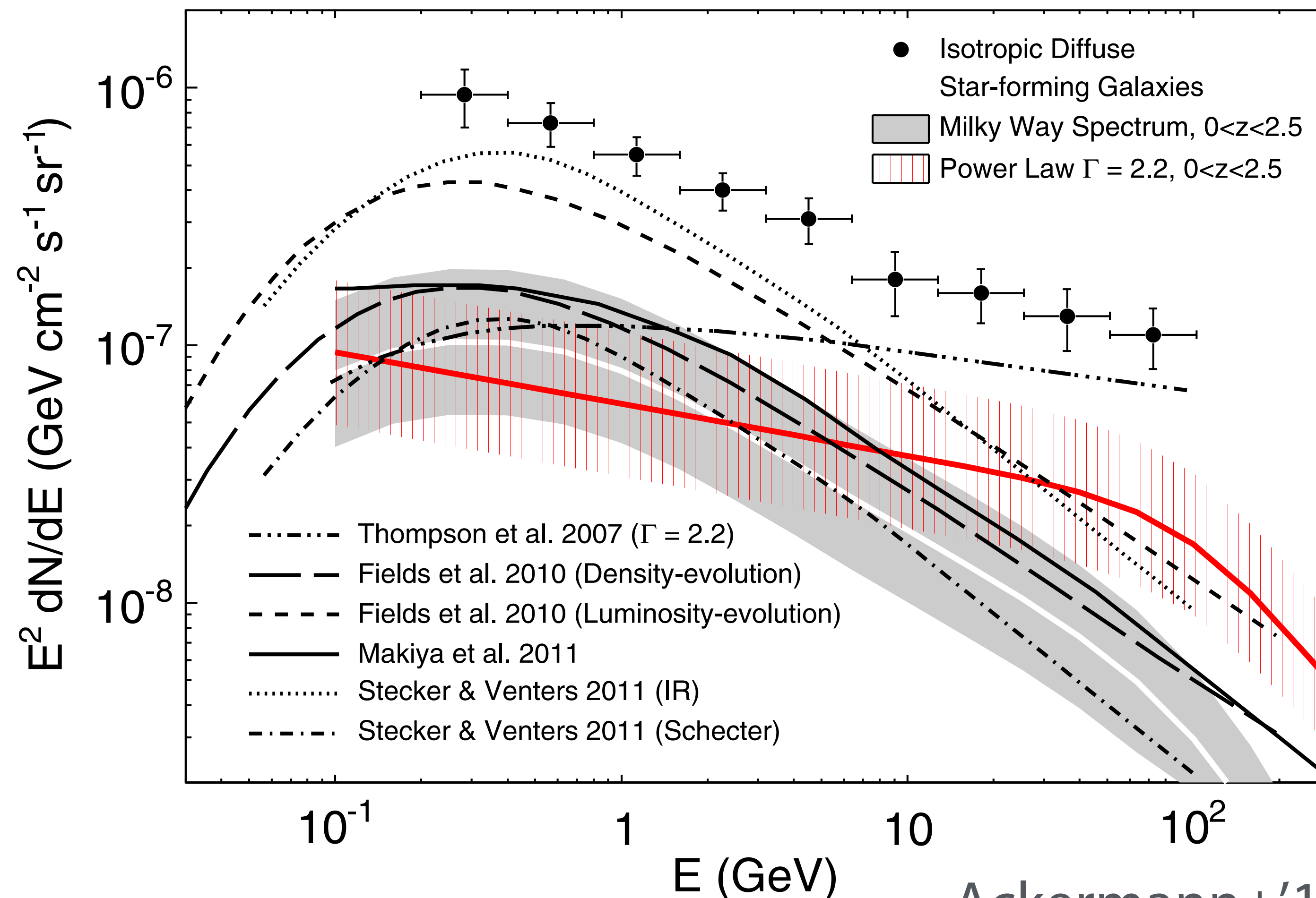
- Strong+'76; Padovani+'93; YI '11; Di Mauro+'13; Zhou & Wang '13

- Use gamma-ray and radio luminosity correlation.
- ~20% of CGB at 0.1-100 GeV.
- But, only ~10 sources are detected by Fermi.

Star-forming Galaxies



Ackermann+'12

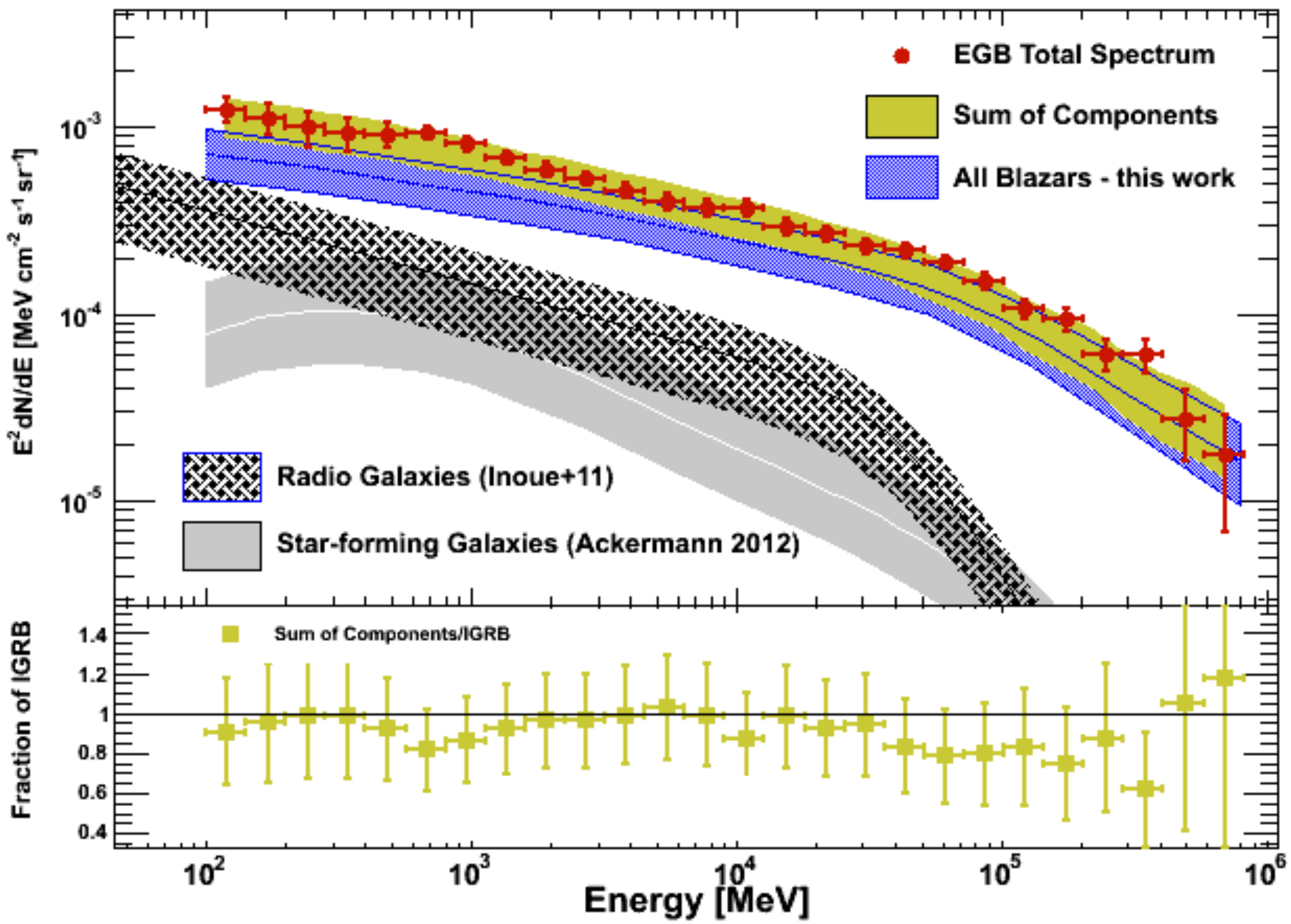


Ackermann+'12

- 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, only ~10 sources are detected by Fermi.

Components of Cosmic Gamma-ray Background



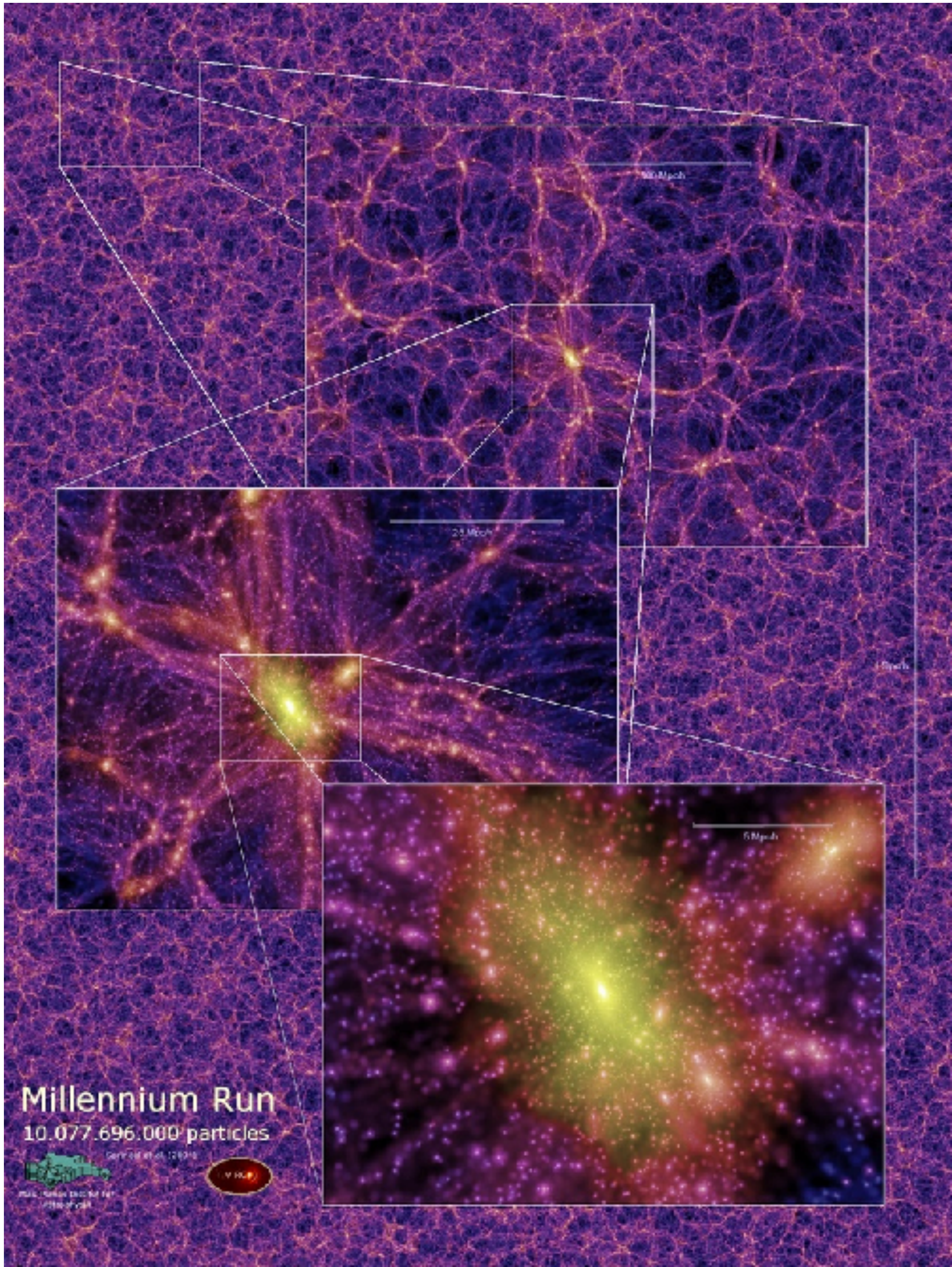
Ajello, YI +'15

- 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.

Dark Matter Contribution to the CGB

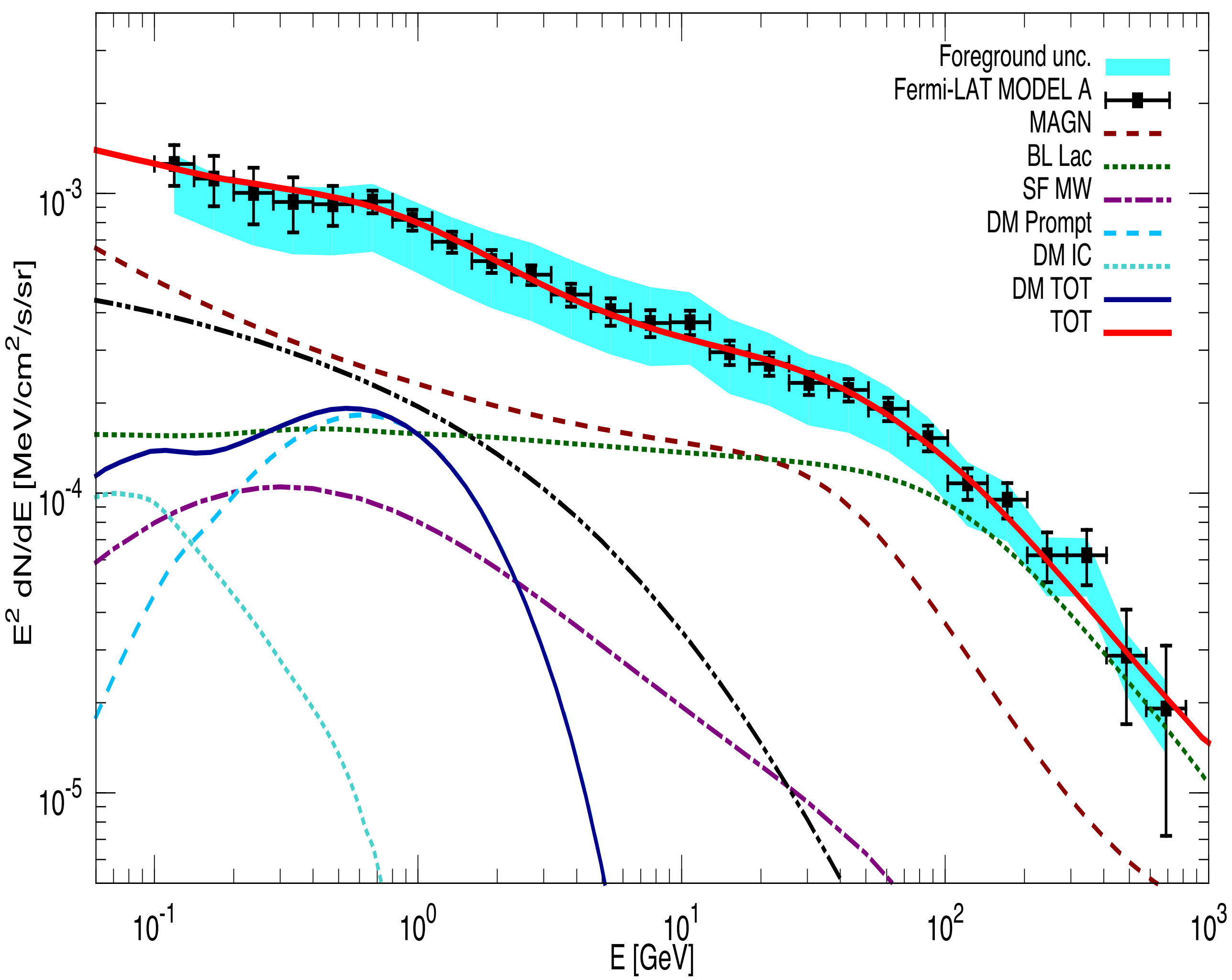
- Dark matter particles should have been annihilating/ decaying since the beginning of the universe.
  - The annihilation flux depends on the square of density.

$$I_\gamma(\hat{n}) \propto \frac{\langle \sigma v \rangle}{m_\chi^2} \int d\chi \; \rho_\chi^2(\chi \hat{n})$$



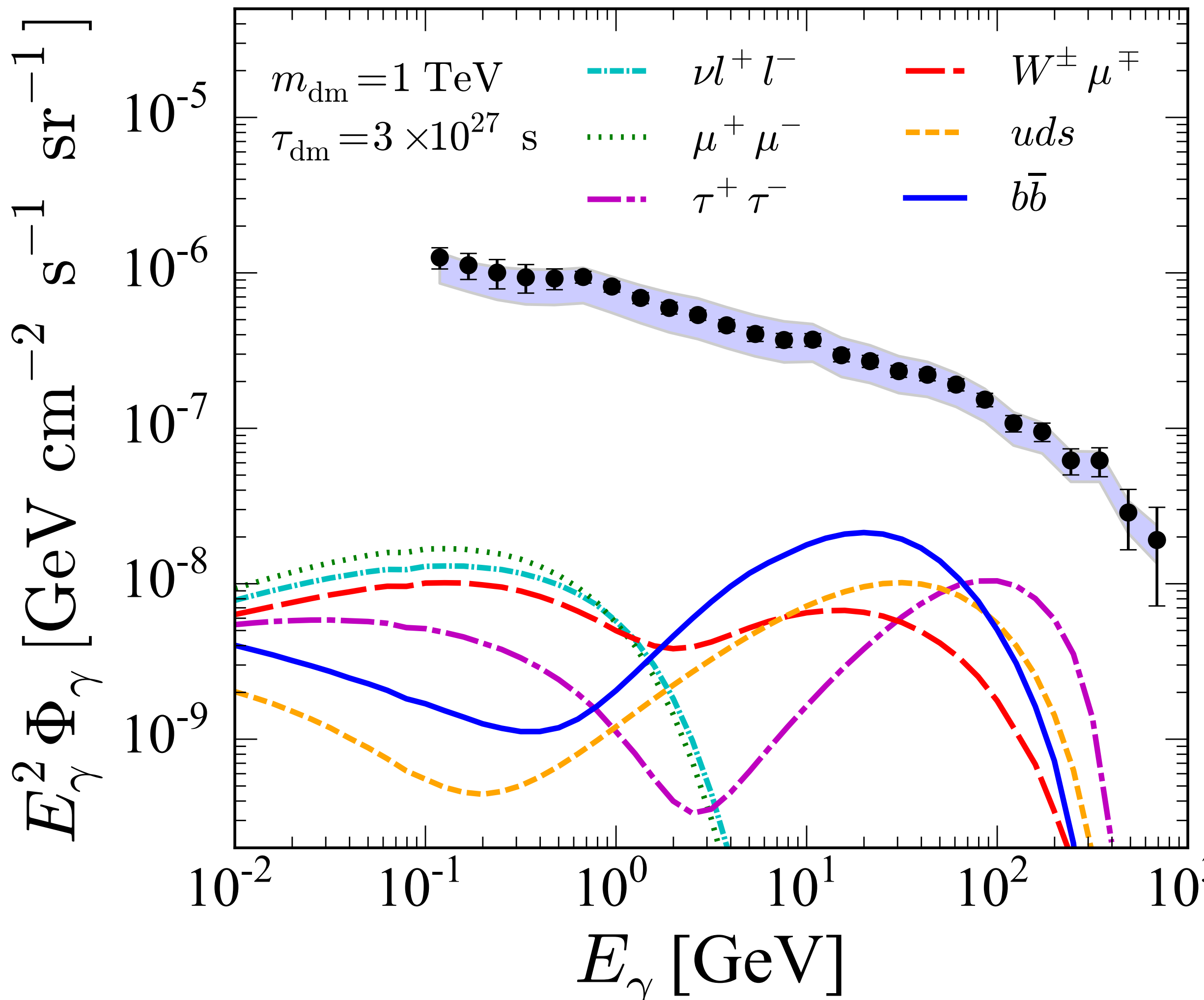
CGB spectrum from DM particles

Annihilation



Di Mauro+'15

Decay

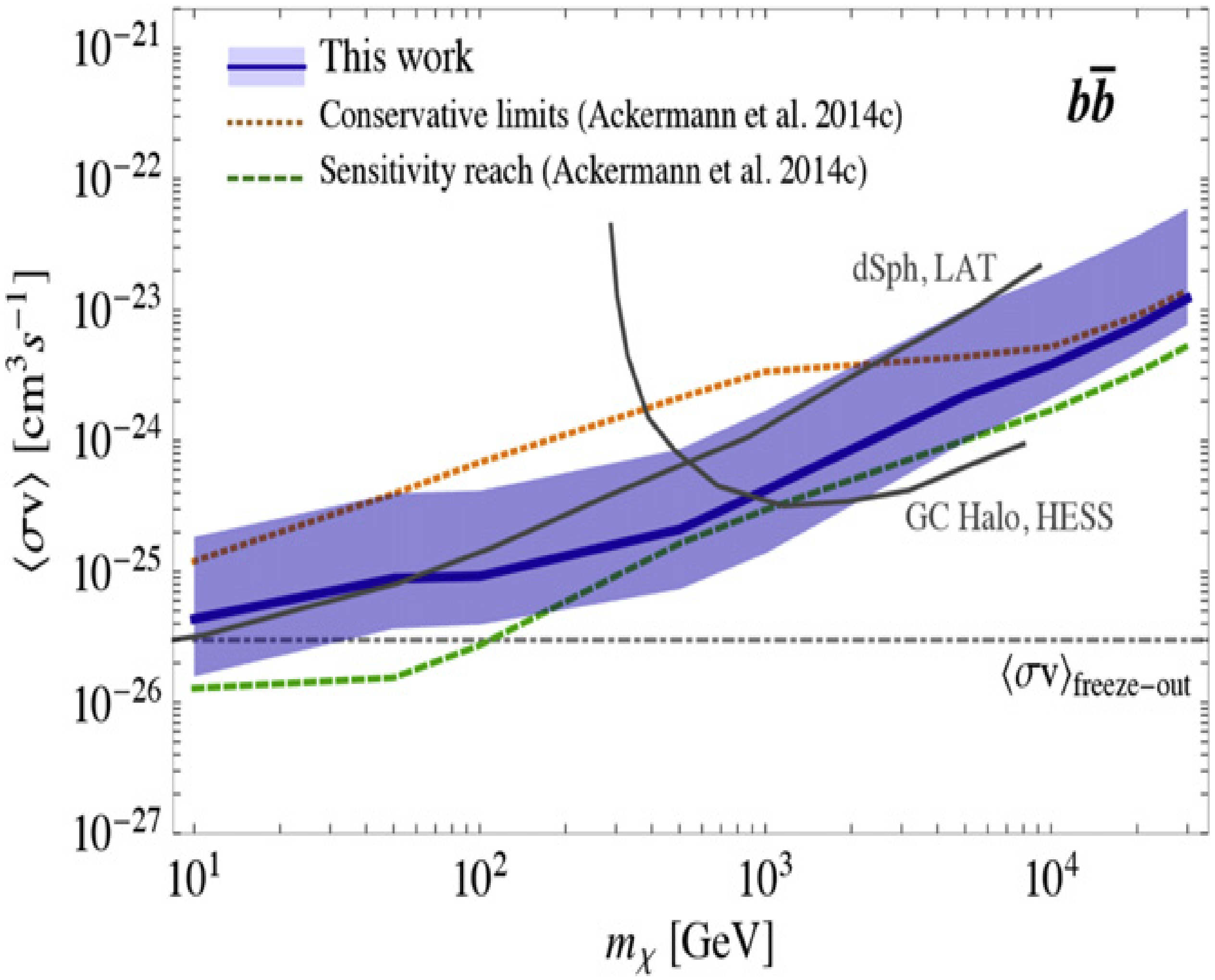


Ando & Ishiwata '15

- DM annihilation/decay creates a feature in the spectrum.

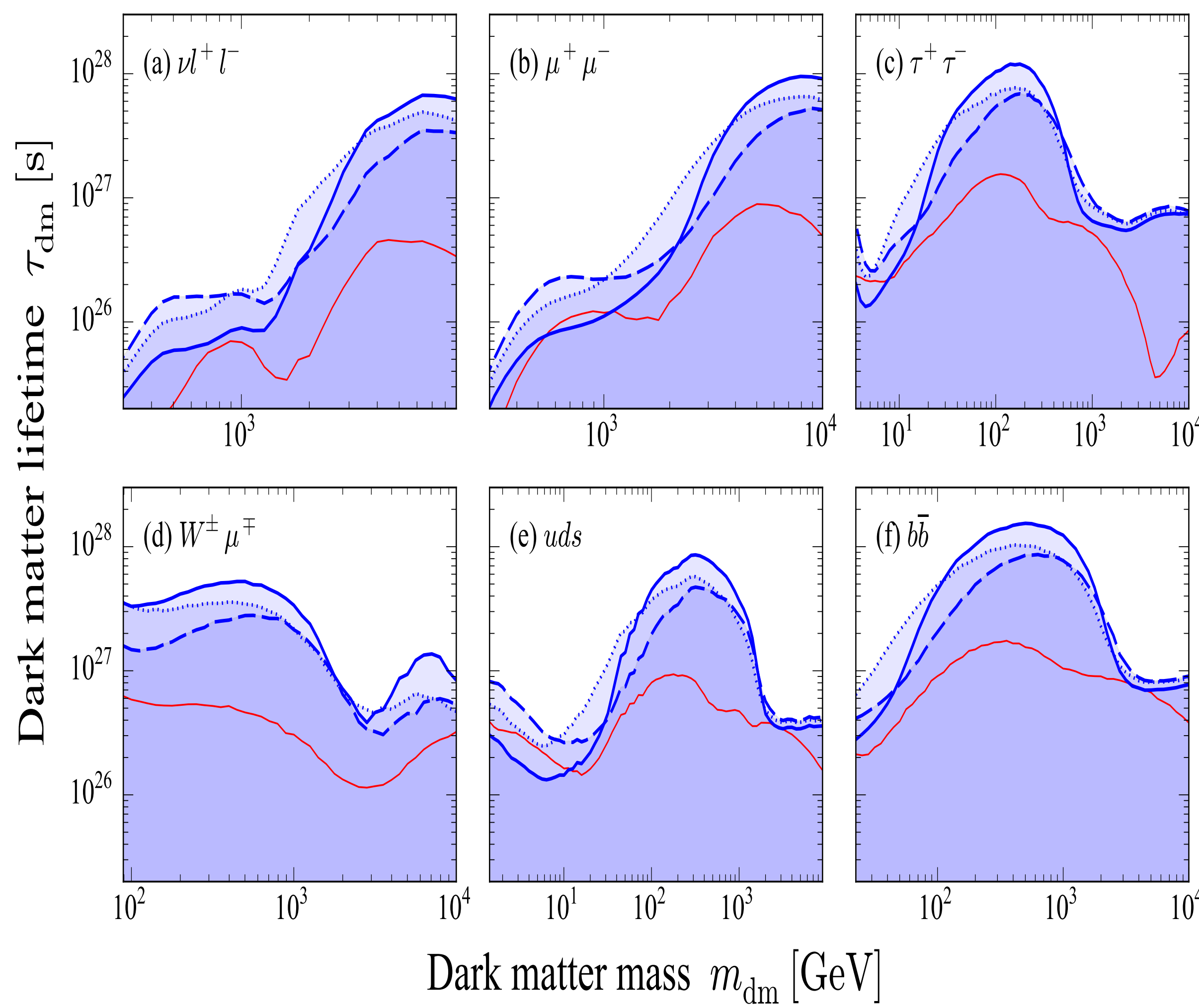
Constraints on DM parameters

Annihilation



Ajello, YI +'15

Decay



Ando & Ishiwata '15

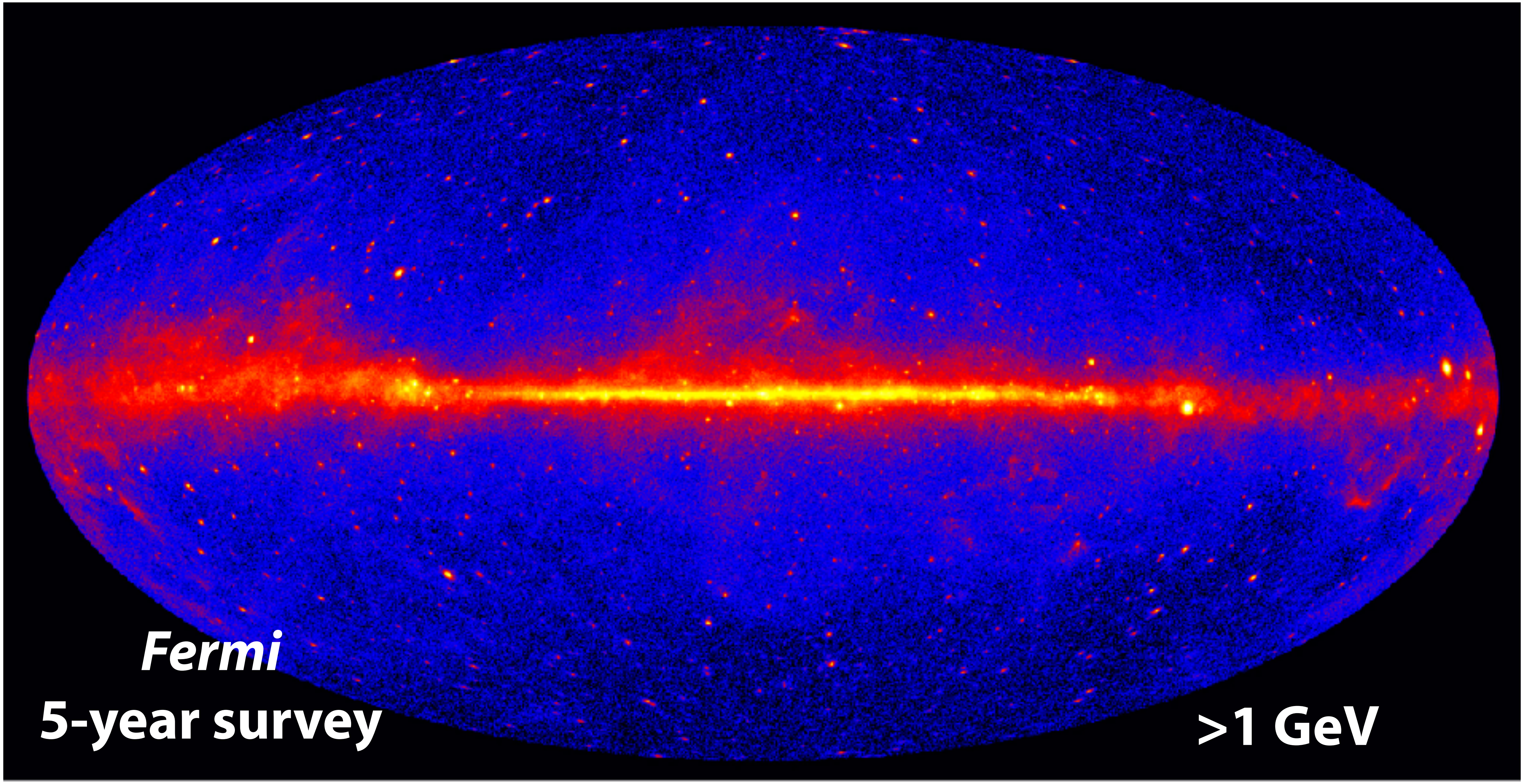
- Annihilation: comparable to constraints from dwarfs by Fermi
- Decay: > 10^{27}s

Future Gamma-ray Astronomy

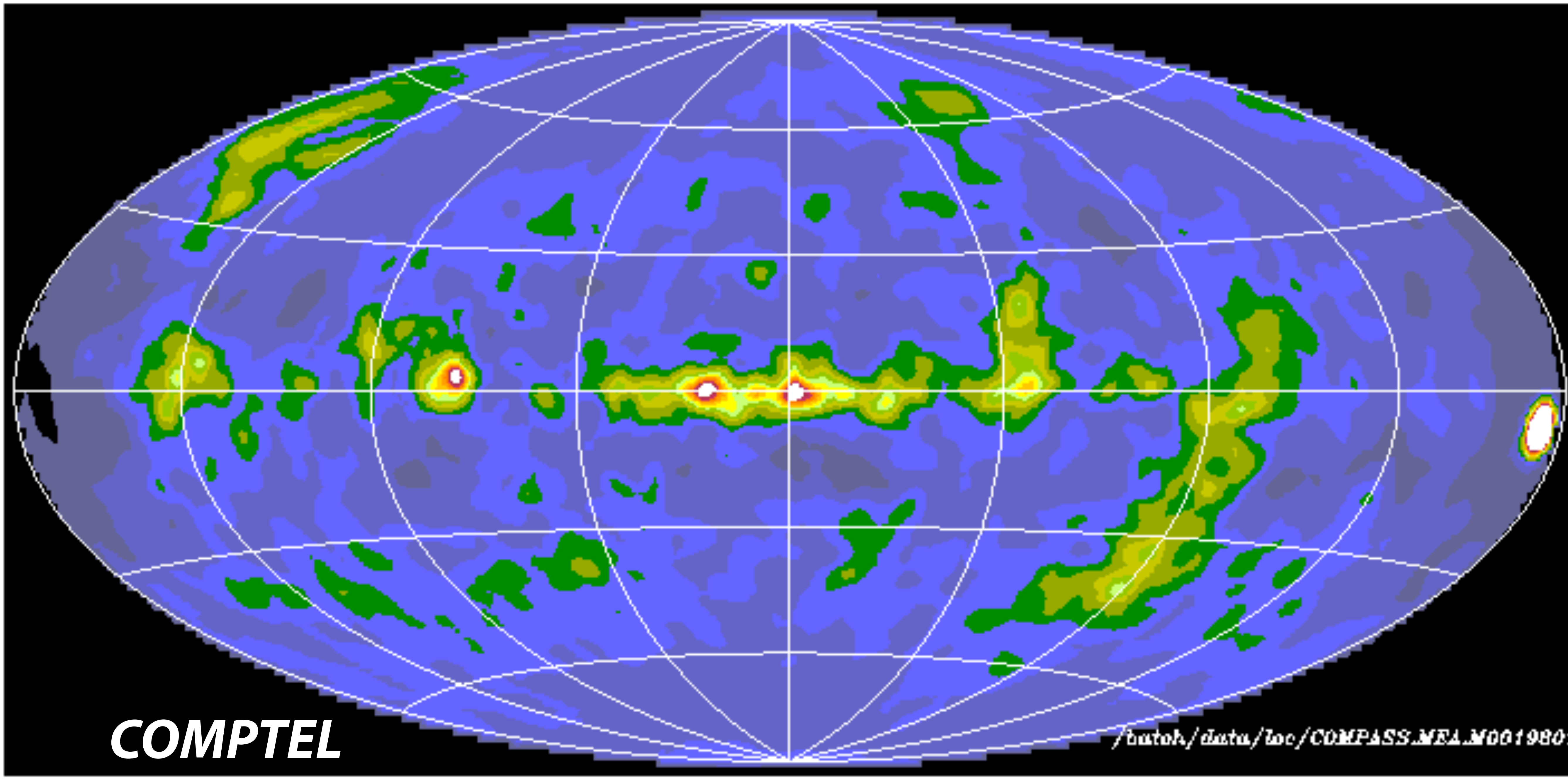
Projects

- CTA, HAWC, LHASSO, DAMPE,,,,
- Further future:
  - MeV Gamma-ray?
    - COSI, GRAINE, e-ASTROGAM, AMEGO,,,,???

GeV Gamma-ray Sky

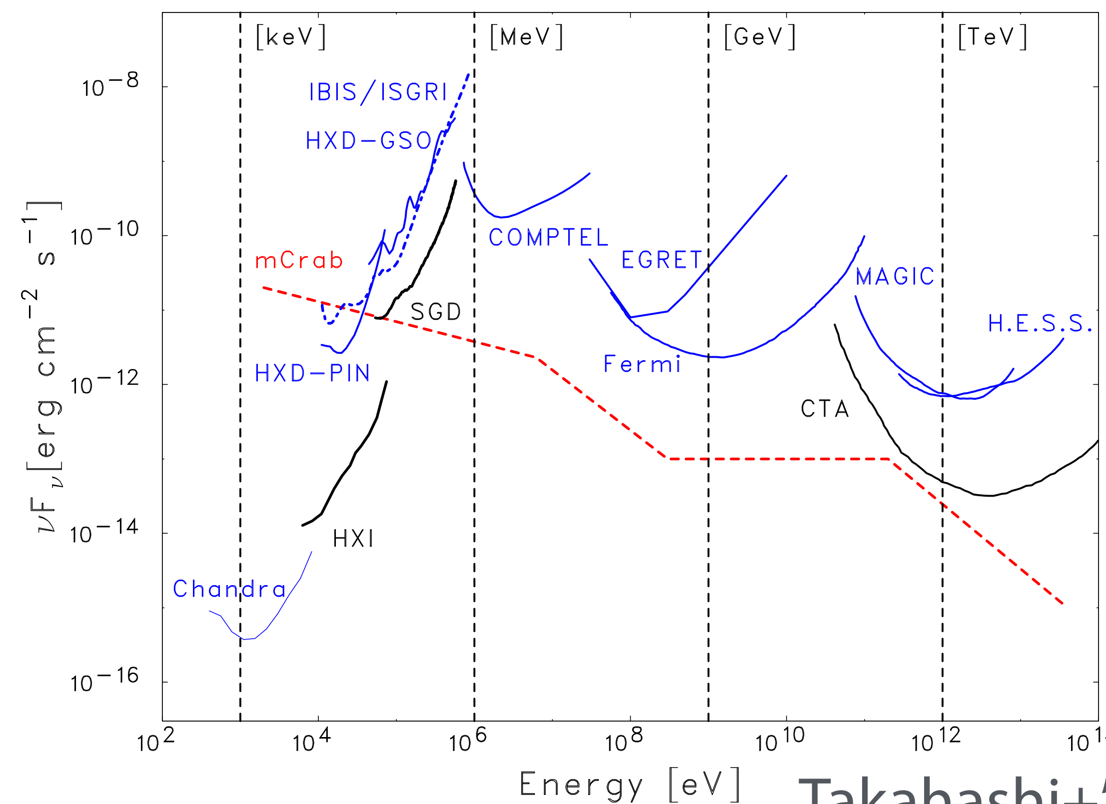


MeV Gamma-ray Sky

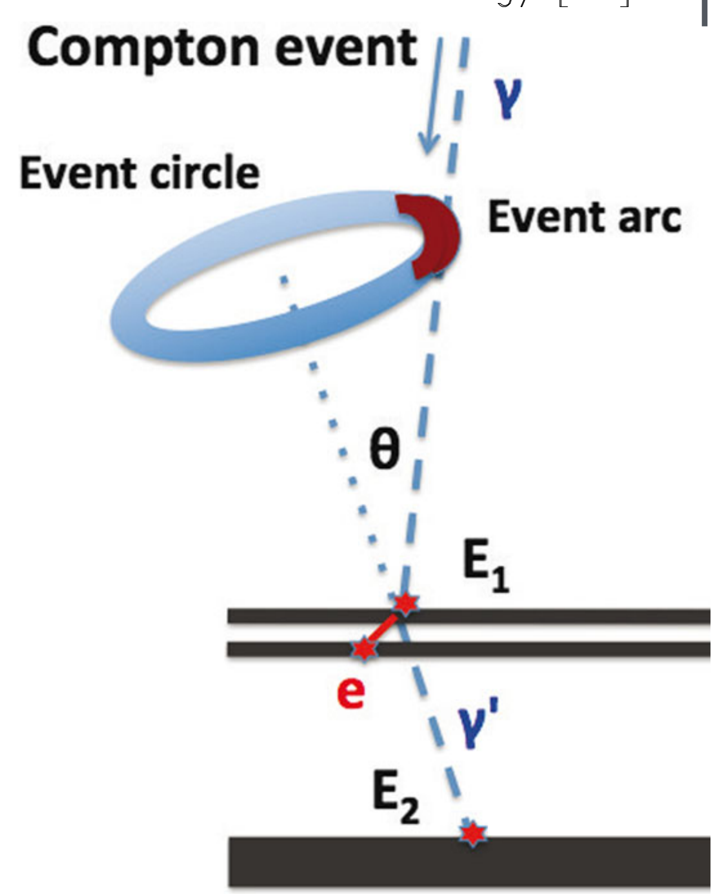


MeV Gamma-ray Observations

- ***Poor sensitivity***
  - 32 srcs in MeV
  - 1.25M srcs in X-ray, 3000 srcs in GeV, ~150 srcs in TeV
- Compton Camera
  - Detect Compton scattering events



Takahashi+'13



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MeV Gamma-ray Science

Gamma-ray bursts

Dark Matter Search

Seyferts

Blazars

Radio Galaxies

Starburst Galaxies

Type-Ia SNe

NS merger

Galactic Center

X-ray Binaries

Pulsars & Magnetars

SNRs & PWN

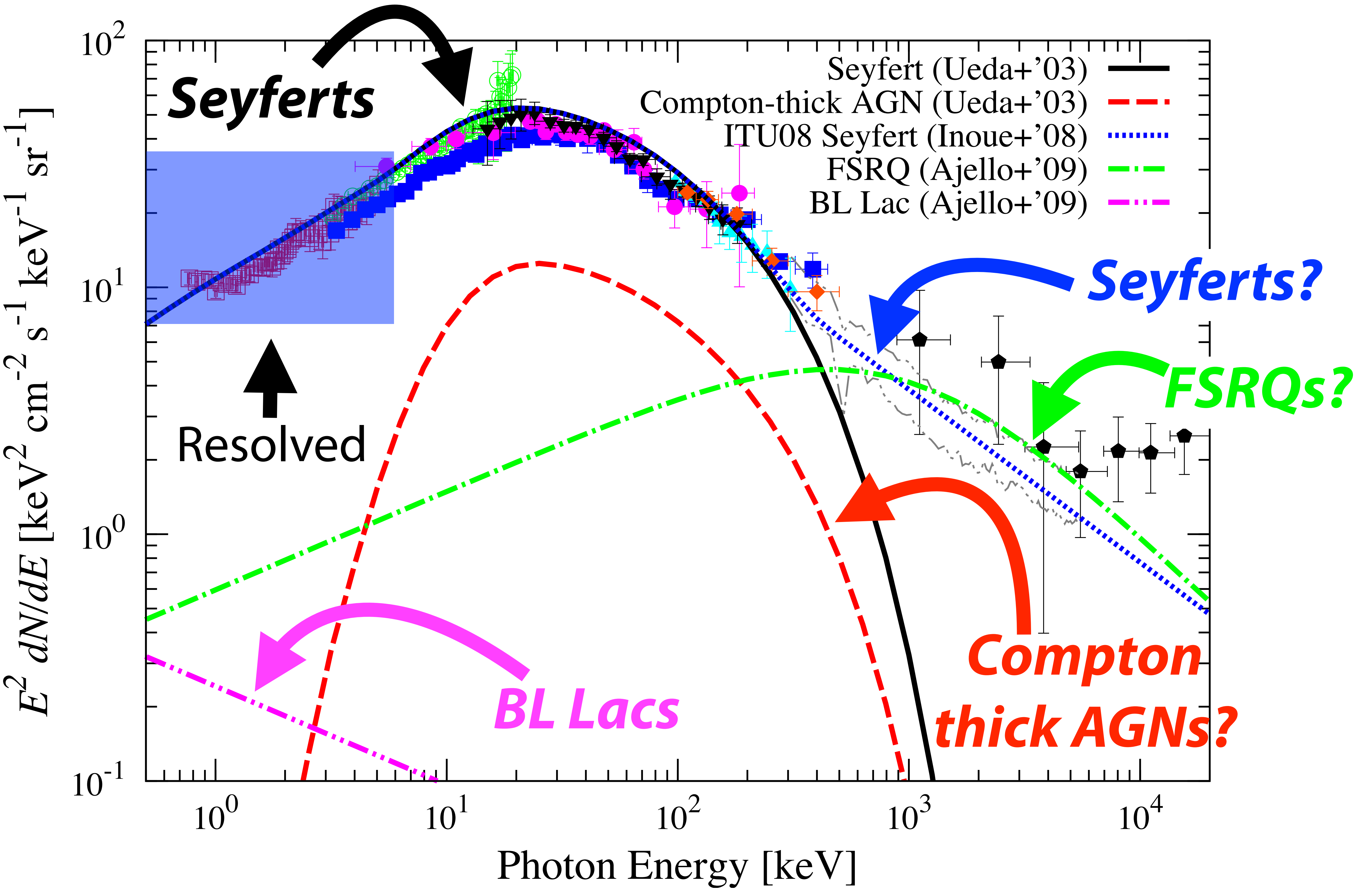
Novae

Sun

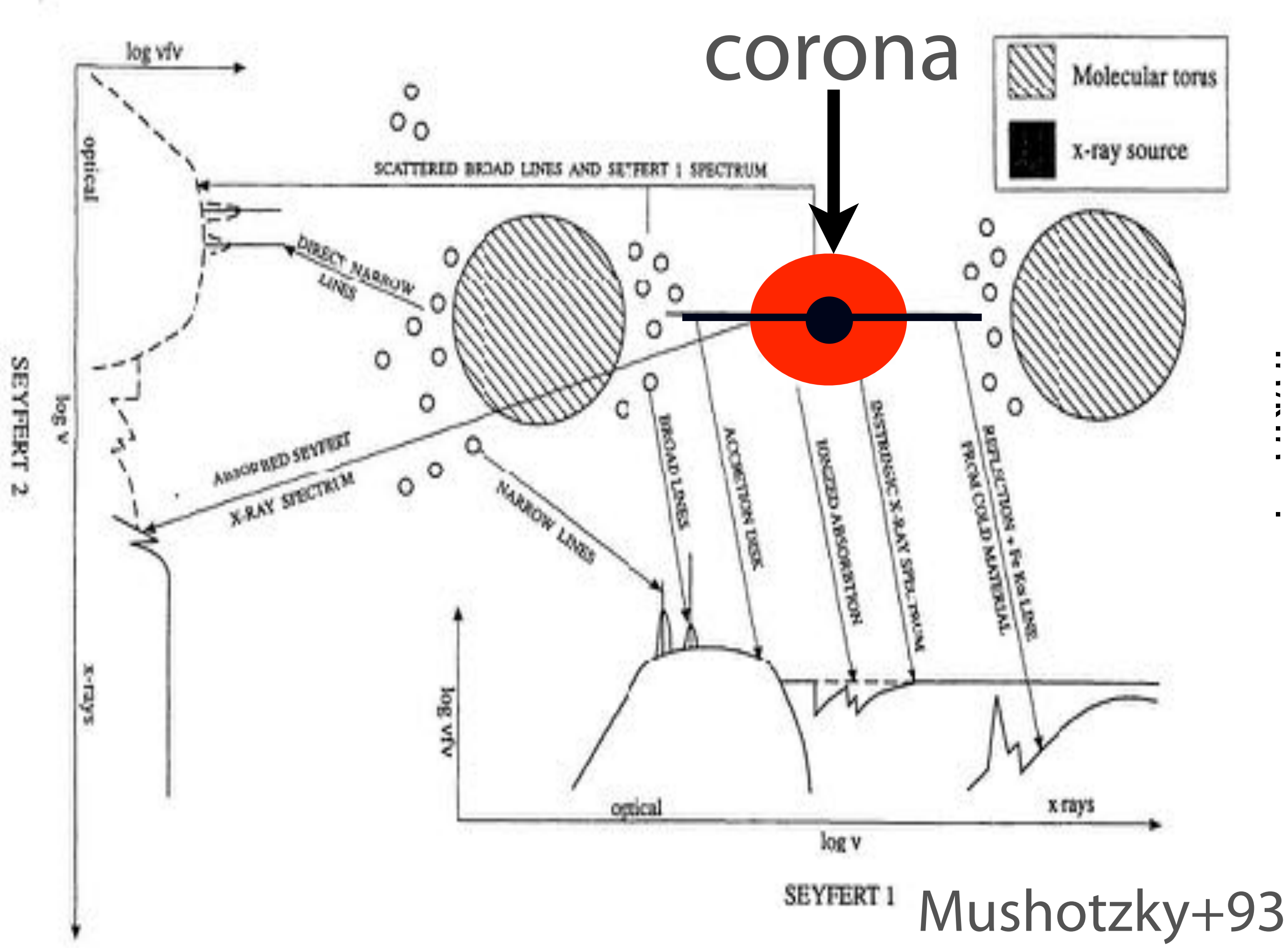
Background

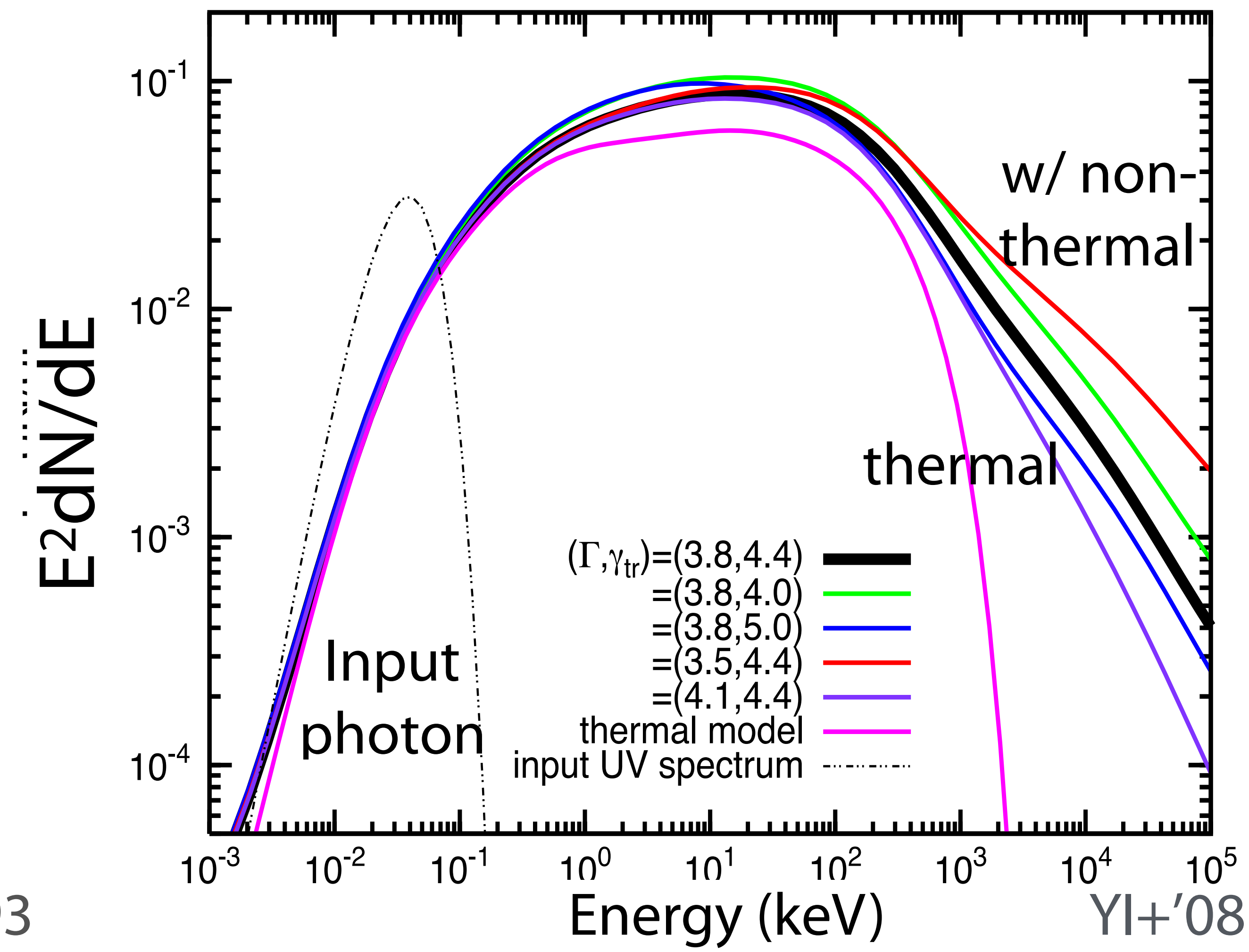
Terrestrial Flashes

Cosmic X-ray/MeV Gamma-ray Background



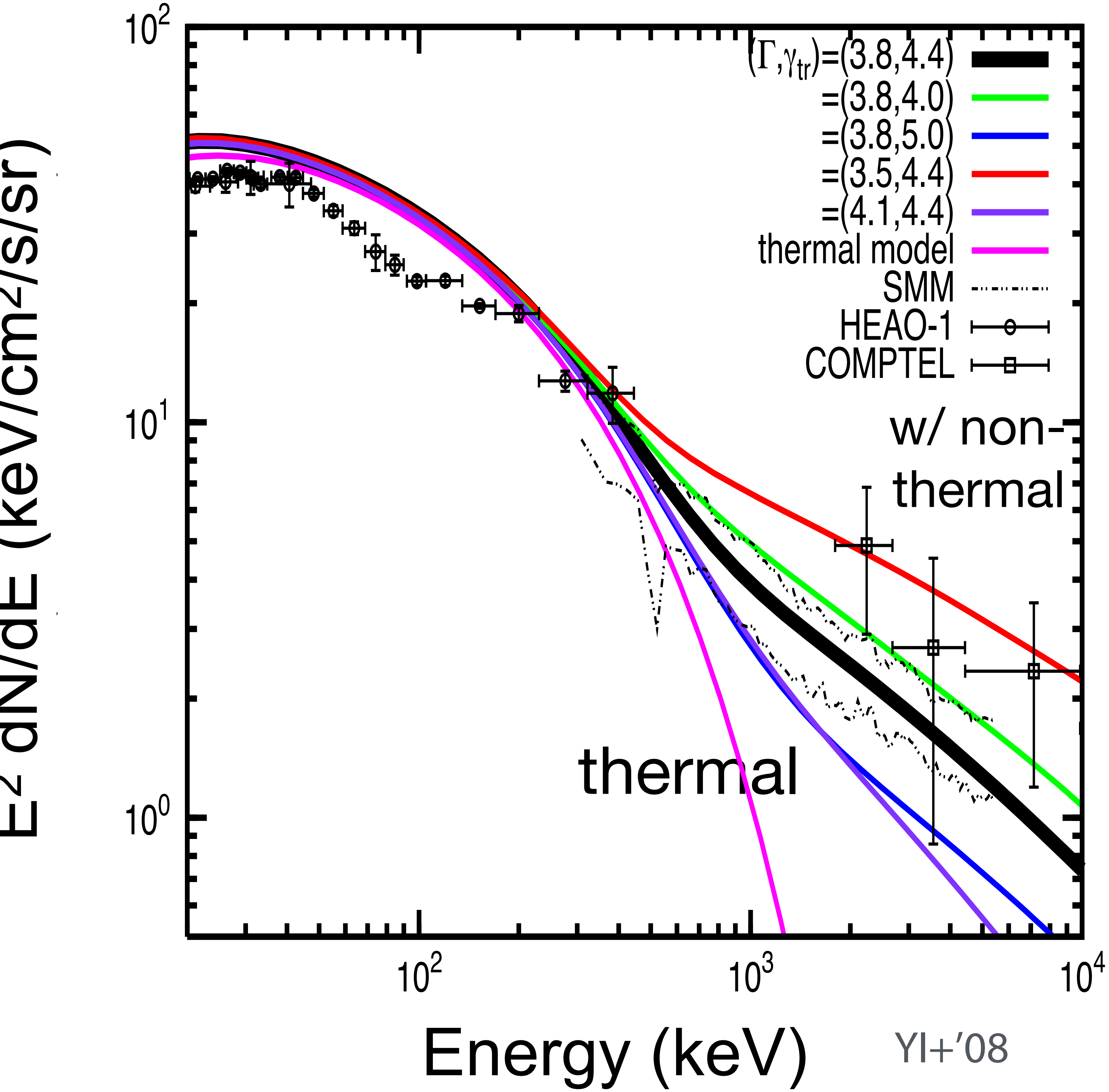
Hard X-ray Spectra (Seyfert)





- Comptonization in a hot corona above the disk.
- If non-thermal electrons exist in a corona, non-thermal tail is expected (e.g. YI+ '08).

Seyferts and Cosmic MeV Gamma-ray Background



YI+'08

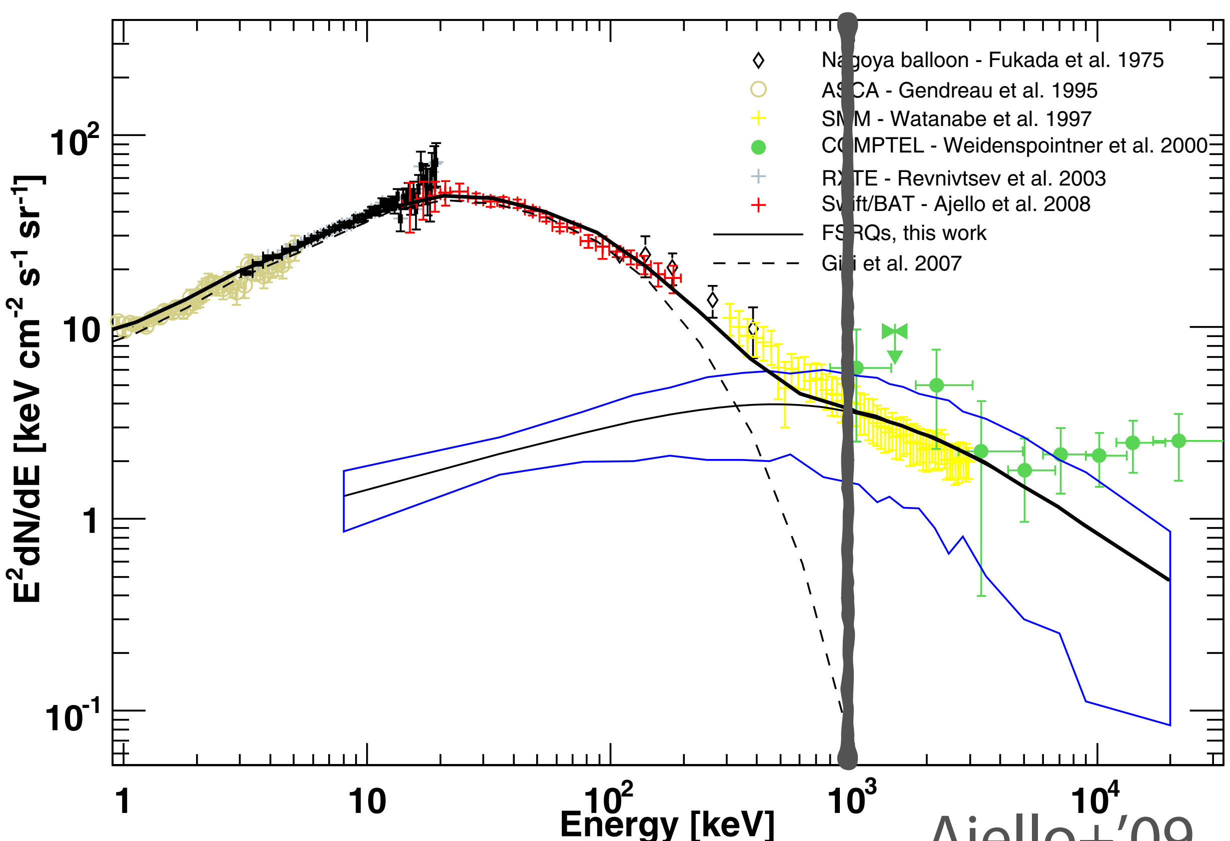
- Required non-thermal electron distribution is similar to that in solar flares and Earth's magnetotail

➡Magnetic reconnection-heated corona?
(Liu, Mineshige, & Shibata '02)

- ALMA may probe the corona heating scenario through synchrotron emission (YI & Doi '14).
  - Yes, we are doing ALMA observations.

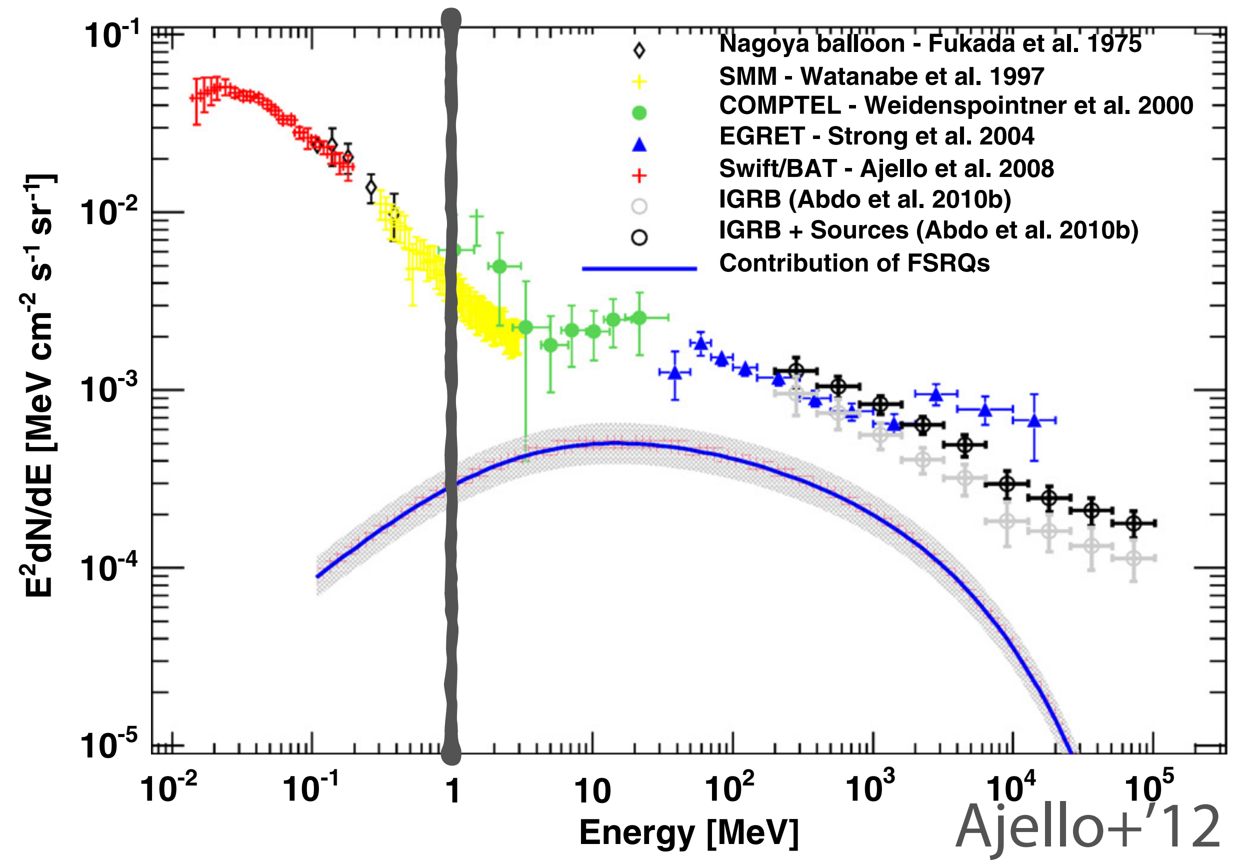
Blazars and Cosmic MeV Gamma-ray Background

Based on Swift-BAT



Ajello+'09

Based on Fermi-LAT

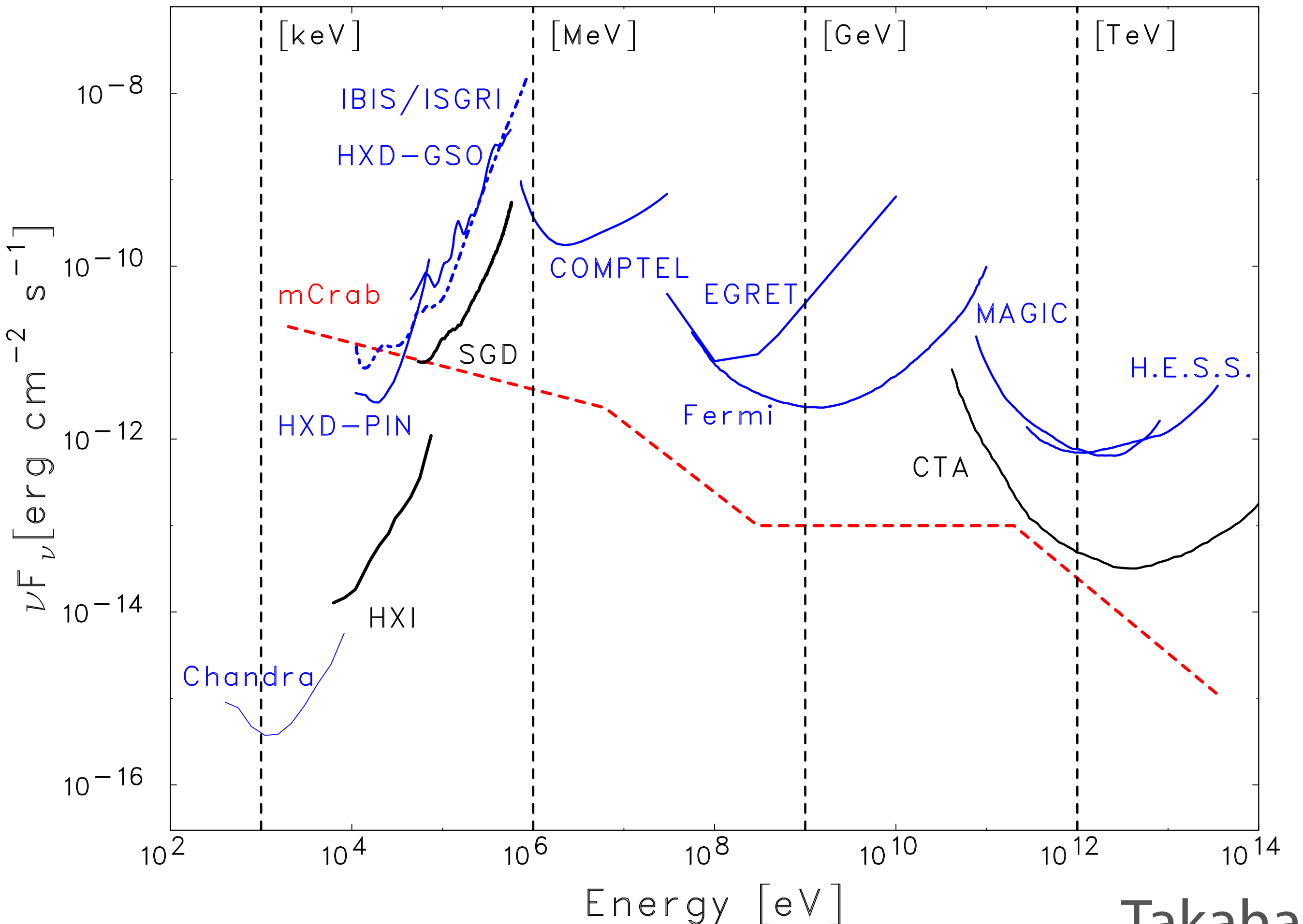


Ajello+'12

- FSRQs contribute to the GeV background with a peak at ~100 MeV
  (e.g. YI & Totani '09, Ajello +'12)
- FSRQs could explain the whole MeV background (Ajello+'09)

➡Two components in gamma-ray spectra or two FSRQ populations?

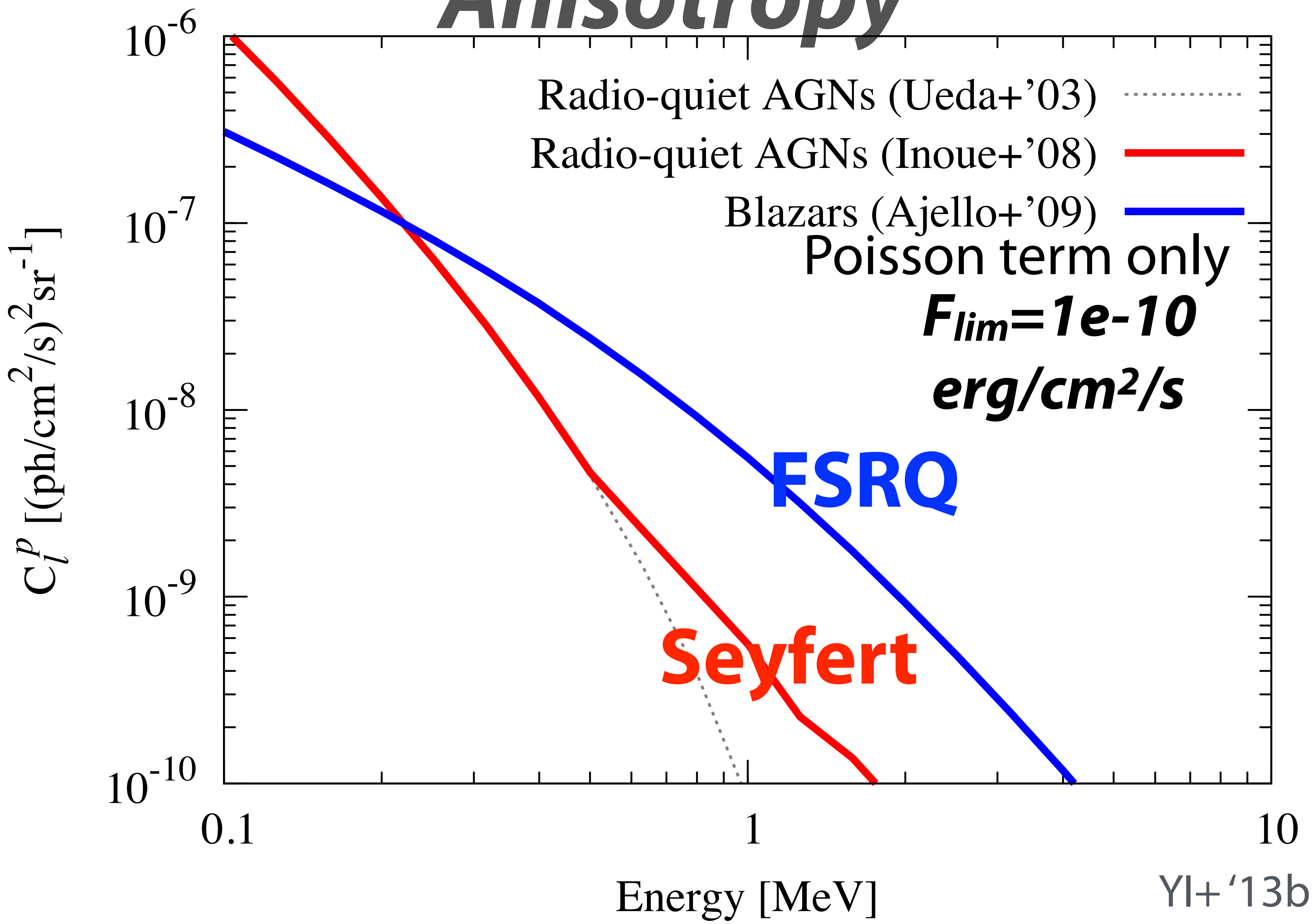
It is not easy to resolve the MeV sky.



Takahashi+'13

- Even achieving the sensitivity of 10^{-11} erg/cm^2/s, it is hard to resolve the MeV sky (***YI+'15***).
- Answers are in "***Anisotropy***".
  - Cosmic background radiation is not isotropic.
  - There is anisotropy due to the sky distribution of its origins.

Cosmic MeV Gamma-ray Background "Anisotropy"



- Future MeV satellites will distinguish Seyfert & blazar scenarios through anisotropy in the sky.

Summary

- A variety of gamma-ray (> 0.1 GeV) objects are detected now.
- You are in the golden era of gamma-ray/MWL astrophysics
  - still a lot of unsolved problems in gamma-ray sciences
- What will you do in the next decade?