Fermi AGN: Open Questions and Looking Forward

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Special thanks to R.D. Blandford, as well as to my Fermi colleagues
C.C. Cheung, J. Kataoka, G. Madejski, and D. Paneque, for many discussions.

Active Galactic Nuclei (AGN)

- AGN activity is powered by the enhanced accretion unto supermassive black holes (SMBHs) residing in galaxy centers. As such, **AGN enable us to study the extreme physics of SMBHs, their accretion disks, and their surrounding media.**

- AGN activity is triggered by galaxy mergers/interactions. As such, AGN activity is directly linked to the structure formation in the Universe. But AGN are not only passive witnesses/by-products of galaxy formation! Outflows, jets, and high-energy radiation produced in AGN may substantially influence the surrounding (galactic and intergalactic) medium, modifying therefore the structure formation itself via some complex feedback process. **Studying how AGN evolve with redshift is therefore important for understanding cosmological evolution of galaxies in general.**

- AGN are established sources of broad-band electromagnetic emission, and the high-energy γ-ray photons in particular. Maximum energies of ultrarelativistic particles produced thereby exceed by orders of magnitude maximum energies accessible in our accelerators. As such, **AGN enable us to study fundamental properties of subatomic particles, cosmic-ray acceleration, and the physics of ionized collisionless magnetized plasma, which is not accessible in our laboratories, but which constitutes a significant part of the baryonic Universe.**

I. AGN Zoo

AGN come in many many flavors… They differ in the properties of their large-scale environments, in the properties of their host galaxies, in the accretion rates and accretion fuels, in the structure and state of the circumnuclear matter, and finally in the properties of their outflows:

- Quasi-Stellar Objects (quasars or QSOs; ~ 10^{-7} Mpc^{-3})
    - Radio-quiet quasars (RQQs)
    - Radio-loud quasars (RLQs)
        - Flat Spectrum vs Steep Spectrum Radio Quasars (FSRQs vs SSRQs)
- BL Lacertae Objects (BL Lacs; ~ 10^{-7} Mpc^{-3})
- Radio Galaxies (RGs; ~ 10^{-6} Mpc^{-3})
    - Broad Line vs Narrow Line Radio Galaxies (BLRGs vs NLRGs)
    - Fanaroff Riley class I vs class II (FR Is vs FR IIs) - but not only!
        - WATs, NATs, XRGs, DDRGs, HYMORS, GPS/CSOs, CSS/MSOs…
- Seyfert Galaxies (Sys; ~ 10^{-4} Mpc^{-3})
    - Type 1 Seyferts - Type 2 Seyferts (Sy 1s - Sy 2s)
    - Narrow-Line Seyferts (NLSys)
- Low-Luminosity AGN (LLAGN; > 10^{-3} Mpc^{-3})
    - Low-Ionization Nuclear Emission-Line Region Galaxies (LINERs)
    - "Regular" Spiral Galaxies…

AGN Unification

GENERAL OPEN QUESTIONS:

What controls the observed diversity of AGN?

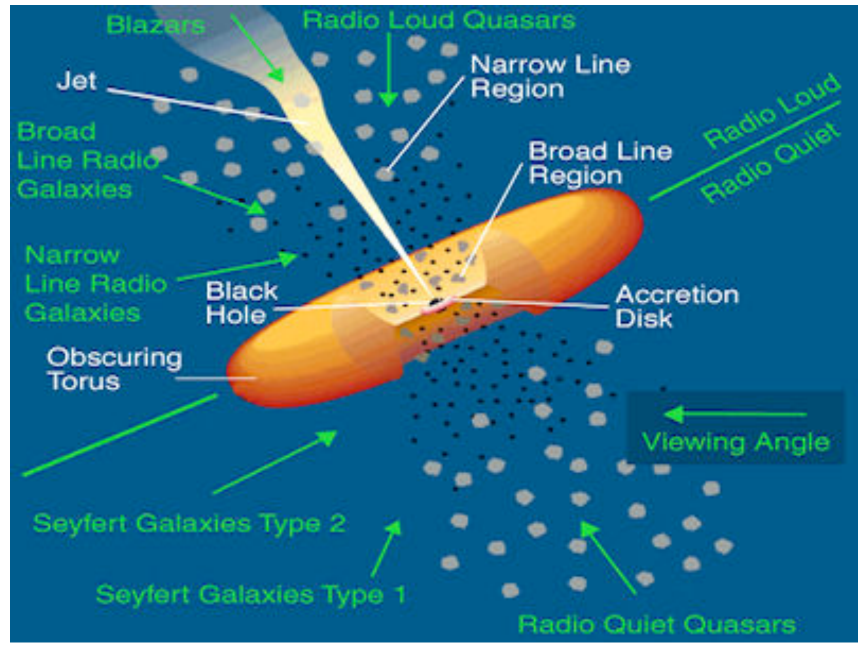
Is our current understanding of the AGN unification sufficiently good?

Why only some AGN are radio loud? What controls jet production efficiency in different types of AGN?

Urry & Padovani

Unification Scheme(s)

- anisotropic obscuration of a nuclear emission
  (Sy 1s ➔ Sy 2s)
- relativistic beaming of a jet emission
  (FSRQs/BL Lacs ➔ SSRQs ➔ BLRGs ➔ NLRGs/FR Is)
- accretion rate
  (QSOs/FR IIs ➔ BL Lac/FR Is)
- black hole mass
  (Sys ➔ NL Sys)
- age of a radio structure
  (CSOs ➔ MSOs ➔ RGs)
- Spin of SMBHs
  (RL ➔ RQ)



OPEN QUESTIONS FOR FERMI (I):

What are the γ-ray properties of different types of AGN?

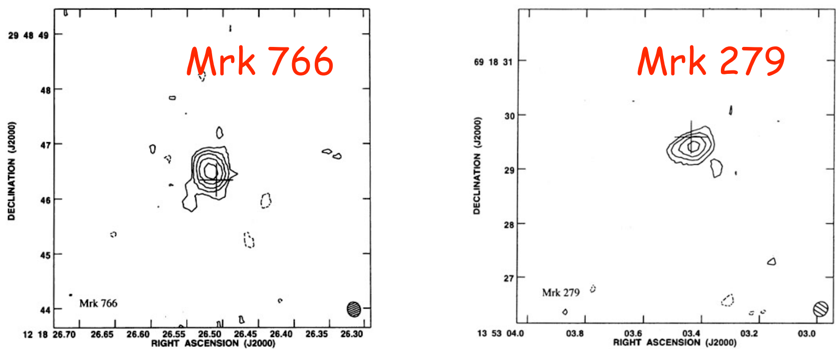
Are radio quiet AGN γ-ray emitters at some level?

Is the γ-ray emission of RL AGN shaped by the jet properties (on small and large scales) and/or by the properties of the accreting matter?

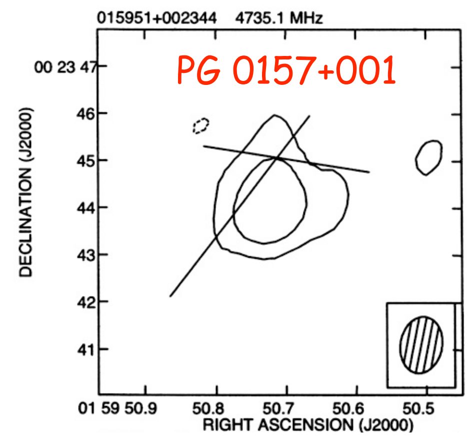
(Fermi AGN: FSRQs, BL Lacs, FR Is, NLSys)

AGN Phenomenon

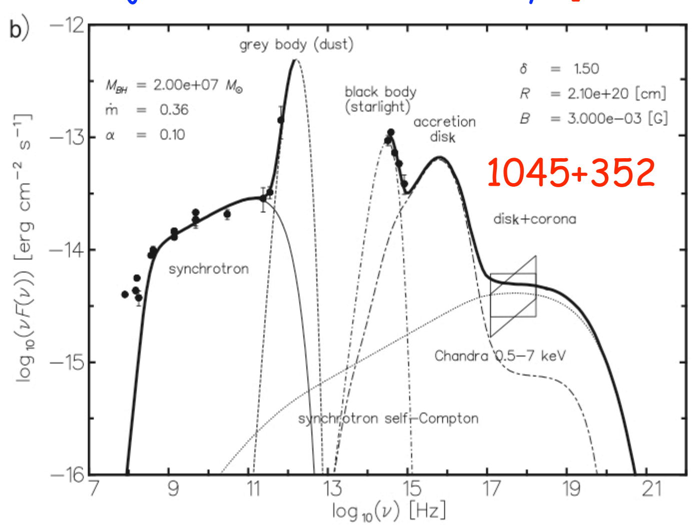
1) All galaxies host SMBHs in their centers (10^{6}-$10^{10}M_{\odot}$)
2) All SMBHs accrete at some level, and all show some AGN-like activity (10^{36}-10^{48} erg/s)
3) Radio quiet AGN are not radio silent!



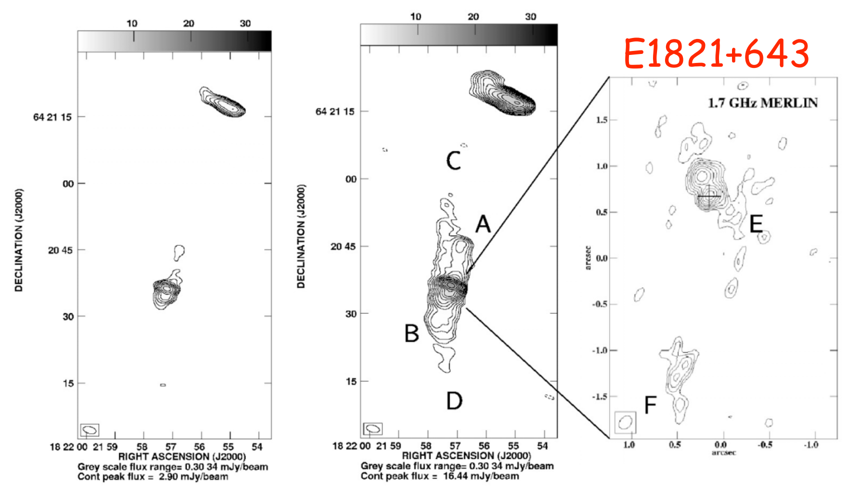
Seyferts, LINERs & Spirals: nuclear and extended radio emission due to the jet or the starburst actvity? [Ho et al.]



Radio Quiet Quasars: nuclear radio emission due to the jet activity, accretion disk/disk coronae, or uncollimated slow disk outflows?



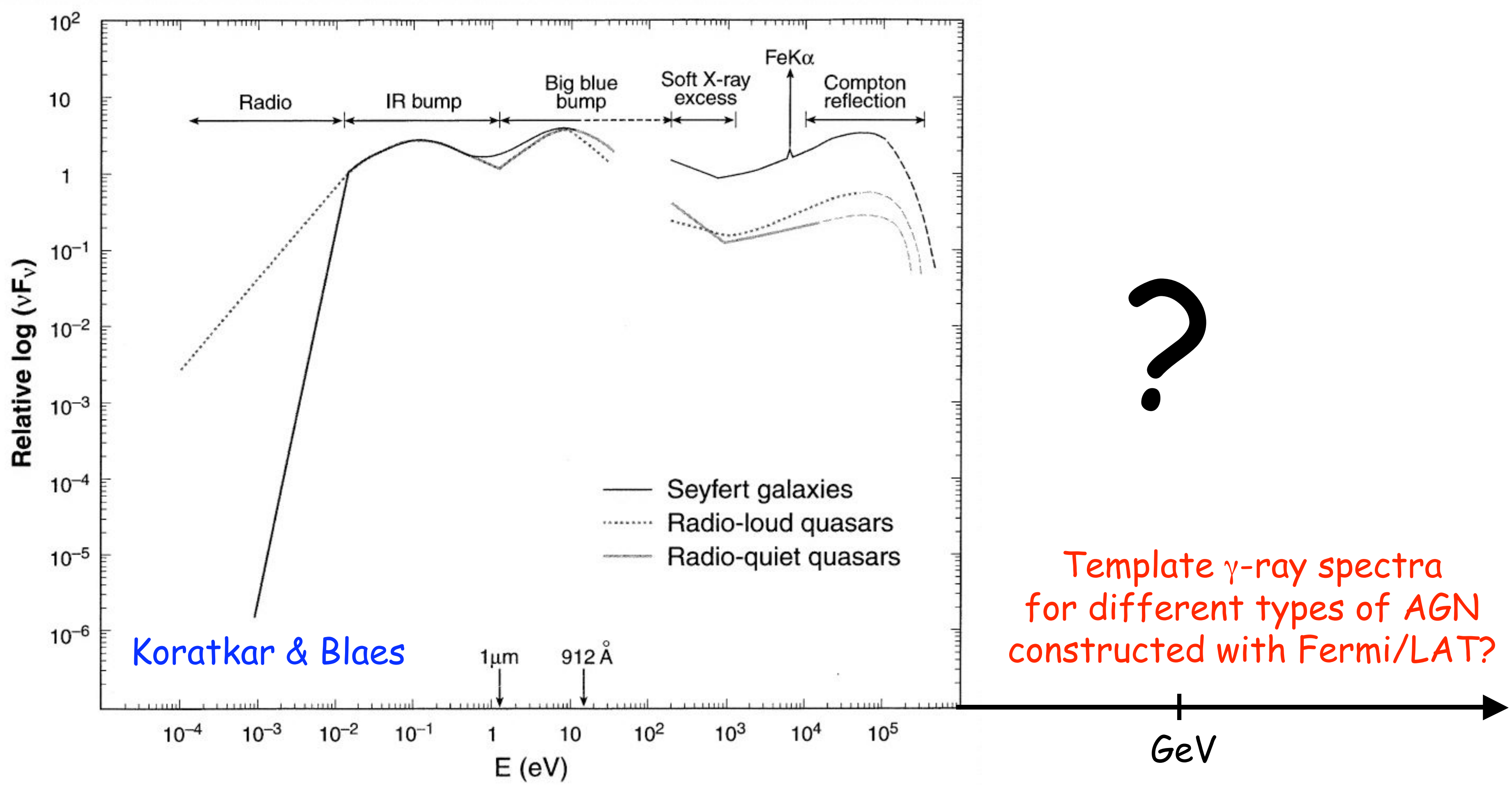
Broad Absorption Line Quasars, believed to be radio quiet as a class, do produce relativistic jets [Siemiginowska et al.]



Radio Quiet Quasars may be sometimes associated with relatively low-power FR I jets [Blundell et al.]

Broad-Band AGN Spectra

4) All AGN are established sources of radio-to-X-ray emission (a mixture of different thermal and non-thermal components). However, the energy range >100 keV is hardly explored in this context…

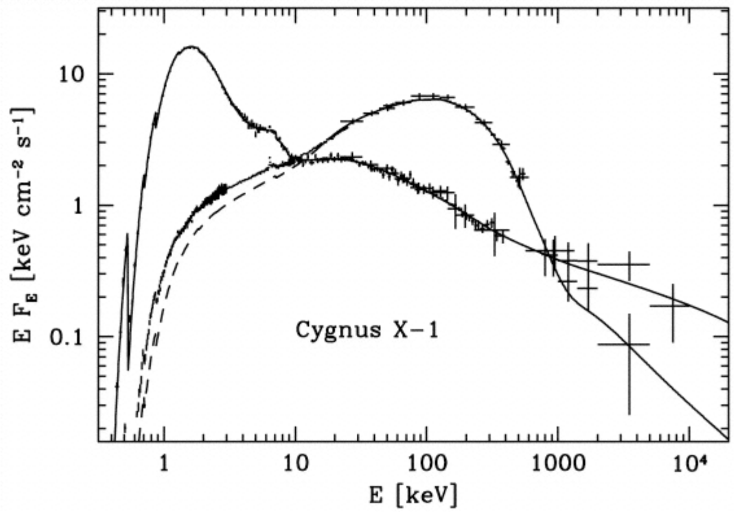


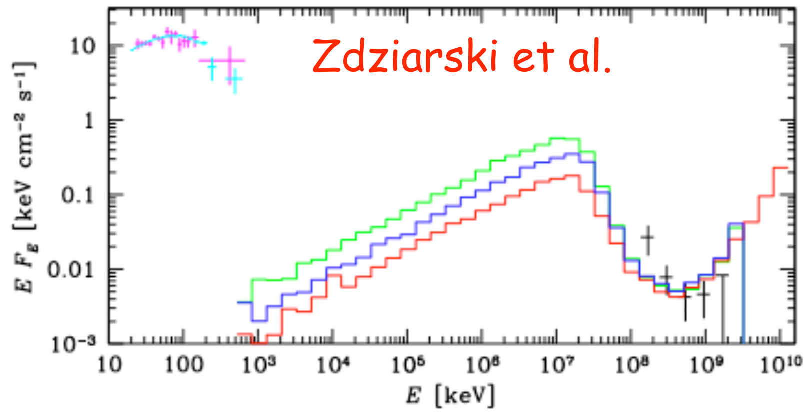
Template γ-ray spectra for different types of AGN constructed with Fermi/LAT?

Need for a careful investigation/identification of low-flux Fermi/LAT sources, stacking analysis for different classes of AGN, etc.

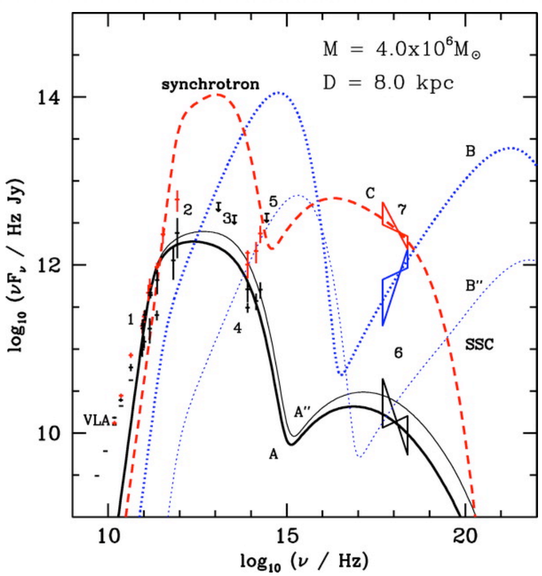
γ-ray Emission of RQ AGN?

One can indeed expect some γ-ray emission from non-jetted AGN due to the efficient particle acceleration taking place in the turbulent and magnetized accretion disks/disk coronae, as possibly observed in some Galactic sources.

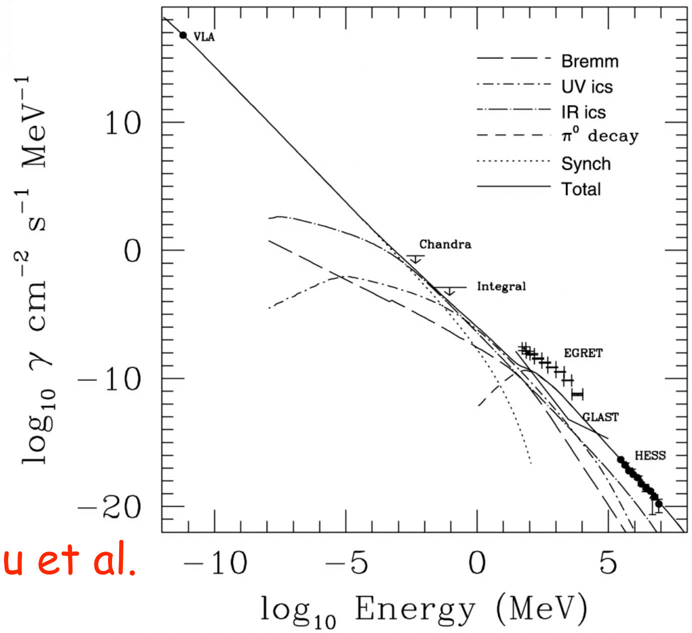




Cygnus X-1 detected at radio, 1-10 MeV and possibly also 0.1-1 TeV photon energies

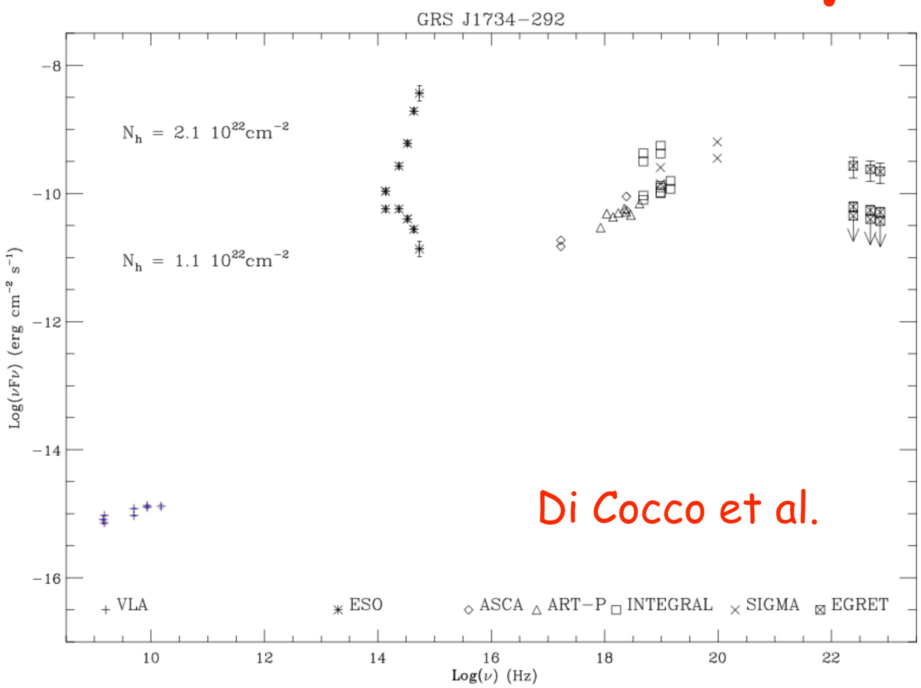


Liu et al.



Galactic Center Sgr A* detected at radio, near infrared, X-ray, and TeV photon energies

Already Detected?



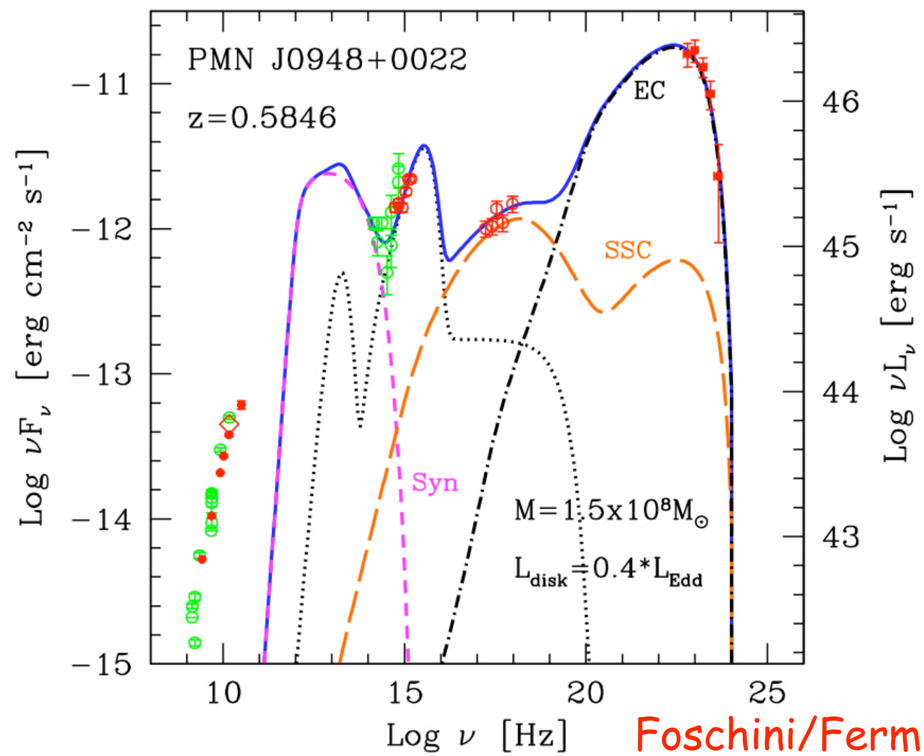
Di Cocco et al.

EGRET source 3EG J1736-2908 has been claimed to be associated with radio quiet Seyfert 1 galaxy GRS 1734-292. This claim has not been confirmed, however.

Still, any meaningful upper limits in the GeV photon energy range, offering robust constraints on the population of relativistic particles in the accretion disks/disk coronae of nearby bright Seyferts, are extremely important.

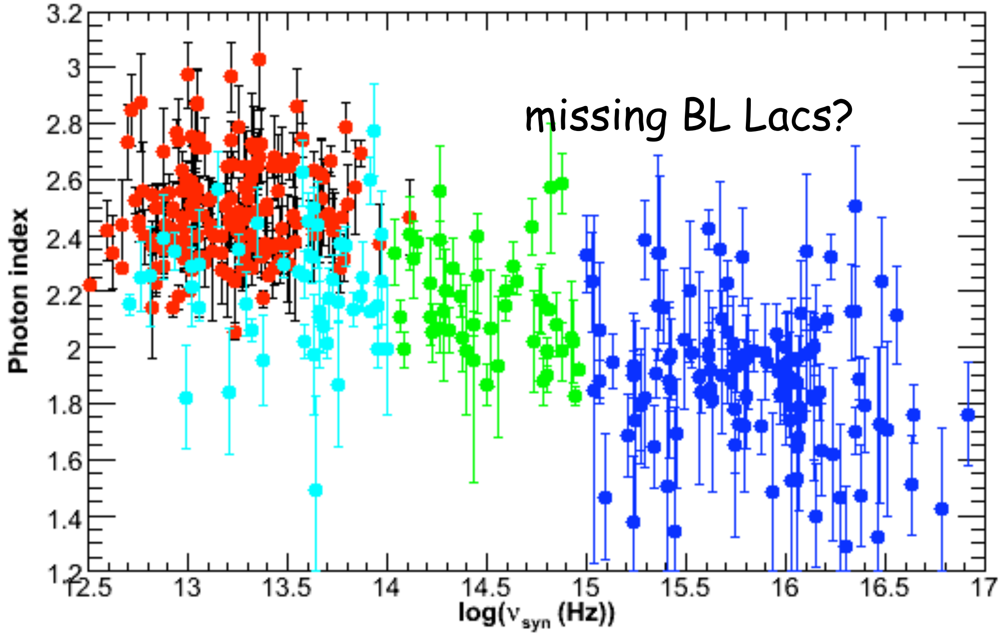
Fermi/LAT has detected Narrow Line Seyfert galaxy PMN J0948+0022. Previously, NL Sys have been considered as radio quiet in general. The particular source PMN J0948+0022 is radio loud, being characterized by a flat-spectrum radio core. So it is "just" a blazar.

The X-ray-to-γ-ray emission of PMN J0948+0022 is modeled in a framework of the blazar scenario (compact relativistic jet close to the SMBH).



Foschini/Fermi

γ-ray Loud Blazars

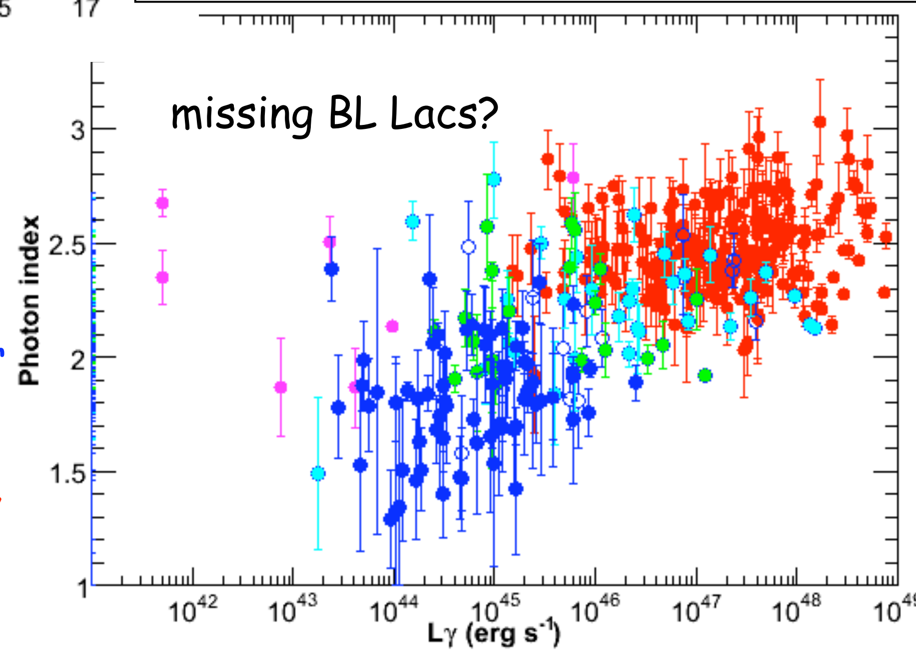


Most of the detected γ-ray loud AGN are blazars (FSRQs and BL Lacs).

It may seem that some general correlations for those have been already established.

Is it indeed the case? Ce we already assure we are not missing some steep-spectrum low-power BL Lacs?

FSRQs **BLLac - LSP**
BLLac - ISP **BLLac - HPBs**

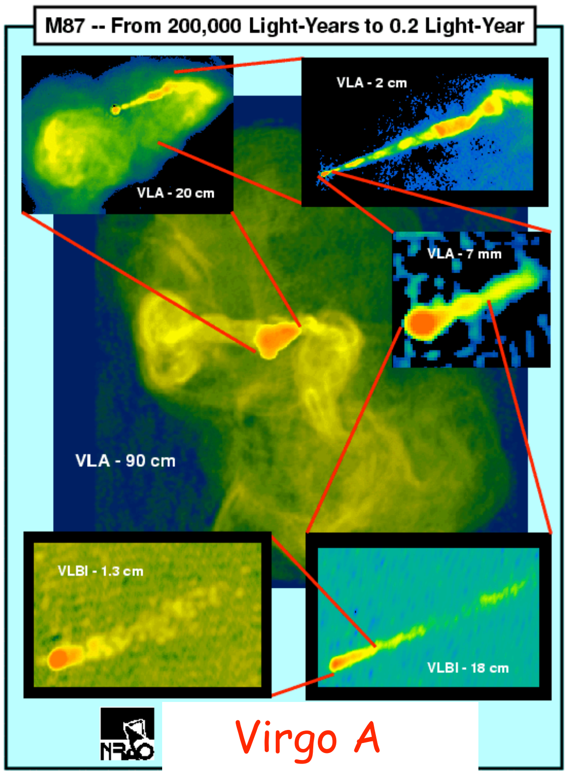


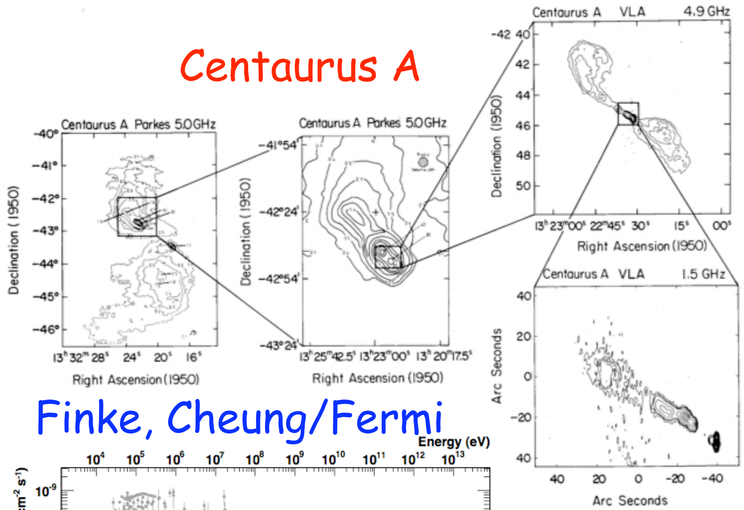
What seems to be a robust finding, is that we do not miss powerful blazars (FSRQs) with flat GeV spectra, $\Gamma_\gamma < 2$. This implies that the mean electron energies in those sources are relatively low, $\langle E_e \rangle <$ GeV.

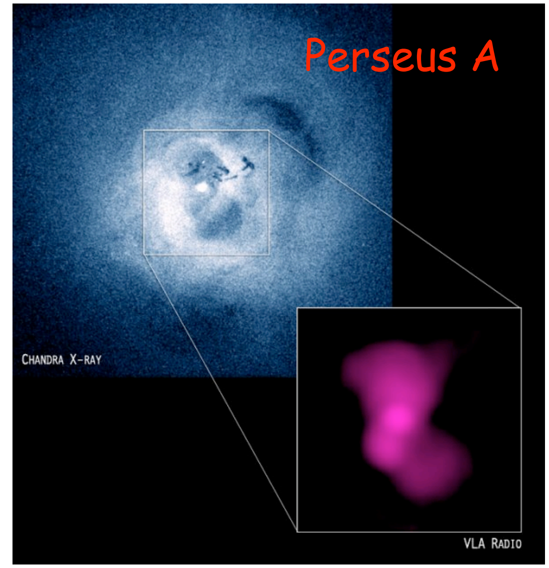
Is it simply due to the intense circumnuclear photon field in FSRQs, and therefore the enhanced radiative cooling of jet electrons?

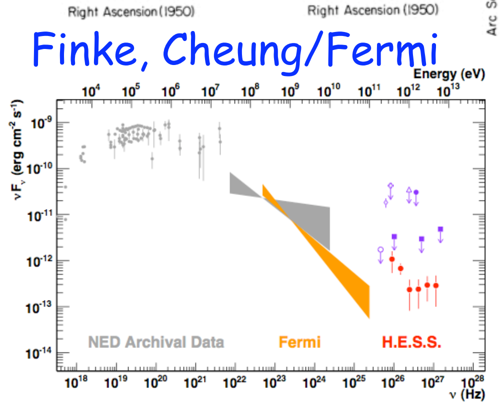
It may be also noted that BL Lacs form very diverse population with respect to their broad-band spectral properties!

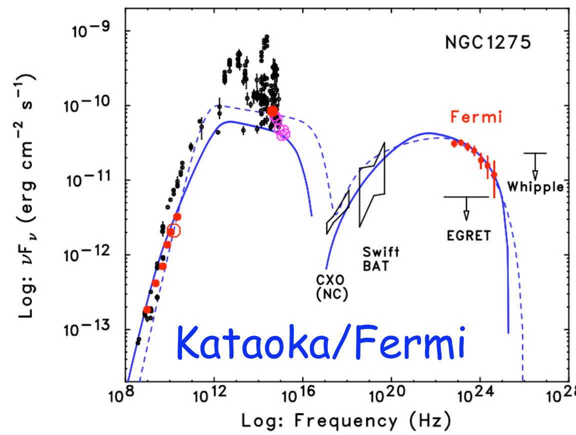
γ-ray Loud Radio Galaxies

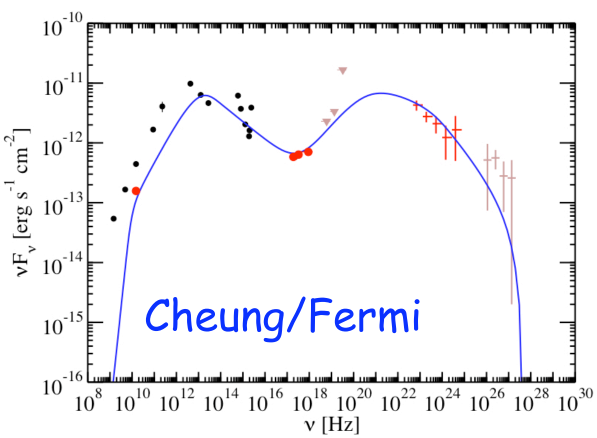












The γ-ray emission detected by Fermi/LAT from Virgo A, Centaurus A, and Perseus A radio galaxies is modeled in a framework of the blazar scenario (compact jet close to the SMBHs) with moderate beaming.

All three radio galaxies are unusual FR Is: nearby, bright and moderately beamed sources with different circumnuclear environment, different large-scale environment, and complex large-scale radio morphologies due to the recurrent jet activity.

We need a larger sample to address common properties of γ-ray loud RGs!

II. Cosmological Context

AGN are detected up to the highest cosmological distances corresponding to redshifts up to $z = 6$ and beyond, probing thus uniquely and directly the Universe which was less than Gyr-old (< 10% of its present age). Unfortunately, huge diversity in the emission properties of active galaxies hampers using them as standard candles. Nevertheless, if sufficiently understood, such distant objects should reveal several fundamental aspects of an early Universe.

The other issue is the role of accreting SMBHs, and in particular of the jets/outflows formed by these, in formation of the structures in the Universe. It is already established that the growth of SMBHs is strictly connected with the growth of galaxies, and that this connection is highly non-linear, with accreting SMBHs influencing substantially the global structure of the forming system via radiative and mechanical feedback. Yet the physics involved remains vague.

Di Matteo et al.

AGN & Cosmology

GENERAL OPEN QUESTIONS:

What is the physics behind the feedback process?

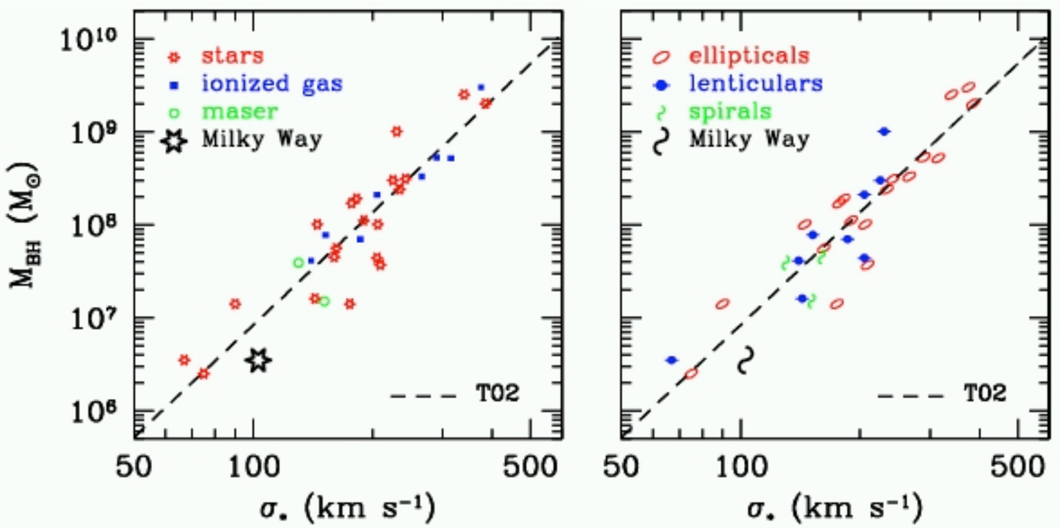
How do AGN jets/outflows interact with the interstellar and intergalactic medium?

Are AGN jets/outflows powerful enough to quench starformation in elliptical galaxies and to heat intracluster gas in cooling flows?

Recent findings:

- First quasars forms together with first galaxies.
- AGN activity is linked to the onset of and quenching of the starformation in merging systems.
- AGN activity dominates production of cosmic background radiation at least in X-ray frequencies.

Ferrarese & Merritt



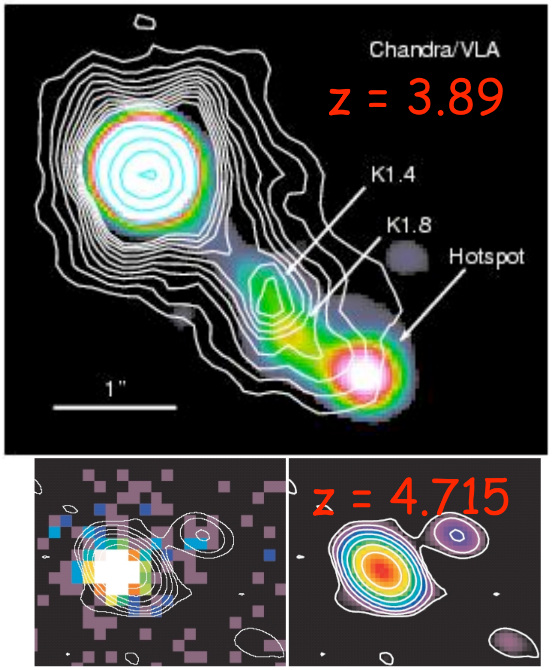
OPEN QUESTIONS FOR FERMI (II):

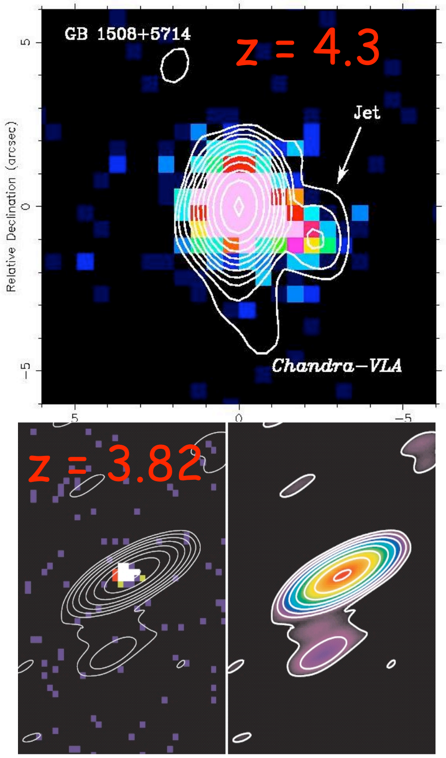
What are the γ-ray properties of high-redshift AGN?

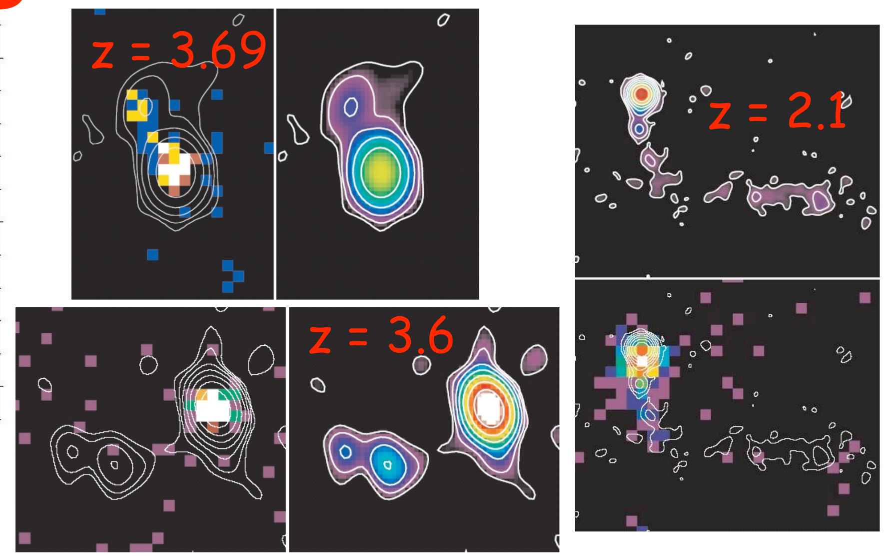
Can we probe the evolution of extragalactic background light at optical/UV frequencies with the γ-ray emission of distant AGN?

Can we explain the extragalactic γ-ray background with the known classes of γ-ray loud AGN?

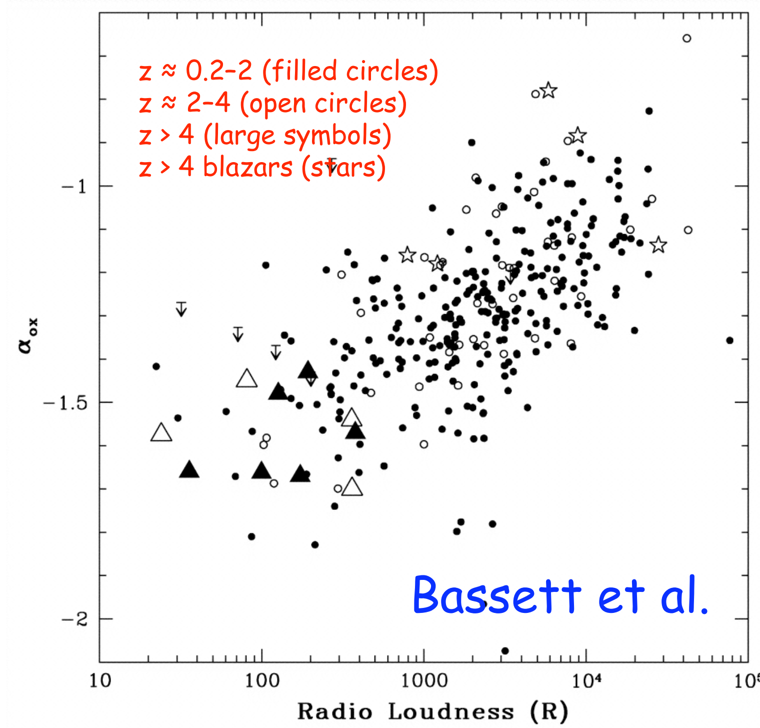
RL AGN at High Redshifts







Cheung et al.

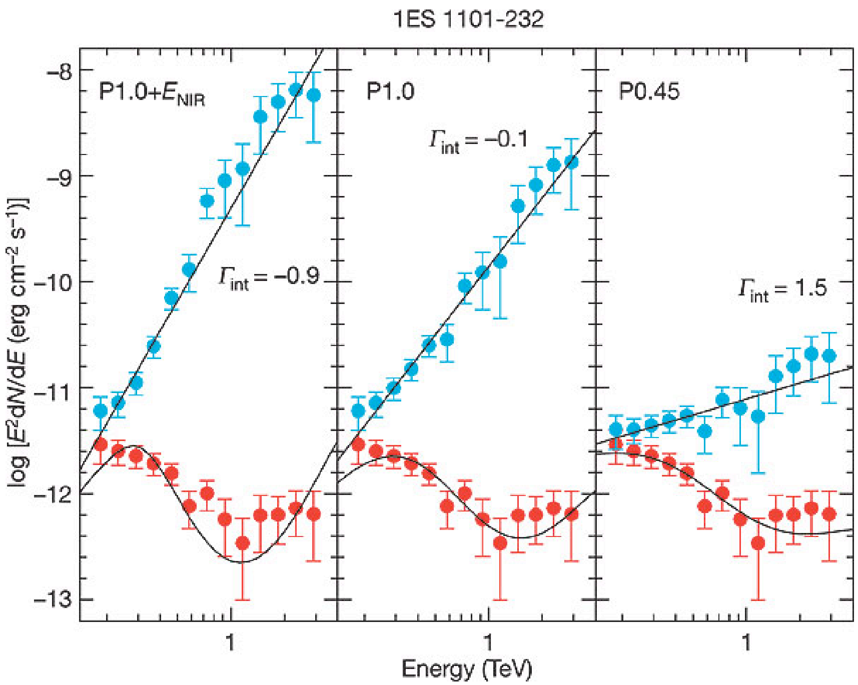


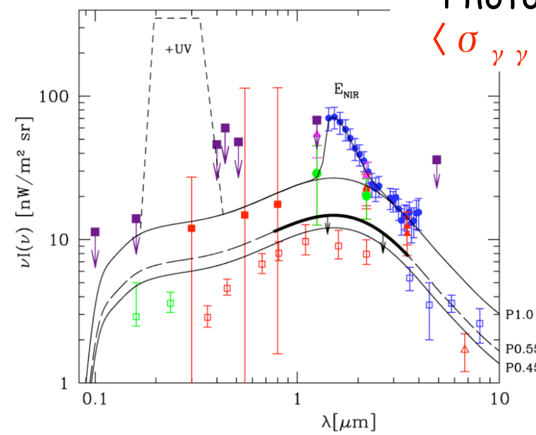
All the detected radio loud AGN at high redshifts are very similar in the spectral properties of their cores or in the large-scale jet morphologies to their low-redshift analogs.

This is already an exciting finding!

It also suggests that radio loud AGN at high redshifts may be powerful γ-ray emitters.

TeV Absorption on EBL



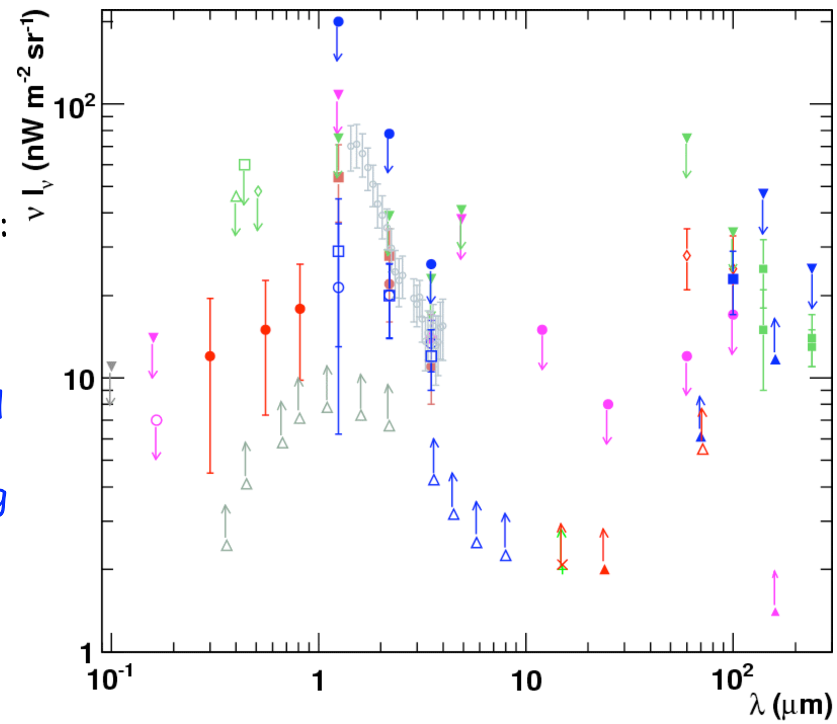


Photon-photon annihilation:

$\langle \sigma_{\gamma\gamma} \rangle \sim 0.2\ \sigma_T\ \delta(\varepsilon\ \varepsilon_0 - 1)$

HESS, Magic, and VERITAS observations of distant BL Lacs established that the Universe is surprisingly transparent for TeV photons.

Aharonian et al/HESS

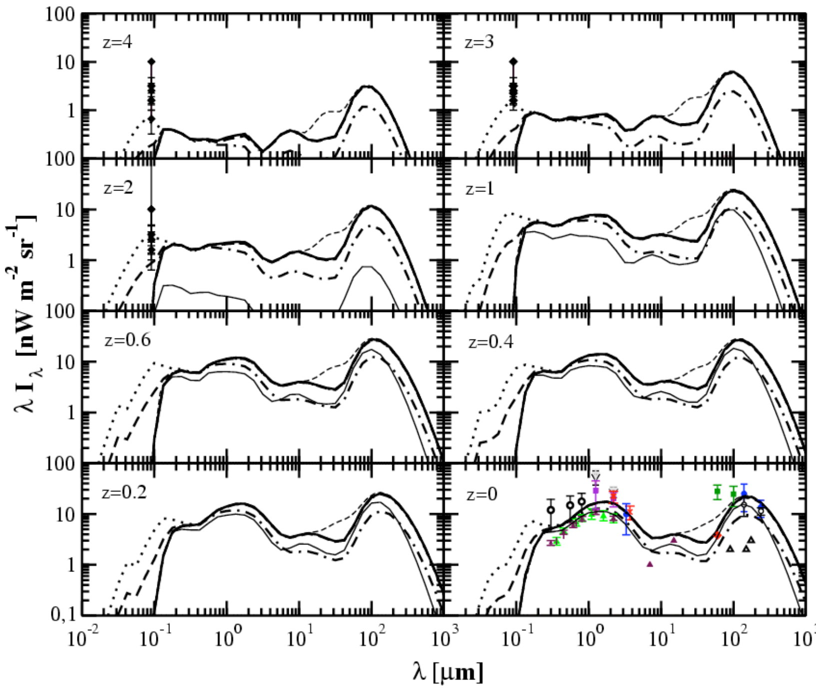


Still, modern Cherenkov Telescopes probes only narrow (NIR) segment of the extragalactic background light (EBL: 0.1-1000 μm), and relatively nearby Universe (z < 0.2).

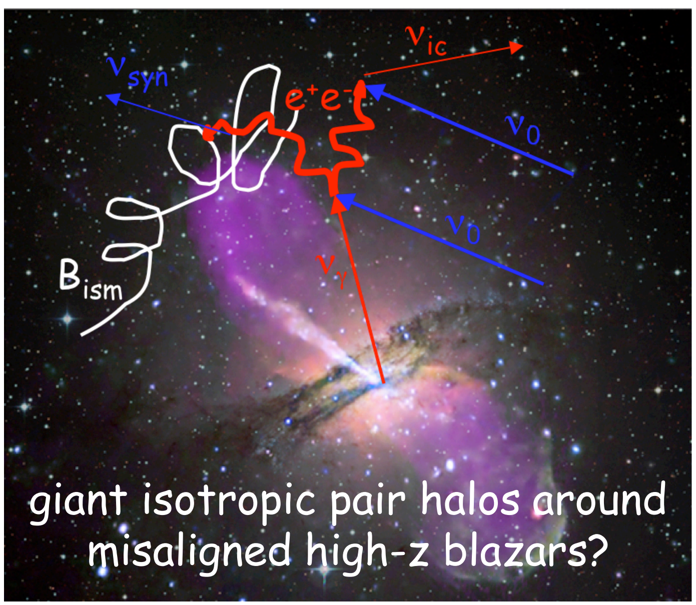
Direct measurements of EBL are difficult due to strong foreground emission. EBL spectral shape reflects star and dust formation history, and therefore probes galaxy evolution models. Even small uncertainties in the absorbing photon number density, $n_0(\varepsilon_0) \propto \tau_{\gamma\gamma}$, translate to large uncertainties in the γ-ray attenuation:

$$S_{obs}(\varepsilon) = S_{int}(\varepsilon) \times \exp[\tau_{\gamma\gamma}(\varepsilon)]$$

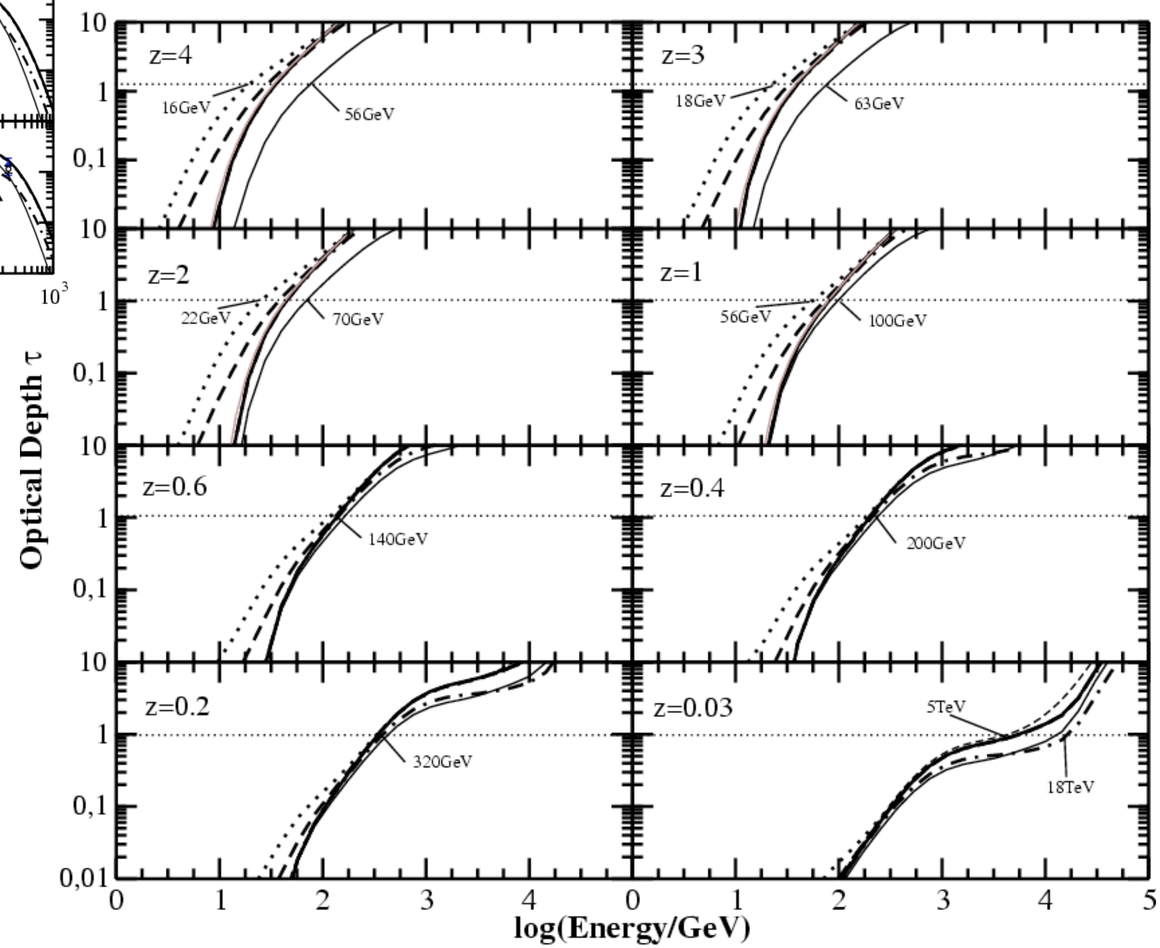
GeV Absorption on Evolving EBL?



In principle, with Fermi/LAT we can probe very high-redshift Universe via absorption of 10-100 GeV photons on the evolving extragalactic background light at UV/optical frequencies.



Kneiske et al.



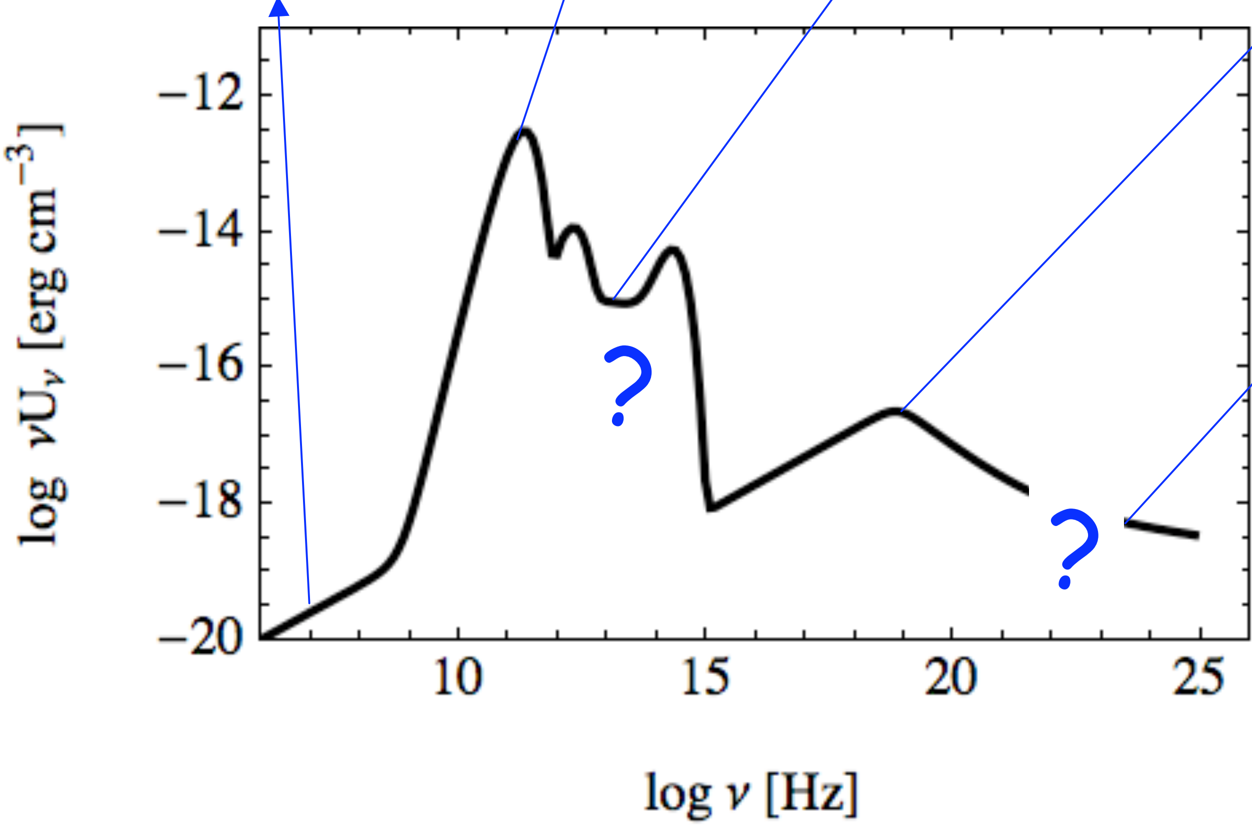
Broad-Band Cosmic Background

Radio background due to all types of AGN and starforming galaxies (missing 70% of sources)

CMB

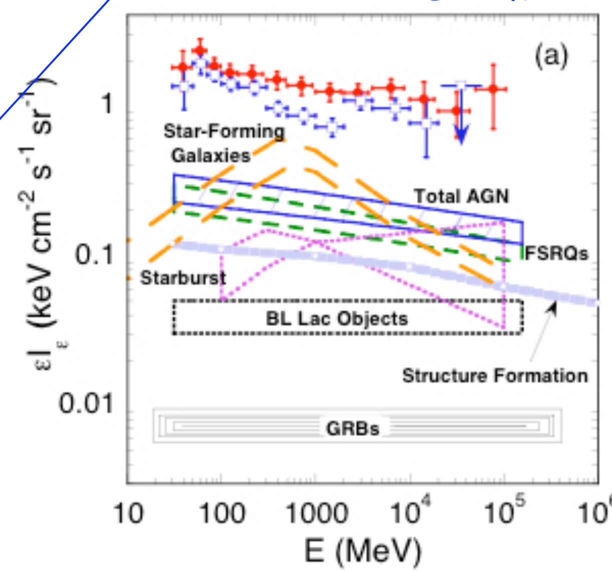
IR-UV background due to stars and dust (relatively uncertain)

X-ray background due to all types of AGN (missing 60% of sources in the hard X-ray band)



γ-ray background due to …???

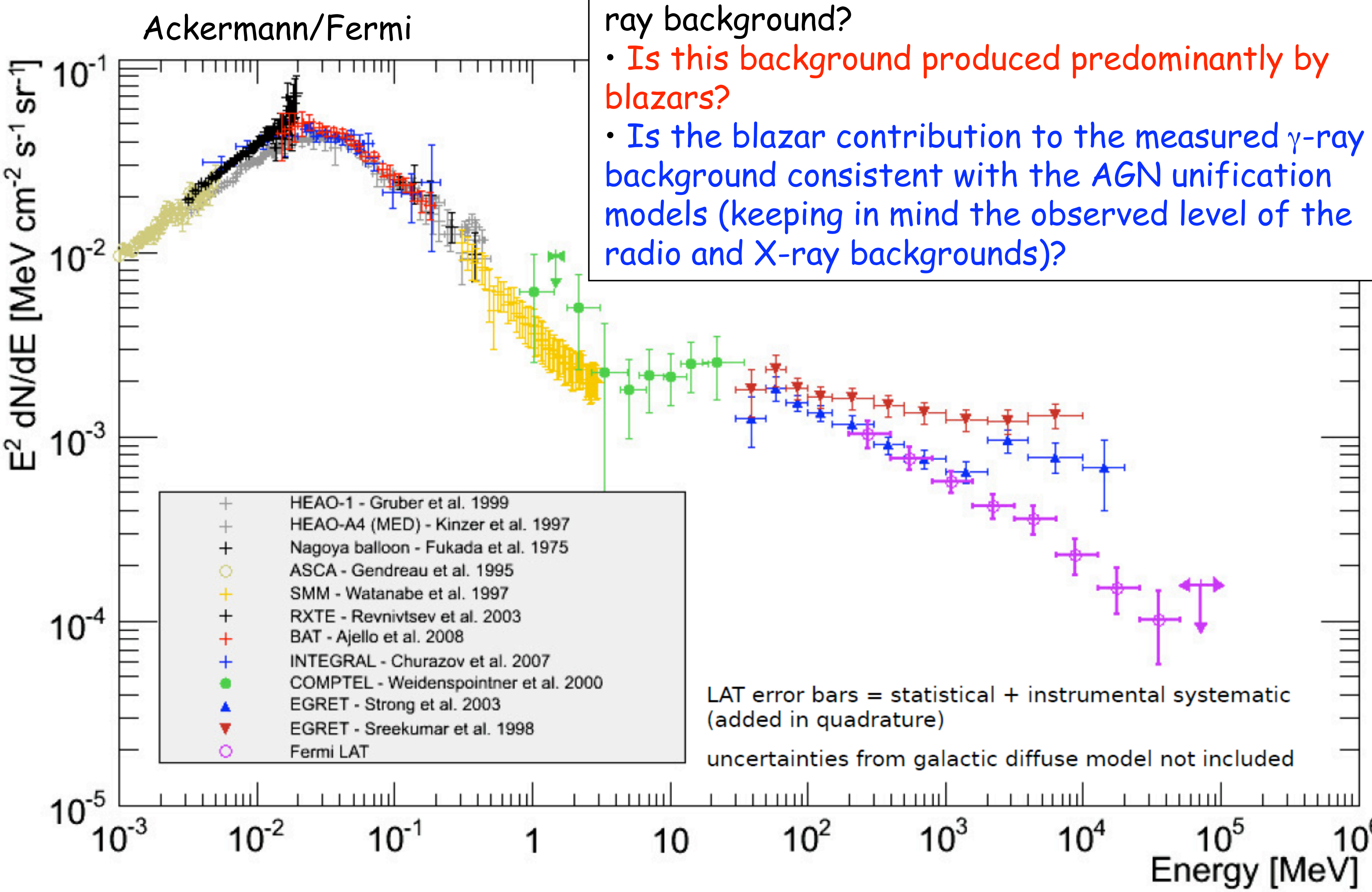
Dermer



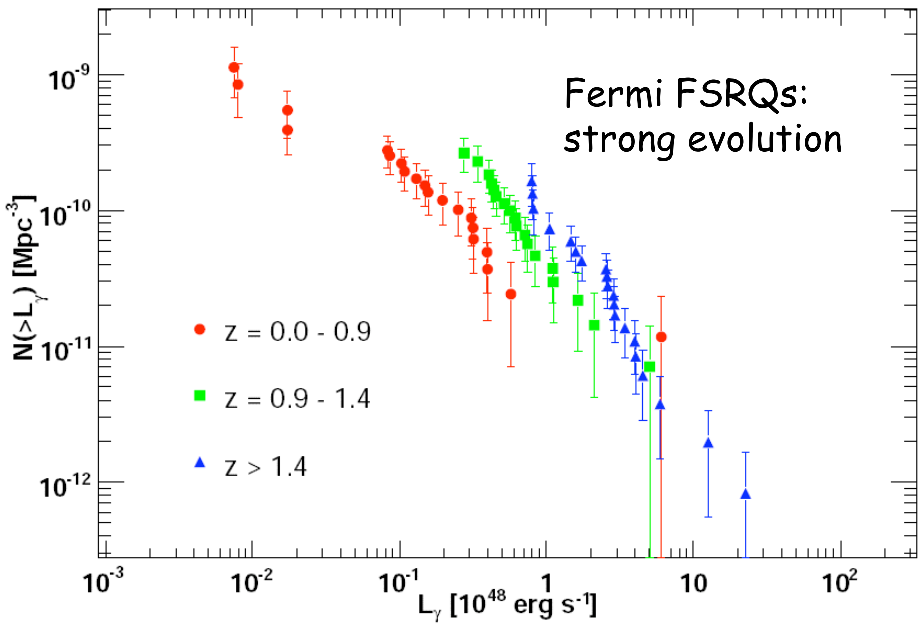
We should aim for a self-consistent interpretation of the recently characterized broad-band extragalactic background light (in agreement with the structure formation and AGN unification models!).

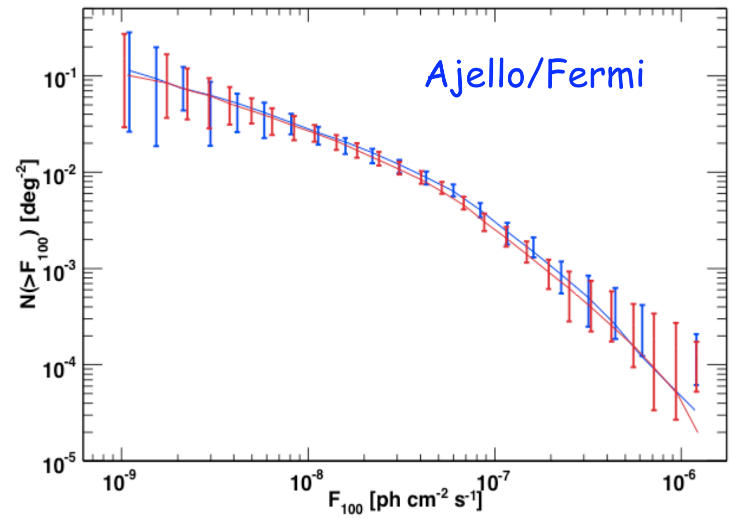
Extragalactic γ-ray Background

- Are we close to resolving all the extragalactic γ-ray background?
- Is this background produced predominantly by blazars?
- Is the blazar contribution to the measured γ-ray background consistent with the AGN unification models (keeping in mind the observed level of the radio and X-ray backgrounds)?

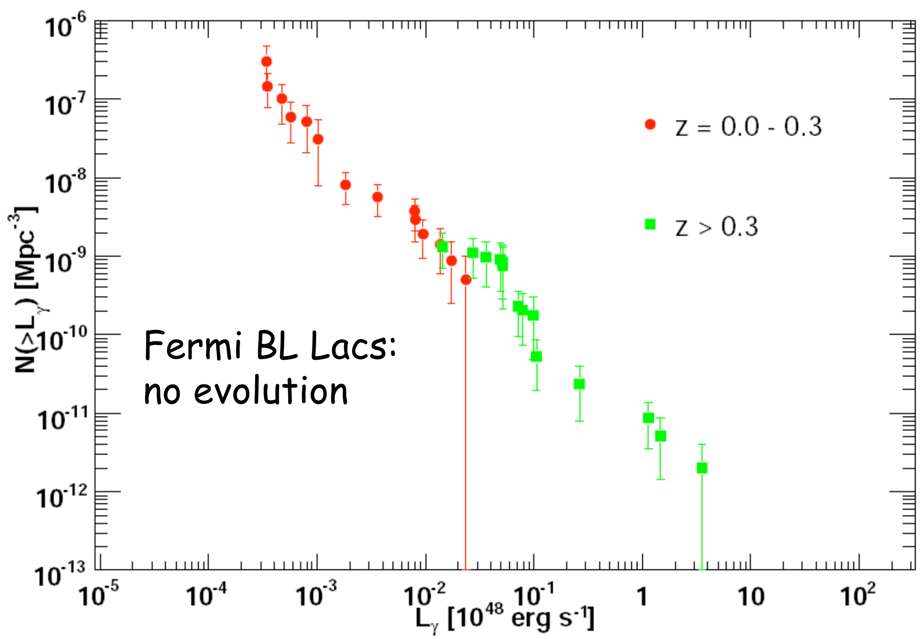


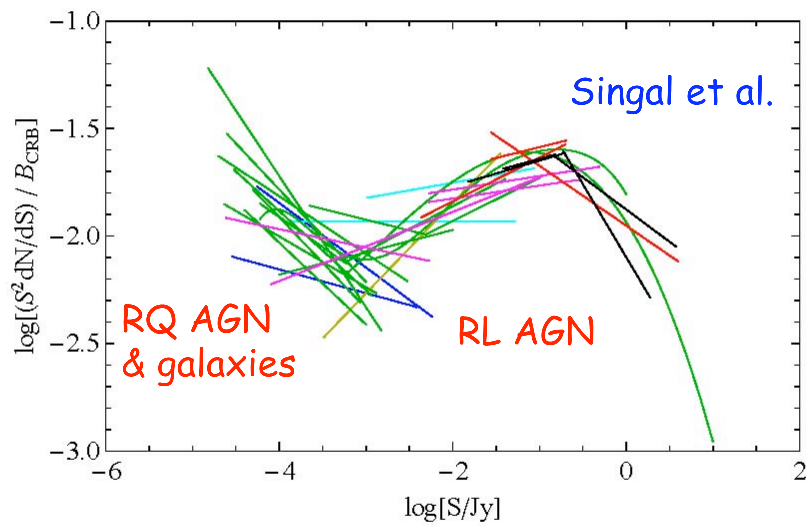
Population Studies with Fermi





Fermi sources: 30%-100% contribution to the measured γ-ray background

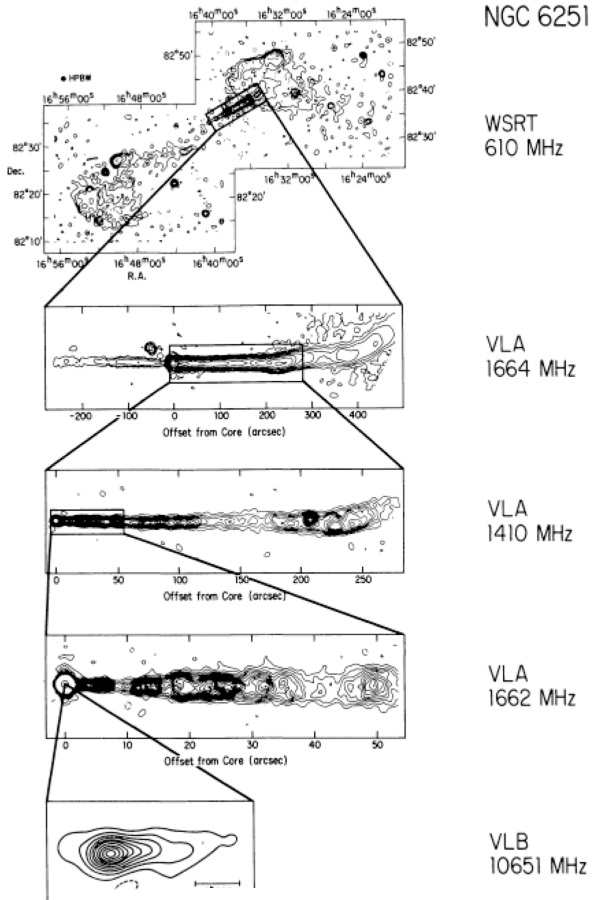




Known radio sources: 30% contribution to the measured radio background

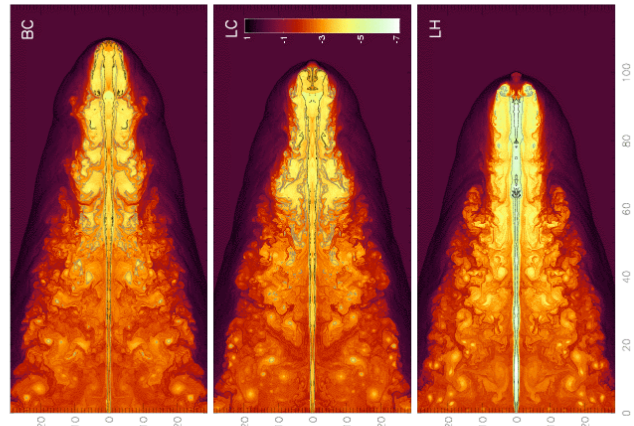
III. Elusive Relativistic Jets

10^{21}-10^{24} [cm]
matter dominated?



10^{14}-10^{18} [cm]
magnetic dominated?

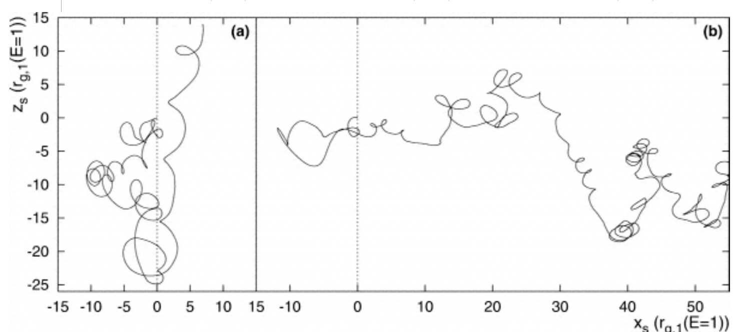
only non-thermal emission!
(no standard plasma diagnostics...)



Global large-scale structure of extragalactic relativistic jets

$R_j \sim 10^{21}$ - 10^{24} [cm]

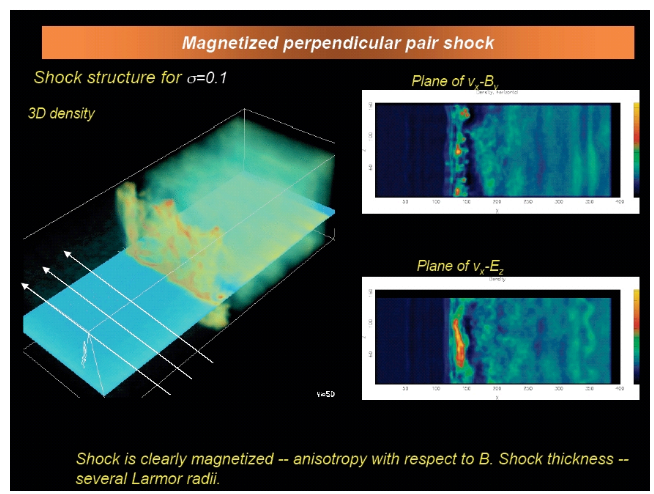
can be modeled with MHD simulations



Non-thermal process

$r_g \sim E_e/eB$
$\sim 10^9$ - 10^{21} [cm]

can be studied with MC simulations



Microphysics of collisionless magnetized plasma

$\lambda_e \sim c/\omega_e$
$\sim 10^8$-10^9 [cm]

can be investigated with PIC simulations

Jet Physics

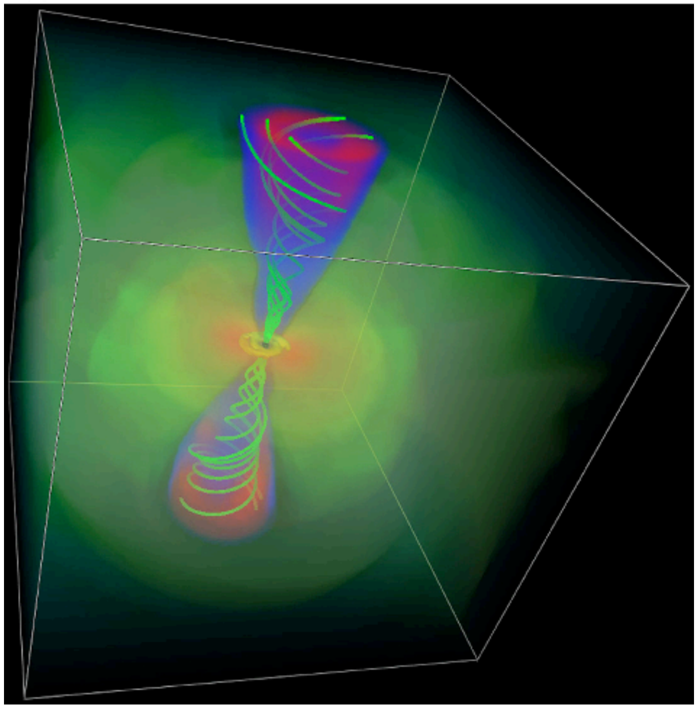
GENERAL OPEN QUESTIONS:

How are relativistic jets launched from the vicinities of SMBHs?

What is the jet content? Is the jet composition changing along the outflow?

What are the main processes controlling energy dissipation and particle acceleration processes in relativistic jets?

McKinney et al.



Merging agreement:

- Jets are launched as **Poynting flux**-dominated outflows from the ergospheres of SMBHs and/or the innermost parts of their accretion disks.
- Homogeneous one-zone blazar models require the jets to be dynamically dominated by (cold) **protons**.
- The observed non-thermal broad-band jet emission is predominantly **leptonic** in origin (implying the presence of 1-100 TeV energy electrons).

OPEN QUESTIONS FOR FERMI (III):

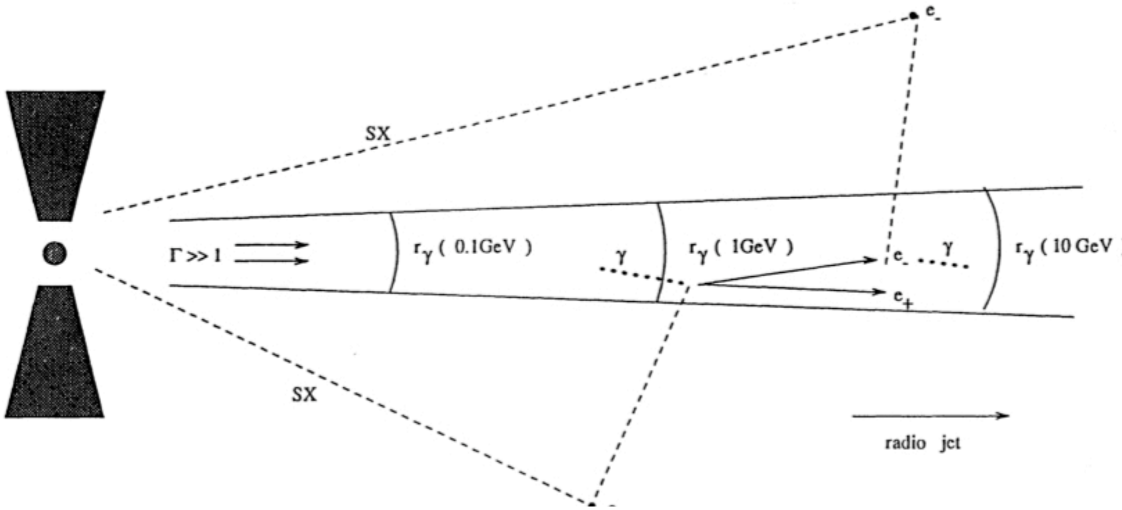
What is the location and structure of γ-ray-emitting regions in AGN jets?

What are the γ-ray spectra of different types of AGN jets?

What are the underlying electron energy spectra and the particle acceleration processes involved?

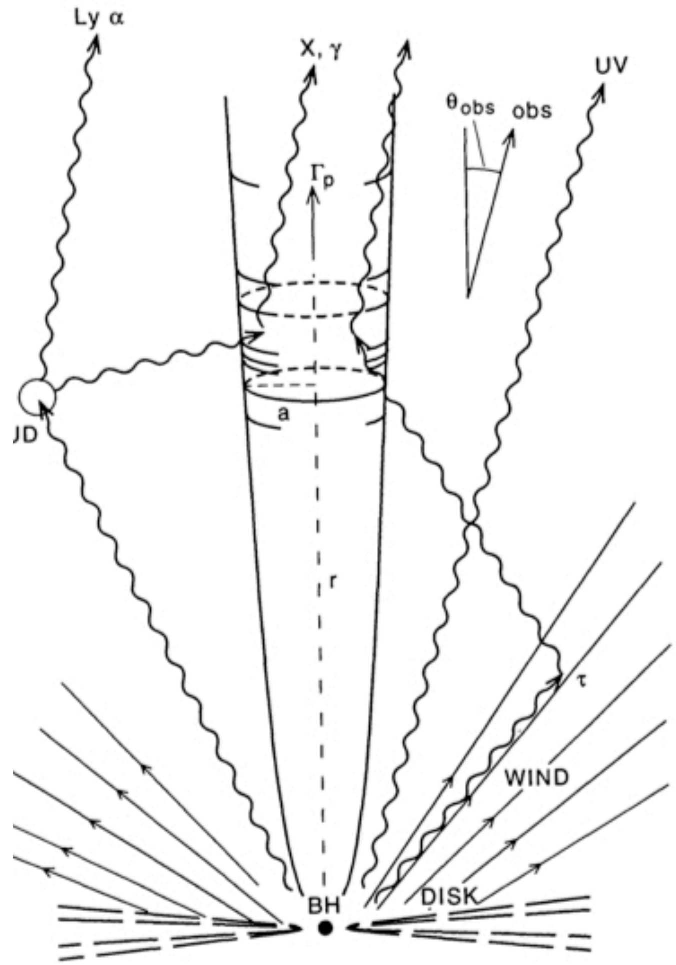
What is the γ-ray duty cycle of blazars? What controls γ-ray variability of blazar sources?

Blazar Emission Zone



* One zone or multiple zones?
* Homogeneous region or stratified region?

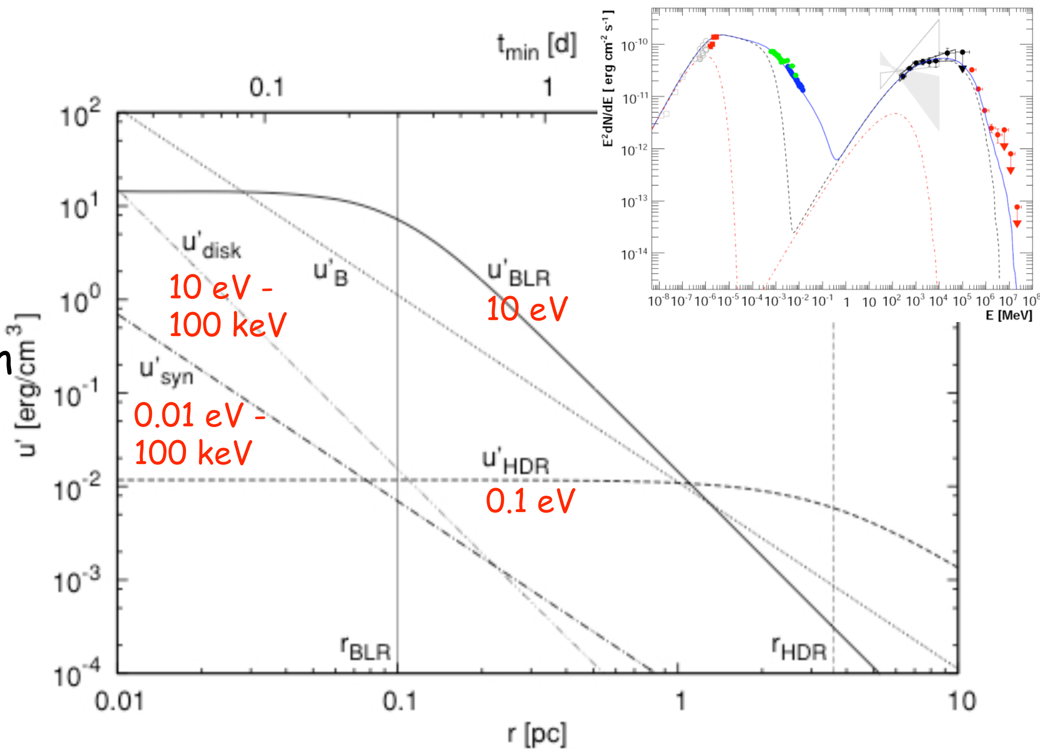
In a framework of the "standard" leptonic blazar scenario, one-zone homogeneous emission zone is assumed (Maraschi et al. 91, Dermer & Schlickeiser 93, Sikora et al. 94). This simple model is relatively successful in explaining several blazar properties established so far. If this is the case indeed, the question to be asked is why there is only one, well defined and very compact region of the enhanced energy dissipation within the outflow, instead of a superposition of different emission zones (Blandford & Levinson 95)? Also, is it a moving blob or a stationary feature within the jet? With Fermi/LAT observations accompanied by truly simultaneous broad-band campaigns, we can finally confront different model predictions with the observations, and try to answer these questions!



Where Is Blazar Emission Zone?

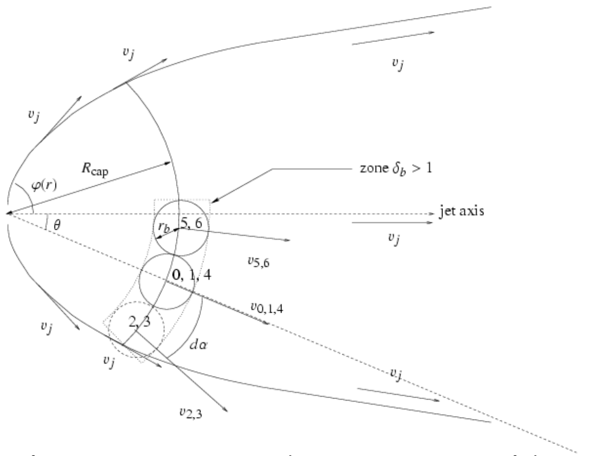
We can use the following constraints:

1. Characteristic (PSD) and shortest (flux doubling) variability timescales
2. Opacity for the observed γ-ray photons (both internal and external to the emission zone)
3. Luminosity ratios between synchrotron and inverse-Compton components
4. Spectral position of the peak frequencies for the synchrotron and inverse-Compton components
5. Presence and position of different spectral breaks (radiative cooling breaks, Klein-Nishina breaks, etc.)
6. Lack of bulk-Compton and absorption features in broad-band spectra
7. Correlations between variable fluxes in different frequency ranges
8. Correlations between high-energy flares with morphological changes of resolved radio structures
9. Correlation between high-energy flares with changes in radio/optical polarization

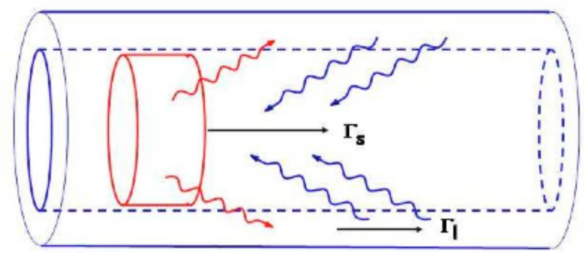


Detailed modeling of the broad-band blazar spectra performed so far typically suggests that the blazar emission zone in FSRQs is located relatively far from SMBHs, ~ 10^{18} cm ~ 10^4 R_g. Still, distances outside of this range <u>are not</u> excluded. In particular, for BL Lacs the blazar emission zone seems to be located much closer to SMBHs. Fermi/LAT data will enable to critically re-examine all the discussed constraints!

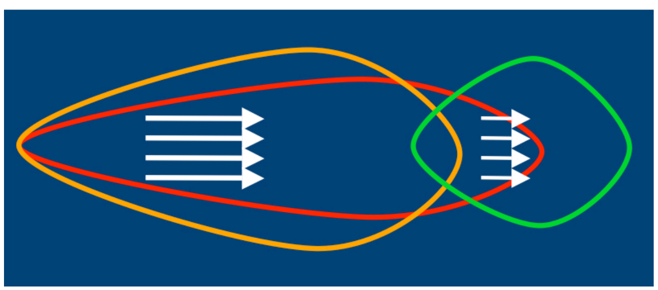
Structure of the Blazar Zone



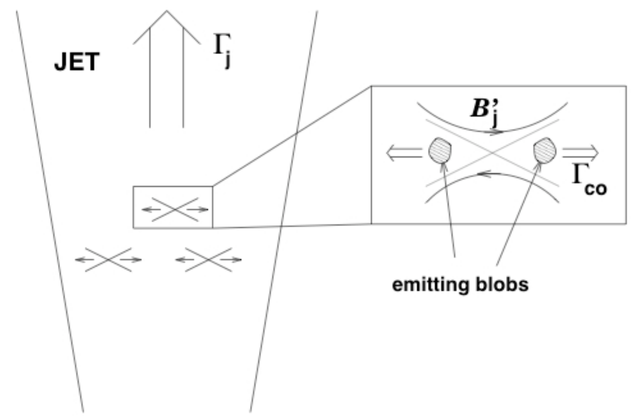
Multi-blob scenario (Lenain et al.)



Spine - shear layer scenario (Ghisellini et al.)



Decelerating jet scenario (Georganopoulos et al.)



Jet-in-jet scenario (Giannios et al.)

Complex (confusing!) pattern of a broad-band rapid variability established for several sources, as well as the detections of radio galaxies at high energy γ-ray photon energy range, let to the emergence of stratified models for the blazar emission zone.

More truly simultaneous broad-band data for a larger sample of objects are needed to verify the proposed scenarios, and to understand the true structure of the emission region.

High Energy Blazar Spectra

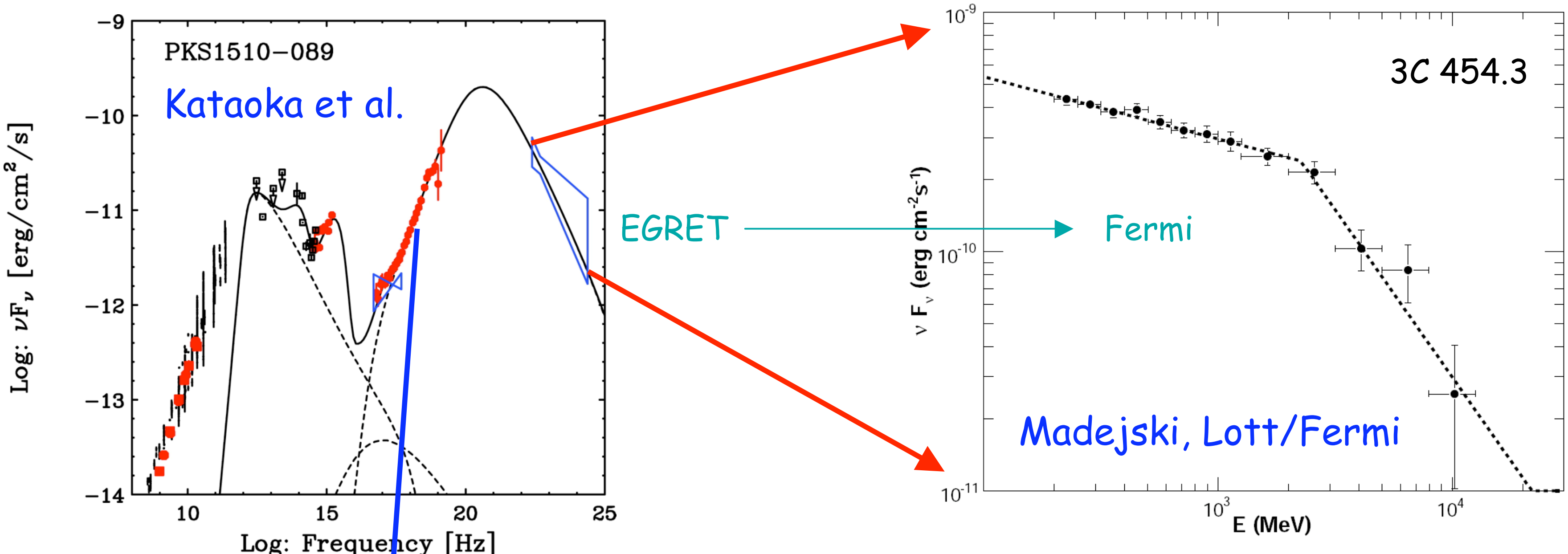


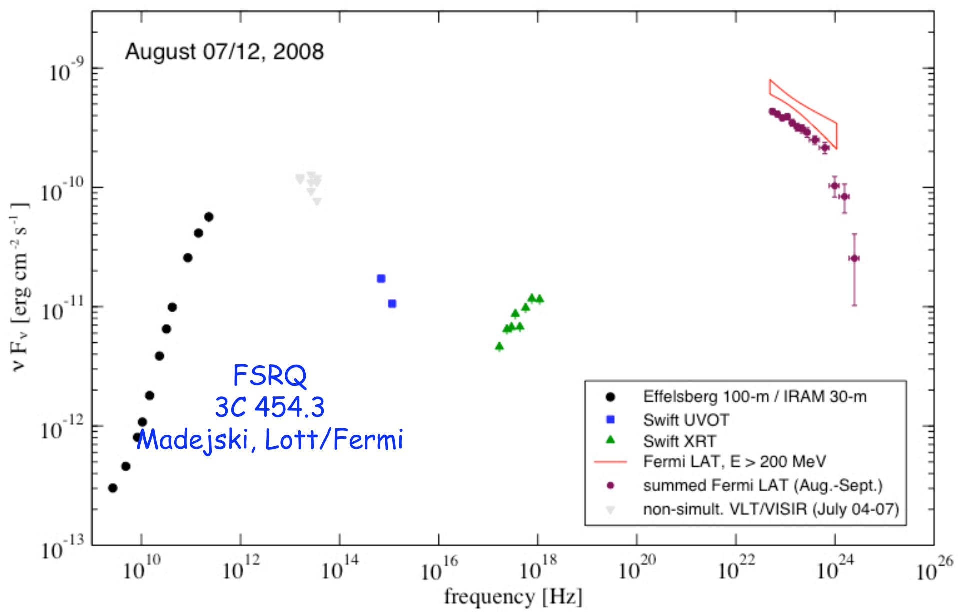
Table 1
Luminous Blazar Sources with the Hardest Recorded X-ray Spectra

Name (1)	z (2)	α_x (3)	α_γ^E (4)	α_γ^F (5)	Reference (6)
S5 0212+73	2.367	0.32 ± 0.19	...	...	Sambruna et al. (2007)
PKS 0229+13	2.059	0.39 ± 0.09	...	...	Marshall et al. (2005)
PKS 0413-21	0.808	0.39 ± 0.12	...	...	Marshall et al. (2005)
PKS 0528+134	2.060	0.12 ± 0.26	1.46 ± 0.04	1.54 ± 0.09	Donato et al. (2005)
PKS 0537-286	3.104	0.27 ± 0.02	1.47 ± 0.60	...	Reeves et al. (2001)
PKS 0745+241	0.409	0.35 ± 0.12	...	...	Marshall et al. (2005)
SWIFT J0746.3+2548	2.979	0.17 ± 0.01	...	...	Watanabe et al. (2009)
PKS 0805-07	1.837	0.20 ± 0.20	1.34 ± 0.29(?)	...	Giommi et al. (2007)
S5 0836+710	2.172	0.34 ± 0.04	1.62 ± 0.16	...	Donato et al. (2005)
RGB J0909+039	3.200	0.26 ± 0.12	...	...	Giommi et al. (2002)
PKS 1127-145	1.184	0.20 ± 0.03	1.70 ± 0.31	1.69 ± 0.18	Siemiginowska et al. (2008)
PKS 1424-41	1.522	0.20 ± 0.30	1.13 ± 0.21	...	Giommi et al. (2007)
GB 1428+4217	4.715	0.29 ± 0.05	...	...	Fabian et al. (1998)
PKS 1510-089	0.360	0.23 ± 0.01	1.47 ± 0.21	1.48 ± 0.05	Kataoka et al. (2008)
PKS 1830-211	2.507	0.09 ± 0.05	1.59 ± 0.13	...	De Rosa et al. (2005)
PKS 2149-306	2.345	0.38 ± 0.08	...	...	Donato et al. (2005)
PKS 2223+210	1.959	0.31 ± 0.26	...	...	Donato et al. (2005)
3C 454.3	0.859	0.34 ± 0.06	1.21 ± 0.06	1.41 ± 0.02	Donato et al. (2005)

Notes. (1) Name of a source; (2) redshift of a source, z; (3) X-ray spectral index, α_x; (4) EGRET γ-ray spectral index, α_γ^E (Hartman et al. 1999); (5) *FERMI* γ-ray spectral index, α_γ^F (Abdo et al. 2009b); and (6) references.

Bright FSRQs reveal repeatedly very flat X-ray spectra of power-law forms with photon indices $\Gamma_X \leq 1.5$, and steep γ-ray spectra of broken power-law form with photon indices $\Gamma_\gamma > 2$ with breaks $\Delta\Gamma > 0.5$. Such high-energy (inverse-Compton) spectra deviate substantially from the ones expected in a framework of a "standard" scenario (a low-energy $\Gamma_{low} = 1.5$ continuum modified at high energies by radiative cooling to give $\Gamma_{high} = 2.0$). The high energy spectral breaks observed by Fermi/LAT seem to be due to intrinsic breaks in the underlying electron energy distribution.

Underlying Electron Spectra



The most surprising finding is that the revealed photon (and therefore electron) spectra do not depend on the activity state of a source! This, again, is not what we have expected to observe....

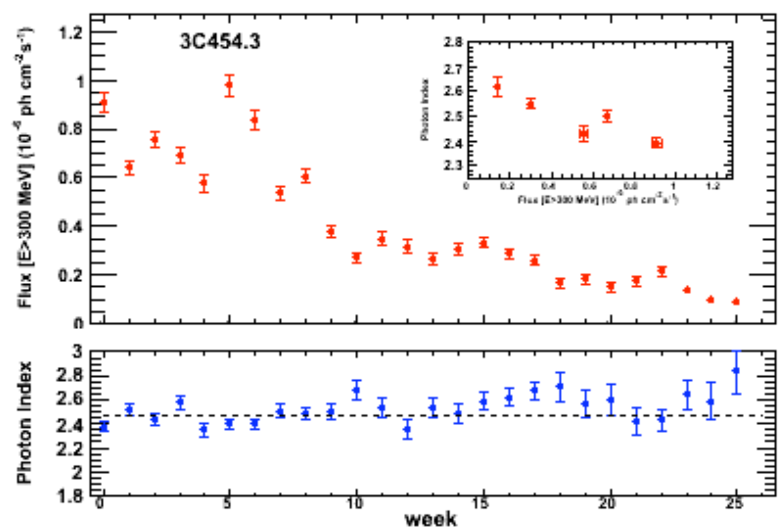
At the moment, the theory of particle acceleration in relativistic regime is not quantitative enough to make robust predictions regarding emerging particle spectra. Fermi observations will help to develop theoretical models of particle acceleration in relativistic plasma!

In FSRQs, the energy distribution of the radiating electrons seem to be of the form $n_e(E) \propto$

E^{-s1}	for	$E_{min} < E < E_{br}$
E^{-s2}	for	$E > E_{br}$

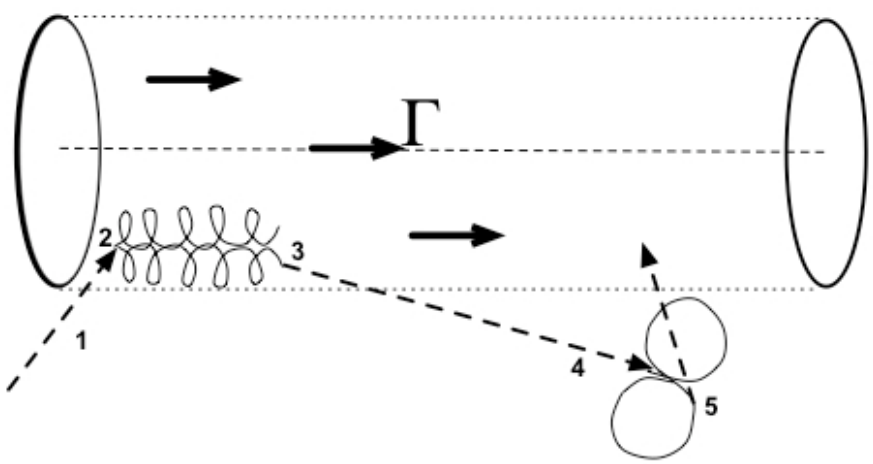
with

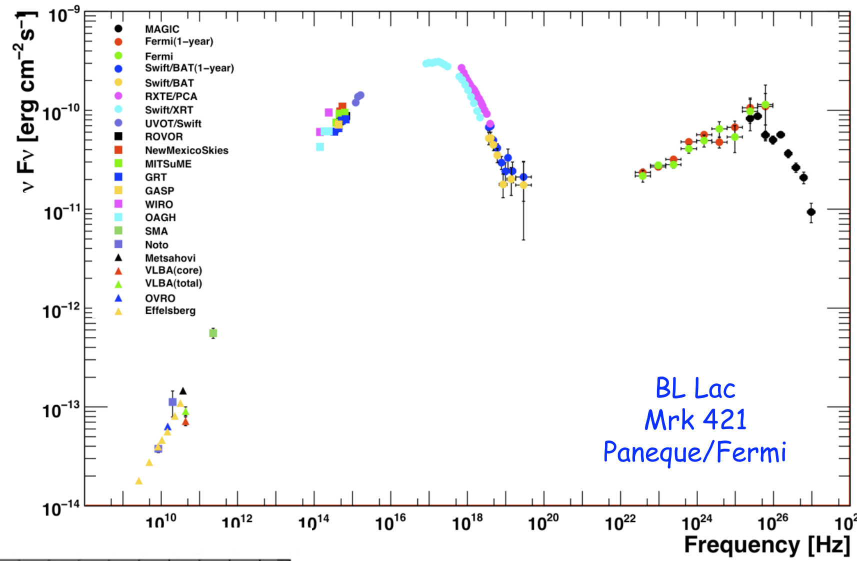
$s_1 \leq 2$, $s_2 > 2$, $E_{min} \sim$ MeV, $E_{br} \sim$ 0.1-1 GeV

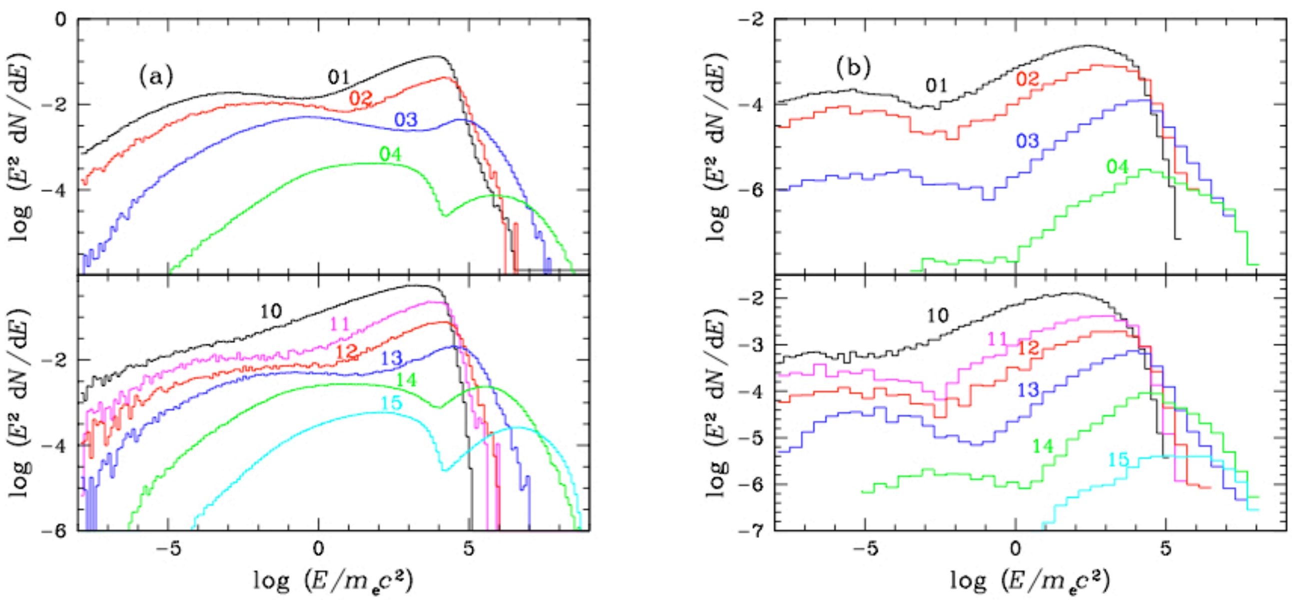


Such electron spectra differ substantially from the ones expected in the case of a diffusive shock acceleration (non-relativistic test-particle limit).

“Supercritical” Phenomena?







For example, “photon breeding” model by Stern & Poutanen.

What about “supercritical” phenomena, which are at some level inevitable for relativistic outflows in a dense radiative environment? In general, what about absorption effects and emission of secondary particles? Can we find any spectral signatures for such? Excellent Fermi data will enable to look for these.

Looking Forward

- This is an exciting time for AGN research, since for the very first time truly multiwavelength and simultaneous high-quality data can be gathered for a large number of sources.

- Despite intense investigations in the past, the physics of AGN and their relativistic outflows still remains elusive. On the other hand, during the last years a substantial progress in this field has been made, mostly due to the development in numerical modeling and observational techniques.

- Fermi/LAT will definitely help to answer several open questions regarding the physics of AGN in a near future, for example:

    1. What are the γ-ray properties of different types of AGN?
    2. Are radio quiet AGN γ-ray emitters at some level?
    3. Is the γ-ray emission of RL AGN shaped by the jet properties (on small and large scales) and/or by the properties of the accreting matter?
    4. What are the γ-ray properties of high-redshift AGN?
    5. Can we probe the evolution of extragalactic background light at optical/UV frequencies with the γ-ray emission of distant AGN?
    6. Can we explain the extragalactic γ-ray background with the known classes of γ-ray laud AGN?
    7. What is the location and structure of γ-ray-emitting regions in AGN jets?
    8. What are the γ-ray spectra of different types of AGN jets?
    9. What are the underlying electron energy spectra and the particle acceleration processes involved?
    10. What is the γ-ray duty cycle of blazars? What controls γ-ray variability of blazar sources?