Gamma-Raying the Universe

Gamma-Ray Diagnostics of the Extragalactic Background Light, Intergalactic Magnetic Fields, and New Physics

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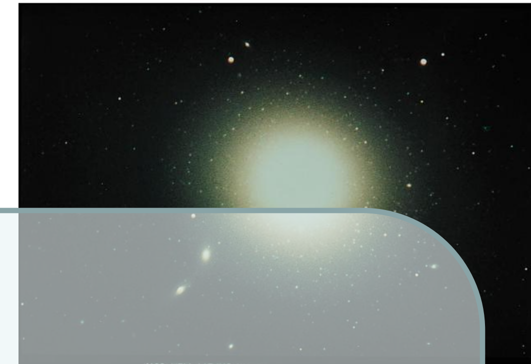
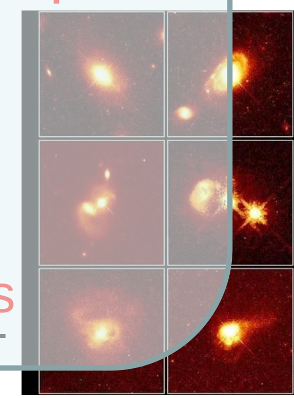
Active Galactic Nuclei (AGN)





Thermal Dominated

90 %

Spirals

Ellipticals

Radio loud

Radio quiet

Radio quiet quasars

Seyferts

Radio spectrum

Flat

Steep

Jets viewed

Head-on

Side

Steep Spectrum Radio Quasars

Emission lines

Broad and narrow

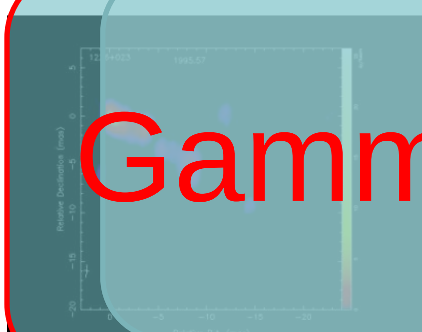
Narrow

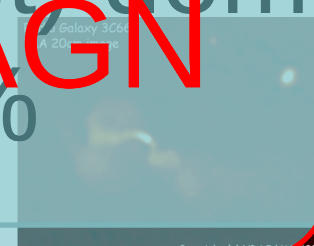
Seyfert 1

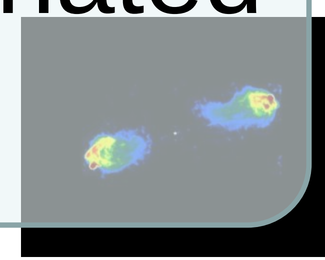
Seyfert 2

Radio galaxies

Blazars







Emission lines

Weak/absent

Strong

BL Lac Objects

Flat Spectrum Radio Quasars

FR I

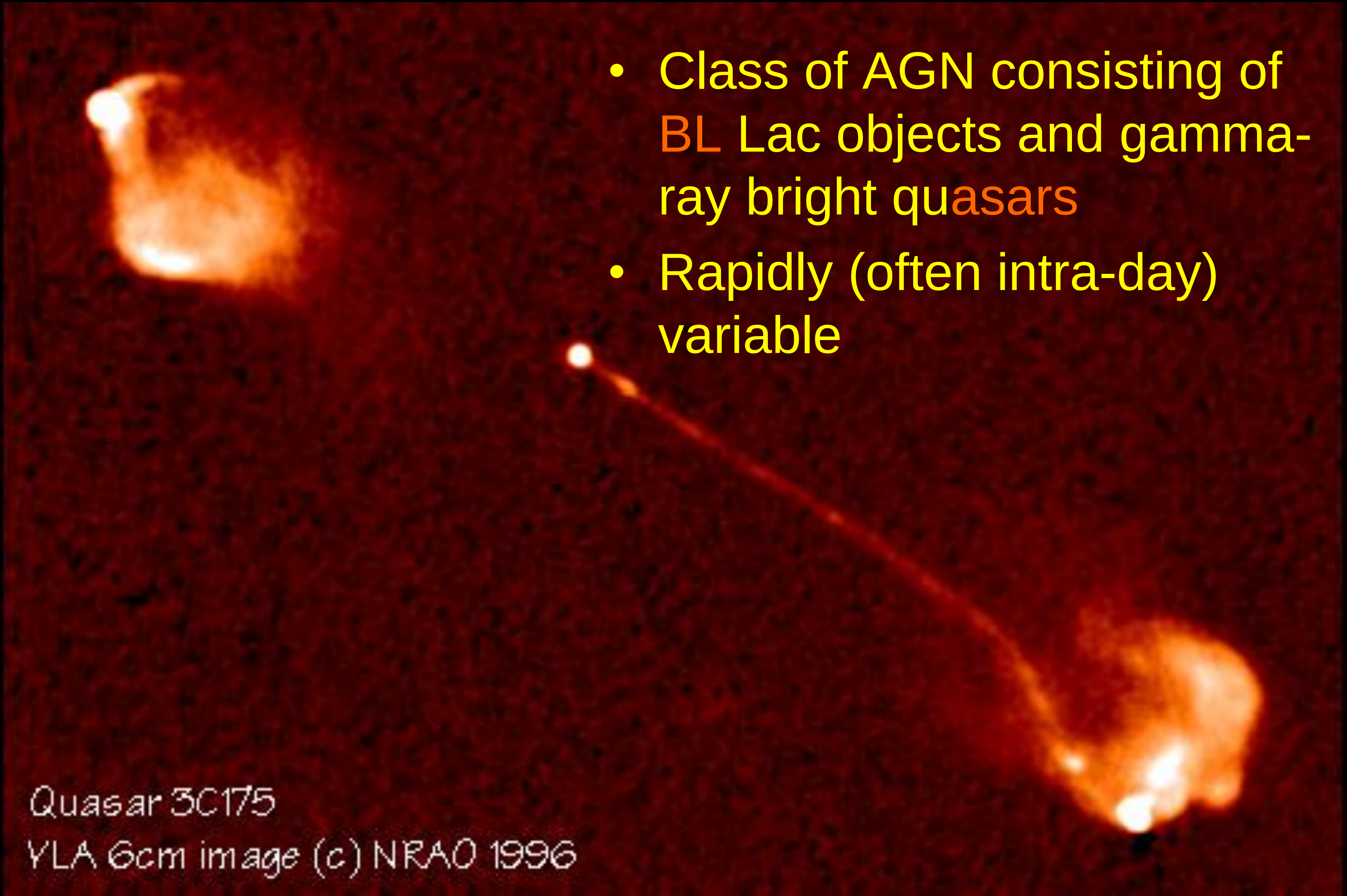
Non-Thermal (jet) dominated

10 %

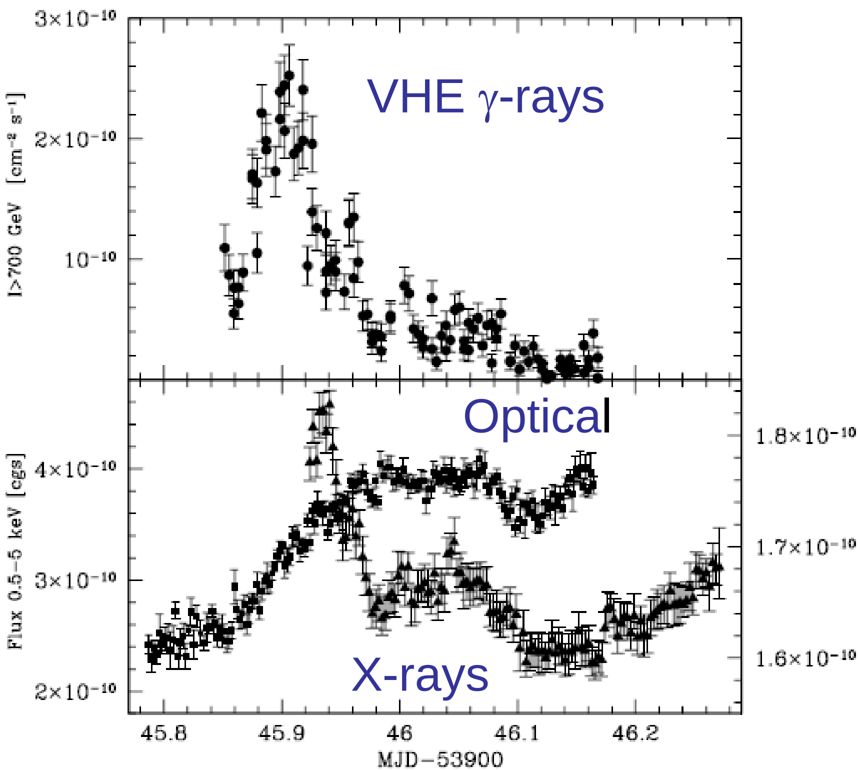
Gamma-Ray Loud AGN

Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable

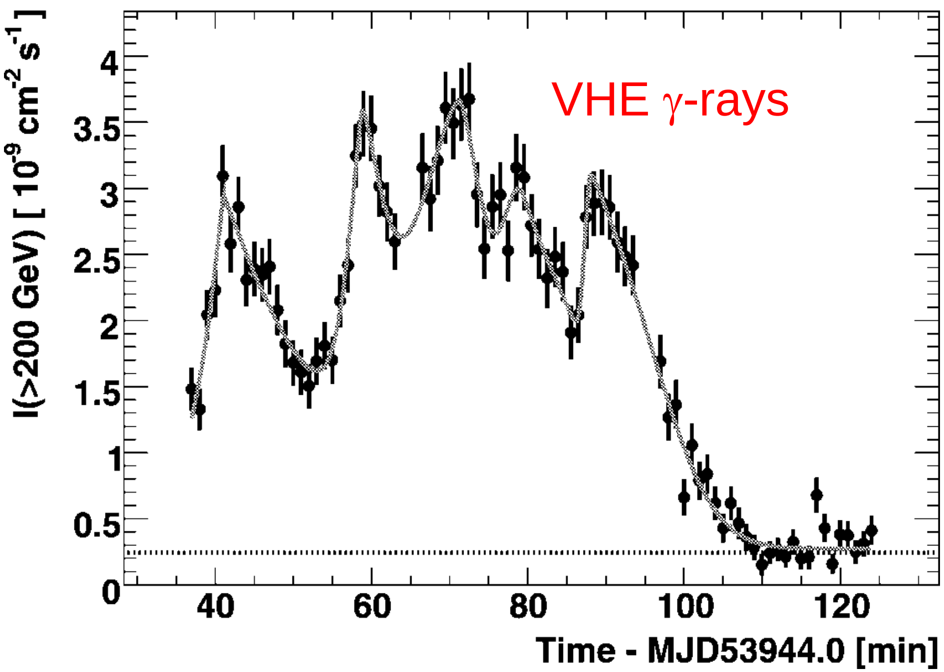


Blazar Variability:
Variability of PKS 2155-304



(Costamante et al. 2008)

VHE γ-ray and X-ray variability often closely correlated



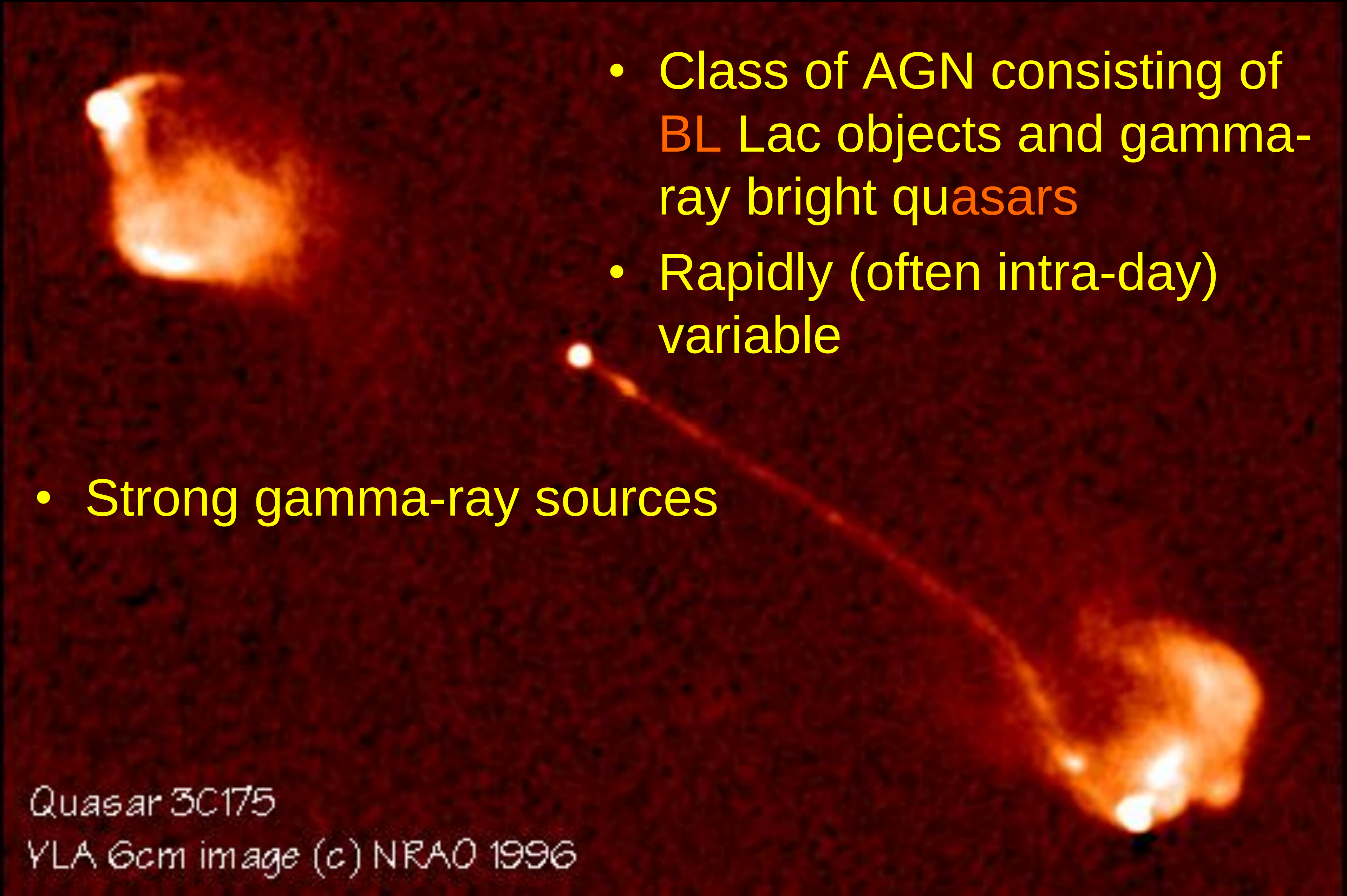
(Aharonian et al. 2007)

VHE γ-ray variability on time scales as short as a few minutes!

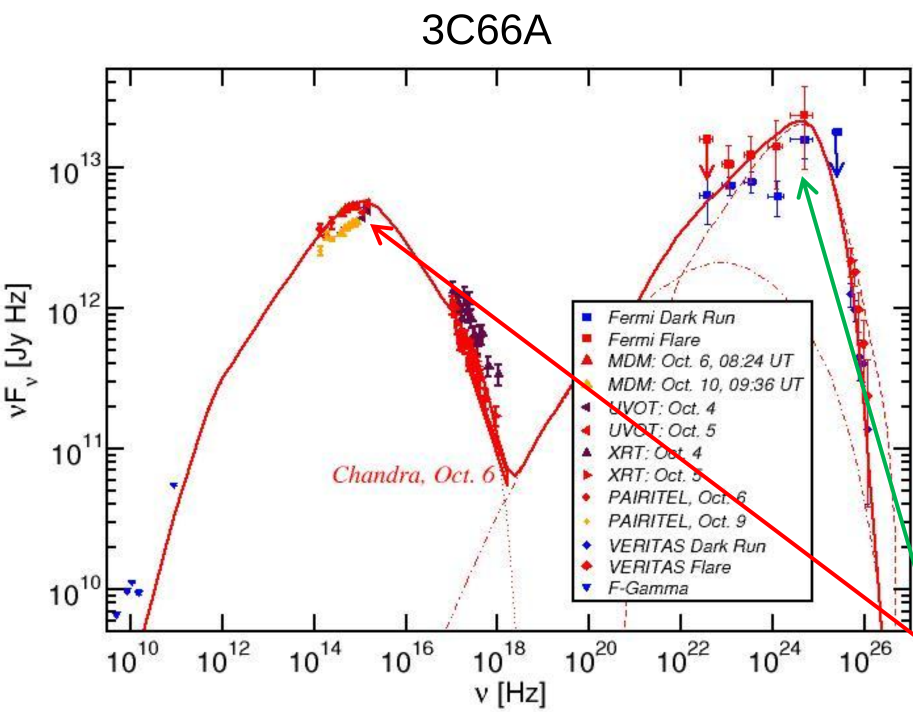
Blazars

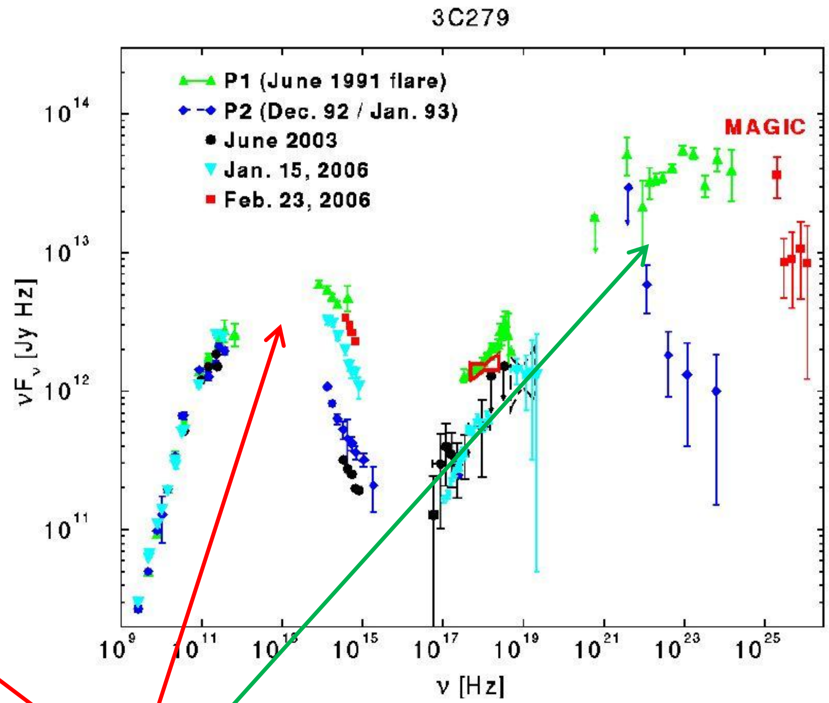
- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable

- Strong gamma-ray sources



Blazar Spectral Energy Distributions (SEDs)

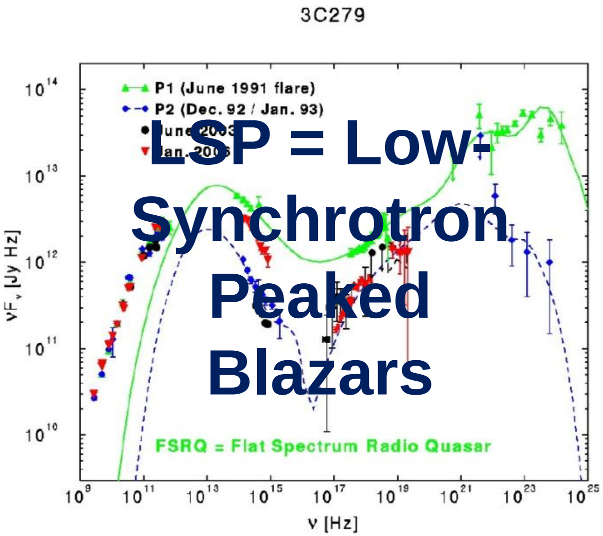




Non-thermal spectra with two broad bumps:

- Low-energy (probably synchrotron): radio-IR-optical(-UV-X-rays)
- High-energy (X-ray – γ-rays)

Blazar Classification



LSP = Low-Synchrotron Peaked Blazars

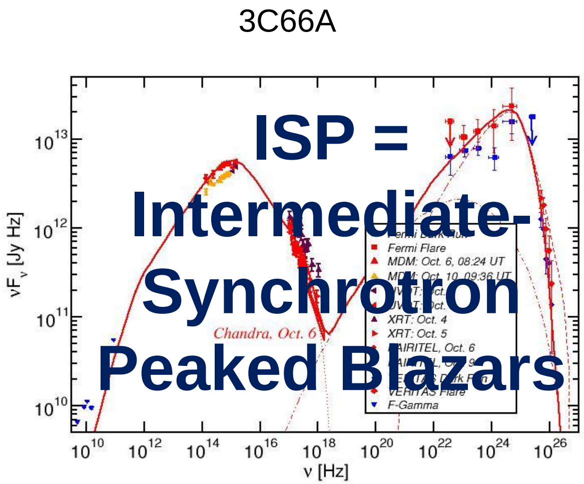
(Hartman et al. 2000)

Flat Spectrum Radio Quasars (FSRQs):

Low-frequency component from radio to optical/UV,

$\nu_{sy} \leq 10^{14}$ Hz

High-frequency component from X-rays to γ-rays, often dominating total power



ISP = Intermediate-Synchrotron Peaked Blazars

(Abdo et al. 2011)

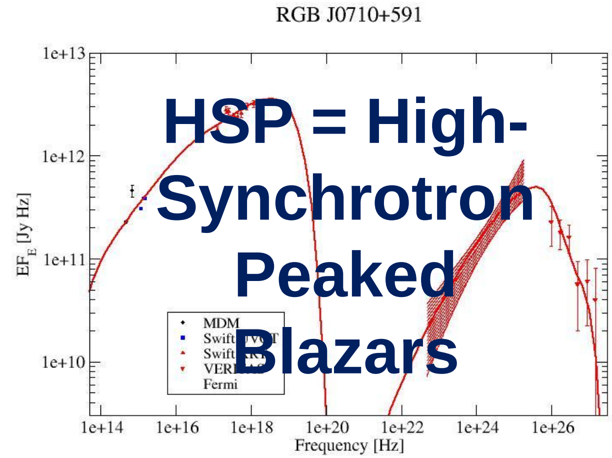
Low-frequency peaked / Intermediate BL Lacs (LBLs/IBLs):

Peak frequencies at IR/Optical and GeV gamma-rays,

10^{14} Hz $< \nu_{sy} \leq 10^{15}$ Hz

Intermediate overall luminosity

Sometimes γ-ray dominated



HSP = High-Synchrotron Peaked Blazars

(Acciari et al. 2009)

High-frequency peaked BL Lacs (HBLs):

Low-frequency component from radio to UV/X-rays,

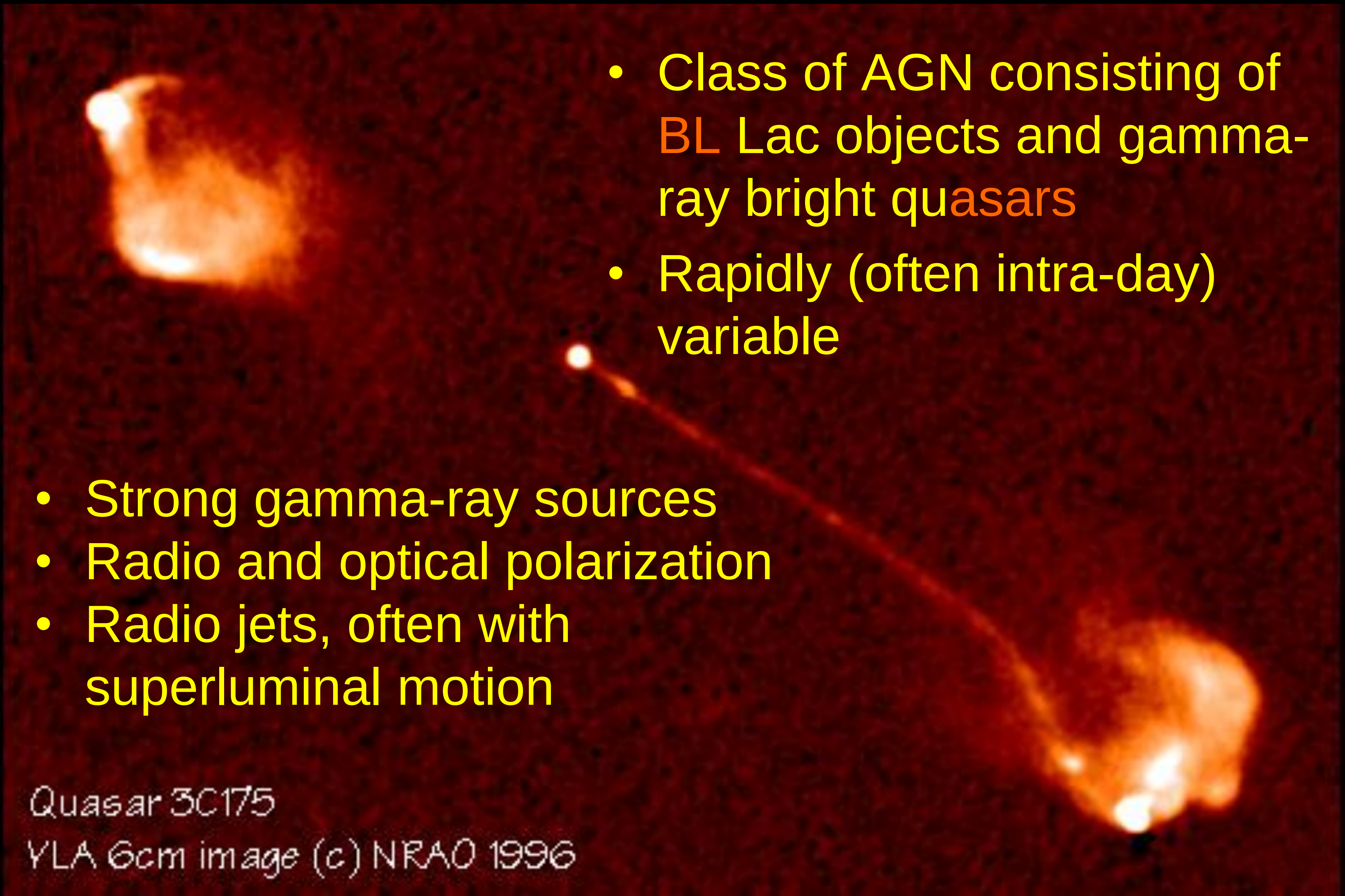
$\nu_{sy} > 10^{15}$ Hz

often dominating the total power

High-frequency component from hard X-rays to high-energy gamma-rays

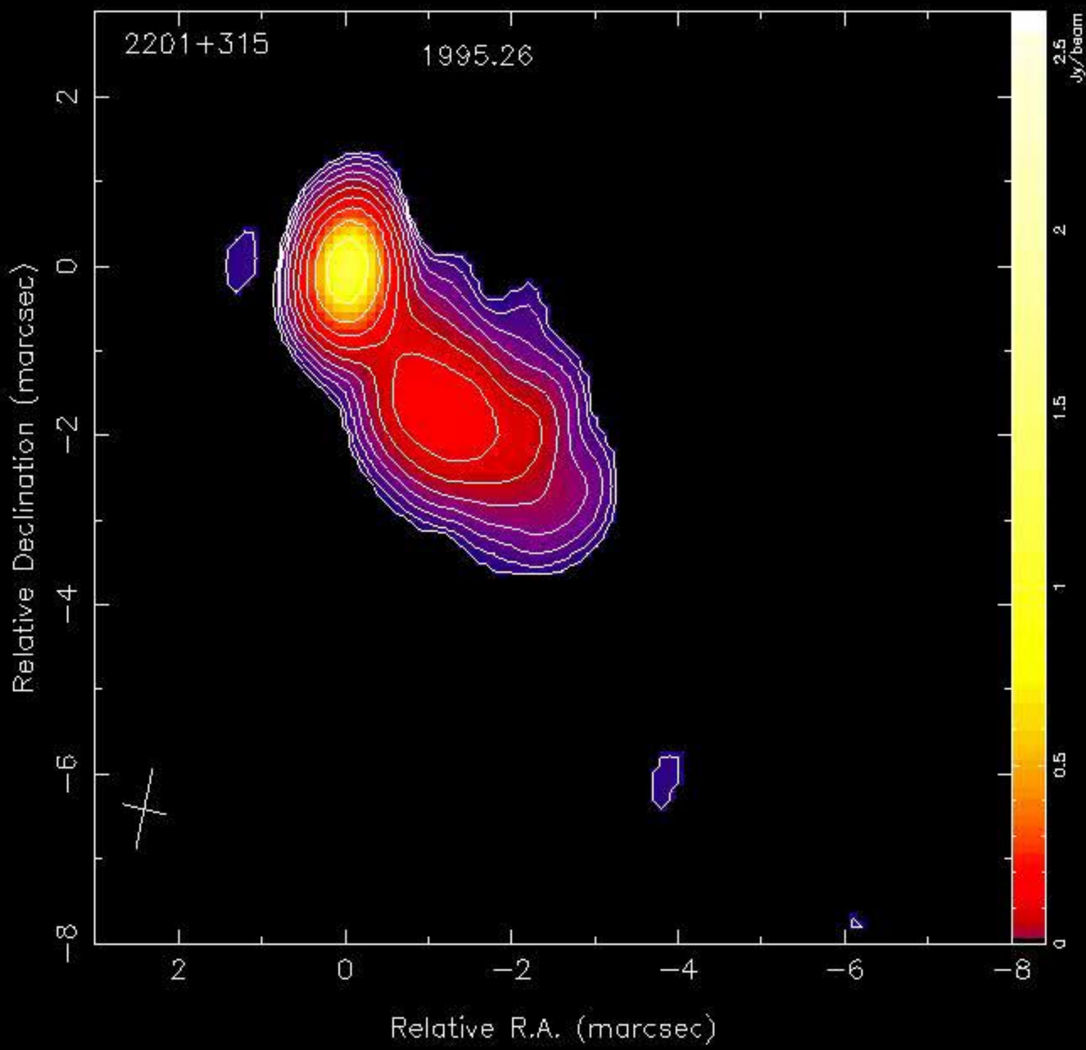
Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable



- Strong gamma-ray sources
- Radio and optical polarization
- Radio jets, often with superluminal motion

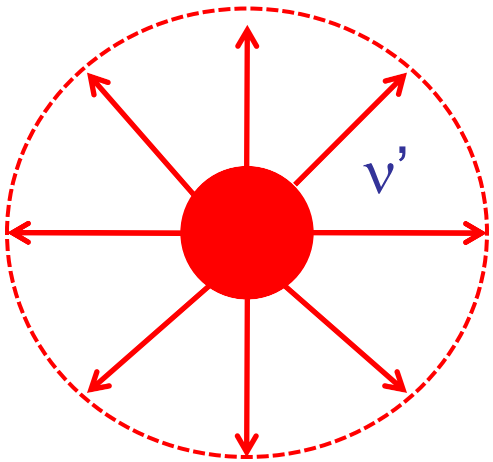
Faster than the speed of light?



(The MOJAVE Collaboration)

Relativistic Beaming / Boosting

In the co-moving frame of the emission region:



Isotropic emission $I'_{\nu'}$ at frequency ν’

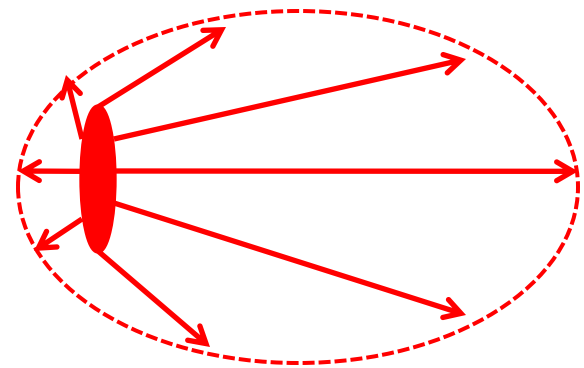
Time interval t'_{var}

$\Gamma = (1 - \beta_\Gamma^2)^{-1/2}$

In the stationary (observer’s) frame:

$\delta = (\Gamma[1 - \beta_\Gamma \cos\theta])^{-1}$:

Doppler boosting factor



Beamed emission:

$I_\nu = \delta^3 I'_{\nu'}$ $\nu = \delta \nu'$

For power-law $F_\nu \sim \nu^{-\alpha}$:

$F_\nu = \delta^{(3+\alpha)} F'_\nu$

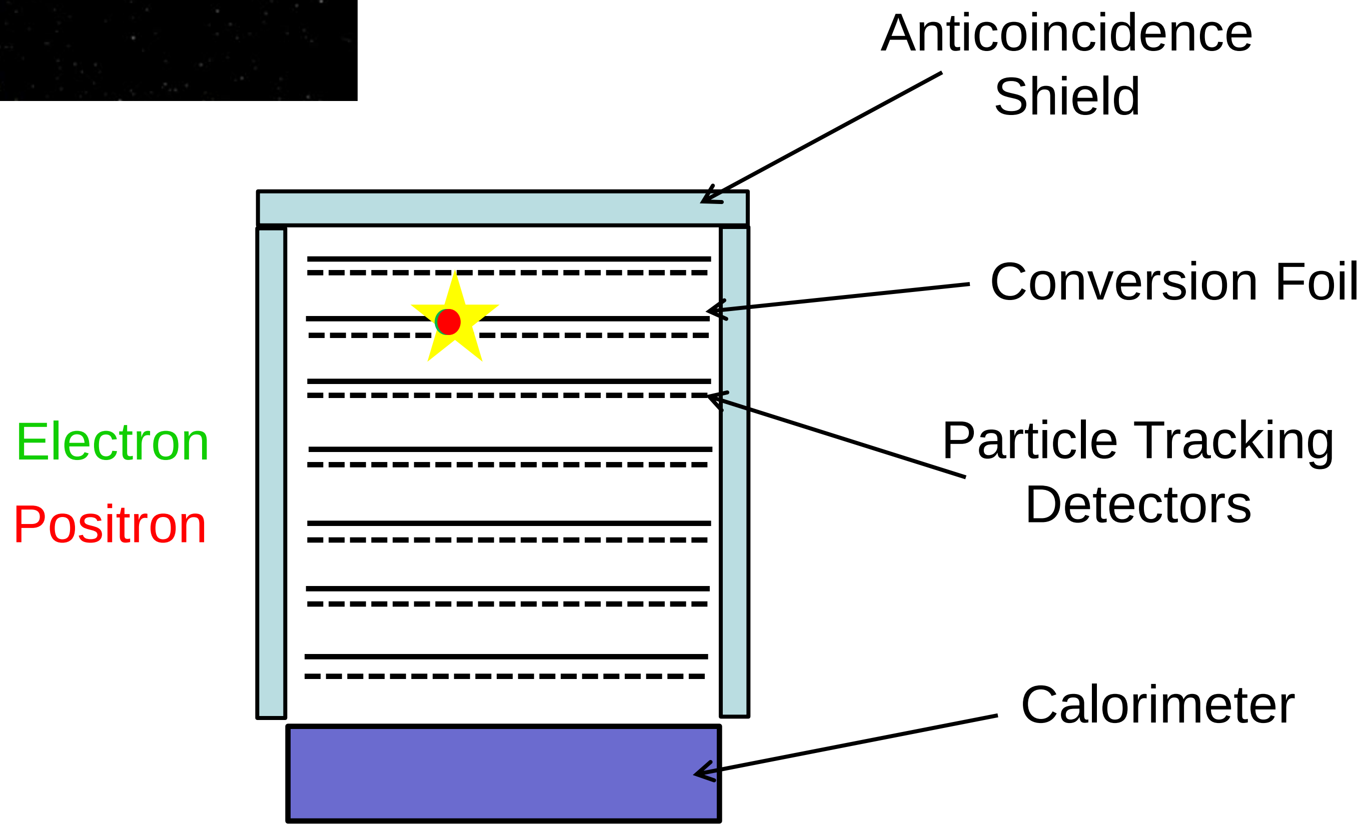
Time interval

$t_{var} = t'_{var} / \delta$

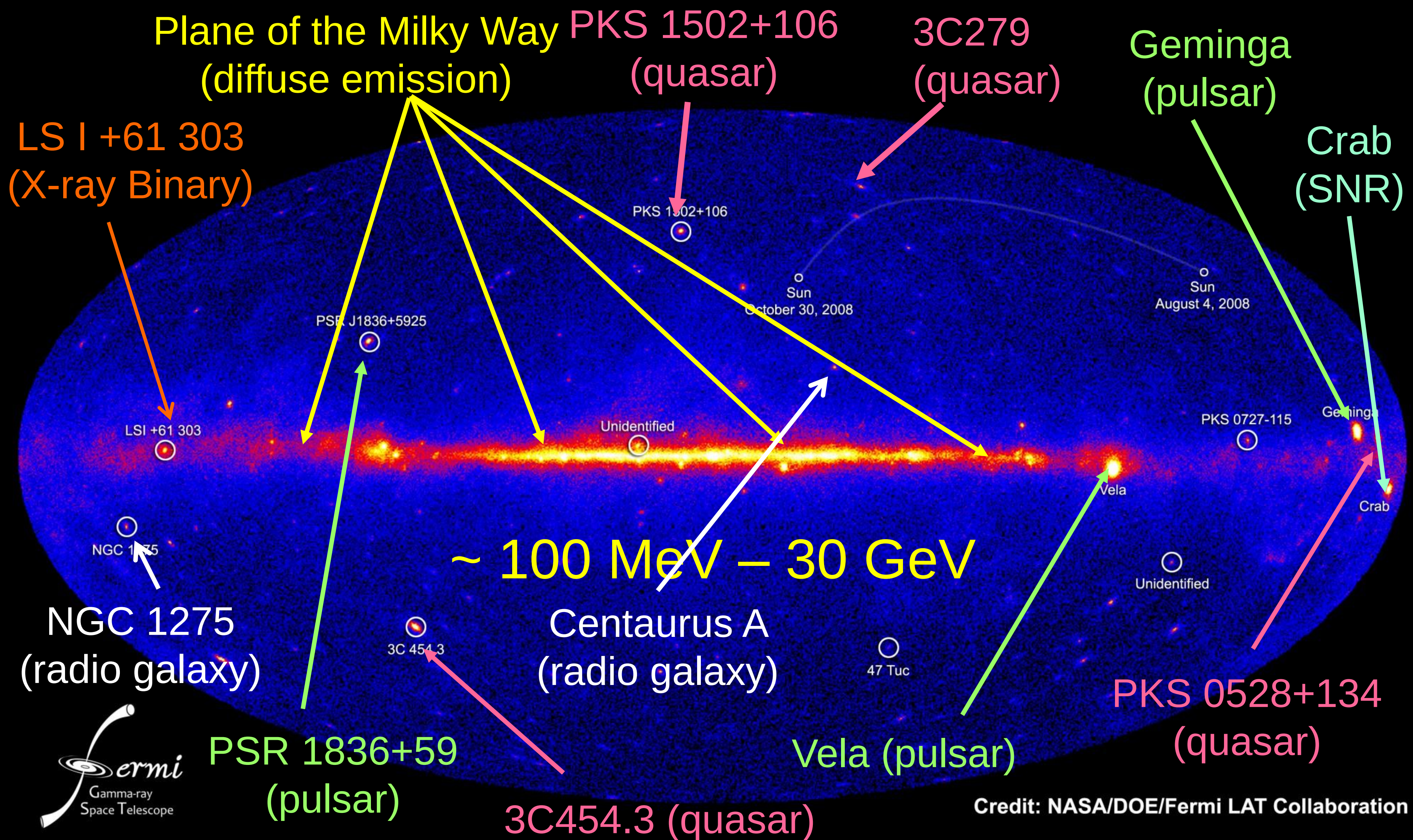
Detecting Gamma-Rays with Fermi

Fermi Gamma-Ray Space Telescope:
Launched June 11, 2008

- High-Energy γ-Ray
  (30 MeV – 100 GeV)



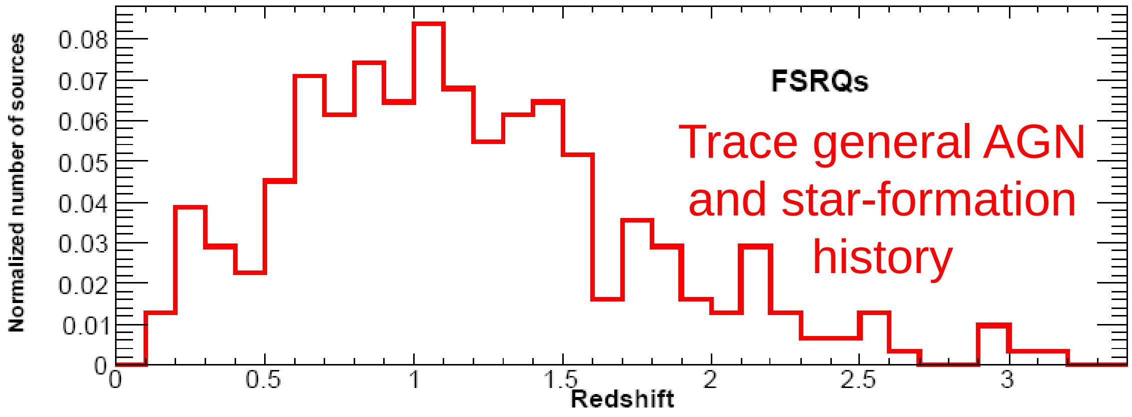
The Fermi Gamma-Ray Sky

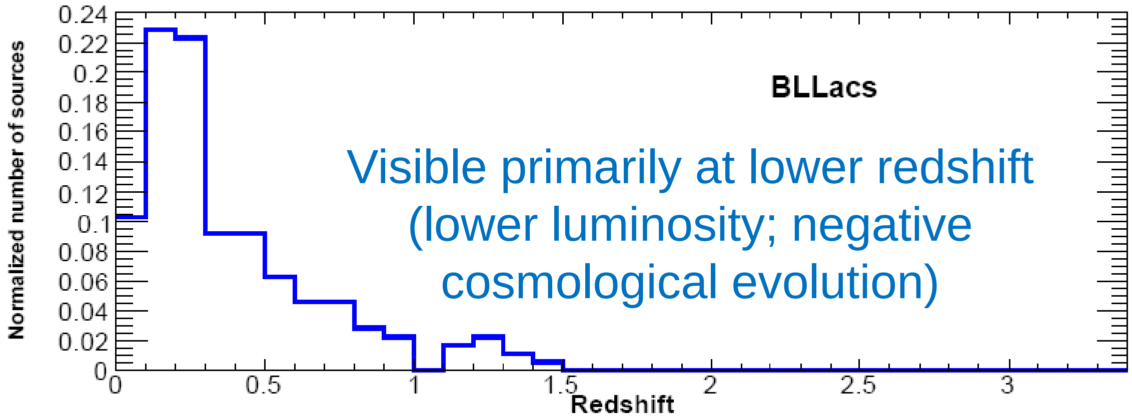


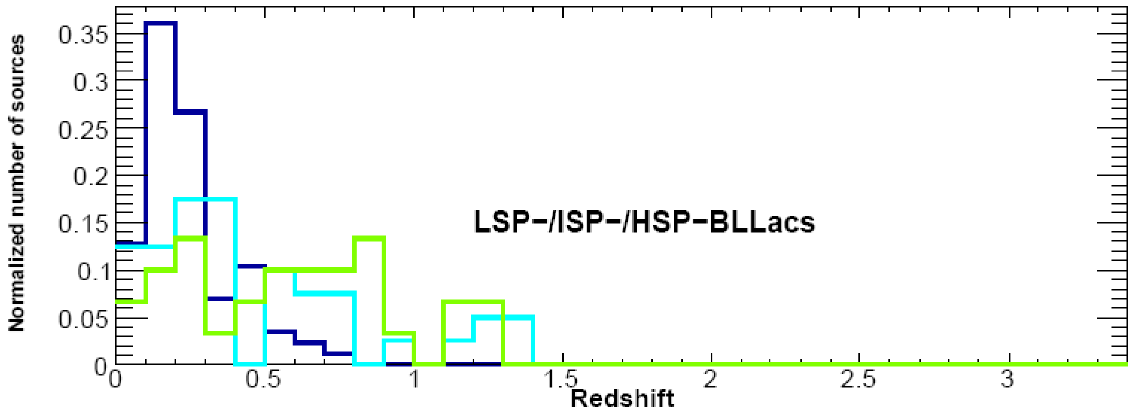
Redshifts of Fermi Blazars

Gamma-Ray Blazars (FSRQs) easily visible out to redshift of ~ 3.

(2nd LAT AGN Catalog: Ackermann et al. 2011)

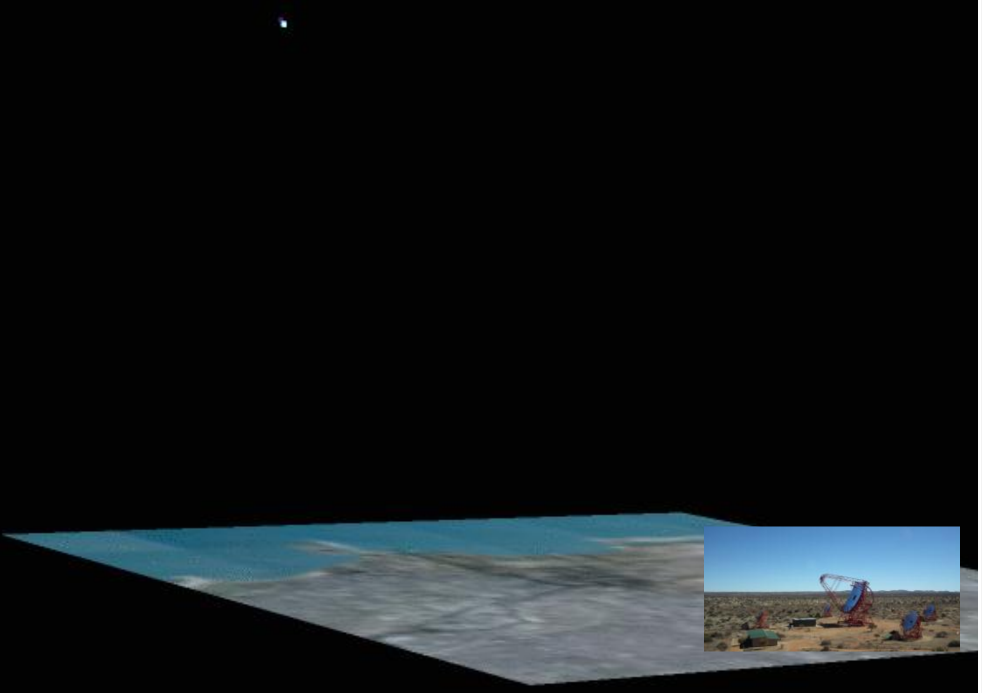


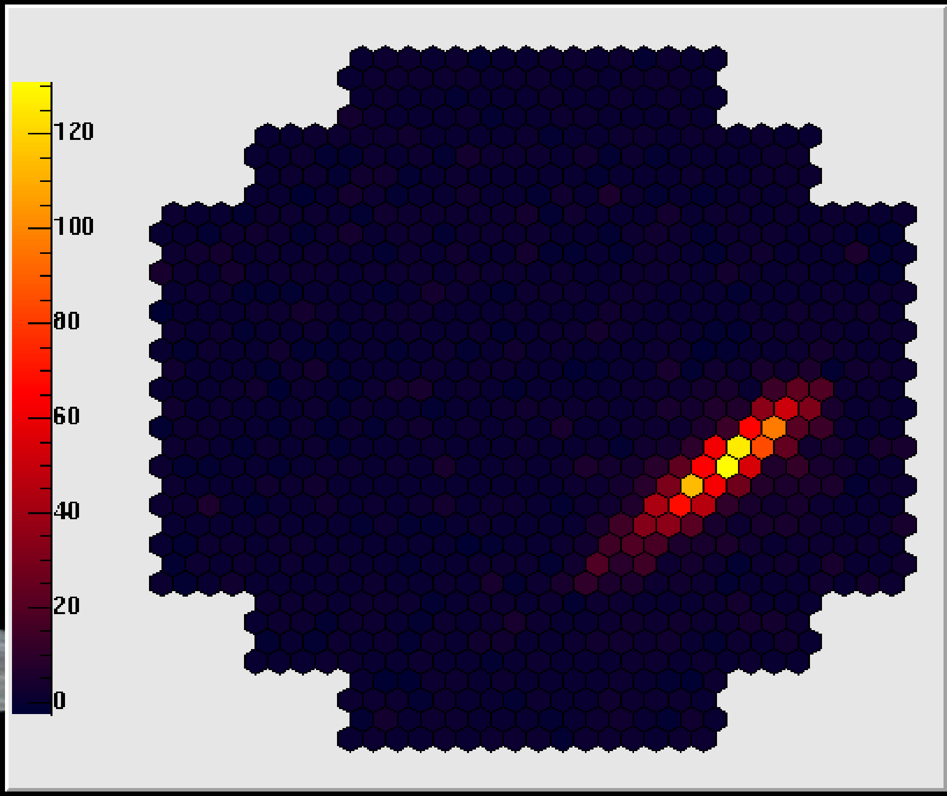




Detecting Very-High-Energy (> 100 GeV) Gamma-Rays with Cherenkov Telescopes

Cherenkov light from secondary particles (muons, electrons, positrons) in air showers initiated by very-high-energy gamma-rays in the atmosphere.

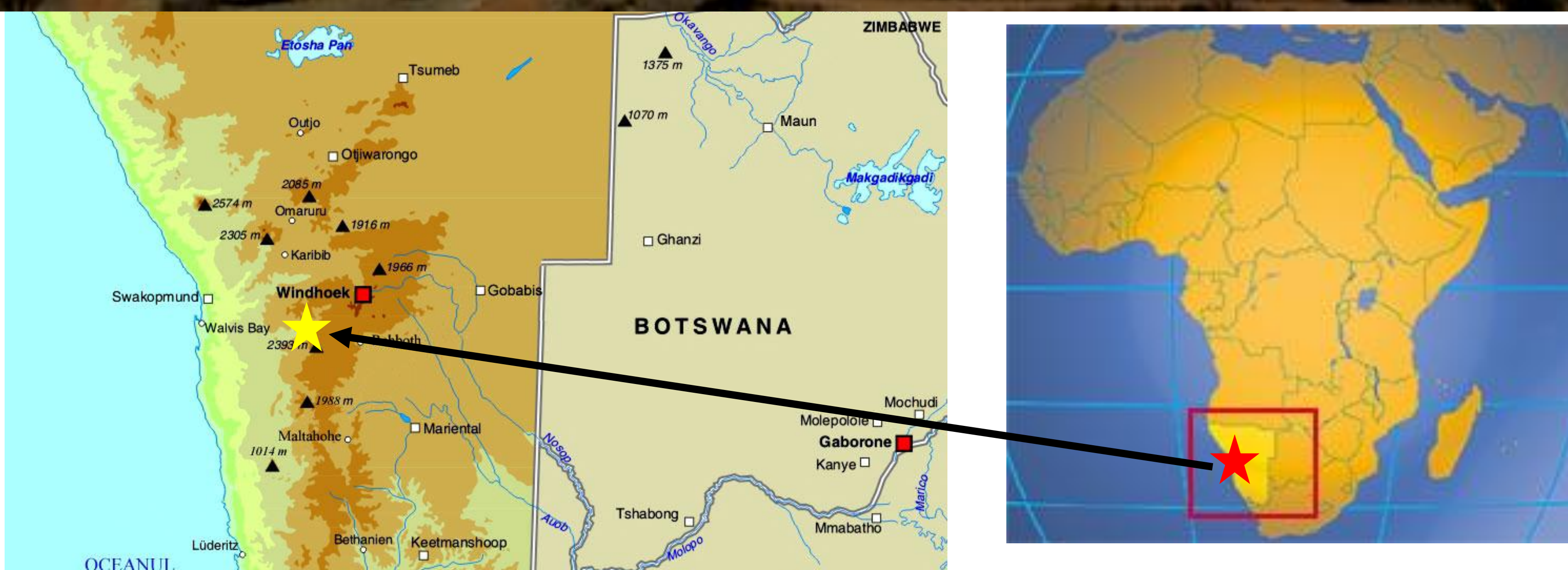




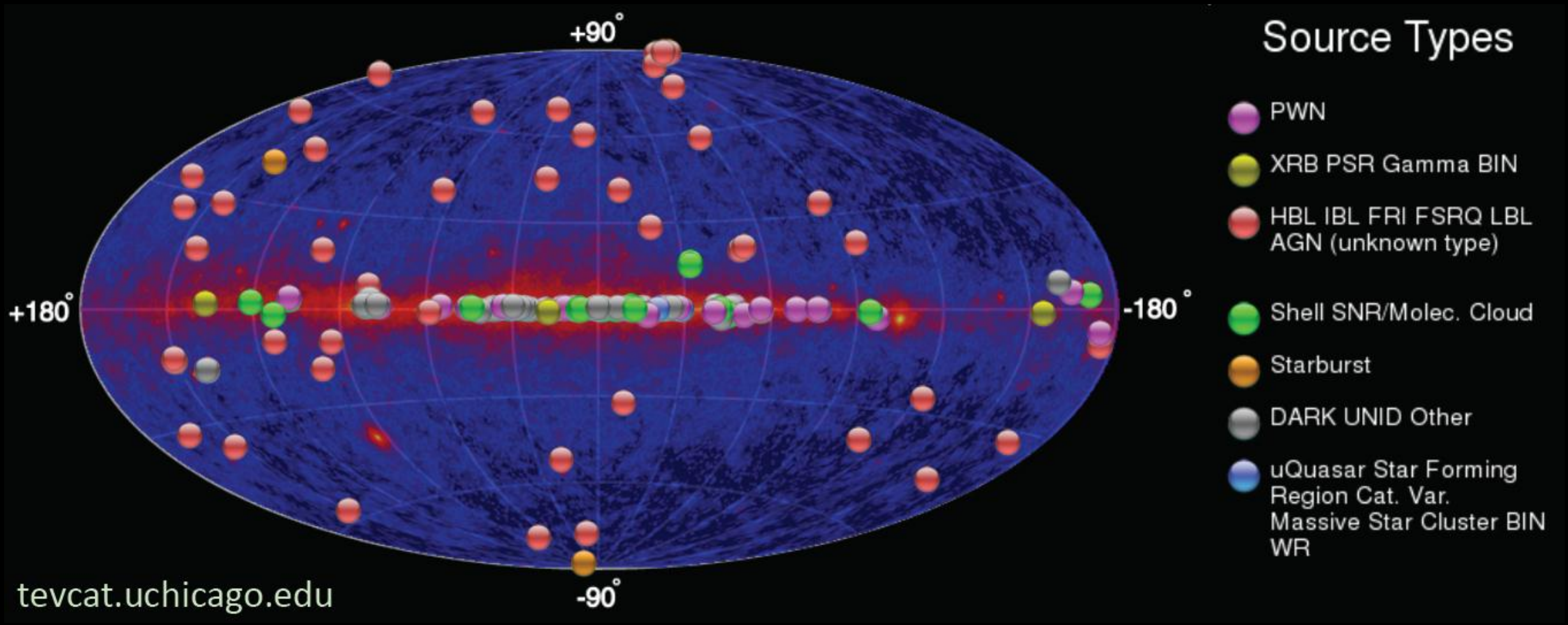
H.E.S.S.

High Energy Stereoscopic System

Khomas Highlands, near Windhoek, Namibia

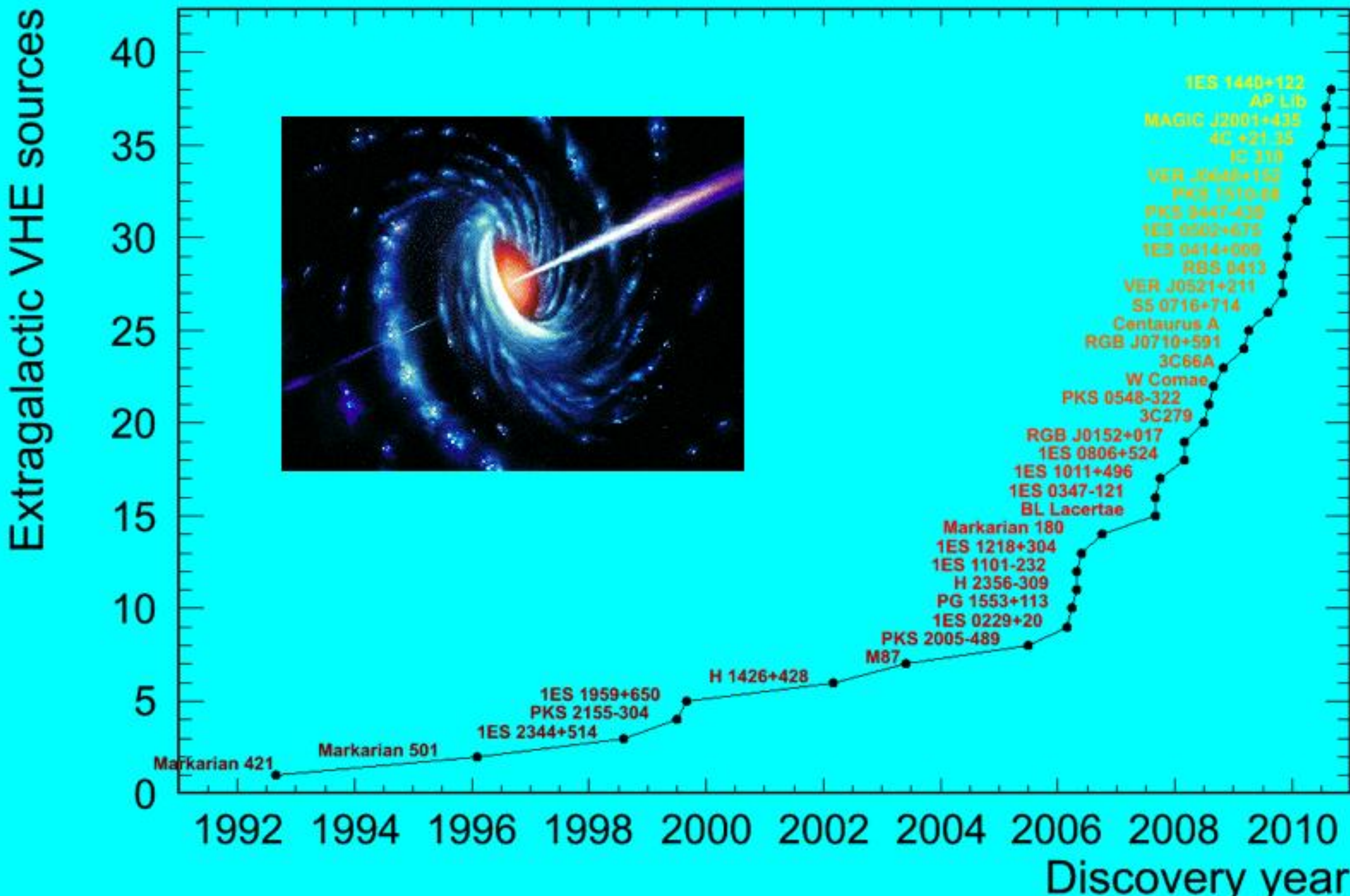


The VHE Gamma-Ray Sky



- Over 140 VHE γ-ray sources
- Most extragalactic VHE sources are blazars

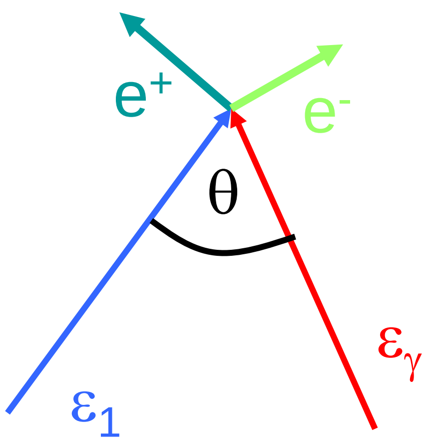
Progress of VHE Astronomy



Gamma-Gamma Absorpton / Pair production

The inverse process of pair annihilation can absorb γ-rays with energies E > 511 keV.

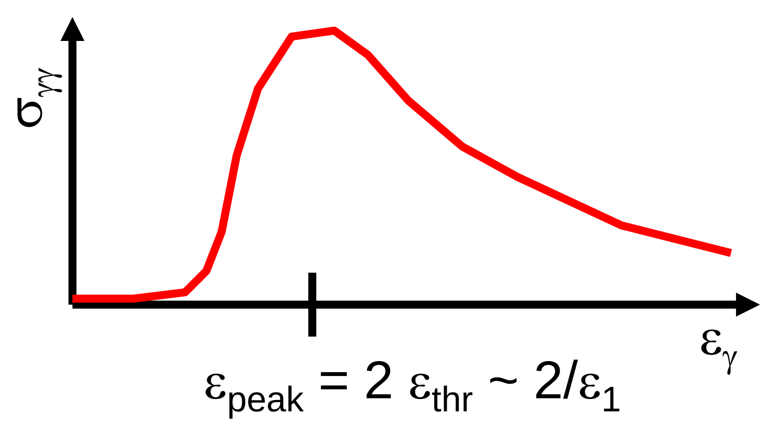
Threshold energy E_{thr} for a γ-ray interacting with a background photon field of photons with characteristic photon energy E_1:



$$\varepsilon_{thr} \sim 1/\varepsilon_1$$

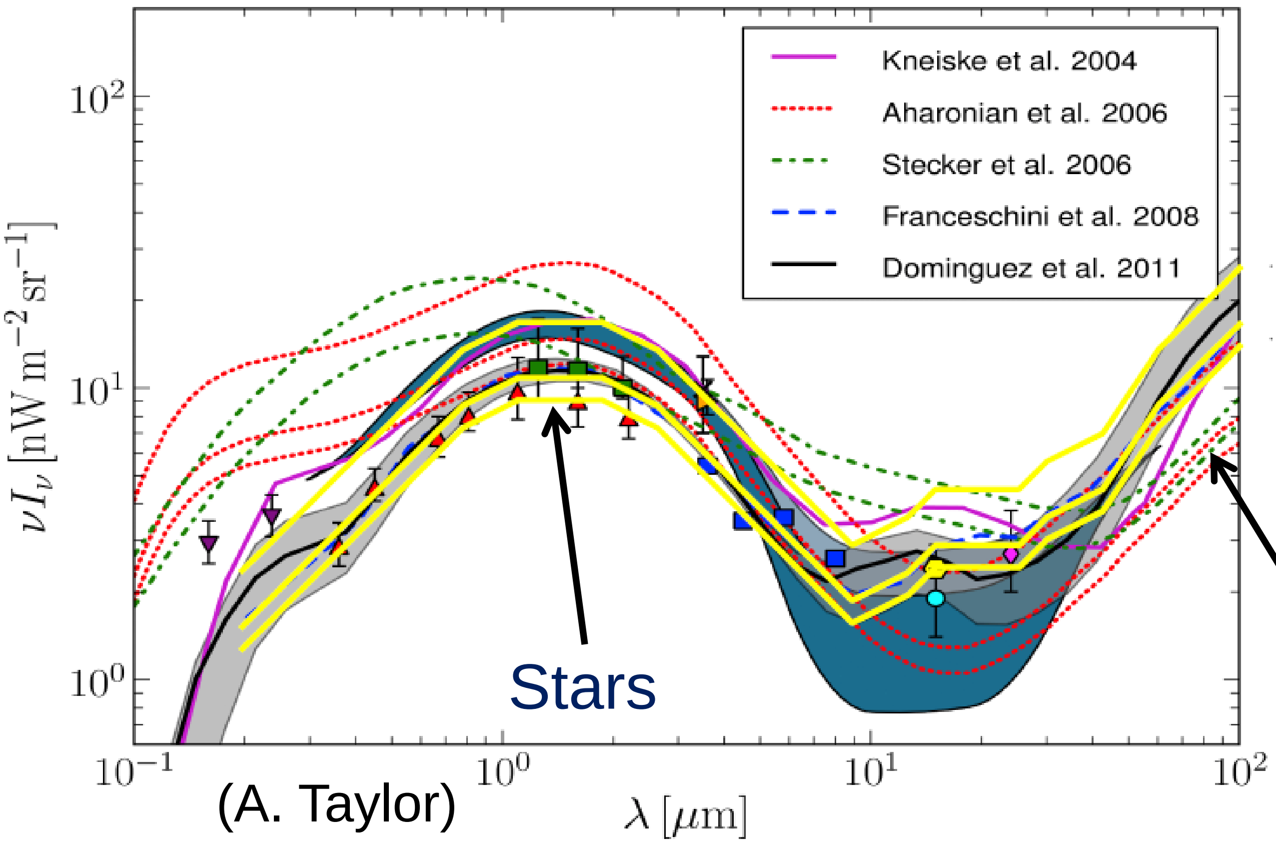
$\varepsilon = E_{ph}/(m_e c^2)$

100 GeV – TeV photons are absorbed in intergalactic space by interacting with the Extragalactic Background Light (EBL)!



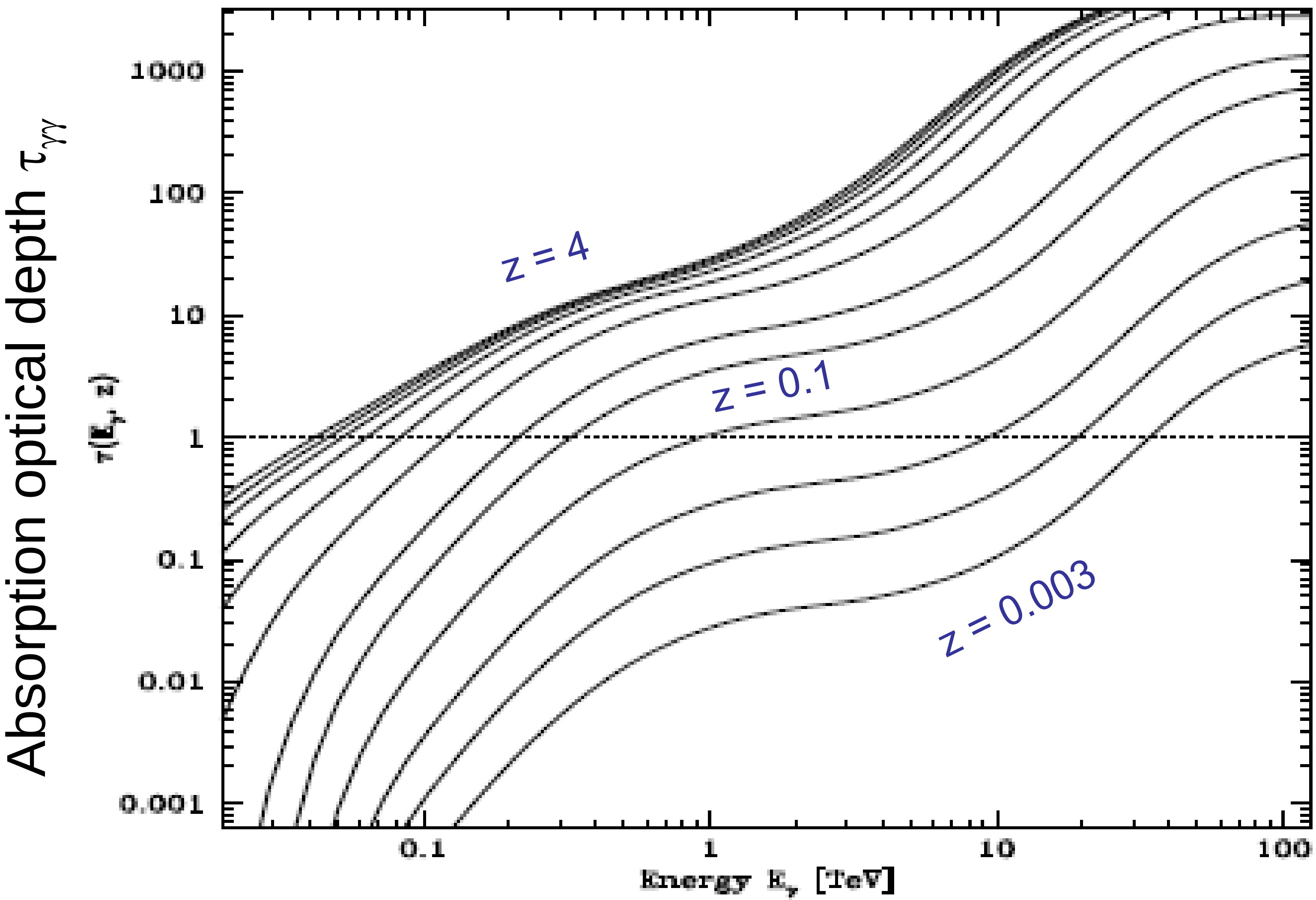
The Extragalactic Background Light (EBL)

- Carries the imprint of the star formation history of the Universe.
- Notoriously difficult to measure because of Galactic and solar-system foregrounds.
- Direct galaxy counts set lower limits; galaxy formation/evolution models needed to develop realistic estimates.
- Reasonably well known at low z, but very uncertain at high z.



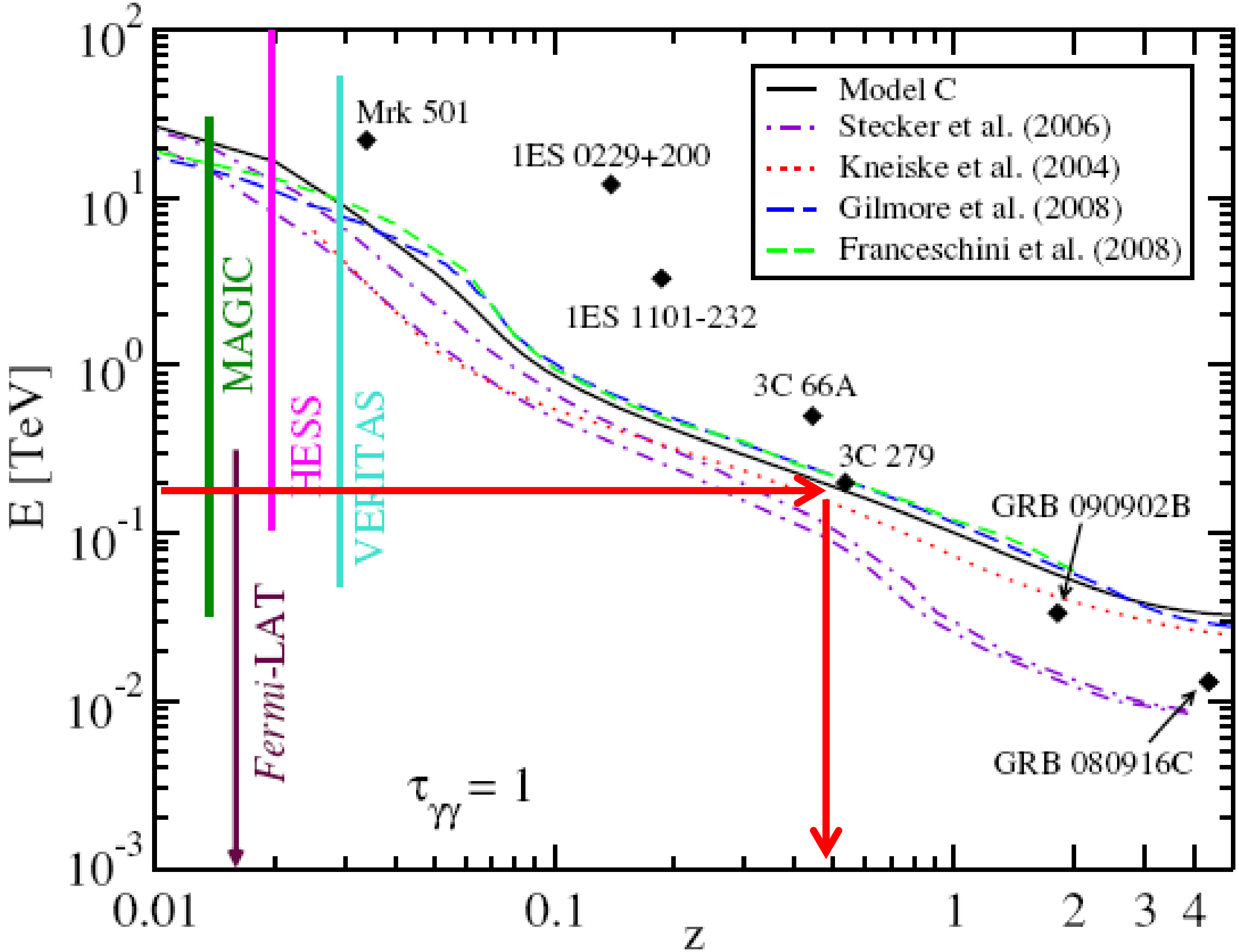
(A. Taylor)

Gamma-Gamma Absorption by the EBL



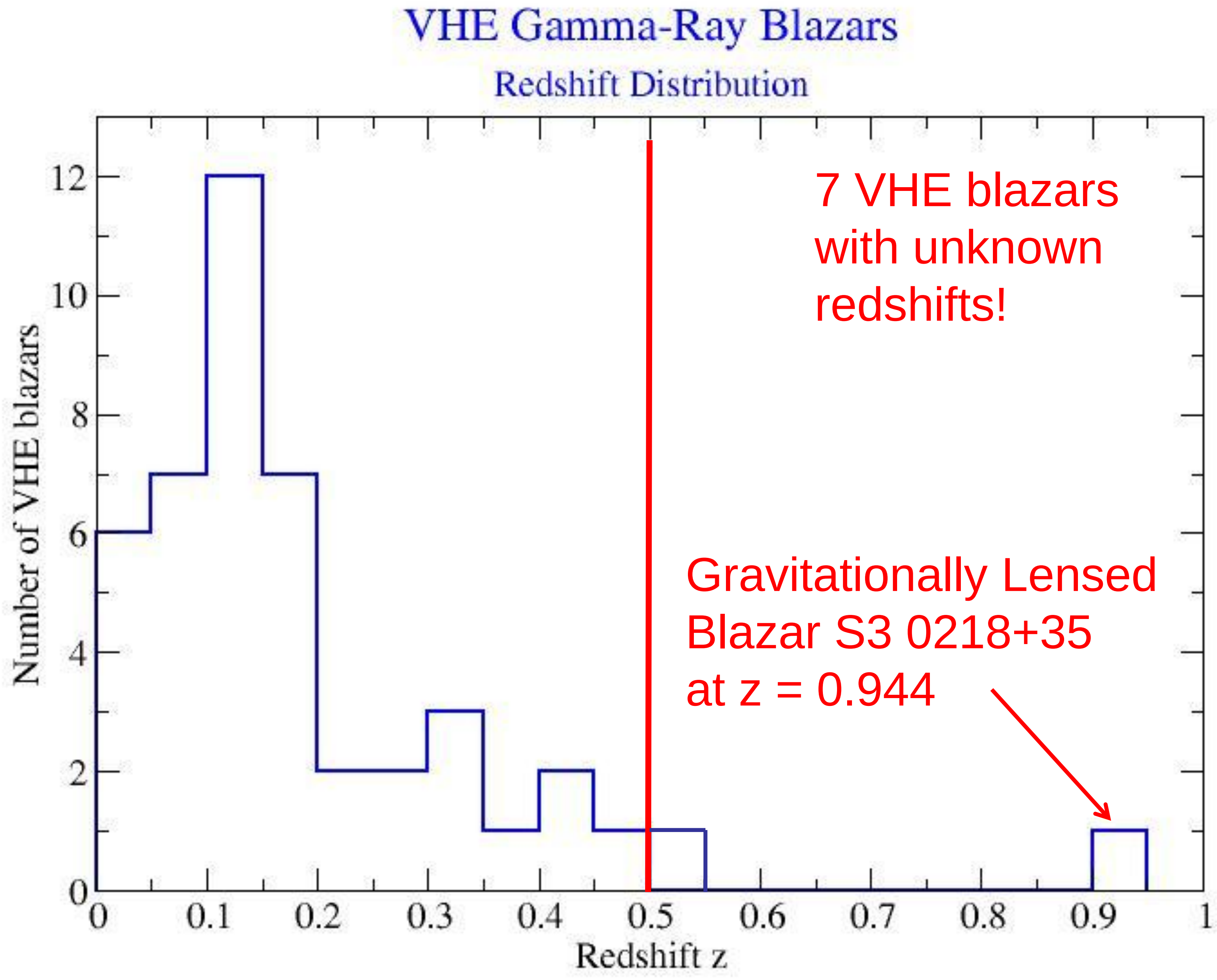
Franceschini et al. (2008)

The VHE Gamma-Ray Horizon



(Finke et al. 2010)

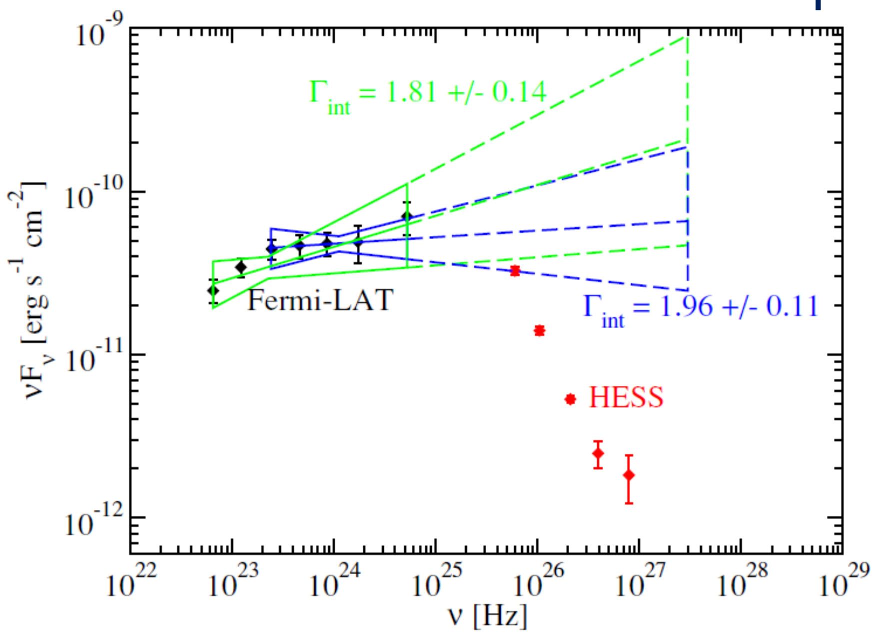
=> Don't expect any VHE blazars at z > 0.5



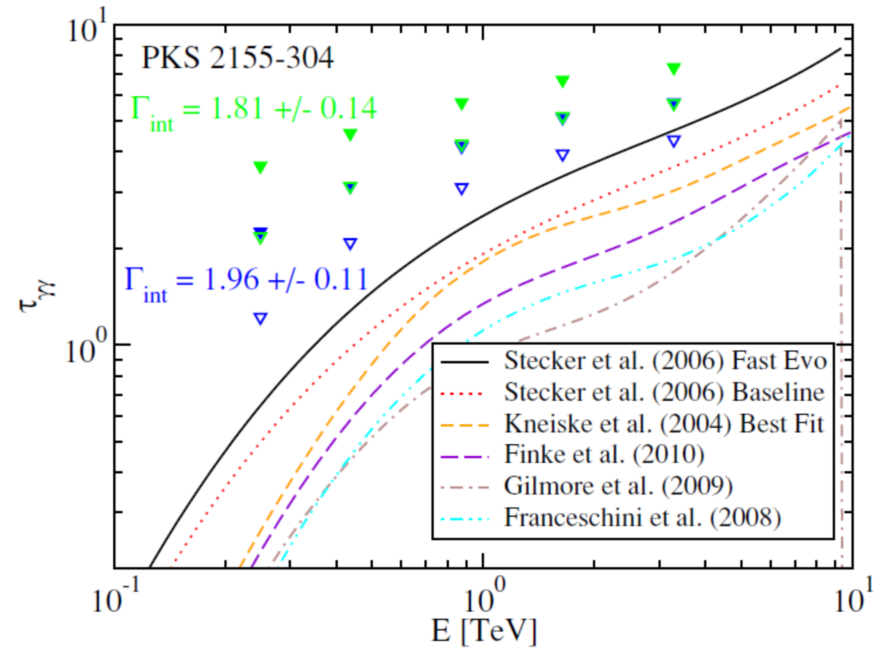
VHE Gamma-Ray Blazars
Redshift Distribution
Number of VHE blazars
Redshift z
0
2
4
6
8
10
12
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
7 VHE blazars
with unknown
redshifts!
Gravitationally Lensed
Blazar S3 0218+35
at z = 0.944

Redshift Lower Limits from EBL Absorption

- Assumption: intrinsic VHE spectrum is not harder than extrapolation from GeV (Fermi)
- Apply EBL correction to Fermi extrapolation to match the observed VHE spectrum -> UL on z



(Georganopoulos et al. 2010)



More precise methods take into account curvature of intrinsic spectrum (e.g. from detailed SED modeling)

Example:

PKS 1424+240 (z = ???)

First TeV blazar detection prompted by Fermi: IBL with hard GeV γ-ray spectrum (α_{phot} = 1.73)

-> Multiwavelength Observing Campaign in 2009

Biggest problem for theory interpretation: Unknown z:

SIMBAD: **z = 0.16** (but no reference)

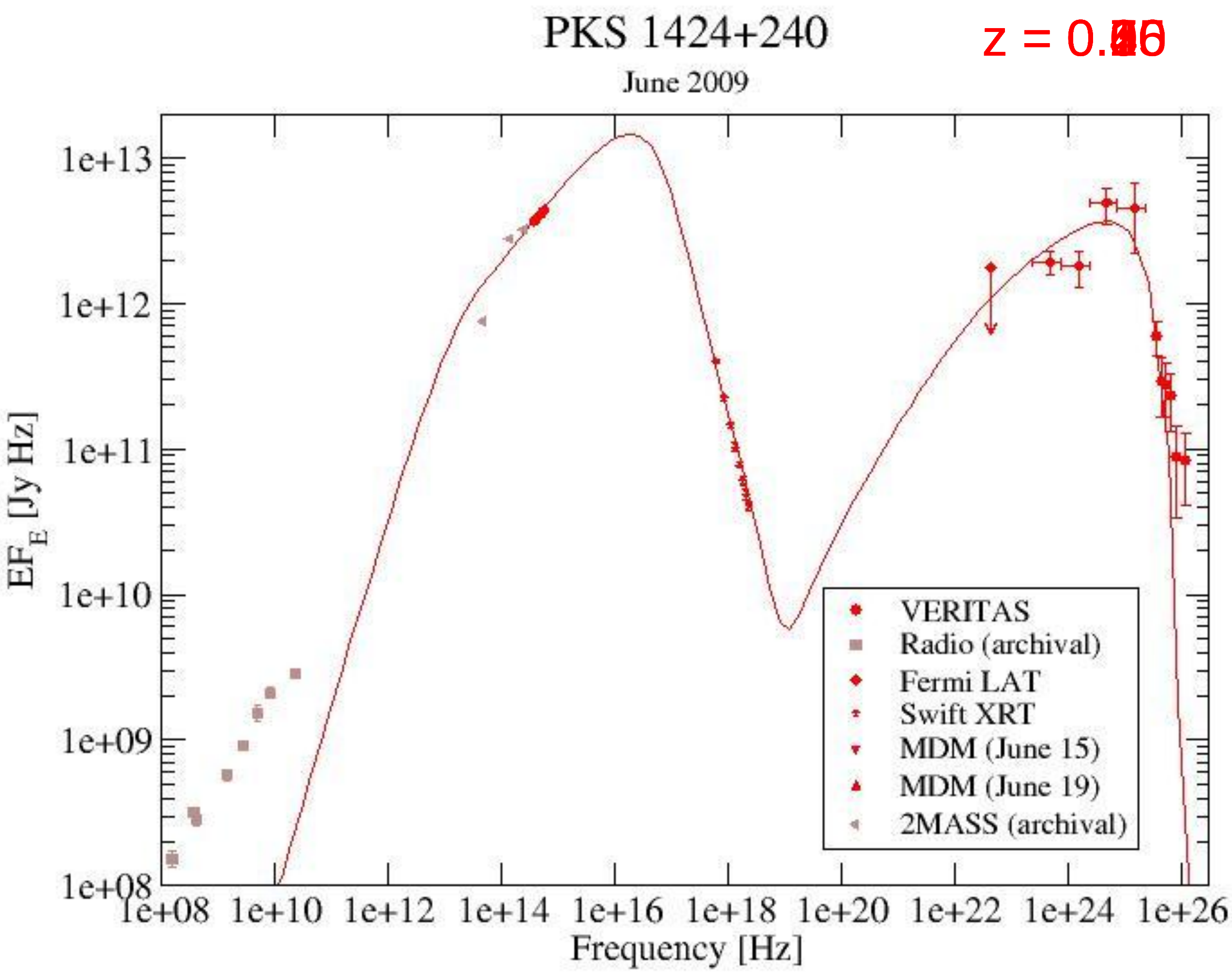
Sbarufatti et al. (2005): Limit from non-detection of host galaxy: **z > 0.67**

Extrapolated Fermi spectrum + EBL absorption: **z <~ 0.6**

PKS 1424+240

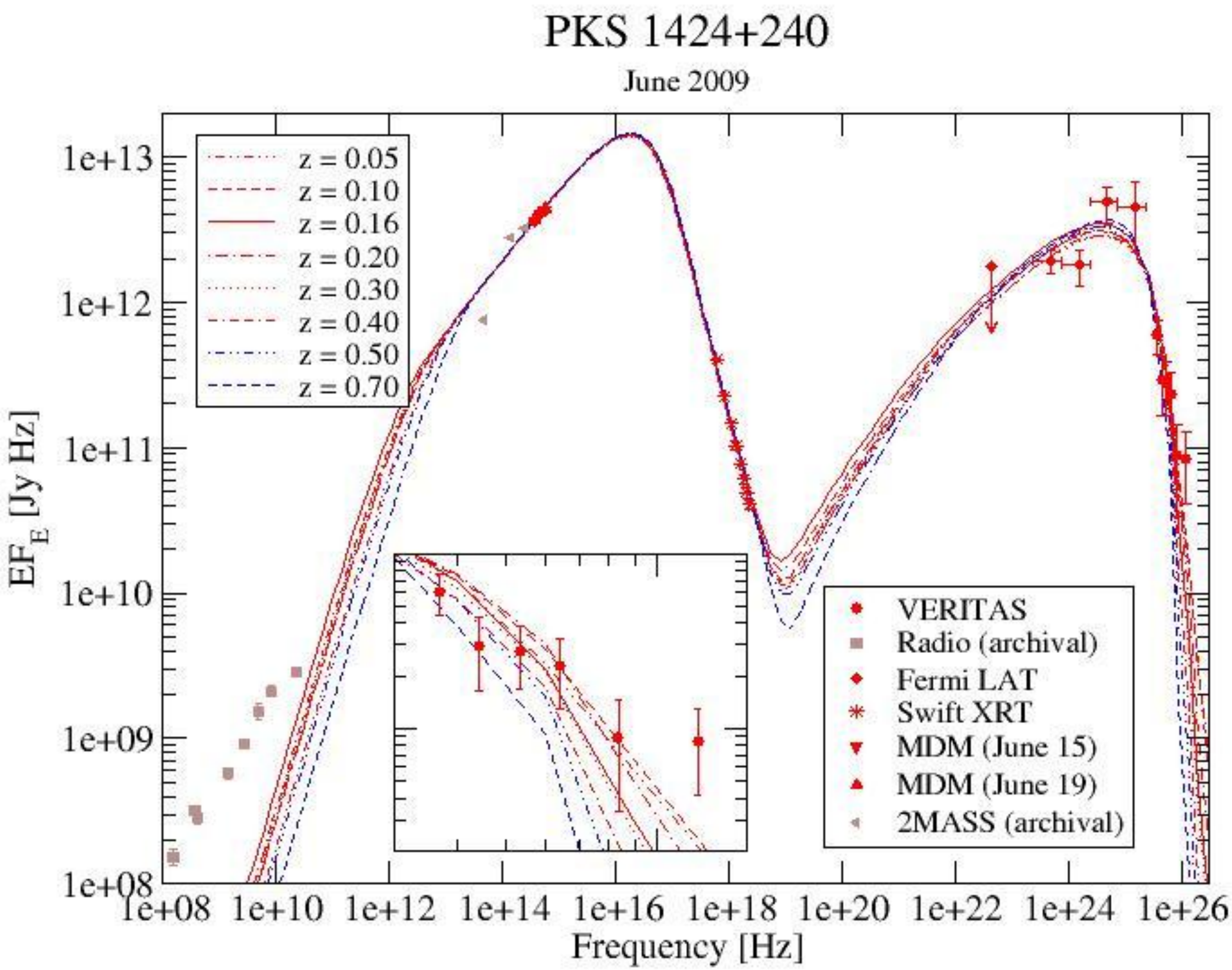
Model fits with pure SSC models for a variety of redshifts

z = 0.[illegible]



(Acciari et al. 2010)

PKS 1424+240



(Acciari et al. 2010)

- Pure SSC models provide a reasonable fit; no EC component required.
- For larger redshift, increasing discrepancy with VHE γ-ray spectral index

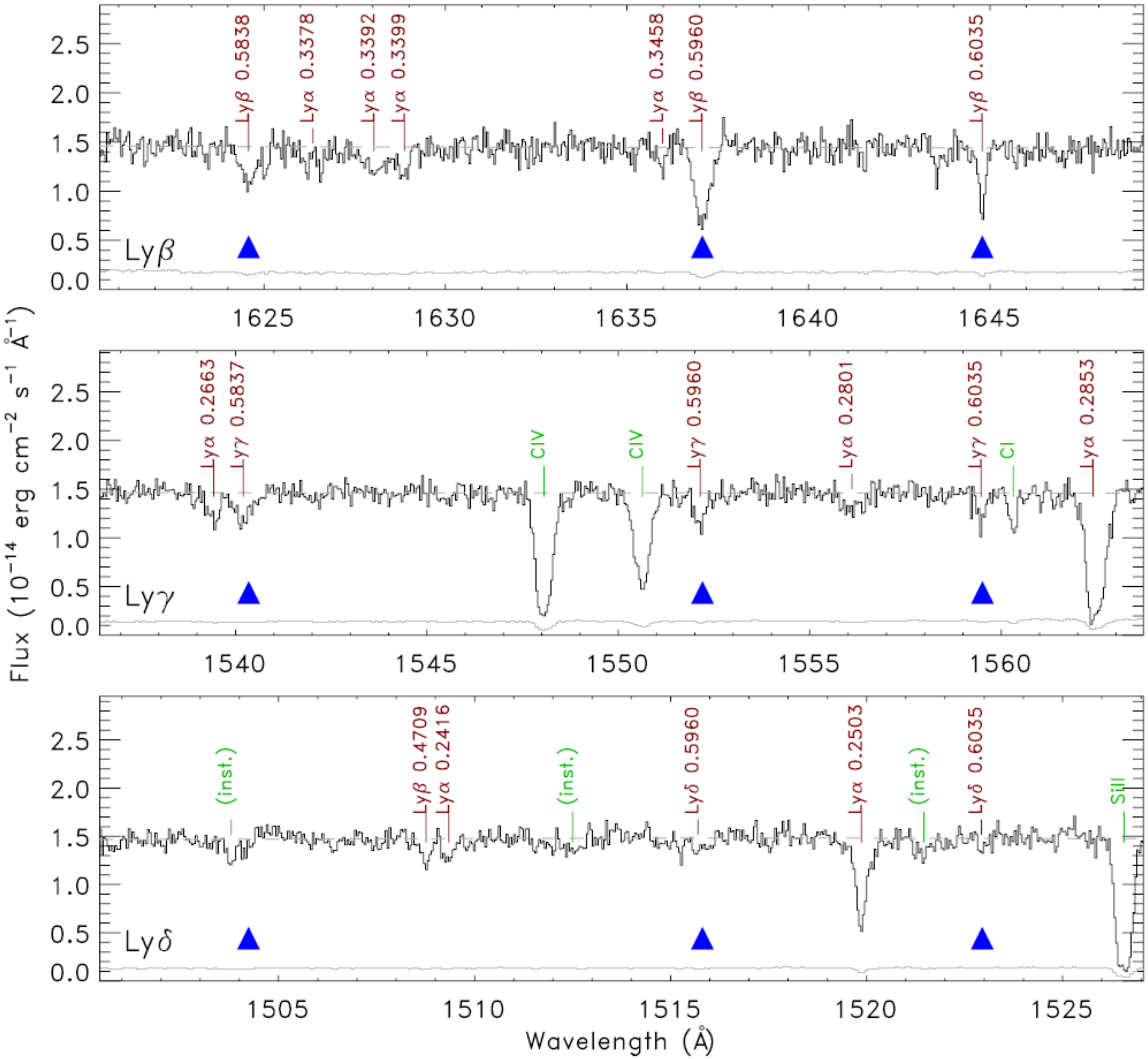
→ z <~ 0.3

... or maybe not ...

PKS 1424+240
(z < 0.3)

Firm lower limit on z from UV absorption-line systems:

z > 0.6035



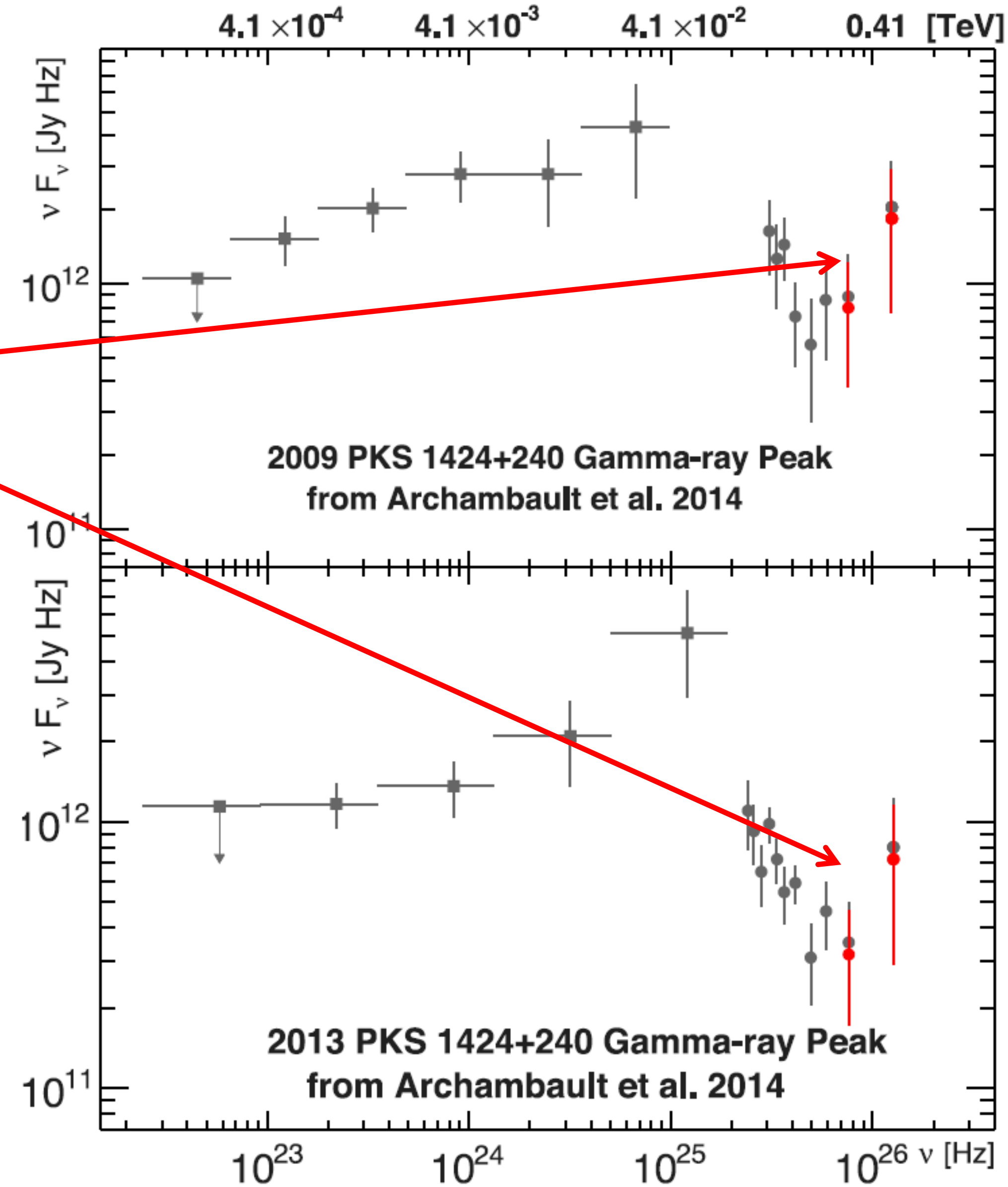
Furniss et al. (2013)

Problems with EBL Absorption

PKS 1424+240
(z ≥ 0.6)

EBL de-absorption with lowest conceivable EBL level, for z = 0.6

=> Unphysical (?) upturn of the spectrum at the highest energies!



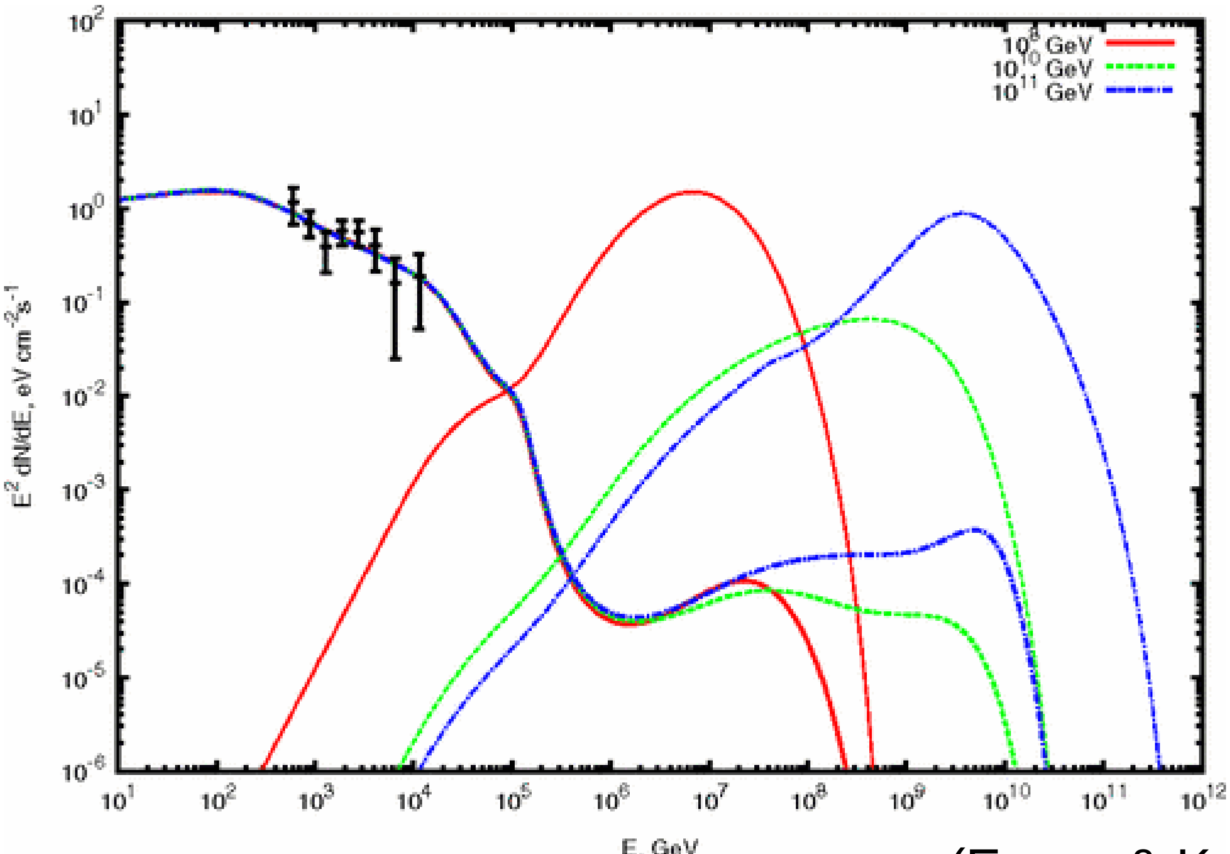
Furniss et al. (2015)

Lowering EBL Absorption Effects

1) Blazars = Cosmic-Ray Sources (?)

=> Cosmic-Rays interact with CMB

$p_{CR} + \gamma_{CMB} \rightarrow n + \pi^+$ => $\pi^+ \rightarrow \mu^+ + \nu_\mu$ => $\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$



Compton scattering of EBL/CMB photons

=> Resulting VHE γ-ray spectra are almost independent of EBL!

(Essey & Kusenko 2010)

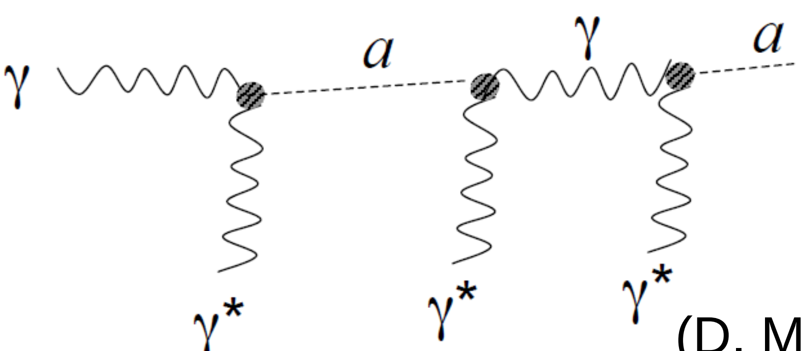
Lowering EBL Absorption Effects

2) Axion-like Particle (ALP) Conversion

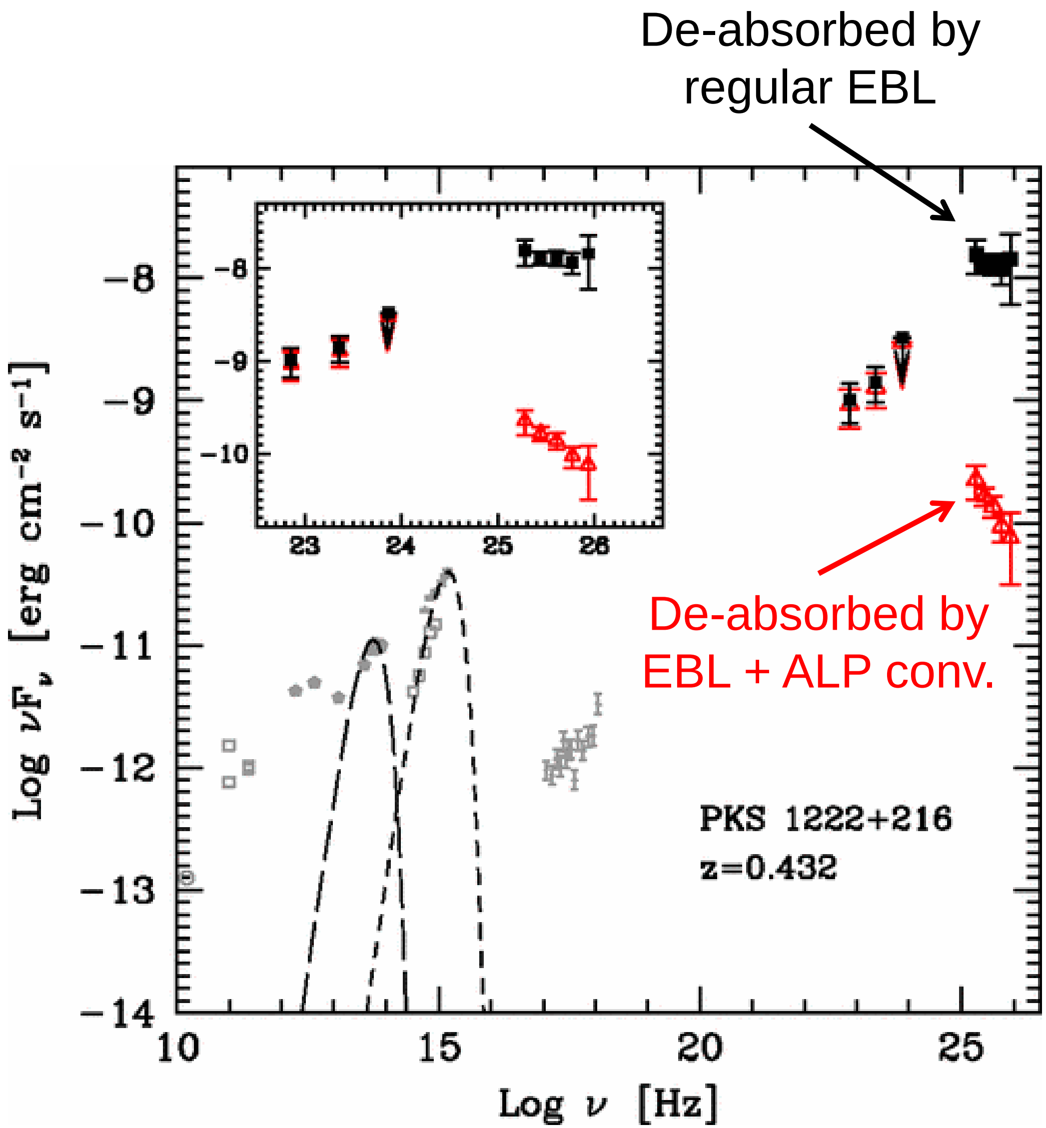
=> ALPs not subject to EBL absorption!

$$\gamma + \mathrm{B} \rightarrow \mathrm{a} \rightarrow \gamma + \mathrm{B}$$

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$



(D. Montanino)



(Tavecchio et al. 2012)

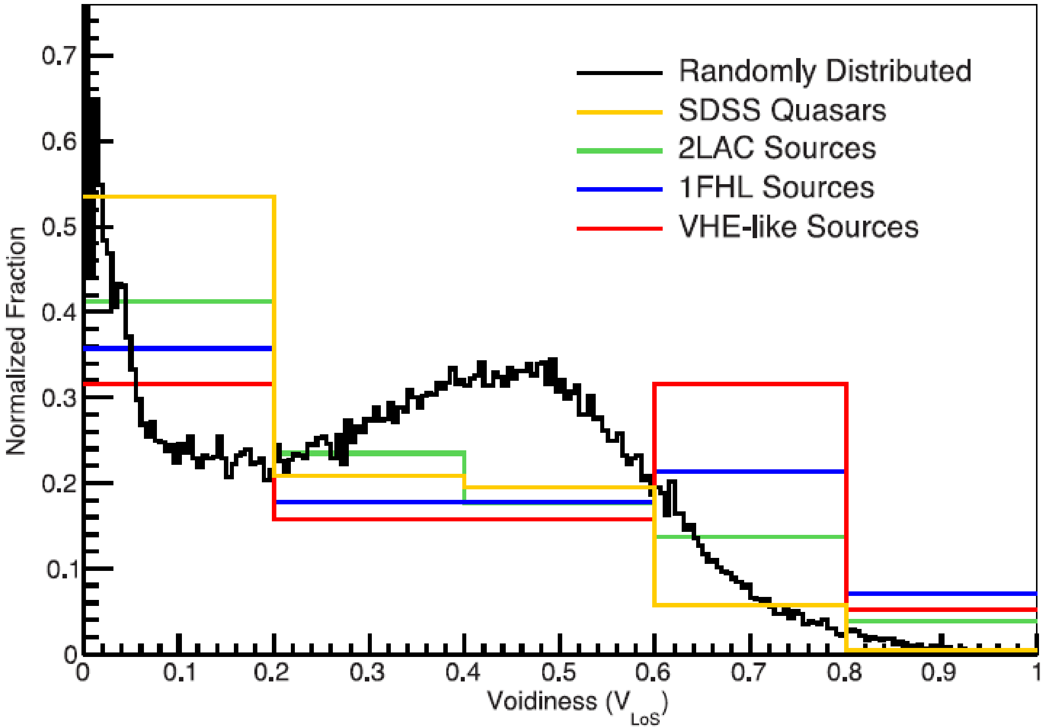
Lowering EBL Absorption Effects

3) Inhomogeneous EBL (?)

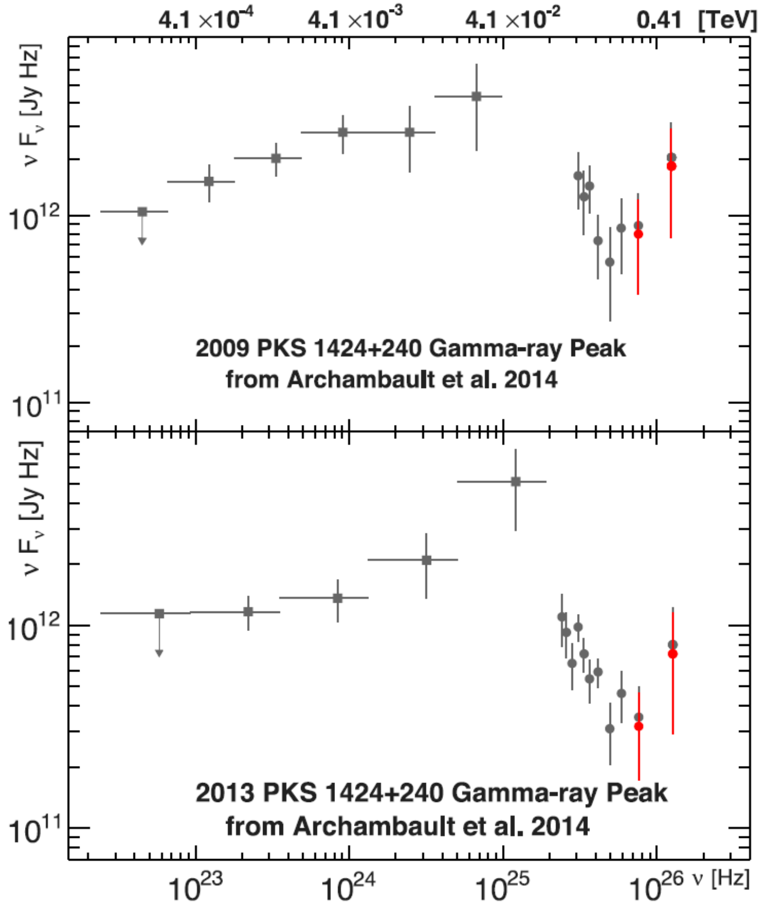
=> "VHE-like" blazars located preferentially behind low-density lines of sight (voids)

But not sufficient to solve EBL discrepancy:

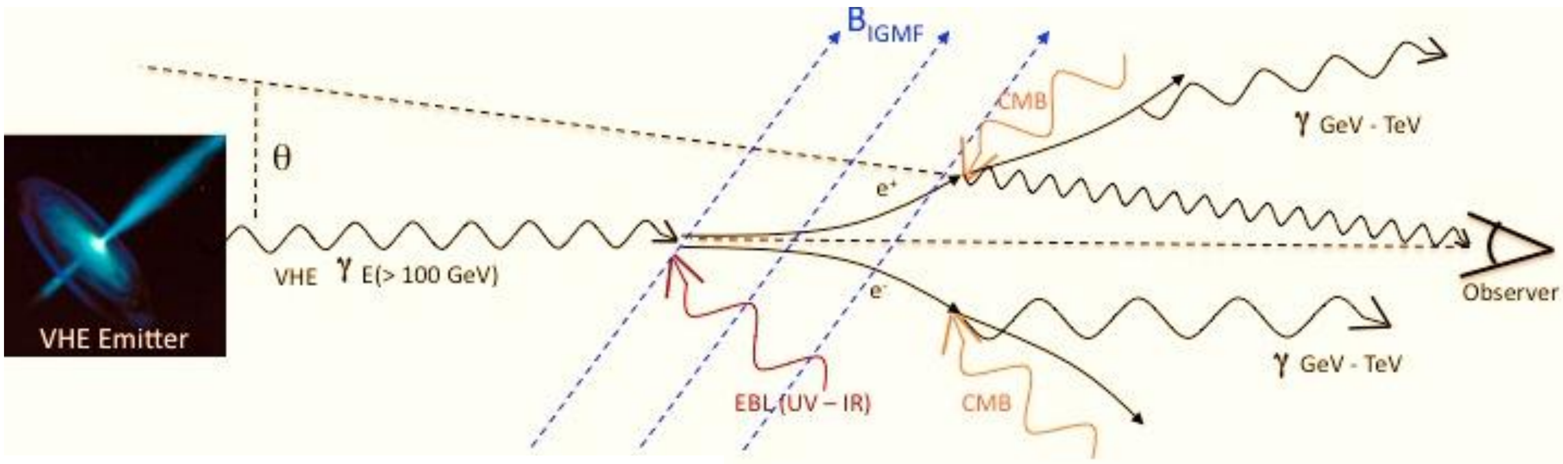
For PKS 1424+240: $\Delta\tau_{\gamma\gamma}$ <~ 10 %

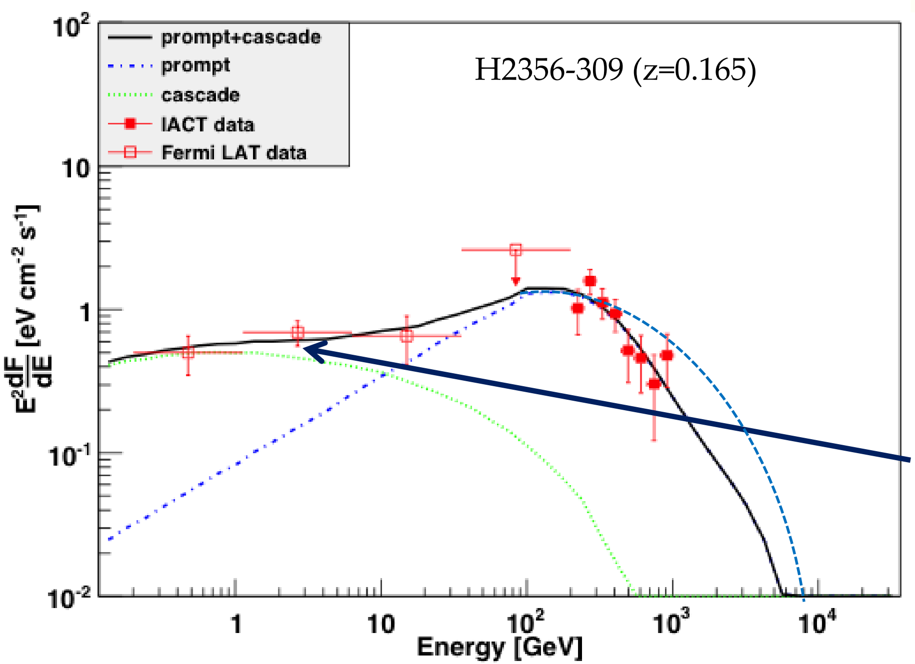


(Furniss et al. 2015)



Intergalactic Cascading and Magnetic Fields

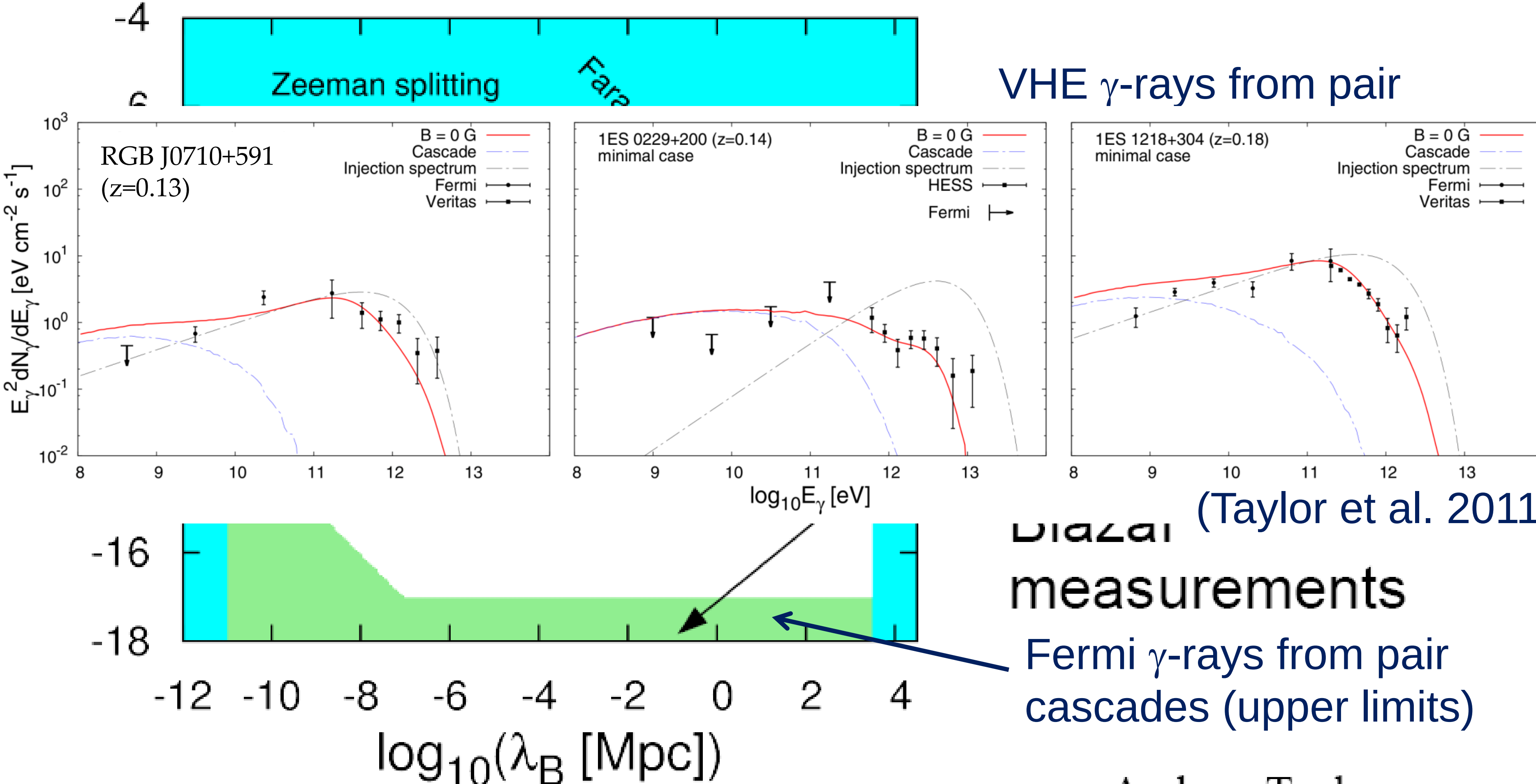




EBL-absorption of VHE γ-rays produces e^+e^- pairs → Compton scattering of EBL photons → GeV (Fermi) γ-rays

Upper limits on GeV emission → Lower limits on B

Intergalactic Cascading and Magnetic Fields



VHE γ-rays from pair

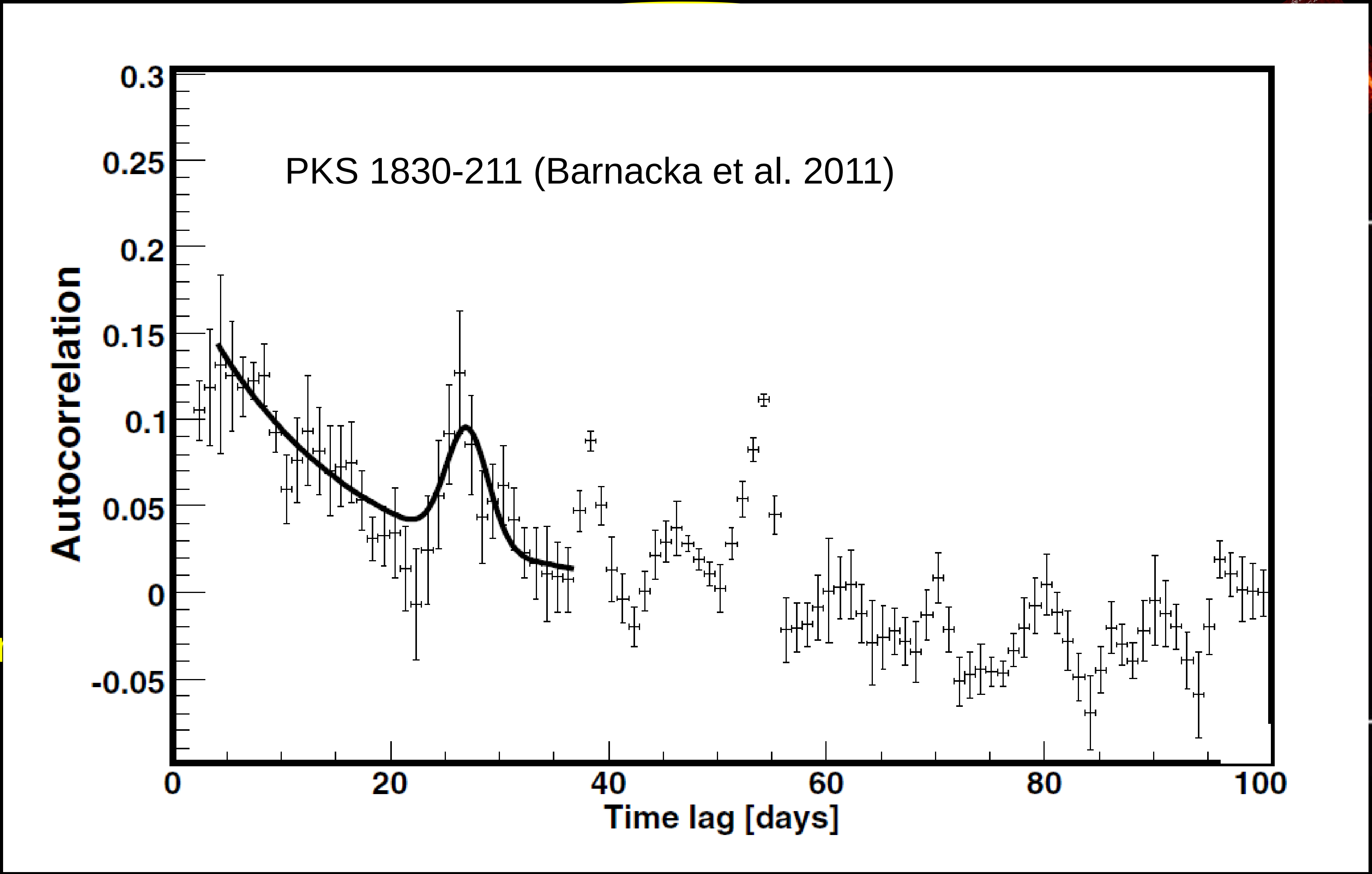
(Taylor et al. 2011)

measurements

Fermi γ-rays from pair cascades (upper limits)

Andrew Taylor

Gravitational Lensing of Gamma-Ray Blazars

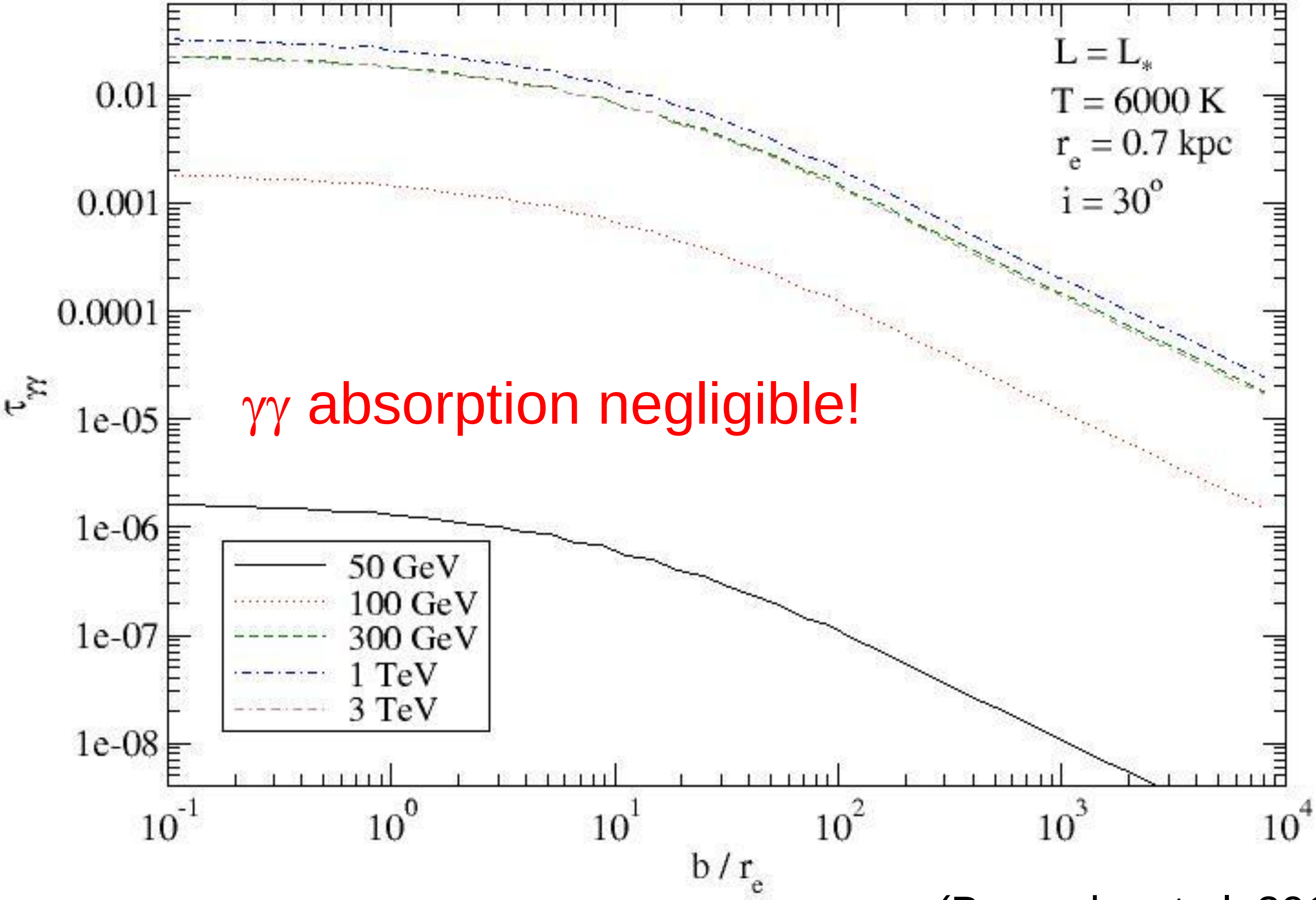


Gr

– What about γγ-absorption?

γγ-Absorption in Gravitational Lenses?

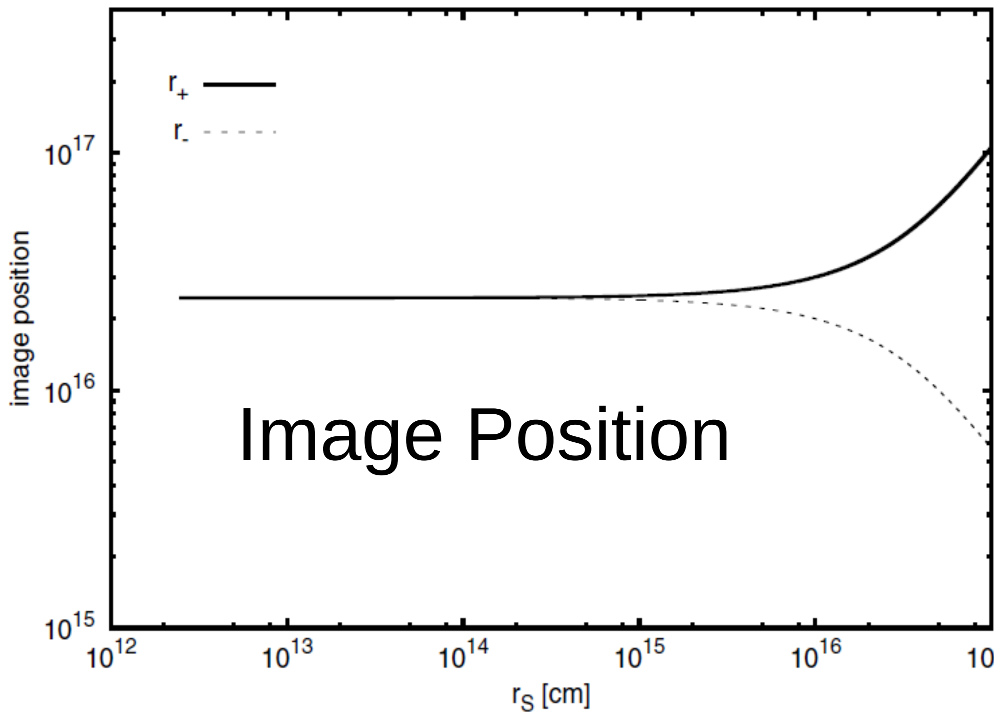
- Intervening Lensing Galaxies (Macrolensing):



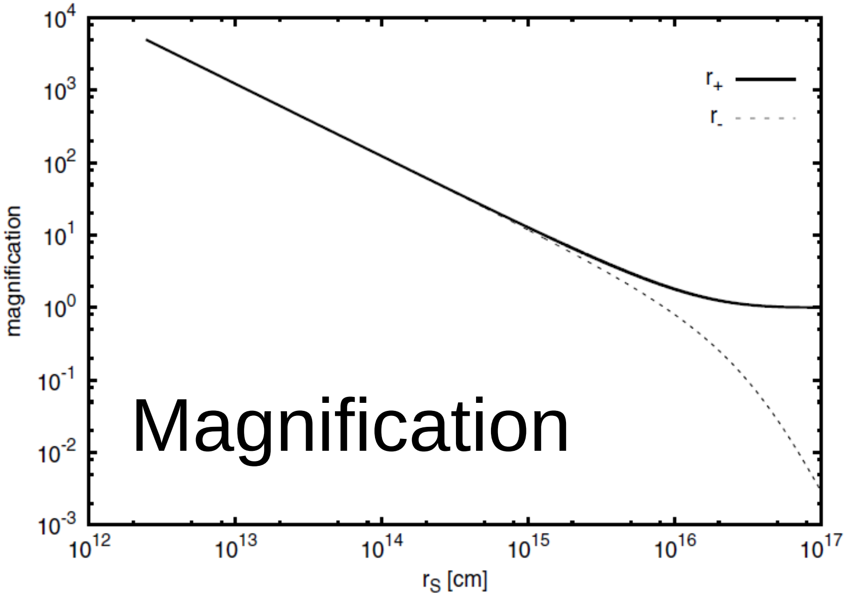
(Barnacka et al. 2014)

$\gamma\gamma$-Absorption in Gravitational Lenses?

- Stars in Intervening Galaxies (Microlensing):



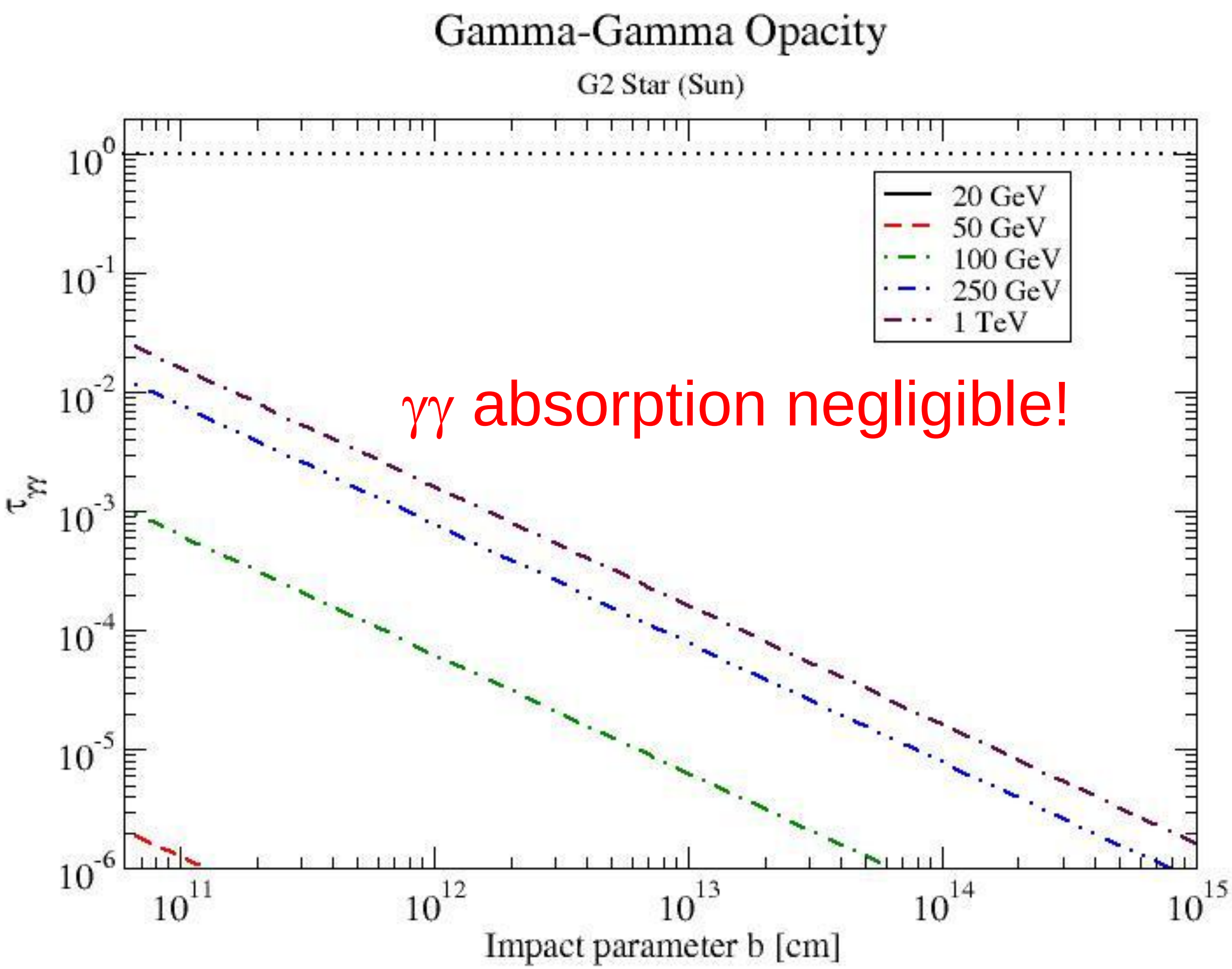
(Barnacka et al. 2014)



Position of visible image always > $2 \cdot 10^{16}$ cm $*(M/M_0)$ from the lensing star!

$\gamma\gamma$-Absorption in Gravitational Lenses?

- Stars in Intervening Galaxies (Microlensing):



(Barnacka et al. 2014)

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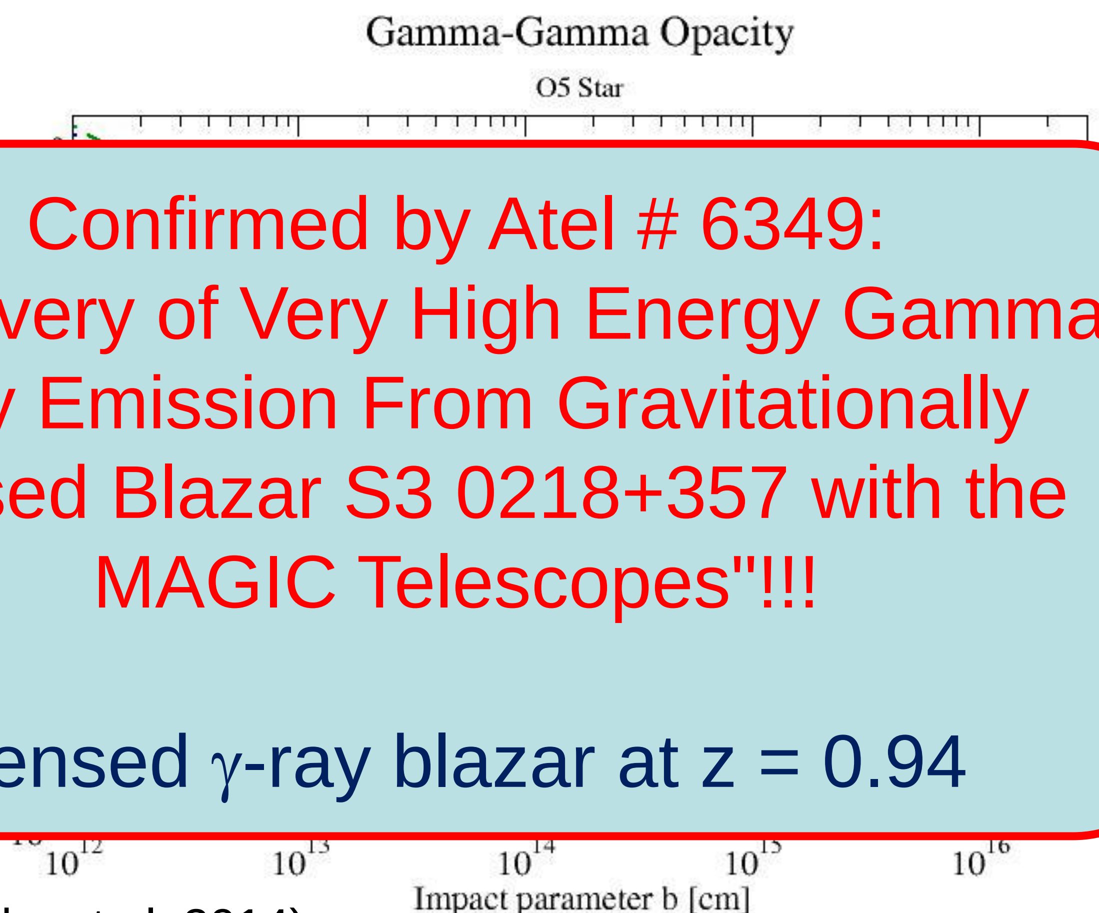


Confirmed by Atel # 6349:
"Discovery of Very High Energy Gamma-Ray Emission From Gravitationally Lensed Blazar S3 0218+357 with the MAGIC Telescopes"!!!

Lensed γ-ray blazar at z = 0.94

(Barnacka et al. 2014)

=> Gravitational lensing helps γ-rays avoid γγ-absorption!

Summary

1. The EBL carries the signature of the star formation history of the Universe, but is difficult to measure directly.

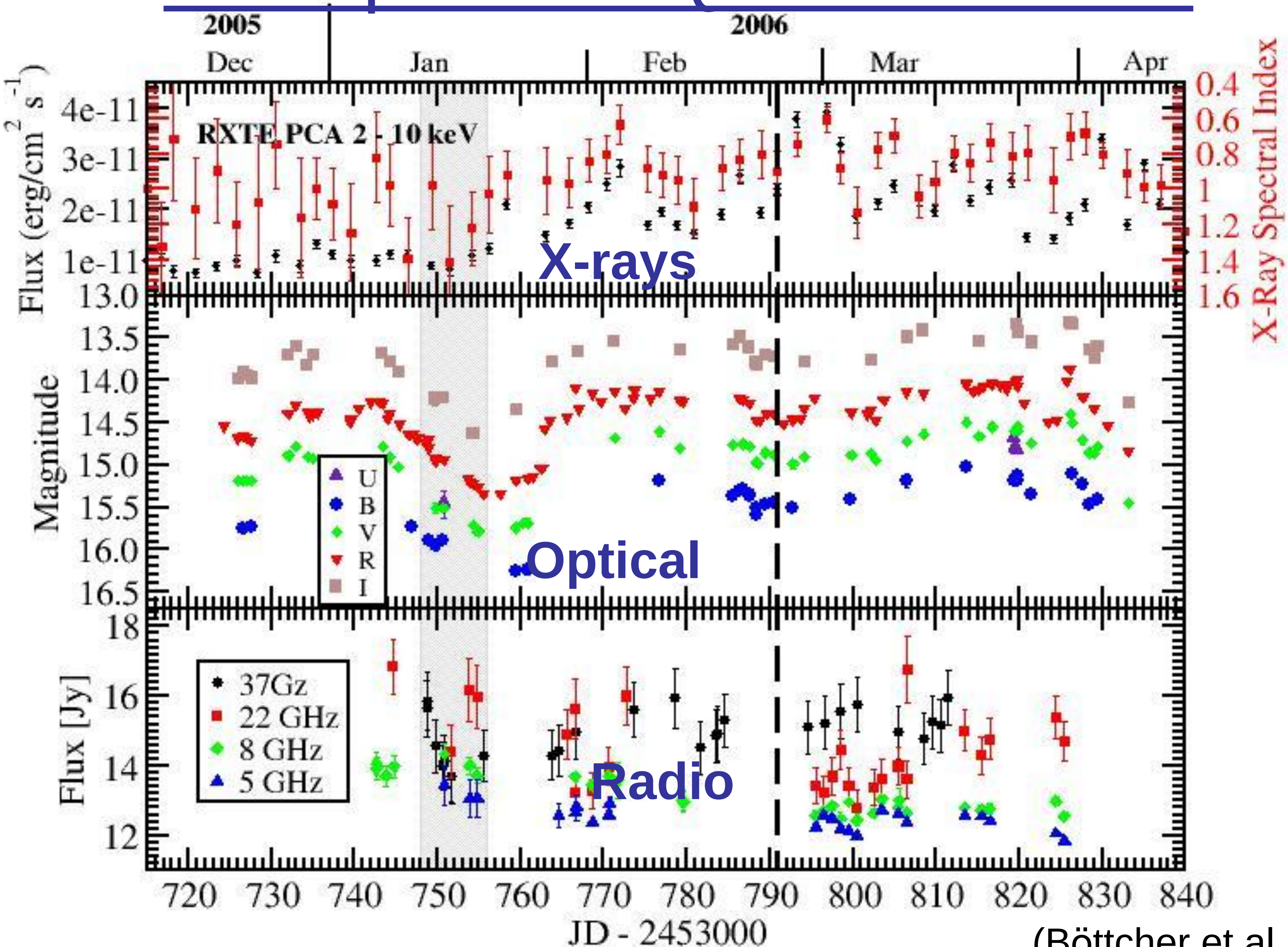
2. The EBL can be probed through its $\gamma\gamma$-absorption effect on VHE γ-rays → EBL absorption appears to be lower than predicted (from galaxy counts + galaxy evolution models).

3. Possible solutions: Cosmic-Ray induced γ-rays; ALP conversion; low-density LOS (not sufficient by itself).

4. EBL absorption – pair cascading can be used to set lower limits on the Intergalactic Magnetic Field ($B_{IGMF} > 10^{-17}$ G).

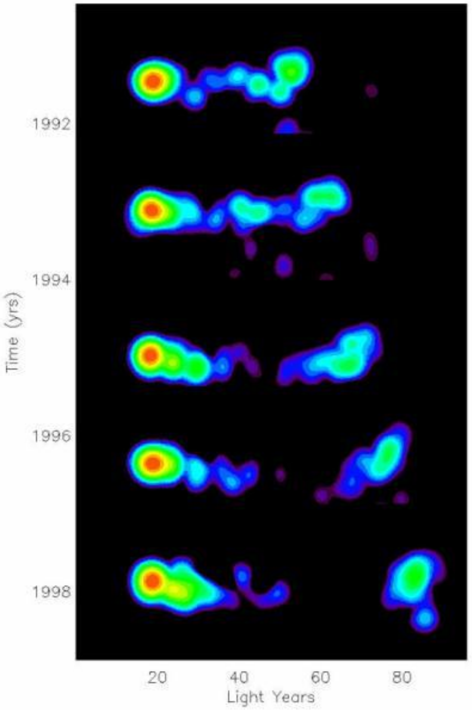
5. Gravitational lensing may help expand the VHE γ-ray horizon; $\gamma\gamma$-absorption by the radiation field of the lens will not interfere!

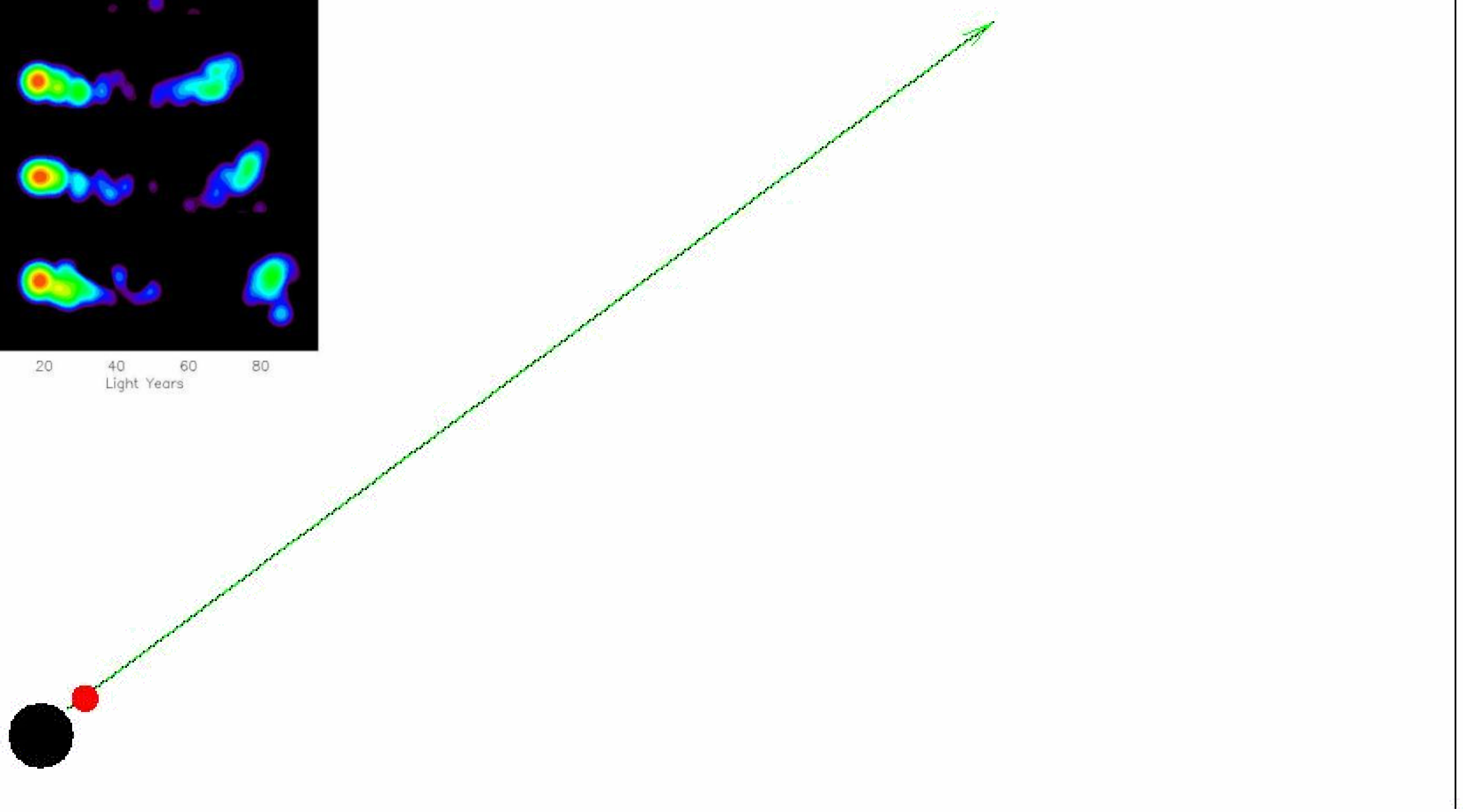
Blazar Variability: Example: The Quasar 3C279



(Böttcher et al. 2007)

Superluminal Motion

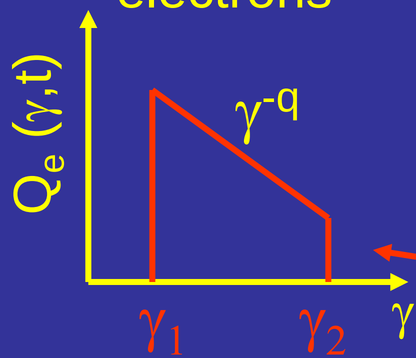




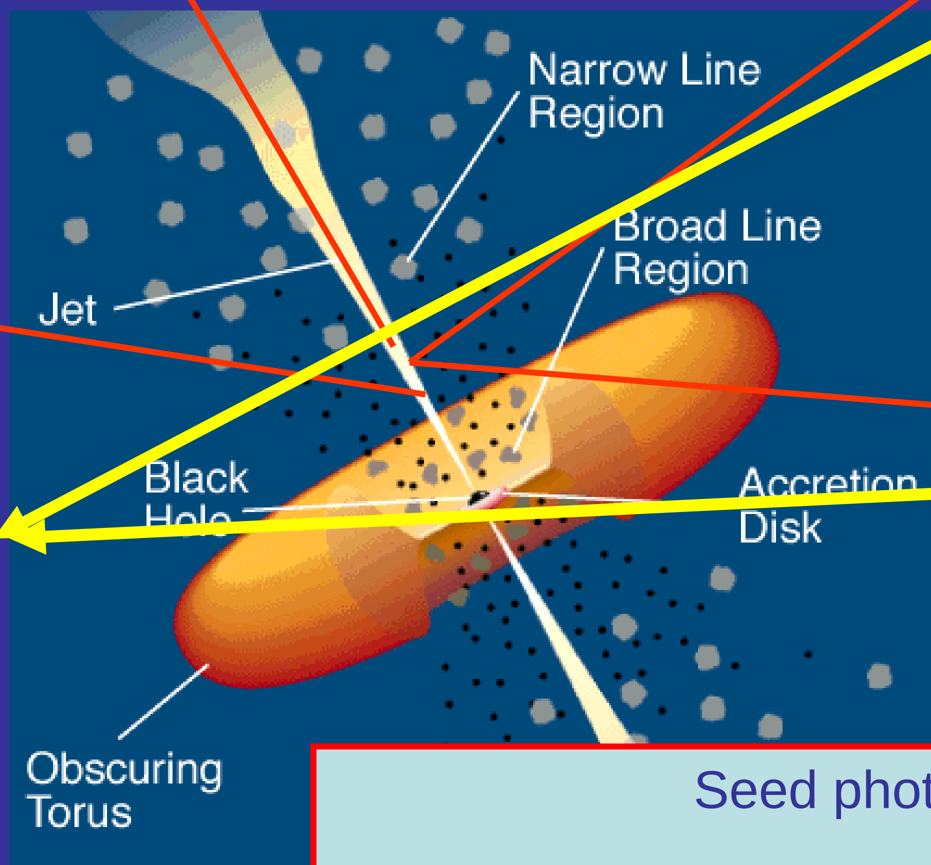
Apparent motion at up to ~ 40 times the speed of light!

Leptonic Blazar Model

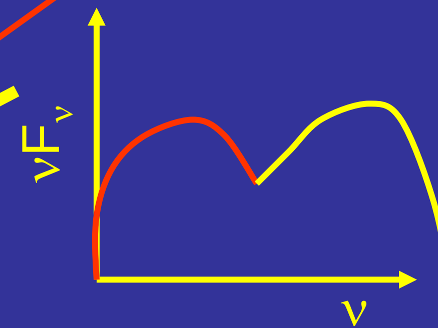
Injection, acceleration of ultrarelativistic electrons



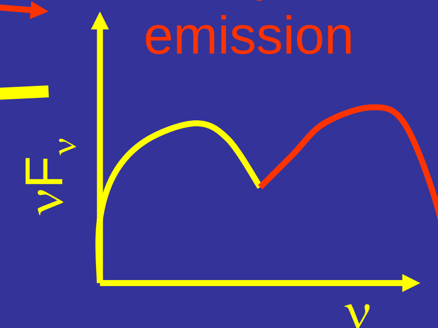
Relativistic jet outflow with $\Gamma \approx 10$



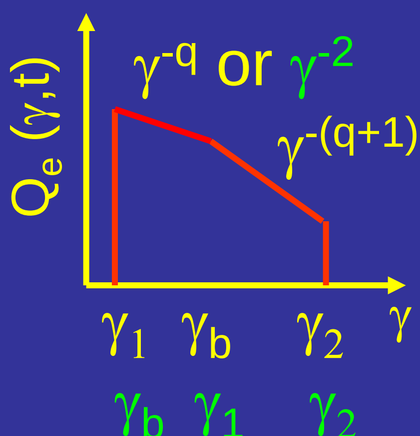
Synchrotron emission



Compton emission



Radiative cooling ↔ escape =>



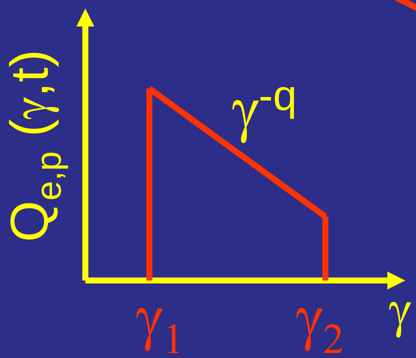
γ_b: $\tau_{cool}(\gamma_b) = \tau_{esc}$

Seed photons:

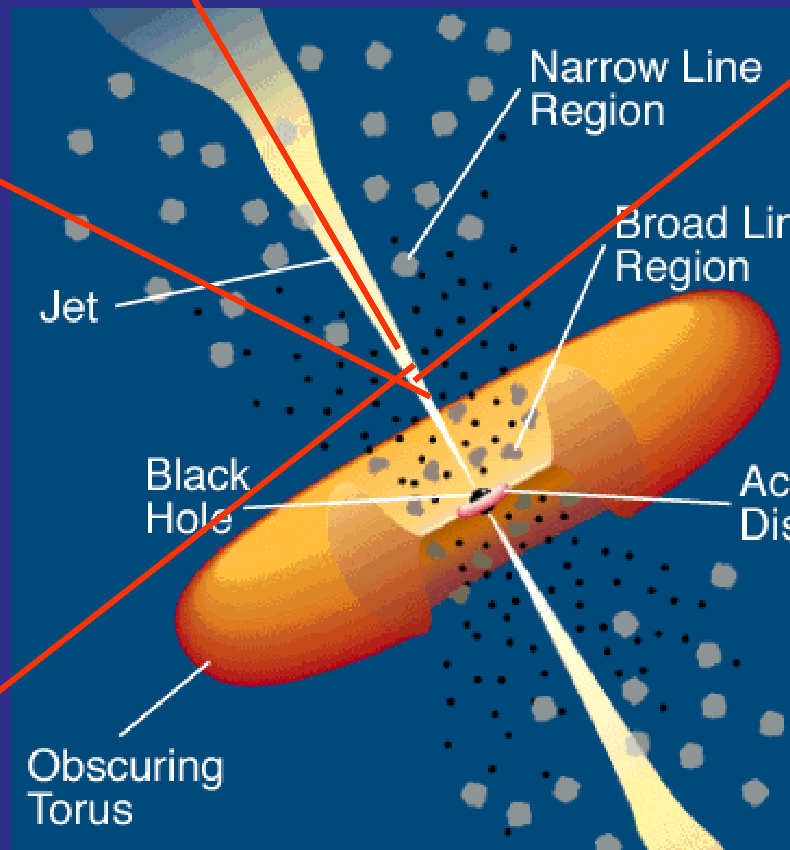
Synchrotron (within same region [SSC] or slower/faster earlier/later emission regions [decel. jet]), Accr. Disk, BLR, dust torus (EC)

Hadronic Blazar Models

Injection, acceleration of ultrarelativistic electrons and protons

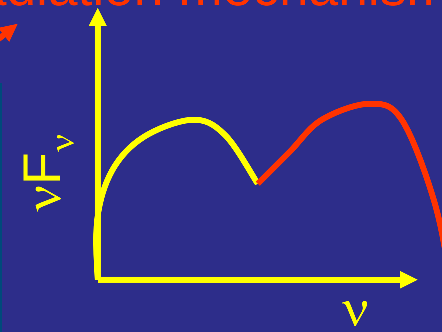


Relativistic jet outflow with $\Gamma \approx 10$

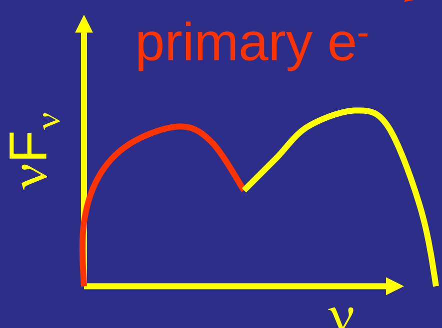


(Mannheim & Biermann 1992; Aharonian 2000; Mücke et al. 2000; Mücke et al. 2003)

Proton-induced radiation mechanisms



Synchrotron emission of primary e^-



- Proton synchrotron
- $p\gamma \rightarrow p\pi^0$
  $\pi^0 \rightarrow 2\gamma$
- $p\gamma \rightarrow n\pi^+ ; \quad \pi^+ \rightarrow \mu^+\nu_\mu$
  $\mu^+ \rightarrow e^+\nu_e\overline{\nu_\mu}$
  $\rightarrow$ secondary μ-, e-synchrotron
- Cascades …

Sources of External Photons (↔ Location of the Blazar Zone)

Direct accretion disk emission (Dermer et al. 1992, Dermer & Schlickeiser 1994)
→ d < few 100 – 1000 R_s

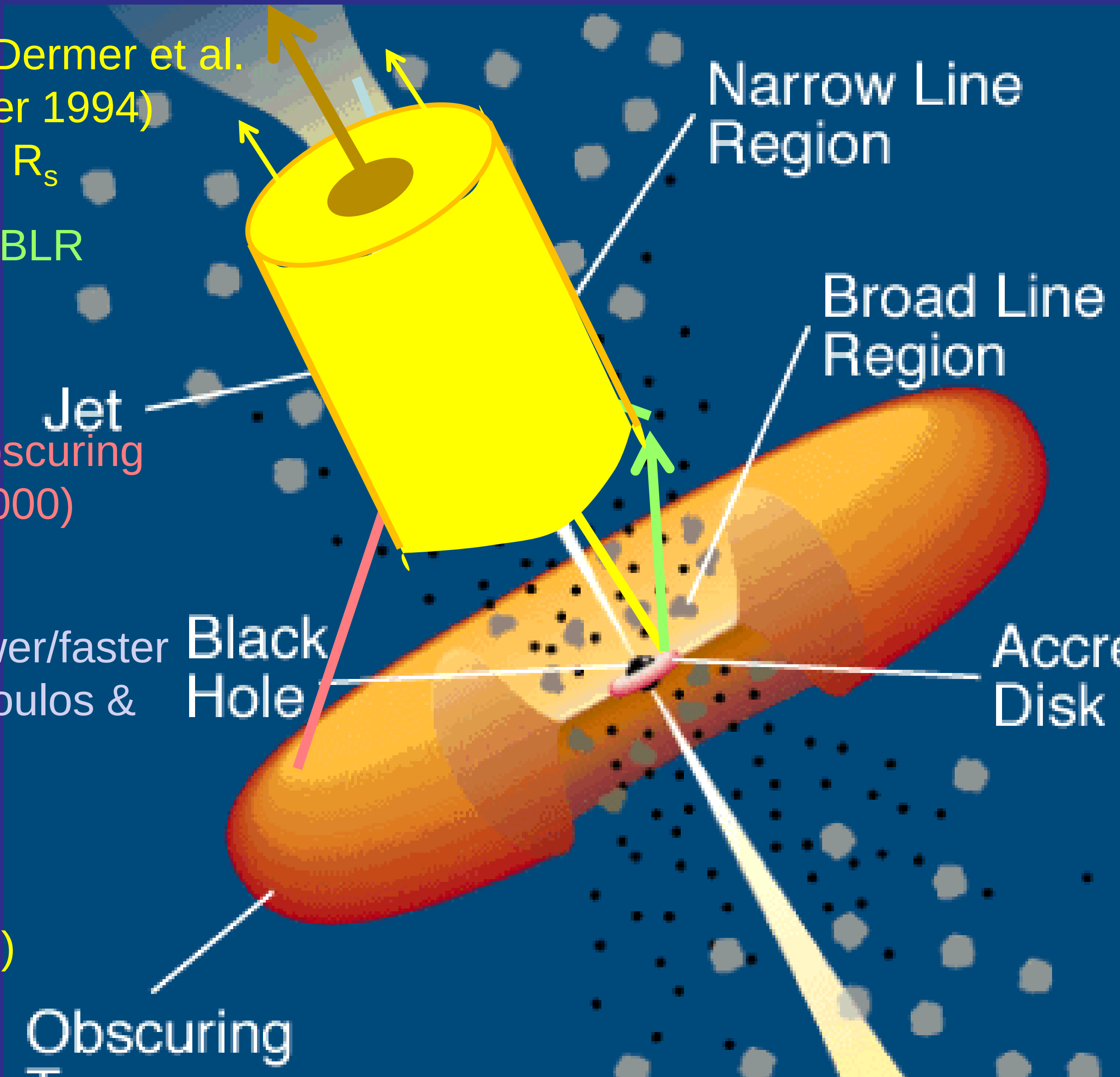
Optical-UV Emission from the BLR (Sikora et al. 1994)
→ d < ~ pc

Infrared Radiation from the Obscuring Torus (Blazejowski et al. 2000)
→ d ~ 1 – 10s of pc

Synchrotron emission from slower/faster regions of the jet (Georganopoulos & Kazanas 2003)
→ d ~ pc - kpc

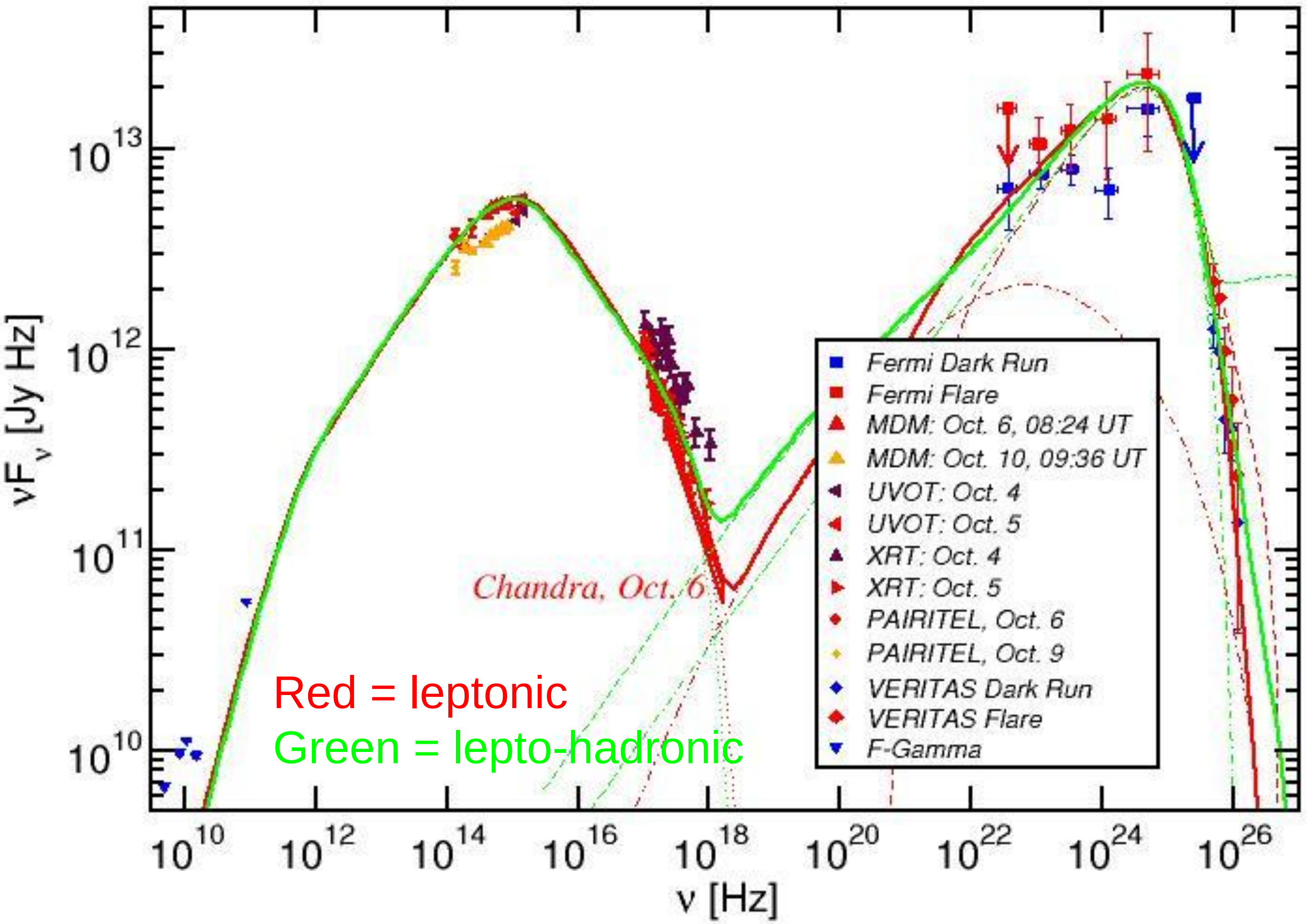
Spine – Sheath Interaction (Ghisellini & Tavecchio 2008)

→ d ~ pc - kpc



Leptonic and Hadronic Model Fits Along the Blazar Sequence

3C66A (IBL)



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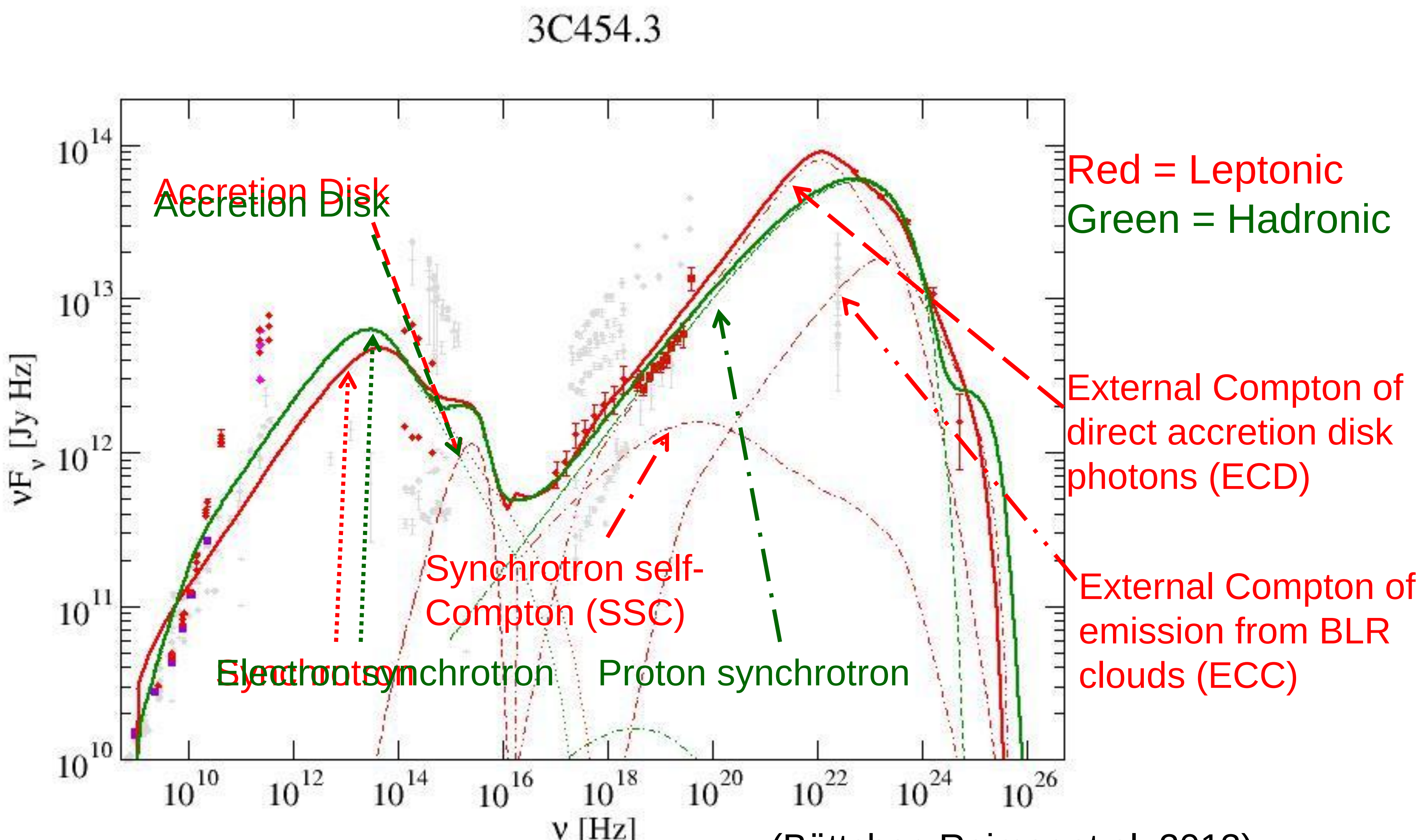
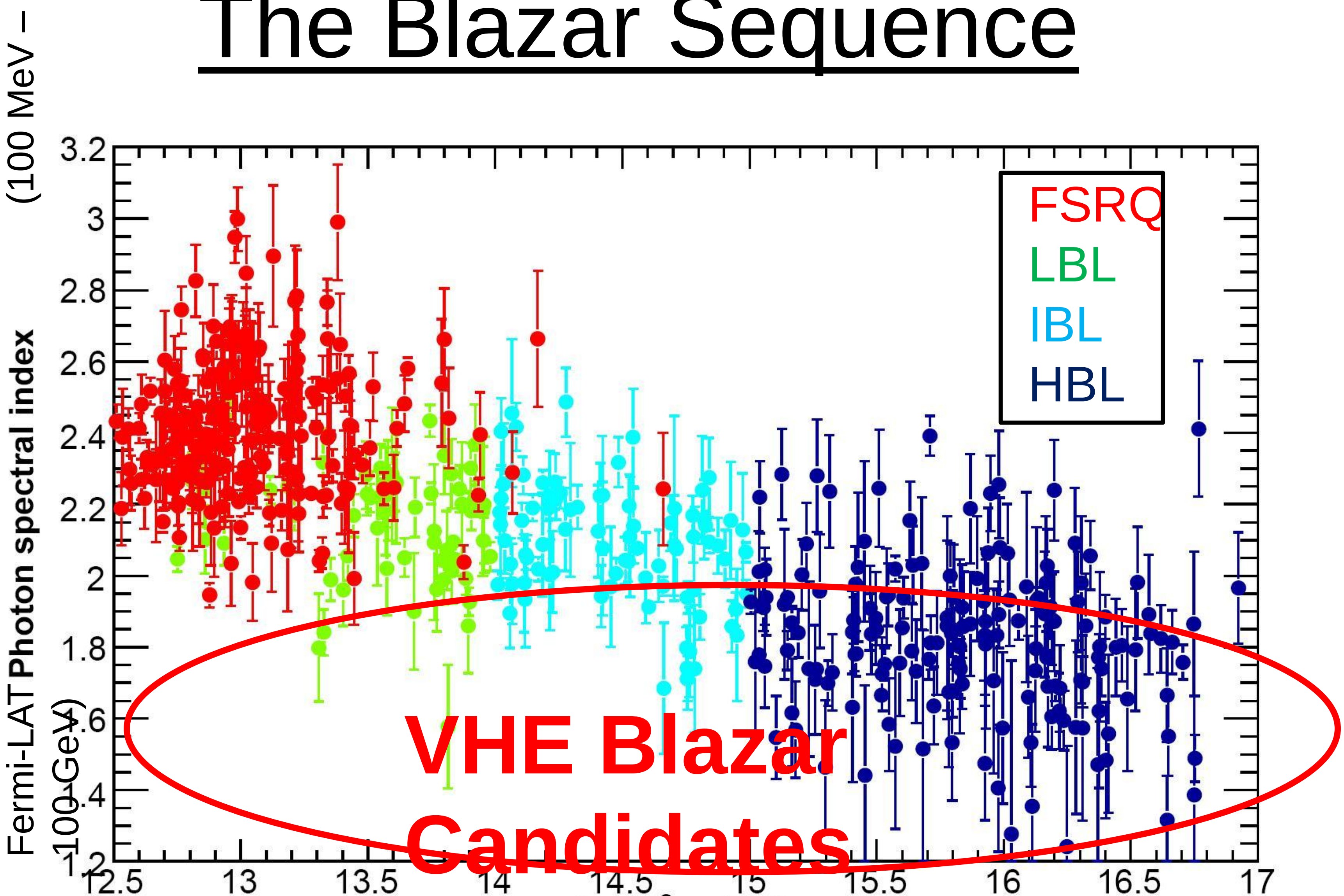


(Böttcher, Reimer et al. 2013)

The Blazar Sequence



(2nd LAT AGN Catalog: Ackermann et al. 2011)

VHE γ-Ray Blazars

Name	Class	z	Date
Mrk421	HBL	0.031	08/1992
Mrk501	HBL	0.034	01/1996
1ES 2344+514	HBL	0.044	07/1998
Mrk 180	HBL	0.045	09/2006
1ES1959+650	HBL	0.048	08/1999
AP Lib	LBL	0.049	07/2010
1ES 1727+502	HBL	0.055	11/2011
PKS 0548-322	HBL	0.069	07/2007
BL Lacertae	LBL	0.069	05/2005
PKS 2005-489	HBL	0.071	06/2005
RGBJ0152+017	HBL	0.08	02/2008
SHBL J001355.9…	HBL	0.095	09/2010
W Comae	IBL	0.102	08/2008
1ES 1312-423	HBL	0.108	12/2010
PKS 2155-304	HBL	0.116	06/1999
RGB J0710+591	HBL	0.125	03/2009
1H 1426+428	HBL	0.129	02/2002
1ES 1215+303	LBL	0.130	01/2011
1ES 0806+524	HBL	0.138	02/2008
1ES 0229+200	HBL	0.14	02/2006
1RXS J101015.9…	HBL	0.142	12/2010

Name	Class	z	Date
1H 2356-309	HBL	0.165	04/2006
RX J0648.7+1516	HBL	0.179	03/2010
1ES 1218+304	HBL	0.182	05/2006
1ES 1101-232	HBL	0.186	04/2006
1ES 0347-121	HBL	0.188	08/2007
RBS 0413	HBL	0.19	10/2009
PKS 0447+439	HBL	0.20	12/2009
1ES 1011+496	HBL	0.212	09/2007
PKS 0301-243	HBL	0.26	07/2012
1ES 0414+009	HBL	0.287	11/2009
S5 0716+714	LBL	0.318	04/2008
1ES 0502+675	HBL	0.341	11/2009
PG1553+114	HBL	0.35	03/2006
PKS 1510-089	FSRQ	0.36	03/2010
4C+21.35	FSRQ	0.432	06/2010
3C66A	IBL	0.444 ?	03/2008
RGB J0136+3905	HBL	> 0.4	07/2012
3C279	FSRQ	0.536	06/2008
KUV 00311-1938	HBL	0.61(?)	07/2012
PKS1424+240	IBL	???	06/2009
1ES 0033+595	HBL	???	10/2011
RGB J0521.8+2112	HBL	???	10/2009

PKS 1424+240

SSC fit parameters for a variety of redshifts

Parameter	z = 0.05	z = 0.10	z = 0.16	z = 0.30	z = 0.40	z = 0.50	z = 0.70
L_e [10^{43} erg/s]	1.60	4.12	8.07	18.9	29.2	47.1	88.8
L_B [10^{43} erg/s]	1.66	5.47	12.2	31.1	45.9	49.8	66.2
ε_B	1.04	1.33	1.50	1.65	1.57	1.06	0.75
B [G]	0.37	0.31	0.30	0.24	0.25	0.18	0.14
D	15	18	20	30	35	45	60

L_e = kinetic power in relativistic electrons
L_B = Poynting flux
$\varepsilon_B = L_B/L_e$ = magnetic-field equipartition fraction
D = Doppler factor

Fits for $z \geq 0.5$ require large Doppler factors