

# Introduction to gamma-ray blazars

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OUTLINE

1. Active galactic nuclei
2. Blazars
3. Models of blazar emission
- 4. The Fermi blazars**
- 5. The TeV blazars**
6. The GeV–TeV Connection
7. The extra-galactic background light
8. Intergalactic magnetic fields
9. Characterising variability

# Active galactic nuclei

- 1/9 -



# Active Galactic Nuclei

## CHARACTERISTICS

- \* **central nucleus outshines the rest of the galaxy**
- high luminosity (normally)
- **emission across entire spectrum ... radio to keV, MeV, TeV**
  - non-thermal
- strong variability
- **radio-loud sources:**
  - relativistic jets ... superluminal motion



# Active Galactic Nuclei

**TAXONOMY**

## ACTIVE GALAXIES

**Looking In On A Galaxy With Jets**



The long view of an active galaxy is dominated by lobes of radio emission caused by highly focused jets of matter streaming out from the galaxy nucleus.



Closer in, a torus of dust and gas can be seen, orbiting outside a faster disk of swirling gas.



In an extreme close-up, the black hole in the center is surrounded by a fast accretion disk of rapidly orbiting material. The jets are emitted at right angles from the plane of the disk, driven by physics still not well understood.

<http://glast.sonoma.edu>

What we see depends on how we view it ...

An active galaxy is one in which a tremendous amount of energy is emitted from the nucleus. Active galaxies take many forms; some have exquisitely bright nuclei pouring forth high-energy photons, some have high-energy nuclei but appear to be surrounded by a more-or-less "normal" galaxy, while some have long, narrow jets or beams of matter streaming out from the center. Displayed here is an illustration of an active galaxy that has jets. The nucleus of this galaxy contains a supermassive black hole -the engine that powers the phenomena we see. Following its launch, the Gamma-ray Large Area Space Telescope (GLAST) will see thousands of these types of active galaxies.

All the images are artist's conceptions unless otherwise noted.



**Different Angles On A Galaxy With Jets**

**Viewing down the jet**



The observation of the blazar 3C 279 shows gamma rays streaming from the vicinity of the central black hole. The blazar's rapid motion and its light of 3C 279 is another active galaxy, a source called 3C 279.

When we are looking down the jets, the emission is dominated by high-energy photons such as x-rays and gamma rays. In this case the active galaxy is called a blazar.

Top Left: NASA/ESA; Credits: Science Photo Library; NASA

**Viewing at an angle to the jet**



When seen from an angle, the blazar jets are dimmer, and features near the galaxy's nucleus are more easily seen. Gamma rays are not detected, although the central source is still bright in x-rays and lower energies down to radio.

The observation of Centaurus A - a nearby active galaxy - is from Centaurus A, which is emitting x-rays observably. It shows a ring from one of the jets, diffuse gas in the galaxy, and numerous point sources near the galaxy's center.

Top Right: NASA/ESA; Credits: Science Photo Library; NASA

**Viewing at 90° from the jet**



When seen from the side, the relatively weak emission from the lobes becomes dominant. The jets powered by the black hole travel "hand-in-glove" thousands of light years before breaking the huge clouds of radio-wave emitting gas.

The observation from the new Large Area Space Telescope shows the radio emission from the lobes of matter in the active galaxy Centaurus A. The central region of the galaxy can be seen as well as the jets, which are long and fan out into a wide area. The long and fan-out jets are somewhat double over 300,000 light years from the central black hole.

Top Left: NASA/ESA; Credits: Science Photo Library; NASA

### Definitions

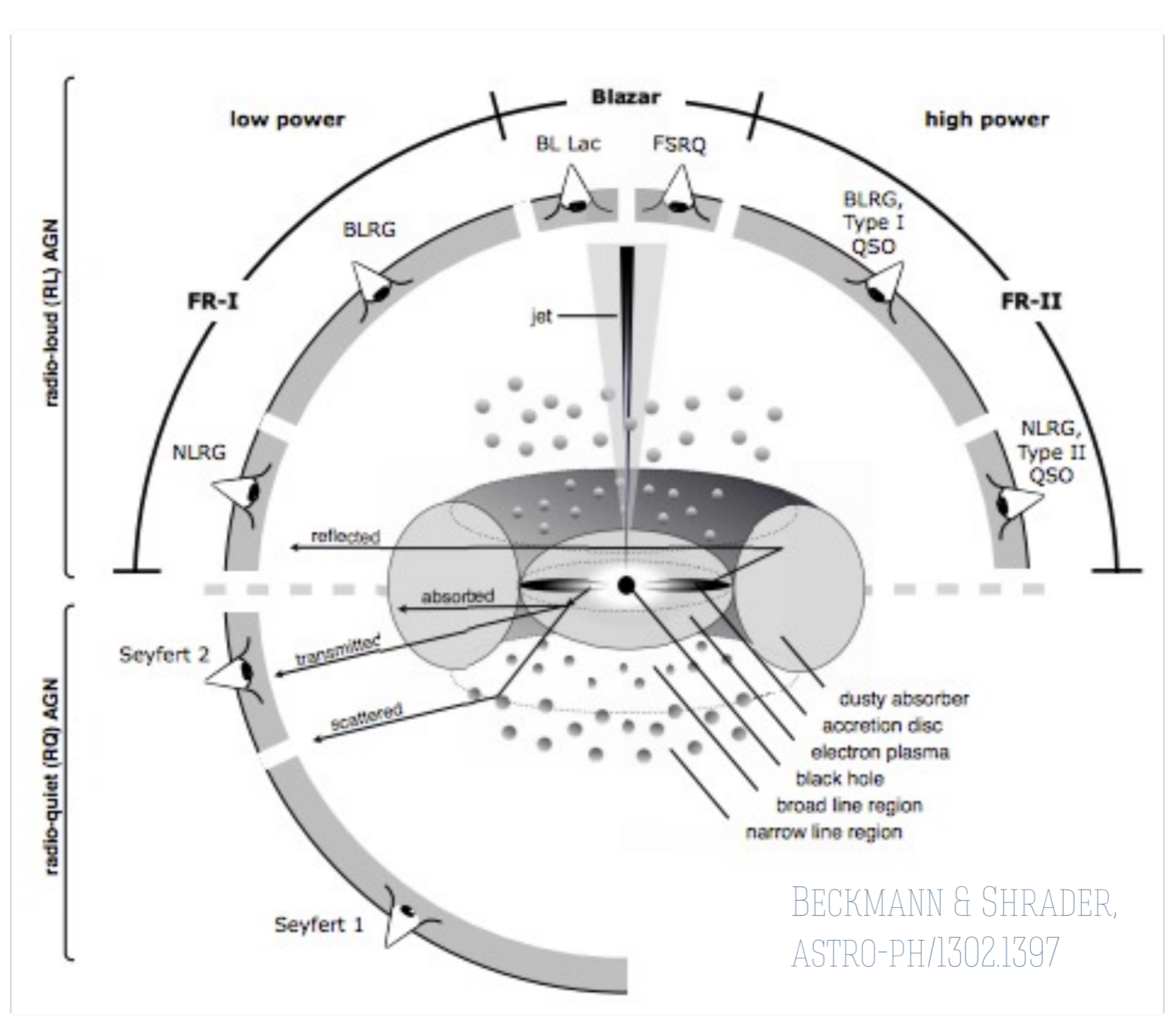
<p><b>Accretion Disk:</b> The flattened disk of matter swirling just outside the black hole.</p> <p><b>Active Galaxy:</b> A galaxy with an unusually large amount of energy emitted from the nucleus.</p> <p><b>Black Hole:</b> An object so small and dense that the escape velocity is faster than the speed of light. In an active galaxy, the central black hole may have millions or even billions of times the Sun's mass.</p>	<p><b>Blazar:</b> A quasar that one is viewing directly down the jet axis.</p> <p><b>Jet:</b> A thin, highly focused beam of matter and energy emitted from the nuclei of some active galaxies. Jets can be hundreds of thousands of light years long.</p> <p><b>Nucleus:</b> The central region of a galaxy.</p> <p><b>Quasar:</b> An active galaxy so distant it appears star like.</p>	<p><b>Radio Lobe:</b> A large radio wave-emitting cloud of matter located at the ends of the jets in some active galaxies, formed when the matter from the jet is slowed by intergalactic material.</p> <p><b>Ring:</b> A doughnut-shaped object. Gas and dust within the accretion disk in an active galaxy orbit the central black hole in a torus-shaped region.</p>
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**GLAST**

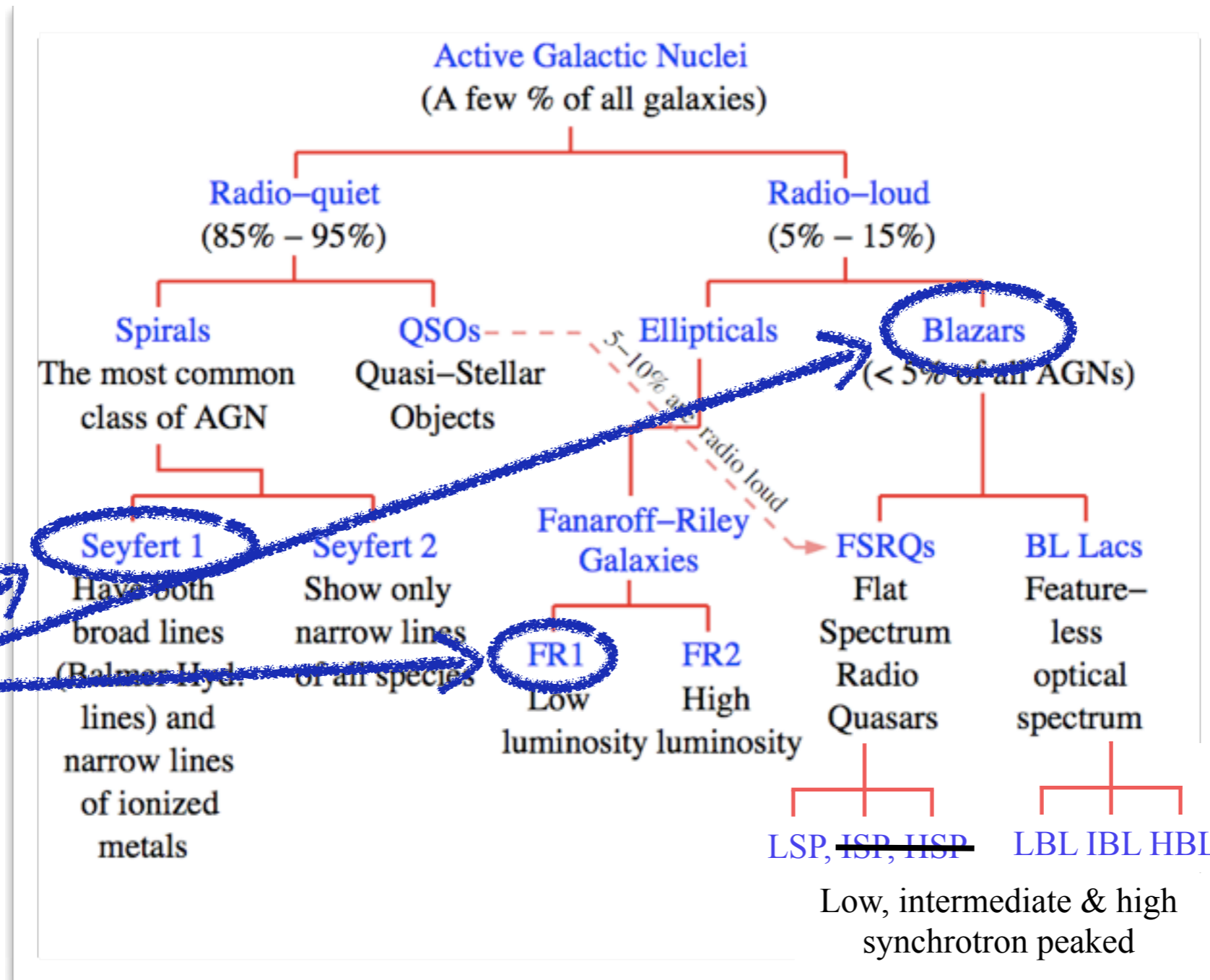
Art Design by Aurora Simonsen, Text by Phil Plait.

# Active Galactic Nuclei



# Active Galactic Nuclei

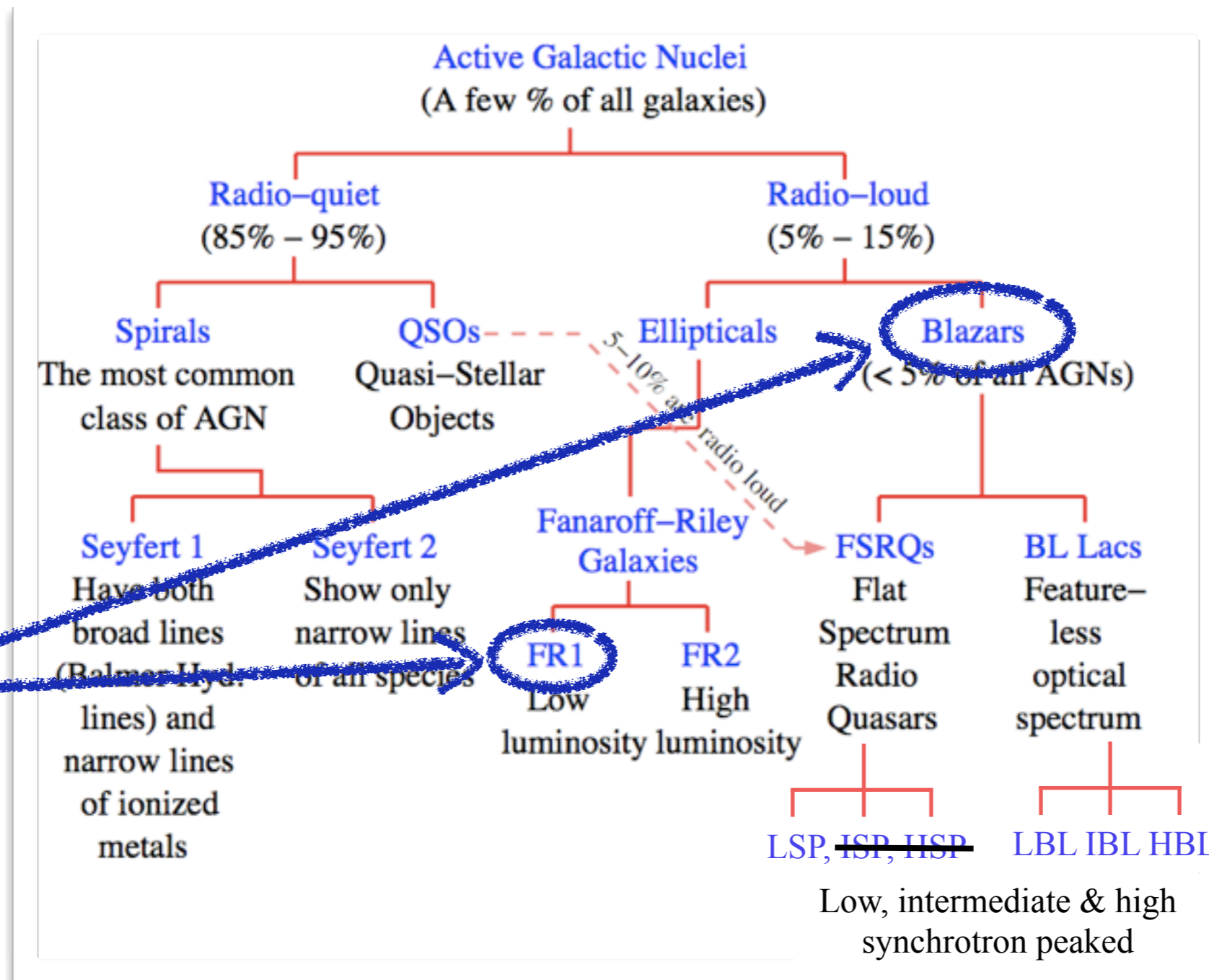
# CLASSIFICATION



identified  
as Fermi  
sources

# Active Galactic Nuclei

# CLASSIFICATION



identified  
as TeV  
sources



Blazars

2/9



# Blazars



## CHARACTERISTICS

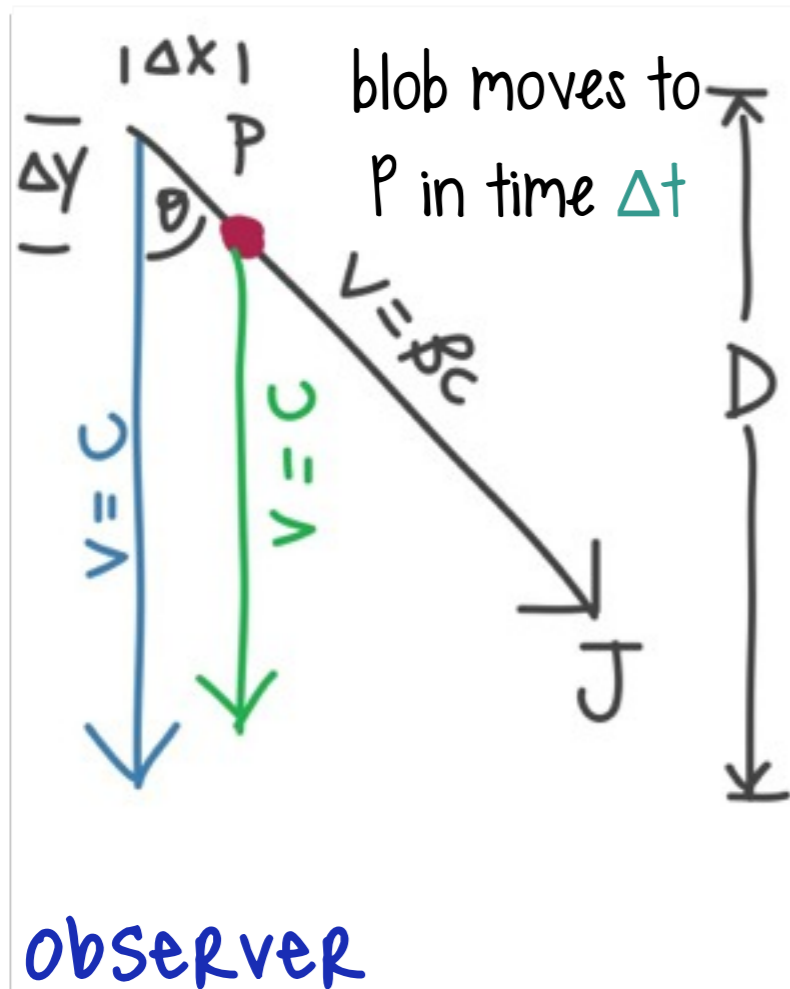
- \* <5% of all AGN
- jet points “at” us
- flat radio spectrum
- **radio loud AGN**
- large amplitude variability
- **optical polarisation**
- **spectral energy distribution**



# Blazars

## Superluminal motion

FIRST PROPOSED BY REES IN 1966 (NATURE, 211, 468) YEARS BEFORE IT WAS FIRST OBSERVED WHEN VLBI TECHNIQUES WERE DEVELOPED



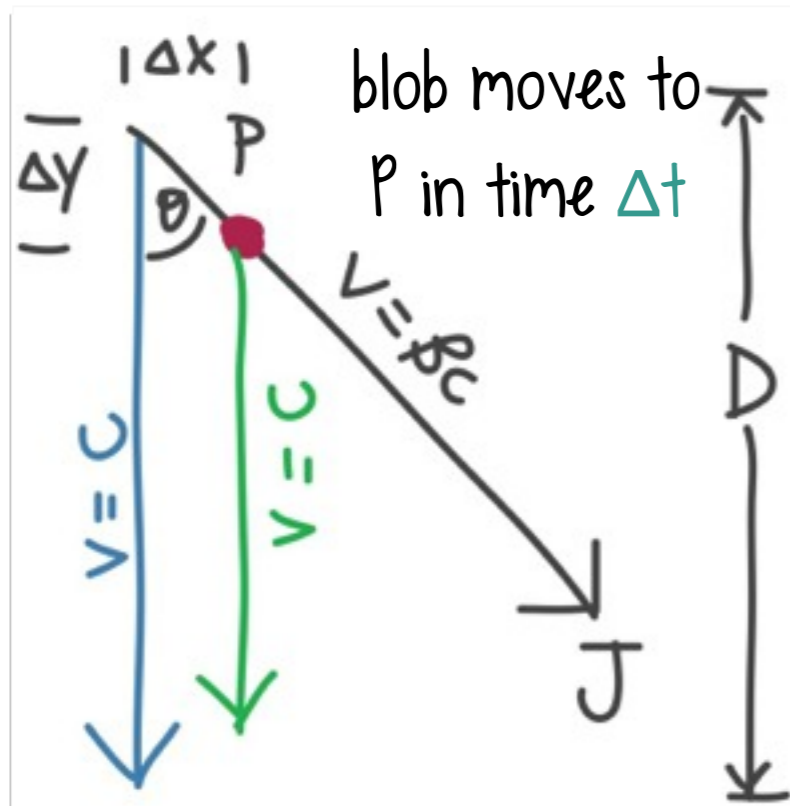
first pulse travels to observer in time  $D/c$ ; the second, emitted time  $\Delta t$  later, has a shorter distance to travel:  $D - \Delta y$ .

Difference in arrival time is:

$$\Delta t_{\text{obs}} = \left[ \Delta t + \frac{(D - \Delta y)}{c} \right] - \left[ \frac{D}{c} \right]$$

# Blazars

## Superluminal motion



Difference in arrival time is:

$$\Delta t_{obs} = \left[ \Delta t + \frac{(D - \Delta y)}{c} \right] - \left[ \frac{D}{c} \right]$$

substitute for  $\Delta y$  & rearrange:

$$\Delta t_{obs} = \Delta t (1 - \beta \cos \theta)$$

measured transverse velocity,  $v_{obs}$

$$v_{obs} = \frac{\Delta x}{\Delta t_{obs}} = \frac{\beta c \sin \theta}{(1 - \beta \cos \theta)}$$

therefore:

$$\beta_{obs} = \frac{\beta \sin \theta}{(1 - \beta \cos \theta)}$$

# Blazars

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## Superluminal motion

So, if the plasma velocity was  $0.95c$  and the angle to the observer was  $5\text{deg}$ , the apparent velocity would be  $1.5c$ . The effect is maximised when  $\cos\theta = \beta$

$$\beta_{\text{obs}} = \frac{\beta \sin\theta}{(1 - \beta \cos\theta)}$$

# Blazars

## Relativistic beaming

- Another relativistic effect occurs because the knots of plasma are moving at velocities close to that of light
- When an emitting plasma has a bulk relativistic motion relative to a fixed observer, its emission is beamed in the forward direction in the fixed frame
- The flux density is thus changed by relativistic time dilation so an observer sees much more intense emission than if the plasma were at rest
- The observed emission,  $S_{obs}$  is boosted in energy over that emitted in the rest frame,  $S$

Definitions:

The Doppler factor is a measure of the strength of the beaming:  $\delta = [\Gamma (1 - \beta \cos \theta)]^{-1}$

The Lorentz factor:  $\Gamma = \frac{1}{\sqrt{1 - \beta^2}}$  where  $\beta = \frac{v}{c}$

$$S_{obs} = S [\Gamma (1 - \beta \cos \theta)]^{-3}$$

If plasma velocity is  $0.95c$  and  $\theta$  is  $5\text{deg}$ , the boosting factor will be  $\sim 198$

# Blazars

## Pair-production optical depth

\*DONDI & GHISELLINI (1995) MNRAS, 273, 583

\*\*URRY & PADOVANI (1995) PASP, 107, 803

- High energy gamma rays collide with softer radiation to produce  $e^+e^-$  pairs
- For gammas to escape from a source, the optical depth for this process  $\tau_e$  must be sufficiently low
- The cross section for this process is maximized for collisions between gamma rays of energy ...

$$X_\gamma = \frac{h\nu_\gamma}{mc^2} \quad \text{and target photons of energy ...} \quad X_{\text{target}} = \frac{1}{X_\gamma}$$

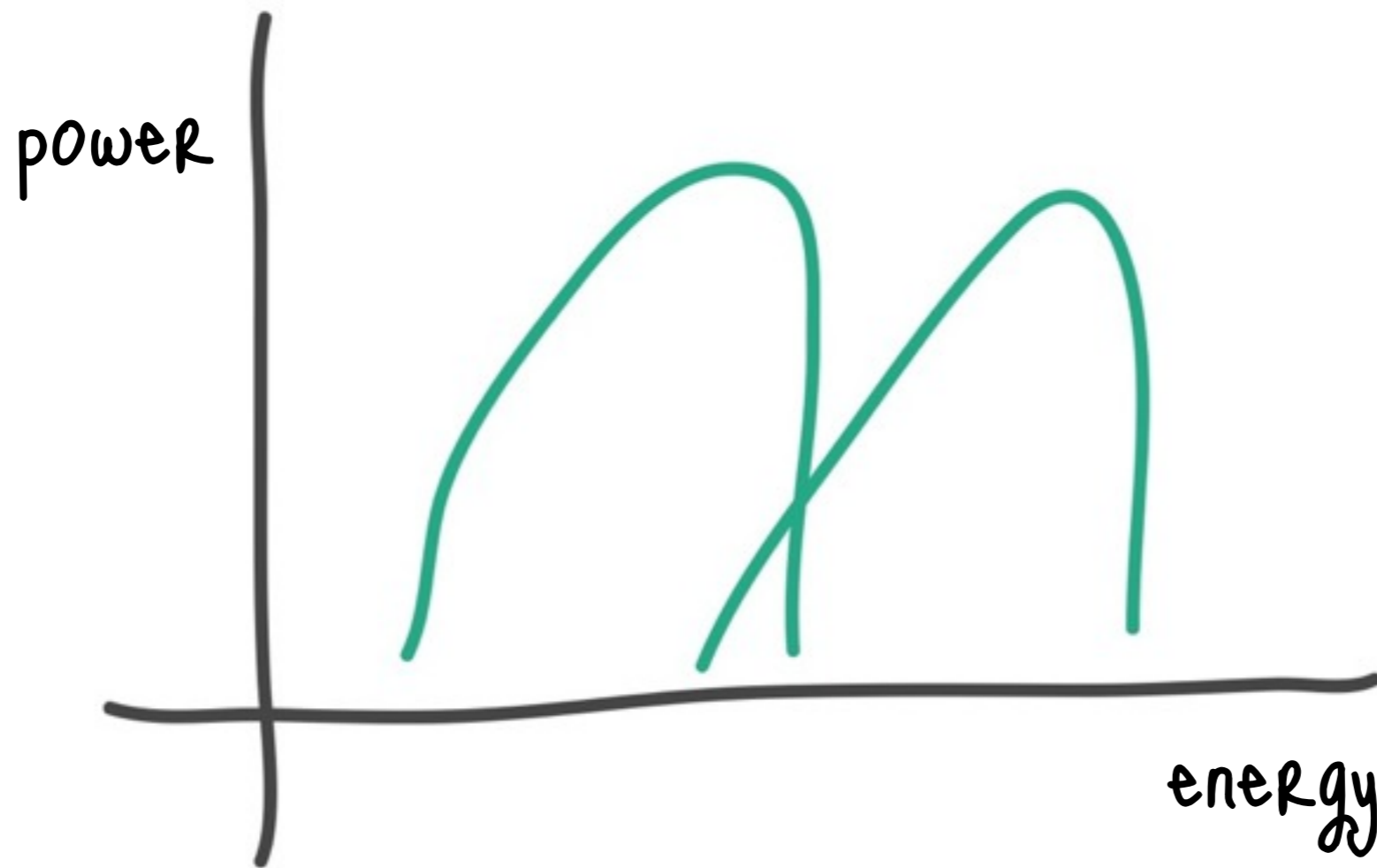
- The optical depth is then defined as:  $\tau_{e^\pm} = \frac{\sigma_T}{5} N X_{\text{target}} R$   
... where  $N$  is the number of soft photons,  $R$  is the radius of the plasma "blob" (assumed shape) and  $\sigma_T$  is the Thompson-scattering cross section\*
- A useful parameter that can then be derived\*\* is the compactness of the source - it is a direct measure of the importance of the pair-production process

$$l = \frac{L}{R} \frac{\sigma_T}{m_e c^3}$$

- The criterion for gammas to escape from a source is ...  $\tau_{e^\pm} \sim \frac{l}{40} \ll 1$

# Blazars

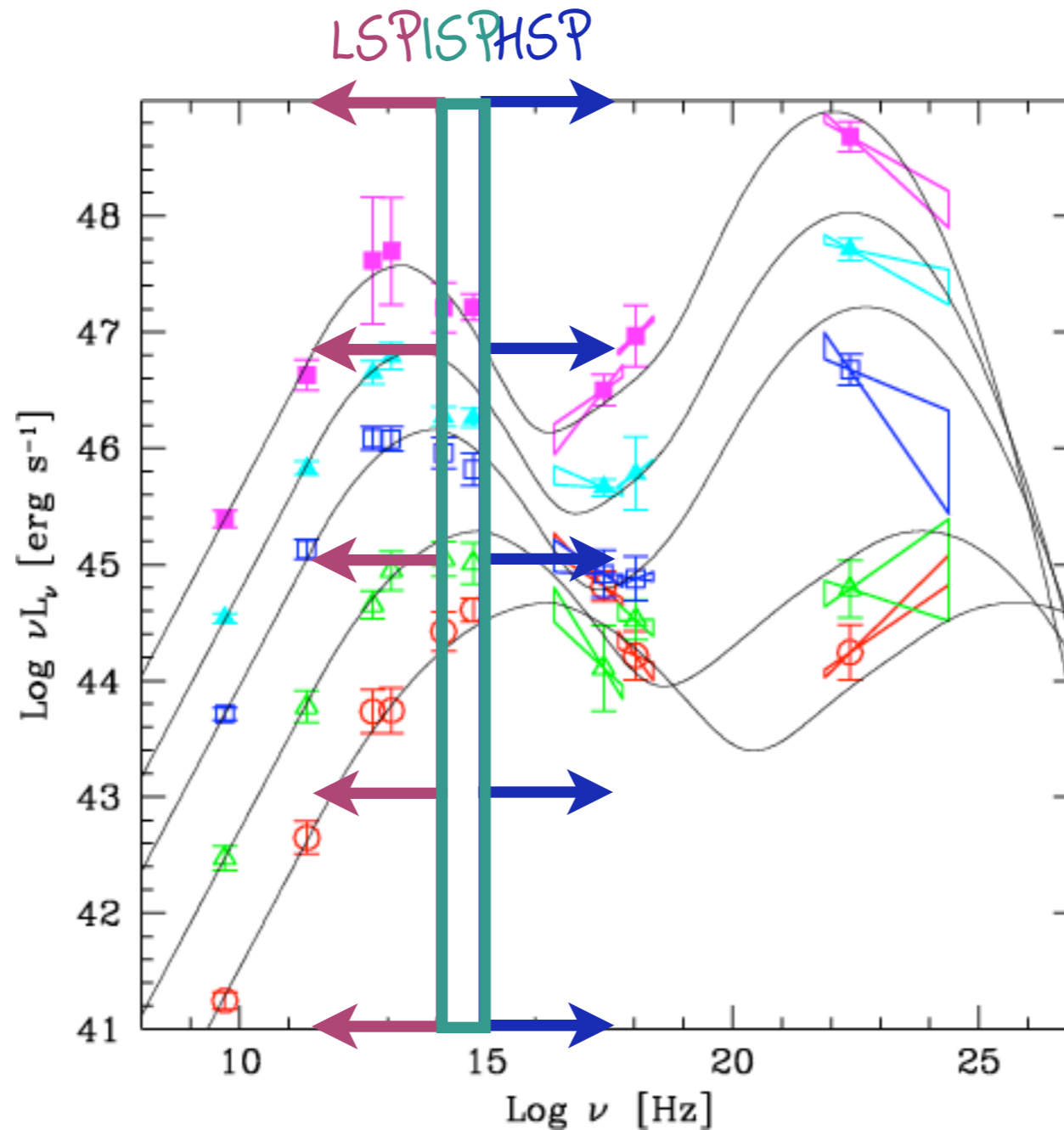
## SPECTRAL ENERGY DISTRIBUTION





# Blazars

## SPECTRAL ENERGY DISTRIBUTION



Before, definitions were based on ratio of flux at 5GHz to that at 1 keV

Models of blazar emission

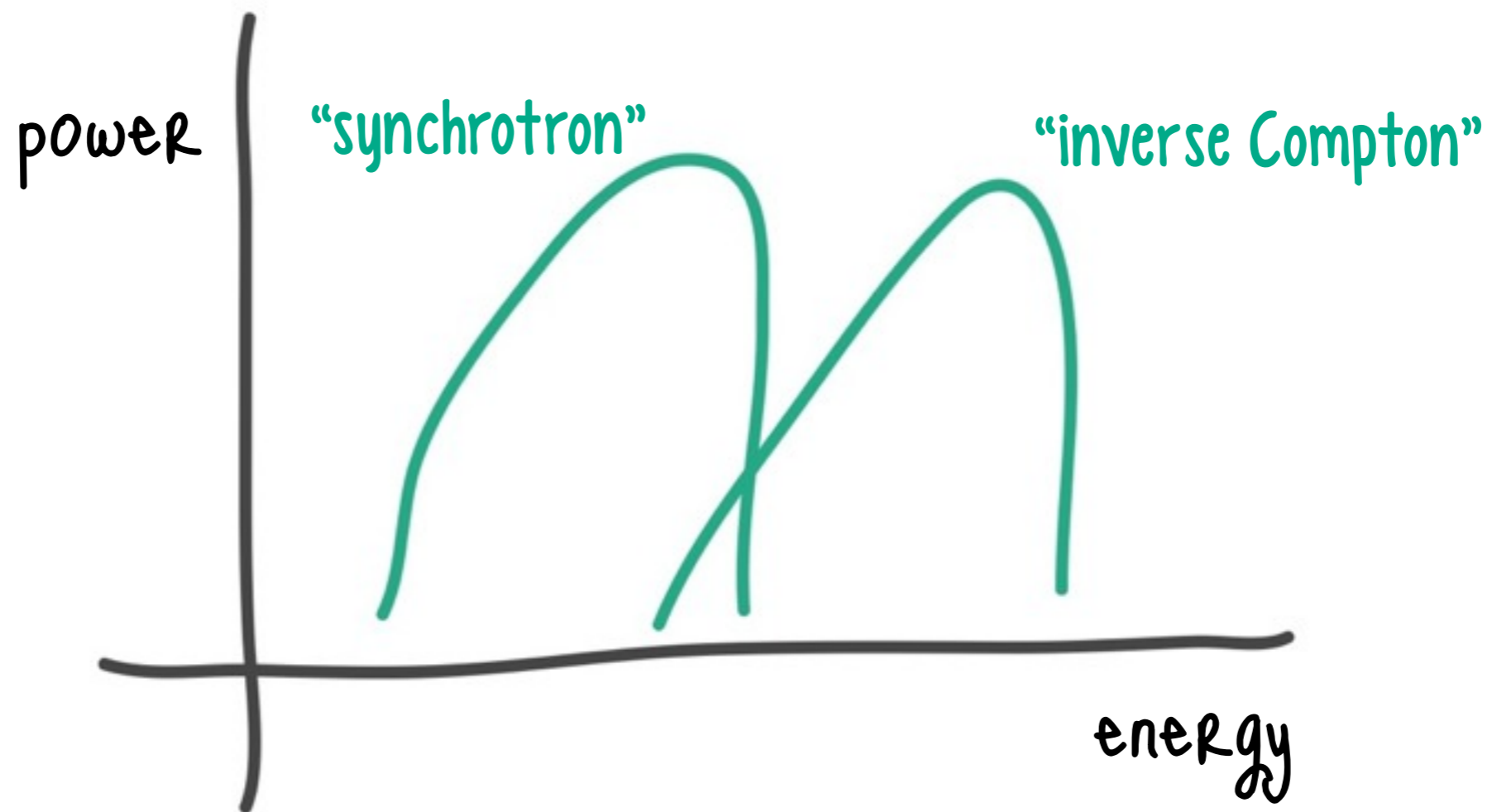
3/9



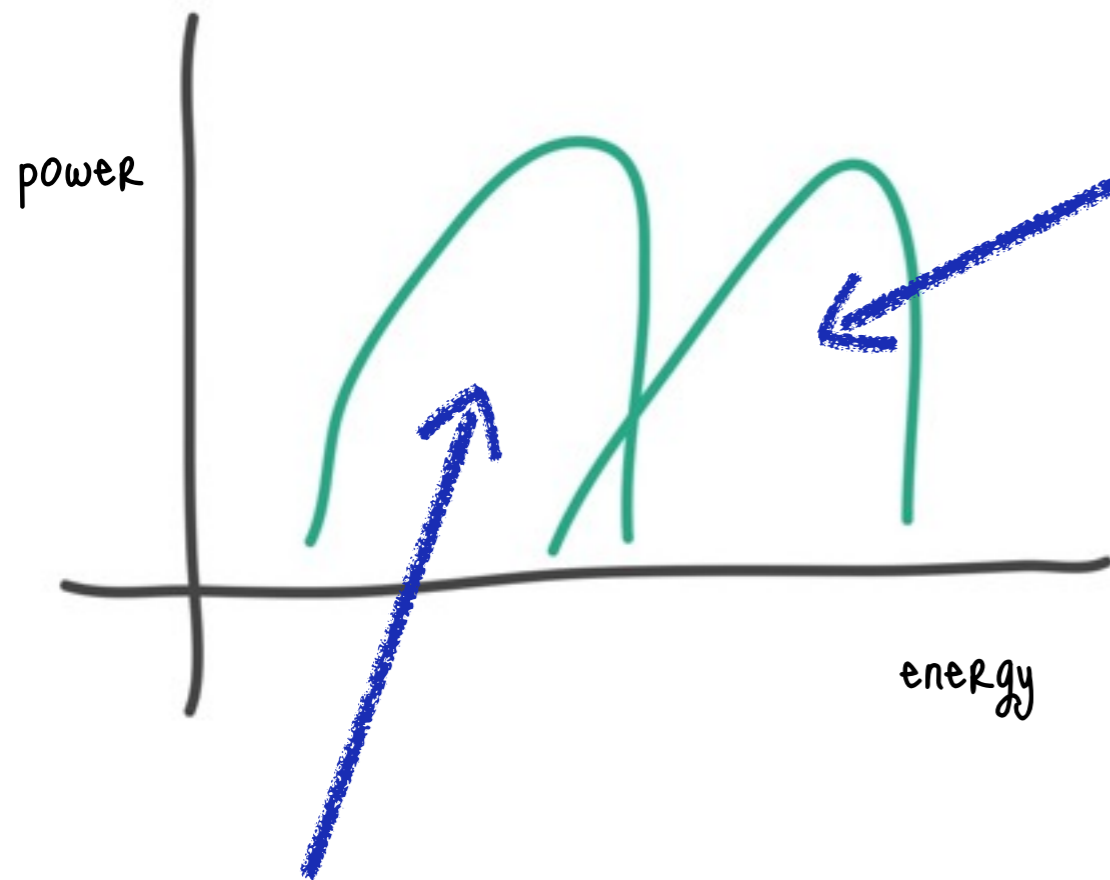
# Models of blazar emission

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## SPECTRAL ENERGY DISTRIBUTION



# Models of blazar emission

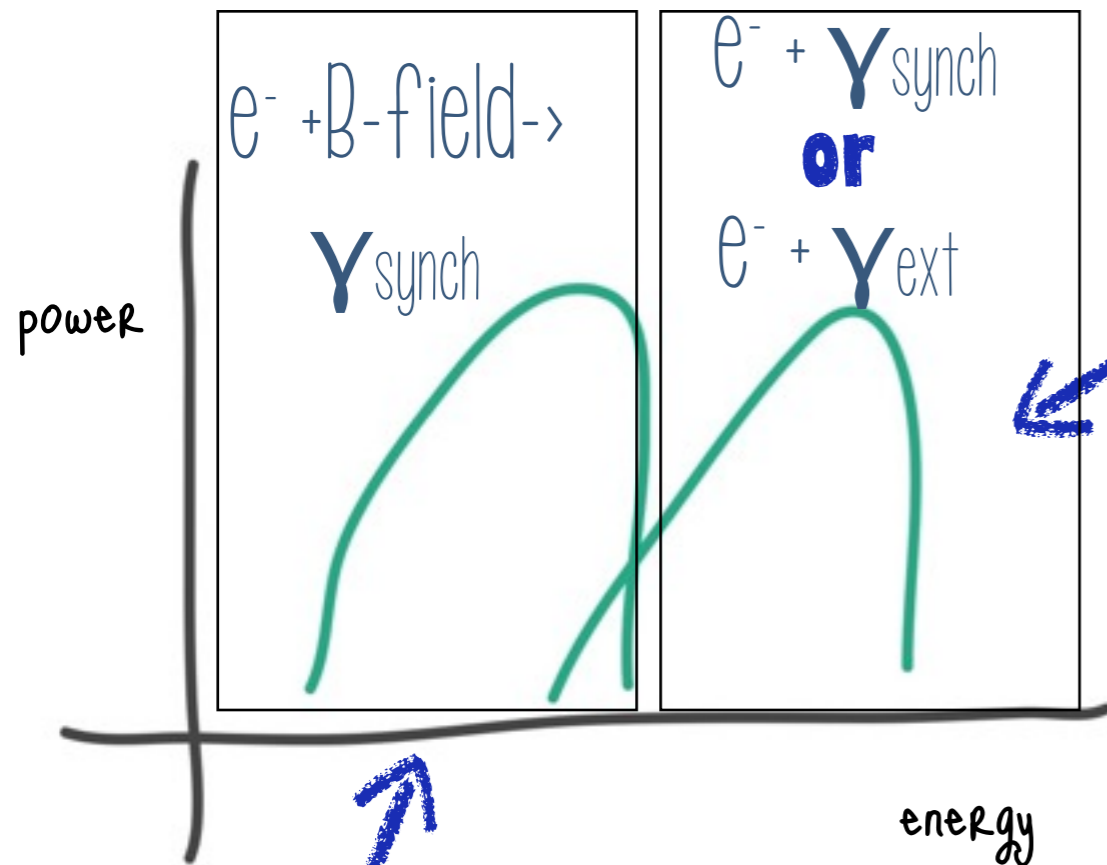


Two fundamentally different approaches to explain the higher energy emission

- Leptonic & Hadronic

Lower energy emission due to synchrotron emission from relativistic  $e^-$ s in the jet

# Models of blazar emission



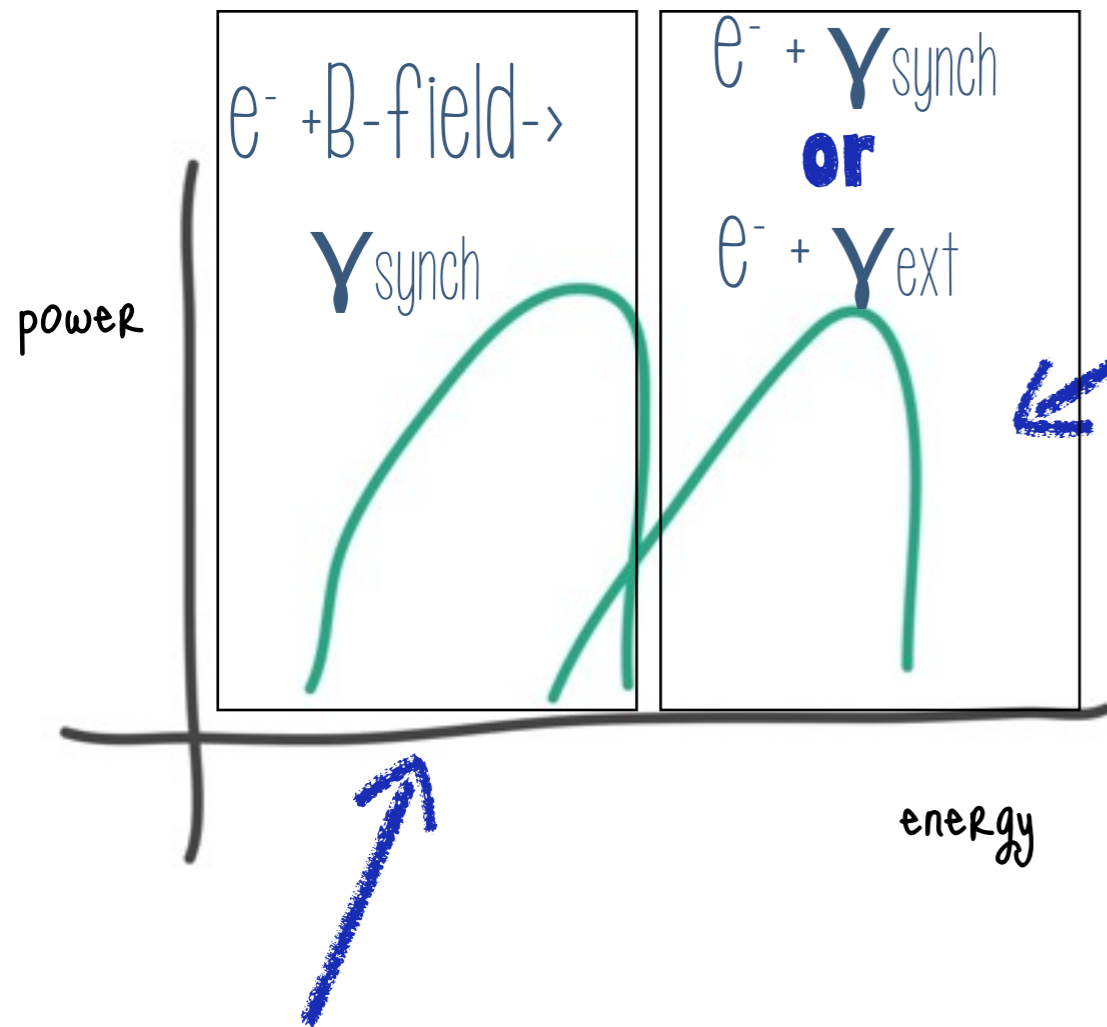
Lower energy emission due to synchrotron emission from relativistic  $e^-$  in the jet

Two fundamentally different approaches to explain the higher energy emission

## • Leptonic & Hadronic

- radiative output dominated by  $e^-/e^+$
- high-energy photons most likely the result of inverse Compton scattering by the same  $e^-$ s that produced the synch
  - upscatter the low-energy photons responsible for first bump
    - synchrotron self-Compton
  - upscatter photons from the broad-line region, disc, torus ...
    - external Compton

# Models of blazar emission



Lower energy emission due to synchrotron emission from relativistic  $e^-$ s in the jet

BOETTCHER, M. (2012) FERMI & JANSKY, ASTRO-PH/1205.0539  
BOETTCHER M. (2013), APJ (IN PRESS), ASTRO-PH/1304.0605

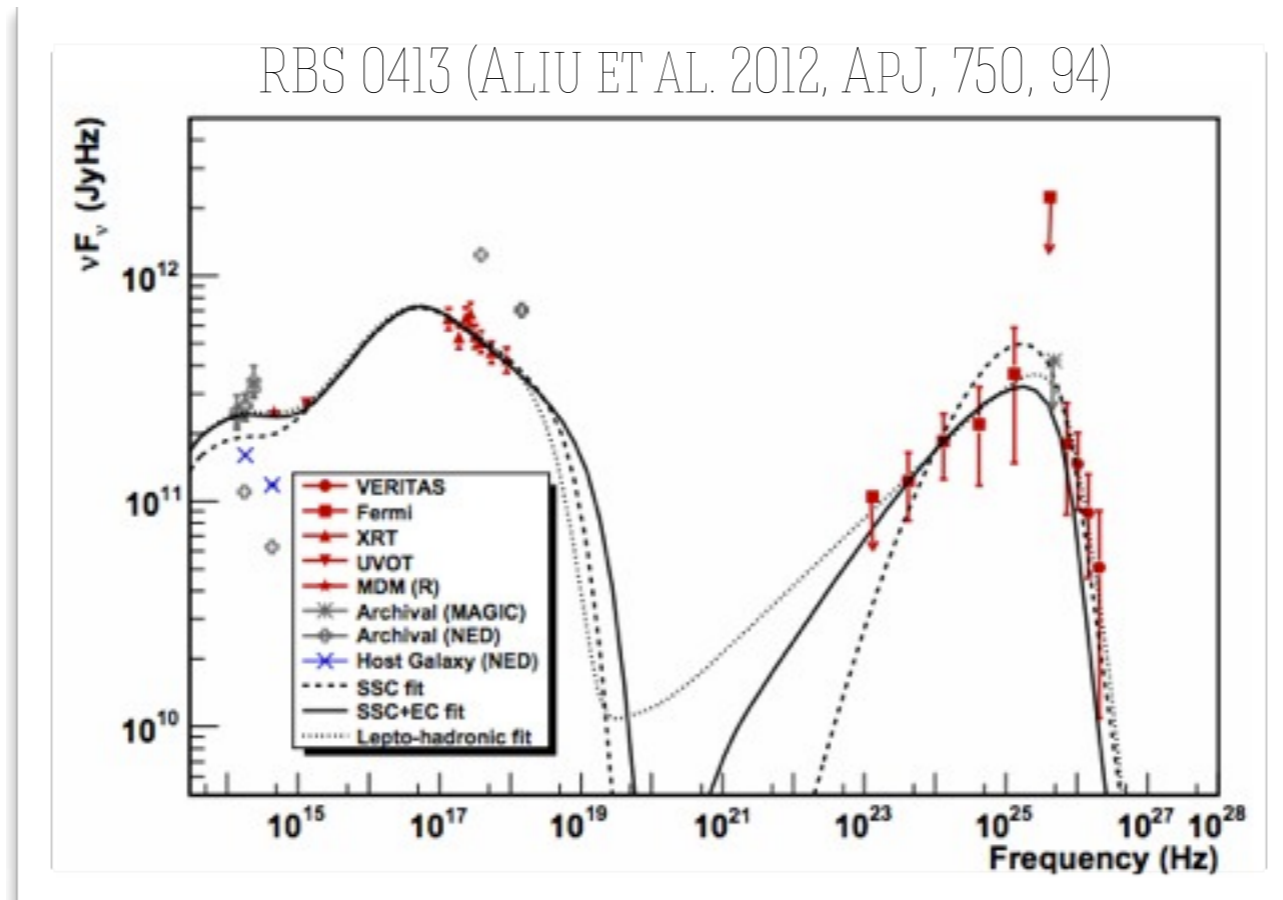
Two fundamentally different approaches to explain the higher energy emission

## • Leptonic & Hadronic

- both  $e^-/e^+$  and  $p$  accelerated to ultra-relativistic energies
- $p$ 's exceed threshold for  $p\gamma$  photo-pion production on soft photon field in emission region
- high energy emission dominated by
  - proton synchrotron
  - $\pi^0$  decay products
  - synchrotron and Compton emission from secondary products of charged pions
    - external Compton

# Models of blazar emission

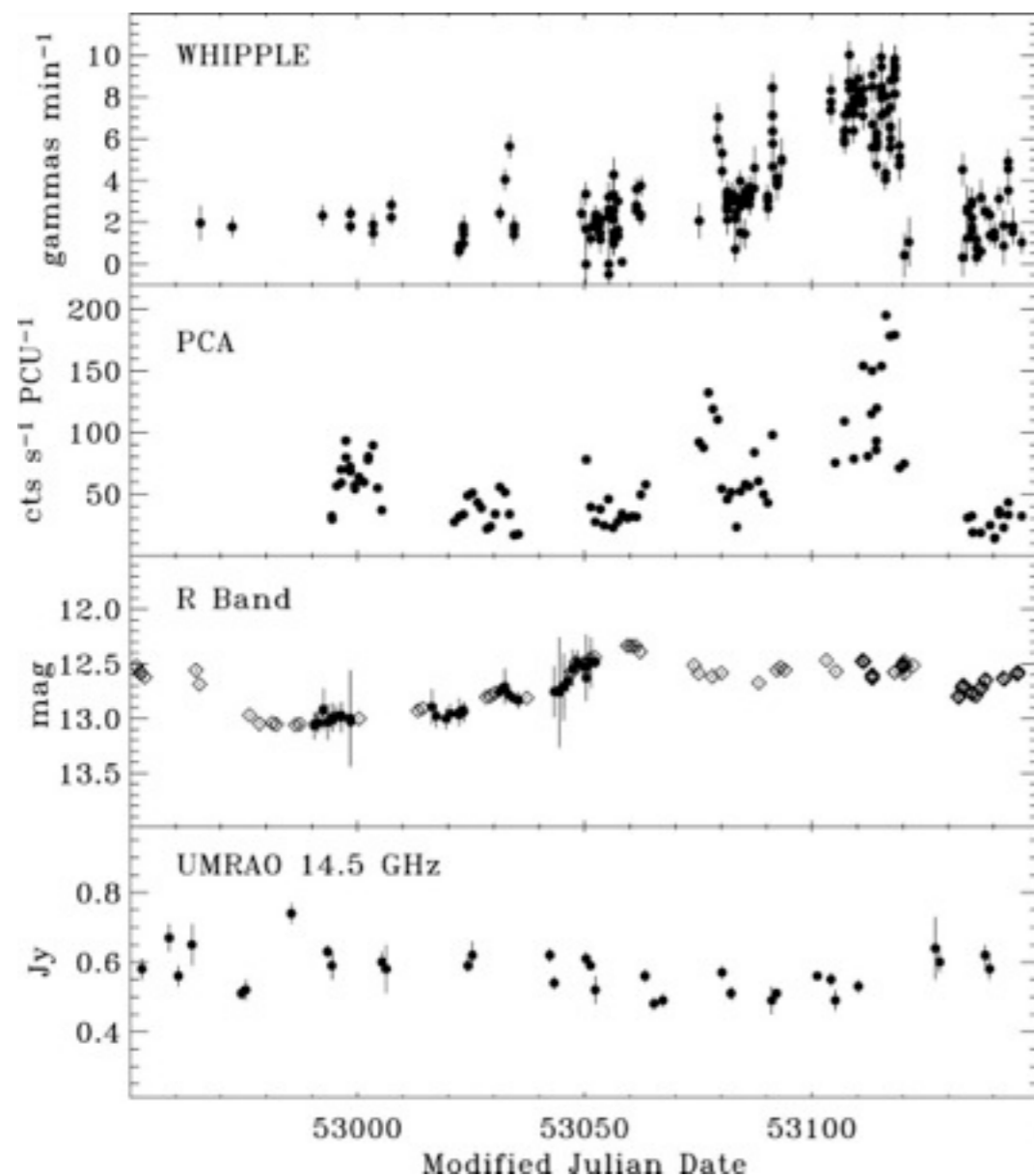
- leptonic models provide good fits to many blazars



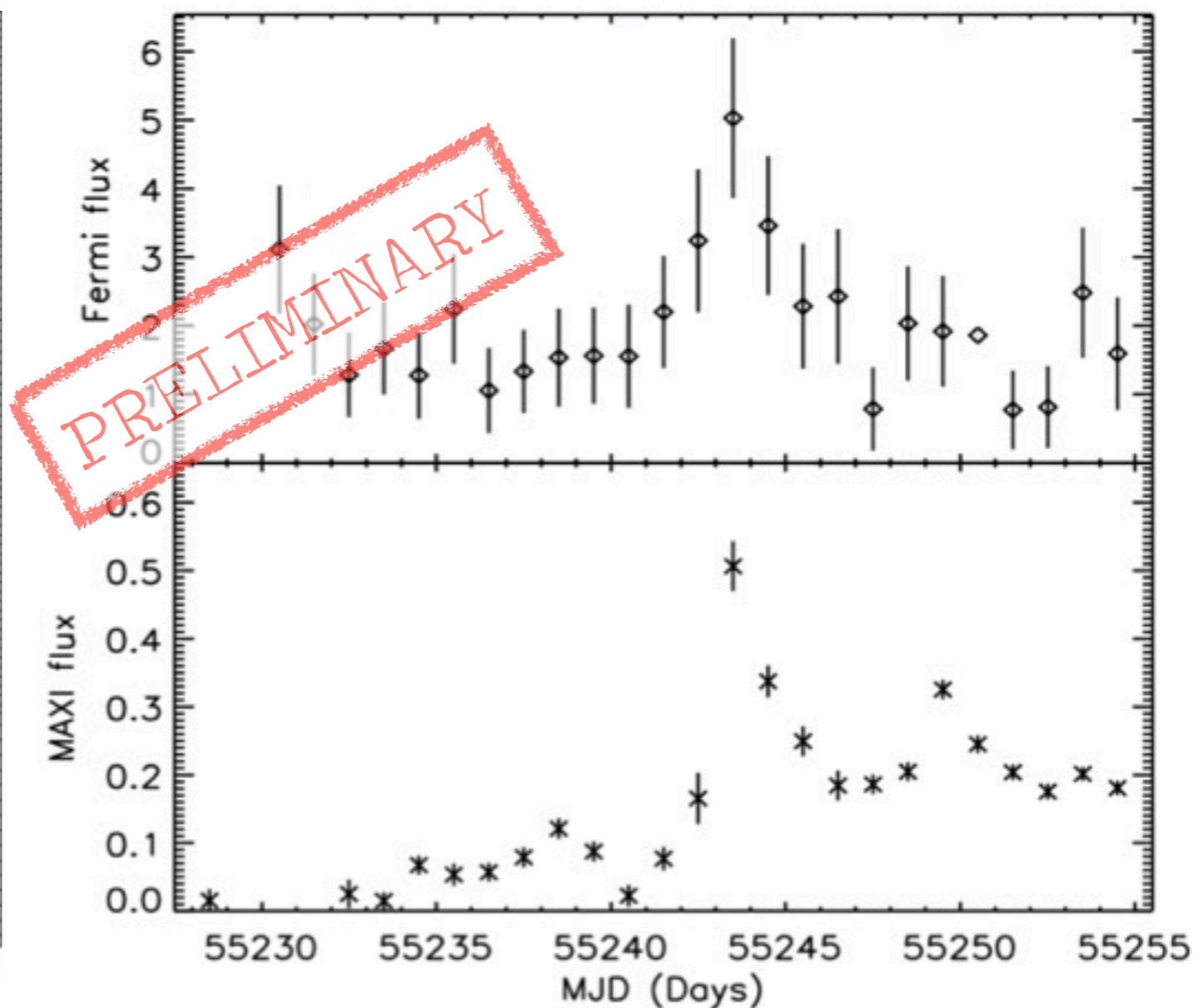
# Models of blazar emission

- leptonic models provide good fits to many blazars
- **X-ray and gamma-ray emission often correlated - a fact naturally explained by SSC models**

BLAZEJOWSKI, M. ET AL. 2005, APJ, 630, 130



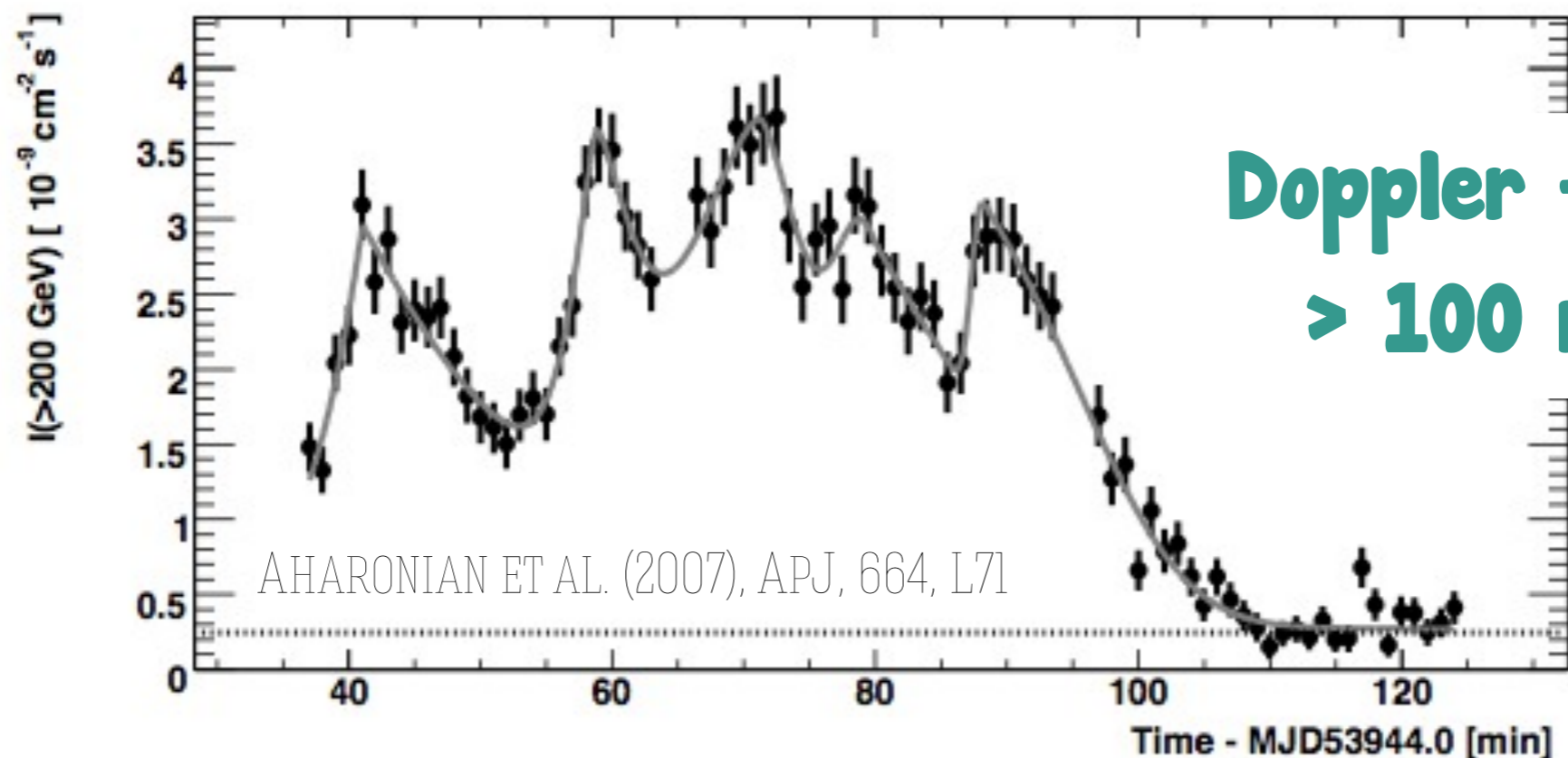
FORTSON ET AL. (2012) GAMMA 2012





# Models of blazar emission

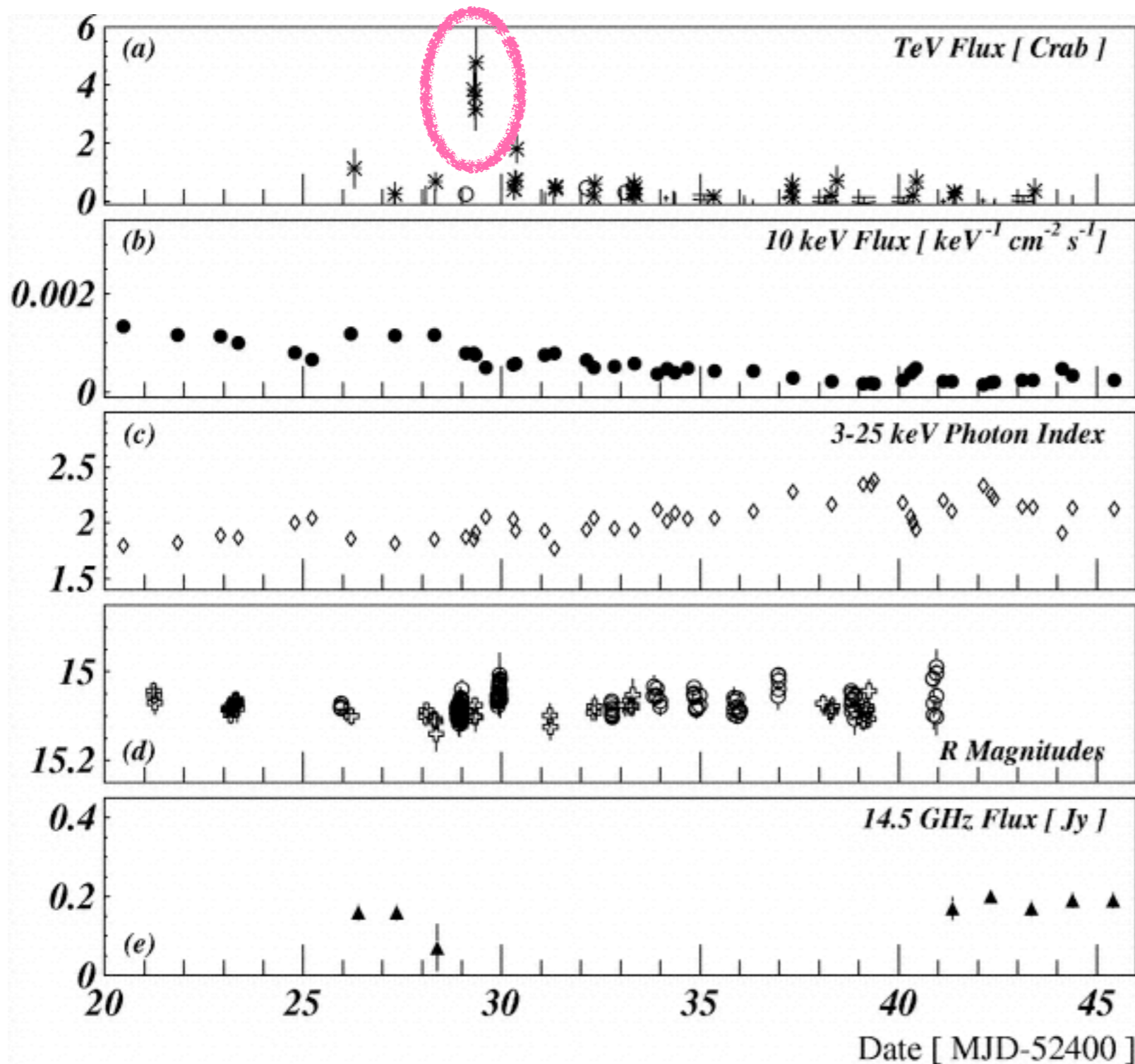
- leptonic models provide good fits to many blazars
- **X-ray and gamma-ray emission often correlated - a fact naturally explained by SSC models**
- in hadronic models, the cooling times are longer, which makes it more difficult to explain the rapid variability often seen in blazars
  - proton synchrotron can produce rapid variability with very high energy protons in extremely magnetised, compact regions HOLDER, J. (2012), ASTROPART. PHYS., 39, 61



**Doppler factors of  
> 100 required**

# Models of blazar emission

KRAWCZYNSKI ET AL. (2004), APJ 601, 151



“orphan” flare  
from TeV blazar,  
1ES 1959+650

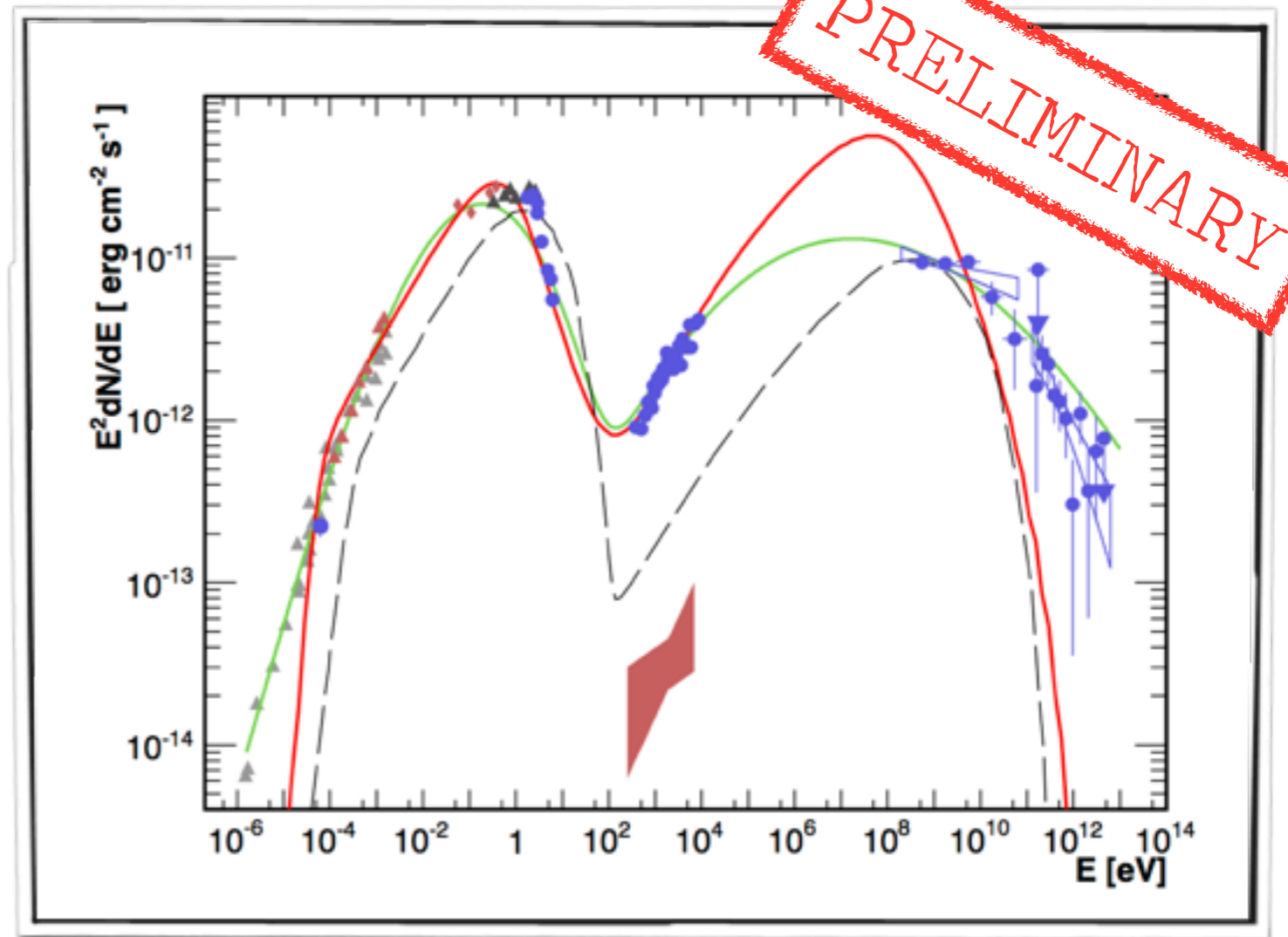
hadronic models have  
been invoked to  
explain this behaviour

E.G., BOETTCHER (2005), APJ, 621, 176  
SAHU ET AL. (2013), PHYS. REV. D  
... (IN PRESS) ASTRO-PH/1305.4985

# Models of blazar emission

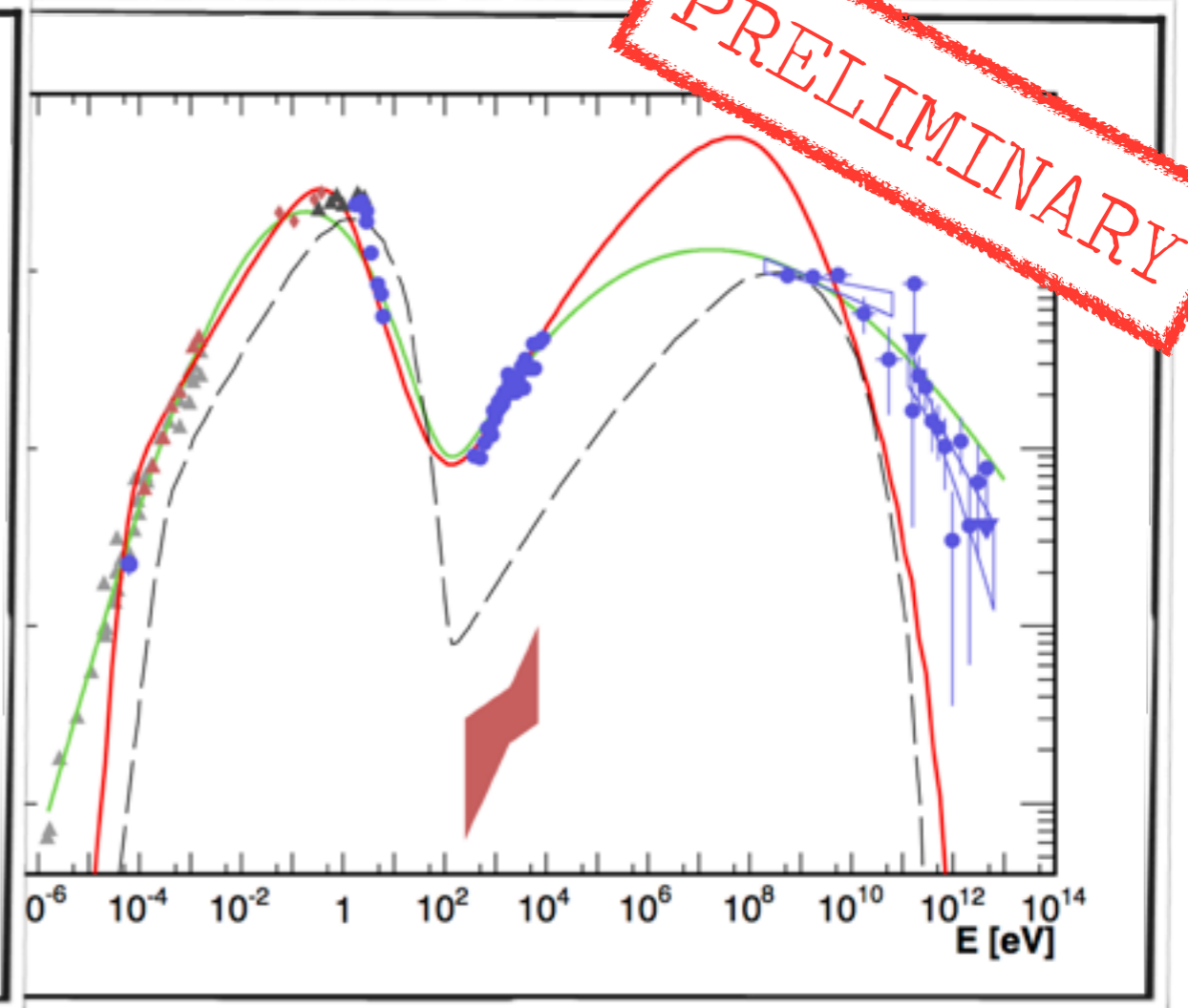
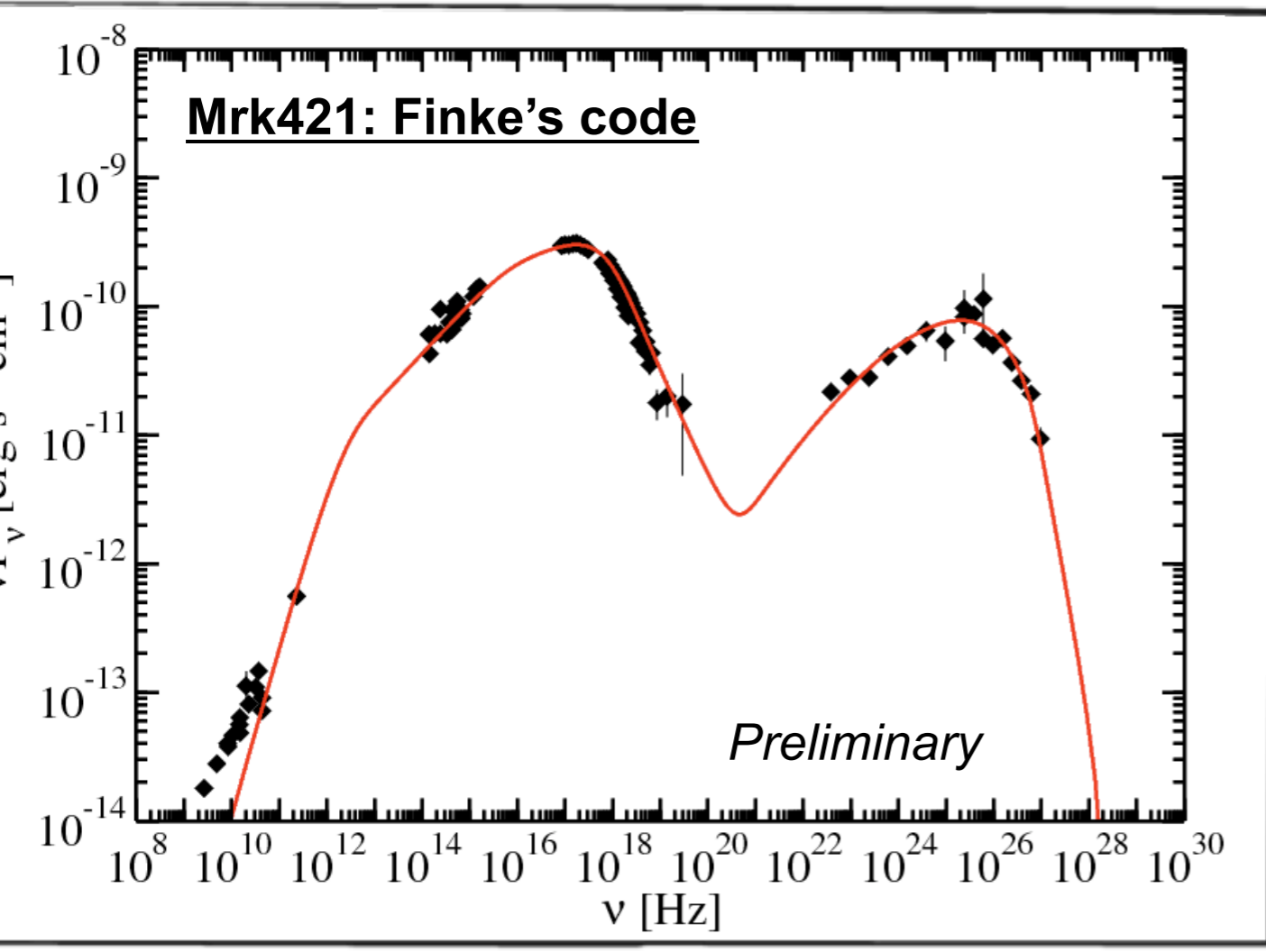
H.E.S.S. COLLABORATION ET AL. (2013 - IN PRESS) DAVID SANCHEZ & PASCAL FORTIN

- VHE emission discovered by H.E.S.S. (ATel July 2010)
- Hard Fermi spectrum (2.1) and nearby ( $z=0.049$ )
  - ➔ excellent candidate for TeV emission
- X-ray observations taken simultaneously with VHE reveal onset of HE component at unusually low energies for a TeV BL Lac



# Models of blazar emission

H.E.S.S. COLLABORATION ET AL. (2013 - IN PRESS) DAVID SANCHEZ & PASCAL FORTIN

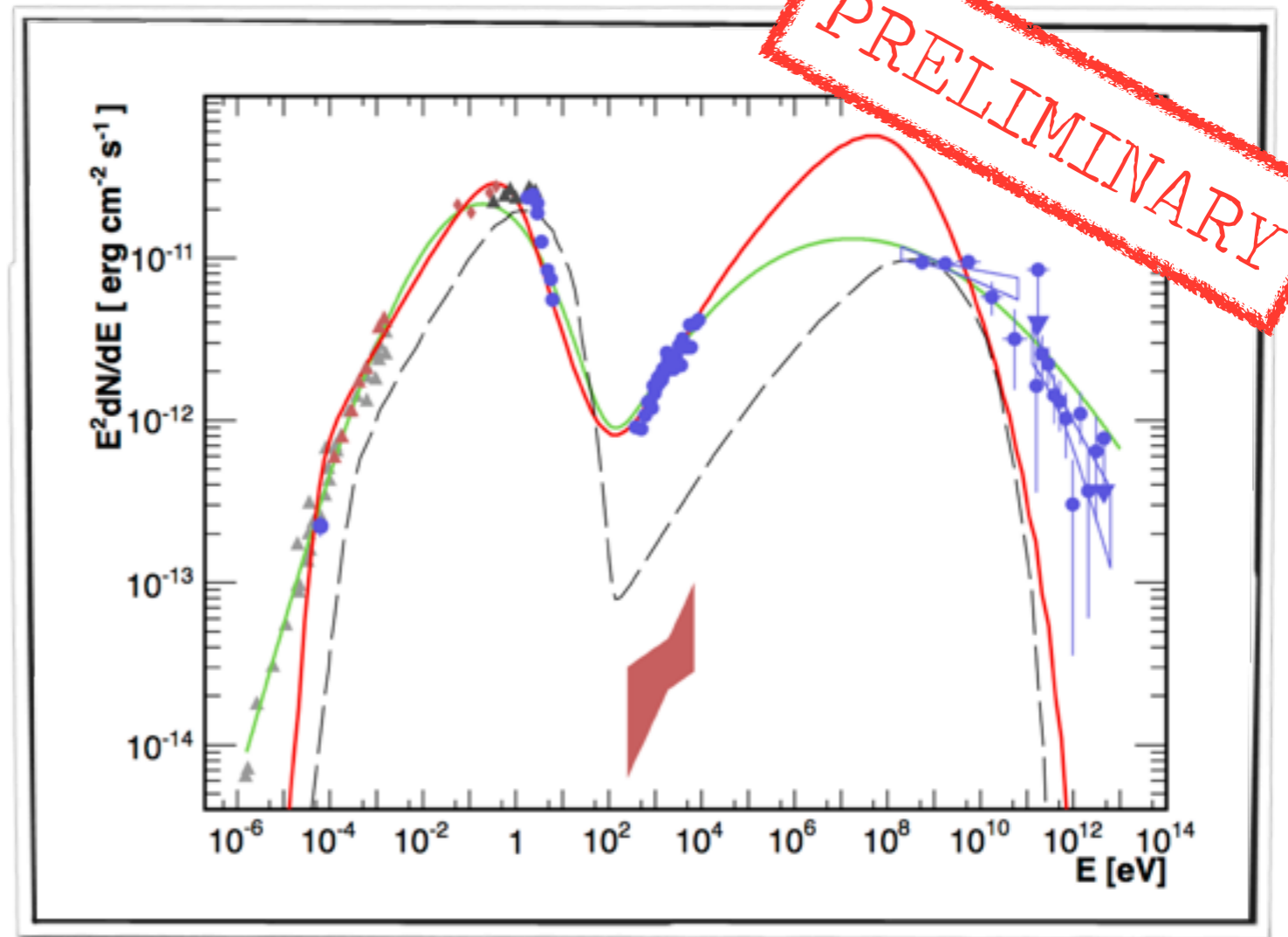


at unusually low energies for a TeV BL Lac

# Models of blazar emission

H.E.S.S. COLLABORATION ET AL. (2013 - IN PRESS) DAVID SANCHEZ & PASCAL FORTIN

- VHE emission discovered by H.E.S.S. (ATel July 2010)
- Hard Fermi spectrum (2.1) and nearby ( $z=0.049$ )
  - ➔ excellent candidate for TeV emission
- X-ray observations taken simultaneously with VHE reveal onset of HE component at unusually low energies for a TeV BL Lac



Difficult to model with a single zone homogeneous SSC model due to the unprecedented width of the HE component compared to the LE component

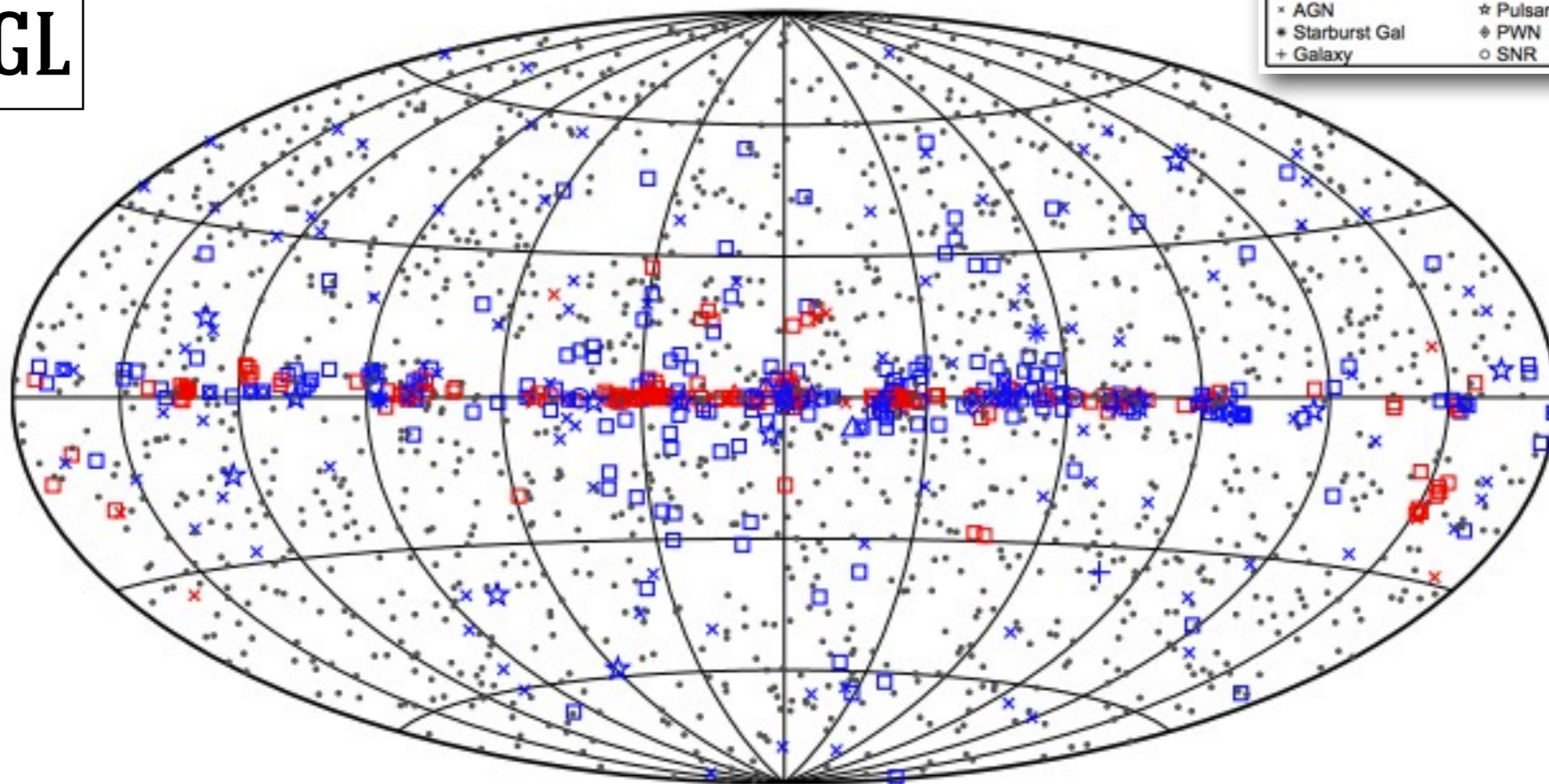
# **The Fermi blazars**

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# The Fermi blazars

2FGL



- |                  |  |                    |
|------------------|--|--------------------|
| □ No association | ★ Possible association with SNR or PWN | △ Globular cluster |
| ★ AGN            | ★ Pulsar                               | ■ HMB              |
| ★ Starburst Gal  | ◆ PWN                                  | ● Nova             |
| + Galaxy         | ○ SNR                                  |                    |

NOLAN ET AL. (2012), APJS, 199, 31



**1873 SOURCES**  
**1298 IDENTIFIED/ASSOCIATED**

**84%**  
**AGN\***

\*74%  
blazars

# The Fermi blazars

1 **LBAS** (Abdo et. al 2009, ApJ 700, 597)

Based on OGL, 3 months data,  $\sim 10\sigma$

106 high-confidence blazars

2 **1LAC** (Abdo et. al 2010, ApJ 715, 429)

Based on 1FGL, 11 months data,  $\sim 5\sigma$

523 (blazars) / 599 (total) in clean sample

3 **2LAC** (Ackermann et. al 2011, ApJ 743, 171)

Based on 2FGL, 24 months data,  $\sim 5\sigma$

862 (blazars) / 886 (total) in clean sample

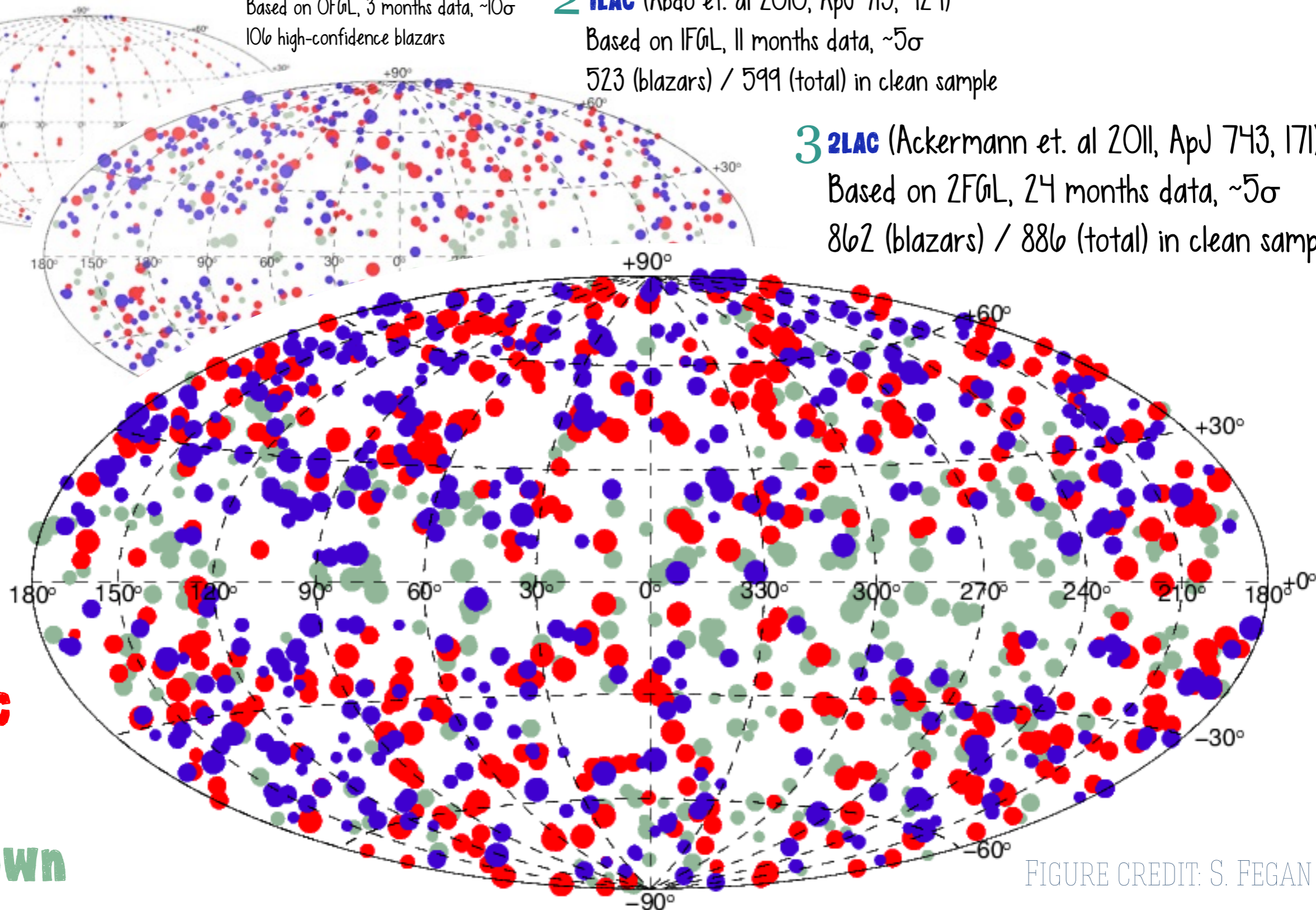
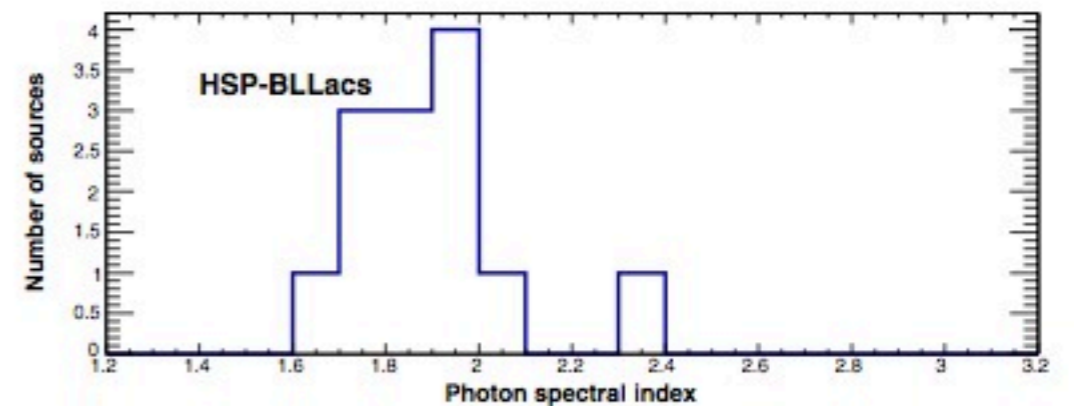
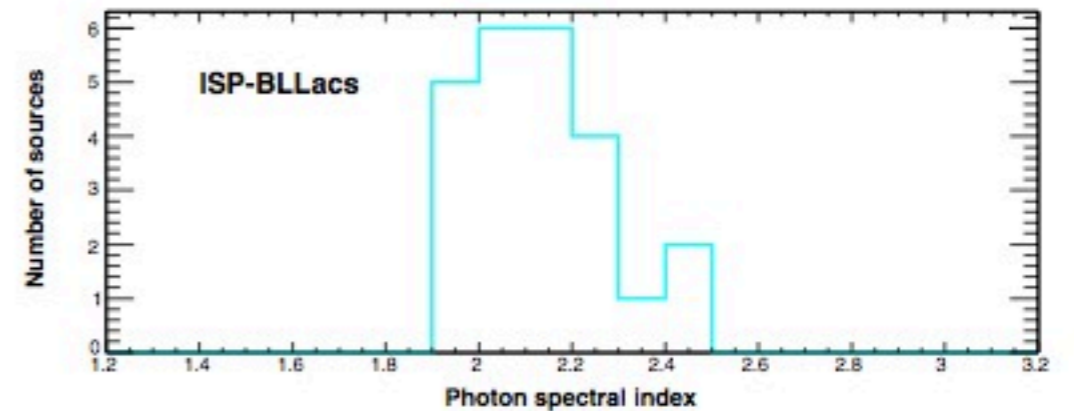
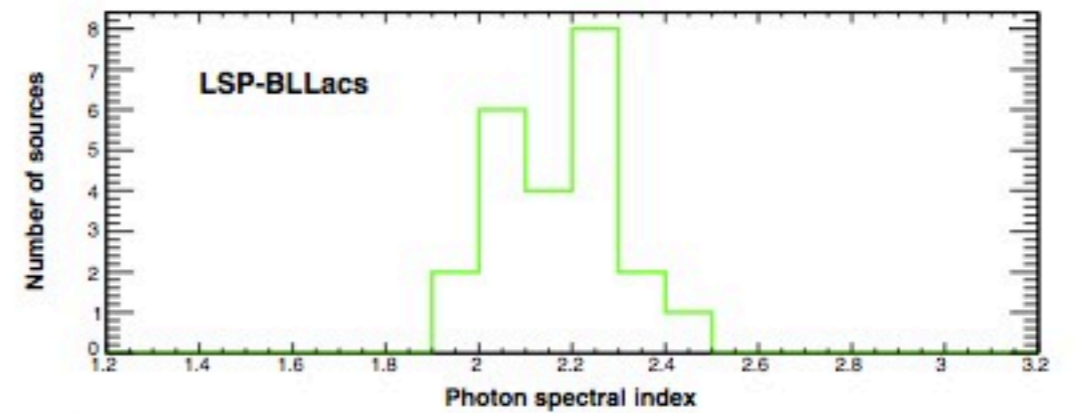
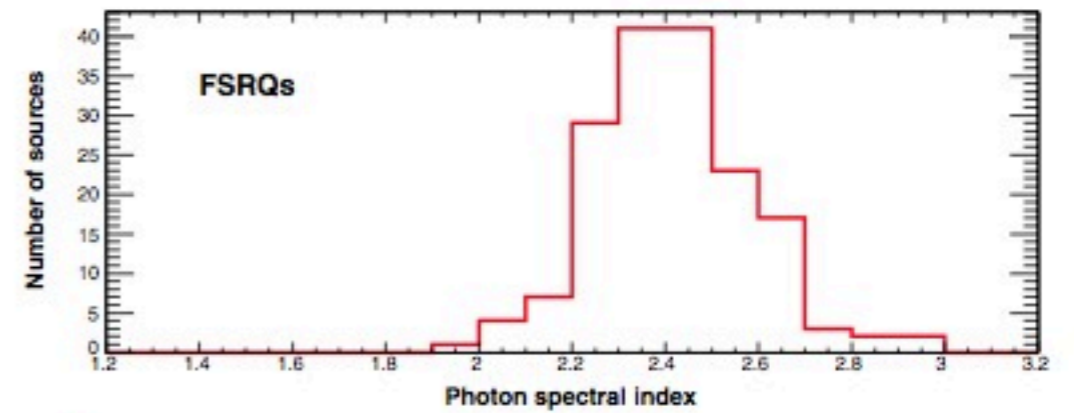
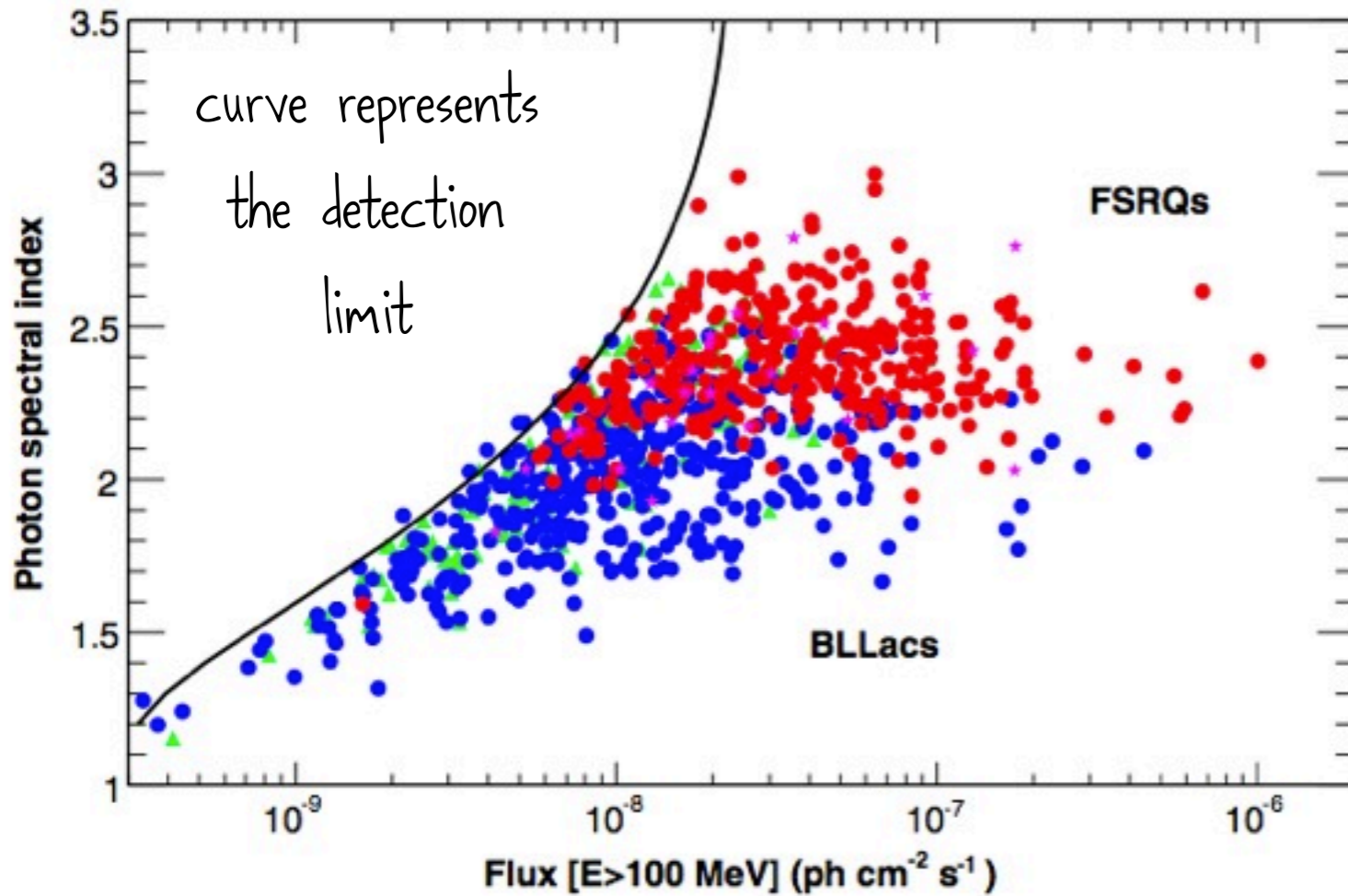


FIGURE CREDIT: S. FEGAN



# The Fermi blazars



ACKERMANN ET. AL 2011, APJ 743, 171

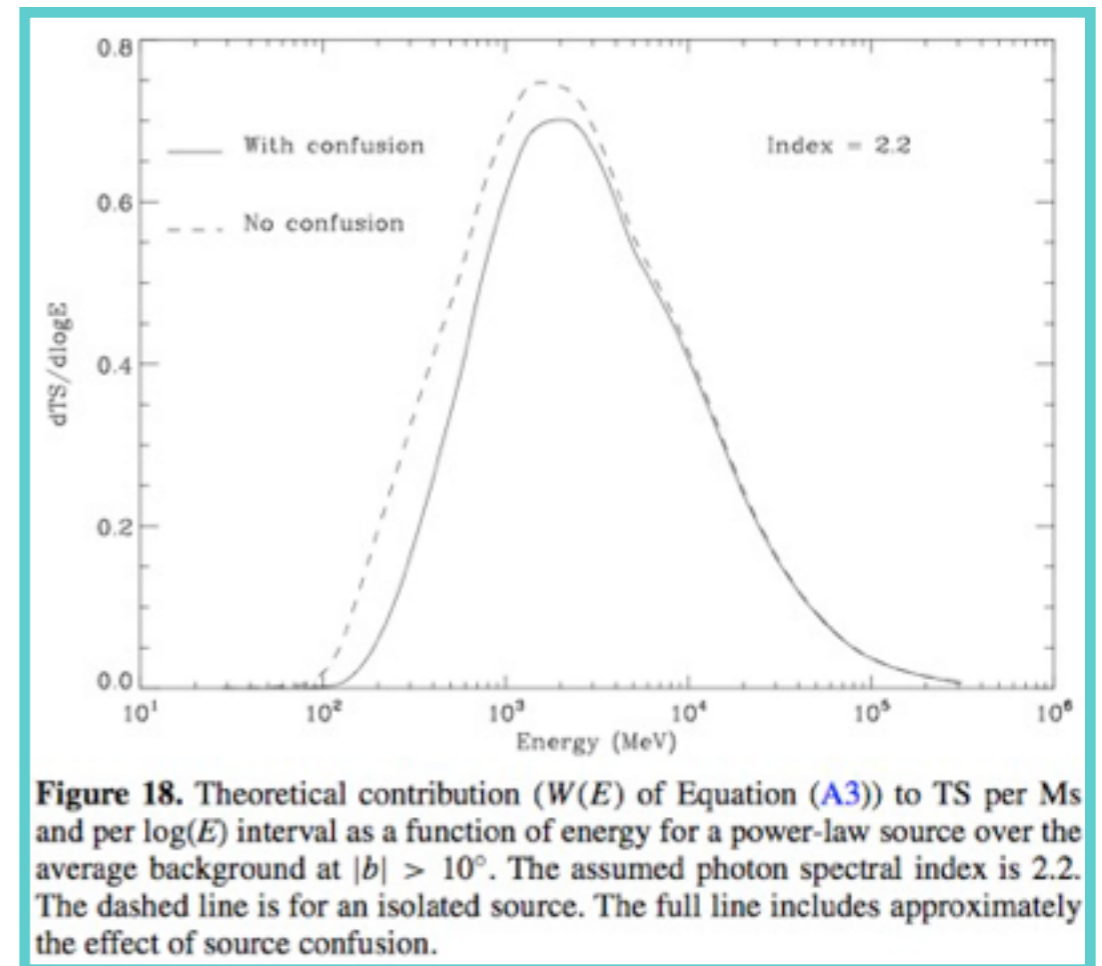
# The Fermi blazars

**Table 5**  
Census of Sources

AGN Type	Entire 2LAC	2LAC Clean Sample <sup>a</sup>	Low-lat Sample
All	1017	886	104
FSRQ	360	310	19
LSP	246	221	7
ISP	4	3	2
HSP	2	0	0
No classification	108	86	10
BL Lac	423	395	16
LSP	65	61	3
ISP	82	81	3
HSP	174	160	5
No classification	102	93	5
Blazar of unknown type	204	157	67
LSP	24	19	10
ISP	13	11	3
HSP	65	53	13
No classification	102	74	41
Other AGNs	30	24	2

**Note.** <sup>a</sup> Sources with single counterparts and without analysis flags. See Section 5 for the definitions of this sample.

ACKERMANN ET. AL 2011, APJ 743, 171

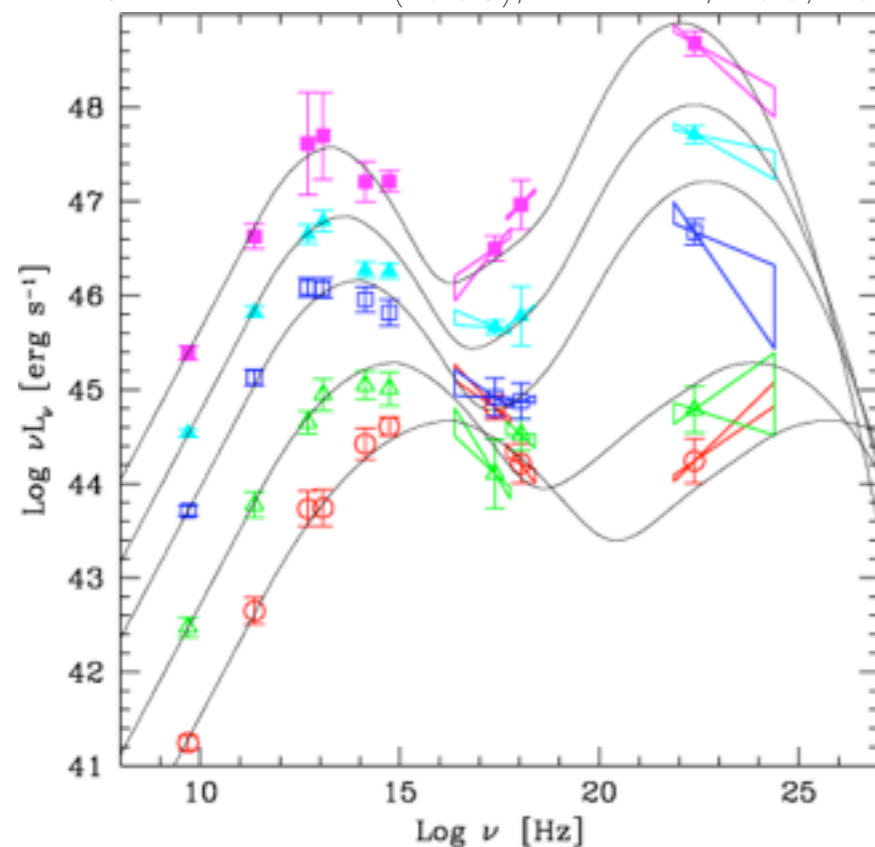


ABDO ET. AL 2010, APJS 188, 405

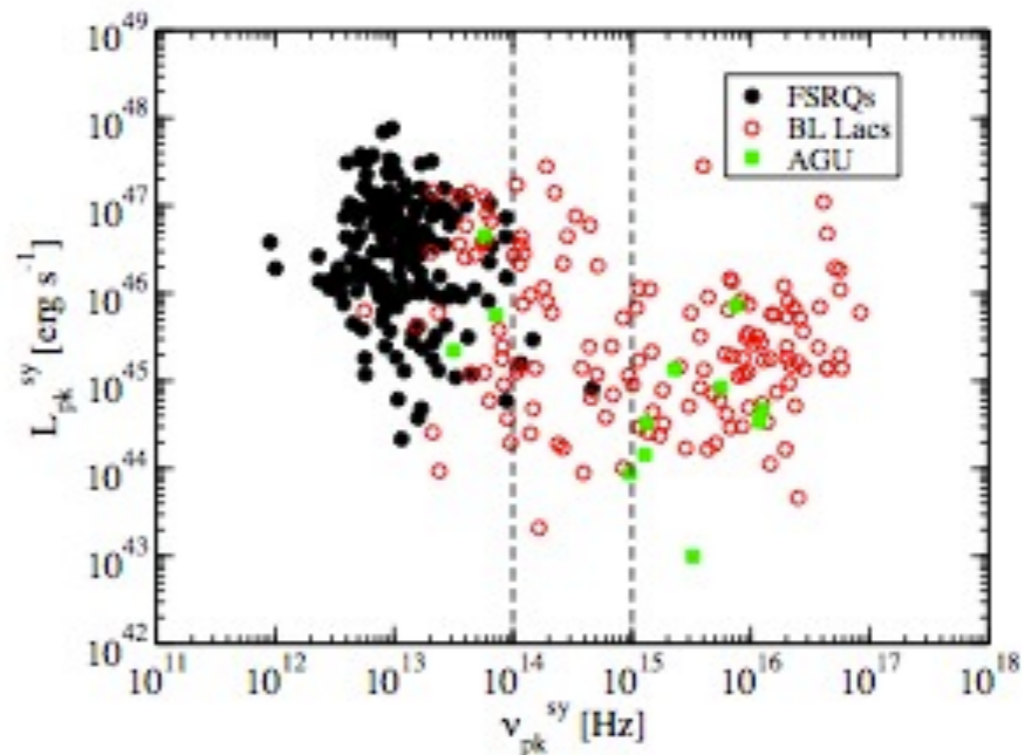
**\*8 misaligned blazars**  
**4 NLSy1s**  
**10 AGN of other type**  
**2 starbursts**

# The Fermi blazars

FOSSATI ET AL. (1998), MNRAS, 299, 433

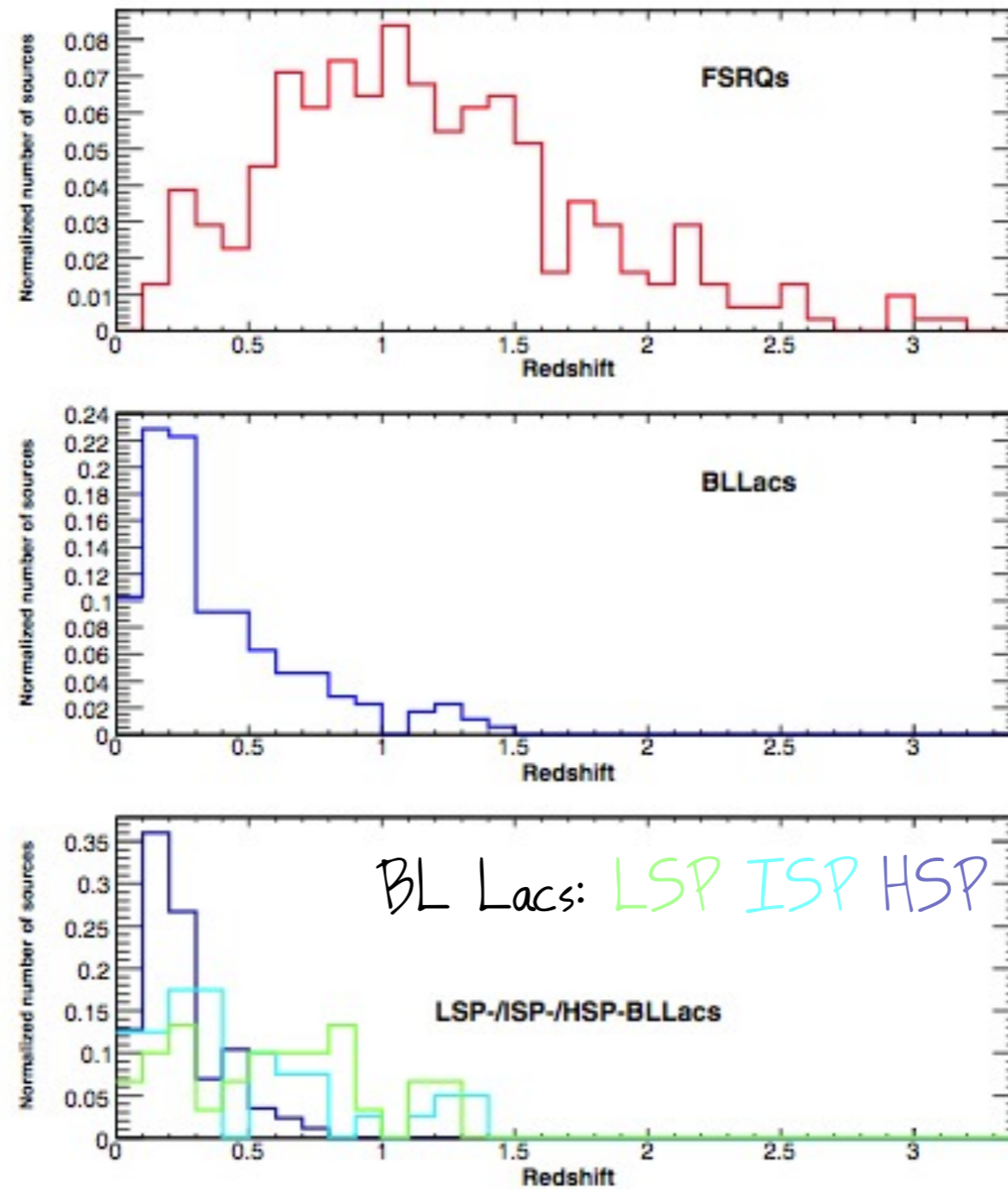


FINKE, J. (2012), FERMI-JANSKY (ASTRO-PH/1301.6081)



"If the seed photon source for external Compton scattering is the broad line region (BLR), and the BLR strength is correlated with the power injected into electrons in the jet, one would expect that more luminous jets have stronger broad emission lines and greater Compton cooling, and thus a lower  $\nu_{sy}$ . As the power injected in electrons is reduced, the broad line luminosity decreases, there are fewer seed photons for Compton scattering, and consequently the peak synchrotron frequency moves to higher frequencies. This is also reflected in the lower luminosity of the Compton-scattered component relative to the synchrotron component as  $\nu_{sy}$  moves to higher frequencies." FINKE, J. (2012), FERMI-JANSKY (ASTRO-PH/1301.6081)

# The Fermi blazars



ACKERMANN ET. AL 2011, APJ 743, 171

# The Fermi blazars

## The Hard Source List - a catalog above 10 GeV

D. PANEQUE, FERMI SYMPOSIUM (2012)

- Work is underway to publish the 1st Fermi-LAT catalog of sources  $> 10$  GeV
- Shape of the spectrum at  $> 10$  GeV might not be well characterized if we use a single fit in the energy range 0.1 GeV - 100 GeV

→ Lower energies

- The variability at lowest energies, which

**SEE LAMB & MACOMB (1997), 488, L872**

which may radiate from the same/different location

from that at the emission of particles

→ Are sources more variable at HE than at LE ? or the other way around ?

- Understand better the population of sources emitting above 10 GeV

→ What are the sources dominating the highest LAT energies?

- **IDENTIFY PROMISING CANDIDATES FOR IACTS ... NEW VHE DISCOVERIES**

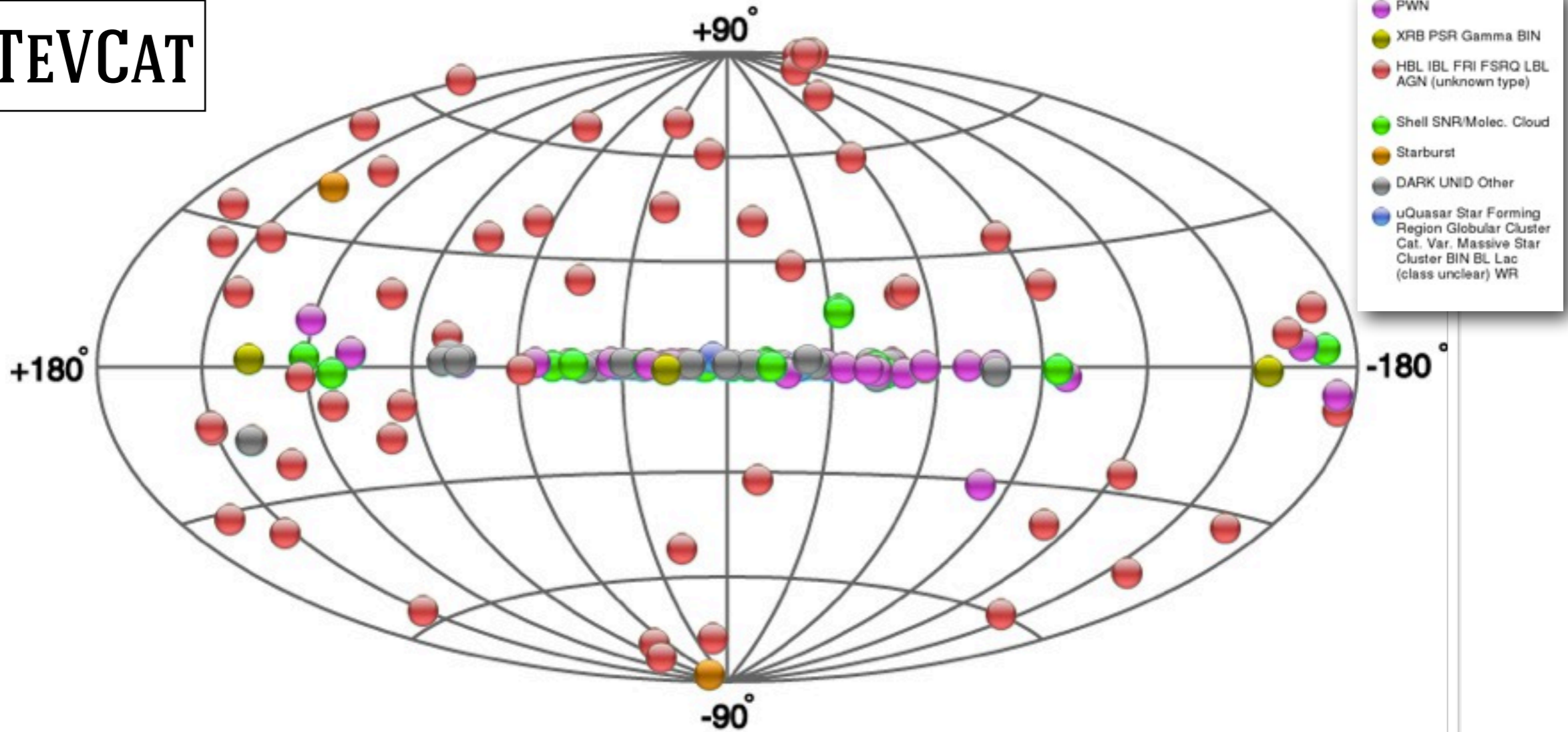
# The TeV blazars

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# The TeV blazars

TEVCAT



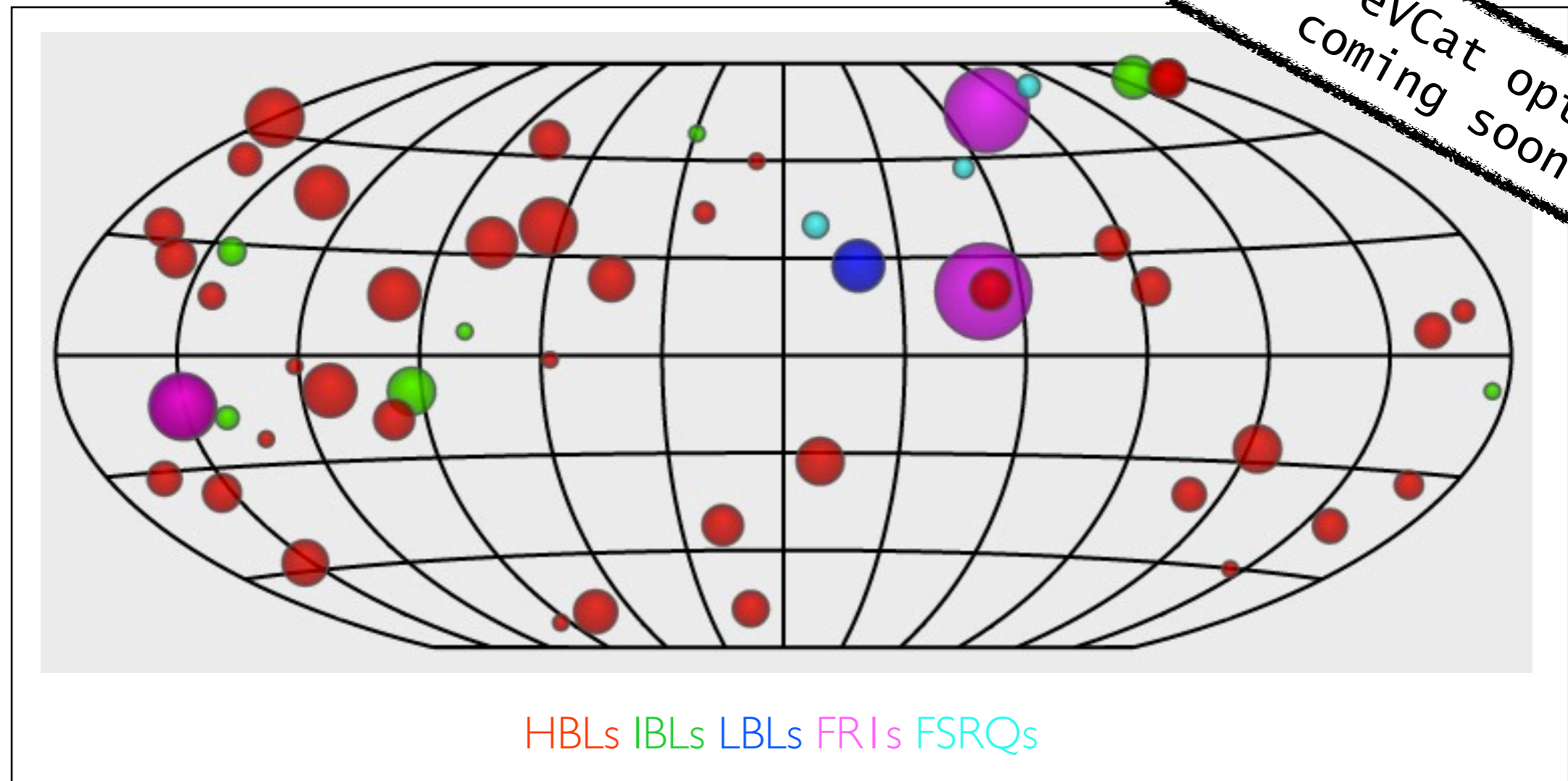
145 sources  
114 identified/associated

84%  
AGN\*

\*95%  
blazars

# The TeV blazars

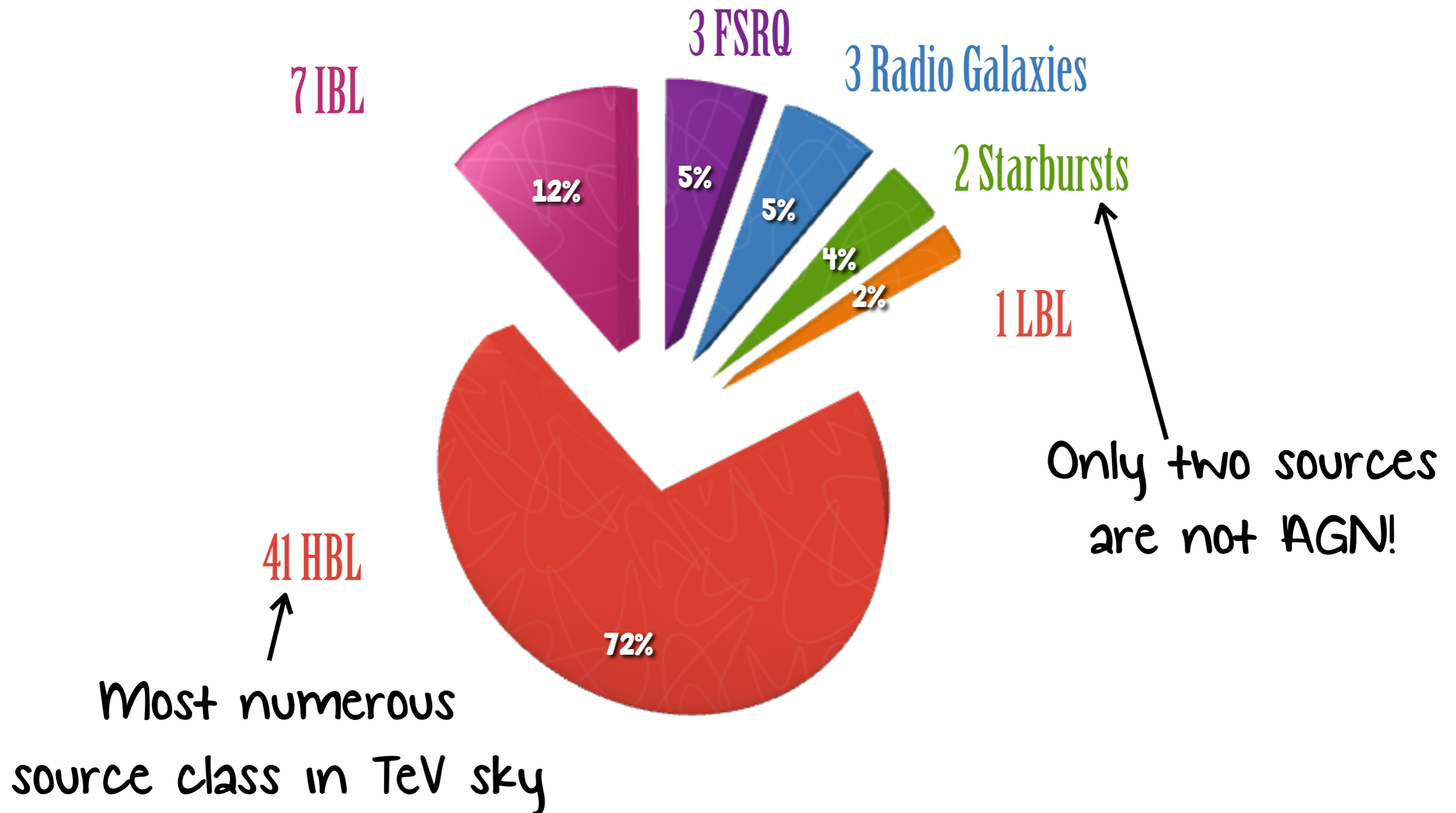
As of writing this talk, there are 145 sources in TeVCat - 57 Extragalactic





# The TeV blazars

As of writing this talk, there are 145 sources in TeVCat - 57 Extragalactic

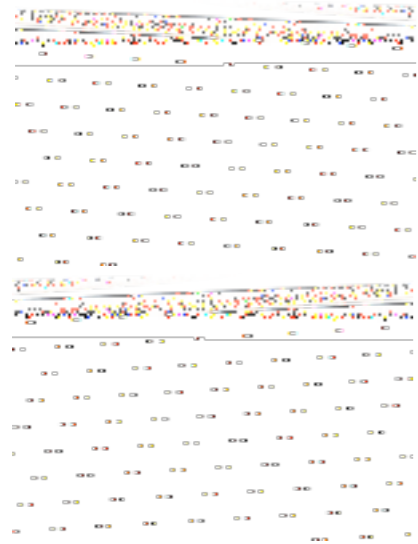


# The GeV–TeV Connection

6/9

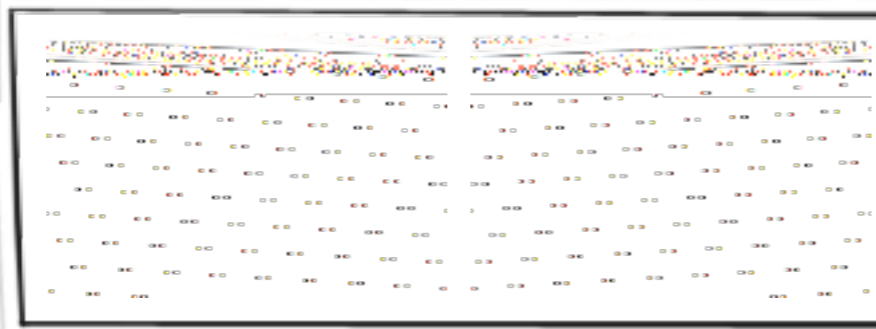


# The GeV–TeV Connection



	Total No. Sources	Total No. Identified*	No. AGN	% AGN that are blazars
GeV ... Fermi 2FGL	1873	1298 (69%)	1092 (84%)	74%
TeV ... TeVCat	145	117 (81%)	55 (47%)	96%

\*Identified / Associated

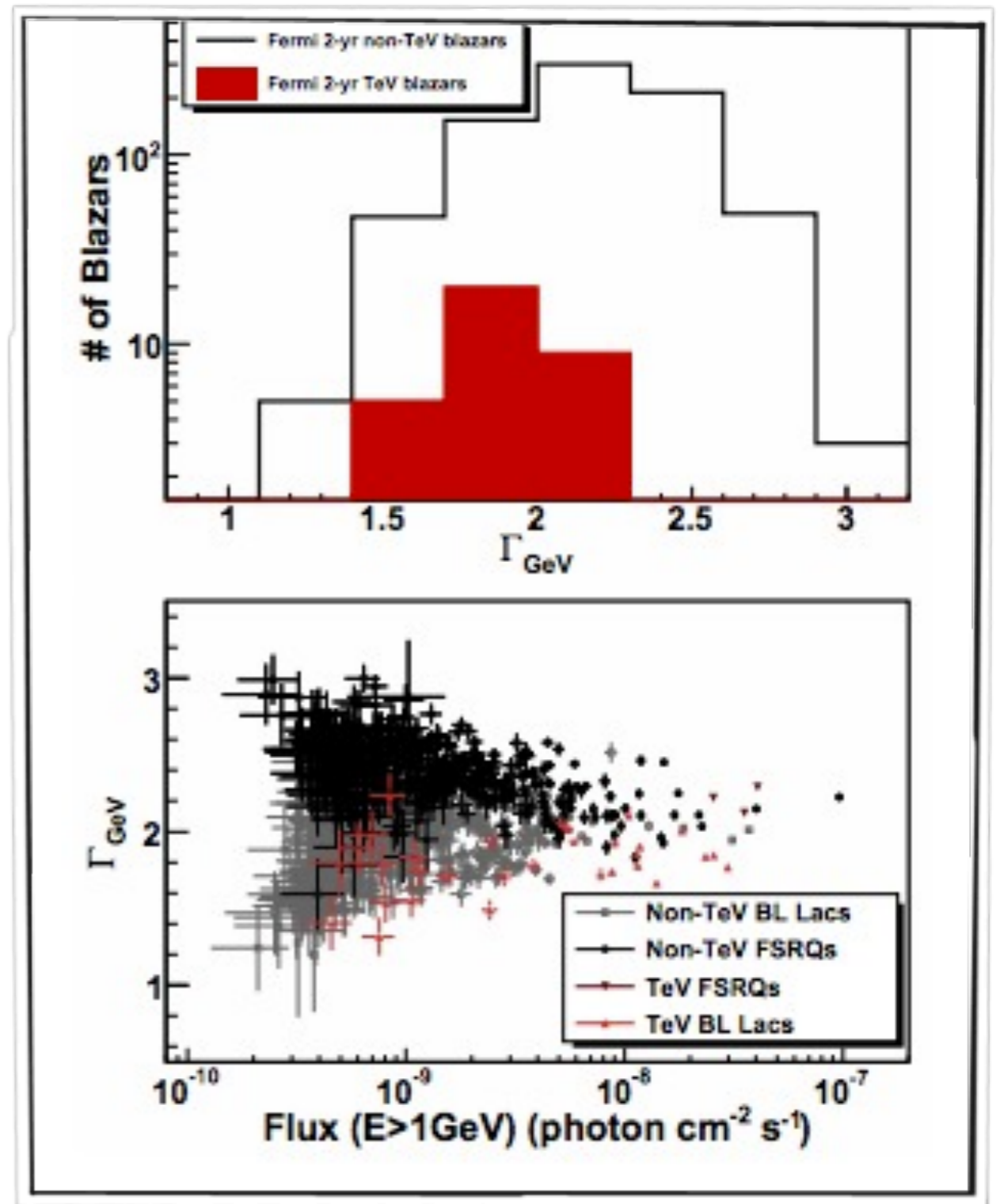


49 of the 55 TeV AGN are in 2FGL

# The GeV–TeV Connection

SENTURK, ERRANDO, BÖTTCHER & MUKHERJEE (2013), APJ 764, 119

- **Analysed 27 months of Fermi data for the TeV AGN that had spectral information available (26 objects)**
- Compared the TeV AGN with the AGN from 2FGL
- Computed SEDs for all objects
- The combined GeV–TeV spectra of some blazars (IES 0229+200, IES 0347-121, IES 1101-232, IES 1218+304, H 1426+428) suggest an inverse-Compton peak beyond 1 TeV



# The GeV–TeV Connection

- TeV instruments are pointed and have relatively small fields of view

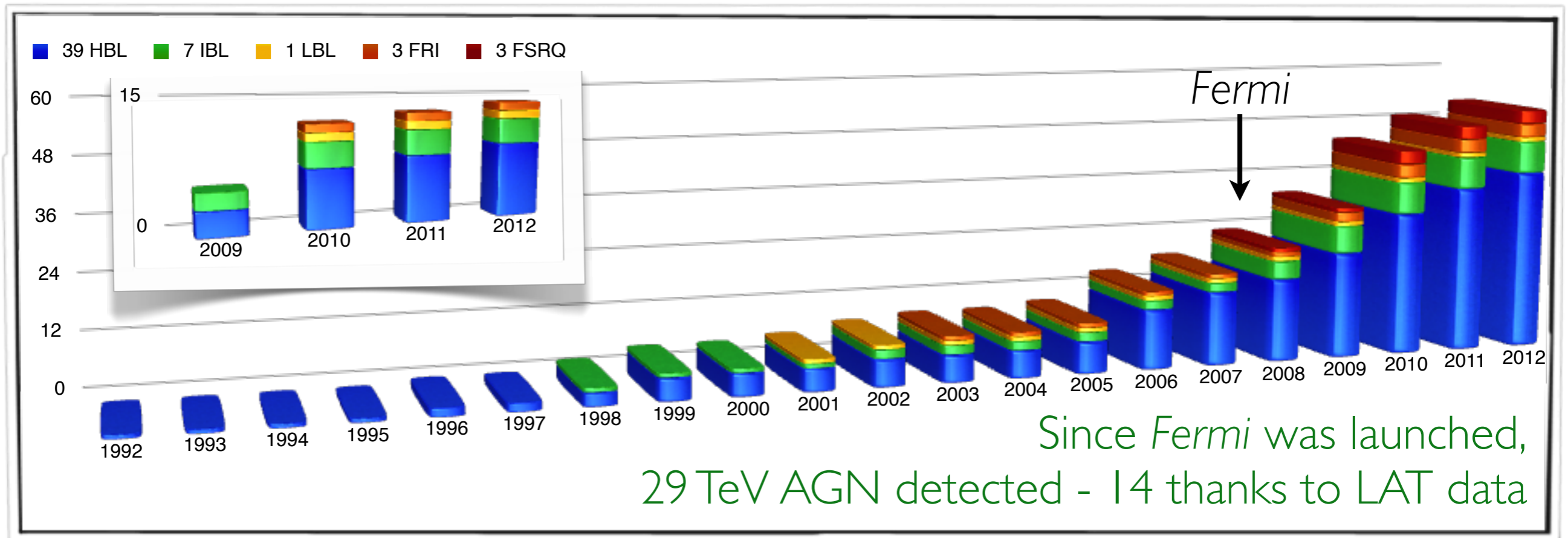
- Low duty cycles (~10%)

→ **Need targets**

- Fermi has a very large field of view - sees a fifth of the sky at any given time

- Surveys entire sky every three hours

→ **Transients, cataloging**



# The GeV–TeV Connection

- At the time of publication, there were 6 TeV AGN that were not detected in 2FGL
- Since then, 8 TeV AGN have been detected - they were all in 2FGL

➔ **still 6 TeV AGN not in 2FGL**

- all HBL
- among the weakest TeV AGN
- 3 have subsequently been reported as detections (non-Fermi pubs)



49 of the 55 TeV AGN are in 2FGL

Name	Class	% Crab
SHBL J001355.9-185406	HBL	1.0
IES 0229+200*	HBL	1.8
IES 0347-121*	HBL	2.0
PKS 0548-322*	HBL	1.3
IES 1312-423	HBL	0.4
HESS J1943+213	HBL	1.5

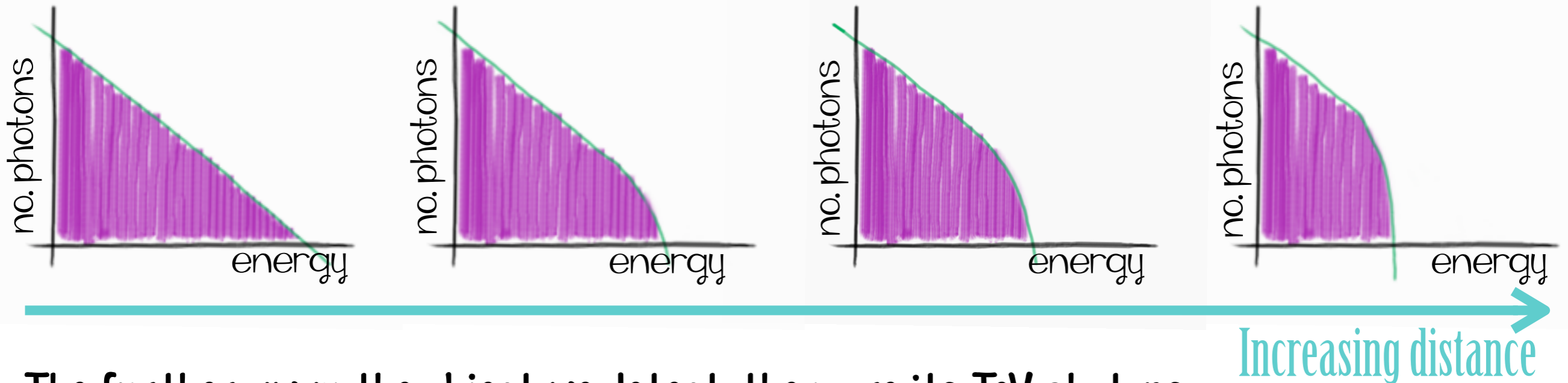
\*Detections reported in the literature since 2FGL

# The extragalactic background light

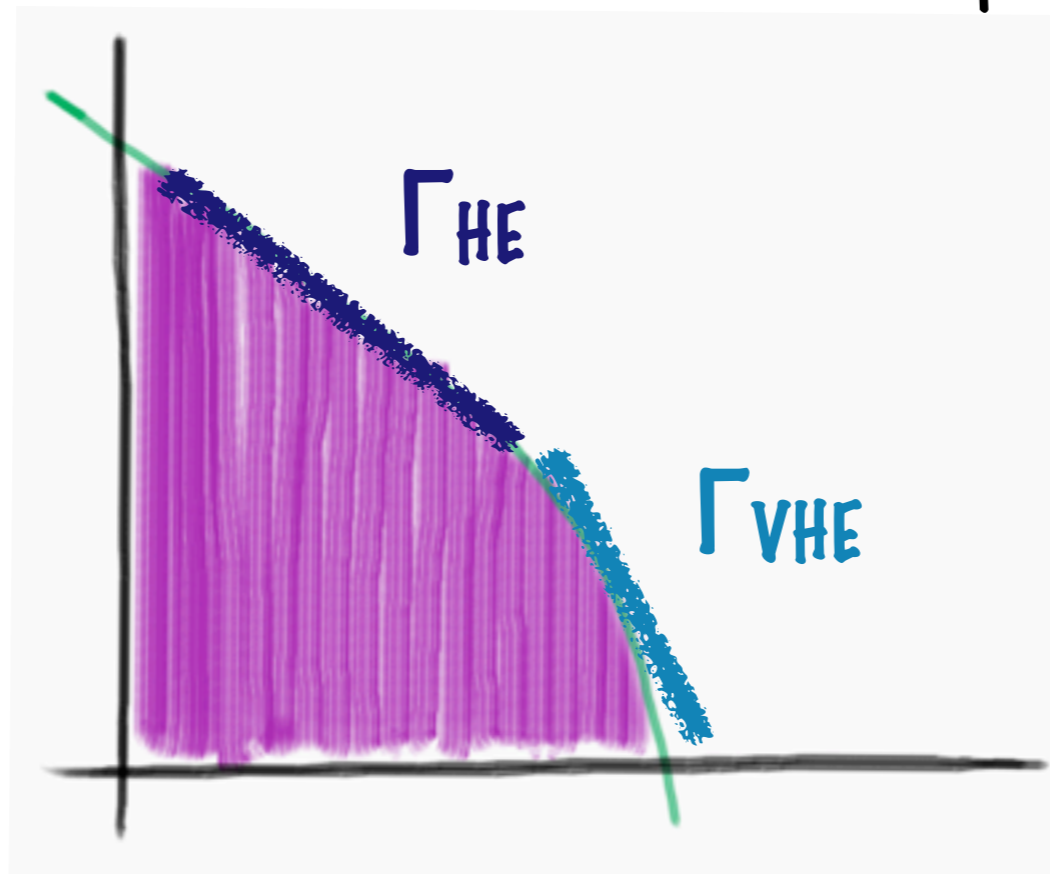
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# The extra-galactic background light

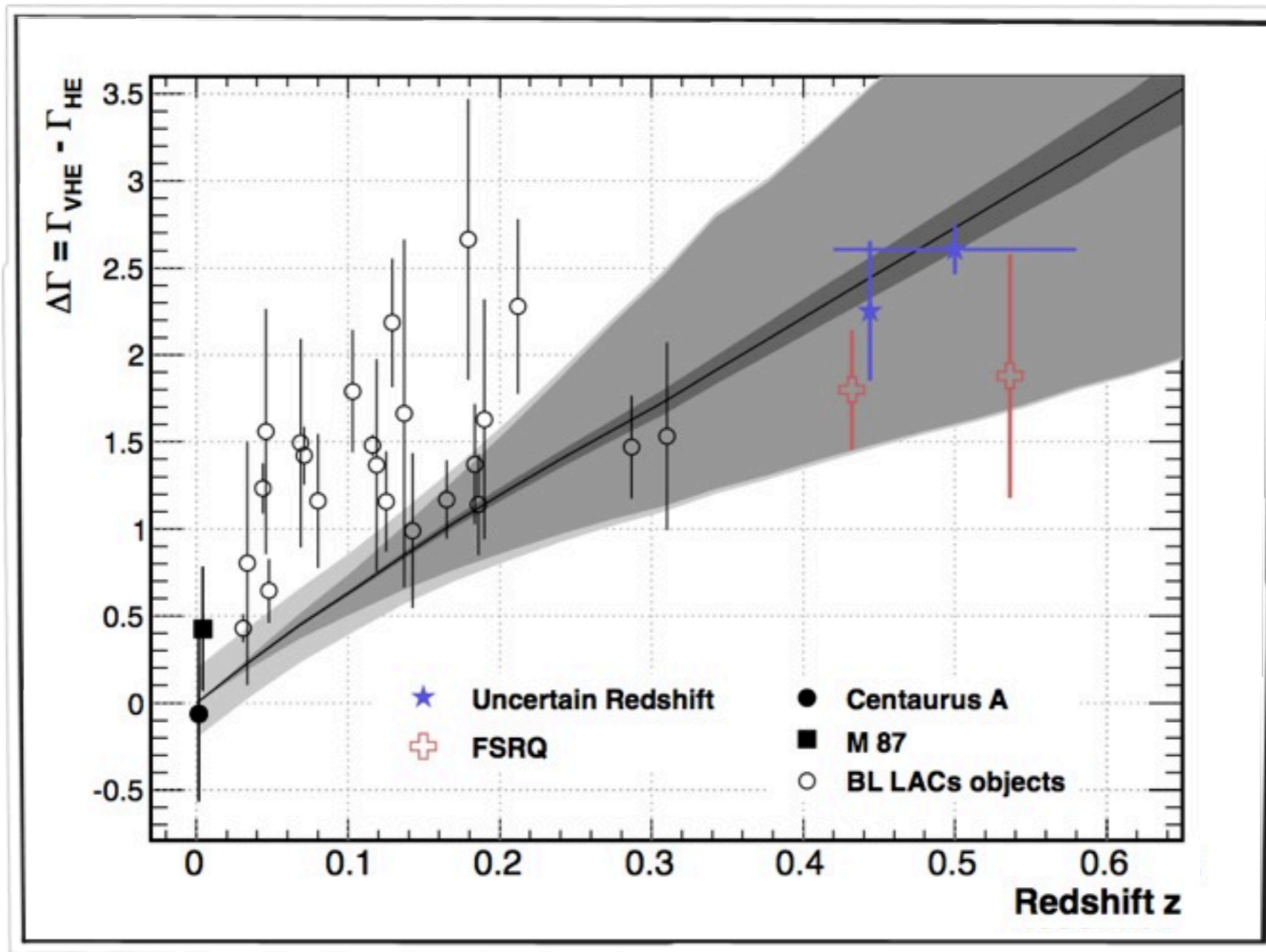


The further away the object we detect, the more its TeV photons are absorbed by the EBL - this results in a break in the spectrum





# The extra-galactic background light



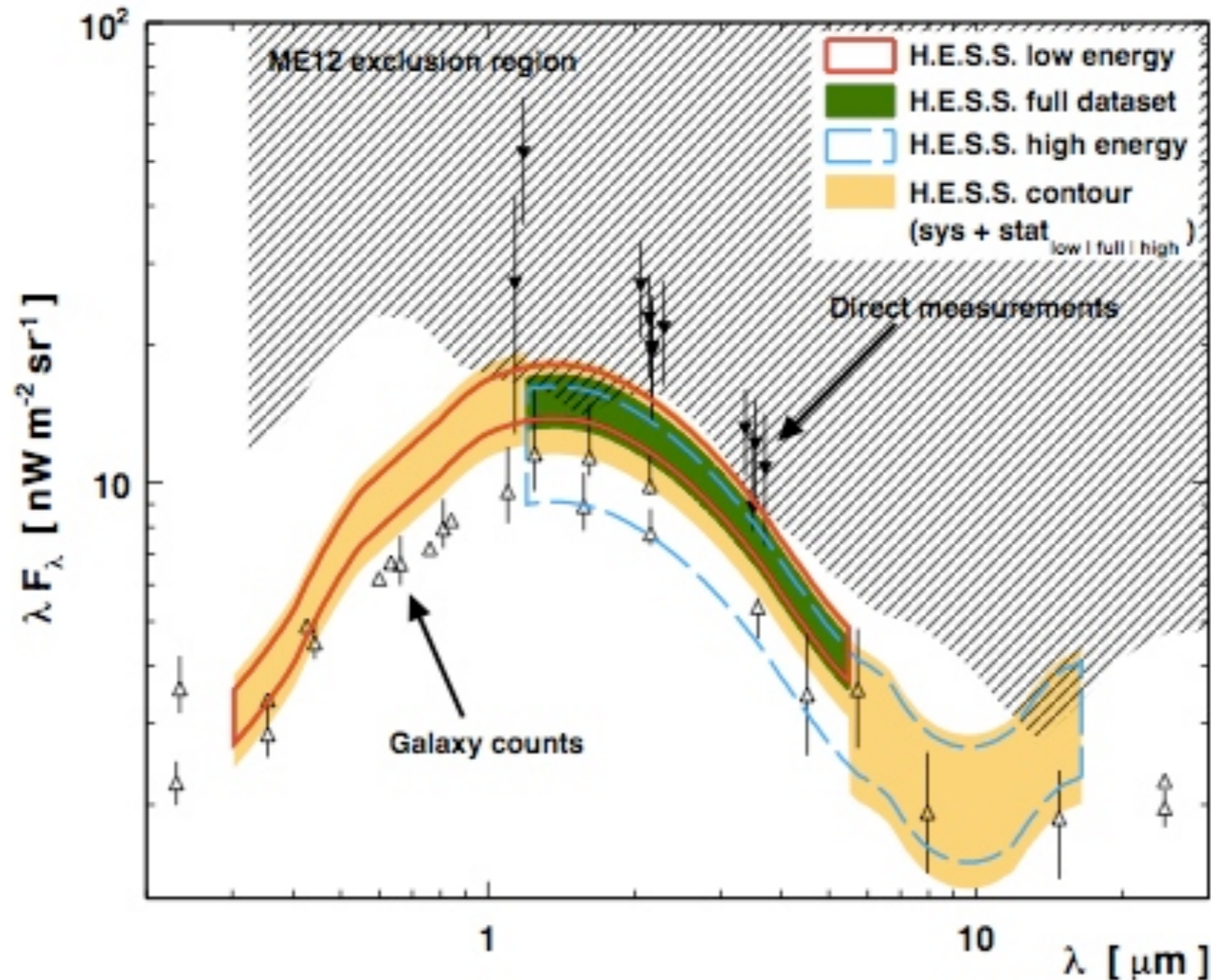
ABDO ET AL. (2009), APJ, 707, 1310

SANCHEZ, FEGAN, GIEBELS (2013) IN PRESS, ASTRO-PH/1303.5923

# The extra-galactic background light

WWW.MPI-HD.MPG.DE

ASTRO-PH/1212.3409



HESS data on seven blazars were used to search for the absorption signature of the EBL - it was detected at 9 sigma - results are only slightly above the lower limits calculated by summing galaxies visible in sky surveys

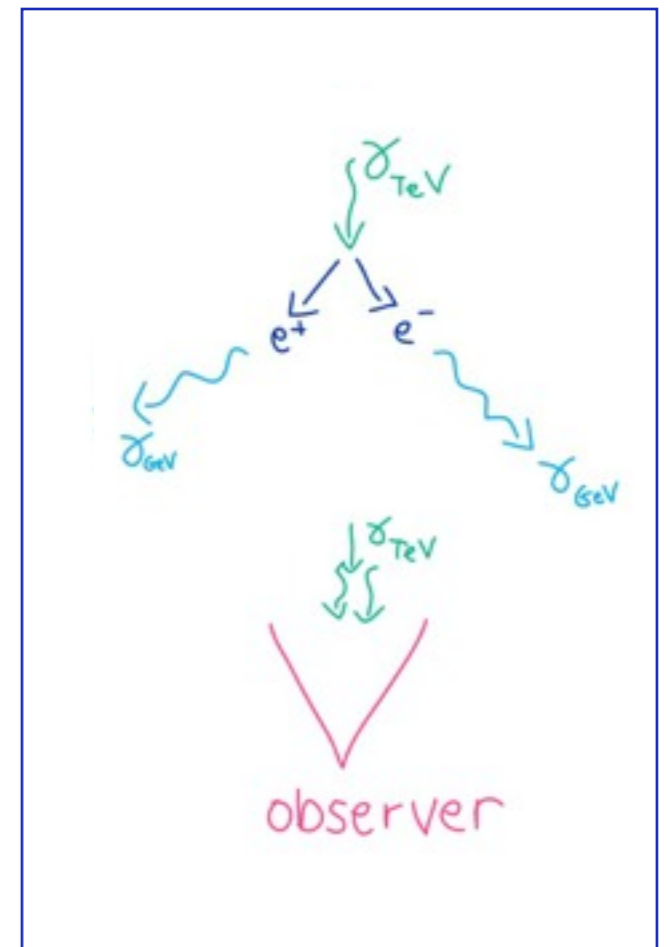
# Intergalactic magnetic fields

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# Intergalactic magnetic fields

- when we detect TeV gamma rays from a distant source, we know that the signal has already been attenuated - only a fraction of those emitted arrive on Earth
- the gamma rays collide with photons of the EBL en route from the source and pair produce
- ➔ if there were NO magnetic fields in the universe, these charged pairs would not get deflected, they would travel in original direction until they Compton upscattered an EBL photon to MeV-GeV energies\*
- in this way, the original TeV gamma rays get reprocessed to lower energy radiation
- IF we could identify a distant, steady\*\* TeV source which had NO GeV emission, this could be an indication that the B-fields between the source and us deflected the charged pairs such that the reprocessed lower energy emission was "removed" (scattered) from the signal

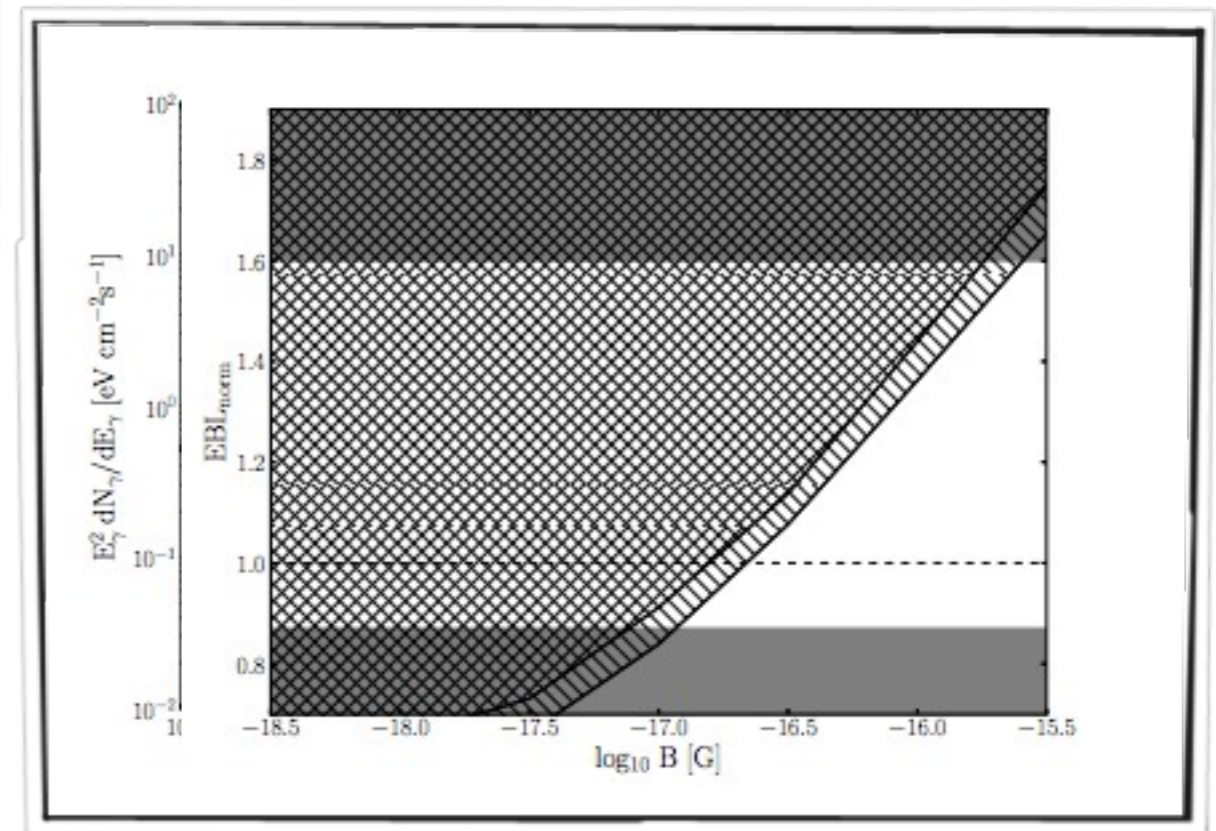
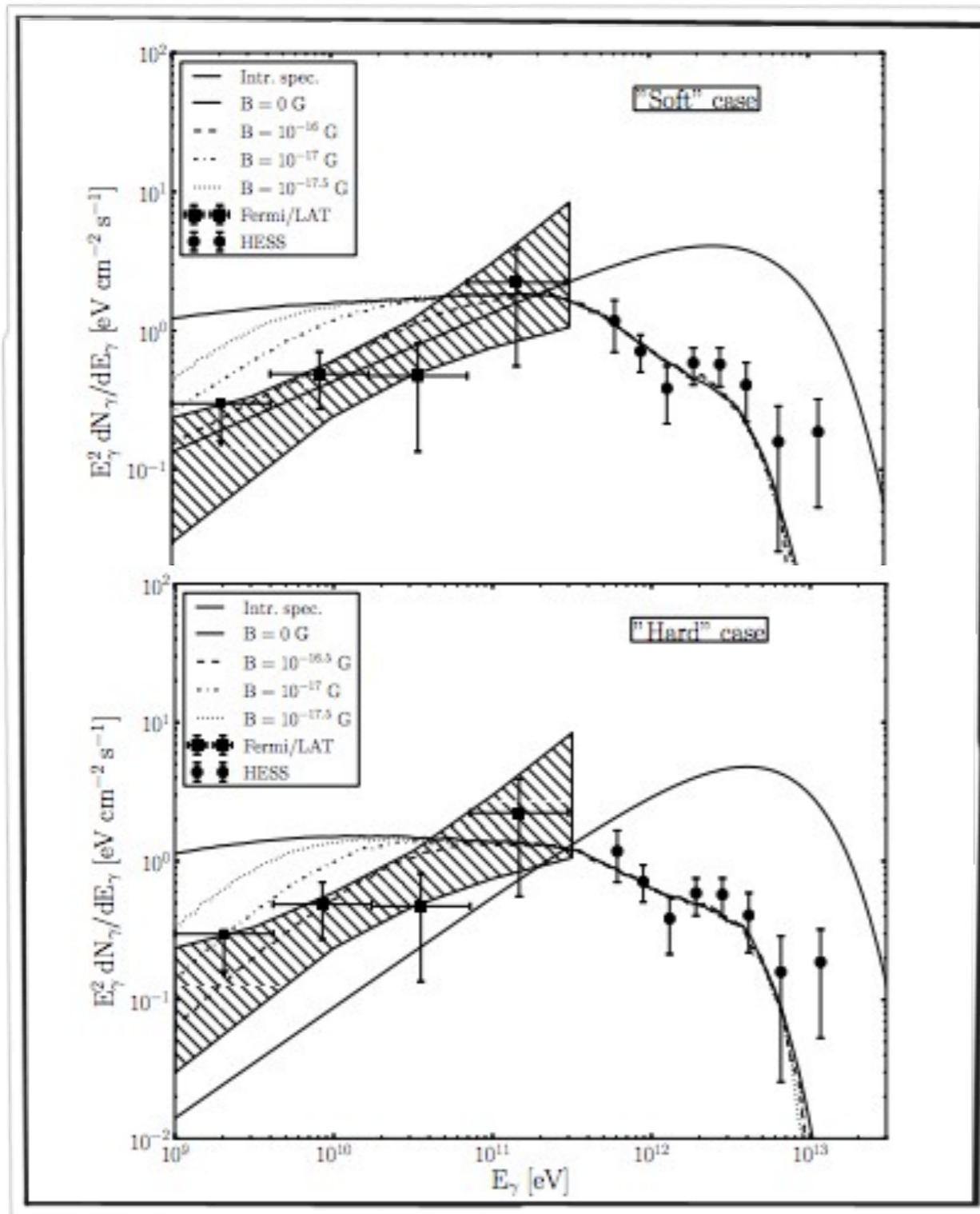


\* the mean free path for  $e^+/e^-$  is low  $\sim$ kpc \*\* if the source is at a lower level now than when the TeV emission that we are detecting was emitted, it could be argued that, since the radiation due to the deflected pairs has longer to travel, it would be delayed by some time - and it hasn't arrived yet

# Intergalactic magnetic fields

VOVK, TAYLOR, SEMIKOZ & NERONOV (2012), APJ, 747, L14

Place constraints on the intergalactic B-field strength using the direct and cascade components of the GeV-TeV spectrum of IES 0229+200



Characterising variability

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# Characterising variability

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## Quantifying the variability of blazars

excess variance

NANDRA ET AL. (1997) APJ 476, 70

$$\sigma_{\text{rms}}^2 = \frac{1}{N\mu^2} \sum_{i=1}^N \left[ (X_i - \mu)^2 - \sigma_i^2 \right]$$

$N$  points in each light curve  $X_i$

$\mu$  is the unweighted arithmetic mean of the  $X_i$

# Characterising variability

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## Putting an upper limit on the excess variance

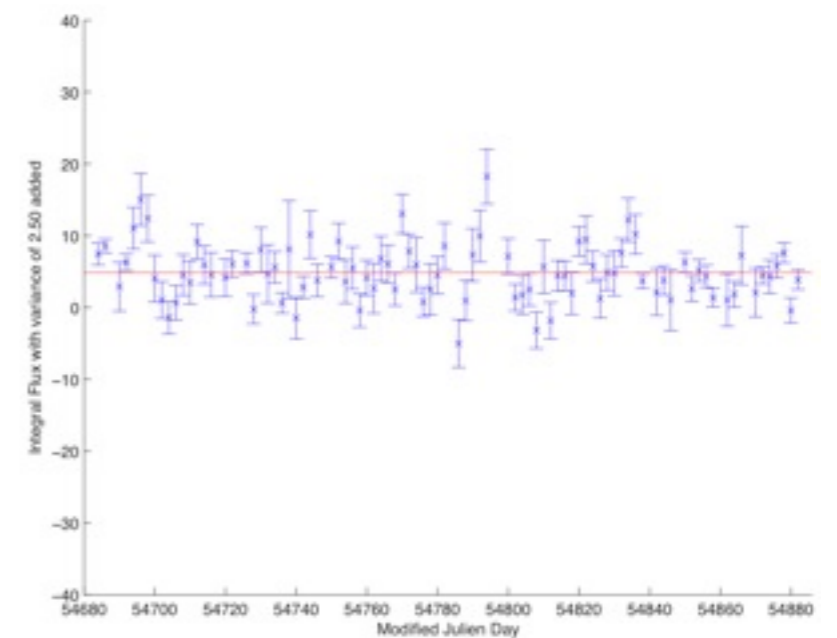
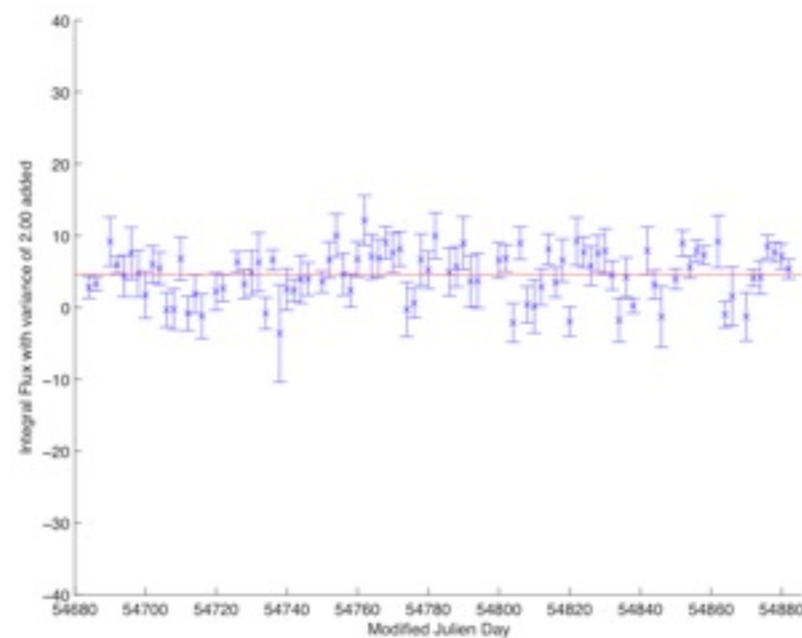
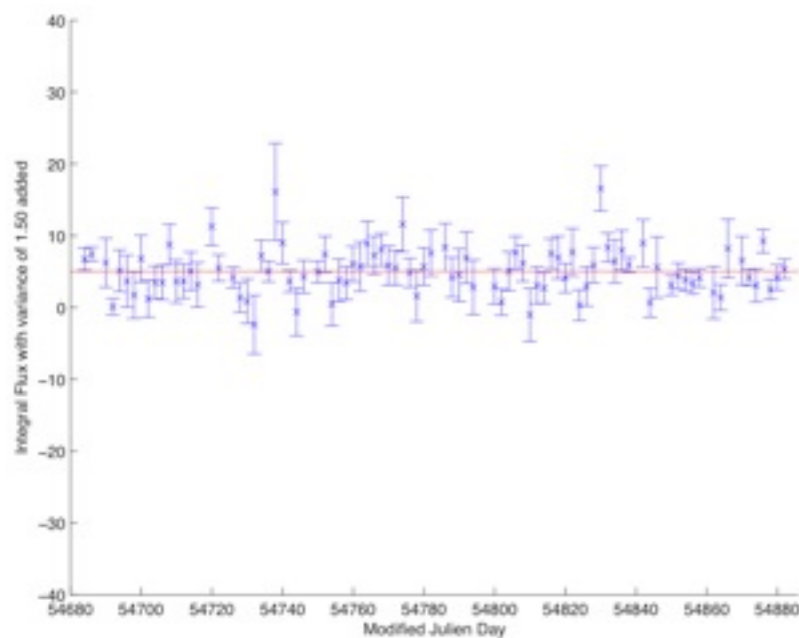
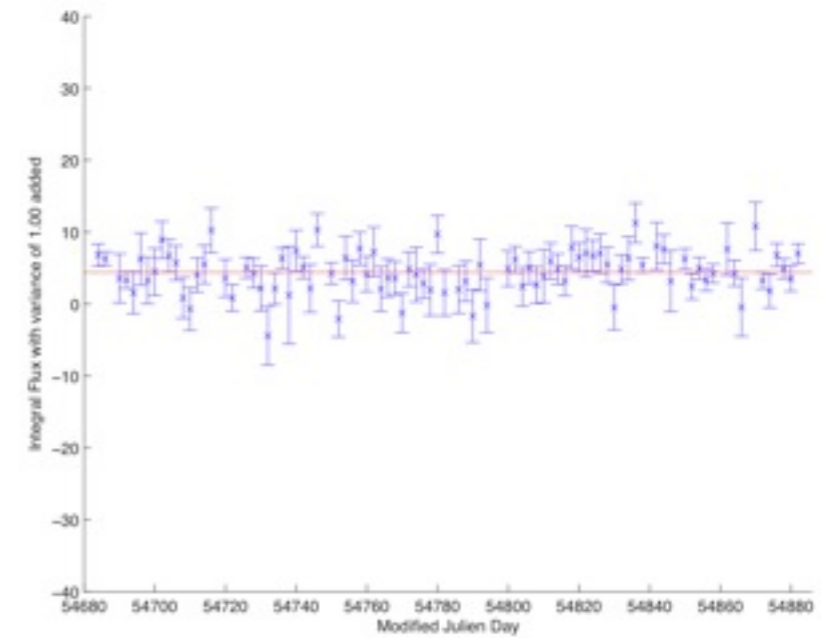
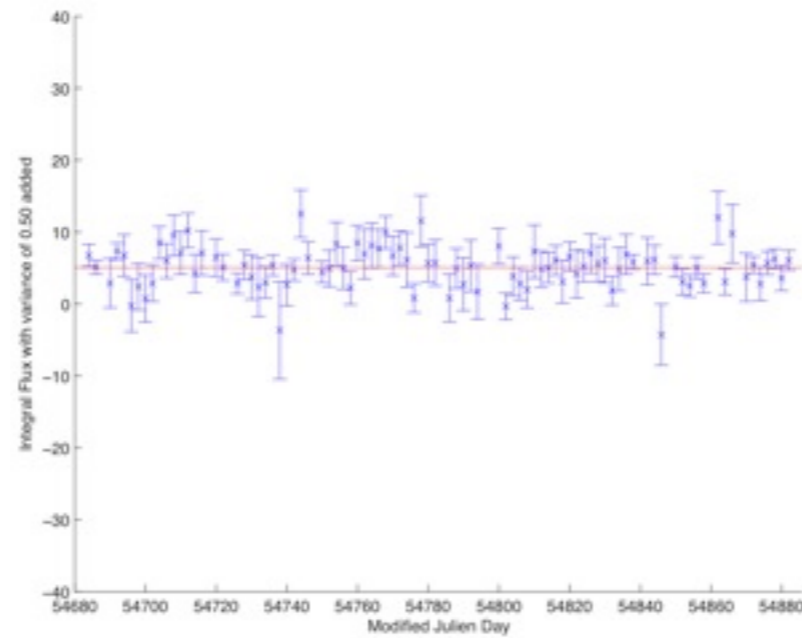
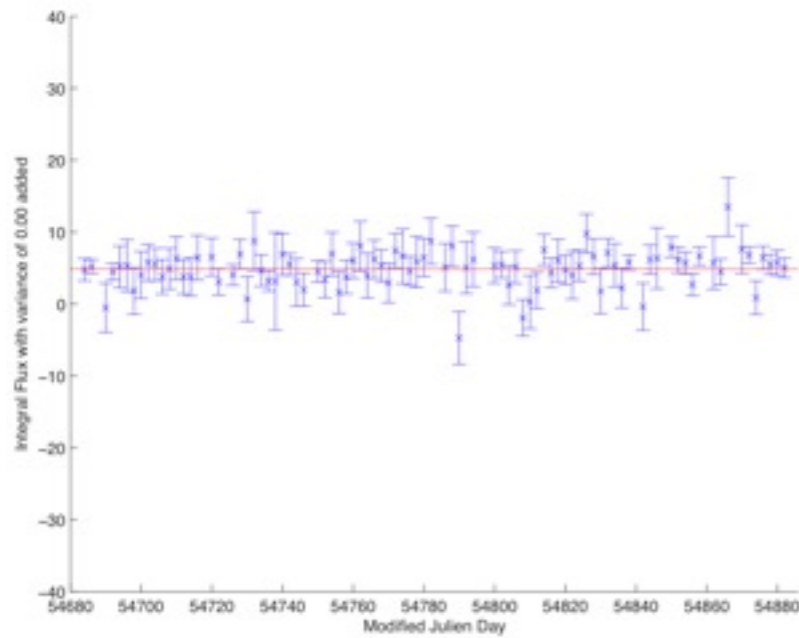
→ When no (negative) excess variance is measured in the data, we can estimate the level of intrinsic variance that could be present in the lightcurve but that would still allow us to arrive at this value for **excess variance**

1. Simulate lightcurves by generating, for each datapoint  $F_i \pm dF_i$  ( $F$  is the  $i$ th data point and  $dF$  is the  $i$ th uncertainty,  $i = 1:N$ ), a normal distribution centred on the mean of the measured lightcurve with width of  $\sqrt{dF_i^2 + \text{VARIANCE}^2}$
2. For each level of **VARIANCE**, generate a large number of lightcurves



# Characterising variability

## Sample lightcurves for different levels of VARIANCE



# Characterising variability

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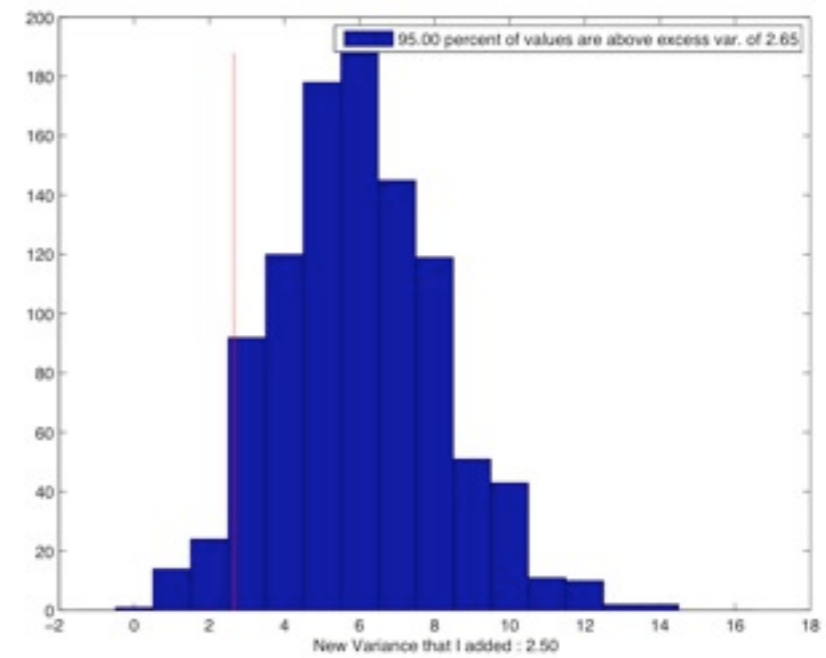
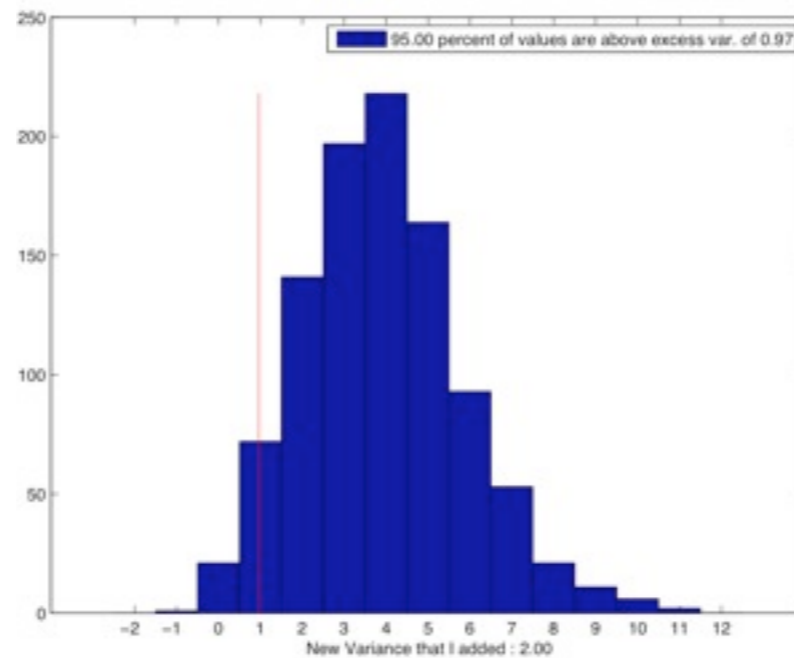
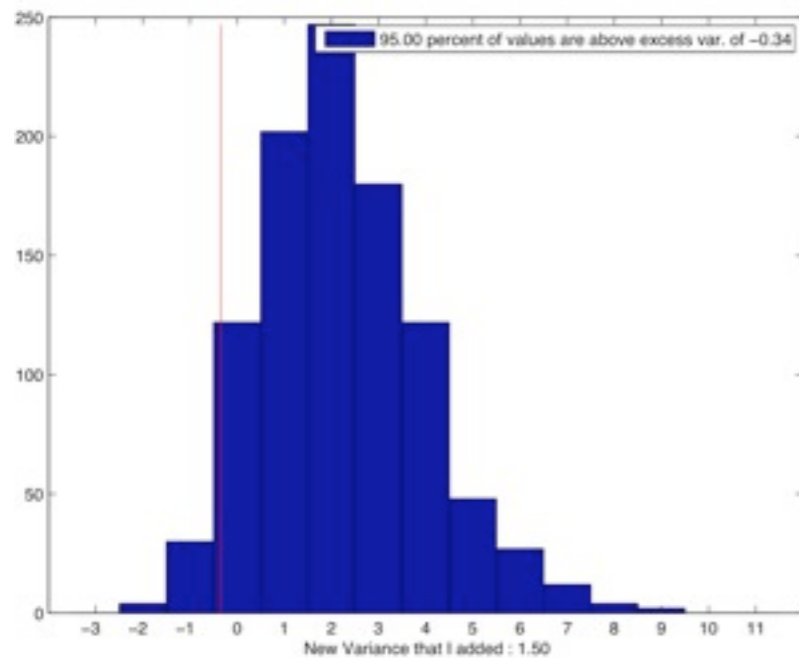
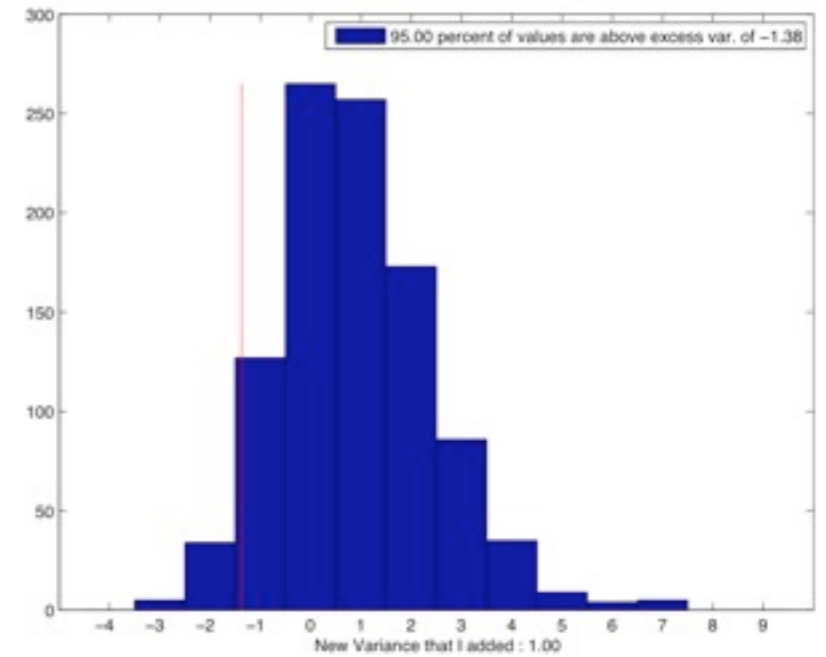
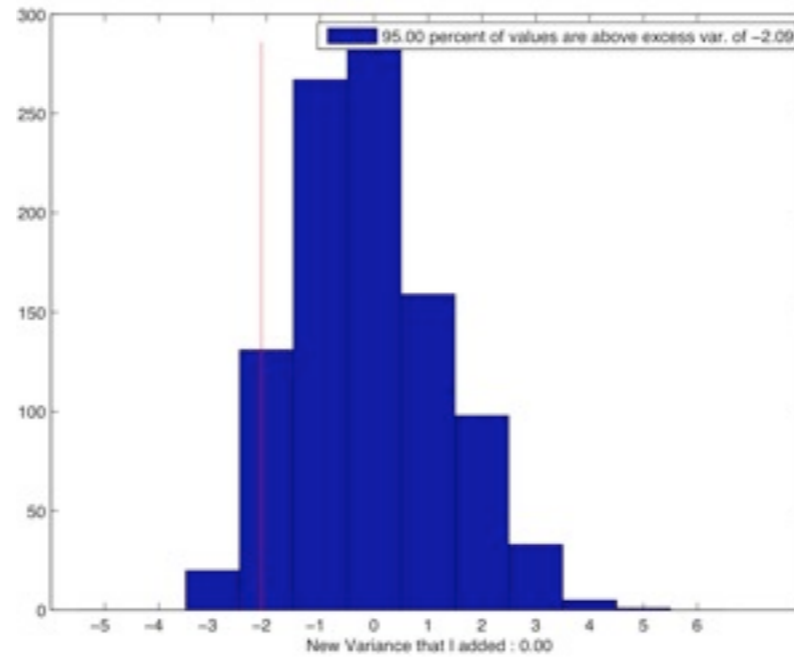
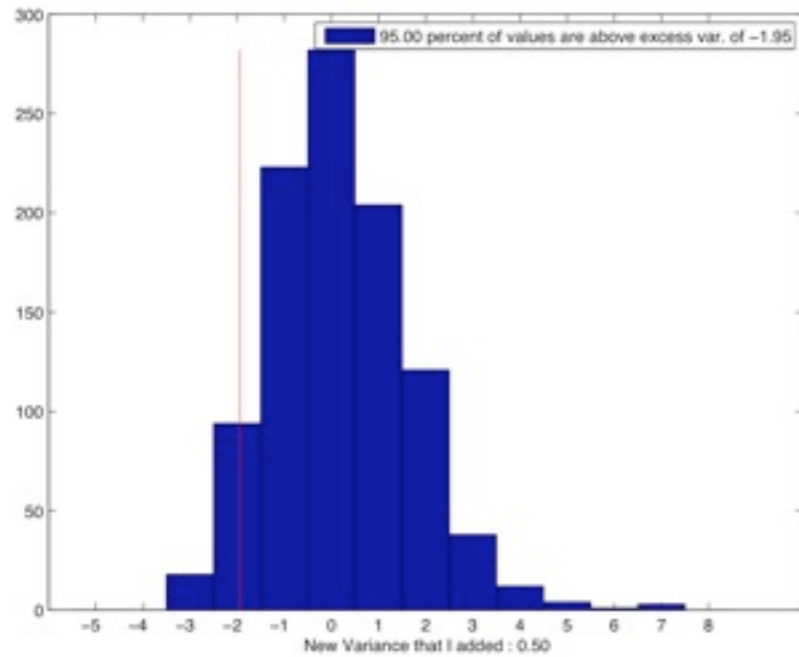
## Putting an upper limit on the excess variance

→ When no (negative) excess variance is measured in the data, we can estimate the level of intrinsic variance that could be present in the lightcurve but that would still allow us to arrive at this value for **excess variance**

1. Simulate lightcurves by generating, for each datapoint  $F_i \pm dF_i$  ( $F$  is the  $i$ th data point and  $dF$  is the  $i$ th uncertainty,  $i = 1:N$ ), a normal distribution centred on the mean of the measured lightcurve with width of  $\sqrt{dF_i^2 + \text{VARIANCE}^2}$
2. For each level of **VARIANCE**, generate a large number of lightcurves
3. Calculate the **excess variance** for each of these lightcurves and histogram these for each level of **VARIANCE**

# Characterising variability

Histograms of excess variance for each **VARIANCE** added



# Characterising variability

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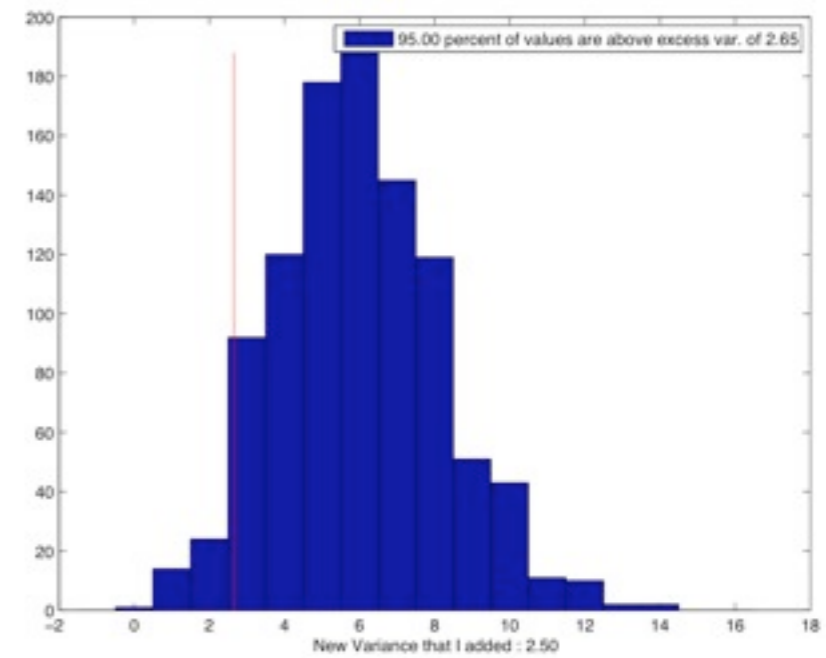
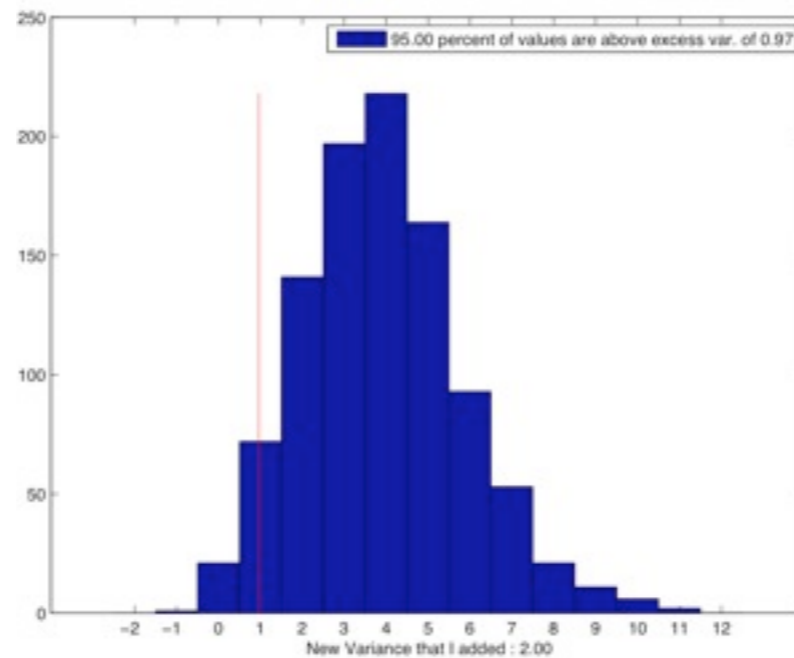
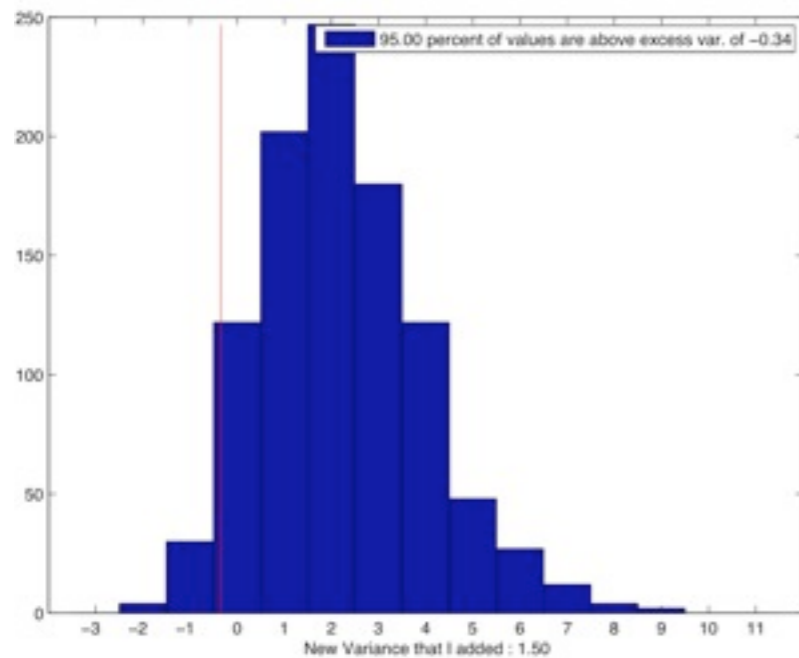
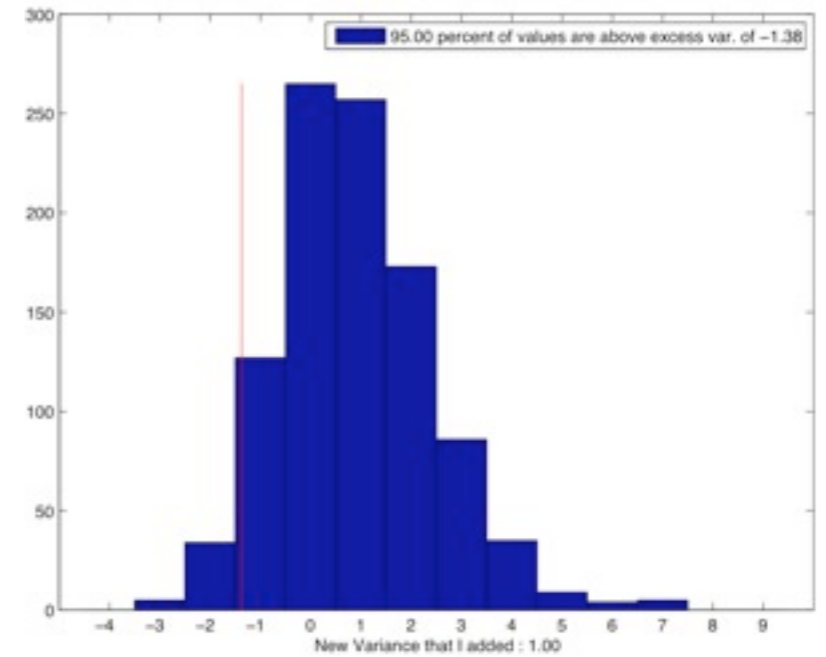
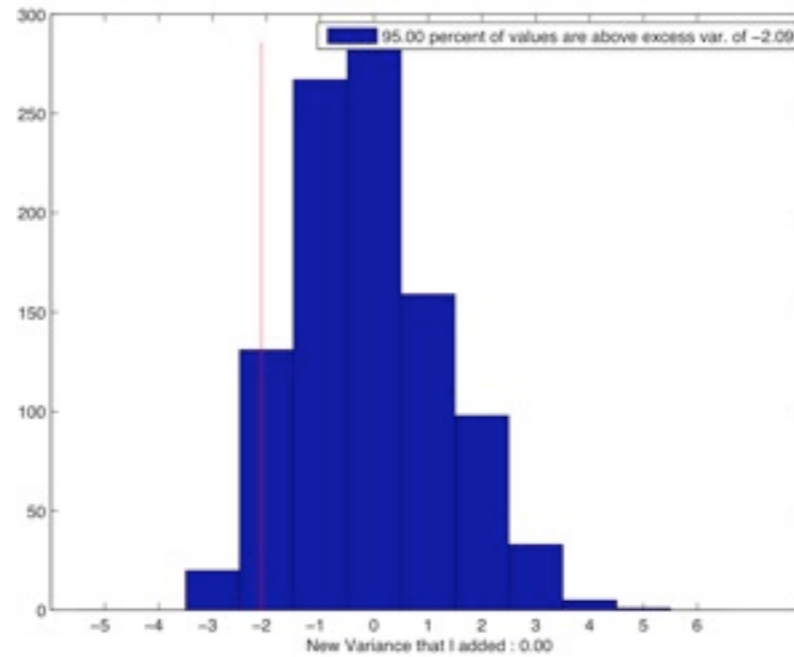
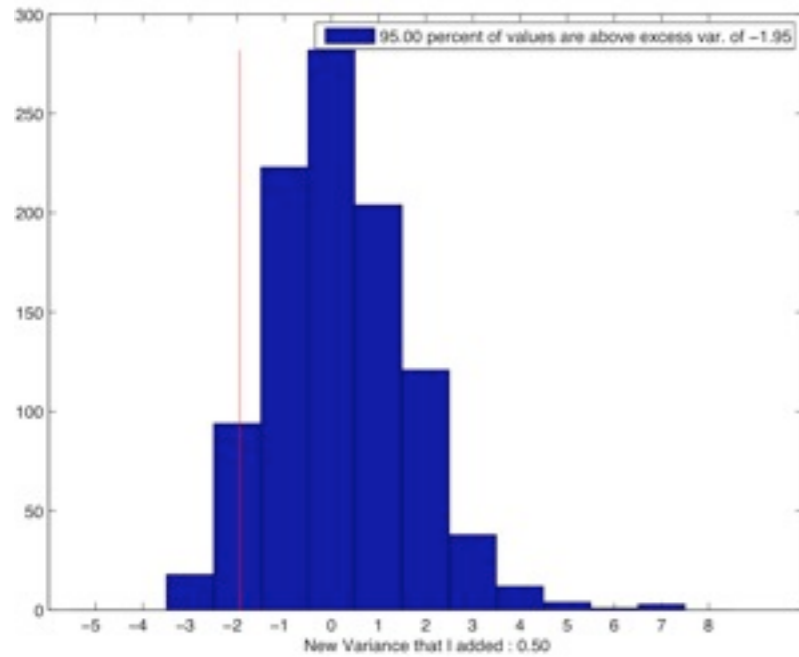
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2. For each level of **VARIANCE**, generate a large number of lightcurves
3. Calculate the **excess variance** for each of these lightcurves and histogram these for each level of **VARIANCE**
4. For each **VARIANCE** level, find the **excess variance** that 95% (or whatever your required confidence level is) of the **excess variances** are above

# Characterising variability

Histograms of excess variance for each **VARIANCE** added



# Characterising variability

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## Putting an upper limit on the excess variance

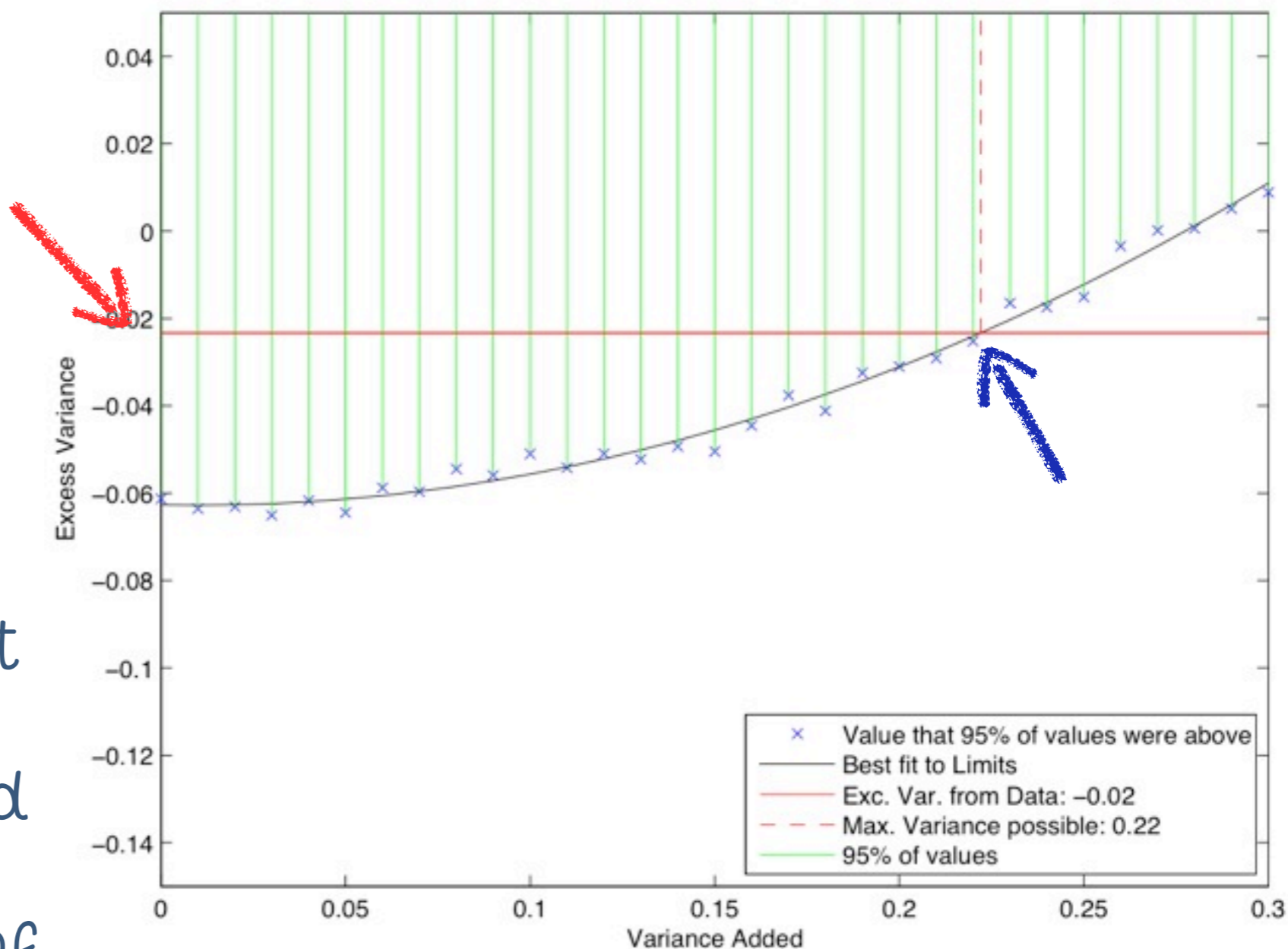
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# Characterising variability

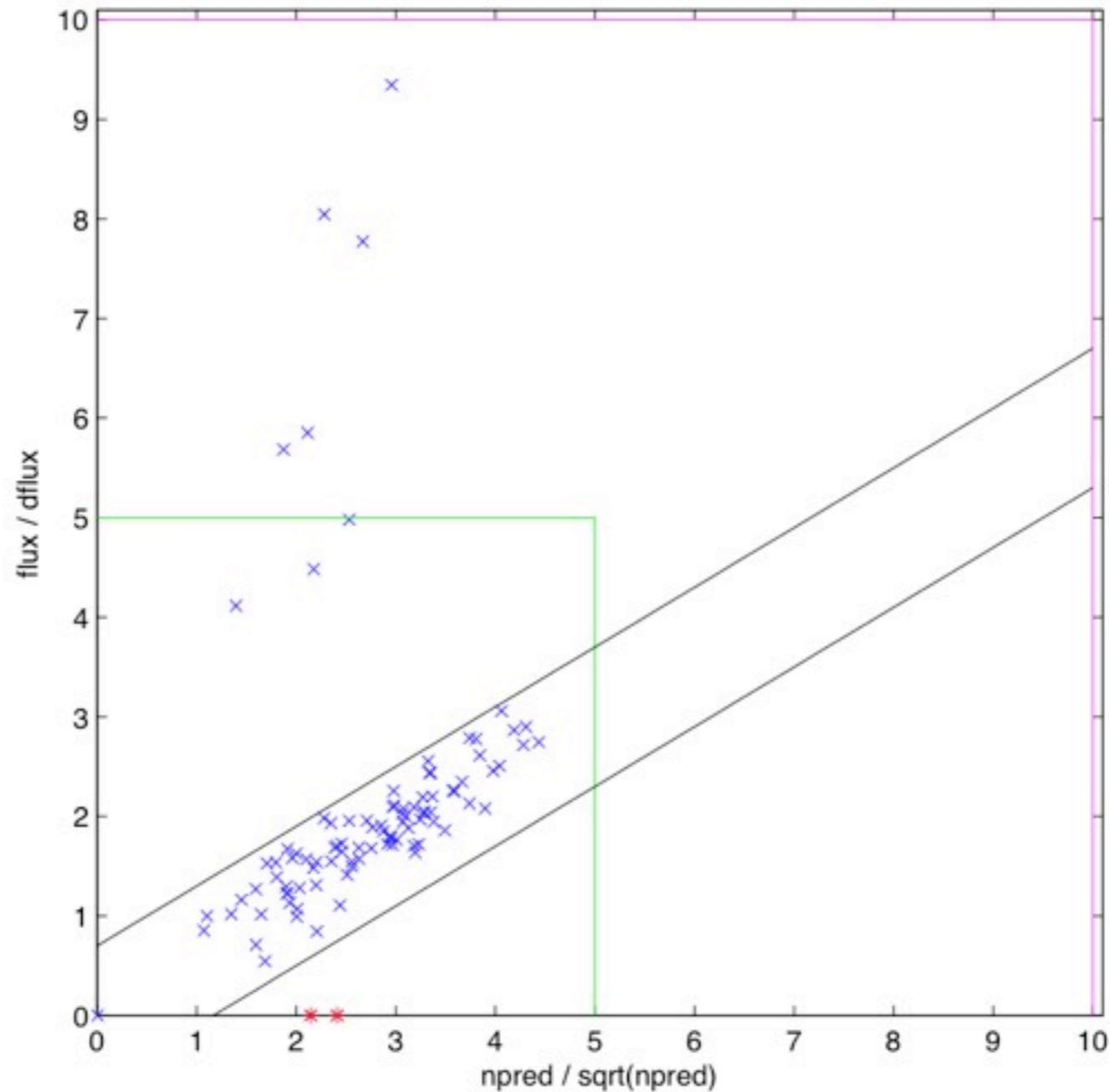
## Putting an upper limit on the excess variance

→ By finding where the measured value of excess variance intersects with the curve generated by the 95% values, we can determine the level of **VARIANCE** that could be present in the lightcurve but that would still lead to us getting the measured value 5% of the time or less



# Characterising variability

Note on rate and its uncertainty in Fermi data





Thank you  
for  
listening  
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