AGN at (Very) High Energy gamma-ray

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l'Observatoire de Paris — LUTH
Laboratoire de l'Univers et de ses Théories

OVERVIEW

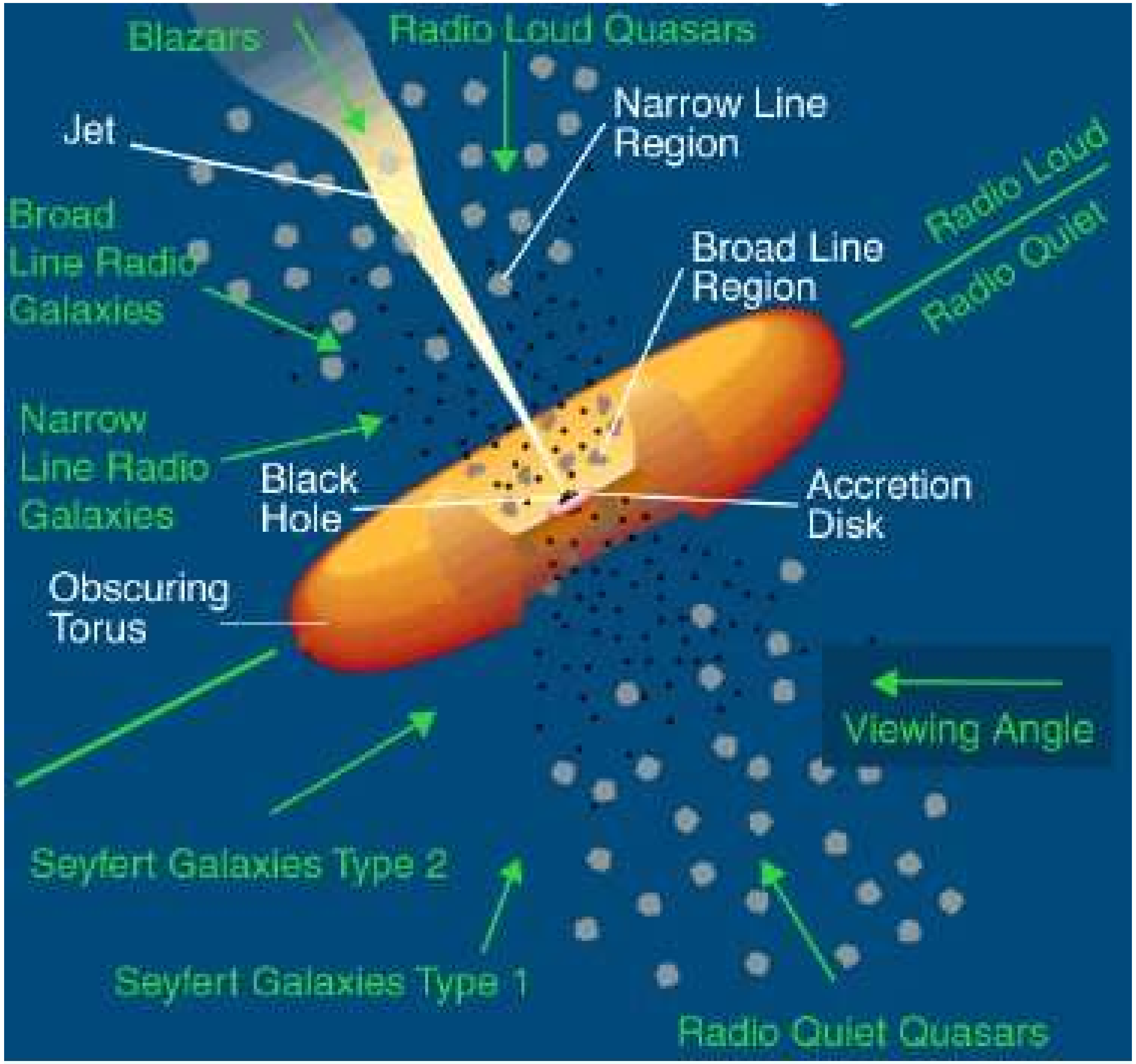
AGN as a population

New era for gamma ray astronomy

The future

CTA AGN kee science project conveners:
Daniel Mazin, Susumu Inoue, Andreas Zech

Active Galactic Nuclei



SMBH $10^6 – 10^9$ solar masses
Rotating accretion disk
Jets, winds

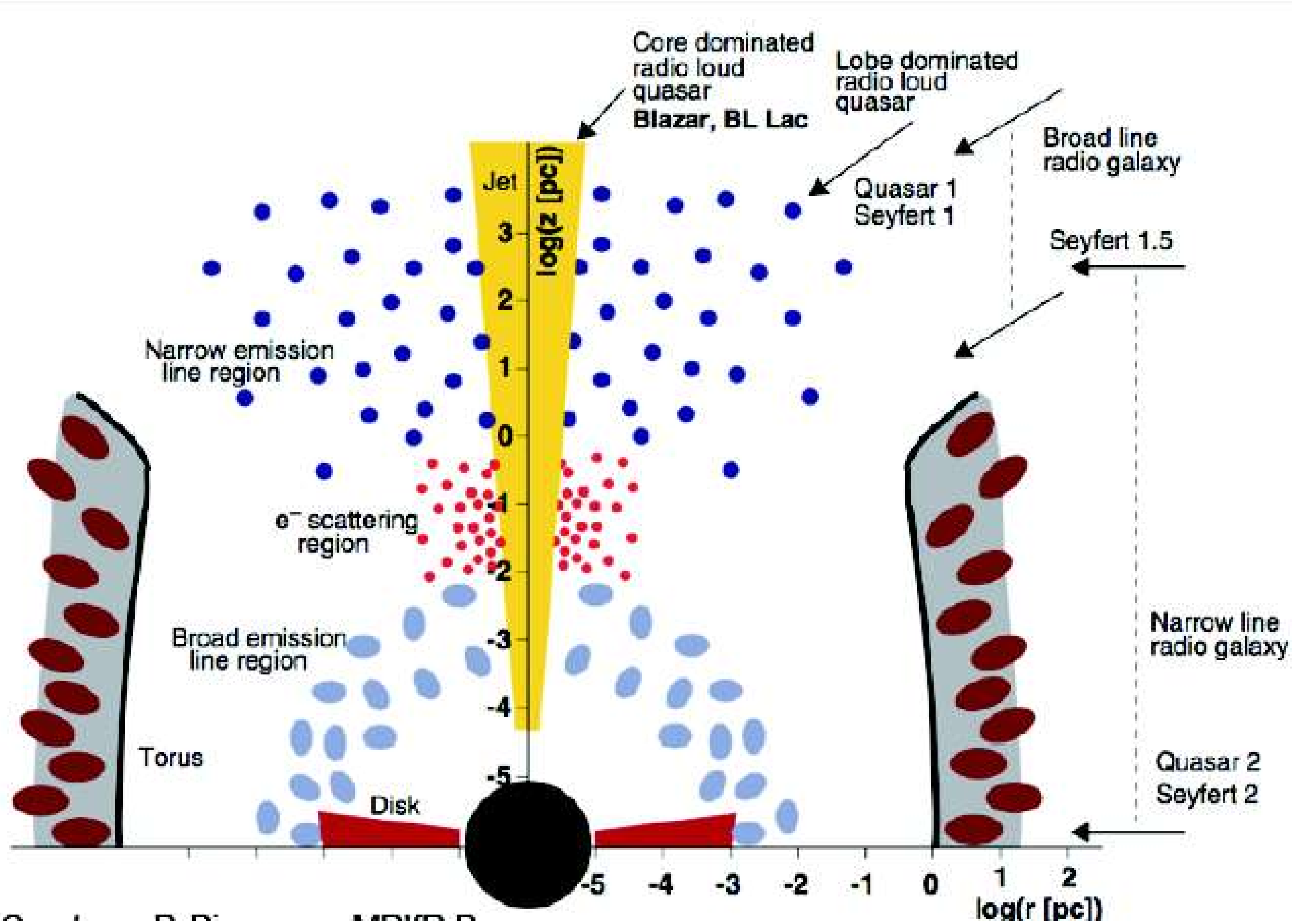
- Accretion dominated
- Radio-quiet QSO
- Seyfert galaxies
- Obscured AGN

→ about 90% of AGN

- Non-thermal radiation dominated
- Blazars (FSRQ + BL Lac)
- Radio galaxies

→ about 10% of AGN

Blazars



- Highly variable at all frequencies
- Highly polarized
- Radio core dominance
- Superluminal speeds
- Relativistic boosting, high Doppler factors

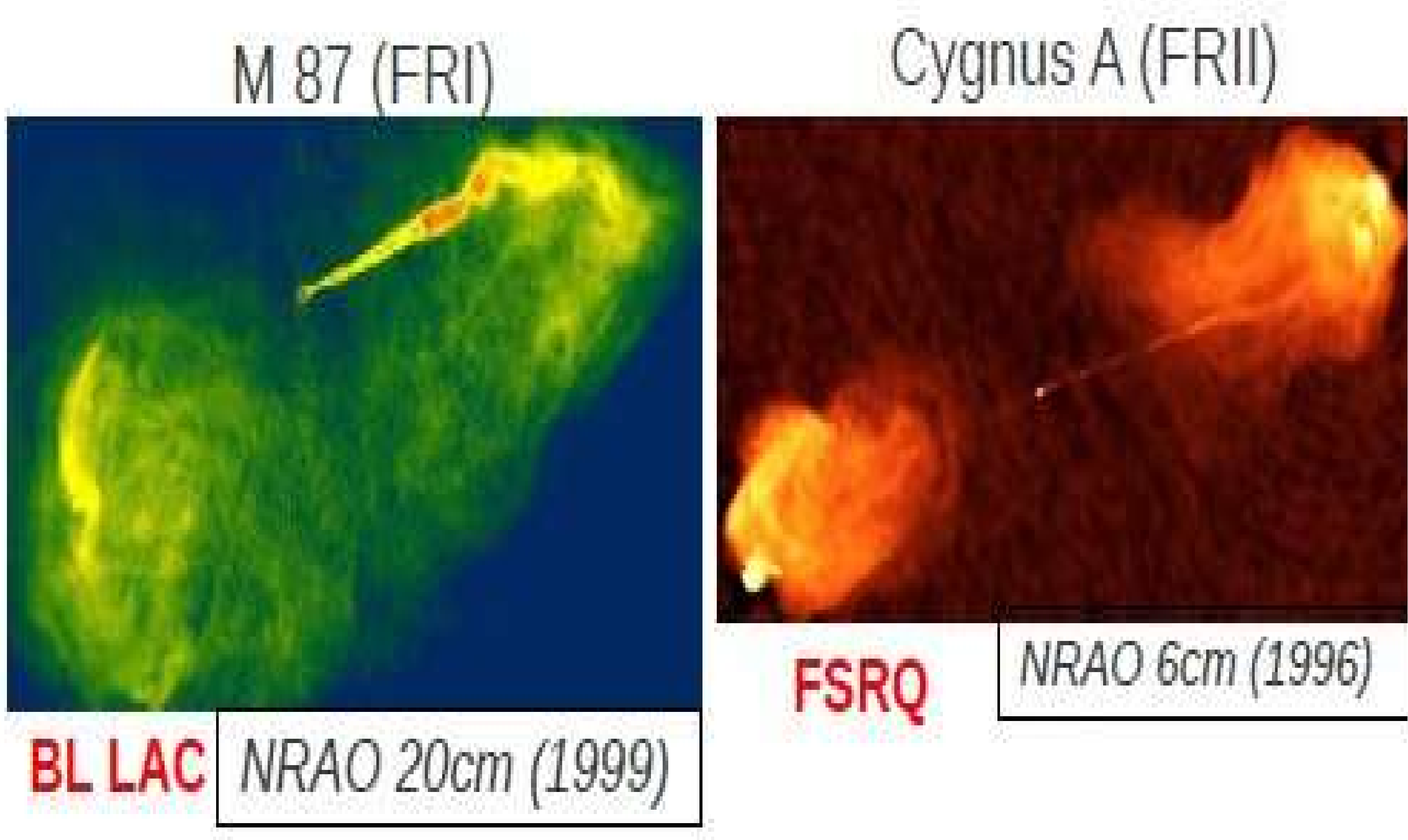
Observed at small angle to the jet, thus rare AGN : 5-8% of all AGN (but only at optical or X-ray frequencies!)

Blazars are the dominant population of extragalactic point sources at

- Gamma-ray
- TeV
- Microwave frequency

@ Biermann

AGN population



- FSRQs + BL Lacs = blazars
  Small viewing angle wrt the jet

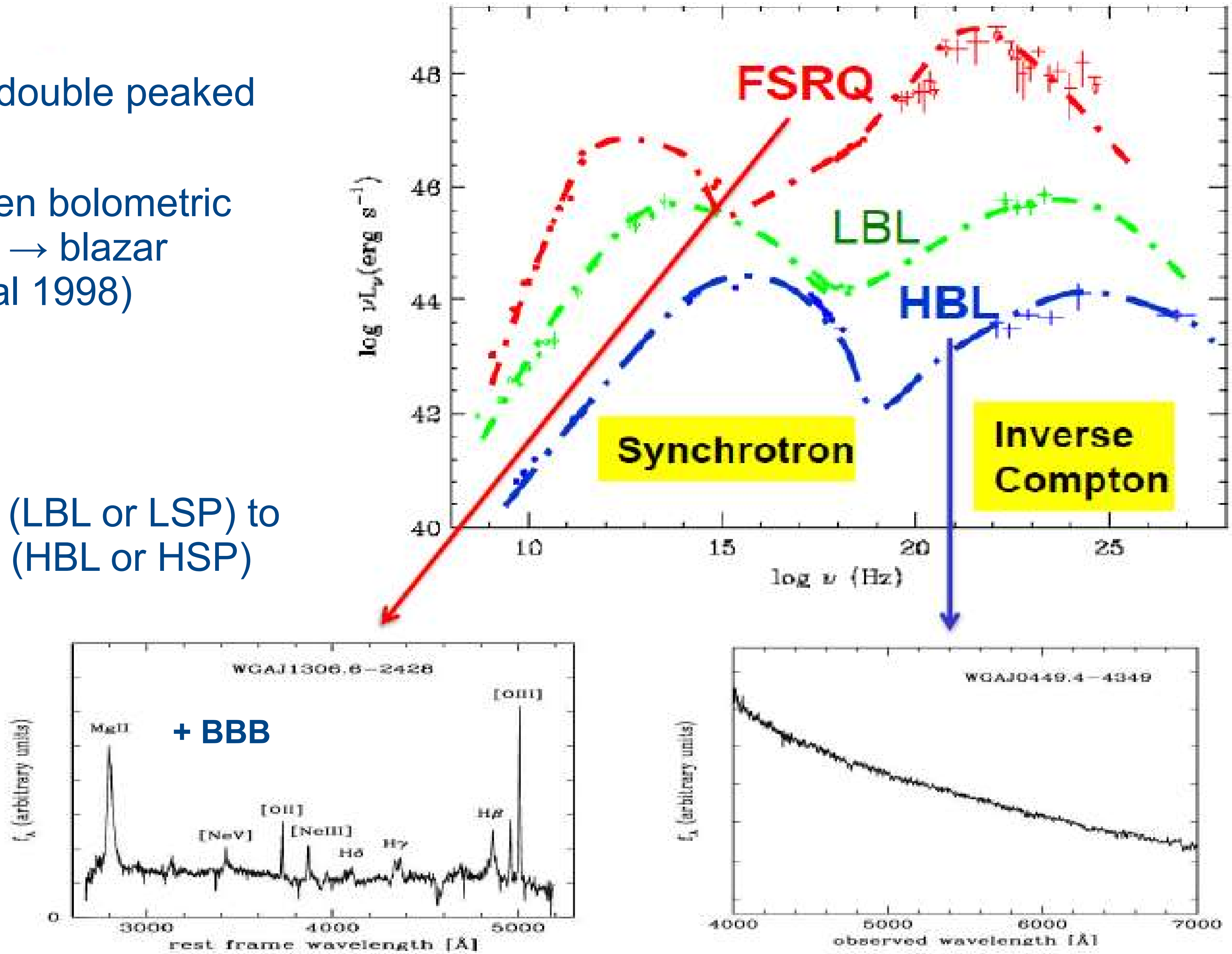
- Large viewing angle wrt the jet
  → FR I and FR II (Fanaroff & Riley 1974)

c nsidered as parent populations of blazars

Blazar sequence(s)

Characteristic SED is double peaked

- Anti-correlation between bolometric luminosity and E peak → blazar sequence (Fossati et al 1998)
- FSRQs to BL Lacs
- Low synchrotron peak (LBL or LSP) to high synchrotron peak (HBL or HSP) BL Lacs



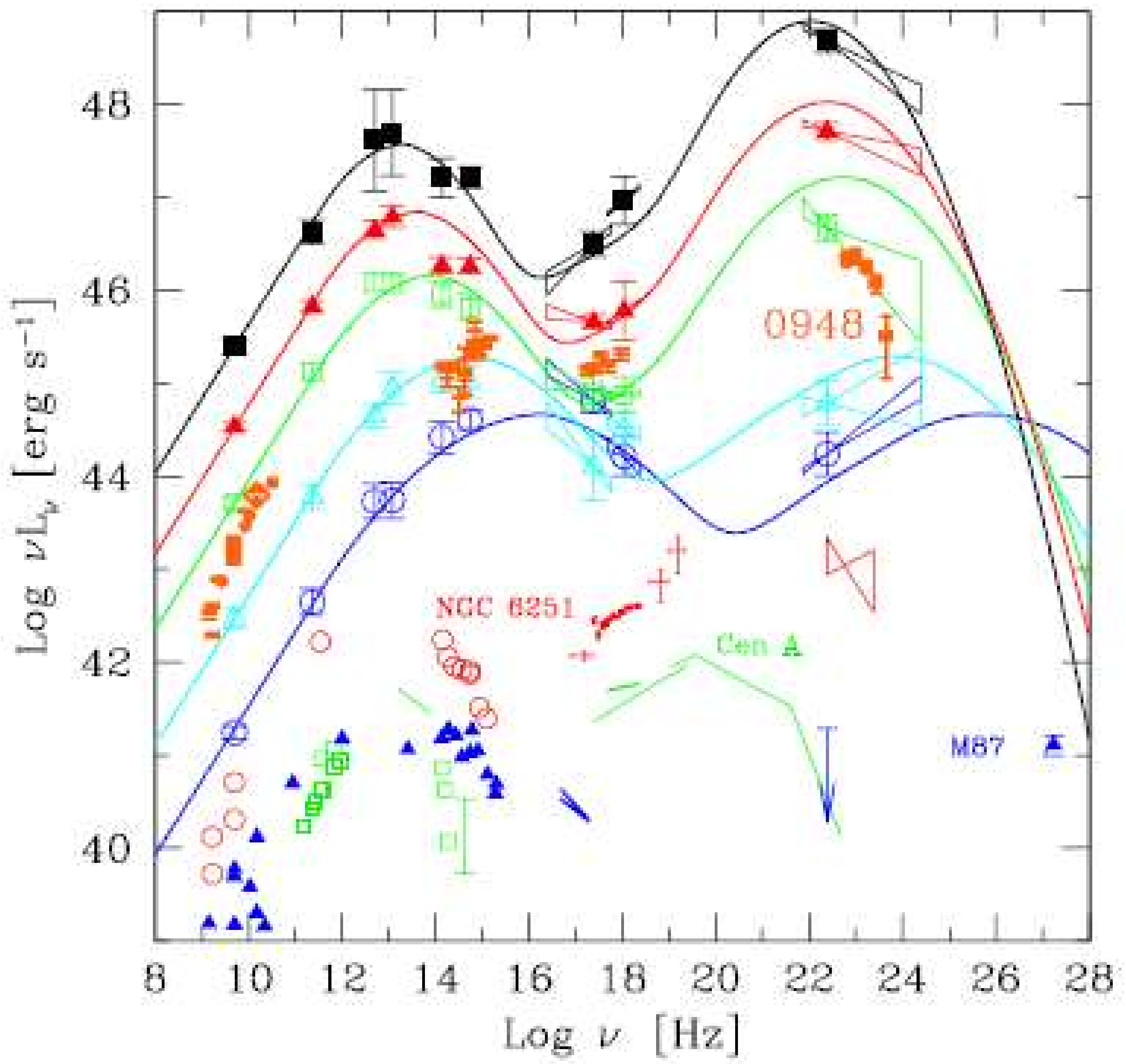
@ J. Ballet

Blazar sequence(s)

Characteristic SED is double peaked

- Strong anti-correlation between bolometric luminosity and E peak → blazar sequence (Fossati et al 1998)
- Cooling model with external radiation for FSRQs (Ghisellini et al.1998)
- Physical models → galaxy evolution through reduction of fuel from surrounding gas and dust (Böttcher & Dermer, 2002)

The NLS1 (PMN J0948+0022, z=0.585) detected by Fermi does not fit in the picture.



Foschini et al. (2009)

Blazar sequence(s)

Indeed, varying mix of

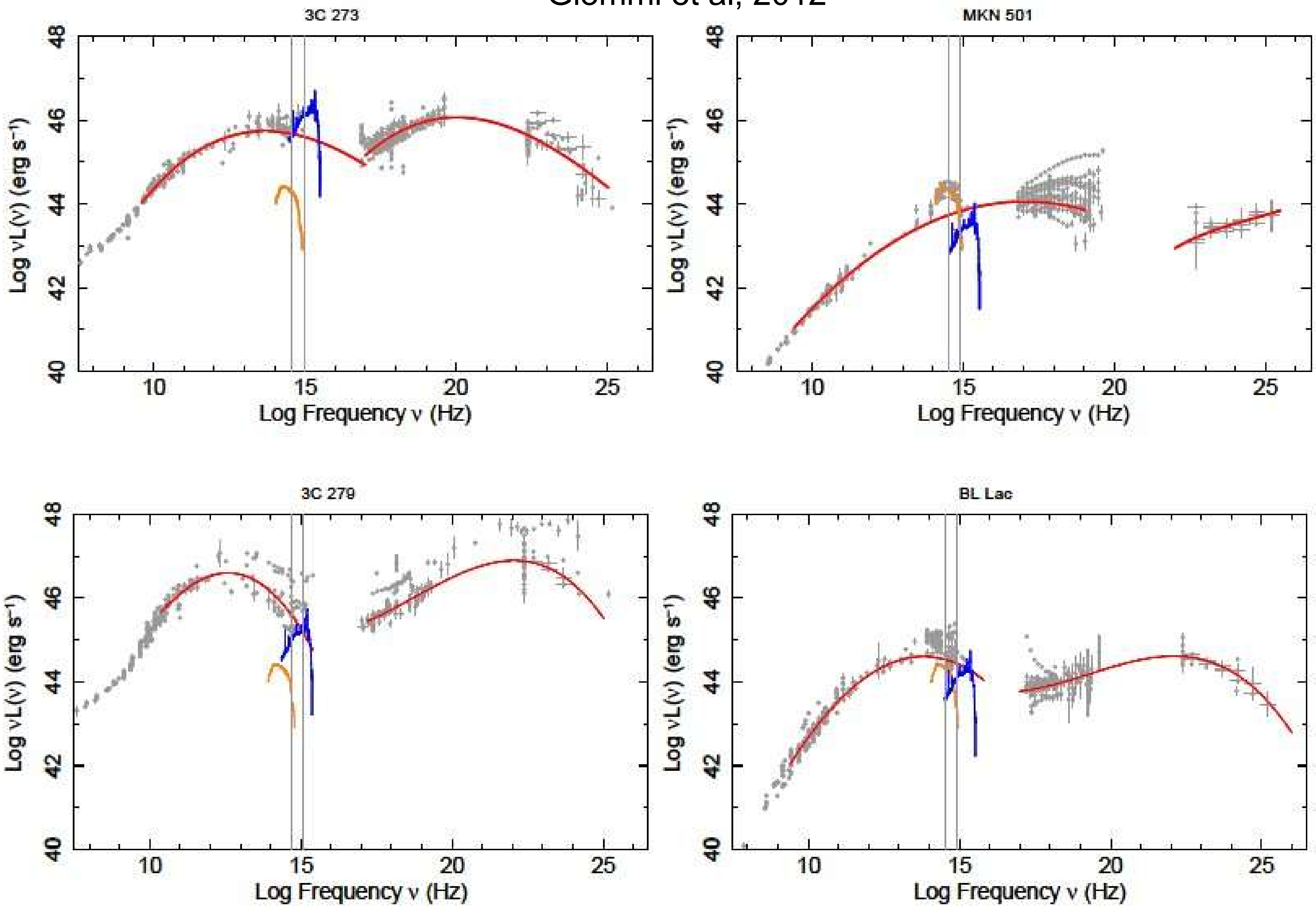
- Doppler boosted, radiation from the jet emission
- radiation from the accretion disk
- from the BLR
- the host galaxy

↓

Anti-correlation most likely due to selection effect :

bright radio sources drawn from high end luminosity function while BL Lac in flux limited samples are mostly high synchrotron peaked.

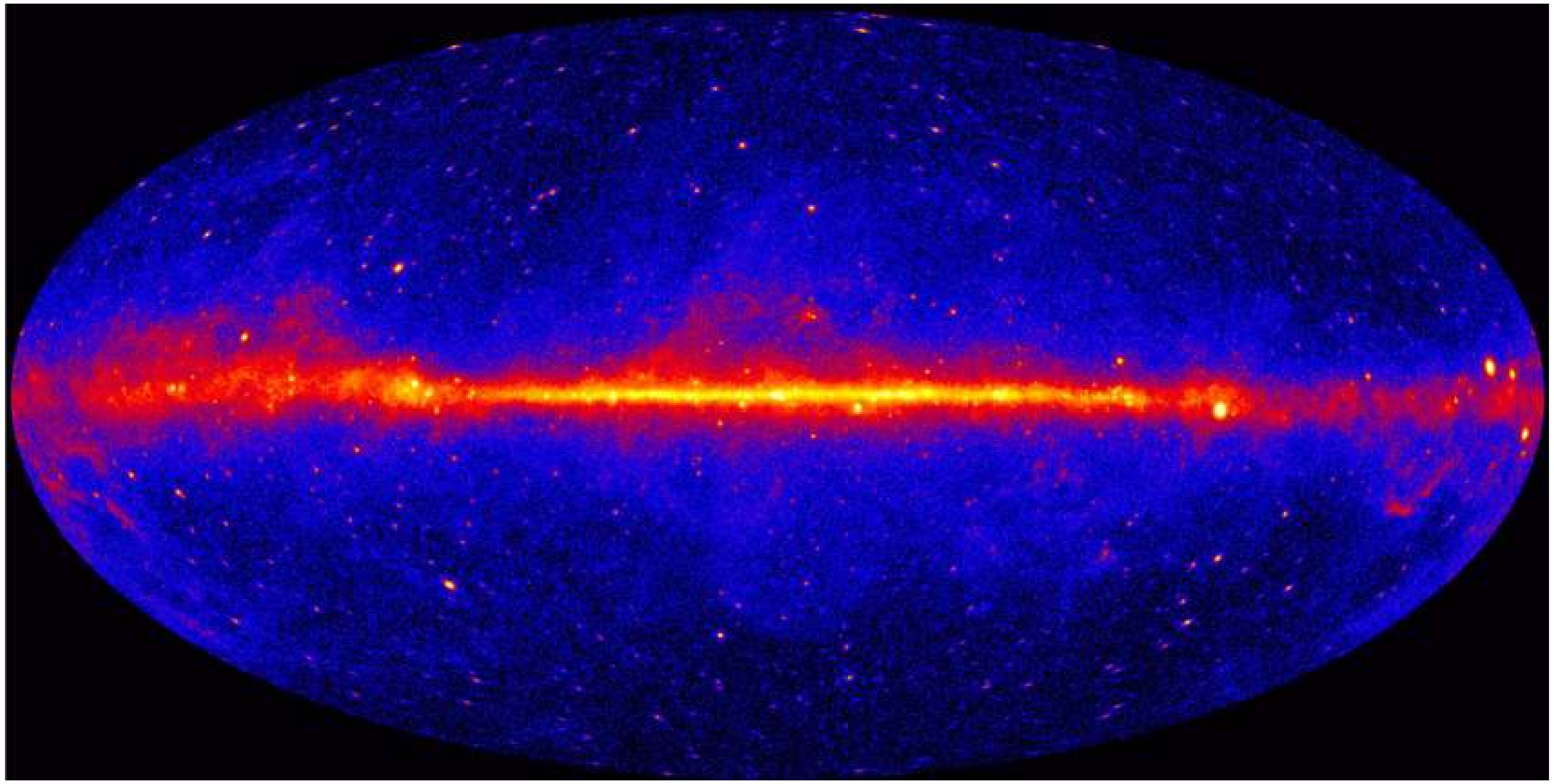
Giommi et al, 2012



FSRQs

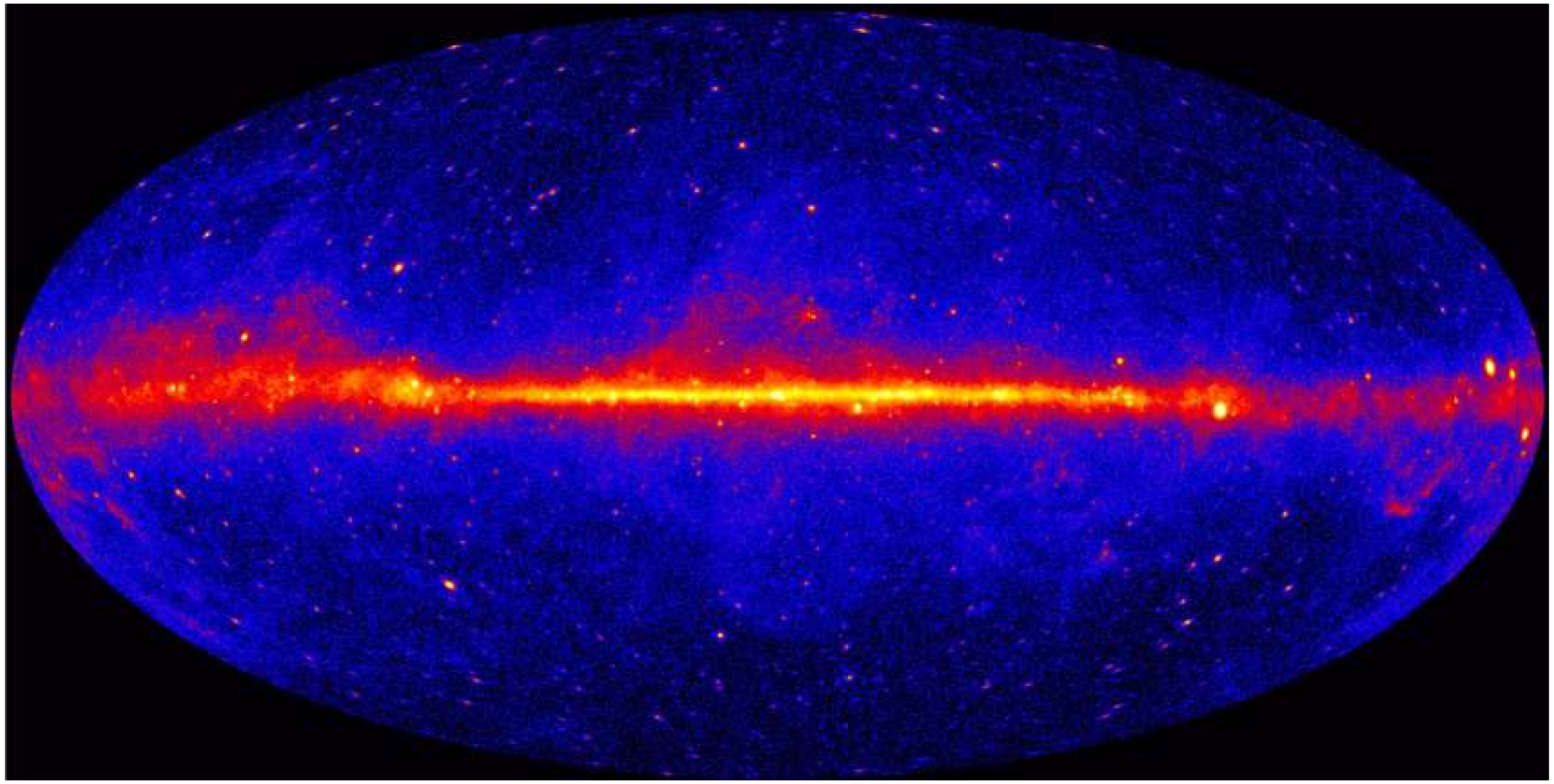
BL Lacs

High Energy Sky > 1 GeV



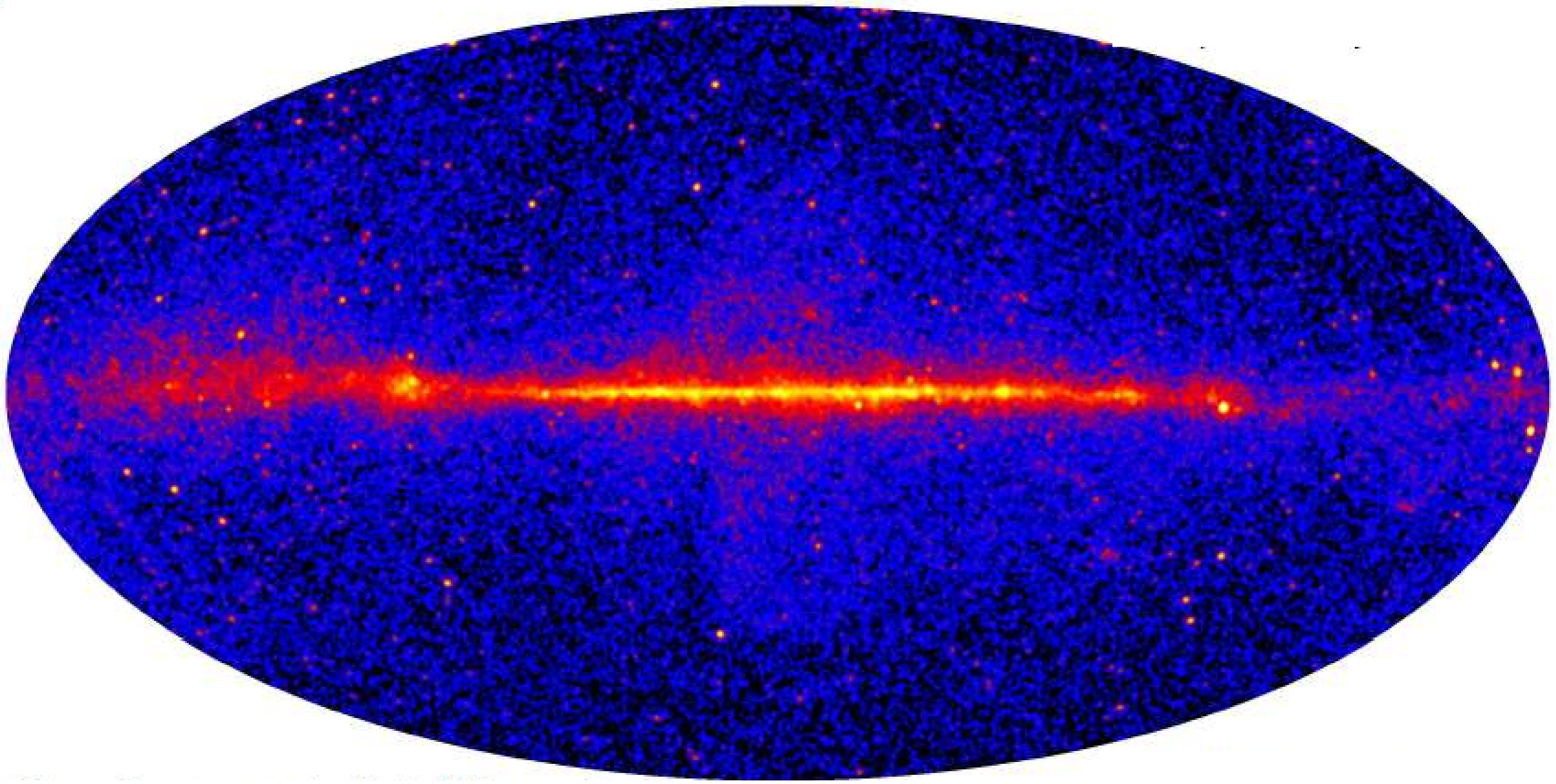
2FGL (2 years): 1873 sources (Nolan et al 2012)
Upcoming 3FGL (4 years): ≈3000 sources

High Energy Sky > 1 GeV



2FGL (2 years): 1873 sources (Nolan et al 2012)
Upcoming 3FGL (4 years): ≈3000 sources

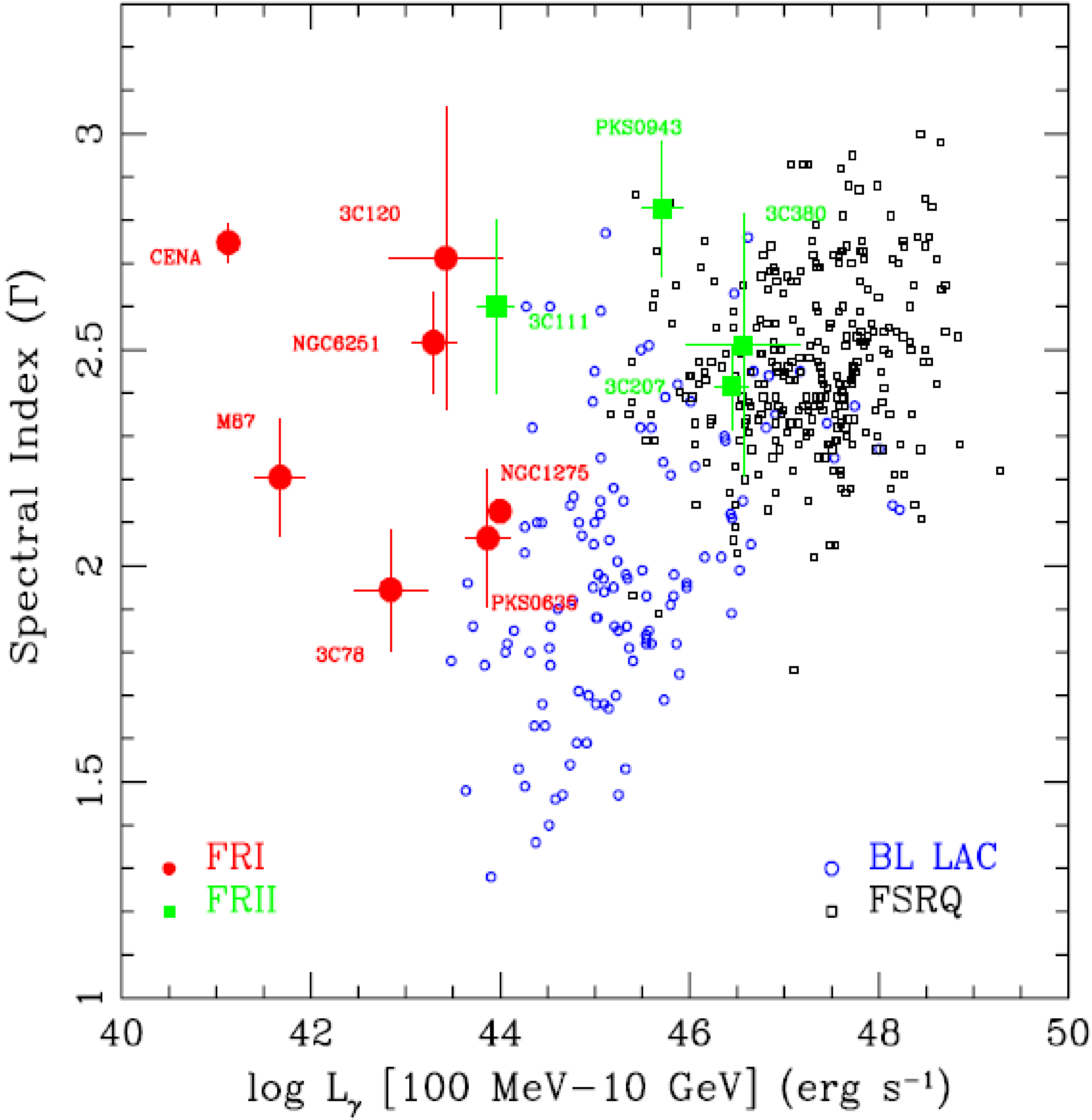
High Energy Sky > 10 GeV



1FHL (3 years) Ackermann et al 2013
514 sources

FERMI census

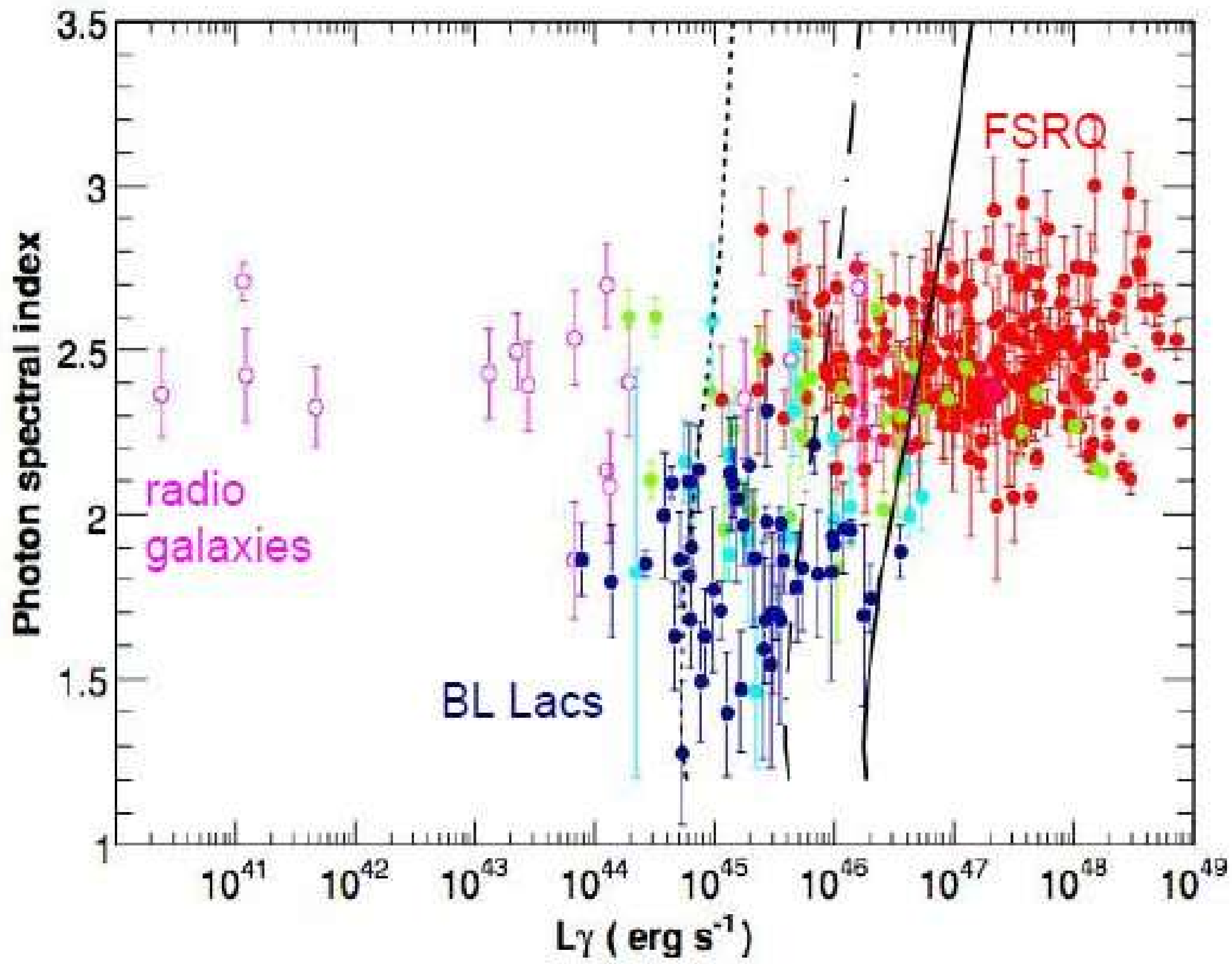
- ~ 1000 AGN
- Only a few non blazar detected
- No radio-quiet Seyfert detected at a level of 1% of their bolometric luminosity



Abdo et al. (2010) (MAGN)

FERMI census

- ~ 1000 AGN
- Only a few non blazar detected
- No radio-quiet Seyfert detected at a level of 1% of their bolometric luminosity
- Luminosity is correlated with photon index (and blazar class):
  higher luminosity ↔ steeper spectrum
  → consistent with blazar sequence



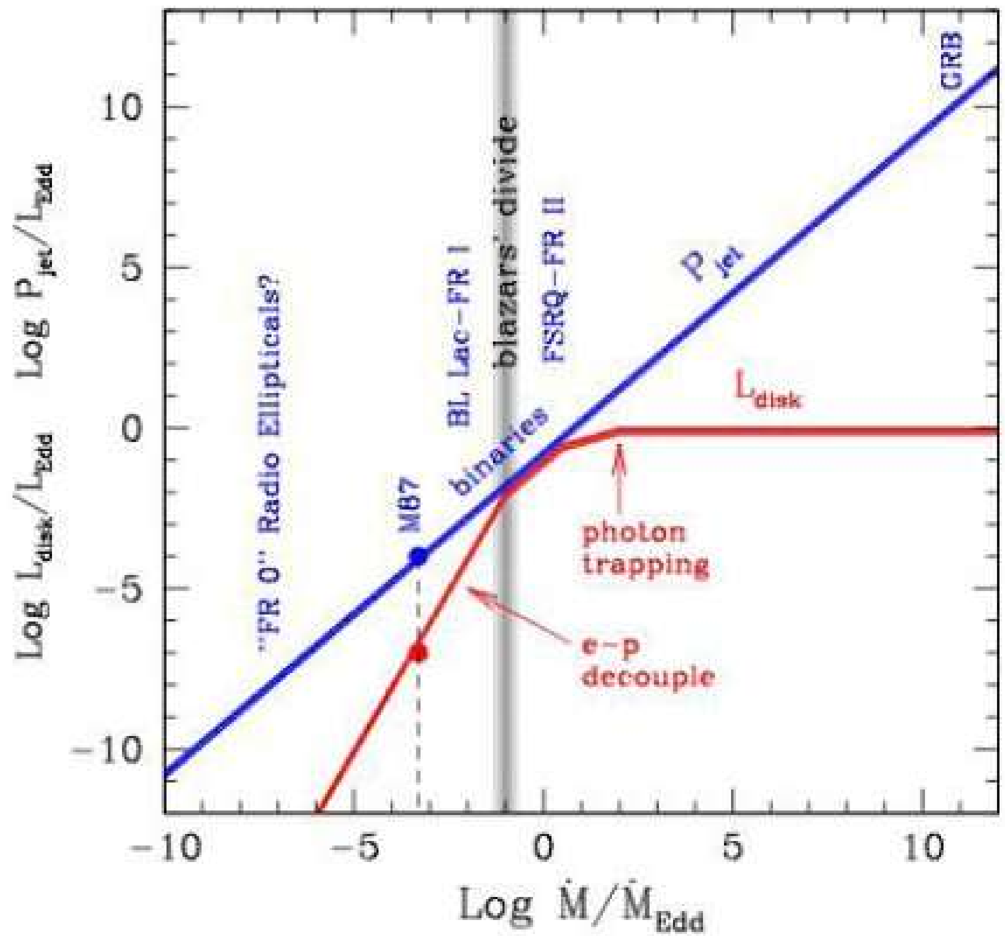
FERMI census

- Jet power Pjet / LEdd depends directly on the accretion rate (dM/dt) / (dMEdd /dt) (and on the black hole mass)

- Blazar's divide occurs for Ldisk ~ 10^{-2} Ledd.

  below: disk radiatively inefficient
  above: disk radiation ionizing BLR

  → evolution of FSRQs into BL Lacs due to evolution in accretion rate ?
  (Ghisellini, Tavecchio, MNRAS 387, 1669, 2008



Ghisellini (2010)

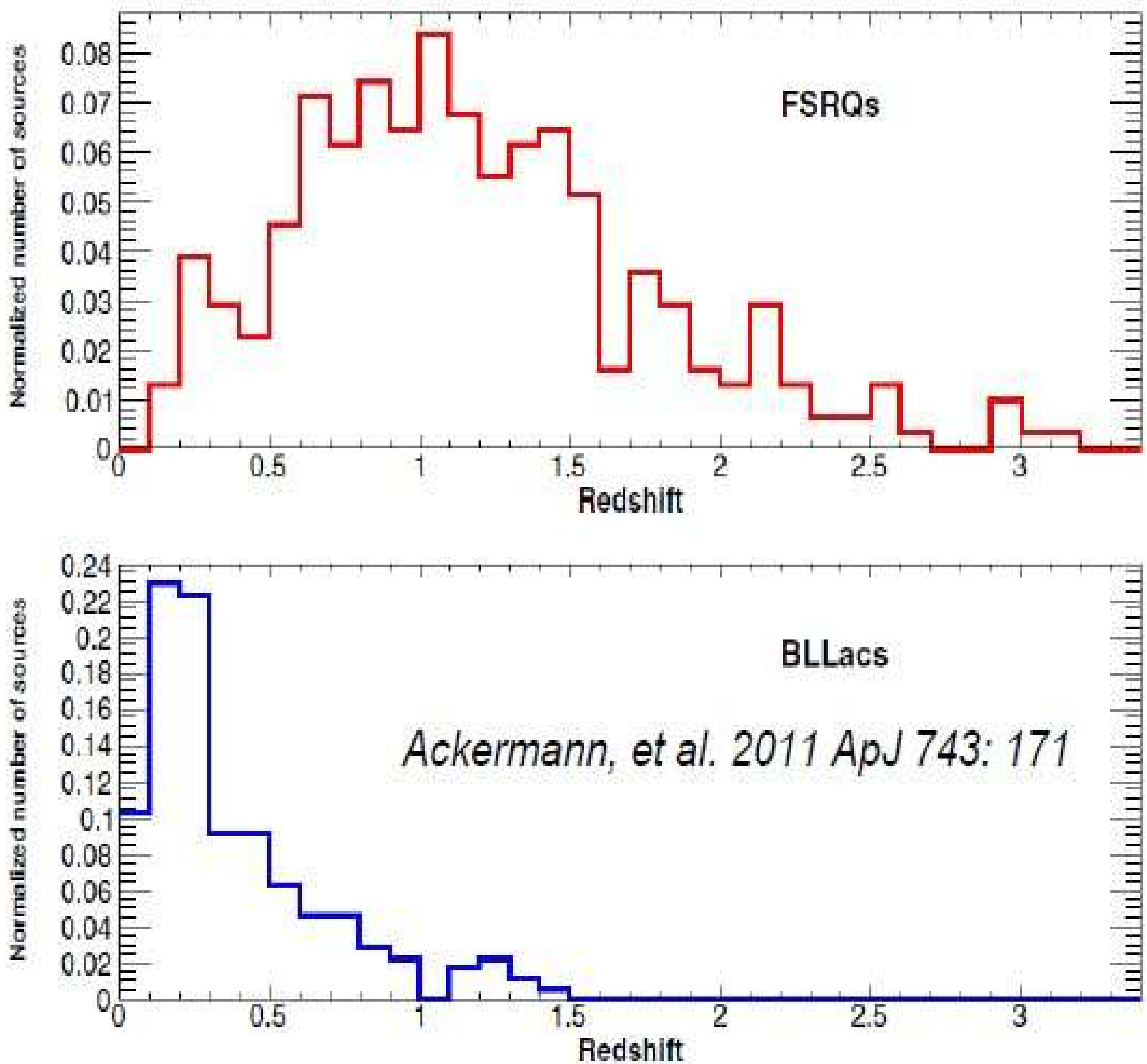
FERMI census

- Low ratio FR II / FR I indicative

  - of less efficient particle acceleration in their jets, different jet structure and/or different beaming pattern

  - of suppresion of gamma emission by γ-γ absorption (eg Reimer 2007)

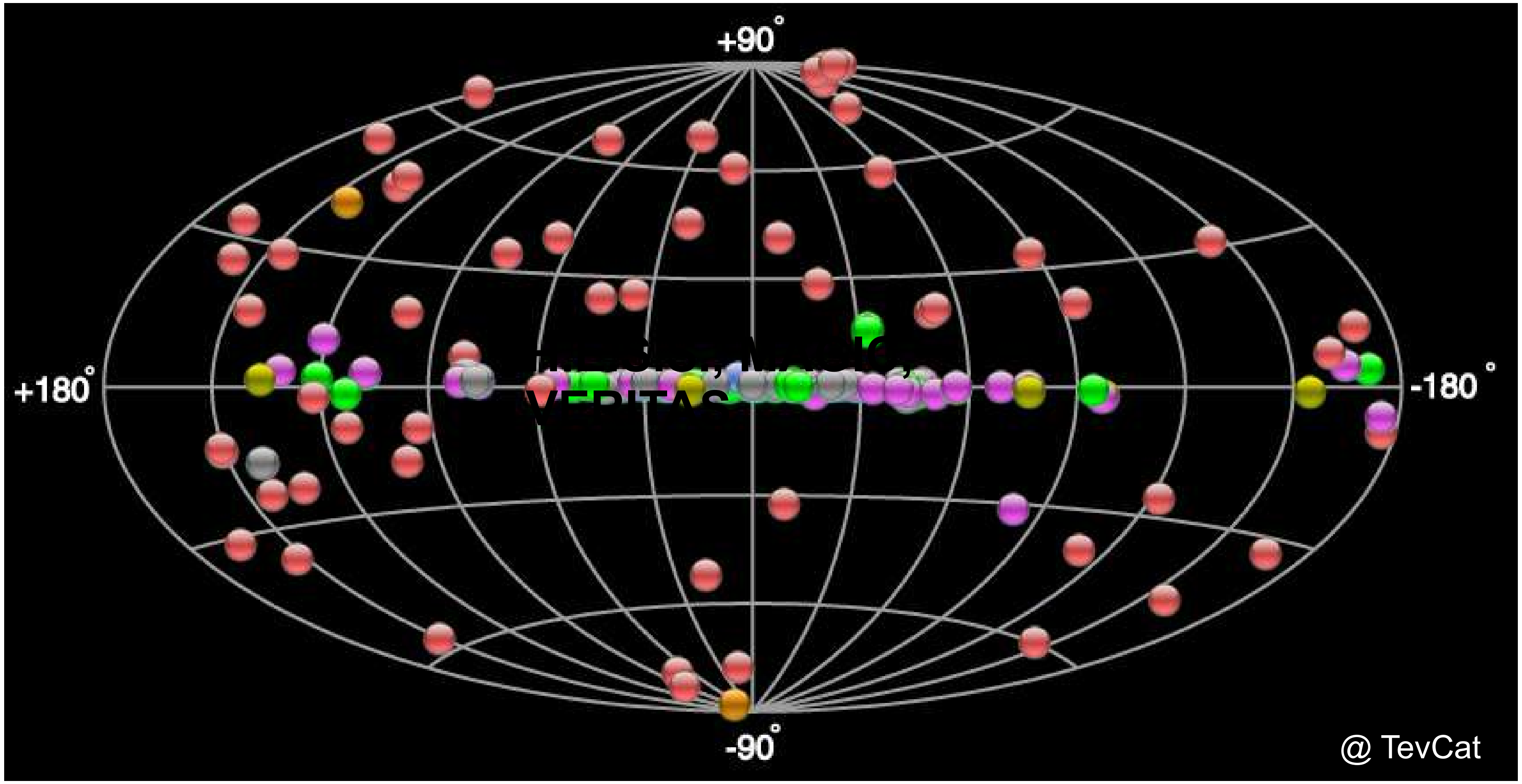
  - FRII are intrinsically less numerous



H.E.S.S. VERITAS MAGIC

Plus smaller projects (FACT, HAGAR, SHALON…)

High Energy Sky > 100 GeV

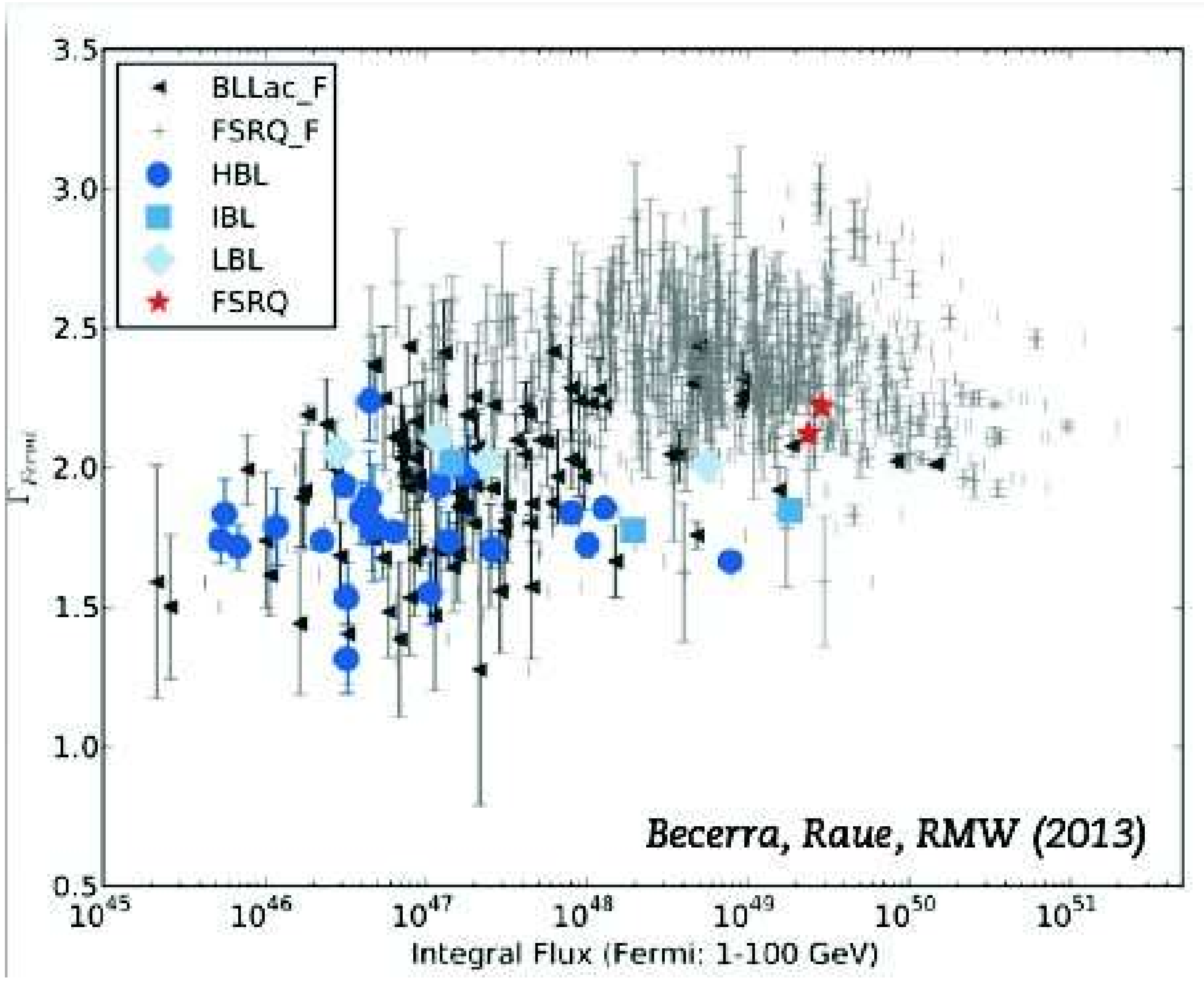


H.E.S.S.
MAGIC
VERITAS

55 blazars, 2 starburst
150 sources

The extragalactic TeV sky is dominated by blazars (mainly BL Lacs)

HE and VHE AGN

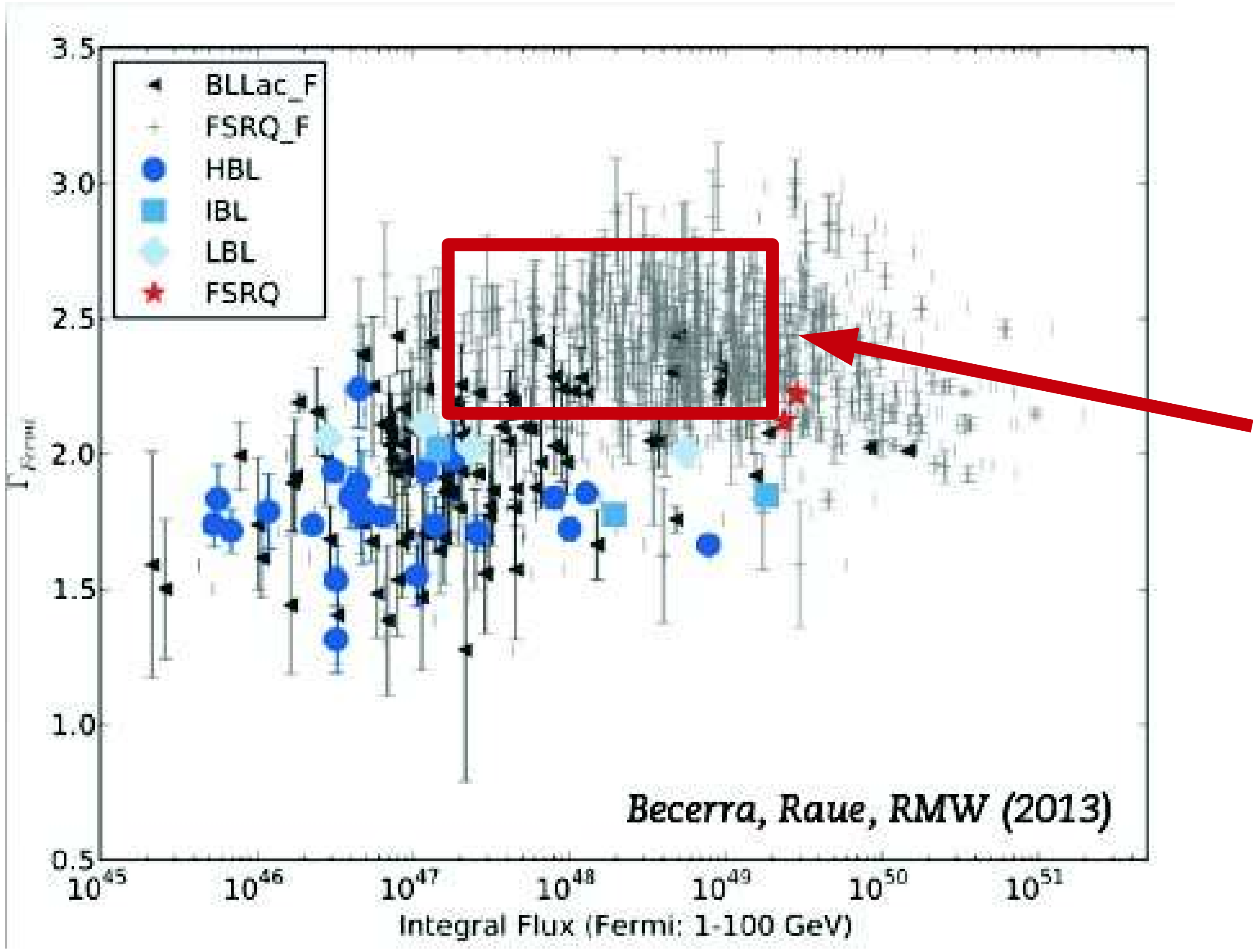


- TeV sources cover same area plot as Fermi AGNs

Fermi catalog contains 1052 AGN (435 BL Lacs, 370 FSRQs), 36 TeV emitters

@ R. Wagner, Quy Nohn 2013

HE and VHE AGN



- TeV sources cover same area plot as Fermi AGNs
- None detected with $F \gtrsim 10^{47}$ erg/s and $\Gamma \gtrsim 2.0$

Fermi catalog contains 1052 AGN (435 BL Lacs, 370 FSRQs),
36 TeV emitters

Highly biased VHE samples

- ➔ Entirely biased towards large Doppler boosting :
  100% of boosted sources (except possibly FR I ?).

- ➔ Biased towards active states : due to present sensitivity limits and strategy of observation (VHE and multi-lambda alerts).

- ➔ Possibly biased towards low redshifts : due to strategy of observation to optimize detection probability despite EBL absorption effect

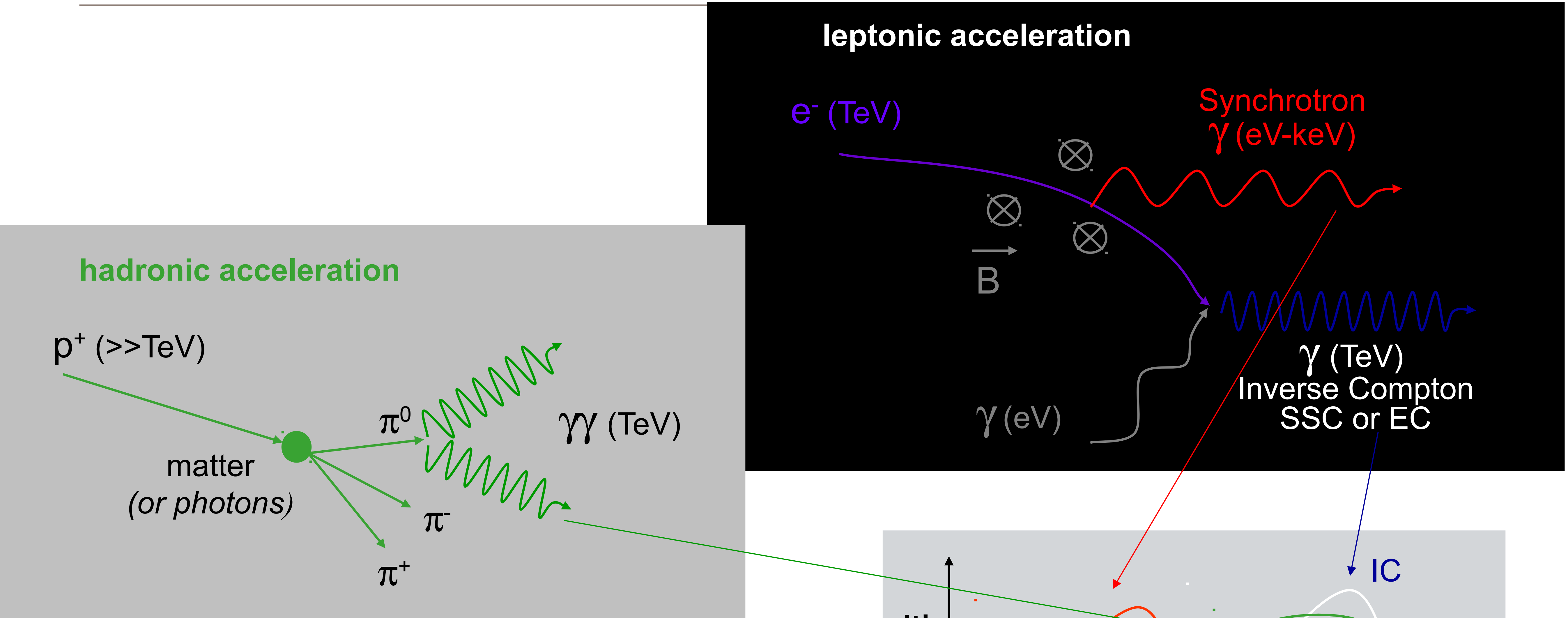
Difficulties of VHE observations:

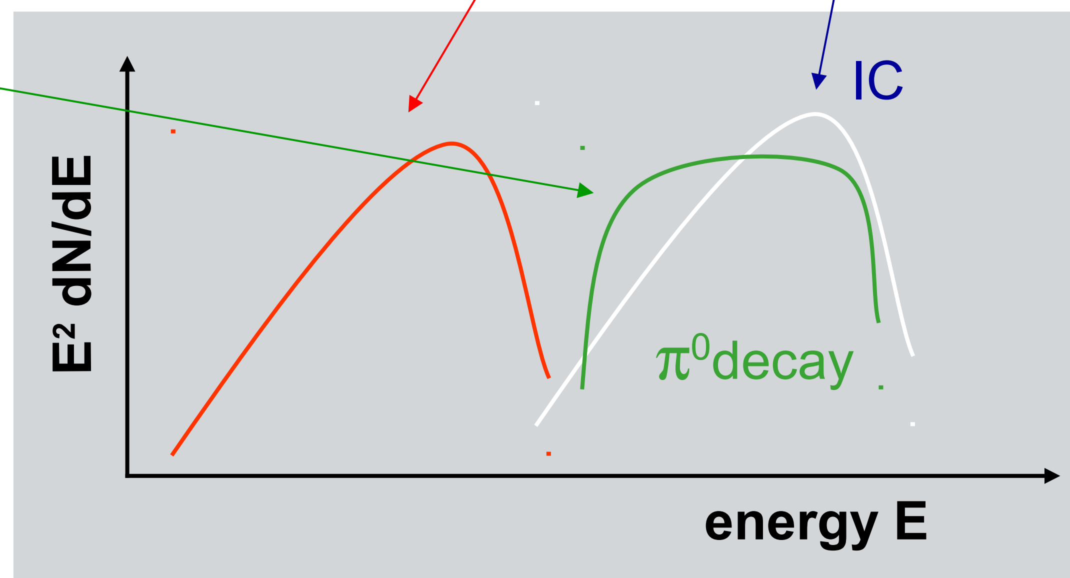
- ✔ Lack of spatial resolution.
- ✔ Observation of anisotropic emission and uncertain viewing angles.
- ✔ Limited information from continuum energy spectra.

Luminosity functions at VHE still difficult to derive:

- ✔ Poor statistics
- ✔ Poor time coverage

Basic scenarii for SED modeling



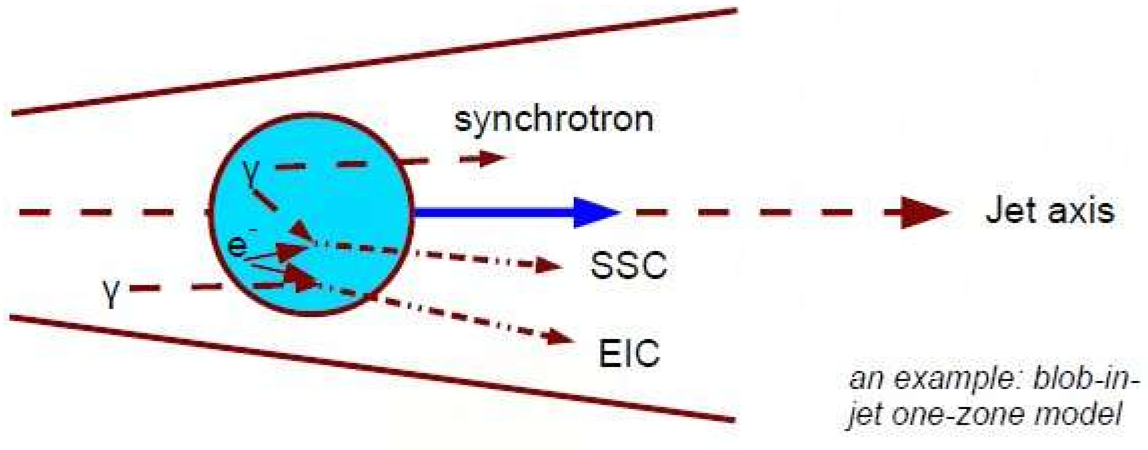


AGN emit in a wide frequency range

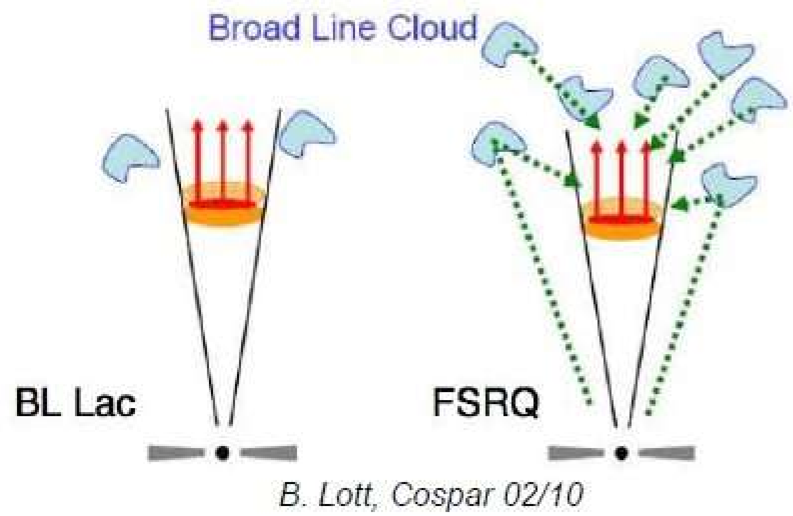
MWL data mandatory to constrain SED/lightcurves and models

(adapted from De Lotto, 2009)

Standard model – SSC / EIC



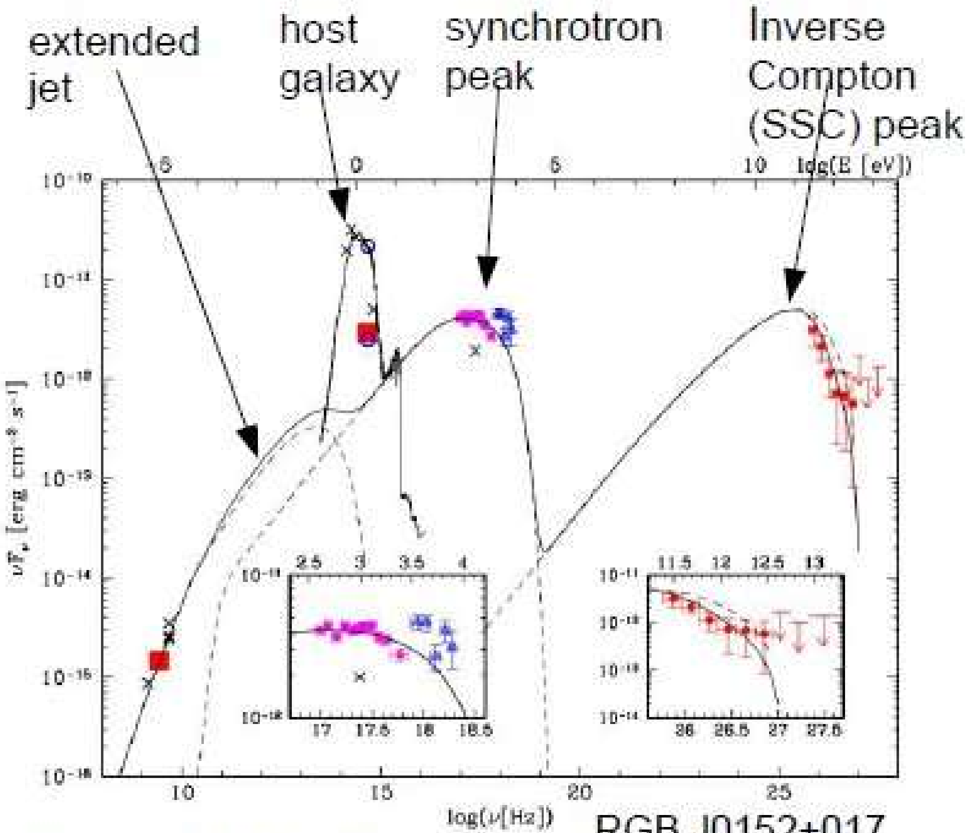
@ A. Zech



- plasma blob inside jet with turbulent magnetic field and high energy electrons
- γ-rays from Synchrotron Self-Compton or External Inverse Compton diffusion (on BLR or torus photons)
- other leptonic models exist (e.g. stratified jet, decelerating jet,...), but basic emission processes are the same.

Modelling of blazar spectra

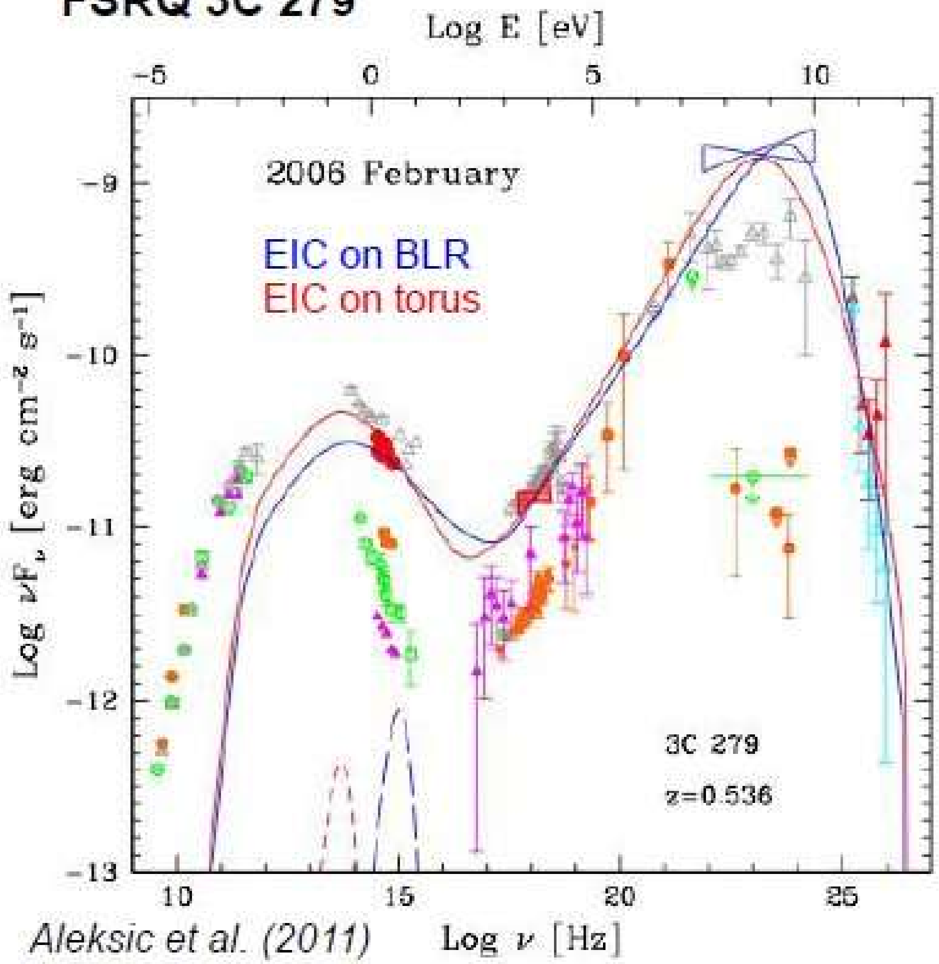
BLLac object RGB J0152+017



Aharonian et al. (2008)

parameters:
B ~ 0.10 G
δ ~ 25
R ~ 1.5 x 10^{15} cm

FSRQ 3C 279

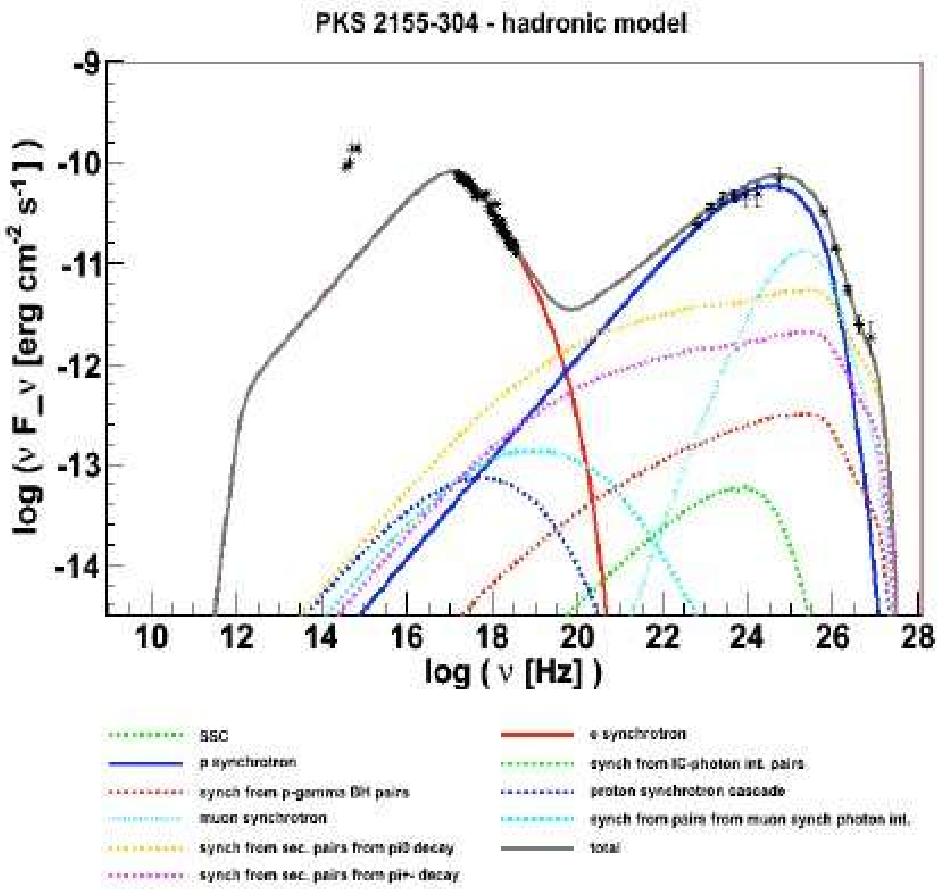


Aleksic et al. (2011)

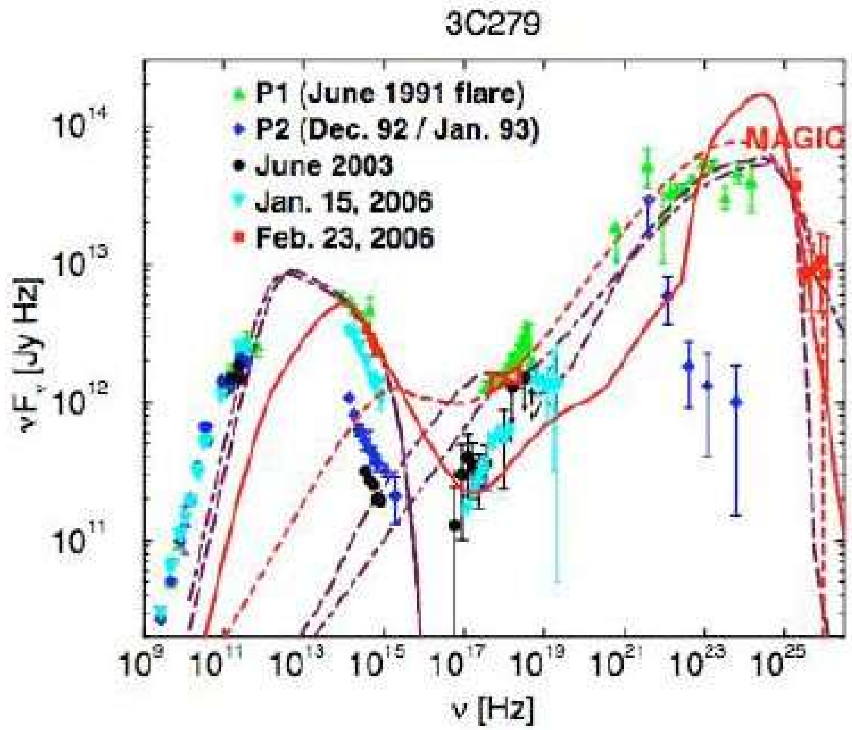
parameters for BLR case:
B ~ 0.15 G
δ ~ 20
R ~ 5 x 10^{16} cm

Lepto-hadronic models

Hadronic scenarios remain an option to explain !-ray emission from AGN.



M. Cerruti, AZ, C. Boisson, S. Inoue, conf. proc. of Gamma 2012



M. Böttcher, A. Reimer, A.P. Marscher, ApJ 703 (2009) 1168

e.g. for a BL Lac

e.g. for an FSRQ

Cherenkov Telescope Array facts

- **High sensitivity**

  > 4 orders of magnitude dynamic range in flux between strongest and faintest sources; a factor of 10 more sensitive than current IACT

- **Wide spectral range**

  > 4 orders of magnitude coverage in energy from 10 GeV to above 100 TeV;

  10-15% energy resolution; overlap with FERMI bridging the gap

- **Well-resolved light curves**

  Minute-scale variability of many AGN

- **Resolved source morphology**

  Up to 0.02 deg. angular resolution; 10-20" source localization

- **Large field of view (5 to 10 deg)**

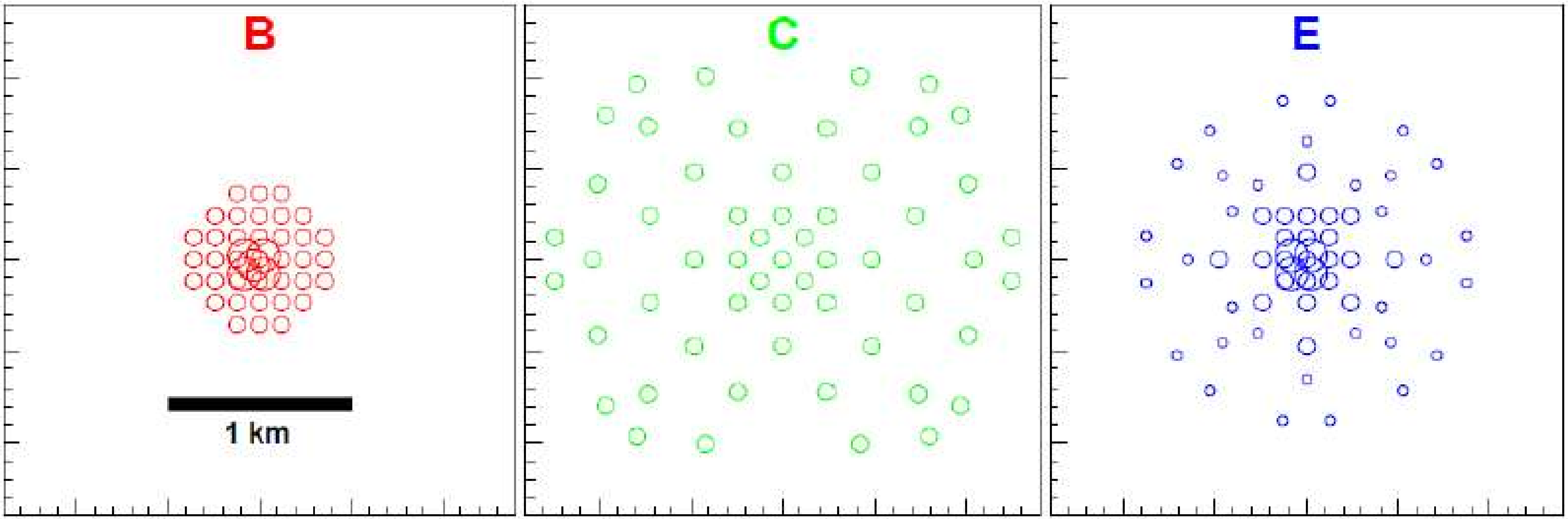
  serendipitous AGN discoveries

- **Surveying capabilities**

  full-sky survey at 1% Crab in about 1 year ; sub-array observing mode

CTA facts

Three different arrays used in the preliminary
Monte Carlo Prod-1 simulations



Densely packed array of 12 m and 24 m telescopes
→ focus on low E

Wide spread array of 12 m telescopes
→ focus on mid and high E

Mixed array of 7, 12 and 24 m telescopes
→ Balanced sensitivity over large E-range

POPULATION STUDIES

Main Science Goal:
Understand nature of blazar emission & unification of blazar classes.

This involves:
- study of emission mechanism and particle population with leptonic and hadronic models
- study of source energetics (e.g. jet power vs. accretion rate...)
- population studies → need high-quality spectra for different blazar types → access a range of redshifts (blazar evolution, distinguish EBL effects)

Why should this be done with CTA ?
- Not sufficient sources (other than HBLs) accessible at VHE with current arrays
- VHE only way to probe weak internal photon fields.
- Important information on jet power in gamma-rays.
- Study of the high-energy end of the spectra (and particle populations)

Follow-up of sources detected at lower frequencies

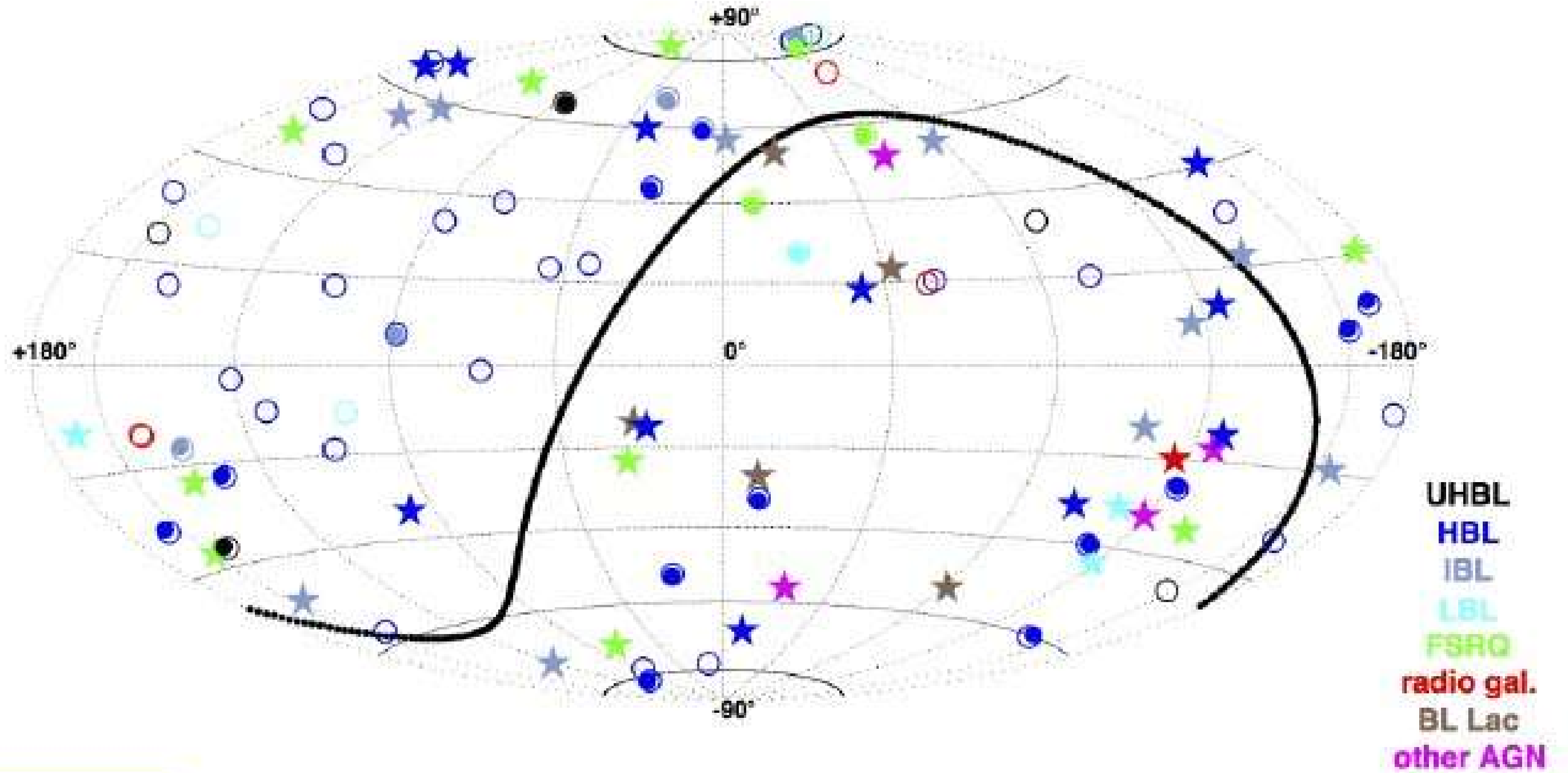
- Extrapolating from Fermi sources
  - Unaffected by γ-ray absorption on EBL
  - Fermi & CTA → 5 decades in energy
  - 85% of known VHE AGN are in 2FGL (Abdo et al, 2011)

Effective areas and cosmic bkgs simulations for different configurations
→ instrumental response.
Detection = 5 sigma, a minimum of 7 excess events, > 3% of bkg
Array configuration B, best sensitivity at low energies

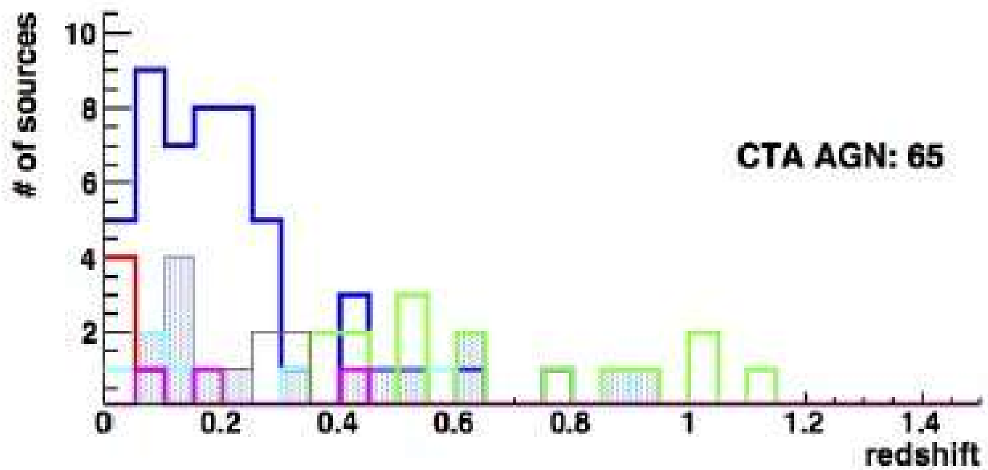
Only sources with known redshift

Population studies – Pointed observations

Open symbol : detected source
Filled symbol : prediction from Fermi



coverage of ~ 8% of the sky with ~20h average exposure per FoV !



Extragalactic survey

Key Science Questions

- What is the Gamma-Ray Luminosity Function?
- Does the blazar sequence hold?
- Is there a strong population of hard spectra extreme blazars?
- Are there VHE source classes other than blazars and radio galaxies?

- Are there dark accelerators?
- Is there a correlation with UHECR and HE neutrino events maps?
- What is the origin and strength of the diffuse γ-ray background?
- Large scale anisotropies (related to dark matter distribution?)

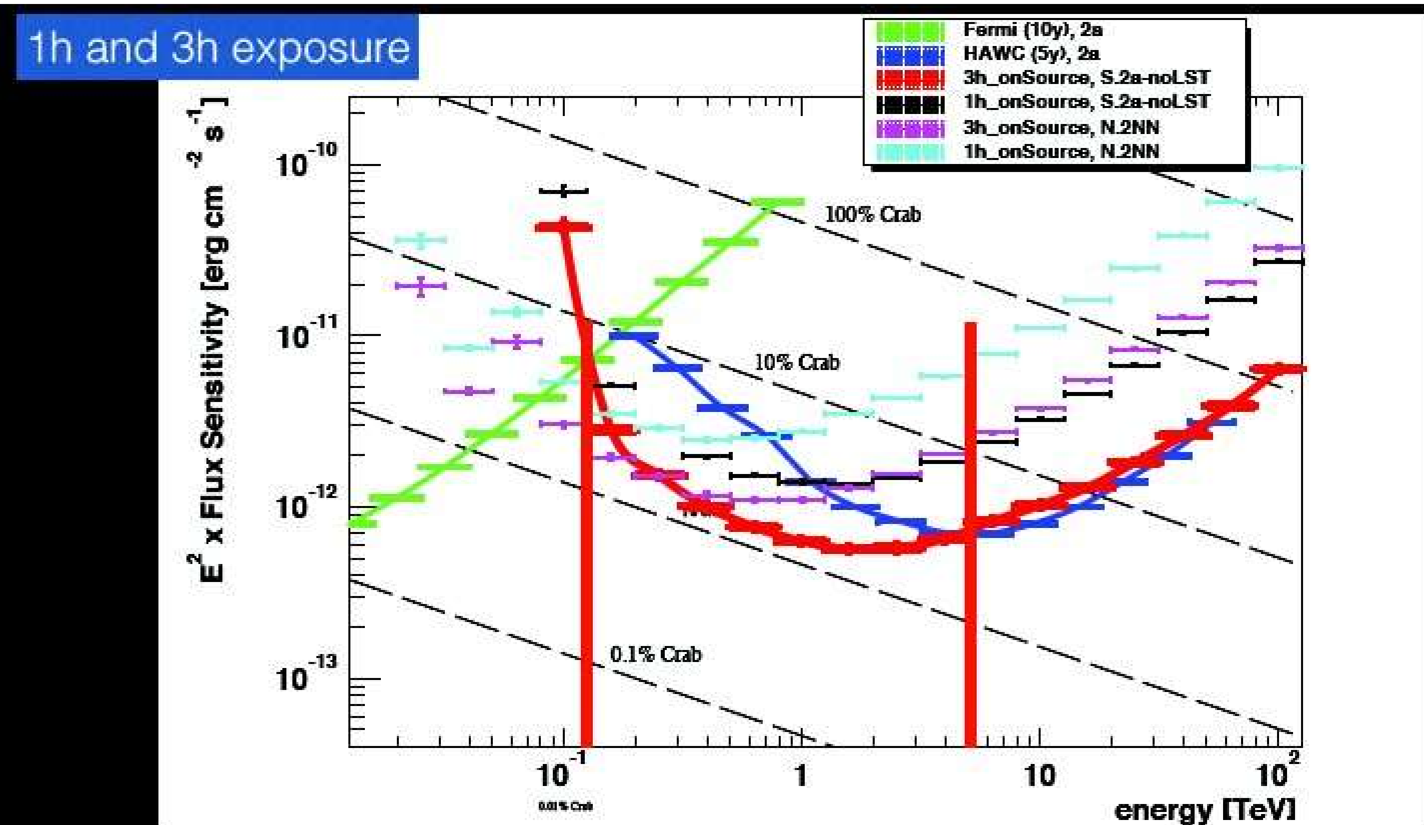
Extragalactic Blind Survey

- Will answer some key questions (e.g. logN/logS)
- Legacy project for the community
- Needs long exposure (600h-1000h)
- Analysis will be more complicated than for the individual sources
- May profit from a special pointing mode: divergent mode

Only 8% of the sky covered
25% is a step forward

Extrapolation 1FHL → 10 to 35 sources detectable out of ~60

Results from HAWC should help anticipating the proba of detecting AGN in blind survey.



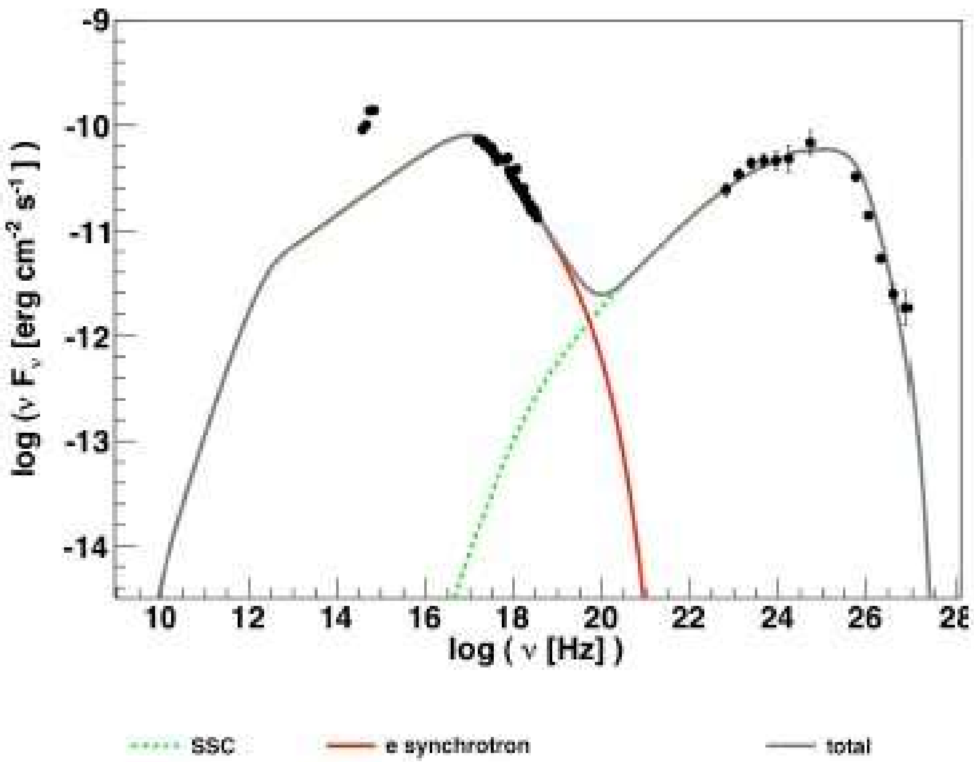
- If we aim for 1/4 sky, effective exposures of 2-3 hrs are feasible. On-source sensitivities for 1 and 3 h are shown above

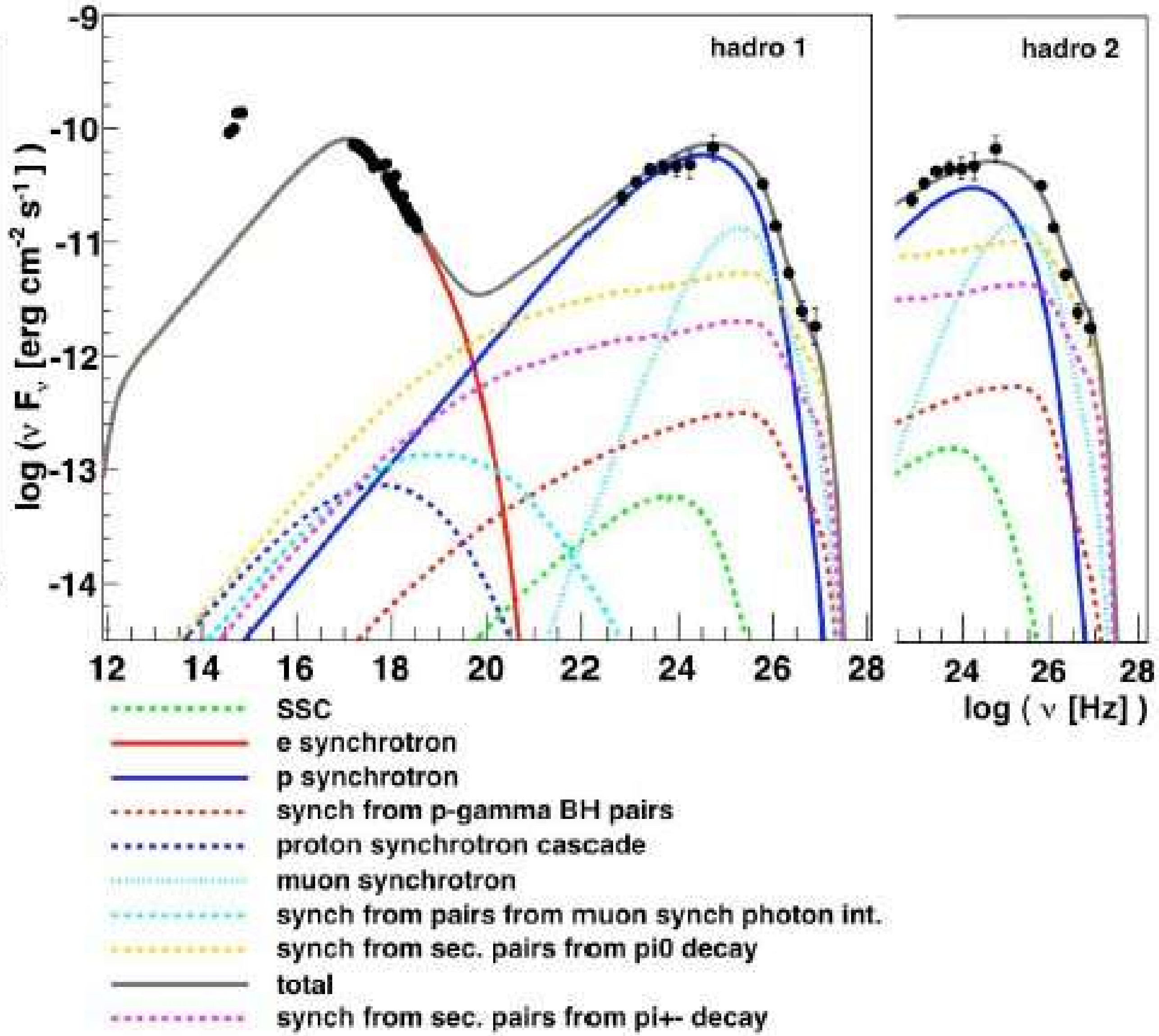
Particle acceleration - Emission process

- Leptonic versus hadronic ? → lepto-hadronic models

  detectable spectral features in HE and VHE range

PKS 2155-304 - a case study





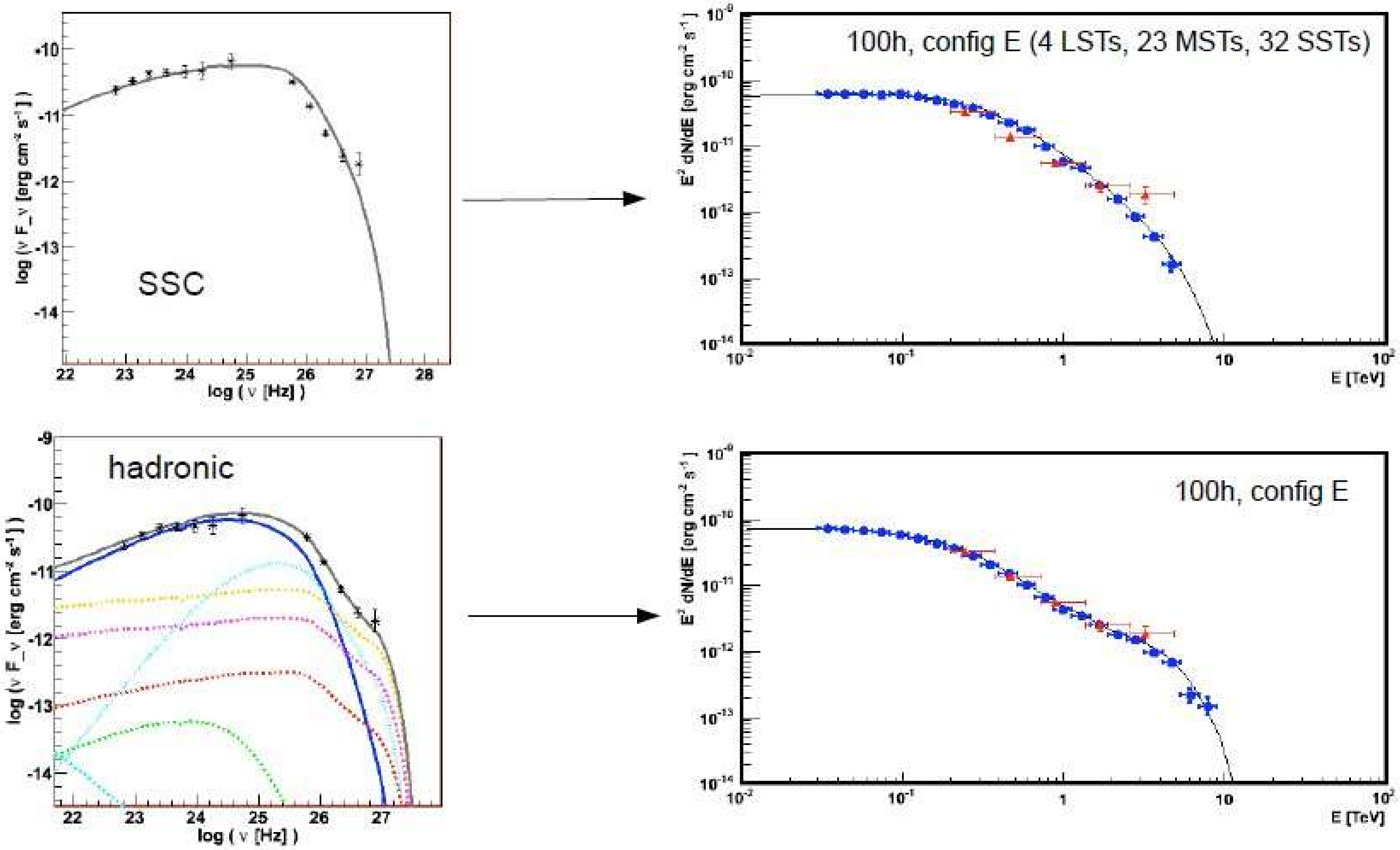
SSC:
δ=30
B = 0,07 G
R = 2e16 cm
L=4e43 erg/s

hadro 1:
δ=30
B = 80 G
R = 5e14 cm
γ_p,max = 1e9
density_p = 1e4 @ γ=1
L=4e45 erg/s

hadro 2:
δ=30
B = 50 G
R = 3e14 cm
γ_p,max = 1e9
density_p = 6e4 @ γ=1
L=2e45 erg/s

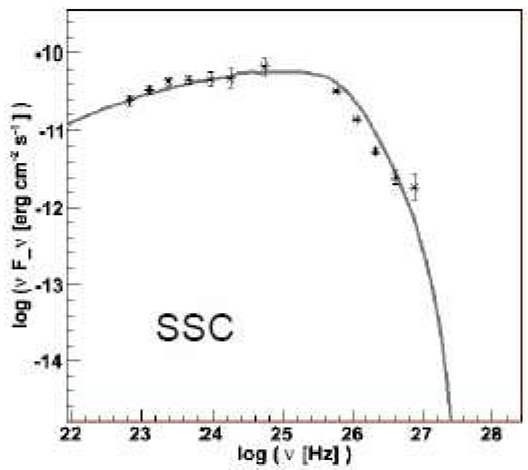
-> level of cascade contribution depends on the ratio of B-field to proton & photon density.

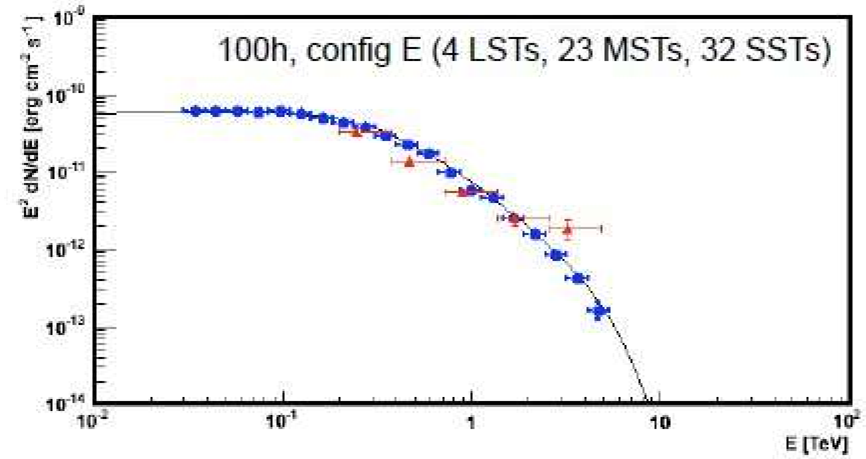
Simulating CTA spectra

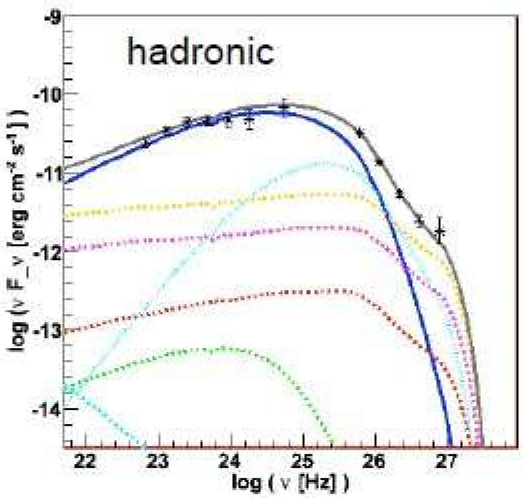


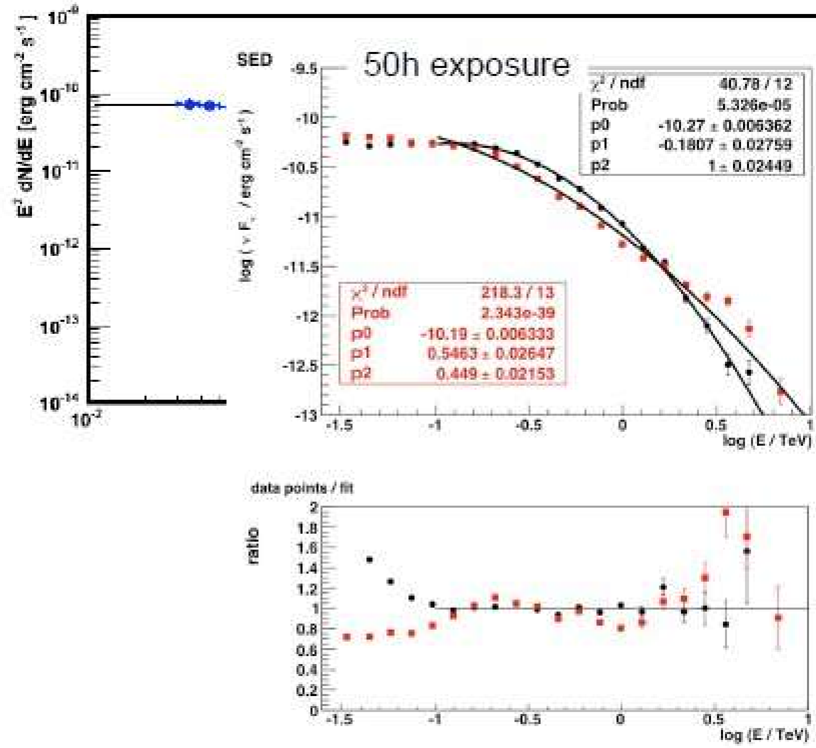
Simple logparabolic fits to the VHE spectrum show how hadronic solutions appear statistically different from leptonic SSC scenario.

Simulating CTA spectra



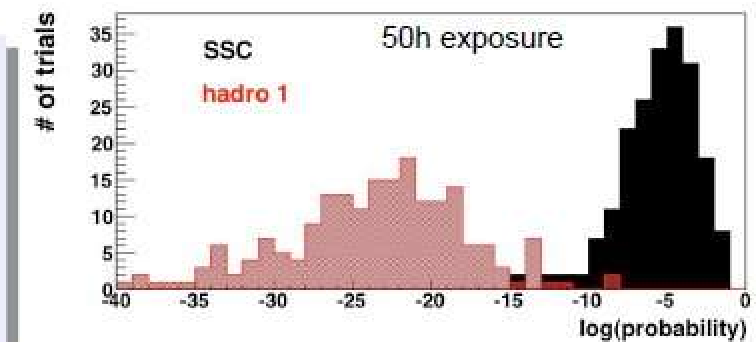


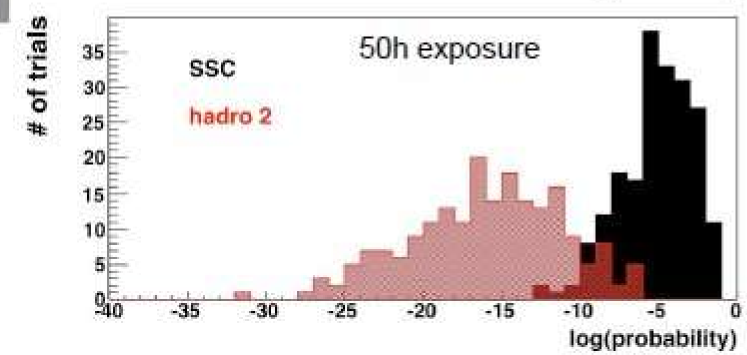




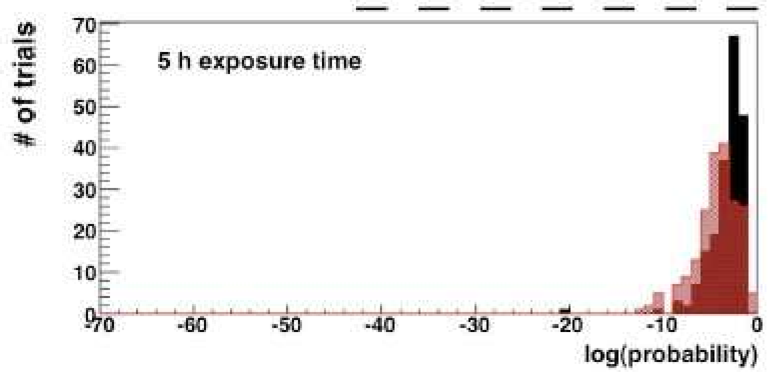
a simple logparabolic fit arrives at a discrimination of SSC and hadronic spectra

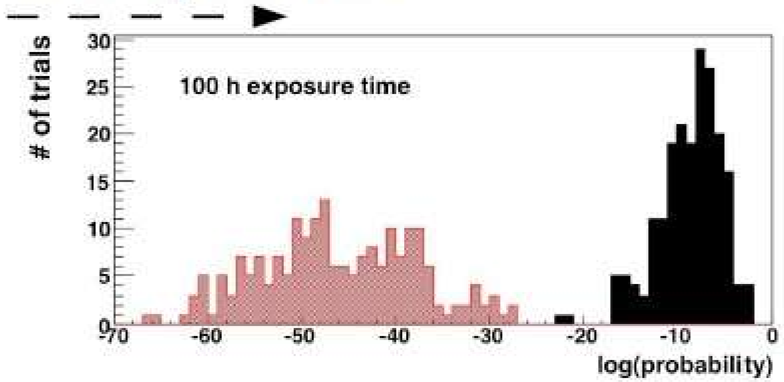
(200 simulated spectra with statistical fluctuations)





The discriminative power increases with exposure time.





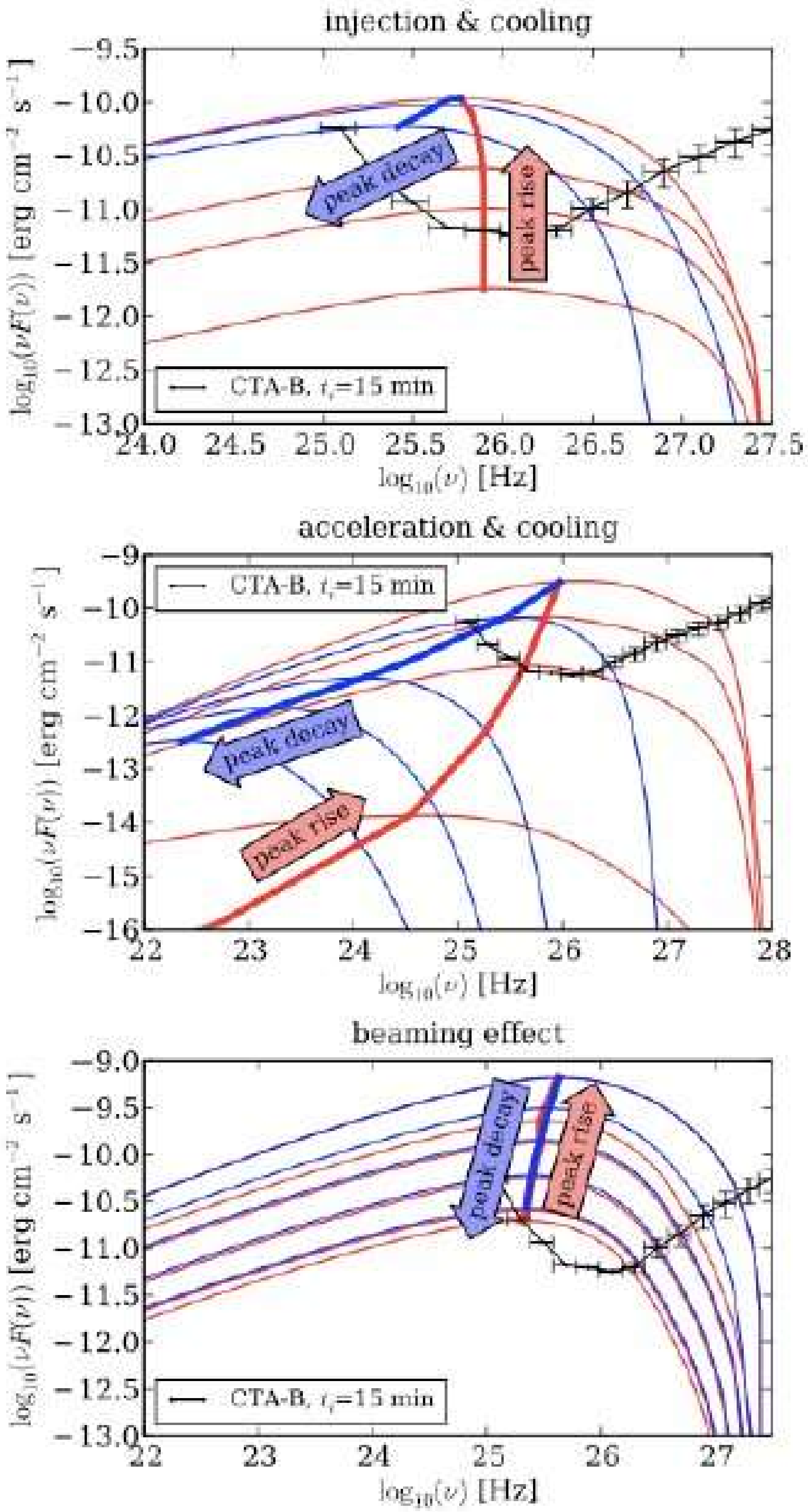
@ Cerruti, Zech

- Leptonic versus hadronic ? → lepto-hadronic models

  detectable spectral features in HE and VHE range

- Direct info from short time scale variability studies
  - Constraints on models
  - high variability at VHE : support leptonic scenario
  - extension beyond TeV : support hadronic scenario

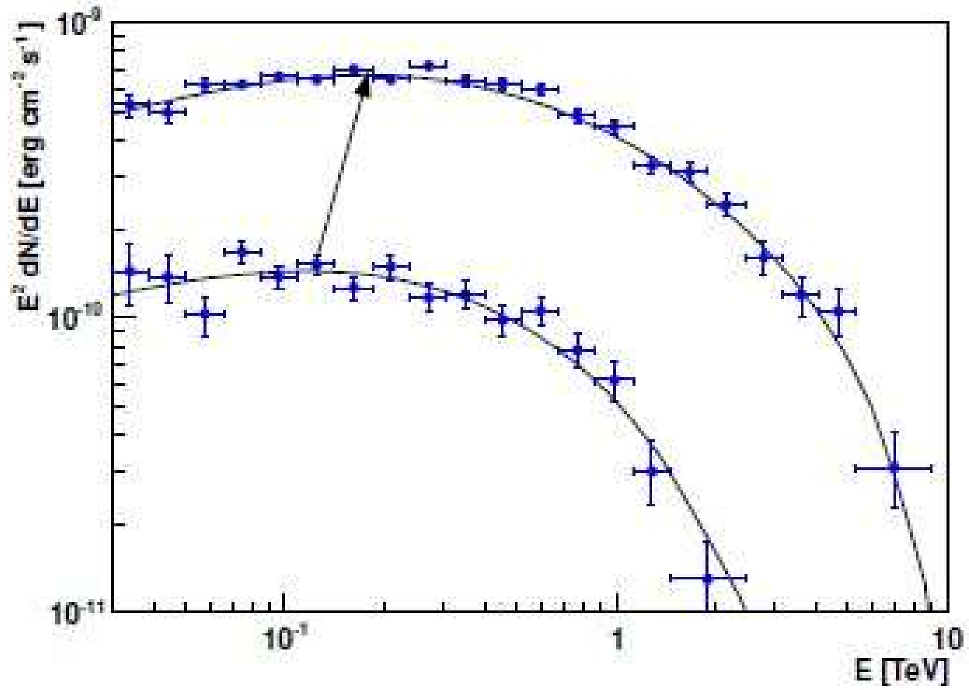
Variability



High quality monitoring of the evolution of the IC peaks should strongly constrain SSC scenarii

Direct signature of mechanisms at work and origin of variability (rapid injection, acceleration, radiative coooling...)

CTA 15mn versus H.E.S.S. 50hr



Sol et al, 2013

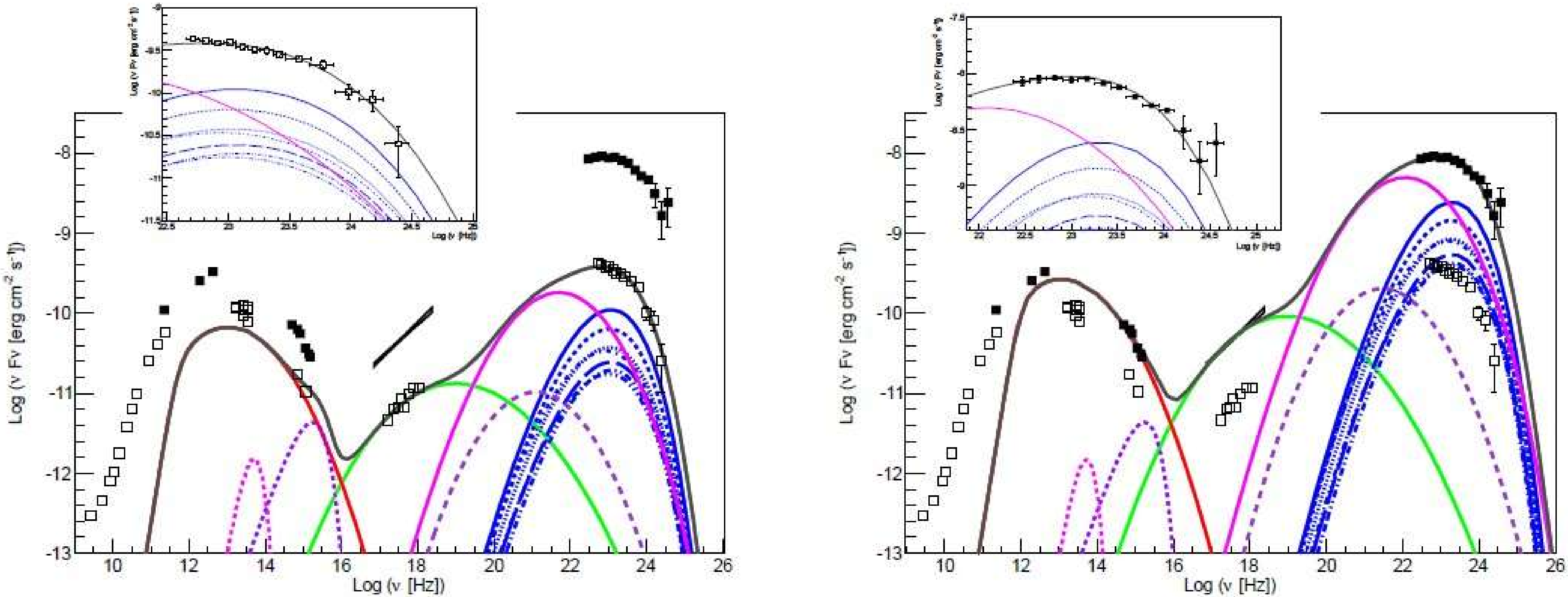
- Leptonic versus hadronic ? → lepto-hadronic models

  detectable spectral features in HE and VHE range

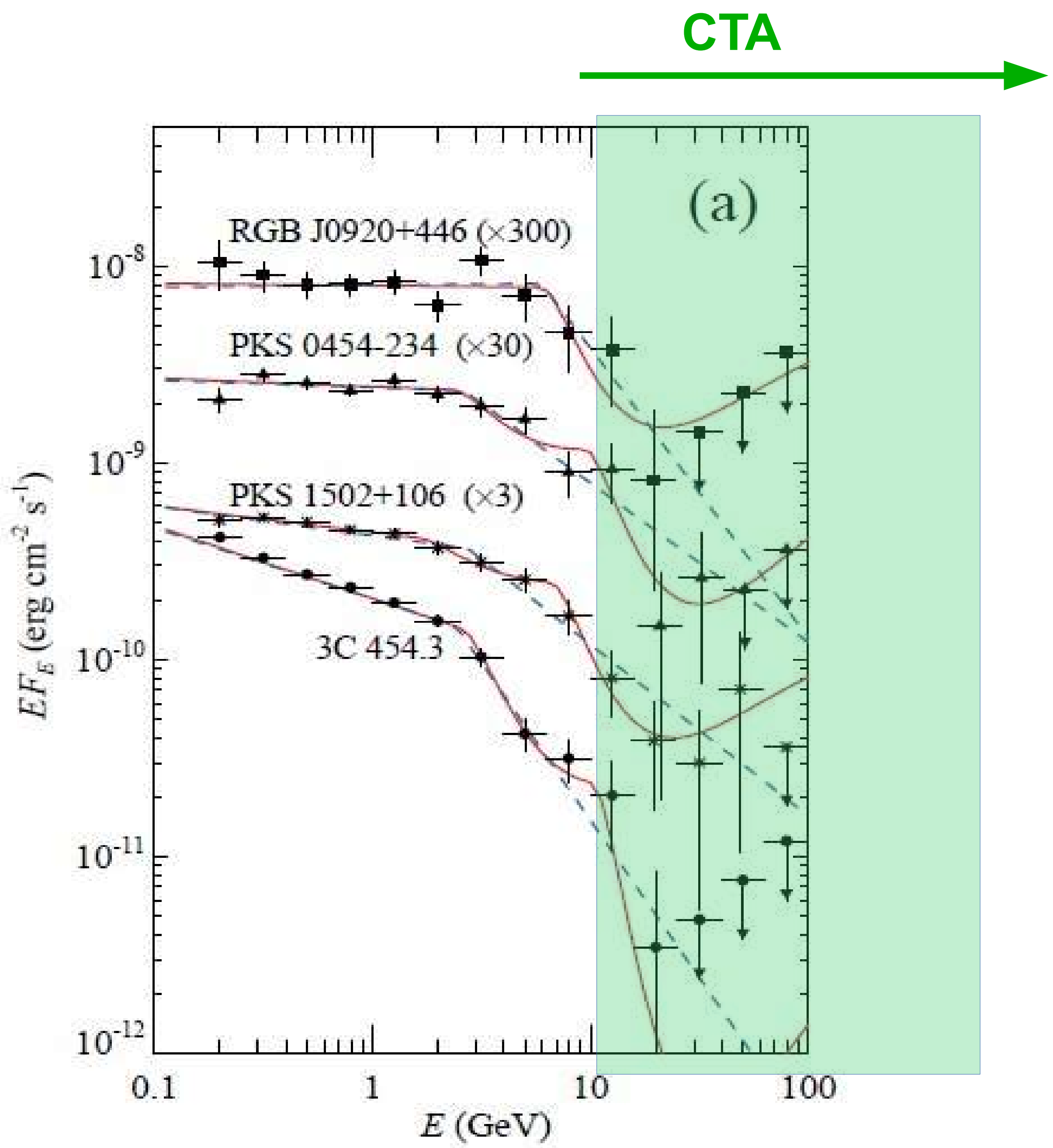
- Direct info from short time scale variability studies
  - high variability at VHE : support leptonic scenario
  - extension beyond TeV : support hadronic scenario

- Photon-photon (γ-γ) absorption features:
  - detected by Fermi
  - further studies with CTA (~ 10% spectral resolution) to map BLR structure

→ link VHE emisssion to Broad Line Region physics



Explain GeV spectral cutoff by scattering Ly □ radiation (Cerruti et al. 2013)



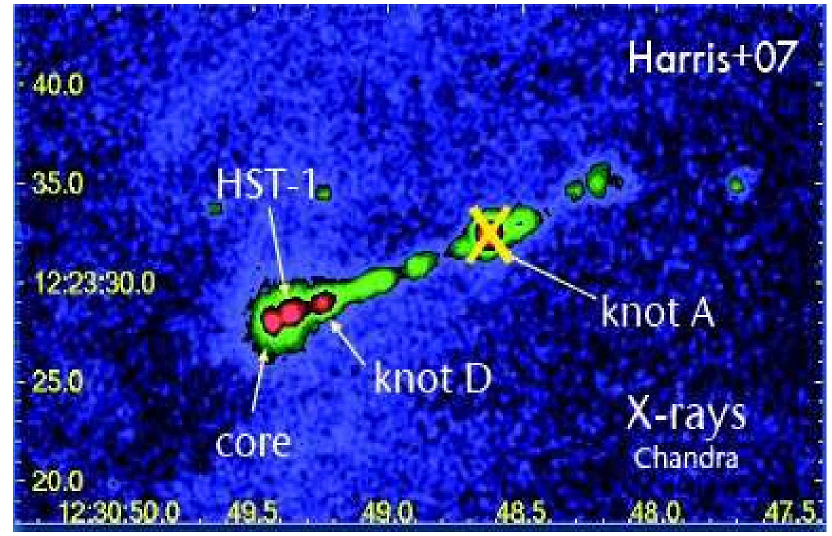
@ Poutanen, 2011

Gev spectral cutoff

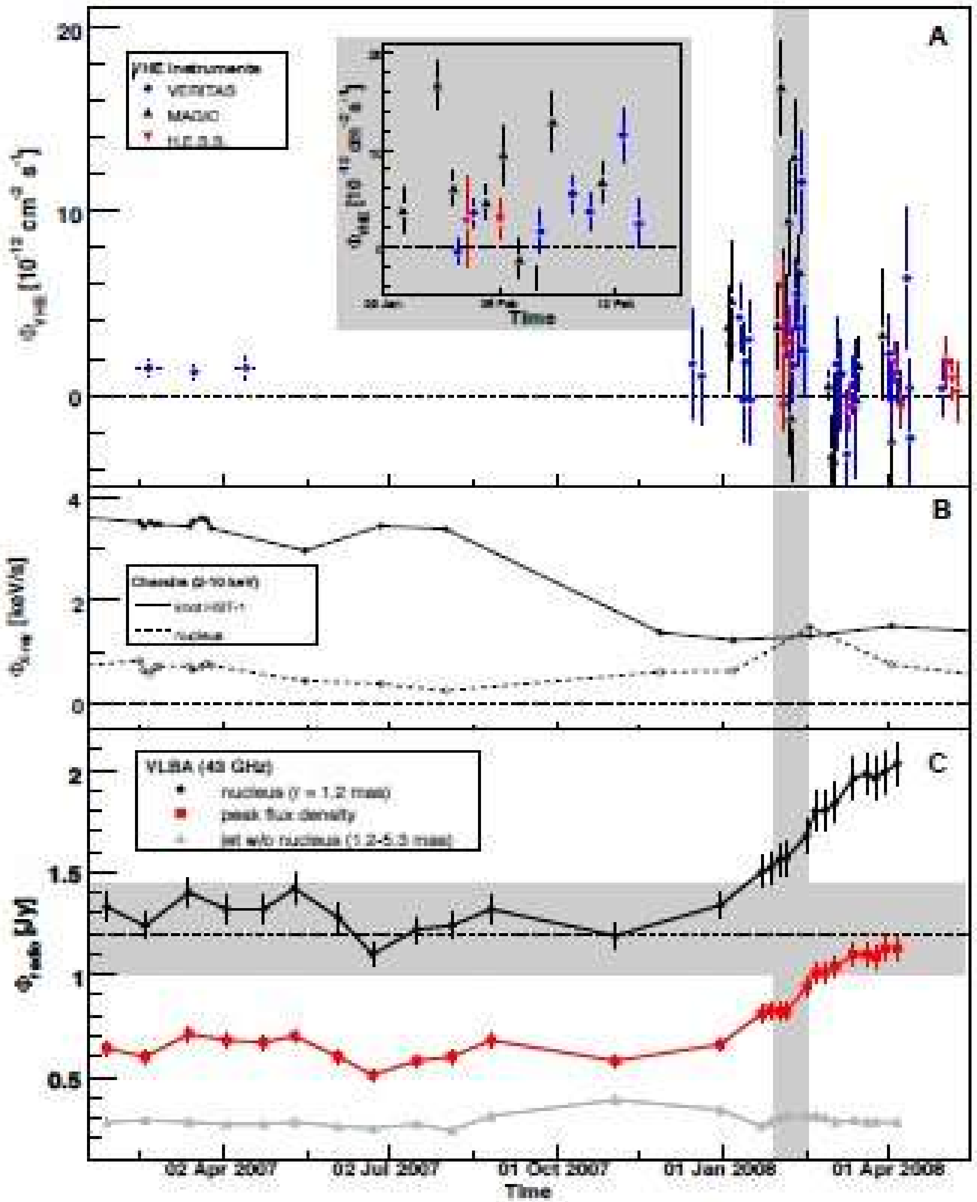
- γ-γ absorption on the hydrogen and He II LyC
  → blazar zone has to be located within or close to the high-ionization zone of the BLR

CTA observations of spectral breaks (and upturns) up to a few 100 GeV to assess Relation to BLR physics.

Radiogalaxies



2008 campaign



@ Acciari et al, 2009

M87 -
MWL campaign (H.E.S.S., MAGIC, VERITAS, Chandra, VLBA)

VHE day variability → 3 possible emitting zones: peculiar knot HST-1, ~ 65 pc from the nucleus, the inner VLBI jet, the central core and the black hole environment.

- simultaneous X-ray flare from nucleus (and NOT from HST1)
- coincides with rise in radio flux from nucleus
→ favours scenarios with TeV emission from inner jet or central core.

Inner jet :

- Spine-layer SSC+EC scenario (Tavecchio,+ 2008)
- Multi-blob SSC scenario at 100 Rs (Lenain et al, 2008)

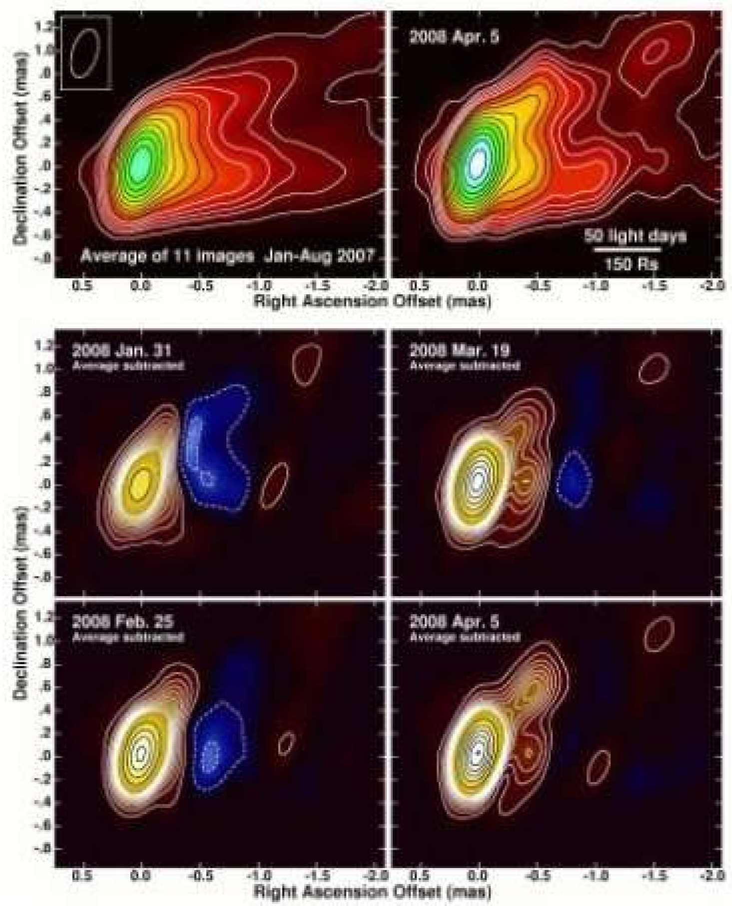
Core :

Acceleration in Black Hole magnetosphere (Neronov, Aharonian, 2007; Rieger, Aharonian, 2008; Istomin, Sol, 2009)

2010 campaign:

VHE monitoring by MAGIC & VERITAS (ToO: H.E.S.S., Chandra, VLBA)

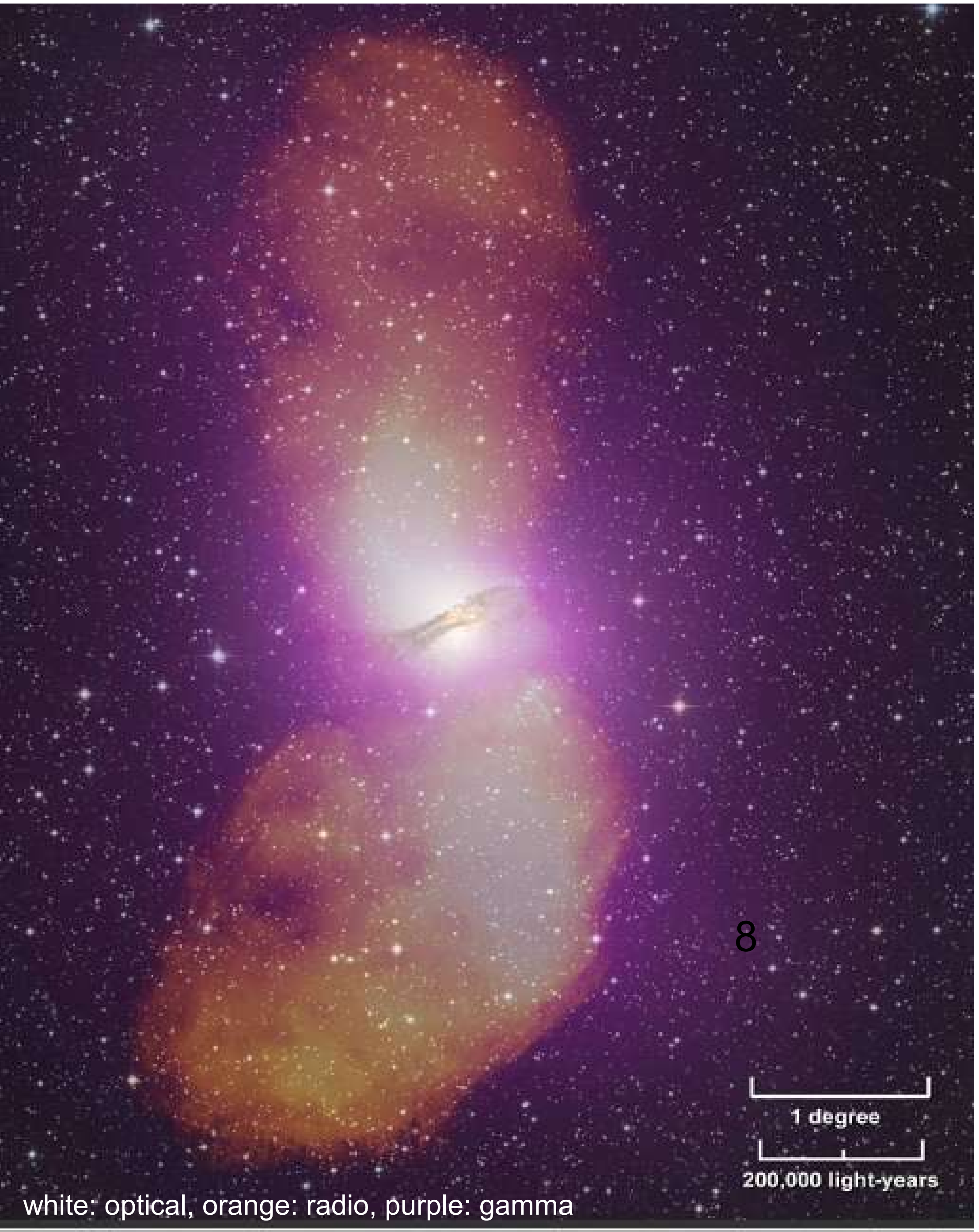
- VHE flare: < 1 day variability (excellent sampling)
- No rise in the 43 GHz radio core emission
- Enhanced X-ray core emission (Chandra)



So, origin of the VHE emission?

No unique solution?
2005: HST-1?   2008: Core?   2010: ? ..
but X-ray core (2008/10)

Radiogalaxies



white: optical, orange: radio, purple: gamma

@ Abdo et al, 2009

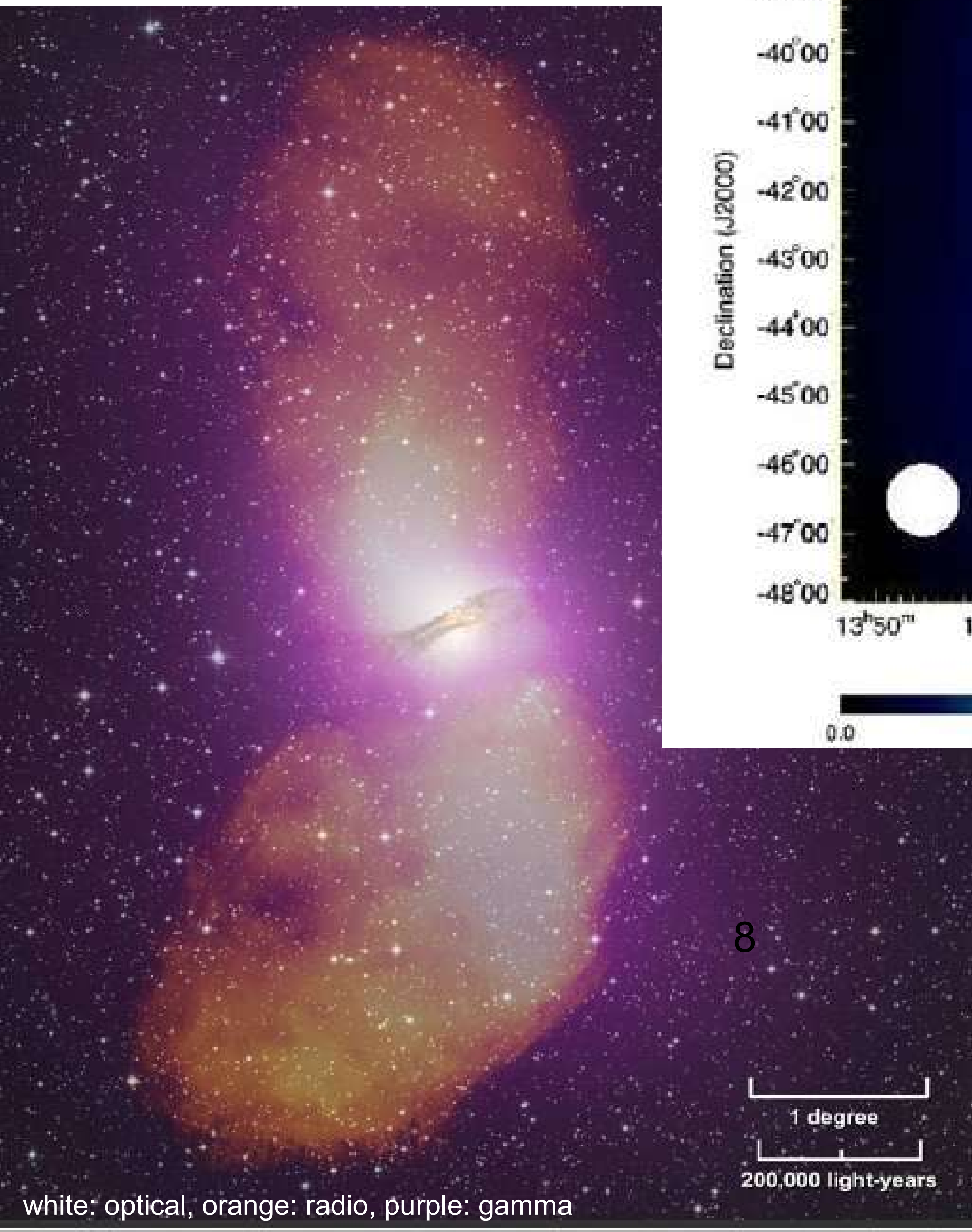
Cen A – Radio core and kpc jet within error bars of its position on sky

→ many possible emssion zone :
Black hole magnetosphere, base of the jet, large scale jet, inner lobes, pair halo in the host galaxy.

Extended diffuse Y-ray emission detected by Fermi

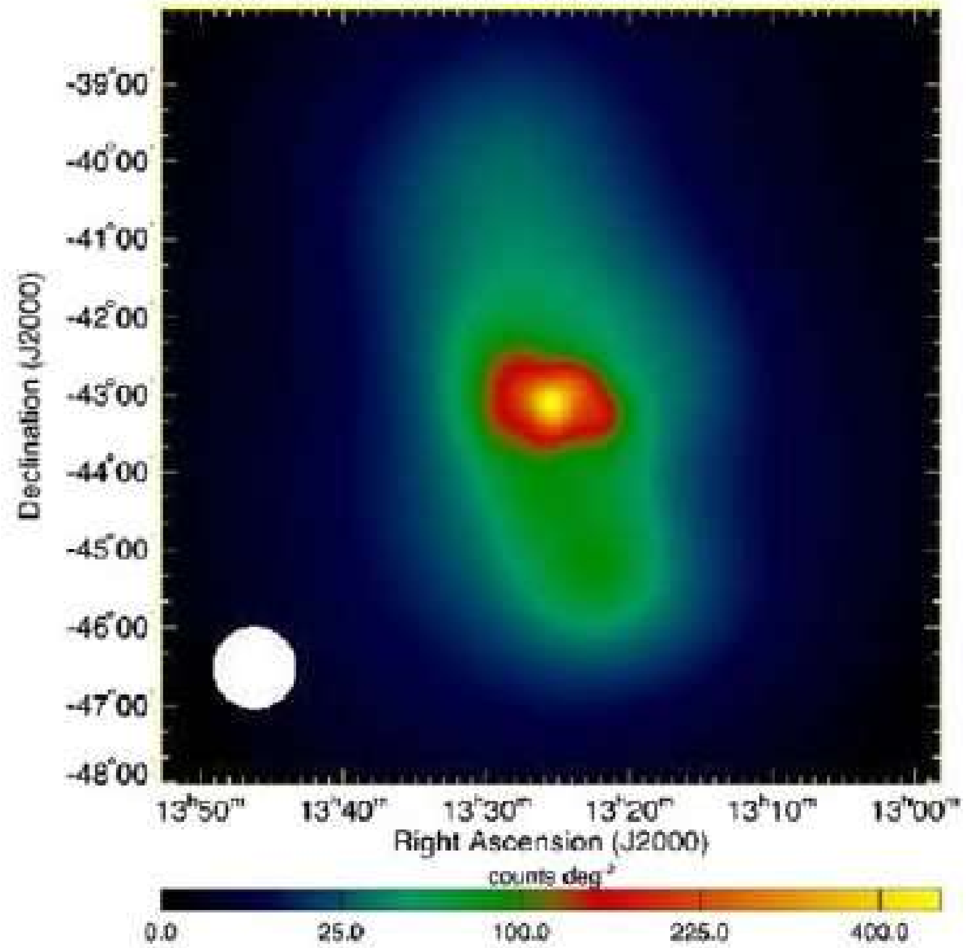
TeV: dominant core or dominant extended component emission ?

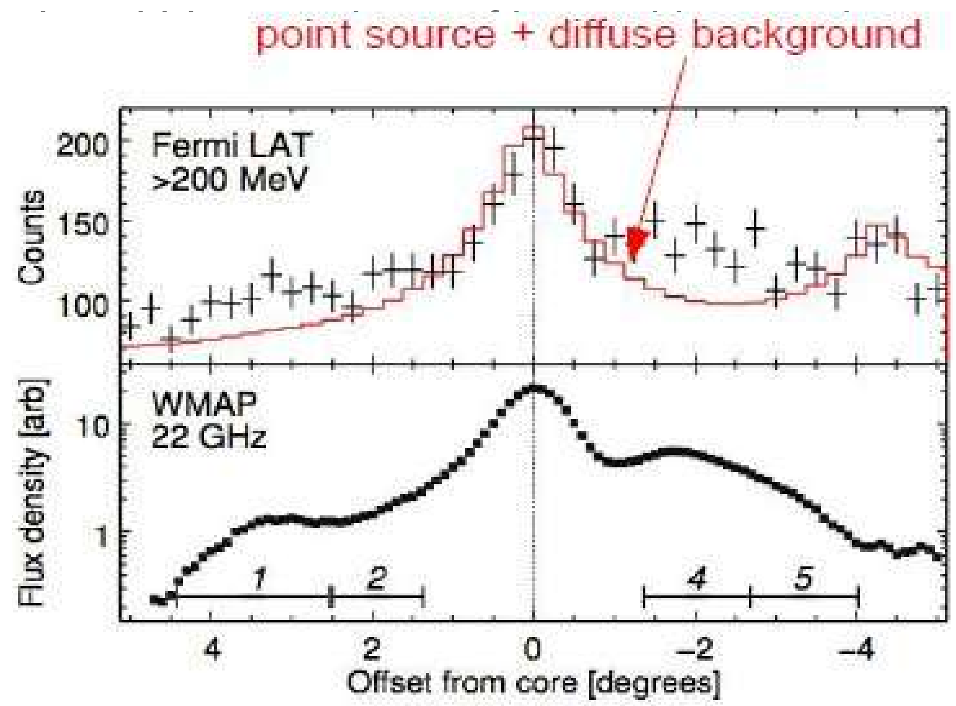
Radiogalaxies



white: optical, orange: radio, purple: gamma

@ Abdo et al, 2009





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TeV: dominant core or dominant extended component emission ?

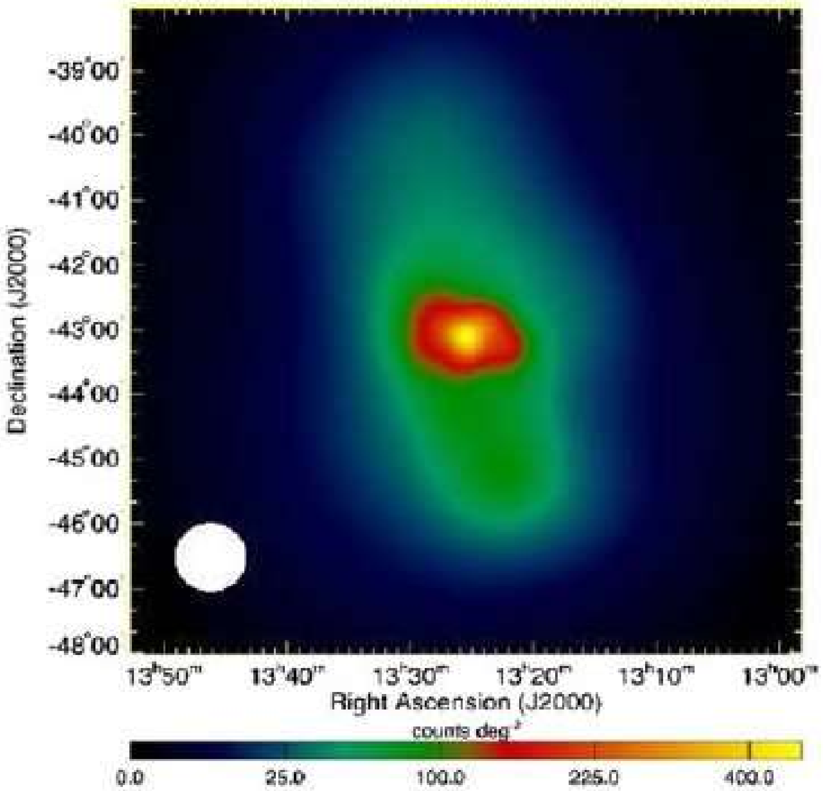
- CTA: improved astrometric & angular resolution
- CTA: improved sensitivity
- MWL campaigns / Long term monitoring

→ pin down the emission region

→ look for (map ?) extended emission

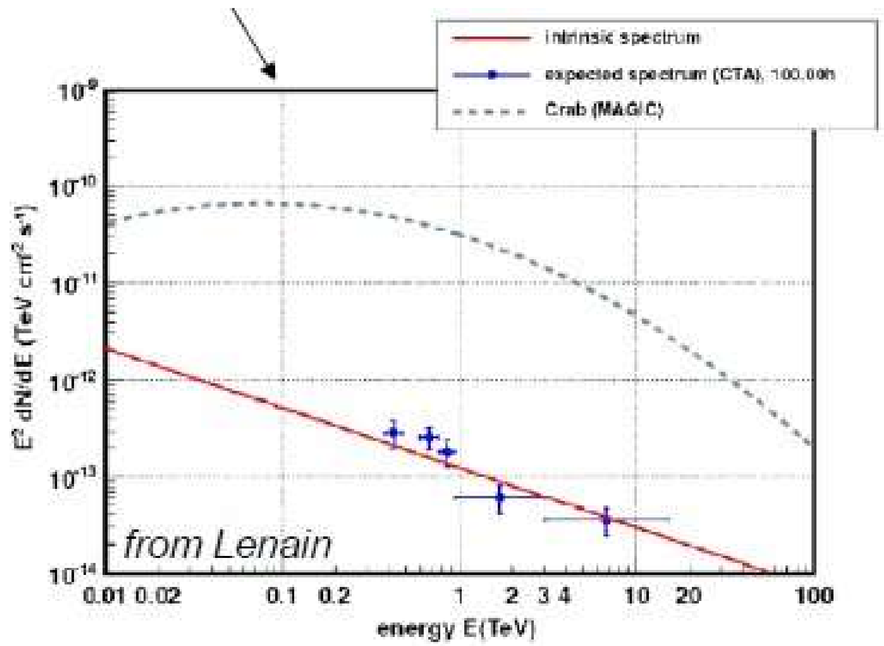
→ explore link between SMBH magnetospheres and the physics of jets and extended radiosources

Radiogalaxies



A halo of 0.2° with a flux of 50% of the total low state flux of M87 would be detectable with CTA.

Here the CTA generated spectrum for array I and 100 hours.



Origin of the variability

Variability dominated by processes

within the jet (e.g. turbulence)

or

outside the jet (accretion disk perturbations)?

Needs full pattern of variability :

- Long-term correlated programs
- All activity states: quiescent, high, flaring
- Weekly?, Over years

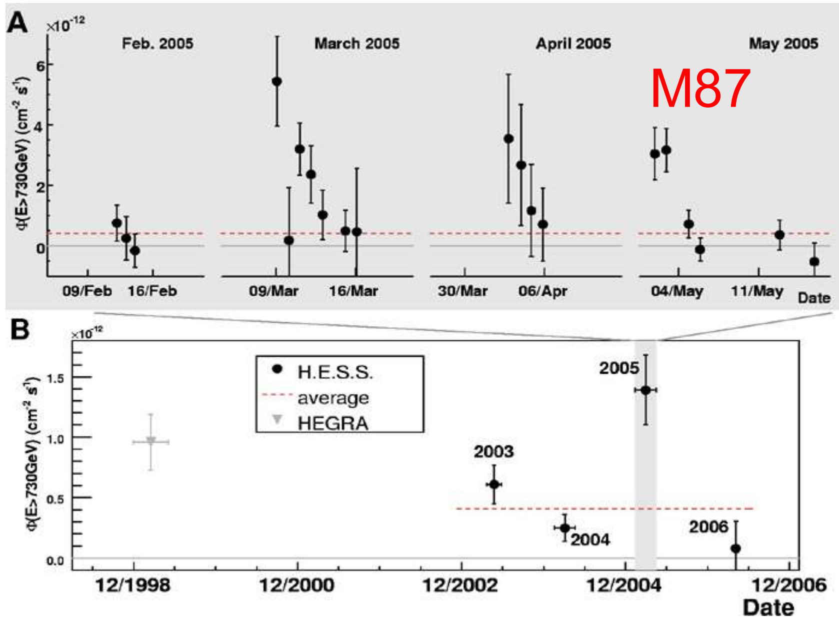
Study in both temporal and Fourier space with:

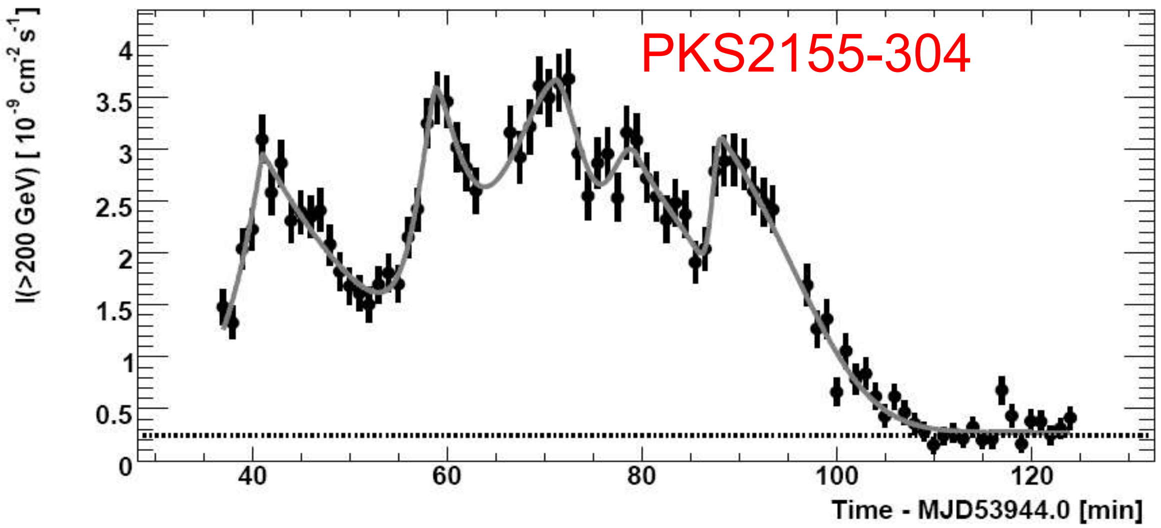
- lower energy threshold
- increased sensitivity and frequency sampling

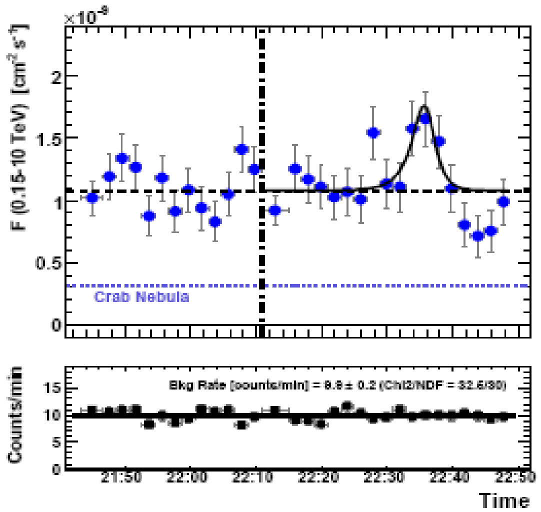
Right now gamma-ray PSD are poorly determined

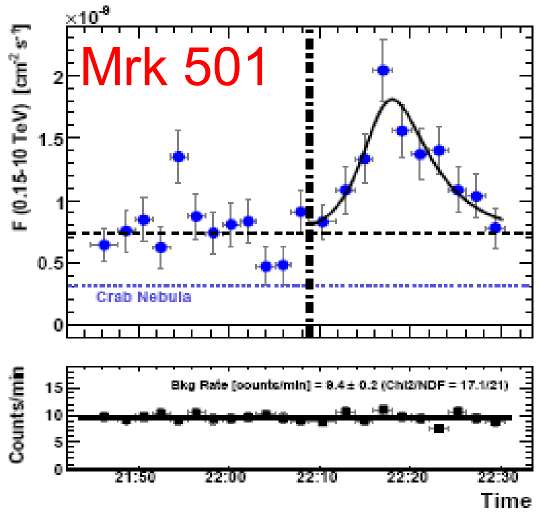
Correlated multi-band variations but overall poor gamma-ray/other band correlation

Size constraints from variability









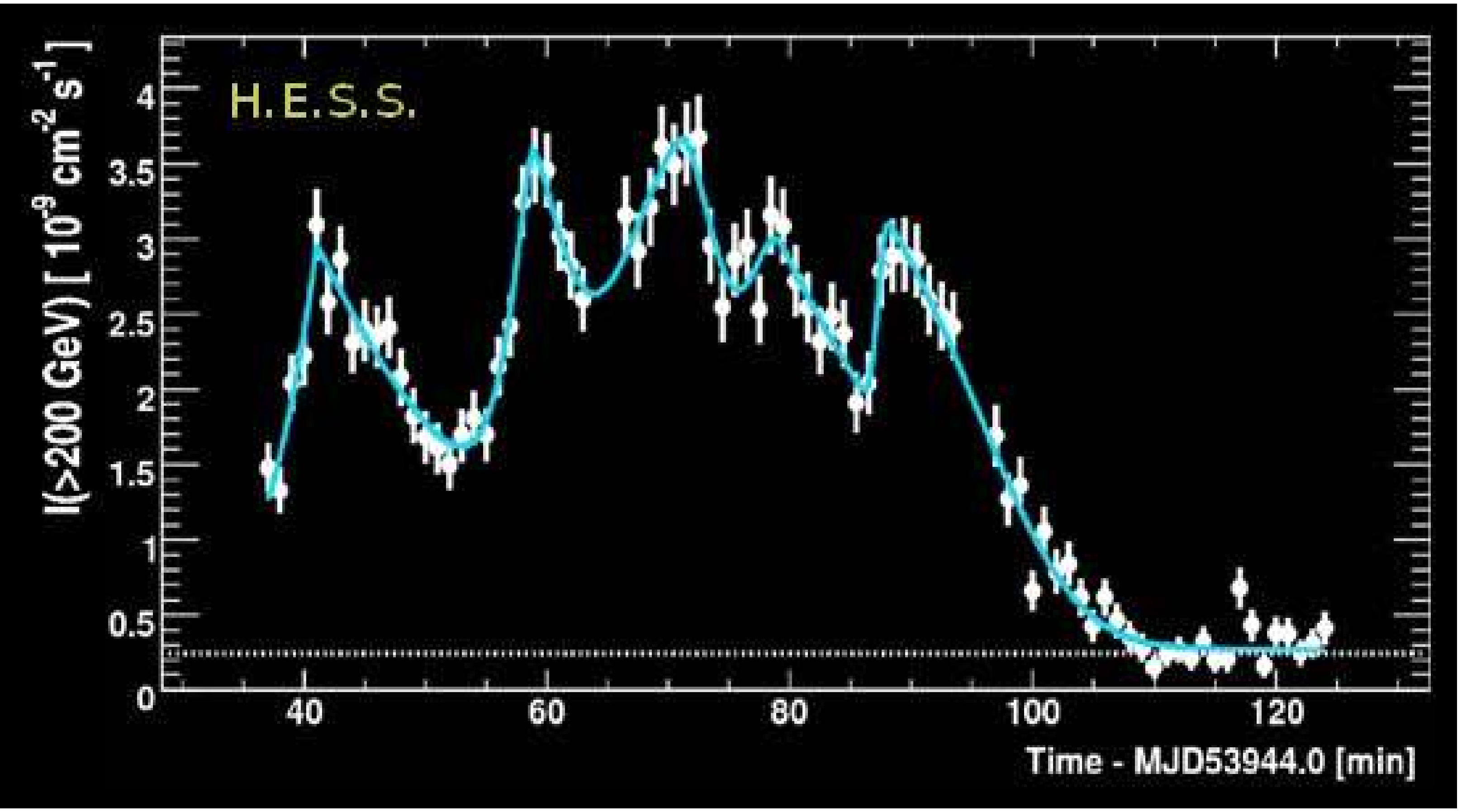
TeV variability of M87, PKS2155-304, Mrk501, PKS 12 22+21, 3C279… requires very small emitting zone, of the order of a few r_g or even less (even for high δ) under causality argument.

- **Challenge** to efficiently accelerate particles in such small zones (core around BH, or very inner jet).

Fermi processes in shocks and turbulence are widely invoked

Alternatives : magnetic reconnection, direct electric forces, centrifugal force

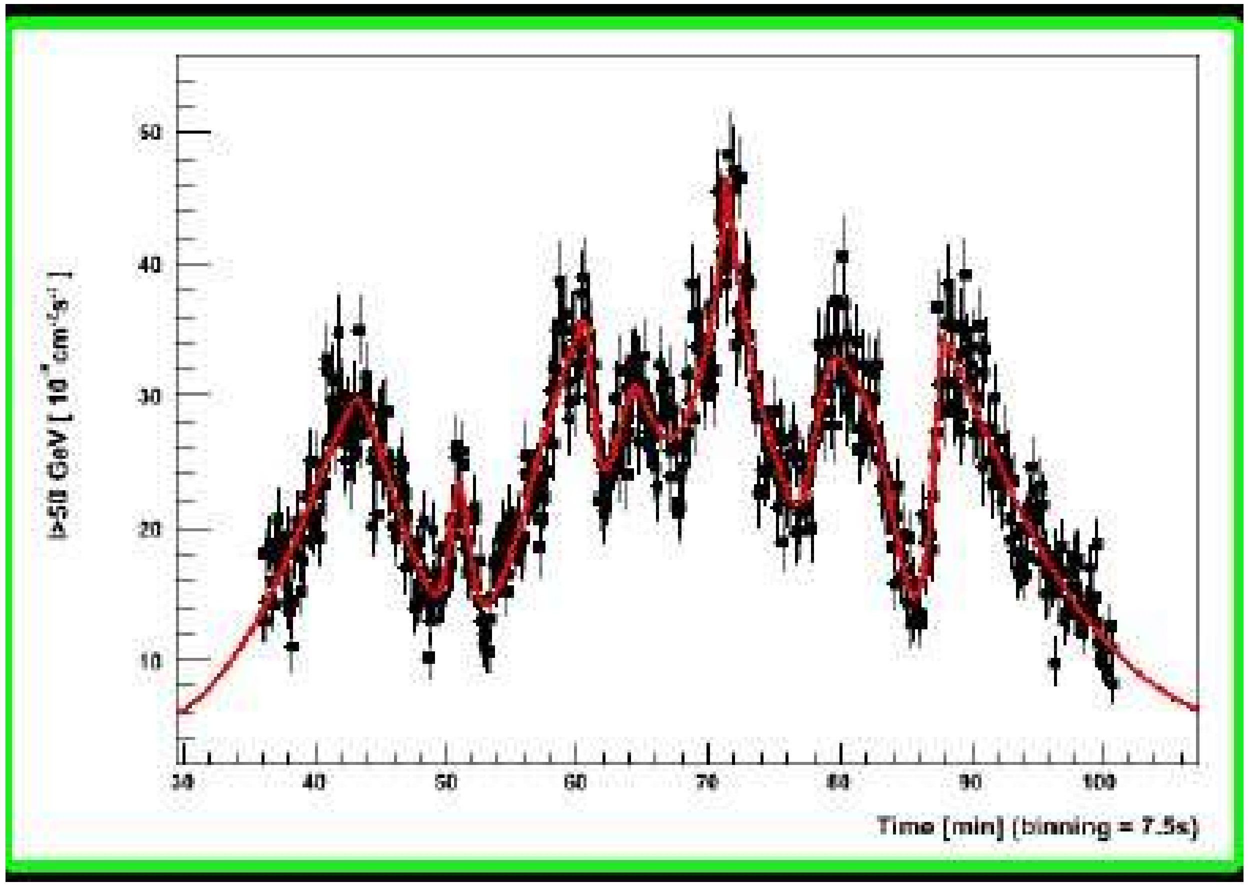
Analyze the evolution at all timescales to connect the events of microphysics to fluid mechanics
→ long MWL campaigns



- First major AGN flare for a source
  -
- Variability on 5 min (or less) scales

Evolution of light curves at different timescale from months down to minutes to connect the events of micro-physics to fluid mechanics

Simulation of PKS 2155-304 flare as monitored by CTA



@ Biteau, 2011

Elaborating from the 2006 event.
Extension of red noise behaviour to high frequencies, 50 – 200 GeV, bin 7.5 sec interval

Short time scale structures are generated
Shortest significant rise time accessible would be 25+-4s (7 times better than H.E.S.S. observations.)

Bayesian approach shows that more typically variability timescales would be 4 – 5 min (10min for similar events with current IACT) assuming an order of magnitude increase in sensitivity and sampling.

AGN related topics

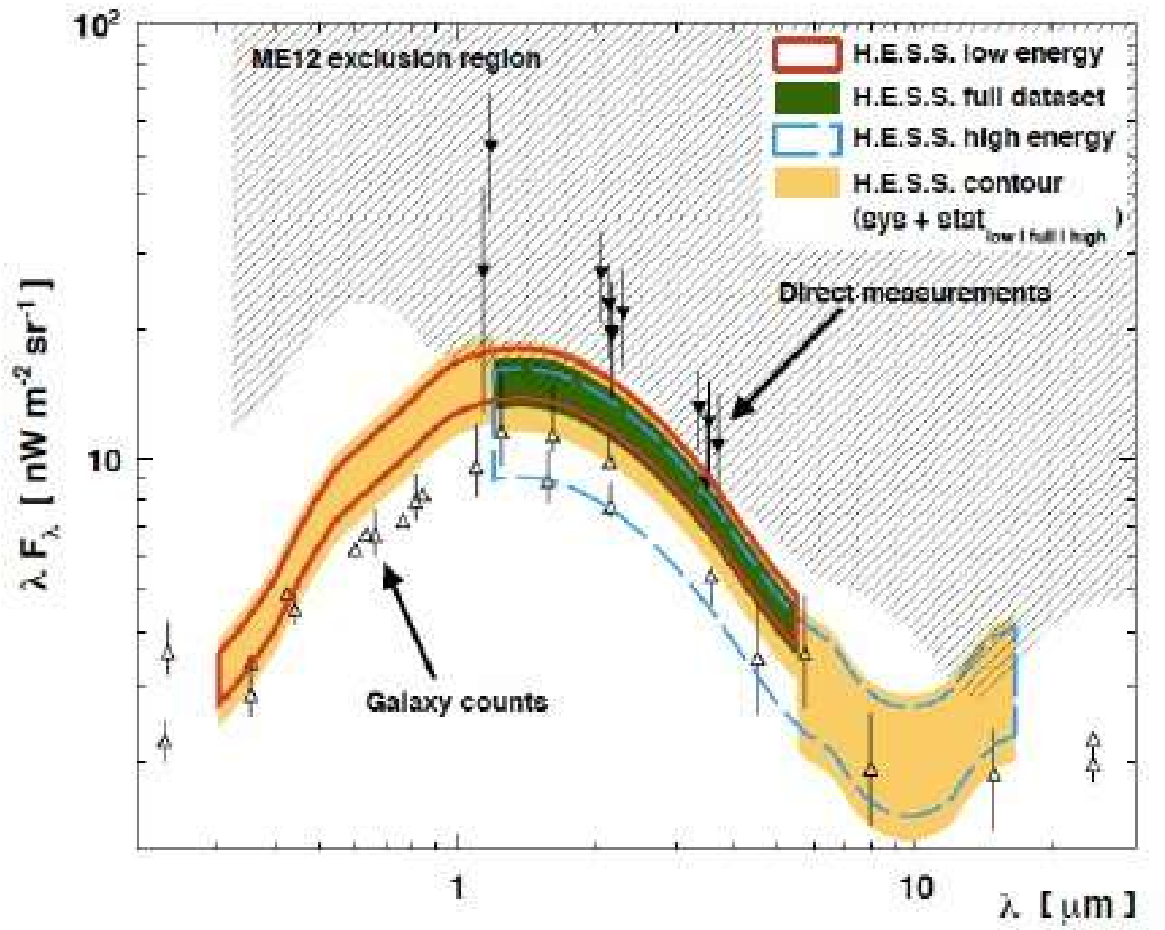
AGN as bright beacons to analyze the intervening media as:

- EBL
- EGMF
- Quantum gravity

  …

Multi-messenger approach

EBL



- H.E.S.S. measurement of the EBL imprint using 105 photons from
  - 7 nearby blazars
- Idea: joint simultaneous fit of EBL optical depth and intrinsic spectra of sources
- Method reveals EBL signature on the 8.8 sigma level and allows for a measurement of the EBL for the first time.

Still need to increase the sample.

See F. Krennrich talk

Pair Haloes

Probing intergalactic magnetic fields

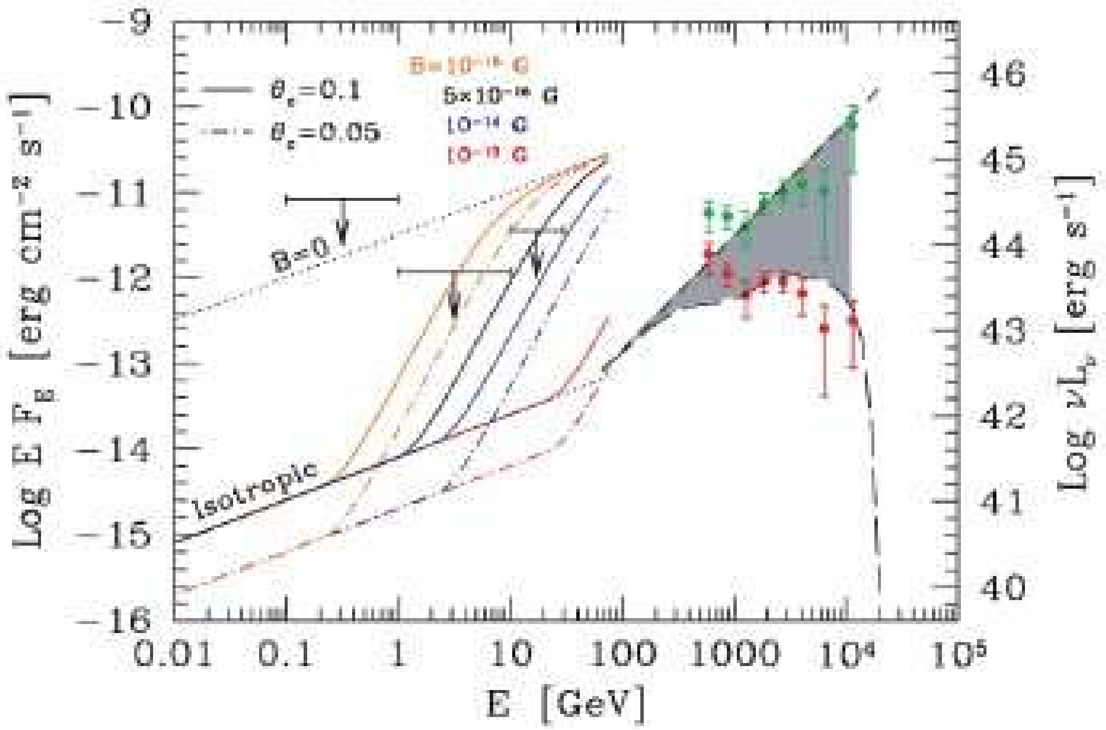
- TeV ɣ rays are absorbed in interactions with the extragalactic background light
- As a result, e+e- pairs with energy are produced in the intergalactic space
- e+-e- pairs upscatter CMB radiation and produce secondary, GeV photons
- The trajectories of created e+e- pairs are deflected by the extragalactic magnetic field (EGMF) → an additonal, extended emission component can appear around the projected direction of the source

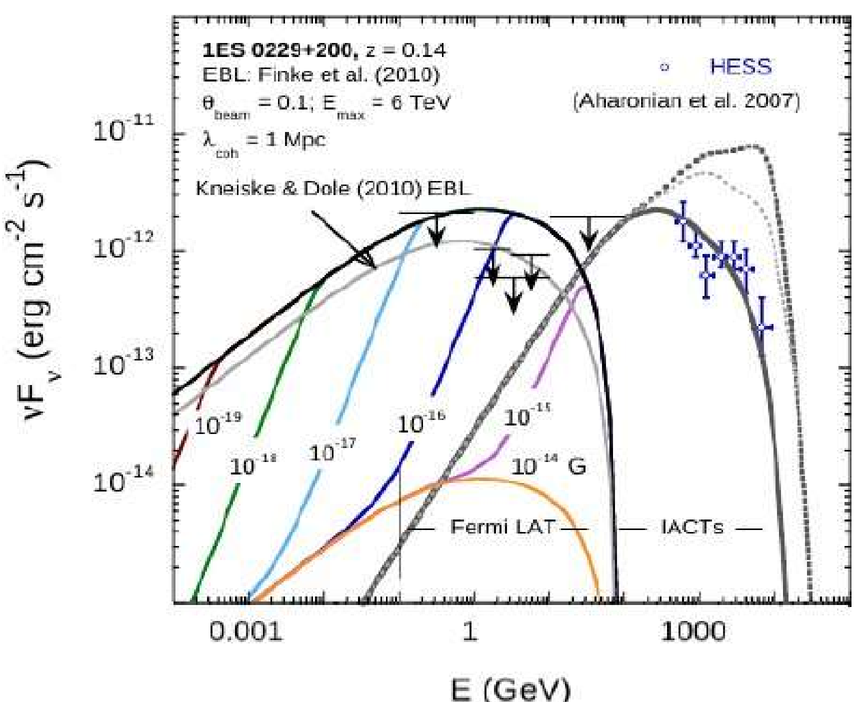
⇒ search for delayed “echoes” of multi-TeV AGN flares/GRBs

Aharonian, Coppi, Voelk 1994 & Plaga, 1995

Pair haloes

@ Tavecchio et al, 2010





@ Dermer et al. 2011

- No GeV detection of hard spectrum TeV sources, opposite to what is expected for vanishing EGMF → B > 10^{-17}-10^{-15} G

Such an EGMF can deflect cascade → spatial & temporal spread of the cascade emission → reduces expected cascade flux to a level consistent with Fermi observations.

- Time delay studies

EGMF → B > a few 10^{-19} G

- No pair halo detected yet

- Observations of the pair-halo effect could shed light on the formation of the extra-galactic magnetic field

via phase transition in the early Universe, or in stars, galaxies & galaxy clusters by dynamo effect that amplified the tiny “seeds” fields ($B > 10^{-21}$G) or even compression and amplification by turbulence of the seeds fields.

- Sensitive search for the cascade emission: measure of angular and temporal properties.

If EGMF close to the present limits, detection of the cascade emission from z=0.1-0.2 possible.

High S/N measurement to study radial profile of the halo emission.

- The pair-halo effect may be used as a secondary probe of the EBL, in conjunction with extinction studies.

Other AGN related topics

- Further developments on AGN contribution to diffuse VHE gamma-ray background
- Passive black holes and the Galactic Center, as a « dormant » AGN (eclipses in VHE ?, tidal disruption of stars)
- More exotic issues (primordial BH evaporation; isolated BH; connection with gravitational wave events; axion-like particles …)
- …

Conclusions

AGN science will largely benefit of CTA

It is as going from broad band photometry to “spectroscopy” with an increase in astrometry.

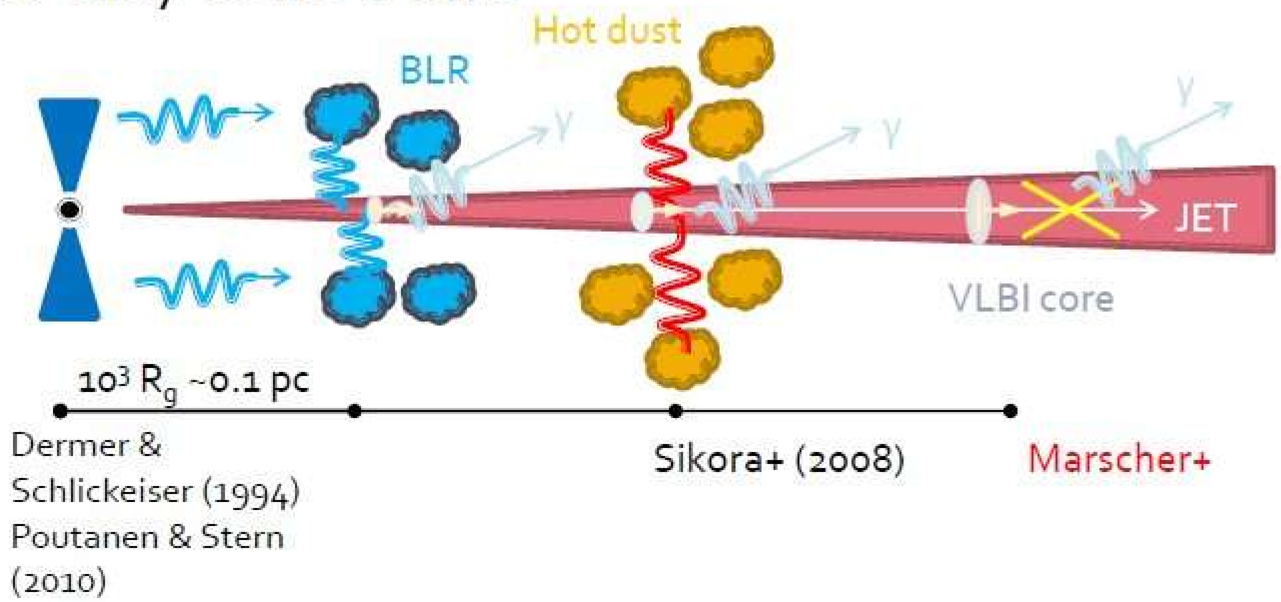
- Measure flux and spectral variability of bright sources with high accuracy
  - Long term monitoring of samples (emission mechanism; origin of variability; spectral features, absorption; extended emission …)
  - Deep exposures/detailed monitoring on few sources (emission mechanism; spectral features, absorption; extended emission; EBL/EGMF...)

- Search for faint and high redshift sources → blind survey

(luminosity functions; beaming models; unified schemes; …)

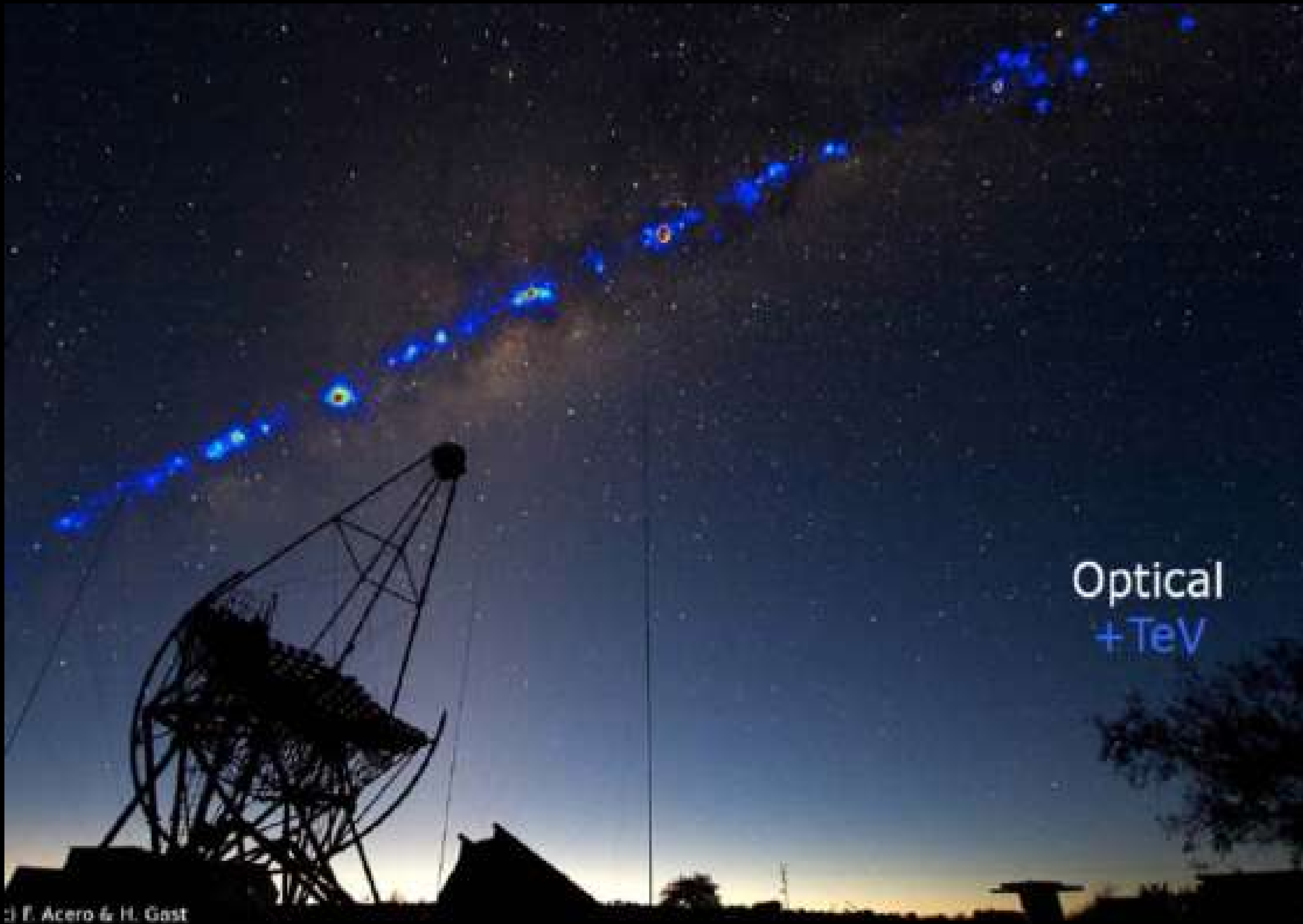
In all case, multi-frequency campaigns need to be organized.

The central question of the FmJ workshop: where do they come from?



- Multiple sites in a single jet?
- Different regions for different source classes?

Fermi meet Jansky meeting, 2011


Optical
+TeV
(c) F. Acero & H. Gast