Observation of Extragalactic Sources of Very High Energy Gamma Rays

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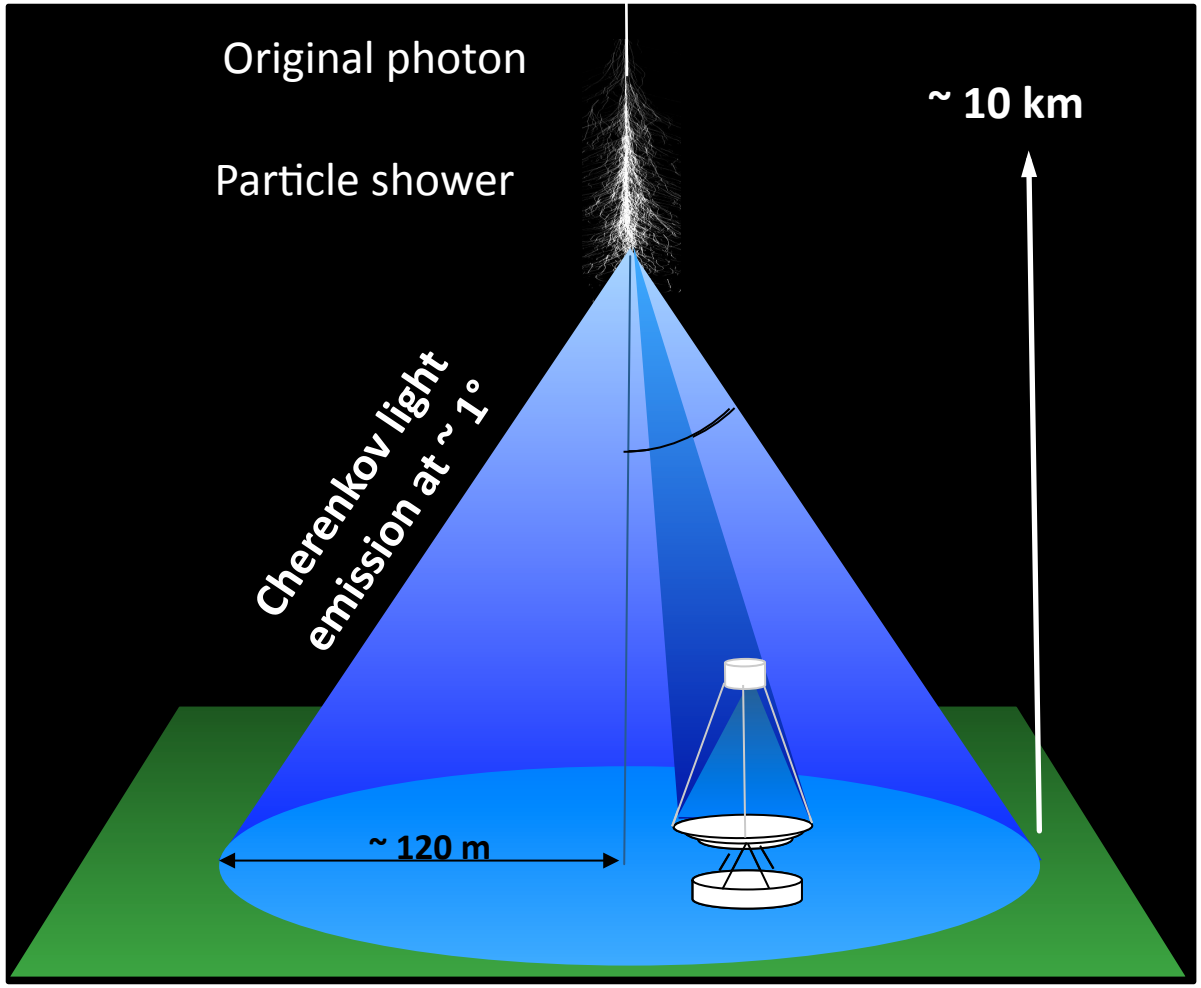
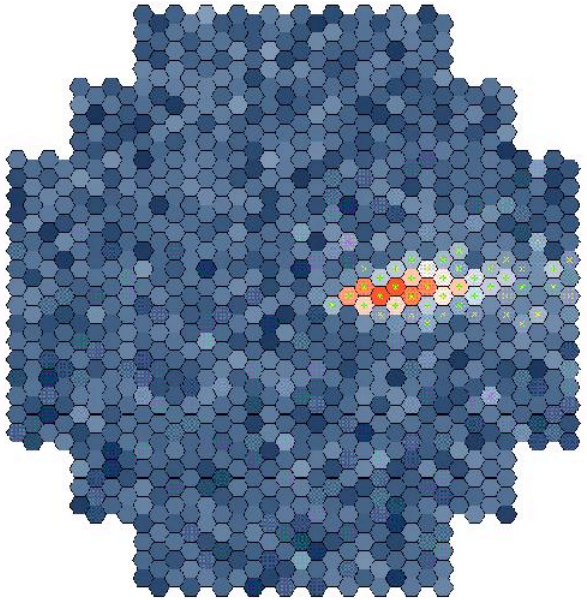
Detection of VHE γ radiation

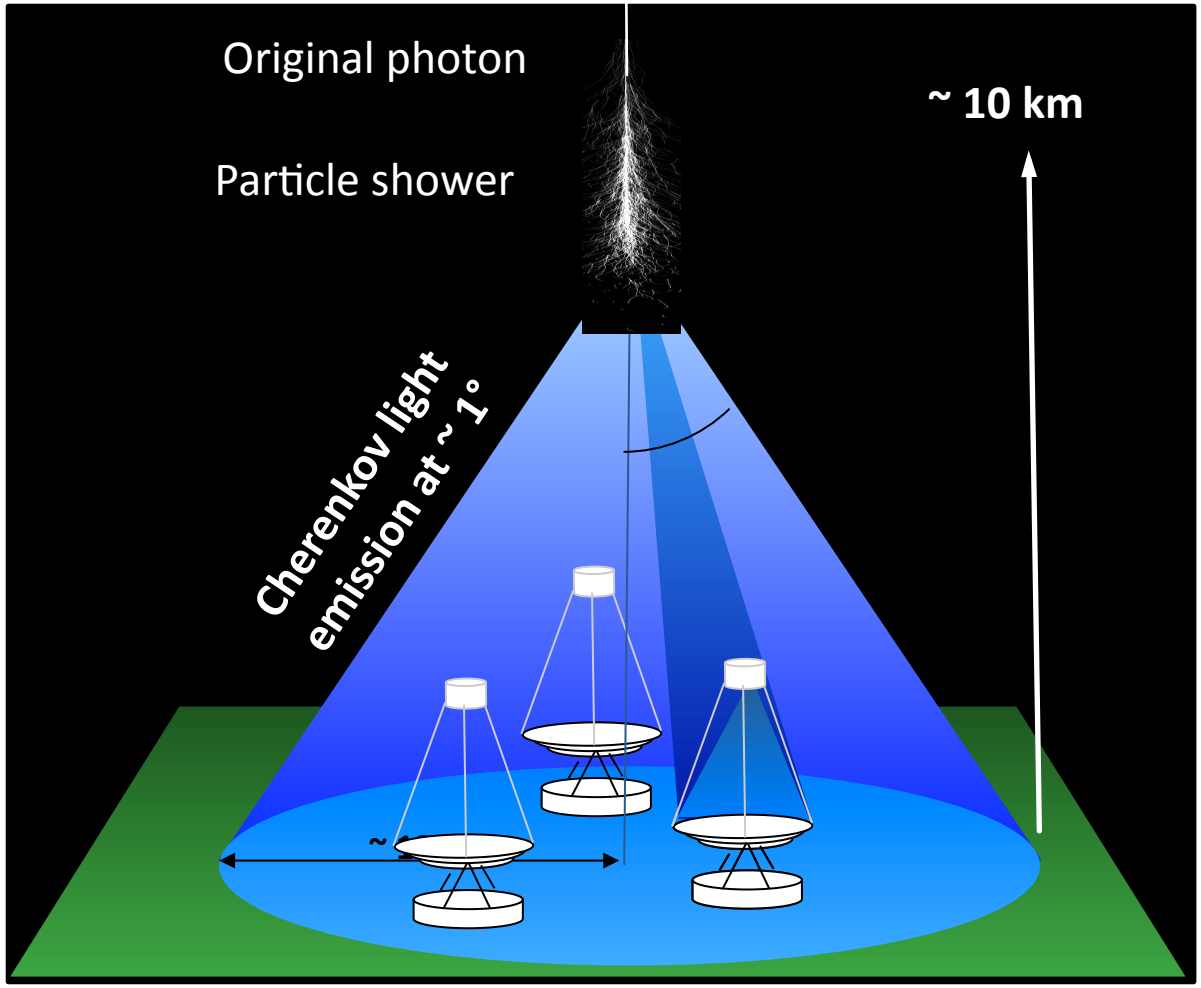




Detection area ≥ 5 x 10^4 m²
for a single telescope

For large arrays detection
area could be ≥ 1 km²

Detection of VHE γ radiation



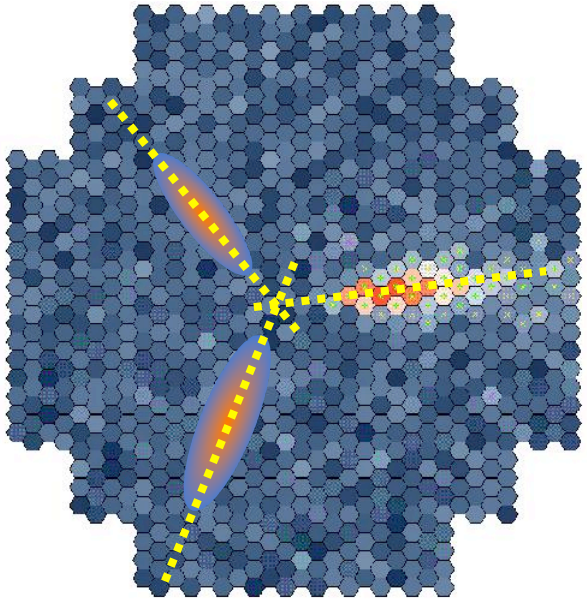


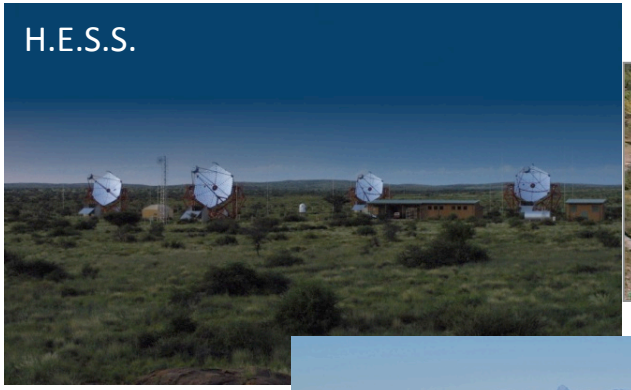
Image intensity ~ shower E

X-point - impact

Image shapes ~ particle type

Main Players

H.E.S.S., VERITAS & MAGIC



Parameters of VERITAS almost matching those of H.E.S.S.

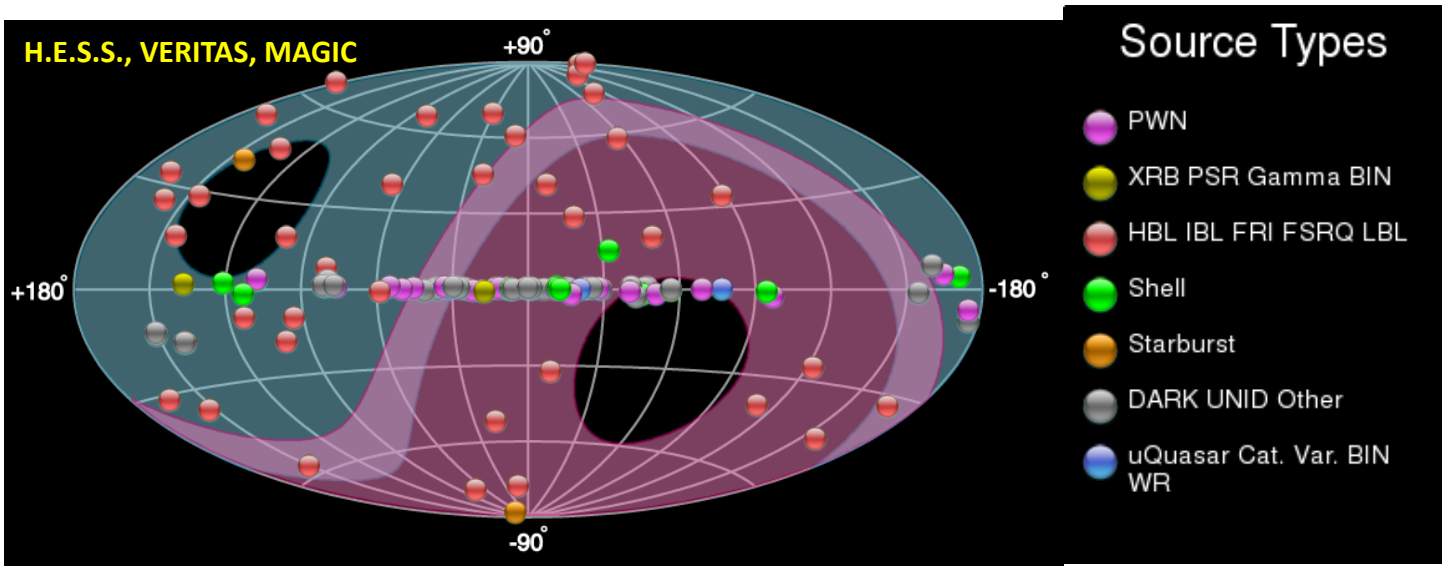
	H.E.S.S.	MAGIC
# telescopes	4	2
Field of view	5°	3.5°
Reflector diameter	12 m	17 m
Energy threshold	160 GeV	55 GeV (25 GeV – special trigger)
Sensitivity:	1.0 % Crab (25 h)	0.8 % Crab (50 h, E ≥ 260 GeV)

Where are we in ground-based VHE γ-astrophysics ?

• The 1st strong signal (9σ) reported by the Whipple team in Arizona was measured from the Crab Nebula in 1989

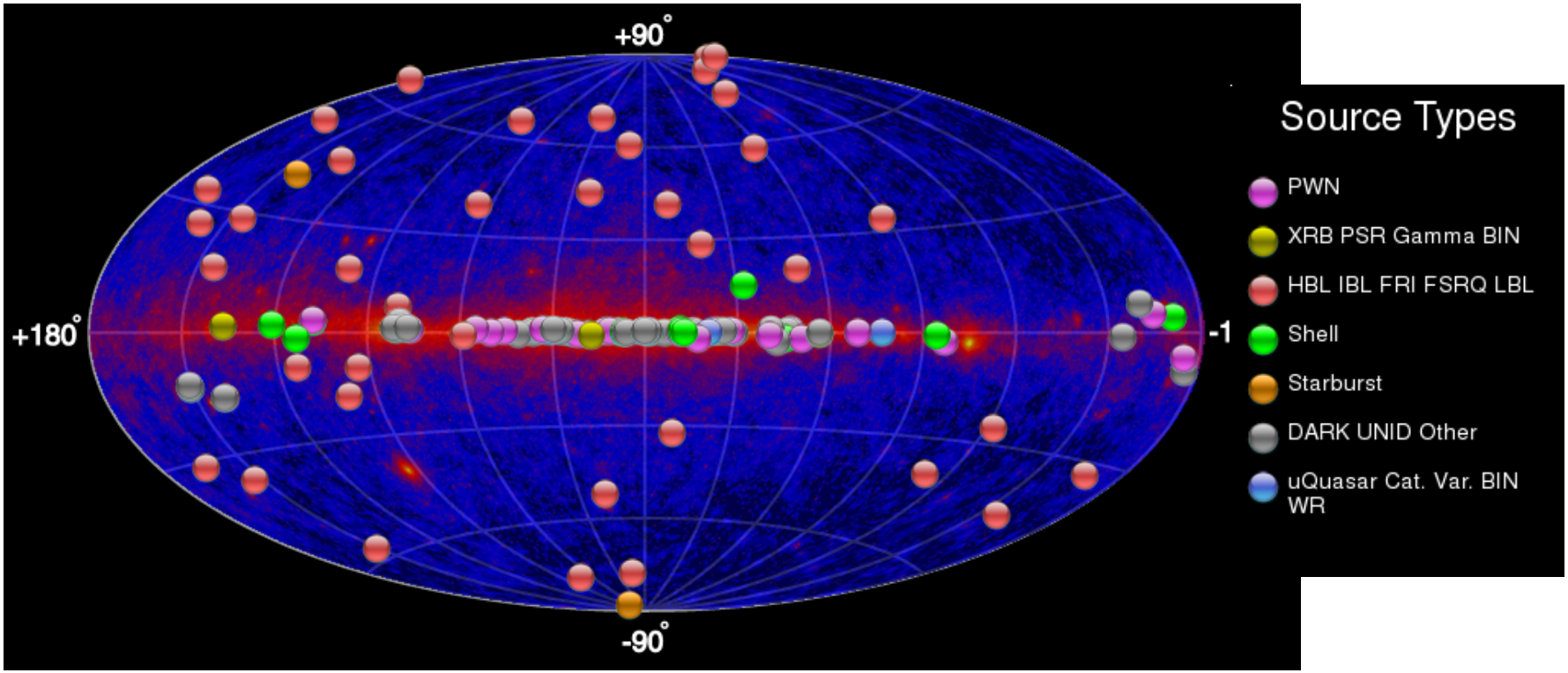
• The 1st Extragalactic source (and the 2nd source at all) Mkn-421 was reported by the Whipple team in 1992

• Today, after ~ 20 years, there are 117 VHE gamma sources reported (this number, as of yesterday, was taken from http://tevcat.uchicago.edu/)

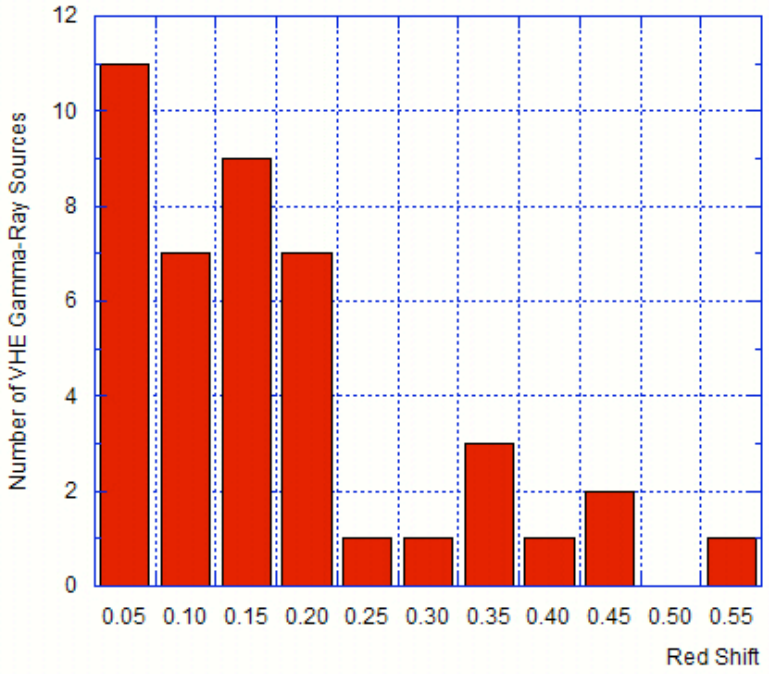


Where are we in GeV - TeV γ-astrophysics ?

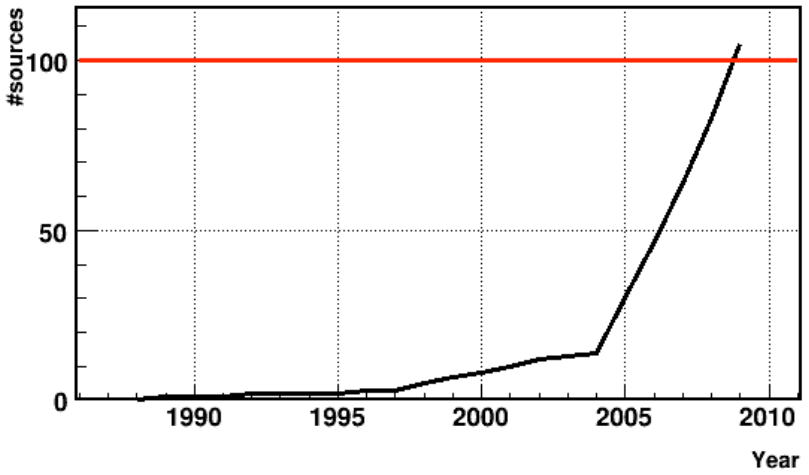
The FERMI satellite mission has revolutionized the > 100 MeV γ sky, after 2.5 years of flight some 1500 sources are reported



Number of known VHE extragalactic sources versus the red shift



Number of VHE discovered Sources vs. time



Starburst Galaxy: solving long-standing puzzle

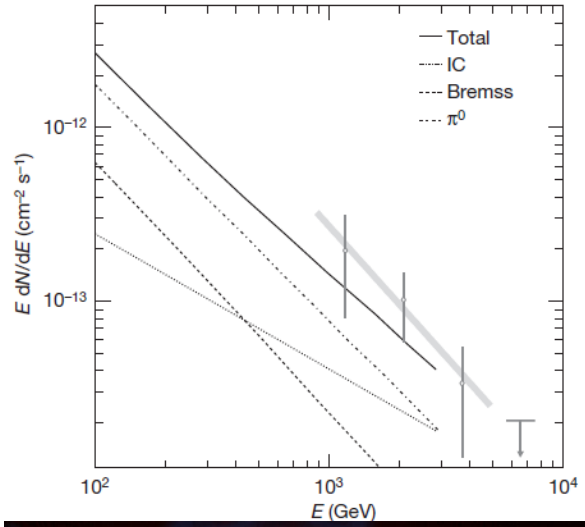
- One expects γ from the central part: high rate of massive star formation ➔ CR (could be linked)
- VERITAS discovery of M82 in 137h obs. (Nature 2009)
- Discovered flux ~ predicted ones
- CR density ~ 250 ev/cm³ (~ x500 higher than in Milky Way)
- SN + massive star winds ➔ favourite CR production sites ?

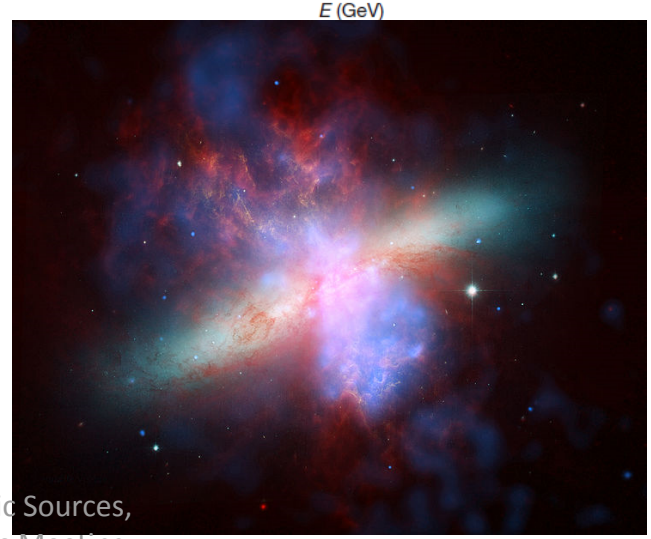
M82

D = 4.3 Mpc

Ø = 12.3 kpc

0.9 % Crab, G ~ 2.5 (> 700 GeV), both hadron and e- models could contribute into emission. Radio synchrotron from e- can constrain the γ flux @ 20 GeV (assuming B=0.8 nT)

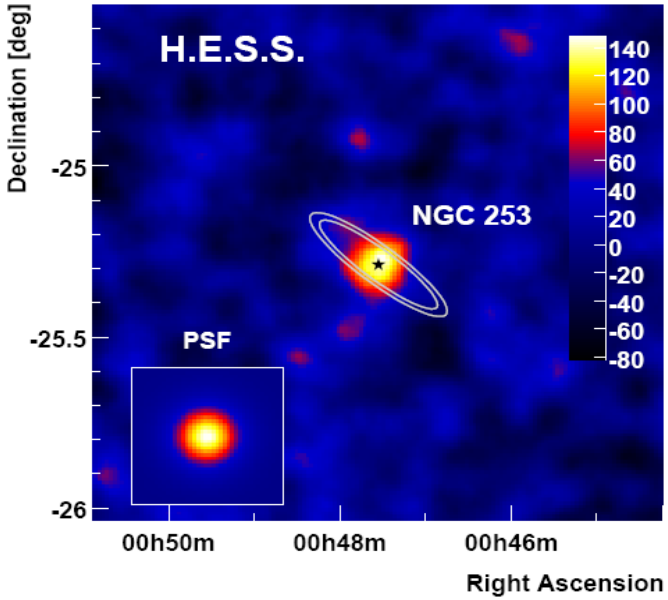


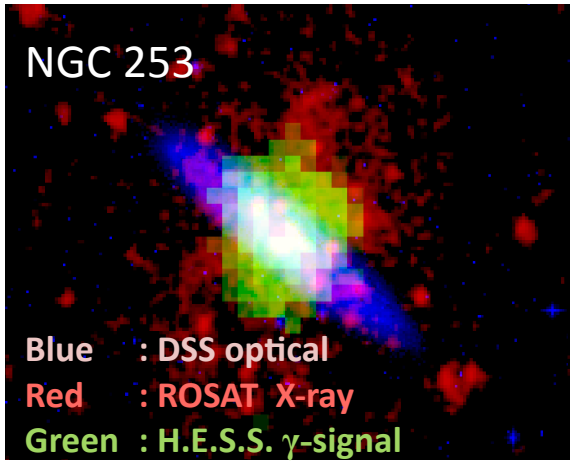


Starburst galaxy NGC 253

- Its a „normal“ spiral galaxy
- Distance is ~ 2.5 - 3.9 Mpc
- Central (starburst) part
  - Few x 100 pc large
  - Supernova - Rate: ~ 0.03/year (similar to Milky Way)
  - Gas density: ~ 600/cm³ (~ 1200 times higher than in Milky Way)

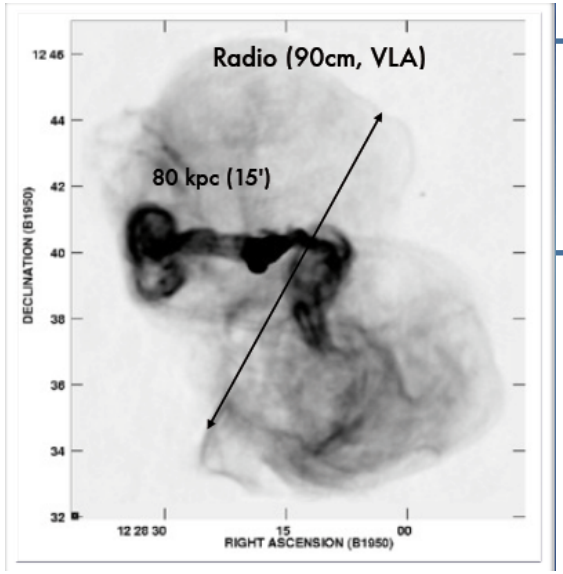
- H.E.S.S. observations revealed
  - 0.6 % Crab Nebula flux



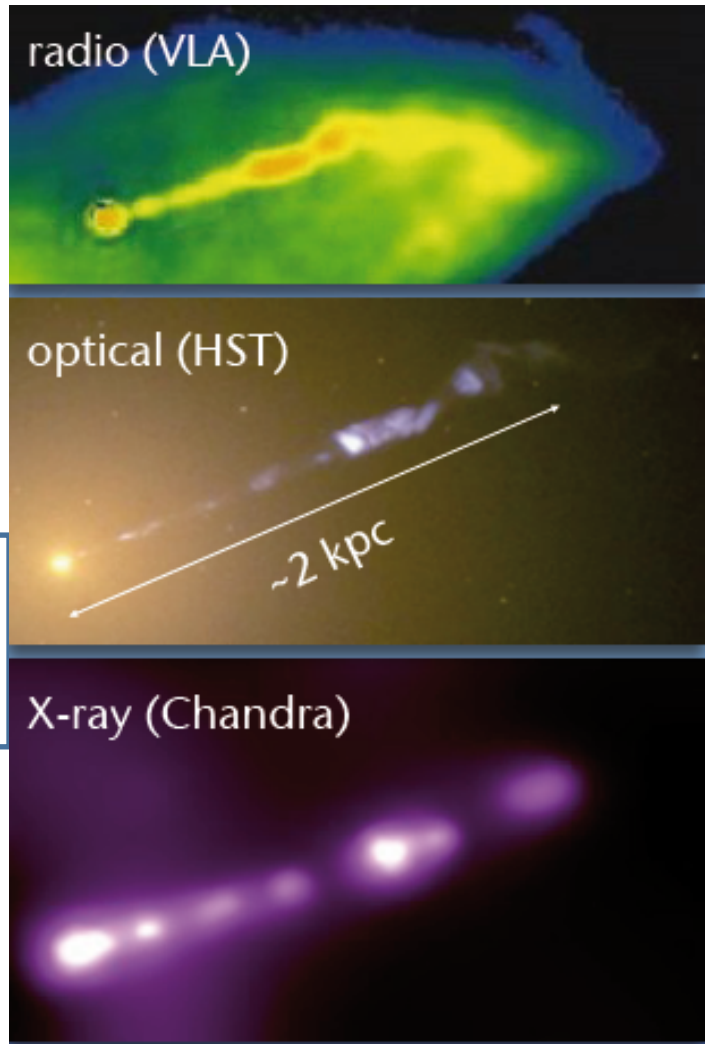


Radio Galaxies

- „Mis-aligned“ blazars
  - (FR I = BL Lacs, FR II = FSRQ)
- Radio galaxies that are measured in VHE γ‘s:
  - **M-87, Cen A, IC 310, NGC 1275**

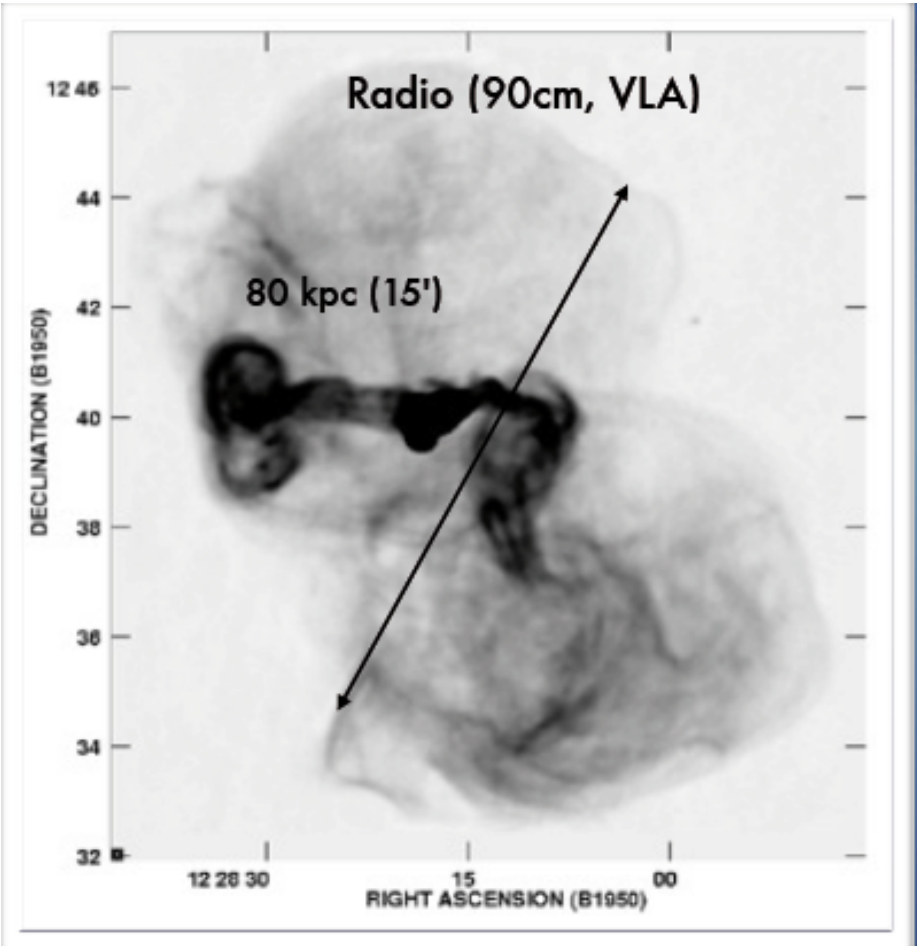


M87



M87 – Giant Elliptical Radio Galaxy

- Distance: 16.7 Mpc
- Jet angle: 30° (in inner region < 19°)
- Black Hole: 6 x 10^9 Solar mass
- Giant outer lobs: 0.2° x 0.2°
- High polarisation in radio
- Superluminal motion
- A very interesting „nearby laboratory“ for studying

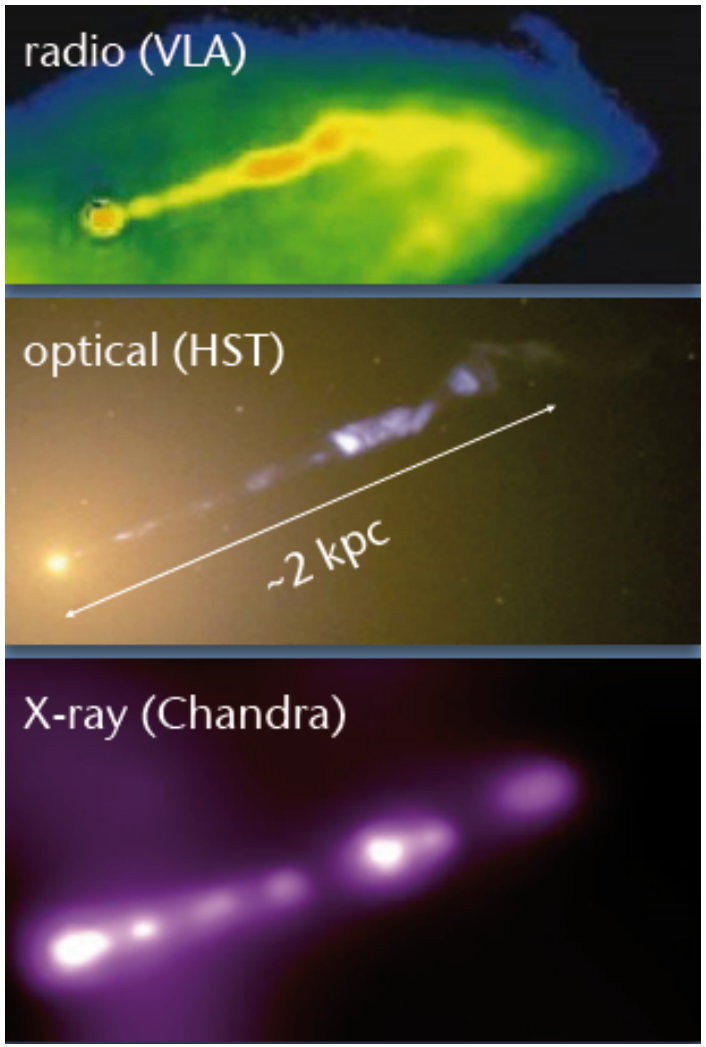


M87 Plasma Jet

- Highly structured jets with knots

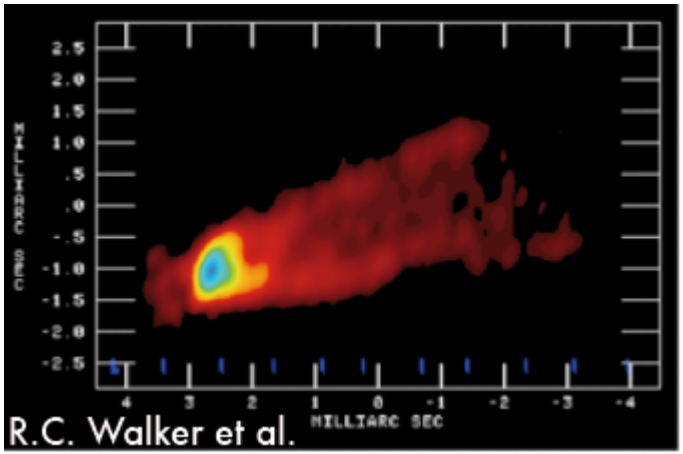
(shocks ?) in Radio, optical, X-rays

- Radio-optical similar polarisation (also X-rays ?)
- Variability scale: weeks – years
- Inner jet: superluminal motion ~ 2 x c (relativistic particles)
- Jet can flare, from radio to X-rays



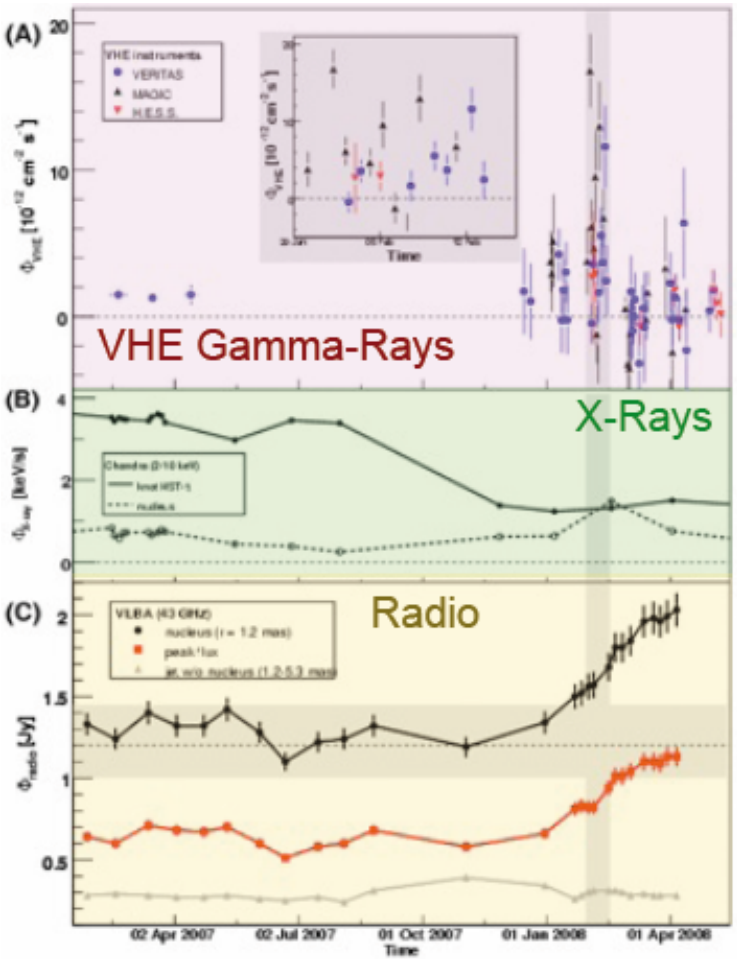
M87: Radio + VHE Instruments

- VLBA observes M87 jets @ 43 GHz; jet formation of 30 x 60 Schwarzschild radii



VHE flare accompanied by radio flare from the really close vicinity of the Black Hole vicinity

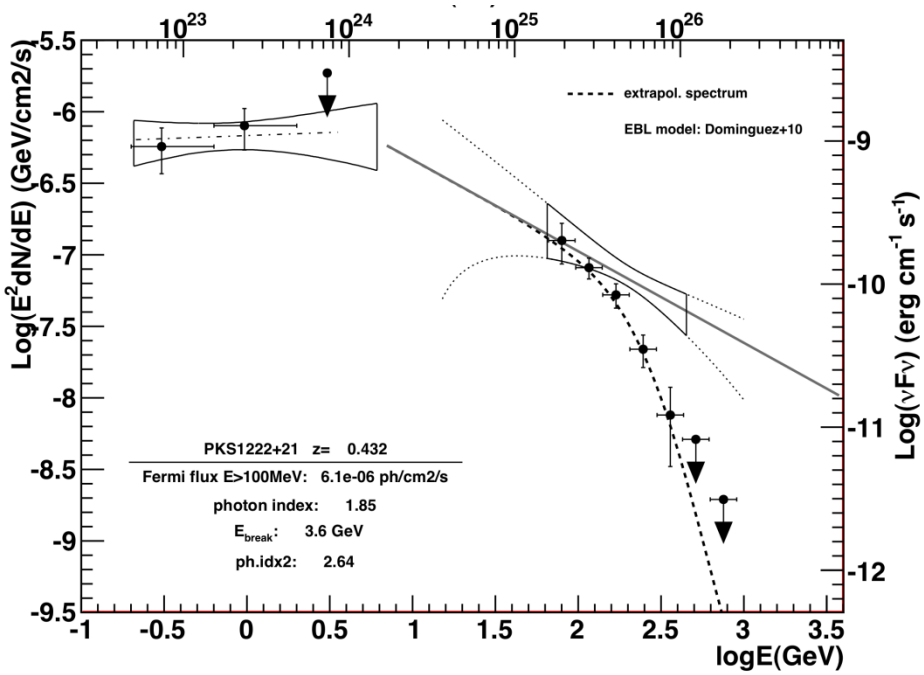
Science (2009)



Flat Spectrum Radio Quasar PKS 1222 +216 (4C 21.35)

- Discovered recently by MAGIC
- z = 0.432 (after 3C279 2nd most distant (reliable z) measured source)
- measured signal strength ~ 8.5σ in 0.5h
- Along with 3C279 and PKS 1510-089 this is the 3rd FSRQ
- Variability time scale: ~ 10'
- SED and light curve conflict

FERMI & MAGIC data: 0.1 – 400 GeV



When the signal shows intrinsic delays

Violation of the Lorentz Invariance?

Light dispersion expected in some QG models, but interesting "per-se"

$$V = c\,[1 +- \xi\,(E/E_{s1}) - \xi_2\,(E/E_{s2})^2 +- \ldots]$$

1st order $\Delta t \sim \xi \frac{E}{E_{QG}} \frac{z}{H_0} = \xi \frac{E}{E_{QG}} \frac{L}{c}$

MAGIC Mkn 501, PLB08

$E_{s1} \sim 0.03\ M_p$

$E_{s1} > 0.02\ M_p$

HESS PKS 2155, PRL08

$E_{s1} > 0.06\ M_p$

Whipple 1999, PRL 83(99)2108

$E_{s1} > 0.005\ M_p$

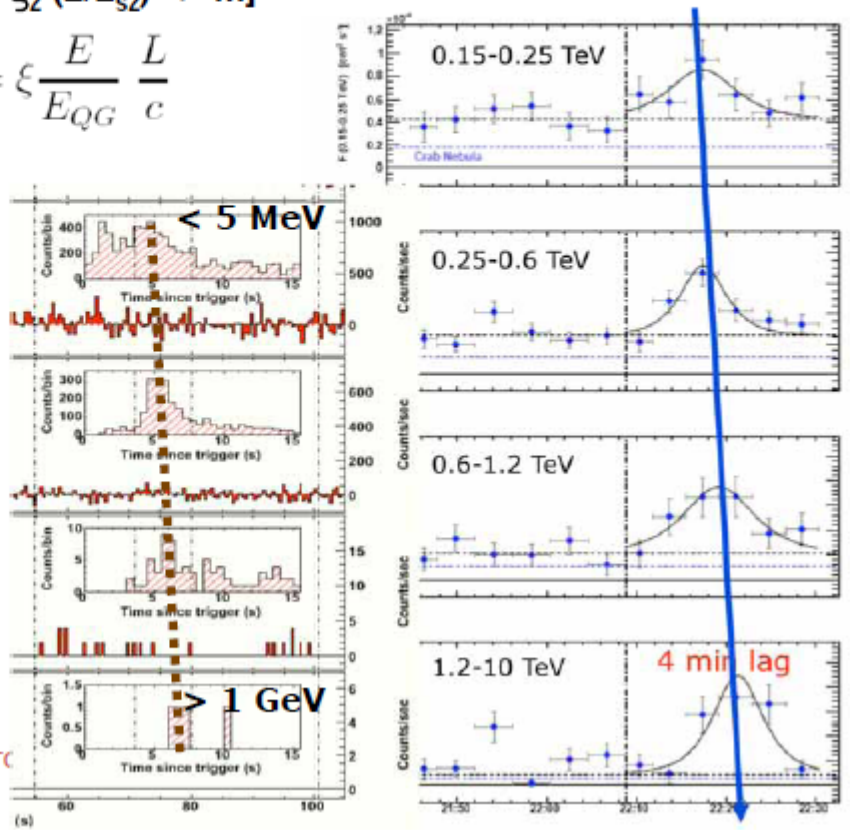
GRB X-ray limits:

$E_{s1} > 0.11\ M_p$ (Fermi, but…)

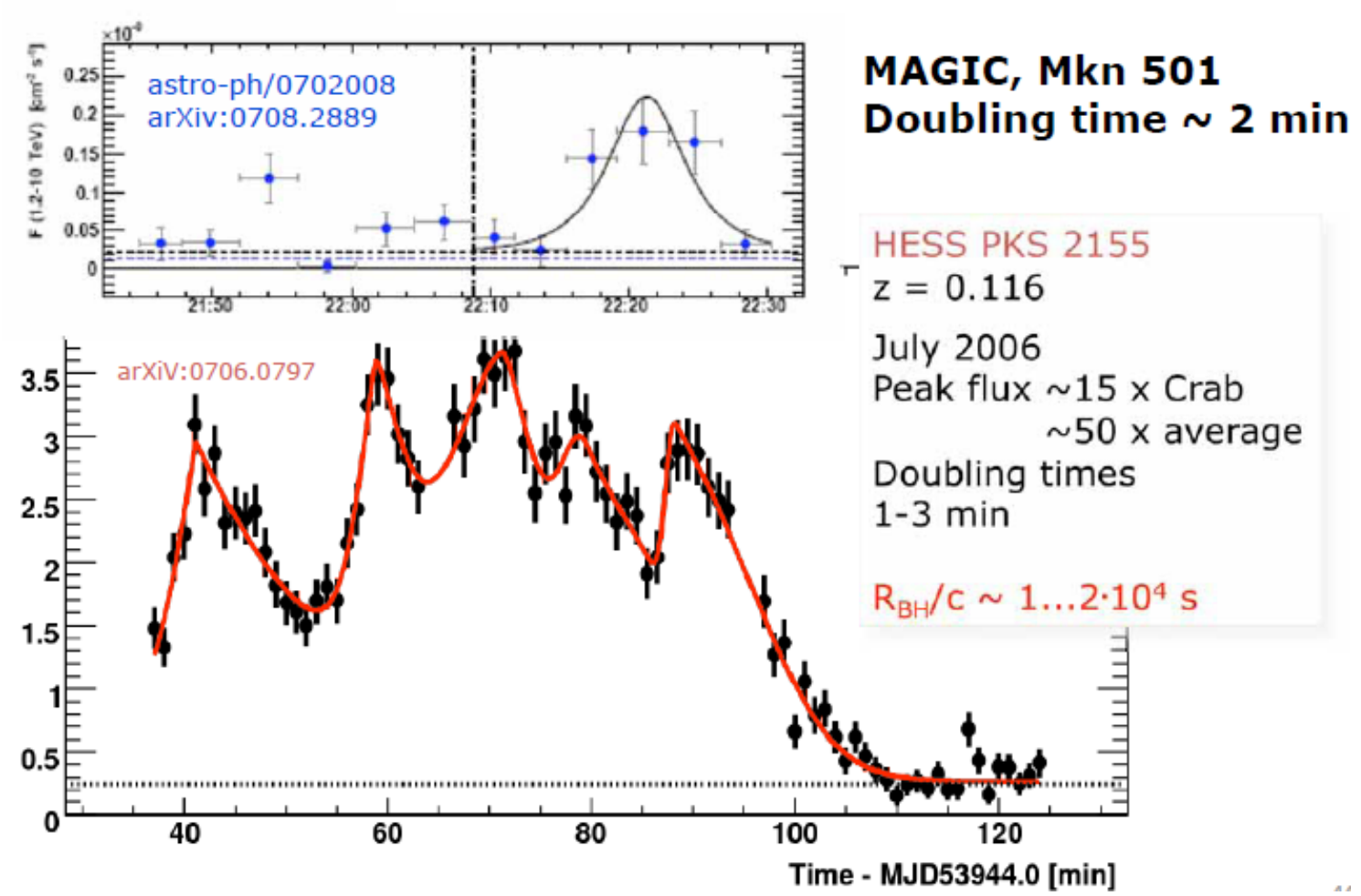
… but in most scenarios

$\Delta t \sim (E/E_{s\alpha})^{\alpha}$, $\alpha > 1$

- VHE gamma rays are the best pr
- Mrk 501: $E_{s2} > 3 \cdot 10^{-9}\ M_p$, $\alpha = 2$

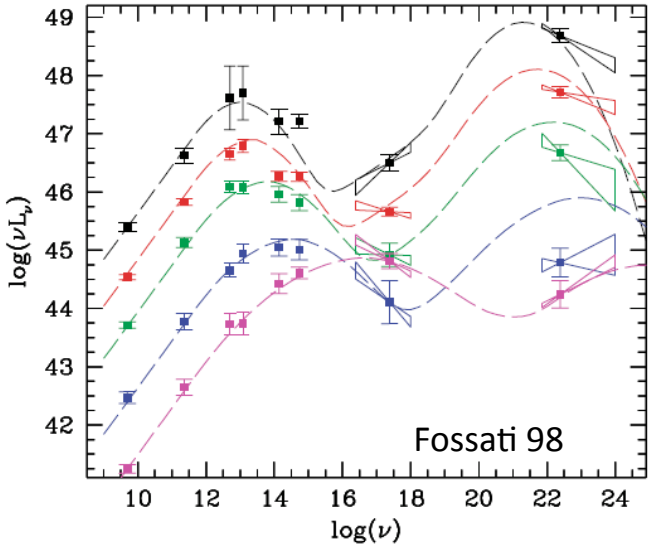


And fast time variability

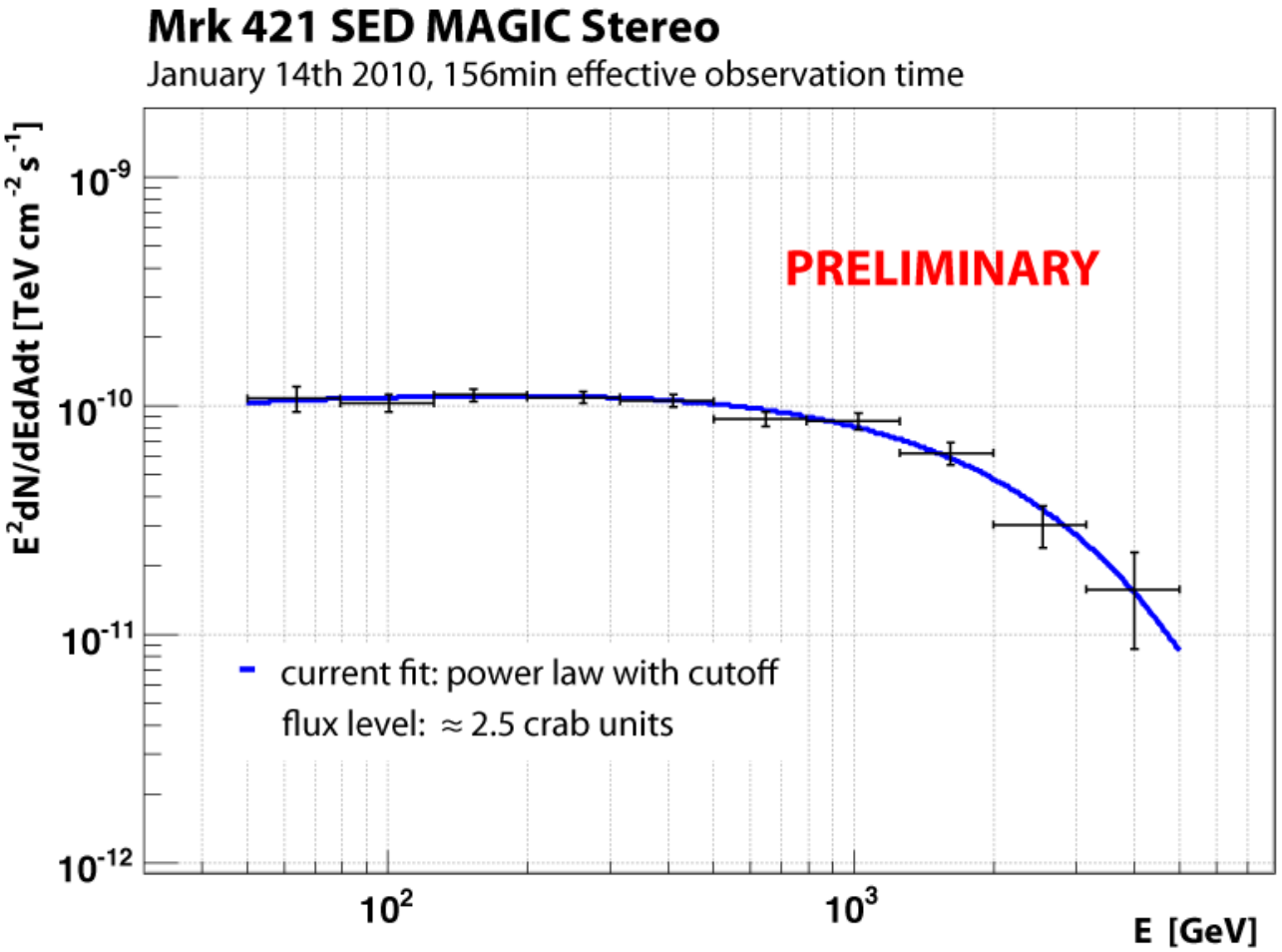


VHE Active Galactic Nuclei

- I could count 27 HBL, 3 LBL, 4 IBL + 4 radio galaxies
- The sources appear faster than their classification happens
- ~ 70 % are HBL (non-HBL could „catch“ mostly when flaring)
- Due to EBL absorption, threshold and sensitivity issues mostly sources are observed < z=0.2
- Distant blazars harden than expected (hint on low EBL-level)
- Variability time scale ≥ 2 min.

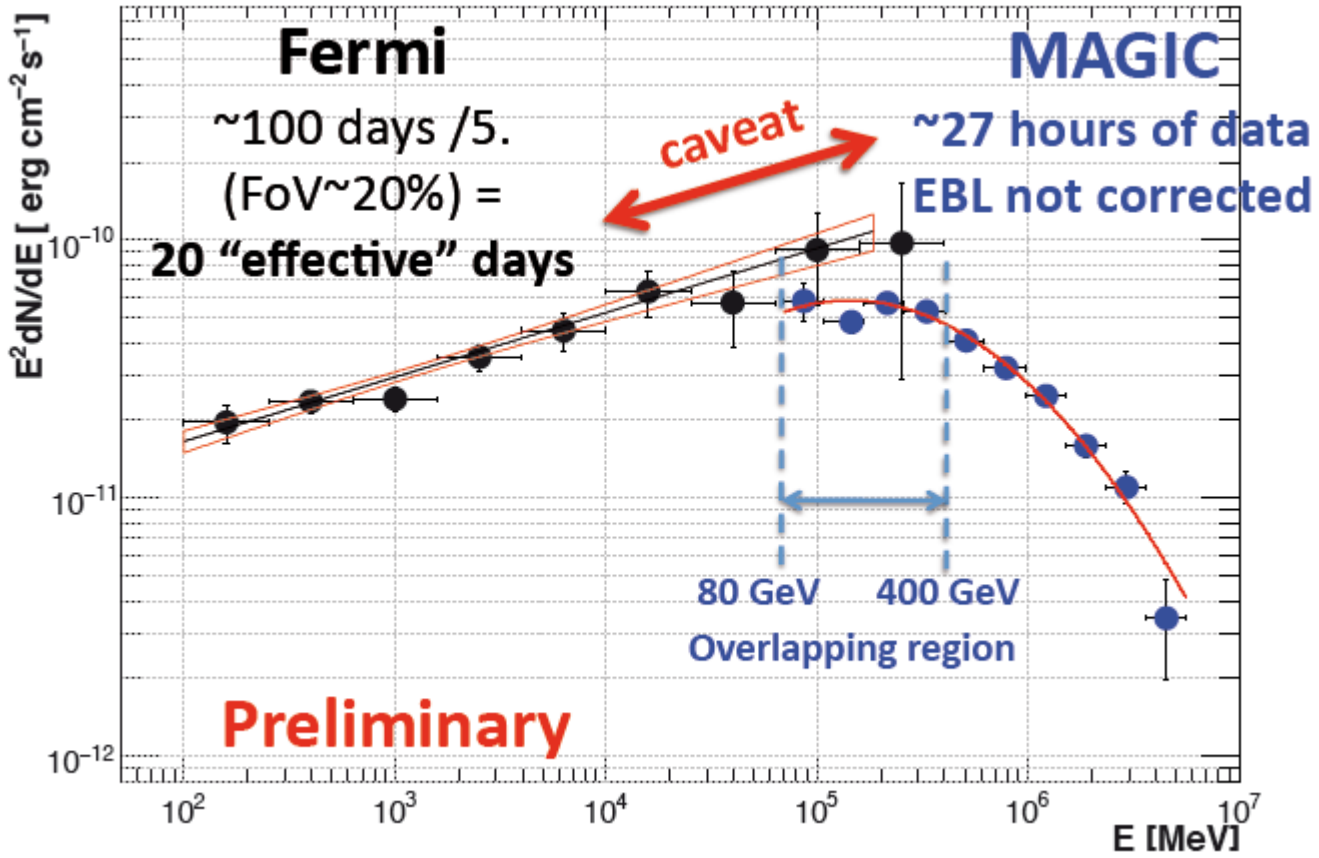


Mkn-421 Flare on Jan. 14 2010



A VHE instrument (MAGIC) could measure the spectrum of a strong source at energies as low as ~ 50 GeV providing an overlap with a space-born γ instrument (FERMI)

Full energy coverage for selected sources by FERMI & a VHE instrument

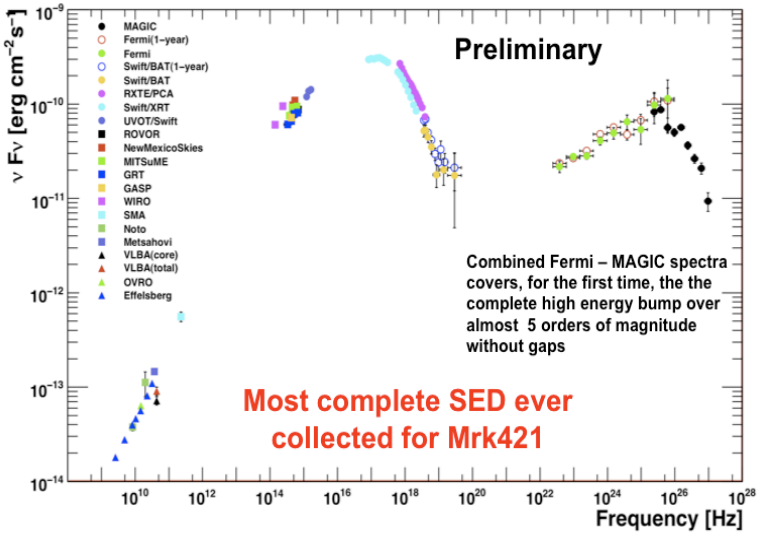


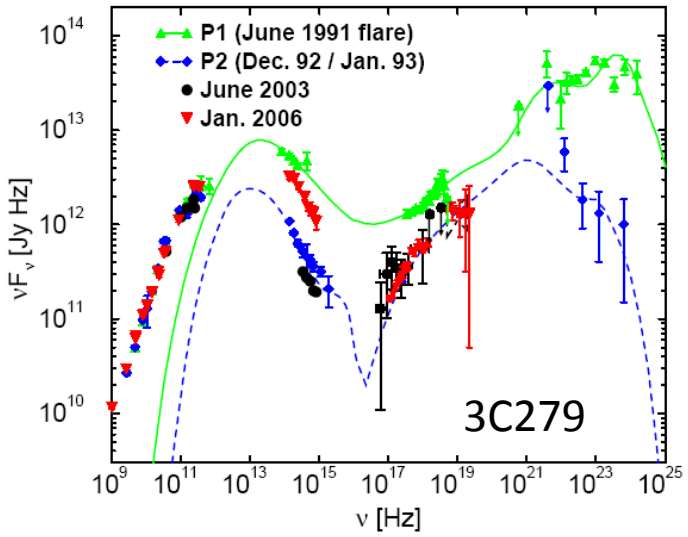
- This is a new quality that many of us were dreaming since long ago

One needs still to clarify some calibration issues between the very different techniques

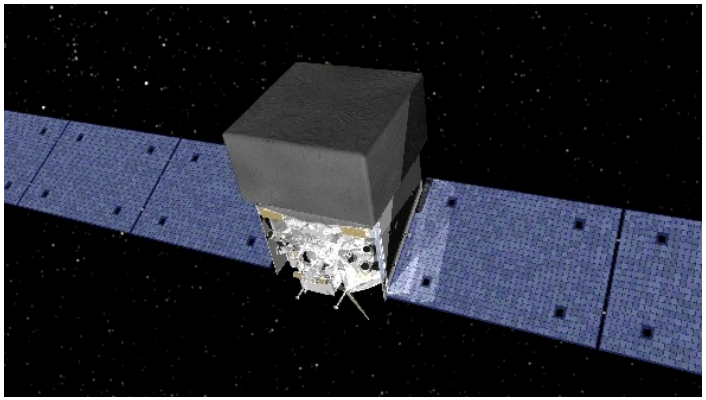
Blazar modeling

- MWL data is mandatory, best from radio till VHE gammas
- The sources are highly variable, SED changes
- Which model fits best, leptonic or hadronic , which types ?
- It became usual to start a MWL with LAT, SWIFT, AGILE, Chandra, XMM, RXTE, many other optical and radio telescopes

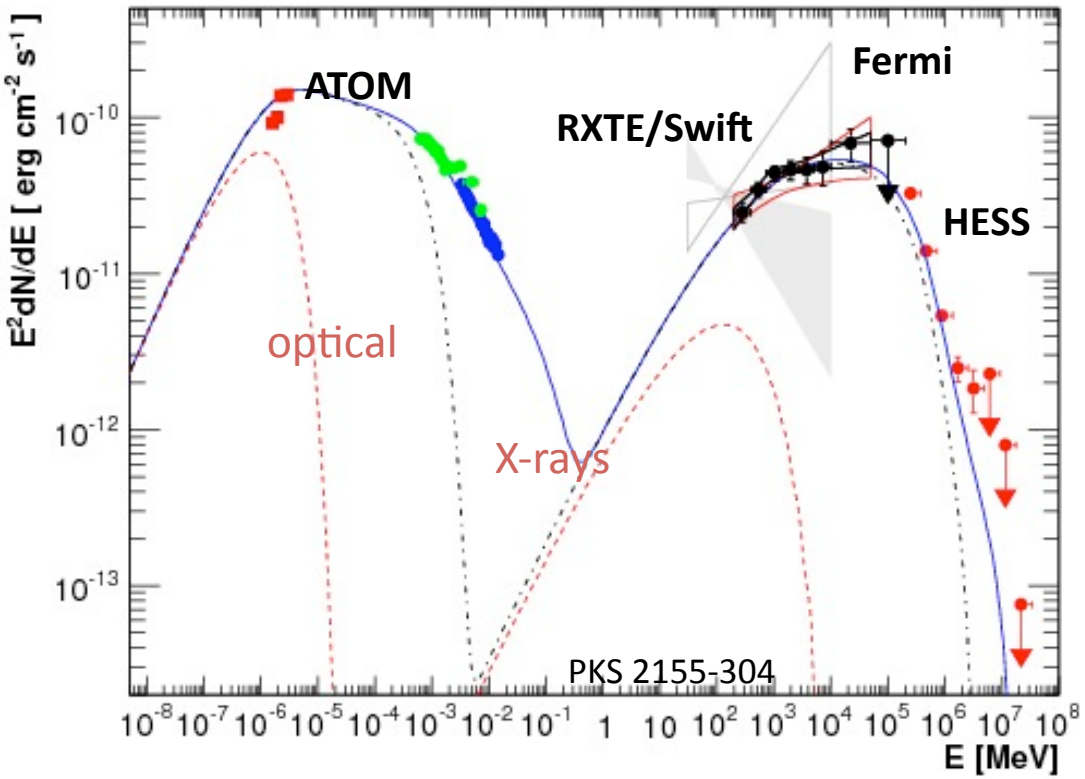




Multiwavelength campaigns



Fermi & H.E.S.S., arXiv:0903.2924

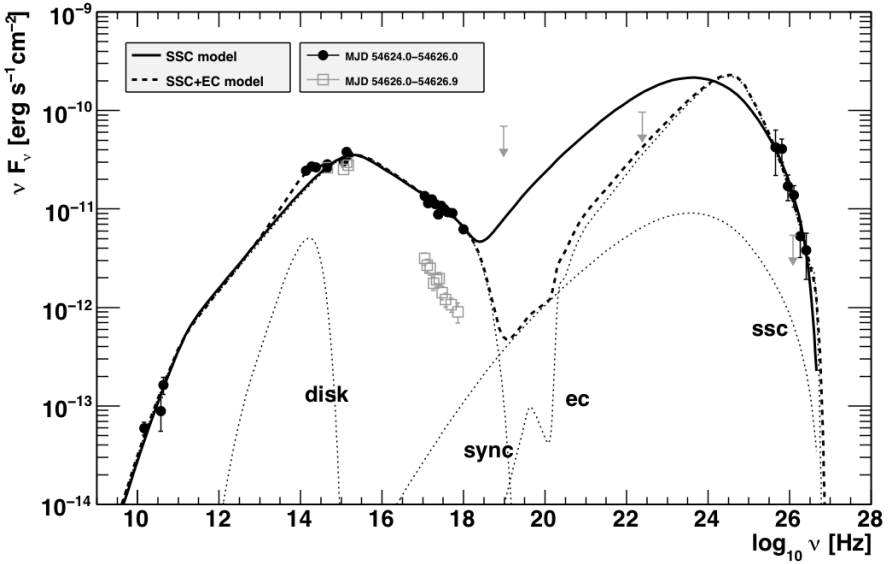


- Optical, X-ray and γ observations of the Bl Lac object PKS 2155-304
- Data August-September 2008
- Clear optical VHE correlation observed
- Evidence of X-ray and γ spectral index correlation
- In contrary to previous observations no correlation could be found between X-ray/VHE

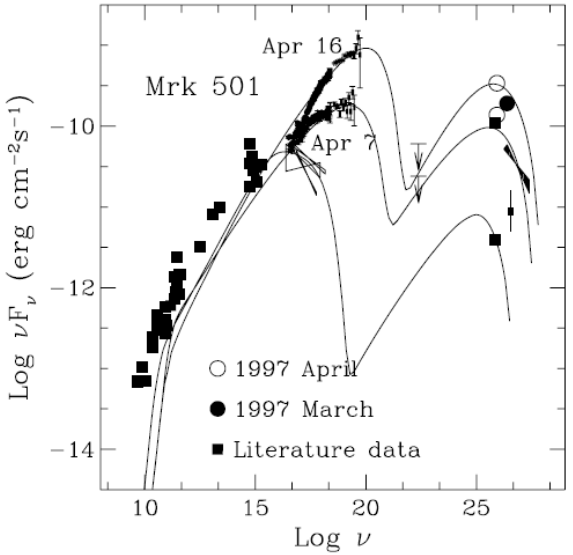
SSC models are frequently invoked for SEDs of Bl Lacs. But in this case these models are at odds with the correlated variability in different energy bands

Modeling sources

VERITAS discovery 2008



W Comae (z=0.102) is an IBL. MWL in radio, Optical, + SWIFT, XMM, AGILE. SSC and SSC + External IC has been invoked. Simple SSC has difficulties. SSC + IC on thermal photons from the accretion disc can describe satisfactory. X-ray/TeV Variability on day scale makes important to measure simultaneously



Mrk-501, TeV blazar. Dramatic Tev and X-ray flares in 1997. Mostly good X-ray/TeV correlation. Source luminosity increased, both peaks moved to right, providing higher energy (in contrast to Blazar sequence). Some X-ray flares lacking TeV counterpart.

VHE γ Astrophysics in FERMI Era

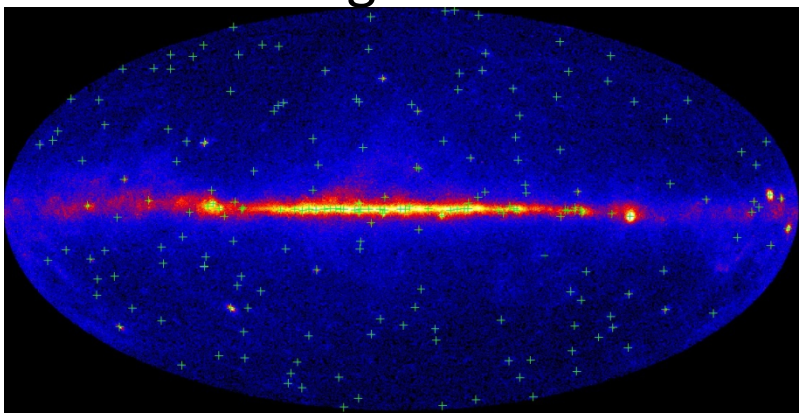
• Flying few 100 km high-up and every six hour watching the entire sky and providing hints or indications for TeVinstruments (flux > 30, 50, 80, 100 GeV) about where to look

• Already now a very reach VHE source harvest thanks to FERMI !

• FERMI provides in most cases the low energy spectrum continuation of what the ground-based VHE instrum. can observe

• Combined power is very strong for source understanding

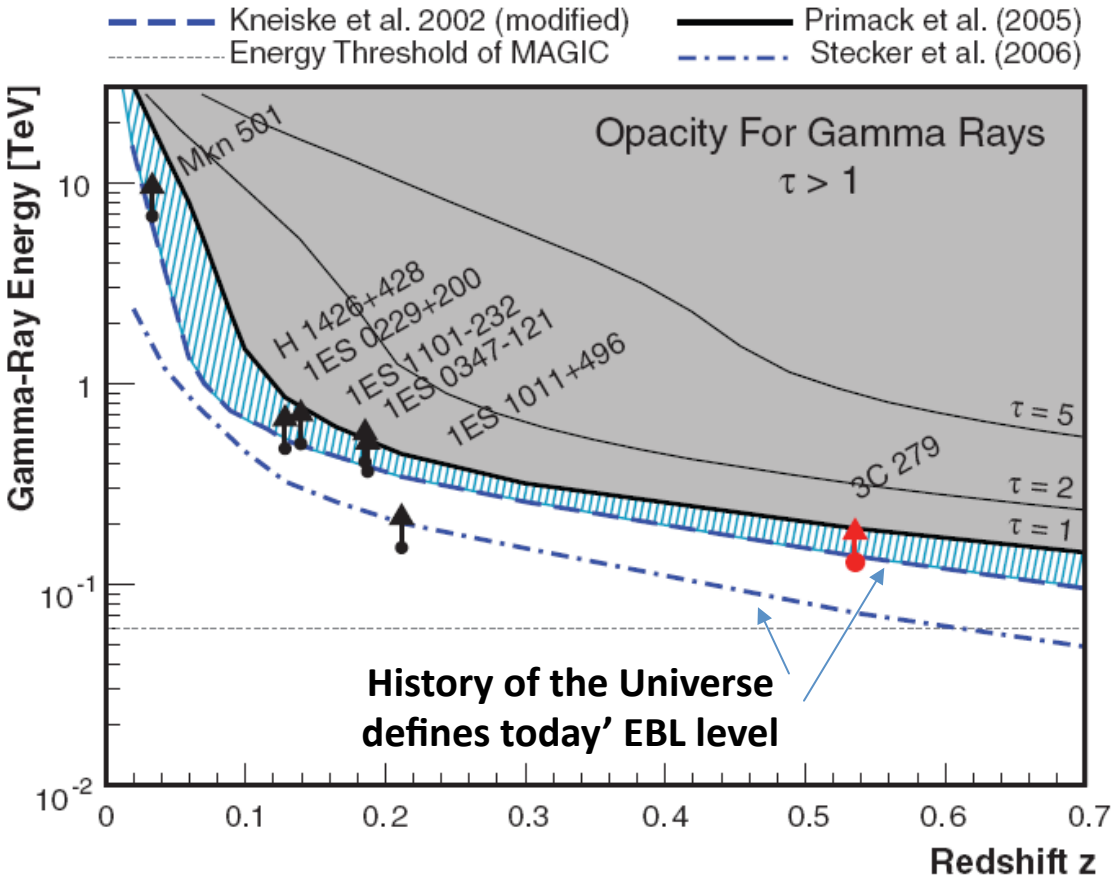
• In lucky cases one can obtain a spectrum starting from 0.1 GeV and stretching till several tens of TeVs, i.e. within 5 - 6 orders of magnitude in energy!



MWL crucial for studying sources

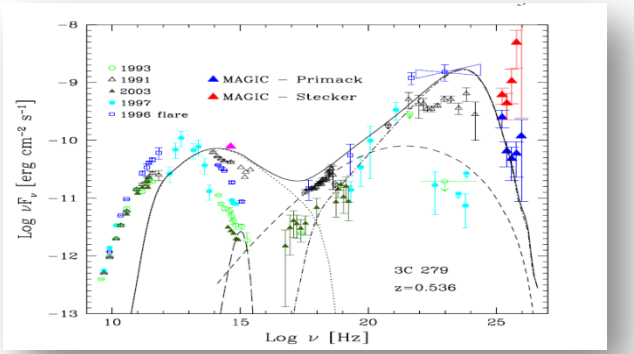
- Best is simultaneous MWL data for SED modeling
- For HBL the SSC seems working well, X-ray/VHE correlation, harden w/ flux increase
- IBL usually detected when flaring. Some evidence that SSC + External Compton can work.
- Strong EBL limits from H.E.S.S. are further supporetd by recent data
- From time to time major flares from some sources providing very valueable data (M87, Mrk-421, PKS 1222,…)
- For M87 the emission zone near the BH
- M82 and NGC 253 could provide CR origin related information
- A side remark: the net (varying) flux from the mentioned sources is ~ on the level of few x Crab Nebula

Probing EBL with VHE photons



MAGIC
Science (2008)

Relevant λ for EBL: 0.2-10 μm



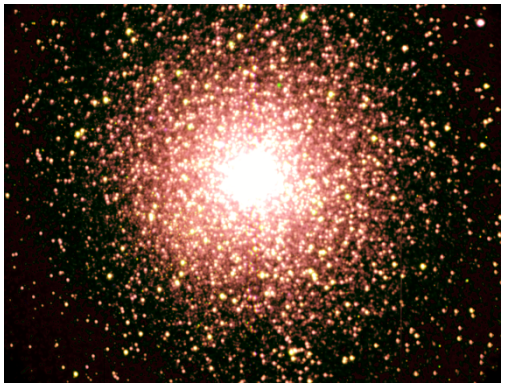
(see D. Mazin's talk for details)

Dark Matter Search (indirect)

DM candidate source could be

- Dwarf spheriodals Draco, Ursa Minor, Wilman 1, Boötes 1, Canis Major, Sagittarius Dwarf, .. (high light/mass ratio)
- Galactic center
- Globular clusters
- Local group galaxies M32, M33
- Clusters of galaxies: Perseus, ...

Though the estimated IACT sensitivity fails by few orders of magnitude for detecting the assumed type „classical“ DM, still it is a challenge to measure the candidates

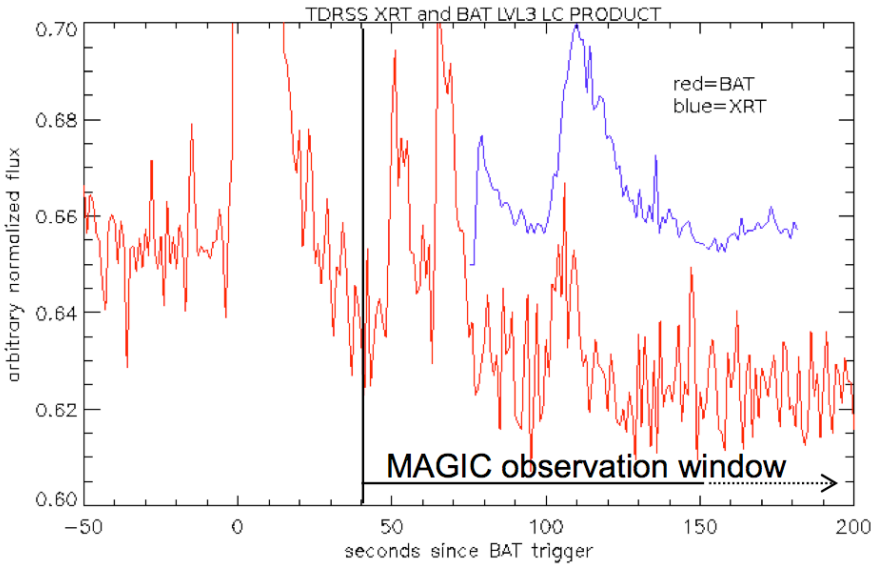


Gamma Ray Bursts and afterglow

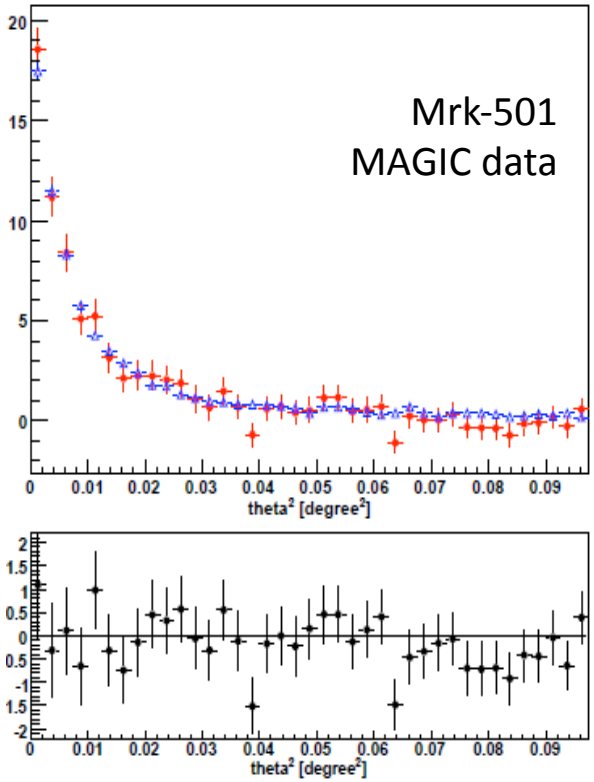
- Very interesting for studying the rapid variability of the most luminous objects in the Universe
- Interesting for LIV studies
- Could help in modeling the high-energy end of GRBs
- Propagation and absorption effects could be studied
- 2 populations: < 1 sec. and few tens of seconds; even the latter need very fast reaction time
- Also afterglow has a high chance

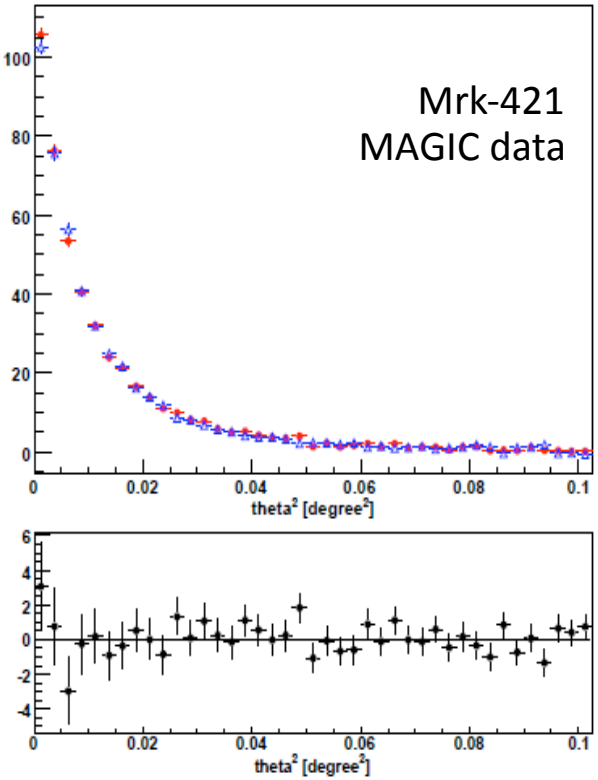
GRB050713A

The telescope started measuring in 27s after the GCN signal arrived; no signal



Halo Around AGN Sources

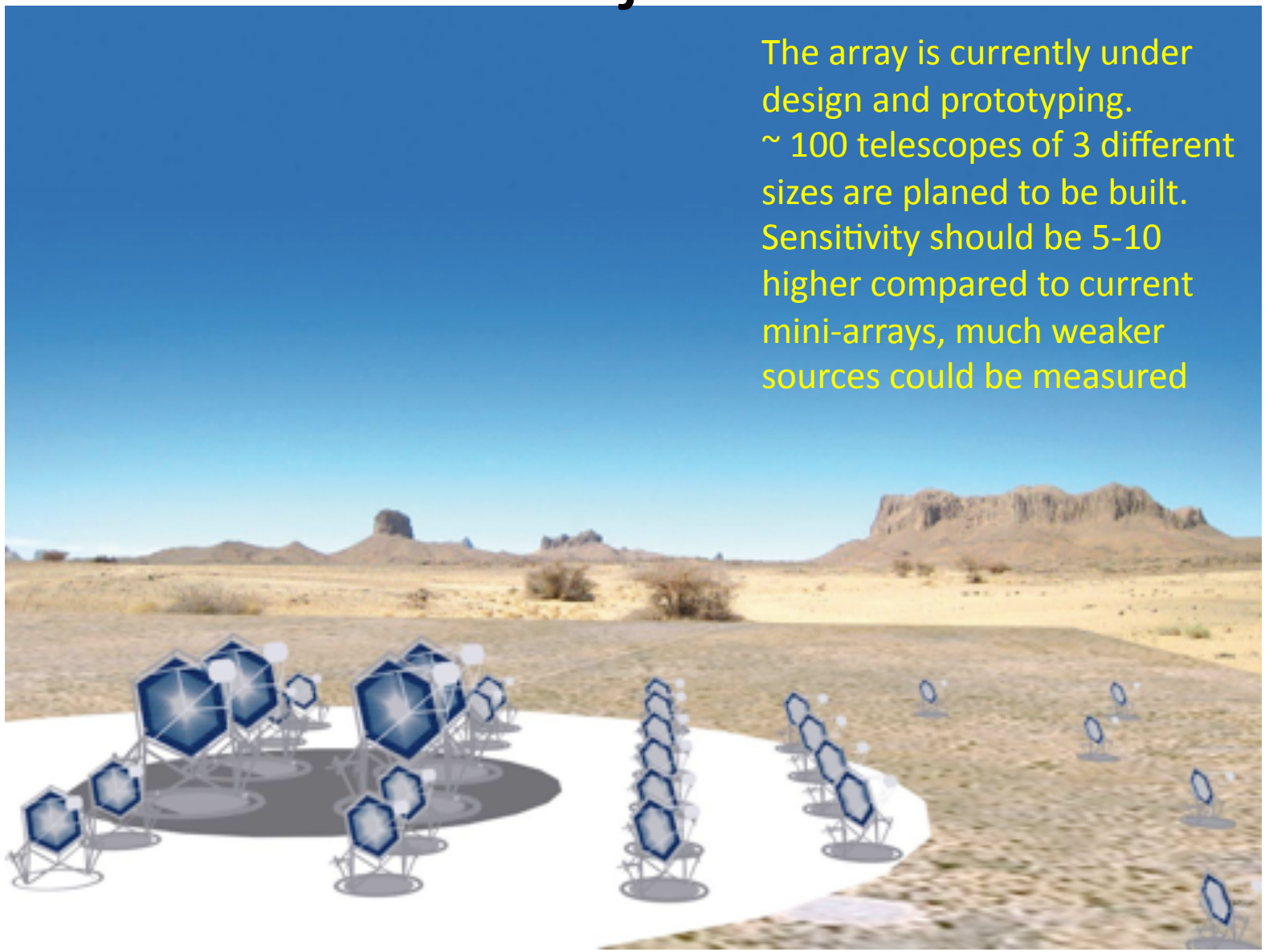




Both checked sources are compatible with a point-like source. Upper limit on 4 % Crab level for Mrk-421. Some Constraints on the EGMF strength.

- 1st suggested by Aharonian, et al., (1994)
- The idea is developed further by several researchers
- VHE γs cascade on EBL/CMB
- The trajectories of created e^+e^- pairs bend in the extragalactic magnetic field (EGMF) → an additional, extended emission component can appear around the projected direction of the source
- A low-level signal may appear as a quiescent one

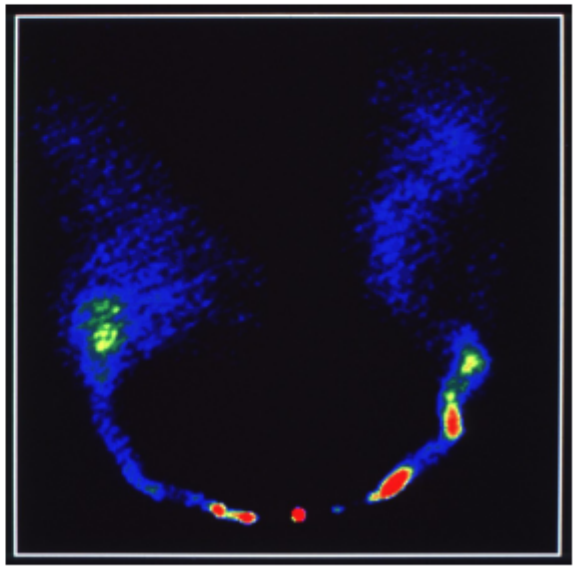
Cherenkov Telescope Array (CTA) Project



IC310: 1st Head-Tail Galaxy in TeVs

- Located in Perseus cluster (80 Mpc) → 5x more distant than M87
- Detected by MAGIC: [ATel 2510, March 2010]
  - 6σ from 20h stereo data (2010) and 38h MAGIC-I data (2008 to 2010)
  - Preliminary emission level: ~2.5% of Crab Nebula flux ($E > 300$ GeV)
- Also detected by FERMI/LAT above 100 GeV [arXiv:1003.4615]

- "Relative" in Perseus cluster: NGC1265
  (radio image on the right)
  → Not detected in VHE regime!
- How are γ-rays produced in IC310?
  - Close to central BH like in M87?
  - Or by interaction of relativistic outflow with intracluster medium?
- Important to check variability!
- Detailed publication in preparation



[Courtesy of NRAO/AUI, C. O'Dea/F. Owen]