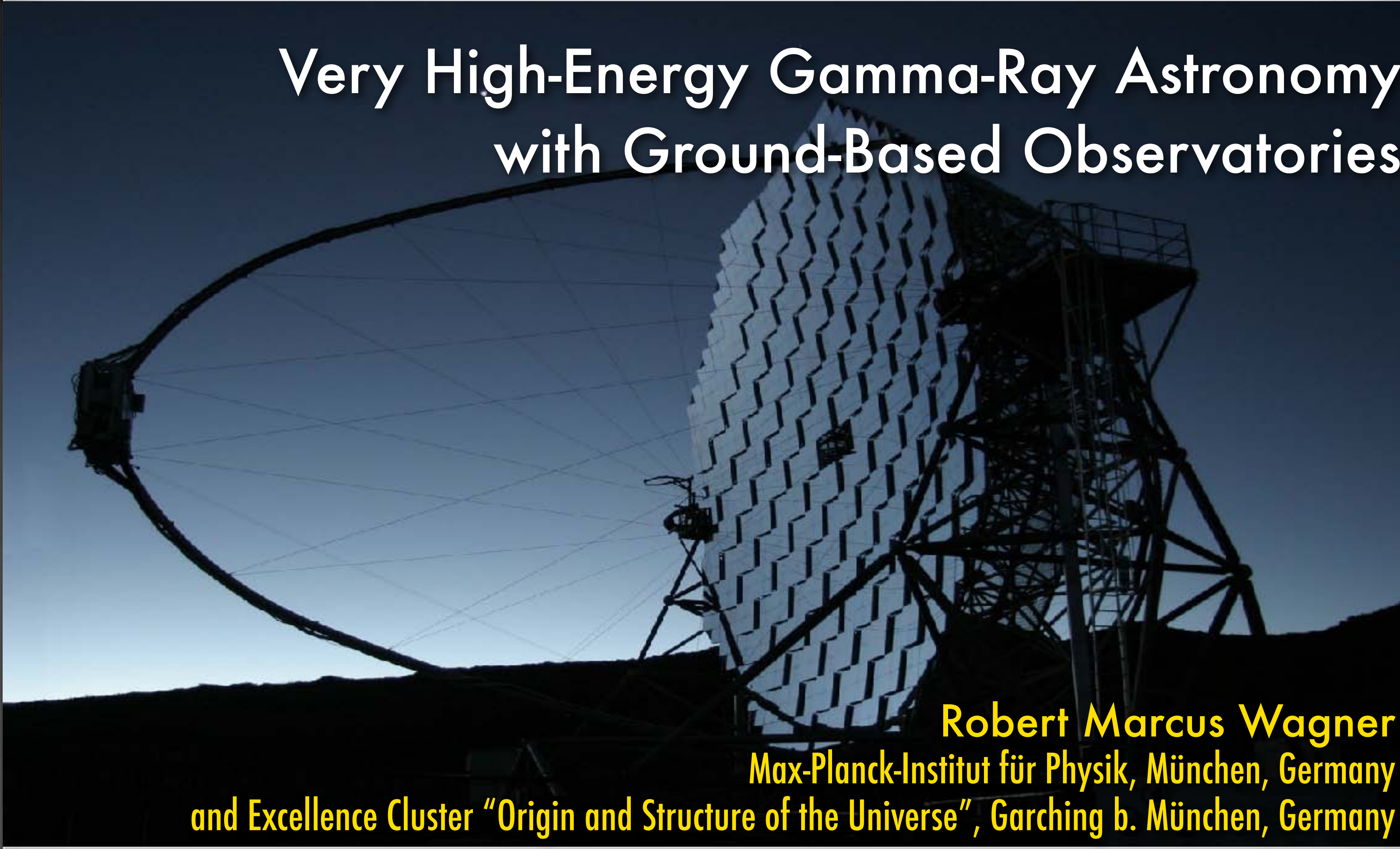
Very High-Energy Gamma-Ray Astronomy with Ground-Based Observatories



Robert Marcus Wagner
Max-Planck-Institut für Physik, München, Germany
and Excellence Cluster "Origin and Structure of the Universe", Garching b. München, Germany

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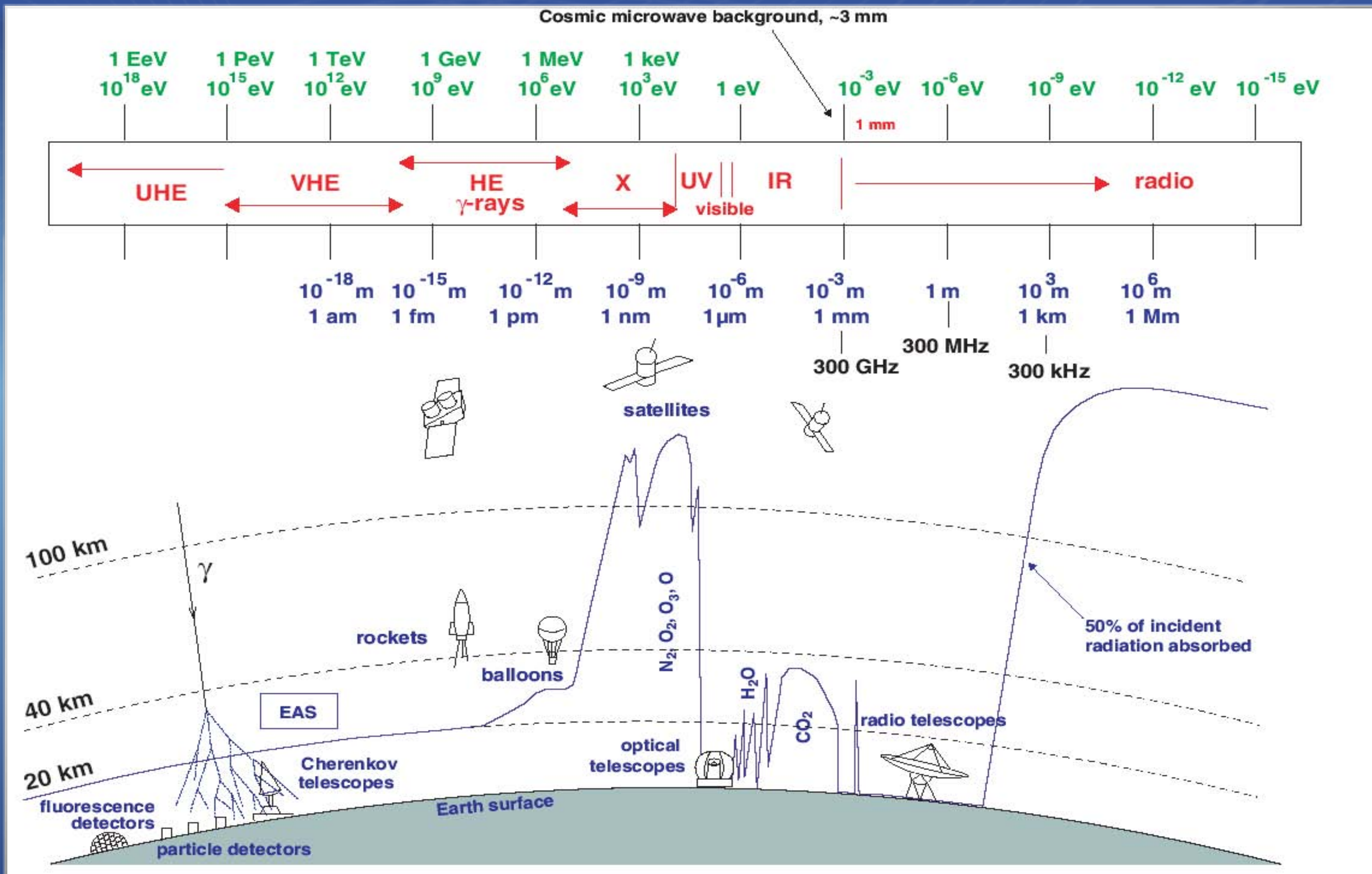
Multiwavelength Astronomy



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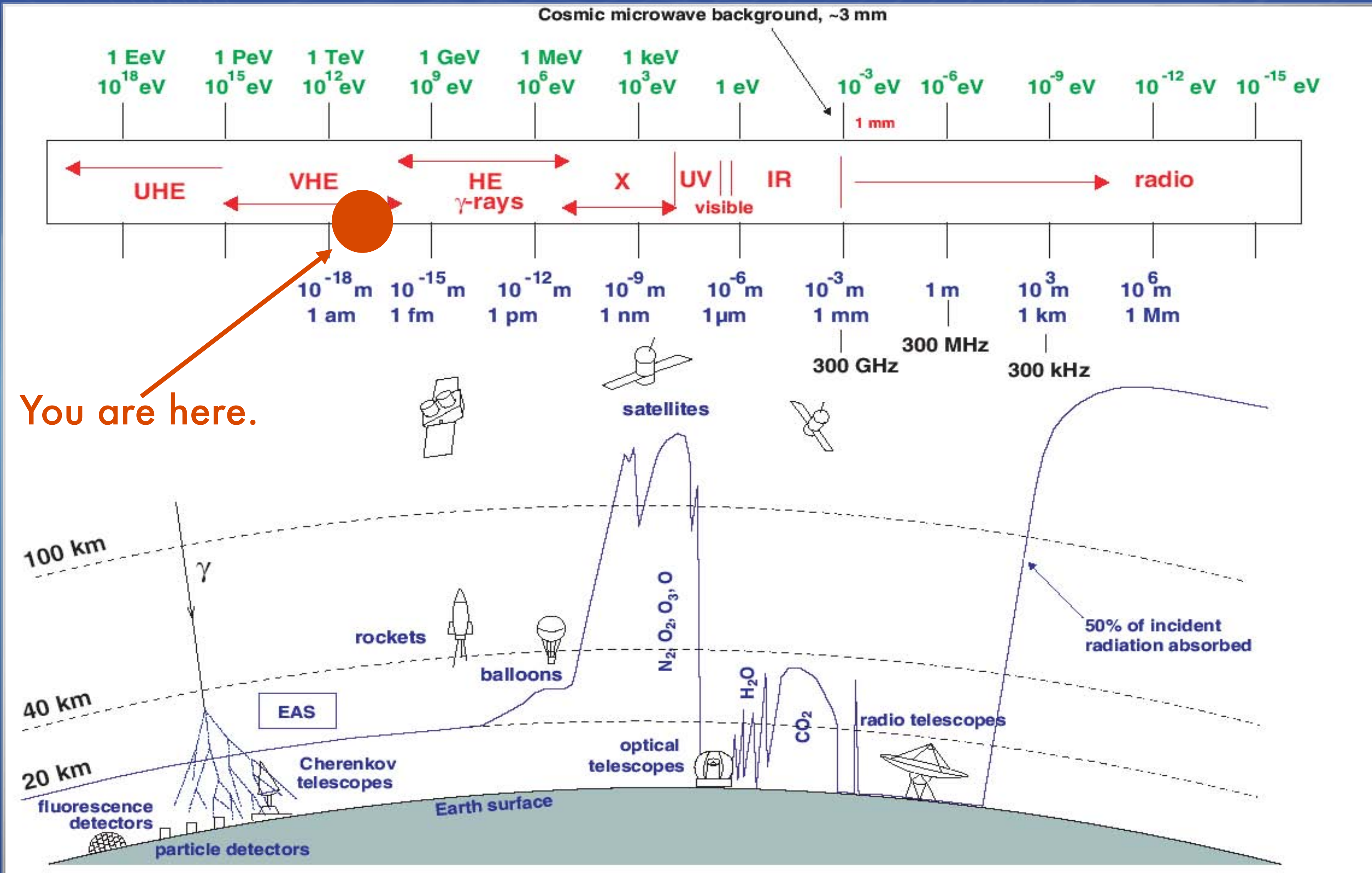
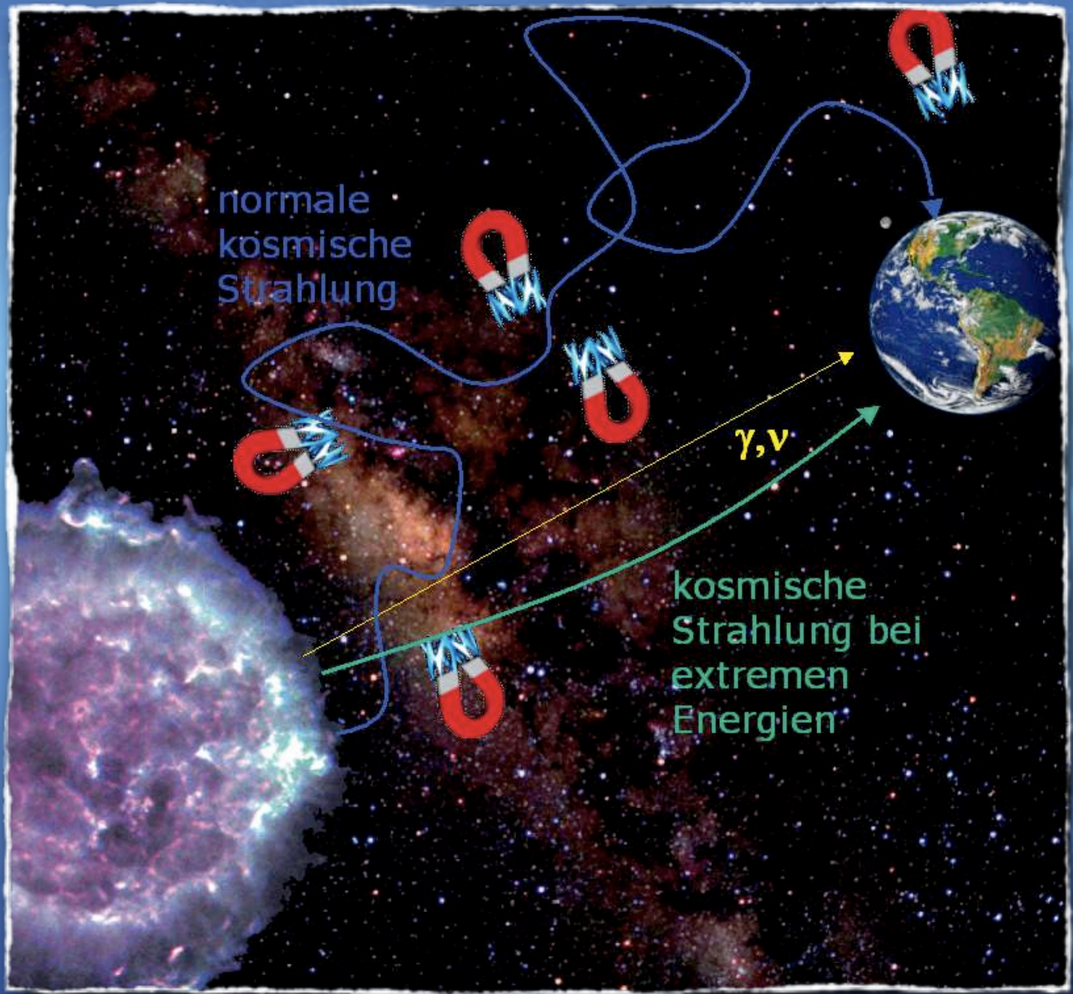


Very High Energy Gamma-Ray Astronomy

- Gamma-rays are ideal messenger particles
- Trace non-thermal particle acceleration processes



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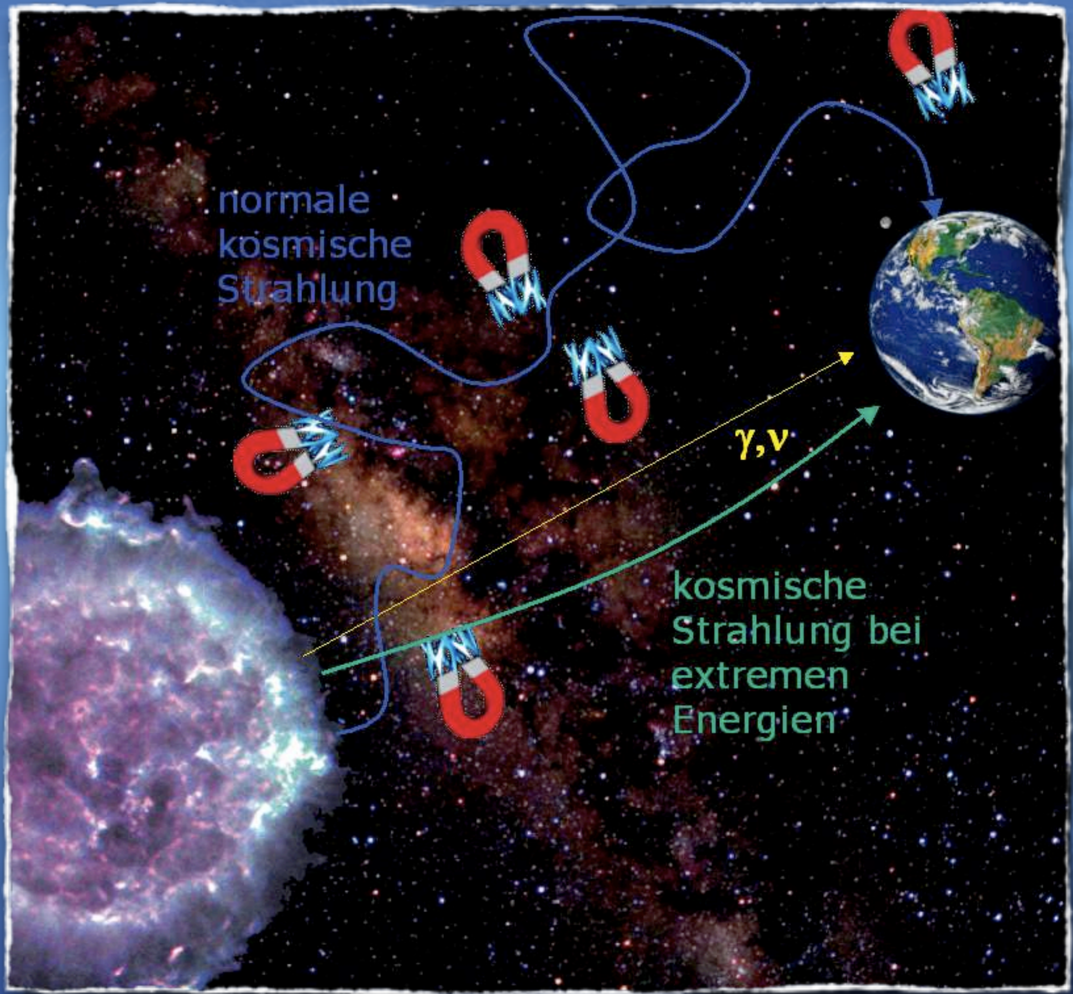
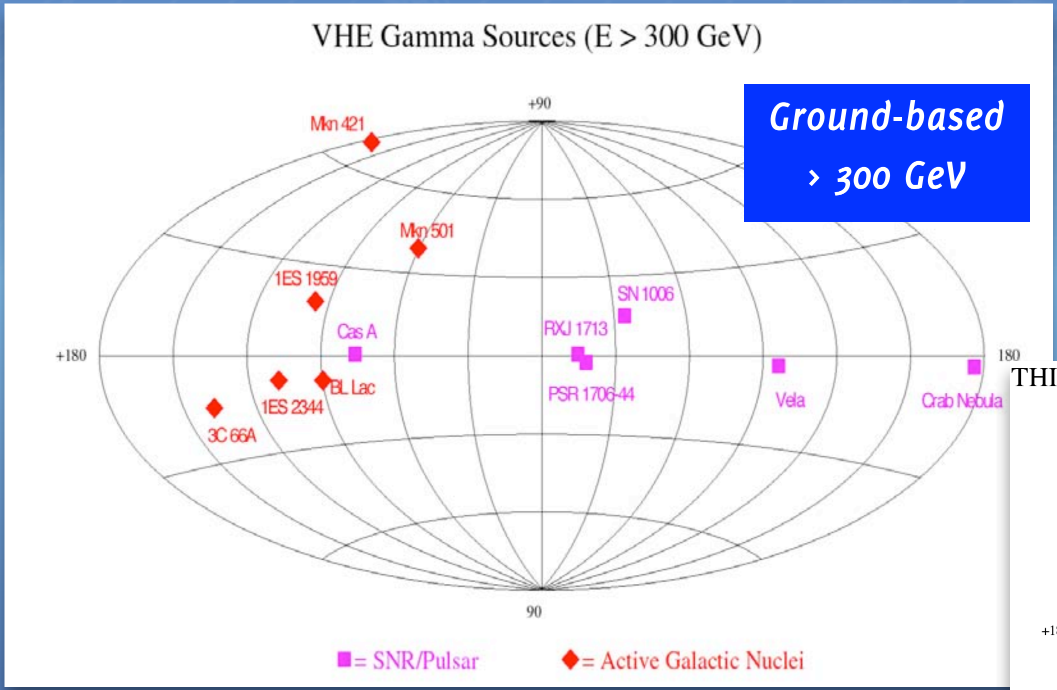


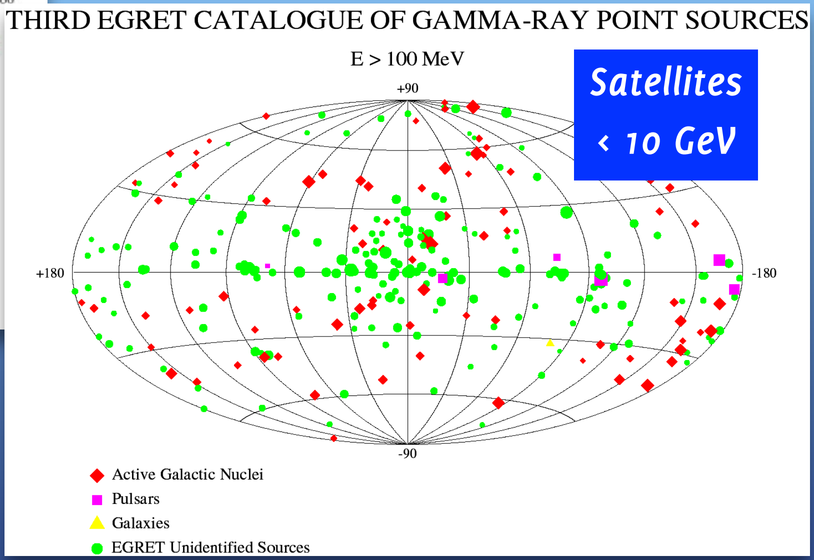
- Ubiquitous power-law spectra:
- Satellite detectors like Fermi
  - are sensitive ≤ 100 GeV only
  - have large FOV, but no sensitivity at small time scales
- Ground-based instruments: small FOV, but high sensitivity! ... and rather inexpensive

The dawn of VHE γ-Ray *Astronomy*

Situation before ≈2004:

- Energy gap between satellite-borne detectors (<10 GeV) and ground-based telescopes (>300 GeV).
- For extragalactic sources → absorption due to Extragalactic Background Light (EBL).





Ground-Based γ-ray Astronomy

- Today a crucial window in the electromagnetic spectrum of cosmic radiation
- Today we can speak of “astronomy” because
  - >100 objects discovered
  - Images (skymaps, morphology, …)
  - Spectra over almost 3 orders of magnitude in energy and flux
  - Light curves
  - Surveys,
    multi-wavelength campaigns,
    triggers to other facilities

IACT installations: the Key Players

IACT installations: the Key Players

HAWC, ARGO-YBJ
(DeYoung, Vernetto)

Performances of IACTs

Observatory	Elevation (km)	Telescopes (#)	Mirror Area (m^2)	FoV (°)	Threshold (GeV)	Sensitivity (% Crab*)
H.E.S.S.	1.8	4	428	5	120	0,5
VERITAS	1.3	4	424	3.5	120	0,5
MAGIC	2.2	2	2x236	3.5	50(30)	0,7

(*) Crab Nebula is the standard candle for TeV astronomy. Fluxes are usually expressed in terms of Crab fluxes

- And also:
  - Typical effective area >>10^5 m^2
  - Typical angular resolution <0.1°
  - Typical energy resolution ~15%

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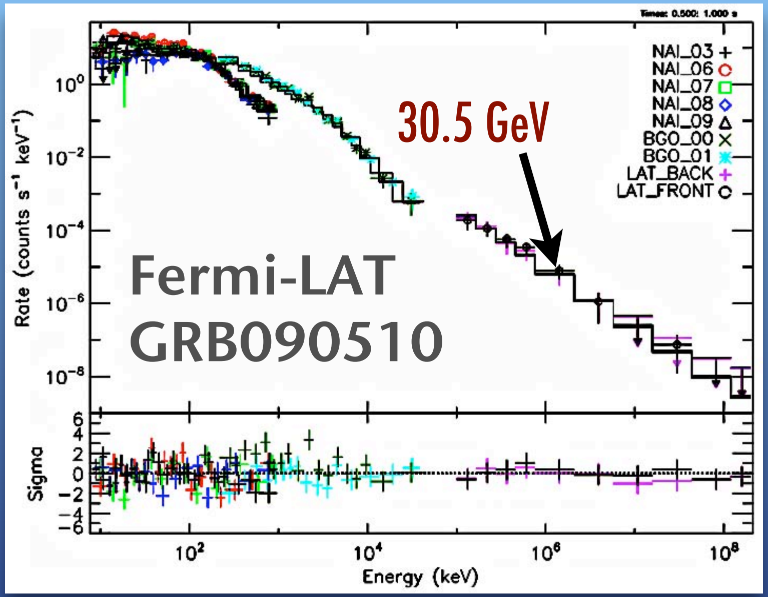
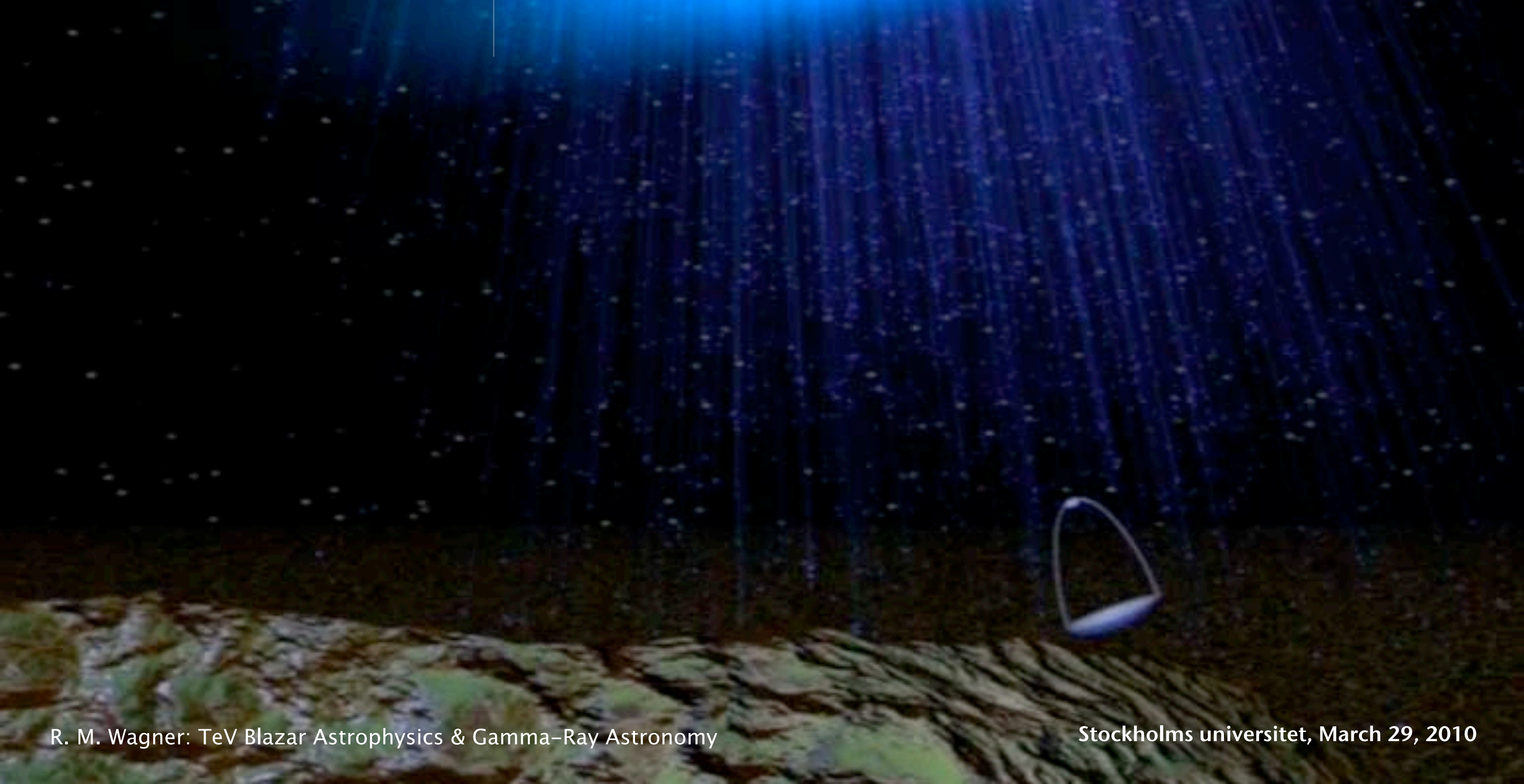
10^5 more photons!



The Imaging Air Cherenkov Technique

- Extended Air Shower initiated in atmosphere
- Detect the Cherenkov radiation from charged particles in EAS
- A mirror reflects and concentrates the light
- An image of the shower formed in a photomultiplier camera



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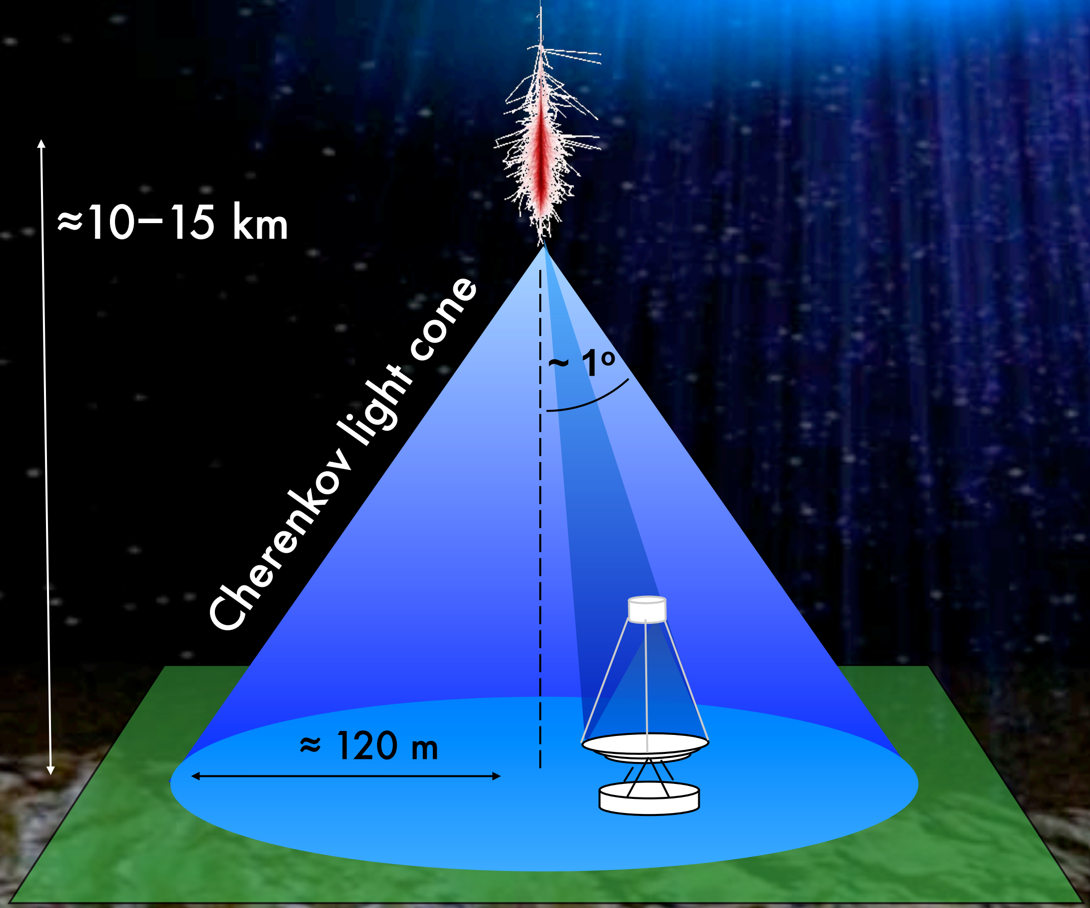

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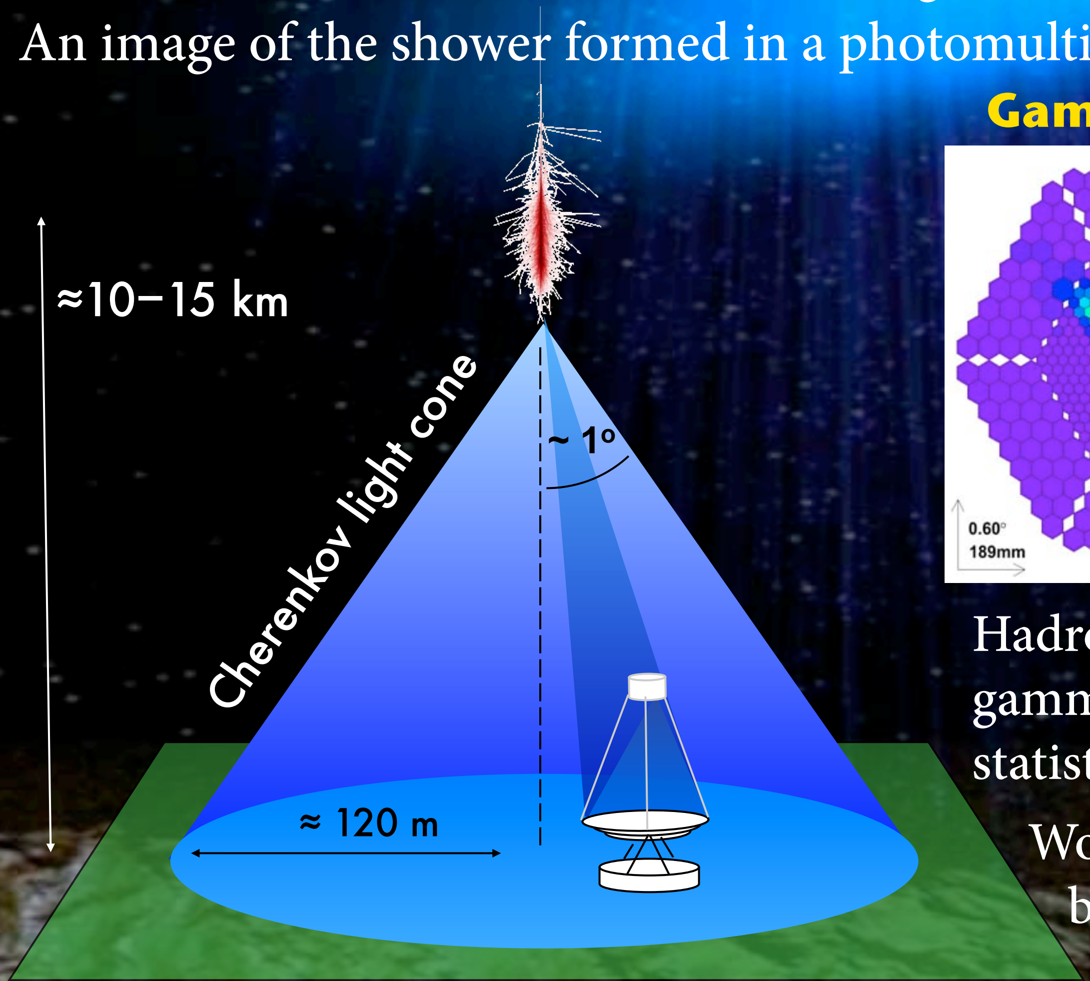
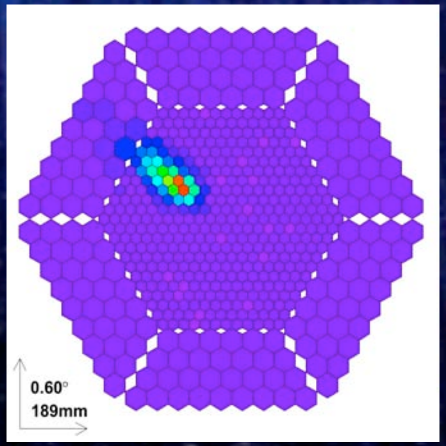
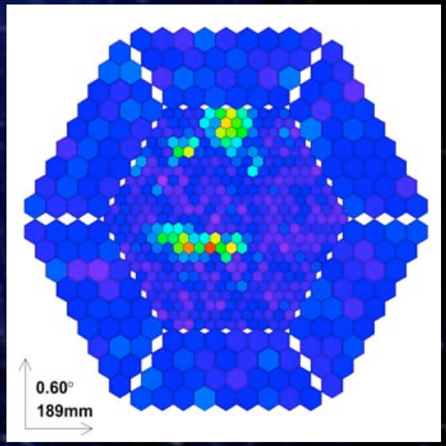


Gamma event



Hadron event



Hadrons (background) dominate over gammas (signal). They must be rejected statistically in the analysis

Works excellent > 100 GeV
but challengng < 100 GeV

Scientific Objectives

TeV astronomy reviews e.g.,
Hinton 07, Horns 08, De Angelis+08

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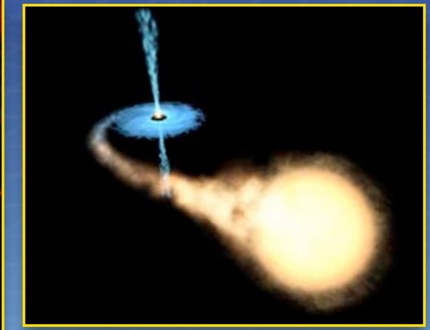
SNRs

Pulsars
and PWNe



Microquasars
X-ray binaries

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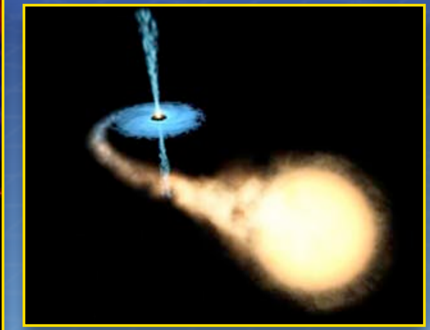

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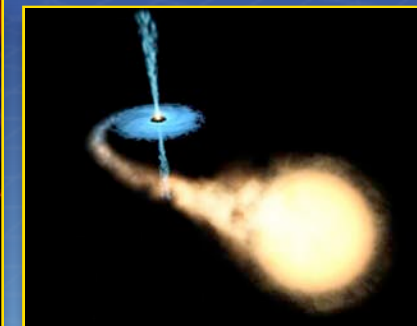

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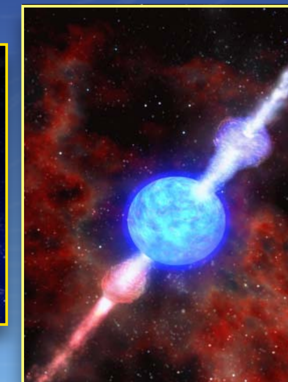

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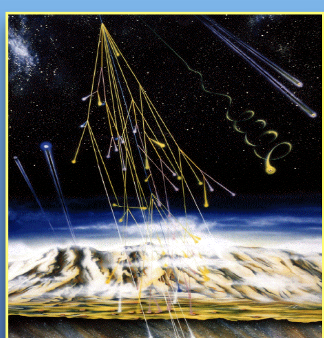
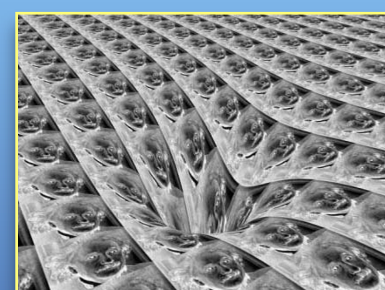
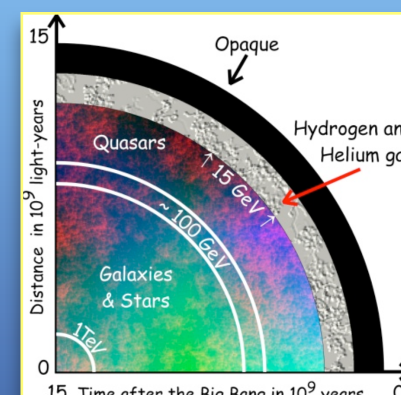


Origin of cosmic rays

Dark matter



Fundamental Physics



Cosmology

Scientific Objectives

TeV astronomy reviews e.g.,
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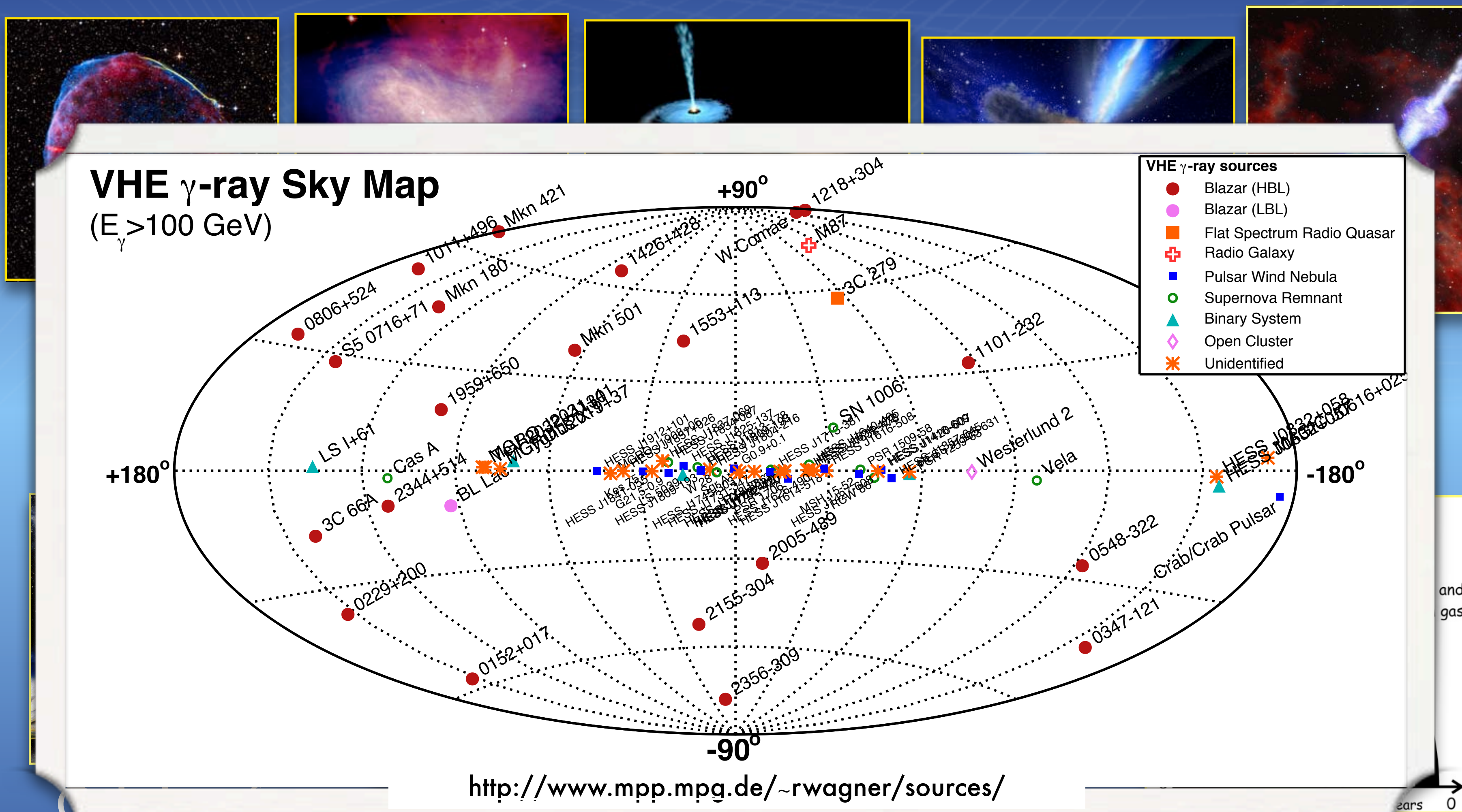


cosmic rays

Dark matter

Physics

Cosmology

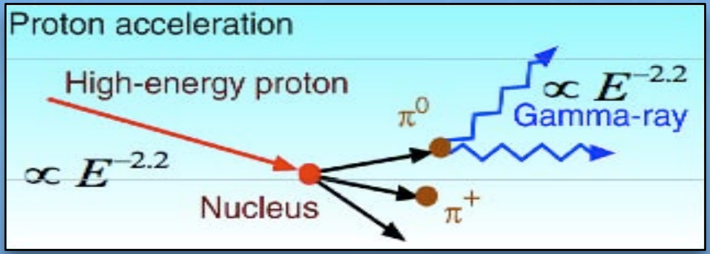
Seminal discoveries since 2003

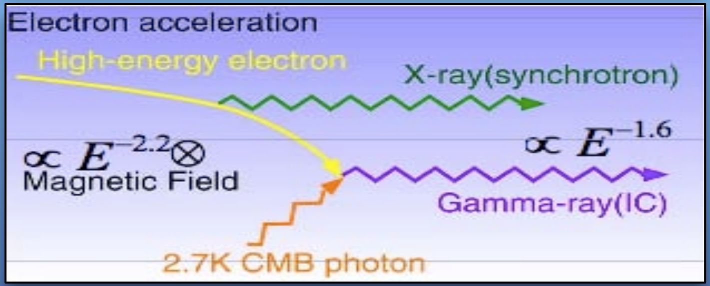
- **Massive flares** of Active Galactic Nuclei
- **Imaged** Supernova Remnant Shells
- Galaxy is full of **VHE pulsar-wind nebulae**
- **Pulsed VHE emission** from pulsars
- **Galactic Center** Source: accreting SMBH?
- Binary systems: **VHE modulation**
- **Diffuse gamma rays** from **interacting molecular clouds and star-forming regions**
- **Starburst galaxies**
- **Dark accelerators**
- Constraints on **Extragalactic Background Light**
- Constraints on **Lorentz invariance** violation
- Cosmic ray **electron and iron spectra**

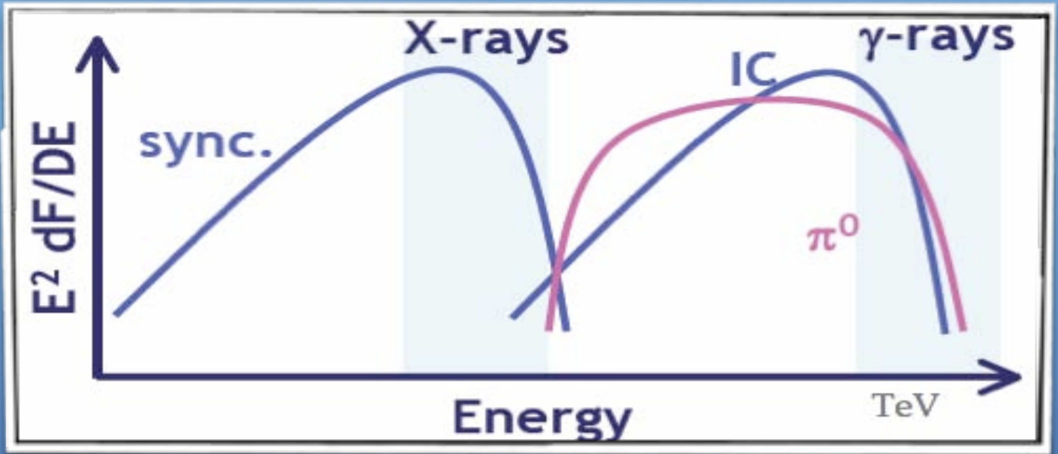
Origin of VHE γ-rays

After acceleration of charged particles,
two processes can produce TeV emission:

- π^0 decay: accelerated ions collide with ambient medium, producing $\pi^0 \rightarrow \gamma\gamma$
- Inverse Compton (IC): accelerated electrons up-scatter ambient photons



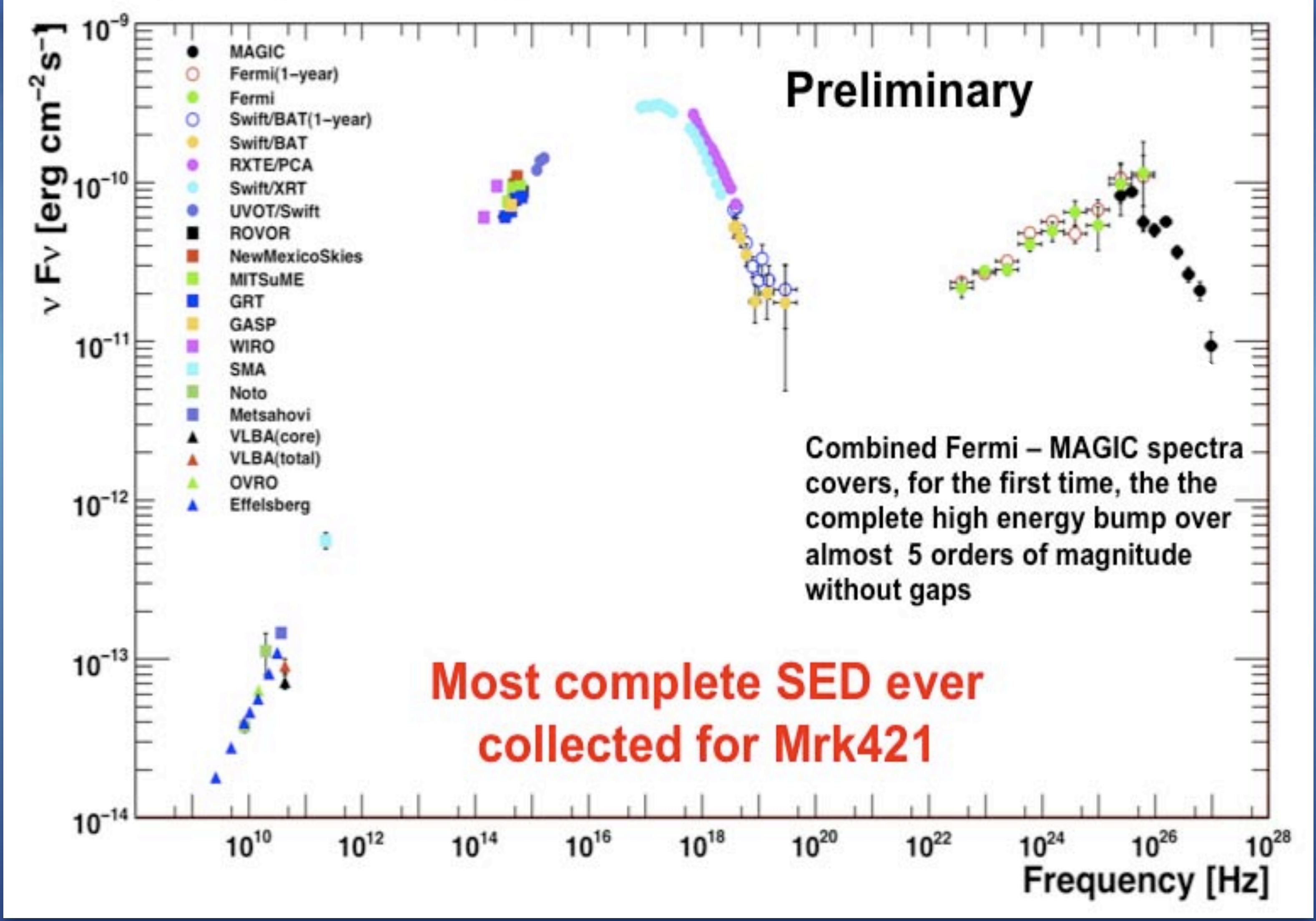


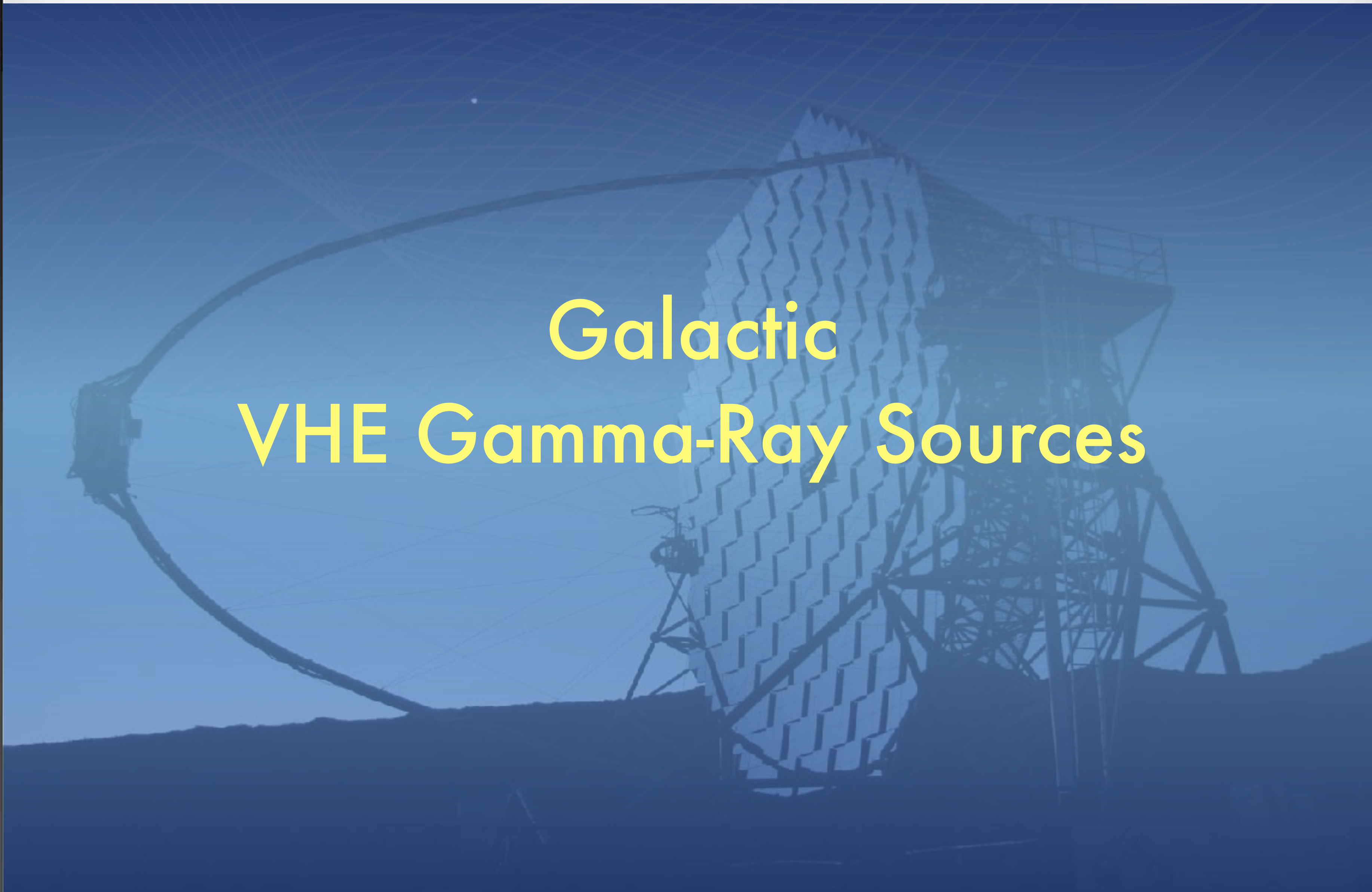


- γ-rays produced after the annihilation of neutralinos in regions with high ρ_{DM}: e.g., Galactic center, Clusters of Galaxies, Spheroidal Dwarfs, Intermediate-mass BHs

Overlap with Fermi-LAT

(High-Energy peak, X-calibration)

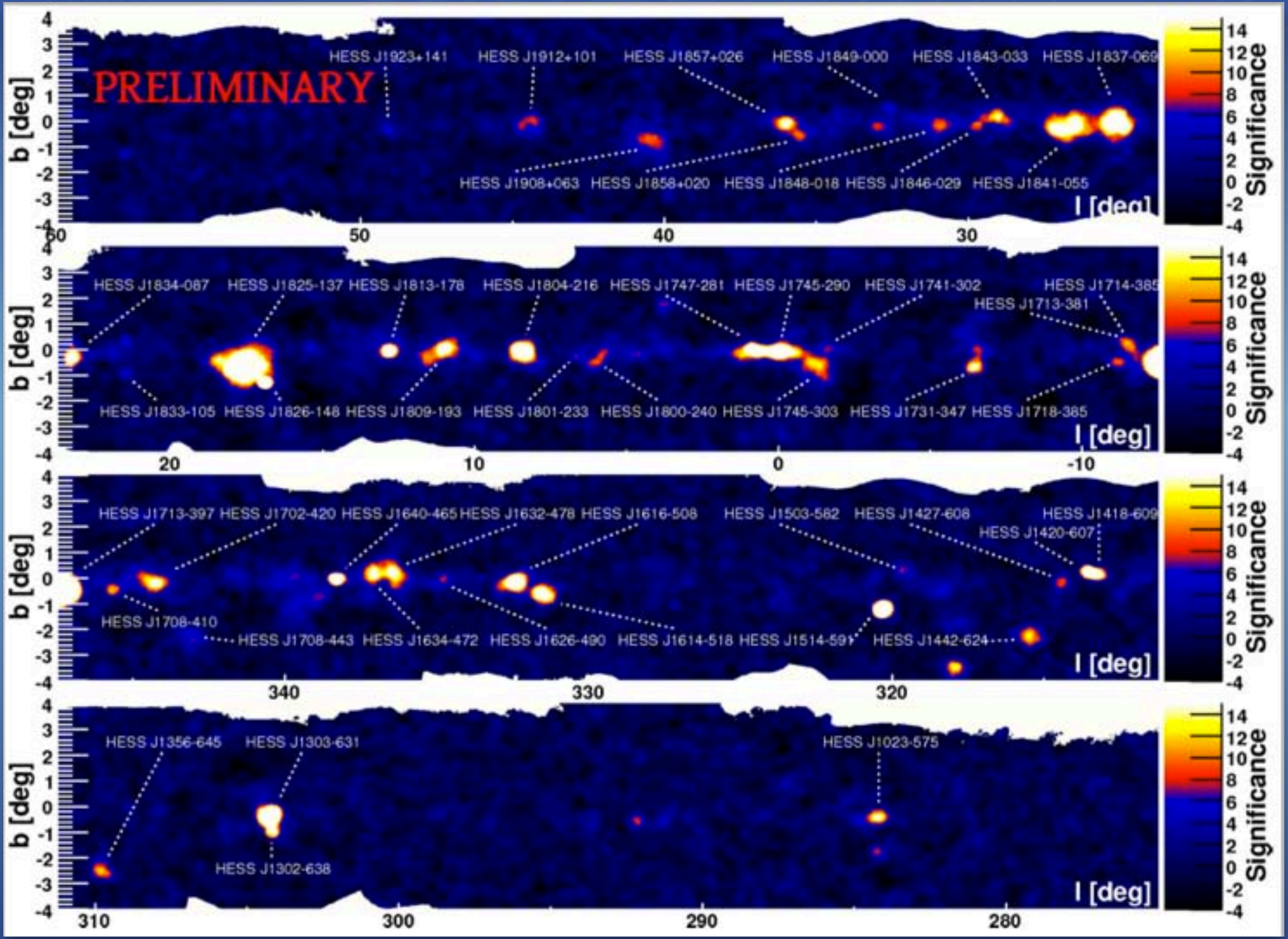


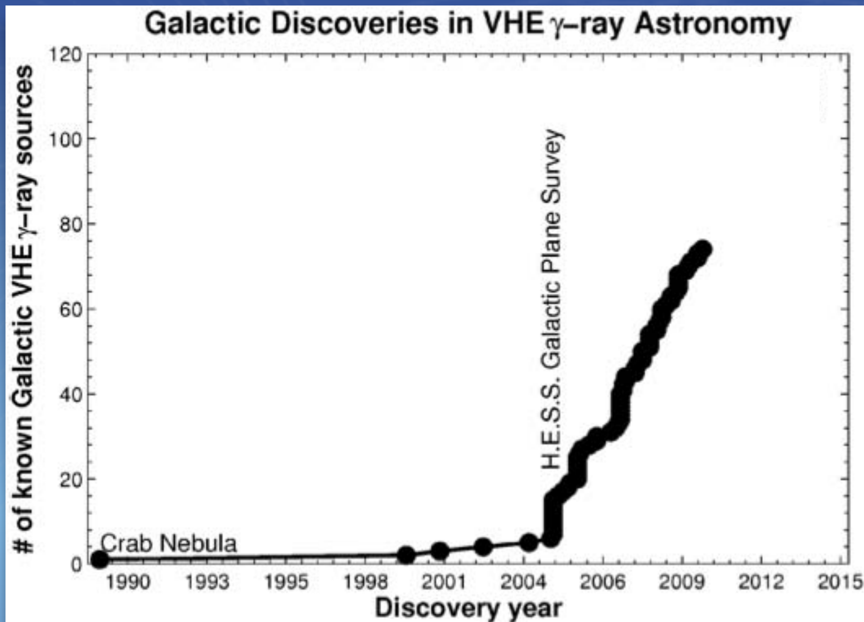


Galactic
VHE Gamma-Ray Sources

HESS Galactic Plane Scan

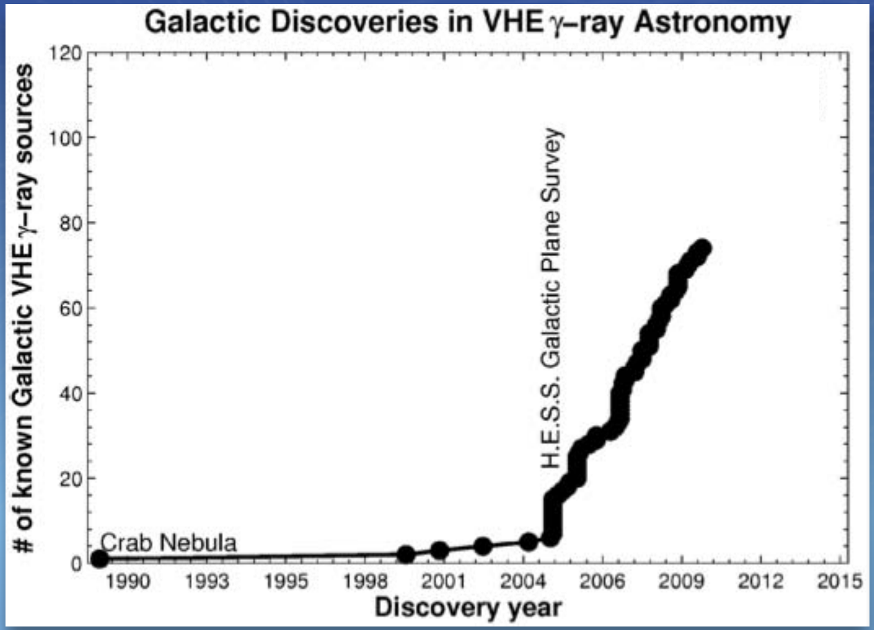
Eger, HESS galactic observations
Thu parallel

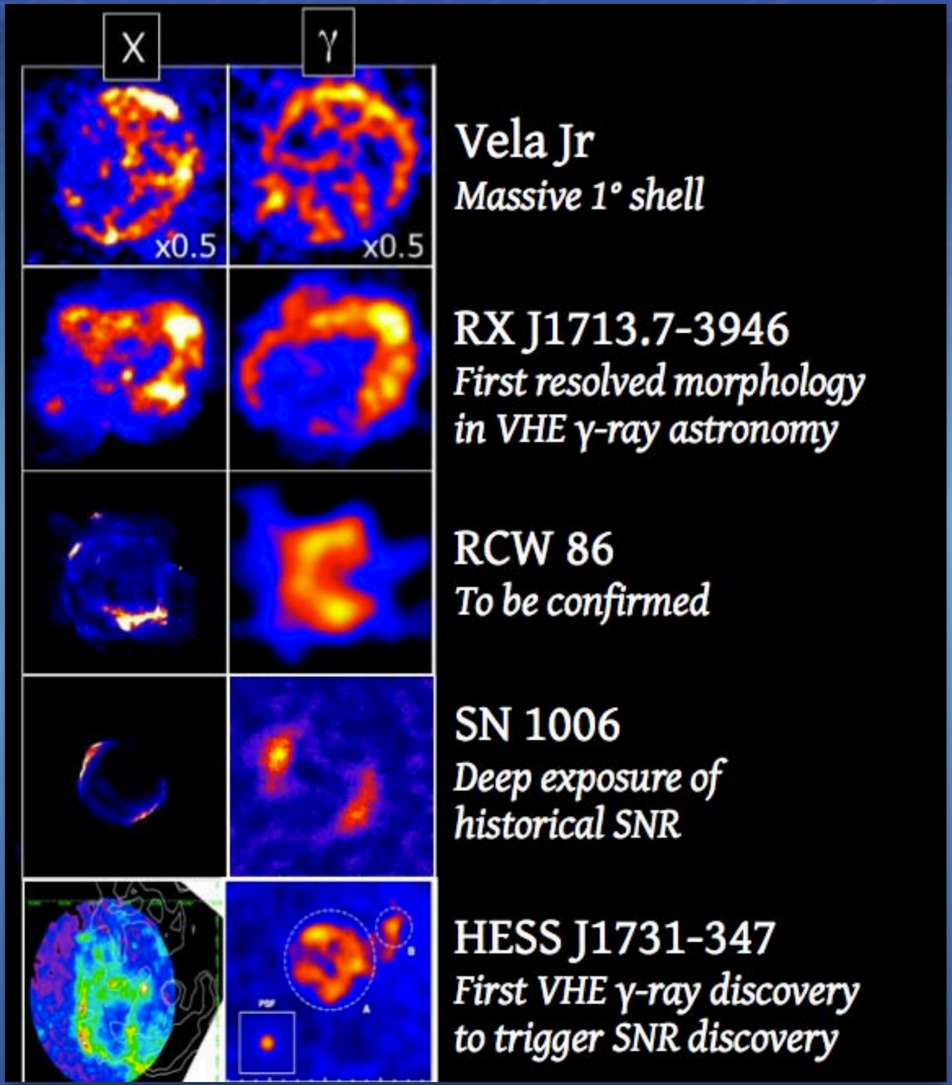



Galactic Discoveries in VHE γ-ray Astronomy
# of known Galactic VHE γ-ray sources
Discovery year
Crab Nebula
H.E.S.S. Galactic Plane Survey
0
20
40
60
80
100
120
1990
1993
1995
1998
2001
2004
2006
2009
2012
2015

Investigating Morphology

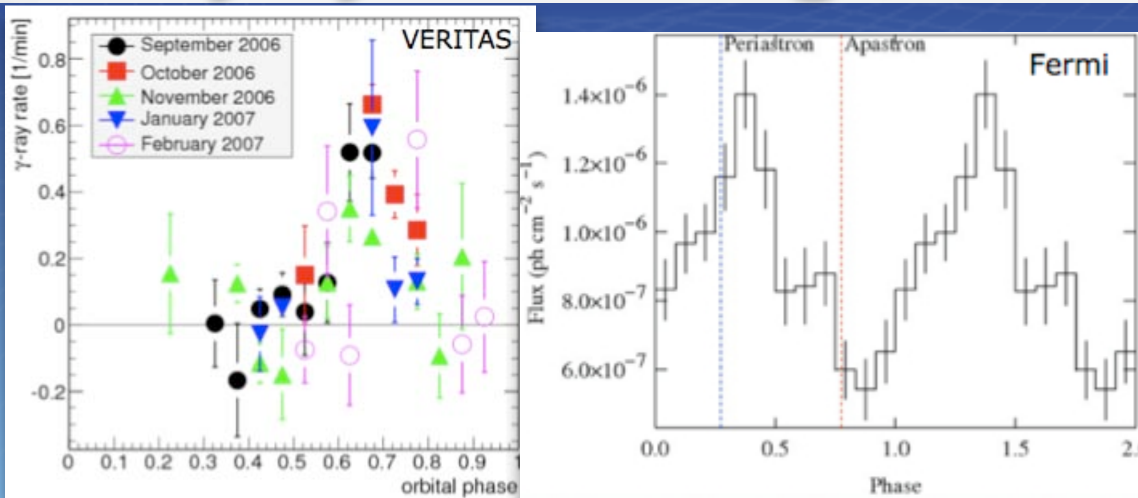
Eger, HESS galactic observations
Thu parallel

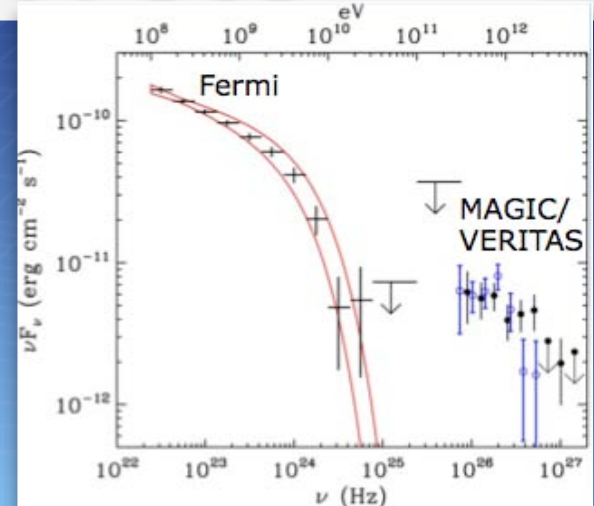




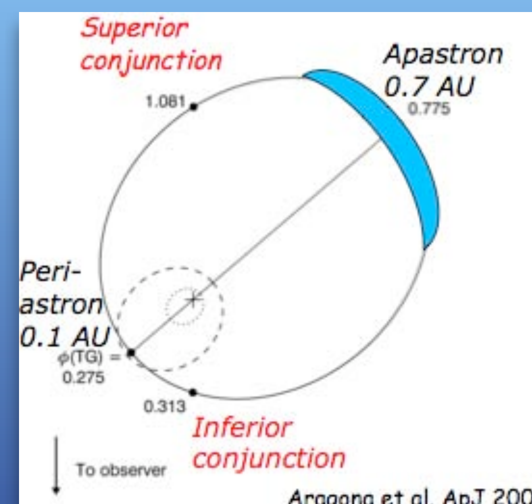
- In all cases, VHE gamma rays trace nonthermal X-rays

Binary Systems: e.g., LS I +61 303





- Compact object orbiting an B0Ve companion (12M☉)
- 26.5 day, inclined orbit, e=0.54, circumstellar disk
- Whipple upper limits only, detected by MAGIC, then VERITAS ($\Gamma=2.4\pm 0.16_{stat} \pm 0.2_{sys}$). **Strong emission only detected near apastron (ϕ=0.5-0.8)**
- Detected by Fermi-LAT (BSL)
  - Orbital modulation well measured. Emission peaks near periastron
  - Cut-off at 6 GeV observed between LAT and TeV (but not contemporaneous data)

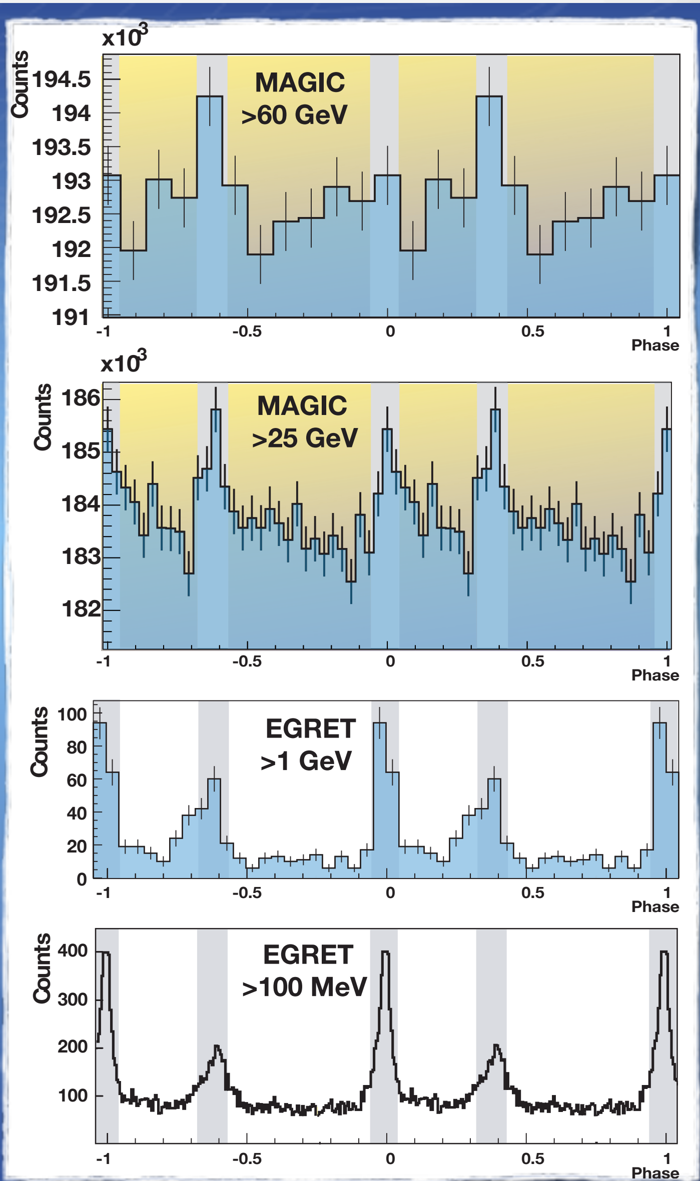


Crab pulsar

MAGIC Collaboration,
Science 322 (2008) 1221

Observations from October 2007 to February 2008

- Novel trigger system:
  threshold from 50-60 GeV down to **25 GeV**
- Observed about 8.5k pulsed γ-ray events
- clear **pulsed signal** at a 6.4 σ confidence level
- pulses in phase with EGRET



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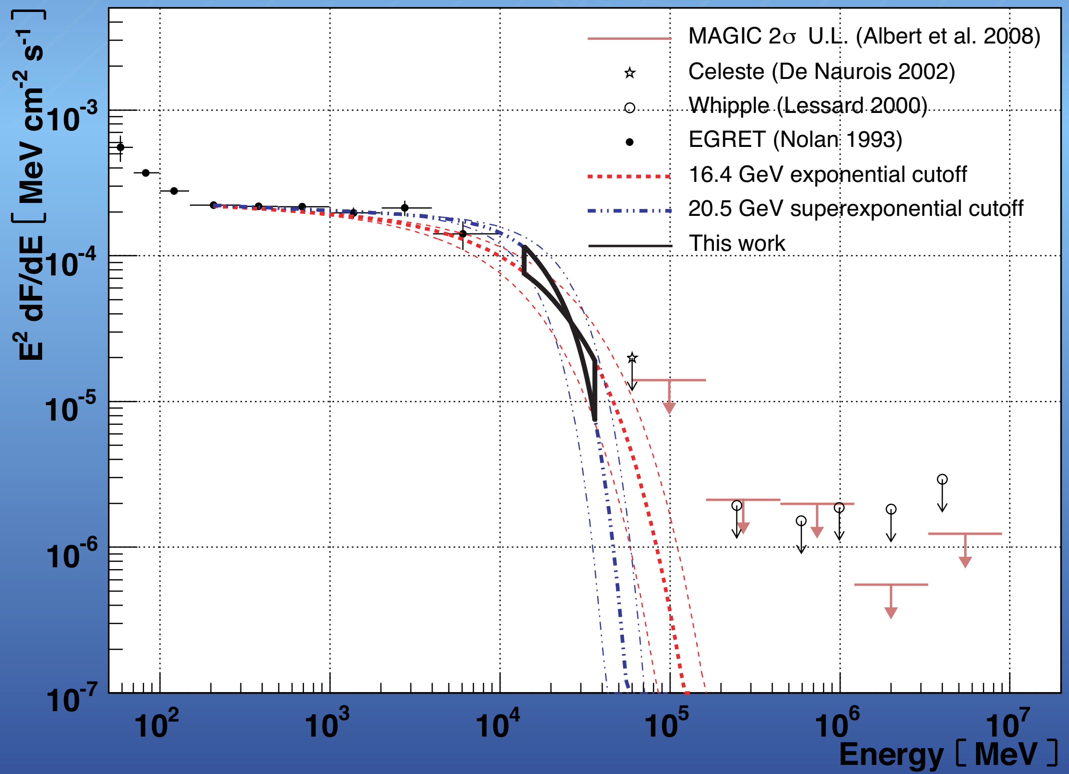

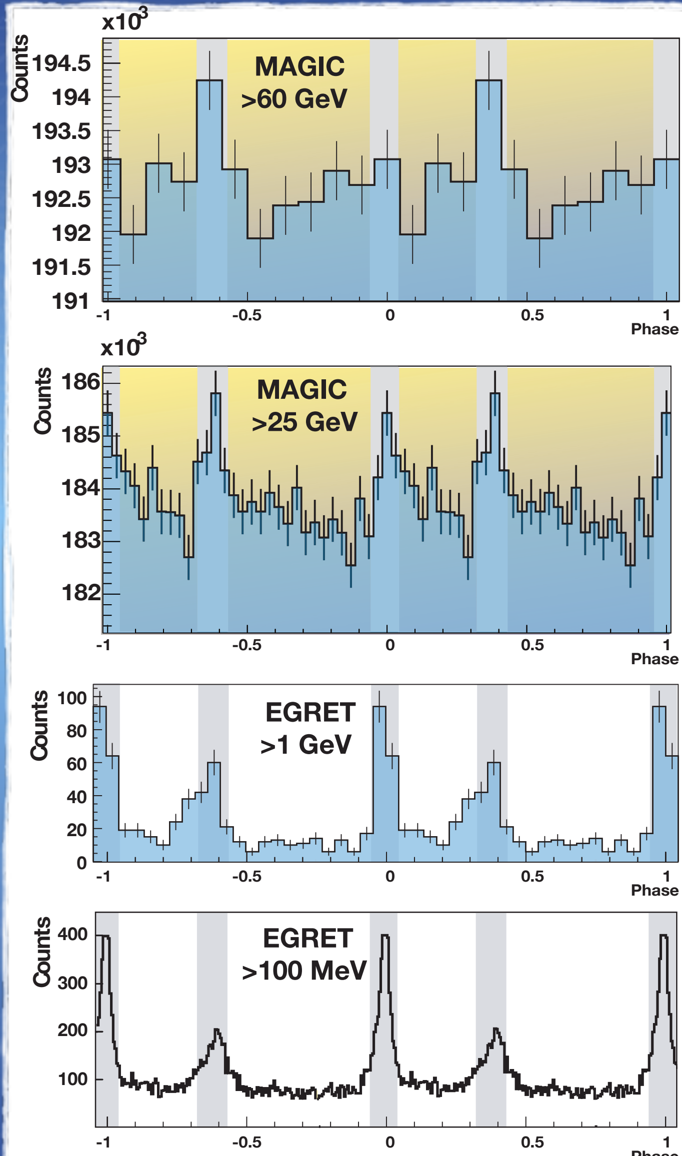

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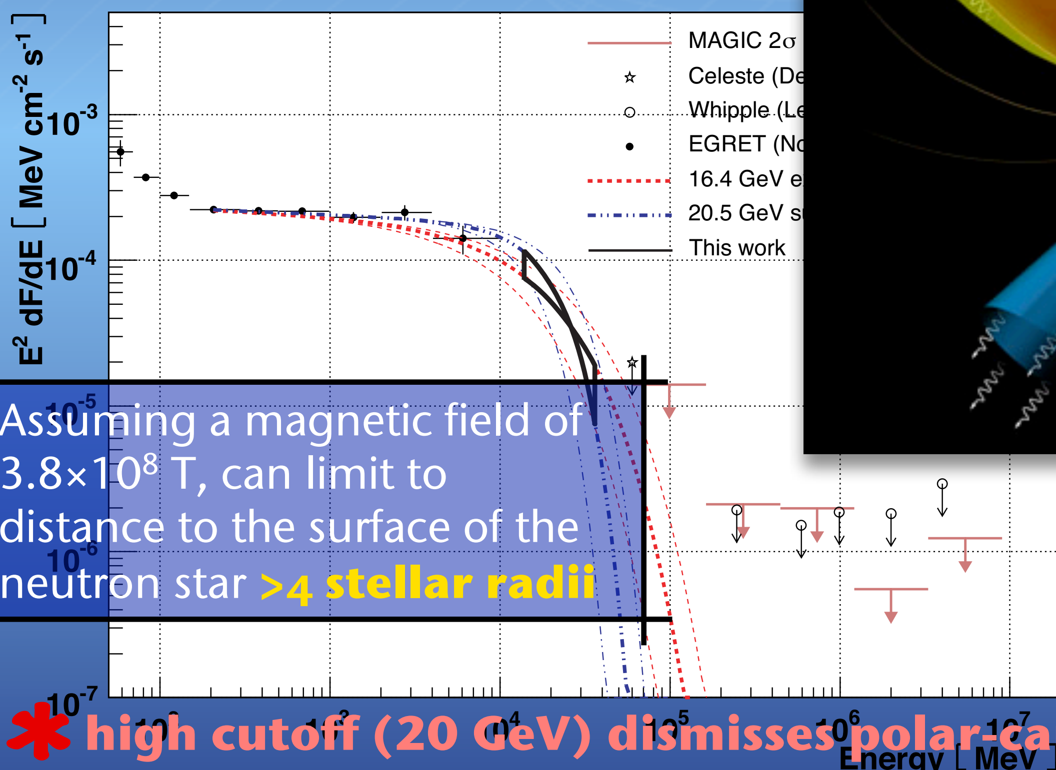
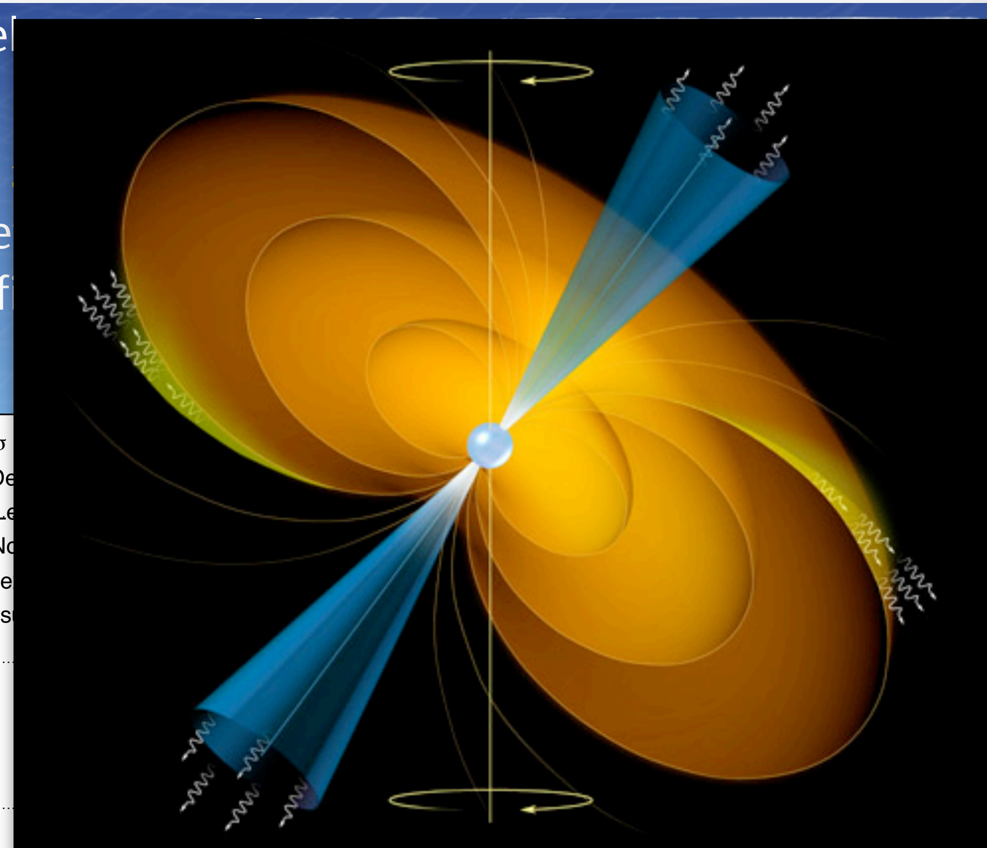
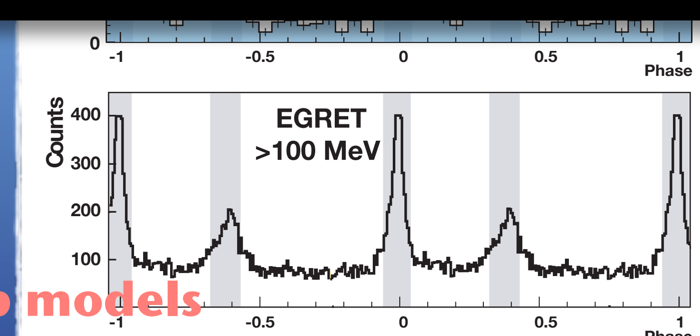


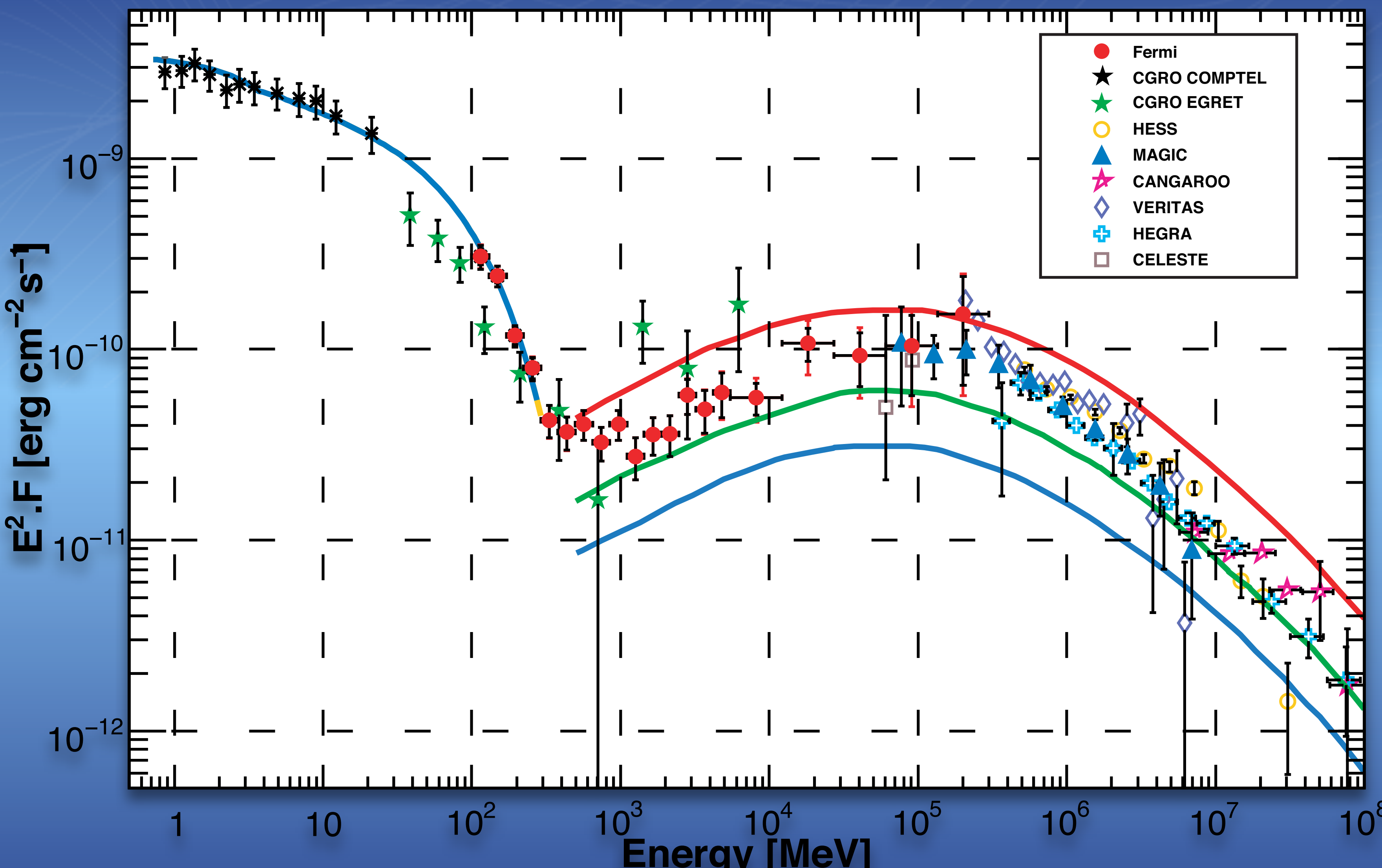




Assuming a magnetic field of 3.8×10^8 T, can limit to distance to the surface of the neutron star **>4 stellar radii**

✱ **high cutoff (20 GeV) dismisses polar-cap models**

DC Signal from the nebula 50-80 GeV



Extragalactic VHE Gamma-Ray Sources: Blazars and Radio Galaxies

AGNs & the Blazar Phenomenon

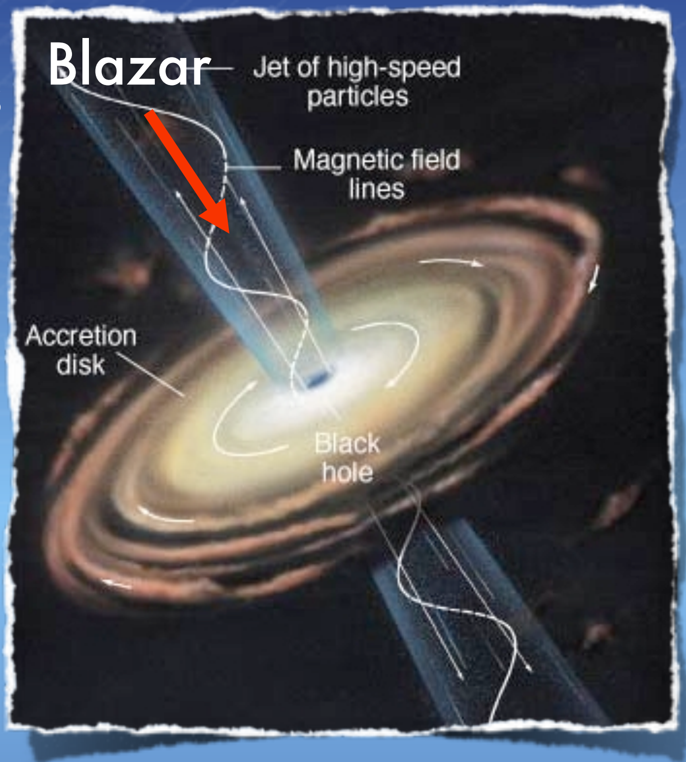
Urry+Padovani 95

- Small fraction of observed galaxies are “active”
- Supermassive black holes of $10^6 - 10^{10}$ solar masses
- Rotating accretion disk
- Emission of collimated, relativistic jets

Blazars:

- Factories of violent, broad-band (up to very-high energy) non-thermal radiation
- **Jets viewed under small angle**
- Relativistic boosting, high Doppler factors
- Acceleration of relativistic “blobs” or in shocks
- **High variability** at all wavelengths

Radio galaxies: “Misaligned blazars”? Other mechanisms?



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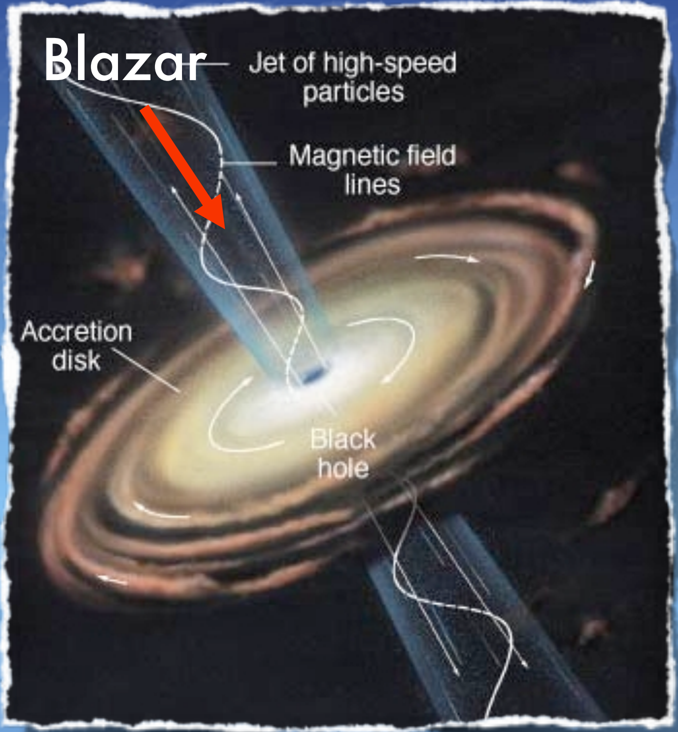
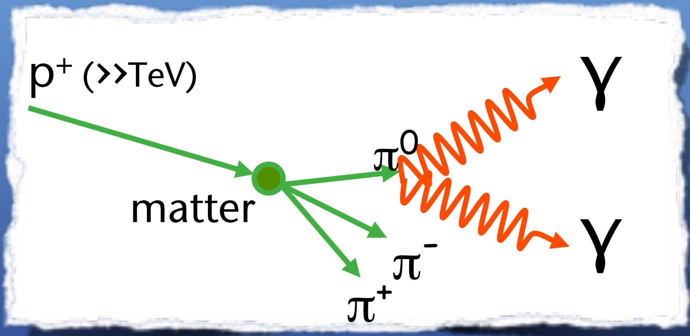
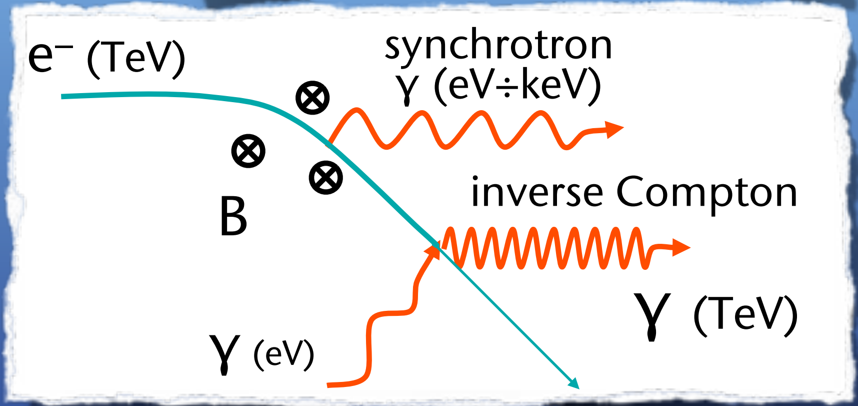




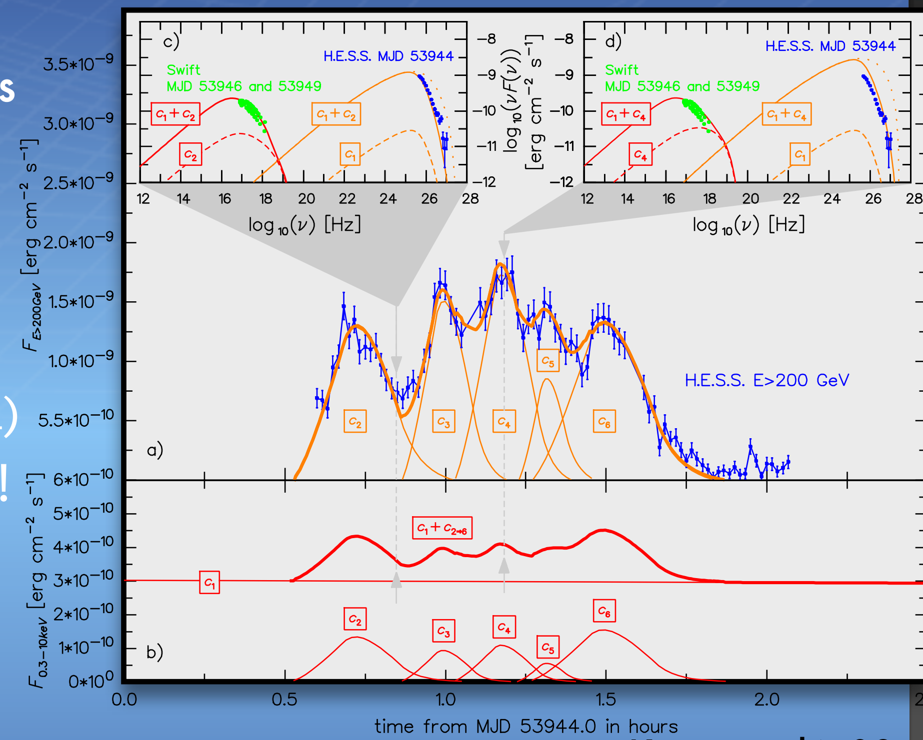


Particle Acceleration in Blazars

How can TeV observations help? γ-rays are **crucial messengers:**

➡Dynamics of emission regions in the jets
➡Study acceleration & energy loss timescales
➡Decide: leptonic vs hadronic acceleration?

- leptonic models favored:
  - X-ray/TeV correlation found in some blazars (Mkn 421, Mkn 501, PKS 2155-304)
  - Fast flaring: down to minutes!
    e.g., PKS 2155-304 flare 2006

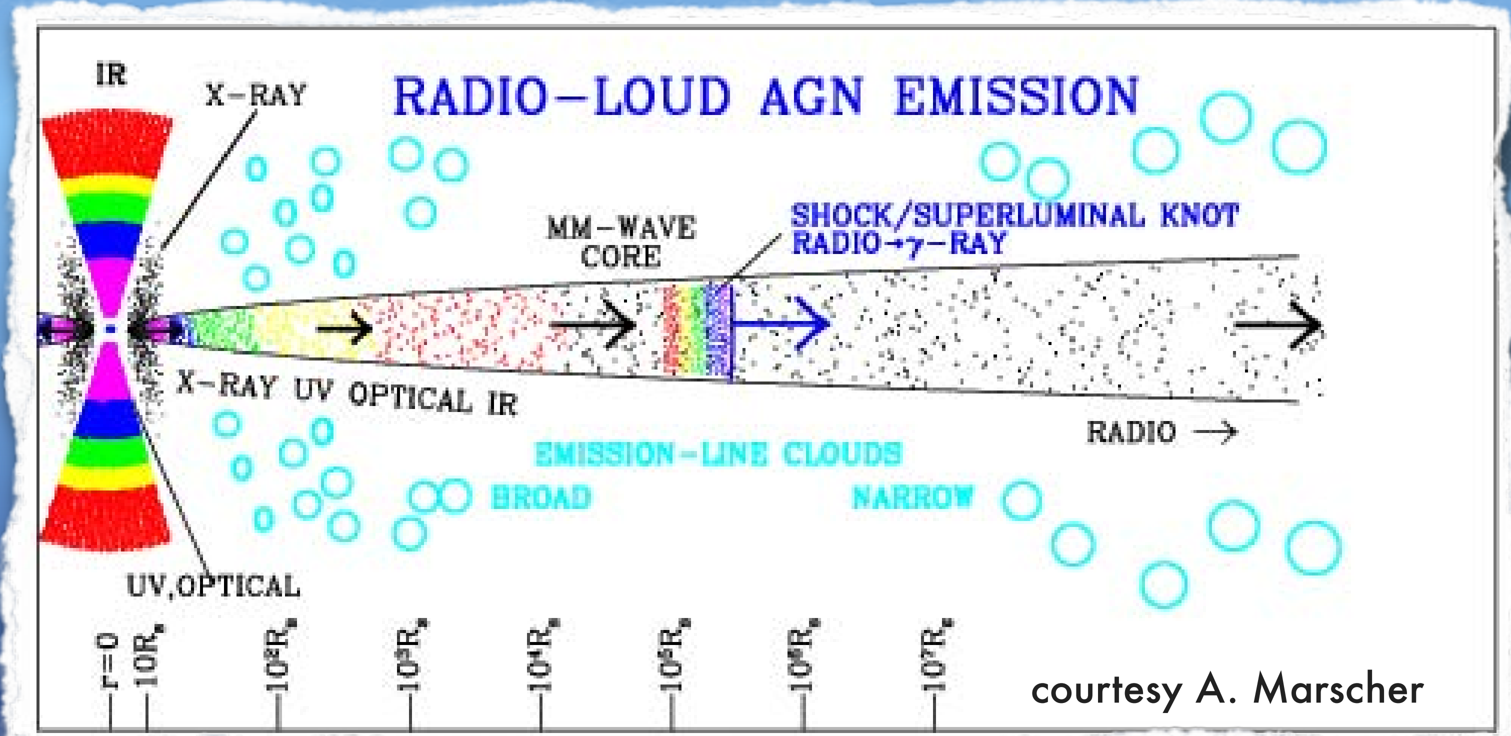


Katarzynski+08

- Hadronic models challenged by observed X/VHE correlations and by very rapid γ-ray variability
- Variability needs to be explained: Matter crossing the jet? sub-shocks? ...jet structure
- Shape of spectrum, multiwavelength observations

Particle Acceleration in Blazars

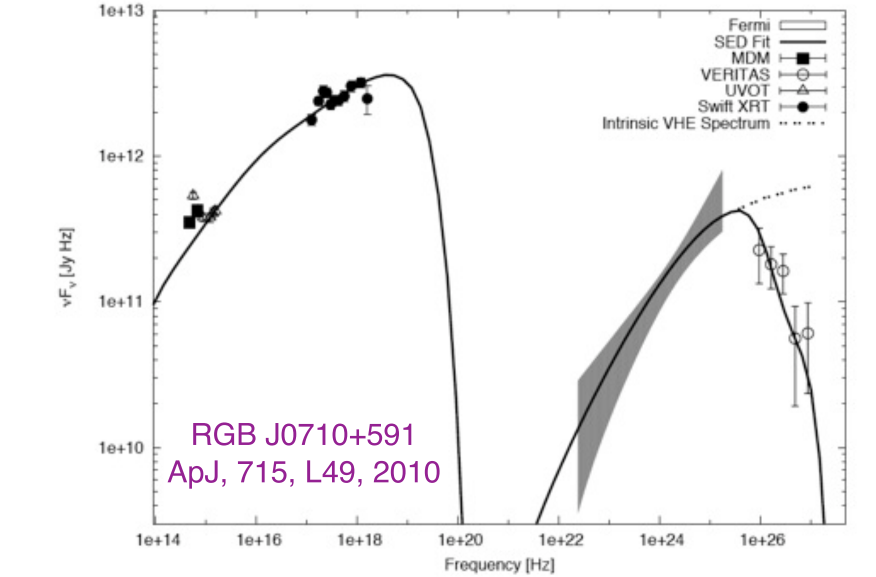
- **We still do not know:**
  - Variability time scales?
  - Other correlations (optical, radio)?
    successful MAGIC ToOs! E.g., Lindfors+08
    TeV/radio in M78, VERITAS-MAGIC-HESS 09
  - Exact location of the blazar engine
- **Open questions:**
  - Spatial origin of γ-rays?
  - Physical conditions in the jet?
  - Reason for the variability?

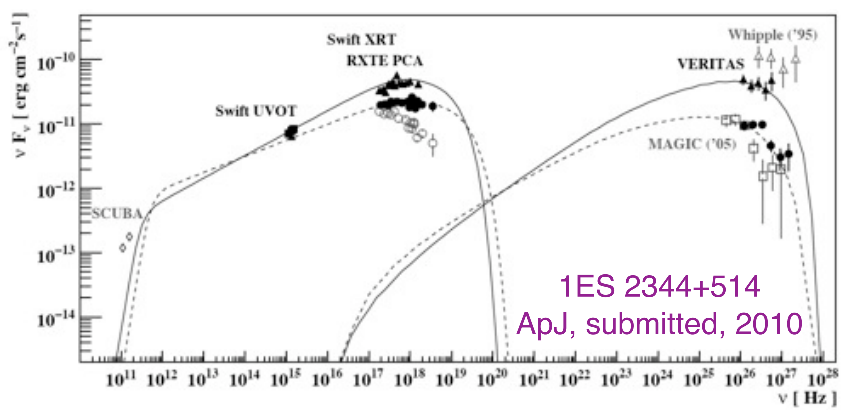


courtesy A. Marscher

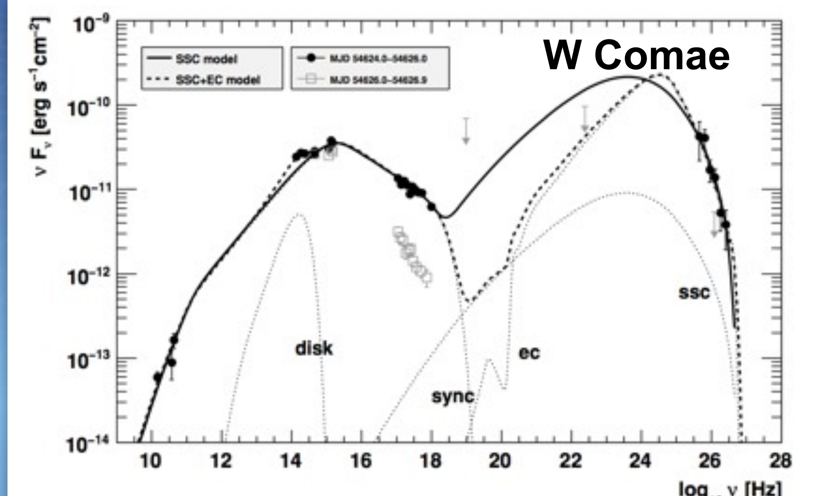
Blazar Highlights: SED Modeling

- SSC appears to work for HBLs incl. flare states.

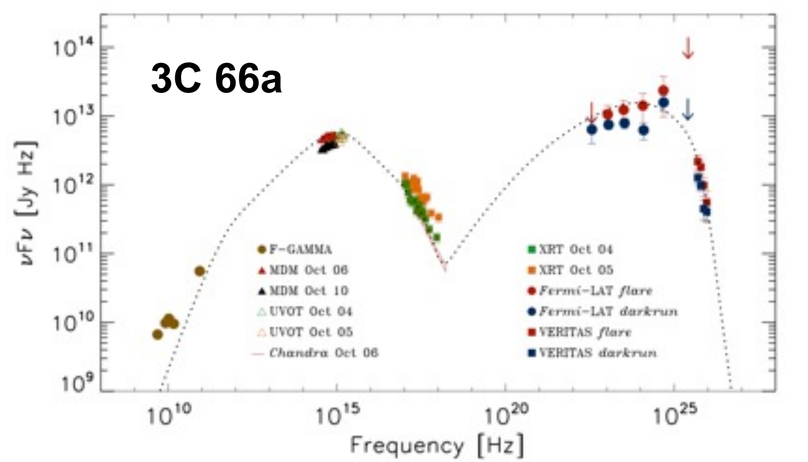




- IBLs 3C 66a and W Comae need SSC + EC components.



ApJL 684, 73, (2008) ApJ 707, 612 (2009)

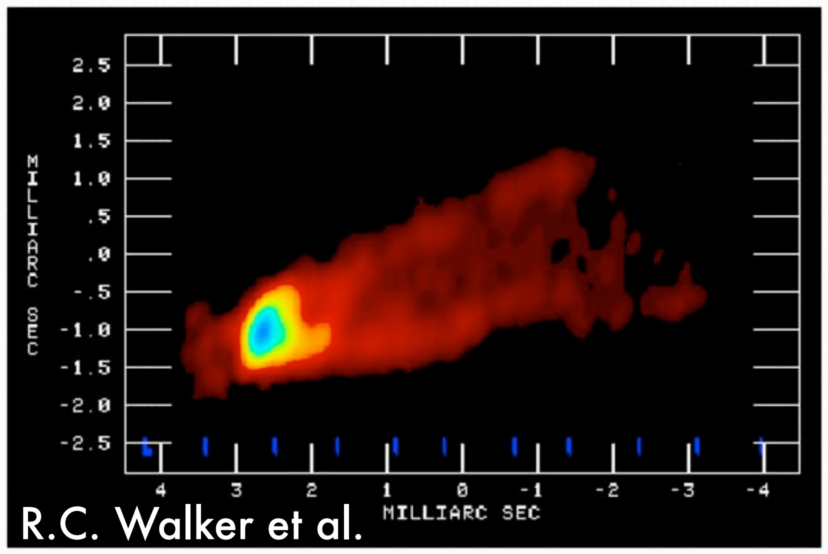


ApJL 693, 104, (2009) ApJ submitted (2010)

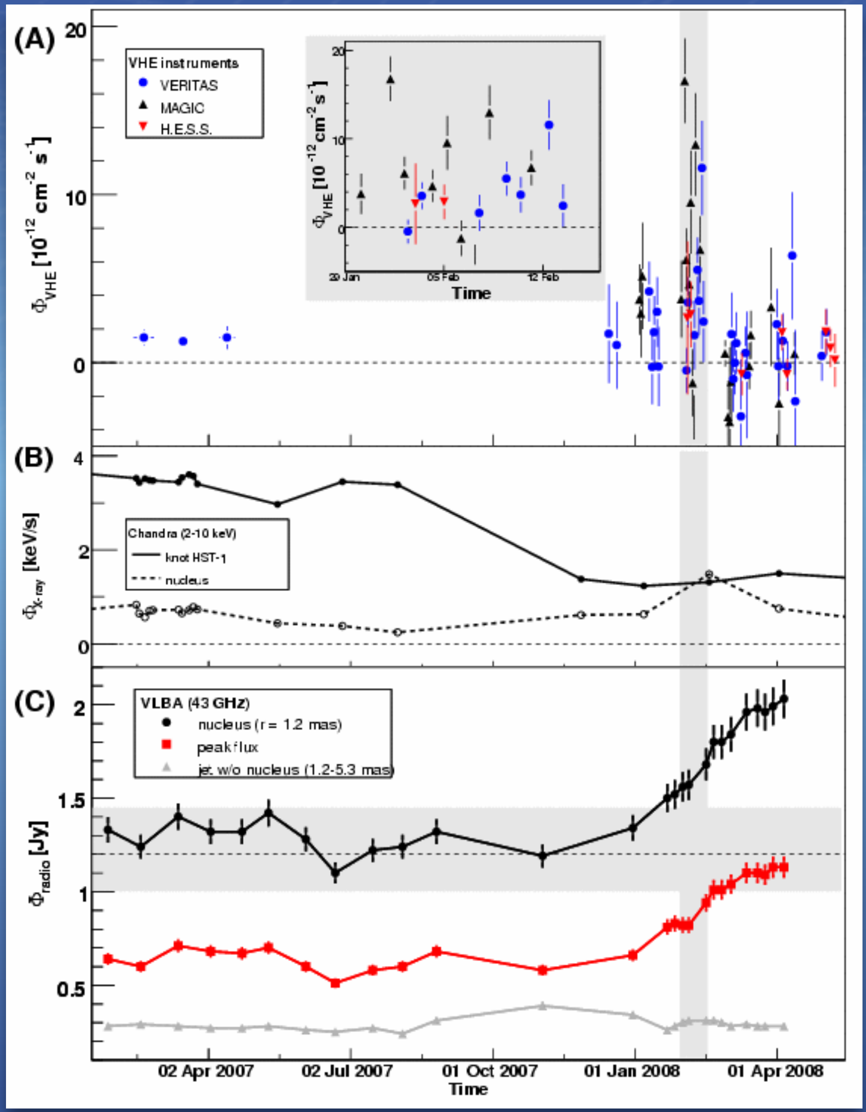
VHE/Radio Collaboration Reveals...

Science 325 (2009) 444

- VLBA Monitoring of the M87 jet at 43 GHz (2007/8), Walker et al.
- Resolution: 0.43x0.21 mas
  100 Schwarzschild radii
  = 0.37 mas (1 mas = 0.078 pc)

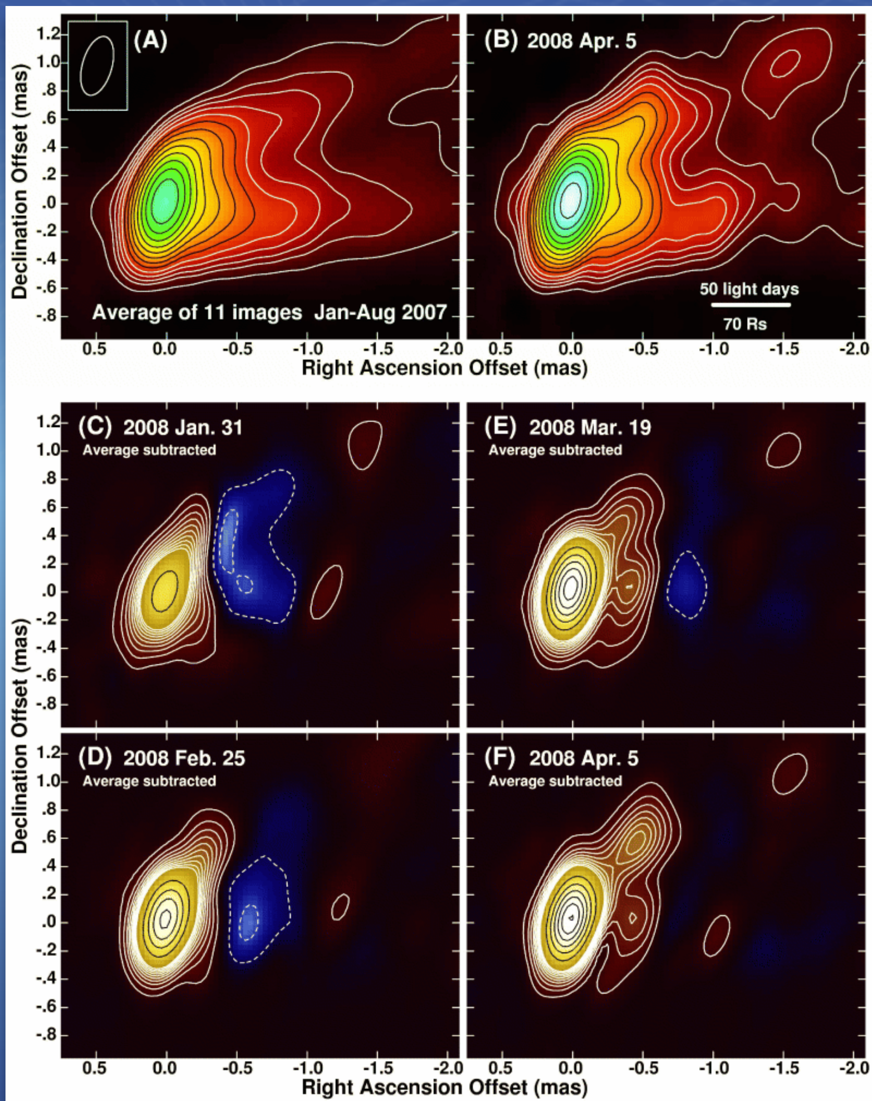


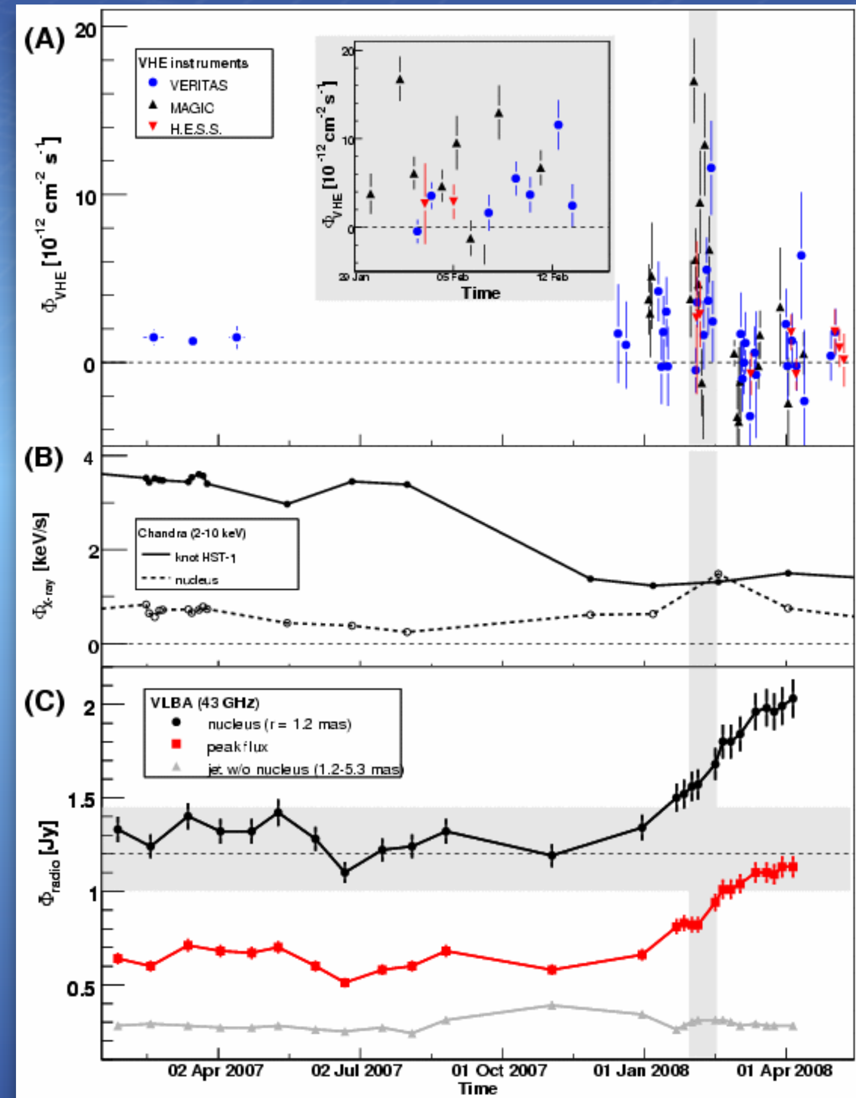
- Jet formation @ 30 x 60 R_S
- VHE flare accompanied by radio flare from BH vicinity



VHE/Radio Collaboration Reveals...

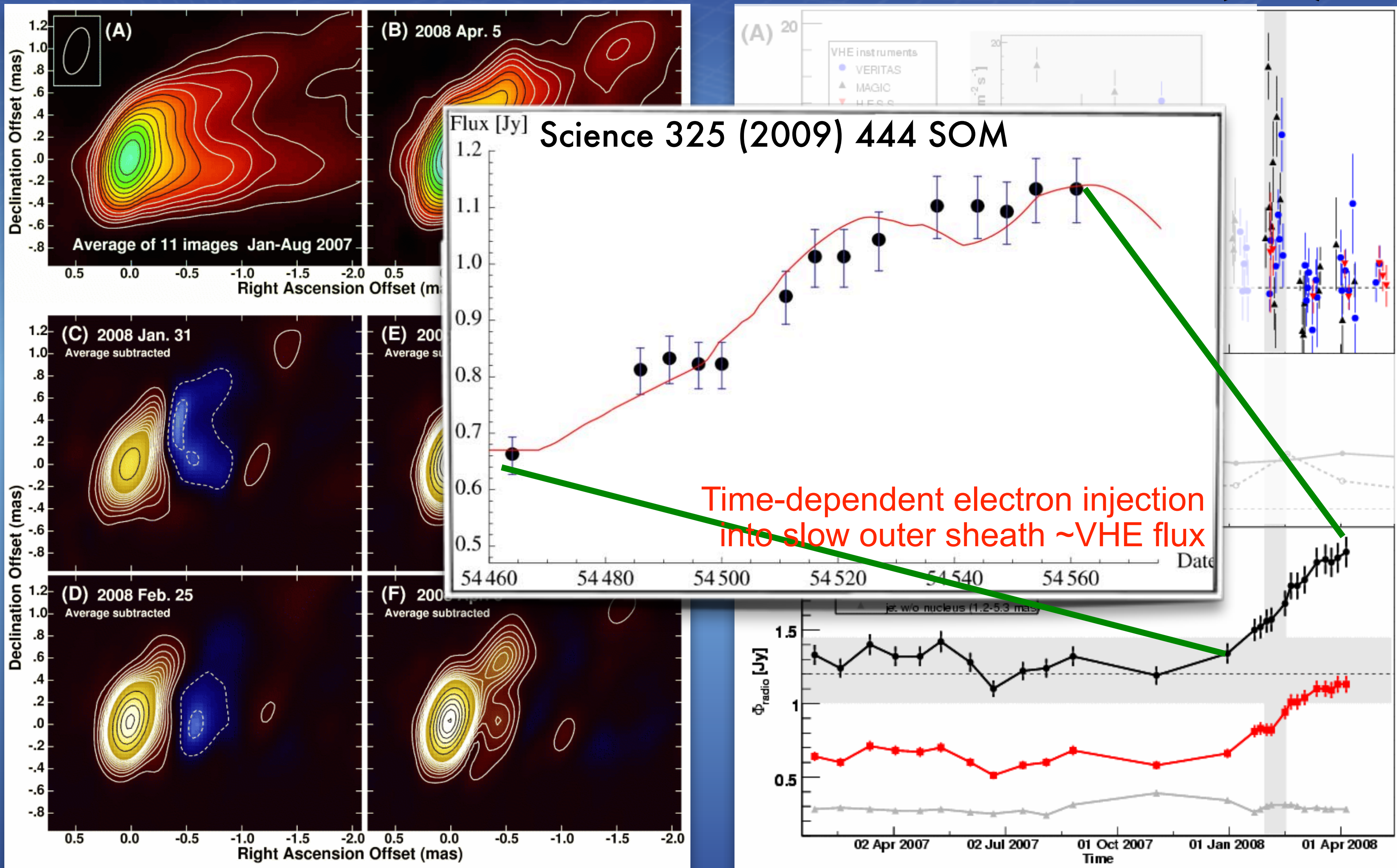
Science 325 (2009) 444





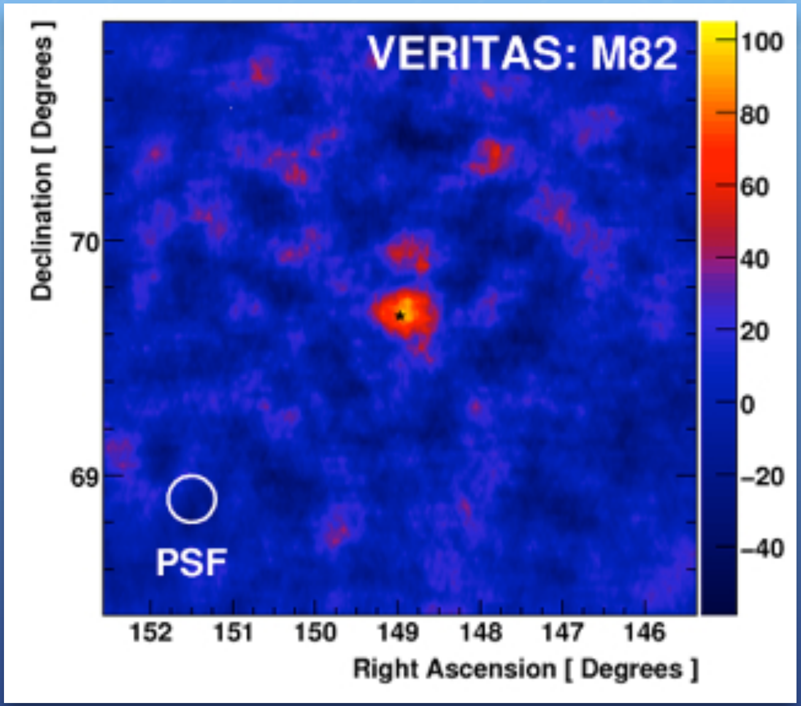
VHE/Radio Collaboration Reveals...

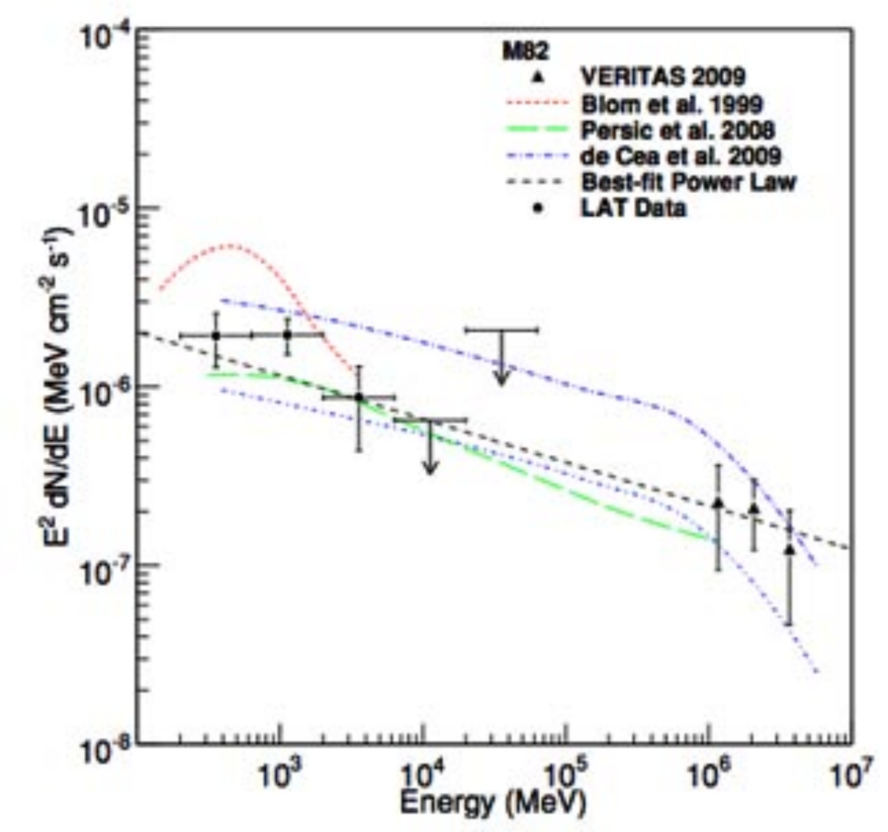
Science 325 (2009) 444



Starburst Galaxies NGC 253 & M82

- a new TeV source class
  - Gamma rays expected from interaction of cosmic rays and interstellar gas and radiation.
  - e.g. M82: TeV emission level close to predictions (model of Persic et al., 2008)
  - CR density: 250 eV cm^{-3}; ~500 x that of Milky Way
  - Both NGC 253 (HESS) and M82 detected by Fermi LAT.





Abdo et al., ApJ 709, L152 (2010)

Very Distant Sources

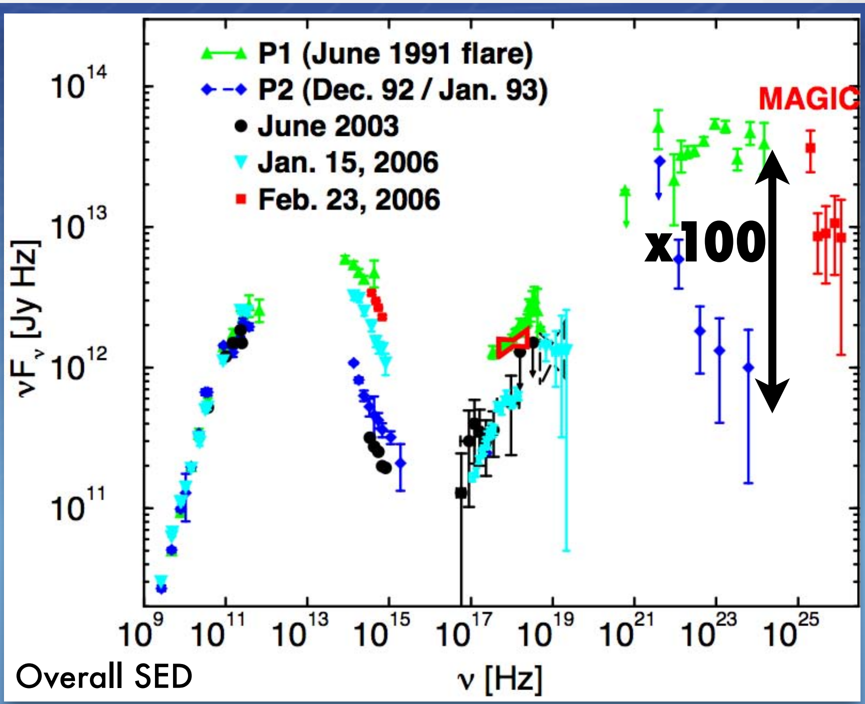
3C 279, PKS 1222+21

Background image: 3C 279 EGRET Skymap

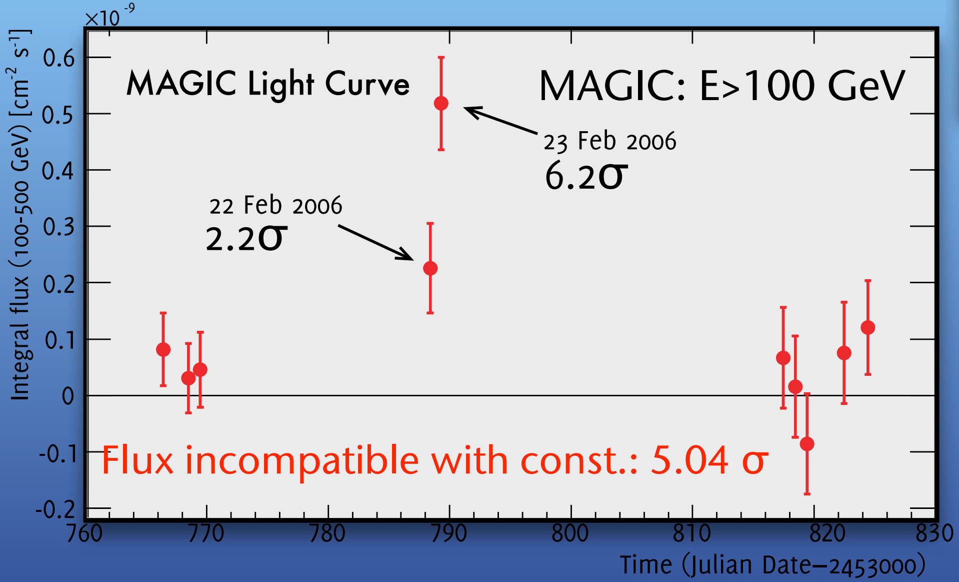
3C 279: Famous EGRET Blazar

Teshima, RMW et al. 2007 (ICRC07)
MAGIC Coll., Science 320 (2008) 1752

- Flat Spectrum Radio Quasar at z=0.536
- Apparent luminosity ≈ 10^{48} erg/s
- Gamma-ray flares in 1991 and 1996: High dynamical range in EGRET data
- Fast time variation: ΔT ~ 6hr in 1996 flare

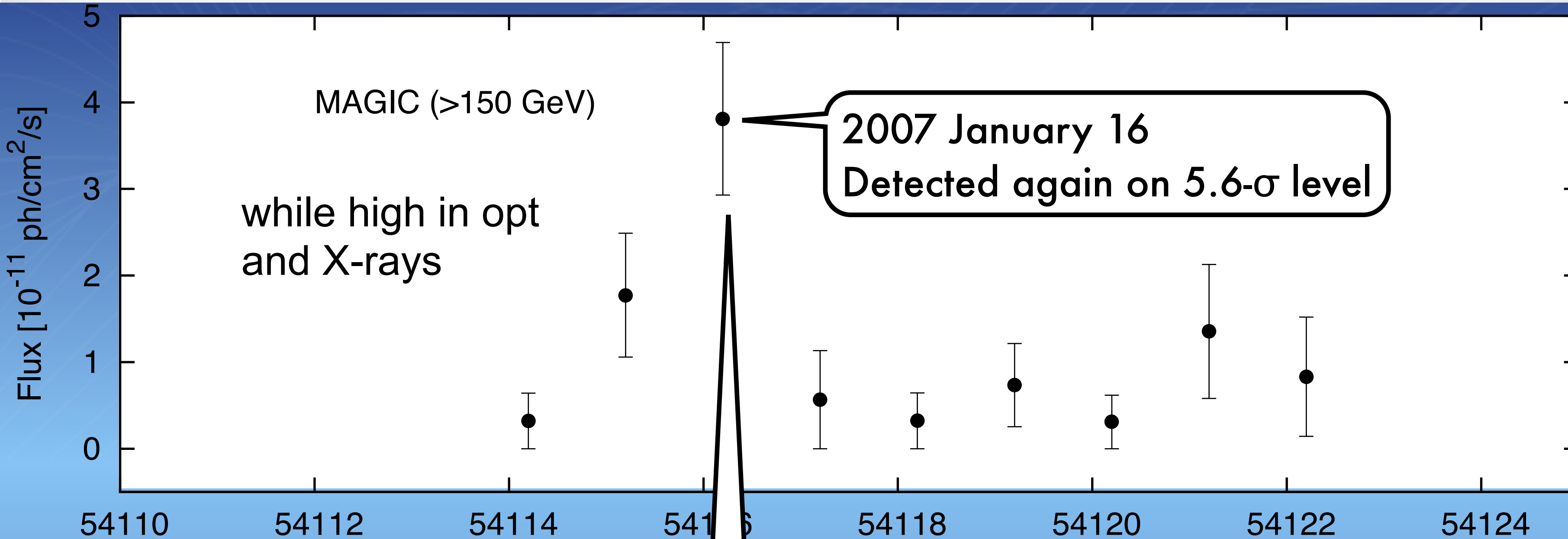


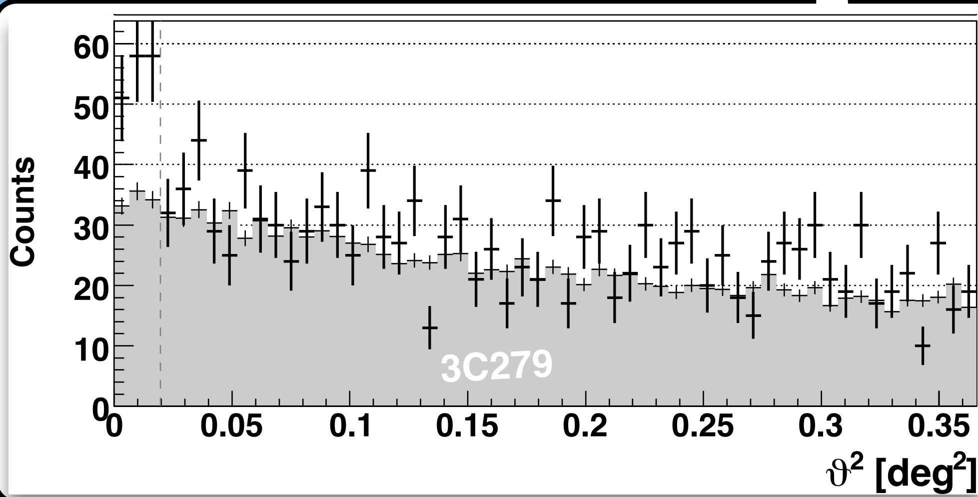
- z=0.536! Major jump in redshift
- First FSRQ in TeV gamma-rays:
- **Can be used to constrain Extragalactic Background Light models**

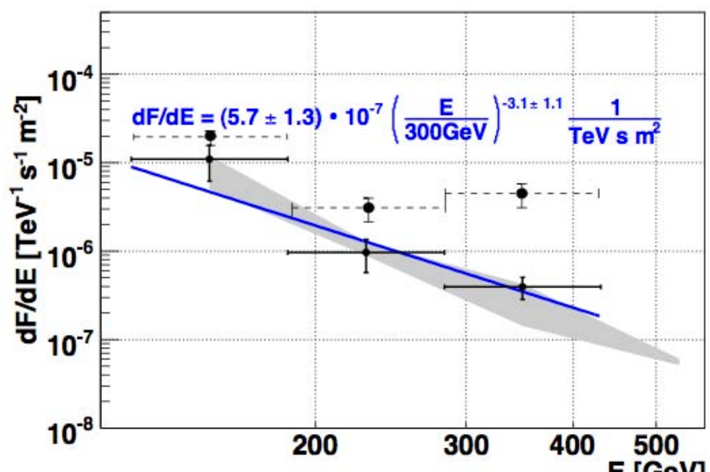


3C 279: Re-detected in 2007

MAGIC Collab.
A&A 2011

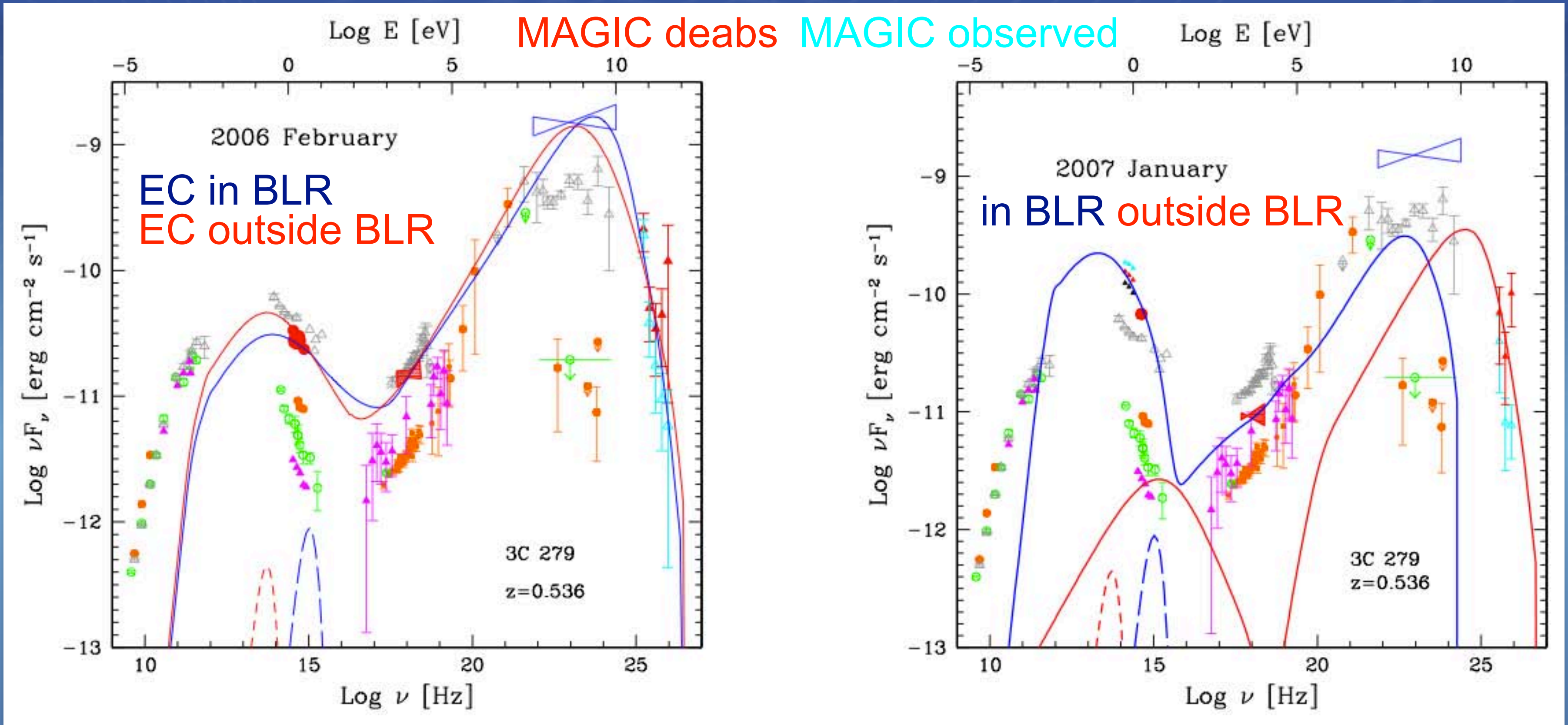






3C 279: SEDs 2006 / 2007

MAGIC Collab.
A&A 2011

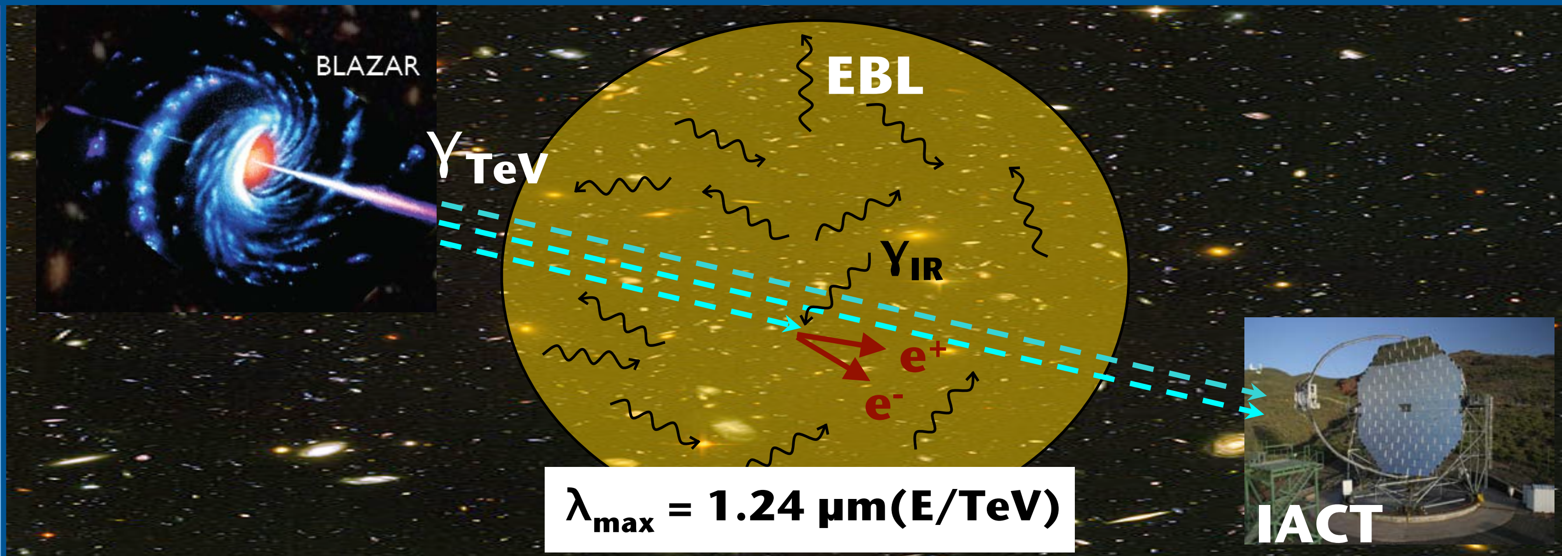


One-zone model hardly works
EC/BLR and EC/IR do

Two-zone: VHE outside BLR,
minimizes gamma absorption

Likely different mechanisms for 2006 and 2007 flare

AGN Emission Passes Through EBL



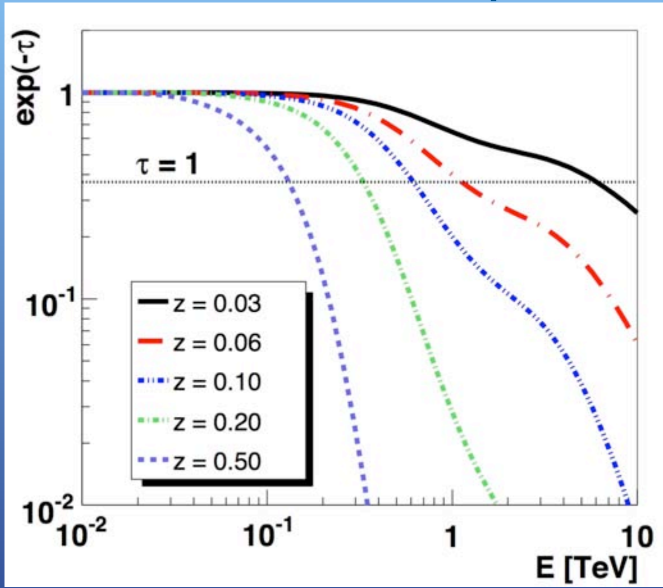
- Absorbs γ-rays by pair production:

$$\gamma + \gamma \rightarrow e^+ + e^-$$

- Imprint of the EBL density and shape in the measured GeV-TeV spectra
- Cross-section peaks sharply:

  $E_{CM} \approx 1.8 \times (2m_e c^2) \Leftrightarrow \lambda_{max} = 1.24\ \mu m(E/TeV)$

- GeV-TeV spectra can be used to test EBL density under certain assumptions about the intrinsic spectra

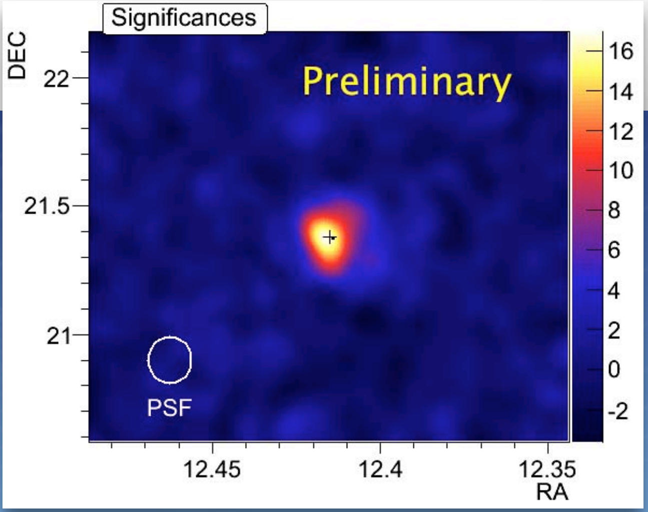


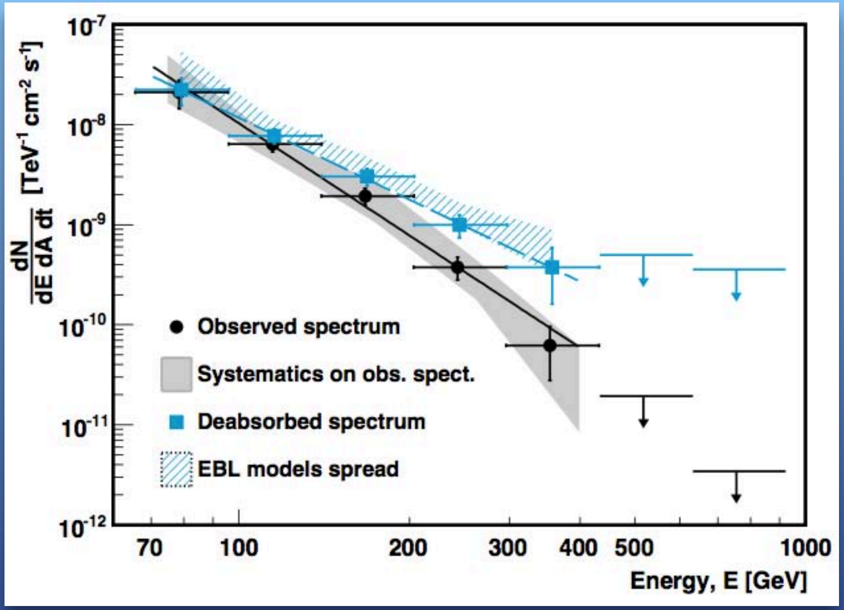
4C +21.35 aka PKS 1222+21

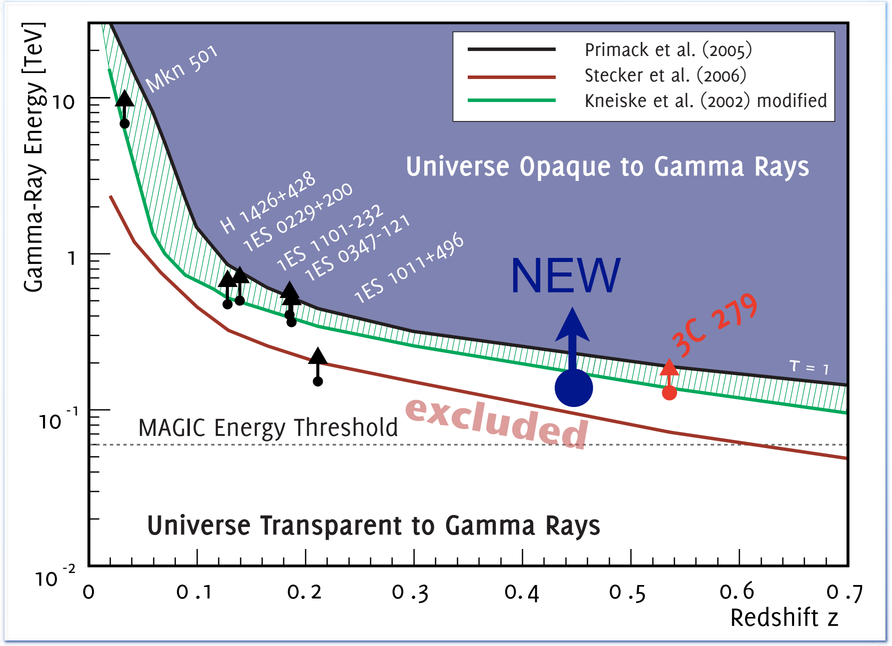
- 2010 June 17, flare state
- PKS 1222+21 (4C +21.35) is a high redshift (z=0.43) FSRQ

  (only 3C279, PKS1510-089 so far)
- Observations triggered by a high state reported by Fermi-LAT
- Can be used for EBL studies

MAGIC Coll., A&A subm.







Science 320 (2008) 1752

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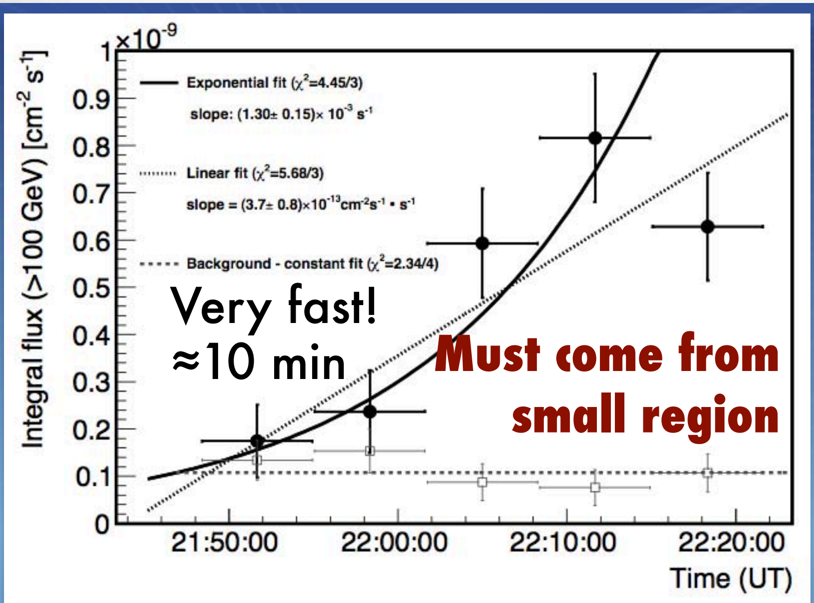

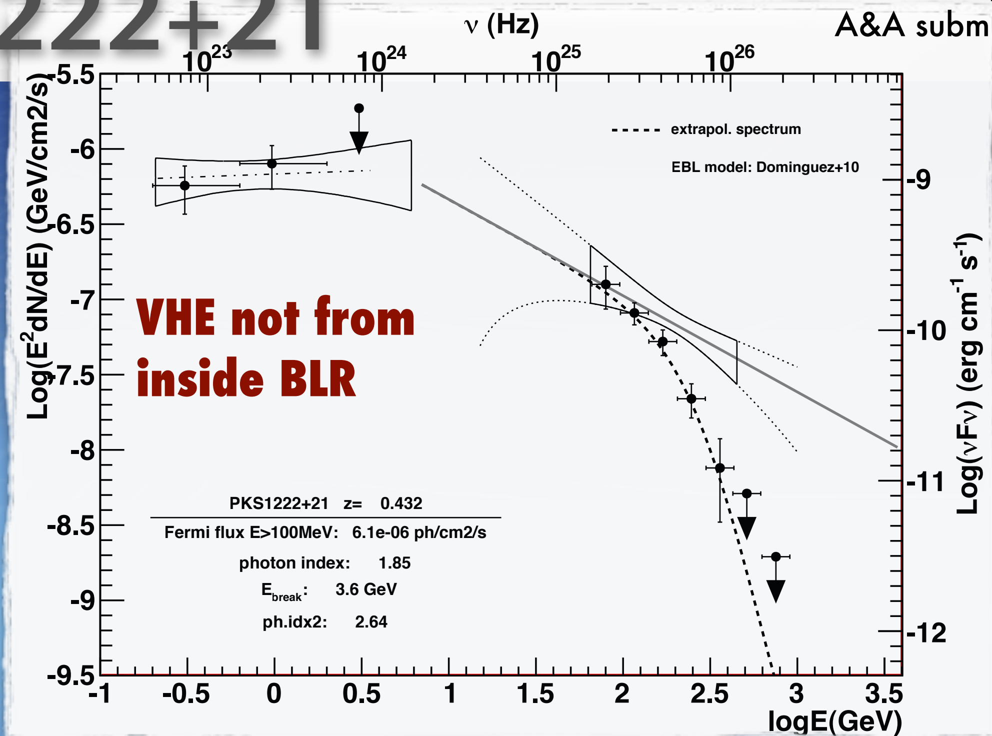

- **A strong signal of 8.7 σ significance in just 0.5h of observations!**
  - → allows short-term variability studies
- Preliminary analysis shows a flux ≥30% of the Crab Nebula flux
- Also detected by *Fermi*-LAT in 100-300 GeV energy range

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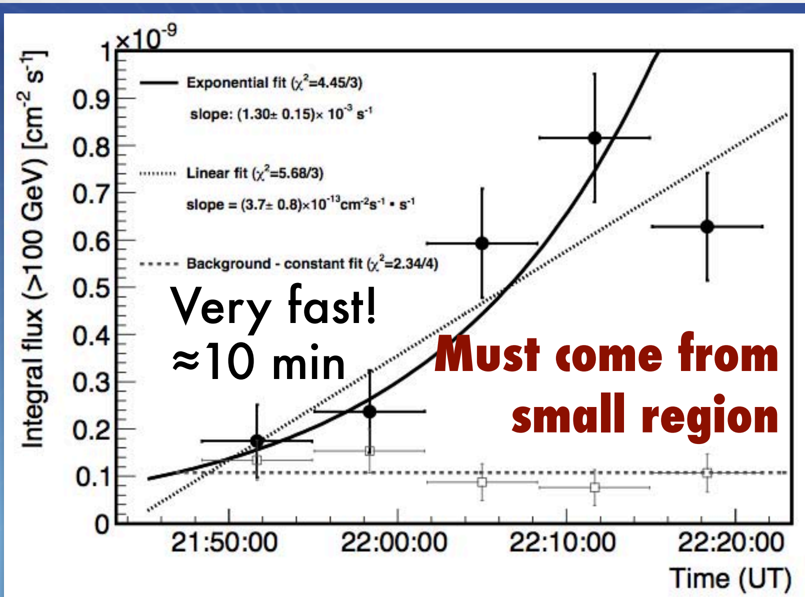

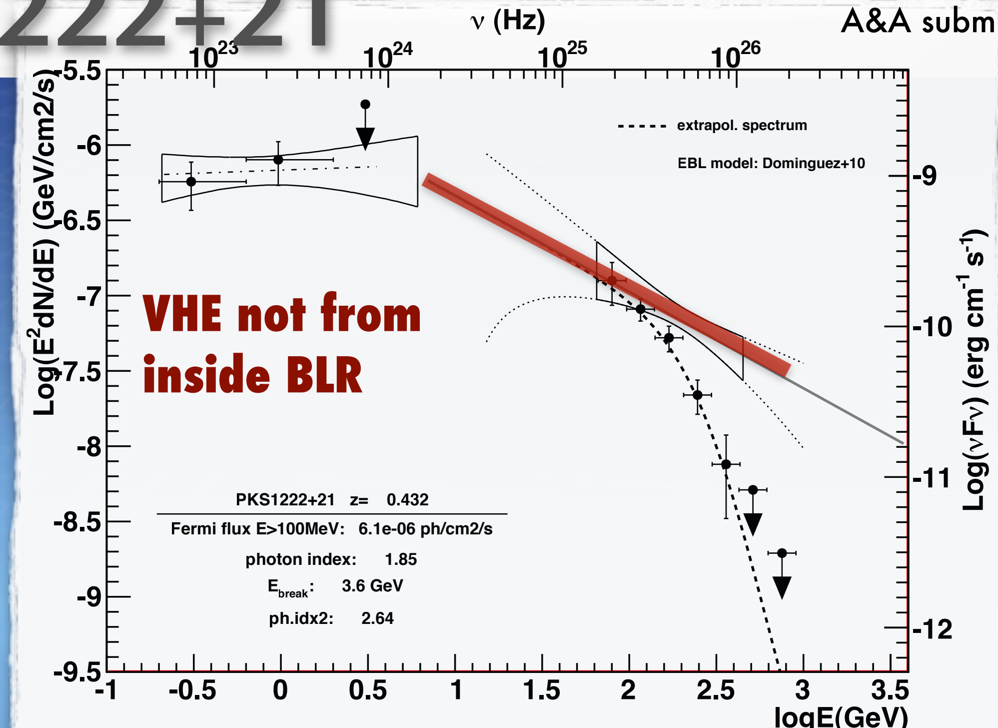

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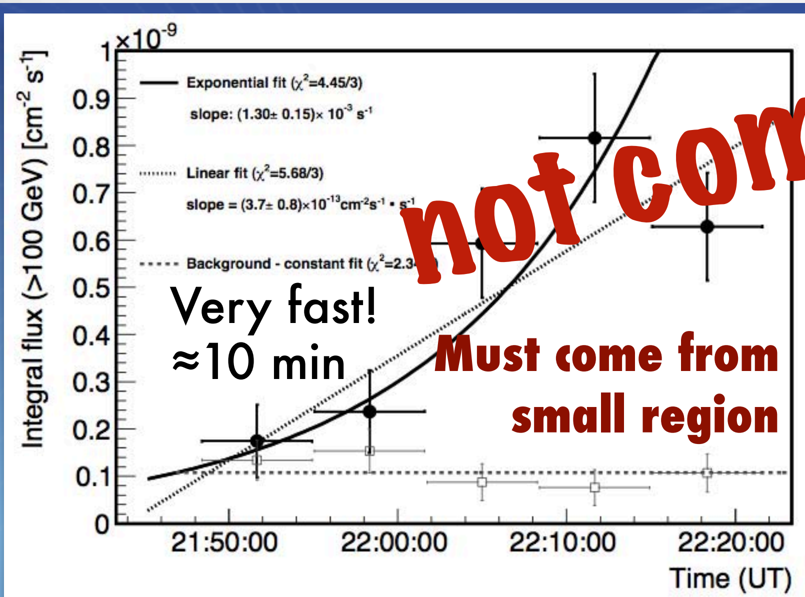

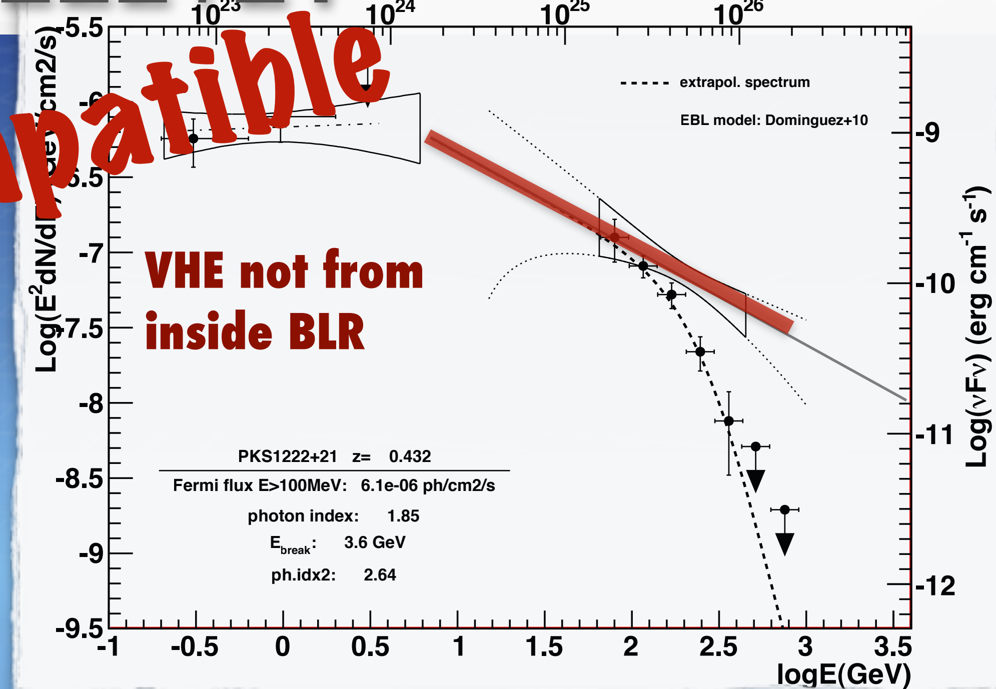

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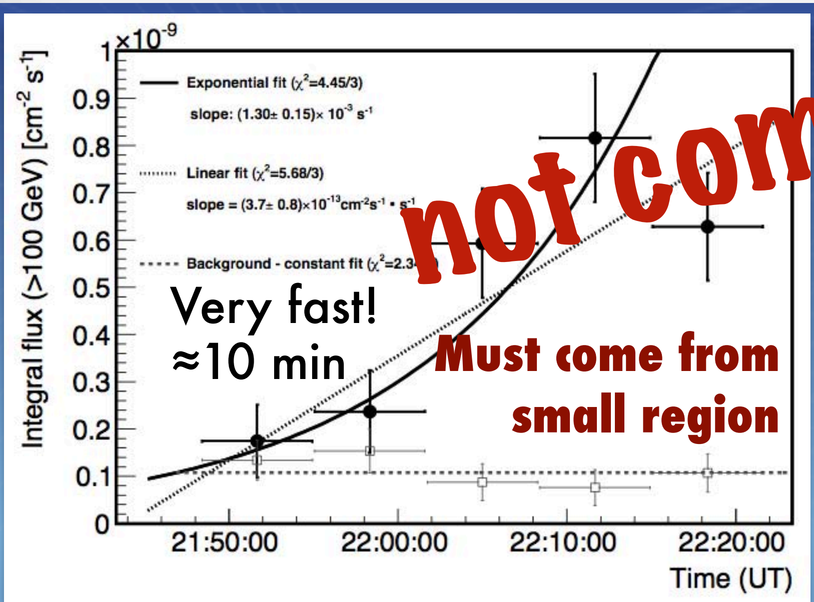

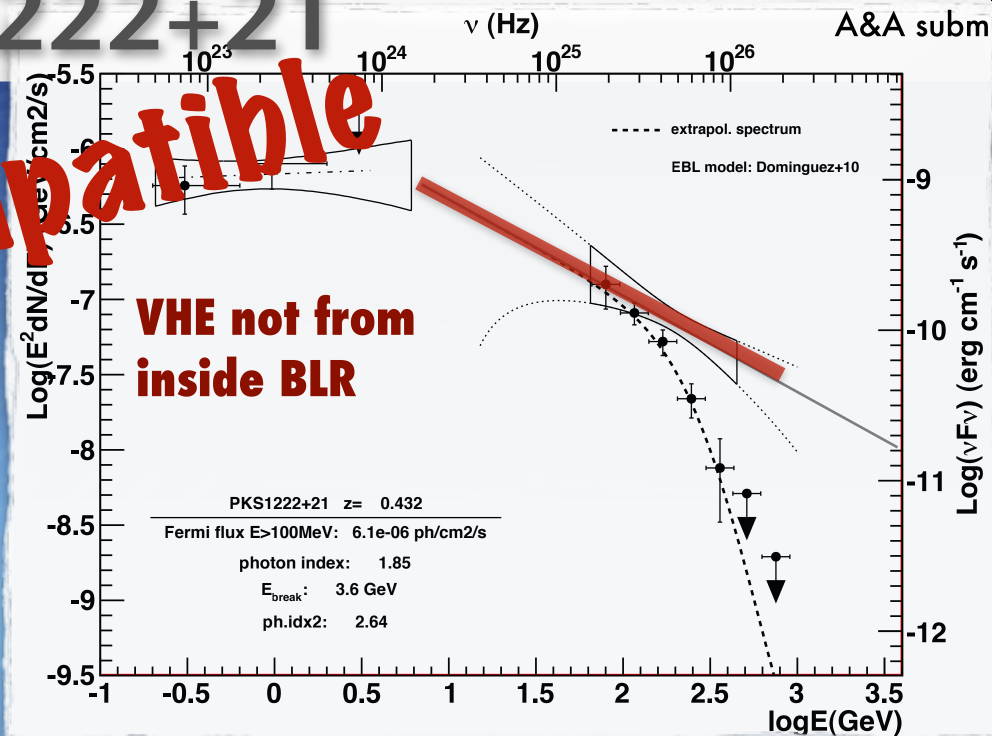

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Possible solutions:

- Strong recollimation of the jet
  e.g. Nalewajko&Sikora 2009
  Bromberg & Levinson 2009
- "Needles" or "minijets" inside of the jet. Already proposed for PKS 2149-306 e.g. Ghisellini et al. 2008, 2009, Giannios et al 2009, Nalewajko et al. 2010, Marscher &Jorstad 2010

Gamma Astronomy at this meeting

- Aharonian, coming up next
- Ragan, VERITAS status, Thu plenary
- Vernetto, ARGO-YBJ, Thu plenary
- Doro, MAGIC stereo system, Thu parallel
- Beilicke, VERITAS galactic center, Thu parallel
- Eger, HESS galactic observations, Thu parallel
- Antonelli, CTA, Fri plenary
- DeYoung, HAWC, Fri plenary

Summary

Today

★ Consolidation of Cerenkov telescopes as astronomical instruments
→ transition from "VHE experiments" to "telescopic installations"

★ Big observational step in the last few years:

- quantitatively – >10 x number of detected sources, now > 100
- *qualitatively* – unprecedented detailed studies in
  Spectra, Morphology, Time Variability

- Stereoscopic systems (MAGIC with low energy capabilities and 28m HESS-2 coming up) extremely successful
- ***closed the energy gap between predecessor-generation of IACT and EGRET/Fermi between 30 GeV and 300 GeV***
  overlap with satellite detector Fermi-LAT; Crab pulsar detected
- Use ground-based telescopes to study:
  Nature and mechanism of particle acceleration and gamma-ray production in galactic and extragalactic objects
- Showed recent (extremely) selected results
- Importance of MWL, skipped GRB results, MMSG efforts
- Keep an eye on IACT and CTA, exciting times pertain.