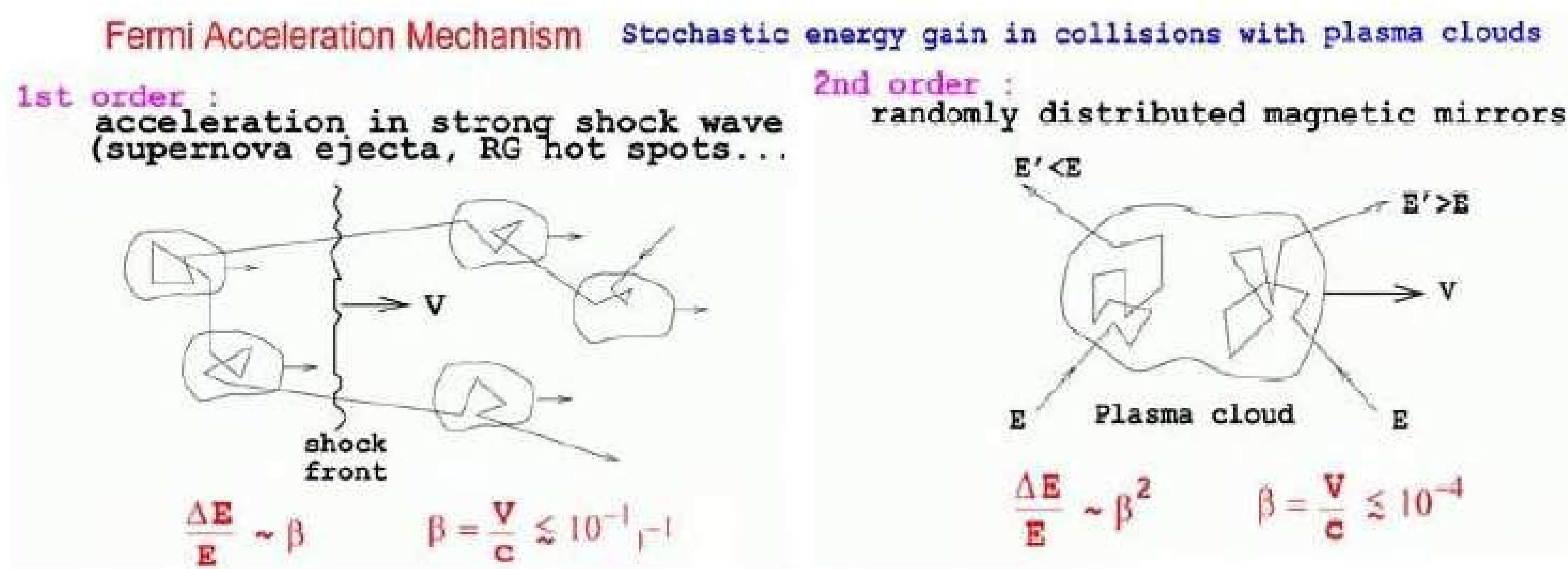
Massimo Persic
INAF+INFN Trieste

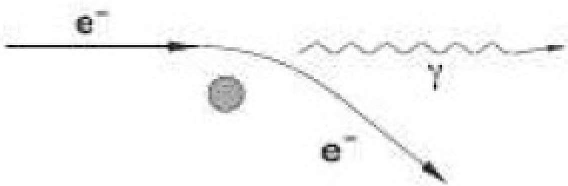
The restless γ-ray universe

Non-Thermal plasma: $T_{ion} \neq T_{electron}$
f(***v***) of either species non-Maxwell Boltzmann

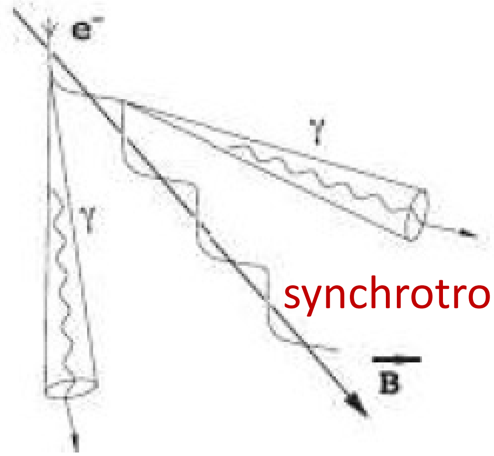
Particle Acceleration



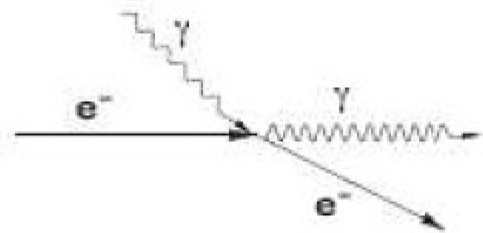
Radiation mechanisms 1.



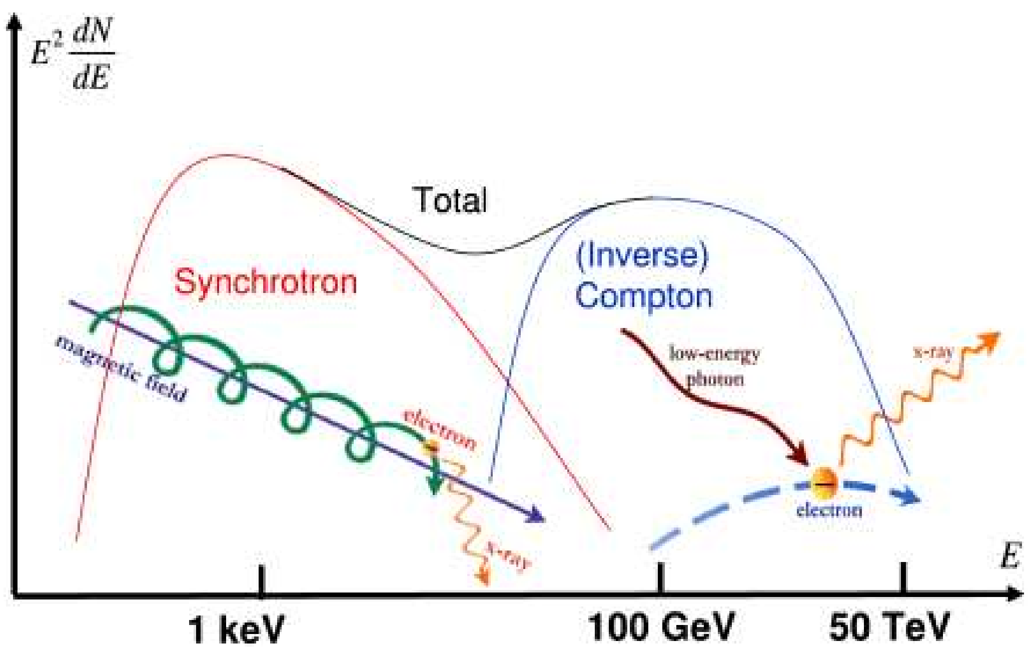
bremsstrahlung



synchrotron

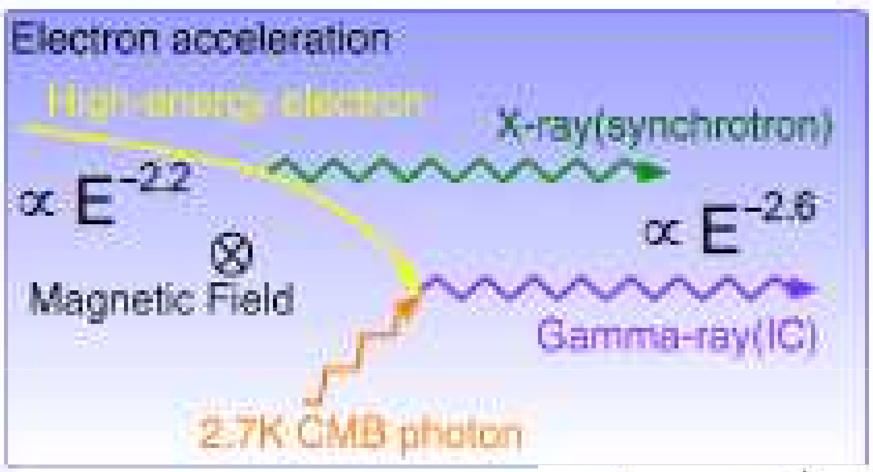


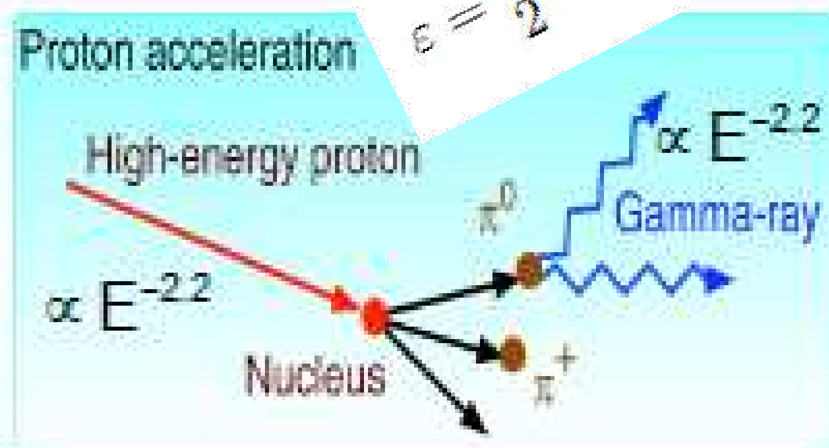
Inverse Compton



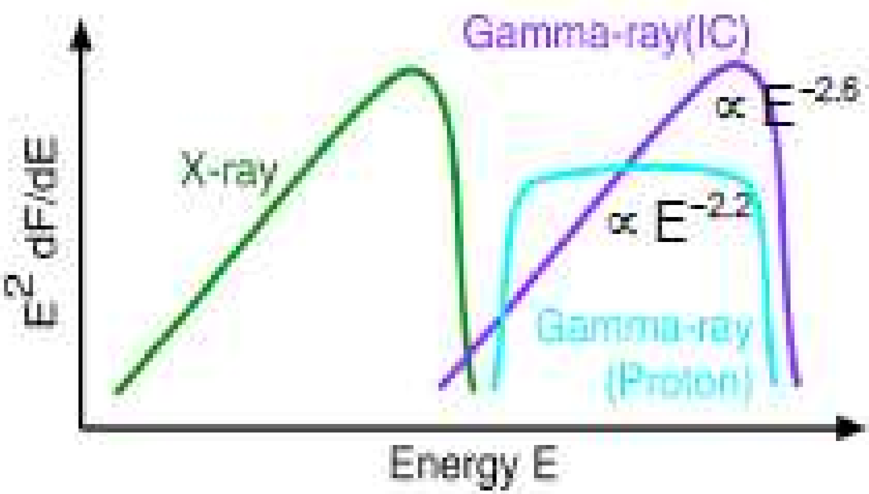
Radiation mechanisms 2.

$$\varepsilon = \frac{1}{2} m_\pi c^2 \frac{1+\beta\cos\theta}{\sqrt{1-\beta^2}}$$



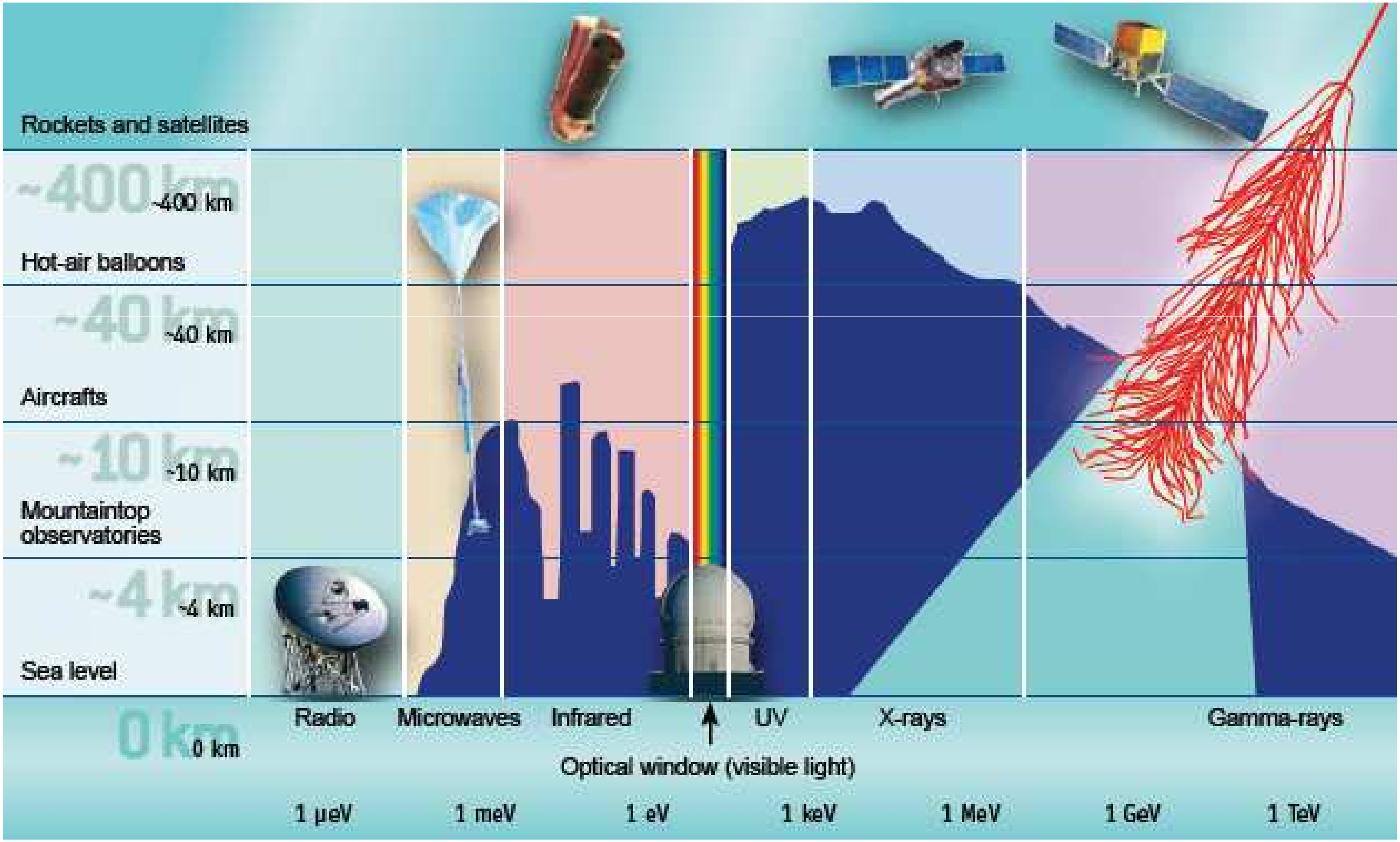


$$p + p \to \pi^+ + X \to \mu^+ + \nu_\mu + X \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu + X$$

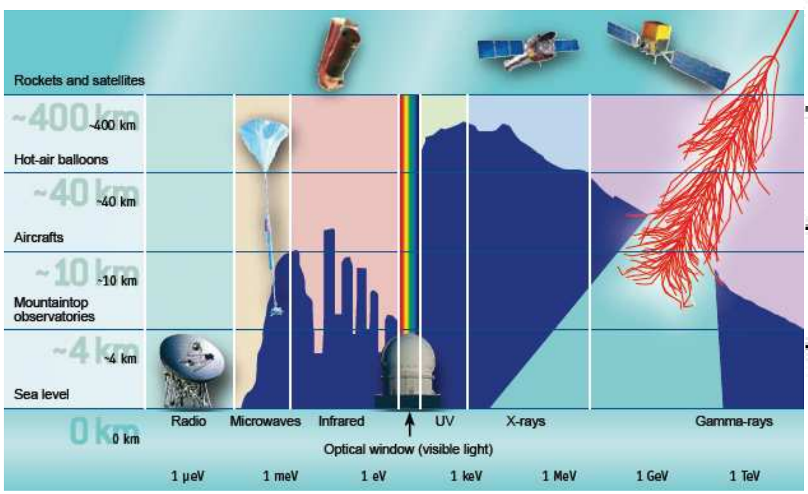


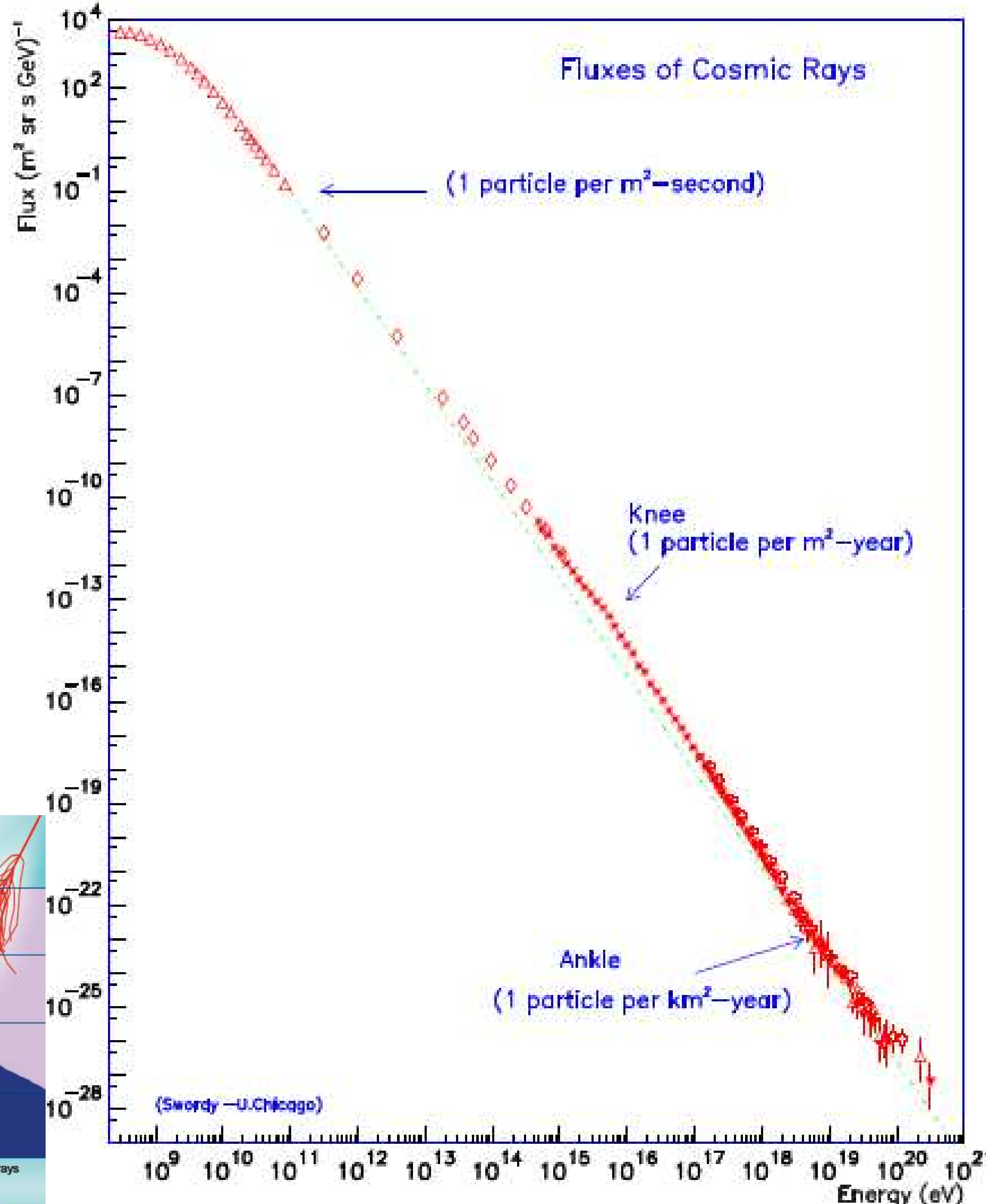
- Background photons:
  - CMB, IR (UV heating), soft thermal X-rays
- Acceleration @ shocks:
  - In relativistic winds (pulsars, young stars)
  - Shell-type SNRs
  - Pulsar magnetosphere
- Variability:
  - Fast in compact sources

Transparency of atmosphere – Detection techniques

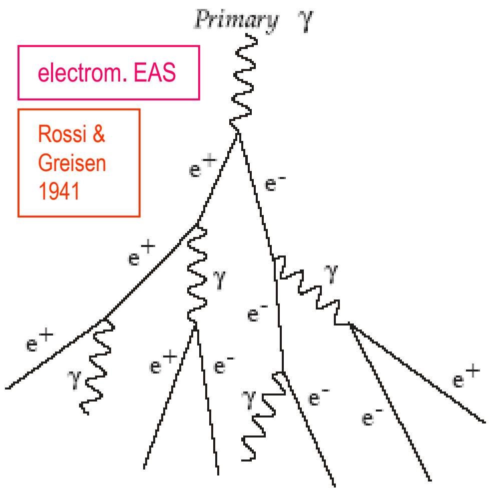


Spectral Flux of Cosmic Rays



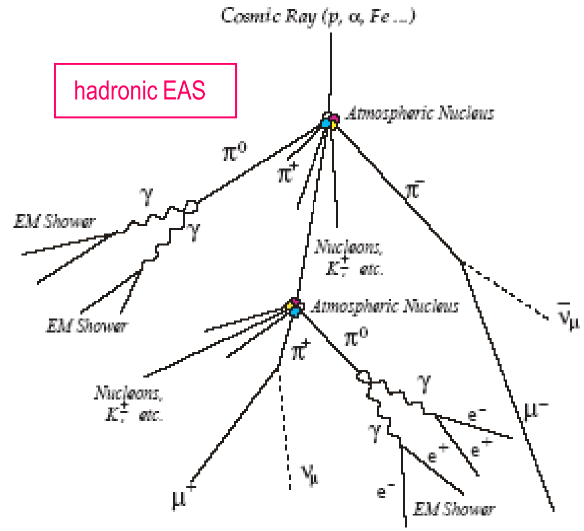


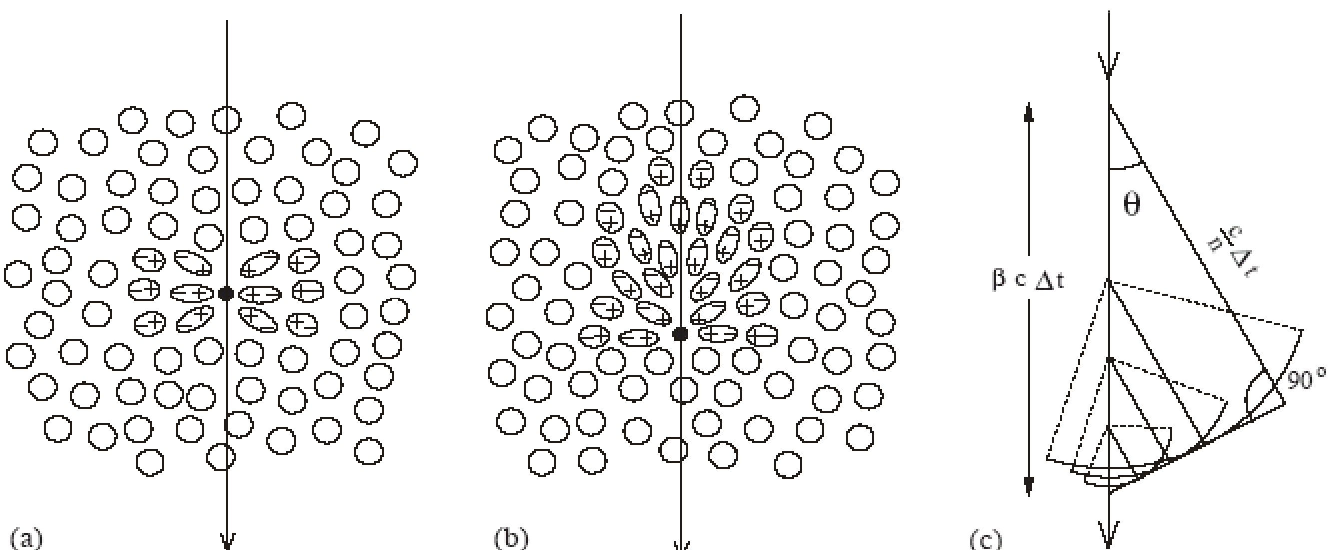
Cherenkov Observational Technique.1



[redacted]

$$E_{\check{c}}^{thr} = \frac{m_0 c^2}{\sqrt{1-\beta_{min}^2}} = \frac{m_0 c^2}{\sqrt{1-(1/n)^2}}$$





[redacted]

Cherenkov Observational Technique.2

Development in atmosphere

Greisen 1956, 1960

vertical $$\rho(r,t,E_0) = \frac{N_e(t,E_0)}{r_M^2}\left(\frac{r}{r_M}\right)^{s-2}\left(1+\frac{r}{r_M}\right)^{s-4.5}\frac{\Gamma(4.5-s)}{2\pi\Gamma(s)\Gamma(4.5-2s)}$$

lateral $$N_e(t,E_0) = \frac{0.31}{\sqrt{\ln(E_0/E_c)}}e^{t[1-1.5\ln(s)]}$$

E_0: primary γ's energy
t: depth along shower axis
(in units of radiation lengths)
s: shower age (0<s<2)
R: lateral distance
(in units of scattering radius)

$$\rho(h) = \rho_0 \cdot \exp\left(-\frac{h}{h_0}\right)$$

$$n(h) = 1 + n_h = 1 + n_0 \cdot \exp\left(-\frac{h}{h_0}\right)$$

$$E_{\check{c}}^{thr} \simeq \frac{m_0c^2}{\sqrt{2n_h}}$$

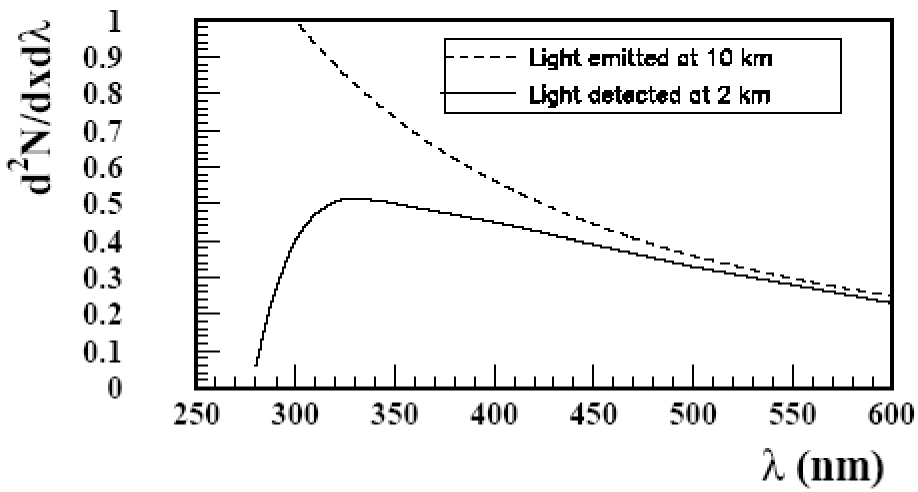
$$\cos\theta_{\check{c}}^{max} \simeq \sqrt{2n_h}$$

SPECTRUM

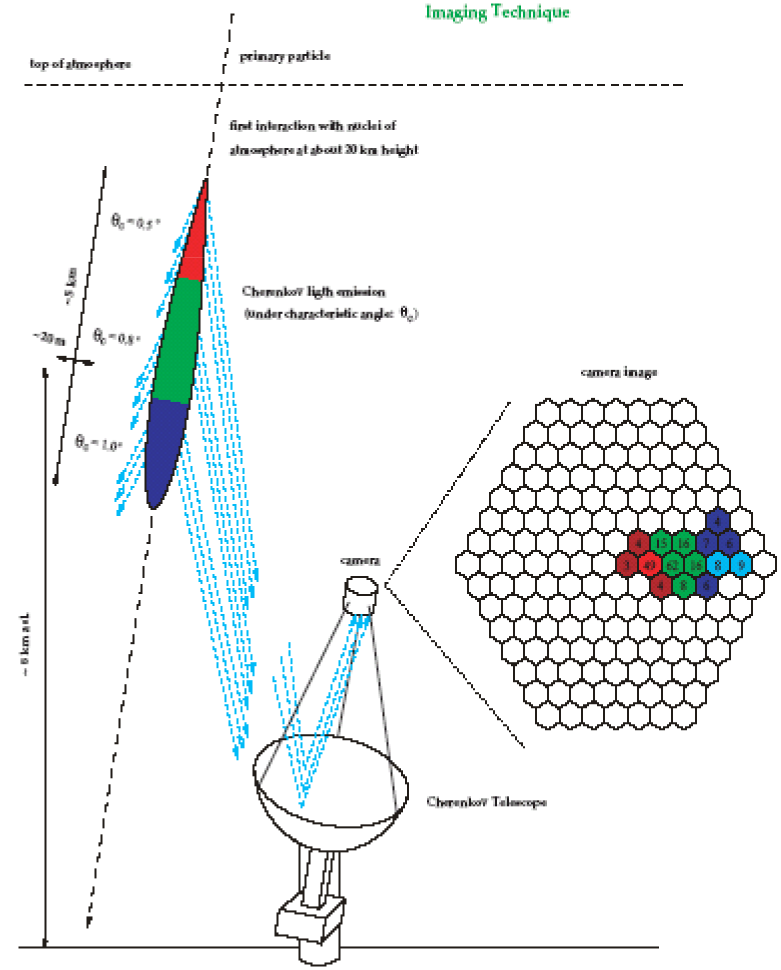
$$\frac{dN^2}{dxd\lambda} = 2\pi\alpha Ze^2\left(1-\frac{1}{\beta^2\cdot n^2(\lambda)}\right)\frac{1}{\lambda^2}$$

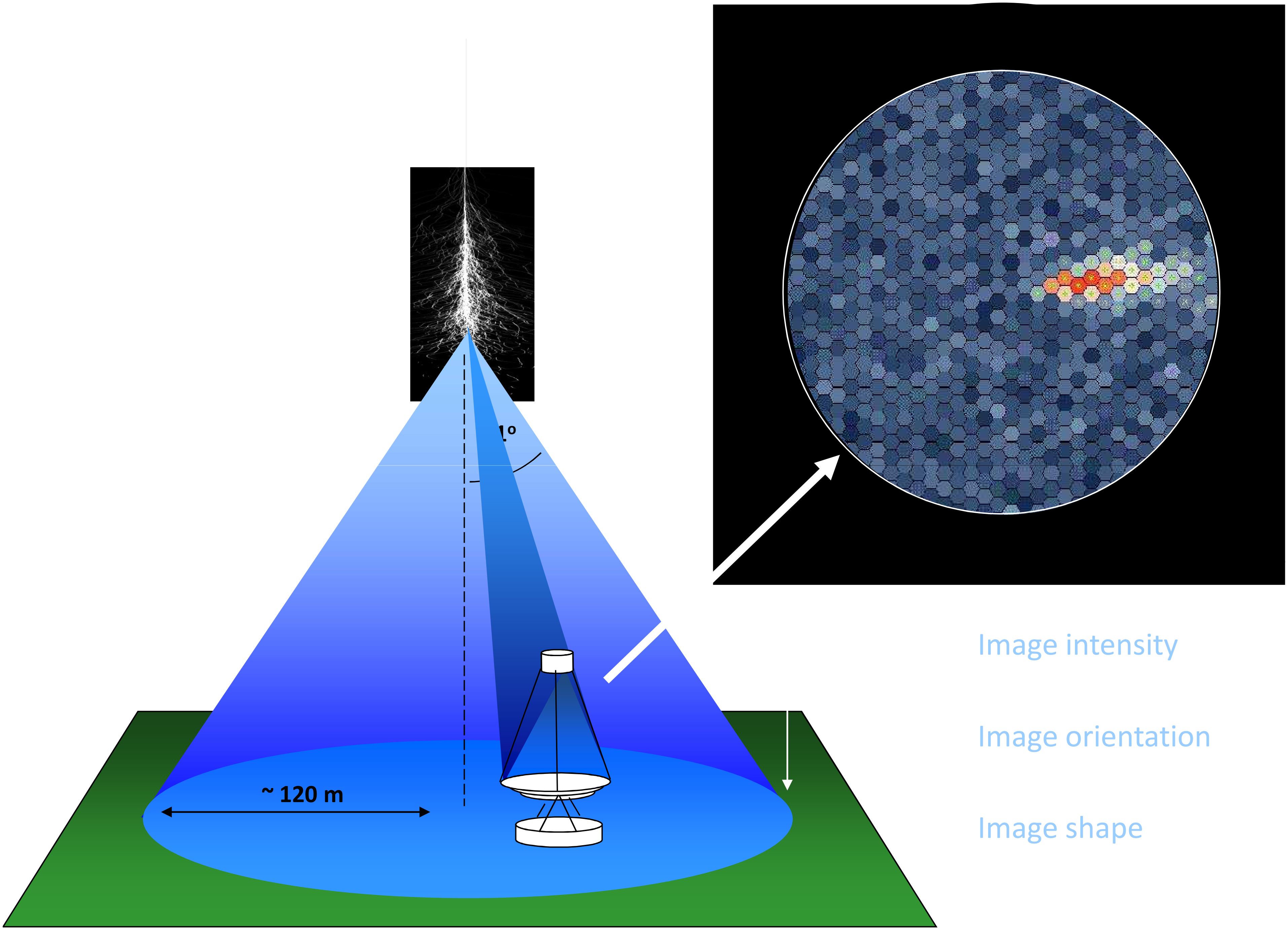
optical/UV light

… but Rayleigh scattering λ^{-4}



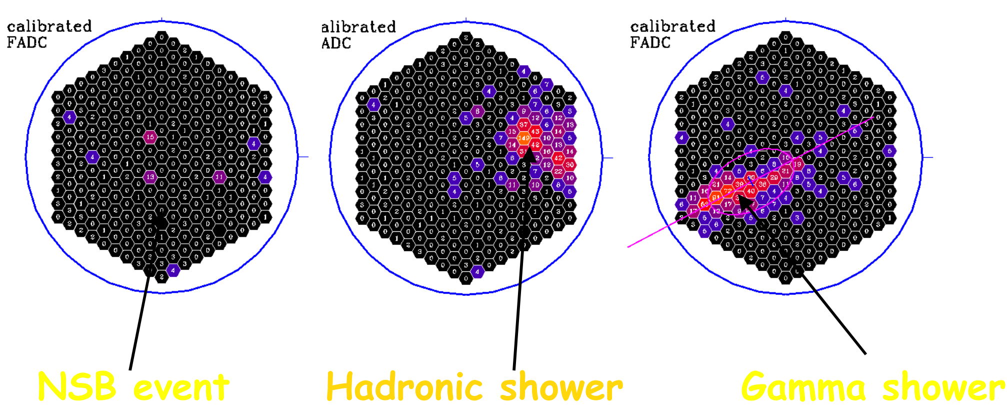
Principle of the Imaging Technique

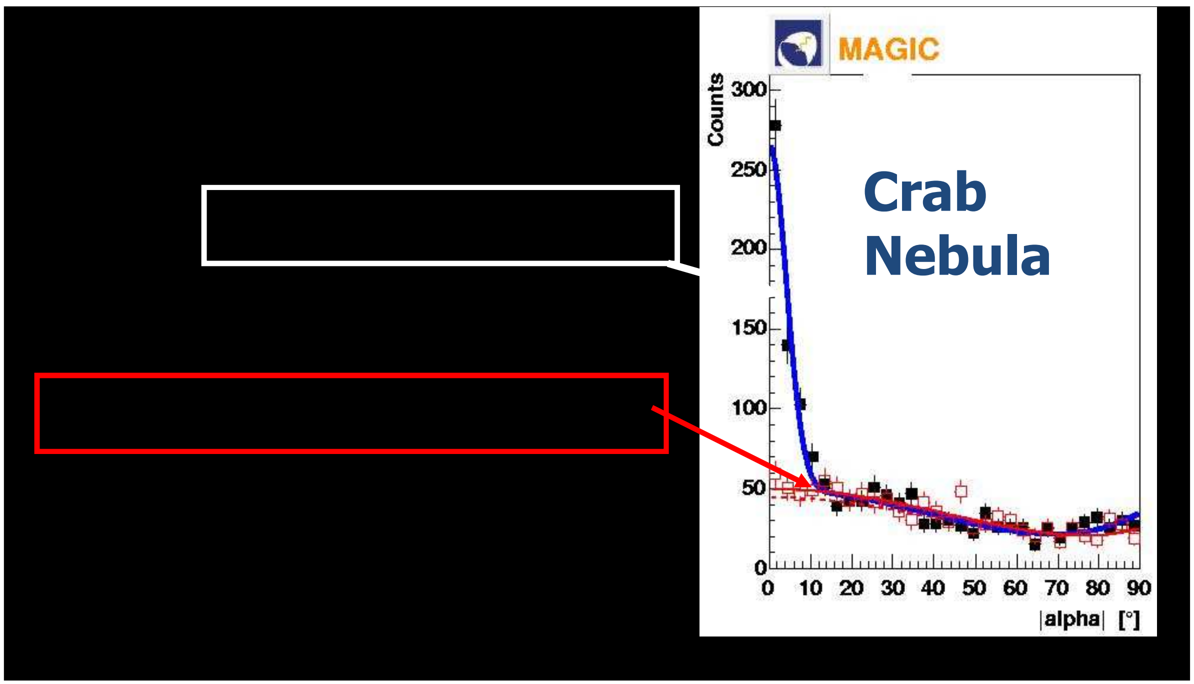


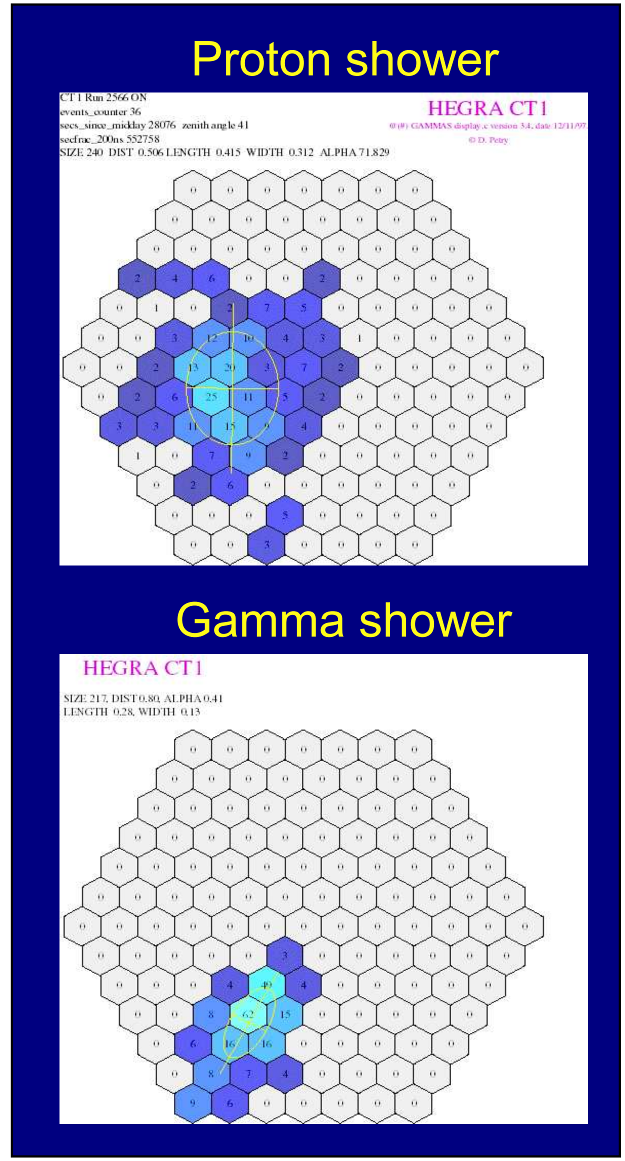


1°
~ 120 m
Image intensity
Image orientation
Image shape

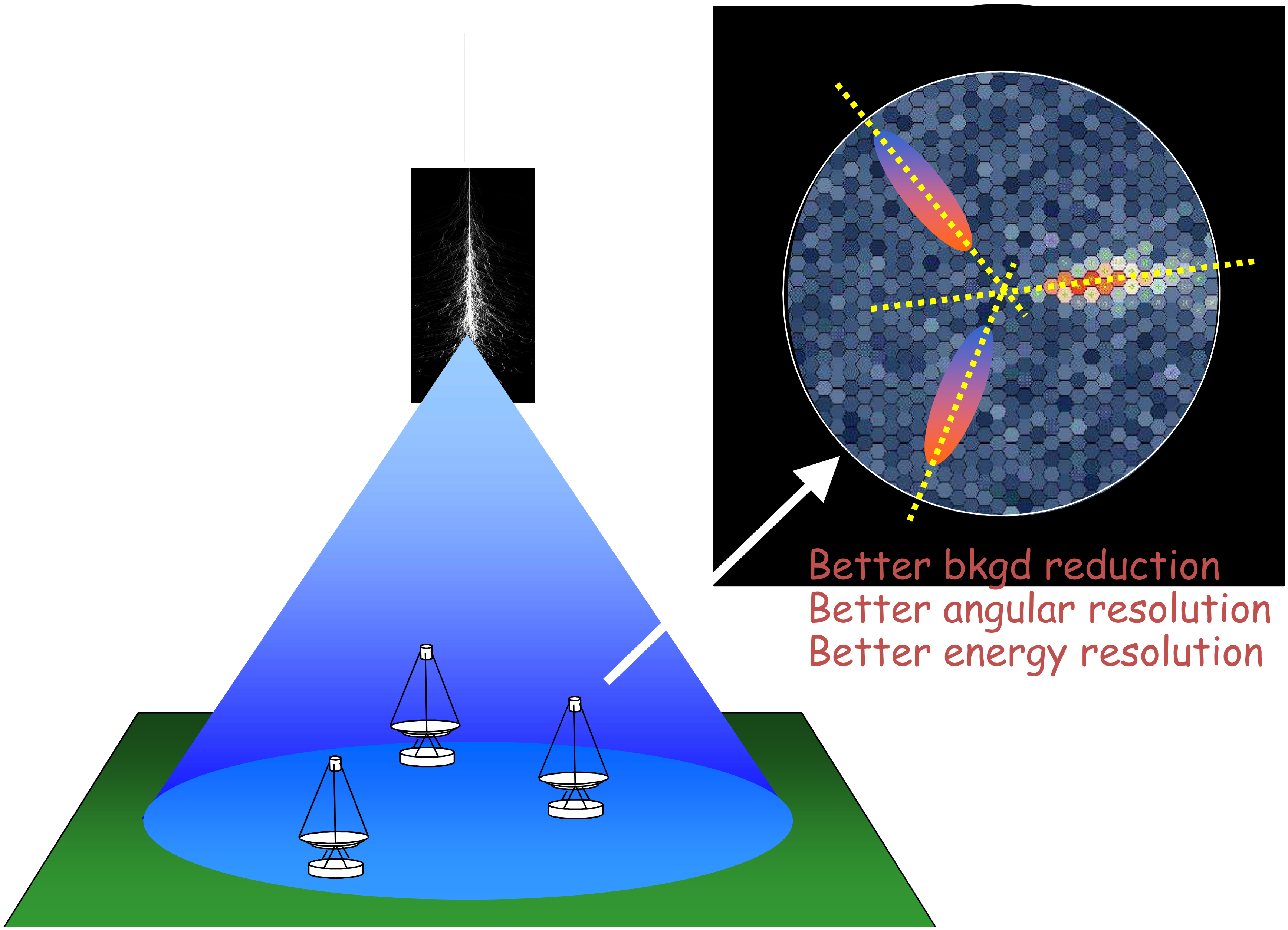
γ/h separation







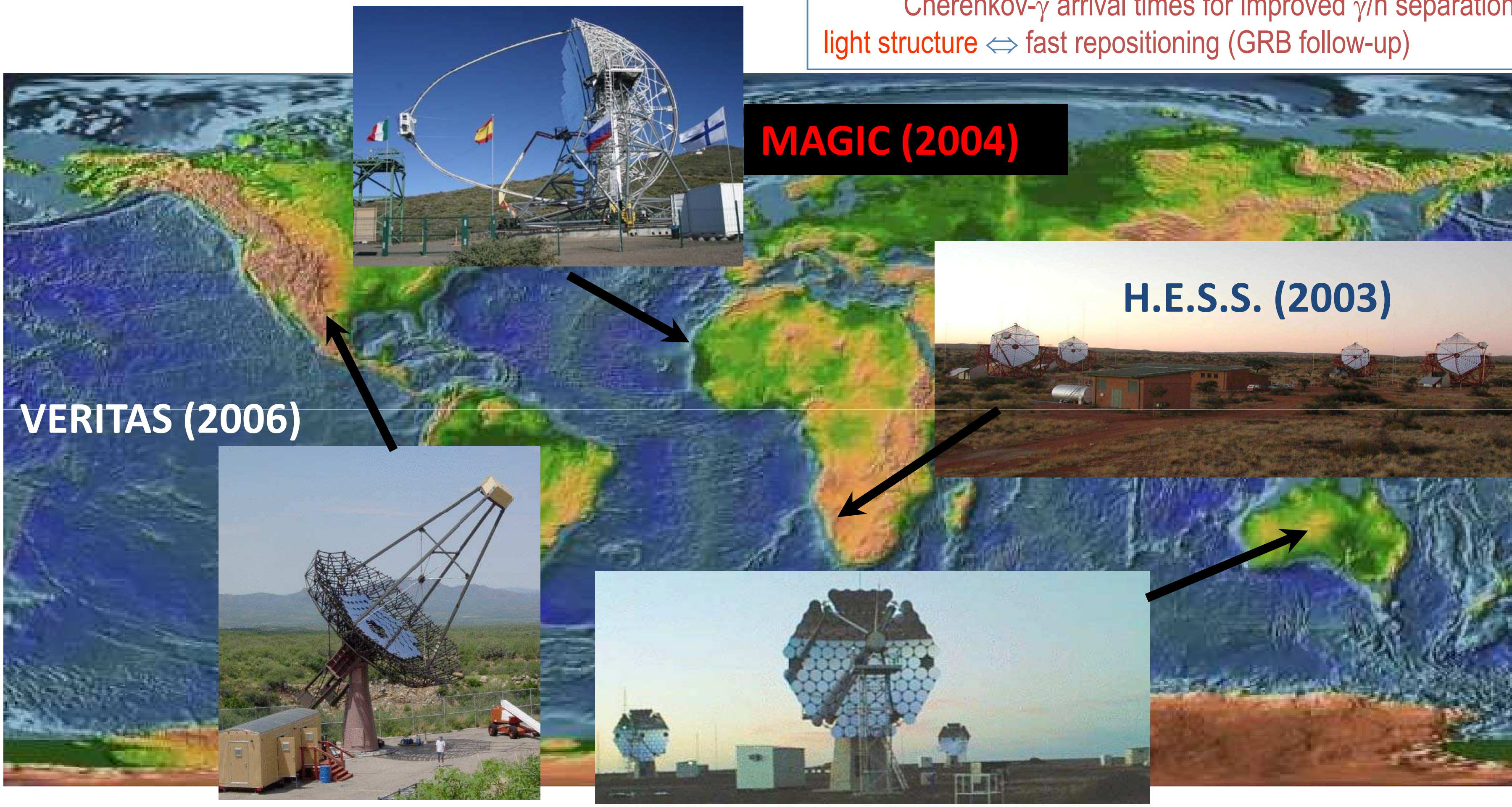
Systems of Cherenkov telescopes



Better bkgd reduction
Better angular resolution
Better energy resolution

Current-generation IACTs

reduced threshold ⇔ larger telescopes
improved sensitivity ⇔ better γ/h separation
wide-field camera ⇔ surveys, serendipities
isochronous mirror, fast digitization ⇔
Cherenkov-γ arrival times for improved γ/h separation
light structure ⇔ fast repositioning (GRB follow-up)

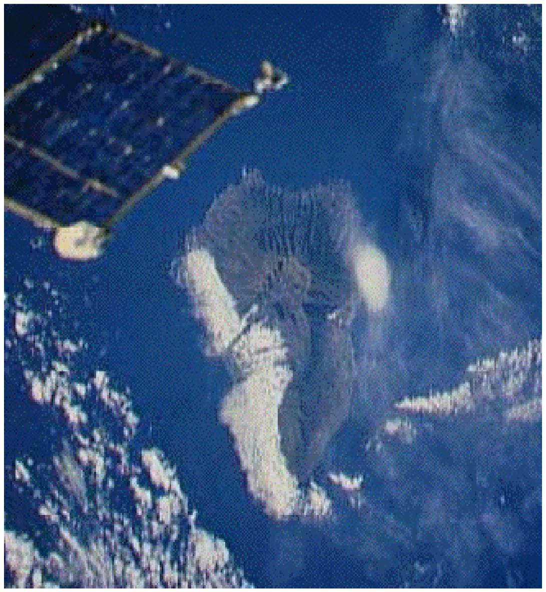


IACTs established as astronomical tools (experiments → telescopes)
Big step within last few years:

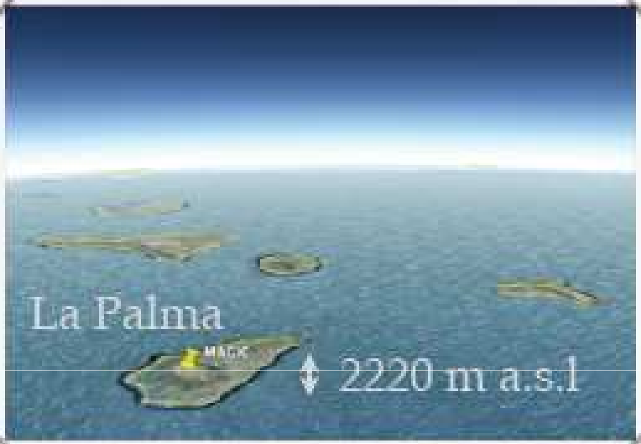
- quantitative (x5 detected sources)
- qualitative (unprecedented high quality)

MAGIC's site

La Palma, IAC
28° North, 18° West



The MAGIC telescopes



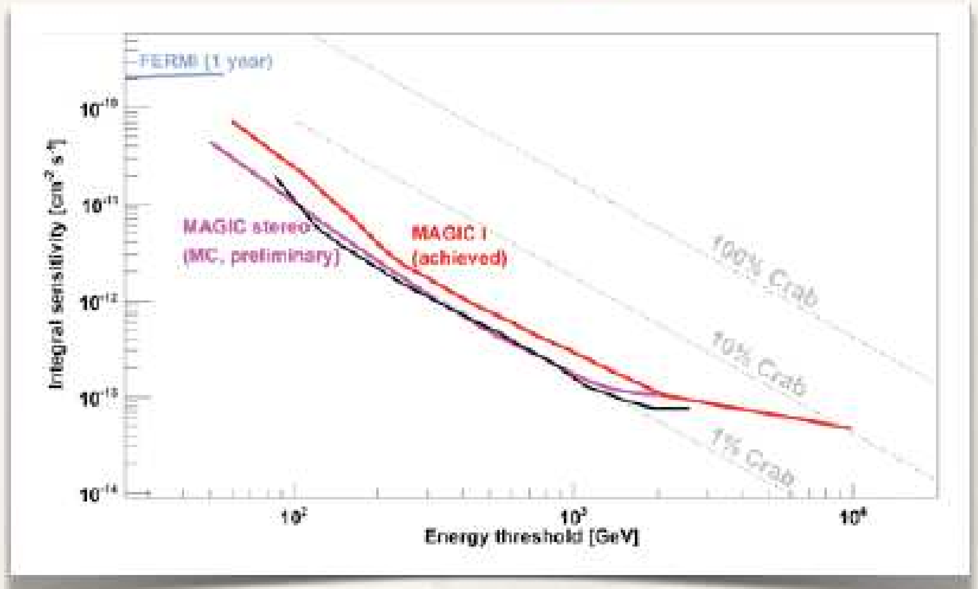
- Cherenkov Imaging Telescopes
  - Recording Air Showers from γ-rays
  - Phase **I**: Monoscopic, since 2004
  - Phase **II**: Stereoscopic, since 2009
- Low energy optimized:
  - Analysis > 60 GeV (I), > 50 GeV (II)
    - for pulsars: > 25 GeV (M-I "sum" trigger)
  - huge 17 m diameter mirror dishes
  - fast, high-efficiency PMTs & readout
  - 20 - 40 s repositioning for GRBs

Performance: Sensitivity

Phase I: 1.6% Crab
(5σ in 50h)

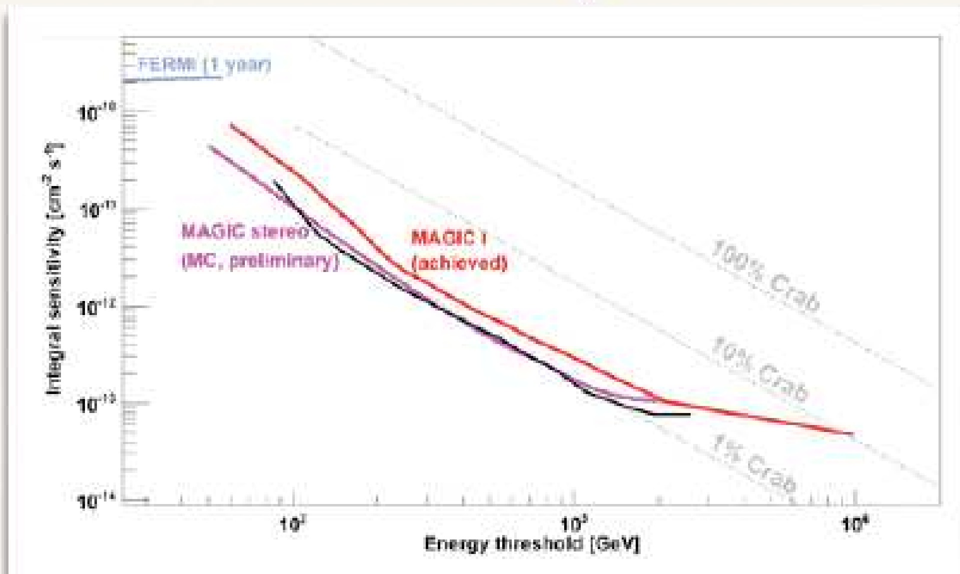
- slightly more eff. area
- ~ 1/3 background rate
- Less systematic biases, especially at low energies

Phase II: < 1% Crab



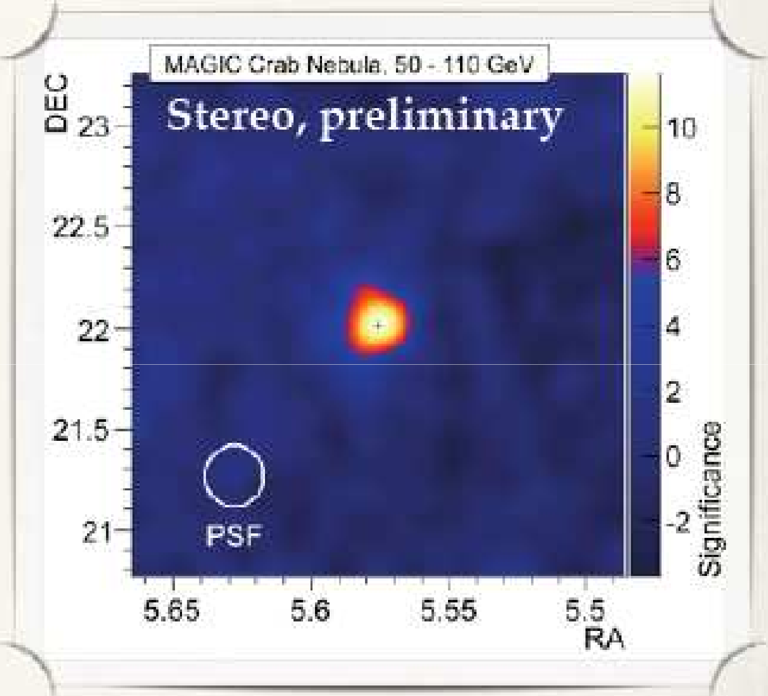
Performance: Sensitivity

Phase I: 100 h → **Phase II: < 40 h**

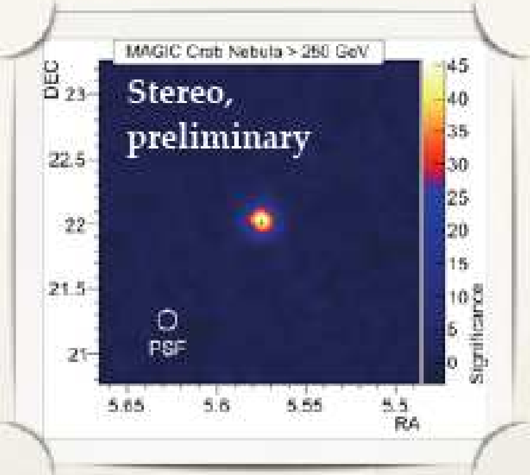


Performance: Resolution

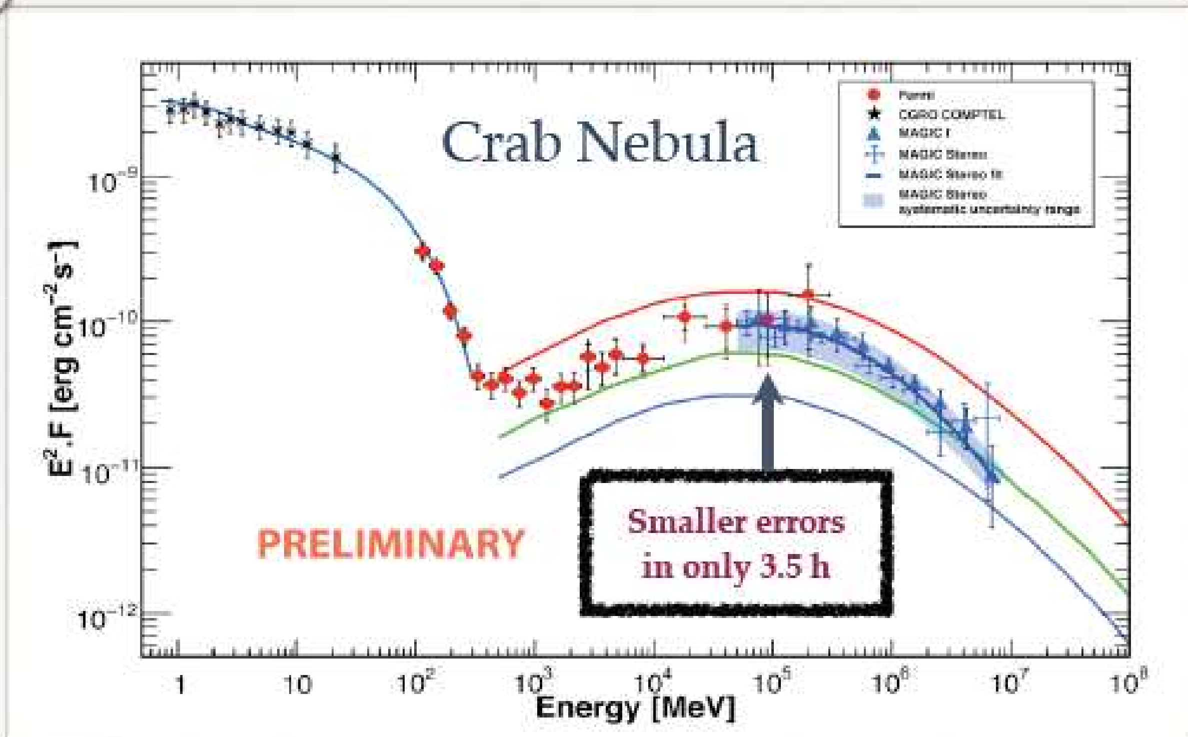
- Energy: 25% (I) → 15% (II)
  (RMS, > 300 GeV)
- Direction: 0.1° (I) → 0.07° (II)
  (σ of 2D gaussian, i.e. 39%, > 300 GeV)
  - 0.1° at 100 GeV (II)
  - < 0.025° sys.



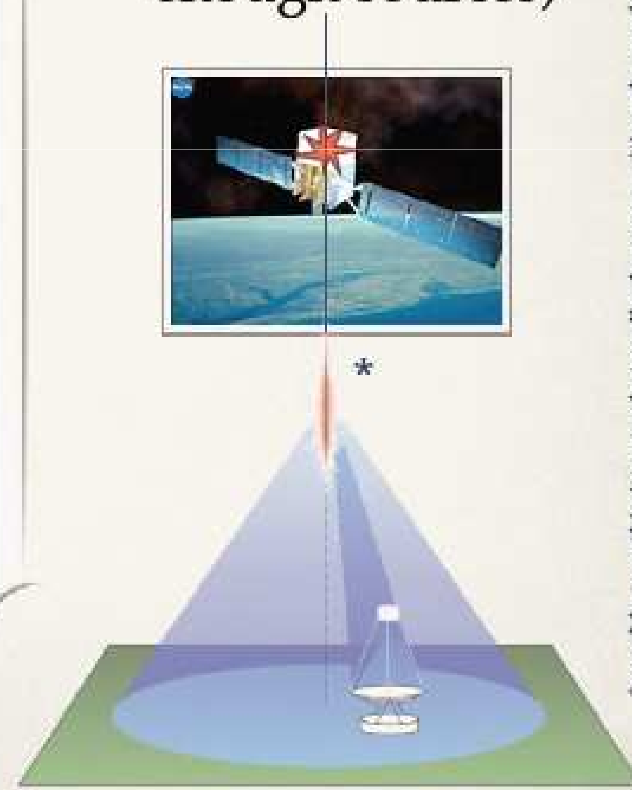
(lowest published MAGIC-I map was 110-240 GeV)



Performance: MAGIC & Fermi



- The gap is closed
- (...for strong enough sources)



*yes, I know, this is not what really happens - it's only symbolic

Next:

... a review of important VHE γ-ray results highlighting particle acceleration ...

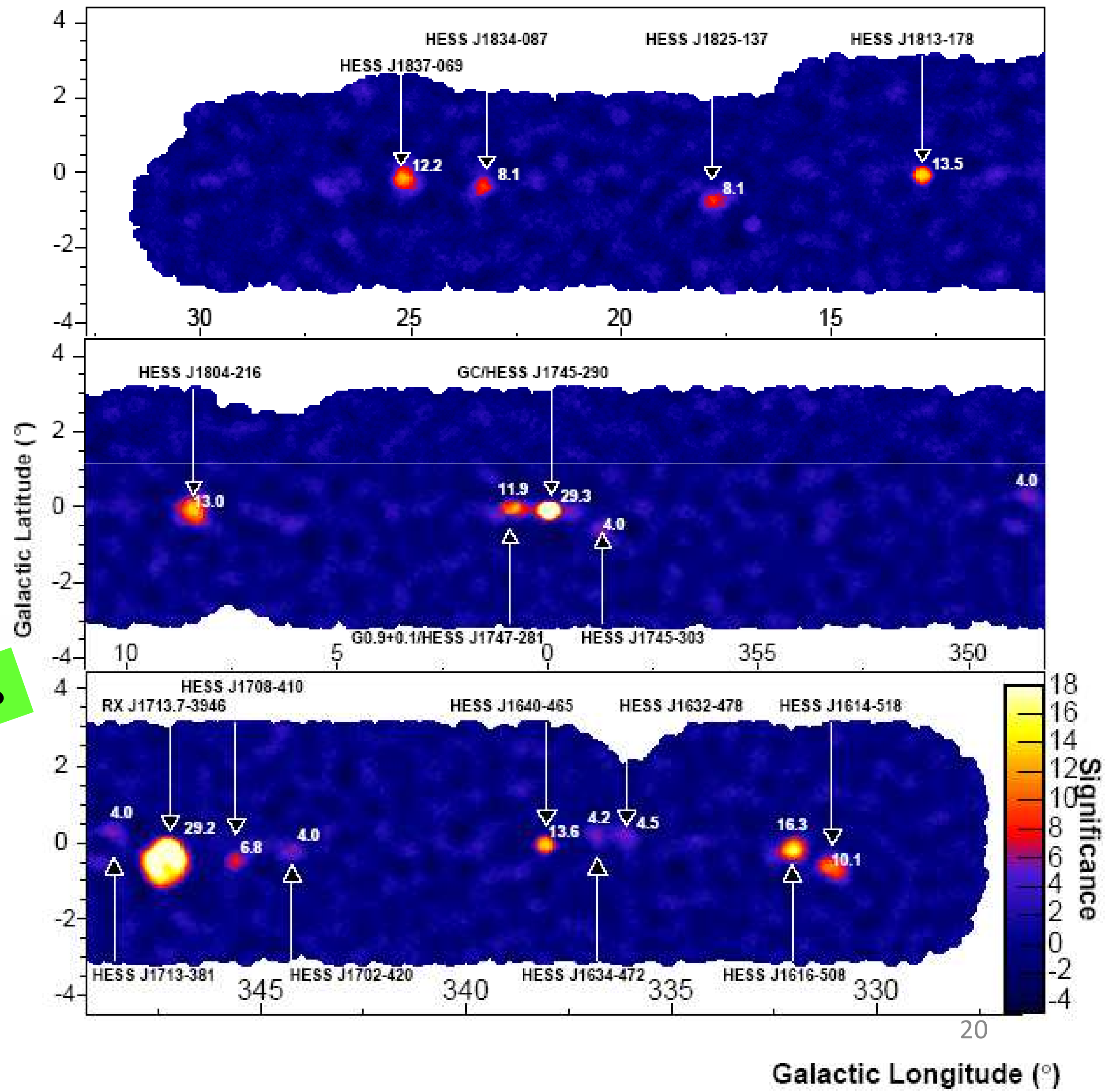
H.E.S.S. Galactic Plane Survey

First breakthrough @ VHEs → southern hemisphere

Sources : 40 in GP scan !!
35 new !!

Typically:
- Shell-type SNRs
- Pulsar-Wind-Nebulae
- Unidentified

post-SN sources



… estimating the TeV luminosity of GP sources …

Assume:

- SN-accelerated CRp, downstream particles $n \propto p^{-\alpha}$ with $\alpha = \frac{3}{2}(\gamma+1)\frac{M^2}{M^2+1}$,
strong shock (M>>1) → $\alpha = 4$ → $\phi(\varepsilon) \propto \varepsilon^{-2}$
- pp interaction with ambient gas, $\pi^0 \rightarrow \gamma\gamma$
- Emissivity: $j_{\geq E} = 10^{-17}(\frac{E}{TeV})^{-1.1} s^{-1}(erg/cm^3)^{-1}(H-atom)^{-1}$ (Drury+ 1994)
- $L_{\geq E} = \int_V j_{\geq E} n U_{CR} dV$
- Giant molecular cloud (massive-SF site): $L_{>0.2TeV} \approx 5\times10^{35}\, ph/s$

  with $M_{H_2} \approx 10^4 M_\oplus, R \approx 10 R_\oplus, n_{H_2} \approx 50 cm^{-3}$ (→ HESS Galactic-plane survey)

- Hadron illumination of ISM: $L_{\geq E}^{gas} \approx 2\times10^{37}(E/TeV)^{-1.1}(U_{CR}/eV)(M^{gas}/10^9 M_\oplus)$ phot / s

SNR RX J1713.7-3946

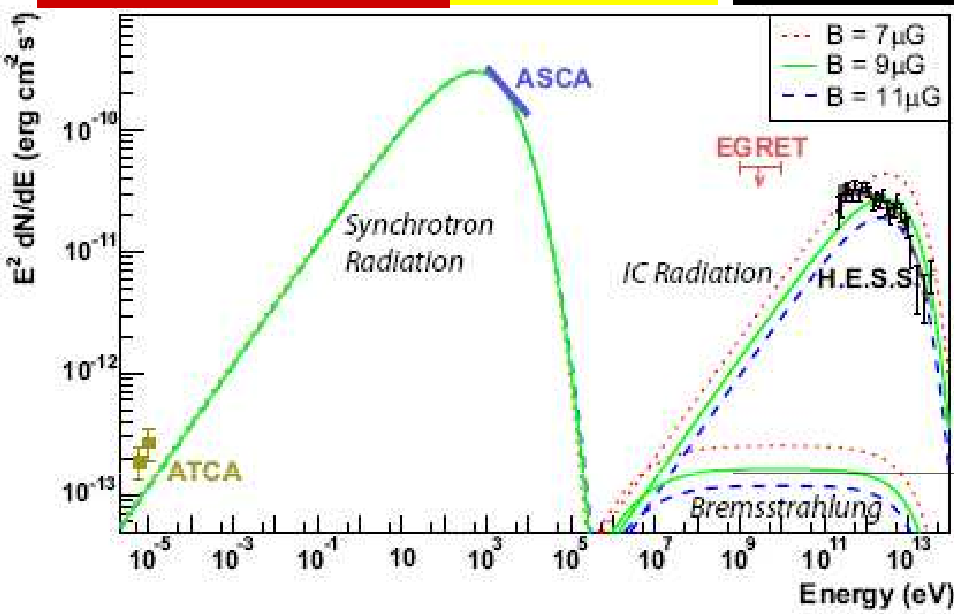
H.E.S.S.

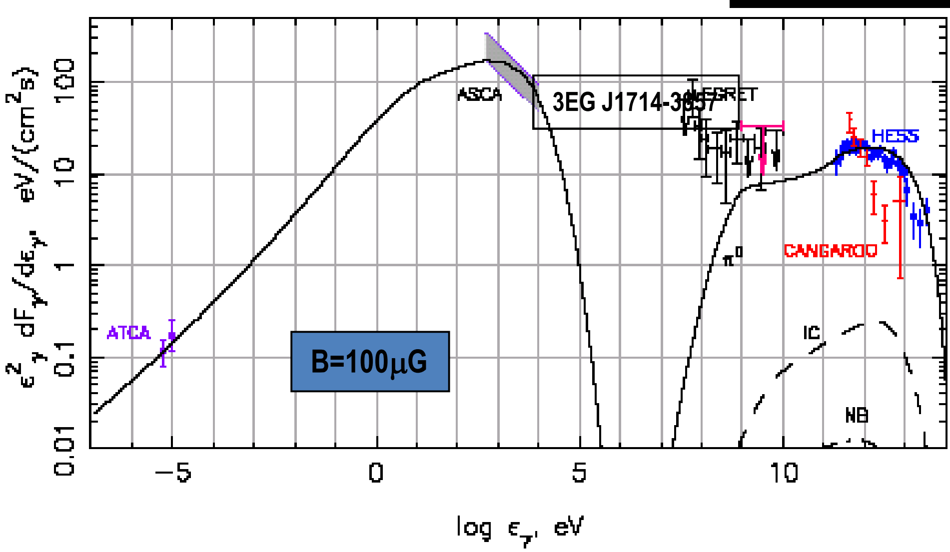
SNR shell → particle acceleration

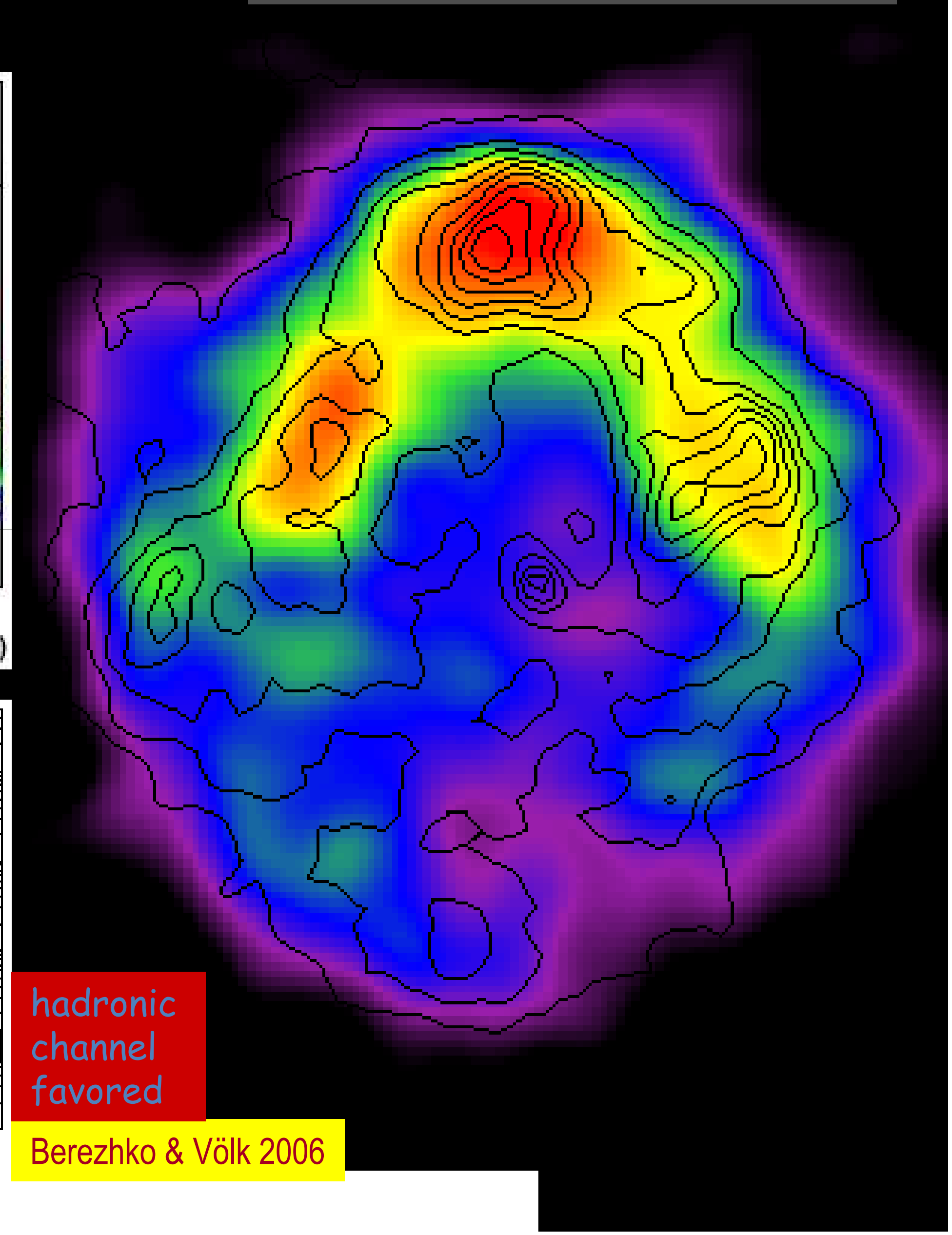
Resolved shell in VHE-γ-rays

γ-rays from leptonic or hadronic channels?

leptonic channel fav'd | Aharonian+ 2006

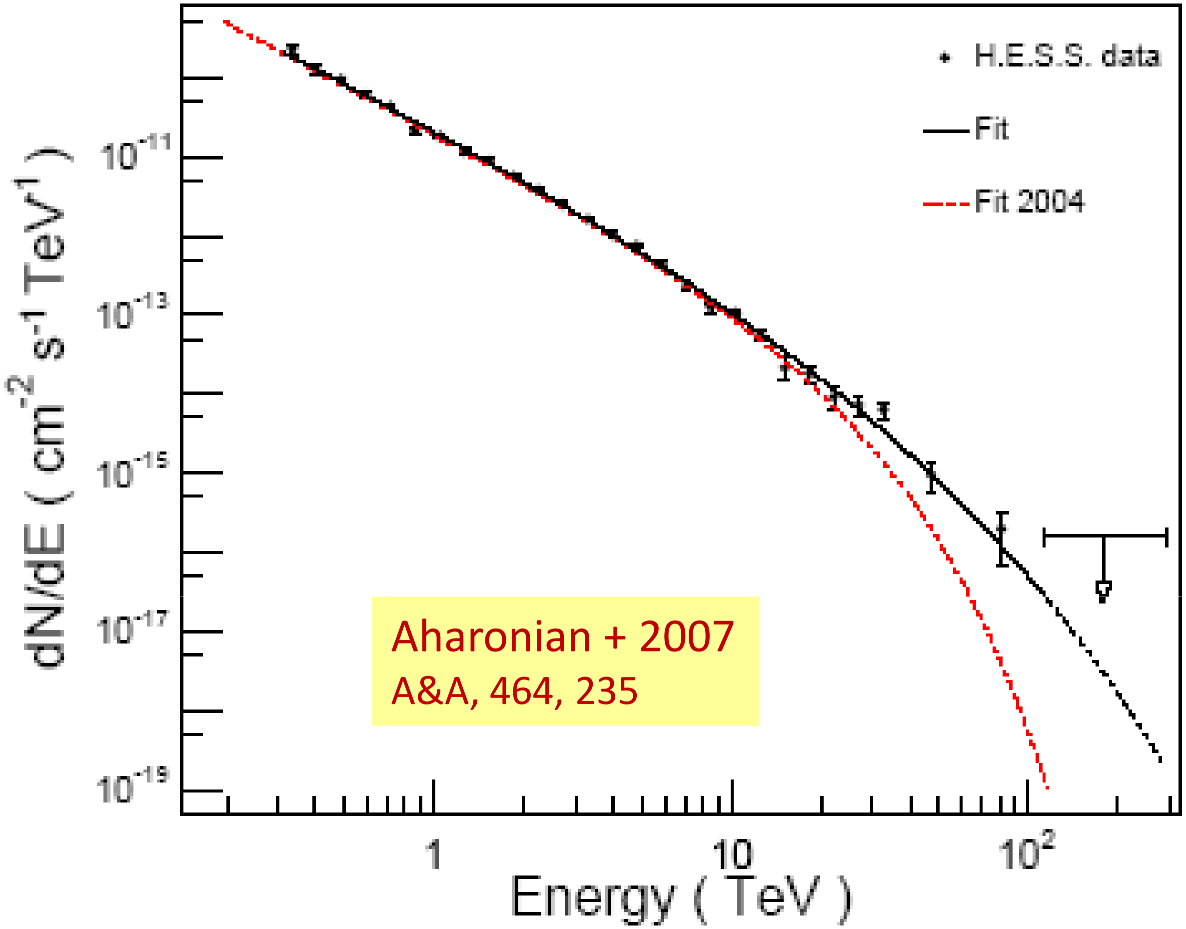






hadronic channel favored

Berezhko & Völk 2006



Leptonic:

$E_e \sim 20\ (E_\gamma)^{1/2}$ TeV

~ 110 TeV … but KN sets on ..

→ ~100 TeV

Hadronic:

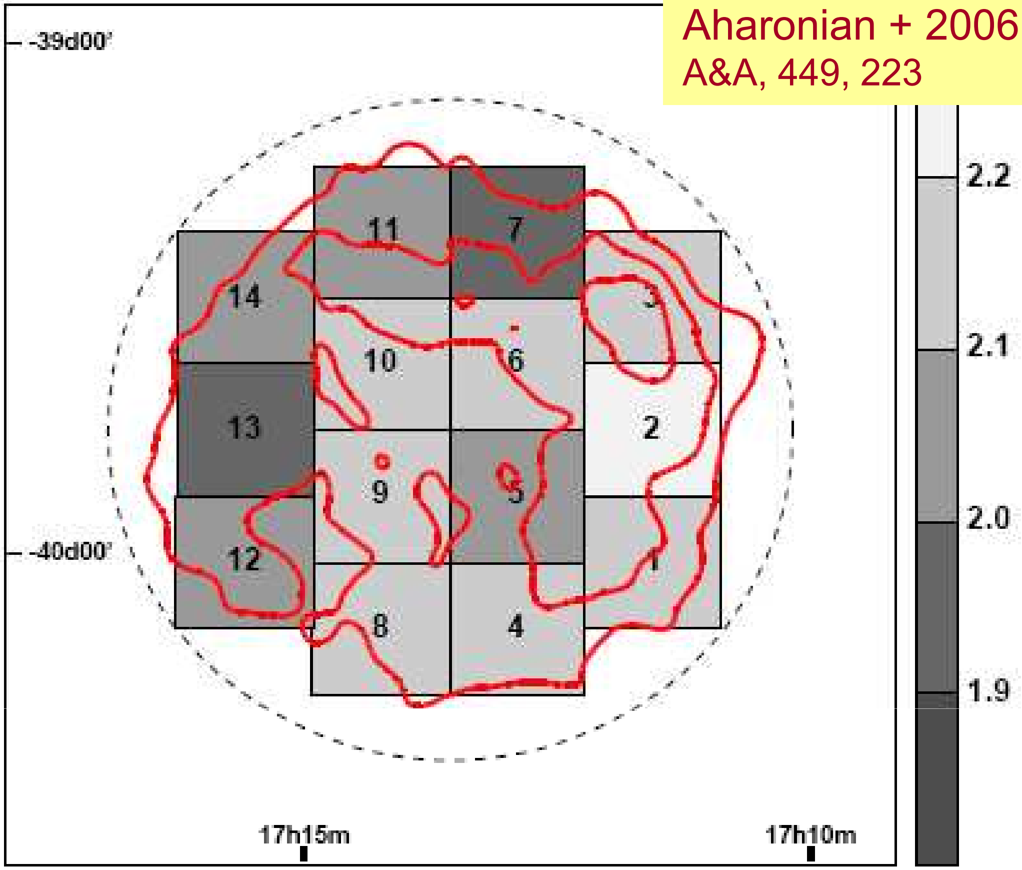
$E_p \sim E_\gamma / 0.15 \sim 30 / 0.15$ TeV ~

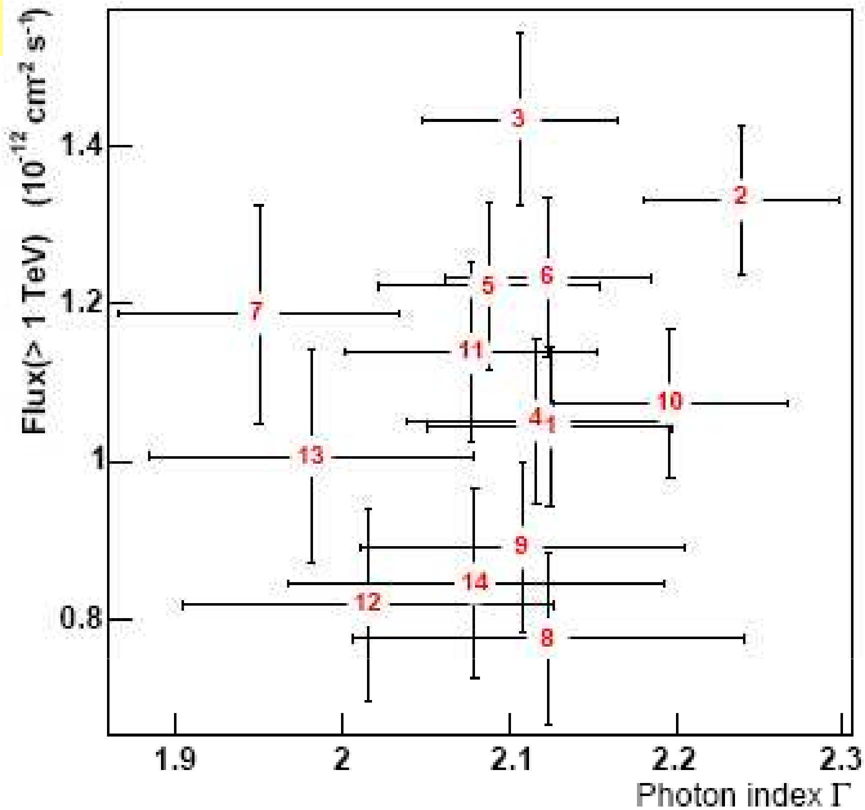
~ 200 TeV

▸▸ Acceleration of primary particles in SNR shock to well beyond 100 TeV

... but: is SN statistics enough to fit CR energy density?

Aharonian + 2006
A&A, 449, 223





- index Γ~2–2.2 (strong shock)
- little variation across SNR

GeV+TeV → spatially resolved spectroscopy

- young SNRs ($t<t_{cool}$ (p,e)):

CRp spectrum γ = **1+2α** + **b**

from VHE

from radio

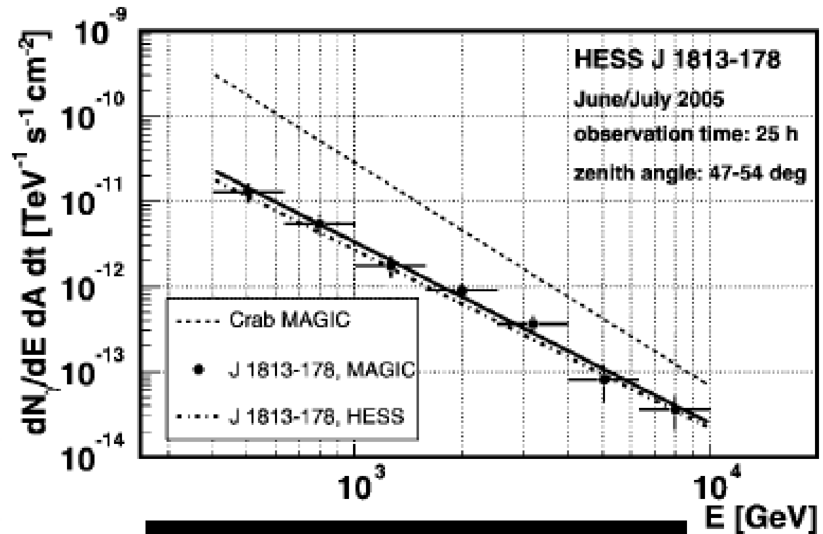
$\kappa = p^b$ ... b~0.6 ?
from B/CNO ratio

→ measure $\kappa(p)$ as a function of p

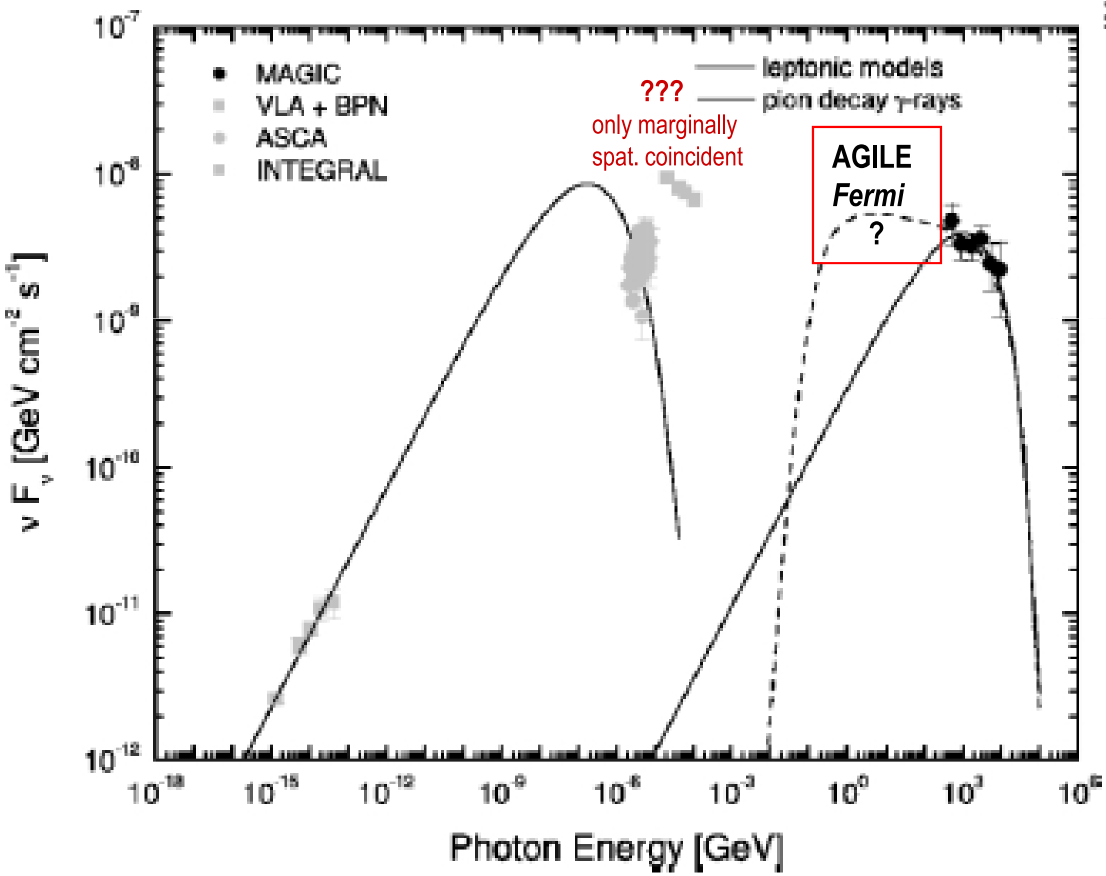
H.E.S.S. J1813-178

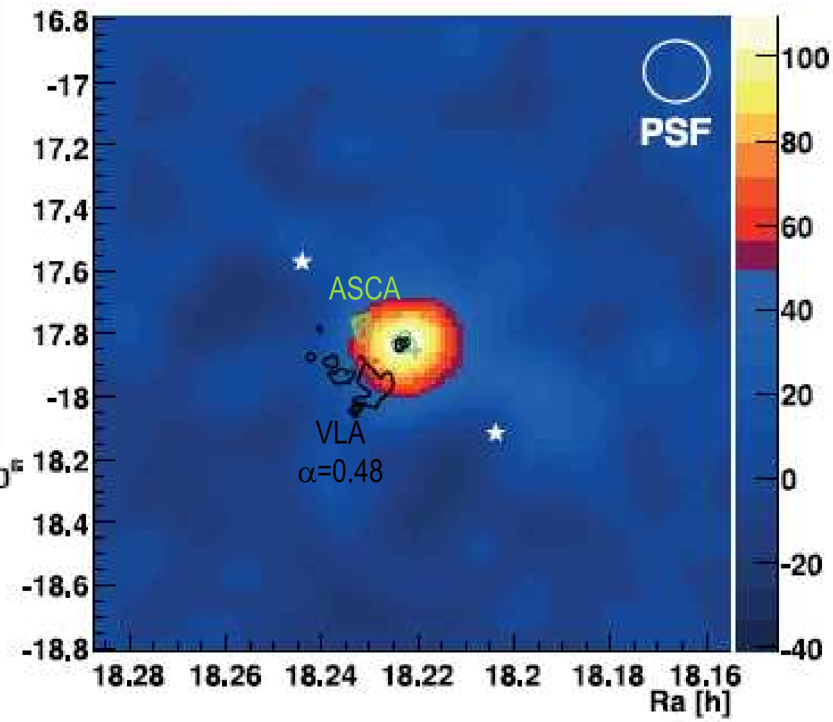
G12.82-0.02

Albert+ 2006, ApJ, 637, L41



$\Gamma = 2.1 \pm 0.2_{stat} \pm 0.2_{sys}$





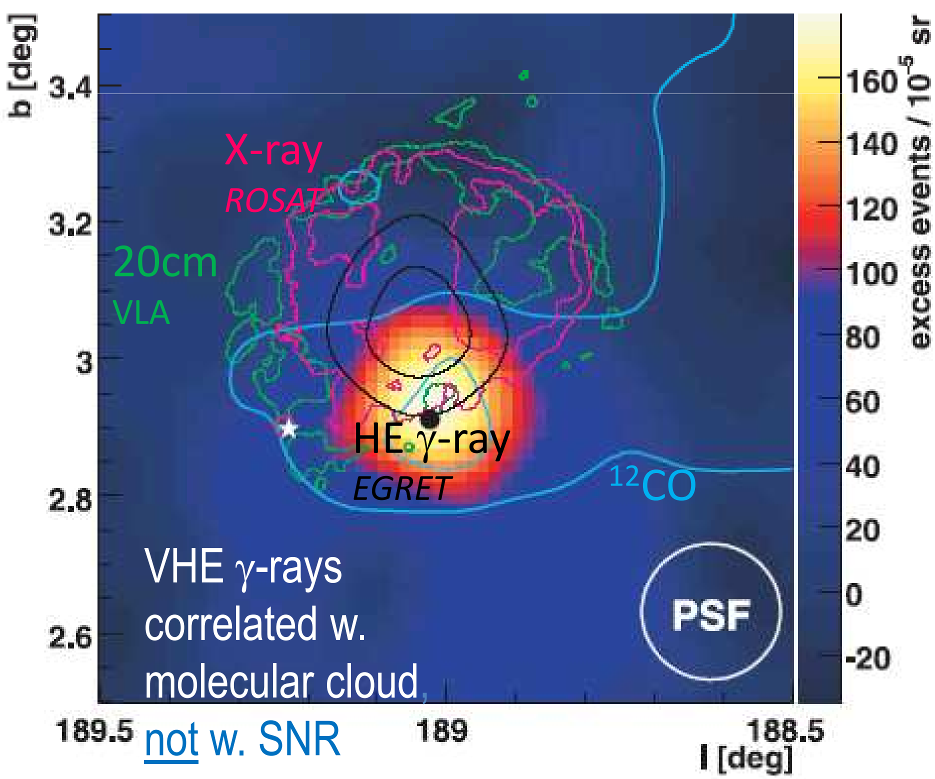
<u>Hadronic</u>: $2M_\odot$ of target gas, exp-cutoff proton distrib: α=2.1, E_c=100 TeV, n_p=6cm^{-3}, L(0.4-6TeV)=2.5×10^{34}erg/s

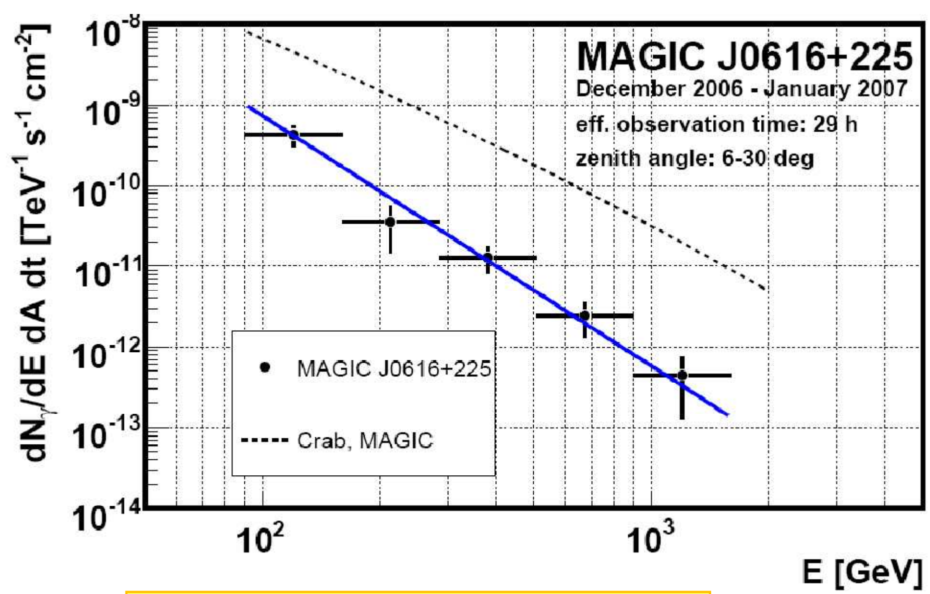
<u>Leptonic</u>: B=10mG, exp-cutoff electron distrib: α=2.0, E_c=20TeV

IC 443

MAGIC J0616+225

- Asymmetric shell-type SNR (45''), seen at radio, x-rays, and γ-rays.
- New source discovered by MAGIC.
- F(>150 GeV) = 0.06 c.u.
- Soft 0.1-1 TeV spectrum ($\Gamma = -3.1 \pm 0.3_{stat} \pm 0.2_{sys}$), no break.
- Extension below MAGIC angular resolution (~0.1°).
- MAGIC source displaced w.r.t. center of EGRET source.
- MAGIC source displaced to south of SNR center – correlated w. a molecular cloud and maser emission.
- Hadronic origin of VHE emission favored.

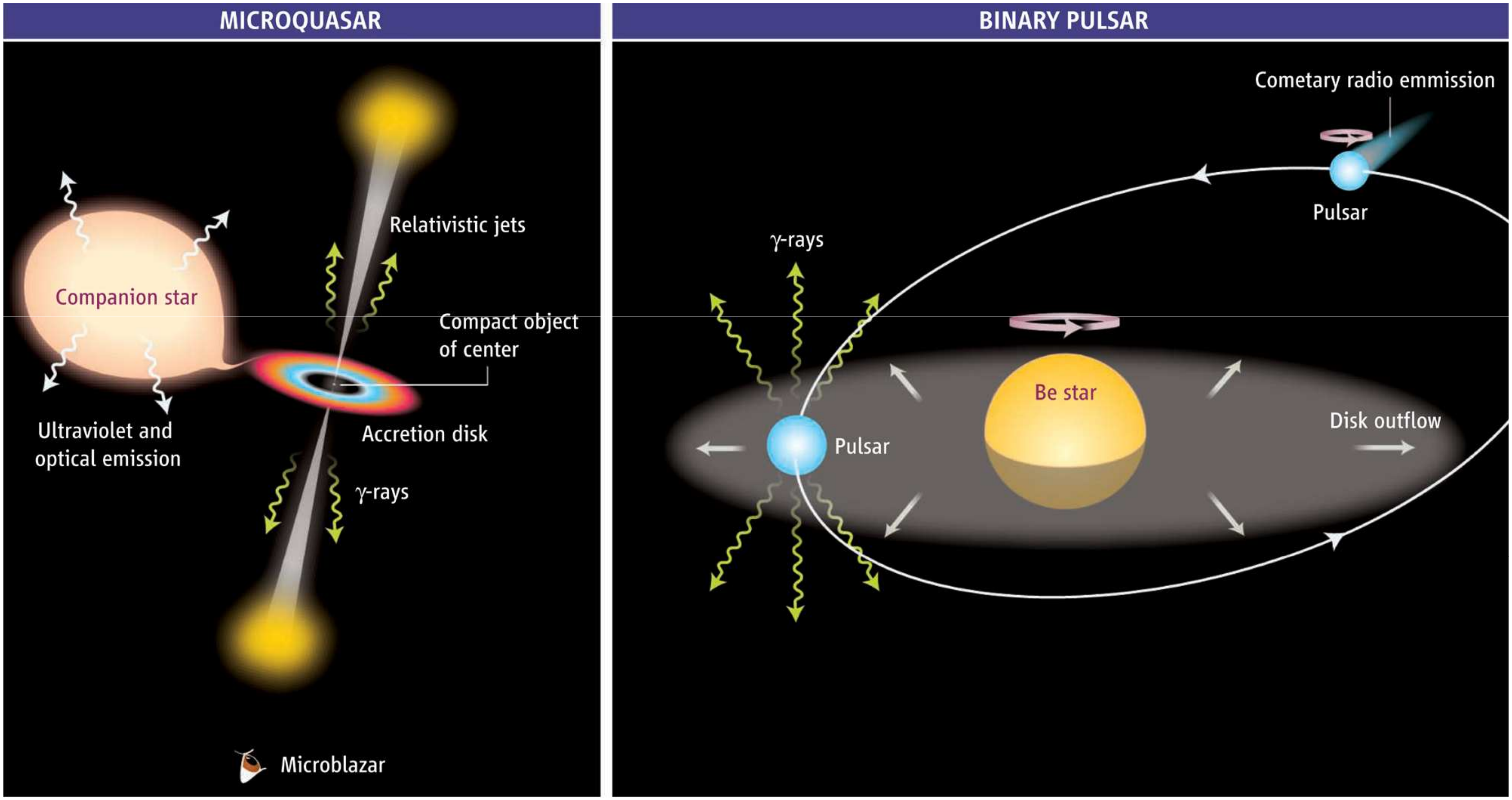




Albert+ 2007, ApJ, 664, L87

Microquasar vs Binary Pulsar?

Competing scenarios for VHE γ-ray emission



LS I +61 303

X-Ray binary system with radio jet → μQSO?? (other known γ-ray binaries: LS 5039, PRS B1259-63, by HESS
Cygnus X-1, by MAGIC)

Orbit: high eccentricity (ε~0.7), P=26.5 d

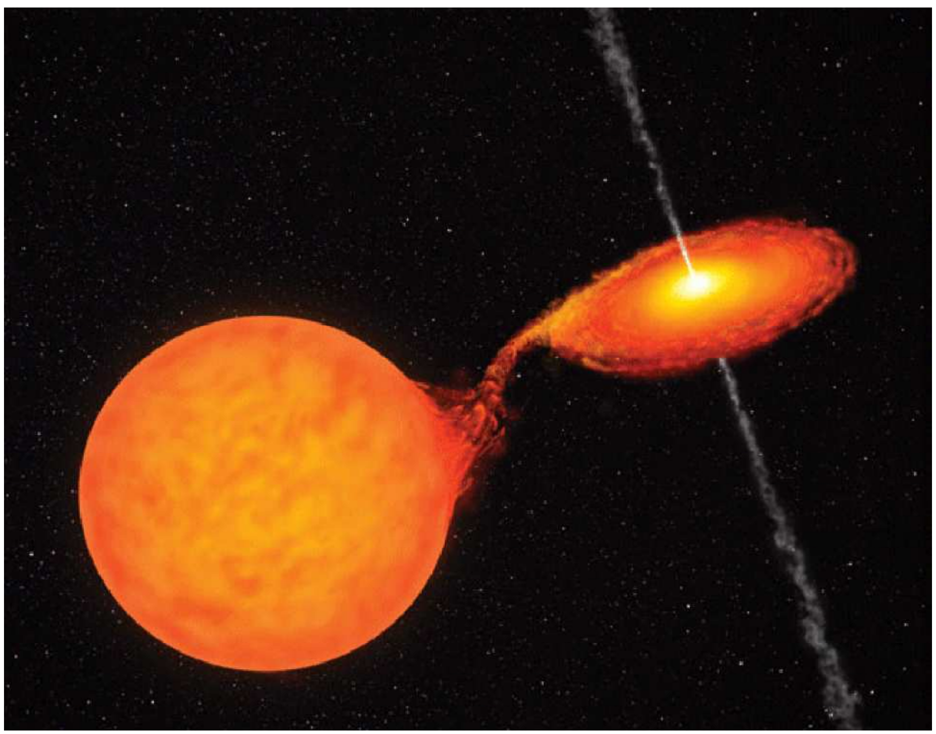
Normal star: B0 main sequence star, ~18$M_{\otimes}$, a Be star with circumstellar disc

Compact star: BH / NS < 4$M_{\otimes}$

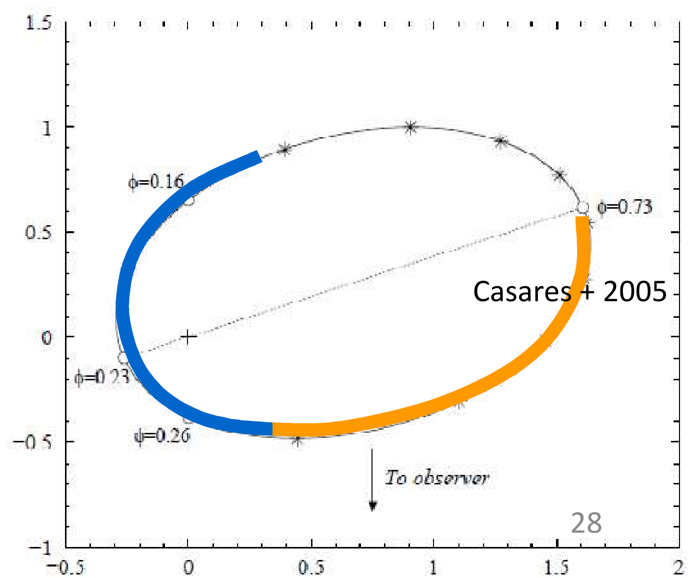
Distance ~2 kpc

Albert+ 2006, Science, 312, 1771

D = 2 kpc
Binary: Be + compact, P = 26.5 d
Compact: NS or BH
Periodic radio bursts
X-ray bursts at f=0.4-0.6 (Rosat, RXTE)
Radio jets (precessing): → μQSO?
>100 MeV mesured by COS B
→ correlation w. radio bursts
GeV emission (EGRET) variable, max. at φ=0.5 → correl. with X-ray variability
TeV emiss. & variability (MAGIC)
X-ray vs TeV correlation
jets longer than binary separation
→ leptonic channel favored

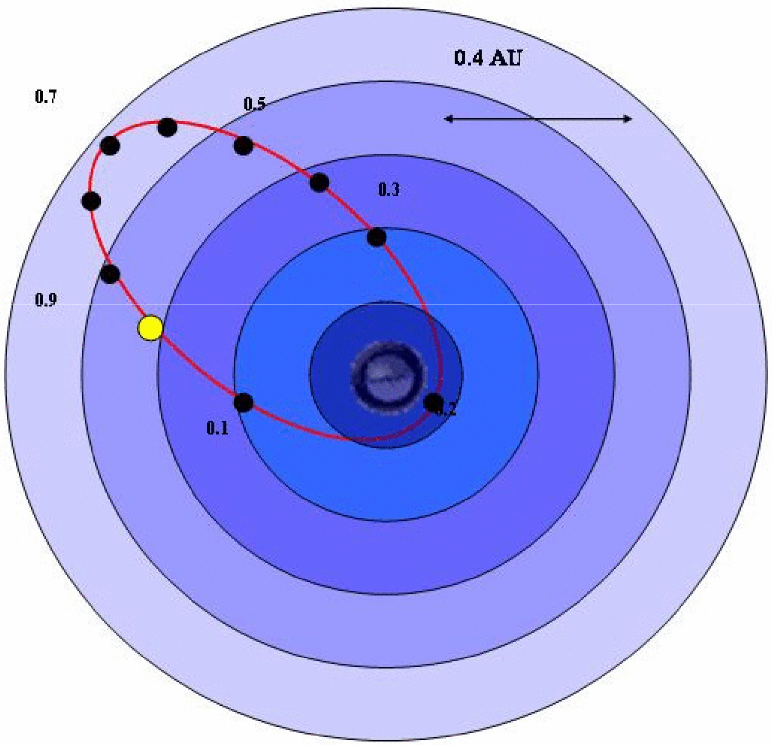


MAGIC observation: 54hrs total

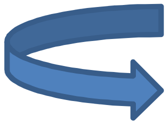


LS I +61 303
… cont'd

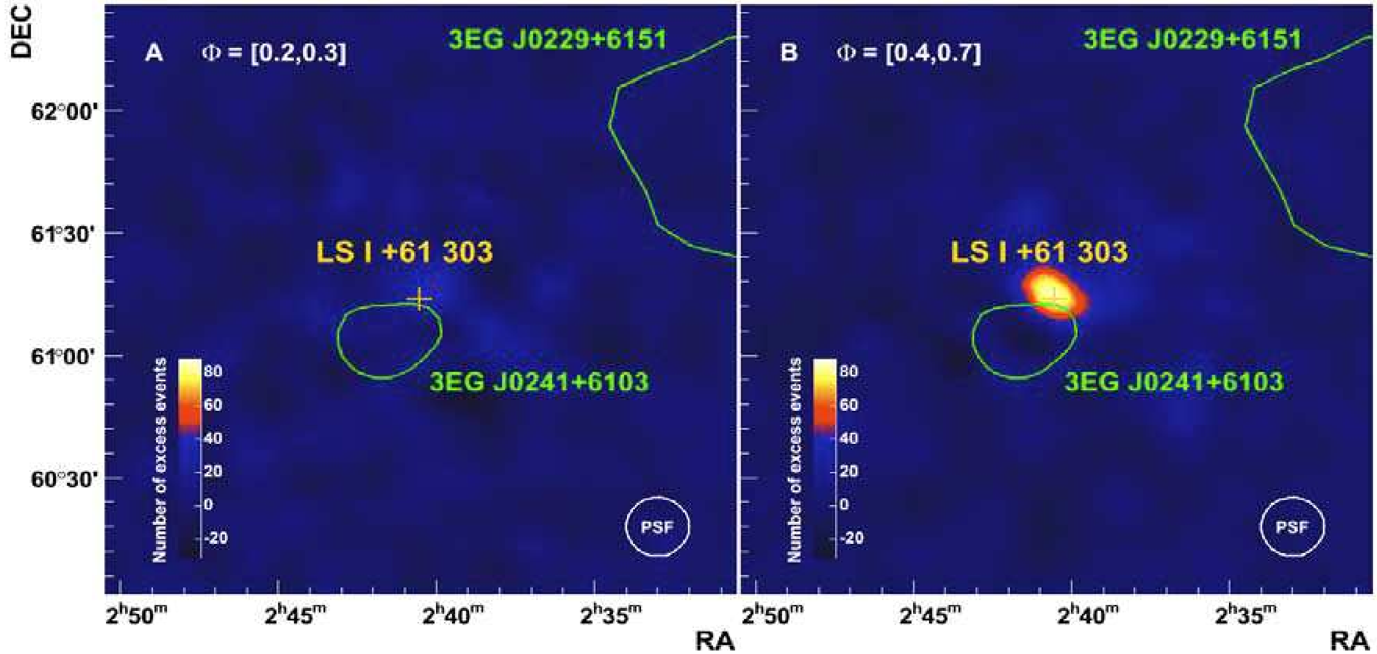
- **X-ray binary system**: Be star orbiting unknown object (P_{orb} = $26^d.4950$)
- VHE flux variable in the phases 0.5-0.9
- Point-like TeV peak @ **ϕ=0.65** (quiet @ periastron)
- **Constant slope:** Γ (E > 400 GeV) = -2.6±0.2 ($\Delta\Gamma_{sys}$ = 0.2)
- Maximum of ~ **16%** Crab flux.

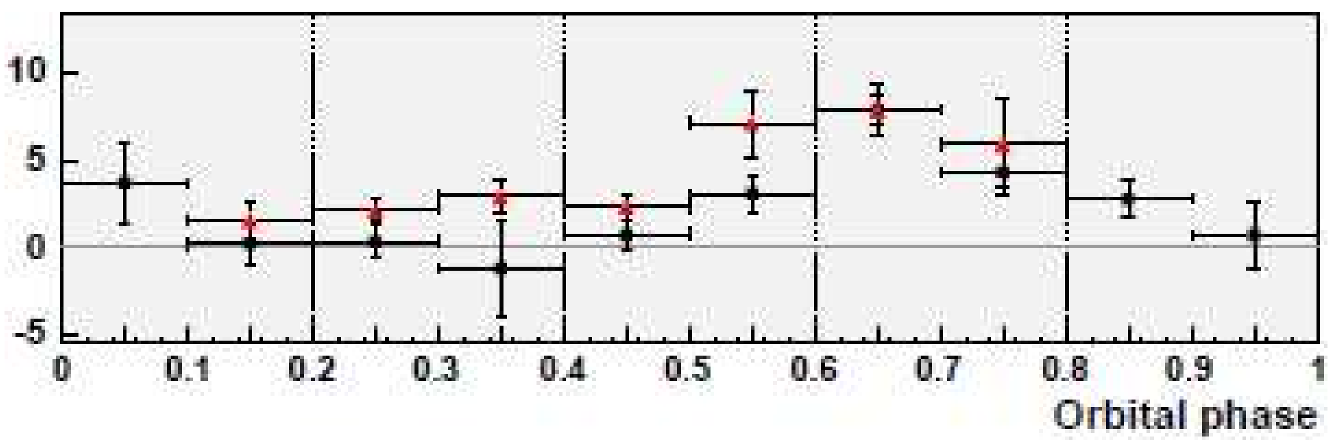


Ten points at equal phase intervals from Φ = 0 to Φ = 0.9, with MAGIC observations (where available) on the right. The periastron is at Φ = 0.2.



LS I 61+303
... cont'd





Albert+ 2008,
ApJ, 684, 1351

Variability averaged over several orbits

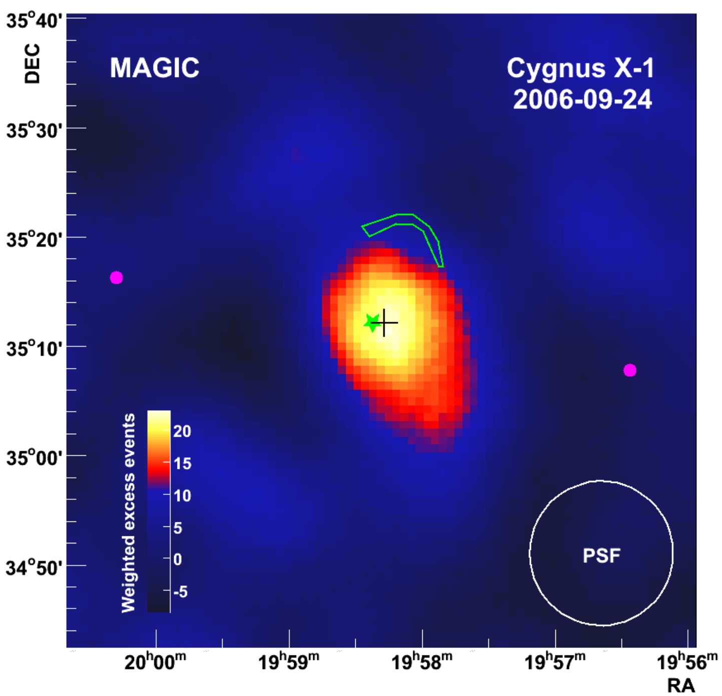
→ … conclusions on LS I +61 303

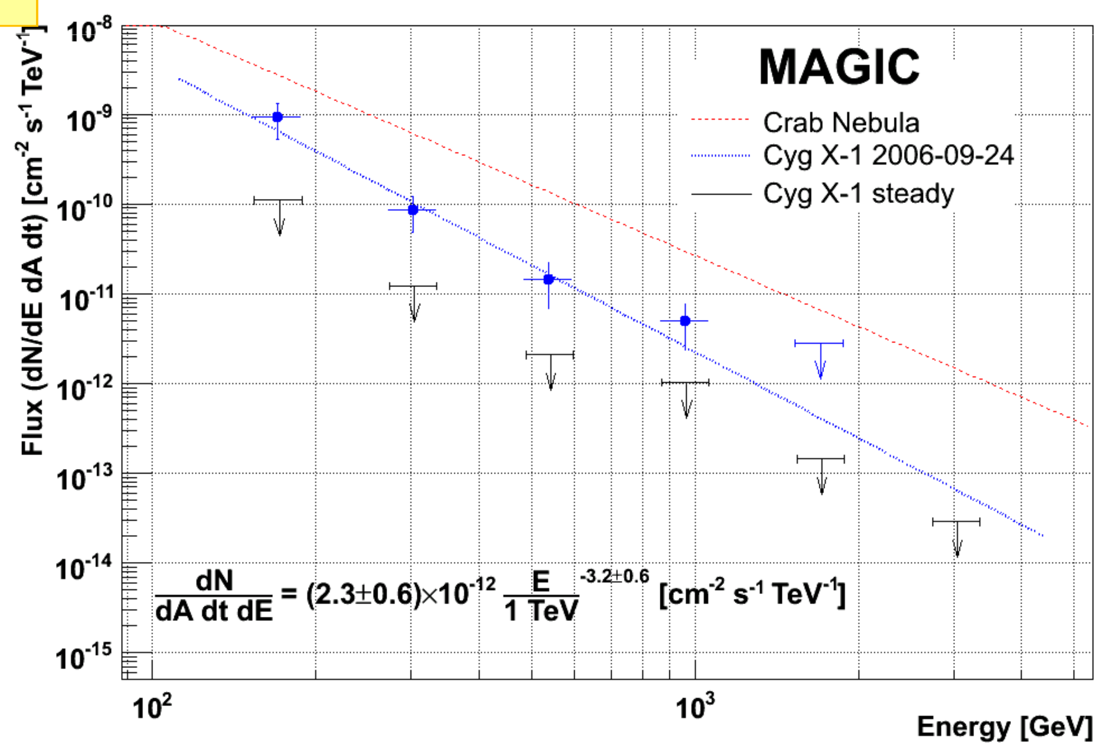
- **periodic (26.8 ± 0.2 d^{-1}) VHE γ-ray emitter**
- **spectrum compatible w. PL for all obs's (Γ = 2.6)**
- **No radio / VHE γ-ray correlation found**
- **X-ray / VHE γ-ray correlation found**
- **Leptonic production of both emission (SSC) favored**

Cygnus X-1 (1)

- BH binary: (21±8) $M_\oplus$ BH and (40±10) $M_\oplus$ O9.7 *I*ab, $P = 5.6$ d, $i = 25º\text{-}65º$.
- High/soft, low/hard x-ray spectral states: function of d*M*/dt ?
- Steady VHE flux, <~0.01 c.u. .
- Strong evidence (4.1σ post-trial significance) of intense short-lived [1h-24h] flaring episode discovered by MAGIC on 24-09-2006.
- VHE flare coincident w. x-ray flares (*Swift*/BAT, *R*XTE/ASM and INTEGRAL).
- Soft 0.1-1 TeV spectrum ($\Gamma = 3.2 \pm 0.6_{stat} \pm 0.2_{sys}$), no break.
- Extension below MAGIC angular resolution (~0.1°).
- Radio-nebula produced by the jet (Gallo '05) interaction with the interstellar medium excluded.

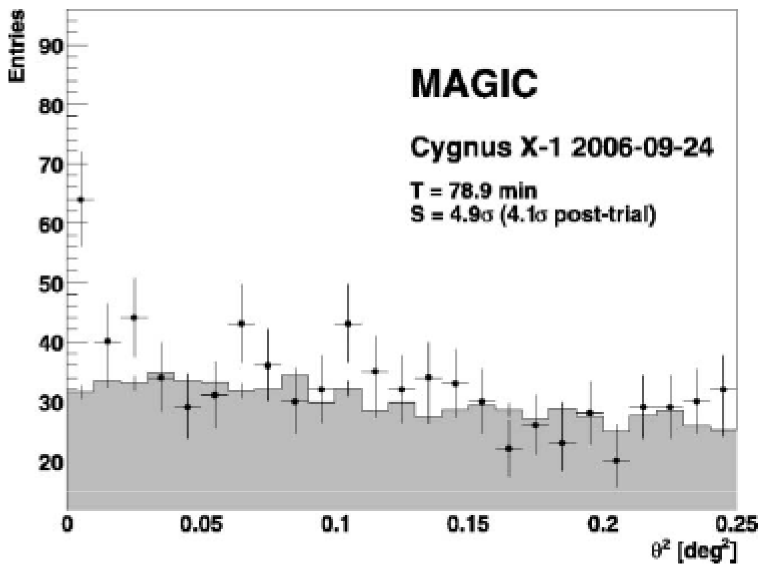
Albert+ 2007 ApJ 665, L51

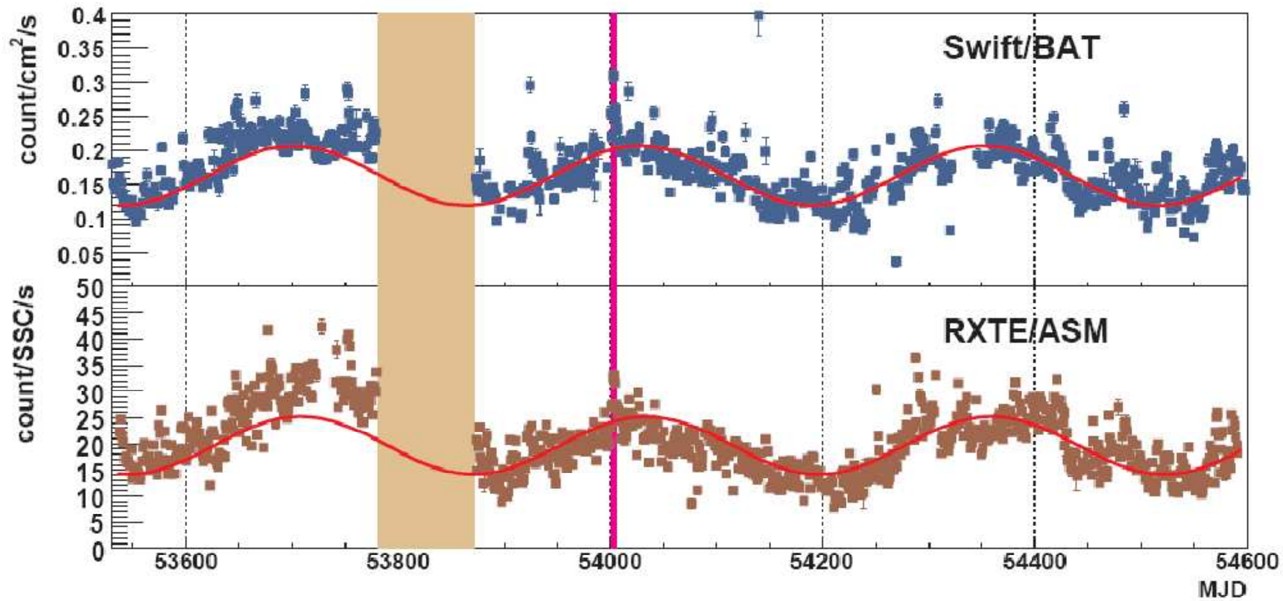


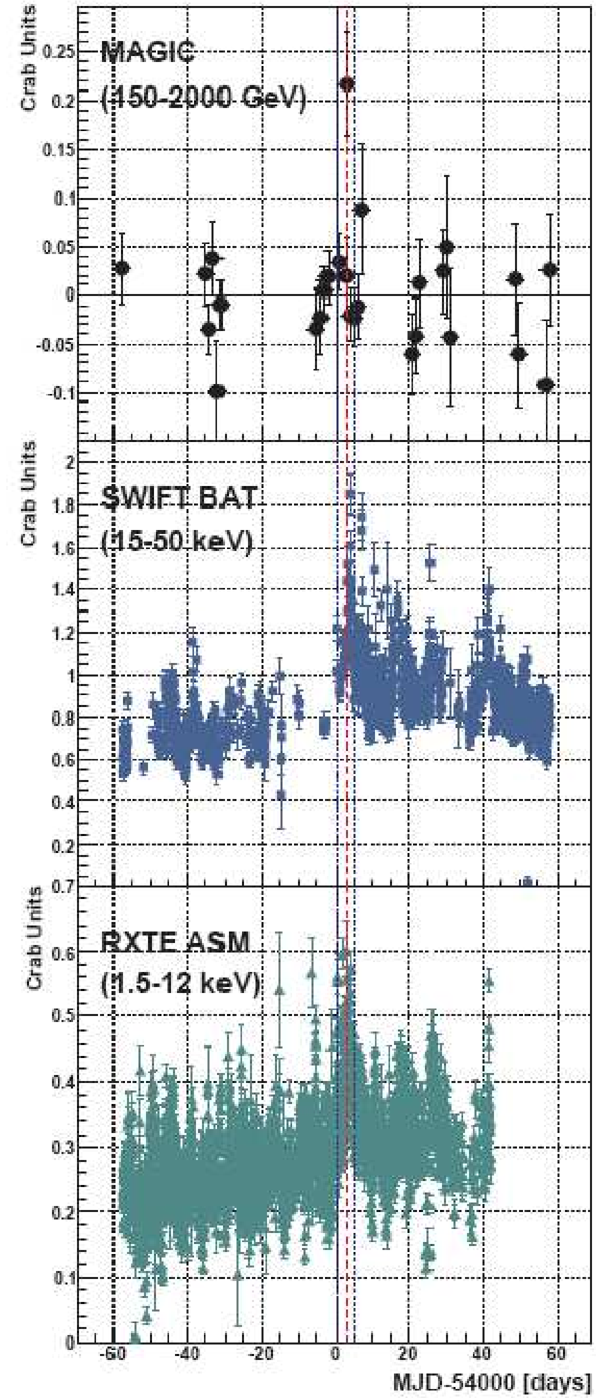


Cygnus X-1 (2)

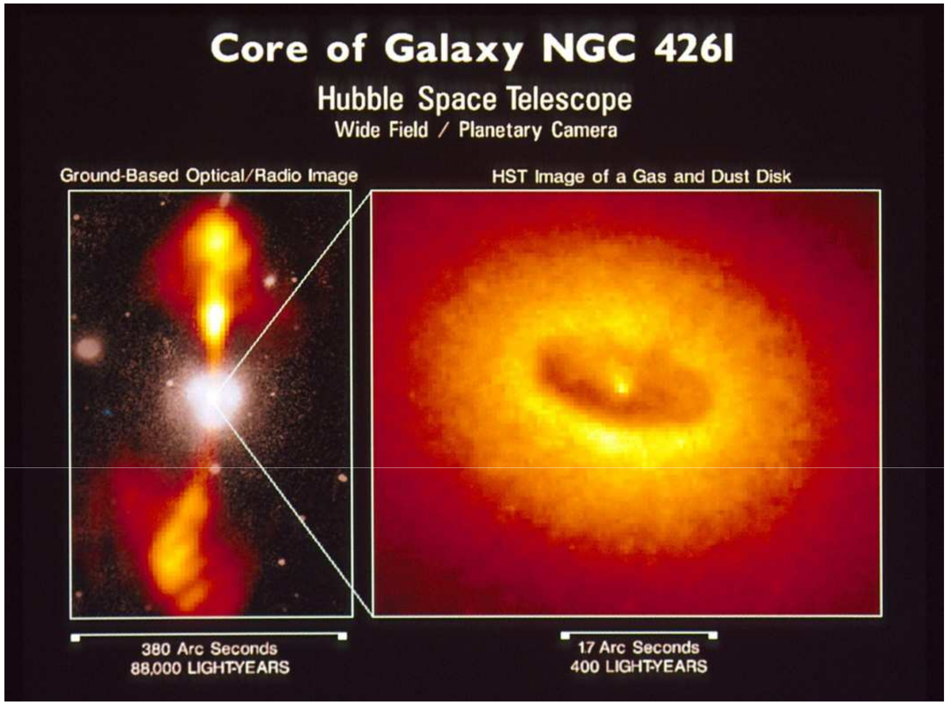
- These flares happen near the max of a ~326d super-orbital modulation (Rico'08), thought to be caused by precession of accretion disk.



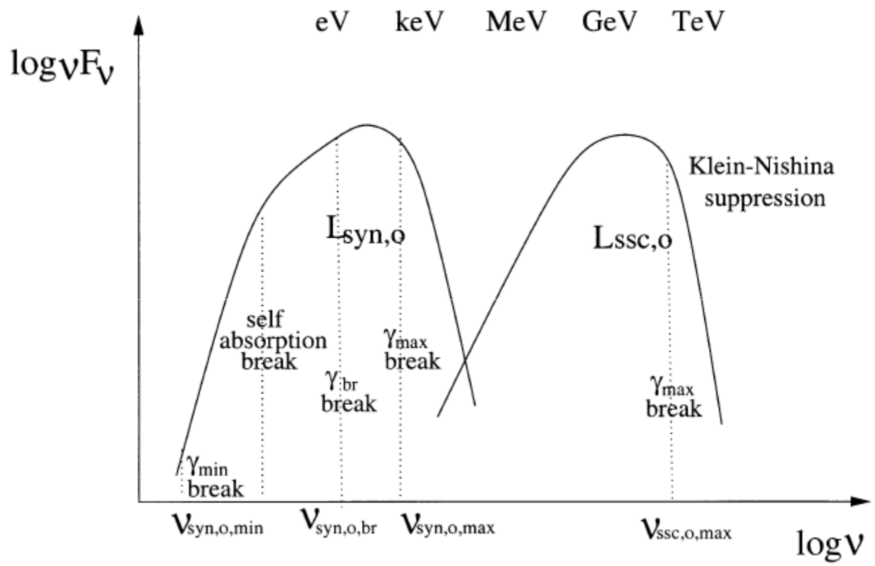




TeV Blazars



Spectral Energy Distribution

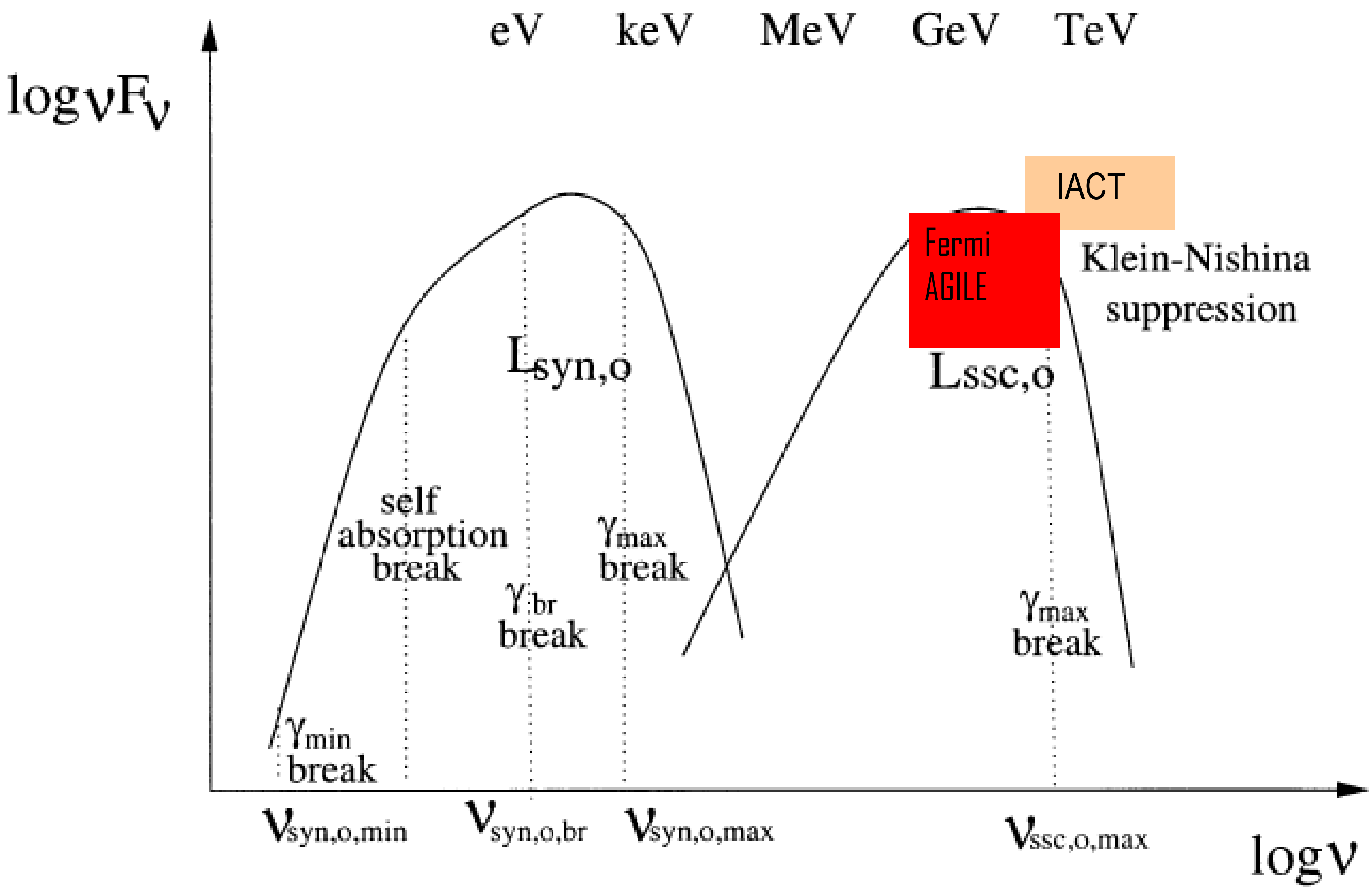


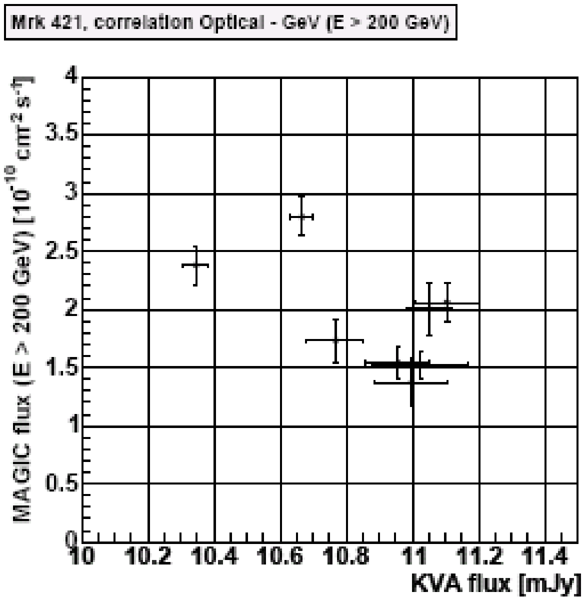
Kino+ 2002, ApJ, 564, 97

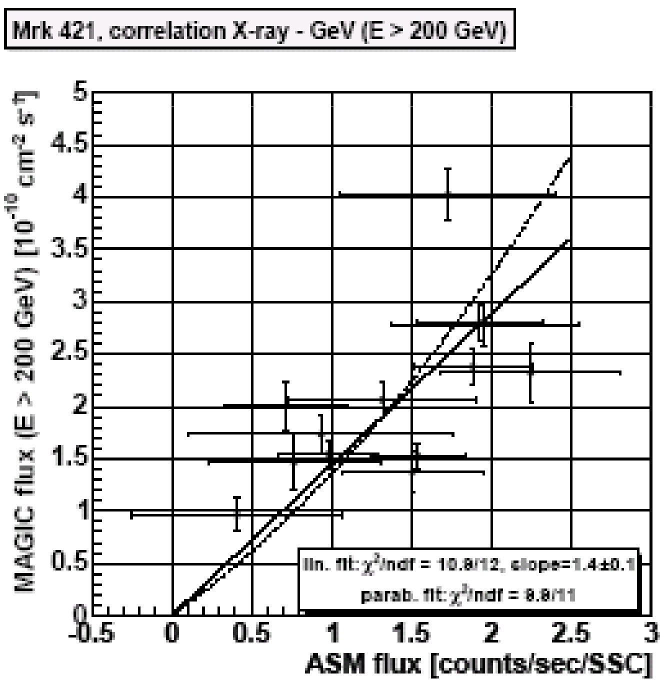
- TeV blazars: highly variable, NT emission
- All but one are HBL (high-peaked BL Lacs)
- Emission: leptonic (mainstream)

SSC model parameters:
Plasma blob: R, B, δ_j
Electron pop: n_0, α_1, α_2, E_{br}, E_{min}, E_{max}
EBL: $u_{EBL}(z)$

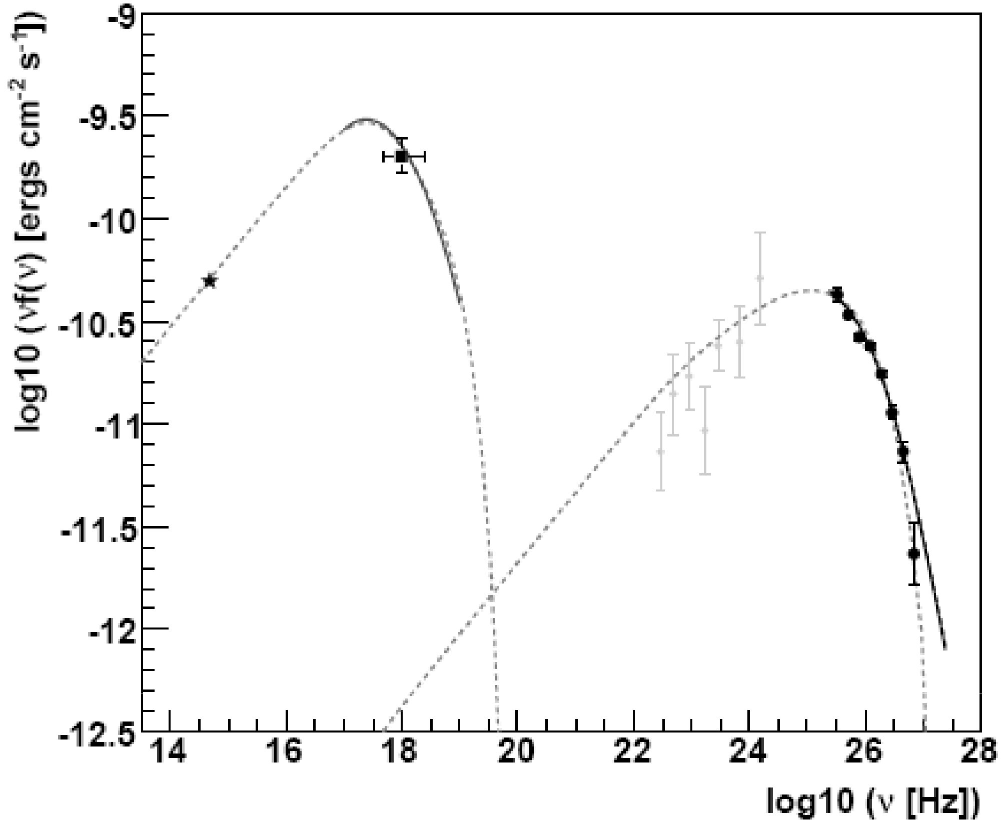
Active Galactic Nuclei



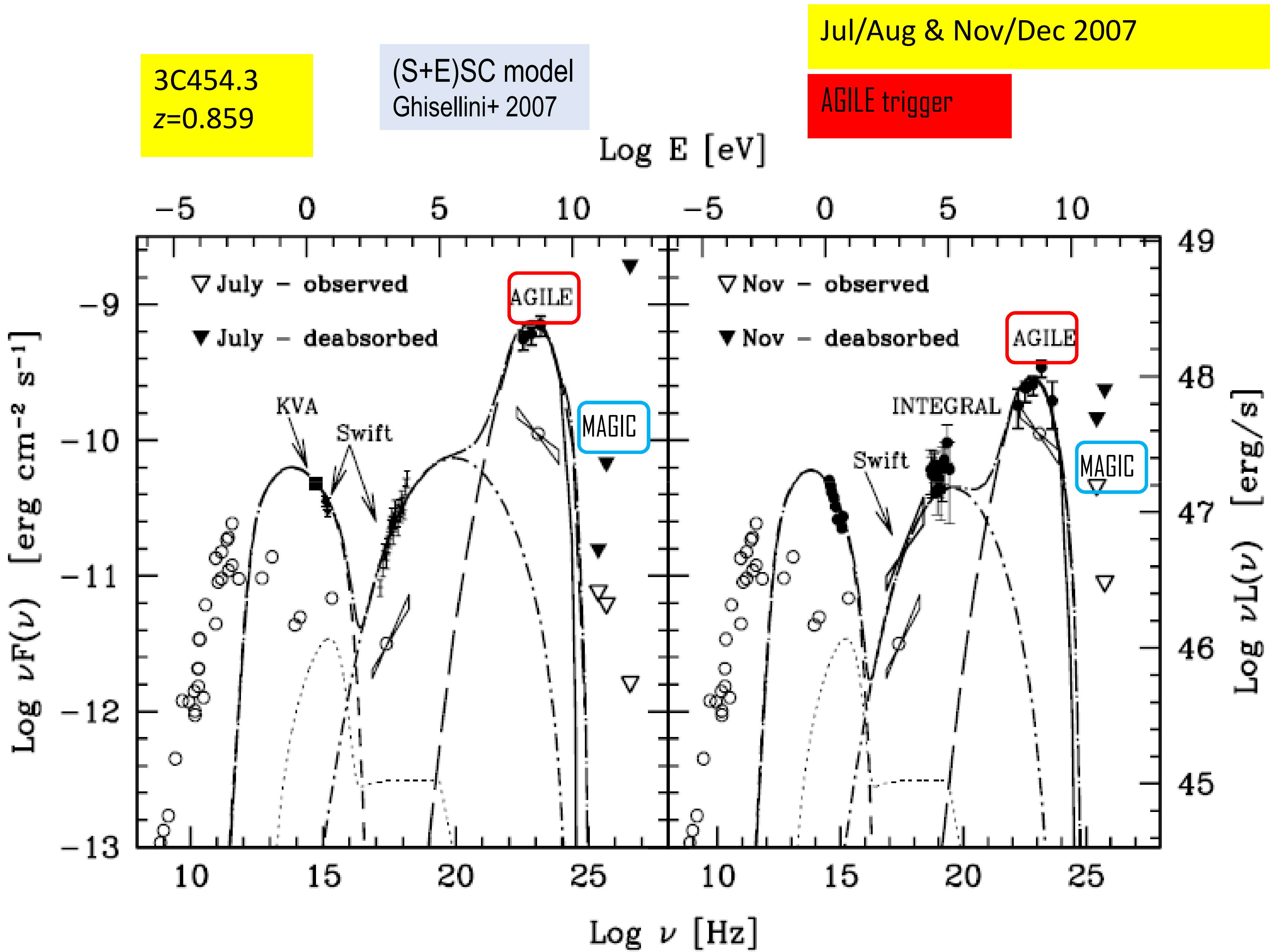


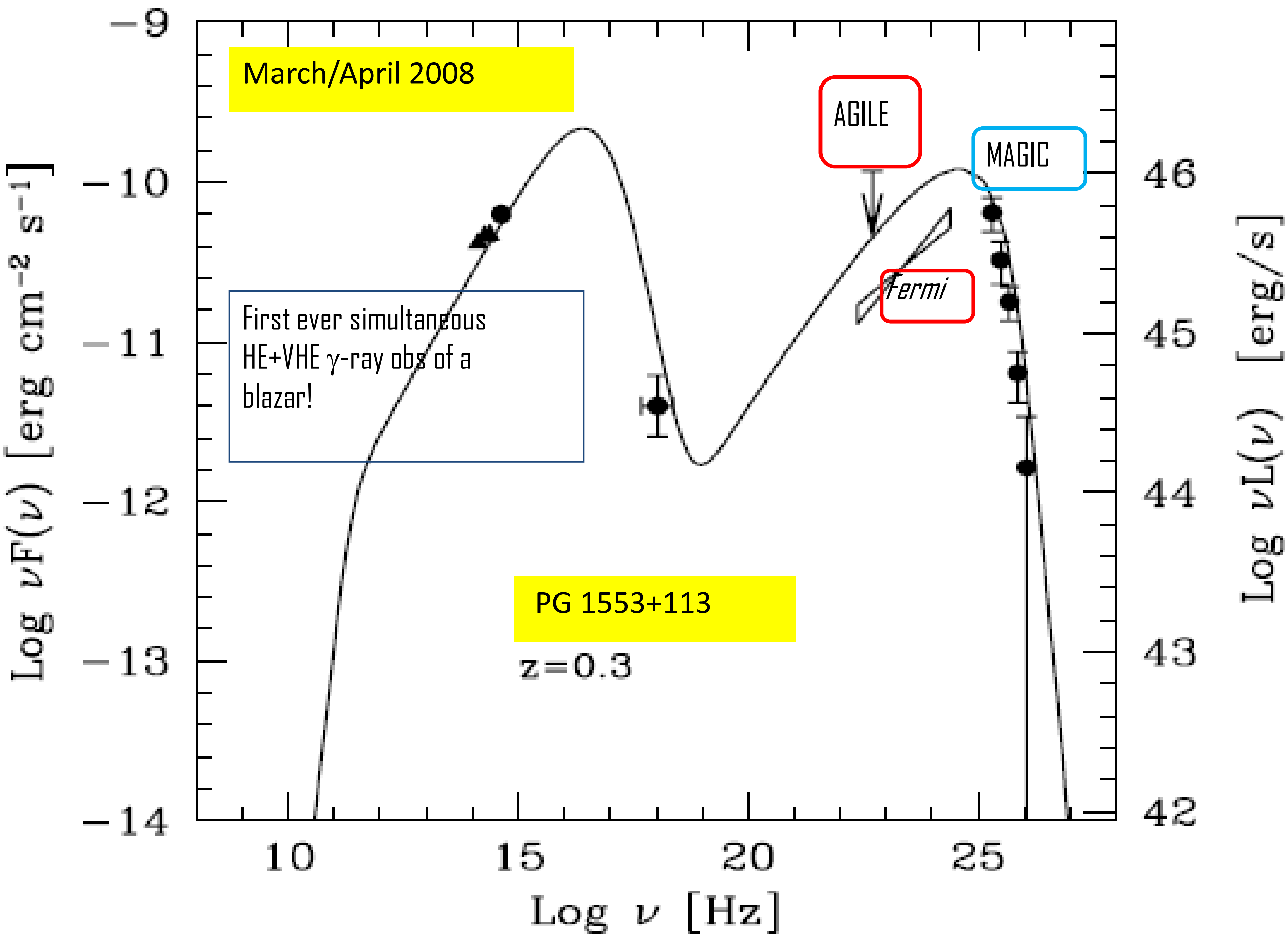


Mrk 421



spherical blob with:	
Doppler factor	15
magnetic field	0.20 Gauss
radius of emitting region	1.6×10^{16} cm
injected electron spectrum:	
electron energy density	0.06 erg/cm^3
$5 < \log10(E[eV]) < 10.9$	index 2.31
$10.9 < \log10(E[eV]) < 11.6$	index 3.88


3C454.3
z=0.859
(S+E)SC model
Ghisellini+ 2007
Jul/Aug & Nov/Dec 2007
AGILE trigger
Log E [eV]
−5
0
5
10
∇ July – observed
▼ July – deabsorbed
∇ Nov – observed
▼ Nov – deabsorbed
AGILE
MAGIC
KVA
Swift
INTEGRAL
−9
−10
−11
−12
−13
49
48
47
46
45
Log νF(ν) [erg cm⁻² s⁻¹]
Log νL(ν) [erg/s]
Log ν [Hz]
10
15
20
25



March/April 2008
AGILE
MAGIC
Fermi
First ever simultaneous HE+VHE γ-ray obs of a blazar!
PG 1553+113
z=0.3
Log νF(ν) [erg cm⁻² s⁻¹]
Log νL(ν) [erg/s]
Log ν [Hz]
−9
−10
−11
−12
−13
−14
46
45
44
43
42
10
15
20
25

Particle acceleration in AGNs: where?

Radio Imaging of the Very-High-Energy γ-Ray Emission Region in the Central Engine of a Radio Galaxy

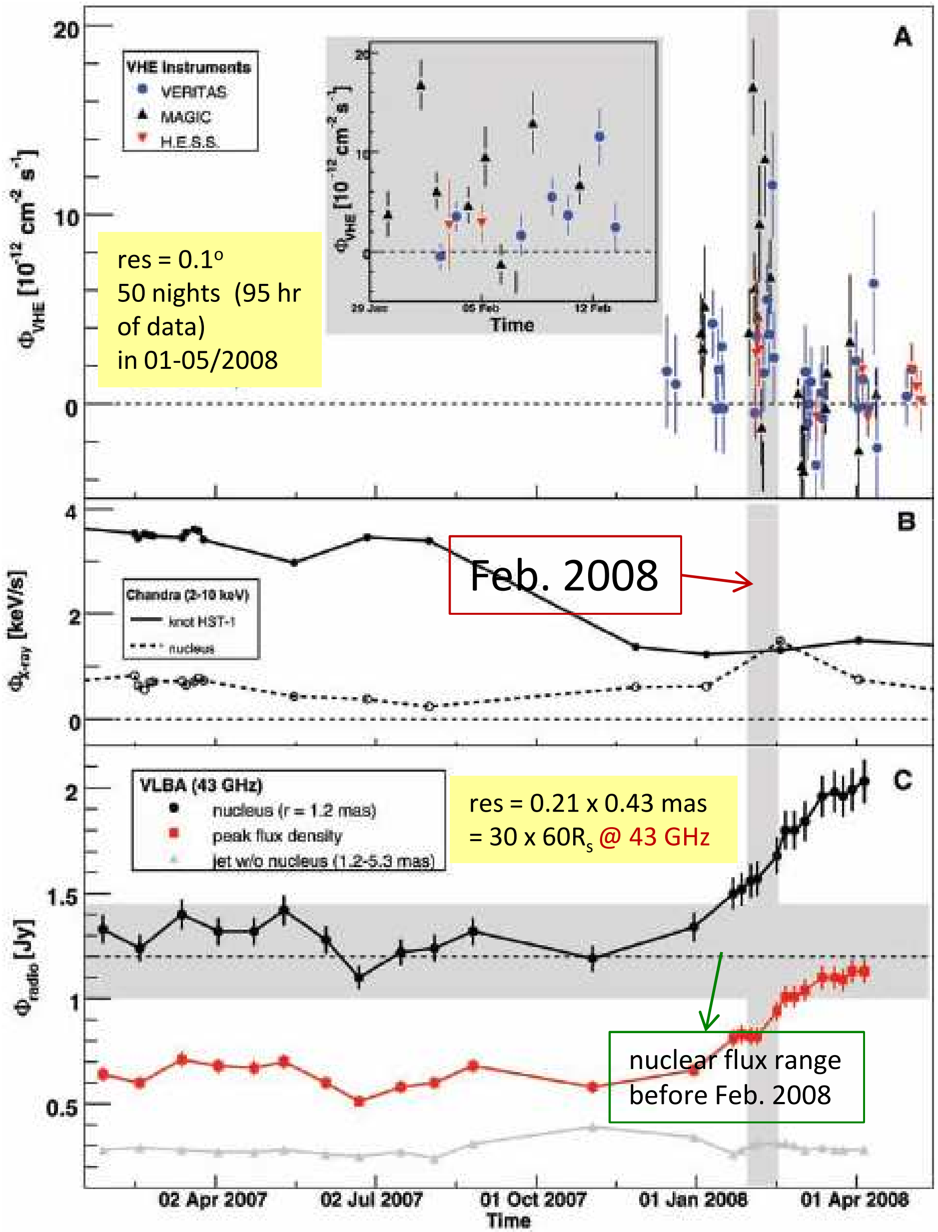
The VERITAS Collaboration, the VLBA 43 GHz M87 Monitoring Team, the H.E.S.S. Collaboration, the MAGIC Collaboration*

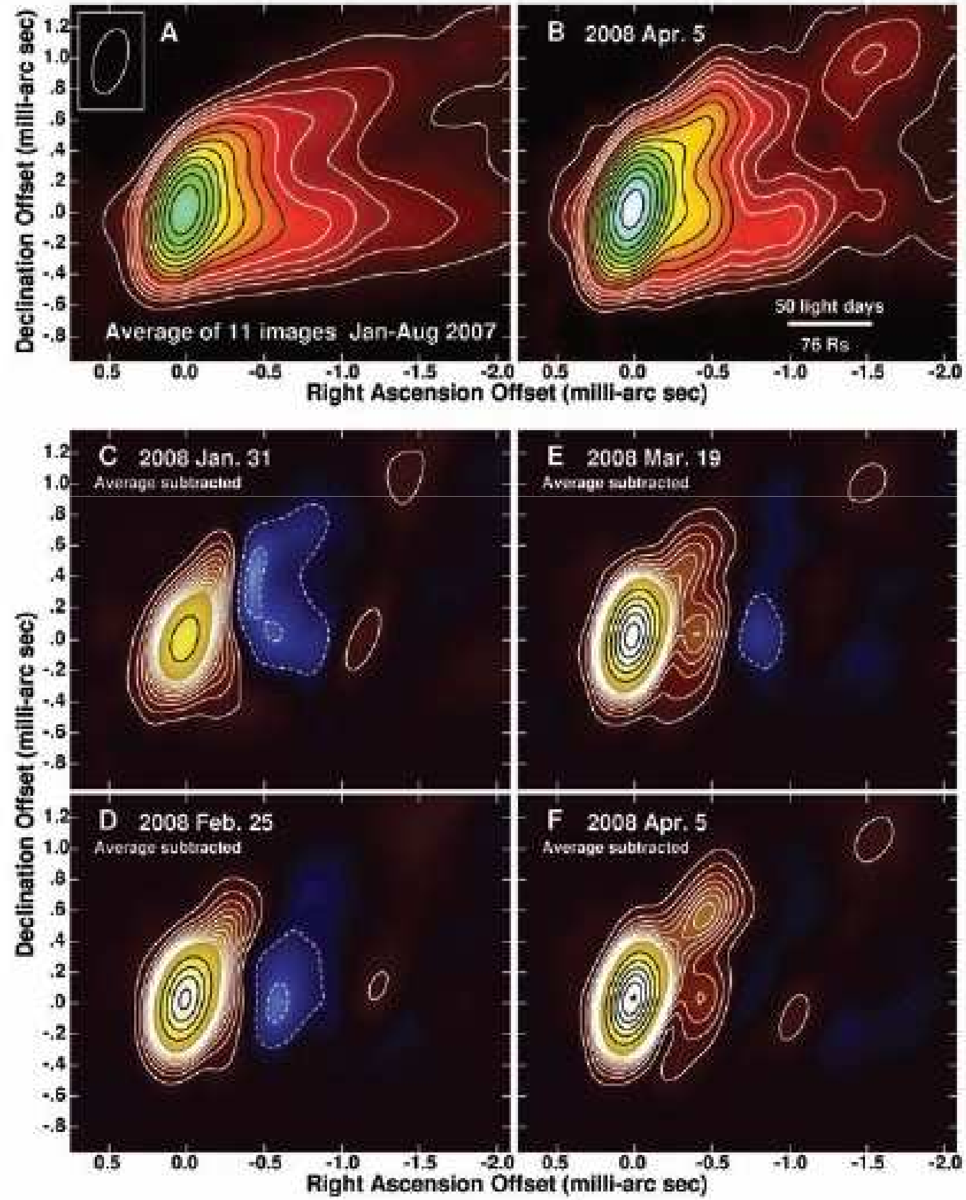
The accretion of matter onto a massive black hole is believed to feed the relativistic plasma jets found in many active galactic nuclei (AGN). Although some AGN accelerate particles to energies exceeding 10^{12} electron volts and are bright sources of very-high-energy (VHE) γ-ray emission, it is not yet known where the VHE emission originates. Here we report on radio and VHE observations of the radio galaxy Messier 87, revealing a period of extremely strong VHE γ-ray flares accompanied by a strong increase of the radio flux from its nucleus. These results imply that charged particles are accelerated to very high energies in the immediate vicinity of the black hole.

Science 325, 445 (2009)

M87: VHE γ-rays, X-rays, radio

δt_{var} ~ days (← MAGIC)





M87: Conclusion

Temporal correlation of nuclear radio/x-ray and VHE emission.

Brightening of M87 nucleus within 50 R_s.

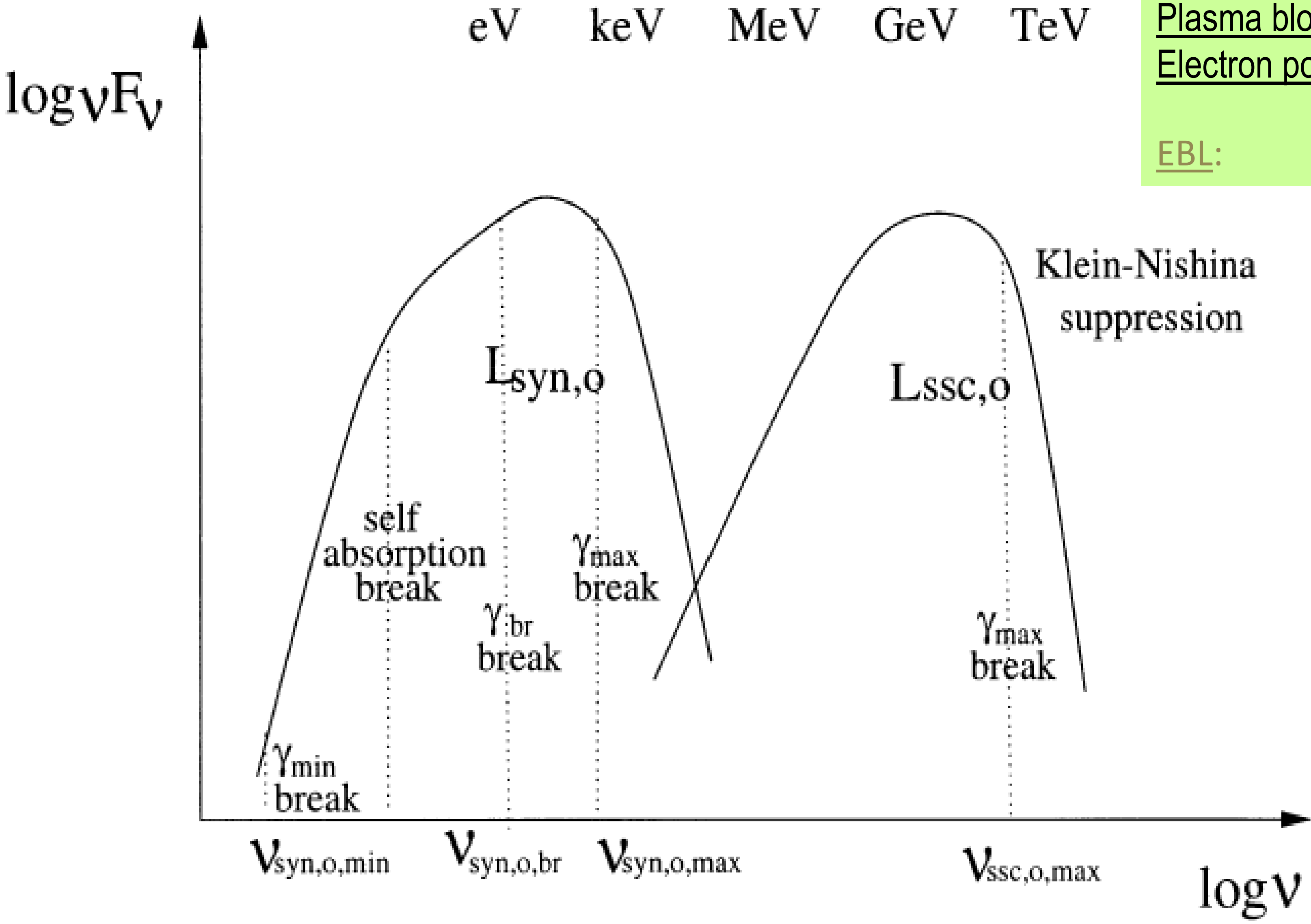
Region of particle acceleration in proximity to BH.

VHE obs’d first (no strong intrinsic $\gamma\gamma$ asorption),
peak radio flux delayed because of synchro self-absorption.

Importance of high-frequency, high-resol. radio obs’s.

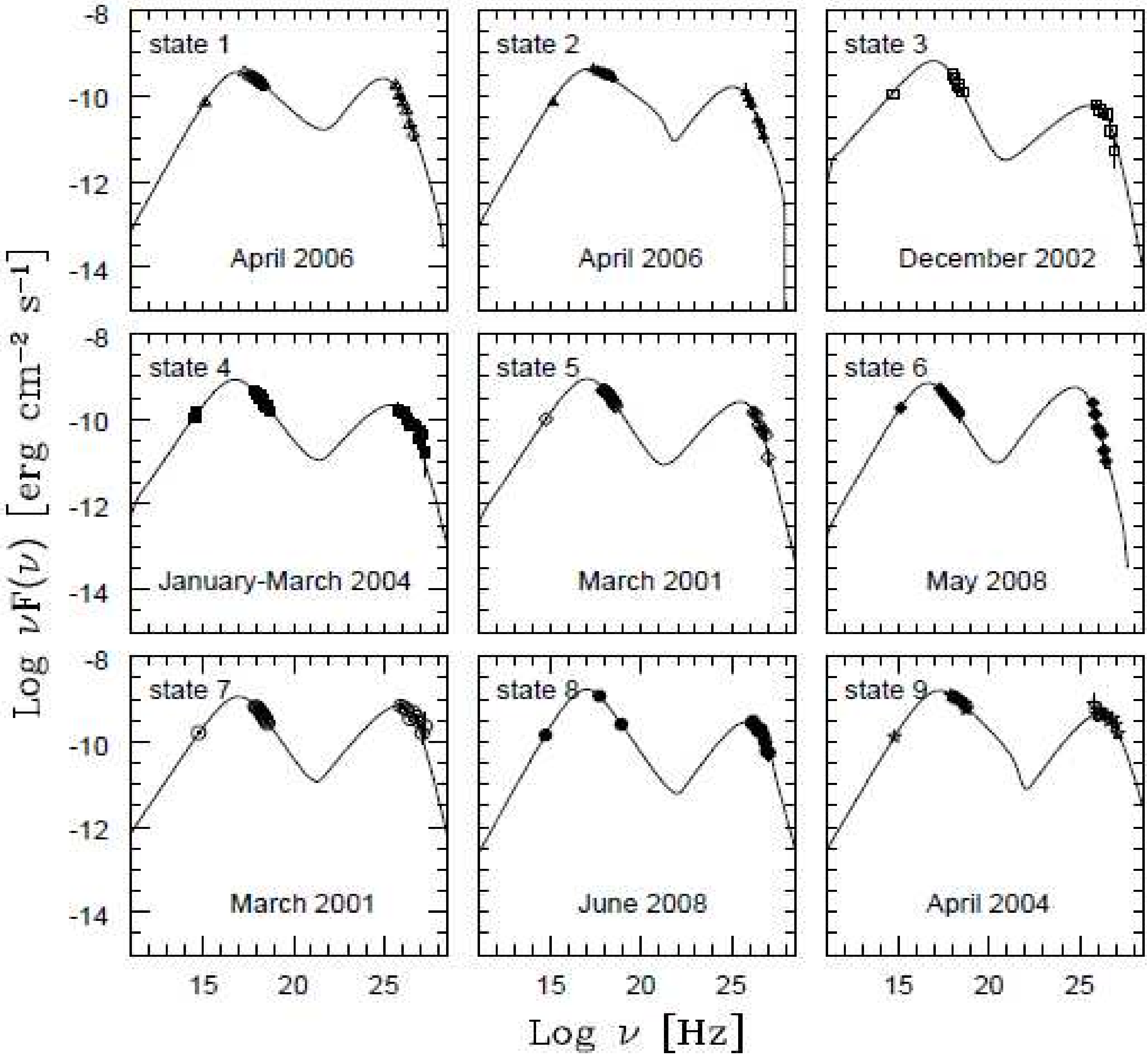
Synchrotron-Self-Compton emission: what changes as a function of activity states?

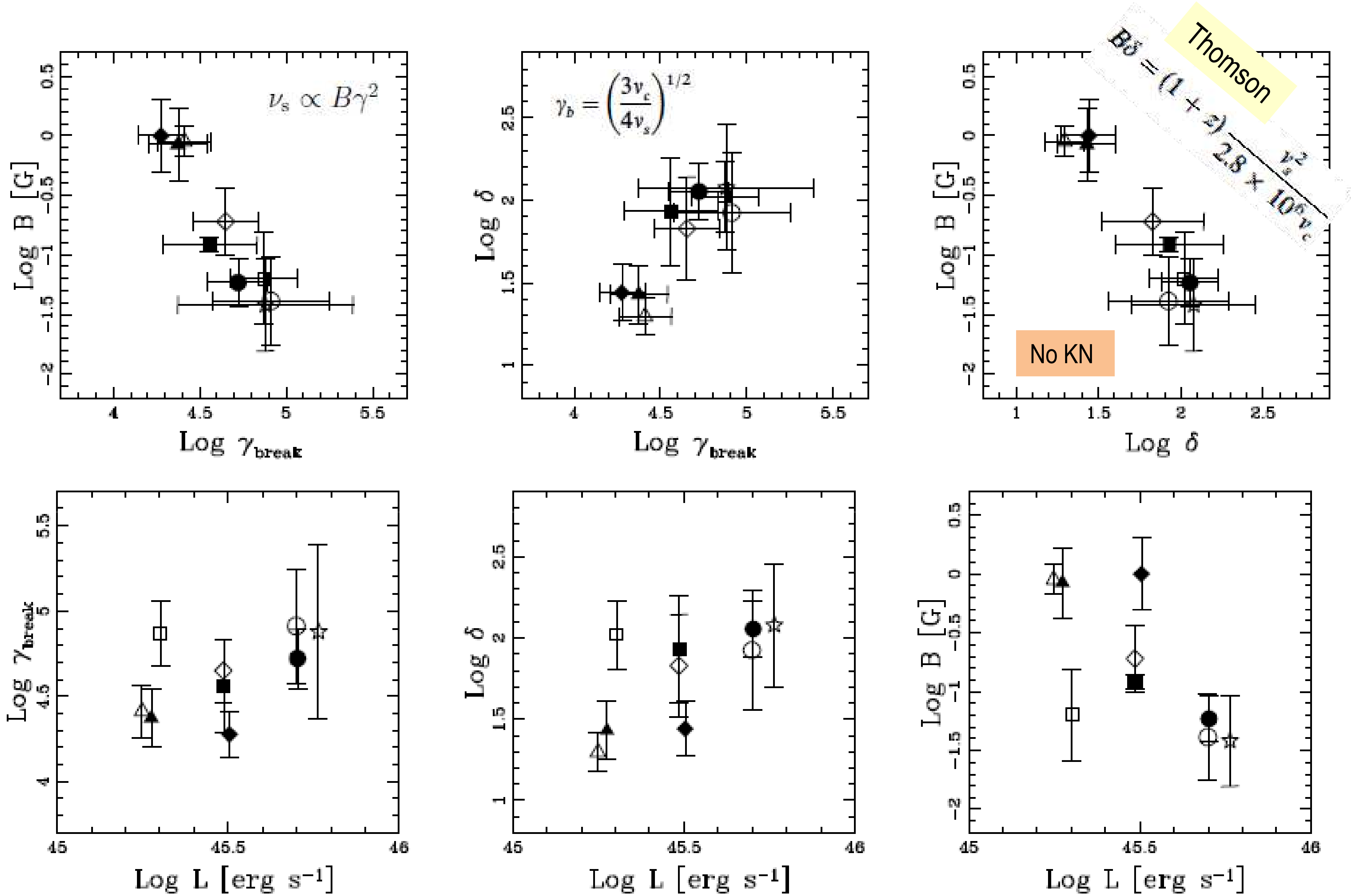
SSC model parameters:
Plasma blob: R, B, δ_j
Electron pop: n_0, α_1, α_2, γ_{br}, γ_{min}, γ_{max}
EBL: $u_{EBL}(z)$



… SSC parameters vs source activity: Mrk 421

Mankuzhiyil, Ansoldi, MP, & Tavecchio 2011, ApJ, accepted



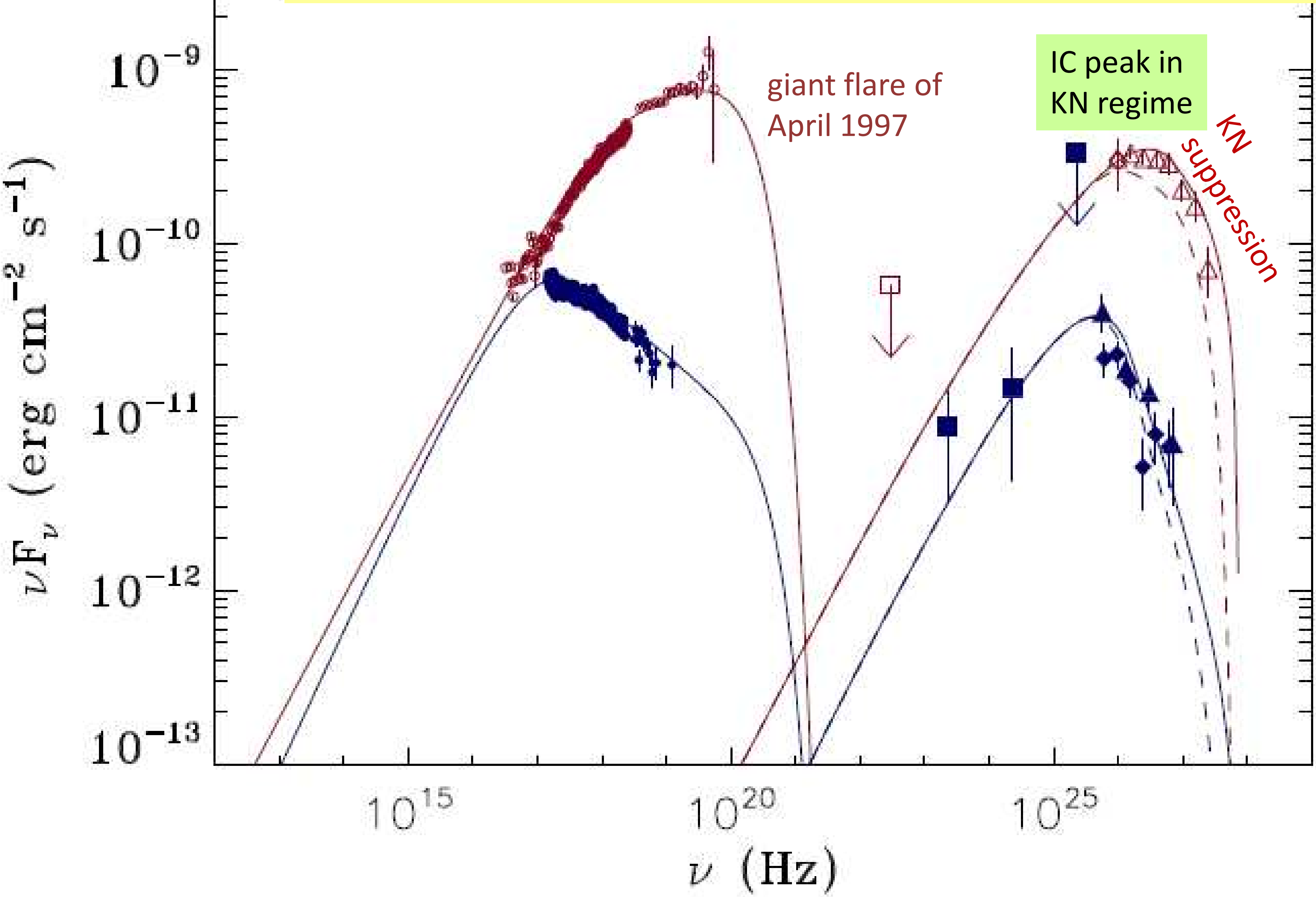


Mrk421's jet activity correlates only w. γ_{break}, **B**, δ

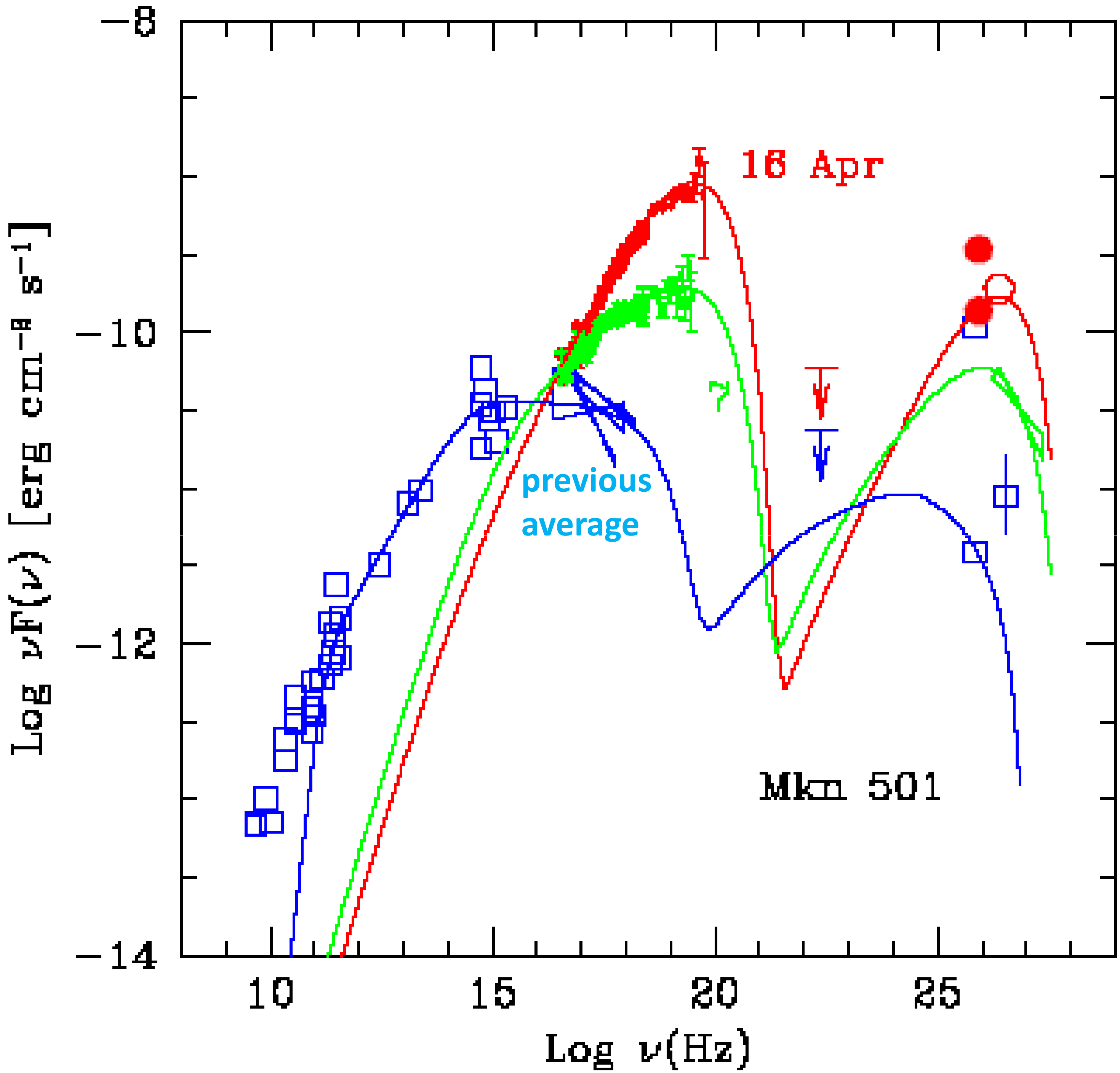
IC peak in Thomson regime

… different variability pattern →

Mrk 501: Suzaku, Fermi/LAT, VERITAS, MAGIC (Acciari et al. 2011 in press)



Pian + 1998



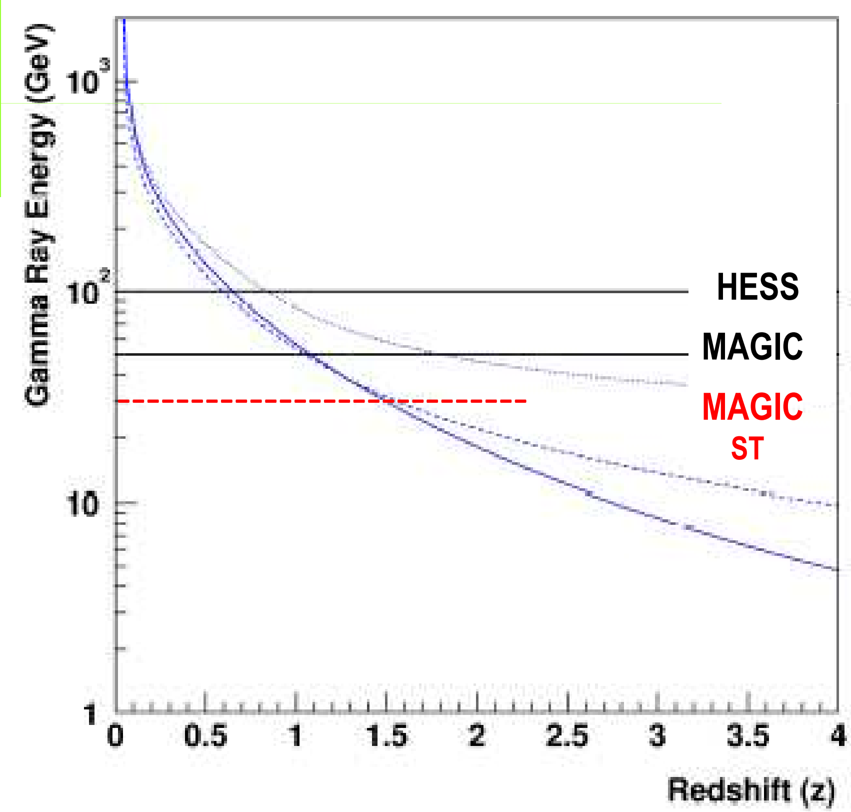
16 Apr
previous
average
Mkn 501
Log νF(ν) [erg cm⁻² s⁻¹]
Log ν(Hz)
−8
−10
−12
−14
10
15
20
25

Conclusion on Mrk 421 variability

- Only *B*, γ_{break}, δ appear correlated with source state.
- γ_{break} increases in high states $\Rightarrow$
  high state $\leftrightarrow$ particle acceleration.
- *B* and γ_{break} are anticorrelated as implied by synchro emissivity
  if ν_{sync} ~ const.
- Even in high states: Compton component is in Thomson regime.

Gamma-**R**ay **B**ursts (**GRB**s)

- Most energetic explosions since Big Bang (10^{54} erg if isotropic)
- Astrophysical setting unknown (hypernova?)
- Emission mechanism unknown (hadronic vs leptonic, beaming, size of emitting region, role of environment, … …)
- Cosmological distances ($z >> 1$)
  but ... missed *naked-eye* GRB 080319B (z=0.937)



HE+VHE data crucial to constrain/unveil emission mechanism(s)

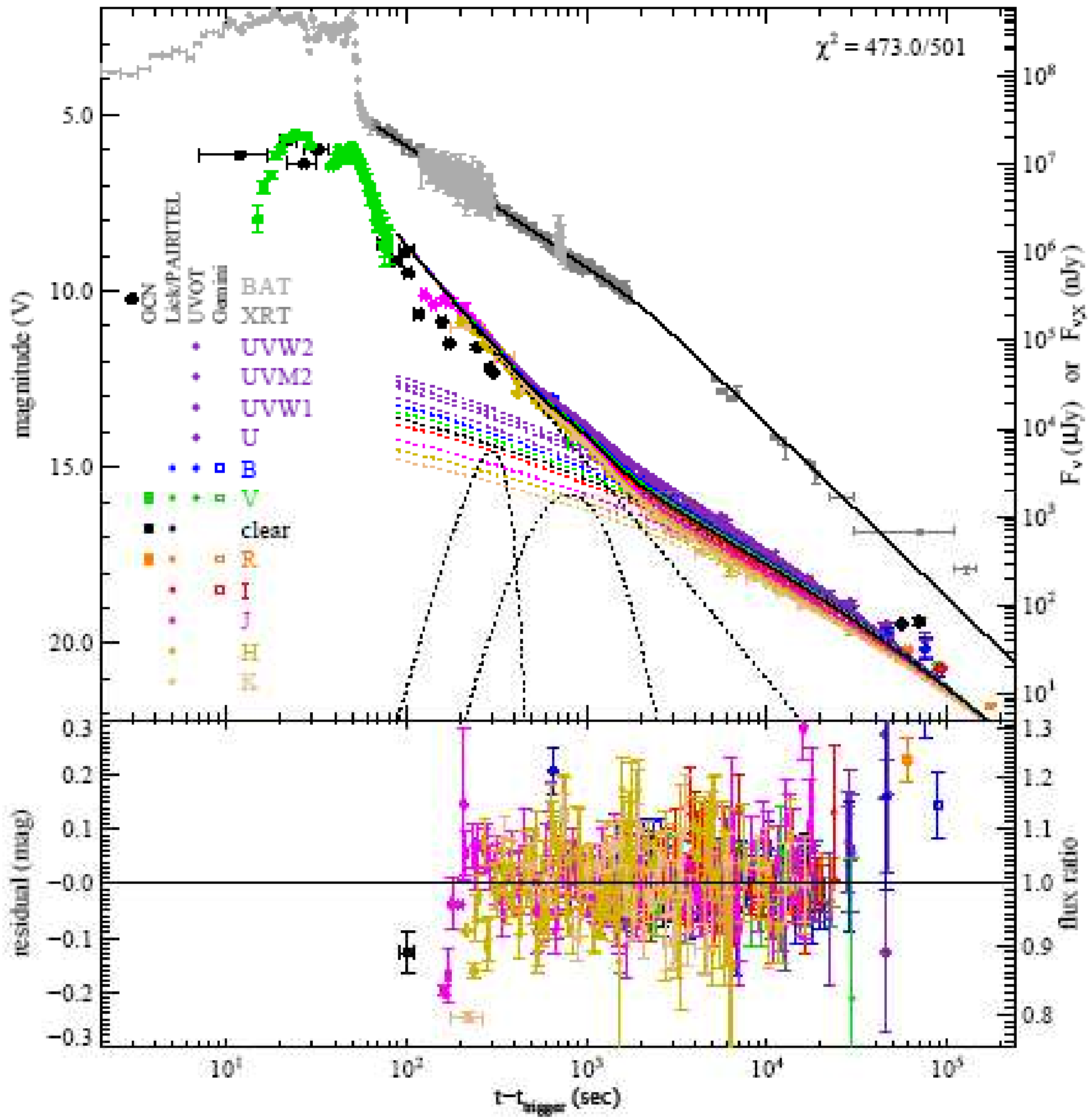
GRBs

080319B → missed obs of "naked-eye" GRB

Intrinsically:
Nearby: z=0.937
Brightest ever observed in optical
Exceedingly high isotropic-equivalent in soft γ-rays

Swift/BAT could have observed it out to z=4.9
1m-class telescope could observe out to z=17

Missed by both AGILE (Earth screening) and MAGIC (almost dawn)



next BIG ONE awaited !!

Quantum gravity effects (involving GRBs)

Amelino-Camelia+ 1998

Stecker 2003

Search for dispersion of light from GRBs $\delta v \sim E/E_{QG}$

QG effect induced by deformed dispersion relation $c^2 p^2 = E^2 [1 + f(E/E_{QG})]$

$f(E_{QG})$: model-dependent function of effective QG scale $E_{QP} \sim E_P \approx 10^{19}$ GeV

If Hamiltonian eq. of motion: $\dot{x}_i = \partial H / \partial p_i$

→ energy-dependent velocities for massless particles $c + \delta v$

→ implications for EM signals from distant astrophysical sources

At $E \ll E_{QG}$: $c^2 p^2 = E^2 \left[1 + \xi E/E_{QG} + \mathcal{O}(E^2/E_{QG}^2)\right]$, with $\xi = \pm 1$ dependent on dynamical framework

Energy-dependent velocity $v = \frac{\partial E}{\partial p} \sim c\left(1 - \xi \frac{E}{E_{QG}}\right)$

→Vacuum responds differently to propagation of patricles of different E → cf. ordinary plasma

→'QG medium' to fluctuate on scale $\lambda \sim L_P \approx 10^{-33}$ cm on timescale $t_P \approx h/E_P$ → cf. thermal fluct's in plasma, $t \approx 1/T$

Time delay (w.r.t. ordinary case of $v=c$): $\Delta t \sim \xi \frac{E}{E_{QG}} \frac{L}{c}$ max. when E, L large and time structure δt small

→ sensitivity factor $\eta \equiv |\Delta t^*|/\delta t$ (being $\Delta t^* \sim \pm E\, L/(c\, E_P)$ and δt the time structure of the signal)

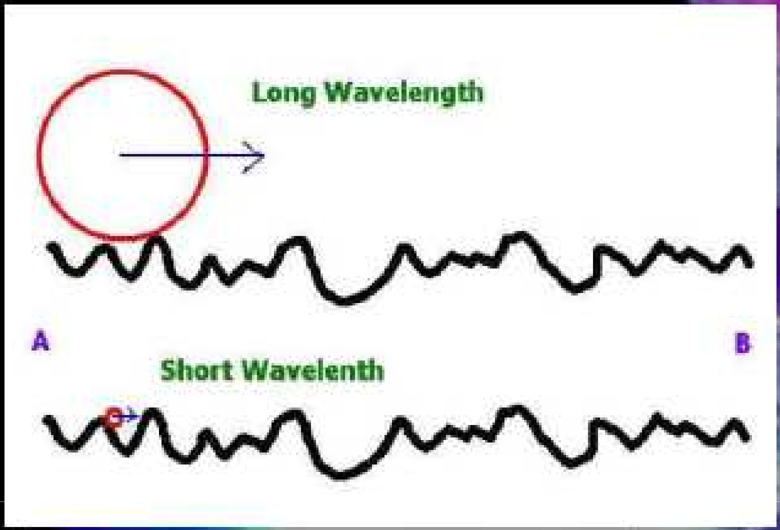
GRBs: $\delta t \sim 0.001$ s, $L \sim 5000$ Mpc, $E \sim 20$ MeV → $\eta \sim 1$

100 s 2 TeV

pulsars: $\delta t \sim \mu s$, $L \sim 3$ kpc, $E \sim$ eV → $\eta \sim 10^{-11}$

SN Ia: $\delta t \sim$ ms, $L \sim 5000$ Mpc, $E \sim$ eV → $\eta \sim 10^{-7}$

Probing Quantum Gravity



$$E_{Pl} = \sqrt{\frac{\hbar c^5}{G}} \approx 1.22 \times 10^{19}\, GeV$$

If Gravity is a Quantum theory,
at a very short distance it may show a very complex "foamy" structure due to quantum fluctuation.

Use gamma ray beam from AGNs/GRBs
to study the space-time structure

Energy 1000GeV ~ $10^{-16} E_{Pl}$
Distance 100~1000Mpc ($10^{16\text{-}17}$sec)

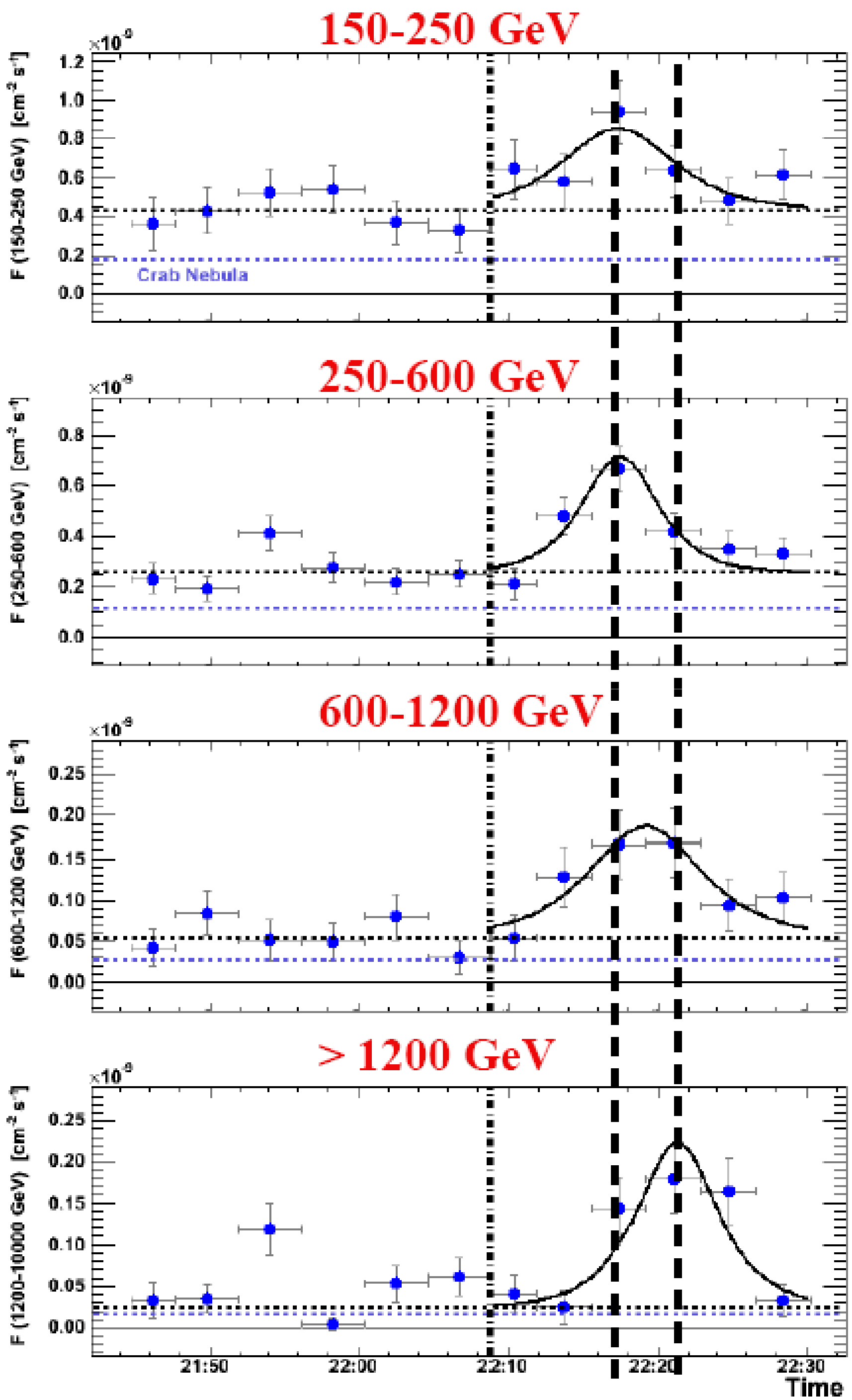
Visible time delay ~ 1 - 10 sec

Linear deviation:

$$\xi_1 < 0; \quad v = c\left(1 - \frac{E}{M_{QG1}}\right); \quad n(E) = 1 + \frac{E}{M_{QG1}}$$

Quadratic deviation:

$$\xi_1 = 0; \quad \xi_2 < 0; \quad v = c\left(1 - \frac{E^2}{M_{QG2}^2}\right); \quad n(E) = 1 + \frac{E^2}{M_{QG2}^2}$$



$E_{QG} \sim 0.05\, M_P$

IF

Photons at different energies were emitted simultaneously
and ∃ no conventional explanations →

$\Delta T = 4 \pm 1$ min; $\Delta E \sim 1$ TeV

$$E_{QG} = \frac{L}{c} \cdot \frac{\Delta E}{\Delta t} = (0.6 \pm 0.2) \cdot 10^{17}\,\mathrm{GeV}$$

... in general:

$$V = c\,[1 \pm \xi\,(E/E_{QG}) \pm \xi_2\,(E/E_{QG})^2 \pm \ldots]$$

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

MAGIC Mkn 501

$E_{QG} \sim 0.03\ M_p$

$E_{QG} > 0.02\ M_p$

HESS PKS 2155

$E_{QG} > 0.04\ M_p$

Whipple 1999, PRL 83(1999)2108

$E_{QG} > 0.005\ M_p$

GRB X-ray limits:

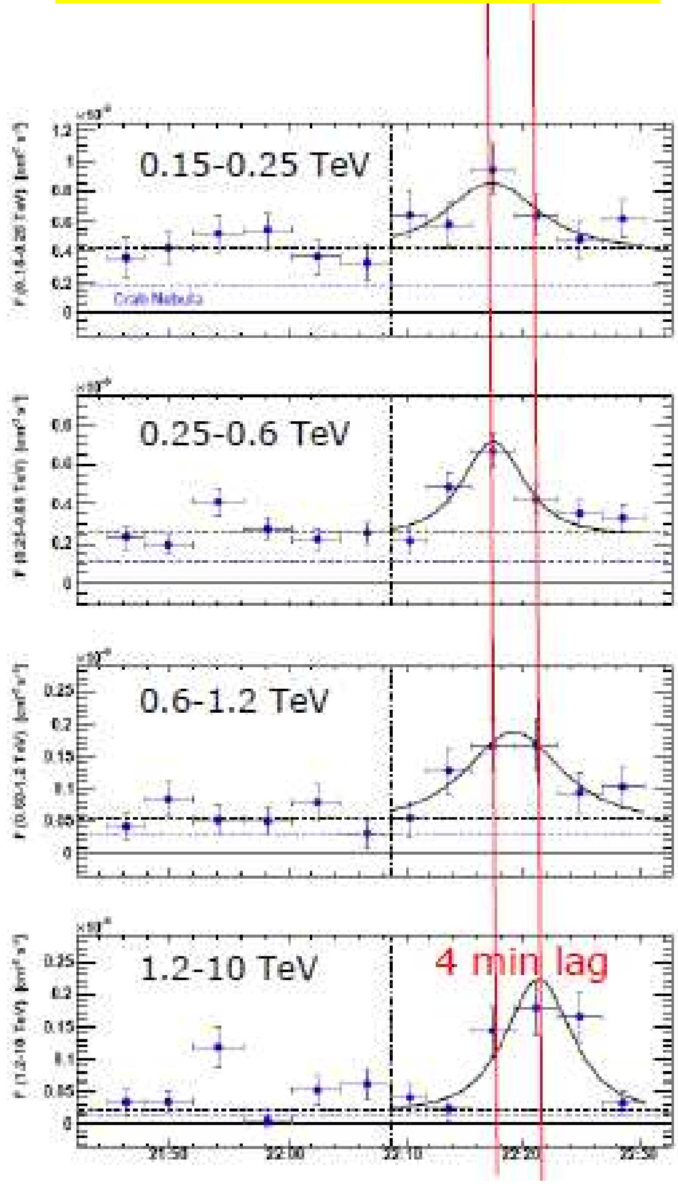
$E_{QG} > 0.001 \ldots 0.01\ M_p$

... but in most scenarios

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

- VHE gamma rays even better
- Mrk 501: $E_{QG} > 3 \cdot 10^{-9}\ M_p$, $\alpha = 2$

Mrk 501: Jul 9, 2005



Cosmic Rays in Galaxies

MP, Rephaeli & Arieli 2008, A&A, 486, 143
Rephaeli, Arieli & MP 2010, MNRAS, 401, 473
MP & Rephaeli 2010, MNRAS, 403, 1569

$N_e(\gamma) = N_{e,0}\,\gamma^{-q} \quad \gamma_1 \le \gamma \le \gamma_2 \quad \ldots\ \gamma_1 = 100$

$F_\nu = 5.67\times10^{-22}\,(r_s^3/d^2)\,N_{e,0}\,a(q)\,B^{(q+1)/2}\,(\nu/4\times10^{+6})^{-(q-1)/2}$ erg/(s cm^2 Hz)

synchrotron

$$\psi \equiv \left(\frac{r_s}{0.1\,\mathrm{kpc}}\right)^{-3}\left(\frac{d}{\mathrm{Mpc}}\right)^{2}\left(\frac{f_{1\,\mathrm{GHz}}}{\mathrm{Jy}}\right)$$

$$N_{e,0} = 5.72\times10^{-15}\,\psi\,a(q)^{-1}B^{-\frac{q+1}{2}}\,250^{\frac{q-1}{2}}$$

$$U_e = N_{e,0} m_e c^2 \int_{\gamma_1}^{\gamma_2}\gamma^{1-q}\mathrm{d}\gamma = 2.96\times10^{-22}\,250^{\frac{q}{2}}\,\psi\,\frac{\gamma_1^{-q+2}}{(q-2)\,a(q)}\,B^{-\frac{q+1}{2}}$$

$$U_p + U_e \simeq \frac{B^2}{8\pi} \qquad \kappa \equiv \frac{U_p}{U_e} = \frac{\int_{T_0}^{\infty} N_p(T)\,T\,\mathrm{d}T}{\int_{T_0}^{\infty} N_e(T)\,T\,\mathrm{d}T}$$

$$B_{eq} = \left[7.46\times10^{-17}\,\frac{(2.5\times10^{-2})^{q/2}}{q-2}\,\psi\,\frac{1+\kappa(q)}{a(q)}\right]^{\frac{2}{5+q}}$$

T_0=few keV

$$\kappa \equiv \frac{U_\mathrm{p}}{U_\mathrm{e}} = \frac{\int_{T_0}^{\infty} N_\mathrm{p}(T)\, T\, \mathrm{d}T}{\int_{T_0}^{\infty} N_\mathrm{e}(T)\, T\, \mathrm{d}T} =$$

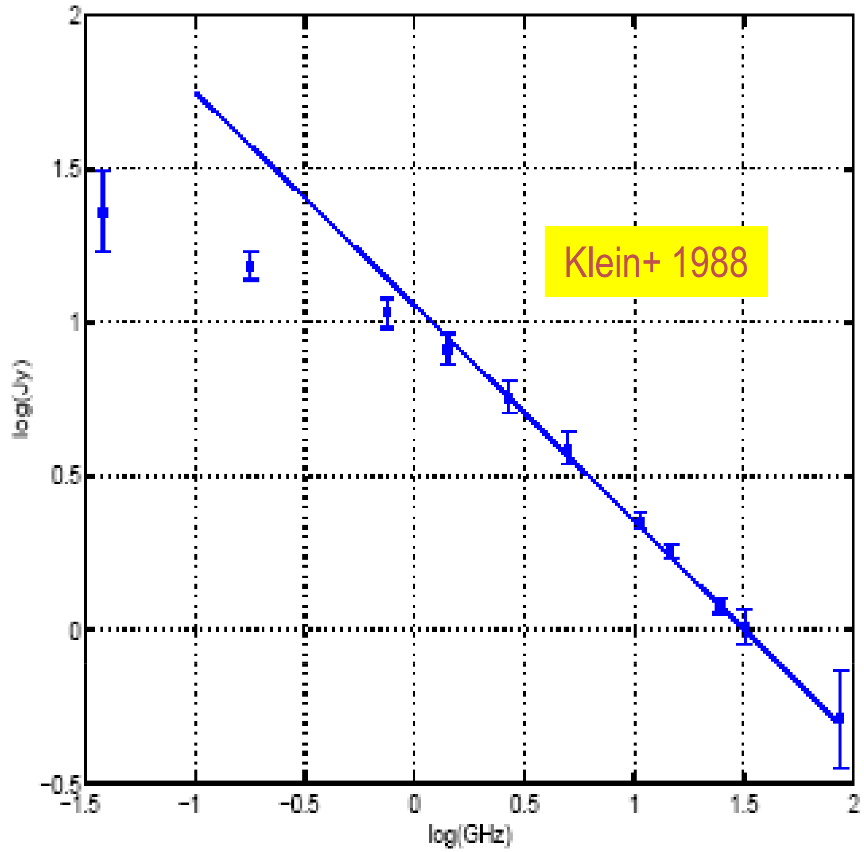
$$= \frac{\left[\frac{T_0^2}{c^2}+2T_0 m_\mathrm{p}\right]^{\frac{q-1}{2}} \int_{T_0}^{\infty} T(T+m_\mathrm{p}c^2)\left[\frac{T^2}{c^2}+2T m_\mathrm{p}\right]^{-\frac{q+1}{2}} \mathrm{d}T}{\left[\frac{T_0^2}{c^2}+2T_0 m_\mathrm{e}\right]^{\frac{q-1}{2}} \int_{T_0}^{\infty} T(T+m_\mathrm{e}c^2)\left[\frac{T^2}{c^2}+2T m_\mathrm{e}\right]^{-\frac{q+1}{2}} \mathrm{d}T}$$

$$\frac{N_\mathrm{p}(T)}{N_\mathrm{e}(T)} \simeq \left(\frac{m_\mathrm{p}}{m_\mathrm{e}}\right)^{\frac{q-1}{2}} \left(\frac{T+m_\mathrm{p}c^2}{T+m_\mathrm{e}c^2}\right) \left(\frac{T+2m_\mathrm{p}c^2}{T+2m_\mathrm{e}c^2}\right)^{-\frac{q+1}{2}}$$

$$\simeq \begin{cases} 1 & T << m_\mathrm{e}c^2\,; \\ [T/(m_\mathrm{e}c^2)]^{\frac{q-1}{2}} & m_\mathrm{e}c^2 << T << m_\mathrm{p}c^2 \\ (\frac{m_\mathrm{p}}{m_\mathrm{e}})^{\frac{q-1}{2}} & m_\mathrm{p}c^2 << T\,. \end{cases}$$

q=2.3 → $\kappa = U_p/U_e \approx 15$ $\quad N_p/N_e \big|_{>>1\mathrm{GeV}} \approx 1.3 \times 10^2$

M82 parameters: d=3.6 Mpc
r(starburst)= 300 pc
f_{1GHz} = 10 Jy
a_r=0.71 → q=2.42



$$B \simeq 95\mu G$$
$$N_{e,0} \simeq 10^{-4} \ \mathrm{cm}^{-3}$$
$$U_e \simeq 20 \ \mathrm{eV\ cm}^{-3}$$
$$U_p \simeq 200 \ \mathrm{eV\ cm}^{-3}$$

L(8–1000μm) = 2.2×10^{44} erg s $^{-1}$

→ SFR ~10 $M_\otimes yr^{-1}$

ν_{SN} ~ 0.3 yr^{-1}

VHE γ-ray emission

analytical approximation

$$L(\geq \epsilon) = \int_V g(\geq \epsilon)\, n\, U_p\, dV \;\; s^{-1}$$

α	$q_\gamma(\geq 100\,\mathrm{MeV})$	$q_\gamma(\geq 1\,\mathrm{TeV})$
4.1	0.46×10^{-13}	1.02×10^{-17}
4.2	0.58×10^{-13}	4.9×10^{-18}
4.3	0.61×10^{-13}	2.1×10^{-18}
4.4	0.57×10^{-13}	8.1×10^{-19}
4.5	0.51×10^{-13}	3.0×10^{-19}
4.6	0.44×10^{-13}	1.0×10^{-19}
4.7	0.39×10^{-13}	3.7×10^{-20}

Drury+ 1994

SB nucleus: r≤0.3 kpc

$M_{H2} = 2\times10^8\ M_\otimes$

U_p = 200 eV cm^{-3}

$L_{>100GeV} = 1.6\times10^{39}\ s^{-1}$ → $F_{>100GeV} = 10^{-12}\ cm^{-2}\ s^{-1}$

External disk: r>0.3 kpc

Gas: flat, thin, exponential disk: $M_g = 2.5\times10^9 M_\otimes$

$U_p = 200\ (R/R_{SB})^{-2}$

$\Sigma(R) = \Sigma(0)\ e^{-R/R_d}$

$\Sigma(0)$ = 7.5E+22 cm-2

R_d = 0.82 kpc

$L_{>100GeV} = 1.5\times10^{40}\ s^{-1}$ → $F_{>100GeV} = 10^{-11}\ cm^{-2}\ s^{-1}$

→ Total flux from M82: $F_{>100GeV} = 1.1\times10^{-11}\ cm^{-2}\ s^{-1}$

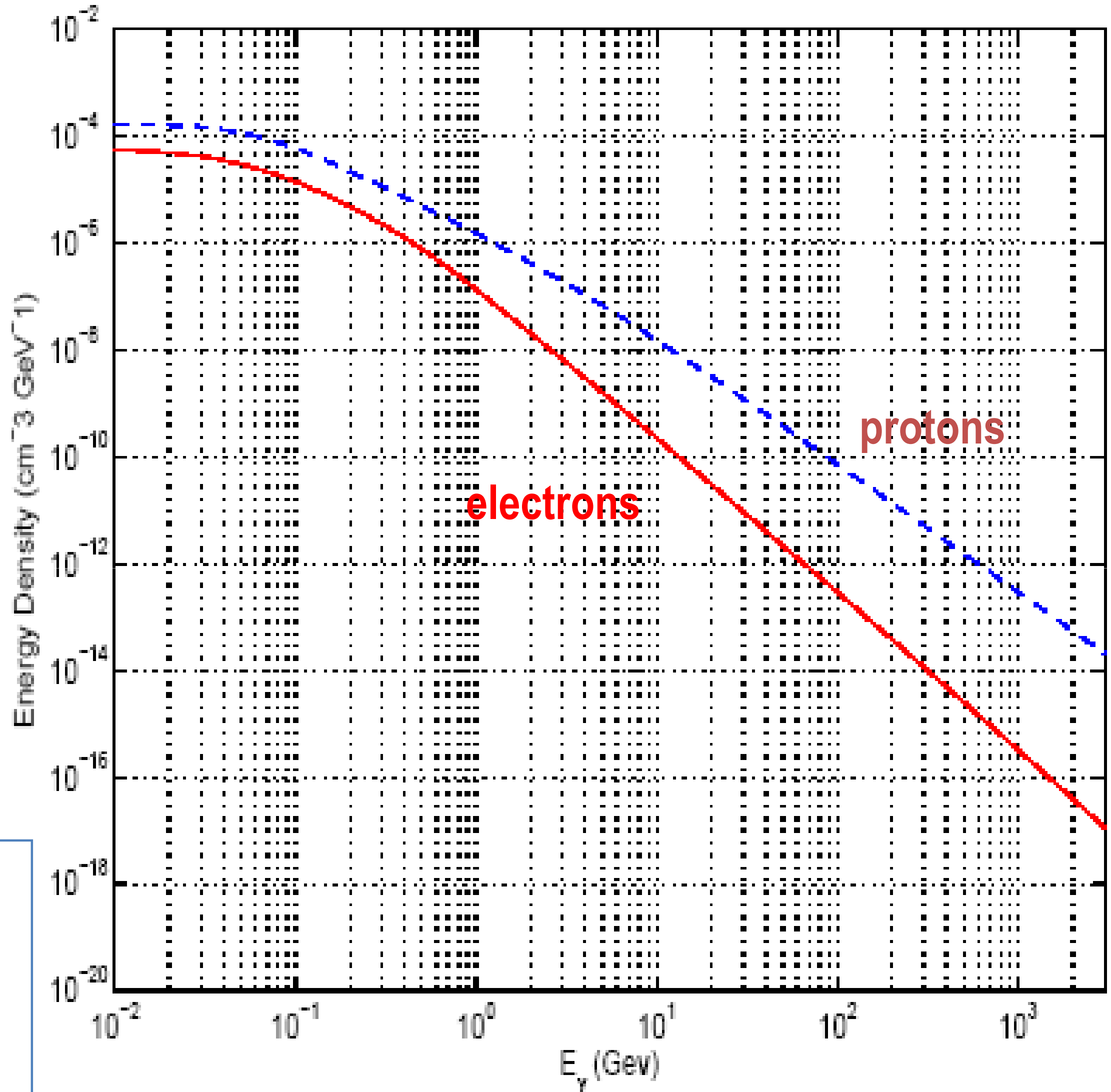
numerical treatment

… same structure parameters, mag. flux frozen in ionized gas ($B \propto n_{HII}^{-3/2}$)

1. Radio synchro em.
   → $B \oplus N_e$

2. Particles vs Field Equip. Energy

injection part. spectrum: q=2
… interactively →
$N_e \sim 10^{-4}\ cm^{-3}$
N_p/N_e (>>1 GeV) ~ 100,
$B_0 \sim 300\ \mu G$

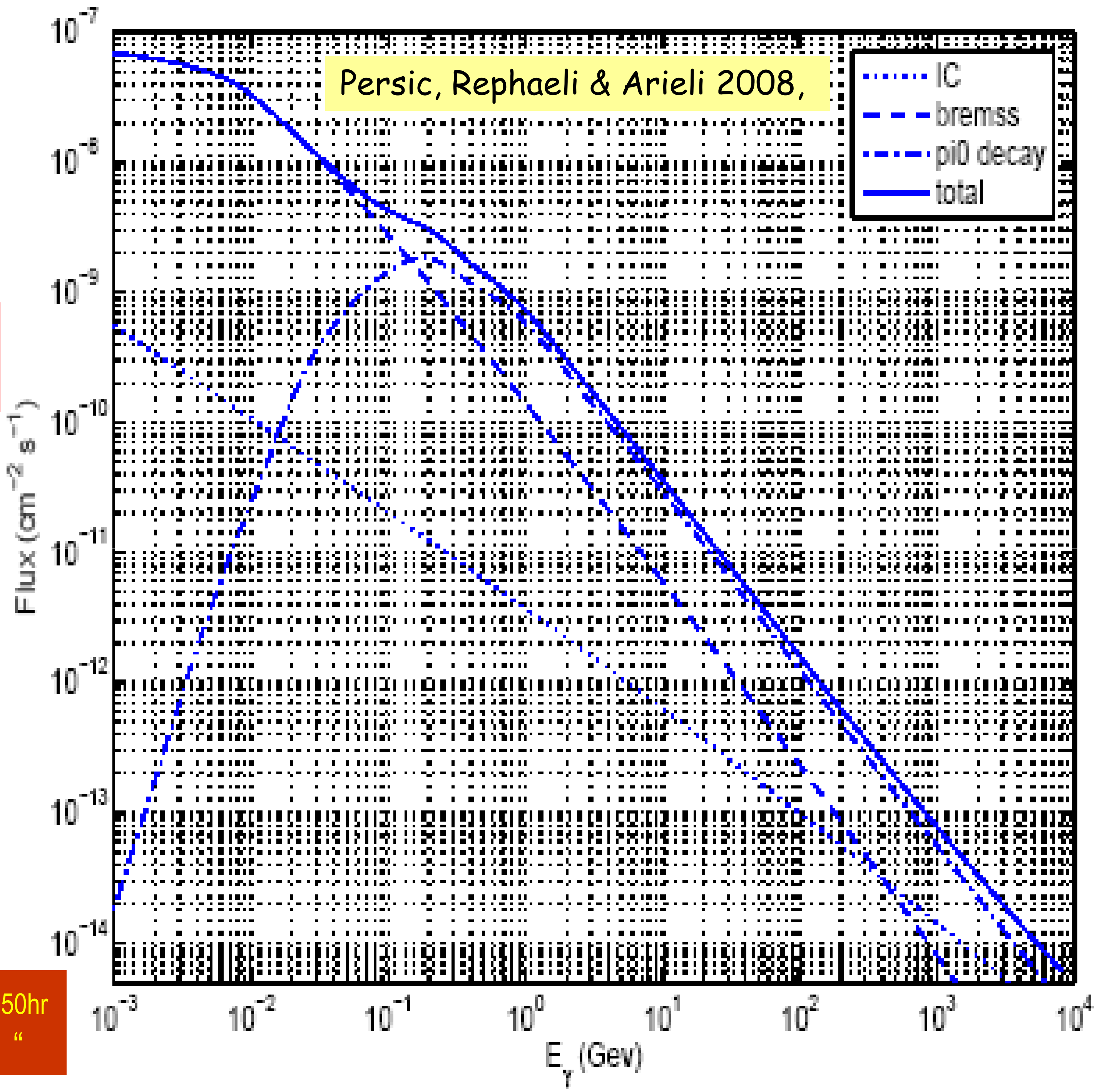


M82

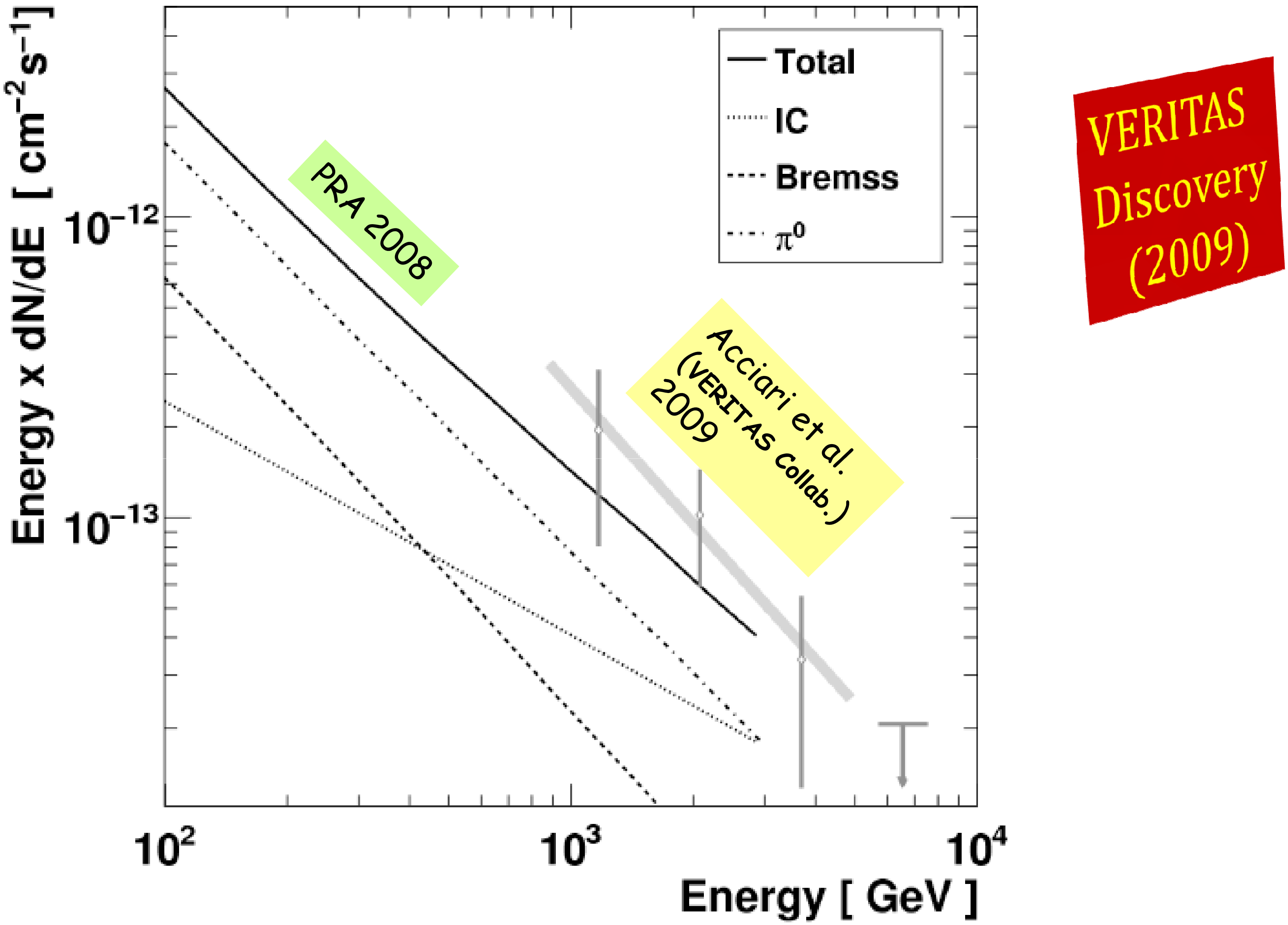
Numerical results

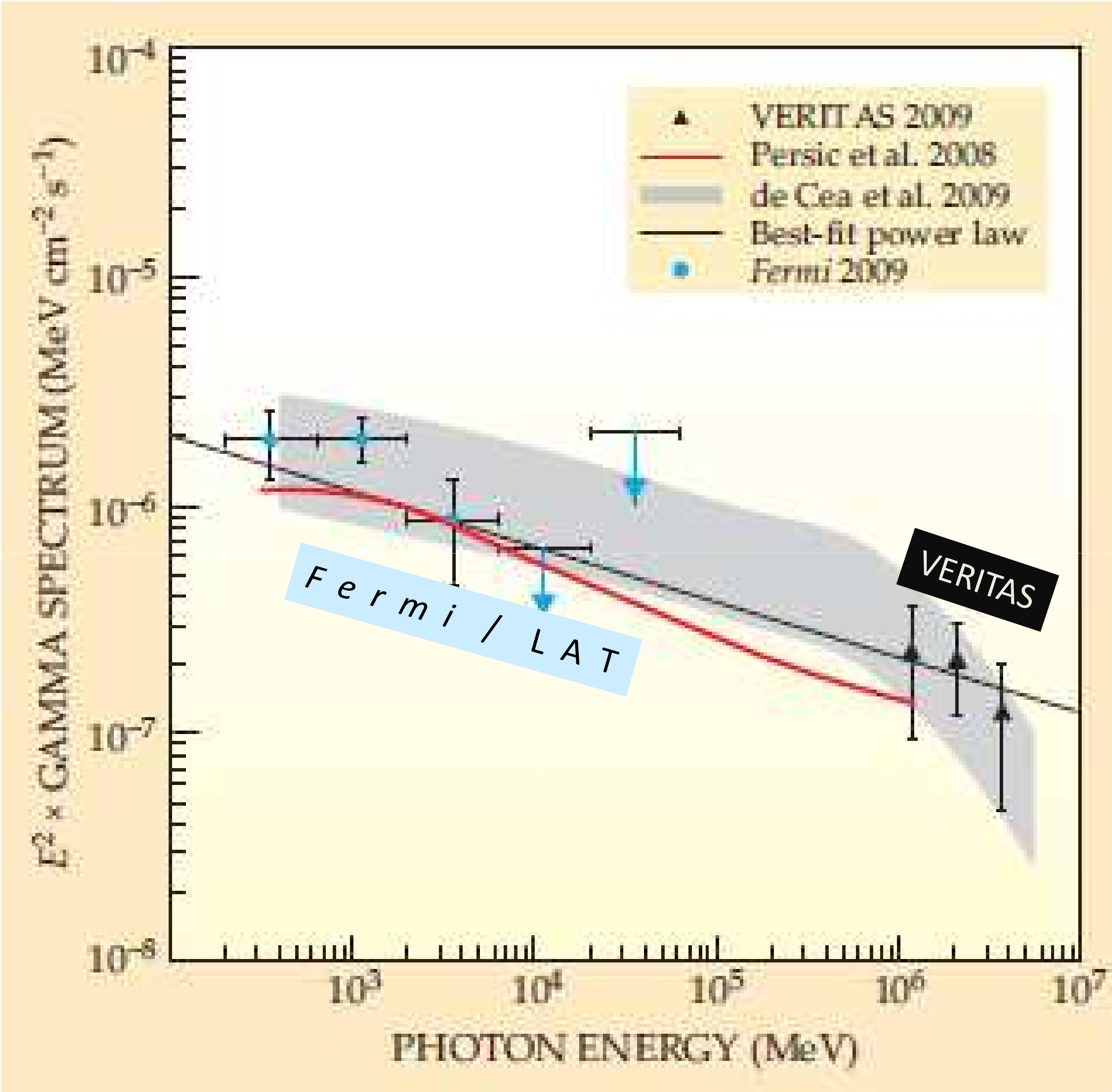
$F_{>100MeV}$ =
= 10^{-8} cm^{-2} s^{-1}

$F_{>100GeV}$ =
= 2.5×10^{-12} cm^{-2} s^{-1}



~1/3 sens. of MAGIC 2 for 50hr
~1/2 sens. of VERITAS " "


Total
IC
Bremss
π^0
PRA 2008
Acciari et al. (VERITAS Collab.) 2009
Energy x dN/dE [cm^{-2}s^{-1}]
Energy [GeV]
VERITAS Discovery (2009)



Physics Today
Jan. 2010

... same goes for NGC 253

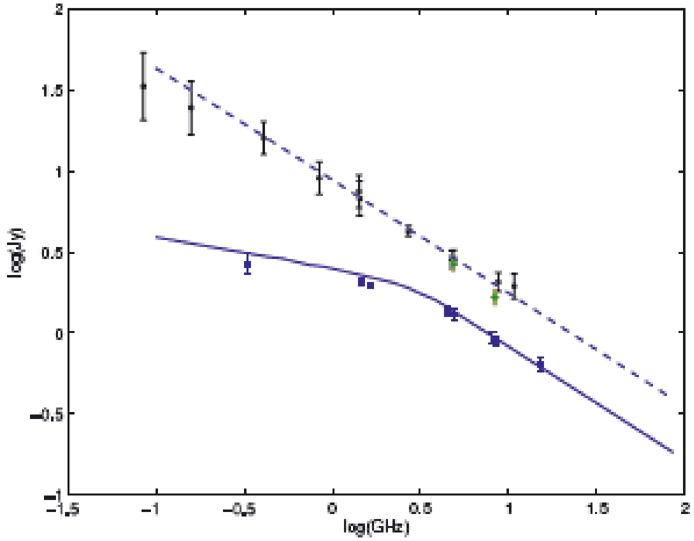


Figure 1. Radio measurements of the SB and entire disc regions of NGC 253. The solid line is our fit to the emission from the SB region; the dashed line is a fit to the emission from the entire disc. Data are from Klein et al. (1983, black dots), Carilli (1996, blue squares) and Heesen et al. (2008, green circles).

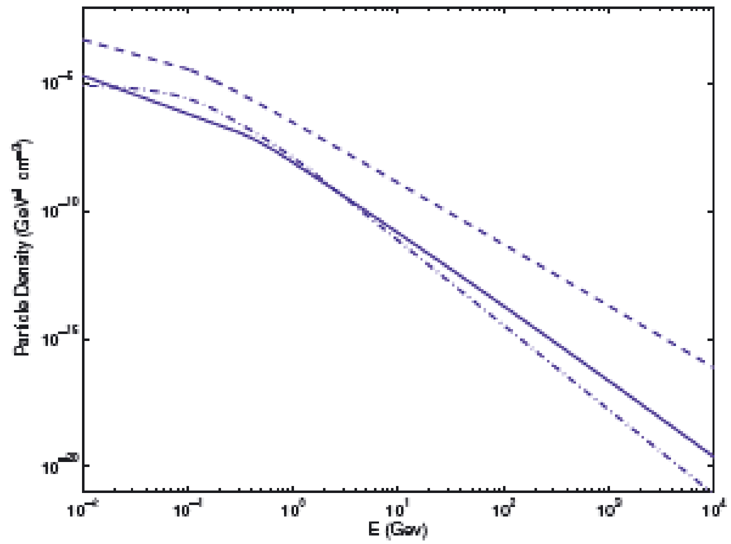


Figure 2. Steady-state primary proton (dashed line), primary electron (solid line) and secondary electron (dash–dotted line) spectral density distributions in the central SB region of NGC 253.

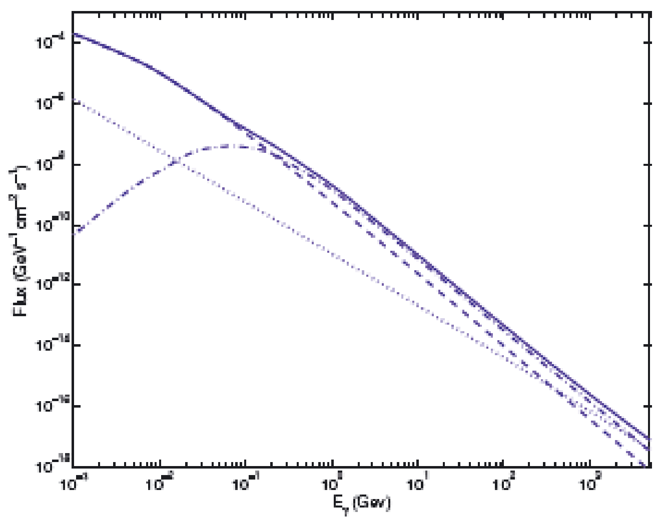


Figure 3. Spectra of HE emission processes in the disc region of NGC 253. Radiative yields are from electron Compton scattering off the FIR radiation field (dotted line), electron bremsstrahlung off ambient protons (dashed line), π^0 decay (dash–dotted line) and their sum (solid line).

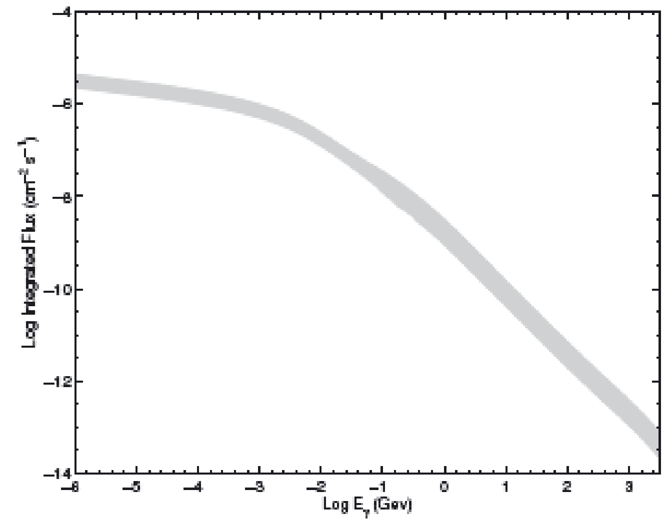
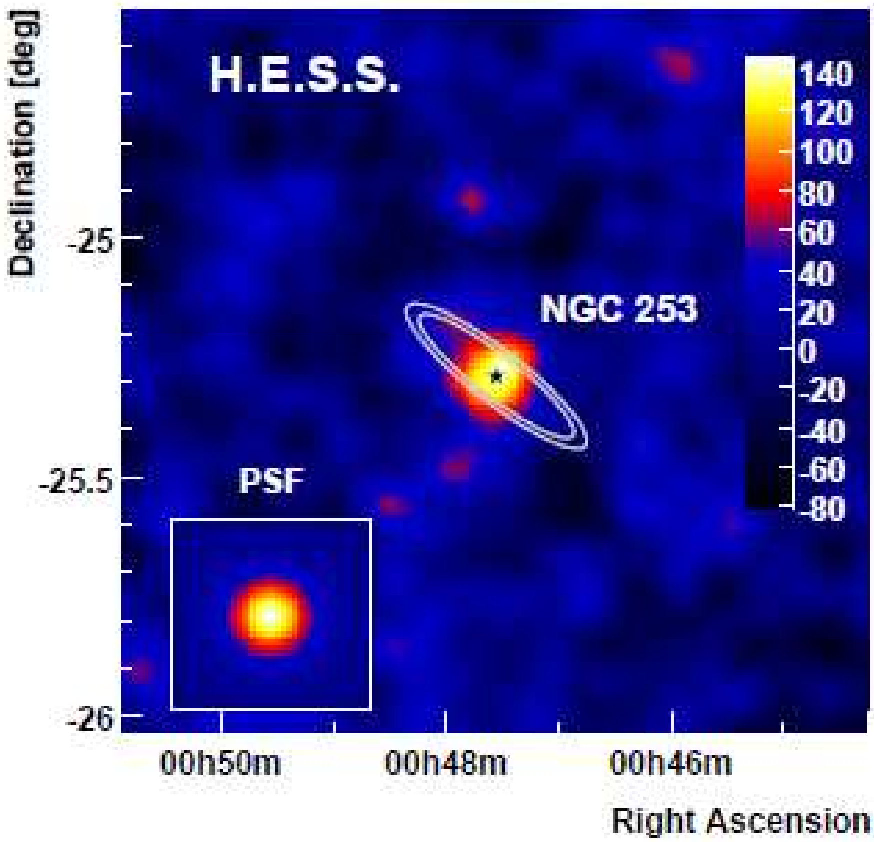
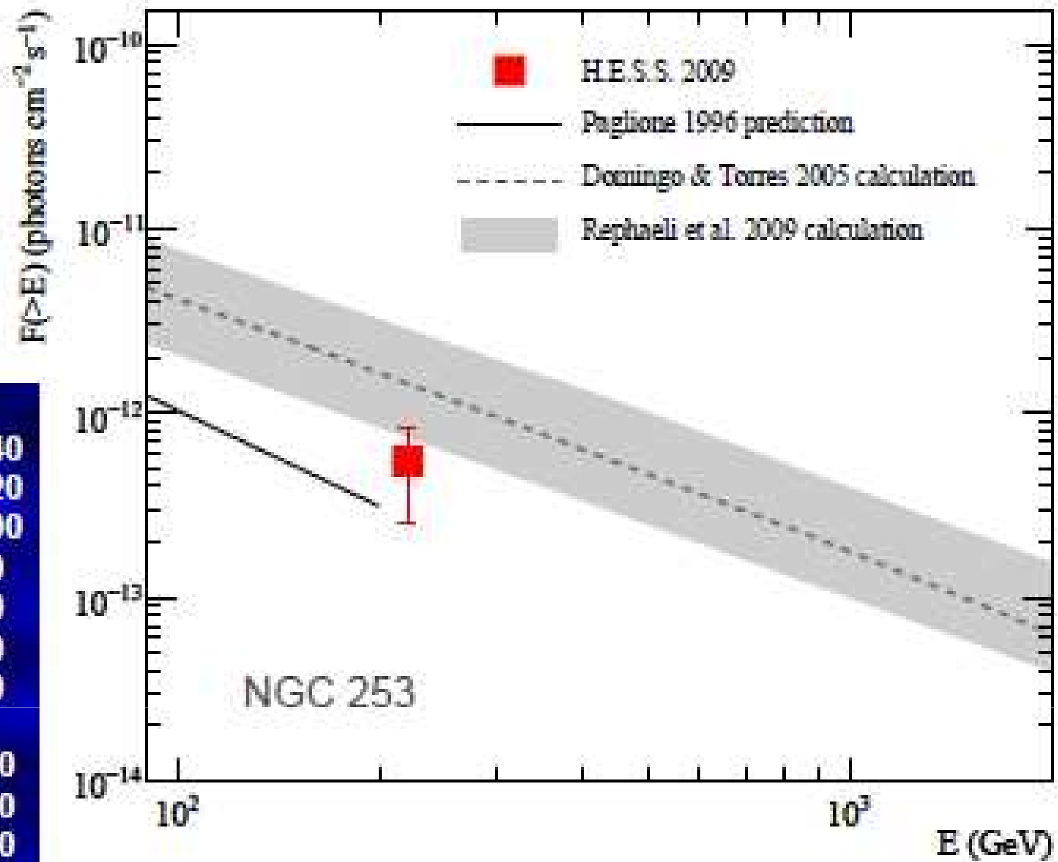


Figure 4. Integrated high-energy emission from the disc region of NGC 253. The total integrated emission from the disc region of NGC 253 is shown in the grey region, reflecting uncertainties in the observationally deduced parameters.

… NGC 253 (cont'd)

Acero et al. 2009, Science in press





Cosmic Rays and Star Formation

CR – SN relation (Ginzburg & Syrovatskii 1964)

- Fermi-I mechanism → SNRs
- SN rates, massive star formation

Test:

γ-ray (direct)

$$U_p \sim \tfrac{1}{4}\ (\nu_{SN}\,\tau_{-})\ (\eta\,E_{ej})\ r_s^{-3}$$

radio (indirect) → field- particles equipartition

observed

Milky Way normalization

observed

Arp 220	→	$U_p \approx$	476	eV cm^{-3}
NGC 253	→		125	
M 82	→		111	
Milky Way	→		1	
LMC	→		0.2	

NGC 253	→ U_p ≈	125 eV cm^{-3}
M 82	→	111
Arp 220	→	476
Milky Way	→	1

$$U_p \sim \tfrac{1}{4}\,(\nu_{SN}\,\tau_-)\,(\eta\,E_{ej})\;r_s^{-3}$$

- SN rate (obs'd)
- particle accel. eff. ($\eta \approx 5\%$)
- SB radius (obs'd)
- electrons' lifetime
- kin. energy of SN ejecta ($E_{ej} \approx 10^{51}$ erg)

$$\tau_- \approx \begin{cases} (\sigma_{pp}\, c n_p)^{-1} \sim 2\times10^7\, n_p^{-1}\ \text{yr} & \text{hadronic} \\ \sim 3\times10^4\,(r_s/0.3\ \text{kpc})\,(v_{out}/2500\ \text{km s}^{-1})^{-1}\ \text{yr} & \text{advection} \end{cases}$$

$$\Rightarrow\; U_p = 85\,\frac{\nu_{SN}}{0.3\,\text{yr}^{-1}}\,\frac{\tau_-}{3\times10^4\,\text{yr}}\,\frac{\eta}{0.05}\,\frac{E_{ej}}{10^{51}\,\text{erg}}\left(\frac{r_s}{0.3\,\text{kpc}}\right)^{-3}\text{eV cm}^{-3}$$

ν_{SN}		r_s
$(0.1-0.2)\,\text{yr}^{-1}$	NGC 253	0.20 kpc
$(0.2-0.3)\,\text{yr}^{-1}$	M 82	0.26 kpc
$(4\pm2)\,\text{yr}^{-1}$	Arp 220	0.25 kpc

CRs $\leftrightarrow$ SF: conclusion

Strong CR production:

- ❖universal acceleration efficiency of SN
- ❖ Fermi acceleration at work (NR strong shock)
- ❖particles/field equipartition

→ use radio data to study CRs in distant SF'ing gal.s

- ❖ γ-ray emission (isotropic ..)

Thanks!