TeV Astrophysics

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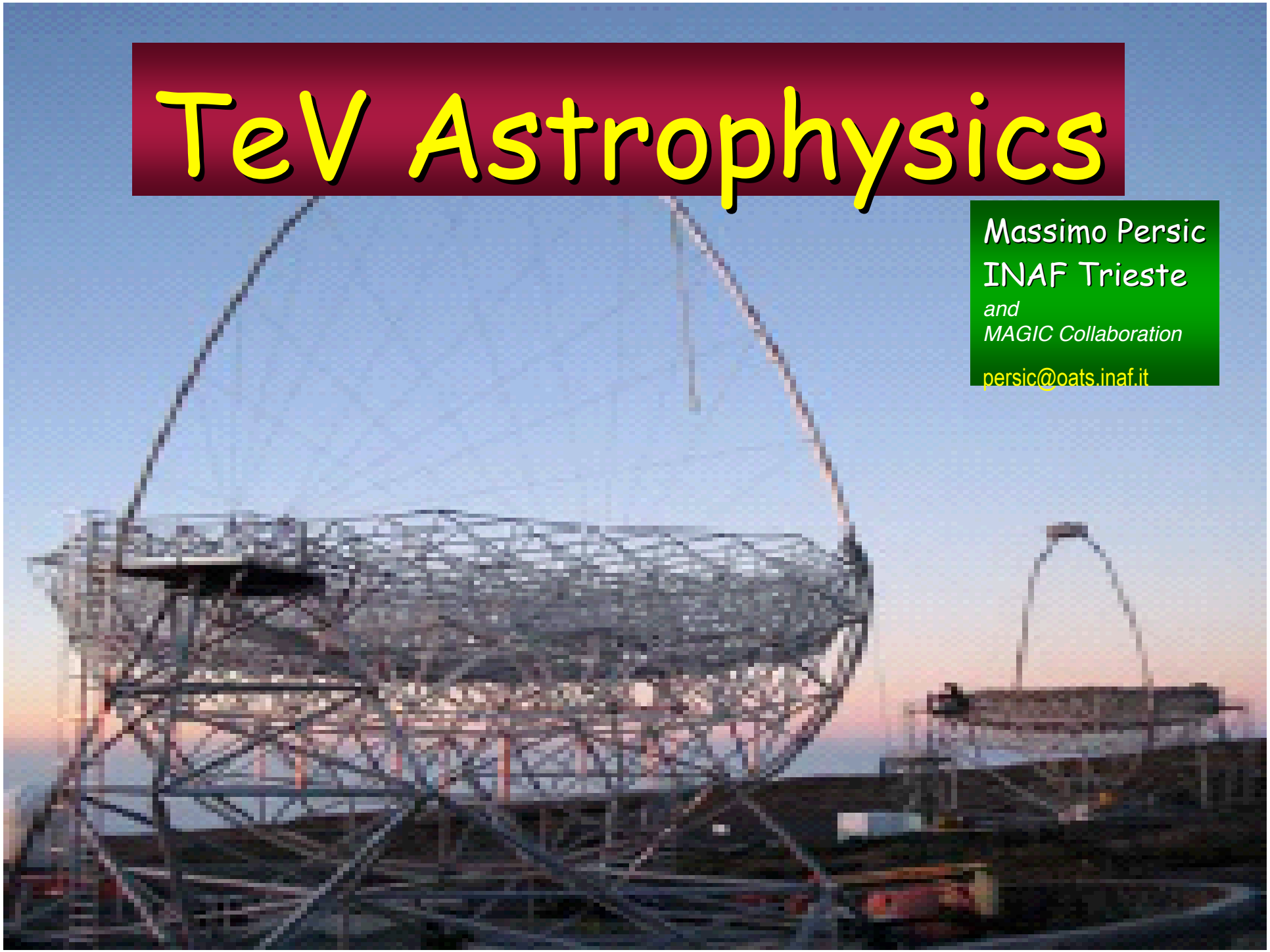
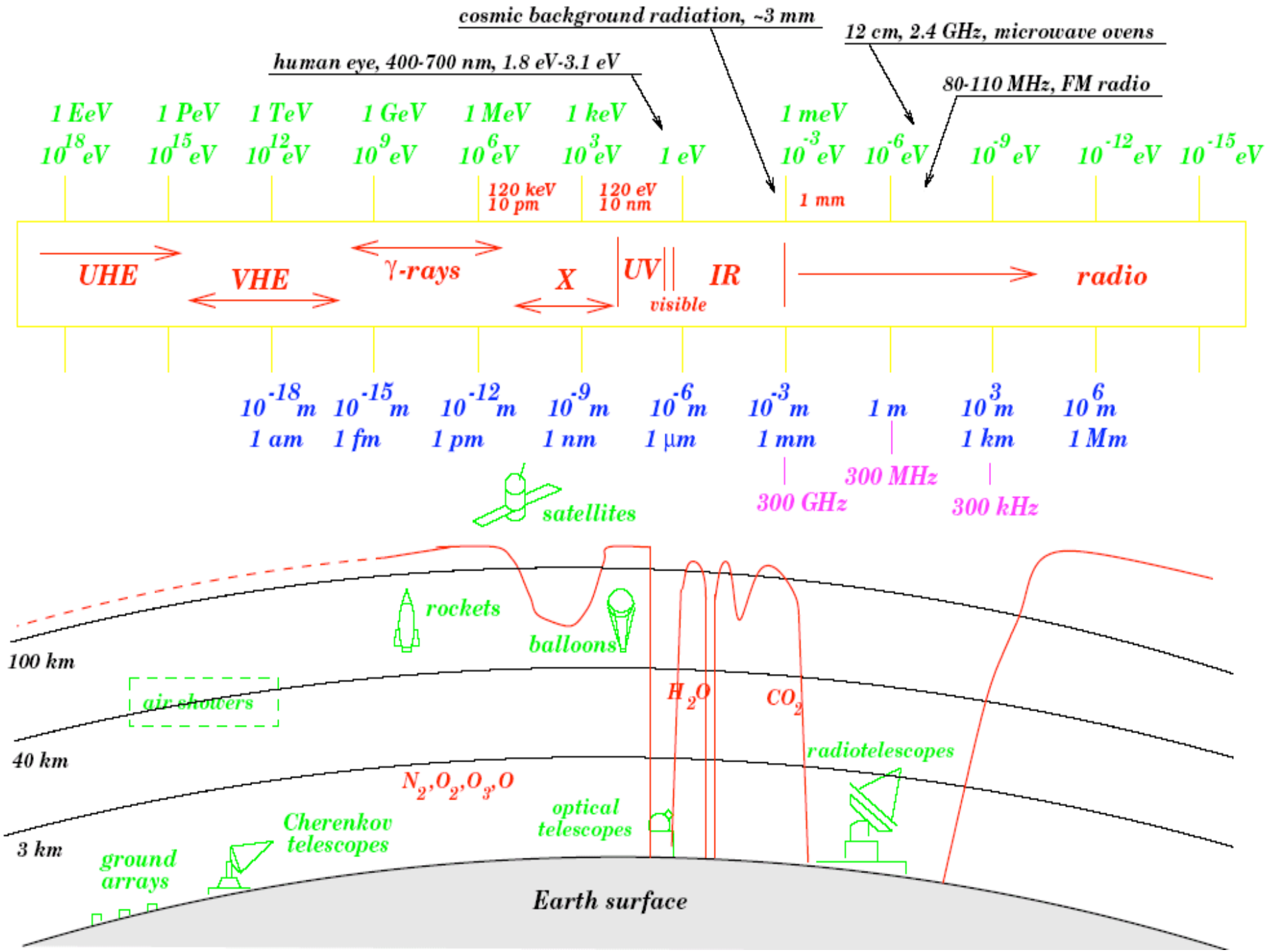
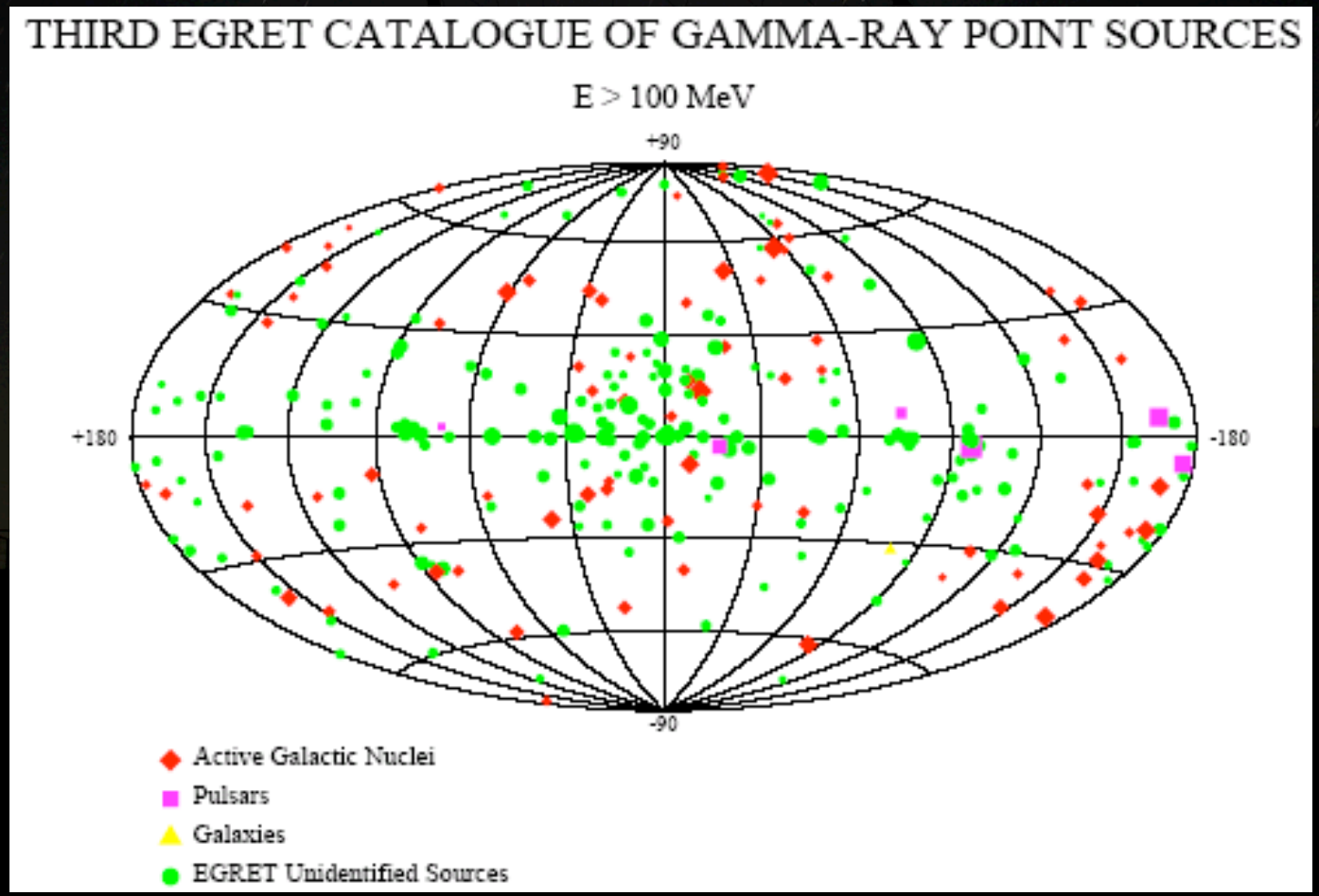



cosmic background radiation, ~3 mm
12 cm, 2.4 GHz, microwave ovens
human eye, 400-700 nm, 1.8 eV-3.1 eV
80-110 MHz, FM radio
1 EeV
1 PeV
1 TeV
1 GeV
1 MeV
1 keV
1 meV
10^{18} eV
10^{15} eV
10^{12} eV
10^{9} eV
10^{6} eV
10^{3} eV
1 eV
10^{-3} eV
10^{-6} eV
10^{-9} eV
10^{-12} eV
10^{-15} eV
120 keV
10 pm
120 eV
10 nm
1 mm
UHE
VHE
γ-rays
X
UV
visible
IR
radio
10^{-18} m
10^{-15} m
10^{-12} m
10^{-9} m
10^{-6} m
10^{-3} m
1 m
10^{3} m
10^{6} m
1 am
1 fm
1 pm
1 nm
1 μm
1 mm
1 km
1 Mm
300 MHz
300 GHz
300 kHz
satellites
rockets
balloons
100 km
air showers
H_2O
CO_2
40 km
radiotelescopes
N_2, O_2, O_3, O
optical telescopes
Cherenkov telescopes
3 km
ground arrays
Earth surface

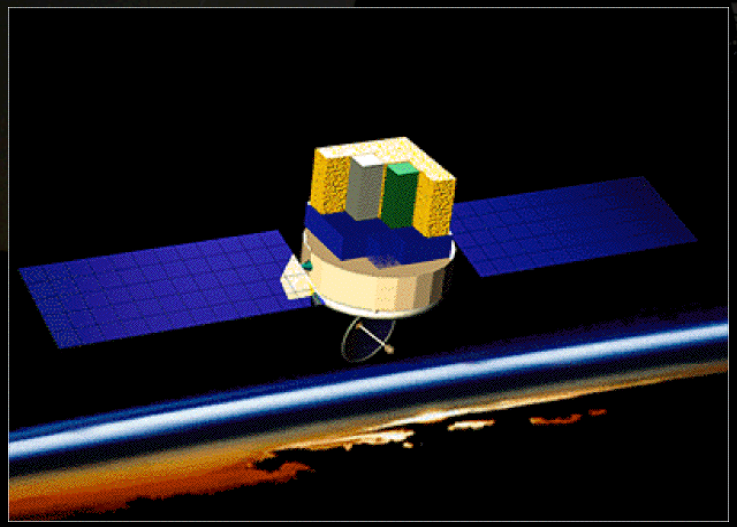
- **Cosmic γ-ray observation:**
  - **directly** from satellites (HE) < O(50 GeV) and
  - **indirectly** from ground-based installations (VHE) > O(50 GeV)
- Satellites: **OSO-3** (1969), **SAS-2** (1972), **COS-B** (1975-1982), **CGRO** (1991-2000)
  EGRET (20 MeV-30 GeV) ⇒ **HE-γ-ray astronomy to maturity**



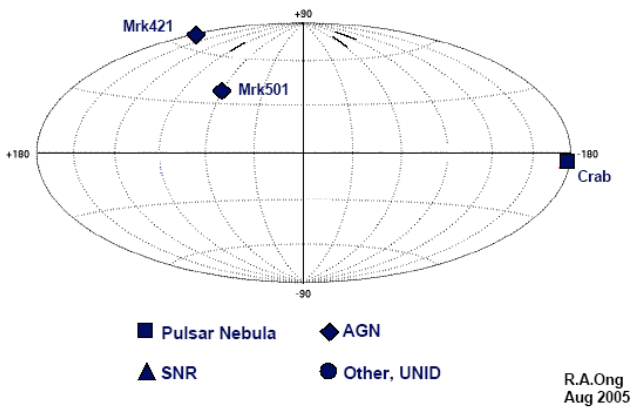
Ground-based vs satellite γ-ray detectors

- **Satellite (HE: E<10 GeV):**
  - primary detection
  - small effective area ~1m^2
    - low sensitivity
  - large angular opening
    - survey
  - large duty-cycle
  - high cost
  - low energy
  - low bkgd

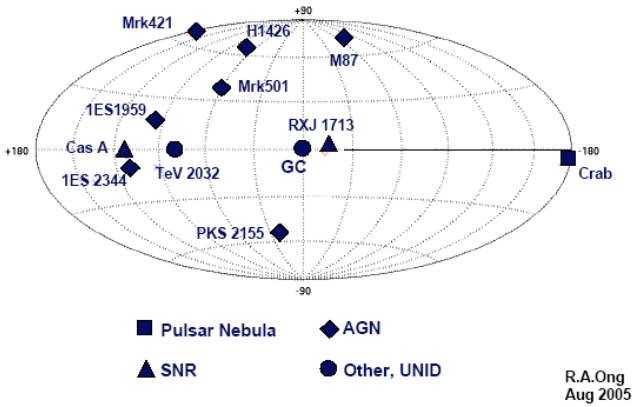
- **IACT/ground based (VHE: E>100 GeV):**
  - secondary detection
  - large effective area ~10^4 m^2
    - high sensitivity
  - small angular opening
    - serendipity search
  - small duty-cycle
  - low cost
  - high energy
  - high bkg



The VHE Sky - 1995



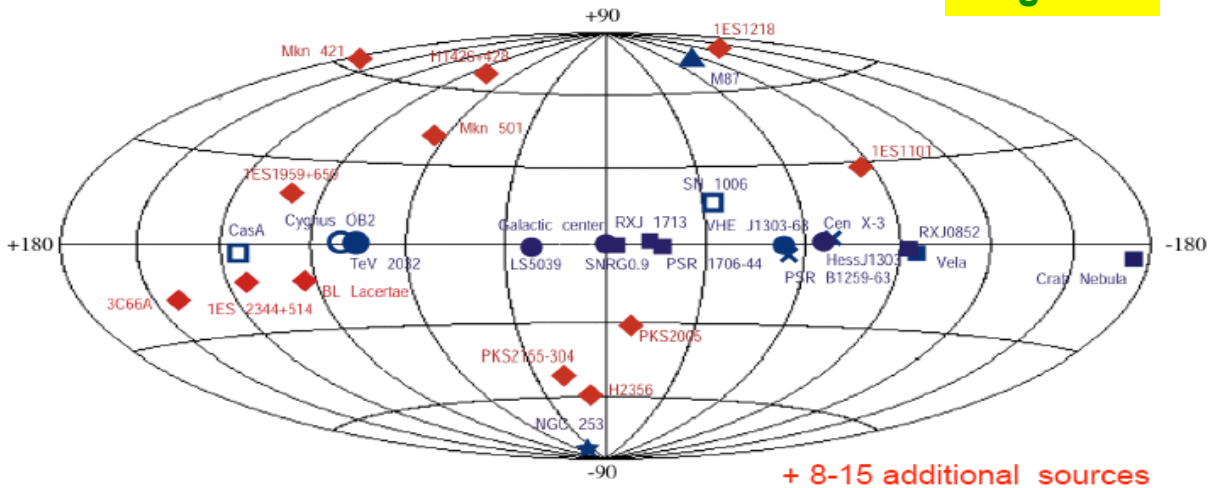
The VHE Sky - 2003



VHE Gamma Sources (E > 100 GeV)

(Status August 2005)

Aug 2005



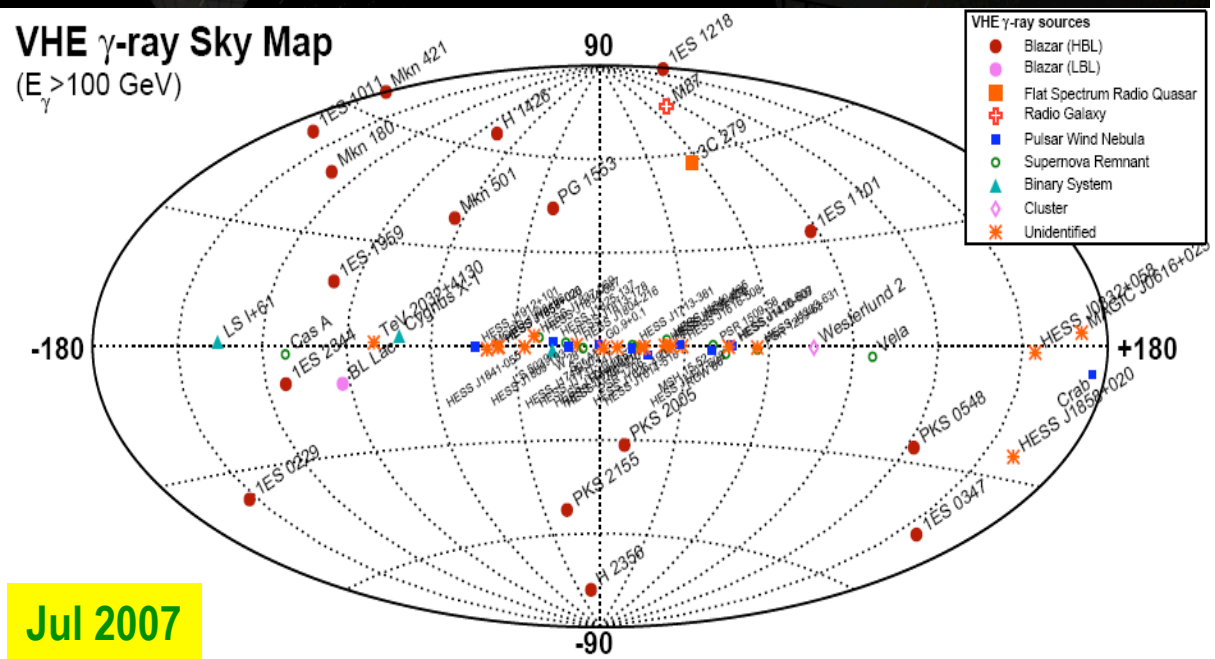
+ 8-15 additional sources in galactic plane.

■ = Pulsar/Plerion ☐ = SNR ★ = Starburst galaxy ○ = OB association

◆ = AGN (BL Lac) ▲ = Radio galaxy ✕ = XRB ● = Undetermined

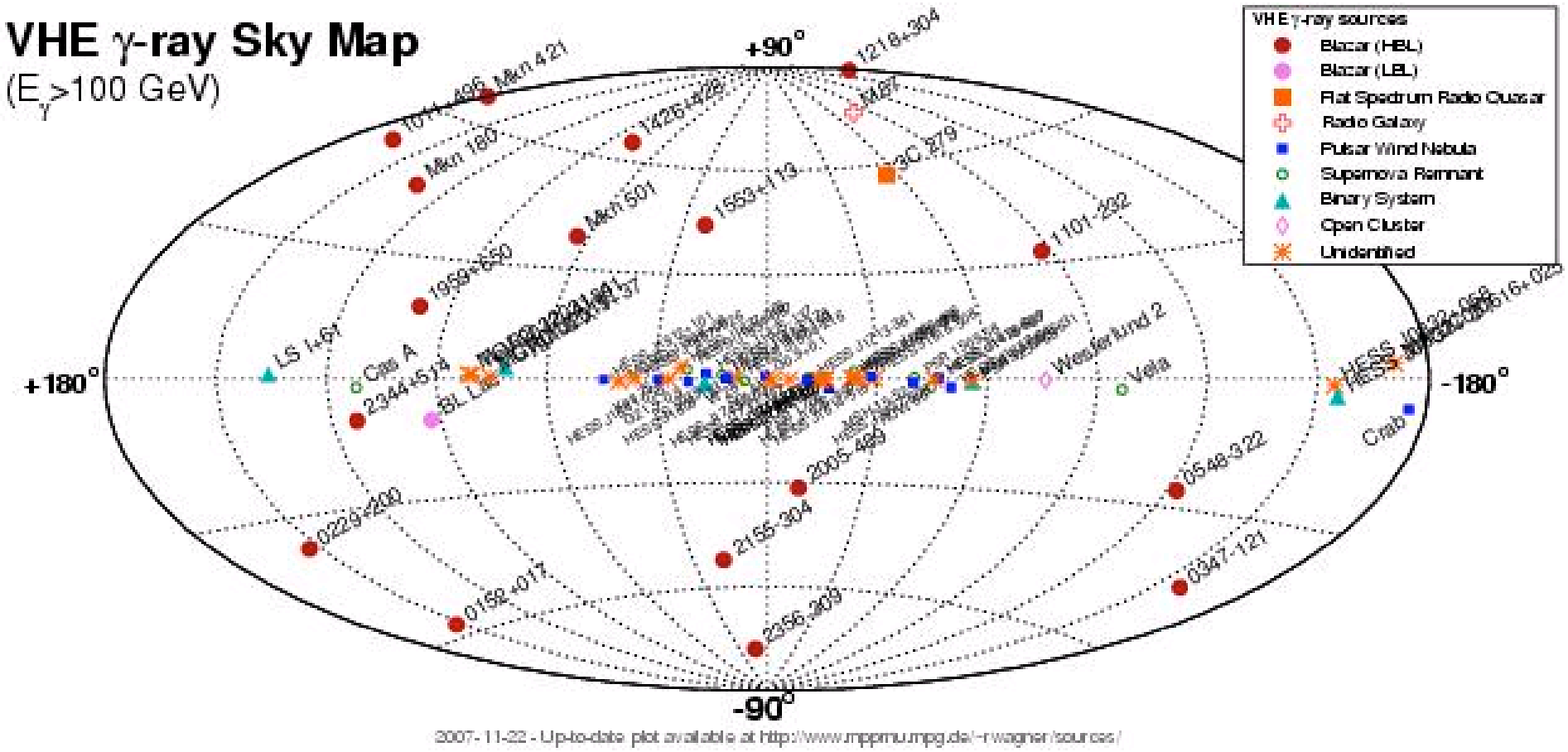
VHE γ-ray Sky Map

(E_γ >100 GeV)



Jul 2007

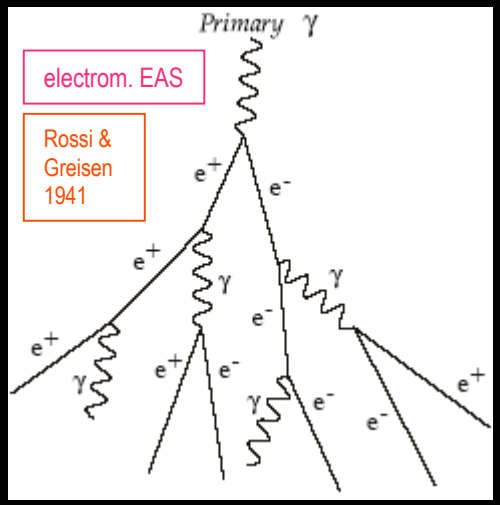
2007-07-15 - Up-to-date plot available at http://www.mppmu.mpg.de/~rwagner/sources/



2007-11-22 - Up-to-date plot available at http://www.mppmu.mpg.de/~rwagner/sources/

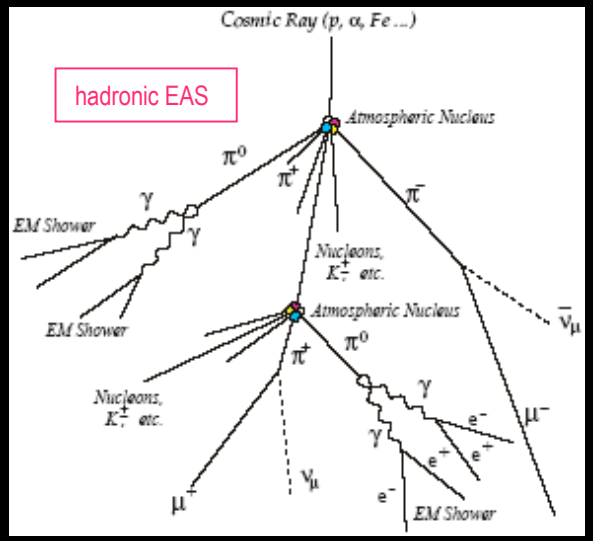
Dec 2007

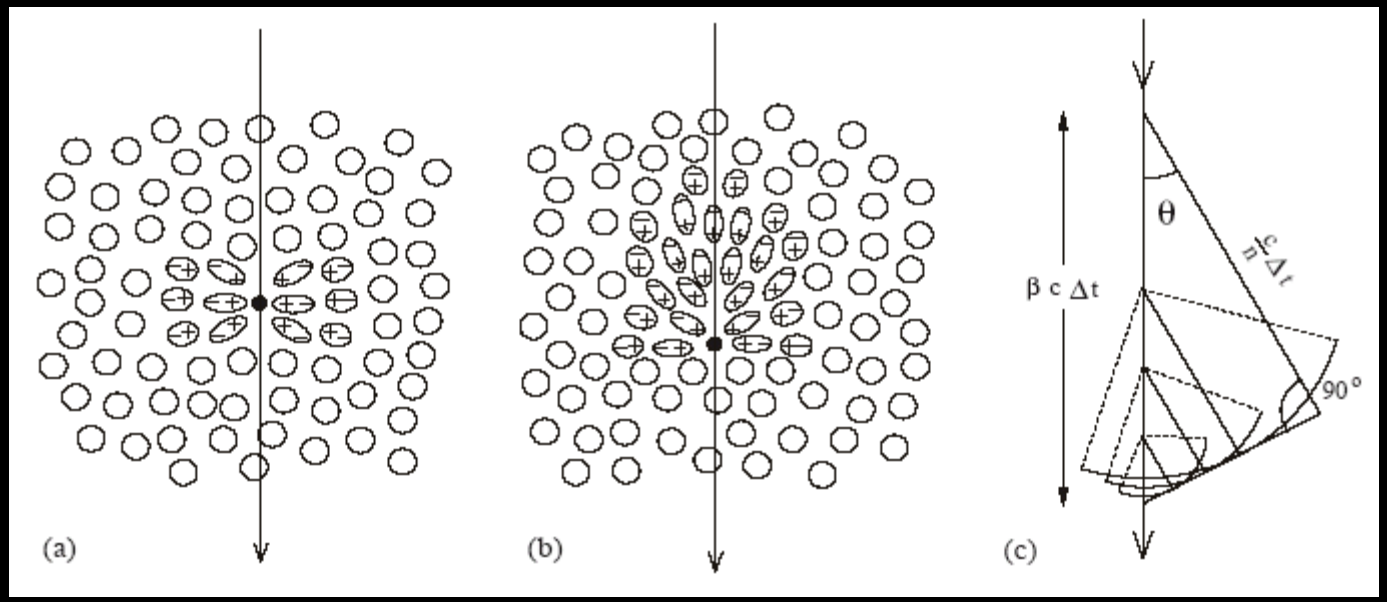
Cherenkov Observational Technique.1



v>c/n → β>1/n

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





cos θ =1/βn ≤ 1/n

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)

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

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

$$E_{\check{c}}^{thr} \simeq \frac{m_0 c^2}{\sqrt{2n_h}}$$

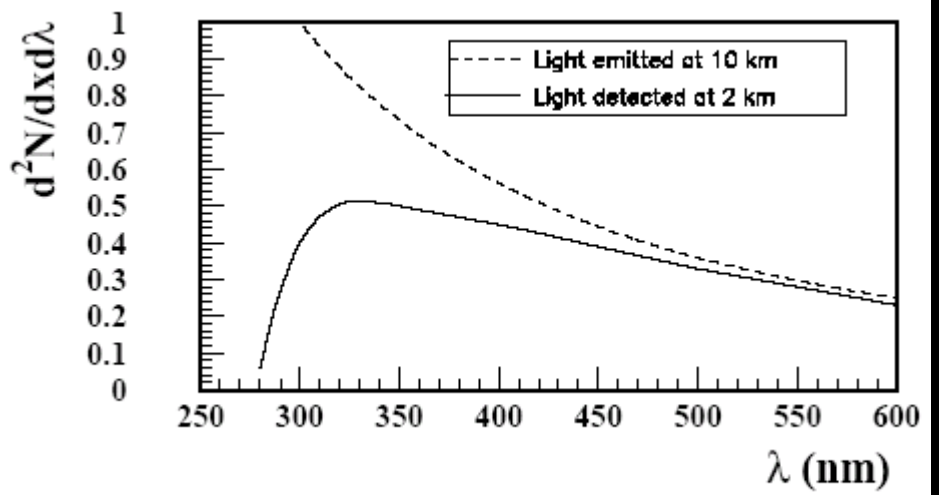
$$\cos\theta_{\check{c}}^{max} \simeq \sqrt{2n_h}$$

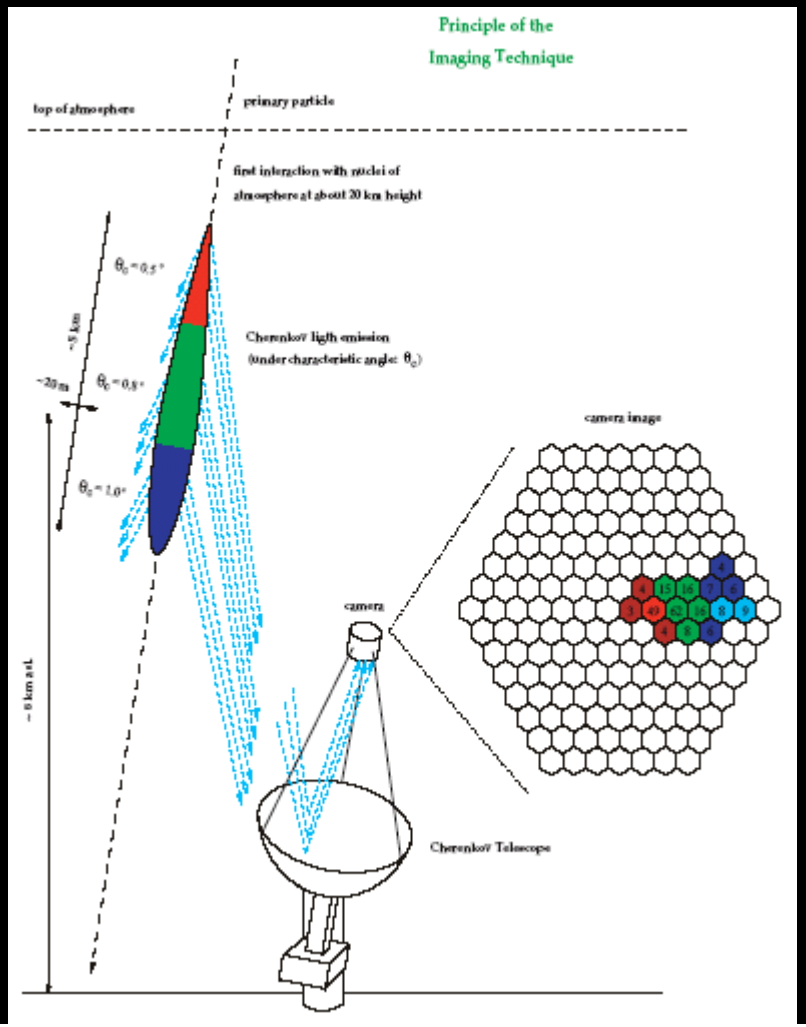
SPECTRUM

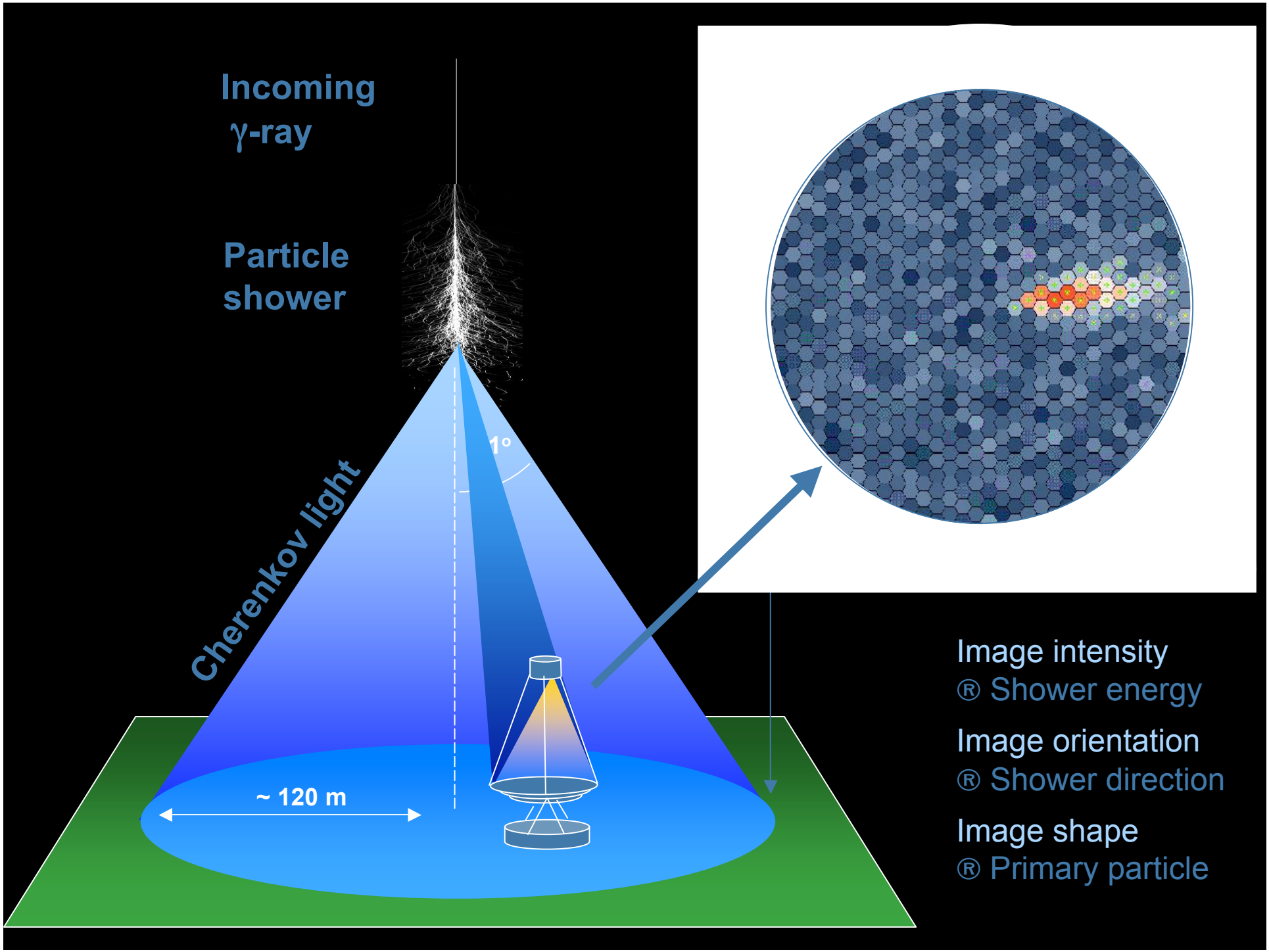
$$\frac{dN^2}{dx d\lambda} = 2\pi\alpha Z e^2\left(1-\frac{1}{\beta^2\cdot n^2(\lambda)}\right)\frac{1}{\lambda^2}$$

optical/UV light

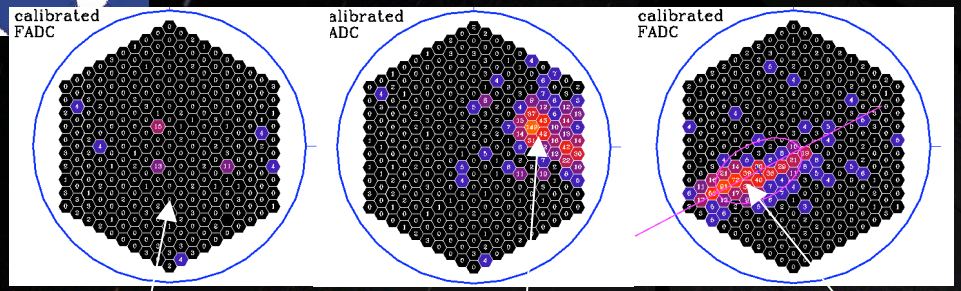
… but Rayleigh scattering λ^{-4}






Incoming
γ-ray
Particle
shower
Cherenkov light
1°
~ 120 m
Image intensity
® Shower energy
Image orientation
® Shower direction
Image shape
® Primary particle

γ/h separation



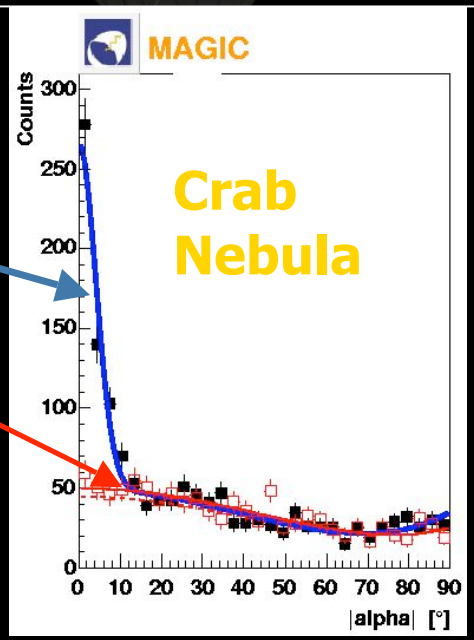
NSB event

Hadronic shower

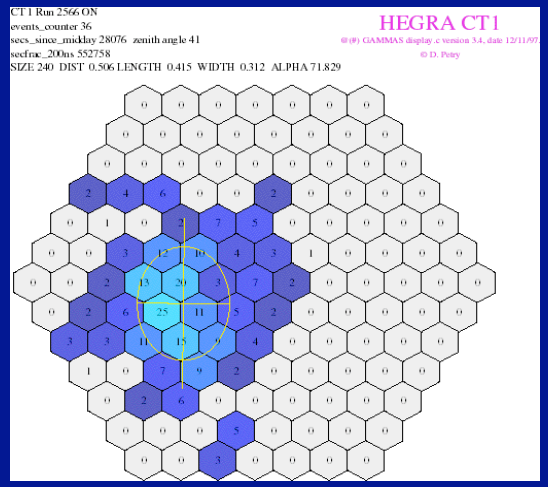
Gamma shower

ON: Pointing to source

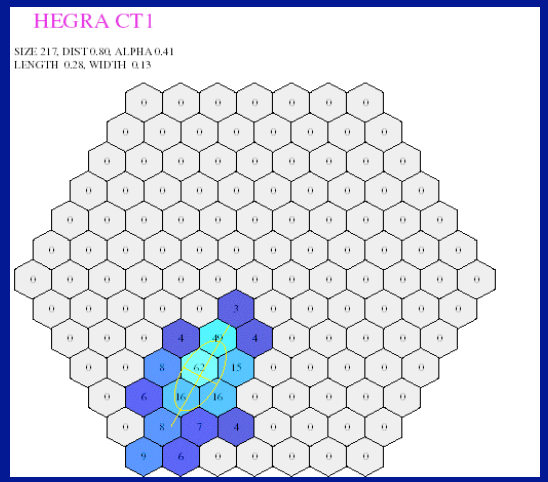
OFF: Pointing somewhere else



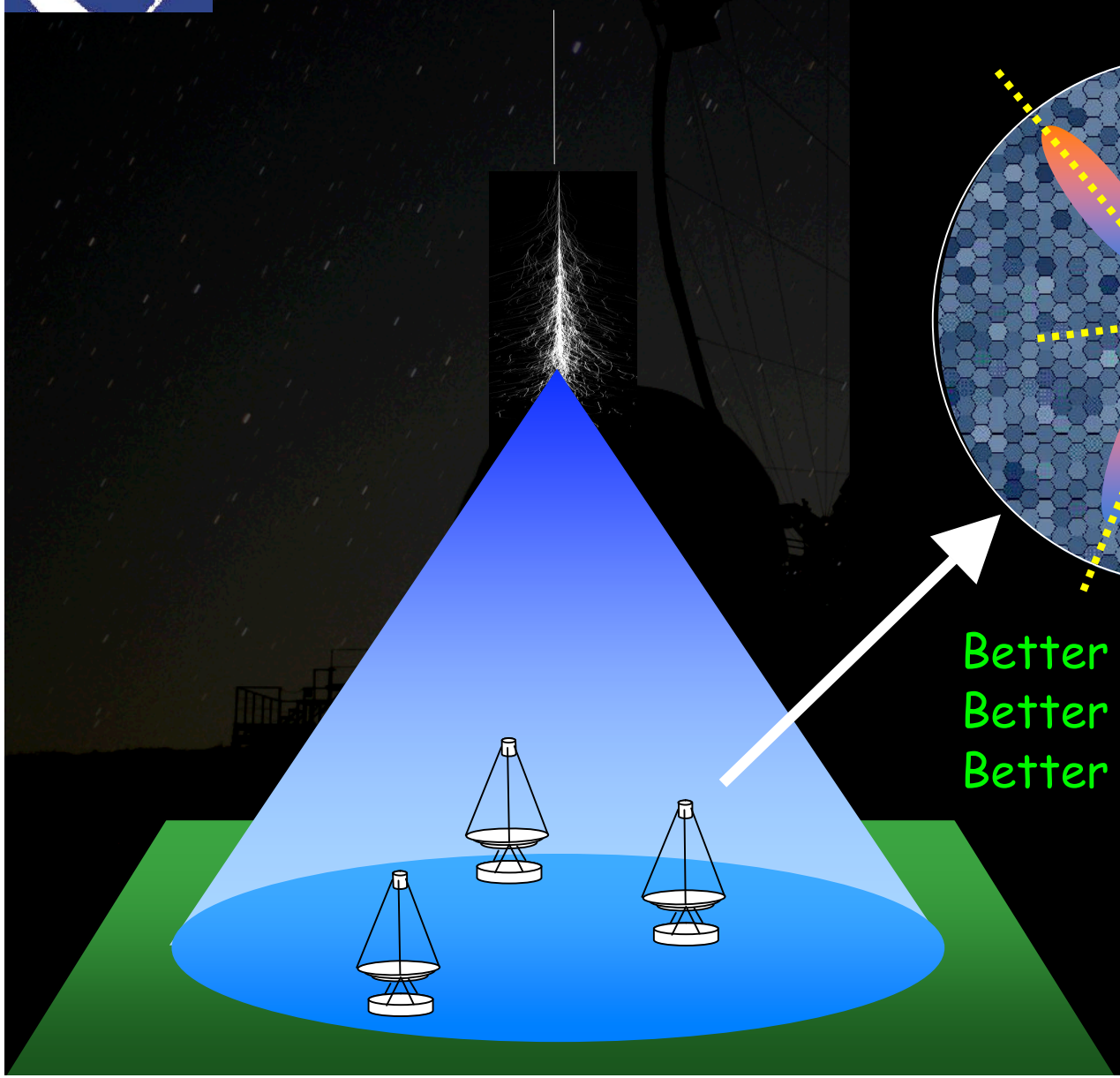
Proton shower

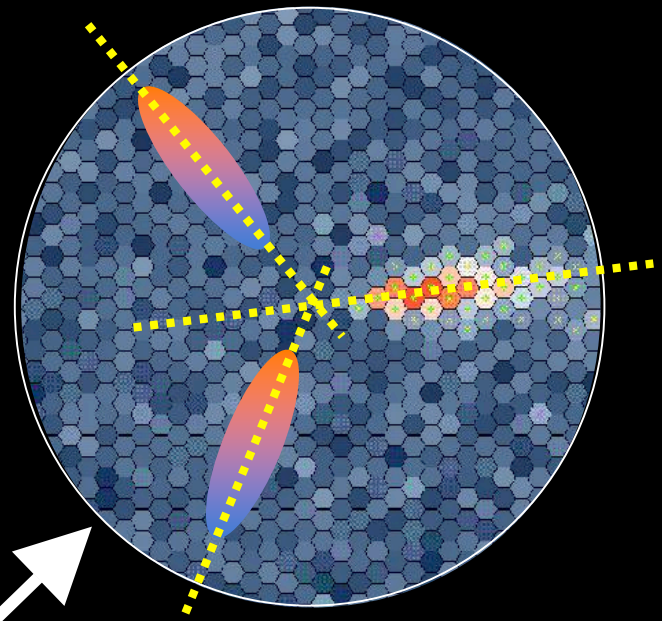


Gamma shower



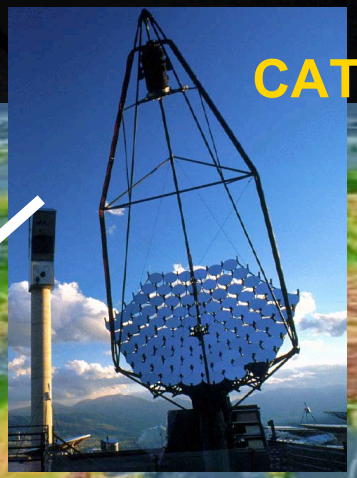
Systems of Cherenkov telescopes





Better bkgd reduction
Better angular resolution
Better energy resolution

First-generation IACTs



CAT (1996-2003)

Whipple (1969!-2003)

Crab nebula (Weekes+ 1989)
Mk 421 (Punch+ 1992)

HEGRA (1993-2002)

CANGAROO (1992-2001)

Second-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)

MAGIC (2004)

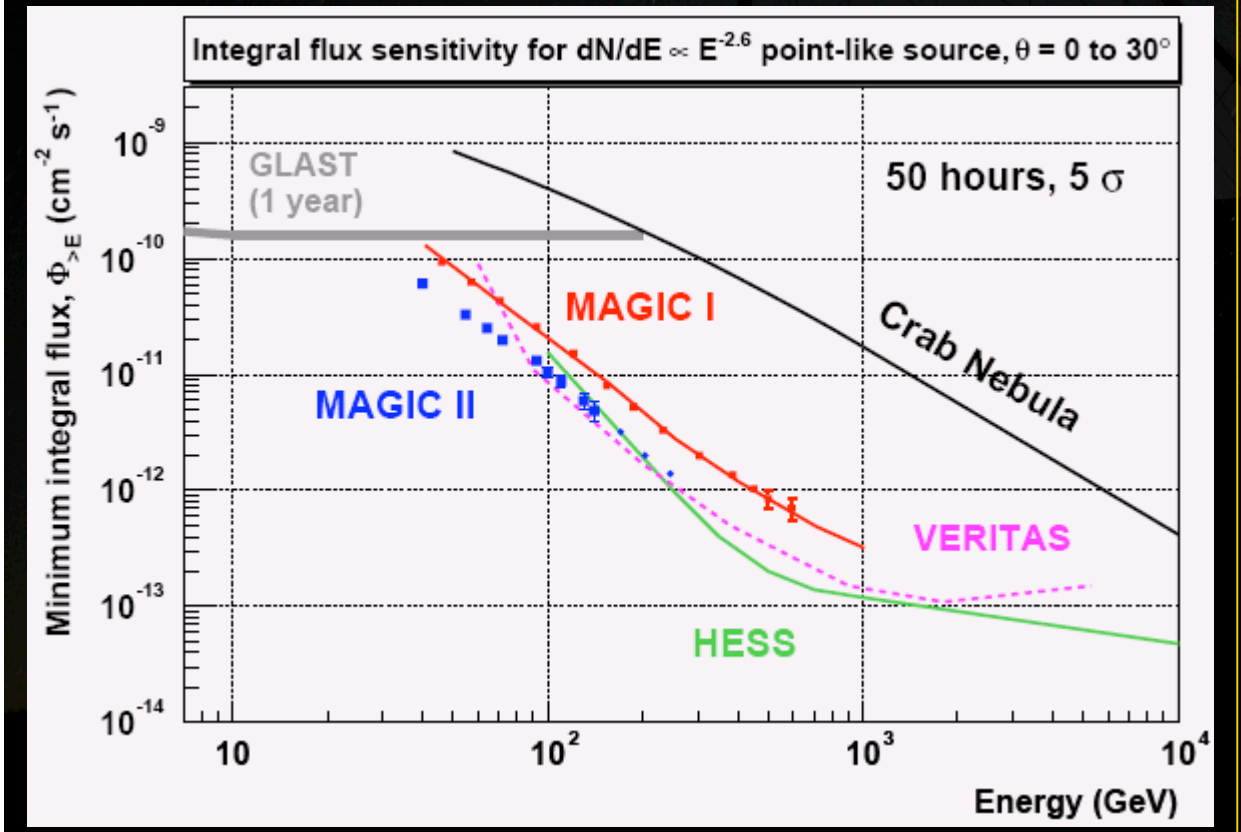
H.E.S.S. (2003)

VERITAS (2006)

CANGAROO-III (2004)

IACTs established as astronomical tools (experiments → telescopes)
Big step within last few years:
- quantitative (x5 detected sources)
- qualitative (unprecedented high quality)

The Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescope



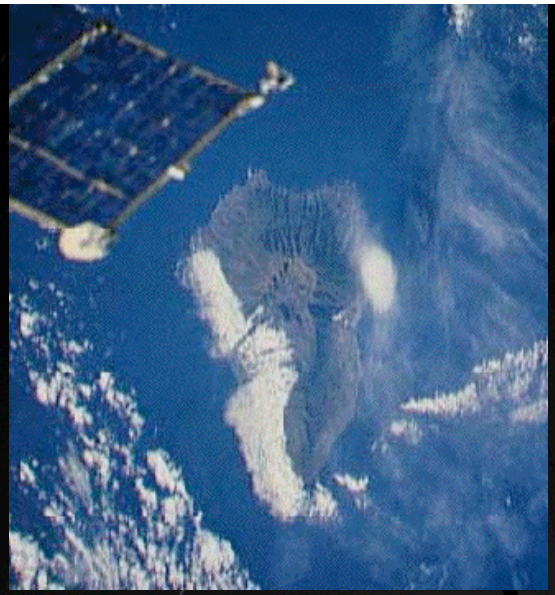
World's largest single-dish IACT

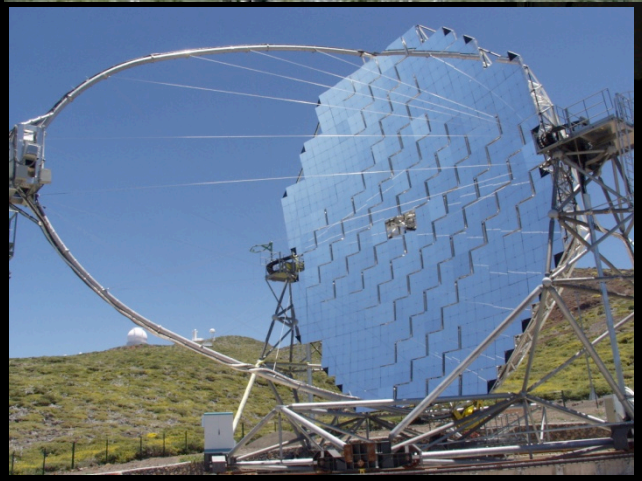
956 0.5m x 0.5m aluminum mirrors
Parabolic shape
Diameter: 17m – area: 234 sq.m
f/D = 1
Al mirrors + *C* fiber → low weight
Slew time ~ 20 s
Hexagonal camera:
- FOV: 3.5° x 3.8°
- comp'd of 397 0.1° photomultipliers

Located: La Palma, Canary Islands
Operation: cycle 1: April 2005/2006
E(threshold) ~ 50-100 GeV
Sensitivity: 0.05 Crab at >0.1 TeV
0.02 Crab at >1 TeV
Angular resol.: 0.1 deg at >0.2 TeV
Tracking accuracy = 0.01°
Energy resol.: 30% at 0.1 TeV
20% at >1 TeV

MAGIC's site

La Palma, IAC
28° North, 18° West





MAGIC

VHE γ-ray emission mechanisms

Hadronic

π^0-decay γ's

$$p+p \rightarrow p+\pi^0 \xrightarrow{t\sim 2\times10^{-16}s} p+2\gamma$$

$E_p > 2m_\pi c^2(1+m_\pi/4m_p) \approx 280$ Mev

... light from the NT side of the universe

Leptonic

γ's from electron bremsstrahlung

- primary
- secondary

$$p+p \rightarrow p+\pi^- \xrightarrow{t\sim 2.5\times10^{-8}s} p+\mu^-+\nu_e+\bar{\nu}_\mu$$

$$p+p \rightarrow p+\pi^+ \rightarrow p+\mu^+ +\bar{\nu}_e+\nu_\mu$$

$$\mu^- \xrightarrow{t\sim 2.2\times10^{-6}s} e^-+\bar{\nu}_e+\nu_\mu$$

$$\mu^+ \rightarrow e^++\nu_e+\bar{\nu}_\mu$$

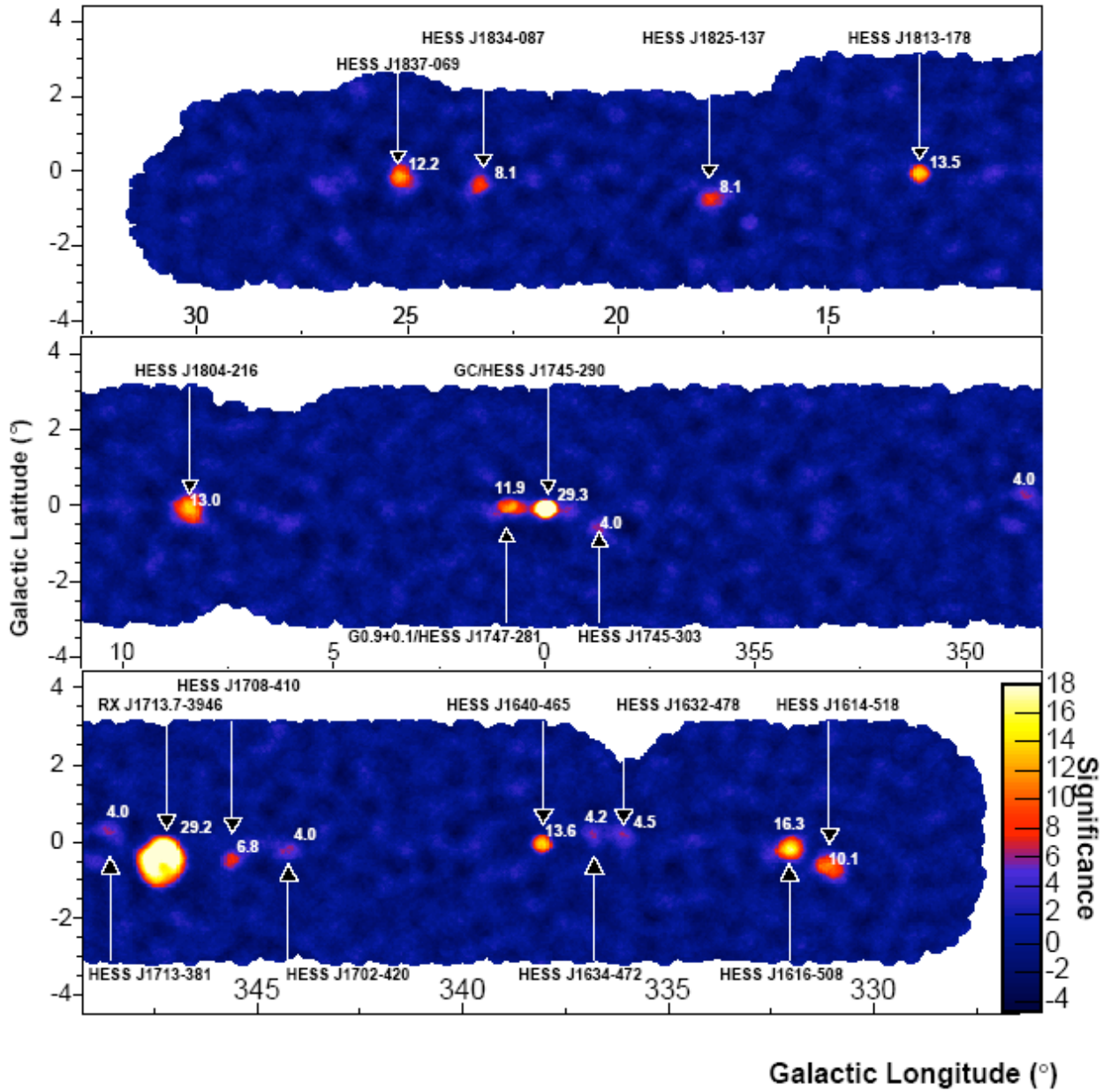
H.E.S.S. Galactic Plane Survey

southern hemisphere

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

Typically:

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



… estimating the TeV luminosity of GP sources …

Assume:

- SN-accelerated CRp, downstream particles $n \propto p^{-\alpha}$ with $\alpha = \frac{3}{2}(\gamma+1)\frac{M^2}{M^2+1}$,

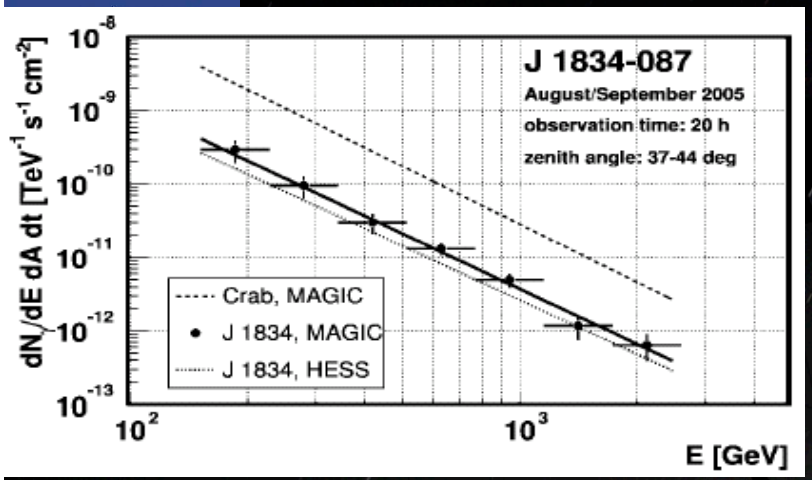
strong shock (M>>1) → $\alpha = 4$ → $\phi(\varepsilon) \propto \varepsilon^{-2}$

- 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)

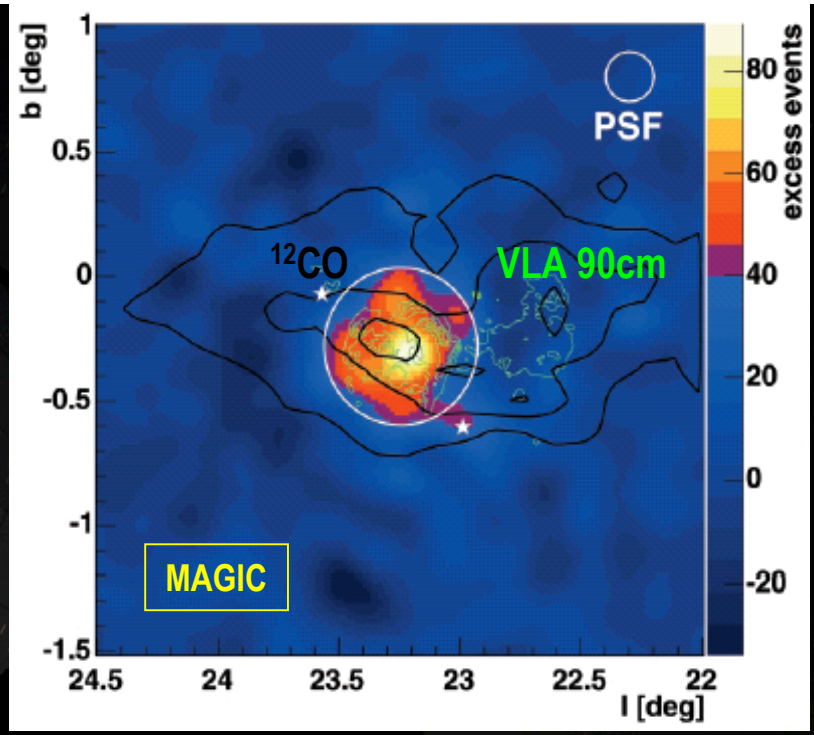
- Hadron illumination of ISM: $L_{\geq E}^{gas} \approx 2\times10^{37}(E/TeV)^{-1.1}(U_{CR}/eV)(M^{gas}/10^9 M_\oplus)$ phot / s

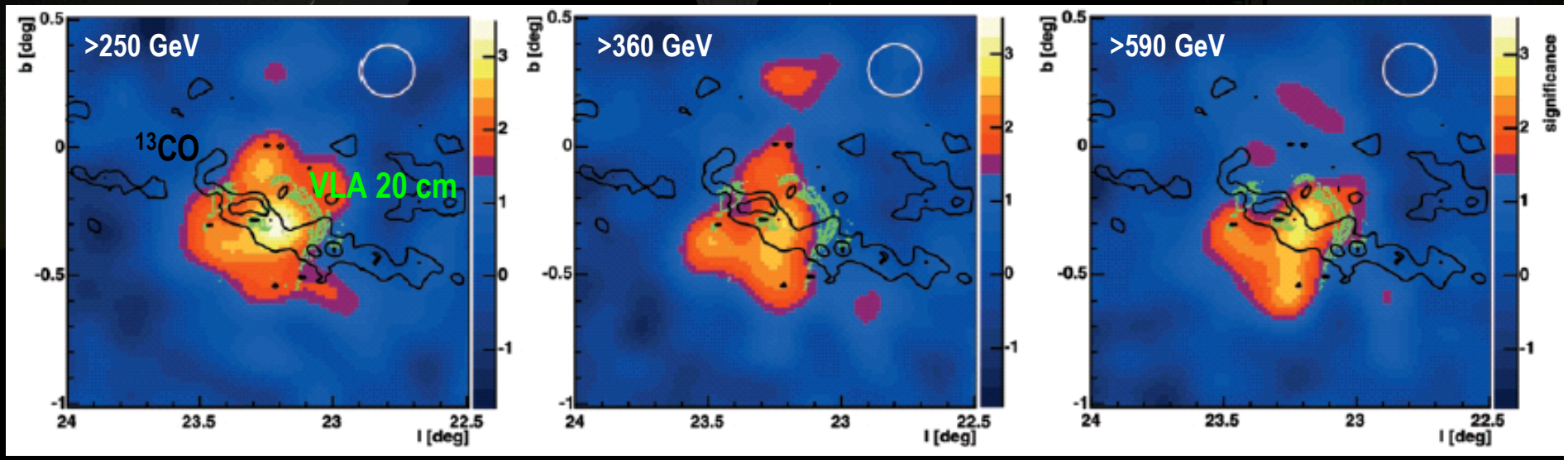
$$dN_\gamma/(dA\,dt\,dE) = (3.7 \pm 0.6) \times 10^{-12}(E/\mathrm{TeV})^{-2.5\pm0.2}$$



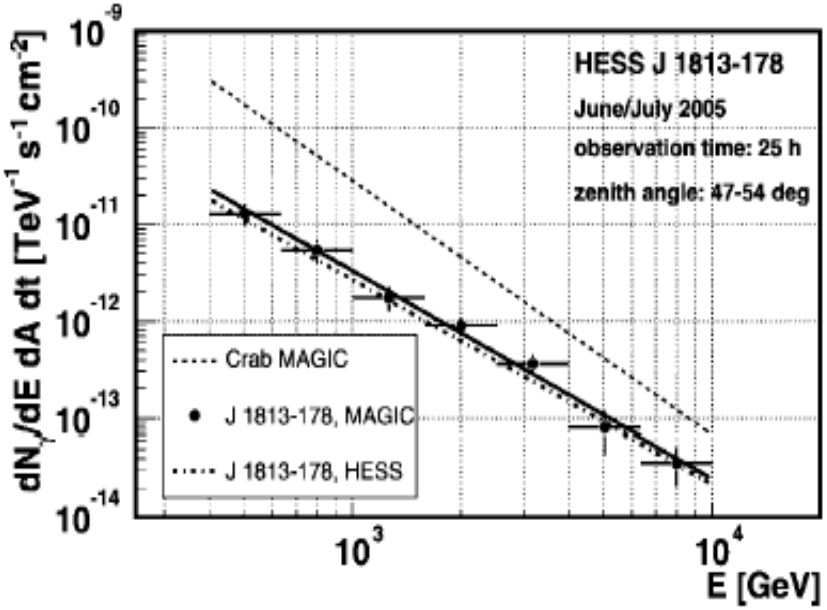
H.E.S.S. J1834-087

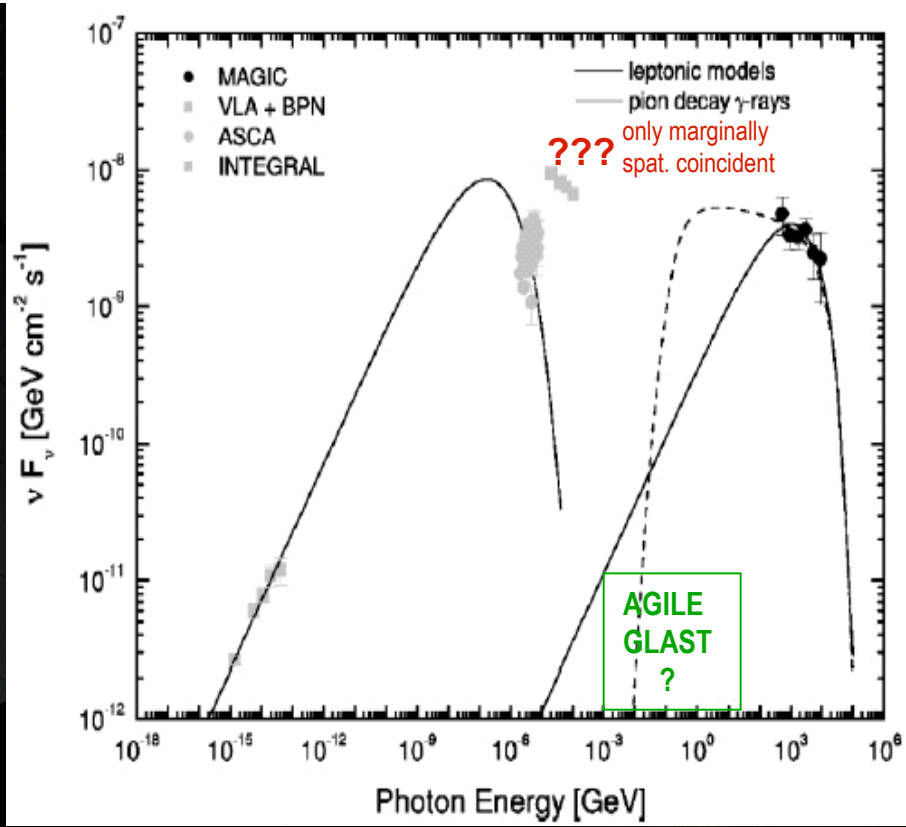
W41 G23.3-0.3

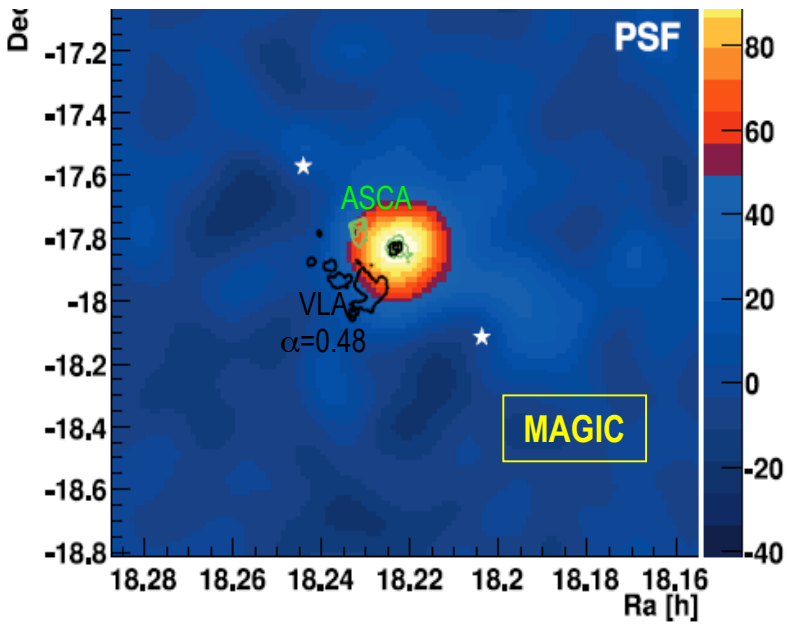




$$\frac{dN_\gamma}{dA\,dt\,dE} = (3.3 \pm 0.5) \times 10^{-12} \times (E/\mathrm{TeV})^{-2.1\pm0.2}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$$







H.E.S.S. J1813-178

G12.82-0.02

D = 4 kpc

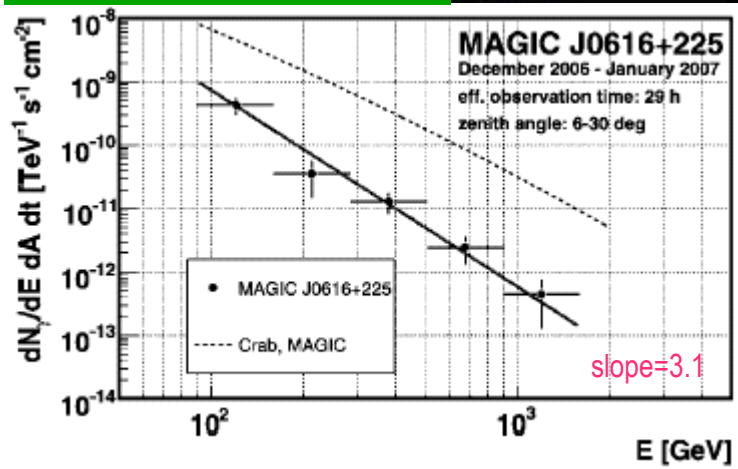
Hadronic: 2M$_\sim$ of target gas, exp-cutoff proton distrib: α=2.1, E_c=100 TeV, n_p=6cm^{-3}, L(0.4-6TeV)=2.5×10^{34}erg/s

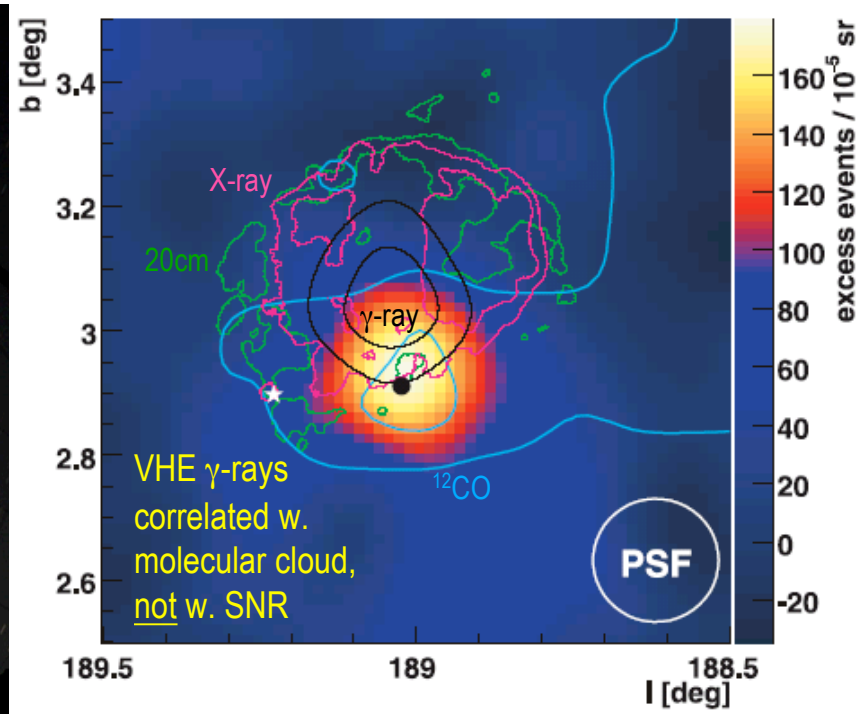
Leptonic: B=10mG, exp-cutoff electron distrib: α=2.0, E_c=20TeV

IC 443

Supernova Remnant

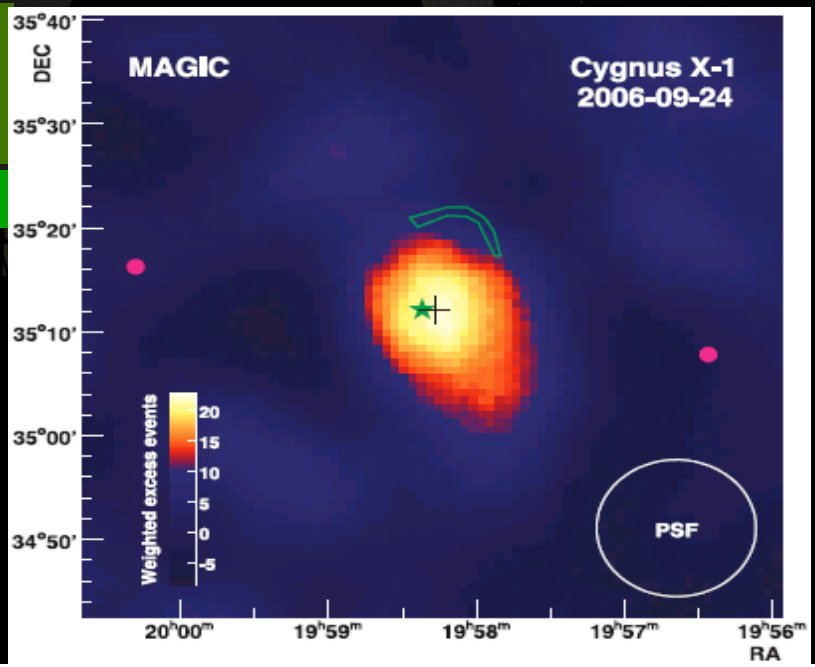
MAGIC 0616+225





CYG X-1

HMXB, stellar mass BH candidate



SNR RX J1713.7-3946

SUPERNOVA REMNANT

H.E.S.S.

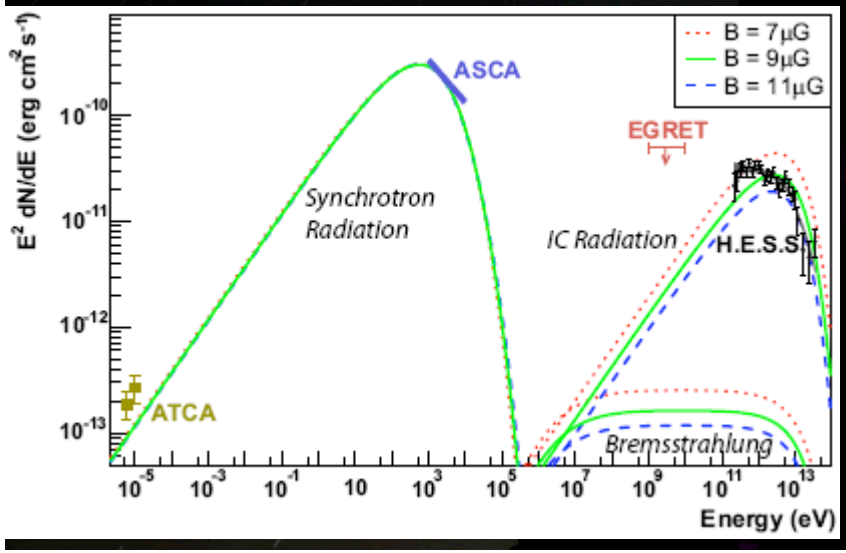
SNR shell → particle acceleration

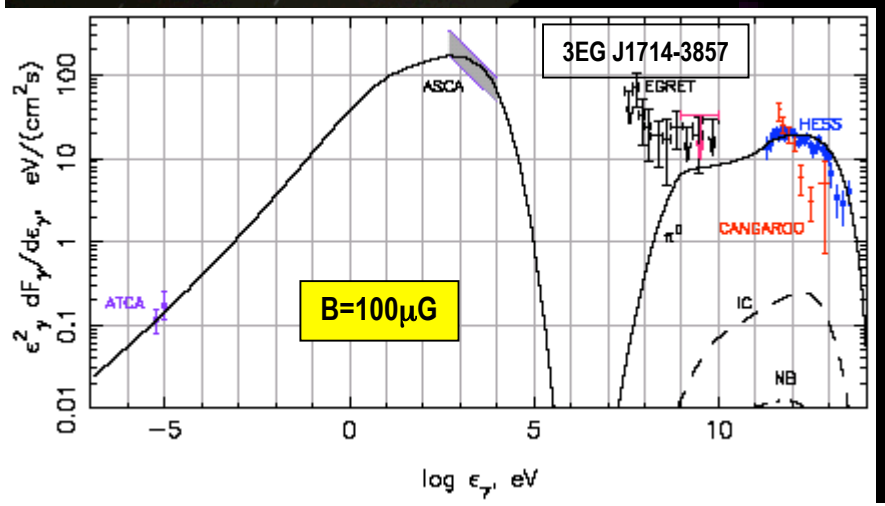
Resolved shell in VHE-γ-rays

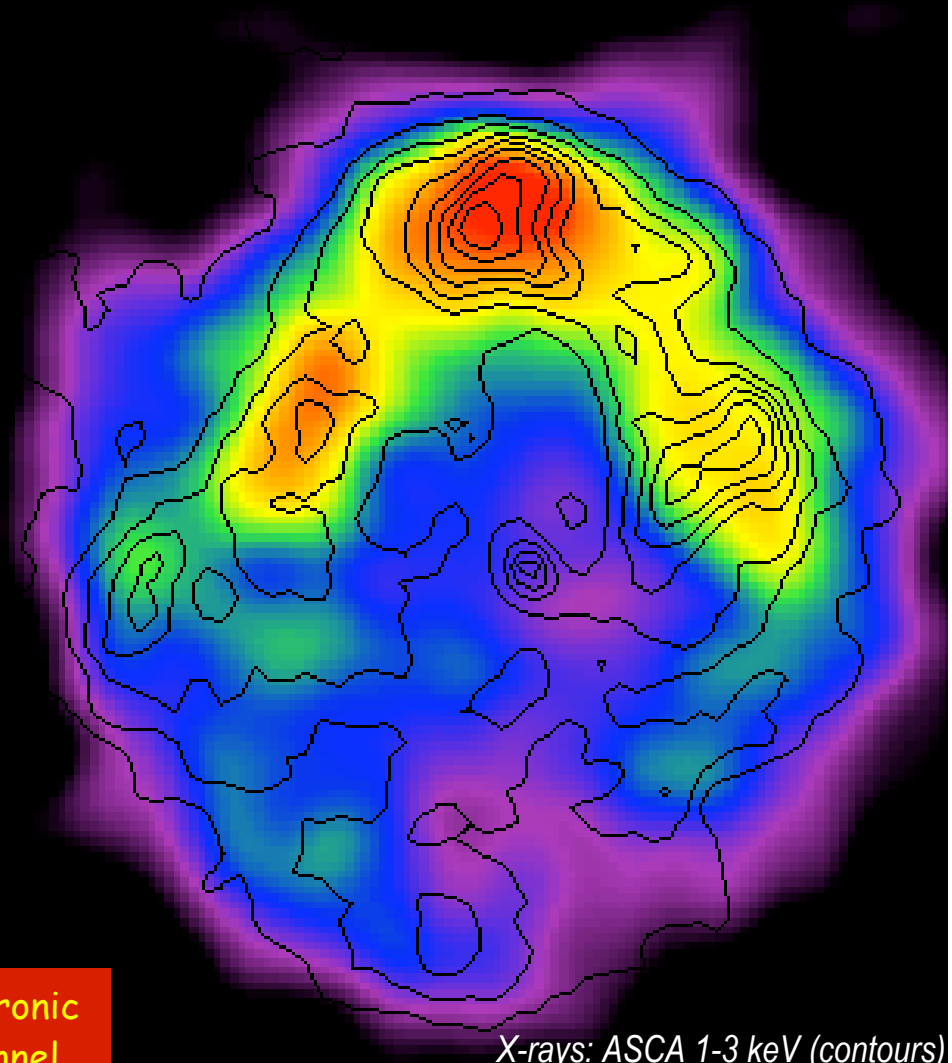
γ-rays from leptonic or hadronic channels?

leptonic channel favored

Aharonian+ 2006







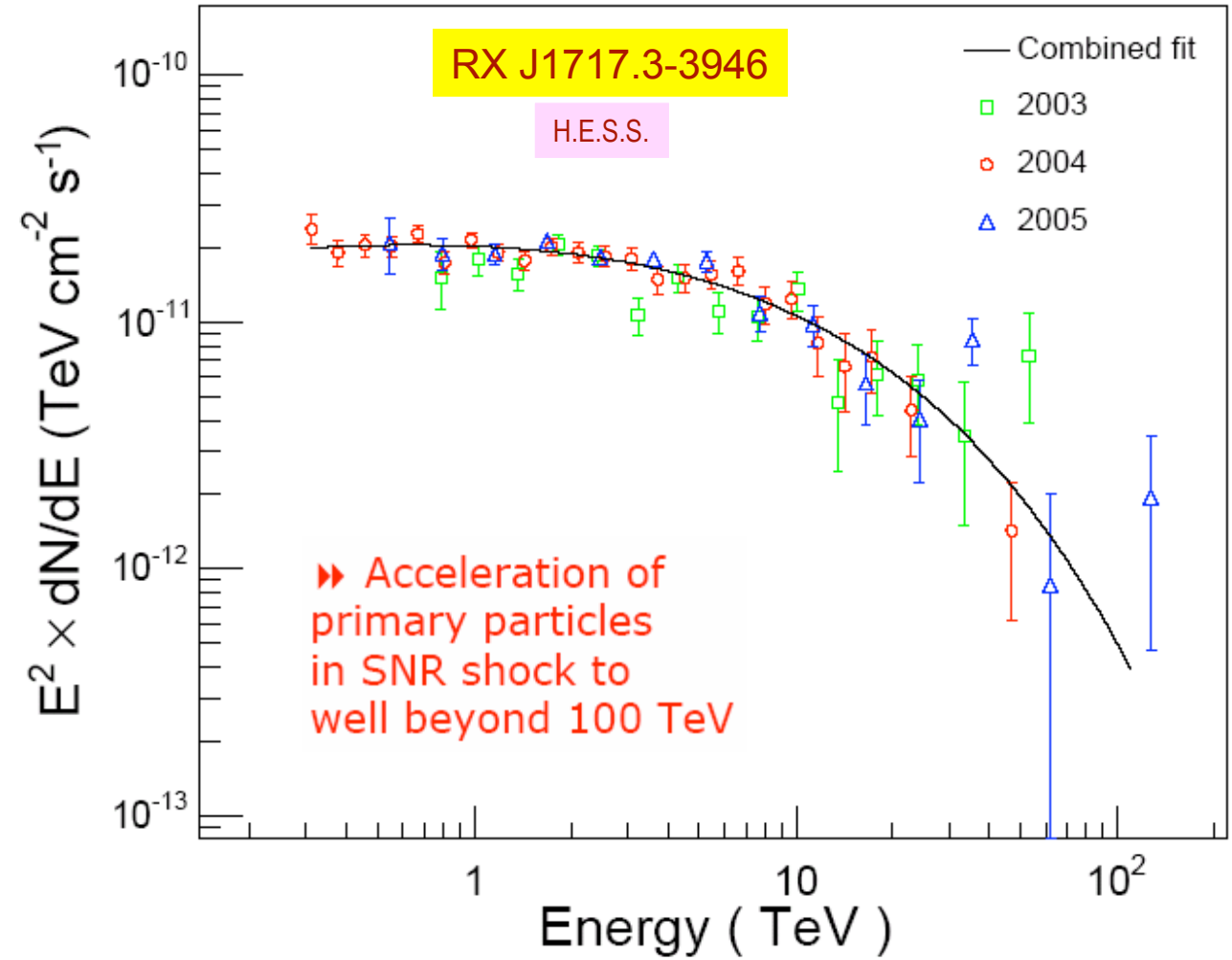
hadronic channel favored

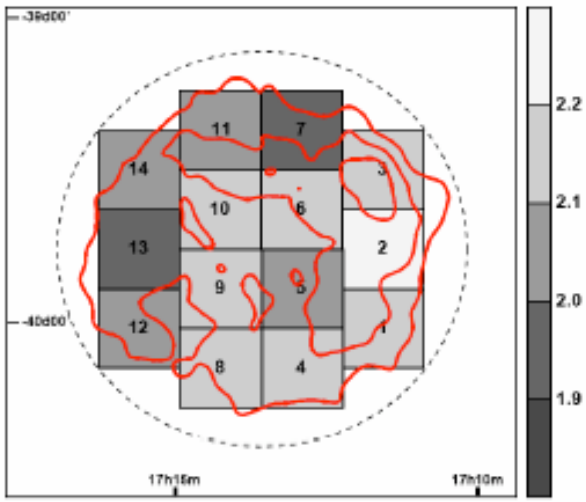
X-rays: ASCA 1-3 keV (contours)

γ-rays: HESS (colour scale)

Berezhko & Völk 2006

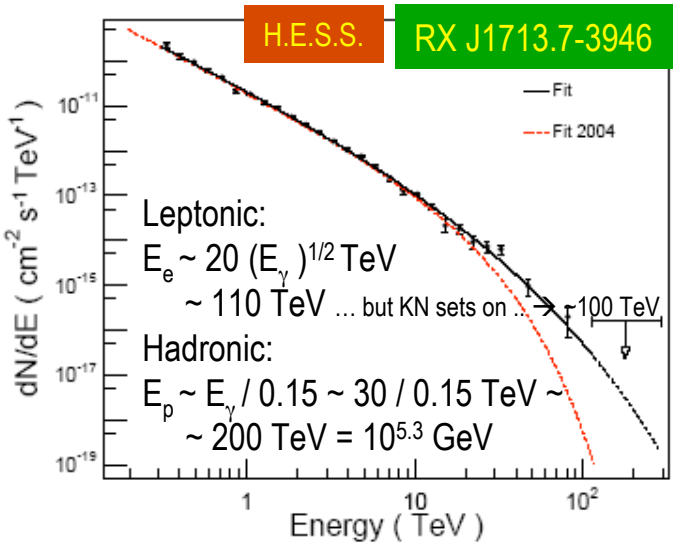
SNRs: accelerators of Galactic CRs ?

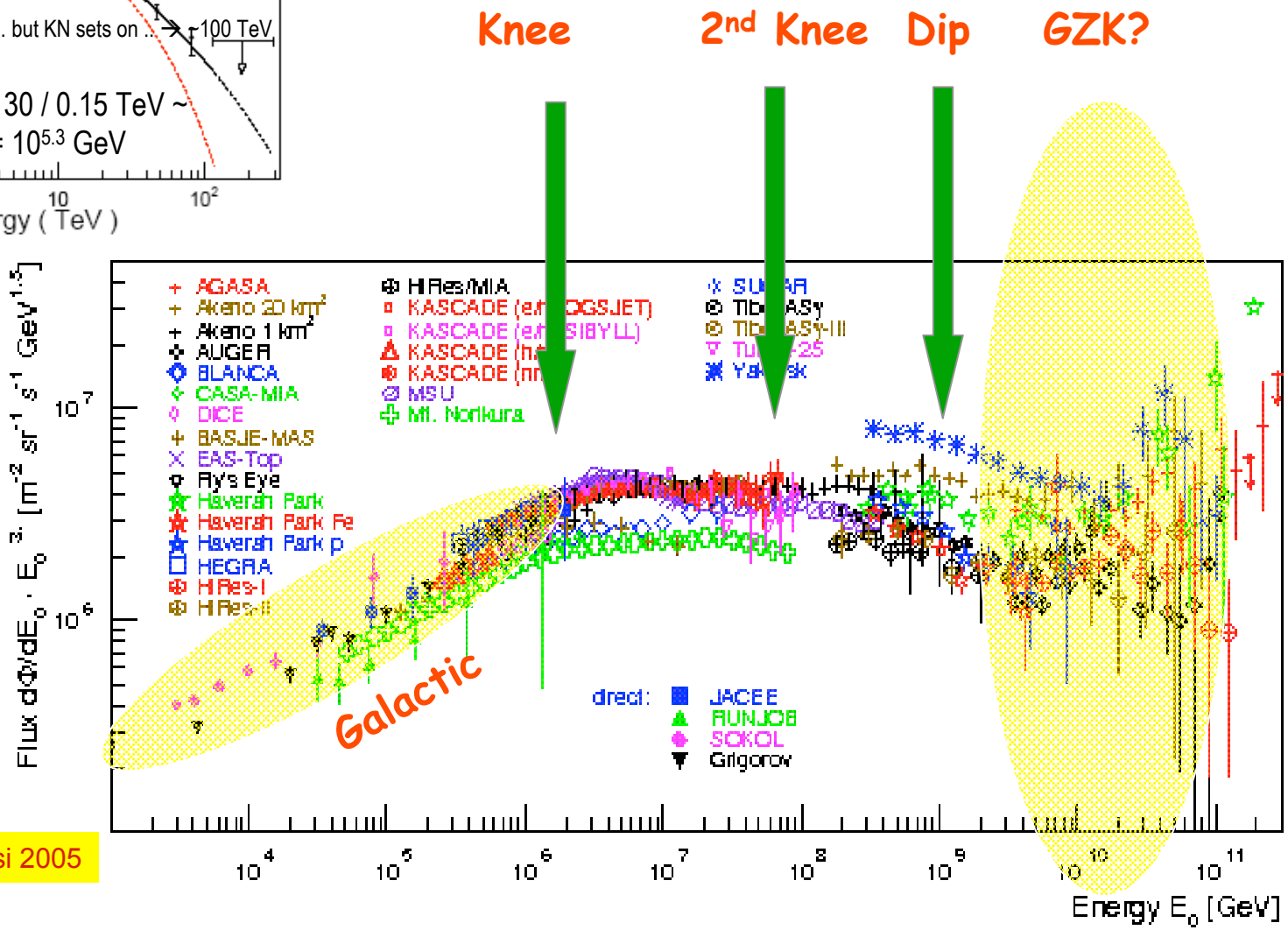




- Index ~ 2.1 – 2.2
- Little variation across SNR
- Cutoff or break at high energy

Cosmic-Ray Spectrum



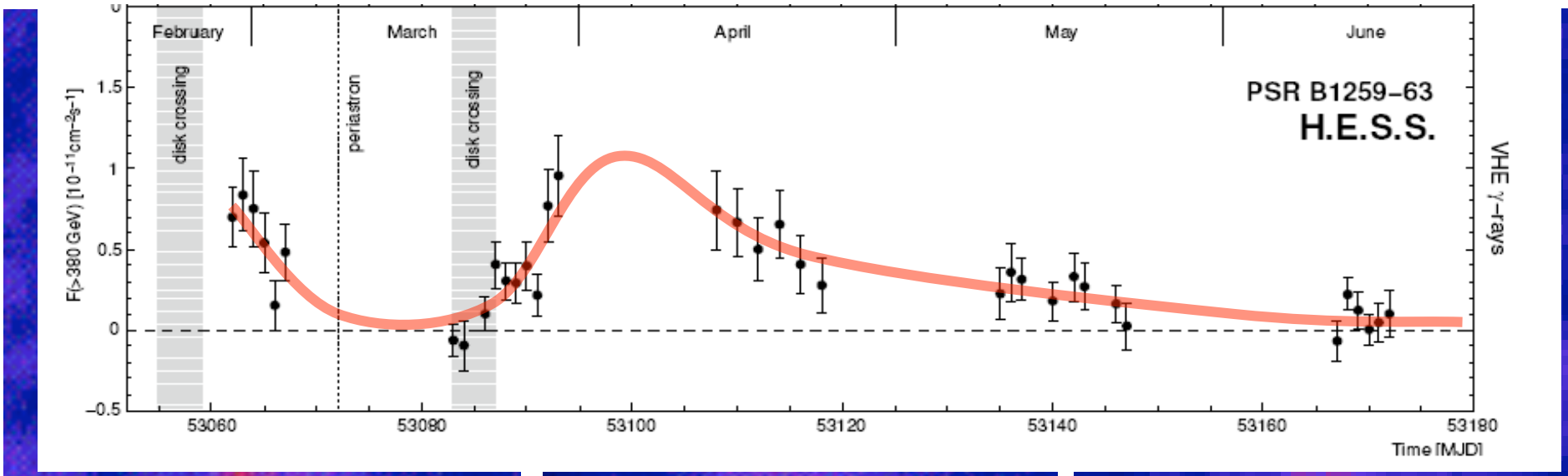


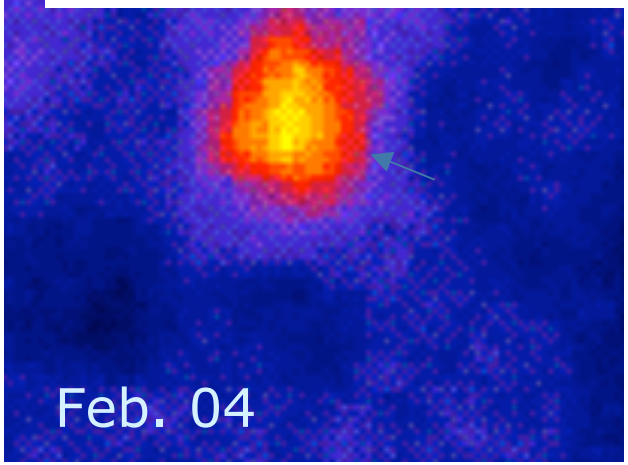
Blasi 2005

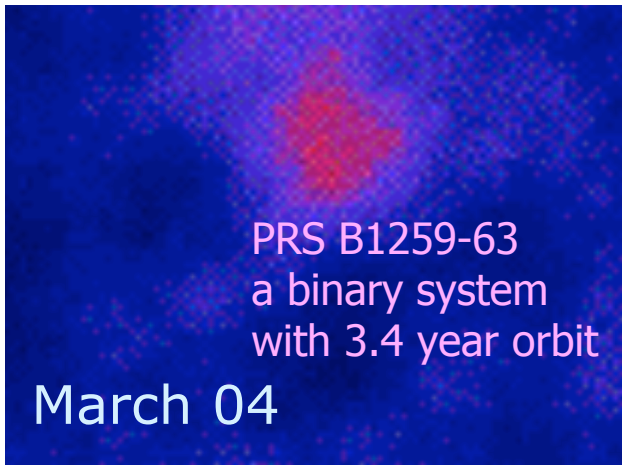
'Dark accelerators'

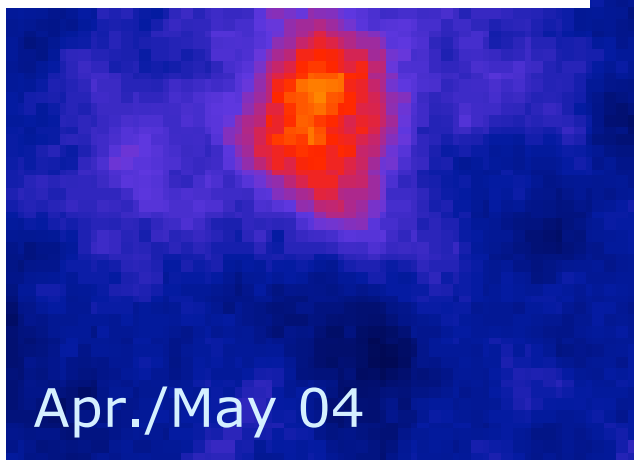
First discovered variable Galactic TeV source

HESS

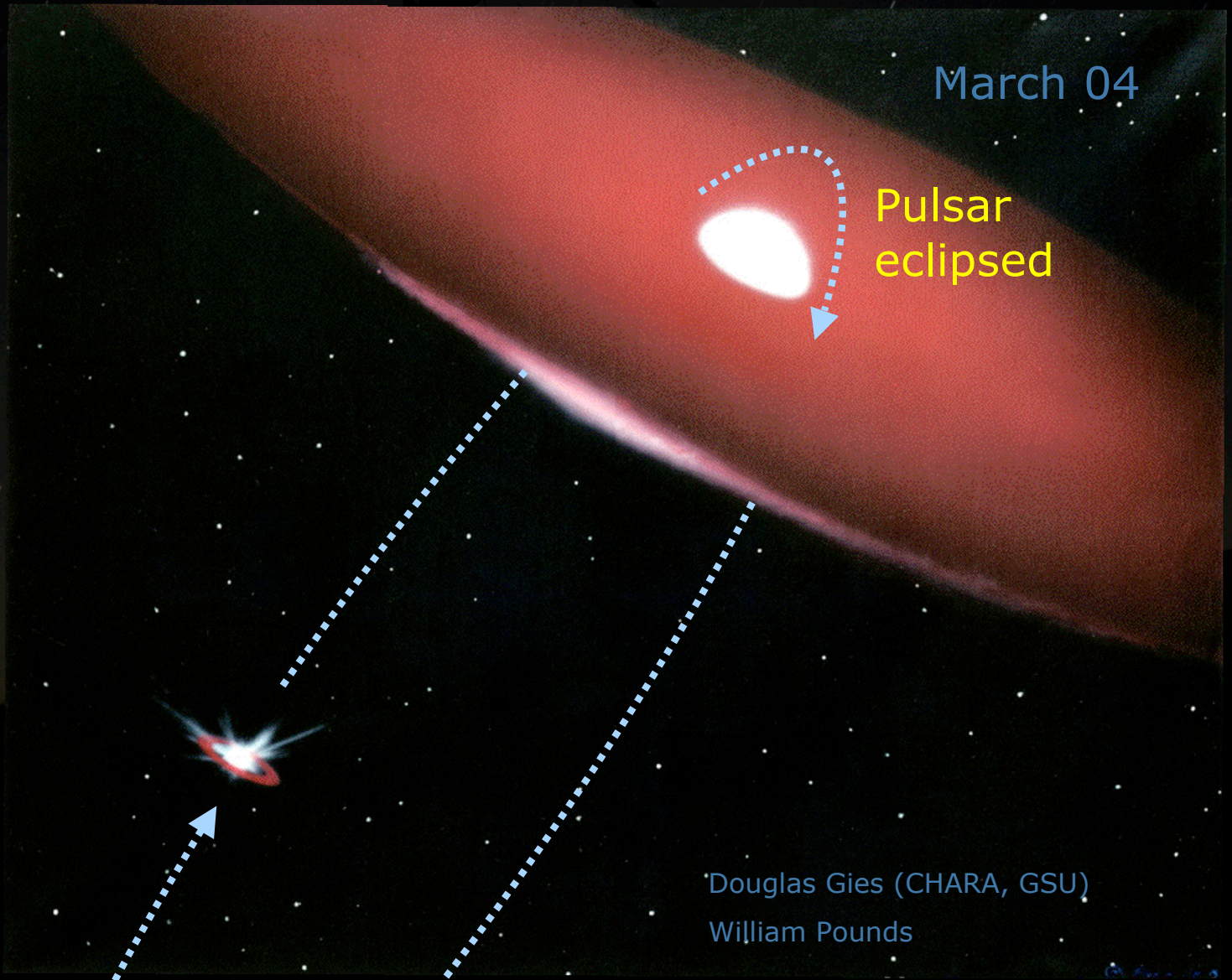








PSR B1259-63: - radio pulsar + ~10 M☉ Be star
- periastron: ~20 stellar radii
- emission: synchro + IC
- 3.4-yr, highly-eccentric orbit
- correlation: HESS, RXTE, INTEGRAL



LS I +61 303

MAGIC

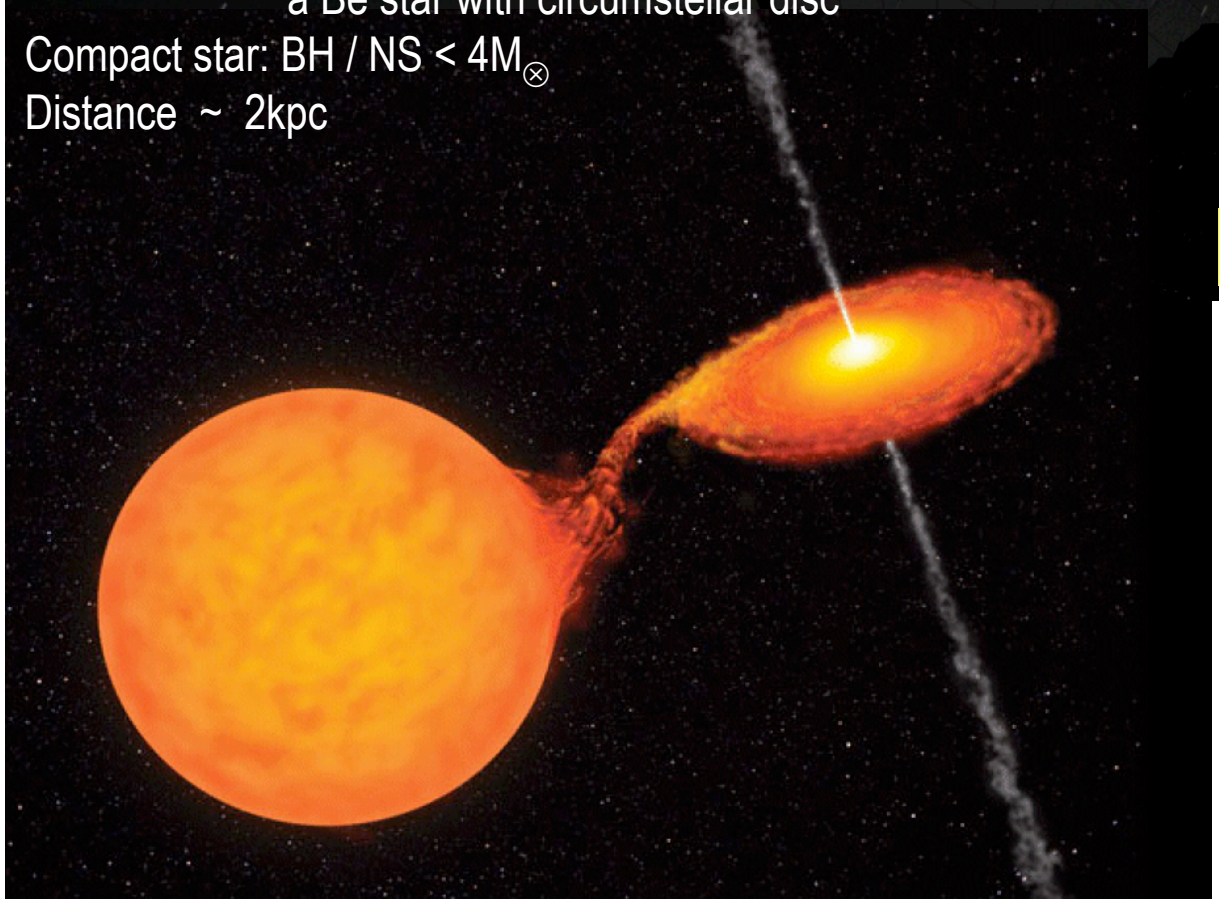
X-Ray binary system with radio jet → μQSO??
(other known γ-ray binaries: LS 5039, PRS B1259-63, by HESS
Cygnus X-1, by MAGIC)

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

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

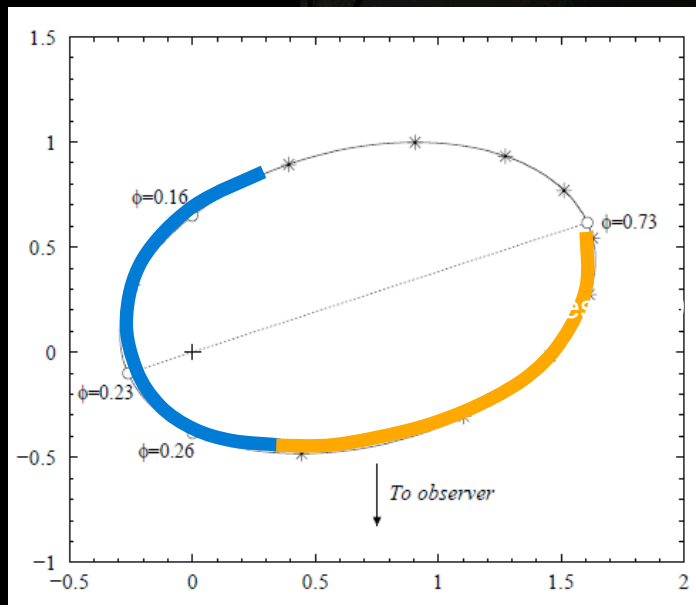
Compact star: BH / NS < 4$M_\odot$

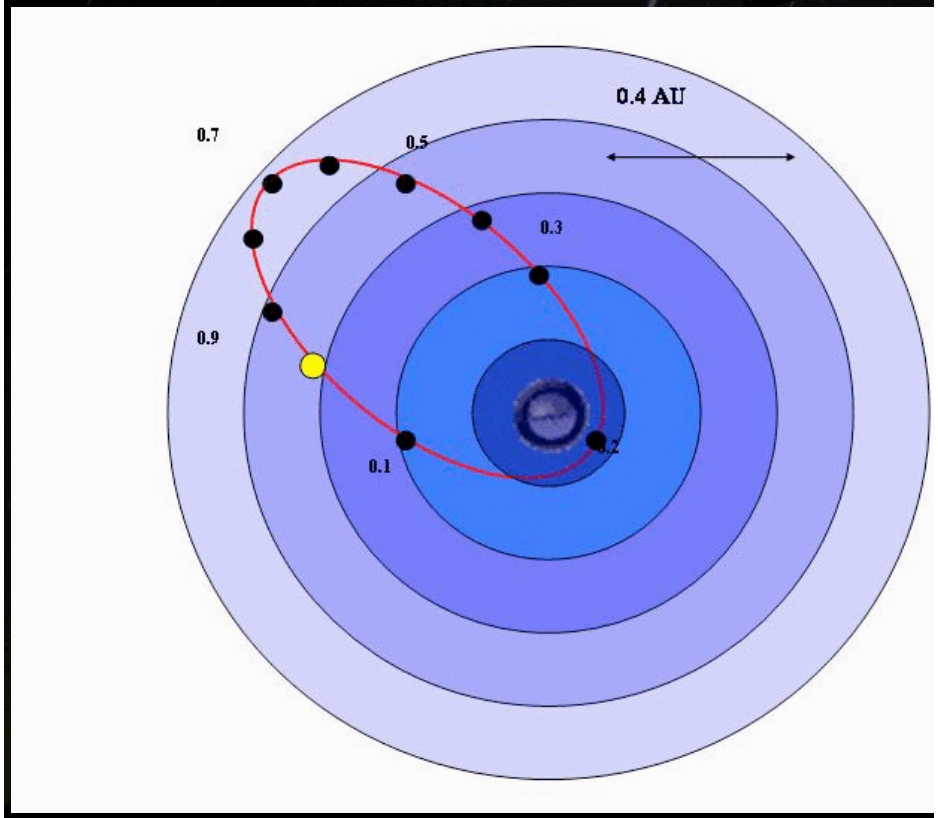
Distance ~ 2kpc



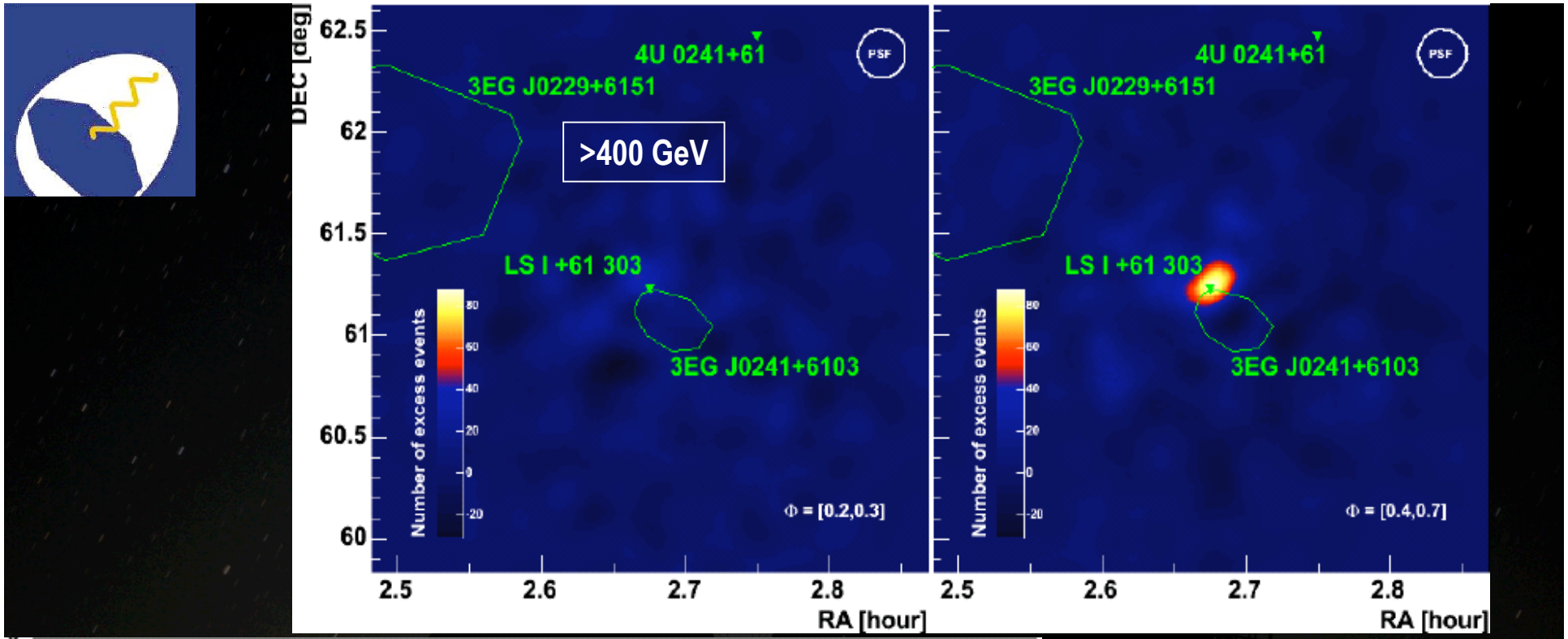
D = 2 kpc
Binary: Be + compact, P = 26.5 d
Compact: NS or BH
Periodic radio bursts
X-ray bursts at f=0.4-0.6 (Rosat, RXTE)
Radio jets (precessing): → μQSO?
>100 MeV mesured by COS B
→ correlation w. radio bursts
GeV emission (EGRET) variable, max. at ϕ=0.5 → correl. with X-ray variability
TeV emiss.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

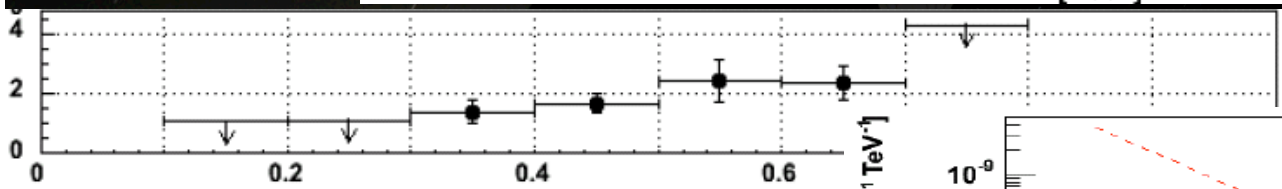
MAGIC observation: 54hrs total



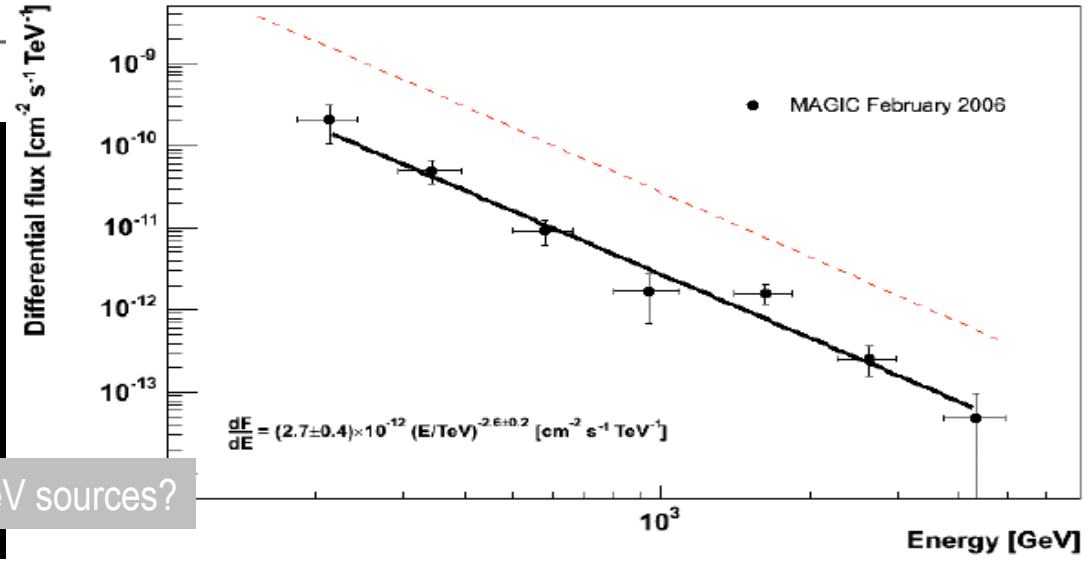


Ten points at equal phase intervals from Φ = 0 to Φ = 0.9, with MAGIC observations (where available) on the right. The periastron is at Φ = 0.2.





Variability averaged over several orbits



MAGIC

LS I 61+303

μQSO

… with LS 5039 (HESS) → new class of Galactic TeV sources?

pulsed or time-modulated signal with the pulsar spin period. The pulsed signal is explained by the copious pair plasma of energetic electrons and positrons in the pulsar magnetosphere which co-rotates with neutron star. The pulsed emission disappears with increased energies, and in the TeV energies, unpulsed emission emerges dominant. The pulsar wind blows out of the magnetosphere, collide with the circumferential matter to form pulsar nebula, and is considered to radiate TeV γ-rays. Thus, the emission mechamism of the GeV and TeV sources are disimilar to each other, except for the Crab nebula, the only known pulsar that has unpulsed signal also at GeV energy.

The Crab pulsar was given birth as a product of supernova explosion a thousand years ago. The pulsar dominates over the activity of the explosion ejecta that forms at present a shell-like structure of SNR. The pulsar wind is interpreted as a relativistic flow of the pair plasma of electrons and positrons, and thus, it is not surprising that the emission is dominated by the electron progenitor and not by protons, as evidenced by the Spectral Energy Distribution (SED) over the "entire" bands consisting of two components of synchrotron and inverse Compton radiations. Radiation from protons is hidden, if exists, below the intense contribution from the electron progenitor. However, electrons will cease to be accelerated, due to the rapid radiation loss, at lower energies than protons. Evidence for the proton progenitor would be possibly found in the energy spectrum beyond TeV energies if studied into more details.

Shell-type SNR that lacks the pulsar activity at the center of the remnant is a good candidate for the objects from which there appear clearly the γ-rays emitted from protons that are shock-accelerated in the supernova shell. Several

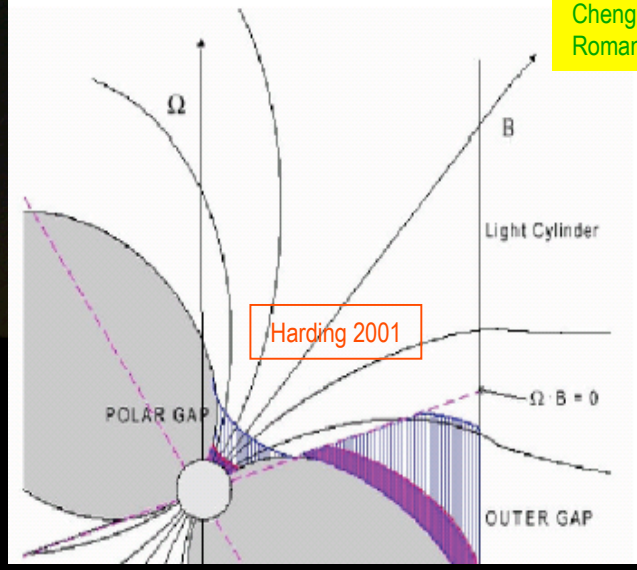
Pulsars

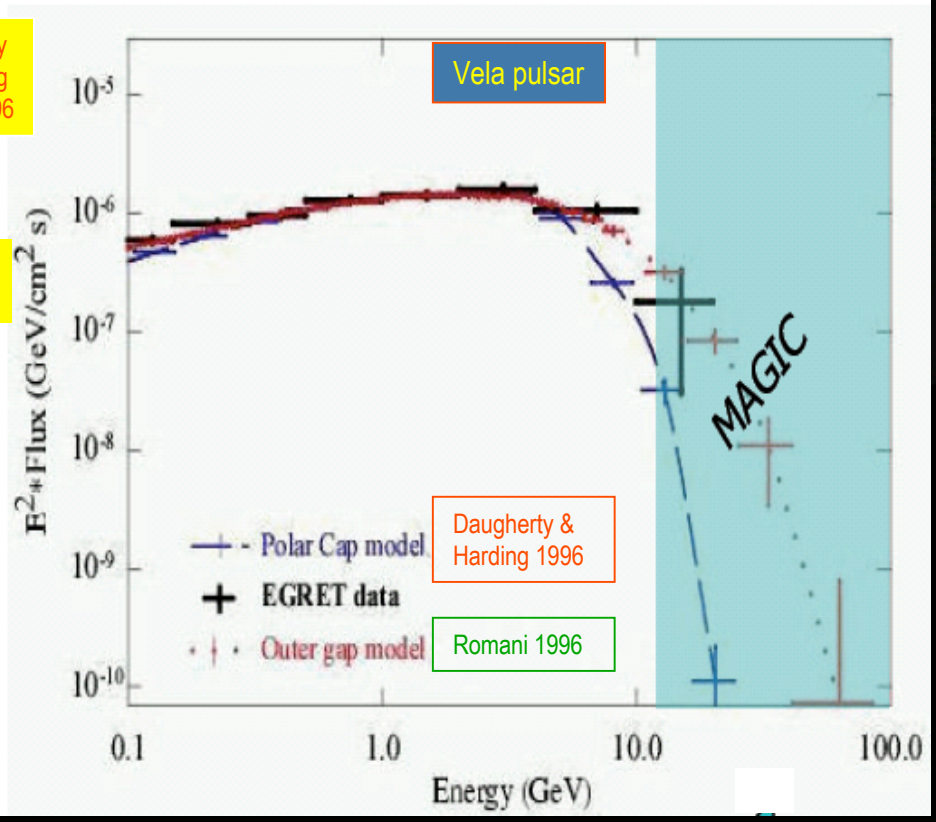
- Single NS powered by fast rotation
- **$B \approx 10^{11-13}$G**
- Magnetospheric TeV detection unlikely: flat GeV spectra steepen at high *E* due to attenuation by γ,B→ e^+e^- in psr B-field:

  cutoff energy E_0 depends on location of emitting region (**polar cap** vs **outer gap**)

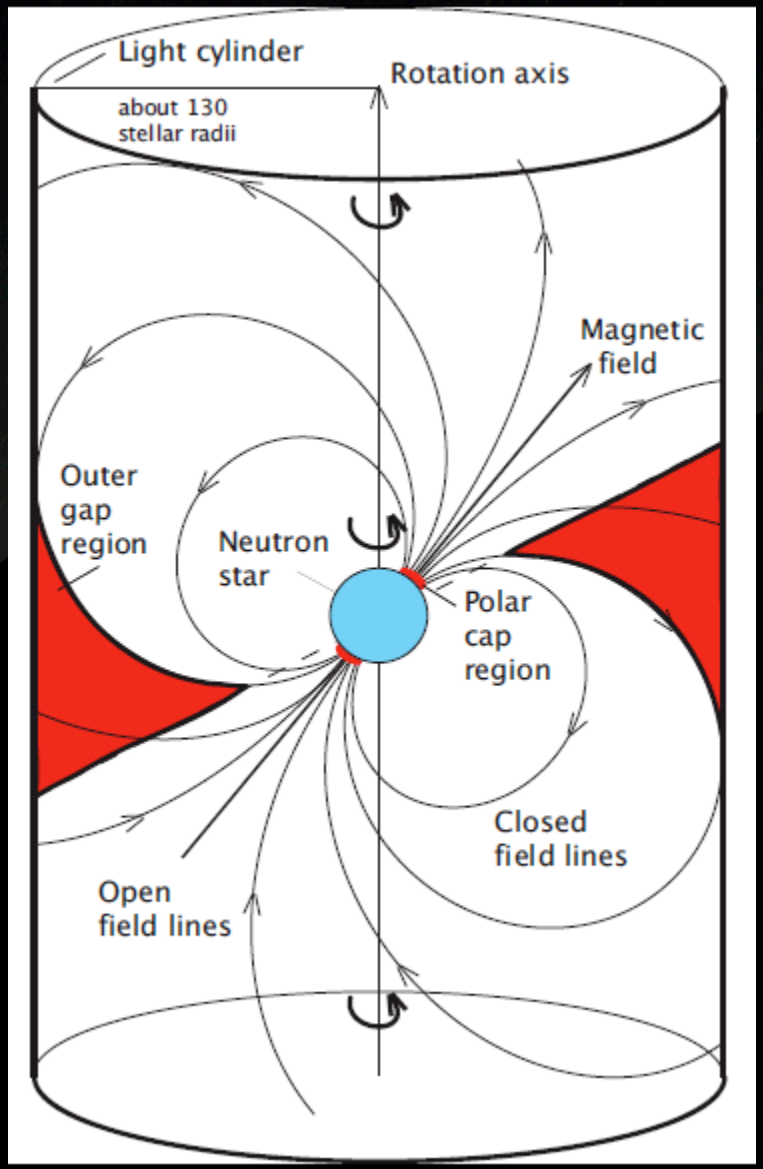
Pulsar γ spectra cutoffs. Two main models:

- Polar Cap: $E_0 \sim 10$ GeV — Daugherty & Harding 1982, 1996
- Outer Gap: $E_0 \sim 100$ GeV. — Cheng+ 1986, Romani 1996





GLAST and low-threshold (<20 GeV) IACT observations to provide crucial test for competing models !


Light cylinder
Rotation axis
about 130
stellar radii
Magnetic
field
Outer
gap
region
Neutron
star
Polar
cap
region
Closed
field lines
Open
field lines

Pair production: strong B field, $\gamma \rightarrow e^+ + e^-$
weak B field, $\gamma+\gamma \rightarrow e^+ + e^-$

If particle acceleration and emission occur

<

near NS surface ($r \sim R_0$) → magnetic pair production
→ super-exp cut → E_{max} <1-10 GeV

farther out ($r > 5R_0$) → $\gamma\gamma$ pair production
→ (sub)exp cut → $E_{max} \geq$ 50-100 GeV

$$\varepsilon_{MAX} \approx 0.4\sqrt{P}\left(\frac{r}{R_0}\right)^{1/2} \max\left\{1, \frac{0.1B_{cr}}{B_0}\left(\frac{r}{R_0}\right)^3\right\} \mathrm{GeV}$$

E_{max} due to magnetic pair production in rotating magnetic dipole (Baring 2004)

Crab pulsar: P=0.033 s
B_0=8_10^{12}G

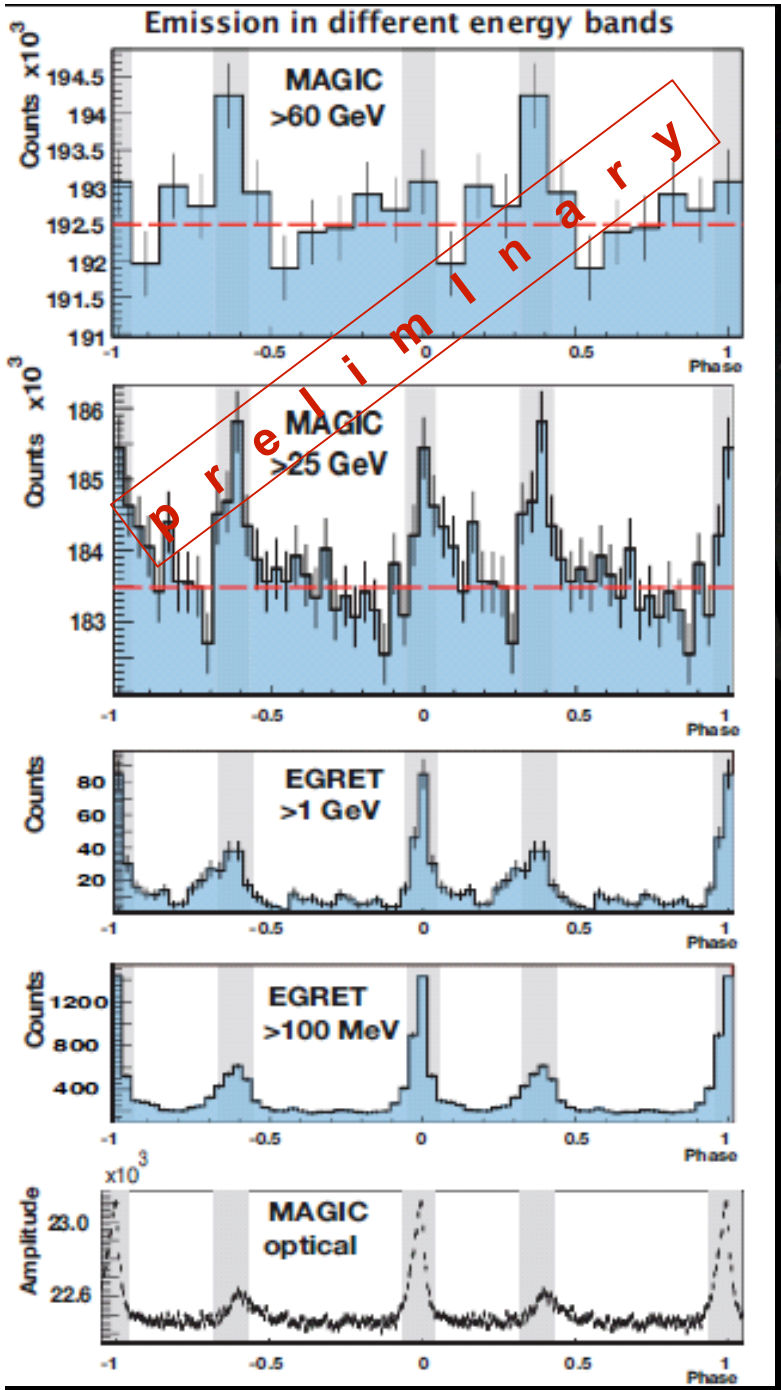
ε_{max} = 0.1 GeV	→	r ~ 1.3 R_0
1	→	2.5
5	→	4
25	→	6.3
60	→	8.1

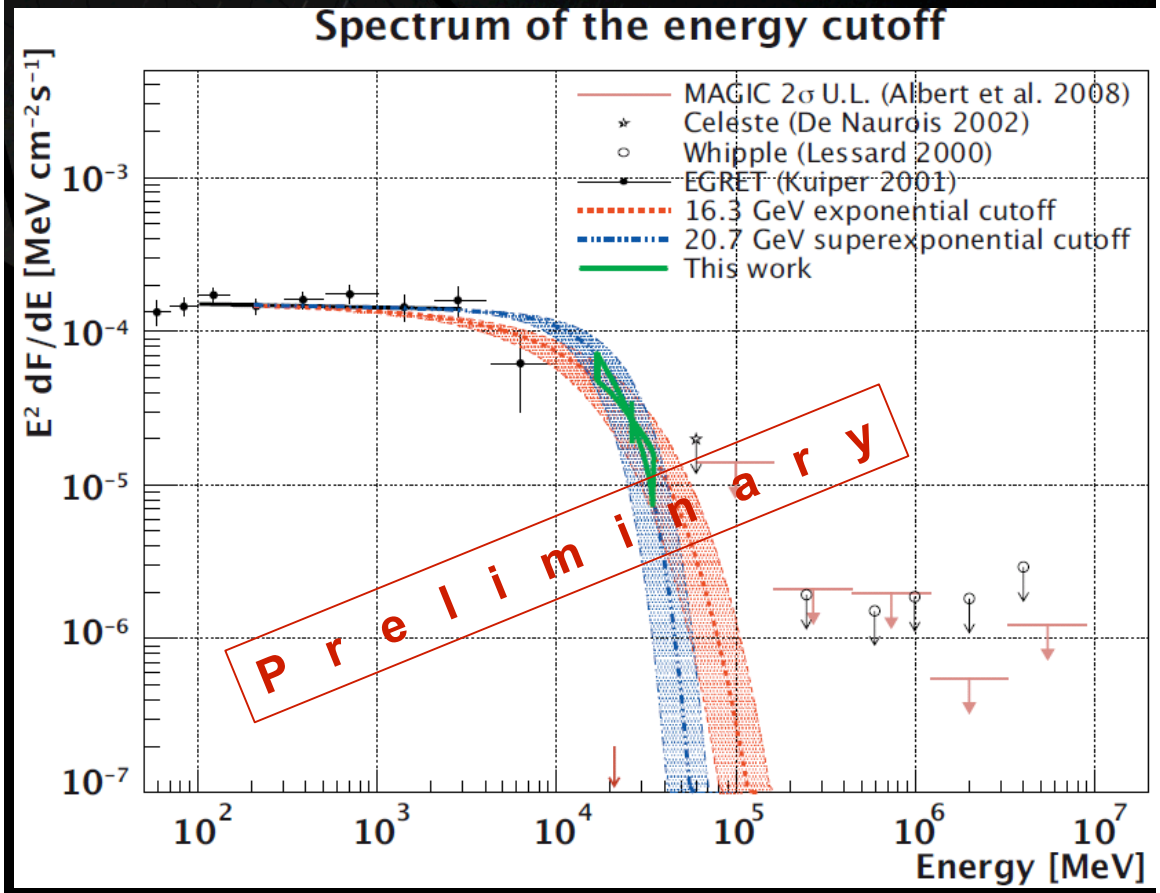
Crab pulsar

MAGIC

First detection of pulsed emission at >25 GeV.
Searches going on for ~35 years!!

EGRET + MAGIC: pl * exp [–E/16.3 GeV)]
pl * exp [–(E/20.7 GeV)^2]

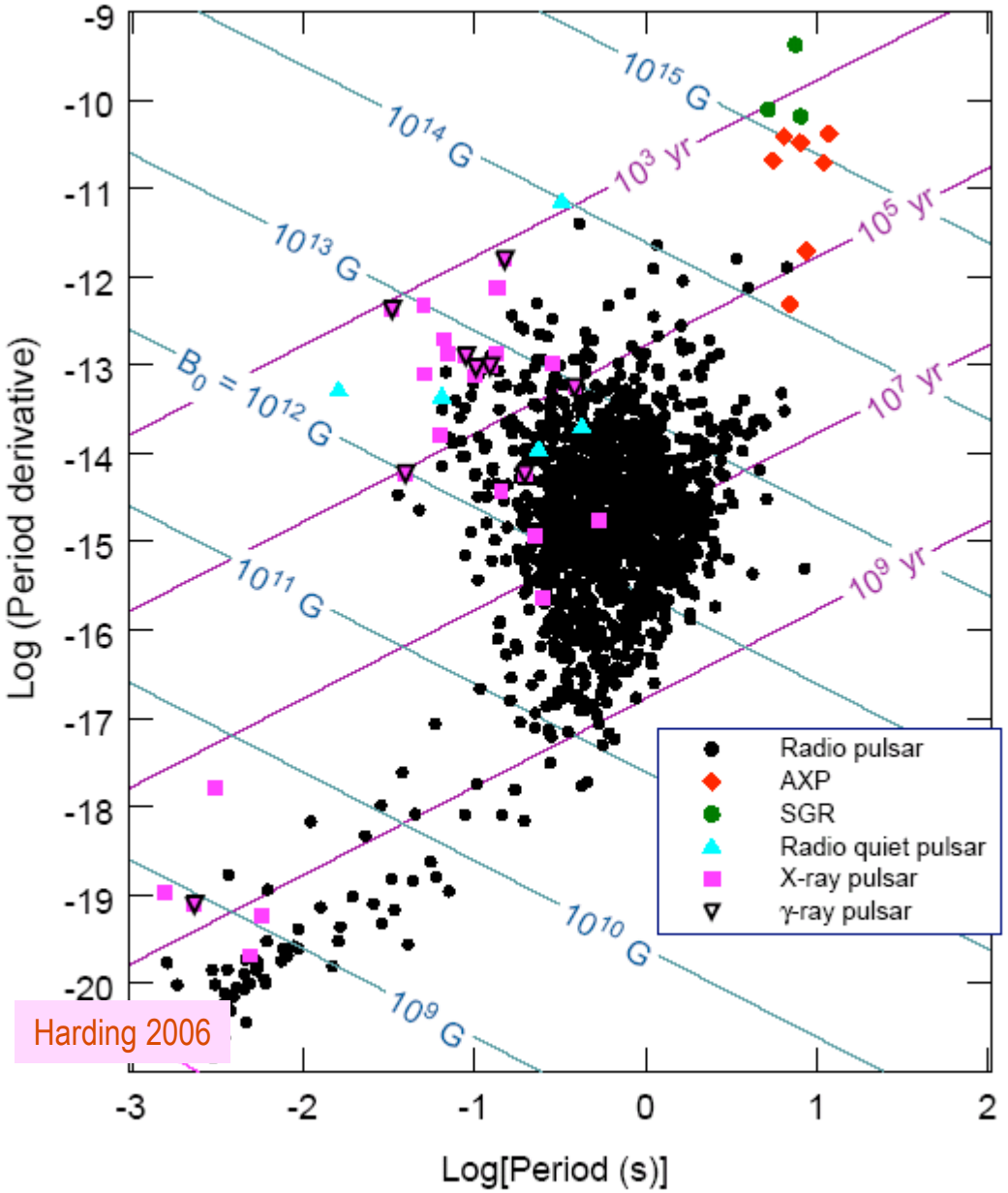




→ at least for Crab pulsar, *polar cap* scenario challenged

More psr obs's: ms pulsars?

Millisecond pulsars (msPSR)



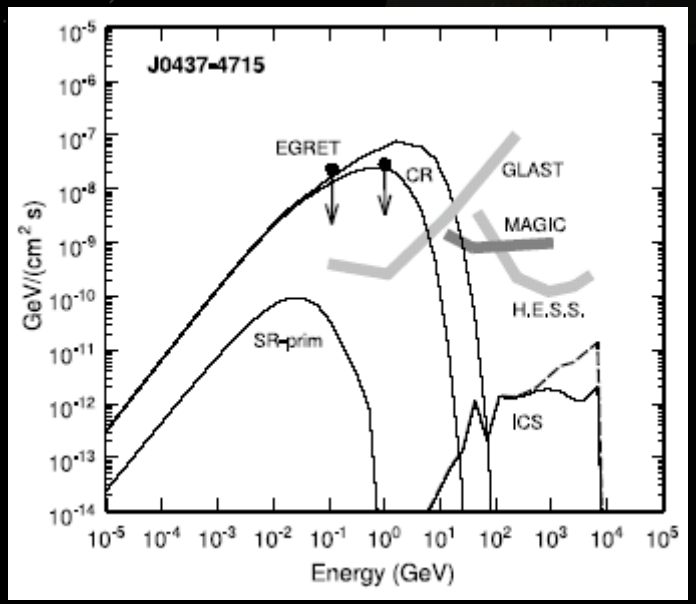
Harding 2006

- Spun-up by accretion torques due to mass flow from companion (→ binary systems)
- $B \approx 10^{8\text{-}10}$G: much lower than for canonical PSRs
- Low P → high potential drop (in spite of low B)
- Low *B* → • inefficient pair-production
  • high E cutoff from pair-production attenuation ($E_0 \propto B^{-1}$)

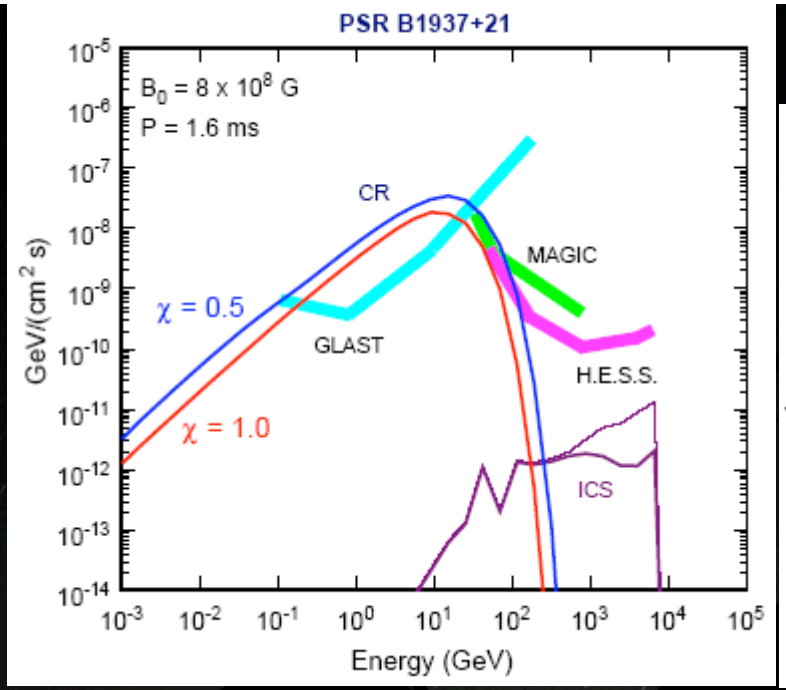
→ Polar-gap model efficient !

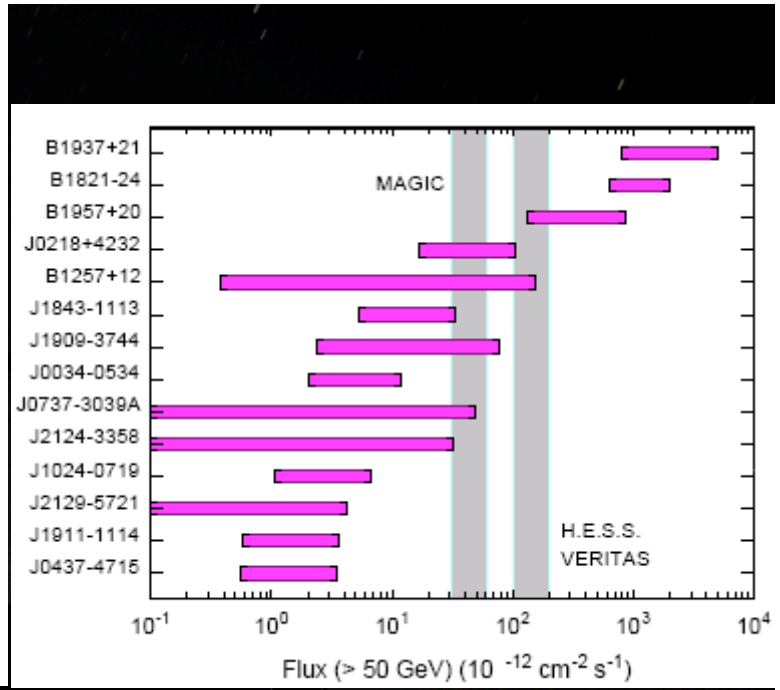
Curvature radiation: hard spectrum $E^{-\Gamma} e^{-E/E_0}$

Harding+ 2005 Γ=2/3, E_0~10-50 GeV



msPSR





MAGIC observed:

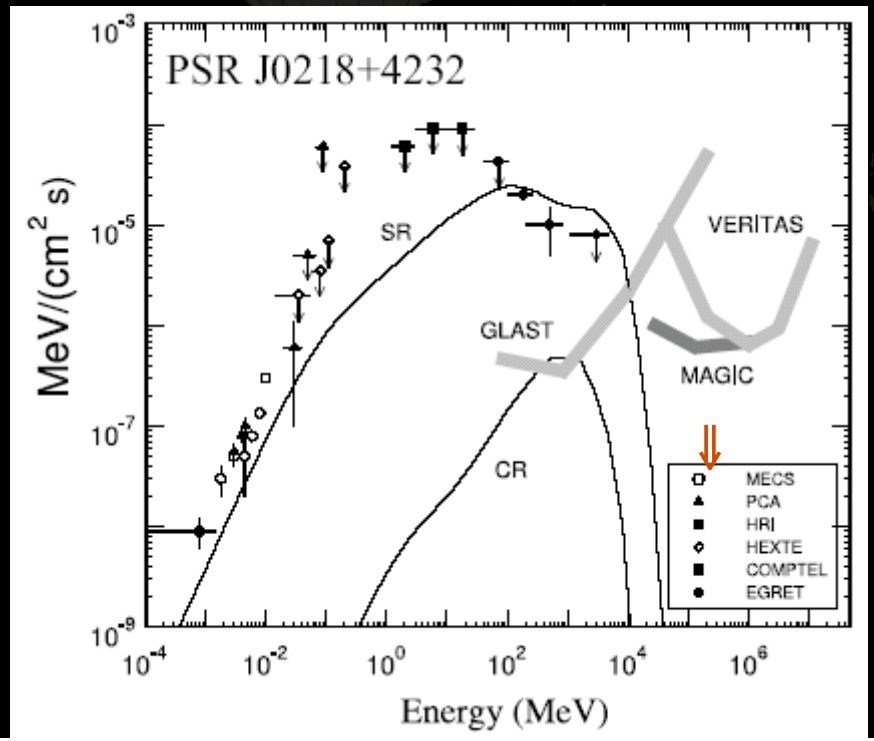
PSR B1957+20

PSR J0218+4232

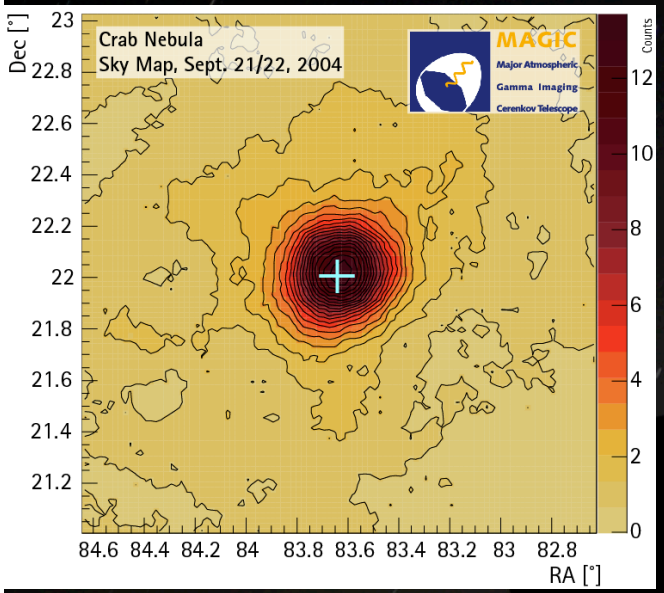
PSR 1951+32

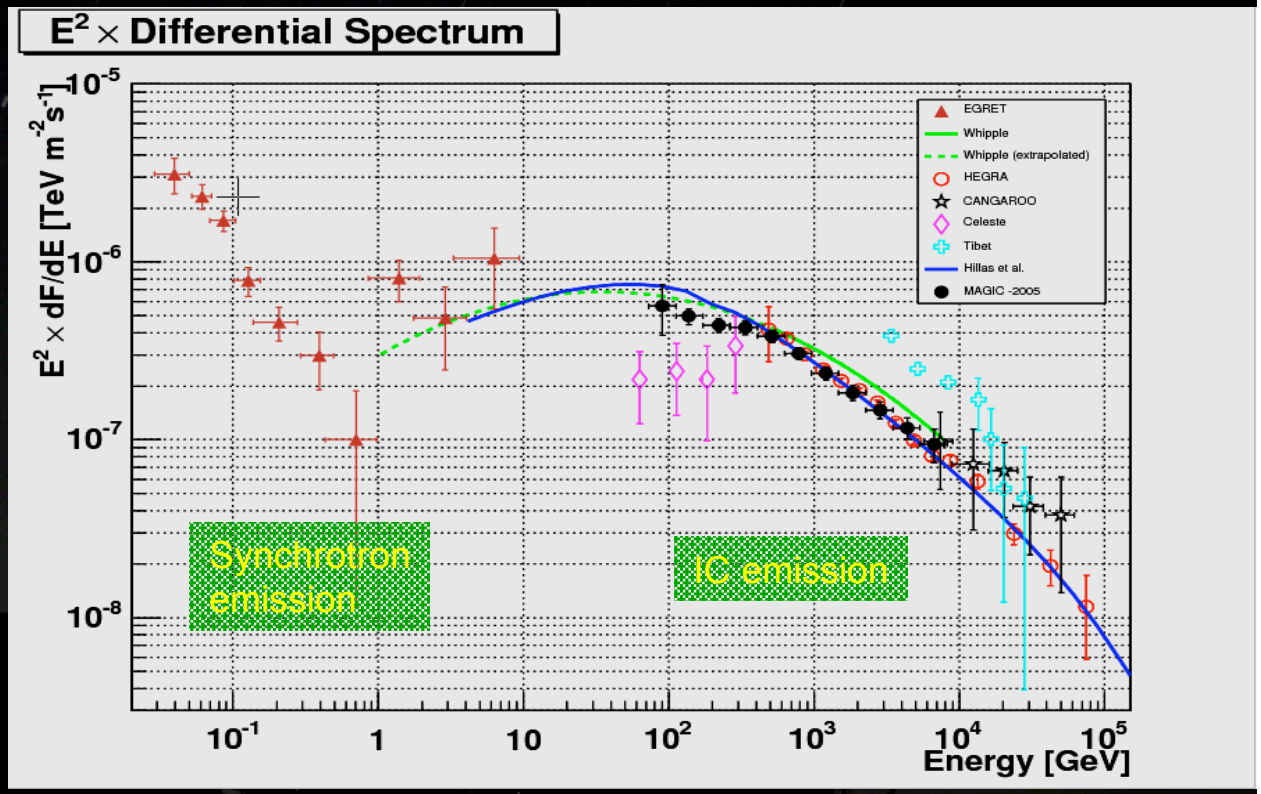
no detection!!

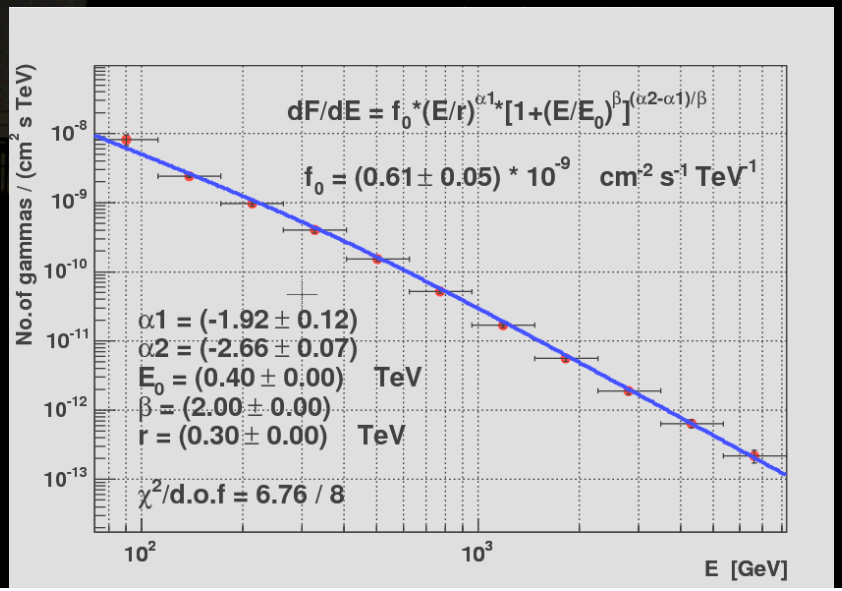
E_c < 32 GeV: constrains Outer Gap models?



Crab PWN



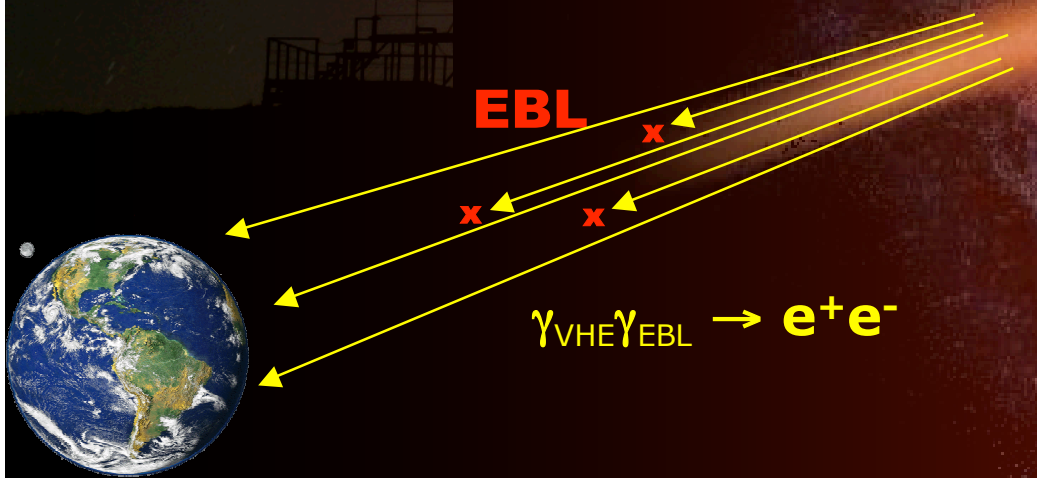




B~0.4 mG: not an effective IC emitter!

Extragalactic VHE astrophysics

- Physics of AGN jets
- Density of cosmological extragalactic background light (EBL)

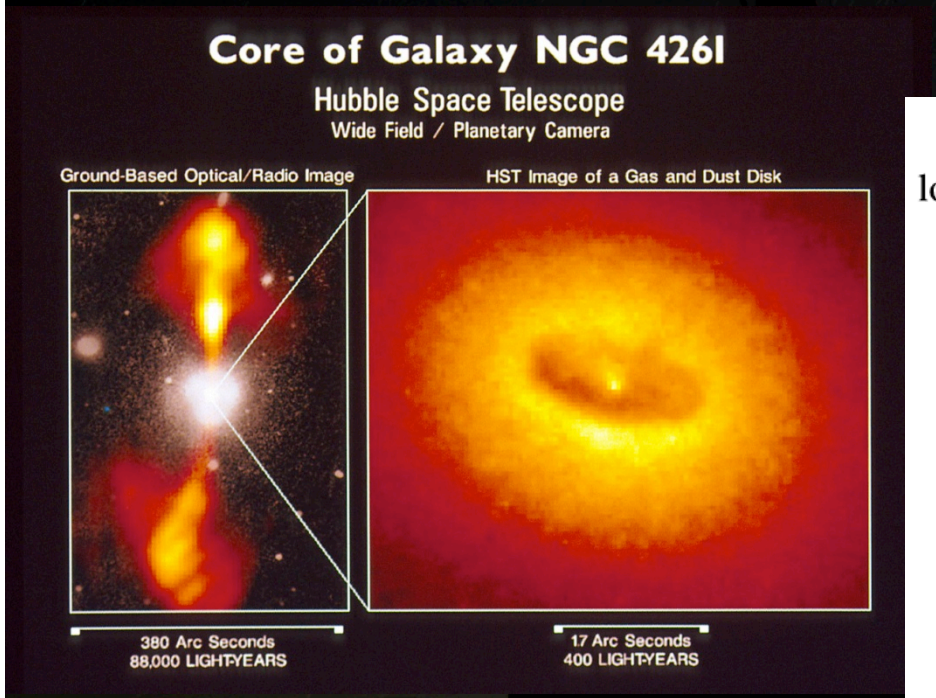


BLAZARS

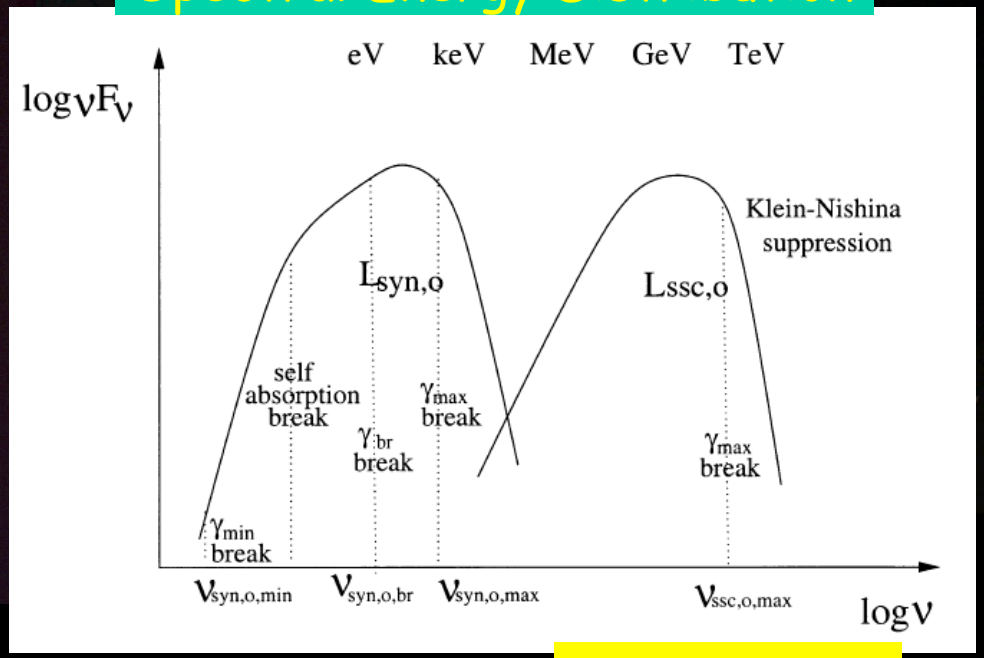
TeV detections: current status

1.	Mrk 421	z=0.031	Whipple	1992
2.	Mrk 501	z=0.034	Whipple	1996
3.	PKS 2344+514	z=0.044	Whipple	1998
4.	Mrk 180	z=0.045	MAGIC	2006
5.	1ES 1959+650	z=0.047	7Tel.Array	1999
6.	BL Lacertae	z=0.069	MAGIC	2007
7.	PKS 0548-322	z=0.069	HESS	2007
8.	PKS 2005-489	z=0.071	HESS	2005
9.	RGB 0152+017	z=0.080	HESS	2007
10.	W Comae	z=0.102	VERITAS	2008
11.	PKS 2155-304	z=0.116	Mark VI	1999
12.	1ES 1426+428	z=0.129	Whipple	2002
13.	1ES 0806+524	z=0.138	VERITAS	2008
14.	1ES 0229+200	z=0.139	HESS	2006
15.	H 2356-309	z=0.165	HESS	2006
16.	1ES 1218+304	z=0.182	MAGIC	2006
17.	1ES 1101-232	z=0.186	HESS	2006
18.	1ES 0347-121	z=0.188	HESS	2007
19.	1ES 1011+496	z=0.212	MAGIC	2007
20.	PG 1553+113	z>0.25?	HESS/MAGIC	2006
21.	3C 279	z=0.536	MAGIC	2007
22.	S5 0716+714	z= ?	MAGIC	2008

TeV Blazars



Spectral Energy Distribution



Kino+ 2002, ApJ, 564, 97

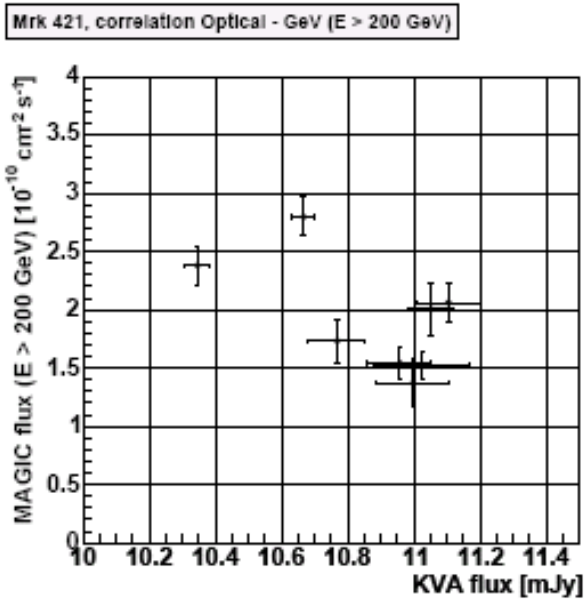
- TeV blazars: highly variable, NT emission
- All but one are HBL (high-peaked BL Lacs)
- Emission: leptonic (mainstream: Costamante & Ghisellini 2002)

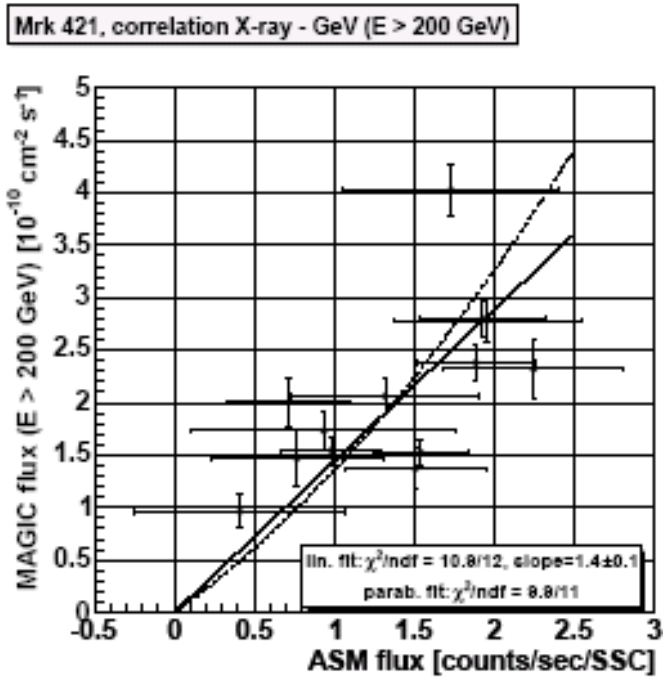
SSC model parameters:

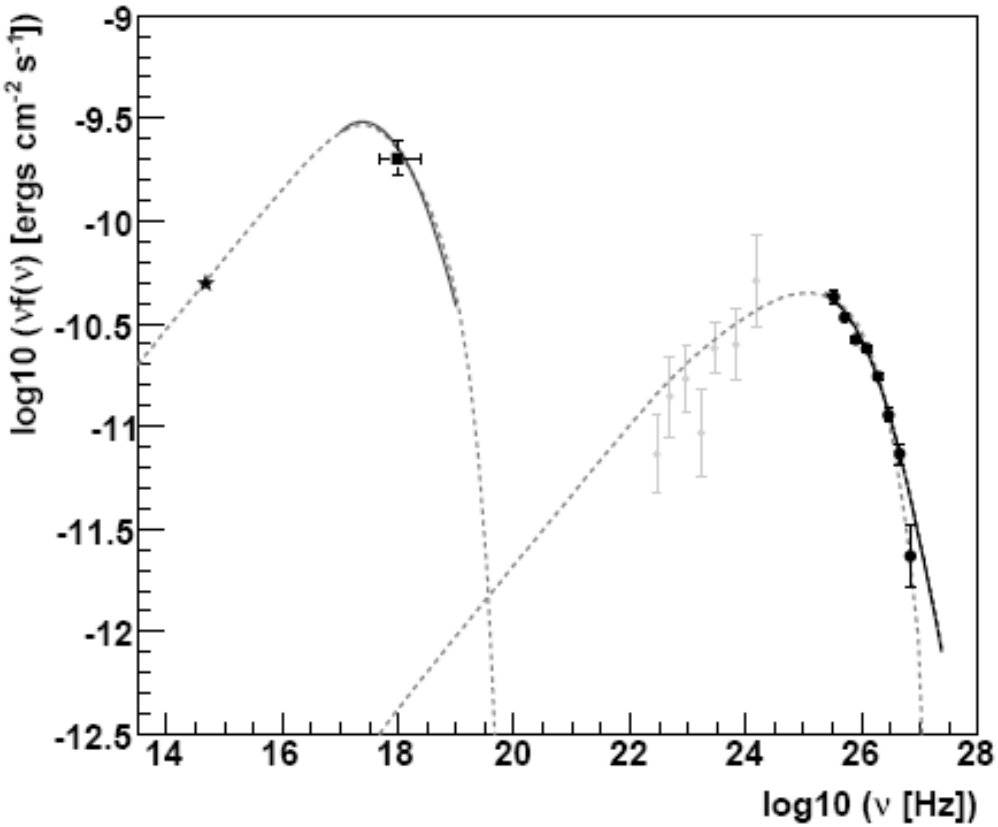
Plasma blob: R, B, δ_j

Electron pop: n_0, α_1, α_2, E_{br}, E_{min}, E_{max}

EBL: $u_{EBL}(z)$



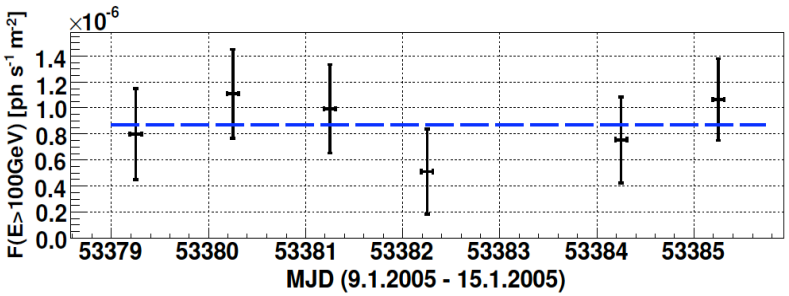


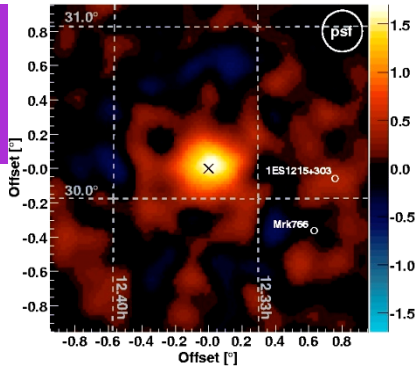


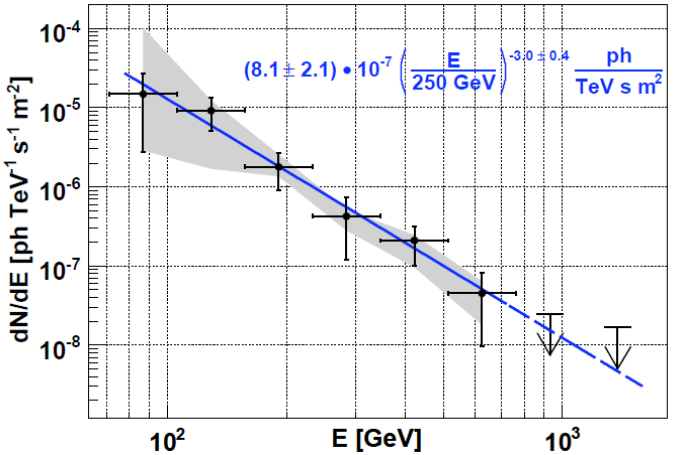
Mrk 421

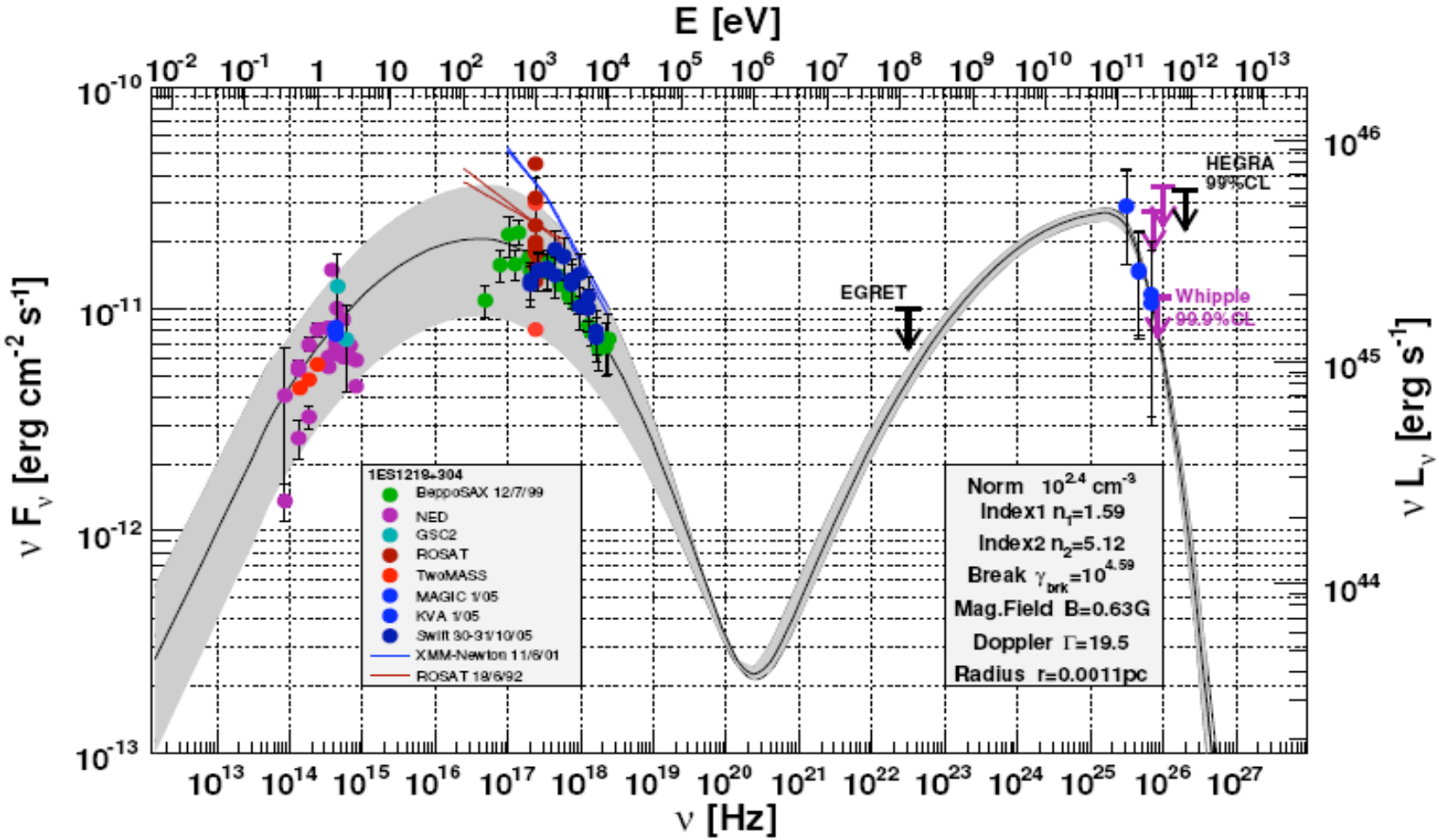
spherical blob with:	
Doppler factor	15
magnetic field	0.20 Gauss
radius of emitting region	1.6×10^{16} cm
injected electron spectrum:	
electron energy density	0.06 erg/cm^3
$5 < \log10(E[eV]) < 10.9$	index 2.31
$10.9 < \log10(E[eV]) < 11.6$	index 3.88

1ES 1218+304 (z=0.182)



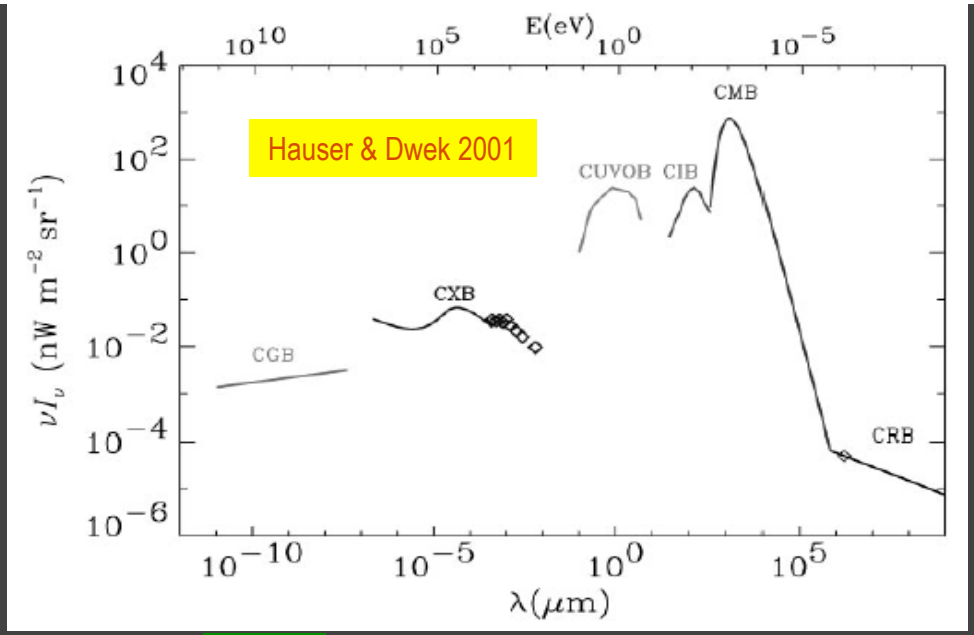


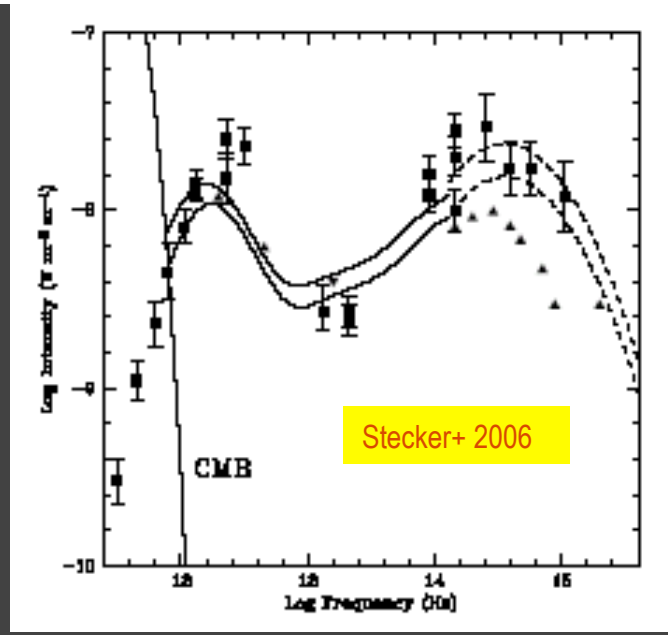




Bretz 2006

IBL





Cross section (differ.):

TeV γ: E
soft γ: ε

$E\epsilon > (mc^2)^2$

$\beta = [1 - (mc^2)^2/(E\epsilon)]^{1/2}$

Heitler 1960

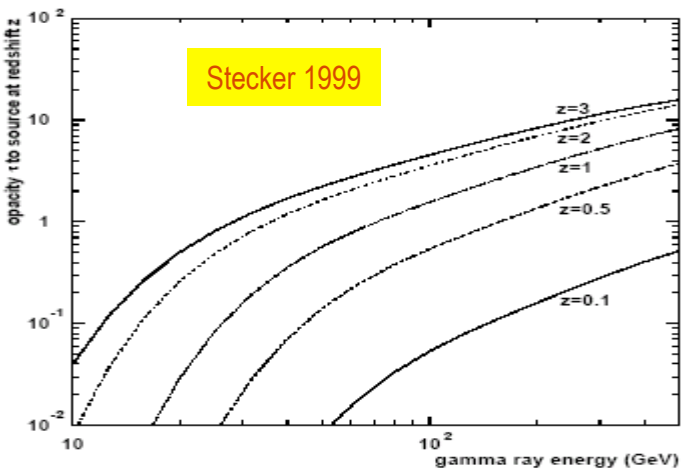
$$\sigma_{\gamma\gamma}(s) = \frac{3}{16}\sigma_T(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right],$$

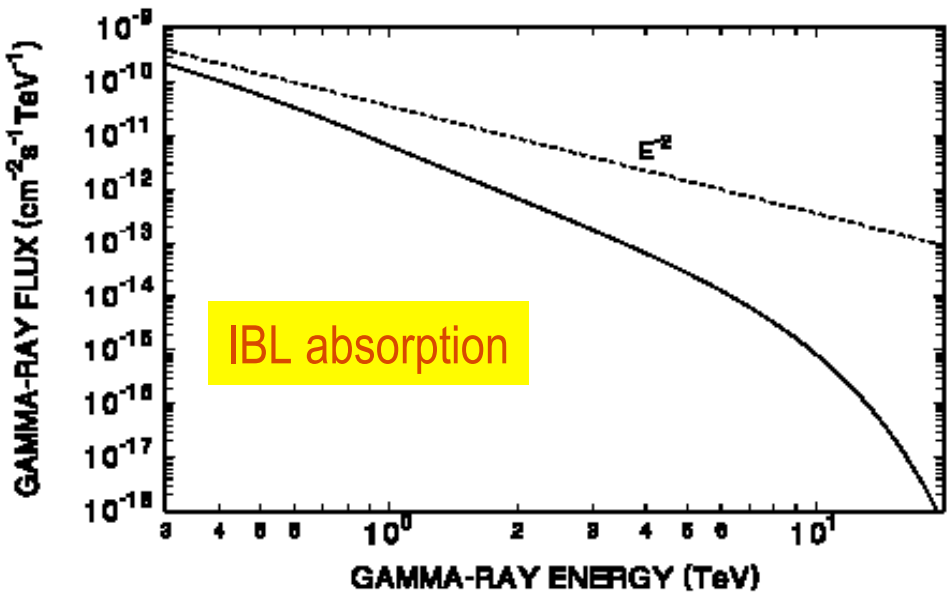
E ~ 1TeV
→ $\sigma_{\gamma\gamma}$ max
for ε~0.5 eV
(~2μm, *K*-band)

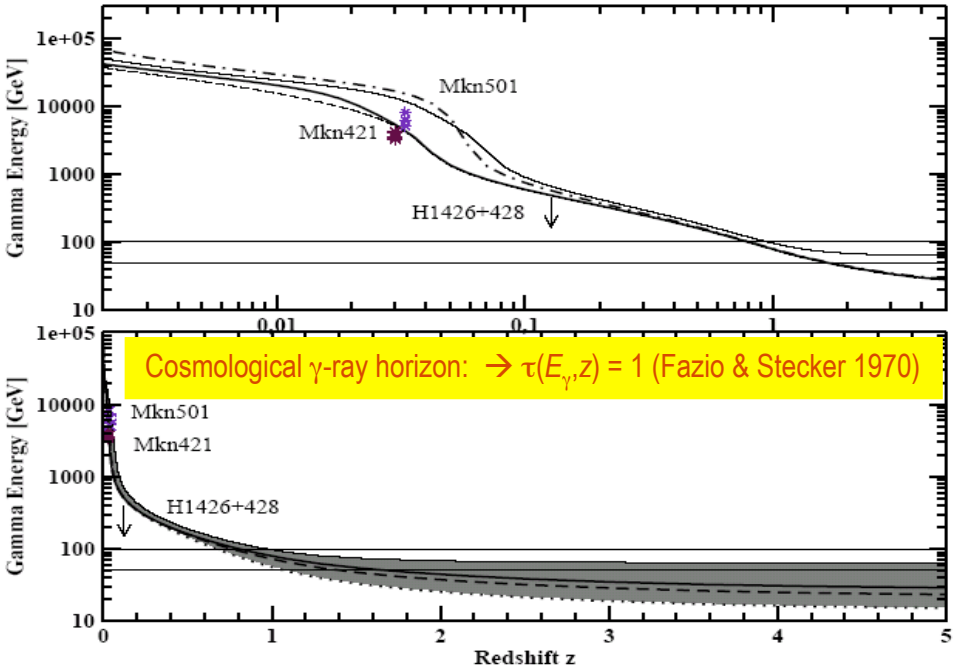
$$\gamma_{HE}\,\gamma_{EBL} \rightarrow e^+ e^-$$

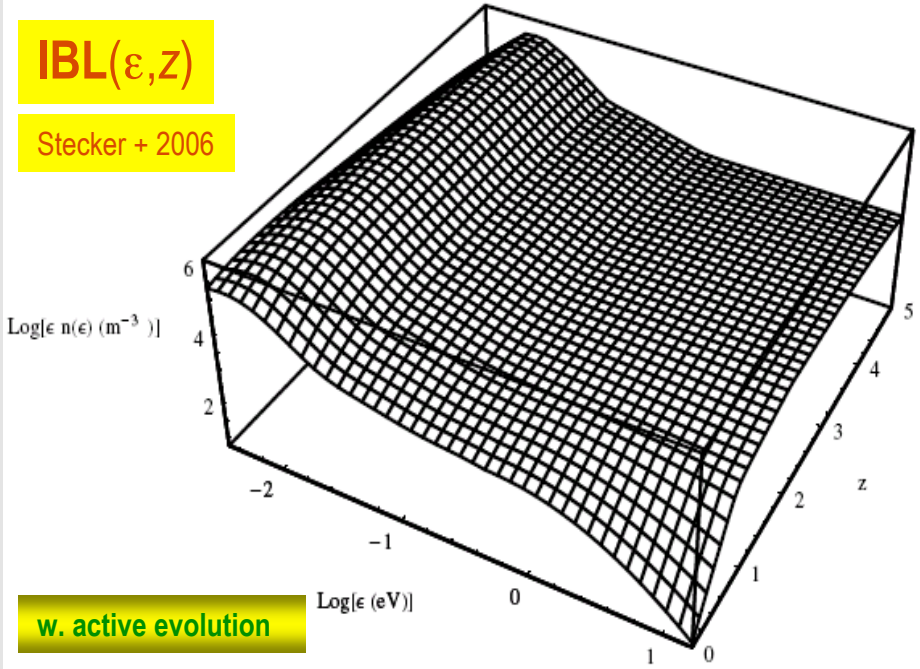
x=1+cosθ

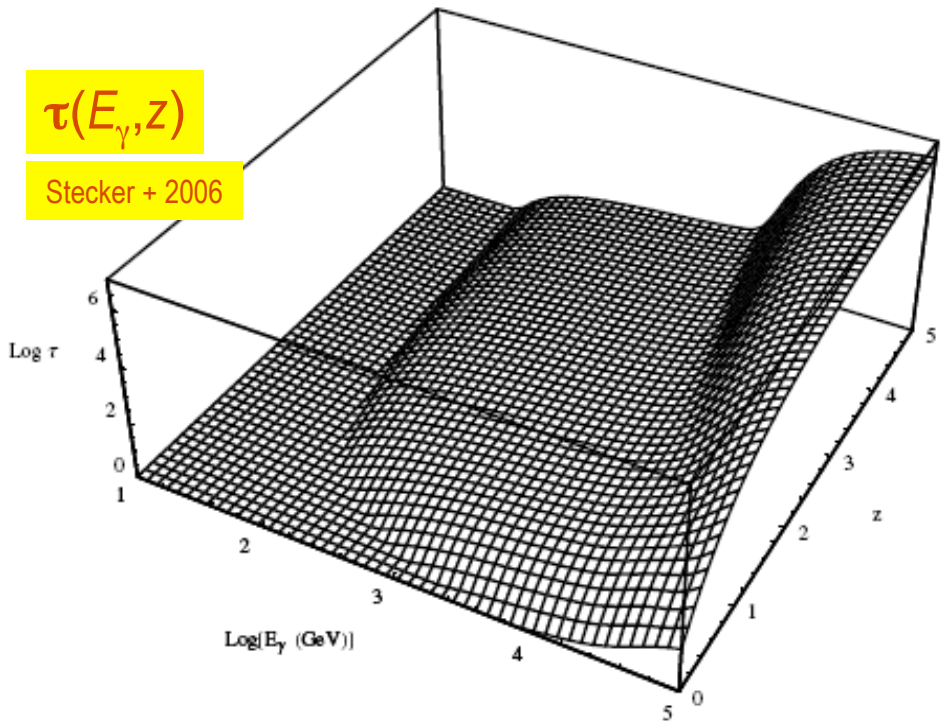
$$\tau(E_0, z_e) = c\int_0^{z_e} dz\,\frac{dt}{dz}\int_0^2 dx\,\frac{x}{2}\int_0^\infty d\nu\,(1+z)^3\left[\frac{u_\nu(z)}{h\nu}\right]\sigma_{\gamma\gamma}(s)$$

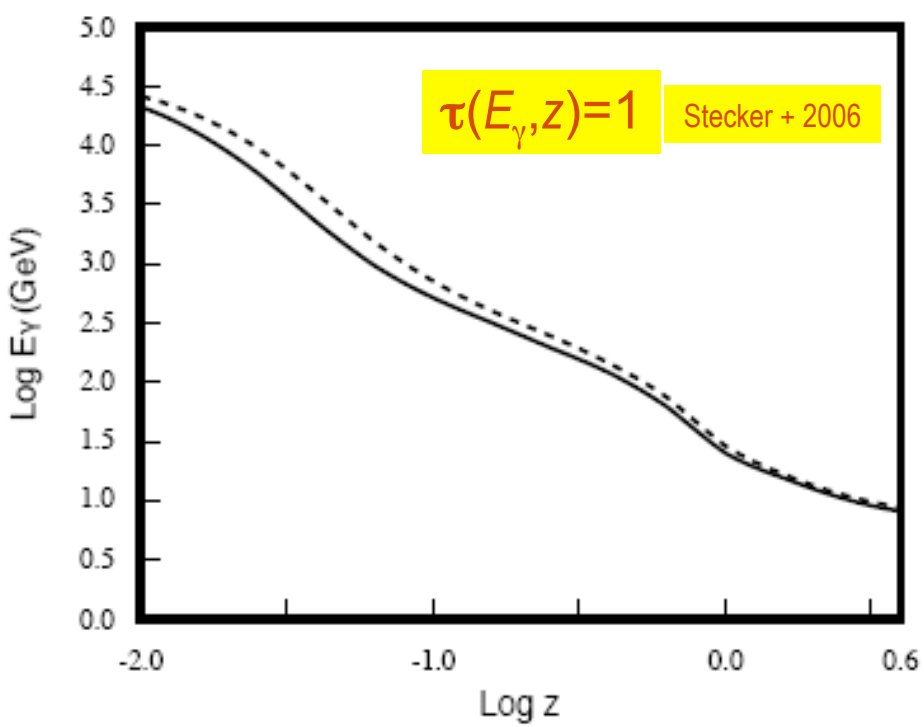





Gamma Energy [GeV]
Mkn501
Mkn421
H1426+428
Cosmological γ-ray horizon: → τ(E_γ,z) = 1 (Fazio & Stecker 1970)
Redshift z


IBL(ε,z)
Stecker + 2006
Log[ε n(ε) (m⁻³)]
Log[ε (eV)]
z
w. active evolution

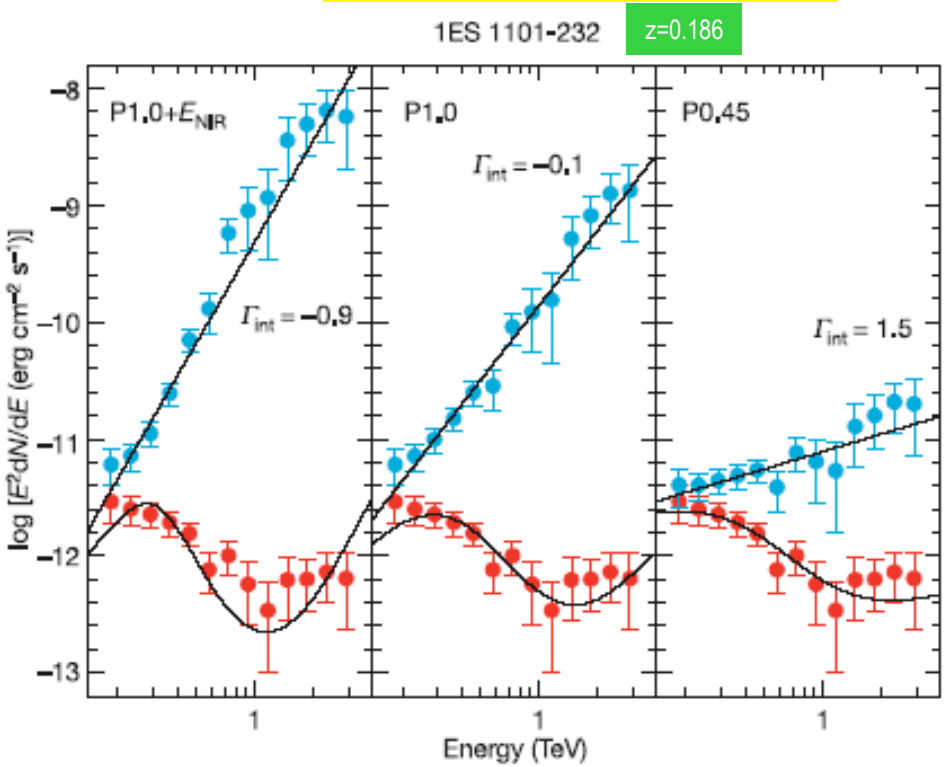

τ(E_γ,z)
Stecker + 2006
Log τ
Log[E_γ (GeV)]
z

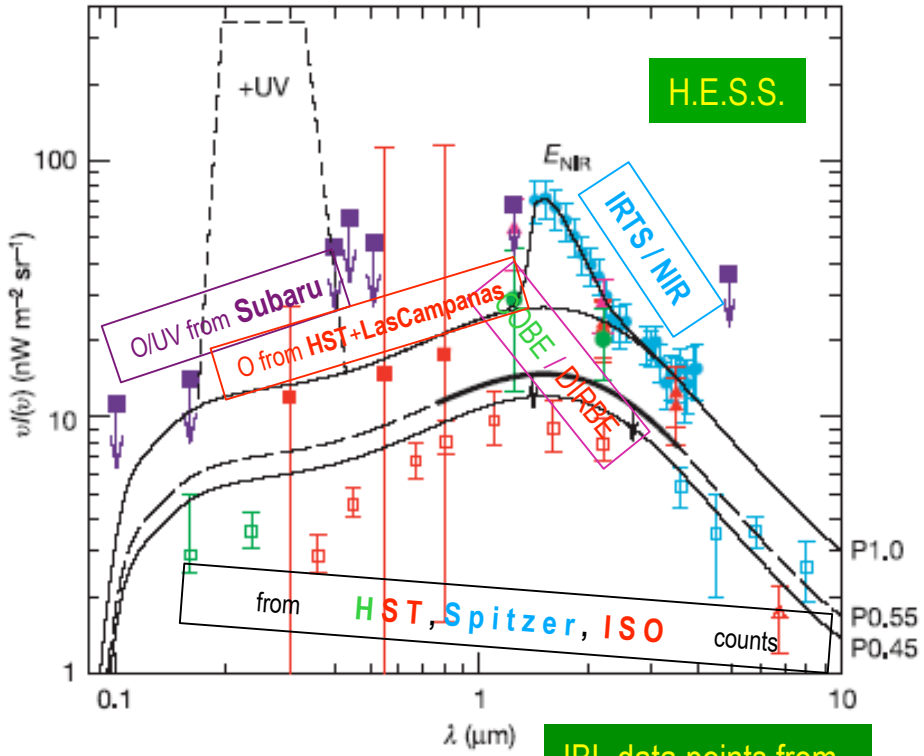

τ(E_γ,z)=1
Stecker + 2006
Log Eγ (GeV)
Log z

A low IBL?

high z, hard spectrum → low IBL?

Aharonian+ 2006



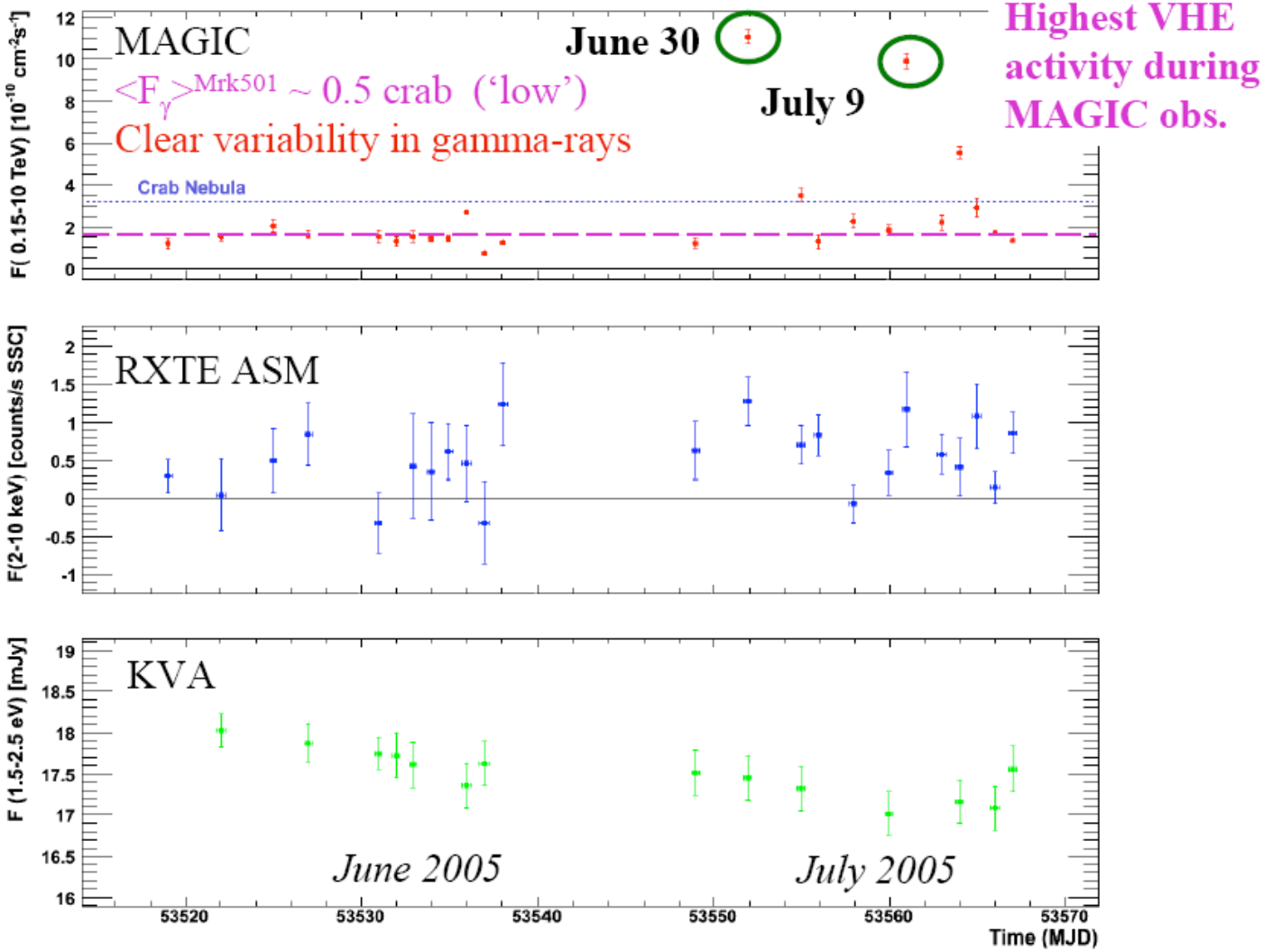


IBL data points from Hauser & Dwek 2001

Mrk 501

MAGIC

Mkn 501 Light curves - Gamma, X-rays, Optical

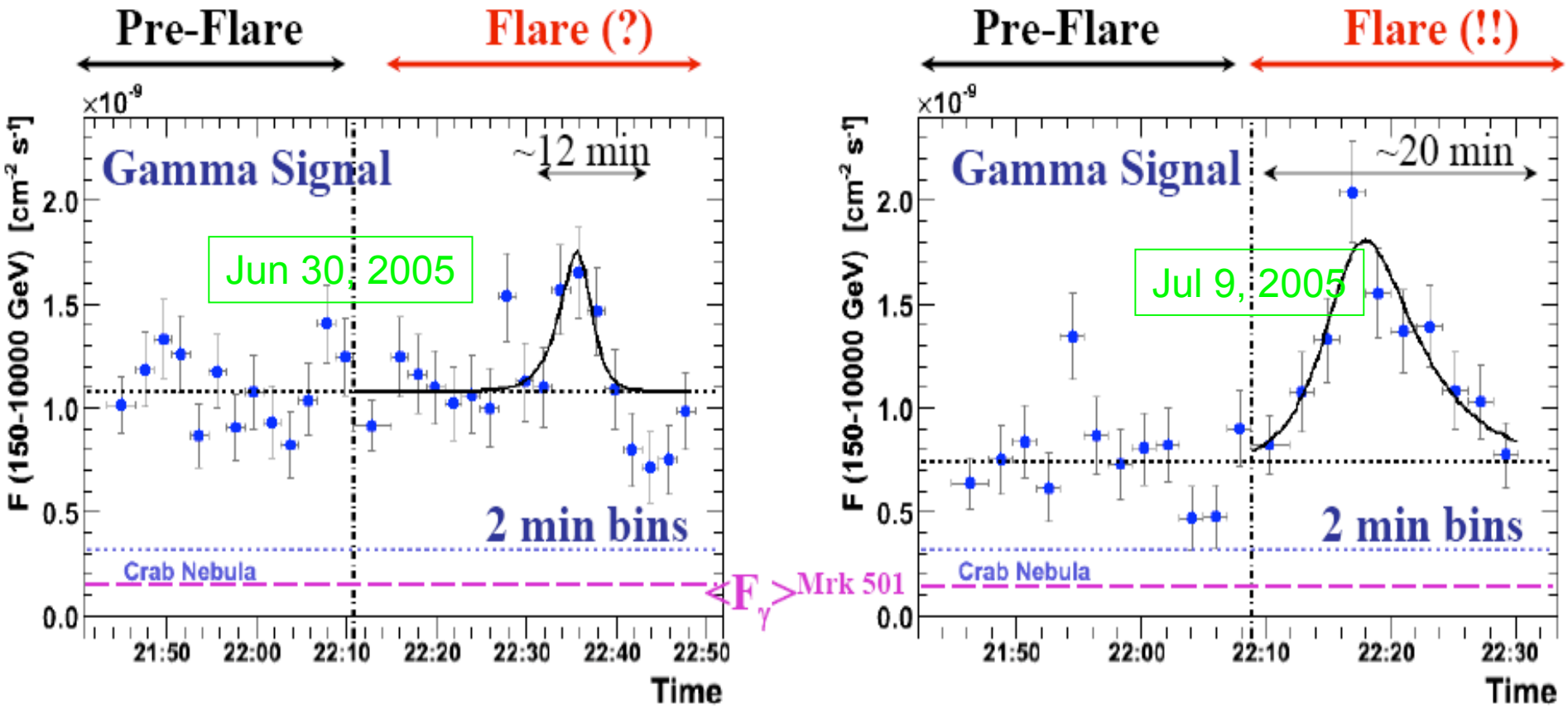


Highest VHE activity during MAGIC obs.

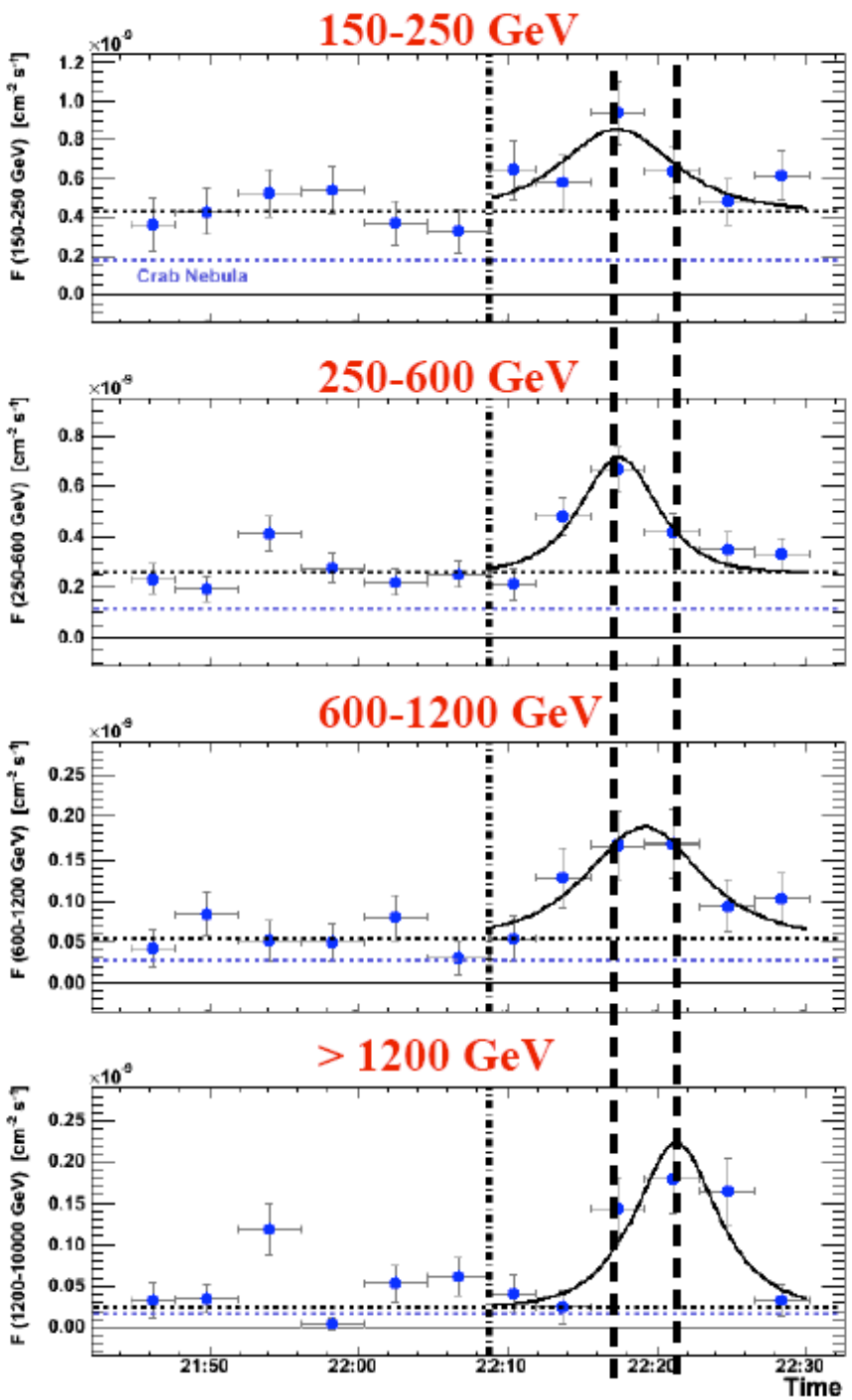
Mrk 501 - cont'd

Intra-night flux variations (E > 150 GeV)

Fastest variability observed in Mrk 501



PKS 2155-304 (H.E.S.S.):
VHE variab. on ~200s timescale



LCs for different energy ranges (4 min bins)

Active night: July 9, 2005

Flare is seen in all energy ranges

Time delay of 4 ± 1 minute between highest and lowest energy ranges

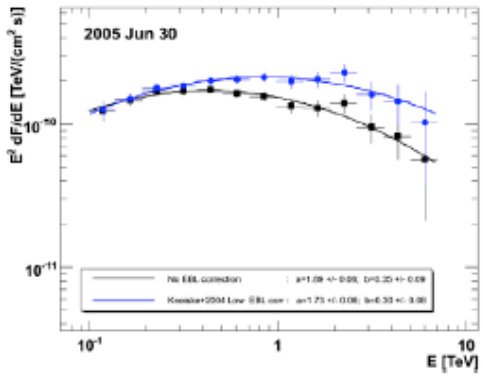
Flux variations larger at the largest energies

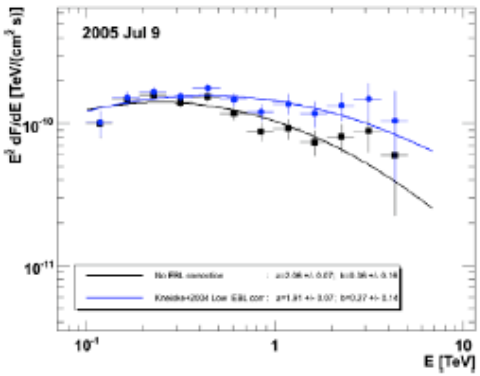
First time in VHE !!

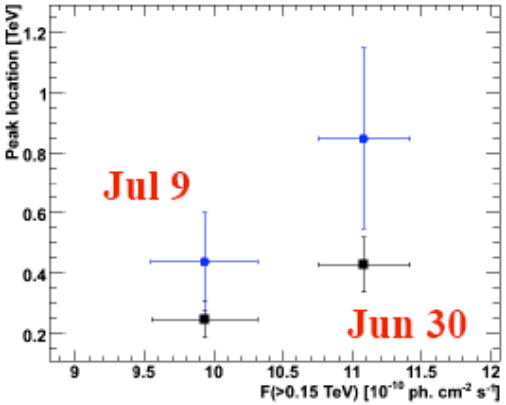
Mrk 501 – cont'd

Position of spectral peak before and after EBL correction

Model used: 'low' EBL from Kneiske et al 2004



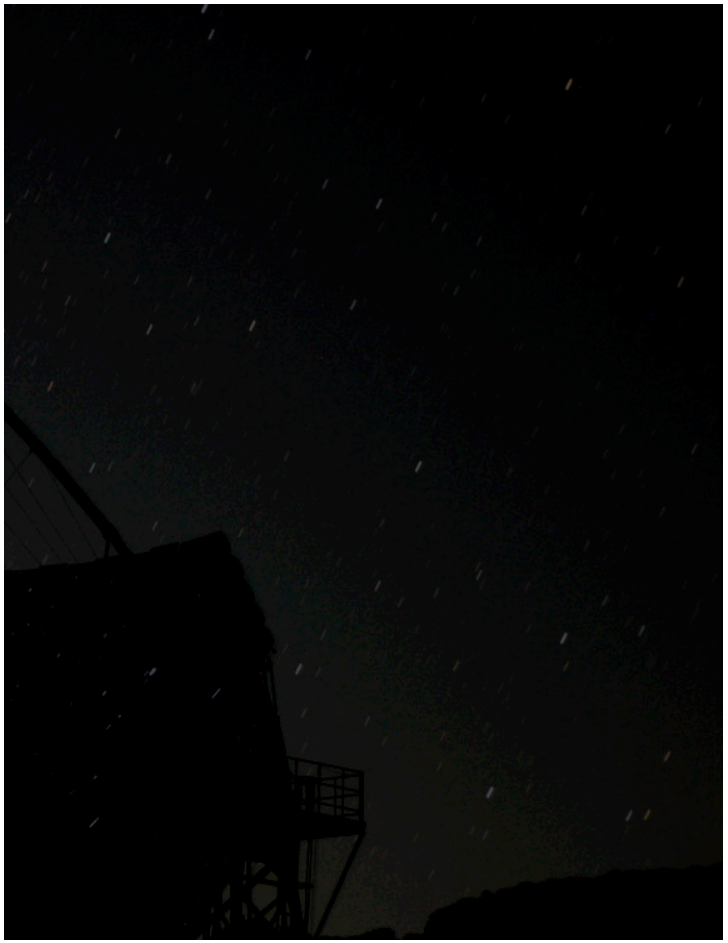


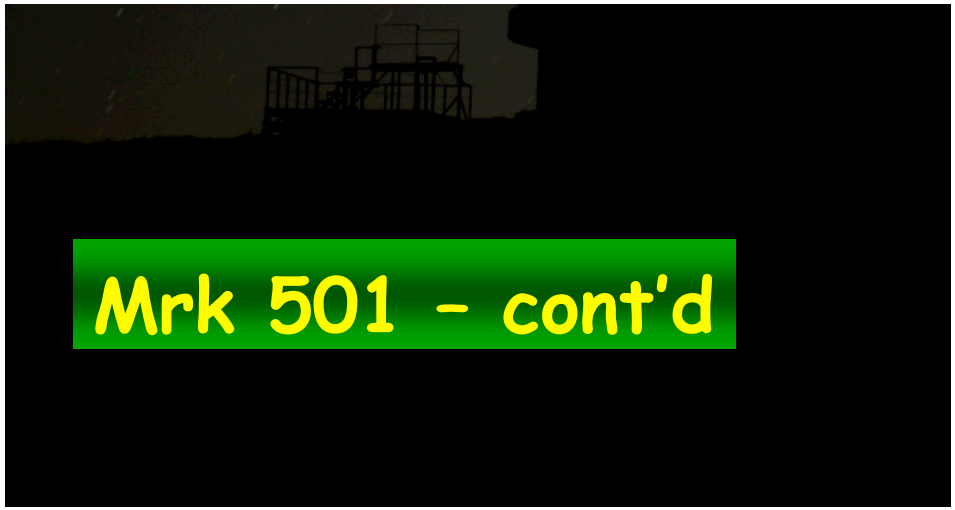


EBL correction moves the spectral peak to higher energies

During the nights of low activity, the flare is not seen at E > 100 GeV

Peak location seems to depend on the source luminosity





Observations of Mrk 501 with MAGIC allowed us to study flux and spectra variations down to 100 GeV on a night by night basis

1 - **Changes in flux and spectra on several timescales:**
months, days, and few minutes

2 - **Intra-day variations with flux-doubling times ~2 minutes**
Much shorter than previous Mrk 501 and Mrk 421 observations

3 - **Flux variability increases with energy**

4 - **Time delay of ~4 minutes between flare location at E <0.25 TeV and E > 1.2 TeV**

5 - **Spectra hardens with flux**

6 - **Detection of the IC peak in the SED for the most active nights**

… round the corner?

Galaxies

- 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
- TeV flux: $\phi_{\geq 0.2TeV} \approx 10^{-12}(U_{CR}/eV)(M^{gas}/10^{9}M_{\oplus})(D/Mpc)^{-2}$ phot / (cm2 s)
- $U_{CR} \propto \dot{\rho}_{SFR}$, $n \propto (\dot{\rho}_{SFR})^{2/3}$ → Baryonic TeV emission: tracer of SF

Promising candidates?

- Minimize distance → local objects!

Non-baryonic signal: Minimize SFR, maximize DM

→ small, no-SF elliptical galaxies:

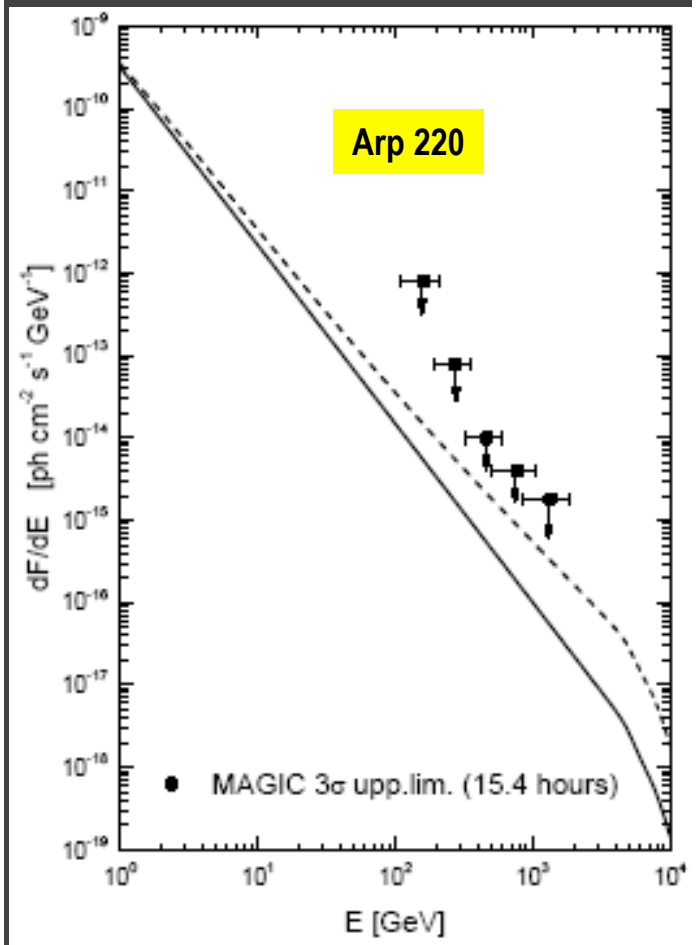
local dwarf spheroidals Fornax, Draco, …

Baryonic signal: minimize DM, maximize SFR

→ large, intensely-SF disk galaxies:

nearby starburst galaxies, luminous IR galaxies (LIRGs: Torres+ 2004)

		$D^{-2}(SFR)^{1.7}$
NGC 253:	D=3.0, SFR=4 (Paglione+ 1996; Torres & Domingo-S. 2005)	1.17
Arp 220:	D=73, SFR=235 (Torres 2004)	2.01
M 82:	D=5.2, SFR=16	**4.12**
NGC 55:	D=1.3, SFR=0.1	0.01
NGC 891:	D=9.6, SFR=4	0.11



M82: most promising candidate (MAGIC)

MP, Y.Rephaeli, Y.Arieli 2008

… round the corner ??

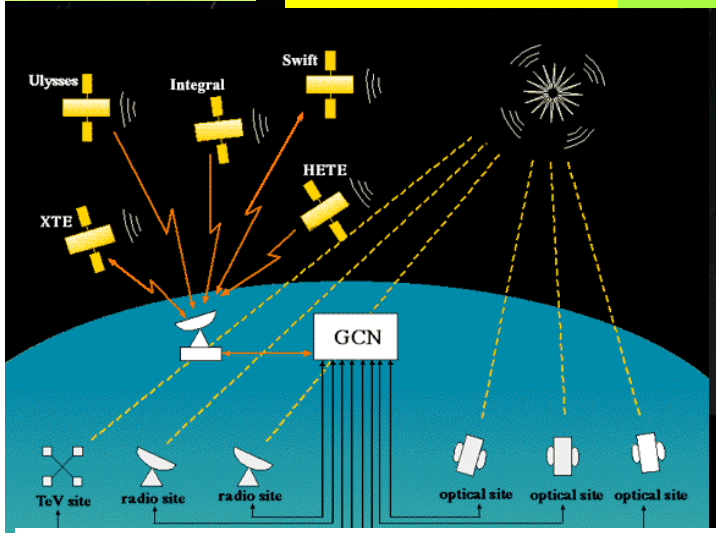
GRBs

MAGIC is ideal to follow-up GRBs

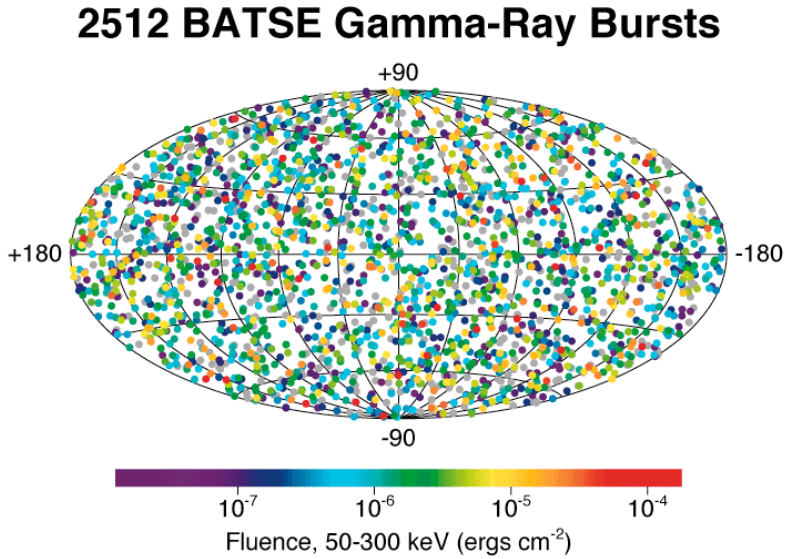
(fast repositioning, low E_{thr})

GCN Network member

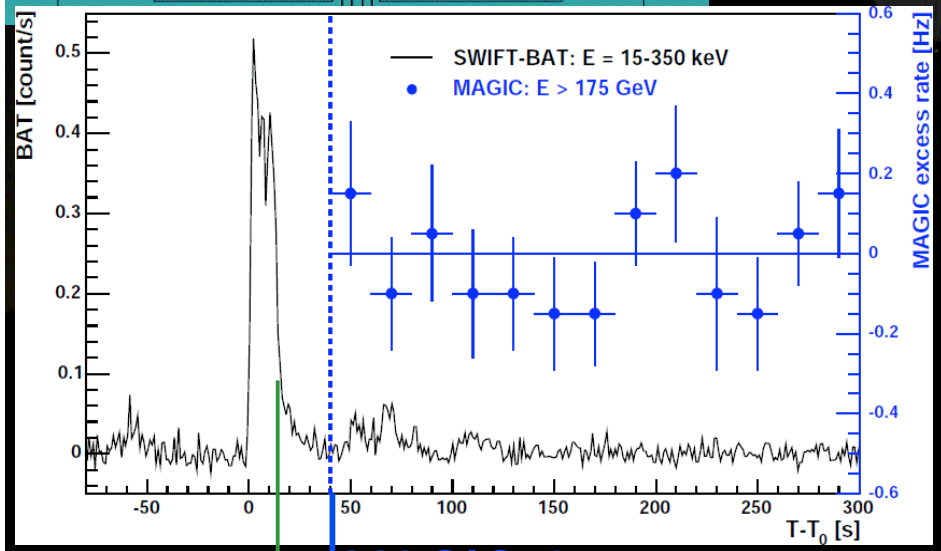
GRB alert active since 04/2005



Whipple, HESS also on track …



high z!
intrinsic TeV src's?



MAGIC data-taking

GRB-alarm from SWIFT

Clusters: channels of TeV emission

Clusters

no IACT detection

TeV sources in clusters:

→ pointlike: AGN
galaxies

→ diffuse: cluster formation (merging, accretion)
DM (diffuse, clumps)

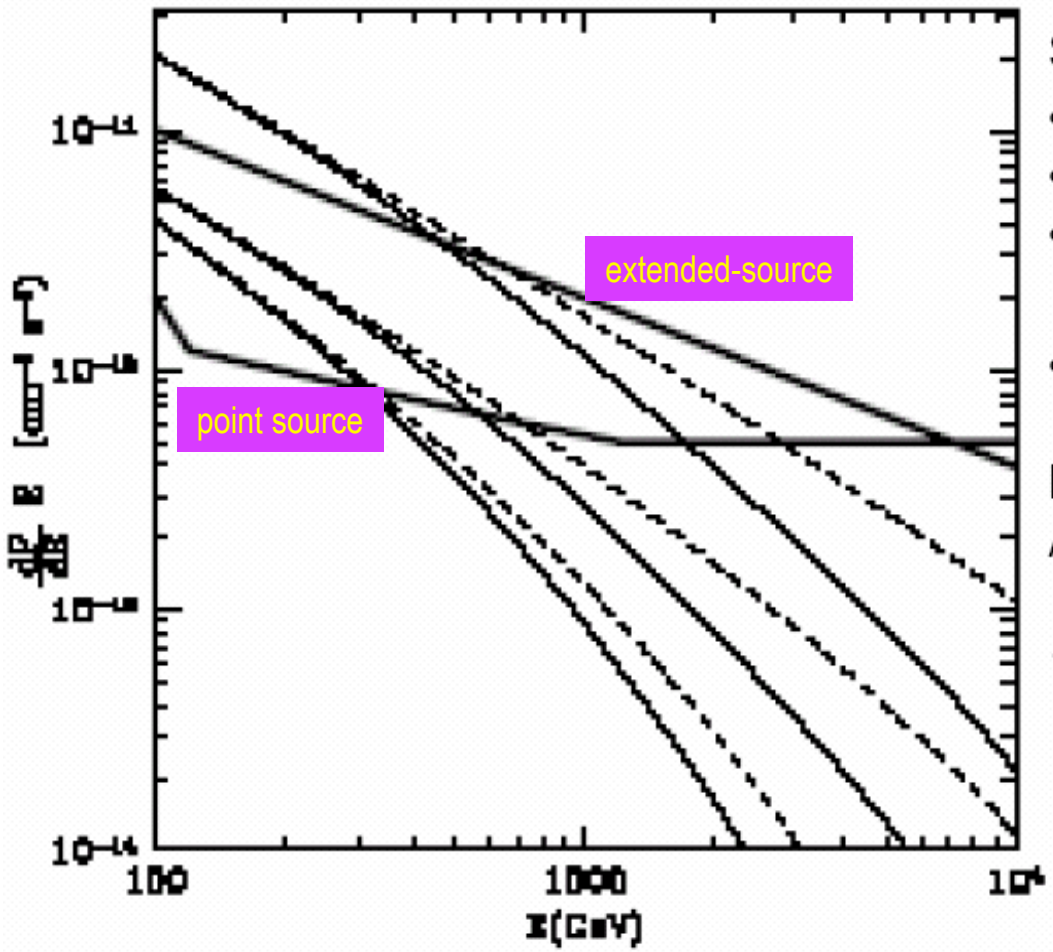
NT side of structure formation

... round the corner ???

Merger-generated shocks → $n(E_p) \propto E_p^{-\alpha}$

minor mergers (continuous accretion) lead to efficient particle acceleration (Gabici & Blasi 2003)

- pp interaction of CRp with ICp → $\pi^{\pm}$, π^0 → diffuse emission from secondaries
  (e^+e^-, γ)
- secondary electrons: synchrotron & Compton losses, Coulomb losses → continuity eq. → equilibrium particle spectrum (e.g., Rephaeli 1979)
- self-consistent modeling of cluster's complete NT SED (e.g.: Blasi & Colafrancesco 1999):
  - synchrotron from secondary electrons: radio (normalization!)
  - comptonized CMB photons from secondary electrons: UV, X-ray
  - bremsstr. from primary & secondary electrons: γ–ray
  - π^0 decay: γ–ray
- Cluster gas distribution: $n_H(r) \propto \left[1+(r/r_0)^2\right]^{-3\beta/2}$, with $\beta \approx 0.7-1.1$



Simulation (Gabici & Blasi 2004):

- shock accel. efficiency η=0.05
- free-fall vel. of gas a virial radius: $v_{ff} = \sqrt{2GM}$
- cosmological baryon density: $\rho_b = \Omega_b \rho_{cr}$ with $\Omega_b = 0.02h^2$.
- power converted at the shock into NT electrons $L^{acc} = \frac{1}{2}\eta\rho_b(1+z)^3 v_{ff} 4\pi r_v^2$

Merger-related shock @ virial radius r_v~3Mpc.
Angular size $\theta \approx 1^\circ(\frac{D}{100Mpc})$ comparable to (exceeding) IACT aperture.

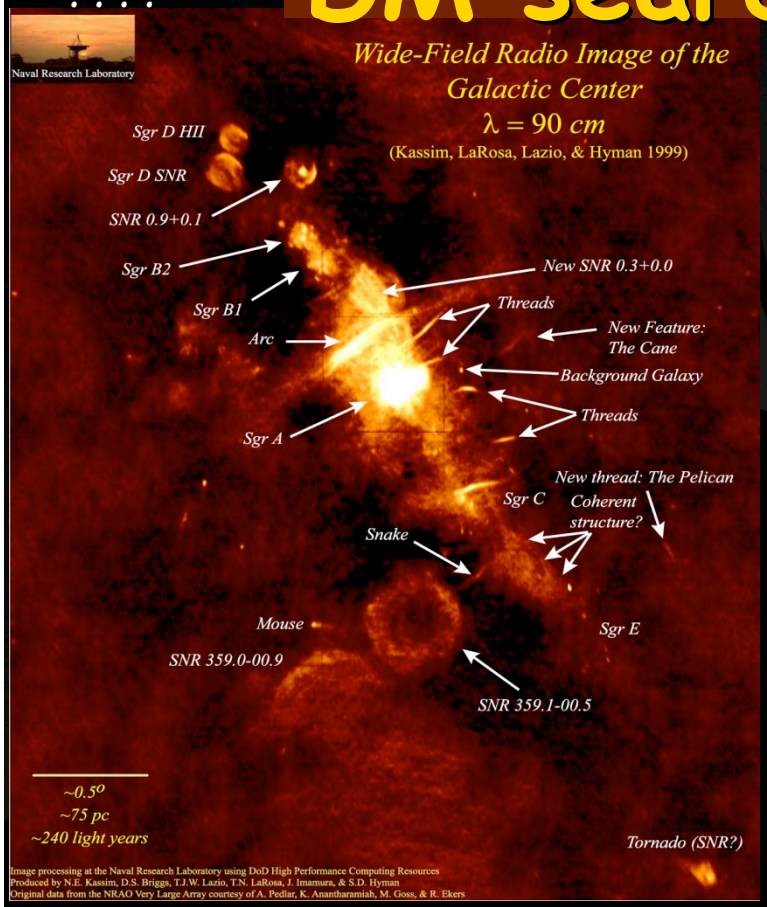
→ Merger-related TeV emission from cluster unlikely to be observed by current IACTs.

Detectability maximized if:

point source $\theta \approx 1^\circ(\frac{D}{100Mpc})$ → large distance
high flux ($\propto D^{-2}$) → low distance
high flux ($\propto \exp(-\tau_{\gamma\gamma}^{EBL})$) → low distance
NT particles → radio halo, PL hard-X-ray spectral component
B_m likely lower than volume-averages indicated by Faraday measts
→ feasibilty of detectable VHE-γ emission enhanced

... round the corner ????

Targets for DM search



Requirements:

1. Not associated with known conventional TeV sources
2. High DM density
3. Close by
4. Not extended

1. Galactic Center

Distance ~ 7.5 kpc → OK

... but:

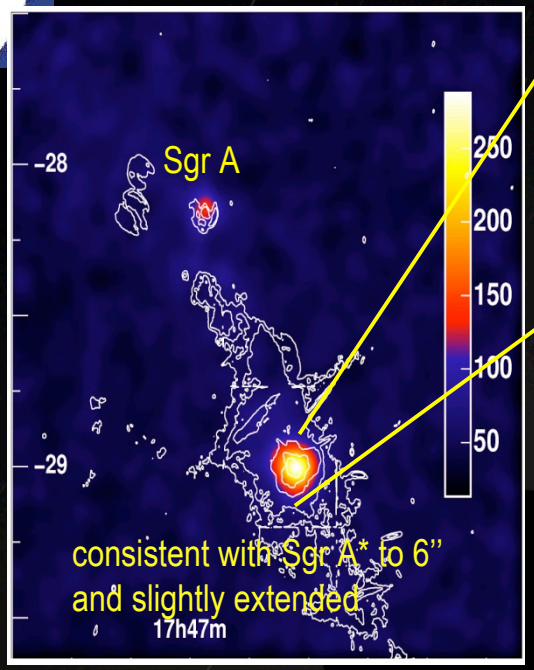
other γ-ray sources in the FOV, i.e. SNR Sgr A East

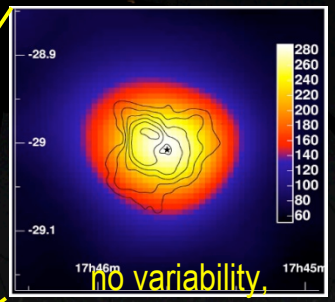
→ competing plausible scenarios

2. Dwarf Sph galaxies

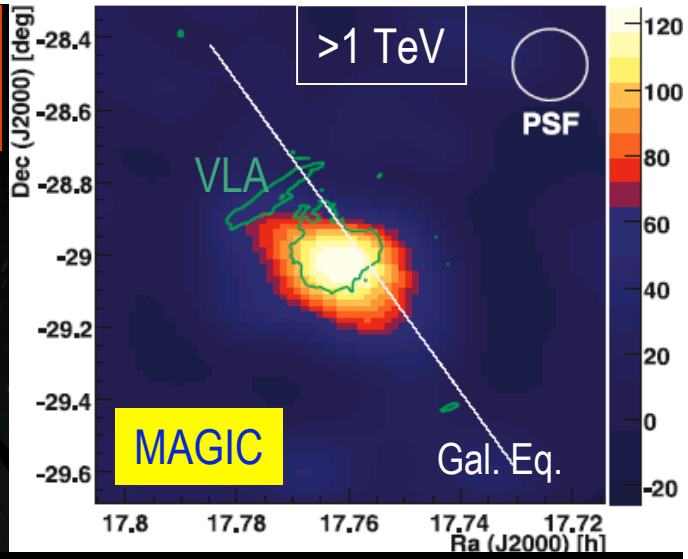
ok 1(?), 2, 3, 4

1. The Galactic Center





no variability,
yr-min scale



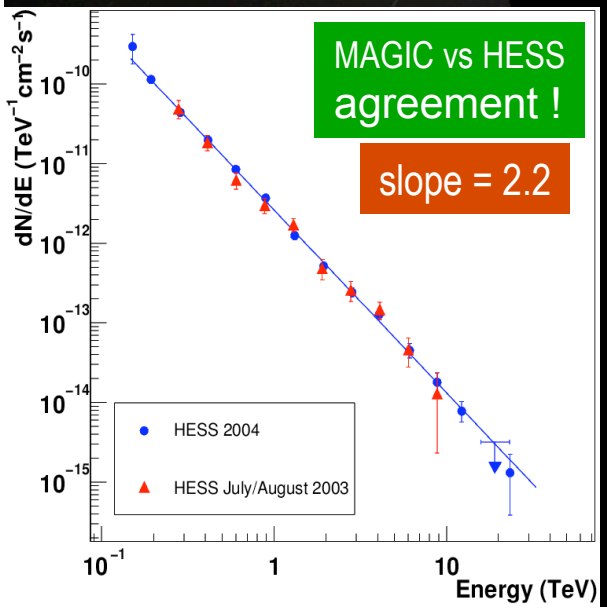
Detected: **Cangaroo 2003**
Confirmed: **HESS 2004**
Confirmed: **MAGIC 2005**

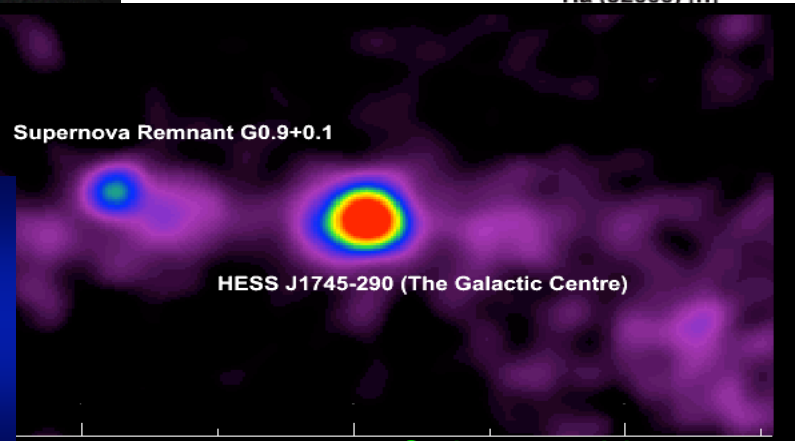
Diffuse GP emission revealed by subtracting strong sources

Correlation with molecular gas

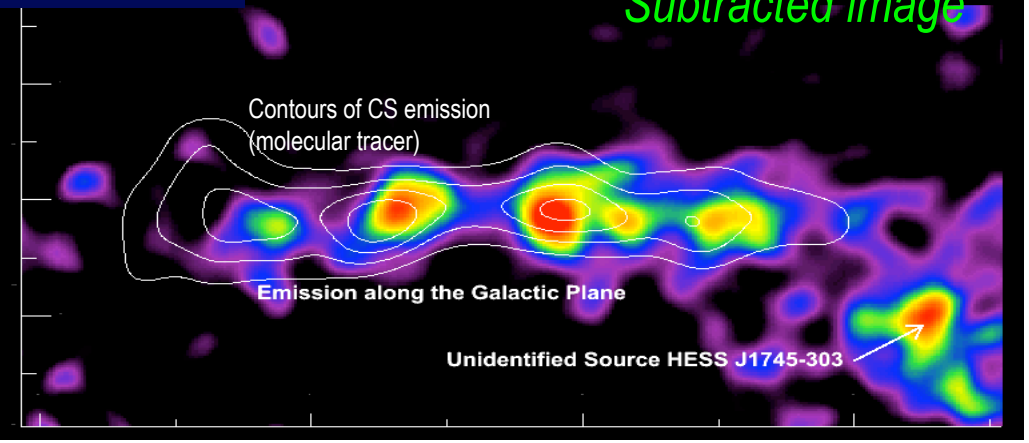
CRs interacting with MCs

GC source coincident w. Sgr A*





Subtracted image



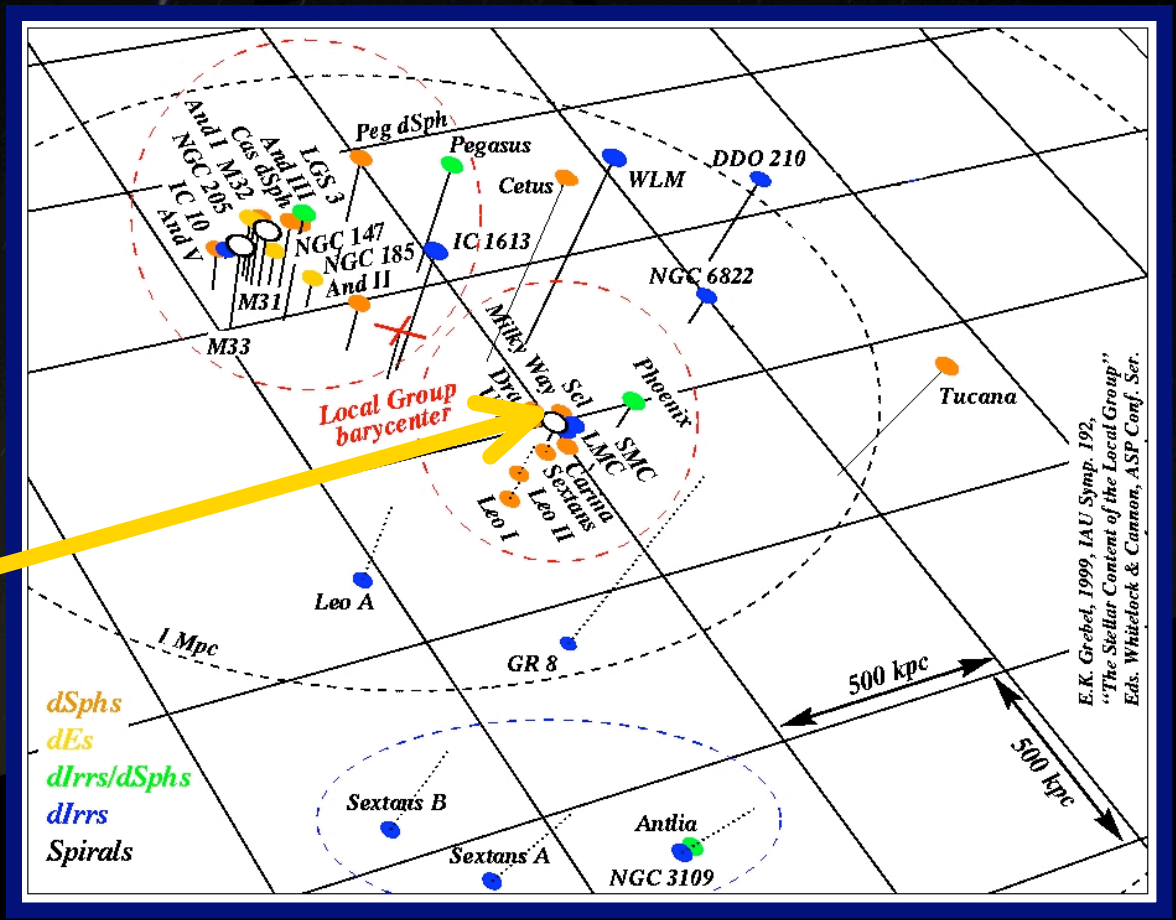
GC signal: unlikely to be DM

2. DRACO dSph

Milky Way surrounded by small, faint companion galaxies

DRACO dSph
high M/L>200
d~80 kpc

Northern source → MAGIC ok !!



- dSph's → very DM-dominated objects.
- Distances, M/L ratios 16<D/kpc<250 kpc, 30<M/L<300

Draco dSph: modeling

d~80 kpc

Bergström & Hooper 2006

total DM annihil. rate

$$\Phi_A = \int_{r_{min}}^{r_a} dr\, 4\pi r^2 \frac{\langle \sigma_A v \rangle}{2} \left(\frac{\rho(r)}{m_\chi} \right)^2$$

$\langle \sigma_A v \rangle$, m_χ: WIMP annihil. cross section, mass

γ-ray flux

$$F_\gamma = \frac{\Phi_A N_\gamma}{4\pi D^2}$$

N_γ: γ-rays / annihil.

$$y = r/r_s$$

upper limit

cusped profile

$$\rho(r) = \frac{\rho_0}{y\,(1+y)^2}$$

$$F_\gamma = \frac{\rho_0^2 r_s^3 N_\gamma}{3 m_\chi^2 D^2} \frac{\langle \sigma_A v \rangle}{2} \left[\frac{1}{(1+y_{min})^3} - \frac{1}{(1+y_a)^3} \right]$$

cored profile

$$\rho(r) = \frac{\rho_0}{(1+y)\,(1+y^2)}$$

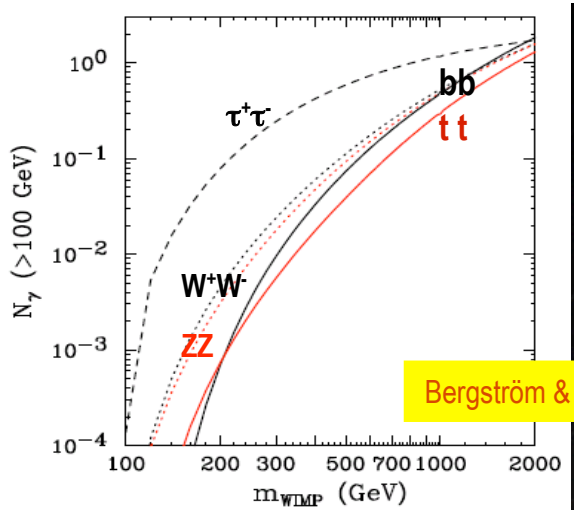
$$F_\gamma = \frac{\rho_0^2 r_s^3 N_\gamma}{4 m_\chi^2 D^2} \frac{\langle \sigma_A v \rangle}{2} \left[\frac{2 + y_{min} + y_{min}^2}{1 + y_{min} + y_{min}^2 + y_{min}^3} + \arctan(y_{min}) - \frac{2 + y_a + y_a^2}{1 + y_a + y_a^2 + y_a^3} - \arctan(y_a) \right]$$

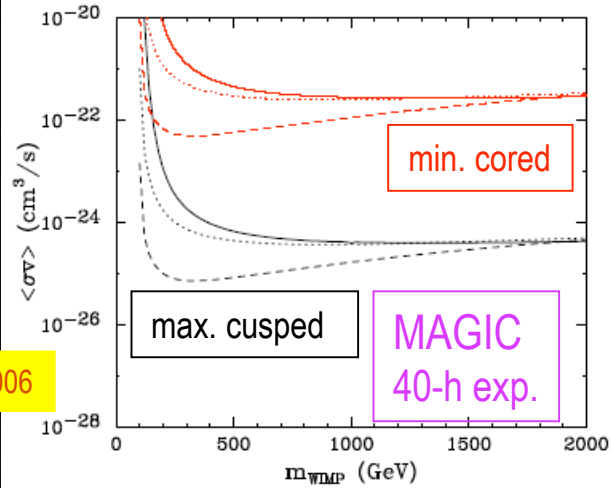
γ-ray flux

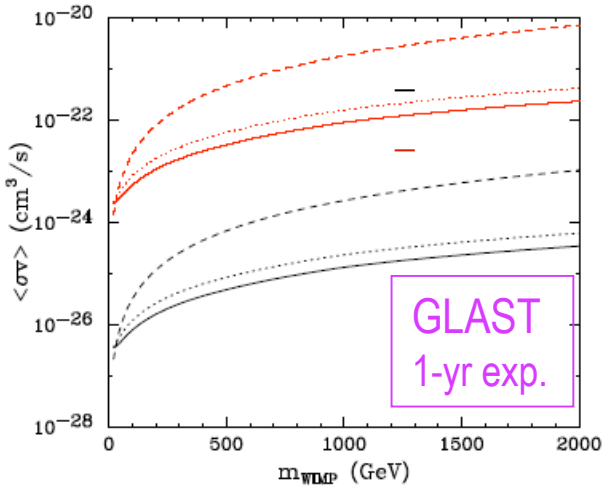
$$F_\gamma = \frac{\rho_0^2 r_s^3 N_\gamma}{3 m_\chi^2 D^2} \frac{\langle \sigma_A v \rangle}{2} \times A$$

Profile Type	$A(r_a = r_s)$	$A(r_a \gg r_s)$
NFW	0.875	1.0
Core	0.160	0.323
Cusp, $\gamma = 1.1$	1.29	1.52
Cusp, $\gamma = 1.2$	2.16	2.63
Cusp, $\gamma = 1.3$	4.03	4.12
Cusp, $\gamma = 1.4$	11.1	12.5
Cusp, $\gamma = 1.45$	25.7	27.4

r_s = 7 – 0.2 kpc
$\rho_0 = 10^7 - 10^9\ M_\sim\ kpc^{-3}$
$\rho_0^2 r_s^3 = 0.03 - 6\ M_\sim^2\ kpc^{-3}$







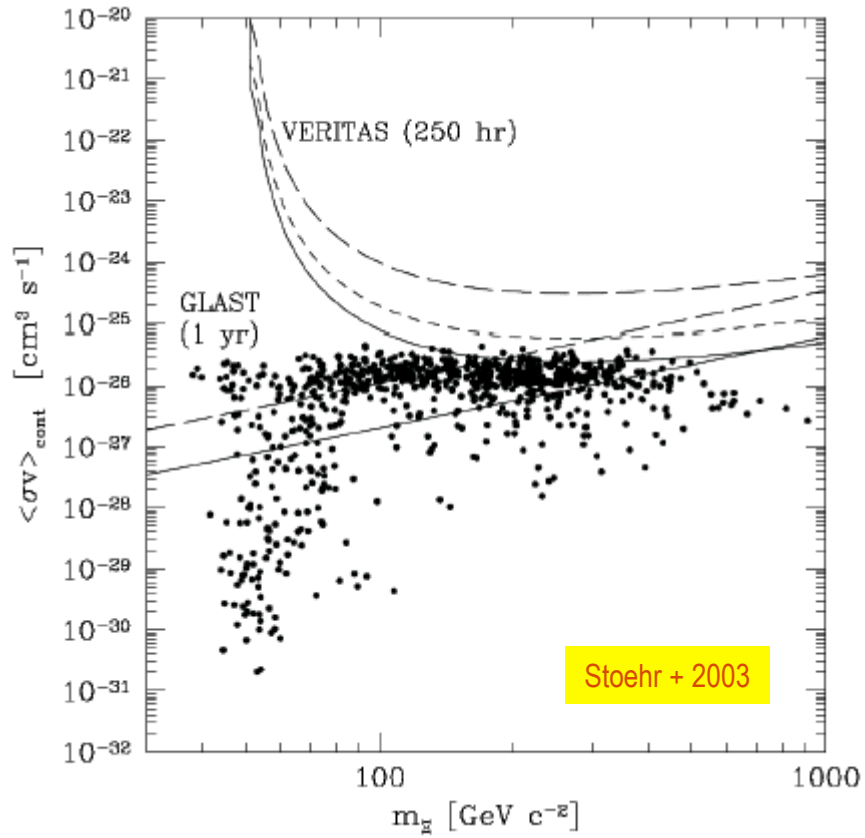
$$F^{max}_{\gamma,NFW} \approx 2.4 \times 10^{-10} \left(\frac{100\ \text{GeV}}{m_\chi}\right)^2 \left(\frac{\langle\sigma_A v\rangle}{3\cdot 10^{-26}\ \text{cm}^3\text{s}^{-1}}\right) \left(\frac{N_\gamma}{10}\right) \text{cm}^{-2}\text{s}^{-1}$$

$$F^{min}_{\gamma,NFW} \approx 9.8 \times 10^{-13} \left(\frac{100\ \text{GeV}}{m_\chi}\right)^2 \left(\frac{\langle\sigma_A v\rangle}{3\cdot 10^{-26}\ \text{cm}^3\text{s}^{-1}}\right) \left(\frac{N_\gamma}{10}\right) \text{cm}^{-2}\text{s}^{-1}$$

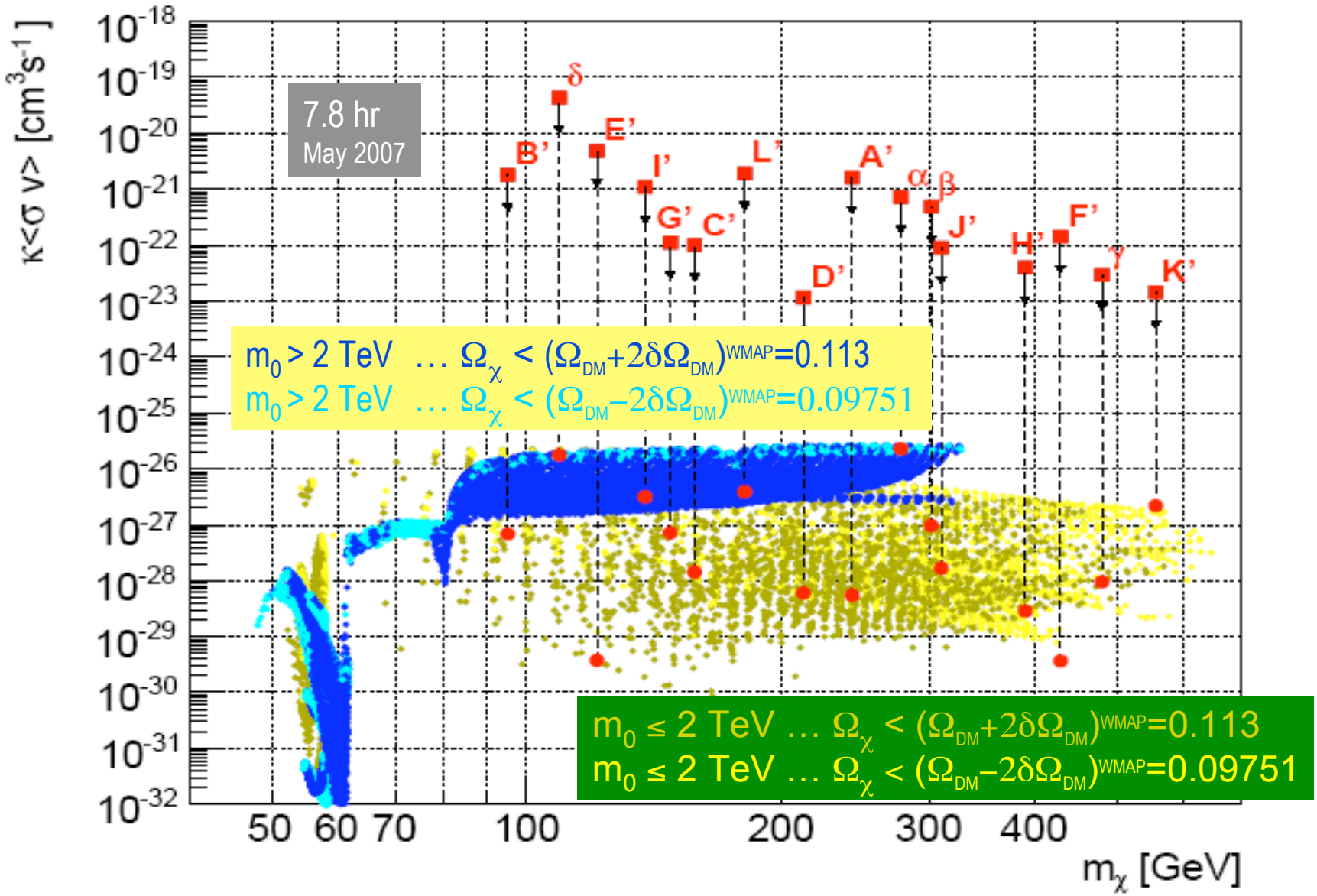
$$F^{max}_{\gamma,core} \approx 4.2 \times 10^{-11} \left(\frac{100\ \text{GeV}}{m_\chi}\right)^2 \left(\frac{\langle\sigma_A v\rangle}{3\cdot 10^{-26}\ \text{cm}^3\text{s}^{-1}}\right) \left(\frac{N_\gamma}{10}\right) \text{cm}^{-2}\text{s}^{-1}$$

$$F^{min}_{\gamma,core} \approx 3.5 \times 10^{-13} \left(\frac{100\ \text{GeV}}{m_\chi}\right)^2 \left(\frac{\langle\sigma_A v\rangle}{3\cdot 10^{-26}\ \text{cm}^3\text{s}^{-1}}\right) \left(\frac{N_\gamma}{10}\right) \text{cm}^{-2}\text{s}^{-1}$$

IACT neutralino detection:
$\langle\sigma_A v\rangle \geq 10^{-25}$ cm^{3}s^{-1}



Draco dSph obs'd MAGIC arXiv:0711.2574



Exotica: QG effects

a non-trivial dispersion relation for light in vacuum

Phenomenologically, the effect can be studied with a perturbative expansion. At 1st order, the arrival delay of photons of different energy, emitted simultaneously from a distant source, is proportional to their energy difference and to the path L to the source.

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 $c^2 \mathbf{p}^2 = E^2 [1 + f(E/E_{QG})]$

$f(E_{QG})$: model-dependent function of effective QG scale $E_{QG} \sim E_P \approx 10^{19}$ 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 $E \ll E_{QG}$: $c^2 \mathbf{p}^2 = E^2 \left[1 + \xi E/E_{QG} + \mathcal{O}(E^2/E_{QG}^2)\right]$, 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 particles 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 → $\eta \sim 10^{-11}$

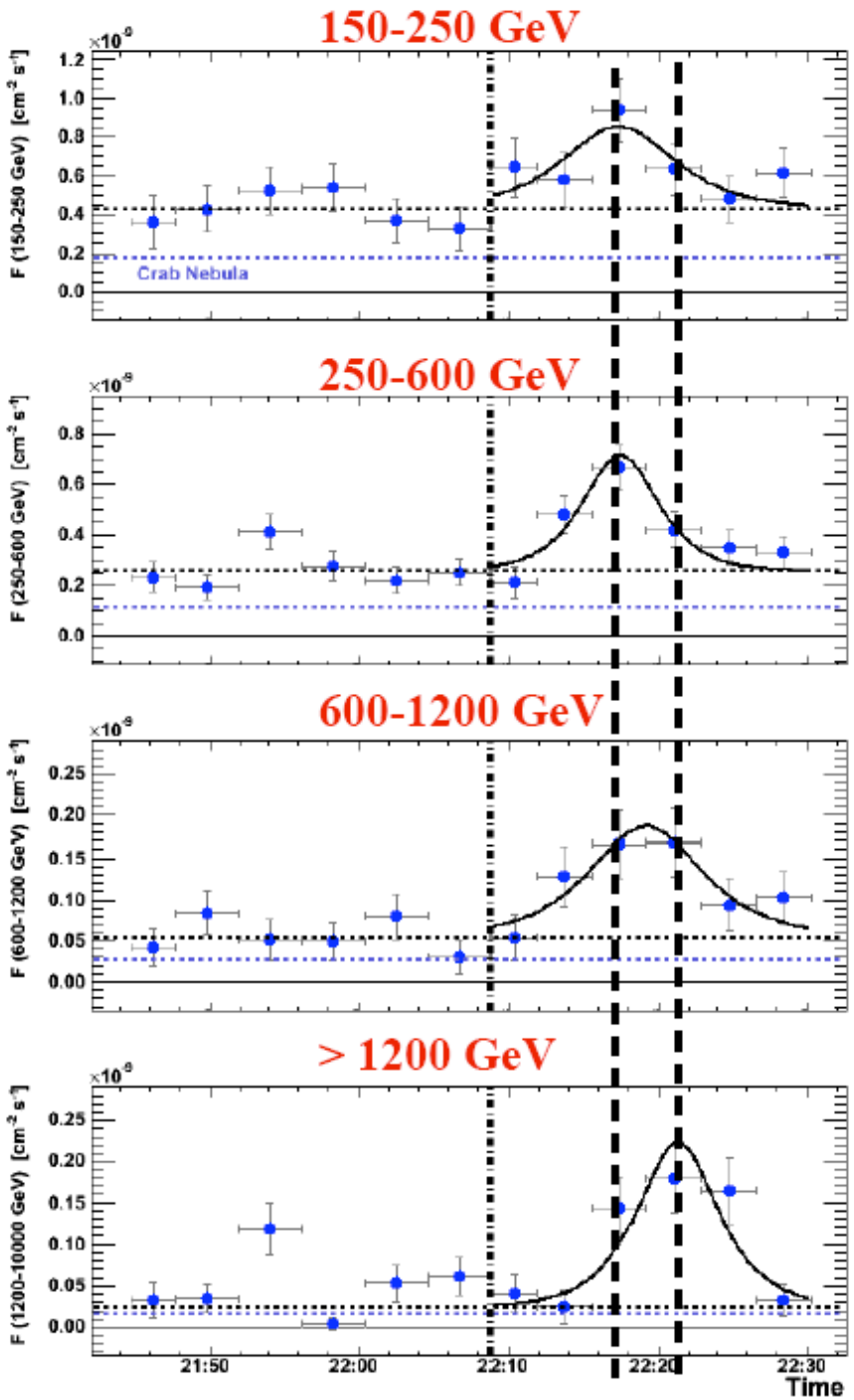
SN Ia: $\delta t \sim$ ms, $L \sim 5000$ Mpc, $E \sim$ eV → $\eta \sim 10^{-7}$

Mk 501: Jul 9 2005 flare

4-min delay between flux variation @ 1-0.25 TeV

⇒ $E_{QG} > 0.6 \times 10^{17}$ GeV

(Ellis+2006: $E_{QG} > 0.9 \times 10^{16}$ GeV)



IF

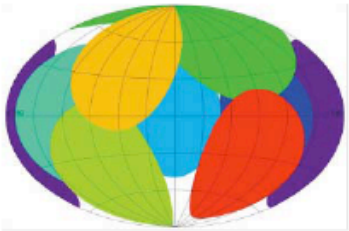
Photons at different energies were emitted simultaneously

and ∃ no conventional explanations →

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

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

AGILE will be launched on April 23, 2007



GLAST
Launch scheduled: >May 2008
Fully operational: ~Fall 2008

	EGRET	AGILE
Mass	1830 kg	130 kg
Energy band	30 MeV – 30 GeV	30 MeV – 50 GeV
Field of view	~ 0.5 sr	~ 3 sr
PSF (68% containment radius)	5.5° 1.3° 0.5°	4.7° (@ 0.1 GeV) 0.6° (@ 1 GeV) 0.2° (@ 10 GeV)
Deadtime for γ-ray detection	~ 100 ms	$\lesssim 200\,\mu s$
Sensitivity for pointlike sources† (ph cm^{-2} s^{-1} MeV^{-1})	8×10^{-9} 1×10^{-10} 1×10^{-11}	6×10^{-9} (@ 0.1 GeV) 4×10^{-11} (@ 1 GeV) 3×10^{-12} (@ 10 GeV)
Required pointing reconstruction	~10 arcmin	~1 arcmin

(†) Obtained for a typical exposure time near 2 weeks for both AGILE and EGRET.

Outlook: What next ? 1.

MAGIC-II: a clone of 1st telescope but:

- Improved 17m telescope (mirror & camera)
- Faster FADCs and a high-QE camera
- First light by fall 2008

New technologies
to lower the threshold energy
17m diameter largest dish
High resolution camera
Ultra-fast read-out system 300M → 2GHz
Analogue signal fiber transmission

VERITAS

4 12-m telescopes at Kitt Peak, AZ

Fully operational since late 2006

HESS-II

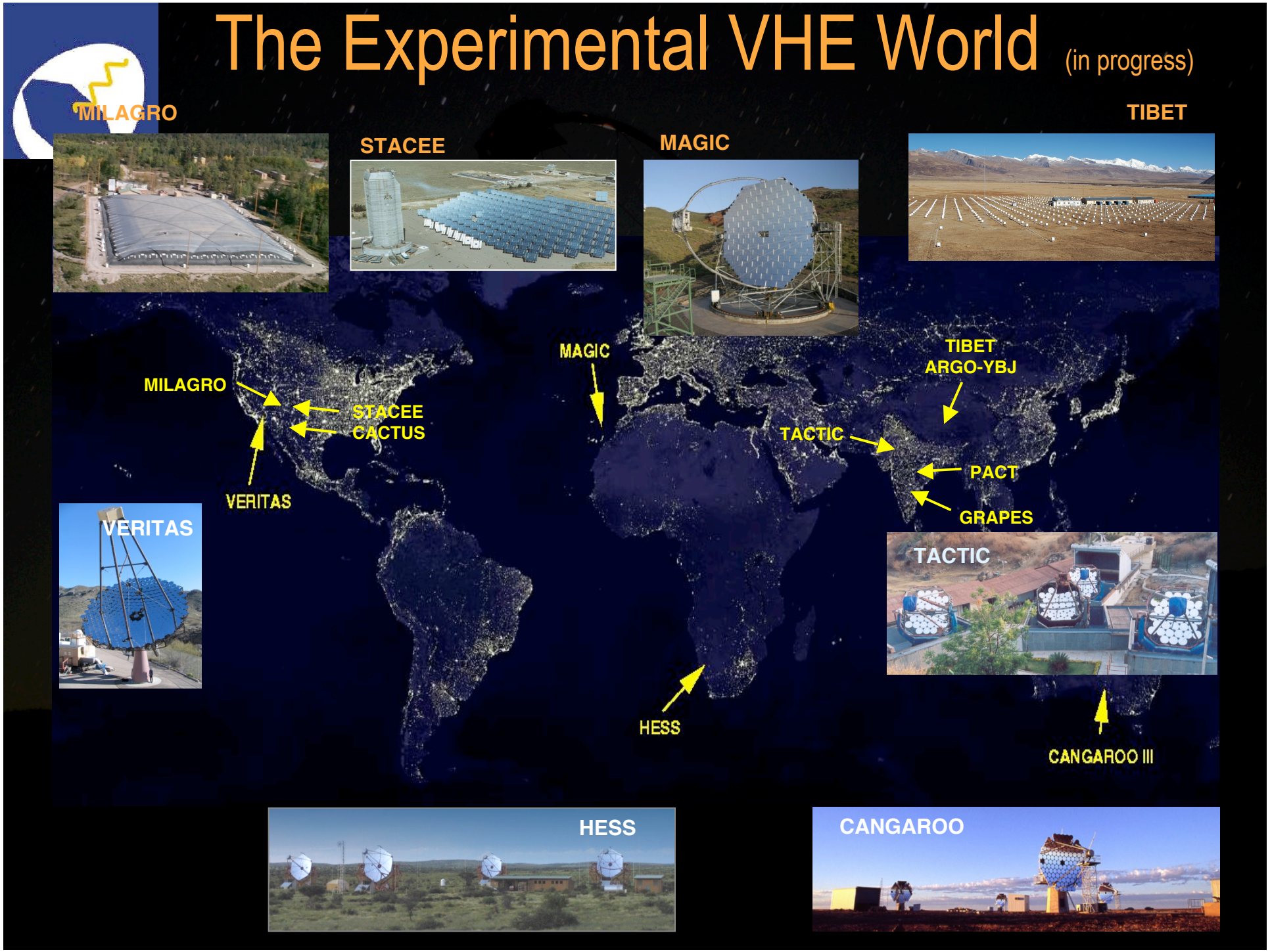
New 28m telescope

2048 pixel camera.

Lower energy 40-50 GeV

First light in 2009 (?)

The Experimental VHE World (in progress)



Outlook: What next ? 2.

The Cherenkov Telescope Array (CTA) facility

- aims to explore the sky in the 10 GeV to 100 TeV energy range
- builds on demonstrated technologies
- combines guaranteed science with significant discovery potential
- is a cornerstone towards a multi-messenger exploration of the nonthermal universe

Conclusion

Breakthrough in VHE γ-ray astronomy: outstanding results from second-generation IACTs

VHE γ-ray installations: observatories, no longer experiments
→ VHE γ-ray astronomy established

New VHE sources: more discovered last 2 years than in previous 20 years!
... more on the way

SNRs, γ-ray binaries, pulsars → particle acceleration

Blazars, EBL → SSC model of jets, measure EBL(z) (→ exotica: QG?)

GRBs → prompt emission detectable (→ exotica: QG?)

SF galaxies → TeV emission: NT indicator of current SFR

Clusters → NT side of structure formation:

Indirect DM searches → ok for IACTs if WIMP parameter space favorable

… see review:
De Angelis, Mansutti & Persic 2008
Nuovo Cimento, 31, 187-245