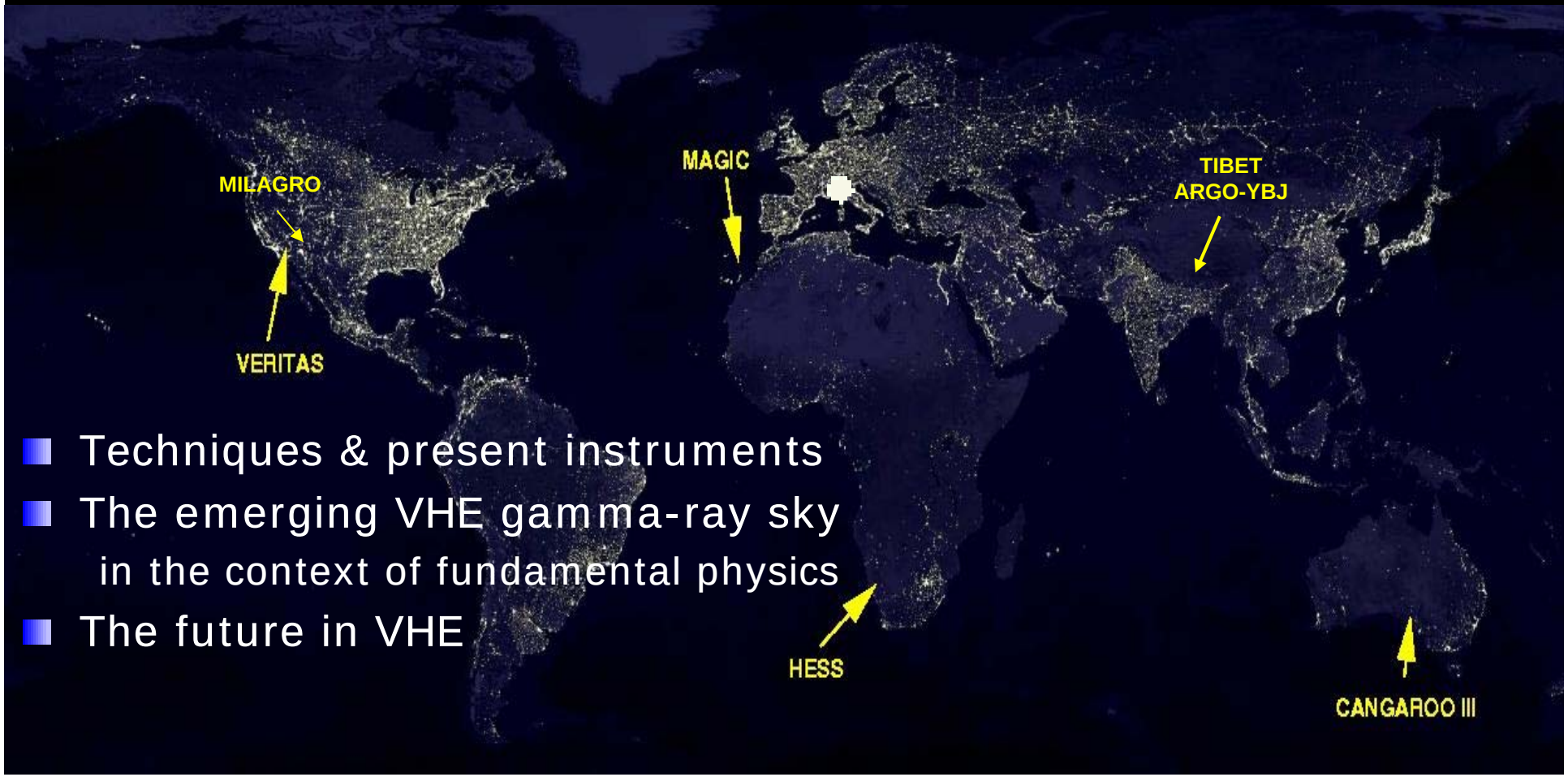
Ground-based gamma-ray astrophysics

arXiv:0712.0315v6 (July 2008)

Alessandro De Angelis, INAF INFN/Univ. Udine & IST La Thuile 09



- Techniques & present instruments
- The emerging VHE gamma-ray sky
  in the context of fundamental physics
- The future in VHE

Limit of γ space telescopes

- Peak eff. area of Fermi: 0.8 m^2

  From strongest flare ever recorded of very high energy (VHE) γ-rays:

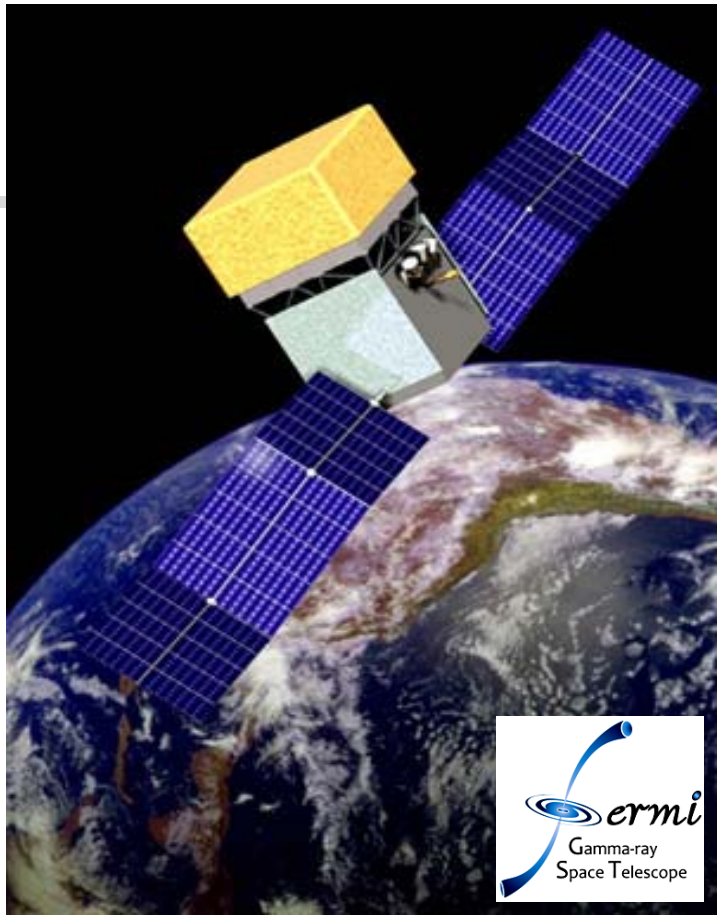
  1 photon / m^2 in 8 h above 200 GeV

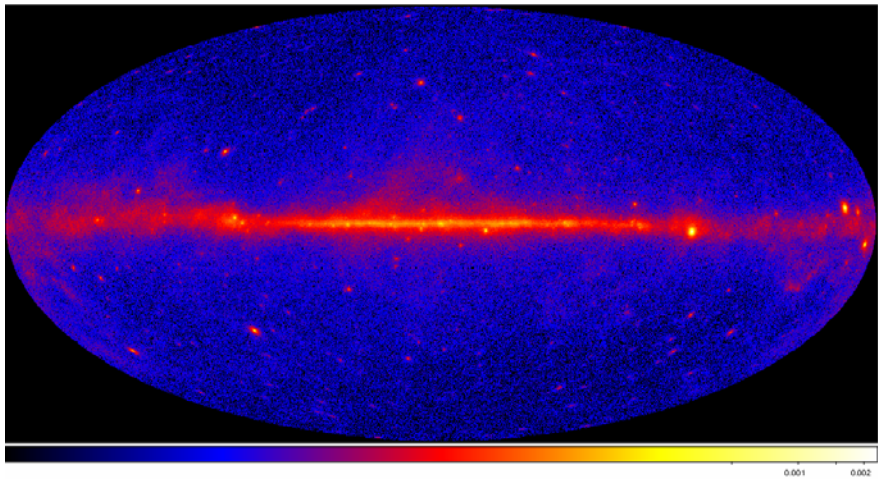
  (PKS 2155, July 2006)

- The strongest *steady* sources are > 1 order of magnitude weaker!
- Besides: calorimeter depth $\leq 10\ X_0$

$\Rightarrow$ VHE astrophysics (in the energy region above 100 GeV) can be done only at ground

Conventionally, VHE > 30(100) GeV



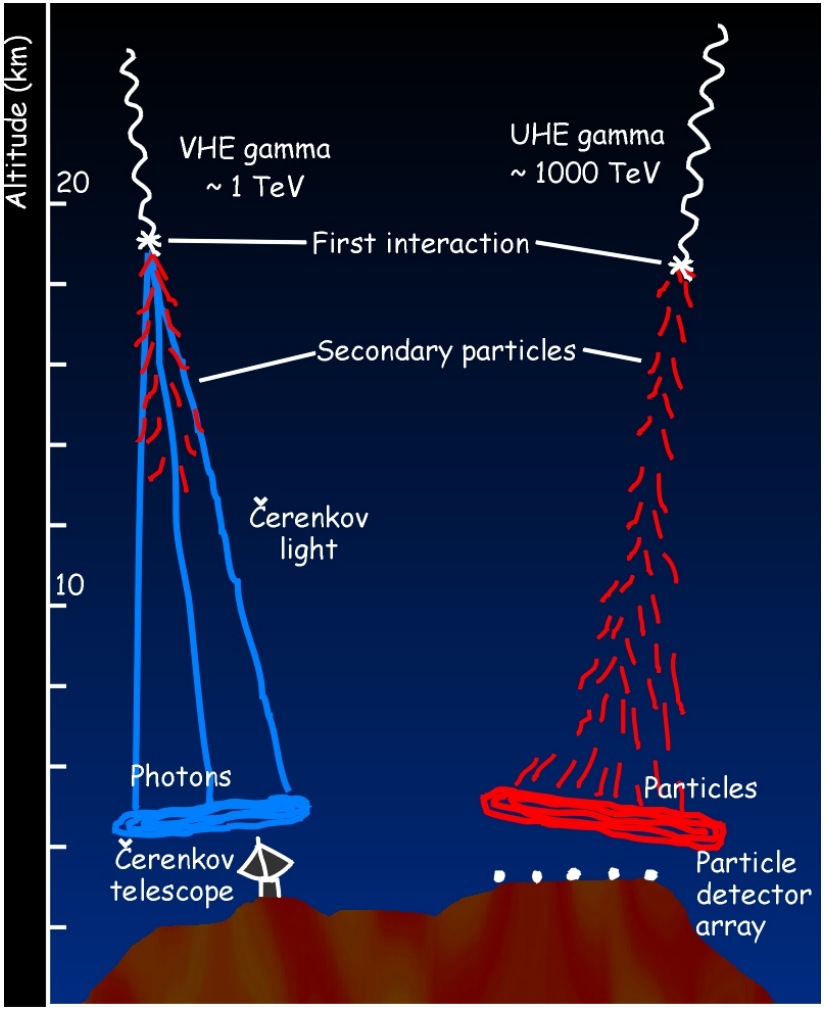


And what physics questions are answered by VHE photons?

- Do emission processes continue at the highest energies?
- Photons produced in hadronic cascades can be a signature of protons at an energy 10 times larger

  => Cosmic Rays
- The highest energies can test fundamental physics in the most effective way
- ...

Ground detectors: EAS vs. IACT (Cherenkov)



- Observe particle showers induced in the atmosphere (28 X_0 at s.l.) by γ-rays

- EAS (Extensive Air Shower): detection of the charged particles in the shower

  (ARGO, MILAGRO)

- Cherenkov detectors (IACT): detection of the Cherenkov light from charged particles in the atmospheric showers

  $\theta_c \sim 1^o$

  e Threshold @ sl: 21 MeV

Maximum of a 1 TeV shower

~ 8 Km asl

~ 200 photons/m^2 in the visible

Angular spread ~ 0.5º

Observational Technique

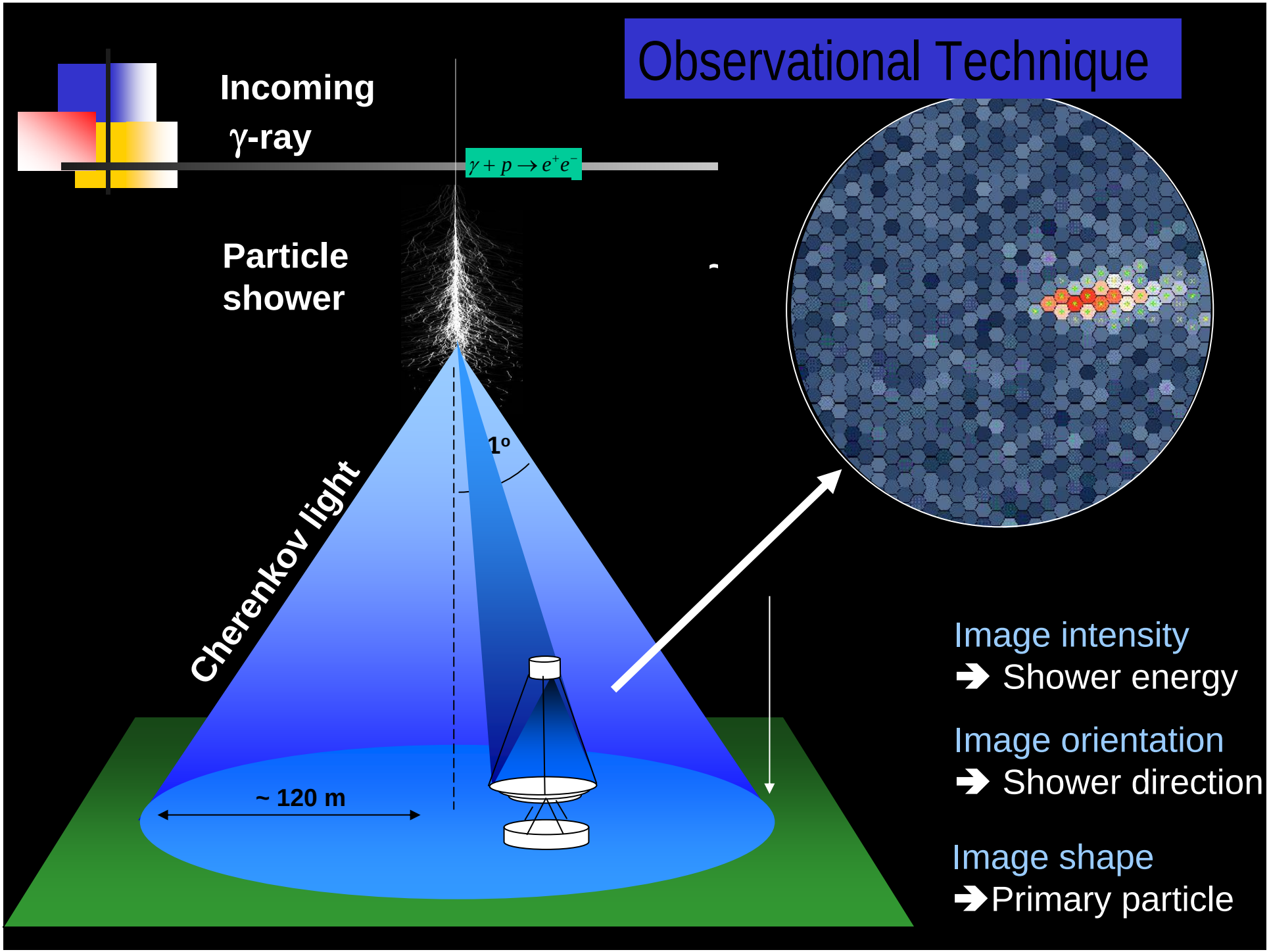
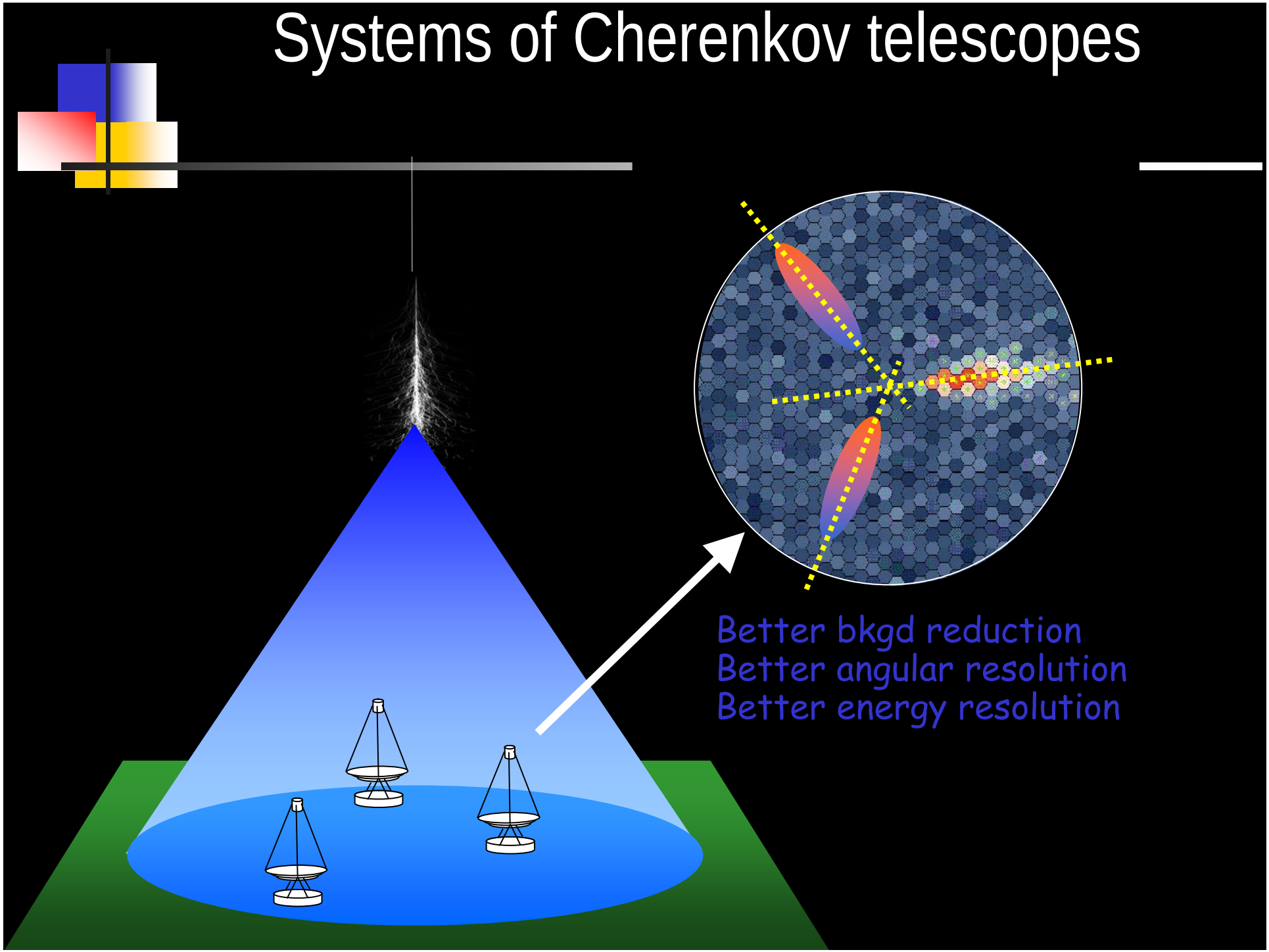


Image intensity
➔ Shower energy

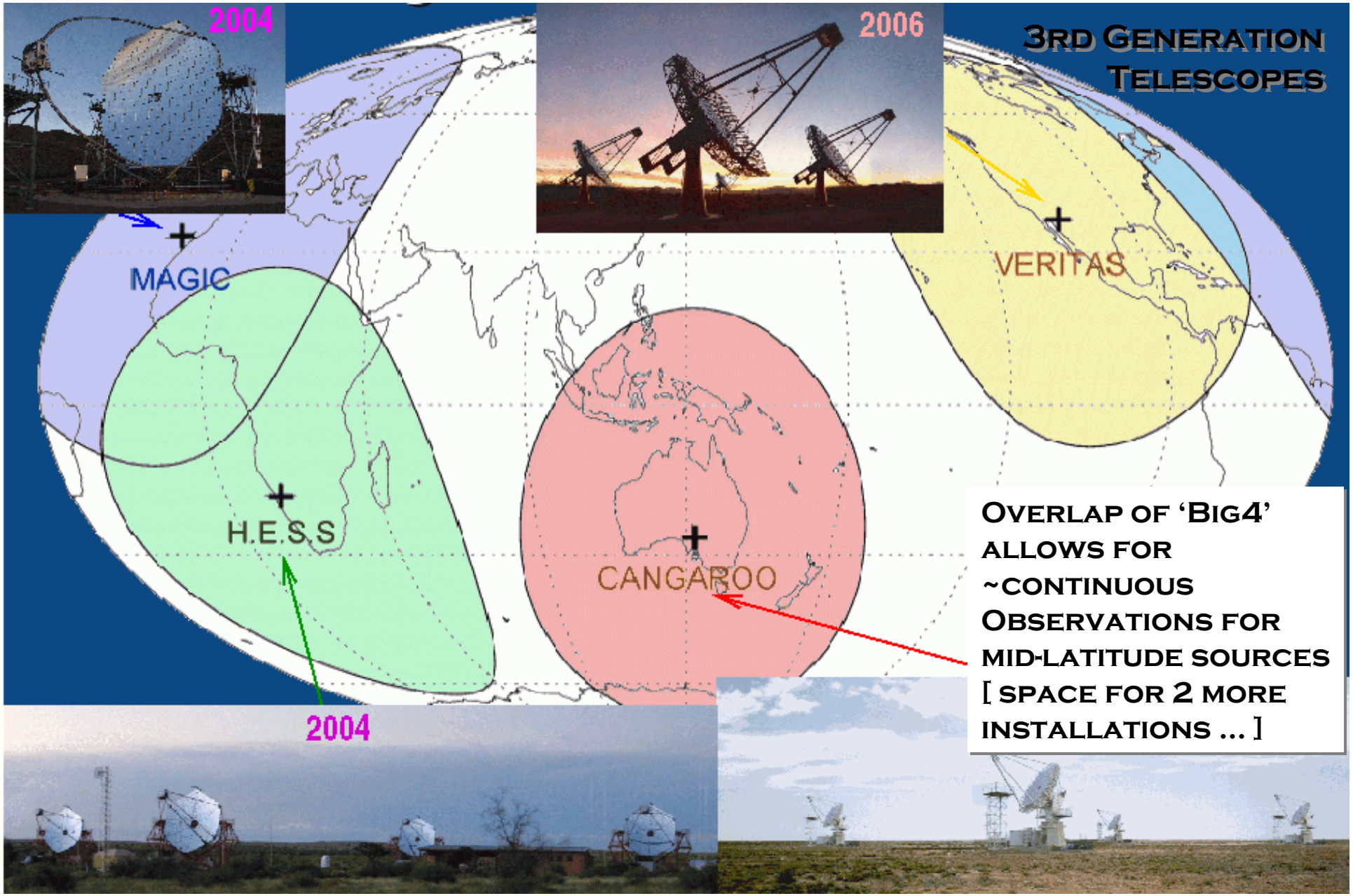
Image orientation
➔ Shower direction

Image shape
➔Primary particle

Systems of Cherenkov telescopes



Better bkgd reduction
Better angular resolution
Better energy resolution

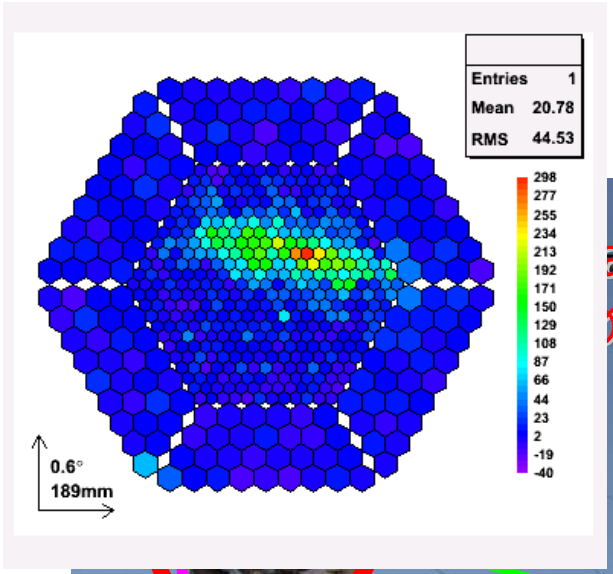


The Big 4 IACT


H.E.S.S.: 4 telescopes operational since 2003


VERITAS: 4 telescopes operational since 2006

MAGIC 1 (SINCE



a:
, 3.5° FoV

17 m

17 m

Analogical
Transmission
(optical fiber)

Trigger
DAQ > 1 GHz
Event rate ~300 Hz

Refl. surface:
236 m², F/1, 17 m ∅

– Lasers+mechanisms for AMC

A summary (oversimplified...)

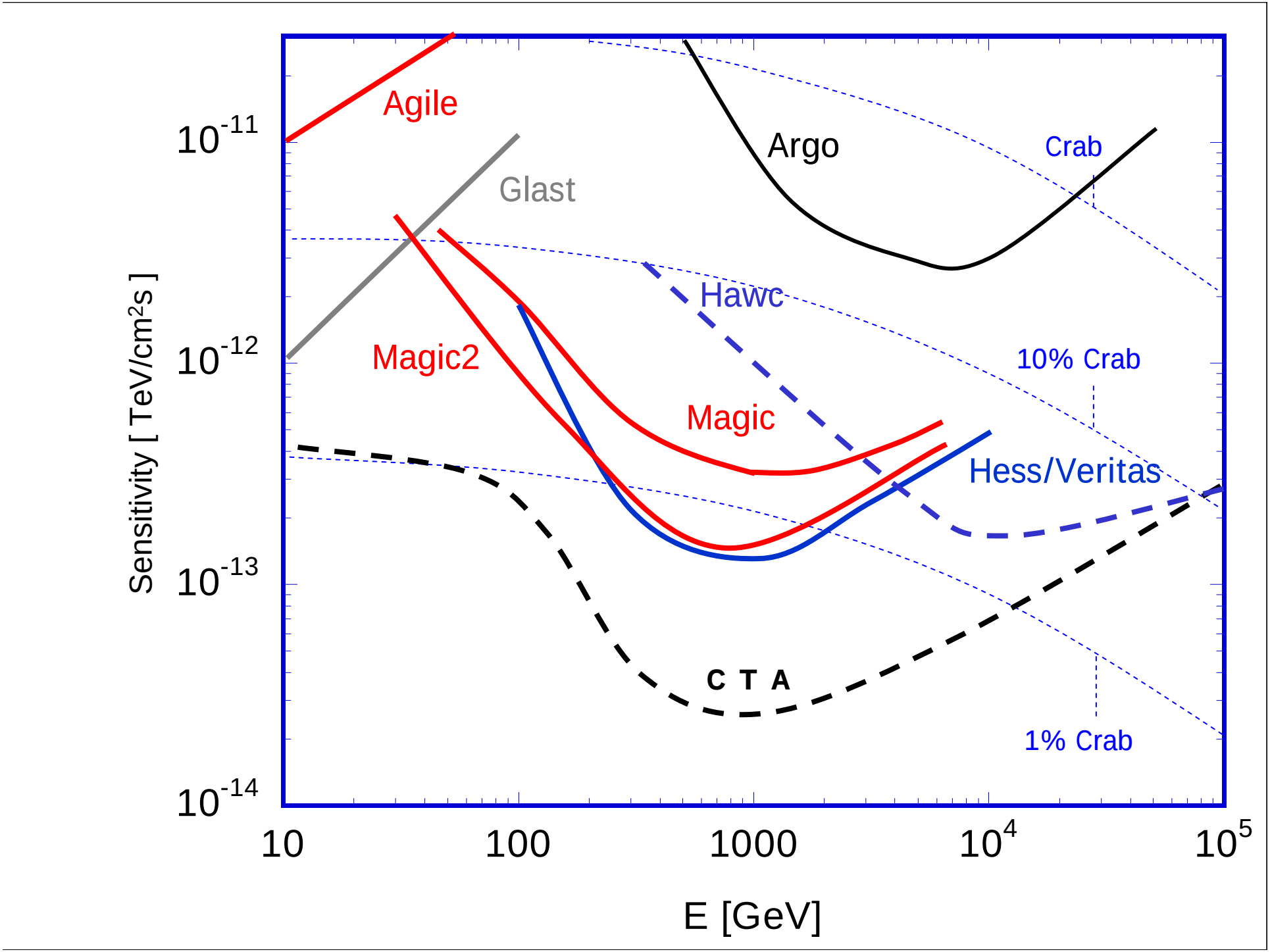
	GLAST	IACTs	EAS'
Energy	20MeV – 200GeV	100GeV – 50TeV	400GeV–100TeV
Energy res.	5-10%	15-25% (*)	~50%
Duty Cycle	80%	15%	>90%
FoV	$4\pi/5$	5deg x 5deg	$4\pi/6$
PSF	0.1 deg	0.07 deg	0.5 deg
Sensitivity (**)	1% Crab (1 GeV)	1% Crab (500 GeV)	0.5 Crab (5 TeV)

(*) Decreases to 15% after cross-calibration with GLAST

(**) Computed over one year for GLAST and the EAS, over 50 hours for the IACTs

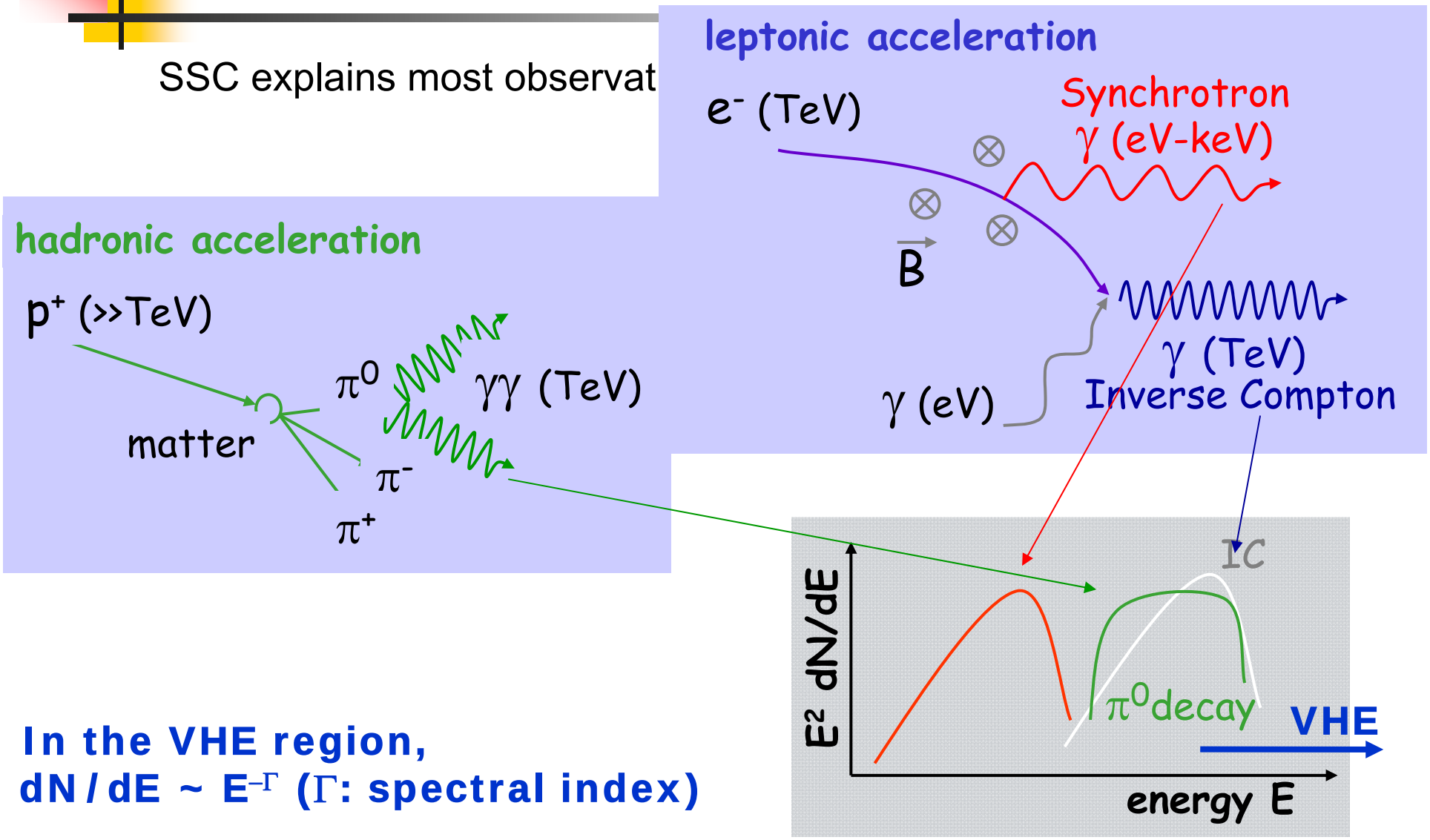
Among IACTs:

- HESS 1 has a better sensitivity (8 mCrab) than MAGIC 1 (15 mCrab) at the TeV
- HESS 1 has a better space resolution (0.06 deg) than MAGIC 1 (0.10 deg)
- MAGIC has lower threshold: sees deeper ($z < 1.2$) Universe than HESS ($z < 0.8$)


Agile
Argo
Crab
Glast
Hawc
Magic2
10% Crab
Magic
Hess/Veritas
C T A
1% Crab
Sensitivity [TeV/cm²s]
10^-11
10^-12
10^-13
10^-14
10
100
1000
10^4
10^5
E [GeV]

Origin of γ rays from gravitational collapses
SSC: a (minimal) standard model

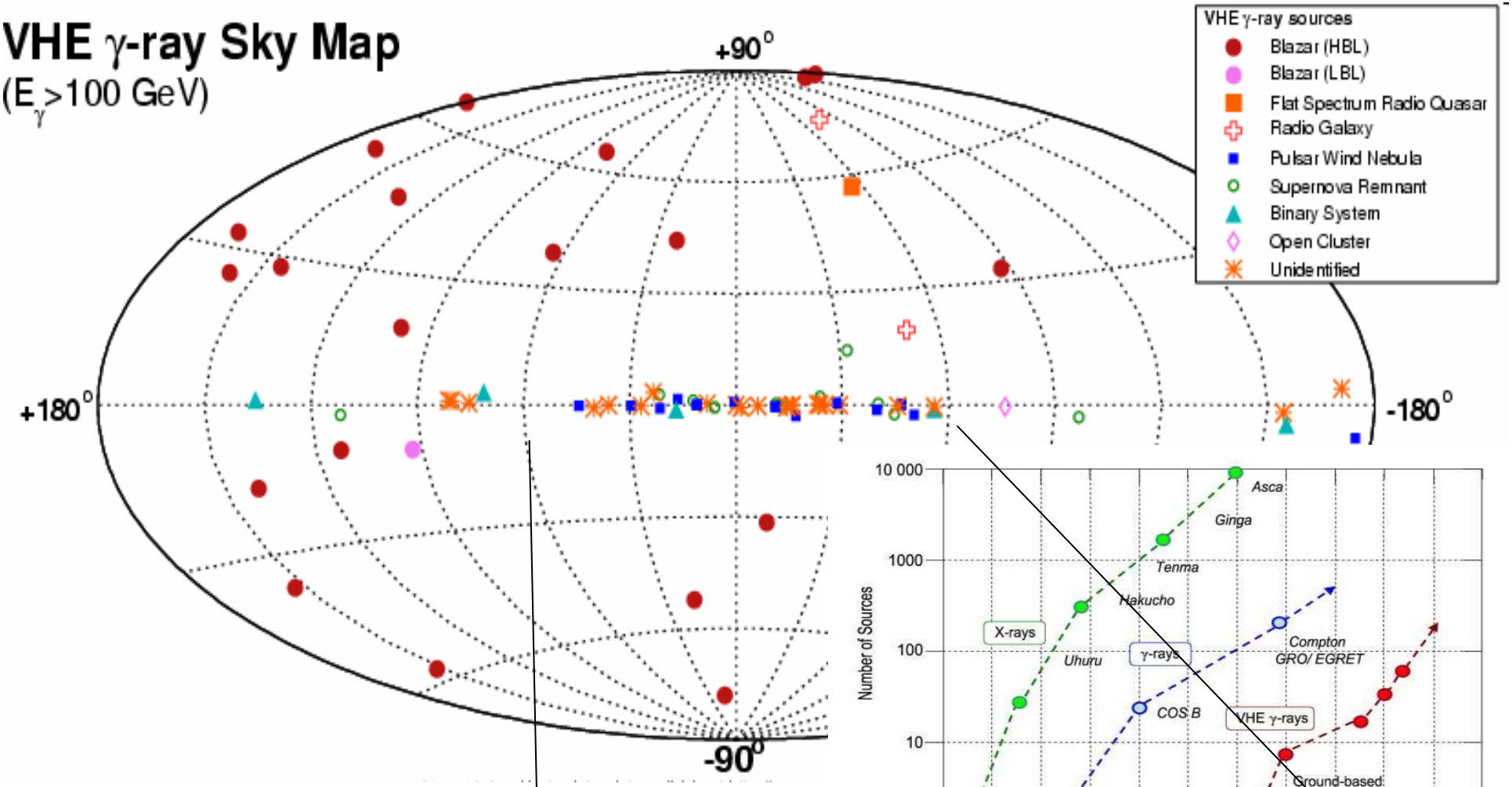
SSC explains most observat



In the VHE region,
dN / dE ~ E$^{-\Gamma}$ (Γ: spectral index)

VHE γ-ray Sky Map

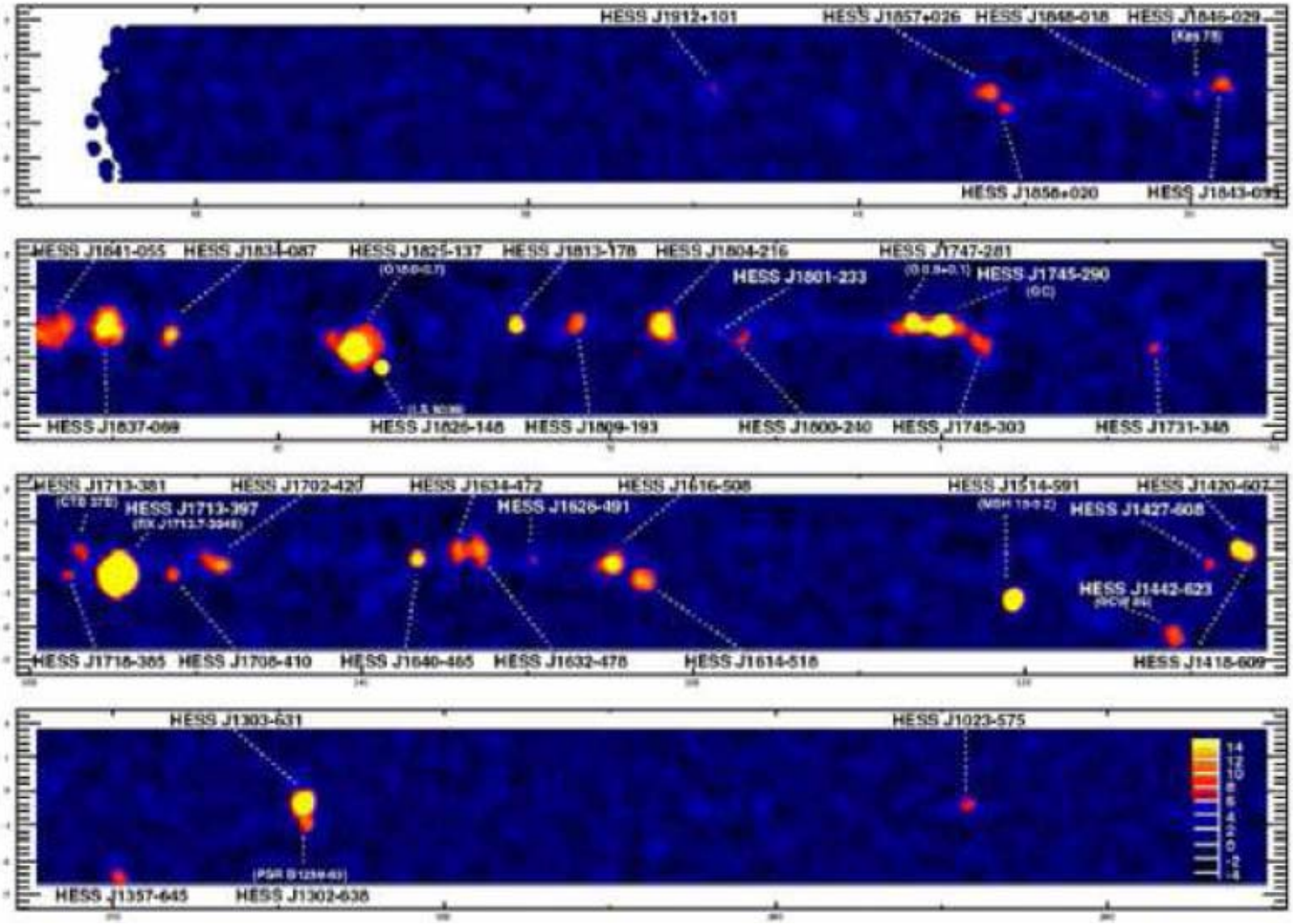
(E_γ>100 GeV)



SNR	**9**
PWN	**19**
Unid. gal.	**21**
GC	
Binary	**4**
AGN	**27**

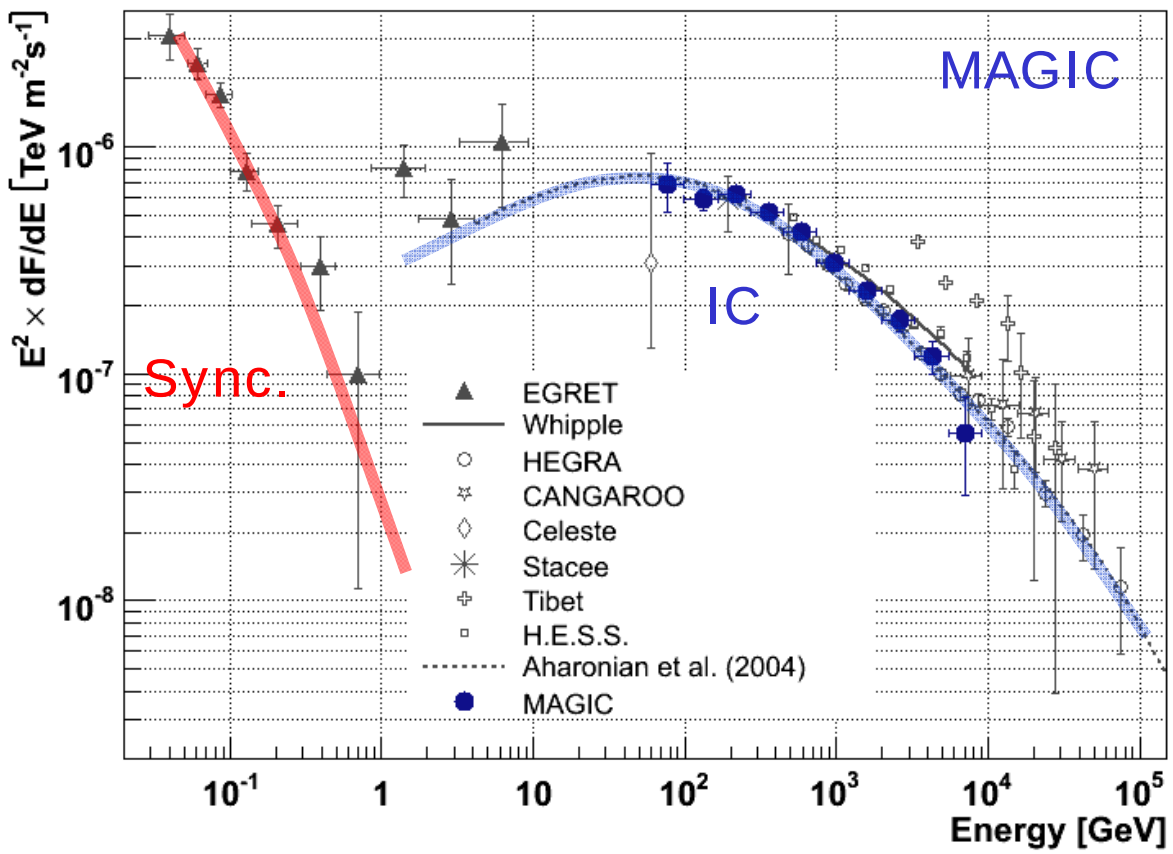
On Feb 25, 2009, 81 sources > 100 GeV

HESS' galactic scan (2003-2007)



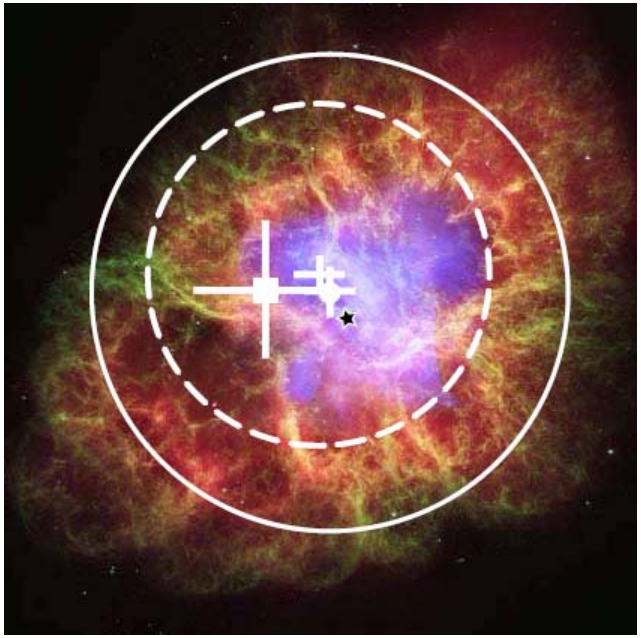
Best studied: the Crab Nebula

Crab seen also by
MILAGRO
Tibet AS-γ
ARGO YBJ
VERITAS...



Turn-over of SED starts to be visible at ~100 GeV
MAGIC 2007, ApJ

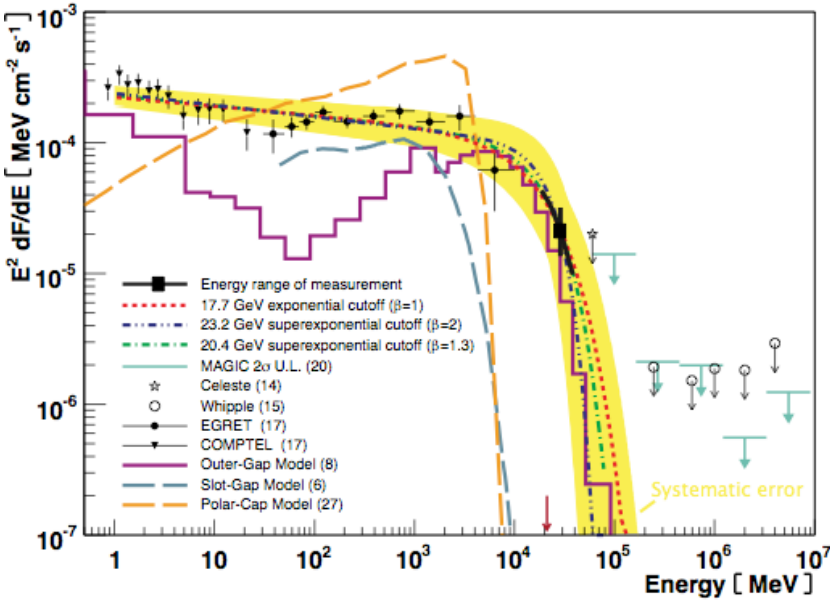
IC peak at ~77 GeV

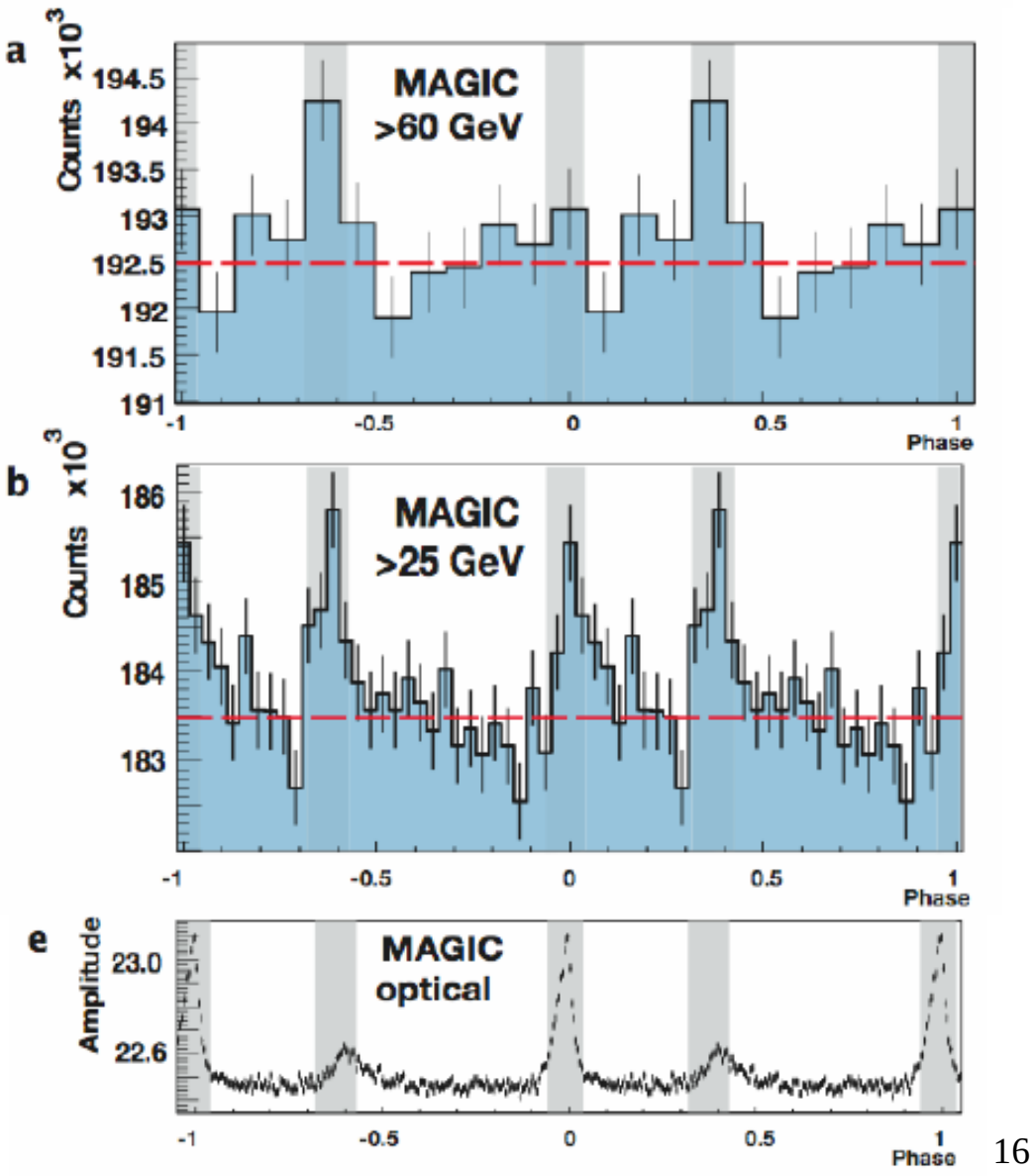


Source size @ 500 GeV < 1.6'

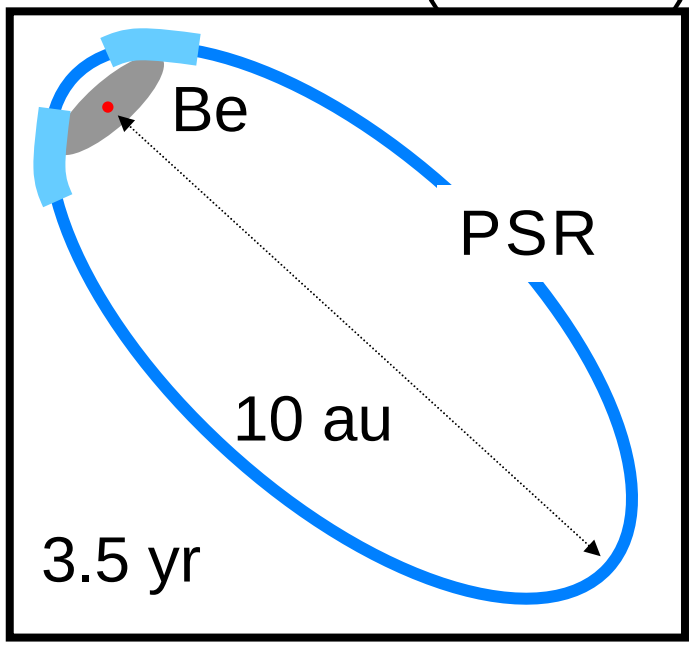
Crab pulsation (Science, November 2008)

- MAGIC detected pulsed γ-rays from the Crab above 25 GeV, revealing a relatively high energy cut-off in the pulsed spectrum
- First observation of pulsed emission at O(10 GeV), first indication of a cutoff

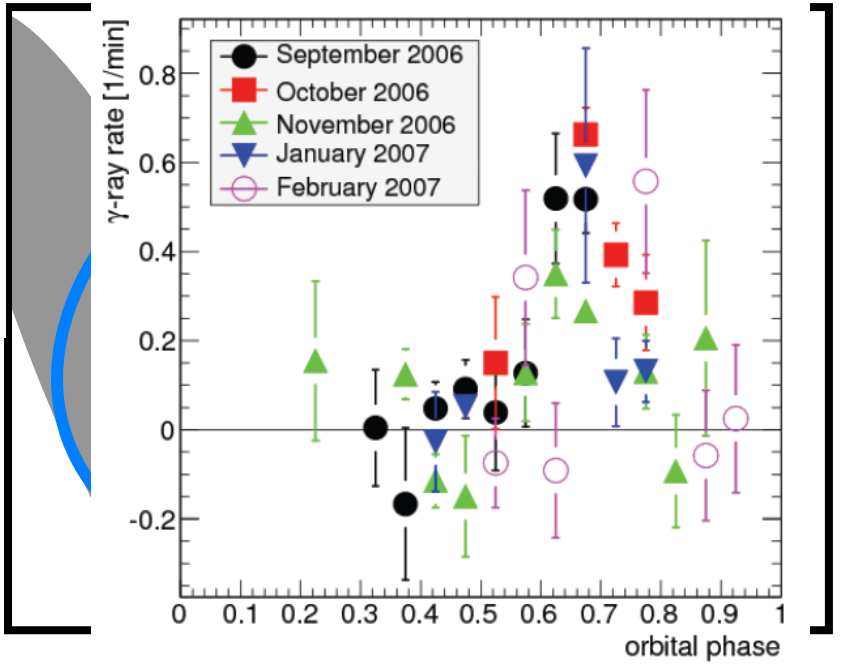




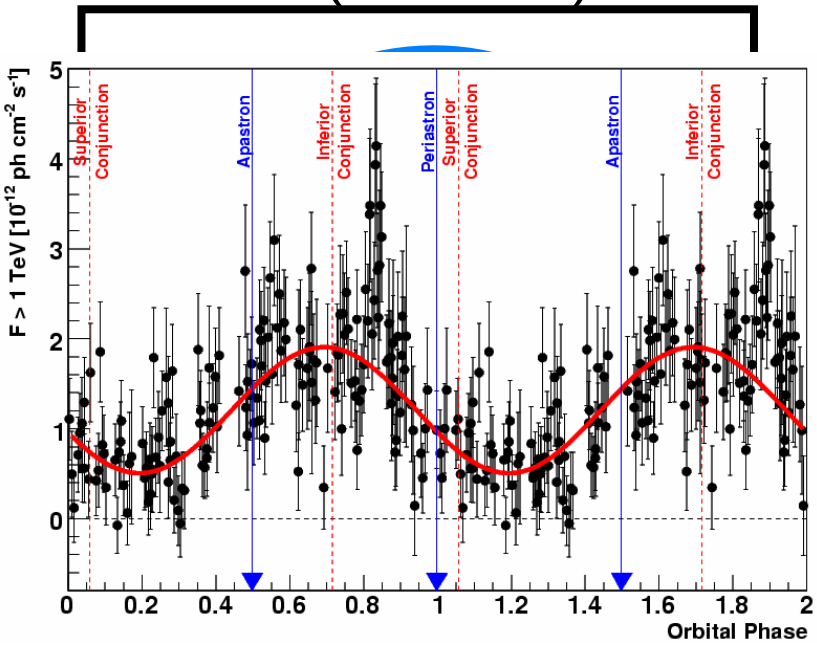
PSR B1259-63 (H.E.S.S.)



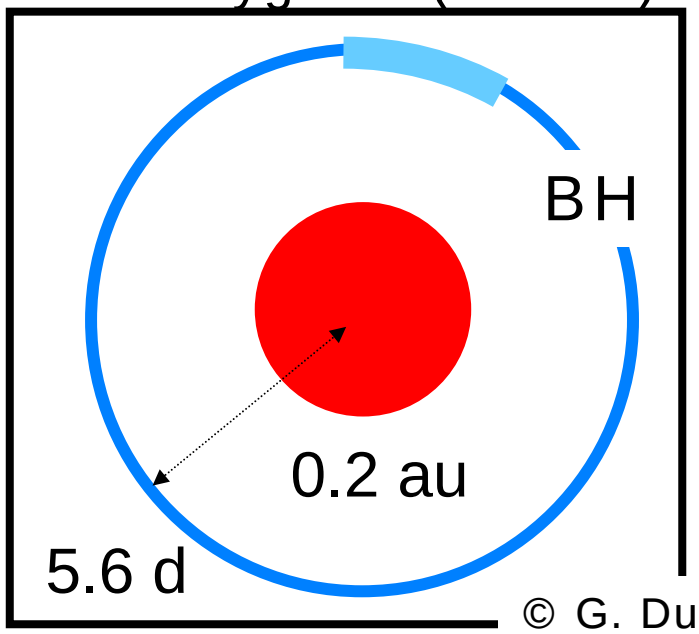
LS I +61 303 (MAGIC+VERITAS)



LS 5039 (H.E.S.S.)

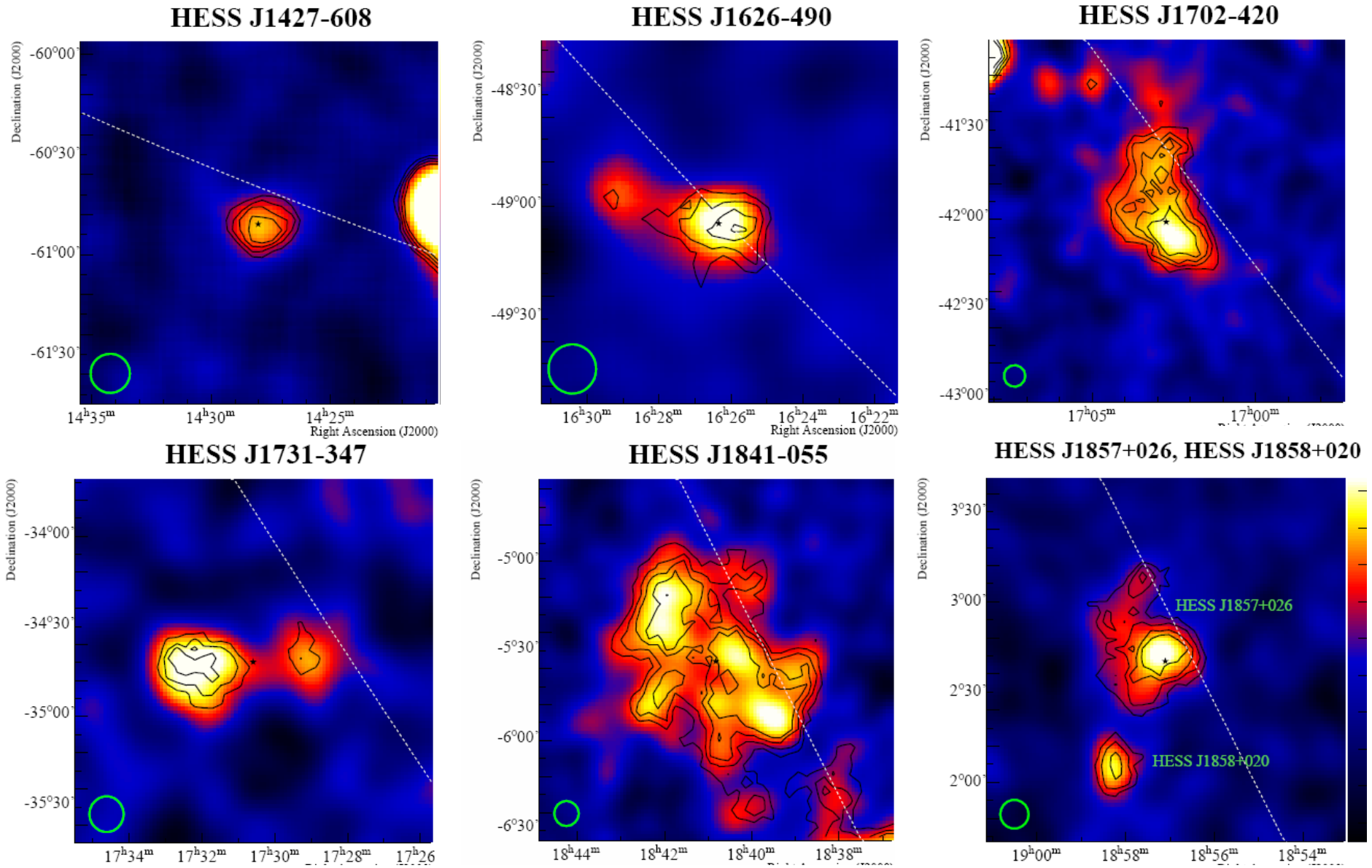


Cyg X-1 (MAGIC)



© G. Dubus

However, ~ 50% without counterpart



DM search
(Majorana WIMPs)

$$\chi\chi \rightarrow q\bar{q} \rightarrow n \times \gamma$$

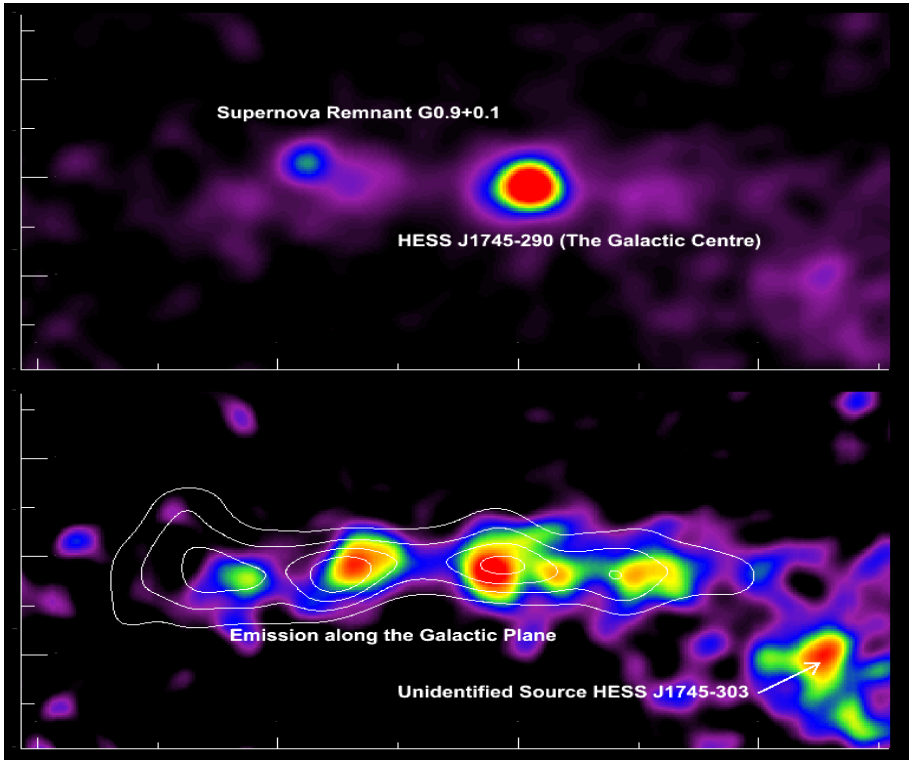
$$\chi\chi \rightarrow \gamma\gamma(Z)$$

$$\frac{dN}{dE} = \frac{1}{4\pi} \underbrace{\frac{\langle \sigma v \rangle}{m_{DM}^2} \frac{dN_\gamma}{dE}}_{Particle\ Physics} \times \underbrace{\int_{\Delta\Omega - los} dl(\Omega) \rho_{DM}^2}_{Astrophysics}$$

Highest DM density candidate:
Galactic Center?
Close by (7.5 kpc)
Not extended

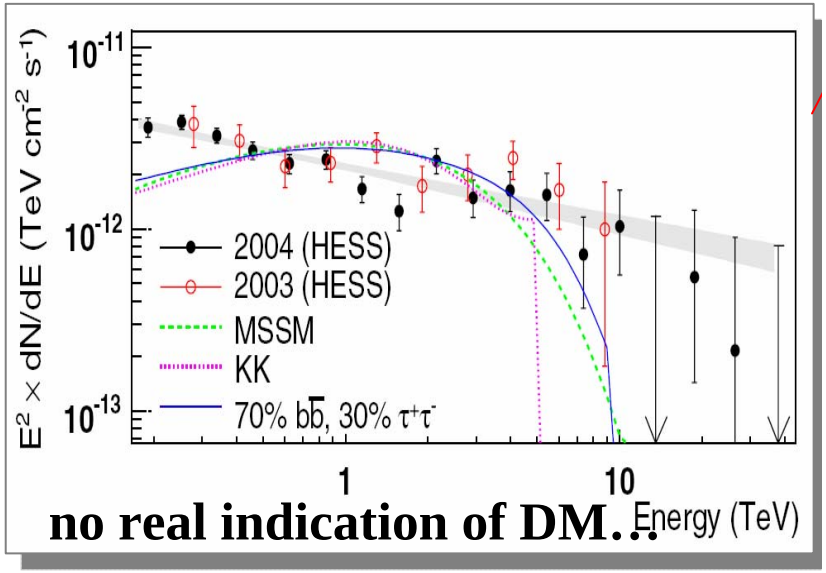
BUT:

- other γ-ray sources in the FoV
=> competing plausible scenarios
- halo core radius: extended vs point-like



γ-ray detection from the Galactic Center

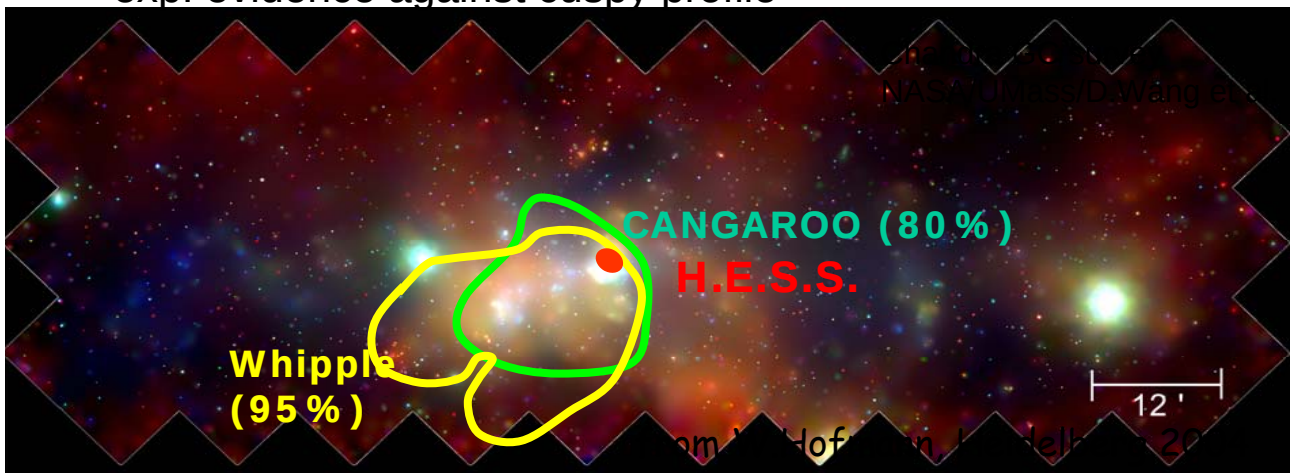
- detection of γ-rays from GC by Cangaroo, Whipple, HESS, MAGIC
- σ_{source} < 3' (< 7 pc at GC)
  - hard $E^{-2.21\pm0.09}$ spectrum
    fit to χ-annihilation continuum spectrum leads to: M_χ > 14 TeV
  - other interpretations possible (probable)



no real indication of DM...

Galactic Center: very crowded sky region, strong exp. evidence against cuspy profile

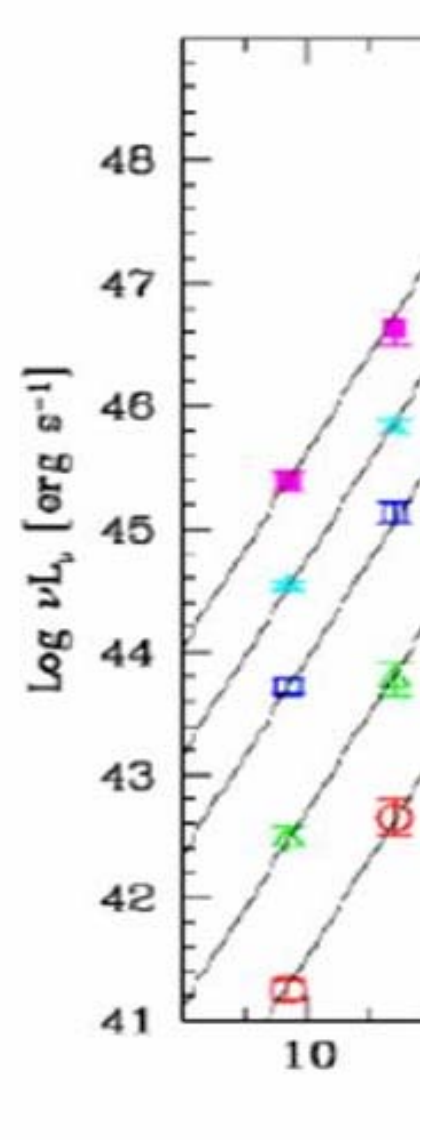
The spectrum is featurless!!!



Milky Way satellites Sagittarius, Draco, Willman1, Perseus, …

- proximity (< 100 kpc)
- low baryonic content, no central BH (which may change the DM cusp)
- large M/L ratio

Active Galactic Nuclei: the sequence



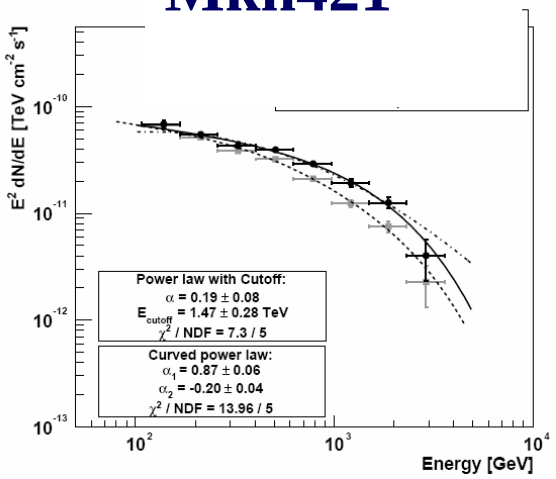
Source	z	α_γ	F_γ	IACT
M 87	0.0044			H
Mrk 421	0.031	2.33 ± 0.08	1.03(±0.03)E-10	M
Mrk 501	0.034	2.28 ± 0.05	1.71(±0.11)E-11	M
		2.45 ± 0.07	3.84(±1.00)E-12	M
1ES 2344+514	0.044	2.95 ± 0.12	1.21(±0.10)E-11	M
Mrk 180	0.045	3.30 ± 0.70	8.46(±3.38)E-12	M
1ES 1959+650	0.047	2.72 ± 0.14	3.04(±0.35)E-11	M
BL Lacertae	0.069	3.60 ± 0.50	3.28(±0.26)E-12	M
PKS 0548-322	0.069			H
PKS 2005-489	0.071	4.00 ± 0.40	3.32(±0.48)E-12	H
RGB J0152+017	0.080	2.95 ± 0.36	4.43(±1.24)E-12	H
W Comae	0.080			V
PKS 2155-304	0.116	3.37 ± 0.07	2.89(±0.18)E-11	H
1ES 1426+428	0.129	3.55 ± 0.46	2.53(±0.43)E-11	W
1ES 0806+524	0.138			V
1ES 0229+200	0.139	2.50 ± 0.19	4.46(±0.71)E-12	H
H 2356-309	0.165	3.09 ± 0.24	2.55(±0.68)E-12	H
1ES 1218+304	0.182	3.00 ± 0.40	1.01(±0.26)E-11	M
1ES 1101-232	0.186	2.94 ± 0.20	4.35(±0.69)E-12	H
1ES 0347-121	0.188	3.10 ± 0.23	3.86(±0.73)E-12	H
1ES 1011+496	0.212	4.00 ± 0.50	6.40(±0.32)E-12	M
PG 1553+113	>0.25	4.20 ± 0.30	5.24(±0.87)E-12	M,H
3C 279	0.536			M
S5 0716+714				M

Observations: New sources and source types

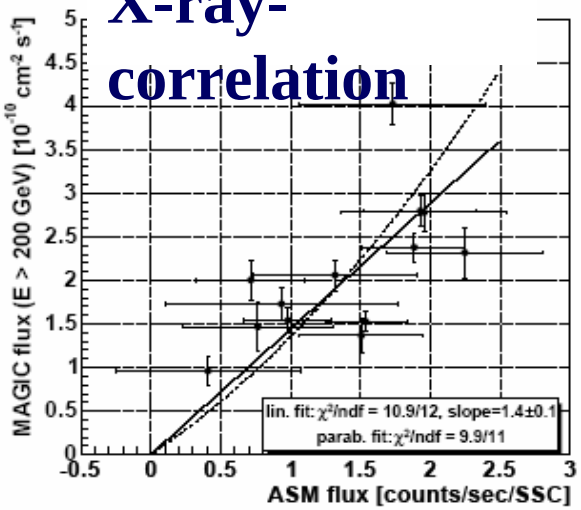
Variability: M87 (the closest), Mkn 421, Mkn501

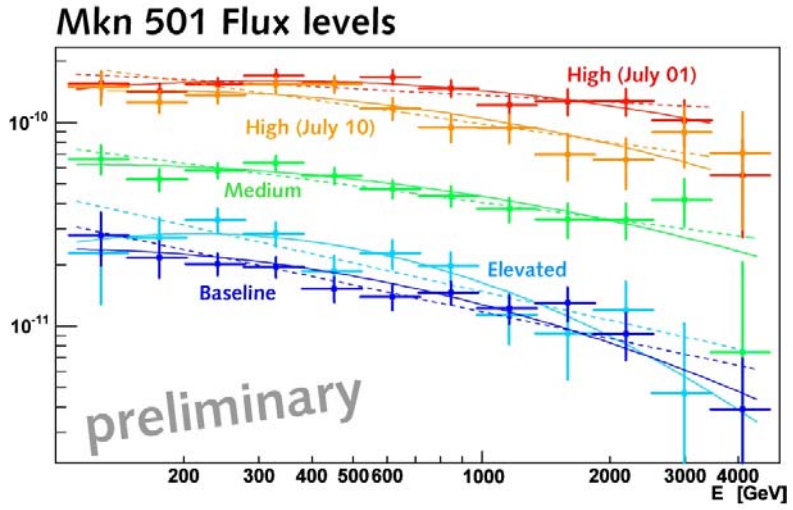
- Two very well studied sources, highly variable
  - Monitoring from Whipple, Magic…
  - TeV-X Correlation
    - No orphan flares…
      - See neutrino detectors

Mkn421



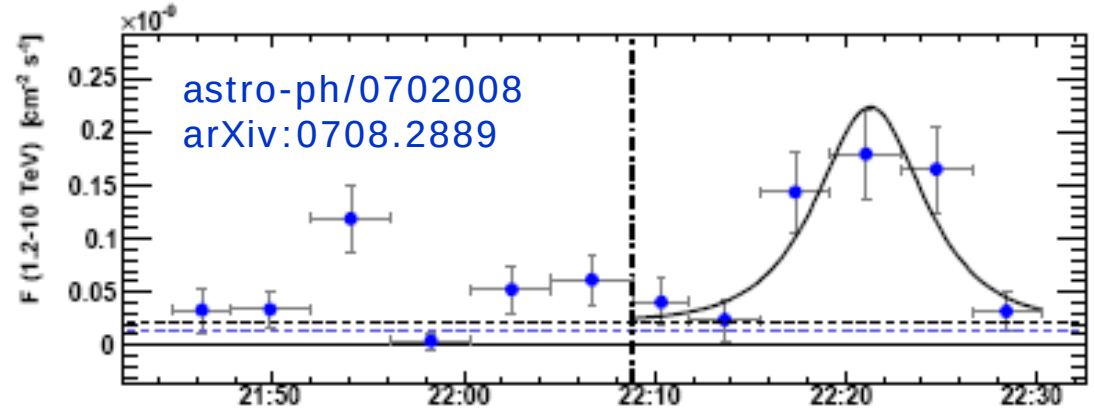
Mkn421 TeV-X-ray-correlation



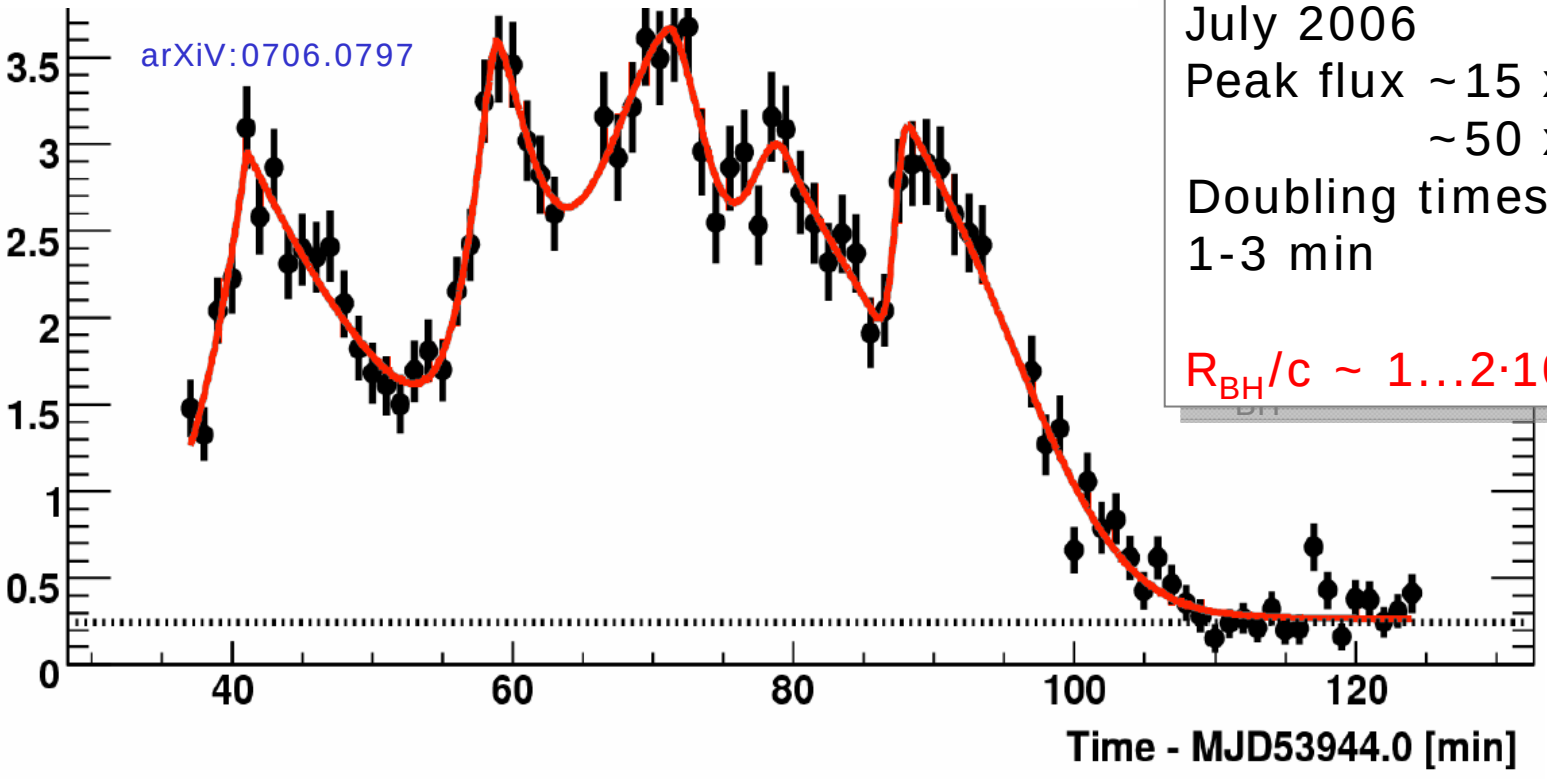


However, recently Fermi/HESS saw no correlation in PKS 2155

Rapid variability



MAGIC, Mkn 501
Doubling time ~ 2 min



HESS PKS 2155
z = 0.116

July 2006
Peak flux ~15 x Crab
~50 x average
Doubling times
1-3 min

$R_{BH}/c \sim 1...2 \cdot 10^4$ s

Violation of the Lorentz-Invariance?

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

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

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

MAGIC Mkn 501, PLB08

$E_{s1} \sim 0.03\ M_P$

$E_{s1} > 0.02\ M_P$

HESS PKS 2155, PRL08

$E_{s1} > 0.06\ M_P$

Whipple 1999, PRL 83(99)2108

$E_{s1} > 0.005\ M_P$

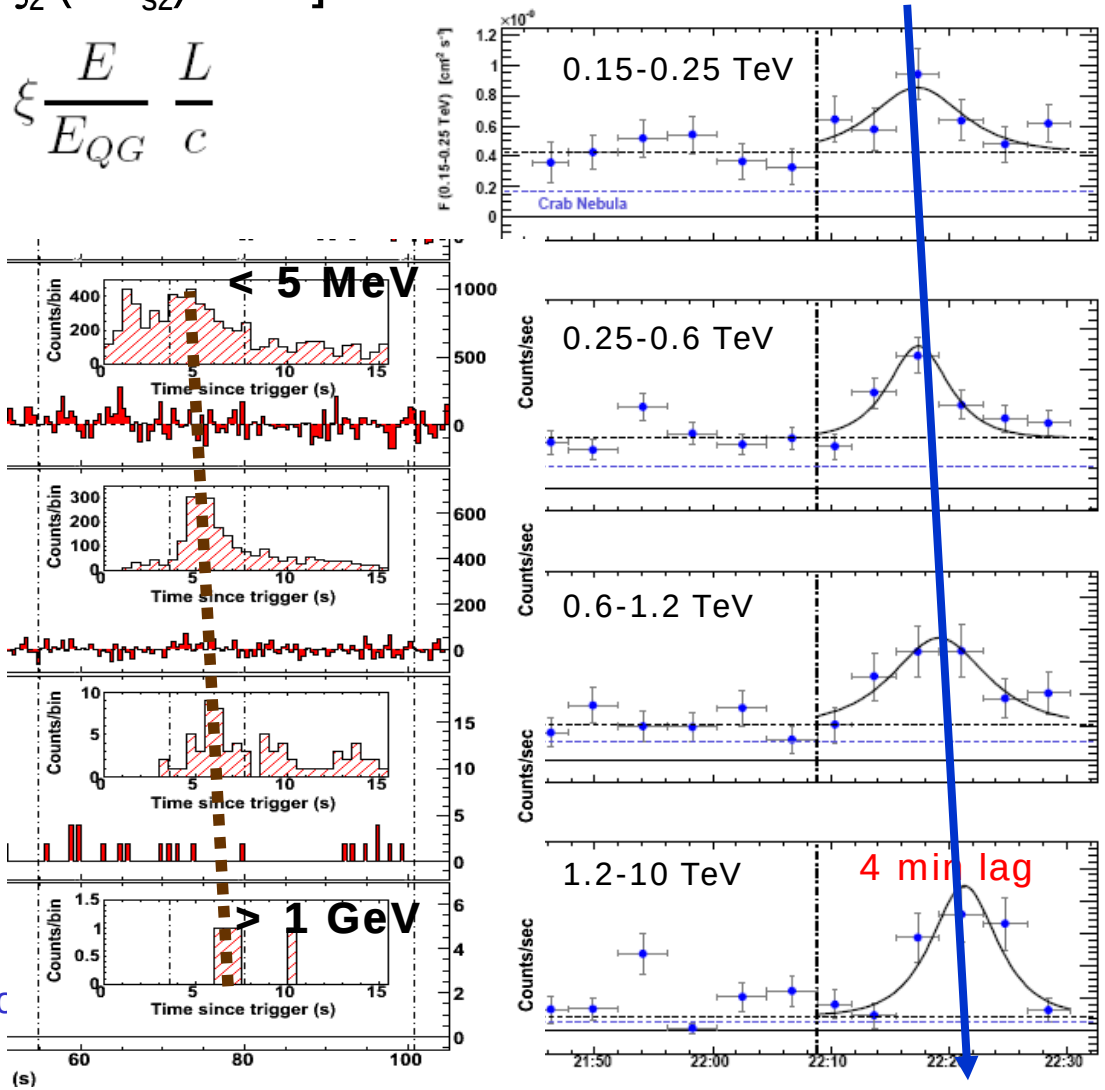
GRB X-ray limits:

$E_{s1} > 0.11\ M_P$ (Fermi, but…)

… but in most scenarios

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

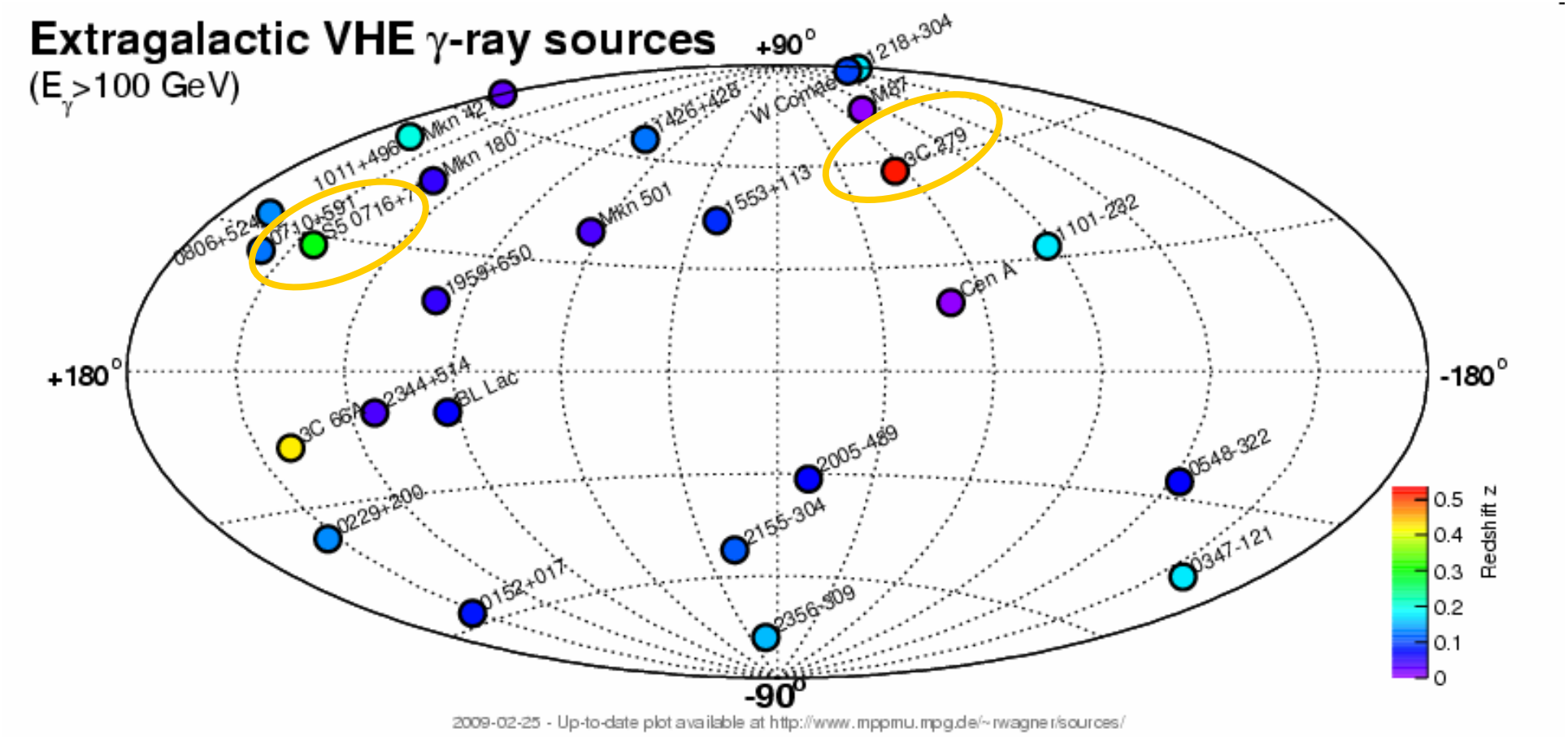
- VHE gamma rays are the best prc
- Mrk 501: $E_{s2} > 3 \cdot 10^{-9}\ M_P$, $\alpha = 2$



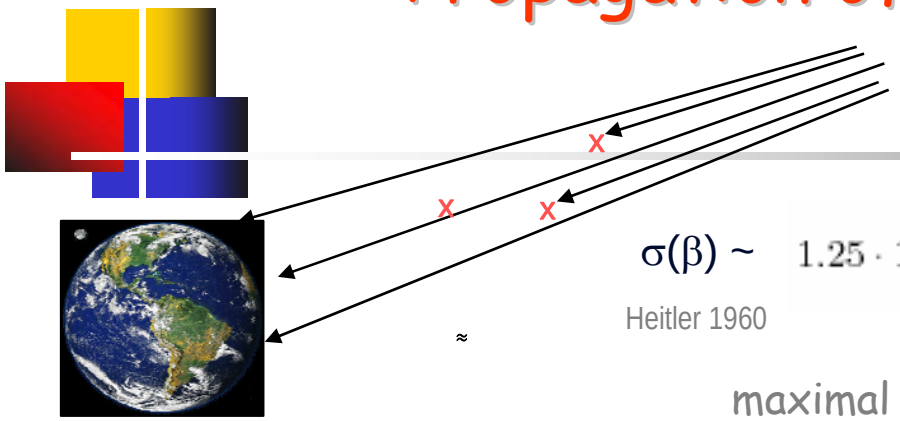
Interpretation of the results on rapid variability

- The most likely interpretation is that the delay is due to physics at the source
  - By the way, a puzzle for astrophysicists
- However
  - We are sensitive to effects at the Planck mass scale
  - More observations of flares will clarify the situation
- In any case: amazing to see light traveling for half a billion light years and keeping a 2 minutes delay

Going far away...



Propagation of γ-rays



dominant process for absorption:

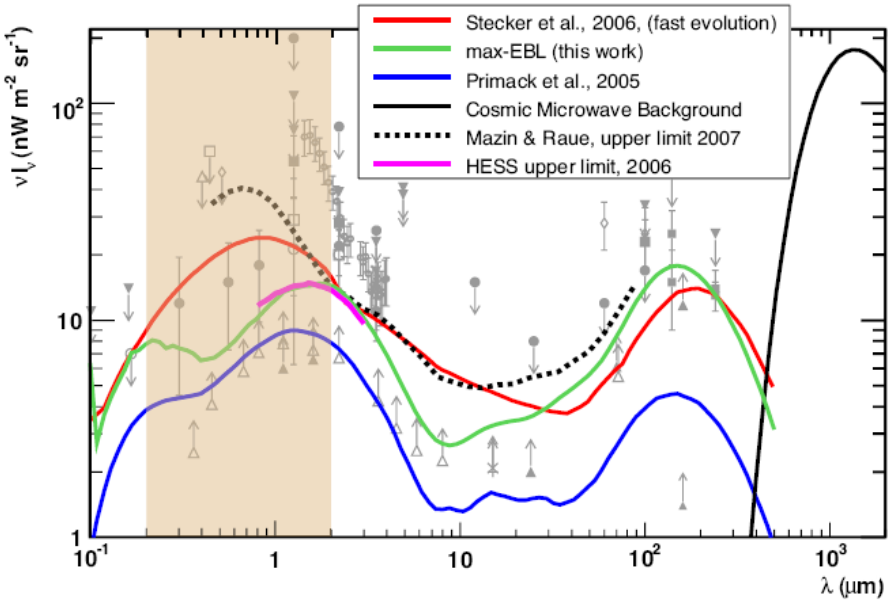
$\gamma_{VHE}\gamma_{bck} \rightarrow e^+e^-$

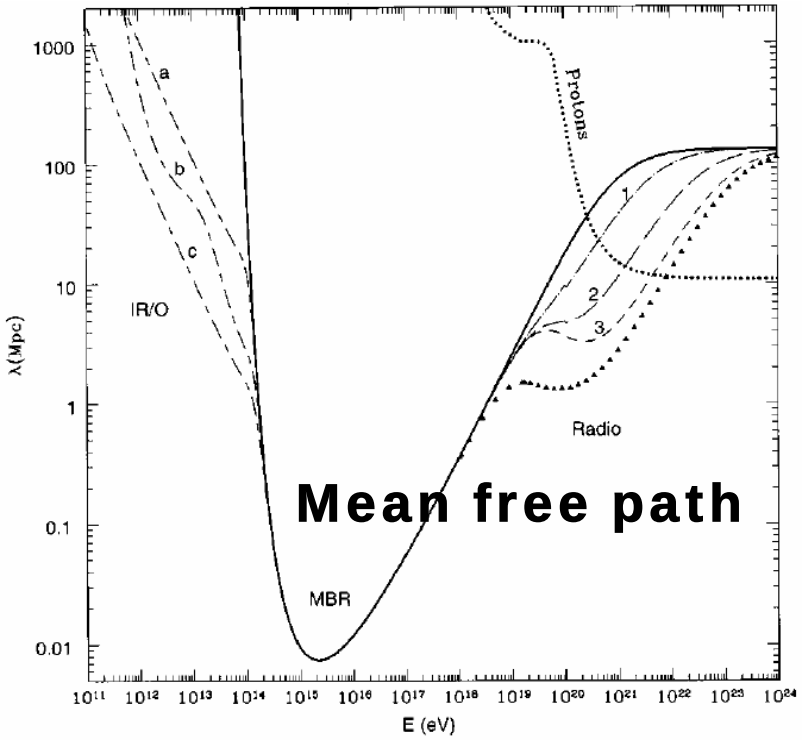
$$\sigma(\beta) \sim 1.25 \cdot 10^{-25}(1-\beta^2) \cdot \left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \mathrm{cm}^2$$

Heitler 1960

maximal for: $\epsilon \simeq \frac{2m_e^2c^4}{E} \simeq \left(\frac{500\,\mathrm{GeV}}{E}\right)\mathrm{eV}$

- For γ–rays, relevant background component is optical/infrared (EBL)
- different models for EBL: minimum density given by cosmology/star formation

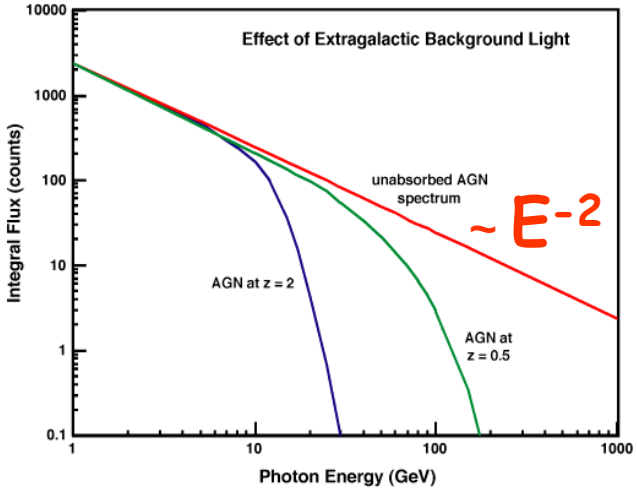




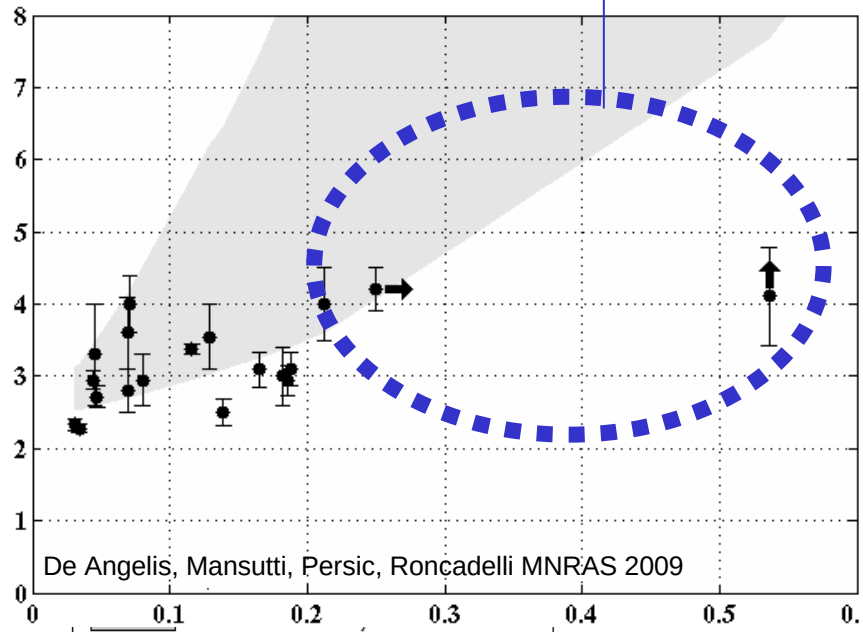
Are our AGN observations consistent with theory?

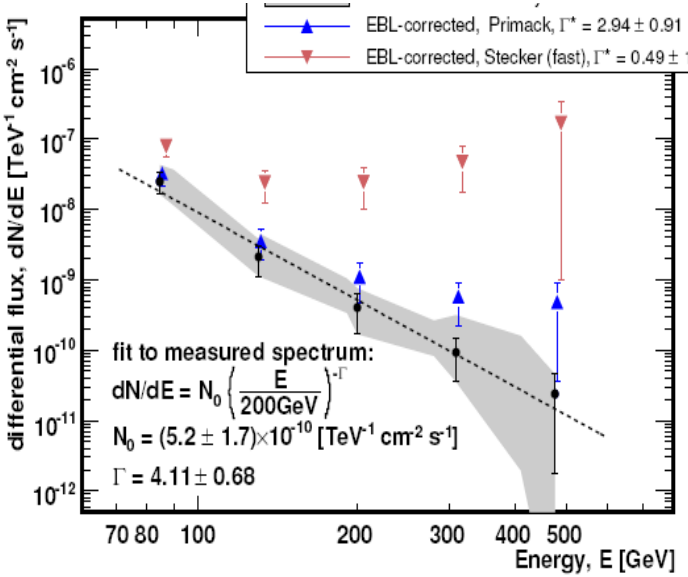
Selection bias?
New physics ?

Measured spectra affected by attenuation in the EBL:



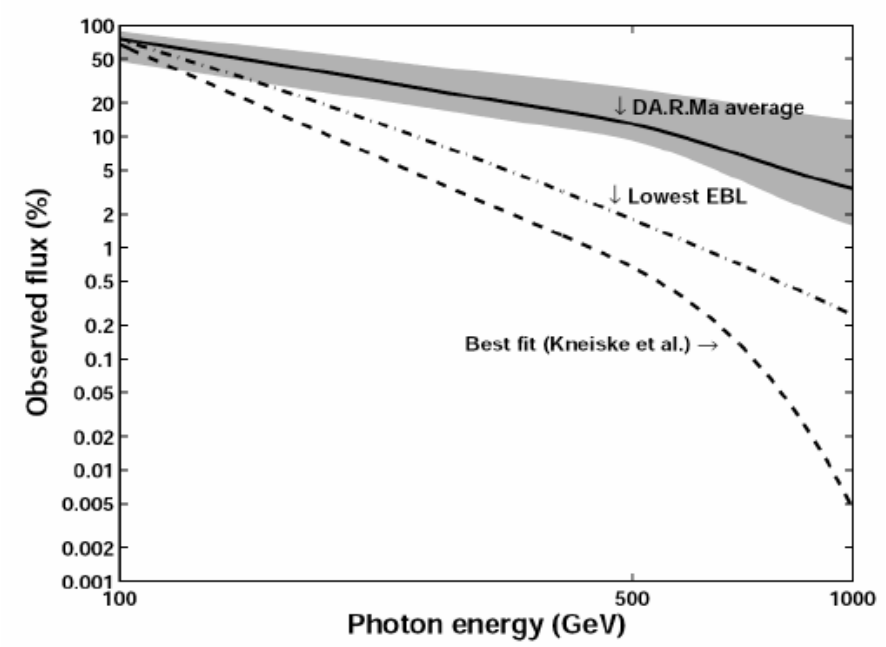
observed spectral index

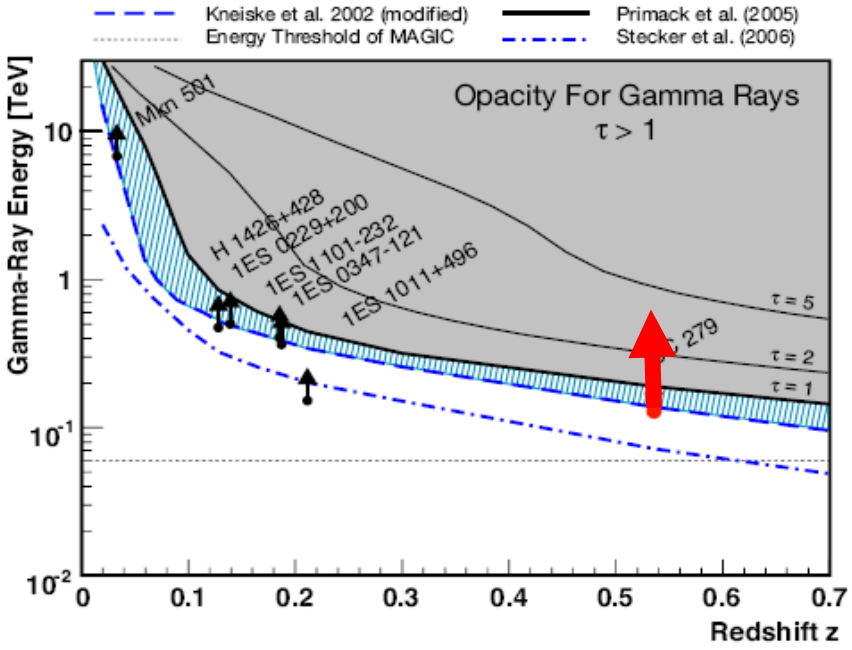




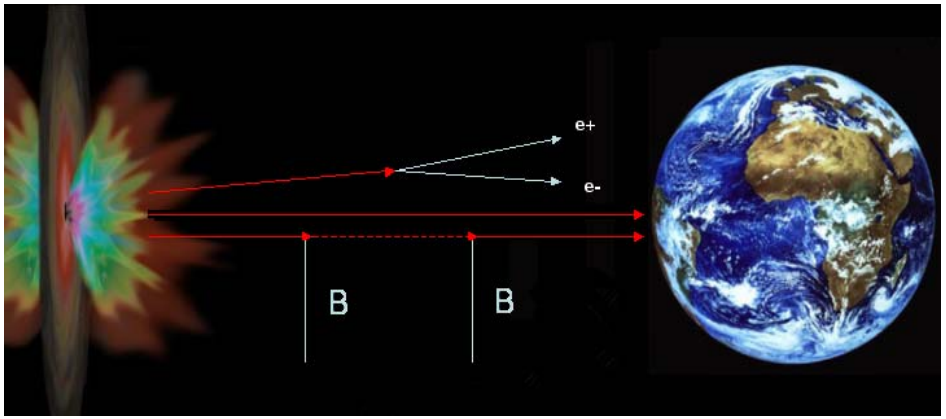
The most distant:
MAGIC 3C 279 (z=0.54)

Could it be seen?





- Explanations go from the standard ones
  - very hard emission mechanisms with intrinsic slope < 1.5 (Stecker 2008)
  - Very low EBL
- to possible evidence for new physics
  - Interaction with a new light "axion"? (DA, Roncadelli & MAnsutti [DARMA], PLB2008, PRD2008)
    - Axion emission (Hooper et al., PRD2008)

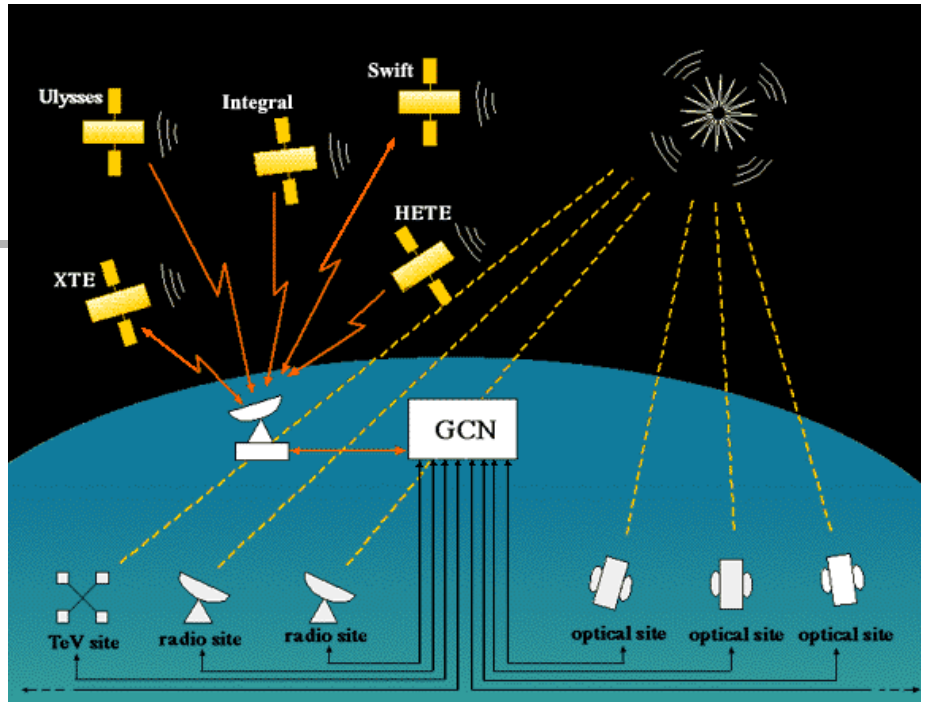


We are (maybe) making two extraordinary claims

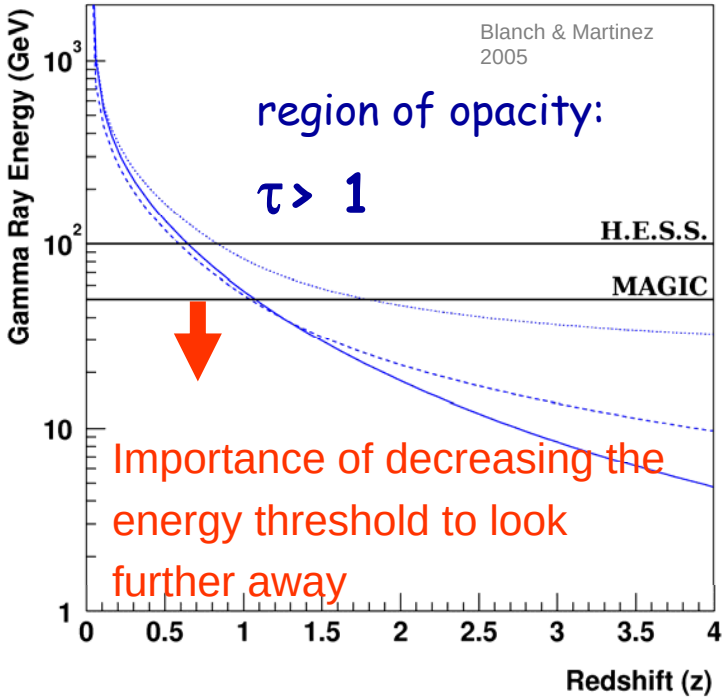
- A possible relation between arrival time and energy
- A signal from sources far away hardly compatible with EBL

- We should keep in mind that
  - Extraordinary claims require extraordinary evidence
    - New Scientist, SciAm blog/news, …, and then?
  - Claims must be followed up
    - If we see this in such sources, what else do we expect?
    - Fundamental implications of unexpected findings?
    - Are we seeing a part of the same big picture?

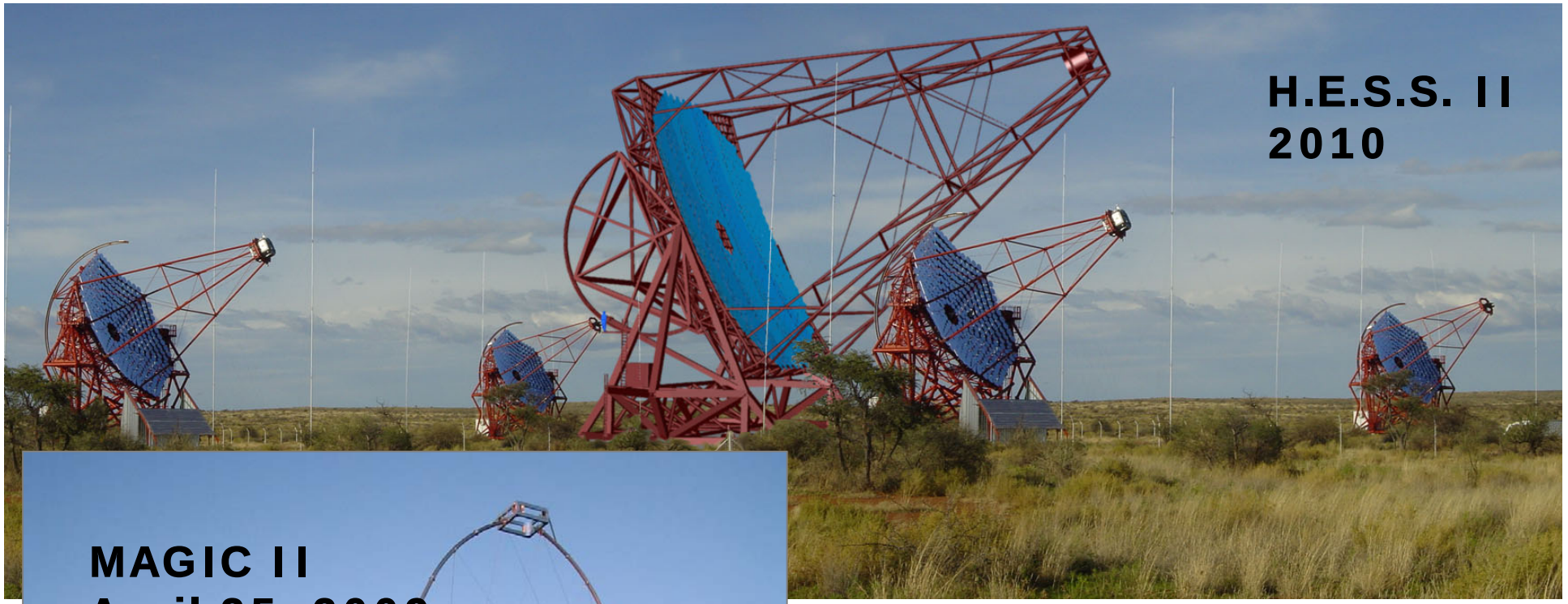
GRBs
Another probe



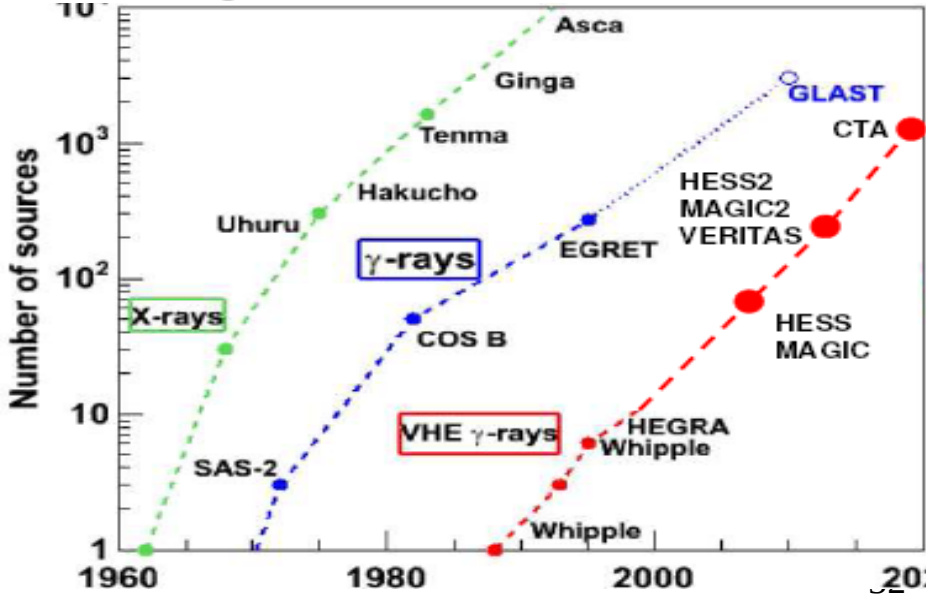
- Interesting for astrophysical reasons, for propagation physics, for rapid variability-LIV
- MAGIC is the best instrument, due to its fast movement & low threshold
  - MAGIC is in the GCN Network
  - GRB alert active since Apr 2005
- Also MILAGRO...



No VHE γ emission from GRB positively detected yet...
(all other observed GRB very short or at very high z)



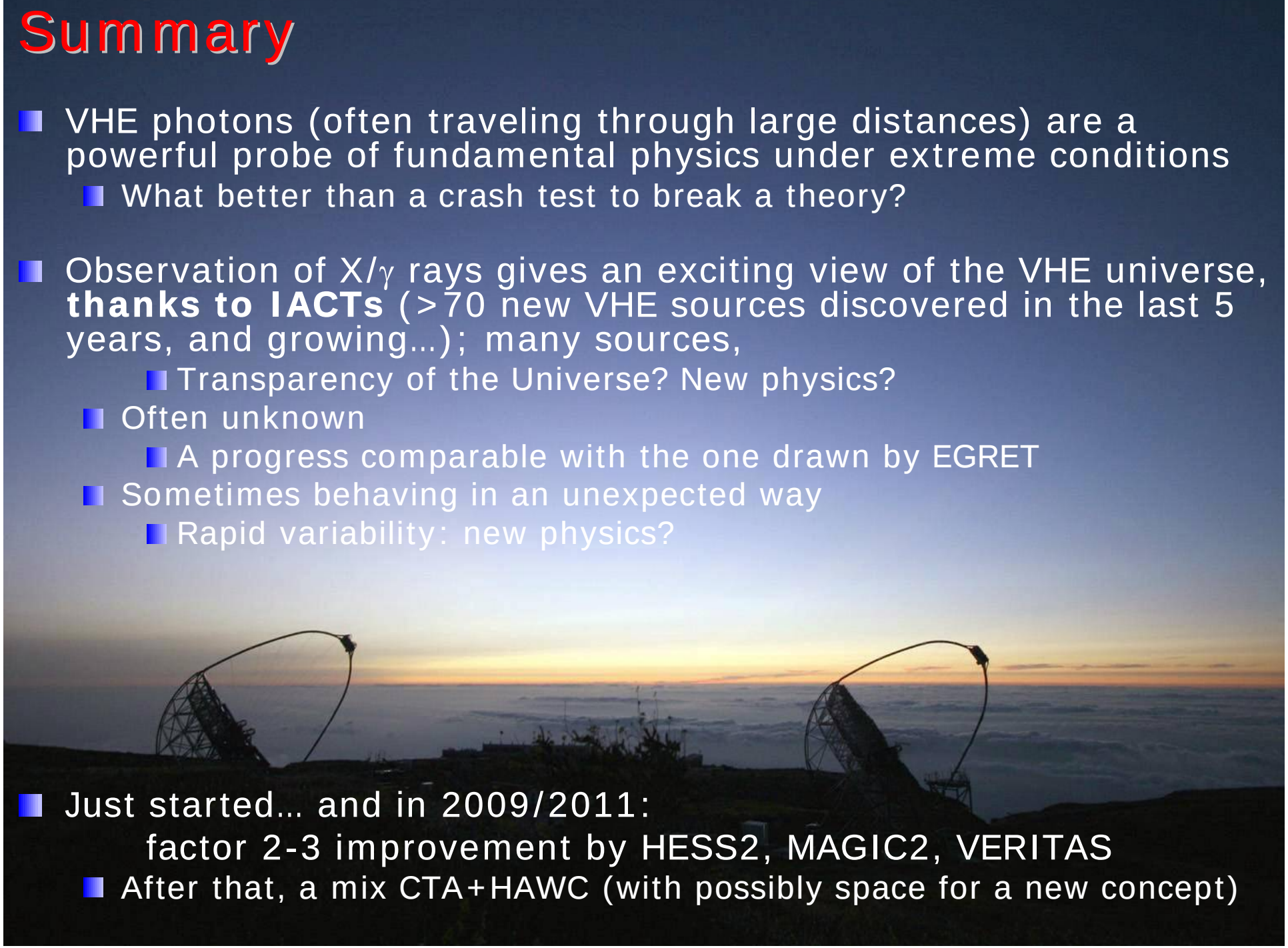
Longer-term future



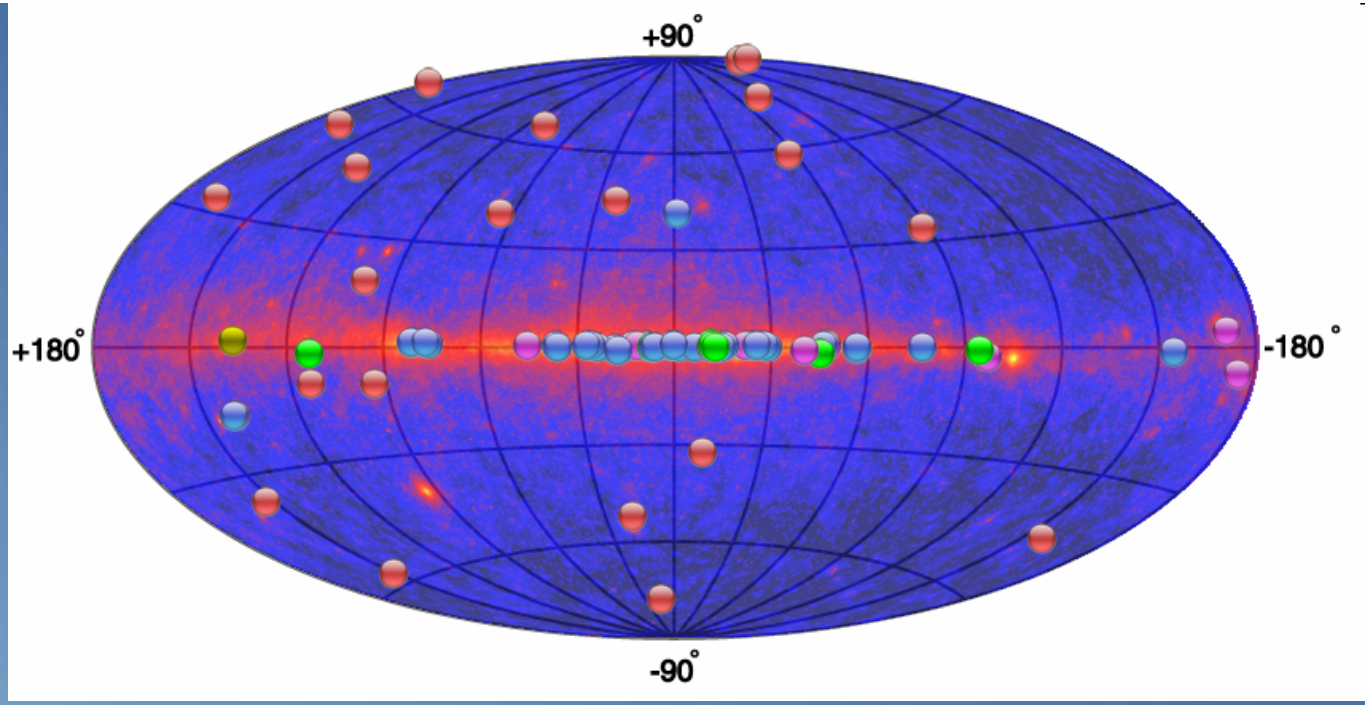
Summary

- VHE photons (often traveling through large distances) are a powerful probe of fundamental physics under extreme conditions
  - What better than a crash test to break a theory?

- Observation of X/γ rays gives an exciting view of the VHE universe, **thanks to IACTs** (>70 new VHE sources discovered in the last 5 years, and growing…); many sources,
    - Transparency of the Universe? New physics?
  - Often unknown
    - A progress comparable with the one drawn by EGRET
  - Sometimes behaving in an unexpected way
    - Rapid variability: new physics?



- Just started… and in 2009/2011:
  factor 2-3 improvement by HESS2, MAGIC2, VERITAS
  - After that, a mix CTA+HAWC (with possibly space for a new concept)



Come to La Palma for the MAGIC2 first light (April 24/25)

Comparison between the “big 4”

Instrument	Lat. (°)	Long. (°)	Alt. (m)	Tels.	Tel. Area (m^2)	Total A. (m^2)	FoV (°)	Thresh. (TeV)	Sensitivity (% Crab)
H.E.S.S.	−23	16	1800	4	107	428	5	0.1	0.7
VERITAS	32	−111	1275	4	106	424	3.5	0.1	1
MAGIC	29	18	2225	1	236	236 (472)(*)	3.5	0.05	1.6 (0.8)
CANGAROO-III	−31	137	160	3	57.3	172	4	0.4	15