Very High Energy γ-ray Astronomy: Status as of early 2008

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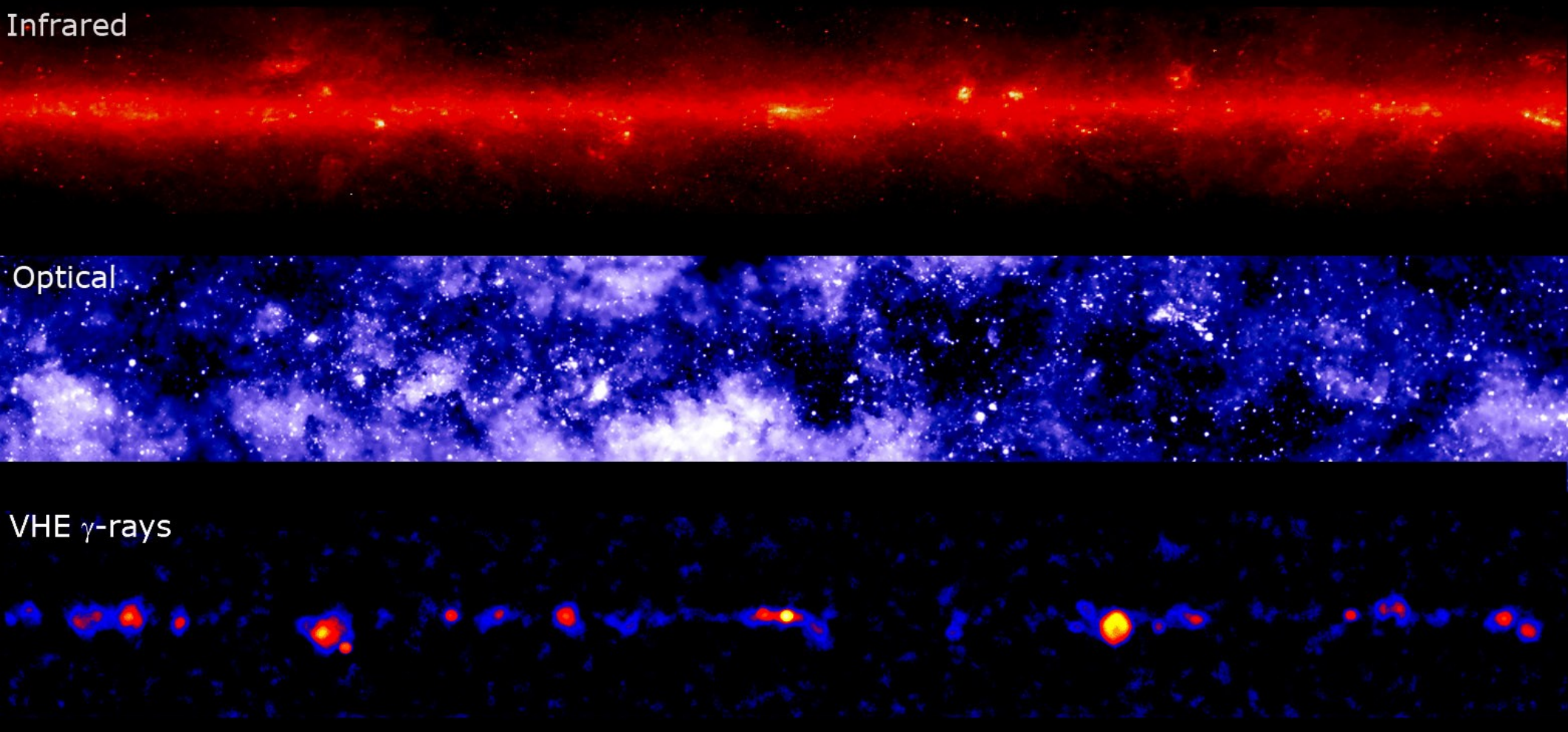
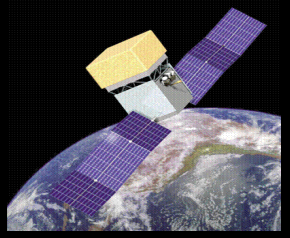


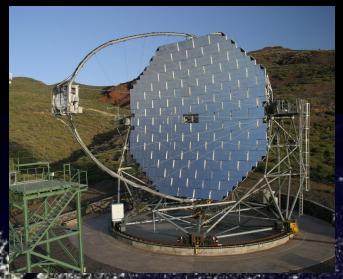
Current VHE γ-ray Instruments



MILAGRO

STACEE

MAGIC

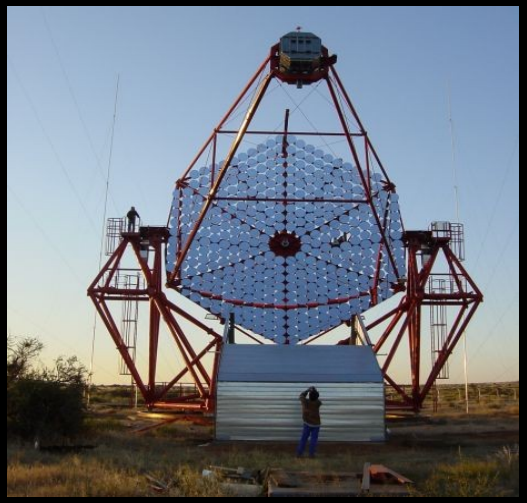


TIBET

Current VHE γ-ray Instruments

High Sensitivity

HESS, MAGIC, CANGAROO, VERITAS



Energy Range .05-50 TeV
Area > 10^4 m^2
Background Rejection > 99%
Angular Resolution 0.05°
Aperture 0.003 sr
Duty Cycle 10%

High Resolution Energy Spectra
Studies of known sources
Surveys of limited regions of sky

Low Energy/Large Aperture

EGRET/GLAST

Energy Range 0.1-100 GeV
Area: 1 m^2
Background Free BUT diffuse γ
Angular Resolution 0.1° – 0.3°
Aperture 2.4 sr
Duty Cycle > 90%

Unbiased Sky Survey (<100 GeV)
Extended Sources
Transients (AGN, GRBs) <100 GeV
Simultaneous ν Observations

Large Aperture/High Duty Cycle

Milagro, Tibet, ARGO, HAWC

Energy Range 1-100 TeV
Area > 10^4 m^2
Background Rejection > 95%
Angular Resolution 0.3° - 0.7°
Aperture > 2 sr
Duty Cycle > 90%

Unbiased Sky Survey
Extended Sources
Transients (GRB's)
Simultaneous ν Observations

Adapted from G. Sinnis/ CTA Workshop APC-Paris

Outline

Focus on recent and/or most interesting (astrophysics) discoveries

Evolution of the VHE field

GALACTIC sources, physics topics

EXTRAGALACTIC sources, topics

Will not cover :

AGN Multiwave-length campains

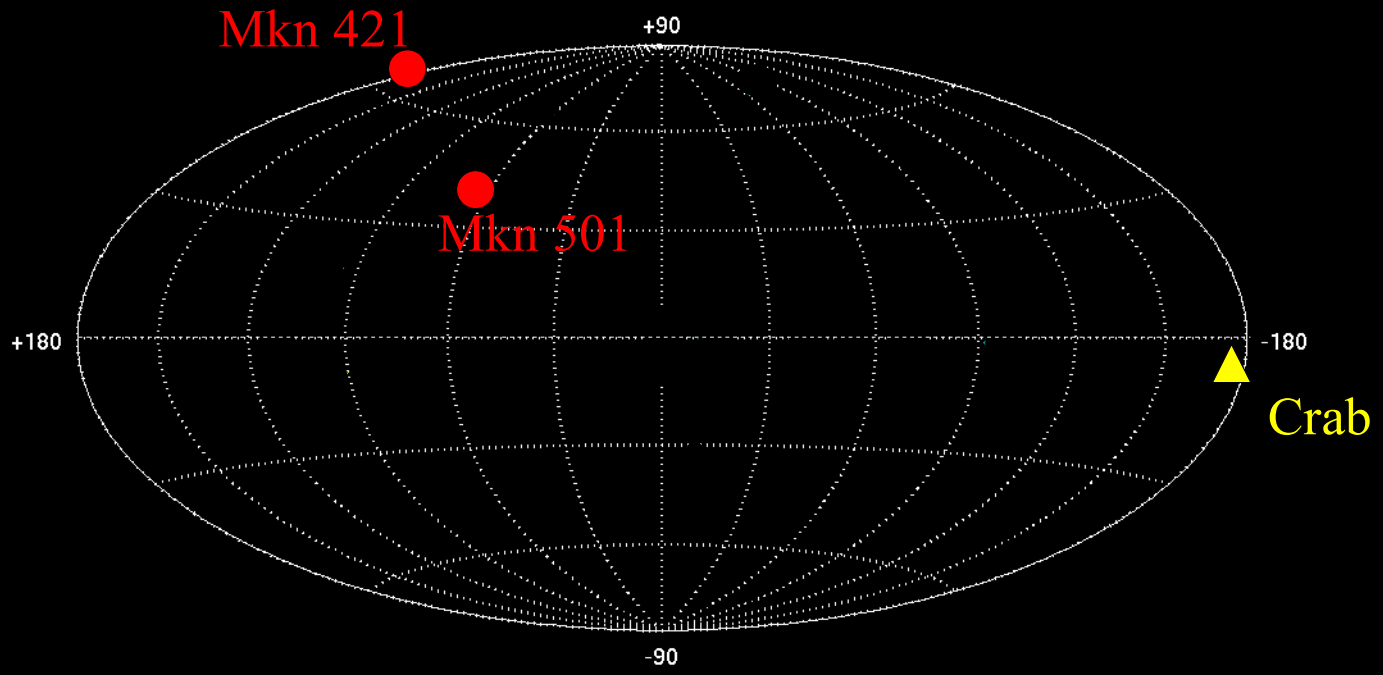
Neutrino expectations (one word on young SNRs)

GRB's

Lorentz Invariance Violation & QG UIs

TeV Sky 1995

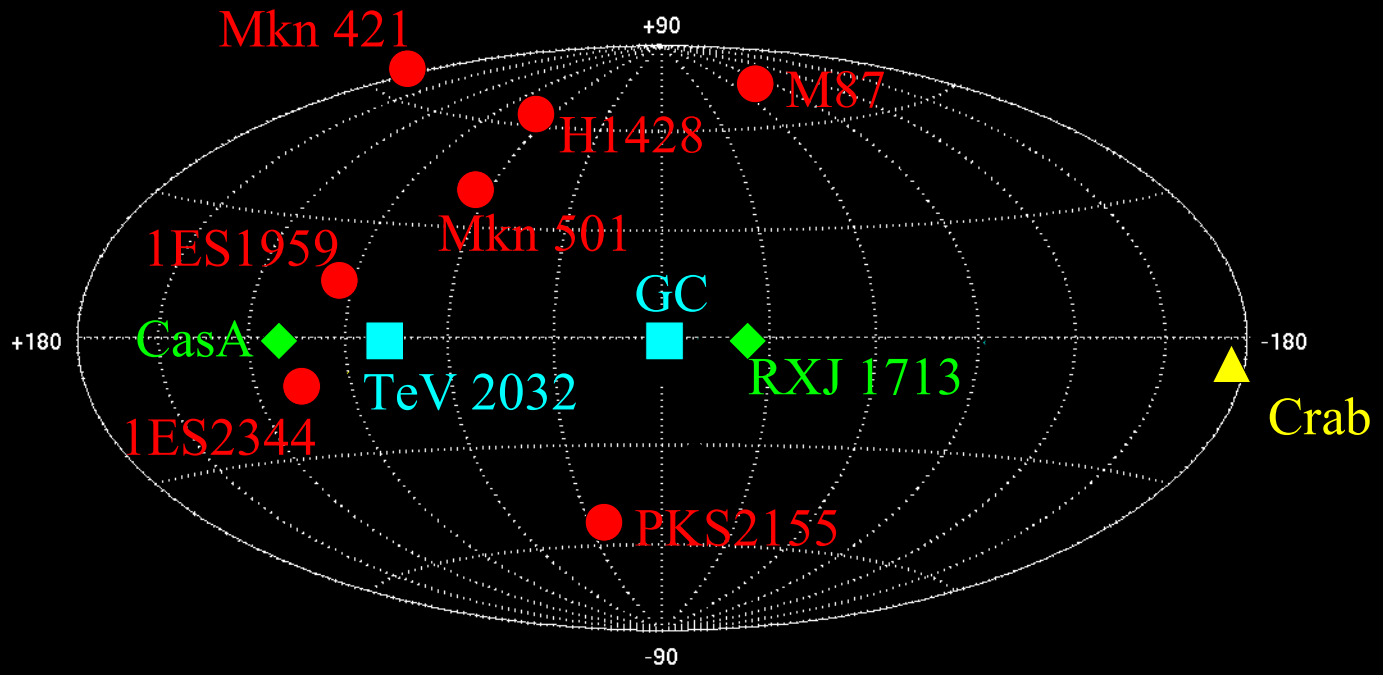
3 sources



▲ Pulsar wind nebulae
● AGNs
◆ SNRs
■ UIDs

TeV Sky 2003

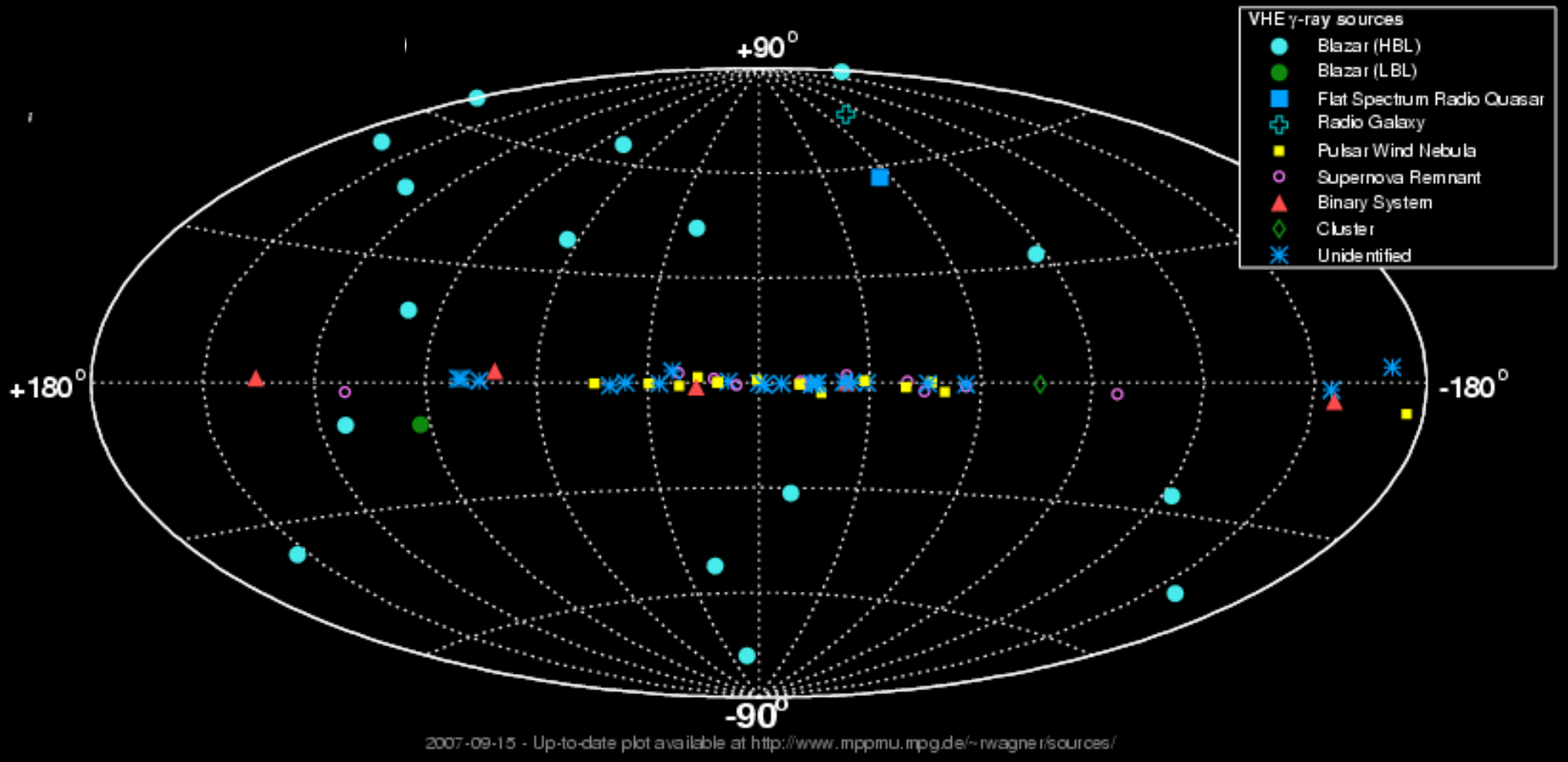
12 sources, 6 firm detections



Pulsar wind nebulae
AGNs
SNRs
UIDs

TeV Sky 2008

> 70 Sources



VHE γ-ray sources

A wealth of new sources of different types → many science topics:

GALACTIC :

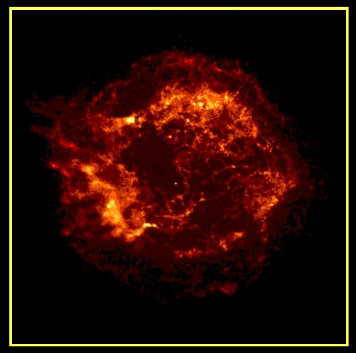
- Young Shell type Supernova Remnants (a word on expected neutrinos)
- Older and/or Interacting SNRs
- Composite SNRs
- Pulsar Wind Nebulae (PWN)
- Binary Systems (LS 5039, LSI +61 303)
- Variable PWN in binary
- Open Stellar Clusters
- Galactic Center
- Galactic diffuse emission
- Unidentified sources ...

EXTRAGALACTIC :

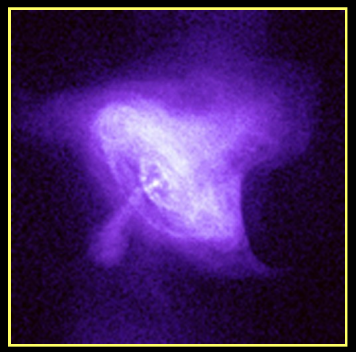
- Blazars
- Radiogalaxies (FRII: M87+?)
- Flat Spectrum Radio Quasars (3C 273, recent)
- Extragalactique Background Light (EBL)
- Multiwave-length campains
- Starburst Galaxies (UL)
- GRBs (UL)
- ...

Science topics

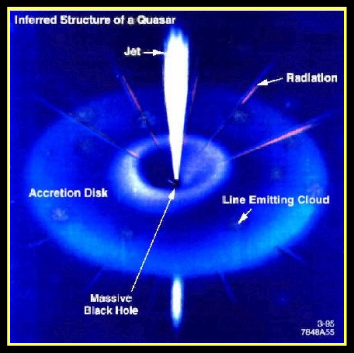
Origin of cosmic rays



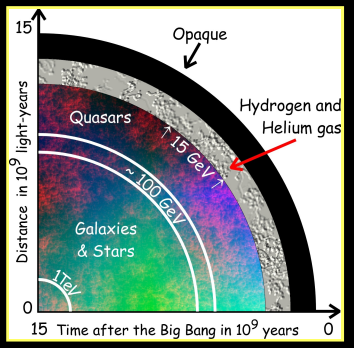
SNRs



Pulsars and PWN

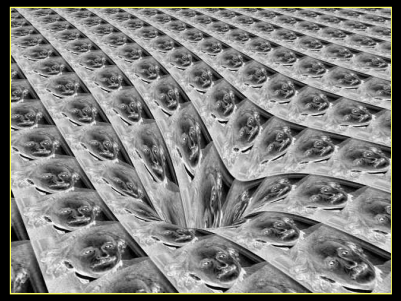


AGNs

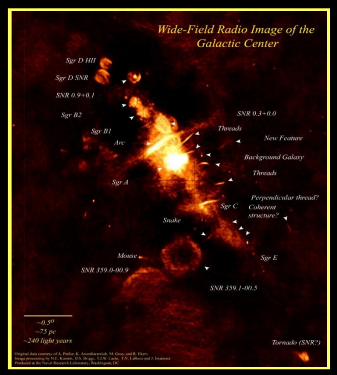


Cosmology

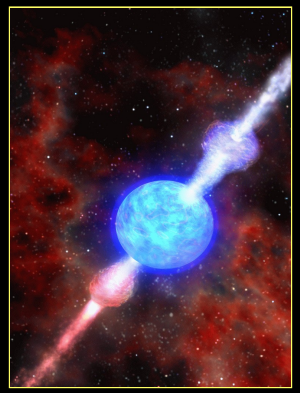
Space-time & relativity



Dark matter



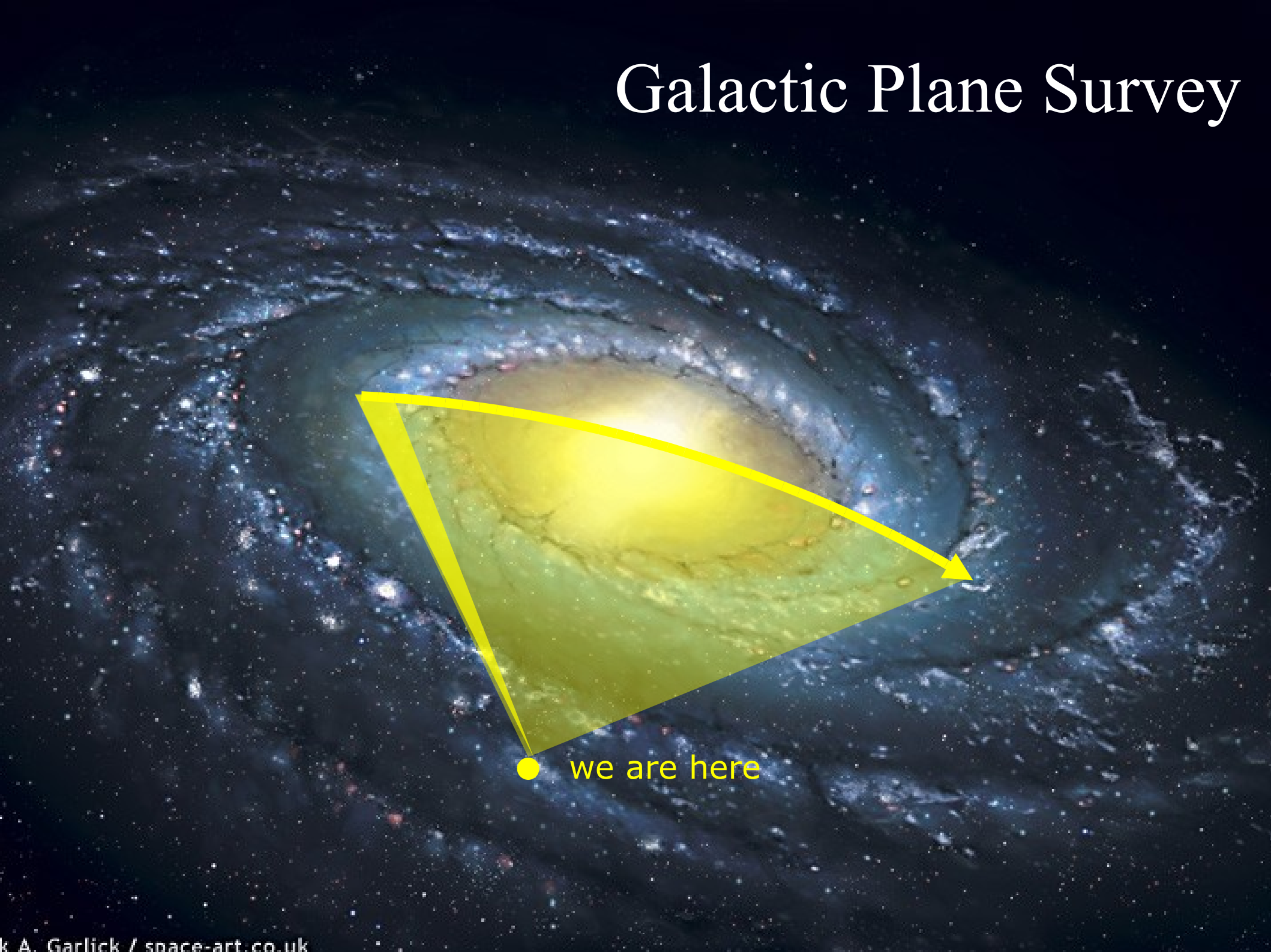
GRBs

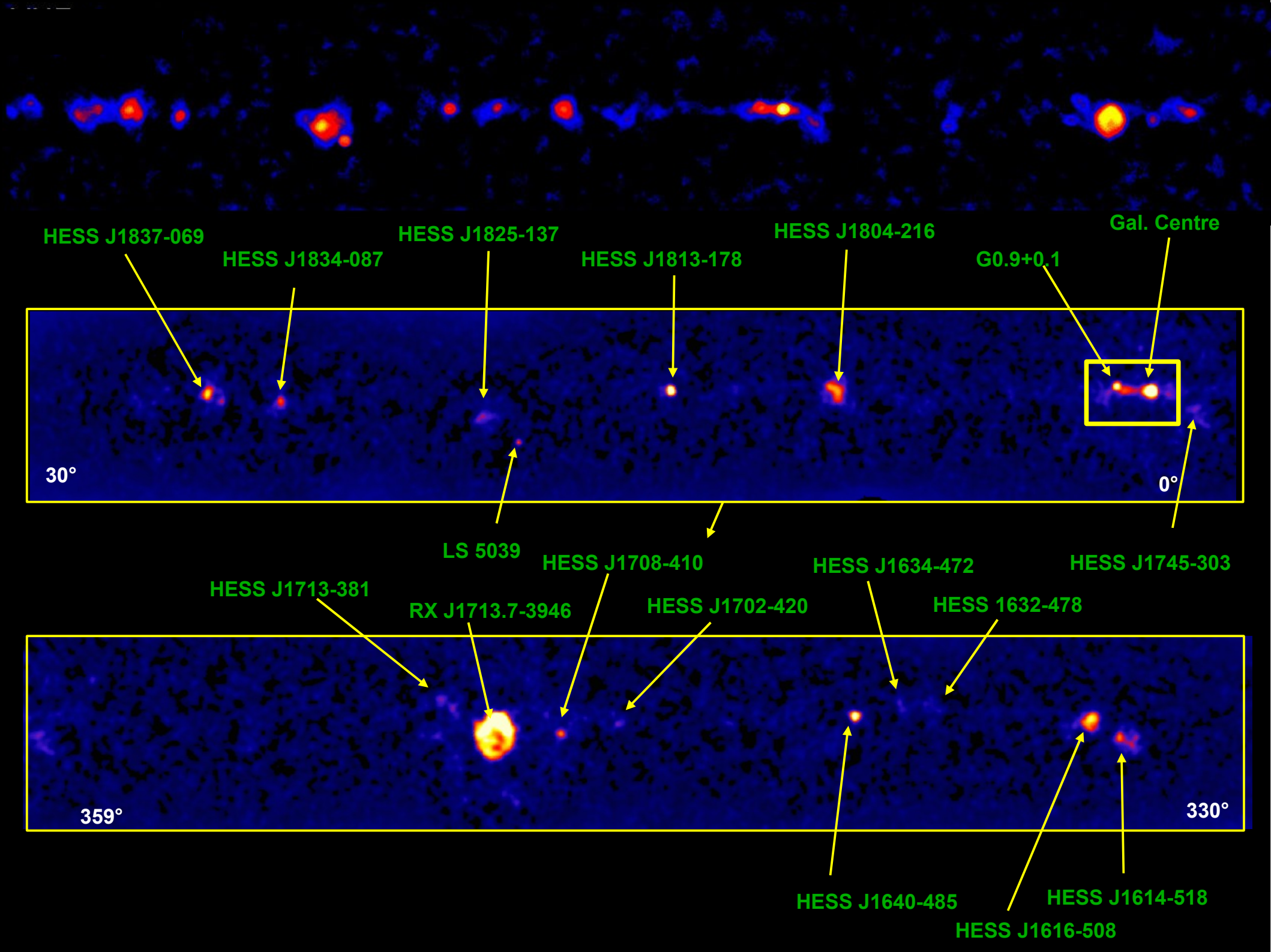


2004-2007
Galactic plane survey
by HESS

Key location: Namibia

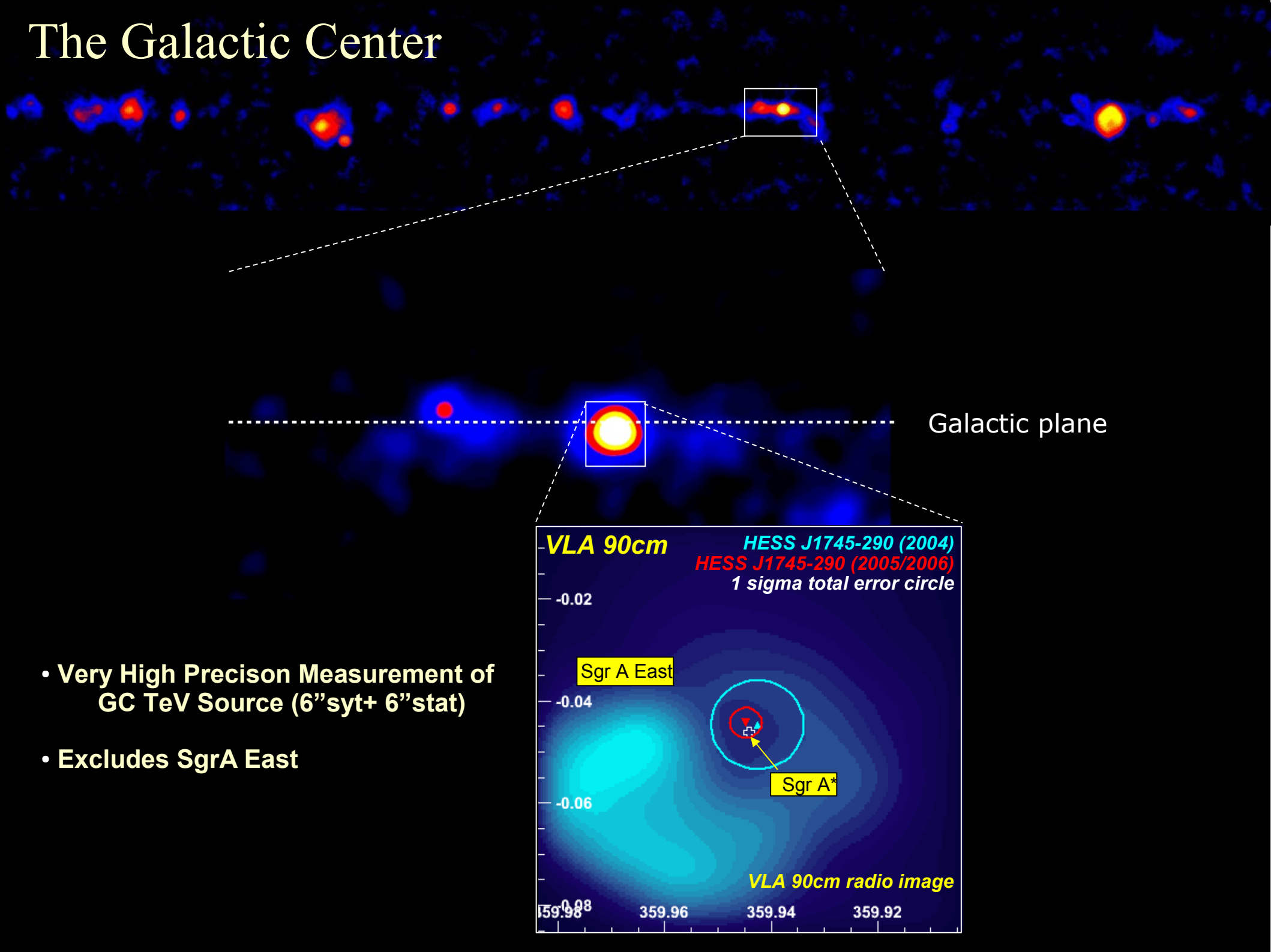
Galactic Plane Survey




HESS J1837-069
HESS J1834-087
HESS J1825-137
HESS J1813-178
HESS J1804-216
G0.9+0.1
Gal. Centre
30°
0°
LS 5039
HESS J1708-410
HESS J1634-472
HESS J1745-303
HESS J1713-381
RX J1713.7-3946
HESS J1702-420
HESS 1632-478
359°
330°
HESS J1640-485
HESS J1614-518
HESS J1616-508

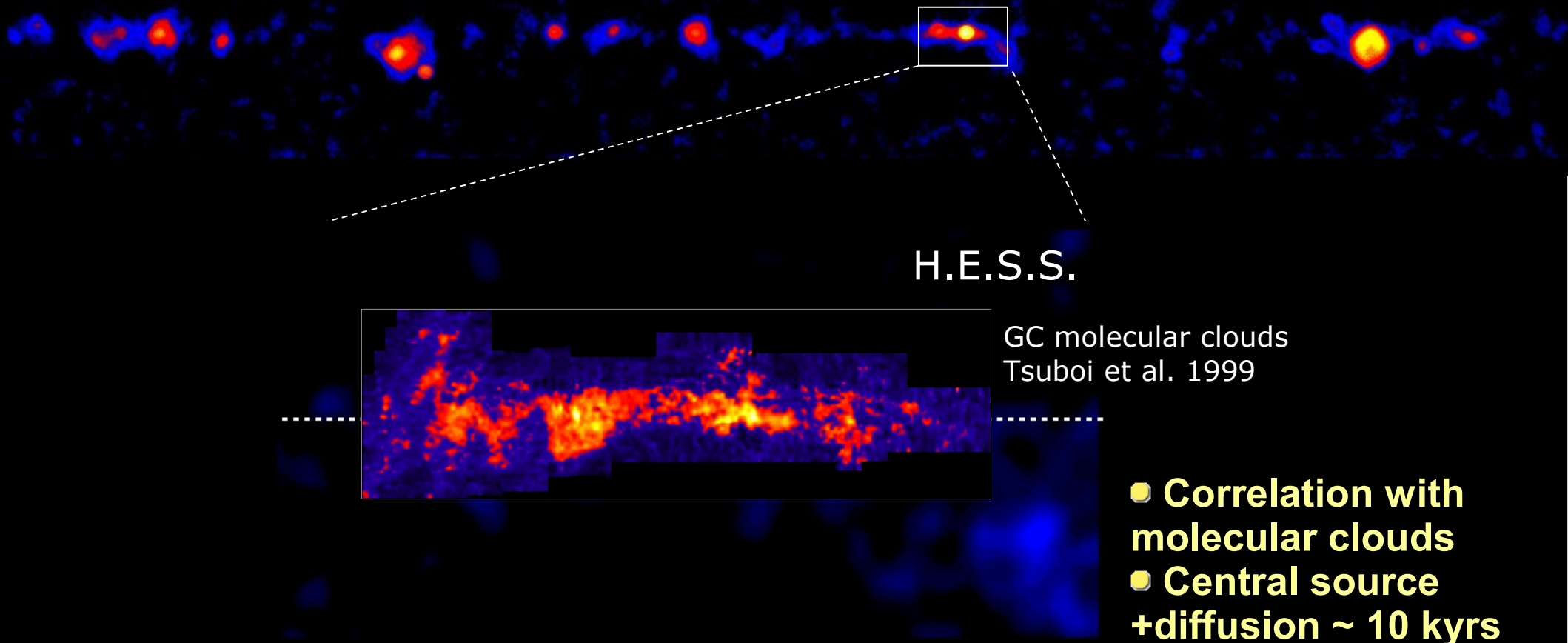

The Galactic Center

The Galactic Center

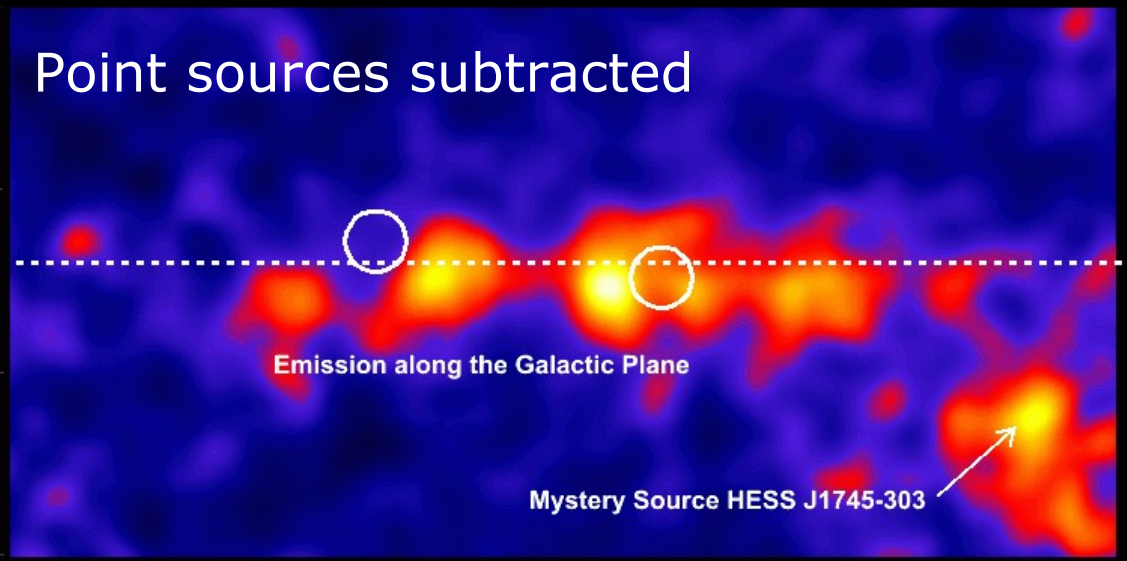


- **Very High Precison Measurement of GC TeV Source (6”syt+ 6”stat)**
- **Excludes SgrA East**

The Galactic Diffuse emission @ central 100 pc

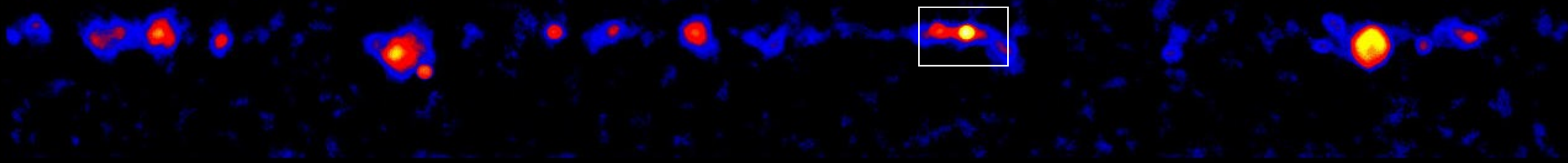


- **Correlation with molecular clouds**
- **Central source +diffusion ~ 10 kyrs**



- **HESS flux implies**
  Higher CR density
  Harder spectrum

ORIGIN OF GC TeV Gamma-Rays?

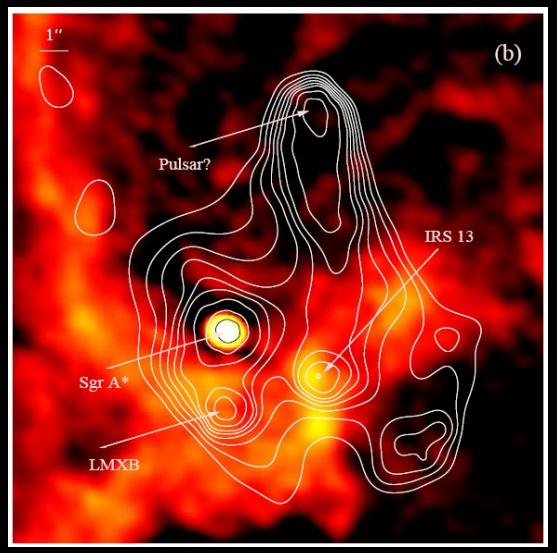


Normal :
- Curvature radiation of UHE protons near SgrA* ?
- Shocks in SgrA* accretion flow or wind?
- Decaying UHE neutrons?
- The PWN G359.95-0.04?

Top down:
- Annihilation of dark matter particles

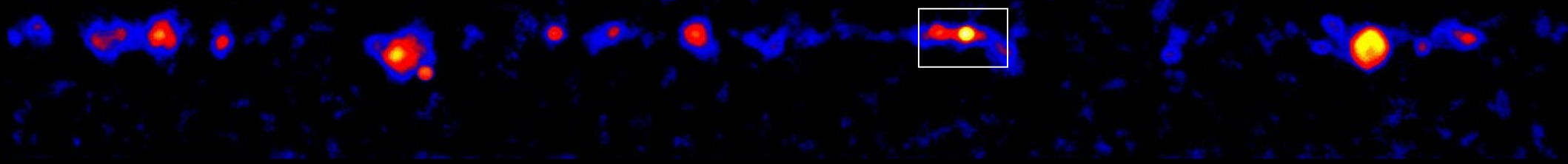
$\chi\chi \rightarrow qq, gg$

Spectrum?

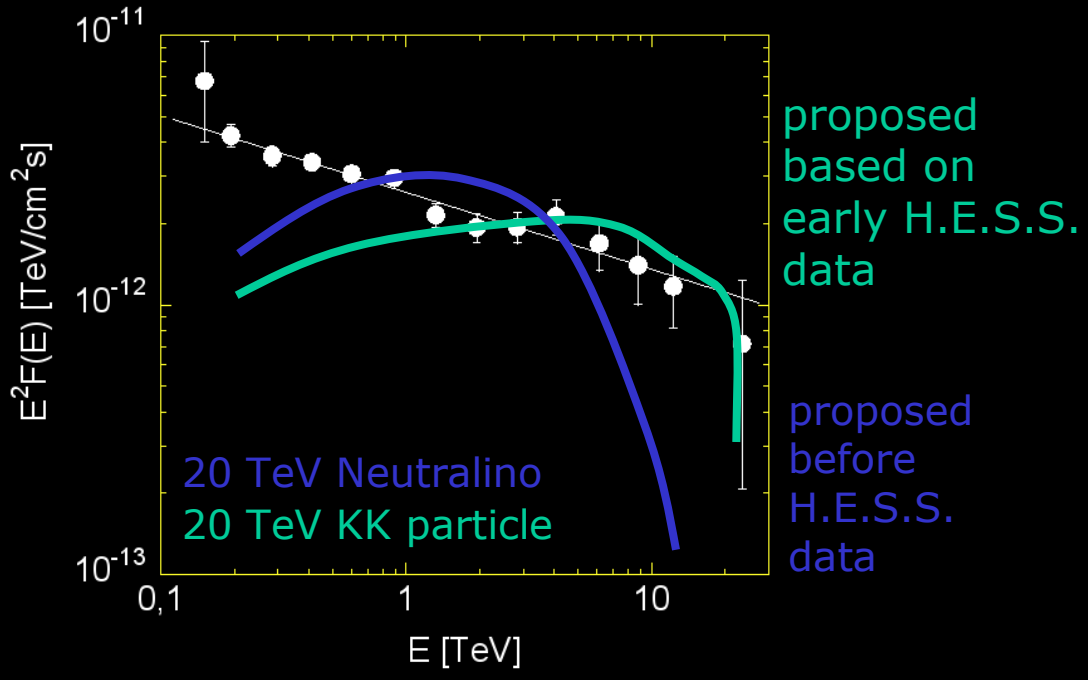


Chandra contours
Weng et al. 2005

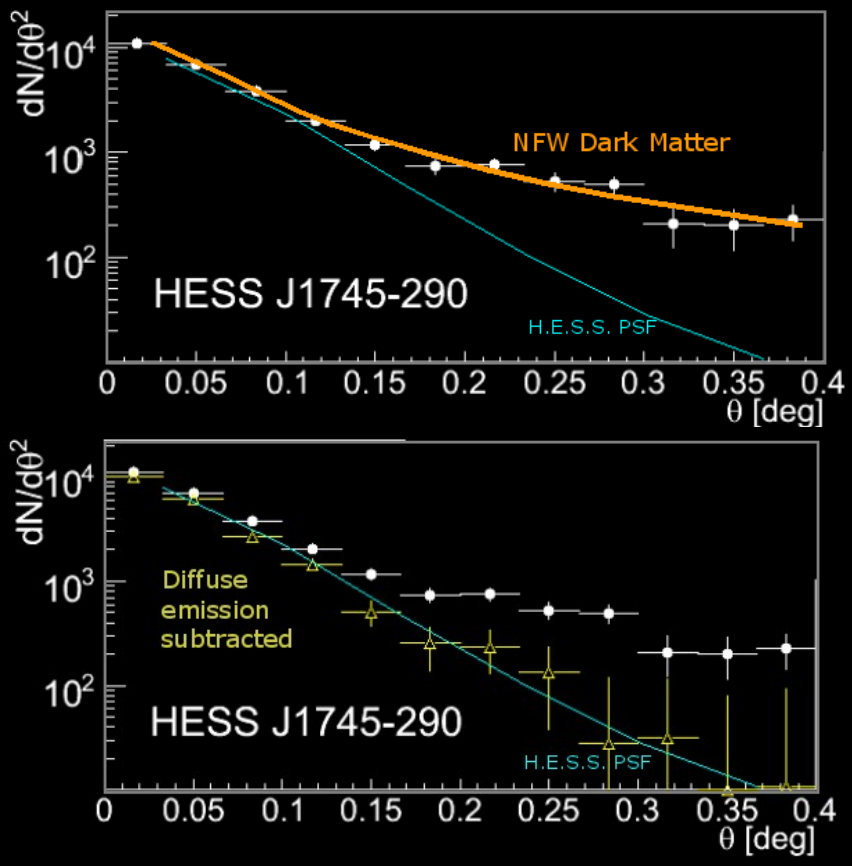
ORIGIN OF GC TeV Gamma-Rays?



Top down:
- Annihilation of dark matter particles
- $\chi\,\chi \rightarrow qq,\ gg$
- Spectrum?

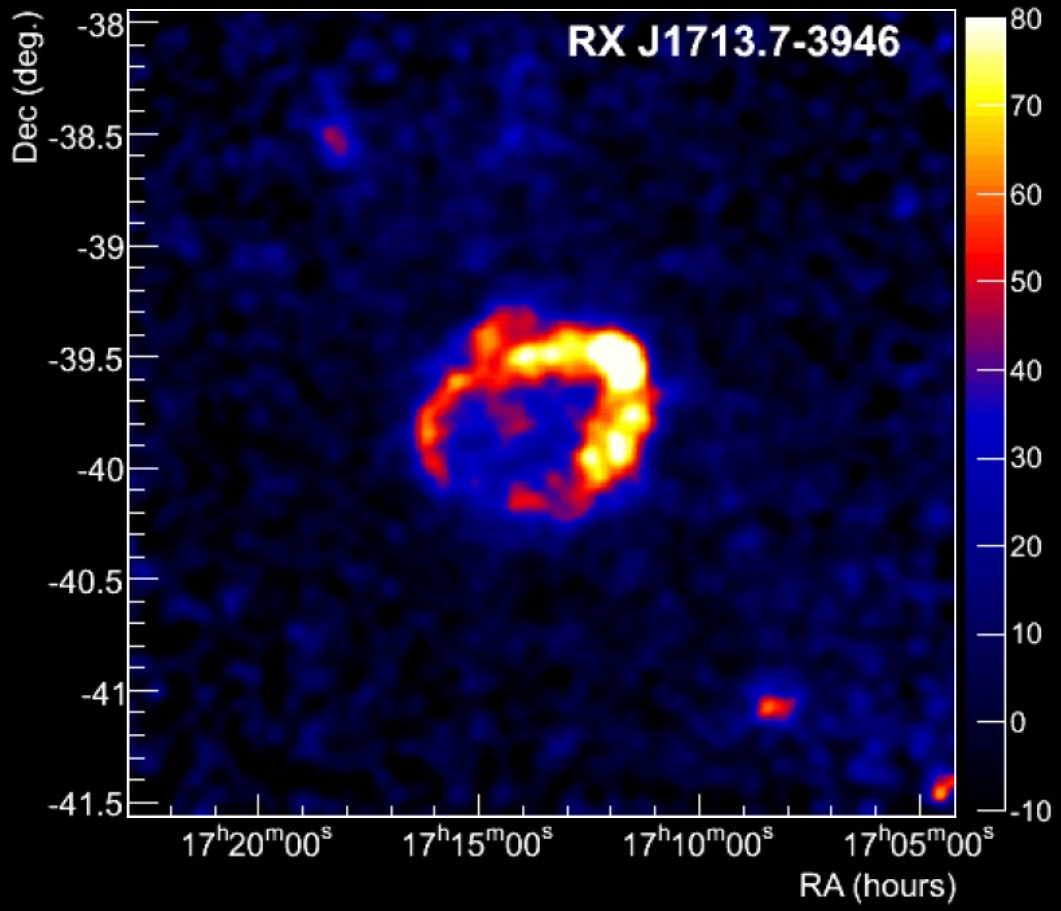


- Angular distribution?

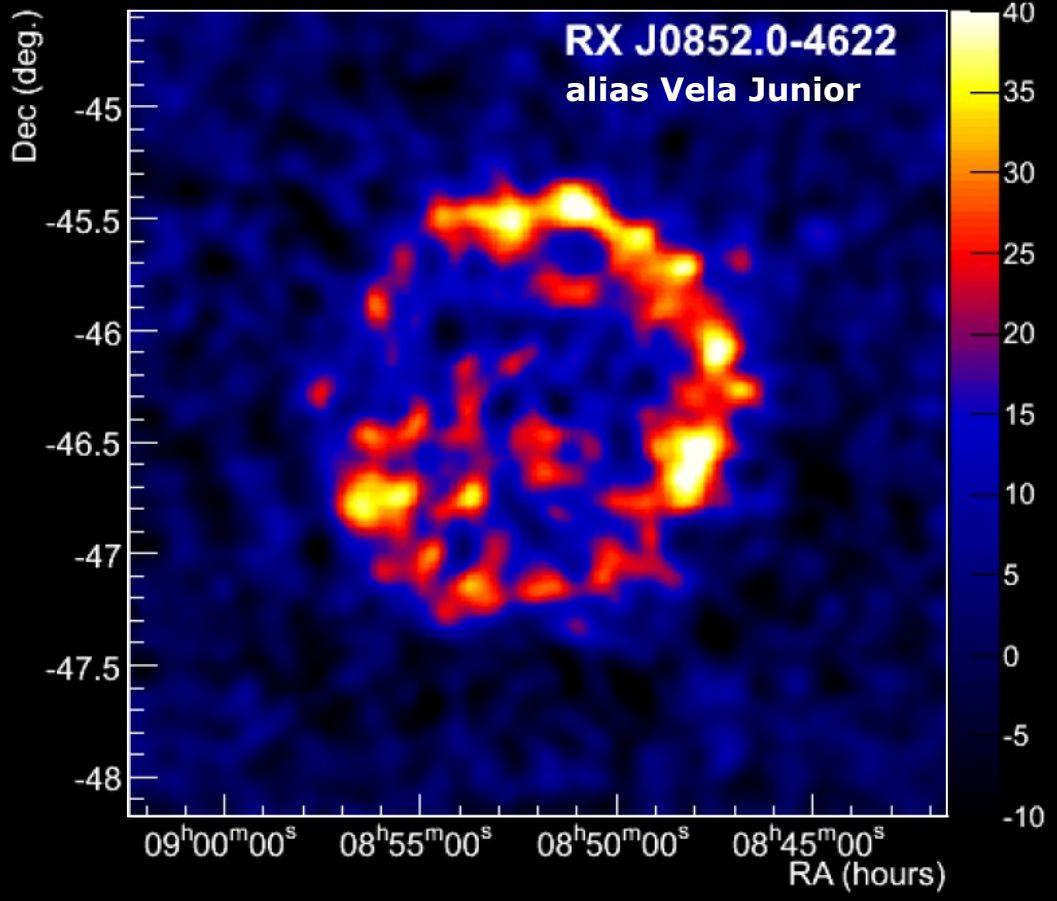


Young Shell type SNRs

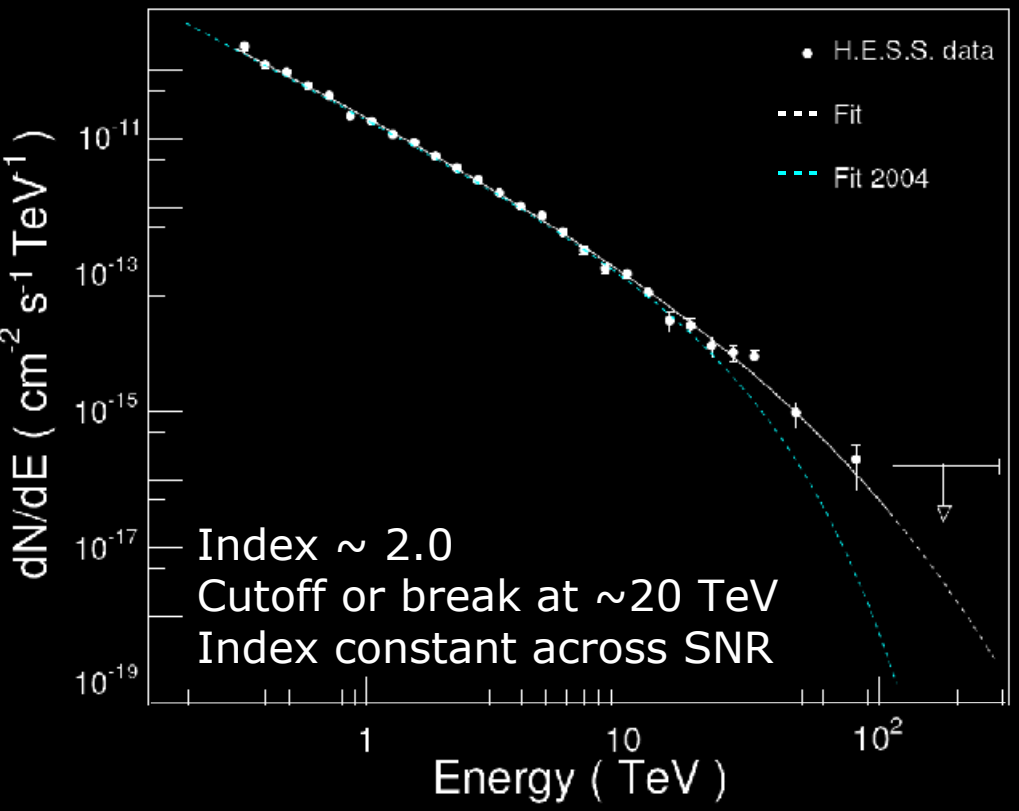
RX J1713.7-3946
First-ever resolved γ-ray source
Strong correlation with X-rays: ~80%



RX J0852.0-4622 (Vela jr)
Thin shell resolved with HESS
Correlation with X-rays: ~65%
+ Correlation with Radio

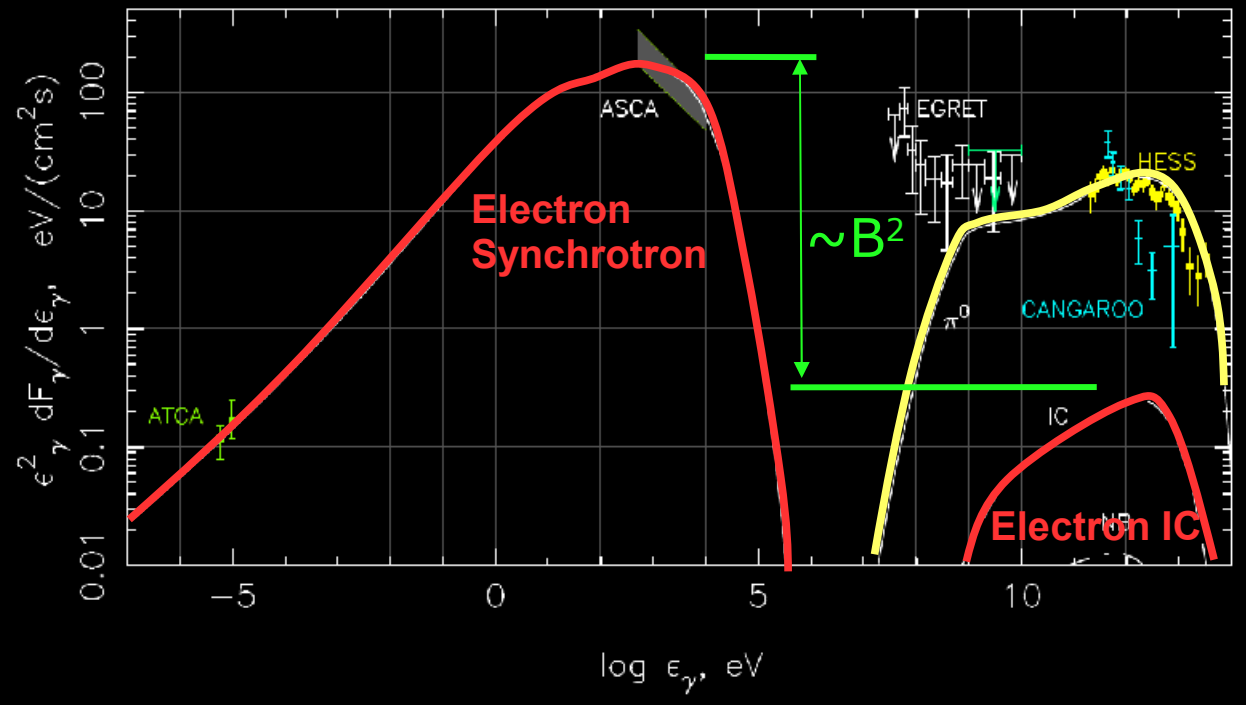


RX J1713.7-39.46 : high energy spectrum end?



- **Higher Statistics : E > 40 TeV**
- **Particles up to >100 TeV**
- **If hadrons**
  primary energy >200 TeV
- **If leptons**
  primary energy >100 TeV (KN)

Hadronic vs Leptonic emission: B-field strength



B = 126 μG
e/p = 10^{-4}

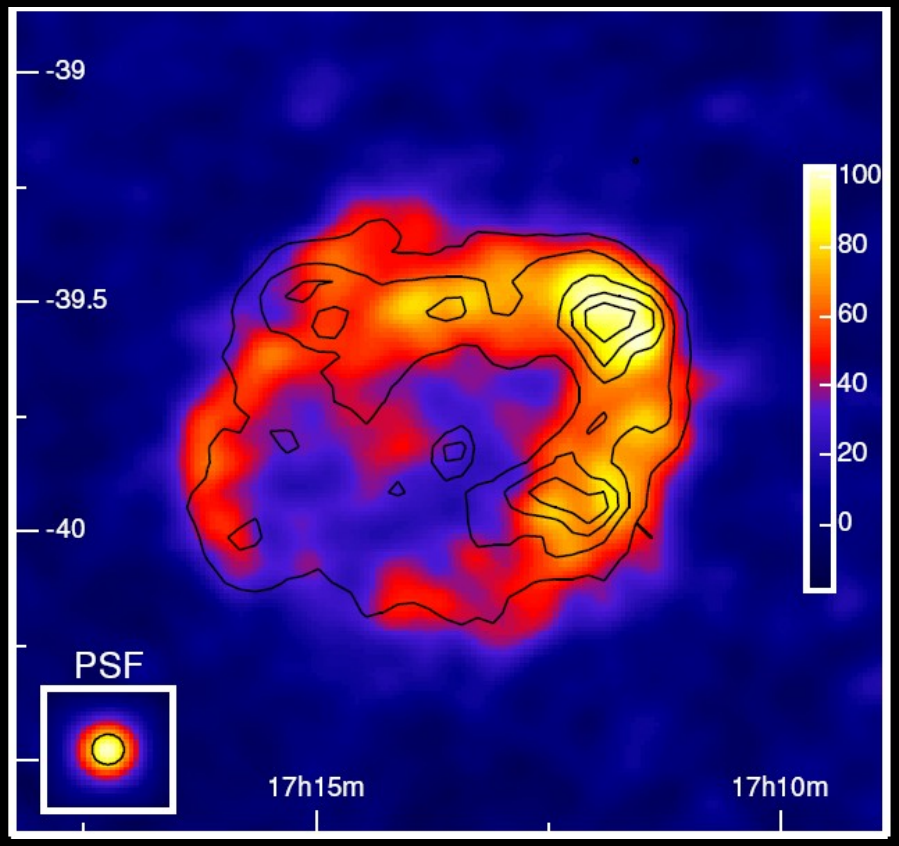
B ~10 μG

d = 1 kpc
E = $1.8 \cdot 10^{51}$ erg
M = 3.5 $M_\odot$
ρ(r) = 0.01 … 10 /cm³

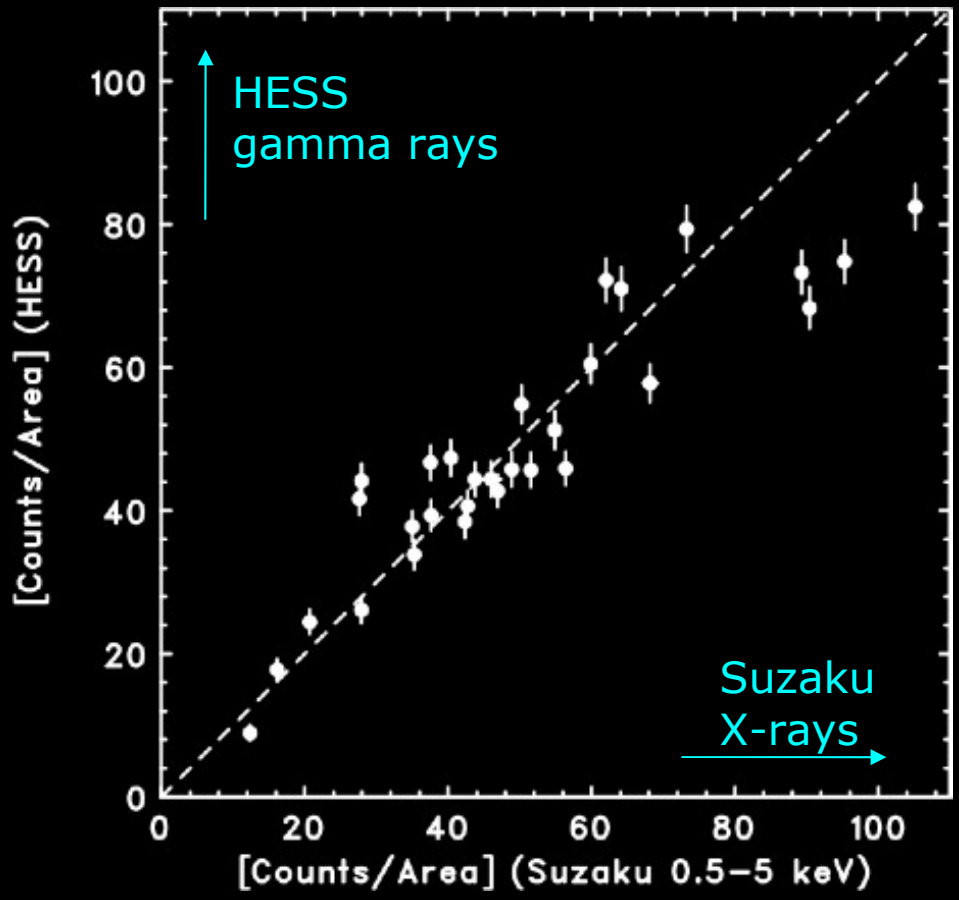
- **High B-fields suppress IC emission**
- **Non-linear effects of efficient CR acceleration can lead to B-field amplification (e.g. thin filaments in SN1006)**

- **Real Question : what proportion of leptons/hadrons i.e. hybrid modelling**

X-ray vs γ-ray correlations



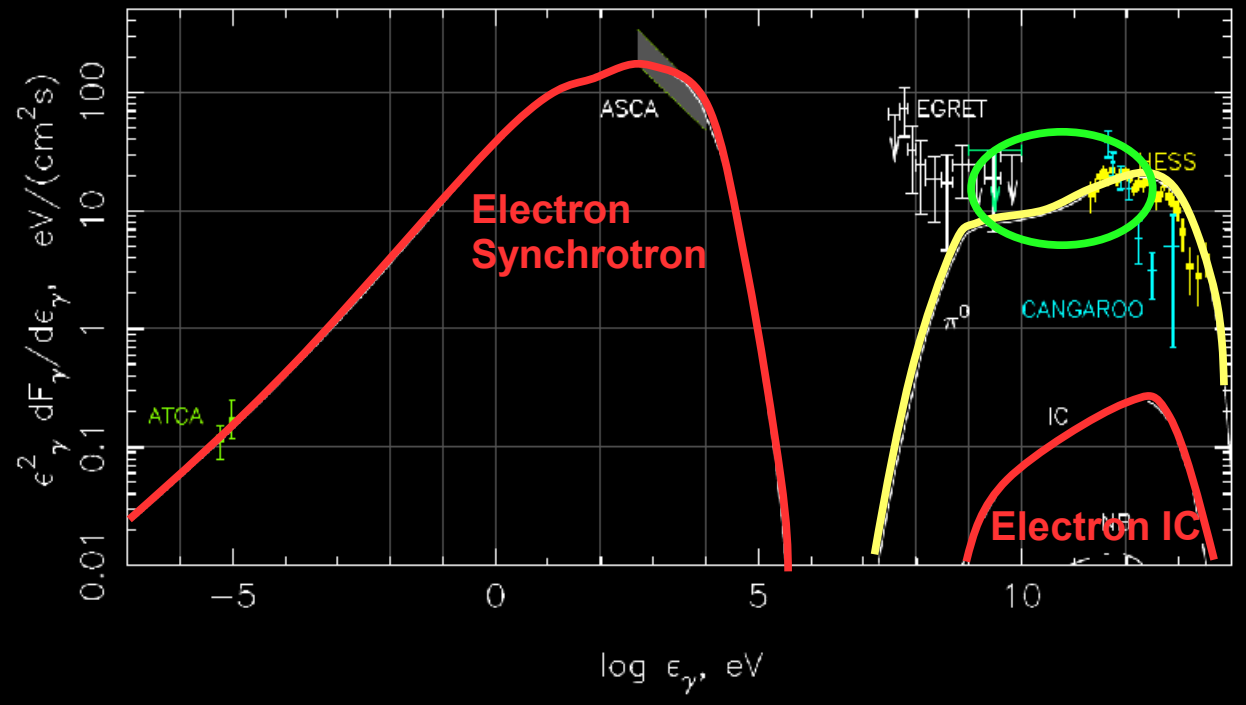
Contour lines: ASCA X-rays
Y. Uchiyama et al. 2002



- Very close morphologies for X-ray & γ-ray
- 80% Correlation
- What does that mean? Leptonic domination?

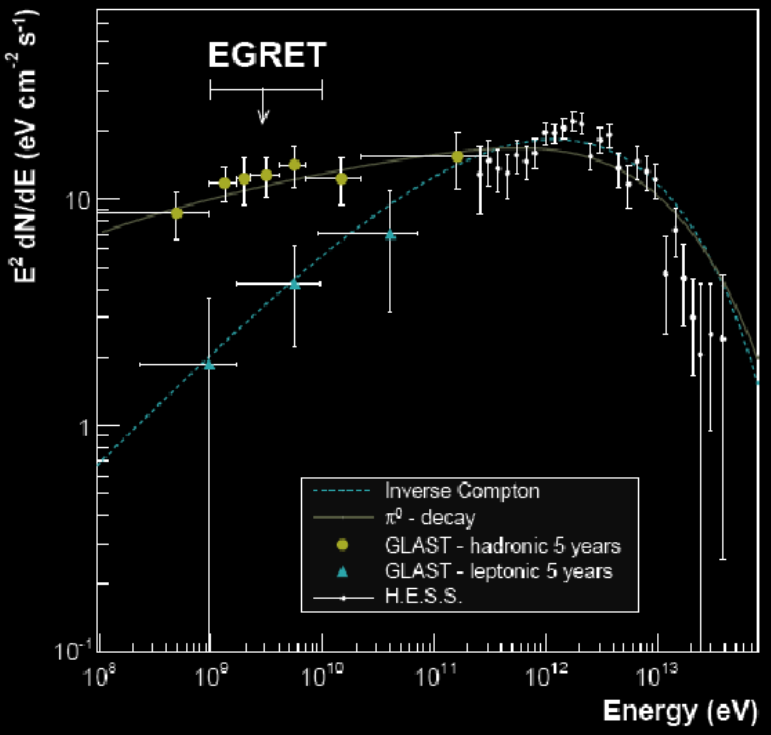
- TeV (if hadronic) **protons ⊗ ρ_{gas}**
- keV (electrons) **electrons ⊗ B^2**
- TeV (if electrons) **electrons ⊗ U**
- But **electrons ∝ protons**
- And **$B^2 \propto \rho_{gas}$**
- Conclusion ??

B-field amplification signature?

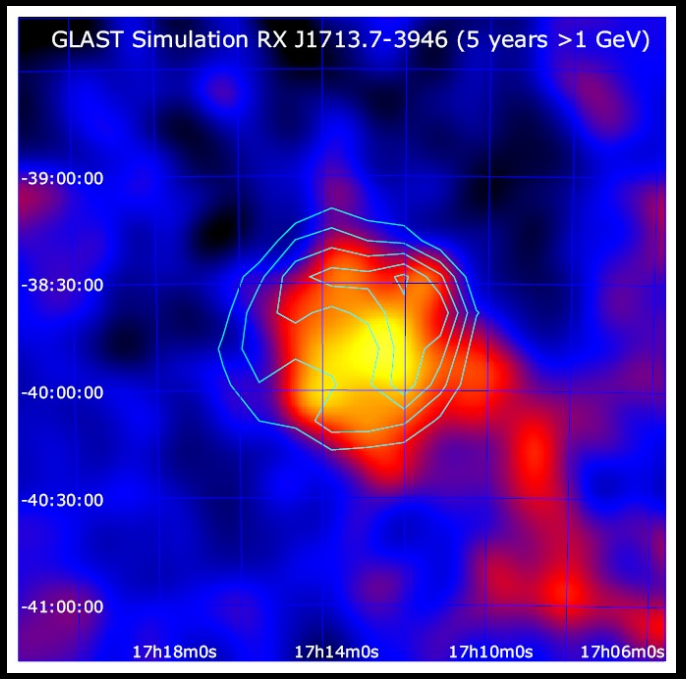


- Lower energy particles do not experience the same shock front
- Acceleration less efficient
- Expect a dip in the power output

What will GLAST and ν's tell us ?



5 years, >1 GeV



[S. Funk et al. 2007]

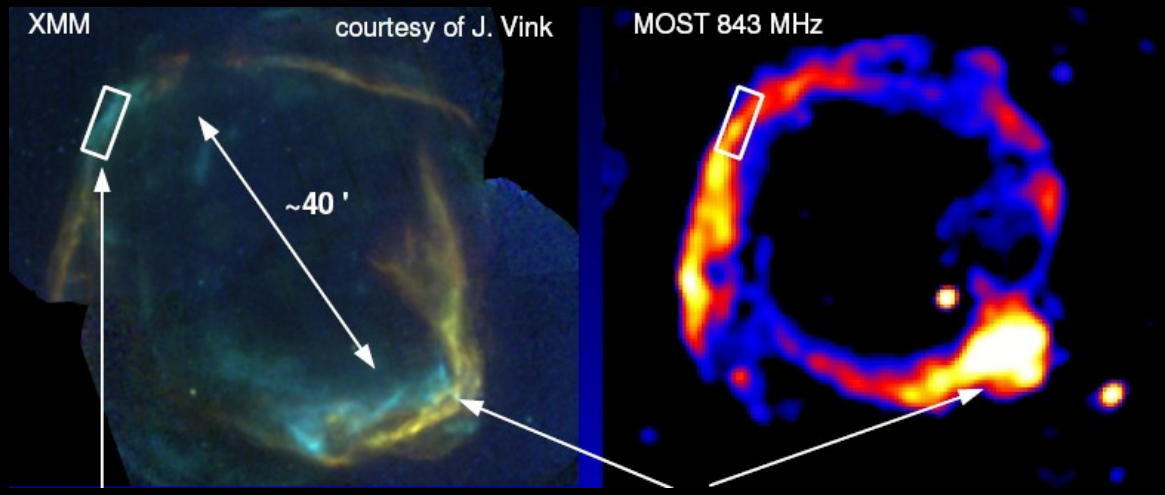
- **Rather difficult source for GLAST:**
  A 5xbright Egret source nearby
- **Expected ν rates (KM3NET, 5 yrs)**

[A. Kappes et al. astro-ph/0607286v3] :

E > 1 TeV 11 over 41 bg. : 5 over 15 after reconstruction
E > 5 TeV 5 over 8 bg.

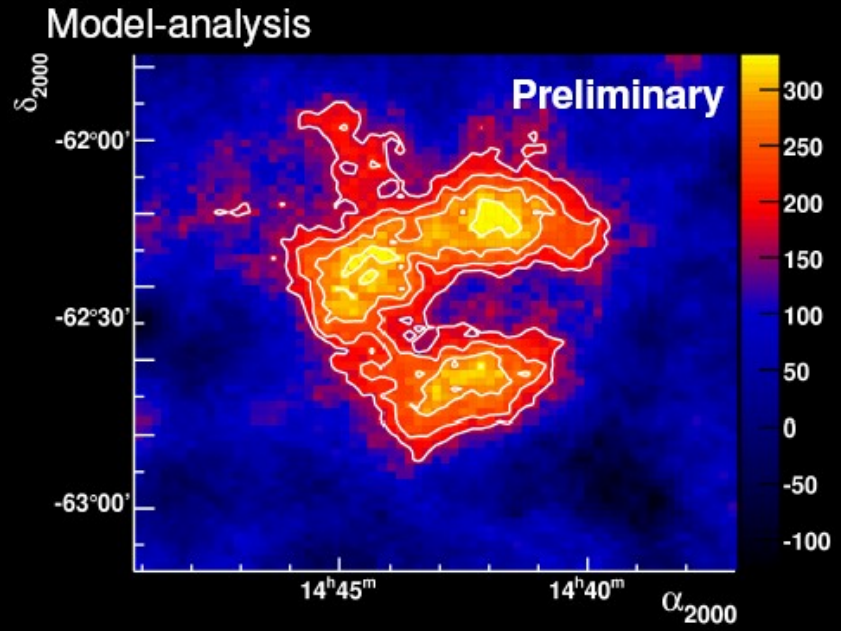
New TeV source : RCW86

~1kyr young 40' Shell



radio & X-ray sunchrotron

Expanding shell interacts with compact region

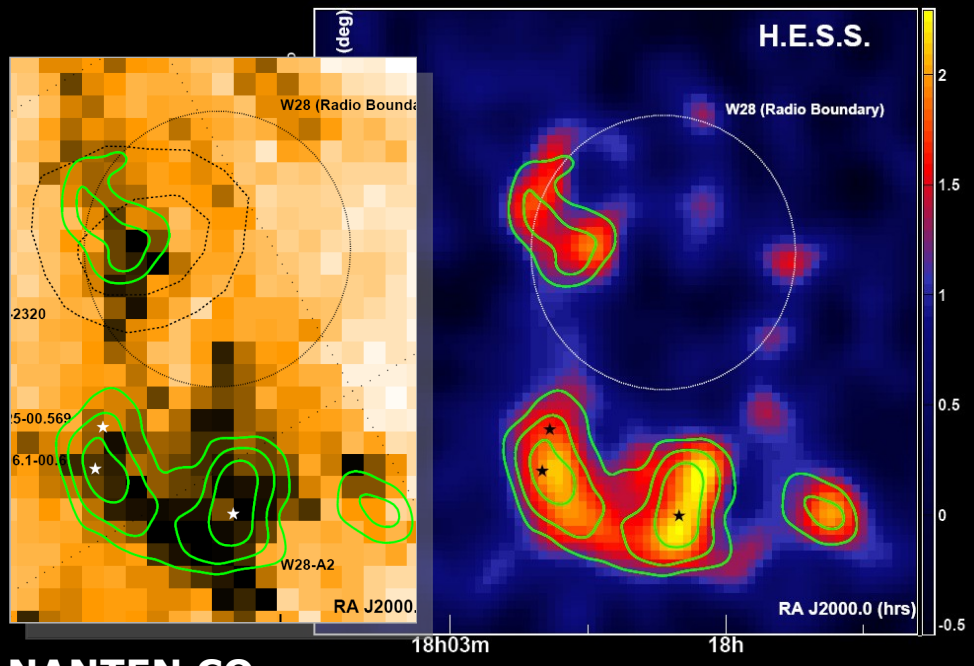


- **Probable new Shell-type TeV emitter**

Older Shell type SNRs : W28

- W28 @ 2-3 kpc
- 35 – 150 kyr age

- TeV emission coincident with molecular clouds revealed by HESS
- OH masers trace shocks
- Expected B-field high →
- First evidence for p-p in SNR/ cloud interaction



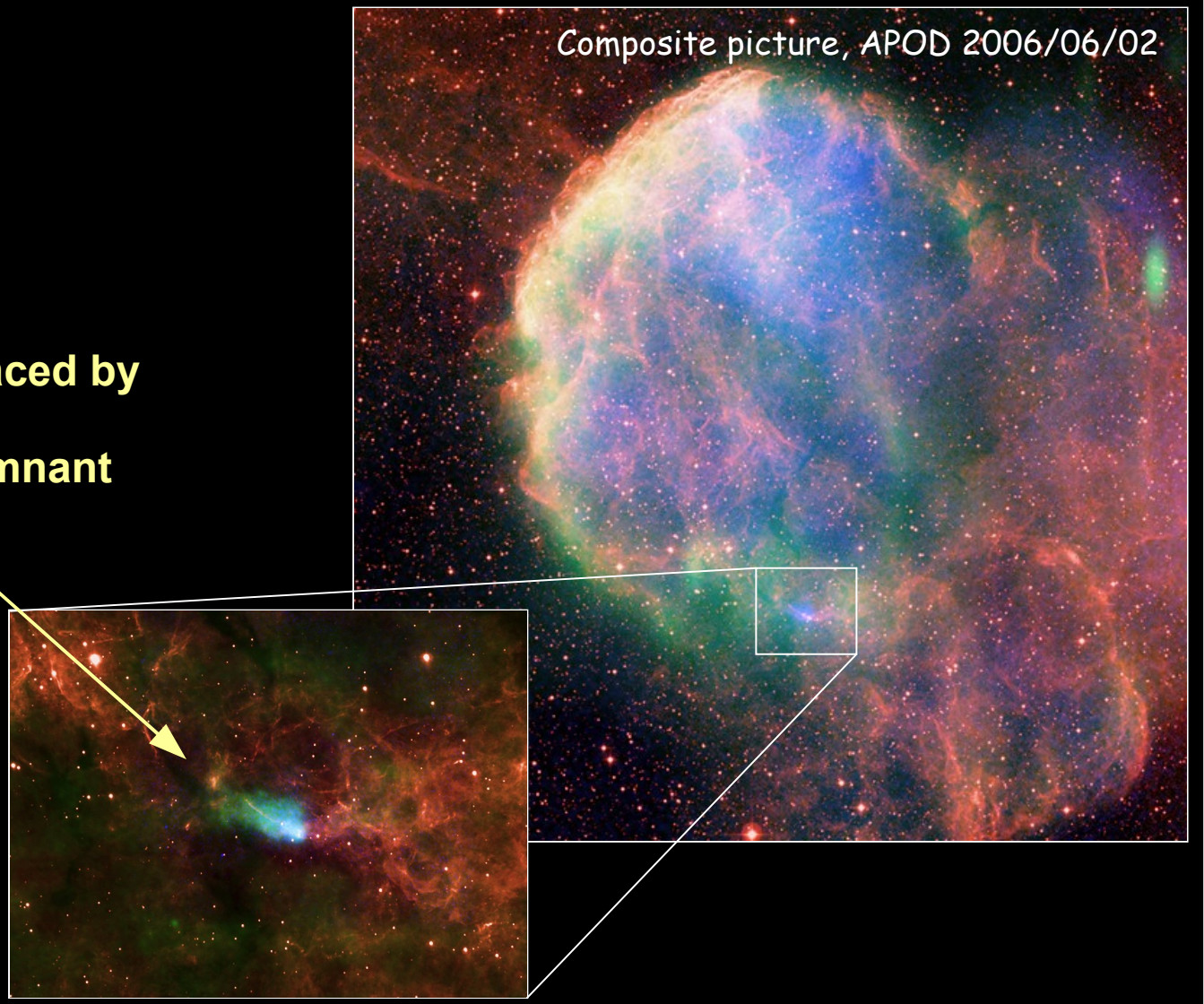
NANTEN CO
10-20 km/s

20/90 cm VLA
MSX 8 micron

Older Shell type SNRs : IC 443

- ~30 kyr old 45' Shell SNR
- 1.5 kpc

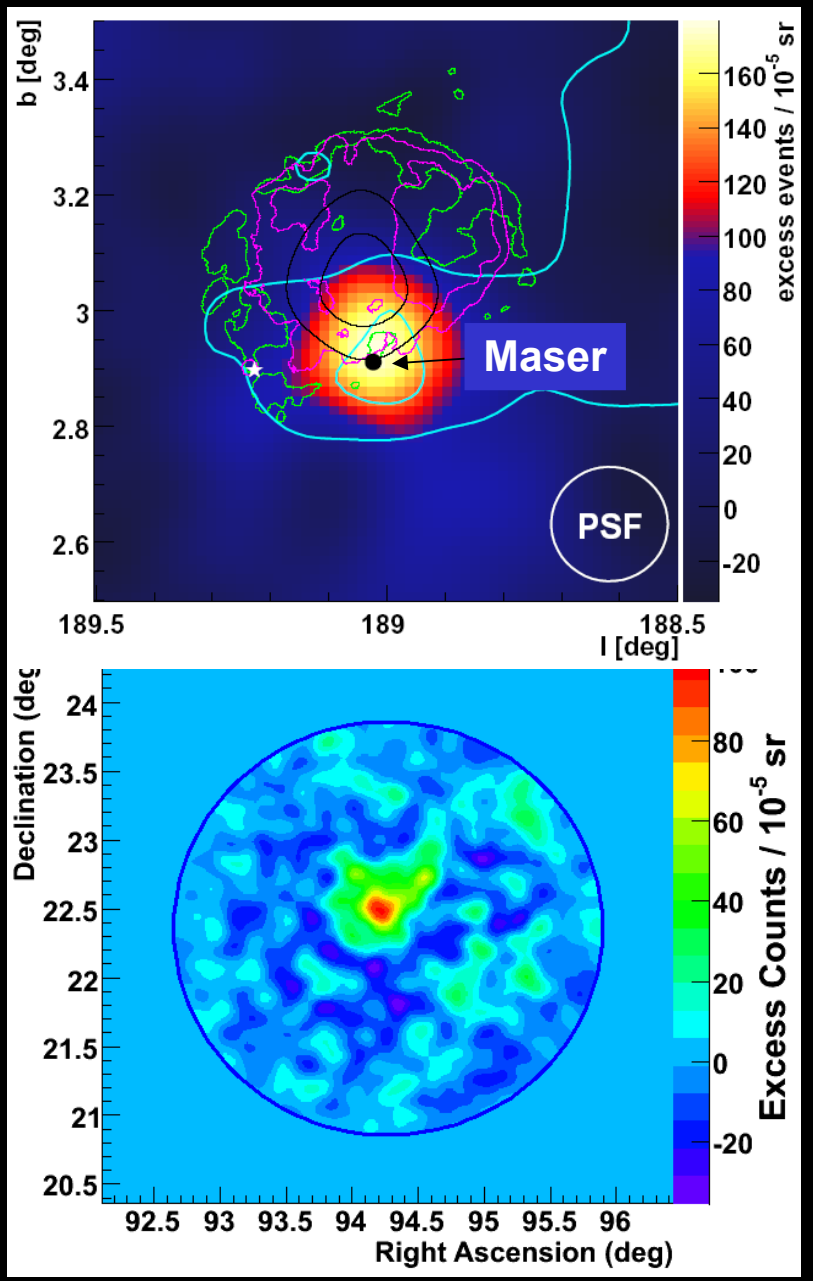
- Shocked Molecular gaz traced by Maser
- PWN at the edge of the remnant



Older Shell type SNRs : IC 443

- MAGIC : 5.7σ in 29 h
  - Steep spectrum n~3.1
- VERITAS : 7.1σ in 16 h
  - Consistent position
- Position compatible with
  - Dense gas
  - Not PWN
  - Not Shell

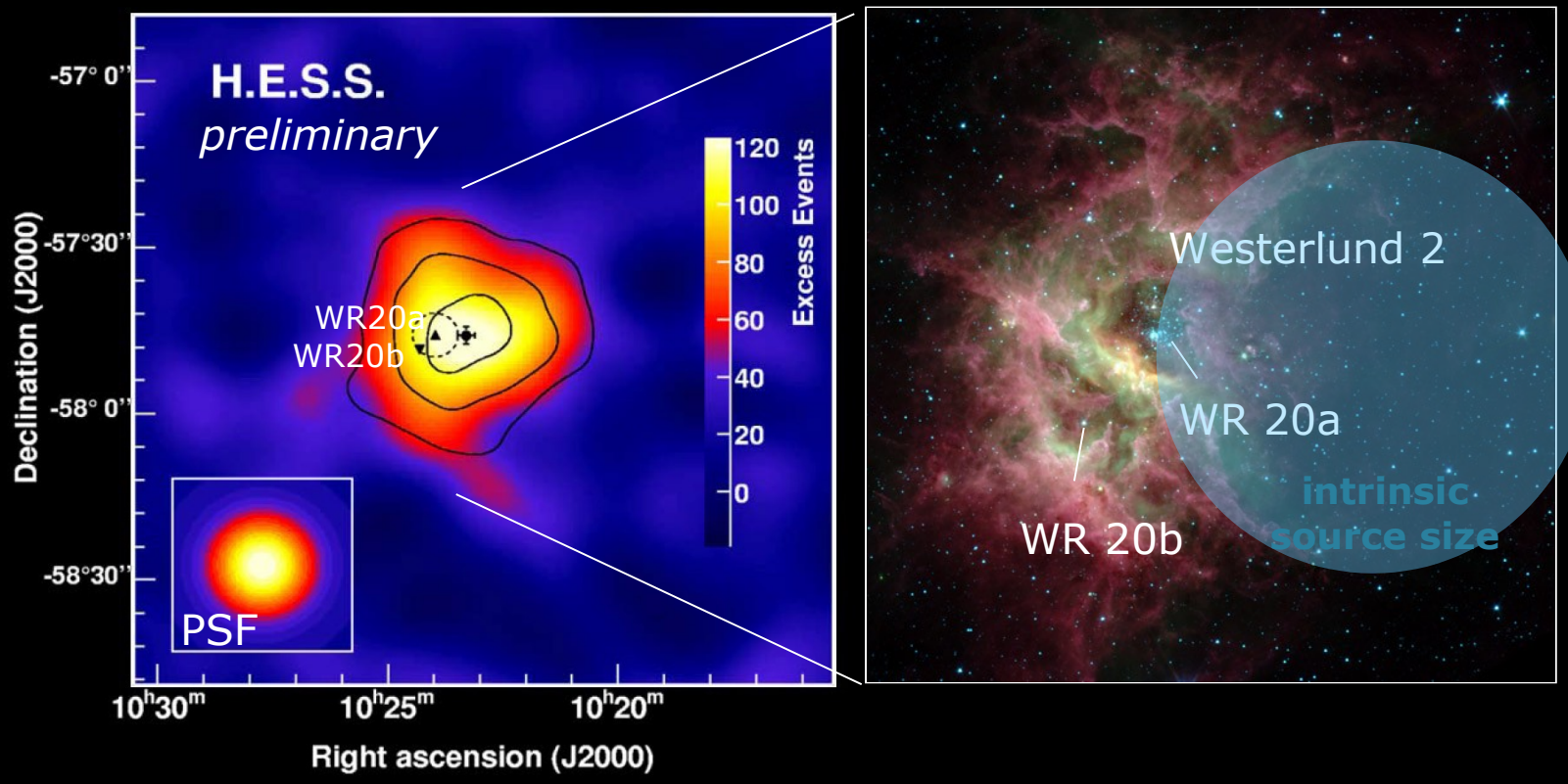
- Interaction of hadrons accelerated in SNR?
- Morphology maybe key to interpretation



Stellar clusters: A new type of TeV source?

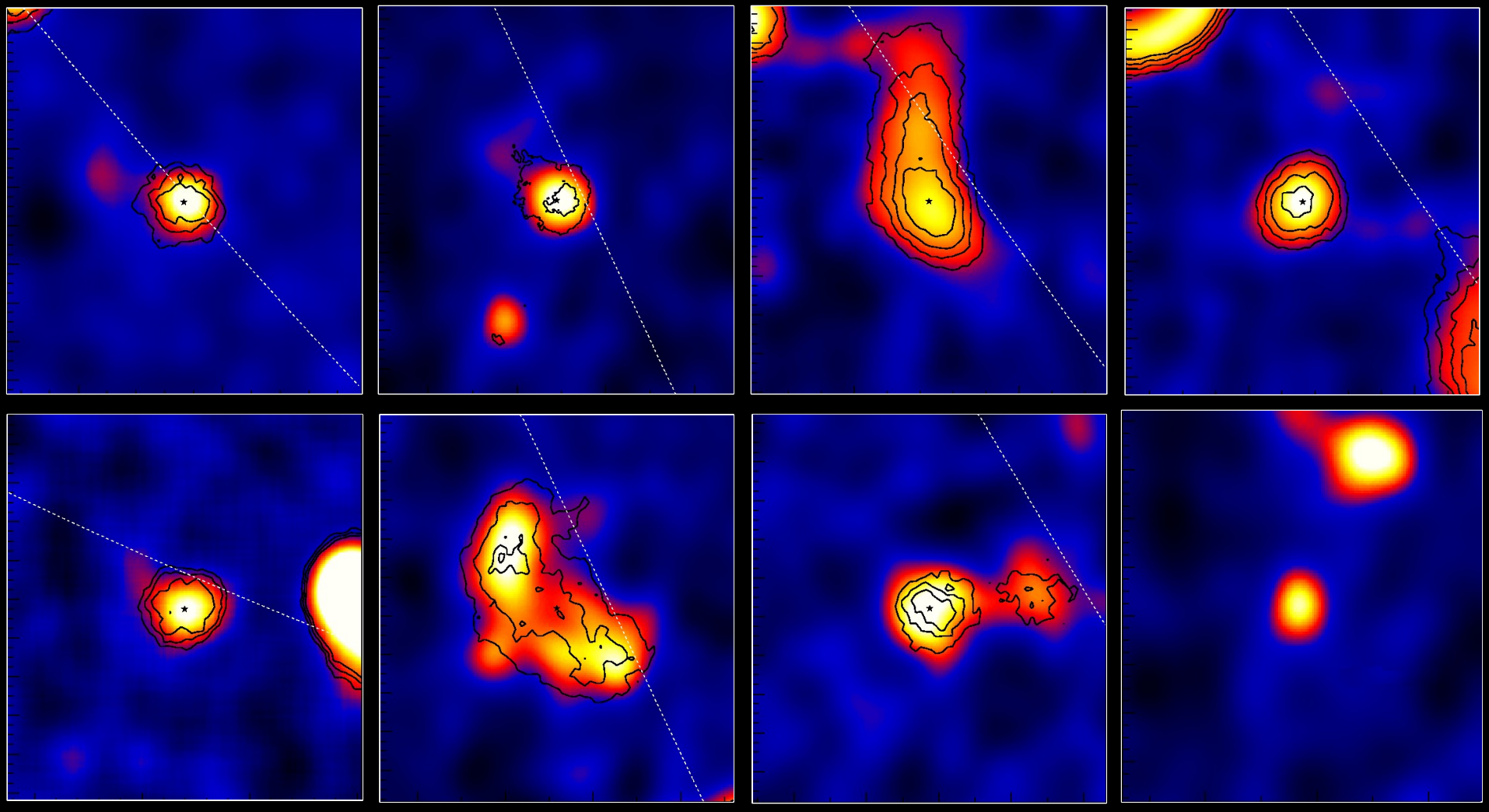
- Open Cluster Westerlund 2 : thousands of solar masses
  Wolf-Rayet & young stars
- Winds excavating bubbles in the ISM

- HESS source coincides with the most proeminent one in RCW 49
- Acceleration through collective wind effects or DSA at the boundary?
- Systematic search program undertaken with HESS



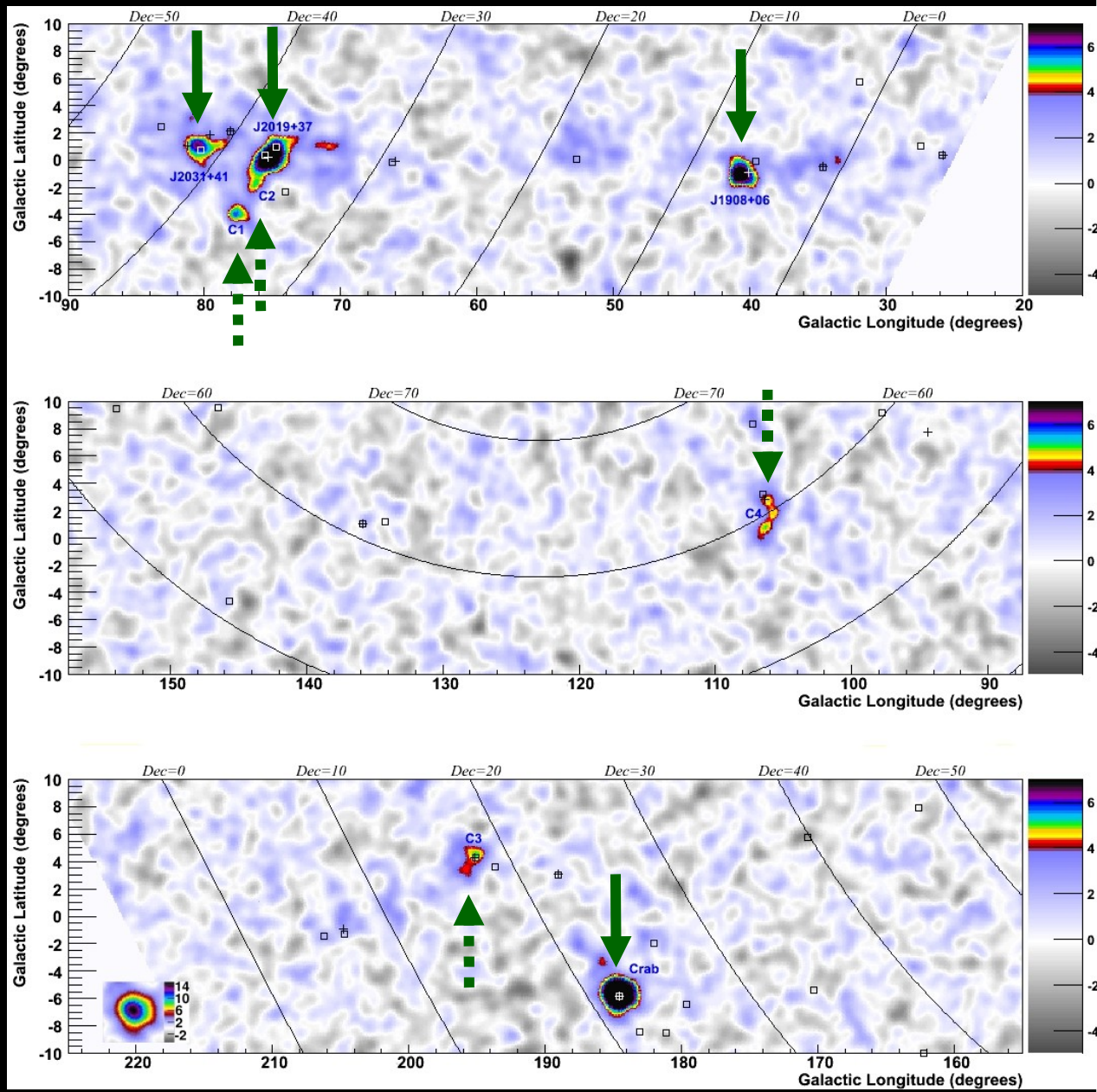
Dark Sources!

- Seem to shine only in gamma-rays : rather hard spectra and mostly extended
- No plausible counterparts in radio, x-rays, ...
- Two of HESS dark sources out of 10 have been identified recently:
  1 PWN (faint but young & energetic pulsar) , 1 SNR (composite source)
- New type of CR accelerators? (if leptons expect x-rays, radio !)



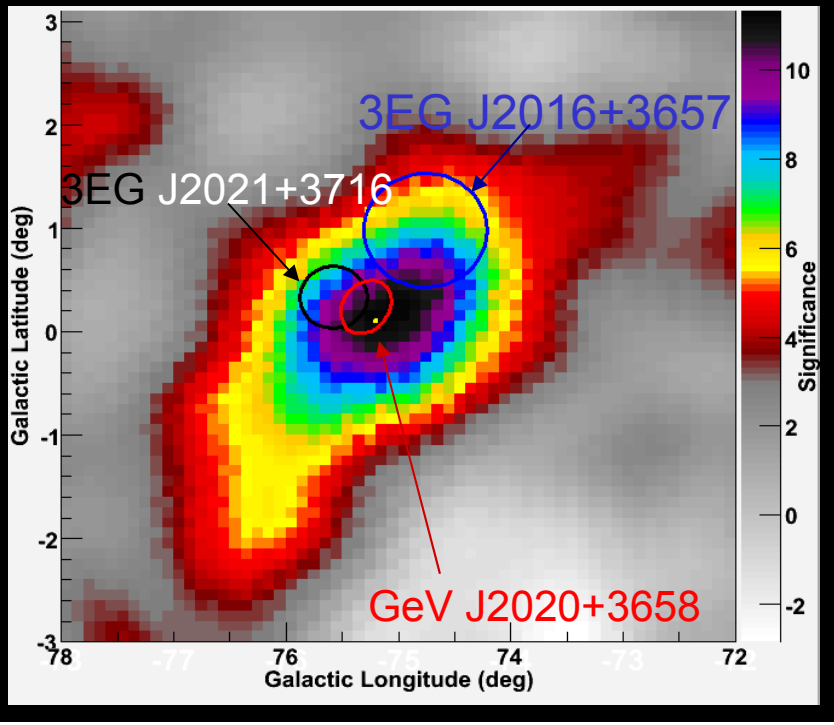
MILAGRO sky-survey

- 7 years of integration
- Median energy ~ 20 TeV
  due to γ/hadron
  separation cuts
- 3 new sources significant post-trials
  - J1908+06
  - J2019+37
  - J2031+41
  - Crab
- 4 'hotspots'
- Bright +Hard+extended sources : Pevatrons?
- Identification is difficult due to poor angular resolution (see HESS First confirmation below)

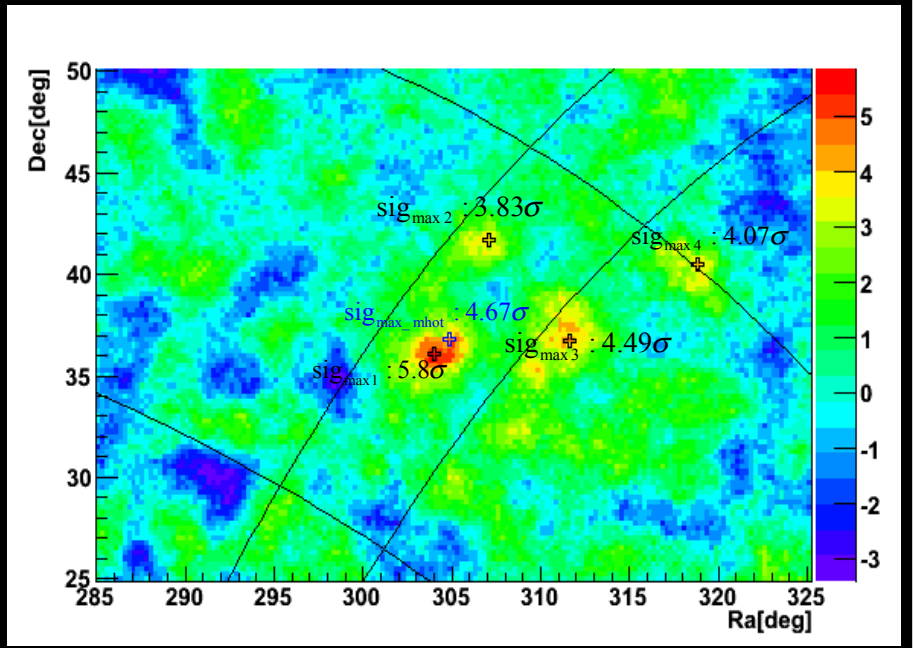


Dark Sources : MILAGRO J2019+37

- **MGRO J 2019+37:**
  - **Bright extended source: 9.3 σ**
  - **In coincidence with GeV Egret source**
- **Tibet Asγ : 5.3 σ close to Milagro position**

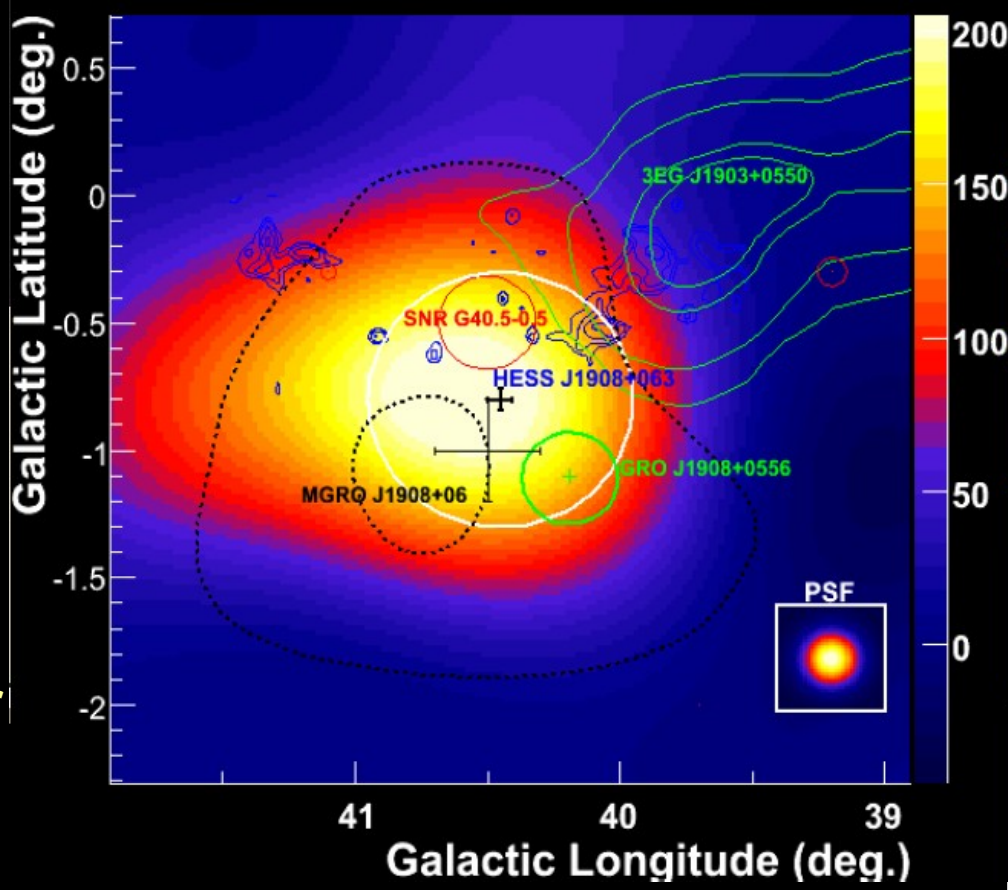


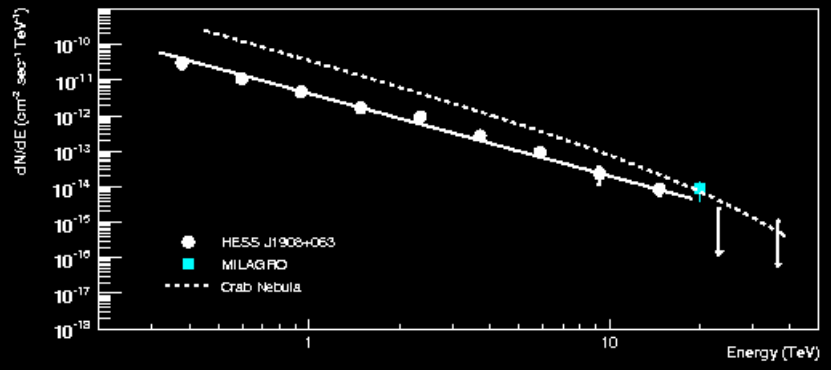
- **Point source limits from MAGIC +VERITAS**
  - **No contradiction to MILAGRO flux**
  - **for hard+extended source**
- **Extended analysis pending**



Dark Sources : MILAGRO J1908+06

- **MGRO J 1908+06:**
  - **Bright extended source: 7.0 σ**
  - **In coincidence with another GeV Egret source**
- **HESS detects a strong source with a compatble position**
- **30% Crab flux > 1 TeV**
- **First confirmation of a Milagro Source**
- **Source position and spectrum much better constrained by HESS**
- **Still no identification**
- **May be a composite source**





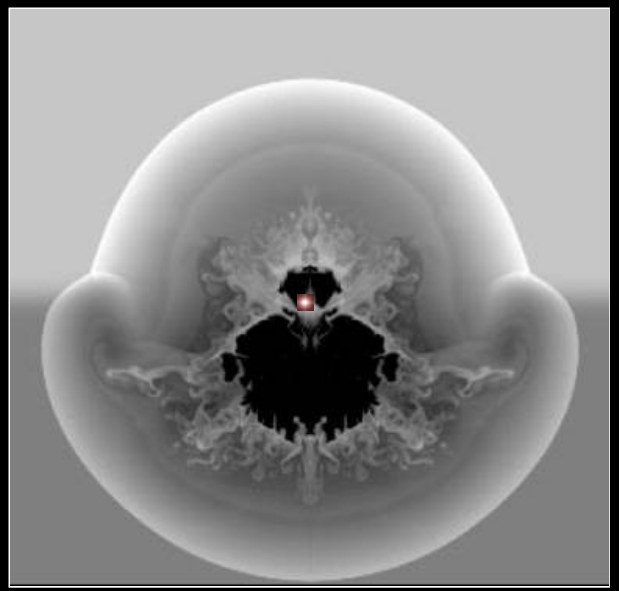
Pulsar Wind Nebulae

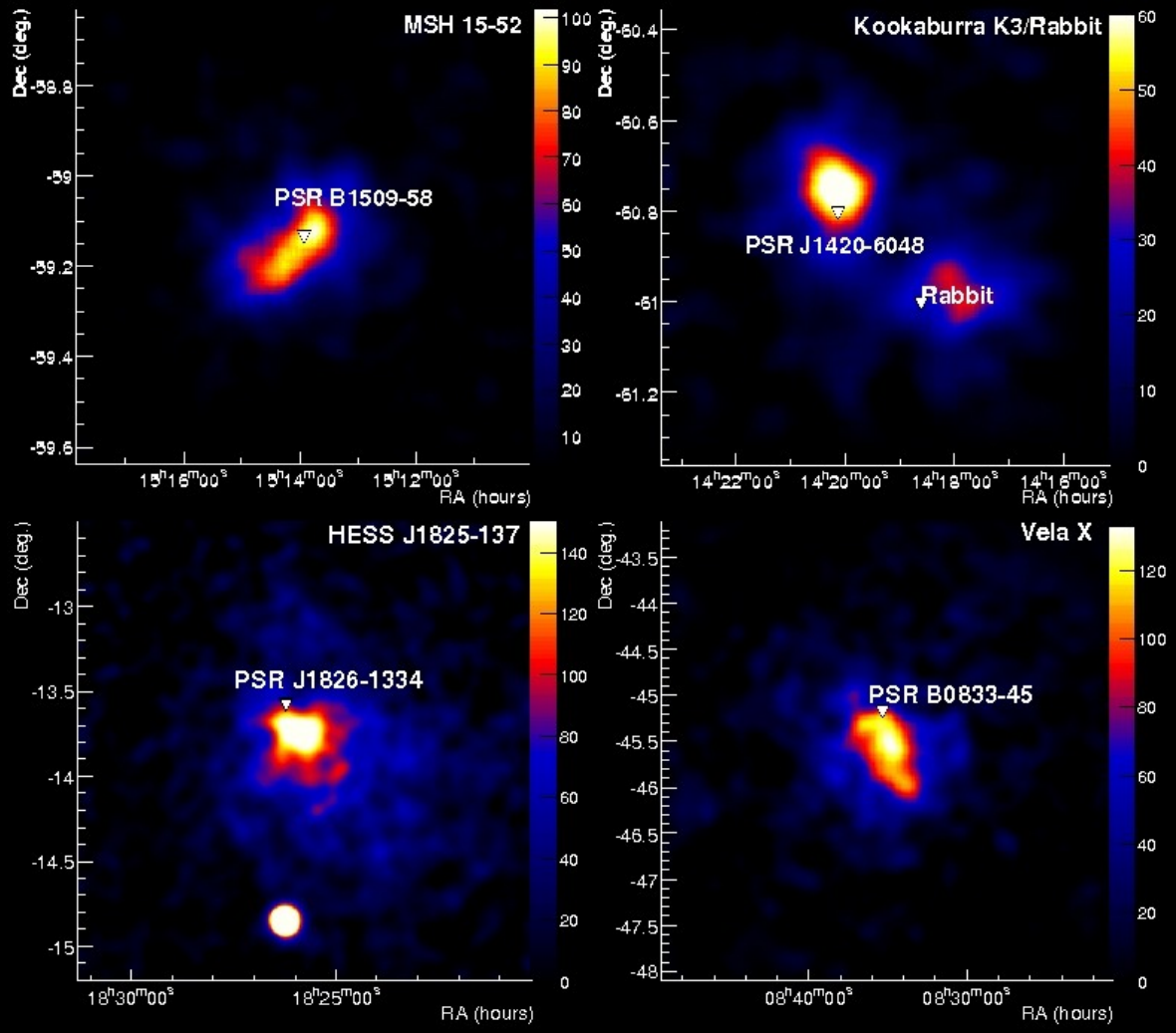
- Major galactic source population

Revealed by HESS galactic scan

- Associated with
  - very young : age < 10^5 yrs
  - energetic: Edot > 10^{35} erg/s
  - pulsars
- TeV emission = Relicelectron

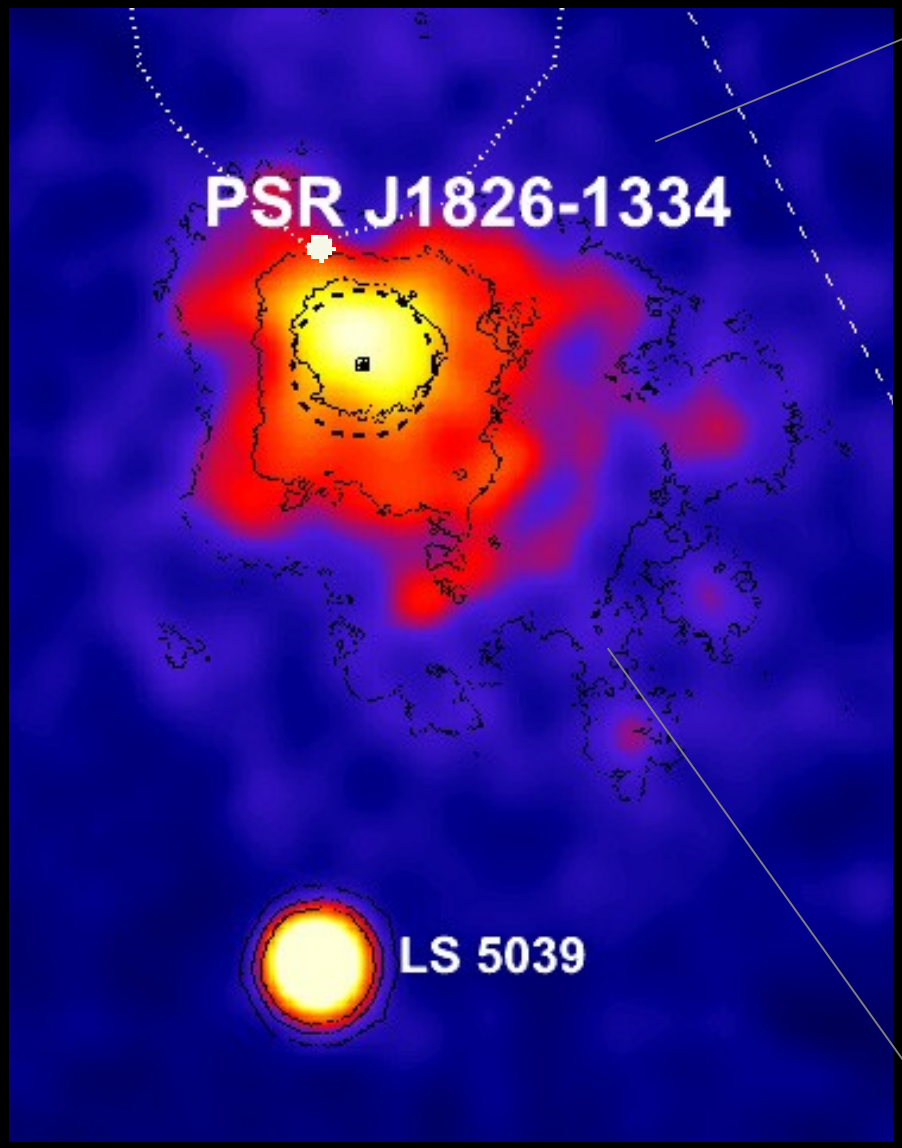
- Nebulae with huge caracteristic sizes ~ few tens of pc
- Mostly displaced TeV emission wrt pulsar position: "Crushed nebulae"

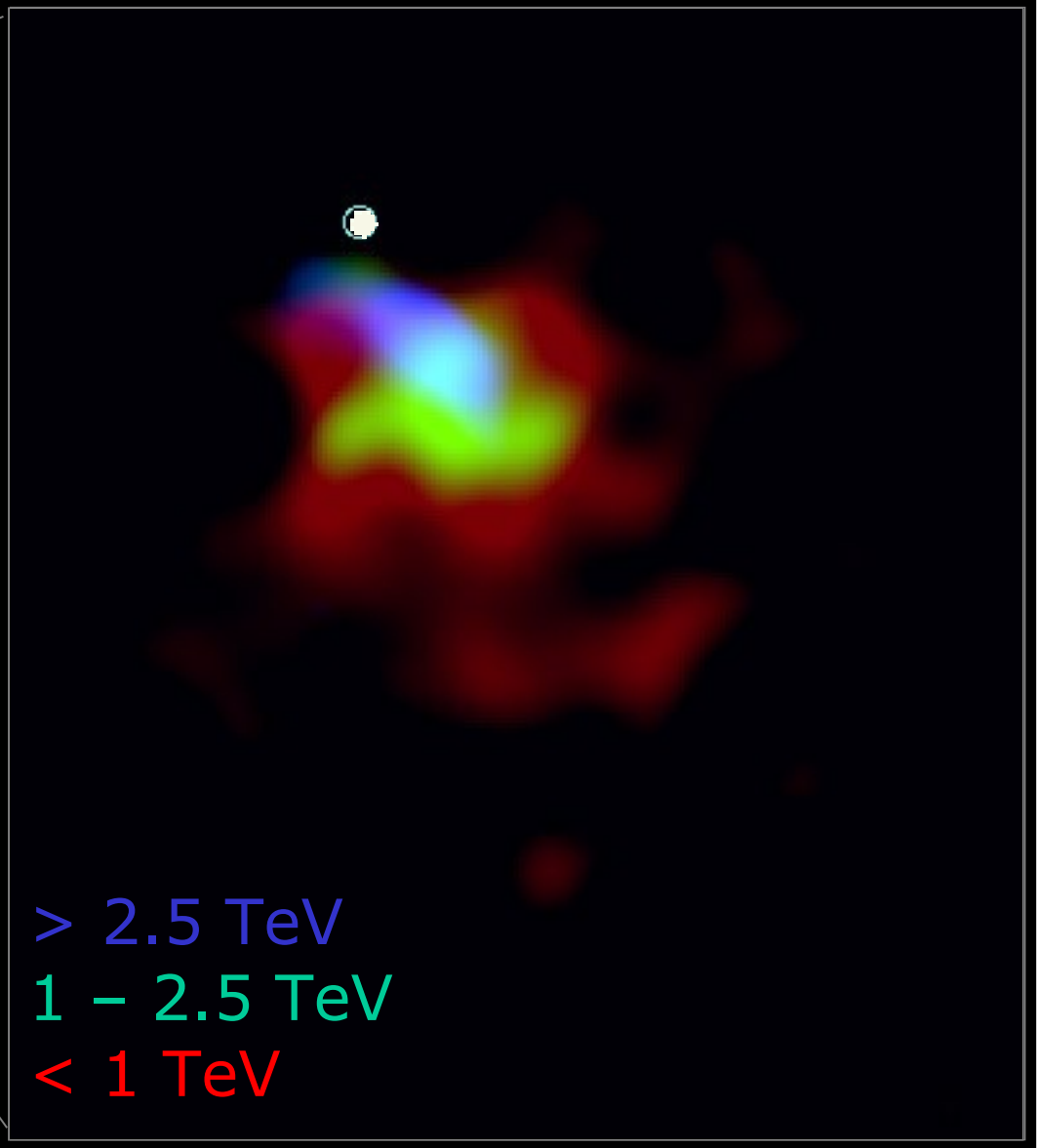




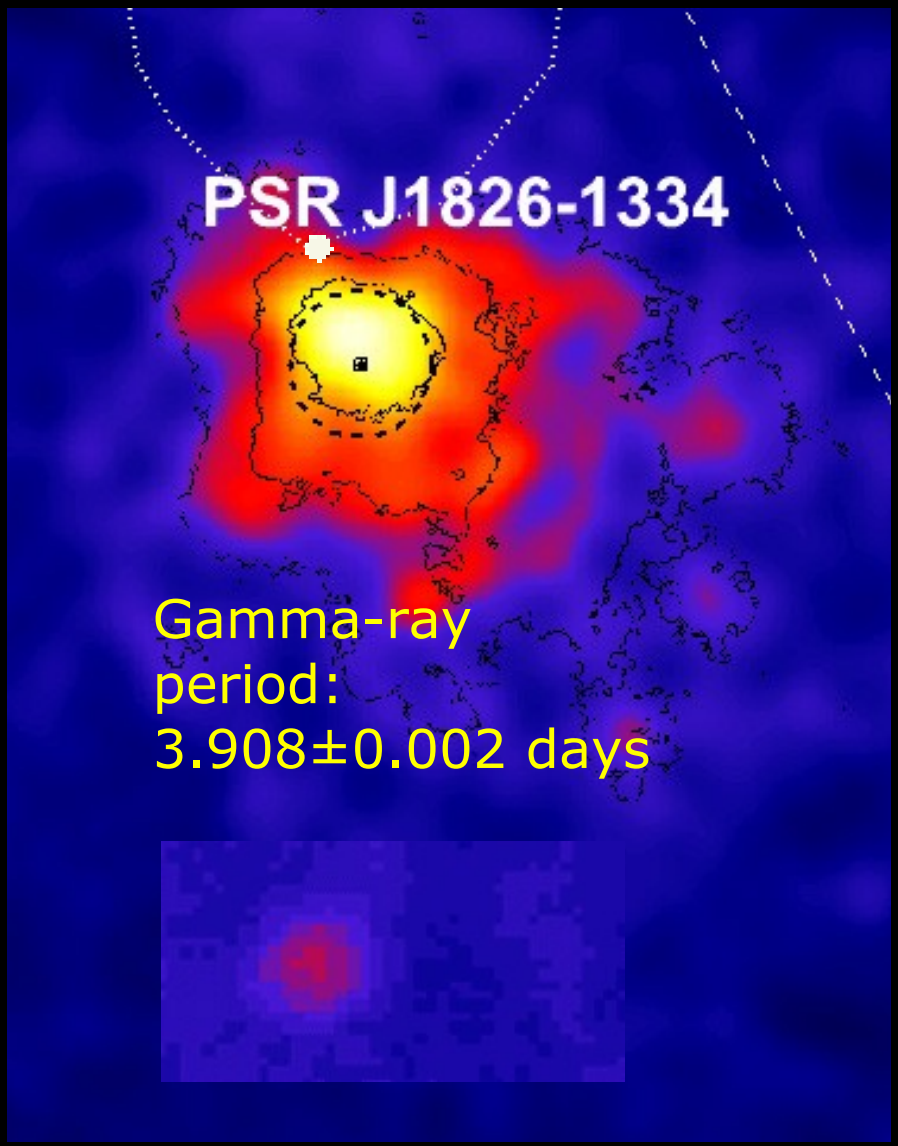
SN Explosion in inhomogenous medium→ reverse shock pushes the nebula

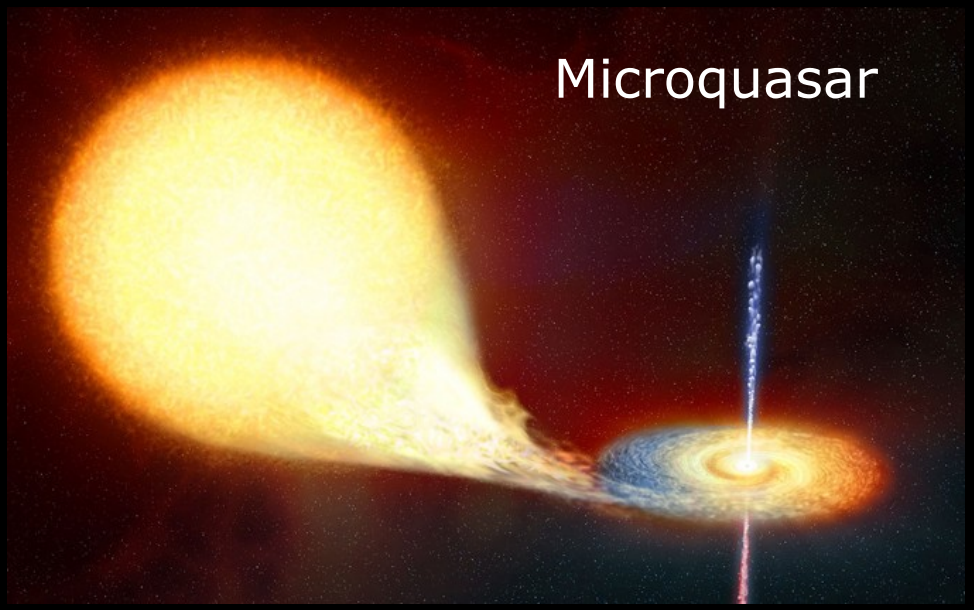
Morpholgy of PWNe: evidence for cooling
Relic electrons at action: HESS J1825-137





Binaires : LS 5039 by HESS

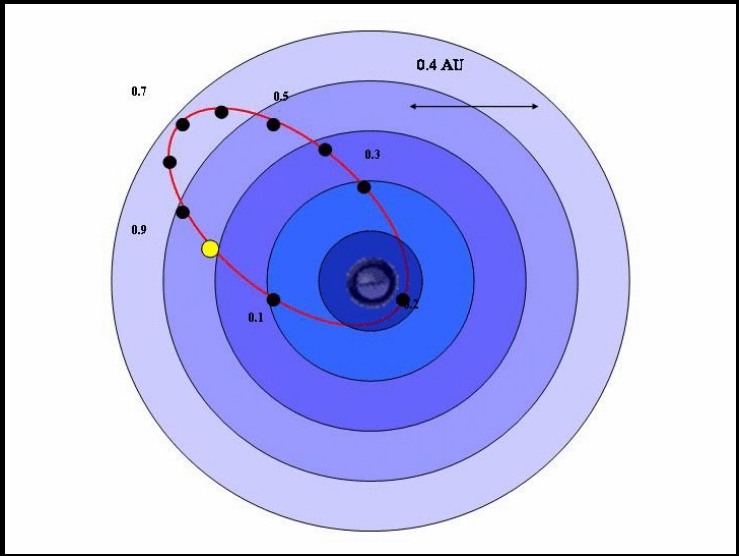


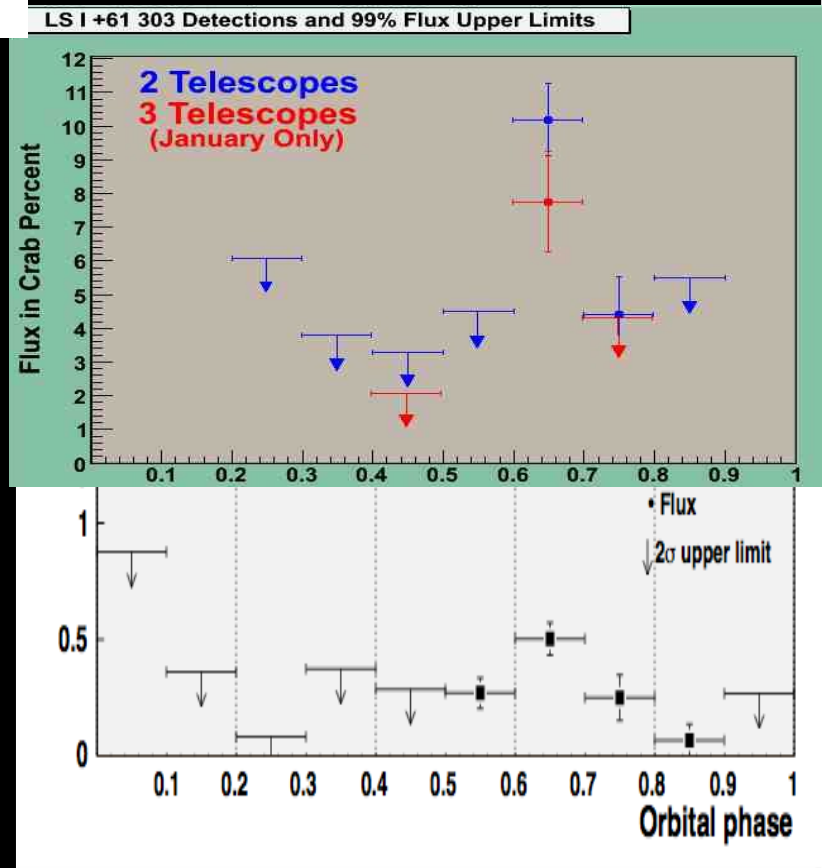


LS 5039

- 4 (?) $M_\odot$ object in eccentric 3.906-day orbit around 20-30 $M_\odot$ star
- closest approach ~10^{12} cm or ~2 stellar radii

Binaires : LSI +61 303 VERITAS+MAGIC

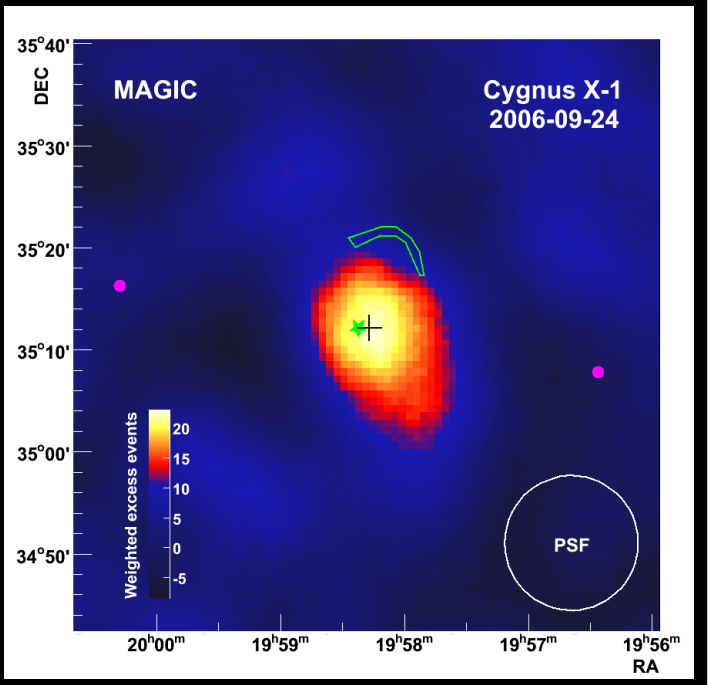


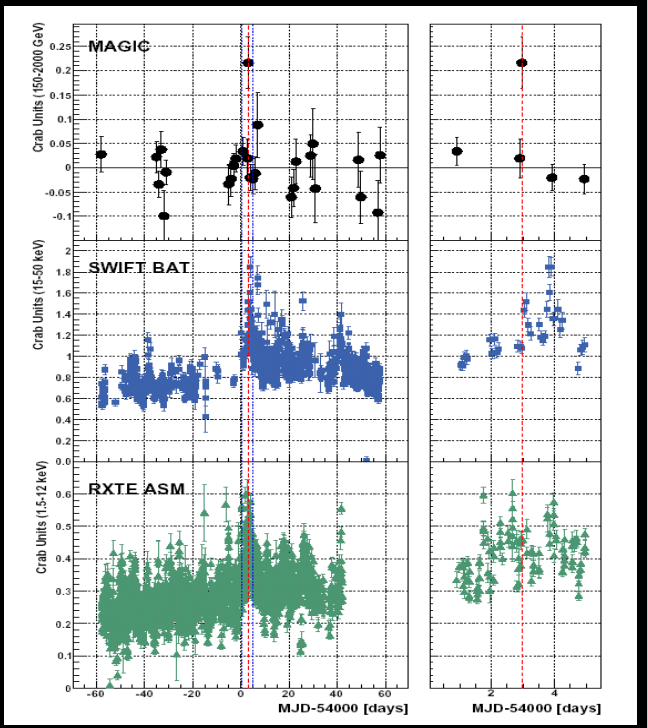


- **Variable (flaring) mostly at phase 0.5-0.85 – but not really periodic?**
- **Overall correlation with X-ray – but many differences**
- **A real challenge to modellers!**

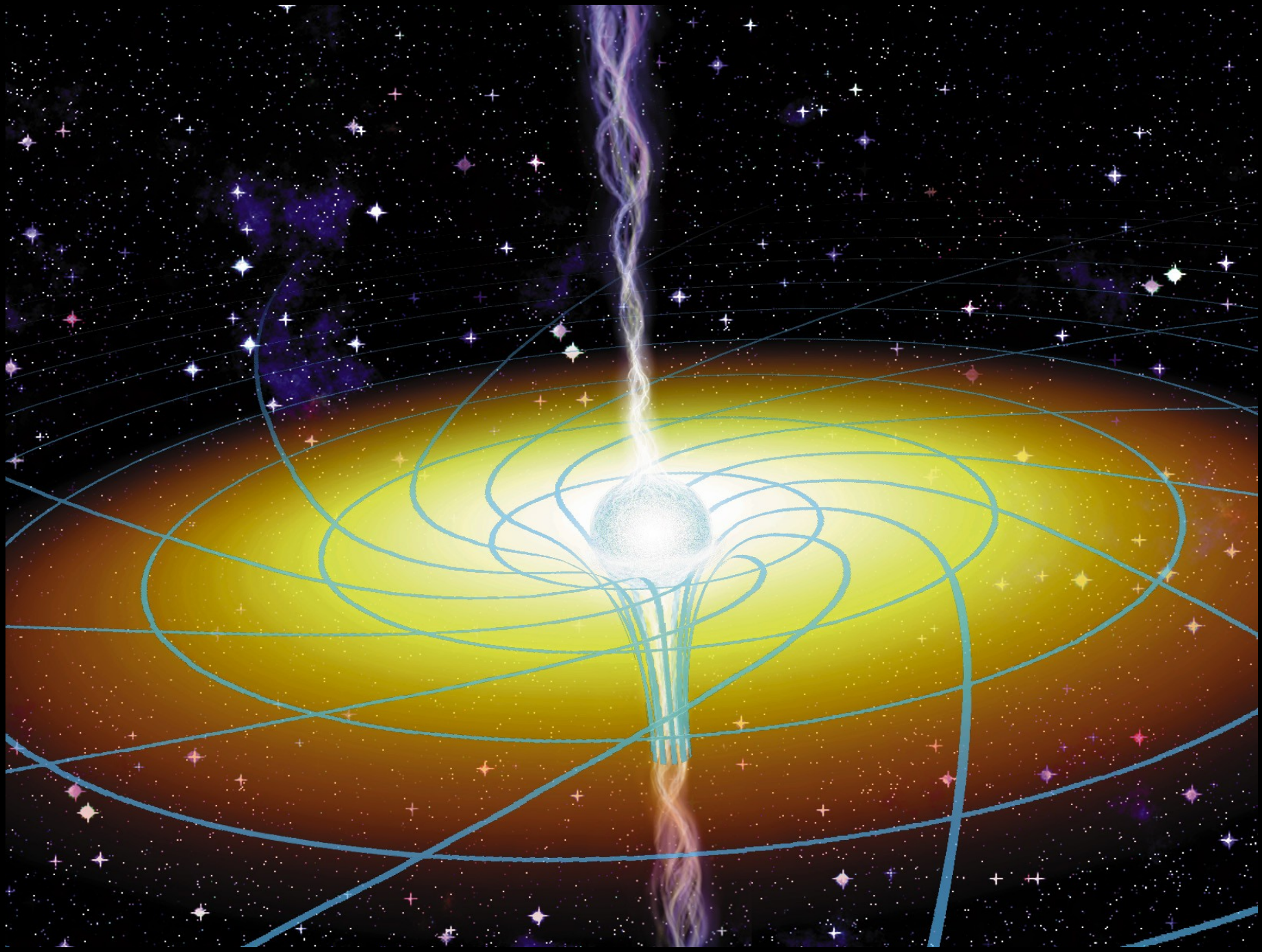
Binaires (BH): MAGIC : claim for Cyg X-1

- Black hole binary M_{BH}>13$M_{\odot}$, M_{star} ~ 30 $M_{\odot}$
- Relativistic jet v > 0.6 c
- 40 hours of MAGIC observations
- 4.9 σ signal seen in one 79 minute time slice
- Estimated significance 4.1 σ after correction for statistical trials
- Very exciting but not yet firmly established as a VHE source



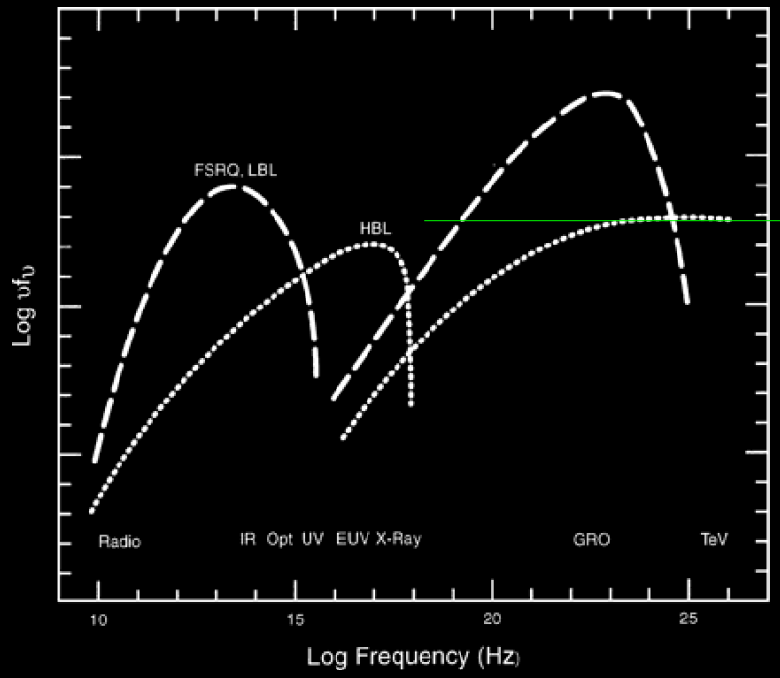


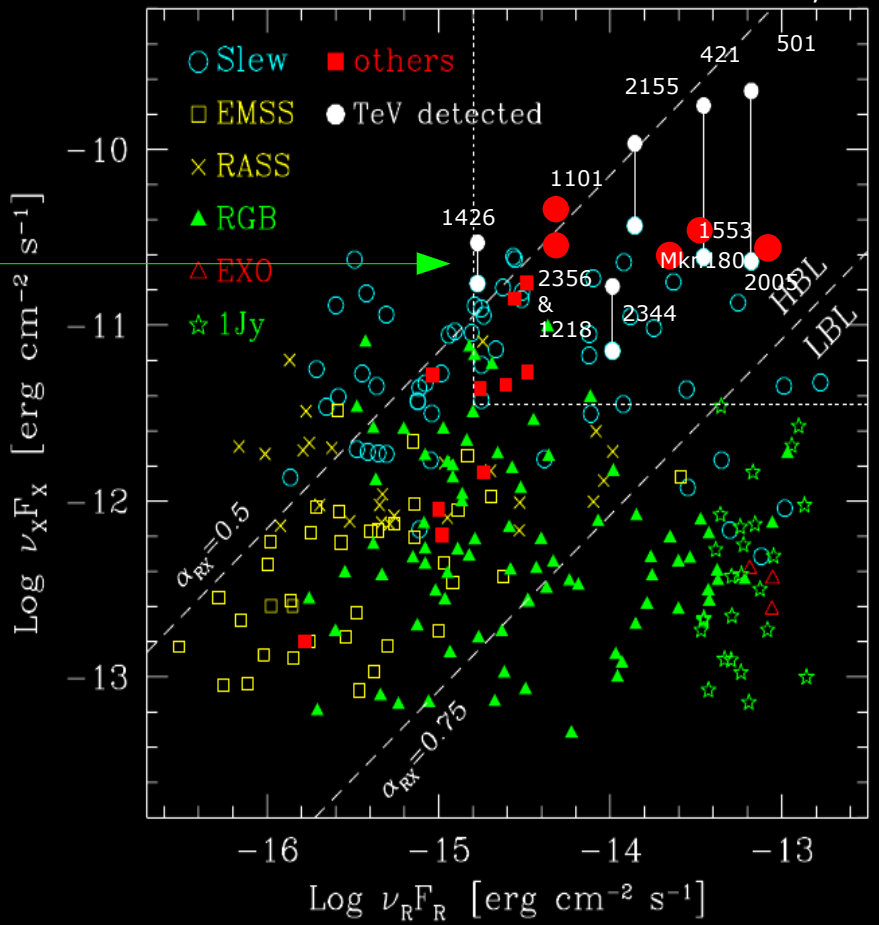
Extrragalctic World



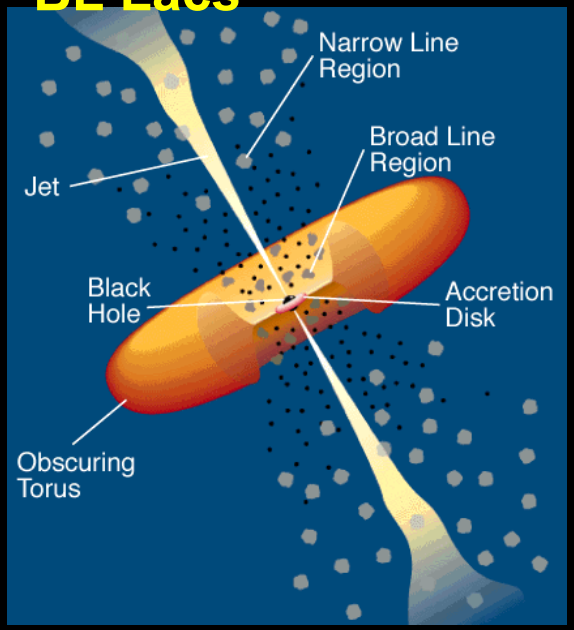
Amost all extragalactic VHE emitters are HBL's

Costamante & Ghisellini, 2002



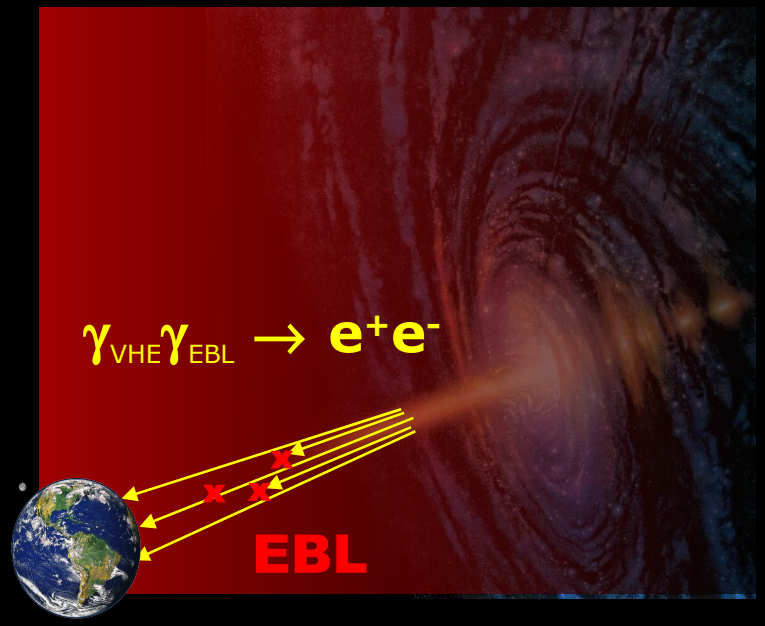


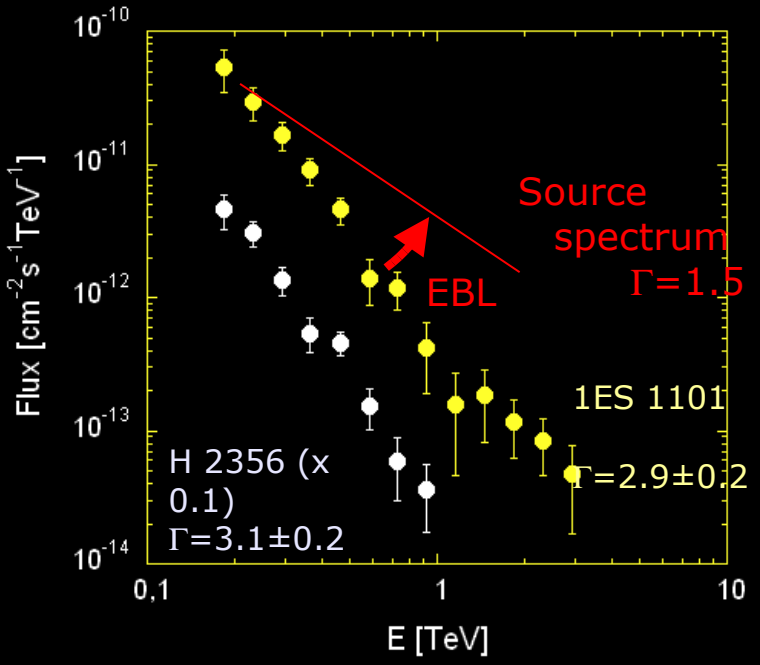
BL Lacs



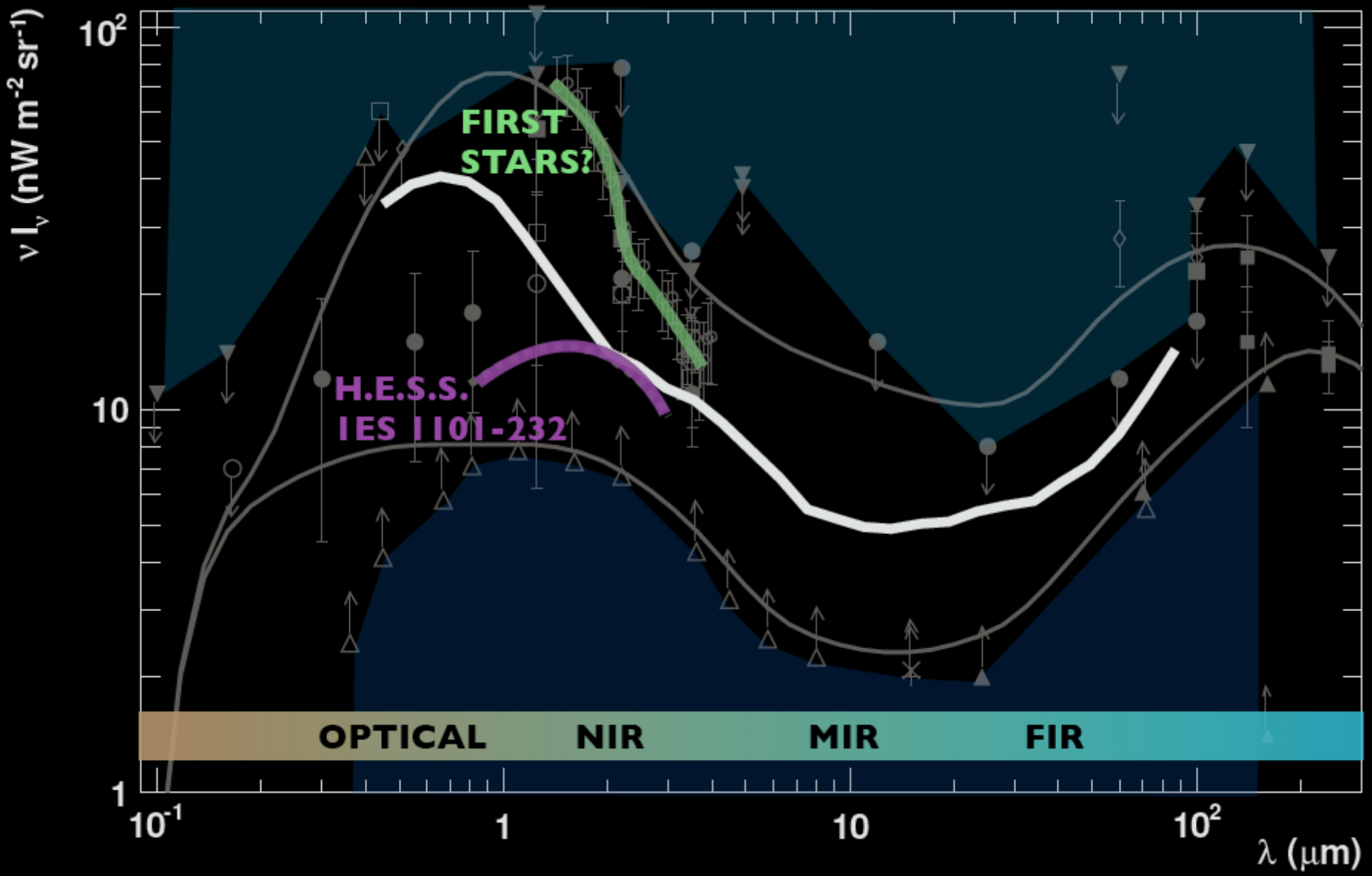
Extrragalctic VHE emitters: 20 sources

Object	Redshift	Type	1st Detection
M 87	0.004	FR I	HEGRA
Mkn 421	0.030	HBL	Whipple*
Mkn 501	0.034	HBL	Whipple*
1ES 2344+514	0.044	HBL	Whipple
Mkn 180	0.046	HBL	MAGIC
1ES 1959+650	0.047	HBL	7-Tel. Array*
BL Lac	0.069	LBL	MAGIC
PKS 0548-322	0.069	HBL	H.E.S.S.
PKS 2005-489	0.071	HBL	H.E.S.S.
RGB 0152+017	0.080	HBL	H.E.S.S.
PG 1553+113	>0.09	HBL	H.E.S.S.
PKS 2155-304	0.116	HBL	Mark VI
H 1426+428	0.129	HBL	Whipple*
1ES 0229+200	0.139	HBL	H.E.S.S.
H 2356-309	0.165	HBL	H.E.S.S.
1ES 1218+304	0.182	HBL	MAGIC
1ES 1101-232	0.186	HBL	H.E.S.S.
1ES 0347-121	0.188	HBL	H.E.S.S.
1ES 1011+496	0.212	HBL	MAGIC
3C 279	0.536	FSRQ	MAGIC

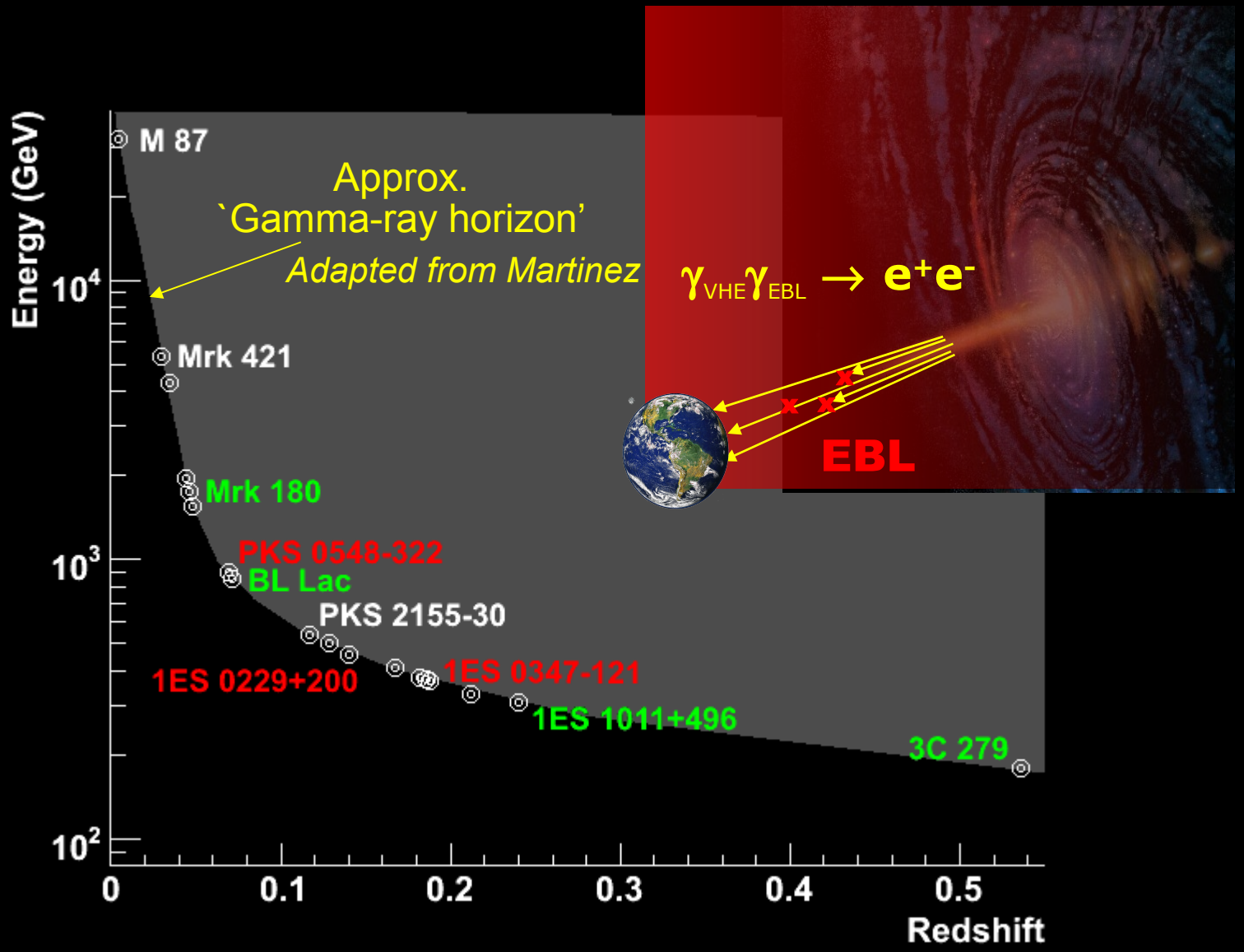




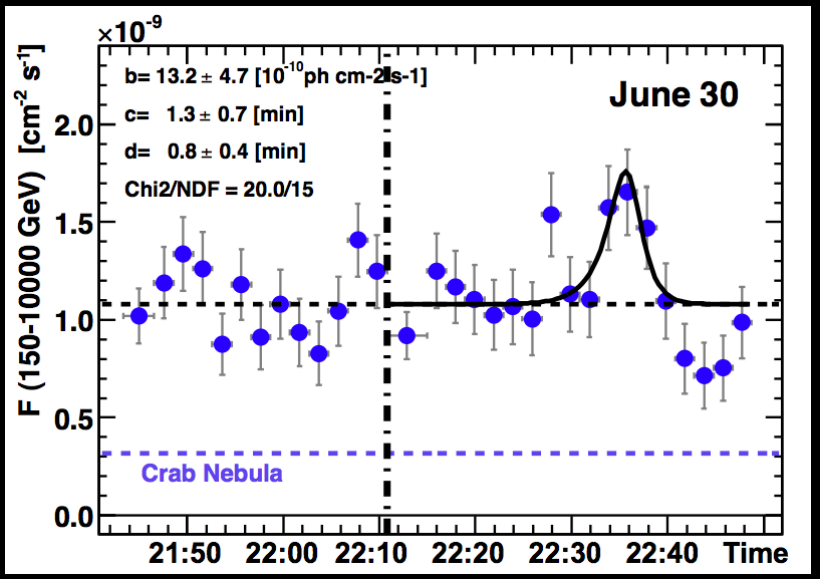
Extrragalctic VHE emitters : Probes for EBL

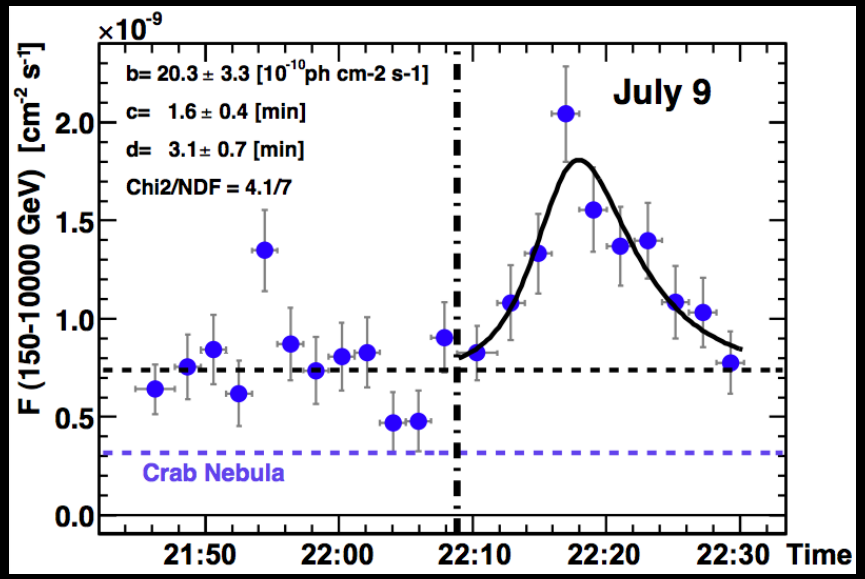


Extrragalctic VHE emitters : Probes for EBL



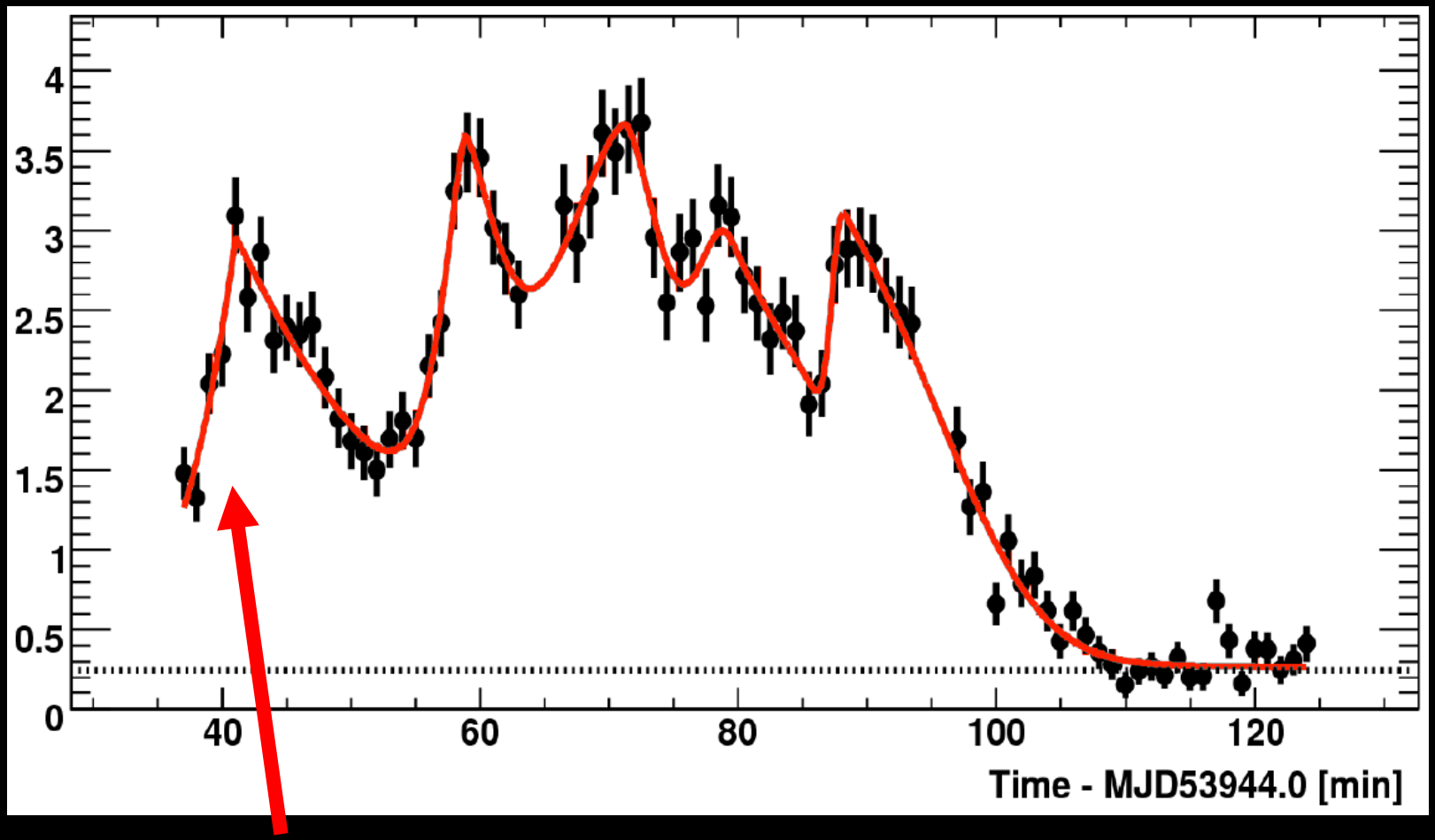
Mkn 501 Flares : MAGIC





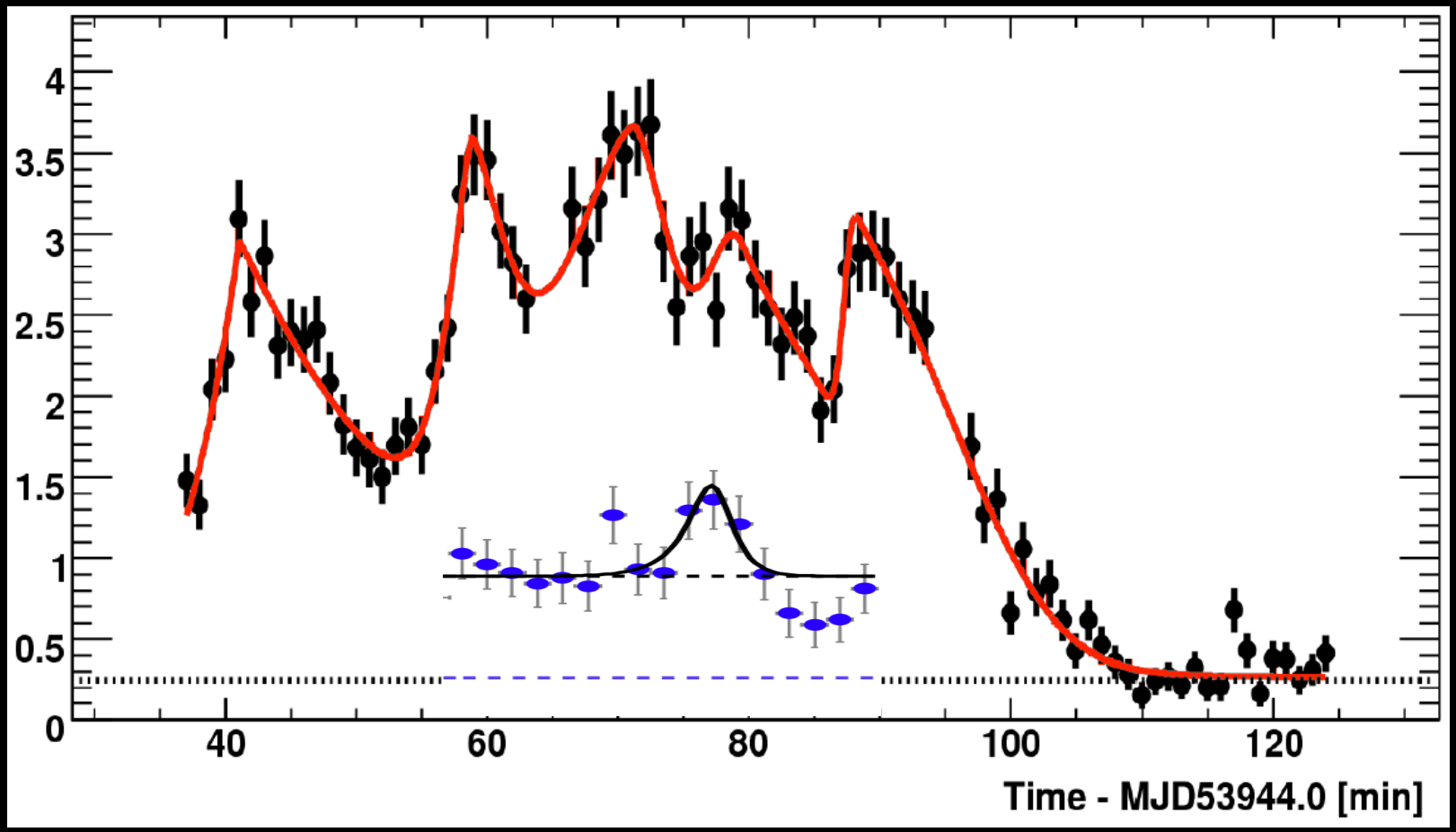
- June 30th flare has ~*3 minute* variability (but is not so strong statistically), July 9th better measured but slower
- First big flare seen by a third generation Cherenkov instrument
- *But…*

PKS2155-304 Flares (summer 2006) : HESS



- *Best measured risetime: 173 ± 28 s*
- Two orders of magnitude brighter then typical state

PKS2155-304 Compared to Mkn 501

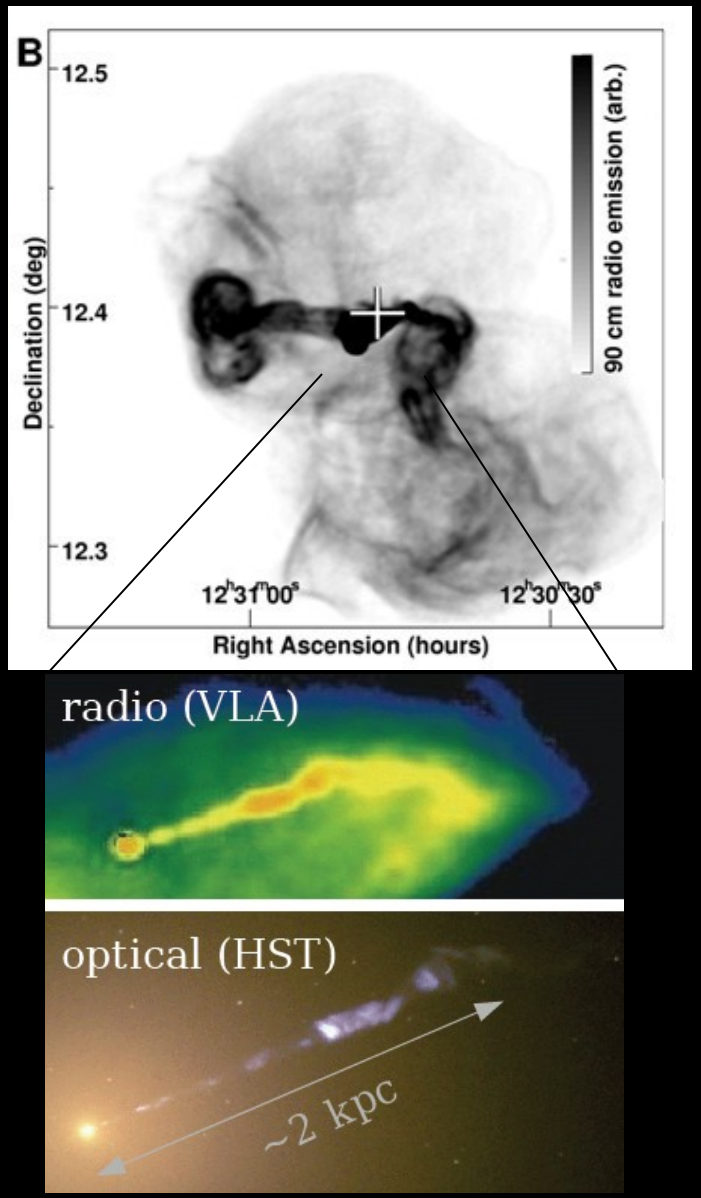


No Comment

M87

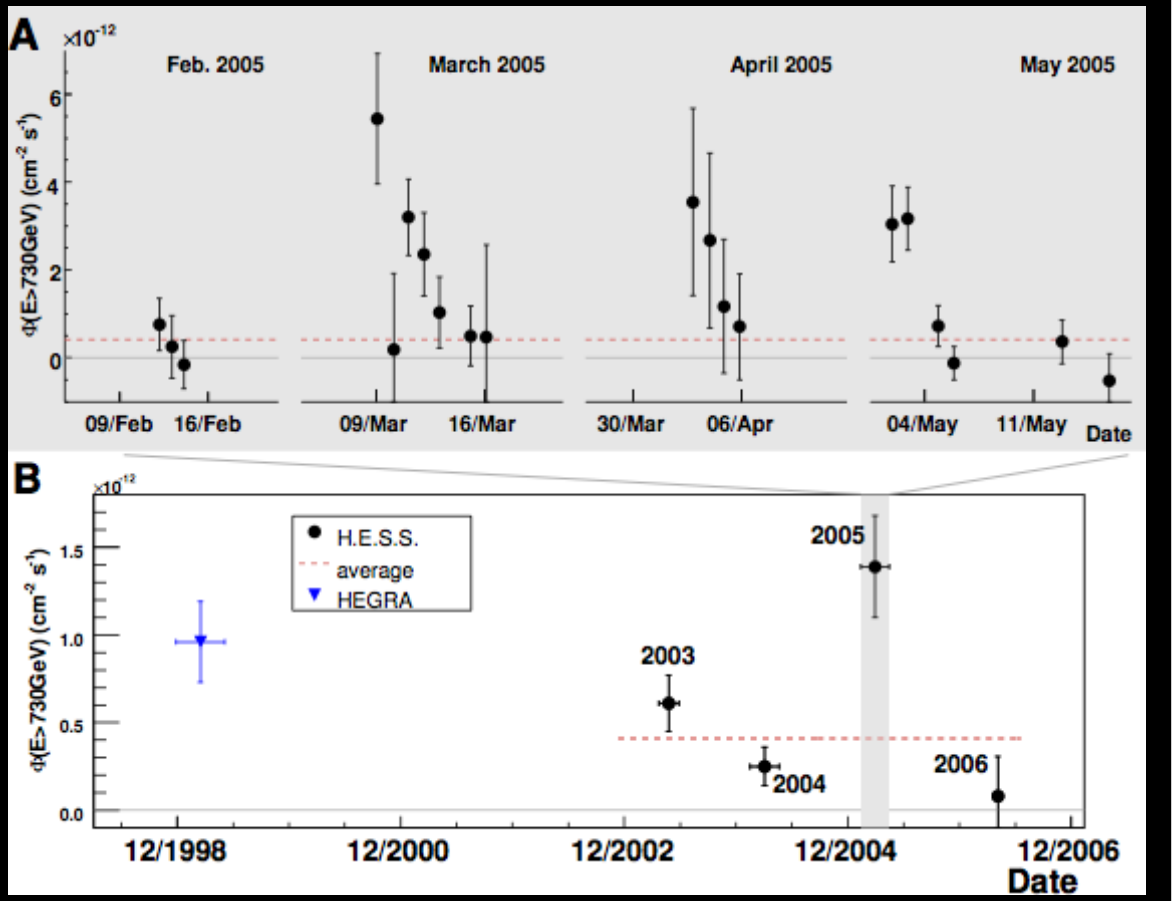
- Famous nearby radio galaxy
  - 16 Mpc, Jet angle ~30°
- HESS 2 day variability
  - Emission region

    $< 5\ \delta\ R_S$
- VERITAS 5.1 σ
  - Observations in 2007
- Emission site?
  - Knot HST1?
  - Very close to SMBH?
- Mechanism?
  - Hard spectrum $\Gamma = 2.2$ is a challenge for ‘standard’ models



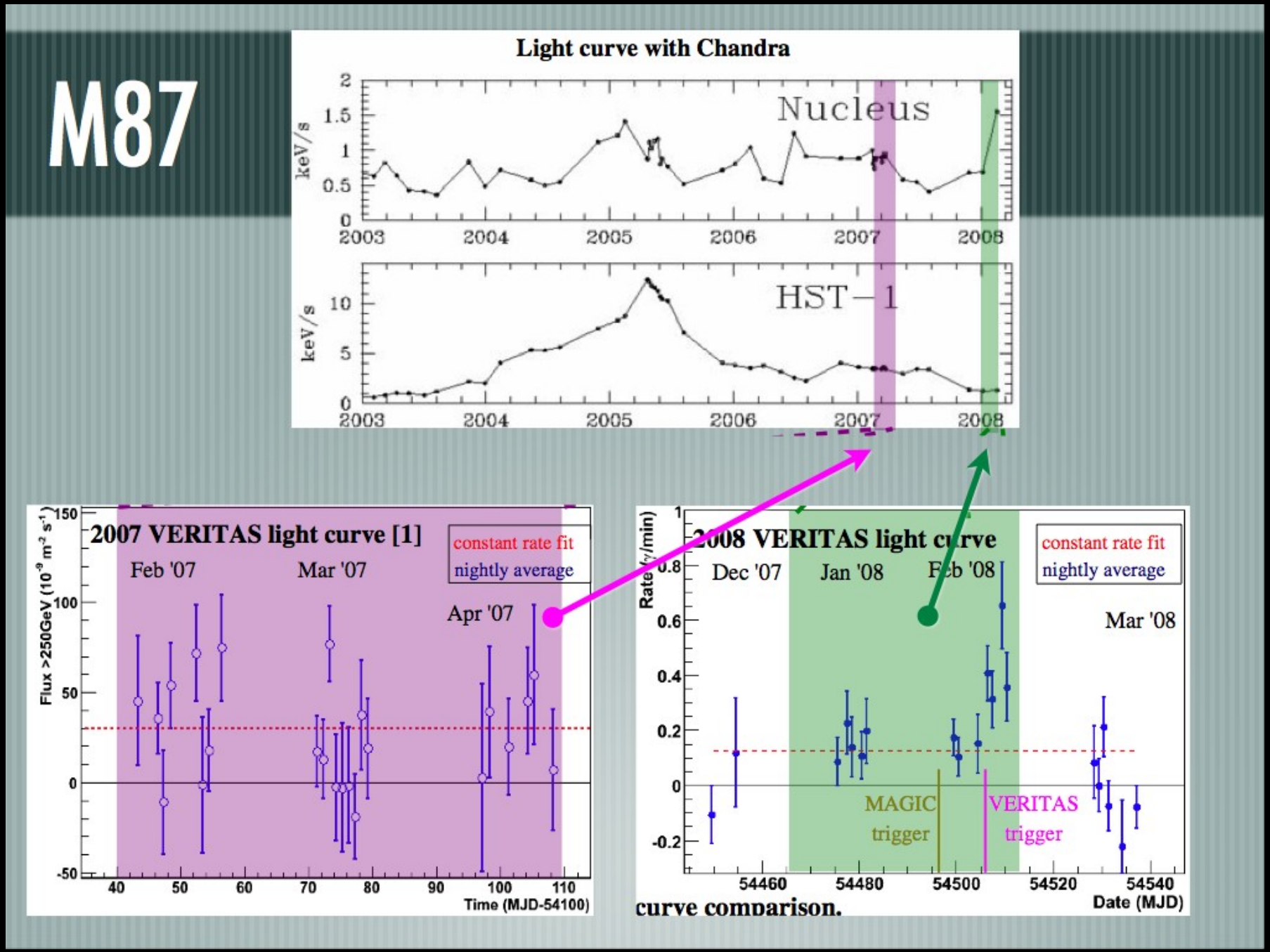
M87

- **HESS: Long** (year) and **short** (days) term **variability**
- Low flux ~1-2% Crab
  High flux ~10-15% Crab



- Monitoring campaign by **HESS**, **MAGIC** & **VERITAS**

M87: Veritas obserrvations

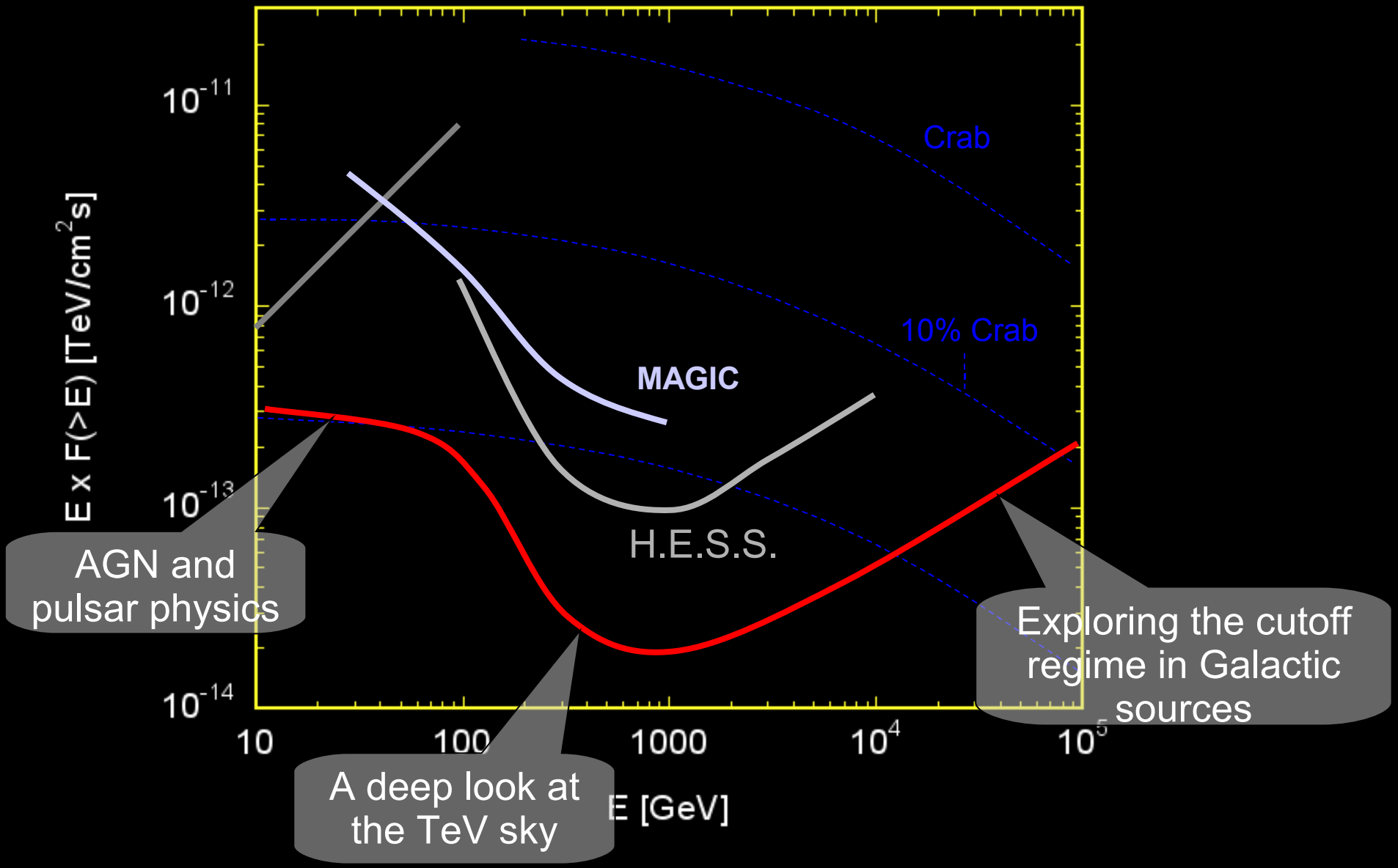


Near term: HESS-II & MAGIC-II

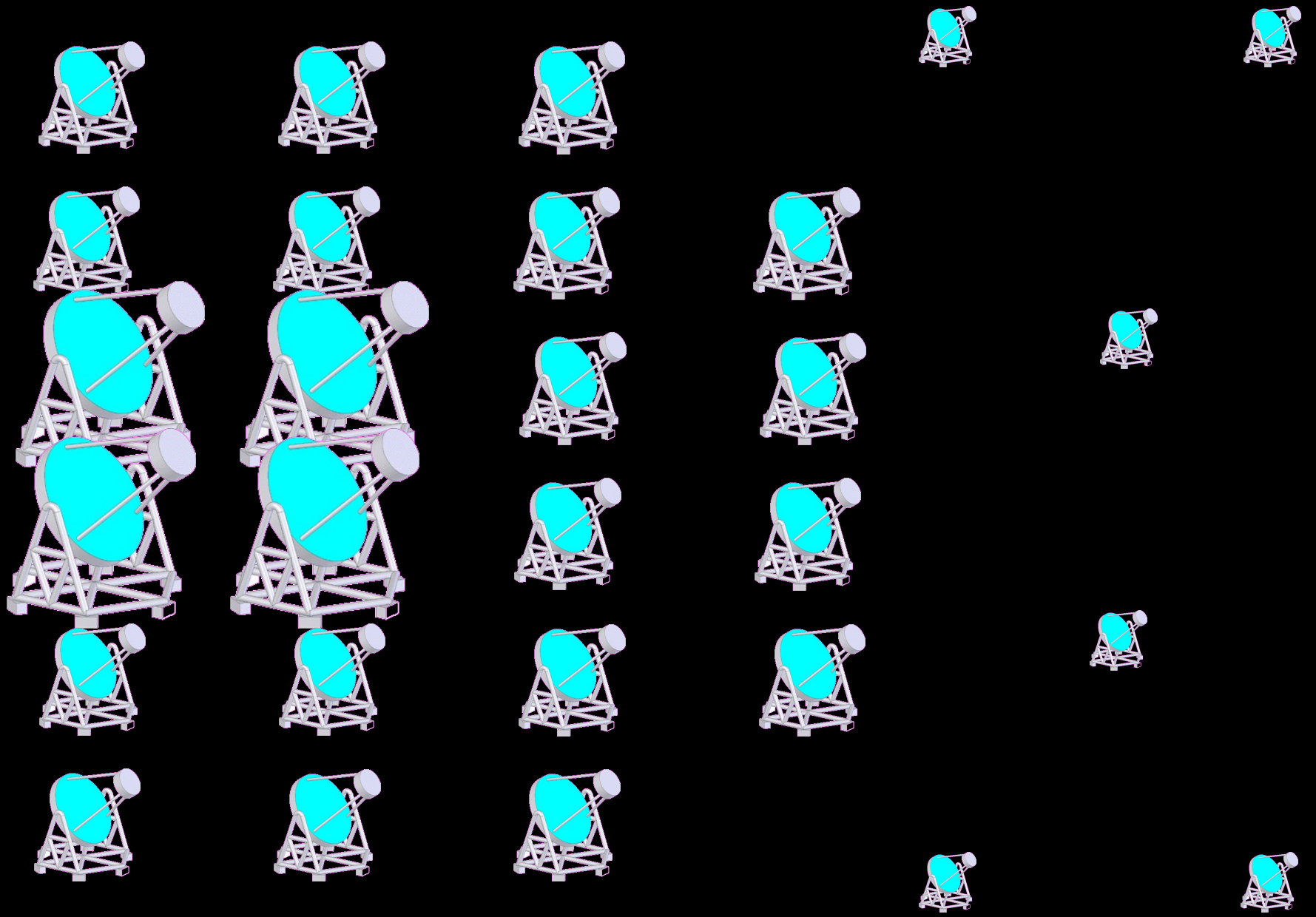
HESS-II : 4x12m +
28m diameter telescope
Lower threshold energy
In 2009

MAGIC-II: 2x17m,
High Q.E. detectors
Lower threshold energy
High Precision
In 2008

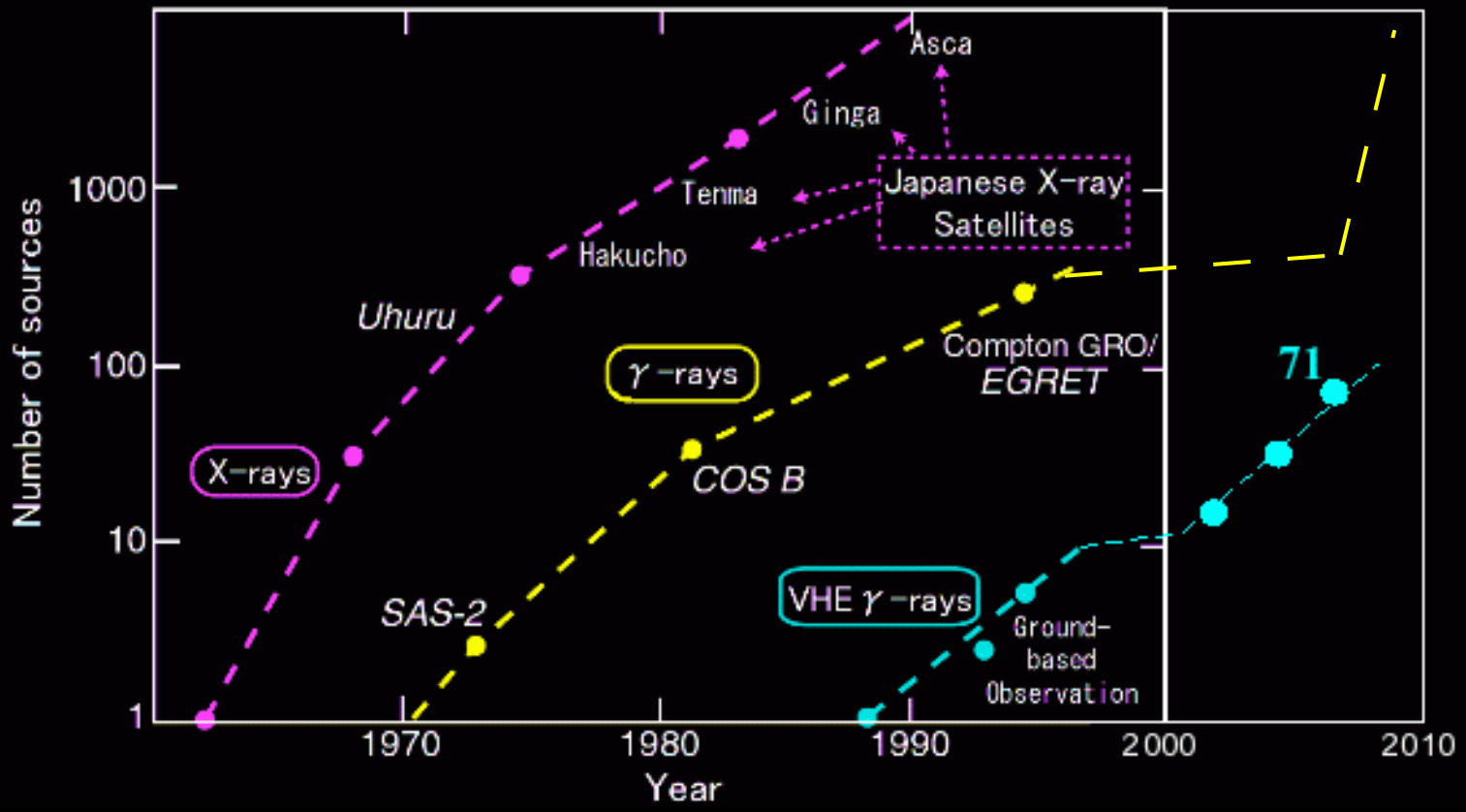
Mid term Project : CTA (Cherenkov Telescope Array)



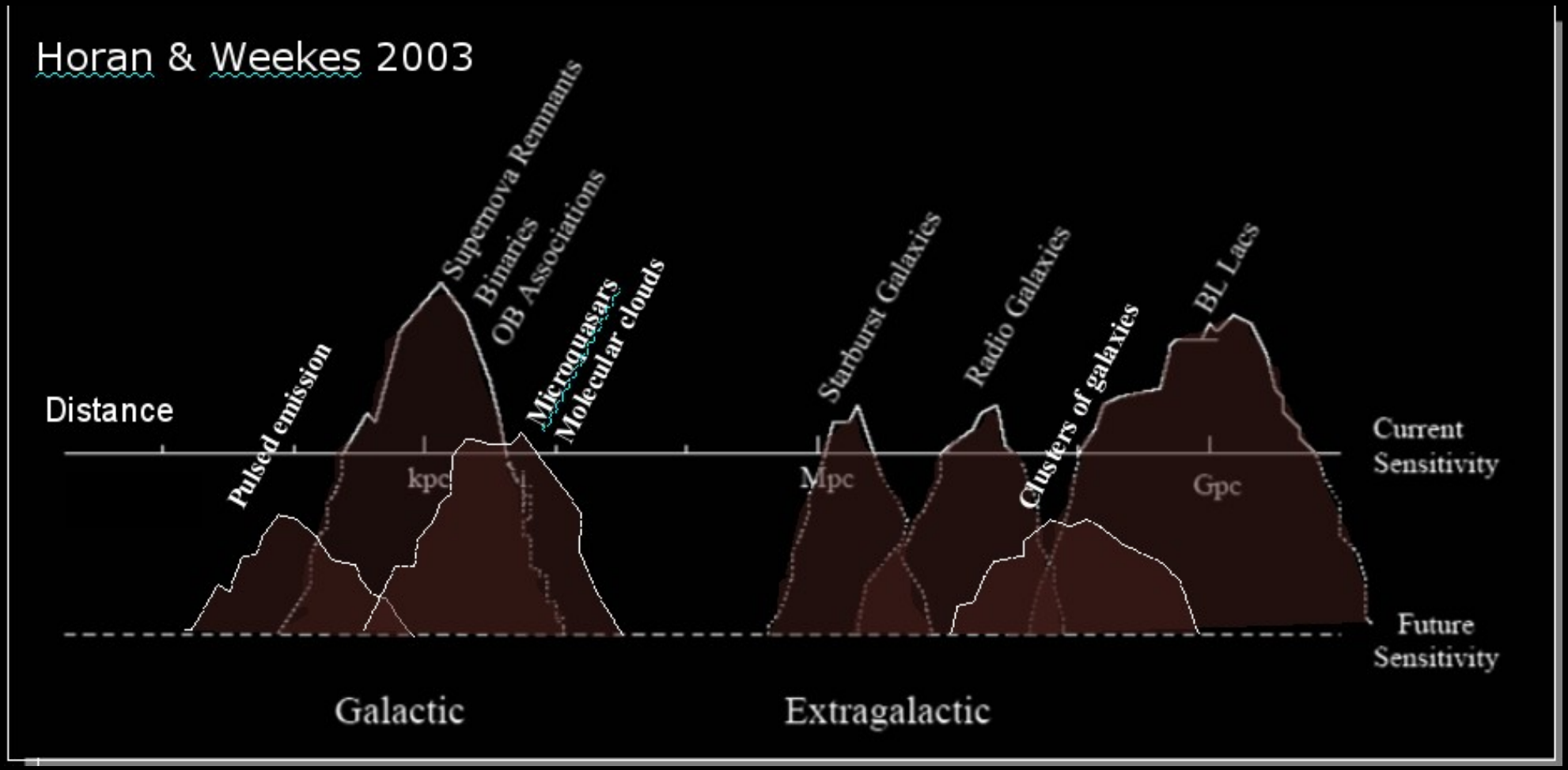
Mid term Project : CTA (Cherenkov Telescope Array)



Perspectives



Perspectives

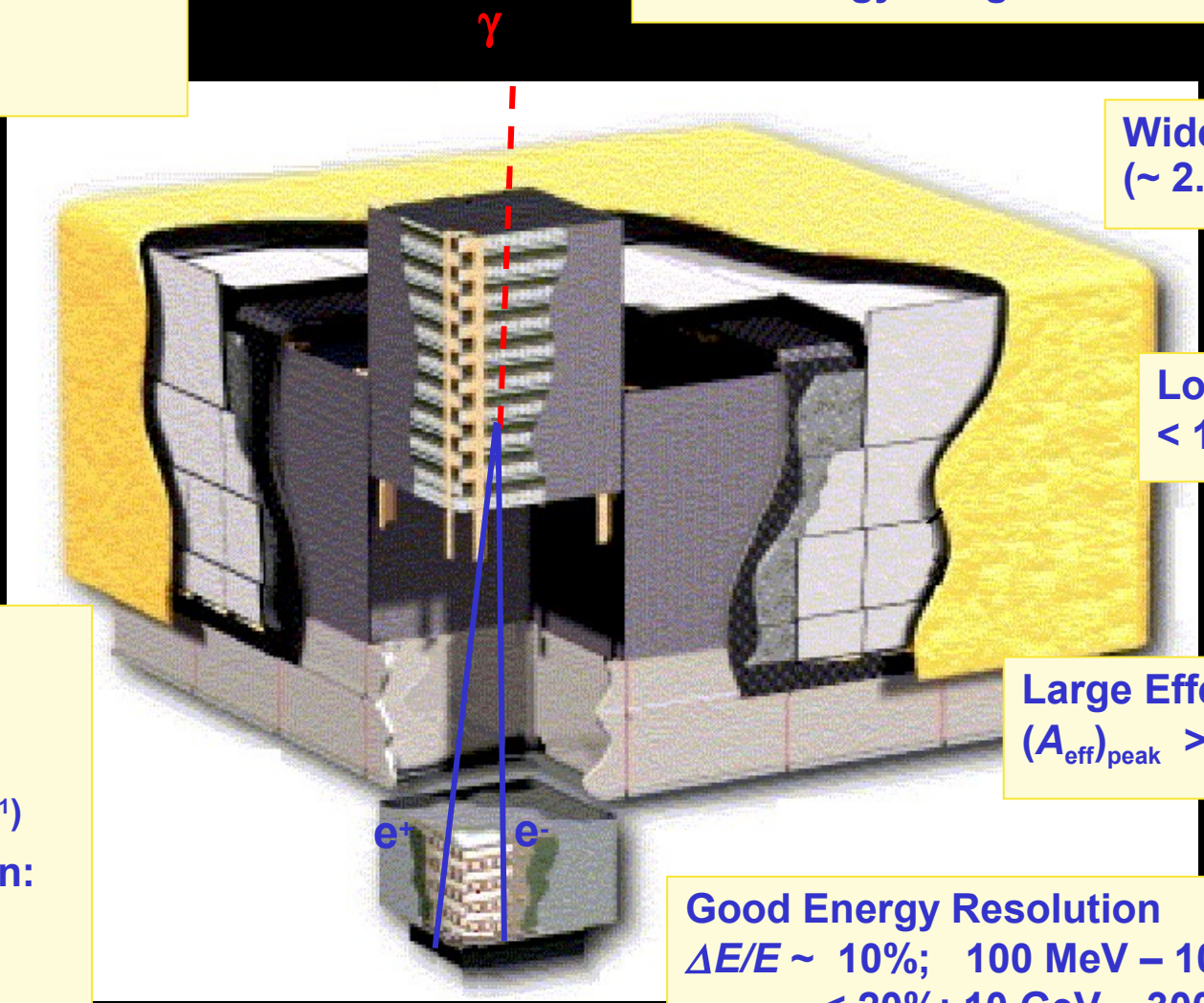


- Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, but this is clearly only the tip of the iceberg
- Broad and diverse program ahead, combining guaranteed astrophysics with significant discovery potential

GLAST measures the direction, energy & arrival time of celestial γ-rays

Single Photon Angular Resolution
3.5° @ 100 MeV
0.15° @ 10 GeV

Wide Energy Range: 20 MeV … ~300 GeV



Wide Field of View
(~ 2.4 sr)

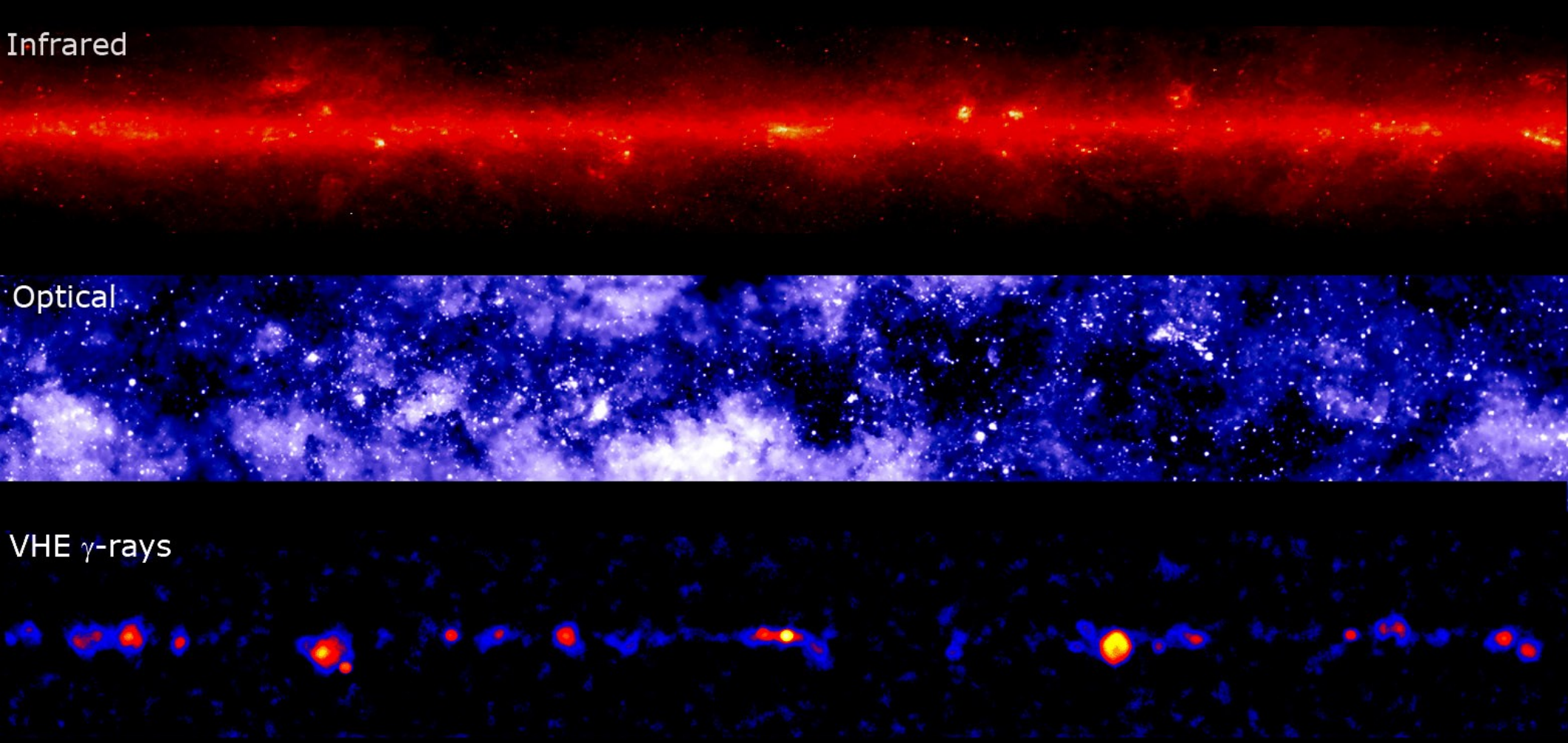
Low dead time:
< 100 μs/event

Point Source Sensitivity:
< 6 x 10^{-9} ph $cm^{-2}s^{-1}$
(est. performance: < 3 x 10^{-9} ph $cm^{-2}s^{-1}$)

Source Localization:
0.3' – 1'

Large Effective Area
$(A_{eff})_{peak}$ > 8,000 cm^2

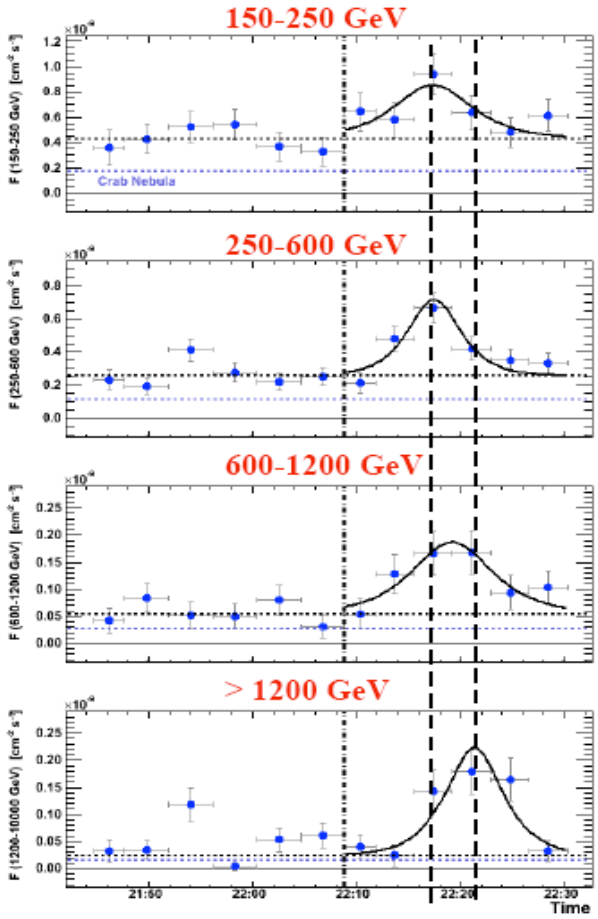
Good Energy Resolution
$\Delta E/E$ ~ 10%; 100 MeV – 10 GeV
~ < 20%; 10 GeV – 300 GeV



The age of real VHE gamma ray astronomy has started

Blazars and Lorentz invariance: MAGIC Claim

Blazar Mrk 501, July 2005 (astro-ph/0702008)



LCs for different energy ranges (4 min bins)

July 9

Flare is seen in all energy ranges

Time delay of 4 +/- 1 minute between highest and lowest energy ranges

13

Blazars and Lorentz invariance: MAGIC Claim

- If that delay would be fully caused by propagation in the vacuum then:
  - for first order (n=1) =>
    $E_{QG} \sim M_P/200$ +- 25%

  - for second order (n=2) =>
    $E_{QG} \sim 8\ 10^{9}$ GeV $\sim 7\ 10^{-10}\ M_P$

- If delay had an astrophysical origin then the above numbers should be considered as lower bounds on the Quantum Gravity scale
- Most relevant: we provide the most stringent limits to date on Lorentz Invariance.