Very High Energy γ-ray Astronomy: A selected tour of sources

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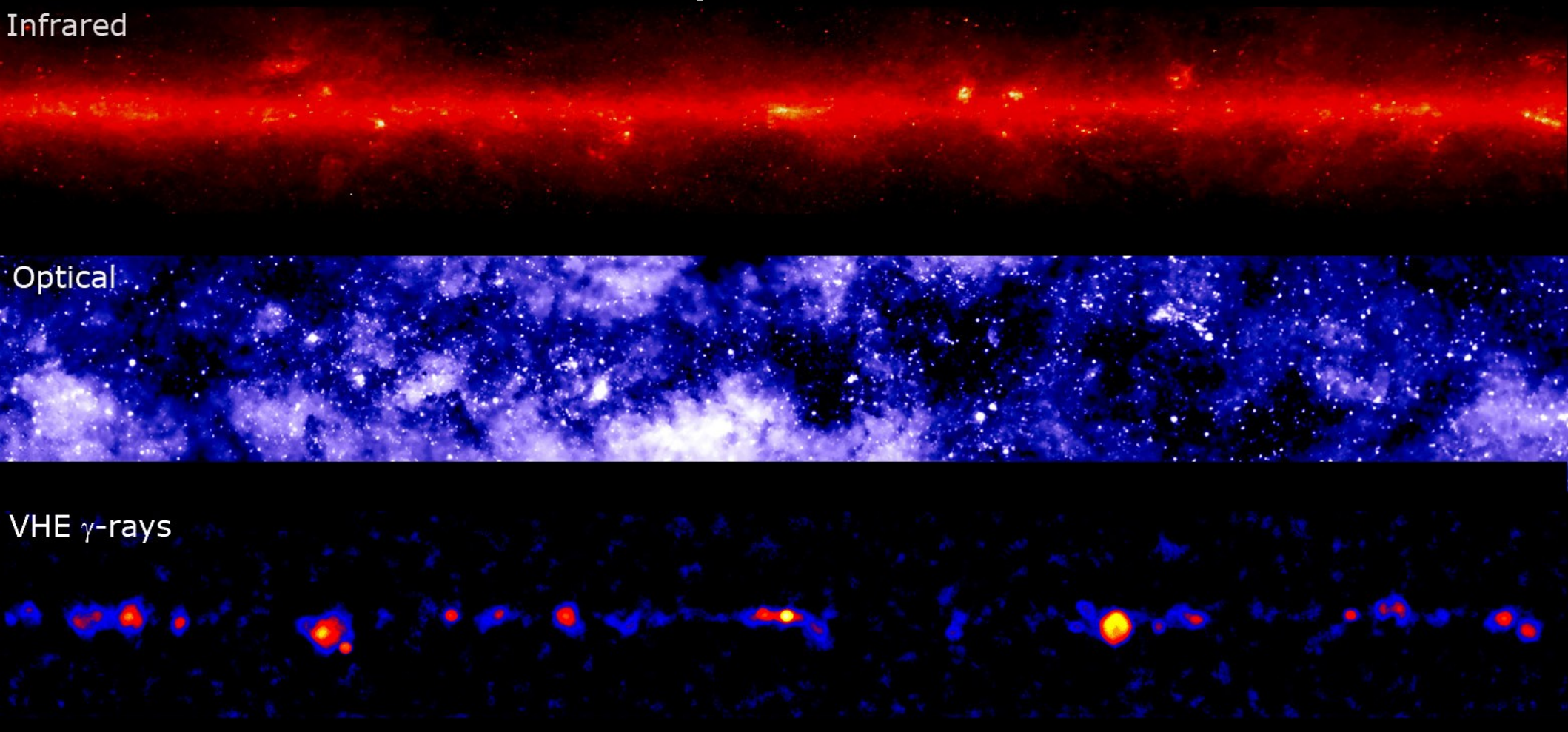
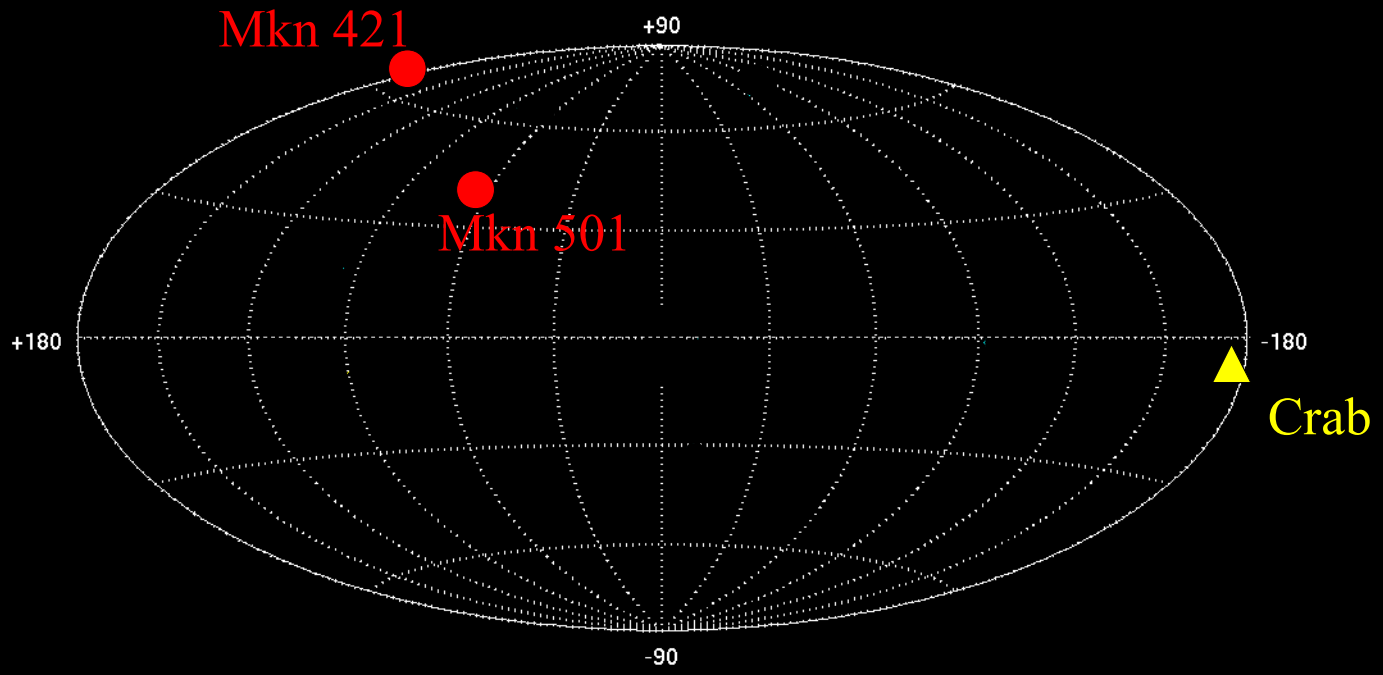
Thanks to many: W.Hofmann, M. Punch,....



TeV Sky 1995

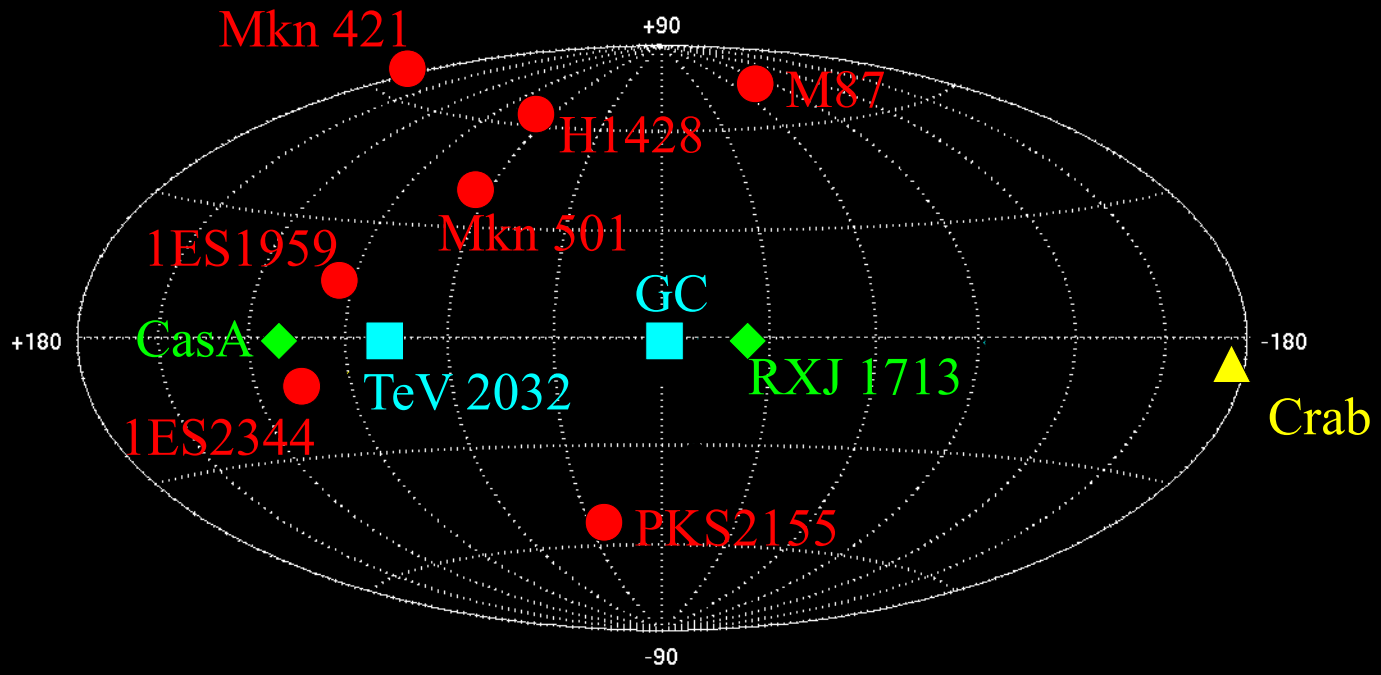
3 sources



▲ Pulsar wind nebulae
● AGNs
◆ SNRs
■ UIDs

TeV Sky 2003

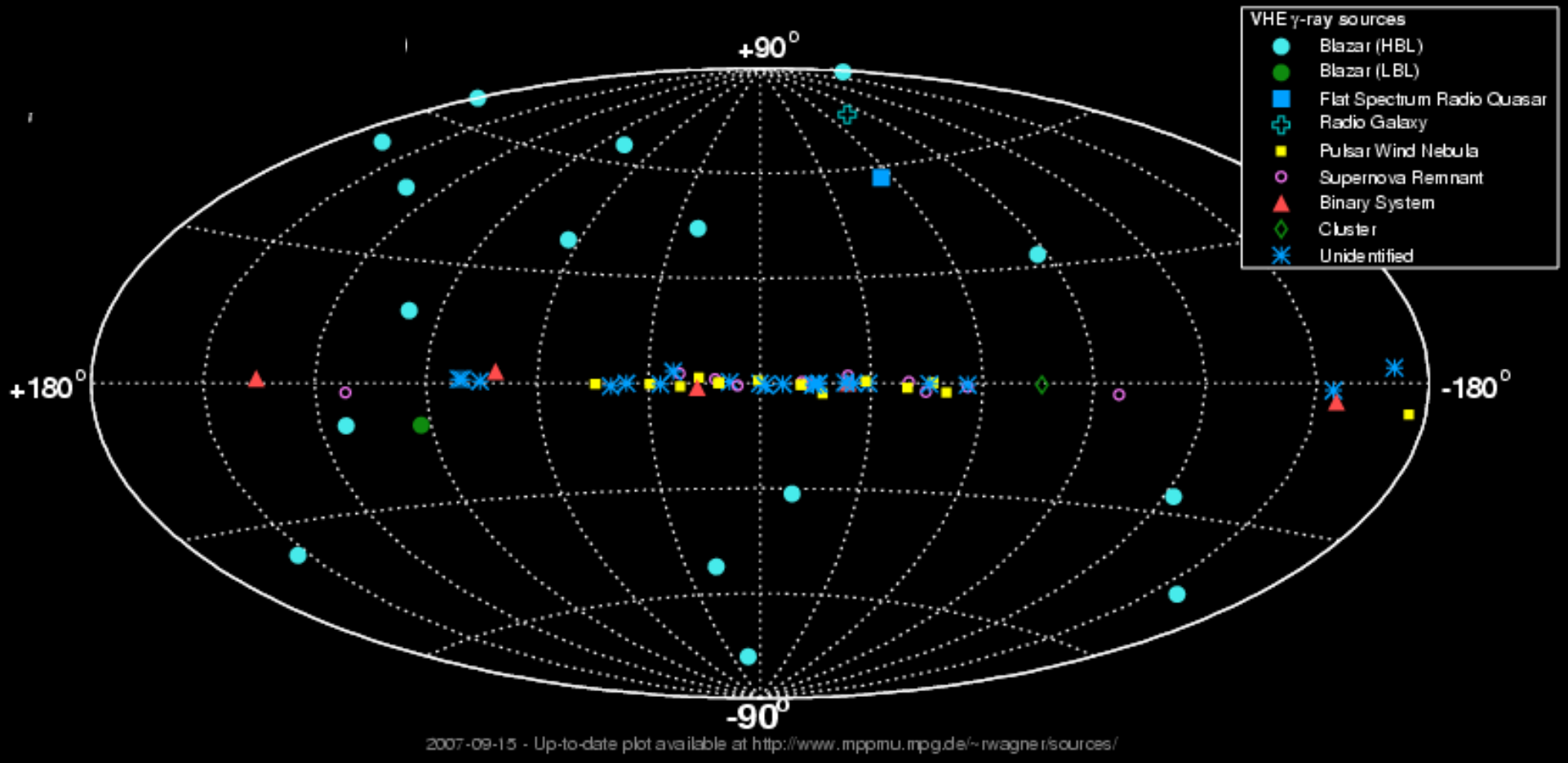
12 sources, 6 firm detections

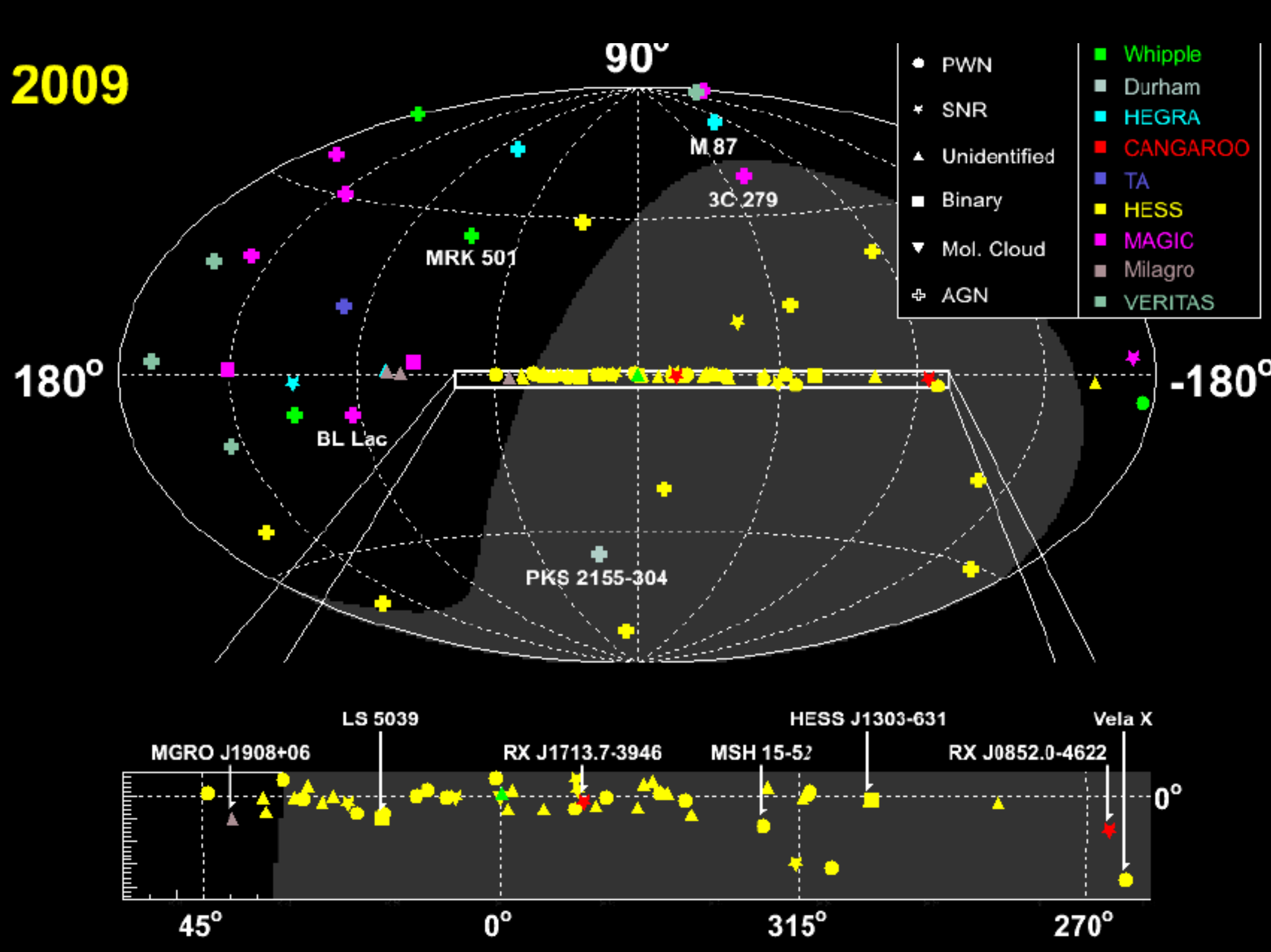


Pulsar wind nebulae
AGNs
SNRs
UIDs

TeV Sky 2008

> 70 Sources




2009
90°
180°
-180°
M 87
3C 279
MRK 501
BL Lac
PKS 2155-304
PWN
SNR
Unidentified
Binary
Mol. Cloud
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
MGRO J1908+06
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
Vela X
0°
45°
0°
315°
270°

VHE γ-ray sources

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

GALACTIC :

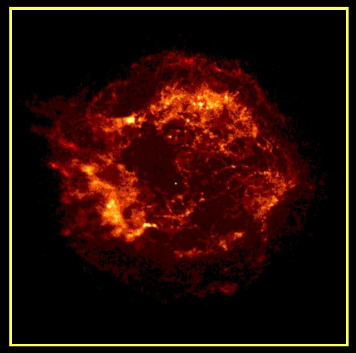
- Young Shell type Supernova Remnants (a word on expected neutrinos)
- Older and/or Interacting SNRs
- Composite SNRs
- Pulsar Wind Nebulae (PWN)
- Binary Systems (LS 5039, LSI +61 303)
- Variable PWN in binary
- Open Stellar Clusters
- Galactic Center
- Galactic diffuse emission
- Unidentified sources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

EXTRAGALACTIC :

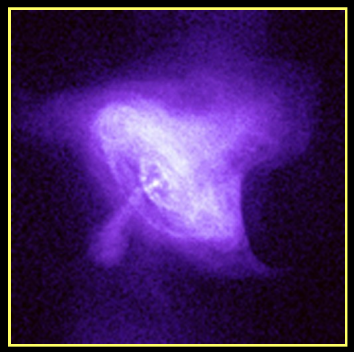
- Blazars
- Radiogalaxies (FRI: M87)
- Flat Spectrum Radio Quasars (3C 273, recent)
- Extragalactique Background Light (EBL)
- Multiwave-length campains
- Starburst Galaxies
- GRBs (UL)
- ...

Science topics

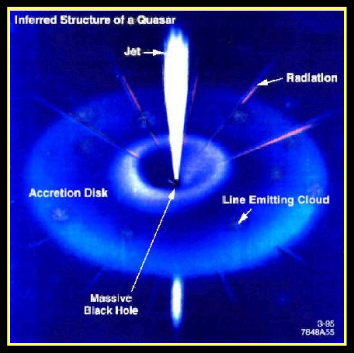
Origin of cosmic rays



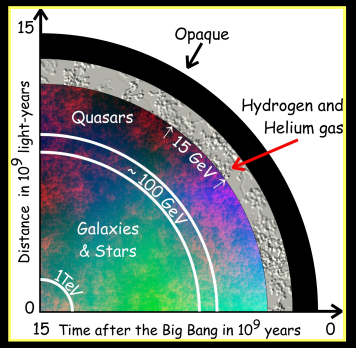
SNRs



Pulsars and PWN

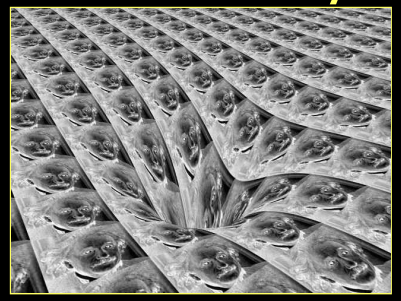


AGNs

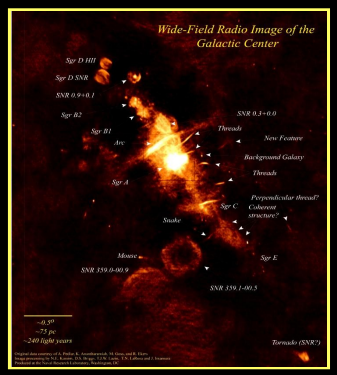


Cosmology

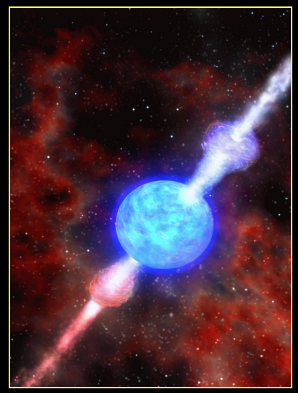
Space-time & relativity



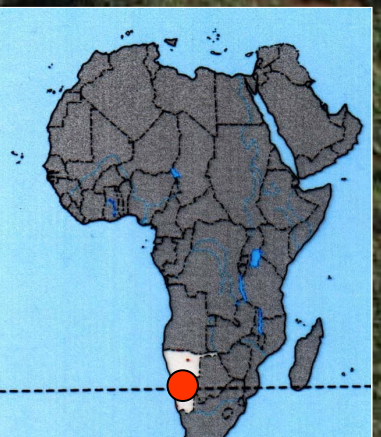
Dark matter



GRBs

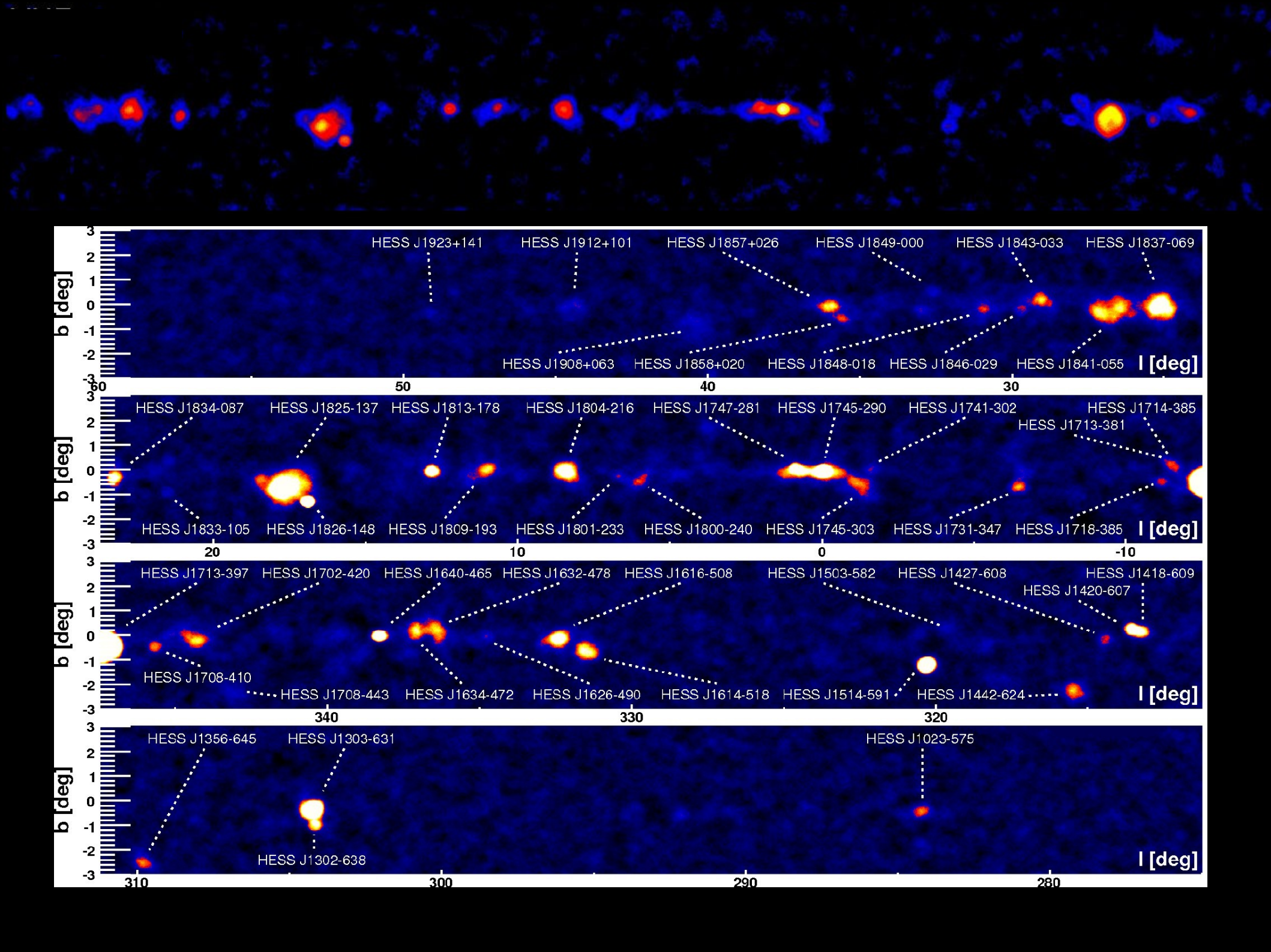


2004-2007
Galactic plane survey
by HESS



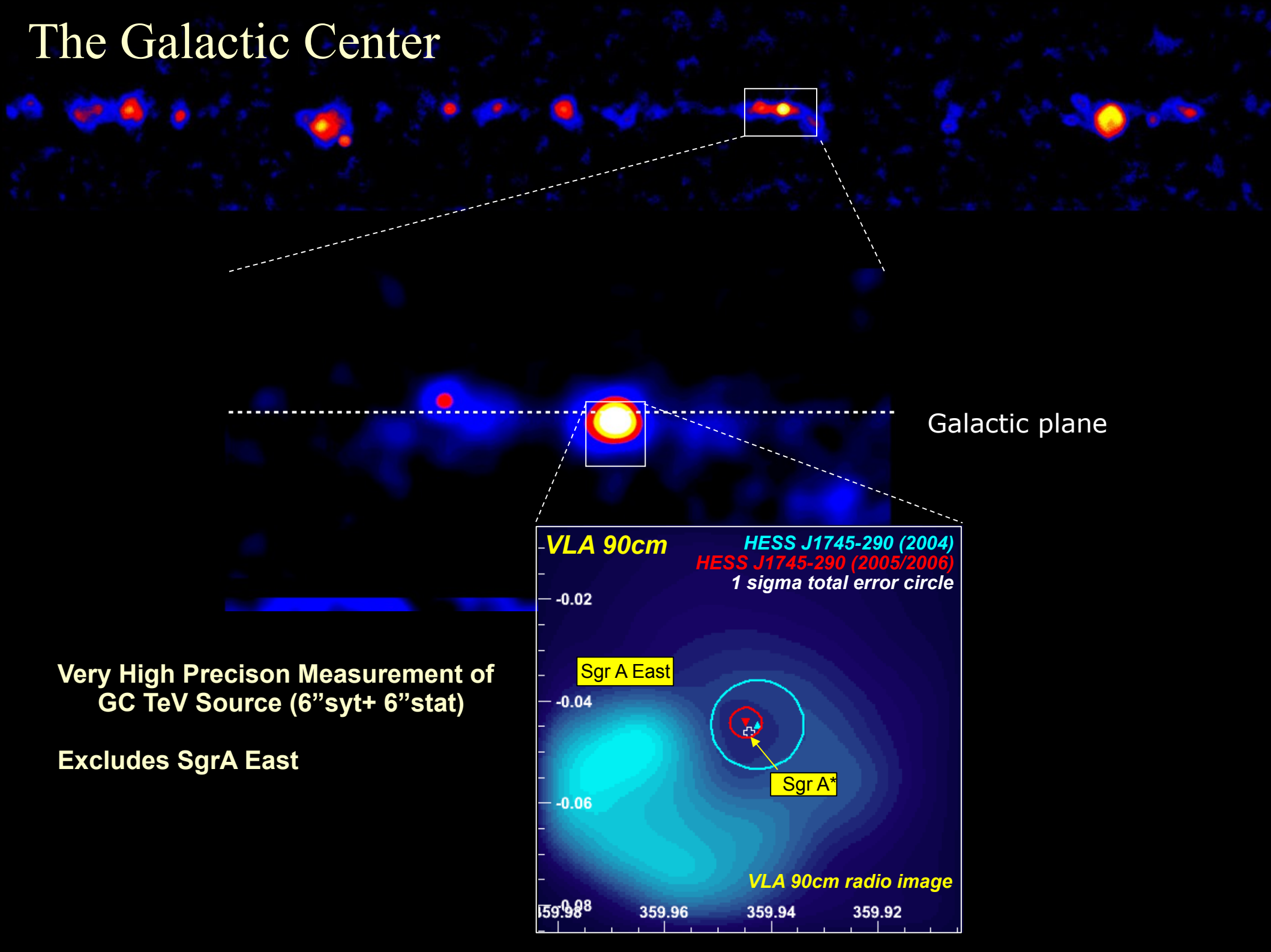
Key location: Namibia

Galactic Plane Survey


HESS J1923+141
HESS J1912+101
HESS J1857+026
HESS J1849-000
HESS J1843-033
HESS J1837-069
HESS J1908+063
HESS J1858+020
HESS J1848-018
HESS J1846-029
HESS J1841-055
HESS J1834-087
HESS J1825-137
HESS J1813-178
HESS J1804-216
HESS J1747-281
HESS J1745-290
HESS J1741-302
HESS J1714-385
HESS J1713-381
HESS J1833-105
HESS J1826-148
HESS J1809-193
HESS J1801-233
HESS J1800-240
HESS J1745-303
HESS J1731-347
HESS J1718-385
HESS J1713-397
HESS J1702-420
HESS J1640-465
HESS J1632-478
HESS J1616-508
HESS J1503-582
HESS J1427-608
HESS J1418-609
HESS J1420-607
HESS J1708-410
HESS J1708-443
HESS J1634-472
HESS J1626-490
HESS J1614-518
HESS J1514-591
HESS J1442-624
HESS J1356-645
HESS J1303-631
HESS J1023-575
HESS J1302-638
b [deg]
l [deg]

The Galactic Center

The Galactic Center

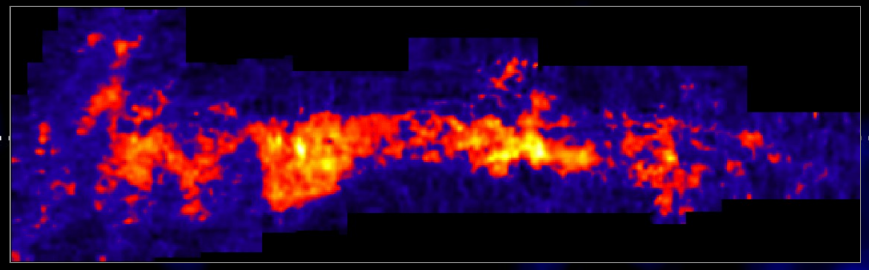


Very High Precison Measurement of GC TeV Source (6”syt+ 6”stat)

Excludes SgrA East

The Galactic Diffuse emission @ central 100 pc

H.E.S.S.



GC molecular clouds
Tsuboi et al. 1999

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

Point sources subtracted

Emission along the Galactic Plane

Mystery Source HESS J1745-303

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

ORIGIN OF GC TeV Gamma-Rays?

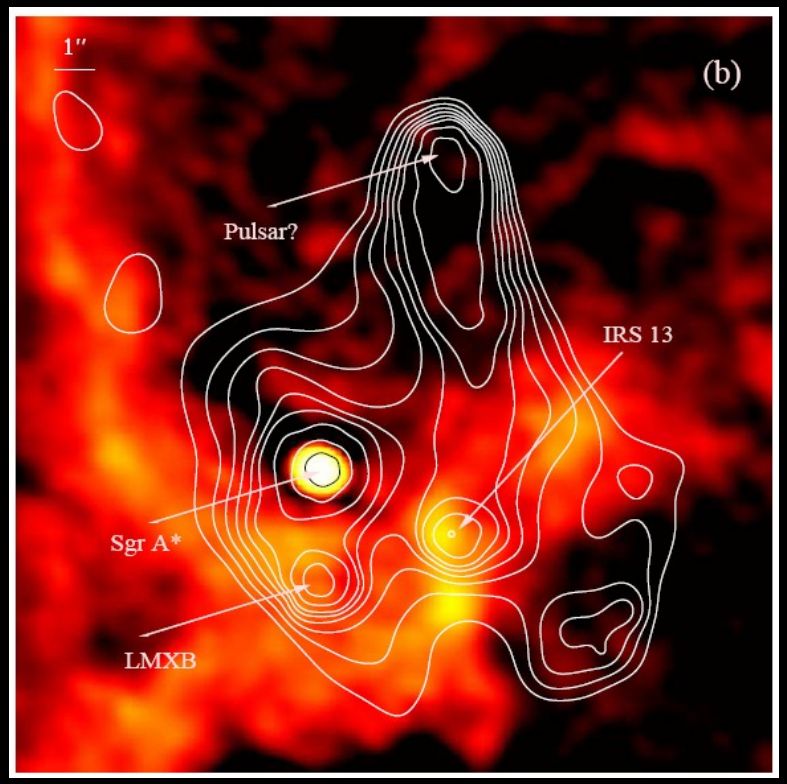
Normal :

Curvature radiation of UHE protons near SgrA* ?

Shocks in SgrA* accretion flow or wind?

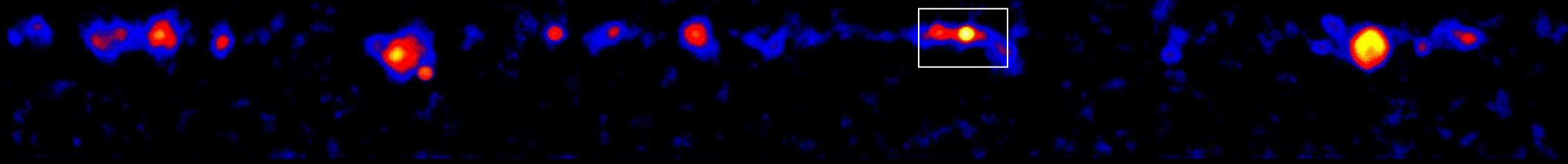
Decaying UHE neutrons?

The PWN G359.95-0.04?



Chandra contours
Weng et al. 2005

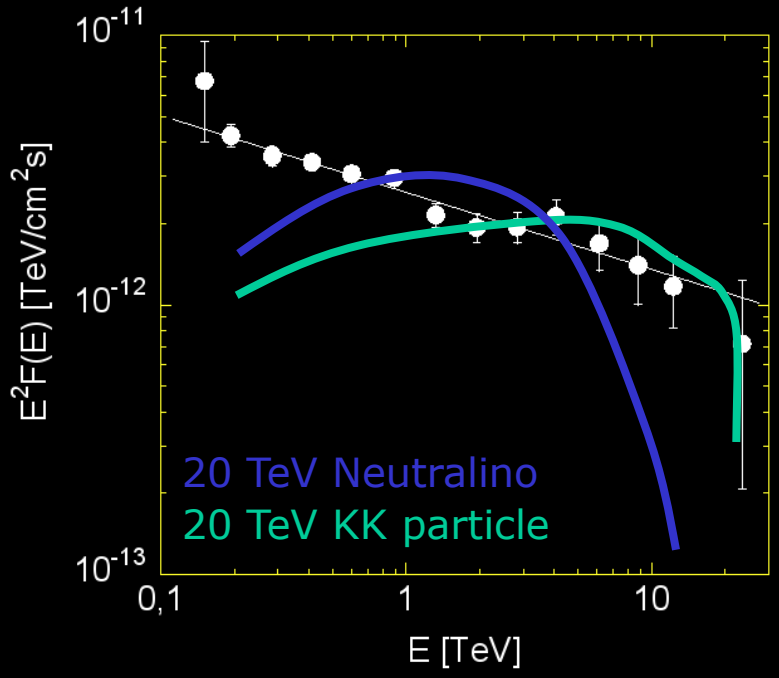
ORIGIN OF GC TeV Gamma-Rays?



Top down:
Annihilation of dark matter particles

$\chi\,\chi \rightarrow qq,\ gg$

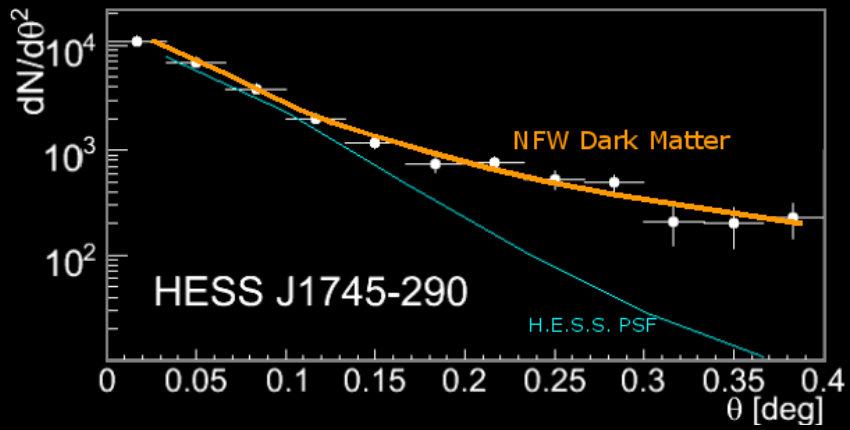
Spectrum?

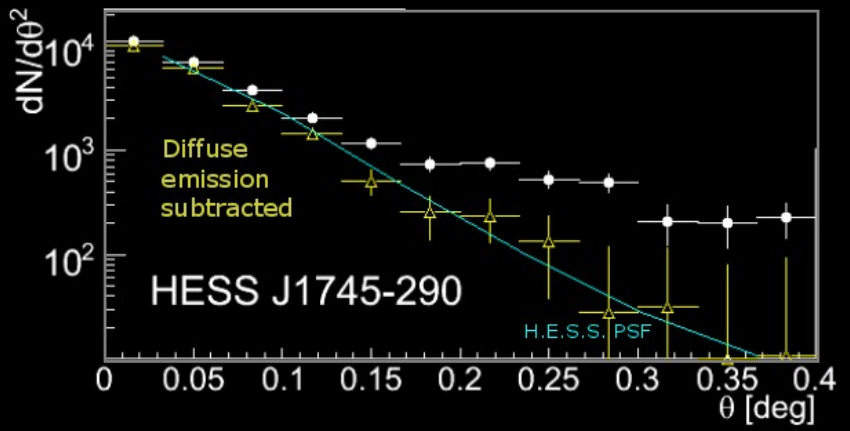


proposed based on early H.E.S.S. data

proposed before H.E.S.S. data

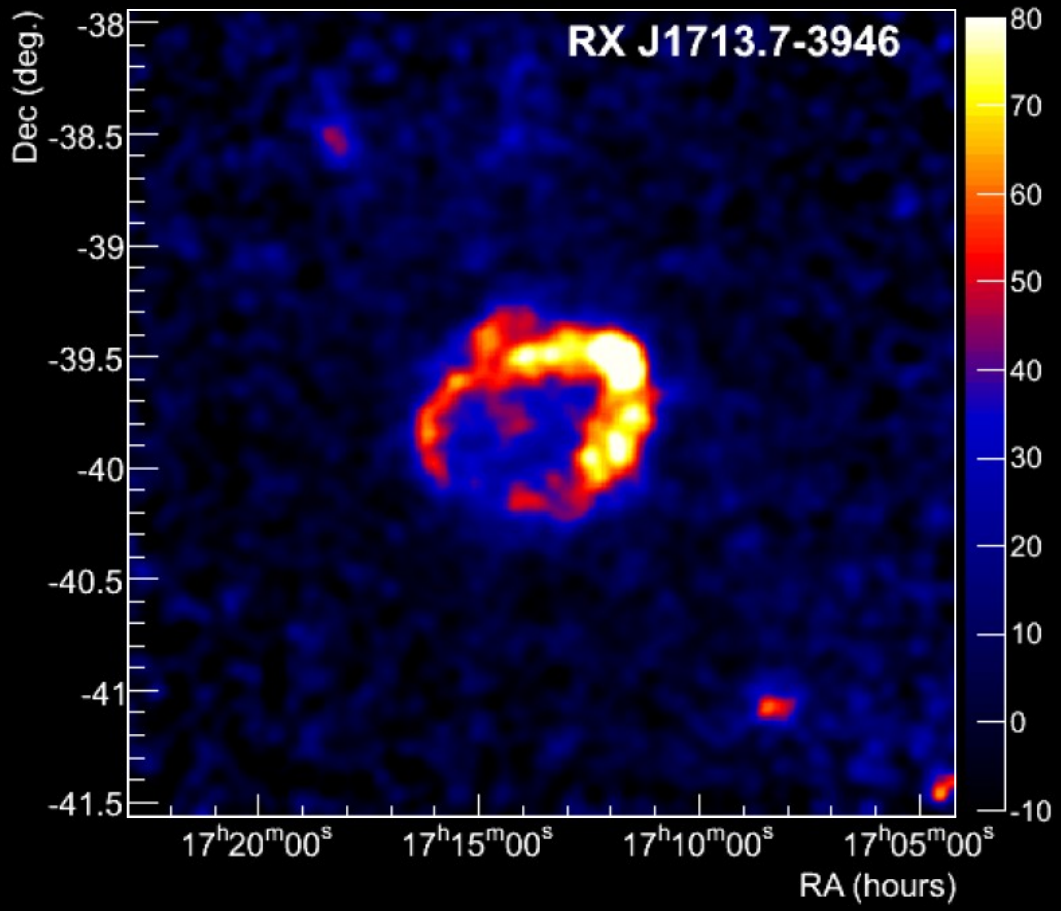
Angular distribution?



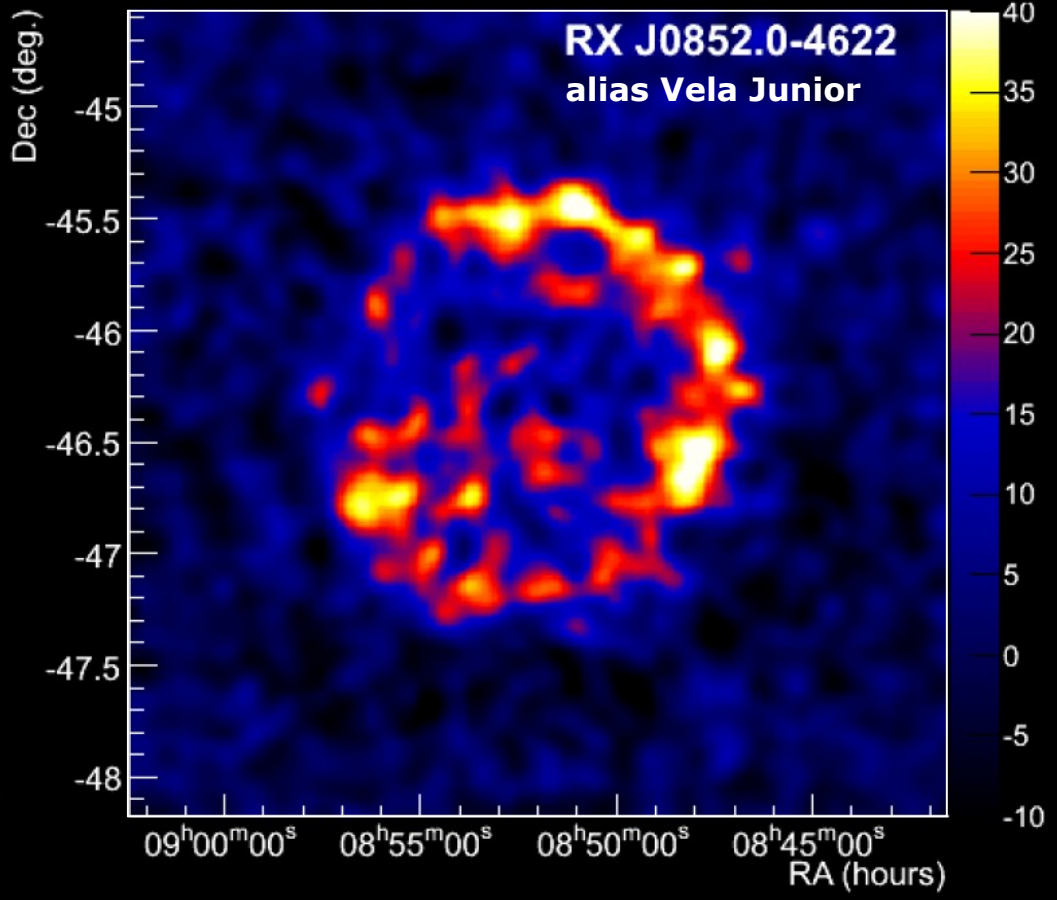


Young Shell type SNRs

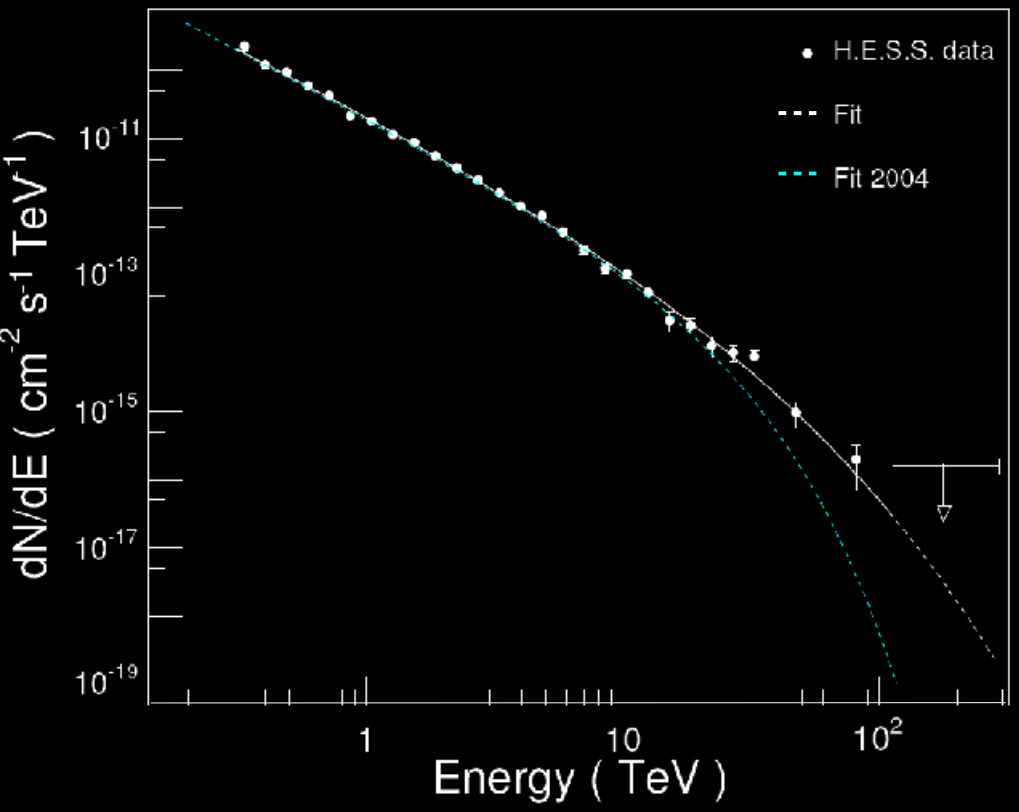
RX J1713.7-3946
First-ever resolved γ-ray source
Strong correlation with X-rays: ~80%



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

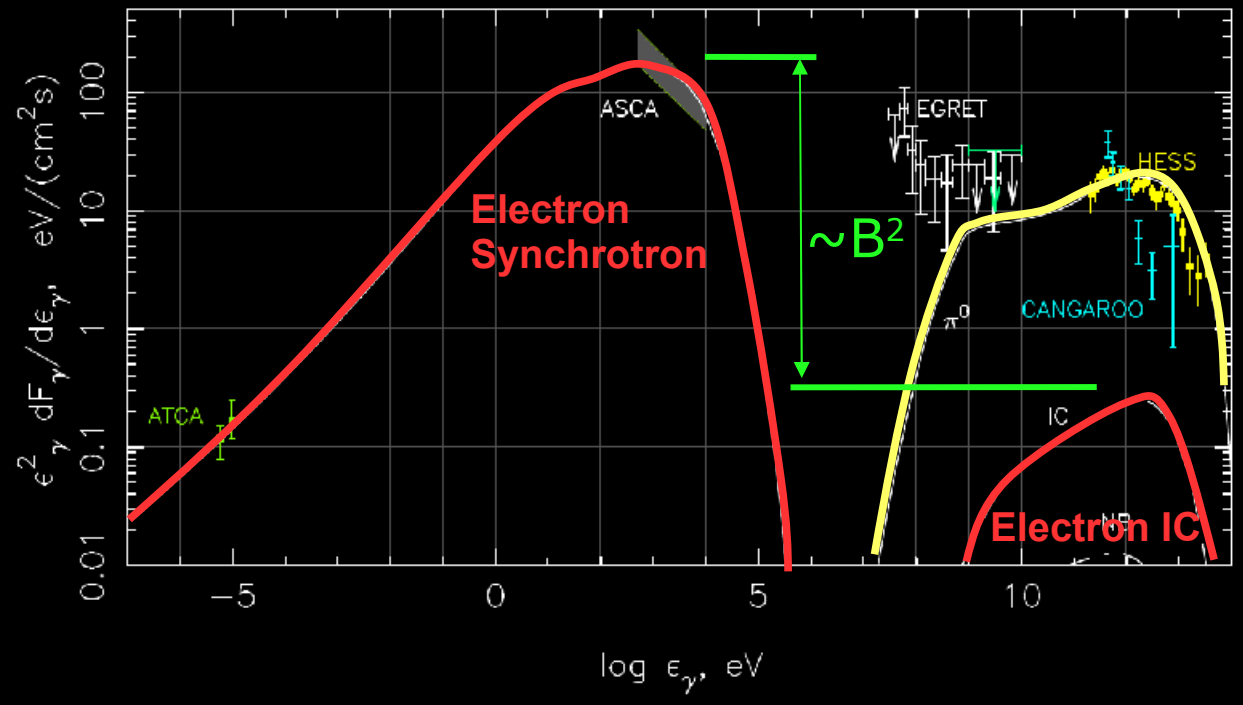


RX J1713.7-39.46 : high energy spectrum end?



- **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



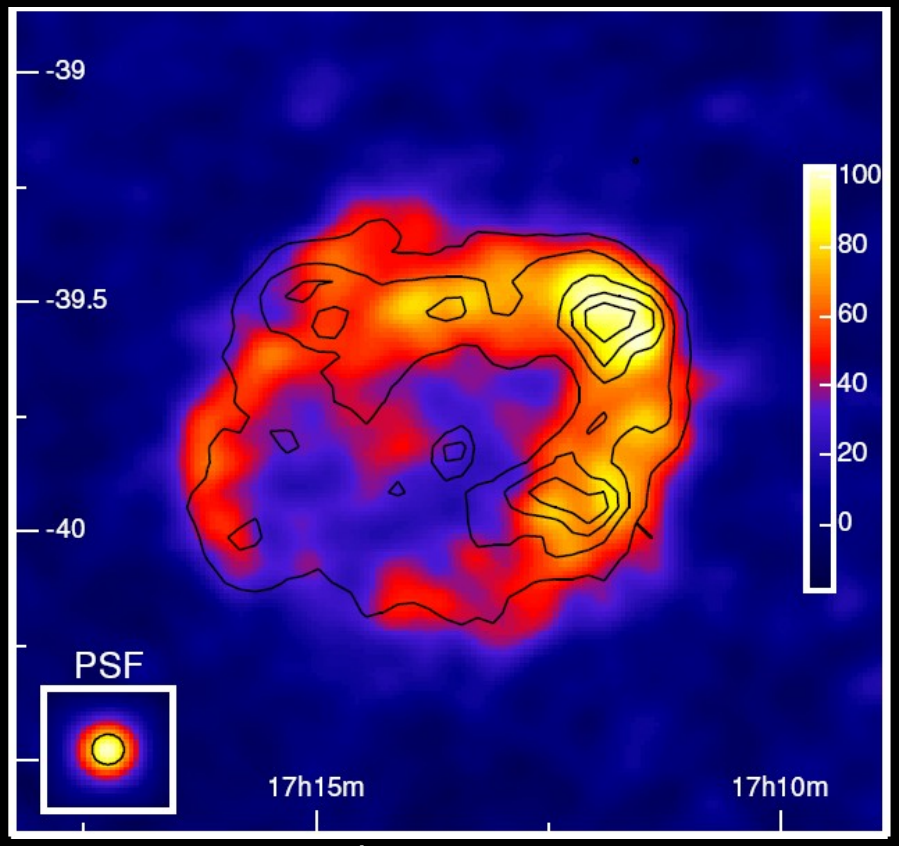
B = 126 μG
e/p= 10^{-4}

B ~10 μG

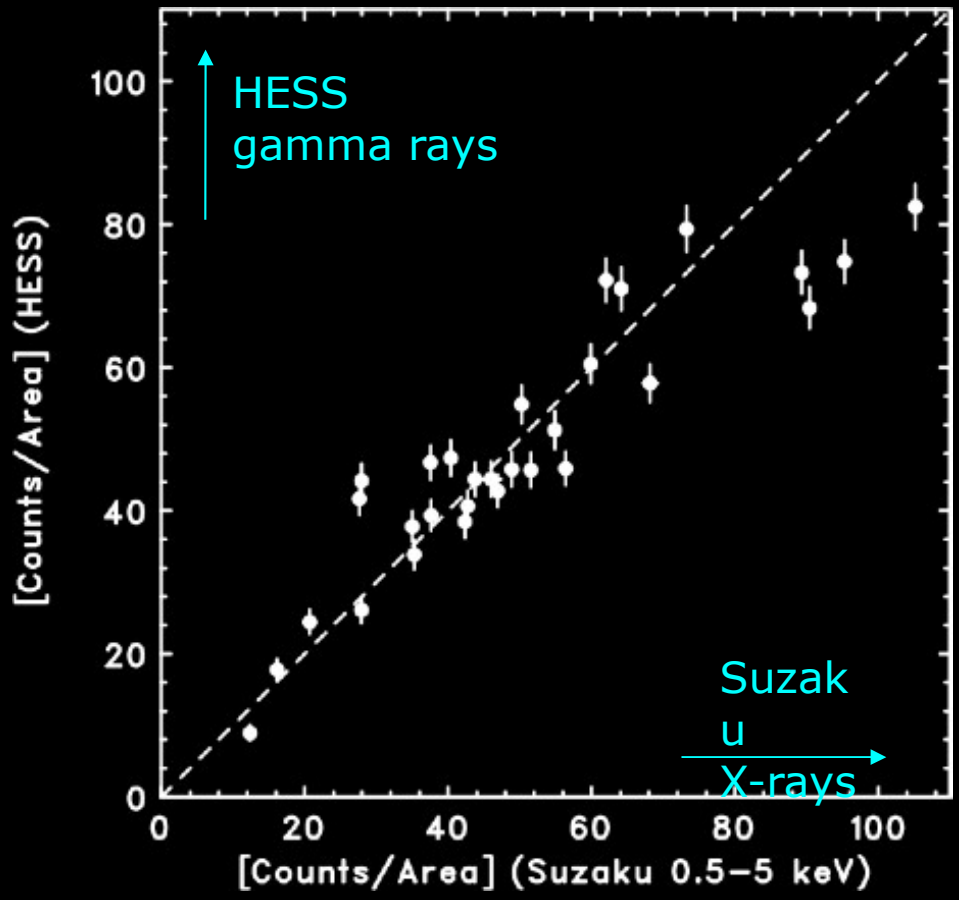
- **High B-fields suppress IC emission**
- **Non-linear effects of efficient CR acceleration can lead to B-field amplification (e.g. thin filaments in SN1006)**

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

X-ray vs γ-ray correlations



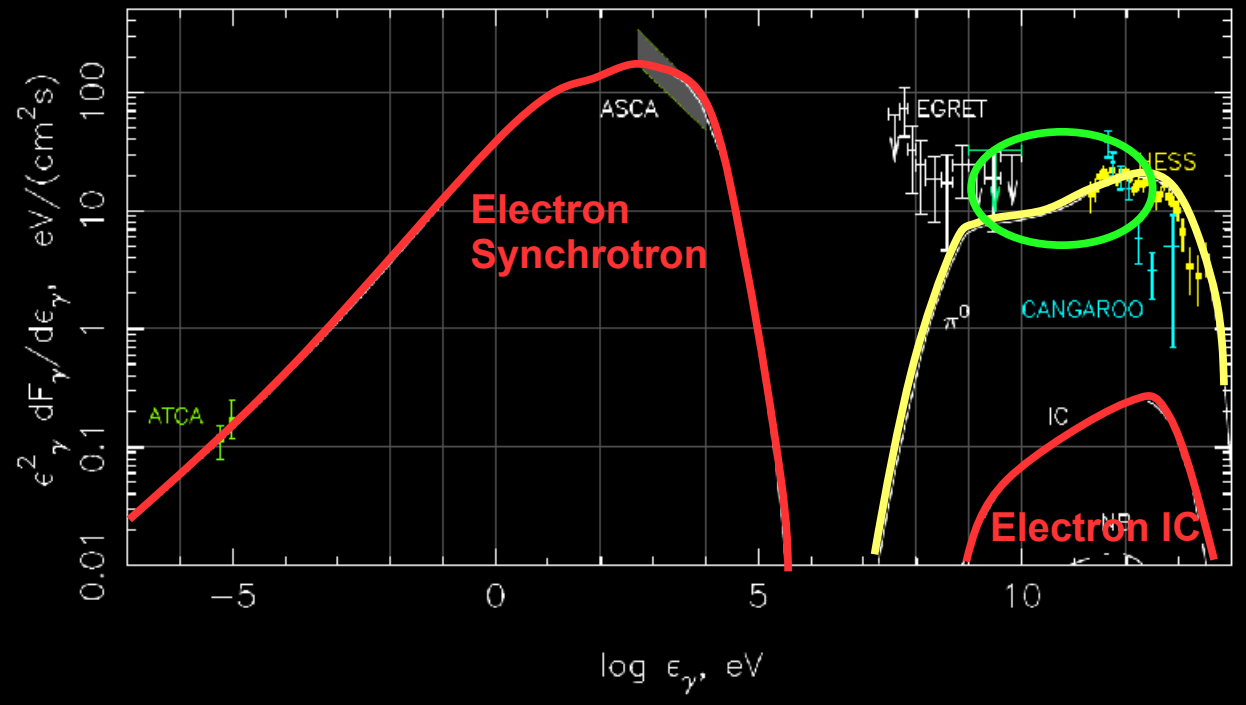
Contour lines: ASCA X-rays
Y. Uchiyama et al. 2002



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

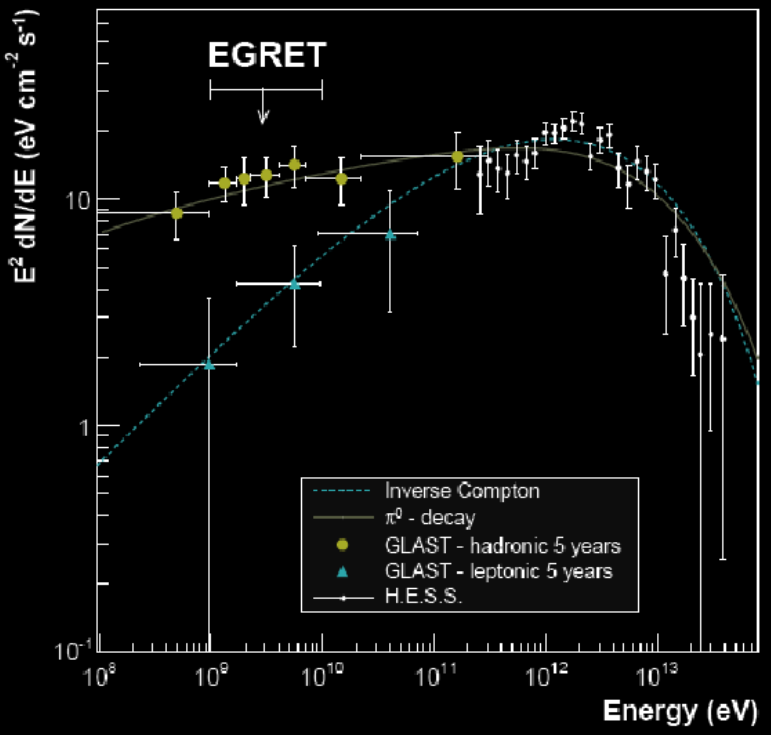
- TeV (if hadronic) **protons ⊗ ρ_{gas}**
- keV (electrons) **electrons ⊗ B^2**
- TeV (if electrons) **electrons ⊗ U**
- But **electrons ∝ protons**
- And **$B^2 \propto \rho_{gas}$**
- Conclusion ??

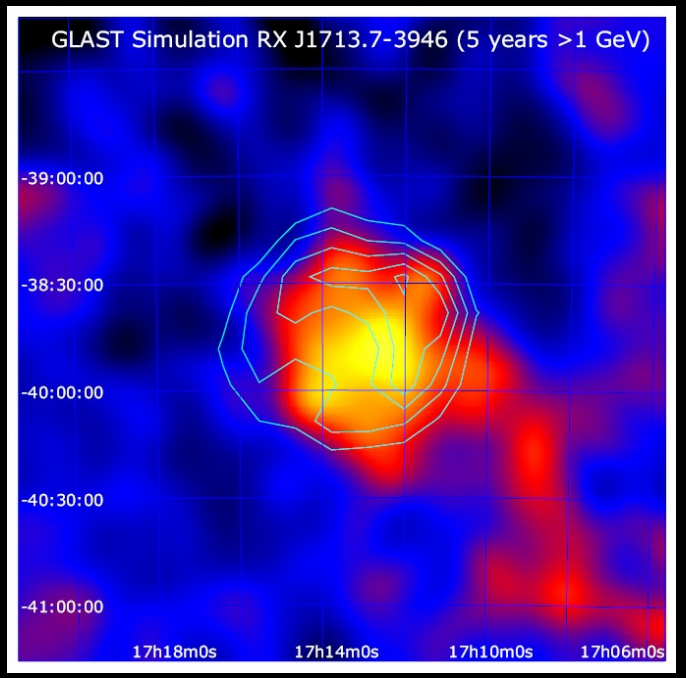
B-field amplification signature?



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

What will Fermi and neutrinos tell us ?





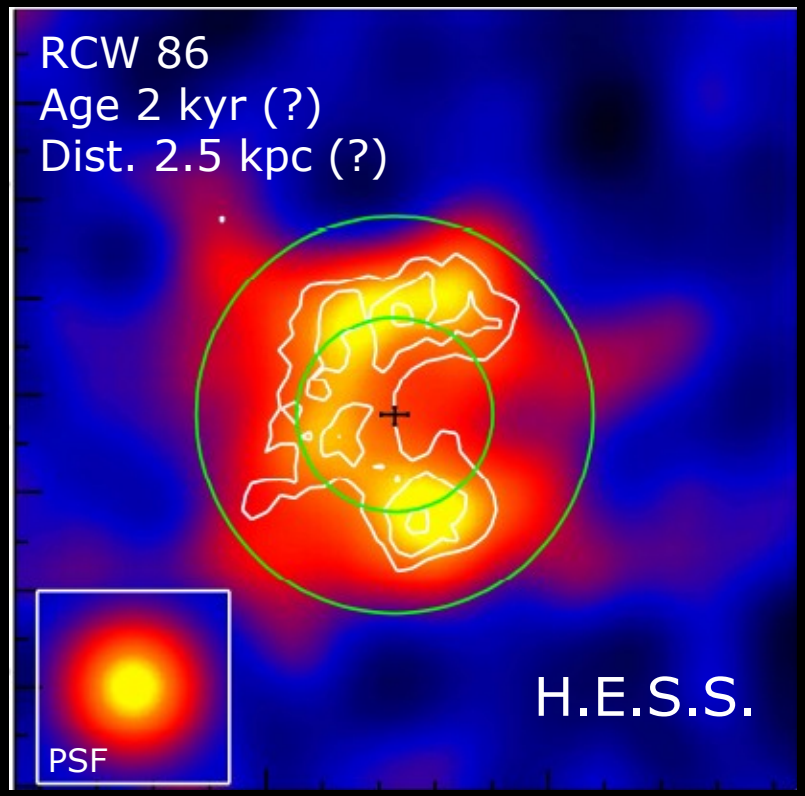
[S. Funk et al. 2007]

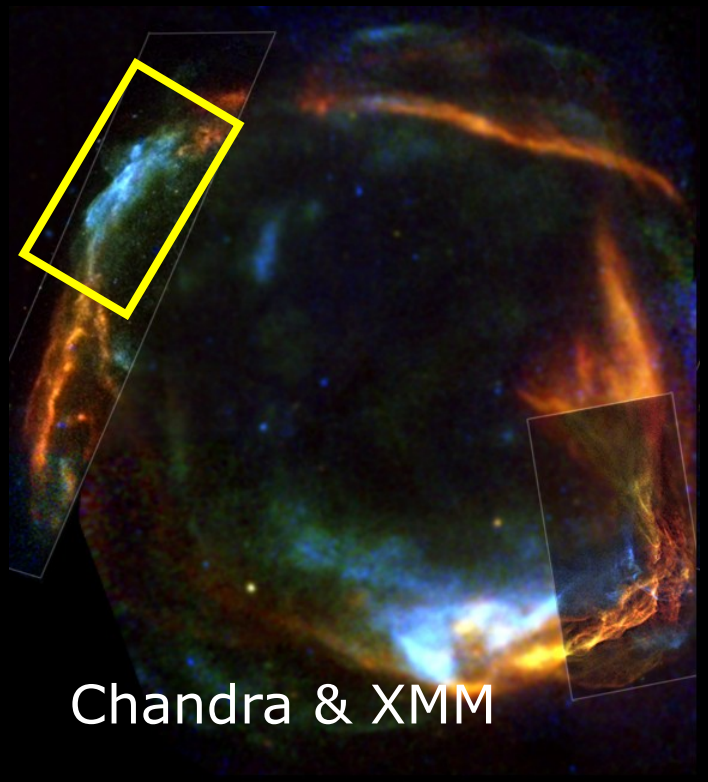
- **Rather difficult source for GLAST:**
  A 5xbright Egret source nearby
- **Expected neutrino rates (KM3NET, 5 yrs)**

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

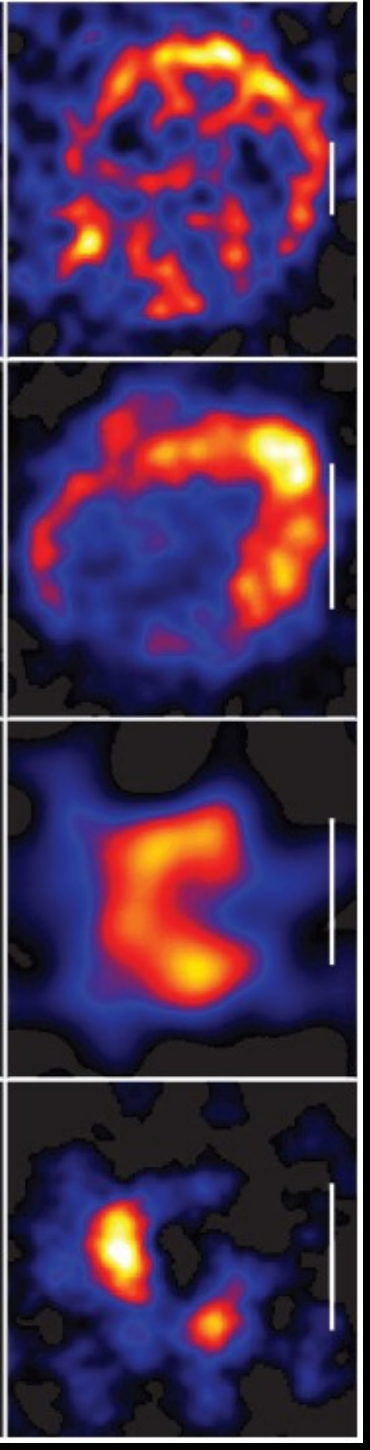
E > 1 TeV 11 over 41 bg. : 5 over 15 after reconstruction
E > 5 TeV 5 over 8 bg.

SNR acceleration efficiency: RCW 86





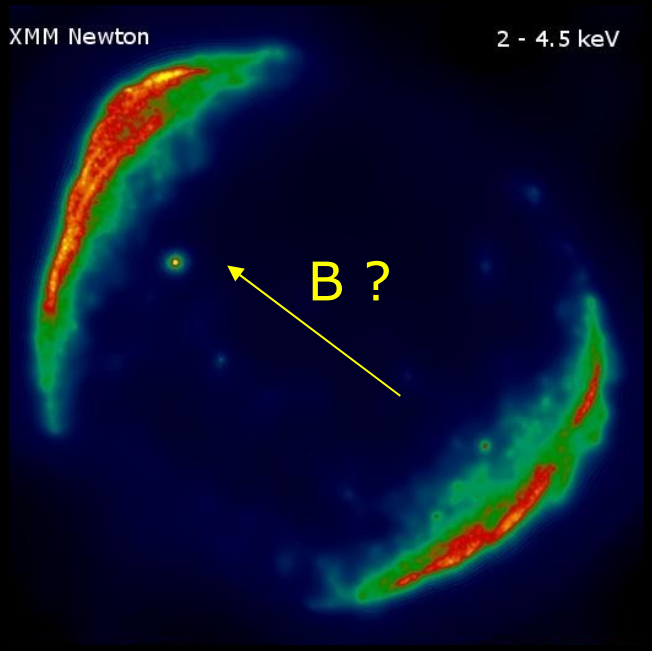
Measured shock velocity 6000±2800 km/s (Chandra 2004,07)
Expected post-shock gas temperature 42…70 keV
Measured post-shock temperature 2.3±0.3 keV (Hα line width)
➔ **>50% of energy in non-thermal component** (C.L. ?)



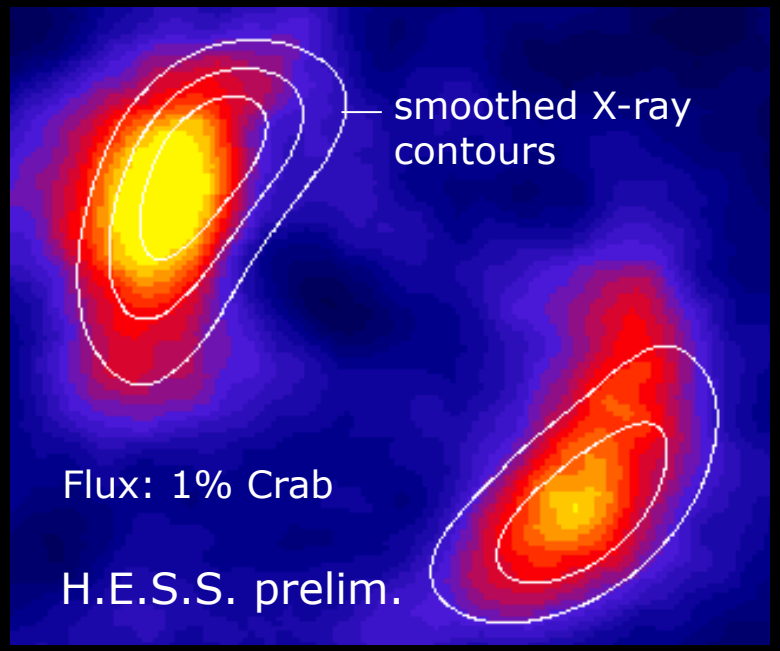
SRN with resolved shells

Latest addition: SN 1006
expands in uniform environment above the Galactic plane

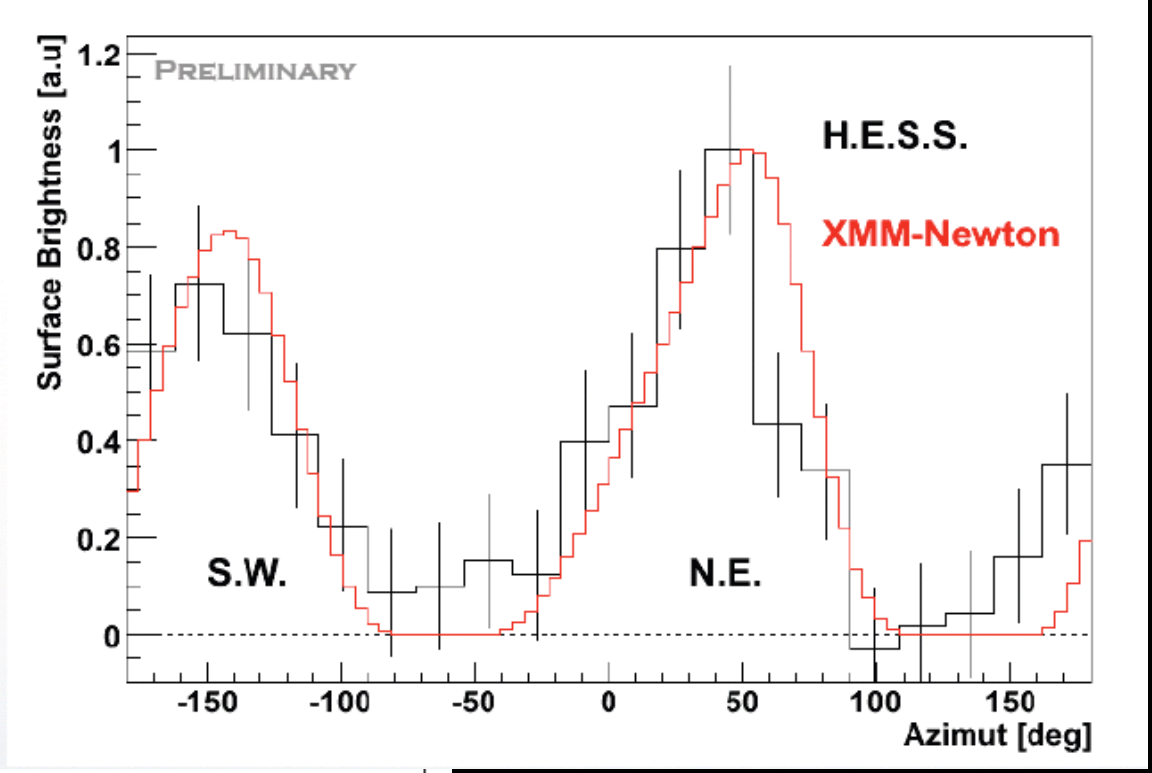
2 – 4.5 keV X-rays

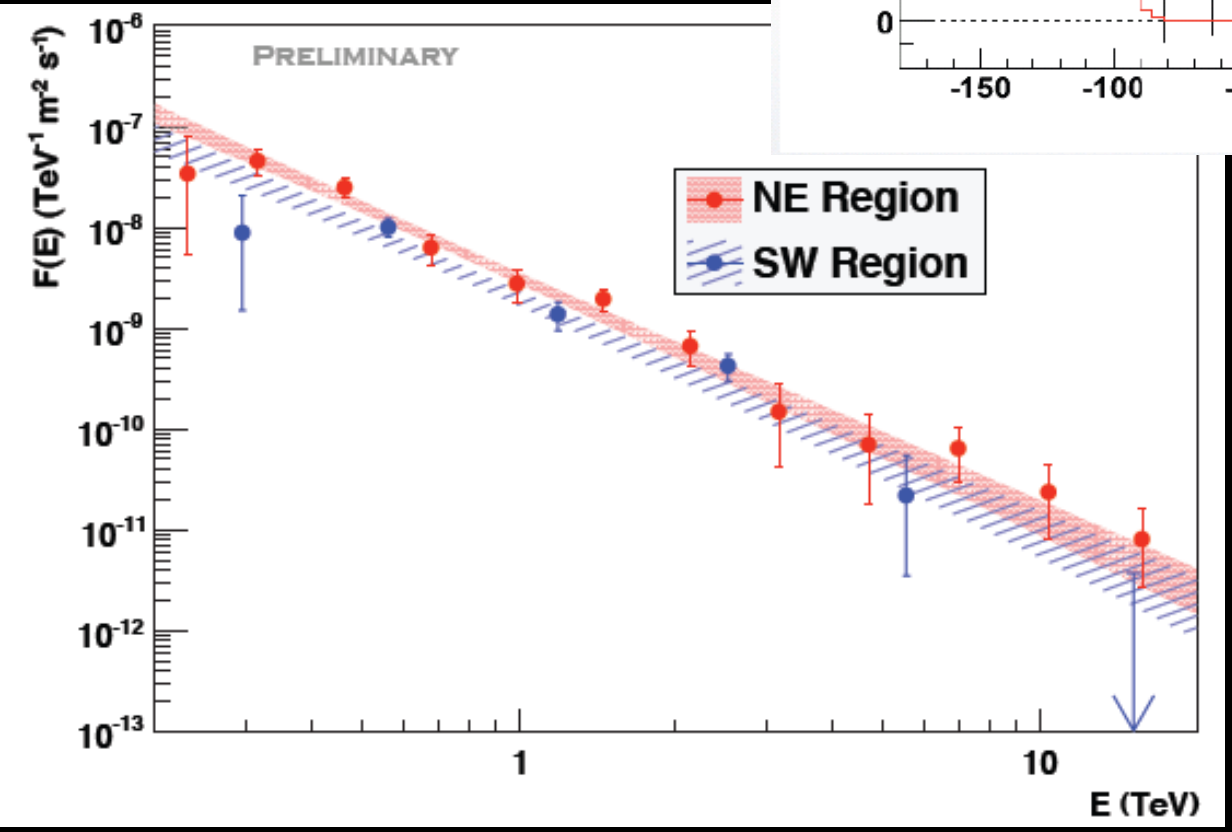


VHE γ-rays



Azimuthal profile
VHE vs X-rays





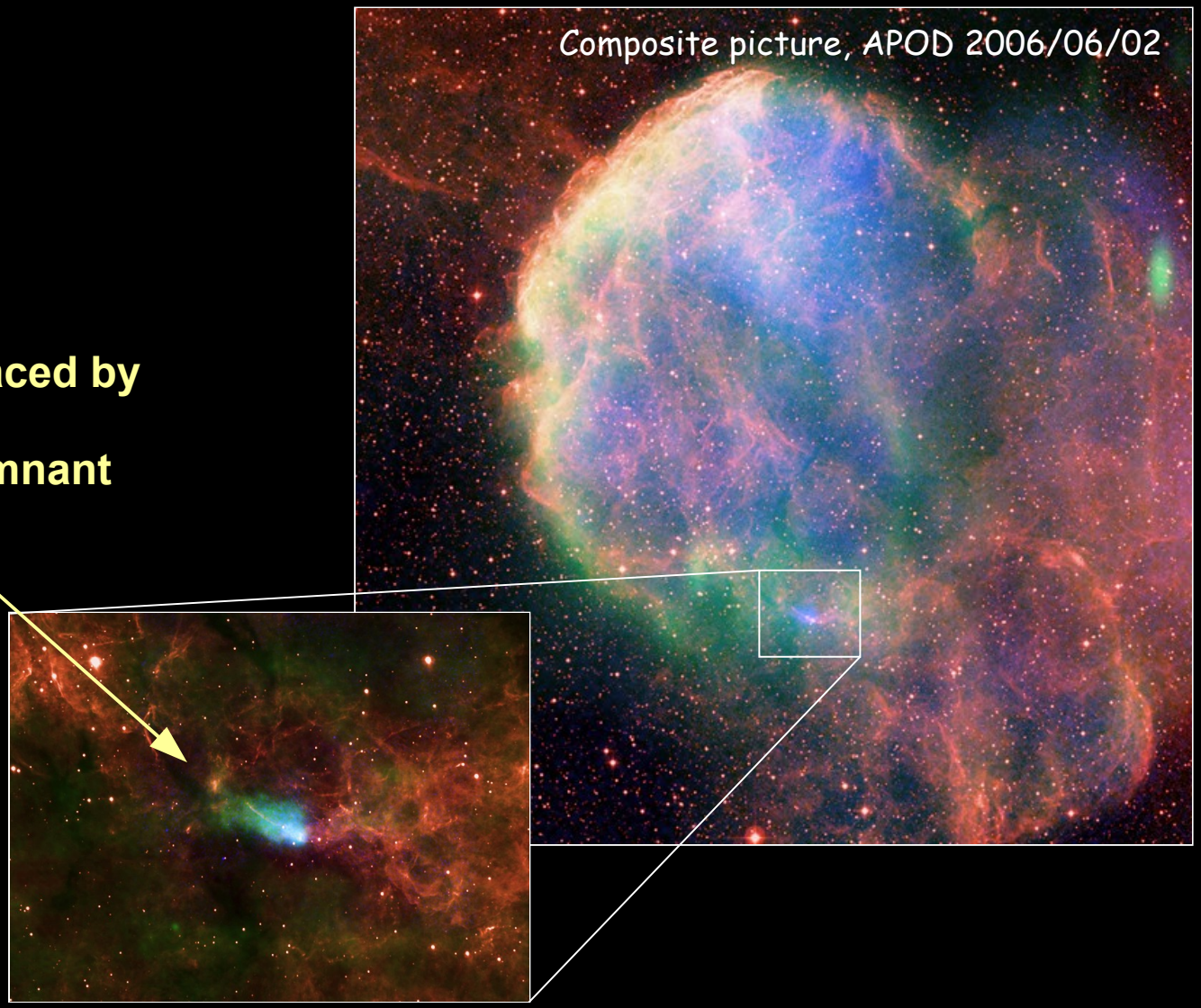
M. Naumann-Godo
ICRC 2009
Moriond 2009

Energy spectra
For both regions

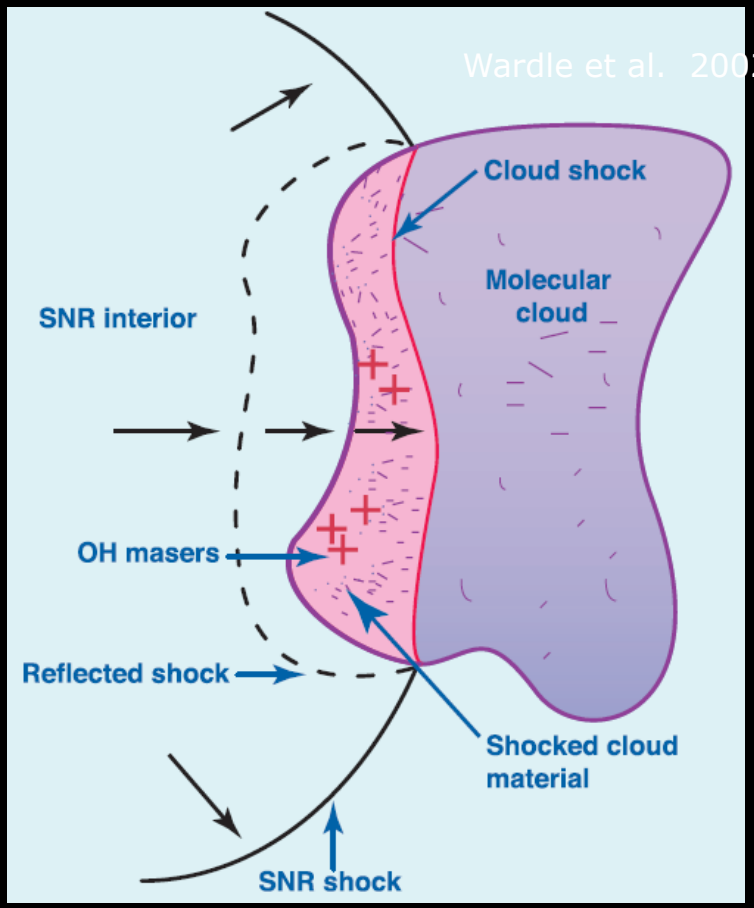
Older Shell type SNRs : IC 443

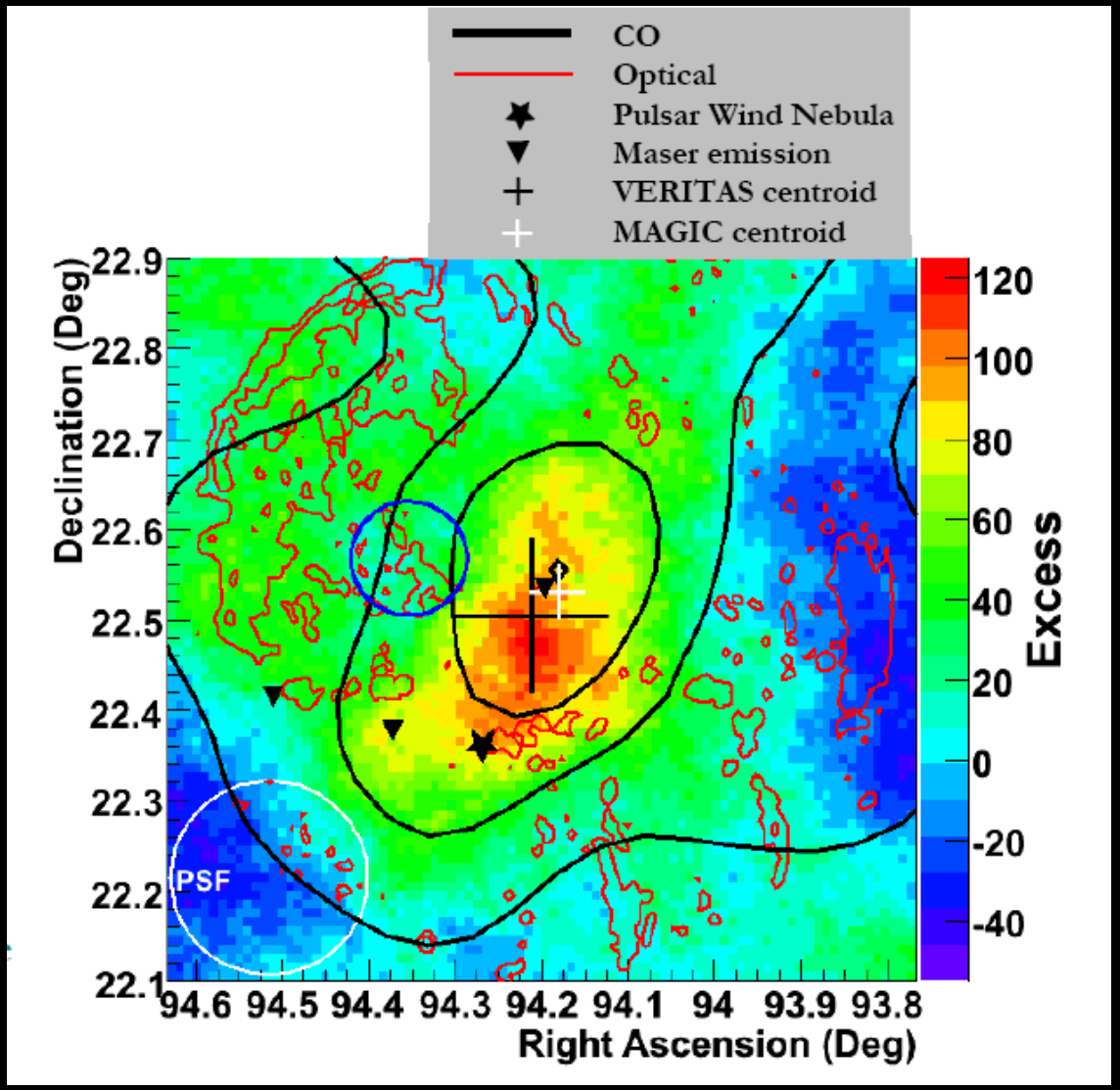
- ~30 kyr old 45' Shell SNR
- 1.5 kpc

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



SNR interacting with cloud : IC 443

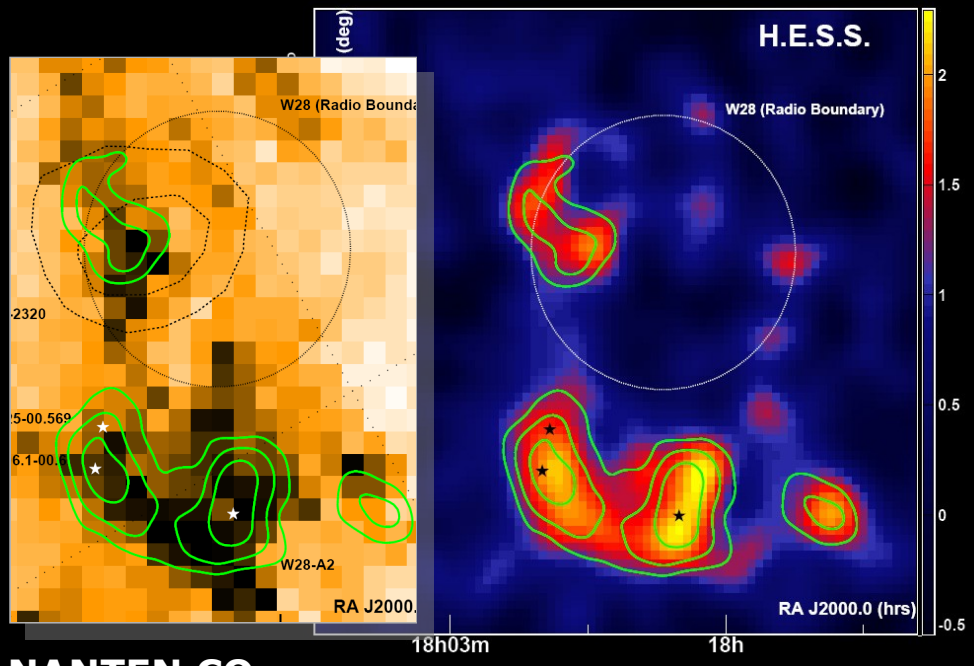




Older Shell type SNRs : W28

- 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

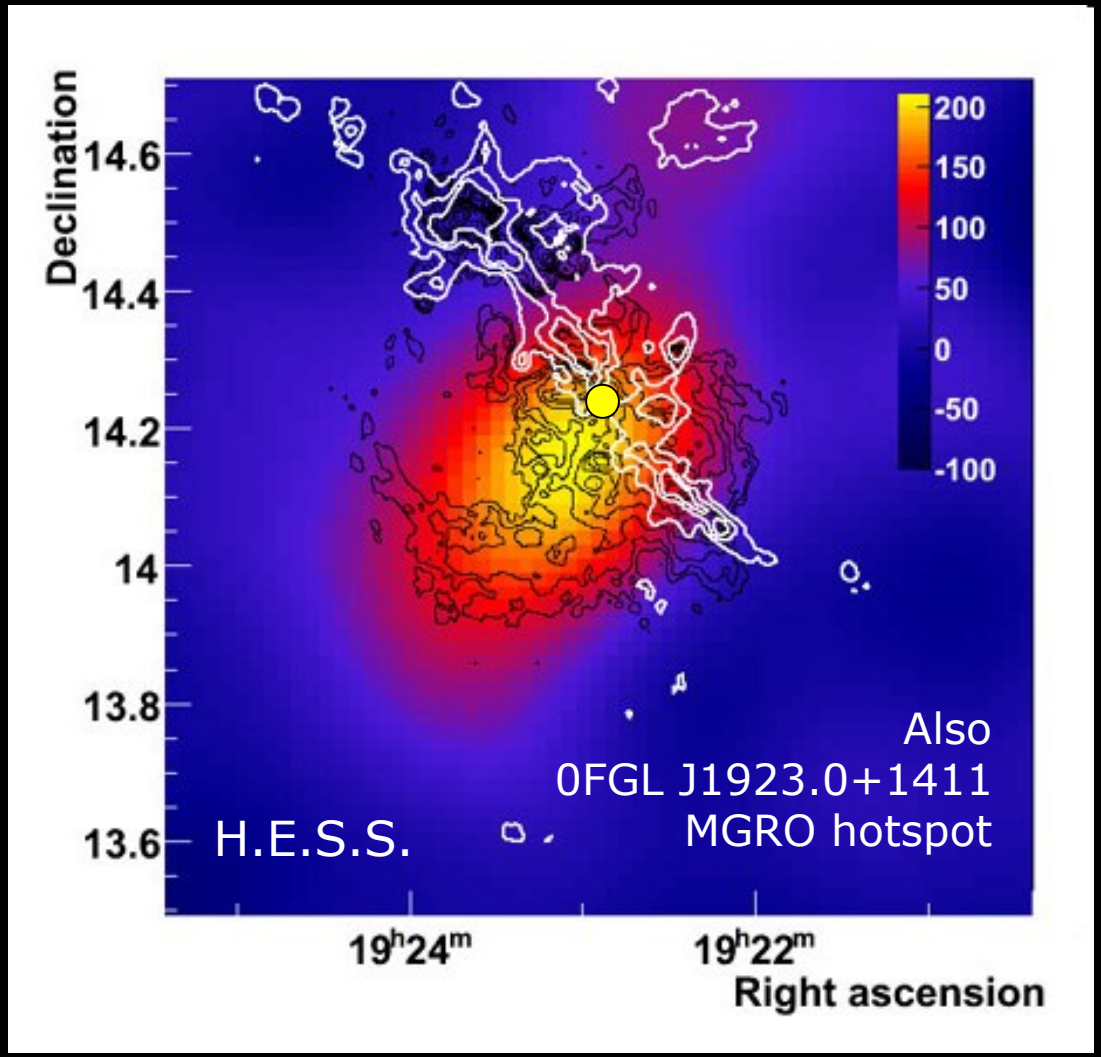


NANTEN CO
10-20 km/s

20/90 cm VLA
MSX 8 micron

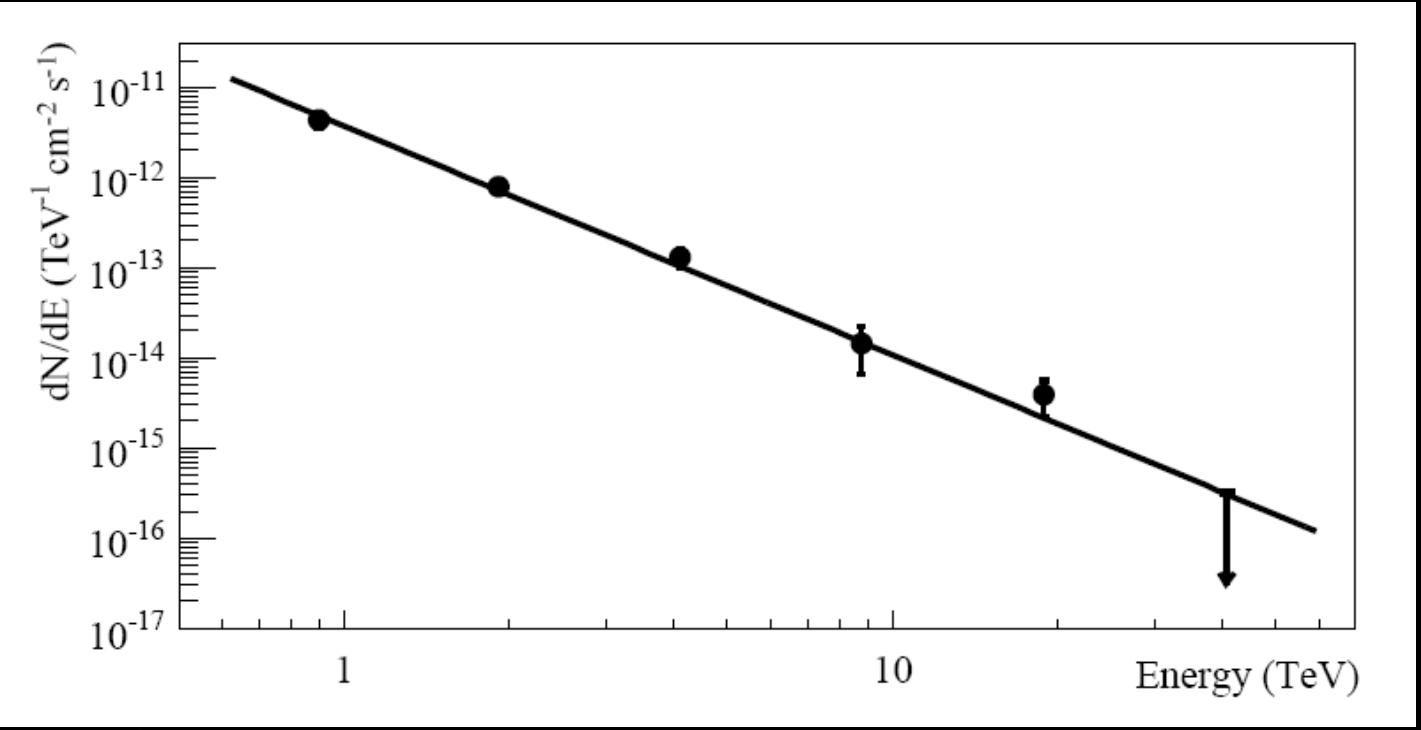
W 51 / G49.2-0.7

A. Fiasson,
ICRC 2009



Where are the Pevatrons?

(A) Lack of gamma-ray statistics



(B) Lack of source statistics

With decreasing shock speed, acceleration & CR confinement become less effective

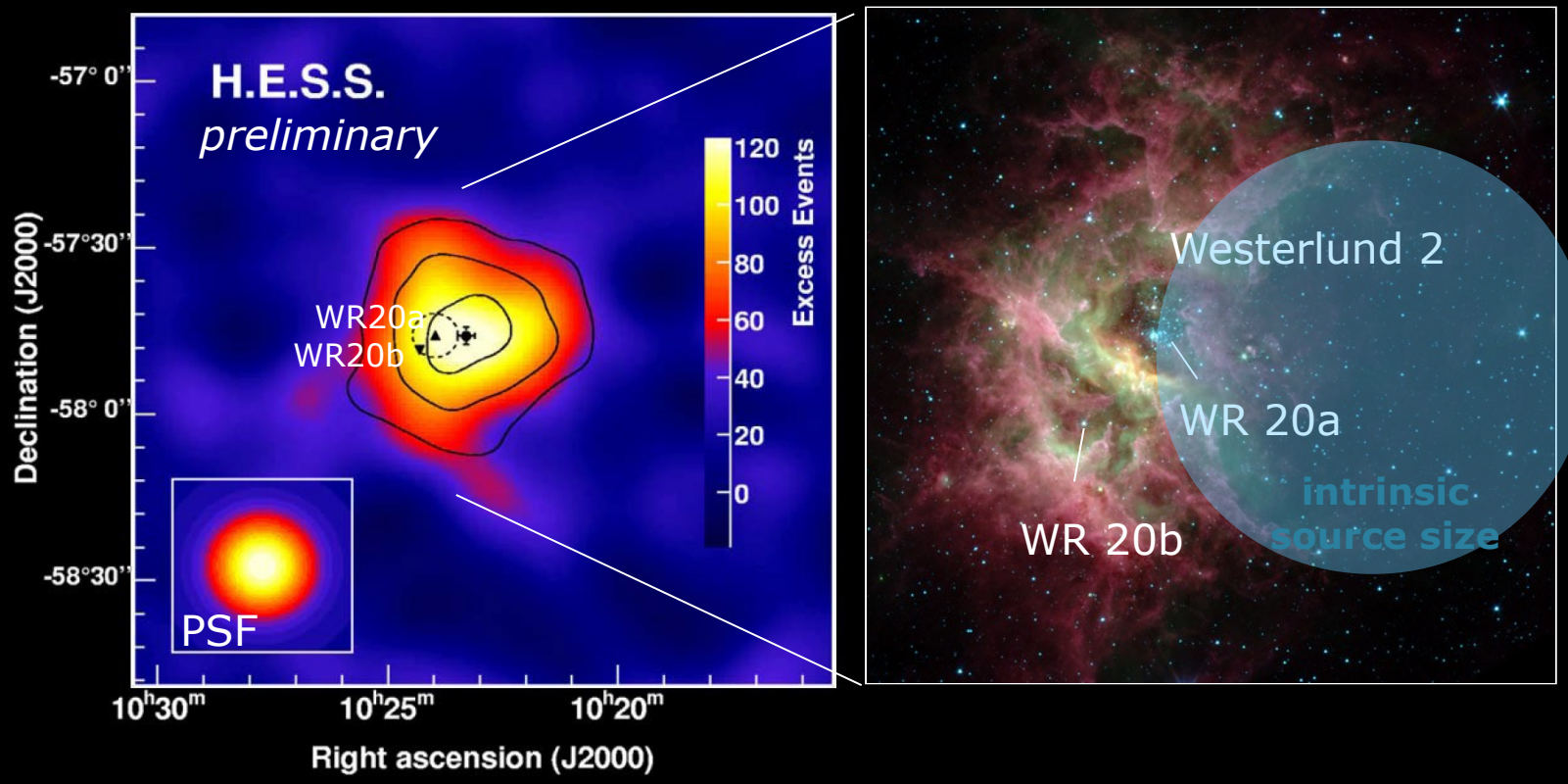
➡ PeV particles only for some 100 … 1000 years

➡ At any time maybe only few pevatrons in Galaxy

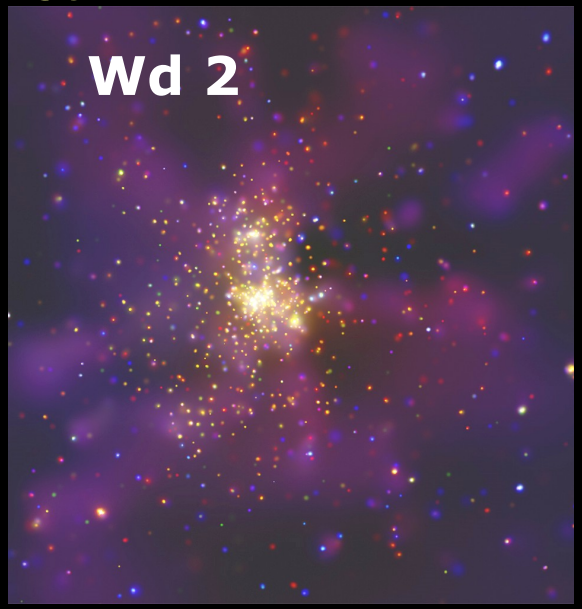
Stellar clusters: A new type of TeV source?

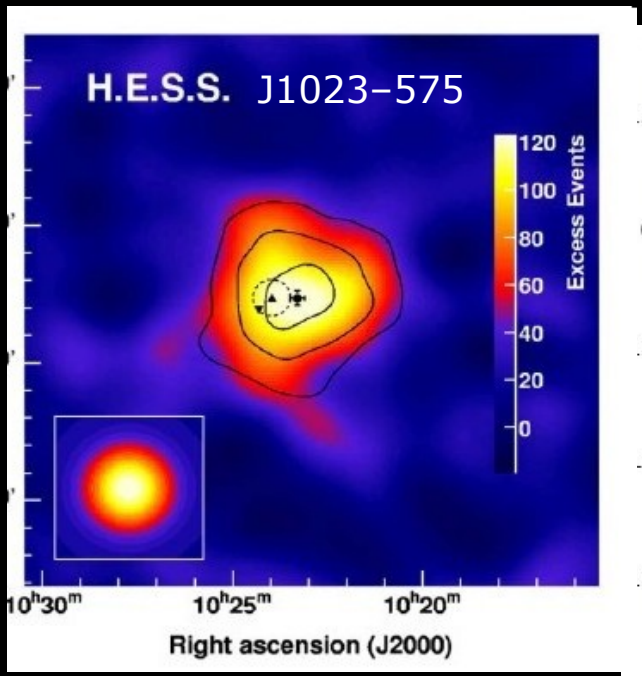
- Open Cluster Westerlund 2 : thousands of solar masses
  Wolf-Rayet & young stars
- Winds excavating bubbles in the ISM

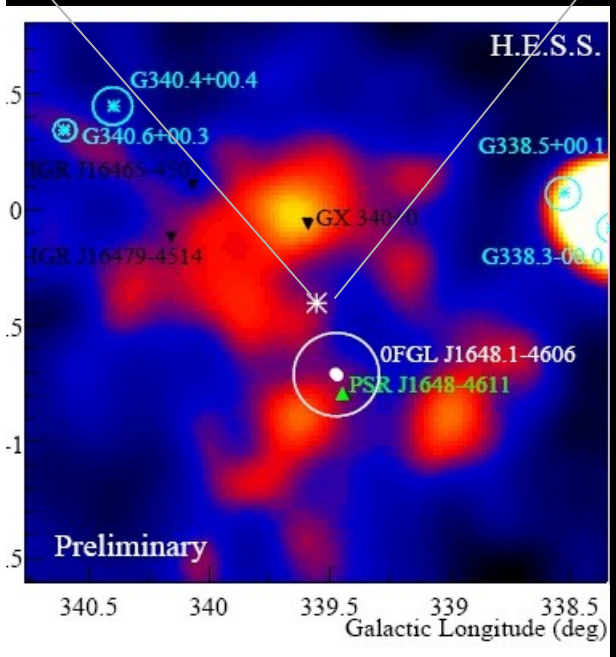
- HESS source coincides with the most proeminent one in RCW 49
- Acceleration through collective wind effects or DSA at the boundary?
- Systematic search program undertaken with HESS

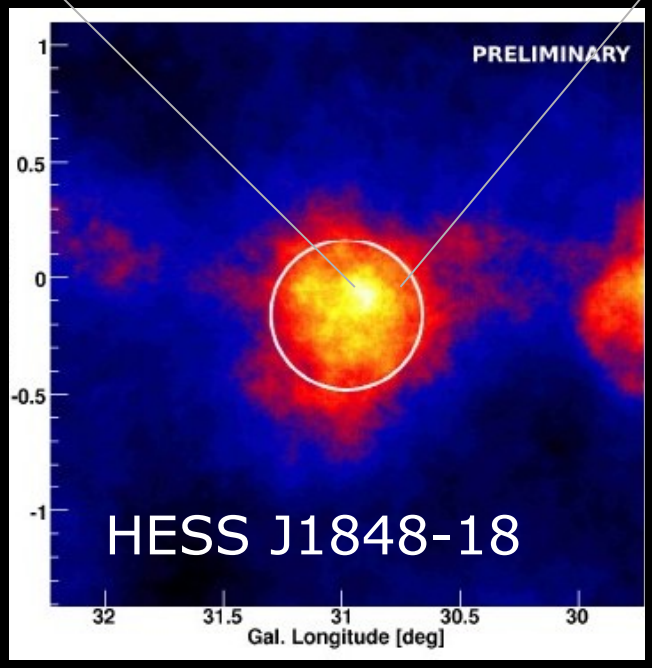


Collective stellar winds (OB, WR) ?
Colliding wind binries ?
First SNR ?
First PWN ?



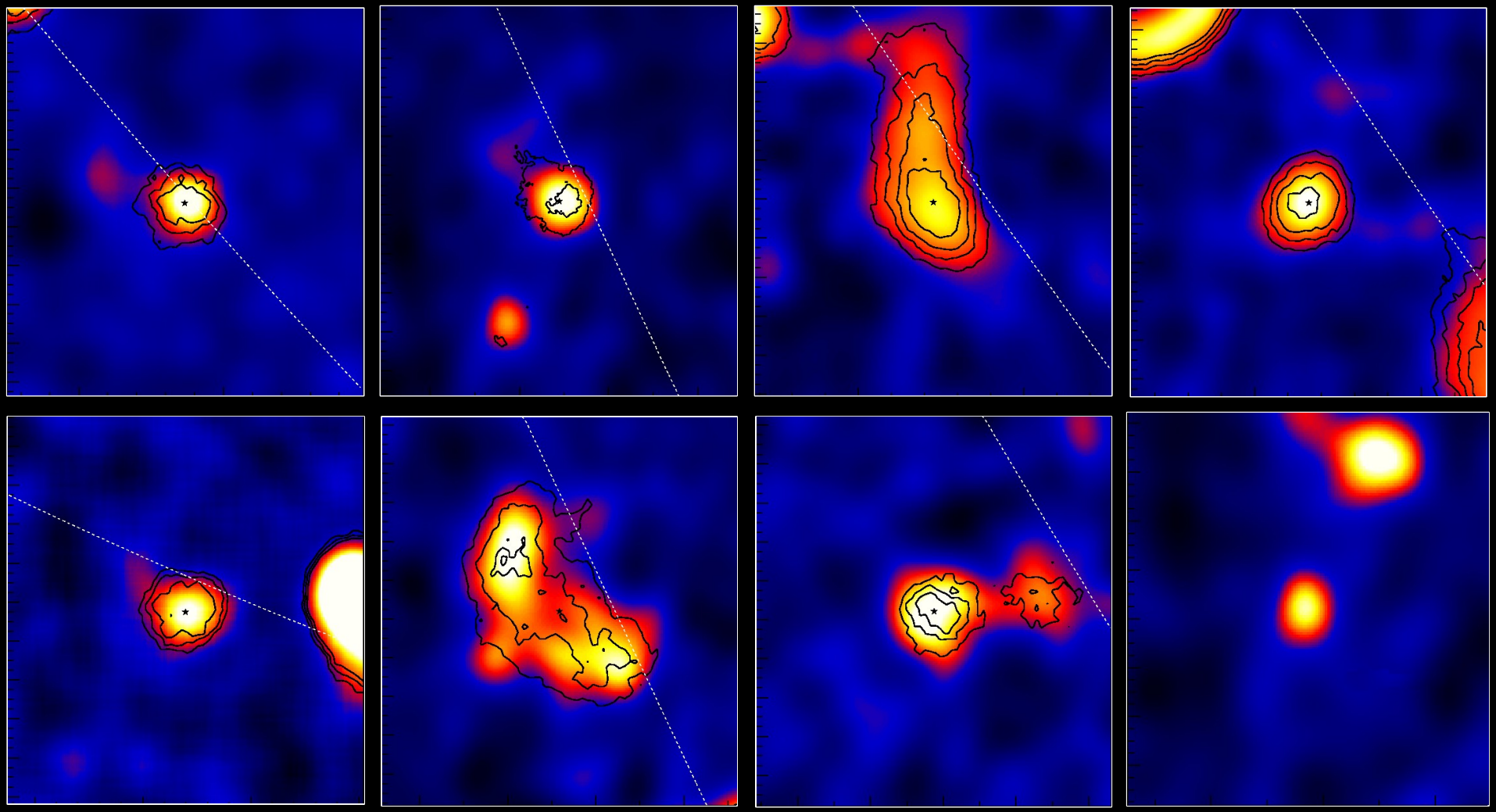






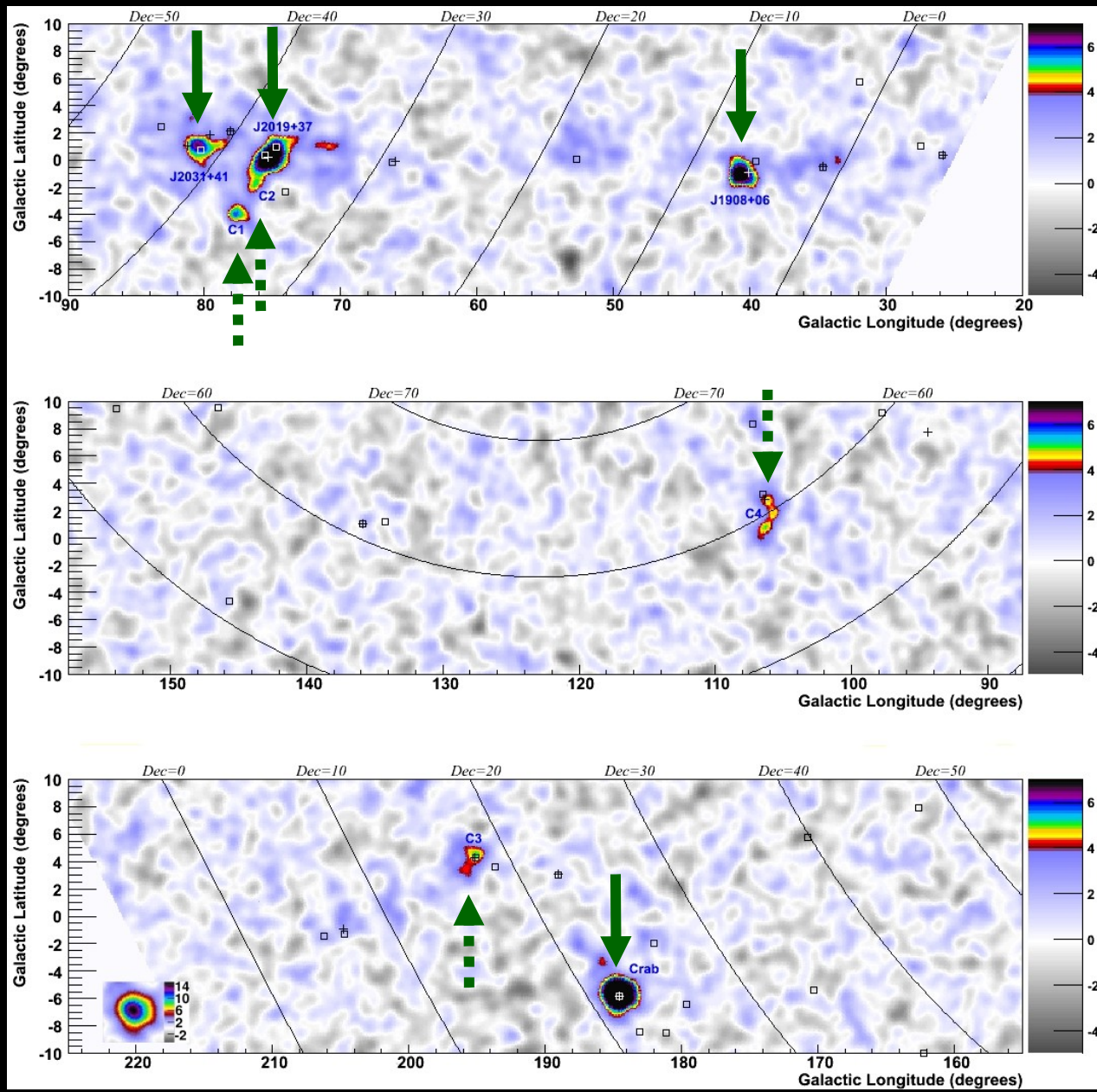
Dark Sources!

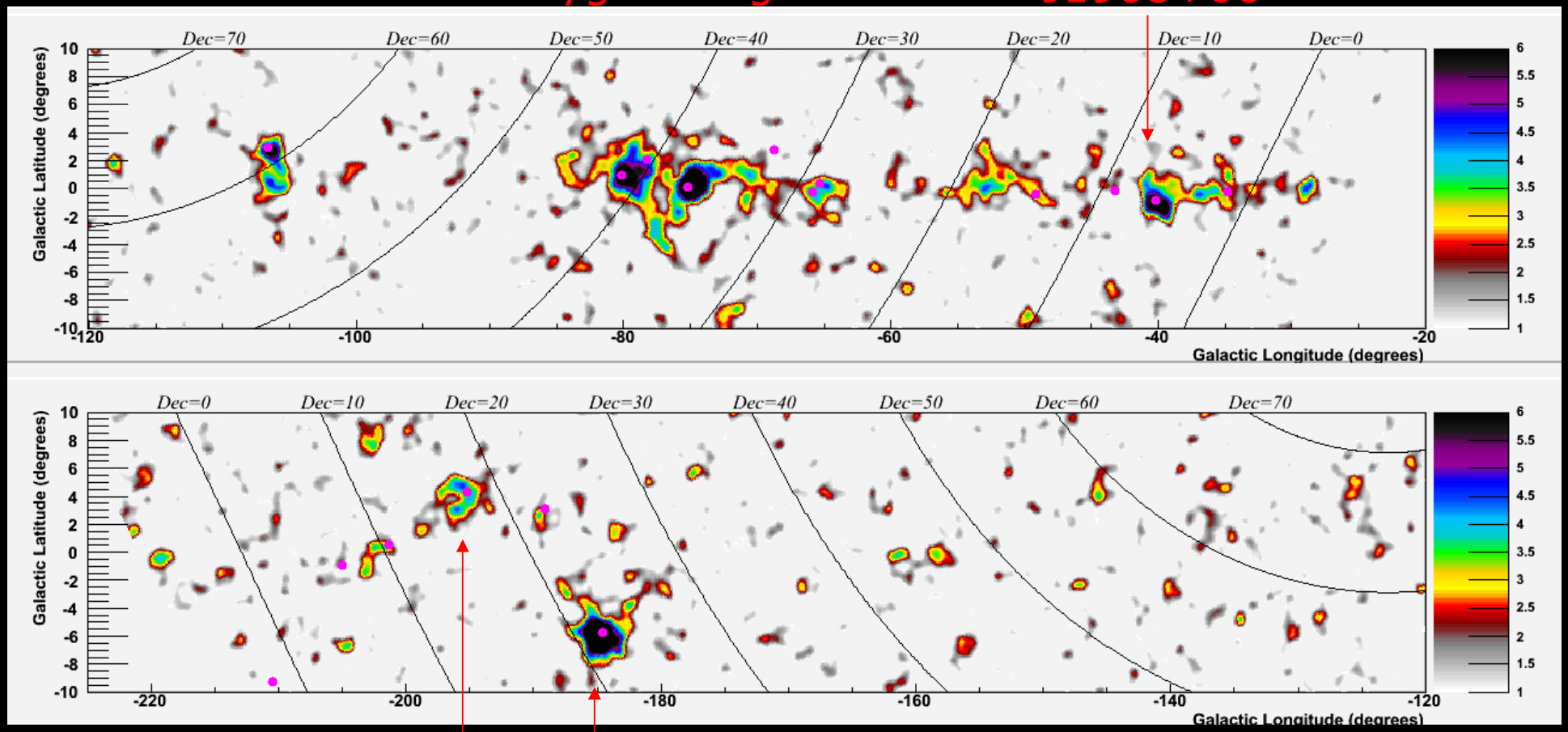
- Seem to shine only in gamma-rays : rather hard spectra and mostly extended
- No plausible counterparts in radio, x-rays, ...
- Two of HESS dark sources out of 10 have been identified recently:
  1 PWN (faint but young & energetic pulsar) , 1 SNR (composite source)
- New type of CR accelerators? (if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



MILAGRO sky-survey

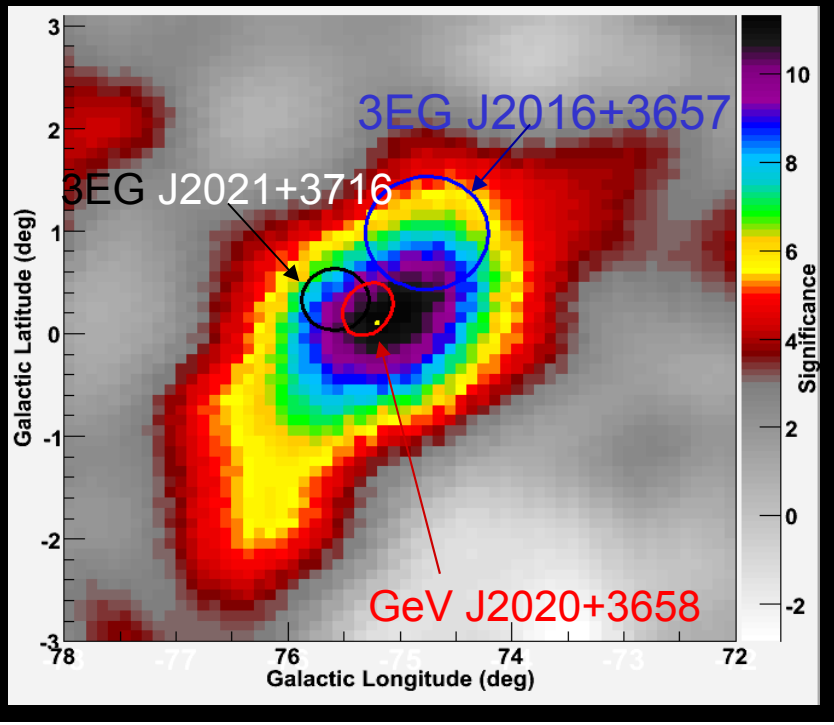
- 7 years of integration
- Median energy ~ 20 TeV
  due to γ/hadron
  separation cuts
- 3 new sources significant post-trials
  - J1908+06
  - J2019+37
  - J2031+41
  - Crab
- 4 'hotspots'
- Bright +Hard+extended sources : Pevatrons?
- Identification is difficult due to poor angular resolution (see HESS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



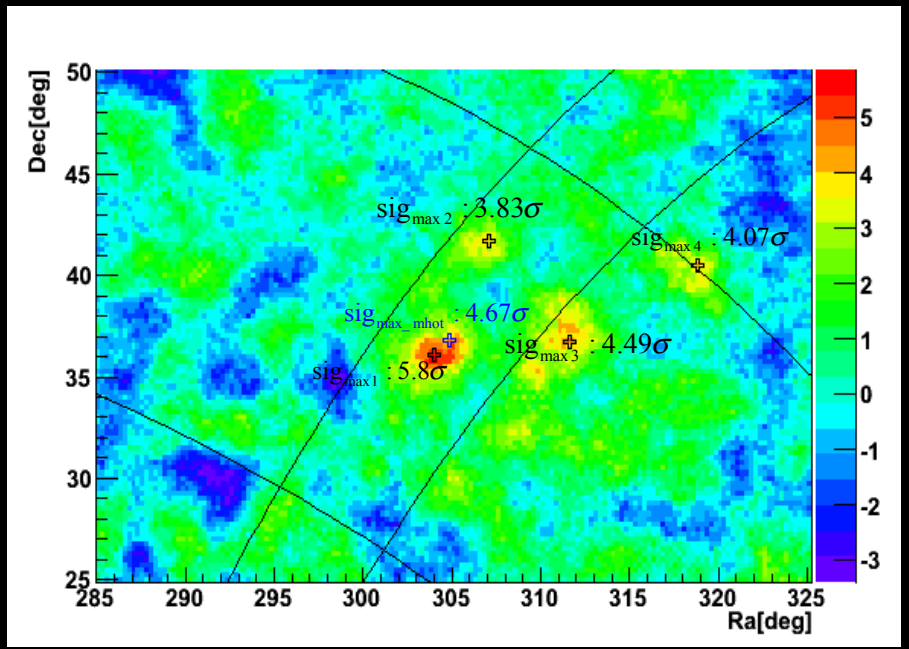

Cygnus region
J1908+06
Dec=70
Dec=60
Dec=50
Dec=40
Dec=30
Dec=20
Dec=10
Dec=0
Galactic Latitude (degrees)
Galactic Longitude (degrees)
Dec=0
Dec=10
Dec=20
Dec=30
Dec=40
Dec=50
Dec=60
Dec=70
Galactic Latitude (degrees)
Galactic Longitude (degrees)
Geminga
Crab

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**

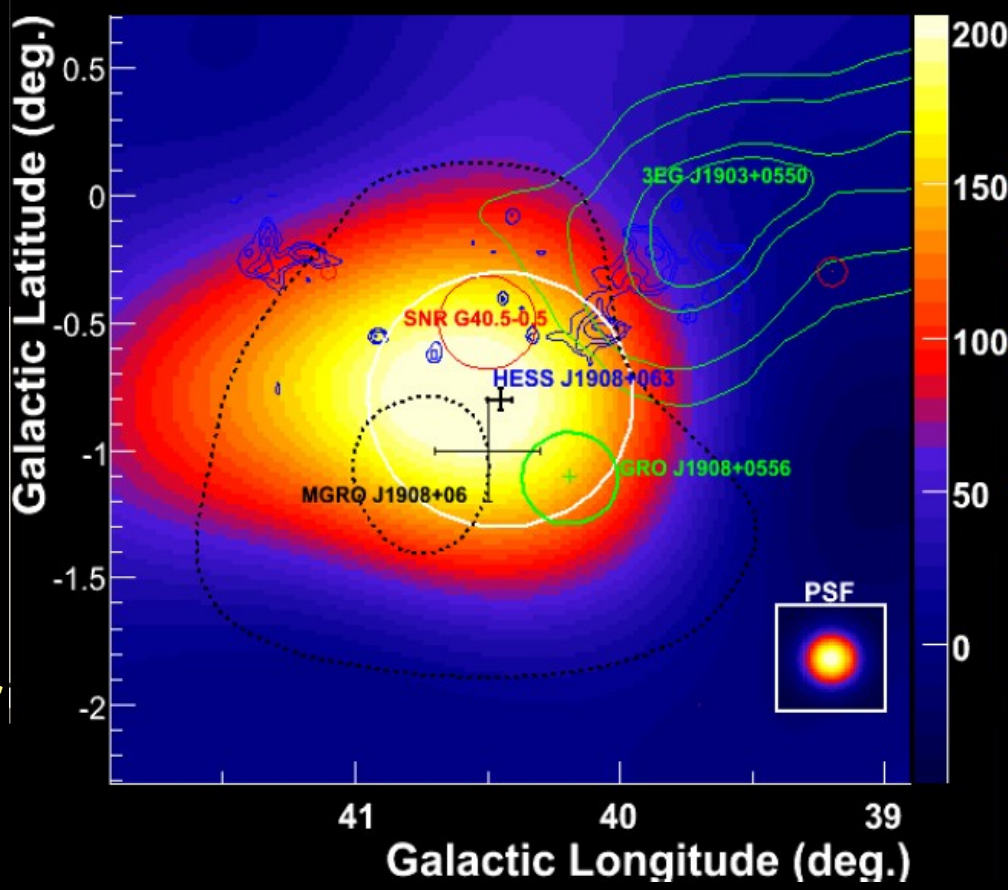


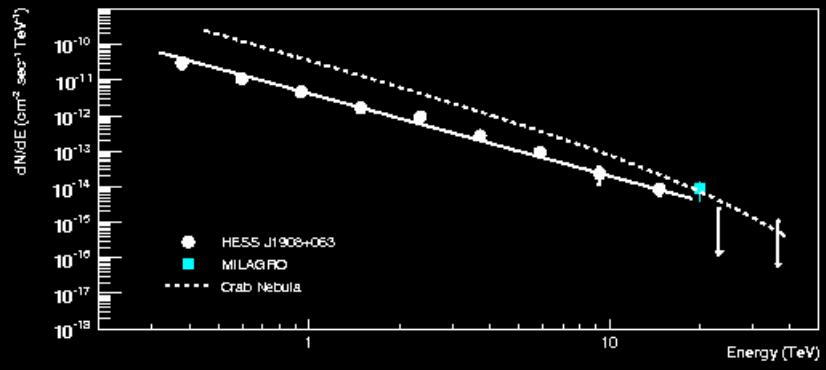
- **Point source limits from MAGIC +VERITAS**
  - **No contradiction to MILAGRO flux**
  - **for hard+extended source**
- **Extended analysis pending**



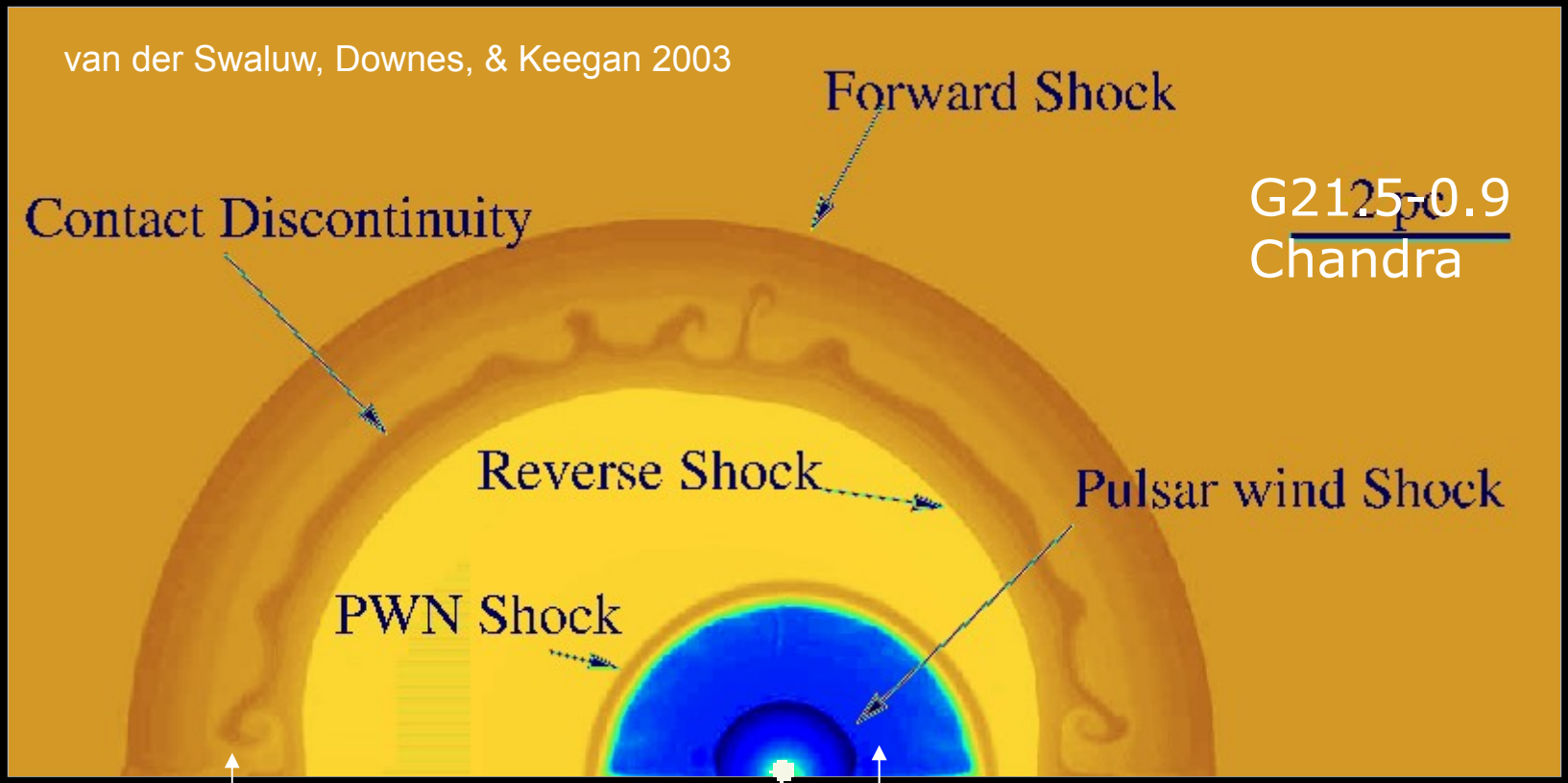
Dark Sources : MILAGRO J1908+06

- 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



SN shock accelerates particles for O(10 ky)

Pulsar sustains pulsar wind nebula for O(100 ky)

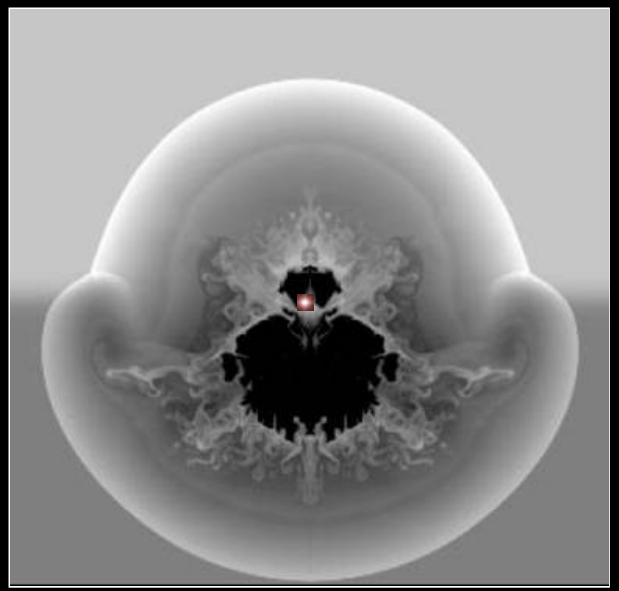
Pulsar Wind Nebulae

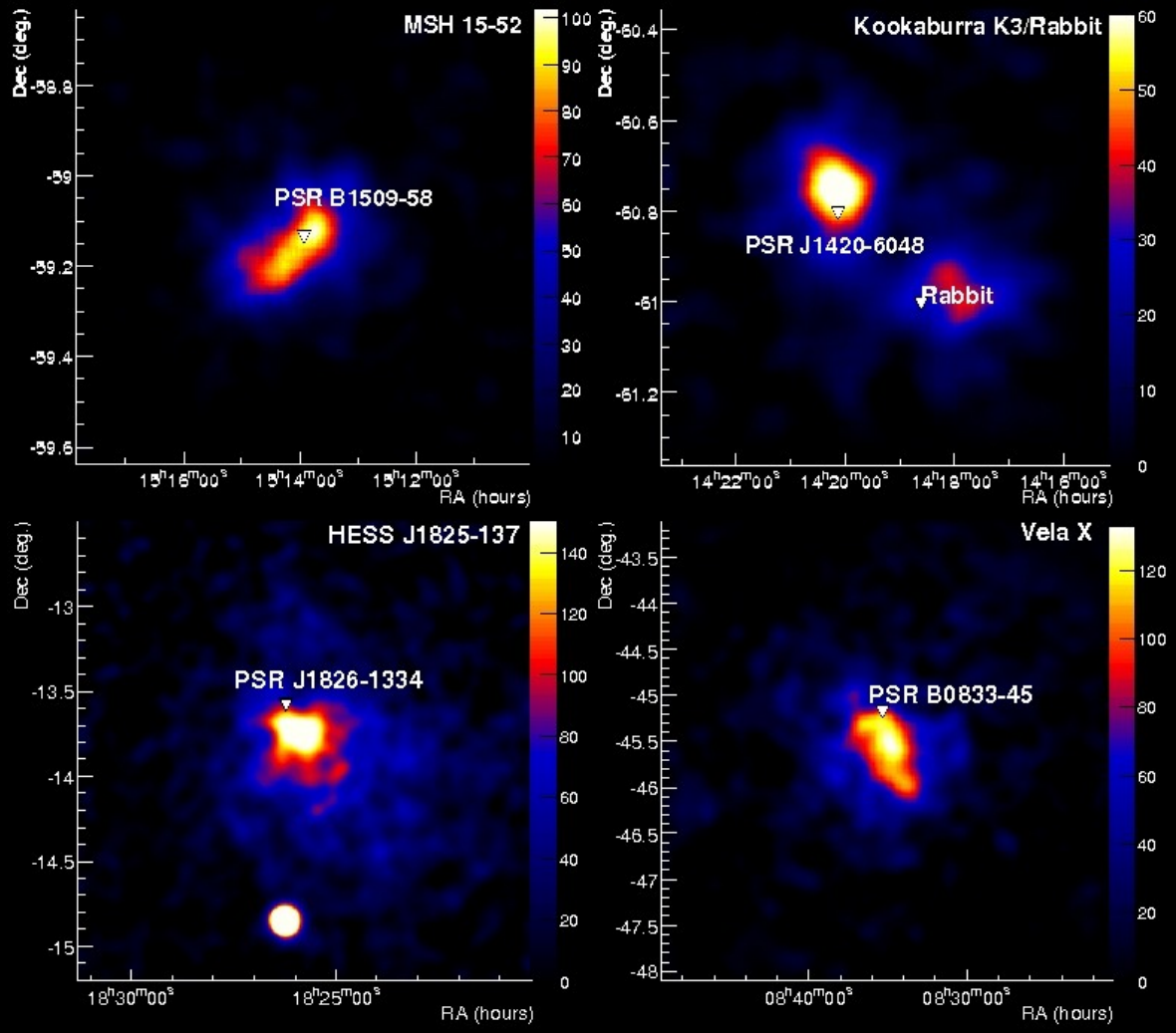
- Major galactic source population

Revealed by HESS galactic scan

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

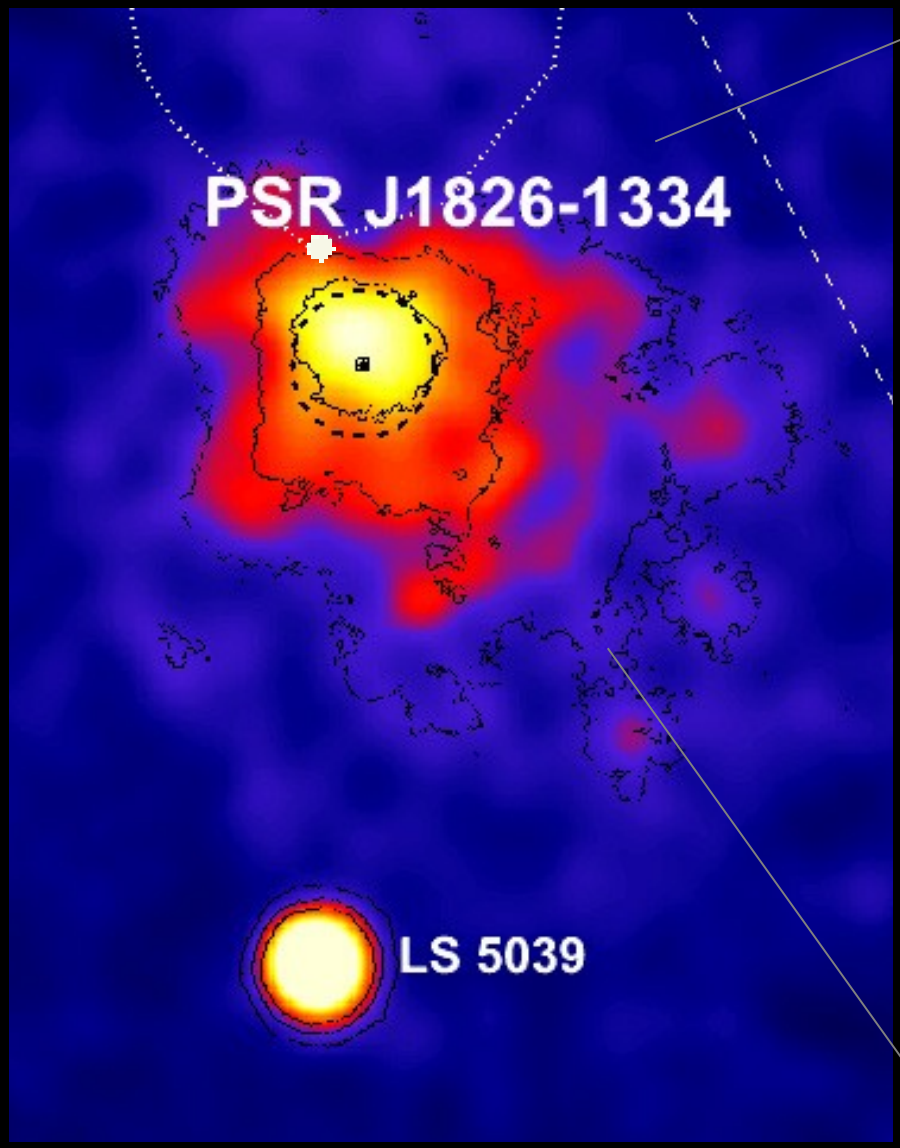
- Nebulae with huge caracteristic sizes ~ few tens of pc
- Mostly displaced TeV emission wrt pulsar position: "Crushed nebulae"

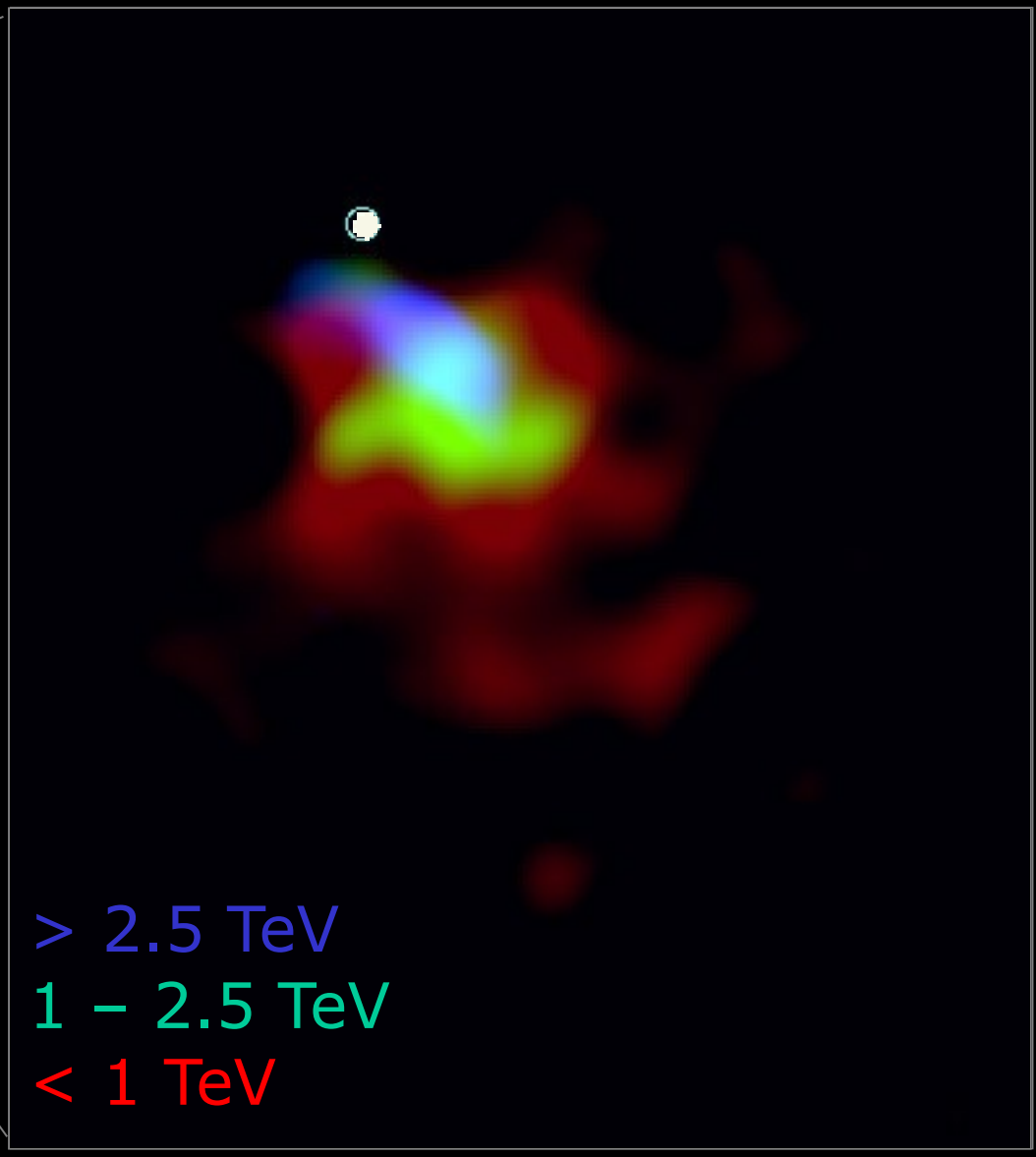




SN Explosion in inhomogenous medium→ reverse shock pushes the nebula

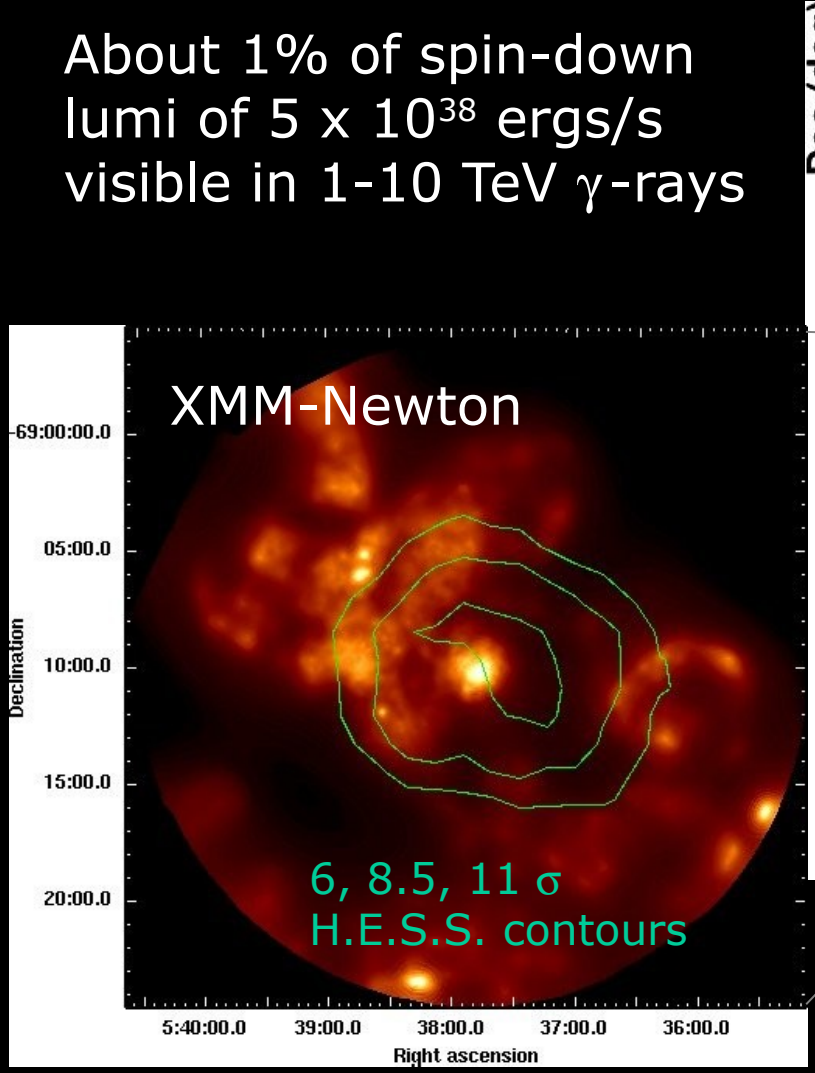
Morpholgy of PWNe: evidence for cooling
Relic electrons at action: HESS J1825-137

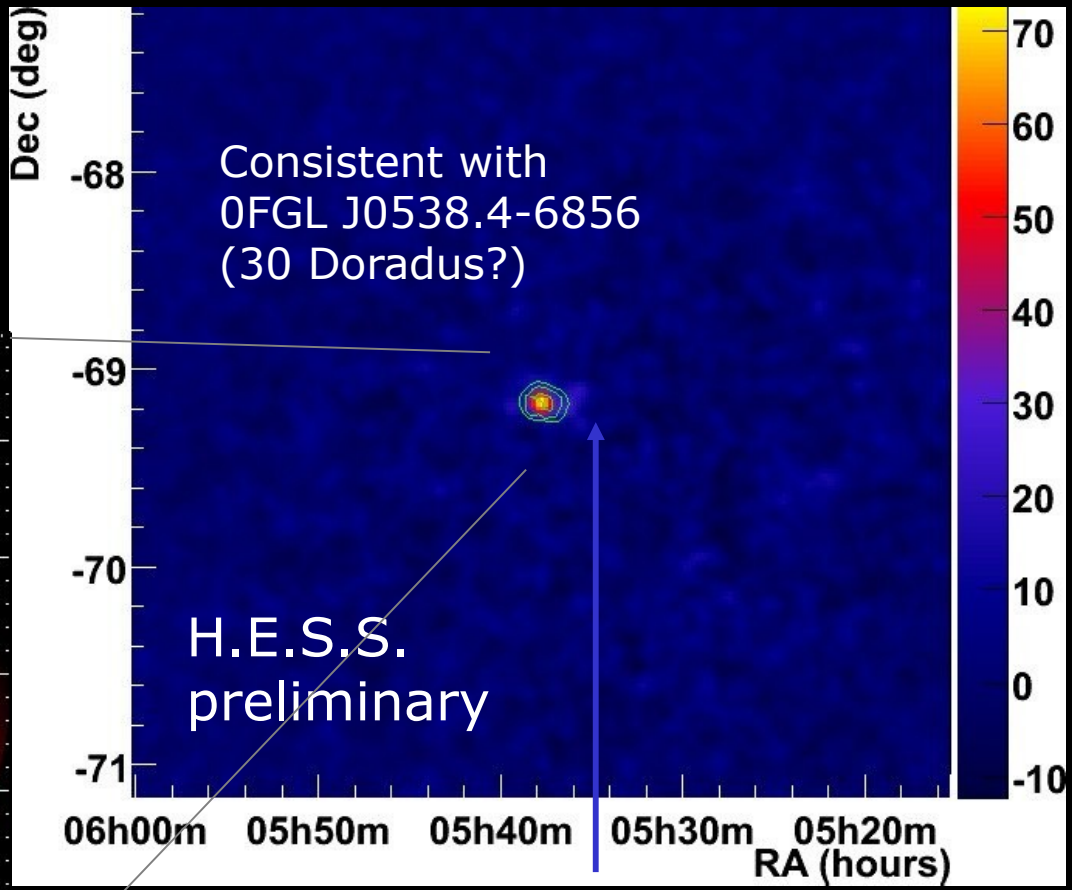




The most distant:
N 157B / PSR J0537-6910 in LMC

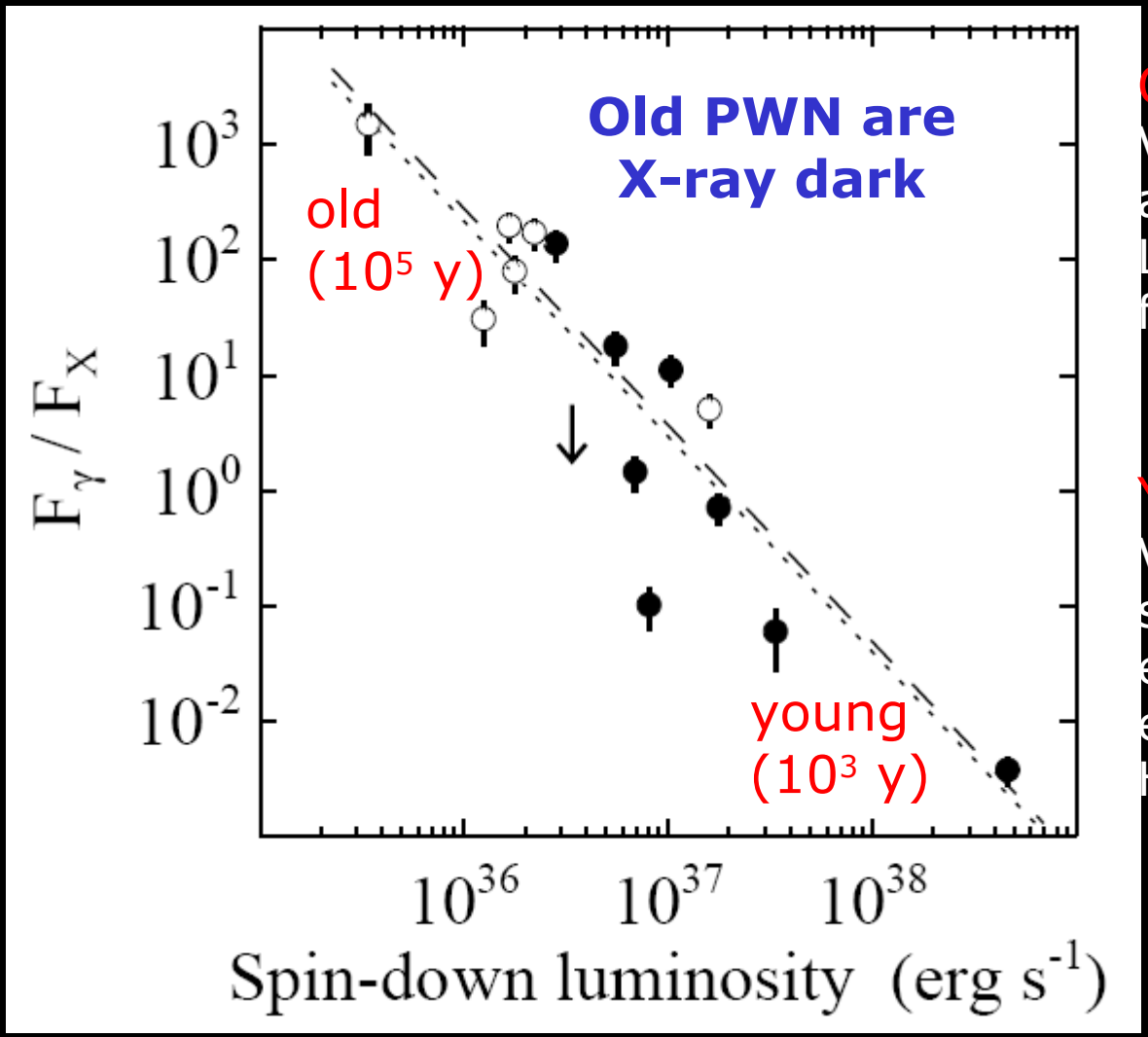
About 1% of spin-down lumi of 5 x 10^{38} ergs/s visible in 1-10 TeV γ-rays





SN 1987a in FoV; upper limits close to predicted flux

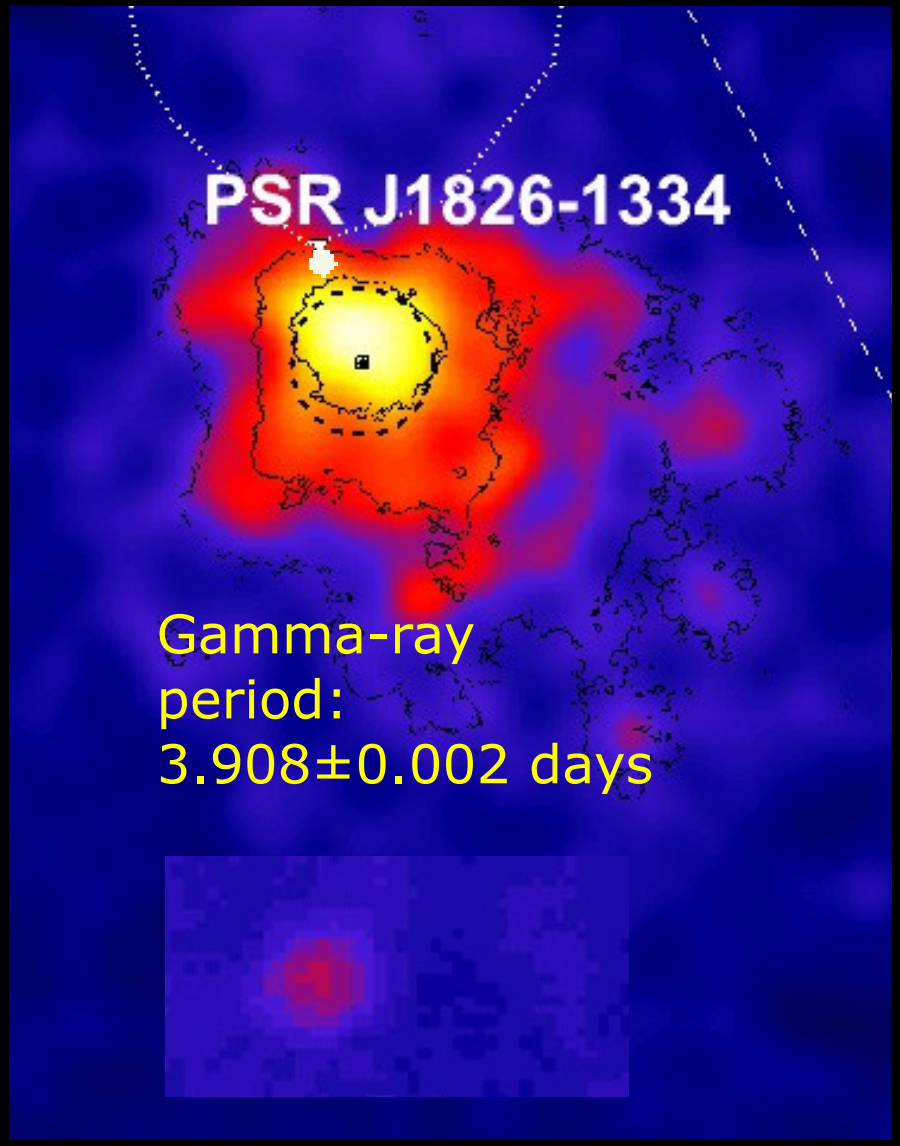
Clearest pattern: X-ray vs VHE luminosity

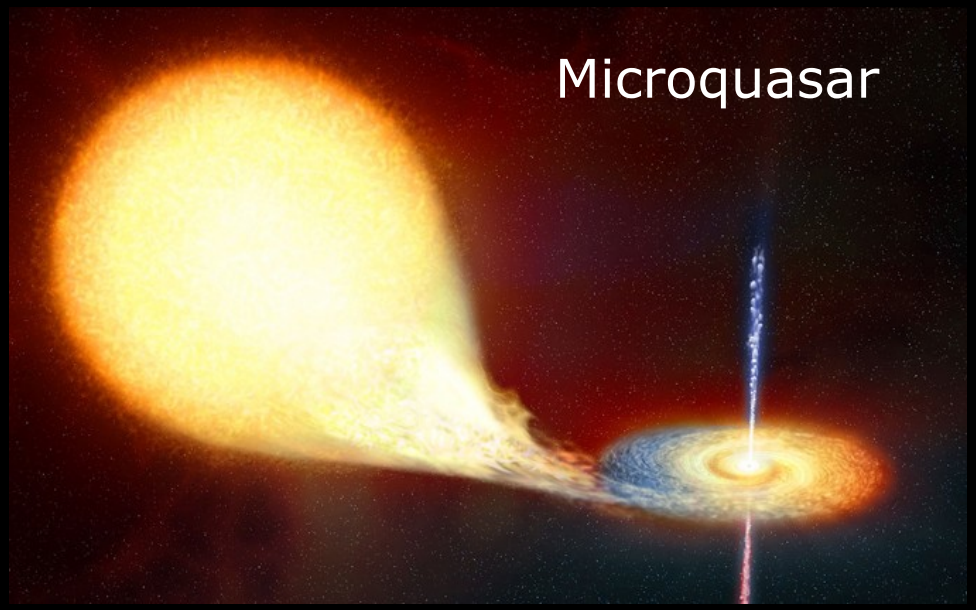


Old pulsars:
VHE emitting electrons accumulate over 10s of kyr
Low B field – synchroton falls below X-ray range

Young pulsars:
VHE emitting TeV electrons still building up; X-ray emitting electrons already in equilibirum
Higher B field

Binaires : LS 5039 by HESS

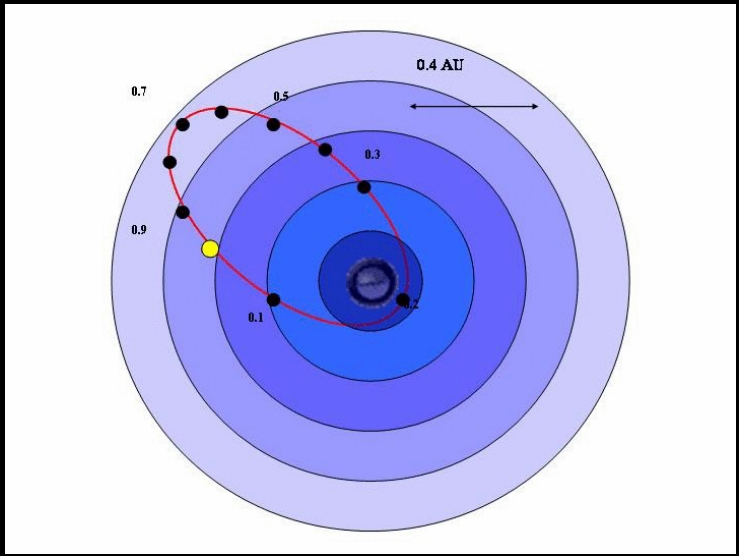


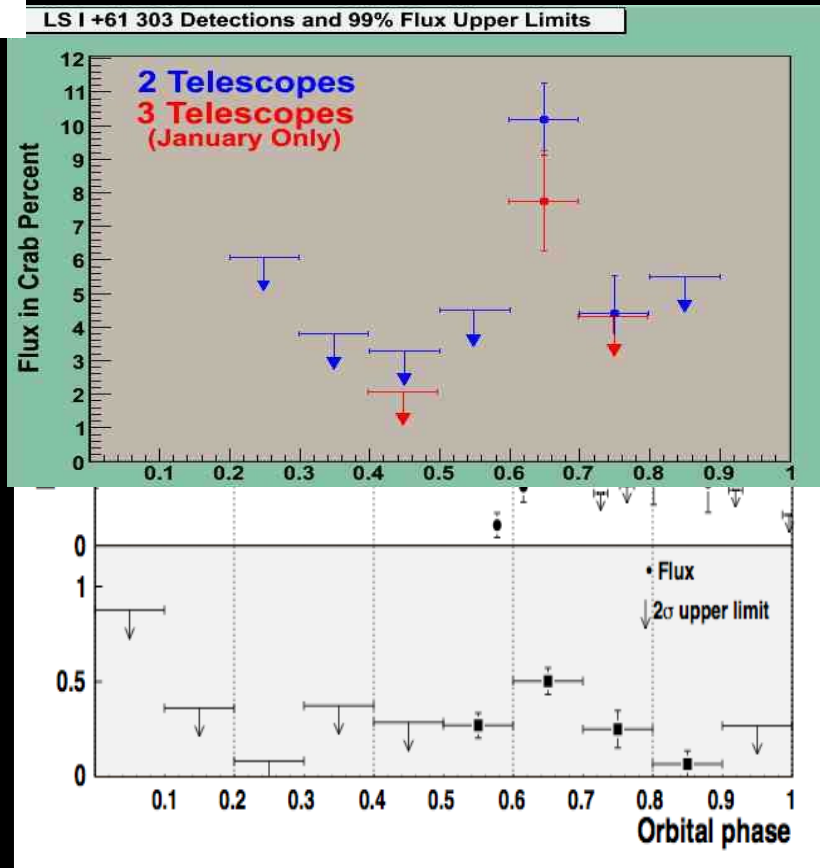


LS 5039

- 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



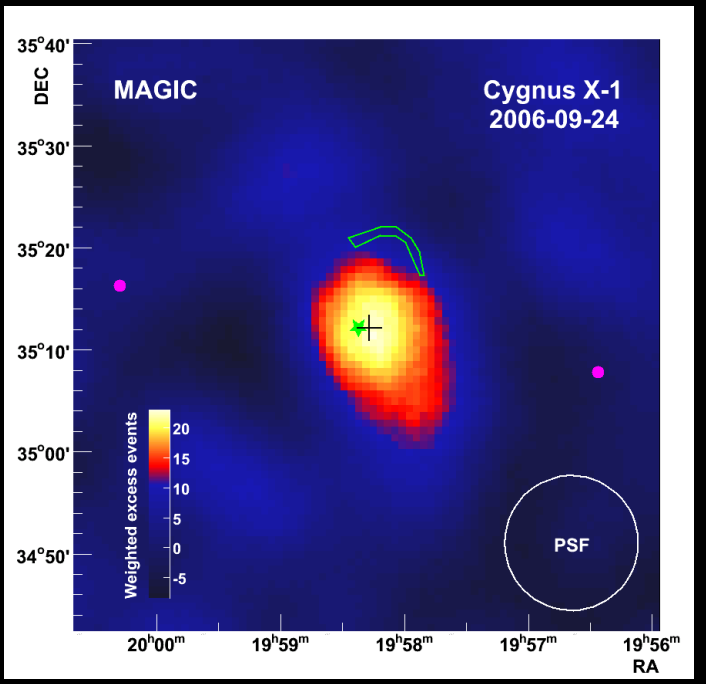


Variable (flaring) mostly at phase 0.5-0.85 – but not really periodic?

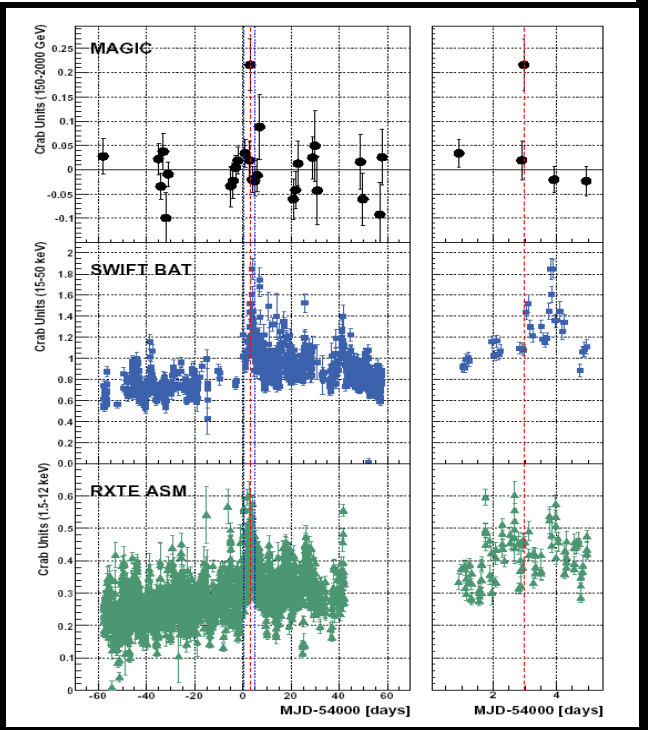
Overall correlation with X-ray – but many differences

A real challenge to modellers!

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

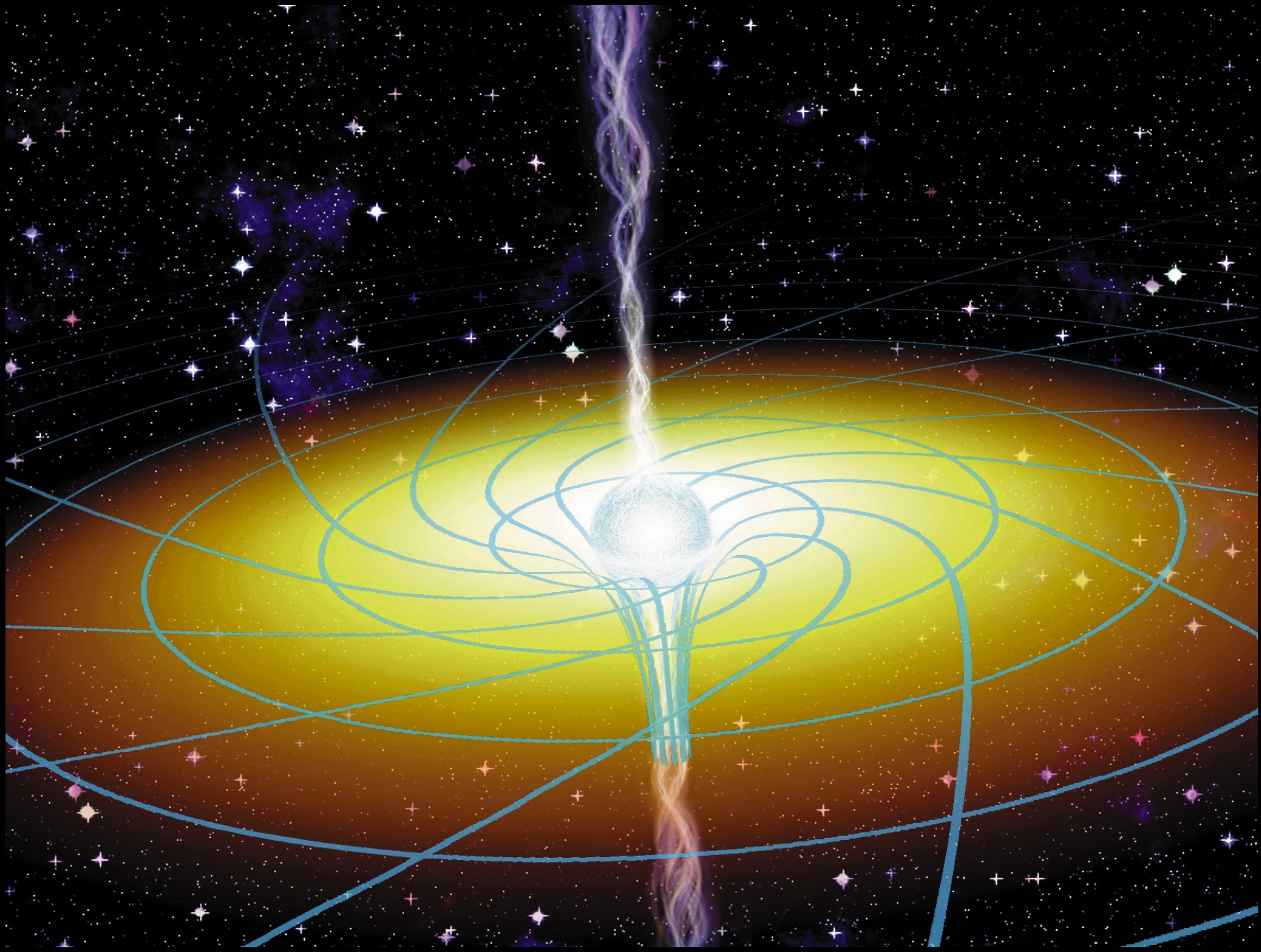


- **Black hole binary M_{BH}>13$M_\odot$, M_{star} ~ 30 $M_\odot$**
- **Relativistic jet v > 0.6 c**
- **40 hours of MAGIC observations**
- **4.9 σ signal seen in one 79 minute time slice**
- **Estimated significance 4.1 σ after correction for statistical trials**
- **Very exciting but not yet firmly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



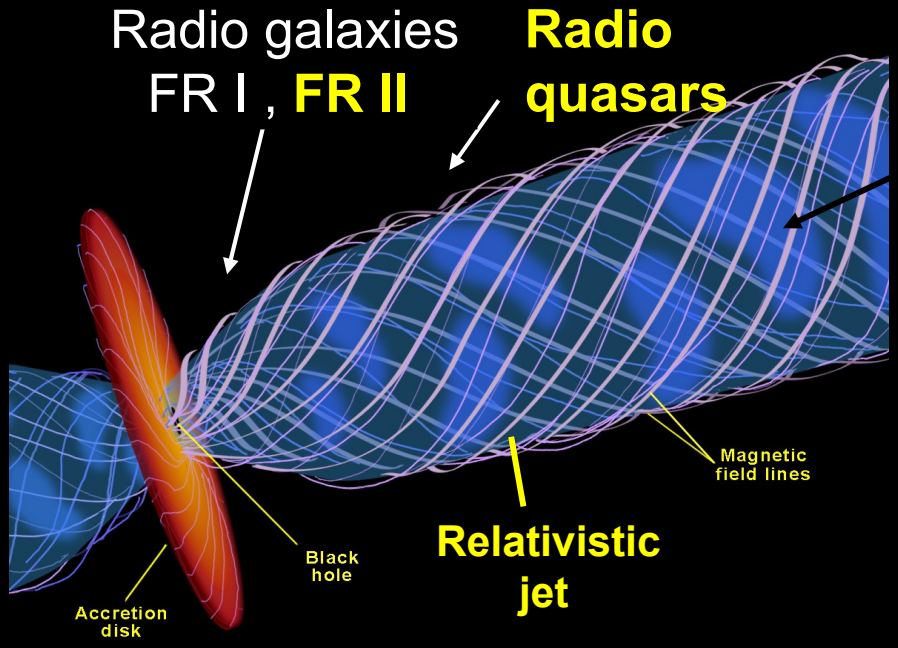
Binaries:
Laboratory to study how particle acceleration reacts to periodically varying conditions (radiation fields, B-fields, …)

Extrragalctic World



Extraglactic sources

- Historically, the “second VHE source”
- Majority of extragalactic sources are distant AGNs (Active Galactic Nuclei), made visible by Doppler beaming/boosting from jet

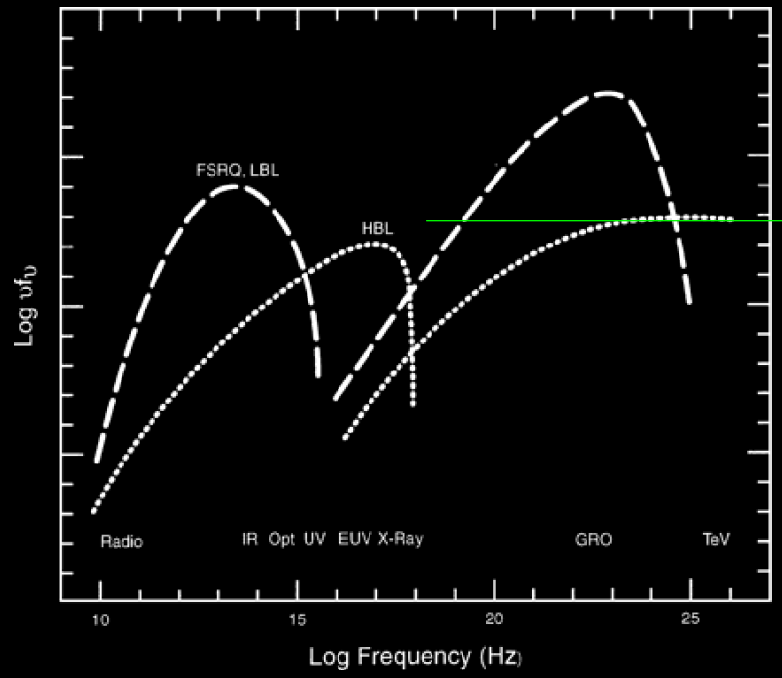


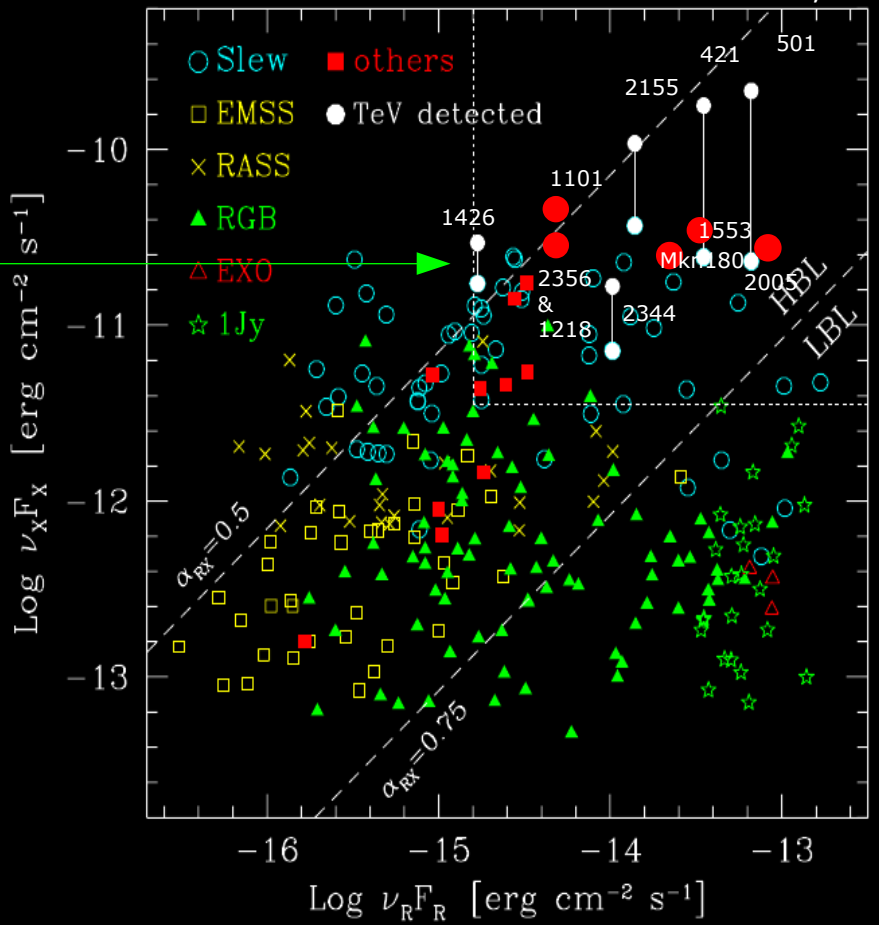
Strong relativistic boosting

- More recently at VHE, detections also of nearby “off-axis” AGNs
- This year, detection of new nearby extragalactic class: “Starburst galaxies”

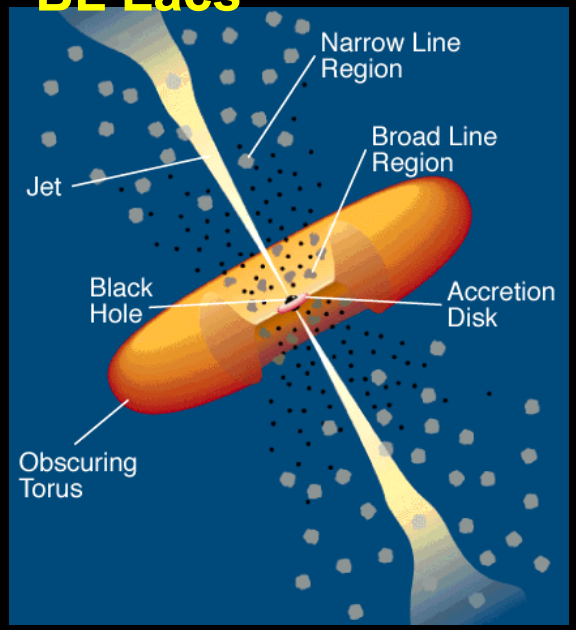
Most of known extragalactic VHE emitters are HBL's

Costamante & Ghisellini, 2002



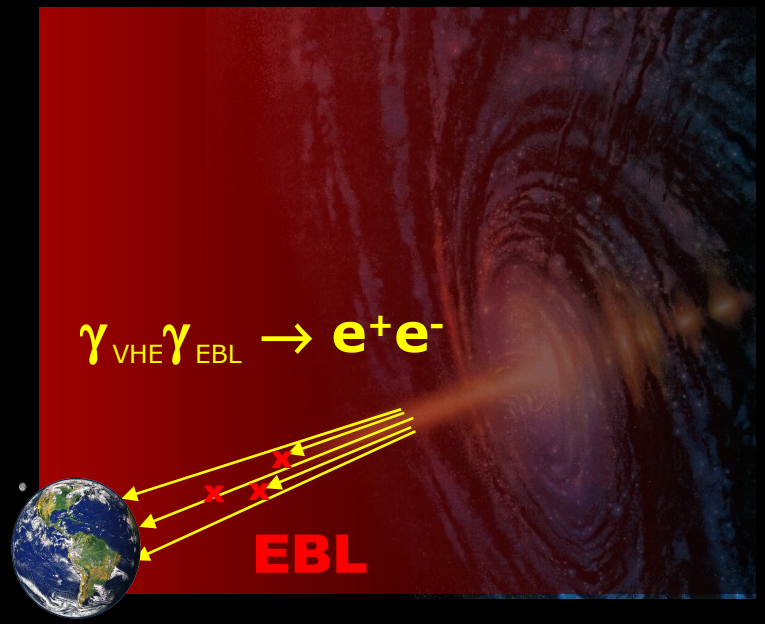


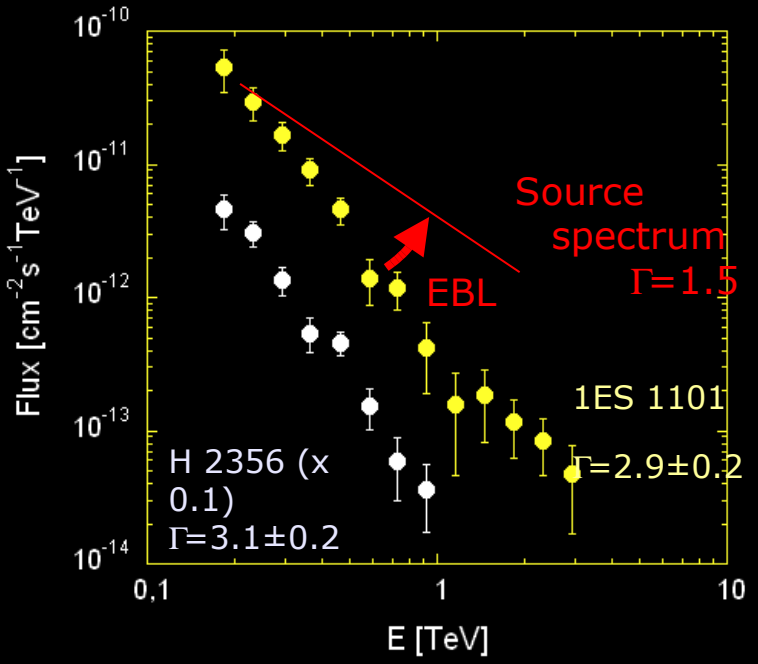
BL Lacs



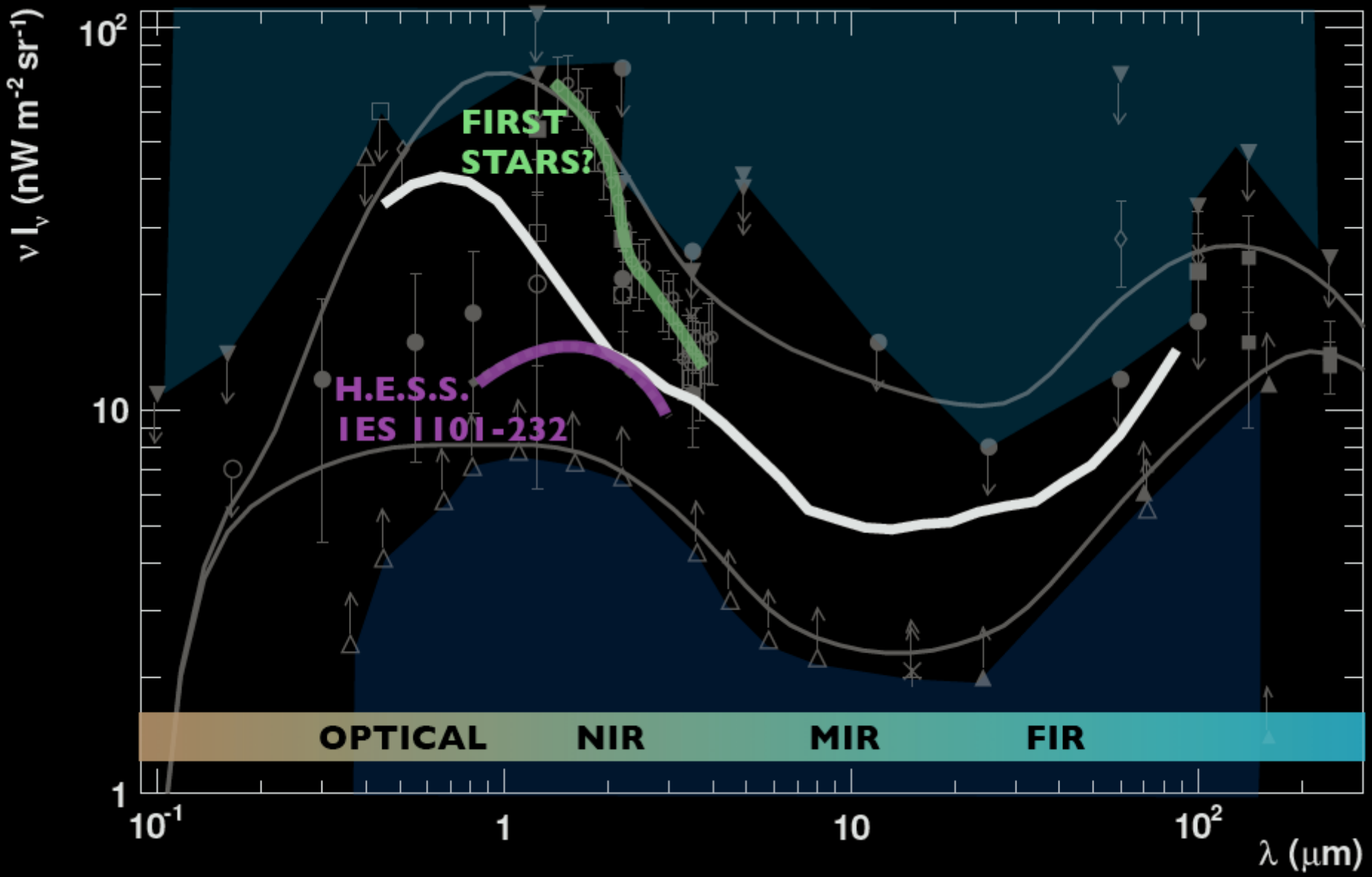
Extrragalctic VHE emitters : 20 sources

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

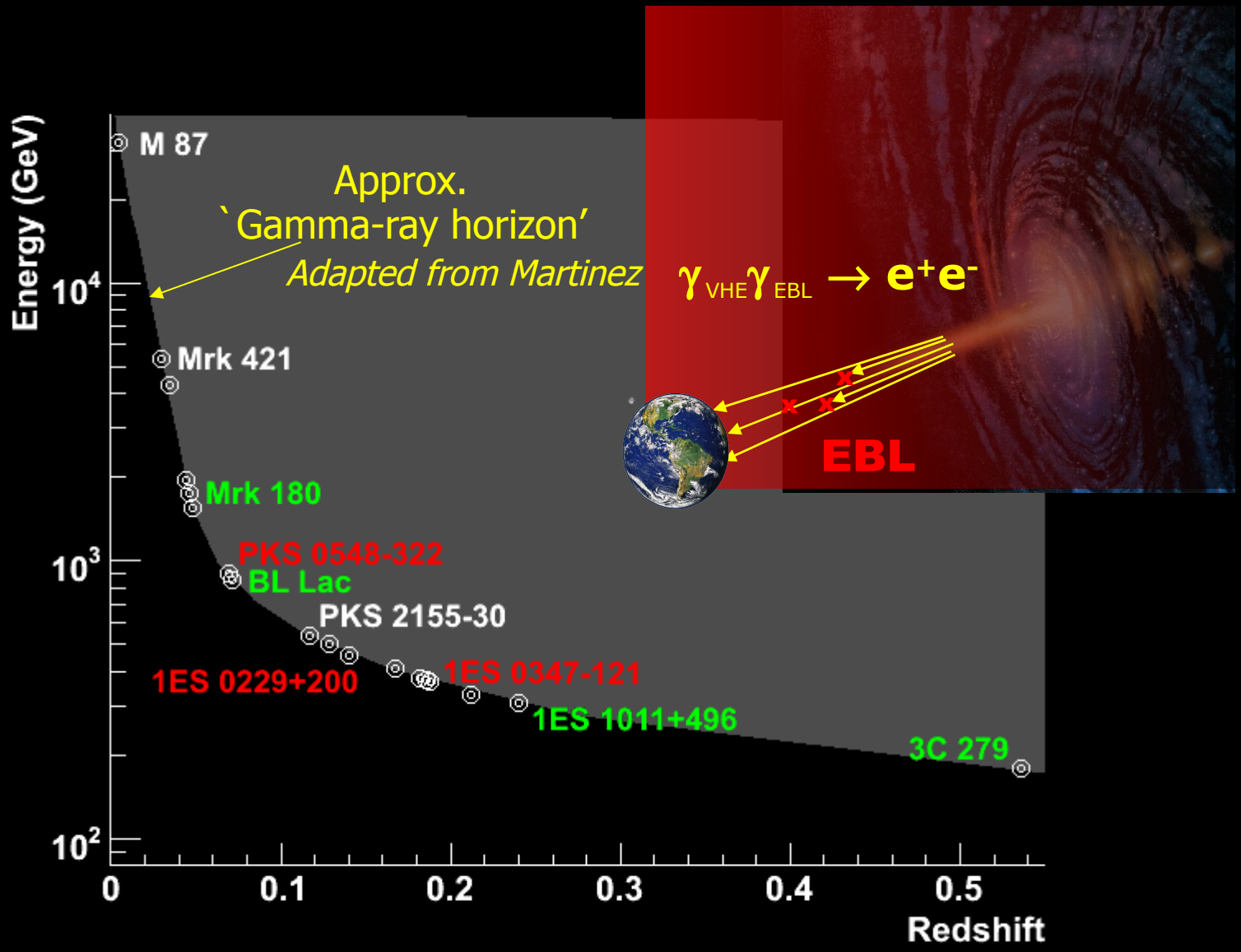


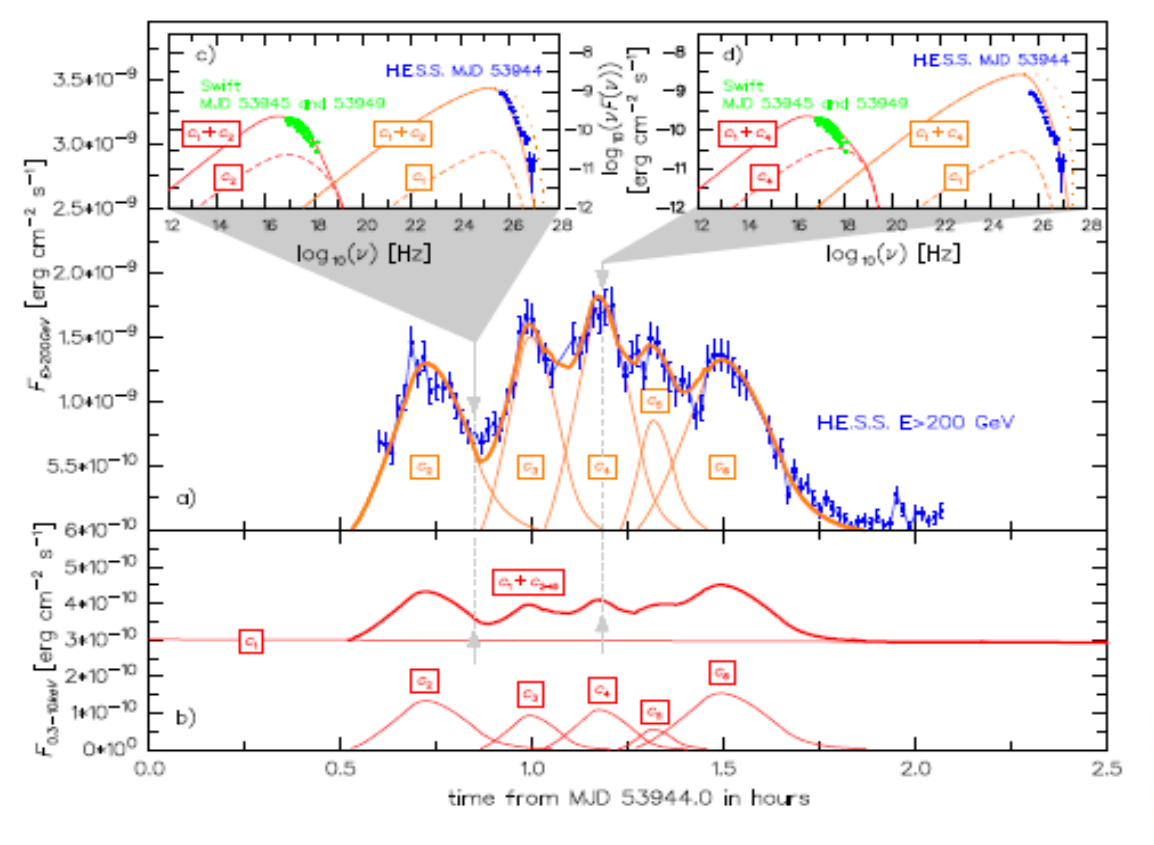


Extrragalctic VHE emitters : Probes for EBL

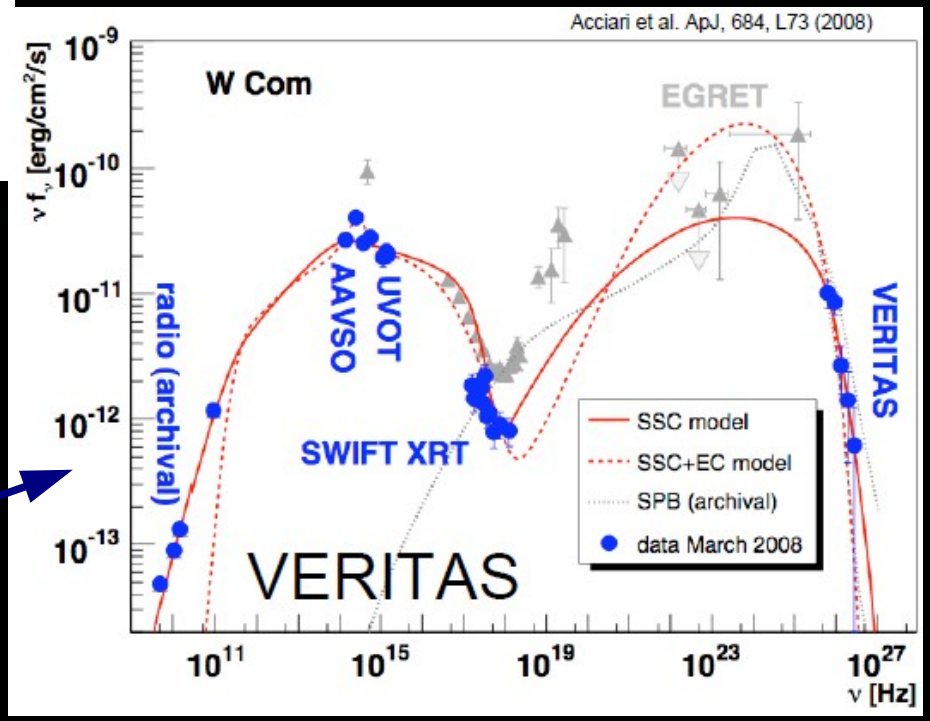


Extrragalctic VHE emitters : Probes for EBL





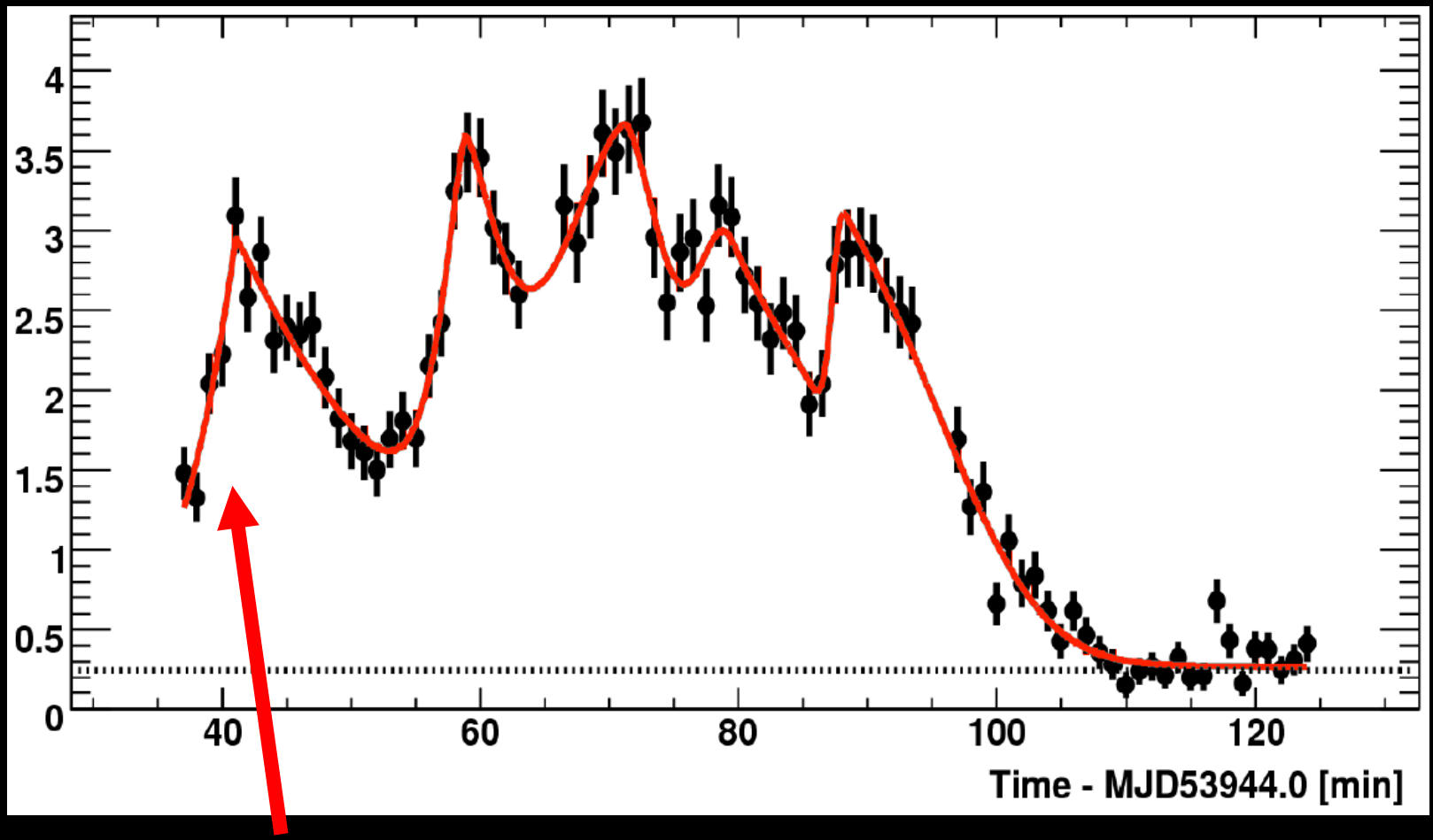
Many efforts to fit, e.g.
Example of modelling light curves and SED by time dependent SSC scenario, with 5 compact components in jet with slightly different parameters + a more extended slowly evolving component



Many other examples, on this and several other sources

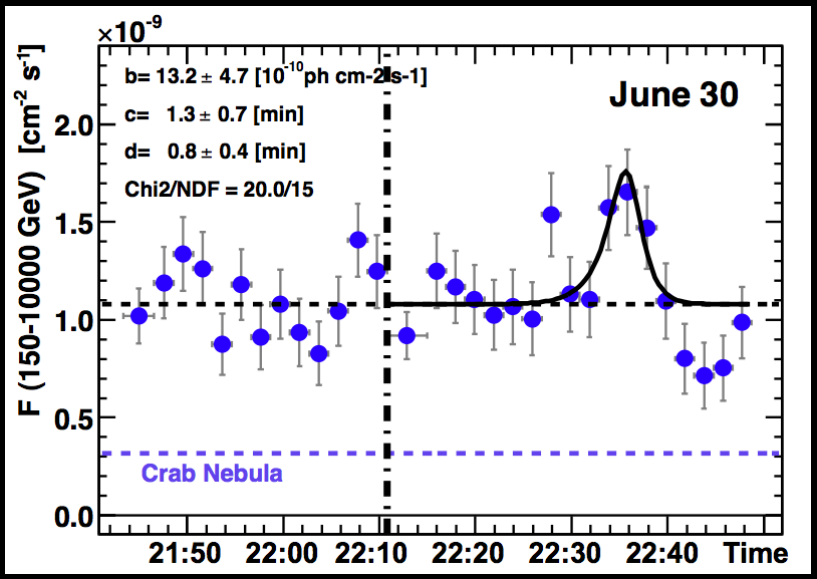
- MWL campaigns (with X-rays, radio, FermiLAT)
- Long-term variability and spectral evolution studies
- Detailed MWL spectral studies

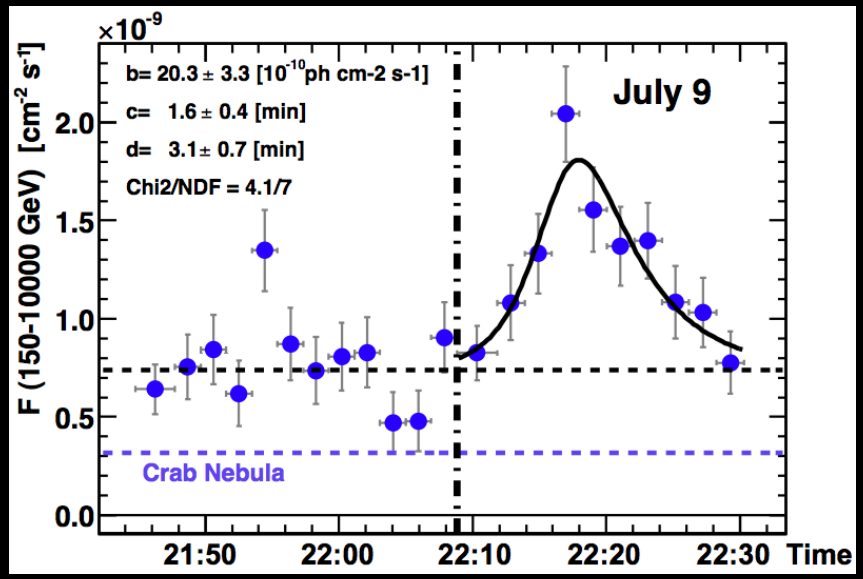
PKS2155-304 Flares (summer 2006) : HESS



- Best measured rise-time: 173 +−28 s
- Two orders of magnitude brighter than typical state
- Time-scale probes size of emitting region if causality applies
- Such measurements also used to test Quantum Gravity (LIV)

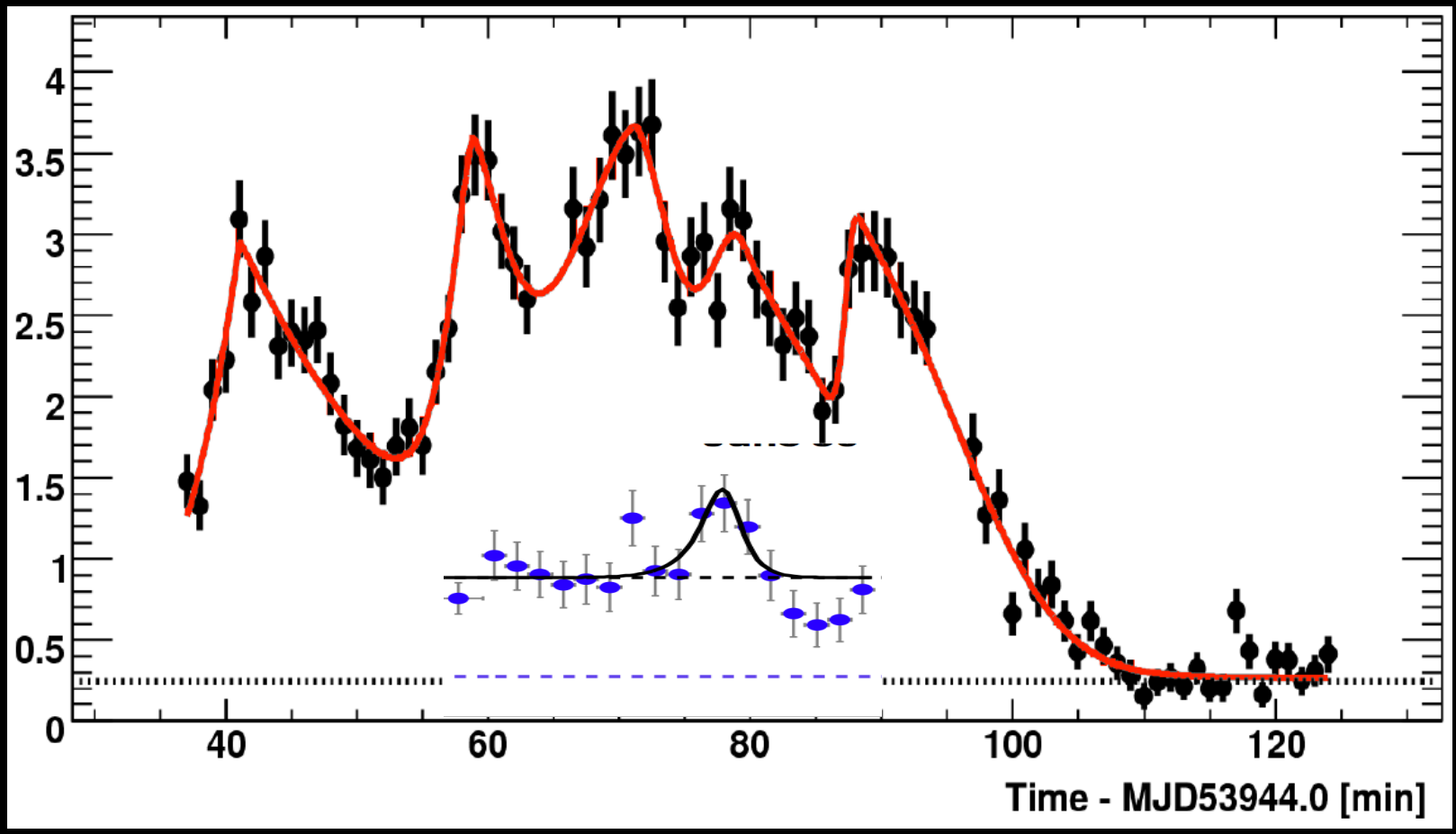
Mkn 501 Flares : MAGIC





But…

PKS2155-304 Compared to Mkn 501



M87

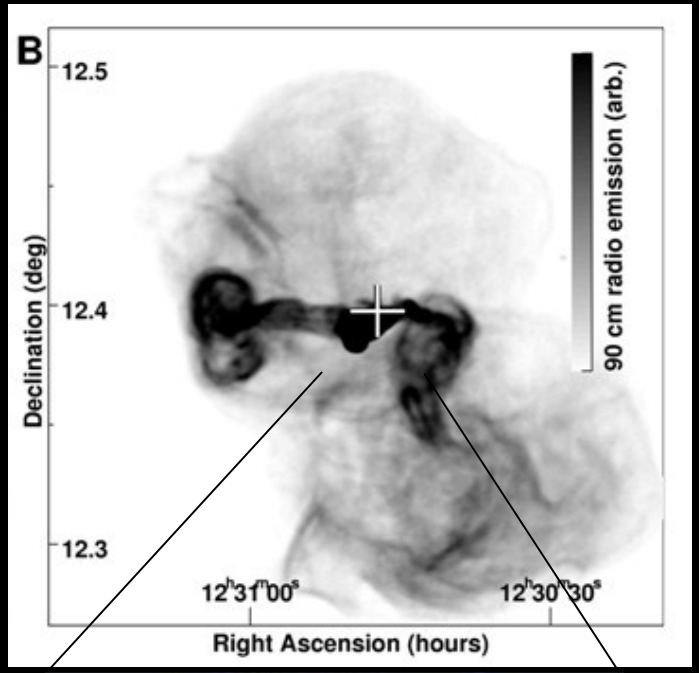
Famous nearby radio galaxy
- 16 Mpc, Jet angle ~30°

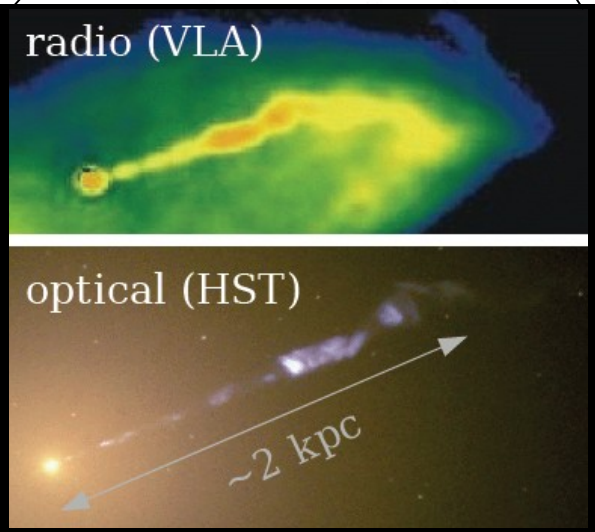
HESS 2 day variability
- Emission region $< 5\,\delta\,R_s$

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





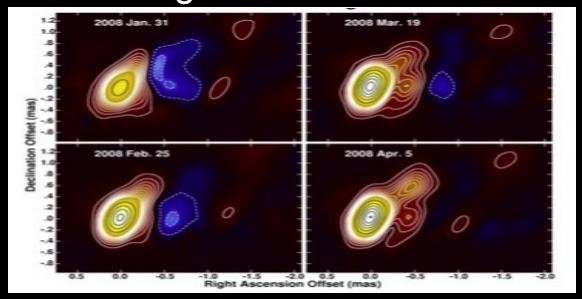
M87 joint observing campaign 2008

Joint VHE campaign:

- MAGIC, HESS, VERITAS
- Jan. - May 2008
- 95 hrs. combined
- MAGIC ToO

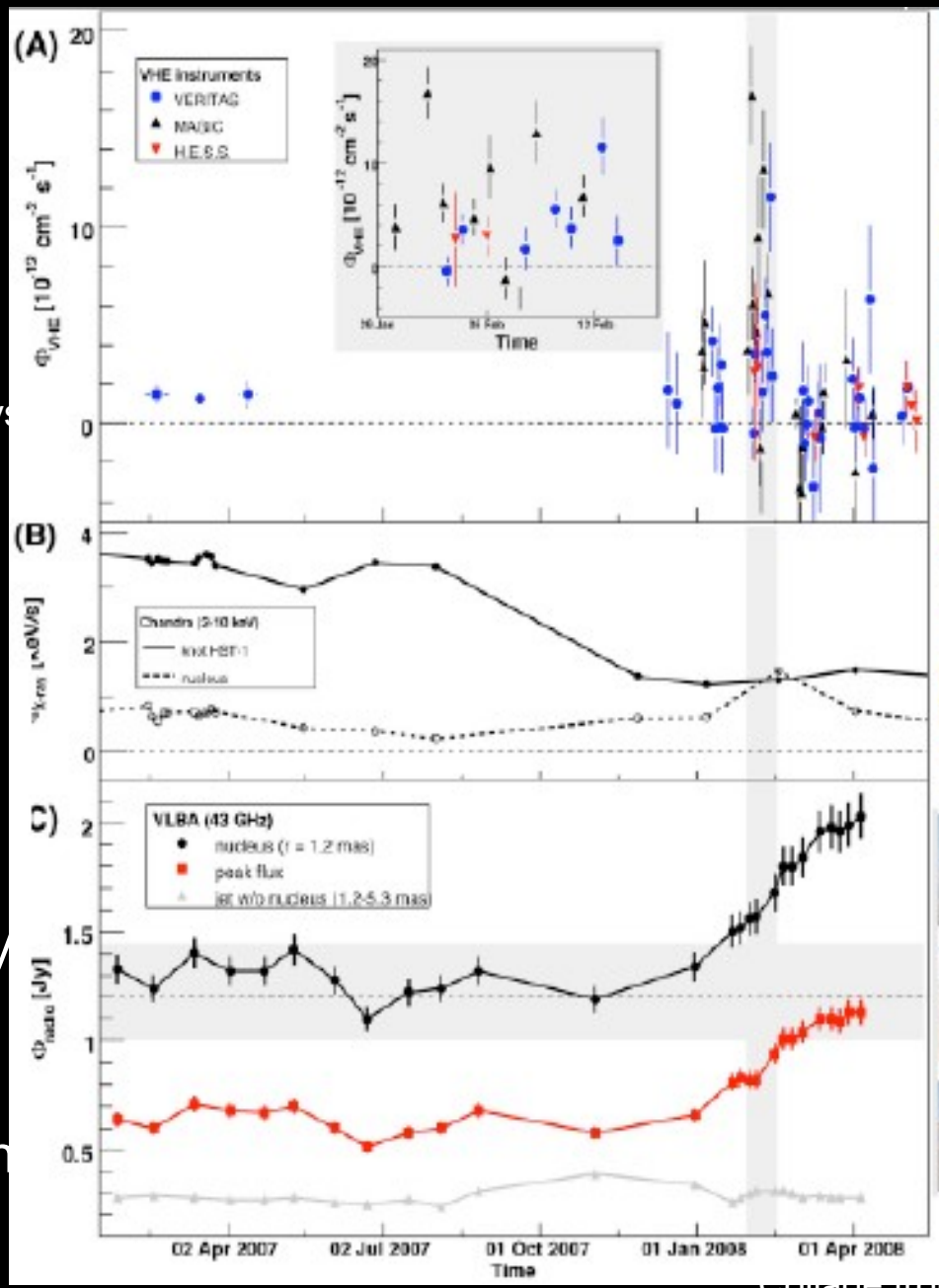
VLBA “movies”

- 14 shots in 2008, every 5 days
- ang. resolution 0.2 x 0.4 mas



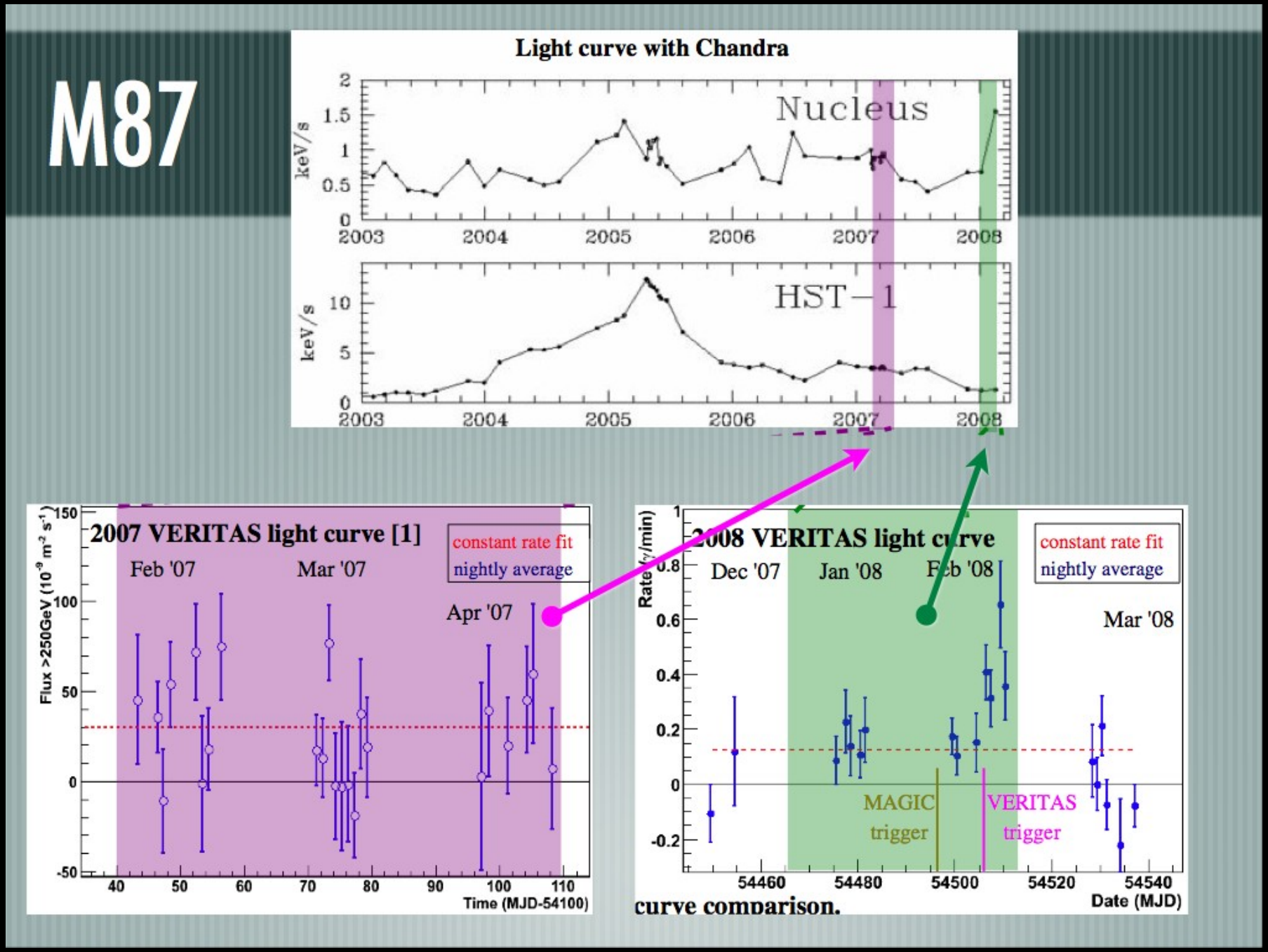
X-ray light curve of HST-1 obtained by Chandra in 2008 does not follow TeV

Correlated core emission (radio, X and VHE)
→ favours scenarios with TeV emission from inner jet or central core.



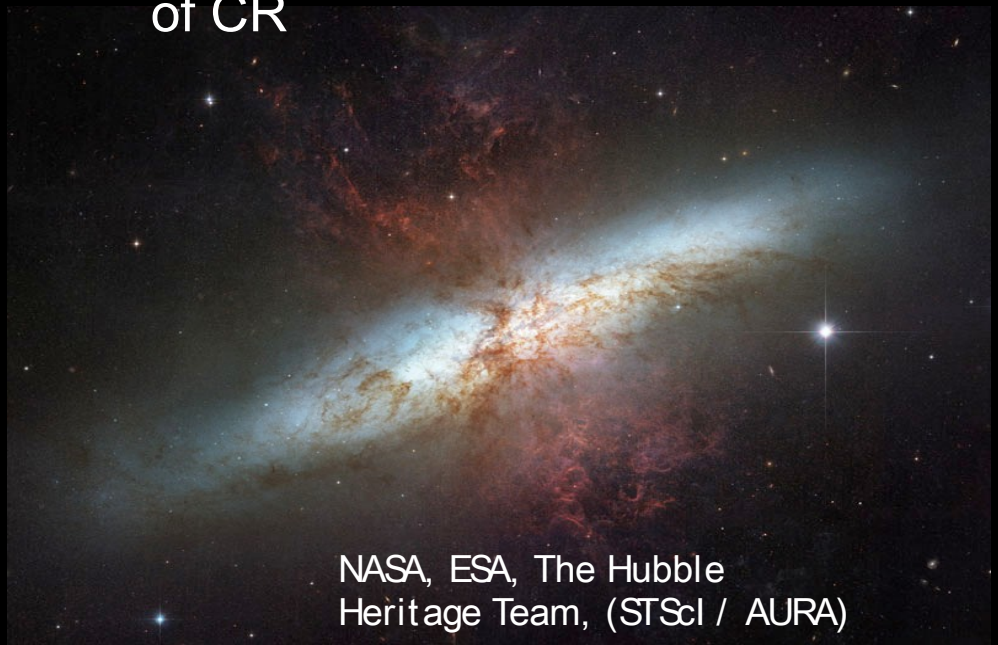
Collage from F. Krennrich, TeVPA 2009

M87: Veritas obserrvations



New source category: Starburst galaxies

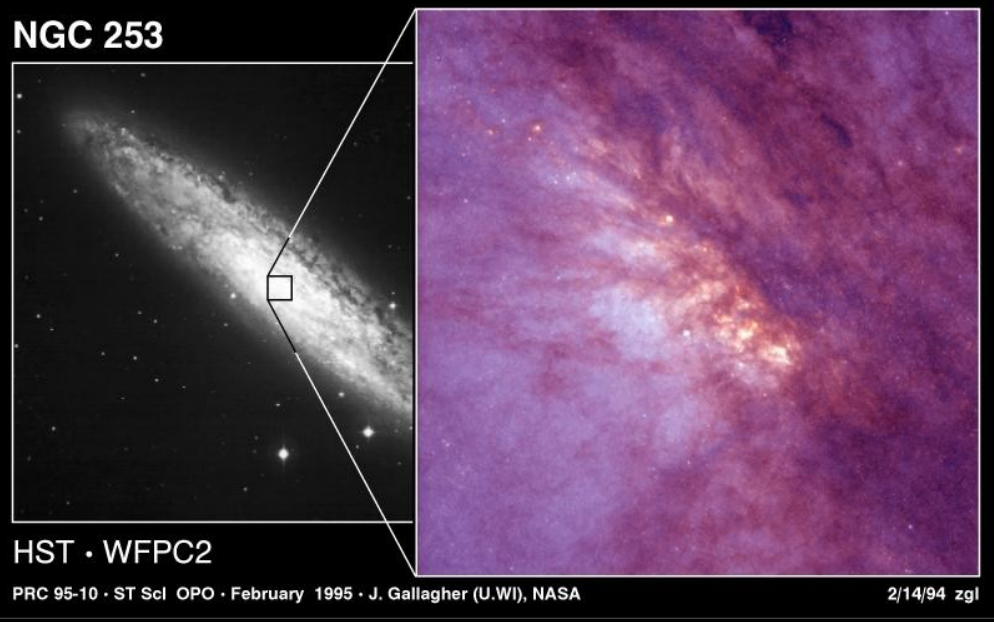
- M82, the prototype starburst galaxy
  - Distance ~ 3.9 Mpc
  - Diameter ~ 1’
  - SMBH ~ 3 x 107 Msolar
  - Interacts with group of galaxies (M81)
  - HST: 200 massive star clusters
  - High supernova rate ~ 0.1 - 0.3 per year
  - High gas density 150 particles/cm3
- ⇒ excellent candidate for cosmic ray interactions & gamma ray emission.
- probing paradigm that SNRs are origin of CR



NASA, ESA, The Hubble Heritage Team, (STScI / AURA)

- NGC 253: Closest spiral galaxy outside the local group
  - Distance 2.5 – 3.9 Mpc
  - Starburst nucleus
  - Supernova rate in central ~100 pc comparable to the rate in all Milky way
  - Central gas density almost three orders of magnitude larger than the average in Milky way
  - Luminous in infrared (dust reprocesses star light)
- Predicted gamma-ray emitter

Paglione et al. 1996; Aharonian et al. 2005, Domingo & Torres 2005, Rephaeli et al. 2009

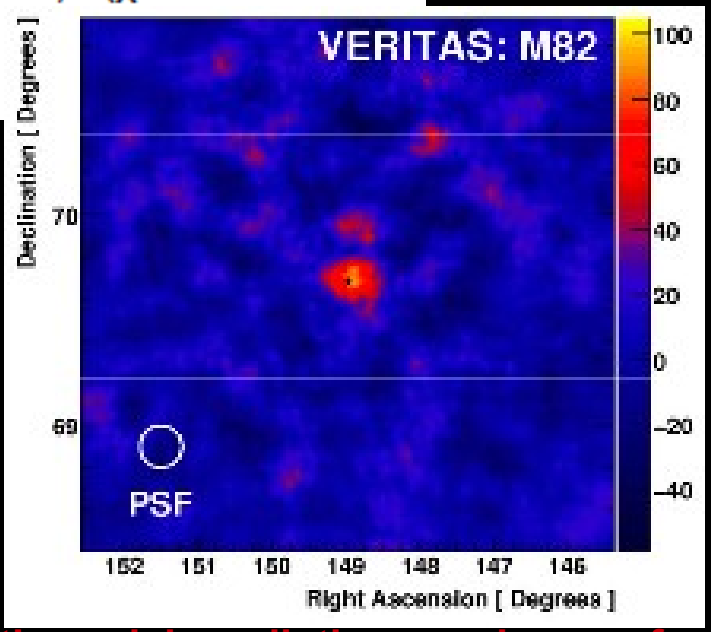


- M82, VERITAS measurements
- 2007-09: 137 h live time.
  Only dark time (no moonlight).
- 5.0 σ excess (pre-trials), 4.8 σ (post-trials).
- E > 700 GeV (LZA observations). Point-like.
- **Among weakest VHE sources ~0.9% Crab**

Fit Range: 875 GeV to ~5 TeV

- Fit to dN/dE ~ (E / TeV)$^{-\Gamma}$
- $\chi^2 = 0.1$, 1 NDF; $P(\chi^2) = 0.7$

$\Gamma = 2.5 \pm 0.6$

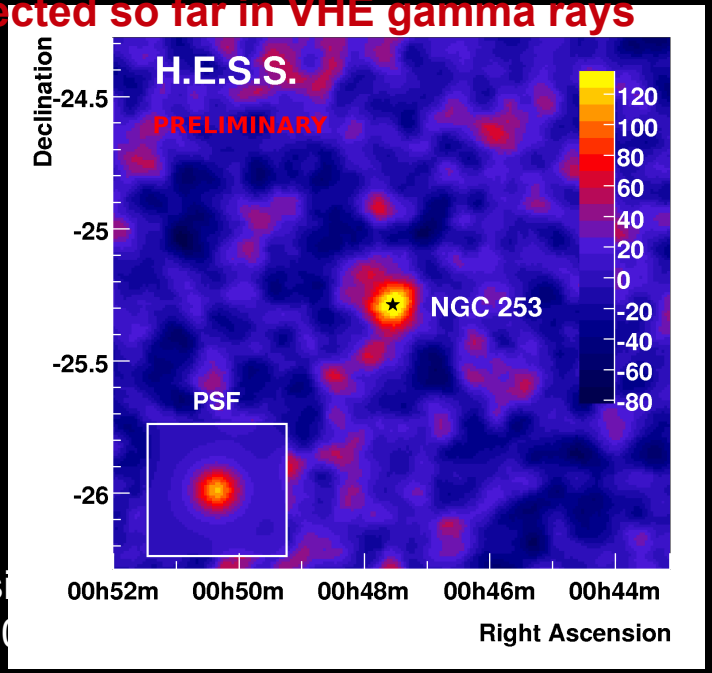


Benbow, ICRC2009

- NGC 253: H.E.S.S. measurement
- Deep observations with the full array,
- 119 hours of good livetime
- Careful data-quality selection
-
- Significance 5.2 σ, 247 excess events, pt-like

$F(>0.22\ \mathrm{TeV}) = (5.5 \pm 1.0_{stat} \pm 2.8_{sys}) \times 10^{13}\ \mathrm{cm^{-2}s^{-1}}$ (0.3% Crab)

Faintest source detected so far in VHE gamma rays



Domainko, ICRC2009

Model analysi
Threshold 22

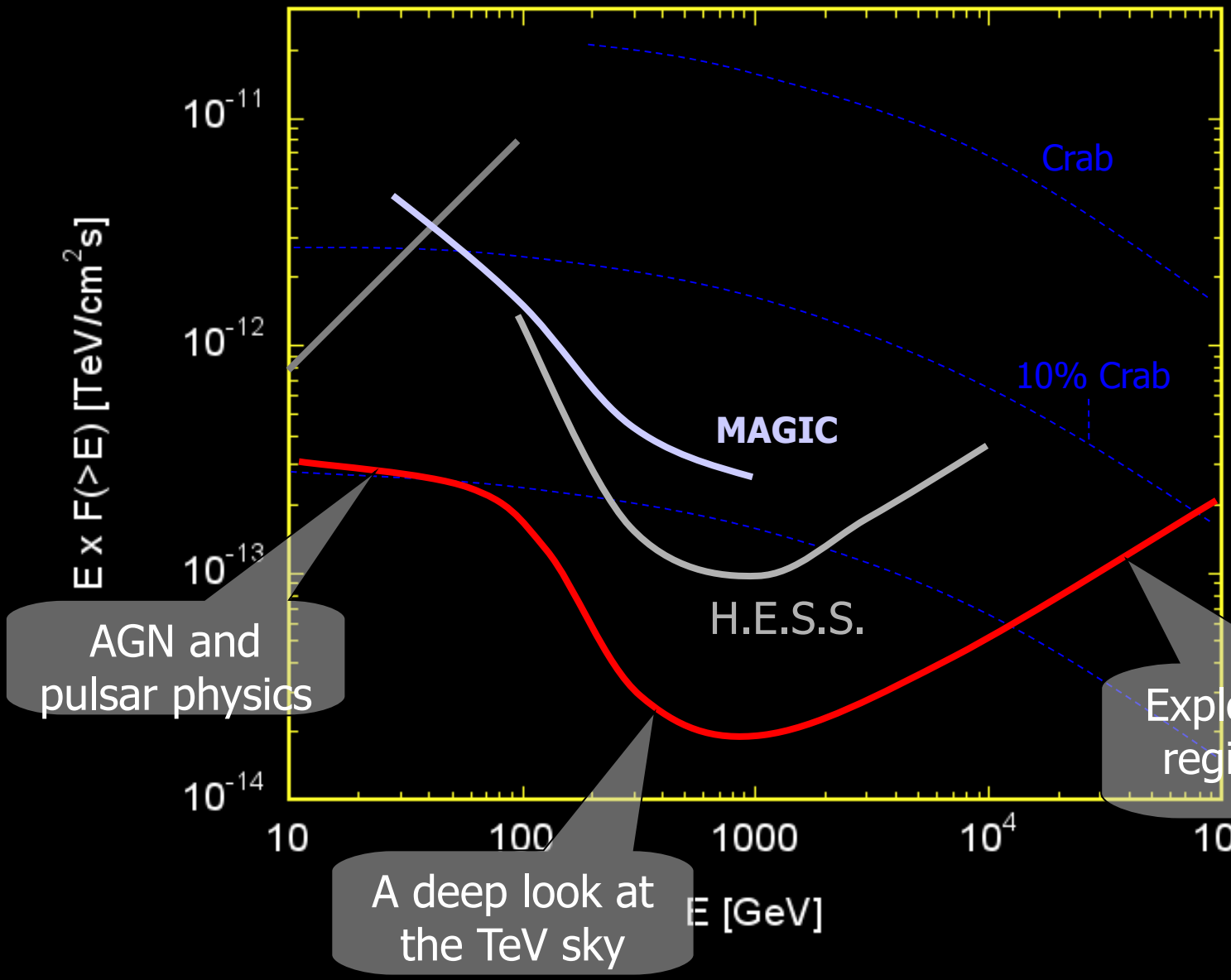
Comparison with model predictions underway, for understanding of CR production and propagation,

Near term: HESS-II & MAGIC-II

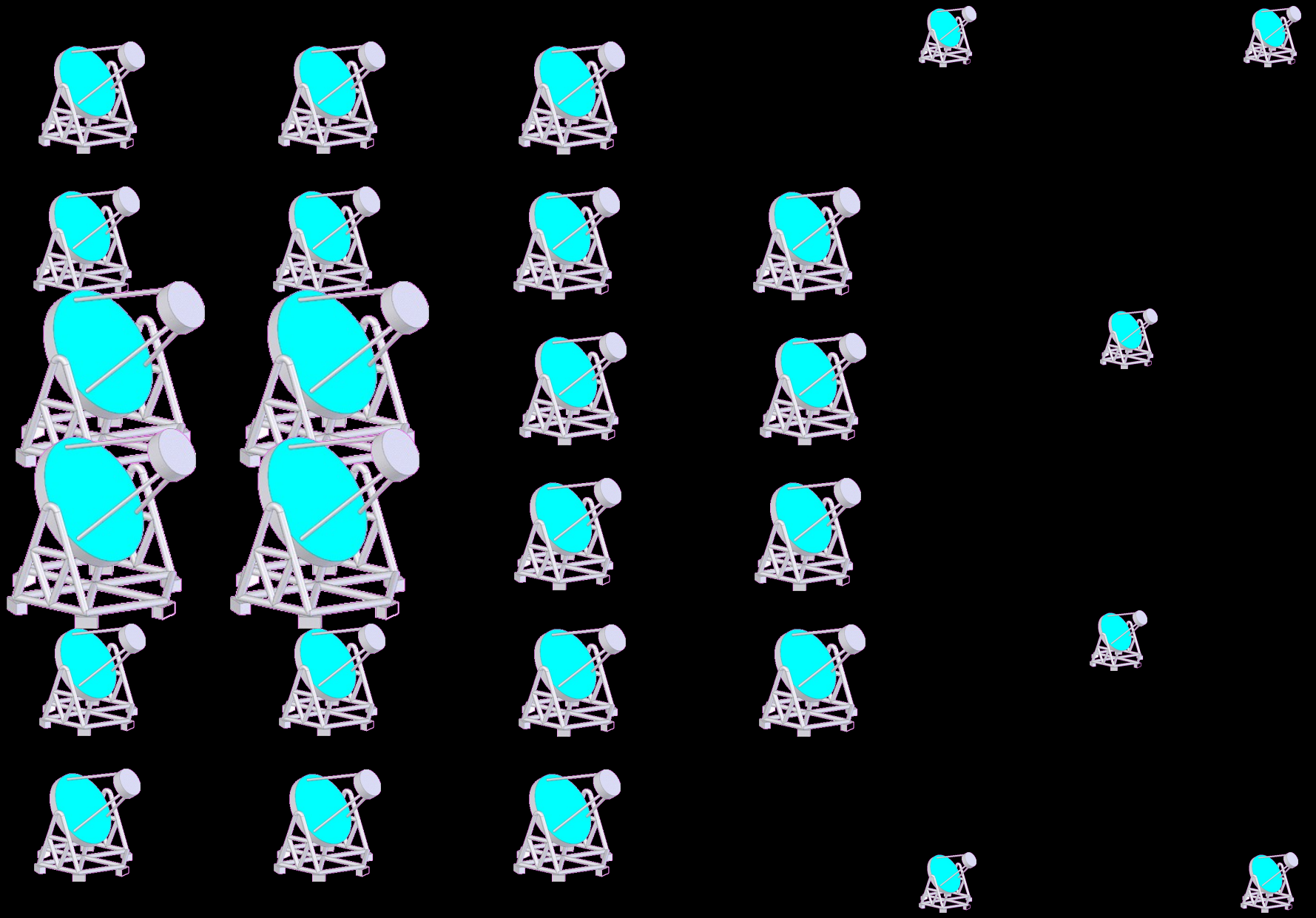
HESS-II : 4x12m +
28m diameter telescope
Lower threshold energy
In 2009

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

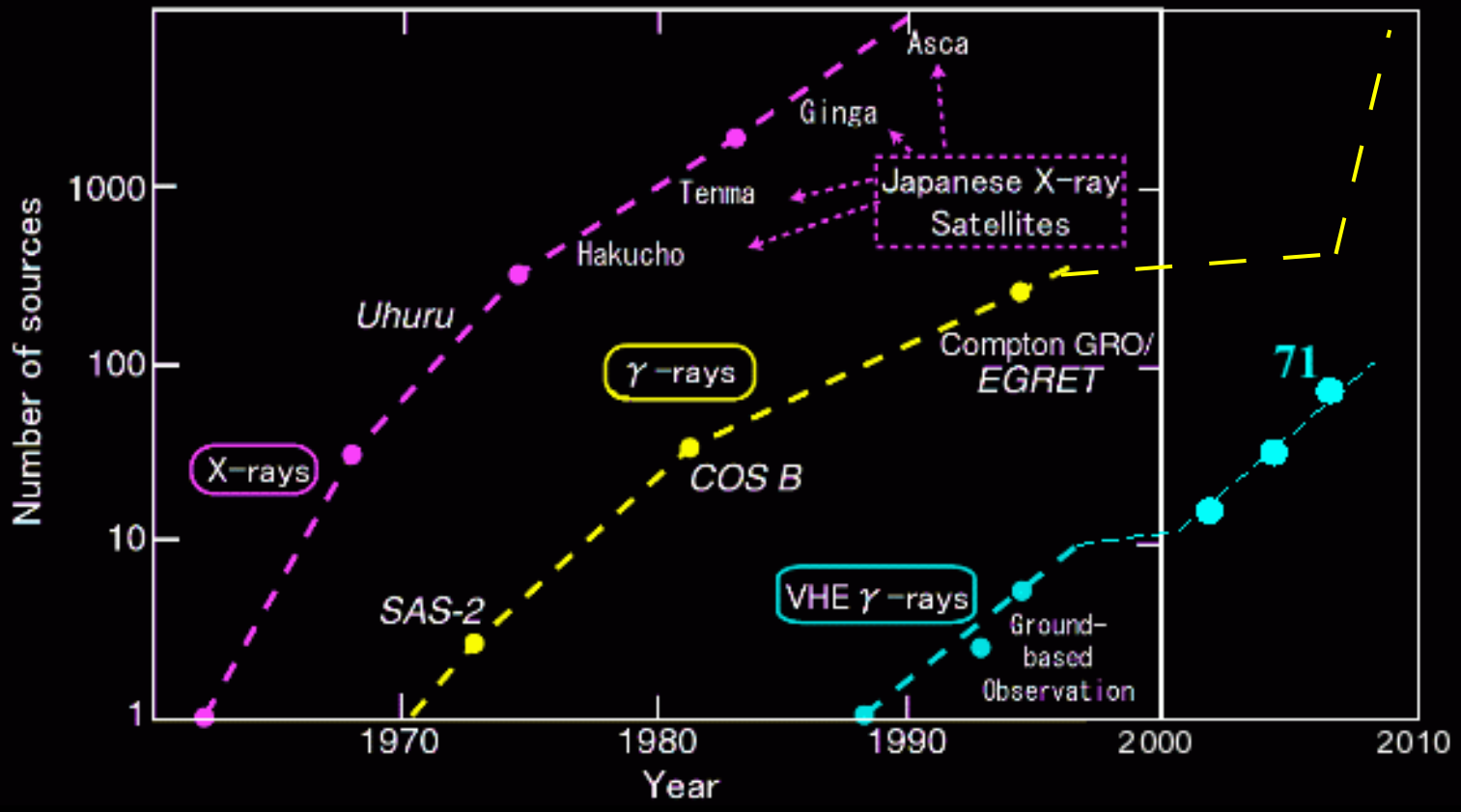
Mid term Project : CTA (Cherenkov Telescope Array)



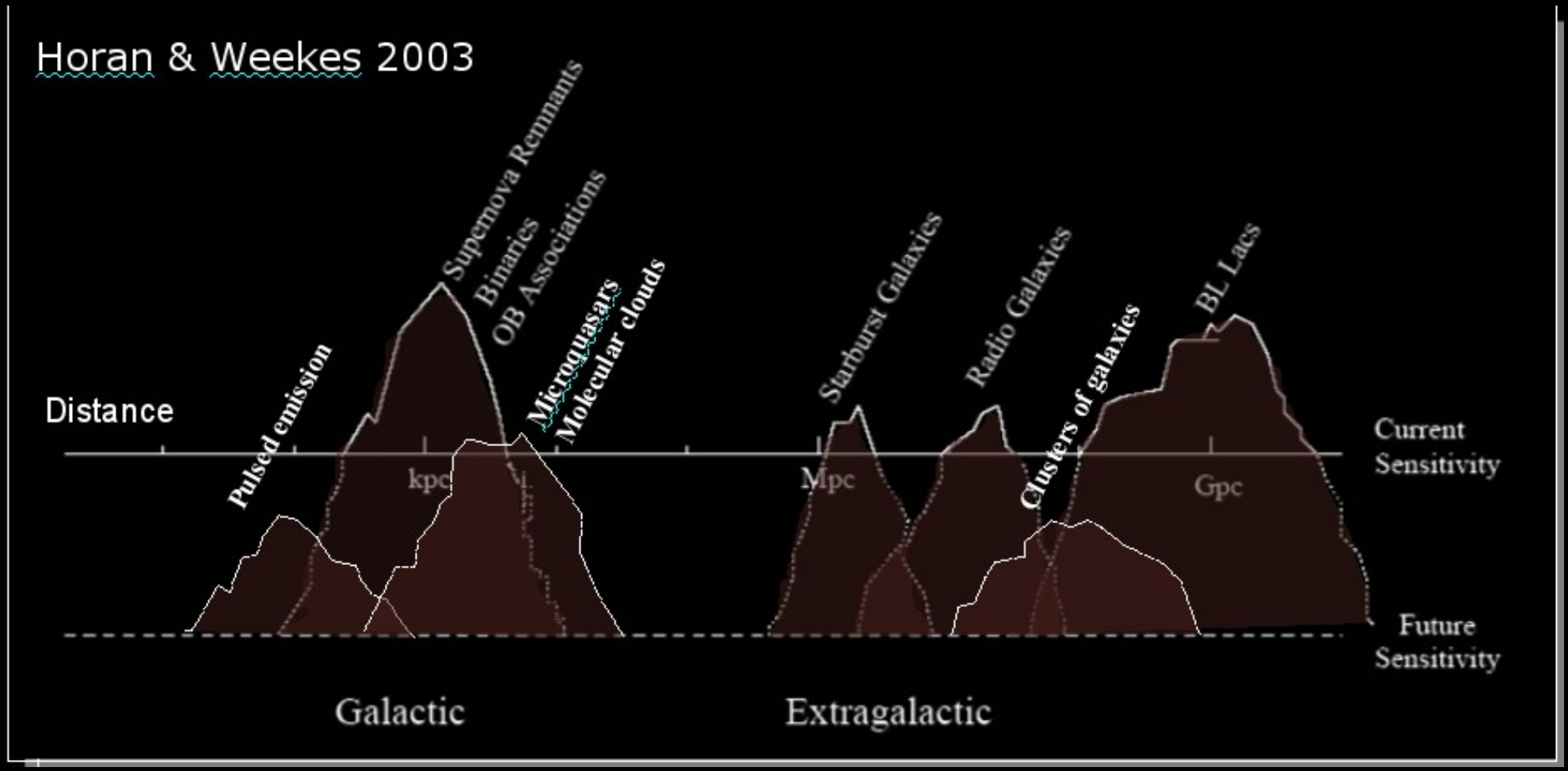
Mid term Project : CTA (Cherenkov Telescope Array)



Perspectives



Perspectives

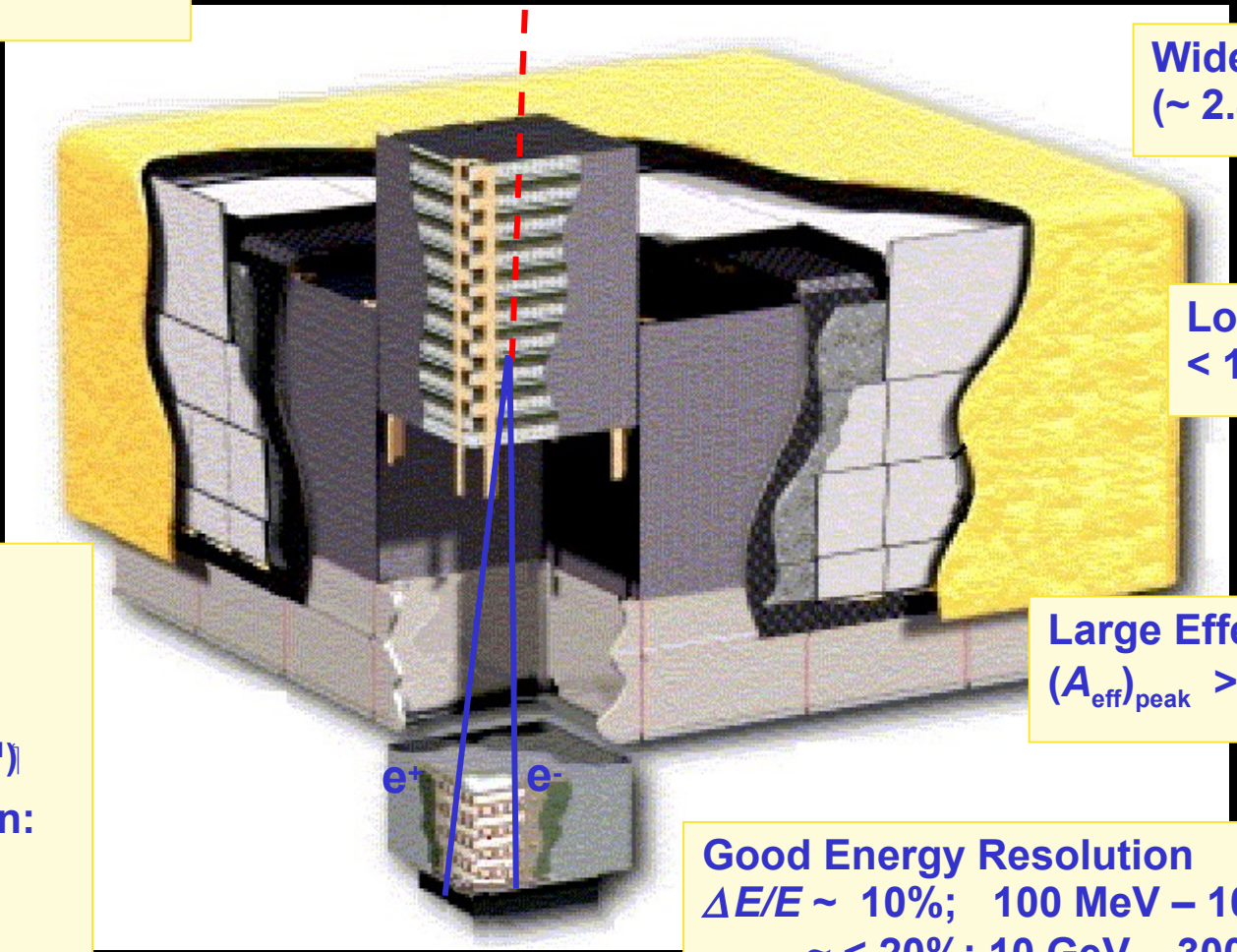


- Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, but this is clearly only the tip of the iceberg
- Broad and diverse program ahead, combining guaranteed astrophysics with significant discovery potential

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)

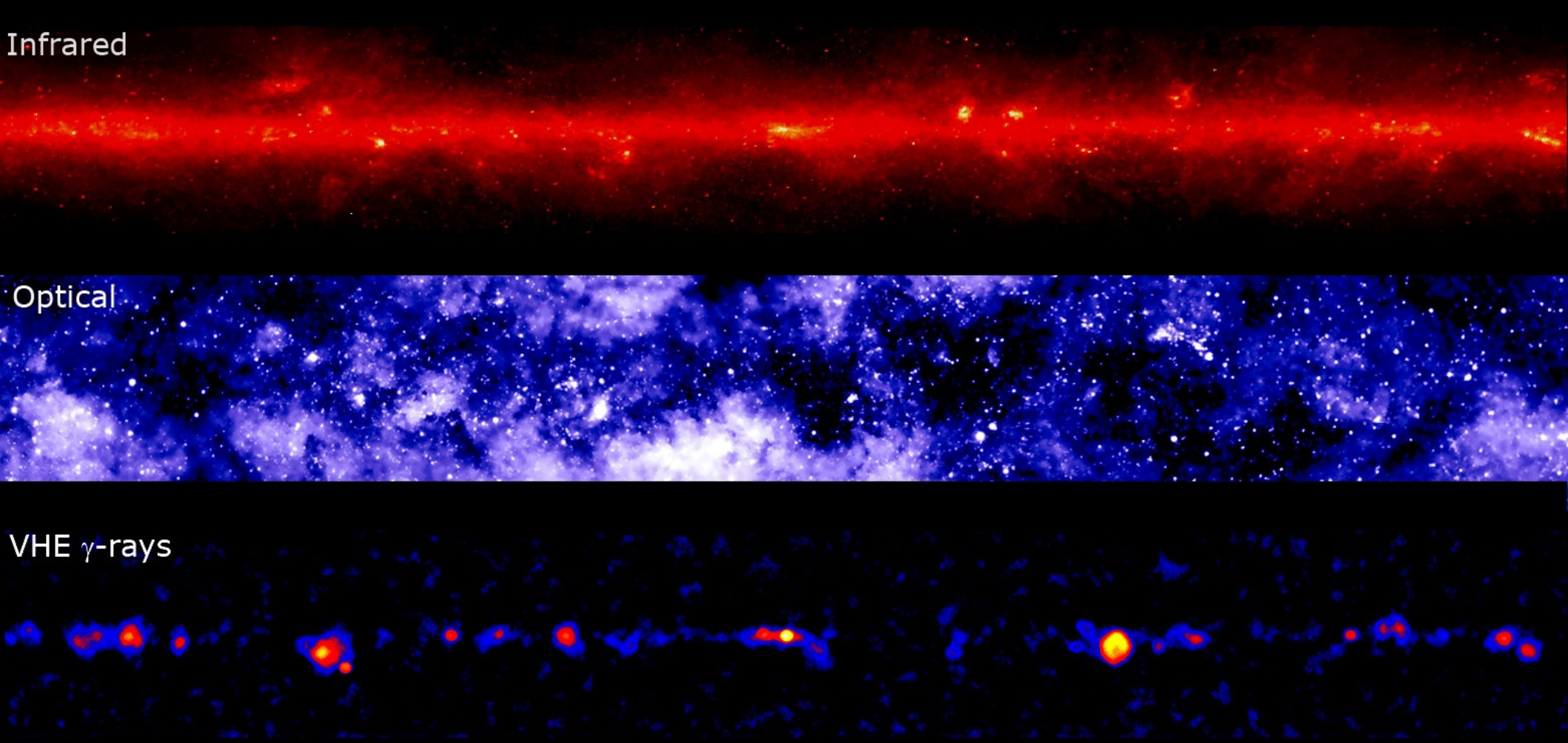
Low dead time:
< 100 μs/event

Large Effective Area
$(A_{eff})_{peak}$ > 8,000 cm²

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'

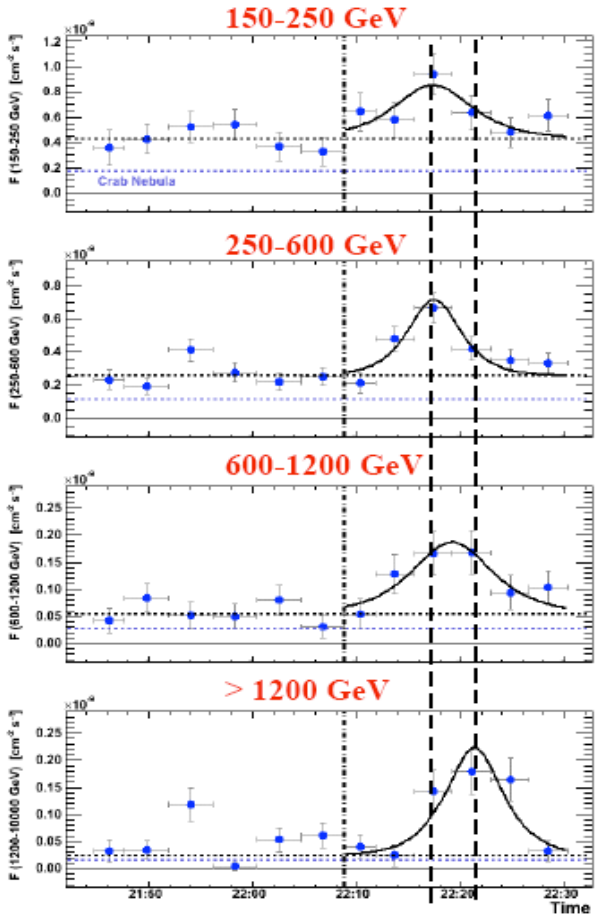
Good Energy Resolution
$\Delta E/E$ ~ 10%; 100 MeV – 10 GeV
~ < 20%; 10 GeV – 300 GeV



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

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.