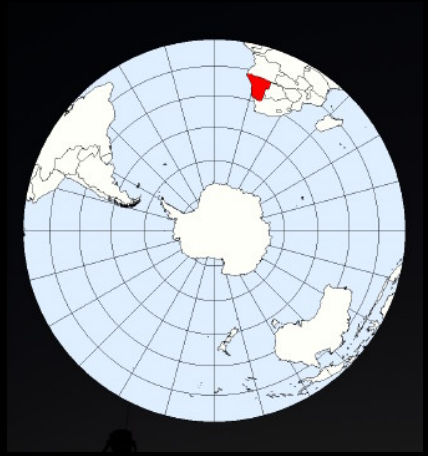
The γ-ray sky seen by H.E.S.S.

Francesca Volpe
MPI-K Heidelberg
On behalf of the H.E.S.S Collaboration

THE HESS experiment

Operating since 2003

Energy threshold	100 GeV
Energy resolution	20%
Field of view	~ 5 deg
Angular resolution	<0.1deg
Sensitivity	1 Crab in 30 sec



Outline

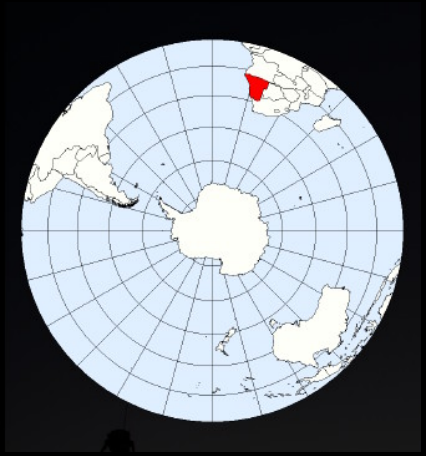
Selected results

The Galactic Survey

- SN1006 + HESS J1731-347: new shell type SNRs
- Other sources (PWNs, massive stellar clusters)

The new extragalactic detections

- TeV blazars and MWL campaign on radio galaxies
- Starburst galaxy in VHE γ-rays



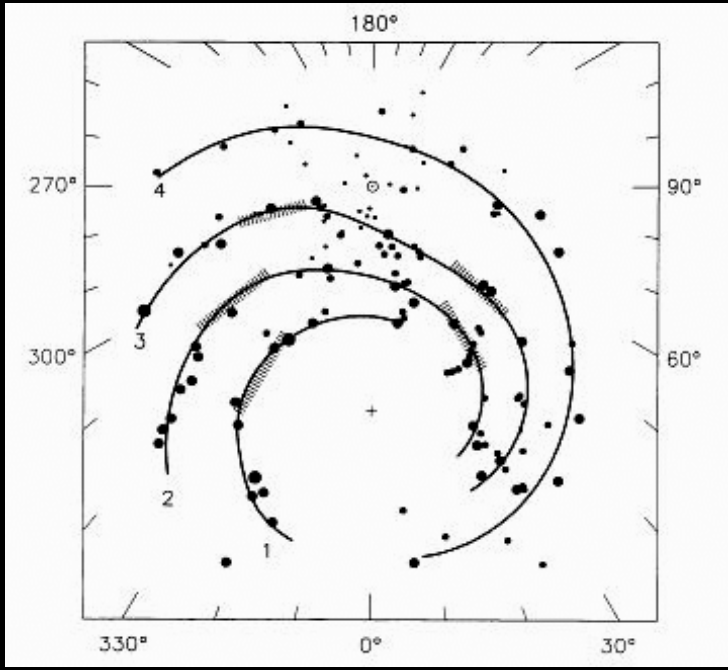
The galactic survey

The initial TeV galactic plane survey (2004)

- Exposure ~95h scan mode + ~135h follow-up/dedicated
- Discovered 14 Galactic sources of TeV radiation

The extended H.E.S.S. Galactic plane survey (2005-2009)

- A much deeper exposure: 1400 h scan mode + dedicated observations
- A more uniform exposure
- Discovered a total of 56 Galactic sources
- very narrow distribution (RMS(b) ~0.3°)



Aharonian et al. 2005 Science, 307
Aharonian et al. 2006, ApJ, 636
Chavez et al. 2009, ICRC Proc.

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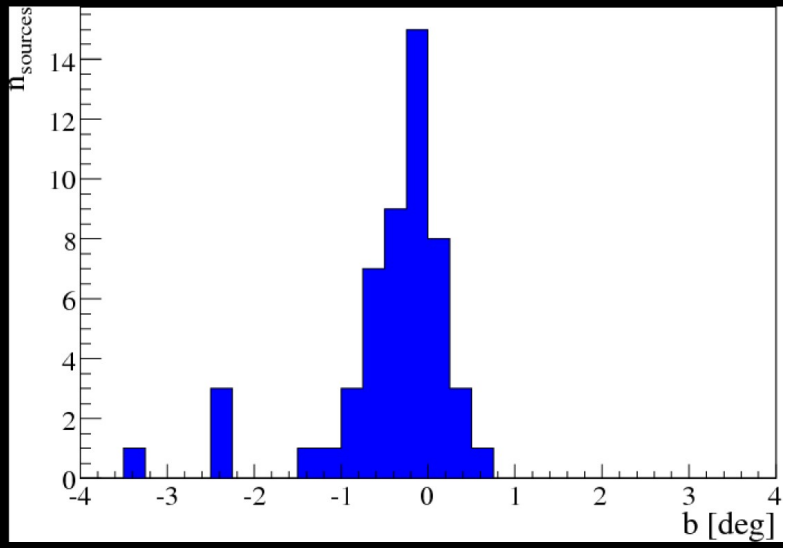

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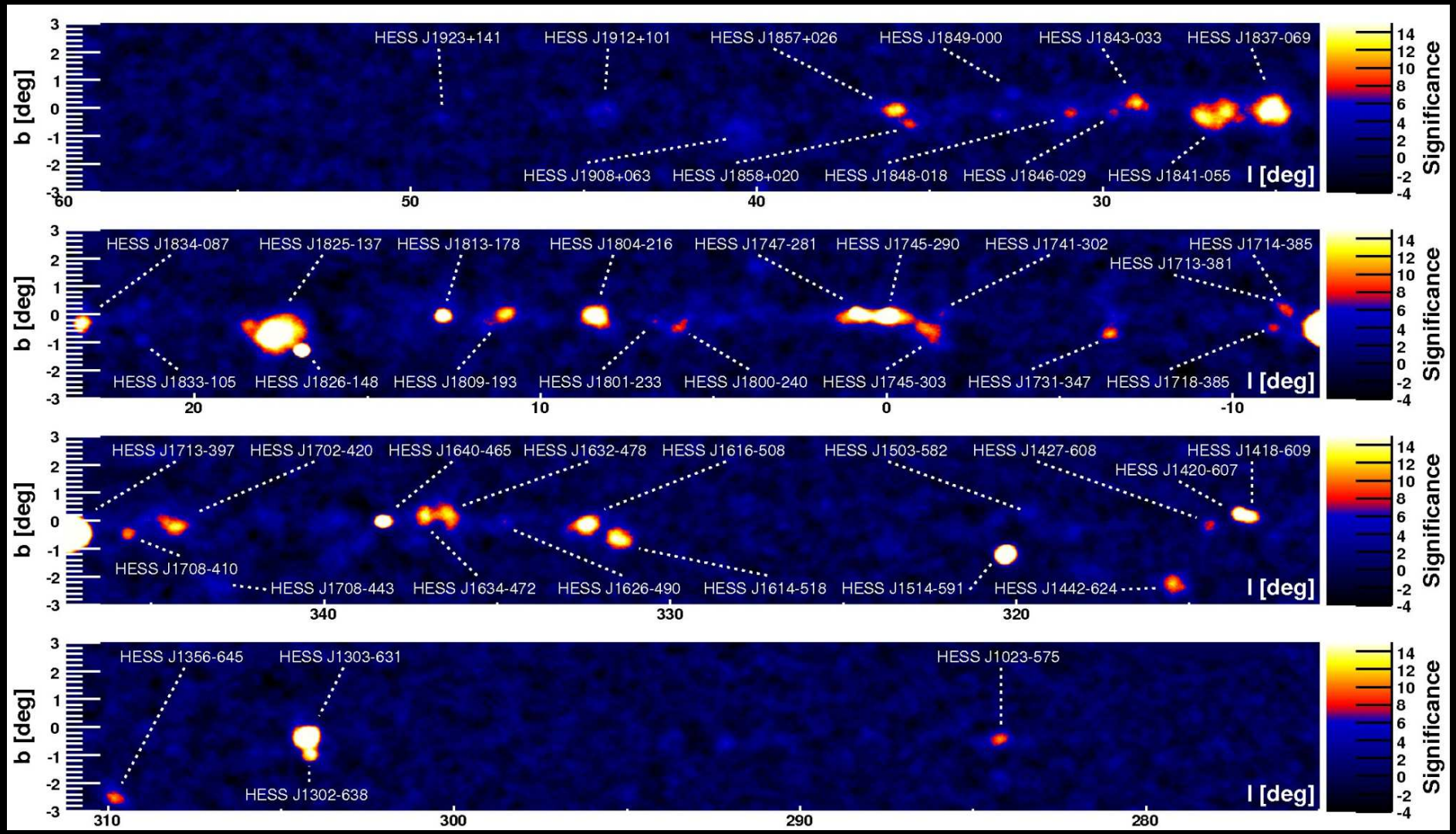
The galactic plane survey



Most of the revealed sources are mildly extended (D > 3 ' to 4 ')

$-80^{o} < long < 60^{o}$

Population: PWN, SNRs, Binary systems, Dark sources, Interacting stellar winds

Shell-type SNRs

- Supernova remnants (SNRs) are suspected to be the main accelerators of galactic cosmic-rays up to the knee
  - Diffusive shock acceleration
  - 10% of the mechanical energy of supernovae can account for the injection of CR's in the Galaxy.
- Thin filaments seen in non-thermal (synchrotron) X-rays prove that electrons are accelerated up to 100 TeV and indicate the shock position.
- SNRs are often extended sources → no clear detection by EGRET (the source does not stand out over the diffuse γ-ray flux)
- H.E.S.S. provided resolved images of several large shell-type SNRs

Particle acceleration in SNR

- Two possible processes:
  - ✓Inverse Compton scattering of VHE electrons on ambient photons (mainly CMB)
  - ✓Hadronic interactions of accelerated protons or ions in the interstellar medium

- Cut-off above 10TeV + significant γ-ray flux (4.8 σ) above 30 TeV
- Primary particle energies:
  - hadronic scenario

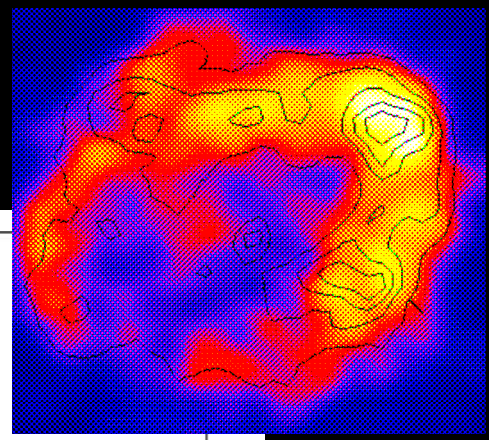
    $E_{proton} \sim 200$ TeV
  - leptonic scenario

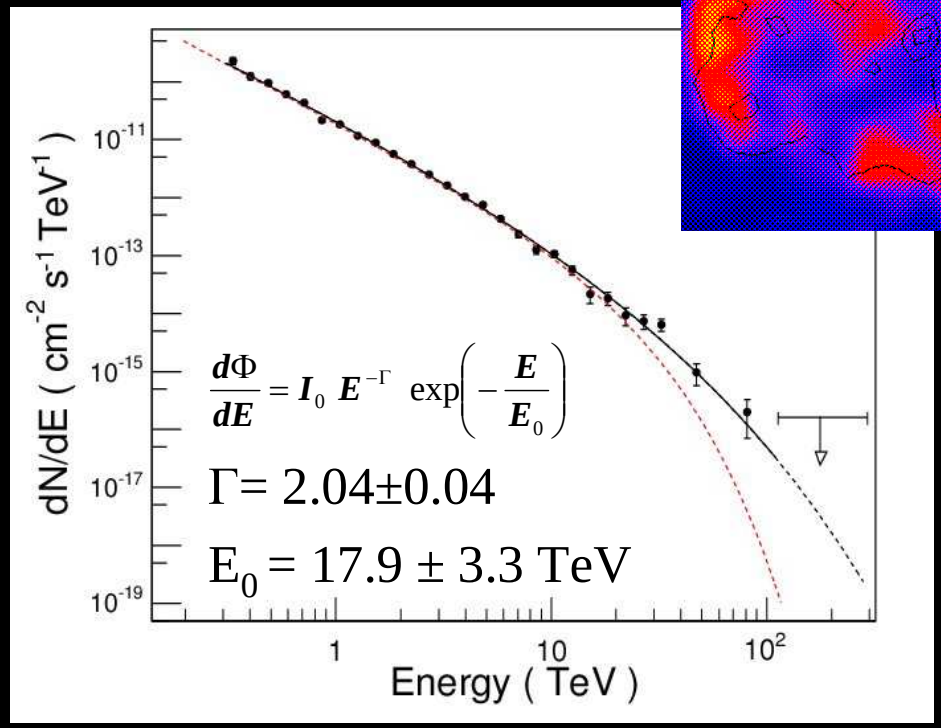
    $E_{electron} \sim 100$ TeV because of KN losses.
- Both scenarios explain the γ-ray emission.

  No conclusive proof

RX J1713-3946

A&A 464 (2007) 235





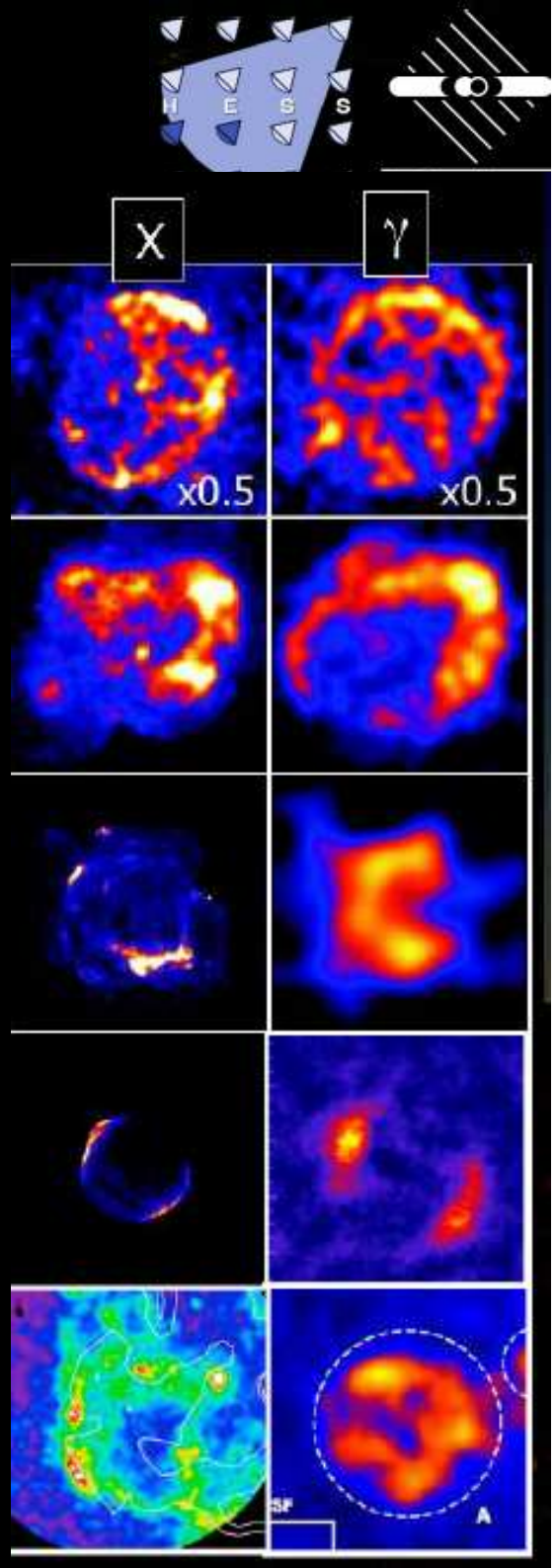
Young (TeV) bright SNRs

✓5 shell-like sources detected in the TeV by HESS

4 are young (< 10^4 years) historical SNRs

- RXJ 1713.7-3946
- Vela Junior
- RCW 86
- SN 1006 (last year)
- HESS J1731-347 (most recent)

✓All show rather clear correlation with non-thermal X-ray emission



Vela Junior

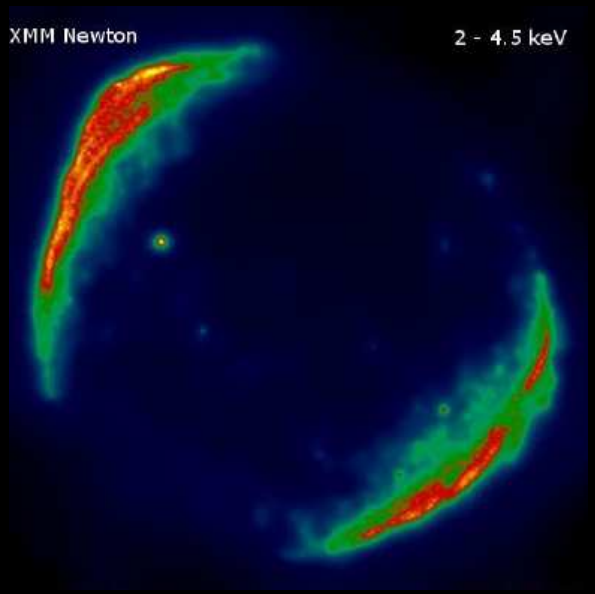
RXJ 1713.7-3946

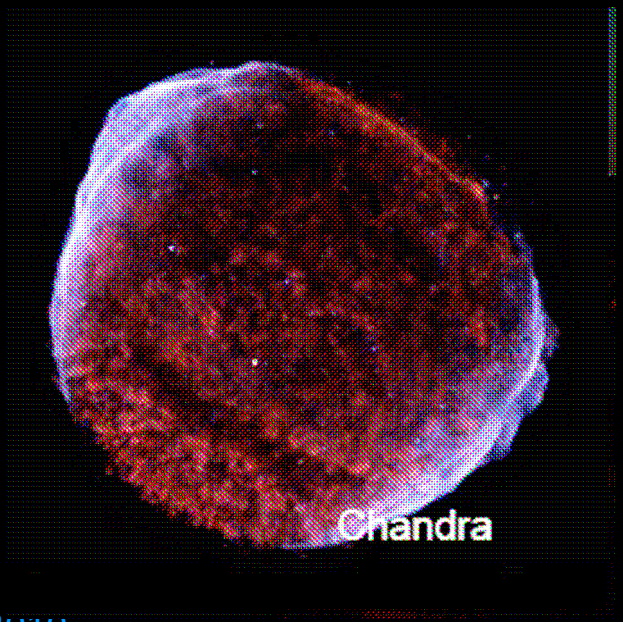
RCW 86

SN 1006

HESS J1731-347

SN 1006



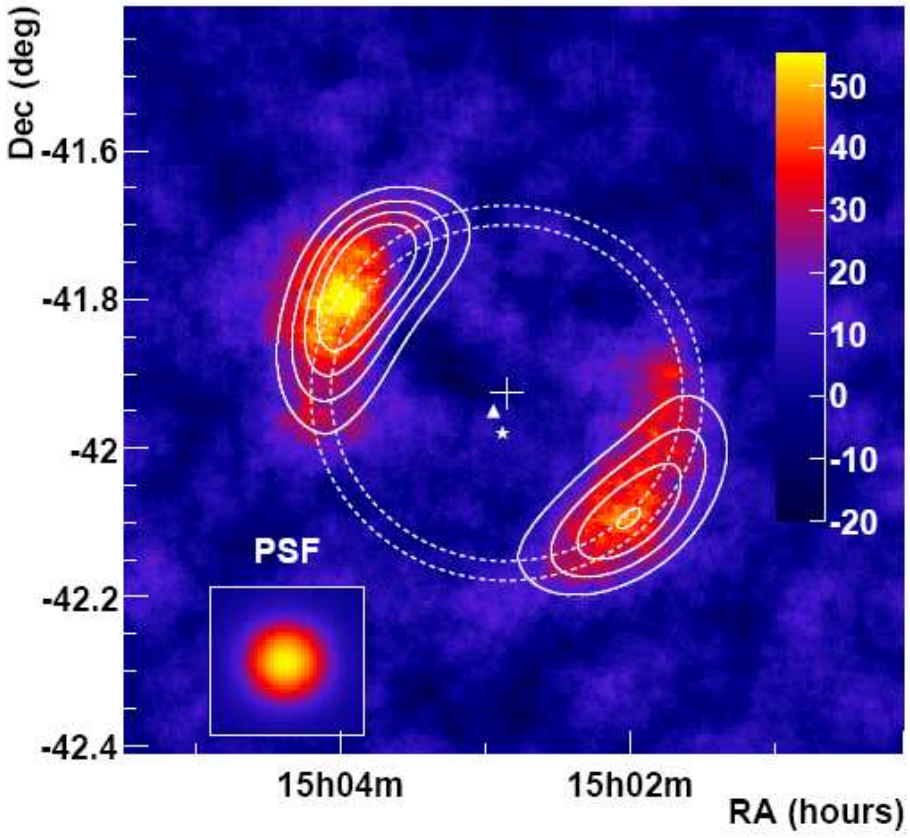


- 2.2 kpc distance
- Type Ia supernova
- Non-thermal X-ray emission observed from the rims

Suggests shock accelerated electrons >100TeV

- Rather uniform, low density environment (0.05 – 0.08 cm^{-3}), above Galactic Plane (clean, easier tests to models)

SN 1006 @ TeV

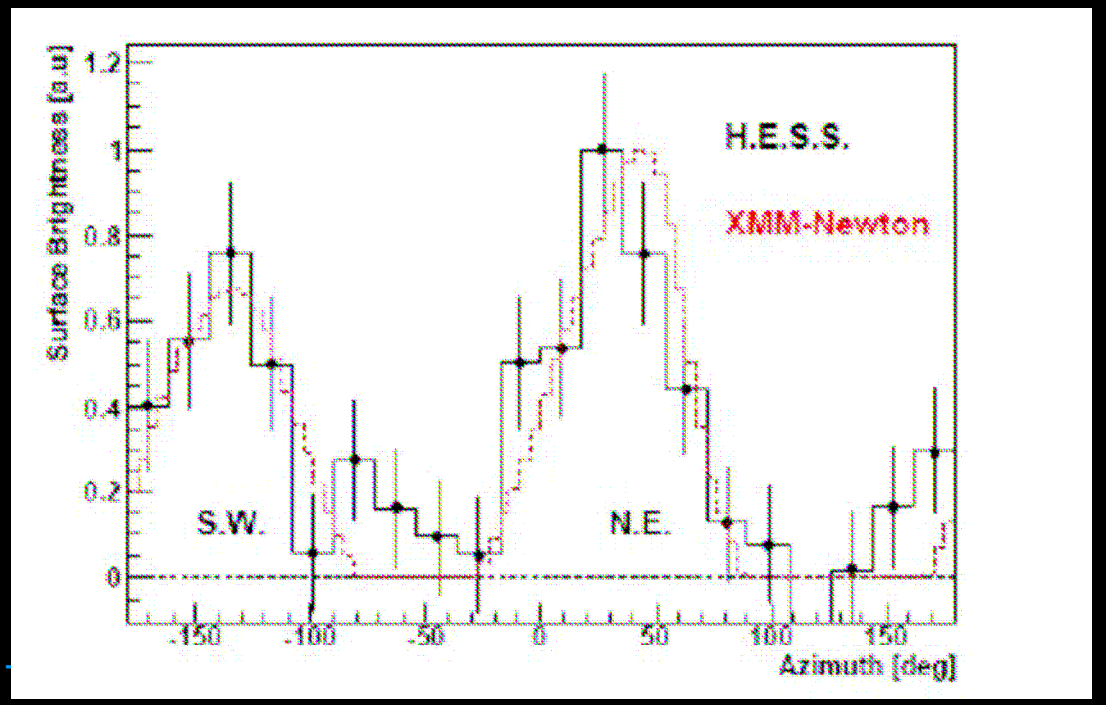


HESS observations

- Bipolar morphology, rim thickness compatible with PSF
- Faint TeV source : 1% of Crab Flux
- Morphology strongly correlated with non-thermal X-rays

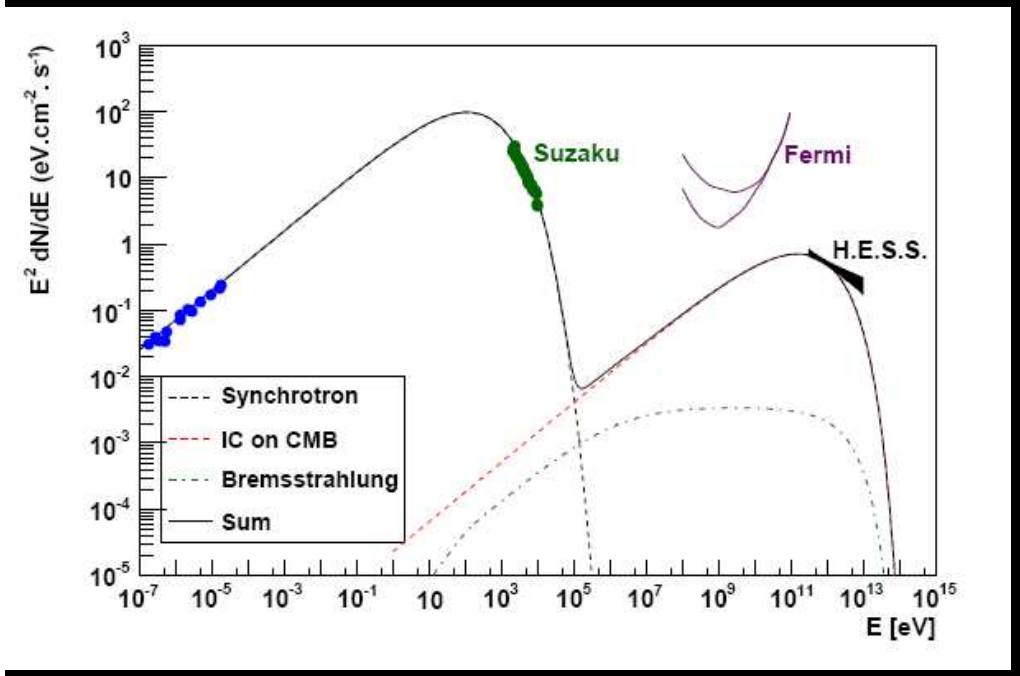
Suggests a common origin

- Ambiguity between leptonic and hadronic acceleration scenarios



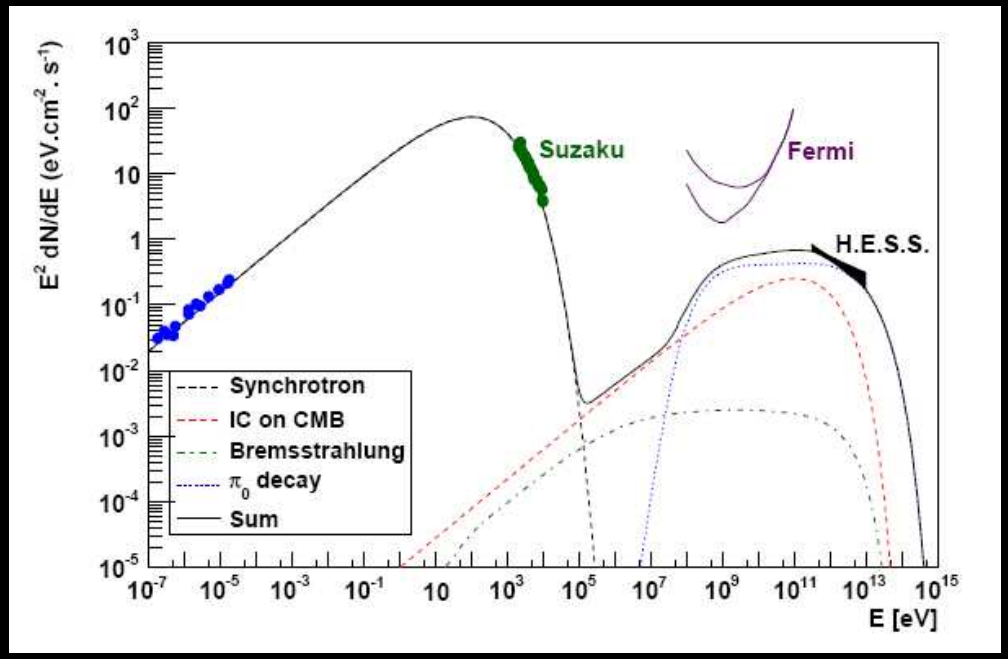
SN 1006

Pure electron population



- Fails to reproduce the slope of the VHE spectrum

Electron+proton population

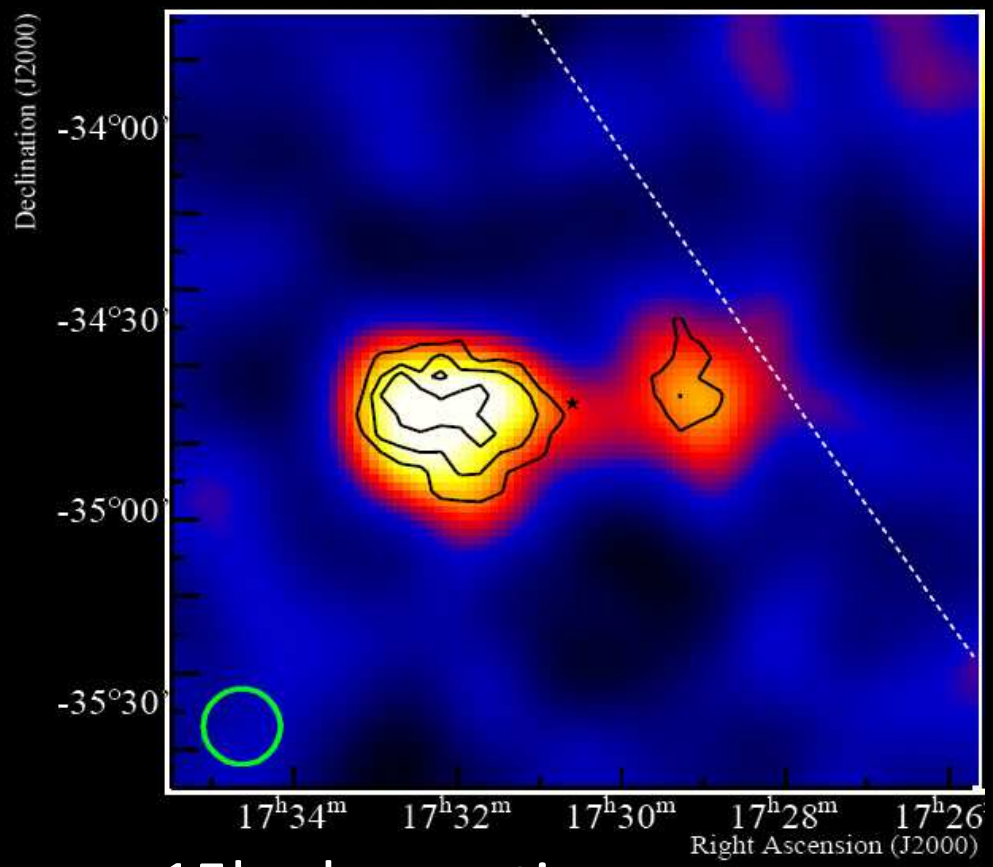


- $W_P \sim 12\% \, W_{SN}$
- Reproduce all multiwave data!

– In any case energy budget dominated by protons

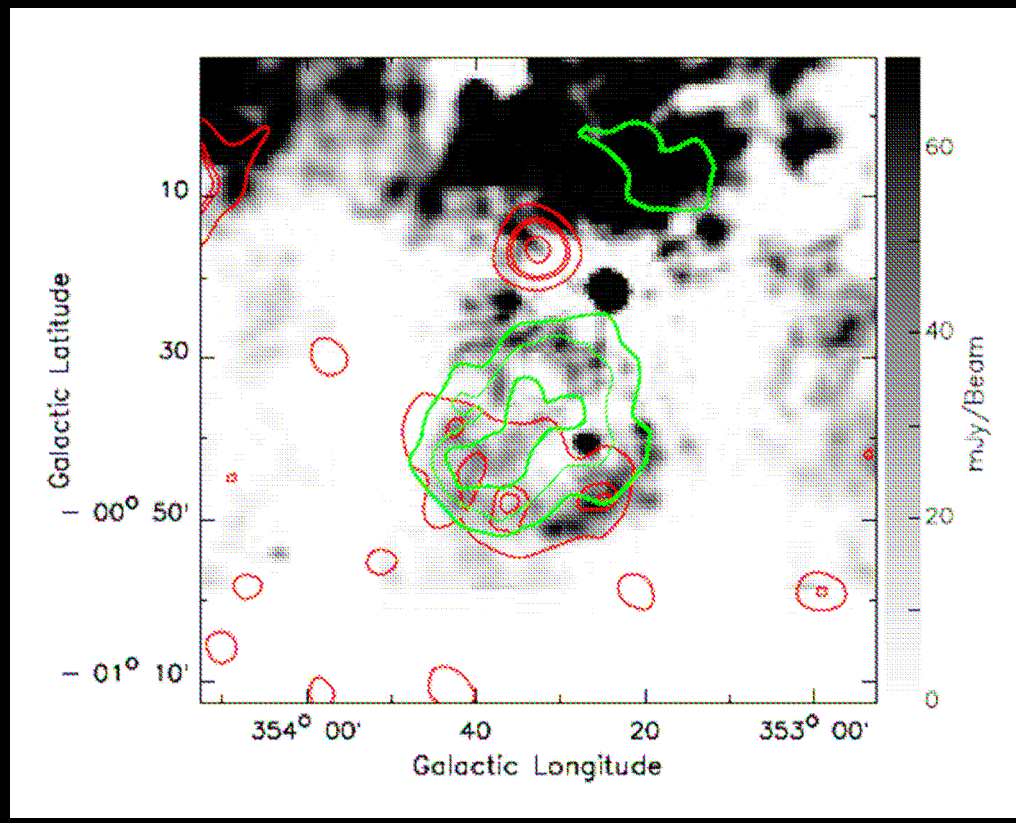
HESS J1731-347

Originally a source with no counterparts
HESS J1731-347
Tian et al., arXiv:0801.3254



15h observation

Aharonian et al. (2008)



RADIO image by ATCA of G353.6-0.7

HESS J1731-347

Originally a source with no counterparts
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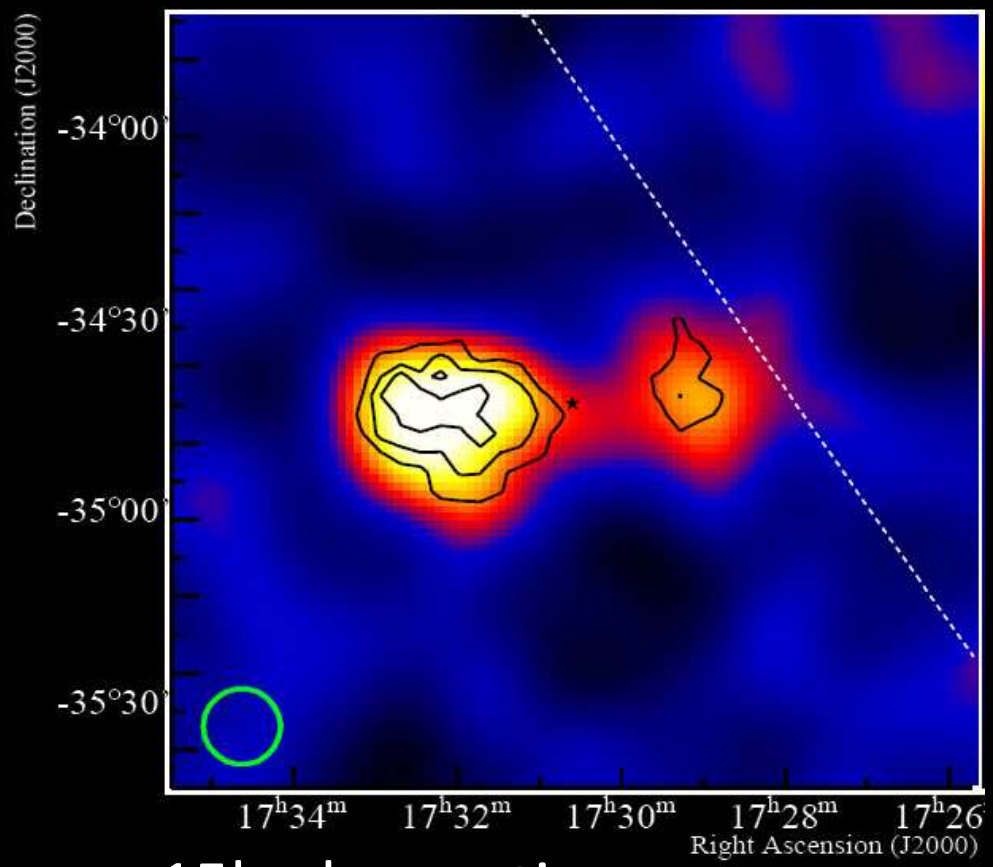
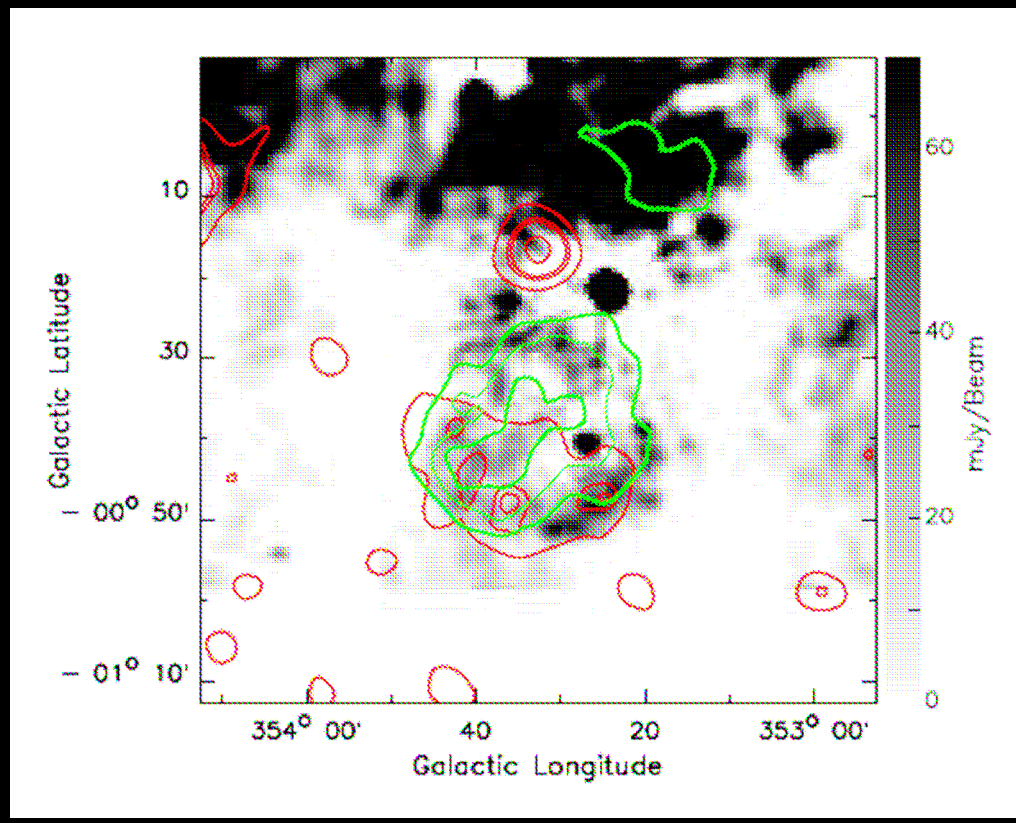
Tian et al., arXiv:0801.3254



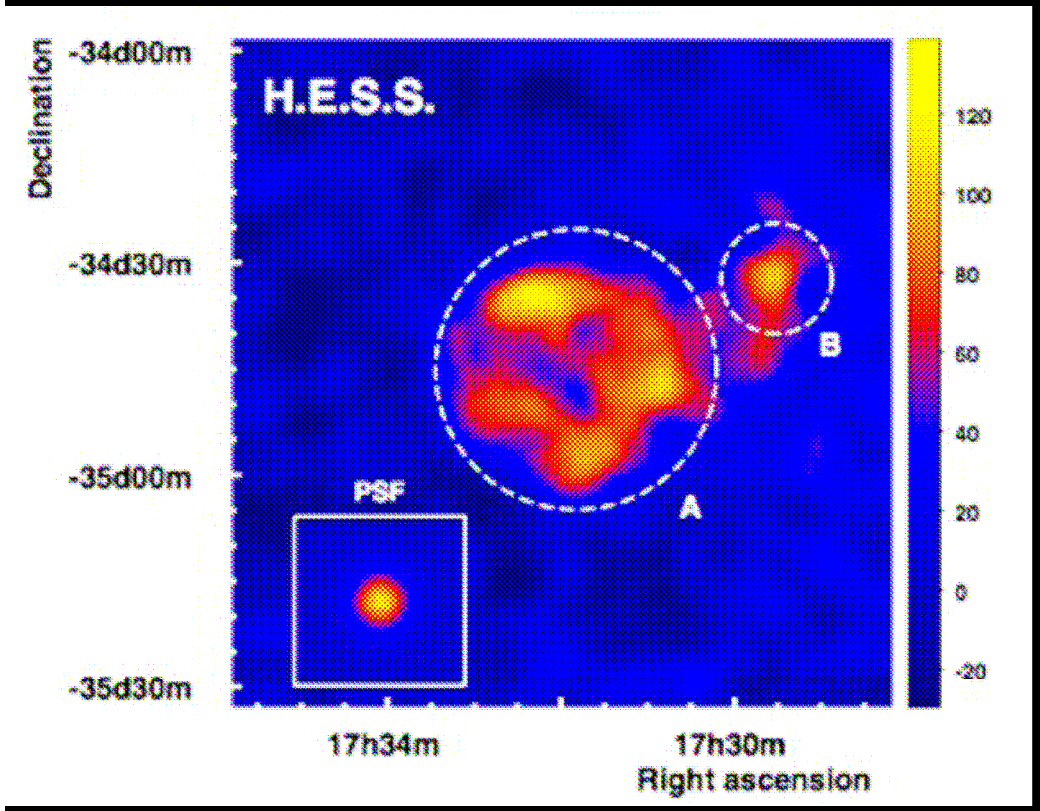


15h observation

Aharonian et al. (2008)

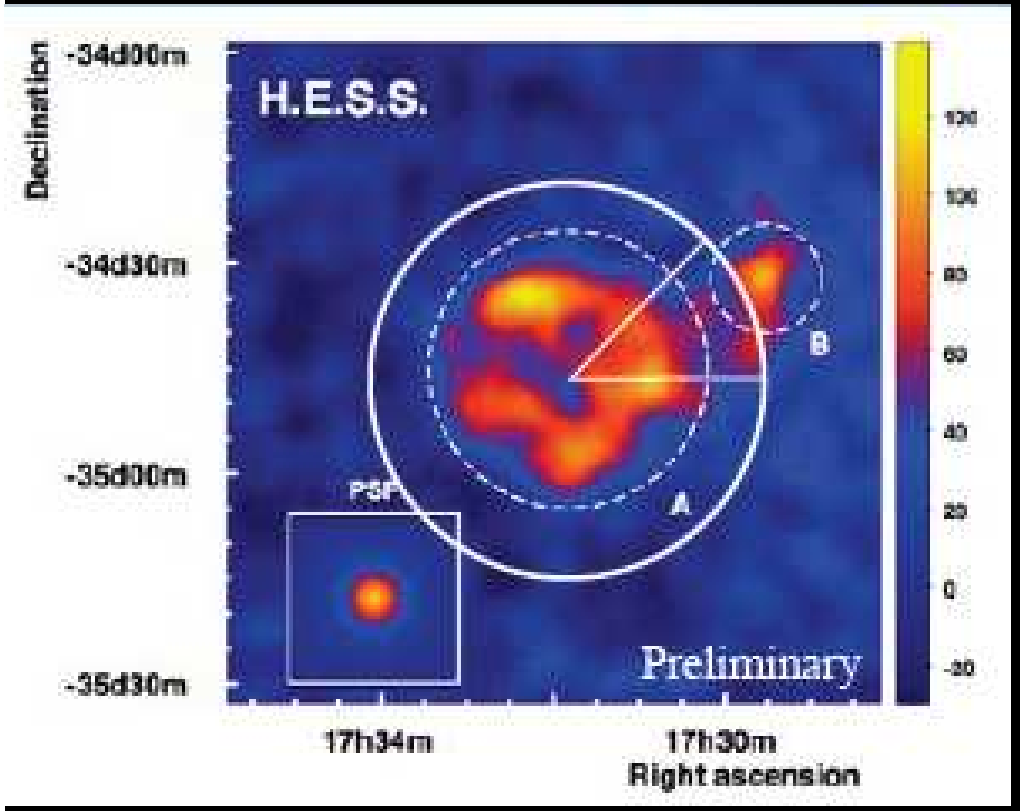
More HESS observations!!

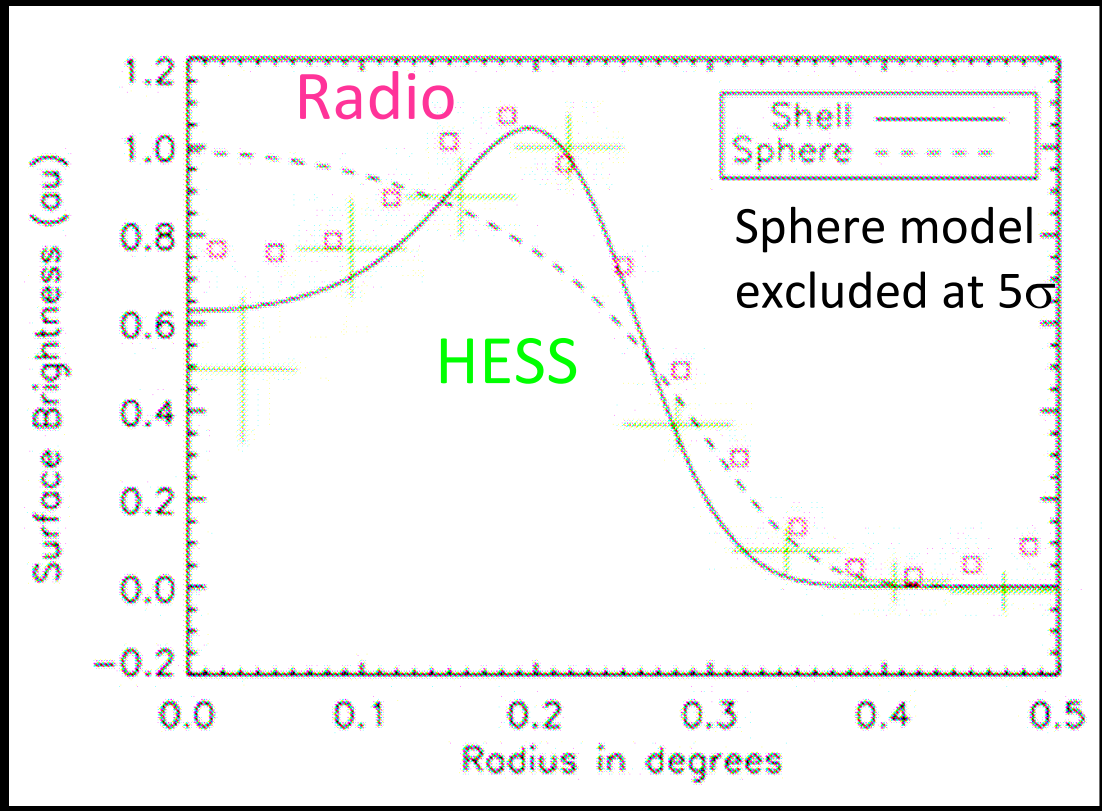
HESS J1731-347



With 60 h observation from 2007 and 2009

Identifying a new TeV shell

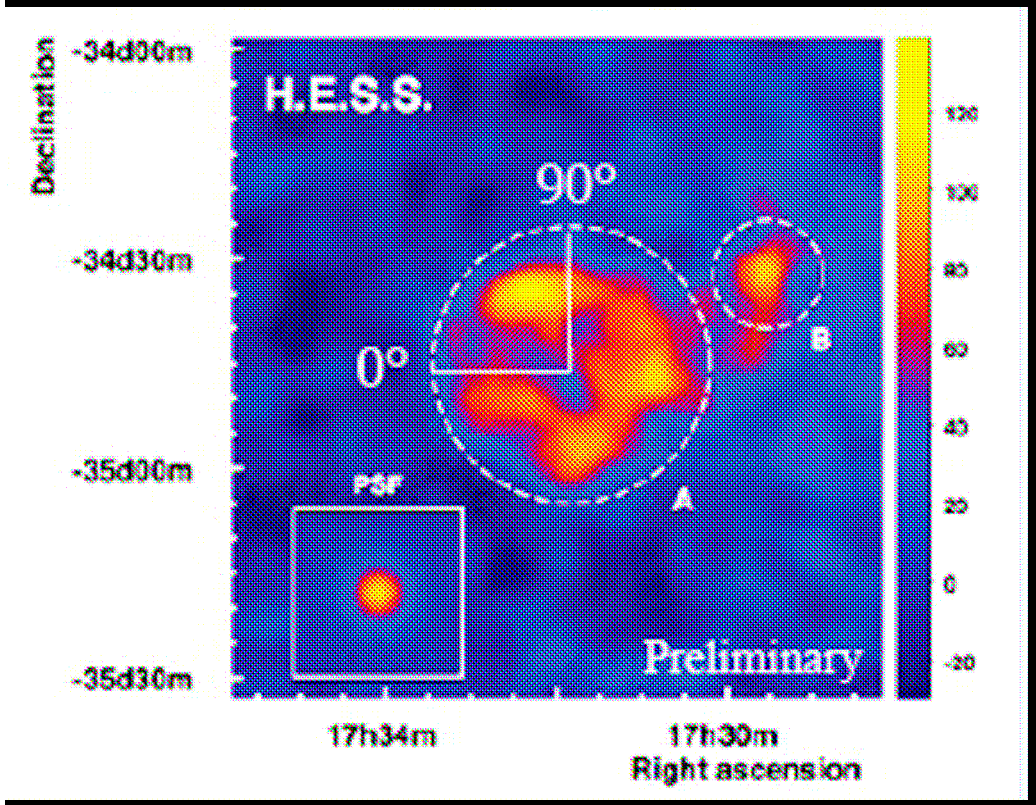


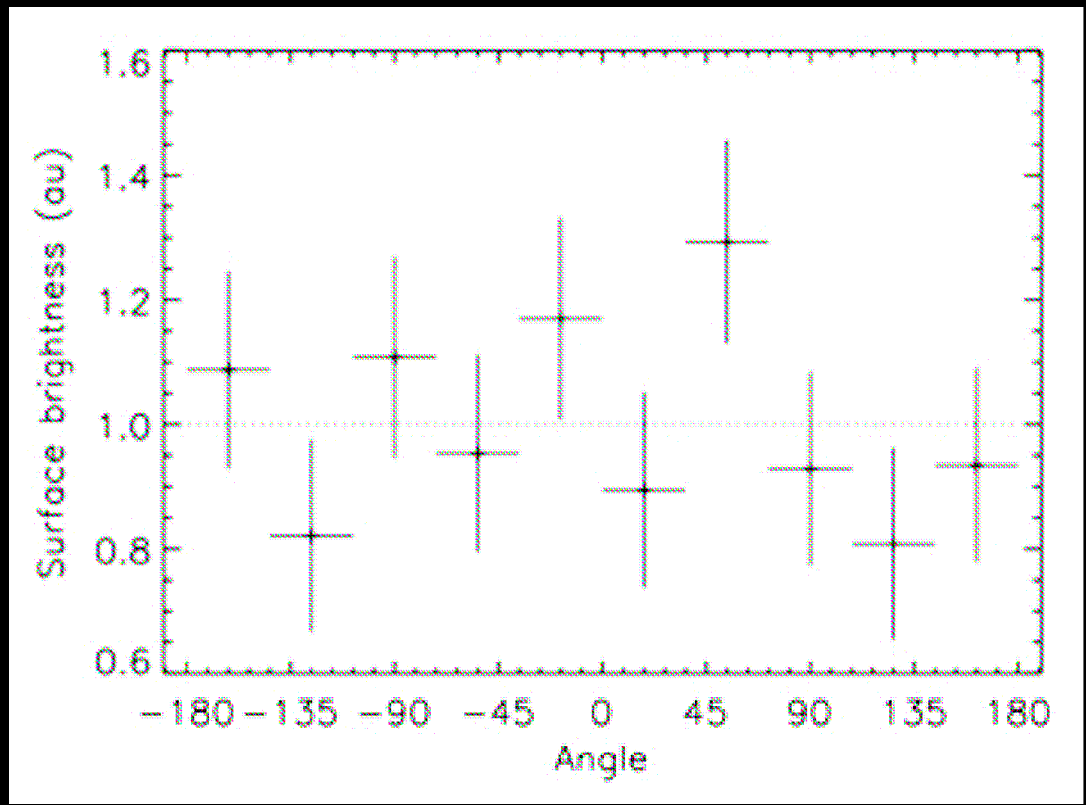


60 h observation

Shell morphology!

HESS J1731-347A

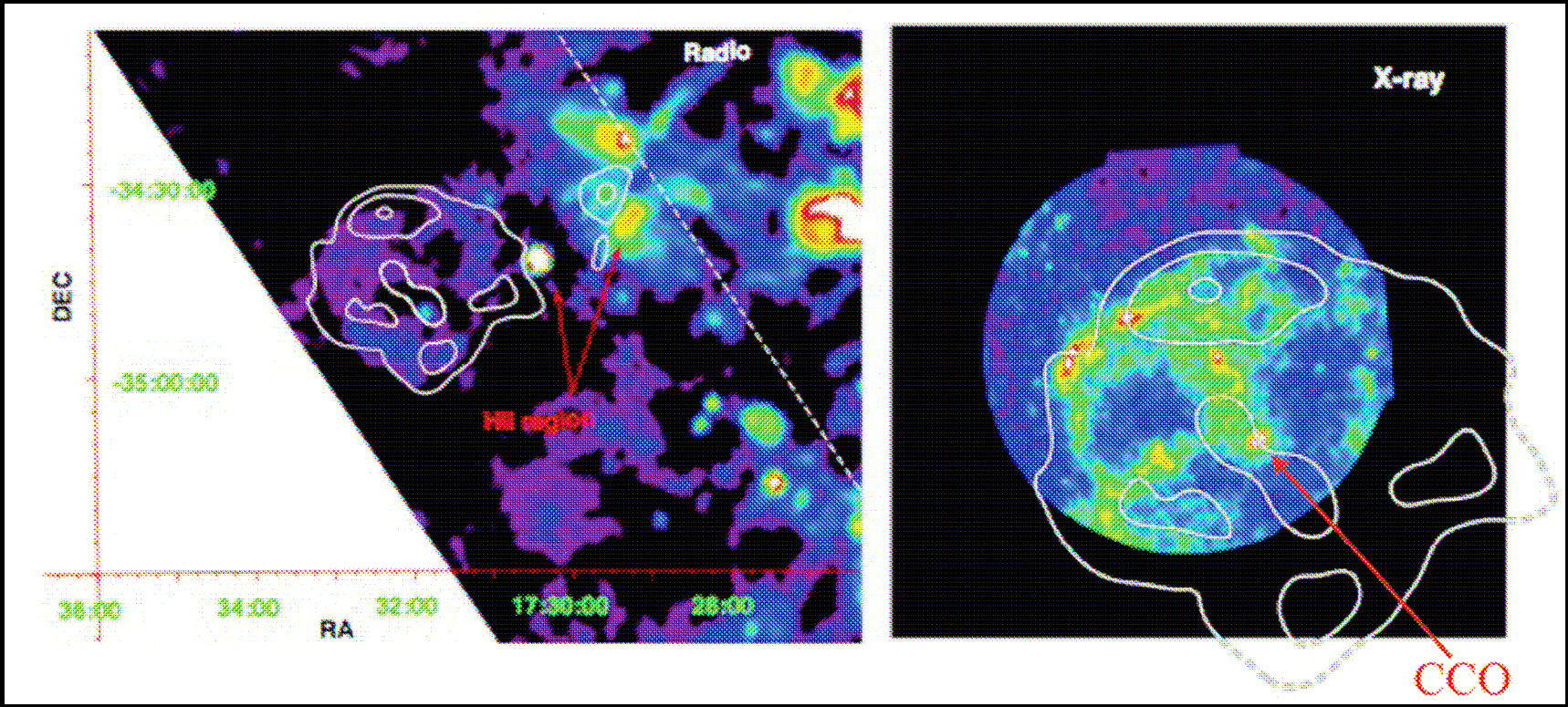




Flat Azimuthal profile (different than SN1006 and RXJ 1713-3946)

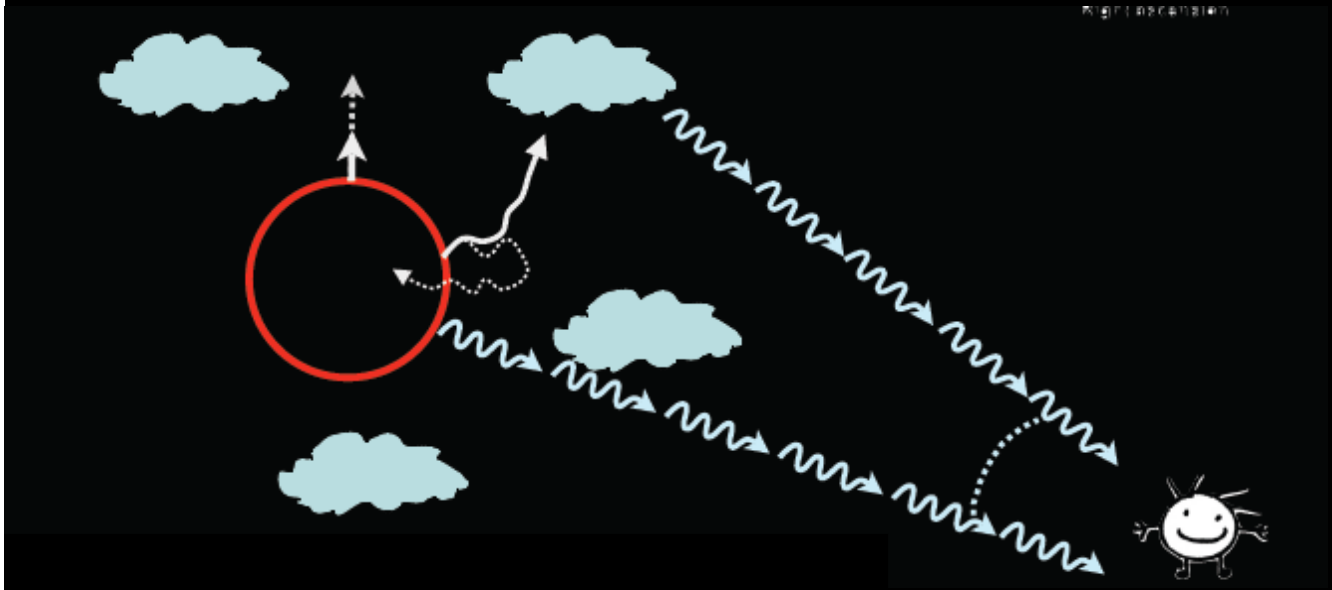
HESS J1731-347 – MWL

HESS significance contours at 4, 6, 8σ

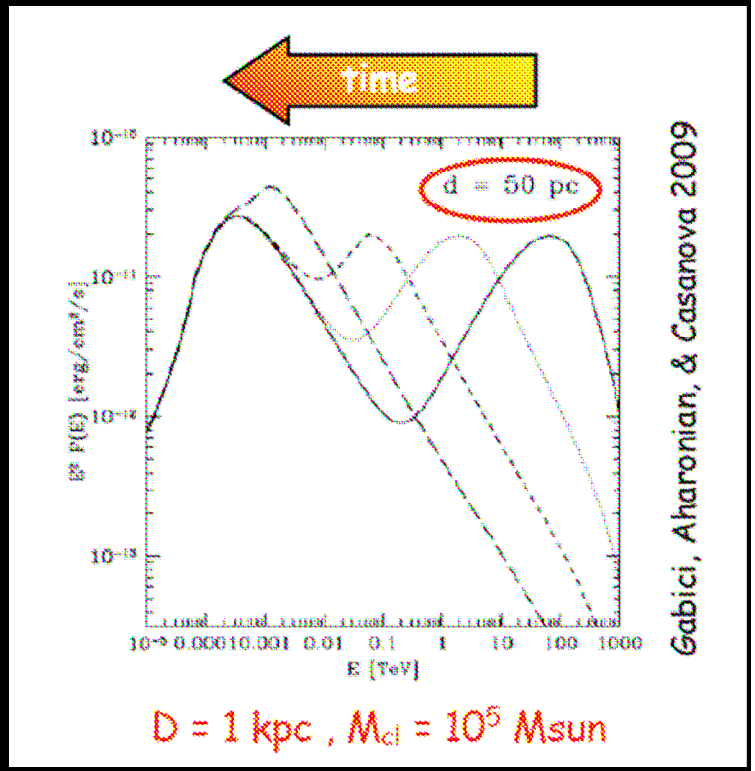


- Non-thermal shell seen in radio, X-rays… and γ-rays
- X-ray observations of (part of) shell reveal rims of emission with non-thermal spectra! (no evidence for thermal emission)
- X-ray absorption gradient suggests SNR lies behind a CO cloud
- D > 3:5 kpc , $L_{1\text{-}10\ TeV} > 2 \times 10^{34}$ erg/s very luminous , R > 15 pc

MC & SNRs



Gabici, Aharonian et Casanova 2009, Casanova et al 2009



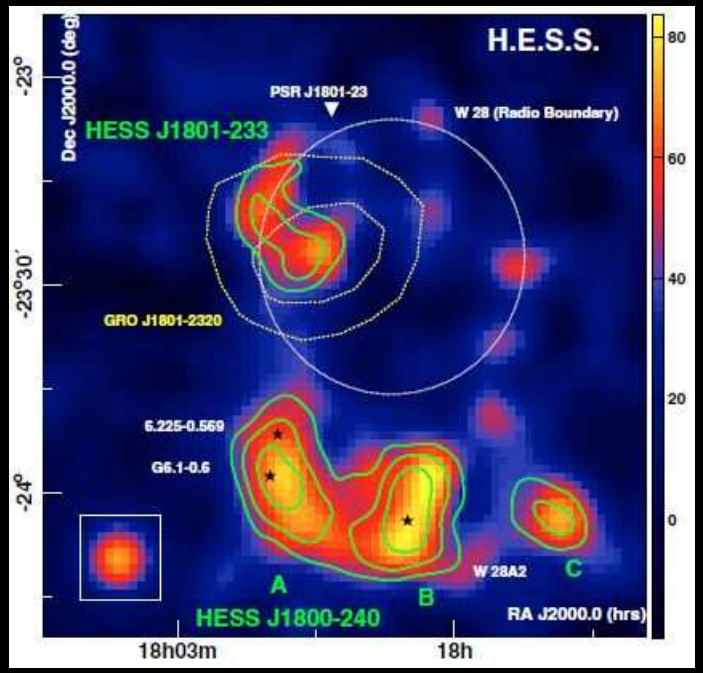
- MCs are ideal targets to amplify the emission produced by CRs accelerated by nearby sources
- Main idea: SNRs are PeVatrons up to ~ 1000 yrs and later the high energy CR escape and can illuminate local molecular clouds.
- CRs contribution (at the location of the cloud) from:

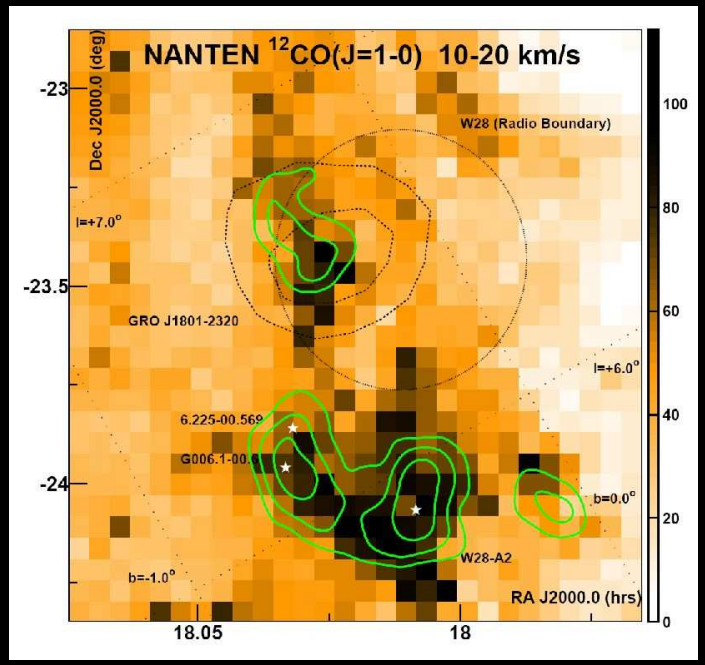
✓Galactic background: steep spectrum, steady in time, peaks at GeV energy region

✓Runaway from SNR: hard spectrum, variable in time

✓Superposition of both: concave spectra, variable in time

W 28





H.E.S.S. A&A 481(2008)401

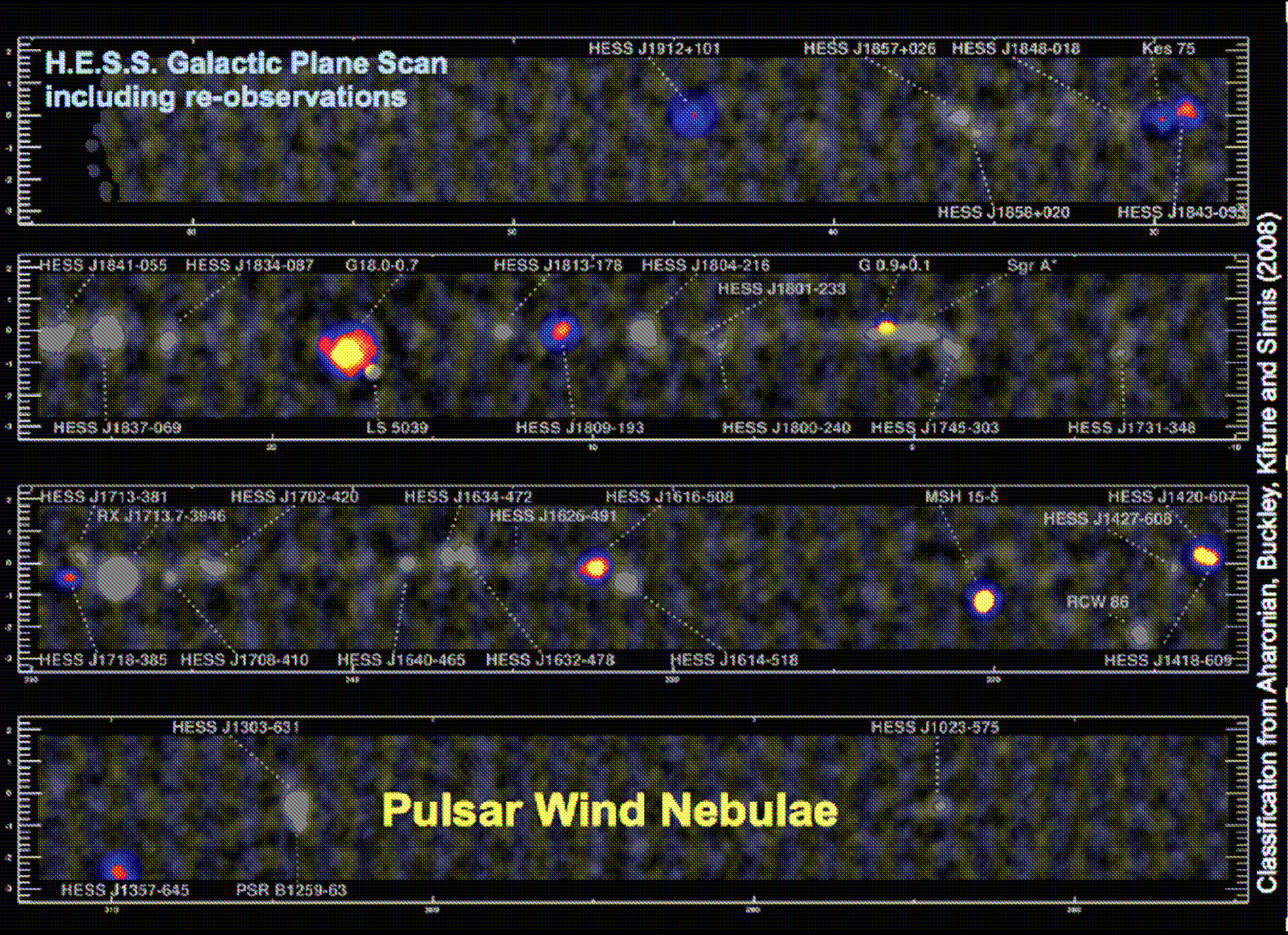
- W28: an old SNR (~35-150 kyrs) and molecular clouds seen in NANTEN CO (J=1-0);

  This association strongly indicates a hadronic origin for HESS J1801-233 and HESS J1800-240

- Presence of 1720 MHz OH masers: molecular clouds are perturbed by SNR. Three other sources: HESS J1745-303, HESS J1714-385 & HESS J1923+141

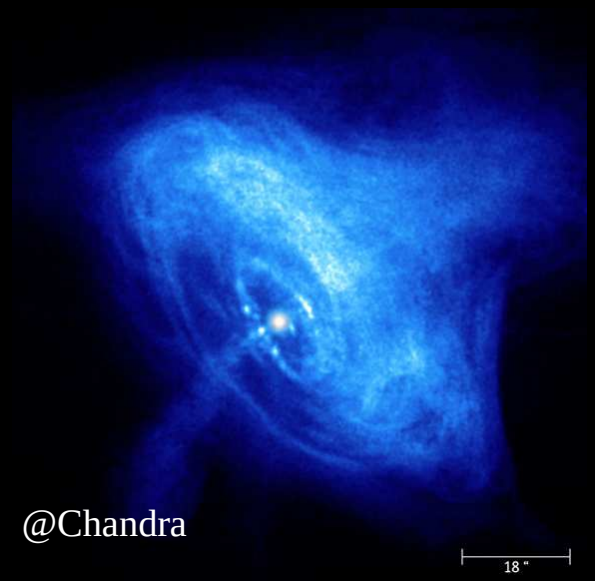
- Hadronic origin favoured -> bright in GeV domain

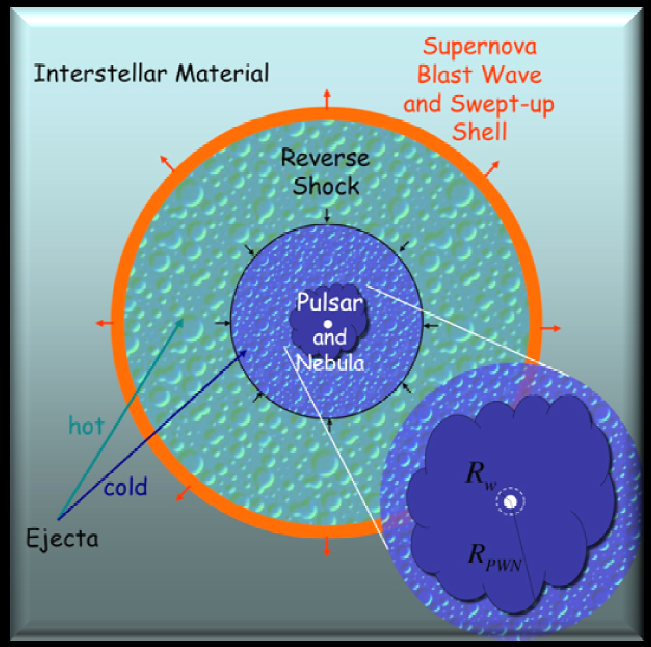
PWNe

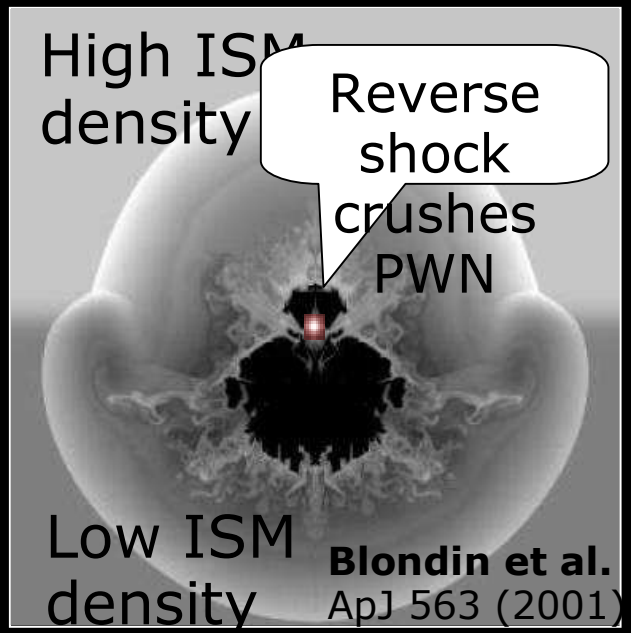


about half (29) HESS Galactic sources are PWNe or candidates

PWNe





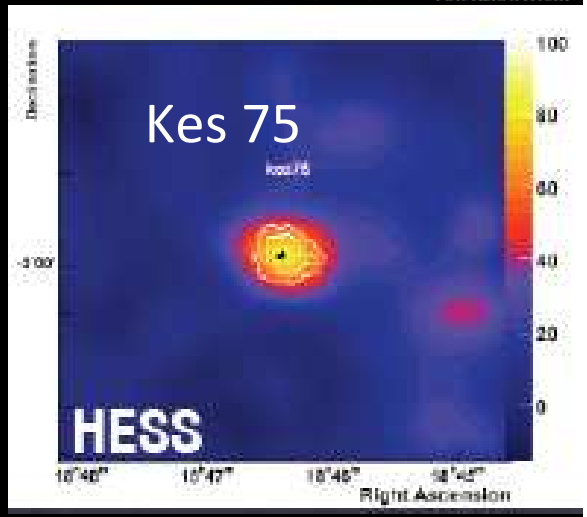


Objects powered by a relativistic particle outflow (e^-/e^+) from a pulsar- confined by SNR of pulsar progenitor

- Efficient conversion of rotation power into relativistic particles
- Associated with young pulsars – high spin-down power
- Expansion in a non-uniform medium may lead to complex morphology
- VHE γ-rays can be generated by IC scattering of relativistic electrons accelerated in the termination shock of the PWN.

Young PWNe

Young pulsar wind nebulae (and composite SNRs)
like Crab Nebula, G0.9+0.1, G21.5–0.9, Kes 75, MSH 15-52...
- compact, generally unresolved by H.E.S.S.

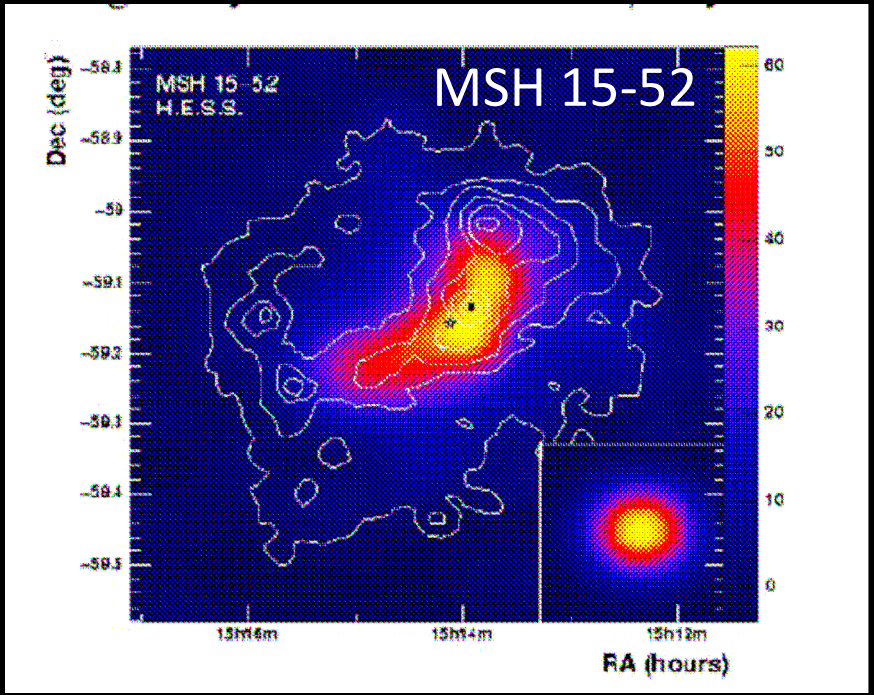


MSH 15–52 :
- first PWN angularly resolved in TeV γ–rays

- X-ray thermal shell and non-thermal "jet-like" nebula

-Assuming (approximately) uniform target photon density, IC directly infers of spatial distribution of electrons

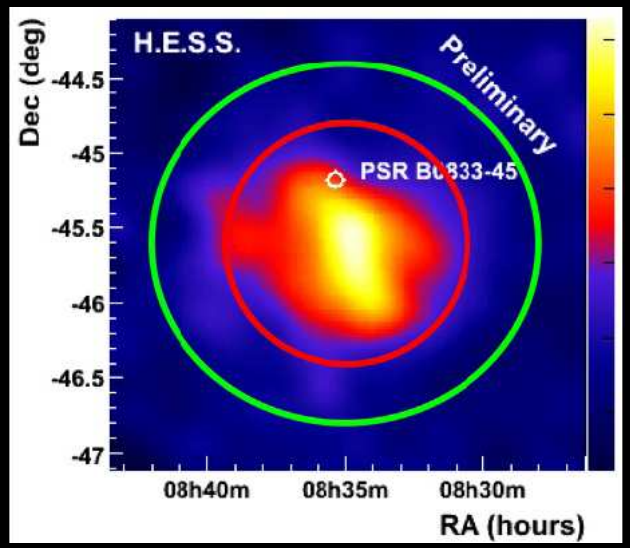
H.E.S.S., A&A 435, L17 (2005)



Evolved PWNe

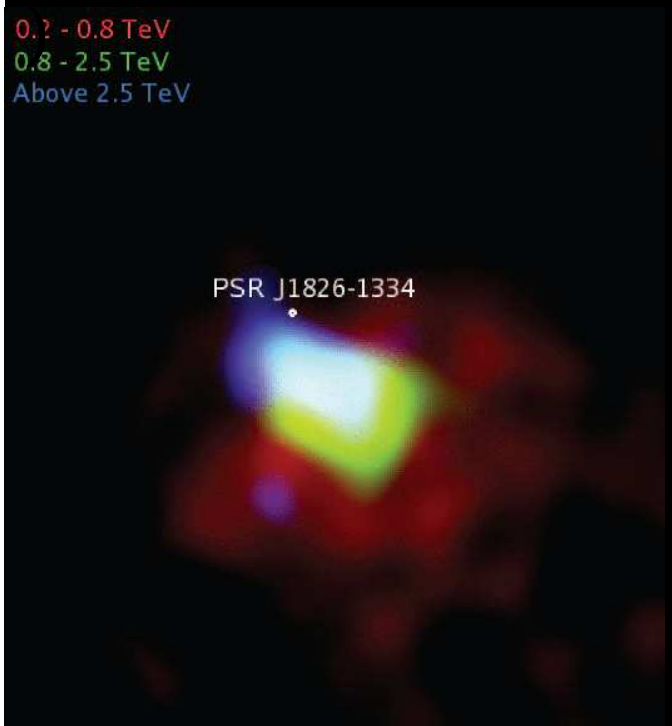
Older pulsar wind nebulae

huge nebula ~few tens of pc,
"offset" pulsar wind nebulae : Vela X



-offset from pulsar can be due to reverse shock
(Blondin et al. 2001)

-VHE emission extends as far as the radio PWN (2° diameter)



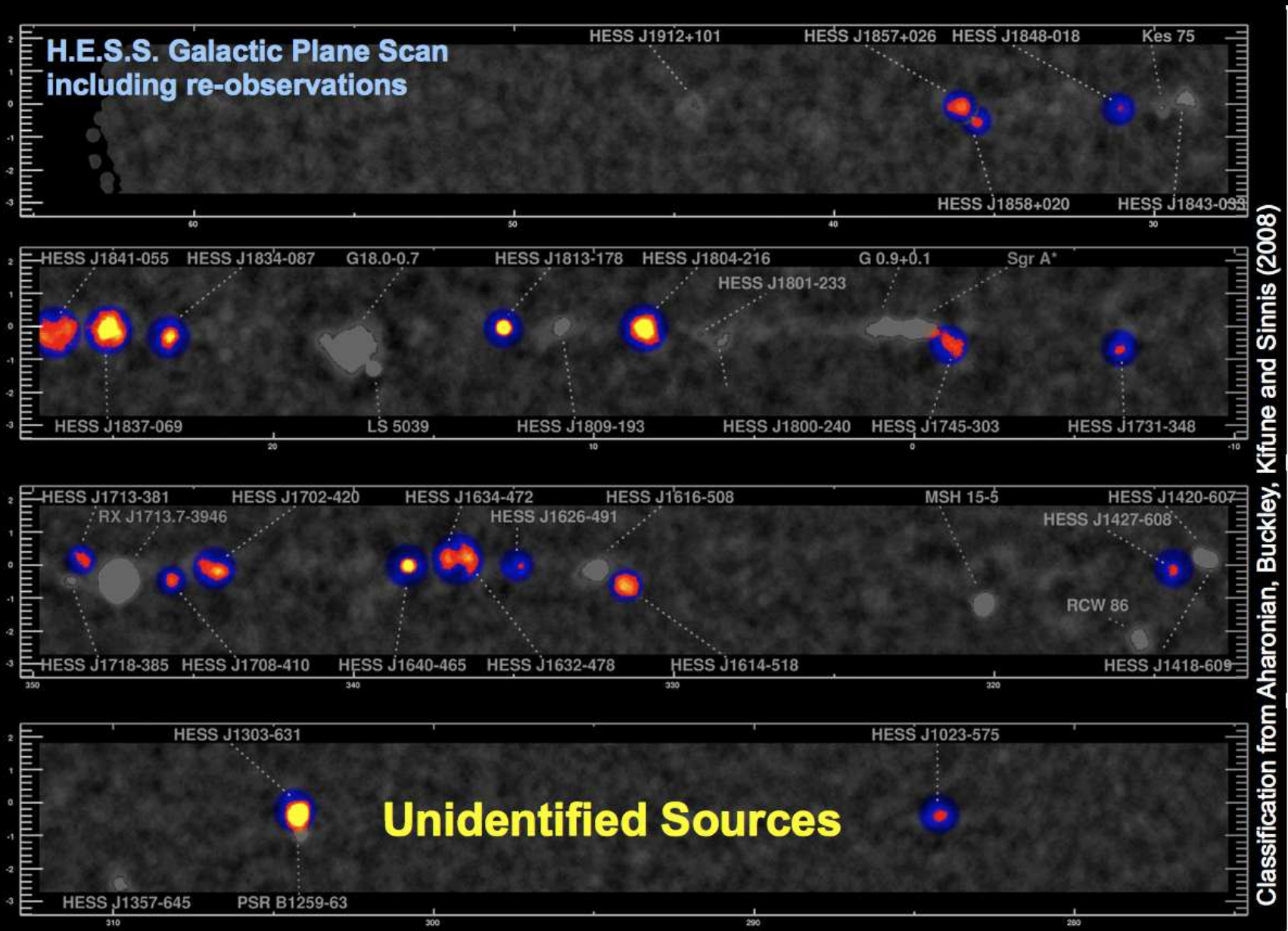
Electron cooling observed ->HESS J1825 –137

✓Spectral steeping away from pulsar

✓⇒ First observation of radiative cooling of electrons

✓Gamma Flux: ~1% of pulsar rotational energy

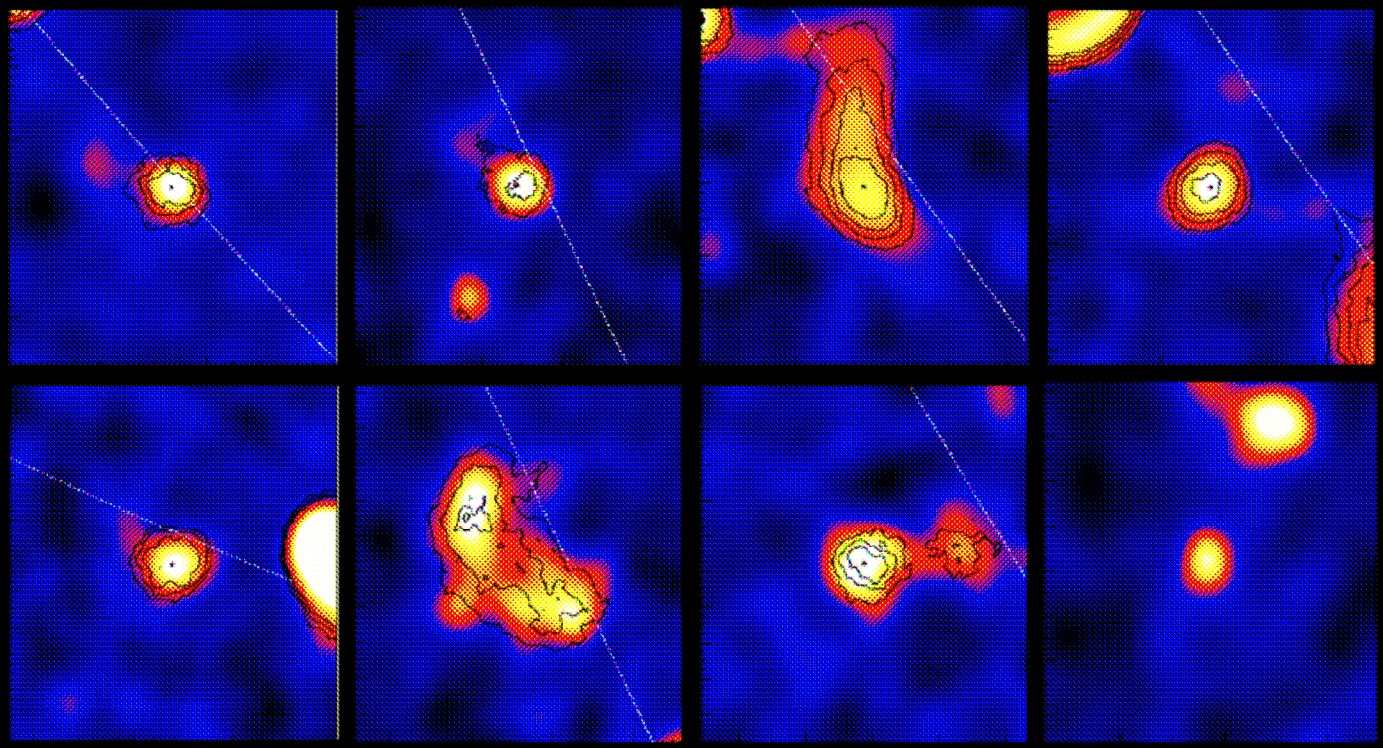
Other sources



Classification from Aharonian, Buckley, Kifune and Sinnis (2008)

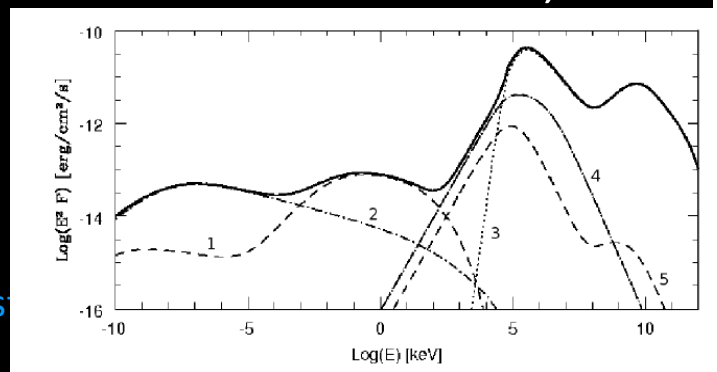
Dark TeV sources

Seem to shine in gamma rays
No plausible counterparts in radio, X-rays



Gabici et al, 2008

- 50% of TeV source
- Old PWN, not seen in other wavelengths?
- Old SNRs, interacting with molecular clouds?



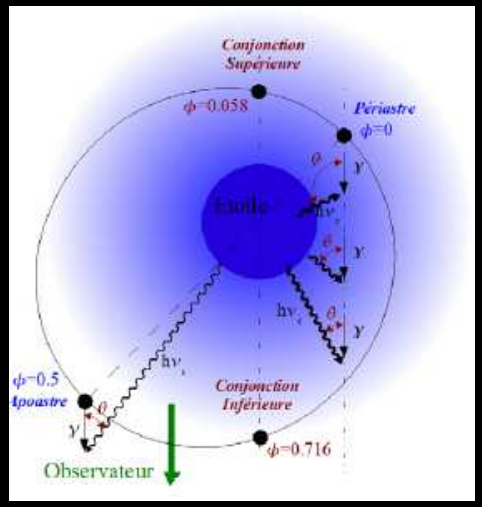
Binary systems

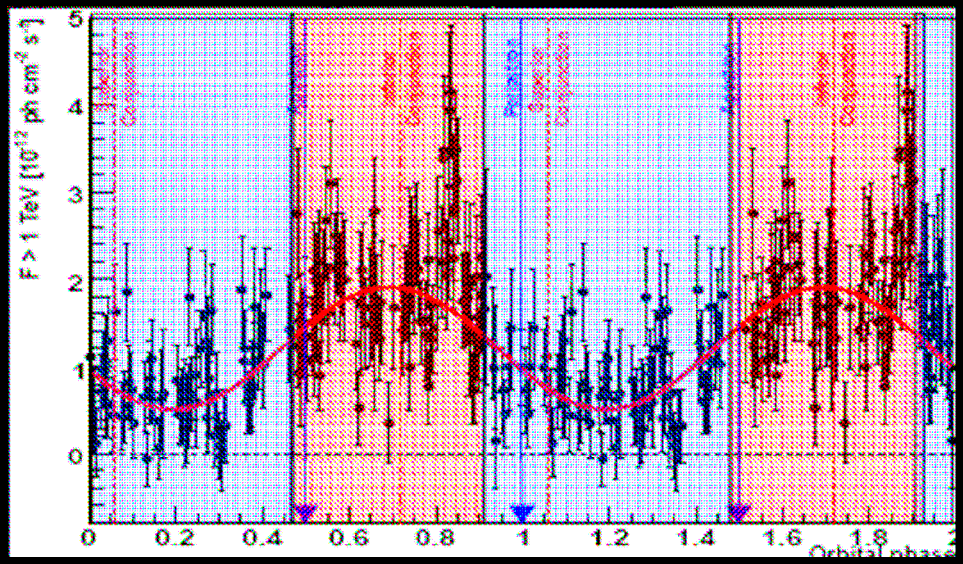
•Compact object orbiting around a massive star. Scaled down versions of AGNs

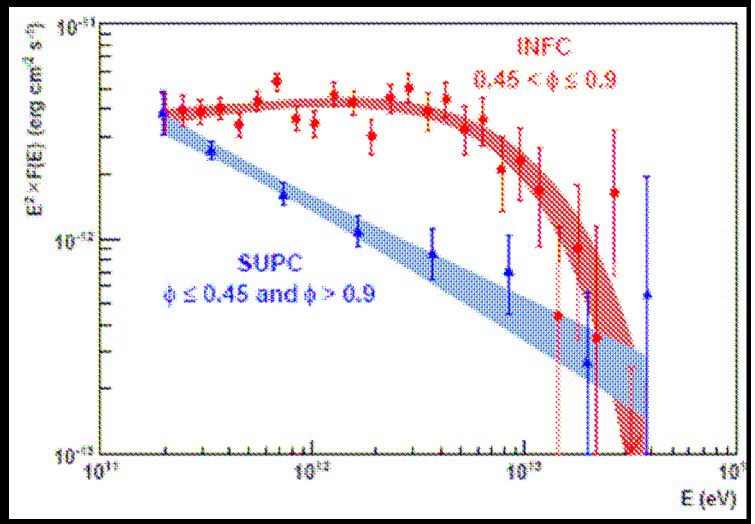
-LS 5039: spectral modulation at orbital phase (3.9 days)

-Interpreted as pair creation on stellar photon field of the companion

-Other cases: PSR B1259-63 and HESS J0632+057





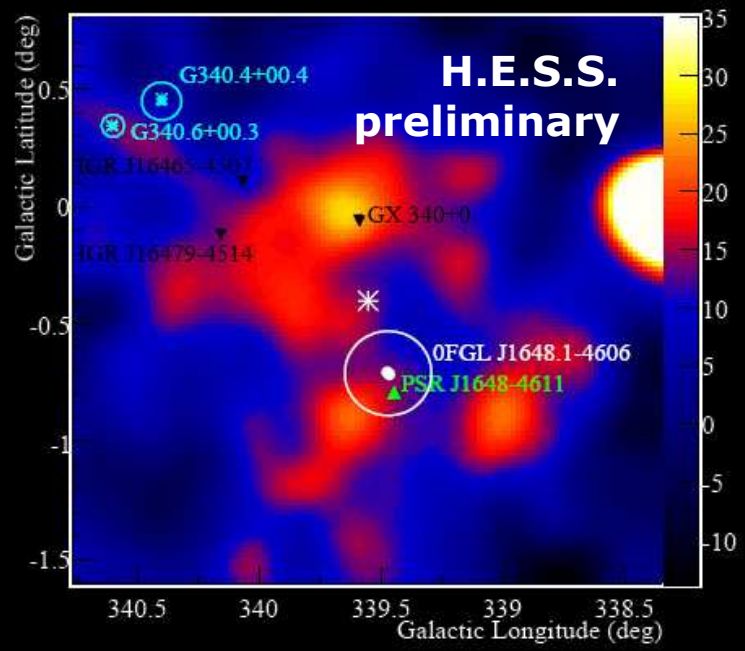


Massive star clusters

- Most massive compact young star cluster
  - ✓24 WR stars, >70% in binary systems
  - ✓80 blue SG stars, 3 red SG
  - ✓ 4-5 kpc, age 5 x 10^6 yrs, 6 x 10^4 M_{solar}
  - ✓Dissipated power in kinetic energy in the wind 10^{39} erg/s
  - ✓Possible acceleration mechanisms: colliding wind binaries, collective stellar winds, supernovae explosions, Pre SN winds might blow superbubbles.
- HESS observation 2004-2008 (34h), 680 GeV energy threshold
- 2° extension of VHE emission, partially correlated with HI shell ⇒ Evidence for hadronic acceleration?

Westerlund 1

Ohm et al, ICRC 2009

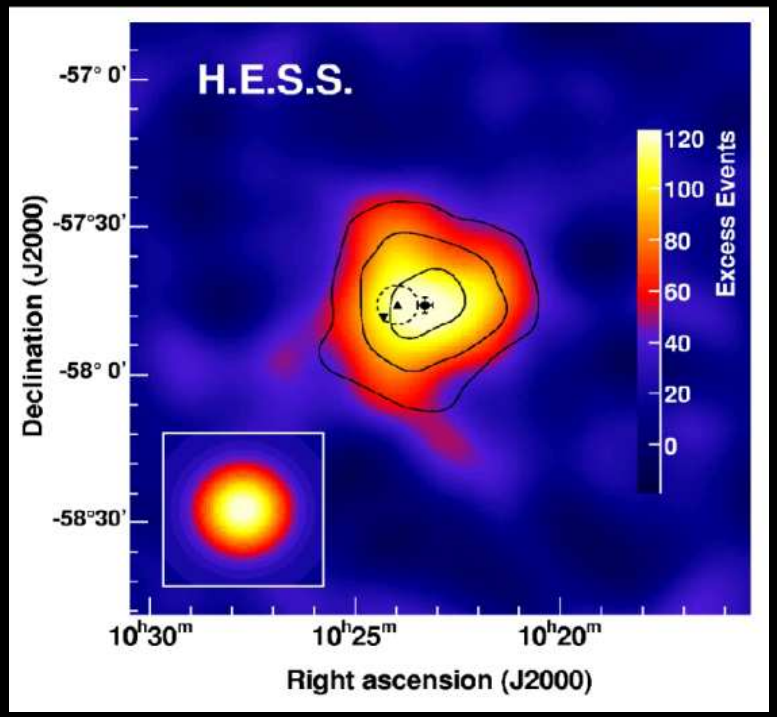


Massive star clusters

Westerlund 2

- Host >24 massive stars + 2 WR stars

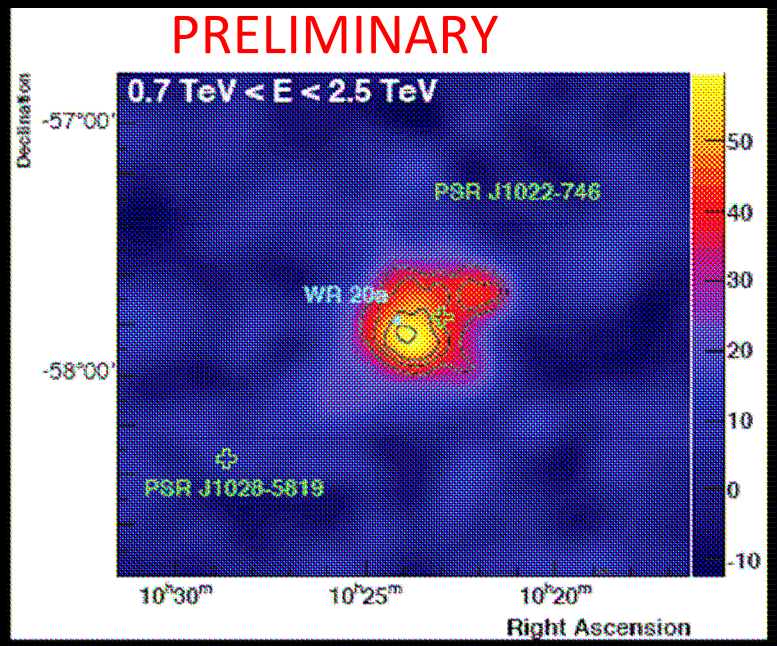
- Origin of the emission from this source
  - WR binary WR20a
  - Cluster itself
  - CR accelerated in bubble interacting with environment
  - PWN and their synchrotron nebulae, Supernova explosions and their expanding remnants.

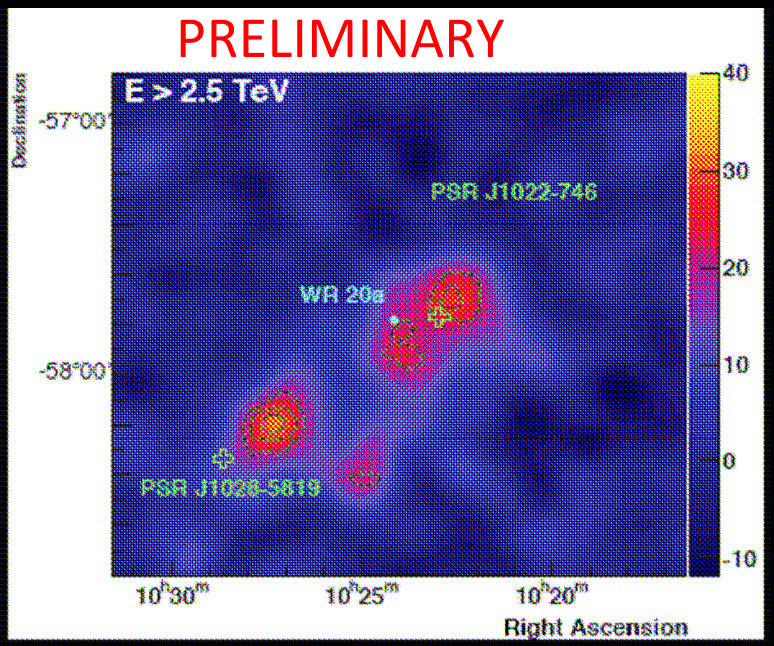


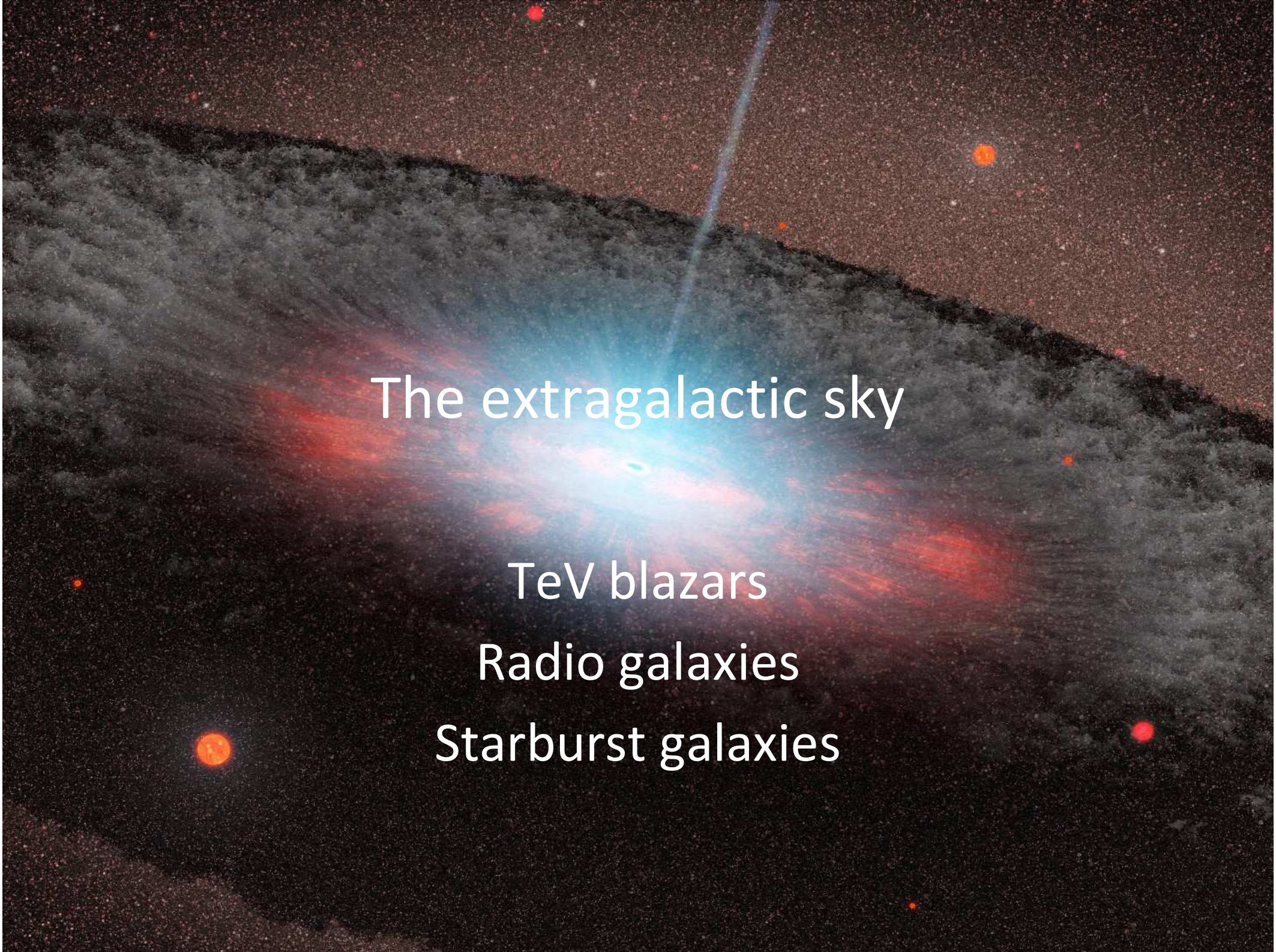
Massive star clusters

Westerlund 2 reobserved this region (total 46h)

- Confirmend HESS J1023-575 - low X-ray emission + molecular clouds, Fermi possible counterpart the recently discovered PSR J1022-5746
- Second peak towards the pulsar PSR J1028-5819 coincident with HESS J1026-582 (suppressed at lower energies)
- Energy dependent morphology







The extragalactic sky

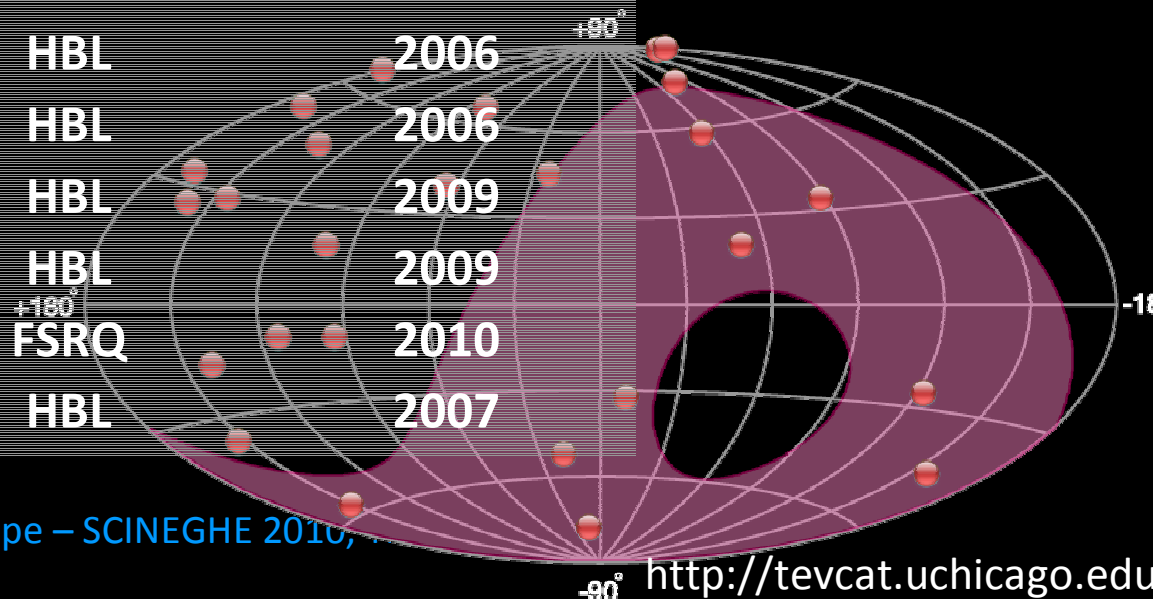
TeV blazars

Radio galaxies

Starburst galaxies

HESS TeV AGN

AGN	redshift	Type	Year
Cen A	0.002	FRI	2009
M87	0.004	FRI	2007
Mkn 421	0.030	HBL	1992
APLib	0.049	LBL	2010
PKS 0548-322	0.069	HBL	2008
PKS 2005-489	0.071	HBL	2007
RGB J0152+017	0.080	HBL	2008
PKS 2155-304	0.115	HBL	2008
1ES 0229+200	0.139	HBL	2008
H 2356-309	0.165	HBL	2006
1ES 1101-232	0.186	HBL	2006
1ES 0347-121	0.188	HBL	2006
1ES 0447-439	0.2	HBL	2009
1ES 0414+009	0.287	HBL	2009
PKS 1510-08	0.3	FSRQ	2010
PG 1553+113	>0.250	HBL	2007



http://tevcat.uchicago.edu

Latest addictions

AGN	redshift	Type	Year
Cen A	0.002	FRI	2009
M87	0.004	FRI	2007
Mkn 421	0.030	HBL	1992
APLib	0.049	LBL	2010
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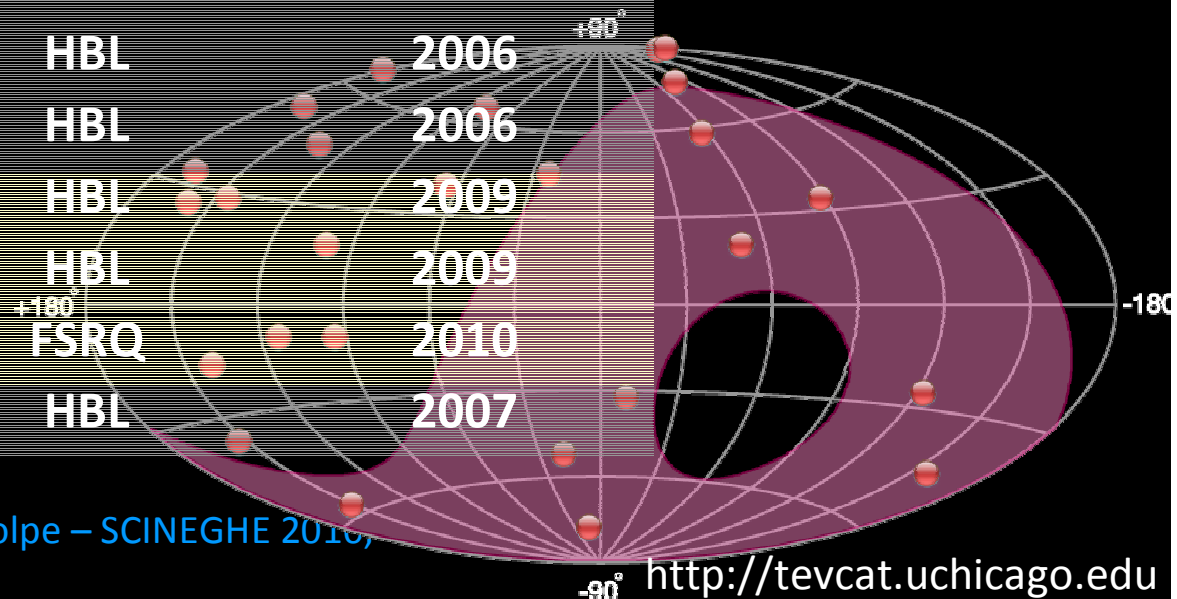


http://tevcat.uchicago.edu

announced

✓1ES 0414+009 z=0.287 (one of the furthest AGN)

Atel#2293

~0.5% Crab flux level. Also FERMI source with an average flux above 1 GeV of $(0.67 \pm 0.21) \times 10^{-9}$ photons cm^{-2} s^{-1}, and a hard spectral index of (1.78 ± 0.23).

✓1ES 0447-439 z=0.2

Atel #2350

Coincident with 0FGL J0449.7-4348, one of the brightest FERMI extragalactic source. Also associated with a Seyfert 1 galaxy located at a redshift of z=0.107

✓PKS 1510-08 z=0.36

announced HEAD conf. 2010

broad-line Quasar, MWL campaign

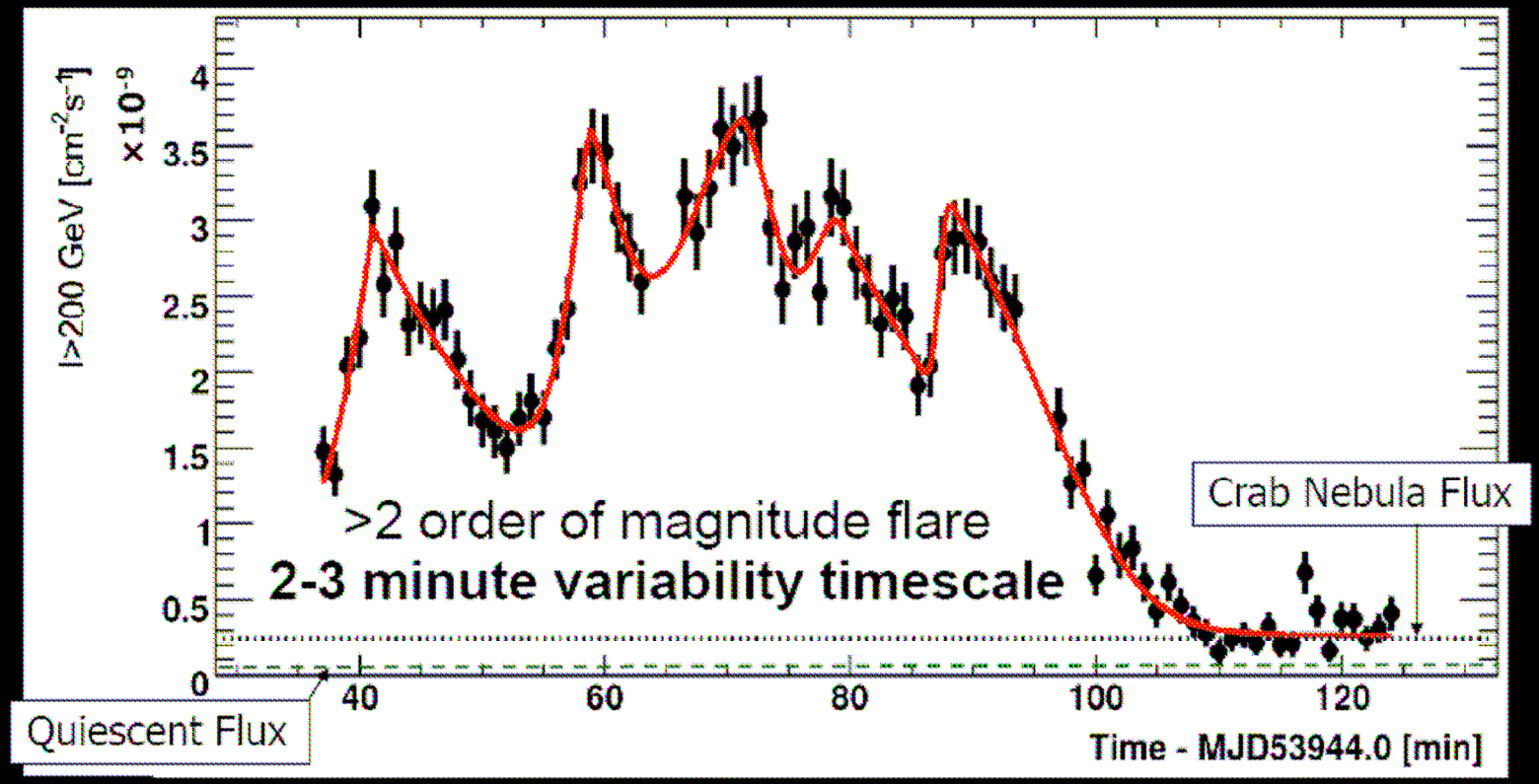
✓AP Lib z=0.049

Atel #2743

Fermi source 1FGL J1517.8-2423 (hard gamma-ray photon index of 2.1+/-0.1).

~2% Crab nebula flux

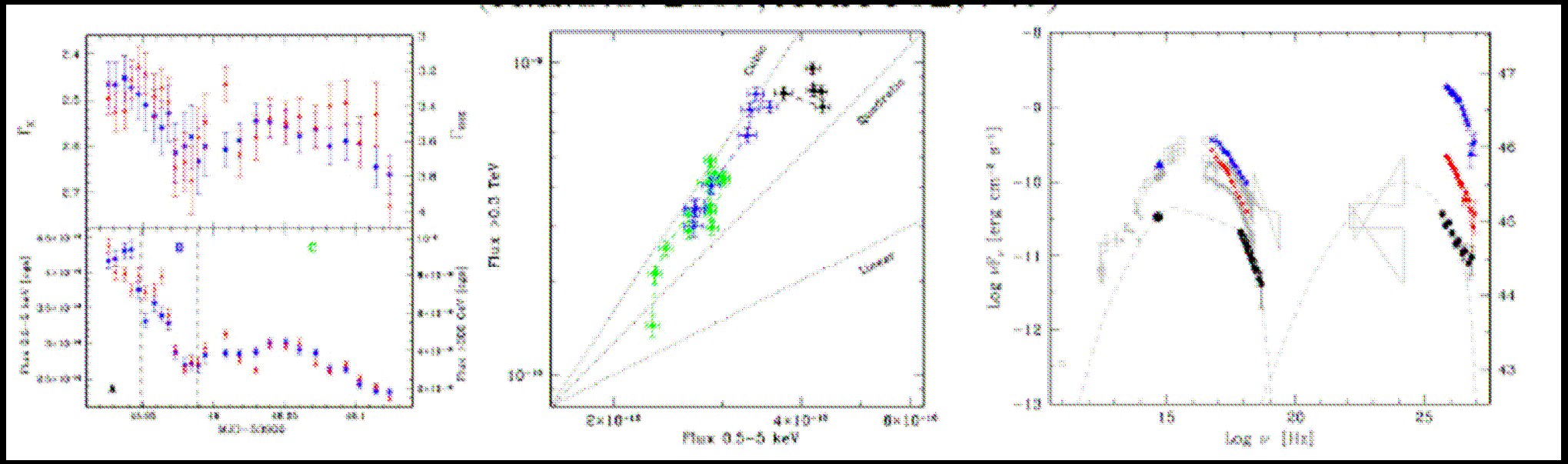
Fast variability in blazars



Short timescale variability (~ few minutes for PKS2155-304 in July 2006) → constraint on the size of the emission zone

Understanding the TeV blazars: PKS 2155-304

Detailed multi-wavelength observations to constrain models (HESS-Chandra simultaneous observations during flares)

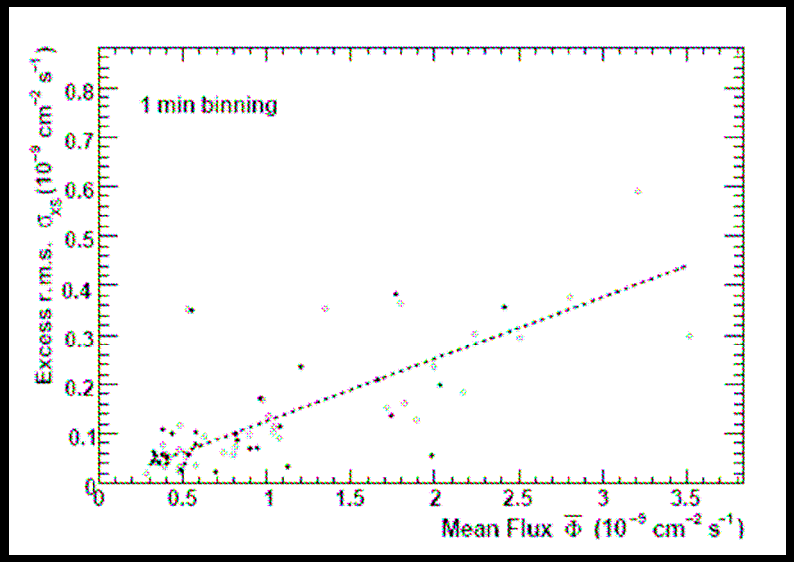


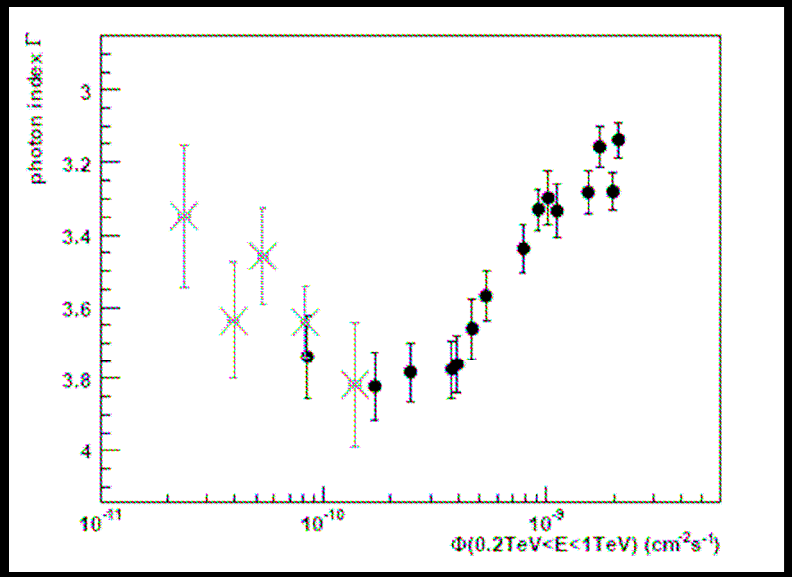
Aharonian et al.(2009)

- ✓Correlated spectral and flux variability, consistent with F_γ / F^3_X
- ✓ Incompatible with one-zone SSC model, need two components.
- ✓Flaring component Compton dominant; must be either very compact or external Compton

Monitoring PKS 2155-304

Abramowski et al 2010





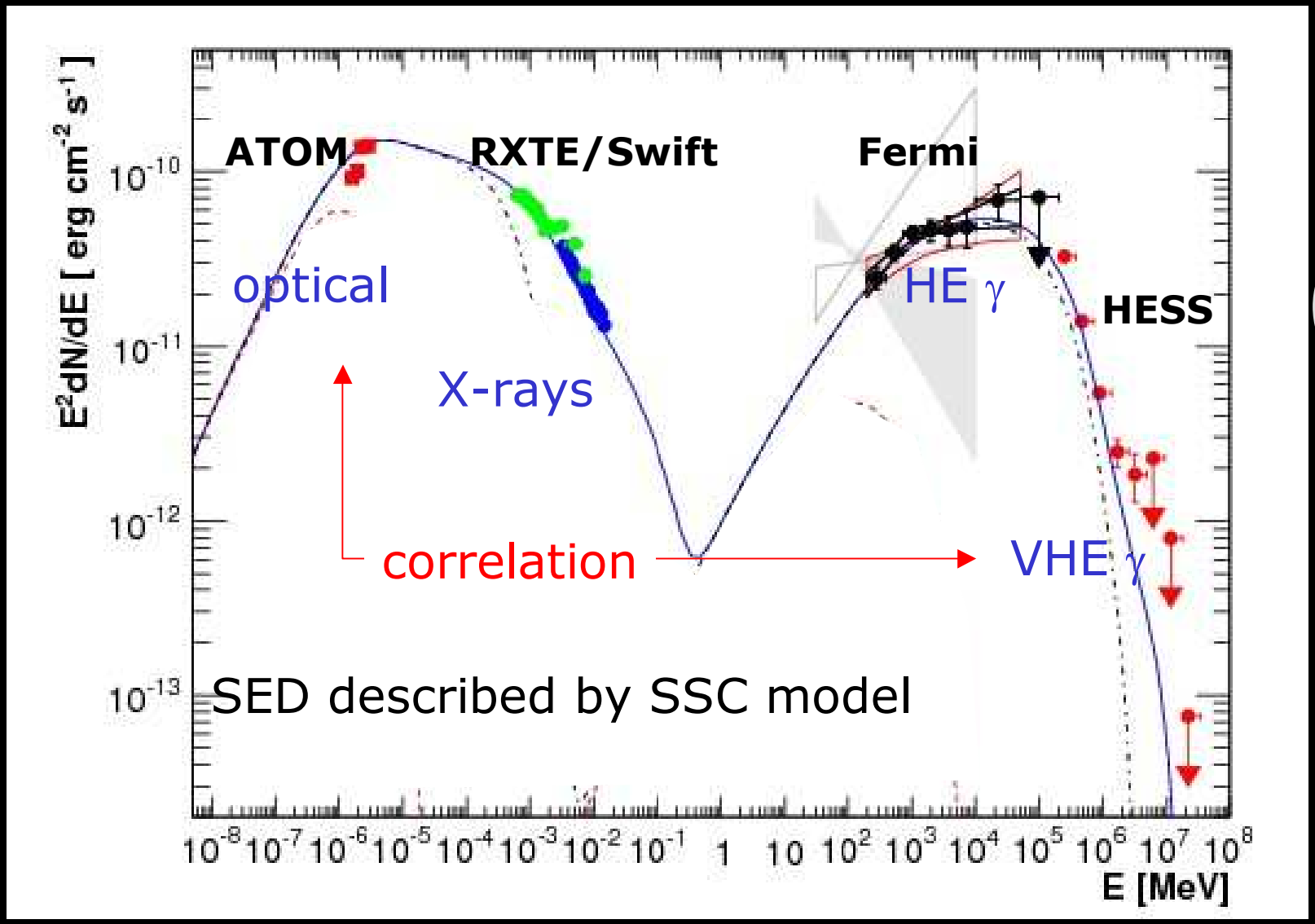
New features:

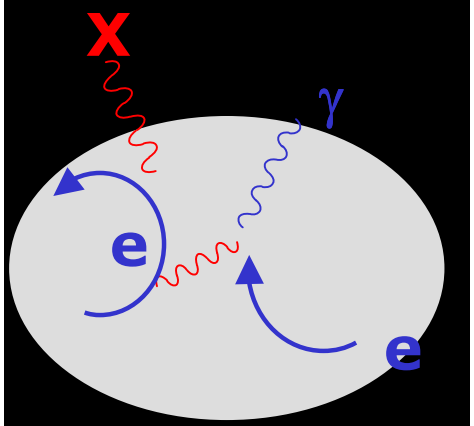
- ✓ Quiescent state
- ✓ Flux-rms correlation observed in many accreting systems (Cyg X-1 type, some Seyfert-1s)
- ✓ Variability described as a lognormal stochastic process (multiplicative)

Challenging how to concile lognormality with rapid variability.

- ✓ New trend of the spectral index *vs* flux

MWL campaign on PKS 2155-304



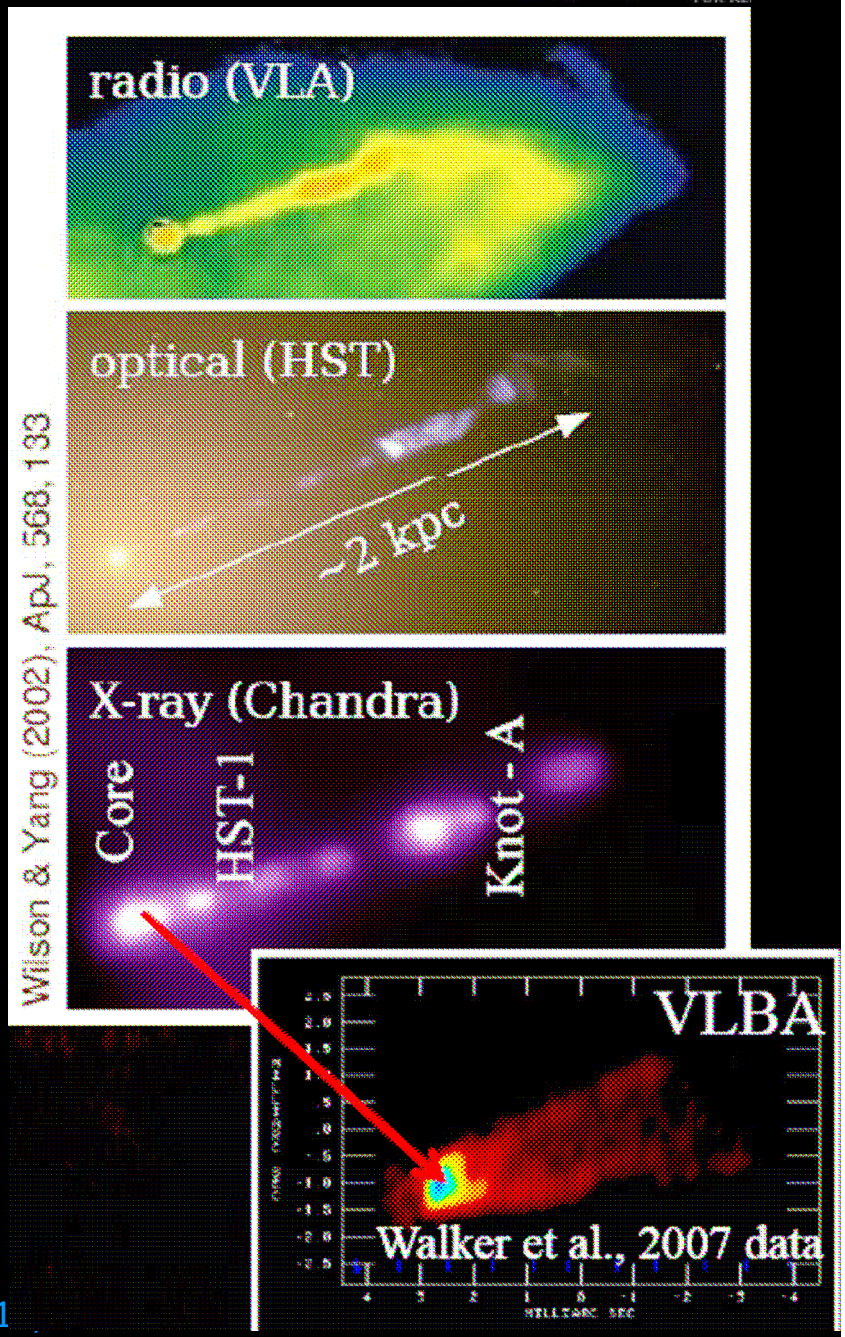


SSC model

"Blob" R ~10^{17} cm
Doppler factor δ ~3
Field B ~ 0.02 G

M 87: joint campaign

2007-2008 :
VERITAS/MAGIC/H.E.S.S./CHANDRA/VLBA campaign - 50 nights (>120 h)

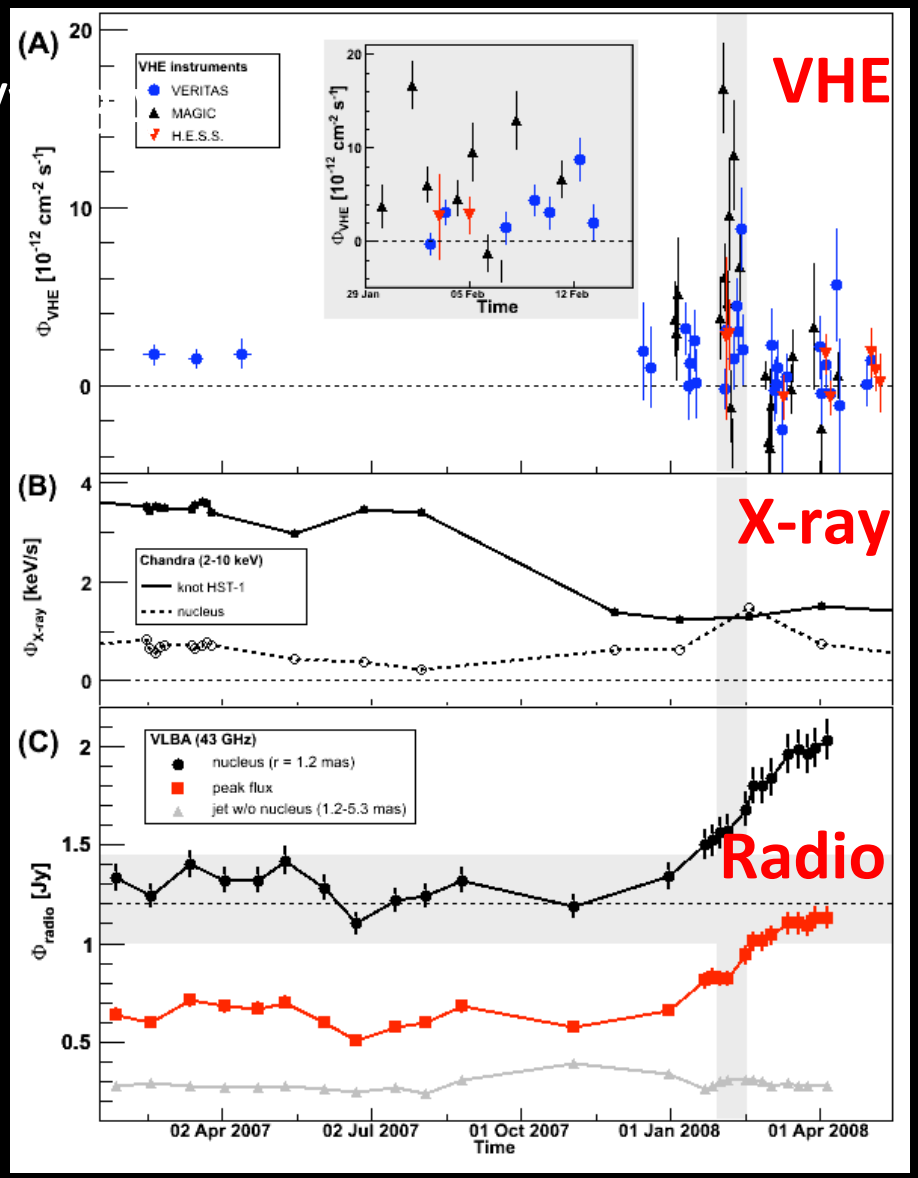


M 87: joint campaign

Acciari et al. 2009, Science

2007-2008 : VERITAS/MAGIC/H.E.S.S./CHANDRA/ campaign - 50 nights (>120 h)

- VHE flare accompanied by radio flare from BH vicinity
- X-ray core (Chandra) fluxes increases
- HST-1 unlikely source of VHE emission
- VLBA (43GHz) resolves jet formation with 30 x 60 Schwarzschild radii



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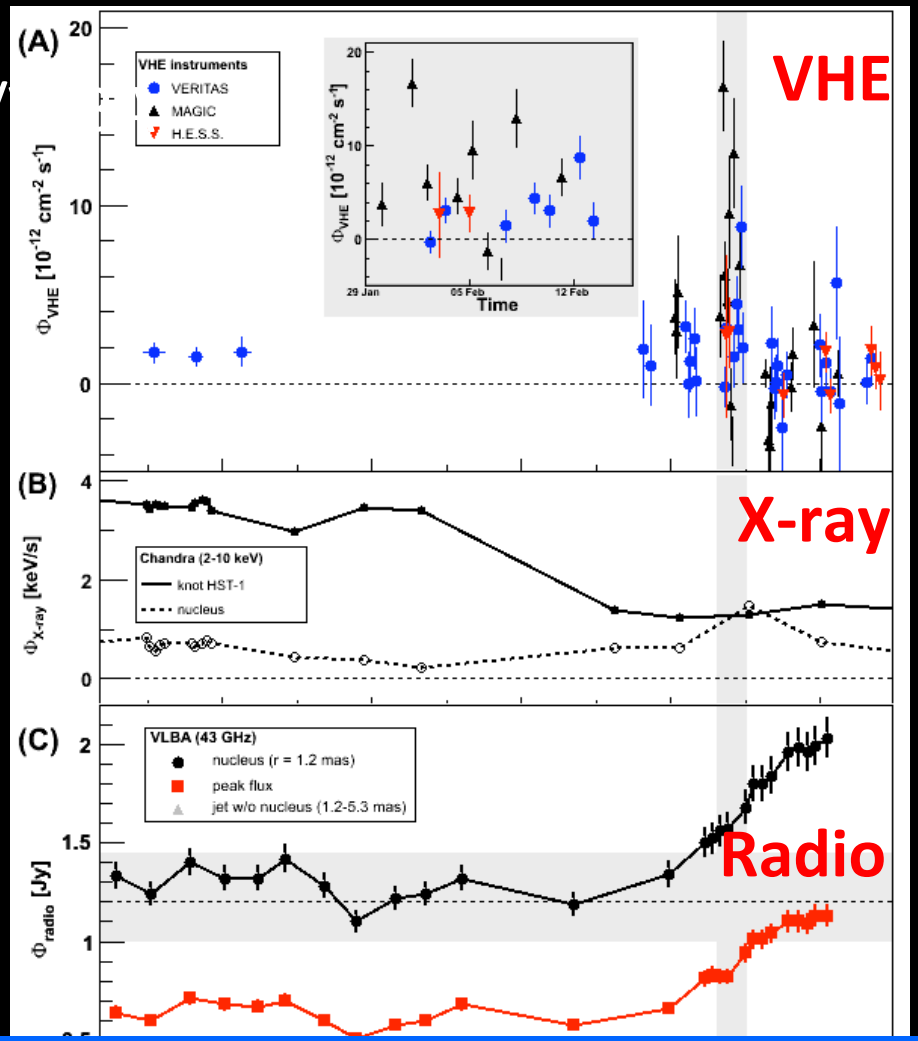
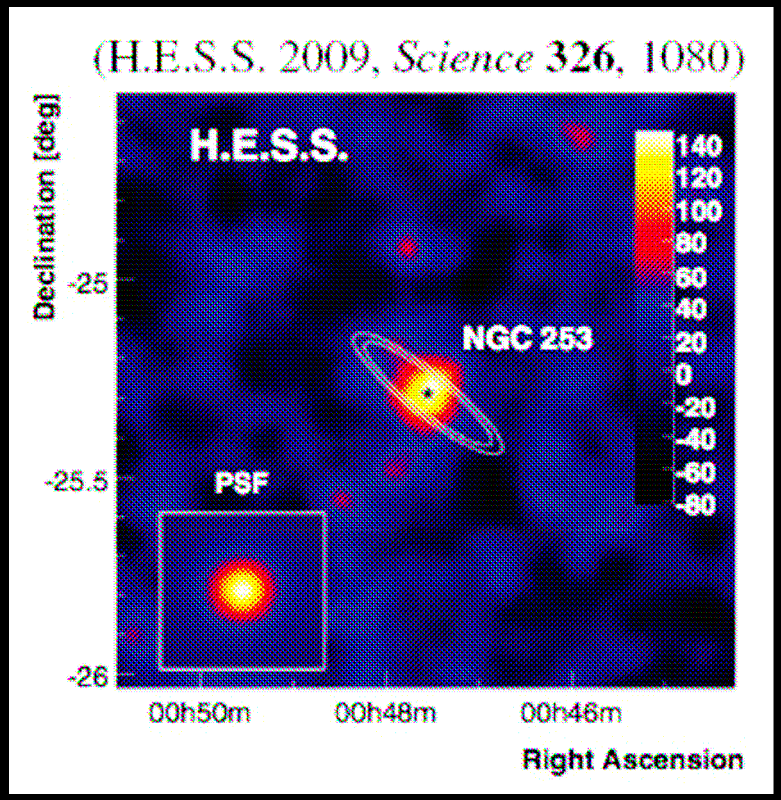
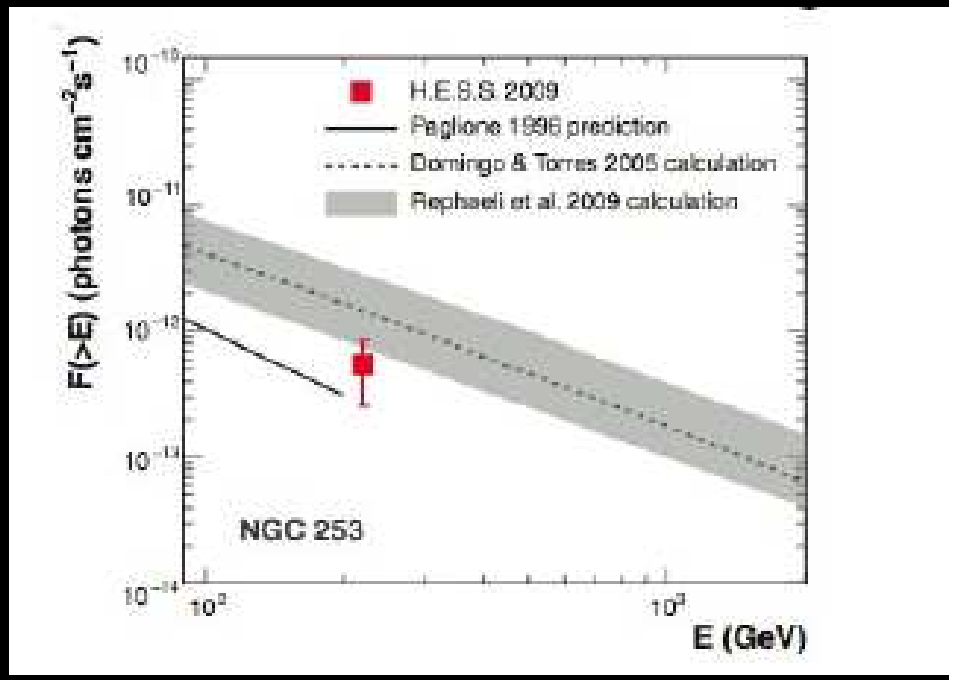


In 2010 new MWL campaign, source in high state. Ongoing analysis

Starburst galaxies: NGC 253

- New class of sources: NGC 253 (HESS)
- Very deep observations (100h), detected flux: 0.3% Crab
- Compact starburst region (a few 100pc) at nucleus, ~0.03 SN/yr
- Very high cosmic ray and gas density n ~ 600/150 cm^{-3} vs ~ 1 in Milky Way

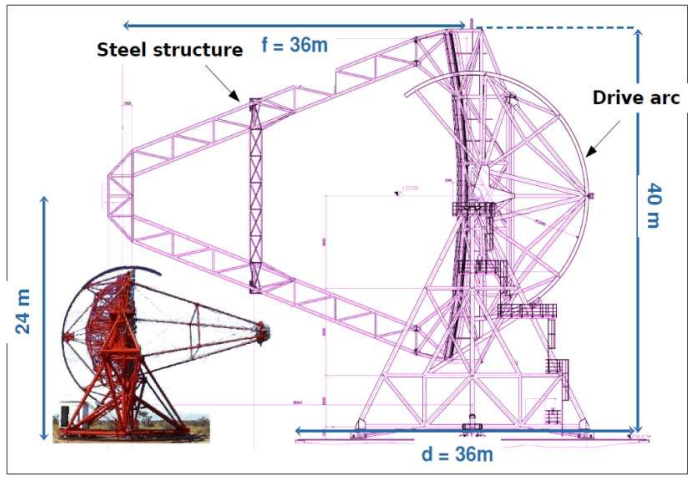




The future: HESS phase II

28 m diameter telescope under construction at the center of the array

Mirror area:	600 m2
Energy threshold:	≈30 GeV
Focal length:	36 m
Weight:	500 tonnes
FoV:	3.2°
Sensitivity	X 2 for E > 200 GeV



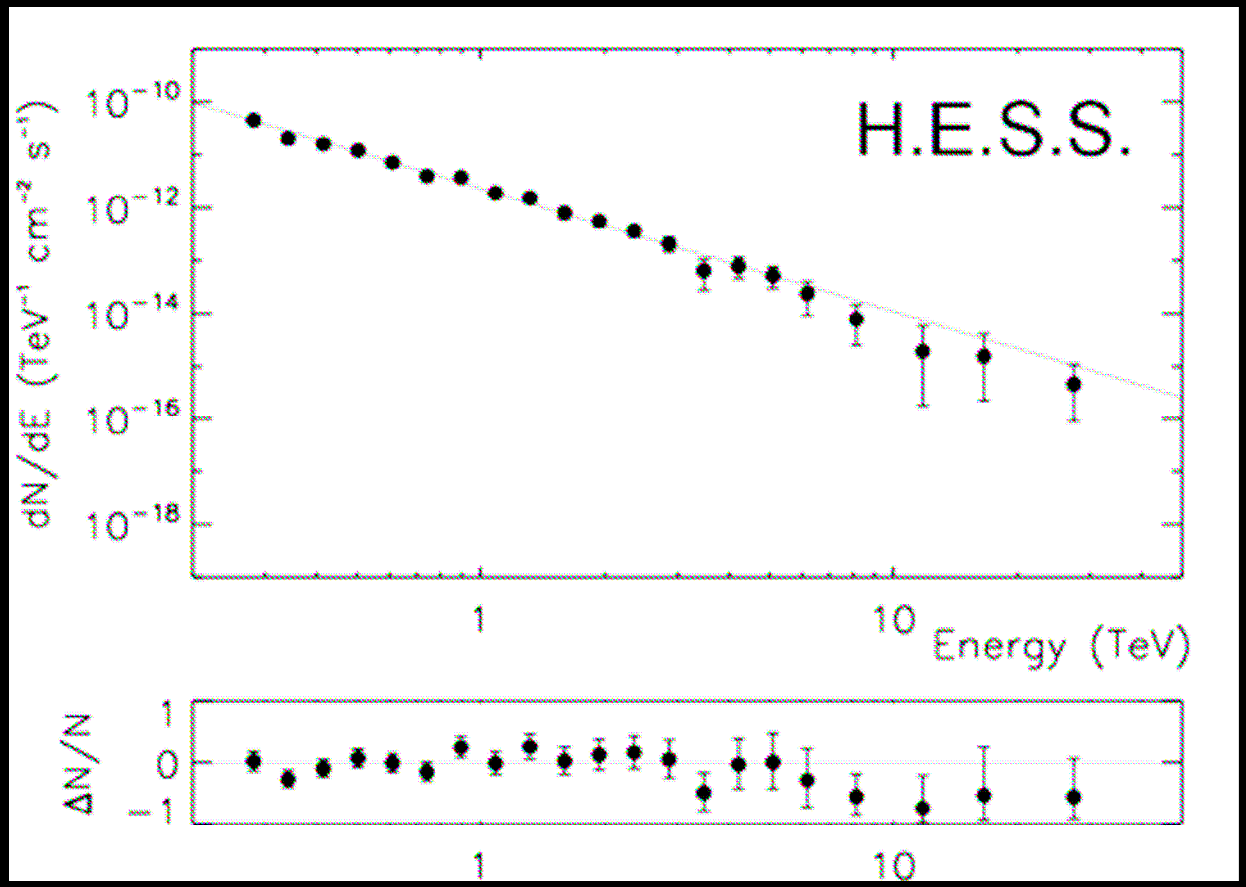
Conclusions

- ✓ Galactic sky bright in TeV, major discoveries since 2003:
  - Imaged supernova remnant shells, old SNR strongly indicate CR acceleration
  - Galaxy is full of VHE pulsar-wind-nebulae
  - Binary Systems: VHE modulation, laboratories for testing models
  - Diffuse gamma rays from interacting molecular clouds and star-forming regions
- ✓ Extragalactic sky: 17extra-galactic sources : blazars, radio-galaxies and the new starburst galaxy.
  - Variability in blazars studied at the limit of the temporal sensitivity
  - MWL campaign very effective to test emission models
- ✓ Still exciting discoveries ahead with HESS …. and H.E.S.S. II should usefully complement satellite observations in the GeV range, particular on variable sources (e.g. AGN).

Thanks

Backup slides

HESS J1731-347 A : spectrum



Index=$2.3 \pm 0.1_{stat} \pm 0.2_{syst}$

Flux(1-10TeV) =
$1.91 \pm 0.17_{stat} \pm 0.41_{syst} \times 10^{-12}$ $cm^{-2}\ s^{-1}$
9% of Crab flux