MCTP Mesoamerican Centre for Theoretical Physics
Centro Mesoamericano de Física Teórica

The origin of Cosmic Rays: the possible role of Unidentified High Energy Sources

Omar Tibolla
Mesoamerican Center for Theoretical Physics

Roma “La Sapienza”, 9th October 2015

CRBTSM conference

A whole conference was recently devoted to it:

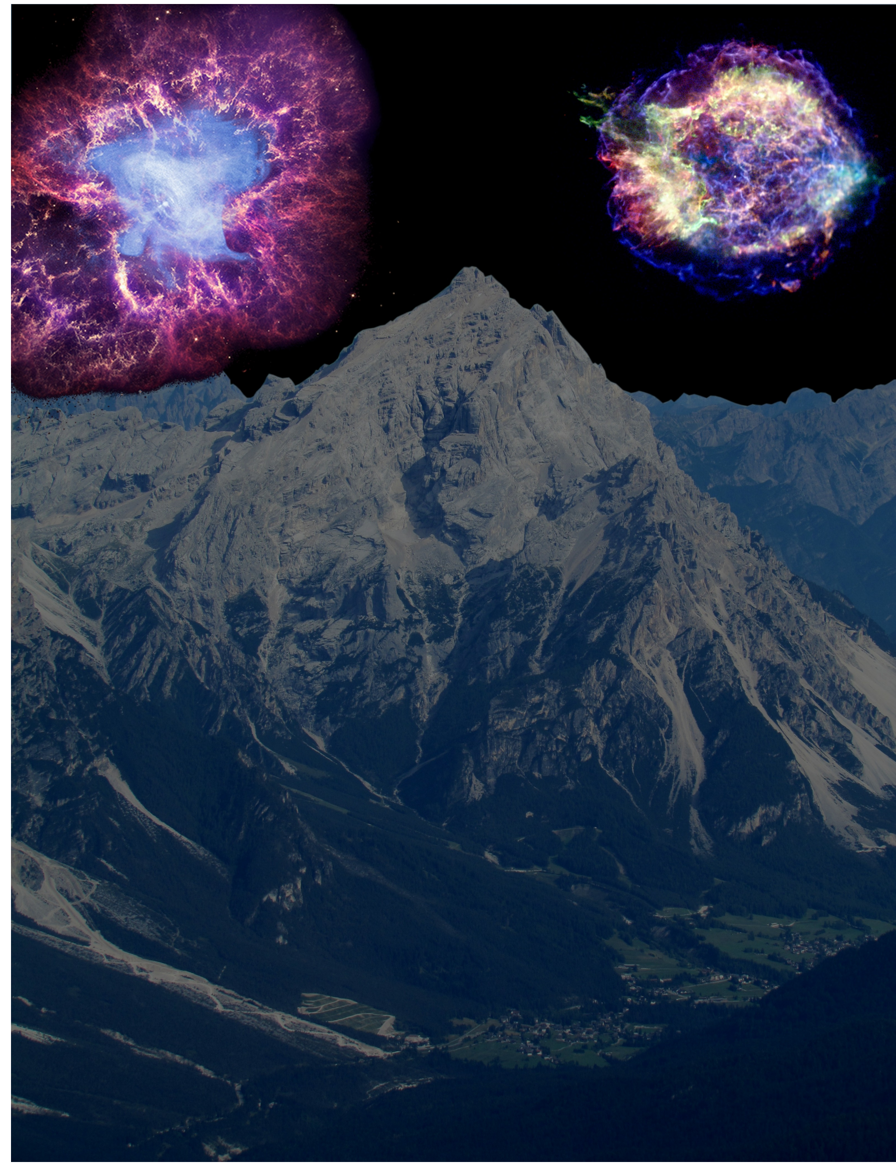
"CR Origin - beyond the standard models"

Conference centre of San Vito di Cadore (Dolomites, Italy),
16-22 March 2014.

SOC: Omar Tibolla (chair)
Luke Drury (co-chair)
Heinz Völk
K.S. Cheng
Jamie Holder
Josep Maria Paredes
Marianne Lemoine-Goumard
Elena Amato
Piergiorgio Picozza
Pat Slane
Jacco Vink

LOC: Würzburg (Karl Mannheim & Omar Tibolla)
Udine & Trieste (Alessandro de Angelis & Massimo Persic), Padova (Denis Bastieri), LSW-Heidelberg (Sarah Kaufmann)

Invited speakers: Roger Blandford, Pasquale Blasi, Marco Tavani, Yoel Raphaeli, Etienne Parizot, Evgeny Berezhko, Peter Meszaros, etc...



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"CR Origin - beyond the standard models"

Conference centre of San Vito di Cadore
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16-22 March 2014

SOC: Om...

If you are interested in going deeper into this subject:

Web-page: http://www.crbtsm.eu

Book:
http://www.sciencedirect.com/science/journal/09205632

Should be open source; anyway a hard copy of it should be available in the libraries here (La Sapienza & Tor Vergata).

LOC: V...
U... ...ngelis &
Massim... ...nis Bastieri),
LSW-He... ...aran Kaufmann)

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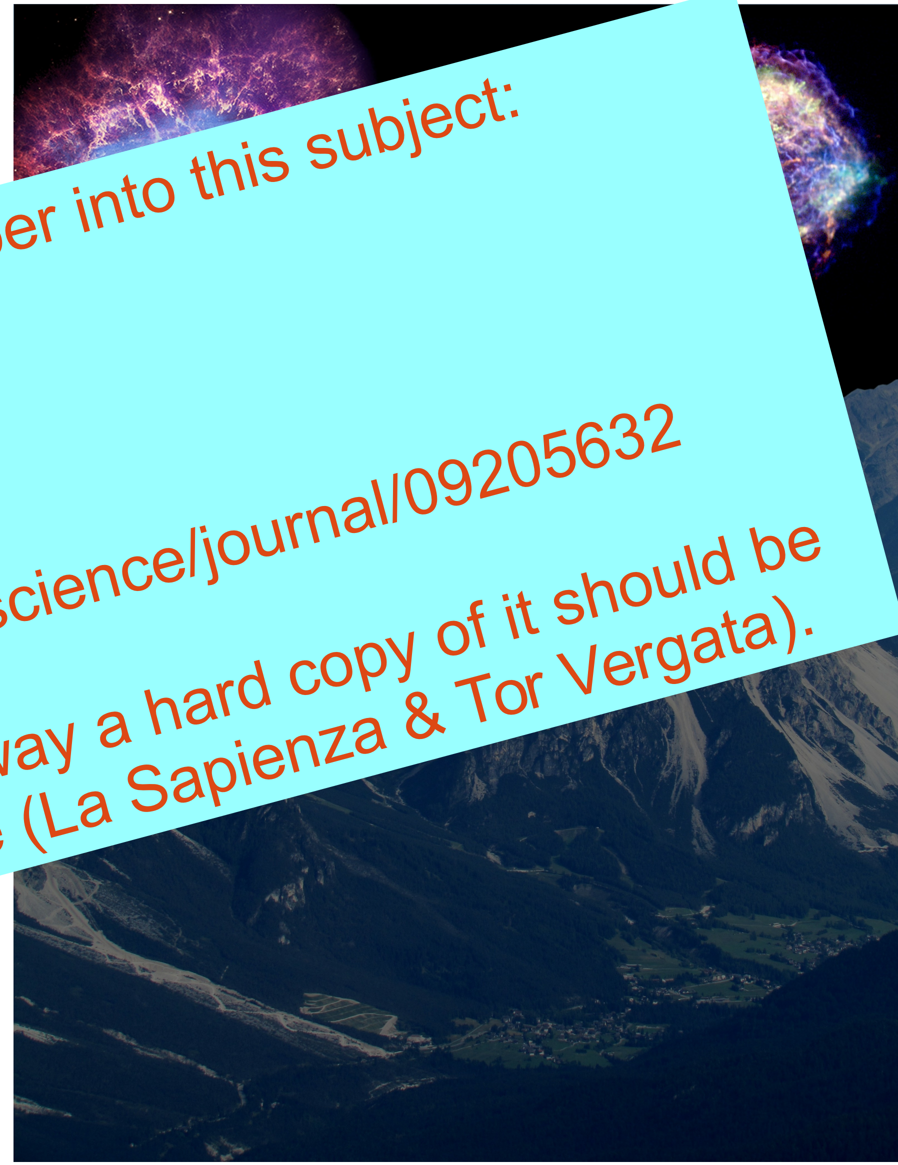

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CRBTSM2 conference

Given the scientific success of CRBTSM 2014...

The Helmholtz Alliance for Astroparticle Physics (HAP) is supporting:

"CR Origin - beyond the standard models II"

Conference centre of San Vito di Cadore
(Dolomites, Italy),
18-24 September 2016.

SOC: Omar Tibolla (chair)
Roger Blandford (co-chair)
...

Rotation between SOC and invited speakers...few changes in the LOC...

LOC: MCTP (Omar Tibolla & Sarah Kaufmann)
Würzburg (Karl Mannheim & Omar Tibolla)
Udine & Trieste (Alessandro de Angelis & Massimo Persic), Padova (Denis Bastieri)....

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Summary- Outline

- Introduction to Cosmic Rays and "standard picture" of their origin.

- Detection techniques (GeV-TeV)

- H.E.S.S. Survey and Galactic unidentified sources

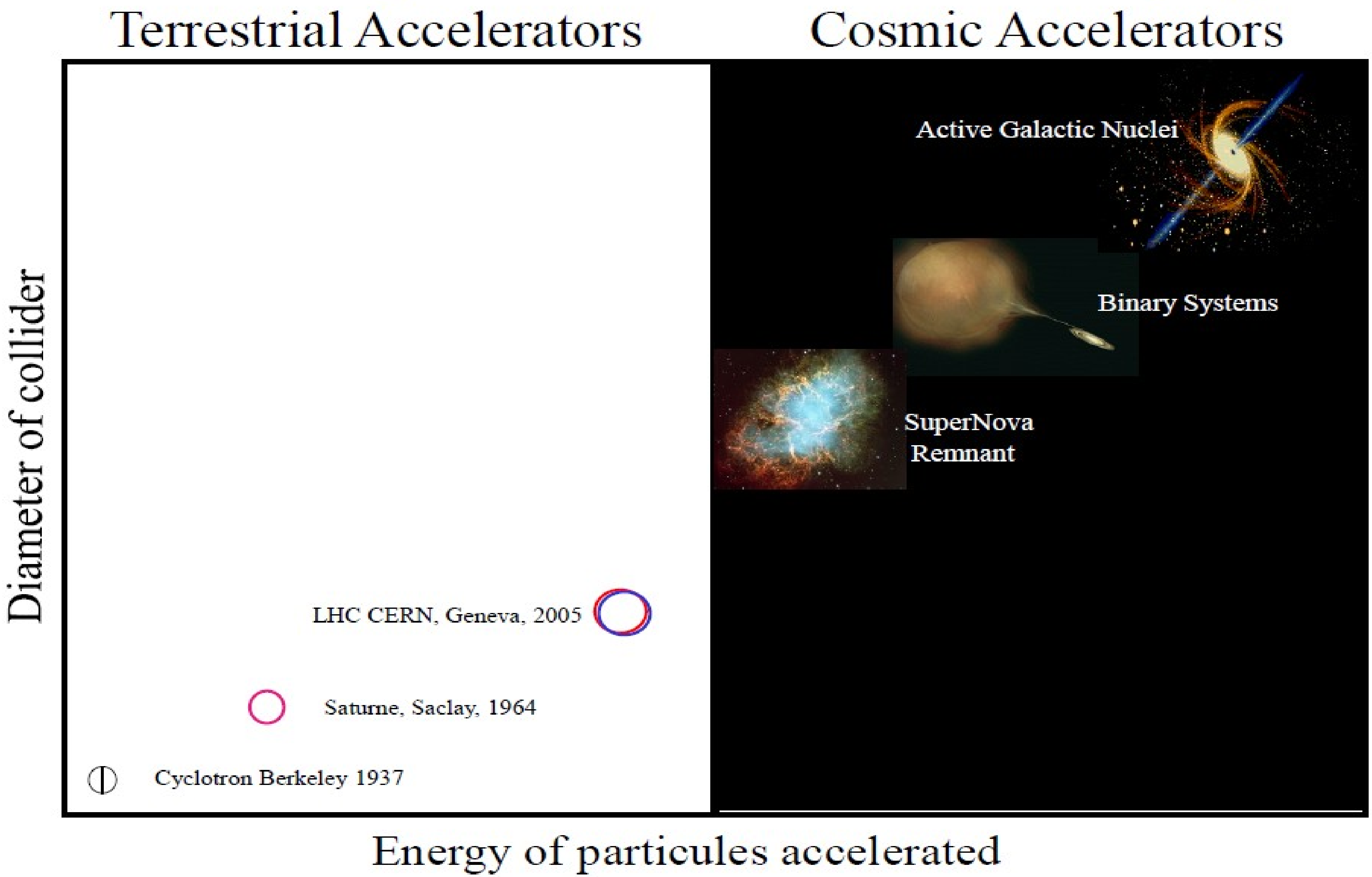
- Examples, Newly discovered sources:
    - HESS J1507-622
        + ancient PWN
    - ~~HESS J1741-302~~

- Conclusions

(+ ~100 backup slides)

Why Cosmic Rays?

Particle Physics ⇒ Particle Astrophysics



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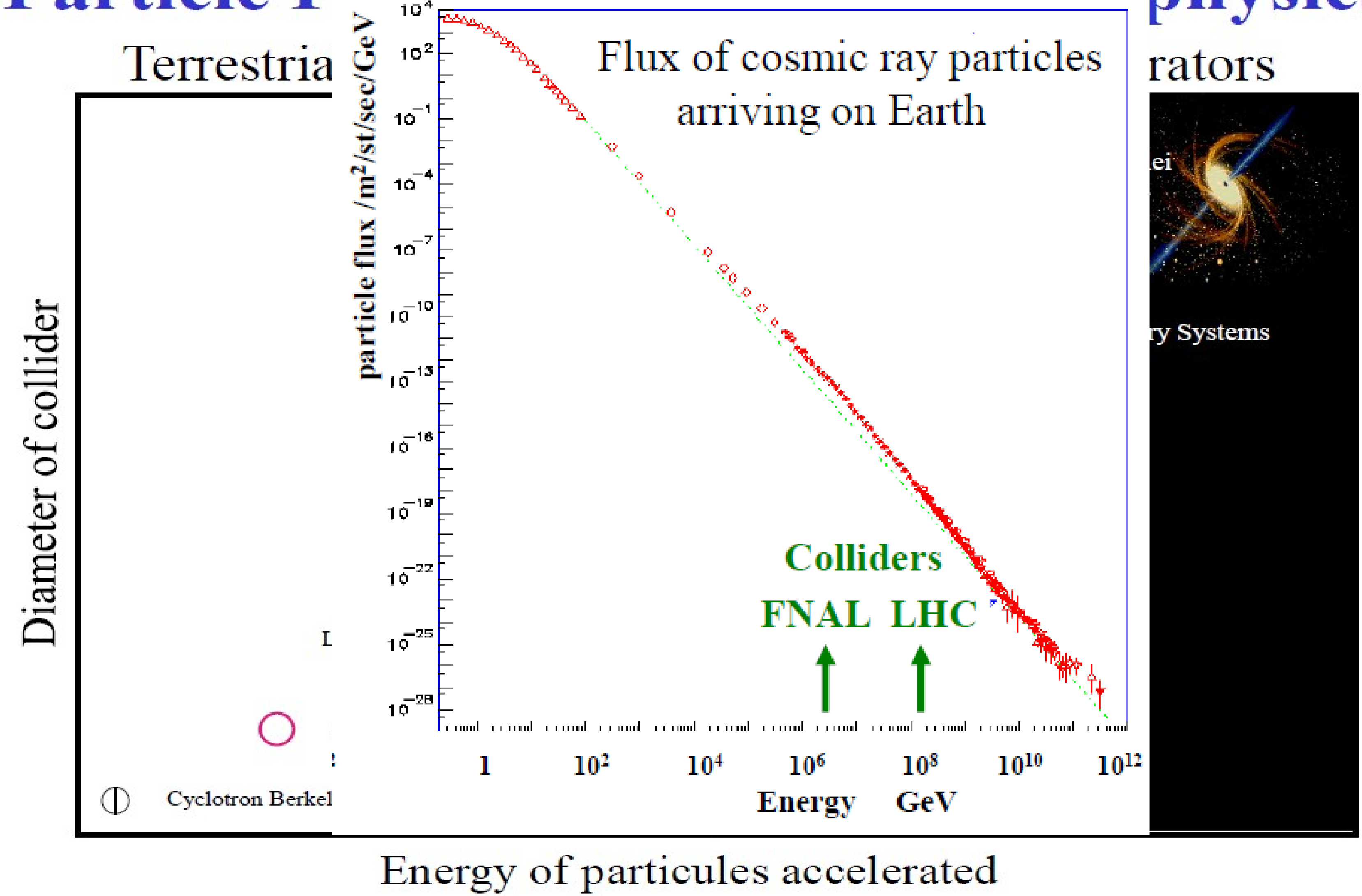
Why Cosmic Rays?

Particle Ph… → …physics

Terrestria… …rators

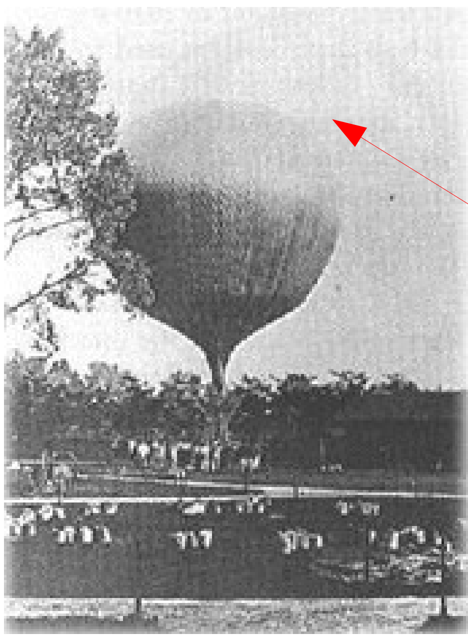


One century after their discovery...

Discovery in water (Bracciano lake & Tirreno sea) D. Pacini 1907-1912

Pacini (1912), Nuovo Cimento, 3, 93.

Discovery on Eiffel Tower T. Wulf 1909 who was also the first who spoke about "hoehenstrahlung"



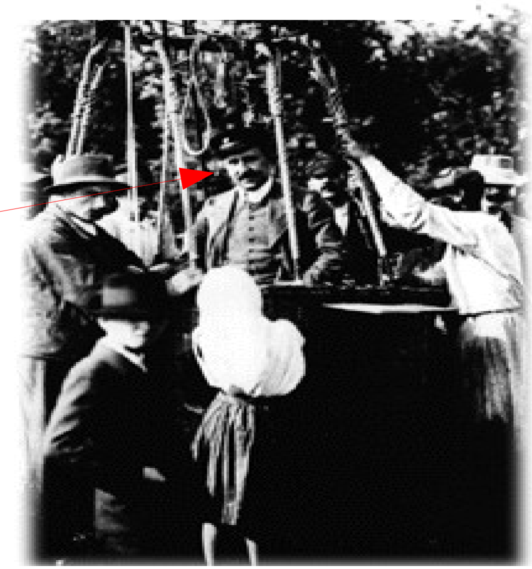
Wulf (1909), Phys. Z., 10, 155.

Balloon Flight:

V. Hess 1912 at 5km

Hess (1913), Phys. Z., 13, 1084.

In 1936 Hess got the Nobel prize for CRs discovery



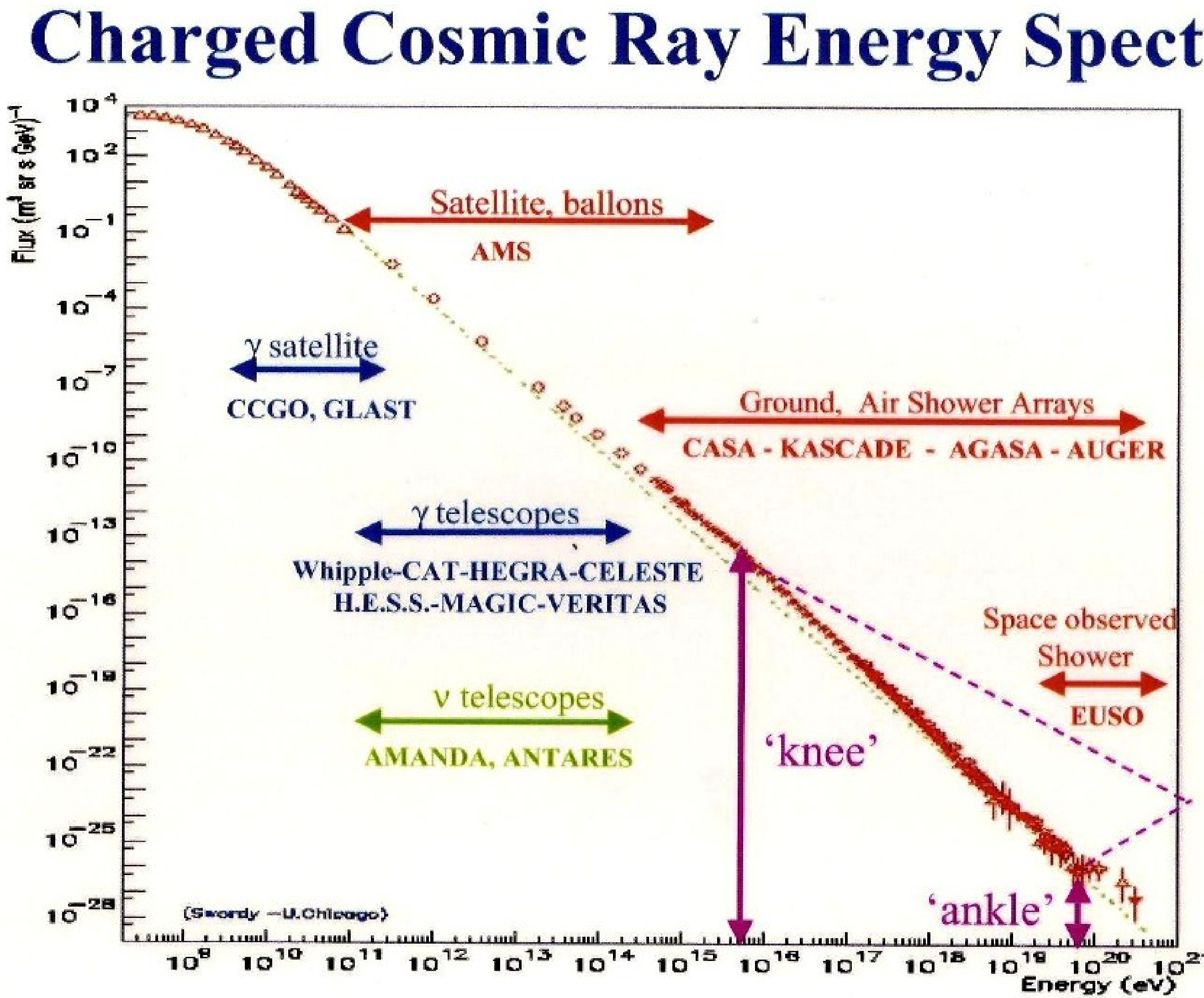
..et al. ..e.g. Colhoster 1914 at 9km

Altitude (km)	Difference between observed ionisation and that at sea-level (ions cm^{-3}) s^{-1}
1	−1.5
2	+1.2
3	+4.2
4	+8.8
5	+16.9
6	+28.7
7	+44.2
8	+61.3
9	+80.4

e.g. Millikan skeptical about "…Cosmic… Rays"

...and we still ignore their origin

Direct and indirect detection



HE > 10^9eV

VHE > 10^{12}eV

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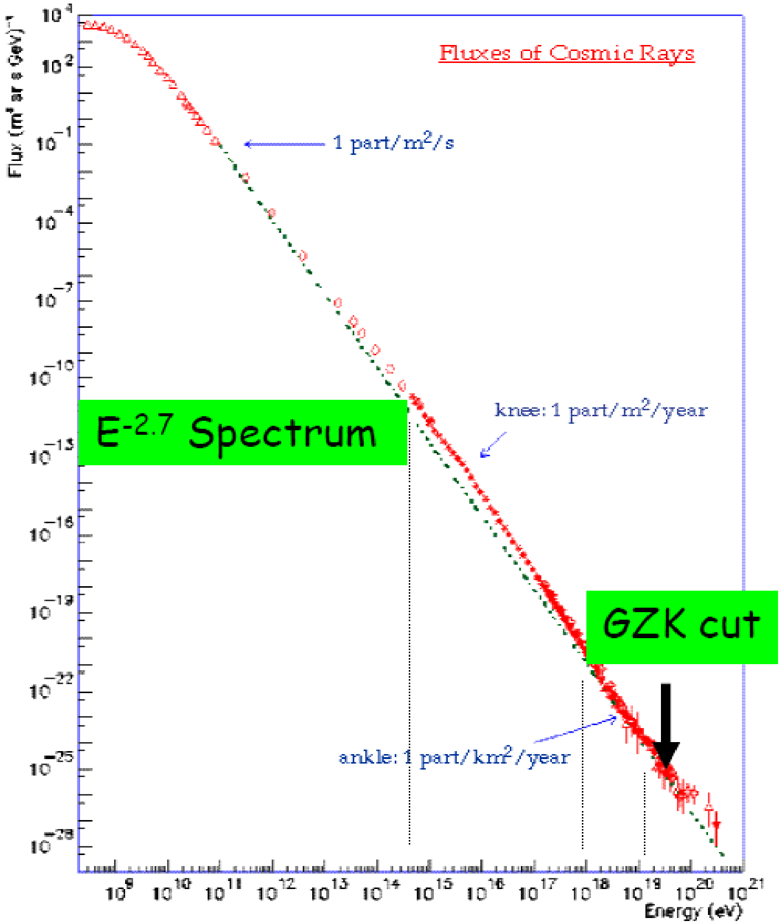
More nomenclature and suggested origin

The primary spectrum



Possible Origins

- $E < 10^{15}$ eV — Galactic
- $10^{15} < E < 10^{18}$ eV — Extra-galactic ?
- $10^{18} < E < 5.\ 10^{19}$ eV — Unknown
- $5.\ 10^{19} < E < 3.\ 10^{20}$ eV — Unexpected

HE > 10^9eV

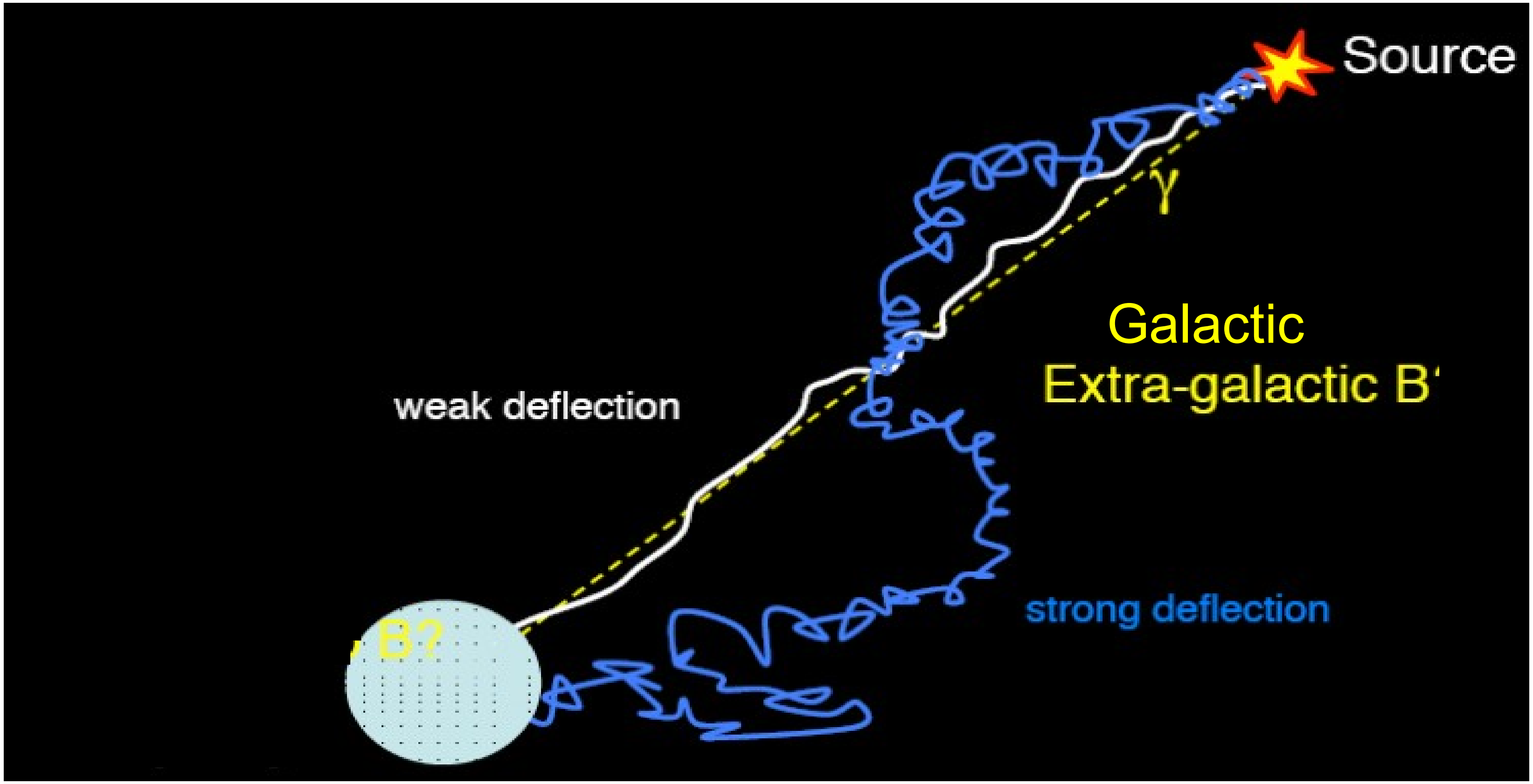
VHE > 10^{12}eV

UHECR

EECR

Gamma-rays (and neutrinos) have one big advantage...

...they are not deflected by Galactic and extragalactic magnetic fields → <u>direction</u>



“Standard” picture

Primary Galactic cosmic-rays up to the so called ”knee“ at about 10^{15} eV, are accelerated in SNRs.
One expects about one supernova event every 30 - 50 years, and, in order to account for the energy density of CRs (about 1 eV/cm^3) and the CRs confinement time deduced from spallation, the typical non-thermal energy release per supernova has to be about 10^{50} ergs, which is about 10% of the total energy released.

(Ginzburg and Syrovatskii (1964), Soviet Astronomy, 8, 342)

This is in good agreement with the typical amount of energy predicted to be produced during the acceleration of relativistic particles in SNR shocks.

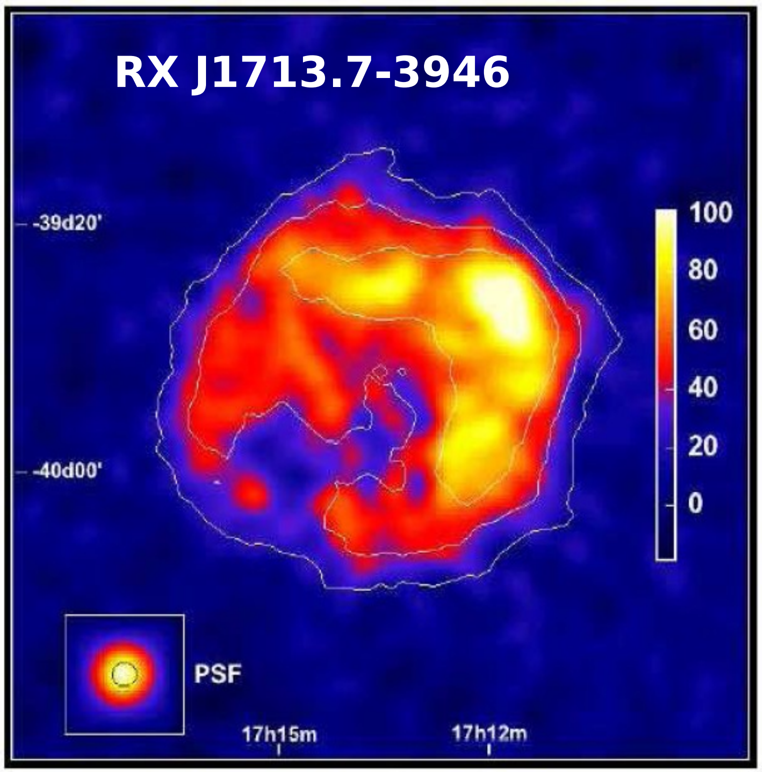
(Drury, Markiewicz and Völk (1989), A&A, 225, 179)

(Völk and Biermann (1988), ApJ, 333, L65)

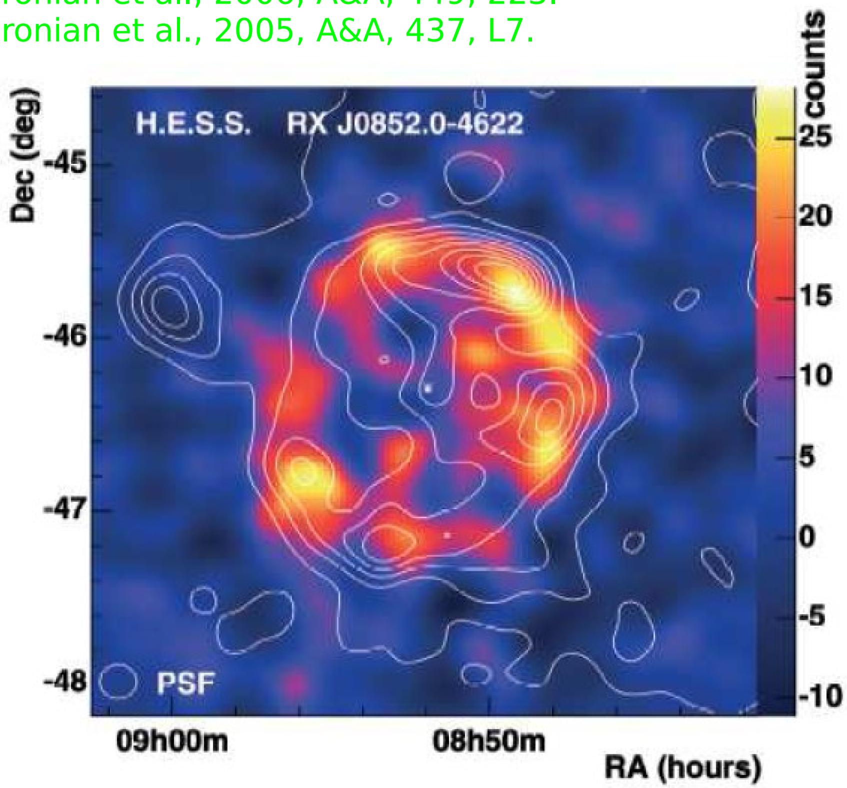
(Drury, Aharonian and Völk (1994), A&A, 287, 959)

TeV gamma-rays detections

The detection by the Imaging Atmospheric Cherenkov Telescopes (IACTs) of TeV gamma rays from supernova remnants (SNRs), spatially coincident with the sites of non-thermal X-ray emission, has strengthened the hypothesis of the “standard” picture of CR origin for up to the ”knee“.



Aharonian et al., 2006, A&A, 449, 223.
Aharonian et al., 2005, A&A, 437, L7.



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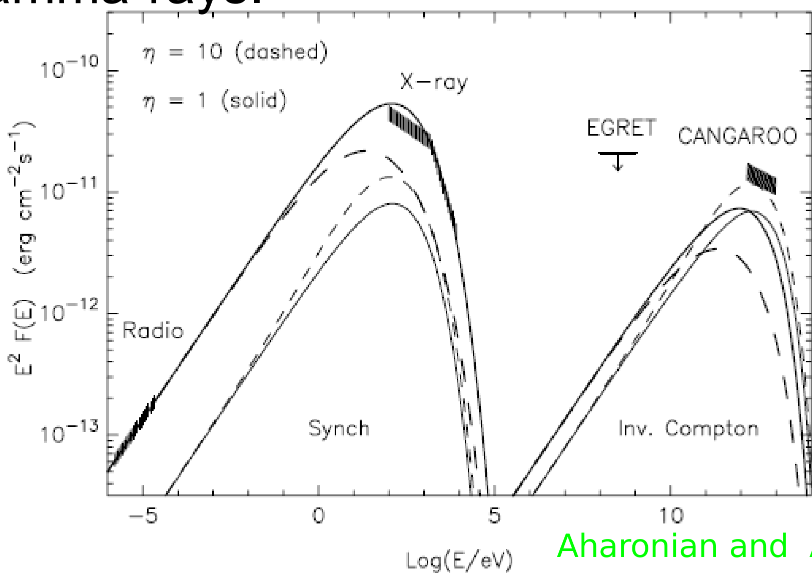
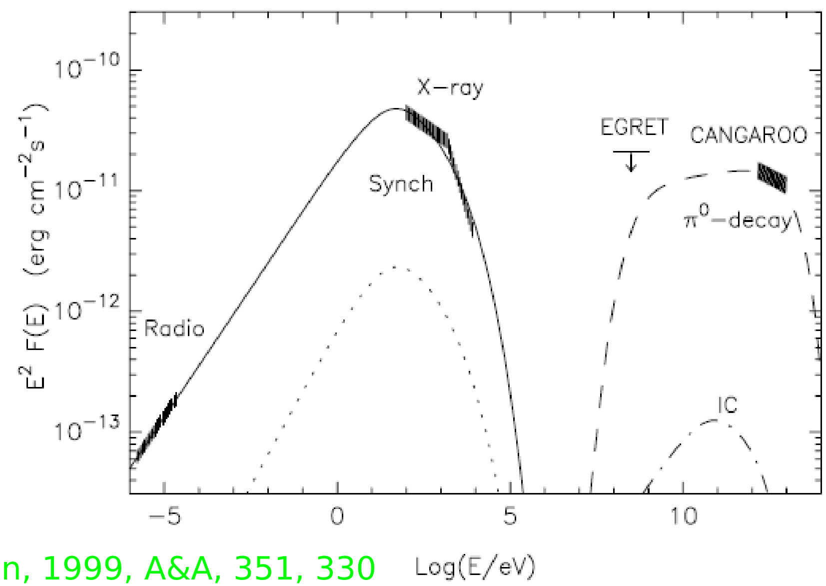
But...it is not enough

The TeV gamma ray signal, can be explained in 2 ways:
- Inverse Compton scattering of relativistic electrons/positrons on background photons (CMB, infrared, X-rays, etc.)
- Neutral pion decay (p-p interaction)

And hadronic and leptonic model are basically indistinguishable at TeV gamma-rays.



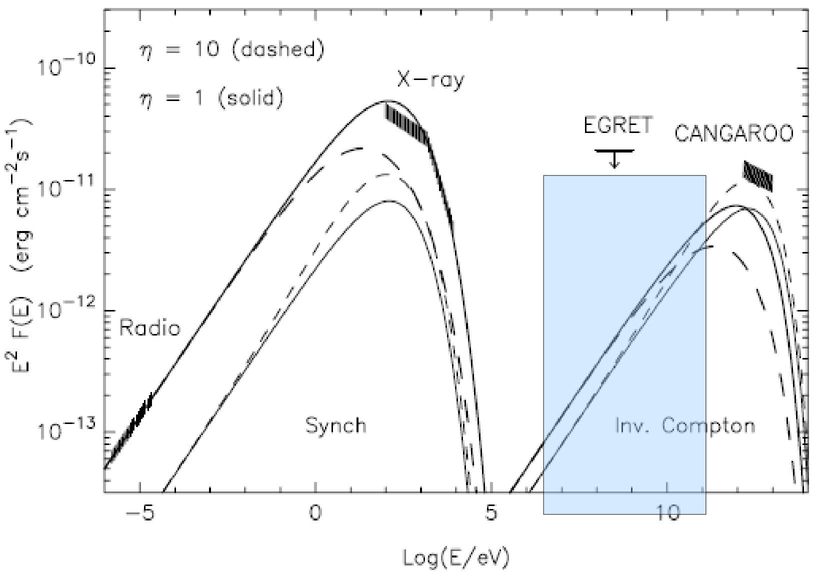


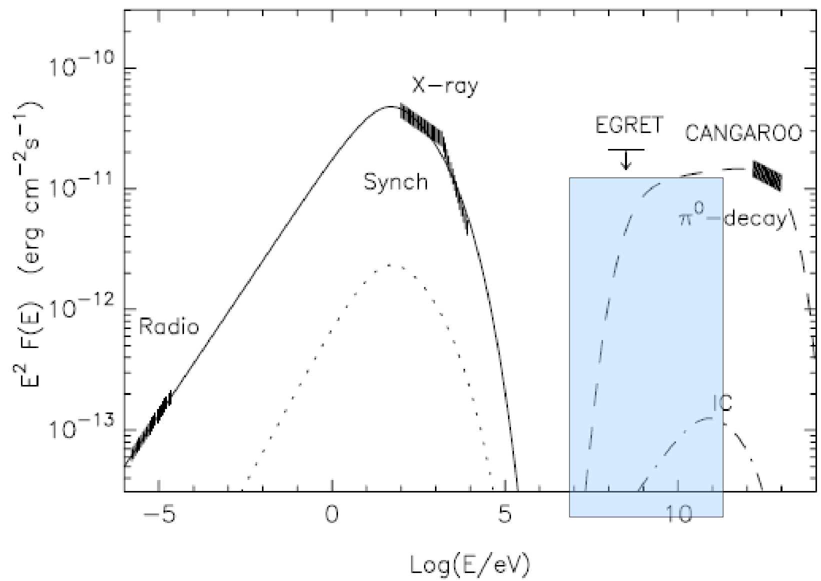
Aharonian and Atoyan, 1999, A&A, 351, 330

SNRs proved to be sources of cosmic ray electrons a decade ago, because of the radio and X-ray emissions detected, no compelling evidence for the acceleration of hadrons (98% of CRs) in SNRs has been found.

However..

Taking the same example...we see that the adjacent GeV gamma-ray band, we can finally prove or disprove it.





Aharonian and Atoyan, 1999, A&A, 351, 330

And it was indeed among the scientific purposes (GLAST Science Brochure 1996; http://glast.gsfc.nasa.gov) of Fermi-LAT, that was projected (also) to be a great observatory for SNRs (e.g. Tibolla 2007, MPLA, 22, pp. 1611-1619).

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Fermi-LAT detected several SNRs (and SNR/MC interactions): references

H. Katagiri et al. (including O. Tibolla), "Fermi Large Area Telescope Observations of the Cygnus Loop Supernovae Remnant", ApJ, 741, id.44 (2011).

T. Tanaka et al. (including O. Tibolla), "GammaRay Observations of the Supernova Remnant RX J0852.04622 with the Fermi LAT", ApJ, 740, id. L51 (2011).

F. Giordano et al. (including O. Tibolla), "FermiLAT Detection of the Young SuperNova Remnant **Tycho**", ApJ, 744, id. L2 (2012)

A. A. Abdo et al. (including O. Tibolla), "Fermi LAT discovery of Extended gamma-ray emission in the direction of SNR W51C", ApJL, 706, L1-L6 (2009).

A. A. Abdo et al. (including O. Tibolla), "GammaRay Emission from the Shell of Supernova Remnant W44 Revealed by the Fermi LAT", Science, 327, pp. 1103 (2010).

A. A. Abdo et al. (including O. Tibolla), "FermiLAT discovery of GeV gamma-ray emission from the young Supernova remnant **Cassiopeia A**", ApJ, 710, pp. L92-L97 (2010).

A. A. Abdo et al. (including O. Tibolla), "Observations of the young Supernova remnant **RX J1713.7−3946** with the FermiLAT", ApJ, 734, id. 28 (2011).

M. Ajello et al. (including O. Tibolla), "Fermi Large Area Telescope Observations of the Supernovae Remnant G8.70.1", ApJ, 744, id. 80 (2012).

A. A. Abdo et al. (including O. Tibolla), "Fermi LAT Observations of the Supernova Remnant W28 (G6.4−0.1)", ApJ, 718, pp. 348-356 (2010).

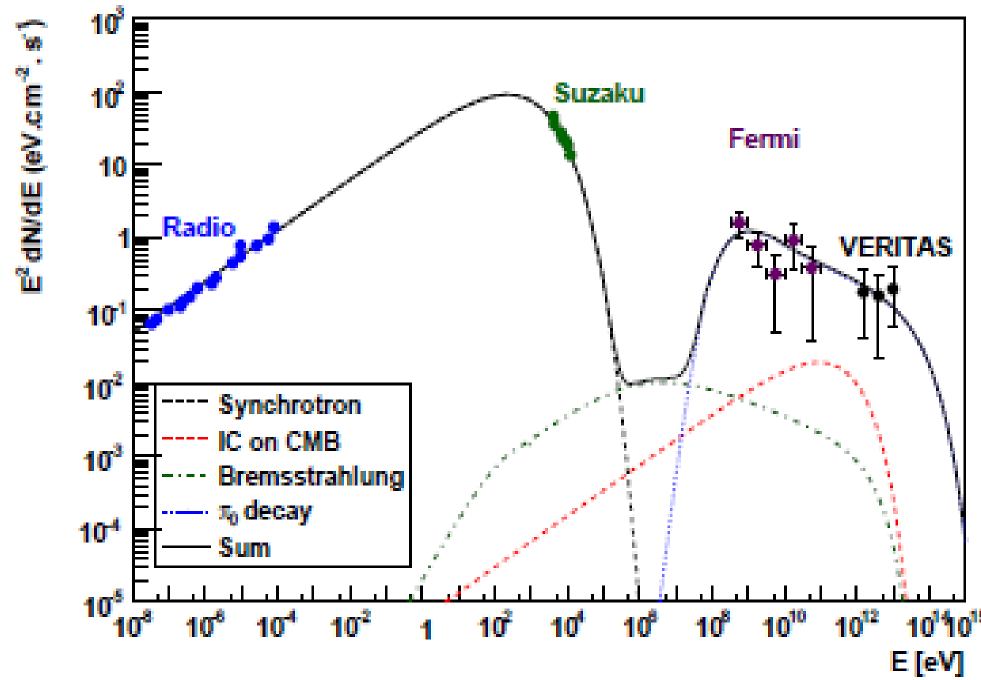
A. A. Abdo et al. (including O. Tibolla), "FermiLAT Study of Gamma-ray Emission in the Direction of Supernova Remnant W49B", ApJ, 722, pp. 1303-1311 (2010).

...but

The "Standard Model" works!!

Among the Femi LAT SNRs sample, a very important discovery is represented by Tycho.
In the case of Tycho, leptonic models are basically disproved (!!!); i.e. Tycho represents the "smoking gun", the "hadronic fingerprint", i.e. the answer to a 60-100 years old question!

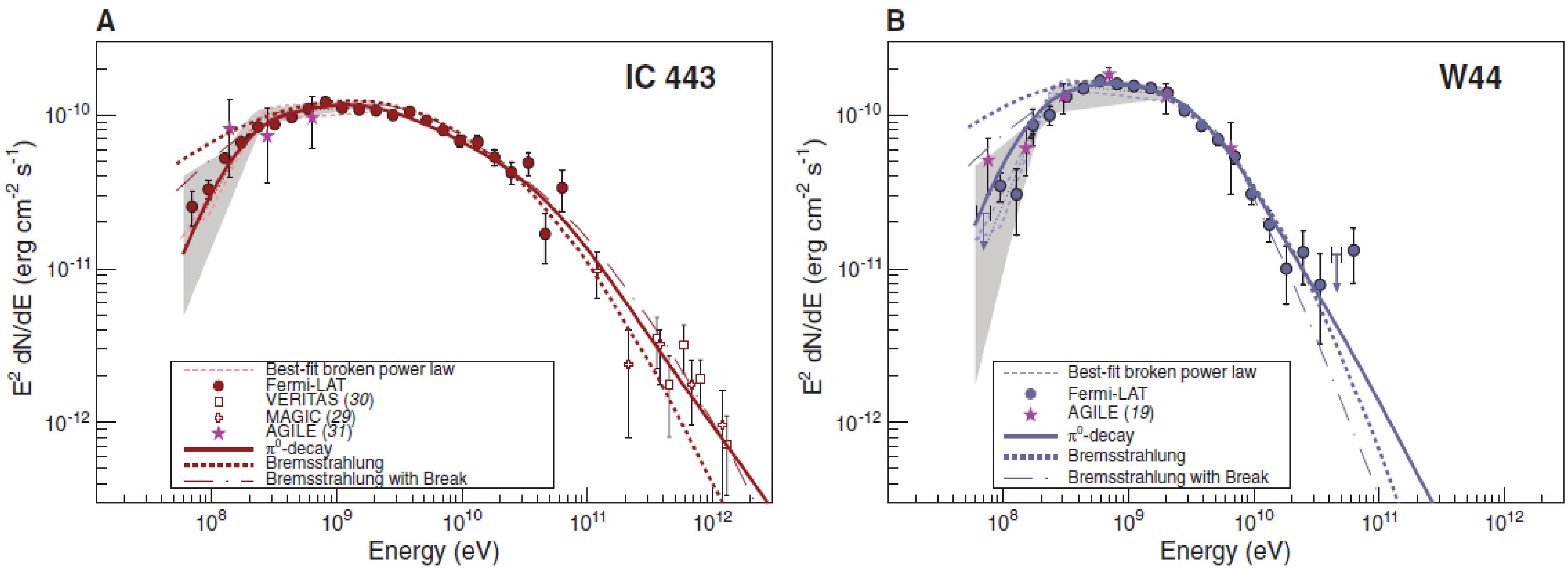
So everything would look solved and every question answered...BUT...



Note (Additional approach):

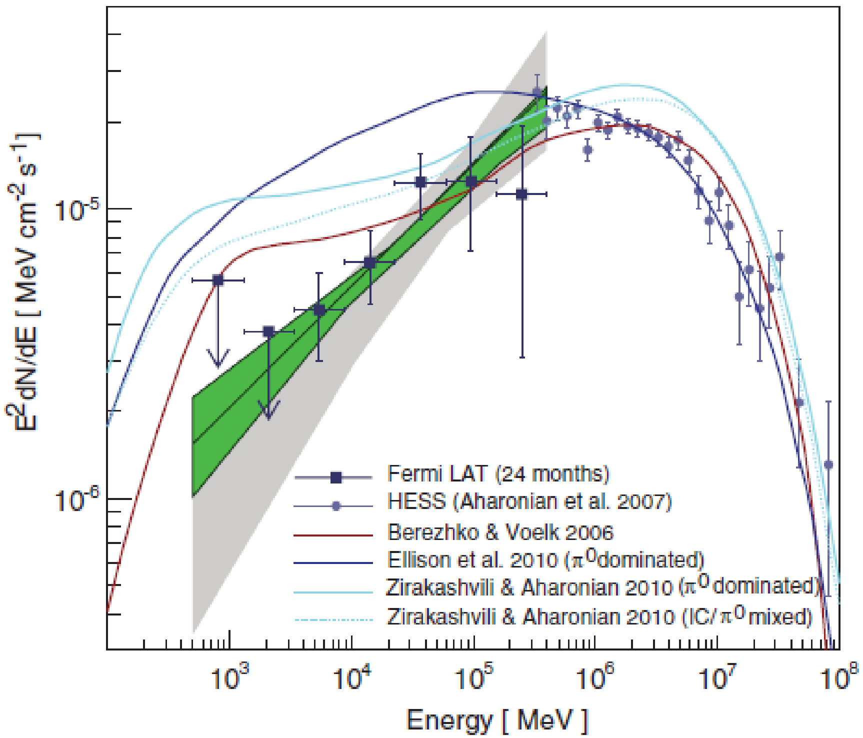
Additionally, we could detect hints of the neutral pion "shoulder" around 100 MeV (for IC 443 and W44): *M. Ackermann et al. (including O. Tibolla), Science, 339, pp. 807-811 (2013).*
...if these two example are less relevant than Tycho SNR since they deal with SNRs/MCs interacting systems...

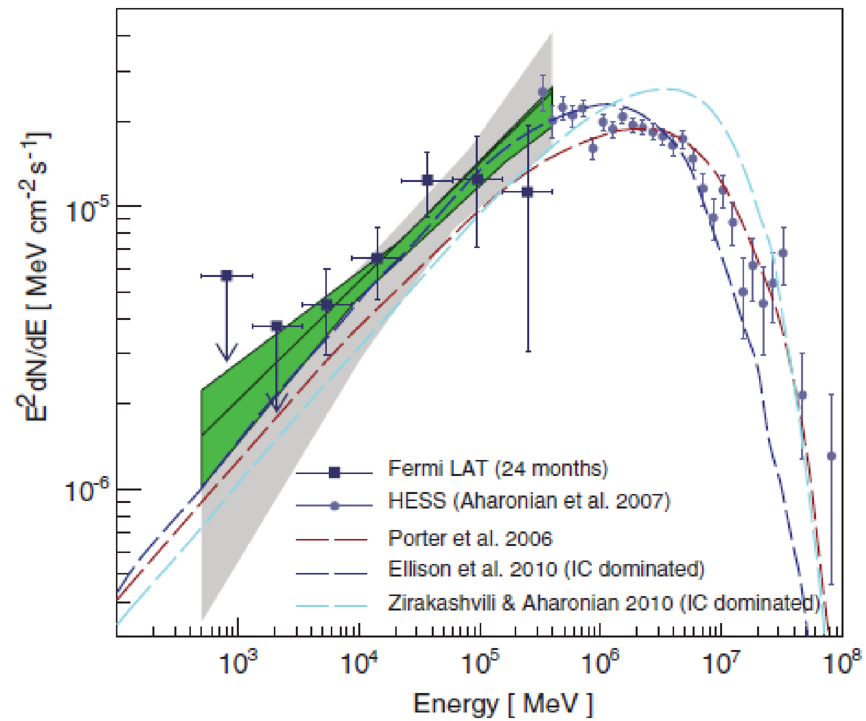
This would seem to underline that everything is solved and every question answered...BUT...



...but

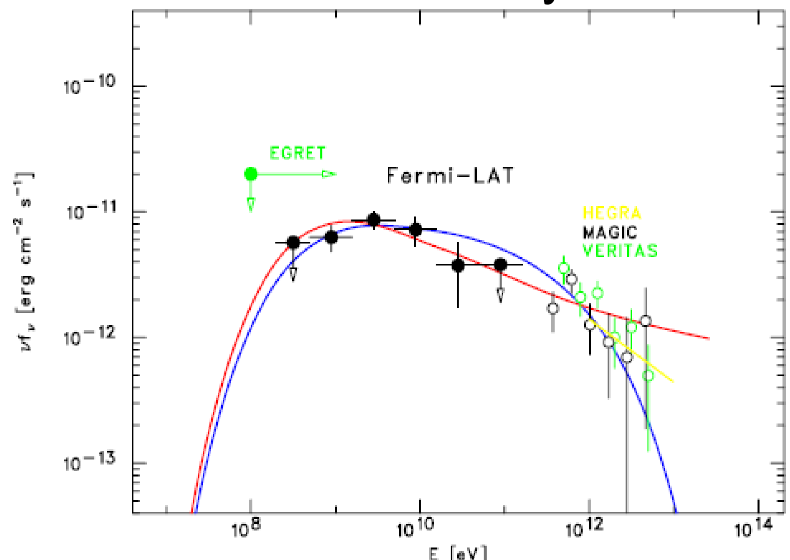
Some shell-type SNRs seem leptonic..
E.g. RX J1713.7-3946 , one of the most promising targets and moreover one of the best threated by theoretical models...





...but (2)

And also among the one that look more likely hadronic (in most of the LAT SNRs, hadronic models are favored..but leptonic ones cannot be fully discarded so far..)
E.g. Cassiopeia A.



Proton power law $Q_p = Q_0\, p^{-2,3}$
with total energy $W_p = \int_{10\ \mathrm{MeV}} Q_p\, p\, dp = 4 \times 10^{40}$ erg/s

Note that this would correspond to ~2% of the SNR kinetic energy.
(for more details O. Tibolla et al., arXiv:1109.3144)

…the question is still open...

Other possibilities...

In order to close possible gaps, people search for other possibilities... Looking the high energy sky (i.e. the “non-thermal sky”), the dominant population is not represented by shell-type SNRs...
Among the known sources, **Pulsar Wind Nebulae (PWNe)** is the most numerous. And indeed it was proposed that at the termination shock of the Pulsar Wind, also hadrons could be accelerated as well as leptons (e.g. Bednarek & Protheroe 1997, PRL, 79, 2616 ; Atoyan & Aharonian 1996, MNRAS, 278, 525 ; Cheng et al. 1990, J. Phys. G, 16, 1115 ; Bednarek & Bartosik 2003, A&A, 405, 689).

But the most numerous population in absolute terms is represented by **Unidentified sources**. In fact almost 50% of the TeV Galactic sources are still unidentified; at GeV energies, 67% of EGRET sources were unidentified and also with the newer generation of gamma-ray satellites we have the same result: in fact, at low Galactic latitudes ($b < 10$ deg), 62% of the Fermi LAT detected sources have no formal counterpart.
Hence understanding the high energy unidentified sources could be a crucial brick in solving the whole riddle of Cosmic Rays origin. And the correlation with PWNe could be very close, at least for the so called “dark sources”.

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- H.E.S.S. Survey and Galactic unidentified sources

- Examples, Newly discovered sources:
    - HESS J1507-622
      + ancient PWN
    - ~~HESS J1741-302~~

- Conclusions

(+ ~100 backup slides)

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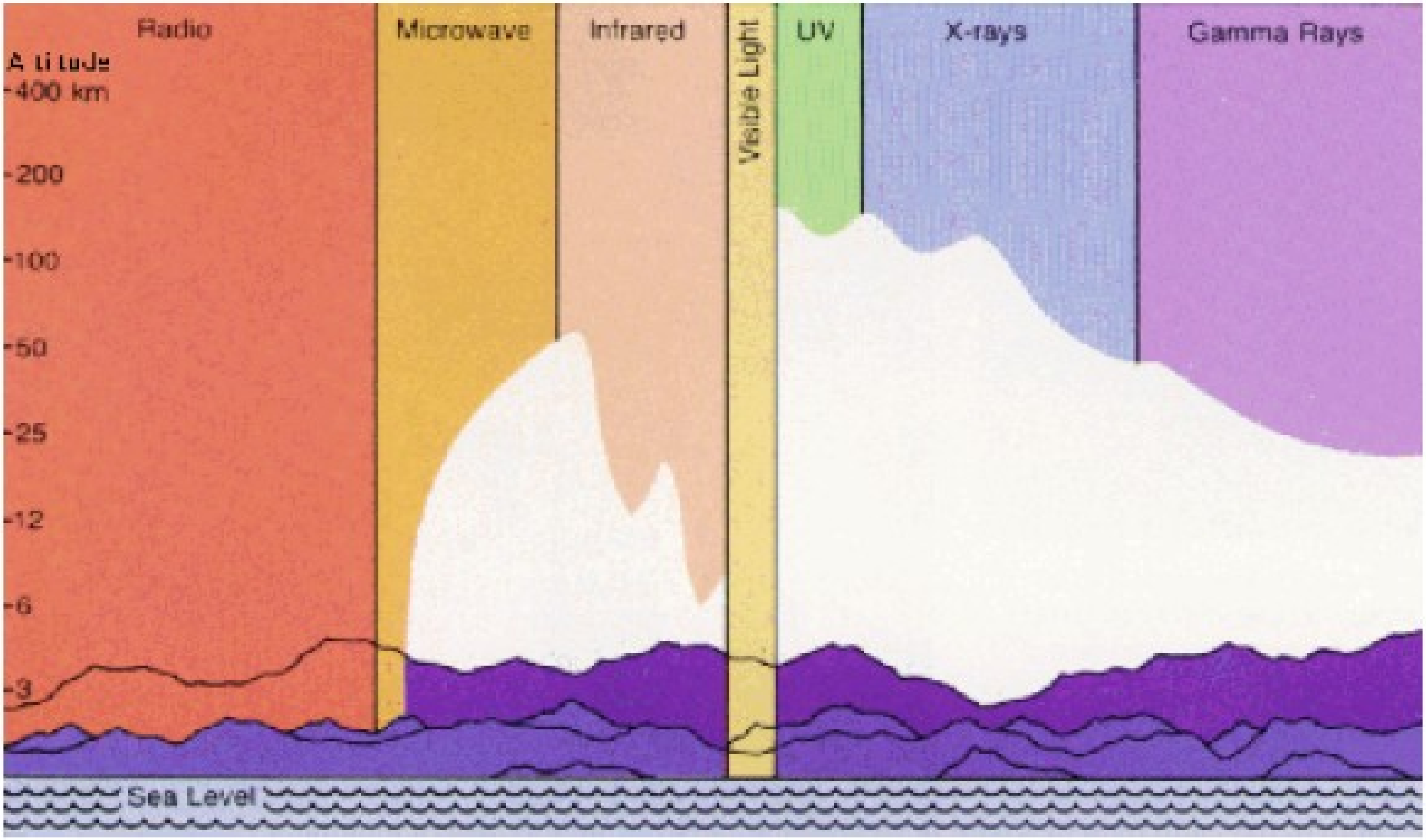
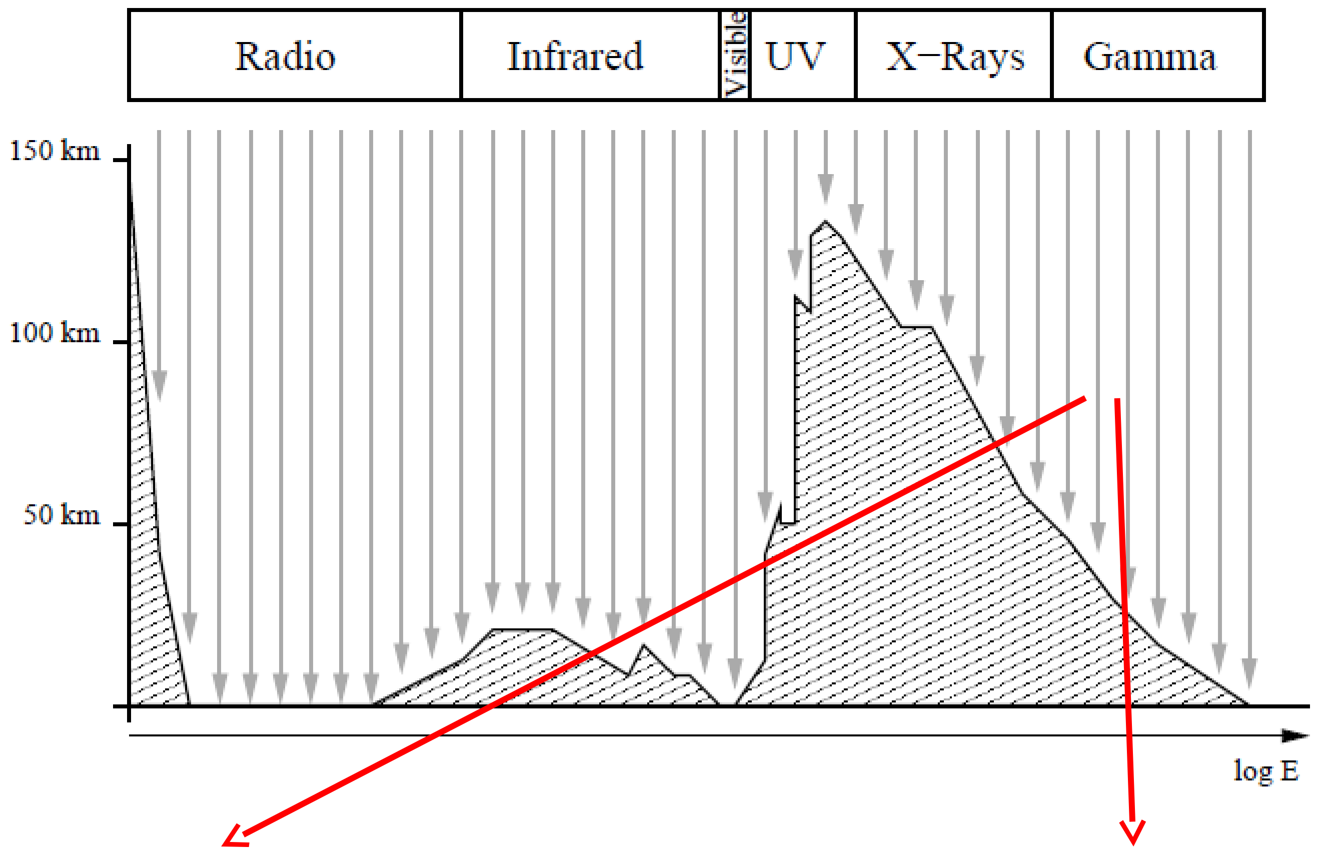
Gamma Ray Astronomy. How??



E.g. IR are stopped by CO_2 and H_20, UV are stopped by O_3, O_2, N_3, and so on…

So…



Either we go outside…
SATELLITES

…or we use our atmosphere as detector
CHERENKOV TELESCOPES

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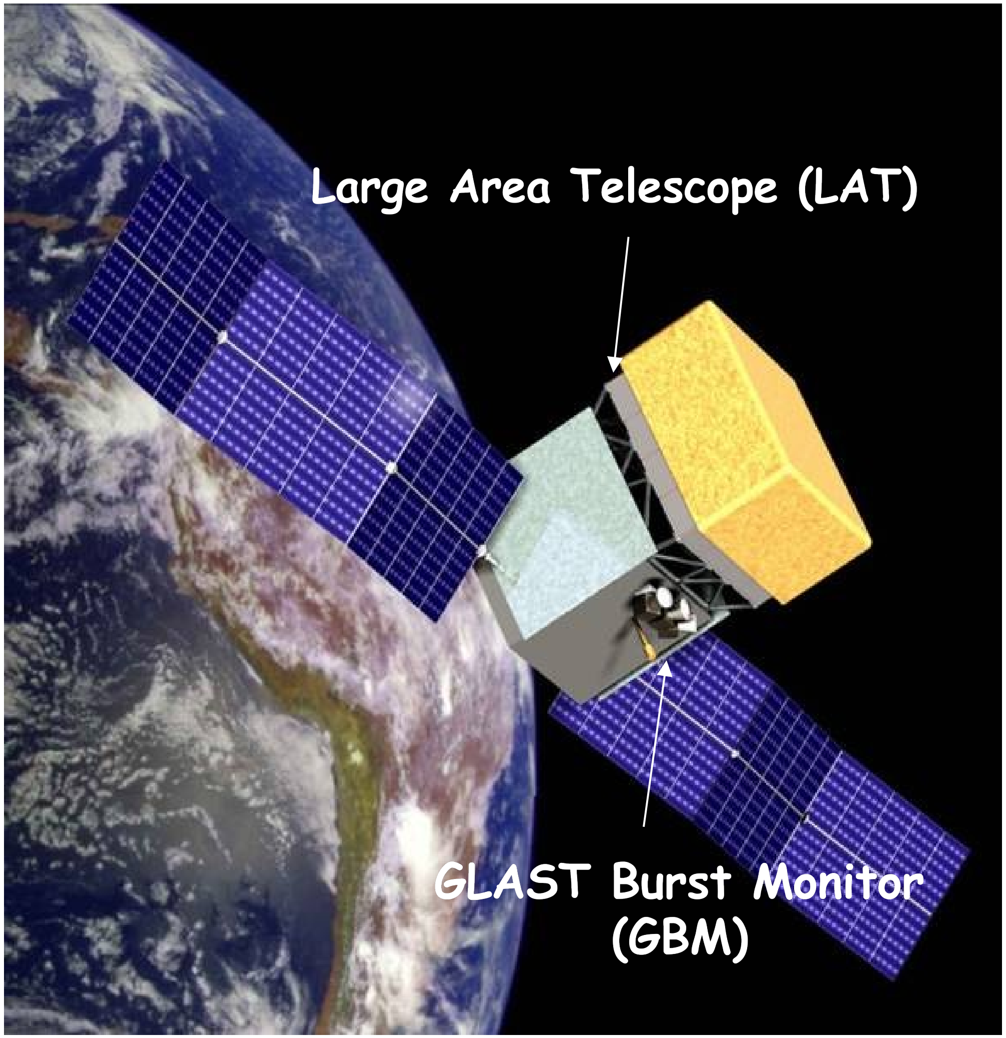
Example: Fermi



Gamma-ray Large Area Space Telescope

-France
-Germany
-Italy
-Japan
-Sweden
-USA

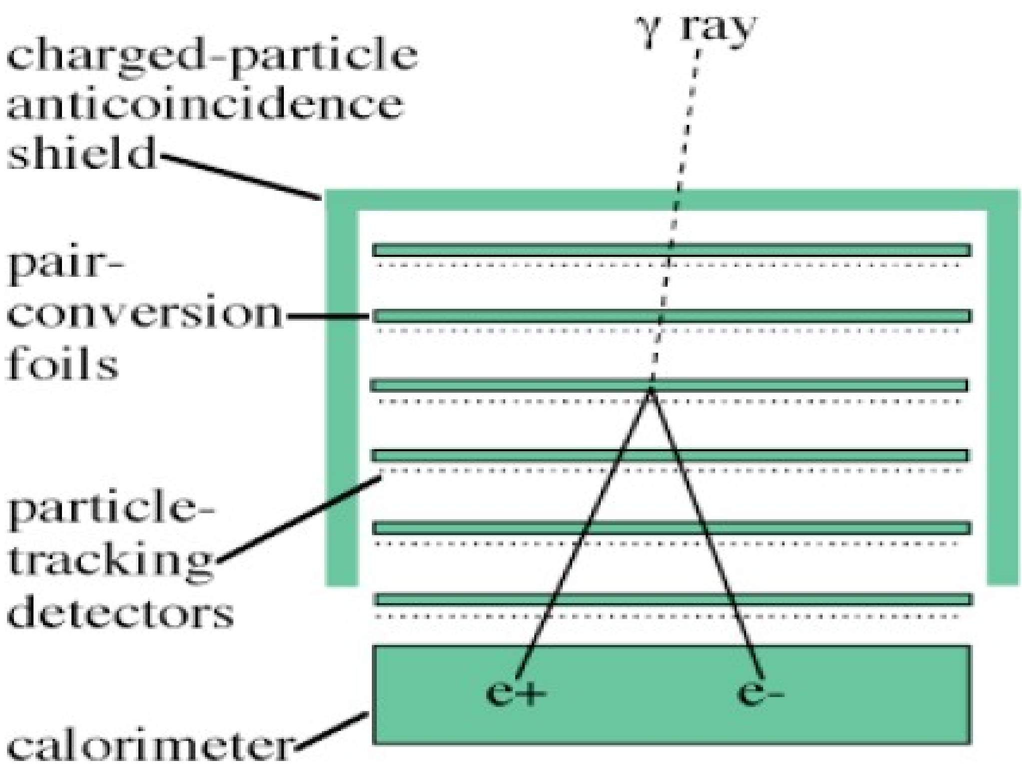
Energy Range 10 keV-300 GeV.

- Imaging gamma-ray telescope (**LAT**)

- a second instrument to study Gamma Ray Bursts (**GBM**).

Detection principle

Pair conversion telescope



Fermi-LAT

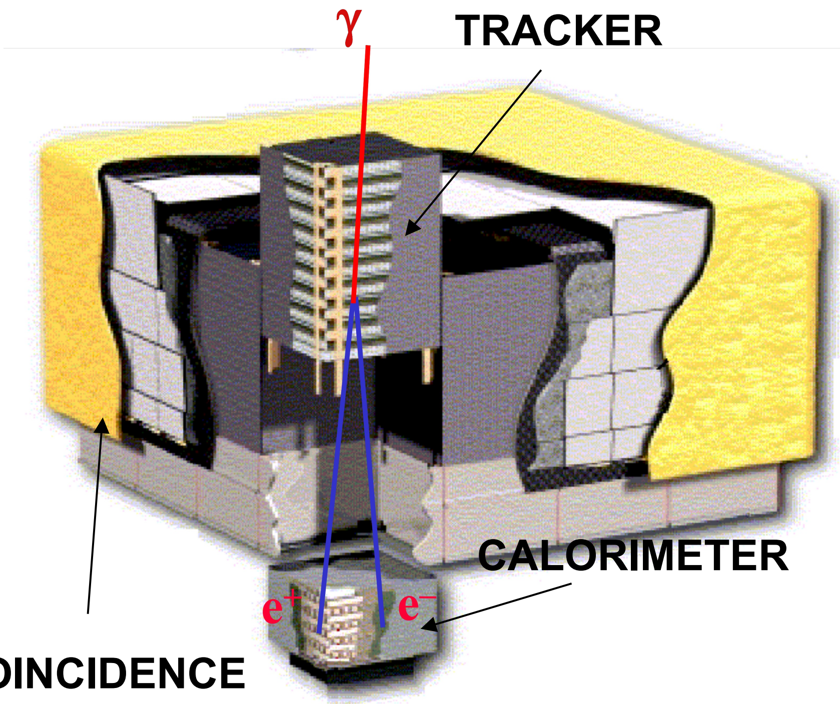
The main instrument is the **Large Area Telescope** (**LAT**): pair conversion telescope

Anticoincidence Shield (**ACD**) made of plastic scintillator (Bicron-408) sensitive to charged; ACD is segmented in order to avoid the self veto from Calorimeter backsplash, that caused 50% of loss in Aeff in EGRET, and also for micrometeorites.

ACD contains 16 towers and each tower is divided in 2 parts:

- the **TRACKER** (**TKR**): 18 layers in each tower
  - Tungsten converter (1.08 χ_0)
  - 2 SSD ortogonal of Silicon microstrips di Silicio to detect electromagnetic "shower".

- the **CALORIMETER** (**CAL**): CsI cristals dopped by Tallium; so the energy deposited by the EM shower is converted in light signal.



Why Cherenkov Telescopes?

What are the advantages of using IACTs instead of satellites?

Advantages:

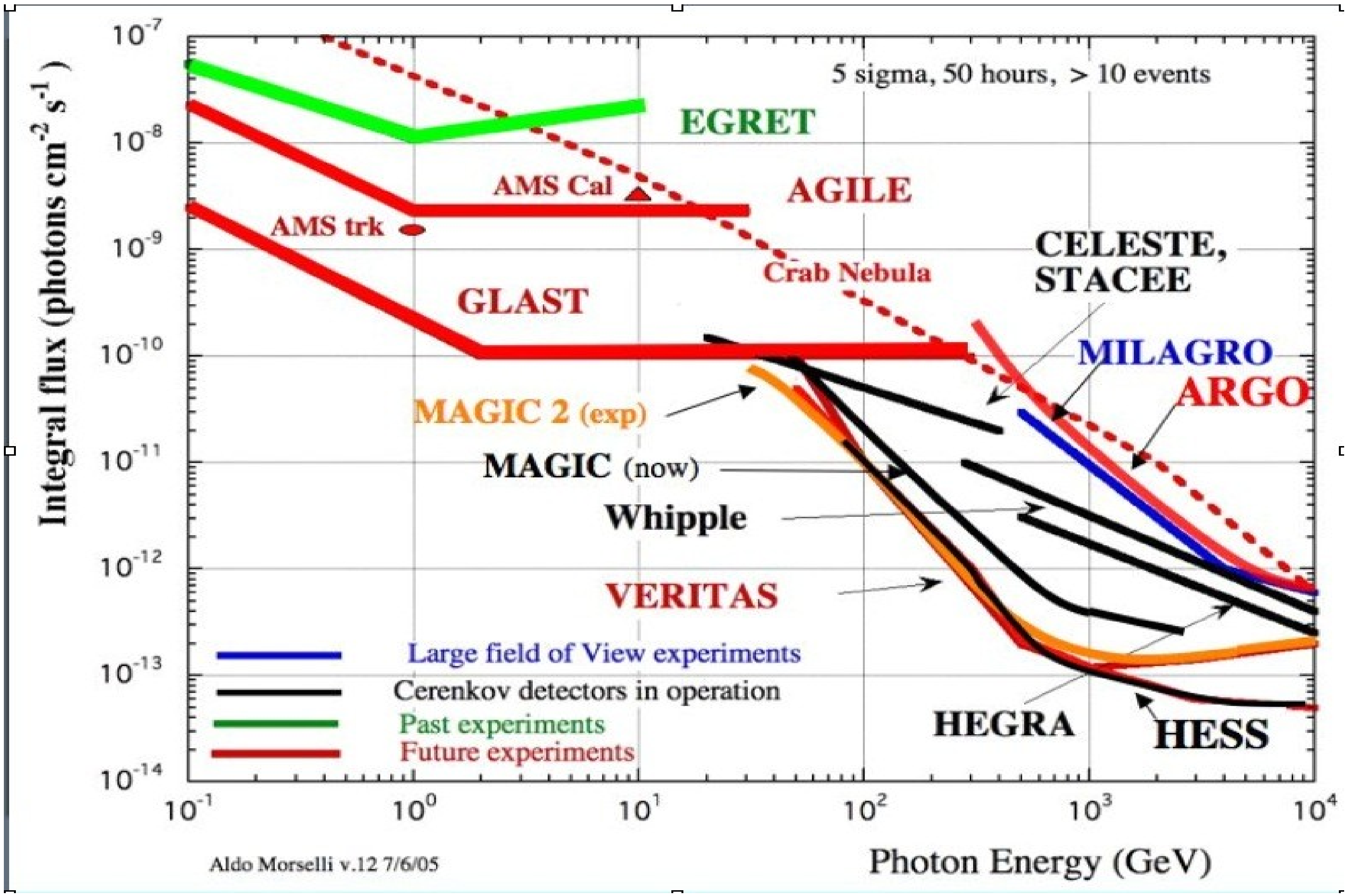
- provides a large detection area (needed at VHE energies)
- good sensitivity
- you could achieve quite large field of view
- good angular resolution
- good energy reconstruction
- built from proven technology

Disadvantages:

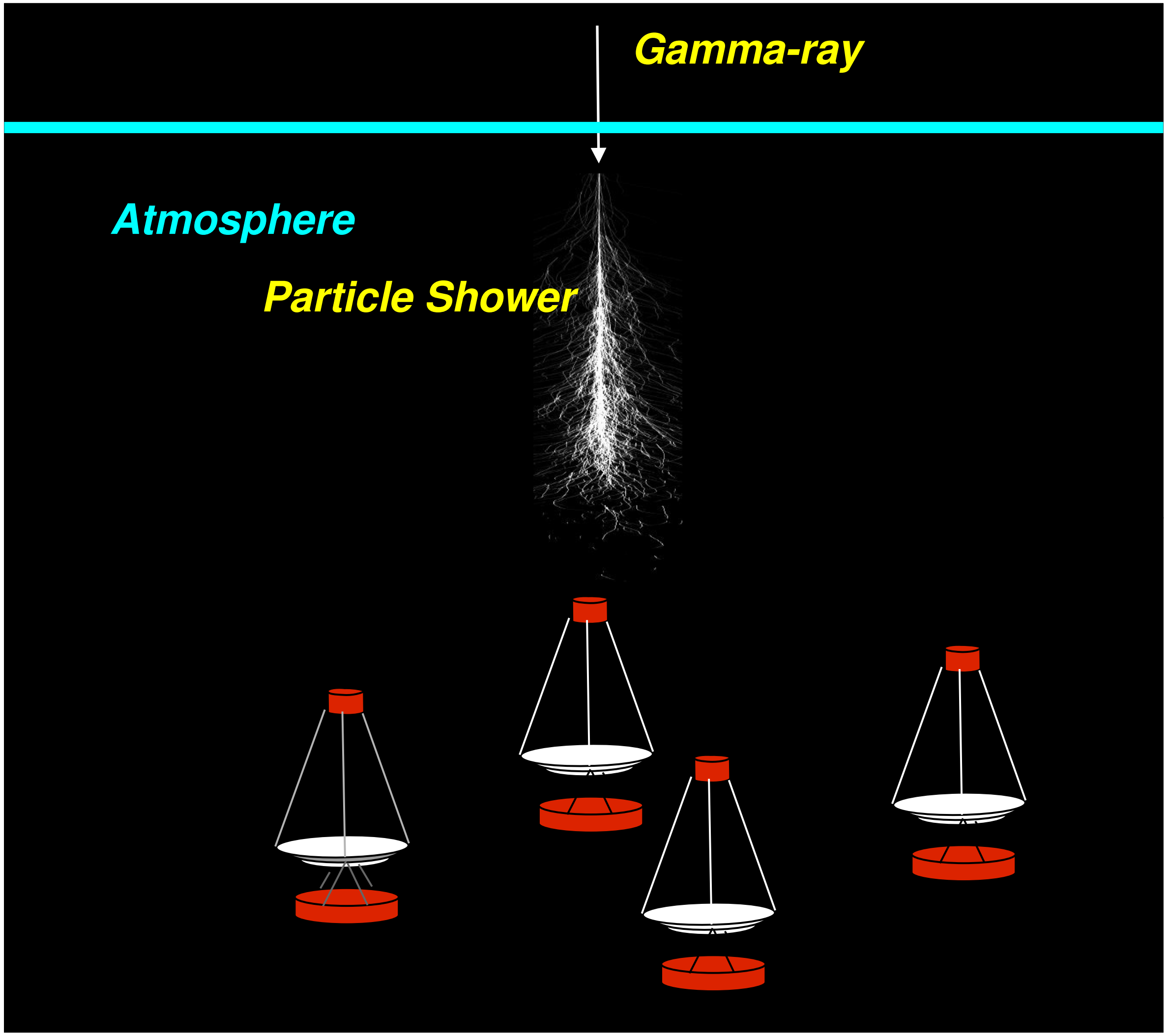
- indirect approach
- large background
- limited duty cycle
- small field of view (if compared to satellites)

Why Cherenkov Telescopes? (2)

IACTs and satellites are complementary:



Detection principle



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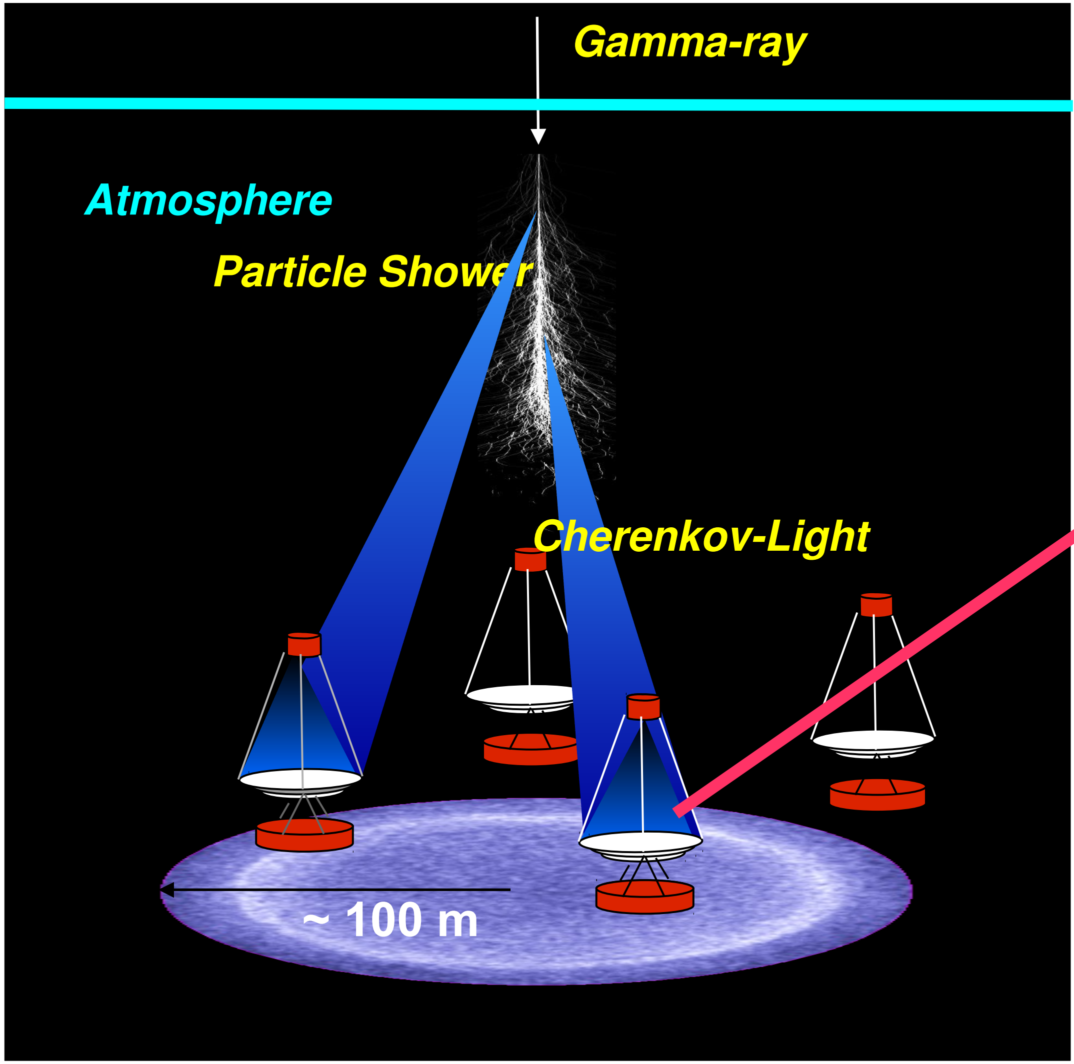
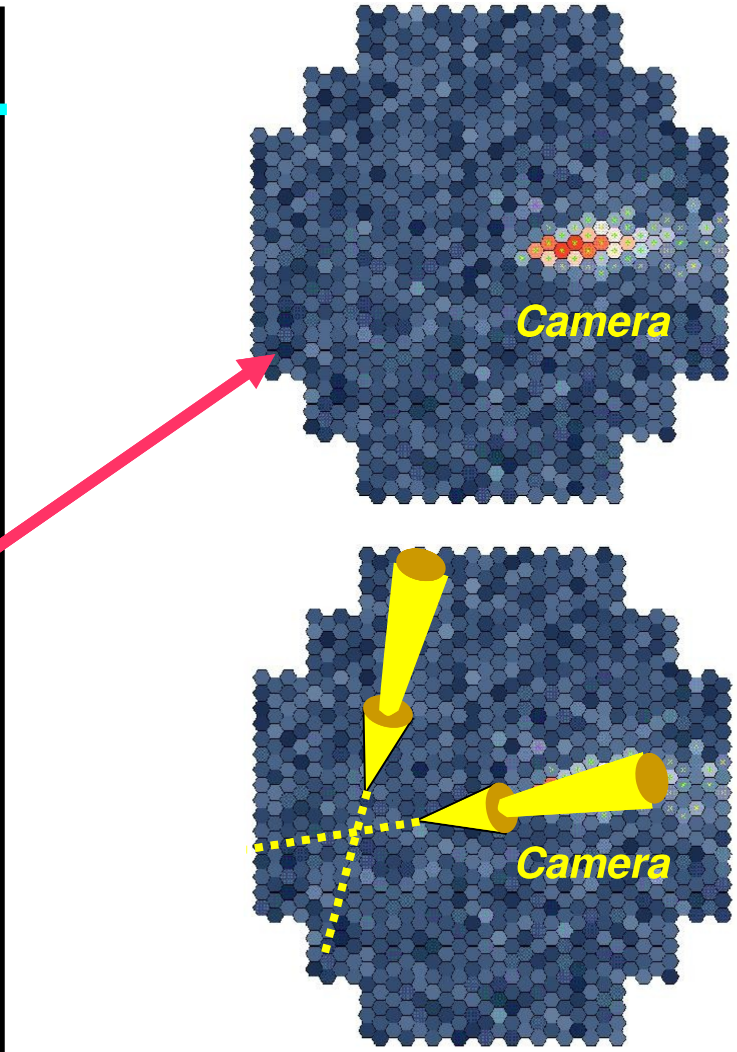
Detection principle: stereo approach





Detection principles

The approach described here is the so called "stereo approach", used by H.E.S.S. (and by VERITAS), and it has 2 important advantages:

- an easy and precise direction reconstruction.
- an improved background rejection (especially for muons)

However there is another approach (used by MAGIC) in which the collecting area is much bigger, in order to have much lower energy thresholds.

In order to have the advantages of both methods:

MAGIC → MAGIC II
H.E.S.S. → H.E.S.S. II

(if you are interested, I have a lot of backup slides on H.E.S.S. and on MAGIC)

...and the next step for both collaborations (together with other experiments, such as FACT and ASTRI) is the:

Cherenkov Telescope Array (CTA).

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ZOO!

- Examples, Newly discovered sources:
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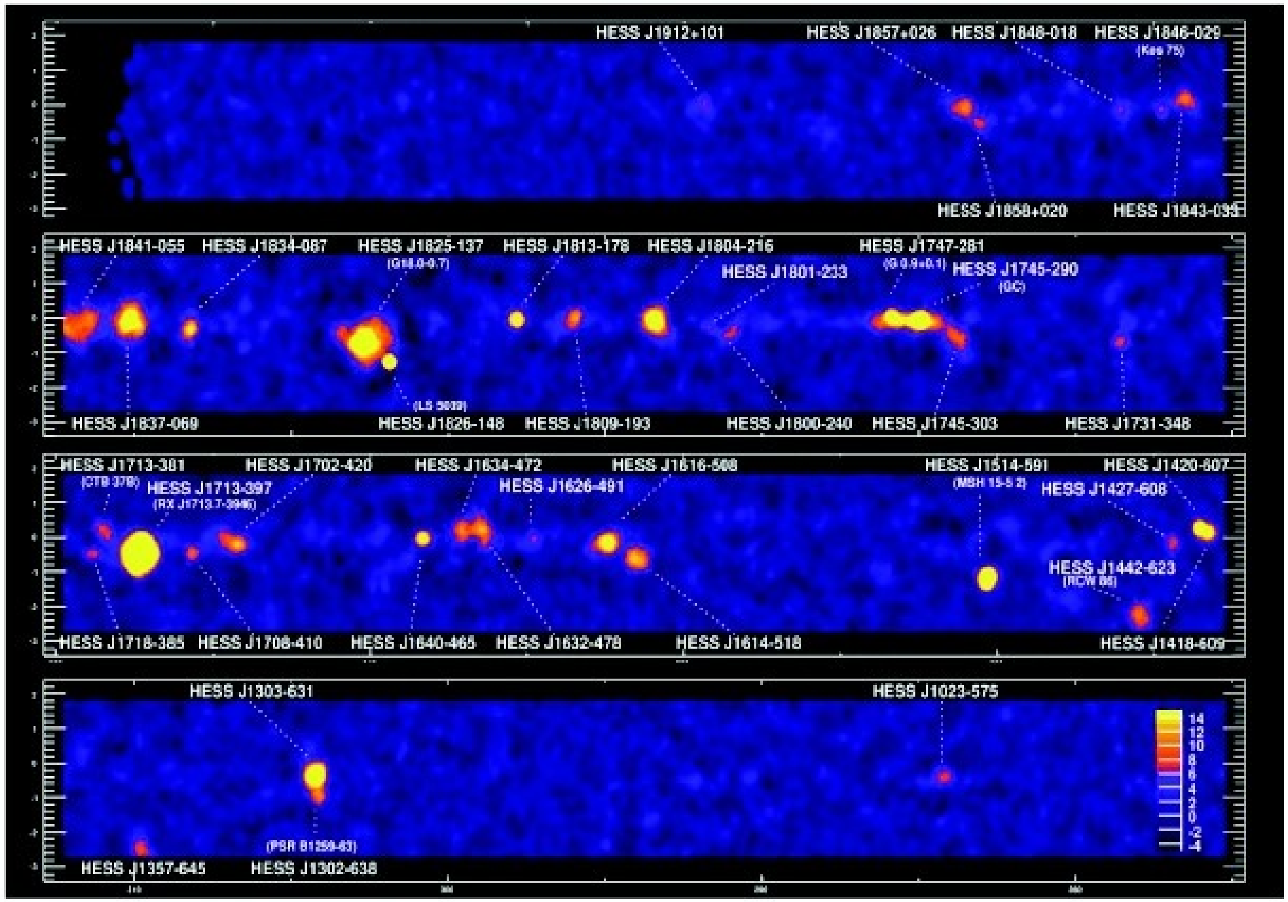
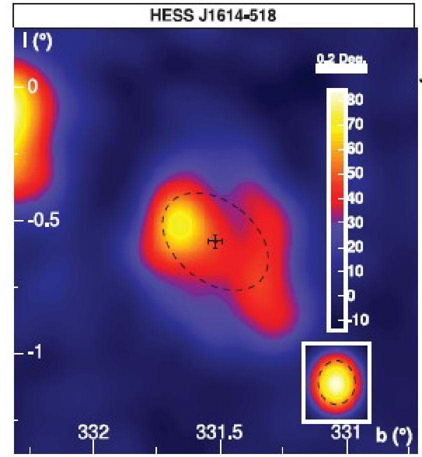
H.E.S.S. Survey

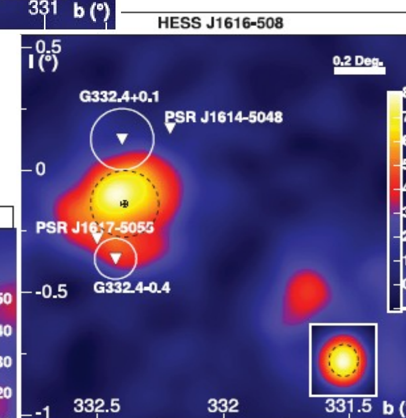


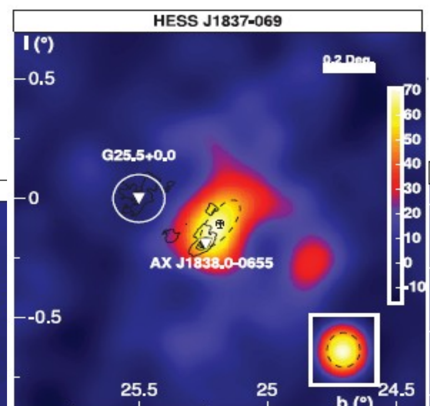
With the famous H.E.S.S. Survey (Aharonian et al., ApJ (2006) 636, 777-797) of 2004/2005, many new TeV gamma-ray sources have been discovered.

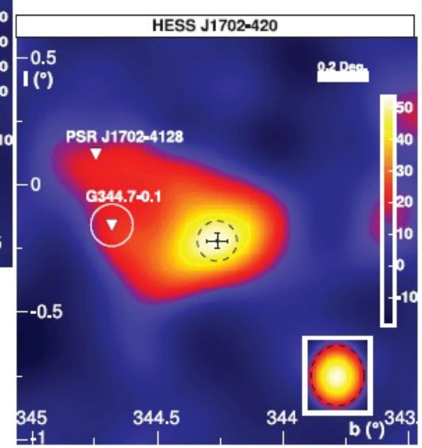
Unidentified sources in the GPS

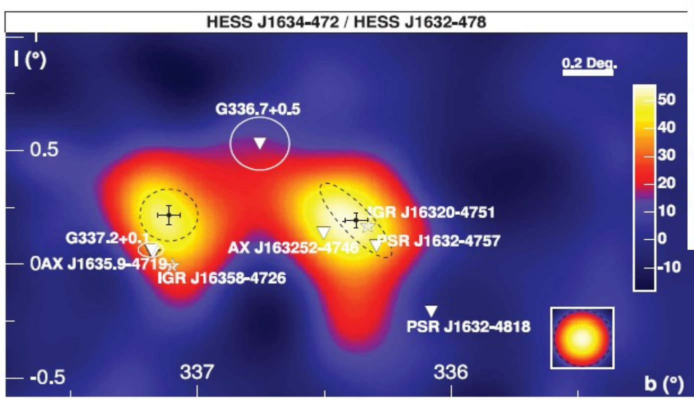
In the GPS many of the sources were unidentified:
HESS J1614-518
HESS J1616-508
HESS J1632-478
HESS J1634-472
HESS J1702-420 (discussed later)
HESS J1708-410 (discussed later)
HESS J1745-303 (discussed later)
HESS J1837-069











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H.E.S.S. Survey extension and VERITAS survey + HAWC

In the meaning while H.E.S.S., in 2006-2010, extended the successful VHE Galactic survey of 2004/2005, discovering a number of new sources, many of which are unidentified.
VERITAS in 2009/2010 started the scan of the northern part of the Galactic Plane.

In total (MAGIC + H.E.S.S. + VERITAS)

~100 Galactic sources discovered so far (and 40-50 extragalactic)

And additionally the "water Cherenkov technique" is reaching, with the HAWC (High Altitude Water Cherenkov) experiment, sensitivities comparable to IACTs ones (reaching higher energies)...
Water Cherenkov experiments have the advantage to be "full sky" experiments, so the number of sources is going to increase.

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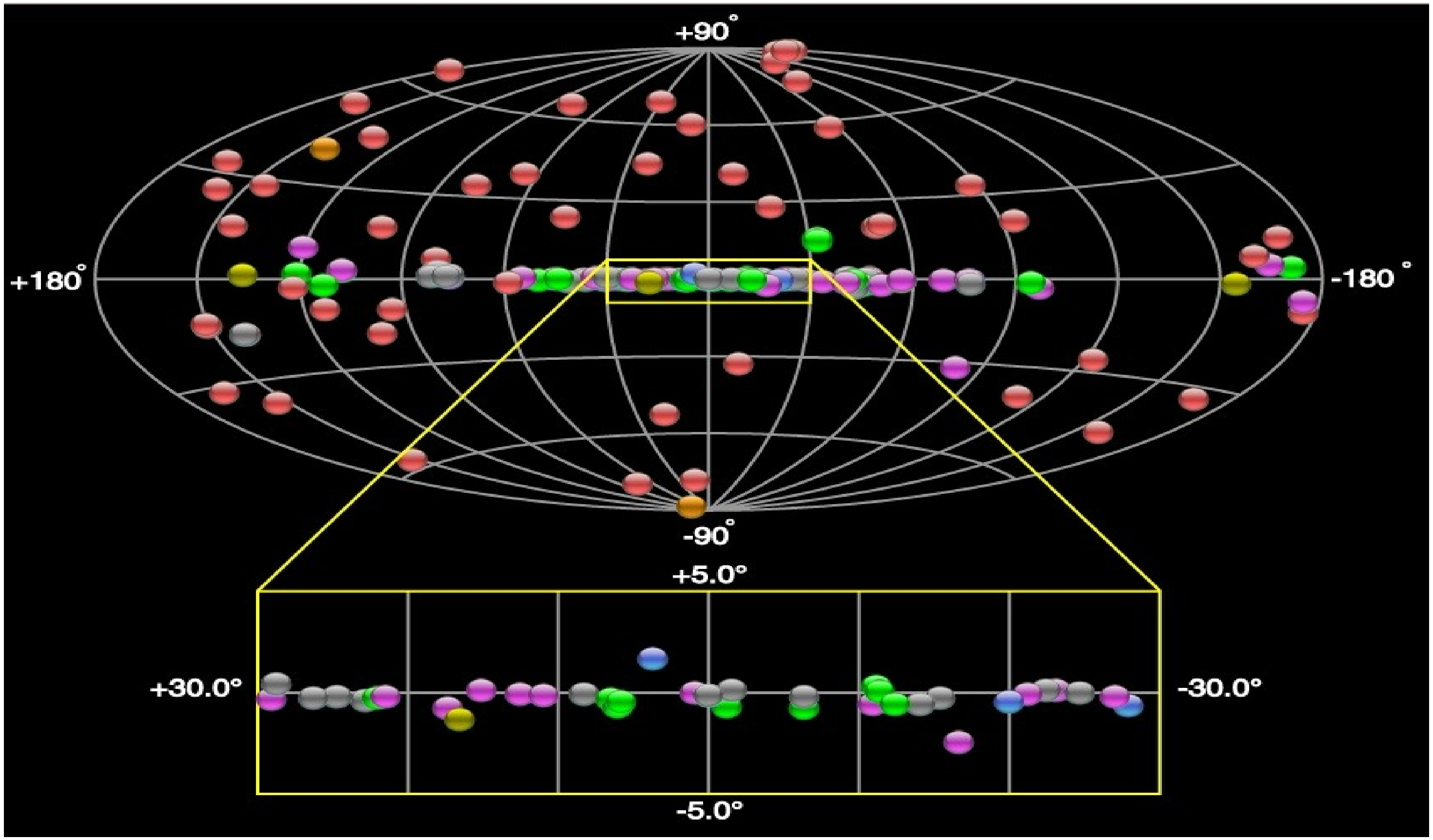
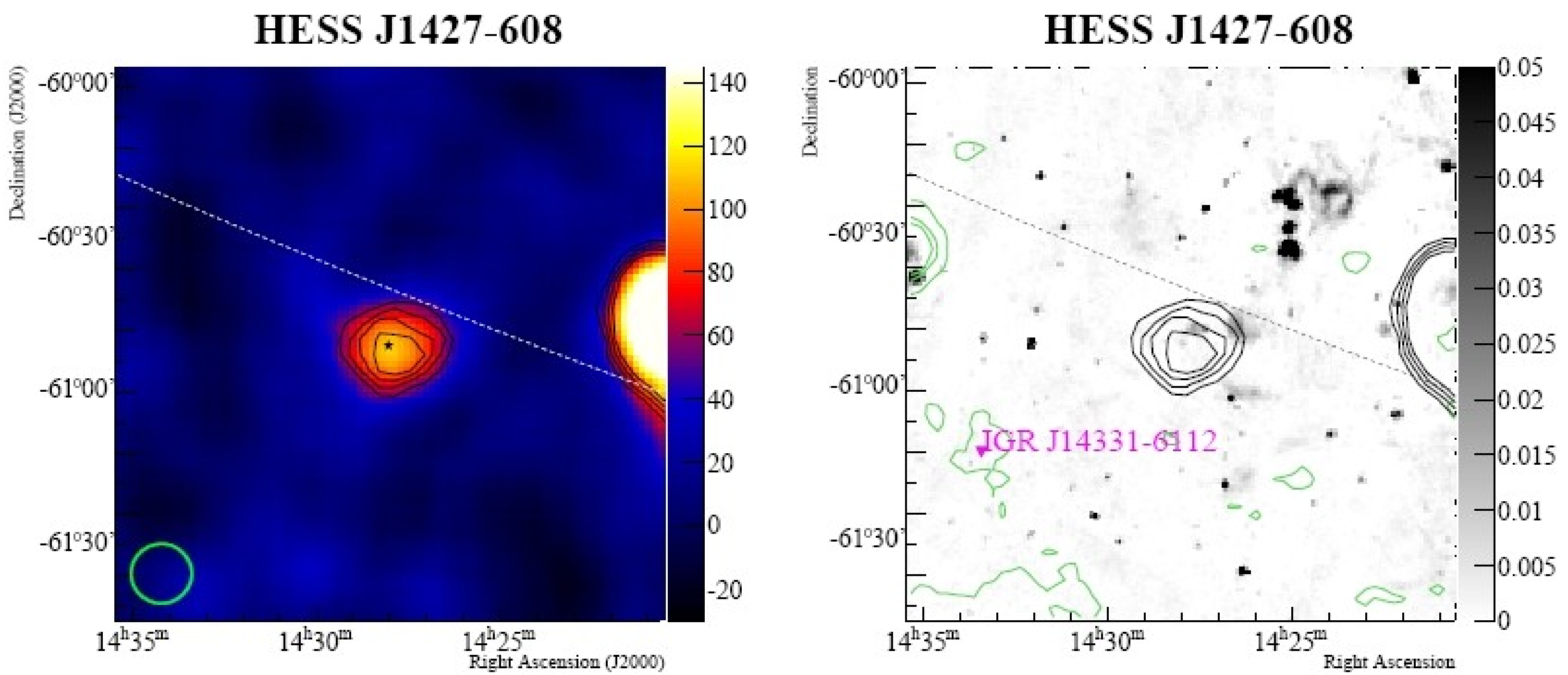
How many sources are unidentified?



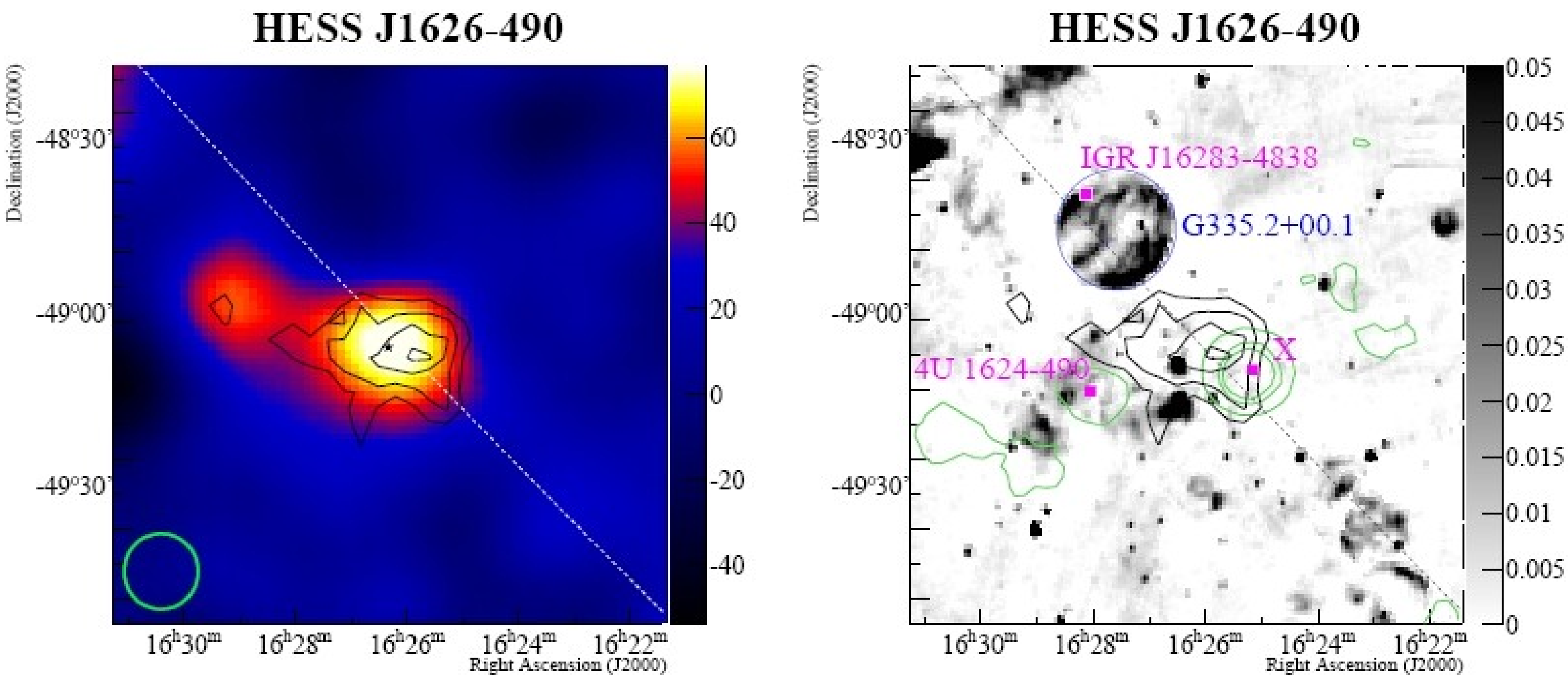
~50% of the H.E.S.S. sources are still unidentified...
(e.g. *Tam, Wagner, Tibolla and Chaves, A&A, 518, id.A8 (2010)*, even if GeV-TeV...)

HESS J1427-608



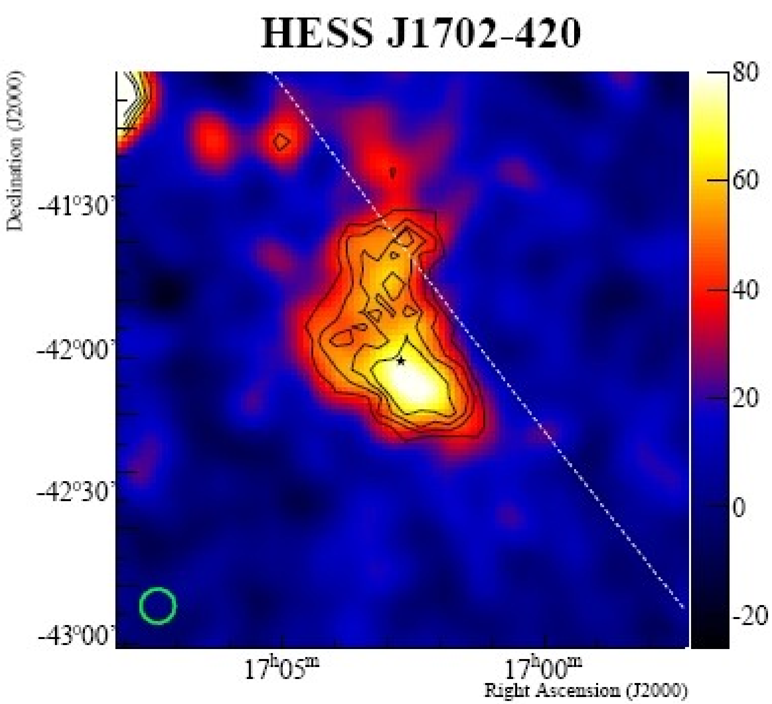
1° away from G313.2+0.3(hard X-ray and GeV γ-ray source in the Kookaburra region).
5.6 σ in 21 hours of observation.
Spectrum fits well with a PL with index ~2.2.
In the right panel Radio (Molonglo survey) data and X-ray (RASS) contours in green.

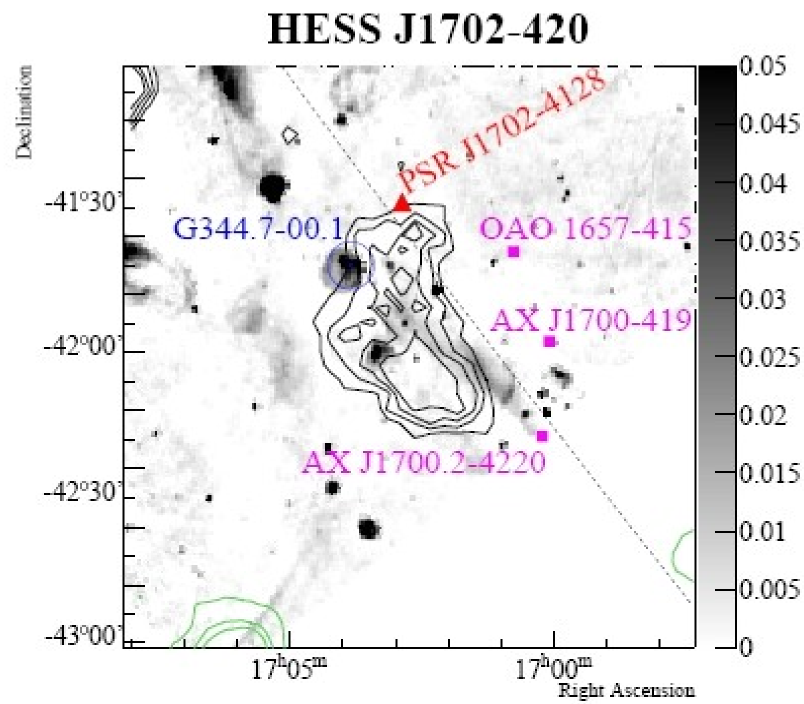
HESS J1626-490



6 σ in 8 hours of observation.
Spectrum fits well with a PL with index ~2.2.
Labeled with an "X" in the right panel, the unidentified X-ray source ***1RXS J162504-490918***, possible counterpart.

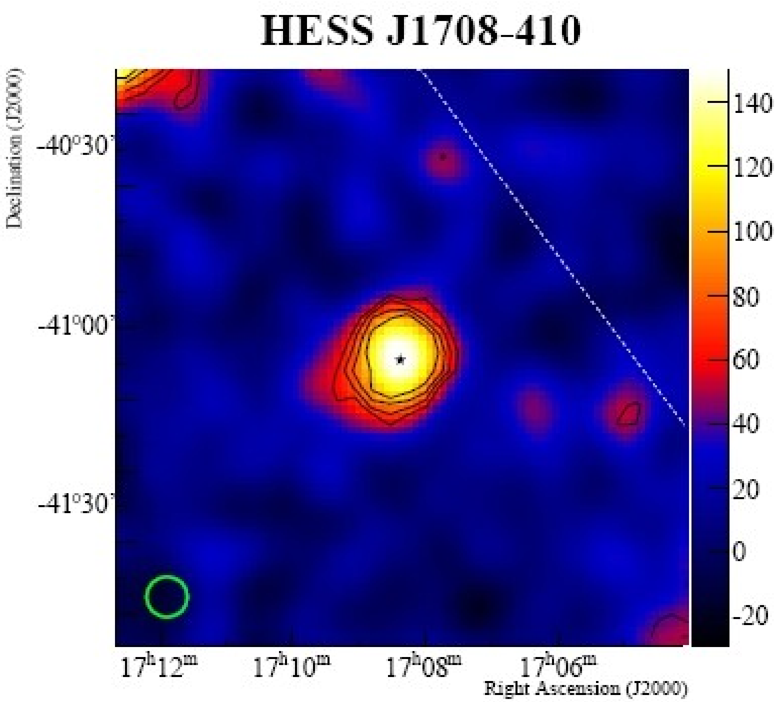
HESS J1702-420

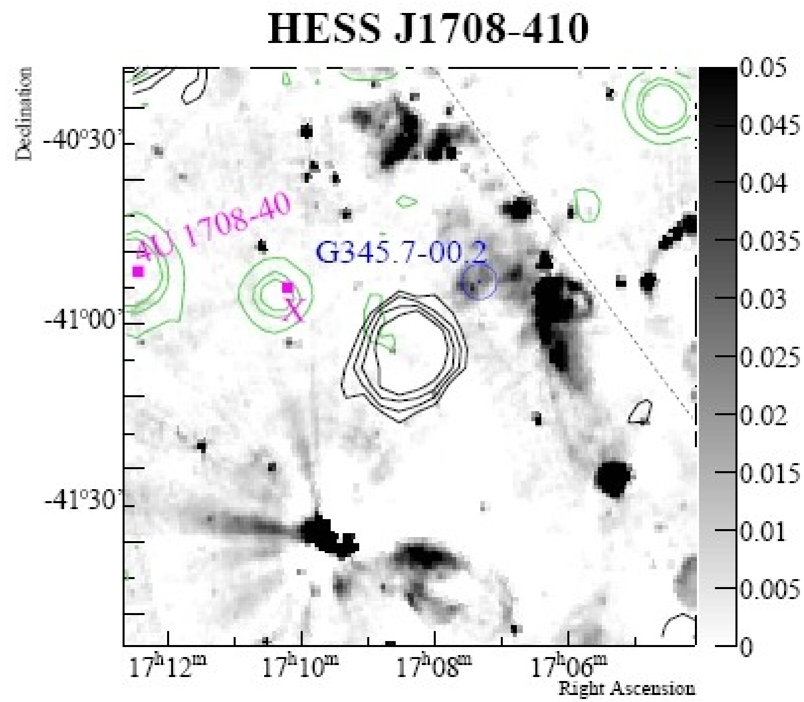




10.6 σ in 7 hours of observation.
Spectrum fits well with a PL with index ~2.1.
PSR J1702-4128 (spin-down luminosity $1.3 \cdot 10^{34}$ erg/s kpc^2) provides enough spin-down energy loss to produce the observed emission. Offset PWN?
There are also a SNR (small in angular size and distant) and 3 XRB.

HESS J1708-410





10.3 σ in 45 hours of observation.
Spectrum fits well with a PL with index ~2.5.
In the FoV: 1RXS J171011.5-405356, the SNR G345.7-00.2 and the XRB 4U 1708-40; no plausible counterparts.

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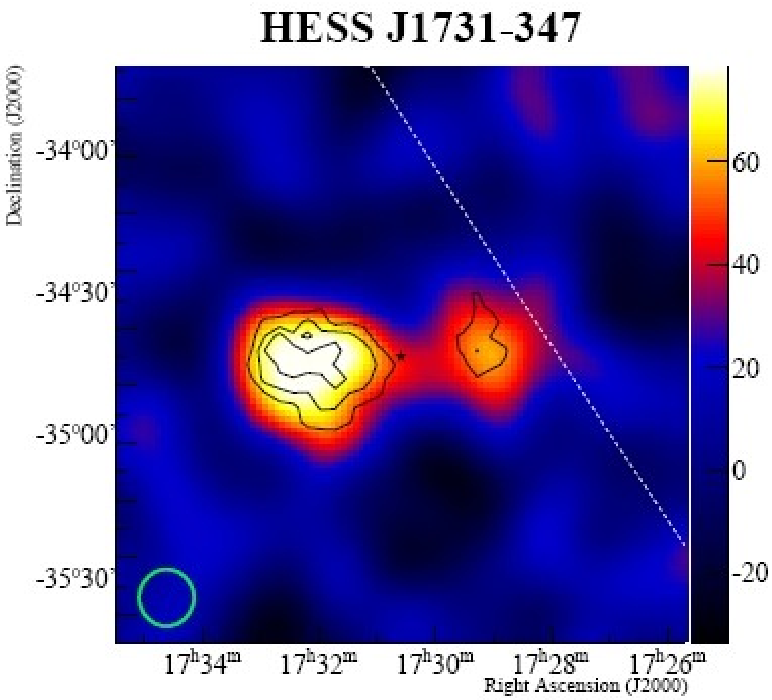
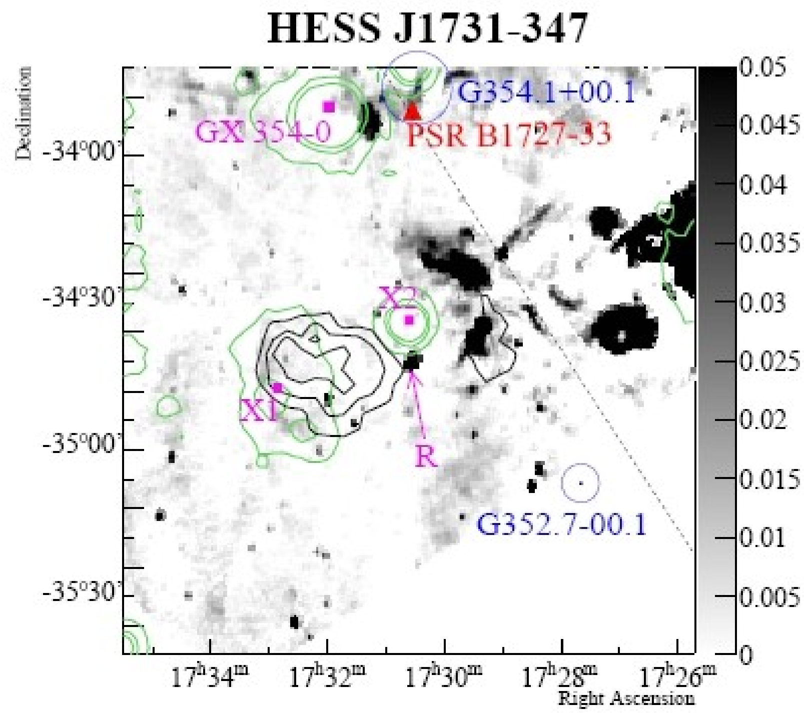
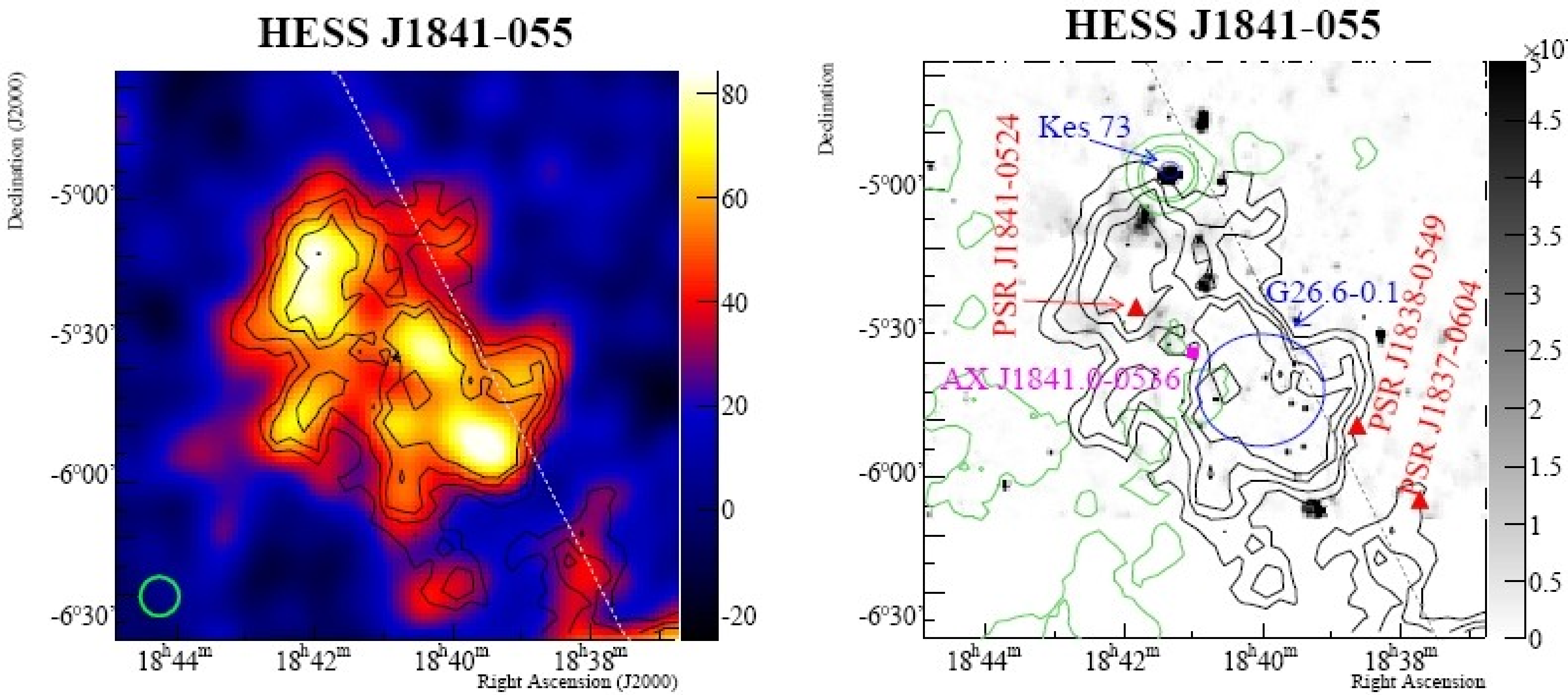
HESS J1731-347





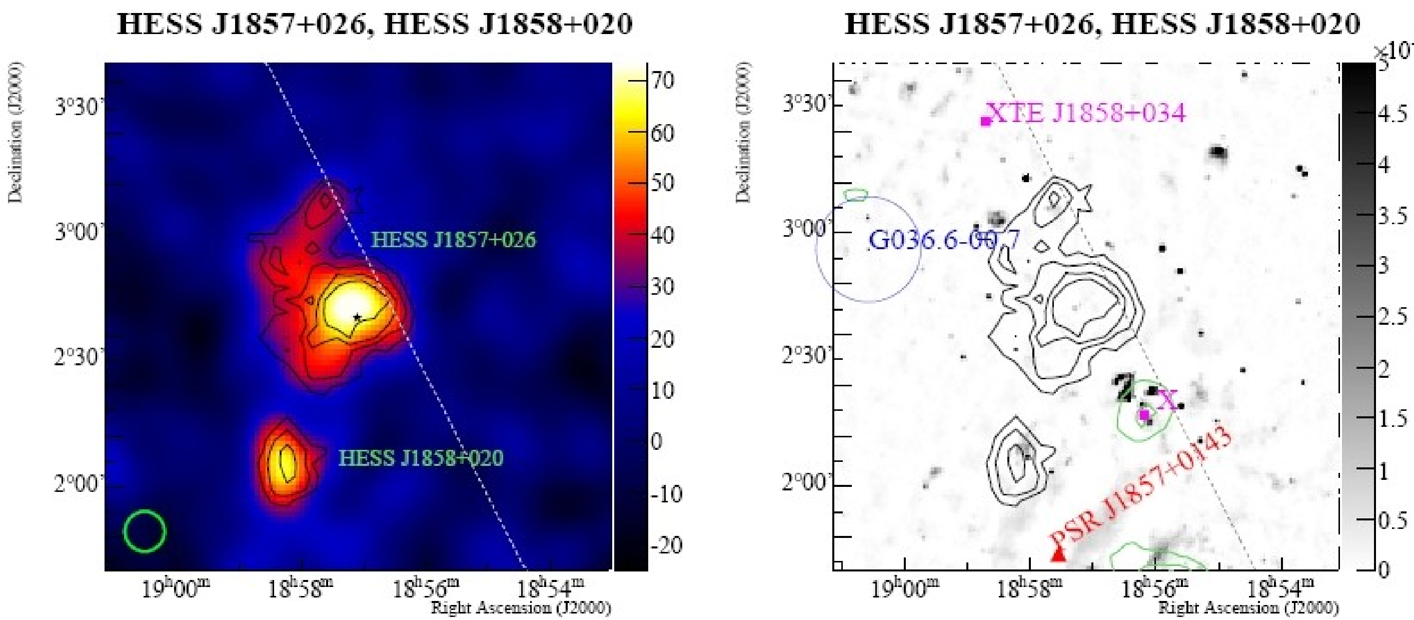
8.3 σ in 11 hours of observation.
Spectrum fits well with a PL with index ~2.3.
X1 is 1RXS J173251.1-344728, R is the radio point source 173028-344144 and X2 is the bright 1RXS J173030.3-343219.
HESS J1731-347 is the first SNR discovery triggered by TeV gamma-rays obs.

HESS J1841-055



10.7 σ in 10 hours of observation.
Spectrum fits well with a PL with index ~2.4.
2 SNRs: Kes 73 (G027.4+00.0) and G26.6-0.1; 3 Pulsars: PSR J1841-0524 (spin-down luminosity $4.4 \cdot 10^{33}$ erg/s kpc^2), PSR J1838-0549 (spin-down luminosity $4.7 \cdot 10^{33}$ erg/s kpc^2) and PSR J1837-0604 (spin-down luminosity $5.2 \cdot 10^{34}$ erg/s kpc^2); and AX J1841.0-0586 (a possible XRB).

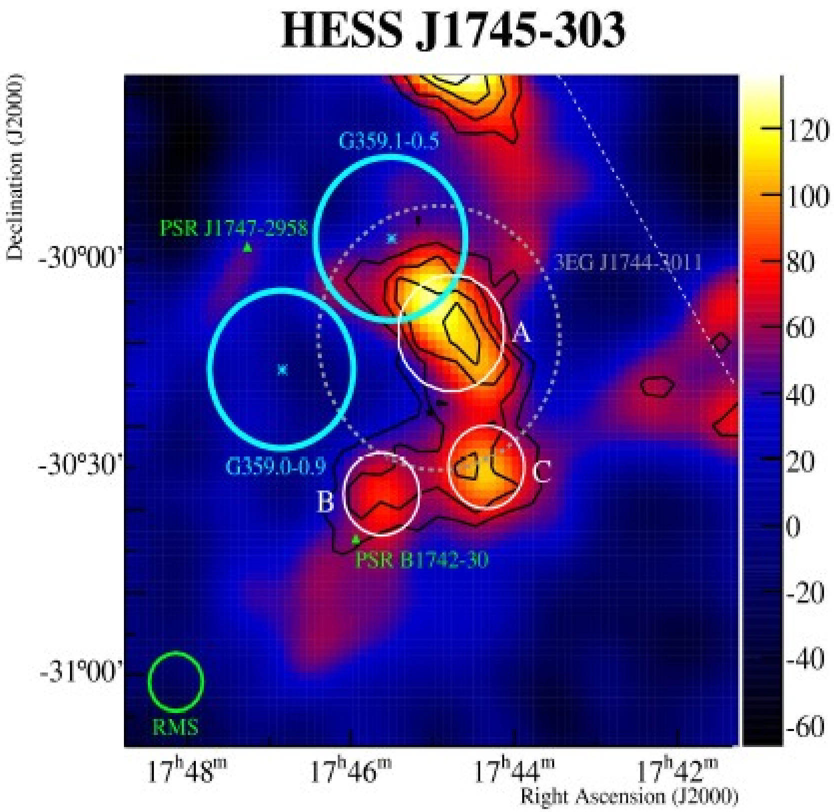
HESS J1857+026 and HESS J1858+020



HESS J1857+026 (recently an identification with a PWN has been proposed):
10.2 σ in 15 hours of observation.
Spectrum fits well with a PL with index ~2.4.

HESS J1858+020 (recently an identification with a SNR has been proposed):
7.4 σ in 23 hours of observation.
Spectrum fits well with a PL with index ~2.2.
(X is 1RXS J185608+0218)

HESS J1745-303 (Galactic Center region)

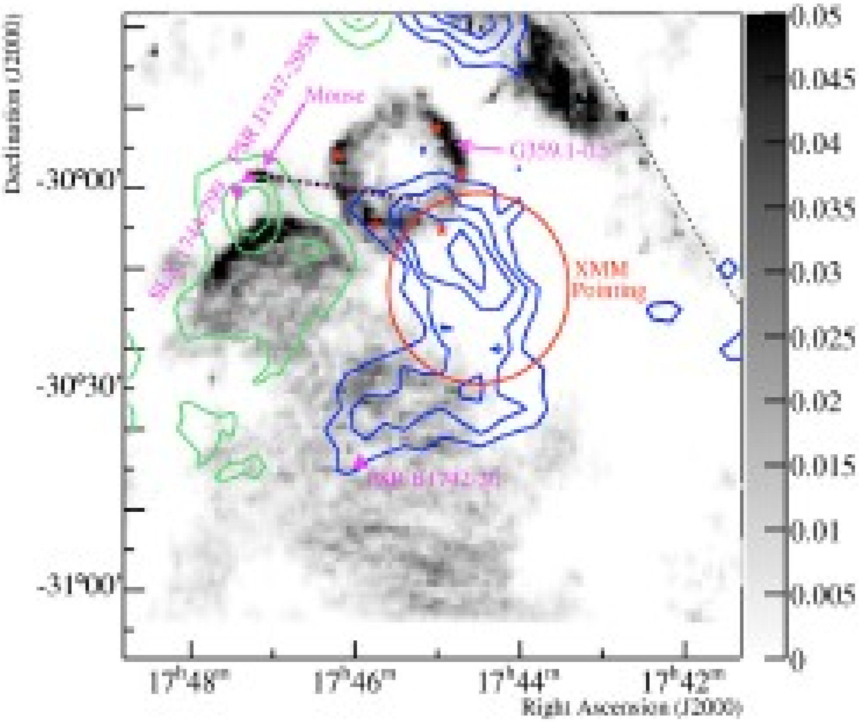


Newer observation has been performed on HESS J1745-303 and the results are published in F.Aharonian et al. *A&A, 483 (2008) 509*.

HESS J1745-303 is rather bright (12 σ in 79 hours of observation) and shows a complex morphology: it can be divided in 3 parts that show a slightly different spectral behavior:

- The spectral index for the full source is ~2.7;
- for part A is ~2.7
- for part B is ~2.9
- for part C is ~2.9

What is HESS J1745-303?



Radio (Monlonglo) and X-ray (ROSAT)

HESS J1745-303 is a very interesting TeV source, since it is one of the few TeV sources, spatially coincident with a source of the Third EGRET Catalog:
3EG 1744-3011.

The hot spot A seems to be correlated with the SNR G359.1-0.5 and Molecular Clouds (T.Dame et al. *ApJ, 547 (2001) 792*).

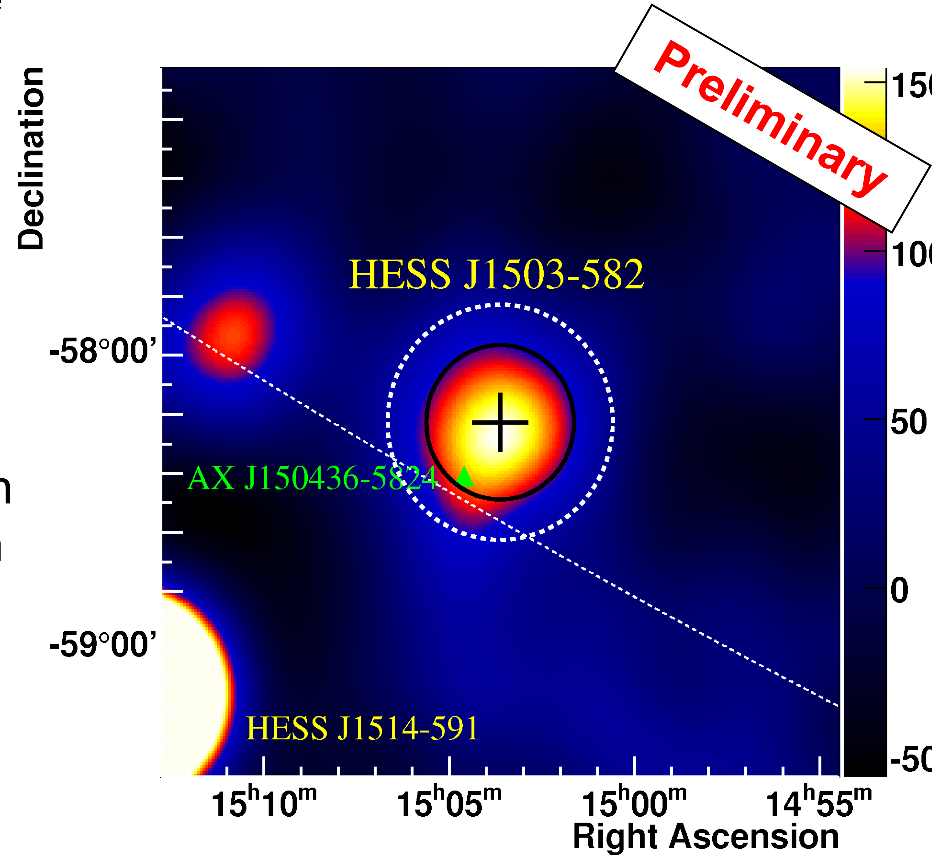
Other possible counterpart could be:
- PSR B1742-30
(spin-down luminosity $2 \cdot 10^{33}$ erg/s kpc^2)
- PSR J1747-2958
(spin-down luminosity $4 \cdot 10^{35}$ erg/s kpc^2)
- the ultra compact XRB SLX 1744-300.

HESS J1503-582

HESS J1503-582: it does not have any of the typical counterparts (SNRs, PWNe, etc.), but it appears to be associate with a FVW (HI 21cm lines structures visible at velocities that deviate from Galactic rotation curve. (dynamical phenomena? E.g. fast moving of HI shells and filaments associated with old SNRs)

HESS J1503-582 shows significance of 6 σ in 24 hours of effective exposure. The spectrum can be fit well by a power law with index Γ= $2.4 \pm 0.4_{stat} \pm 0.2_{syst}$ with a flux above 1 TeV of $6 \times 10^{-12}\,cm^{-2}\,s^{-1}$ (~6 % of the Crab flux).

Note: the FVW hypothesis seems to be in contradiction with more recent VERITAS observations (ICRC 2009).

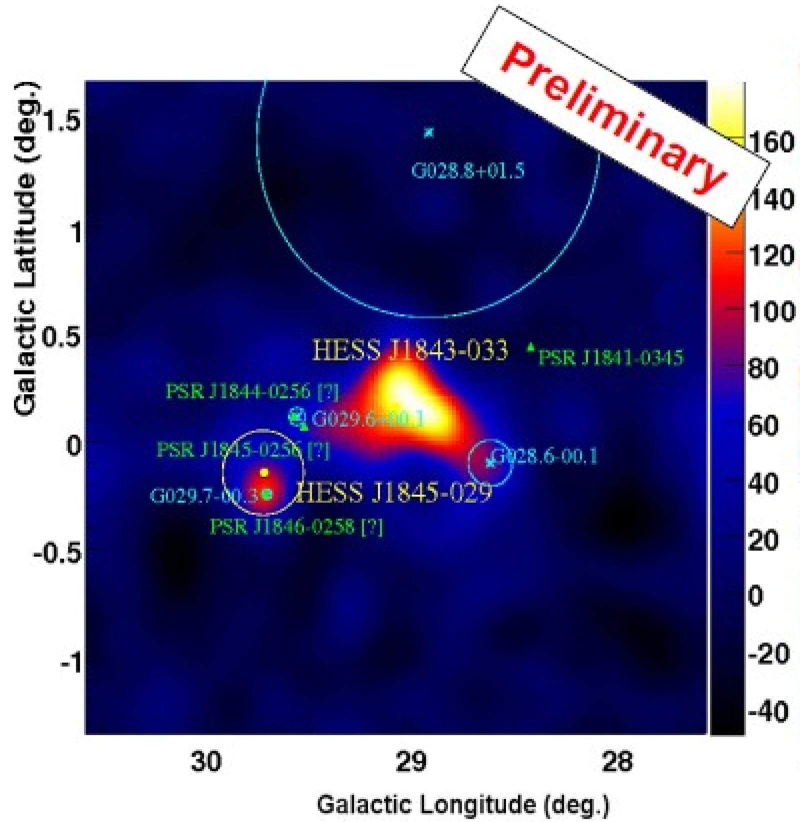


HESS J1843-033

HESS J1843-033 is one of the two brightest sources of the survey extension (9-10% of Crab)! Note: the map shown here is not updated (sorry, but the new results are not public yet).

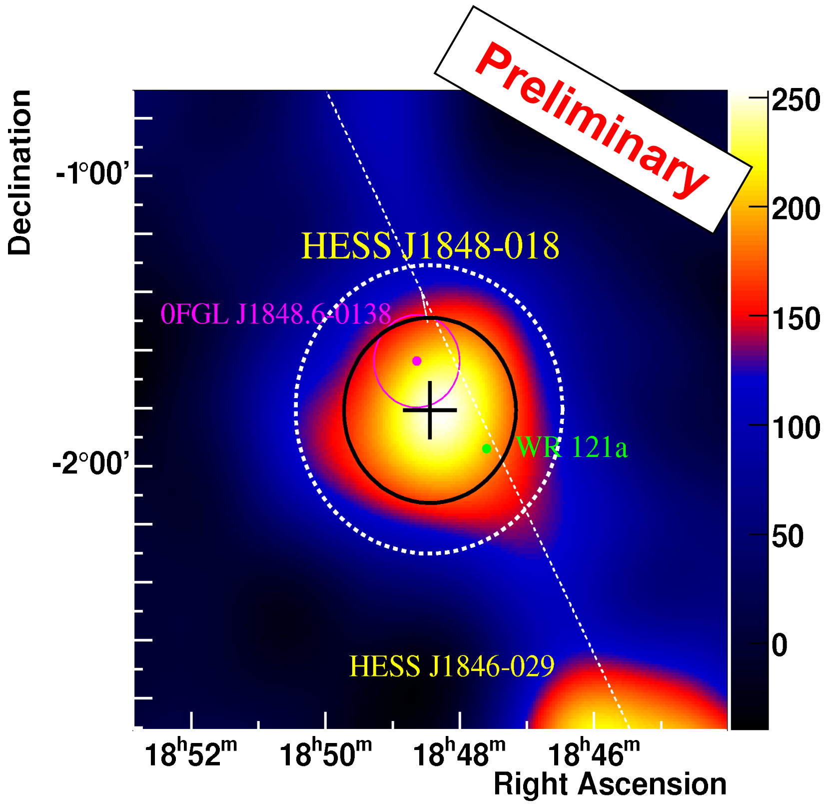
Close to Kes 75. Several object close by, e.g.:
- AX J1843.8-0352 (G28.60.1) is a SNR with a peculiar morphology: Chandra, that discovered a new source within it: CXO J184357-035441, that exhibits a thin thermal spectrum and a jet-like tail.
- AX J1845.0-0258 is another very unclear object: it has been considered as an Anomalous X-ray Pulsar (AXP). Recently Chandra observed in that zone of the sky only one bright source: CXO J184454.6-025653 that is almost 13 times fainter than AX J1845.0-0258.
- A bright Fermi source..

However, the emission peak is not well studied in MWL; I got accepted two XMM-Newton proposals: ID 05563102, lost; ID 06549601 in the AO9



HESS J1848-018

HESS J1848-018: is still without counterparts, but it is slightly offset from the SFR W 43 (suggesting a possible association),which hosts a giant HII region (G30.8−0.2), a giant molecular cloud, and the Wolf- Rayet (WR) star WR 121a in the central stellar cluster.



If HESS J1848−018 is indeed associated with W 43, it would be only the second known case, after Westerlund 2 (or third, Westerlund 1), of VHE gamma-ray emission associated with a SFR.
The coincidence with the BSL Fermi source OFGL J1848.6-0138 is underlined.

The energy spectrum is well fit by a power law with index $\Gamma = 2.8 \pm 0.2_{stat} \pm 0.2_{syst}$ and integrated flux above 1 TeV of ~2 x 10^{-12} erg cm^{-2} s^{-1}, corresponding to ~2% that of the Crab nebula.

Summary- Outline

- Introduction to Cosmic Rays and "standard picture" of their origin.

- Detection techniques (GeV-TeV)

- H.E.S.S. Survey and Galactic unidentified sources

- Examples, Newly discovered sources:
  - HESS J1507-622
    + ancient PWN
  - ~~HESS J1741-302~~

- Conclusions

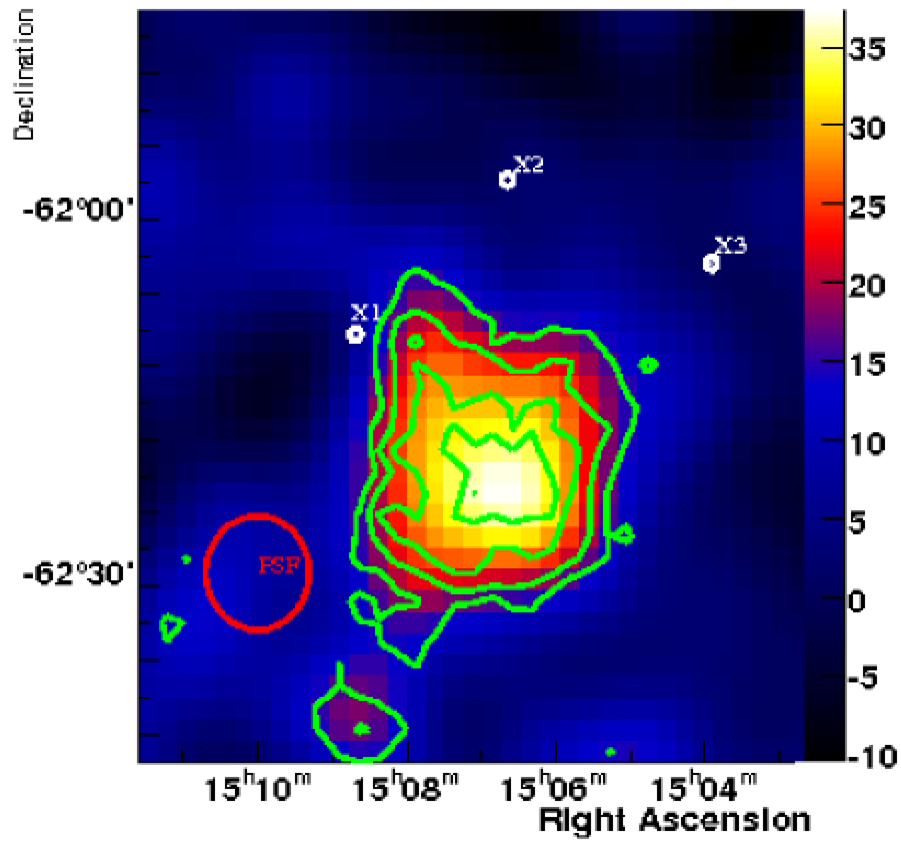
(+ ~100 backup slides)

HESS J1507-622

Unique unidentified source:
~3.5 degrees offset from the Galactic plane!
Very bright (~8% of the Crab).
9.3 σ of peak significance in 9.7 hours.
Slightly extended (~0.16 degrees).

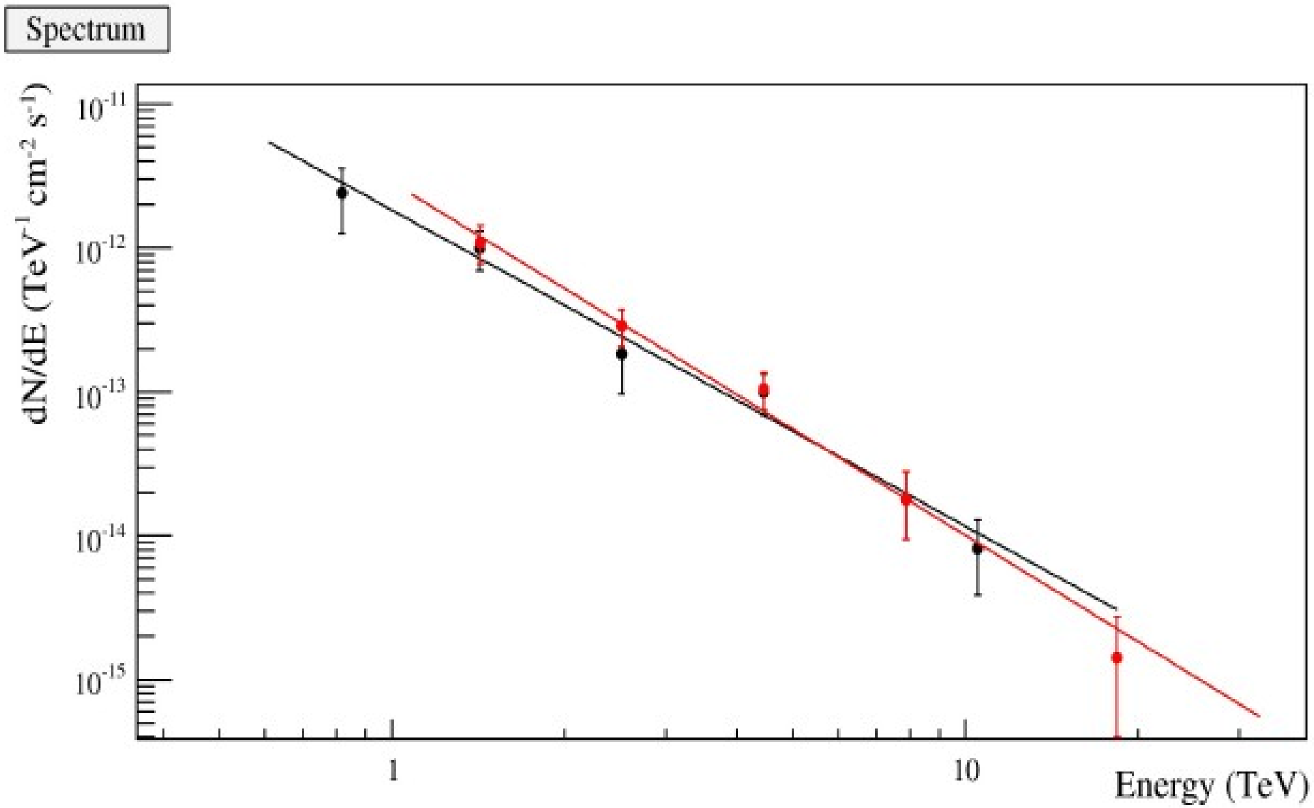
NO plausible counterparts at any wavelength.

Given the brightness and the offset from the Galactic plane, it is really surprising to not find any counterpart in X-rays!



(X indicates the position of three faint RASS (Voges et al. 2000) sources: X1 indicates 1RXS J150841.2-621006, X2 indicates 1RXS J150639.1-615704 and X3 indicates 1RXS J150354.7-620408)

HESS J1507-622: spectra



The spectrum evaluated with *standard cuts* (i.e. lower energy threshold) and with *hard cuts* (i.e. better gamma-hadron separation).
Compatible results;

- spectral index $\Gamma = 2.24 \pm 0.36$ $\Gamma = 2.49 \pm 0.38$
- flux (> 1 TeV): $(1.5 \pm 0.7)\ 10^{-12}$ cm^{-2} s^{-1} ; $(2.1 \pm 1.0)\ 10^{-12}$ cm^{-2} s^{-1}

Counterparts:
IR and Radio

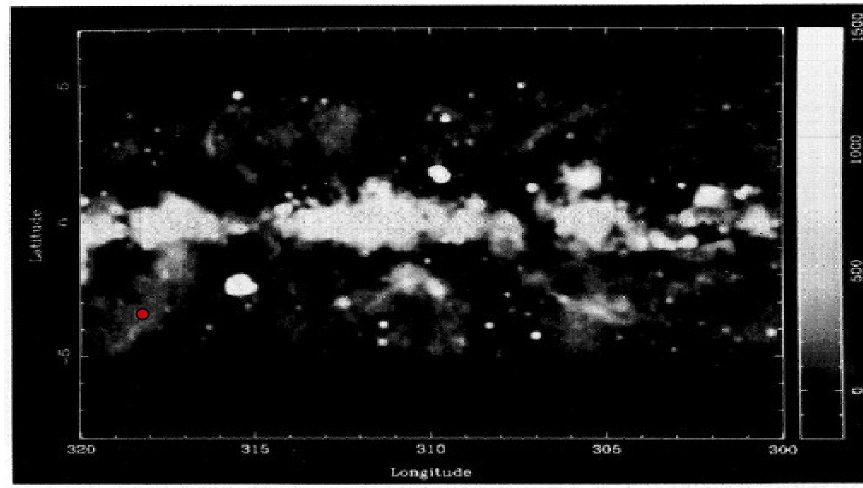
No plausible counterparts found in 1507 region!
At IR and Radio wavelengths:

- no <u>Southern Galactic Plane Survey</u> and <u>Spitzer GLIMPSE</u> coverage.

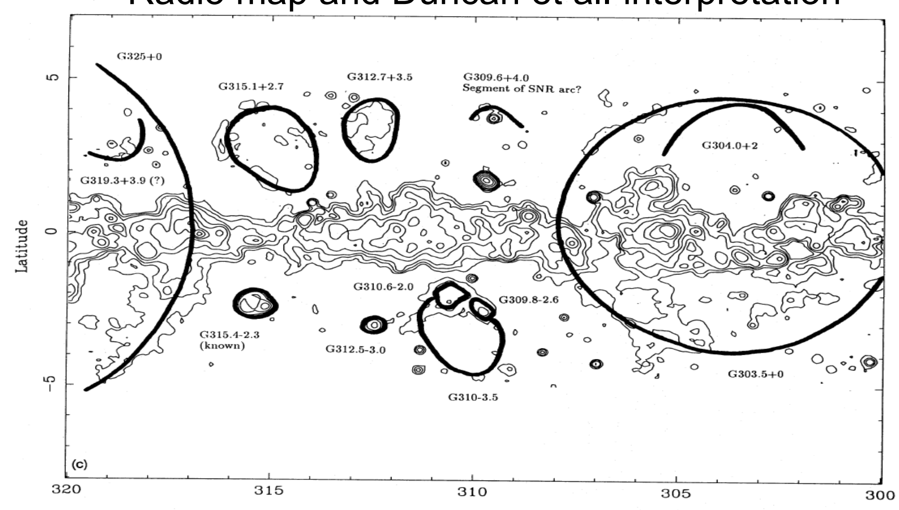
- covered by <u>Midcourse Space Experiment</u> (MSX) and by <u>MOLONGLO</u> Galactic plane survey, but without evidencing any plausible counterparts.

- it is located on a radio filament at 2.4 GHz (Duncan et al. 1995).

- it lies near the edge of a very large CO molecular cloud (5 deg x 2 deg) (Dame catalog).



HESS J1507-622 overlapped into the 2.4 GHz Radio map and Duncan et al. interpretation



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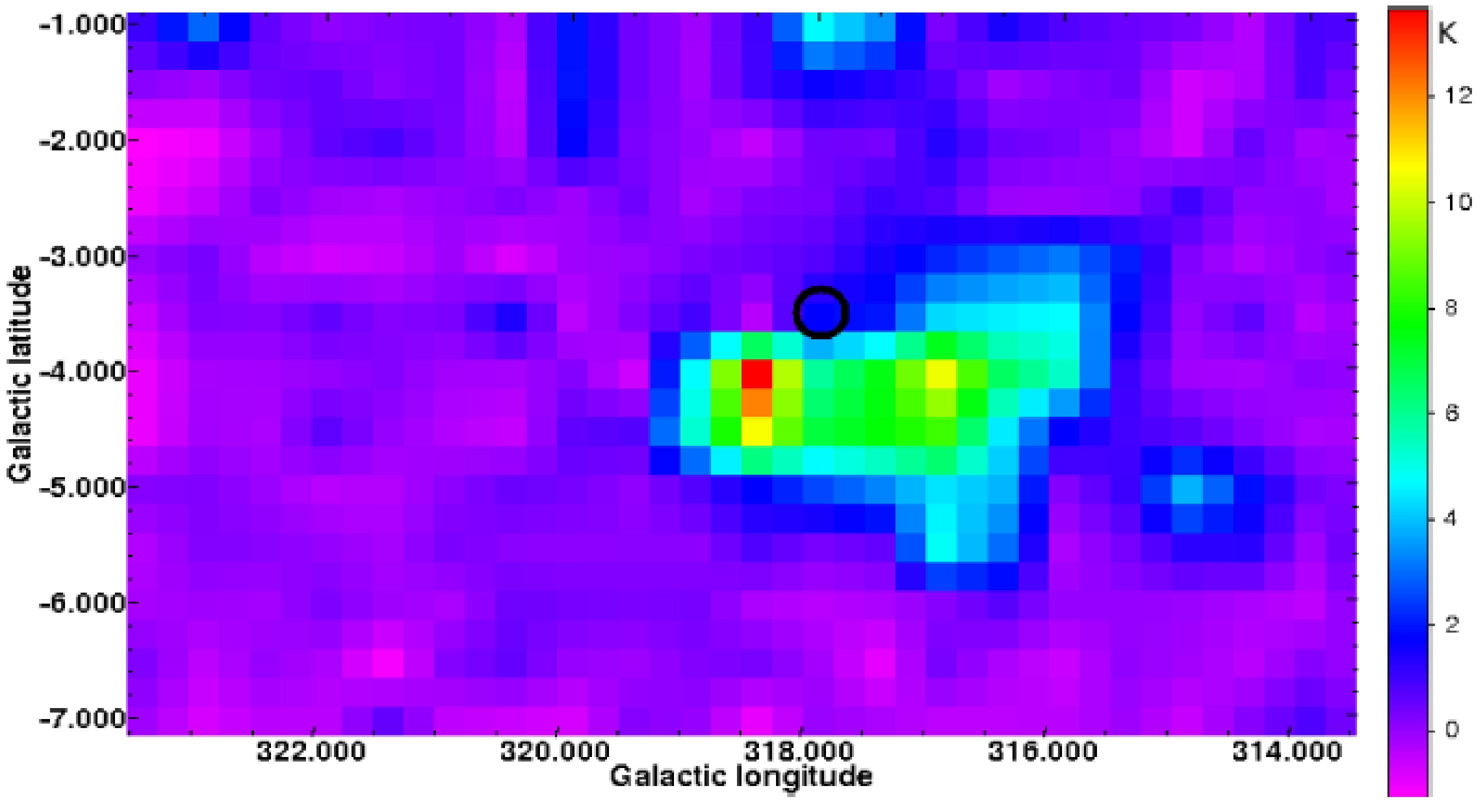
more on CO MCs



In the complete CO survey (Dame et al. 2001), the H.E.S.S. source lies near the edge of a large (~ 5 deg × ~ 2 deg) nearby CO molecular cloud, and the peak velocity of this cloud, around -5 km/s, would most likely place it quite near at a distance of ~400 pc. The substantial difference in extension and, in the case of the CO molecular cloud, the offset of ~ 1 deg from the HESS source centroid, suggest no obvious scenario for an association.

Counterparts and MWL: X-rays

At X-rays (surprising to not find any X-ray counterpart, since we have here ~1 order of magnitude less absorption than in the Galactic plane) :

- ROSAT : no counterparts. 3 near point sources (see slide 49) (in the case that one of them could be discovered to be a PSR, one can imagine an offset PWN scenario).

- XMM-Newton : I got XMM-Newton observations (*Proposal ID #05563102 - AO 7*), but very severely affected by soft proton flare! Detected one point source in the middle of HESS J1507-622 (associated with a star). Re-observation has been obtained (*Proposal ID #06516201 - AO 9*): 35 ks.

- Chandra : I got Chandra observations (*Proposal ID #10400599 – AO 10*), no plausible counterpart, but an extended source has been discovered nearby.

- Accepted deep (80 ks) Suzaku campaign (priority C), and last year we got 80 ks + 40 ks observations.

(More details in Tibolla, Kaufmann and Kosack 2014, A&A, 567, id.A74)

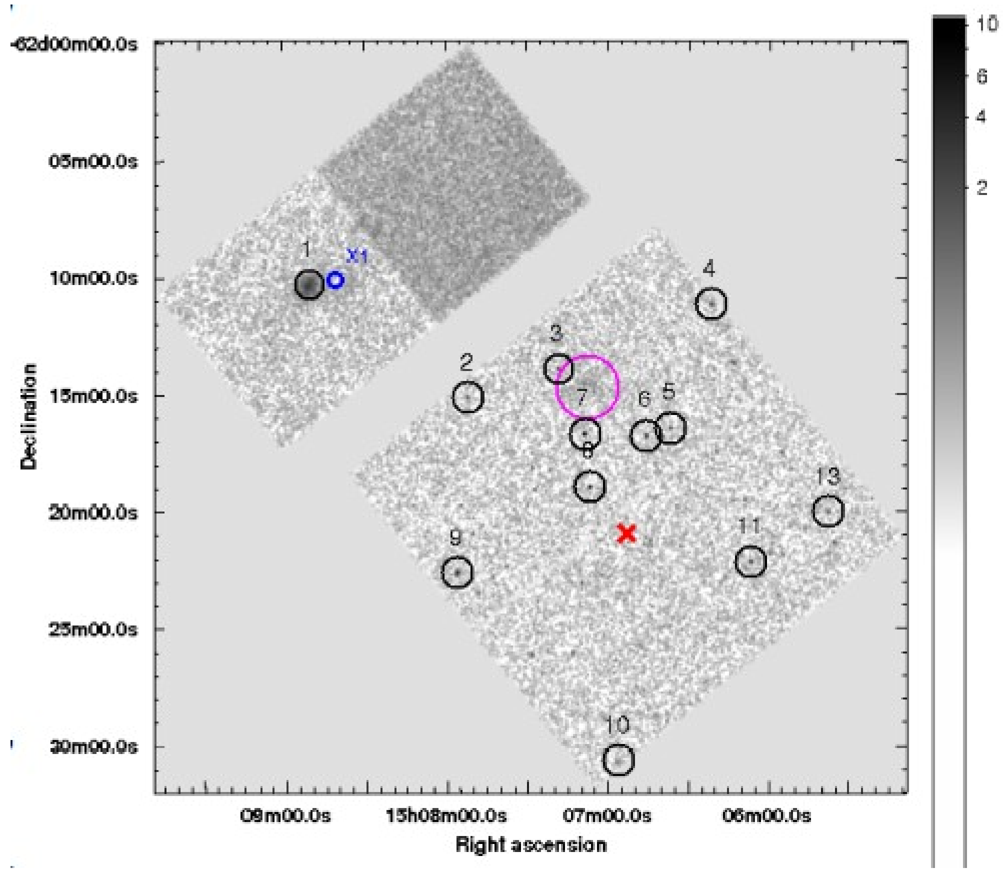
Chandra observations:
the situation is even more complicated

Using *vtpdetect* (confirmed by *wavdetect*) we find a faint extended source that escaped the source *celldetect* but is detected (116 counts over a level of background of 32 counts): 20-25 arcsec.

Much smaller angular size than the VHE source, so an association is not obvious with current data, although the possibility remains that it is a bright part of a larger, weaker source.

But for pulsars older than ~ 1000 years the VHE PWNe are typically 100-1000 times larger than the sizes of the X-ray PWNe (factor 2 for some younger PWNe, like the Crab).

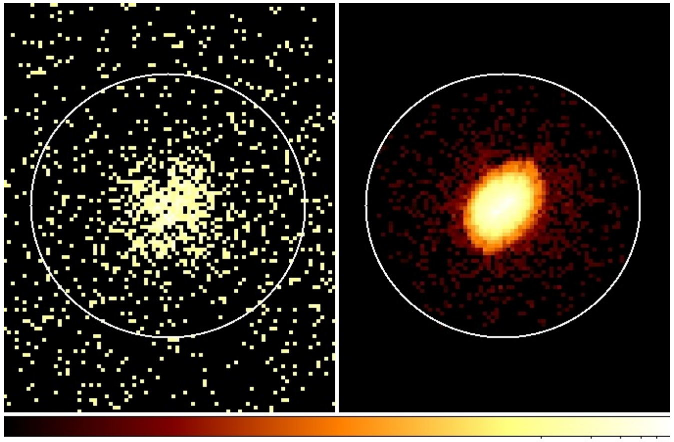
However, in the case of HESS J1507-622, we see no PSR...

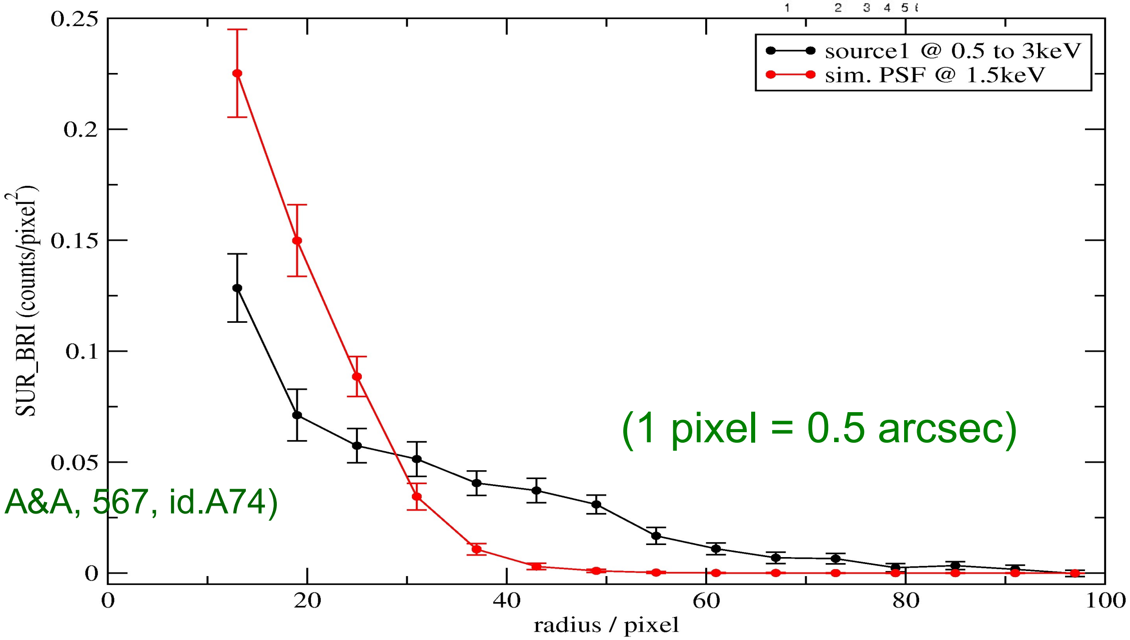


(More details in spare slides)

Source 1 extended?

Simulating the PSF of the instrument (right panel) and comparing it with source 1 (left panel, source 1 seems slightly extended over the PSF of the instrument.



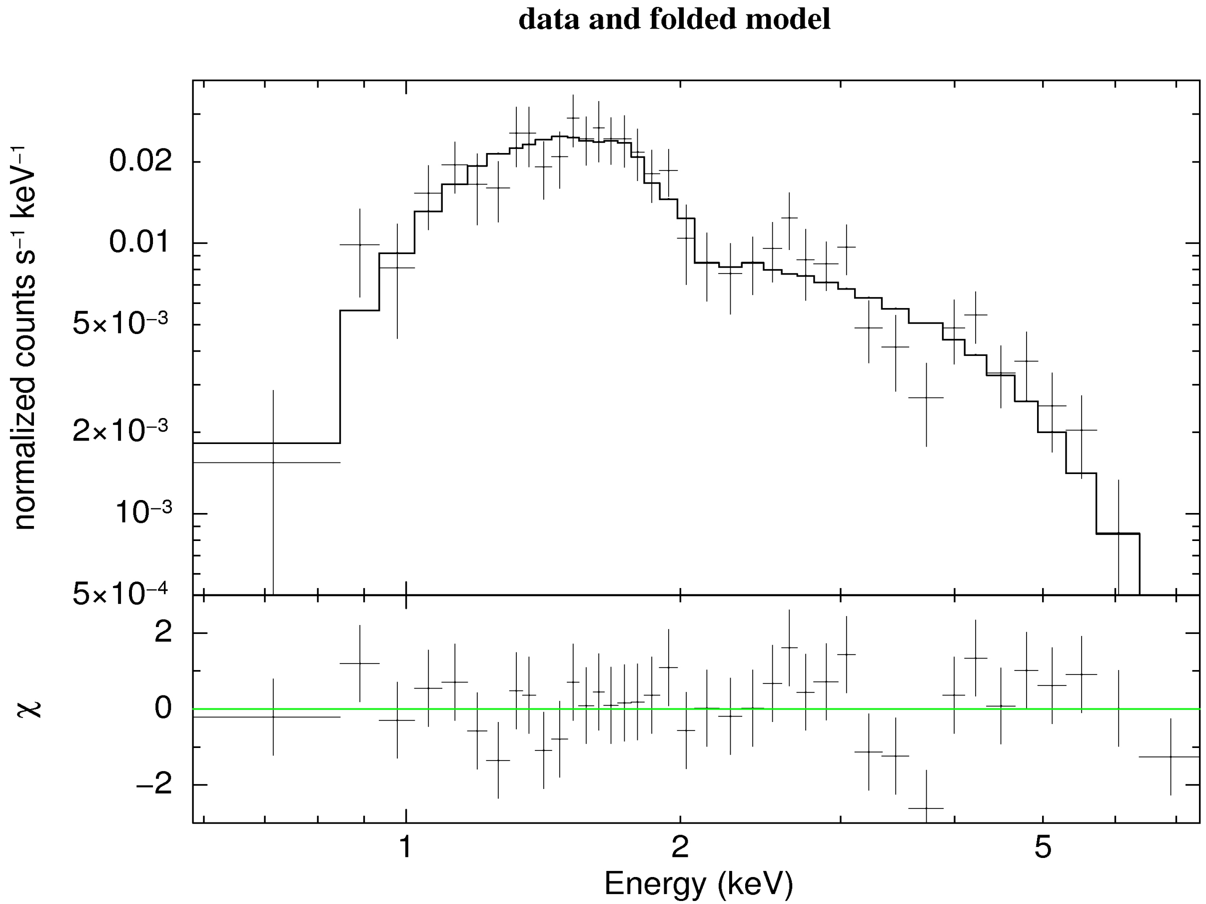


(1 pixel = 0.5 arcsec)

(Tibolla, Kaufmann and Kosack 2014, A&A, 567, id.A74)

Source 1 spectrum

A simple Power Law (+ absorption) fits well the data: reduced χ^2 ~0.9



(Tibolla, Kaufmann and Kosack 2014, A&A, 567, id.A74)

N_H = (0.82 $\pm$ 0.27) 10^{22}cm^{-2}

photon index = 1.98 $\pm$ 0.32

norm = 2.82641E-04 -9.15492e-05/ +0.000138588

flux (2-10keV) = 6.98e-13 ergs/cm^2/s

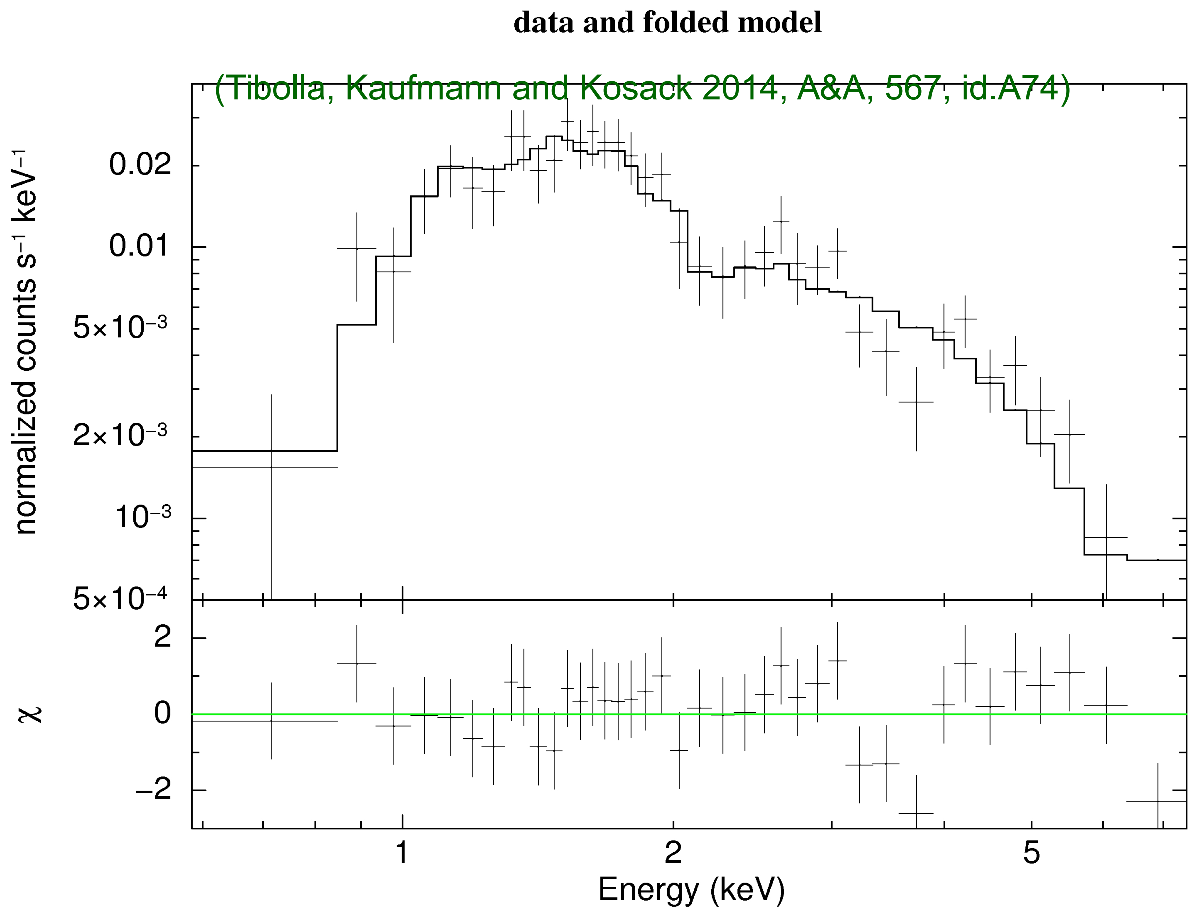
error range (5.533e-13 - 7.582e-13)

Source 1 spectrum (2)

But also a simple thermal plasma fits as well.
reduced χ^2 ~0.9

Now we have another unidentified source in Radio and X-rays.

In any case, this newly discovered source does not seem to be a good counterpart candidate for HESS J1507-622.

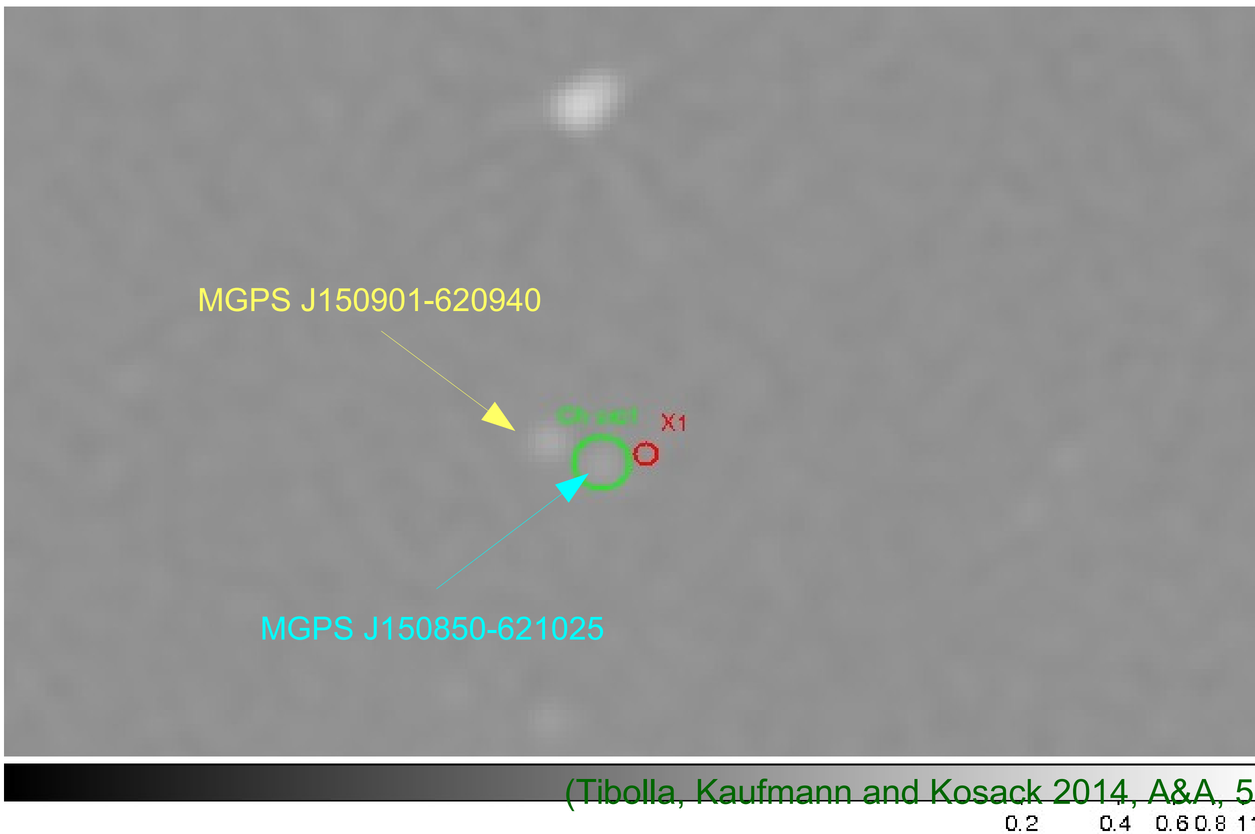


NH = (0.70 ± 0.27) 10^{22}cm^{-2}

mekal kT keV 5.16400 +/- range (3.4028 .. 10.6051)

Note:
MOLONGLO view of src1/X1

Src 1 is also coincident with MGPS J150850-621025 (62" times 50.4")(and close to MGPS J150901-620940: 51" times 50.6").
Overlapped src 1 (40" radius) and X1 (17" positional error).



(Tibolla, Kaufmann and Kosack 2014, A&A, 567, id.A74)

Discussion on HESS J1507-622

HESS J1507-622 doesn't show so far any obvious counterpart and its nature is still unclear. Both hadronic and leptonic scenarios are still under investigation.

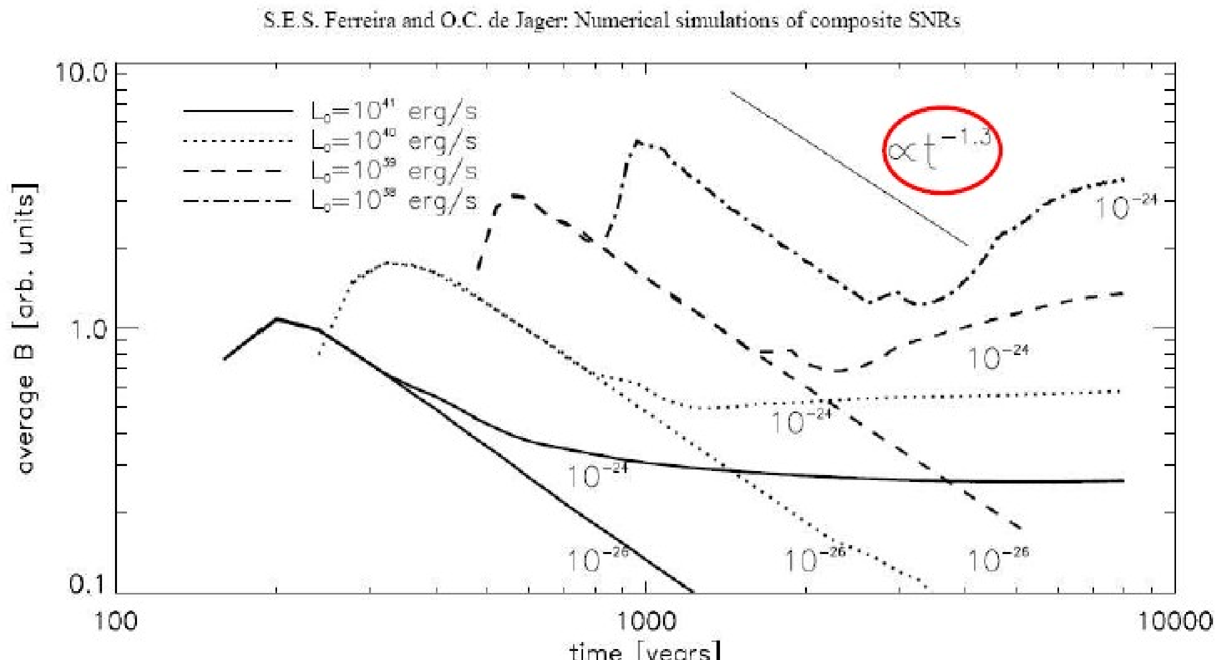
- The offset from the galactic plane (low density..) would suggest a leptonic scenario. A PWN powered by an old PSR could be a possible explanation for this source (in this case a small distance of the object is disfavored), i.e. the so called Ancient PWN scenario (*O. C. de Jager et al. (including O.Tibolla) arXiv:0906.2644*) **Ancient PWNe** are indeed a recent idea that could explain a large fraction of the TeV unidentified sources.

- The absence of counterparts (if confirmed), especially in X-rays, would suggest an hadronic scenario. However hadronic scenarios appears disfavored, unless we would place HESS J1507-622 at a very small distance, since the density of target material off the plane is low (e.g. SN 1006).

As mentioned, the difference in model leads also to a difference in the distance: a leptonic PWN scenario would place this source due to its quite small extension to a distance of several kpc (at least > 6 kpc; e.g Geminga) whereas a hadronic scenario would preferentially locate this object at distances of < 1 kpc where the density of target material is higher.

Ancient Pulsar Wind Nebulae

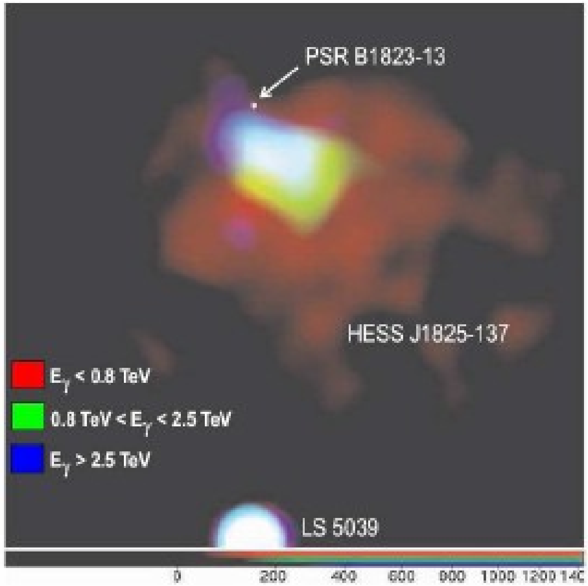
In a scenario where the magnetic field decays as a function of time, the synchrotron emission will also fade as the PWN evolves.
And the B-field is indeed expected to decay as a function of time and the power-law index of the decay of the average nebular field strength has been calculated by means of MHD simulations (Ferreira & de Jager, 2008)



Ancient Pulsar Wind Nebulae (2)

While the synchrotron emission is fading as the PWN evolves, the VHE emission depends on the CMB radiation field, which is constant on timescales relevant for PWN evolution.

For timescales shorter than the inverse-Compton lifetime of the electrons ($t_{IC} \approx 1.2 \times 10^6$ (Ee/1 TeV)$^{-1}$ years), this will result in an accumulation of VHE electrons which will also lead to an increased gamma-ray production due to up-scattering of CMB photons.



Such accumulation of very-high energy electrons in a PWN has indeed been seen in several VHE PWNe (such as the source HESS J1825-137)

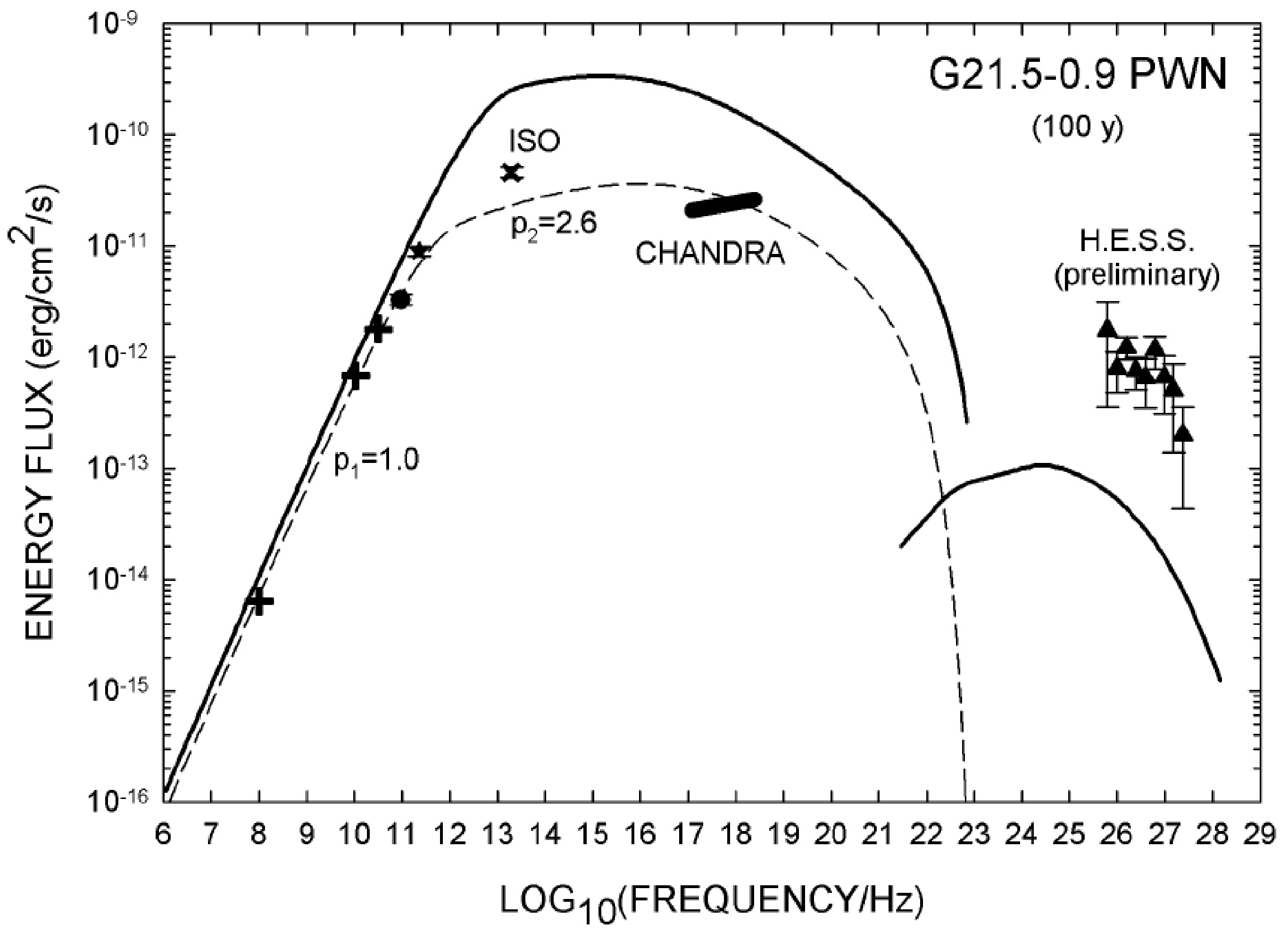
Ancient Pulsar Wind Nebulae (3)

This idea seems supported by the fact that the VHE PWNe sizes generally increase with pulsar age while the X-ray PWNe sizes show the opposite trend.
Moreover, for pulsars older than $\sim 10^3$ years the VHE PWNe are typically 100−1000 times larger than the sizes of the X-ray PWNe, while the difference is only a factor 2 for some younger PWNe, like the Crab Nebula (e.g. Kargaltsev & Pavlov 2010).

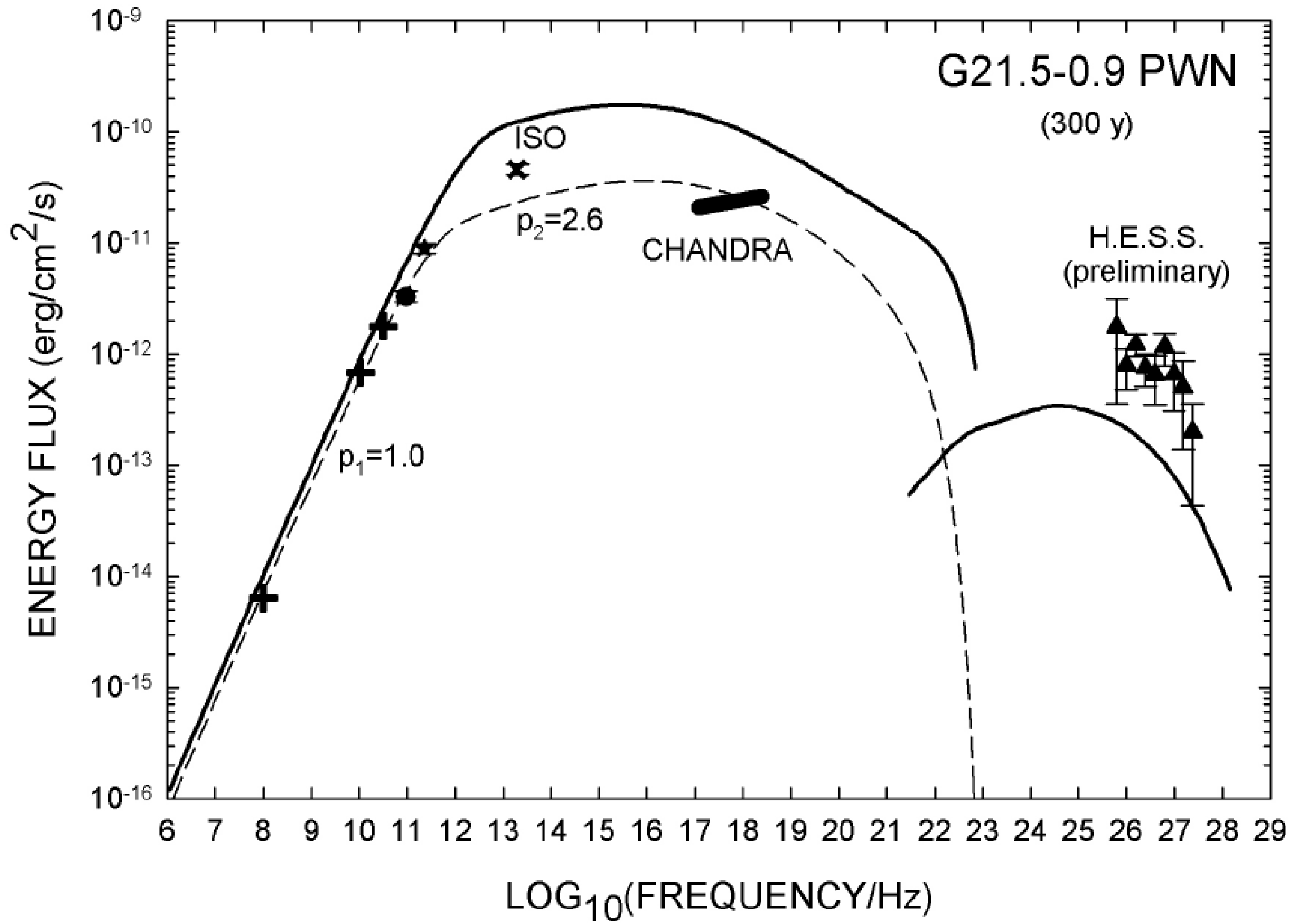
To summarize, during their evolution PWN may appear as gamma-ray sources with only very faint low-energy counterparts and this may represent a viable model for many unidentified TeV sources.

This effect can be clearly seen in the following example shown by Okkie de Jager in 2008.

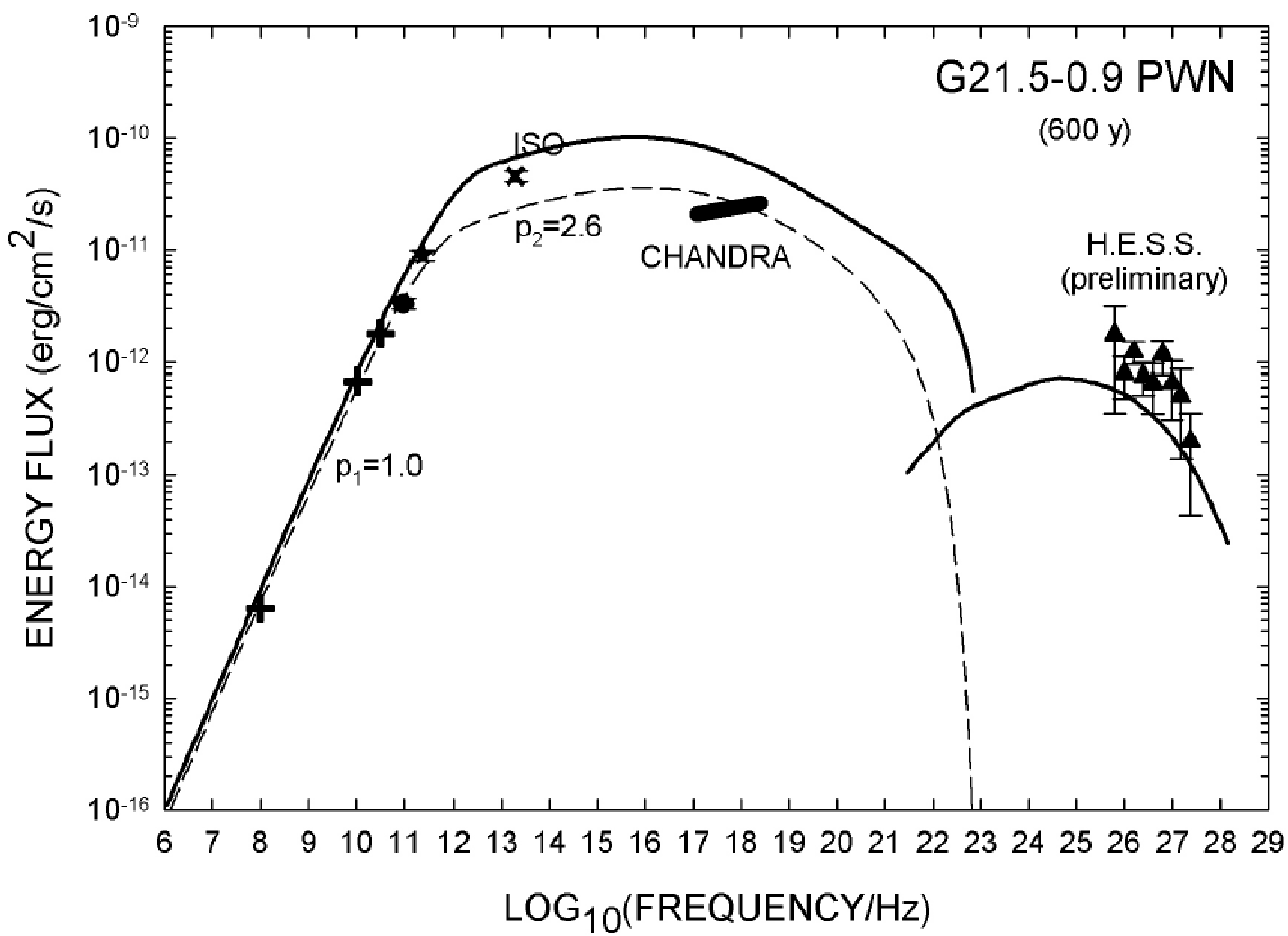
Example: G21.5-0.9 in the first 25 kyrs (100 y)



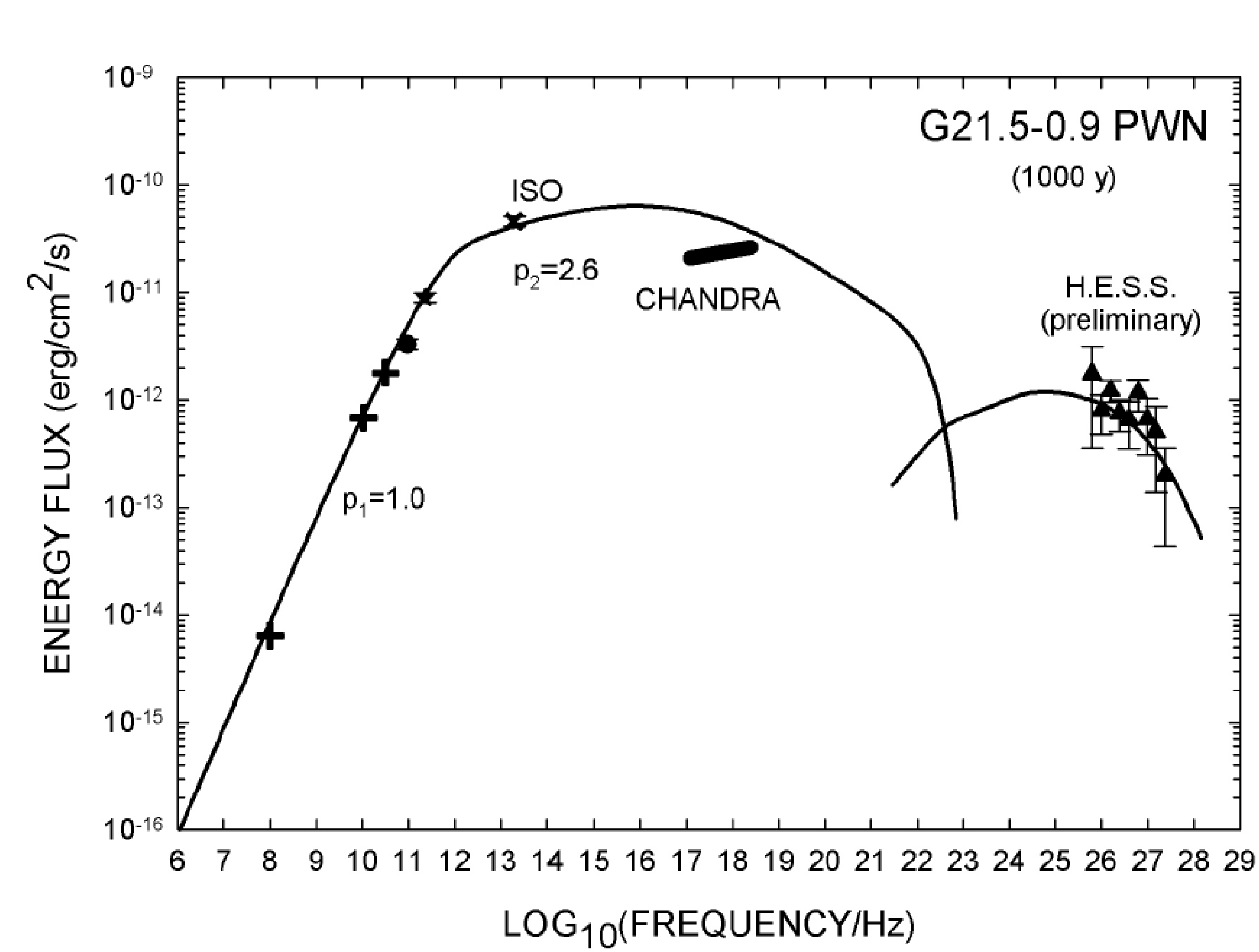
Example: G21.5-0.9 in the first 25 kyrs (300 y)



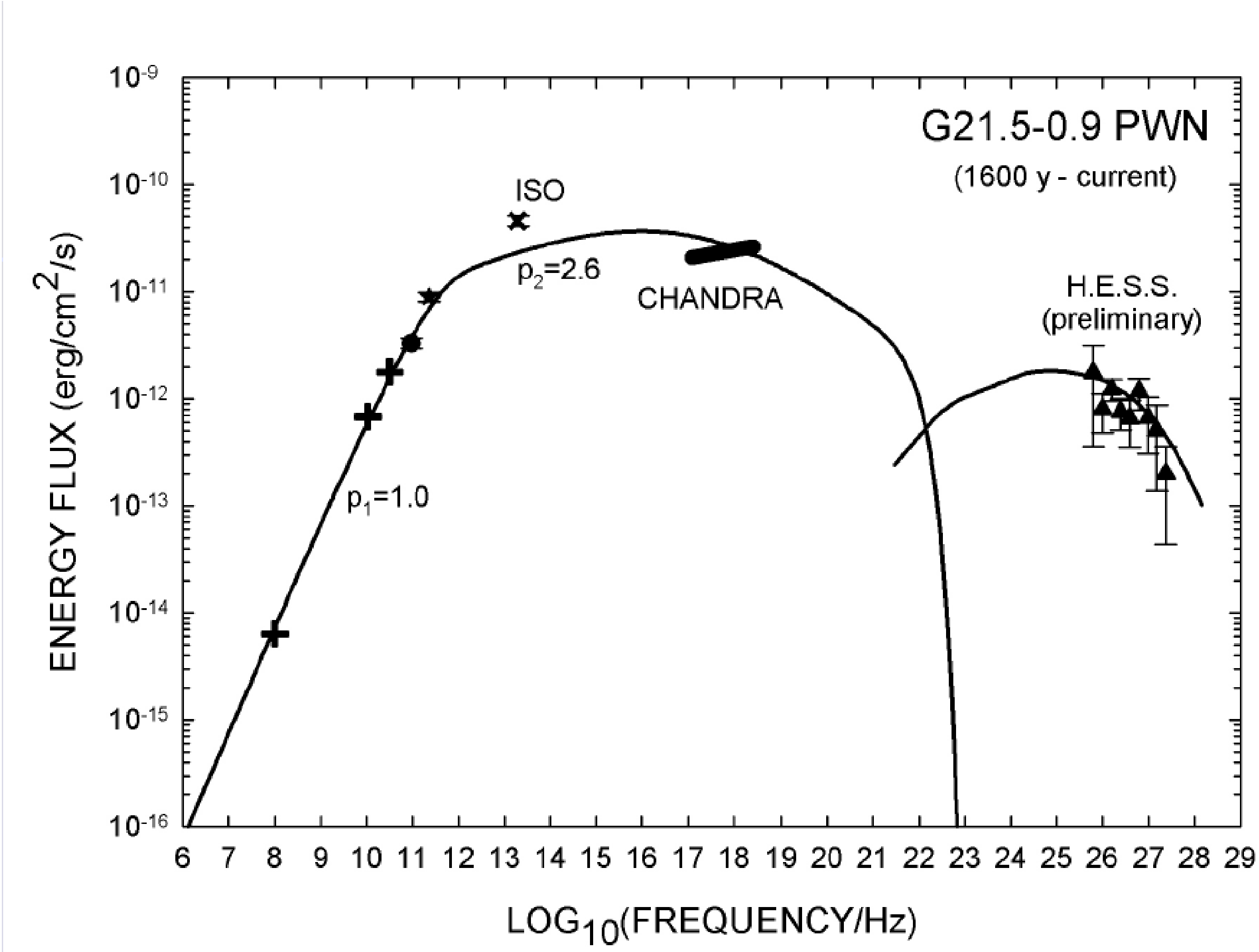
Example: G21.5-0.9 in the first 25 kyrs (600 y)



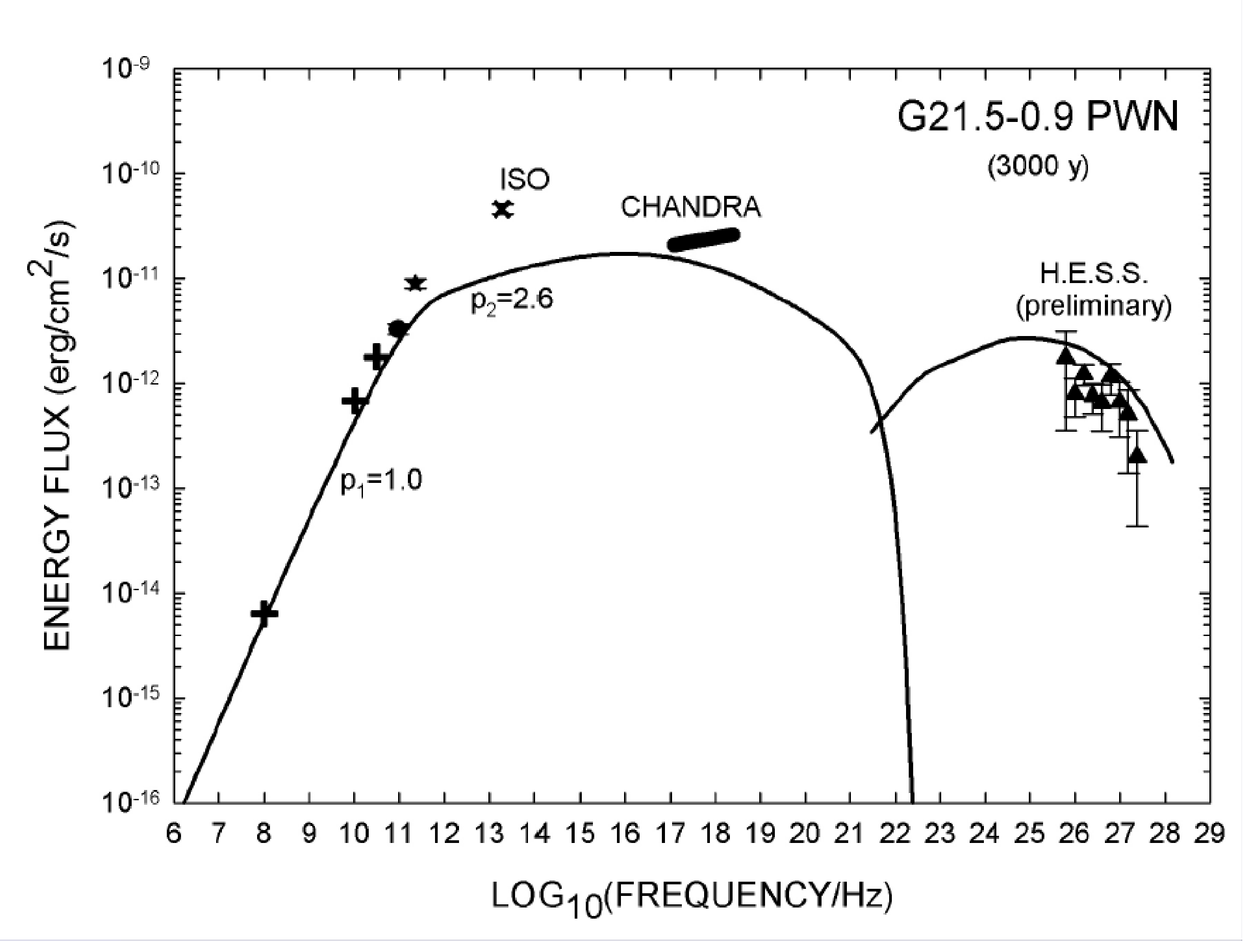
Example: G21.5-0.9 in the first 25 kyrs (1000 y)



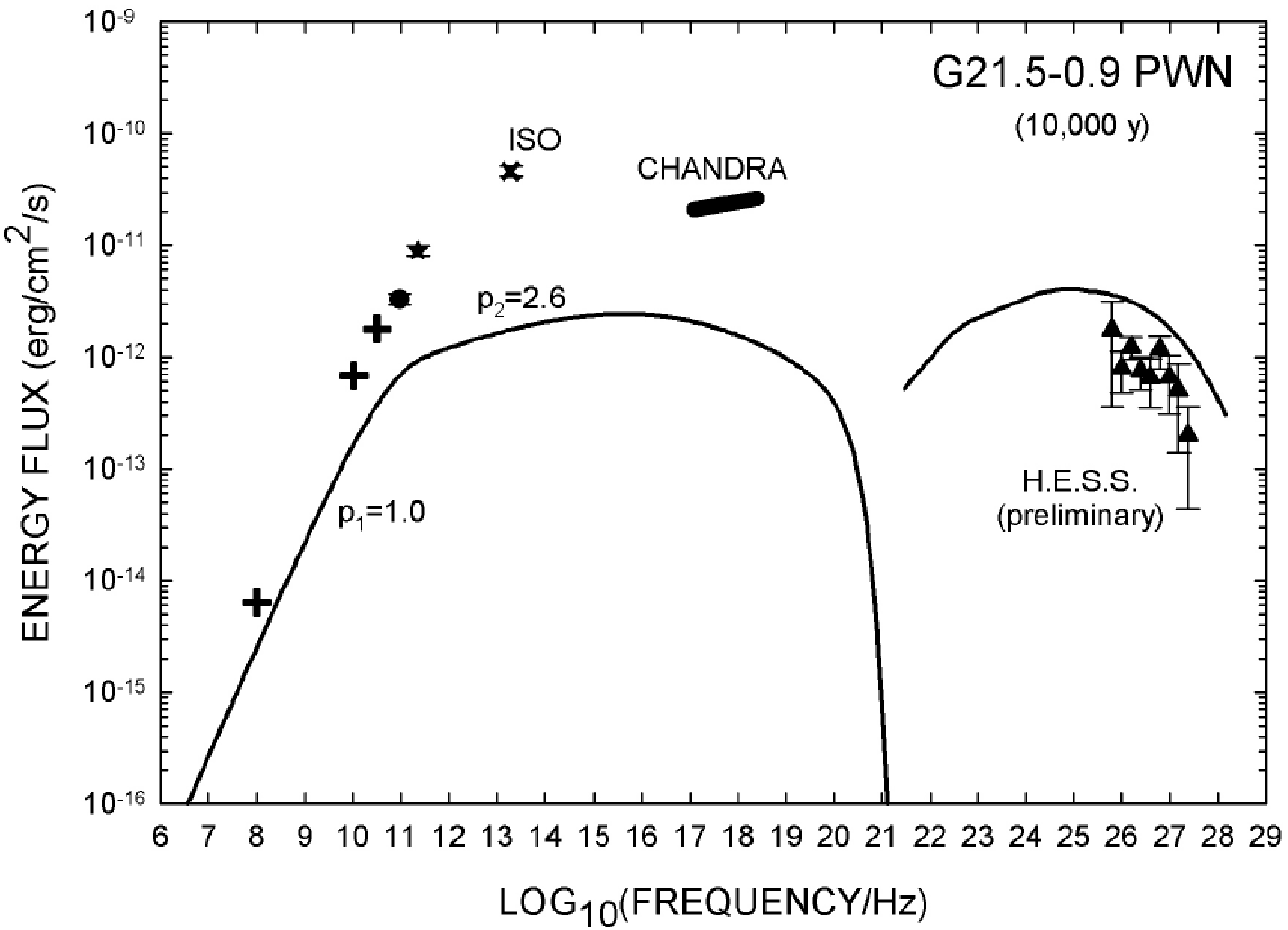
Example: G21.5-0.9 in the first 25 kyrs (1600 y)



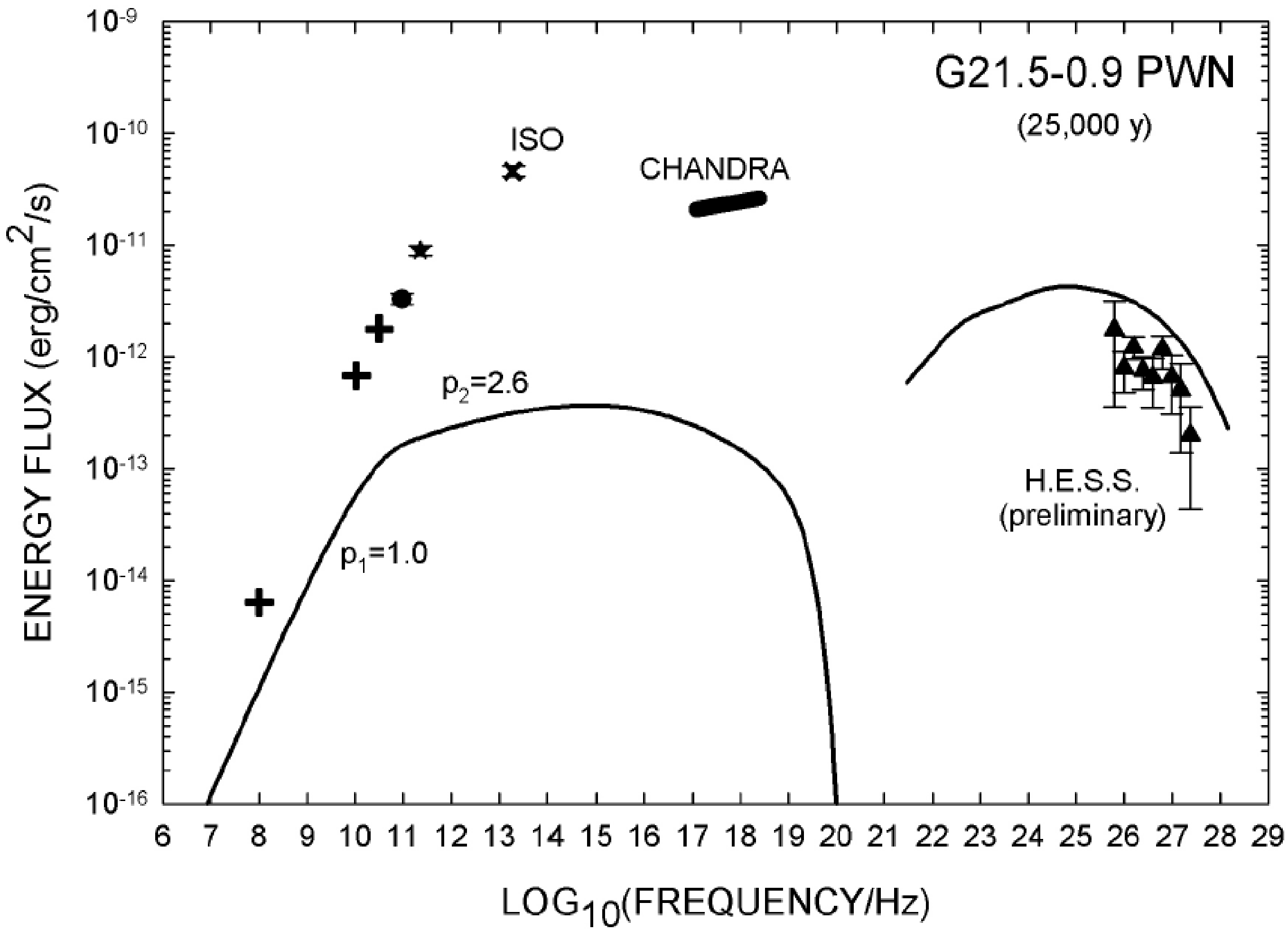
Example: G21.5-0.9 in the first 25 kyrs (3000 y)



Example: G21.5-0.9 in the first 25 kyrs (10 kyrs)

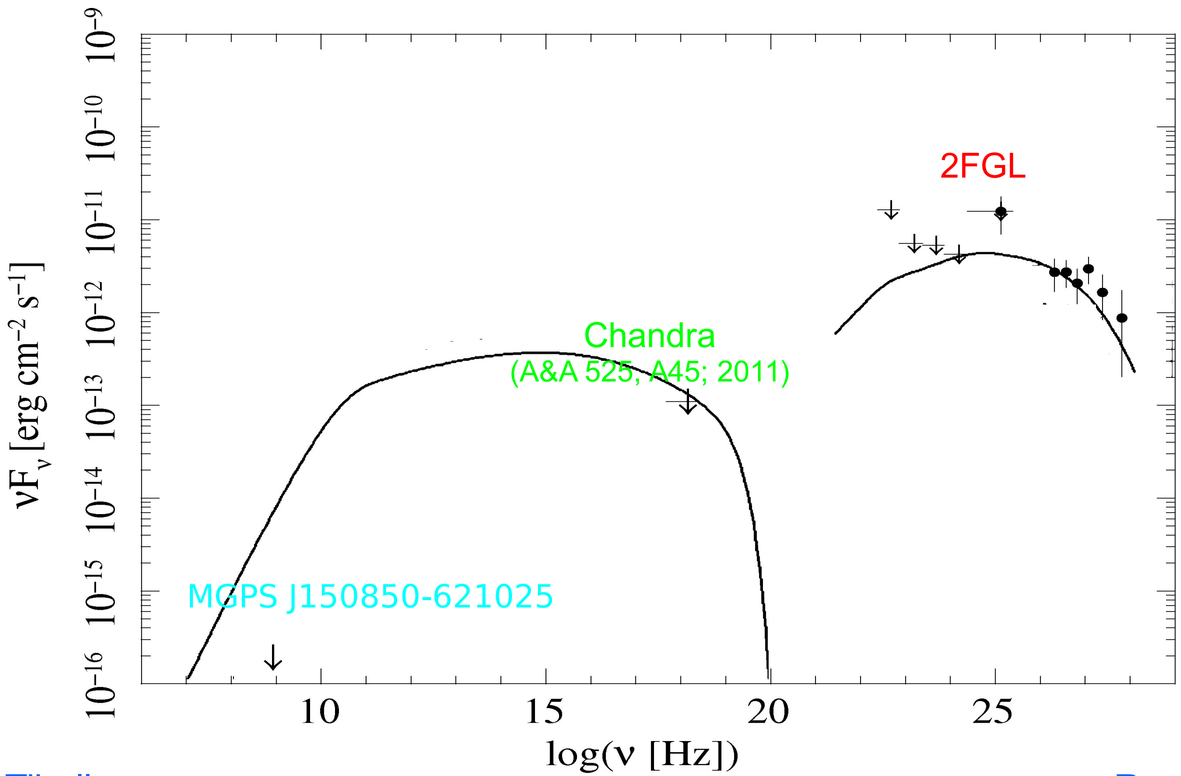


Example: G21.5-0.9 in the first 25 kyrs



HESS J1507-622 (25 kyrs)

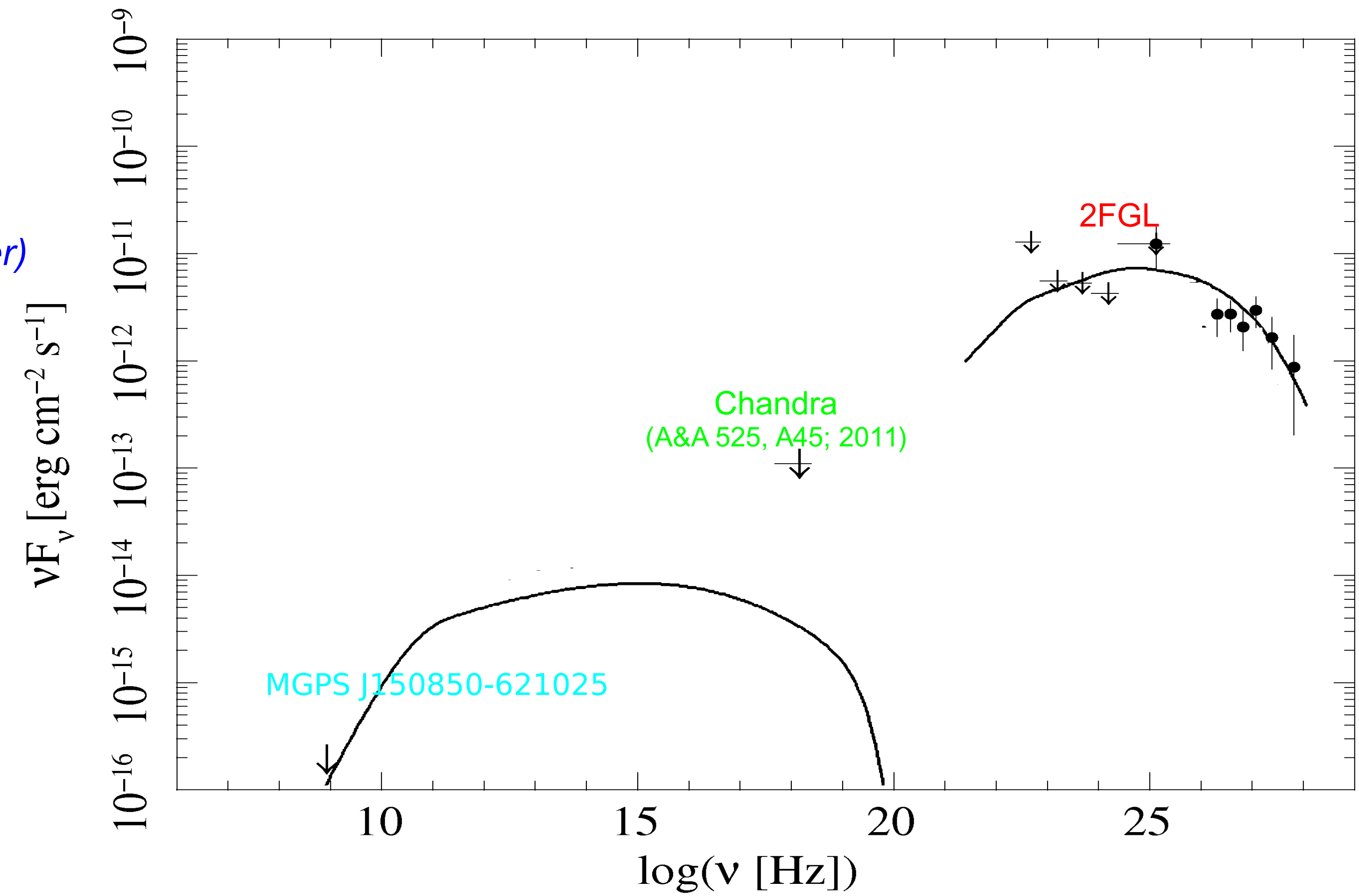
HESS J1507-622 does not have any SNR as possible counterpart and does not show any Pulsar close-by or coincident.
This is expected (PSR already spun-down, and X-ray nebula faded away below the sensitivity of current X-ray instruments), however it request a choice of the initial conditions for modeling (e.g. G21.5-0.9/PSR J1833-1034).



(from Tibolla et al. (in memory of O. de Jager) arXiv:1109.3144)

HESS J1507-622 (>50 kyrs)

(from Tibolla et al. (in memory of O. de Jager) arXiv:1109.3144)



We were having (A&A, 525, A45) constrains about the distance, now we have about the age...

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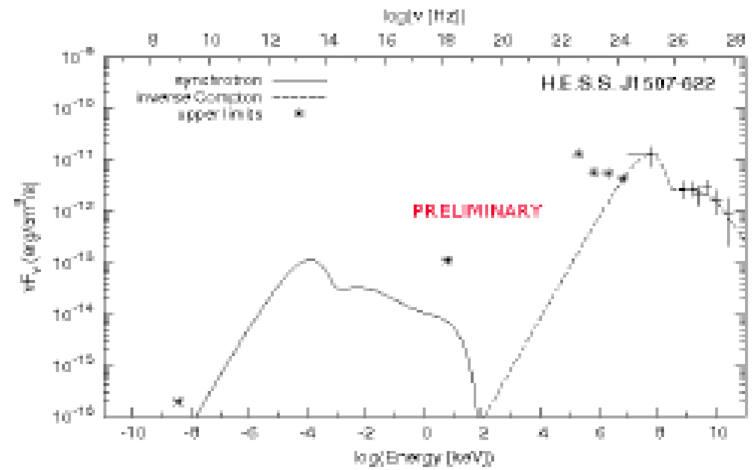
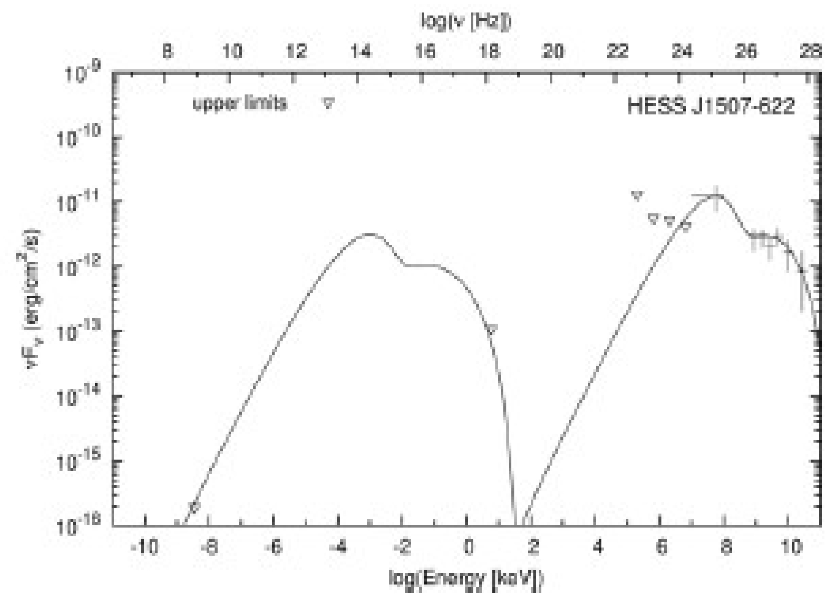
More “evolved” models

I showed here the basic idea, however, using much more stringent models (such as a “leaky box” and our new time dependent PWN model) we obtain exactly the same results.



(from Tibolla et al. 2012, arXiv:1201.2295)

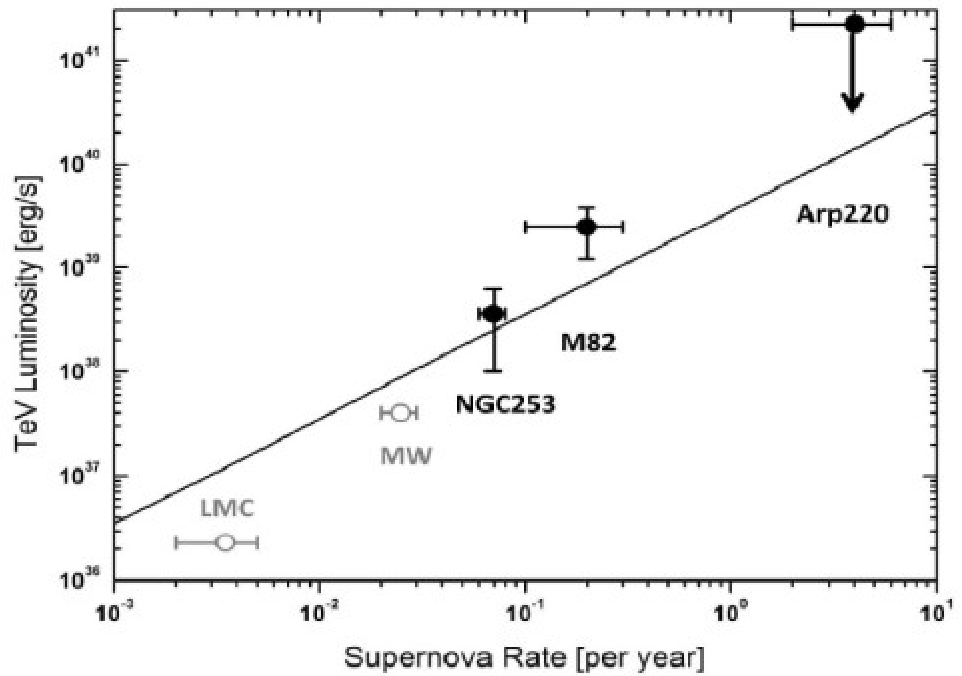


(from Vorster, Tibolla, Kaufmann and Ferreira 2013, ApJ, 773, id.139)

Another corollarium: Starburst Galaxies

Another important consequence of these long-living γ-ray sources regards starburst galaxies: in fact it has been recently shown (Mannheim, Elsaesser and Tibolla 2012, Astroparticle Physics, 35, pp. 797-800) that PWNe are important and not negligible in explaining the TeV emission detected from NGC 253 and from M82.

PWNe associated with core-collapse supernovae in SFRs can readily explain the observed high TeV luminosities. The proof of this could arrive from deeper gamma-ray observations on other galaxies



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What do we learn?

According to me, we learn 2 things:

1- Ancient PWNe seems a very natural way to explain unidentified high energy sources.
And the ancient PWN models seem to be able to explain most of these unidentified sources (e.g. Tibolla et al. 2013, arXiv:1306.6833).

2- If indeed at the termination shock of the Pulsar Wind also hadrons could be accelerated as well as leptons, not only PWNe but also unidentified sources (i.e. the dominant population at HE and VHE) can help in solving the CRs riddle.

3- Please note that, while an efficiency of 10% is required for SNRs shells, an efficiency of ~0.01% would be enough for PWNe, since we demonstrated that they can live ~1000 times longer than SNRs shells.

Summary- Outline

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- Introduction to Cosmic Rays and "standard picture" of their origin.

- Detection techniques (GeV-TeV)

- H.E.S.S. Survey and Galactic unidentified sources

- Examples, Newly discovered sources:
  - HESS J1507-622
    + ancient PWN
  - ~~HESS J1741-302~~

- Conclusions

(+ ~100 backup slides)

Conclusions

1- no real conclusions => The question about the Origin of CRs is more open than ever

2- Additional CRs sources or much different models/scenarios seems to be required (in order to supply the missing CR fraction).

3- ONLY deep MWL studies can help.

4- regarding Unidentified Sources, they could really help, under the hypothesis of hadron acceleration at the pulsar wind termination shock.

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Thanks for your attention!