Gamma-ray observations of Pulsar Wind Nebulae

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Supernova Remnants II: – An Odyssey in Space after Stellar death
Chania, 2019 June 6

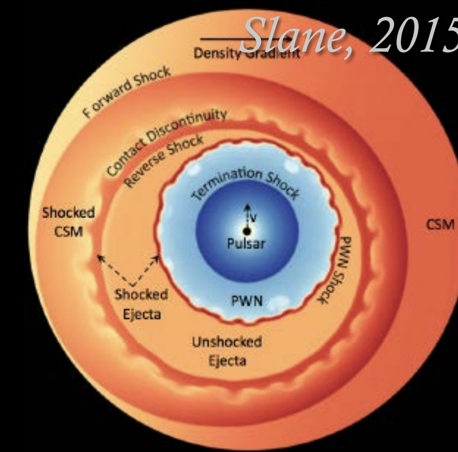
GeV/TeV emission mechanisms in PWNe

See also talk by T. Temim on Wednesday

- Non-thermal photon emission :
  - Synchrotron emission
  - Inverse Compton scattering
  - Bremsstrahlung
  - Proton-proton interaction

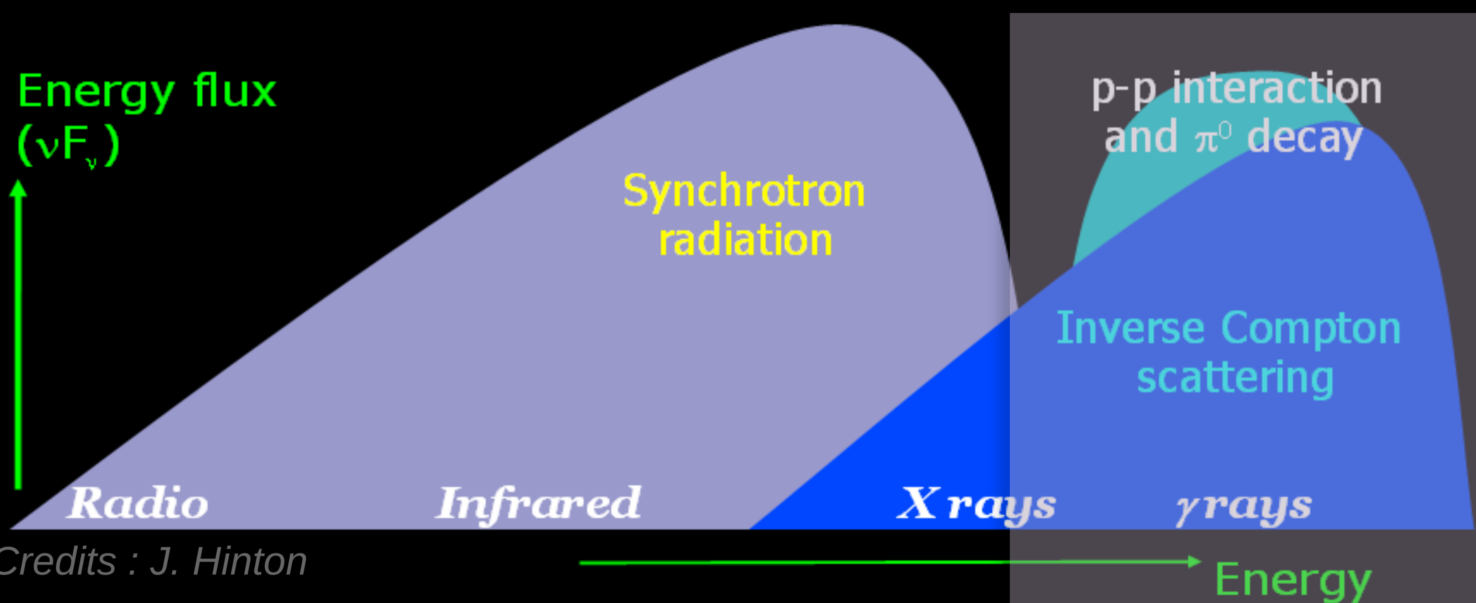
Electrons

Protons



Slane, 2015

- Observations in the GeV/TeV range → disentangle between the radiation processes
- Multi-wavelength observations → constrain the physical properties of the sources



Credits : J. Hinton

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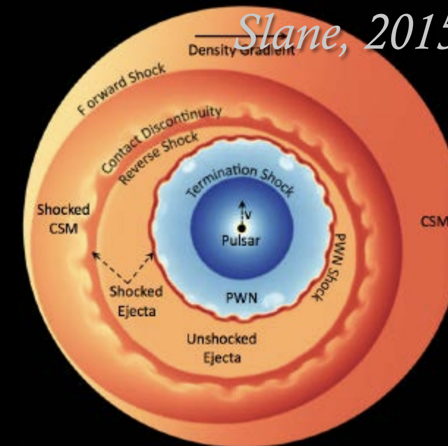

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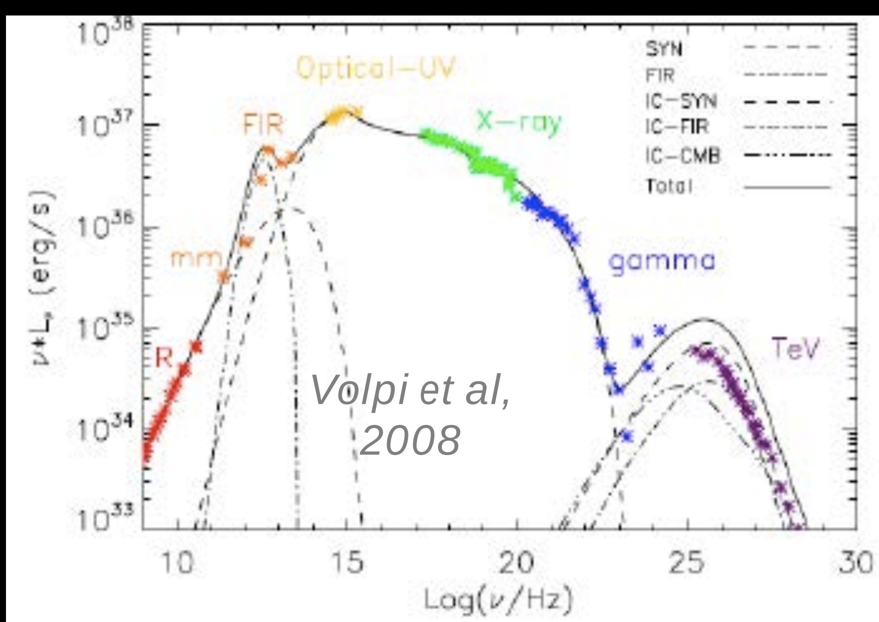
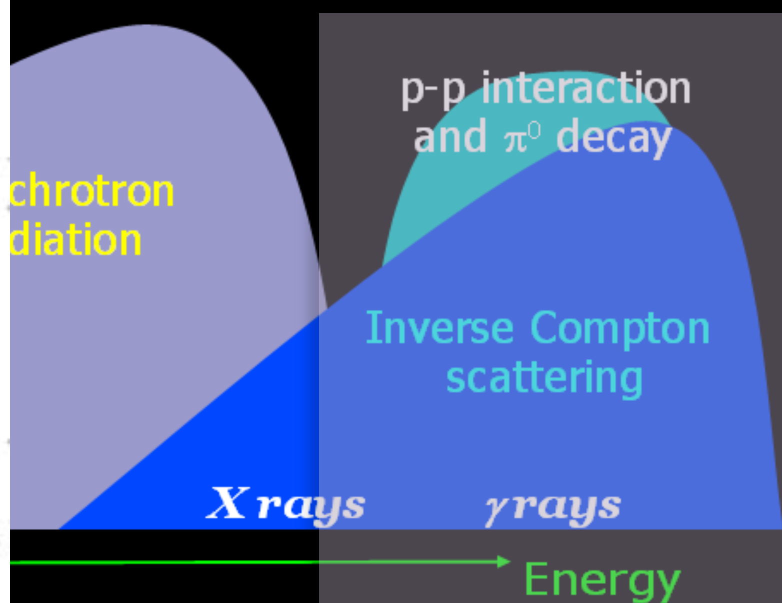
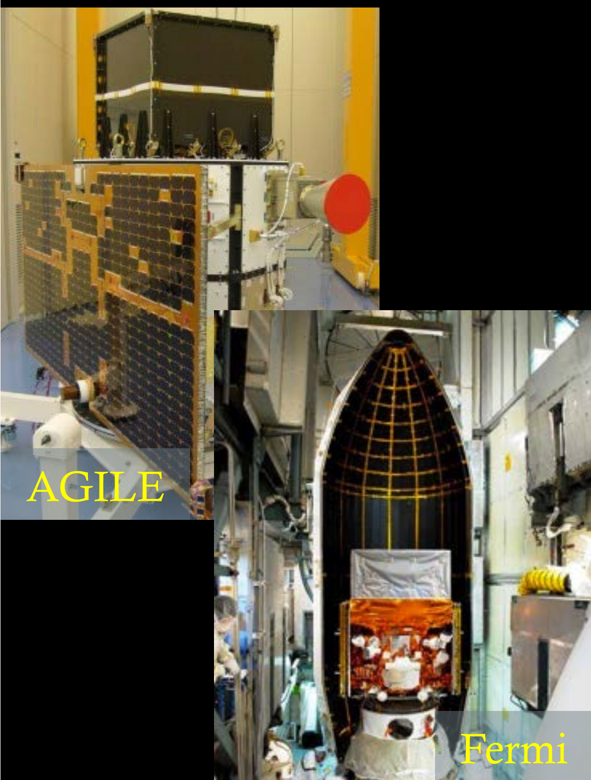
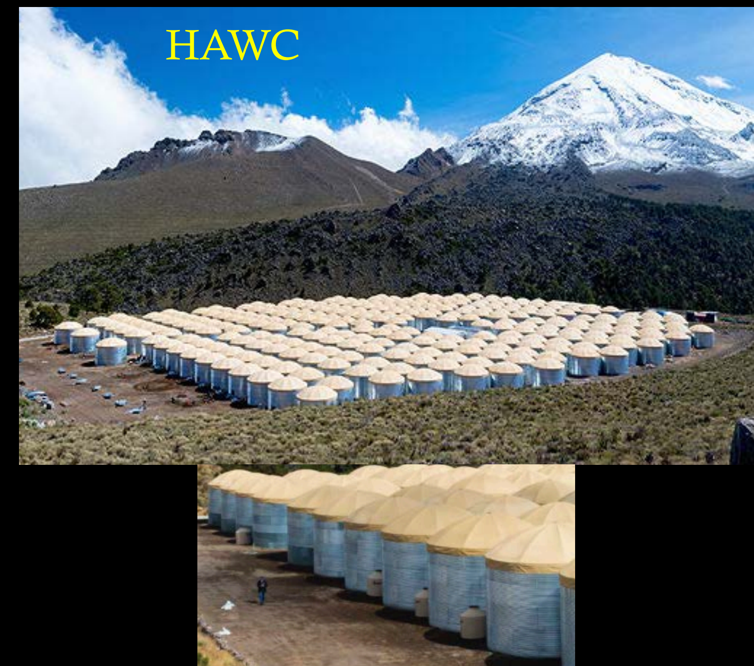




Gamma-ray astronomy : 3 strategies

Energy





Satellites
(e.g. Fermi-LAT :
30 MeV – 300 GeV)

- full sky coverage
- good angular resolution at high energy

Cherenkov telescopes
(e.g. H.E.S.S.:
30 GeV – ~80 TeV)

- small field of view
- excellent angular resolution

Air shower arrays : HAWC
(100 GeV – 100 TeV)

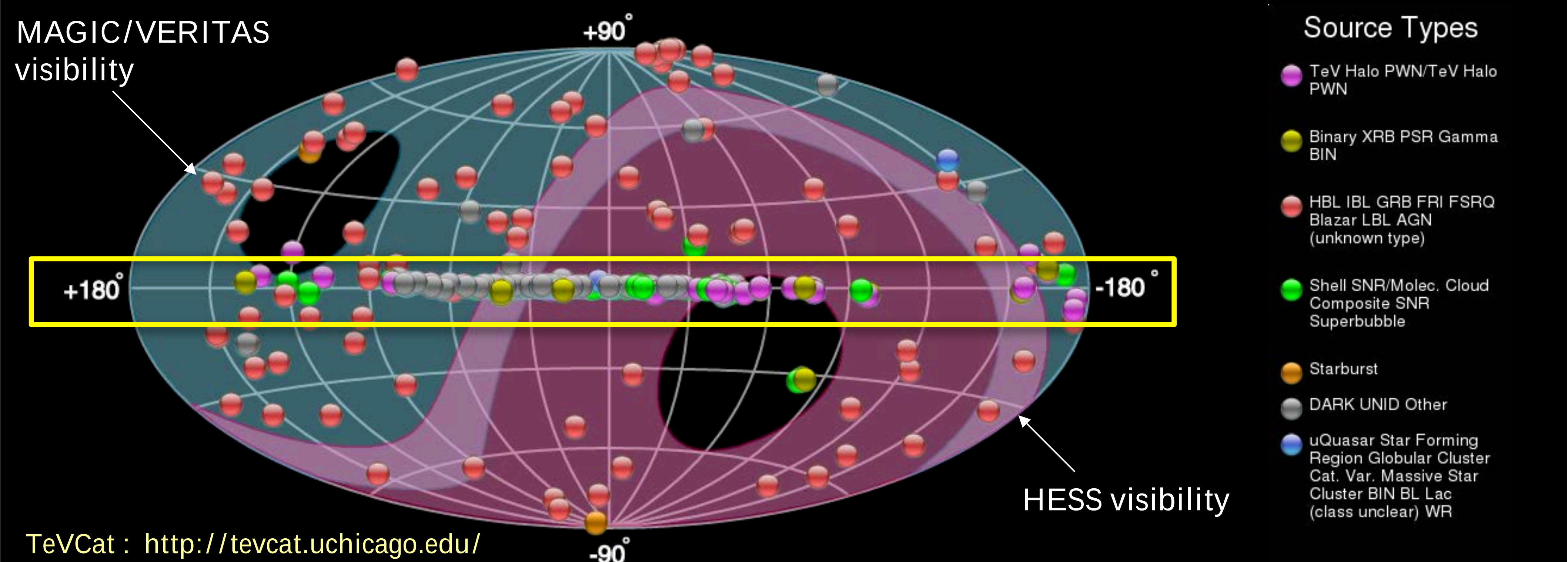
- full sky coverage
- good angular resolution

Status in the TeV range with IACT...

❖ Improved sensitivity of current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs)

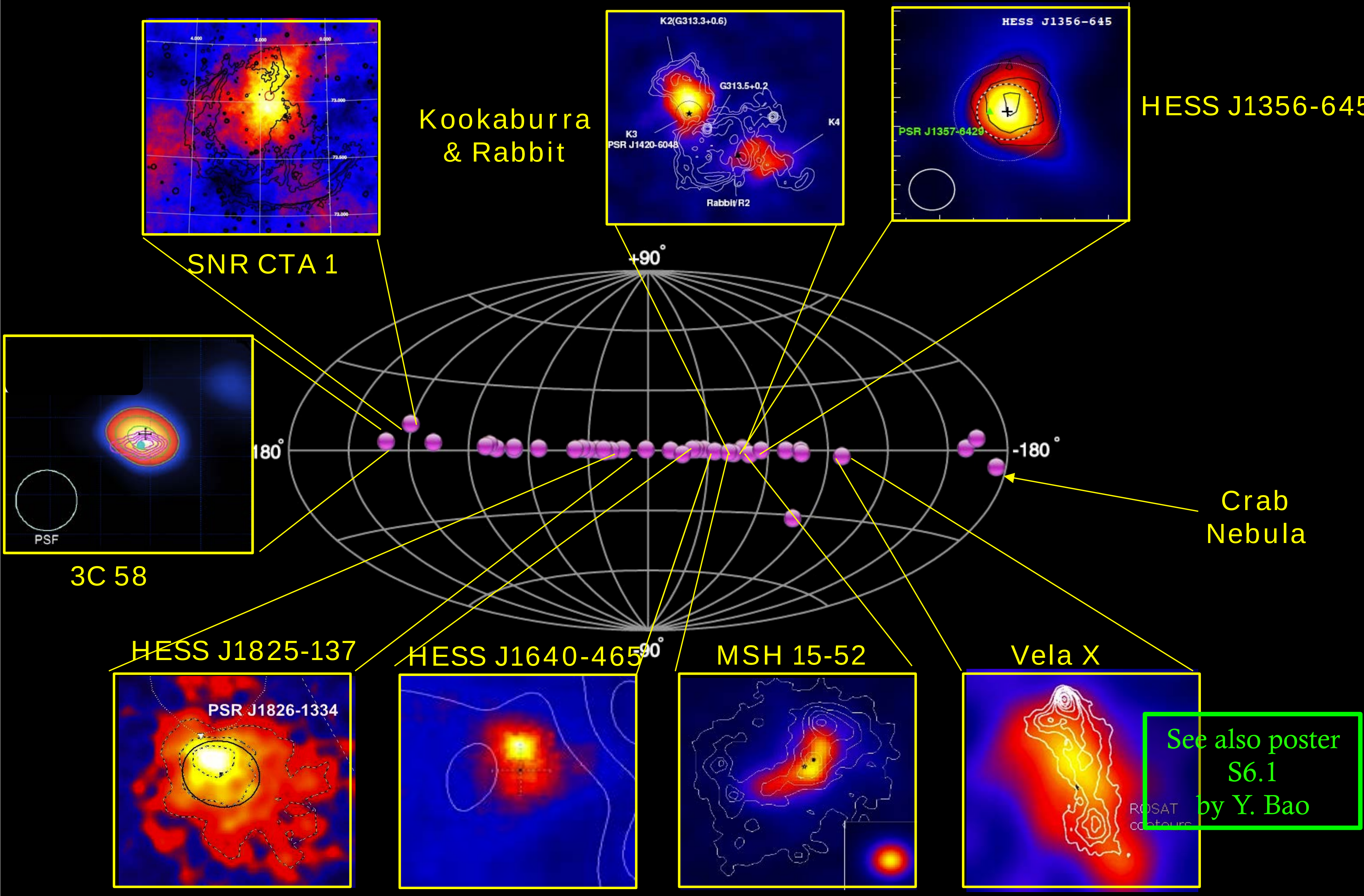
→ detection of ~210 VHE sources

→ ~120 « non-AGN » sources with |b|<5°



TeVCat : http://tevcat.uchicago.edu/

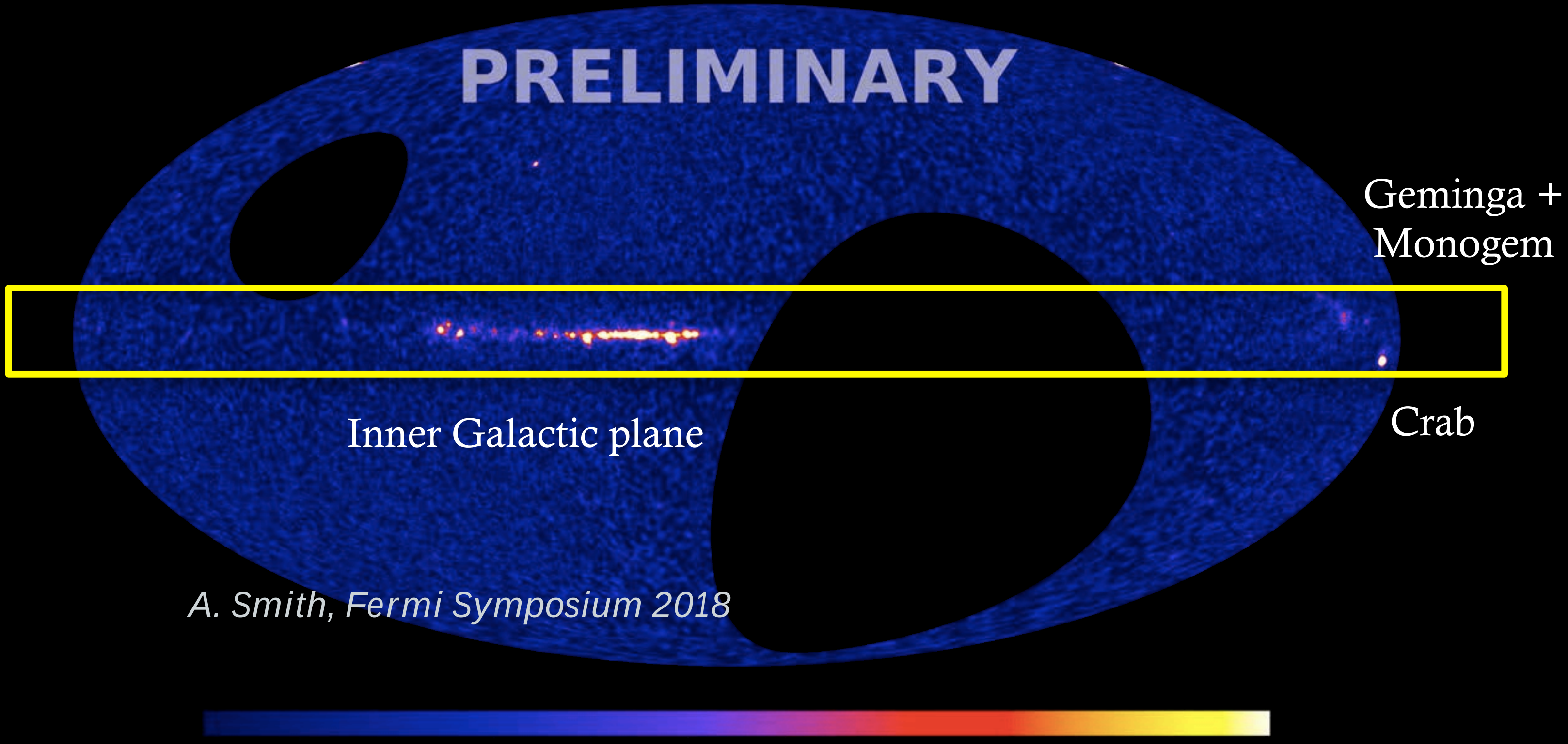
TeV observations of PWNe and candidates



...completed by the HAWC field of view

- HAWC Catalog (2HWC, 2017 with 507 days of livetime) :
  → 39 sources
    → 16 are >1° away from previously reported TeV sources (as in 2017)

HAWC 3.5 year skymap — 1128 days livetime: 2014-11 to 2018-04

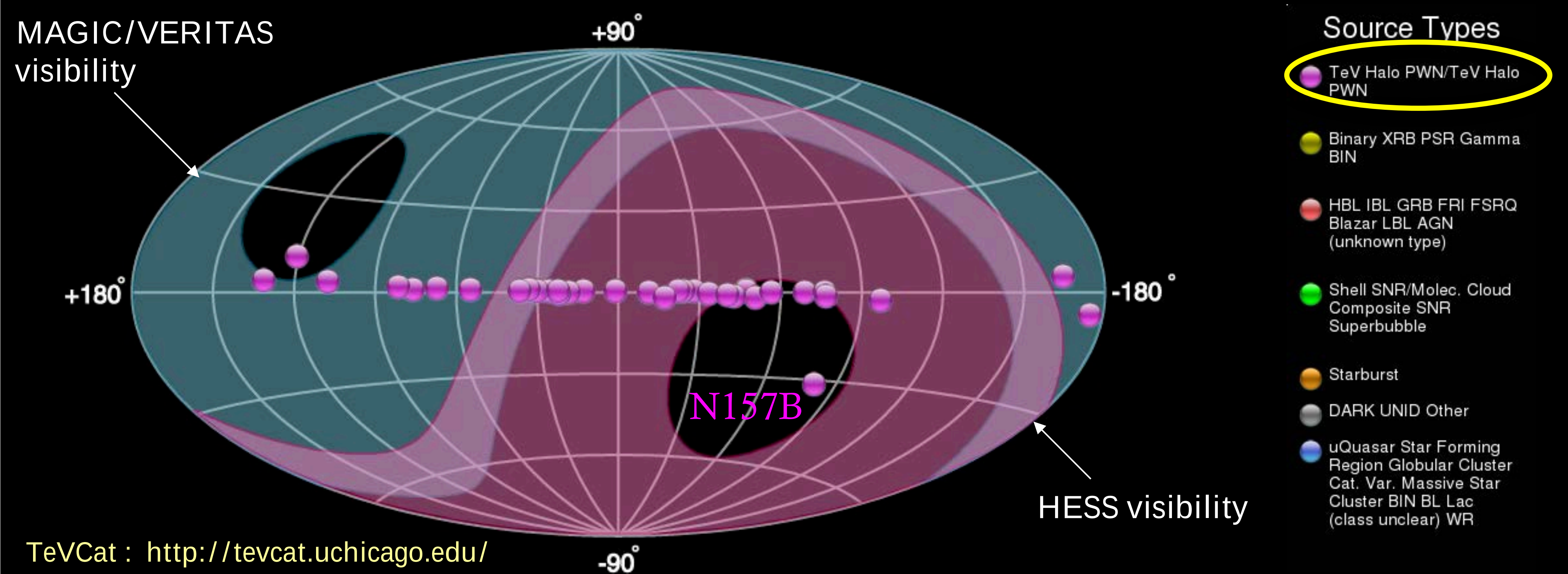


Status in the TeV range (all instruments)

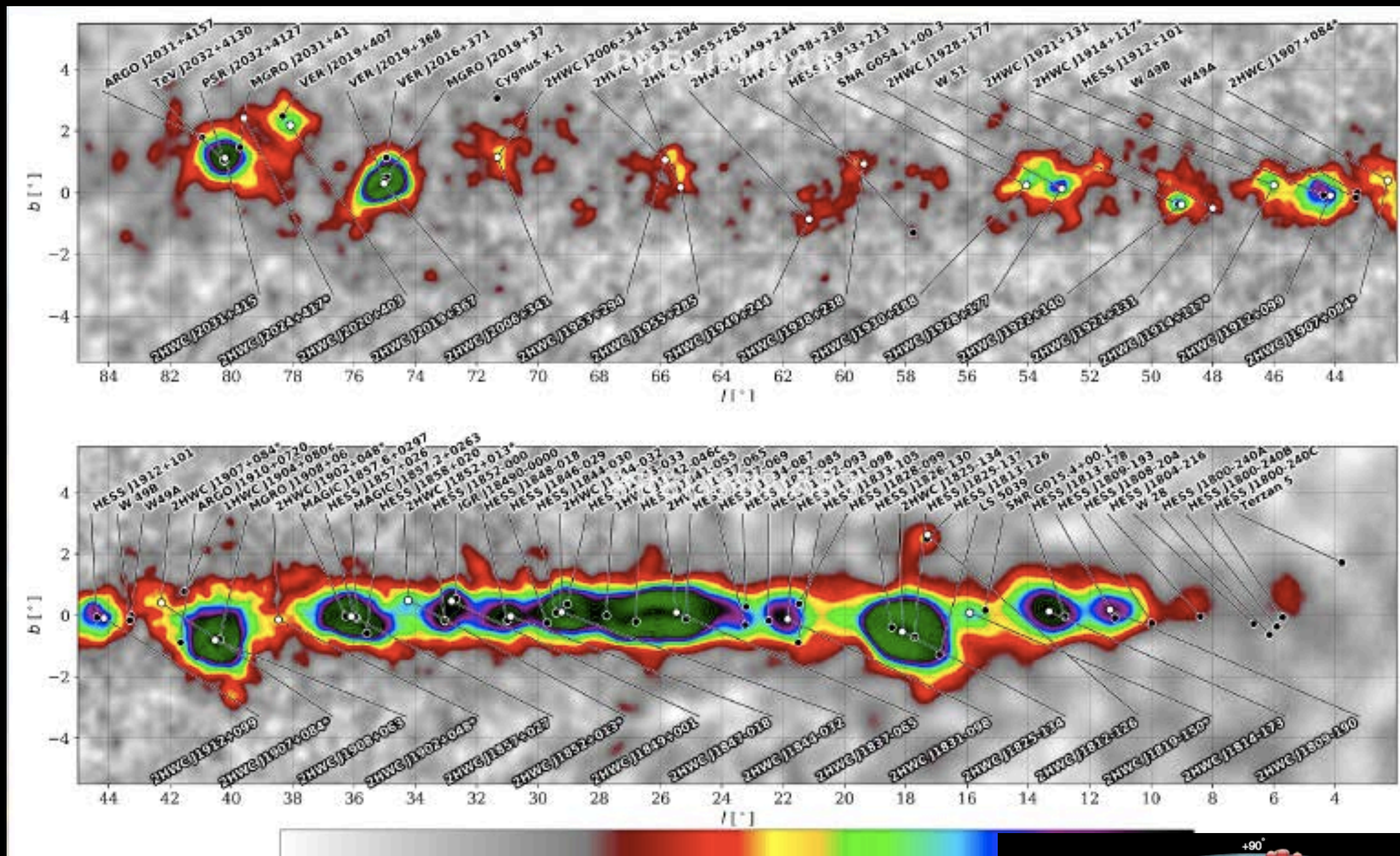
❖ ~125 « non-AGN » sources with |b|<5°

~35 are identified as PWNe, 4 TeV Halos, >15 PWN candidates

+ N157B (LMC)



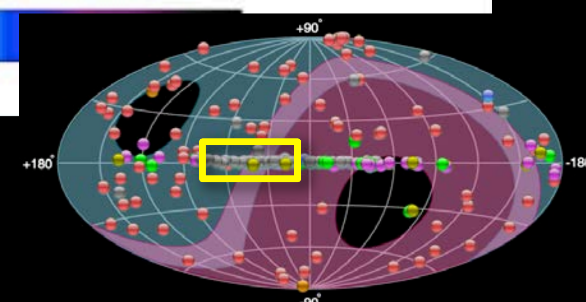
The Milky Way from TeV (HAWC)...



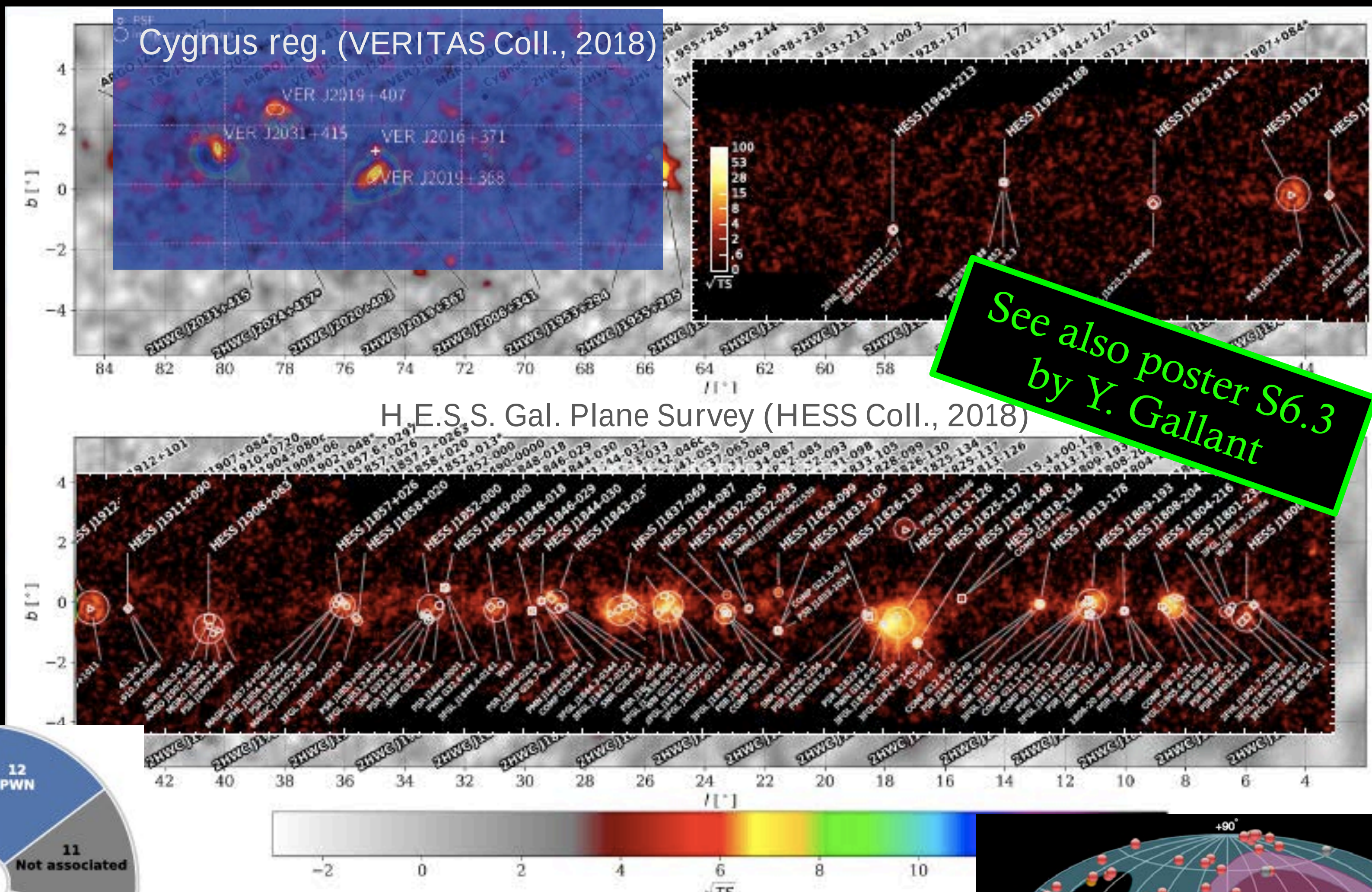
Other TeV names

HAWC names

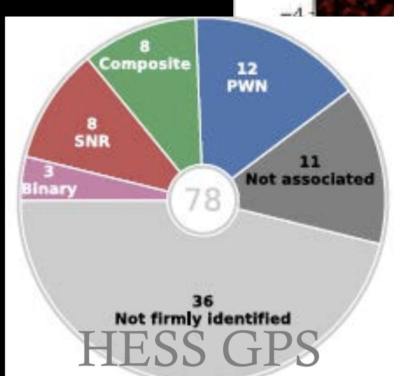
Second HAWC Catalog (2017)

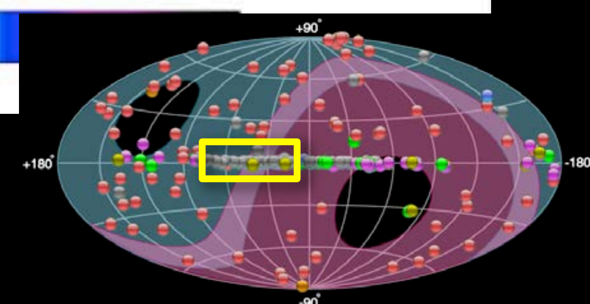


The Milky Way from TeV (HAWC + IACT)...

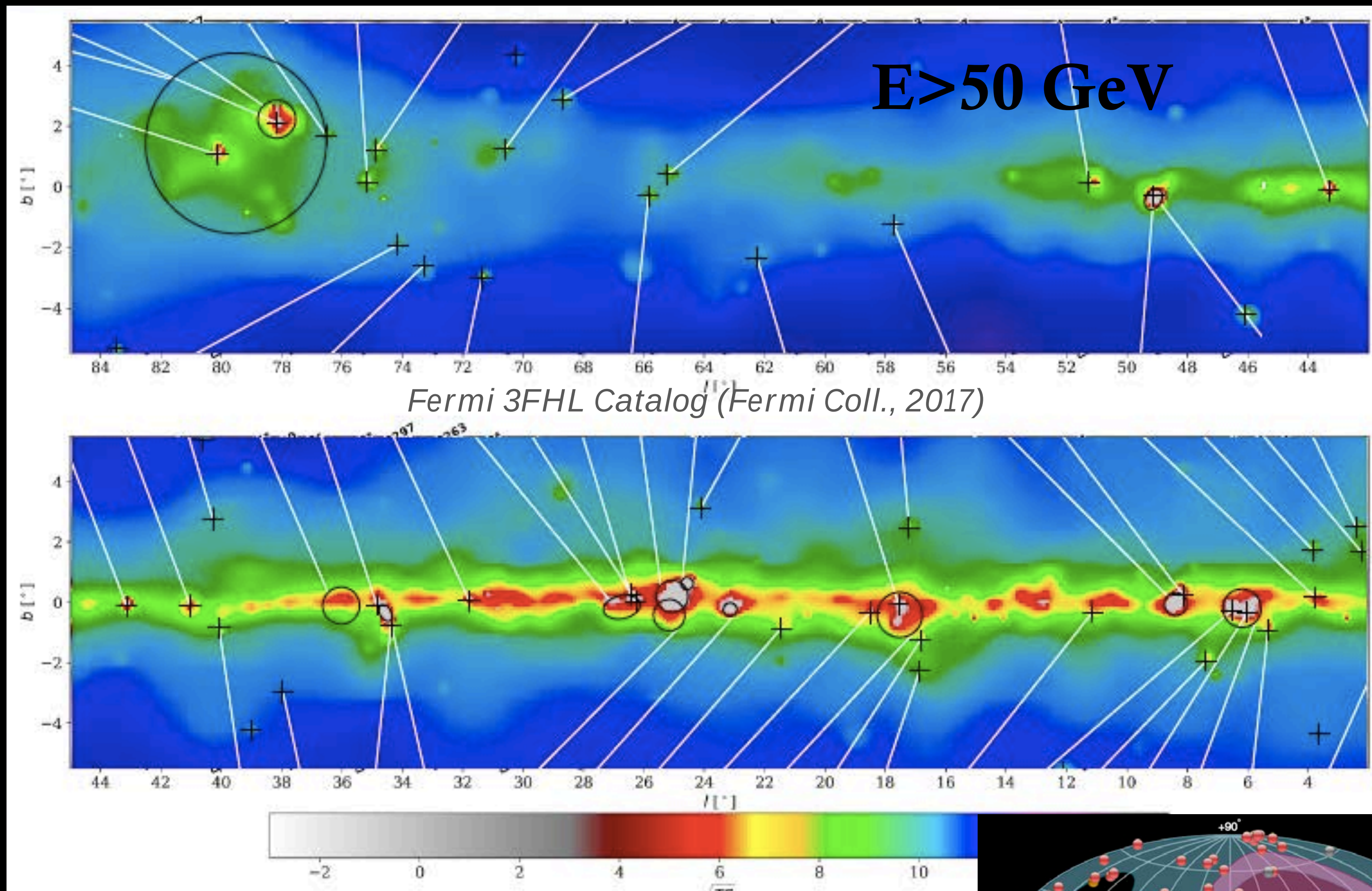


See also poster S6.3 by Y. Gallant

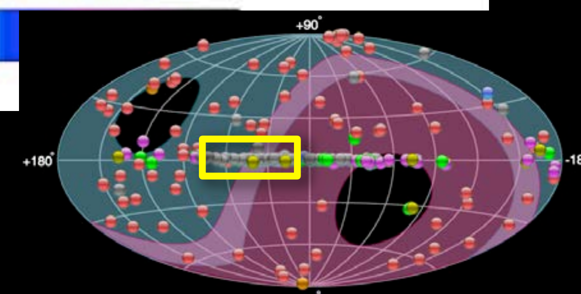




...to GeV (Fermi-LAT)



Fermi 3FHL Catalog (Fermi Coll., 2017)



- 3FHL Catalog (E>50 GeV) : 1556 sources
  - 9 firmly identified PWNe, 8 PWN candidates, 9 composite candidates

Why do we detect so few GeV PWNe ?

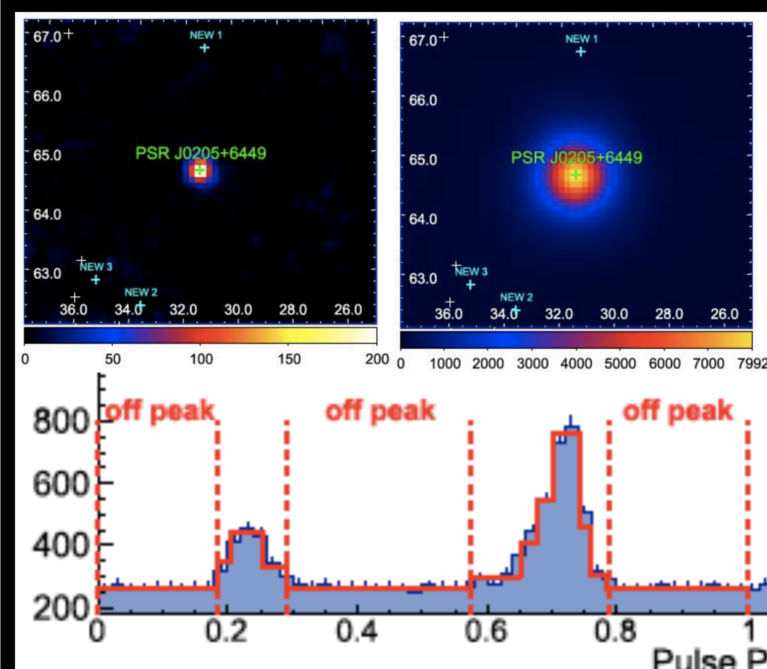
❖ PWN studies (detection, morphological & spectral analyses) require :

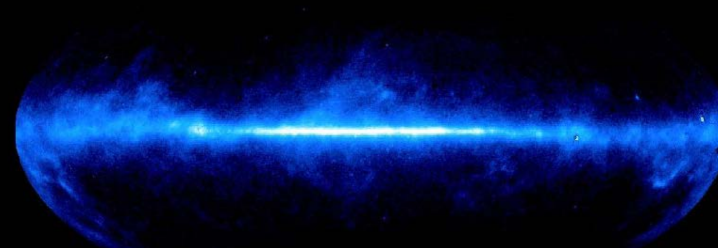
- A temporal analysis of the powering pulsar & substraction of the pulsed component

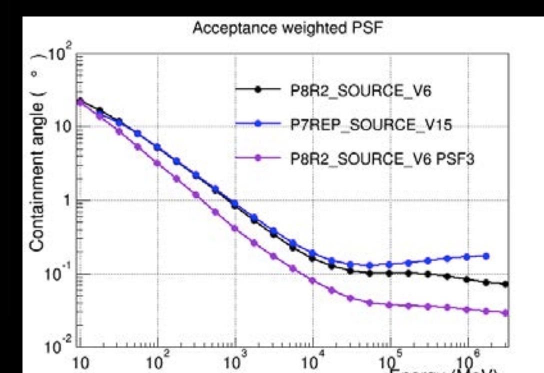
- A good knowledge of :

  - The diffuse background (spatial & spectral structures in the Galactic diffuse emission)

  - The instrumental point spread function (PSF) varying over the LAT range (~5° to 0.1°)







Status in the GeV range

Observations by gamma-ray satellites AGILE (since April 2007) and Fermi (since June 2008)

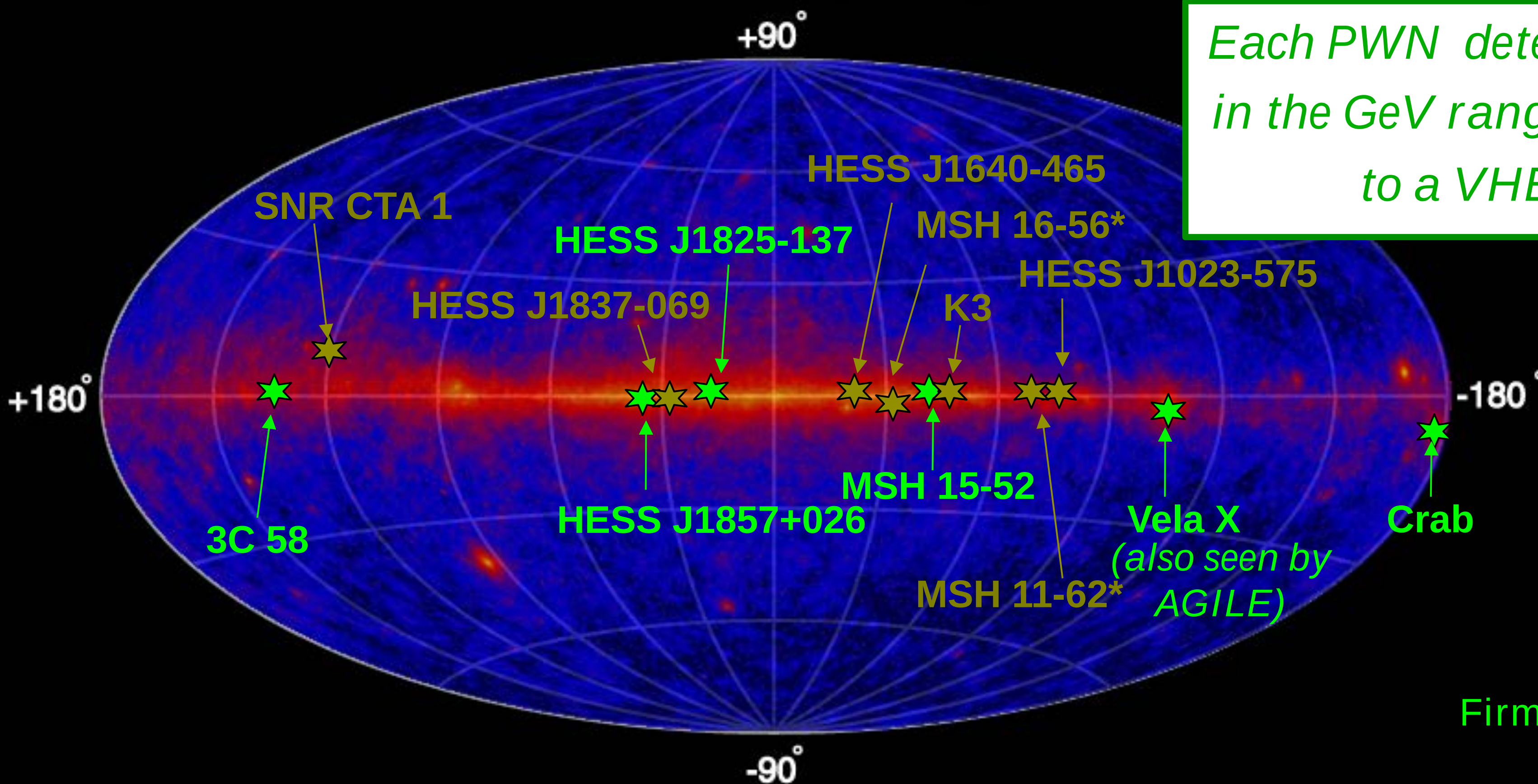
→ detection of >5000 sources from 50 MeV to 1 TeV *(8 yrs, 4FGL Catalog, 2019)*

→ ~25% unassociated sources

→ 18 PWNe or candidates (15 being extended)

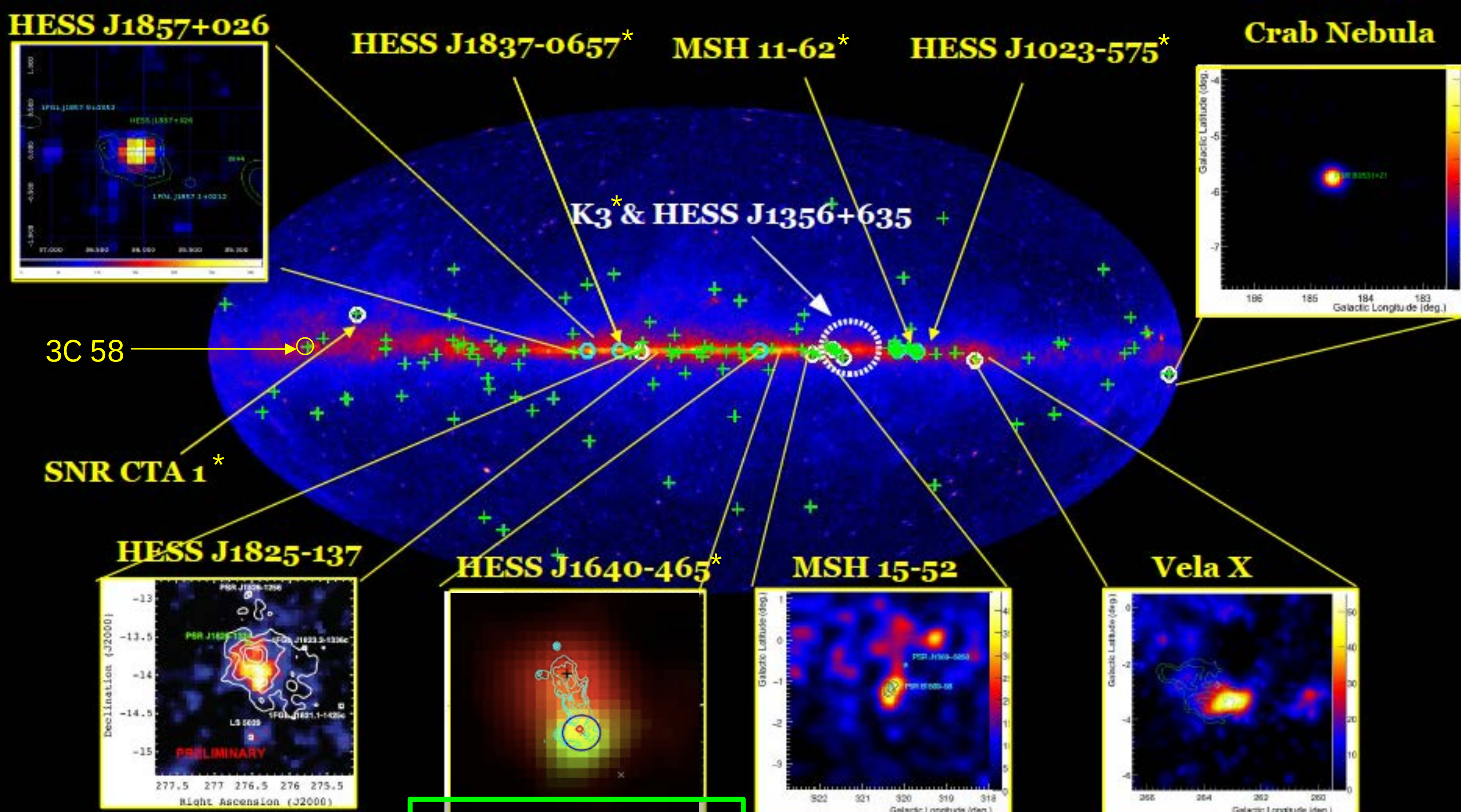
Fermi

*Each PWN detected (except *) in the GeV range is associated to a VHE source*



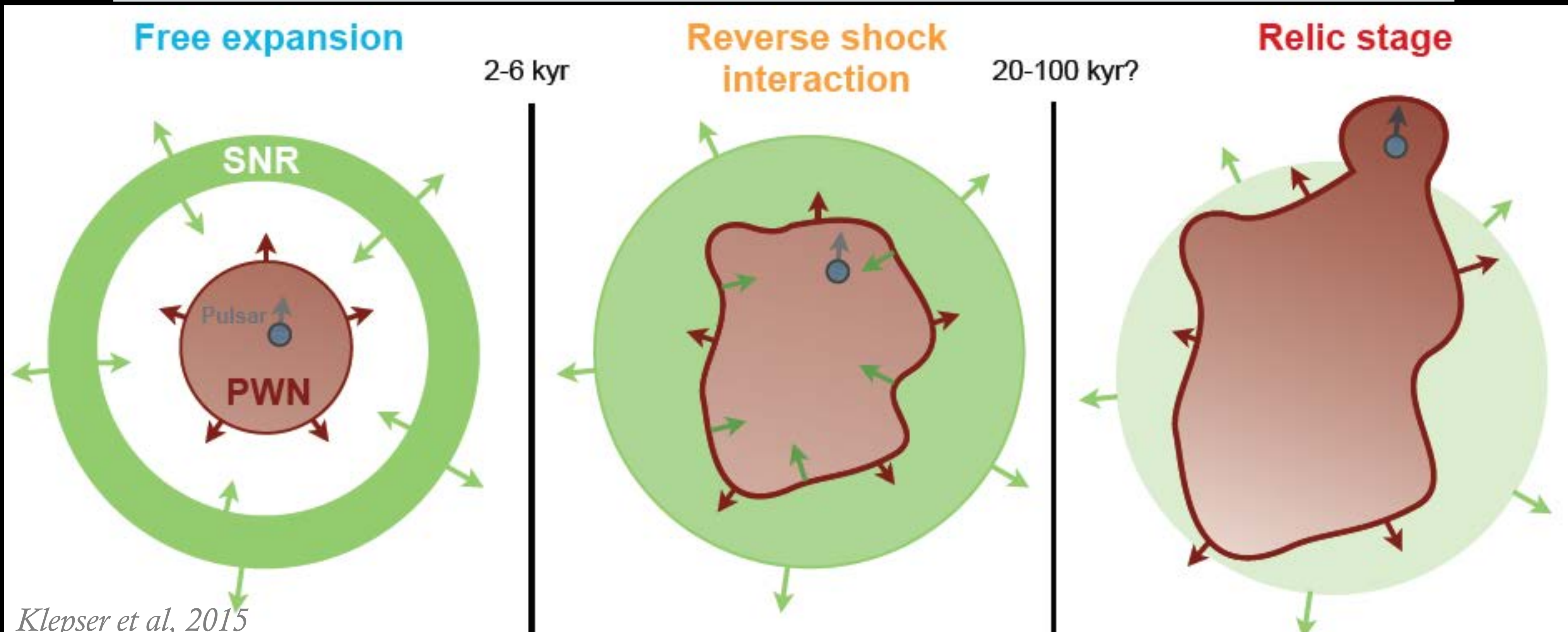
PWN candidates
Firmly identified PWNe

PWNe and candidates in the GeV sky



See also poster
S4.8 by
M. Lemoine-Goumard

PWN evolution in a nutshell



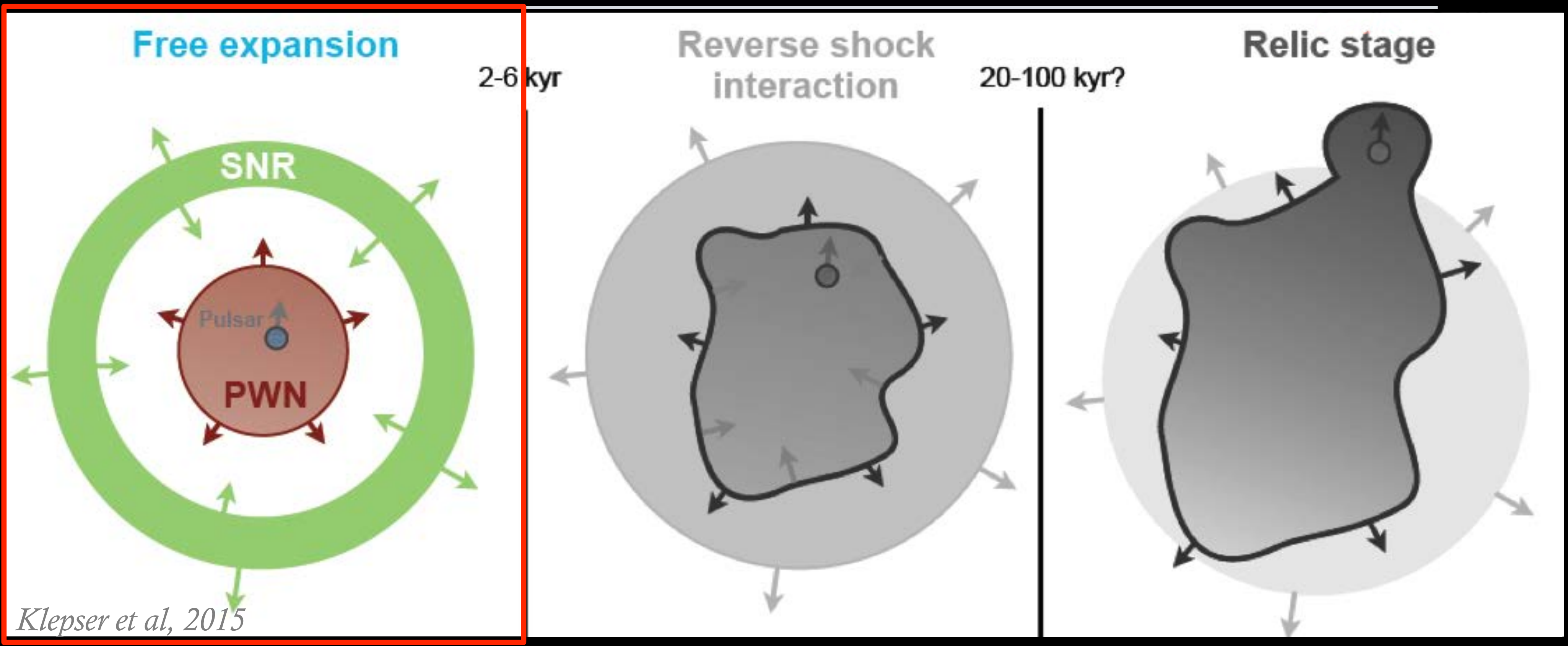
1) Young PWNe

2) Middle-aged /offset PWNe

3) TeV Halos

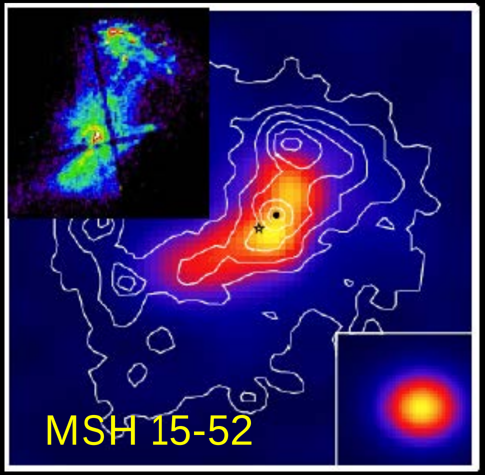
4) PWN candidates

1. Young PWNe



GeV-TeV : Crab Nebula, MSH 15-52, 3C 58

TeV only : SNR G0.9+0.1, SNR G21.5–0.9, Kes 75, HESS J1813–178, SNR G54.1+0.3, Rabbit



The Crab Nebula, the brightest VHE source...

Brightest VHE galactic «steady» source, observed by every Cherenkov experiment & Fermi

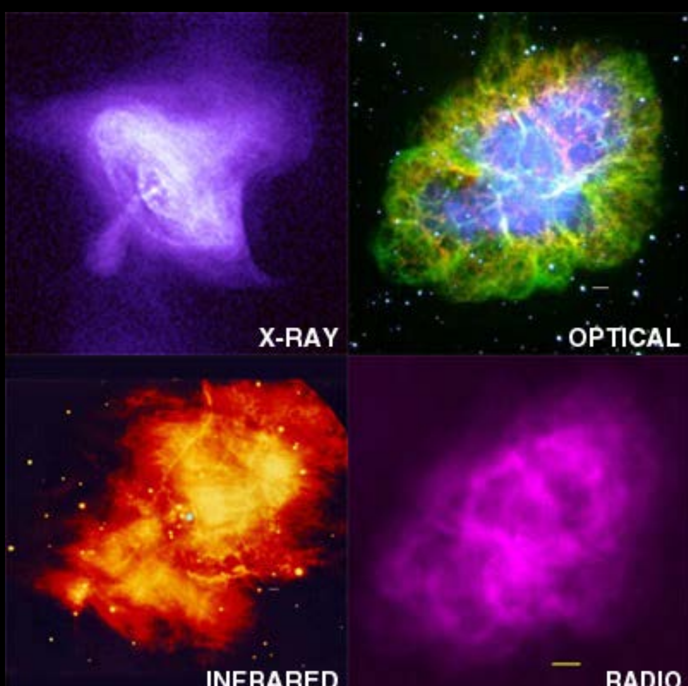
- γ-ray emission below 500 MeV due to synchrotron emission

  → electrons accelerated up to ~1 PeV

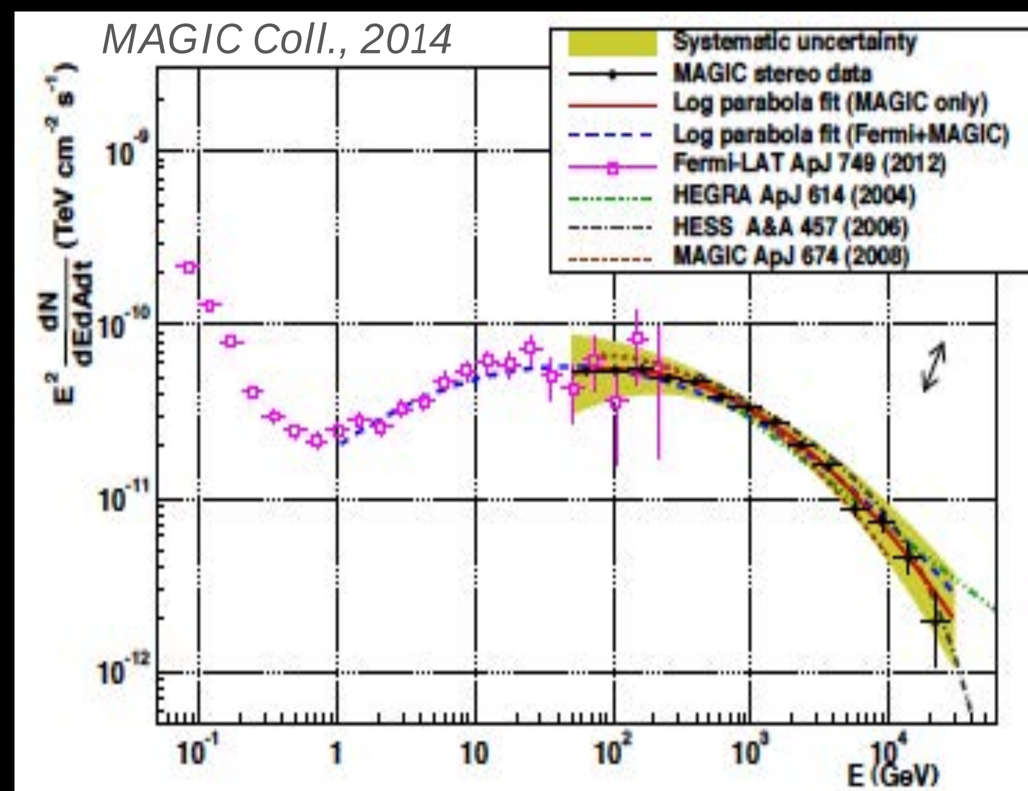
- high energy component due to IC (mainly on synchrotron photons)

  → fit of the IC peak at ~53 GeV (using Fermi and MAGIC results)

  → magnetic field constraint in the 100 – 200 μG range



Radio size : 7’ x 5’ / X-ray : 2,1’



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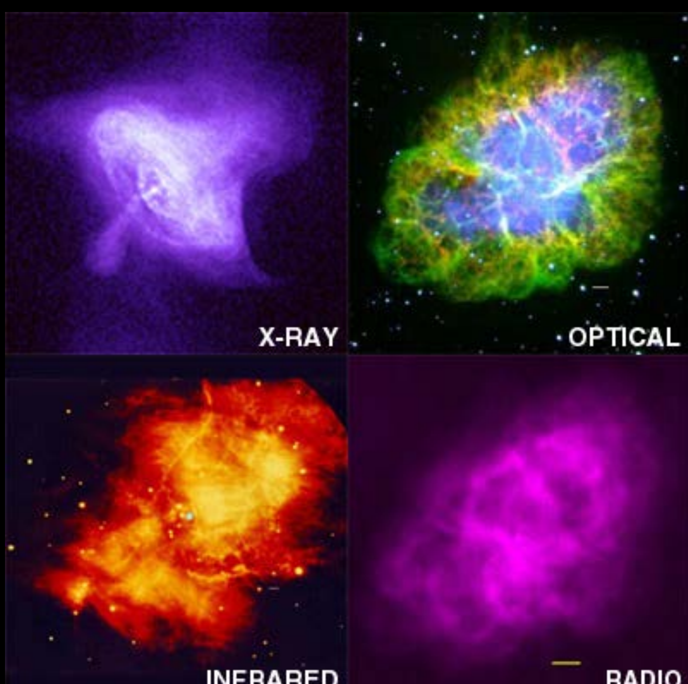

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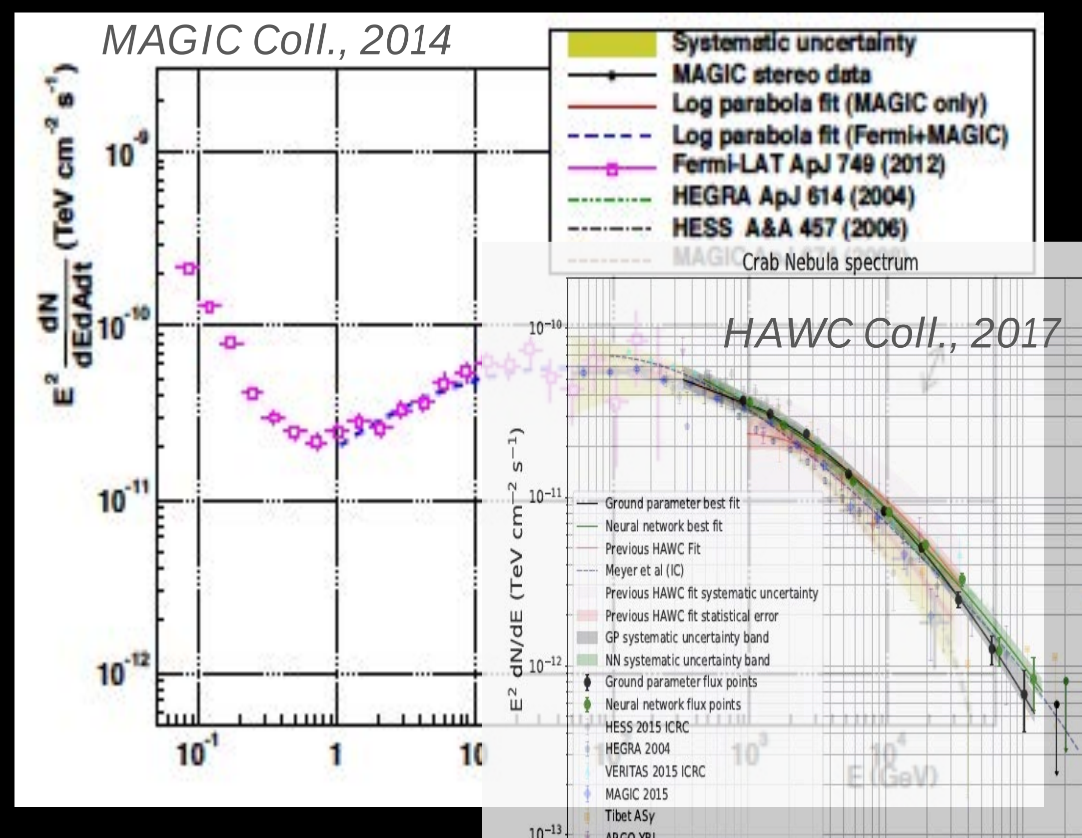
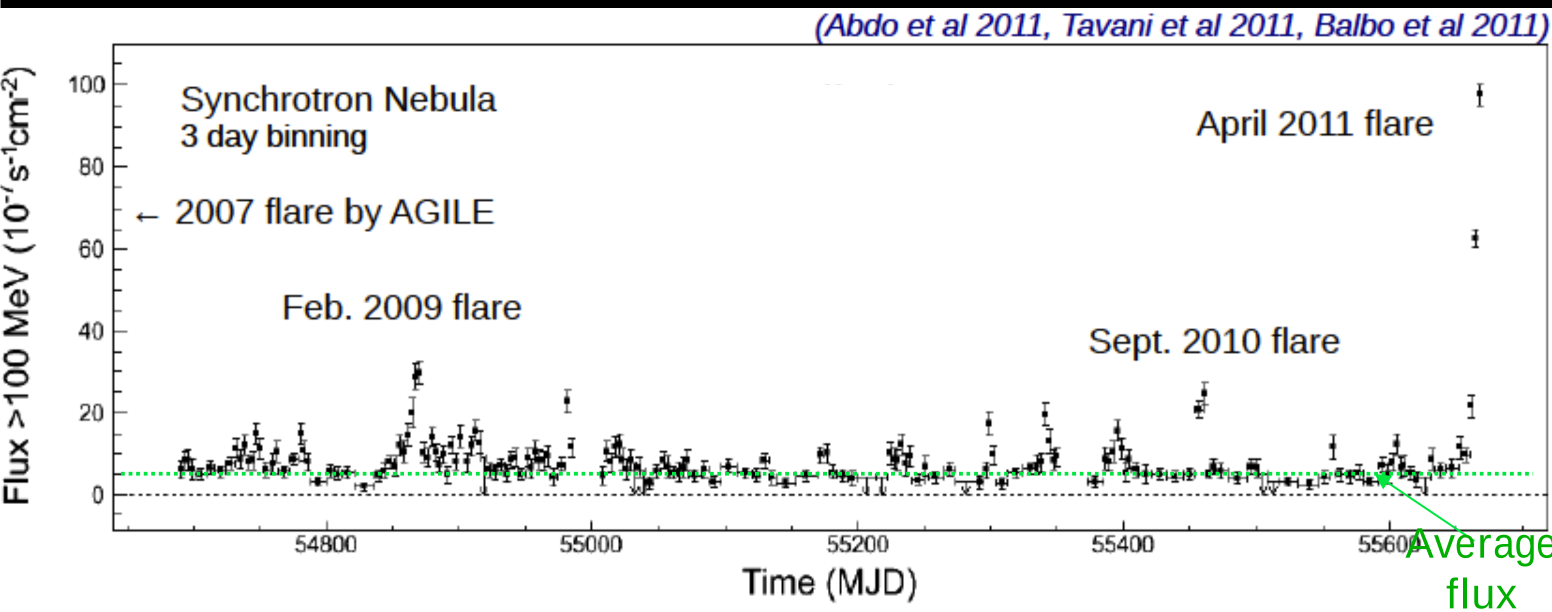
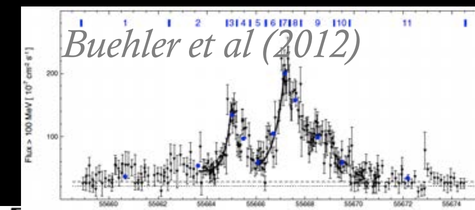
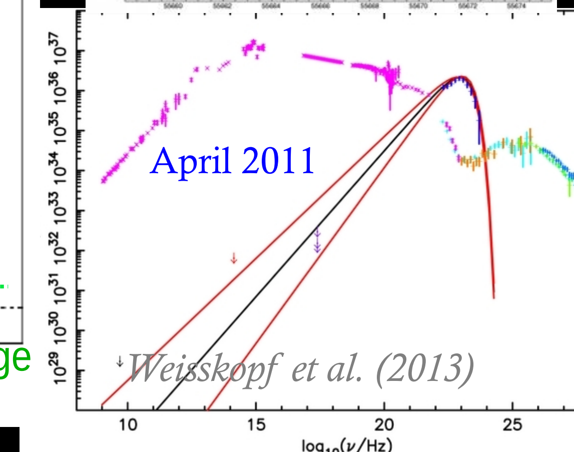


... but no more a standard candle

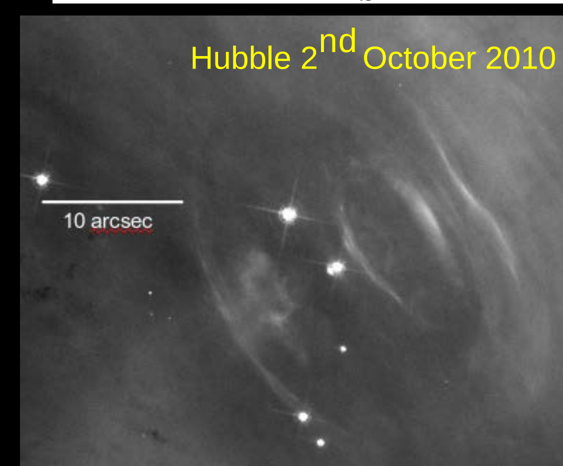
Recent Flares of the synchrotron component (Oct. 2007, Feb. 2009, Sept. 2010, Apr. 2011, July 2012, March 2013, October 2013, March 2014) :







<u>*Three day Crab synchrotron curve*</u>

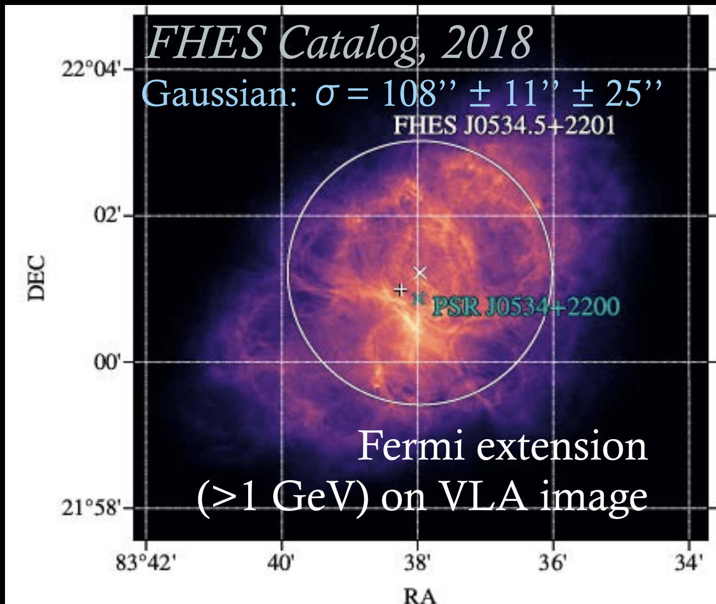


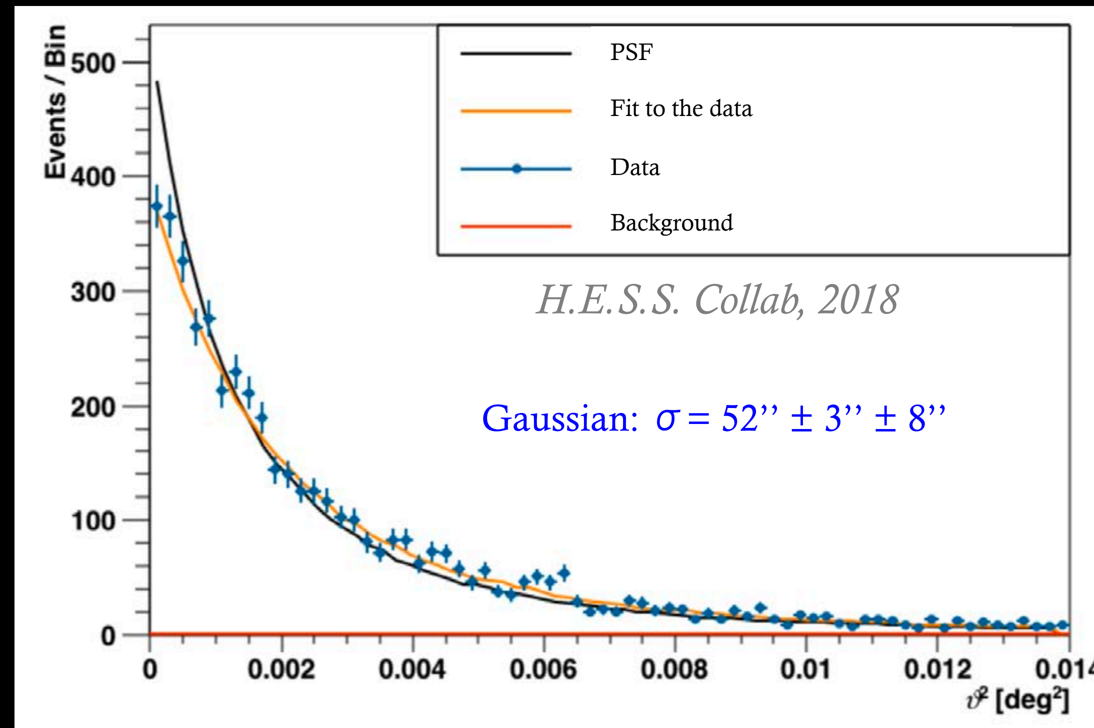
- *Flux increase by ~5-6 during 2009, 2010, March 2013 flares, by ~30 during 2011 flare !*

- *Compact emission region < 0.0004 pc ~ 0.04'' (for D<4)*

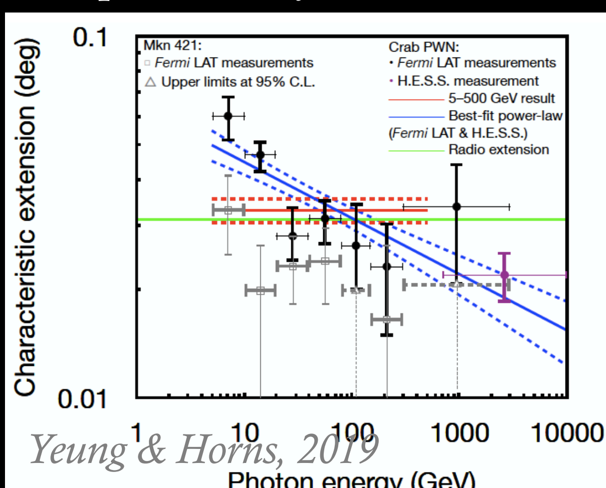
  → *Emission from the inner nebula*

... and now resolved in GeV and TeV

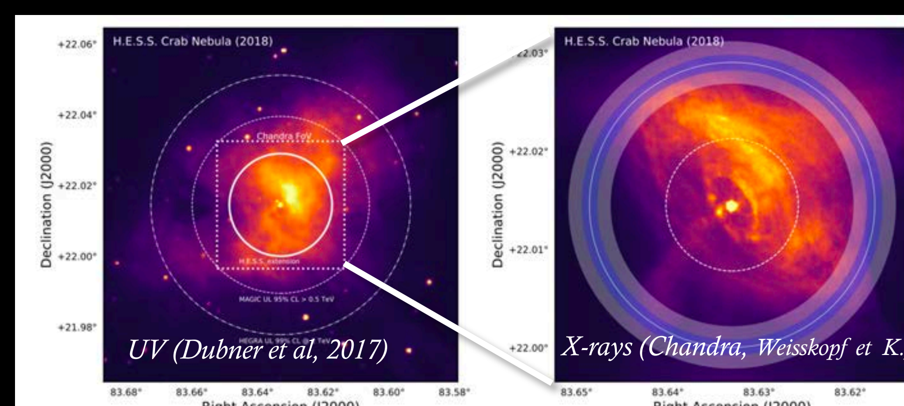




Hint of enery-dependent radius, not consistent with cooling
=> requires a very detailed modeling



TeV size > X-ray size

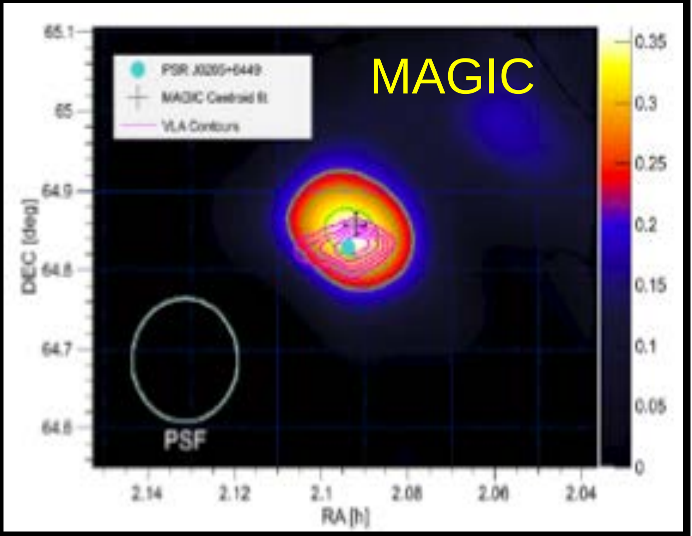


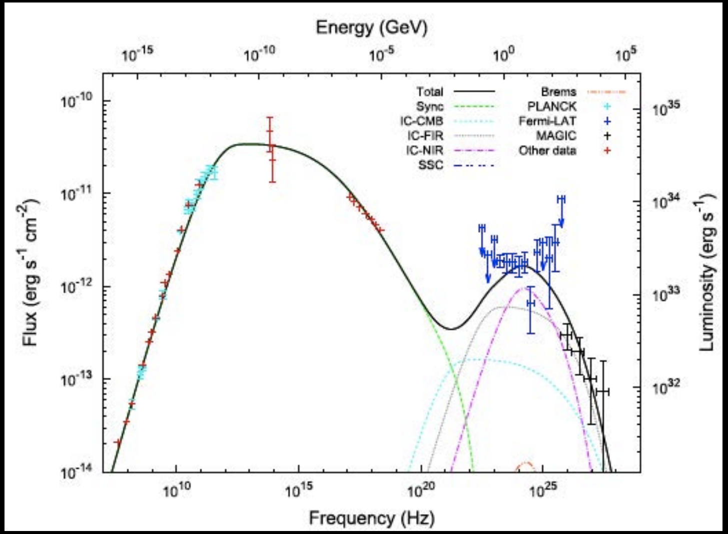
The PWN 3C 58

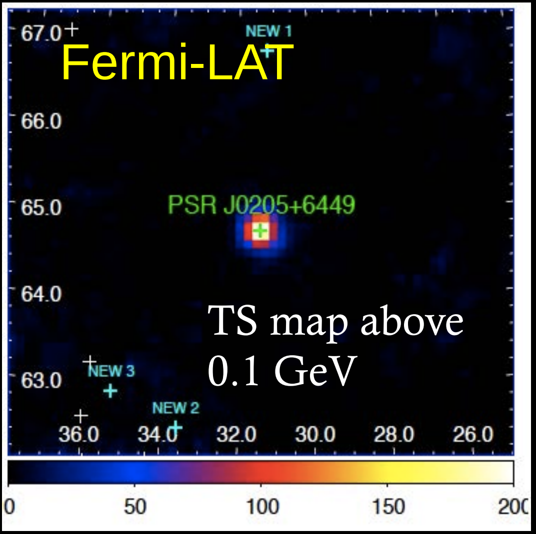
See also poster S6.2 by G. Castelletti

- Associated to the energetic pulsar PSR J0205+6449 ($\dot{E}$ = 2.7×10^{37} erg/s, τ_{char} = 5.4 kyr, P = 65.7 ms)
  - Radio angular size : 6' x 9'
  - Distance : 2 kpc ? 3.2 kpc ?
  - Age : < 1 kyr *(Stephenson 1971, Stephenson & Green 2002)* or ~5 kyr ? (*Murray et al. 2002; Bietenholz 2006; Slane et al. 2002)*
- Detection of gamma-ray emission by :
  - Fermi-LAT *(Ackermann et al, 2013, Li et al, 2018)*
  - MAGIC *(Aleksic et al, 2014)*
- Time dependent spectral modeling *(Torres et al, 2013)* : disfavors the association with SN 1181 C.E.


Chandra (Slane et al, 2008)

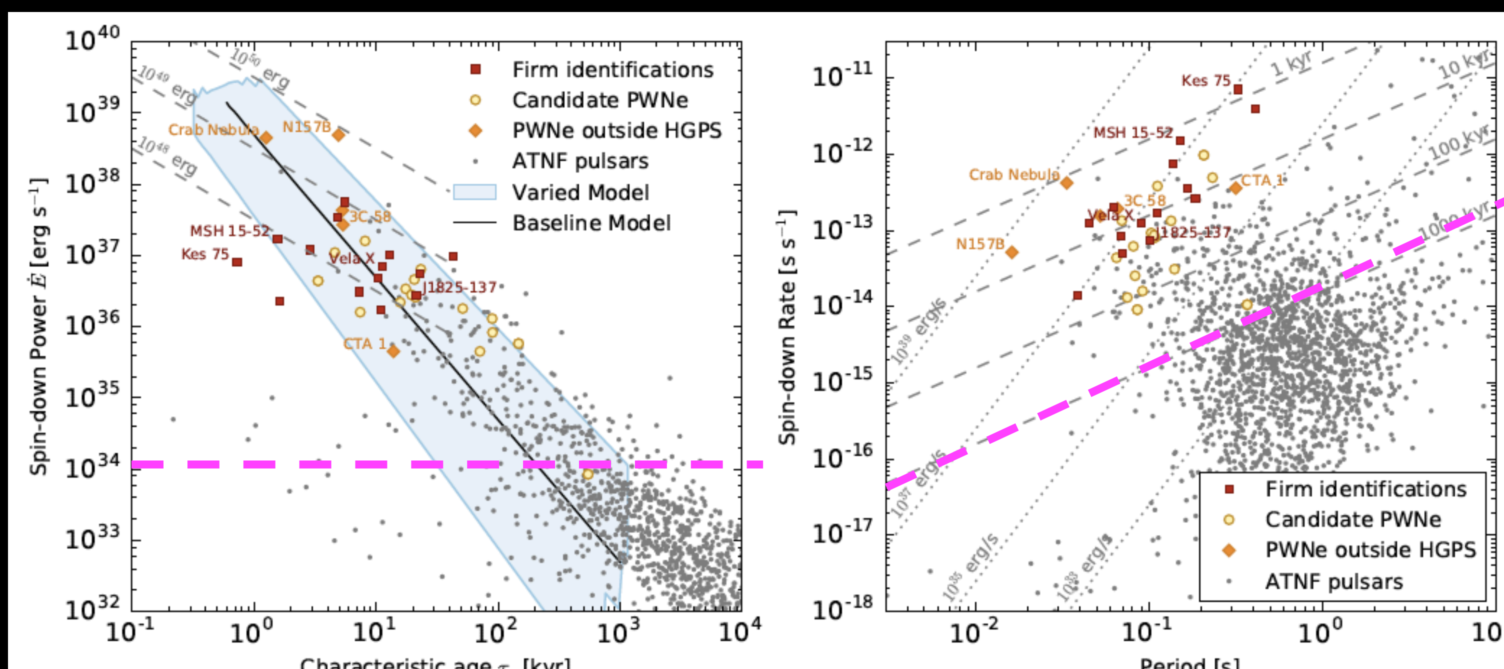






Common trends for young PWNe

- From the H.E.S.S. GPS => Population of TeV PWNe on 14 + 5 firmly identified PWNe and 18 PWN candidates *(HESS Coll, PWN pop, 2017)*
  - TeV PWNe (and some the GeV ones) powered preferentially by young (<100 kyr) and energetic (dE/dt > 10^{34} erg/s) pulsars



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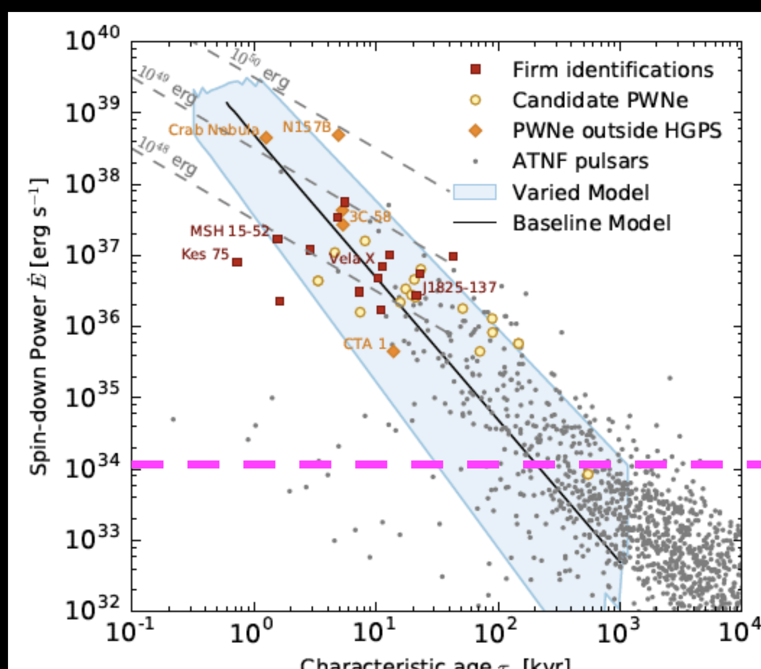
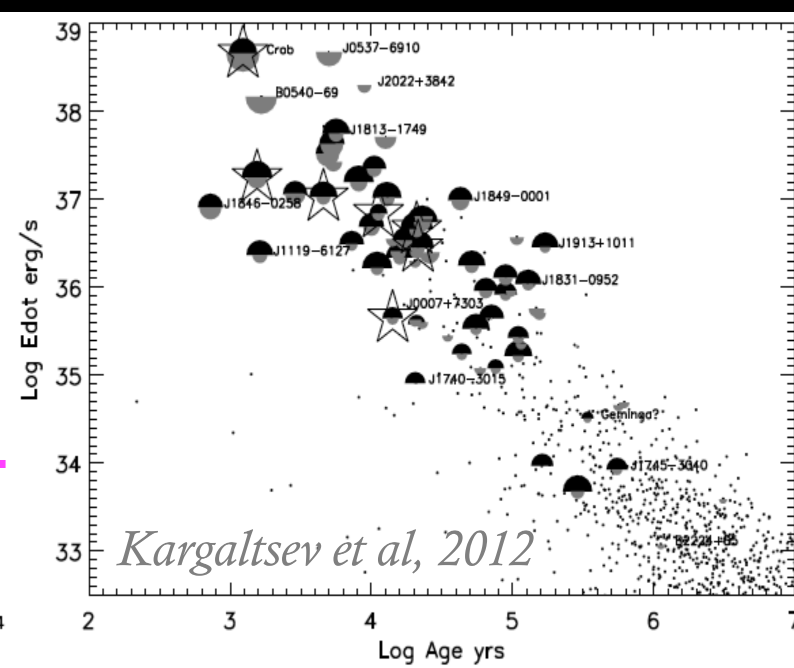
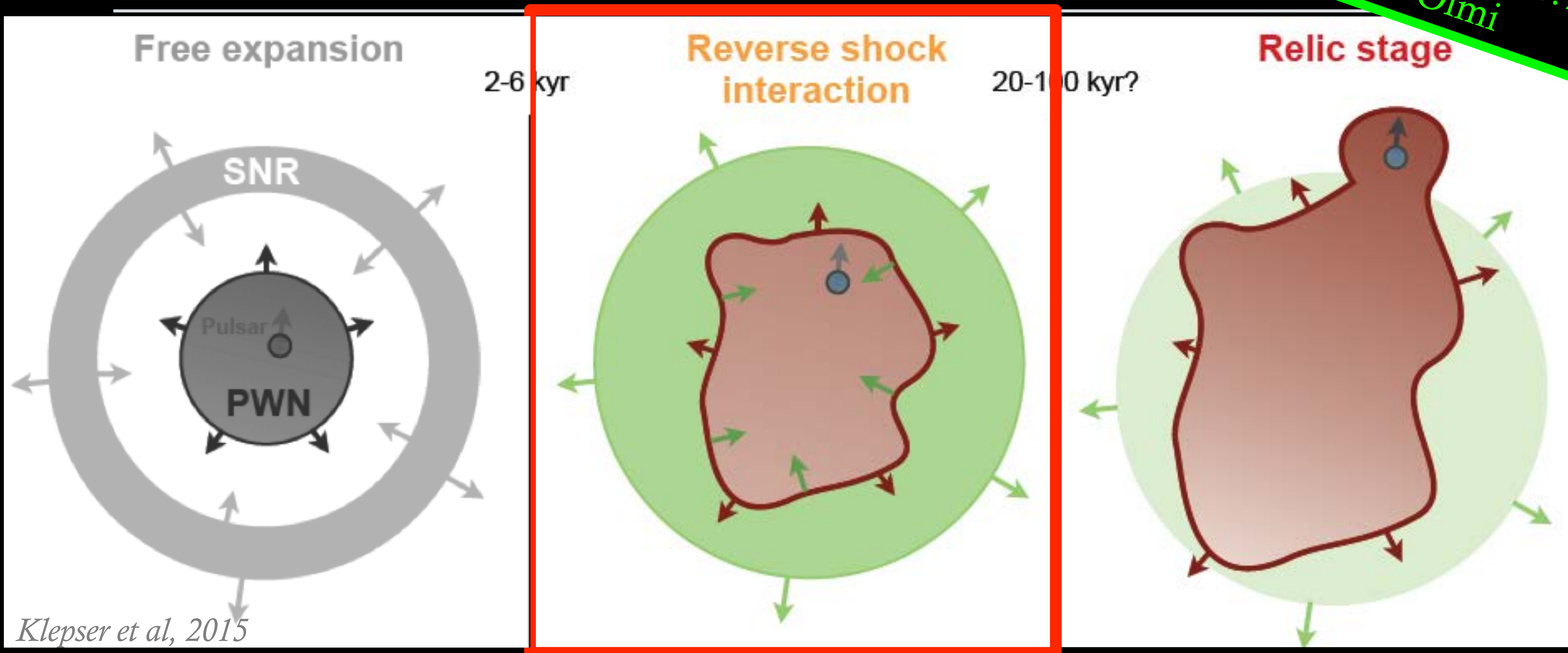




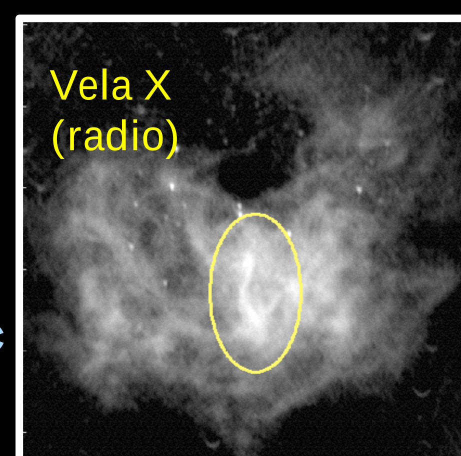
2. Middle-aged/offset PWNe

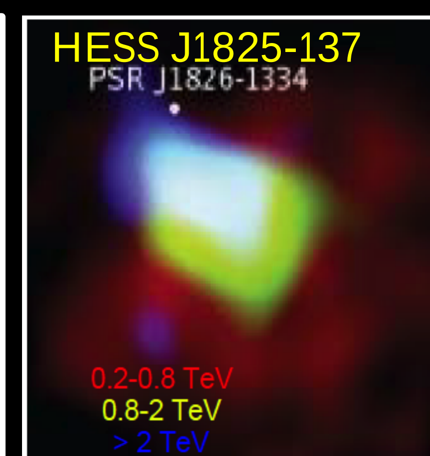
See also poster S6.7 by B. Olmi



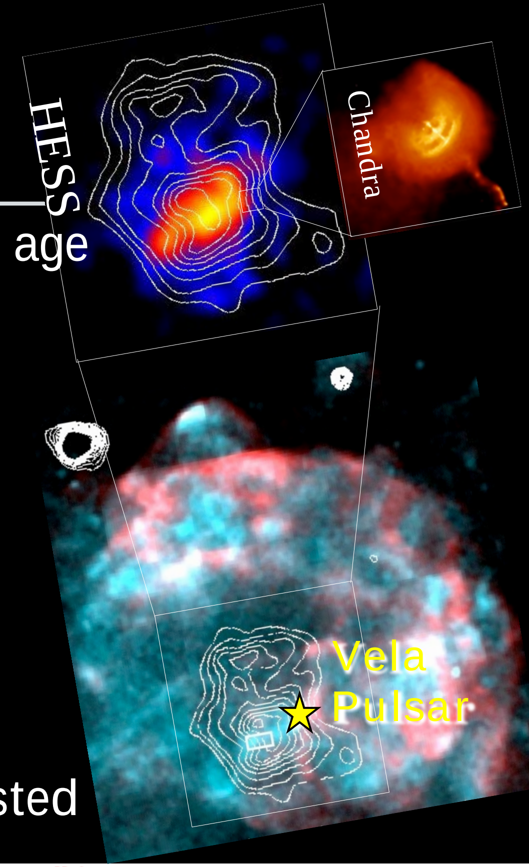
GeV-TeV : Vela X, HESS J1825-137, HESS J1857+026

TeV only : HESS J1303-631, HESS J1356-645, HESS J1837-069

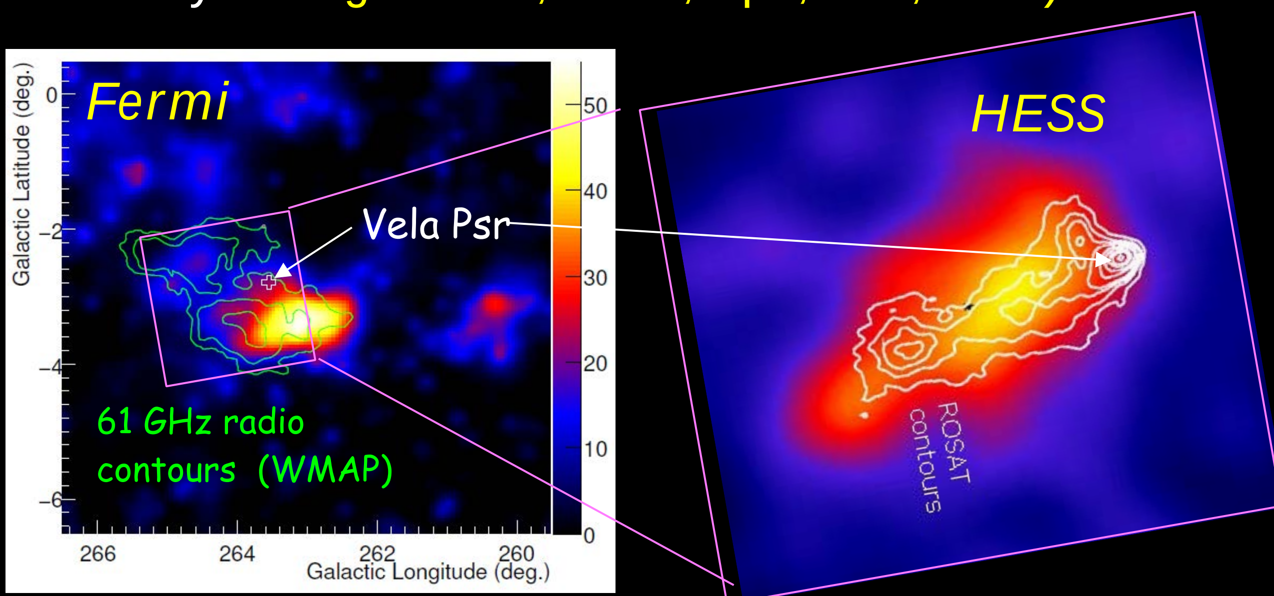


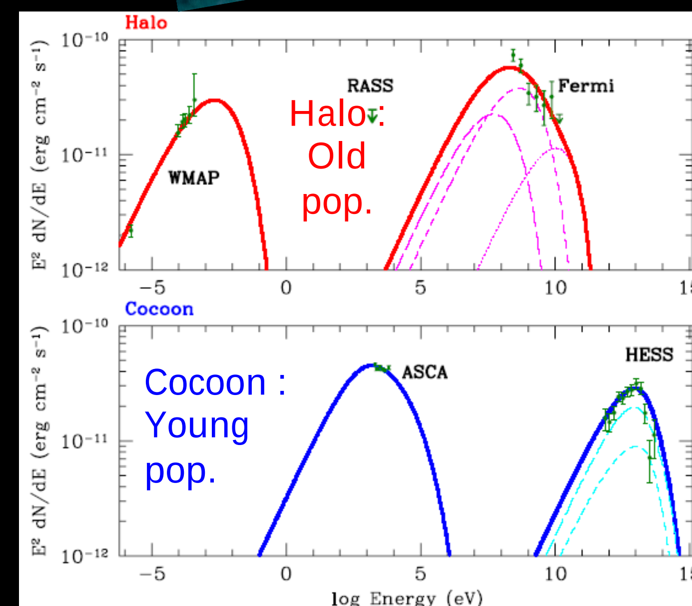


The puzzling Vela X



- Associated with the Vela Pulsar (d = 290 pc, $\dot{E}$ = 7 10^{36} erg/s, age ~11 kyr)
- Offset from the pulsar
- Status in 2011 :
  - Morphology :
    - Radio & HE gamma-rays : Halo (2° x 3°)
    - X-rays & VHE : Cocoon (length < 1°)
  - Multi-wavelength spectrum :
    - strongly favors a two-component leptonic model (suggested by de Jager et al., 2008, ApJ, 689, L125)



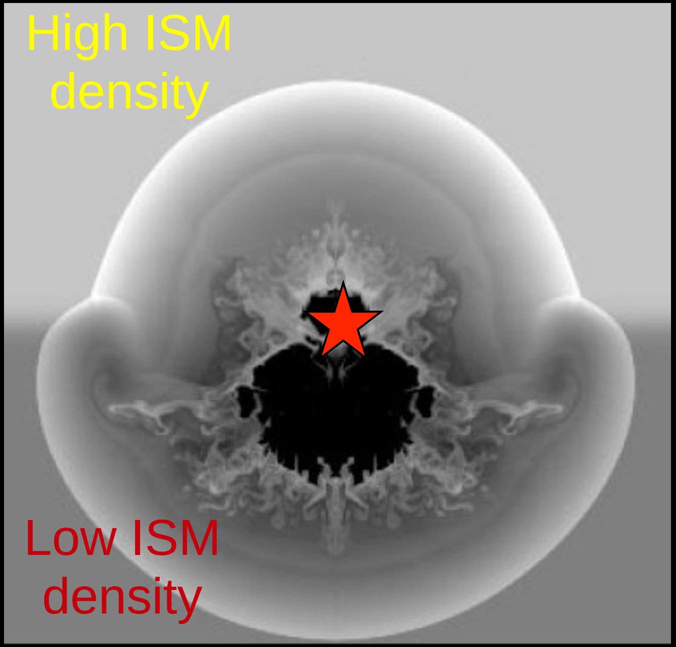


Multi-wavelength spectrum of Vela X

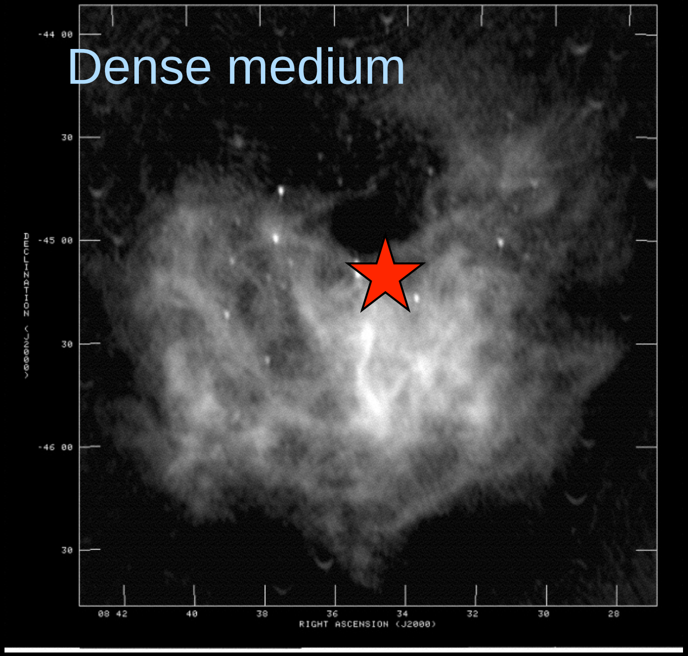
Why is Vela-X offset ?

« ... asymmetries in the surrounding interstellar medium give rise to asymmetries in the position of the PWN relative to the pulsar and explosion site.... »

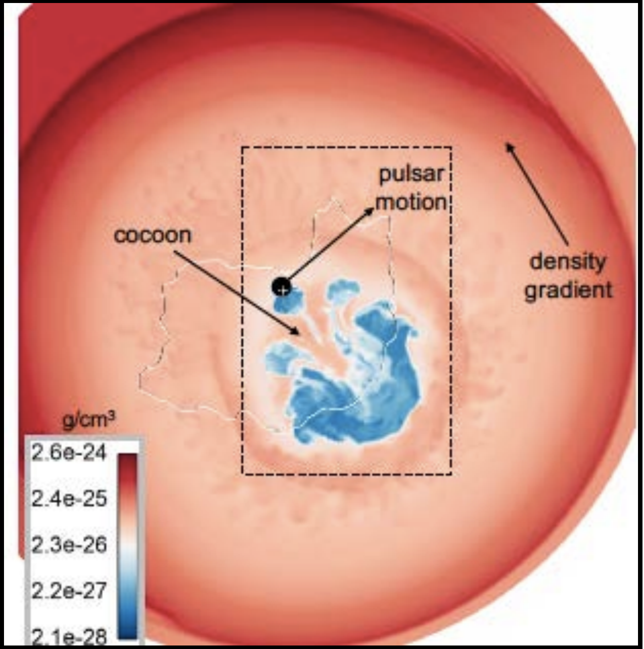
Blondin et al, 2001



Frail et al, 1996

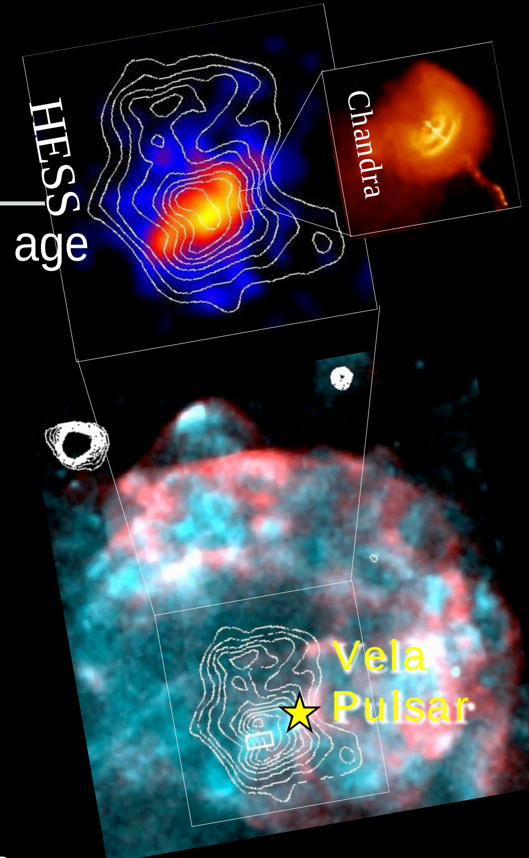


Slane et al, 2018



See also talk by T. Temim on Wednesday

... and even more puzzling !



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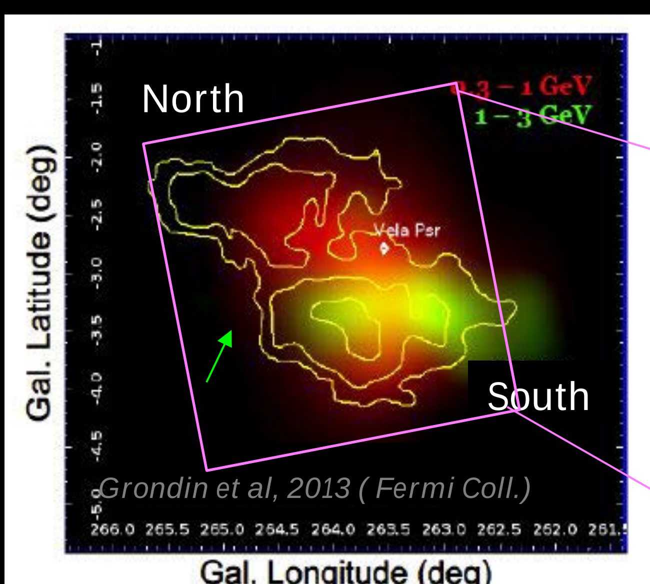
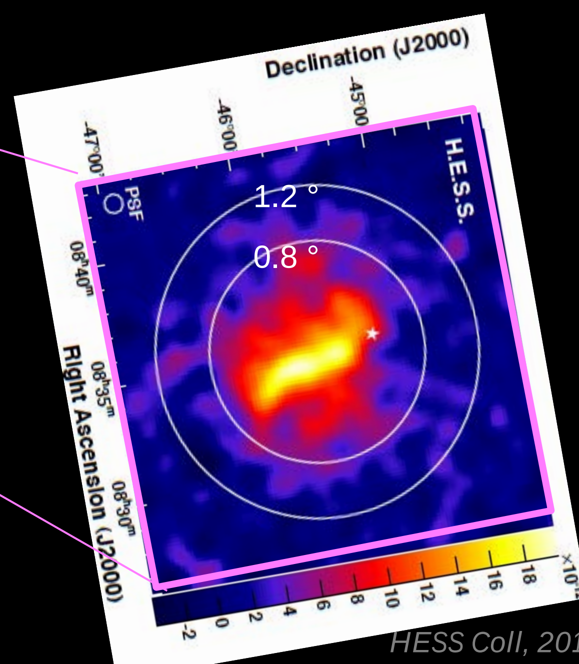
- Offset from the pulsar
- Status in 2011 :
  - Morphology :
    - Radio & HE gamma-rays : Halo (2° x 3°)
    - X-rays & VHE : Cocoon (length < 1°)
- Status in 2012-2013 :
  - Energy dependent morphology seen with Fermi
  - H.E.S.S. : Faint emission extends beyond the X-ray cocoon



Grondin et al, 2013 (Fermi Coll.)

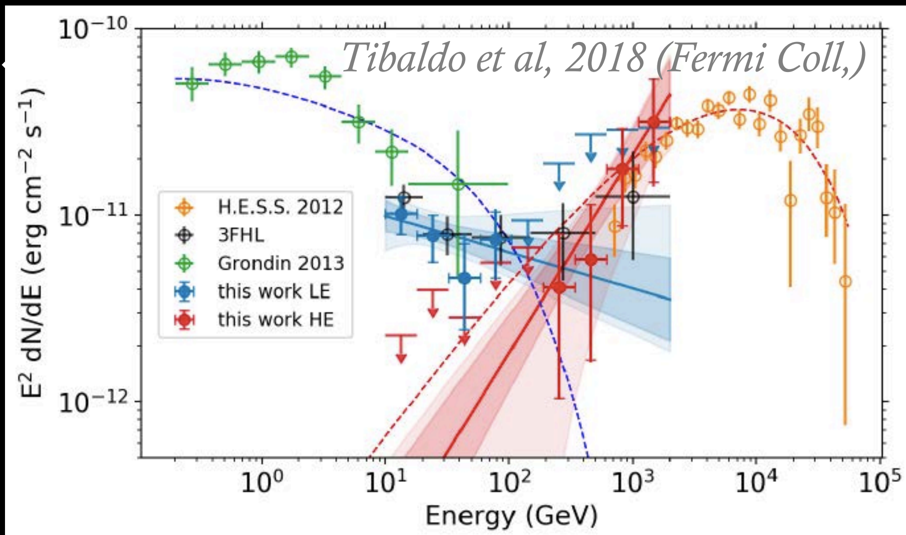


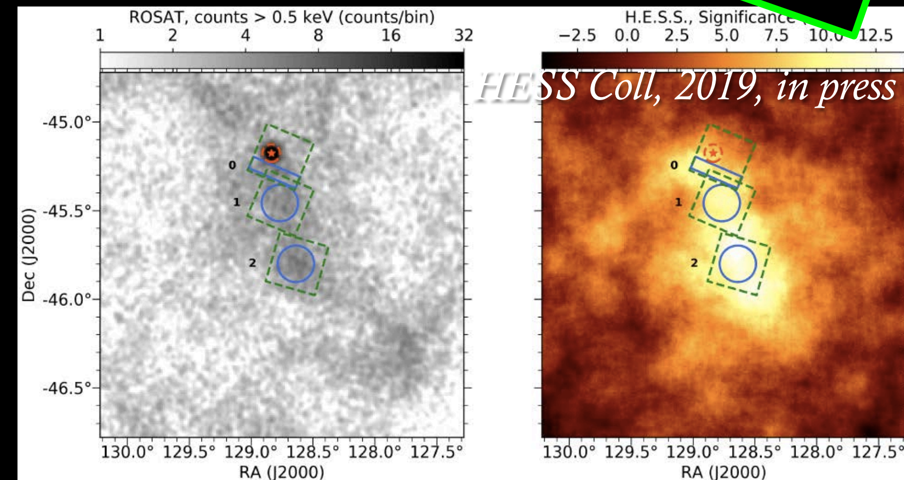
HESS Coll, 2012

What is the origin(s) of the GeV and TeV emission ?

... and even more puzzling (GeV) !

See also poster S6.1 by Y. Bao

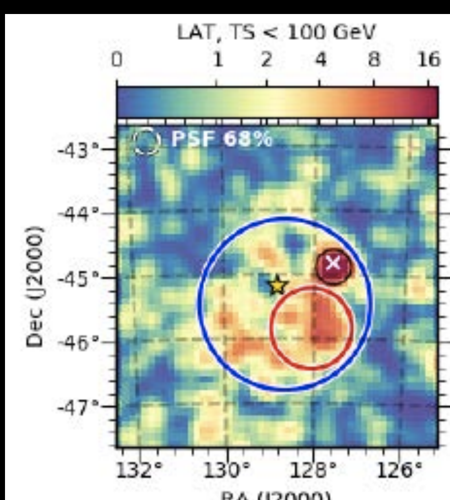


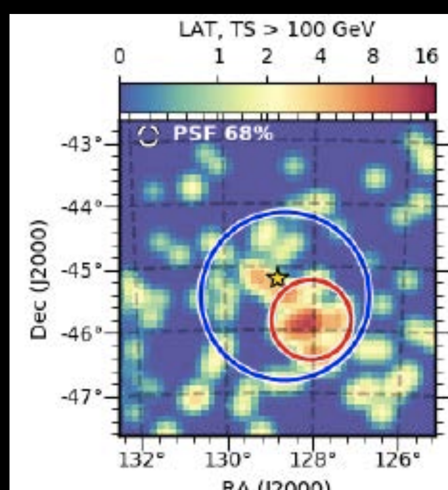


$$\frac{dN_e}{dE_e} = A\left(\frac{E_e}{E_0}\right)^{-\alpha} \exp\left[-\left(\frac{E_e}{E_{\rm cut}}\right)^{\beta}\right],$$

Pointing	W_e (> 1 TeV)[a] (10^{44} erg)	α[b]	$E_{\rm cut}$[b] (PeV)	β[b]	B[c] (μG)	BIC[d]
0	$0.7^{+1.1}_{-0.4}$	$2.2^{+0.3}_{-0.6}$	$0.3^{+4.0}_{-0.2}$	$2.0^{+2.6}_{-1.4}$	$8.6^{+2.8}_{-1.7}$	14.8
1	$1.7^{+0.8}_{-0.6}$	1.8 ± 0.5	$0.05^{+0.07}_{-0.03}$	$0.9^{+0.5}_{-0.2}$	$6.7^{+0.9}_{-0.7}$	18.2
2	$1.6^{+0.7}_{-0.5}$	$1.9^{+0.3}_{-0.6}$	$0.11^{+0.03}_{-0.06}$	$2.0^{+2.3}_{-0.8}$	$5.4^{+0.8}_{-0.6}$	17.3

- Both radio halo and X-ray cocoon can be distinguished
- Cocoon : very hard spectrum (Γ =0.9)

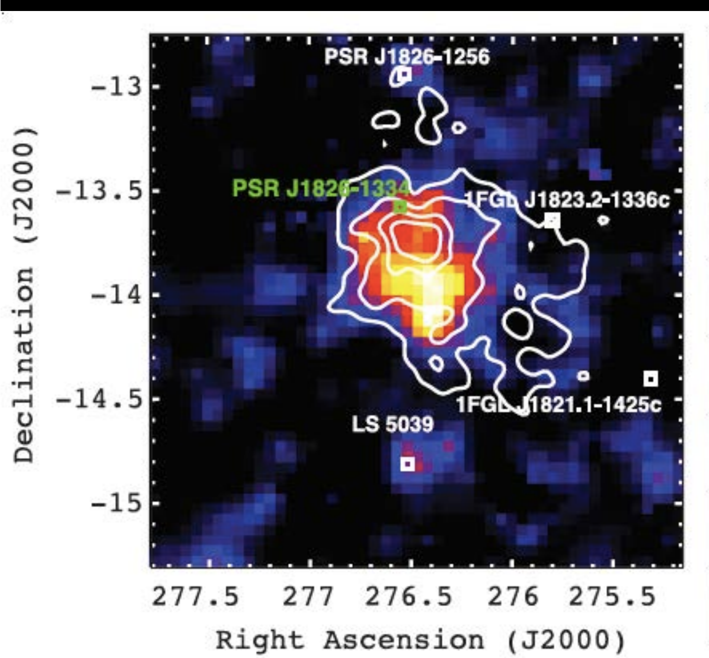




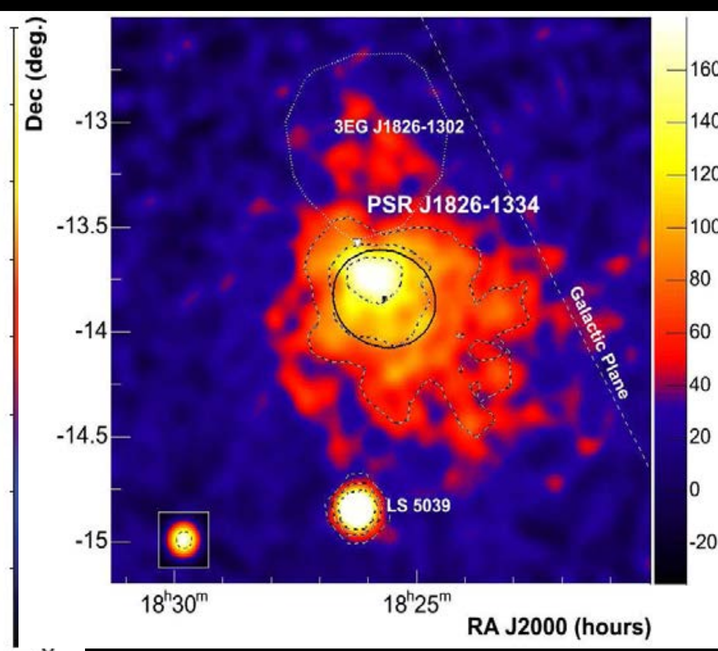
Analysis of Suzaku and H.E.S.S. data :
- harder emission close to the pulsar
- no hint of B turbulence

HESS J1825-137

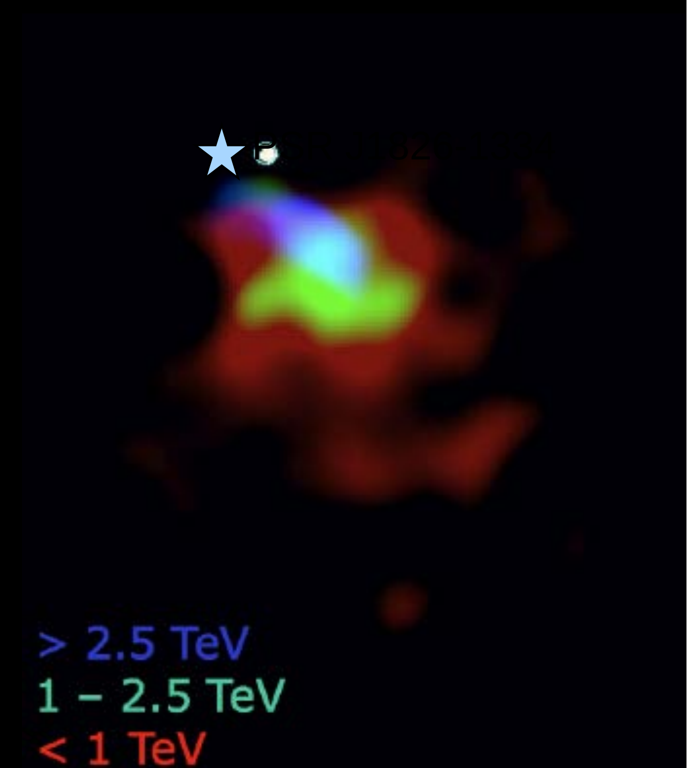
- Source discovered in TeV during the H.E.S.S. Galactic Plane Survey (Aharonian et al, 2005, Science, 307, 1038)
- Identified as the PWN G18.0-0.7, associated to the energetic radio loud pulsar PSR J1826-1334 ($\dot{E}$ = 2.8 x 10^{36} erg/s, age ~20 kyr, distance ~4 kpc)
- Significantly extended (2-D Gaussian of σ = 0.23°)
- Energy-dependent morphology observed at VHE due to cooling mechanisms *(Aharonian et al, 2006, A&A 460, 365)*
- Detected by Fermi *(Grondin et al, 2011)*



Fermi TS Map



H.E.S.S. smoothed excess map



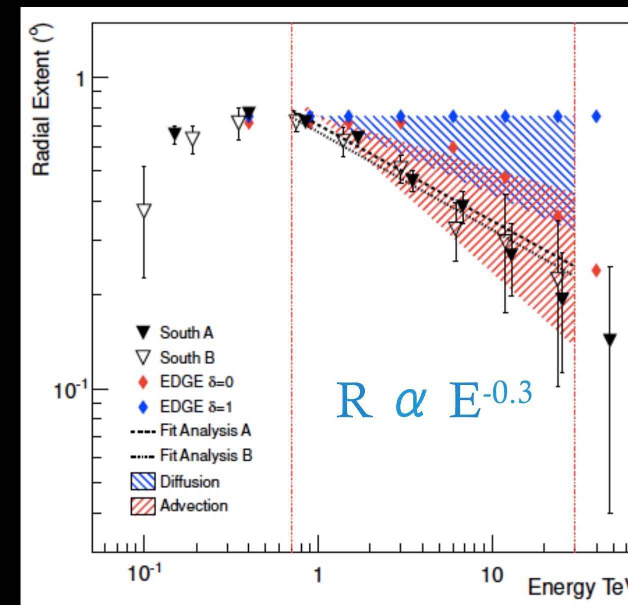
H.E.S.S. : Energy-dependent morphology

Particle transport in HESS J1825-137

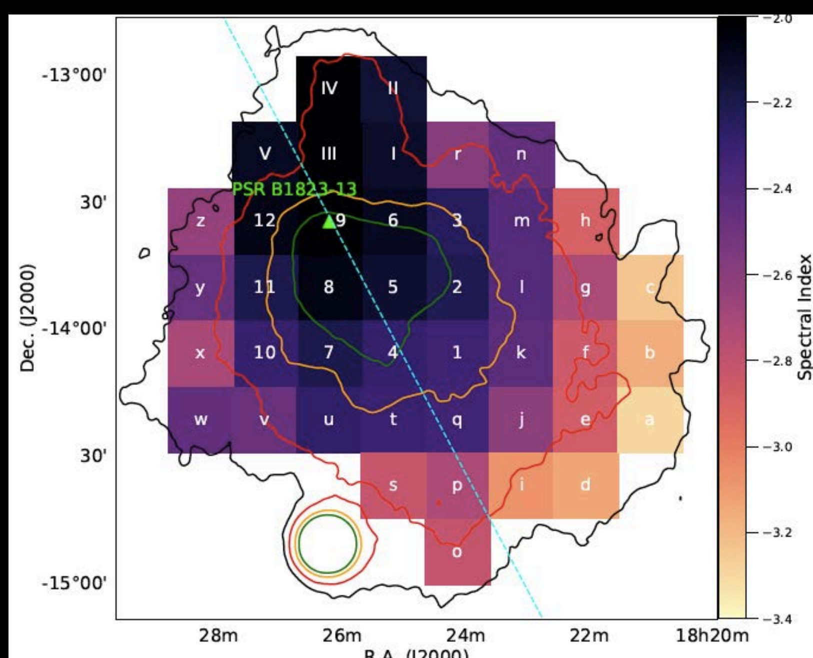
- Clear energy—dependent morphology seen with H.E.S.S. *(HESS Coll., 2019)*
- Softening of the spectral index with distance to the pulsar

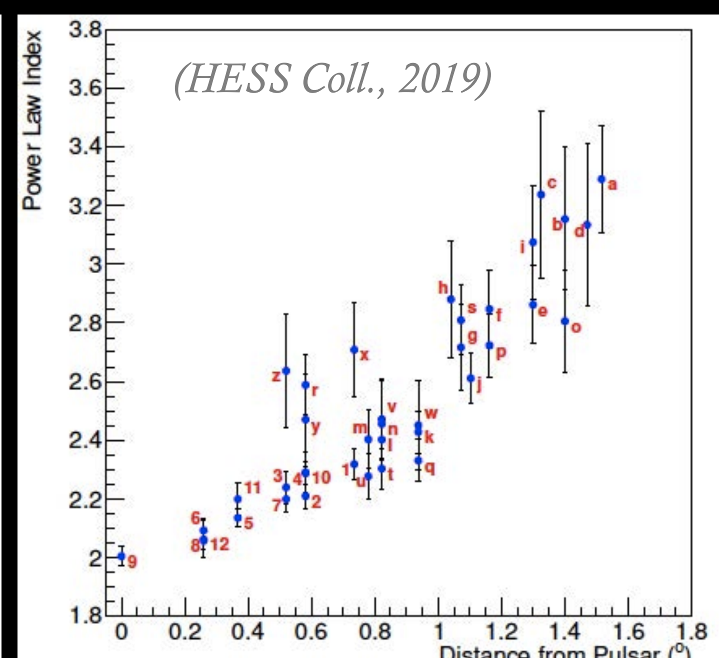
=> cannot be explained by diffusion only

=> confirms that electrons cooling over time are transported away from pulsar



Diameter of 1.5° => physical extension of 100 pc !



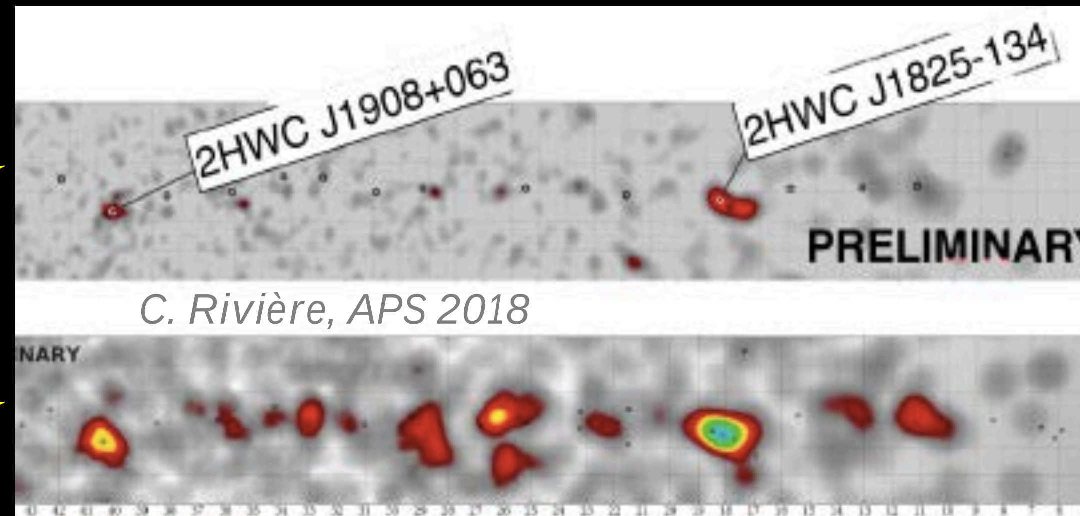


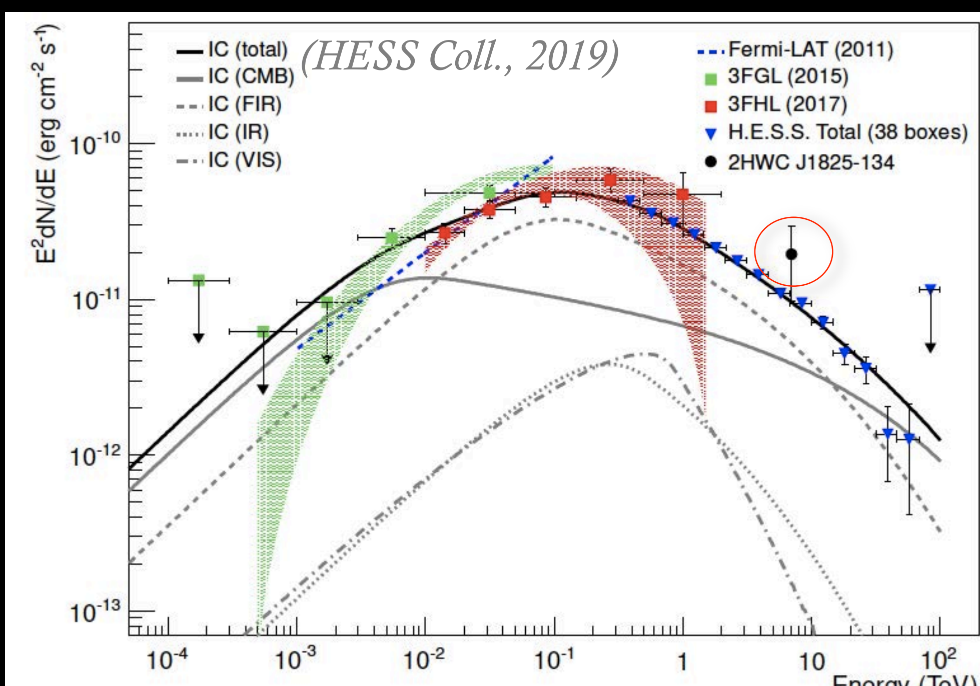
Is HESS J1825-137 a PeVatron ?

❖ Region still significant by HAWC above 100 TeV

>100 TeV

>56 TeV





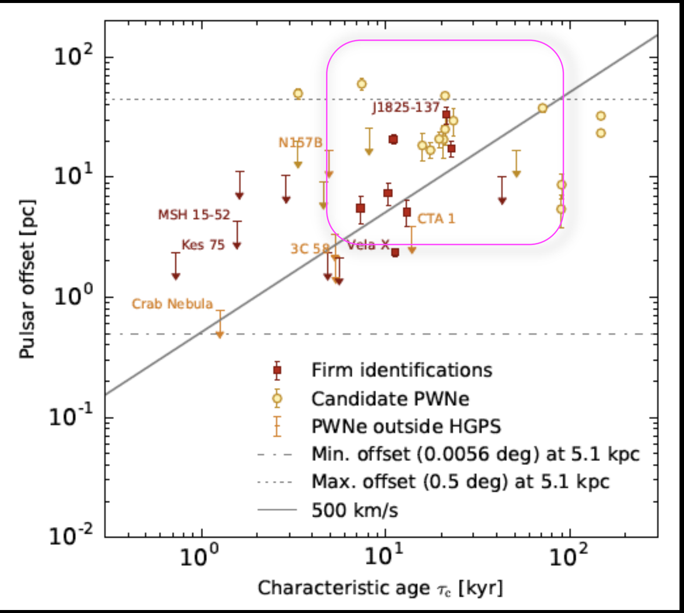
❖ However, HESS J1825 only half of the HAWC measurement

=> impossible to (spatially) disentangle between contributions from HESS J1825 and HESS J1826 in the HAWC data

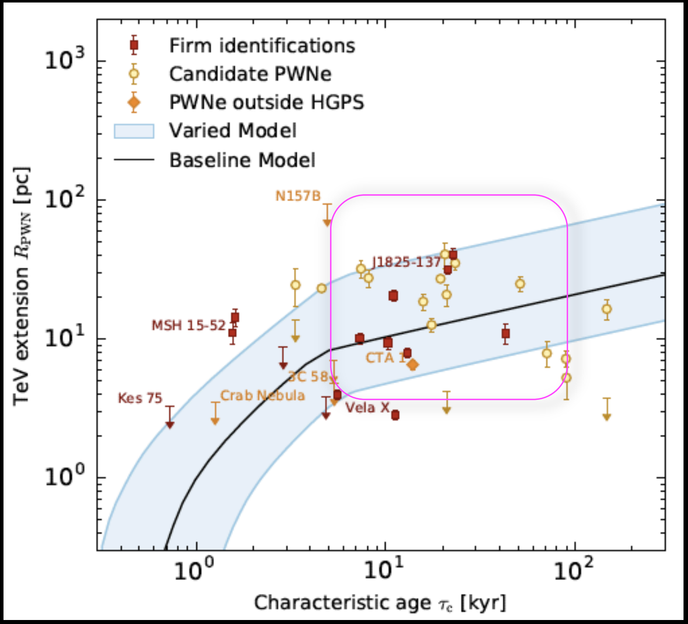
See also poster S6.3 by Y. Gallant and 6.4 by E. Giacani

Common trends for relic TeV PWNe

- Pulsar offset vs characteristic age:
  - older TeV PWNe have large offsets
  - some of them cannot be explained by pulsar proper motions
  - suggests alternative "crushing" scenario *(Aharonian et al, 2015; Temim et al, 2015)*



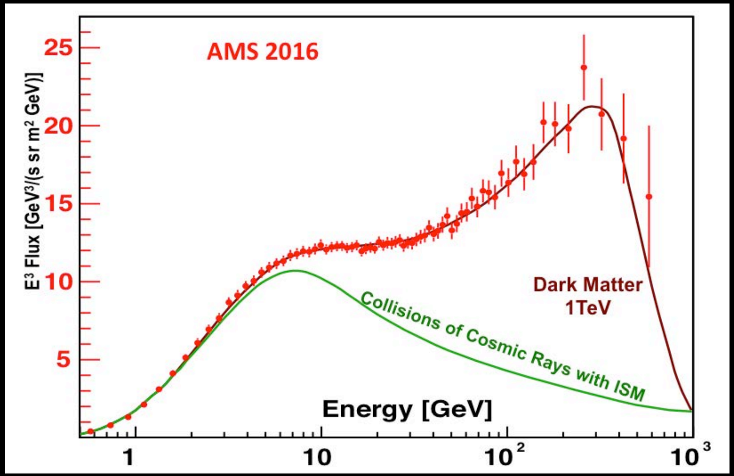
- TeV extension vs characteristic age
  - consistent with PWN free expansion initially
  - then, slower subsonic expansion
  - relic PWNe : gamma-ray size much larger than in X-rays

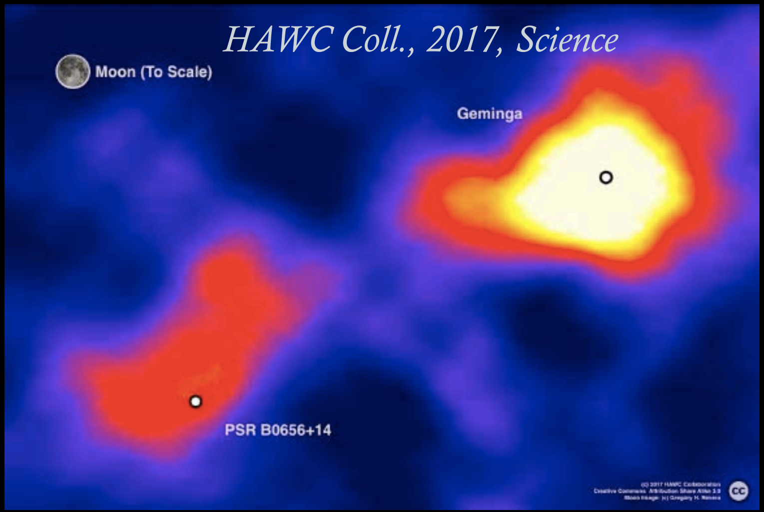


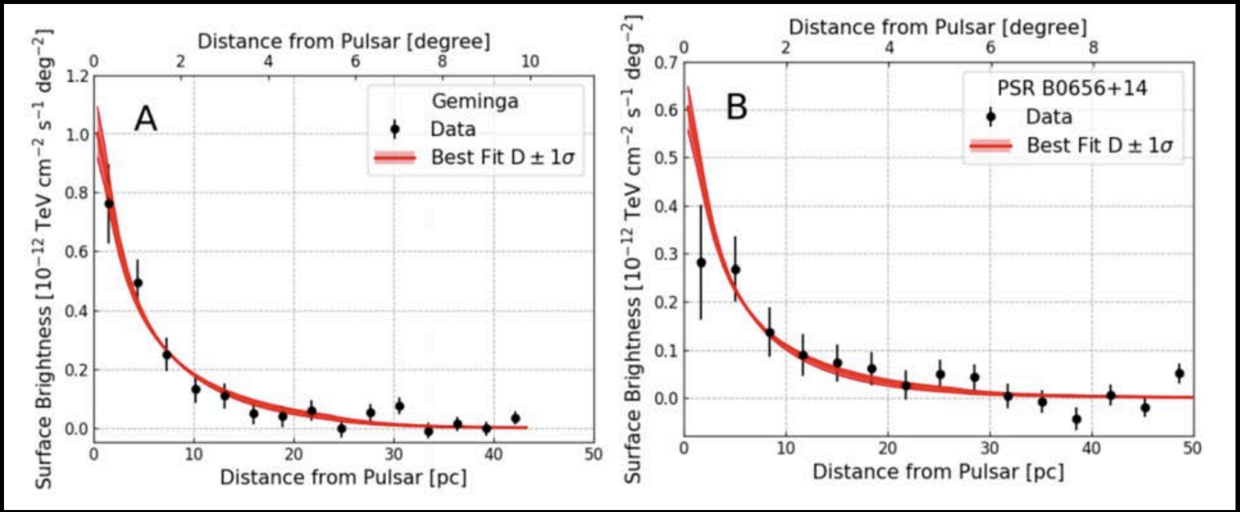
3. A new source class : TeV Halos

Also mentionned by N. Tsuji on Tuesday

- Highly extended (1.7° – 2°) sources detected around two pulsars : Geminga and Monogem (PSR B0656+14)
- Halos much larger than X-ray, much smaller than diffusion through the ISM
- Both pulsars are :
  - associated to the nearest (250/288 pc) and oldest (300/100 kyr) PWNe detected in the TeV range
  - postulated as sources of positron excess *(Hooper et al, 2017 >< HAWC Coll. 2017)*







TeV halos : toward pulsar discoveries ?

- 5 / 39 sources in the 2HWC catalog are correlated with bright, middle-aged (100 — 400 kyr) pulsars.

Linden et al., 2017

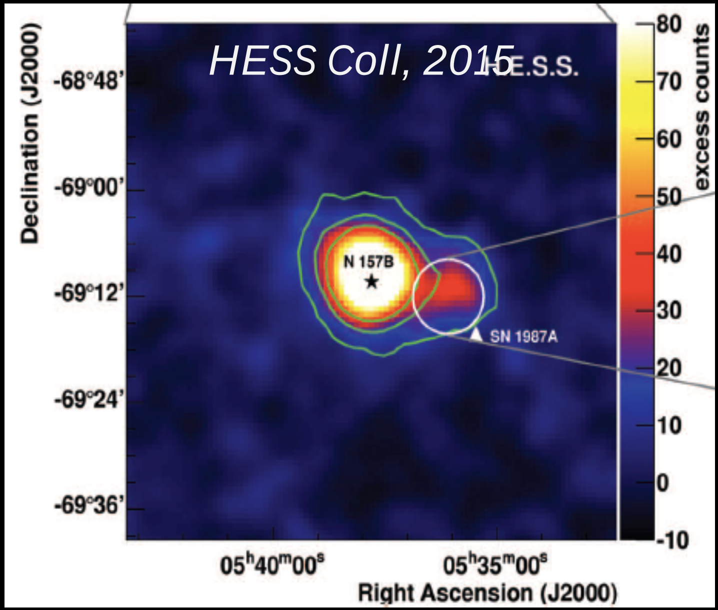
ATNF Name	Dec. (°)	Distance (kpc)	Age (kyr)	Spindown Lum. (erg s^{-1})	Spindown Flux (erg s^{-1} kpc^{-2})	2HWC
J0633+1746	17.77	0.25	342	3.2e34	4.1e34	2HWC J0631+169
B0656+14	14.23	0.29	111	3.8e34	3.6e34	2HWC J0700+143
B1951+32	32.87	3.00	107	3.7e36	3.3e34	—
J1740+1000	10.00	1.23	114	2.3e35	1.2e34	—
J1913+1011	10.18	4.61	169	2.9e36	1.1e34	2HWC J1912+099
J1831-0952	-9.86	3.68	128	1.1e36	6.4e33	2HWC J1831-098
J2032+4127	41.45	1.70	181	1.7e35	4.7e33	2HWC J2031+415
B1822-09	-9.58	0.30	232	4.6e33	4.1e33	—
B1830-08	-8.45	4.50	147	5.8e35	2.3e33	—
J1913+0904	9.07	3.00	147	1.6e35	1.4e33	—
B0540+23	23.48	1.56	253	4.1e34	1.4e33	~~—~~ now detected

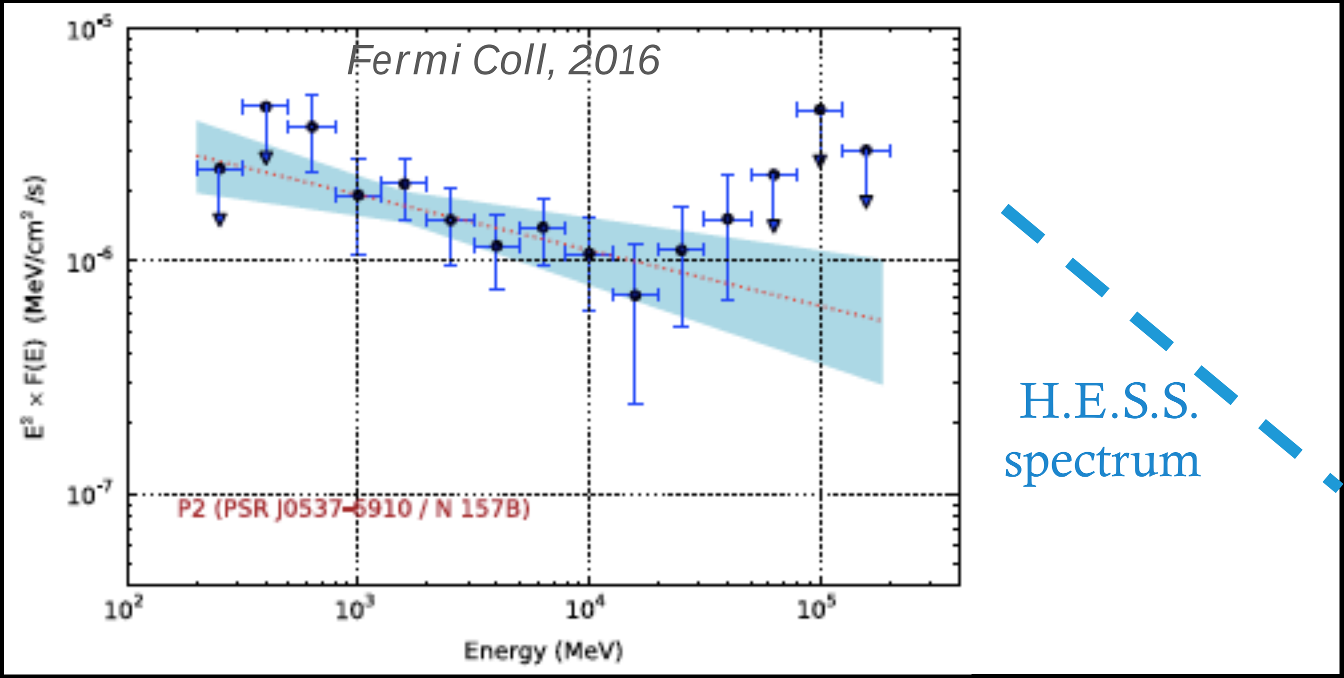
ranked in E^2 / d^2

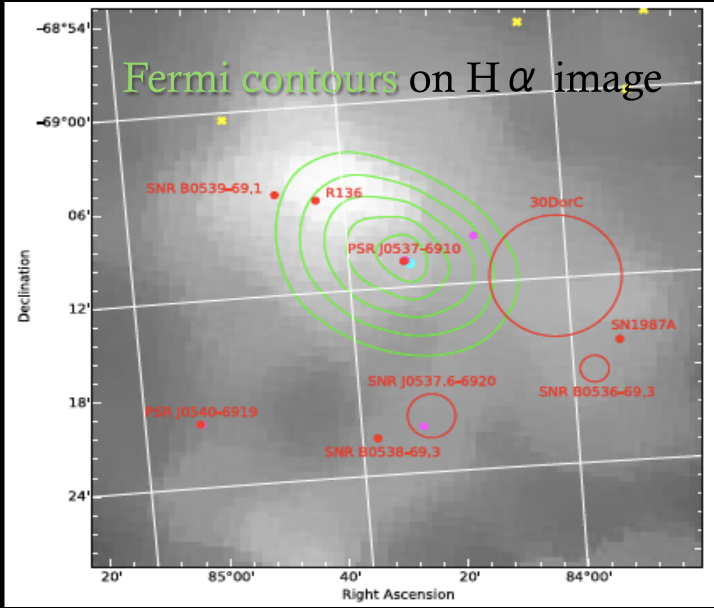
- Upcoming detections of TeV halos could points towards misaligned or faint pulsars

4. PWN Candidate : N 157B

- Located in the Large Magellanic Cloud
- Powered by the <u>most energetic</u> ($4.9\ 10^{38}$ erg/s) known pulsar PSR J0537-6910
- Detection in the TeV band *(HESS Coll, 2015, Science)*
- Detection in the GeV band : sum of PSR + PWN ? *(Fermi Coll, 2016)*
  - but no gamma-ray pulsation detected so far





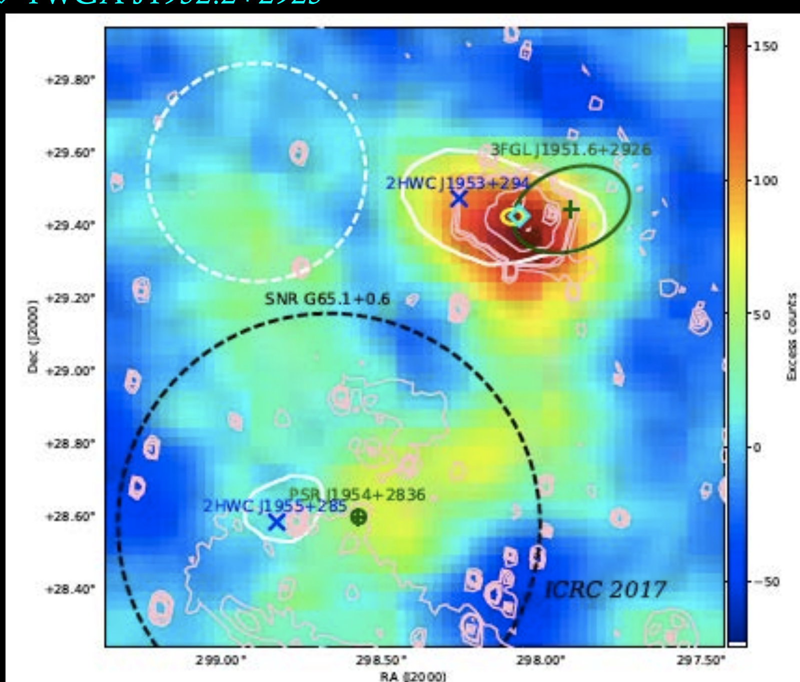


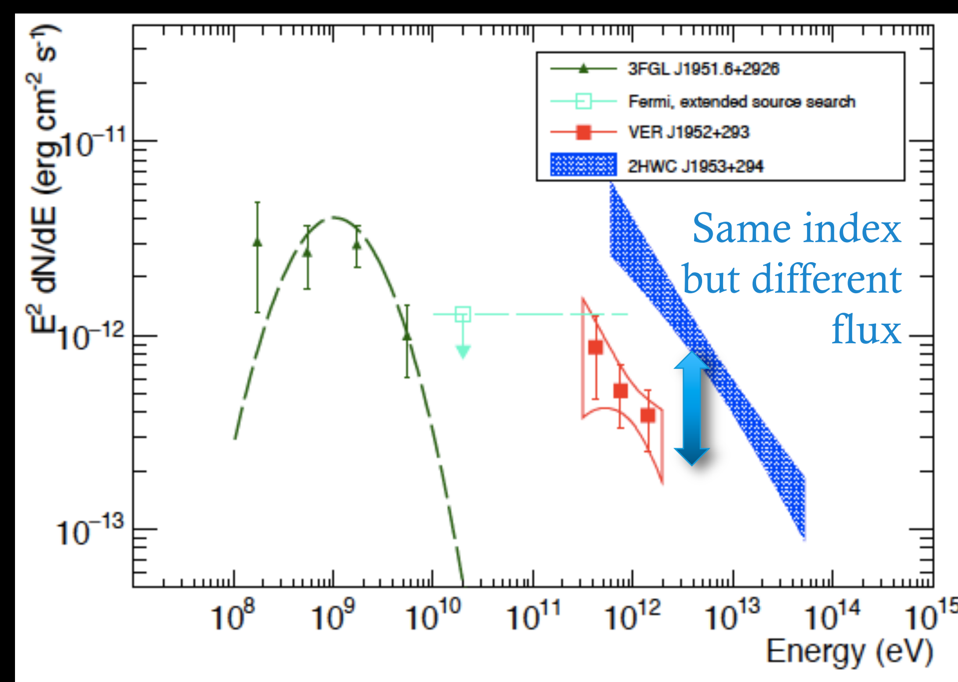
DA 495 : an interesting case in the Cygnus region

- Gamma-ray emission seen by HAWC (2HWC J1953+294), VERITAS and Fermi *(joint article, 2018)* close to SNR G65.7+1.2
- Coincident PWN emission seen in radio and X-rays *(Arzoumanian et al 2008)*
- No pulsations from radio to gamma-rays but Fermi spectrum looks like a psr-like spectrum (misaligned ? old ?)

  => VERITAS and HAWC would detect the associated PWN

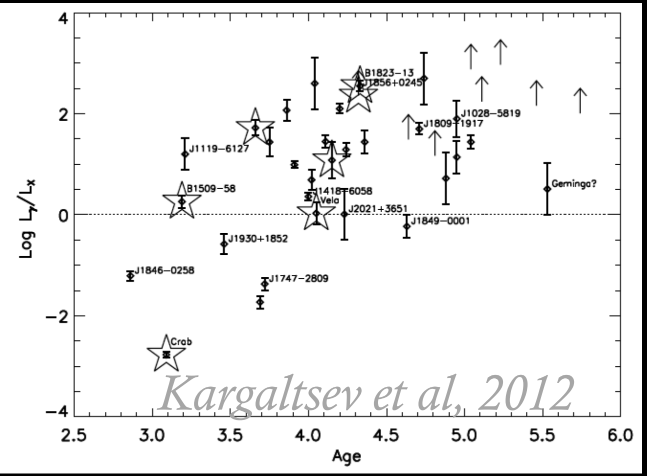
◇ 1WGA J1952.2+2925

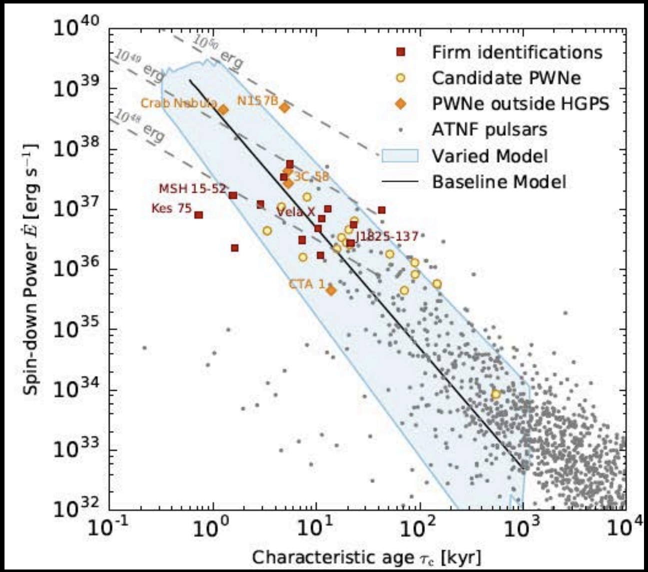


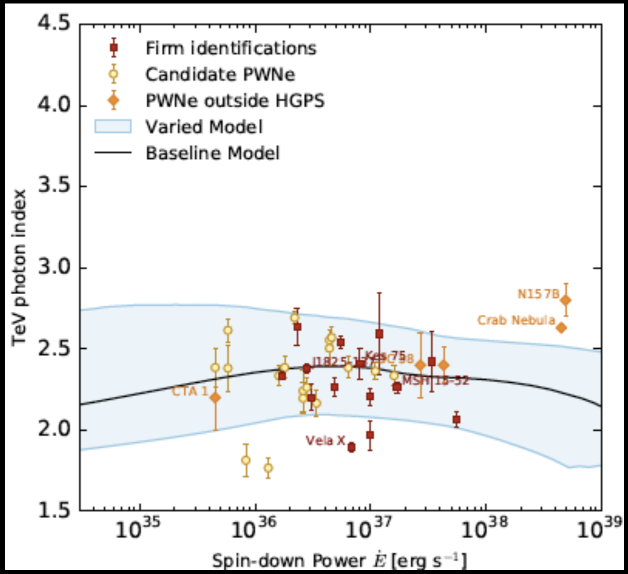


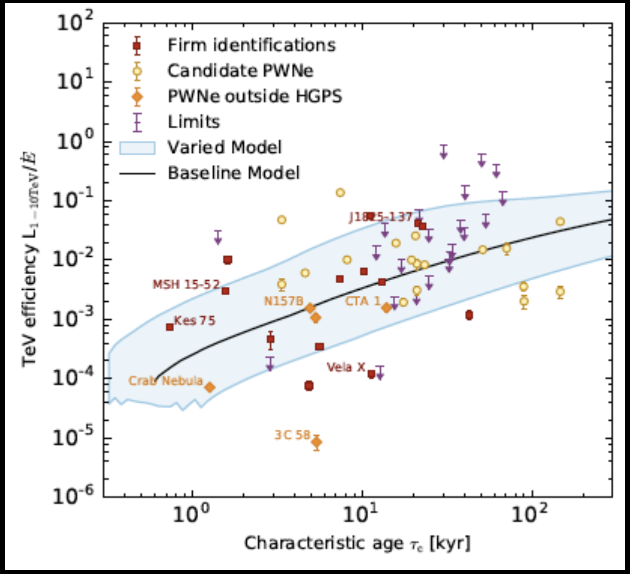
TeV observations of PWNe

- Largest population of Galactic TeV sources (along with SNRs and composite SNRs)
- Many of the still unidentified sources might be PWNe
- Preferentially :
  - either young: associated to energetic pulsars
  - or relic : offset from their pulsar
- More luminous than their X-ray counterpart





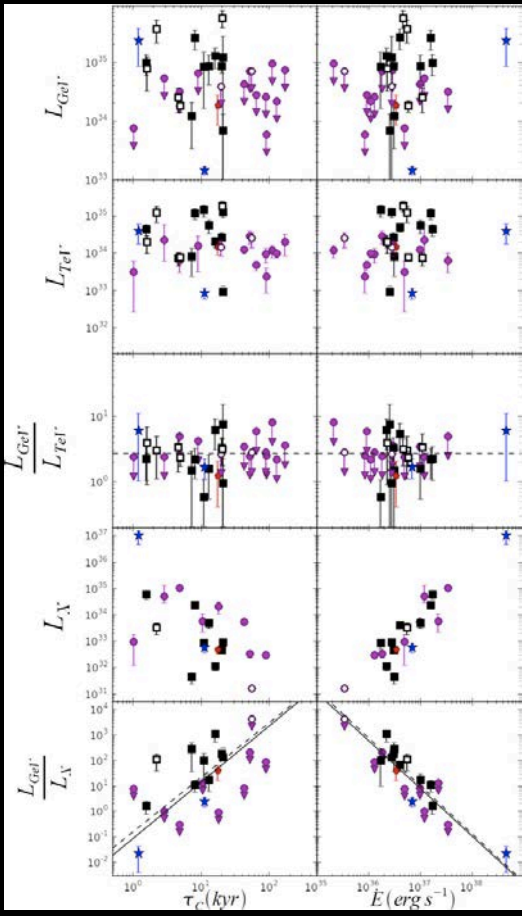




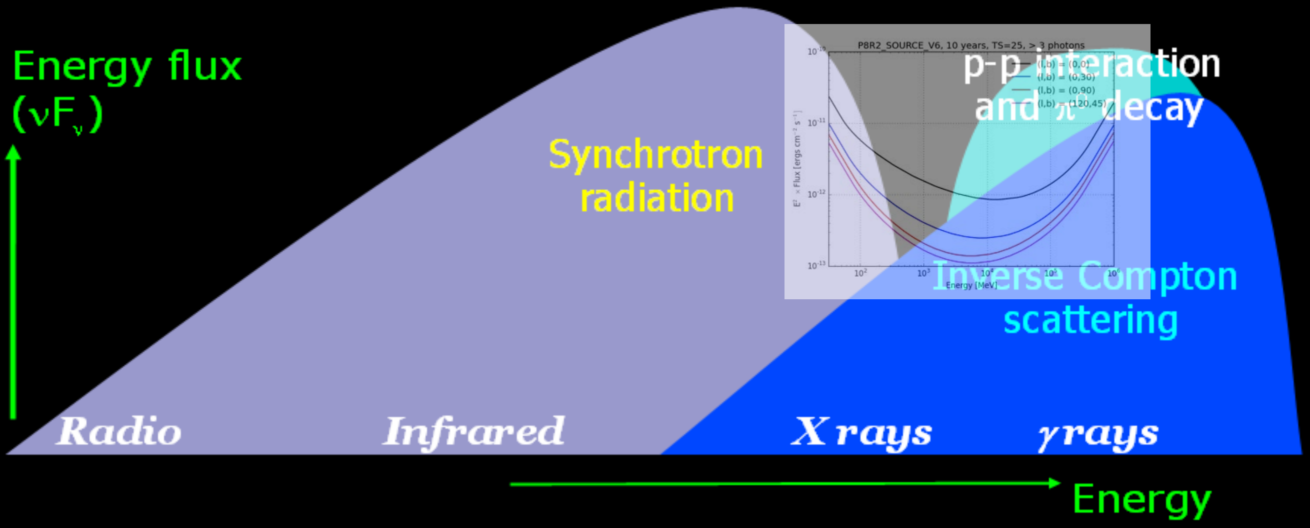
GeV observations of PWNe

Fermi Coll, 2013

- Difficult to detect:
    - wrt bright powering pulsars
    - in the rising edge of the IC component
- Quite young (<10 kyr)
- Associated to TeV sources
- Larger than their TeV counterpart (cooling / two electron population)



Fermi-LAT Pass 8 performance



Summary

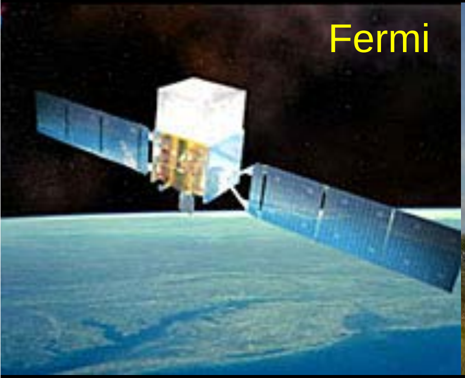
Detection of GeV & TeV gamma-ray PWNe :

- in the TeV range, PWN is the most numerous of identified sources in the Galactic plane

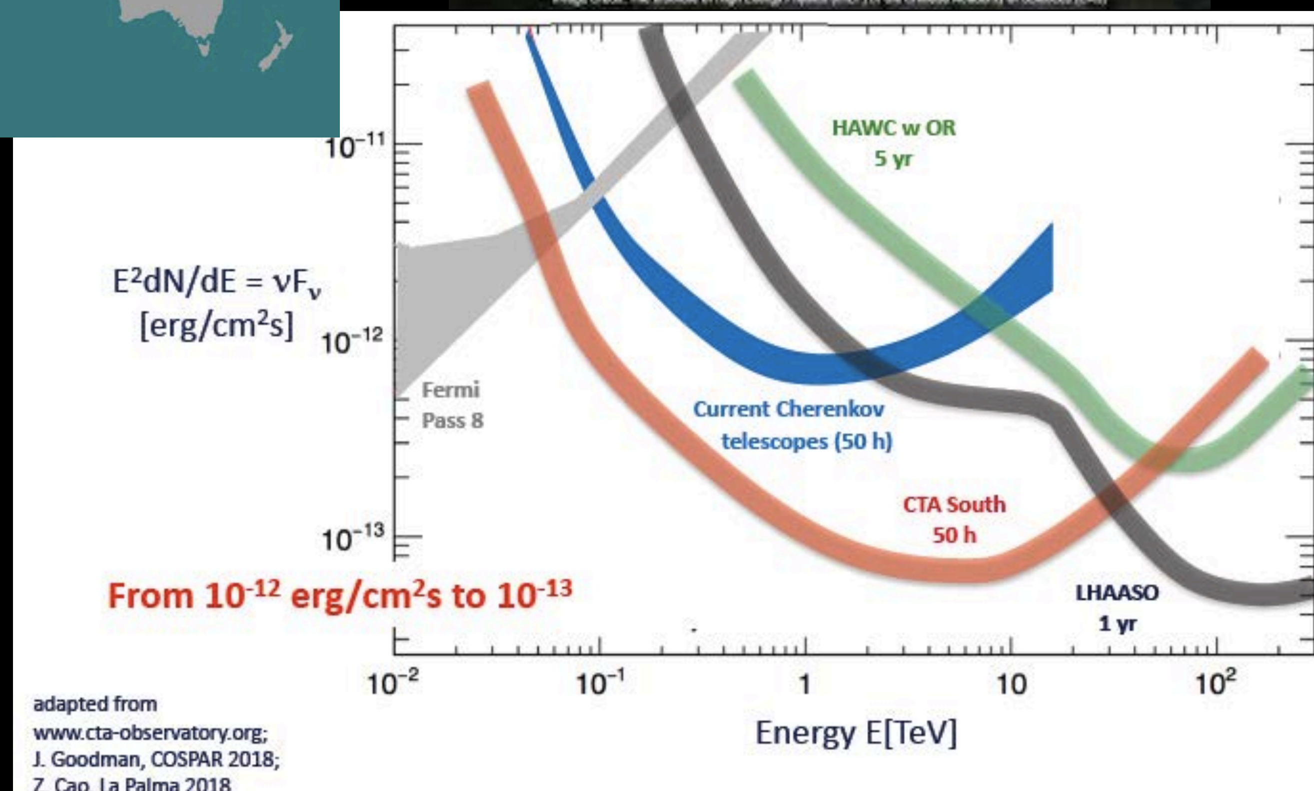
- a leptonic (IC scattering) origin for the high energy component of the spectrum is favored in each case

- Vela X is the first case where the injection of 2 leptonic components is suggested by multi-wavelength data – but puzzling results to be understood
- HESS J1825-137 is the archetype of evolved PWN, in which diffusion can be put in evidence – but not the only responsible for the large offset from the pulsar
- TeV halos detected by HAWC are an interesting case to probe the source of positron excess and find new pulsars

TeV astronomy has opened a new observational window for the study of PWNe, giving a more direct view of the accelerated particle population

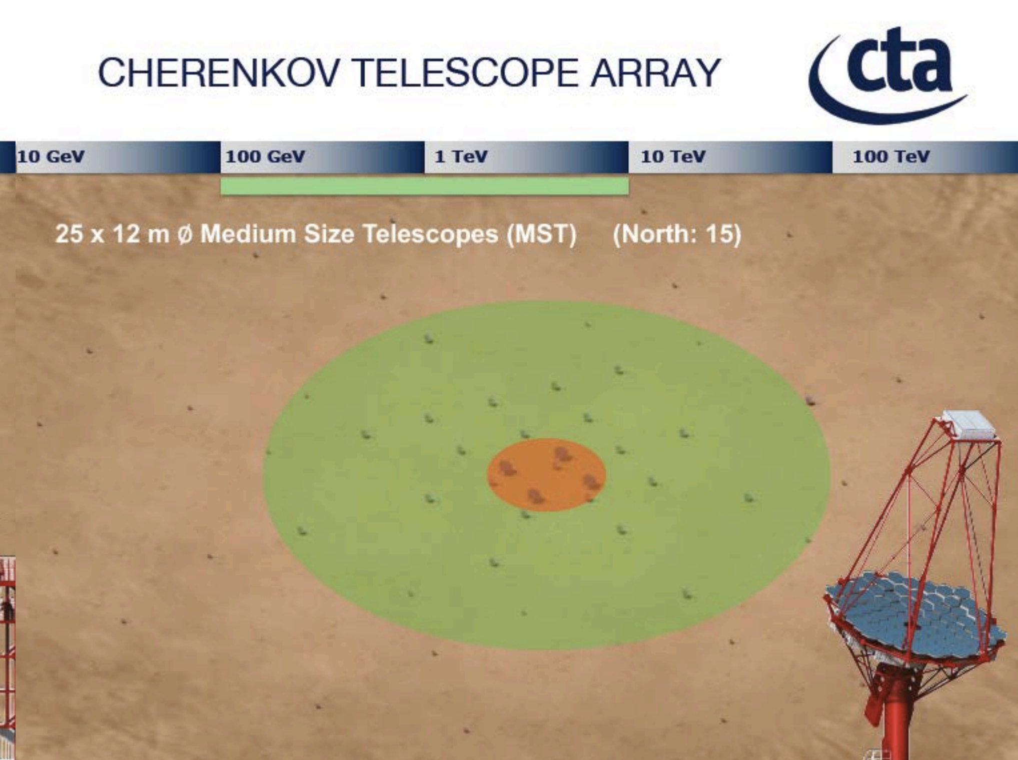


The future in the TeV range

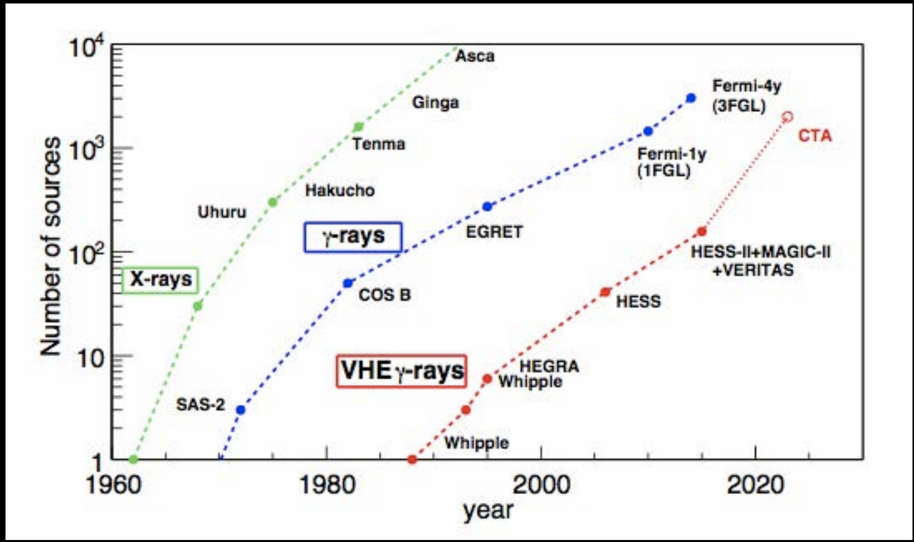


Back-up

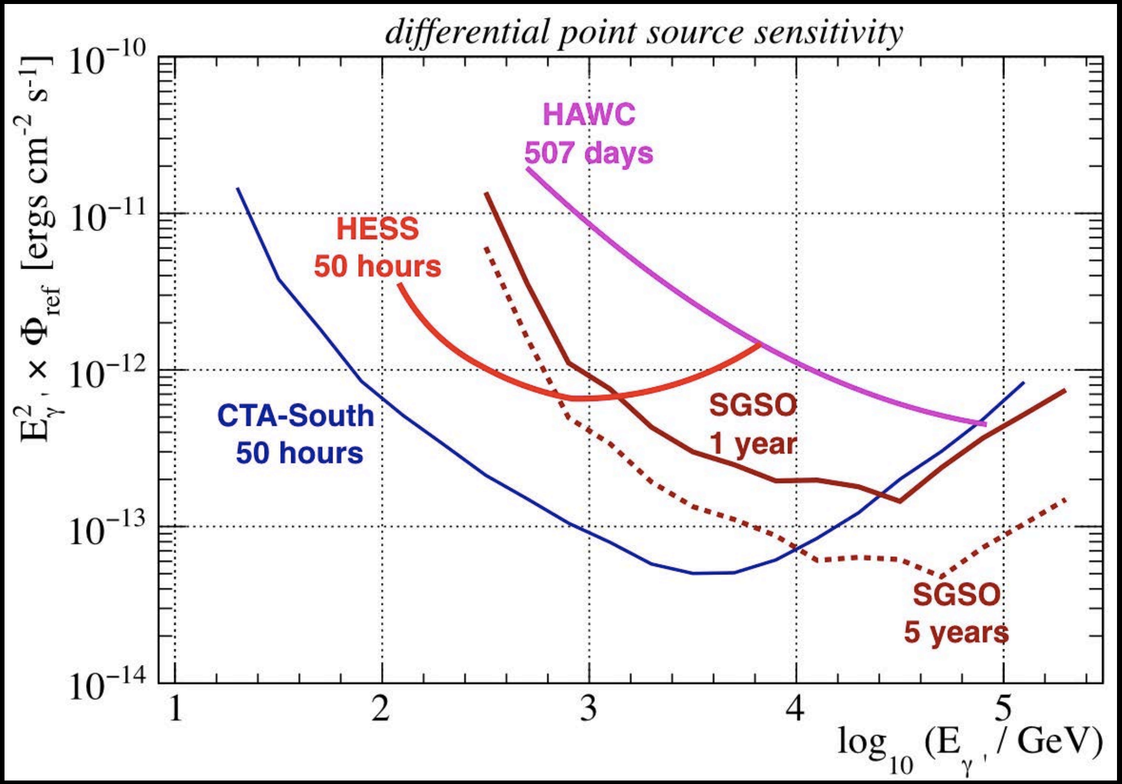

CHERENKOV TELESCOPE ARRAY
cta
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
4 x 23 m ∅ Large Size Telescopes (LST)


CHERENKOV TELESCOPE ARRAY
cta
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
25 x 12 m ∅ Medium Size Telescopes (MST)
(North: 15)

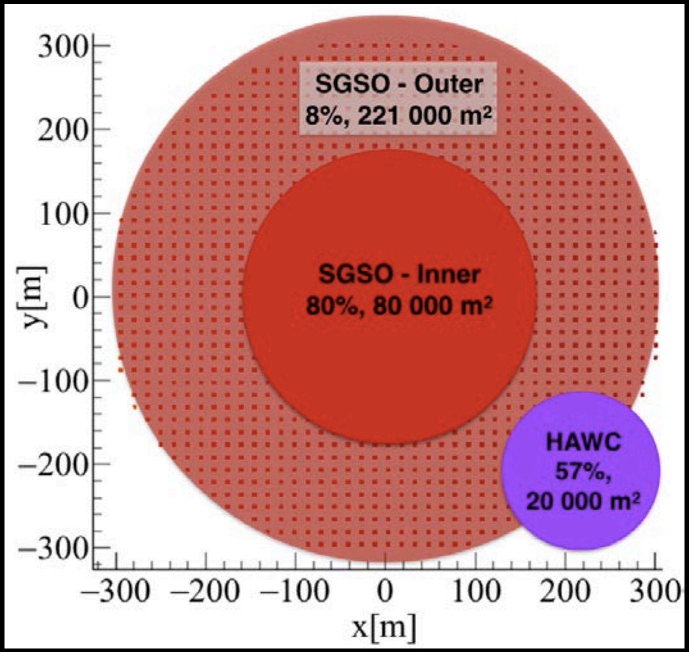

CHERENKOV TELESCOPE ARRAY
cta
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
70 x 4 m ∅ Small Size Telescopes (SST)
(South only)
Compared to current telescopes
▪ 5 to 20 x better sensitivity
▪ over 4 decades coverage in energy
▪ much larger field of view
▪ better angular resolution
▪ up to 400 x increased survey speed

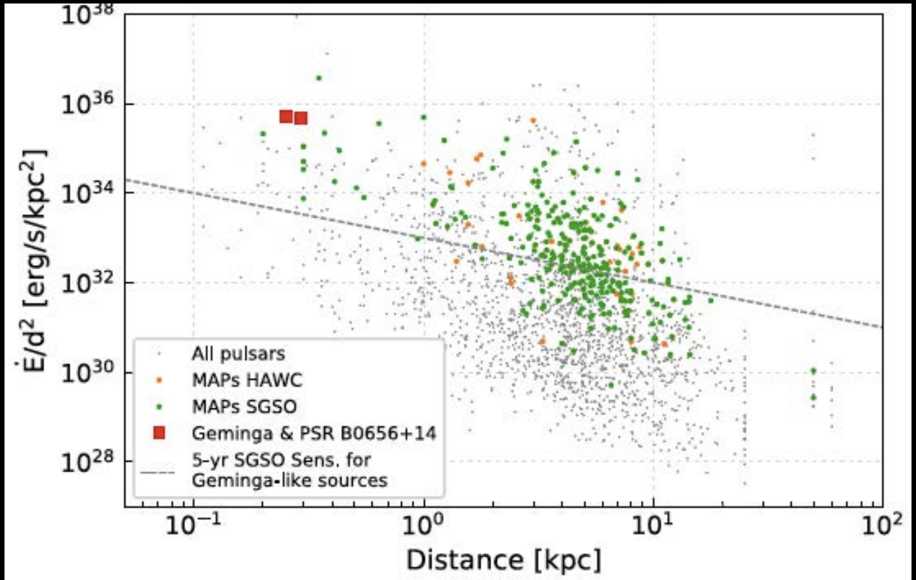

10^4
10^3
10^2
10
1
Number of sources
1960
1980
2000
2020
year
X-rays
Uhuru
Hakucho
Tenma
Ginga
Asca
γ-rays
SAS-2
COS B
EGRET
Fermi-1y
(1FGL)
Fermi-4y
(3FGL)
VHE γ-rays
Whipple
HEGRA
Whipple
HESS
HESS-II+MAGIC-II
+VERITAS
CTA

SW(G)SO

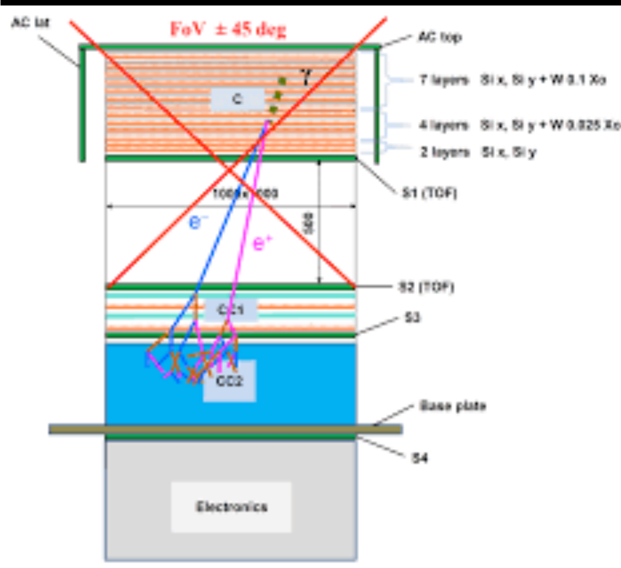


F. Schuessler, VHEPU 2018

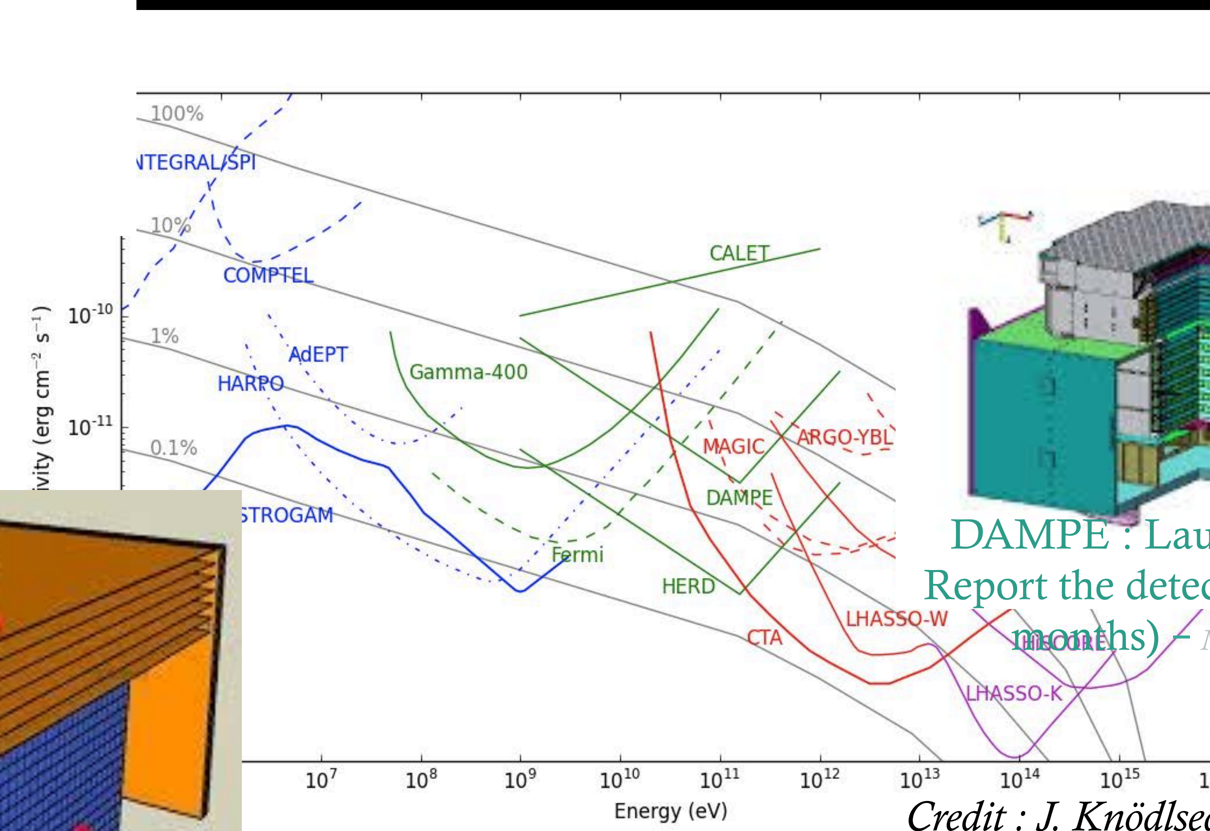




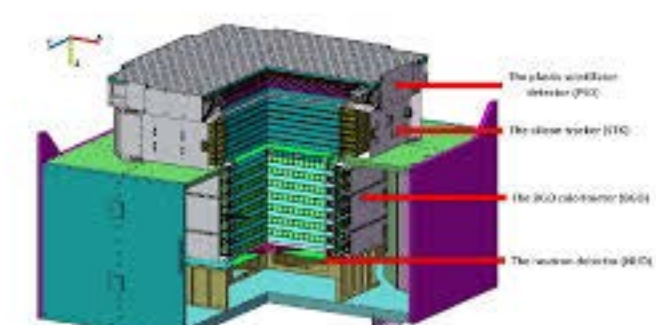
The future in the GeV range



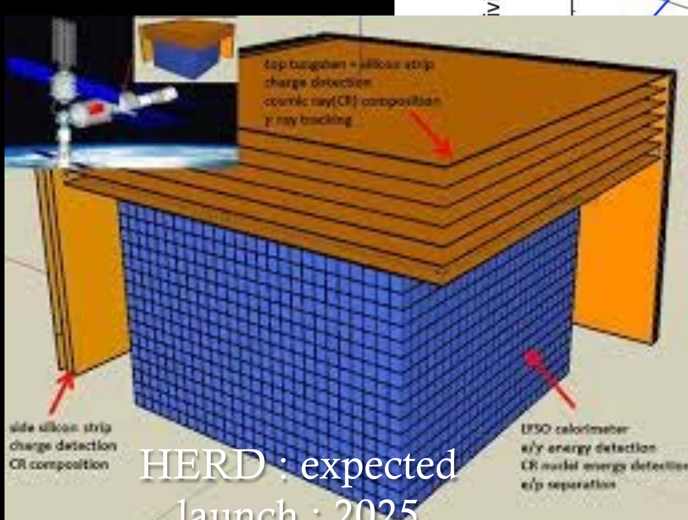
Gamma 400 : Launch in 2025 ?



Credit : J. Knödlseder



DAMPE : Launched in Dec 2015
Report the detection of 3 pulsars (18 months) – *Munoz Salinas et al, 2017*



HERD : expected launch : 2025