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ICREA

A pulsar wind population: issues and prospects

Diego F. Torres

Introduction to PWNe: basics

Pulsar's spin down basics

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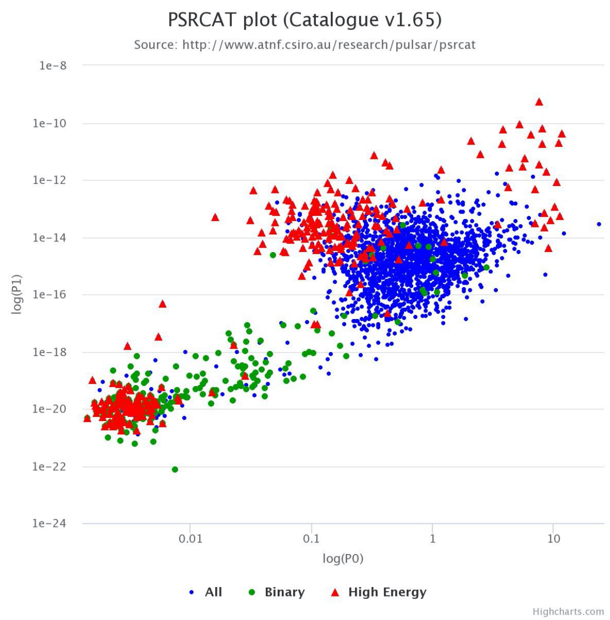
- Pulsars slow down: losing rotational energy

$$E = \frac{1}{2} I\omega^2 = \frac{I}{2}\left(\frac{4\pi^2}{P^2}\right) = \frac{2I\pi^2}{P^2}$$

- Then, the rate of energy release (the spin-down power)

$$\frac{dE}{dt} = \frac{d}{dt}\left(\frac{2I\pi^2}{P^2}\right) = -\frac{4I\pi^2}{P^3}\frac{dP}{dt}$$

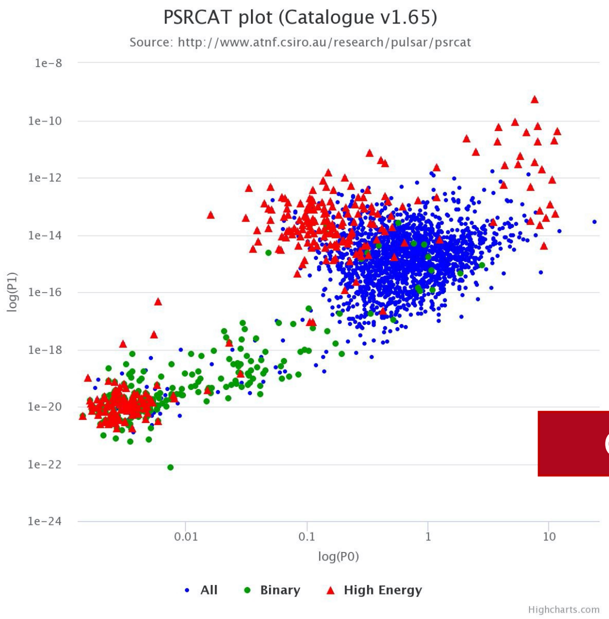


- This is the energy reservoir for everything that happens in the surrounding of the pulsar unless there is an additional source of energy, beyond the rotation itself

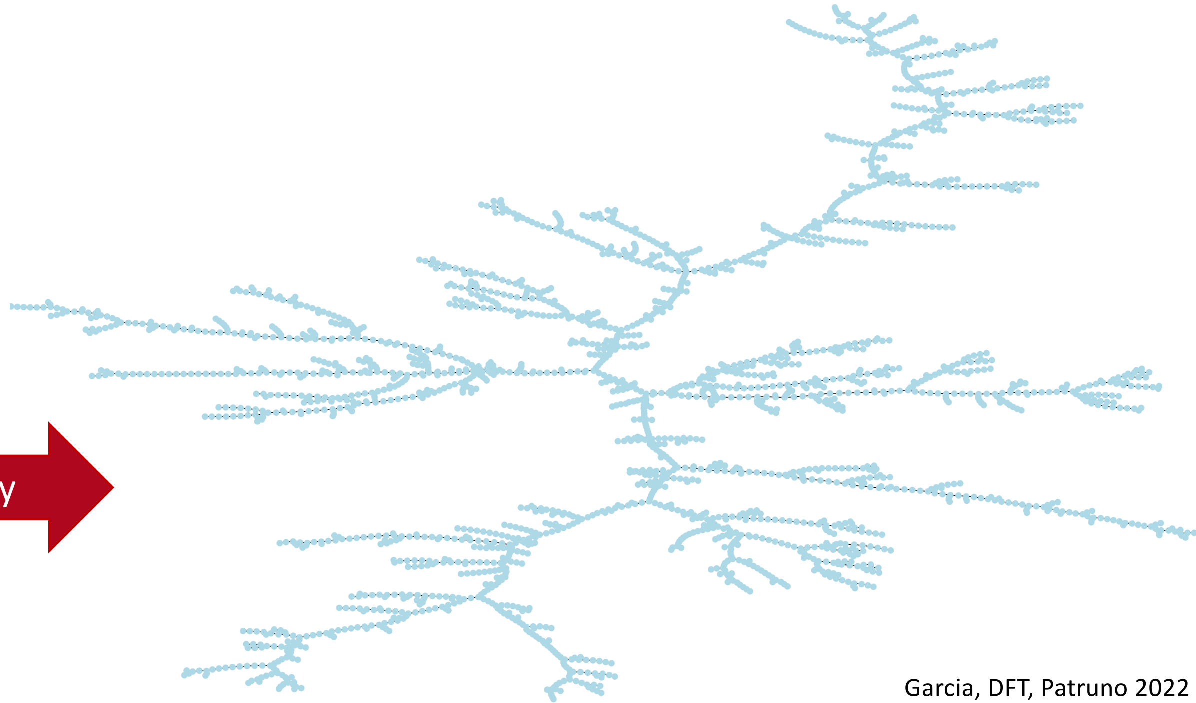
- This power is what is used to emit at all frequencies, and to power the 'wind nebula'.

A fresh look at the pulsar population

http://www.pulsartree.ice.csic.es/



Graph Theory



Garcia, DFT, Patruno 2022

A fresh look at the pulsar population

http://www.pulsartree.ice.csic.es/

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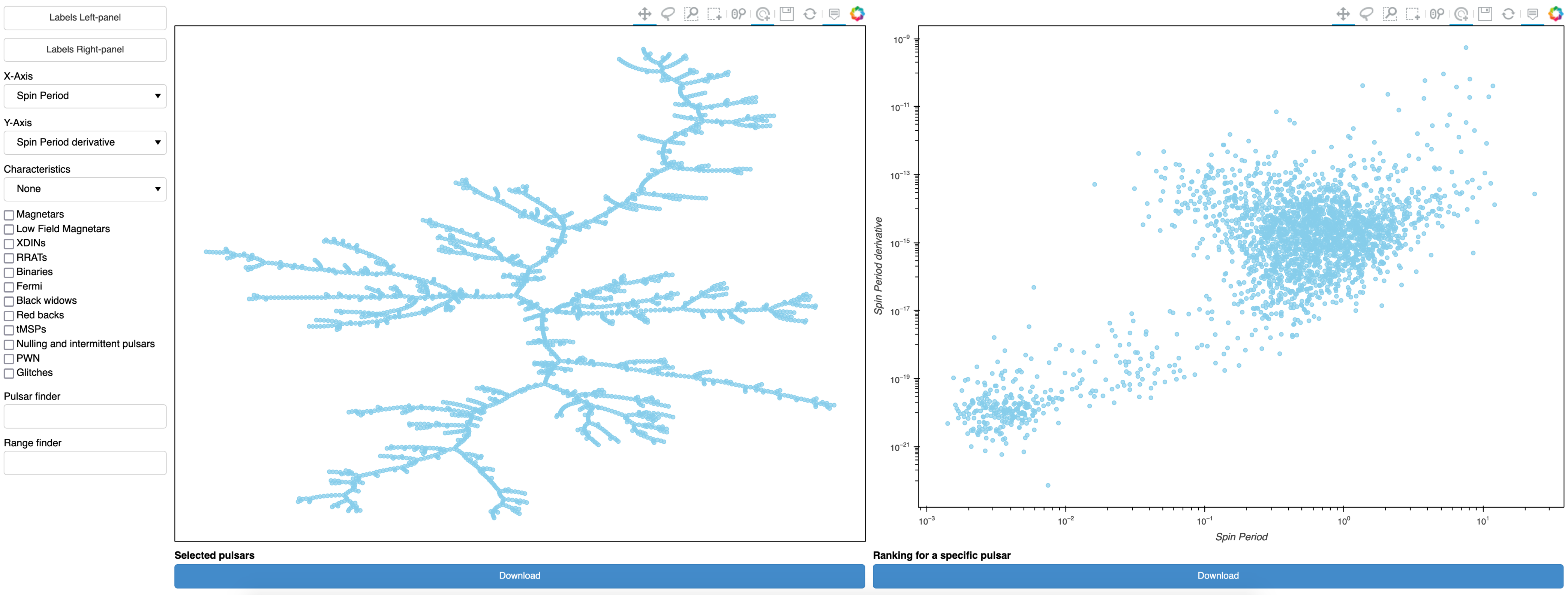
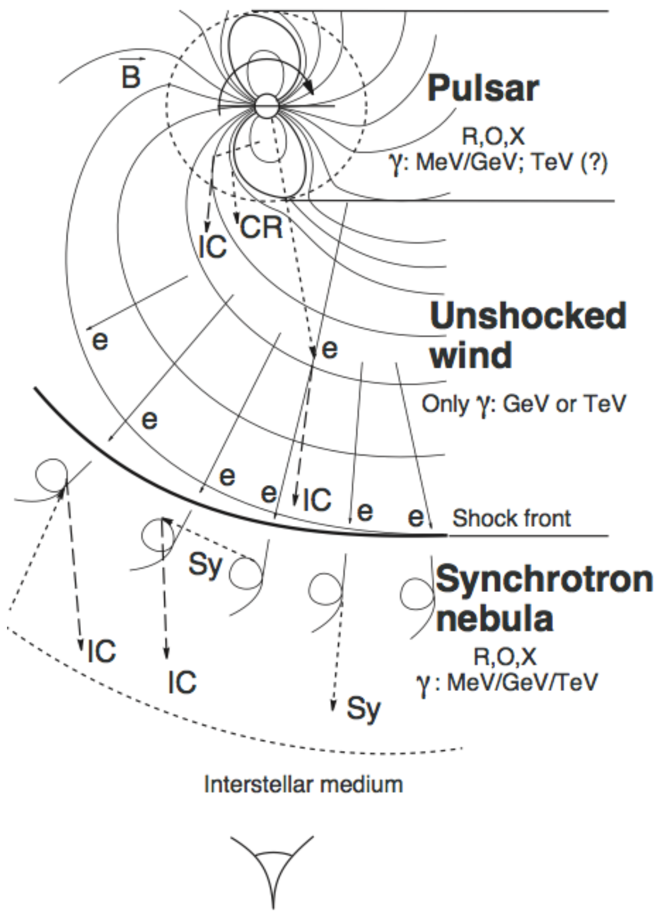
THE PULSAR TREE

Visualizing the pulsar population using graph theory



Radiation from the pulsar complex

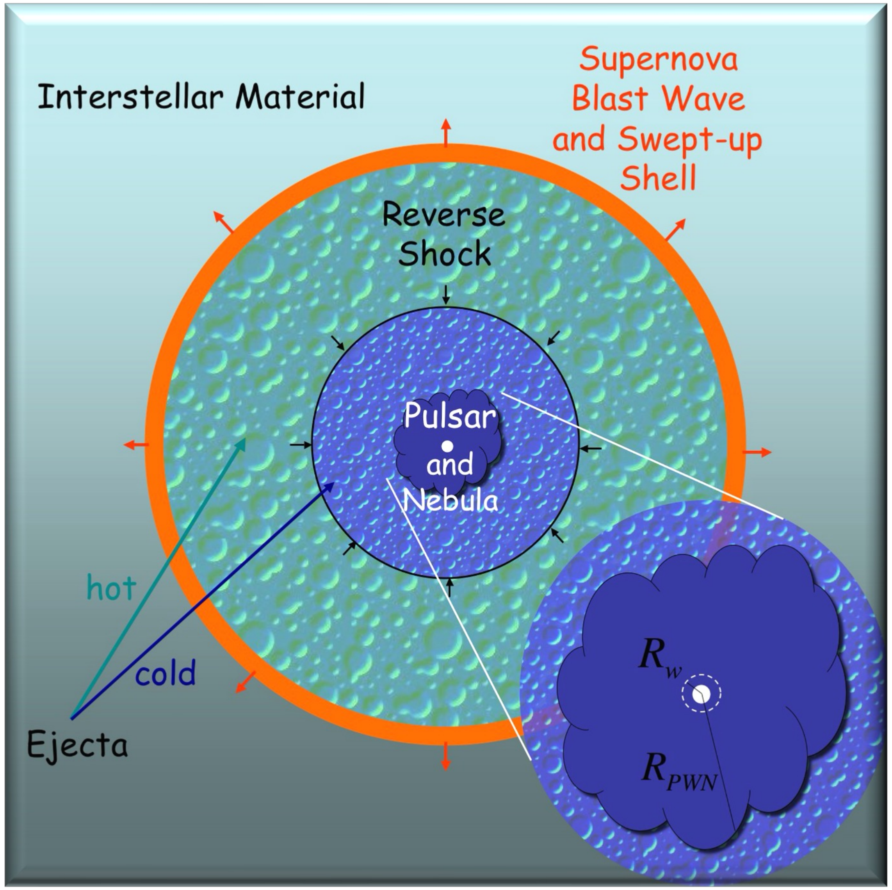


Magnetospheric pulsed emission within the light cylinder: via synchro-curvature, and perhaps IC process at TeV energies

Unshocked wind may shine at GeV and TeV energies via comptonization

Synchrotron nebula produces broad-band emission (synchrotron, IC)

PWNe in the context of SNRs



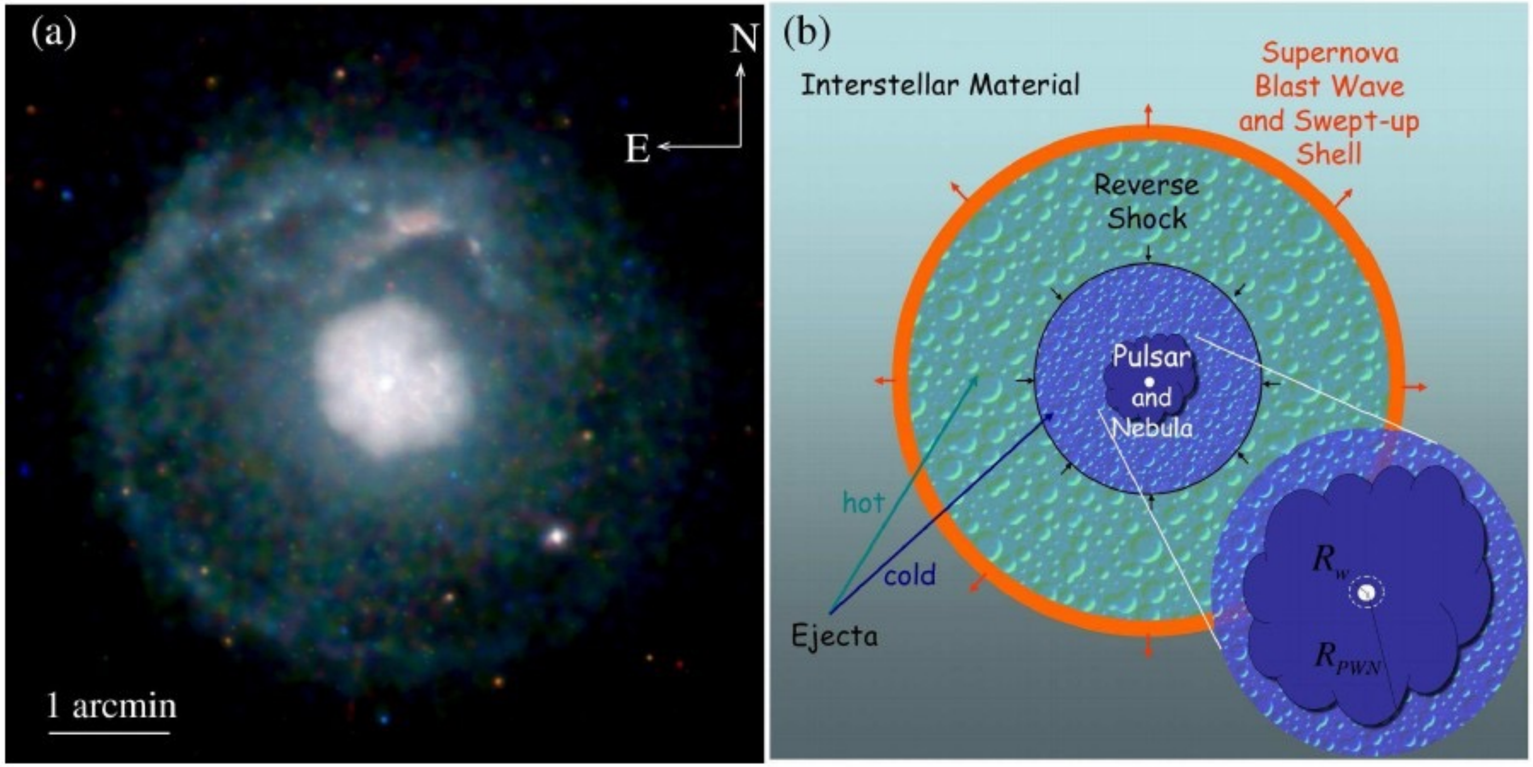
Plot from Gaensler & Slane 2006

• The pulsar wind sweeps up the ejecta; the shock decelerates the flow & accelerates particles; and a PWN forms

PWN: hot bubbles (a.k.a., plerions) of particles and magnetic field, emitting non-thermal radiation (via synchrotron – inverse Compton) from radio to TeV γ-rays

• The Supernova Remnant sweeps up the ISM; and a reverse shock heats the ejecta; and for older PWN, ultimately compresses it

This simple concept works well for some PWN



Plot from Gaensler & Slane 2006 + observations of G21.5-0.9 with Chandra

A young PWN in an isotropic environment

Not so well for others: PSR kicks?

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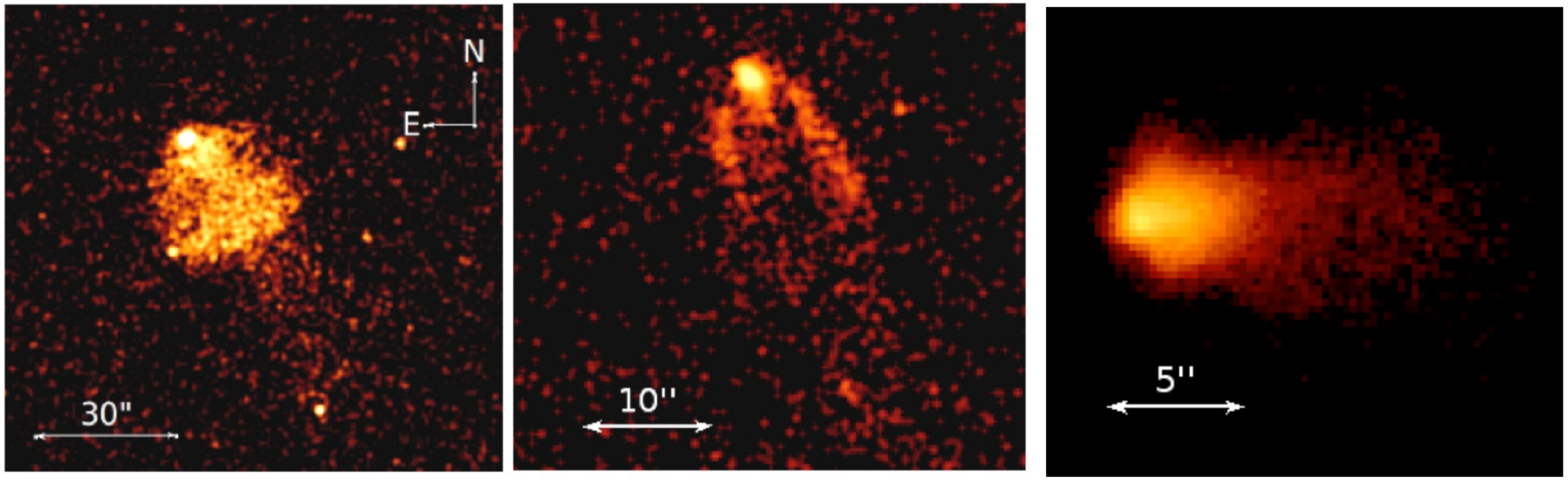
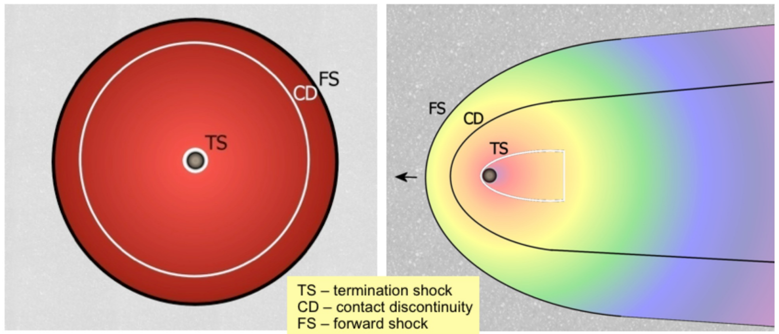


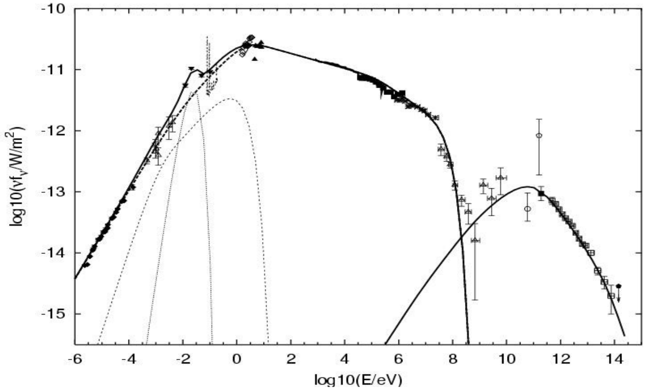
Fig. 9 *Chandra* ACIS images of the head regions of B0355+54, J1509–5058, and Mouse PWNe (left to right). Notice very different morphologies of B0355+54 and J1509–5058 PWNe. The images are produced from archival *Chandra* data.

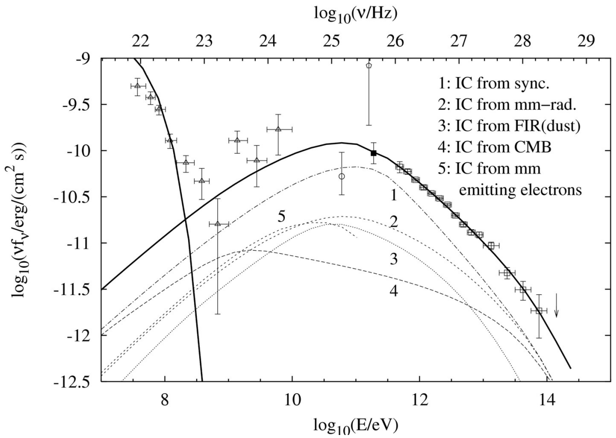
Kargaltsev et al. 2020

The pulsar moves and eventually abandons the PWN



From Crab to the PWN zoo





- Crab Nebula is a very effective accelerator but not an effective IC gamma-ray emitter.
- We see gamma-rays from Crab because of its large spin-down reservoir (~10^{38} erg/s), but gamma-ray luminosity << spin-down power,
- because of a relatively large magnetic field, whose strength also depends on spin-down.

A possible large zoo of PWN:
less powerful pulsar → weaker magnetic field → higher gamma-ray efficiency

(i.e., even when there is less spin-down power available, there is a more efficient sharing between synchrotron and IC losses).

Concept by Okkie de Jager, Felix Aharonian, et al.

From Crab to the PWN zoo

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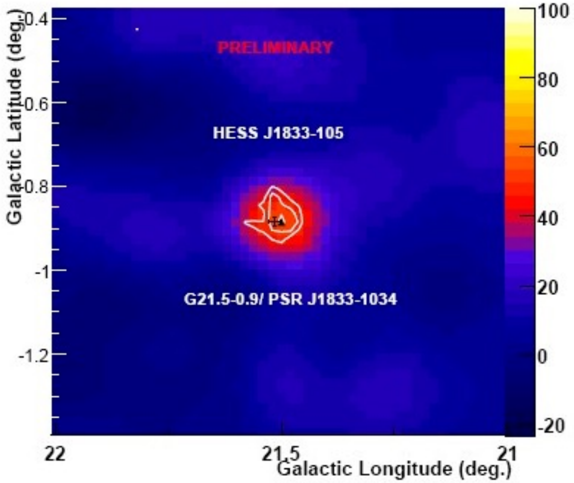
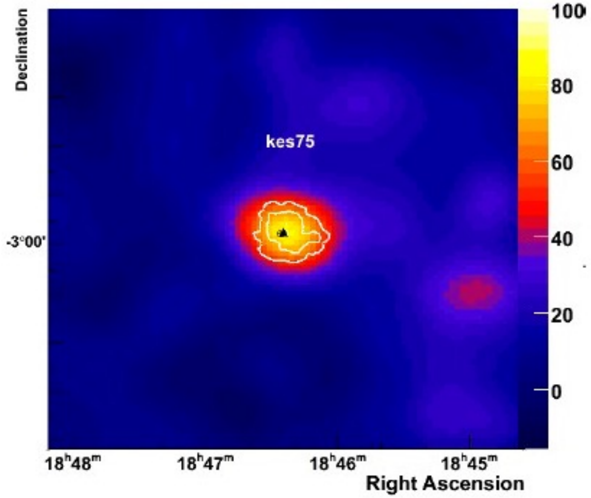
Compare with Crab's L(1-10 TeV) =3.7x10^{33} erg/s and Edot=4x10^{38} erg/s



G21.5/PSR J1833-1034:
τ = 4.7 kyr,
Edot = 3x10^{37} erg/s,
d ~ 5kpc
L(1-10 TeV) = 4x10^{33} erg/s
B ~ 25 μG



Kes75/PSR J1848-0258:
τ < 1 kyr,
Edot = 8x10^{36} erg/s,
d ~ 6 kpc
L(1-10 TeV) = 6x10^{33} erg/s
B ~ 10 μG

Particle dominated nebulae

Why do we care about PWNe

- Pulsations at all frequencies (which depending on geometry, may or may not be seen) take only a few percent of the spin-down power.

- Instead, pulsars lose the bulk of their energy via the production of a relativistic wind, an outflow of relativistic particles that generates a nebula.

- While emitting across the electromagnetic spectrum, PWNe connect with
  - the compact star itself (e.g., via its rotational power and the rate of its decrease),
  - its progenitor and SNR they leave (e.g., via the energy of the explosion, the supernova mass ejecta, the kick velocity of pulsar, the interaction with the reverse shock)
  - the interstellar medium (ISM) and photon density in which they are located.

- Understanding PWN implies getting all these interfaces right: identification and characterization is thus crucial for a broad range of topics in current astrophysics.

Why do we care about PWNe

- Detecting radio and gamma-ray emission from a PWN enables measuring the particle spectrum, the magnetic field strength, and the energy density of the background photon field.

- We could determine the wind composition, estimating how many pairs are produced in the pulsar magnetosphere

- Studying spatial morphology of PWNe allows inferring properties of the progenitor and of the environment, as well as the diffusion and cooling to which particles are subject.

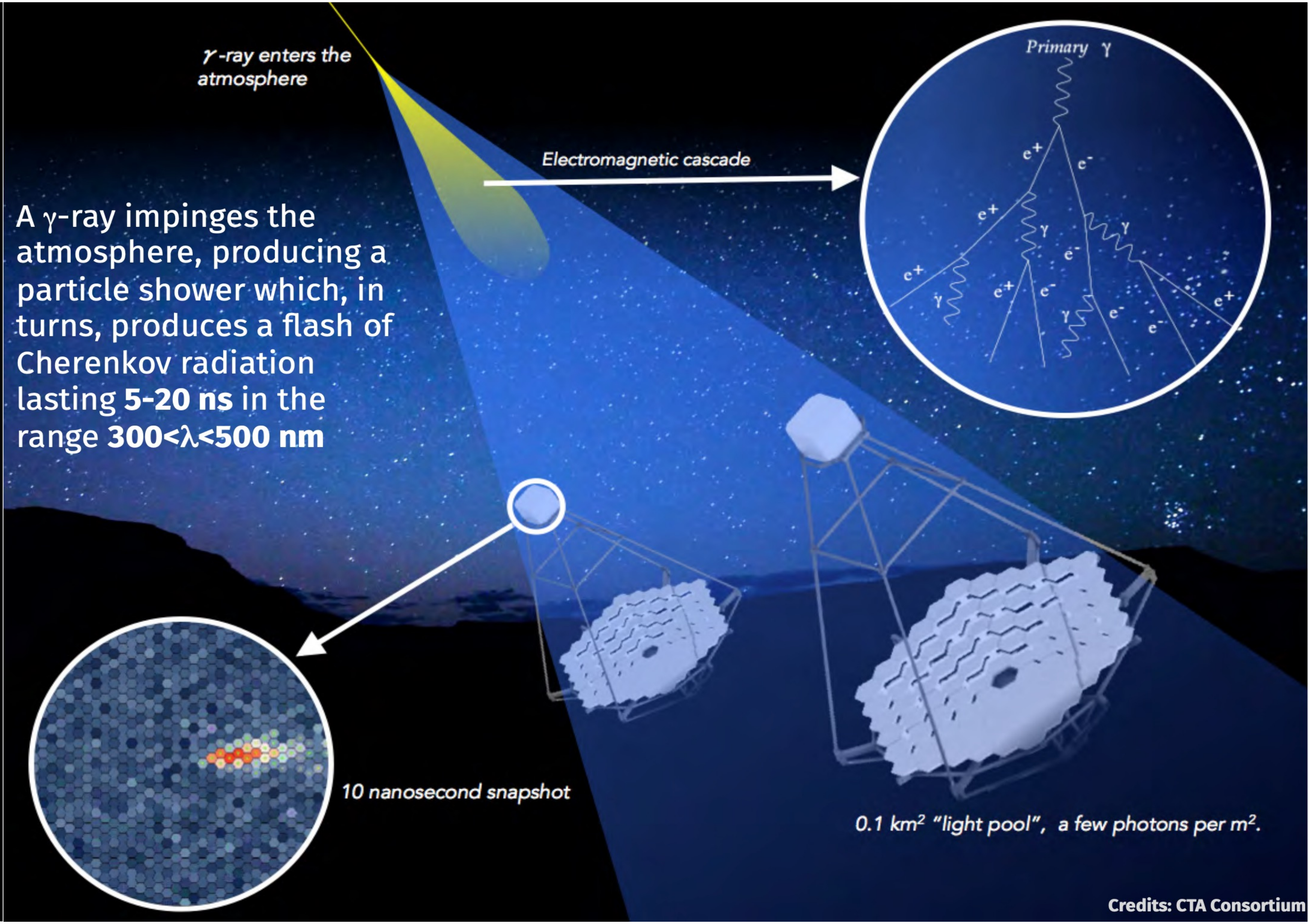
- Since they last thousands of years, providing clues about the historical evolution of radiative plasma and transport of particles/fields

- And they also flare! There should be an efficient & rapid particle acceleration (like in AGNs or GRBs): common mechanisms (magnetic reconnection or shock acceleration)

- Pulsars are connected with FRBs, GWs... multi-messenger objects.

A view to the population brought by TeV astrophysics

The atmosphere is part of the telescope



The current population of PWNe

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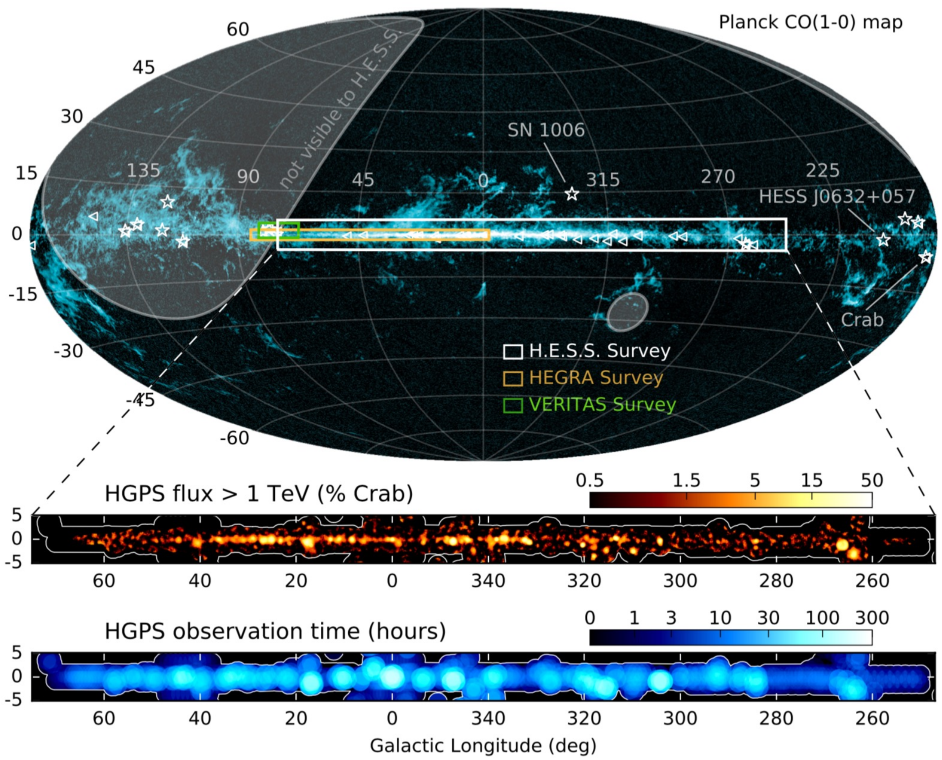
HESS Galactic Plane Survey, HESS Collaboration



The HGPS catalog contains 78 VHE sources.

The current population of PWNe

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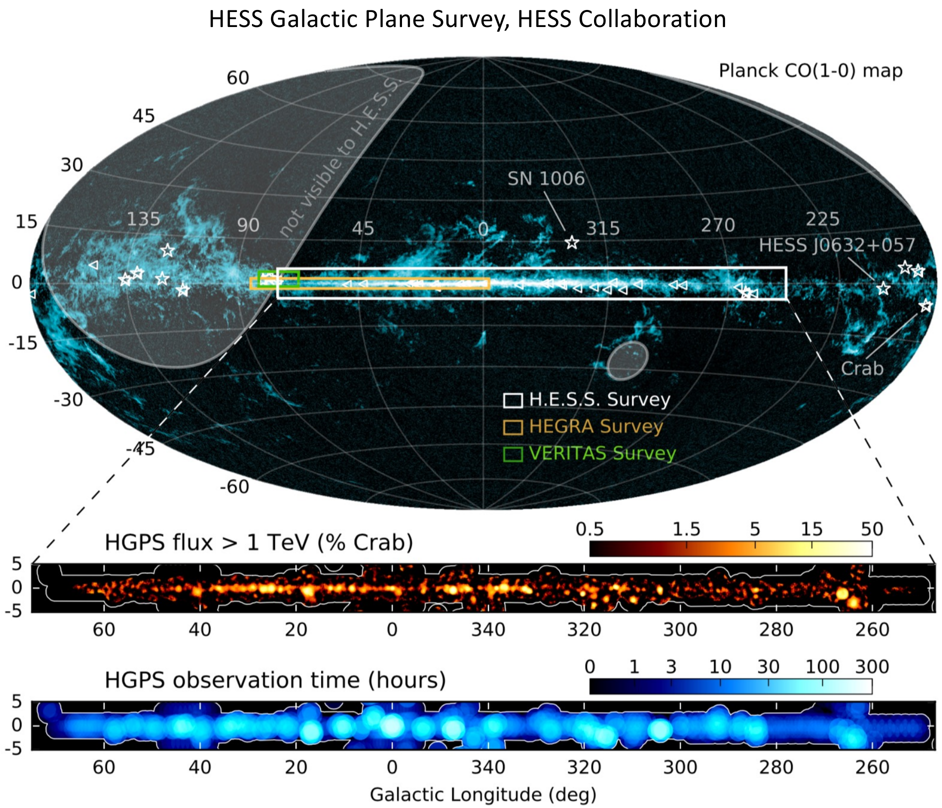
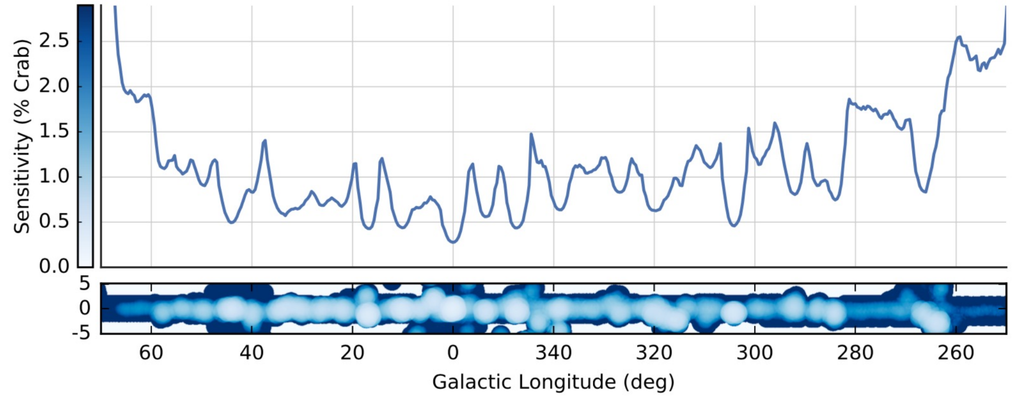
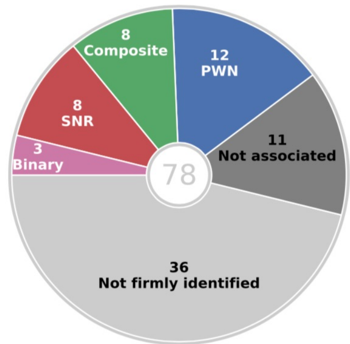




31/78 are firmly identified as pulsar wind nebulae (PWNe), supernova remnants (SNRs), composite SNRs, and a few gamma-ray binaries.

47/78 (>50%) are unidentified

36/47 (>76%) are likely related with PWNe



The HGPS catalog contains 78 VHE sources.

CTA: Three kind of telescopes

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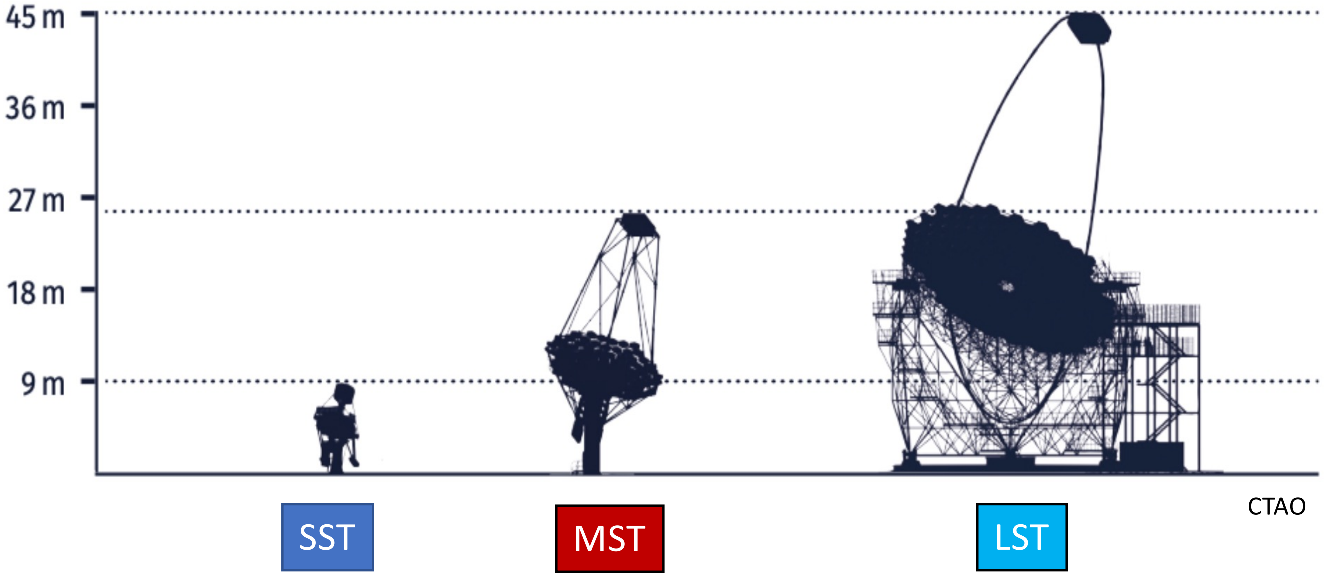

Precision measurements in a still little explored energy range
100TeV range largely unexplored

Deepest sensitivity ever
Arcmin angular resolution
Large FoV
Surveys & precision studies

Lowest energies (tens of GeV)
Cosmological sources
Deepest sensitivity for short timescales
Time domain largely unexplored

Different configurations – science focus

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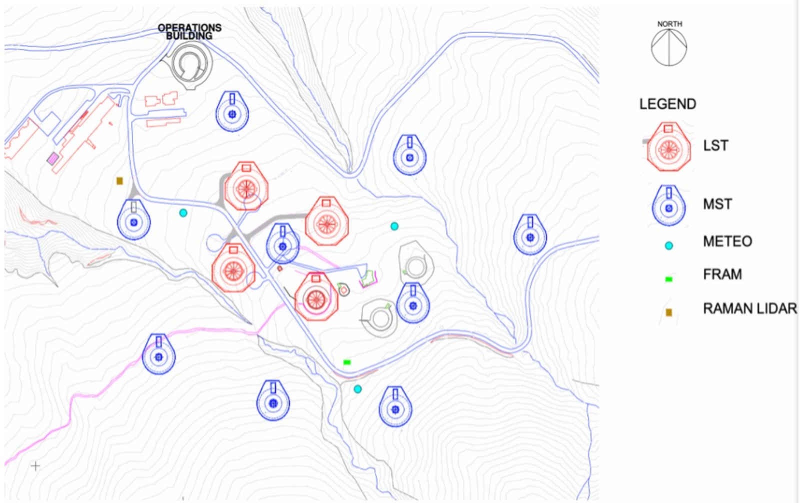
α configuration
CTAO

CTAO Northern Array

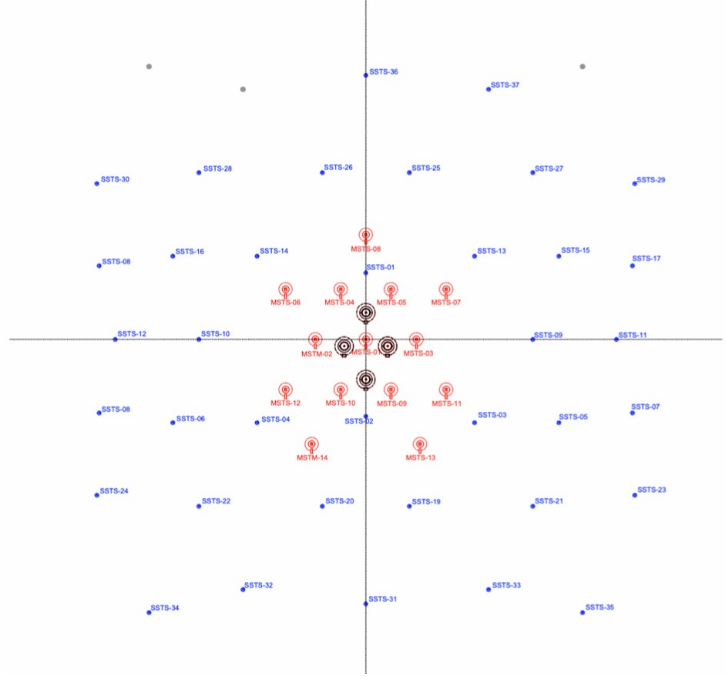
- **4 LSTs + 9 MSTs**
- 0,25 km^2 footprint
- focus on extra-Galactic science



CTAO Southern Array

- **14 MSTs + 37 SSTs**
- 3 km^2 footprint
- focus on Galactic science

+ Italian funding for **2 LST** and **5 SST**



In comparison, sensitivity in 50 hours

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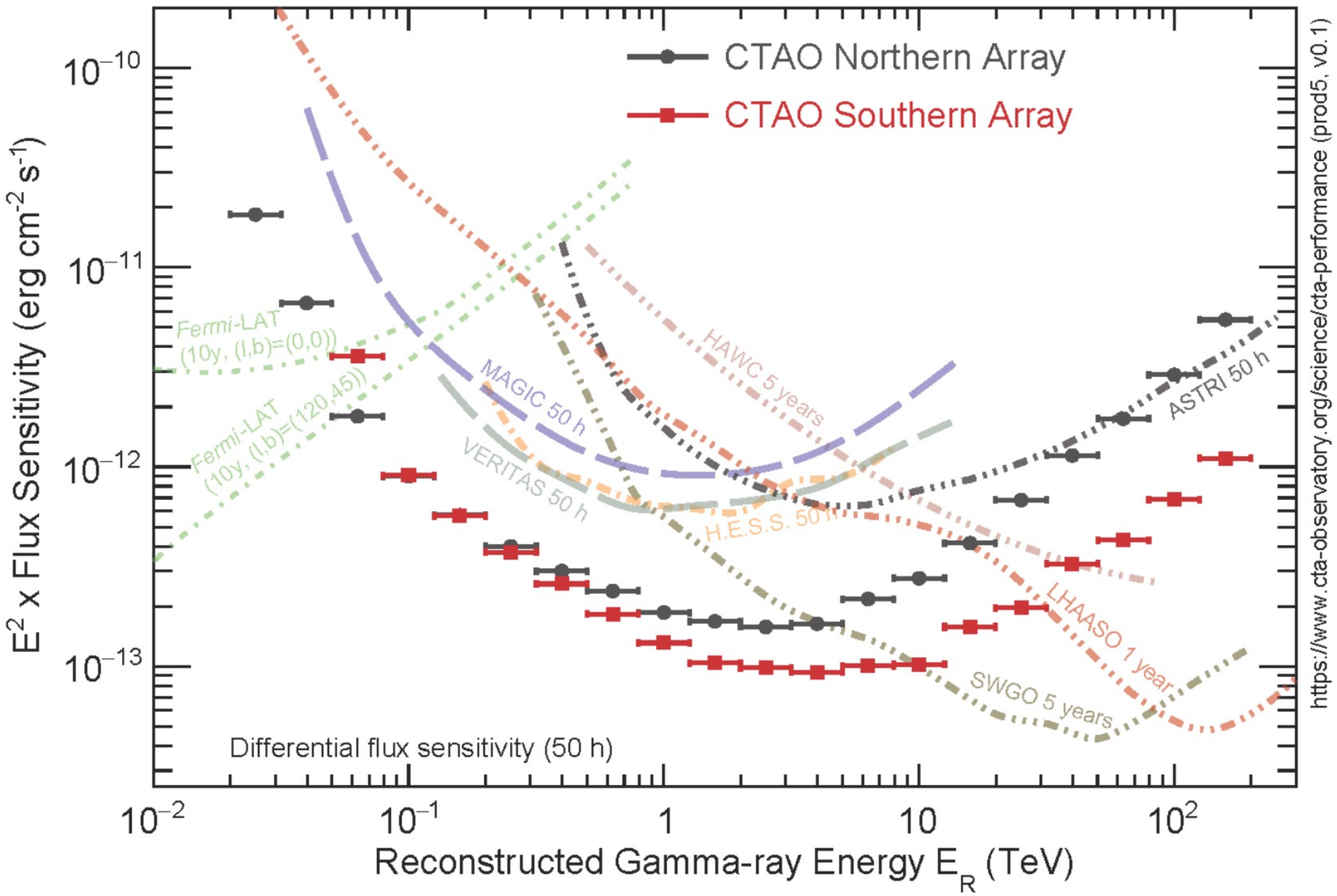

In comparison: sensitivity @ short timescales

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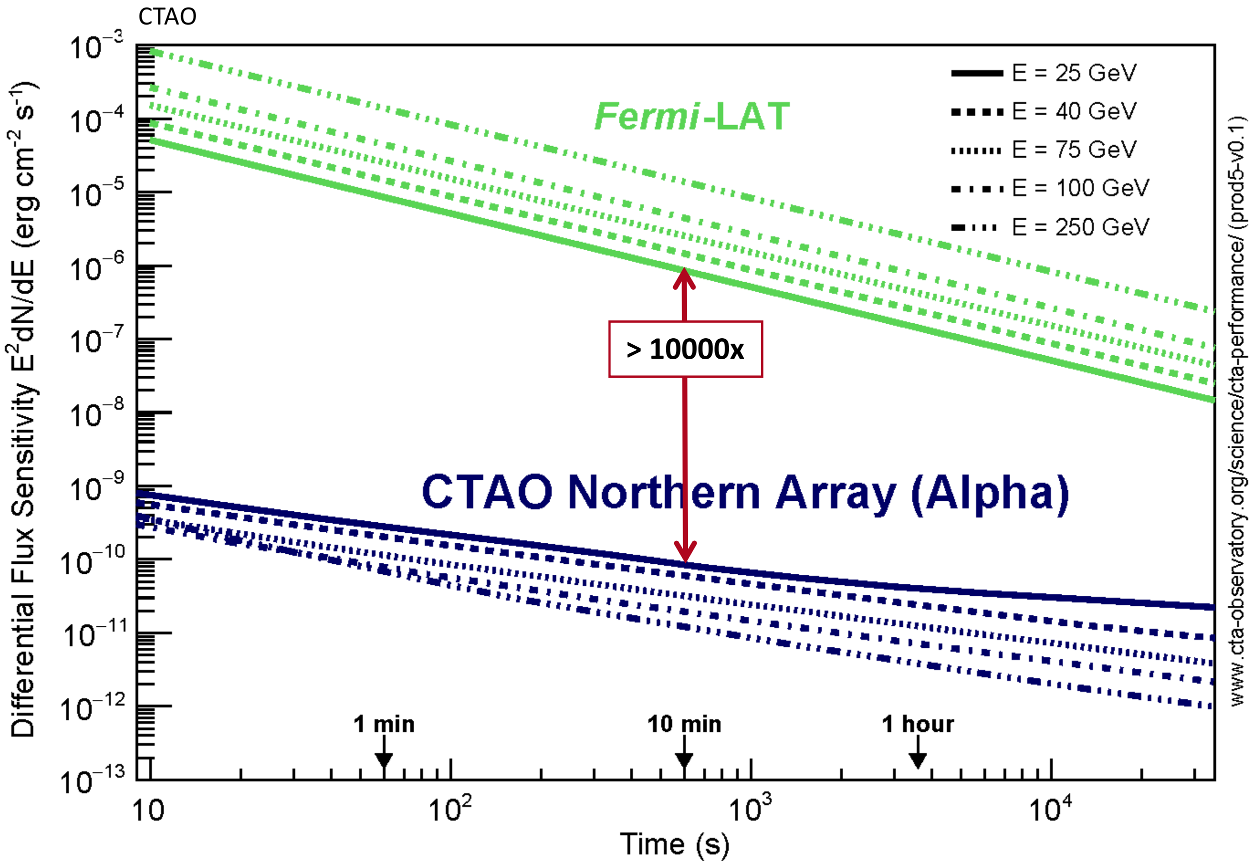
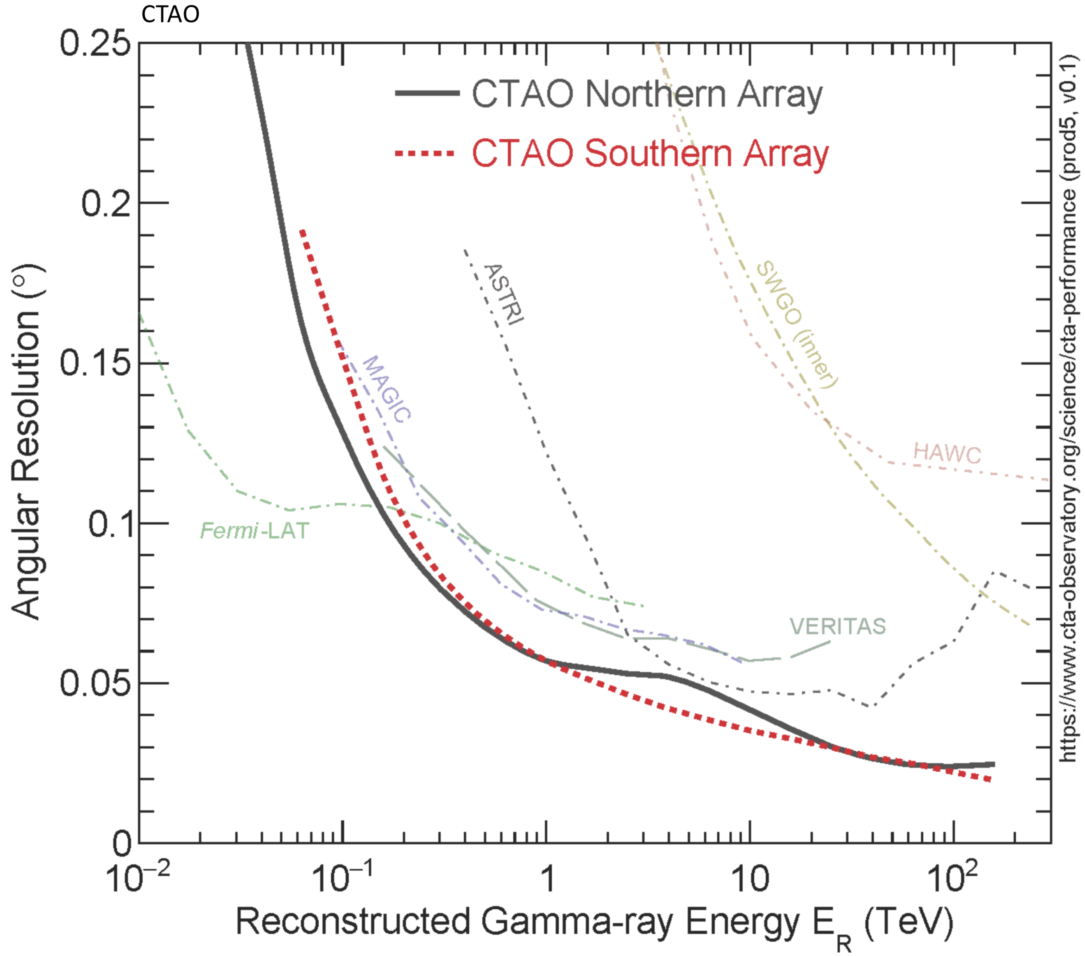
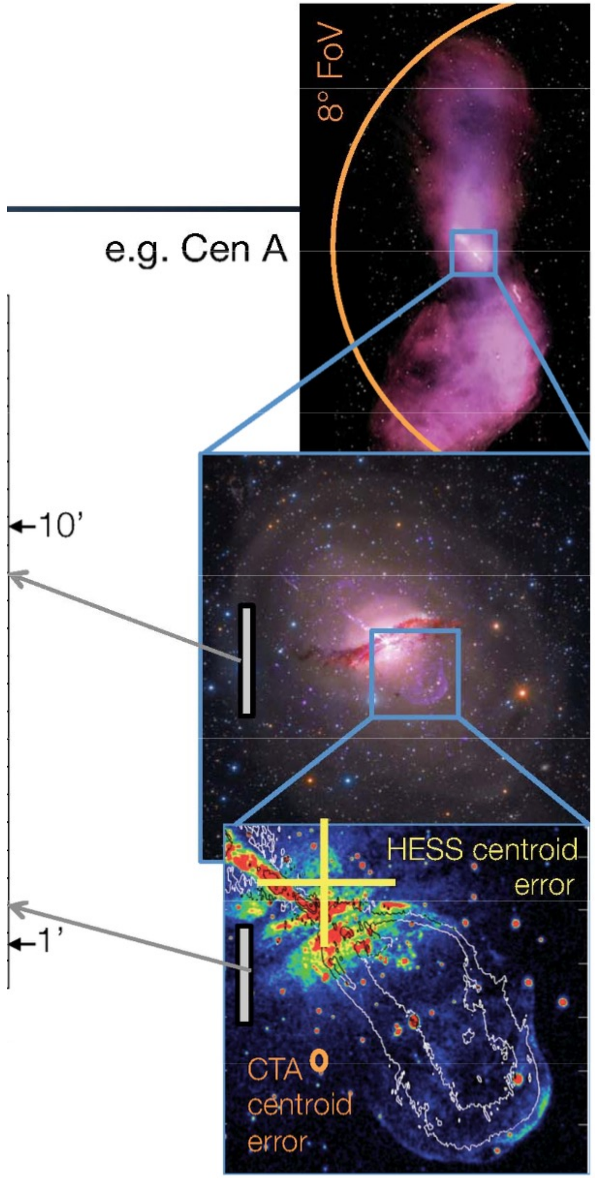


In comparison: angular resolution





Three large themes, critical questions

Theme 1: Cosmic Particle Acceleration

- How and where are particles accelerated?
- How do they propagate?
- What is their impact on the environment?

Theme 2: Probing Extreme Environments

- Processes close to neutron stars and black holes?
- Characteristics of relativistic jets, winds and explosions?
- Cosmic voids: their radiation fields and magnetic fields

Theme 3: Physics Frontiers

- What is the nature of Dark Matter and how is it distributed?
- Is the speed of light a constant?
- Do axion-like particles exist?

Multi-year, deep observations

www.worldscientific.com/worldscibooks/10.1142/10986

1. Dark Matter Programme
2. Galactic Centre
3. Galactic Plane Survey
4. Large Magellanic Cloud Survey
5. Extragalactic Survey
6. Transients
7. Cosmic-ray PeVatrons
8. Star-forming Systems
9. Active Galactic Nuclei
10. Cluster of Galaxies
11. Beyond Gamma Rays

Mixing surveys and deep observations of key objects

Why surveys?

- Favors discoveries of unknown source classes.
- Provide testing ground for new theoretical ideas,
- Facilitate population studies at an unbiased sensitivity threshold.
- Provide legacy datasets for lasting future reference.
- Surveys assist the community in formulating observational proposals.

Surveys in a snapshot

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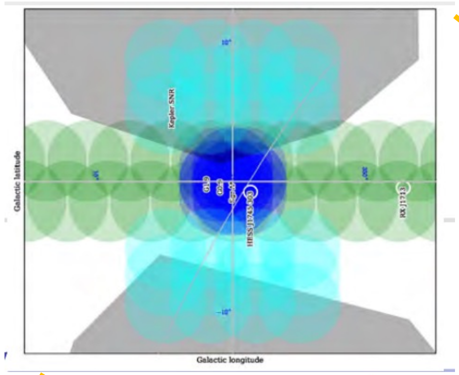
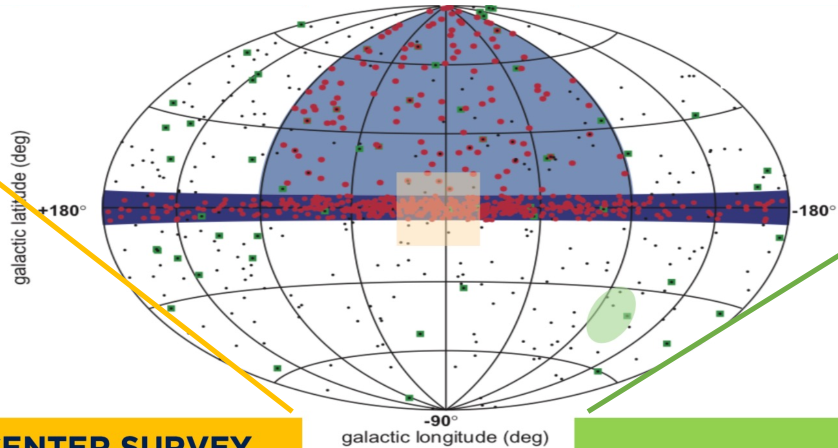
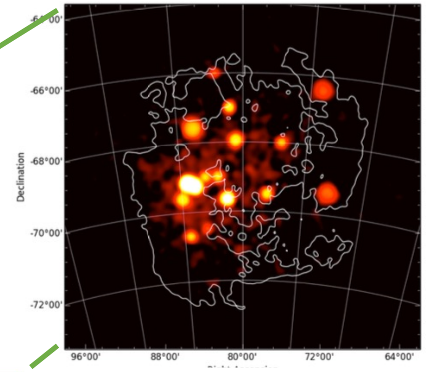
The deepest ever **Galactic plane survey**, with sensitivity comparable to the longest pointings made for any source. GalacNc source populaNon: SNRs, PWNe, etc. PeVatron candidates, early view of GC, O(1620) h
(2-4 mCrab, with first results after 1 year)

The first **extragalactic blind survey** at these energies ~1/4th of the sky out of the Galactic plane). Sensitivity comparable to the faintest AGN currently detected at VHE (~5 mCrab).
Studies of the duty cycle New, unknown sources; O(1000) h





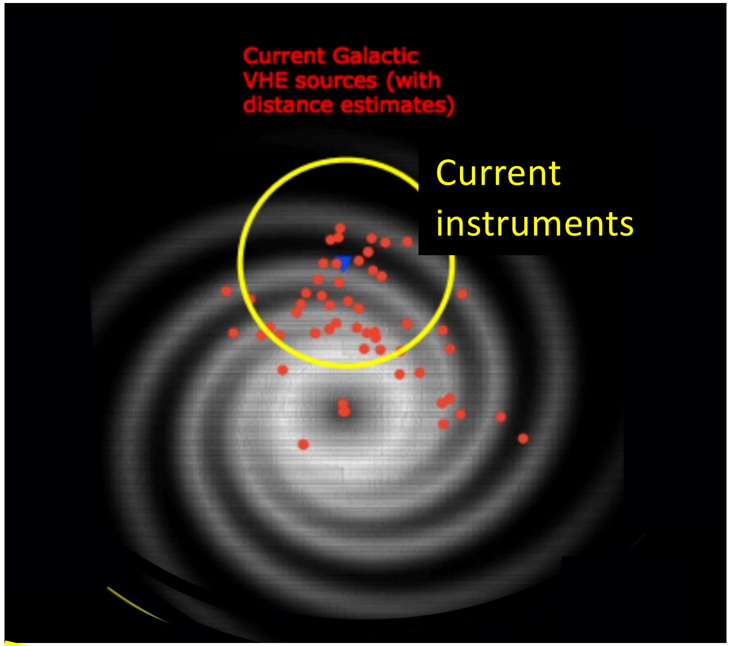


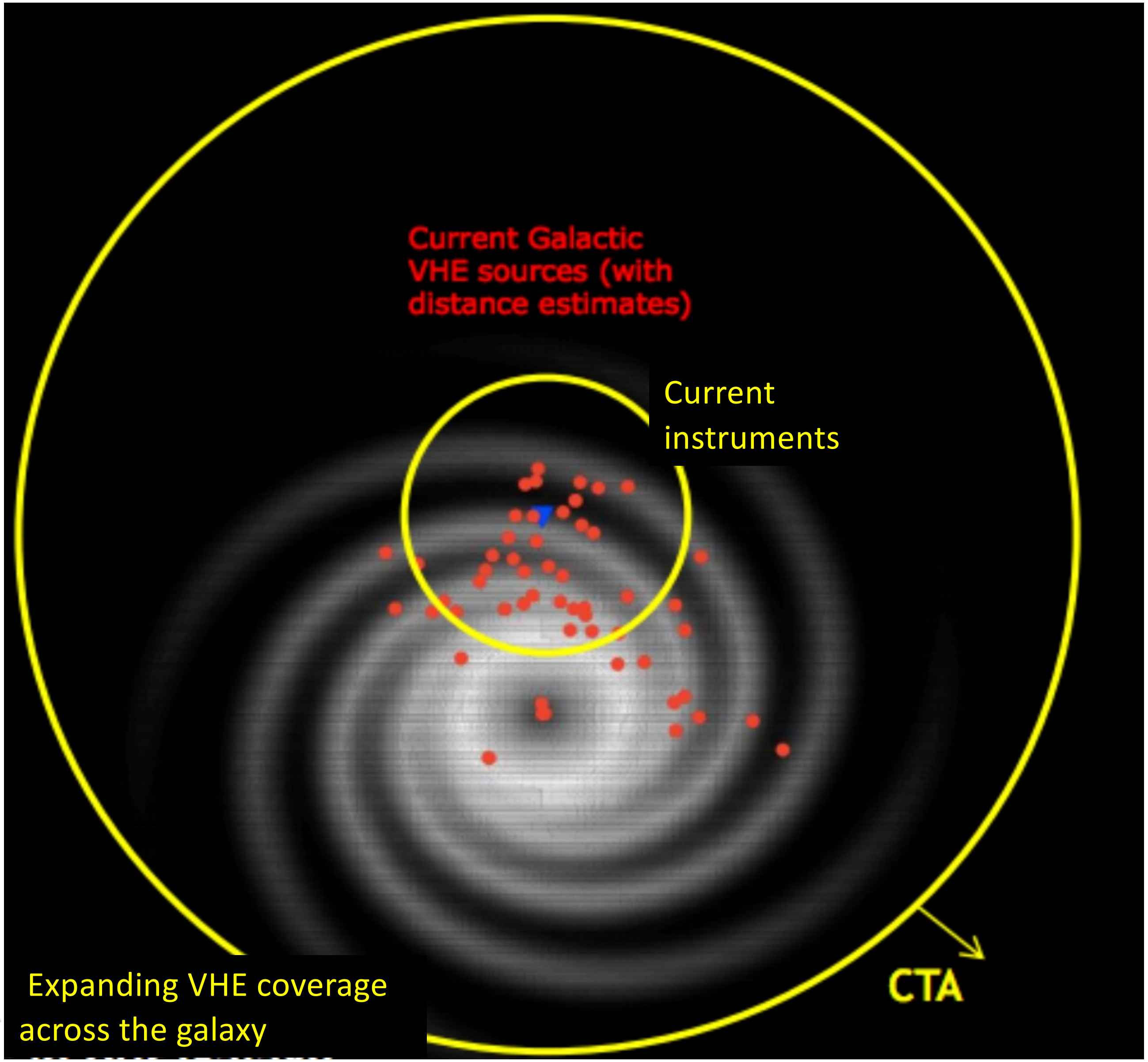
GALACTIC CENTER SURVEY
deeper observations
around the GC
10◦ x 10◦
2 mCrab

LARGE MAGELLANIC CLOUD SURVEY
1.5-2 mCrab

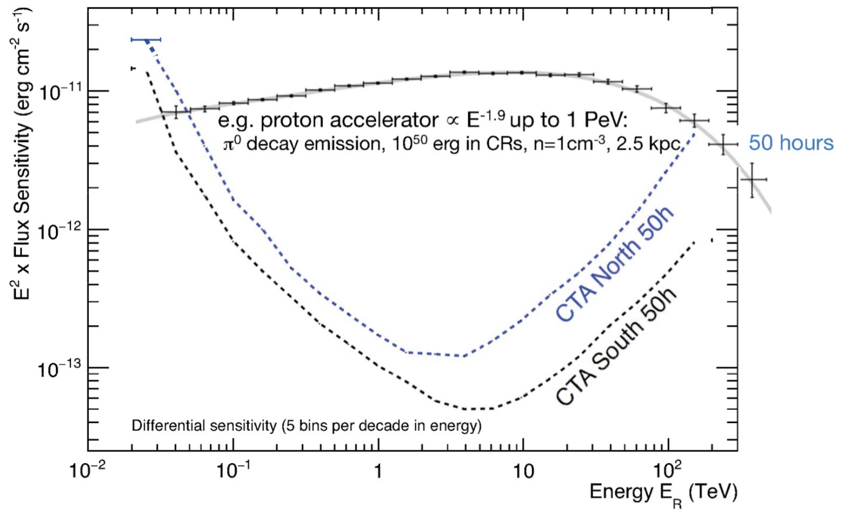
Galactic Coverage

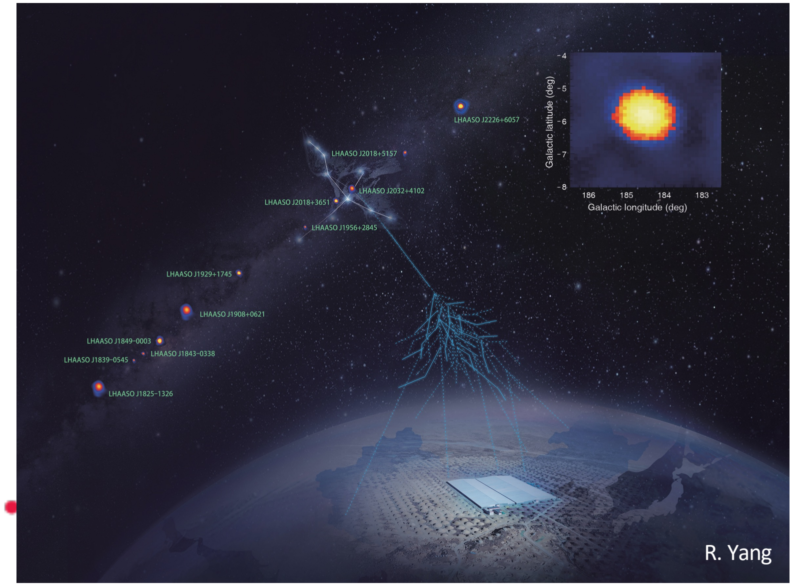
CTAO





Pevatrons, LHASSO sources



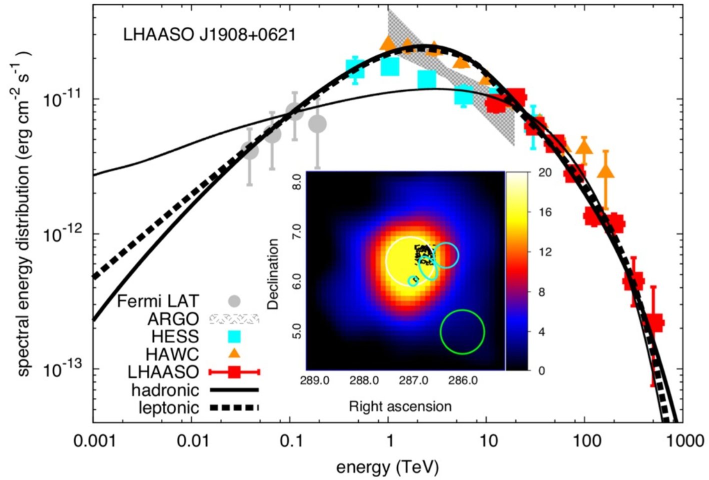


Extended Data Table 2 | List of energetic astrophysical objects possibly associated with each LHAASO source

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

Unclear origin of the emission. Large spatial uncertainty.

Leptonic origin not discarded.



Source populations growth

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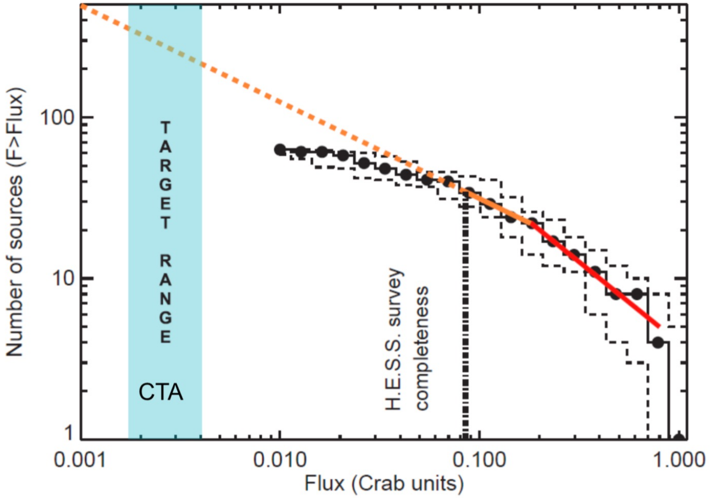
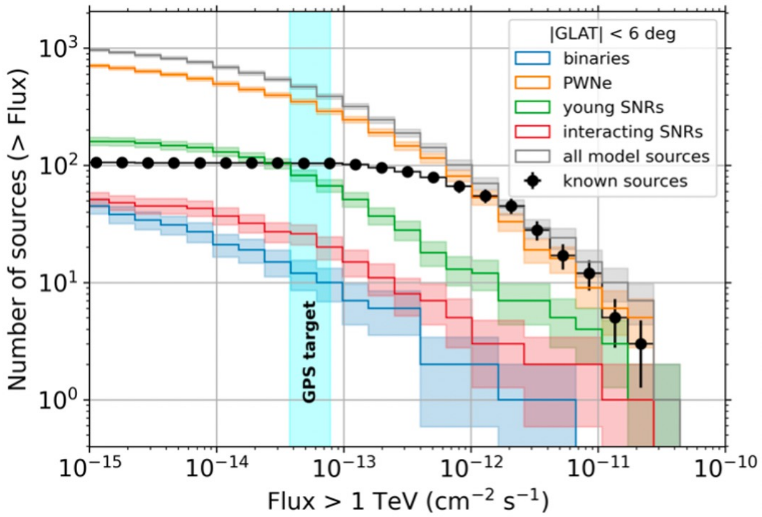
Science with CTA 2019





- Expected increase in the number of sources by 5-10x
- Essentially full coverage of PWN and SNRs across the Galaxy
- Evolutionary studies (not just more of the same, but windows to new problems, e.g., reverberation)
- Confronting confusion

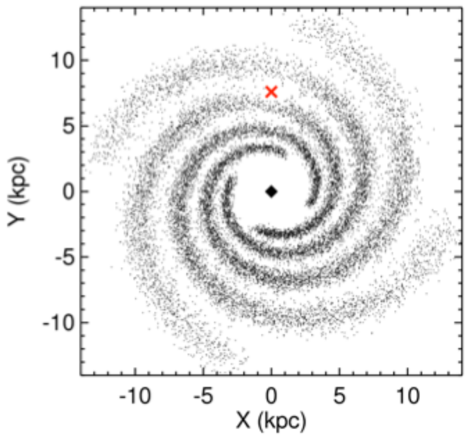
Source populations growth

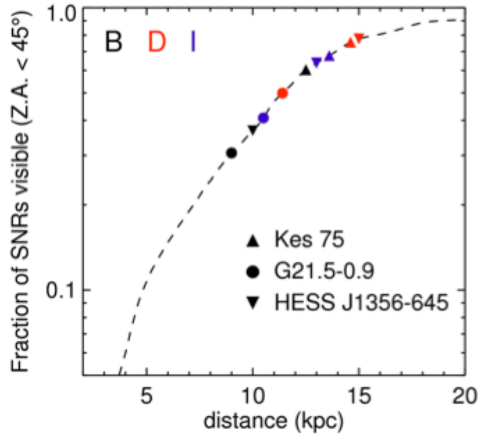
CTA would detect a significant fraction (0.4 to 0.8) of all the PWN expected to shine at higher energies – hundreds of PWNe

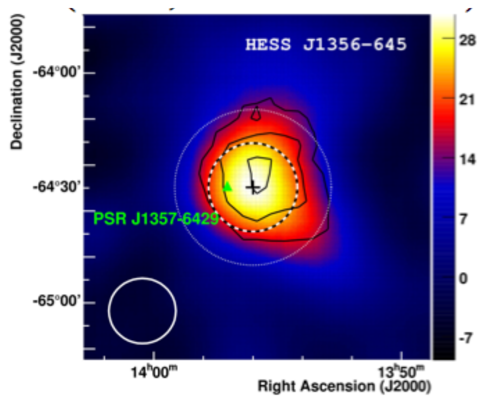
Population of fainter TeV PWNe ($L_{0.3\text{-}30TeV} \sim 10^{34}$ erg s^{-1}) :

Simulate Galactic (core-collapse) SNR distribution (as before)

Ignore displacement from pulsar birth place due to kick velocity







- PWNe with Crab luminosity detectable up to the LMC
- fainter PWNe detectable to 10–15 kpc

Source populations growth

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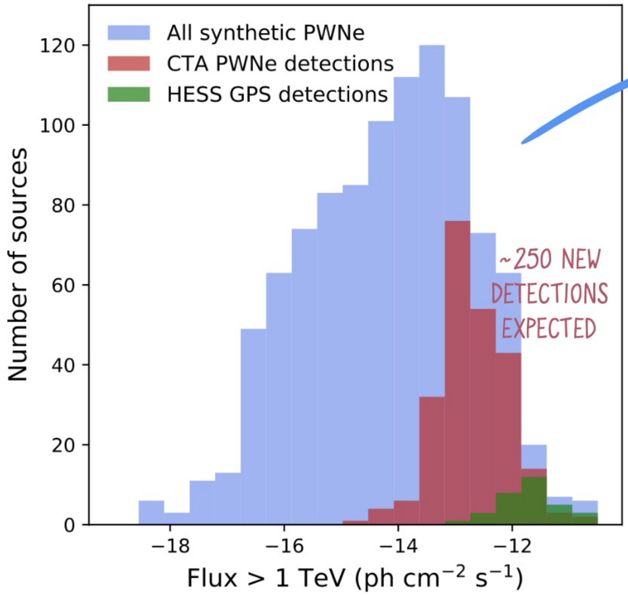
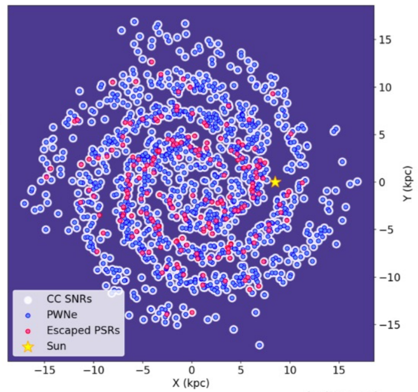
Olmi et al. 2022

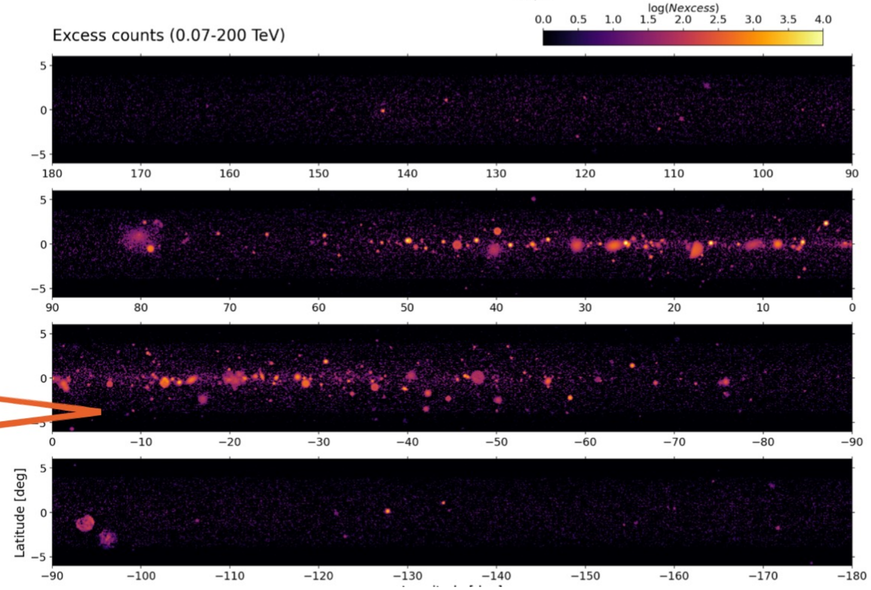
EXPECTED DETECTIONS AT GAMMA-RAYS WITH CTA



DISTRIBUTION OF SYNTHETIC SOURCES IN THE GALAXY



[Fiori et al 2022]



[Q. Remy et al. 2021]

PWNE= 60%
SNRS= 10%

[CTA GPS consortium paper, in prep.]

Source populations growth

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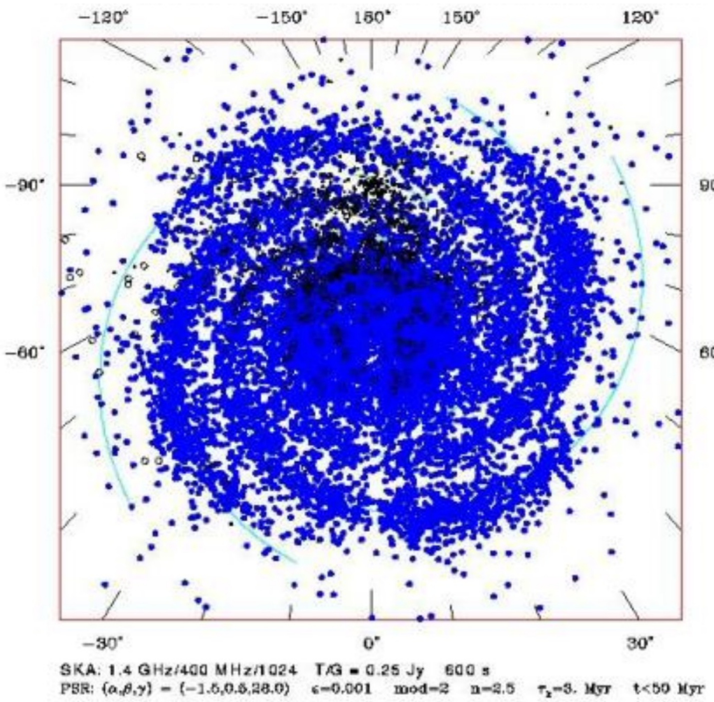


from M. Kramer, Pulsar science with SKA

64 μs samples

1024 channels

600 s per beam

~10^4 psr's

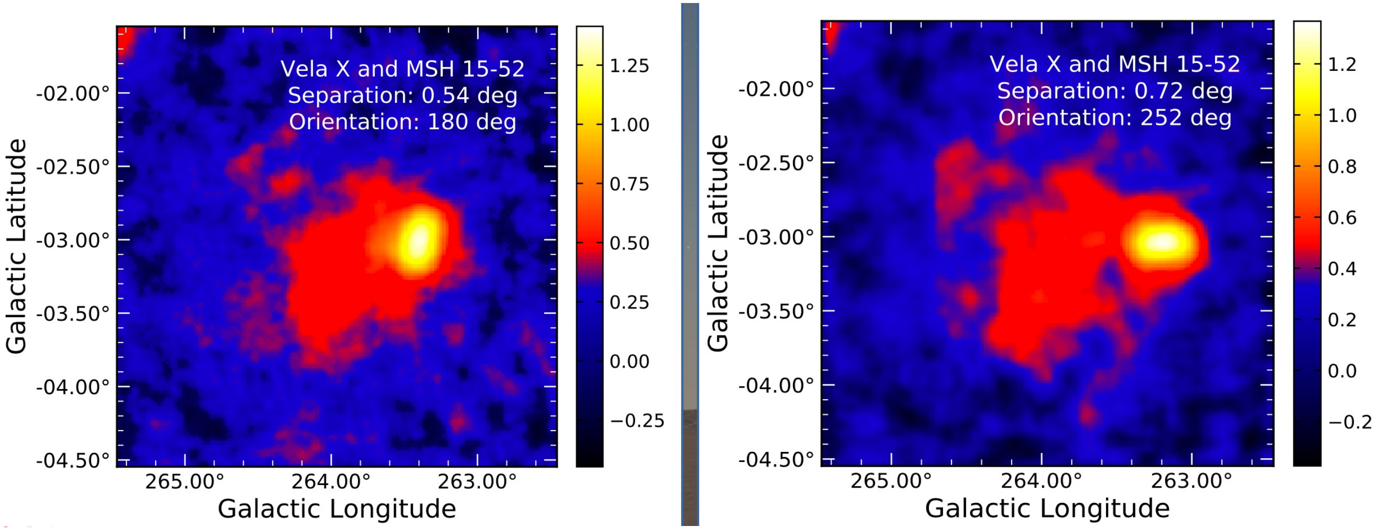
Issues, risks, and opportunities

Confusion

Artificially confused sources

- Using all 12 firmly-identified PWNe in the HGPS. Their fluxes vary in nearly two orders of magnitude
  - The number of confused templates is Nx(N-1)/2, not accounting for orientations, separations... We are limited by the computation time.
  - We fix the distance and fluxes to a reduced number of templates.
  - Distances can be handled by rescaling the template's flux (1/r2) and spatial axes (1/r)
- We confused the templates in pairs with various projected separations and relative orientations (fixed distance).
- The PWNe density, obtained from a source distribution model (for a Galactic central region), is fixed to ~0.5°of average separation (0.25° FWHM).

Mestre, DFT, et al. 2022



Analyzing simulations

1. Hypotheses regarding one source:

All source templates (HTemp. i),
their rotations (HTemp.i,α),
and a Gaussian source model (Hgauss).

2. Confused source hypotheses:
All confused templates; all possible pairings in all setups used (Hconf.).

$$\Delta TS = max\left(TS_{Conf.}\right) - max\left(TS_{Temp.i}, TS_{Temp.i,\alpha}, TS_{Gauss}\right)$$

$$TS_{H_i} - TS_{H_i} = 2 \times \ln\left(L_i / L_j\right)$$

3. If ΔTS > 0, we consider two sources (H_{2src}) corresponding to each template in the best-fit model under the $H_{conf.}$ hypothesis. We perform an unbinned maximum likelihood fit of the sources to retrieve the input model.

Mestre, DFT, et al. 2022

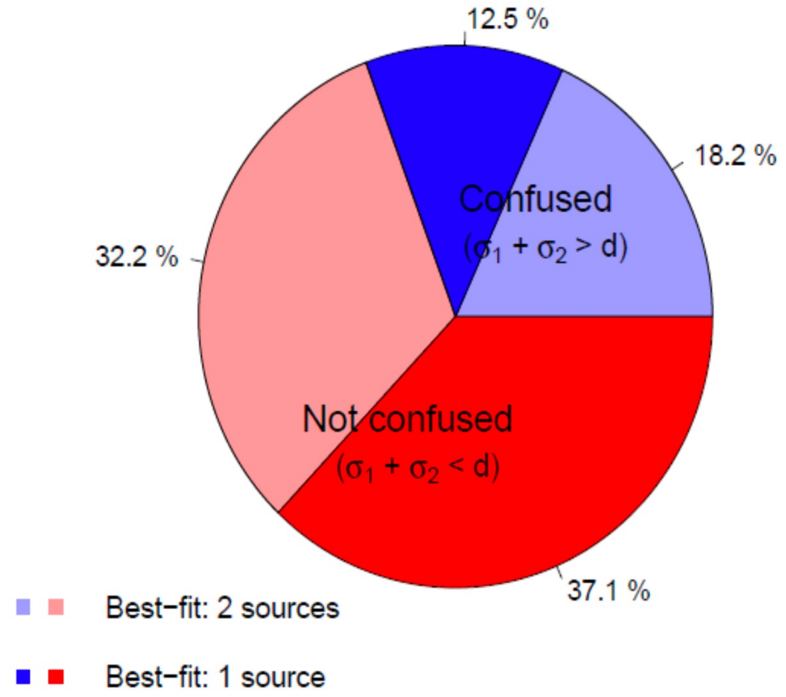
Criterion, and expected confusion

We establish the next criterion:

- Two sources are "strictly confused" if;
  $\sigma_1 + \sigma_2 > d$.

- The PWNe can lie on top of the extended emission of the other despite not being strictly confused due to the angular resolution.

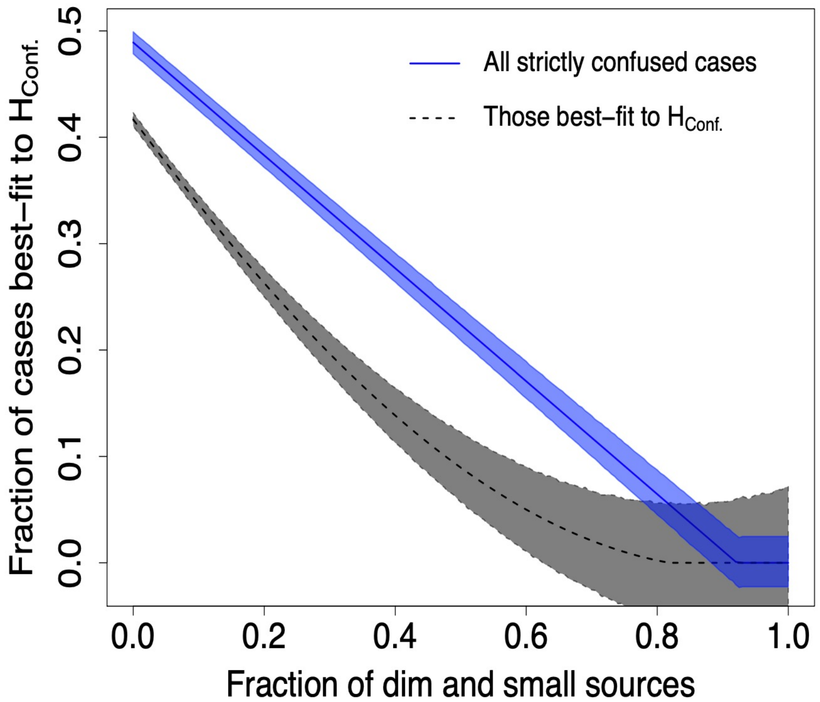
- We classify the results according to ΔTS:
  1. Best-fit to a confused source template (ΔTS > 0).
  2. Any other one source hypothesis (ΔTS < 0).



Mestre, DFT, et al. 2022

How possibly it is to associate a wrong template?

- The events of strict source confusion best-fit to Hconf. conceal wrong associations of templates.
- The amount of plausibly wrong associations depends on how many dim sources we have
- Out of the simulations best-fit to H PWNe, in ~8% one nebula (or both) is wrongly identified.
- Similarly, when we have 50% of faint sources, these percentage can be about 26% of cases conceal a wrong template association



Mestre, DFT, et al. 2022

Assessment (caveats, way forward)

- We do not account for energy-dependent morphologies or variability.

- We do not consider more than two sources in the ROI or the contamination when analyzing two confused sources from other nearby ones.

- We fixed the average projected separation between the sources to 0.5 deg, consider, e.g., a lower sensitivity than expected or regions far from the Galactic center.

Despite the limitations of our method, we constrained:

1.The source confusion in CTA data, particularly regarding Galactic TeV PWNe, considering different ratios of faint and small sources in the expected population of CTA PWNe.

2.The amount of strict source confusion likely to occur; $\sigma 1 + \sigma 2 < d$.

3.The amount of flawed cross-matches expected when comparing CTA data with a library of morphological templates.

Our general approach facilitates:

1. The identification of numerous sources (as our results regarding isolated nebulae illustrate).
2. Resolving source confusion, even if challenging, to some extent (our approach can be easily generalized to other source classes).
3. Matching CTA data with detailed empirical or simulated (MHD, HD or HD+B) source templates (handled by the user).

MW identification techniques too costly, and often ineffective

Issue: Identification techniques
What we do now to identify a PWN?

1) **Use the catalogs of known pulsars to see whether there is a candidate for generating the putative nebula**
   - This spatial coincidence, whose value is dubious if not supported by additional information, may not happen often
   - Only ~1% of the potentially detectable radio pulsars in the Galaxy are known and there is a number of unidentified TeV sources of the current instruments without any such correlation already.

2) **Search the archives and eventually request multi-frequency observations to see whether there is a counterpart of the detection:**
   - X-rays and radio for a map of the continuum as well as for the pulsar search. Both aims can be hampered if the source detected is relatively large with respect to the angular coverage of these instruments.

3) **When the pulsar that may power the putative nebula is known..**
   - do a radiative modelling to which the observed spectrum can be compared.
   - This radiative model is most likely oversimplified (0D, and without reverberation), and many times with limited time-dependence treatment
   - This radiative model is most likely producing no real fit of the data, but a visually ok description

Issue: Identification techniques
What we do now to identify a PWN?

Institute ... Sp...

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3) **...e putative nebula is known..**
   - ...o which the observed spectrum can be compared.
   - ...el is most likely oversimplified (0D, and without reverberation), and many times with ... dependence treatment
   - ...adiative model is most likely producing no real fit of the data, but a visually ok description

Depends on **follow-up observations** with other instruments, …

…implies a **timescale of at least ~1 year** of research per source,

…and is **not always successful**: out of 78 sources in the HESS Galactic Plane Survey,

47 are not yet identified, most of which should be PWNe

Finding the right approach to identify and characterize PWNe

(to study both morphology and spectra of PWNe, able to deal with many sources in an unbiased way, promoting meaningful population studies, and pointing the most interesting individuals)

Issue: Finding the right approach …

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2DMHD?

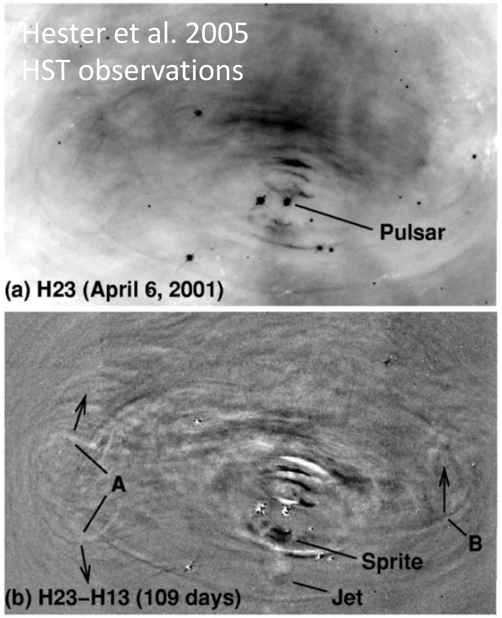
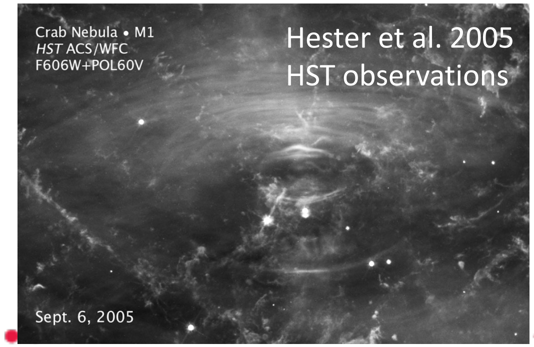
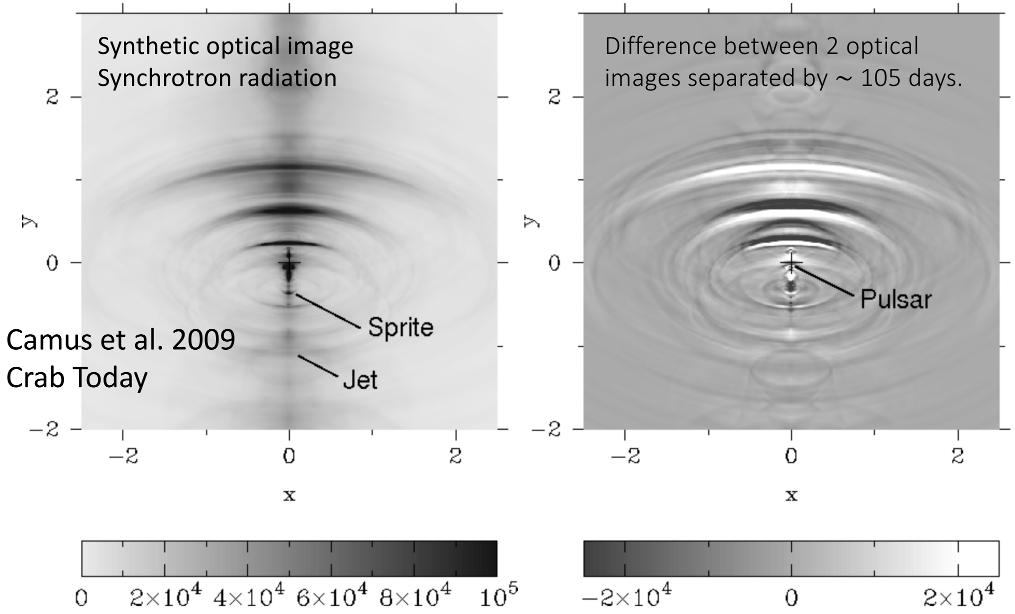


FIG. 1.—(*a*) *HST* image H23 obtained on 2001 April 6. (*b*) Difference between image H23 (*dark*) and image H13 (*light*), taken 109 days earlier. The dark/light patterns show changes in morphology, including wisp motion. The arrows indicate nonradial motions of features A and B.



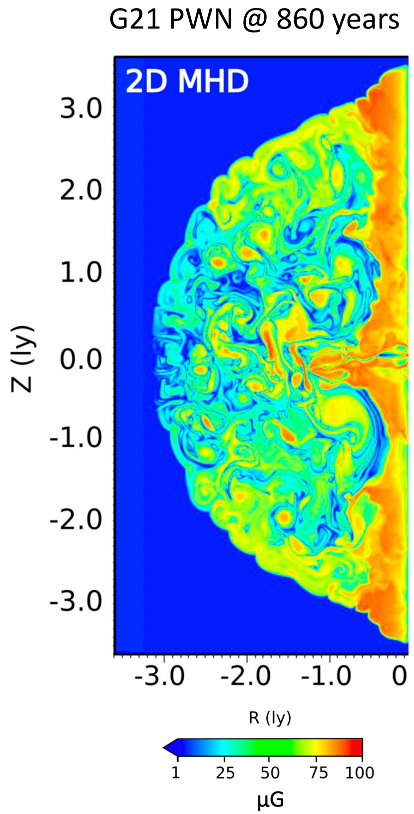


The simulations reveal a highly variable structure of the pulsar wind termination shock (small scales).

The synthetic synchrotron maps show striking similarity with images from HST.

In addition to the jet-torus structure, these maps reproduce the Crab's famous moving wisps whose speed and rate of production agree with the observations

Issue: Finding the right approach …



Field too high at the center, too low at the boundaries strongly affecting the resulting emission.

The volumen-averaged field, too low.

When fitting the morphology, these models cannot fit the spectra:

2DMHD Good for the very inner structure and variability of PWNe, not for general morphology or spectra.

And.. Already numerically costly.

Issue: Finding the right approach …

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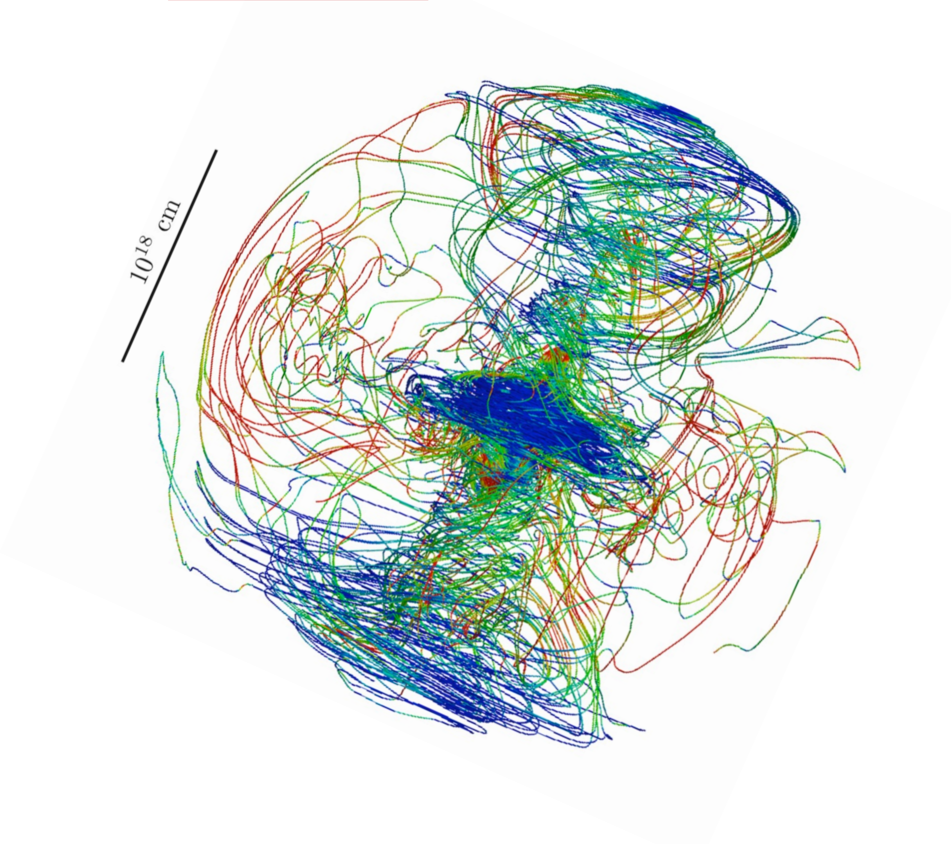
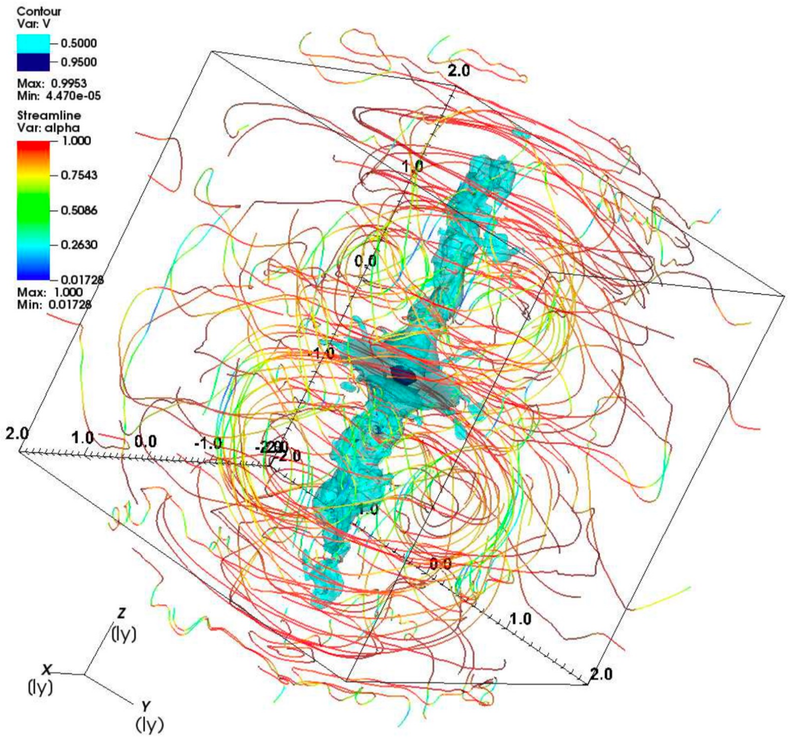
Porth et al. 2014
Crab @ 70 years



Olmi et al. 2016
Crab @ 250 years



Issue: Finding the right approach …

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Porth et al. 2014
Crab @ 50 years

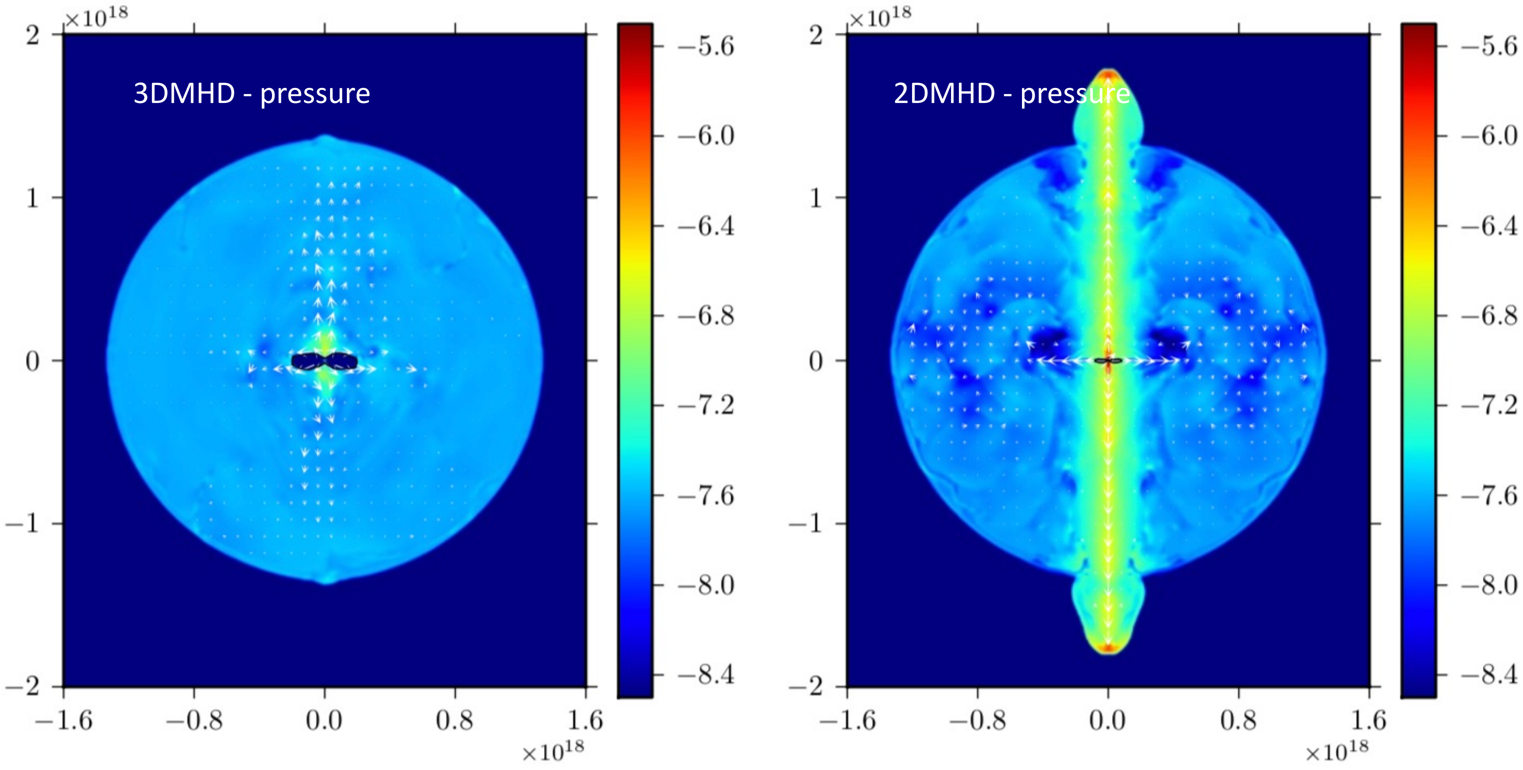
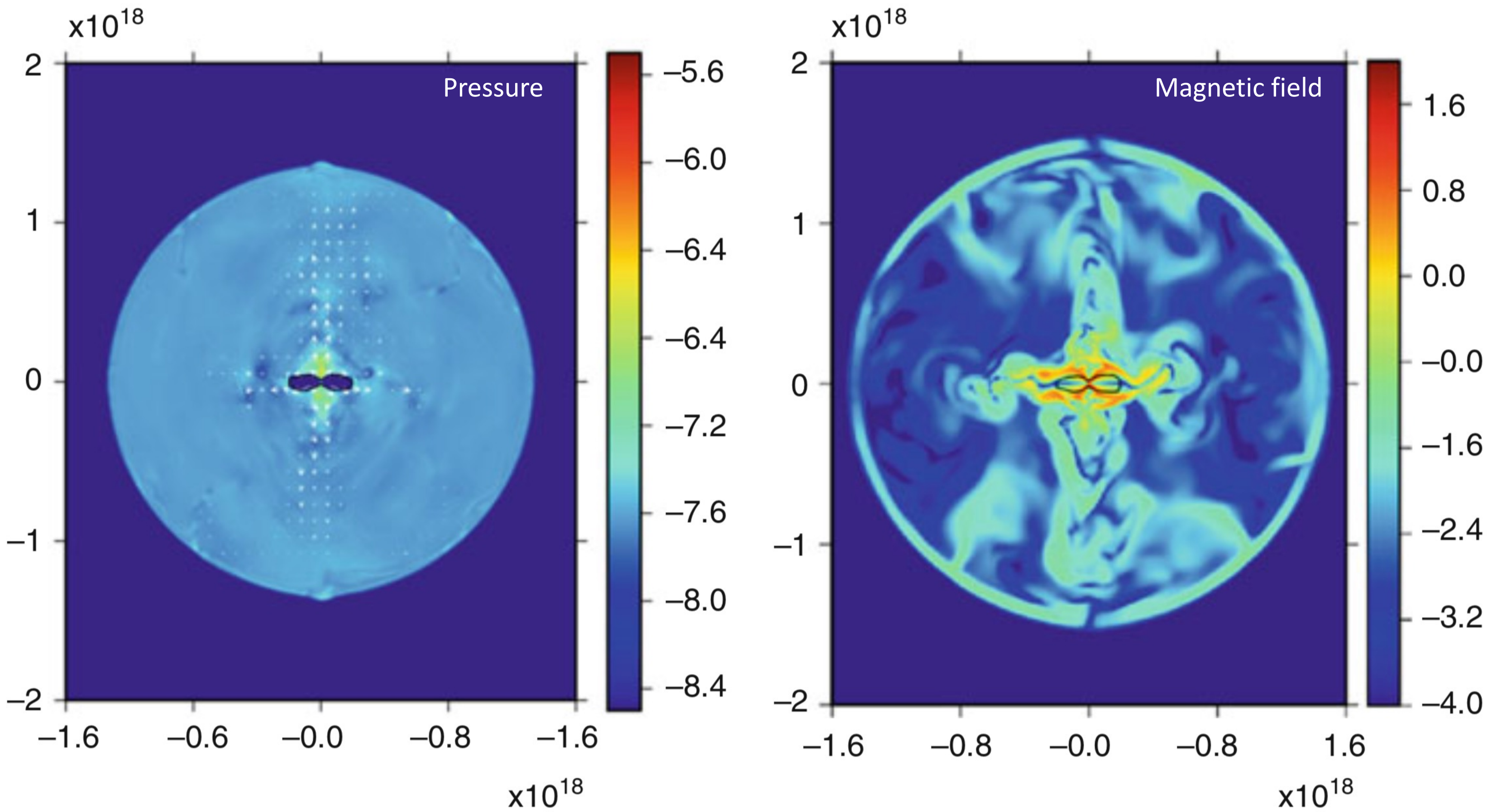


Figure 3. Dependence of the total pressure distribution, $\log_{10} p_{\rm tot}$, on the imposed symmetry. The left panel shows the pressure distribution in the xz-plane of the 3D simulation run B3Dhr and the right panel in the corresponding 2D run B2Dhr, both at the time of 51 years from the start of the simulations. The white arrows show the in-plane velocity vectors. The strong axial compression observed in this and previous 2D simulations is an artefact of the imposed symmetry.

Issue: Finding the right approach …

Porth et al. 2014
Crab @ 50 years



Issue: Finding the right approach ...

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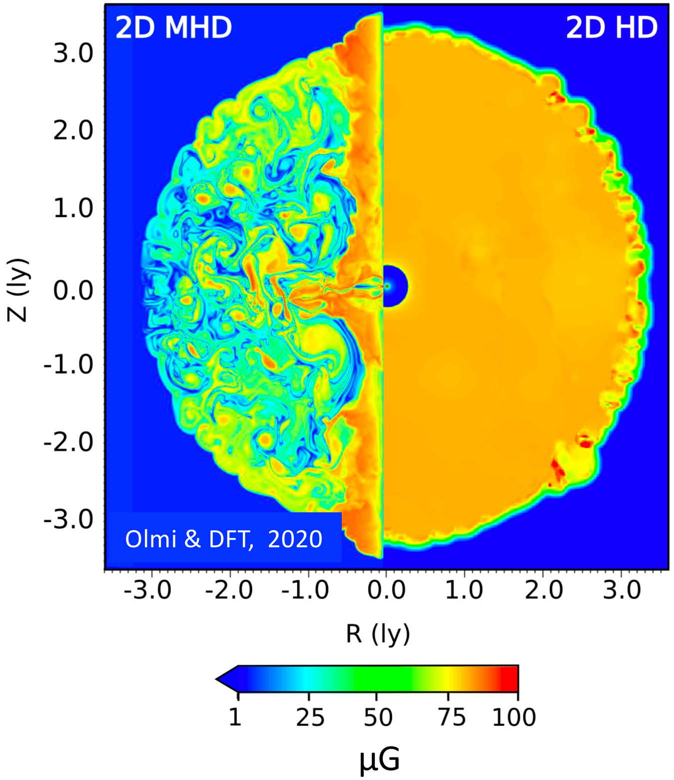
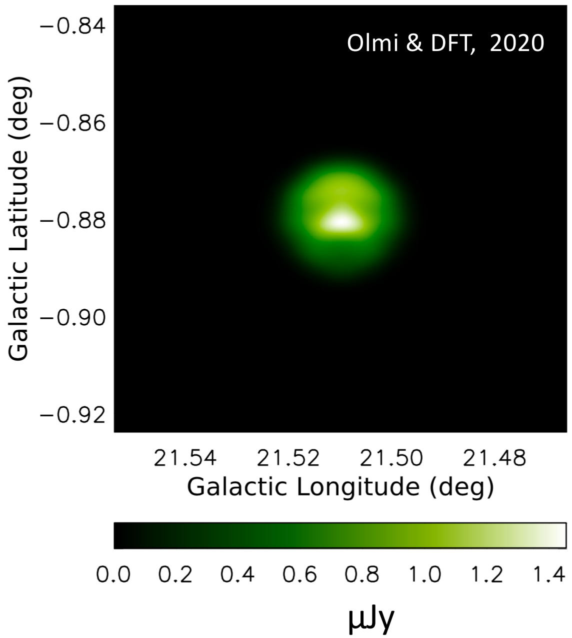


Magnetic field intensity in the nebula (compared with 2MHD)

Size of the PWN matching observations



Radio surface brightness map at ν = 1.4 GHz, in agreement with observations by Bietenholz et al. 2011).

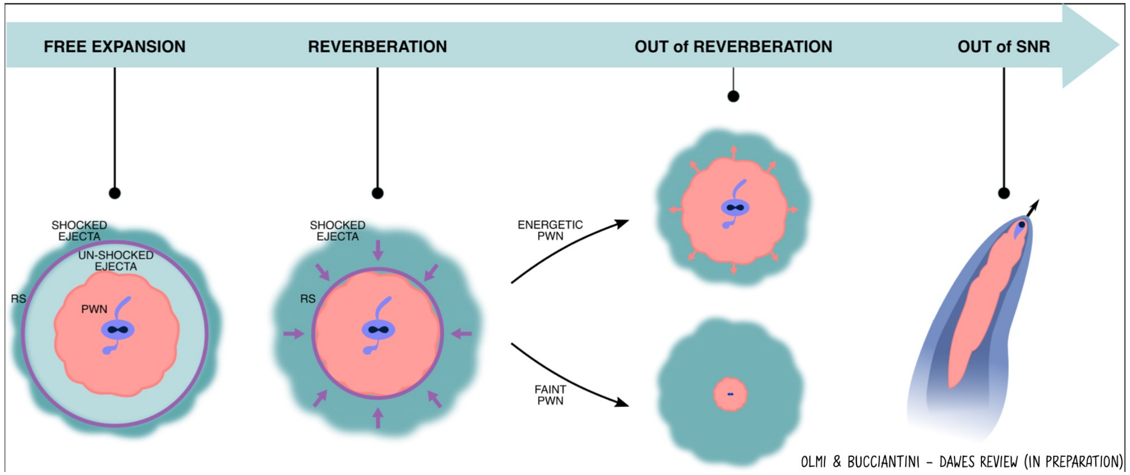
- Our total flux at 1.4 GHz = 7.36 Jy (observed = 7.0 ± 0.4 Jy).
- Maximum intensity of our original map = 0.61 Jy/beam (observed = 0.63 ± 0.03)

HD+B hybrid approach
Olmi & Torres 2020

Mophology with HD sims
Field with Radiative models

Most PWNe are beyond reverberation, need for better theoretical understanding

Reverberation phase



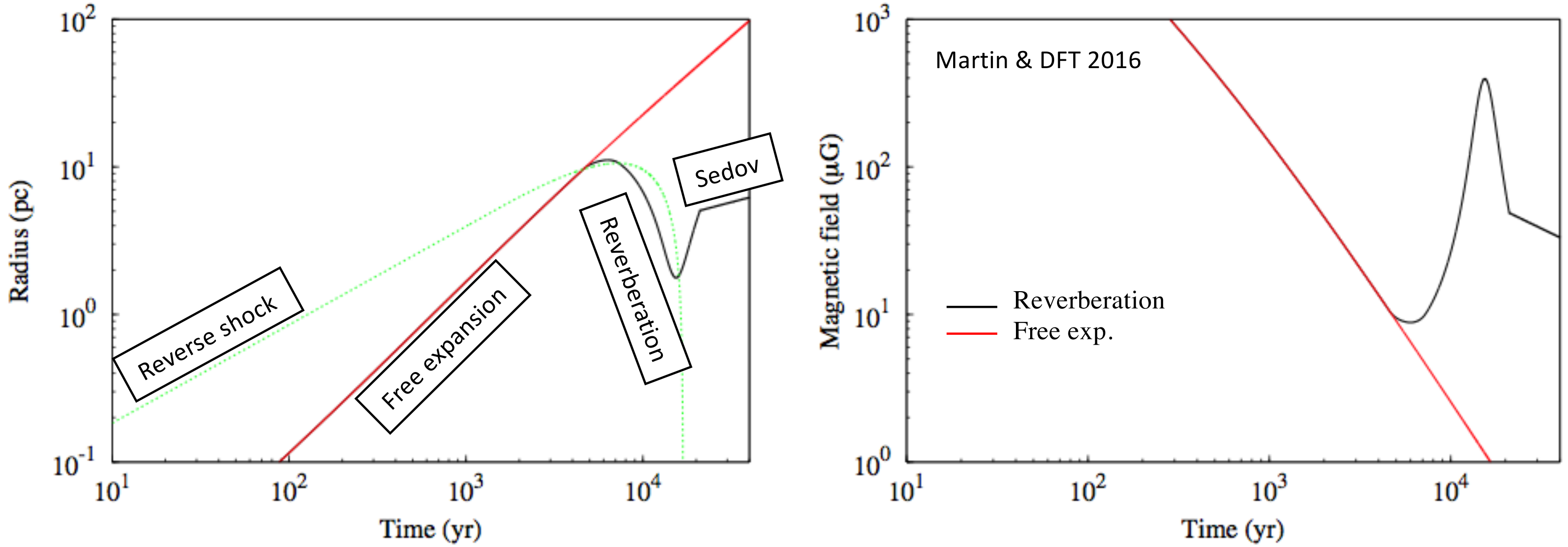
- Free expansion proceeds until the PWN reaches the reverse shock (RS).

- After that time, due to mass accretion as well as to the thermal pressure of the shocked SNR medium, the shell experiences a strong deceleration, which in most cases leads to a compression of the PWN.

- Only when due to compression the PWN internal pressure becomes high enough, the PWN bounces and re-expands again.

- Reveberation (compression-bounce) last for a few kyrs or less

Reverberation



- During reverberation the energy reservoir is no longer the pulsar spin-down power, since the environment is giving energy to the nebula due to its compression
- PWN could be **super-efficient: Lx > L_sd** at the time

Superefficiency

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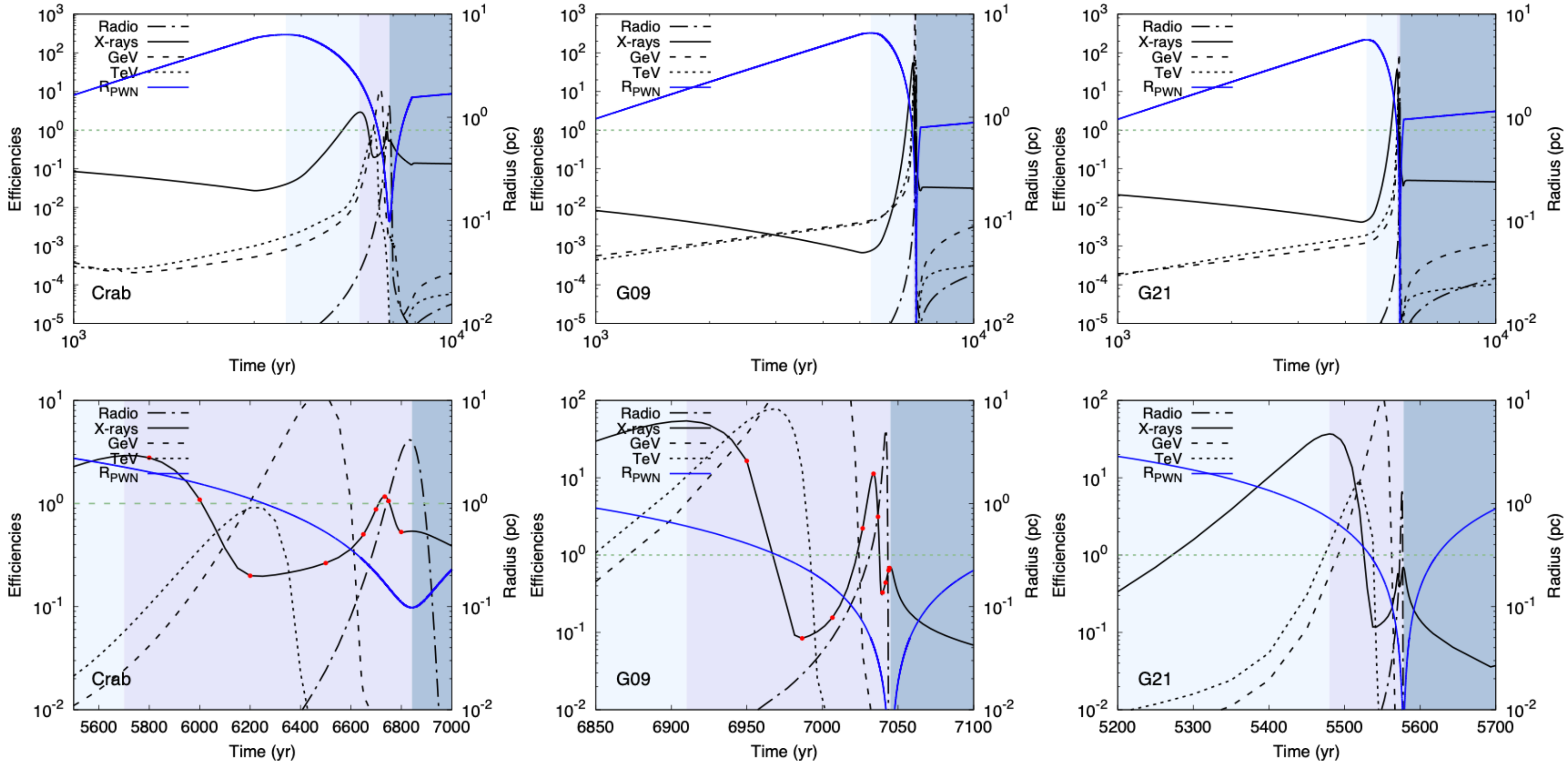
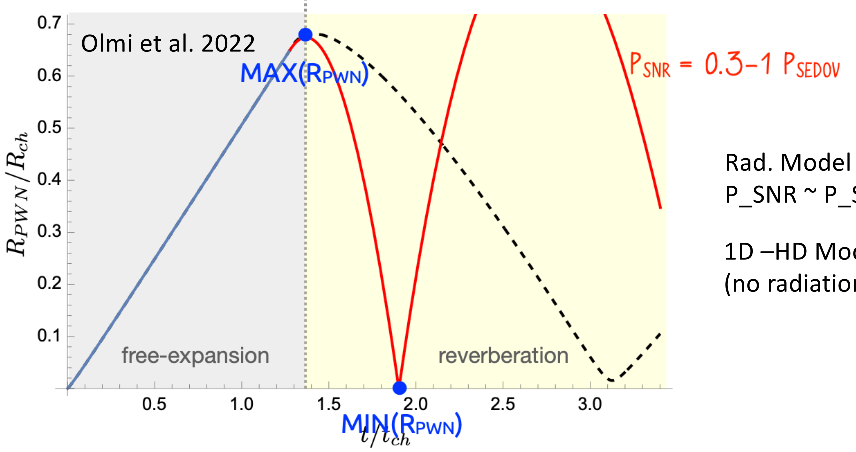


DFT, 2017
DFT, Lin, 2018
DFT, Lin, Coti-Zelati 2019

- During reverberation the energy reservoir is no longer the pulsar spin-down power, since the environment is giving energy to the nebula due to its compression
- PWN could be **superefficient: e.g., Lx > L_sd** at the time

Issue: Most PWN are beyond reverberation
Reverberation theory being developed

COMPARISON OF A STANDARD ONE ZONE MODEL AND 1D HD SIMULATION



Rad. Model
P_SNR ~ P_Sedov

1D –HD Model
(no radiation)

CF=MAX(RPWN)/MIN(RPWN)

0.67/0.0007~960

0.67/0.015~45

factor 20 difference!

Simplified pressure structure beyond the RS (constant); reduction in more complex situations?

Estimates accounting for the loss of internal pressure due radiative losses already show that this can increase 5x-10x.

Hybrid radiative – HD model needed in order to tackle this properly
and provide prescriptions for going through reverberation, allowing meaningful models thereafter

Bandiera, Bucciantini, Martin, Olmi & DFT, 2022

Issue: Most PWN are beyond reverberation
Reverberation theory being developed...

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JOURNAL ARTICLE

Revisiting the evolution of non-radiative supernova remnants: a hydrodynamical-informed parametrization of the shock positions

Get access

R Bandiera, N Bucciantini, J Martín, B Olmi, D F Torres

Monthly Notices of the Royal Astronomical Society, Volume 508, Issue 3, December 2021, Pages 3194–3207, https://doi.org/10.1093/mnras/stab2600

Published: 13 September 2021

JOURNAL ARTICLE

Reverberation of pulsar wind nebulae (I): impact of the medium properties and other parameters upon the extent of the compression

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R Bandiera, N Bucciantini, J Martín, B Olmi, D F Torres

Monthly Notices of the Royal Astronomical Society, Volume 499, Issue 2, December 2020, Pages 2051–2062, https://doi.org/10.1093/mnras/staa2956

Published: 28 September 2020

Reverberation of pulsar wind nebulae (II): Anatomy of the "thin-shell" evolution

R. Bandiera[1], N. Bucciantini[1,2,3], J. Martín[1,4,5], B. Olmi[1,7], D. F. Torres[4,5,6] ⋆

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Bandiera, Bucciantini, Martin, Olmi & DFT, 2022

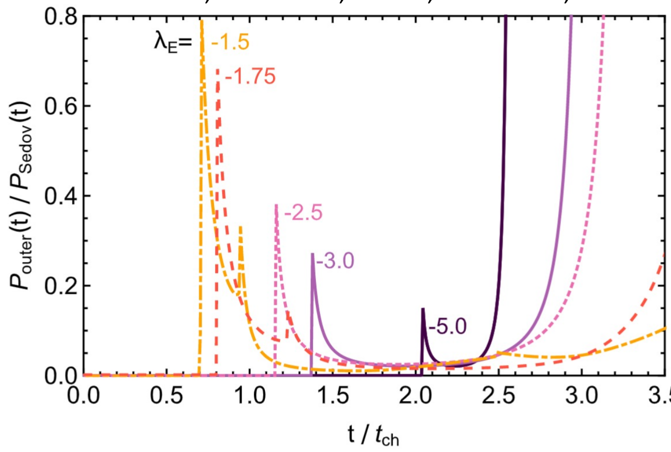

Figure 3. Evolution of the outer pressure, scaled with the FS pressure as from the Sedov model, for some representative values of λ_E as obtained from numerical solutions. Differently from what was assumed in previous works, it is evident here that this quantity is far from being constant in time. In addition, a secondary bump occurs in the two curves with highest λ_E: this is the sign of a reflected shock reaching the shell before its collapse.

Issue: Most PWN are beyond reverberation
Reverberation theory being developed…

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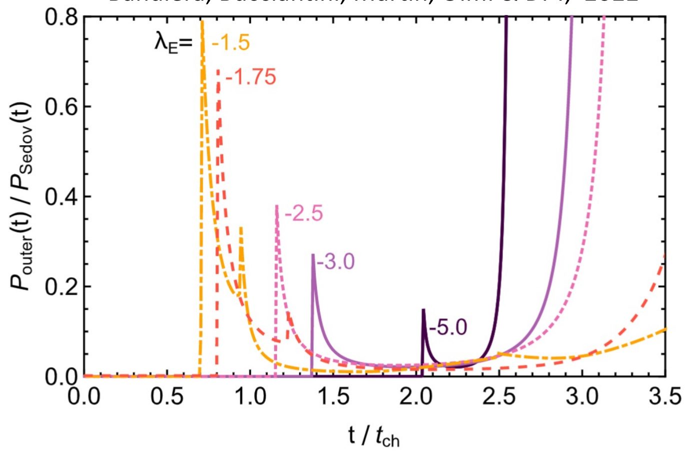
Estimates of the outer pressure via 1D HD simulations of a population of PWNe.

Nothing but a constant.

Next aim: incorporate such a description into a radiative model and provide a prescription to pass through reveration for any PWNe.

Bandiera, Bucciantini, Martin, Olmi & DFT, 2022



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Consistent usage of radiative models

(and their need for update to tackle PWNe after reverberation)

Issue: consistent time-dependent models needed, not always fed by MW data

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$$\text{electron distribution time variation} = \text{injection} - \text{energy losses} - \text{escape}$$

$$\frac{\partial N(\gamma,t)}{\partial t} = Q(\gamma,t) - \frac{\partial}{\partial \gamma}\left[\dot{\gamma}(\gamma,t) N(\gamma,t)\right] - \frac{N(\gamma,t)}{\tau(\gamma,t)}$$

- Inconsistent level of detail
- Dominance of the different terms depends on time
- Real fitting of PWNe multi-frequency data is not usually done

(despite it is common to find the word *fit* in the literature, it rather refer to visually acceptable descriptions when time-dependent, complex models are involved.

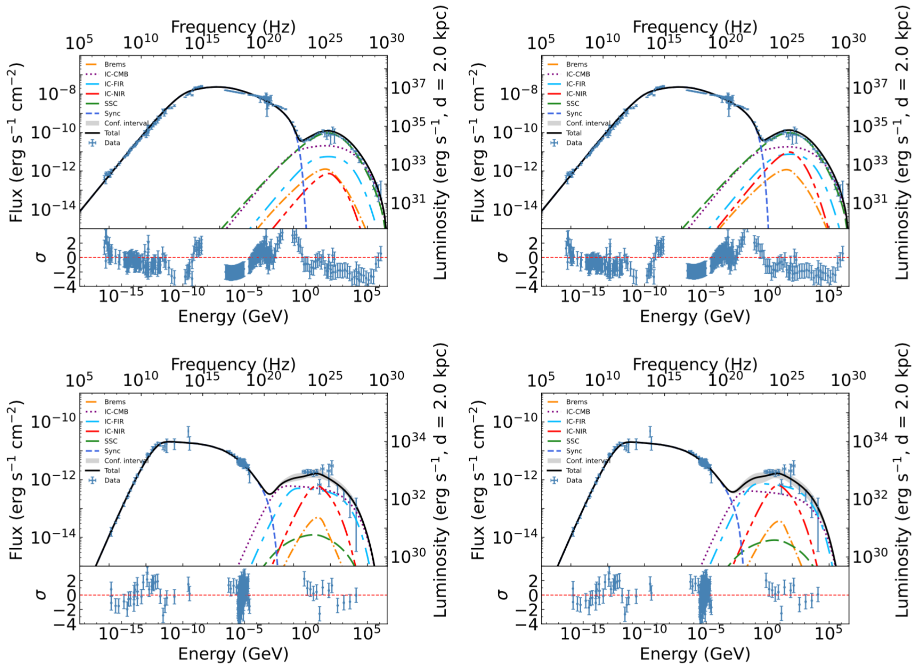

Figure 1: Models fitted for the Crab Nebula (top) and 3C 58 (bottom). On the left column, the age is fixed and on the right, it is a free parameter (see results in Table 3) The data points for Crab are taken from Baldwin (1971); Macías-Pérez et al. (2010), (compilations of radio observations), Bühler and Blandford (2014) (from IR to γ-rays and VHE) and the new points offered by the LHAASO collaboration (Lhaaso Collaboration et al., 2021). For 3C 58, they come from Green (1986); Morsi and Reich (1987); Salter et al. (1989) (radio), Torii et al. (2000) (infrared), Green (1994); Slane et al. (2008) (X-rays), Abdo et al. (2013); Ackermann et al. (2013); Li et al. (2018) (gamma-rays) and Aleksić et al. (2014) (VHE).

Martin, DFT, 2022

Issue: consistent time-dependent models needed, not always fed by MW data

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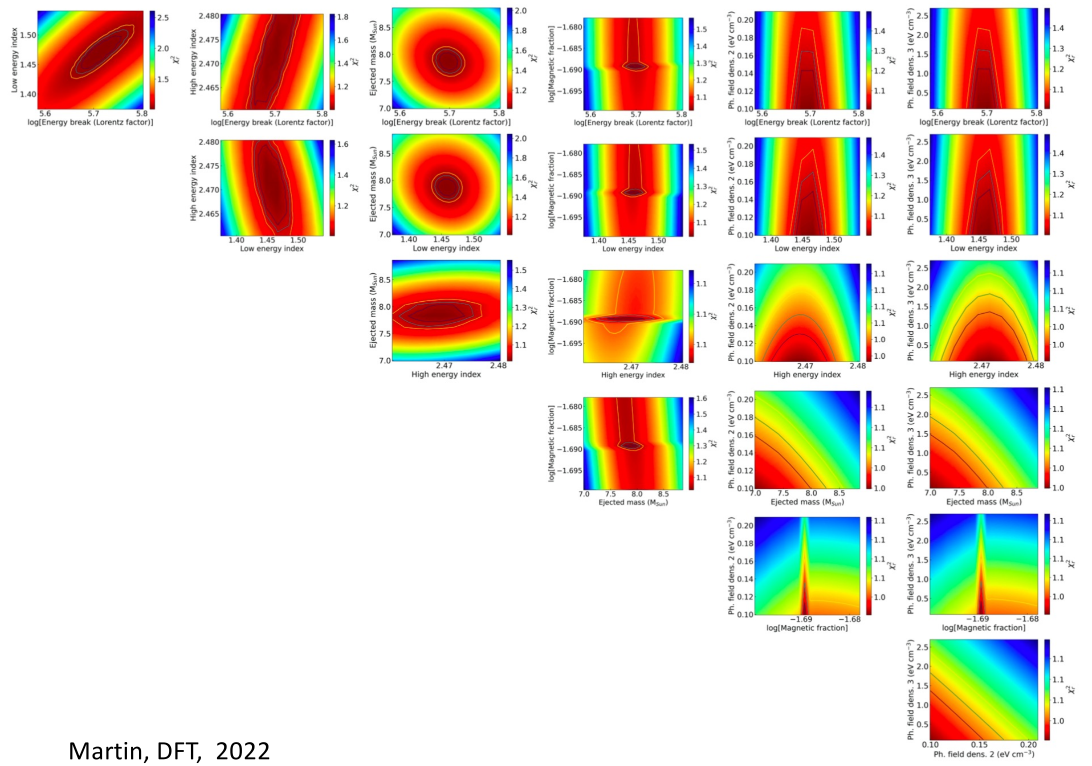
$$\frac{\partial N(\gamma,t)}{\partial t} = -\frac{\partial}{\partial \gamma}\left[\dot{\gamma}(\gamma)N(\gamma,t)\right] - \frac{N(\gamma,t)}{\tau(\gamma,t)} + Q(\gamma,t),$$

- TIDEauto code advanced enough to select focus parameters over which a real fit is used
- Nelder-Mead minimization + parallelization of the electron-positron equation
- Considerations given to data treatment, in particular, how to deal with data separated by many years



Martin, DFT, 2022

Figure 3: Reduced χ^2 maps for Crab Nebula. The dark blue, turquoise and yellow contours correspond to the 1, 2 and 3σ confidence levels.

Coda

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Conclusions

- PWN observational capabilities are about to explode; not only will they lead to a significant increase in the number of PWNe detected, but will position ourselves to study the evolutionary variety of the class.

- It will additionally provide a first-timer for population studies of PWNe at high energy frequencies

- Still, relevant risks remains (confusion, identification techniques), as well as well-founded theoretical challenges (reverberation) that need a consistent and deep work to be solved.

Thank you

https://sites.google.com/view/dft-research

@dft_research

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