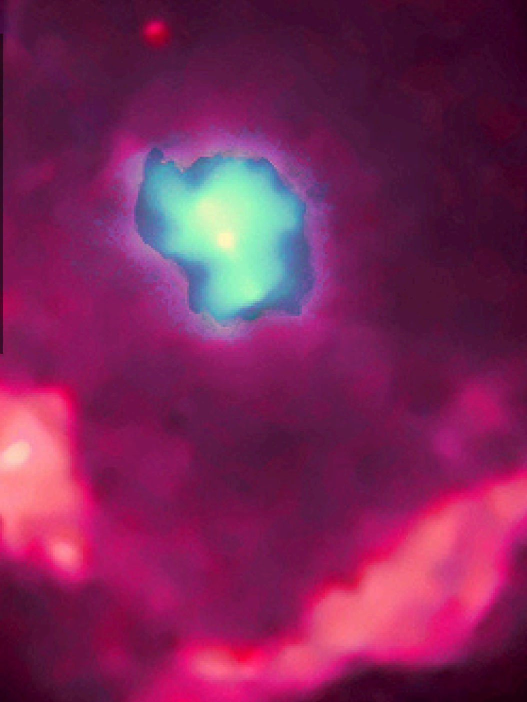
Spending two years putting bubbles around stuff

Lioni-Moana Bourguinat
Carmelo Evoli
Pierrick Martin
Sarah Recchia



Kes 75 complex observed by Chandra
X-ray: NASA/CXC/NCSU/S. Reynolds

What is the stuff?

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- TeV halos

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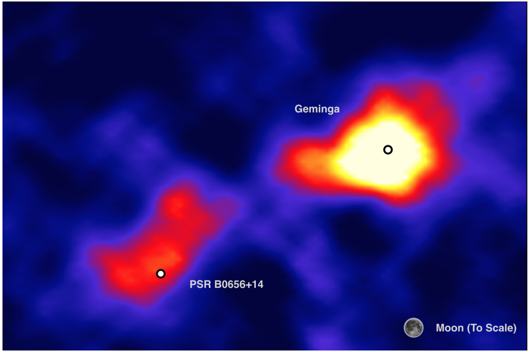
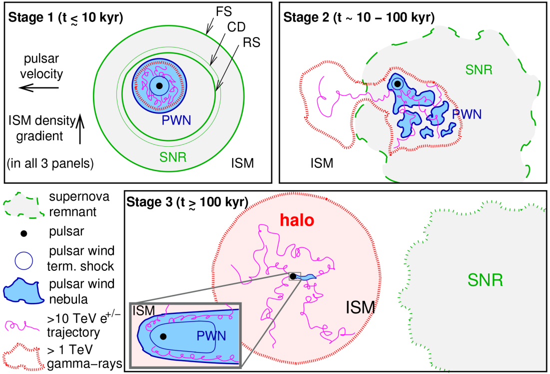
- TeV halos
- Pulsar Wind Nebulae (PWNe)

First project

TeV Halos



HAWC sky map of TeV emission from Geminga and PSR B0656+14.
Credits: HAWC Collaboration



Sketch of the main evolutionary stages of a pulsar wind nebula.
Credits: [Giacinti et al. (2020)]

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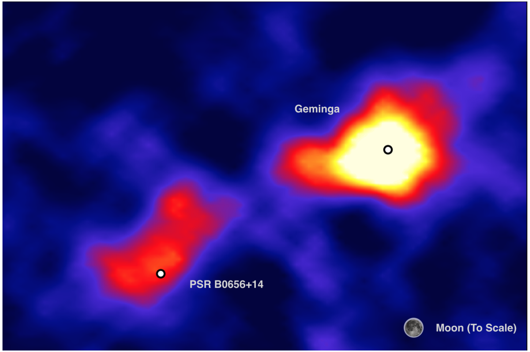

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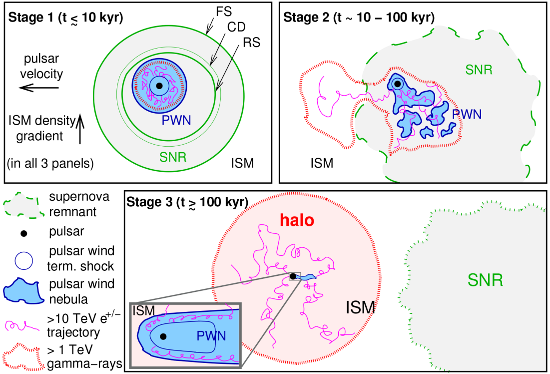

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Standard conclusion

Diffusion coefficient suppressed by a factor 100-1000 in the region of the TeV halo [Abeysekara et al. (2017)].

Explaining the low diffusion coefficient

Theoretical explanations

- Anisotropic transport along the magnetic fields surrounding the pulsar [Liu et al. (2019) and De La Torre Luque et al. (2022)],
- Cosmic ray pairs-induced turbulence [Evoli et al. (2018) and Mukhopadhyay et al. (2022)],
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Which medium are the leptons probing when we see a TeV halo?

$$\Downarrow$$

Where is the pulsar at a given age?

An idea for a solution

Add a bubble!

The circumstellar medium: an ingredient easily forgotten

Pulsars are born from massive stars that carve wind-blown bubbles (WBBs) in the ISM.

Bubble Nebula or NGC 7635 seen by Hubble.
NASA, ESA, Hubble Heritage Team

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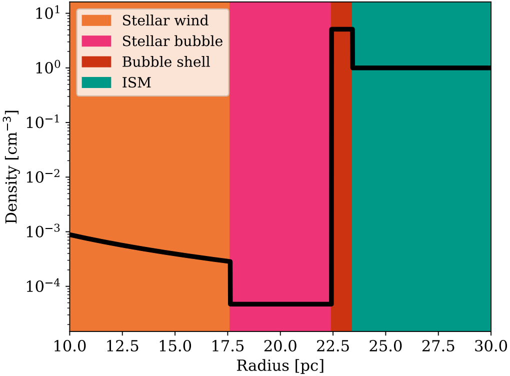

Density profile of a WBB.

[Weaver et al. (1977)]

Goal of this first project

Method

Computation of the position of the pulsar and its associated SNR in the pre-existing parent environment as a function of time for

- **Wind-Blown Bubbles (WBB):** Isolated massive stars
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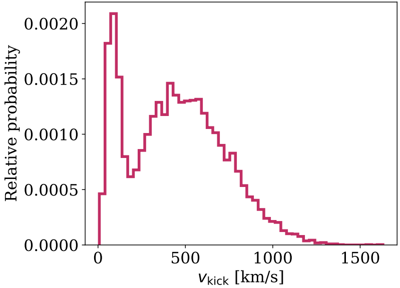

PDF of the kick velocity of pulsars [Igoshev (2020)].

The parent environments

Wind-blown bubbles

Pick a **progenitor mass** $M_{\rm ZAMS}$ from the Initial Mass Function (IMF) with $M_{\rm ZAMS} \in [8; 20]$ $\rm M_\odot$ [Kroupa et al. (2003)],

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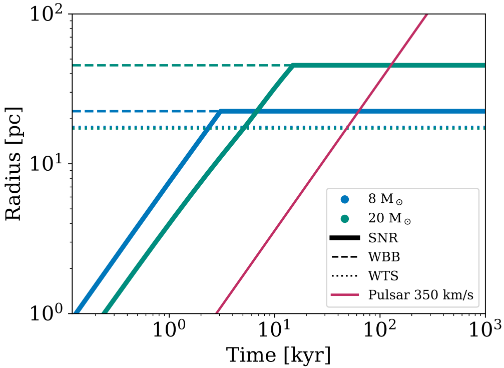
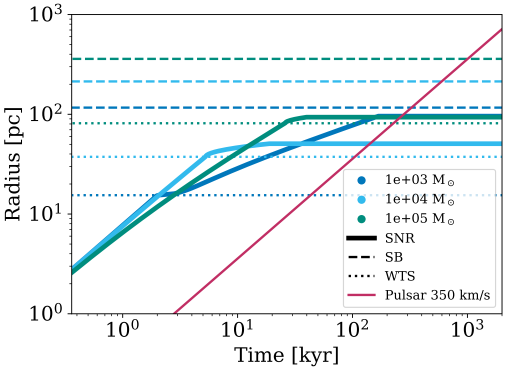
At the end of the life of the progenitor star...

Supernova propagation [Ptuskin et al. (2005)], pulsar creation [Igoshev (2020)].



Evolution of a SNR and pulsar
in a **WBB** for progenitors of 8 – 40 $M_\odot$.



Evolution of a SNR and pulsar
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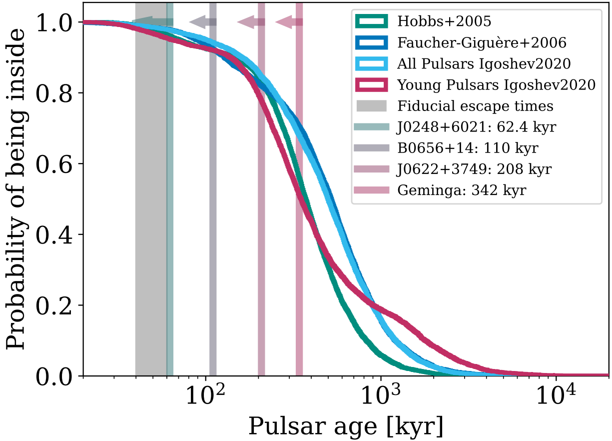
Probability for a Galactic pulsar population



Probability of a pulsar to be found inside its *bubble* as a function of time for a **Galactic** population. Characteristic ages of pulsars are estimations, taken from the ATNF catalog [Manchester et al. (2005)].

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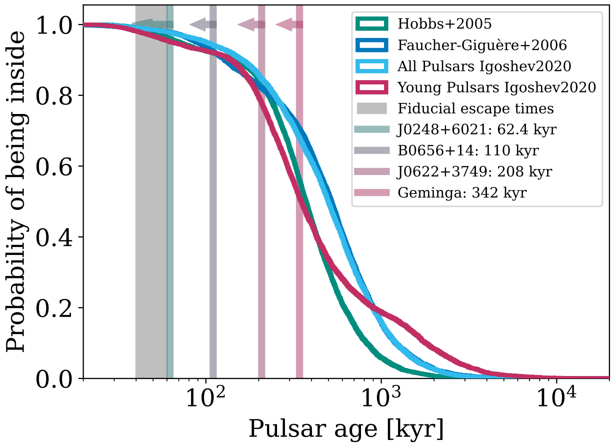

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Most pulsars reach the ISM after 200 kyr and before 1 Myr,

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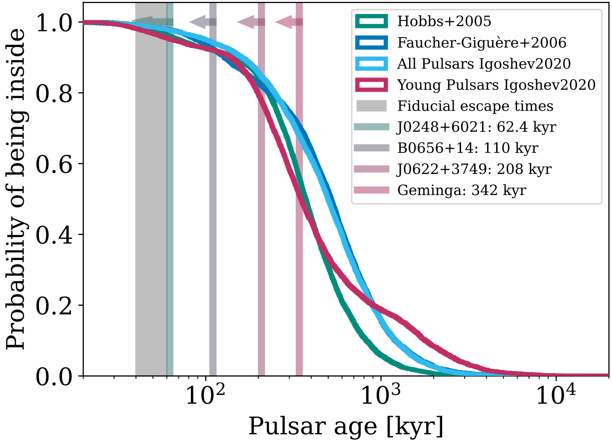

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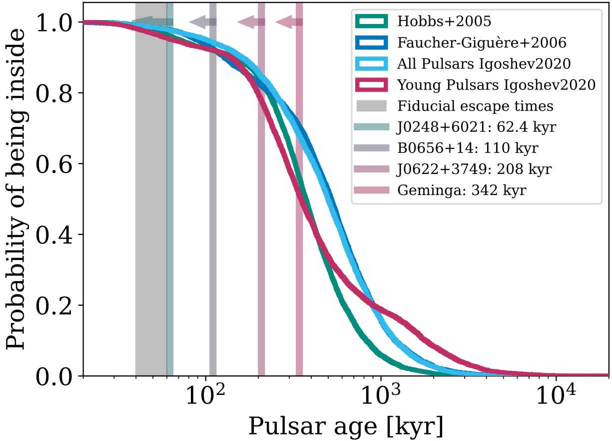

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At the age of Geminga, half pulsars are inside their parent environment

Studying individual pulsars

ATNF pulsars properties

- $\dot{E}/d \geq 10^{33}$ erg/s/kpc,
- 40 kyr $< \tau_{\rm age} <$ 1 Myr,
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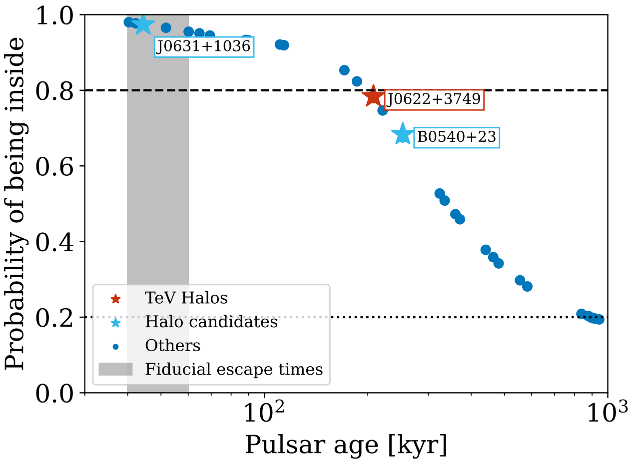
TeV Halos and candidates

- TeV Halos: Geminga (J0633+1746), B0656+14, J0622+3749, J0248+6021 [Abeysekara et al. (2017), Aharonian et al. (2021), and Cao, Aharonian, Axikegu, et al. (2025)],
- Candidates: B0540+23, J0633+0632, J0631+1036 [Celli et al. (2024), Khokhriakova et al. (2024), and Zheng et al. (2024)].

Individual pulsars with no measured proper motion



Probability for a selection of 30 known pulsars within 2 kpc to be found inside their parent environments, as a function of their characteristic ages. Pulsars **without** a measured proper motion.

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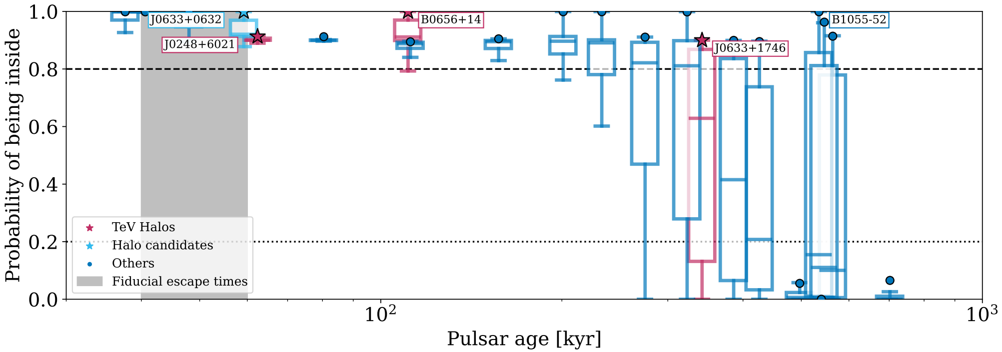
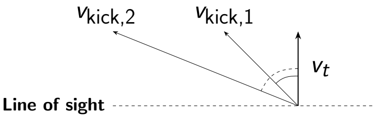


Probability for a selection of 22 known pulsars within 2 kpc to be found inside their parent environments, as a function of their characteristic ages. Pulsars **with** a measured proper motion.



Some numbers

Pulsar name	Prob [%]	1 σ [%]	2 σ [%]	τ_c [kyr]
J0631+1036	97	-	-	44.4
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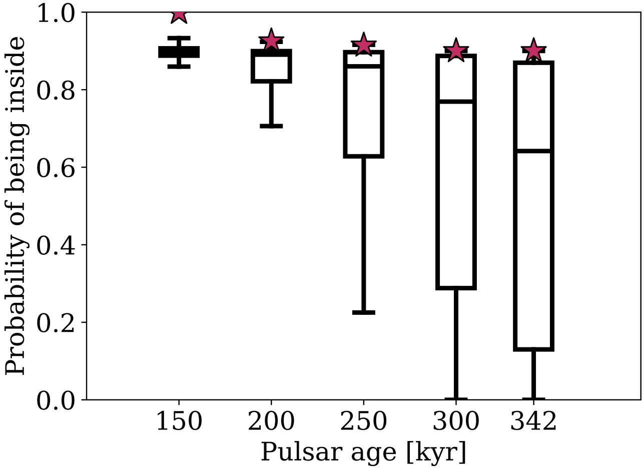
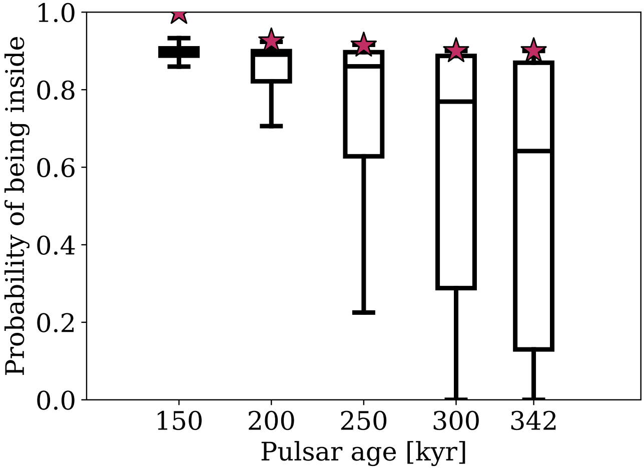
  The 1 and 2 σ interval **does not allow for clear conclusions for Geminga.**



Probability that Geminga resides in its parent environment for five different assumptions on its age.

A focus on Geminga



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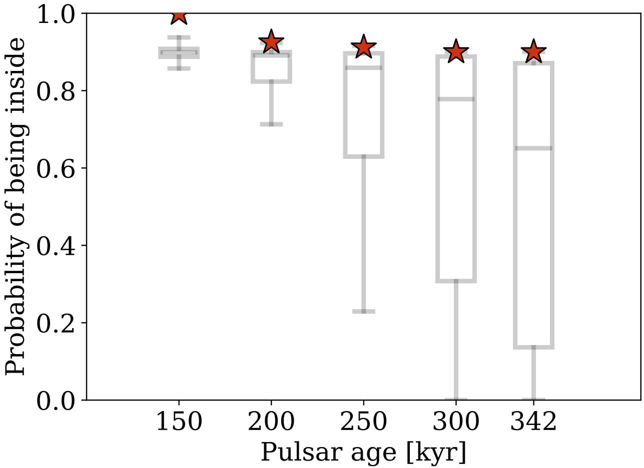
Characteristic age has a strong impact [Suzuki et al. (2021)],



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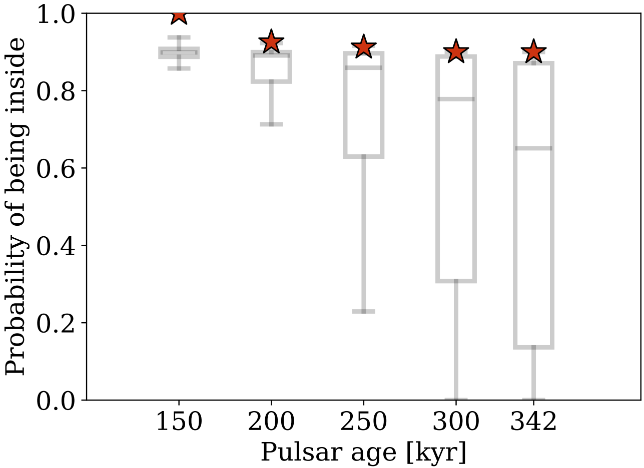

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Summary of the first project

Main questions

Which medium are the leptons probing when we see a TeV halo?
Where is the pulsar at a given age?

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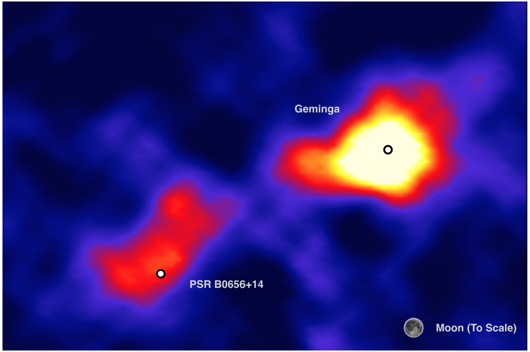
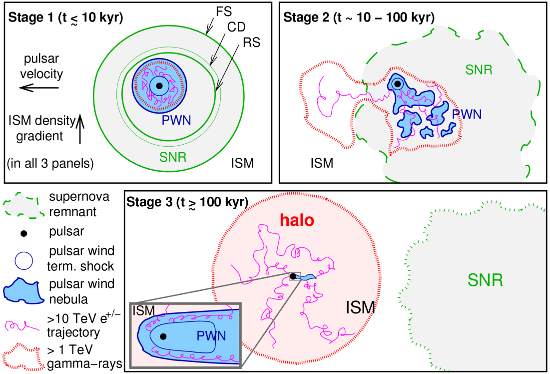
The paper for this work (Submitted to A&A): 2507.01495.

Second project

TeV Halos (again)



HAWC sky map of TeV emission from Geminga and PSR B0656+14.
Credits: HAWC Collaboration



Sketch of the main evolutionary stages of a pulsar wind nebula.
Credits: [Giacinti et al. (2020)]

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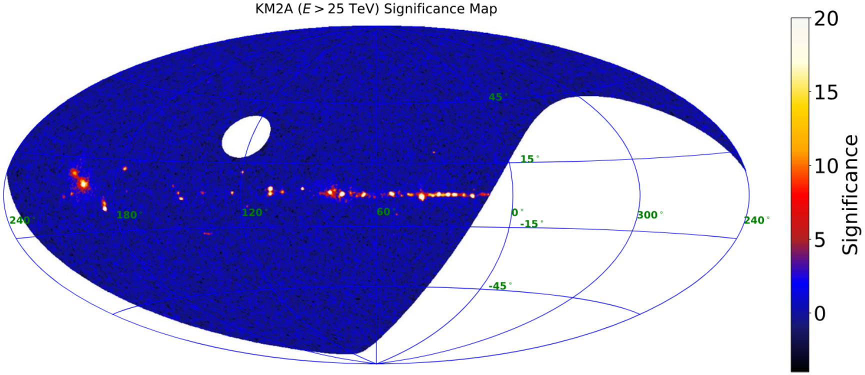
Pulsar wind nebulae



Significance map of the LHAASO field of view.

[Cao, Aharonian, An, et al. (2024)]

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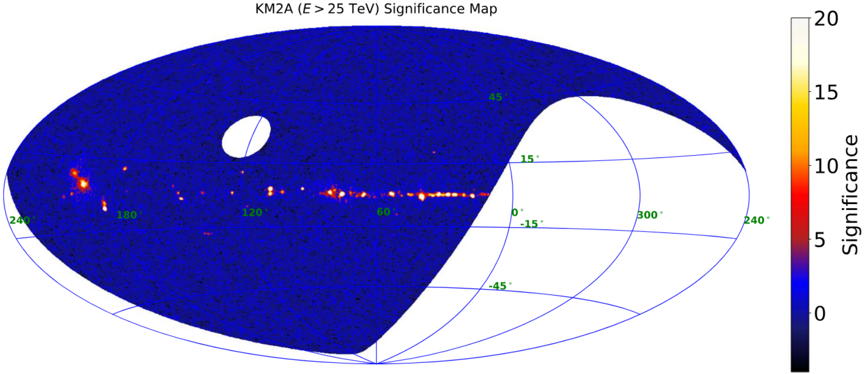

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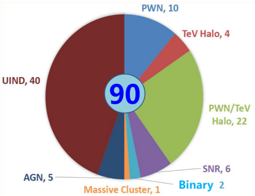
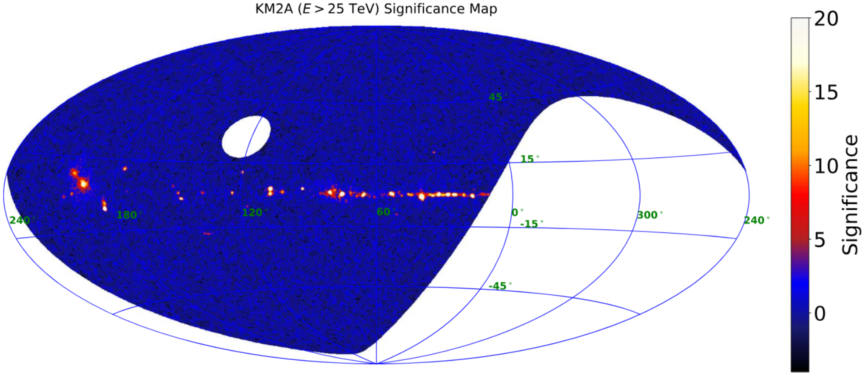
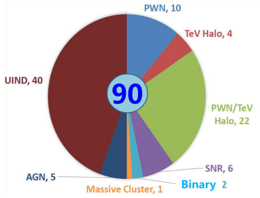


The populations of LHAASO TeV sources.
[Cao, Aharonian, An, et al. (2024)]

Pulsar wind nebulae



Significance map of the LHAASO field of view.
[Cao, Aharonian, An, et al. (2024)]



The populations of LHAASO TeV sources.
[Cao, Aharonian, An, et al. (2024)]

PWNe are the largest population in the LHAASO catalog.

Some of the difficulties in understanding PWNe

Composite view of the Crab PWN.
X-ray: NASA/CXC/ASU/J. Hester et al.; Optical: NASA/HST/ASU/J. Hester et al.; Radio: NRAO/AUI/NSF

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We cannot see the SNR!

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Composite view of the SNR G11.2-0.3.
X-ray: NASA/CXC/NCSU/K.Borkowski et al; Optical: DSS

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X-ray: NASA/CXC/ASU/J. Hester et al.; Optical: NASA/HST/ASU/J. Hester et al.; Radio: NRAO/AUI/NSF

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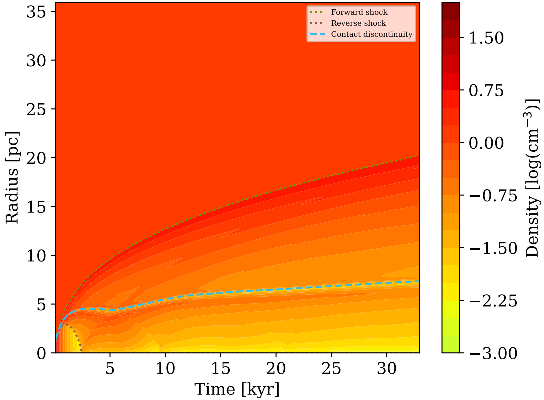
Composite view of the SNR G11.2-0.3.
X-ray: NASA/CXC/NCSU/K.Borkowski et al; Optical: DSS

In general, the observed PWNe are larger than predicted. [Bamba et al. (2010)]

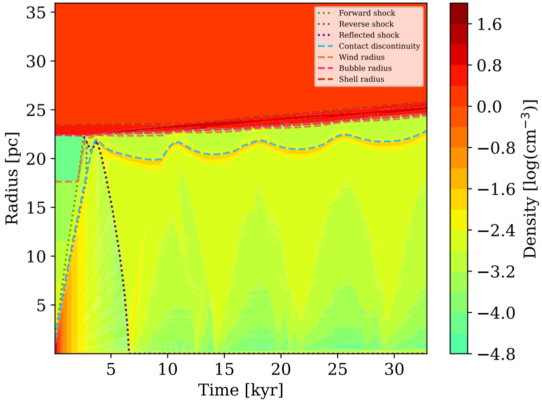
An idea for a solution

Add a bubble!

Impact of the WBB on the SNR

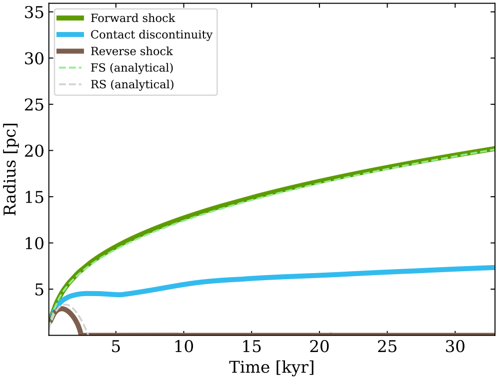


Density map.
SNR in ISM.

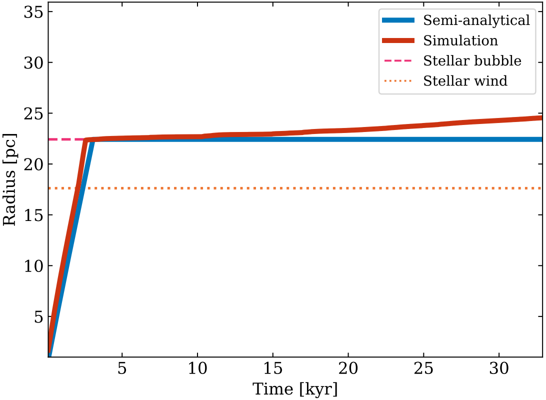


Density map.
SNR in WBB in ISM.

Impact of the WBB on the SNR

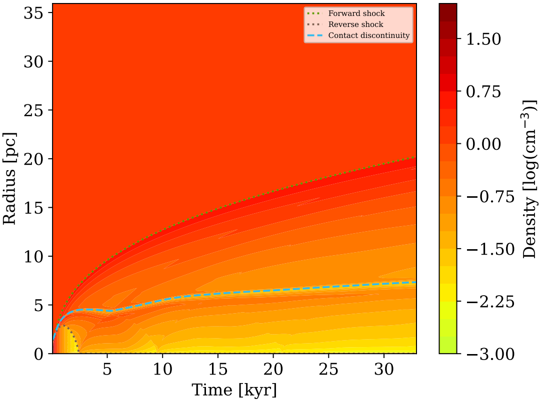


Trajectories.
SNR in ISM.



Trajectories.
SNR in WBB in ISM.

Impact of the WBB on the SNR



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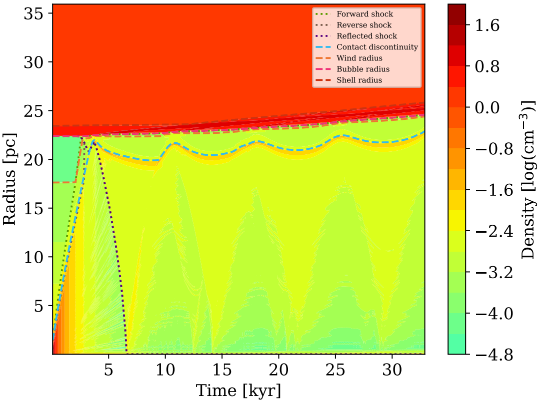
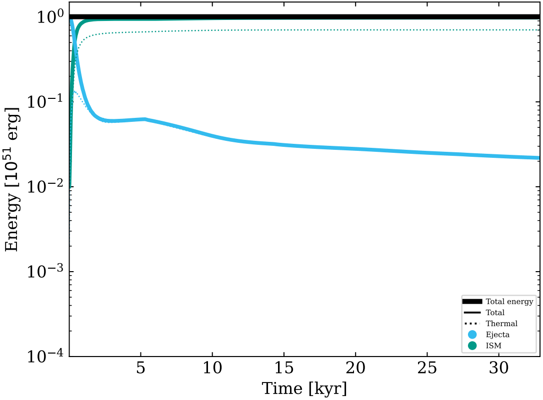


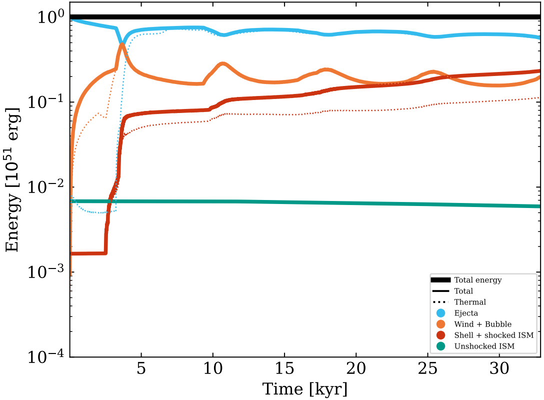
Density map.
SNR in WBB in ISM.

The SNR material extends further and merges with the shell.

Impact of the WBB on the SNR



Energy budgets.
SNR in ISM.



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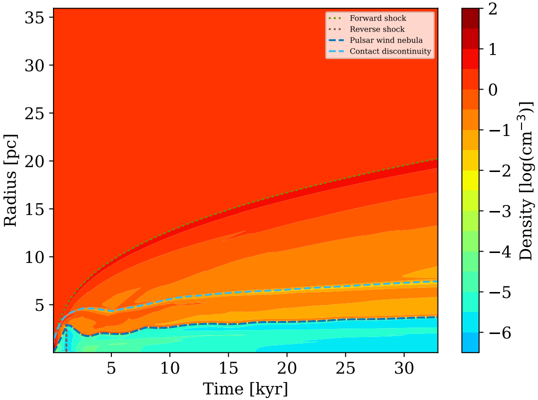
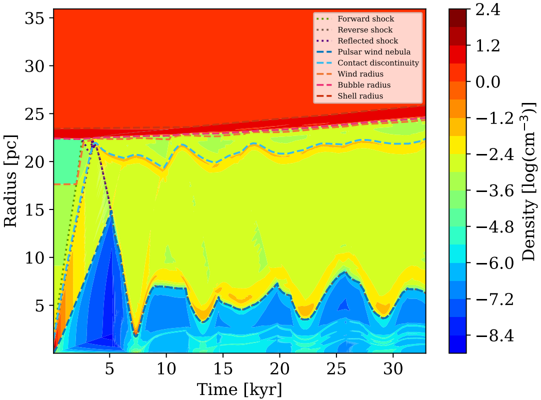


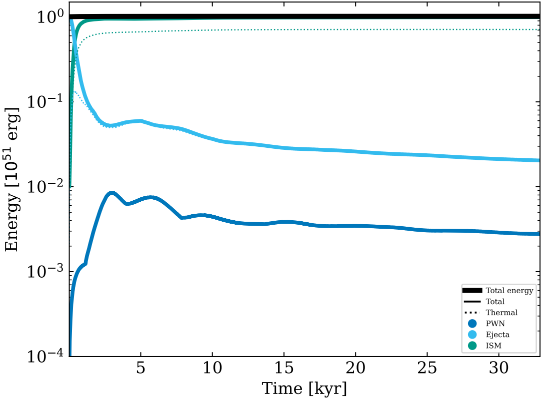
Density map.
PWN in SNR in ISM.



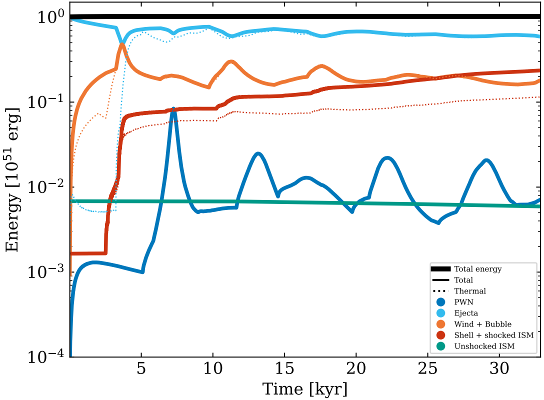
Density map.
PWN in SNR in WBB in ISM.

The PWN has a bigger size.

Impact of the WBB on the PWNe



Energy budgets.
PWN in SNR in ISM.



Energy budgets.
PWN in SNR in WBB in ISM.

Summary of the second project and perspectives

Conclusions

We MUST include the WBB in the modeling of the SNR+PWN system.

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Perspectives

- Add radiative losses, to study the radiative signatures of the system happening later.
- 2D, to study turbulence and asymmetries.
- Study star clusters and superbubbles (**Crab nebula** [Hester (2008)]).

My own personal conclusion to both talks

DON'T FORGET THE BUBBLES!

Conferences, paper, etc...

Conferences

- Talk in person at RICAP-2024, Università Roma Due, Frascati.
- Talk in person at Cosmic Rays and Neutrinos in the Multi-Messenger Era 2024. APC, Paris.
- Talk in person at the ICRC-2025. Geneva.

Workshops

- Participation in person to the Workshop on Numerical Multi-Messenger Modelling by APC, Paris 2024.
- Participation in person to the Conference in memory of Veniamin Berezinskii. GSSI, L'Aquila 2024.
- Two talks in person at Journées de l'ATPEM. LPNHE, Paris 2025.
- Two talks in person + organisation at the TAL Retreat. Osservatori Nazionali Arcetri, Firenze 2025.

Paper

- The environment of TeV halo progenitors (https://arxiv.org/abs/2507.01495).

Visiting

- Stay of 6 months in IRAP, Toulouse. January-June 2025.

Summer School

- Participation in person to the Summer School MPIK-CDY School on the Future of Gamma-Ray Astronomy by the Max Planck Institute fur Kernphysik. Heidelberg 2024.

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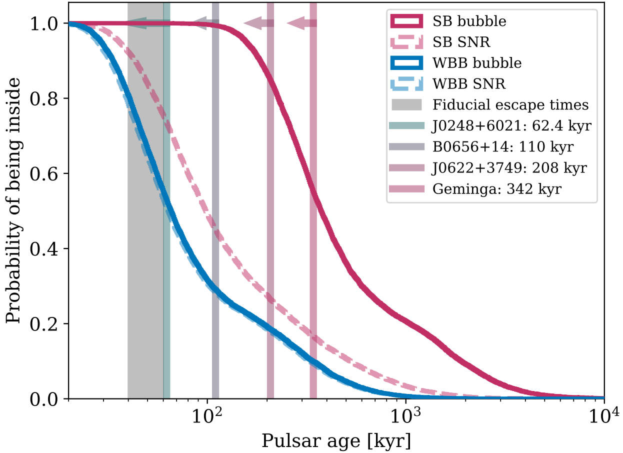
Probability for both WBB and SB models



Probability of a pulsar to be found inside its *SNR* and *bubble* as a function of time for **WBB**, **SB** populations.
Characteristic ages of pulsars are estimations, taken from the catalog of [Manchester et al. (2005)].

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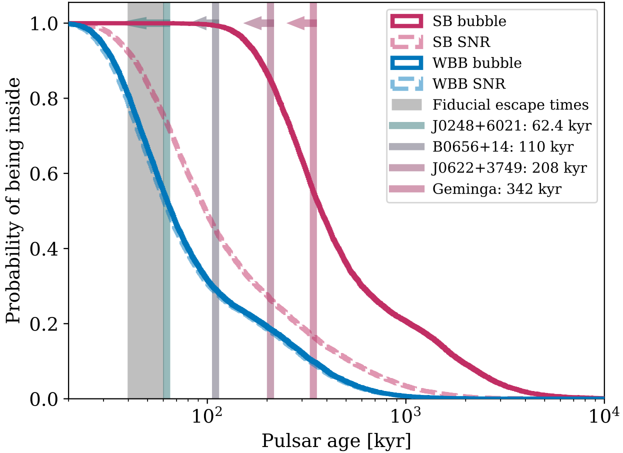

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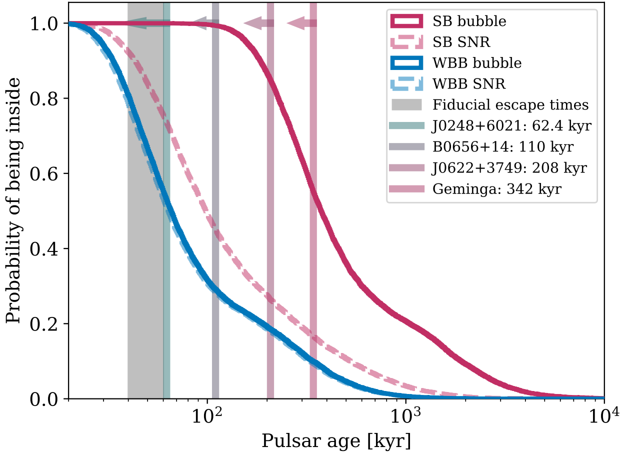

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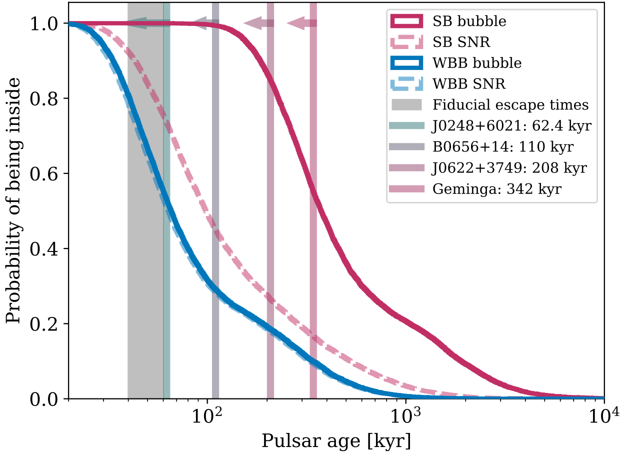

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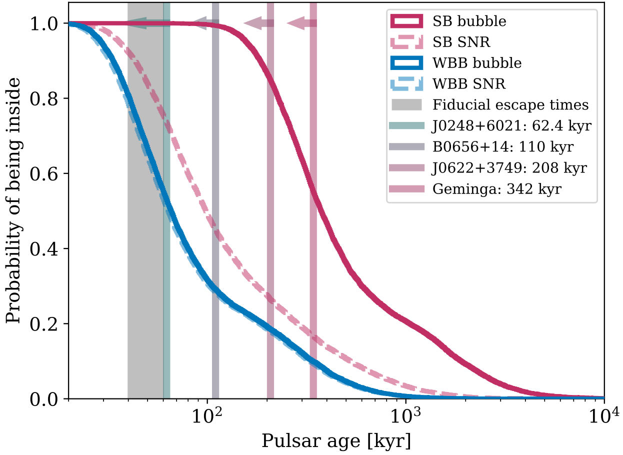
Probability for both WBB and SB models



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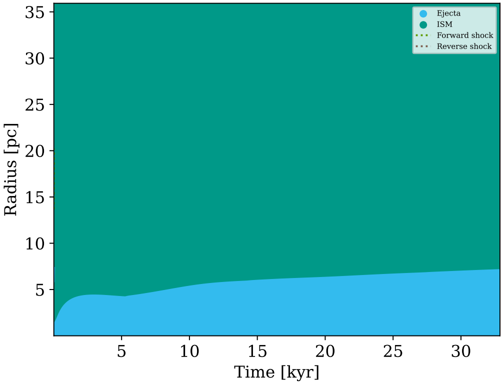
At the age of Geminga, 1/2 pulsars are inside their parent SB. $\sim$ 40% of these are still inside the zone affected by the SNR.

Impact of the WBB on the SNR



Chemically distinct media.
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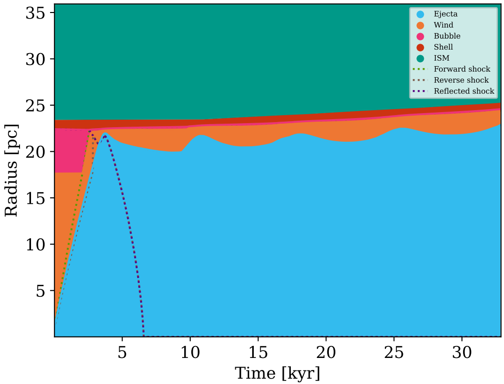

Chemically distinct media.
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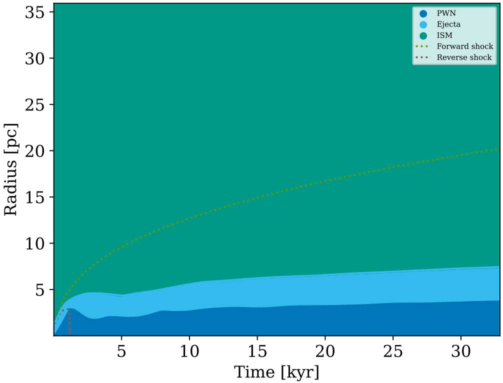
Impact of the WBB on the PWN



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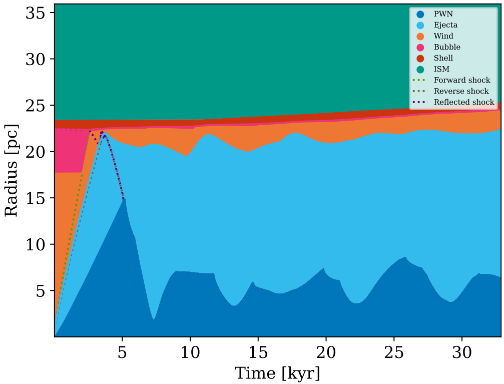

Chemically distinct media.
PWN in SNR in WBB in ISM.