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The environment of pulsar halo progenitors

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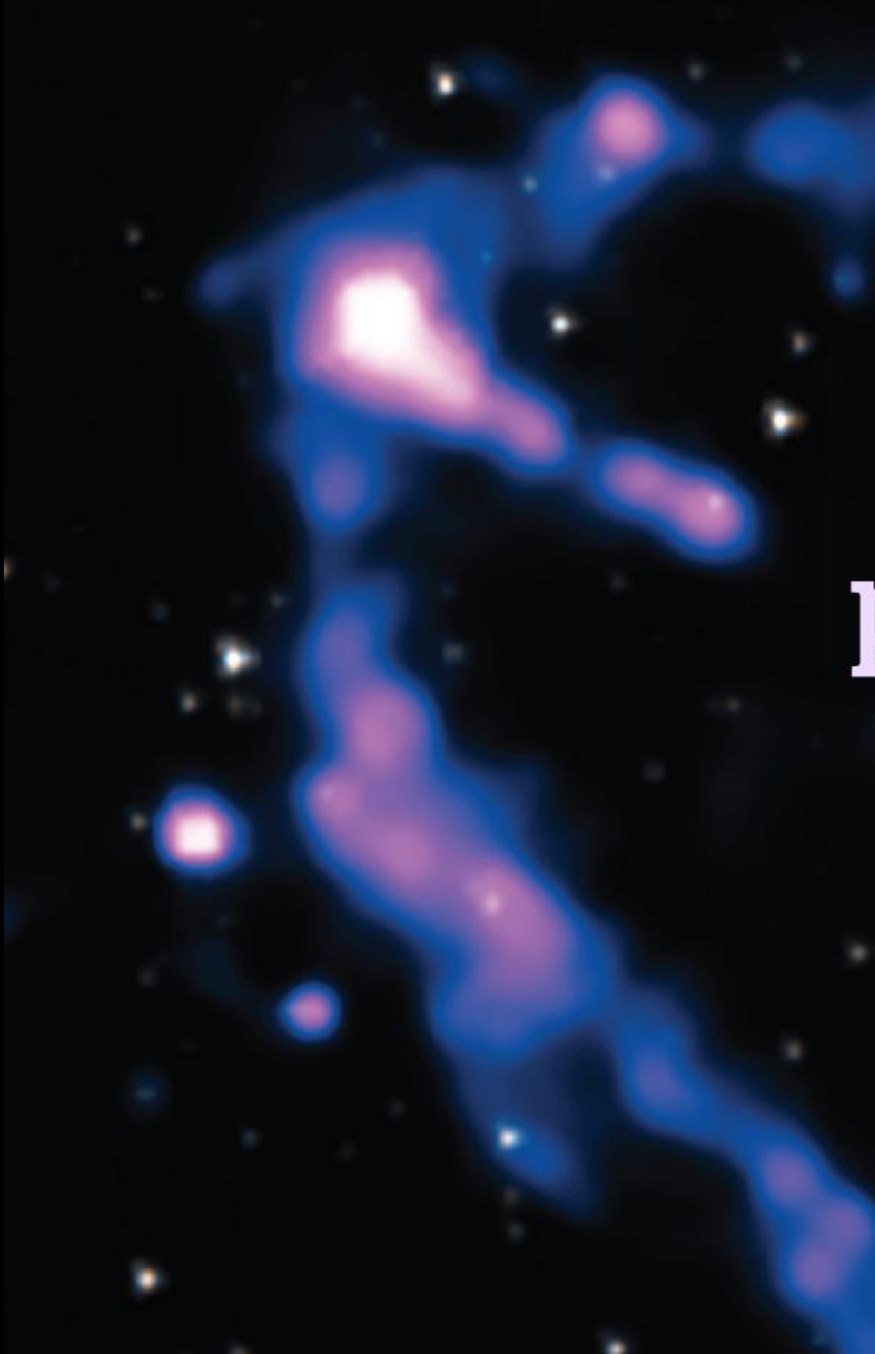

Geminga as seen by Chandra and Spitzer
Credits: X-ray: NASA/CXC/PSU/B. Posselt et al; Infrared: NASA/JPL-Caltech

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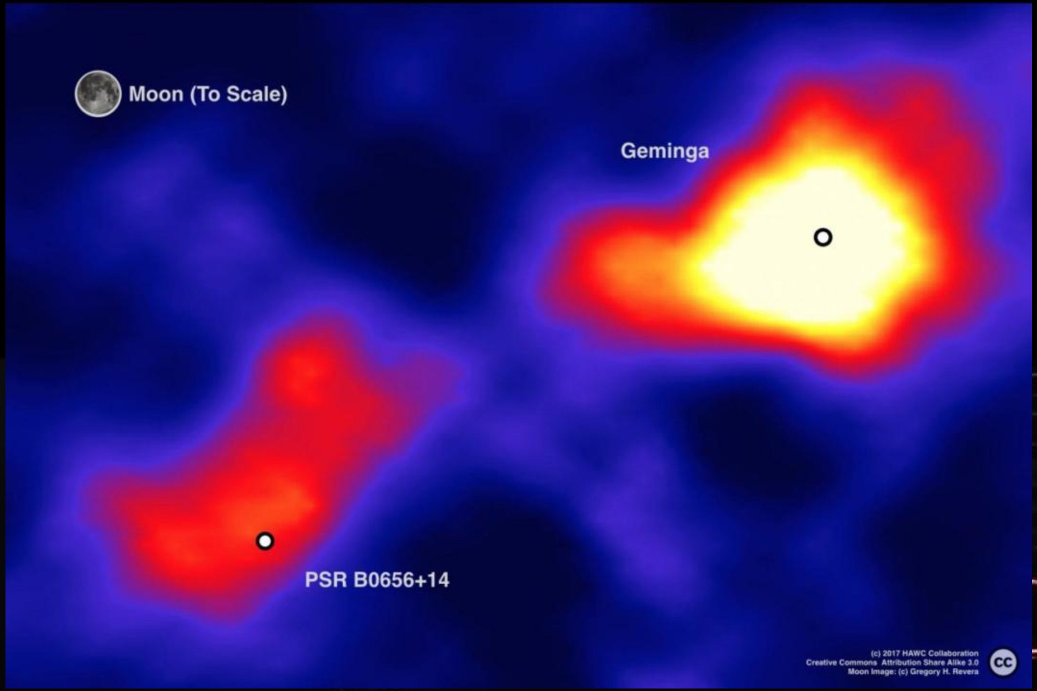
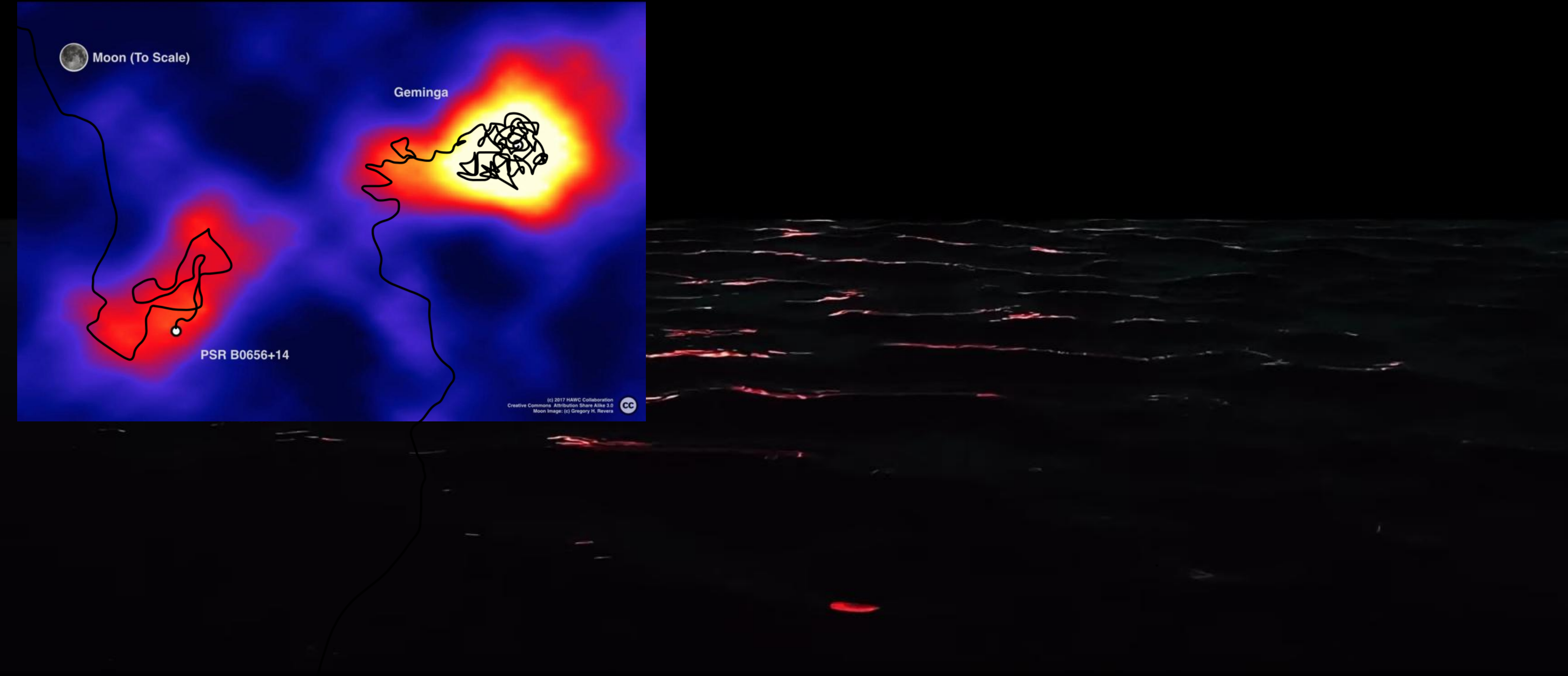


Moon (To Scale)
Geminga
PSR B0656+14
(c) 2017 HAWC Collaboration
Creative Commons Attribution Share Alike 3.0
Moon Image: (c) Gregory H. Revera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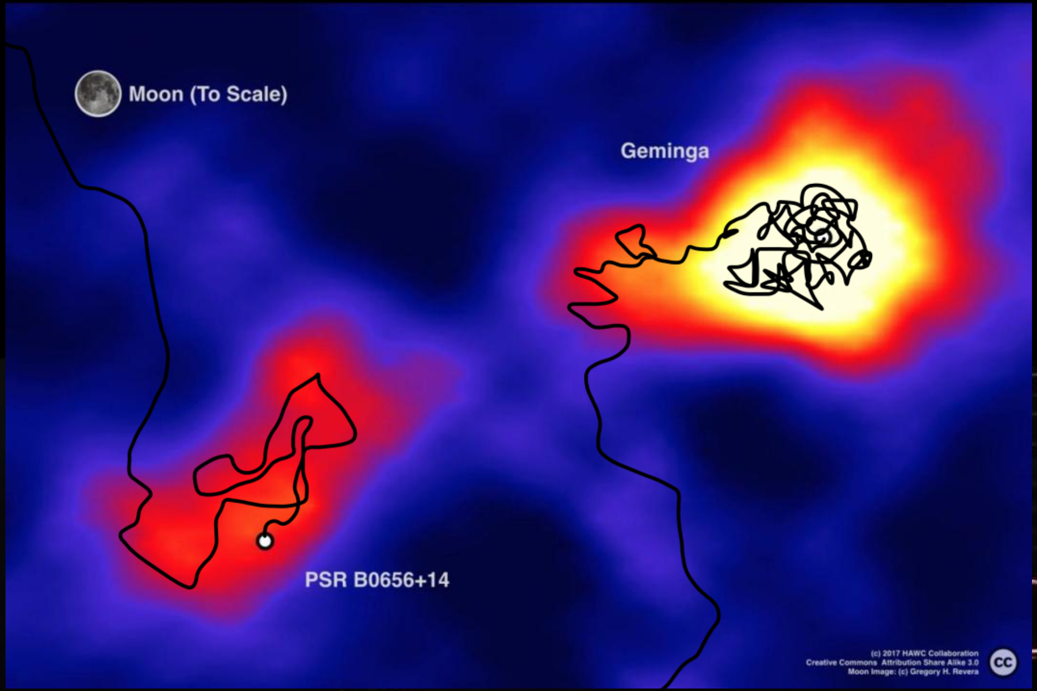

Understanding the Multiwavelength Observation of Geminga's Tev Halo: The Role of Anisotropic Diffusion of Particles

Ruo-Yu Liu,[1,2,*] Huirong Yan,[1,3,†] and Heshou Zhang[1,3]
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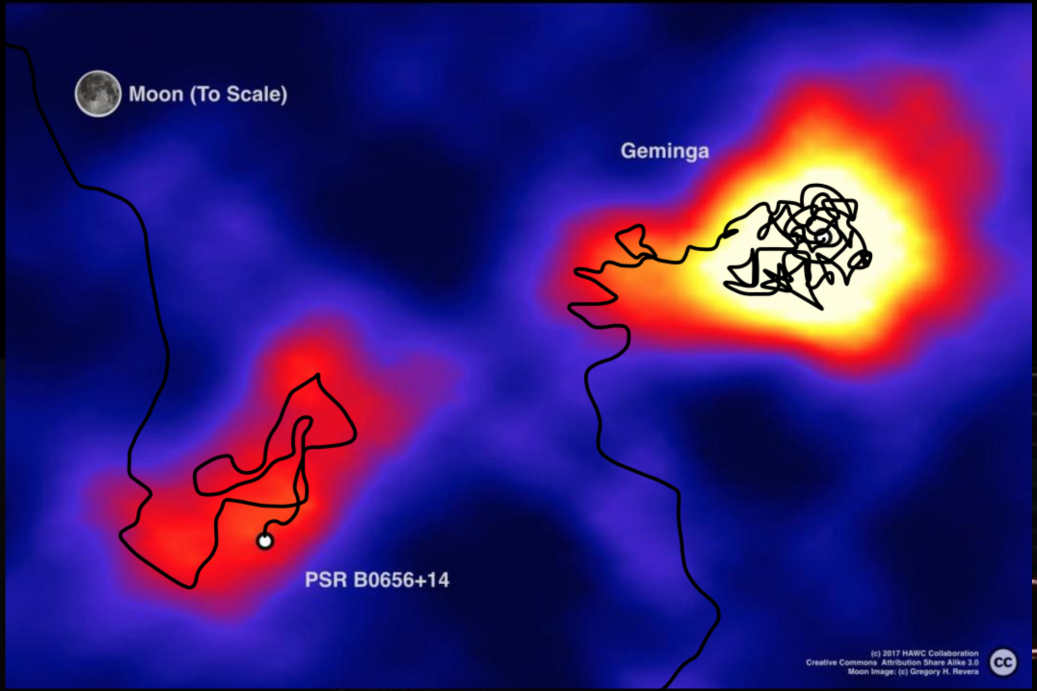
In this Letter, we propose that the x-ray and the TeV observations in the vicinity of Geminga can be understood in the framework of anisotropic diffusion of injected electrons or positrons. This interpretation only requires the turbulence in the vicinity of Geminga to be sub-Alfvénic with the local mean magnetic field direction approximately aligned with our line of sight towards Geminga, without invoking extreme conditions for the environment, such as an extremely small diffusion coefficient and a weak magnetic field of submicrogauss as suggested in previous literature.

DOI: 10.1103/PhysRevLett.123.221103



Anisotropic diffusion cannot explain TeV halo observations

Pedro De La Torre Luque,[1,*] Ottavio Fornieri,[2,3,†] and Tim Linden[1,‡]

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TeV halos are regions of enhanced photon emissivity surrounding pulsars. While multiple sources have been discovered, a self-consistent explanation of their radial profile and spherically symmetric morphology remains elusive due to the difficulty in confining high-energy electrons and positrons within ~20 pc regions of the interstellar medium. One proposed solution utilizes anisotropic diffusion to confine the electron population within a "tube" that is auspiciously oriented along the line of sight. We show that while such models may explain a unique source such as Geminga, the phase space of such solutions is very small and they are unable to simultaneously explain the size and approximate radial symmetry of the TeV halo population.

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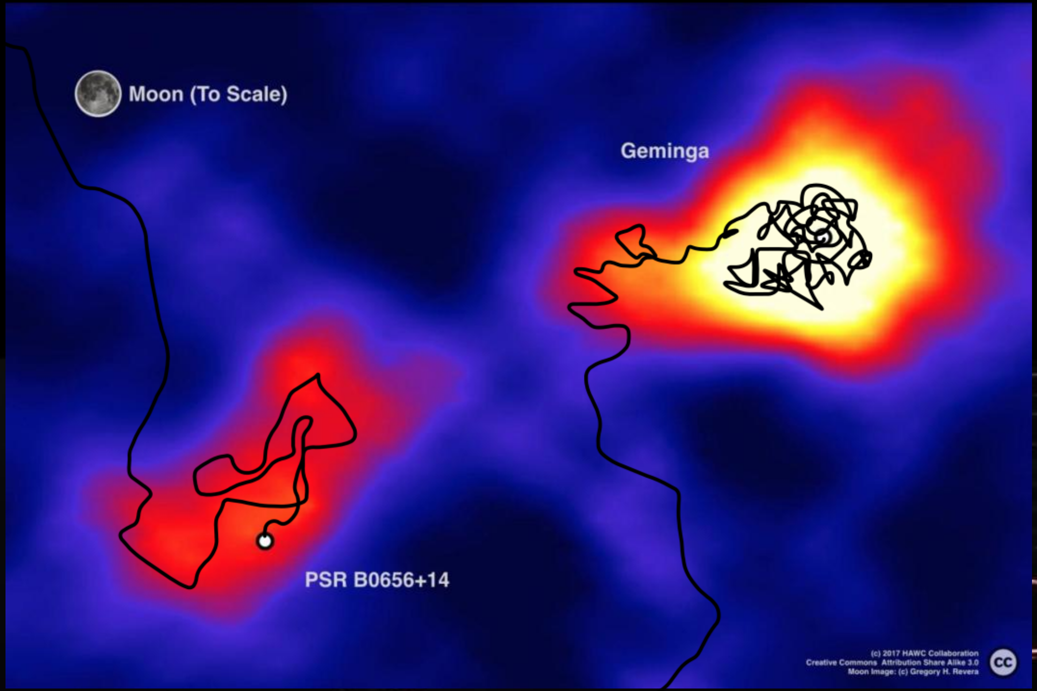

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Does the Geminga, Monogem and PSR J0622+3749 γ-ray halos imply slow diffusion around pulsars?

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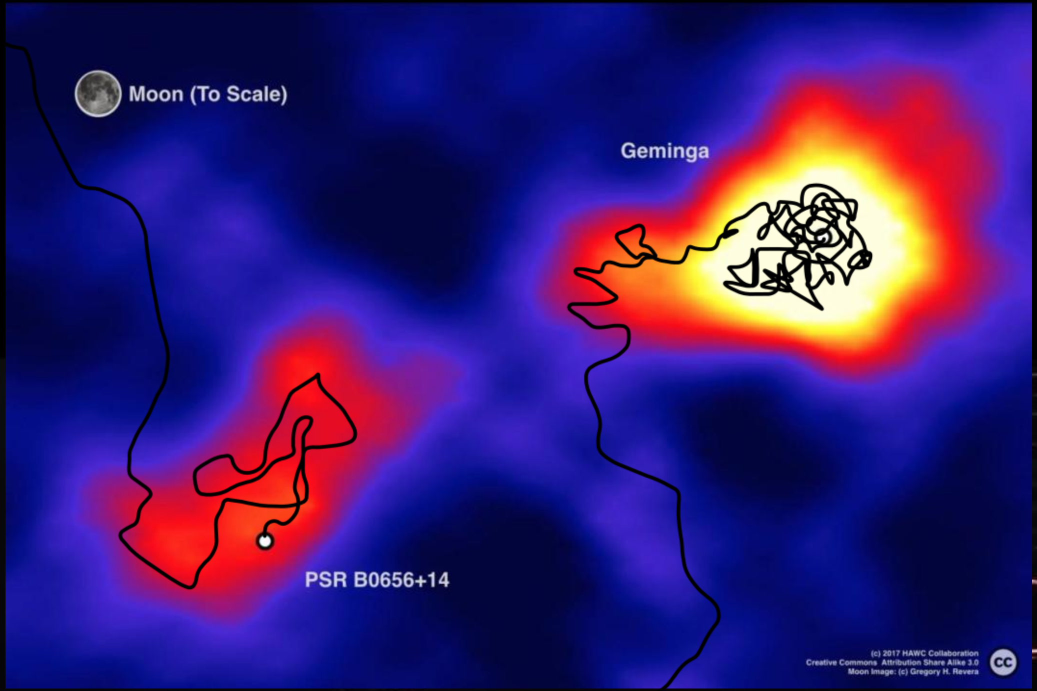
(Dated: October 25, 2021)

The HAWC Collaboration has reported the detection of an extended γ-ray emission around the Geminga and Monogem pulsars of a few degree extension. Very recently, the LHAASO Collaboration released also the data for an extended γ-ray emission around the pulsar PSR J0622+3749. This flux can be explained with electrons and positrons injected from these sources and their inverse Compton Scattering on the interstellar radiation fields. So far the size of such γ−ray halos has been interpreted as the result of the diffusion coefficient around the sources being about two orders of magnitude smaller than the average in the Galaxy. However, this conclusion is driven by the assumption that particles propagate diffusively right away after the injection without taking into account the ballistic propagation. The propagation of cosmic-ray leptons in the proximity of the Geminga, Monogem and PSR J0622+3749 pulsars is examined here considering the transition from the quasi-ballistic, valid for the most recently injected particles, to the diffusive transport regime. For typical interstellar values of the diffusion coefficient, the quasi-ballistic regime dominates the lepton distribution up to distances of a few tens of parsec from the pulsar for particle energies above ~ 10 TeV. In this regime the resulting γ−ray source tends to be rather compact, despite particles travel a long distance. Indeed, for larger values of the diffusion coefficient, particles propagate ballistically up to larger distances with the result of a more point-like γ−ray source. When such transition is taken into account, a good fit to the HAWC and LHAASO γ-ray data around Geminga, Monogem and PSR J0622+3749 is obtained without the need to invoke a strong suppression of the diffusion coefficient.



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Self-generated cosmic-Ray confinement in TeV halos: Implications for TeV γ-ray emission and the positron excess

Carmelo Evoli,[1,2,*] Tim Linden,[3,†] and Giovanni Morlino[1,2,4,‡]
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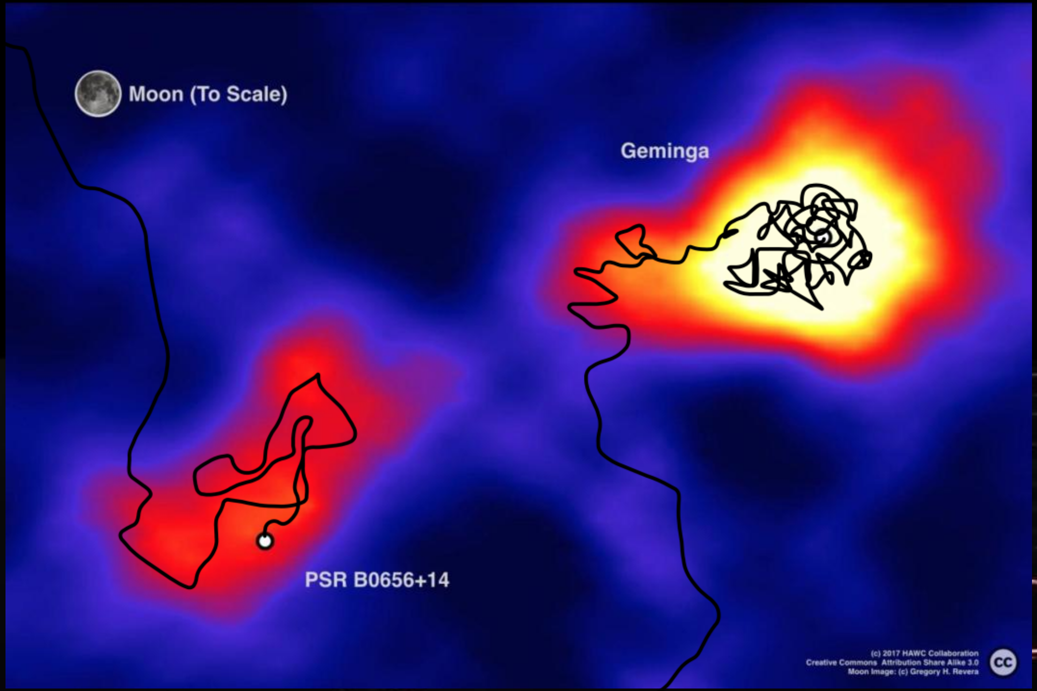
Recent observations have detected extended TeV γ-ray emission surrounding young and middle-aged pulsars. The morphology of these "TeV halos" requires cosmic-ray diffusion to be locally suppressed by a factor of ∼100–1000 compared to the typical interstellar medium. No model currently explains this suppression. We show that cosmic-ray self-confinement can significantly inhibit diffusion near pulsars. The steep cosmic-ray gradient generates Alfvén waves that resonantly scatter the same cosmic-ray population, suppressing diffusion within ∼20 pc of young pulsars ($\lesssim$100 kyr). In this model, TeV halos evolve through two phases, a growth phase where Alfvén waves are resonantly generated and cosmic-ray diffusion becomes increasingly suppressed, and a subsequent relaxation phase where the diffusion coefficient returns to the standard interstellar value. Intriguingly, cosmic rays are not strongly confined early in the TeV halo evolution, allowing a significant fraction of injected $e^{\pm}$ to escape. If these $e\pm$ also escape from the surrounding supernova remnant, they would provide a natural explanation for the positron excess observed by PAMELA and AMS-02. Recently created TeV cosmic rays are confined in the TeV halo, matching observations by HAWC and H.E.S.S. While our default model relaxes too rapidly to explain the confinement of TeV cosmic rays around mature pulsars, such as Geminga, models utilizing a Kraichnan turbulence spectrum experience much slower relaxation. Thus, observations of TeV halos around mature pulsars may provide a probe into our understanding of interstellar turbulence.



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Self-Generated Cosmic-Ray Turbulence Can Explain the Morphology of TeV Halos

Payel Mukhopadhyay[1,2,*] and Tim Linden[3,†]
[1]SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94039, USA
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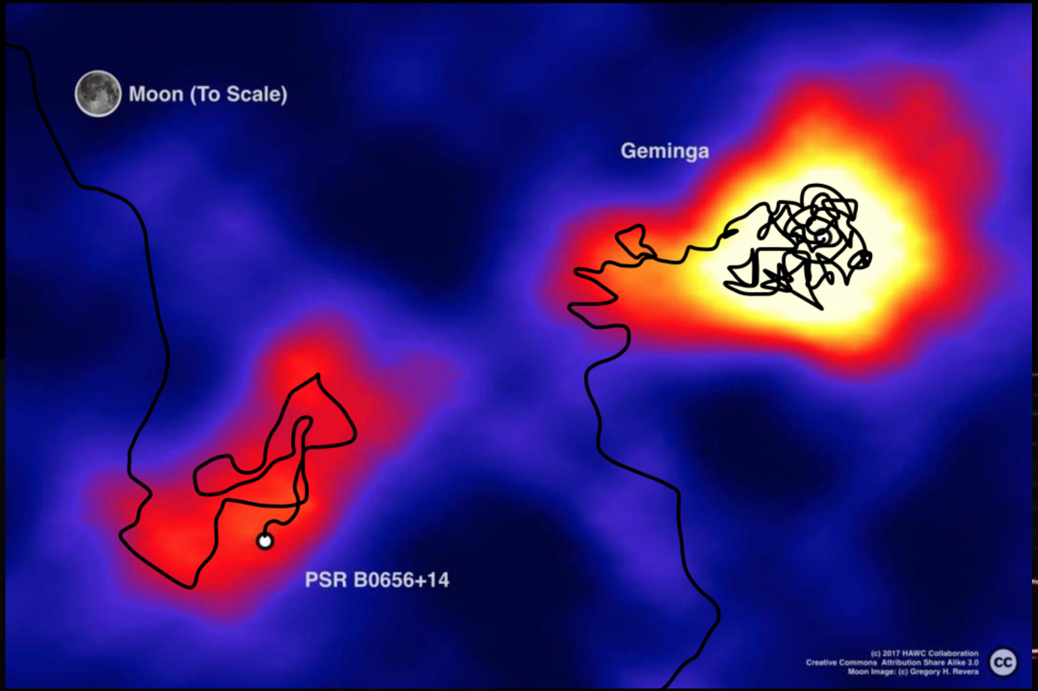
Observations have shown that spatially extended "TeV halos" are a common (and potentially generic) feature surrounding young and middle-aged pulsars. However, their morphology is not understood. They are larger than the "compact" region where the stellar remnant dominates the properties of the interstellar medium, but smaller than expected in models of cosmic-ray diffusion through the standard interstellar medium. Several explanations have been proposed, but all have shortcomings. Here, we revisit a class of models where the cosmic-ray gradient produced by the central source induces a streaming stability that "self-confines" the cosmic-ray population. We find that previous studies significantly underpredicted the degree of cosmic-ray confinement and show that corrected models can significantly inhibit cosmic-ray diffusion throughout the TeV halo, especially when similar contributions from the coincident supernova remnant are included.



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Possible origin of the slow-diffusion region around Geminga

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ABSTRACT
Geminga pulsar is surrounded by a multiTeV γ-ray halo radiated by the high-energy electrons and positrons accelerated by the central pulsar wind nebula (PWN). The angular profile of the γ-ray emission reported by High-Altitude Water Cherenkov Observatory indicates an anomalously slow diffusion for the cosmic-ray electrons and positrons in the halo region around Geminga. In the paper we study the possible mechanism for the origin of the slow diffusion. At first, we consider the self-generated Alfvén waves due to the streaming instability of the electrons and positrons released by Geminga. However, even considering a very optimistic scenario for the wave growth, we find this mechanism *does not* work to account for the extremely slow diffusion at the present day, if taking the proper motion of Geminga pulsar into account. The reason is straightforward as the PWN is too weak to generate enough high-energy electrons and positrons to stimulate strong turbulence at the late time. We then propose an assumption that the strong turbulence is generated by the shock wave of the parent supernova remnant (SNR) of Geminga. Geminga may still be inside the SNR, and we find that the SNR can provide enough energy to generate the slow-diffusion circumstance. The TeV haloes around PSR B0656+14, Vela X, and PSR J1826-1334 may also be explained under this assumption.

Key words: turbulence – cosmic rays – ISM: individual objects: Geminga nebula – ISM: supernova remnants.

:ated Cosmic-Ray Turbulence Can Explain the Morphology of TeV Halos

Payel Mukhopadhyay[1,2,*] and Tim Linden[3,†]
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iversity and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden

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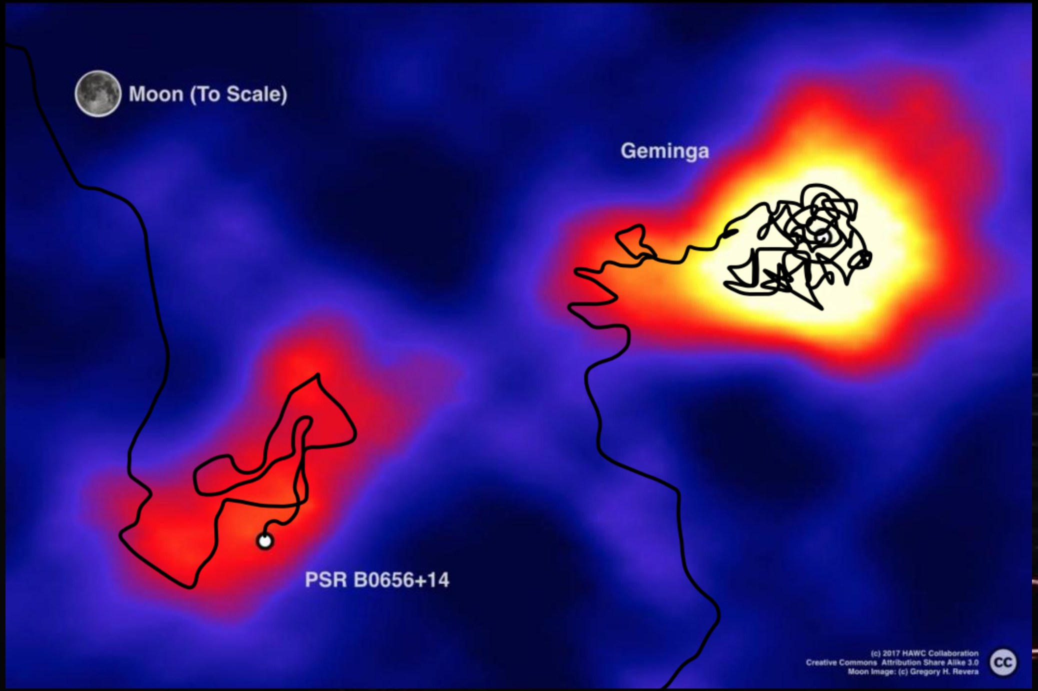

Understanding the Multiwavelength Observation of Geminga's Tev Halo: The Role of Anisotropic Diffusion of Particles

rong Yan,[1,3,†] and Heshou Zhang[1,3]
ESY), Platanenallee 6, D-15738 Zeuthen, Germany
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Universität Potsdam, D-14476 Potsdam, Germany

ot received 17 September 2019; published 26 November 2019)

nd the TeV observations in the vicinity of Geminga can be
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Anisotropic diffusion cannot explain TeV halo observations

Pedro De La Torre Luque[1,*], Ottavio Fornieri[2,3,†] and Tim Linden[1,‡]
[1]*Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*
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TeV halos are regions of enhanced photon emissivity surrounding pulsars. While multiple sources have been discovered, a self-consistent explanation of their radial profile and spherically symmetric morphology remains elusive due to the difficulty in confining high-energy electrons and positrons within ~20 pc regions of the interstellar medium. One proposed solution utilizes anisot...
electron population within a "tube" that is auspiciously oriented along the li...
such models may explain a unique source such as Geminga, the phase space...
and they are unable to simultaneously explain the size and approximate ra...

Does the Geminga, Monogem and PSR J0622+3749 γ-ray halos imply slow diffusion around pulsars?

S. Recchia,[1,2] M. Di Mauro,[2] F. A. Aharonian,[3,4] L. Orusa,[1,2] F. Donato,[1,2] S. Gabici,[5] and S. Manconi[6]
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itute for Theoretical Particle Physics and Cosmology,
hen University, Sommerfeldstr. 16, 52056 Aachen, Germany

(Dated: October 25, 2021)

ation has reported the detection of an extended γ-ray emission around the
pulsars of a few degree extension. Very recently, the LHAASO Collaboration
or an extended γ-ray emission around the pulsar PSR J0622+3749. This
ith electrons and positrons injected from these sources and their inverse
the interstellar radiation fields. So far the size of such γ-ray halos has
esult of the diffusion coefficient around the sources being about two orders
an the average in the Galaxy. However, this conclusion is driven by the
es propagate diffusively right away after the injection without taking into
opagation. The propagation of cosmic-ray leptons in the proximity of the
PSR J0622+3749 pulsars is examined here considering the transition from
for the most recently injected particles, to the diffusive transport regime.
values of the diffusion coefficient, the quasi-ballistic regime dominates the
distances of a few tens of parsec from the pulsar for particle energies above
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Self-generated cosmic-Ray confinement in TeV halos: Implications for TeV γ-ray emission and the positron excess

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[3]*Center for Cosmology and AstroParticle Physics (CCAPP), and Department of Physics, The Ohio State University Columbus, Ohio, 43210, USA*
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Recent observations have detected extended TeV γ-ray emission surrounding young and middle-aged pulsars. The morphology of these "TeV halos" requires cosmic-ray diffusion to be locally suppressed by a factor of
model currently explains this suppression. We
bit diffusion near pulsars. The steep cosmic-ray
me cosmic-ray population, suppressing diffusion
TeV halos evolve through two phases, a growth
c-ray diffusion becomes increasingly suppressed,
ficient returns to the standard interstellar value.

Possible origin of the slow-diffusion region around Geminga

Peng-Fei Yin[1]
h Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
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al form 2019 January 21

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Cosmic-ray generated bubbles around their sources

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ABSTRACT
Cosmic rays (CRs) are thought to escape their sources streaming along the local magnetic field lines. We show that this phenomenon generally leads to the excitation of both resonant and non-resonant streaming instabilities. The self-generated magnetic fluctuations induce particle diffusion in extended regions around the source, so that CRs build up a large pressure gradient. By means of two-dimensional (2D) and three-dimensional (3D) hybrid particle-in-cell simulations, we show that such a pressure gradient excavates a cavity around the source and leads to the formation of a cosmic ray dominated bubble, inside which diffusivity is strongly suppressed. Based on the trends extracted from self-consistent simulations, we estimate that, in the absence of severe damping of the self-generated magnetic fields, the bubble should keep expanding until pressure balance with the surrounding medium is reached, corresponding to a radius of ~10–50 pc. The implications of the formation of these regions of low diffusivity for sources of Galactic CRs are discussed. Special care is devoted to estimating the self-generated diffusion coefficient and the grammage that CRs might accumulate in the bubbles before moving into the interstellar medium. Based on the results of 3D simulations, general considerations on the morphology of the γ-ray and synchrotron emission from these extended regions also are outlined.

Key words: astroparticle physics – instabilities – ISM: magnetic fields – turbulence – cosmic rays – ISM: supernova remnants.

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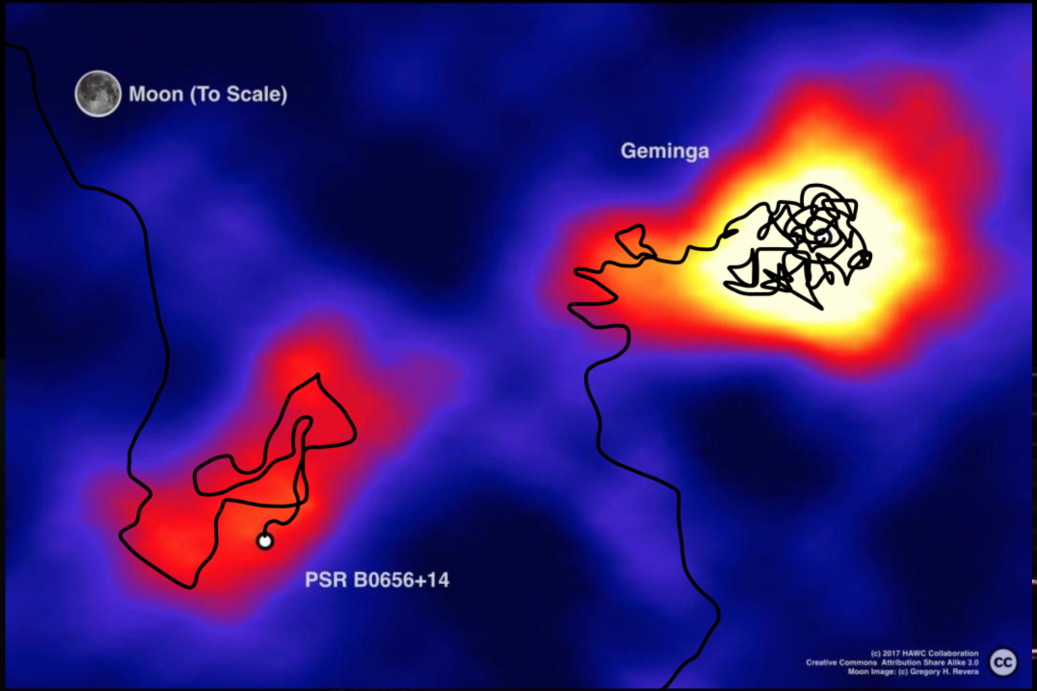

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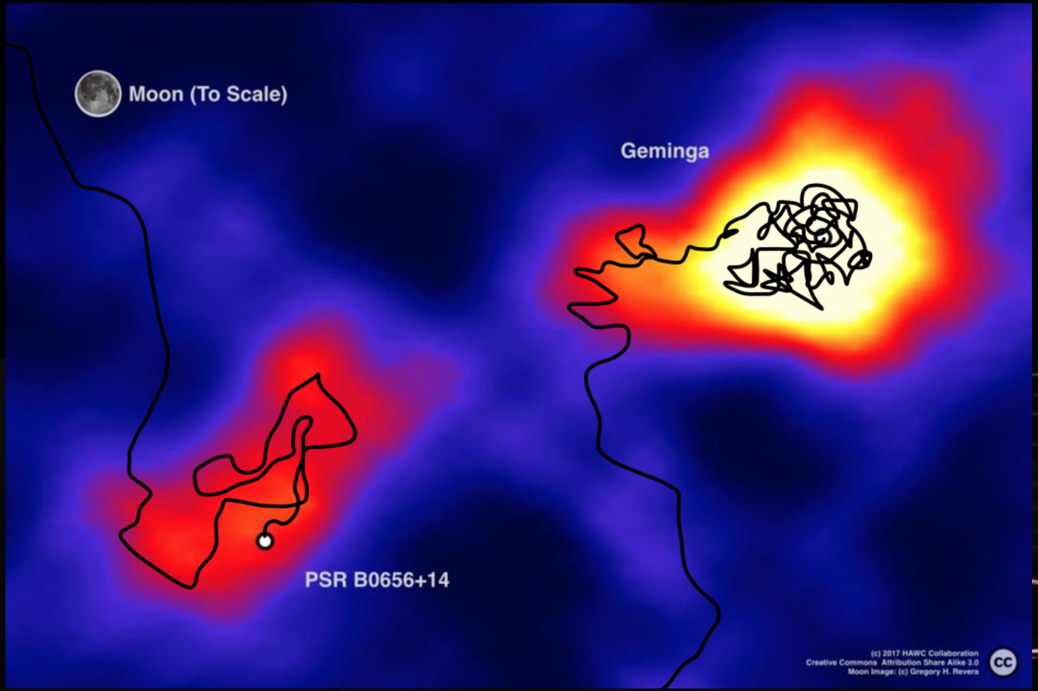

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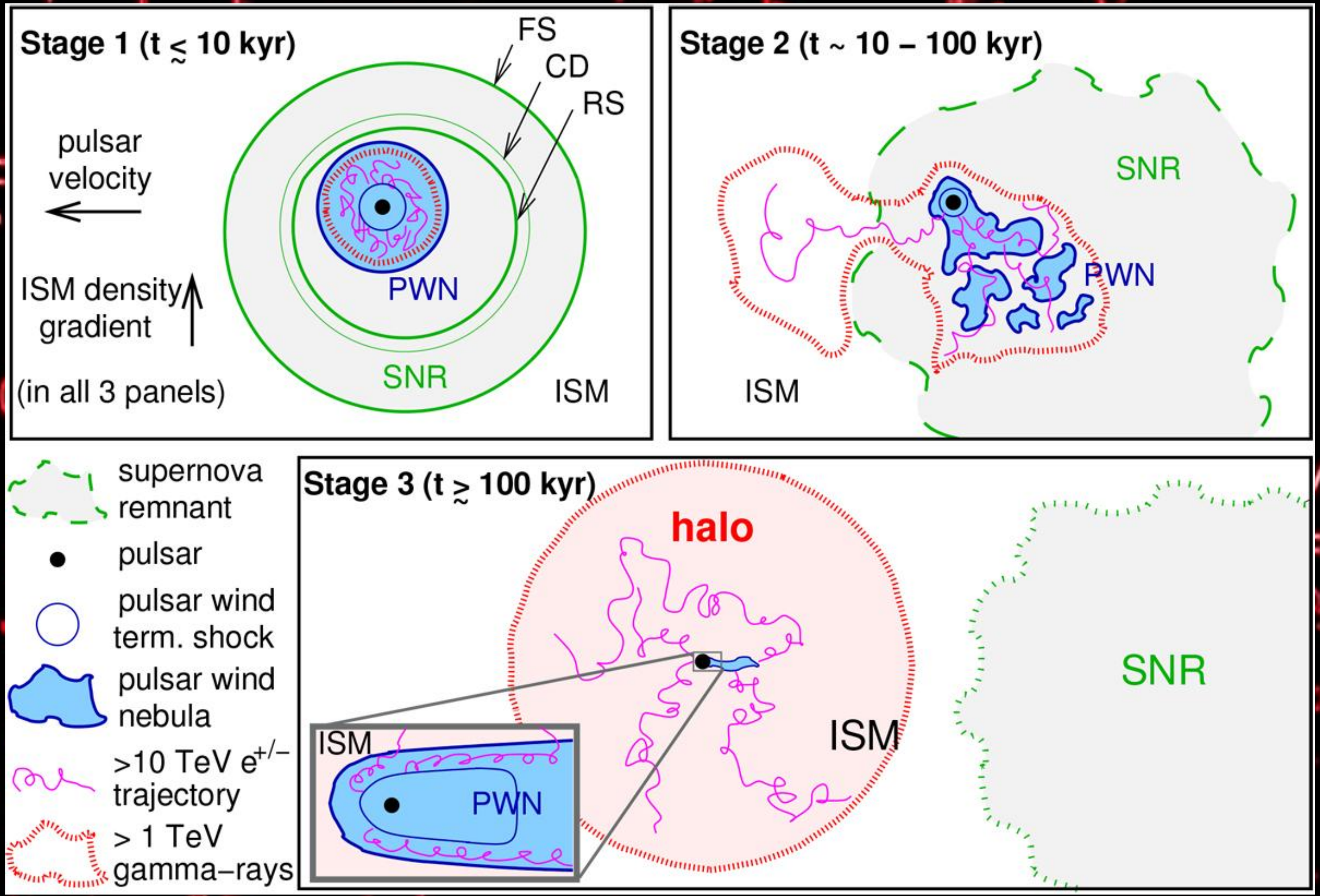
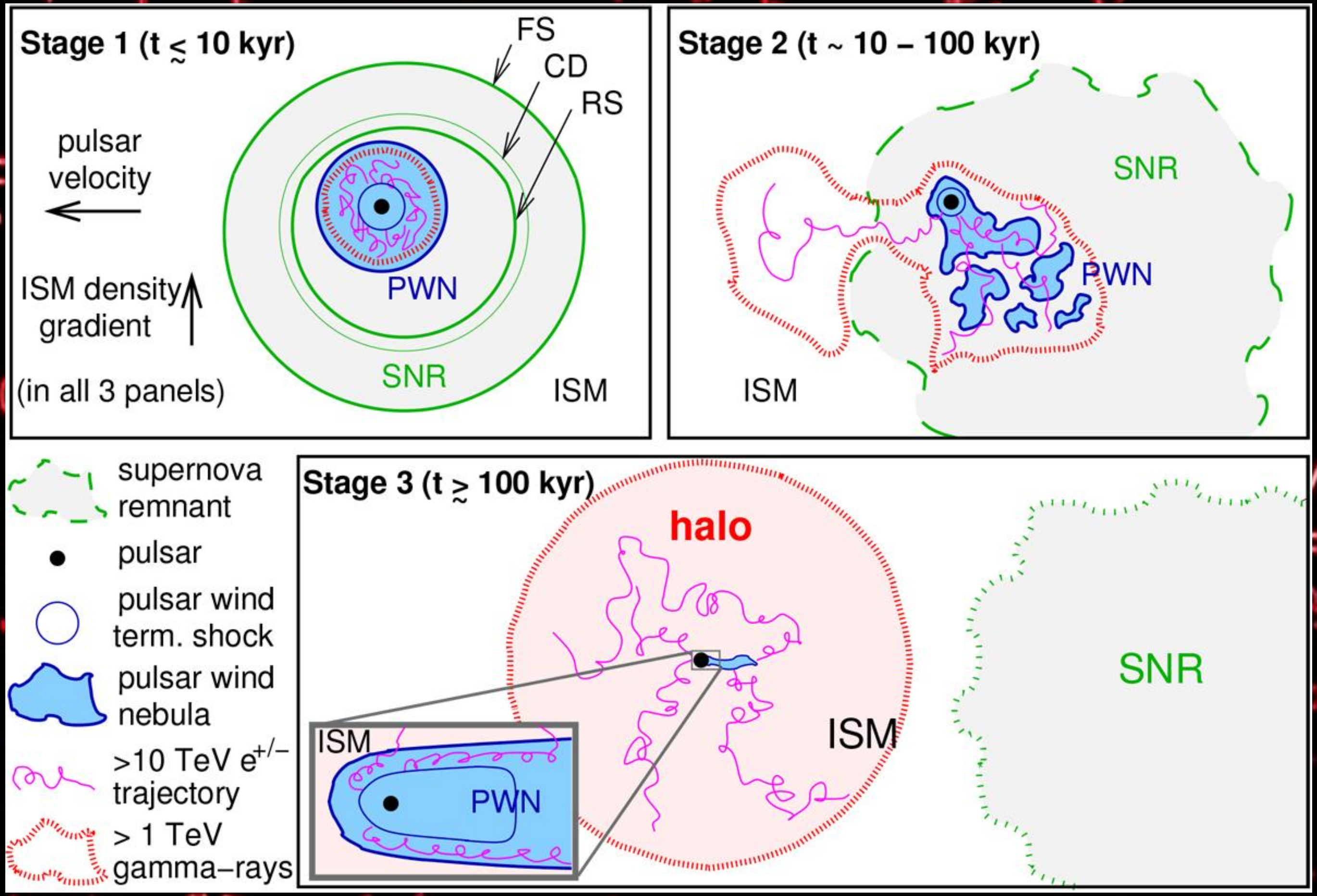
Which medium is the pulsar probing?



Stage 1 (t ≲ 10 kyr)
FS
CD
RS
pulsar velocity
ISM density gradient
(in all 3 panels)
PWN
SNR
ISM
Stage 2 (t ~ 10 – 100 kyr)
SNR
PWN
ISM
supernova remnant
pulsar
pulsar wind term. shock
pulsar wind nebula
>10 TeV e+/− trajectory
> 1 TeV gamma−rays
Stage 3 (t ≳ 100 kyr)
halo
ISM
PWN
ISM
SNR



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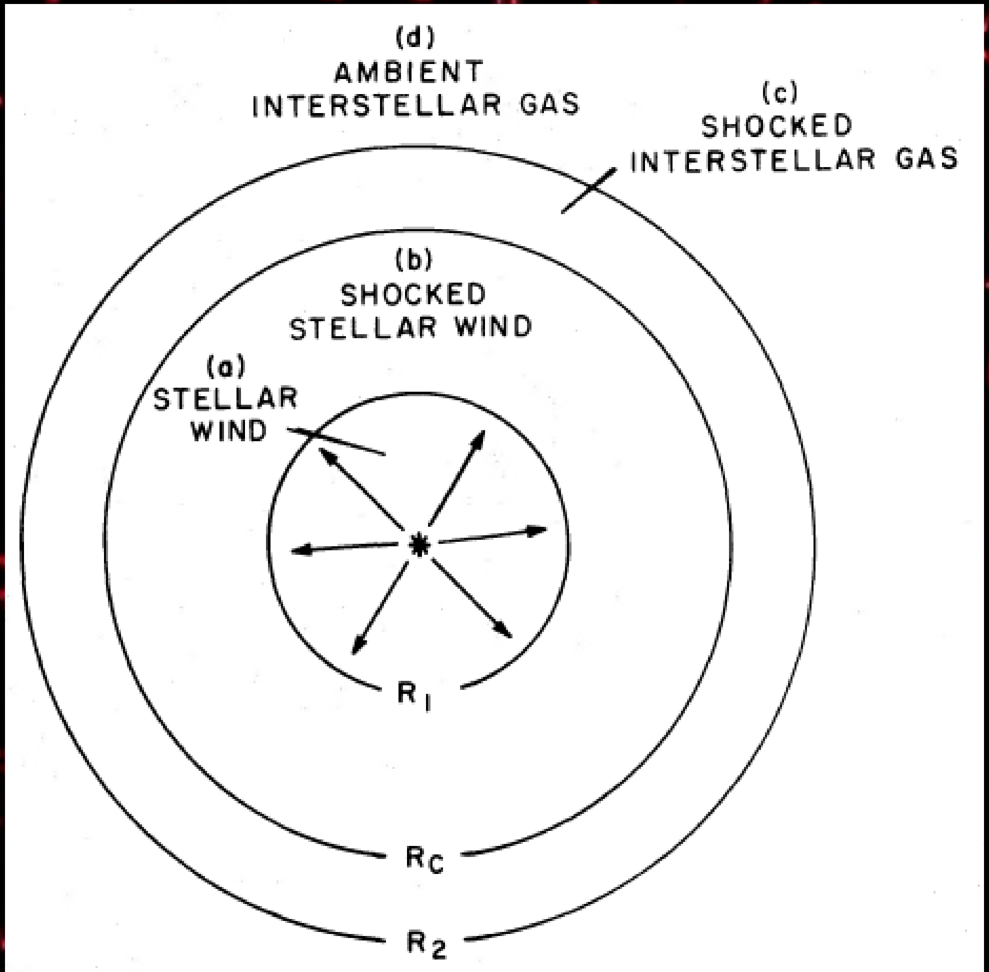
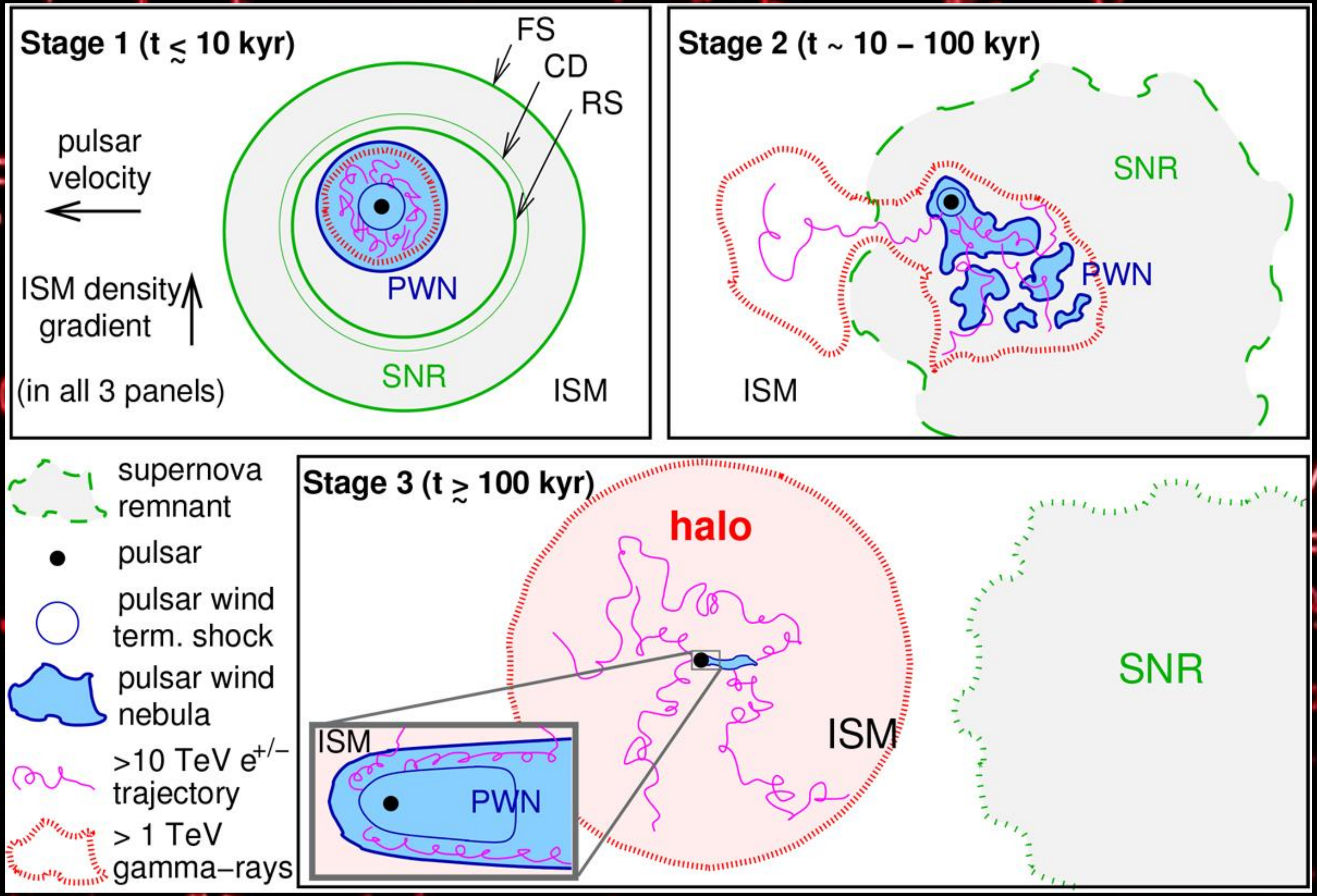


(d) AMBIENT INTERSTELLAR GAS
(c) SHOCKED INTERSTELLAR GAS
(b) SHOCKED STELLAR WIND
(a) STELLAR WIND
R_1
R_C
R_2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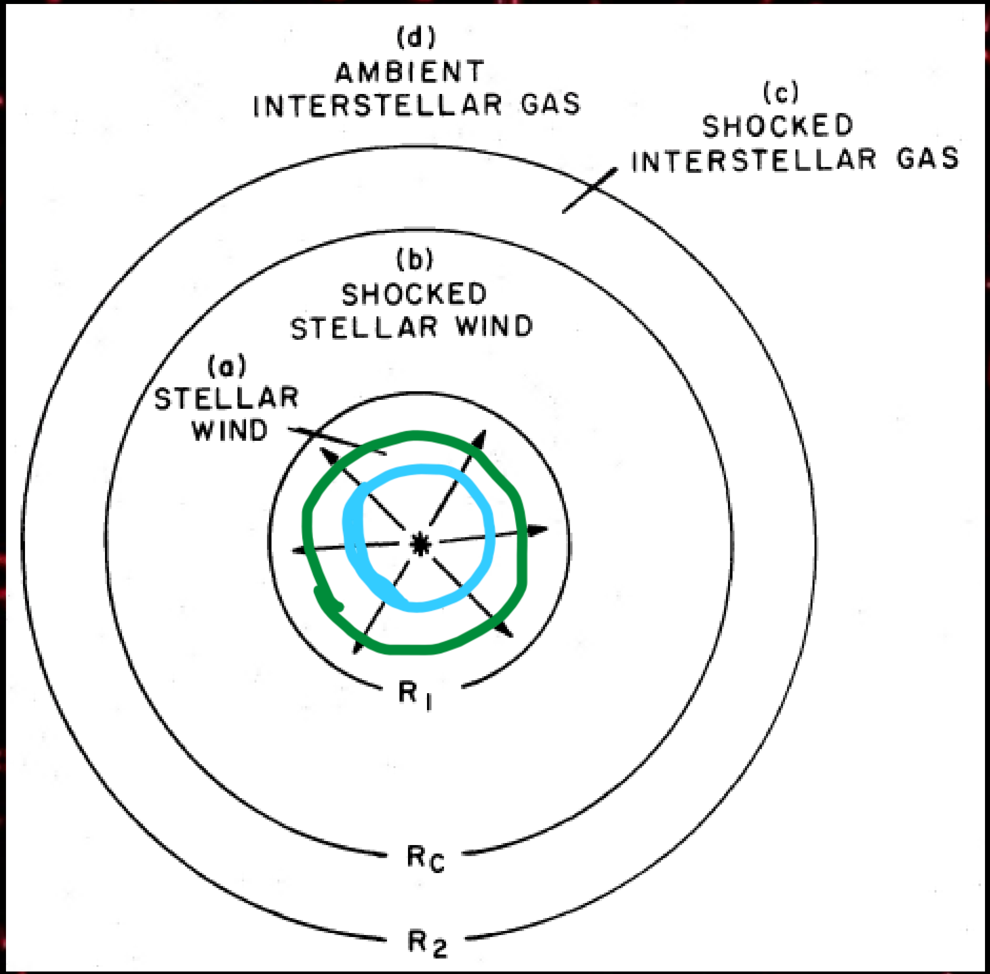
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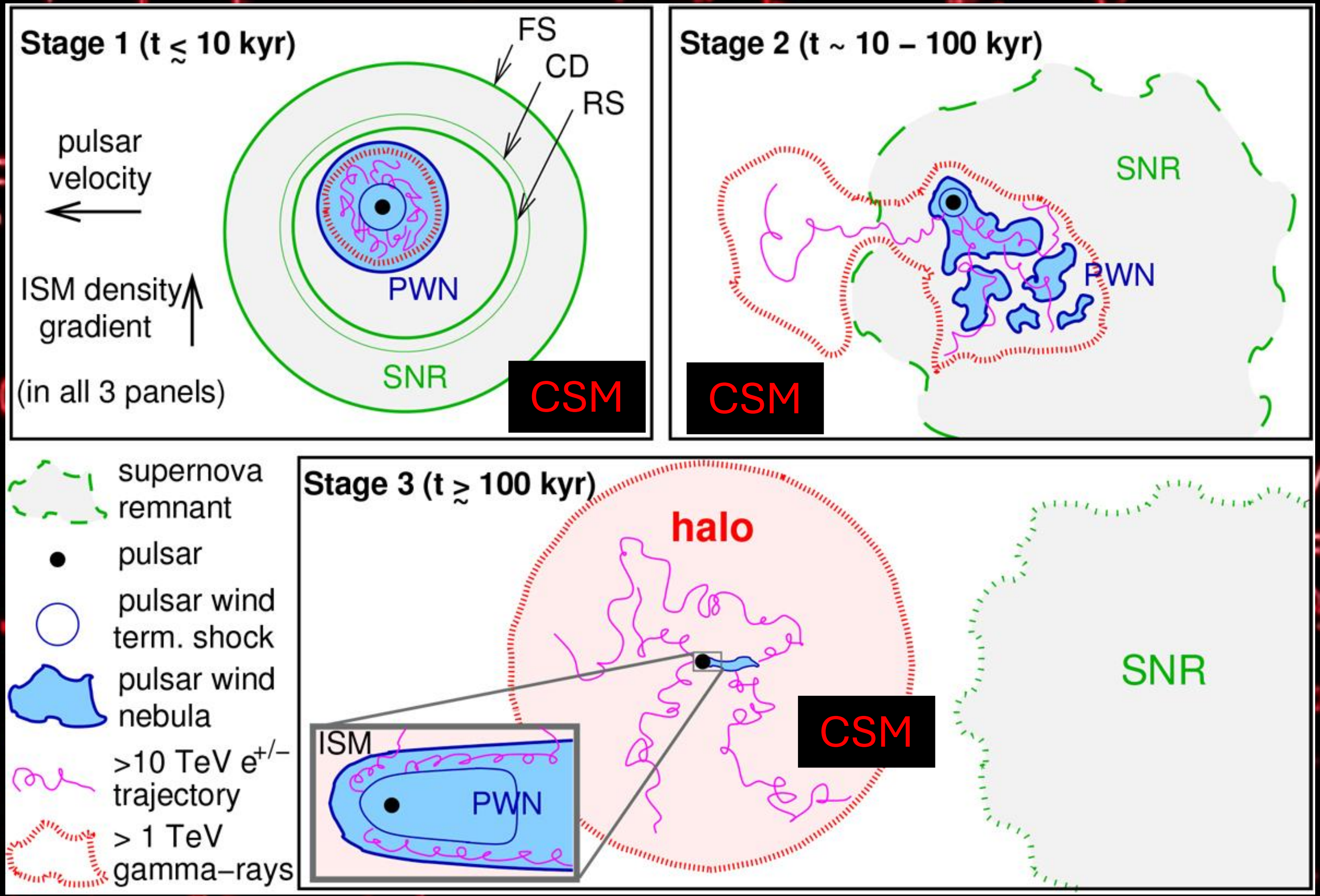
R2



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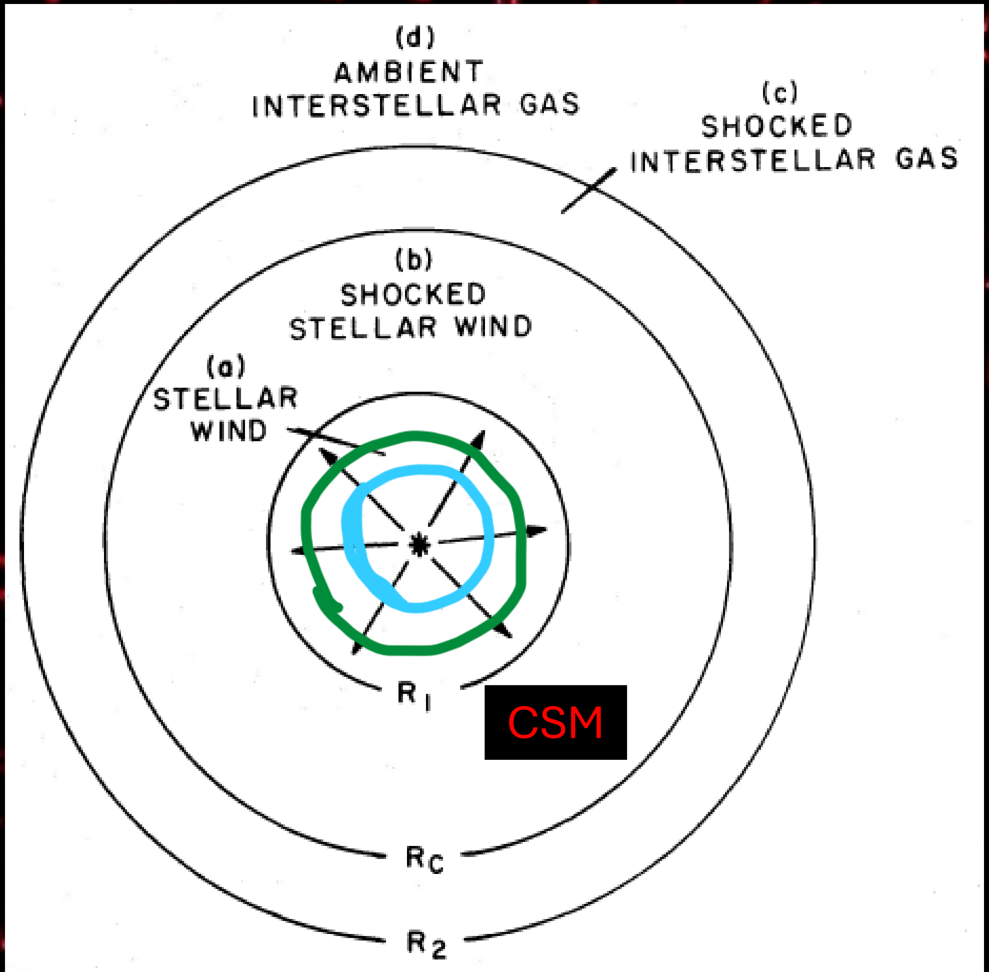

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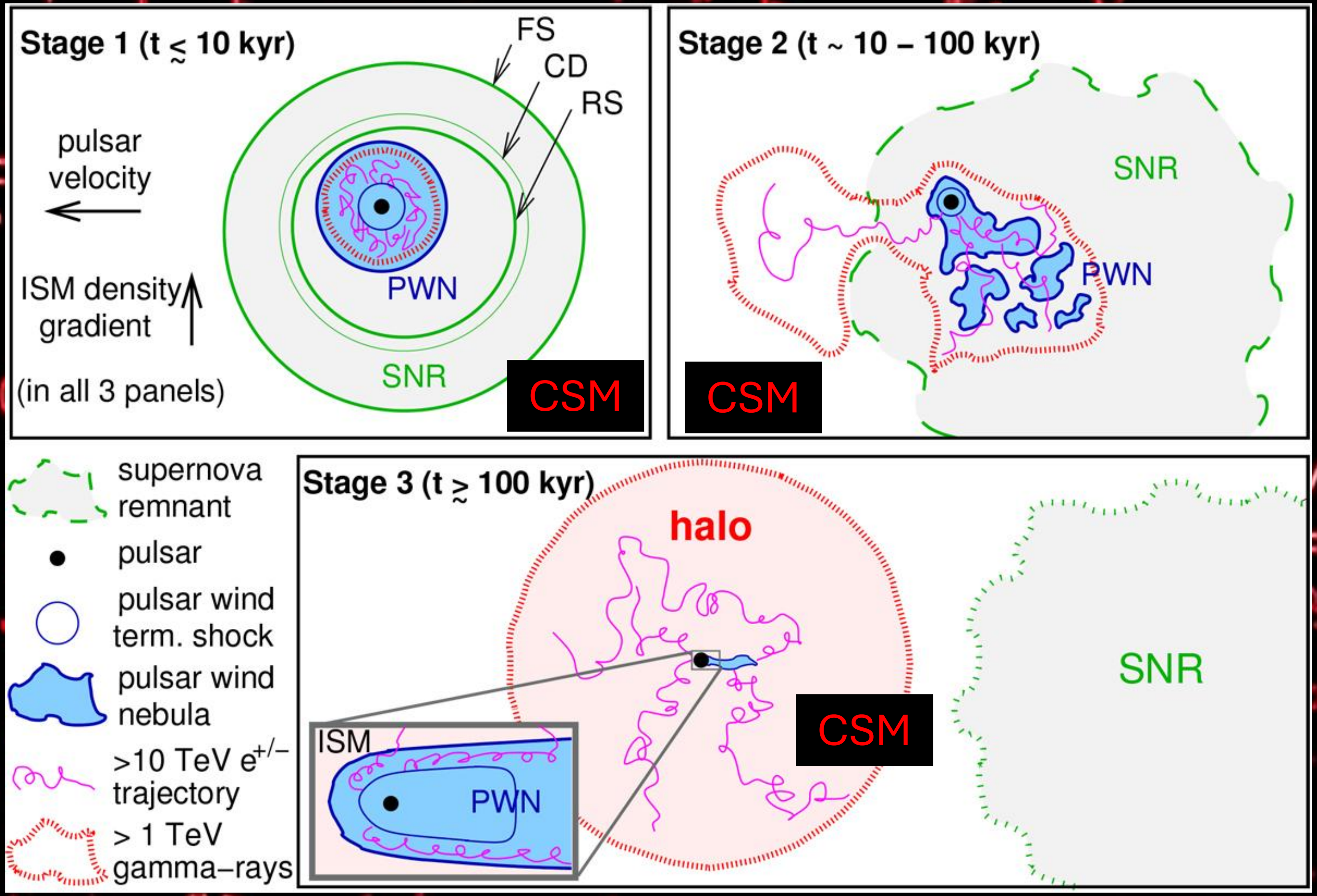
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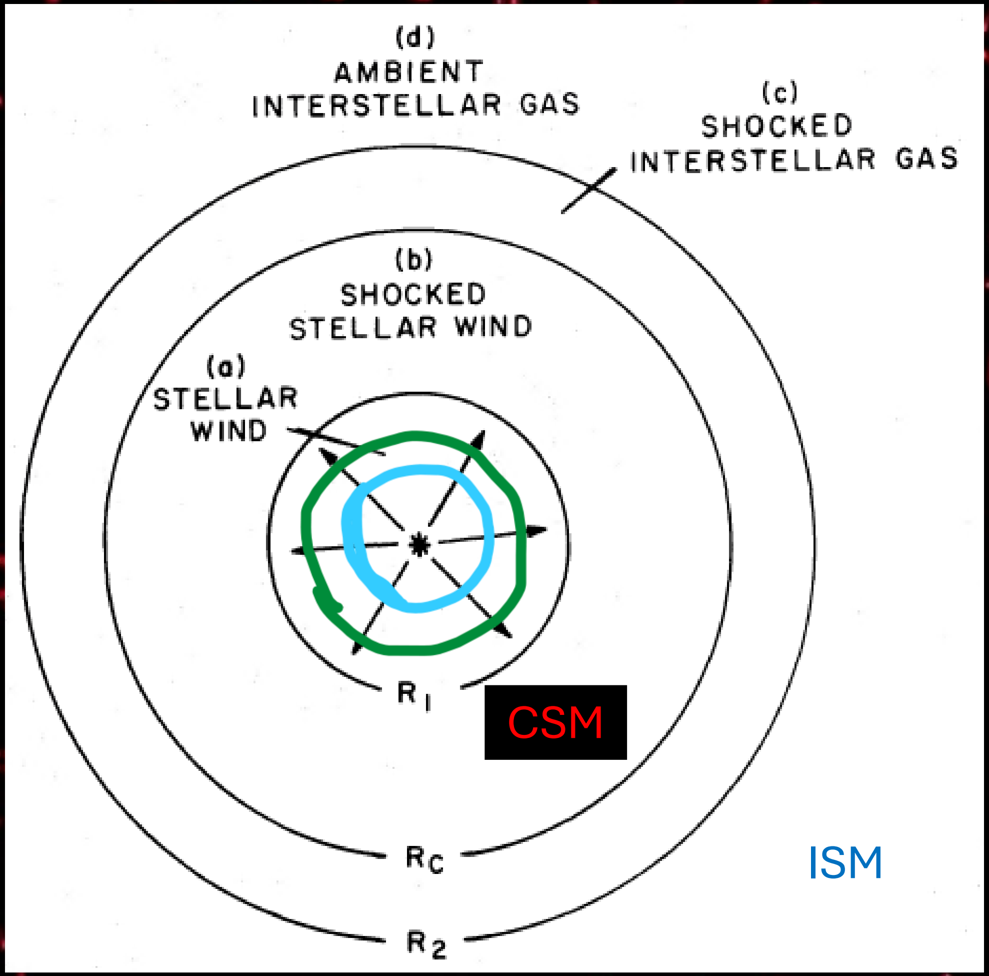
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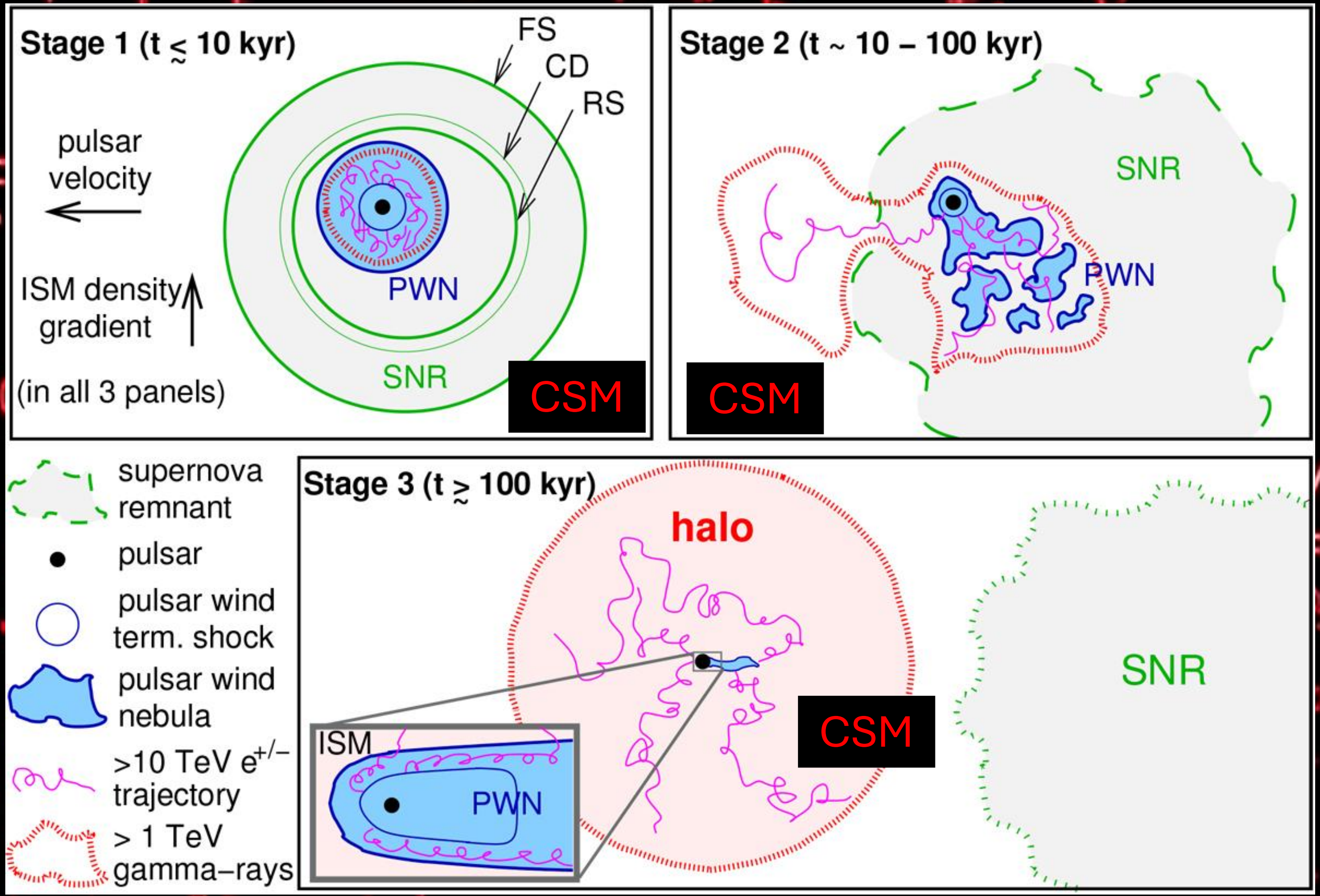
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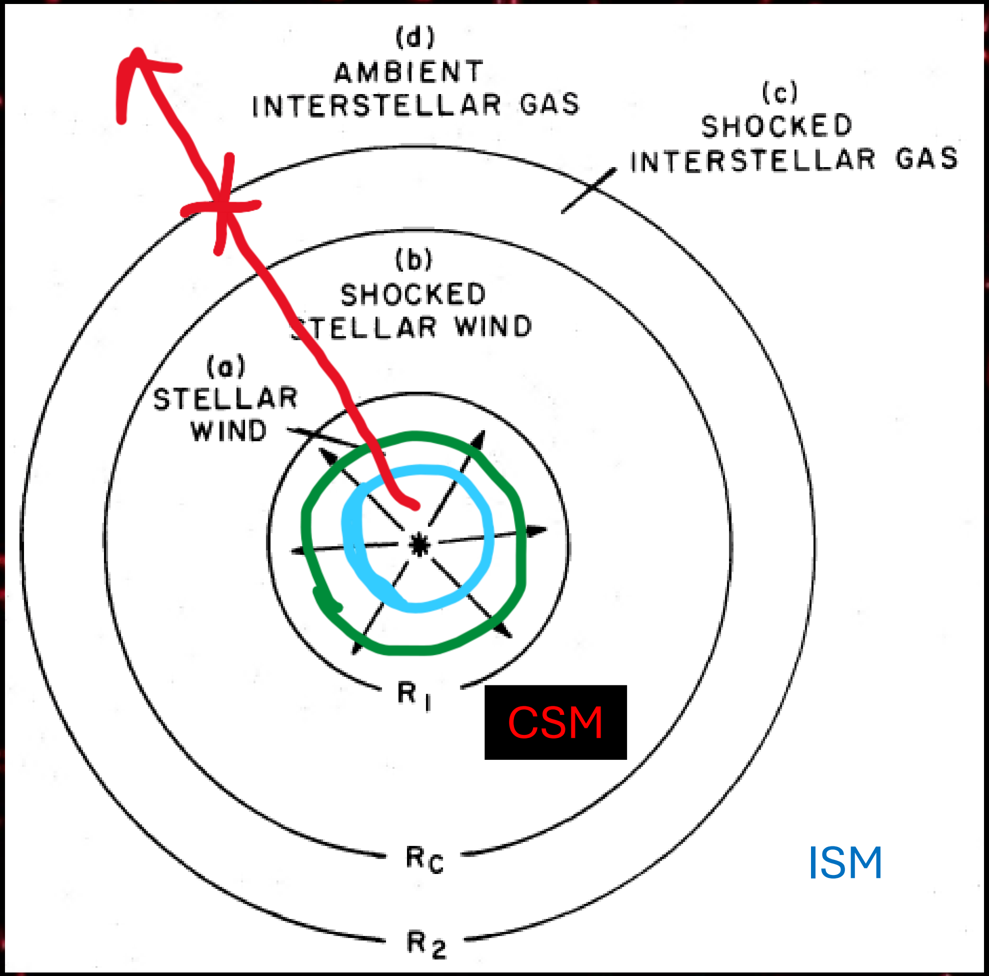
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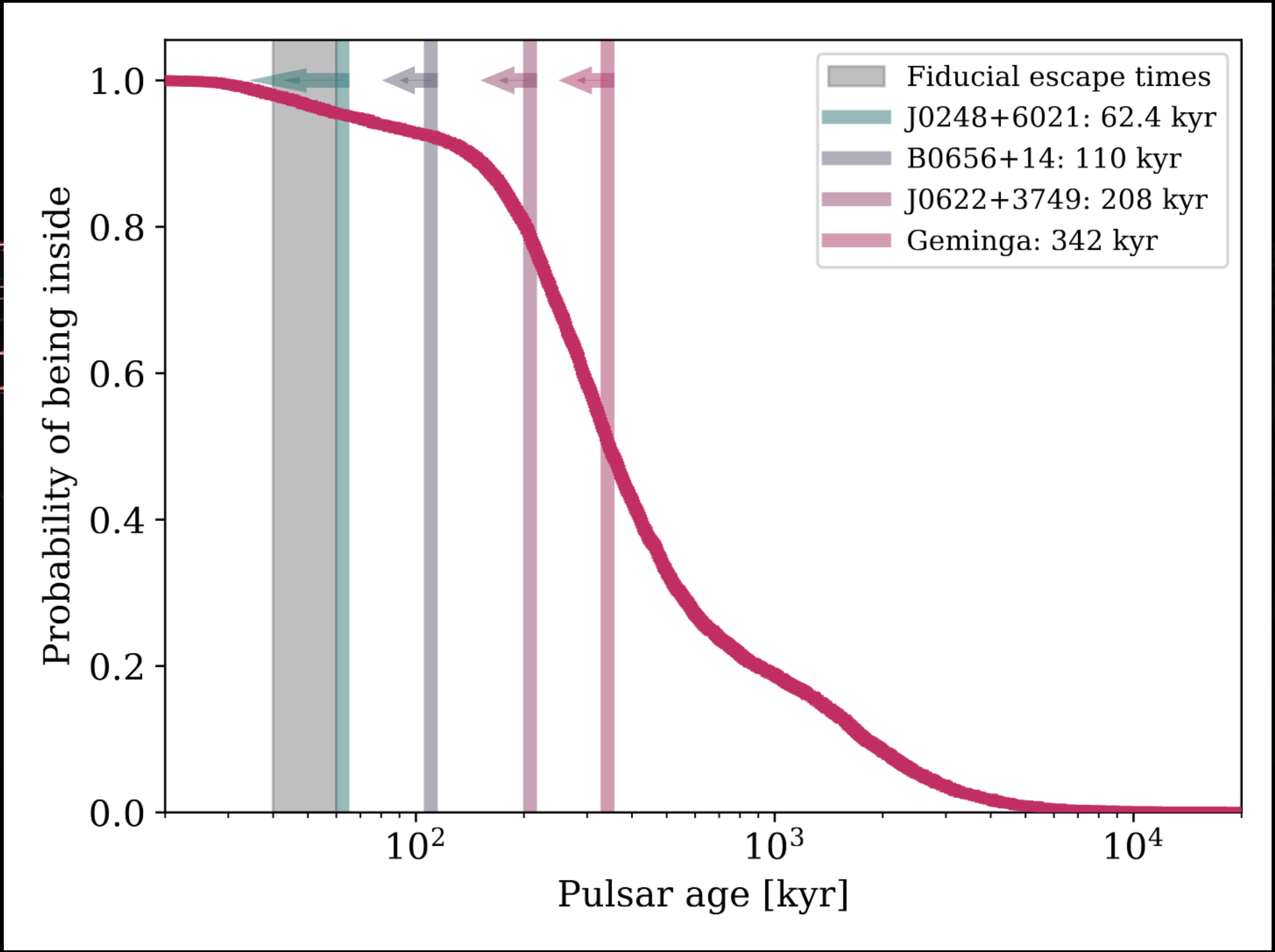

Fiducial escape times
J0248+6021: 62.4 kyr
B0656+14: 110 kyr
J0622+3749: 208 kyr
Geminga: 342 kyr
Probability of being inside
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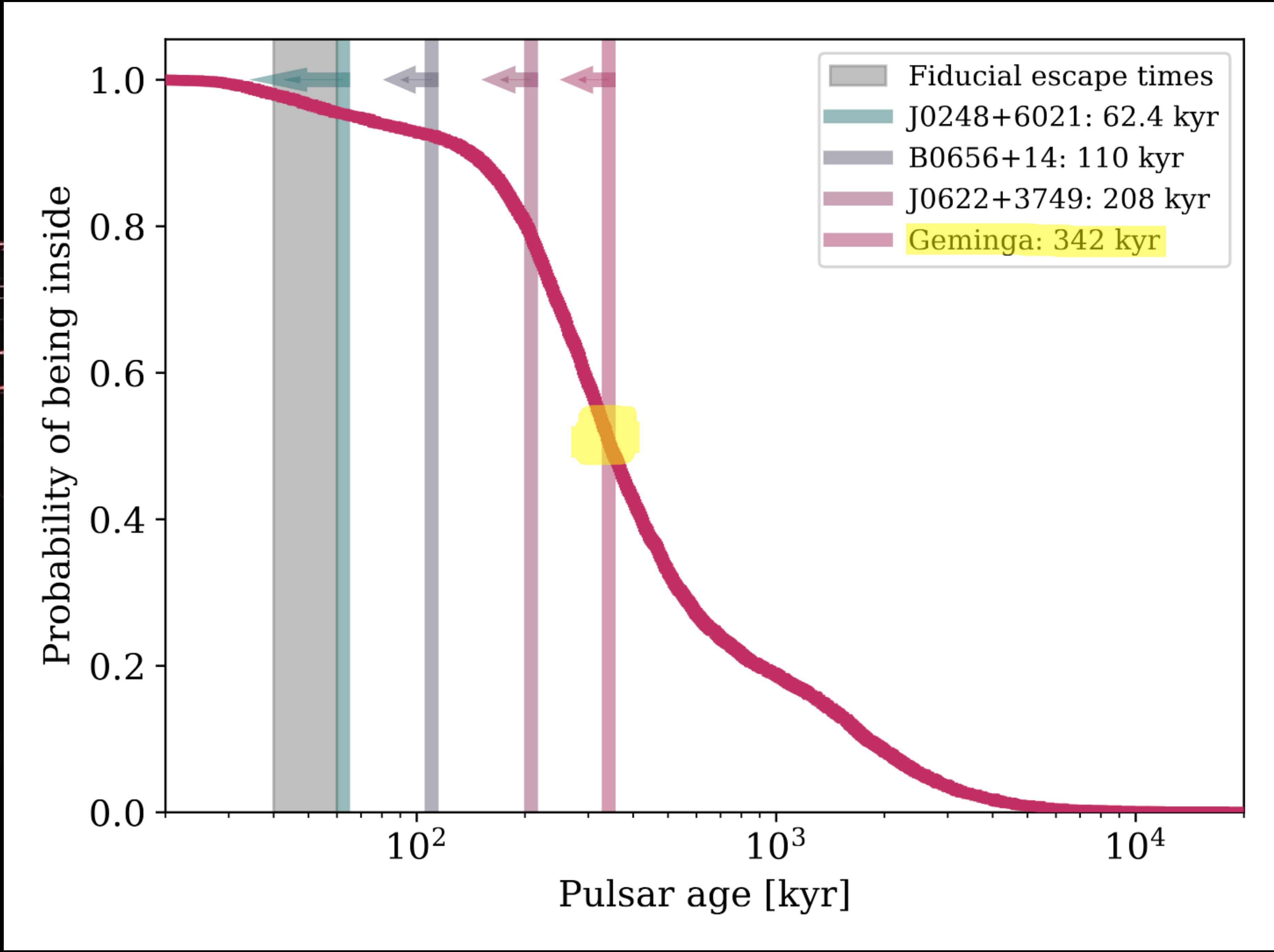
0.8
0.6
0.4
0.2
0.0
10^2
10^3
10^4
Pulsar age [kyr]



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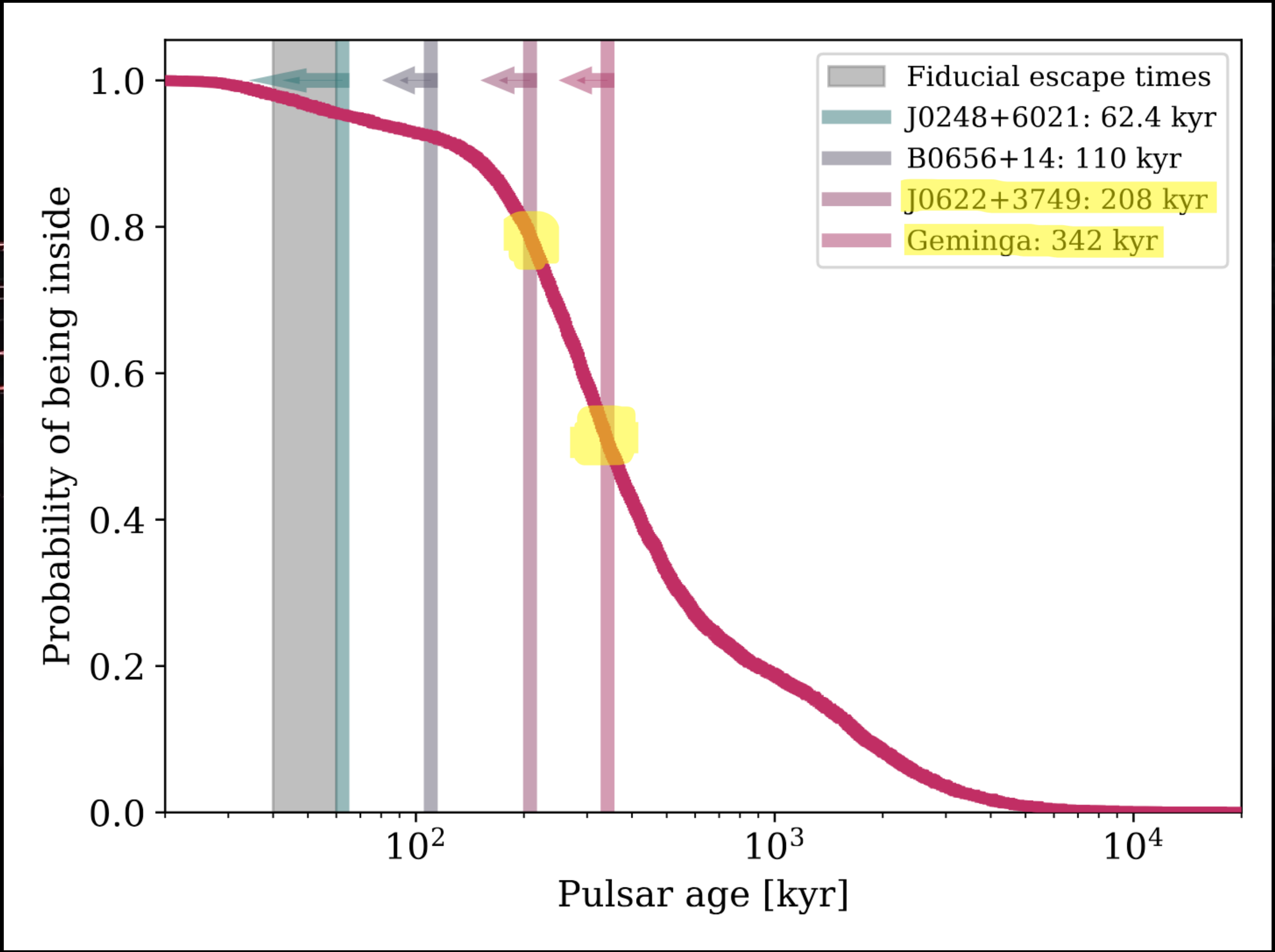

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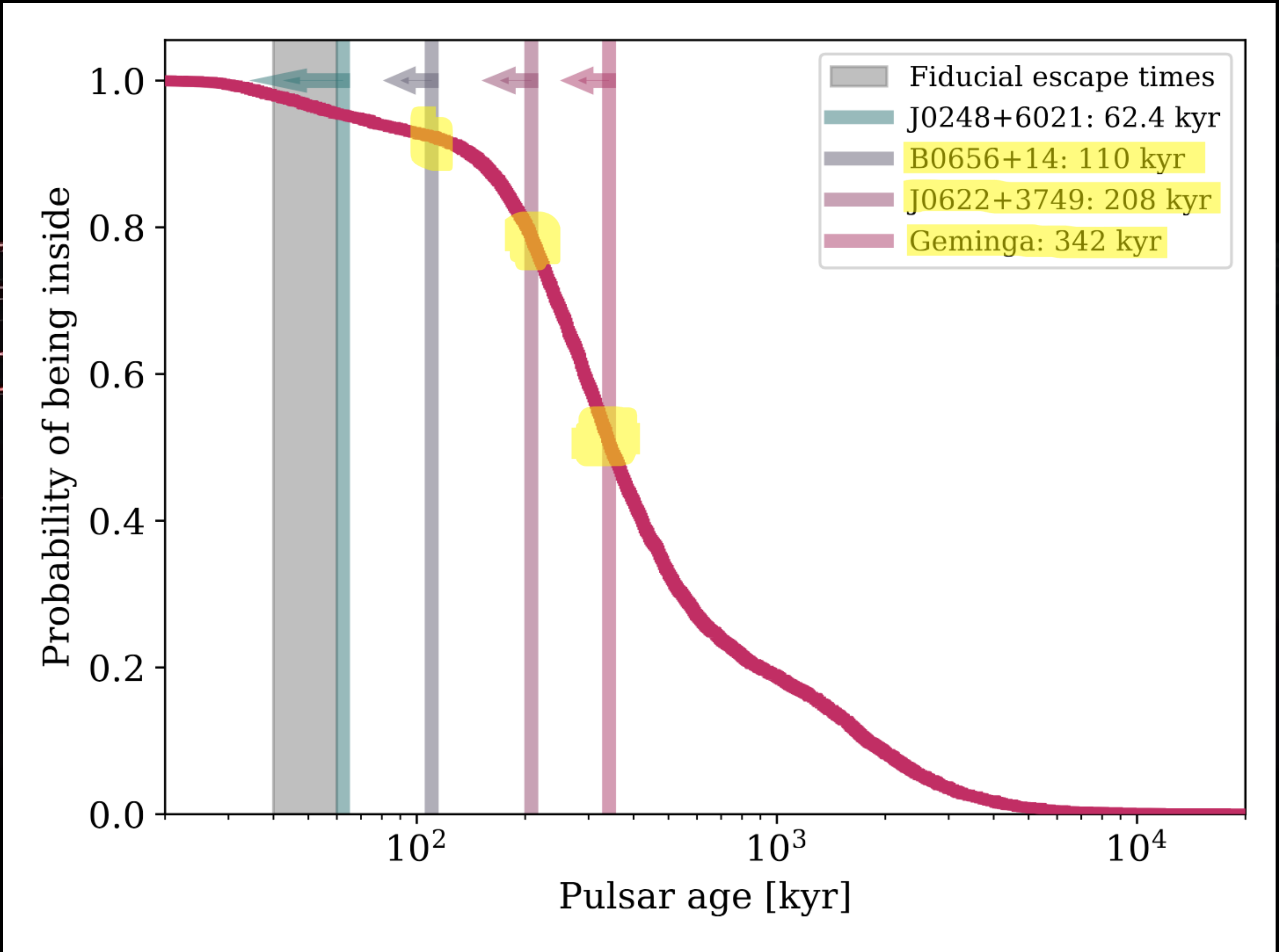
B0656+14: 110 kyr
J0622+3749: 208 kyr
Geminga: 342 kyr
Probability of being inside
1.0
0.8
0.6
0.4
0.2
0.0
10^2
10^3
10^4
Pulsar age [kyr]



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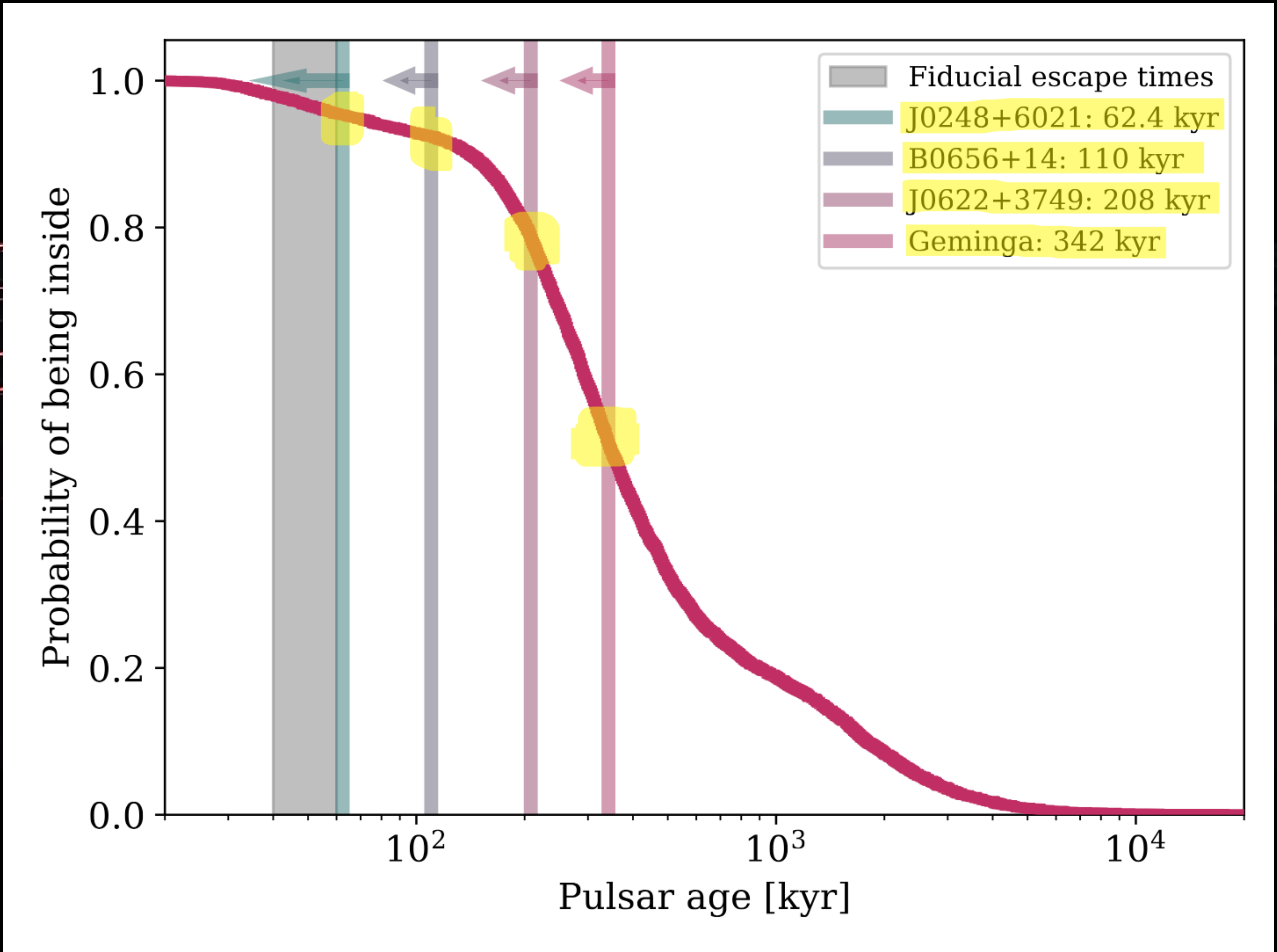

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The environment of TeV halo progenitors

Lioni-Moana Bourguinat[1,2★], Carmelo Evoli[1,2], Pierrick Martin[3], and Sarah Recchia[4]

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ABSTRACT

Context. TeV halos are extended very-high-energy gamma-ray sources found around some middle-aged pulsars. The emission spanning several tens of parsecs suggests an efficient confinement of the ultra-relativistic lepton pairs produced by pulsars in their vicinity. The physical mechanism responsible for this suppressed transport has not yet been identified. In some scenarios, pair confinement may be linked to the medium the pulsars are located in.
Aims. We aim at understanding which type of medium pulsars are probing over their lifetime.
Methods. We developed a model for the environment probed by moving pulsars, from their birth in core-collapse explosions – where they receive a natal kick – until their entry into the interstellar medium. The model involves: (i) a Monte-Carlo sampling of the properties of the massive-star progenitors of pulsars; (ii) a calculation of the structure of the surrounding medium shaped by these progenitors, for the two cases of isolated stars and star clusters; (iii) a computation of the evolution of supernova remnants in these parent environments. Ultimately, from a distribution of neutron star kick velocities, we assess in which medium pulsars are located as a function of time. We first derive the statistical properties of a fully synthetic Galactic population, and then apply the model to a selection of known pulsars to assess the likely nature of their environment.
Results. We show that pulsars escape into the ISM at around 300 kyr, significantly later than the values most commonly used in the literature. Given our assumptions, all known pulsars with a confirmed TeV halo have high probabilities of still being in their parent environment, which suggests that efficient pair confinement is connected to the region influenced by progenitor stars. In order to test this idea, we provide the probability of still residing in the parent environment for a list of known pulsars.

Key words. Astroparticle physics – pulsars: general – ISM: supernova remnants – ISM: bubbles

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