Population synthesis of compact object mergers over cosmic time

2nd “High-energy astrophysics in the multi-messenger era” Workshop, IFSC
São Carlos, 09/04/2024

Lucas M. de Sá
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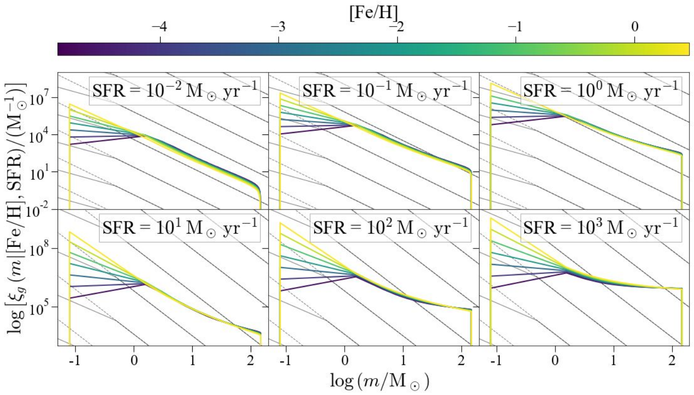
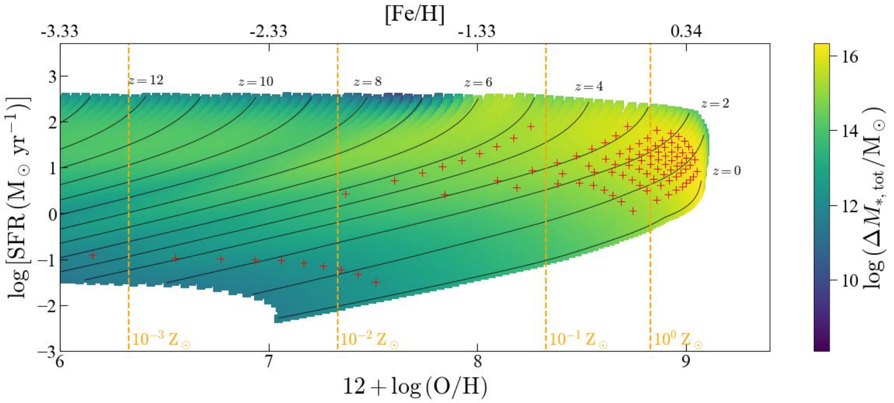
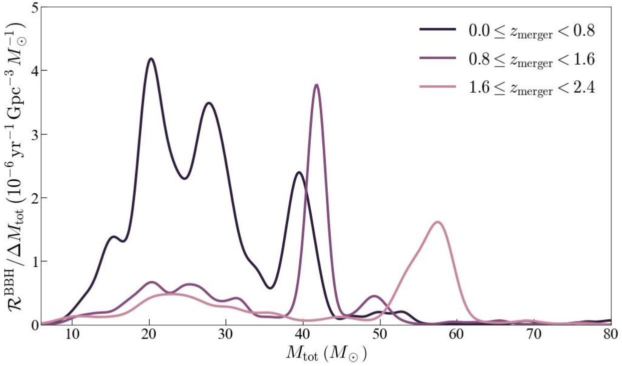
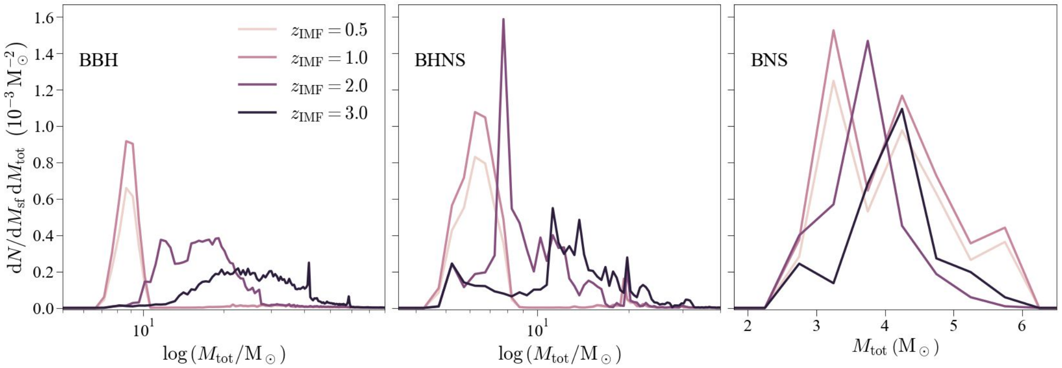
In the first workshop

Very preliminary results,

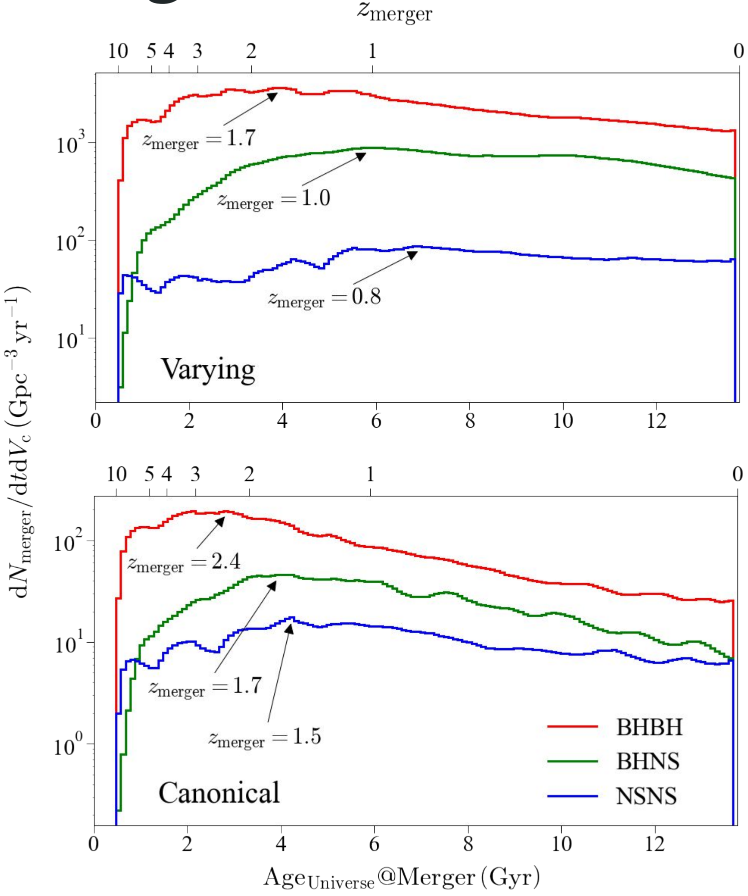


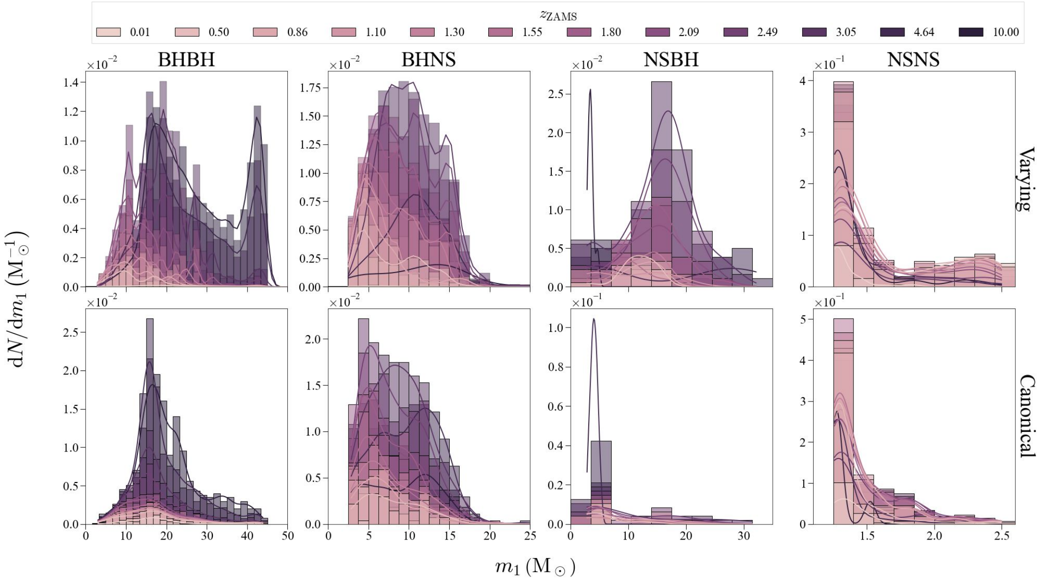






Progress since then





Two papers under review, with the main point being that initial condition uncertainties **are important**, unlike previous argument.

- Beyond absolute merger rates.

Generating a synthetic population of gamma-ray Pulsar Wind Nebulae

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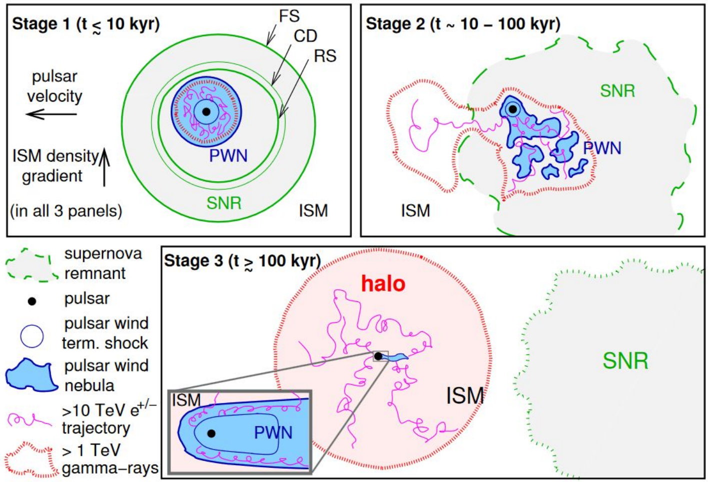
Proposal at the first workshop

"Building an environment-sensitive synthetic TeV halo catalog for HAWC and SWGO observations"



Giacinti et al. (2020)

1. Use **COMPAS**, a BPS code, to generate a synthetic population of pulsars with known properties: P, $\dot{P}$, $\dot{E}$.

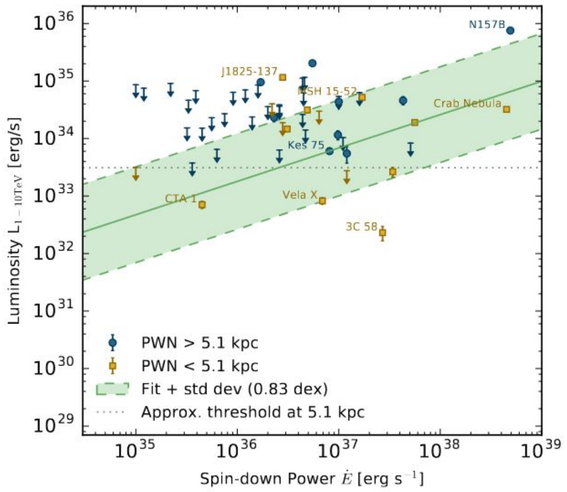
2. Model pulsar halo TeV emission with pulsar parameters as input.

3. Estimate the number of existing halos and expected detections.

Early on we focused on **PWN** TeV emission as a prelude to halo emission, following steps 1-2-3.

Pulsar wind nebula modeling

We model PWNe 1–10 TeV emission based on Abdalla et al. (2018),



Abdalla et al. (2018)

Pulsar			PWN			
t (kyr)	τ_c (kyr)	$\dot{E}$ (10^{38} erg s^{-1})	B_{PWN} (μG)	R_{PWN} (pc)	$L_{1-10\,\mathrm{TeV}}$ (10^{33} erg s^{-1})	Γ
0.10	0.60	1.39×10^{39}	148	0.142	1.27×10^{35}	2.08
0.14	0.63	1.23×10^{39}	140	0.207	1.36×10^{35}	2.11
0.19	0.69	1.05×10^{39}	131	0.316	1.41×10^{35}	2.14
0.26	0.76	8.63×10^{38}	122	0.458	1.42×10^{35}	2.17
0.36	0.85	6.78×10^{38}	113	0.665	1.37×10^{35}	2.19

The population of TeV pulsar wind nebulae in the H.E.S.S. Galactic Plane Survey

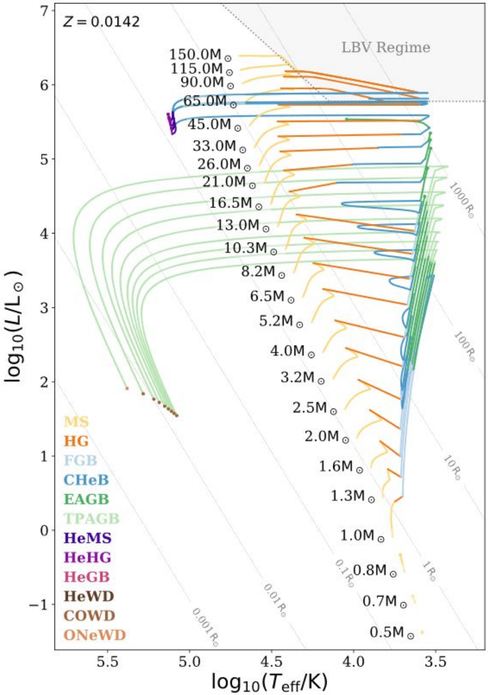
Parameter description			Parameter values *baseline* model	*varied* model	
Braking index	n		3.0	2.5 ... 3.5	Varied
Initial spin-down power	$\dot{E}_0$	(10^{39} erg s^{-1})	2.0	1.0 ... 4.0	
Initial spin-down timescale	τ_0	(kyr)	0.5	0.32 ... 0.77	
Initial magn. field strength	B_0	(μG)	200	110 ... 270	
Reverse shock interaction timescale	t_{rs}	(kyr)	4.0	4.0 ... 8.0	
PWN radius at $t = 3$ kyr	R_3	(pc)	6.0	3.0 ... 12.0	
Adopted const. ISM magn. field strength	B_{ISM}	(μG)	3.0	3.0	Fixed
Lepton conversion efficiency	η		1.0	1.0	
Index of magn. field evolution	α		0.6	0.6	
Index of lepton injection spectrum	β		2.0	1.75 ... 2.25	
Lower bound of lepton energy distribution	E_{min}	(TeV)	0.03	0.03	
Upper bound of lepton energy distribution	E_{max}	(TeV)	300	300	

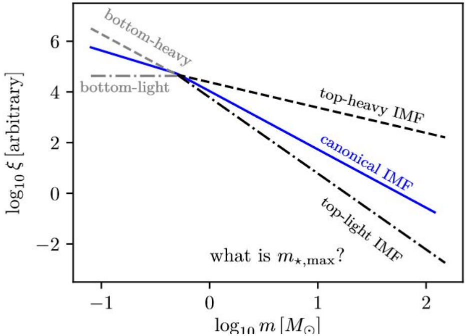
- We go from the Baseline to a Varied model by scaling R_{PWN} and recomputing $\dot{E}$, $L_{1\text{–}10\,\mathrm{TeV}}$.
- We follow the $\dot{E}$ evolution for **each individual pulsar.**

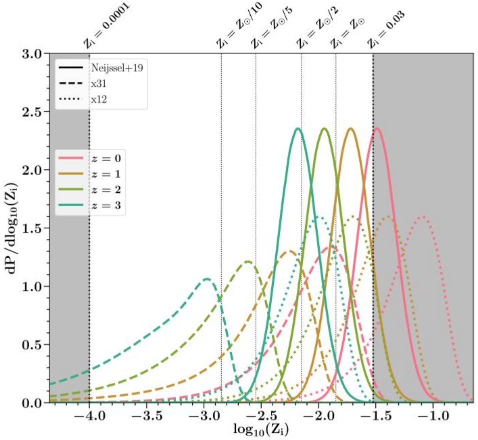
Population synthesis

We build the pulsar population with COMPAS,

Team COMPAS: Riley et al. (2022)







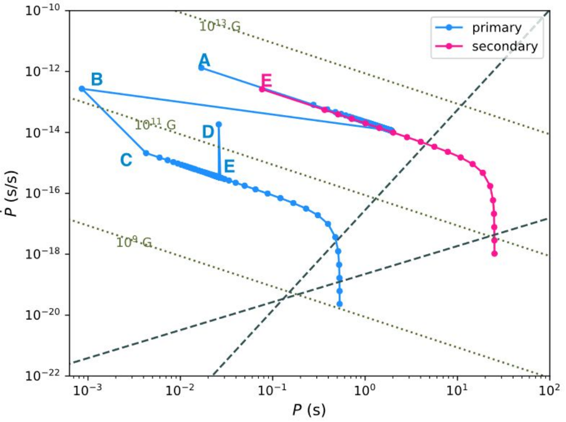
Rapid BPS, as with **COMPAS**, relies on simple stellar evolution models to evolve large populations from ZAMS in short times. Chiefly, it

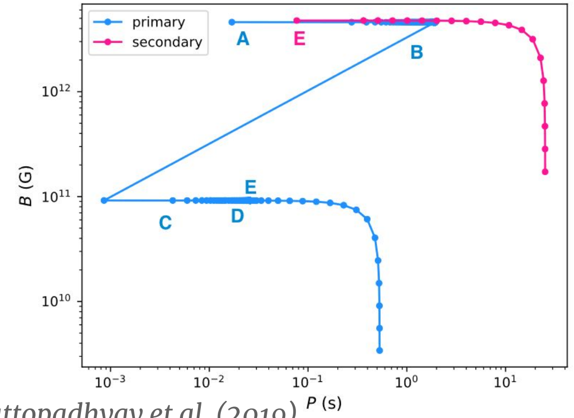
- Allows testing model assumptions (i.e., metallicity, IMF)
- Allows normalizing the population through the IMF.

Note: this is in contrast to two previous PWNe population synthesis studies
(Fiori et al MNRAS 2022 and Martin et al A&A 2022)

Team COMPAS: Riley (2022)
Kroupa & Jerabkova (2018)

Pulsar modeling





Chattopadhyay et al. (2019)

Pulsars are assumed to evolve through dipole spin-down and exponential field decay,

$$\dot{\Omega} = -\frac{8\pi B^2 R^6 \sin^2 \alpha \Omega^3}{3\mu_0 c^3 I} \qquad B = (B_0 - B_{\min}) \times \exp(-t/\tau_d) + B_{\min},$$

The pre- and post-SN parameters are **not** connected. Birth pulsar parameters are sampled from empirical distributions,

$$\mathrm{U}\,(10, 100)\ \mathrm{ms} \qquad \mathrm{LN}\,(10, 13)\ \mathrm{G}$$

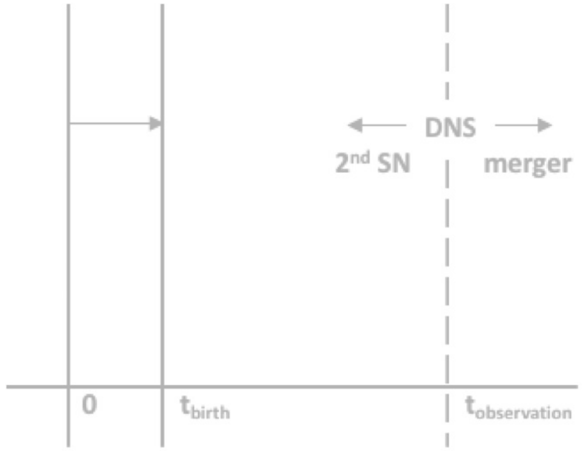
but COMPAS still ties the **pulsar fraction** to physical populations,

$$\mathcal{F}_{\mathrm{PSR}} = \frac{N_{\mathrm{PSR}}}{N_{\mathrm{prog}}}$$

- Although we cannot account for binaries at the moment, they should be important and host **most** compact object progenitors.

Results so far

Population setup



Chattopadhyay et al. (2019)

$$\mathcal{F}_{\rm m} = \frac{\int_5^{40} \frac{{\rm d}M}{{\rm M}_\odot}\xi}{\int_{0.08}^{150} \frac{{\rm d}M}{{\rm M}_\odot}\xi}$$

Progenitors are defined by their mass at ZAMS,

- Sampled in *5–40* $M_\odot$ from a Kroupa IMF.

$$\mathcal{F}_{\rm t} = \frac{\int_{13.65}^{13.7} \frac{{\rm d}t}{\rm Gyr}\,{\rm SFH}}{\int_{\rm MW} {\rm d}t\,{\rm SFH}}$$

A cheap way to increase sample size is resample $t_{\rm birth}$ multiple times.

- Only young (up to *~1,000* kyr) pulsars can have observable PWNe.
- Draw $t_{\rm birth}$ from a homogeneous SFH up to *~50,000* Myr ago (**no redshift evolution**).

$$\mathcal{F}_{\rm isolated} = \frac{N_{*,{\rm isolated}}}{N_*}$$

We also need to account for the **fraction of isolated stars.**

A meaningful result requires the sample to be properly normalized, we considered two ways,

- *A priori*, from fractions of the initial parameter space,
- *A posteriori*, by matching the gamma-ray sky from, e.g., 3HWC,

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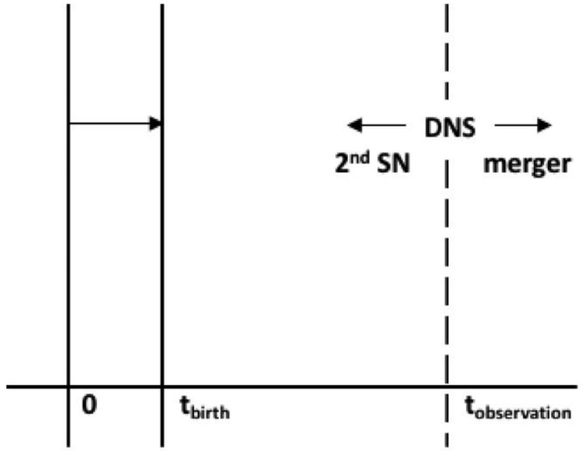

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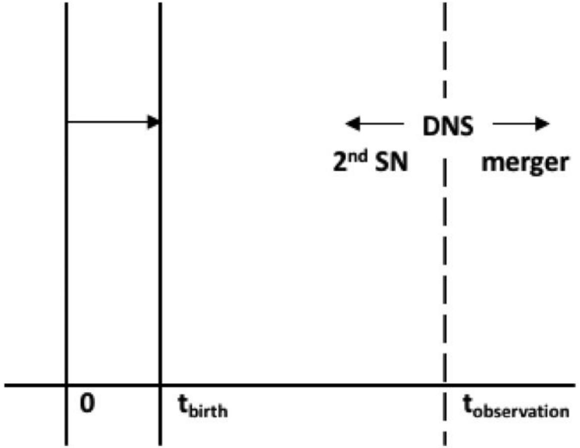

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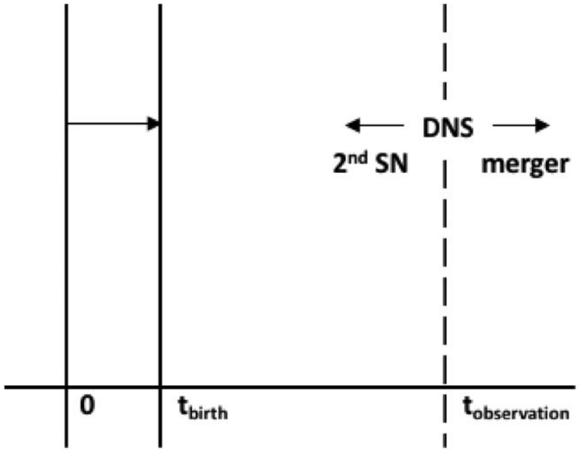

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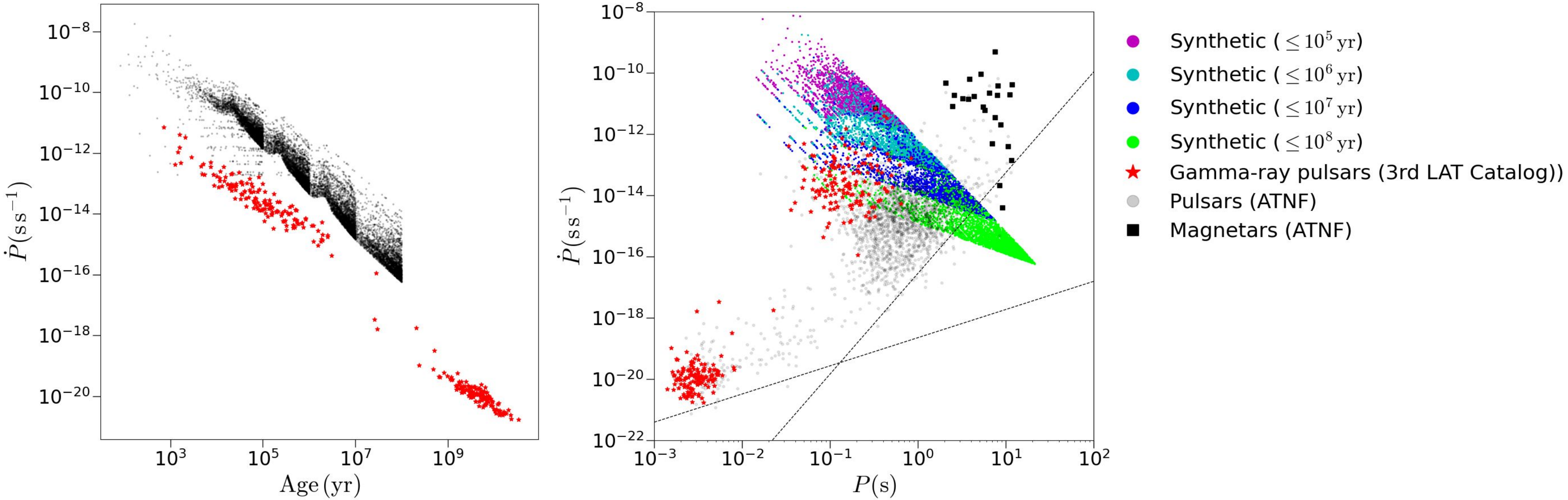
The pulsar population

From *1,000* ZAMS stars, *320* pulsars. Ages are resampled 100 times, yielding a *32,000* sample.

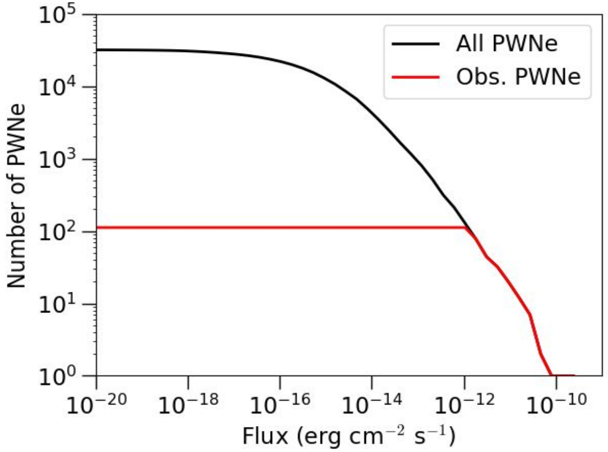


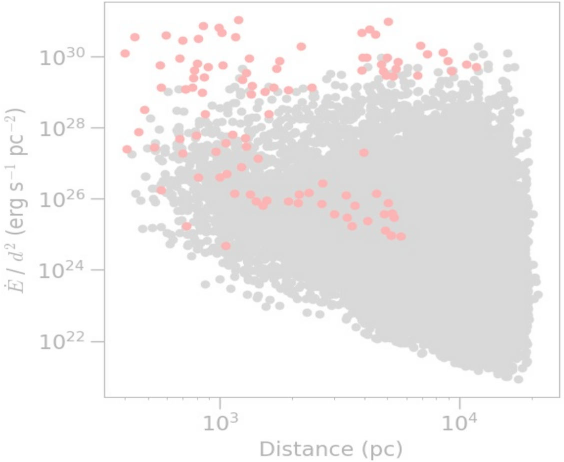
- The synthetic pulsars area shifted up in $\dot{P}$ relative to gamma-ray pulsars → investigate different B_o assumptions.

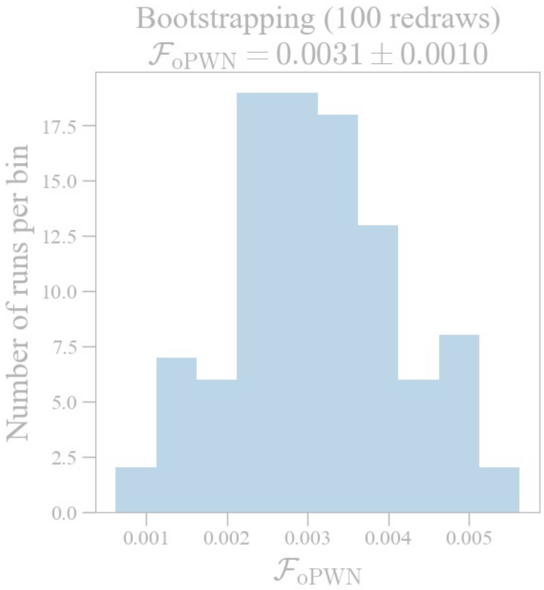
- We will also be able to consider different environments, e.g., SMC and LMC (sub-solar metallicity), and variations of the IMF.

The PWNe population

From a simple threshold at 10^{-12} erg cm^{-2} s^{-1}







- Observability is simultaneously set by distance and $\dot{E}$.
- The Varied model expands the range of observable PWNe.

There is a degree of randomness associated to every run, thus multiple runs are essential (bootstrapping). From a first set of 100 redraws,

$$\mathcal{F}_{\mathrm{oPWN}} = \frac{N_{\mathrm{PWN}}^{\mathrm{obs}}}{N_{\mathrm{PSR}}} = 0.0031 \pm 0.0010$$

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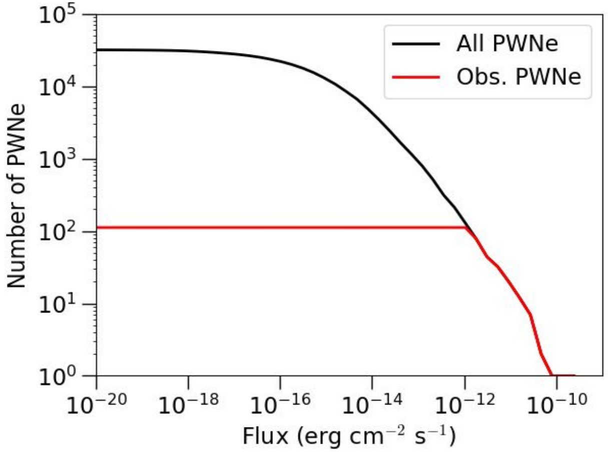

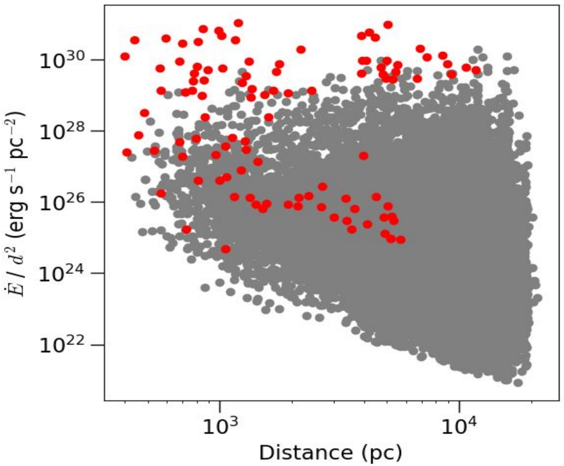

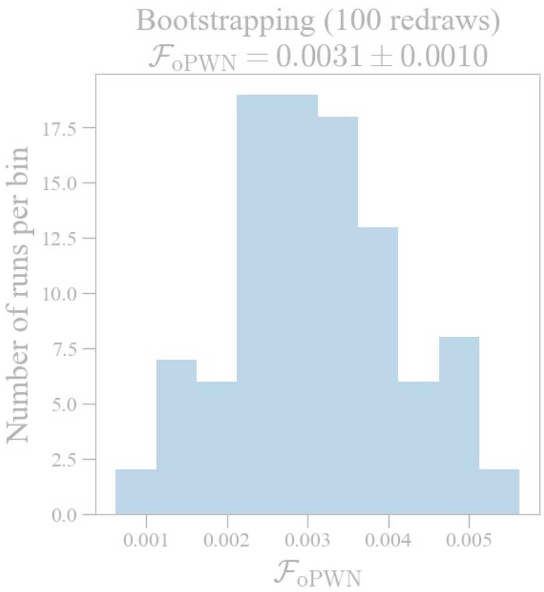

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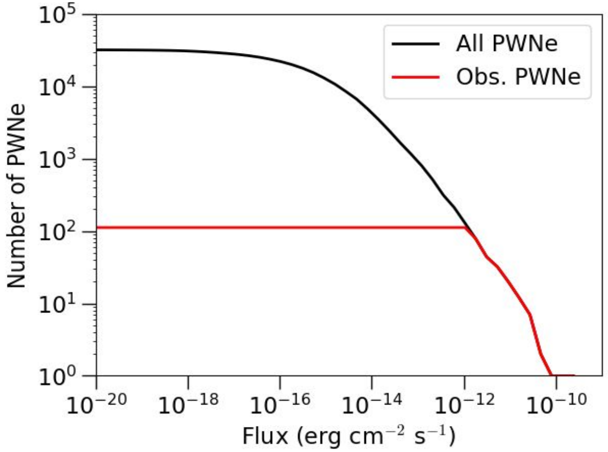
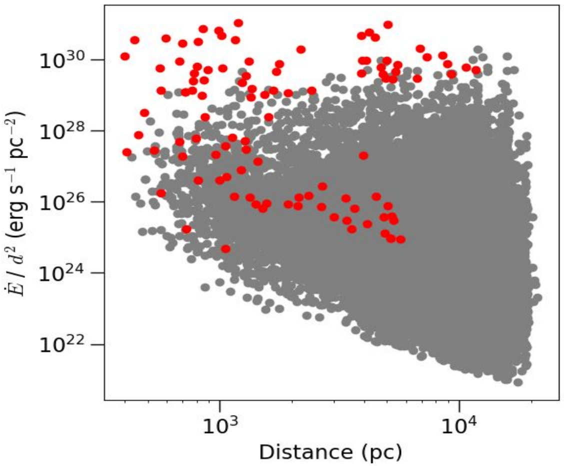
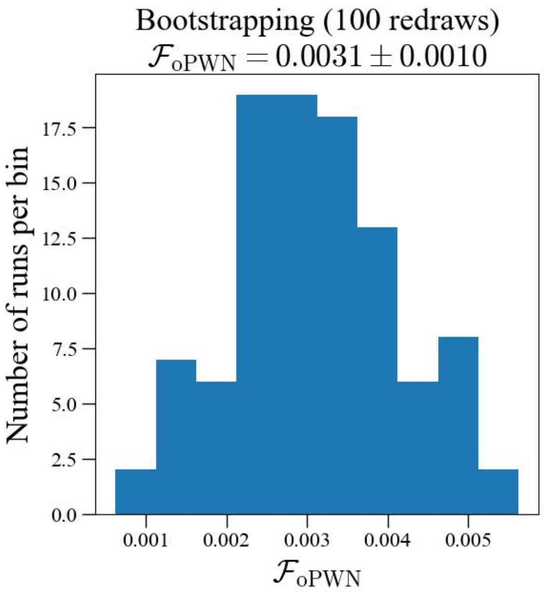
$$\mathcal{F}_{\rm oPWN} = \frac{N_{\rm PWN}^{\rm obs}}{N_{\rm PSR}} = 0.0031 \pm 0.0010$$

The PWNe population

From a simple threshold at *10*$^{-12}$ erg cm^{-2} s^{-1}







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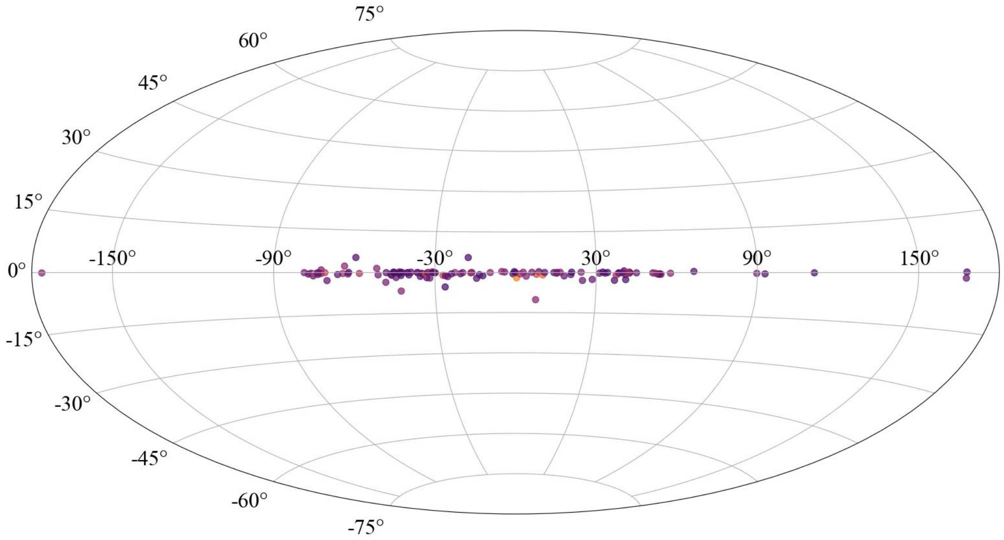
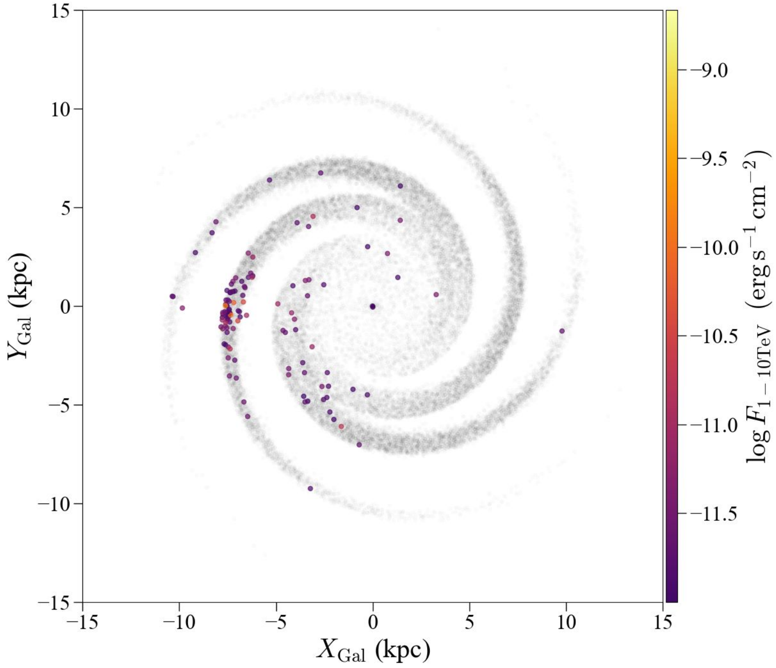
Criterion for observability



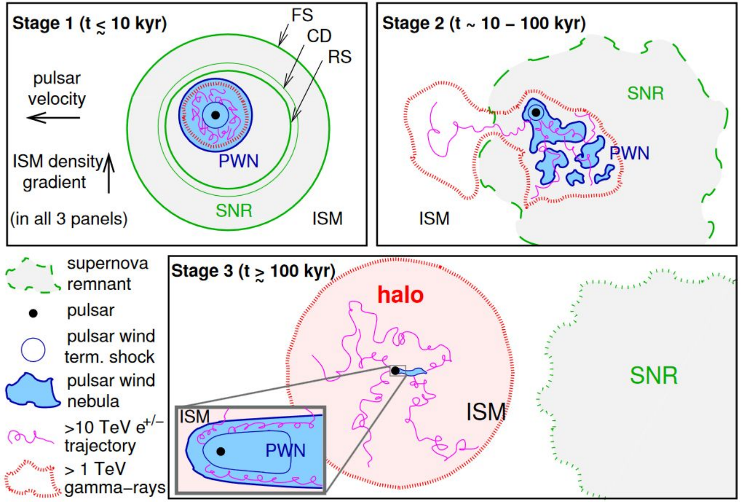


1st option: IRFs, but for SWGO not yet available, and for HAWC not publicly,
2nd option: sensitivity curve+sky area cover

➔ Most importantly, use a simple PSF to account for **source confusion**.

W.I.P.

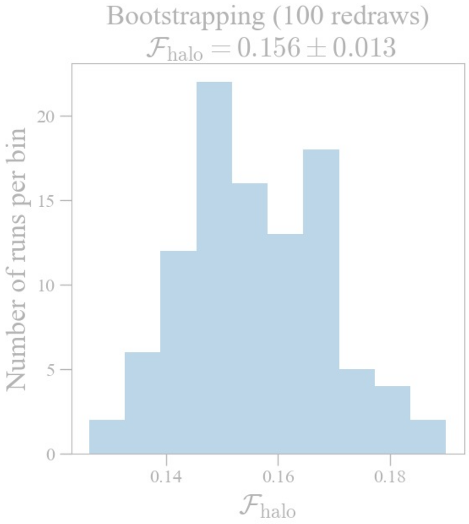
On to pulsar halos



When does a halo develop?

- Following Giacinti et al. (2020), the expanding "nebula" enters the halo phase when $\varepsilon_e < \varepsilon_{ISM} \approx 1$ eV cm^{-3}.

- Tracking the expansion of a ~spherical PWN and the energy injected by the pulsar,



$$\mathcal{F}_{halo} = \frac{N_{halo}}{N_{pulsar}} \approx 0.156 \pm 0.013$$

Full, not observable fraction (yet)

Pulsar halo modeling (W.I.P.)

- Electron energy spectrum,
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- IC spectrum.
- Stopping time

Note: different approach to Martin et al 2022

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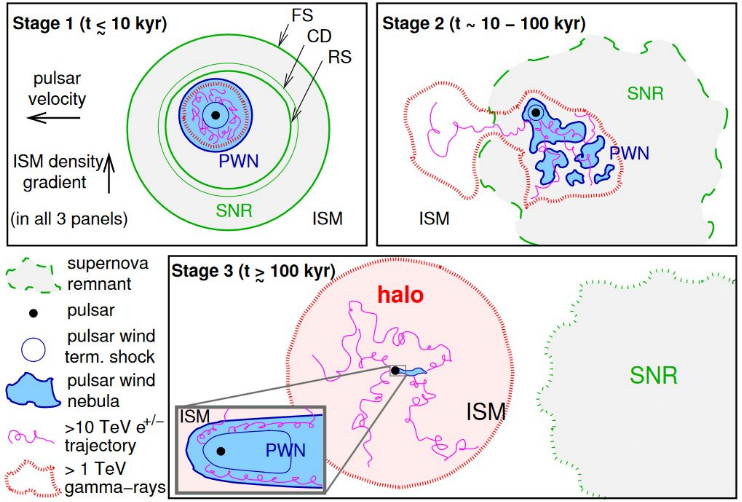

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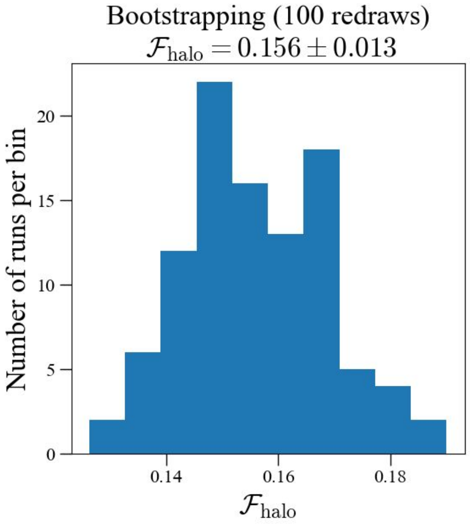

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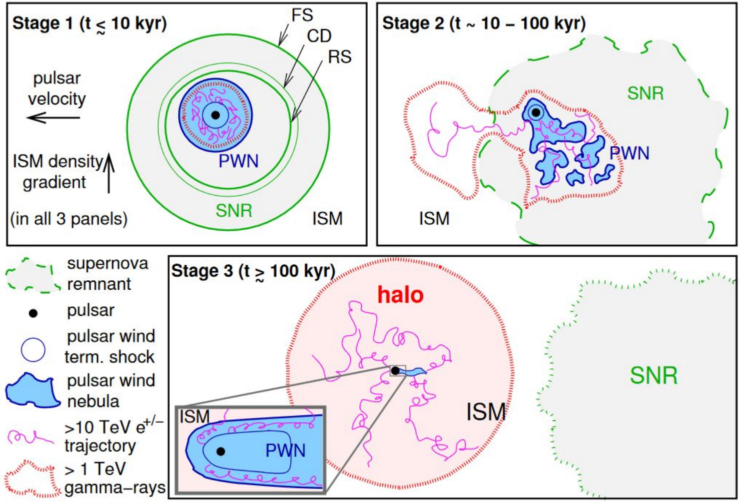

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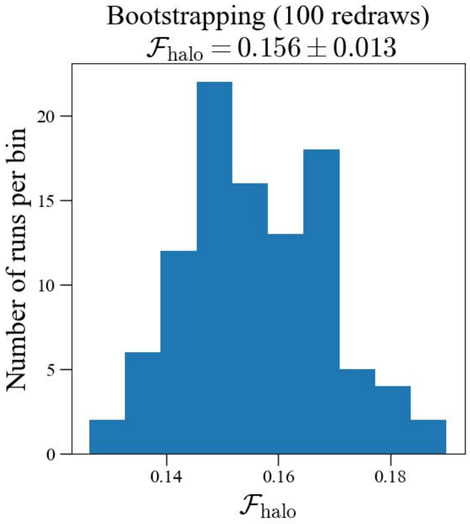

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Conclusions and further work

Using rapid population synthesis and existing models for PWNe evolution, we are able to consistently estimate the number of observable PWNe in the Galaxy,

$$N_{\mathrm{oPWN}}^{\mathrm{MW}} = \mathcal{F}_{\mathrm{oPWN}} \mathcal{F}_{\mathrm{PSR}} \mathcal{F}_t \mathcal{F}_m \mathcal{F}_{\mathrm{isolated}} N_*^{\mathrm{MW}} = 947 \pm 305$$

but we are still missing the *a posteriori* normalization.

Major refinements left are:

1. Generate the gamma-ray sky and convolve it with a PSF, account for source confusion,
2. Evolve halos and estimate observability.

And some further questions...

1. Can we choose more appropriate initial pulsar parameter distributions?
2. What is the effect of metallicity? How many (observable) PWNe should be in, e.g., SMC?
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but we are still missing the *a posteriori* normalization.

Major refinements left are:

1. Generate the gamma-ray sky and convolve it with a PSF, account for source confusion,
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And some further questions...

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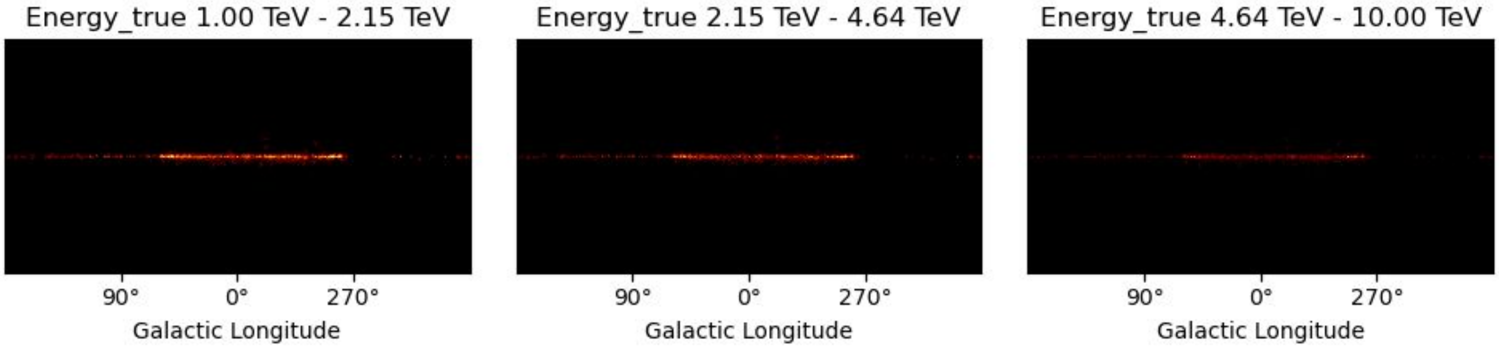

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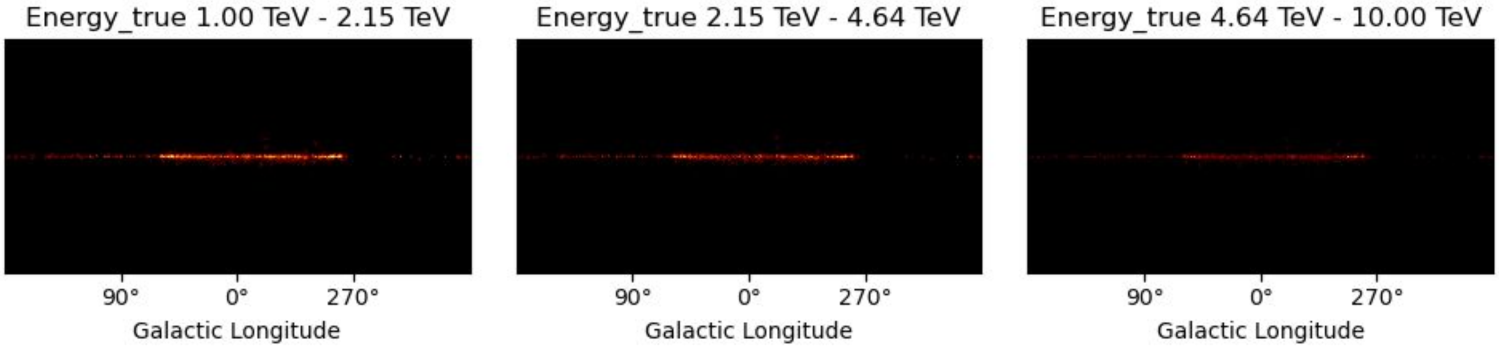
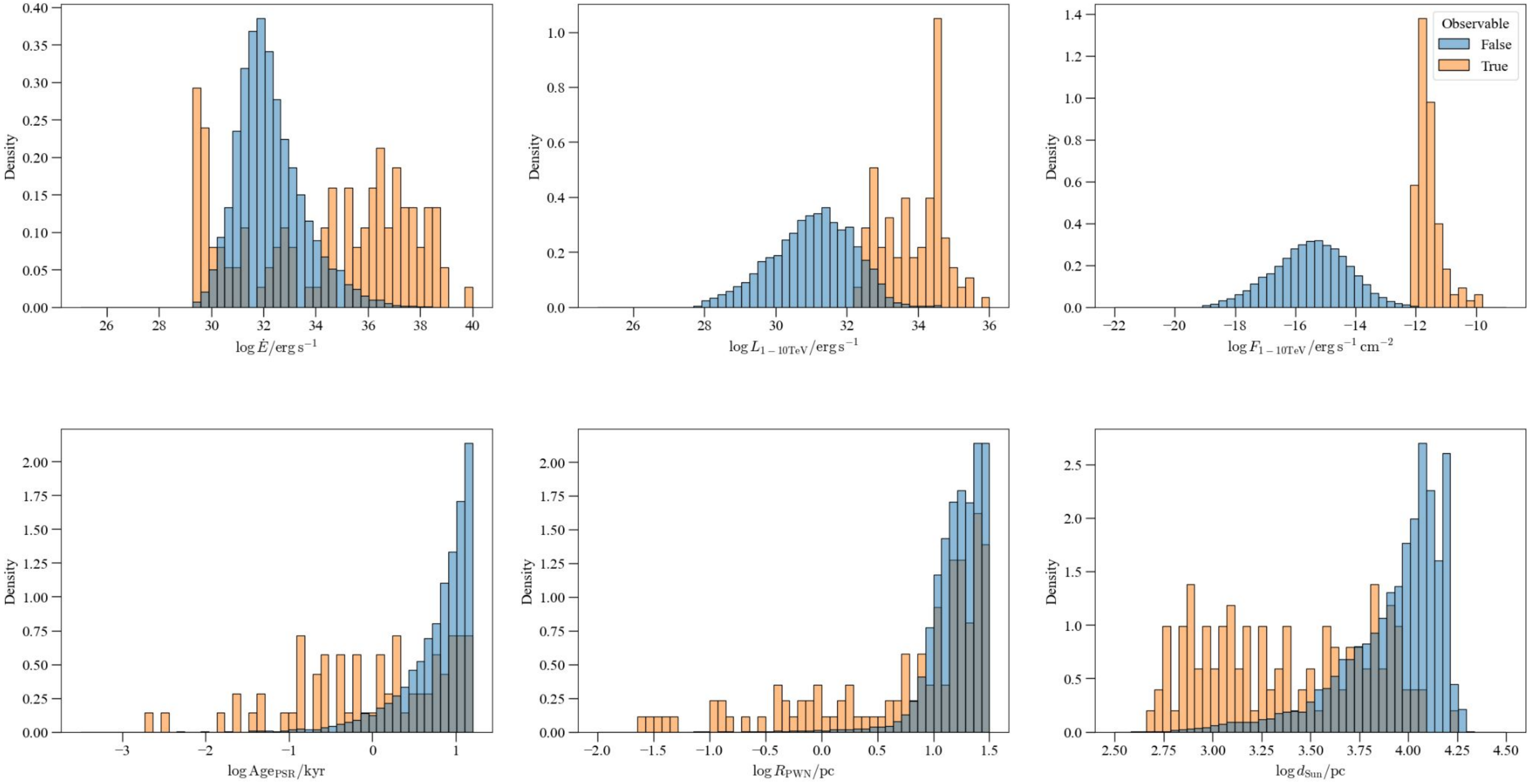


Obrigado!

Appendix

Histograms


Density
log $\dot{E}$/erg s^{-1}
log $L_{1-10\,\mathrm{TeV}}$/erg s^{-1}
log $F_{1-10\,\mathrm{TeV}}$/erg s^{-1} cm^{-2}
Observable
False
True
log Age$_{\mathrm{PSR}}$/kyr
log R_{PWN}/pc
log d_{Sun}/pc