ROYAL HOLLOWAY UNIVERSITY OF LONDON

SKAO

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Isolated Pulsar Evolution in the Period-Period Derivative Plane and Early SKA Insights

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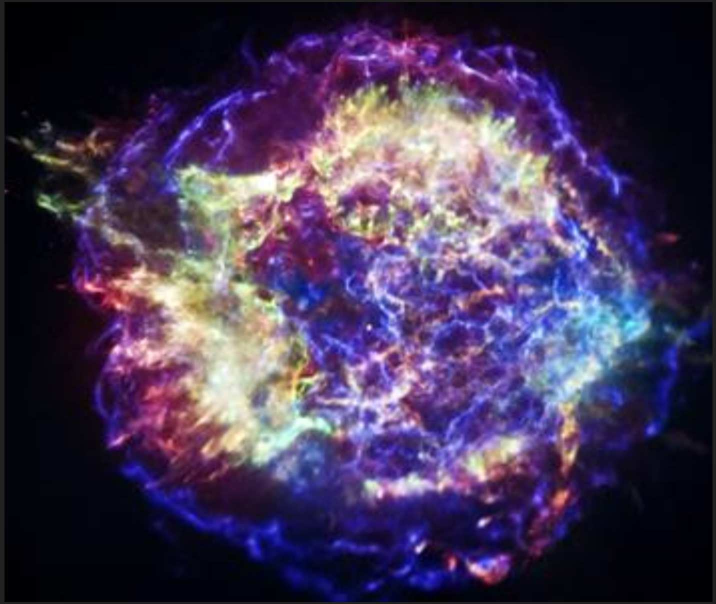
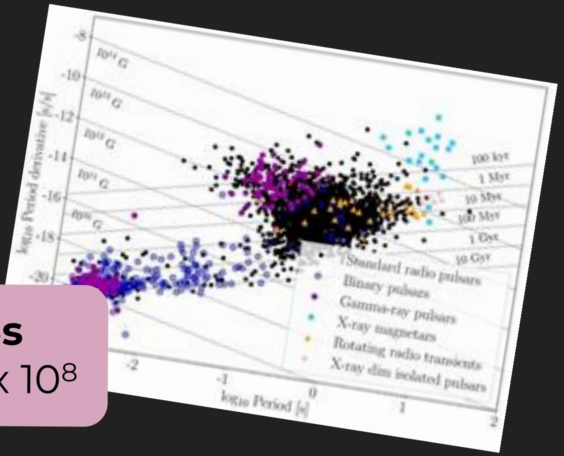
in collaboration with Michele Ronchi, Celsa Pardo Araujo, Nanda Rea and many more



Cassiopeia A supernova remnant (credit: NASA/CXC/SAO)

Population synthesis



- We estimate the **number of Galactic neutron stars**

CC supernova rate ~ 2 per century	x	**Galaxy age** ~ 13.6 billion years	=	**NSs** ~ 2.8×10^8

- We only **detect** a very **small fraction** of all neutron stars. Population synthesis can bridge this gap by focusing on the full population (e.g. Faucher-Giguère & Kaspi 2006, Lorimer et al. 2006, Gullón et al. 2014, Cieślar et al. 2020):

model **birth properties** with Monte-Carlo approach → **evolve properties** forward in time → **apply filters** to mimic observational biases/limits → **compare** mock simulations **to observations** to constrain input

Dynamical evolution

- **Neutron stars are born in star-forming regions**, i.e., in the Galactic disk along the Milky Way's spiral arms and **receive kicks** during the supernova explosions.

- We make the following assumptions:
    - Electron-density model (Yao et al., 2017) + rigid rotation with T = 250 Myr.
    - Exponential disk with scale height h_c = 0.18 kpc (Wainscoat et al., 1992).
    - Single-component Maxwell kick-velocity distribution with dispersion σ_k = 265 km/s (Hobbs et al., 2005).
    - Galactic potential (Marchetti et al., 2019).

Artistic illustration of the Milky Way (credit: NASA JPL)

$$\mathcal{P}(z) = \frac{1}{h_c} e^{-\frac{|z|}{h_c}}$$

$$\mathcal{P}(v_\mathrm{k}) = \sqrt{\frac{2}{\pi}} \frac{v_\mathrm{k}^2}{\sigma_\mathrm{k}^3} e^{-\frac{v_\mathrm{k}^2}{2\sigma_\mathrm{k}^2}}$$

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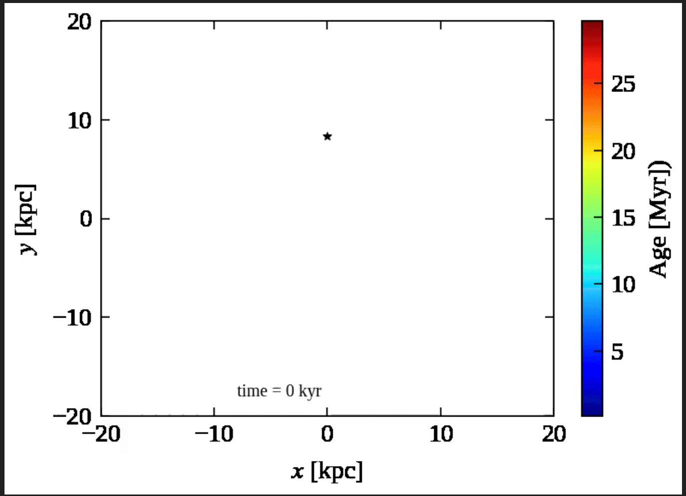


Top view of neutron-star evolution tracks in the Galaxy.

Solve Newtonian equations of motion to determine positions and velocities.

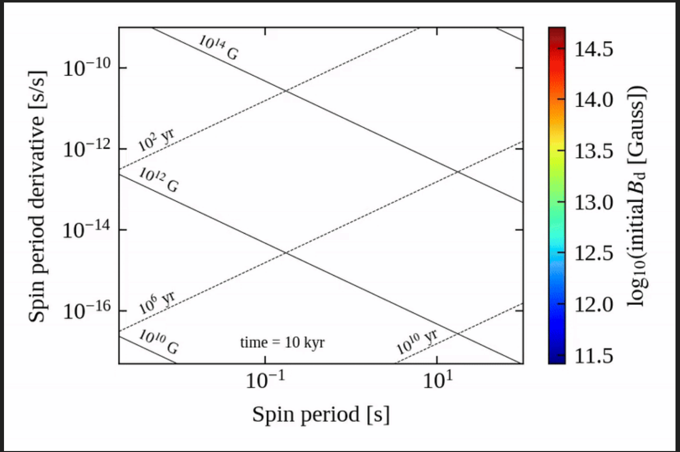
$$\ddot{\vec{r}} = -\vec{\nabla}\Phi_{\mathrm{MW}}$$

Magneto-rotational evolution

- We make the following assumptions:
  - Initial periods follow a log-normal with μ_P and σ_P (Igoshev et al., 2022)
  - Initial fields follow a log-normal with μ_B and σ_B (Gullón et al., 2014)
  - Above $\tau \sim 10^6$ yr, field decay follows a power-law with $B(t) \sim B_0\,(1 + t/\tau)^a$.

- To model B-field evolution $<10^6$ yr, we use 2D magneto-thermal simulations (Viganò et al. 2021) and then numerically **solve two coupled ordinary differential equations** for the period and the misalignment angle (Aguilera et al., 2008; Philippov et al. 2014).

$$\mathcal{P}(\log P_0) = \frac{1}{\sqrt{2\pi}\sigma_P} \exp\left(- \frac{[\log P_0 - \mu_P]^2}{2\sigma_P^2} \right)$$



In the following, we **vary** $\boldsymbol{\mu_P}$, $\boldsymbol{\mu_B}$, $\boldsymbol{\sigma_P}$, $\boldsymbol{\sigma_B}$ and **a**.

Matching to existing surveys

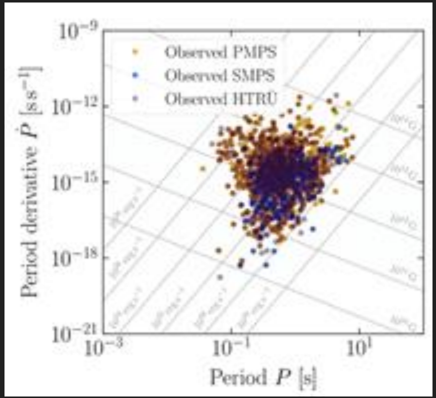
We also **vary** $\boldsymbol{\mu_L}$ and $\boldsymbol{\alpha}$.

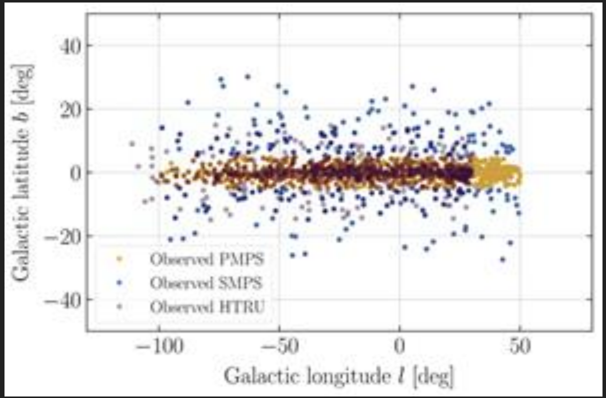
- We model **pulsar emission** and **full beam geometry** with a luminosity law that introduces two more free parameters: the exponent, α, and the mean, μ_L, of the log-normally distributed normalisation factor L_0.

$$L_{\rm int} = L_0 \left(\frac{\dot{E}_{\rm rot}}{\dot{E}_{0,\rm rot}} \right)^{\alpha} ,$$

- We use the radiometer equation to determine if a pulsar is detected and **compare our mock populations with 3 Murriyang surveys** (PMPS, 1045; SMPS, 218; HTRU, 1095).

- Besides P and $\dot{P}$ information, we also use consistent radio flux measurements taken with the MeerKAT telescope (Posselt et al. 2023).





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Can we constrain birth properties by looking at a current snapshot of the pulsar population?

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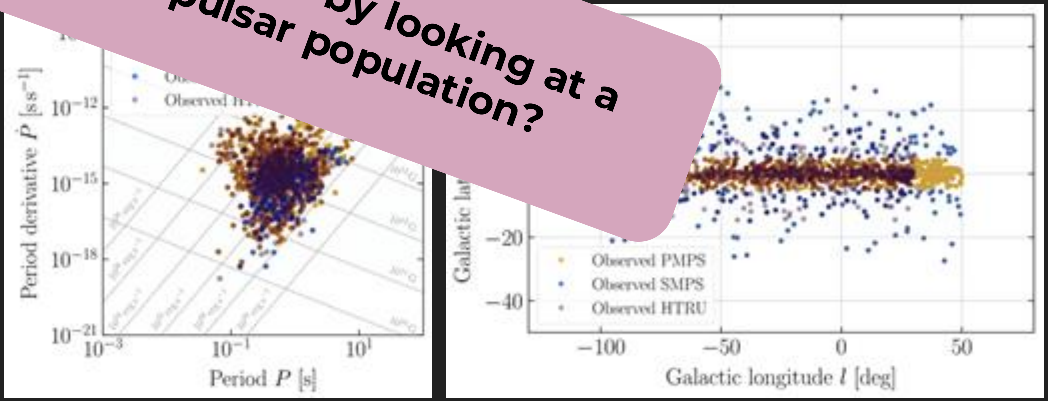
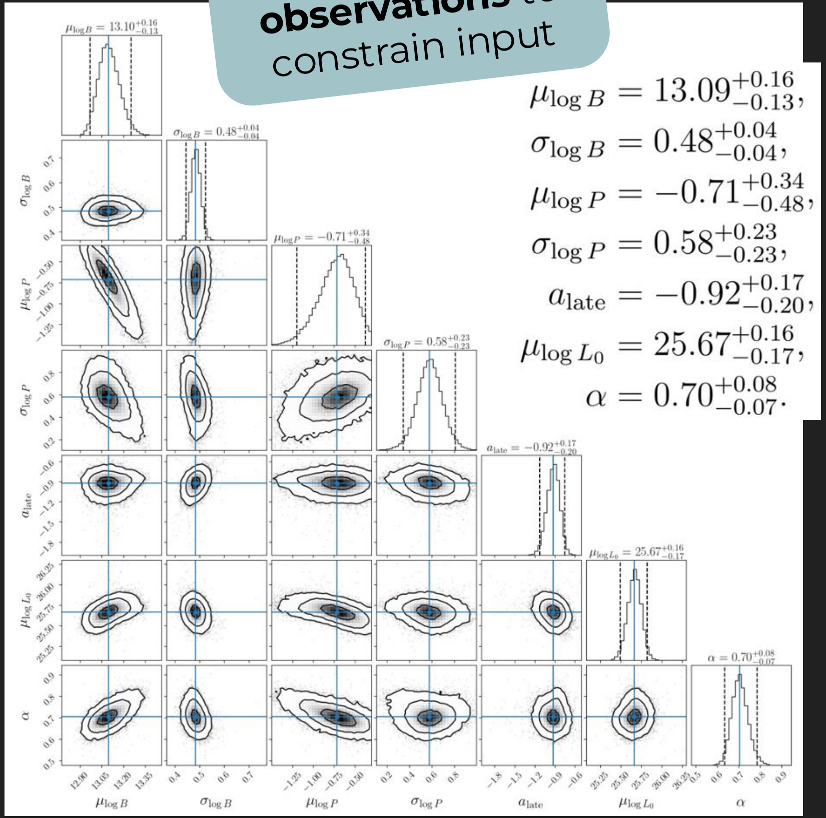


Inference results

compare mock simulations **to observations** to constrain input

- Due to complexity of our simulation framework, we cannot use standard Bayesian inference tools. Instead, we develop a **simulation-based inference** pipeline (Cranmer et al. 2020) and use neural networks to **learn probabilistic associations** between the simulated data and the underlying parameters (Graber et al. 2024, Pardo-Araujo et al. 2025).

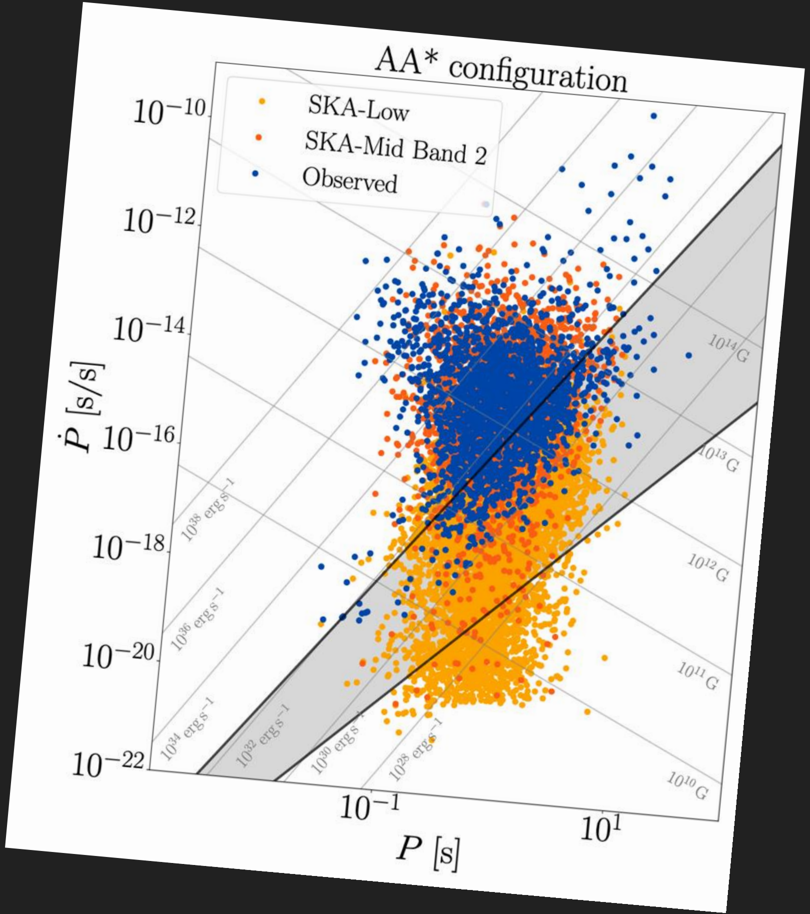
- These results are based on a normally distributed spectral index with μ = -1.45, σ = 0.15 (Keane et al. 2025) and calibrated against the 3 Murriyang surveys.



$P\dot{P}$-plane with SKA AA*

- Based on calibrated model parameters, we evolve a population of 4 x 10^7 neutron stars for 2 x 10^9 yrs, which matches our inferred birth rate of ~2 stars per century.

- We then examine this population using SKA survey specifications for the AA* configuration (Keane et al. 2025) to predict pulsar periods and period derivatives.

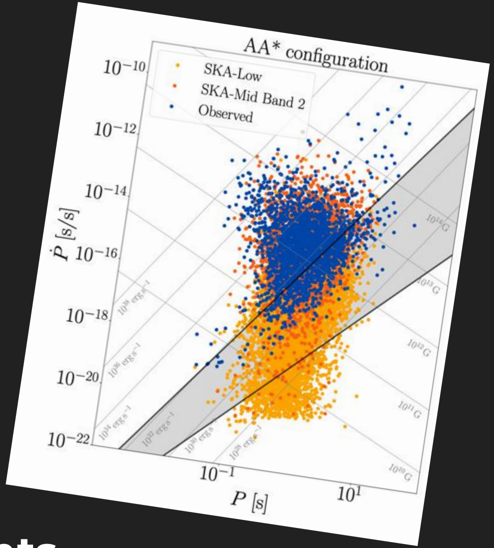


Survey Option 3

Band	Latitude Range
Low	$\lvert b\rvert > 5$ deg
Mid Band 1	N/A
Mid Band 2	$\lvert b\rvert < 5$ deg

Band	full count	above DL
AA*		
Low	8050(30)	7110(20)
Mid Band 1	-	-
Mid Band 2	2570(10)	2540(10)
TOTAL	10620	9650

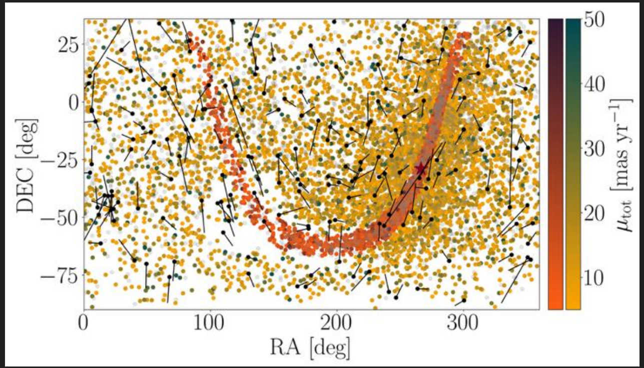
What can we learn from this?



- SKA's increased sensitivity and Low's all-Sky survey capabilities will enable the **detection of many old neutron stars** (at high latitudes) with low $\dot{P}$ and $\dot{E}_{\rm rot}$.

- SKA will enable us to probe the highly uncertain physics of the **pulsar death line**, i.e., probe the region, where pulsar radio emission is thought to switch off. This is crucial to understand **long-period radio transients**.

- Evolutionary populations synthesis is complementary to snapshot approaches (e.g., Bates et al. 2014, Keane et al. 2018, Keane et al. 2025) in that they provide *complete* information on the pulsar population, e.g., period derivatives and proper motions.

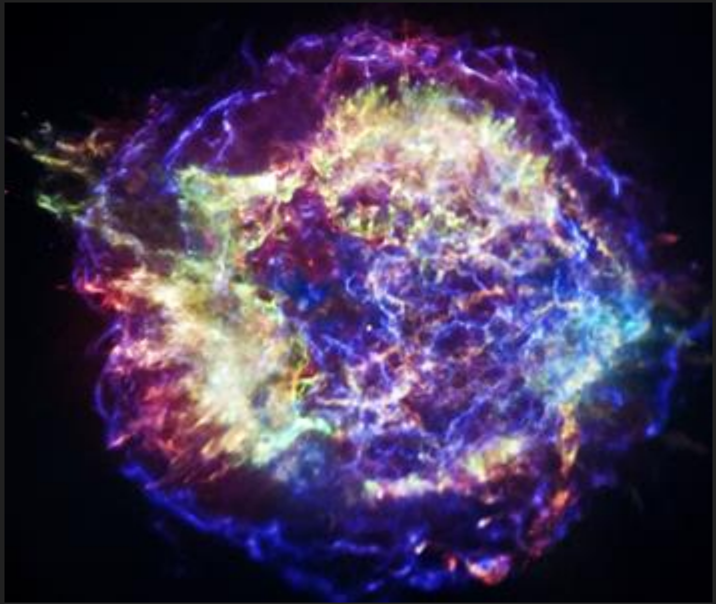


THANK YOU

For more details see

Graber et al. (2024)

Pardo et al. (2025)



Cassiopeia A supernova remnant
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