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Australian Government
Australian Research Council

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Modelling Pulsars in Globular Clusters with NBODY6++GPU

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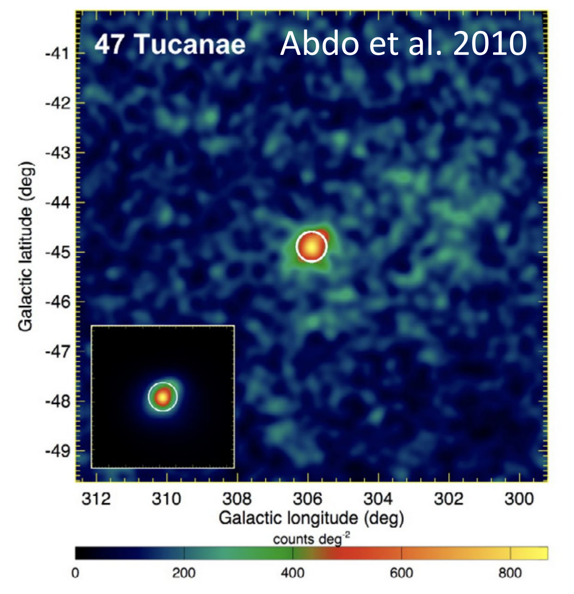
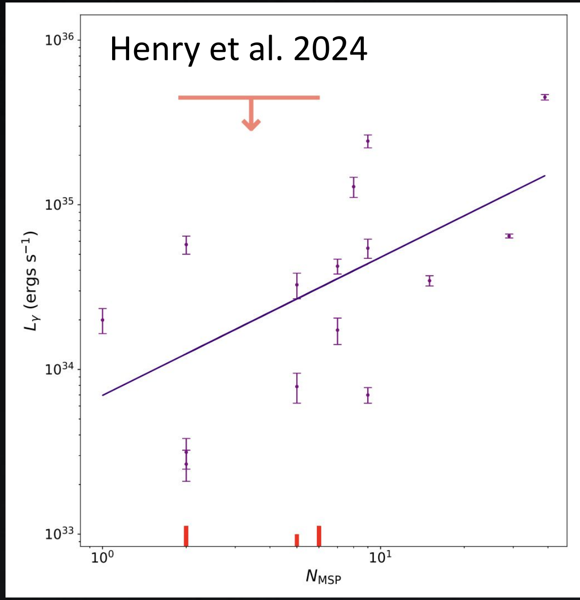
OzSTAR Supercomputing

Swinburne University of Technology · Australian National University · Monash University · The University of Adelaide · The University of Melbourne · The University of Western Australia · CSIRO

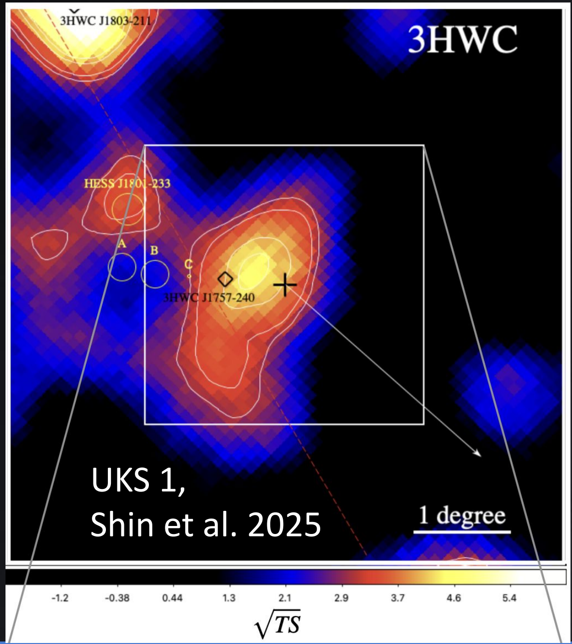
Motivation

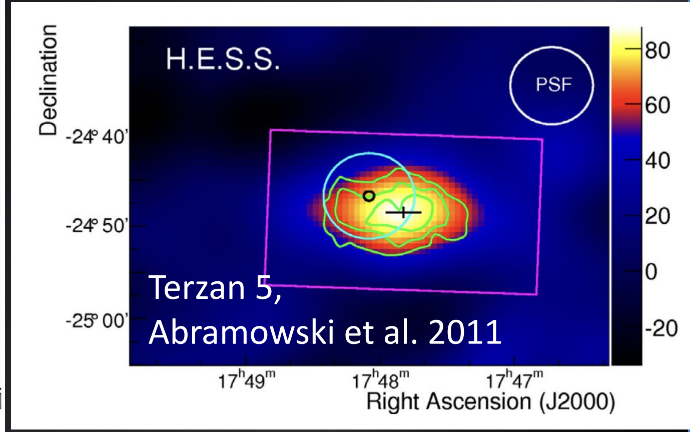
GeV gamma-rays:





TeV gamma-rays:





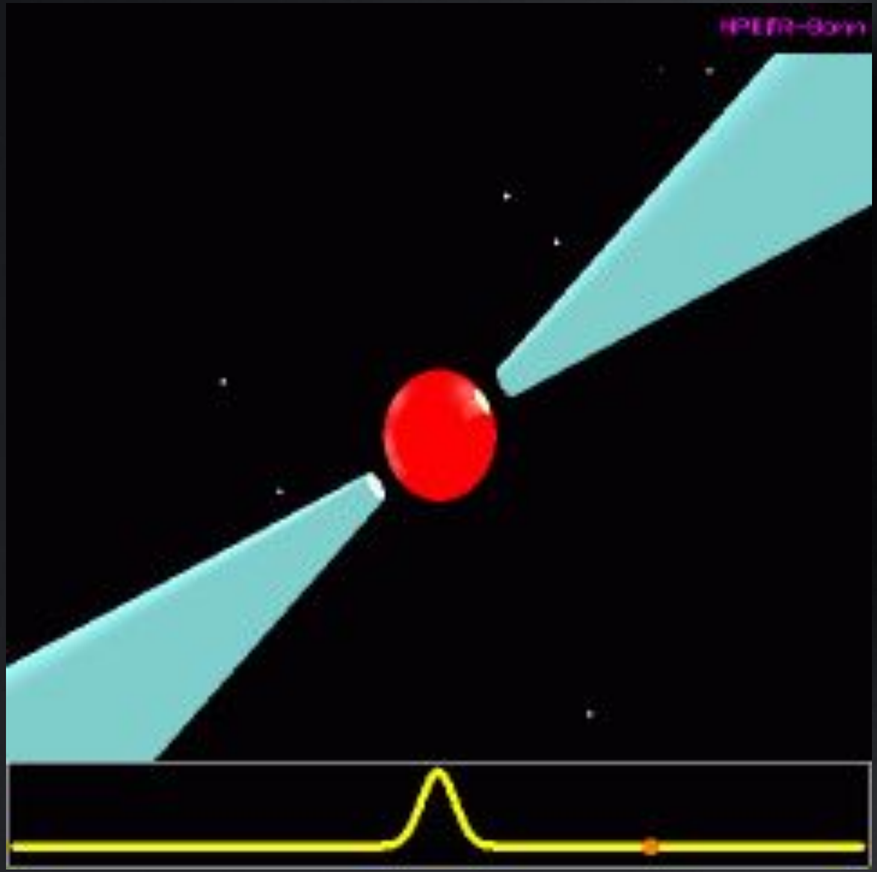
Gravitational Waves:

GW190425:
DNS dynamically
formed in a GC?

Fast radio bursts
in GCs;
Ultra-long period
transients.

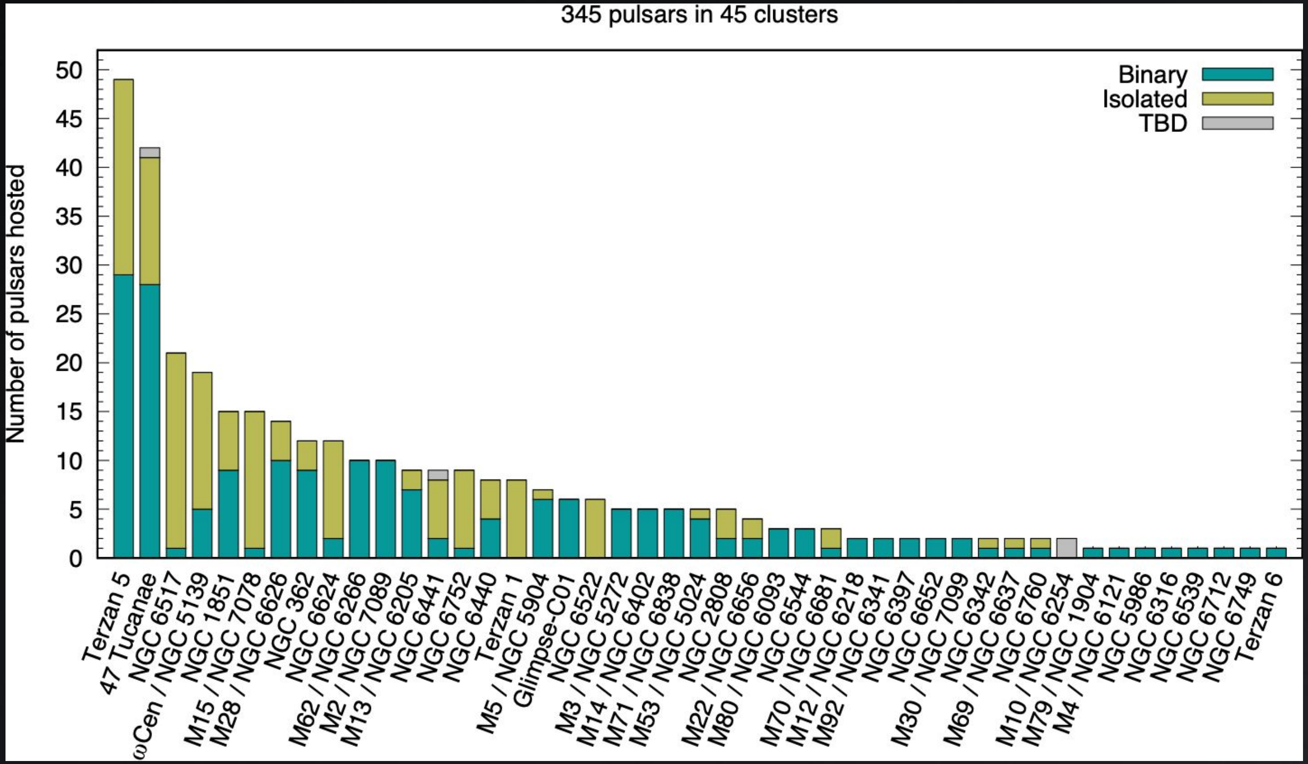
Pulsars

- Highly magnetized, fast rotating neutron stars
- First detected in radio 1967 (Hewish & Bell+ 1968)
- First gamma-ray pulsar detected in 1974 (Kniffen+ 1974)
- Pulsar EM emission is powered by its spindown
- Emission mechanism is still an area of research

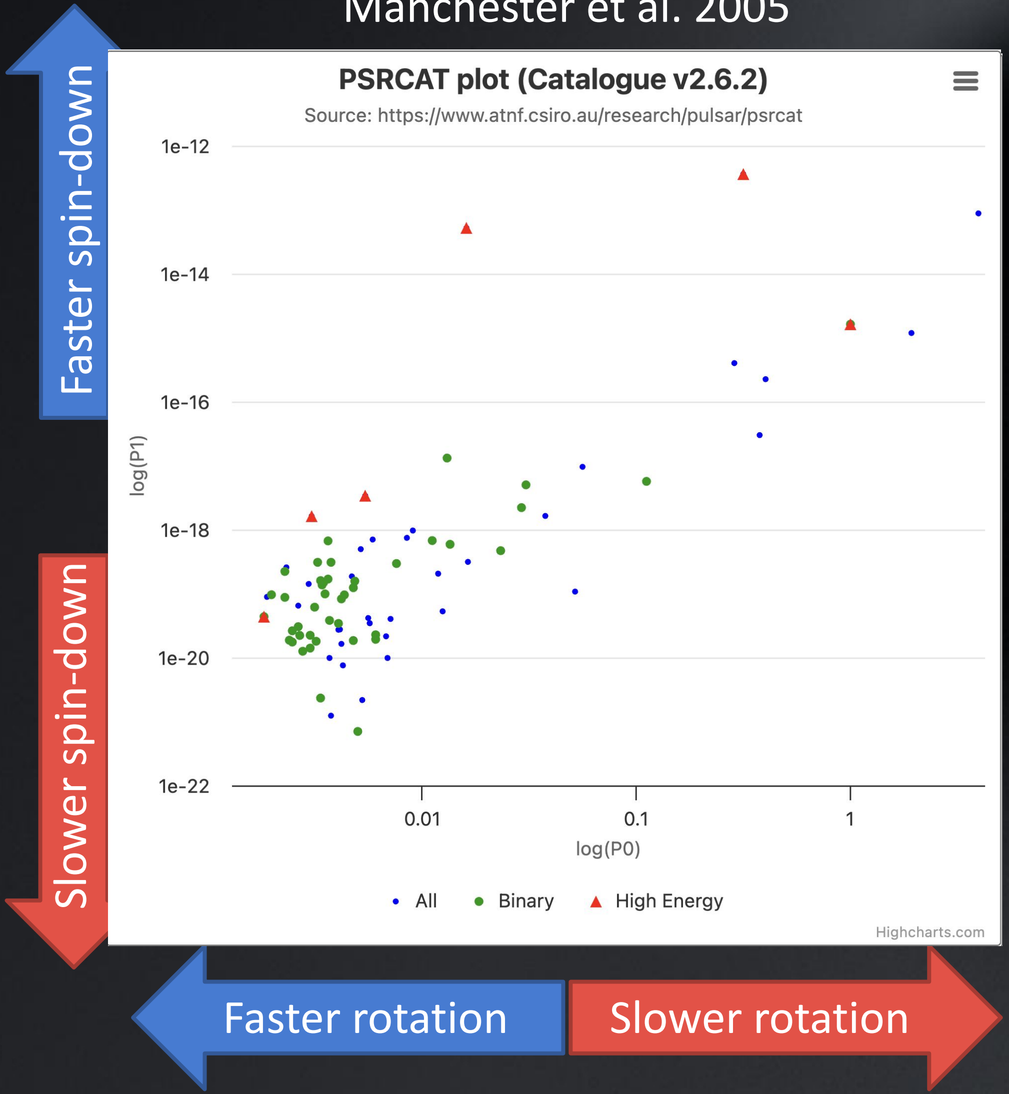


Pulsars

- 3500+ detected so far (Manchester+ 2005)
- 300 in gamma-rays (Smith+ 2023)
- 345 pulsars in 45 globular clusters (Freire catalog)



Manchester et al. 2005



Isolated NS Evolution

- Magnetic field decays exponentially:

$$B_f = (B_i - B_{\min}) \exp(-t/\tau) + B_{\min}$$

- Pulsar spins down:

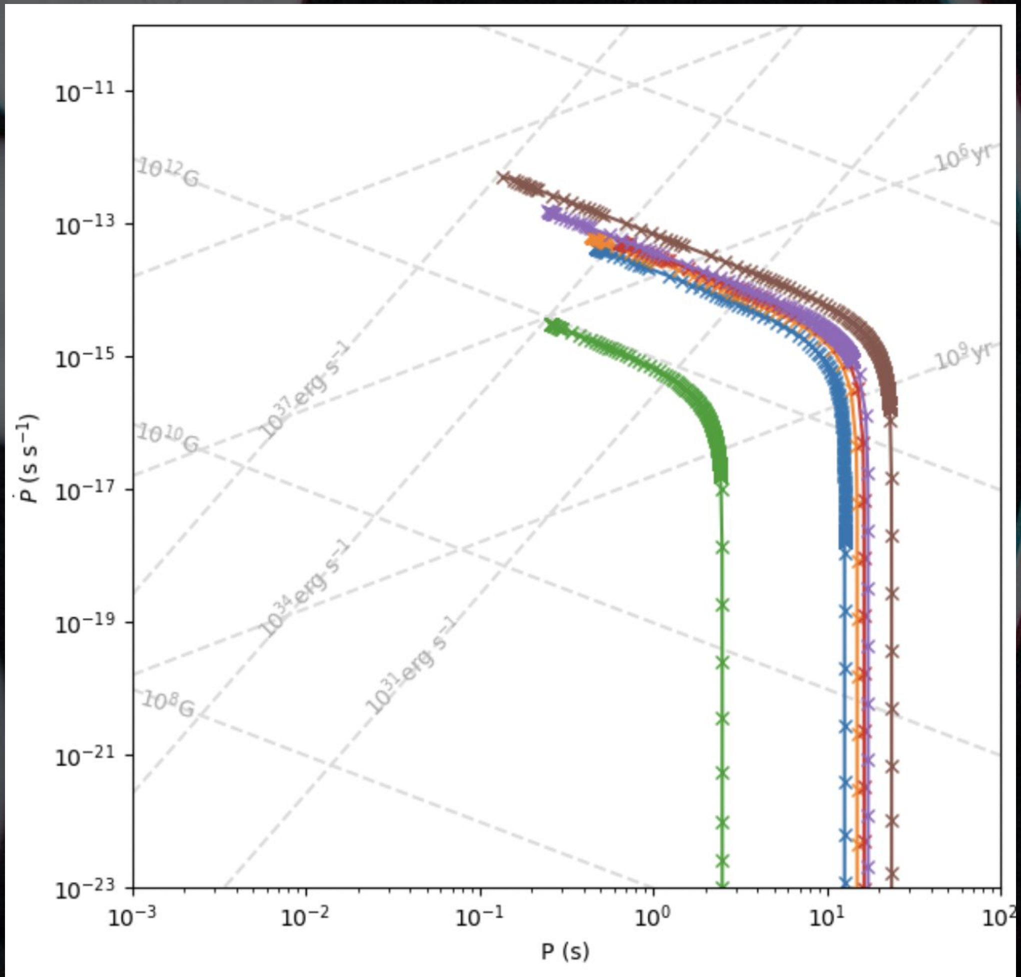
$$P^2 = \frac{16\pi^2 R^6 \sin^2\alpha}{3c^3 I}\left[B_{\min}^2 t - \tau B_{\min}(B_f - B_i) - \frac{\tau}{2}(B_f^2 - B_i^2)\right] + P_0^2$$

- At the rate of

$$\dot{P} = \frac{8\pi^2 R^6 B^2 \sin^2\alpha}{3c^3 I P}$$

Chattopadhyay et al. 2020:
arxiv:1912.02415

Also Song et al. in review:
arXiv:2406.11428

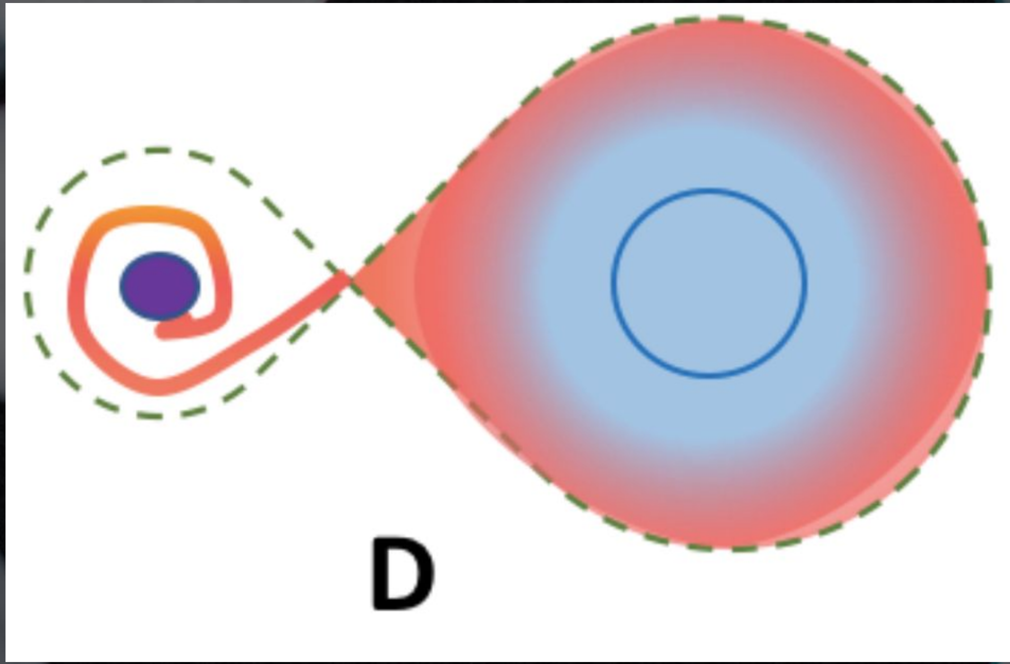


NS Binary Evolution – Roche Lobe Overflow

Chattopadhyay et al. 2020

- When companion star overfills its Roche lobe, mass transfer begins.
- Accretion disk forms around NS.
- Mass transfer through RLOF is Eddington limited

$$\dot{M}_{\mathrm{E}} = \frac{4\pi c m_{\mathrm{p}} R}{\sigma_{\mathrm{T}}} \approx 1.4 \times 10^{-8}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$$



NS Binary Evolution – Roche Lobe Overflow

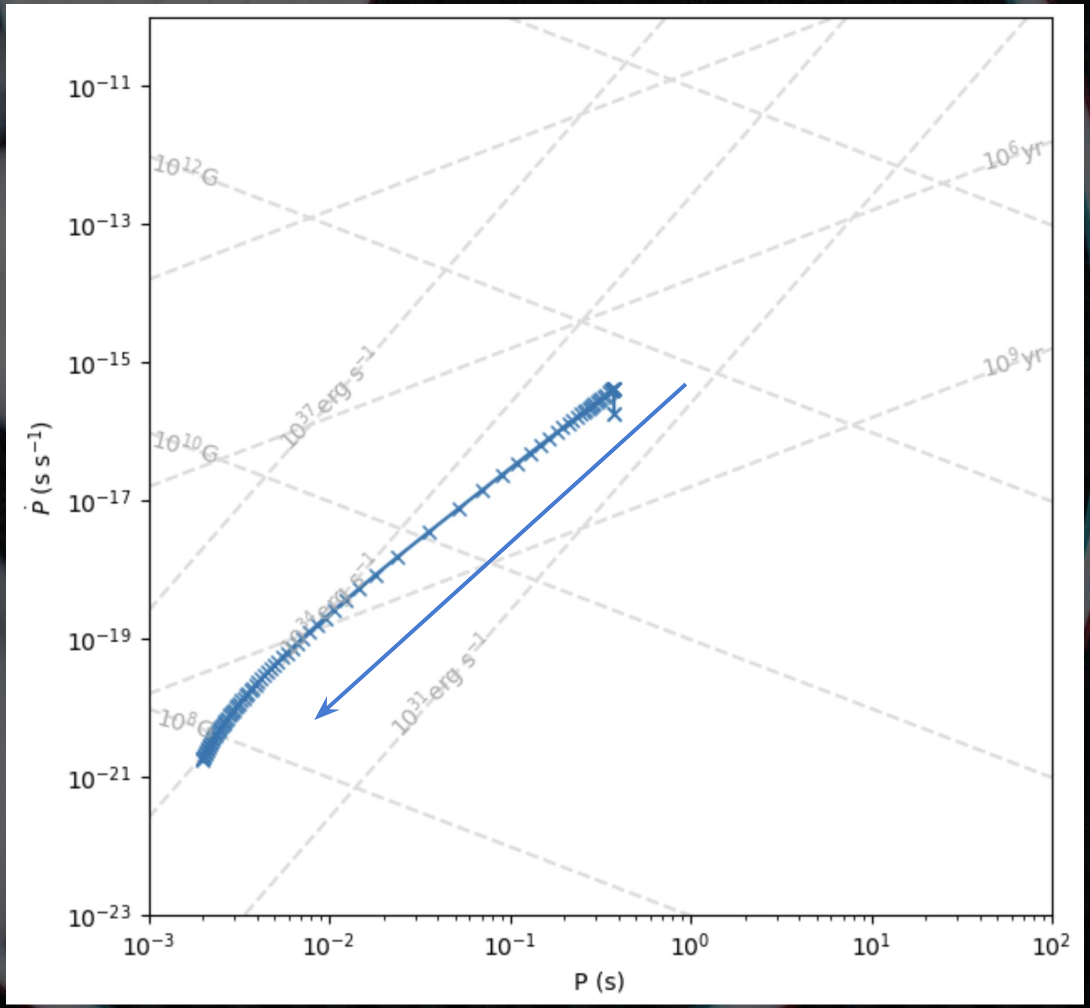
- Mass accreted onto NS buries magnetic field exponentially.

$$B = (B_0 - B_{\rm min}) \times \exp(-\Delta M_{\rm NS}/\Delta M_d) + B_{\rm min}$$

- Angular momentum exchange through infalling mass spins up the pulsar $\dot{J}_{\rm acc} = \epsilon V_{\rm diff} R_A^2 \dot{M}_{\rm NS}$ $\Omega_{\rm i+1} = \Omega_{\rm i} + \frac{\Delta J_{\rm acc}}{I}$

Chattopadhyay et al. 2020

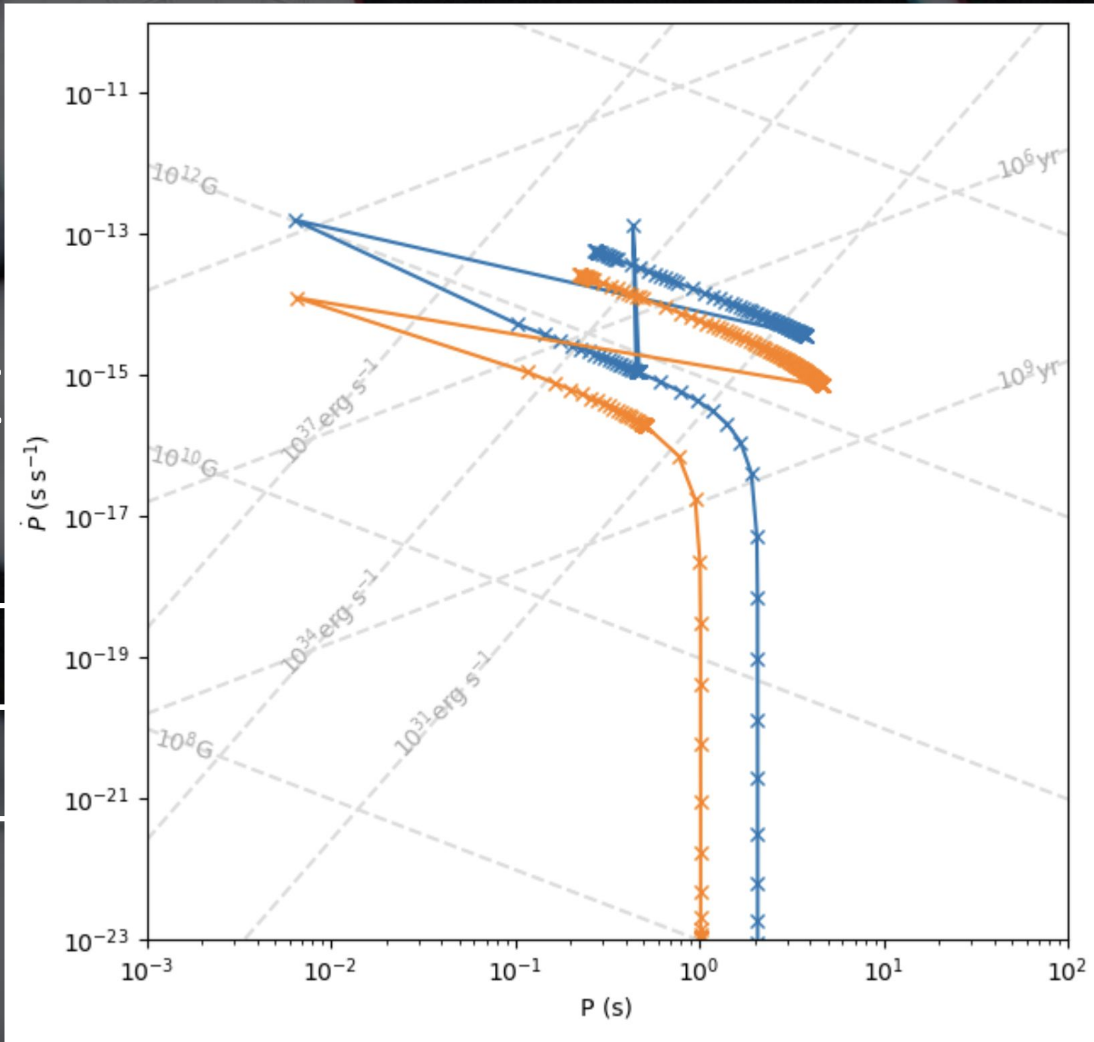
- Propeller effect: NS spins fast enough, no more mass accreted



NS Binary Evolution – Common Envelope

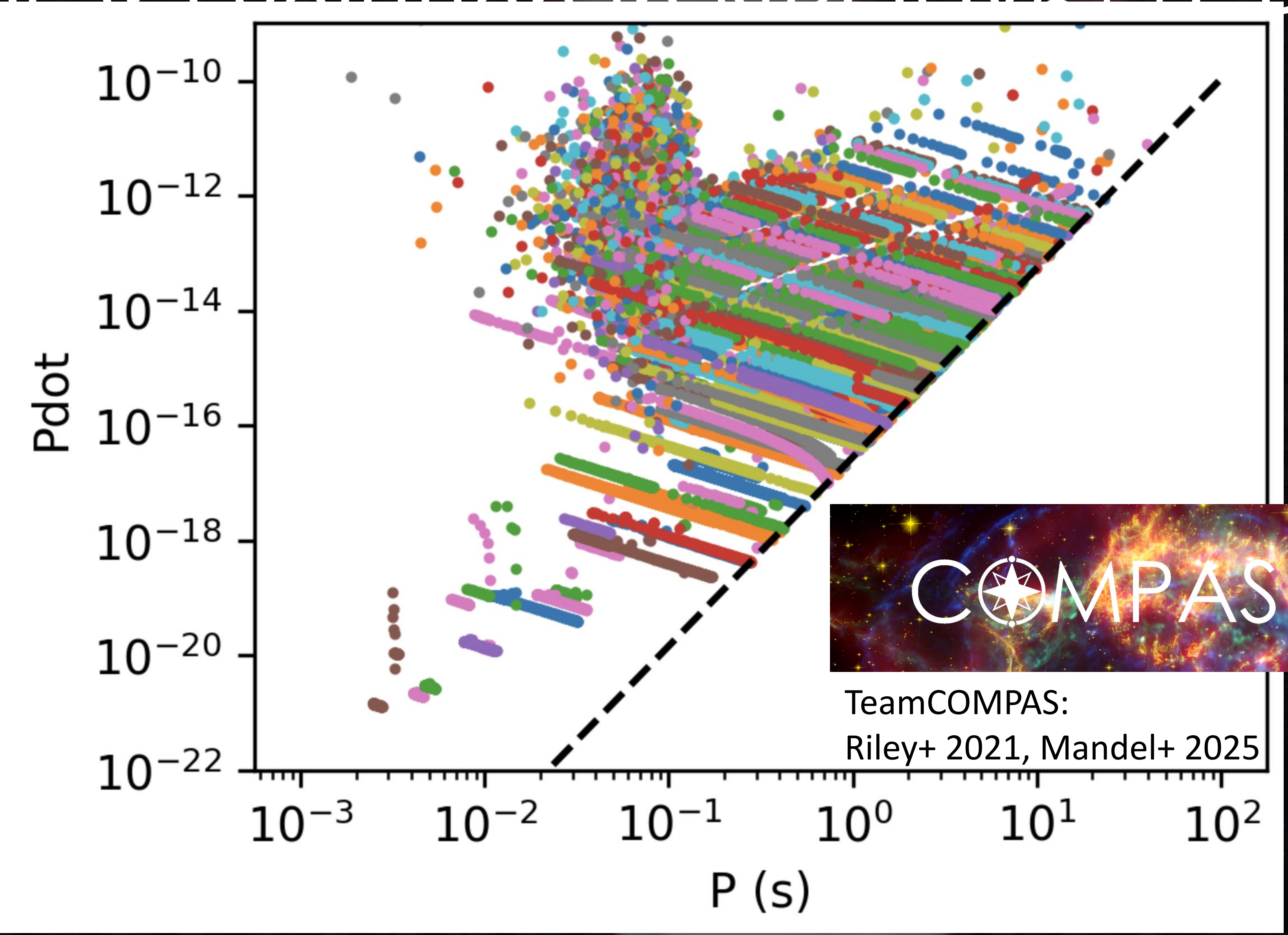
- Expansion of the companion star envelope engulfs both stars.
- Consider an energy formalism of CE
- ~~Mass transferred to NS at a rate described as in MacLoed & Ramirez-Ruis~~

$$\Delta M_{\rm NS}/M_\odot = a(R_{\rm comp}/R_\odot) + b,$$



Chattopadhyay et al. 2020

Pulsar Evolution in NBODY6++GPU



TeamCOMPAS:
Riley+ 2021, Mandel+ 2025

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&INPUL
SPINA=                N=8.0, RADNS=10.0,
TAU=5
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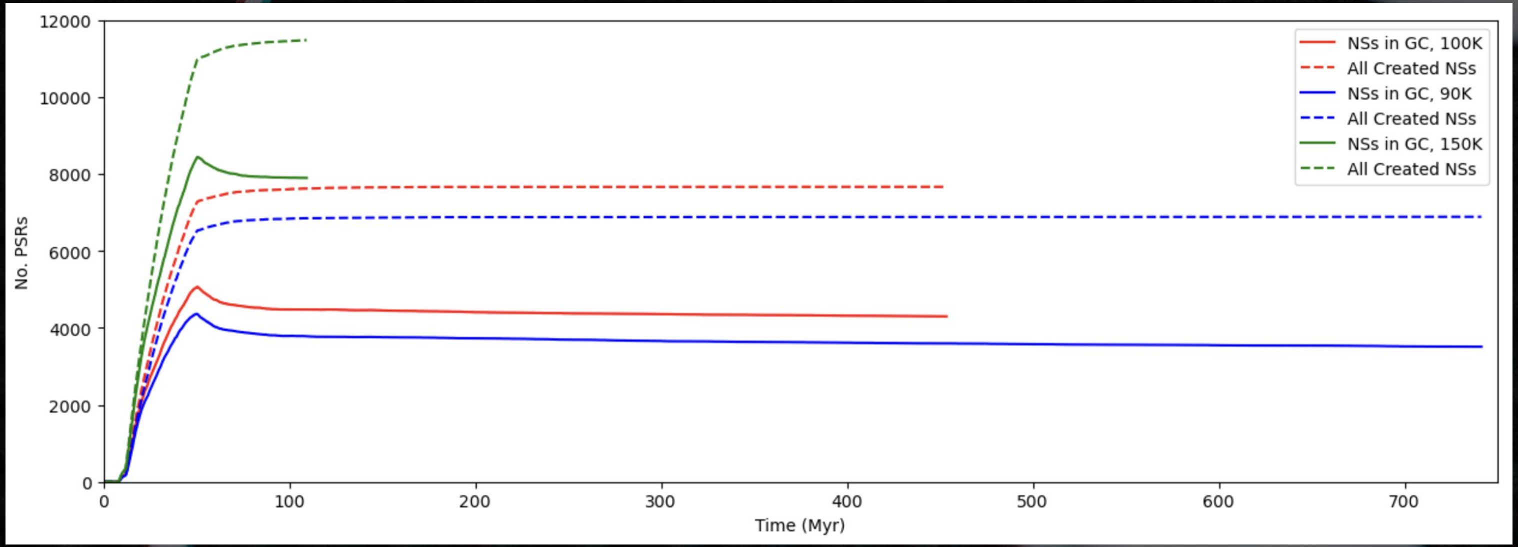
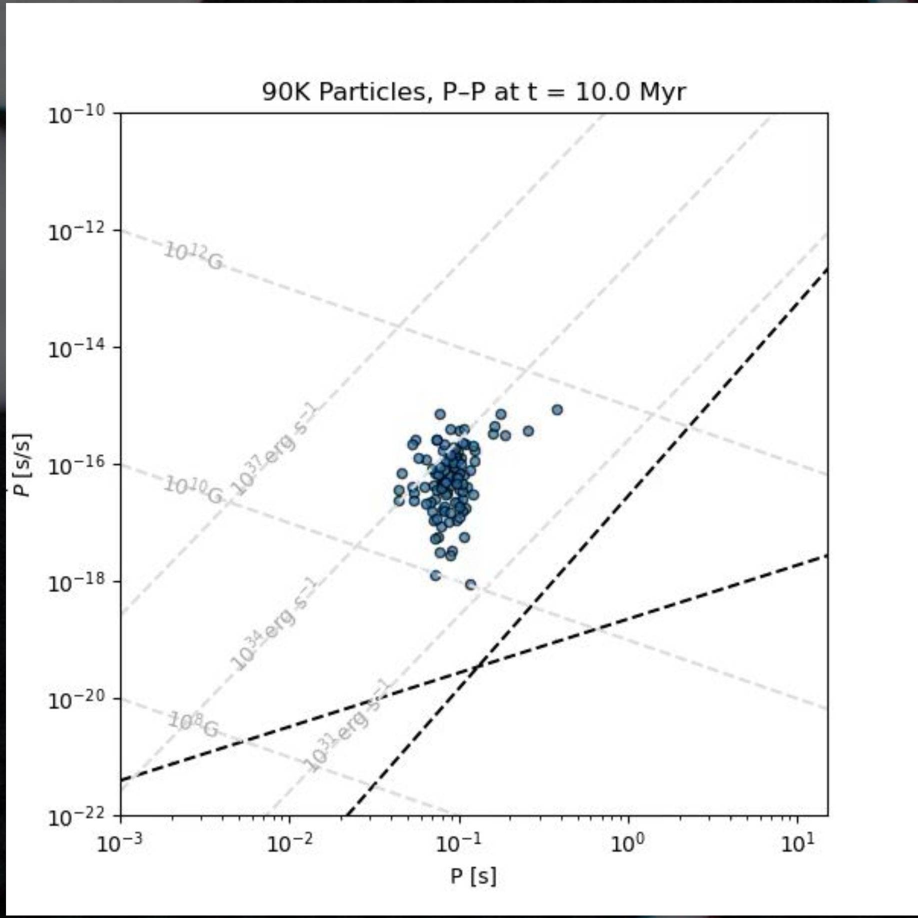
Test Simulations

- 90K/100K/150K particles
- Level C stellar evolution
- 50% binaries
- Kick Maxwellian dist. peak @ 10 km/s
- Kroupa IMF, 1 to 25 Msun
- Solar metallicity.

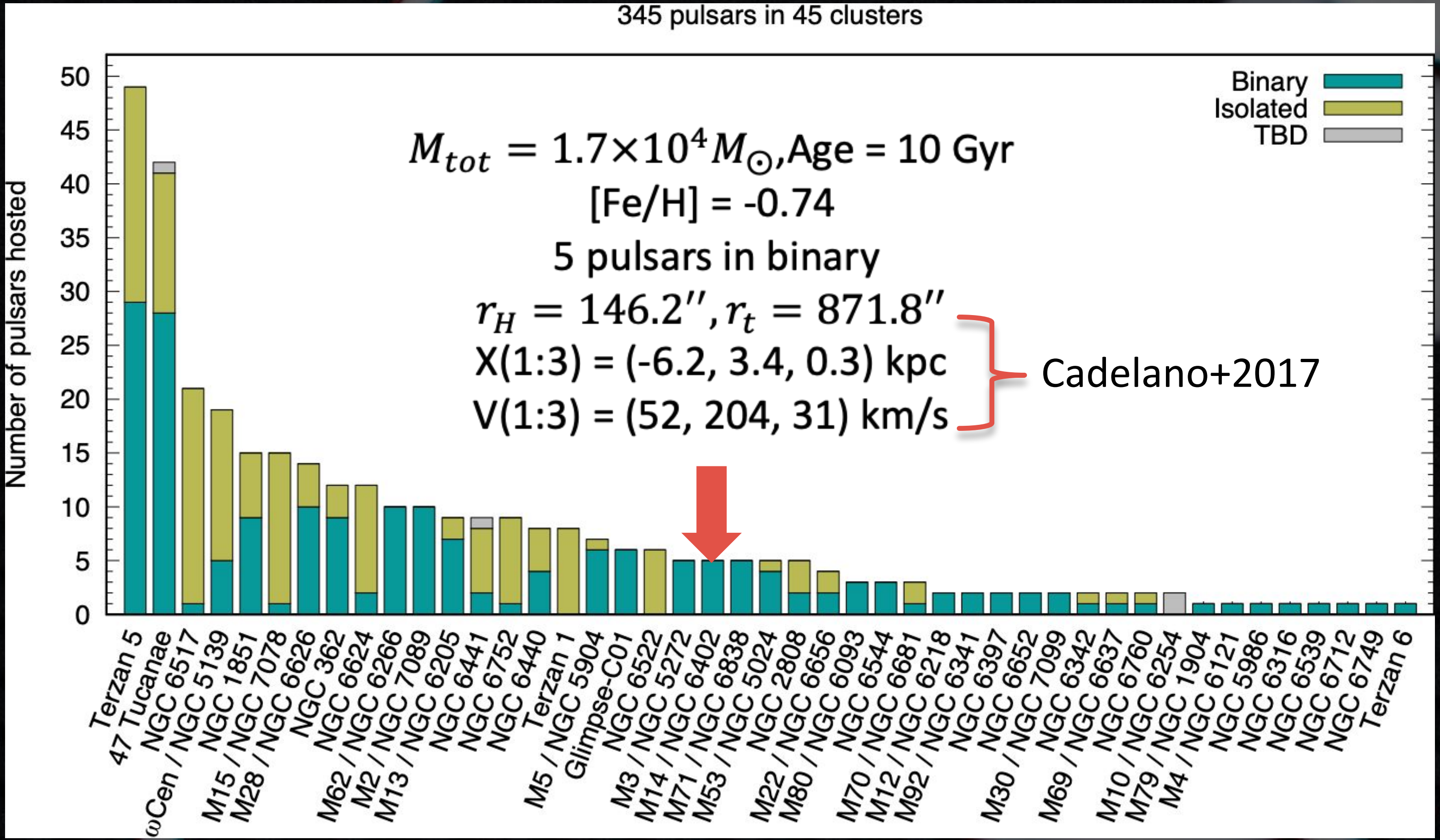
OzSTAR Supercomputing

Ngarrgu Tindebeek





M71 / NGC 6838



$M_{tot} = 1.7\times10^4 M_\odot$,Age = 10 Gyr

[Fe/H] = -0.74

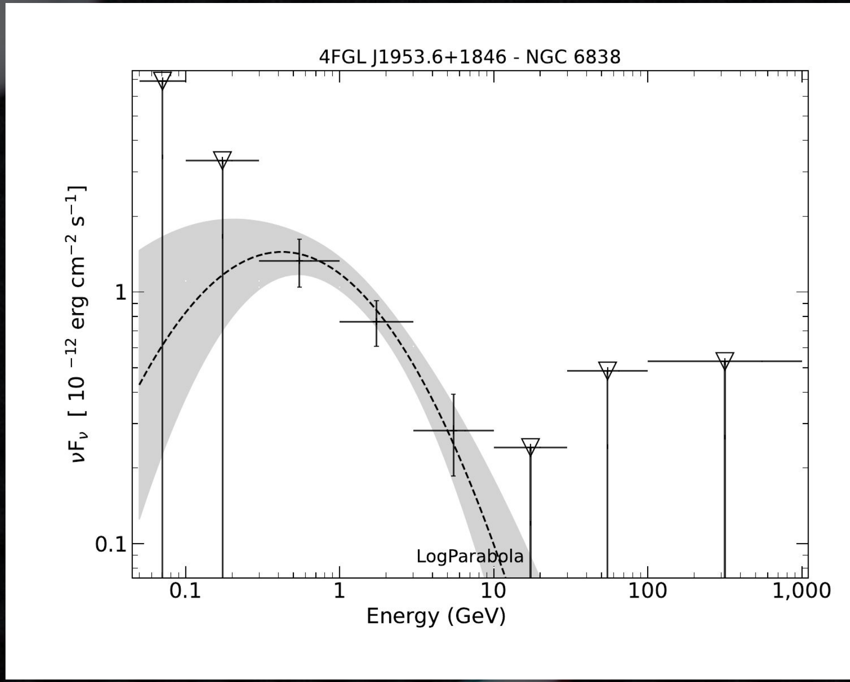
5 pulsars in binary

$r_H = 146.2'', r_t = 871.8''$

X(1:3) = (-6.2, 3.4, 0.3) kpc

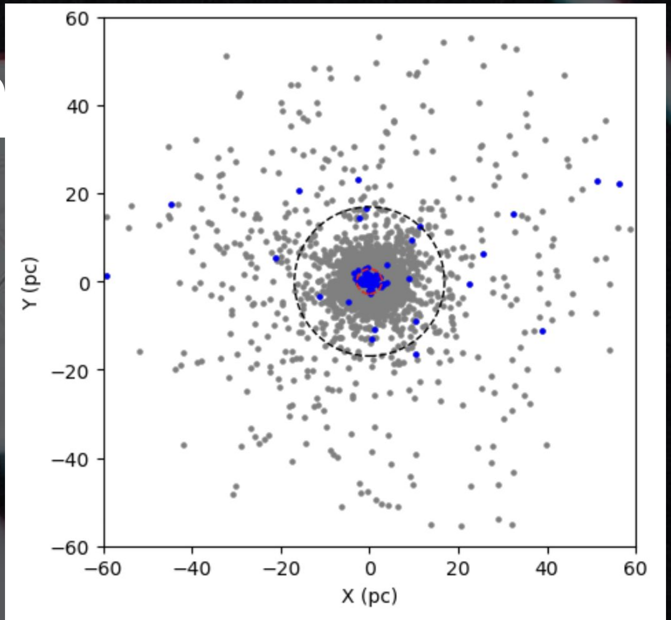
V(1:3) = (52, 204, 31) km/s

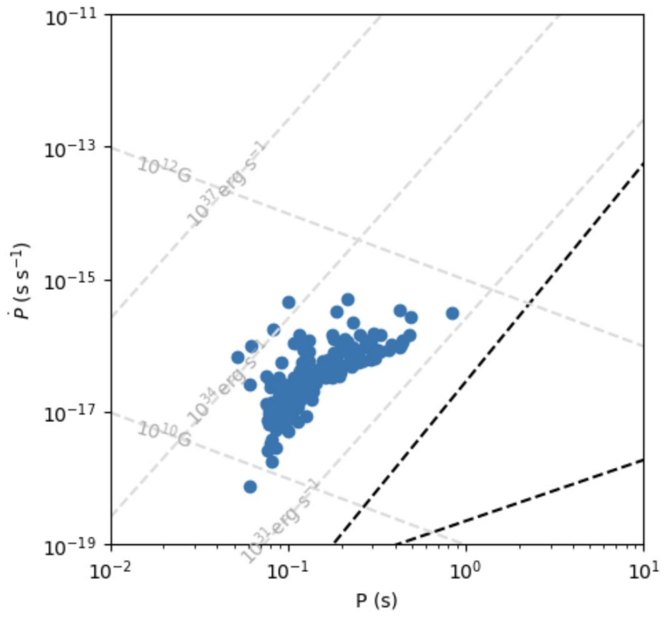
Cadelano+2017



M71 / NGC 6838 - Simulation

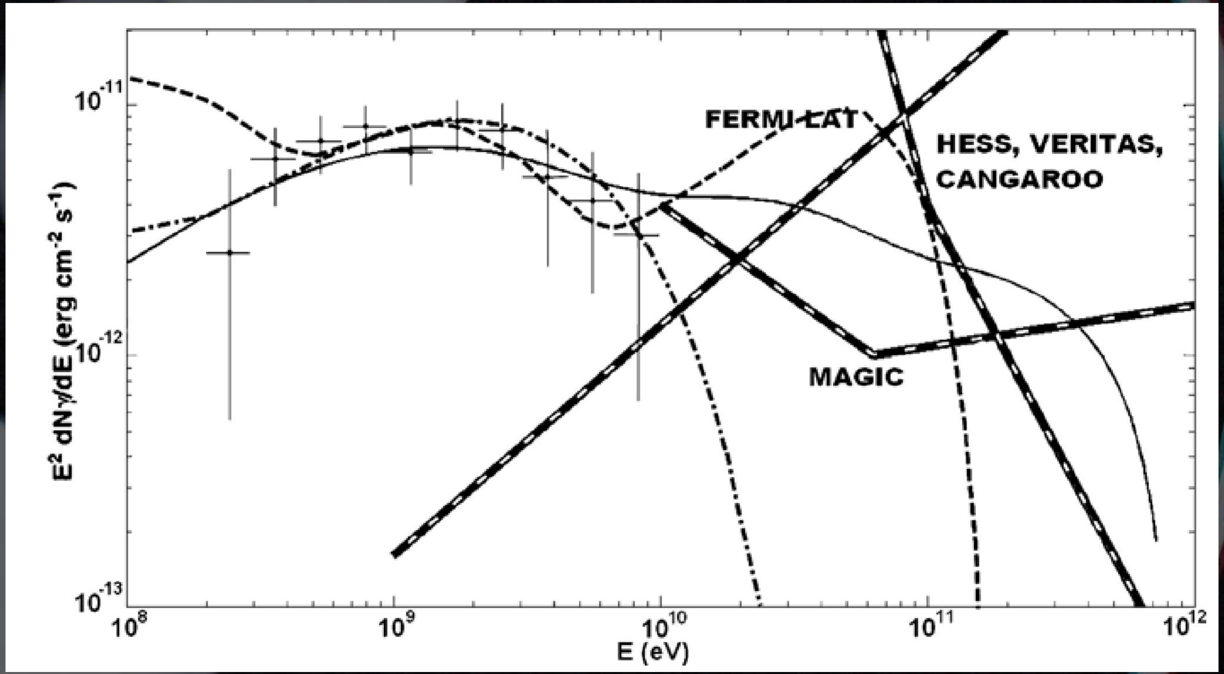
- 200K particles, 10% binaries
- Level C stellar evolution
- Kicks with Maxwellian Dist.
  - 265 km/s CCSNe, 3 km/s ECSNe
- Kroupa IMF, 0.08 to 150 $M_\odot$
- Z = 0.002
- RBAR = 2.17
- Evolved to 20 Myr
- 179 single pulsar, 2 in binaries.





Next Steps

- Include pulsars in DRAGON-III simulations
- Model GC gamma-ray emission
  - Superposition of pulsar gamma-rays
  - Inverse Compton scattering
  - Other possibilities?
- Predictions for CTA detectability



Modelling 47 Tuc with IC model from IR photons Cheng et al. 2010

Next Steps

- Known issues that LMXBs are hard to form in NBODY simulations - hard to form MSPs through recycle.
  - Other channels, e.g. accretion induced collapse (Gautum+ 2022)
- Further development in conjunction with COMPAS
- Comparison project with MOCCA and PeTar

COMPAS

TeamCOMPAS:
Riley+ 2021, Mandel+ 2025

MOCCA

Arkadiusz+2013;
Giersz+2013…

PeTar

Wang+ 2020

Summary

- New pulsar evolution module to be publicly available in NBODY6++GPU soon.
- Test runs provide positive results.
- Progress with modelling M71.
- For questions, suggestions and NS-related issues you'd like to see, contact: yuzhesong@swin.edu.au

Extra slides

Motivation

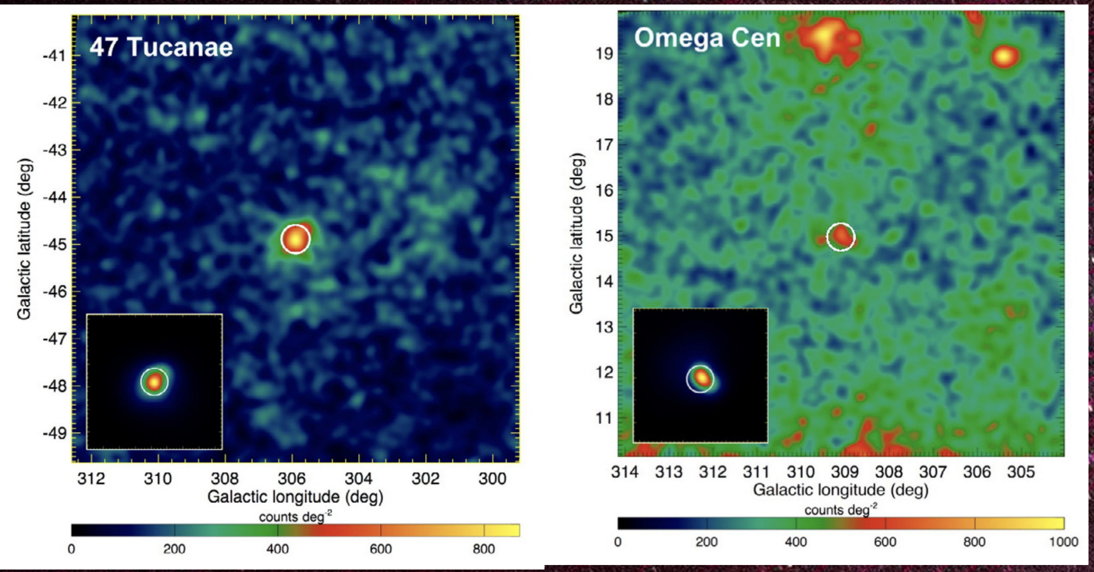
- Gravitational waves:

- GW190425: M_{tot}= 3.4 $M_{\odot}$, possibly formed through dynamical encounter in a GC. (DeCesar et al 2015)
  - High M_{tot} BNSs measured in GCs recently:
    - PSR J0514-4002E in NGC1851, M_{tot}= 3.9 $M_{\odot}$ (Chen & Liu 2024)
    - PSR J1748−2446ao in Ter5, M_{tot}= 3.2 $M_{\odot}$ (Padmanabh et al 2024)

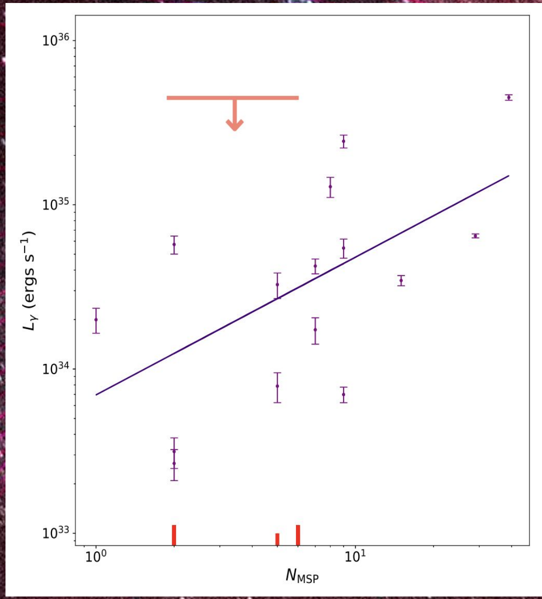
Motivation

- Gamma-ray emission:

GeV detection:
(Abdo et al. 2010)



GeV stacked signal
Henry et al. 2024



Pulsars

- Low e- density close to surface.
- Curvature photon ➡ pair production ➡ secondary particles create synchrotron photons ➡ pair production ➡ …

- Pair production creates larger e- density, screens off acceleration fields.

TIMOKHIN & HARDING

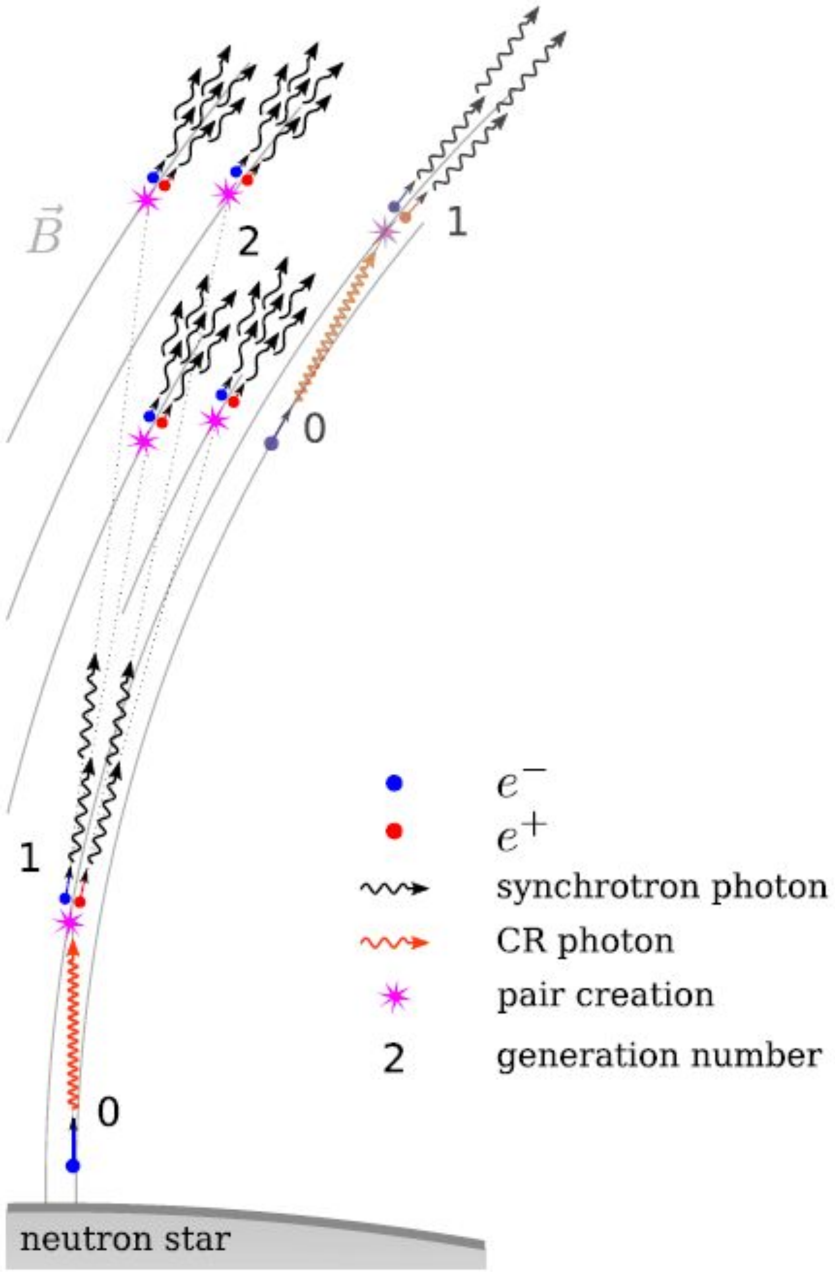


Figure 1. Schematic representation of electron–positron cascade in the polar cap of a young pulsar, see the text for description.