Title: Gravitational attraction: dynamically enhanced formation of millisecond pulsars in globular clusters

Speakers: Claire Ye

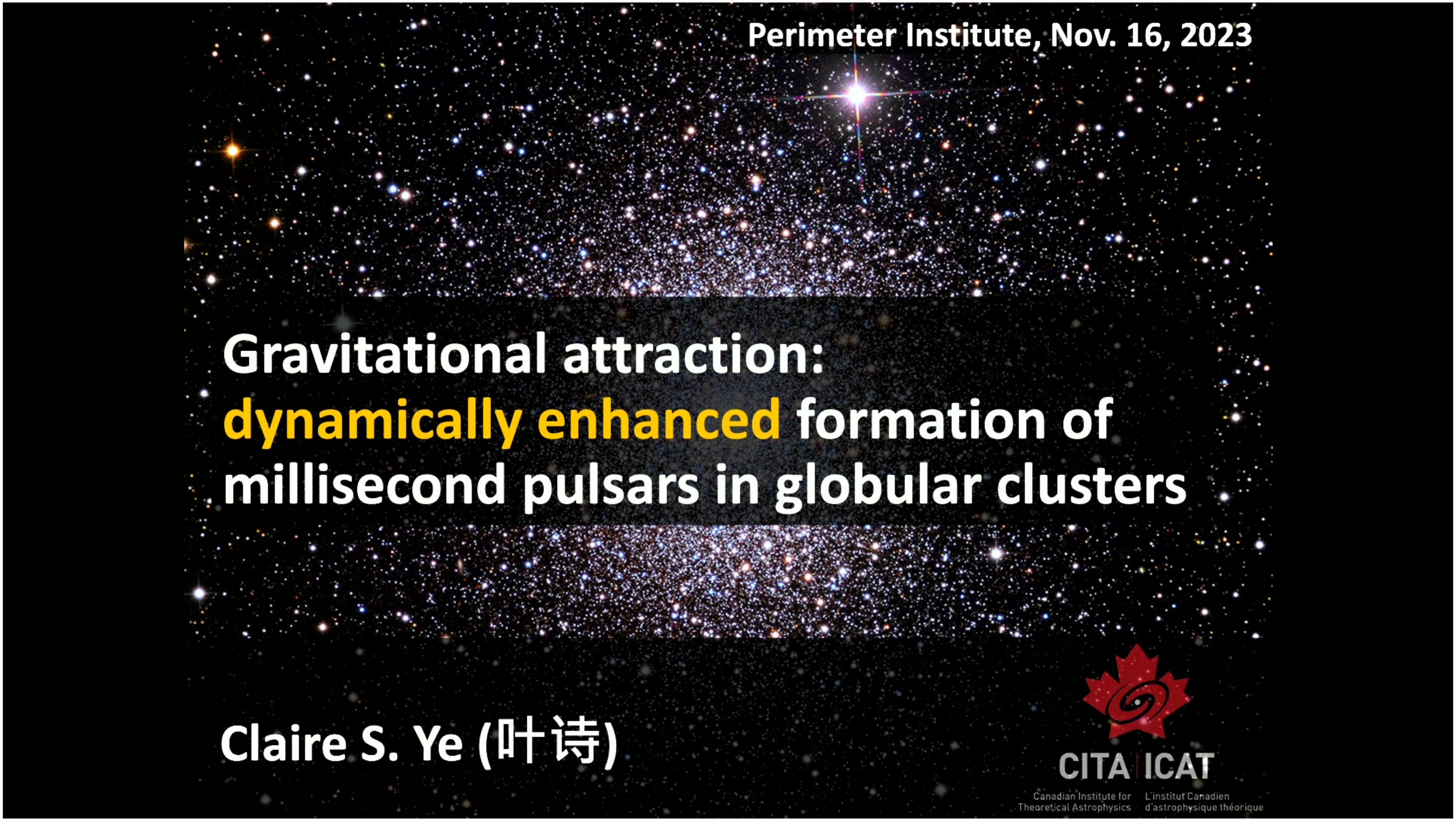
Series: Strong Gravity

Date: November 16, 2023 - 1:00 PM

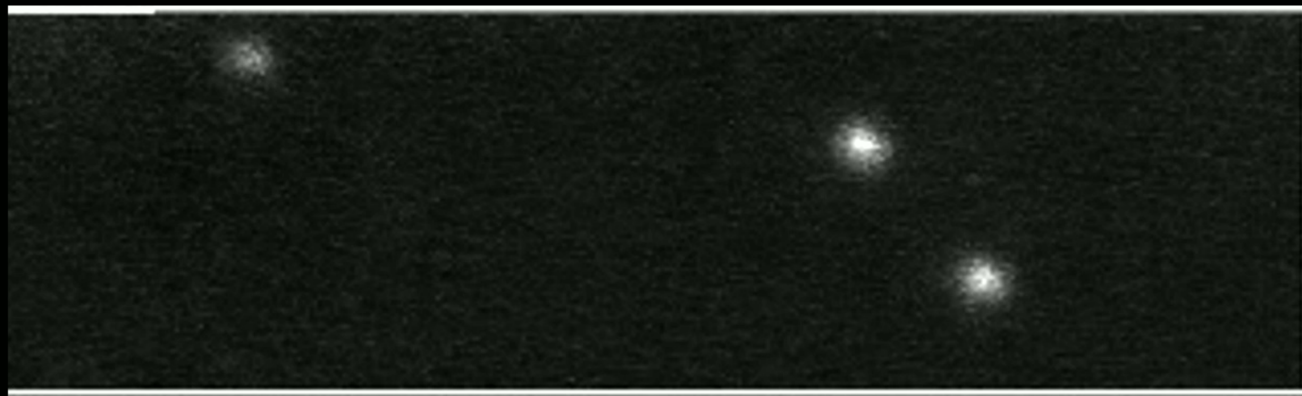
URL: https://pirsa.org/23110067

Abstract: A high specific abundance of millisecond radio pulsars has been observed in globular clusters (GCs), motivating theoretical studies of the formation and evolution of these sources through stellar evolution coupled to stellar dynamics. In this talk, I will first demonstrate how we model millisecond pulsars in GCs using realistic cluster simulations. I will show the importance of electron-capture supernovae for neutron star retention, and how millisecond pulsar formation is greatly enhanced through dynamical interaction processes. I will also present some latest results on isolated millisecond pulsars, which are especially intriguing given the fact that millisecond pulsars are descendants of binary star systems. I will demonstrate the potential formation channels of isolated millisecond pulsars, some of which may also link to the formation of magnetars and the newly discovered fast radio bursts in a GC.

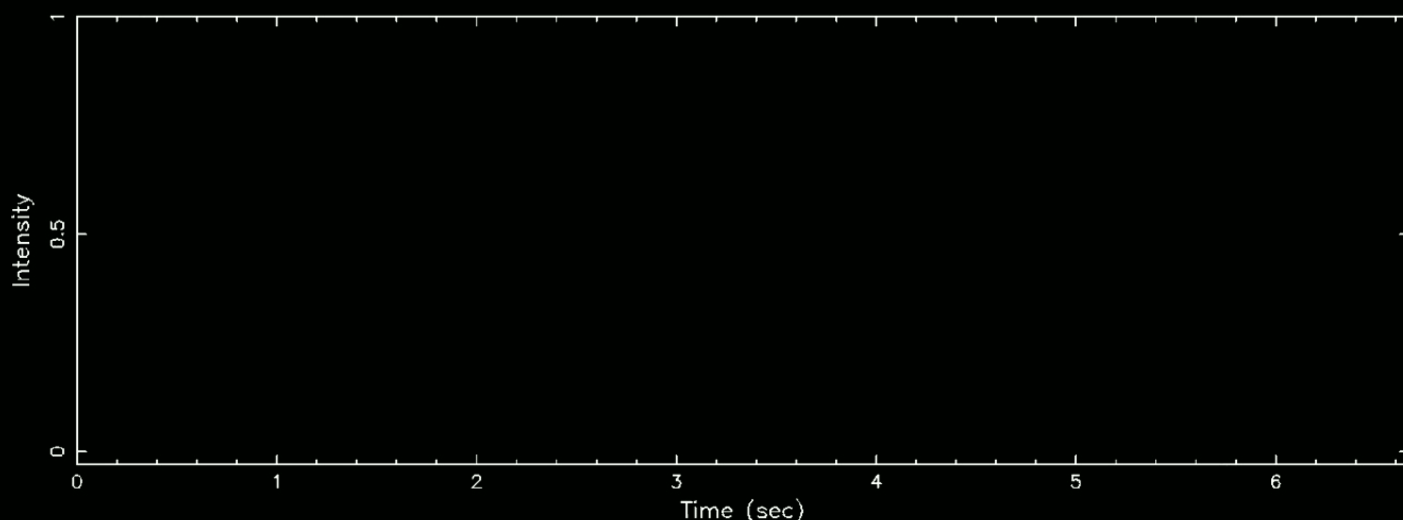
Zoom link https://pitp.zoom.us/j/97622593487?pwd=SHNoM1o3T1JjWVROTkJoZ0NWYmdyQT09


Perimeter Institute, Nov. 16, 2023
Gravitational attraction:
dynamically enhanced formation of
millisecond pulsars in globular clusters
Claire S. Ye (叶诗)
CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique

Crab Pulsar; Credit: Cambridge University Lucky Imaging Group



Pulsar B0329+54 observed with the Lovell telescope at Jodrell Bank



https://www.jb.man.ac.uk/research/pulsar/Education/Sounds/

Crab Pulsar; Credit: Cambridge University Lucky Imaging Group

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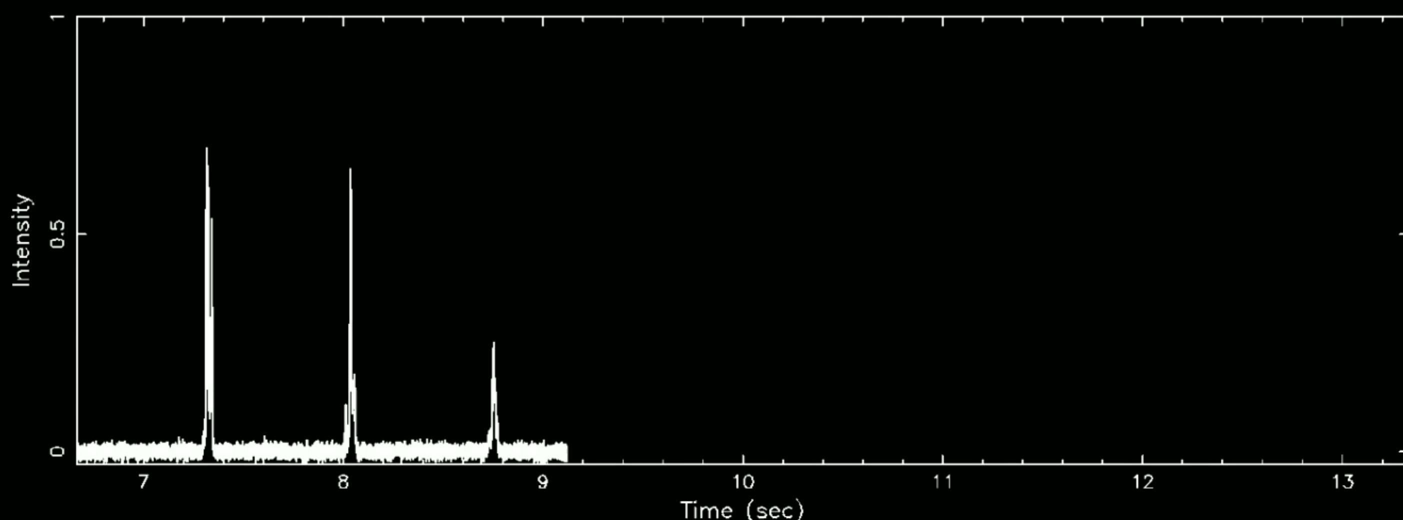
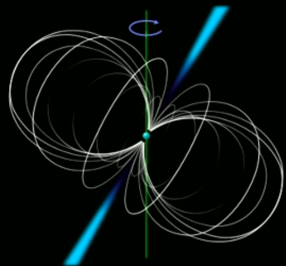


https://www.jb.man.ac.uk/research/pulsar/Education/Sounds/

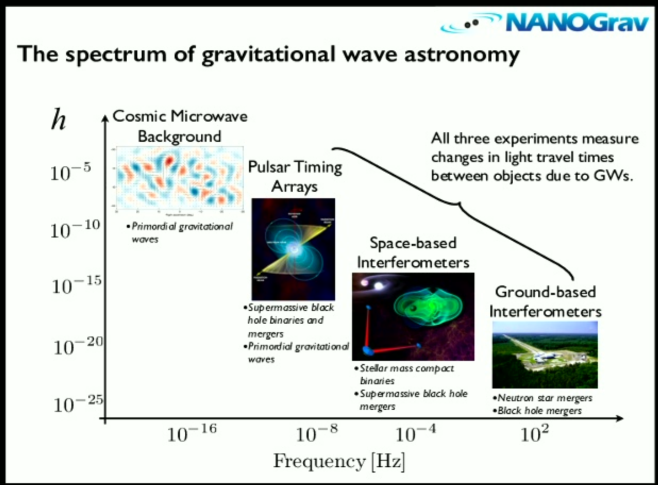
Why study pulsars and neutron stars?

3

Stable and precise clock



Pulsar timing array



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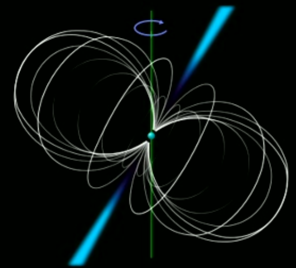

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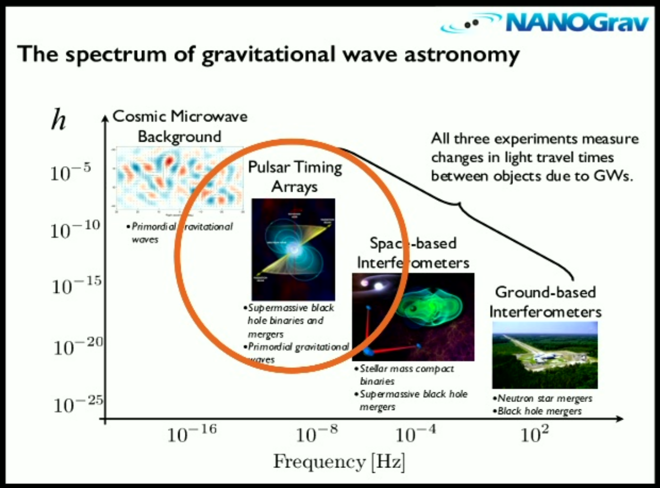
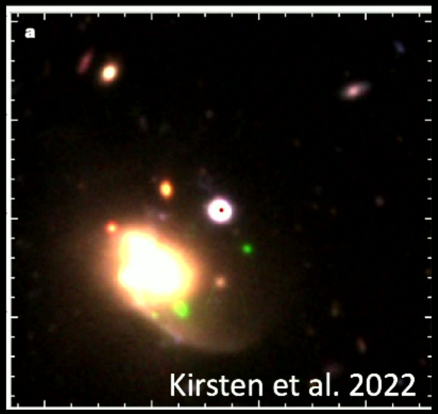
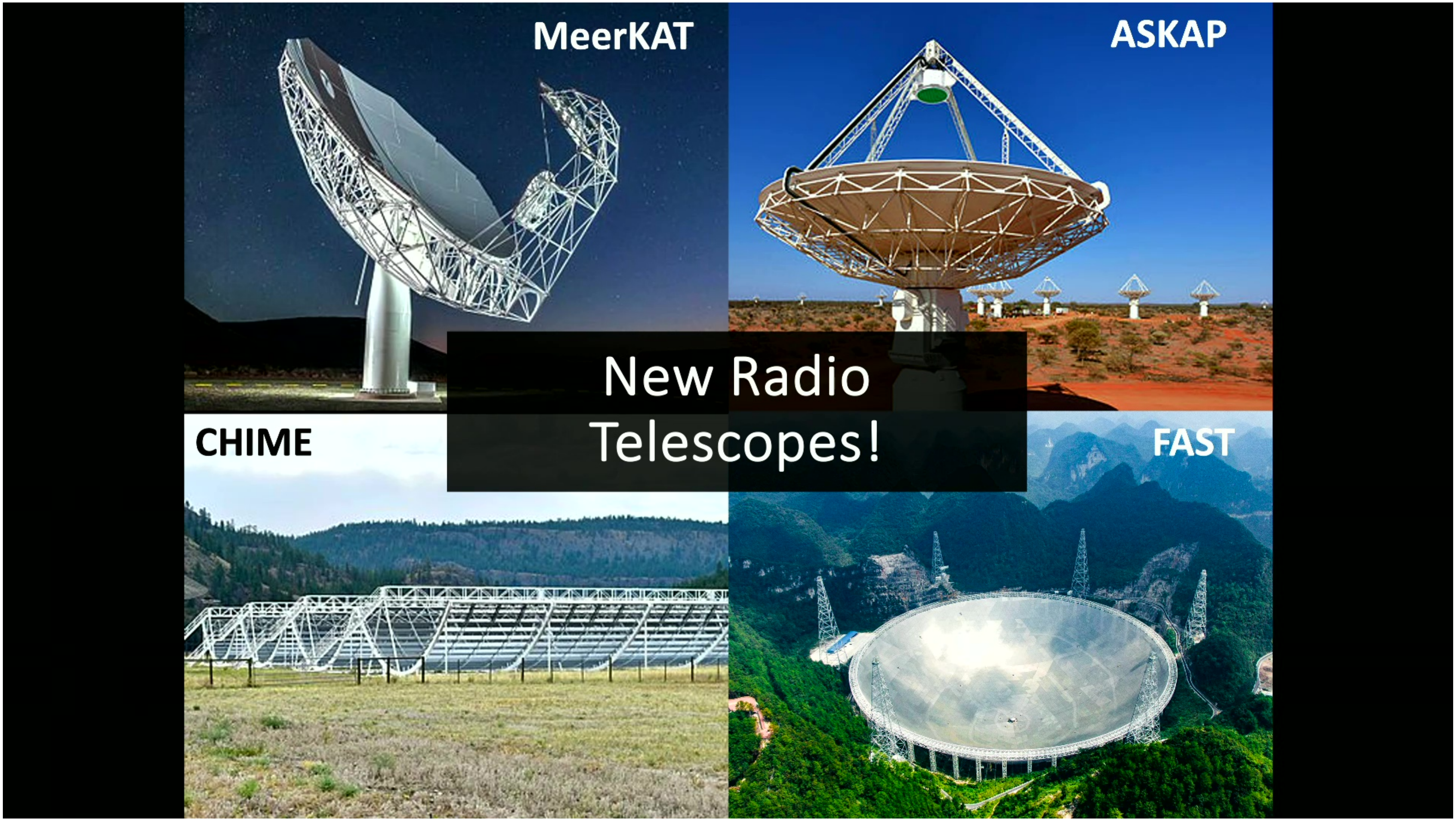


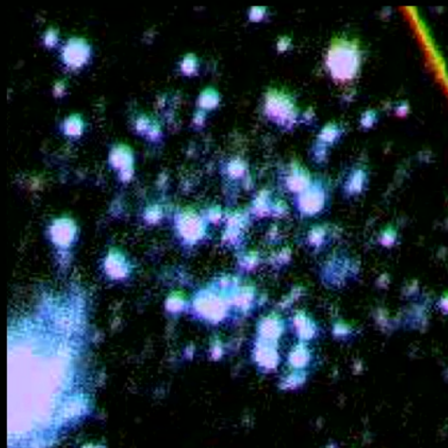
Testing general relativity

Fast radio bursts in a globular cluster




MeerKAT
ASKAP
New Radio
Telescopes!
CHIME
FAST

Dwarf Galaxies



Eri II: 1 GC
(e.g., Crnojevic et al. 2016)

Spiral Galaxies

Milky Way: ~150 GCs
(e.g., Harris et al. 1996)
Andromeda: ~500 GCs
(e.g., Galleti et al. 2004)

Large Ellipticals

M87: ~10,000 GCs
(e.g., Peng et al. 2008)

Globular clusters are found in all galaxies

Globular Clusters

Old (~ 10 Gyr)

Massive ($M \sim 10^5$-$10^6 M_\odot$)

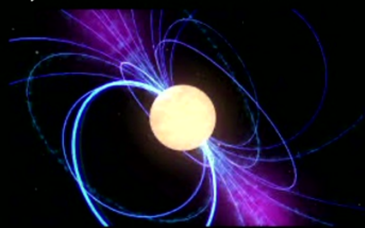
Compact ($r_h \sim$ several pc)

M 80

Globular clusters are efficient factories of a whole zoo of stellar exotica

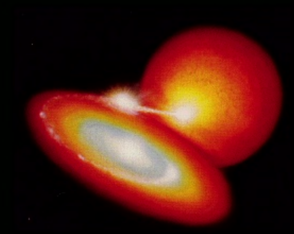
Millisecond pulsars

- e.g., **Ye et al. 2019**, Ransom 2008, Freire 2012, Clark et al. 1975



Cataclysmic variables

- e.g, Ivanova et al. 2006, Knigge et al. 2012

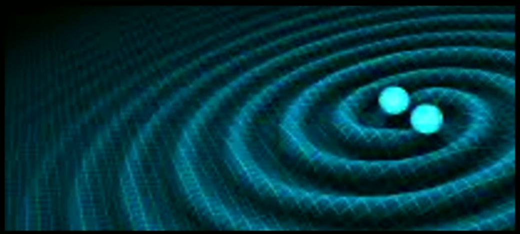


X-ray binaries

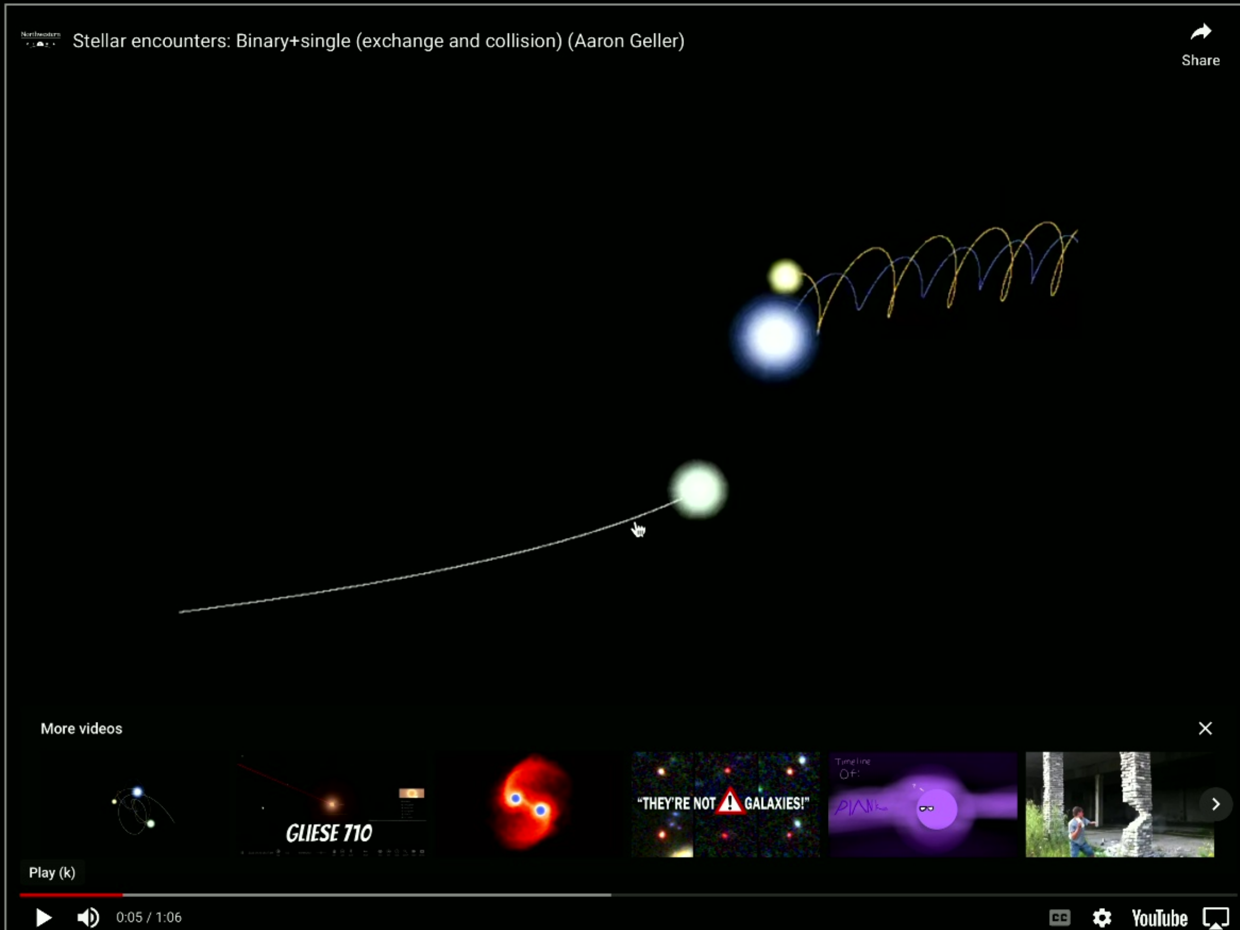
- e.g., Ivanova et al. 2010, 2017, Strader et al. 2012, Naoz et al. 2016, Kremer et al. 2018

Binary black hole mergers

- e.g., Portegies Zwart et al. 2000, Downing et al. 2010, 2011, Rodriguez et al. 2015, 2016



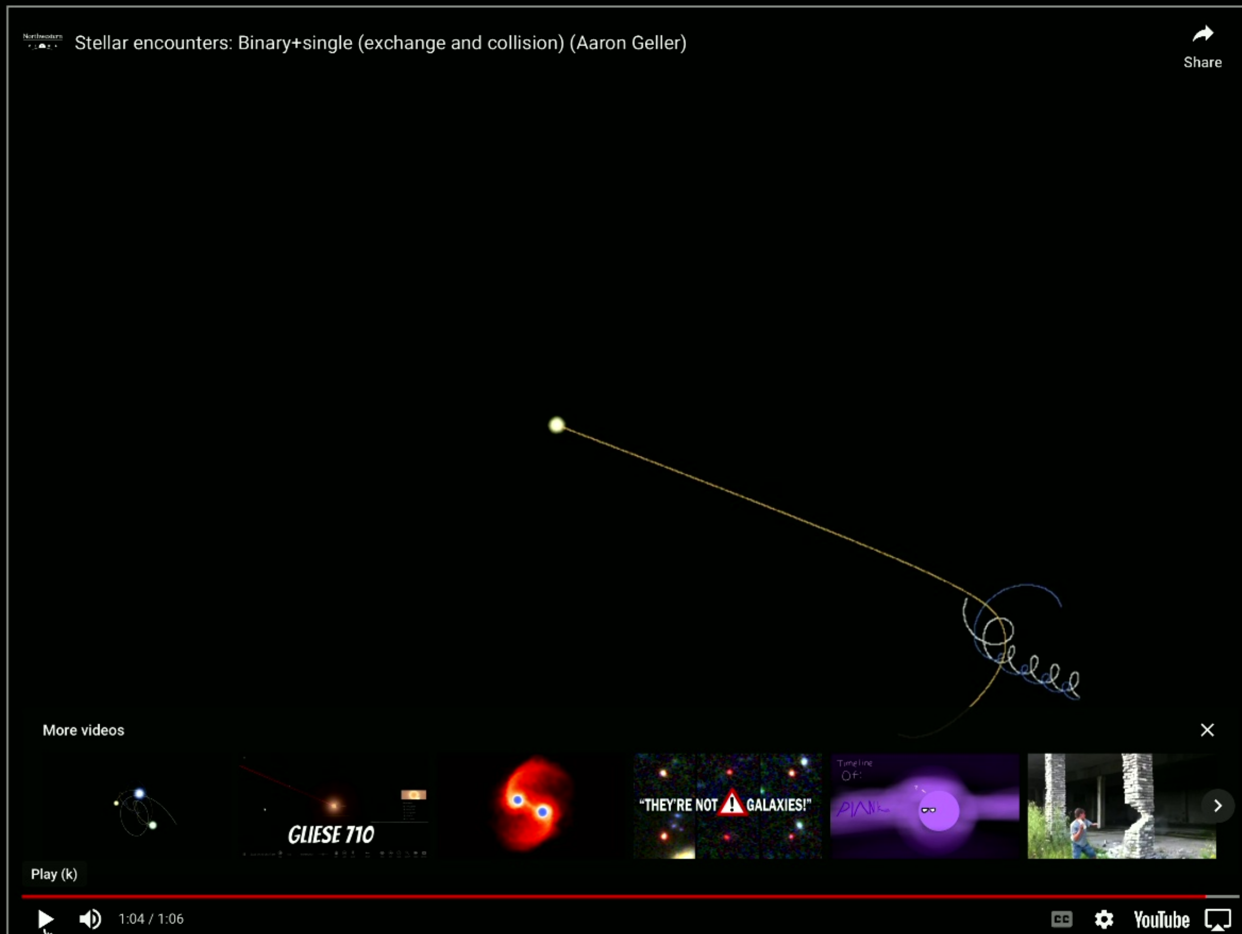
Strong dynamical encounters



Aaron Geller/Northwestern

8

Strong dynamical encounters



Aaron Geller/Northwestern

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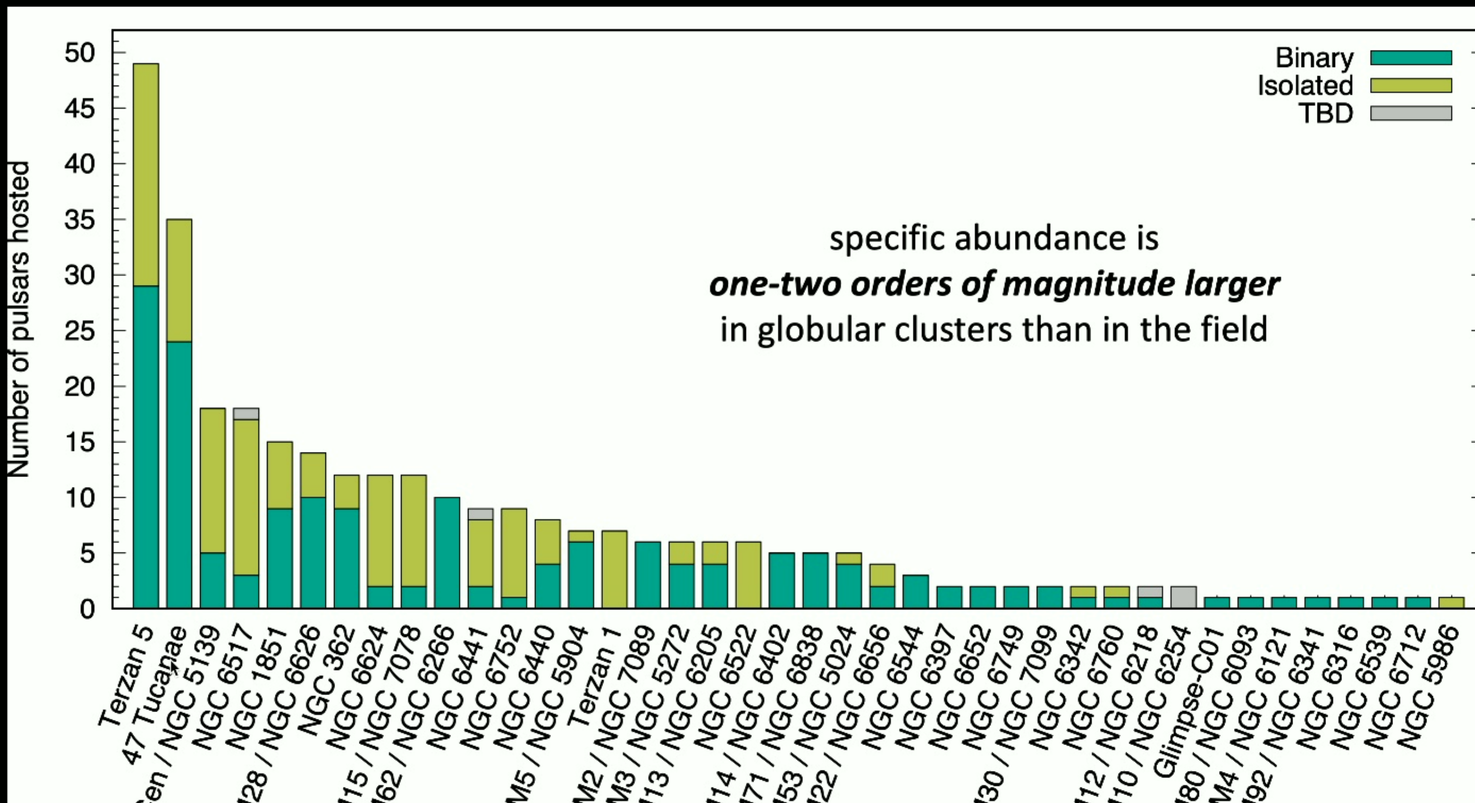
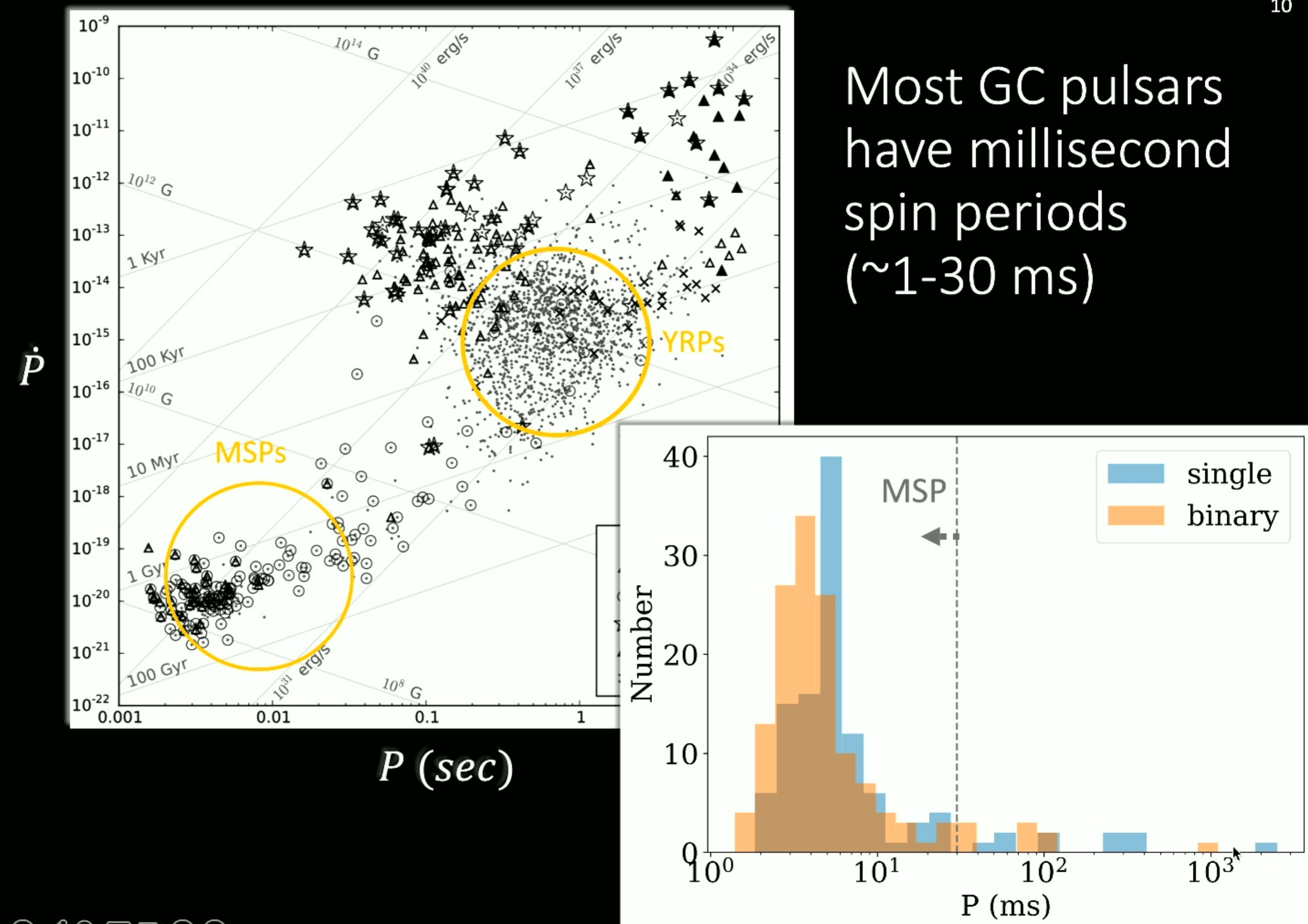
305 pulsars in 40 clusters



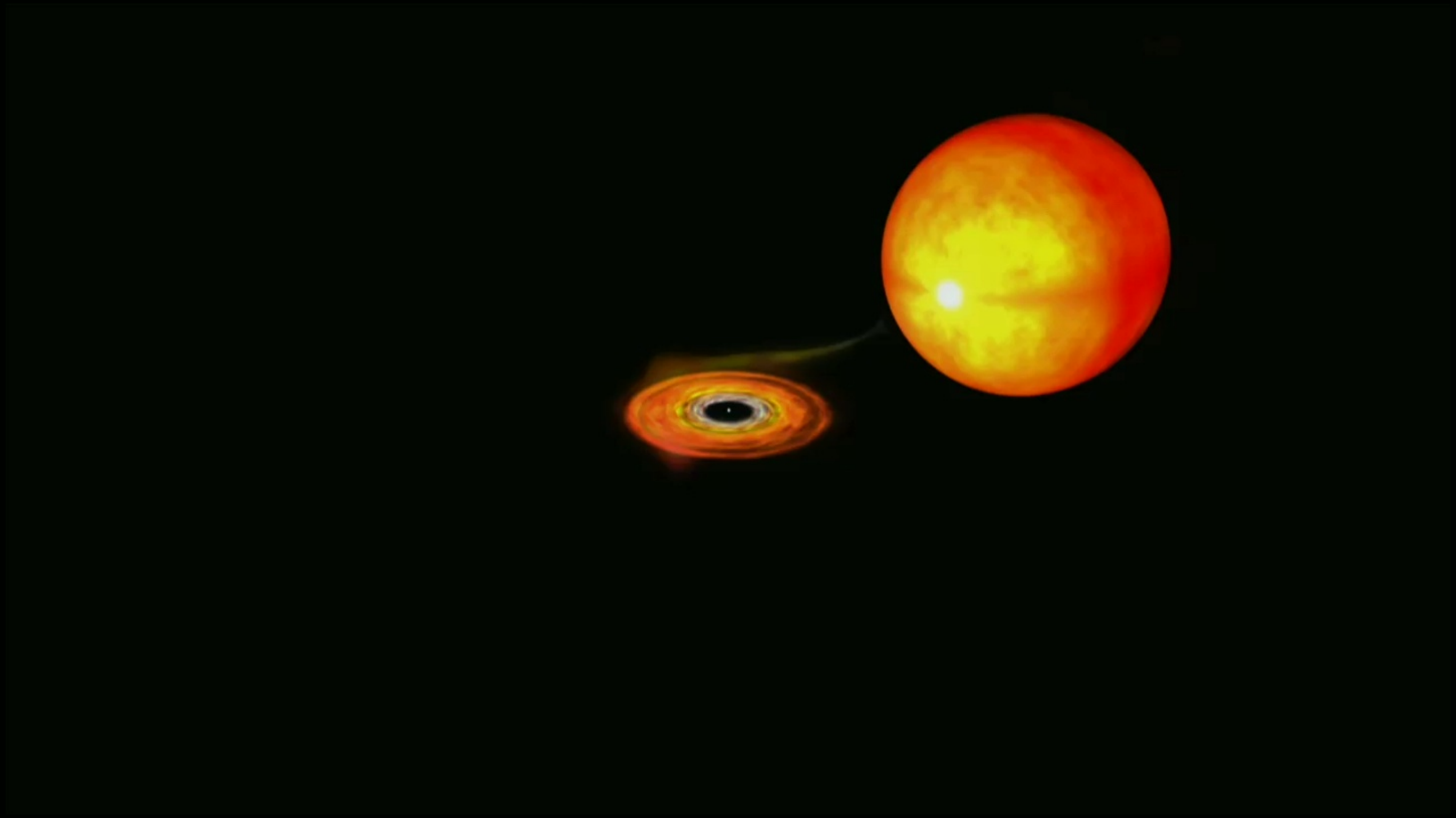
http://www.naic.edu/~pfreire/GCpsr.html

Credit: James J. Condon & Scott M. Ransom



Most GC pulsars have millisecond spin periods (~1-30 ms)

Mass transfer and spin up to millisecond pulsar



NASA

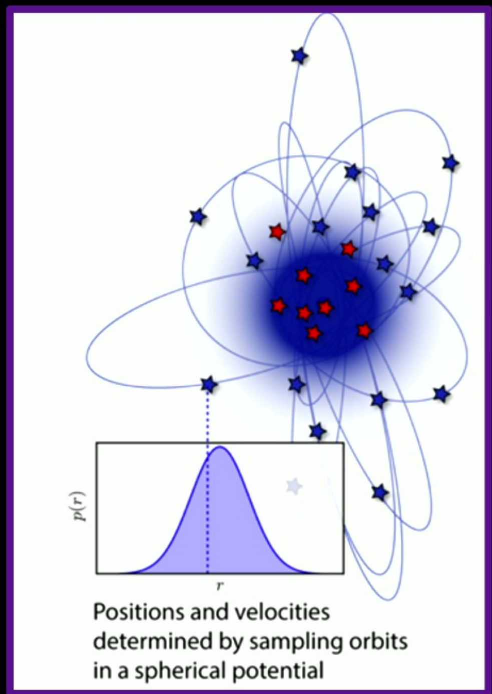
Outline

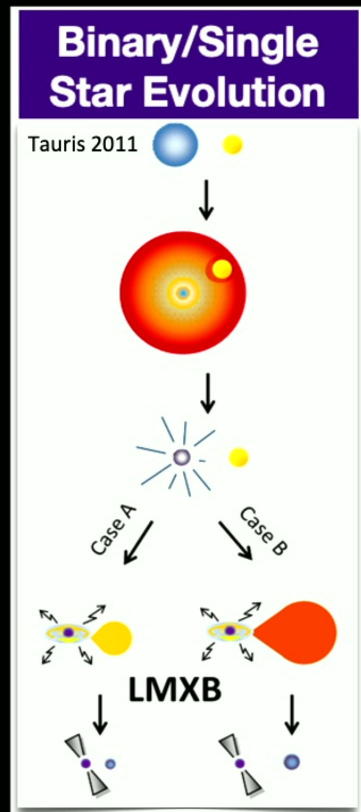
1. **Modeling Millisecond Pulsars**
   - magnetic fields, spin periods, natal kicks

2. **Spider Pulsars and Where They Come From**
   - black widows and redbacks

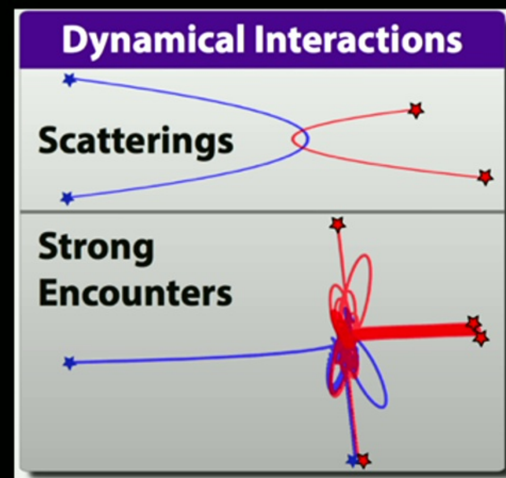
3. **Isolated Millisecond Pulsars**
   - tidal disruption of main-sequence stars
   - white dwarf-white dwarf mergers

Modeling globular clusters with Monte Carlo method





Cluster Monte Carlo code (CMC) allows us to simulate massive star clusters (~10^6 particles) with all relevant physics.



Monte Carlo method: Henon 1971a,b, Joshi et al. 2000, 2001, Fregeau et al. 2003
Stellar evolution: Hurley et al. 2000, 2002, Breivik et al. 2020; **Fewbody:** Fregeau et al. 2004, 2007
Latest updates: Pattabiraman et al. 2013, Chatterjee et al. 2010, 2013, Rodriguez et al. 2018, 2022

1) Magnetic Field and Spin Period Initialization and Evolution

Young Pulsars

B field: $\sim 10^{12} - 10^{14}$ G

Spin Period: ~$30 - 1000$ ms

Special case for MSPs

B field: $\sim 10^{8} - 10^{9}$ G

Spin Period: $3 - 20$ ms

All NSs form as young radio pulsars from supernovae

Kiel et al., 2008, Ye et al. 2019

Evolution

Isolated

$\dot{P} \sim \frac{B^2}{P}$

Dipole Radiation in isolation

$B = B_0 \times \exp\left(\frac{T}{\tau}\right) + B_{bot},$

$\tau = 3\ \mathrm{Gyr}, \quad B_{bot} = 5 \times 10^7\ \mathrm{G}$

Slow magnetic field decay in isolation

Binary

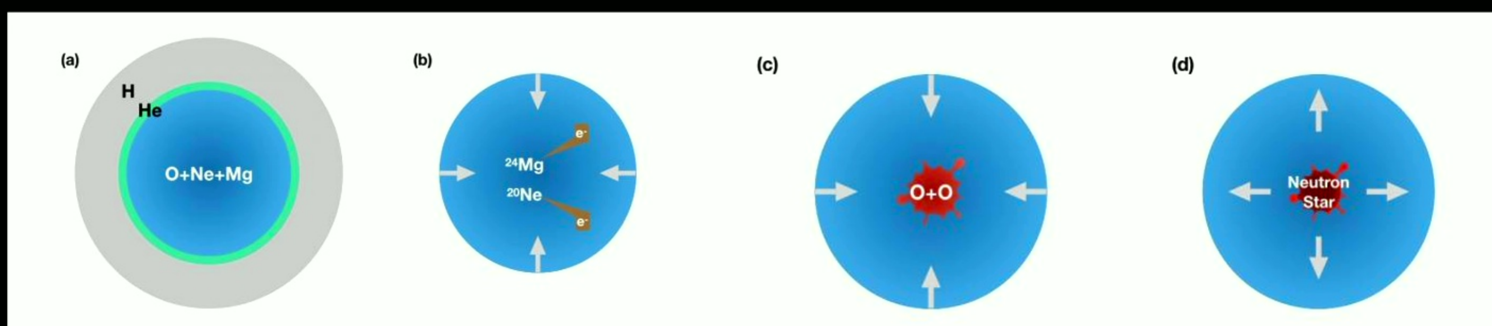
$B = \frac{B_0}{1 + \frac{M_{acc}}{10^{-6} M_\odot}} \times \exp\left(\frac{T - t_{acc}}{\tau}\right) + B_{bot}$

Magnetic field burying during accretion

How the neutron stars are formed

- Core-collapsed supernova (most NSs)
- Electron capture supernova
- Accretion-induced collapse

Electron capture and accretion-induced collapse: An Oxygen-Neon-Magnesium core/white dwarf reaches a critical mass of 1.38 $M_\odot$ and collapses to a neutron star.



Credit: Zha et al./Kavli IPMU

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Low natal kicks of 20 km/s!!

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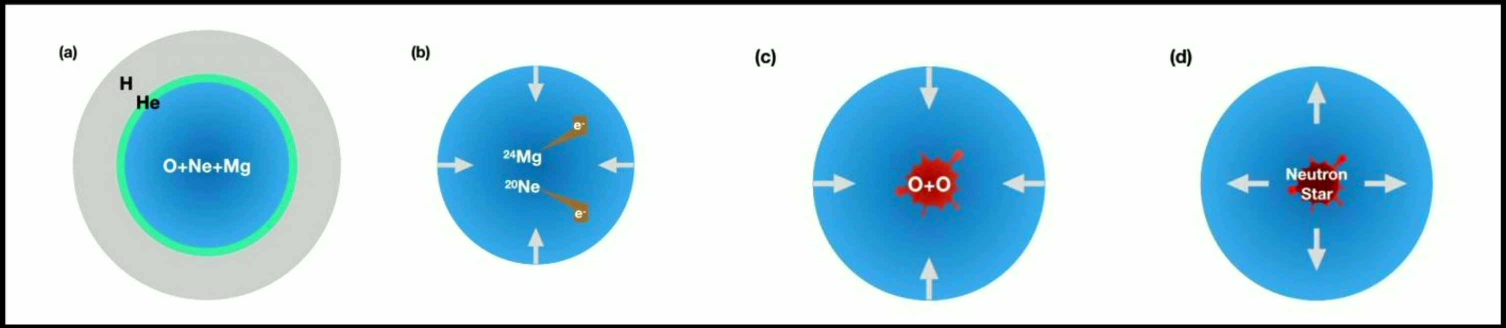
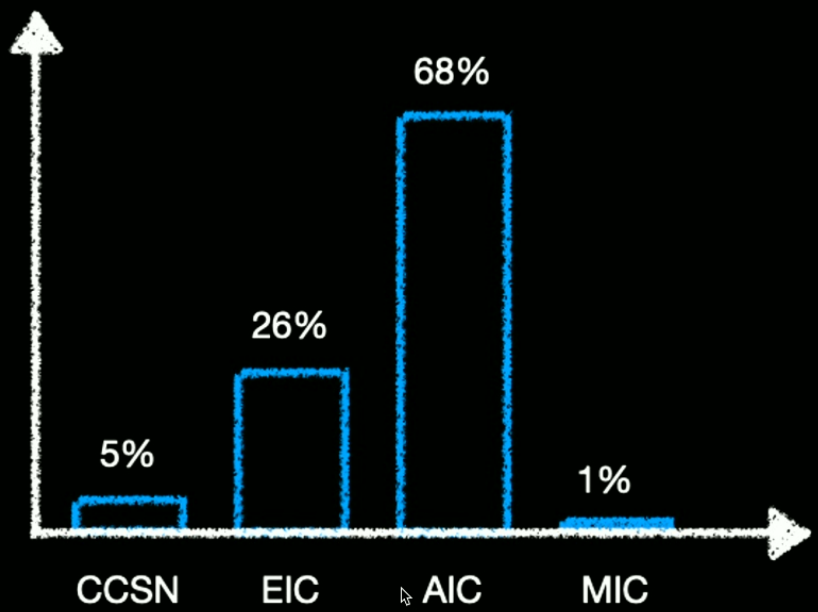


Credit: Zha et al./Kavli IPMU

Results: Neutron star and MSP retentions in simulations



Overall ***~8%*** of all NSs formed are typically retained (Most of them are ECSN NSs)

More than ***90%*** of MSPs are from NSs that formed in ECSN

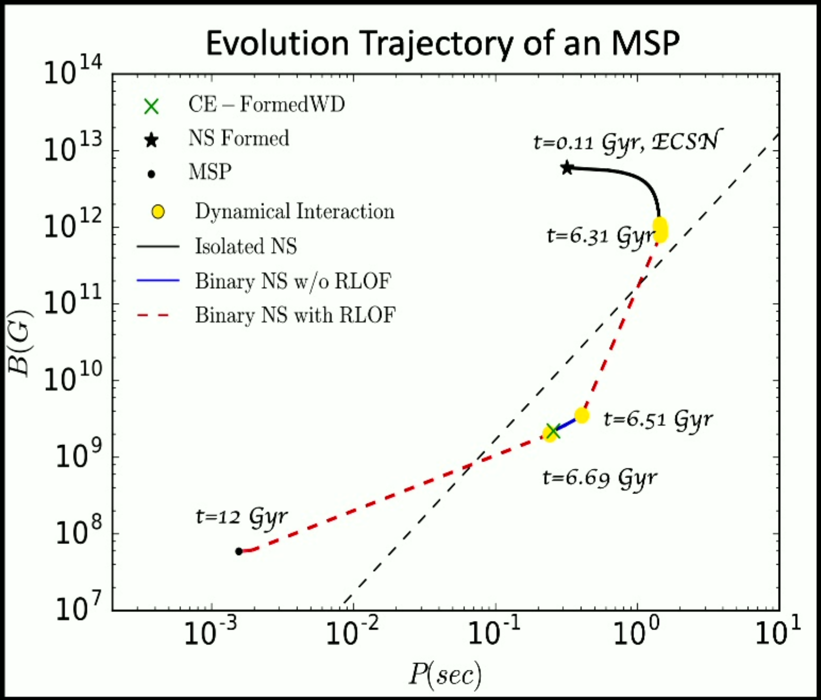
Ye et al. 2019

Dynamical Interactions enhance MSP formation

Retained NSs acquire companions through ***dynamical interactions***

MSPs are formed through ***extended periods of stable mass transfer from companions***

About ***70%*** of the MSPs are formed from NSs with dynamically influenced evolution



Ye et al. 2019

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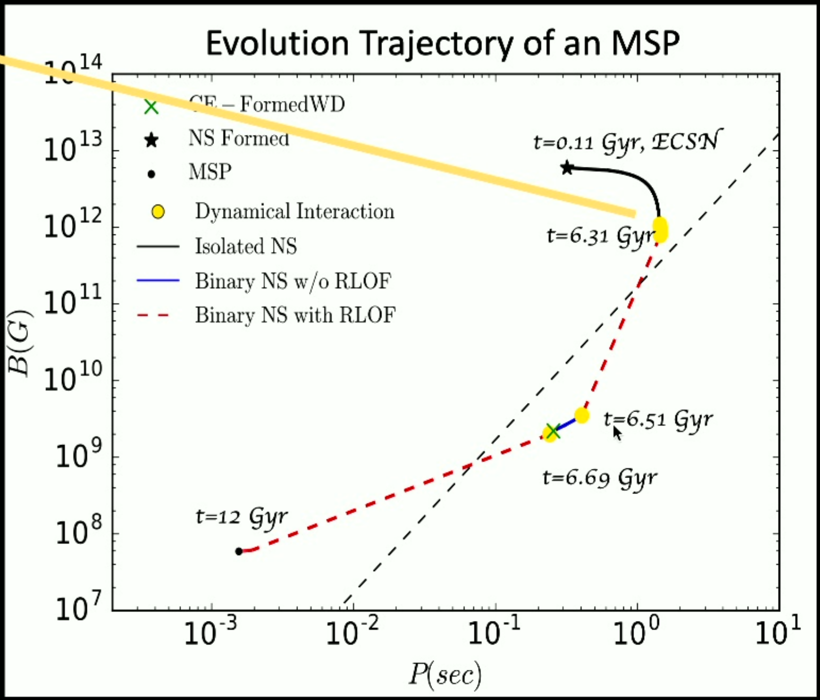

Ye et al. 2019

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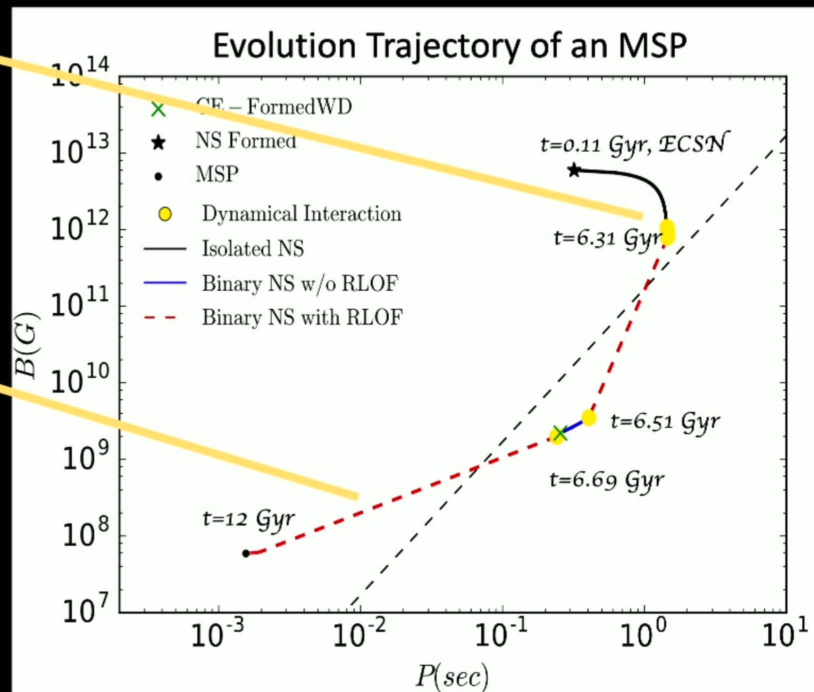
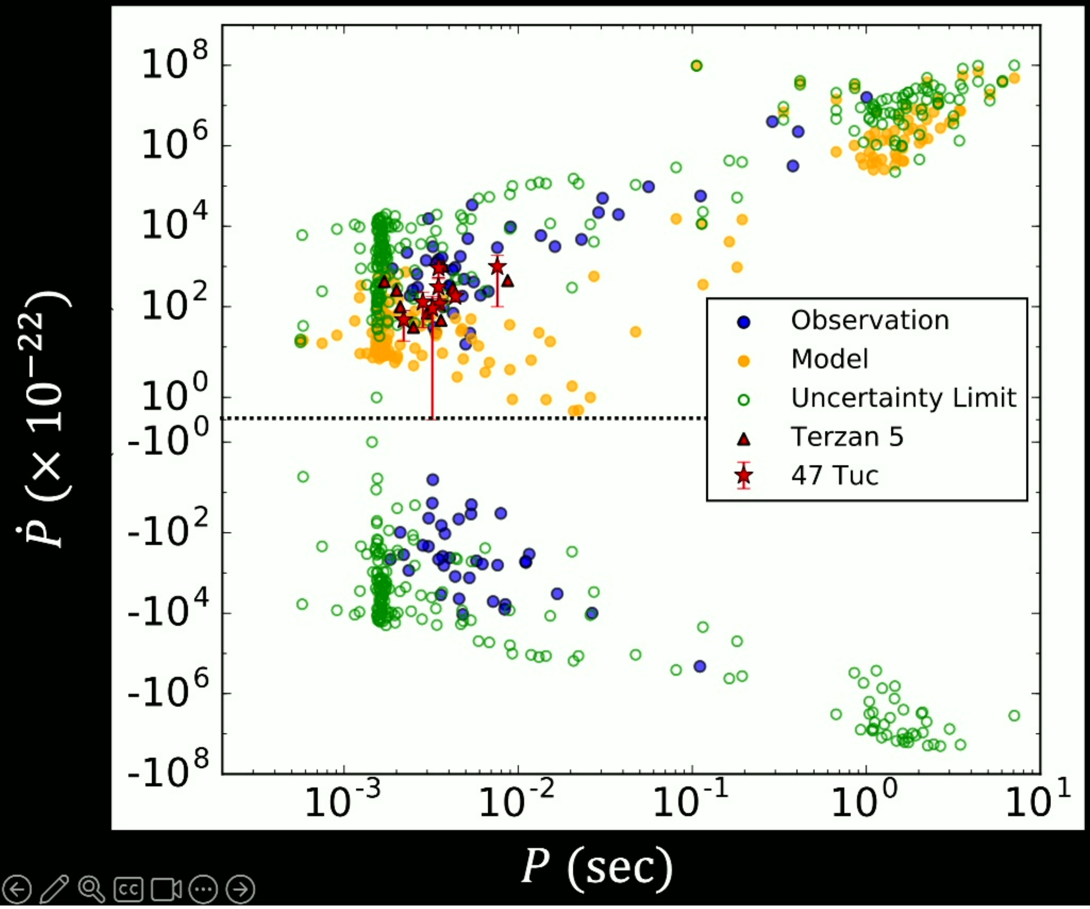


Ye et al. 2019

Models match well with observations



$$\frac{\dot{P}_{obs}}{P_{obs}} = \frac{\dot{P}_{int}}{P_{int}} + \frac{a_l}{c}$$

$$a_l > 0 \text{ or } < 0$$

Ye et al. 2019

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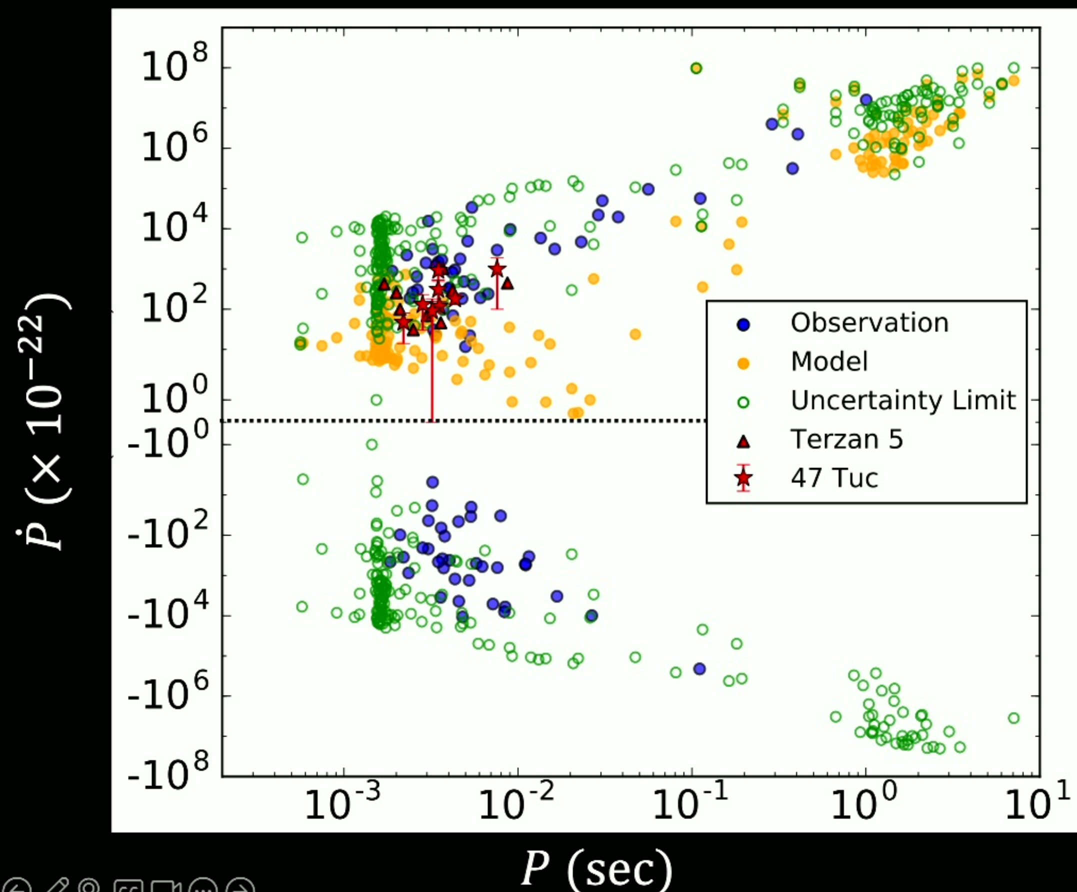


Cluster potential

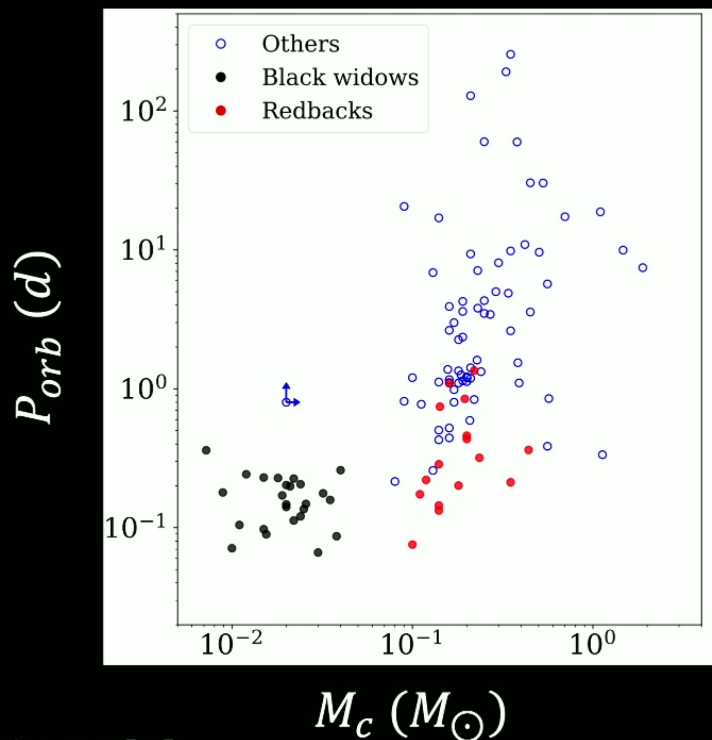
$$\frac{\dot{P}_{obs}}{P_{obs}} = \frac{\dot{P}_{int}}{P_{int}} + \frac{a_l}{c}$$

$$a_l > 0 \text{ or } < 0$$

Ye et al. 2019

2) How to Form Different Types of MSP Binaries?

Observed MSP binaries in GCs



- He WD (~70)

Collision of Giants?

- Black widow (26)

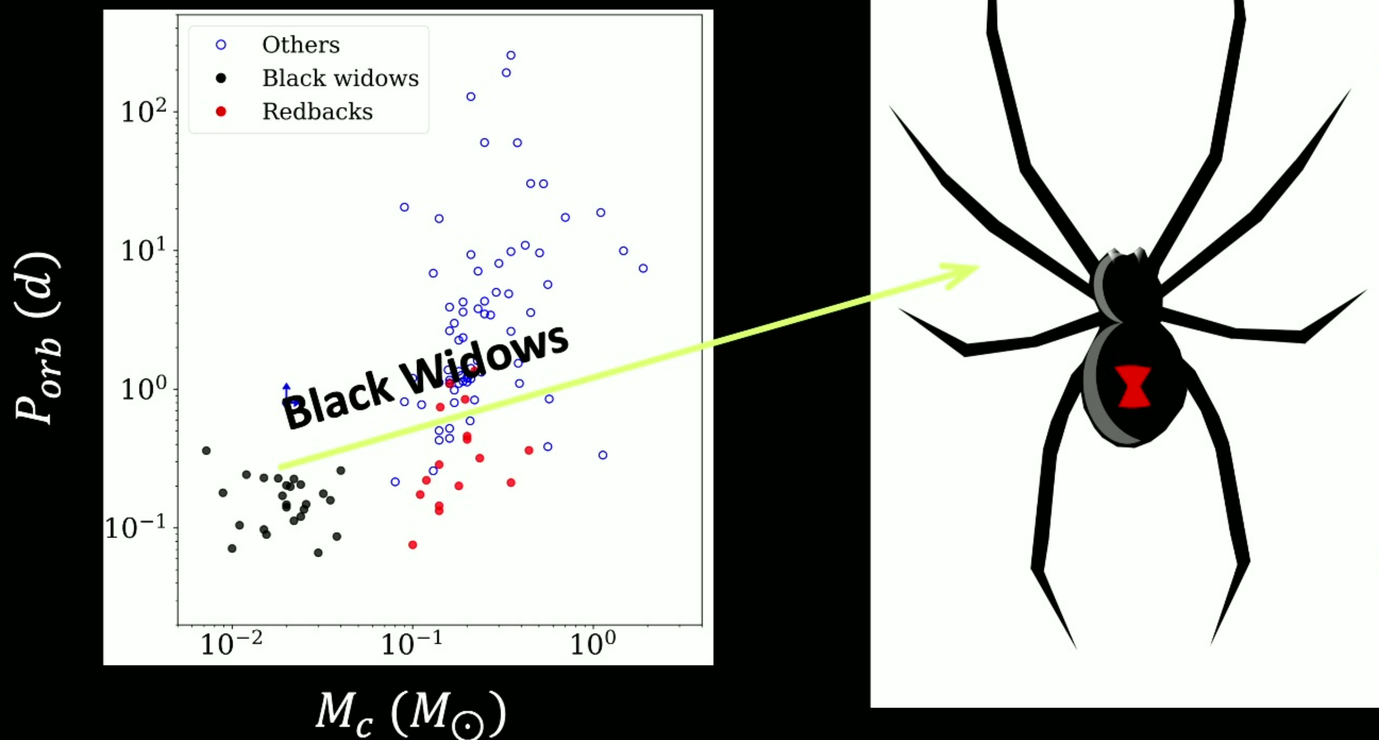
Most of the systems in our simulations.

- Redback (17)

Tidal Capture of NSs and MS stars?

2) How to Form Different Types of MSP Binaries?

Observed MSP binaries in GCs



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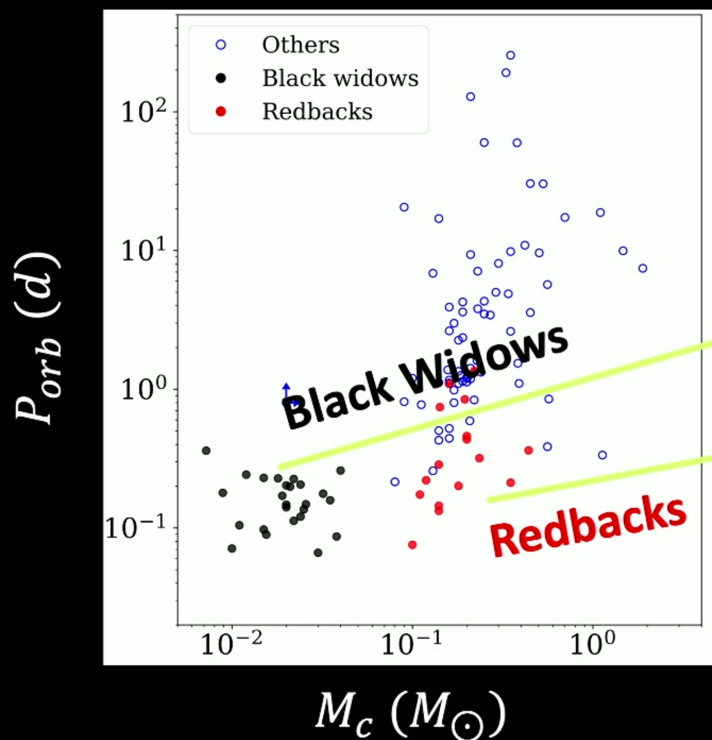
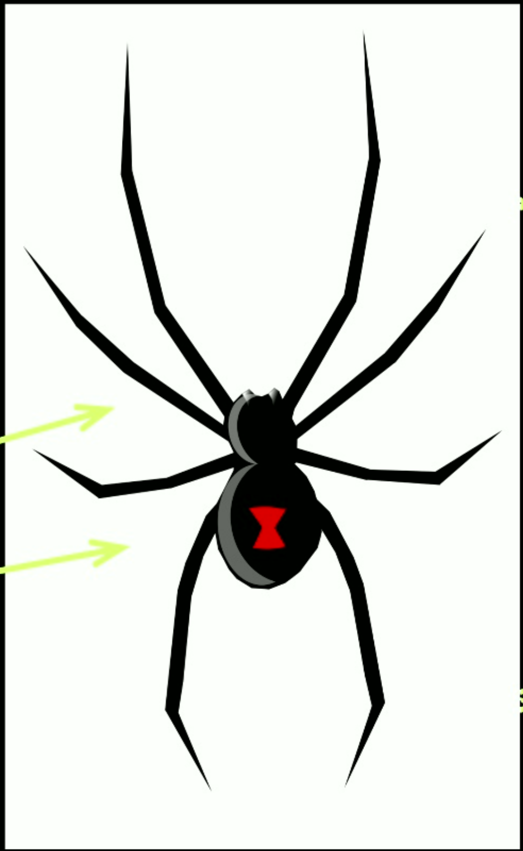




Single-single tidal capture

-> neutron star + main-sequence star?

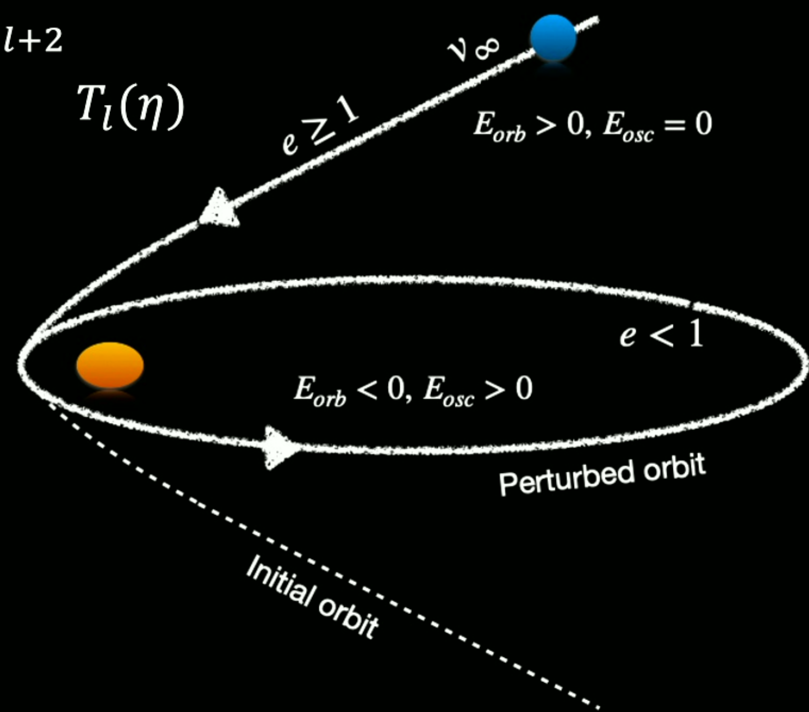
$$E_{osc} = \frac{GM_*^2}{R_*}\left(\frac{M}{M_*}\right)^2 \sum_{l=2}^{\infty}\left(\frac{R_*}{R_{peri}}\right)^{2l+2} T_l(\eta)$$

➕

$$E_{osc} > \frac{1}{2}\mu v_\infty^2$$

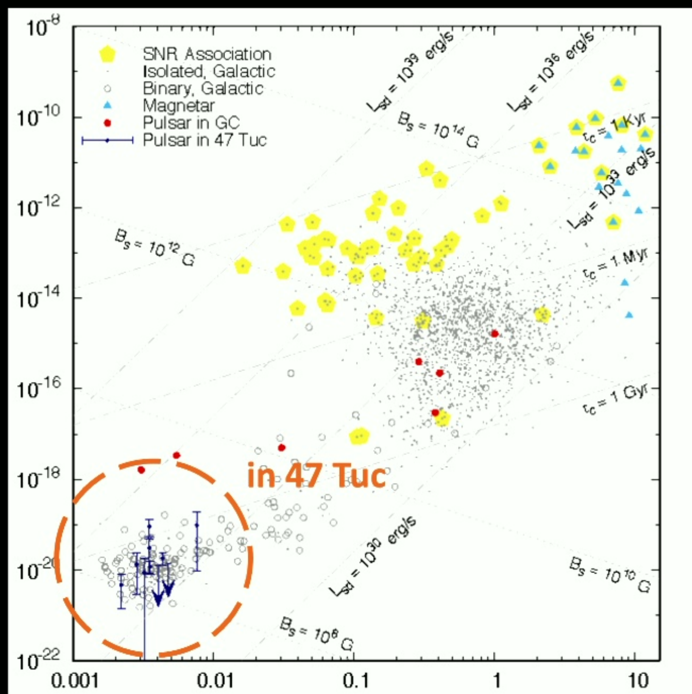
⬇

Stars are bound



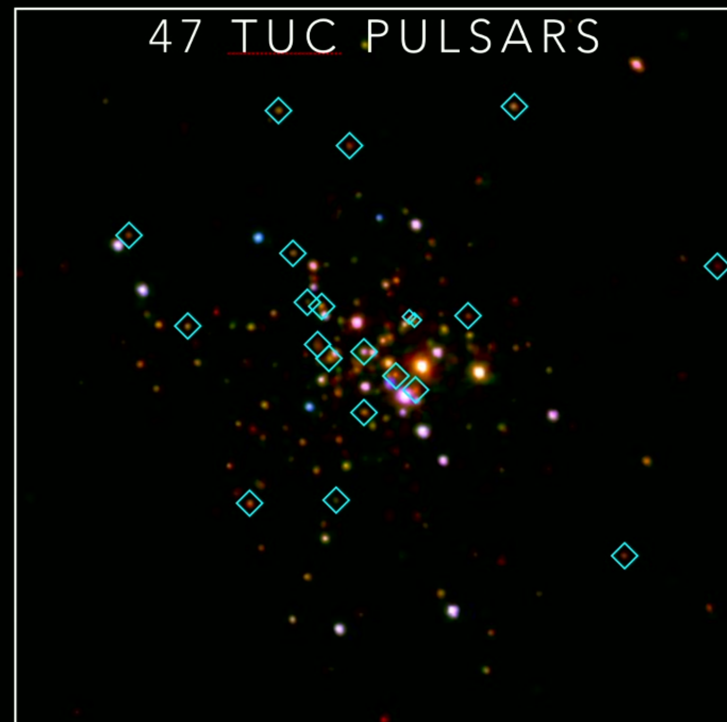
Fabian, Pringle & Rees1975, Press & Teukolsky1977, Lee & Ostriker 1986

Example:
Modeling 47 Tucanae and its pulsar population



$\dot{P}$

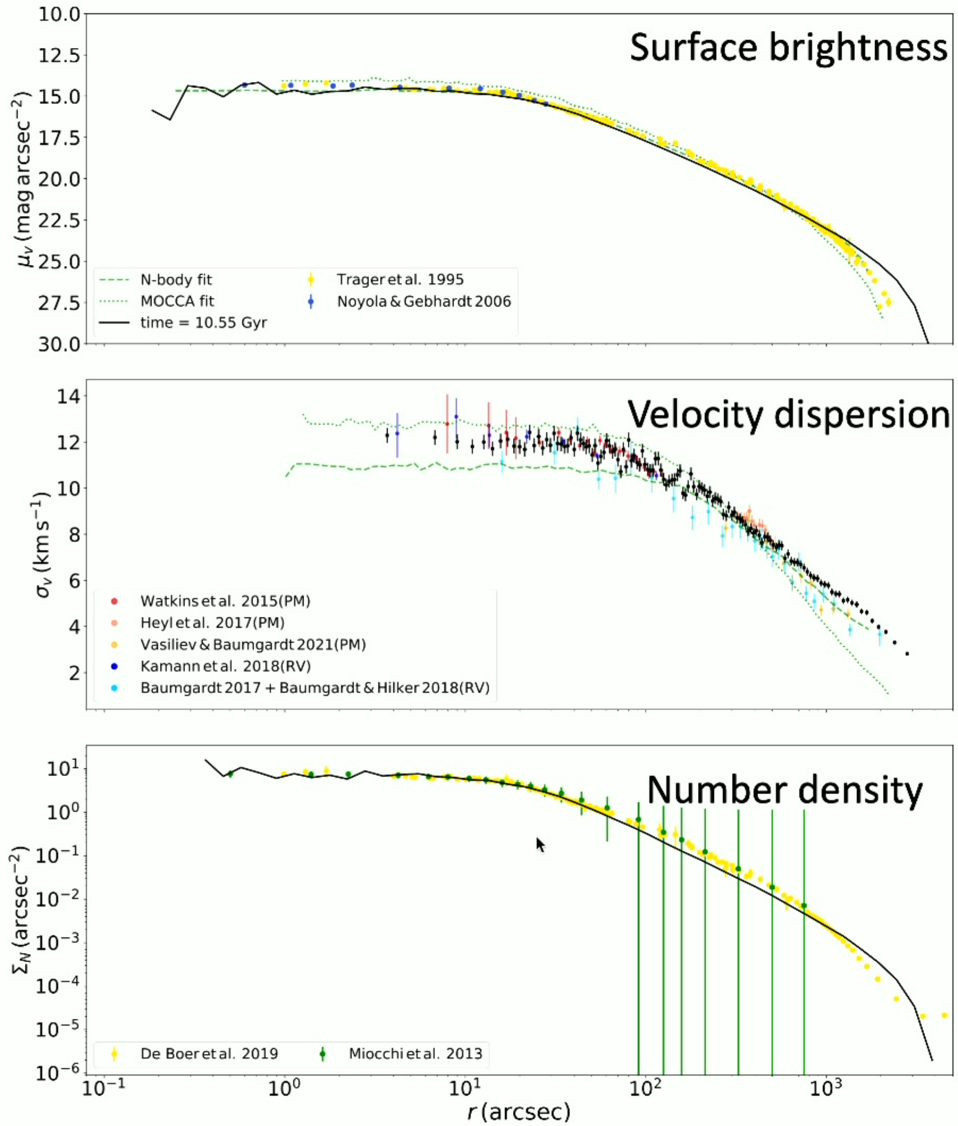
$P\ (sec)$



X-ray map showing pulsars.

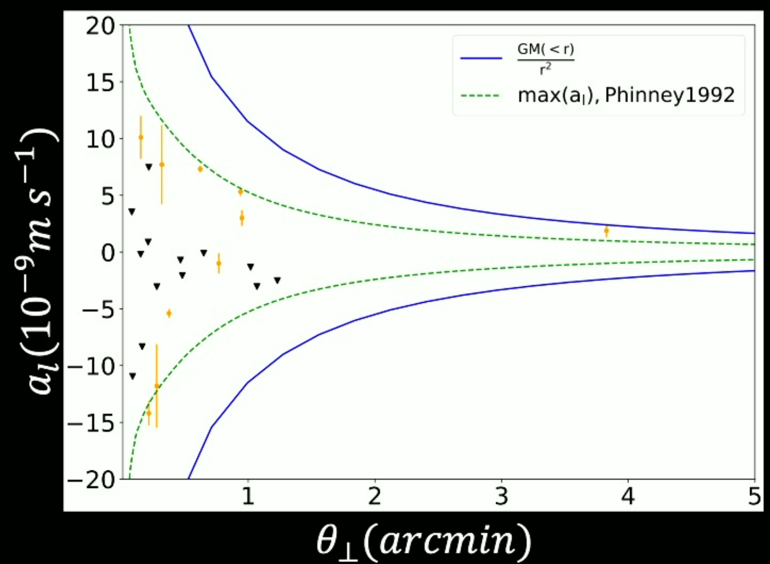
Credit: Craig O. Heinke

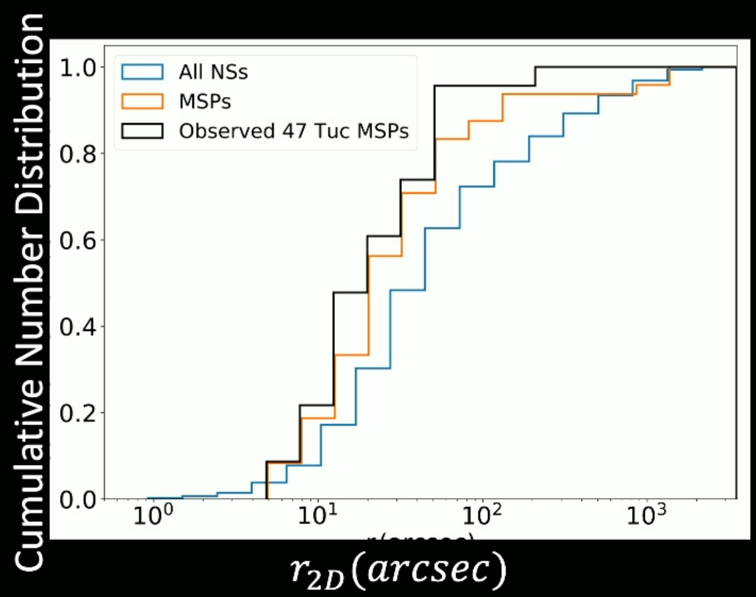
The 47 Tuc model can match various observations simultaneously



Ye et al. 2022

Matching pulsar accelerations and radial distribution

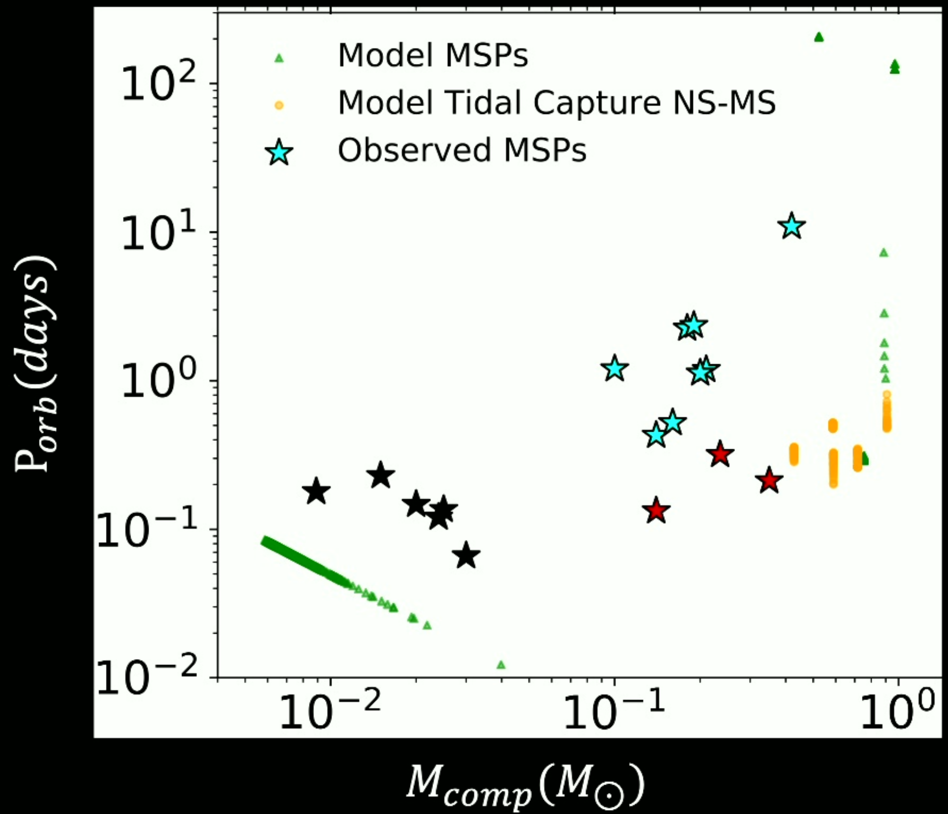




$$\max|a_l| \approx 1.1 \frac{GM_{cyl}(< R_\perp)}{\pi R_\perp^2}$$

Phinney 1992, Ye et al. 2022

Tidal capture likely produce redback millisecond pulsars



Ye et al. 2022

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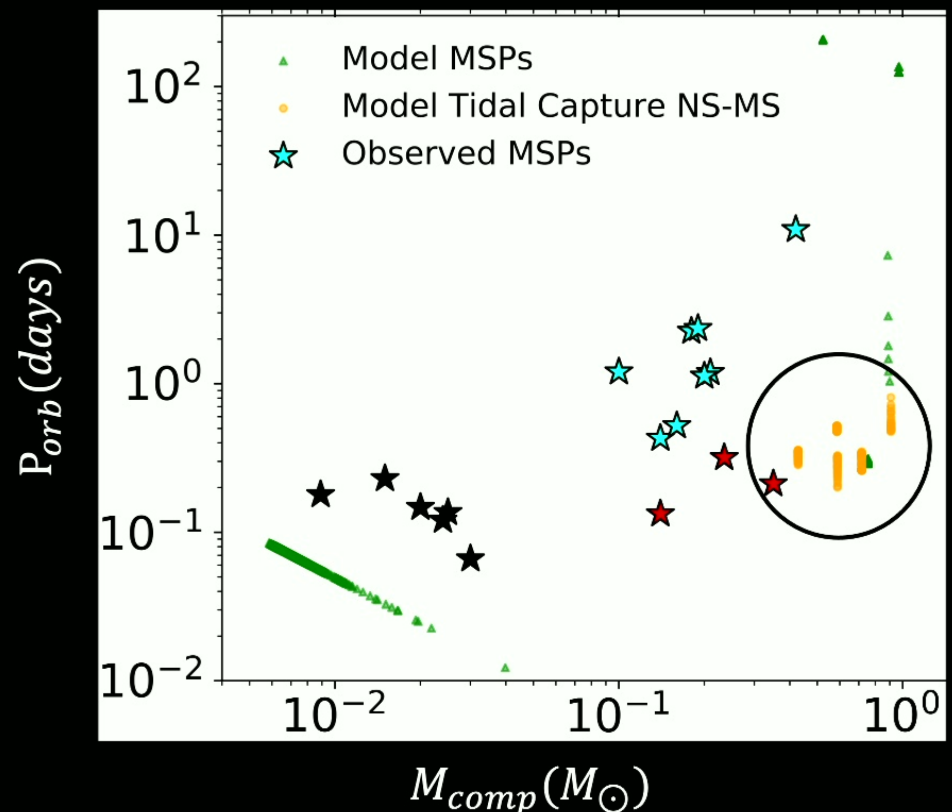
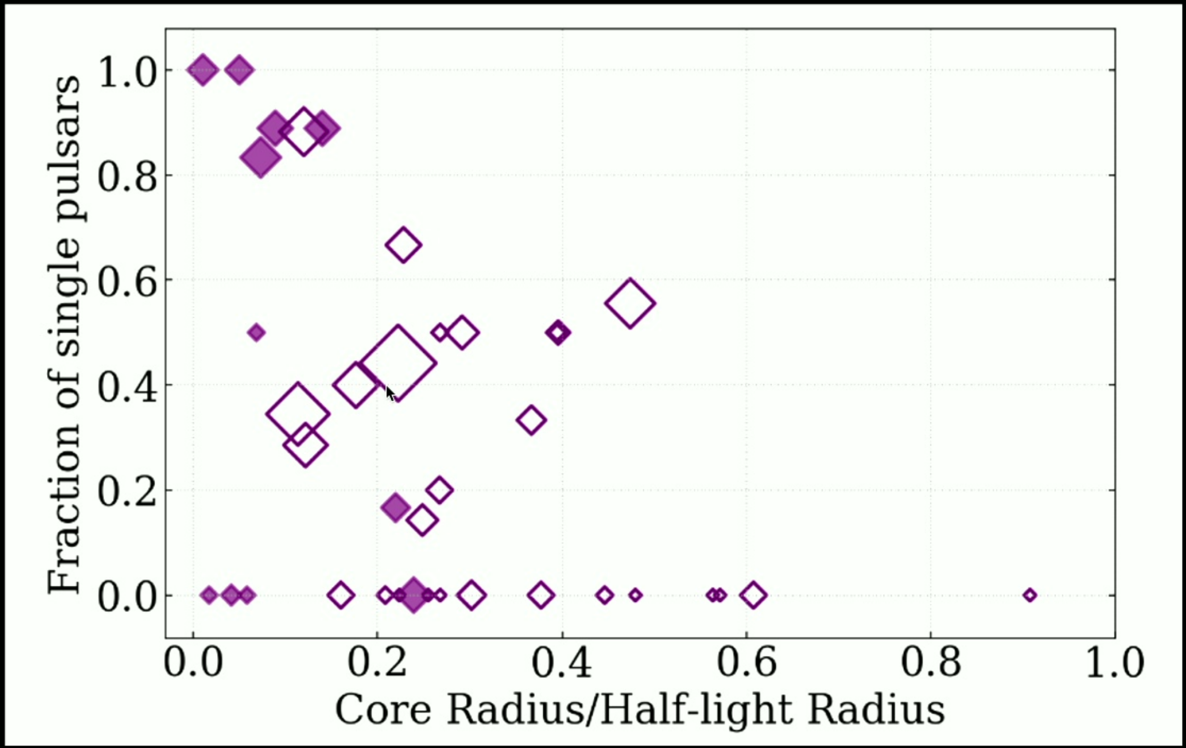


Ye et al. 2022

3) How to Form Single MSPs in Globular Clusters?



Observed denser clusters have higher fractions of single MSPs

Ye et al. arXiv:2307.15740

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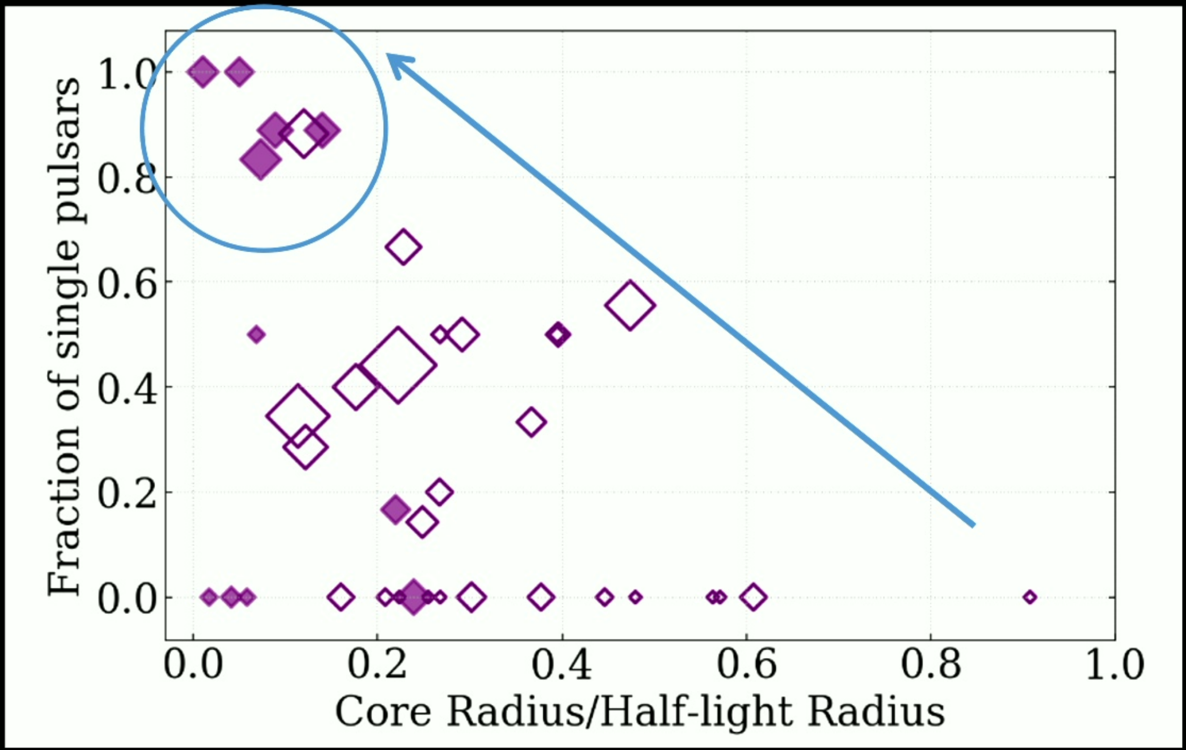

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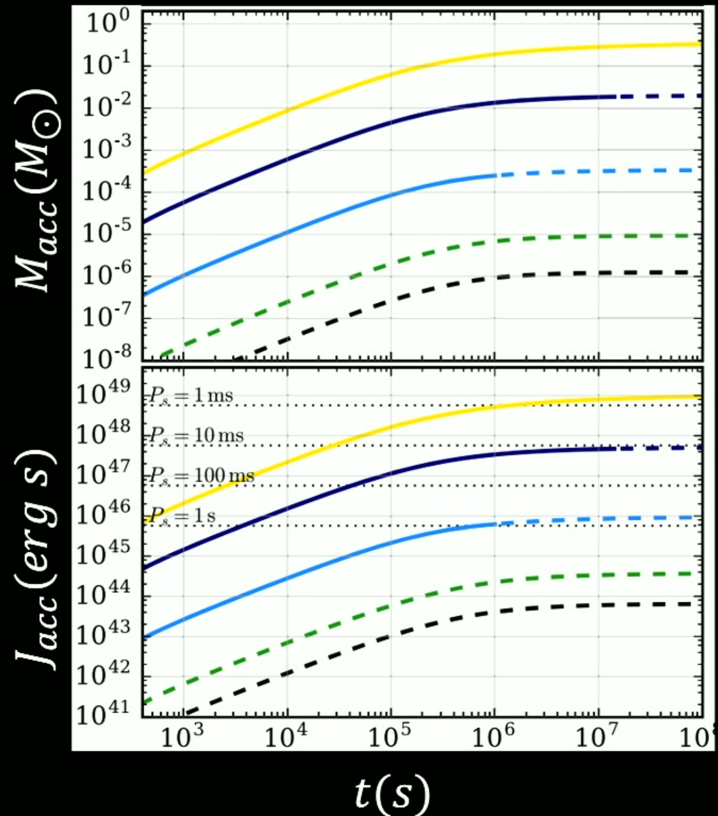
A few ways to form single MSPs

Spin-up of NSs during TDEs



Disruption of binaries
(Verbunt & Freire 2014)

Not enough

NS-main sequence star tidal disruption events (Kremer, Ye et al. 2022)

WD-WD collisions/mergers (Schwab 2021) enhanced by WD-WD tidal capture

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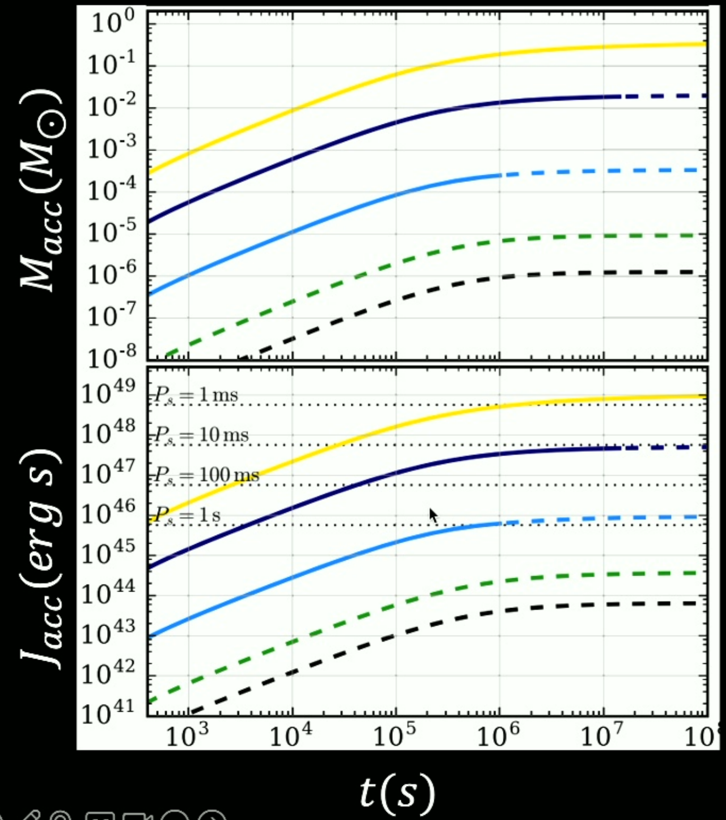

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Tidal disruption of a main-sequence star by a neutron star

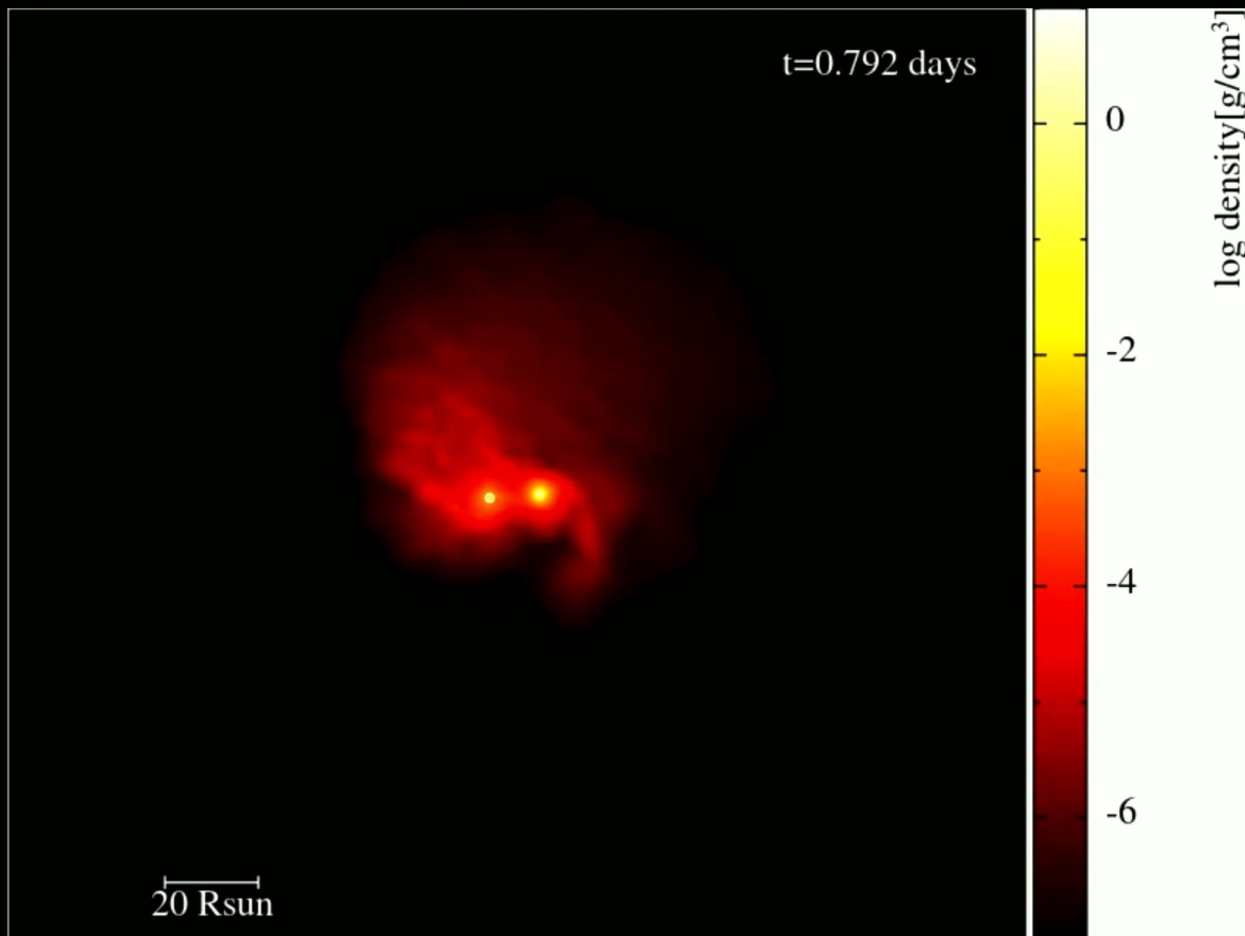
Simulation 6

$$M_* = 1.2\,M_\odot, \quad r_p / r_T = 1$$

Kremer, Ye et al. 2022

28

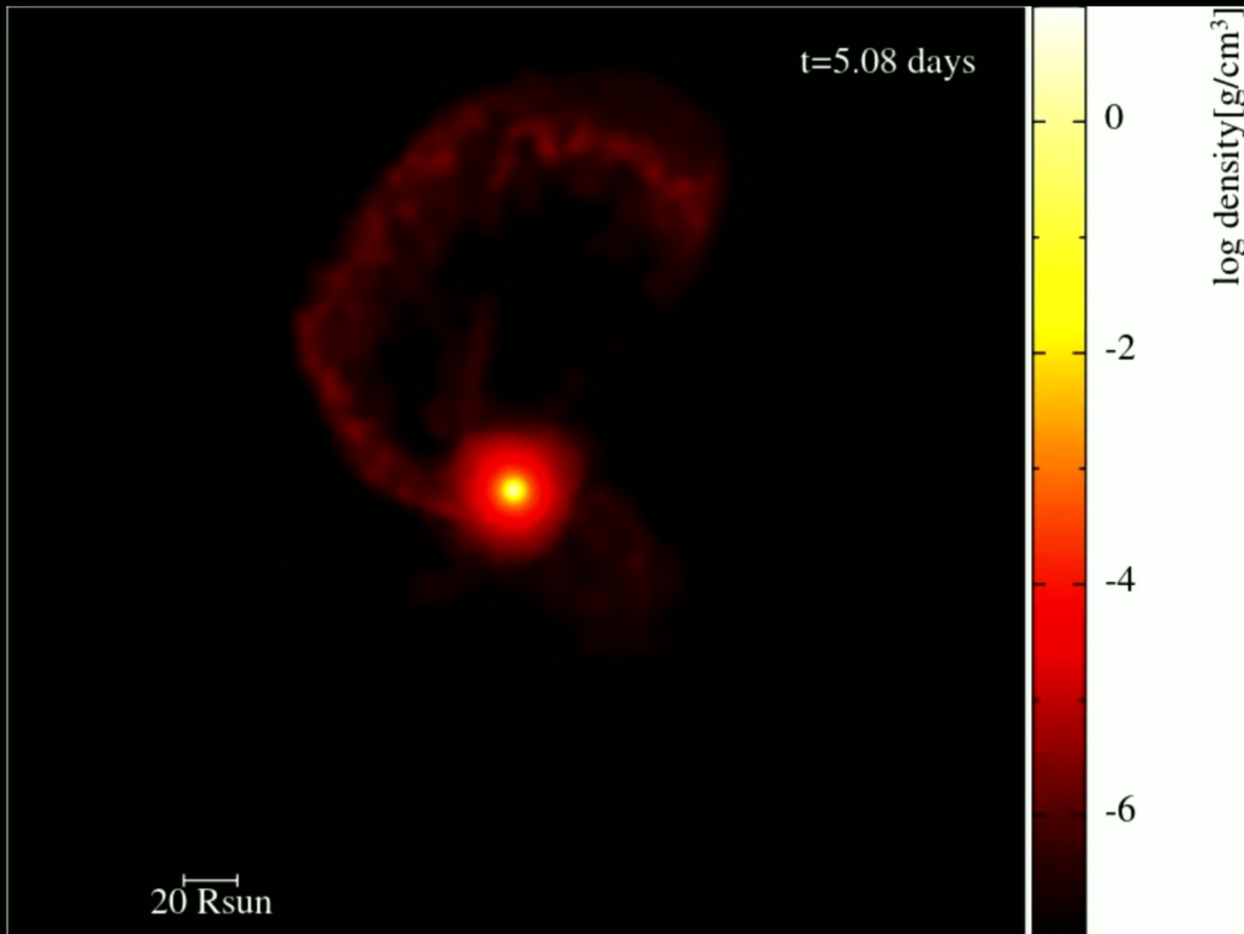
Tidal disruption of a main-sequence star by a neutron star



Kremer, Ye et al. 2022

28

Tidal disruption of a main-sequence star by a neutron star



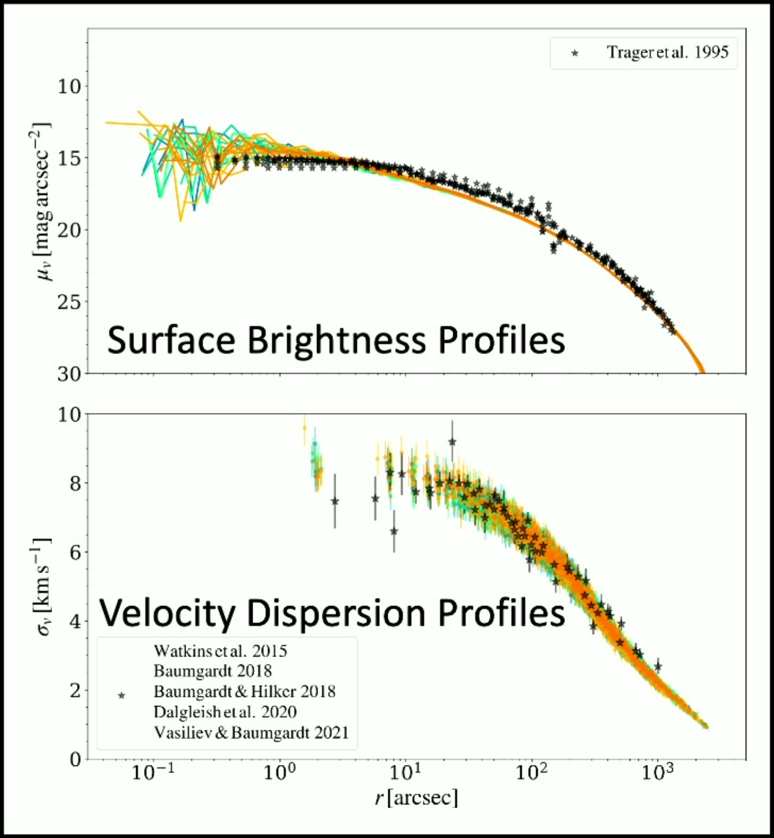
Kremer, Ye et al. 2022

28

Results: core-collapsed cluster NGC 6752

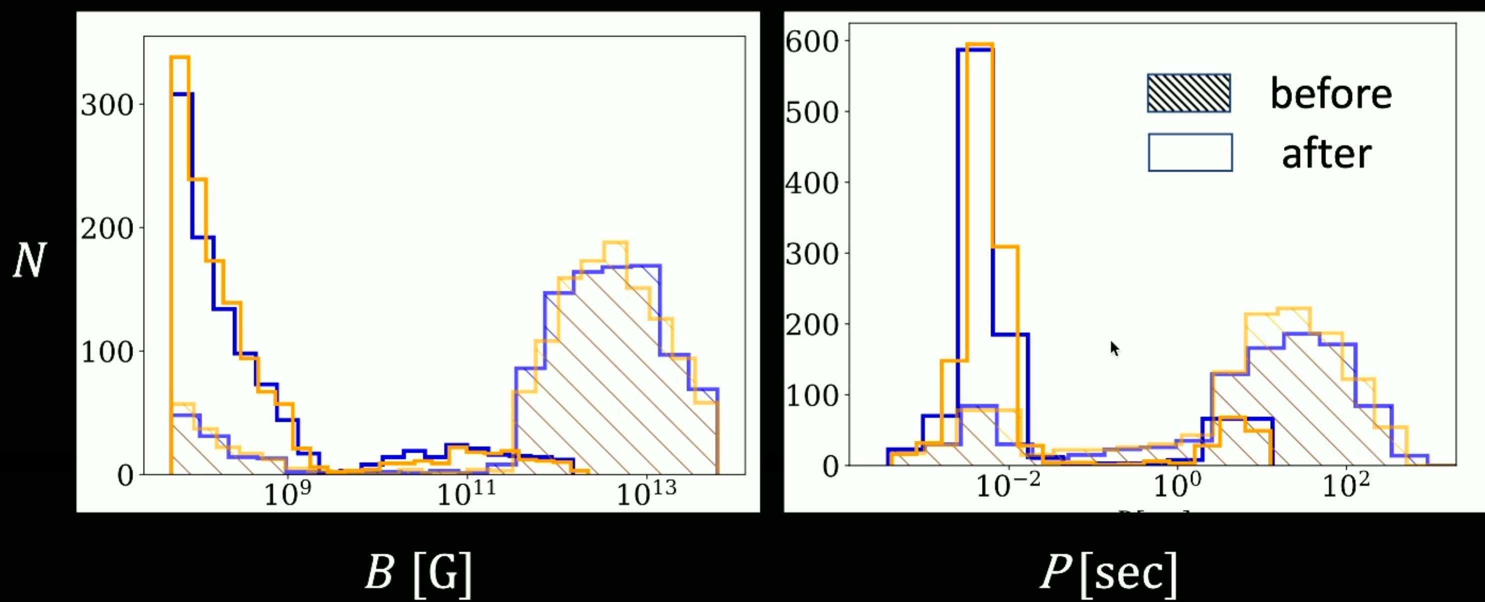
9 observed pulsars, all spinning in the millisecond periods

8 are single, and 1 is in a binary



Ye et al. arXiv:2307.15740

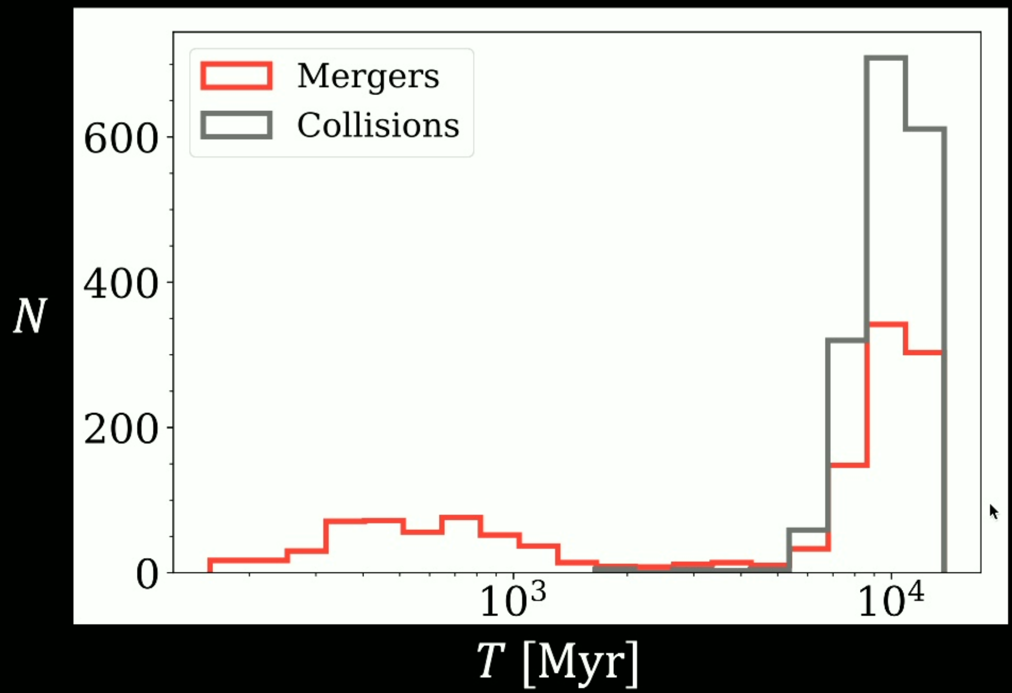
Spin up of neutron stars through tidal disruption and efficient accretion



Ye et al. arXiv:2307.15740

Many WD-WD collisions and mergers in dense clusters

18 models of NGC 6752



Ye et al. arXiv:2307.15740

NS TDEs and WD-WD coalesences can significantly increase the number of single MSPs

Model	# sMSP	# bMSP	Ratio
Obs.	8	1	8
Fiducial	6	8	0.8
TDE	78	8	9.8
WD+WD	84	11	7.6
TDE+(WD+WD)	149	12	12.4

WD-WD coalescences may also produce fast radio burst sources or type Ia supernovae?

Conclusions

1. **How to form millisecond pulsar in globular clusters?**
   - Electron-capture supernova is important for NS retention in GCs.
   - Dynamical interactions greatly enhance MSP formation rates.

2. **Where do spider pulsars come from?**
   - Tidal captures lead to redbacks.

3. **Why some millisecond pulsars are isolated?**
   - NS tidal disruption events and WD tidal captures can increase the number of isolated MSPs.

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