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Royal Astronomical Society

Tracing the orbital evolution of binaries within the Milky Way

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Ongrave

Contents

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Part 1 - Background

Open questions to answer:

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1. How many compact binaries are in the MW?
2. What fraction of neutron star binaries have pulsars?
3. How do spiders form?
4. Can we optimise search strategies?

YOUR QUESTIONS HERE!

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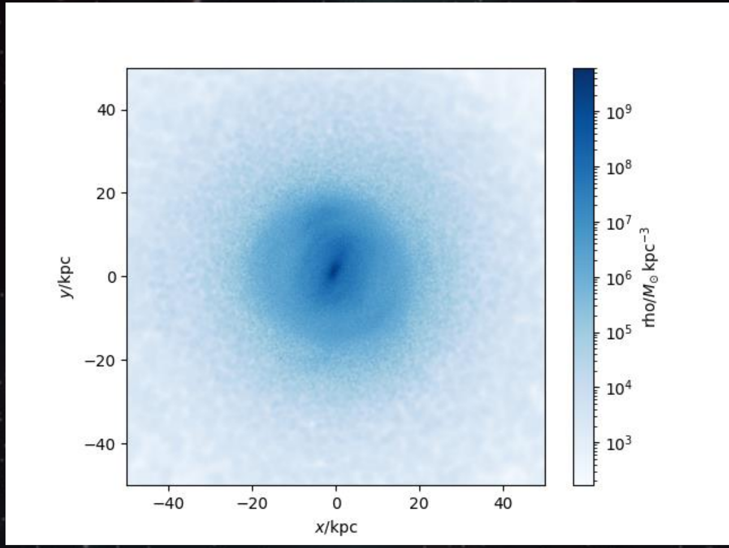
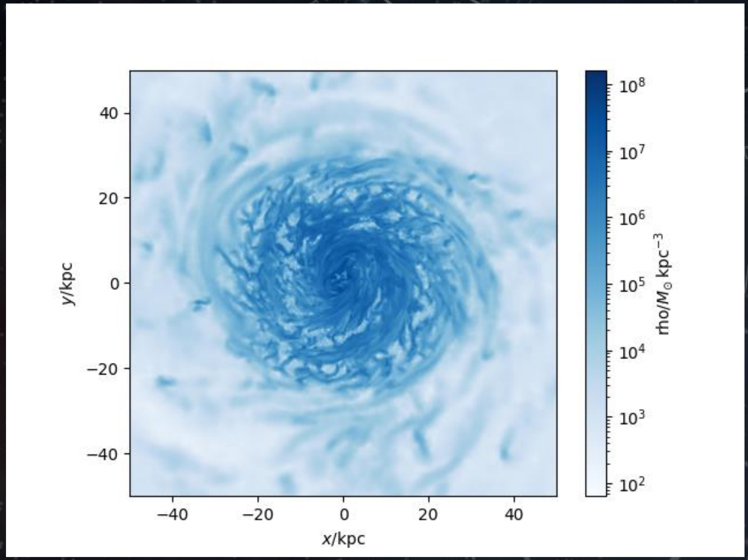
Key aims:

1. Evolving binaries in detailed galaxy potential
2. Explore the zoo of binaries (NSNS/WDWD/NSWD/etc.)
3. Probing Spiders (case study) evolutionary channel



Stellar



Gas

(Using AURIGA – See Grand et al., 2017)

Generating Binary Orbits

Evolving Binary Orbits with OCARINA (Orbital Characterisation of binARIes iN gAlaxies)

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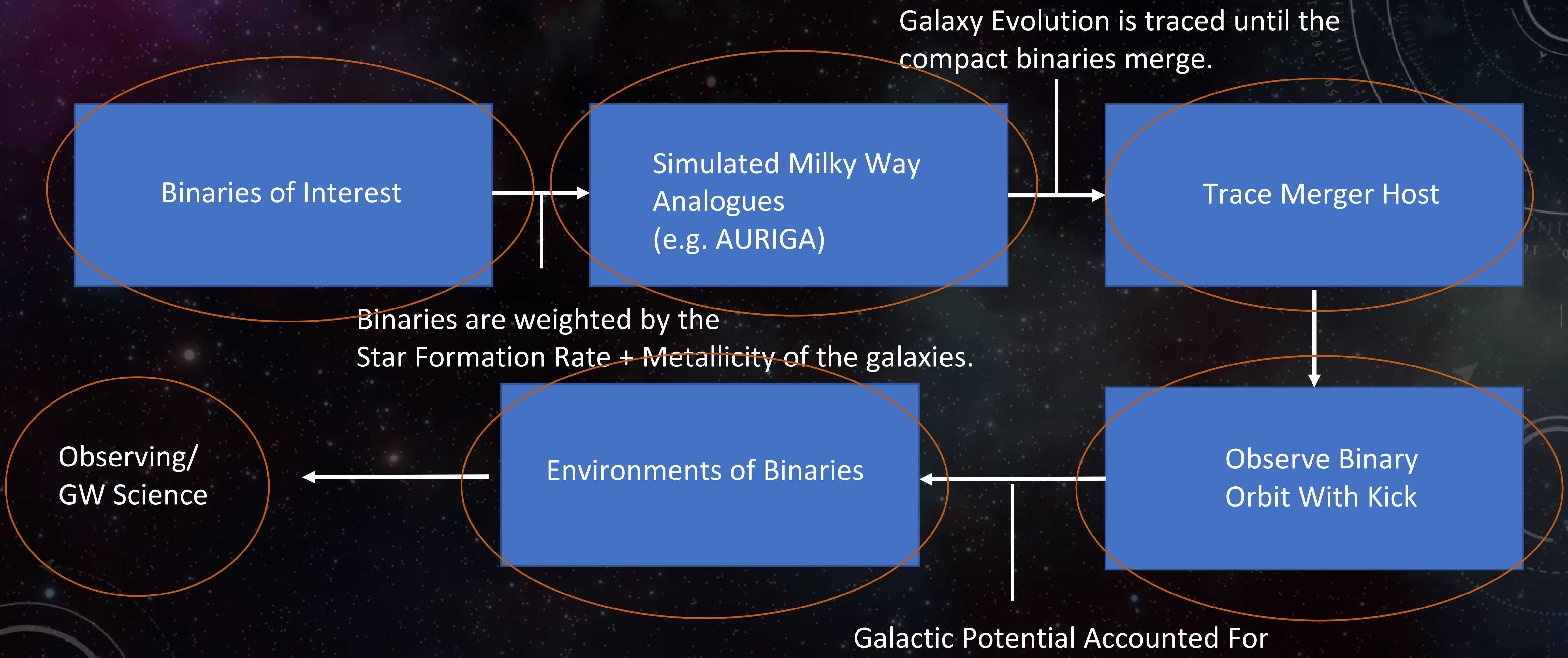
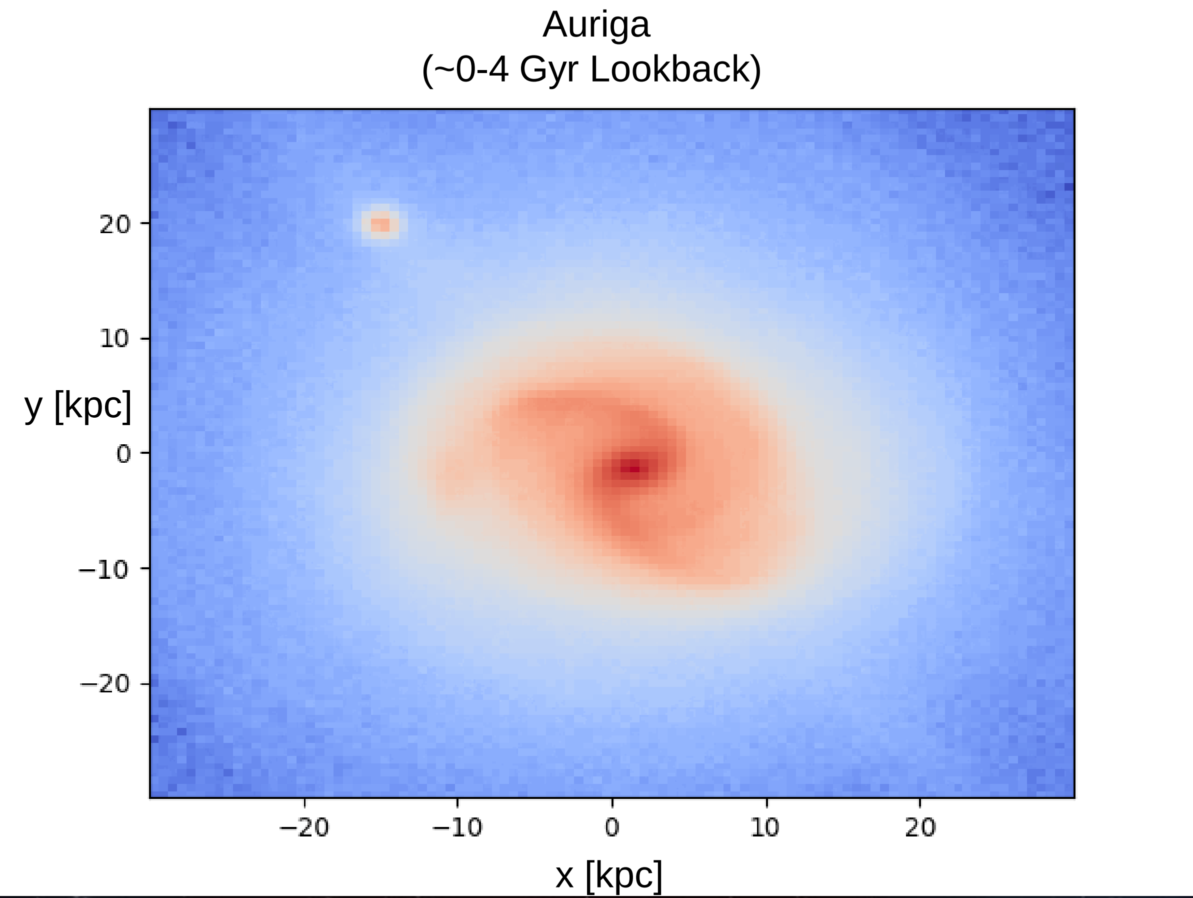


Ingredients

- Population Synthesis Code:
  - BPASS
    - Using Bray & Eldridge, 2016 Configurations
    - NS-NS and BH-NS binaries
  - COSMIC
    - NS+, WD+, BH+
- Cosmological Simulation – EAGLE (Schaye et al., 2014)/Auriga (Grand et al., 2017)/*Gadget 2 derivatives (Springel et al.,)
- zELDA – Redshift Electromagnetic Localisation & Deduction Algorithm (Mandhai et al., 2022)
- Metallicities (Z):
  - 0.004
  - 0.013
  - 0.02



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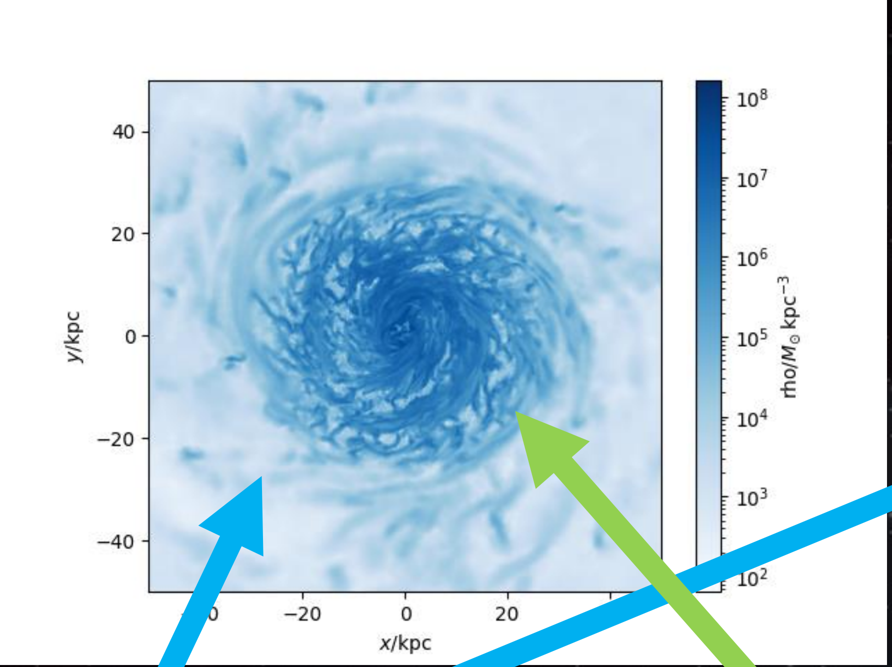
Galaxy Simulation:

Gas



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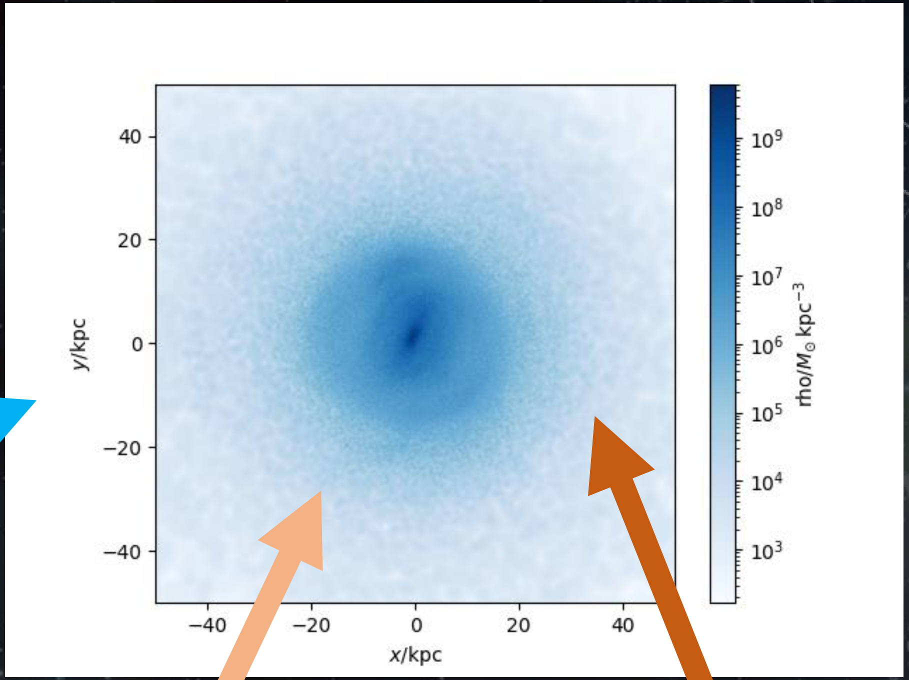


Metallicity

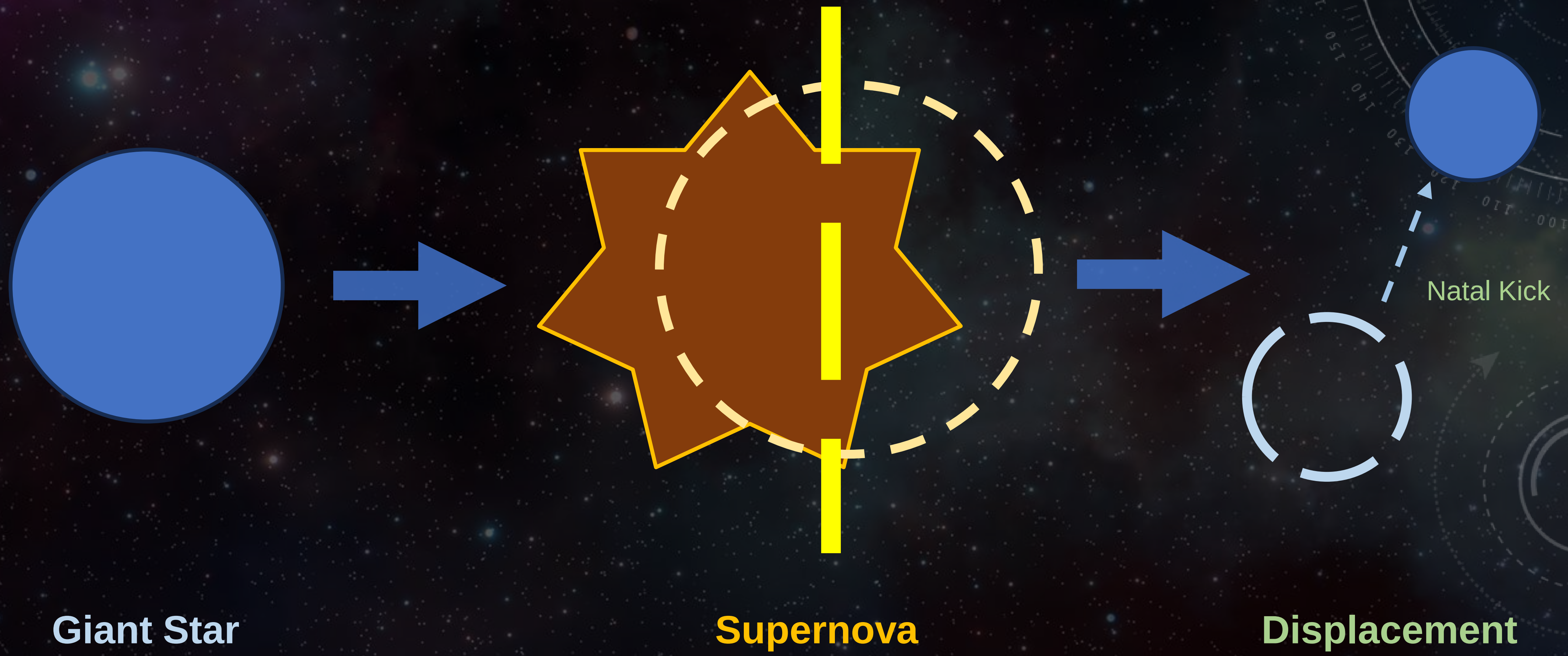
Star Formation

Density

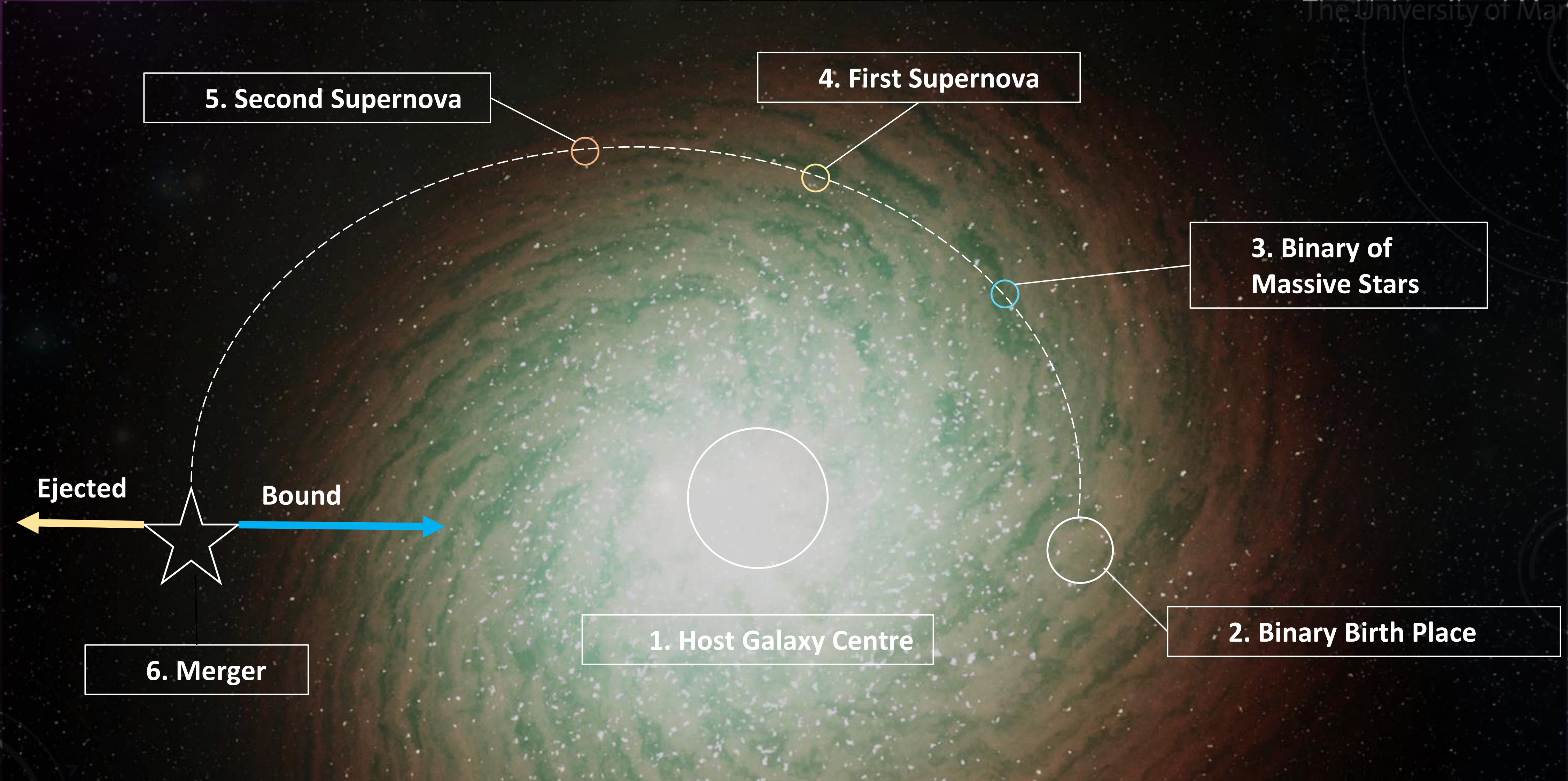
Velocity

(Using AURIGA – See Grand et al., 2017)

Natal Kicks



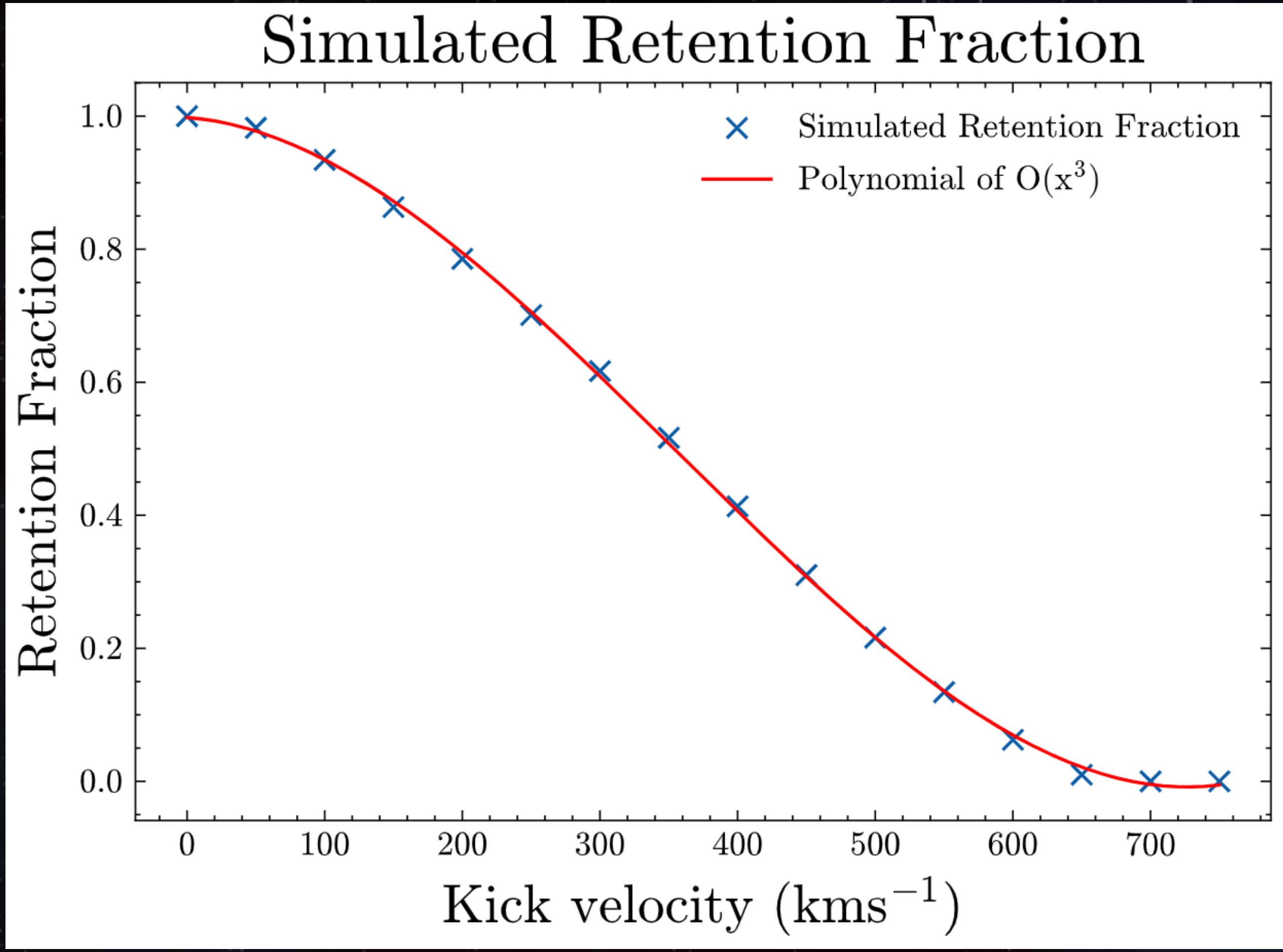
zELDA/OCARINA (Orbital Characterisation of binARIes iN gAlaxies) Schematic:



Orbital Evolution Summarised

- Galaxy simulation broken down into 3 major components:
- Stellar
- Gas
- Dark Matter Halo
- Simulation -> Semi-Analytical Interpolated Potential
- Objects evolved using **galpy (Bovy et al.,)**

BUT WHAT ABOUT KICKS?



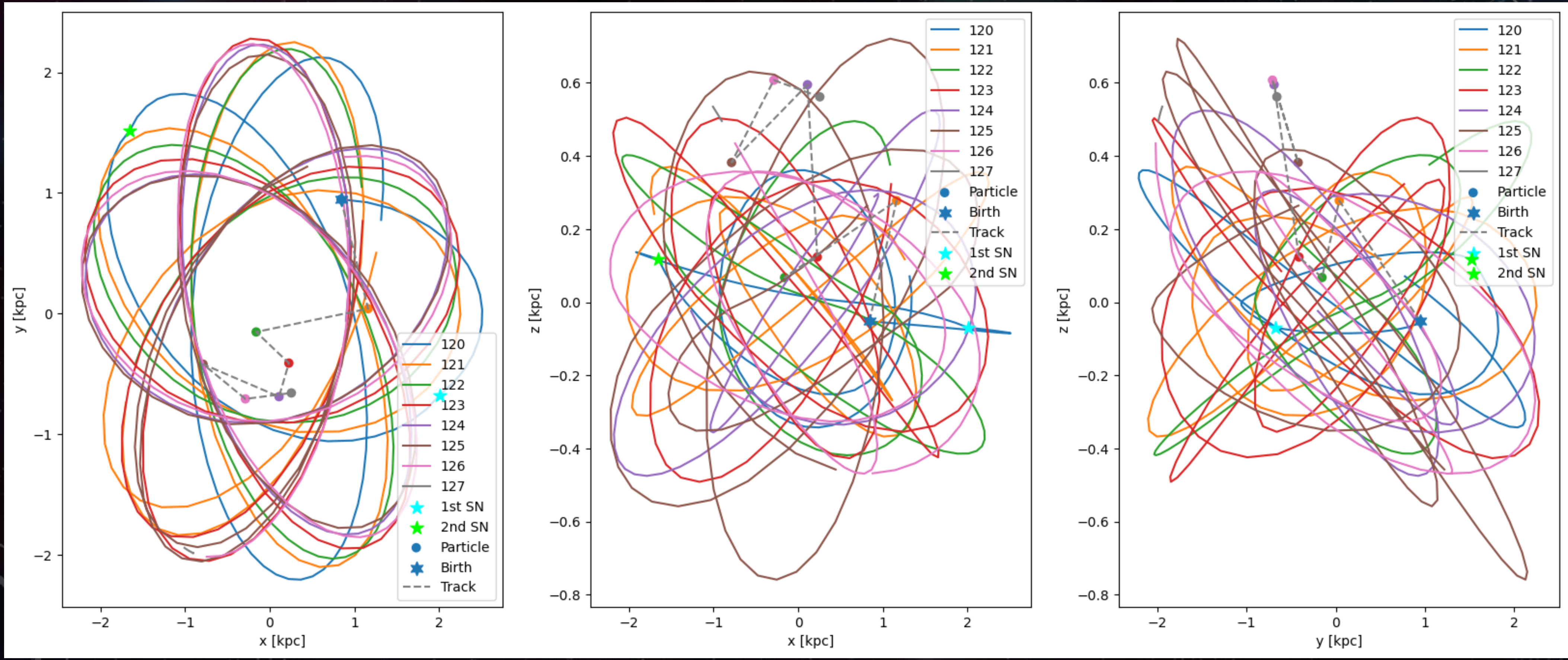
Credit: Mark Janosdeask

WORLD PREMIER

(cue excitement)

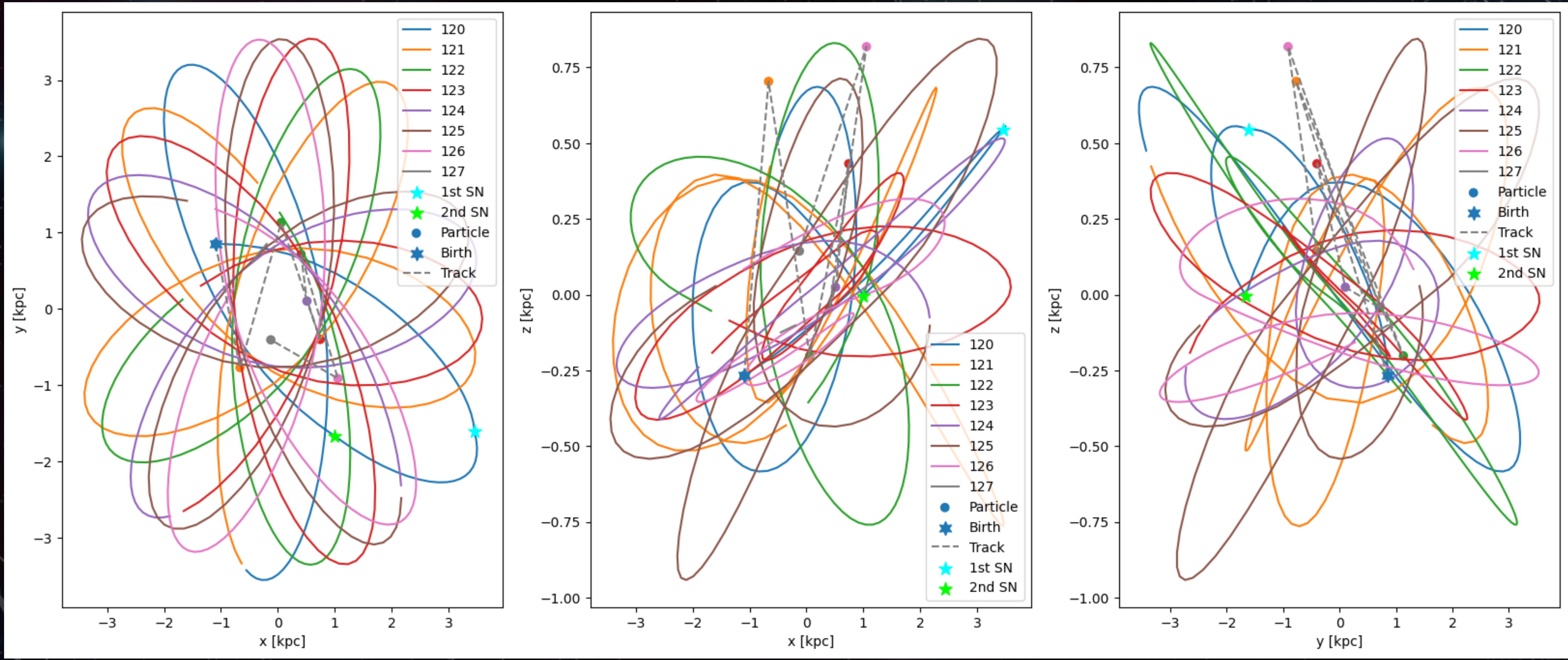
OCARINA Preliminary Results

- Case: Weak Kick (~50 km/s and ~50 km/s)



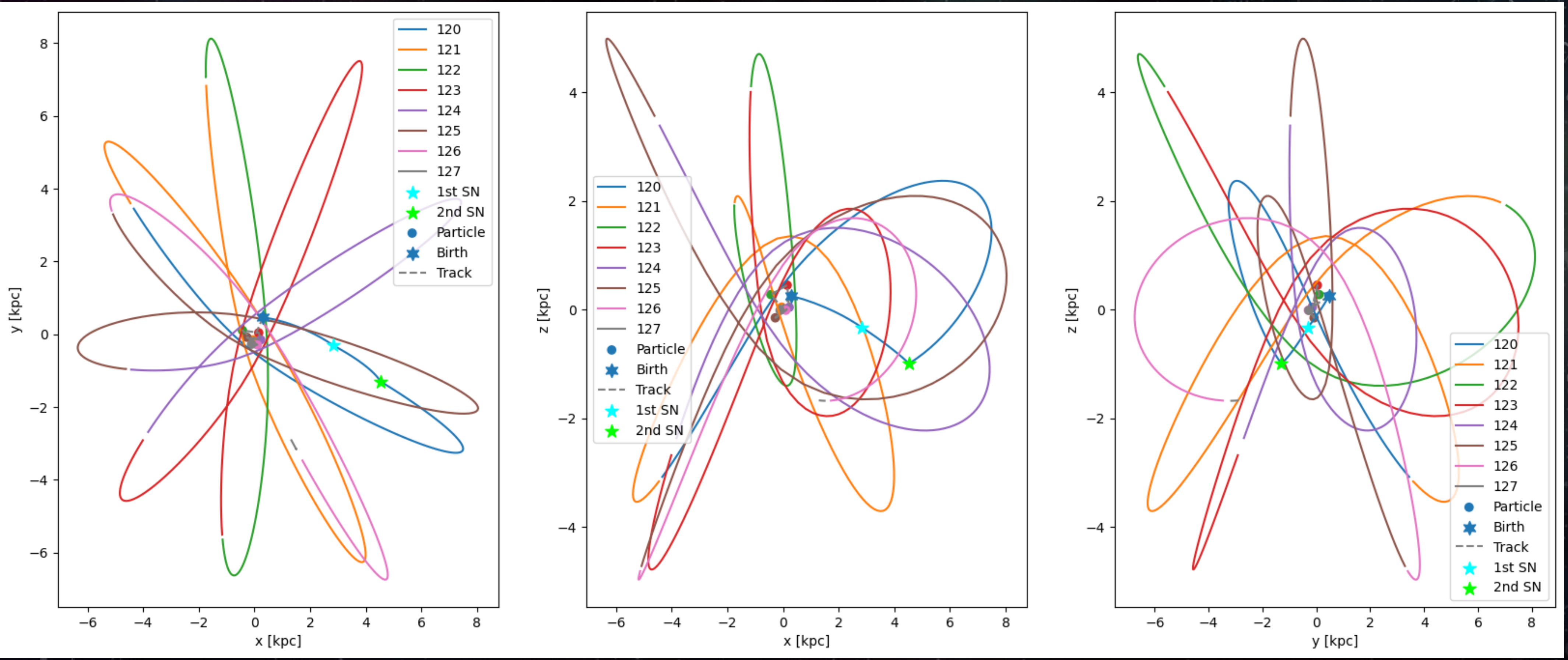
OCARINA Preliminary Results

- Case: Moderate Kick (~30 km/s and ~100 km/s)



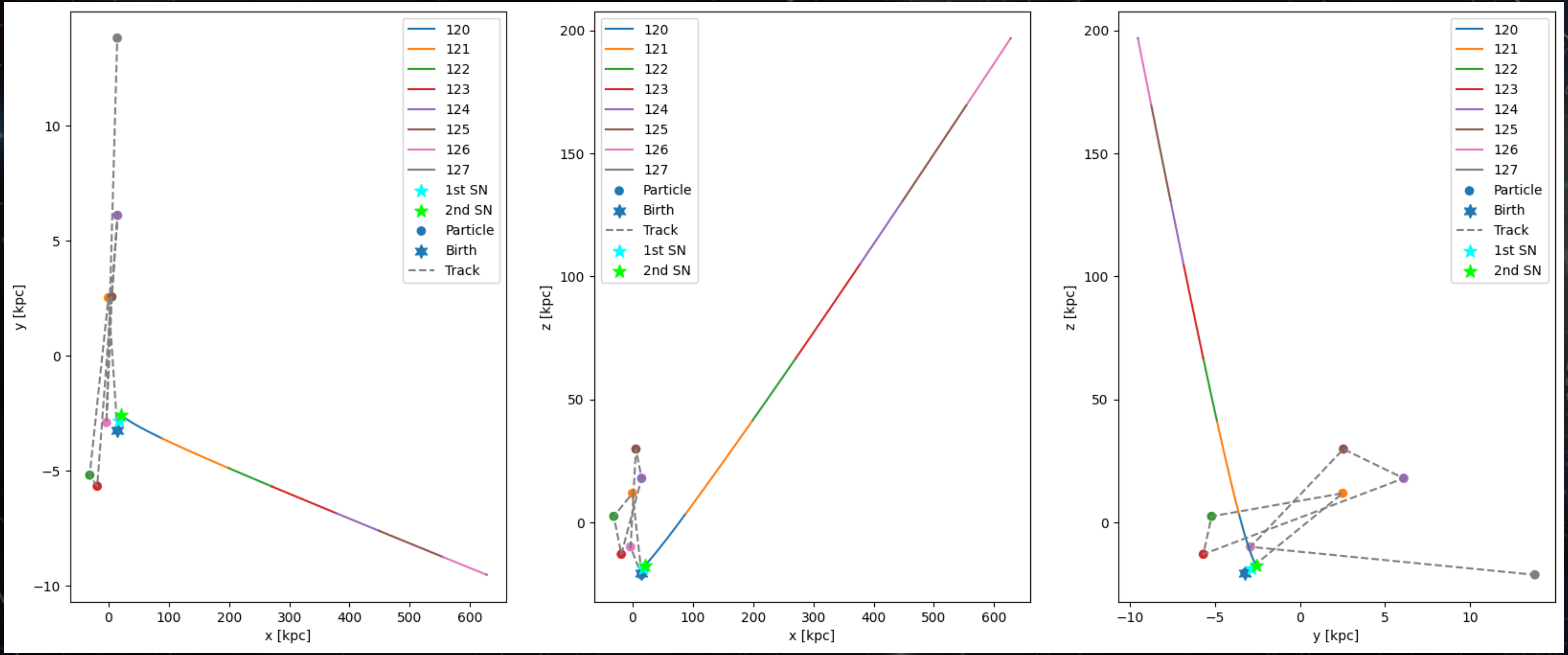
OCARINA Preliminary Results

- Case: High Kick (~70 km/s and ~200 km/s)



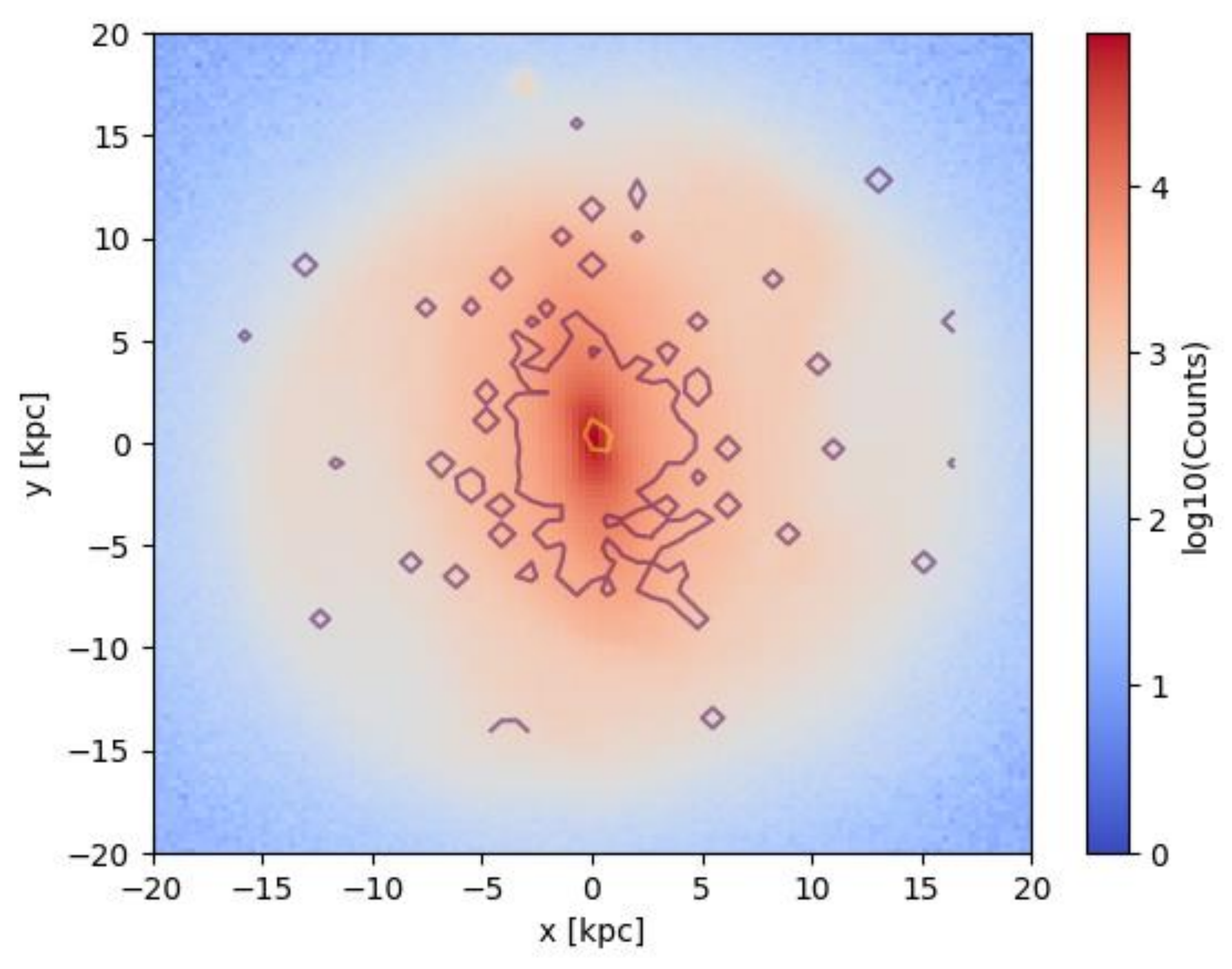
OCARINA Preliminary Results

- Case: EXTRMELY High Kick (~70 km/s and ~360 km/s)



Spatial Distributions of Binaries

- Distribution of seeded binaries 1 Gyr ago (N~2000)



Spatial Distributions of Binaries

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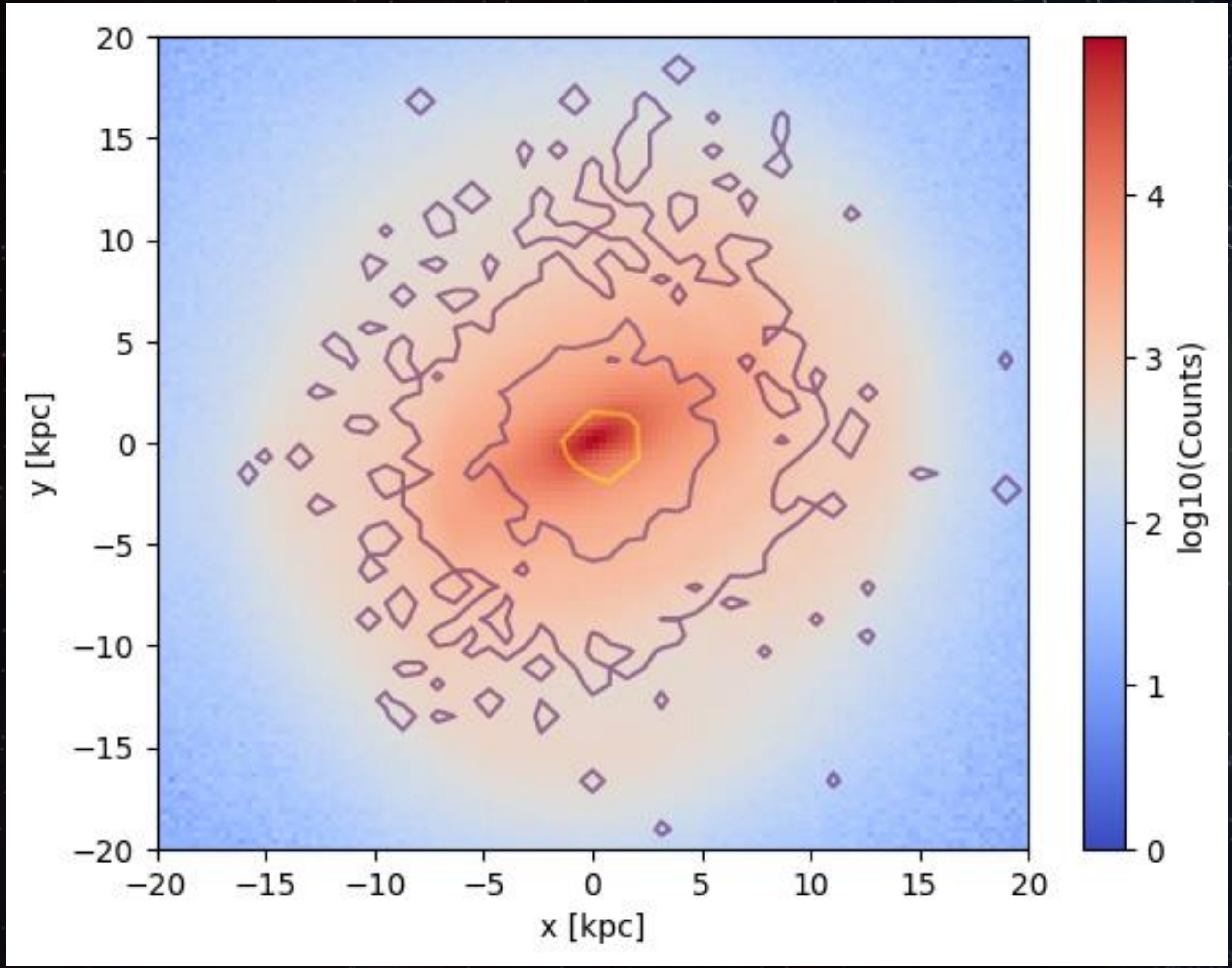
- Binaries evolved into the current epoch (z~0)



Kicked vs Non-Kicked

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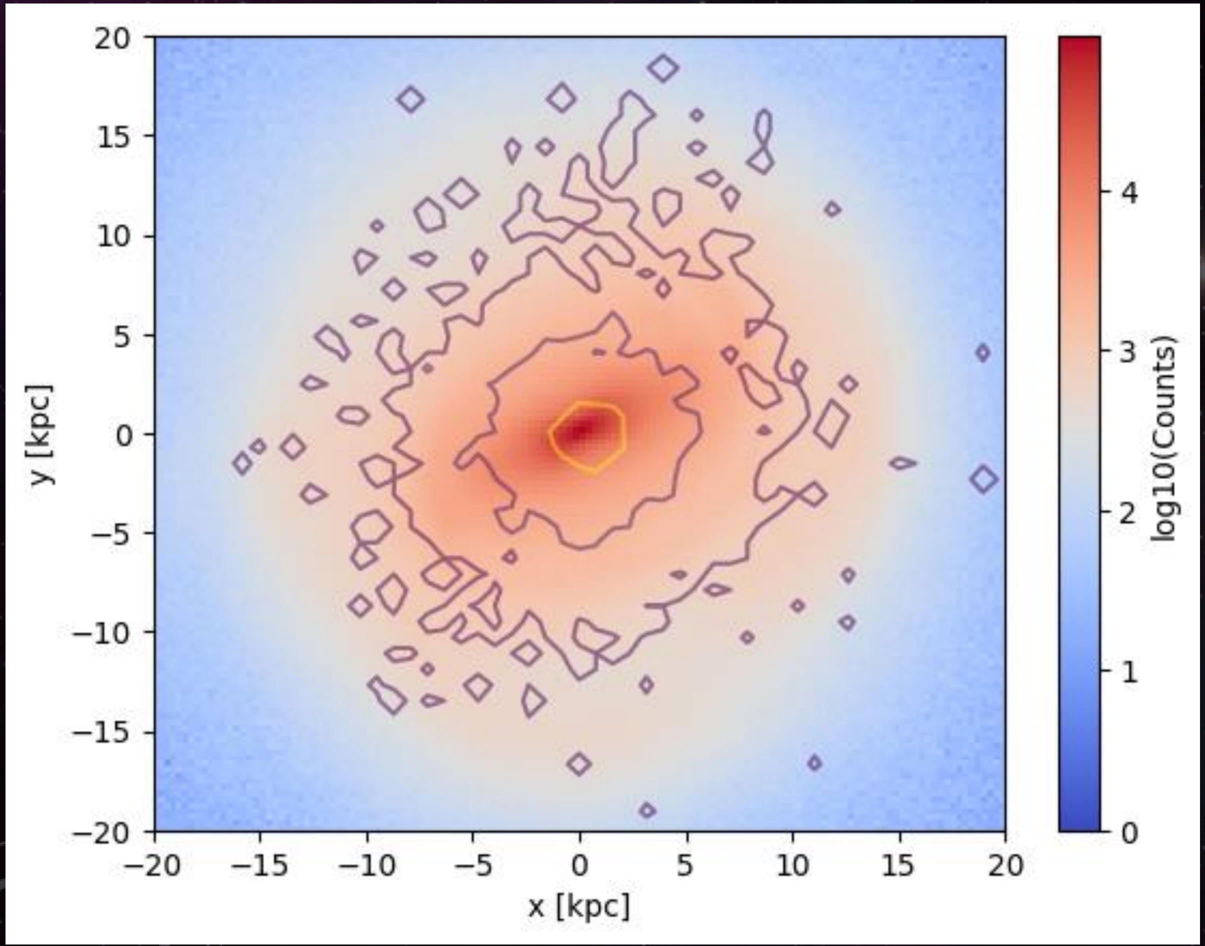

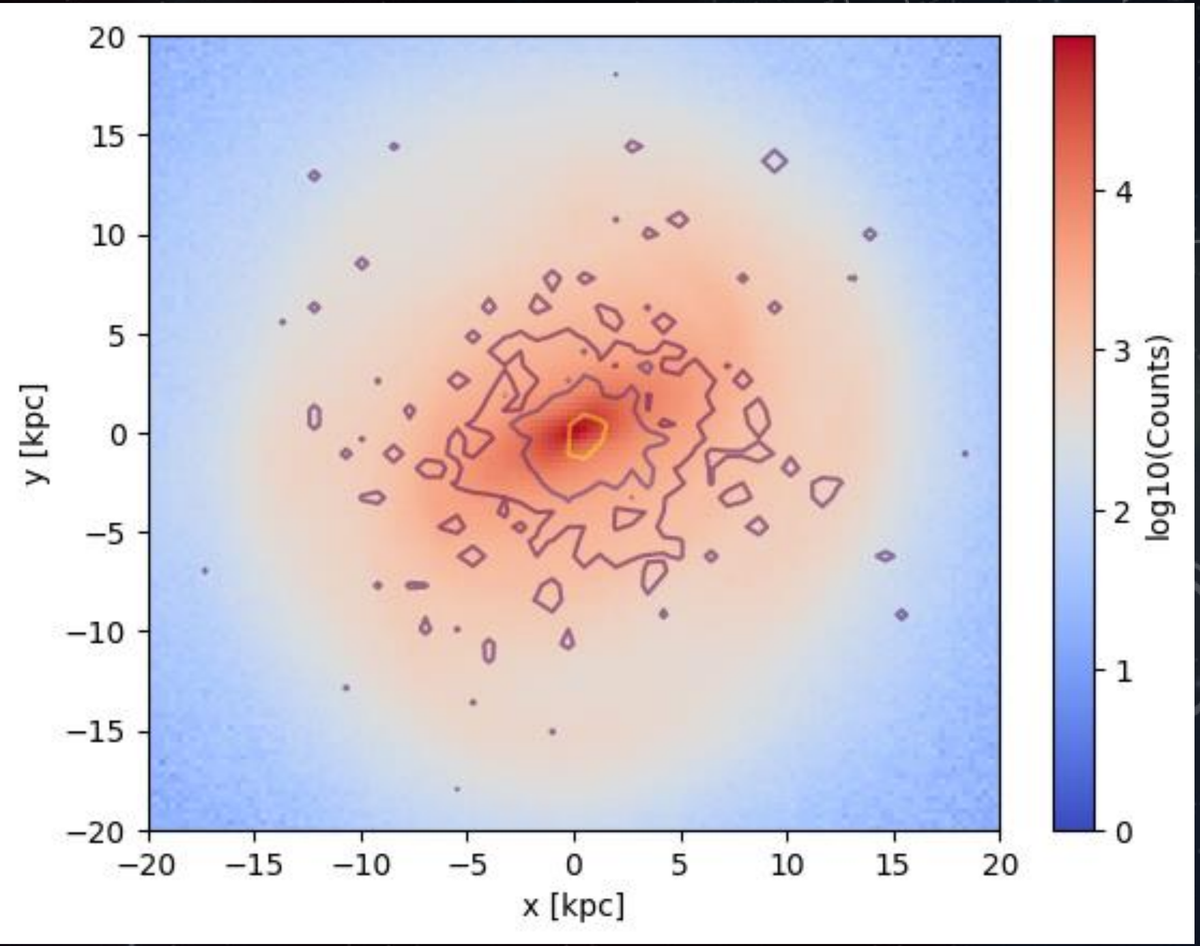

Benefits to Continuous GW Detection Studies

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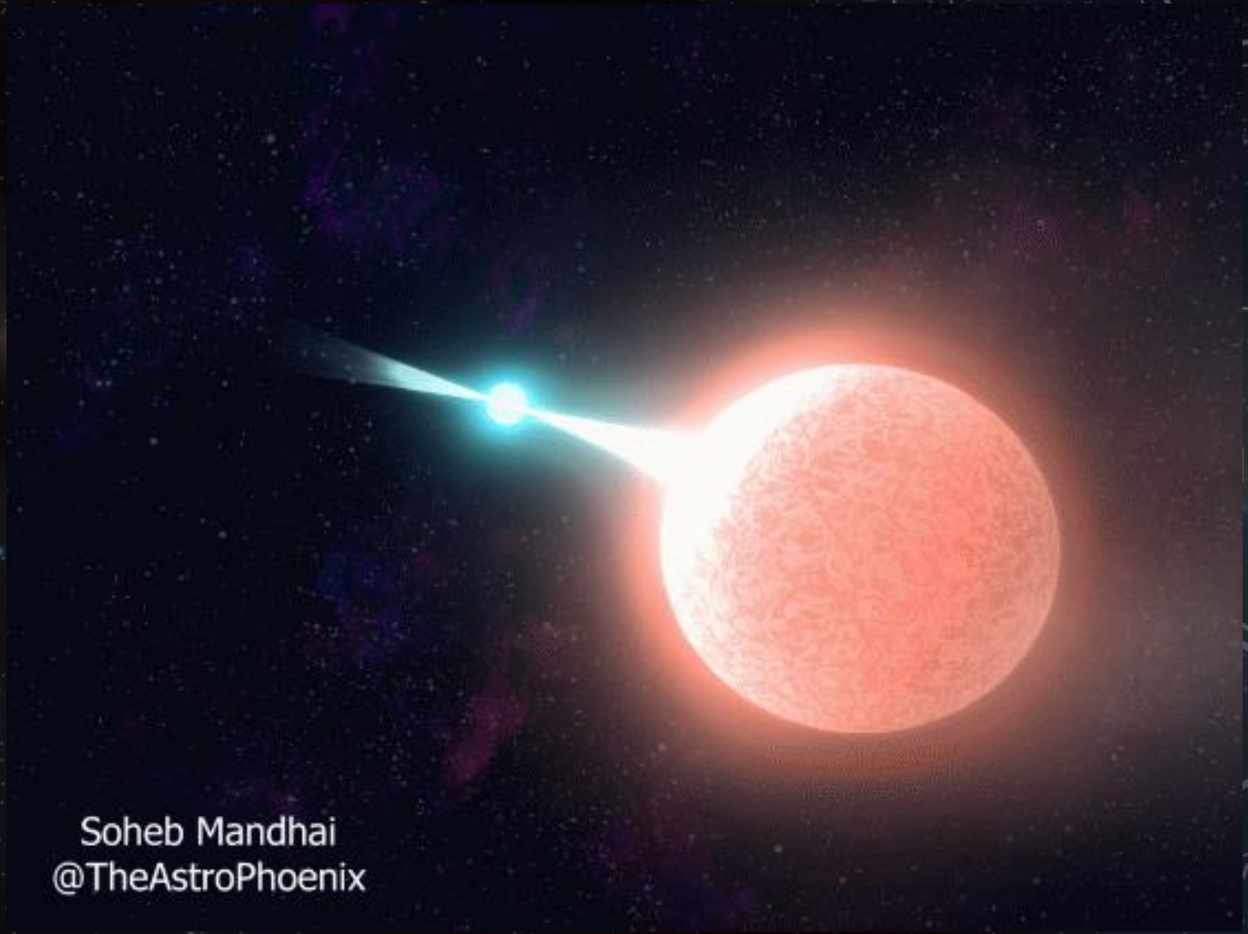
- Population of binaries with known parameters
- Toy models and playgrounds:
  - Can change galaxy simulations:
    - Different Morphologies
    - Different Cosmology
- Test different stellar evolutionary models
- Orbital Parameters for classifying binary orbits:
  - Eccentricities
  - Angular momentum evolution
  - Orbital Plane Inclination

Part 3 - Galactic Binaries
Case Study: Spider Pulsars

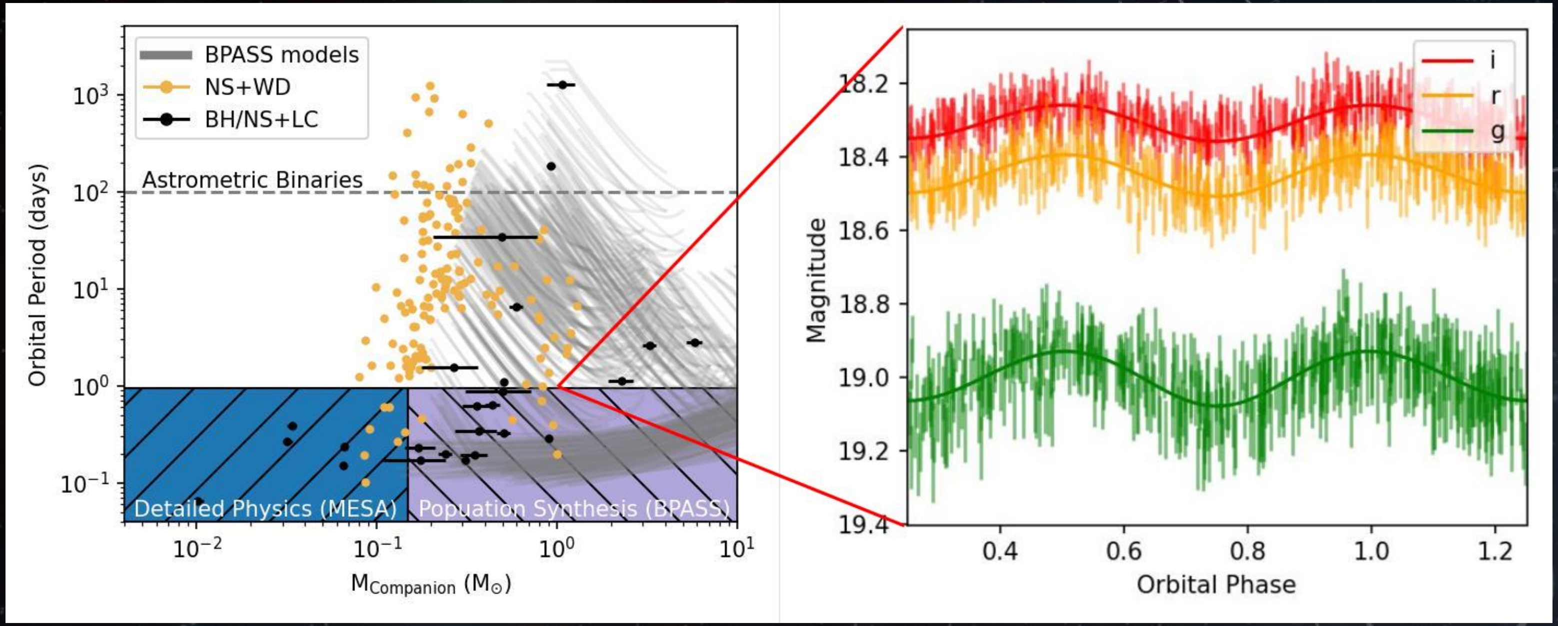
Case Study: What are Spiders?

- Binary: Pulsar + Ablated Low-mass companion (Spidery Pulsar/**Spiders**)
- Orbital periods: <**1 day**
- Non-accreting systems
- ~**80-90** known
- Within a ~few kpc.
- Objective: Identify **densest Spider regions** within the galaxy
- Formulate LISA Science Case



Probing Spider Formation Channels

- Using NS-WD as proxies
- Regular Sky Surveying enables regions of interest to be probed (see GOTO-SpyDer)
- Explore short period binaries within a ~few x kpc
- Provide constraints on MESA modelling of Spiders

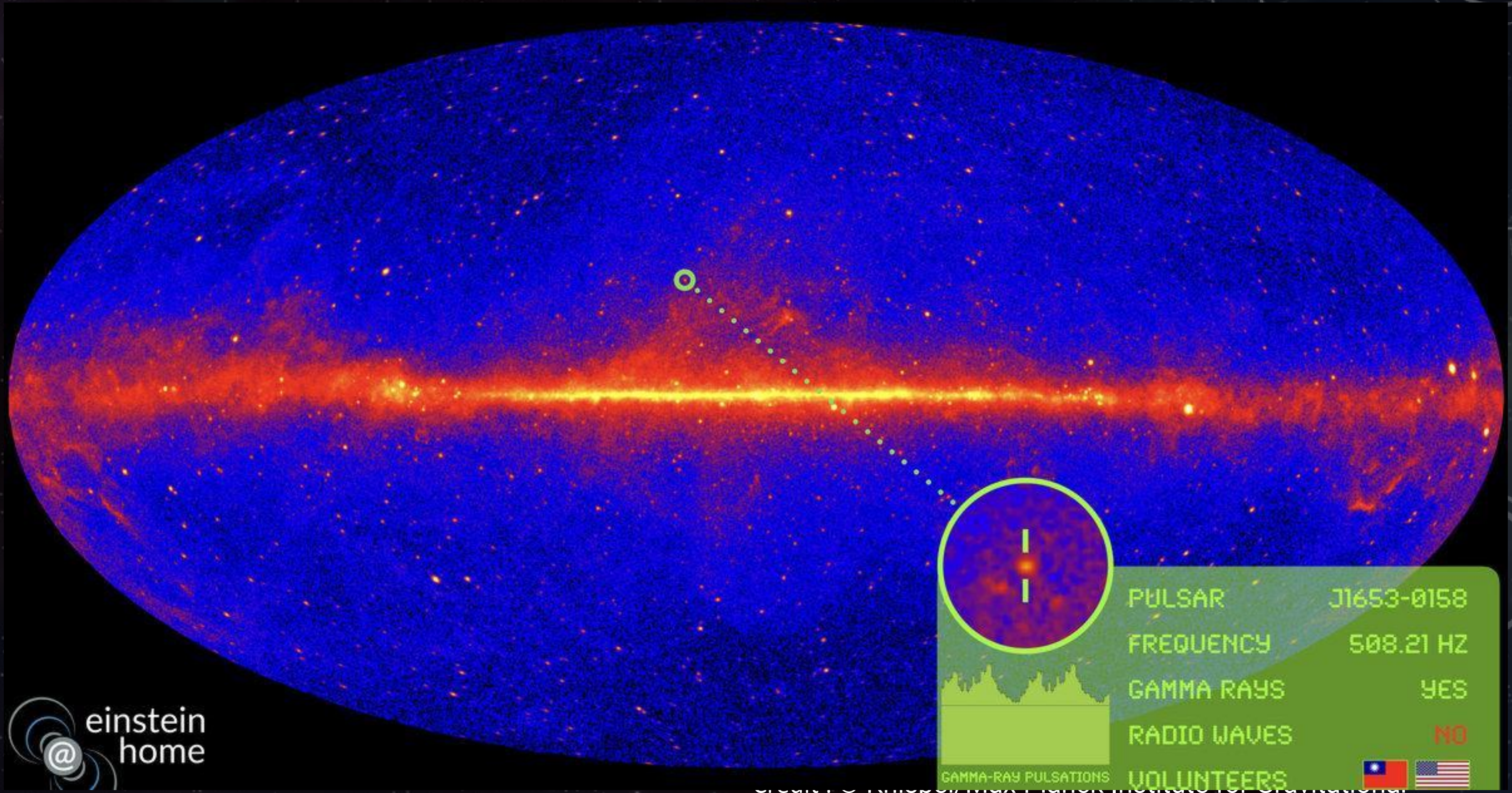


Credit: Mark Kennedy

Optimising Searches

Prior to Fermi:
- Spider Count: 4

With Fermi:
- Spider Count: 80-90



Physics/NASA/DOE/Fermi LAT Collaboration

Summary

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- Created a semi-analytical model of a Milky Way type galaxy using OCARINA
- Evolved the orbits of binaries with kicks
- Future work will aim to develop this further and aid observations
  - Identify more binaries within the MW
  - Prime expectations for future GW campaigns
- Potential to offer insight into optimising searches
- Orbital parameters and spatial distributions can aid continuous GW searches

YOUR RESEARCH INTERESTS/BINARIES WELCOME!

- Get in touch: Soheb.Mandhai@manchester.ac.uk

Extra Slides

Part 3 - Galactic Binaries
Case Study: Neutron Stars

What can we learn?

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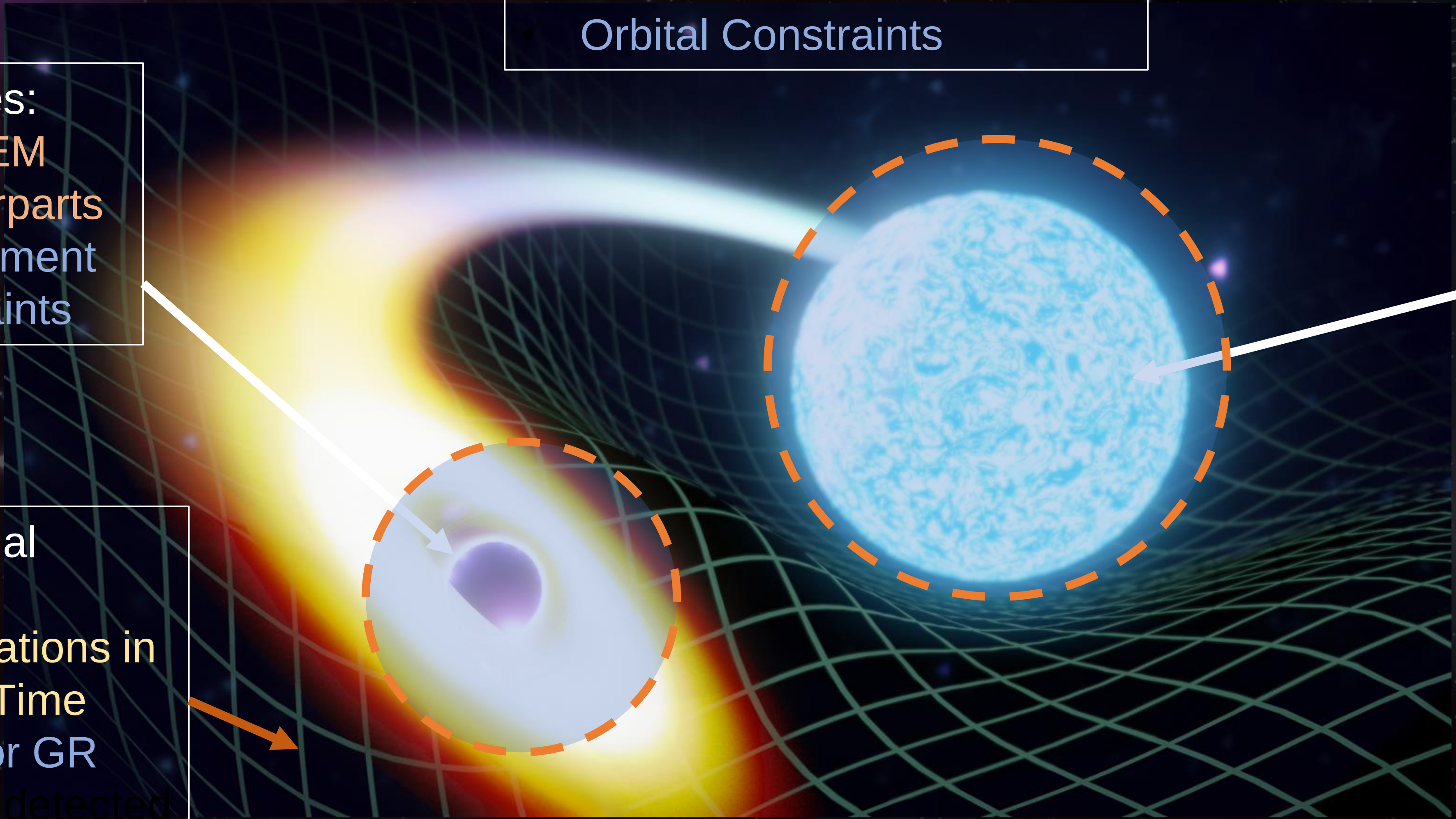
General:
- Insight into Formation Mechanism
- Orbital Constraints

Black-Holes:
- Stifles EM Counterparts
- Environment Constraints



Neutron Star:
- Responsible for EM Emission
- Equation of State
- Constraints on Mass Limits

Gravitational Waves:
- Perturbations in Space-Time
- Tests for GR
- Can be detected

Key:
Progenitor
Astrophysics
Definition

Why are NS Binaries important?

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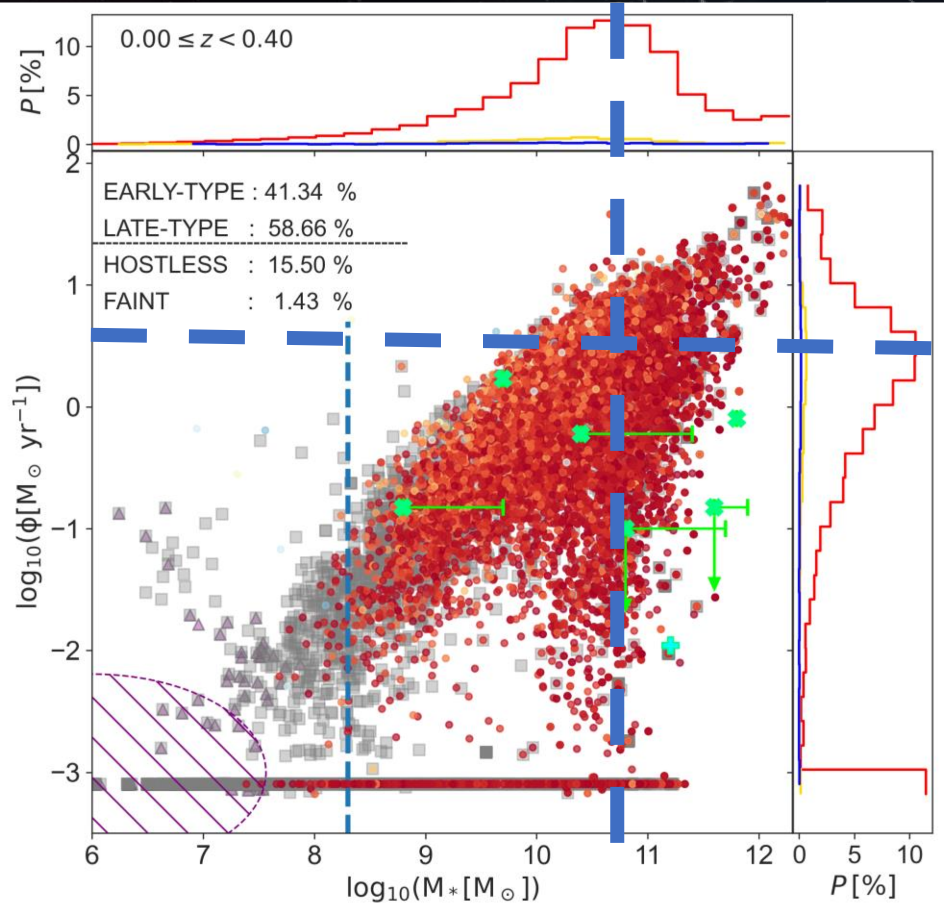
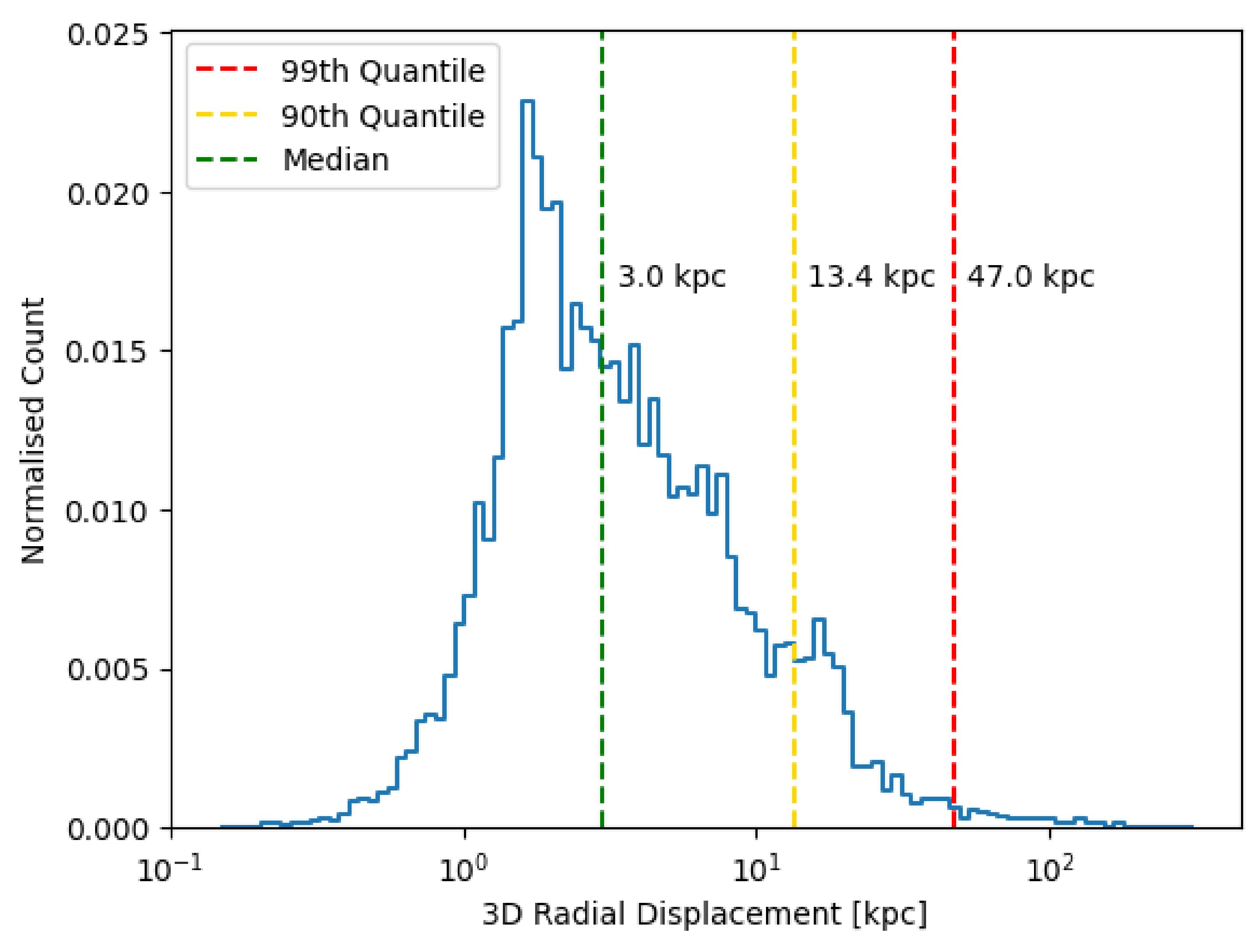
- Laboratories for extreme physics
- Evolution favours supernovae:
  - Natal Kicks
- Detectable with current generations of gravitational waves
- Important for the formation of GRBs/Kilonovae
  - R-process Enrichment of the Universe
- Favour MW type hosts – see zELDA results, Mandhai et al., 2022 (also see works by Artale et al.+, Jiang et al., 2020)
- MW Statistical Studies – Sgalletta et al., 2023

NSNS



General Displacement (w/ kicks)



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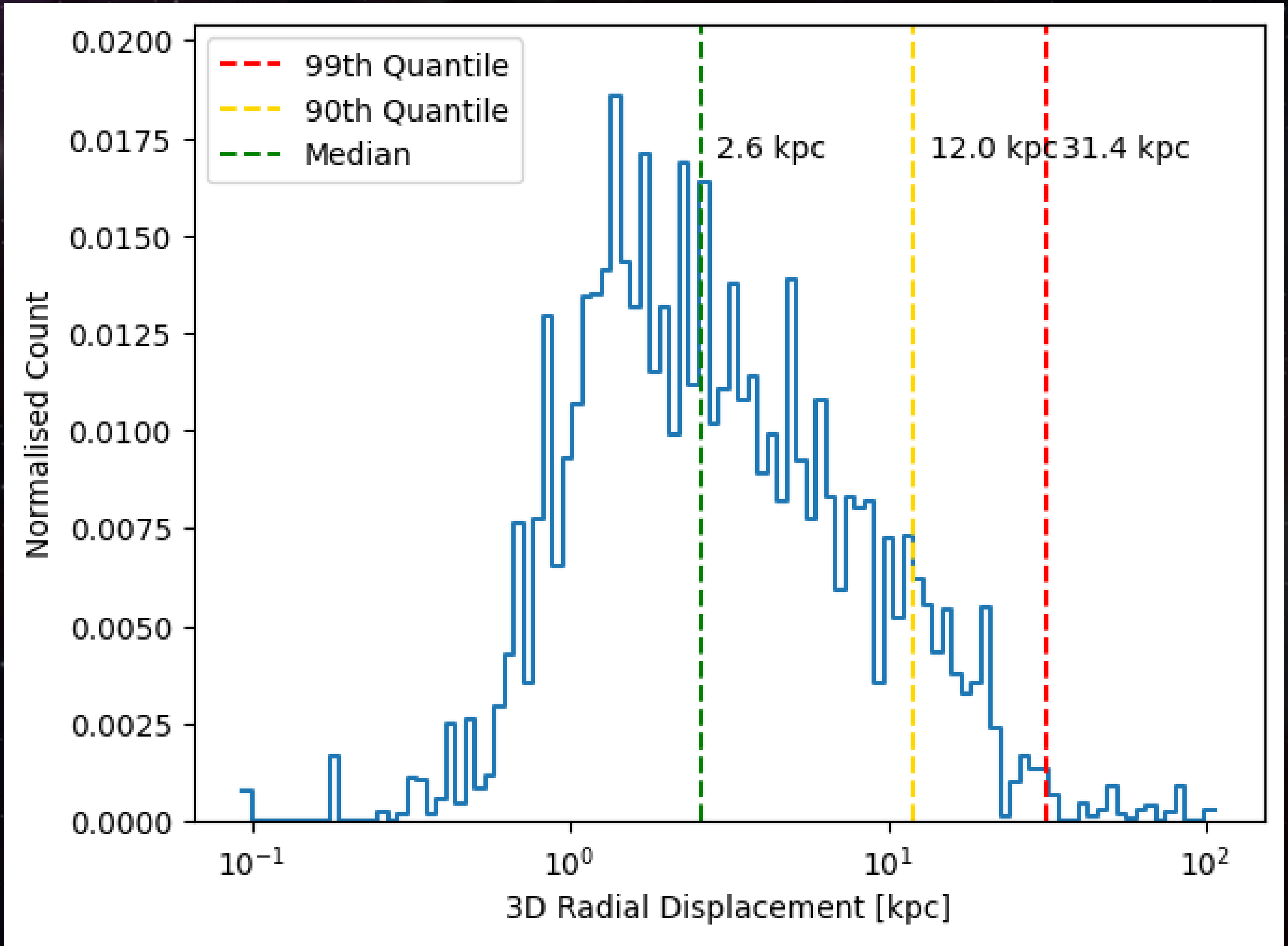
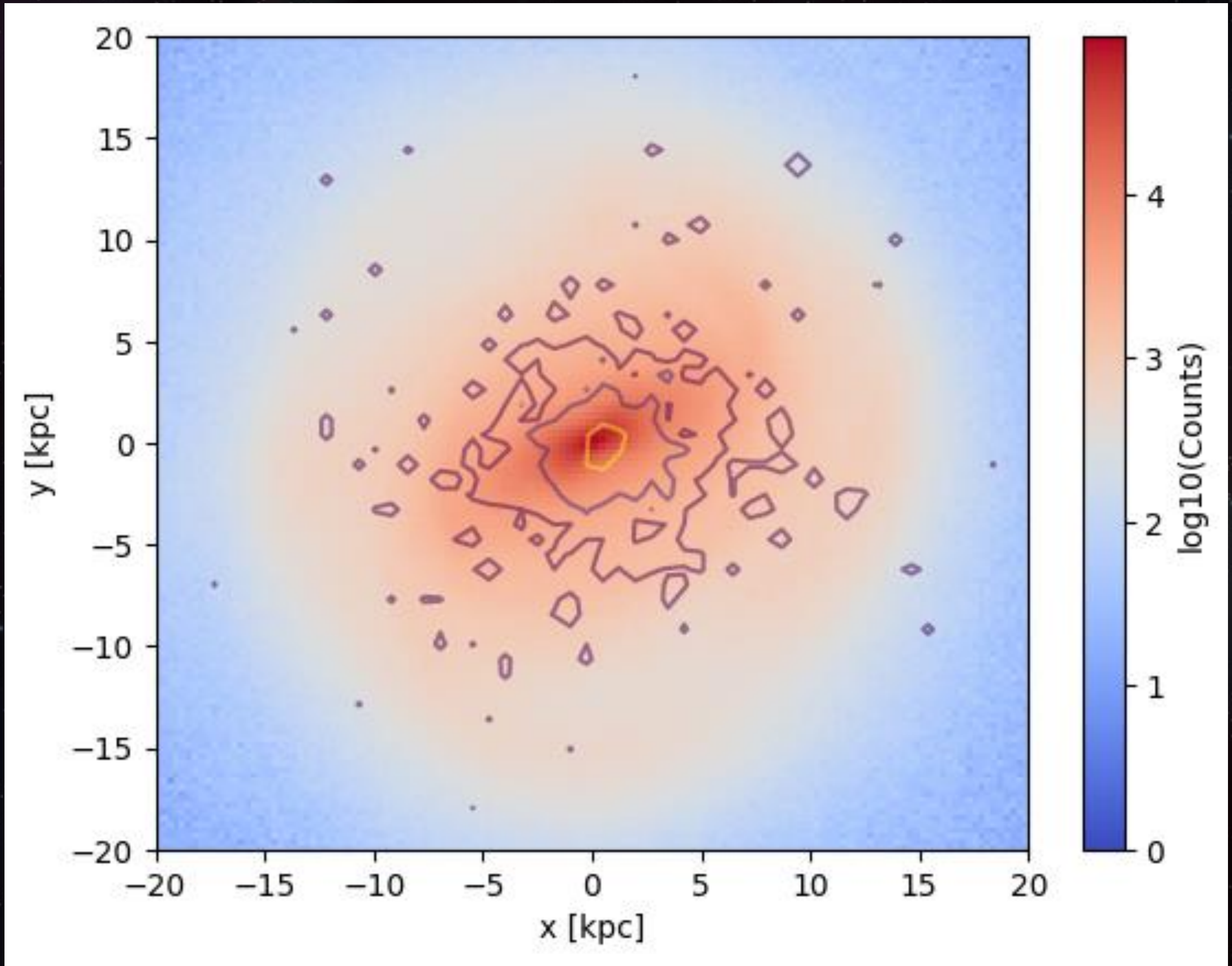
General Displacement (w/o kicks)



Spatial Distribution w/o kicks



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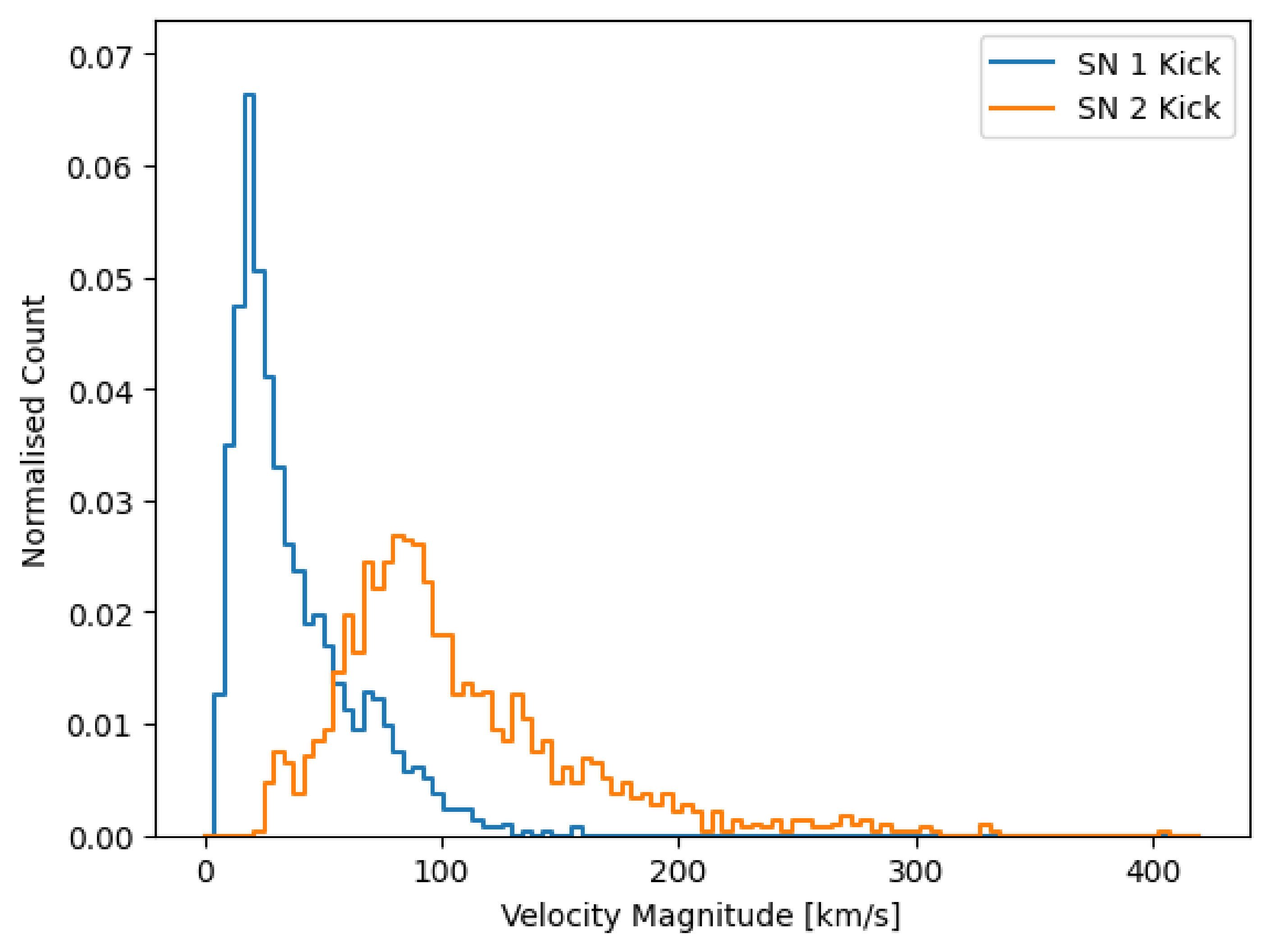
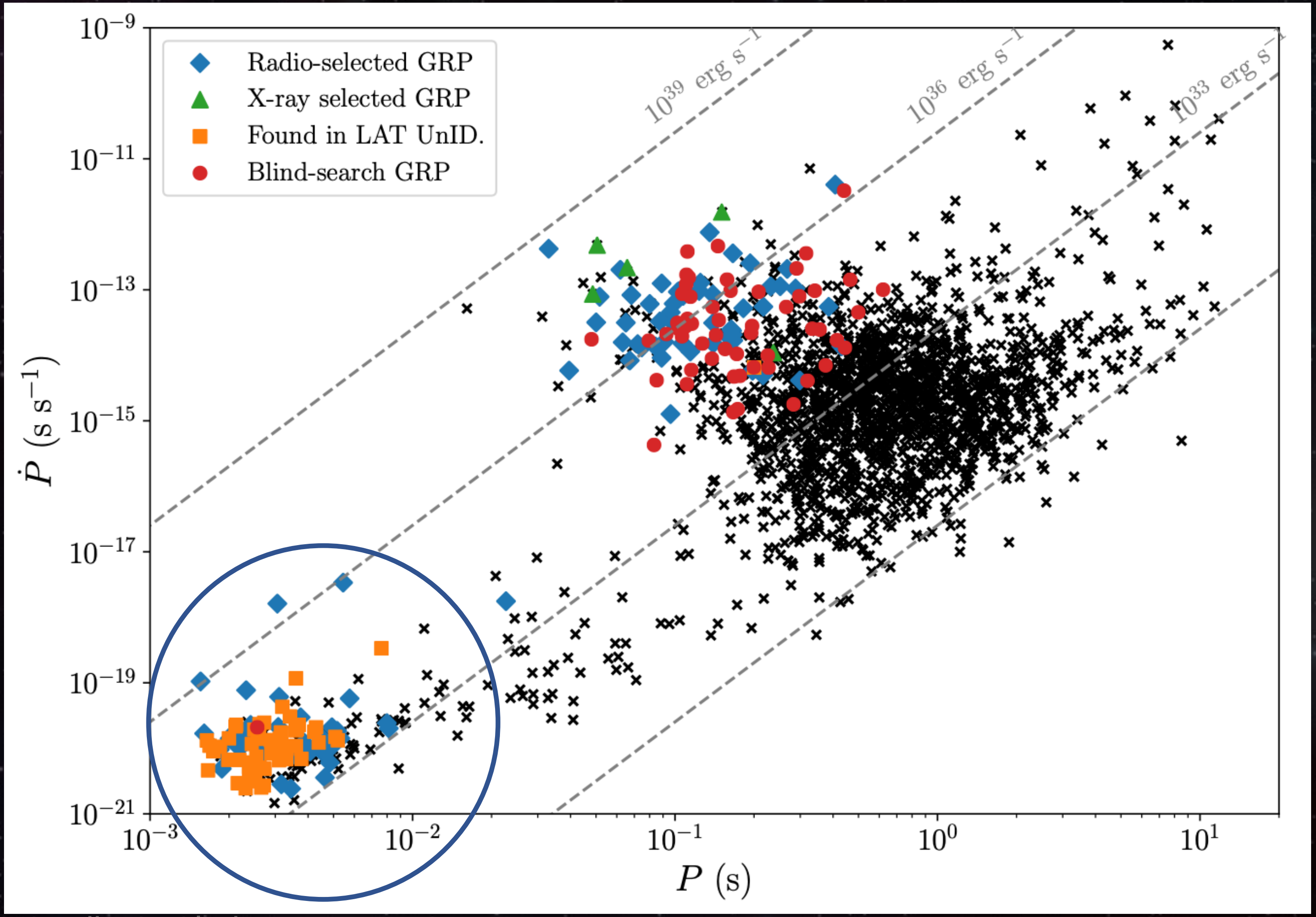
Kick Distribution – Preliminary OCARINA Test



More on Spiders…

P-Pdot Diagram Example



Credit: C. Clark

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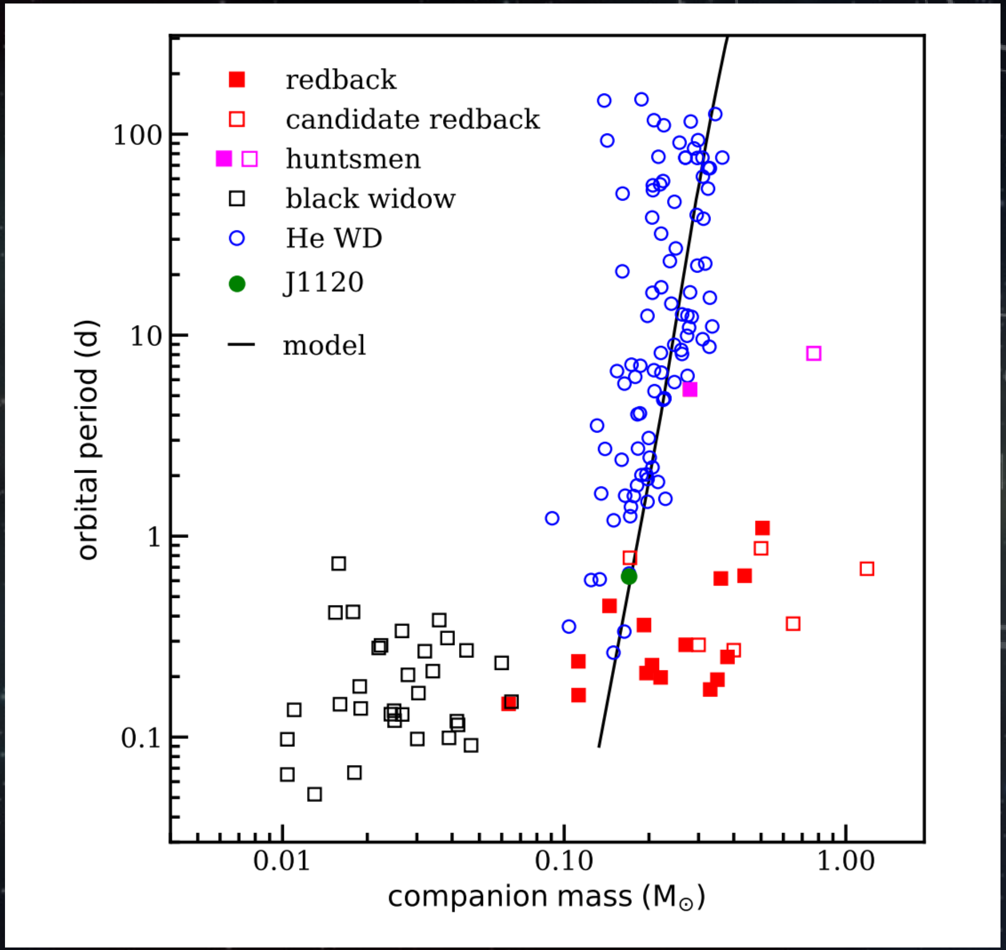
Types of Spiders

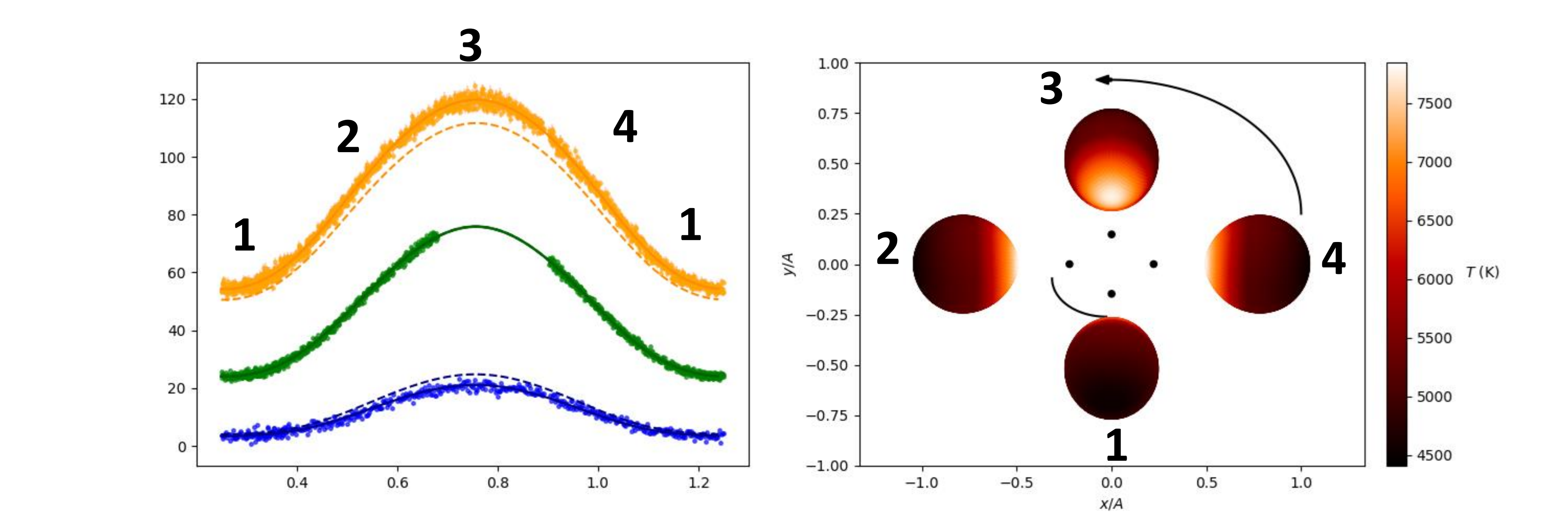
- Typical orbital period ~< 1 day
- Black Widows:
  - Companion Mass < 0.1 Msol
  - Day and night side
  - Deformed
- Redbacks:
  - Companion Mass ~<0.5 Msol
  - Oblate Spheroid
- Huntsman (?)



Credit: Swihart et al., 2022

Phases of orbit

- Observations at different epochs tighten binary parameter space

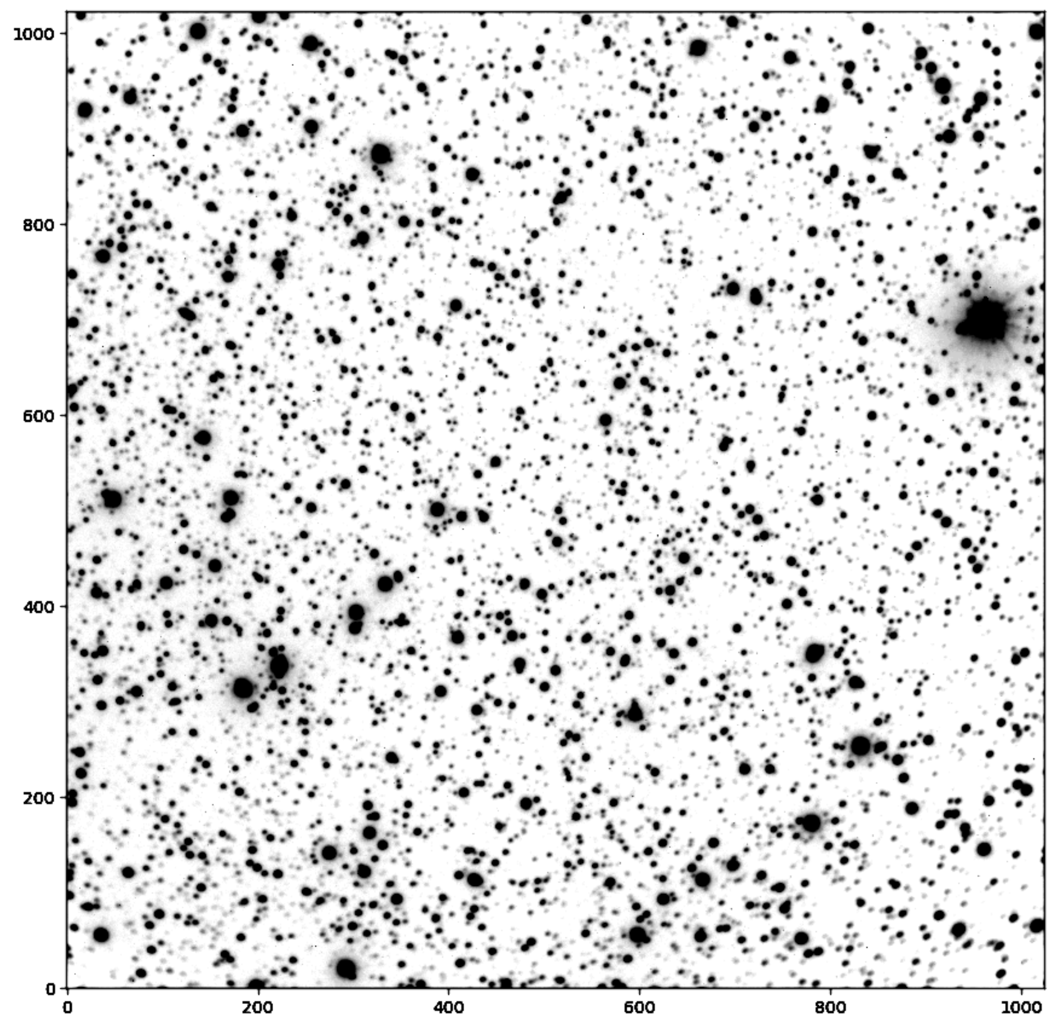


Credit: Oli Dodge

Observational Campaign

- NTT/ULTRACAM search for Spiders
- ~25 Nights of Observations
- 90-100 individual observations
  - 30 unique sources observed.
- Light curve of each source gauged
- Discovery of Asteroids
- Schedule: John Paice

Example Shown: 4FGL J1517.9-5233



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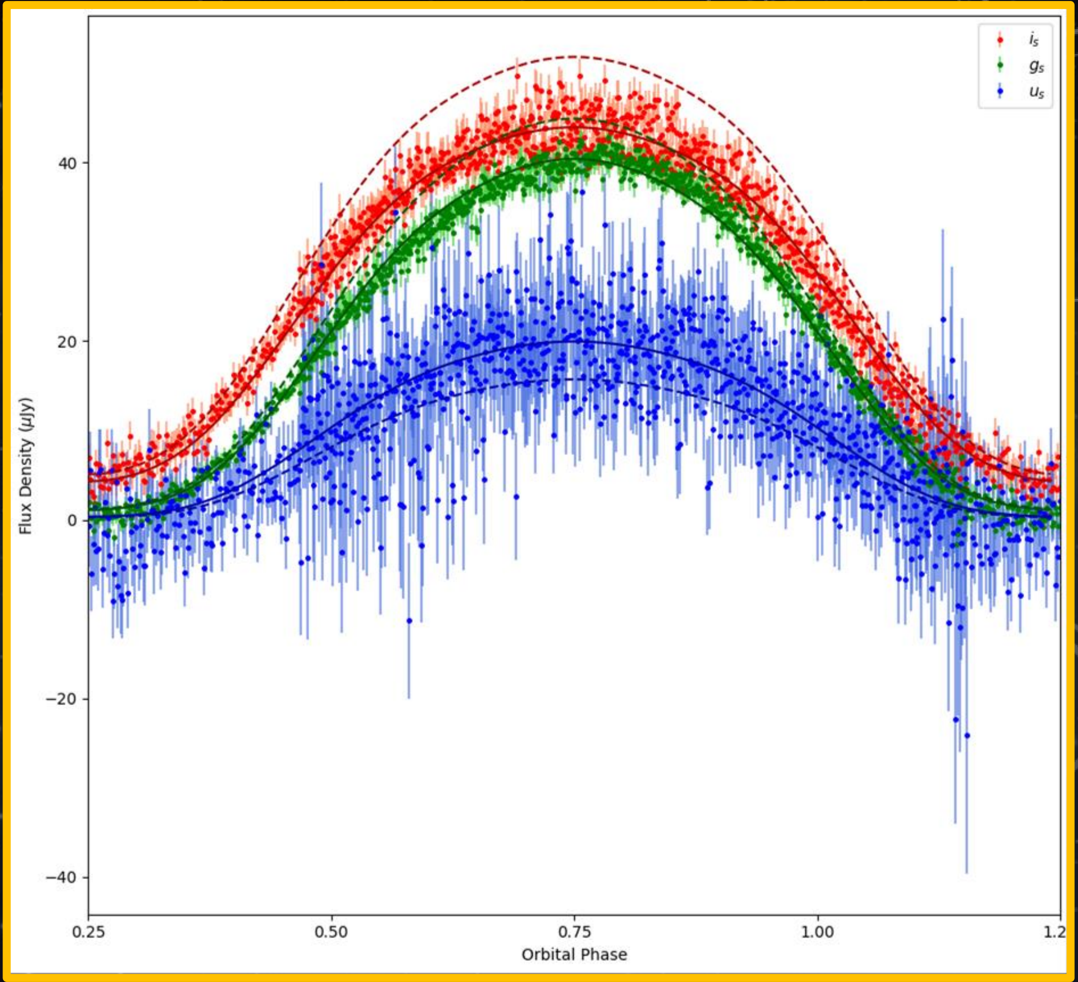
Observational Analysis

- Work by Oli Dodge using ICARUS (Stellar light curve synthesis tool)
- Uses Observational data + estimated parameters
- Can be used to infer the heating of the companion
- Gives insight into eclipsing mechanism



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The challenges…

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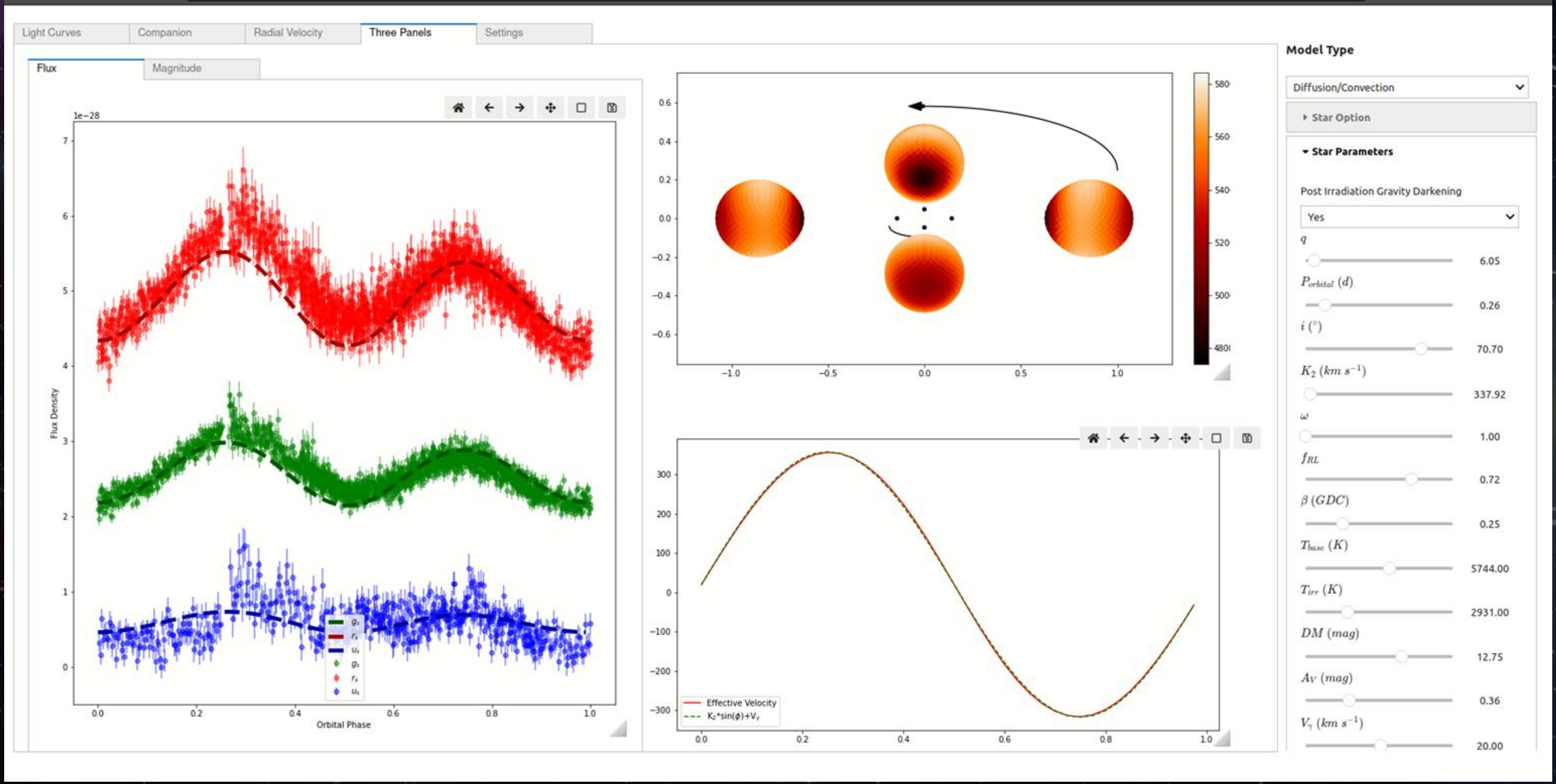
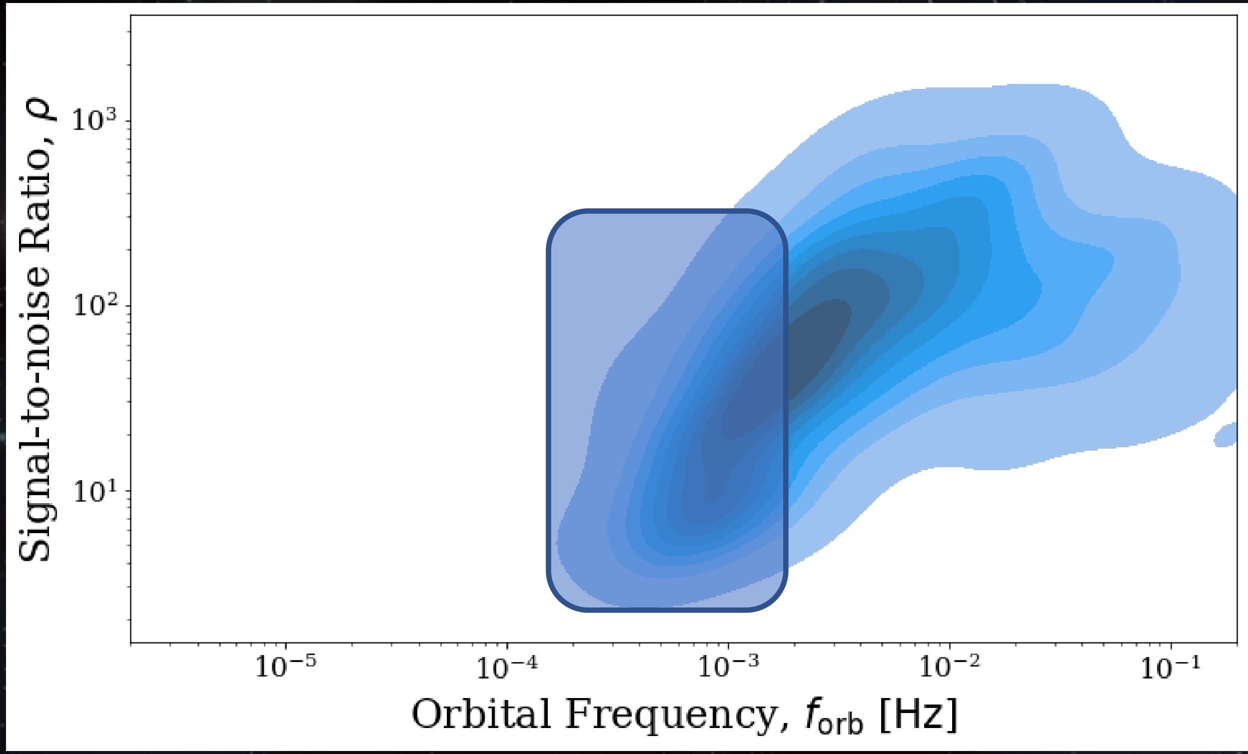


Credit: Adipol Phosrisom

Going forward:

- Create a binary zoo for the Milky Way
- Use similar hydrodynamical simulations to recreate host galaxy environments
- Form strategies for EM follow-up for GW detections, whether LVK or LISA/DECIGO

Example SNR Detectability for Spiders:



Using LEGWORK – See Wagg et al., 2022

More on zELDA/Galaxy Evo…

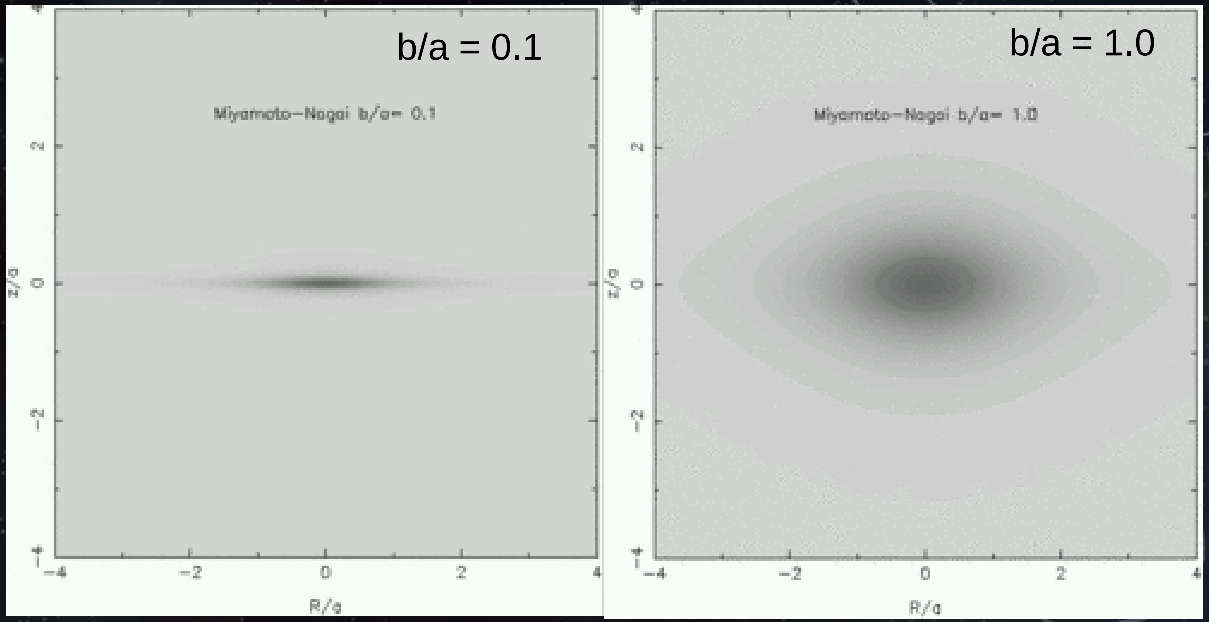
Where do binary mergers occur?

<u>Host Potential:</u>

- Integrated GalPy usage
- Stellar and Gas components = Miyamoto & Nagai Potentials
- DM Halo: NFW Profile
- Approximated based on initial EAGLE parameters

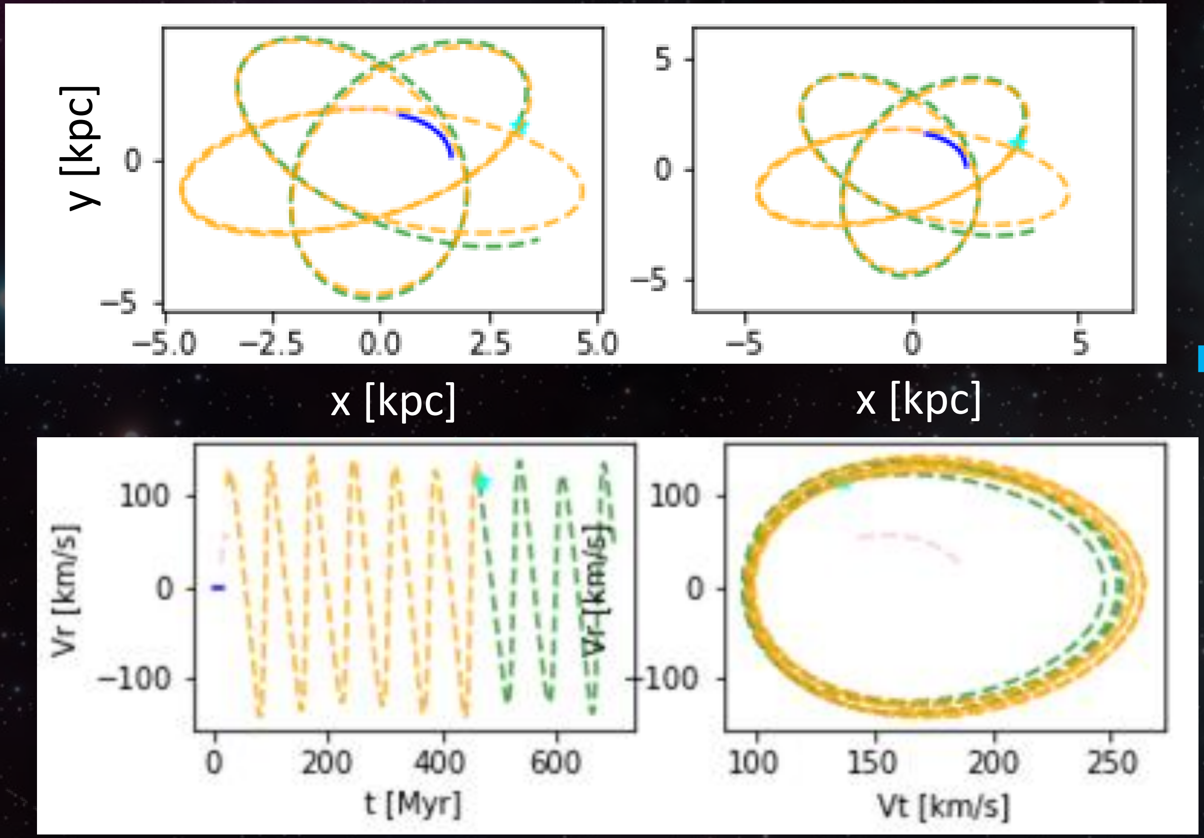
<u>Binary Placement:</u>

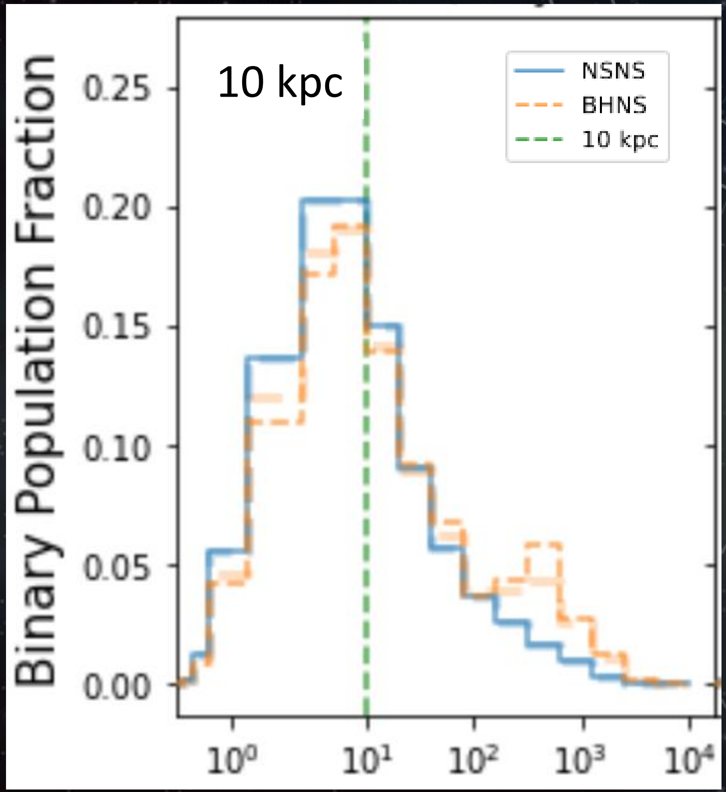
- Isolated binaries from Bray & Eldridge, (2018)
- Weighted by the Stellar Mass profile (z=0)
- Randomly placed



Credit: Chris Flynn

Example Orbits (using zELDA):

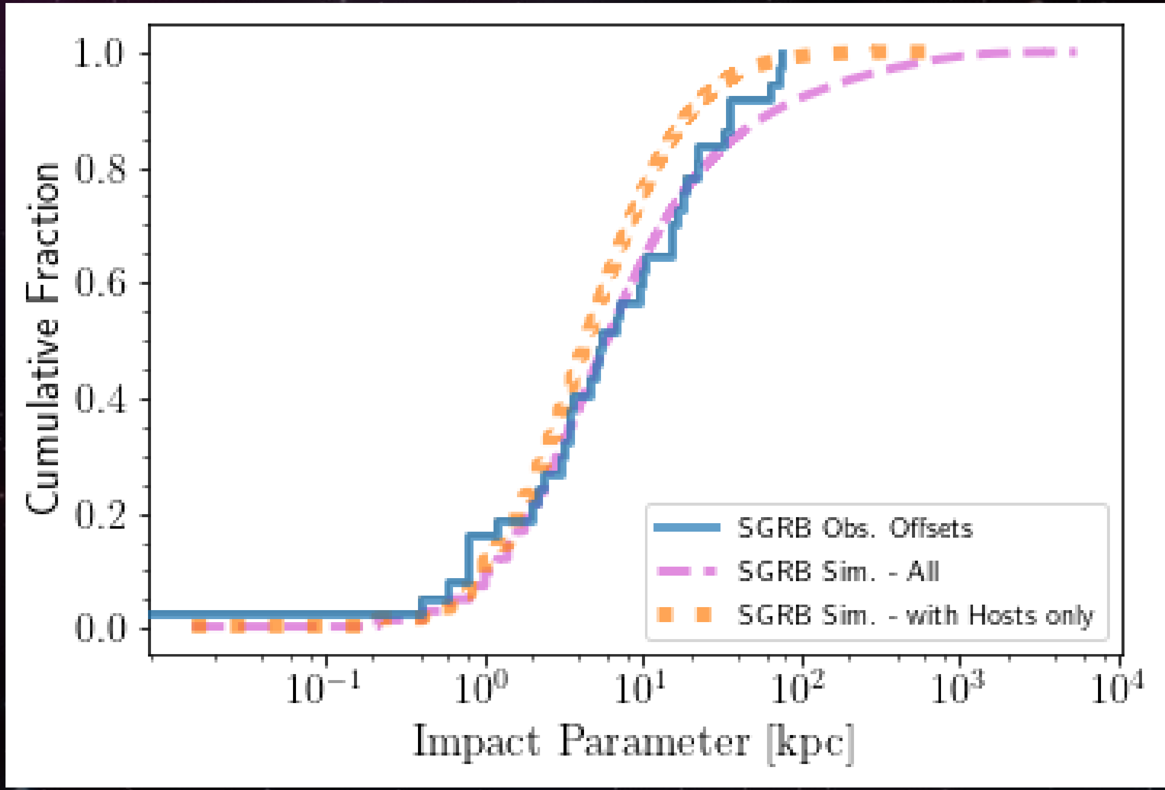


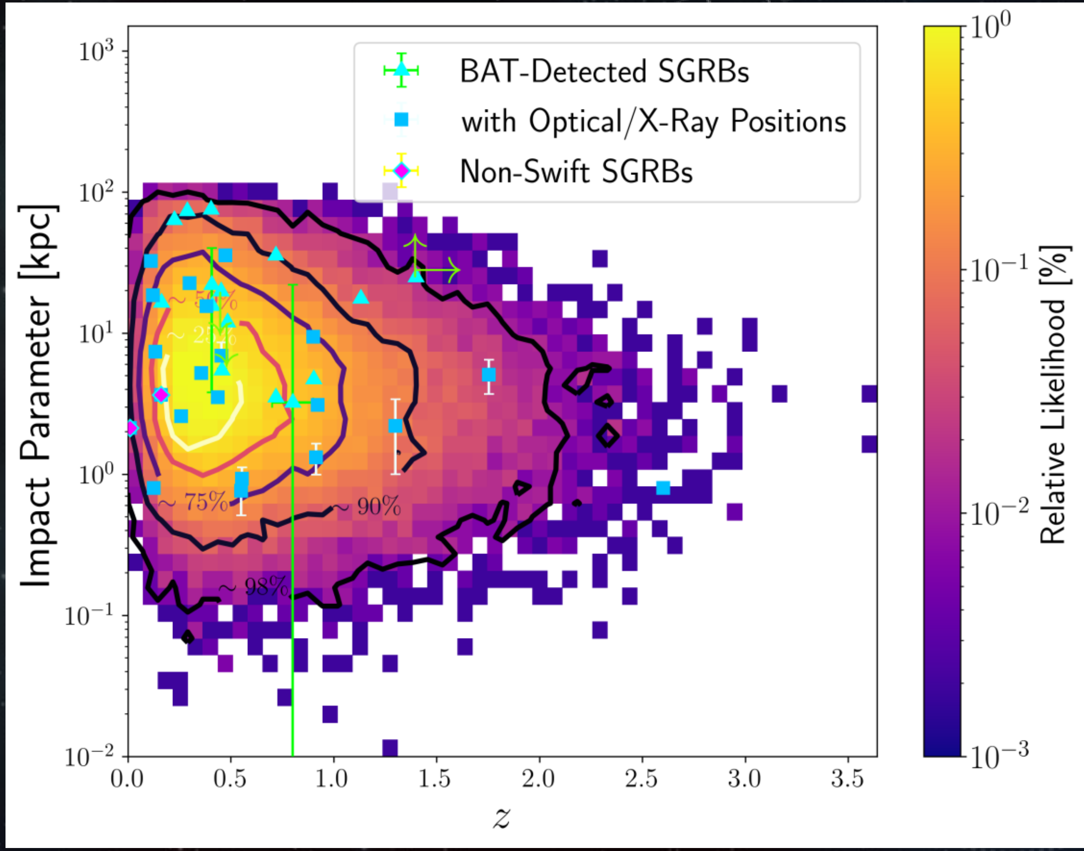


3D Radial Distance [kpc]

Mandhai et al., 2022

GRB Offsets – Predictions vs Observations





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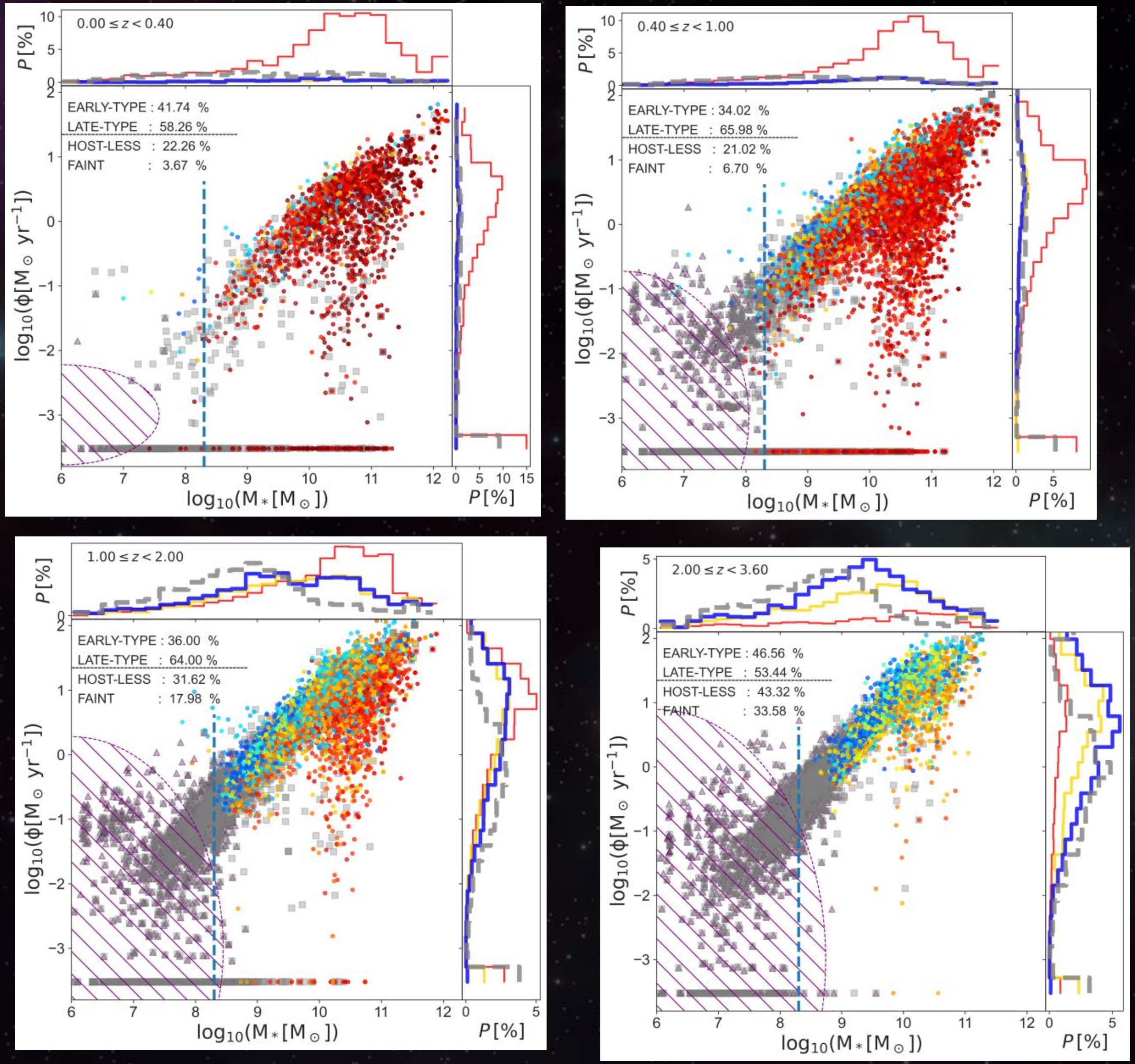

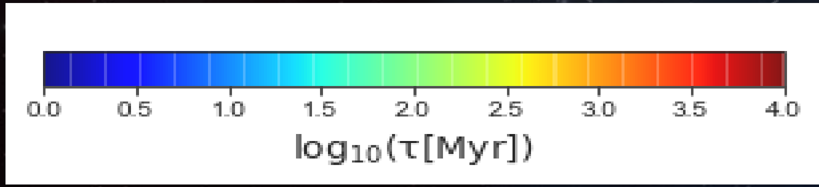

Predicted Binary Demographics

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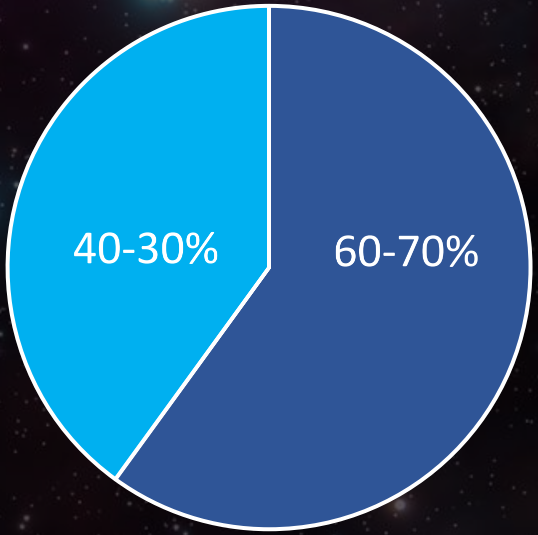
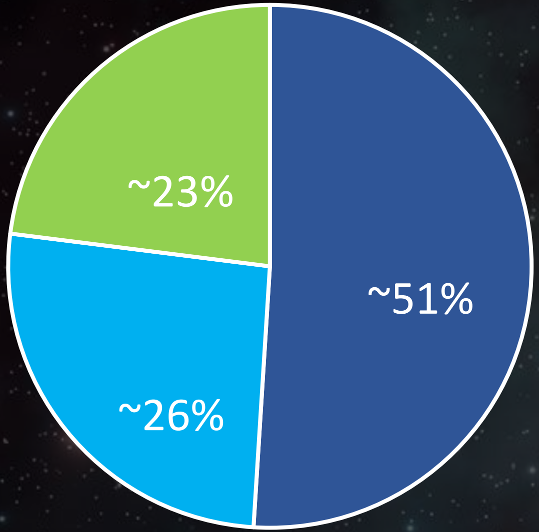
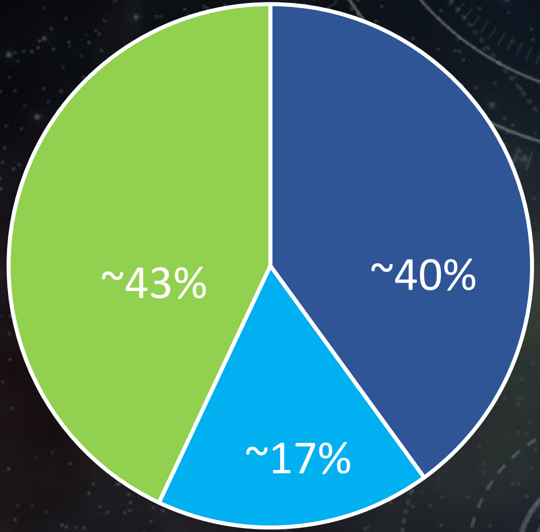
Host Galaxy Morphology*



NSNS



BHNS

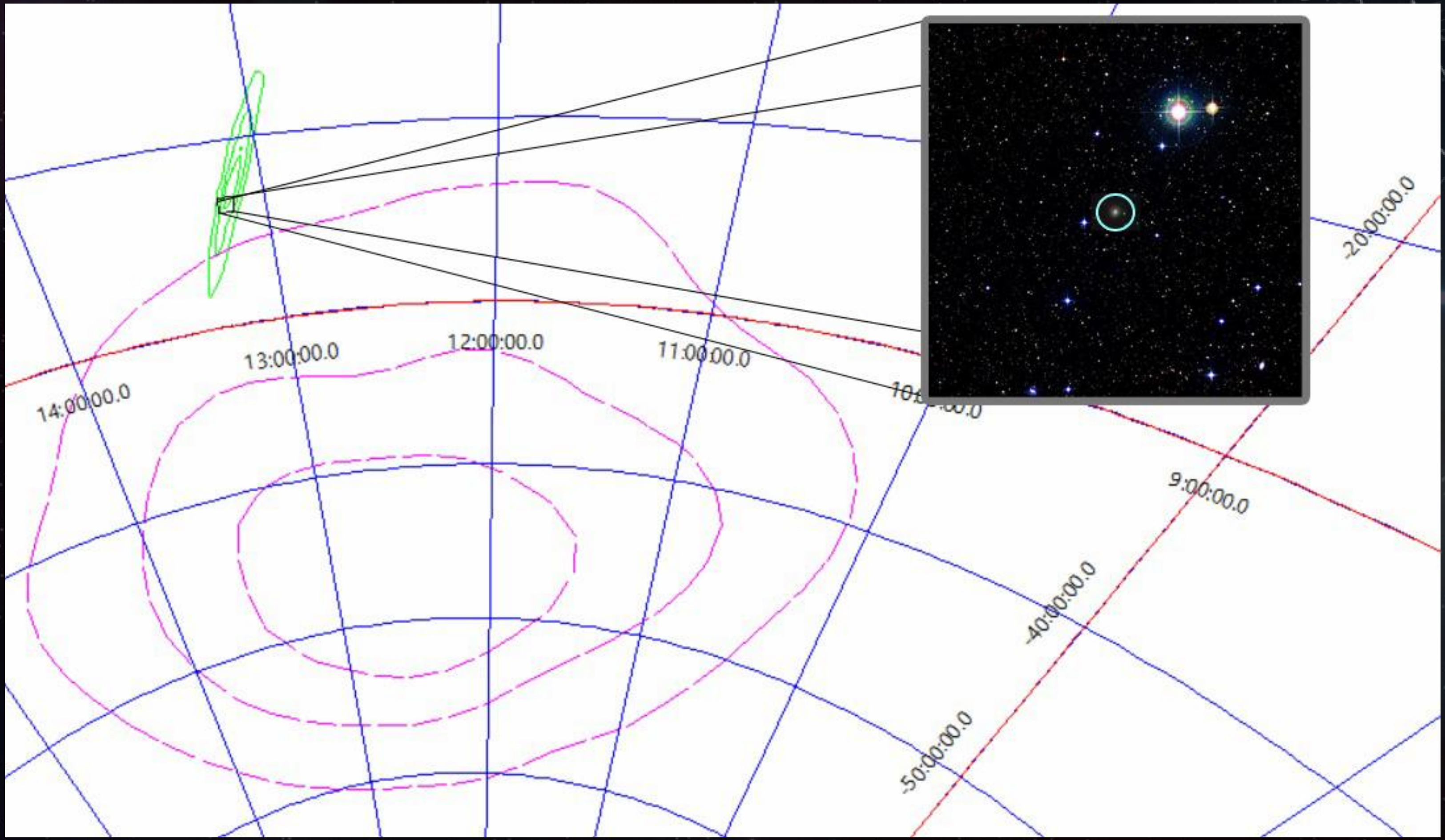


*Averaged across redshift for BHNS/NSNS
** Defined using galaxy shape diagnostic from Thob et al., 2019
*** Have observationally faint hosts and/or merge remotely

Late-Type**
Early-Type**
Host-less***

(Reasonable agreement with Chu et al., 2021 ,Artale et al., 2019 – Also see Artale et al., 2020 a,b)

Advantage of Swift – Great Localisation



Extragalactic: Caveats

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Theory

- Stellar evolutionary models are not necessarily complete
  - BPASS+COSMIC used in this work
- Galaxy morphologies and evolution is not complete
- Kick prescriptions are approximations
- IMF dependence on metallicity is sparsely studied

Computation

- Detailed orbital analysis is computationally expensive
- Concessions need to be made
- Approximations may not be completely physical

Observations

- Host galaxy associations are not definite
- Offsets can be hard to distinguish
- Galaxies require surveying/deep field analysis