CSIRO – Co-Learnium 2022

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Finding Spiders in Your Galaxy

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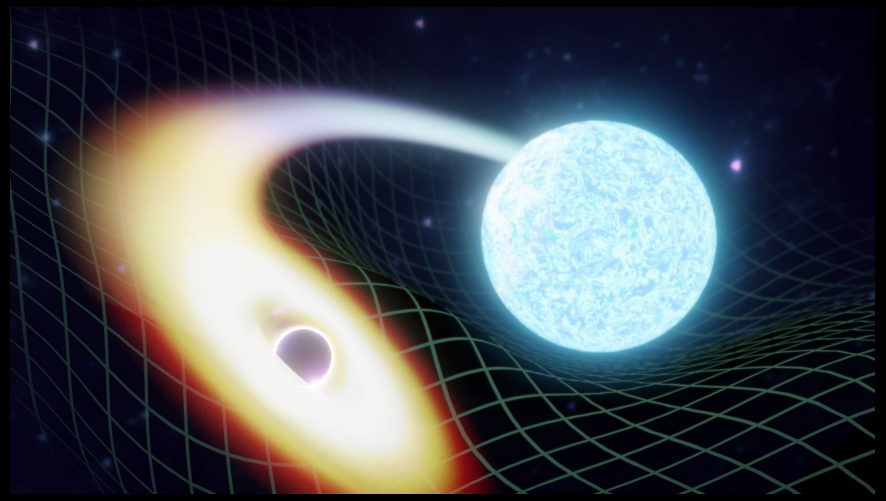
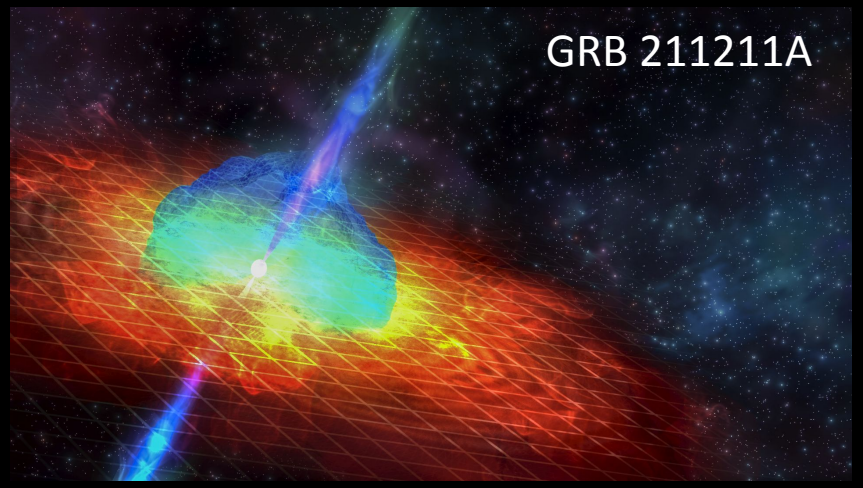
Collaborators: René Breton, Scott Kays, Spider's Group, Nial Tanvir, Gavin Lamb, Chris Nixon, John Bray, Rob Eyles-Ferris, Andrew Levan, Ben Gompertz

About Me!

- Post-Doc: Spiders Group, The University of Manchester
- PhD: University of Leicester
- Thesis Topic: Electromagnetic Counterparts of Gravitational Waves
- Hobbies: Digital Art, Crafting, 3D Modelling (Blender)/Printing, Game Development, Learning Japanese, and Anime
- Created art for press releases!





Spider Team

Rene Breton

Mark Kennedy

Colin Clark

Daniel M. Sánchez

Siraprapa Sanpa-Arsa

John Paice

Soheb Mandhai

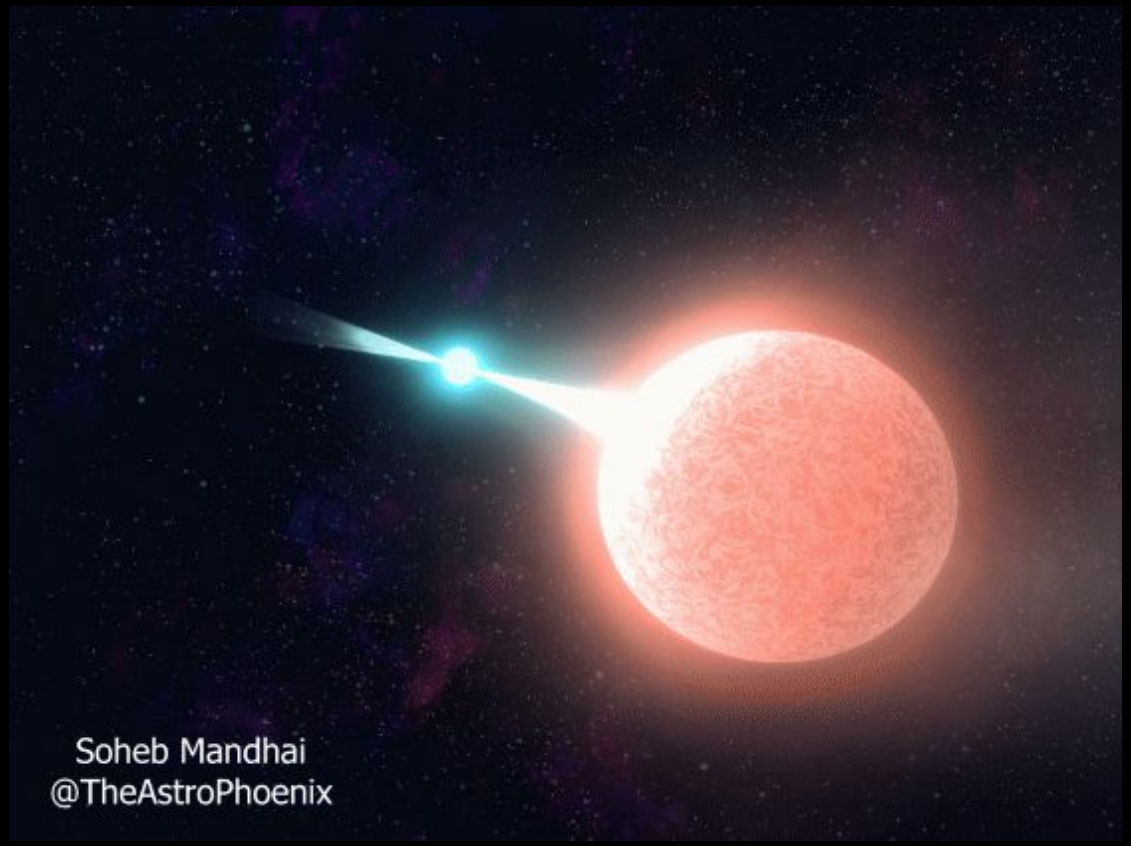
Oliver Dodge

Tinn Thongmeearkom

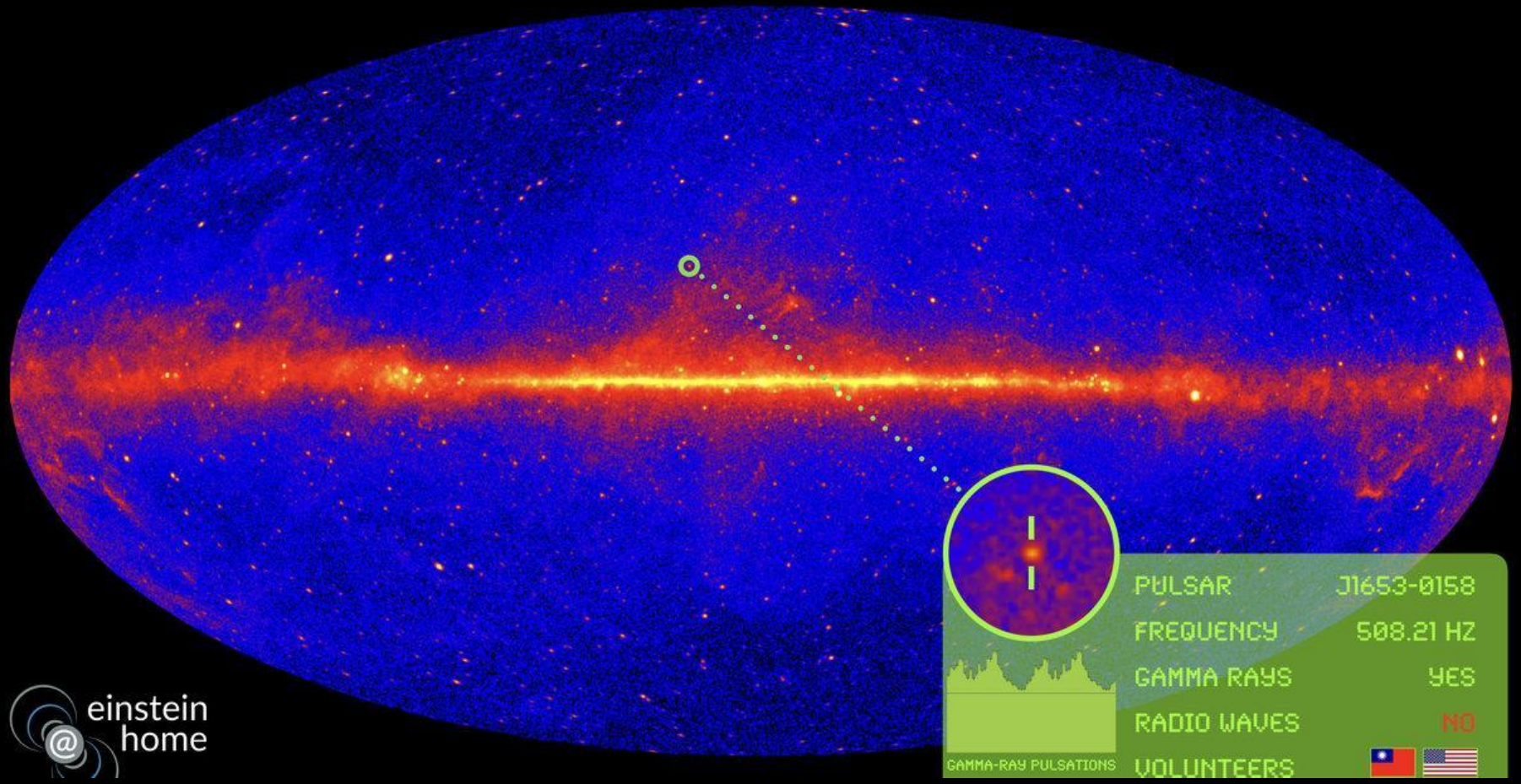
Adipol Phosrisom

What are Spiders?

- Millisecond Pulsar + Ultra-low Mass Companion
- Companion has lost mass due to pulsar winds
- Non/intermittently-accreting system
- Source of gamma-rays
- Two main breeds:
  - Black-Widow -> Companion Mass ~ 0.05 Msol
  - Redback -> Companion Mass ~ 0.1 Msol



Fermi Background

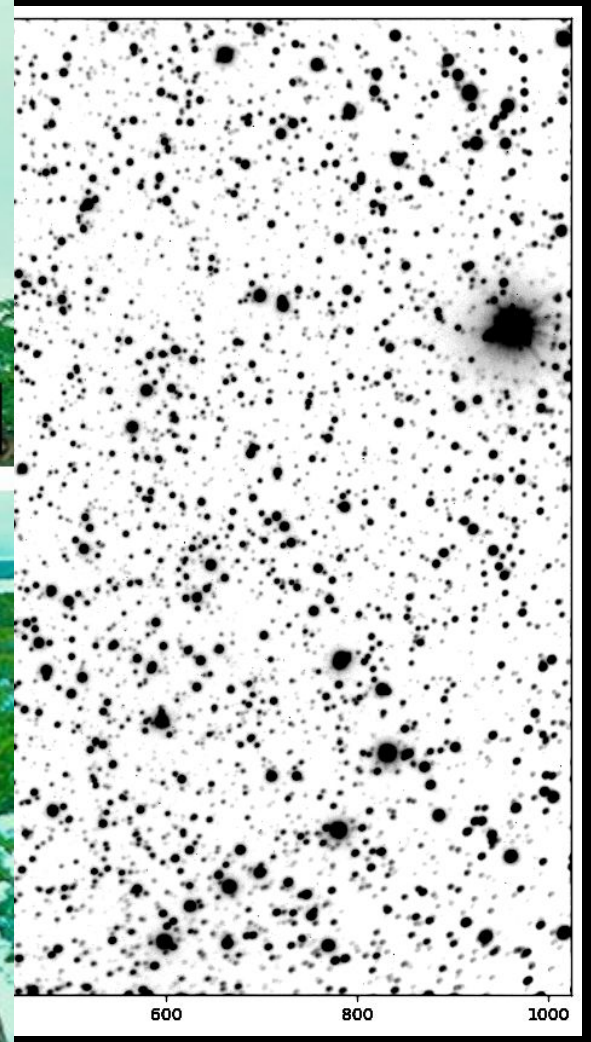


Credit : © Knispel/Max Planck Institute for Gravitational Physics/NASA/DOE/Fermi LAT Collaboration

Observation

- NTT/ULTRACAM search
- 25 Nights of Observatic
- 90 individual observati
  - 30 unique sourc
- Light curve of each s
- Discovery of Asteroi
- Schedule: John Paice

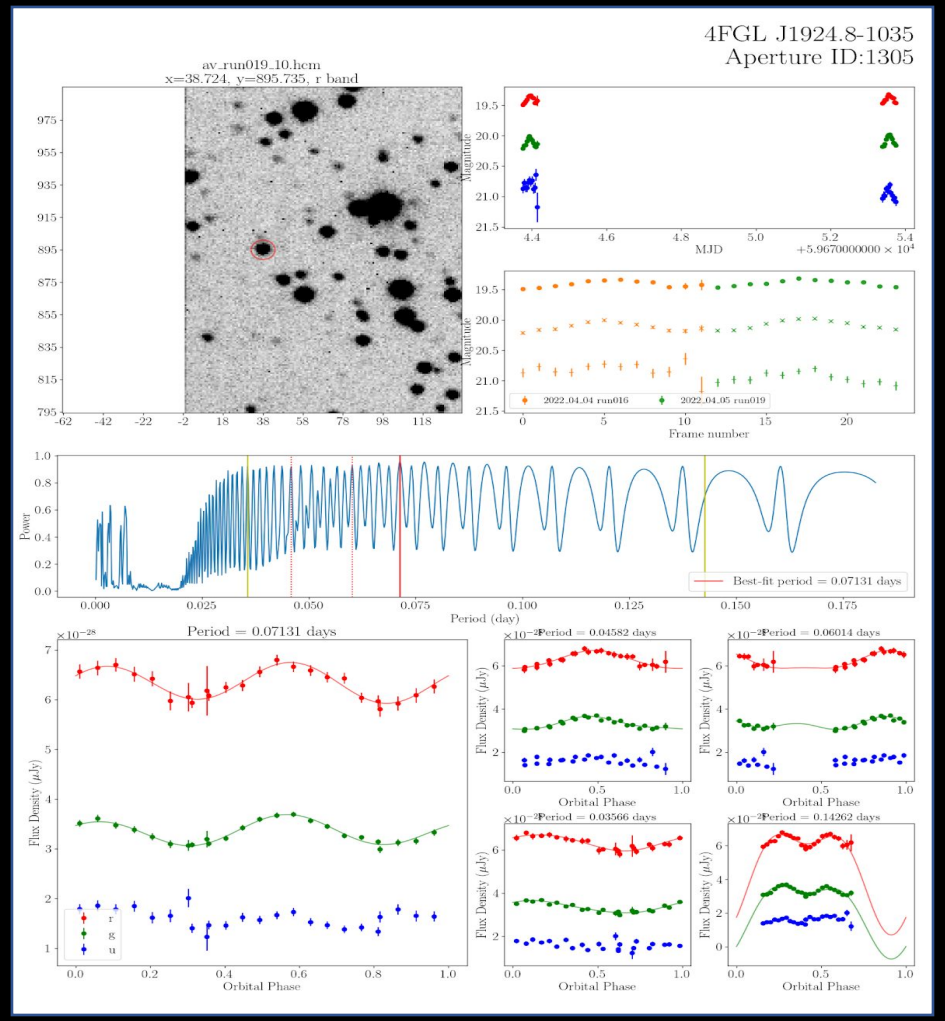
Example Shown: 4



Processing

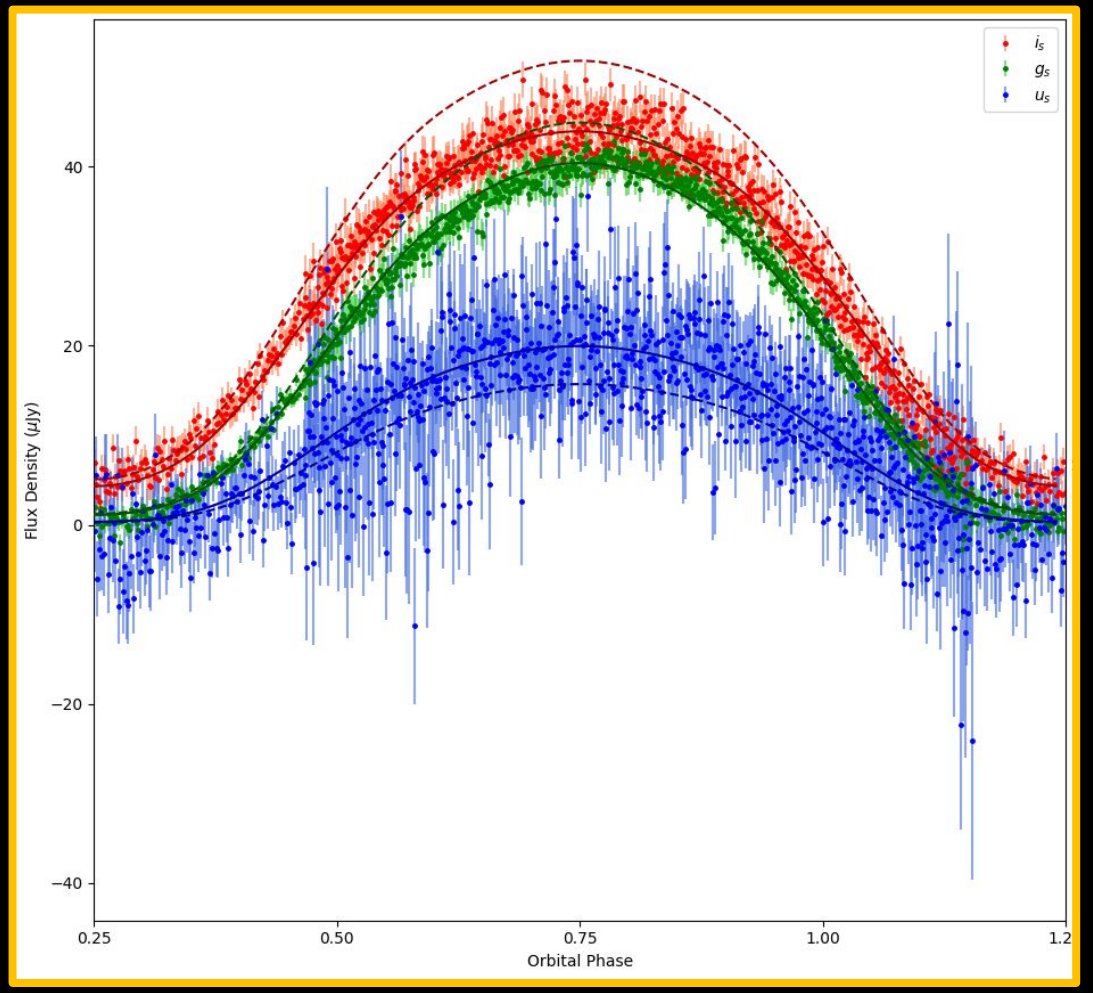
Work by Adipol Phosrisom:

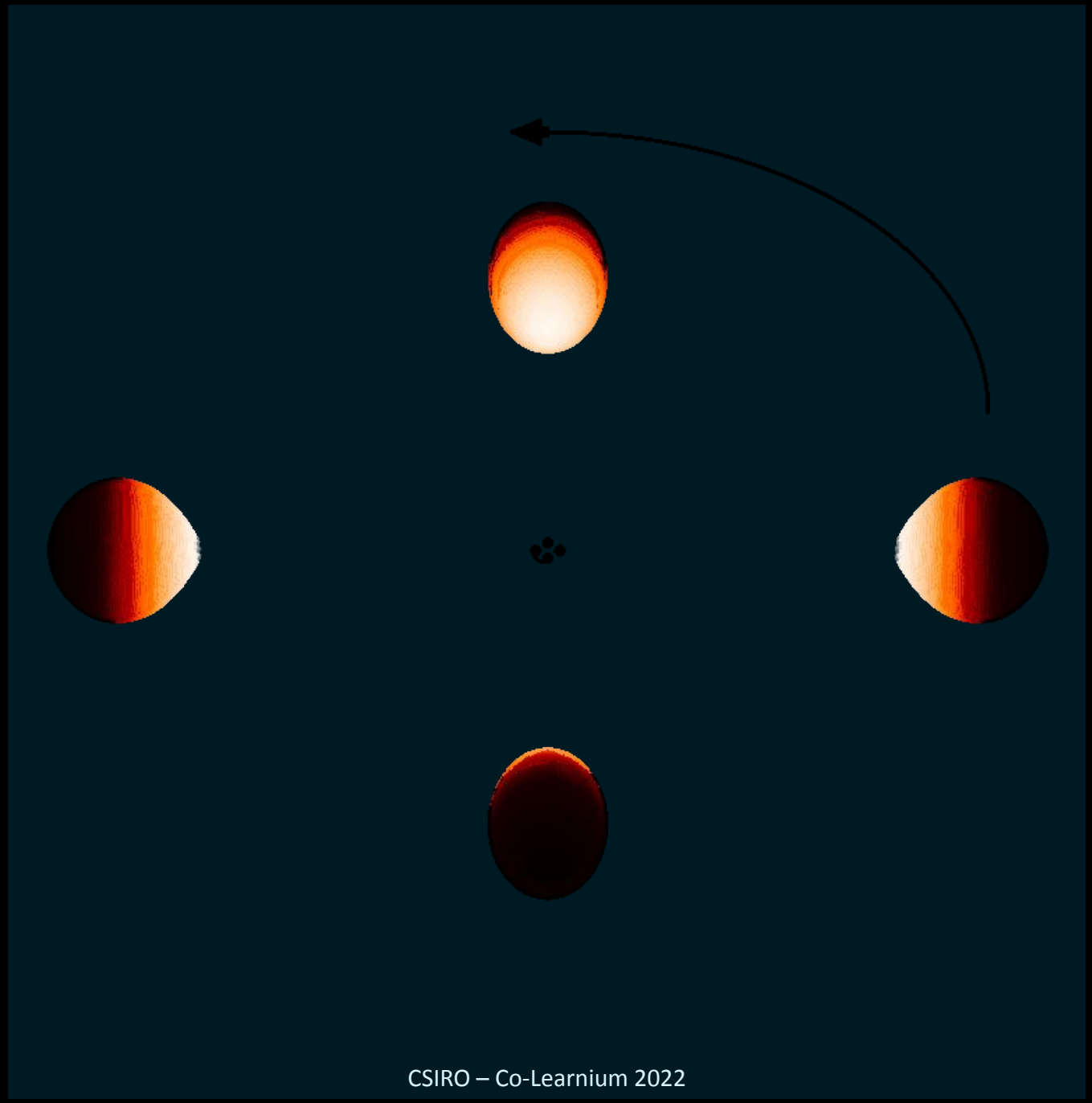
- Creates lightcurves from each star in the field
- Uses Lomb-Scargle Analysis to determine the best fitting binary period



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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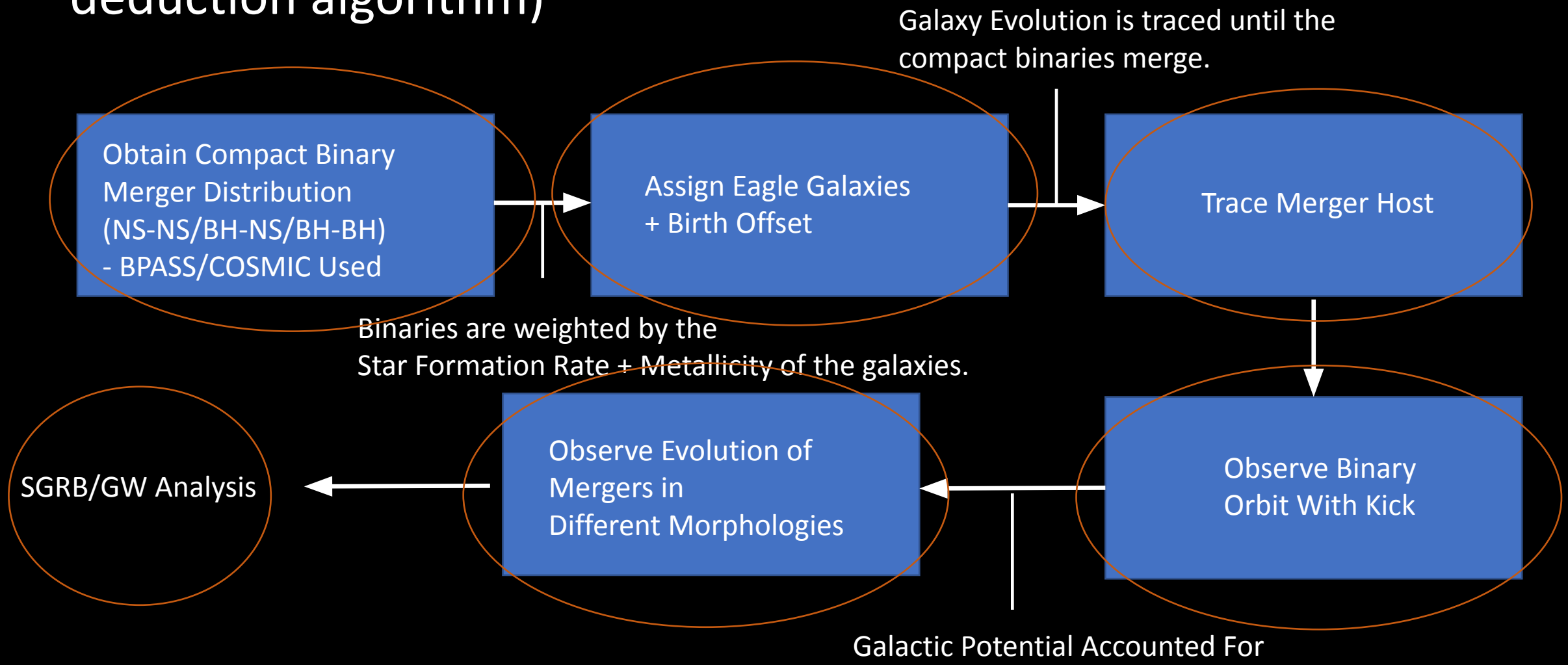
Evolving Spider Orbits - Motivation

- Have an idea of where binaries cluster within the galaxy
- Gauge how formation channels affect binary evolution
  - Effects of supernova kicks
- Identify regions within the Milky Way that are likely to have spiders
  - Cross-match this with Fermi gamma-ray foreground excess
- Create targeted follow-up strategies of regions of interest
- Extend study to the zoo of potential binaries in the Milky Way
- Exploit LISA/DECIGO + other GW science studies

Key Ingredients

- Milky Way Analogue
  - Auriga
- Binary channel for Spider Formation
  - NS+WD
- Kick Prescriptions
  - COSMIC binaries
  - BPASS Bray/Hobbs kicks
- Binary characteristics
  - ZAMS Mass, Age @ SN, Systematic velocities etc.

Background: zELDA Summary (Redshift electromagnetic localisation and deduction algorithm)



Where do binary mergers occur?

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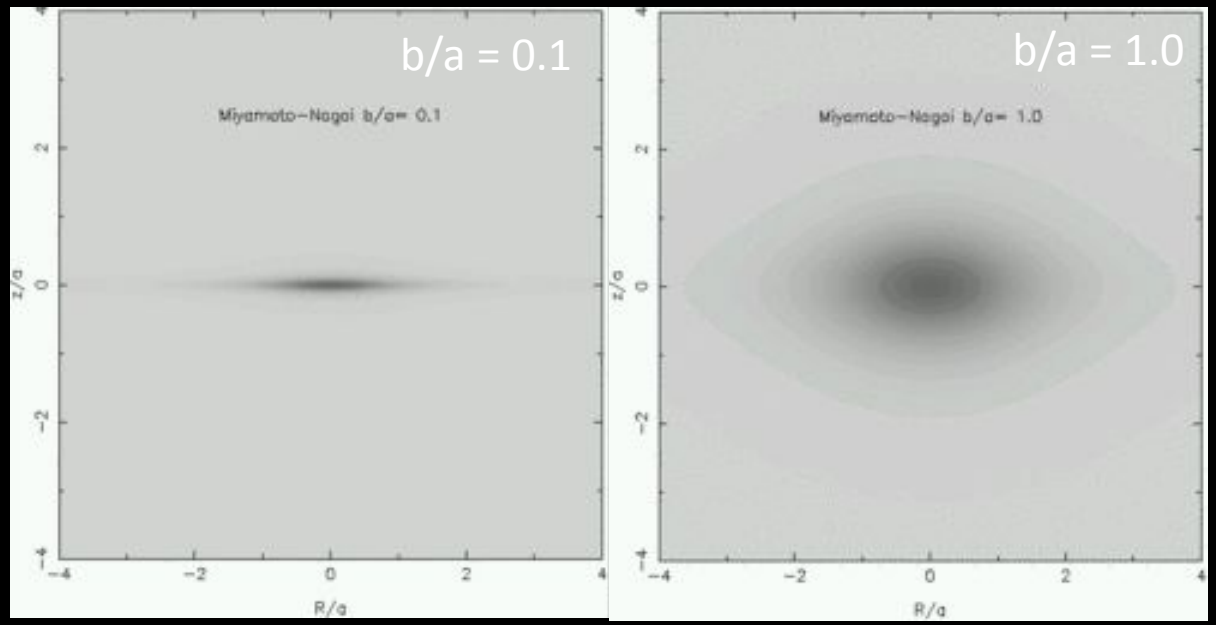
Host Potential:

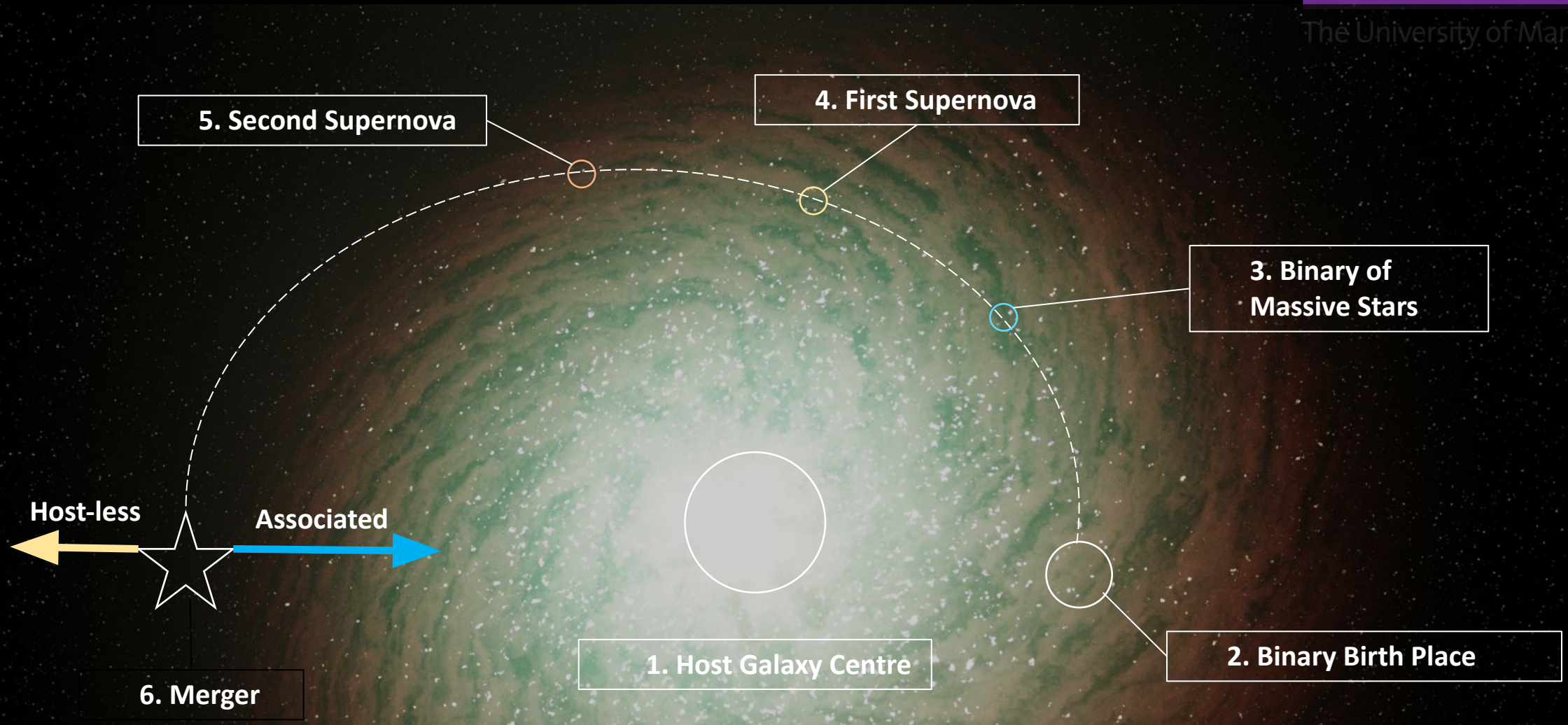
- Integrated GalPy usage
- Stellar and Gas components = Miyamoto & Nagai Potentials
- DM Halo: NFW Profile
- Approximated based on initial EAGLE parameters

Binary Placement:

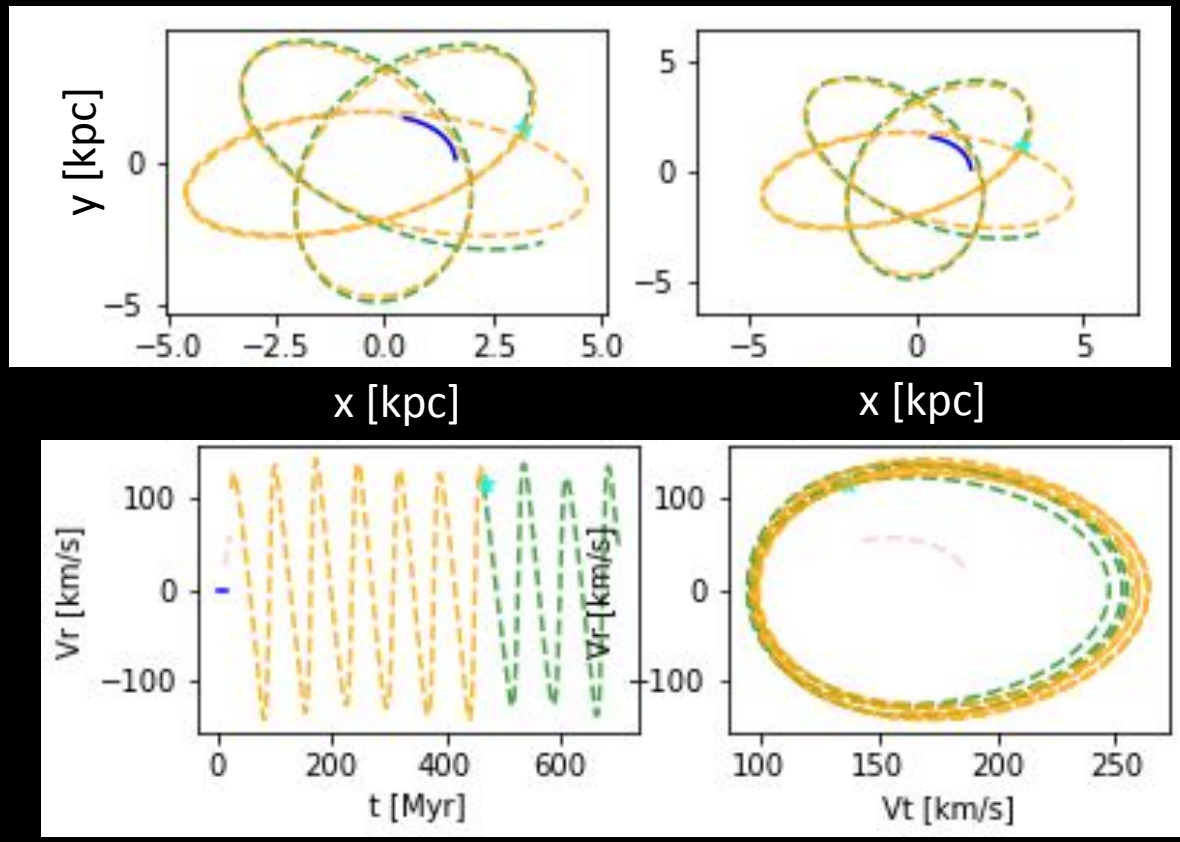
- Isolated binaries from Bray & Eldridge, (2018)
- Weighted by the Stellar Mass profile (z=0)
- Randomly placed

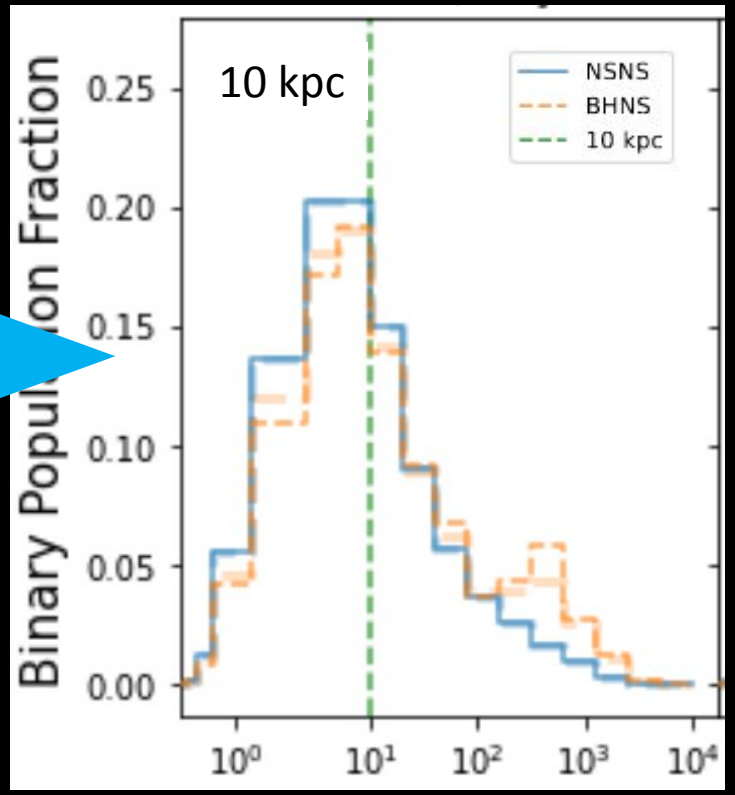


Credit: Chris Flynn

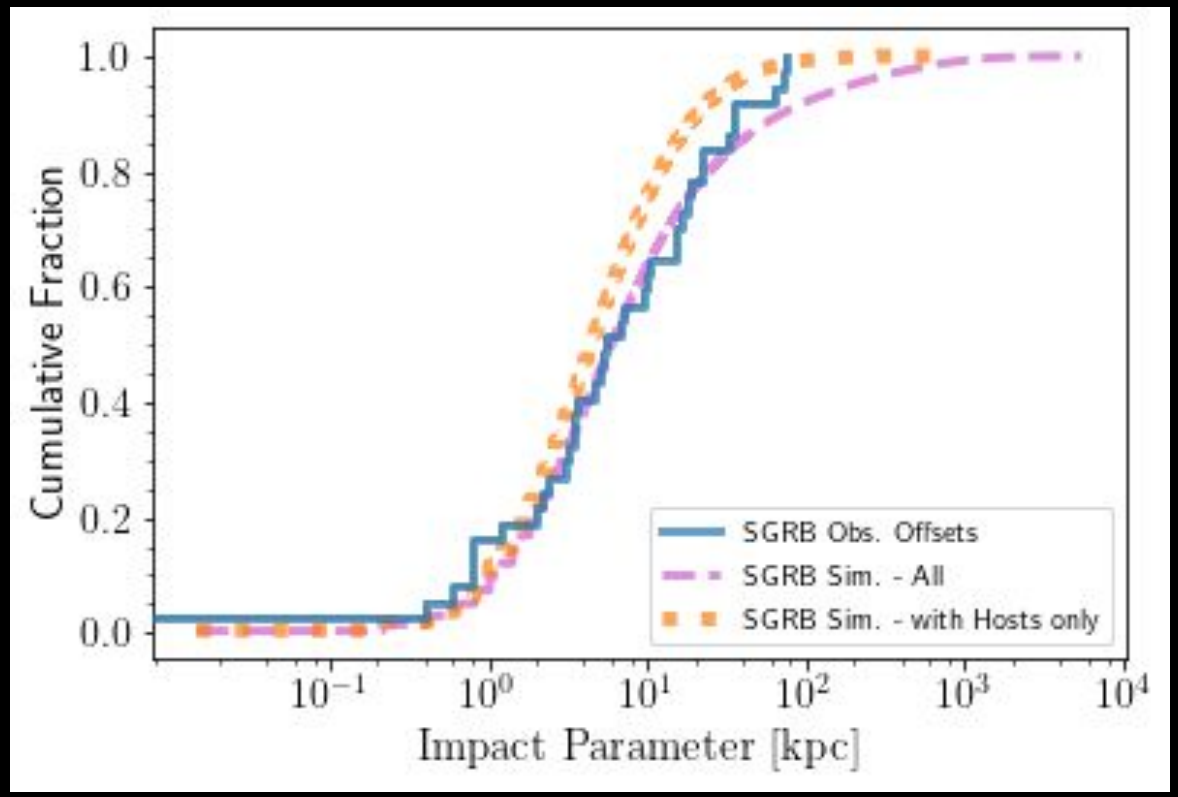

5. Second Supernova
4. First Supernova
3. Binary of Massive Stars
Host-less
Associated
6. Merger
1. Host Galaxy Centre
2. Binary Birth Place

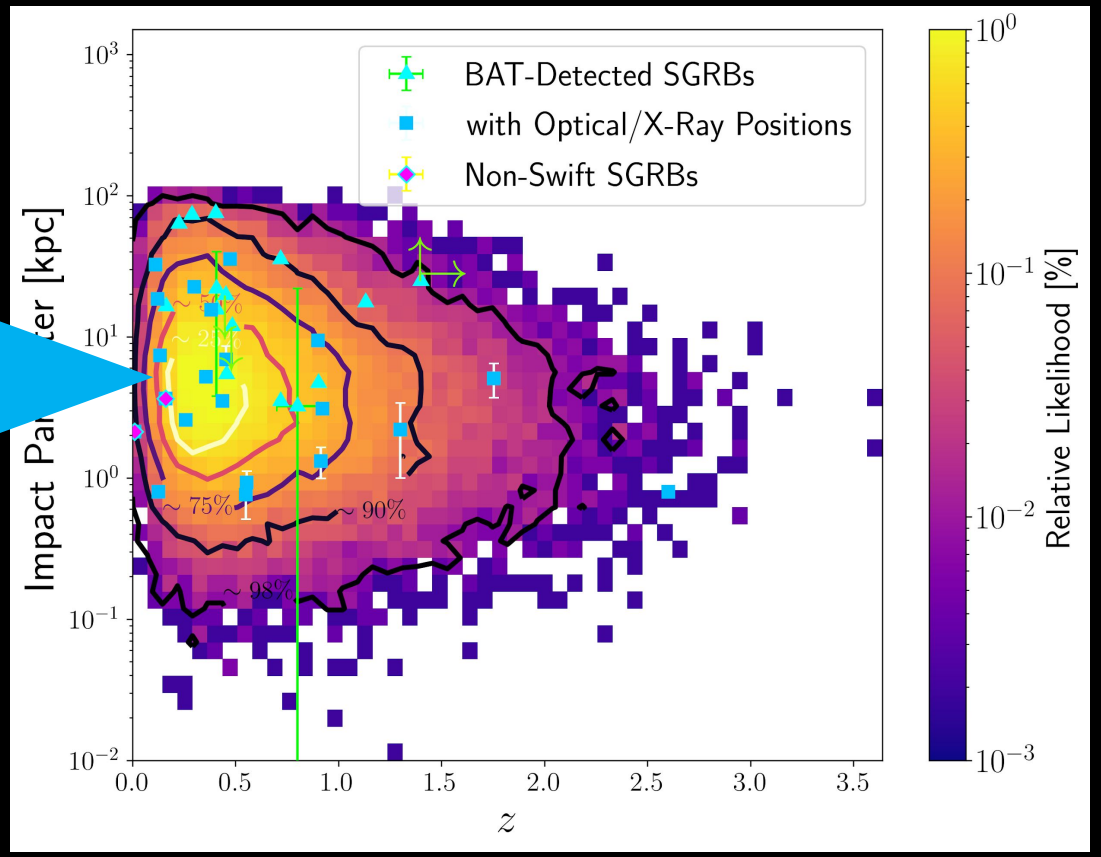
Example Orbits:



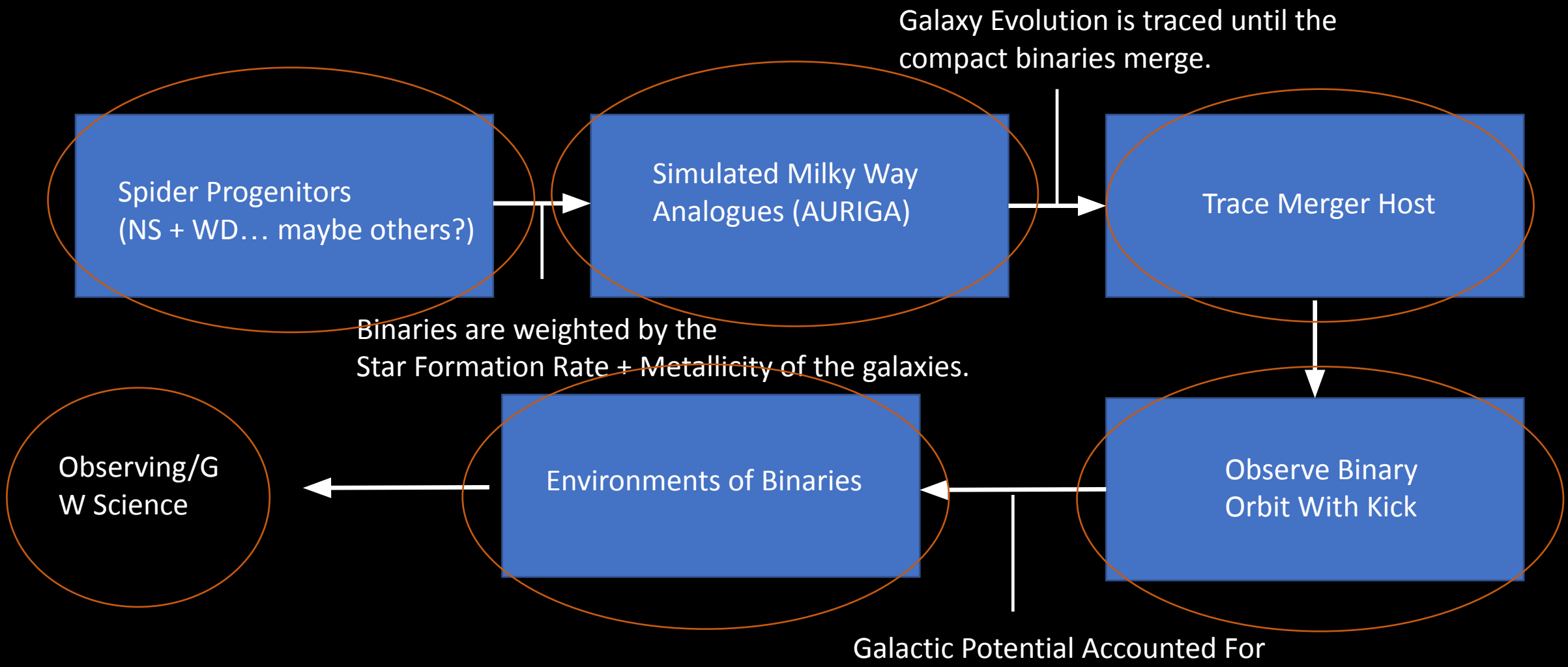


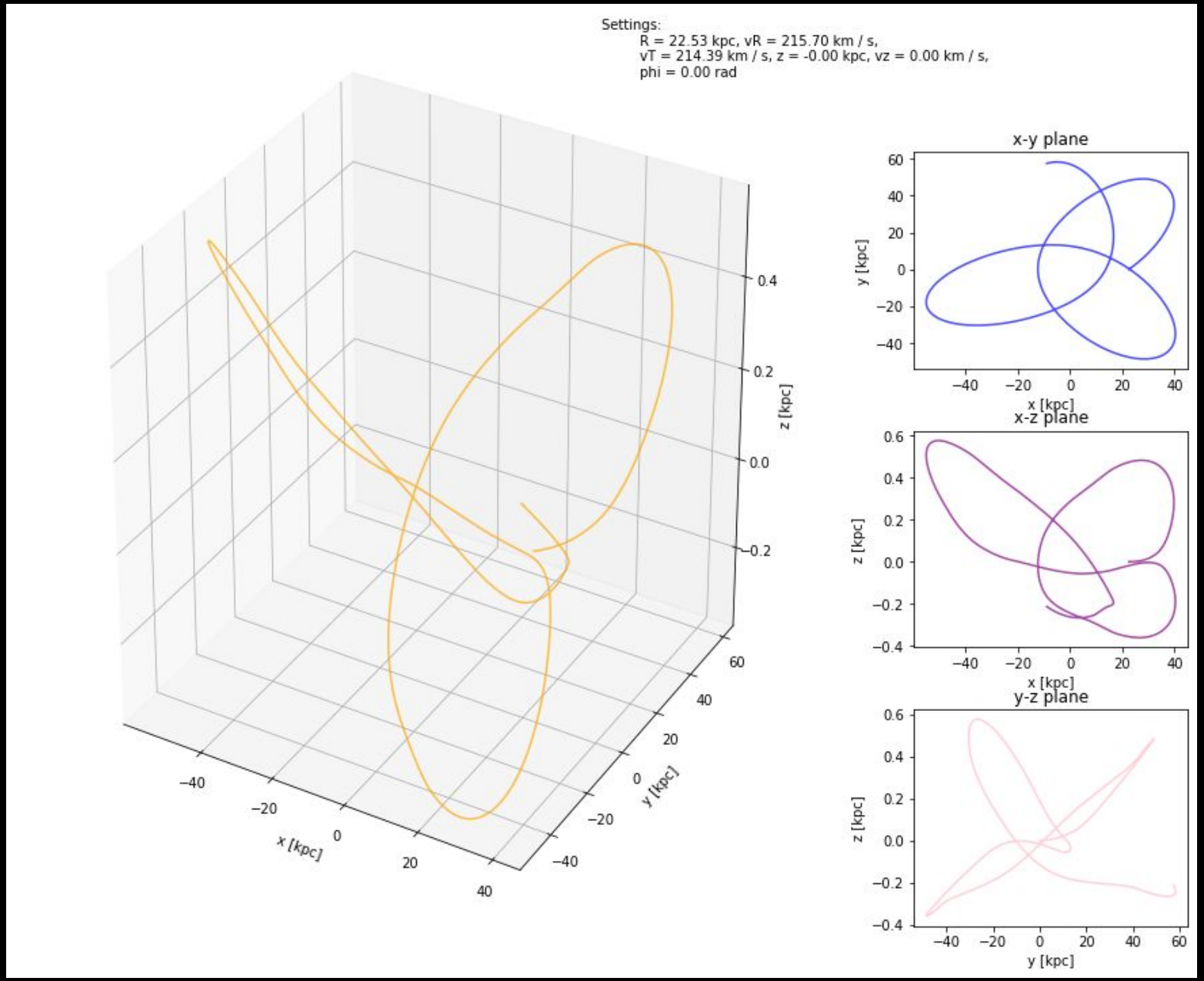
Mandhai et al., 2022


Cumulative Fraction
Impact Parameter [kpc]
SGRB Obs. Offsets
SGRB Sim. - All
SGRB Sim. - with Hosts only


BAT-Detected SGRBs
with Optical/X-Ray Positions
Non-Swift SGRBs
~ 50%
~ 75%
~ 90%
~ 98%
z
Relative Likelihood [%]

Evolving Spider Orbits





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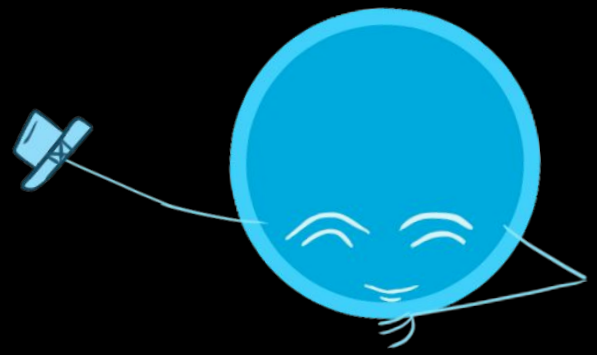
What's next?

- Accurately seed binaries based on their star formation and metallicity
- Ground simulations to reality
  - How can this work be used to improve the efficiency of searches for Spidery pulsars?
- Constrain the stellar evolutionary channels that lead to the formation of spiders.
- Identify the proportion of Spiders in the Milky Way
- Create search algorithms for finding spiders

Summary

- Observed Spider candidates using Fermi Gamma-Ray excess (30 sources observed)
- Created a semi-analytical model of a Milky Way type galaxy
- Evolved the orbits of NS+WD binaries
- Future work will aim to develop this further and aid observations



- Tangent: Host Galaxy – Binary Paper: Mandhai et al., 2022 – arXiv: 2109.09714
- Email: Soheb.Mandhai@manchester.ac.uk

Result: Host Galaxy Demographics

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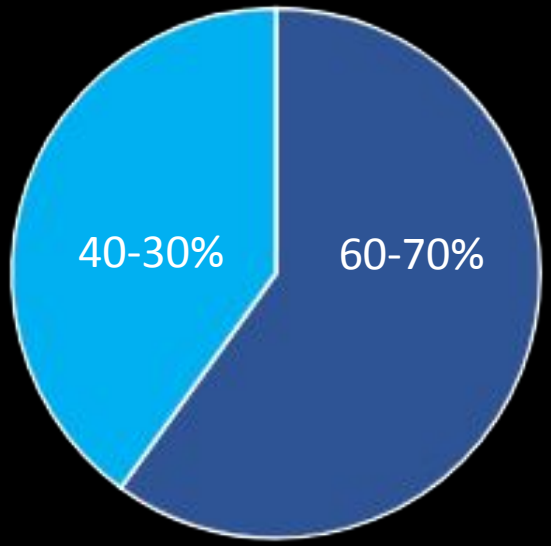
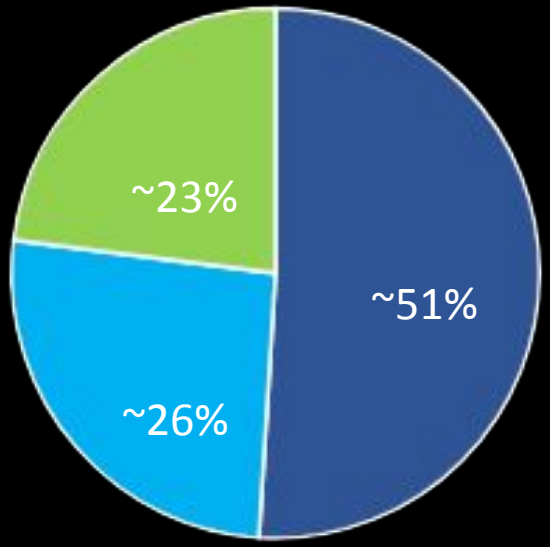
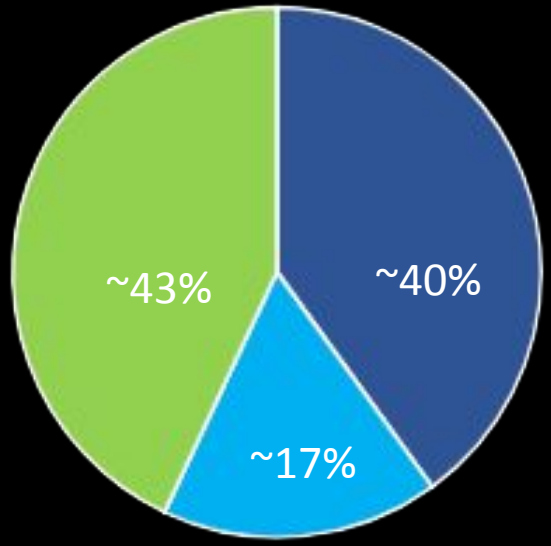
Host Galaxy Morphology*



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**

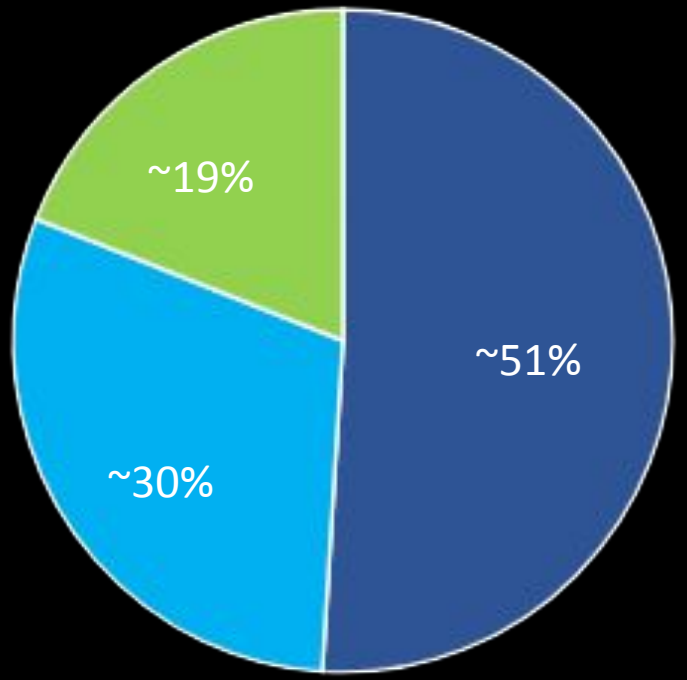
Early-Type**

Host-less***

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

What about SGRBs?

- Short-Duration Gamma Ray Bursts (SGRBs) require sufficient ejecta following NSNS/BHNS mergers
- BHNS binary population limited to $M_{BH}/M_{NS} \leq 3$ (Hayashi et al., 2020)
- SGRB Luminosities Drawn from (Paul, 2018)
- Emulation of Swift/BAT photon detection – sensitivity of 0.2 ph s^{-1} cm^{-2}.



CONSISTENT WITH OBSERVATIONS!

Late-Type**

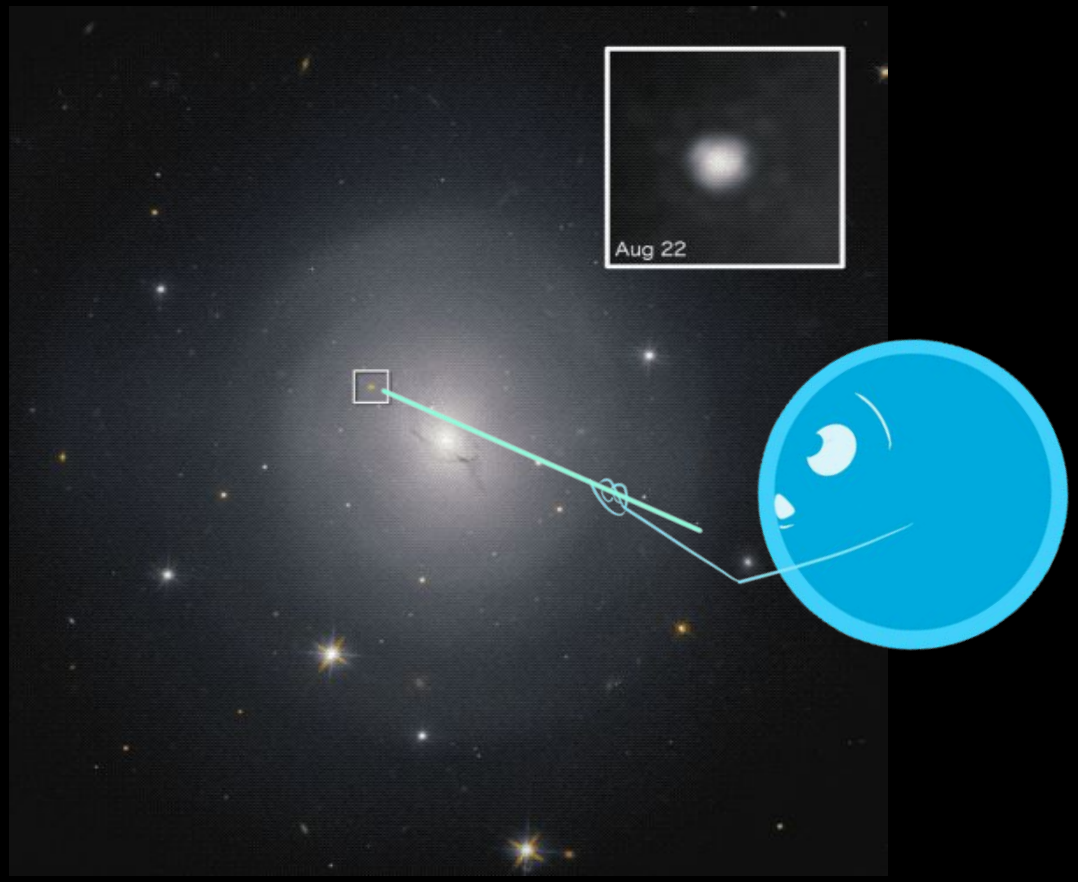
Early-Type**

Host-less***

What have we seen?

- Gravitational waves
- Short Duration Gamma-Ray Bursts (SGRBs)
- Afterglow
- Kilonovae
- All four together! GW170817
  - Merger of two neutron stars
  - Host Galaxy: NGC 4993

Can we find more???



NGC 4993 – EM Counterpart to GW170817
Image Source: NASA and ESA

Afterglow Bright/Faint Populations

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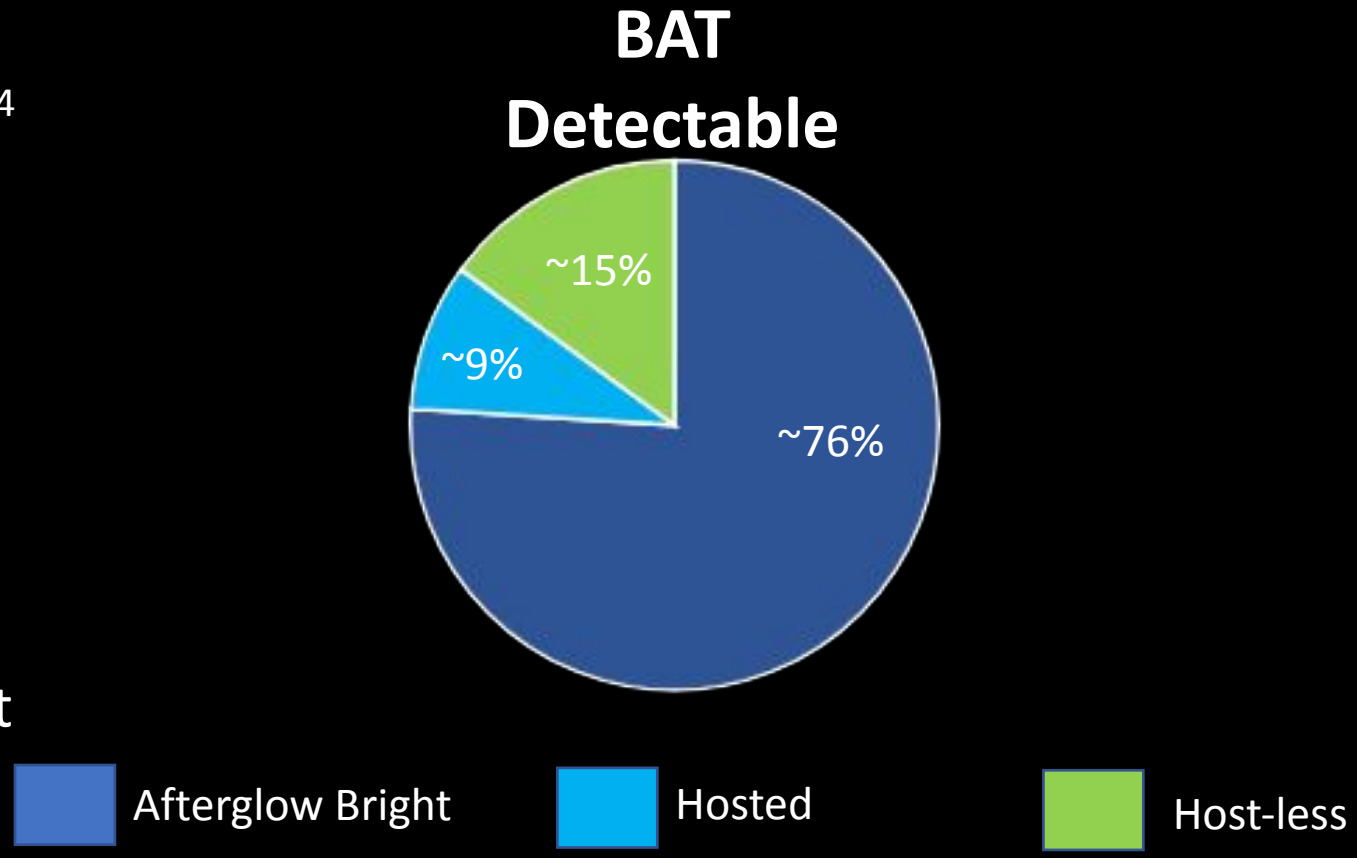
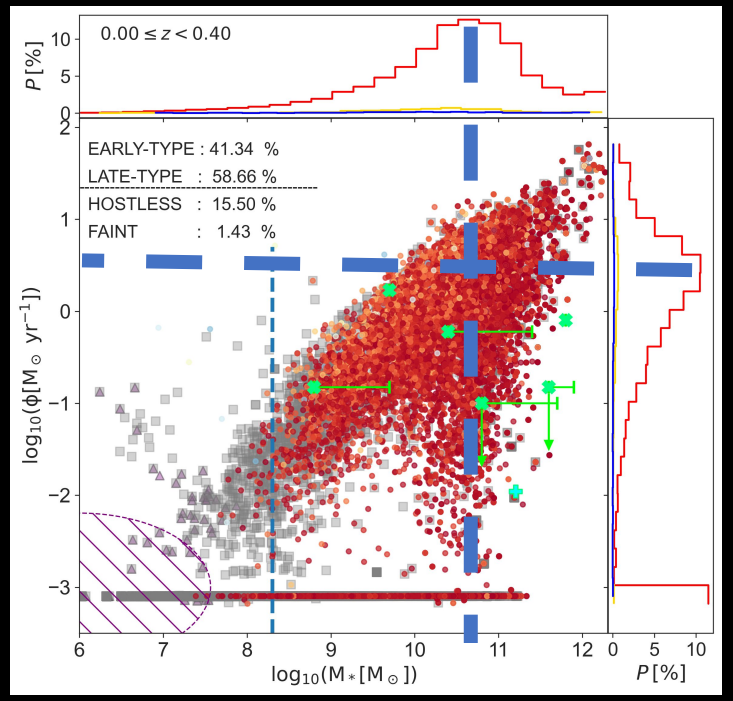
For BAT-Detectable SGRBs:

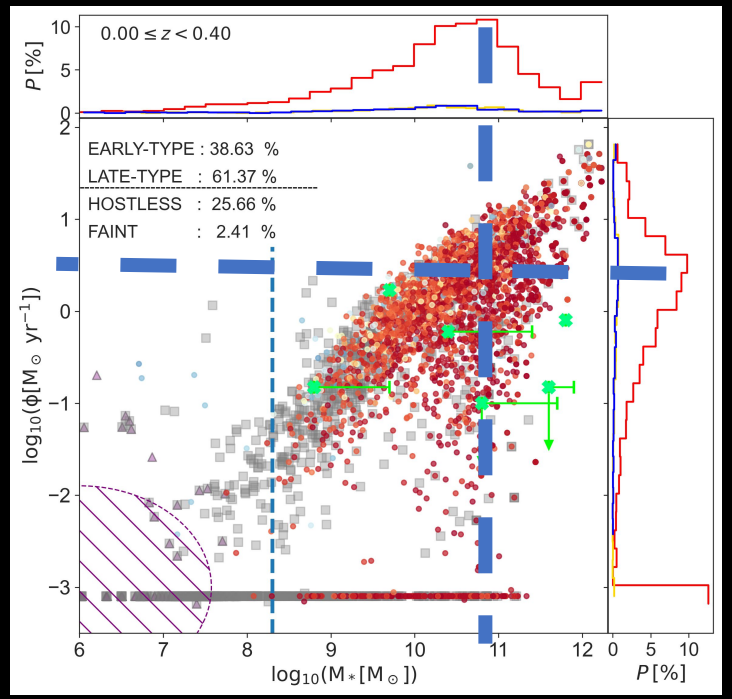
- Ambient density cut at n= 10^{-4} cm^{-3}
- Afterglow faint n< 10^{-4} cm^{-3}
- The majority of zELDA SGRBs merge in ambient dense environments
- Associated binaries may have faint afterglows
- Host-less SGRBs in Afterglow Faint environments consistent with **O'Connor et al., 2020**.



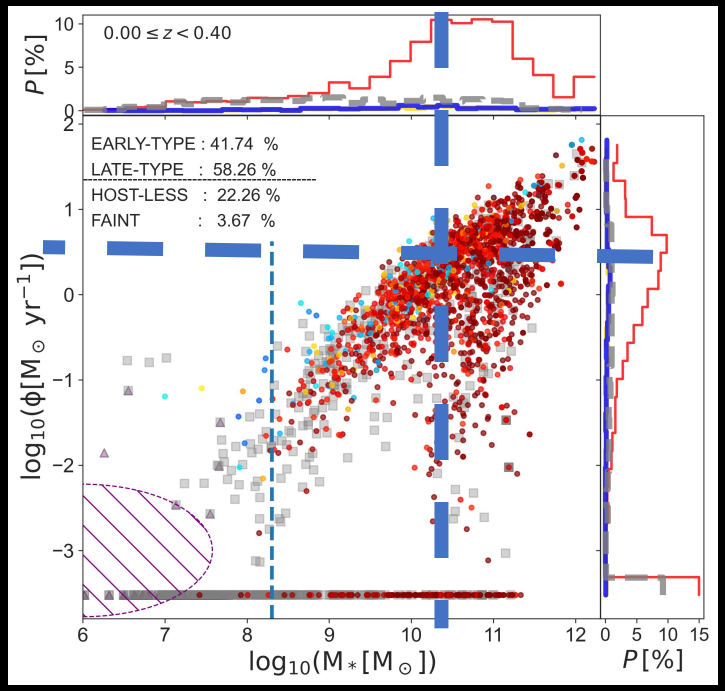
Host Galaxy Type?



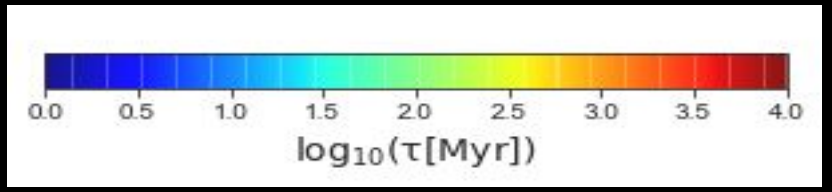
NSNS



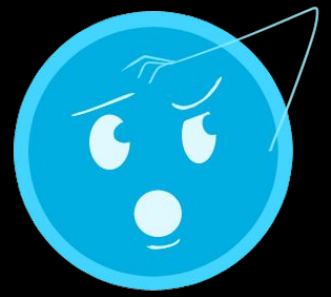
BHNS



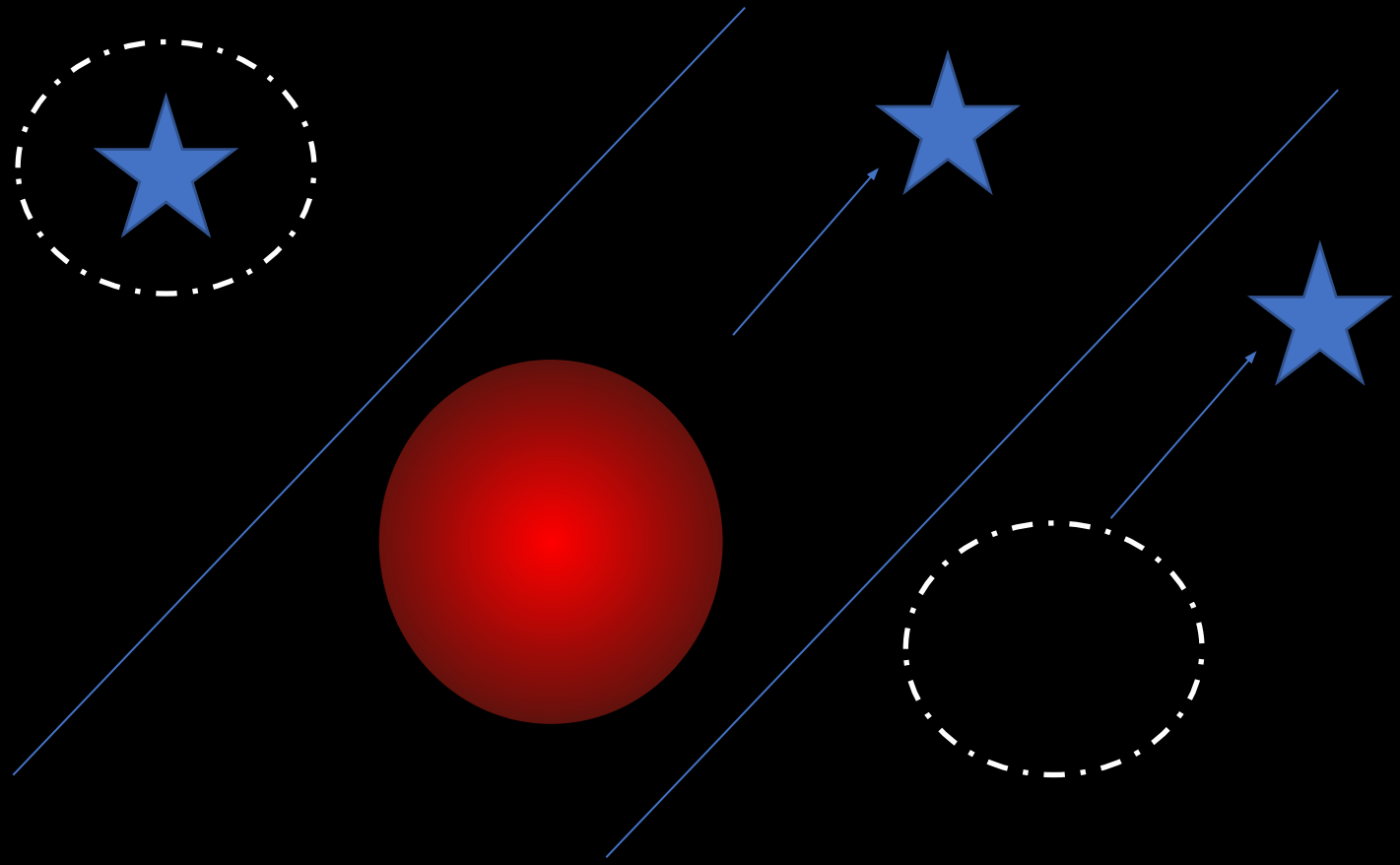
BHBH



What are the challenges?



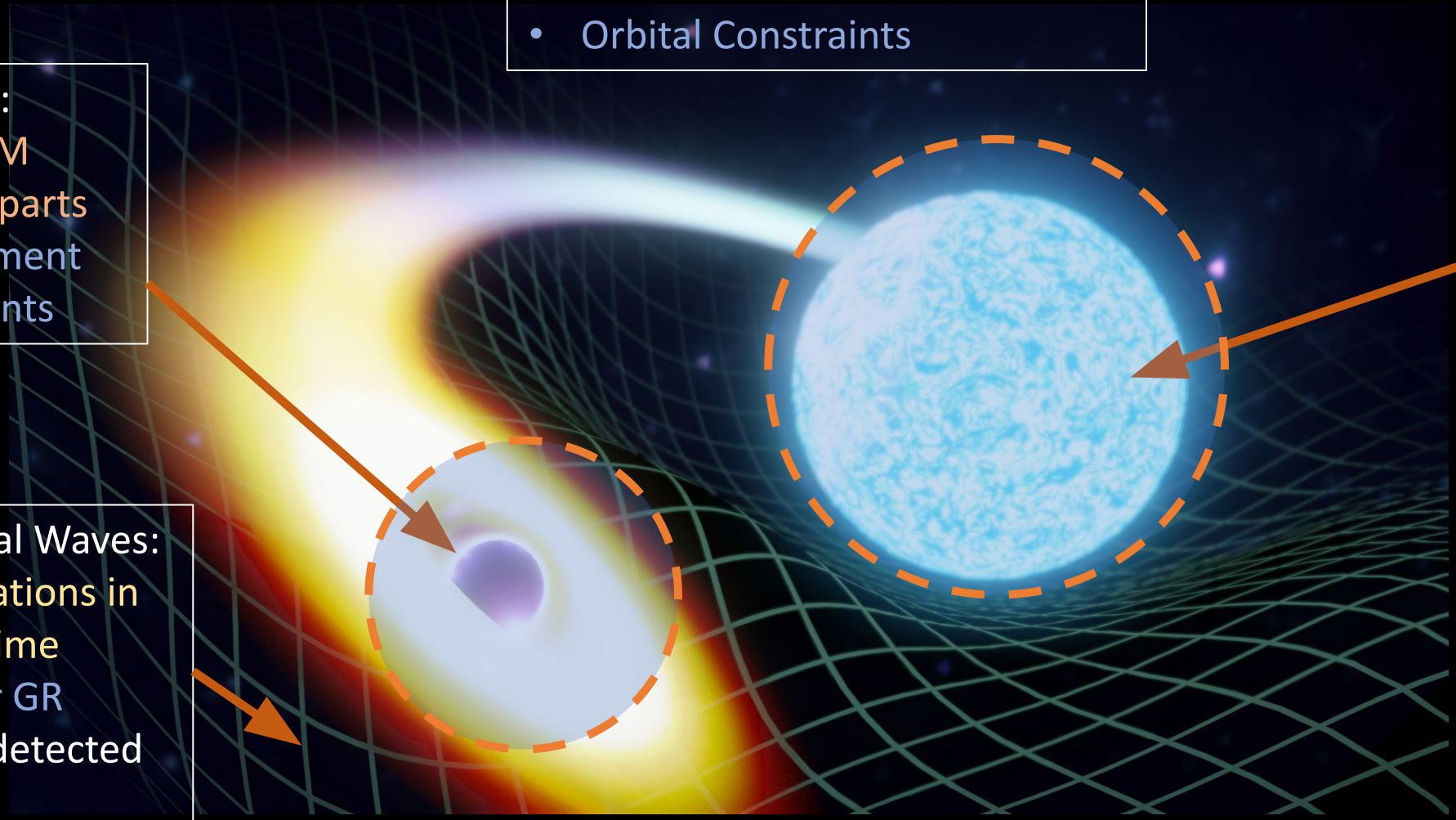
- No Host Identification = no/uncertain redshift
- Galaxies can be faint
- Binaries can get ejected from their galaxies



Breakdown:

General:
- Insight into Formation Mechanism
- Orbital Constraints

Black-Holes:
- Stifles EM Counterparts
- Environment Constraints



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

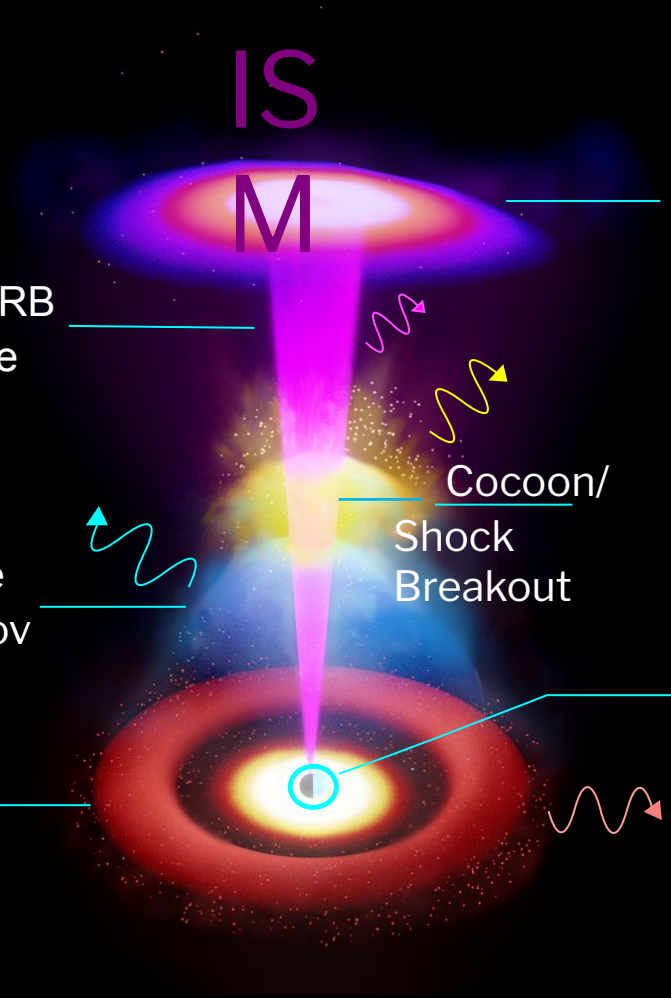
Gravitational Waves:
- Perturbations in Space-Time
- Tests for GR
- Can be detected

Key:
Progenitor
Astrophysics
Definition

What are the “EM counterparts”?

- Beamed Gamma Rays
- Caused by Rapid Accretion on Central Engine

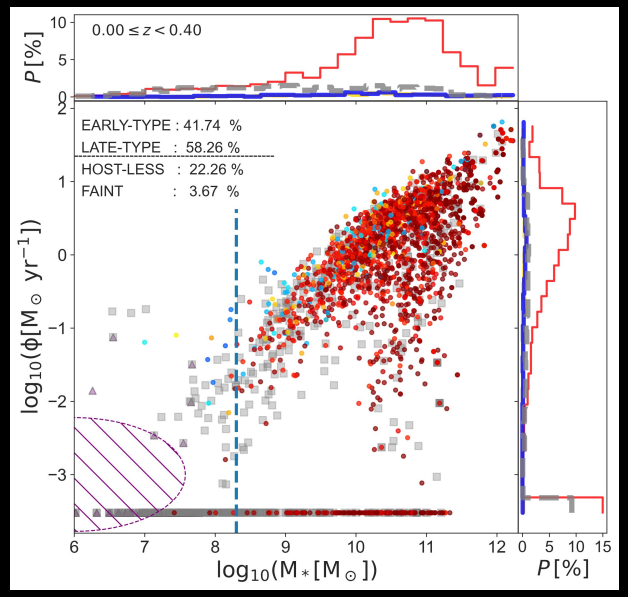
- R-process nucleosynthesis

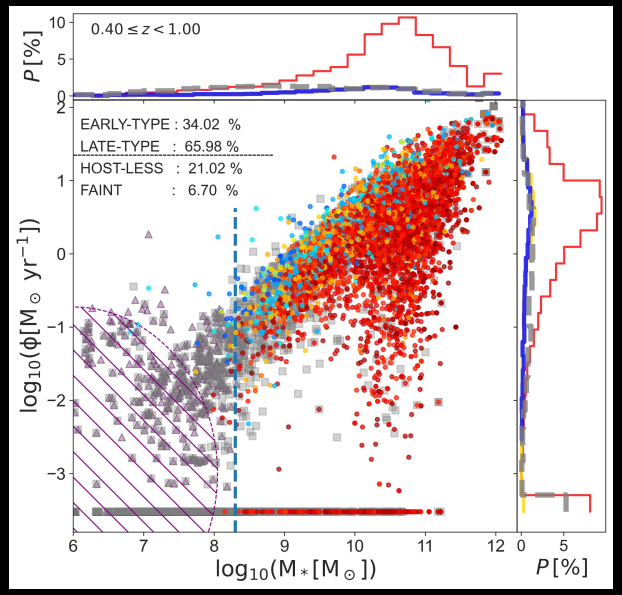


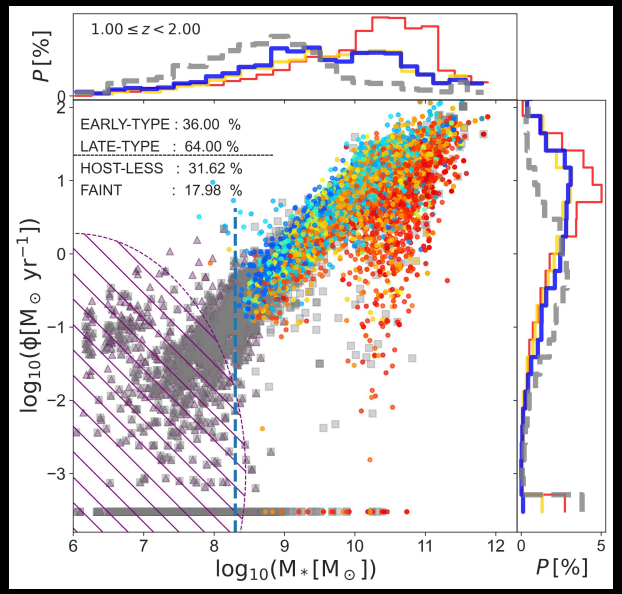
- Caused by synchrotron radiation

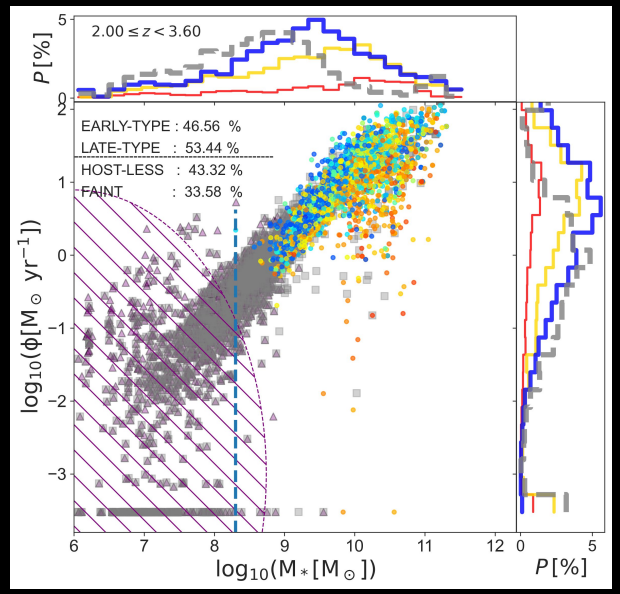
- Neutron Star Or Black Hole

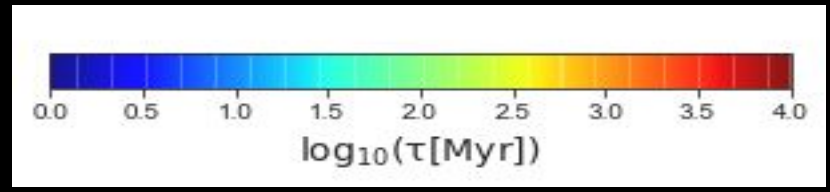
Key:
Progenitor
Astrophysics
Definition

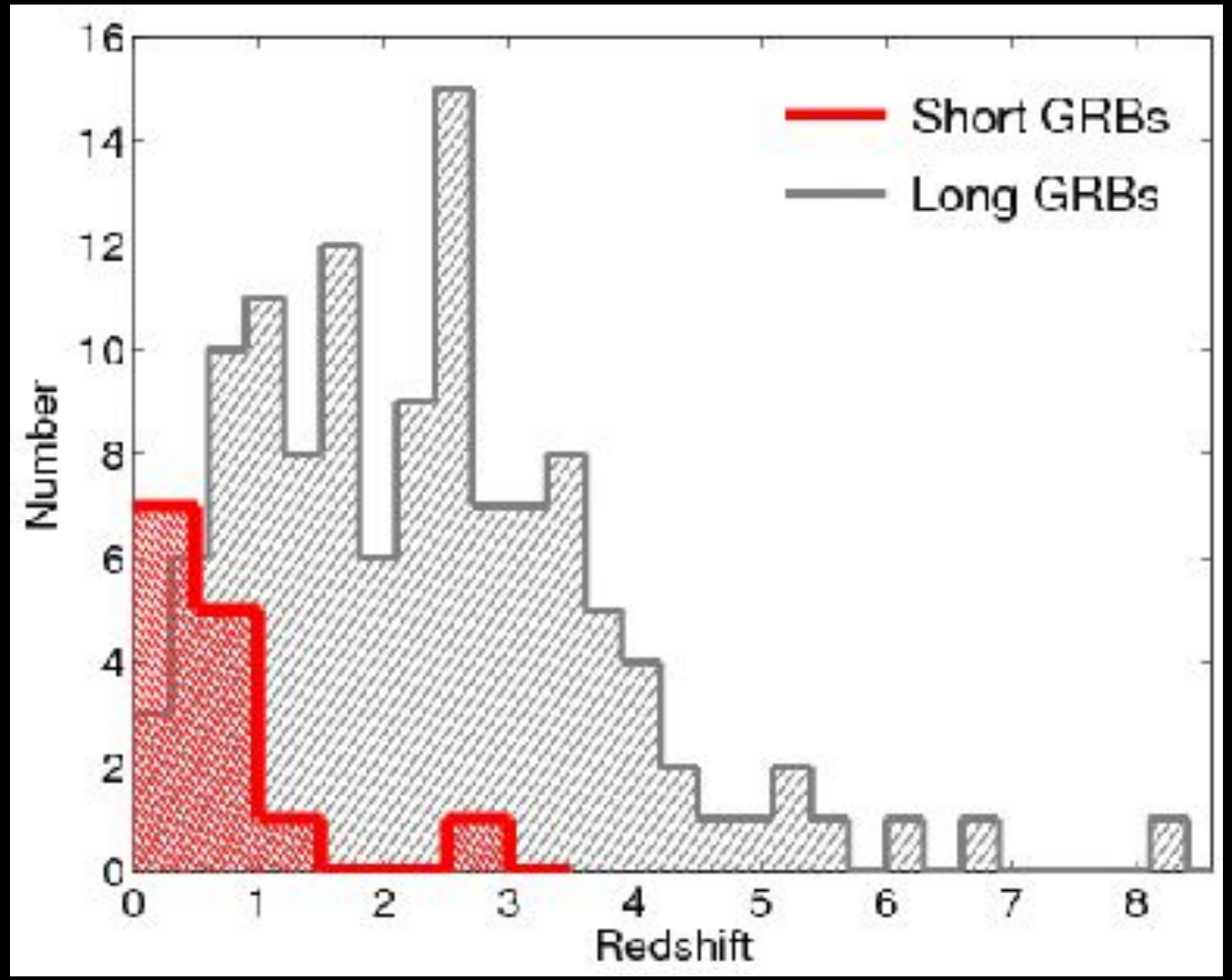

0.00 ≤ z < 0.40
EARLY-TYPE : 41.74 %
LATE-TYPE : 58.26 %
HOST-LESS : 22.26 %
FAINT : 3.67 %
P [%]
log10(ϕ[M⊙ yr−1])
log10(M∗[M⊙])


0.40 ≤ z < 1.00
EARLY-TYPE : 34.02 %
LATE-TYPE : 65.98 %
HOST-LESS : 21.02 %
FAINT : 6.70 %
P [%]
log10(ϕ[M⊙ yr−1])
log10(M∗[M⊙])


1.00 ≤ z < 2.00
EARLY-TYPE : 36.00 %
LATE-TYPE : 64.00 %
HOST-LESS : 31.62 %
FAINT : 17.98 %
P [%]
log10(ϕ[M⊙ yr−1])
log10(M∗[M⊙])


2.00 ≤ z < 3.60
EARLY-TYPE : 46.56 %
LATE-TYPE : 53.44 %
HOST-LESS : 43.32 %
FAINT : 33.58 %
P [%]
log10(ϕ[M⊙ yr−1])
log10(M∗[M⊙])


0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
log10(τ[Myr])


Short GRBs
Long GRBs
Number
Redshift
0
2
4
6
8
10
12
14
16
0
1
2
3
4
5
6
7
8

Key-Points

- Compact binaries -> Good probes for astrophysics
- Multi-messenger Era of Astrophysics!
- In this work -> Predict relationships between:
  - Binary-Galaxy Offsets
  - Galaxy Morphology
  - Cosmological Populations
  - Environments
- Can form observing strategies