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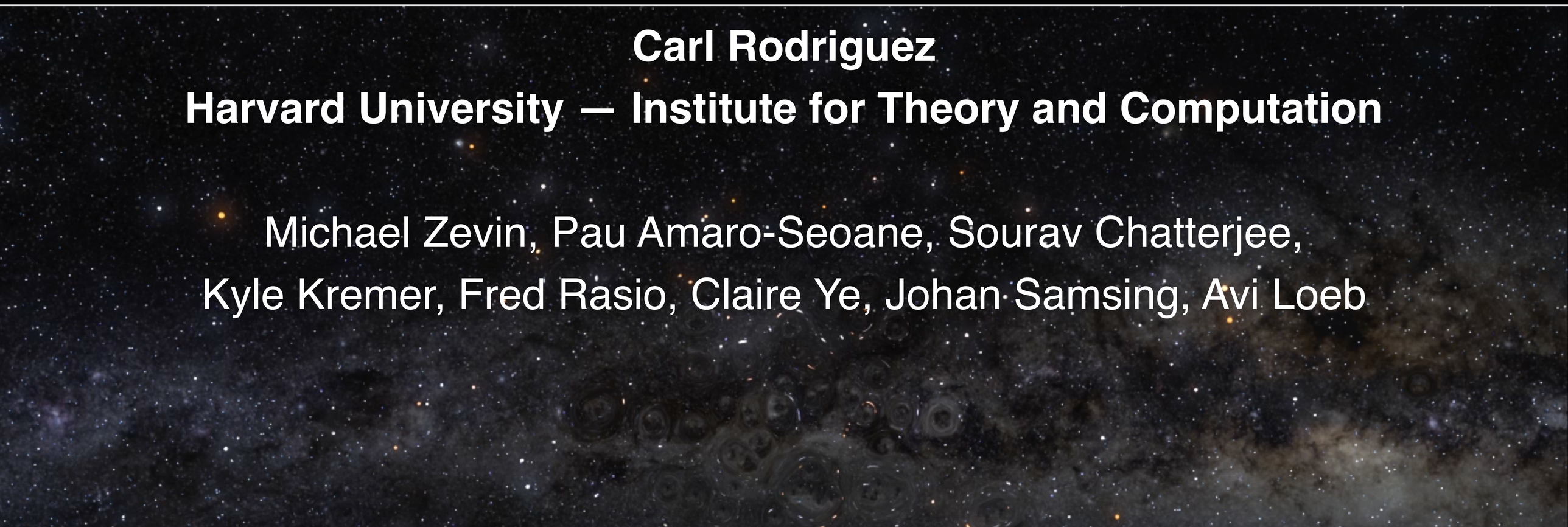
# Dynamical Formation of Compact-Object Binaries

**Carl Rodriguez**
**Harvard University — Institute for Theory and Computation**

Michael Zevin, Pau Amaro-Seoane, Sourav Chatterjee,
Kyle Kremer, Fred Rasio, Claire Ye, Johan Samsing, Avi Loeb



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Portegies Zwart & McMillan 2000, Gültekin et al. 2004, 2006, Kocsis et al. 2006, O'Leary et al. 2006, 2007. Sadowski et al. 2008, Banerjee et al. 2010, 2017, Downing et al. 2010, 2011, Benacquista et al. 2013, Clausen et al. 2014, Bae et al. 2014, Ziosi et al. 2014, 2016, Morscher et al. 2013, 2015, Rodriguez et al. 2015, 2016a,b,c, Mapelli 2016,2017, Abbas et al. 2016, 2017, 2018, Giesler et al. 2017, Samsing et al., 2014, 2017, 2018, Antonini et al., 2016, 2018, Di Carlo et al., 2019

# Forming Black Hole Binaries

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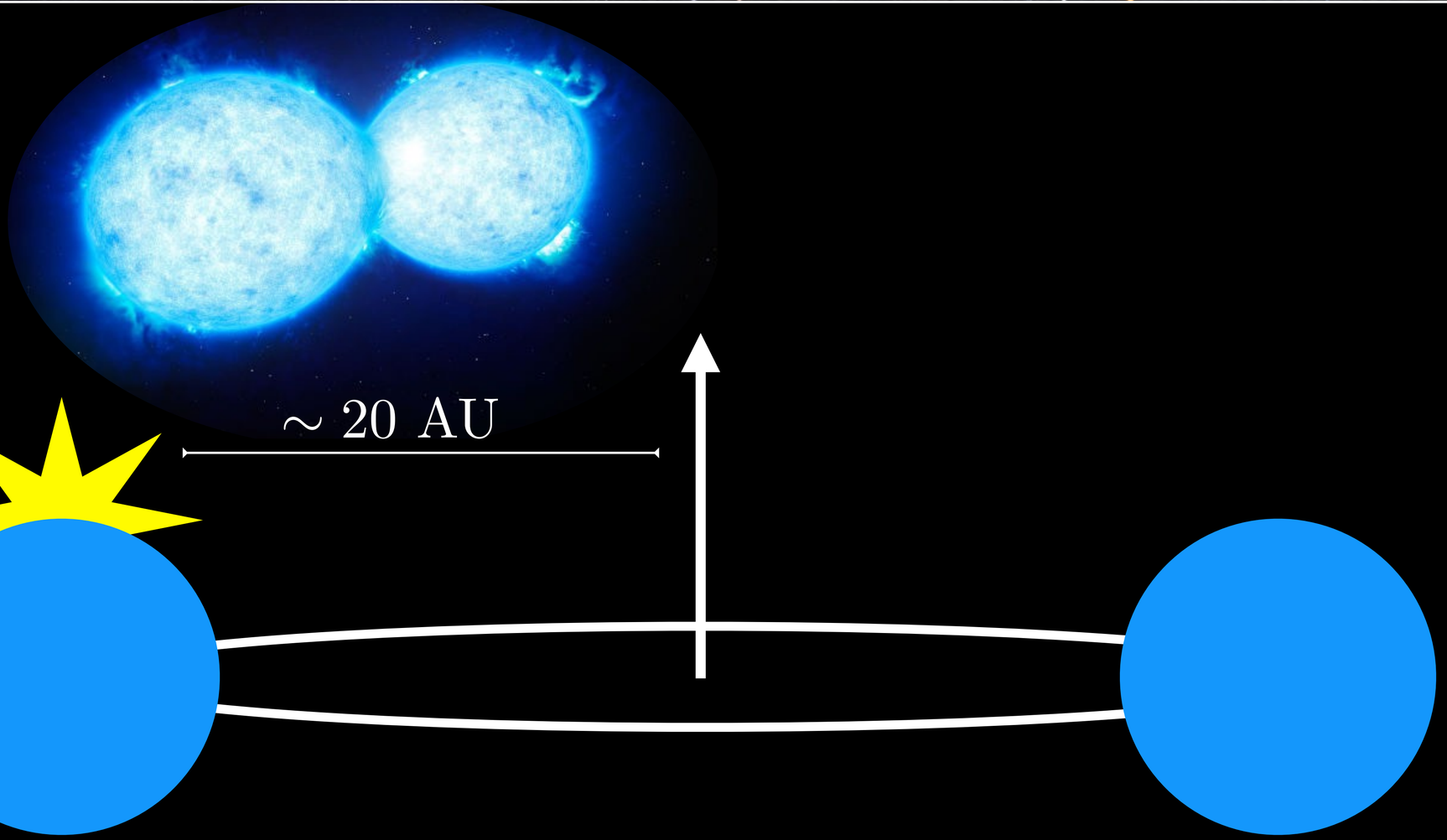

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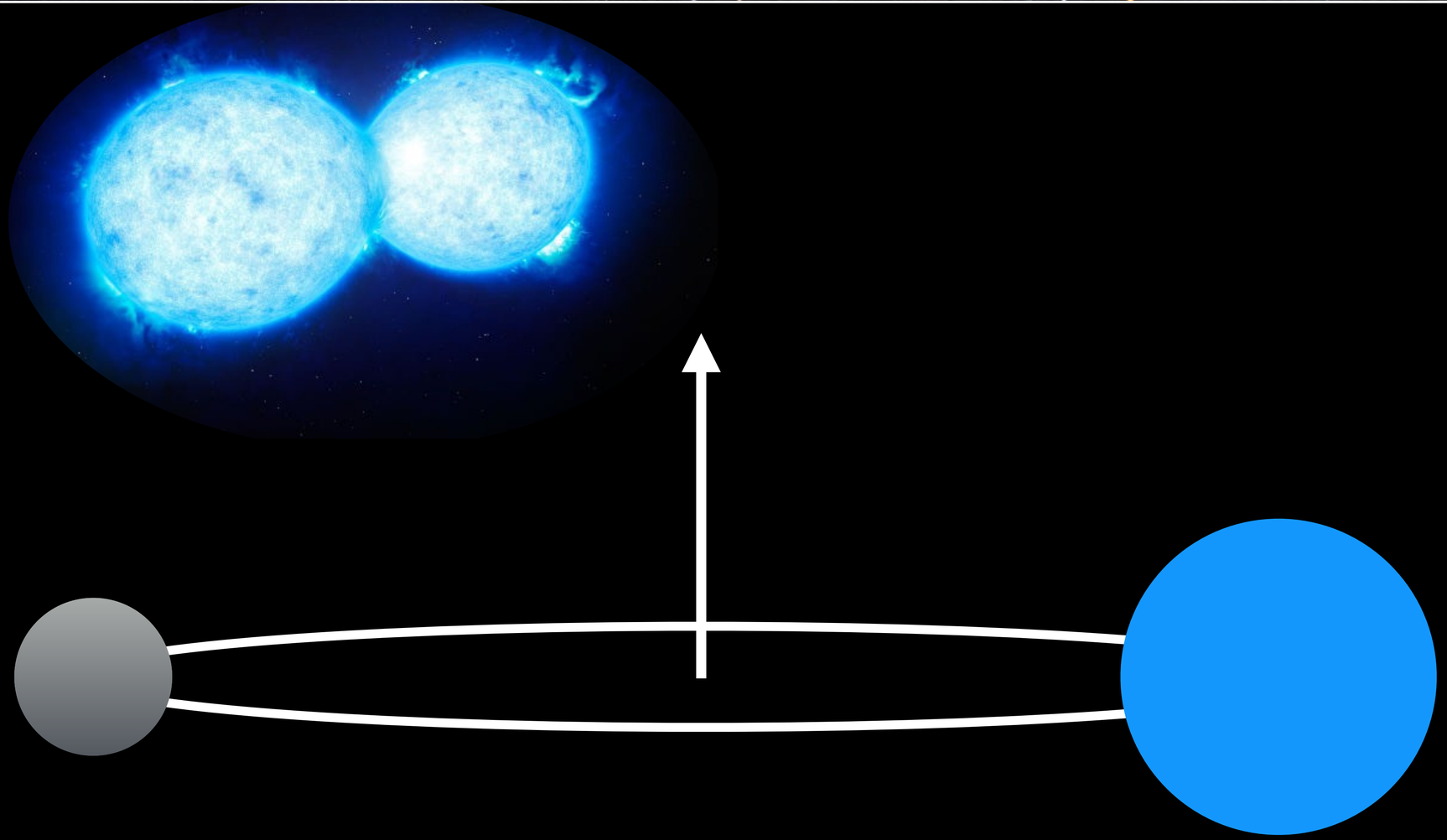

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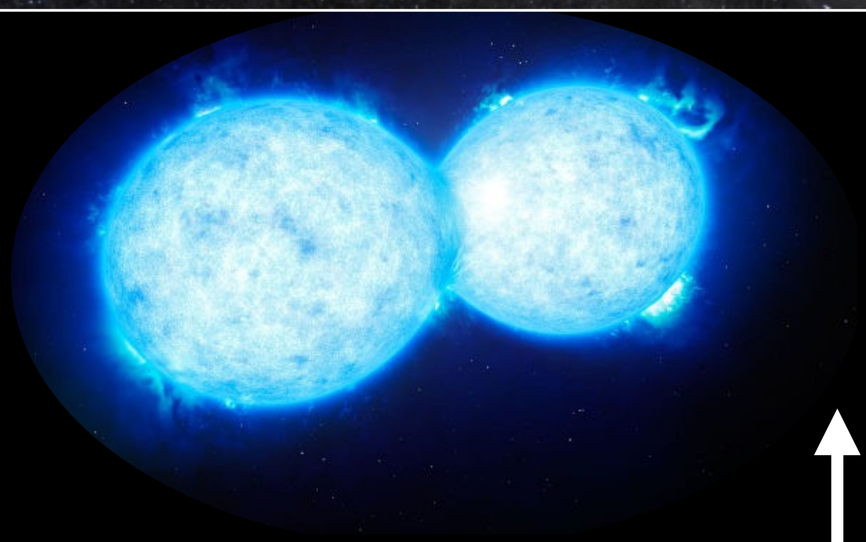

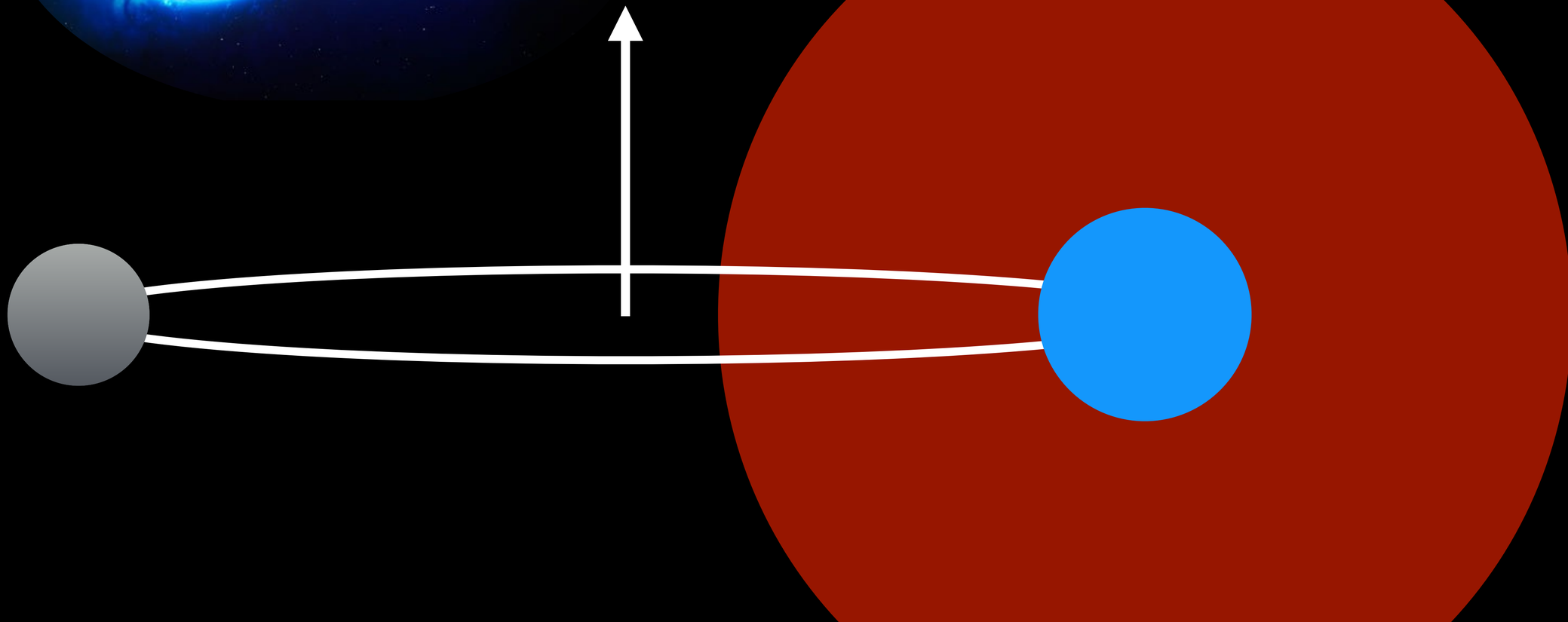

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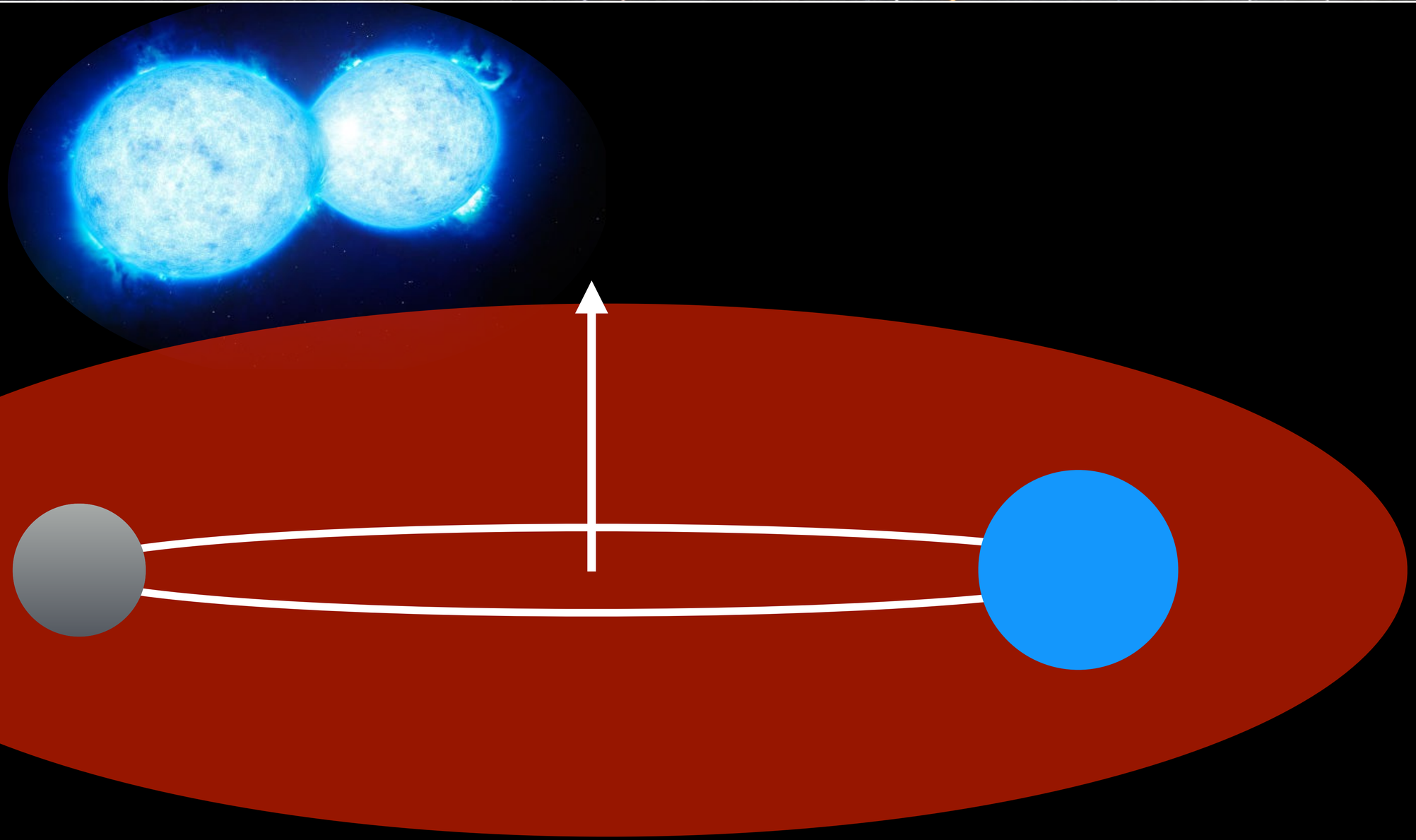

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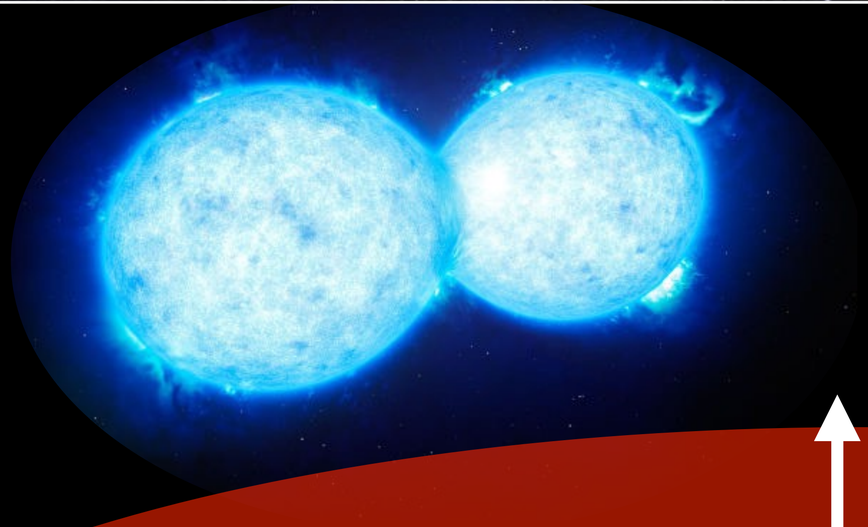

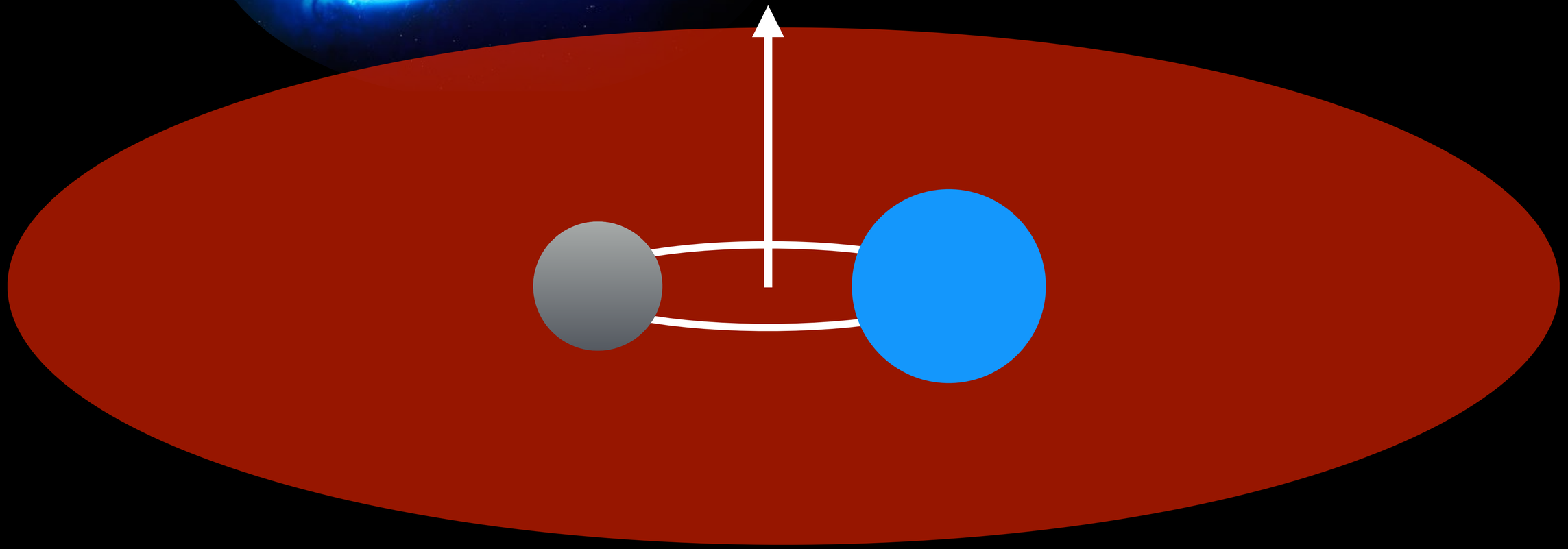

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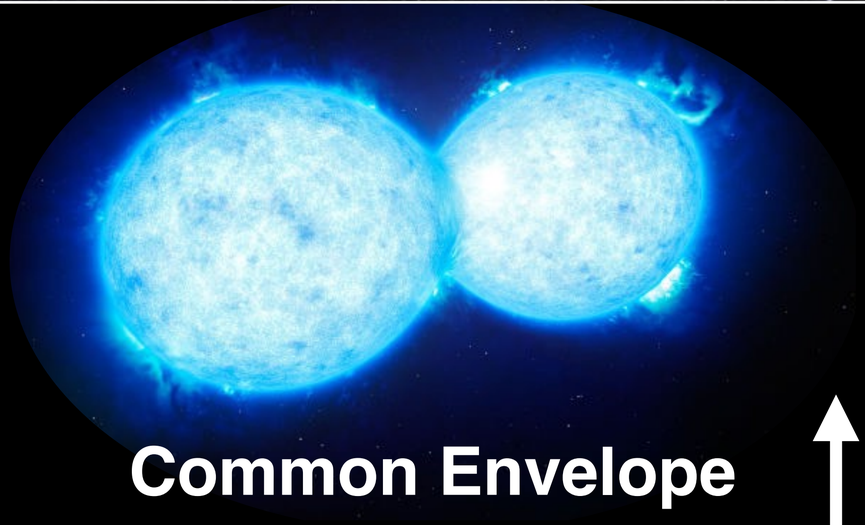

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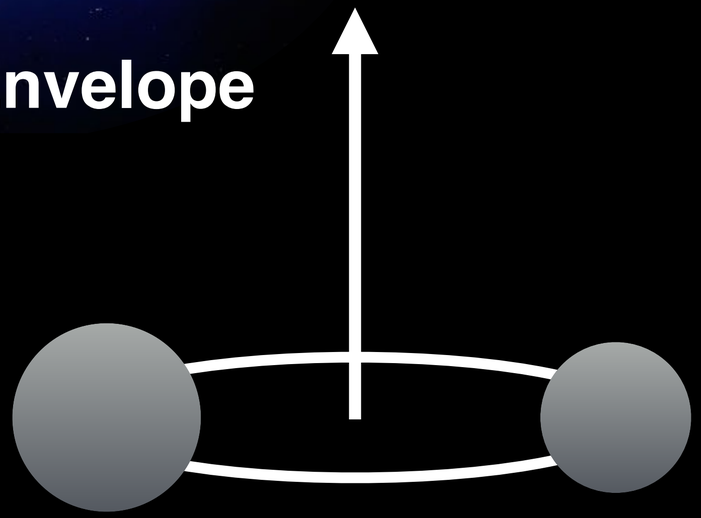

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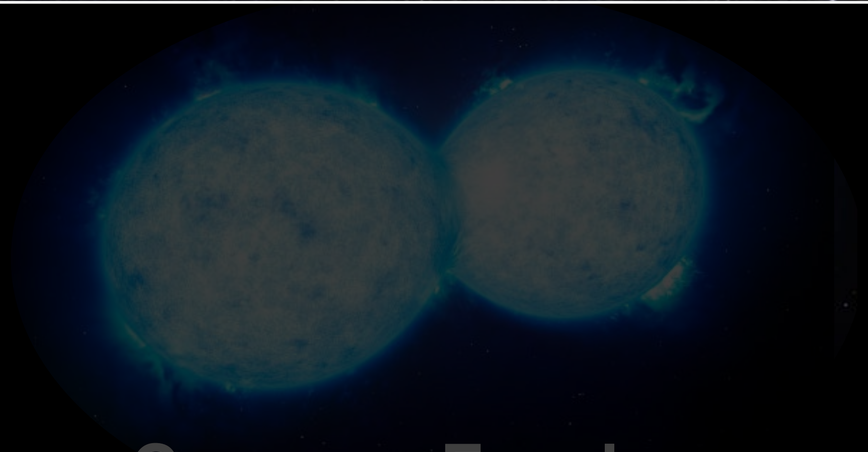

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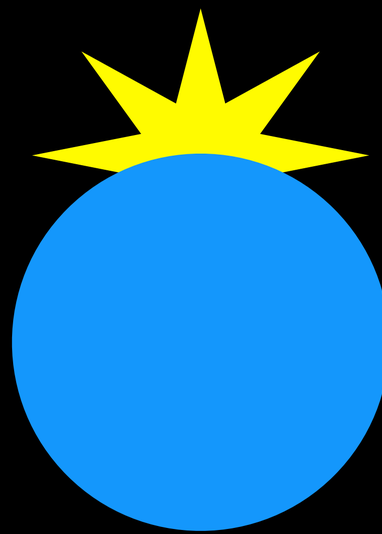

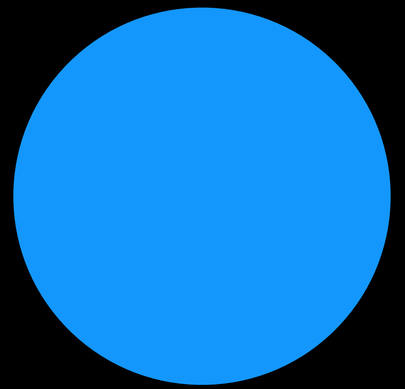

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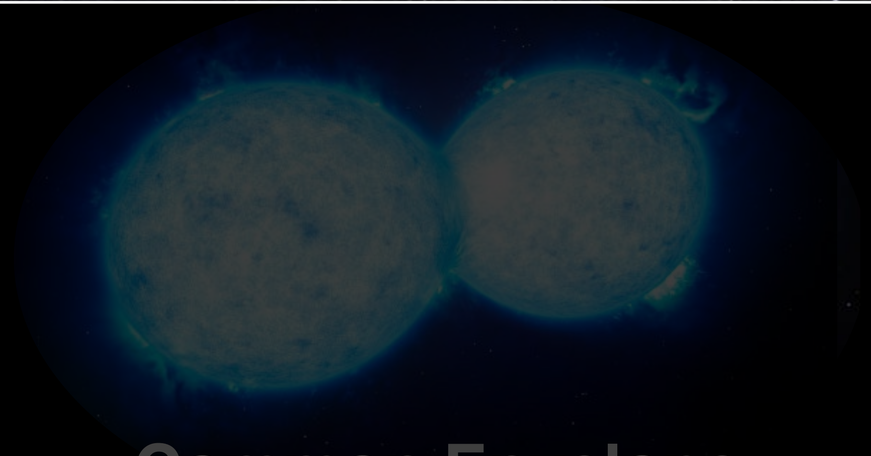

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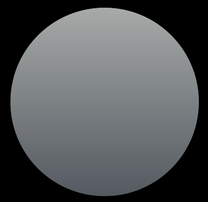

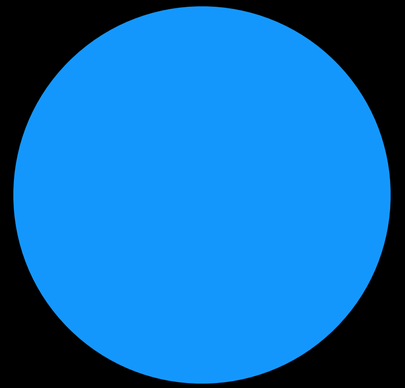

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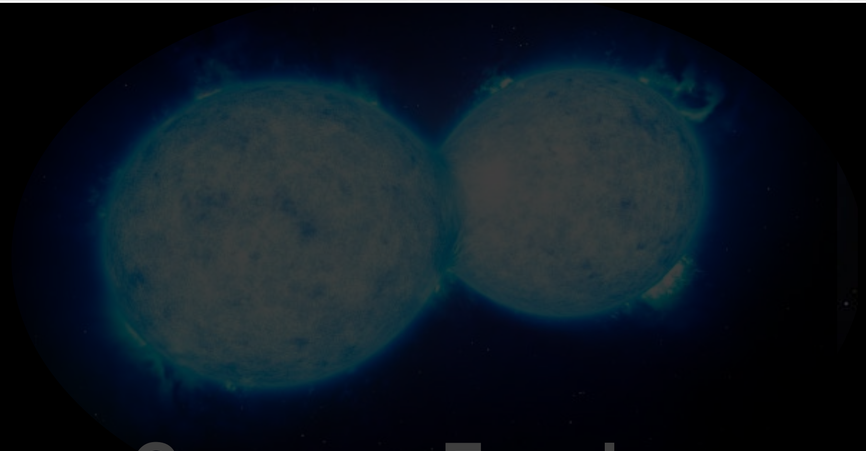

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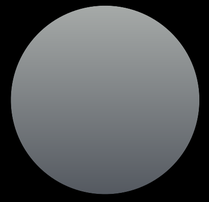

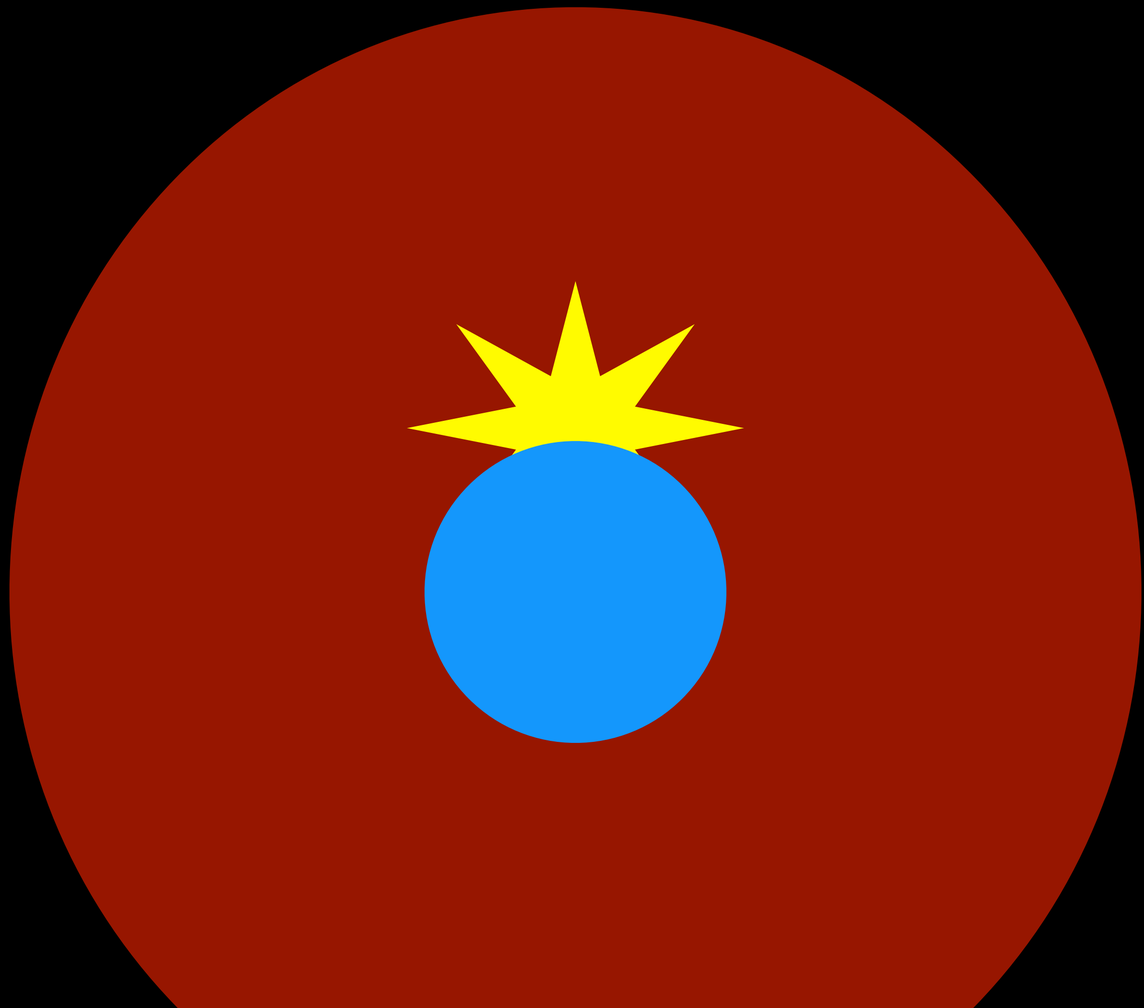

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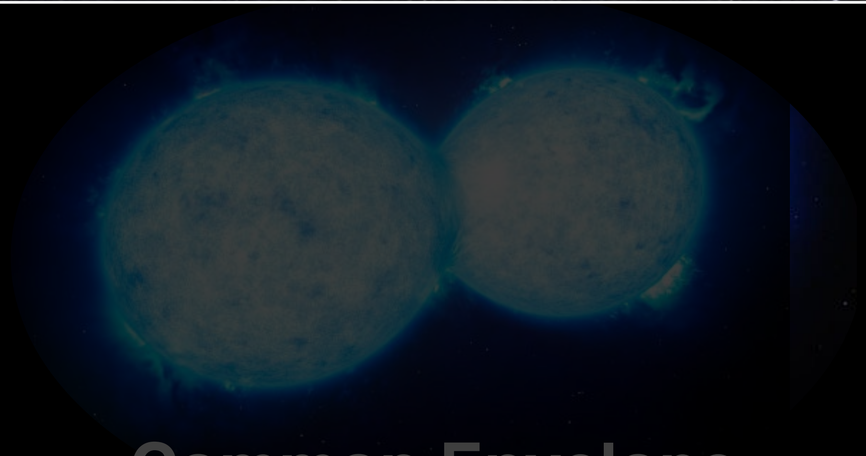
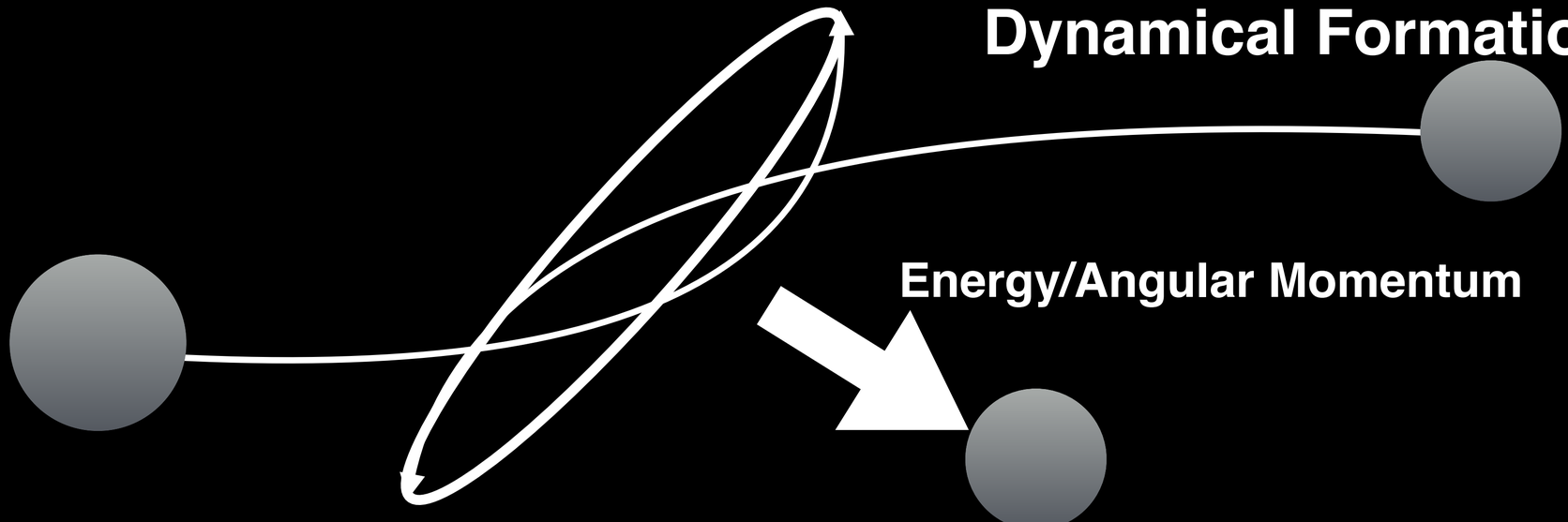


Common Envelope

Dynamical Formation



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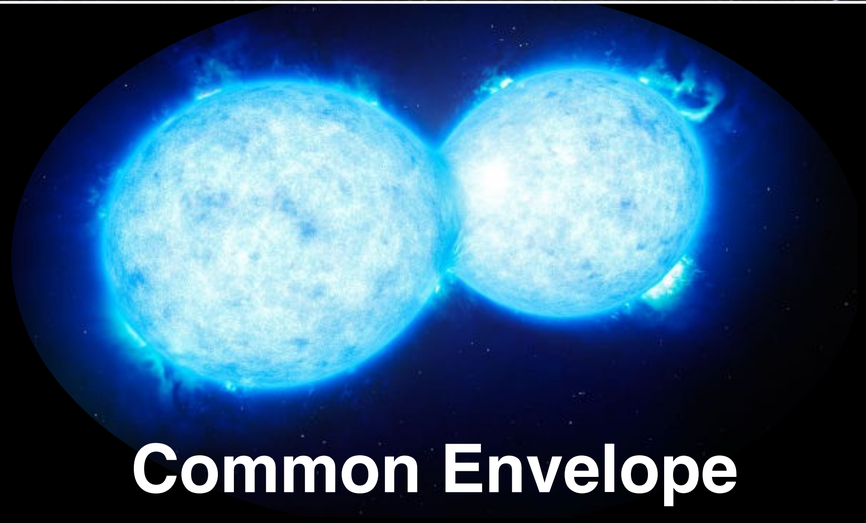

**Common Envelope**

**Dynamical Formation**

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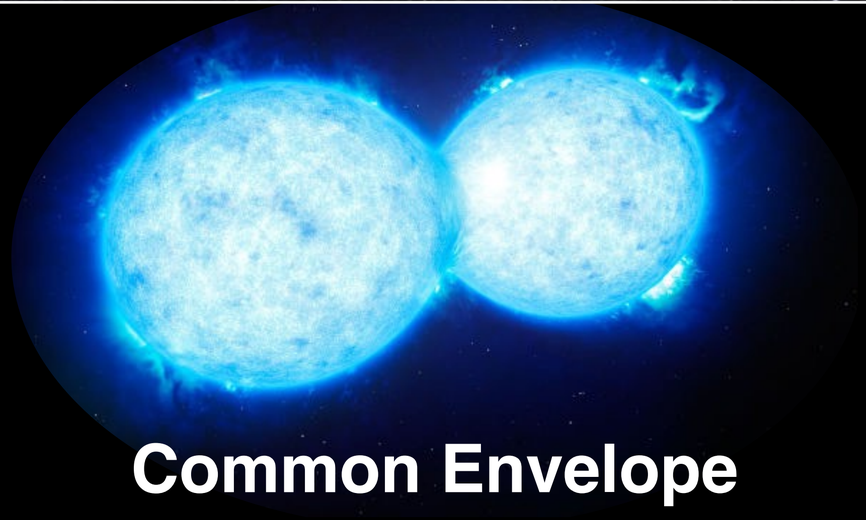

**Common Envelope**

**Dynamical Formation**

- Chemically Homogeneous Evolution
- Triples (Lidov-Kozai)
  - Stellar triples (field or dynamical)
  - Stellar BBH/SMBH
- Primordial black holes
- Highly-eccentric captures in scattering encounters
- Formation in AGN disks
- And many more…

# Forming Black Hole Binaries

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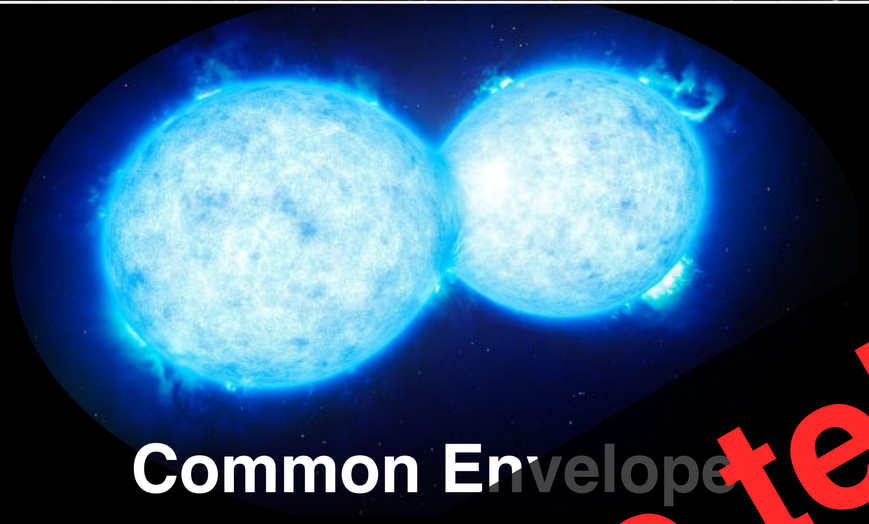

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**Can we tell the difference?**

# Black Holes in Star Clusters

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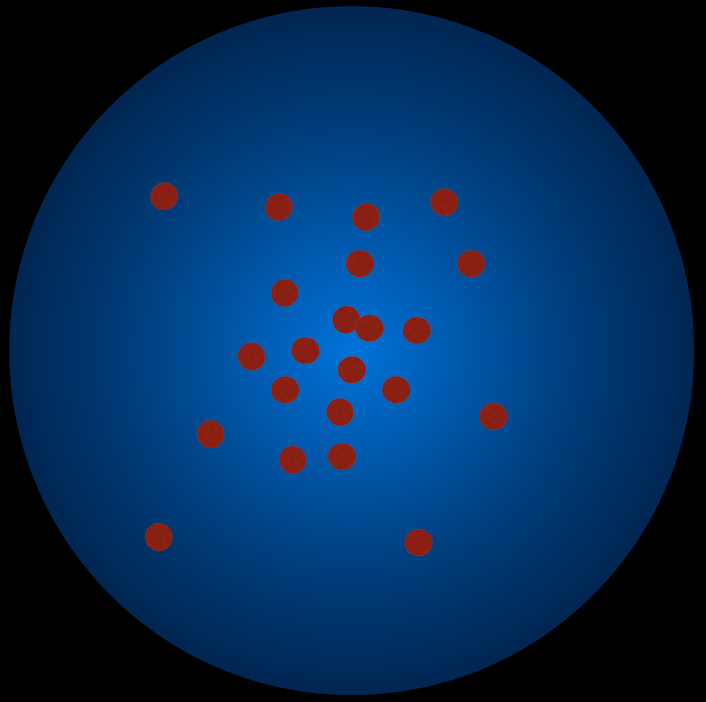

$\sim 10$ Myr

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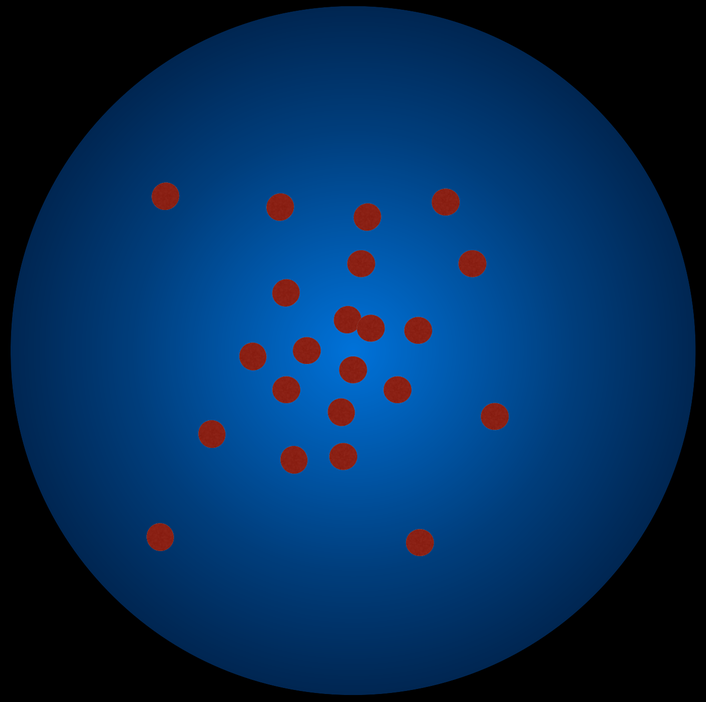

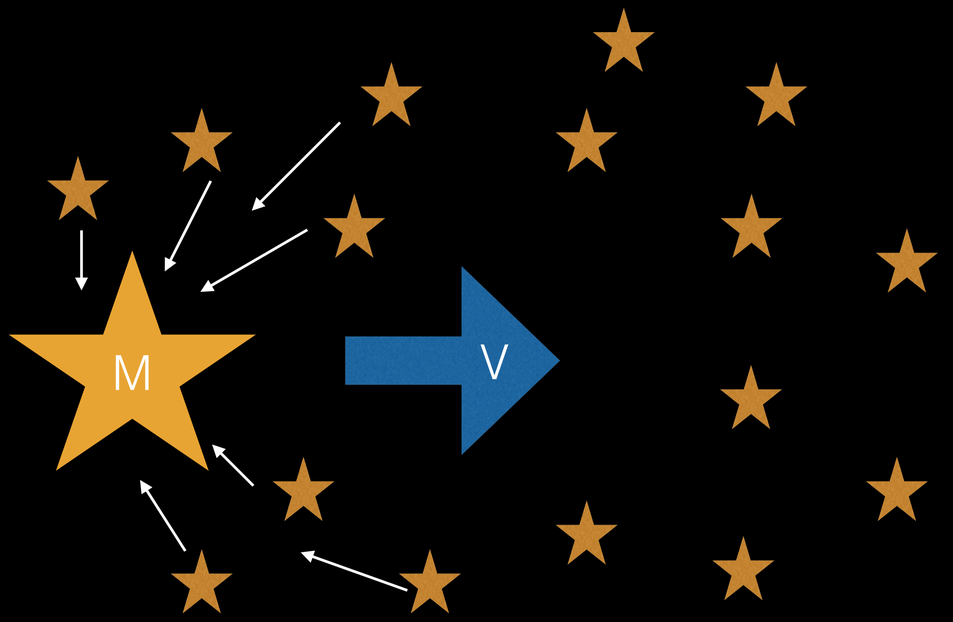

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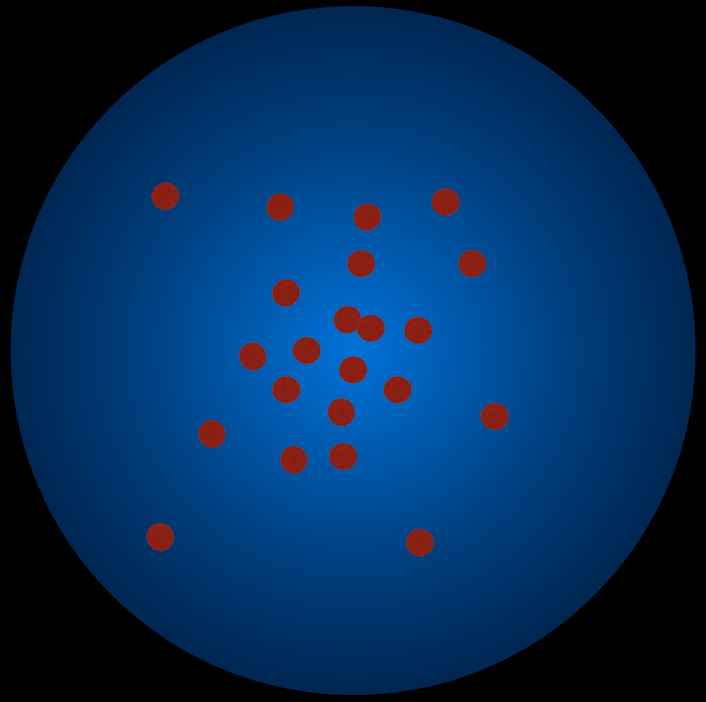

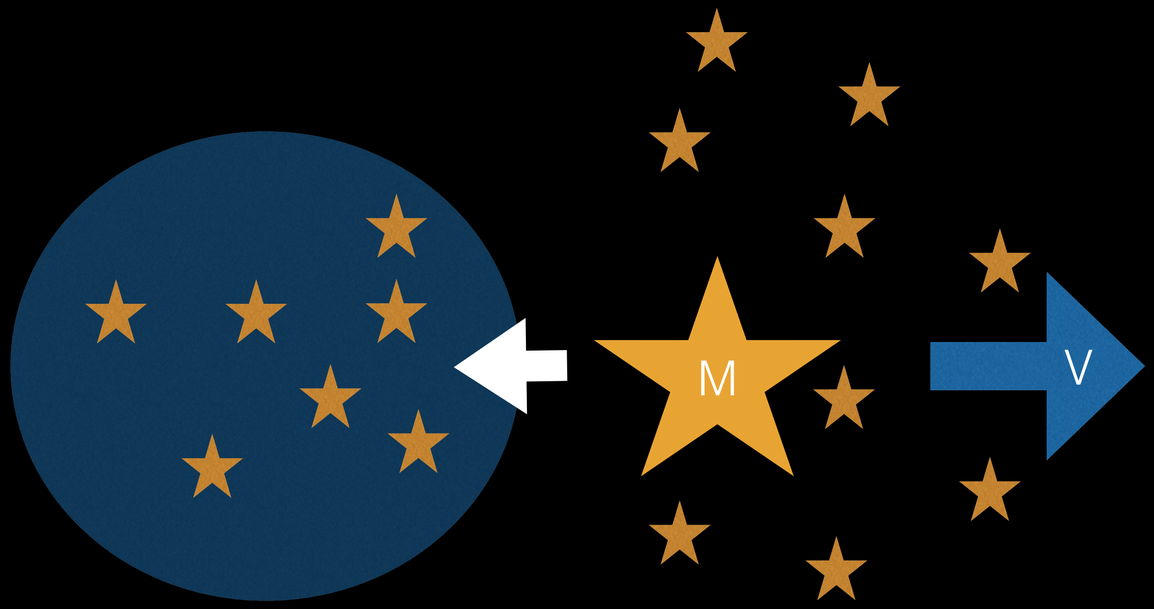


Massive particles will “segregate” into center of the cluster

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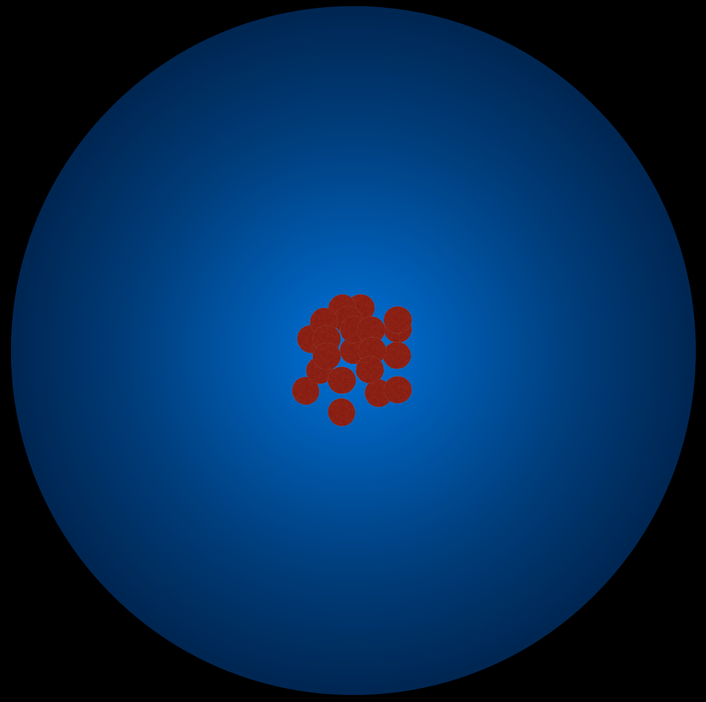
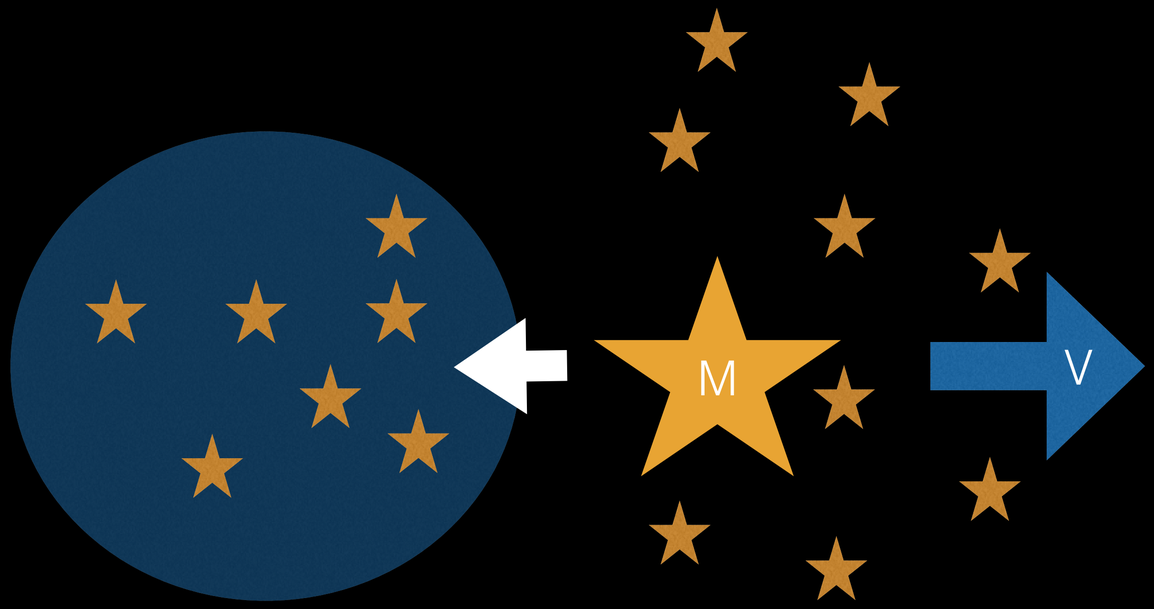


$\sim 100$ Myr

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# Chaotic Interactions

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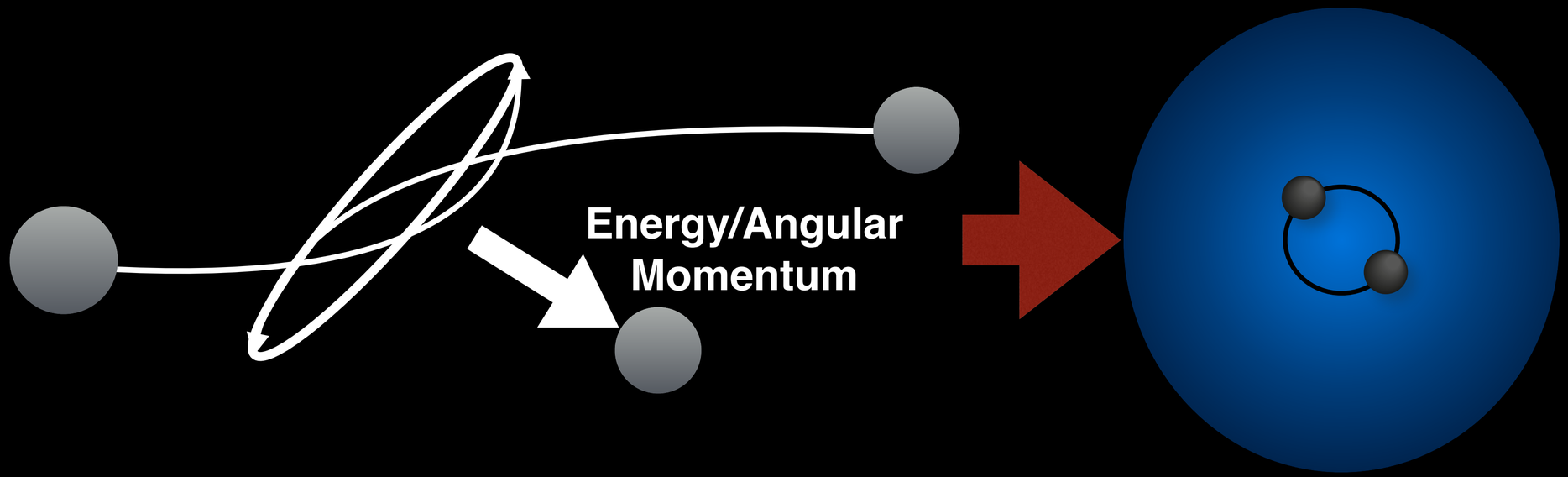

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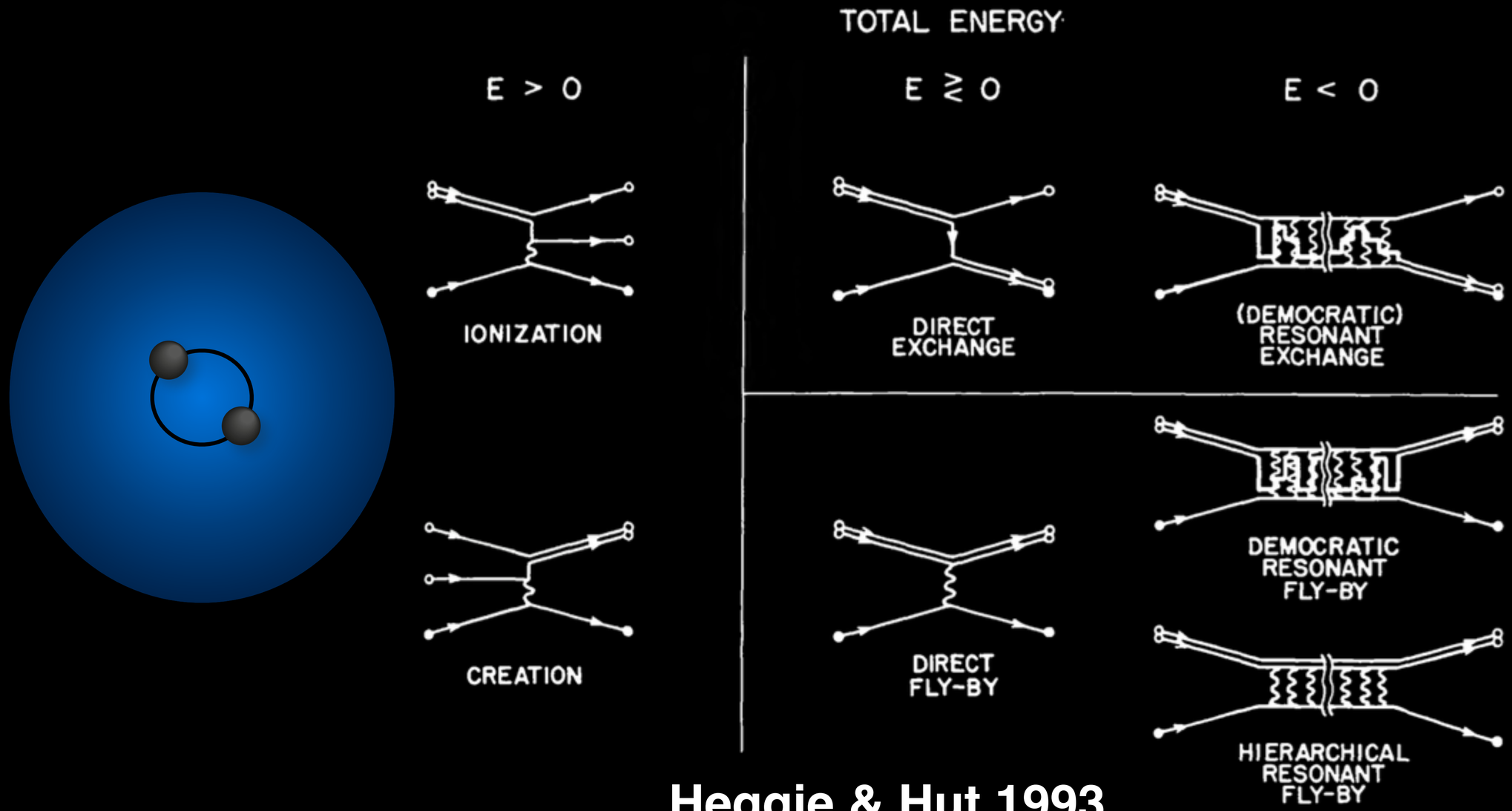


**Heggie & Hut 1993**

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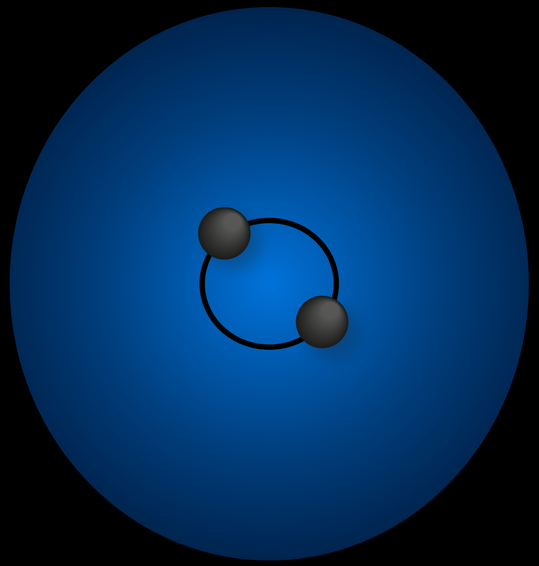

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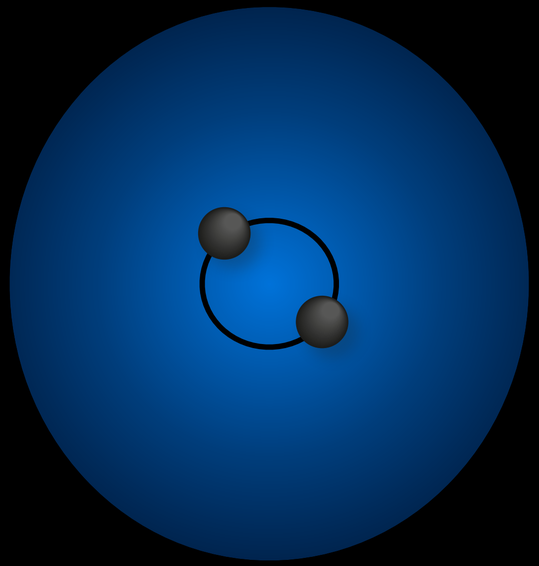

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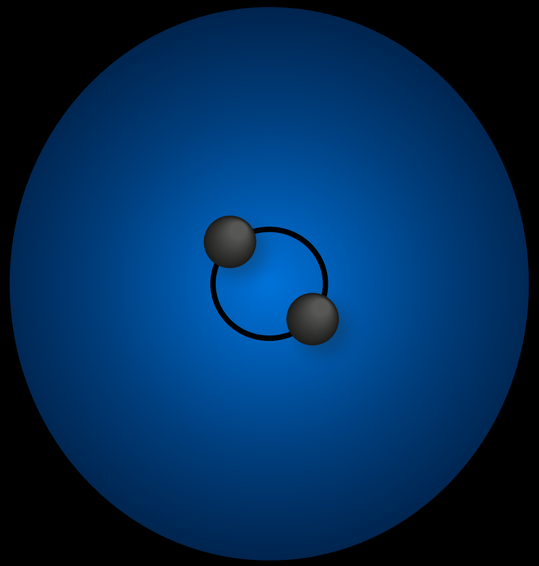

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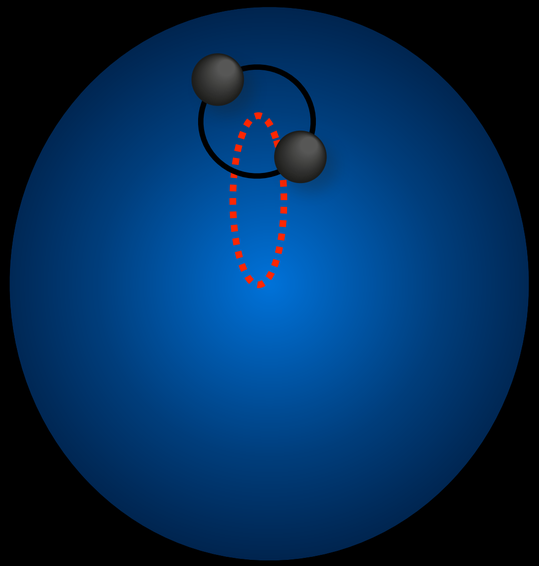

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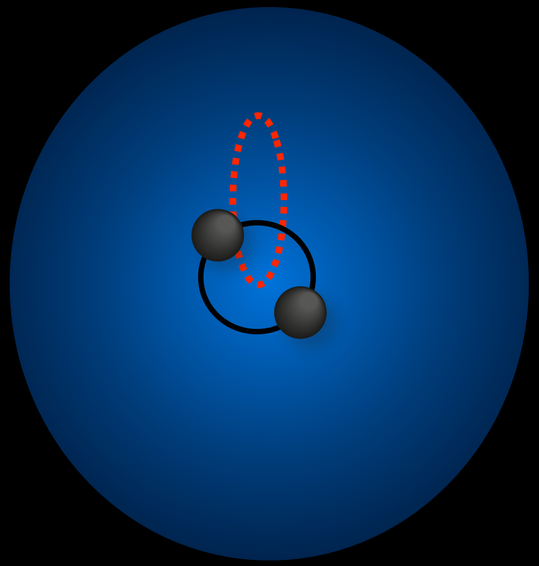

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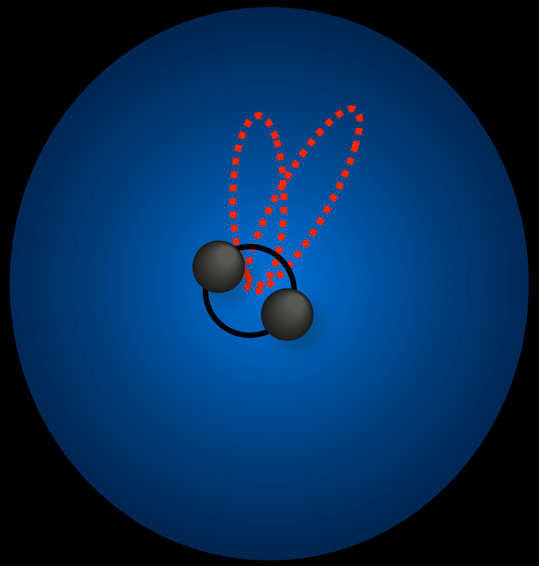

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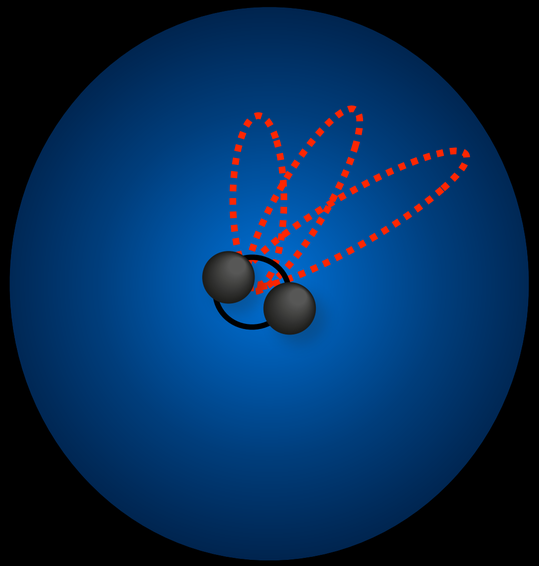

# Merging Binaries

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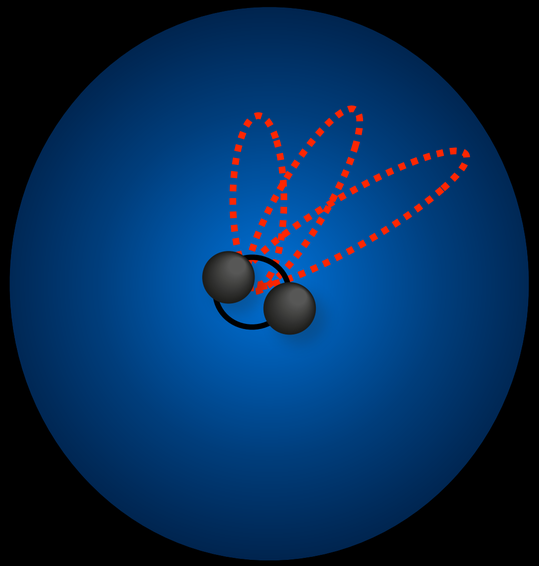
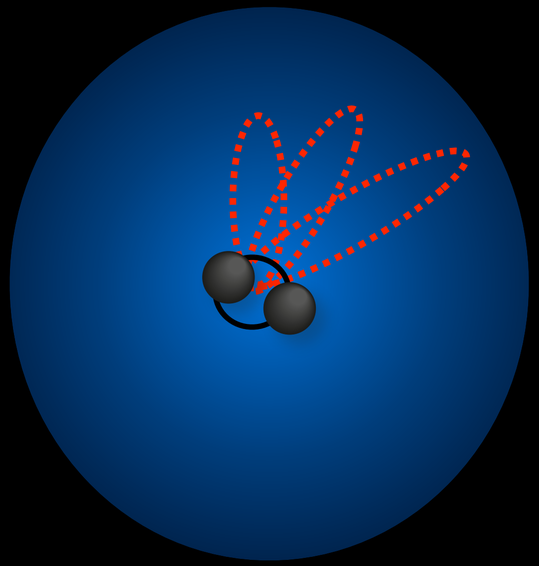
$T_{\rm bs}$



# Merging Binaries



$$T_{\rm bs} \sim (n \Sigma v)^{-1}$$



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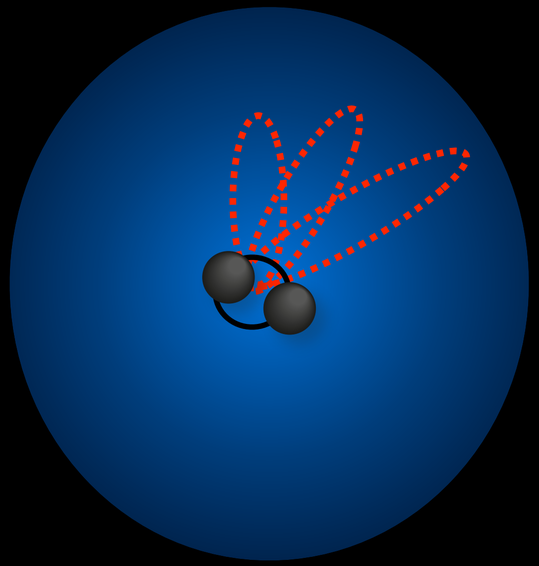
$$T_{\rm bs} \sim (n\Sigma v)^{-1} \propto \left[ na^2\sigma \left( 1 + \frac{GM}{2a\sigma^2} \right) \right]^{-1}$$



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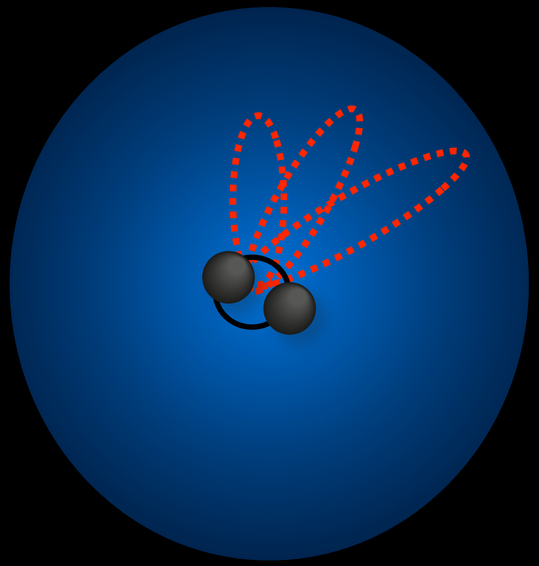

$$a = 0.4 \text{ AU}$$
$$e = 0$$
$$n = 10^6 \text{ pc}^{-3}$$
$$\sigma = 10 \text{ km/s}$$
$$m = 30 M_\odot$$

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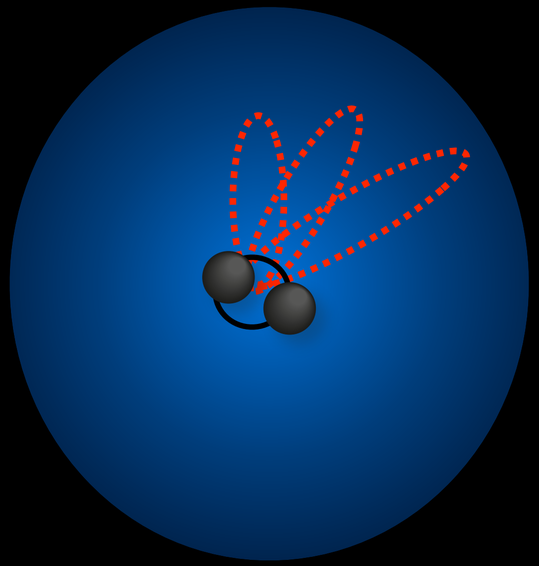

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$$T_{\rm bs} \approx 40 \text{ Myr}$$

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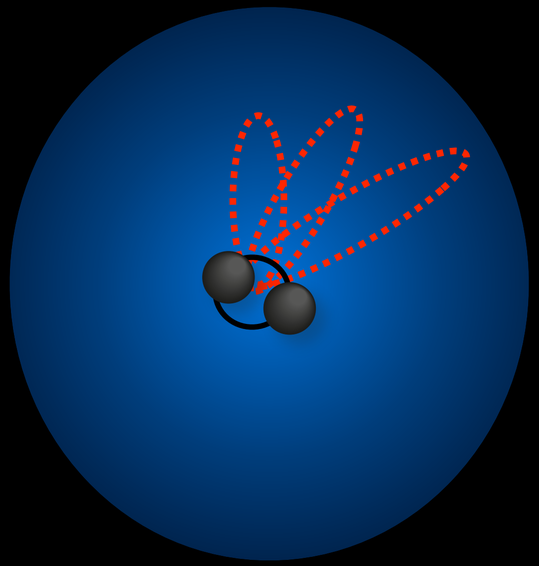

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# Merging Binaries

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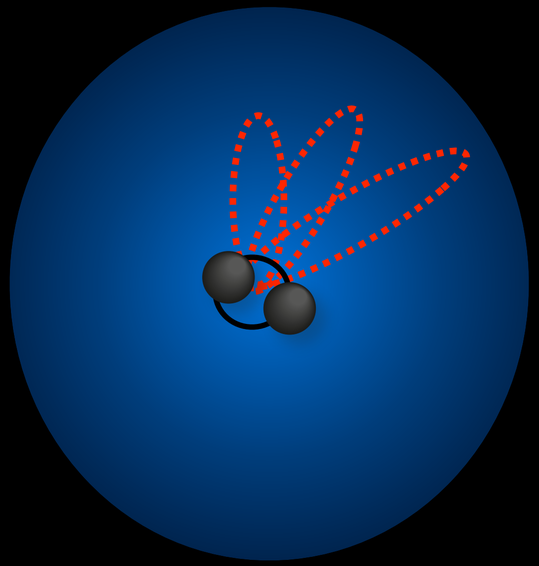
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

$$T_{\rm bs} \sim (n\Sigma v)^{-1} \propto \left[ n a^2 \sigma \left( 1 + \frac{GM}{2a\sigma^2} \right) \right]^{-1}$$



$a = 0.4$ AU
$e = 0$
$n = 10^6$ pc$^{-3}$
$\sigma = 10$ km/s
$m = 30 M_\odot$

$$T_{\rm bs} \approx 40 \text{ Myr}$$

$$T_{\rm GW} \propto \frac{a^4 (1-e^2)^{7/2}}{m_1 m_2 M} \approx 150000 \text{ Myr}$$

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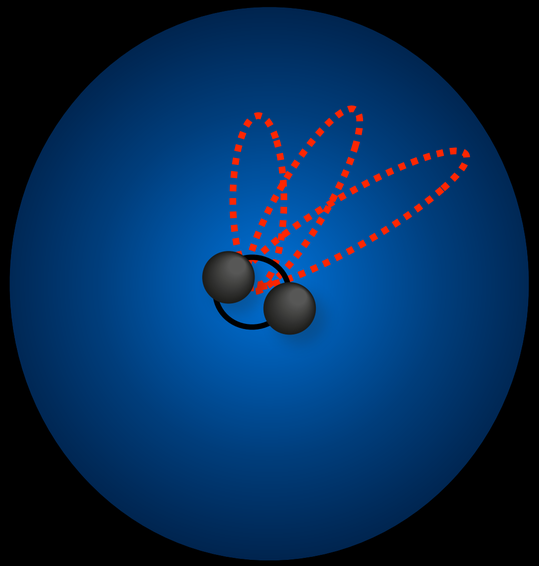

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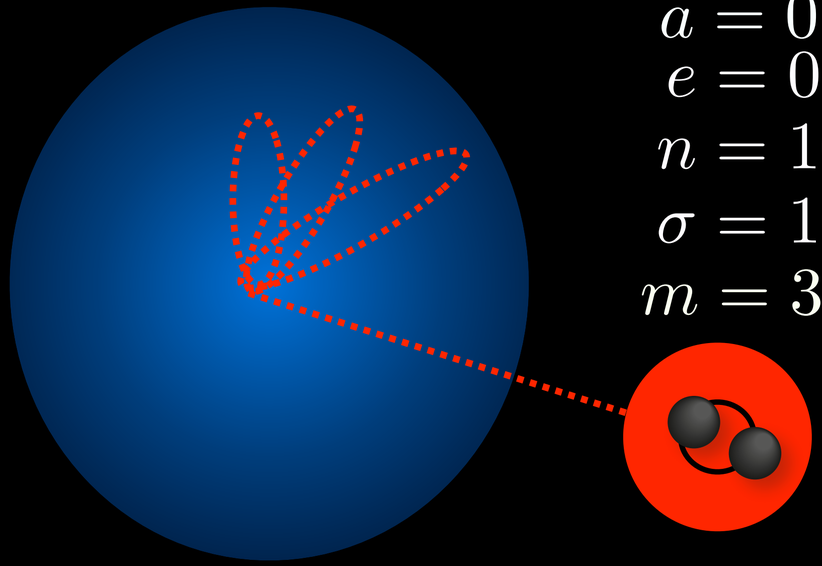

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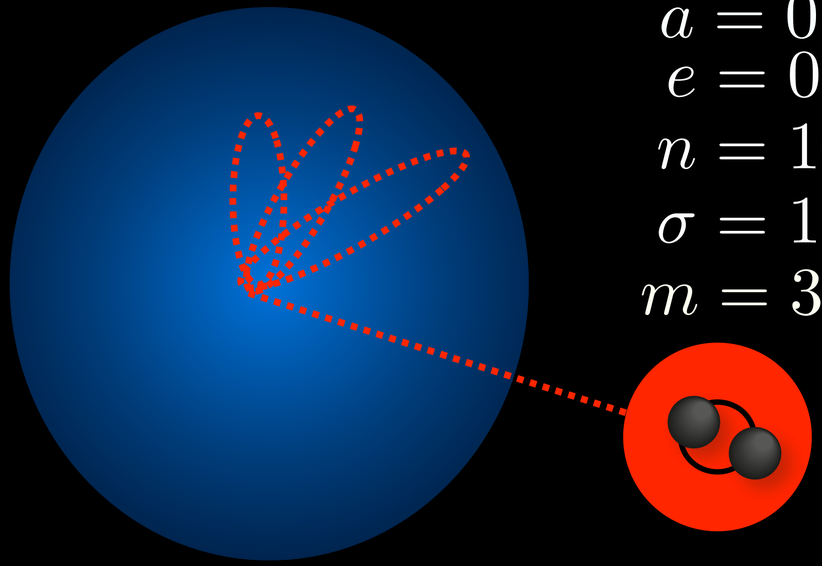

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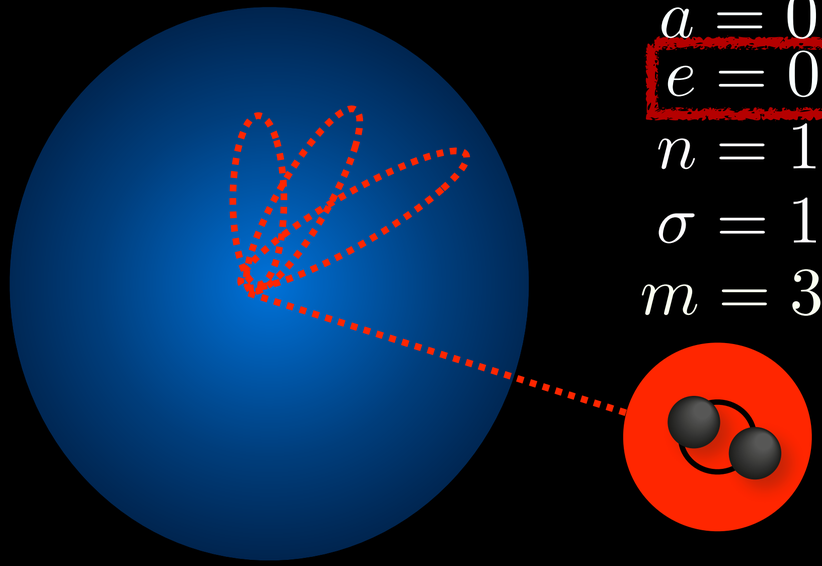

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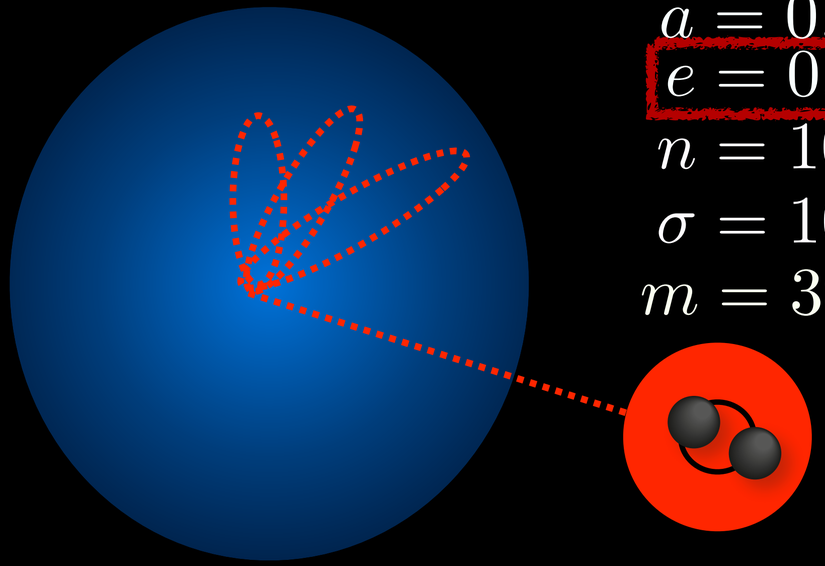

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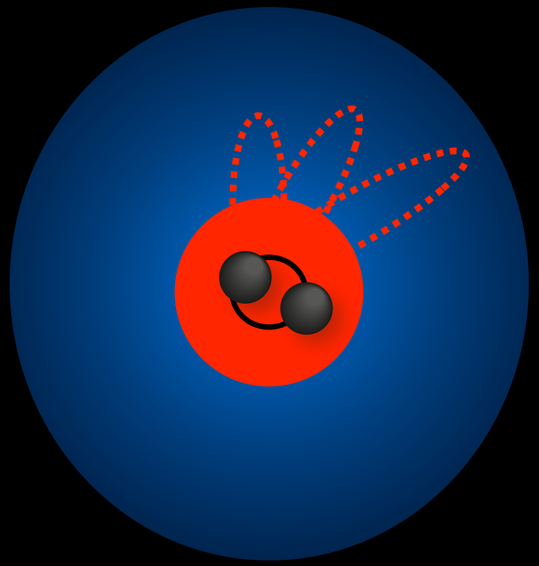

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# *Forming Black Hole Binaries*

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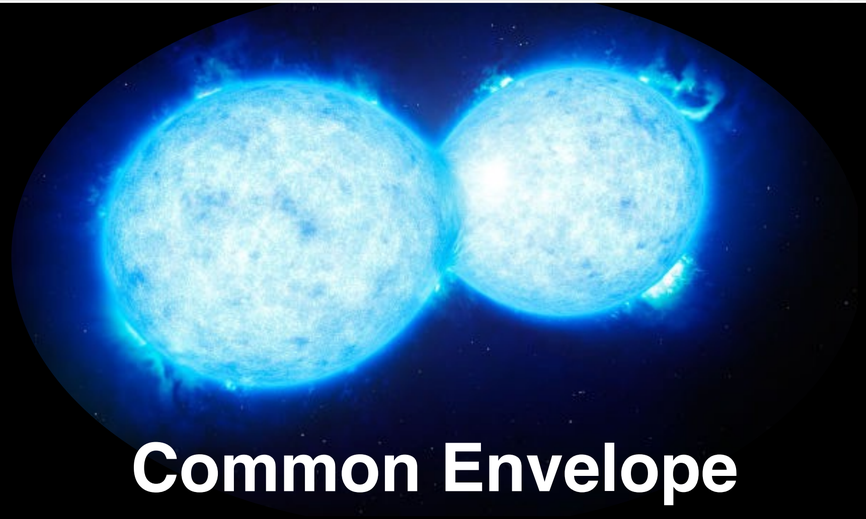

**Common Envelope**

**Dynamical Formation**

- Chemically Homogeneous Evolution
- Triples (Lidov-Kozai)
  - Stellar triples (field or dynamical)
  - Stellar BBH/SMBH
- Primordial black holes
- Highly-eccentric captures in scattering encounters
- Formation in AGN disks
- And many more…

# Forming Black Hole Binaries

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**Can we tell the difference?**

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# Forming Black Hole Binaries

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**Masses**
**Merger Rates**
**Mass Ratios**

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**Can we tell the difference?**

**Dynamical Formation**

# Forming Black Hole Binaries

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Can relativity tell us the difference?

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**Dynamical Formation**

**Spins**
**Eccentricities**
**Masses**

**Can relativity tell us the difference?**

# Eccentricity

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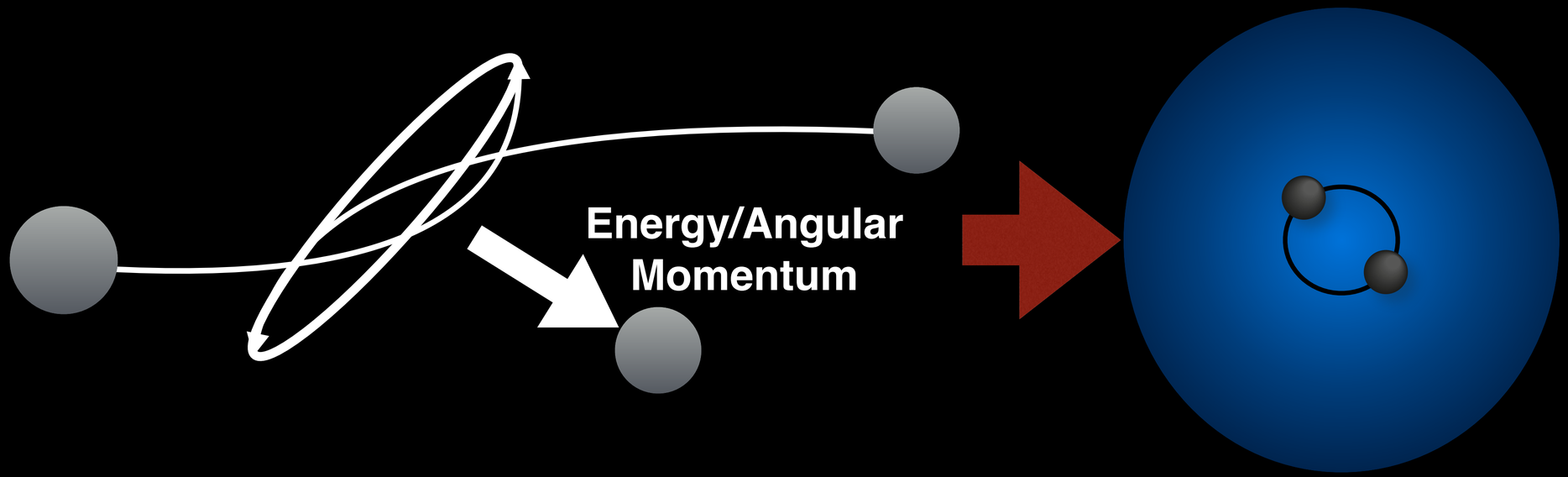

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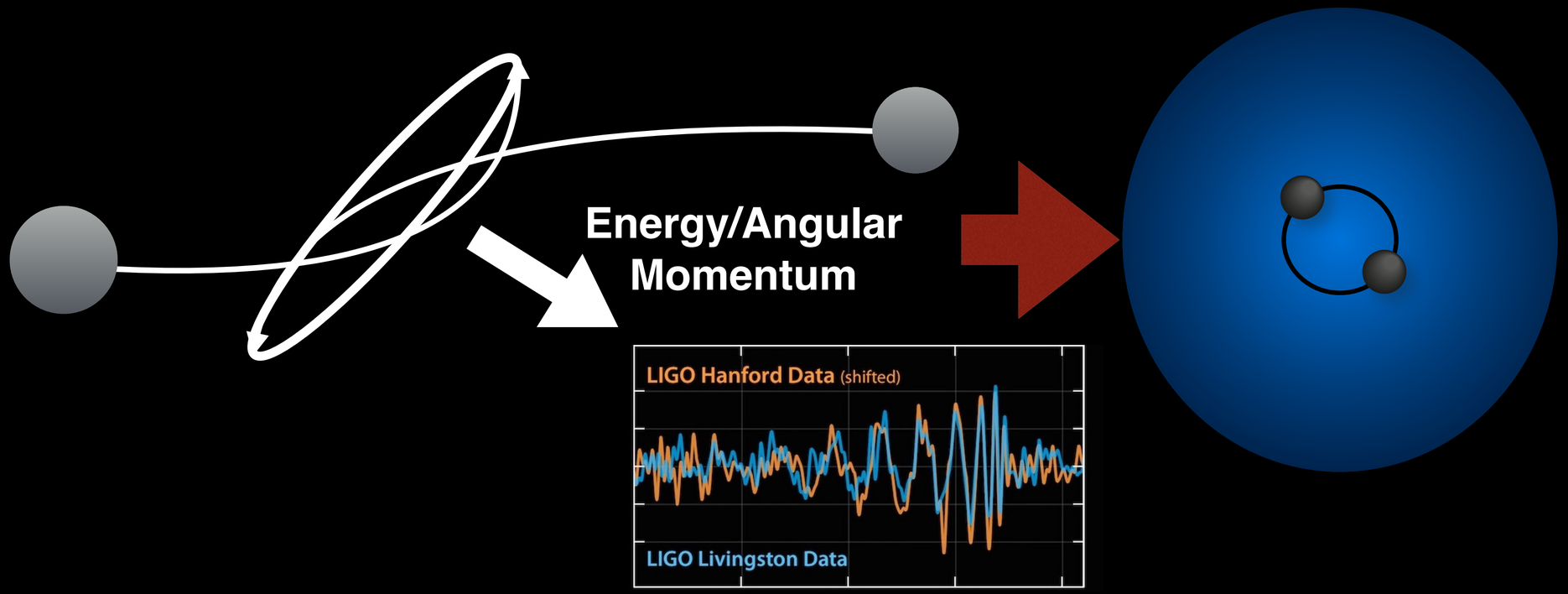

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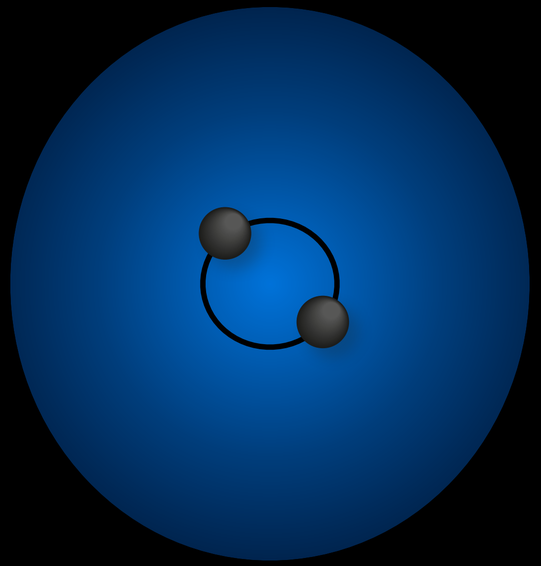

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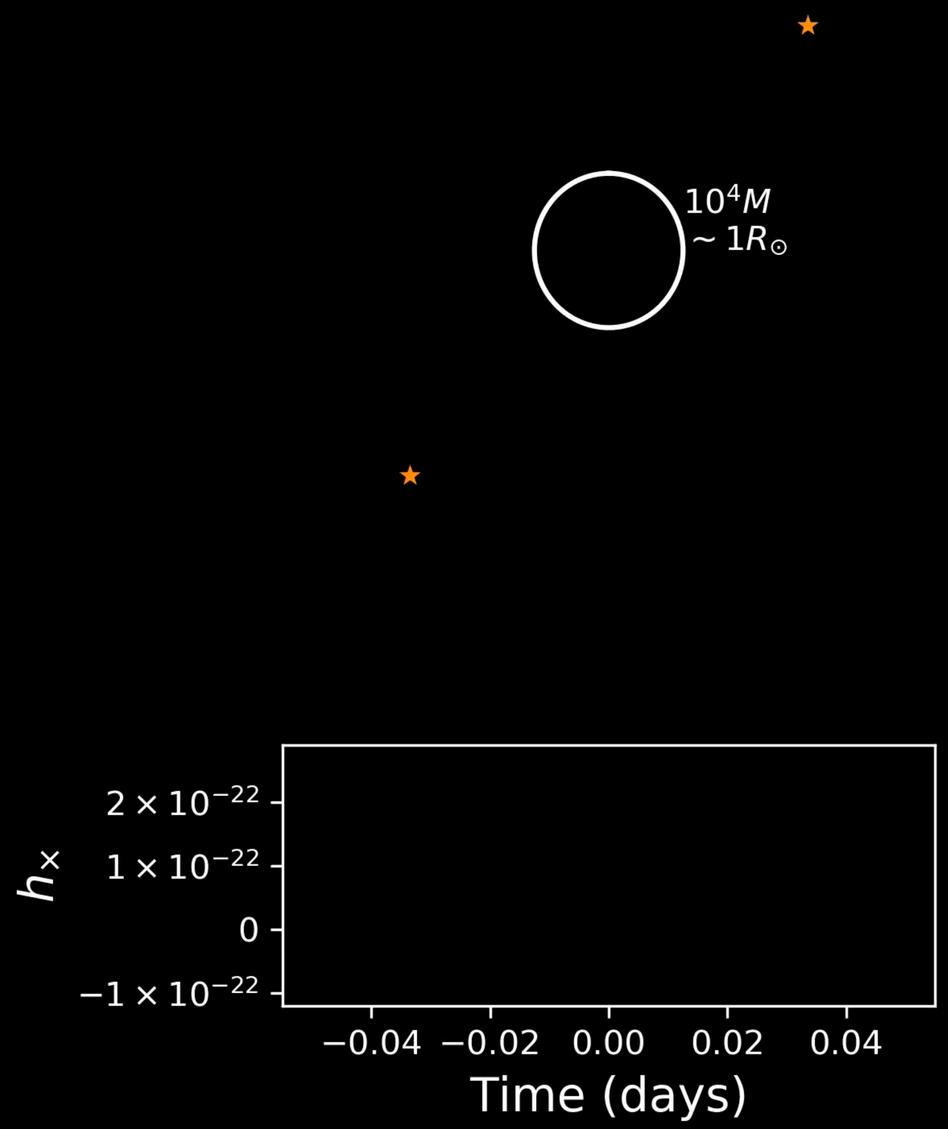


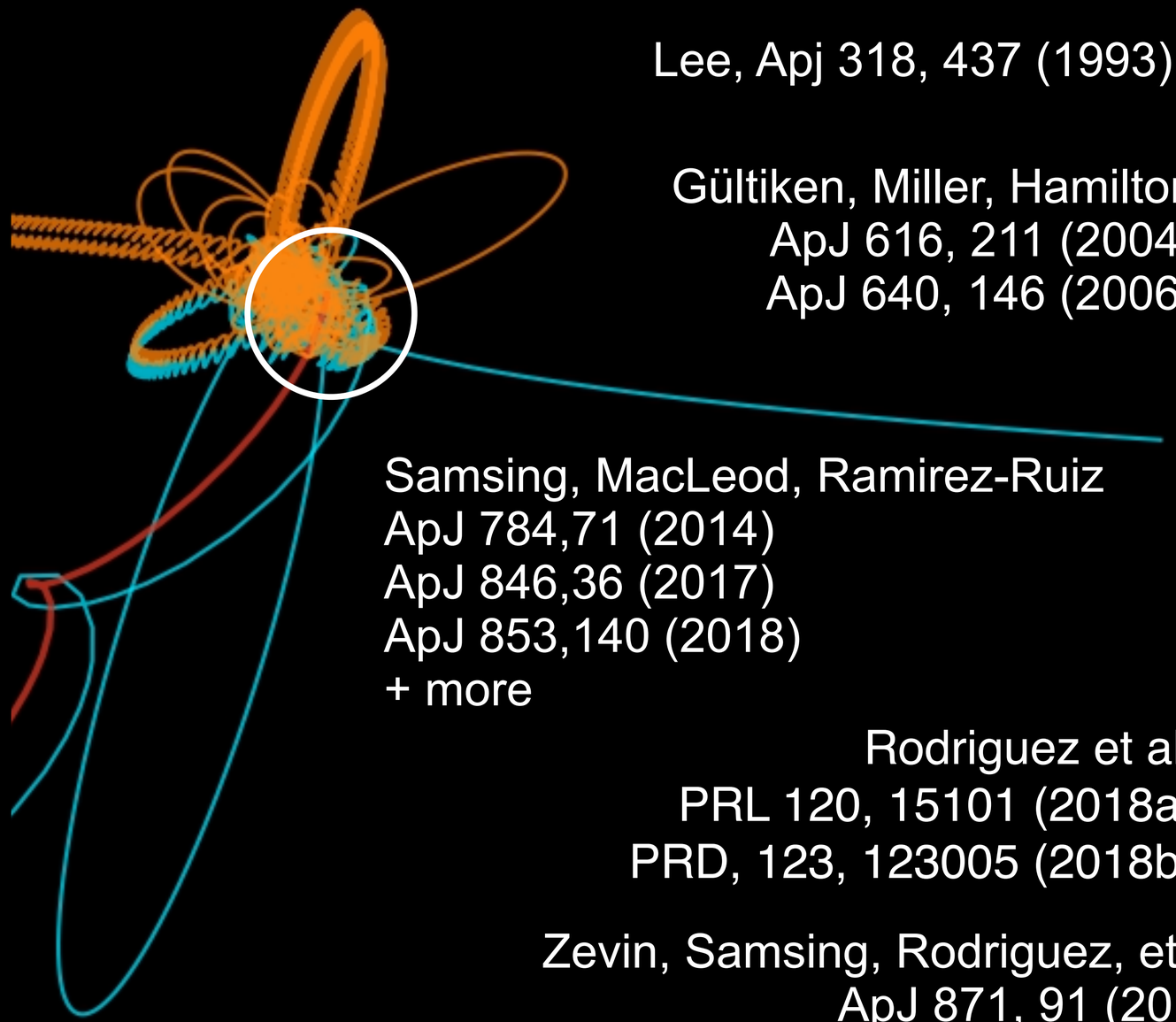

Lee, Apj 318, 437 (1993)

Gültiken, Miller, Hamilton
ApJ 616, 211 (2004)
ApJ 640, 146 (2006)

Samsing, MacLeod, Ramirez-Ruiz
ApJ 784,71 (2014)
ApJ 846,36 (2017)
ApJ 853,140 (2018)
+ more

Rodriguez et al.
PRL 120, 15101 (2018a)
PRD, 123, 123005 (2018b)

Zevin, Samsing, Rodriguez, et al.
ApJ 871, 91 (2019)

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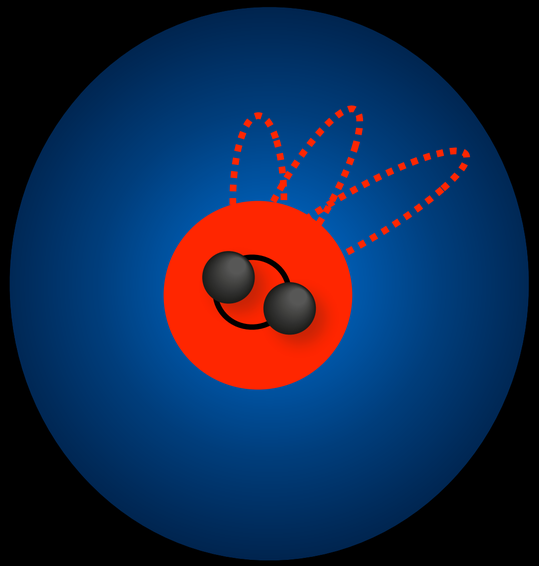
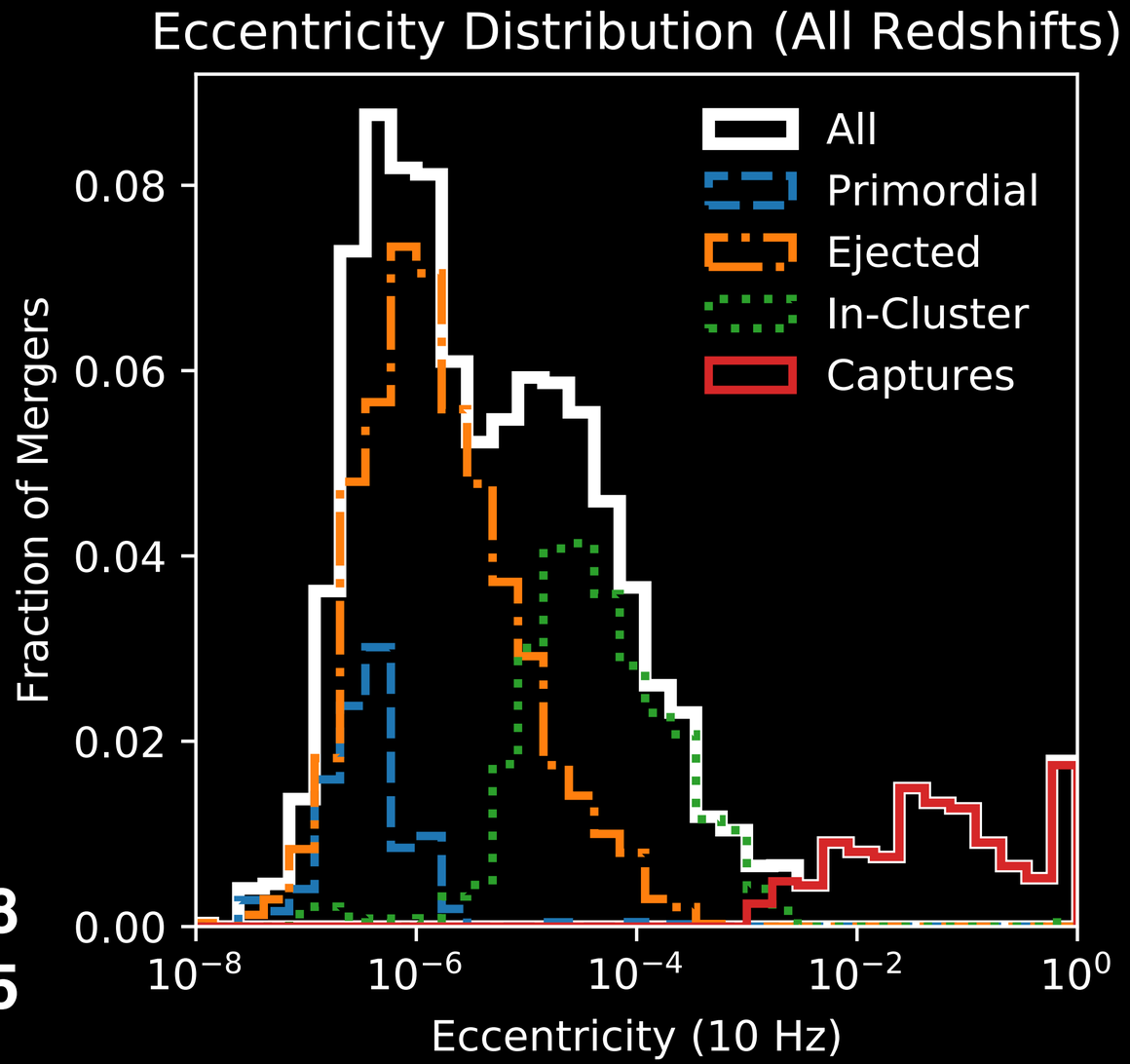


**Rodriguez et al., 2018**
**PRD, 123, 123005**



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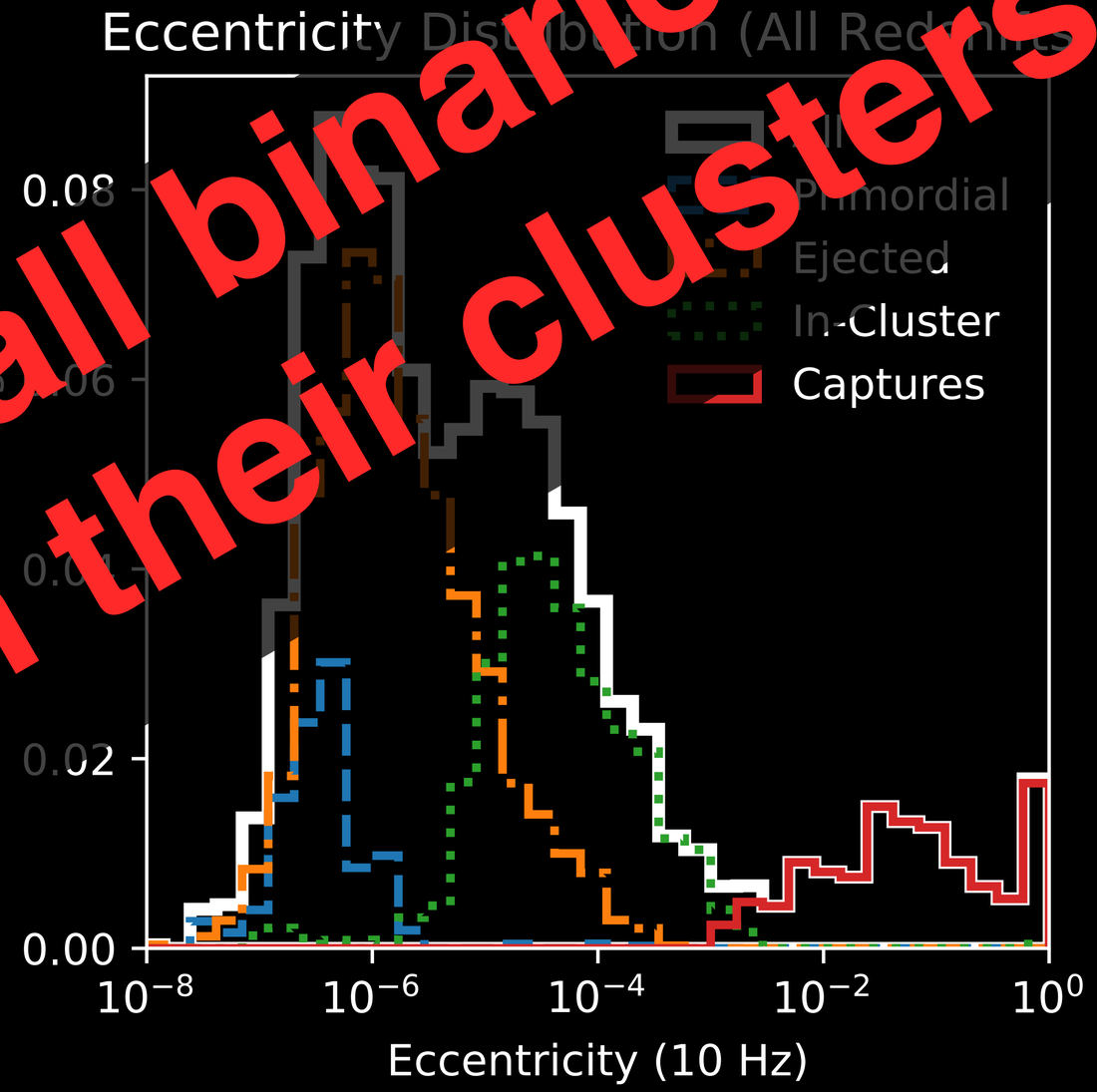
**Half of all binaries merge in their clusters**




Rodriguez et al., 2018
PRD, 123, 123005

# Black Hole Spins

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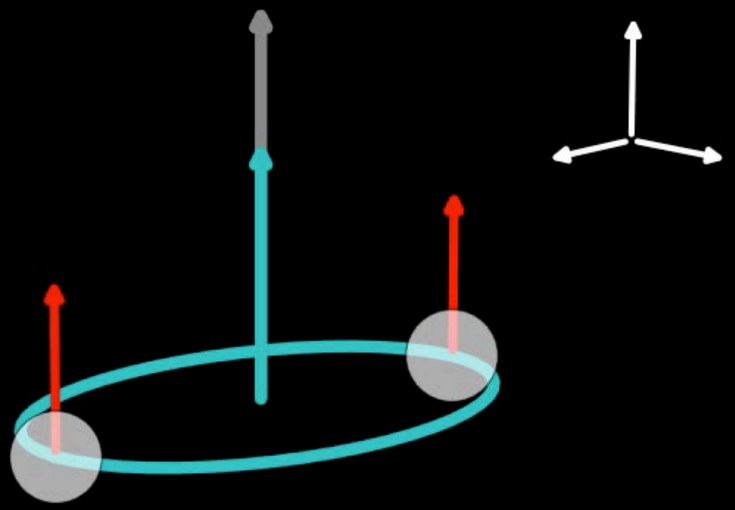

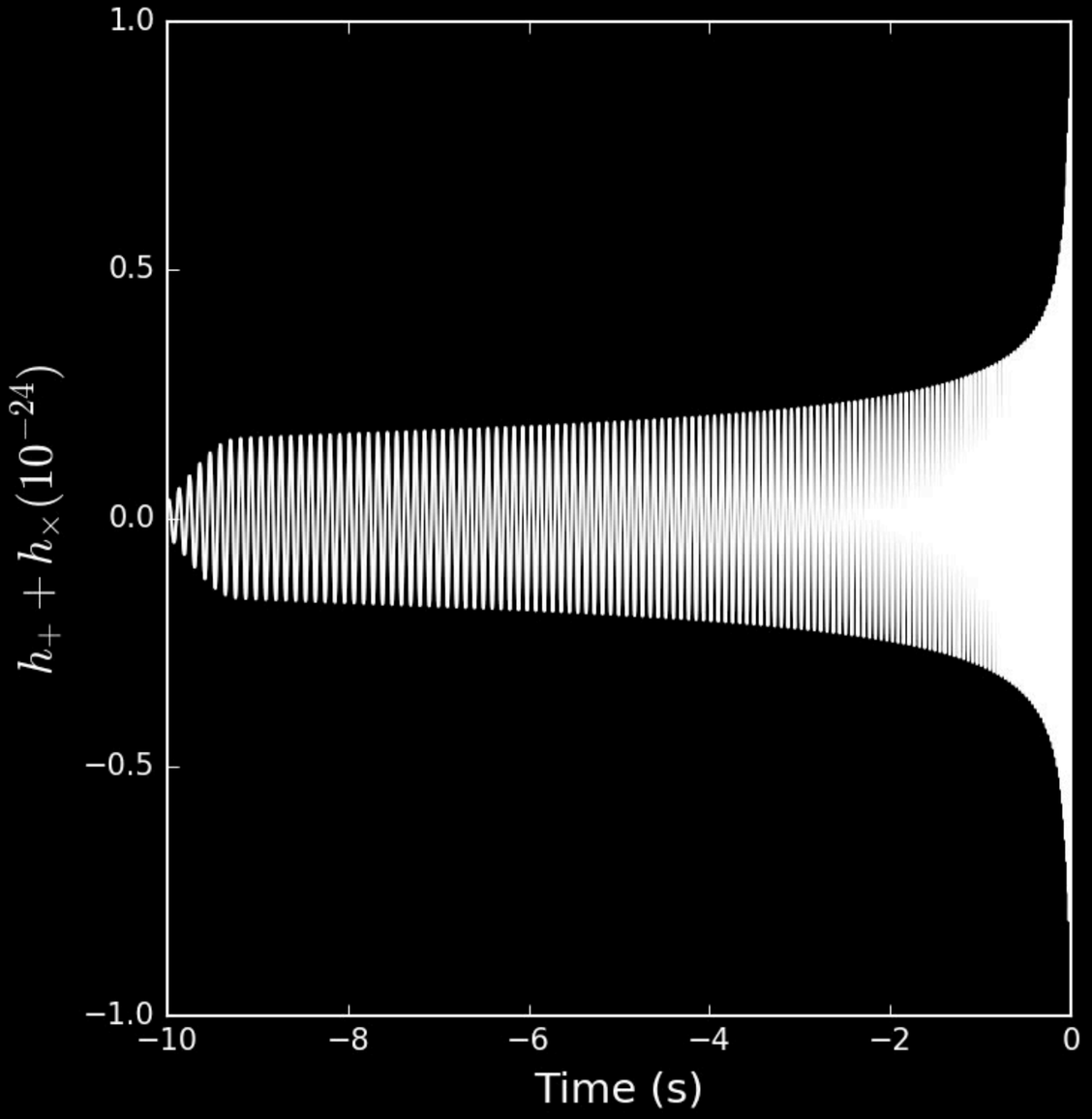

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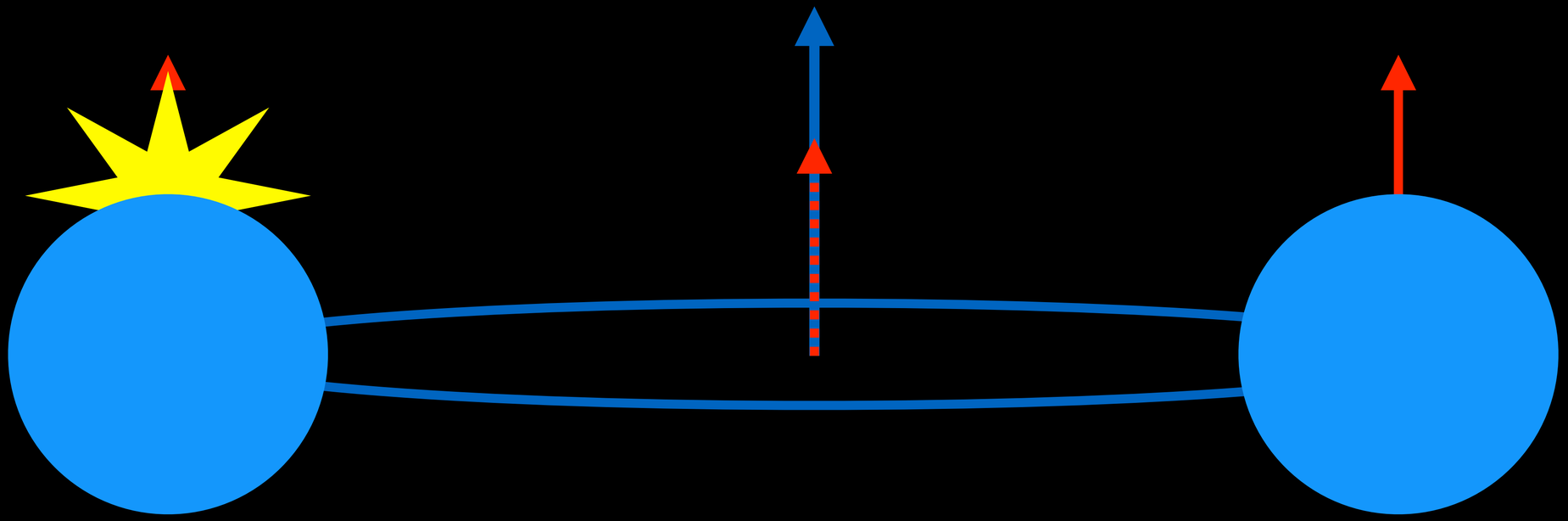

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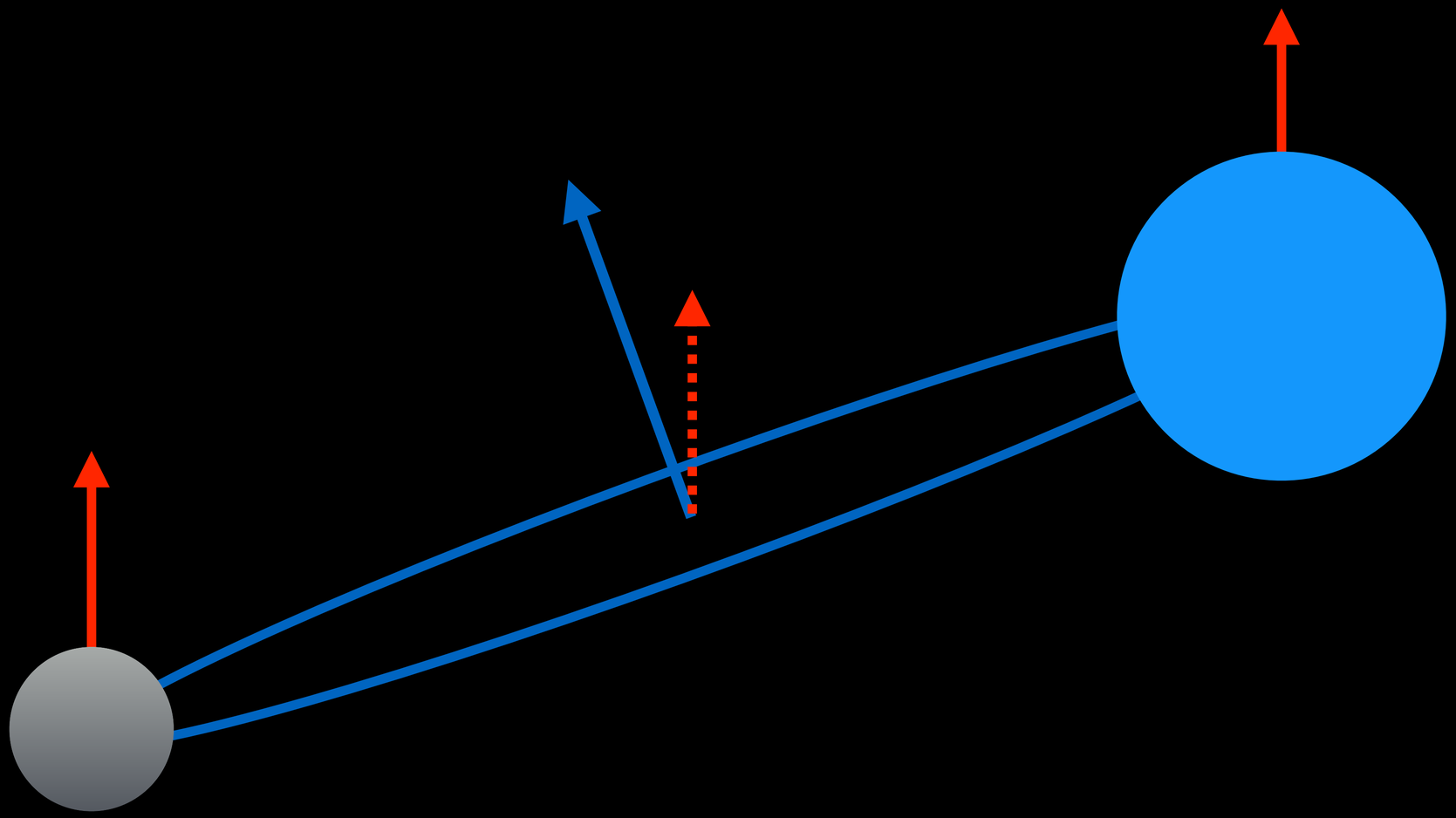

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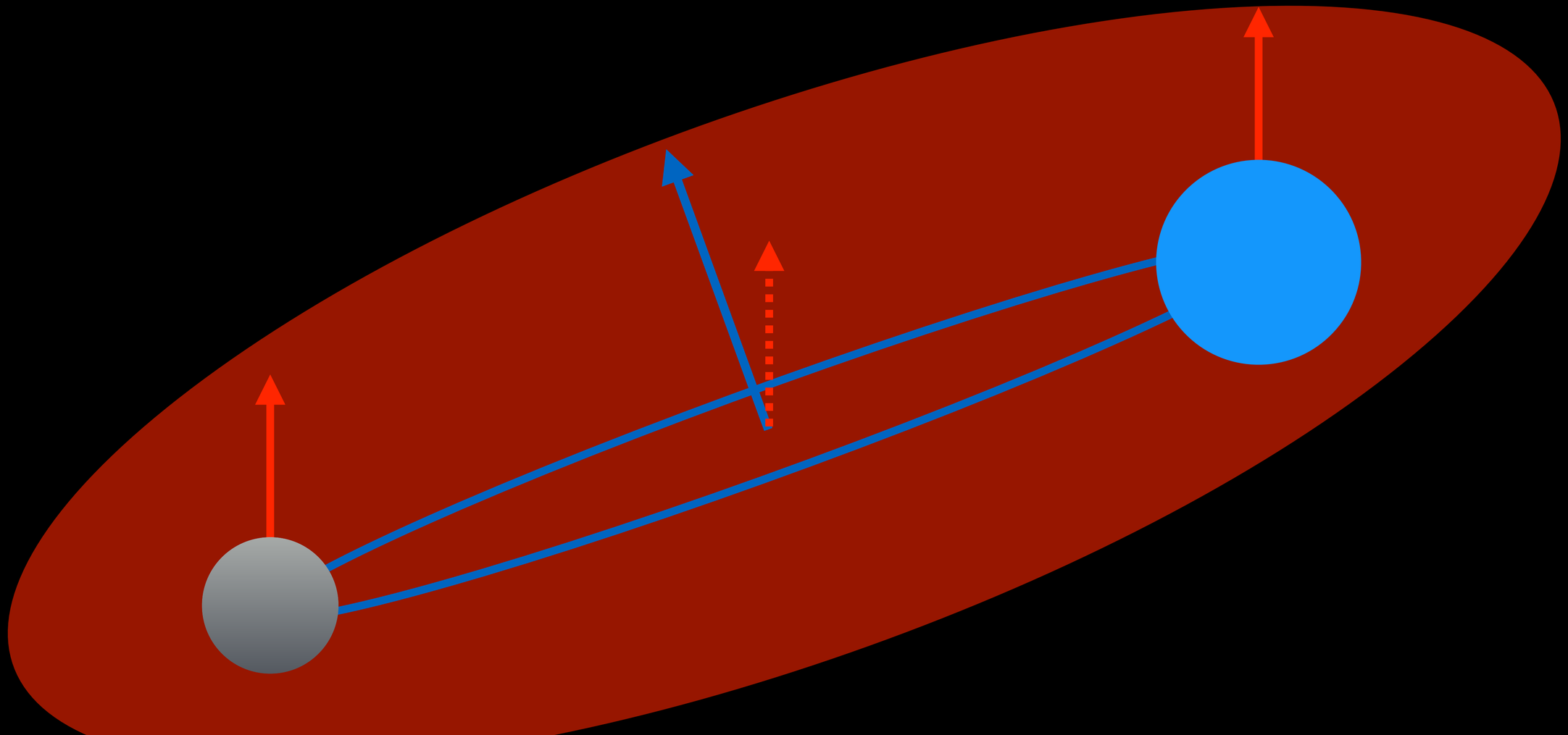

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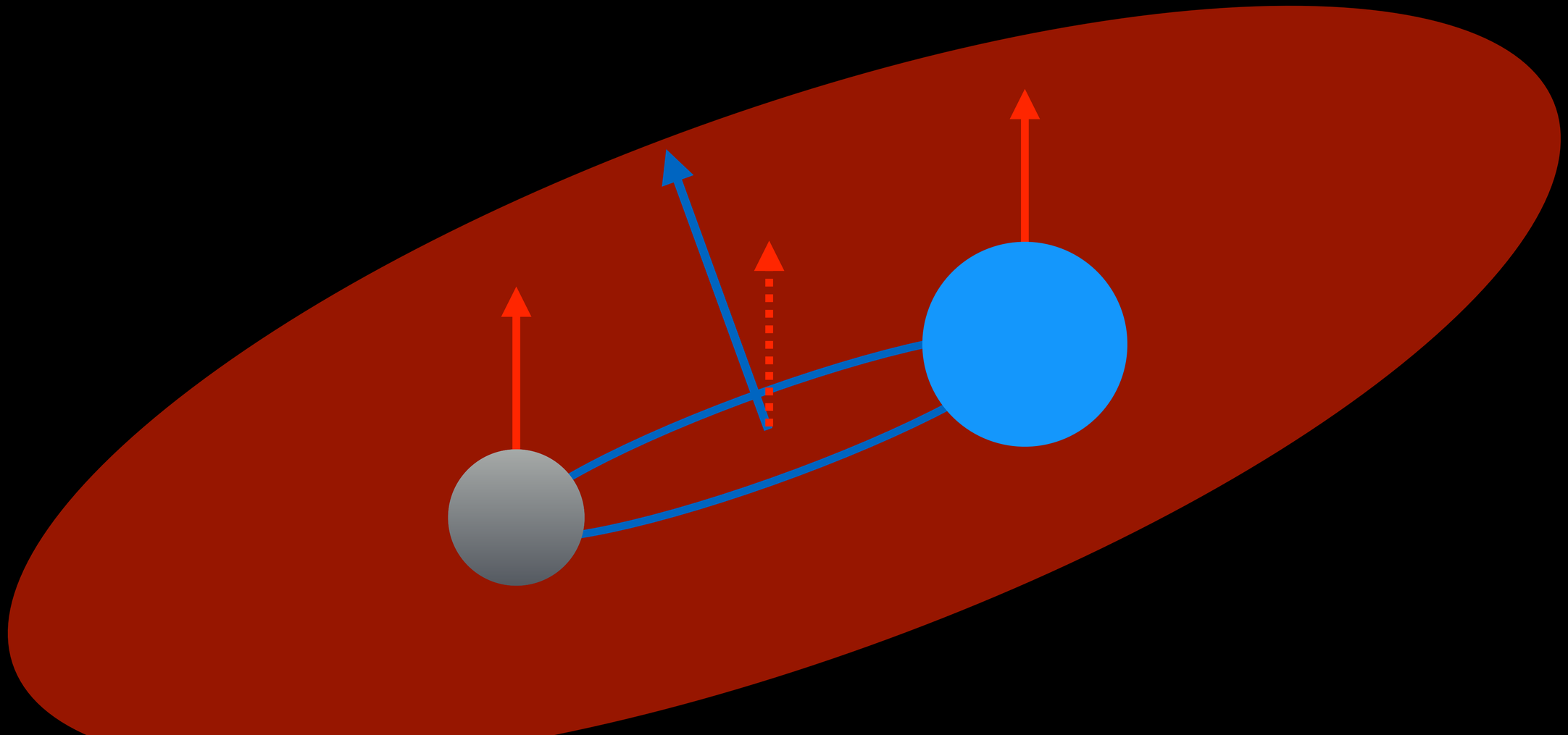

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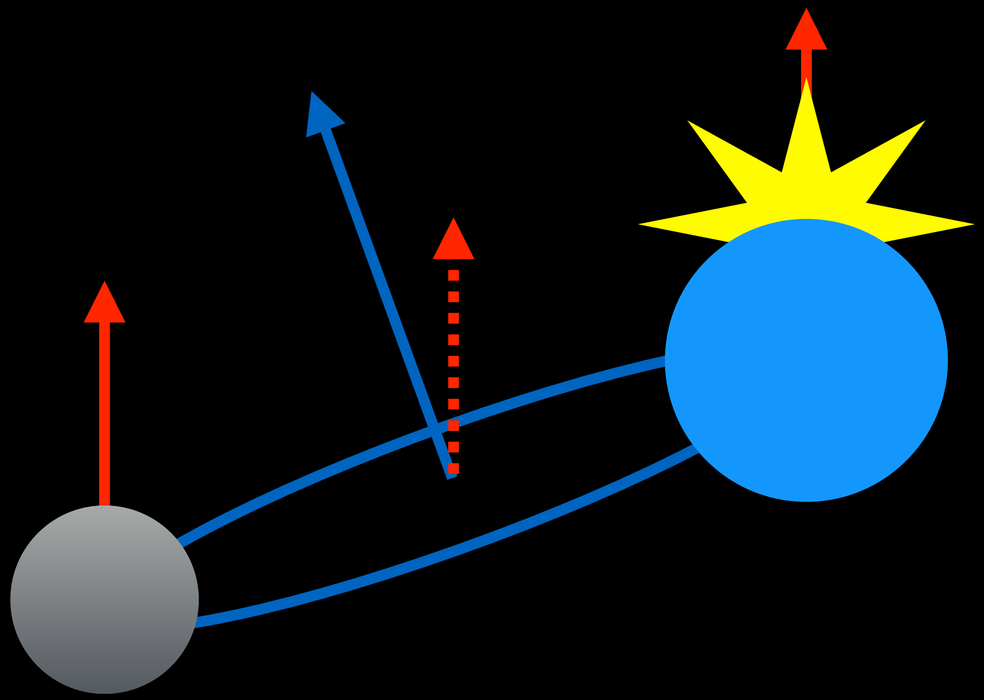

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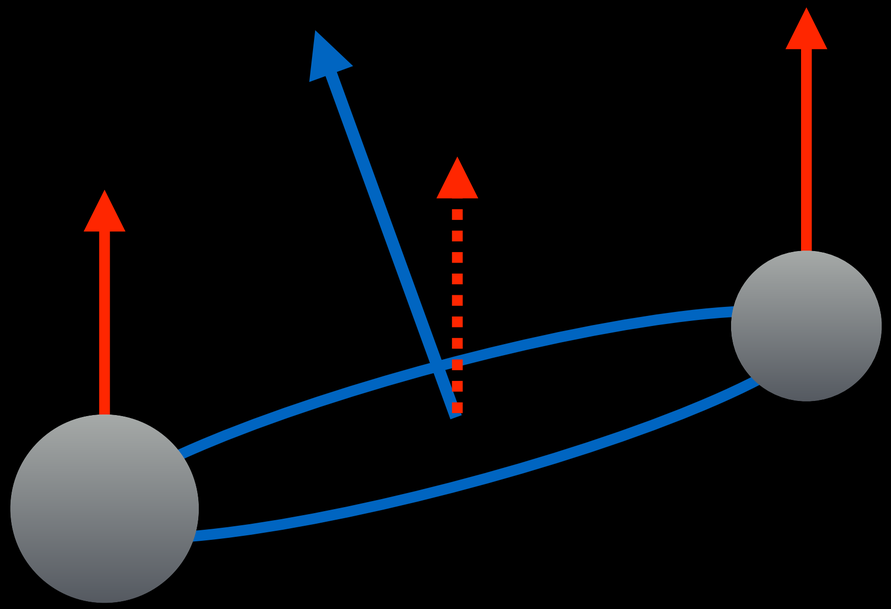

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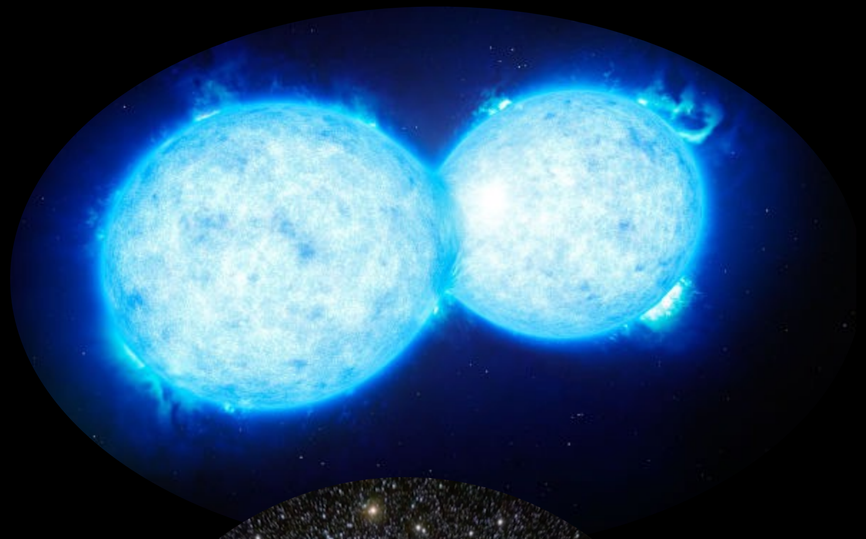

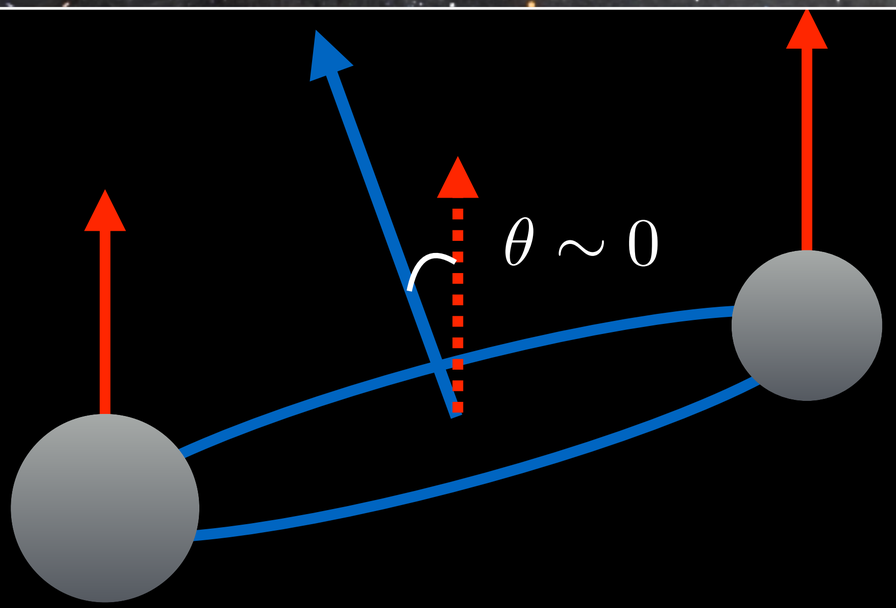


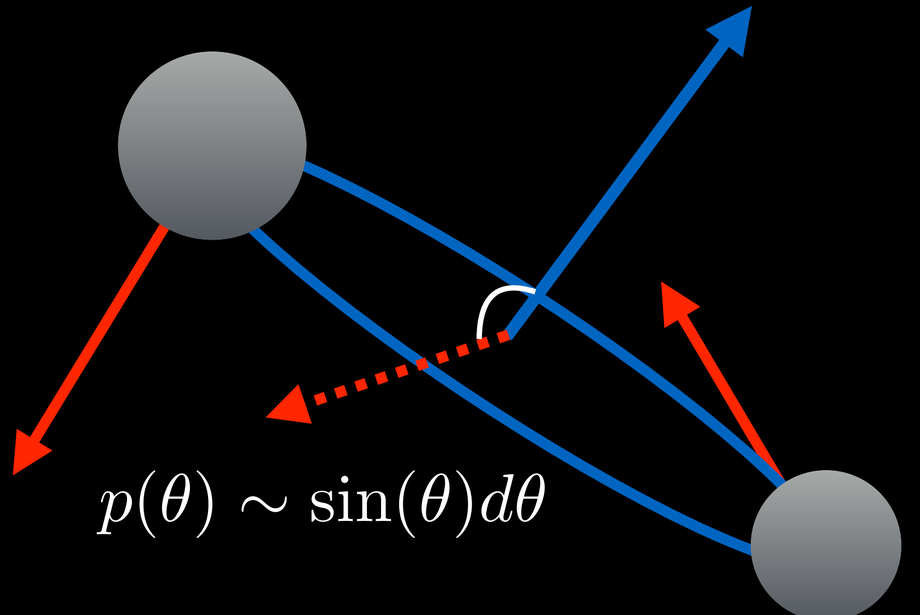

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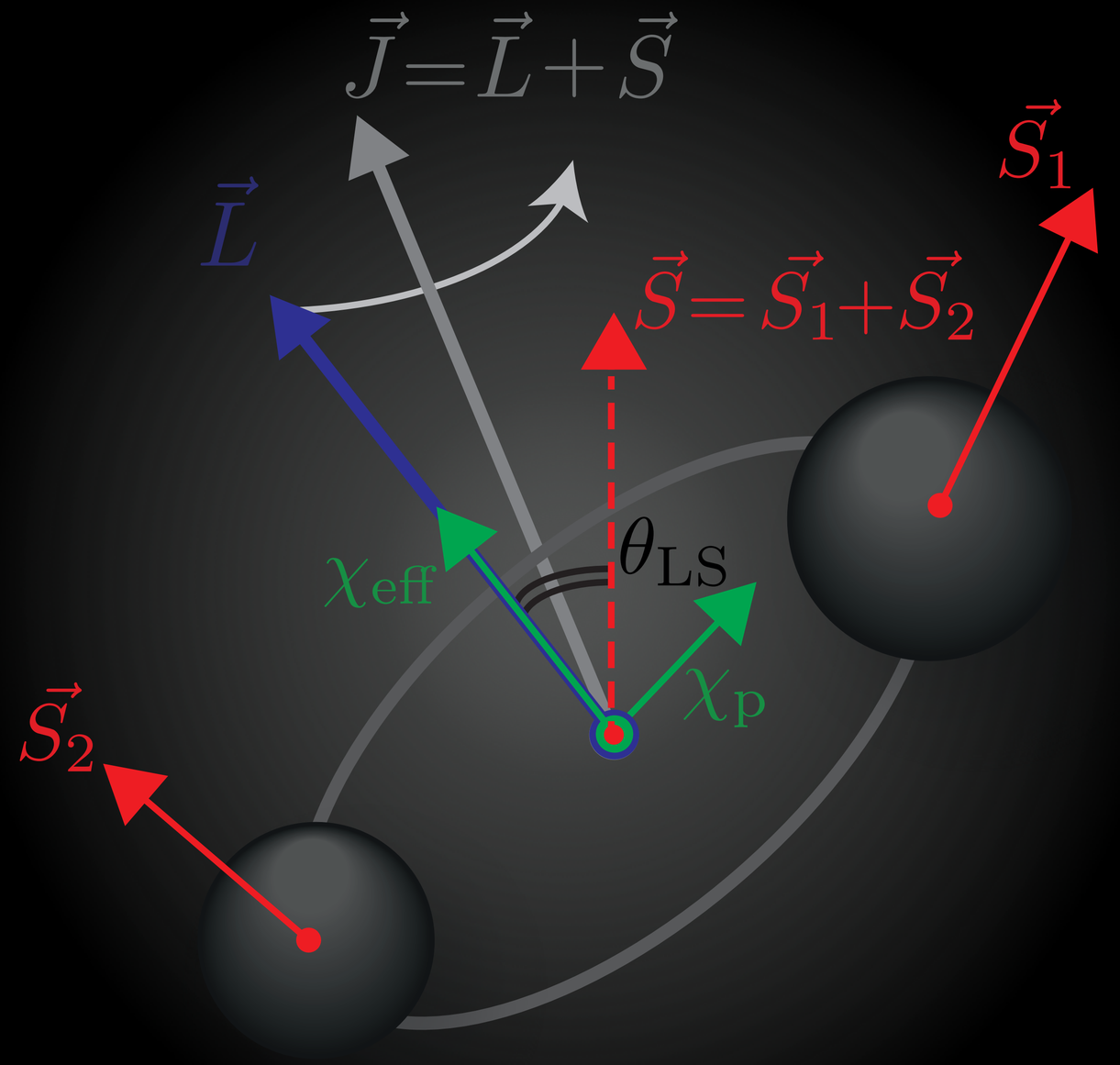

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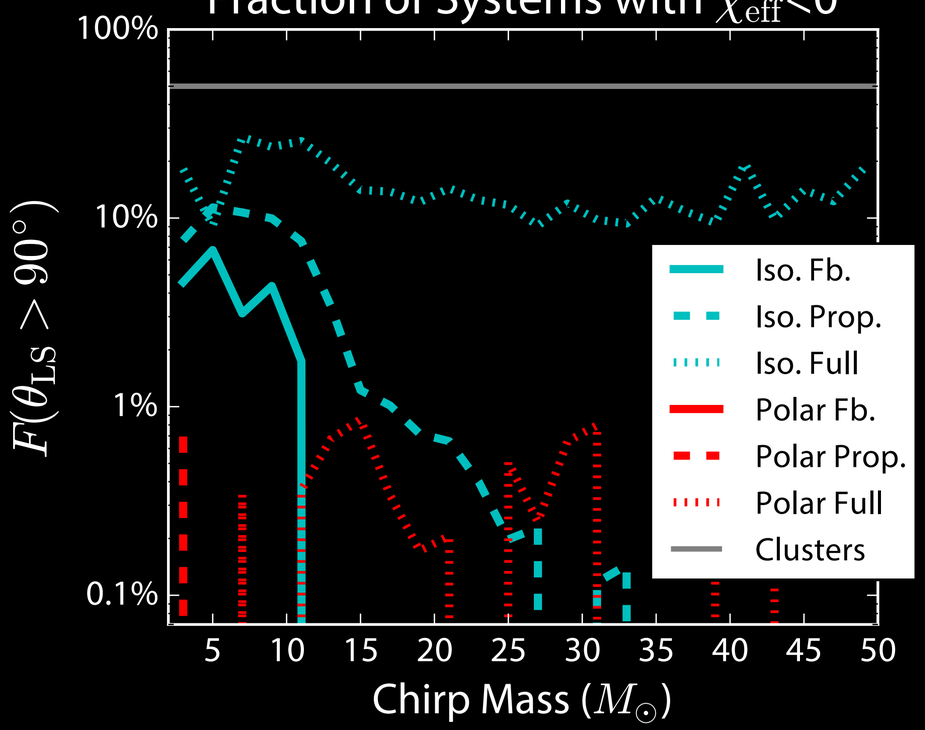
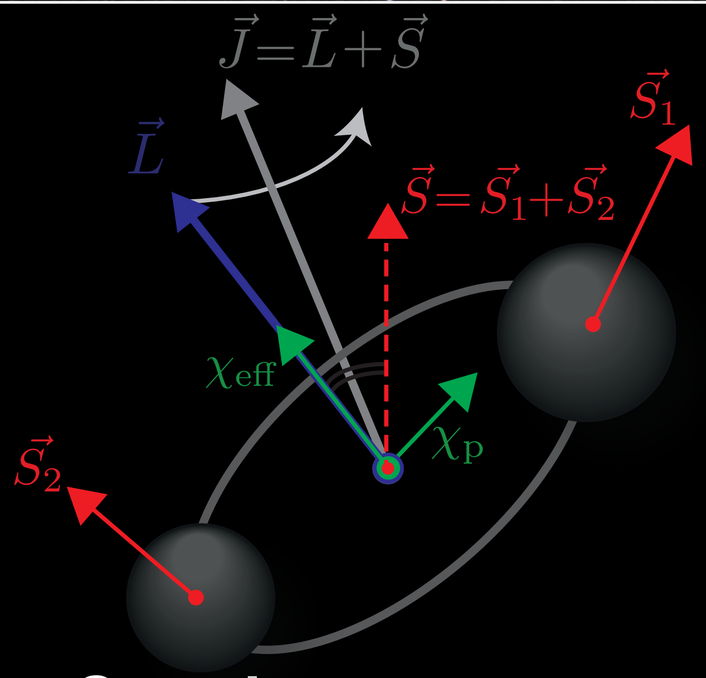


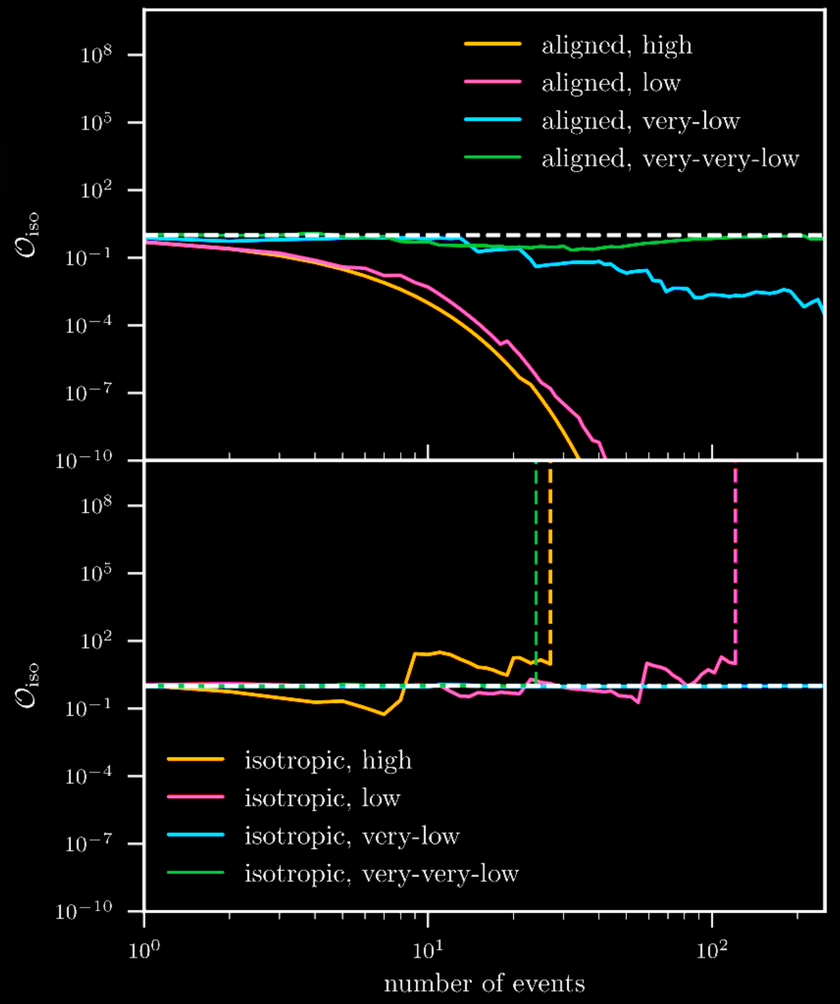

**Rodriguez et al., 2016**
**ApJL, 832, L2**




**See also:**
**Farr et al. 2017**
**Nature, 548, 246**

**Abbott et al., 2018**
**arXiv: 1811.12940**

**Farr, Holz, Farr, 2018**
**ApJL, 854, L9**



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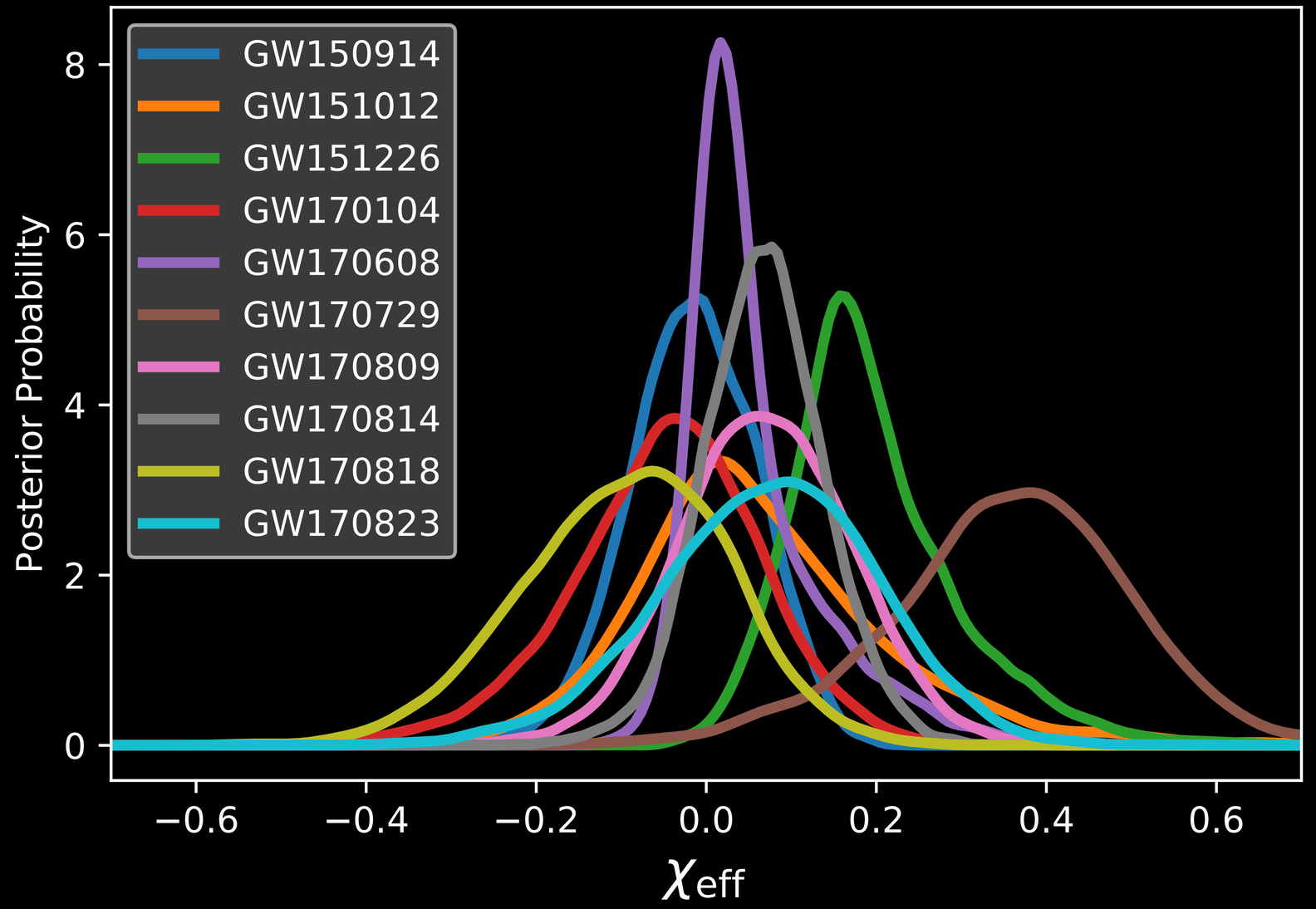


**From LIGO/Virgo O1/O2 Catalog Posterior Samples**

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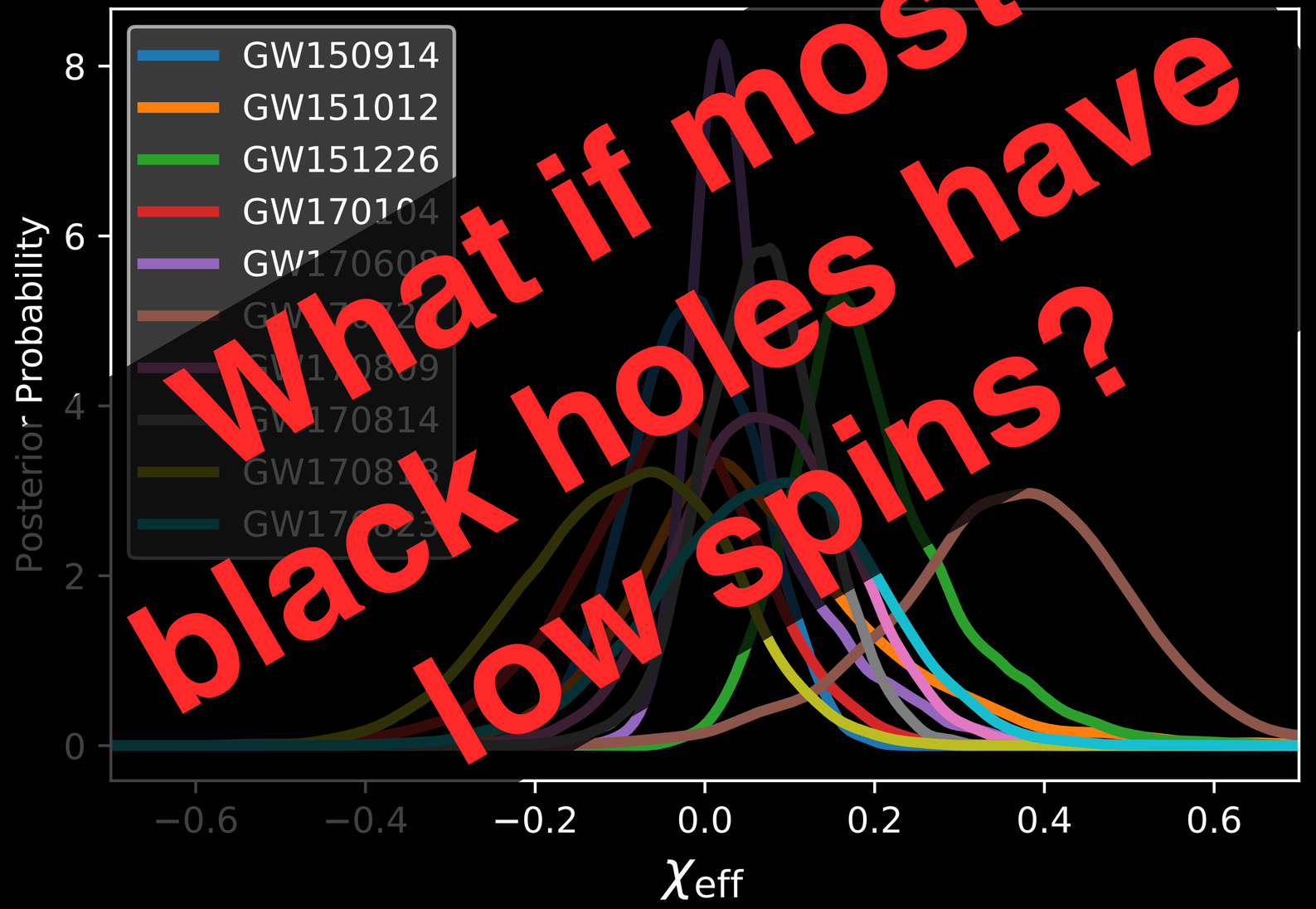


**What if most black holes have low spins?**

**From LIGO/Virgo O1/O2 Catalog Posterior Samples**

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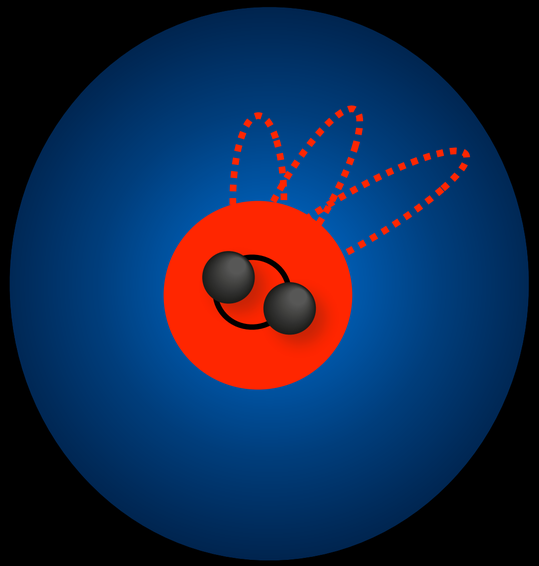

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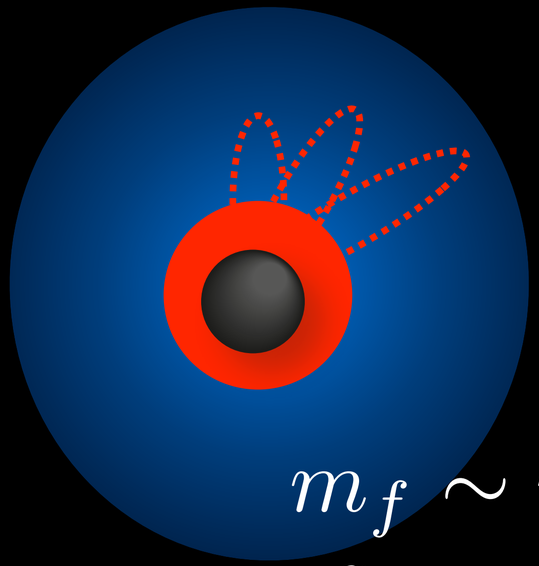

$$m_f \sim m_1 + m_2$$
$$a_f \sim 0.7$$

# Merging Binaries

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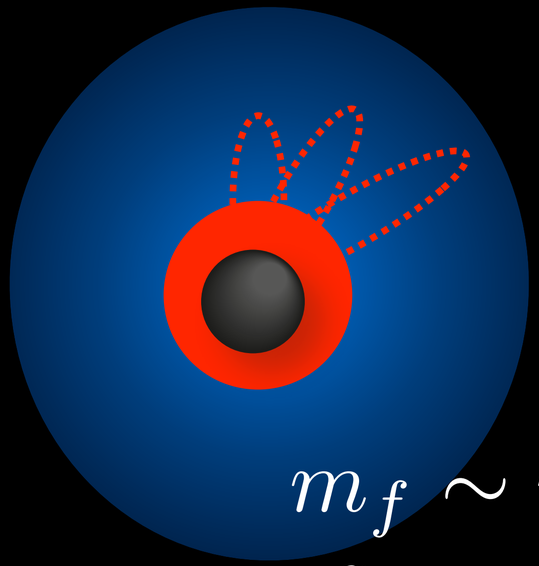
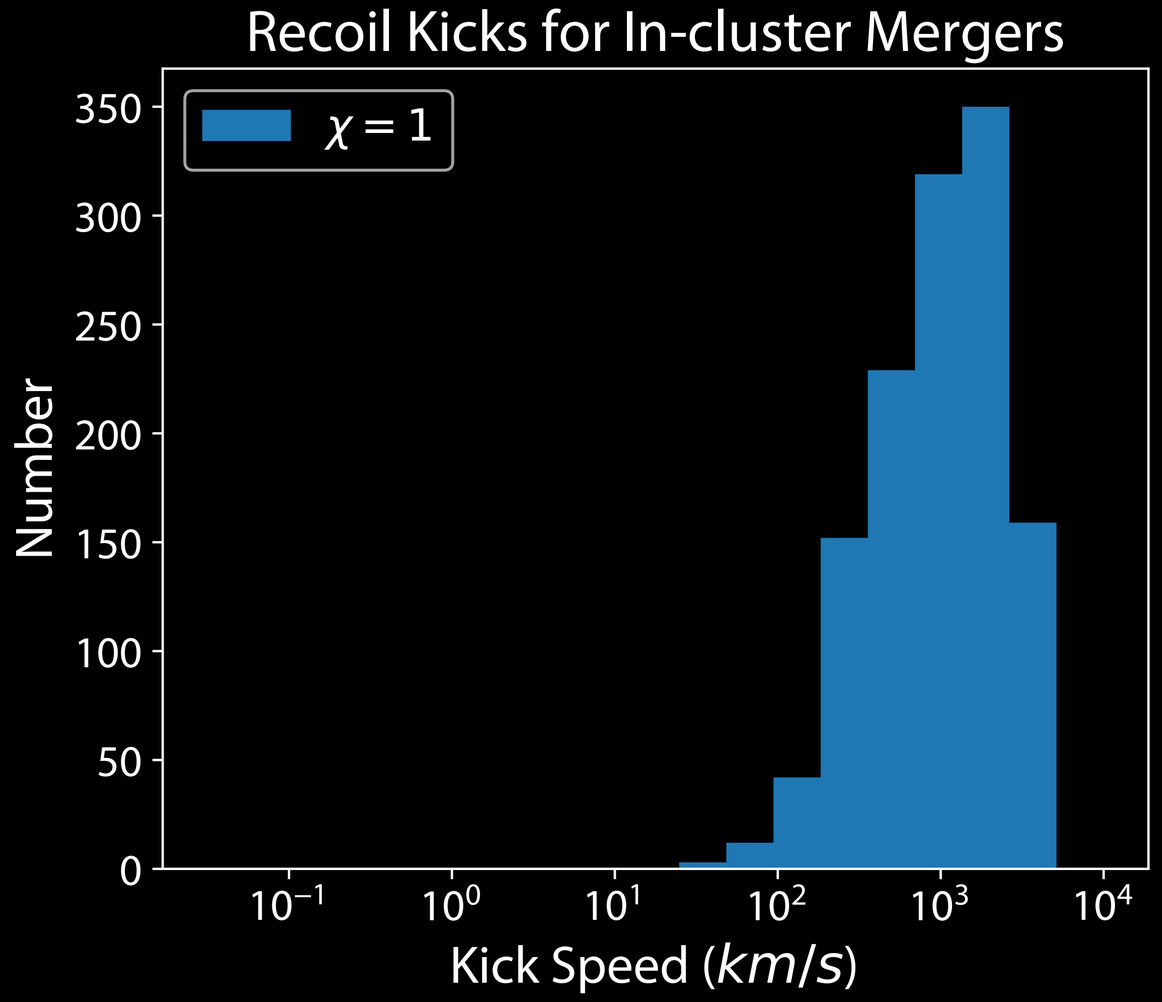
HARVARD & SMITHSONIAN



$$m_f \sim m_1 + m_2$$
$$a_f \sim 0.7$$



# Merging Binaries

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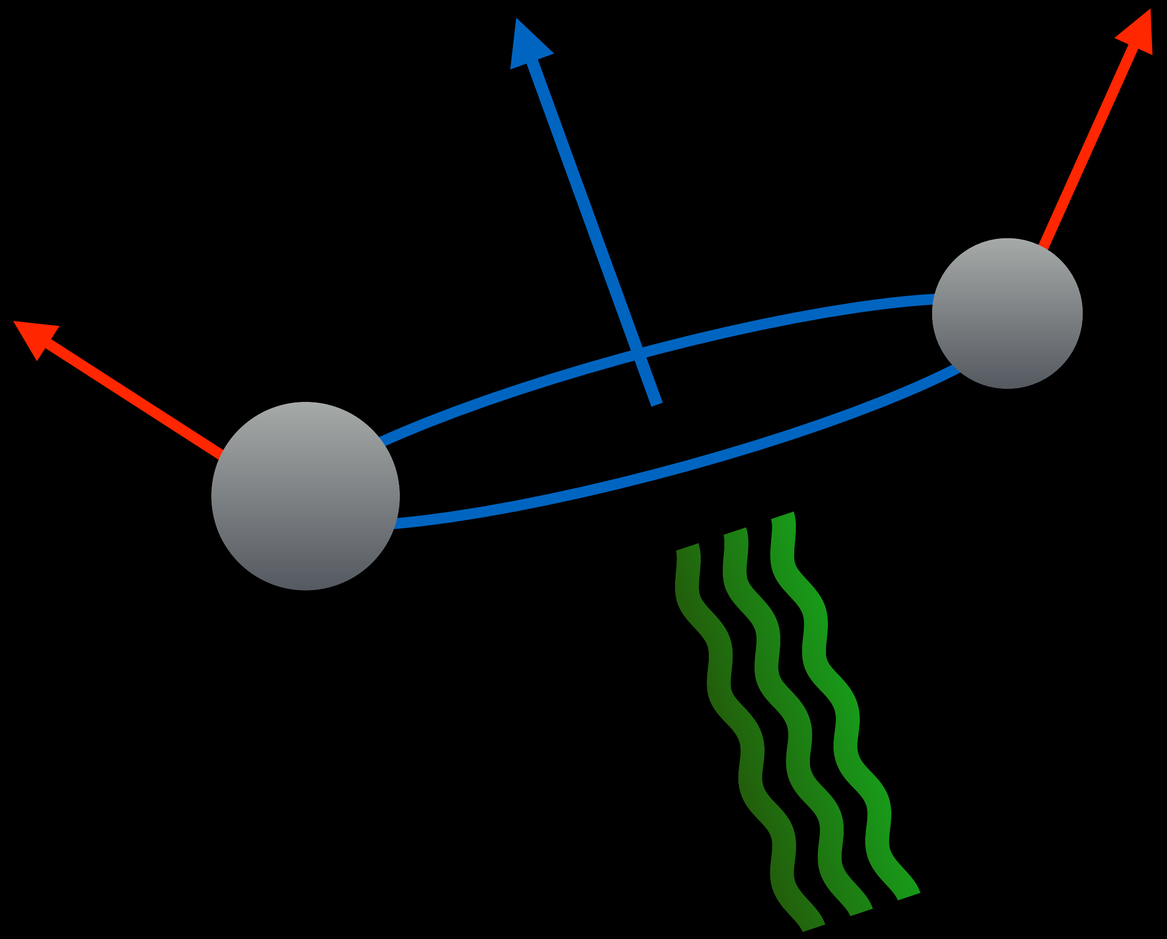
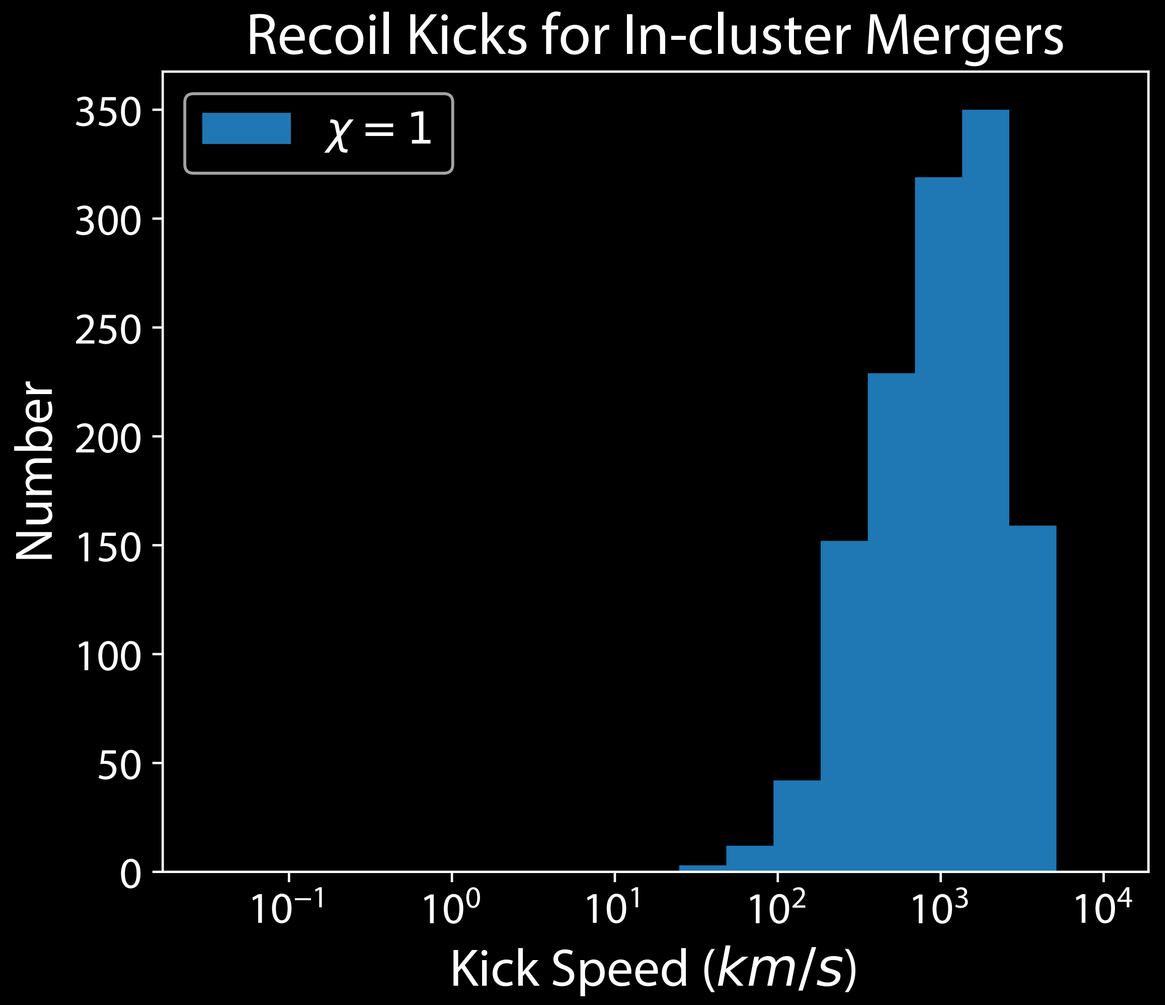
HARVARD & SMITHSONIAN





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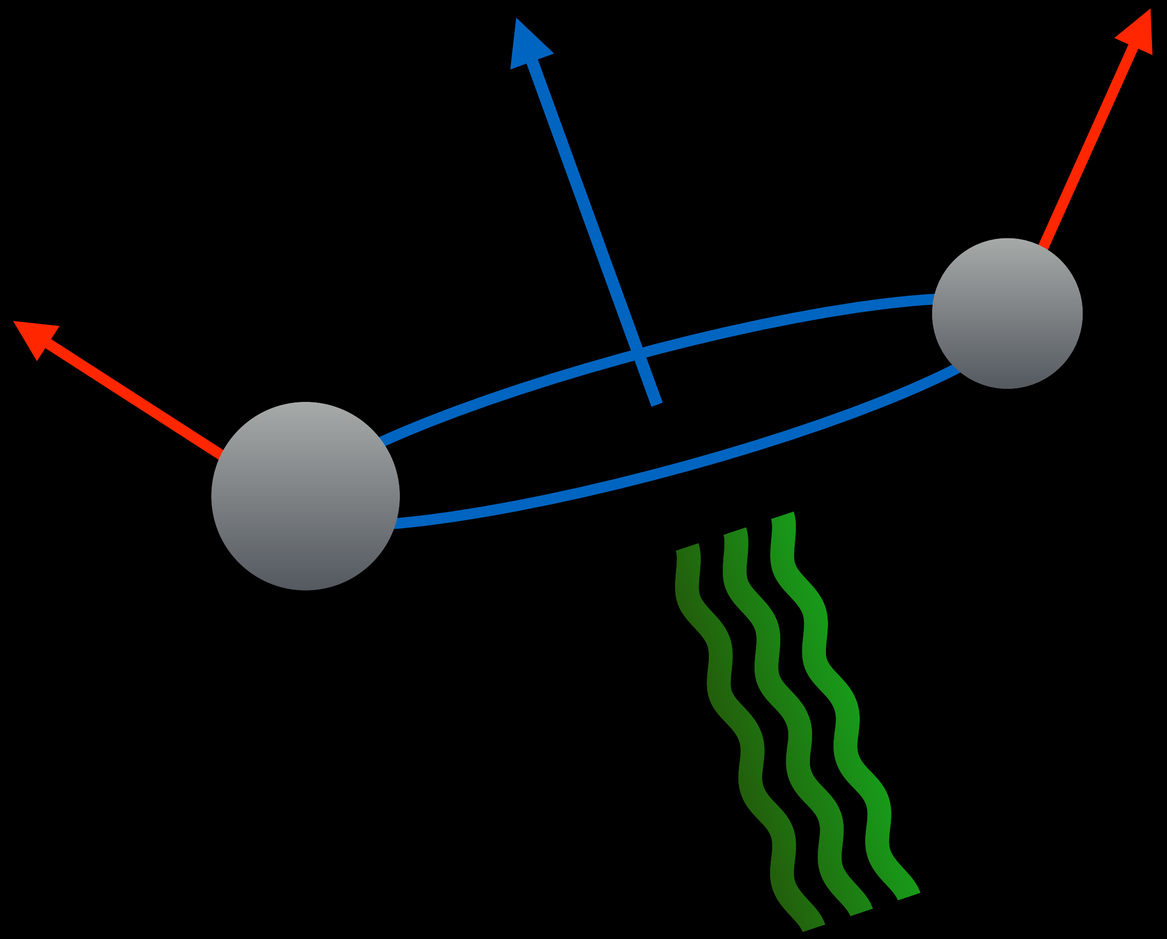

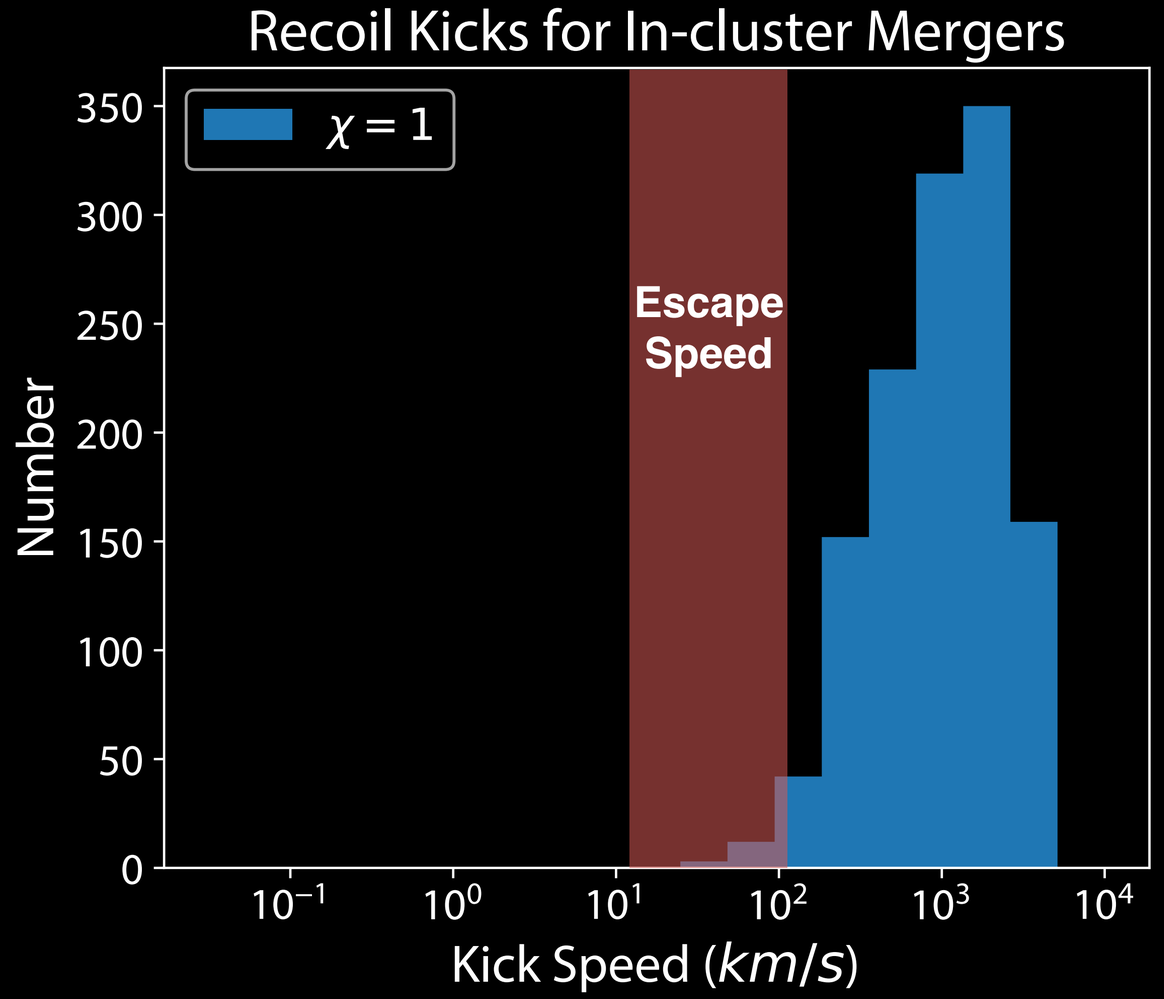

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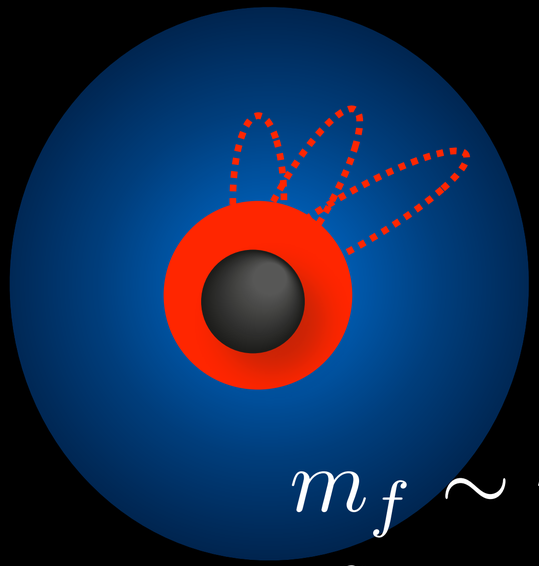

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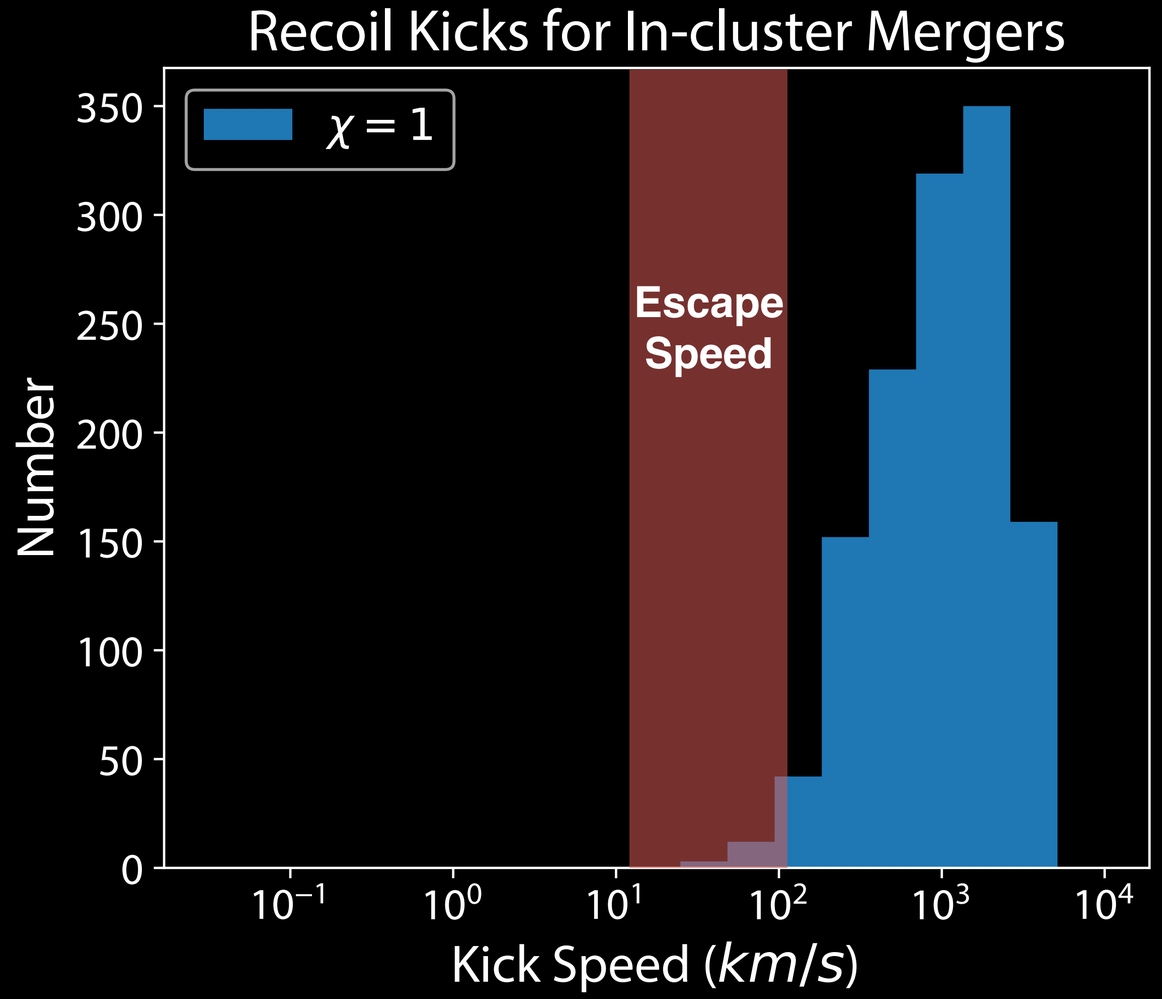

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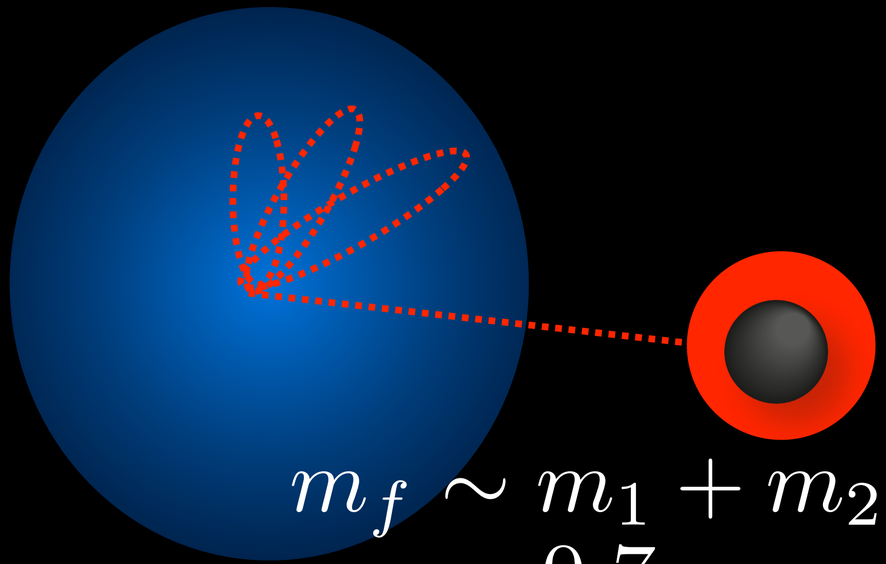

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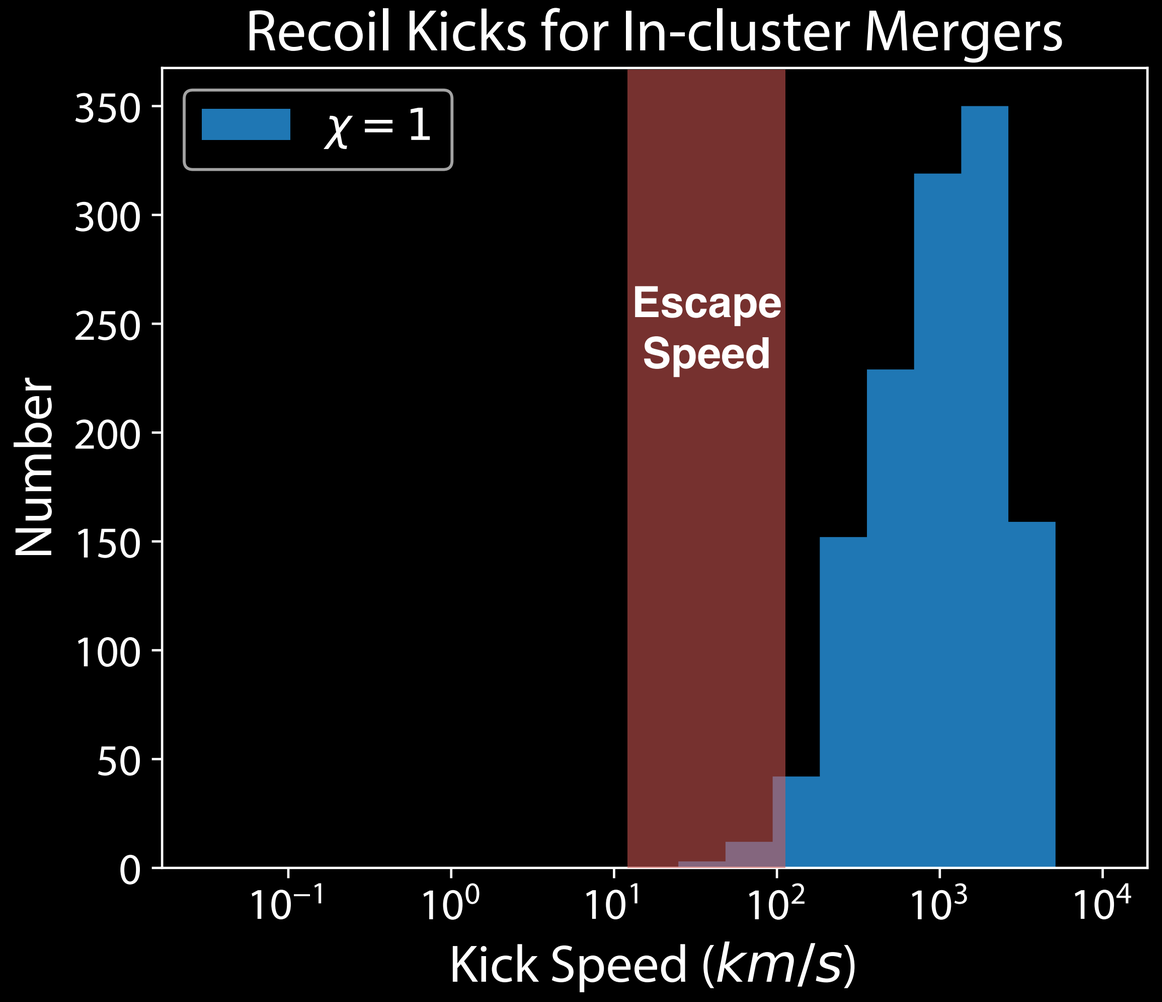

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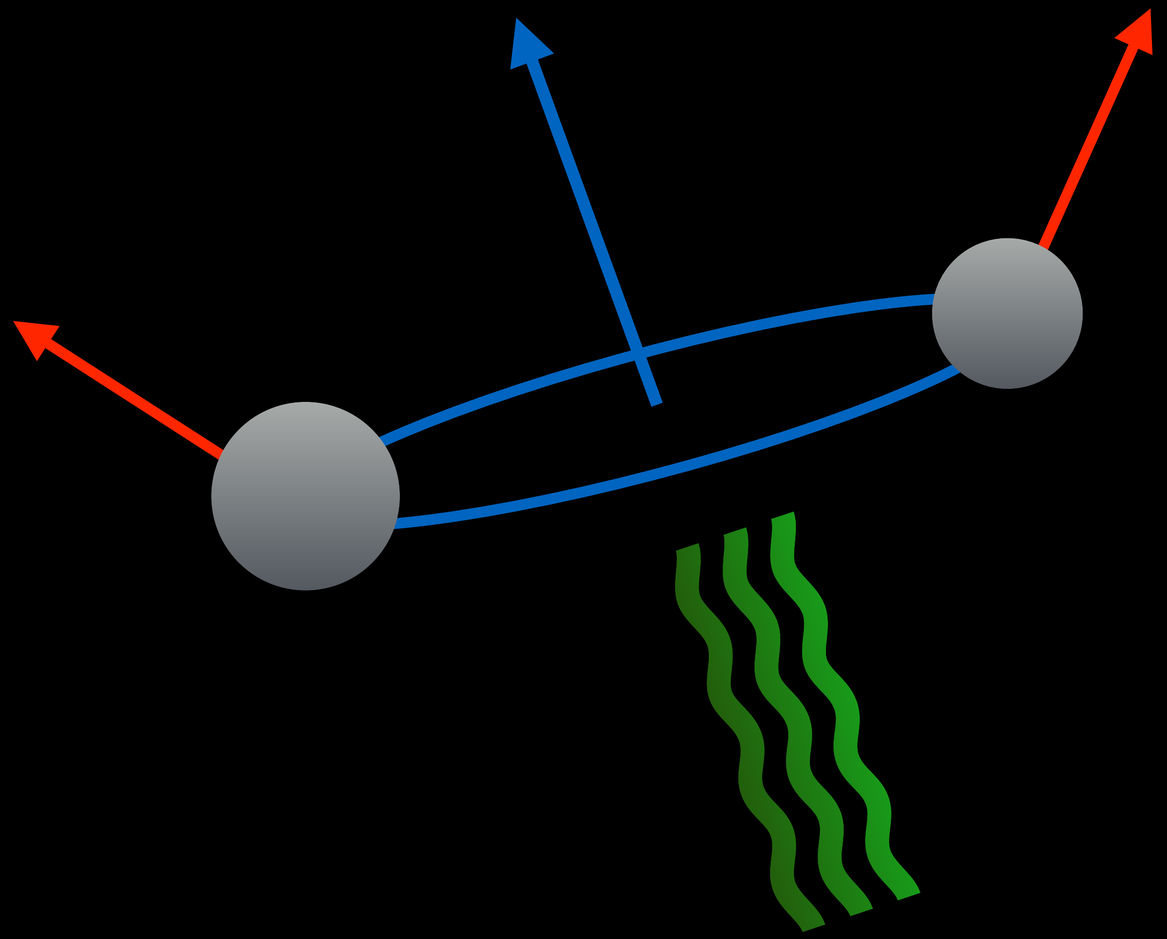

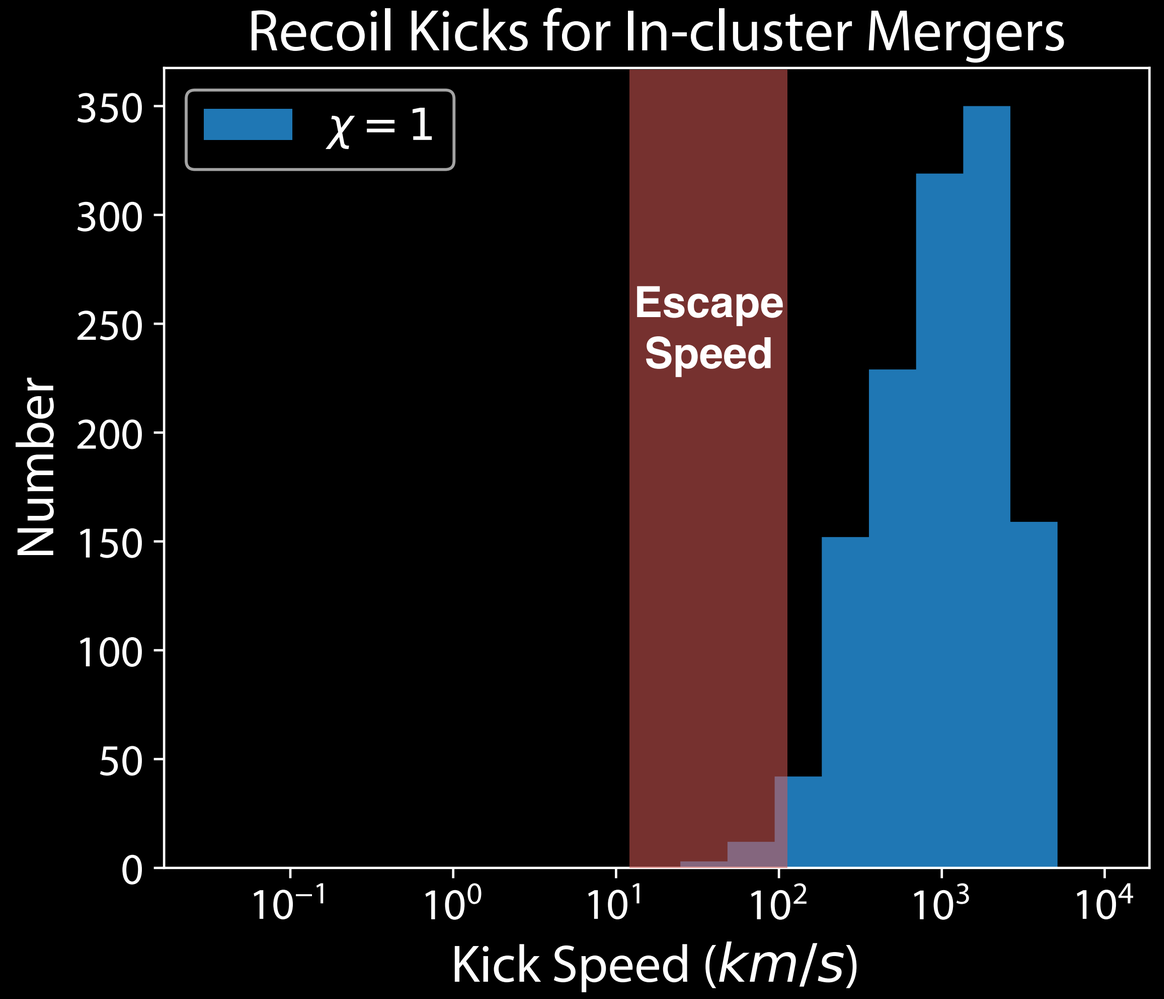

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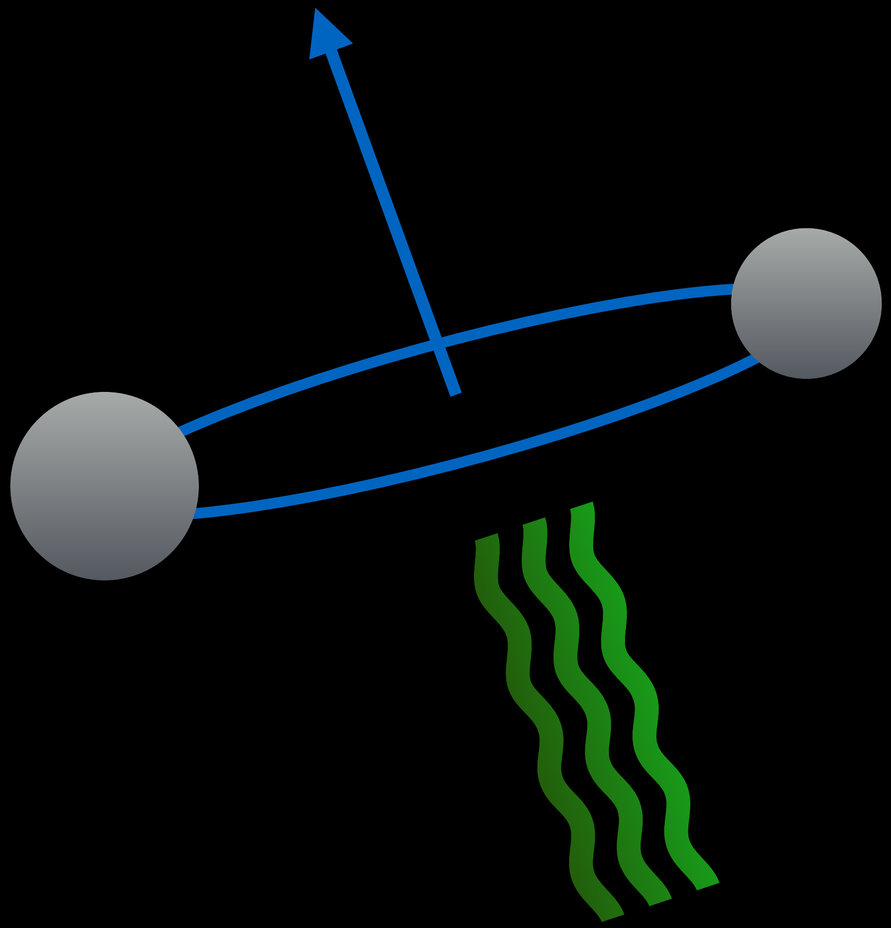

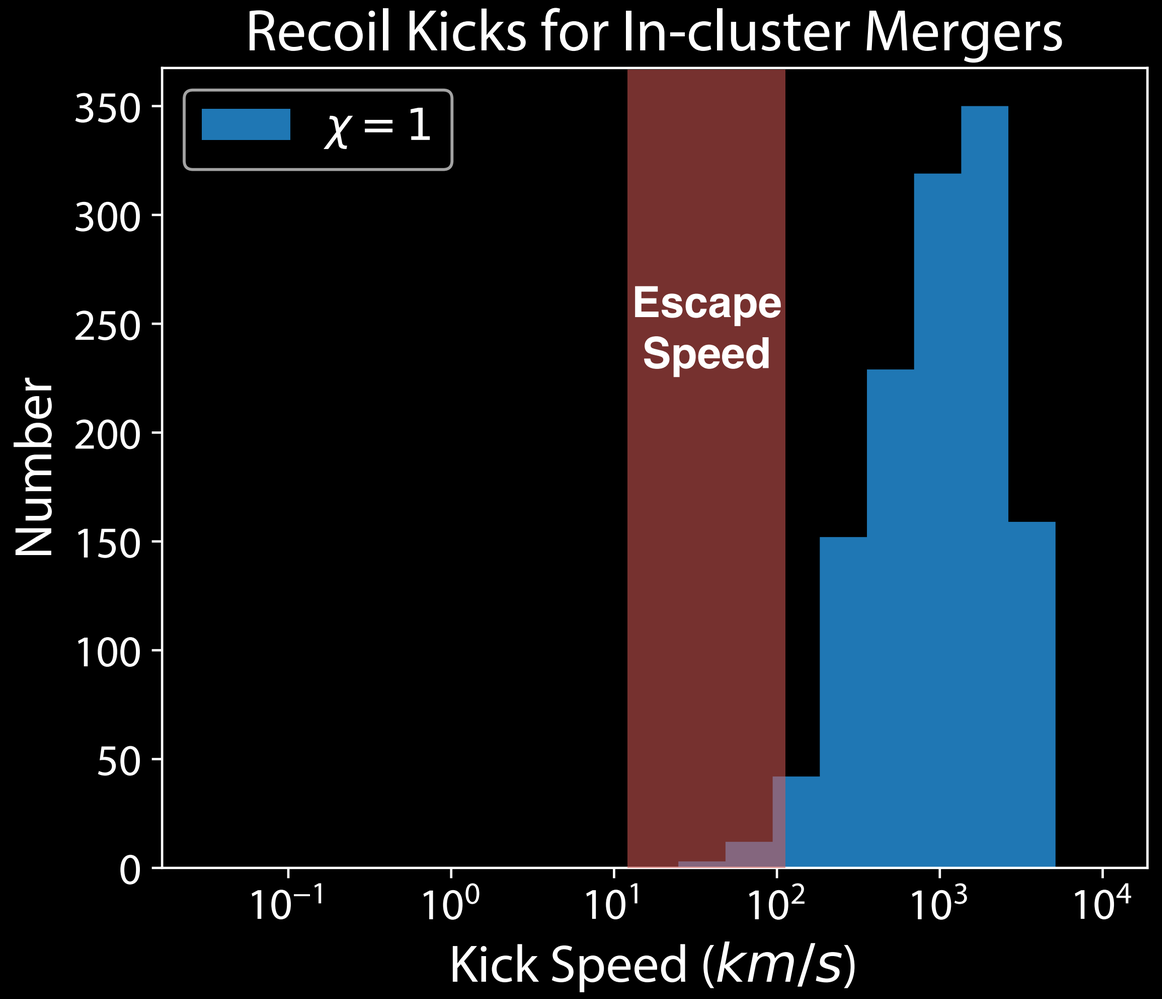

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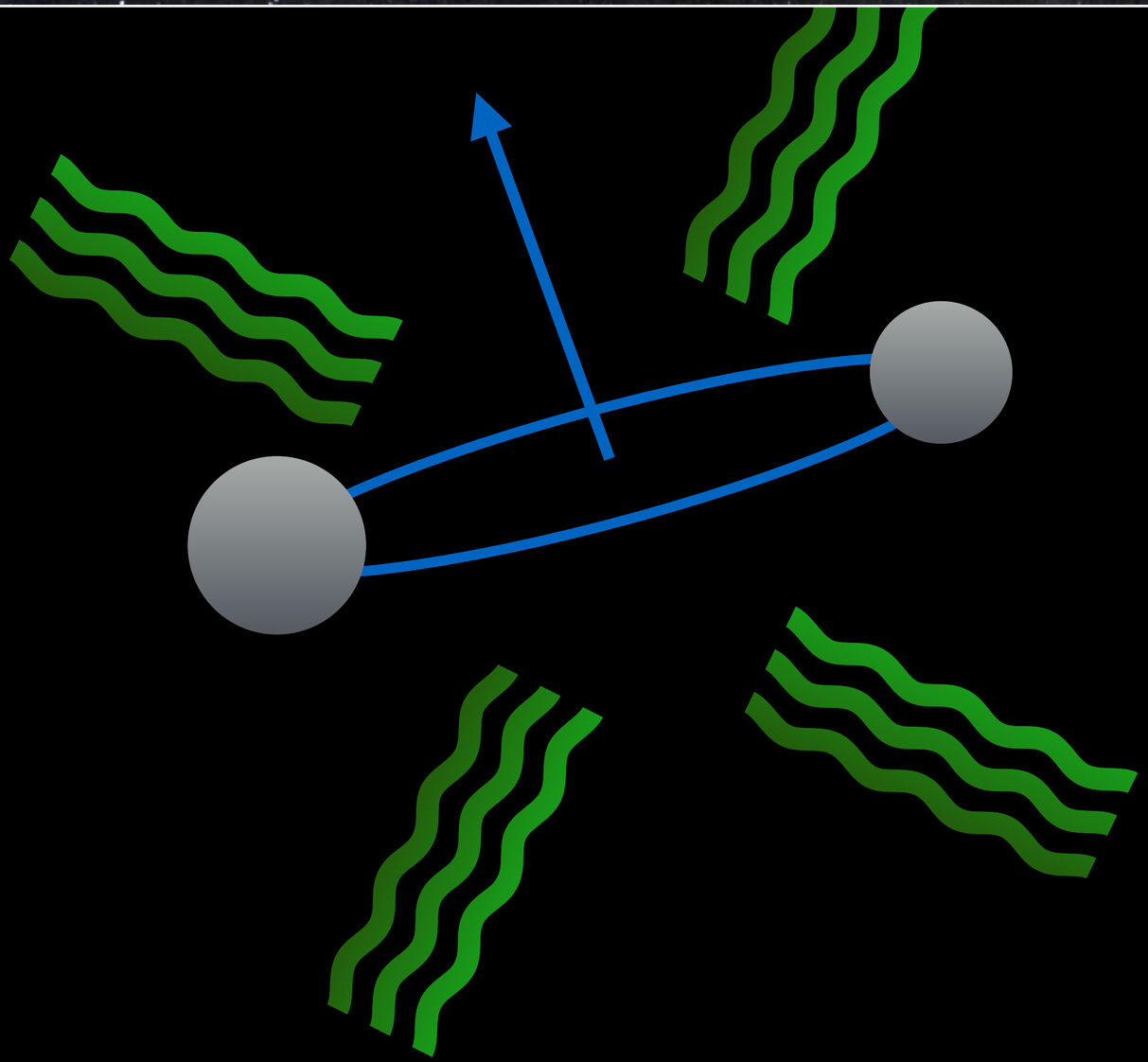

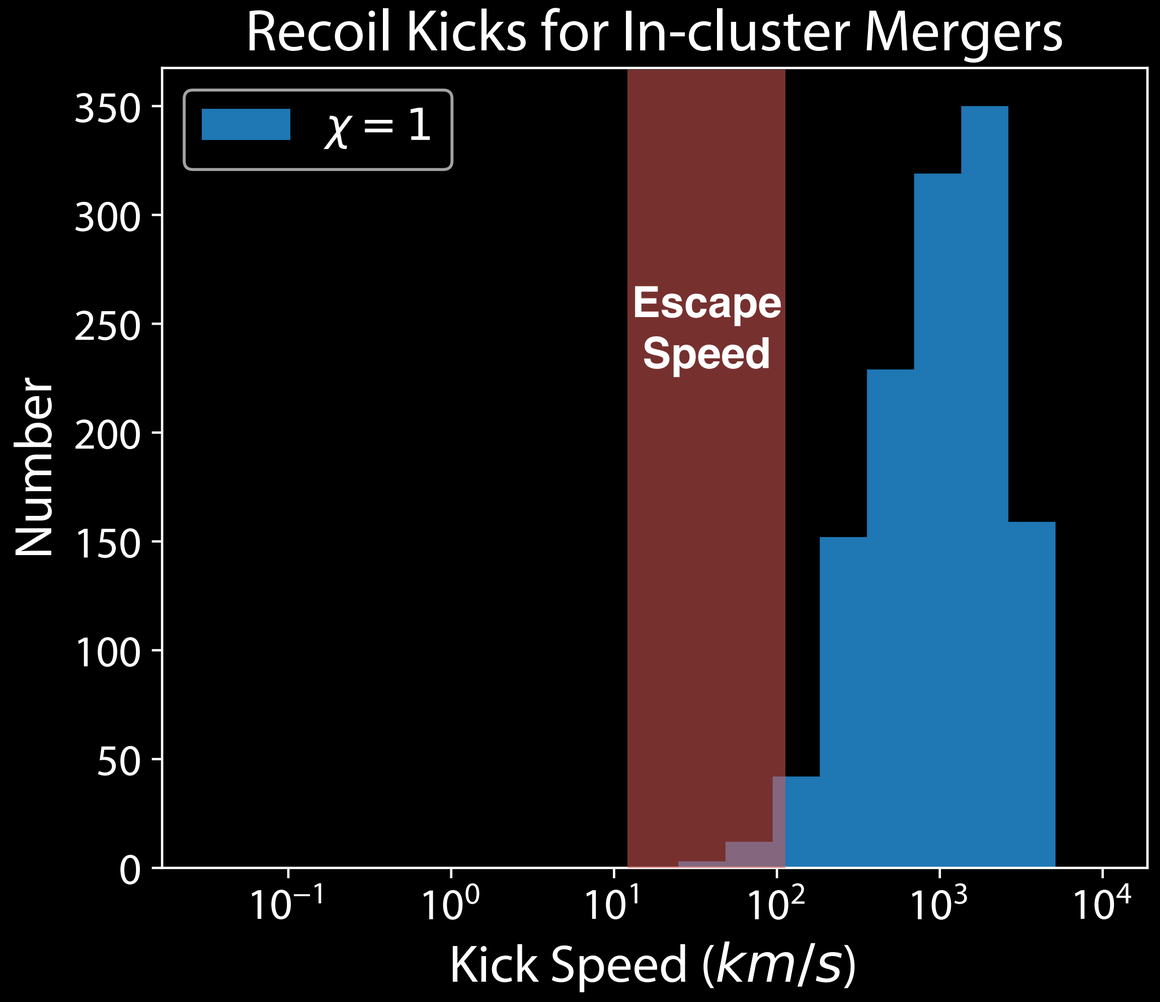

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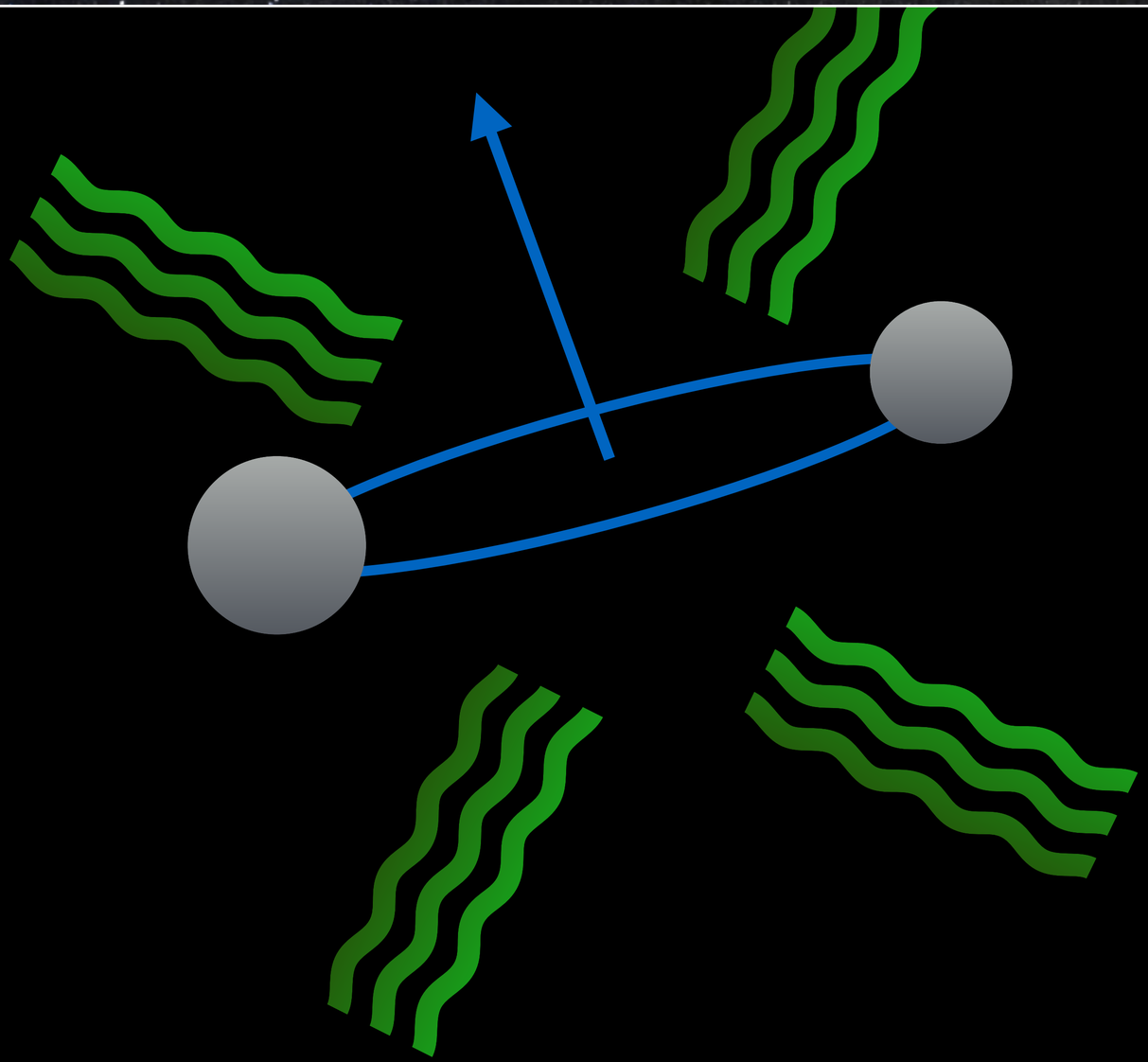

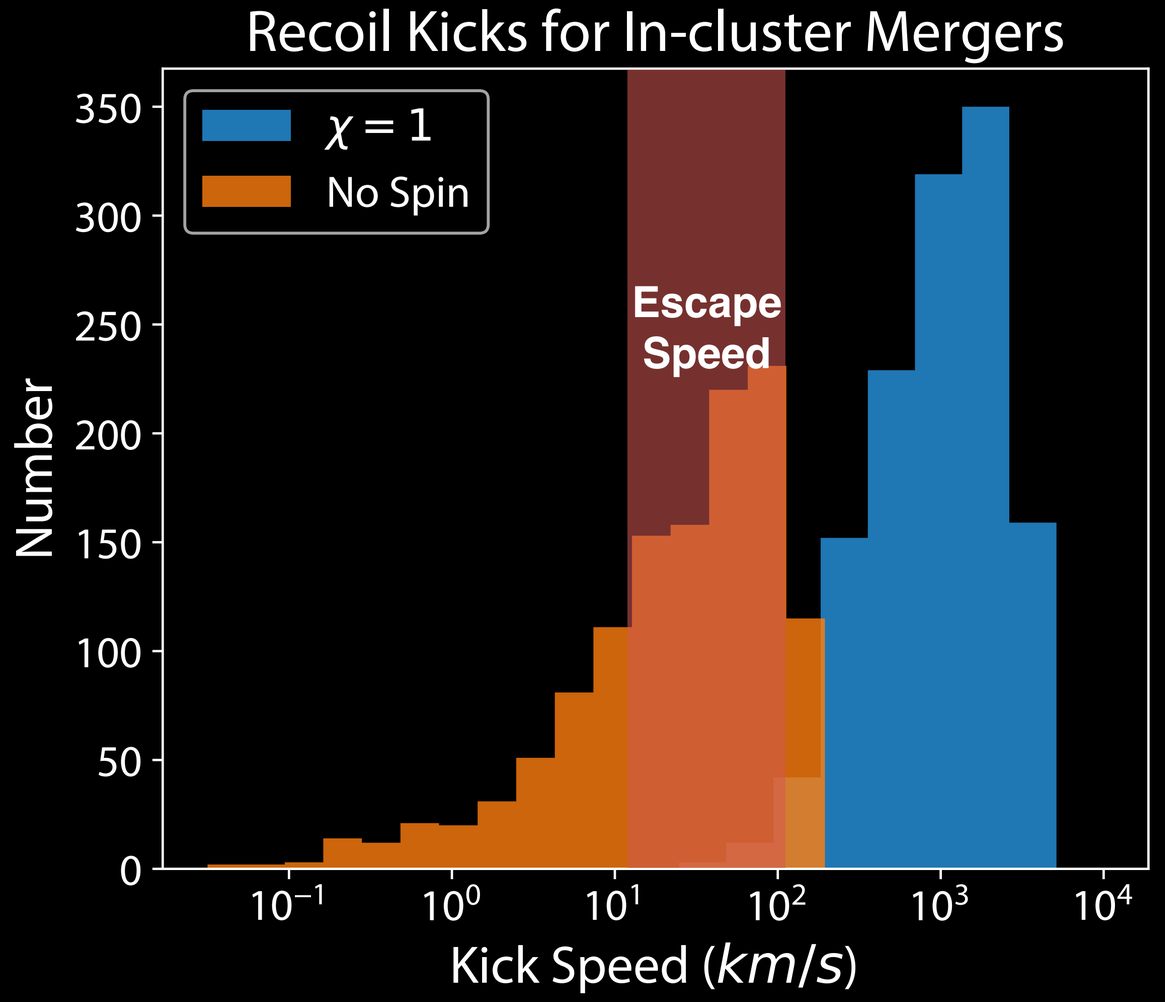

# Multiple Mergers

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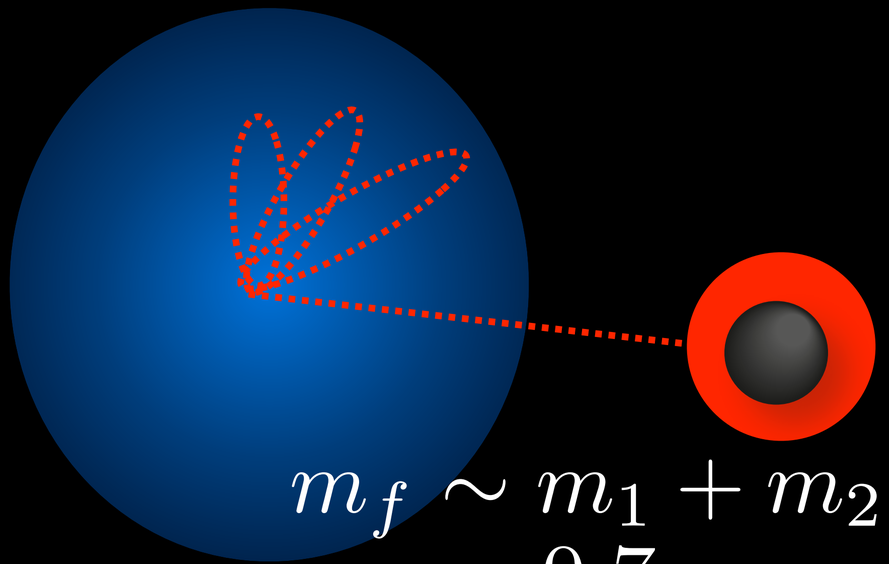
HARVARD & SMITHSONIAN



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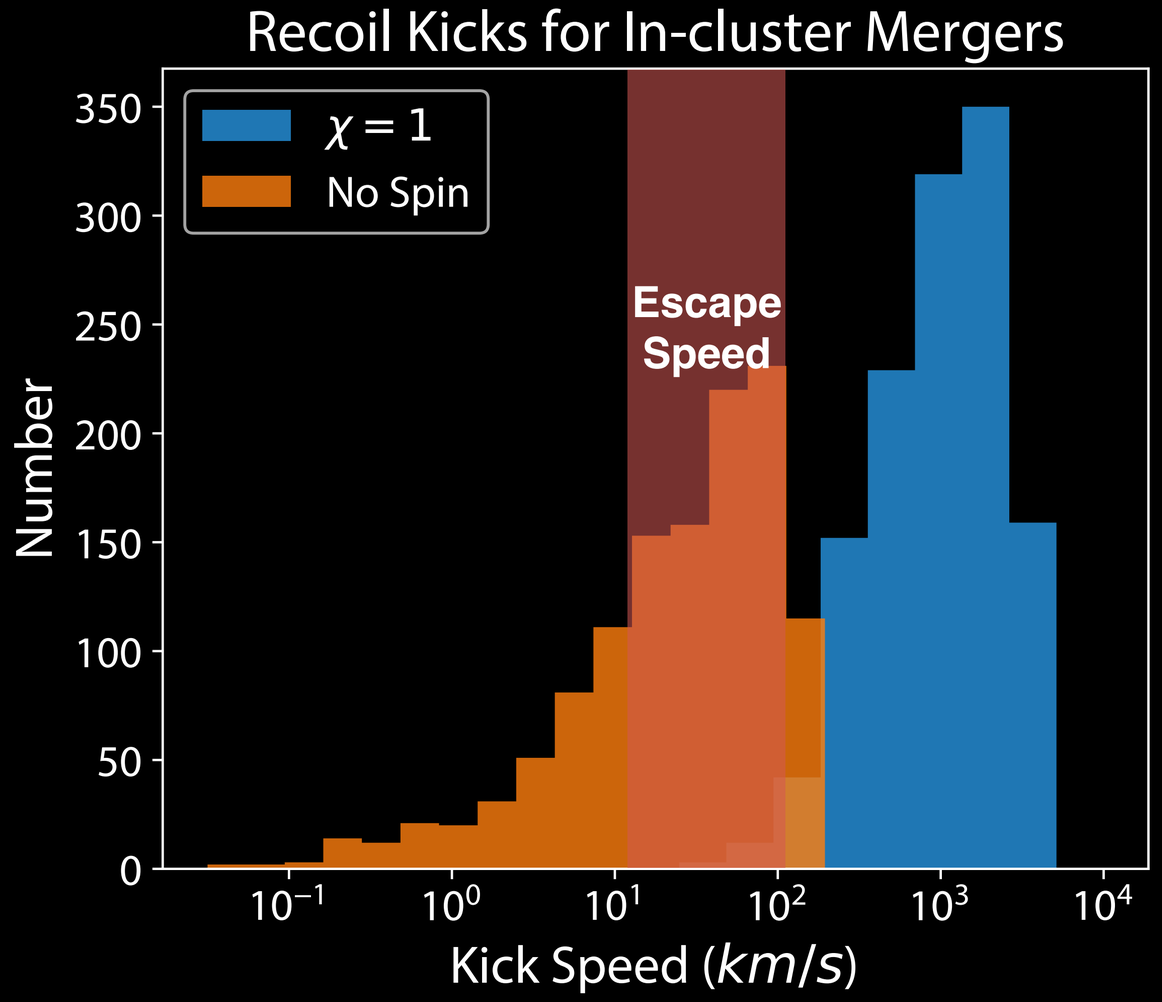

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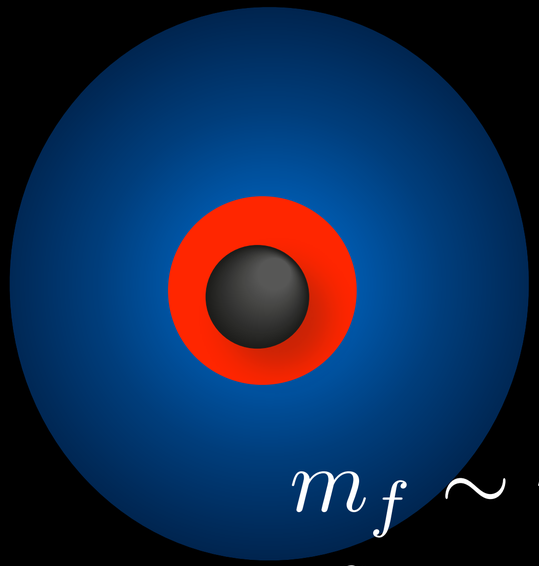

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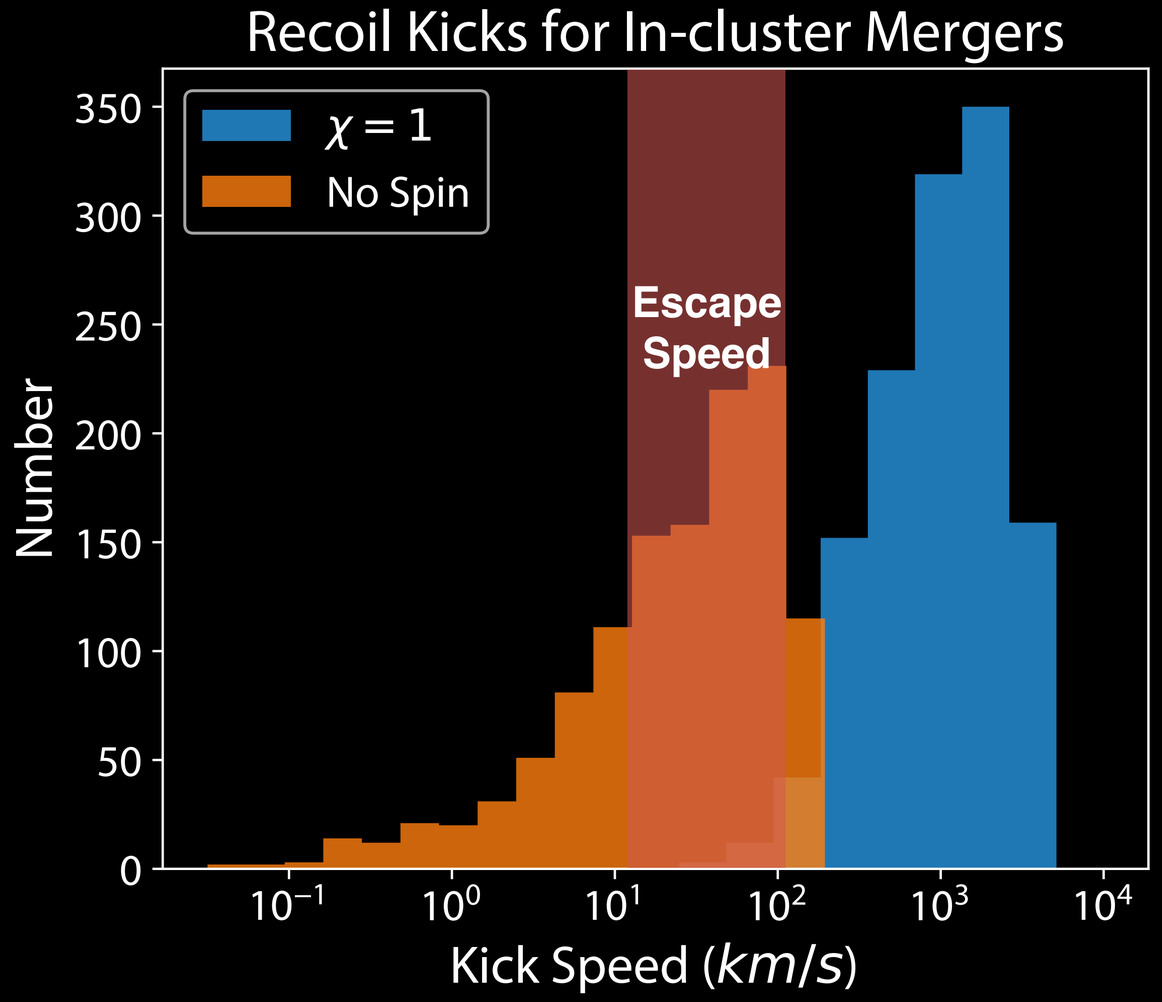

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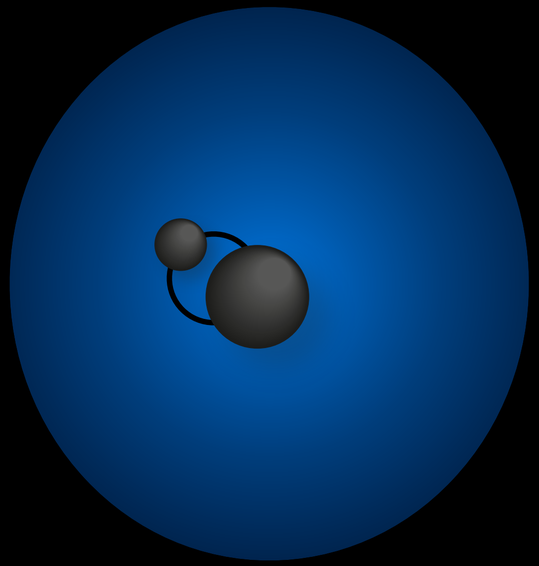

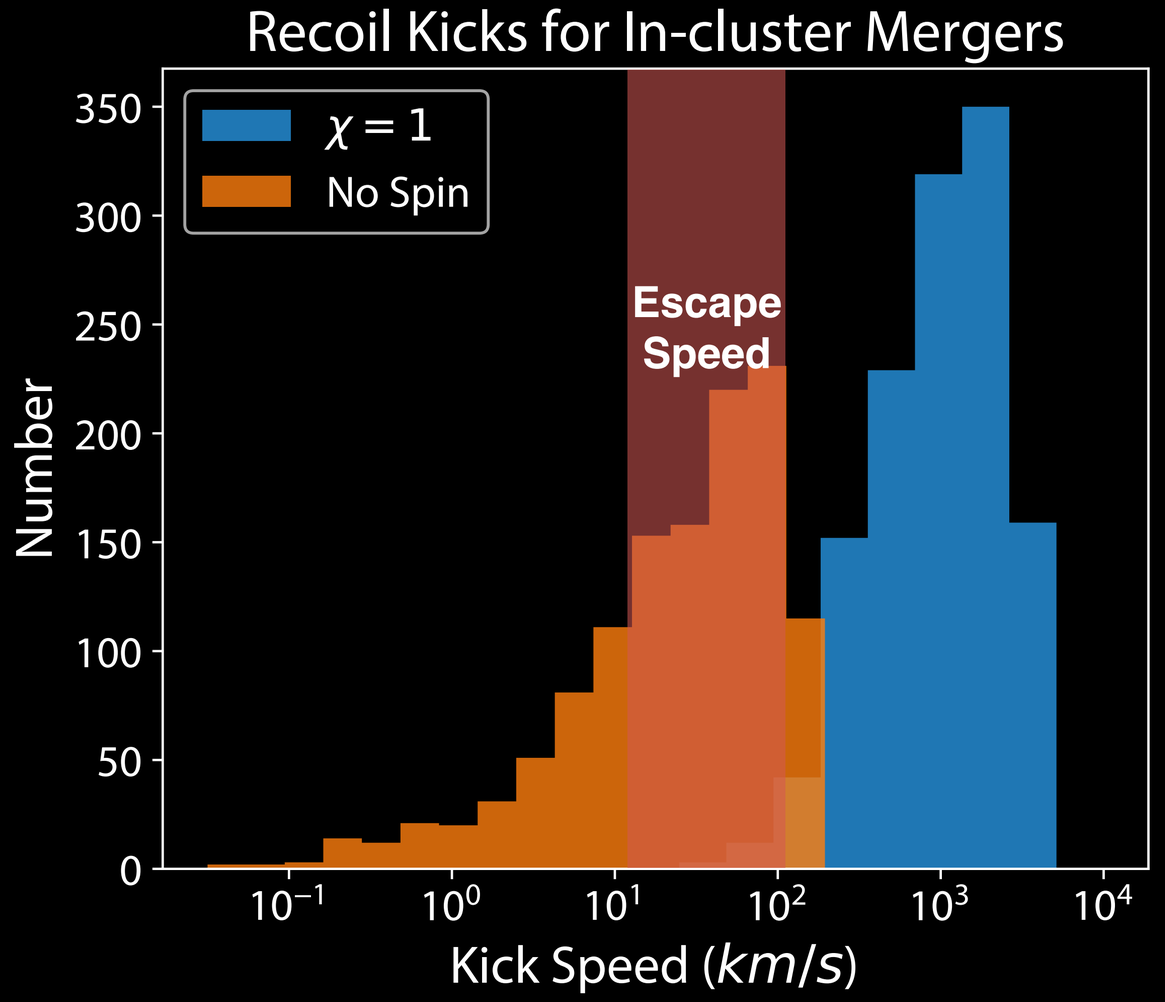

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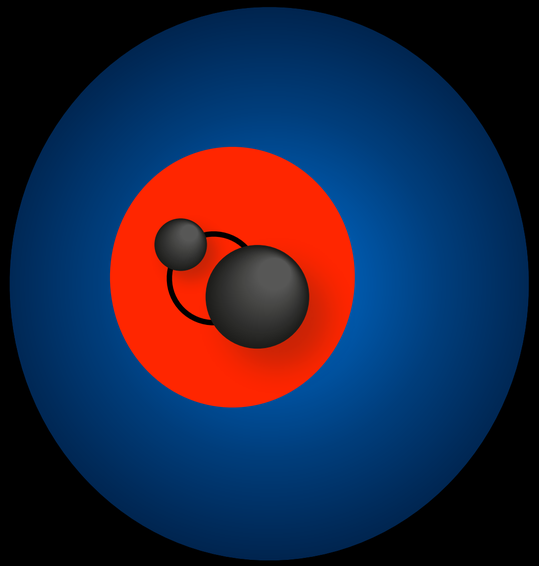

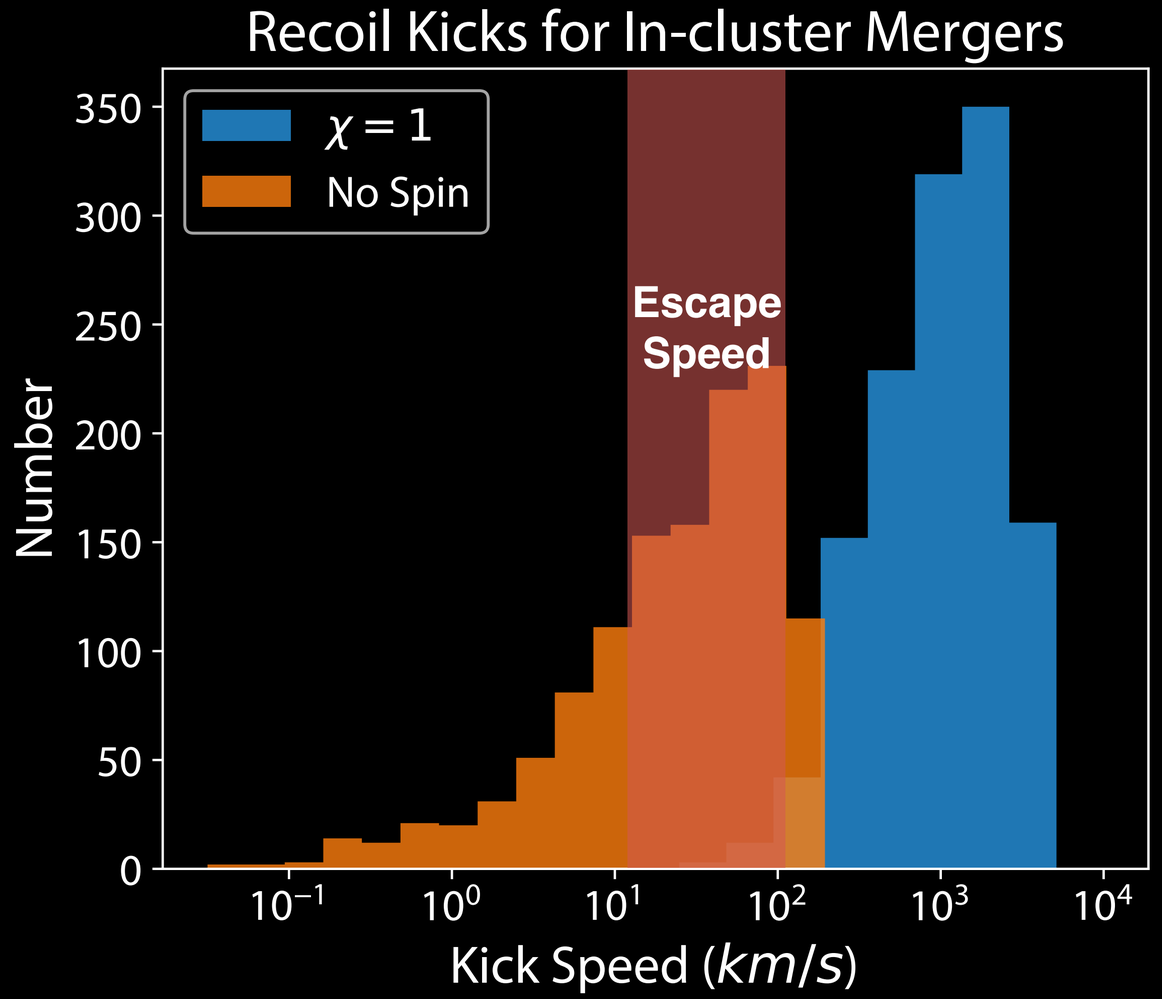

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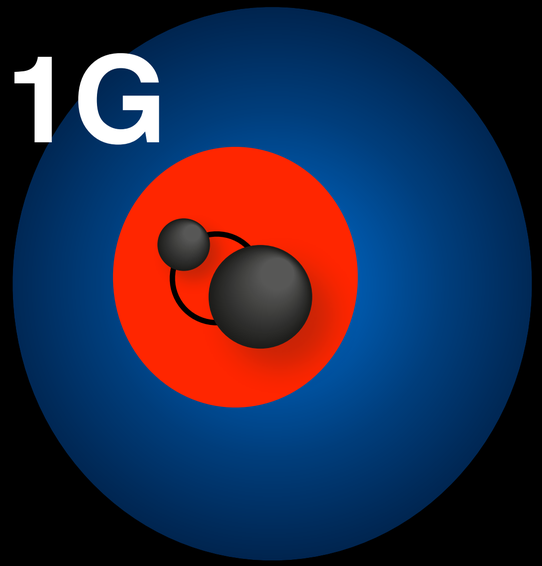


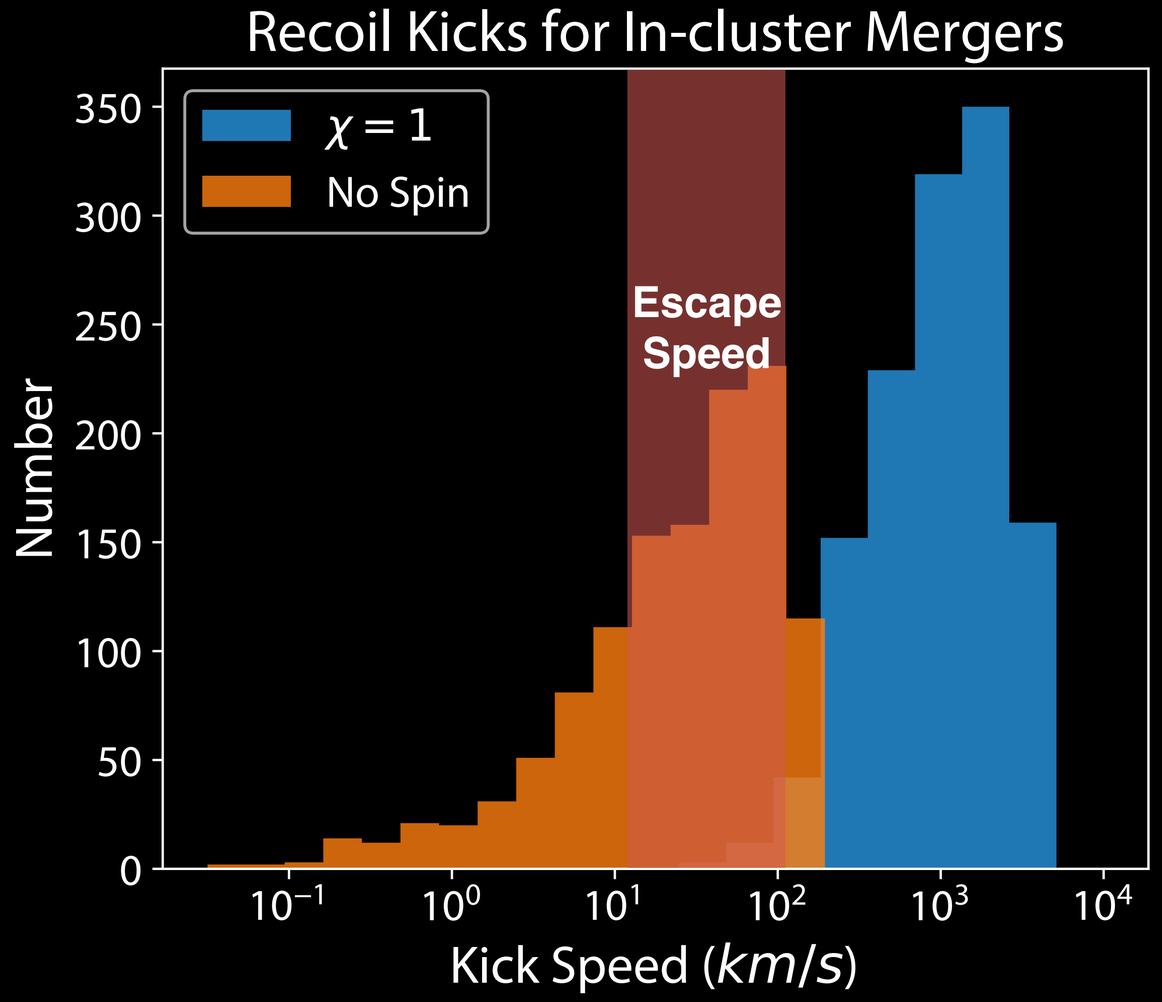

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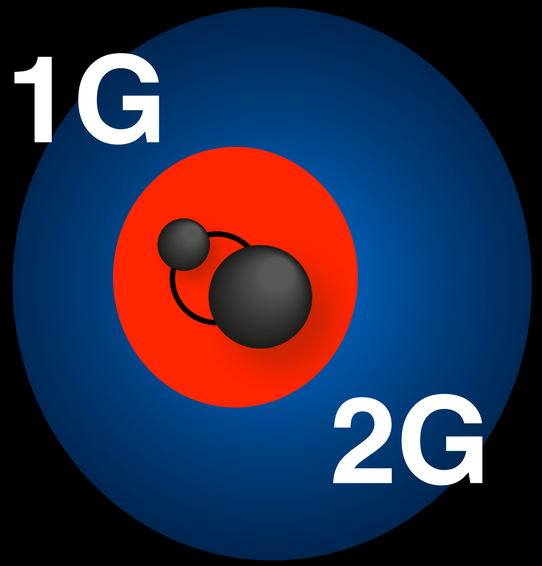


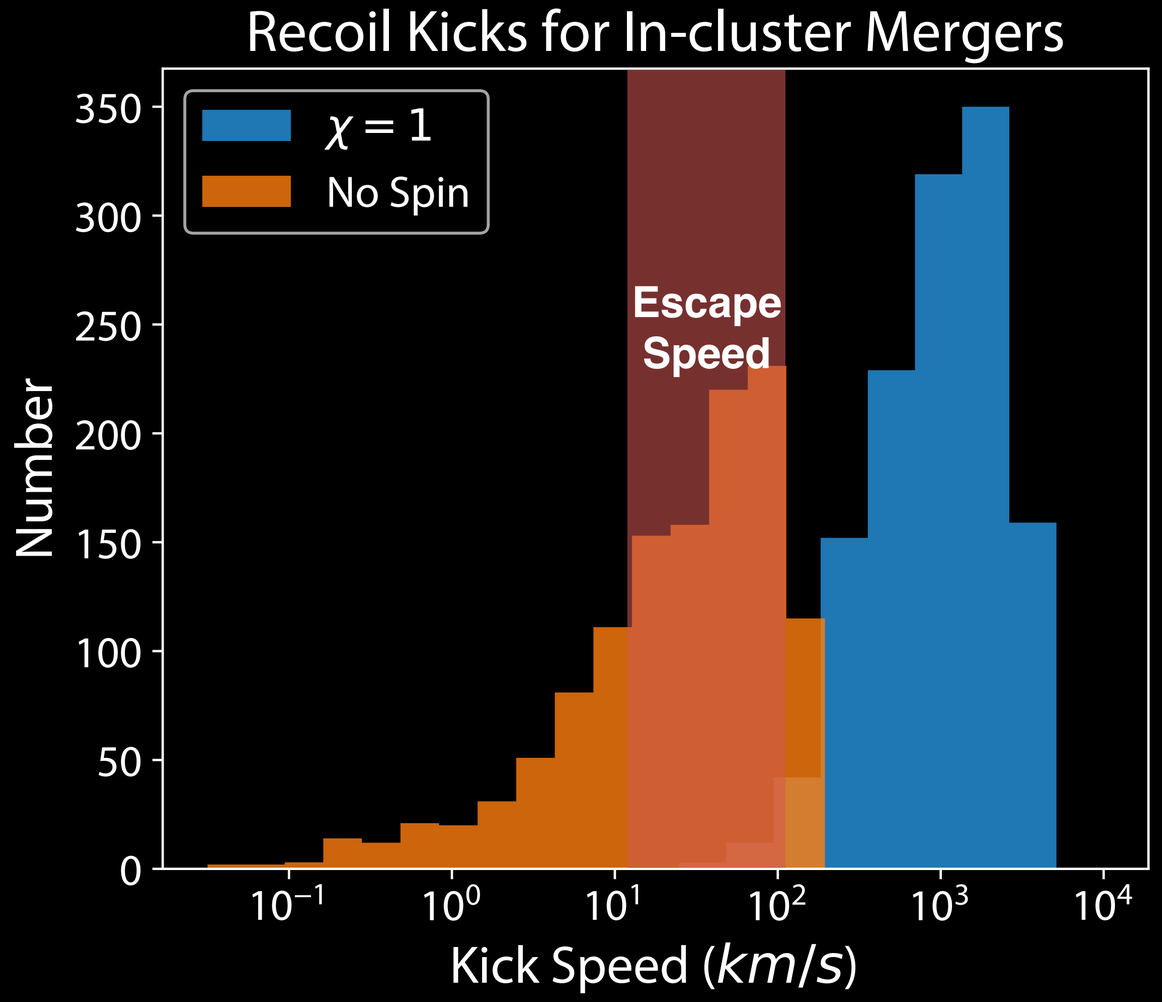

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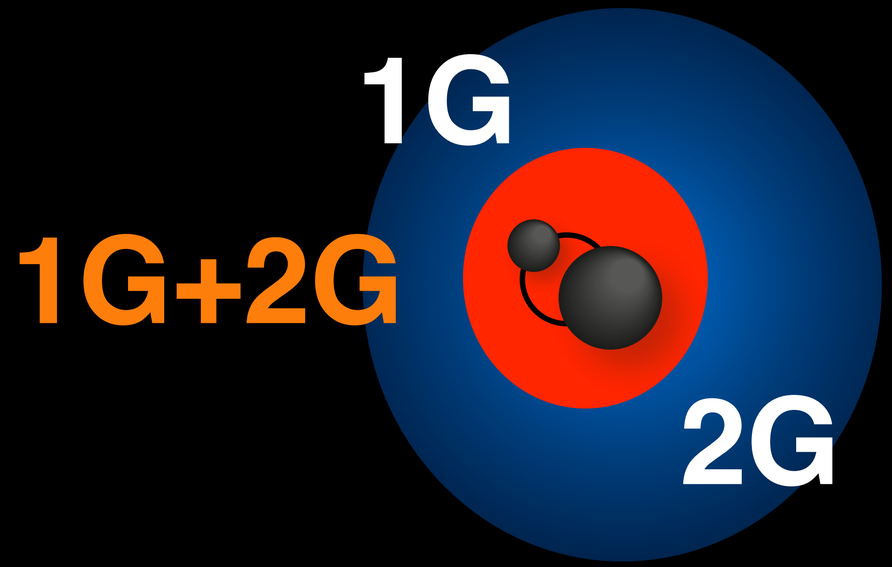


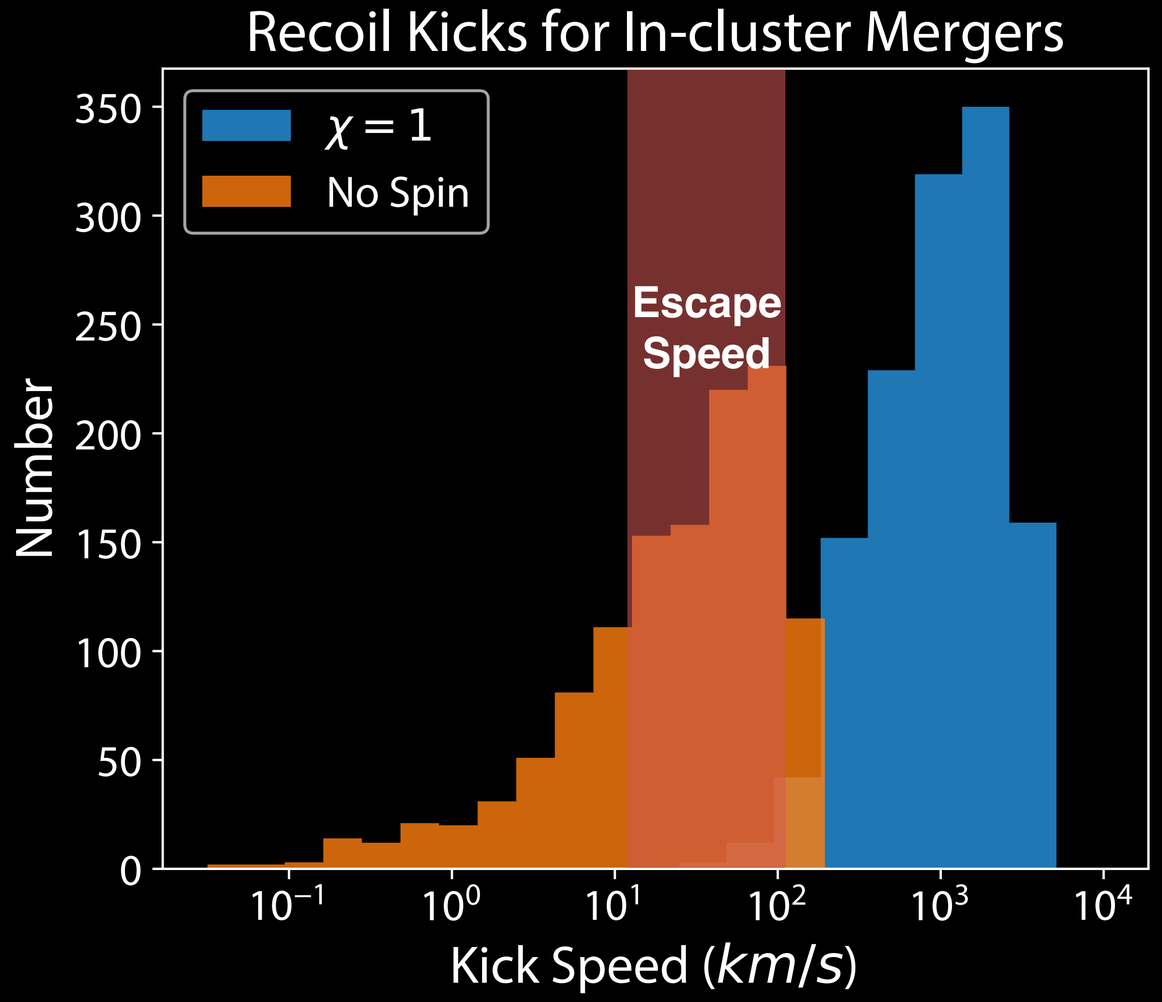

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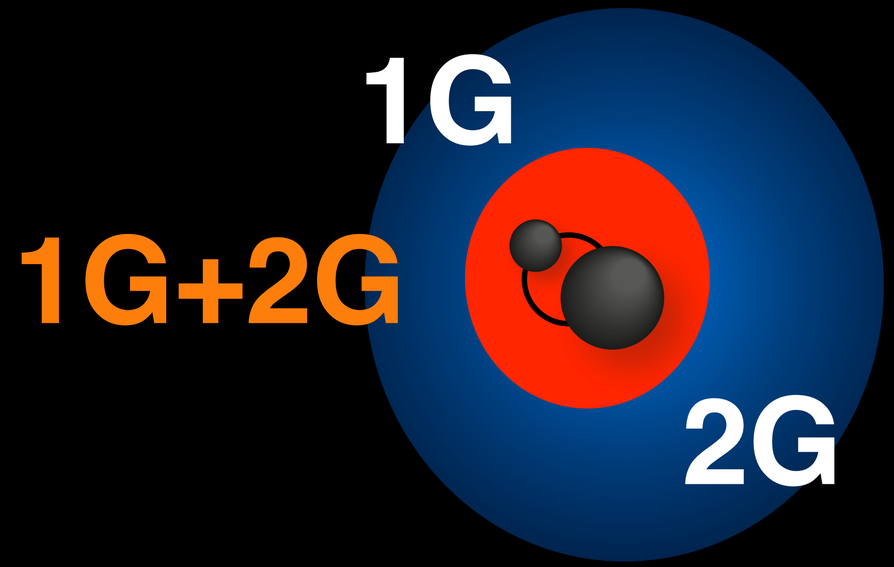


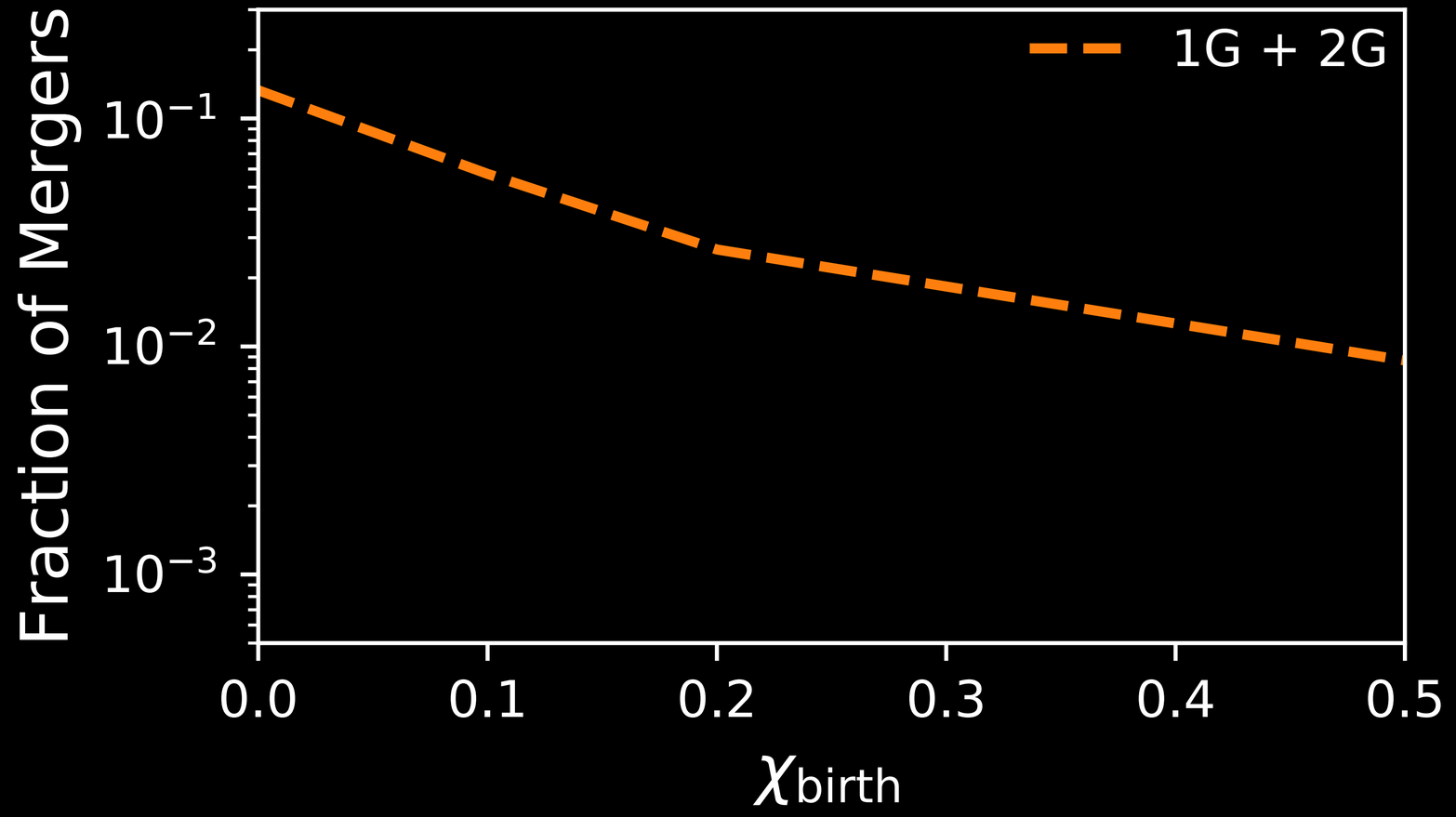

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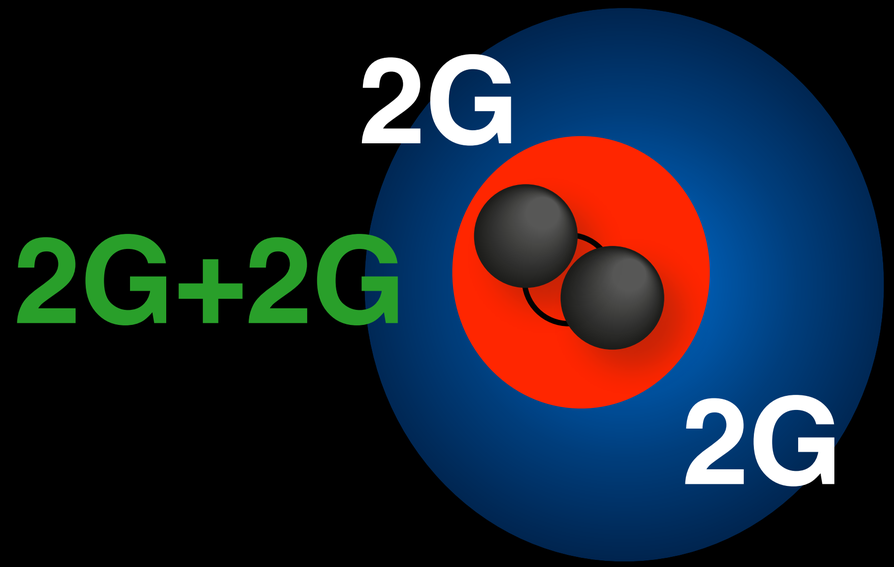


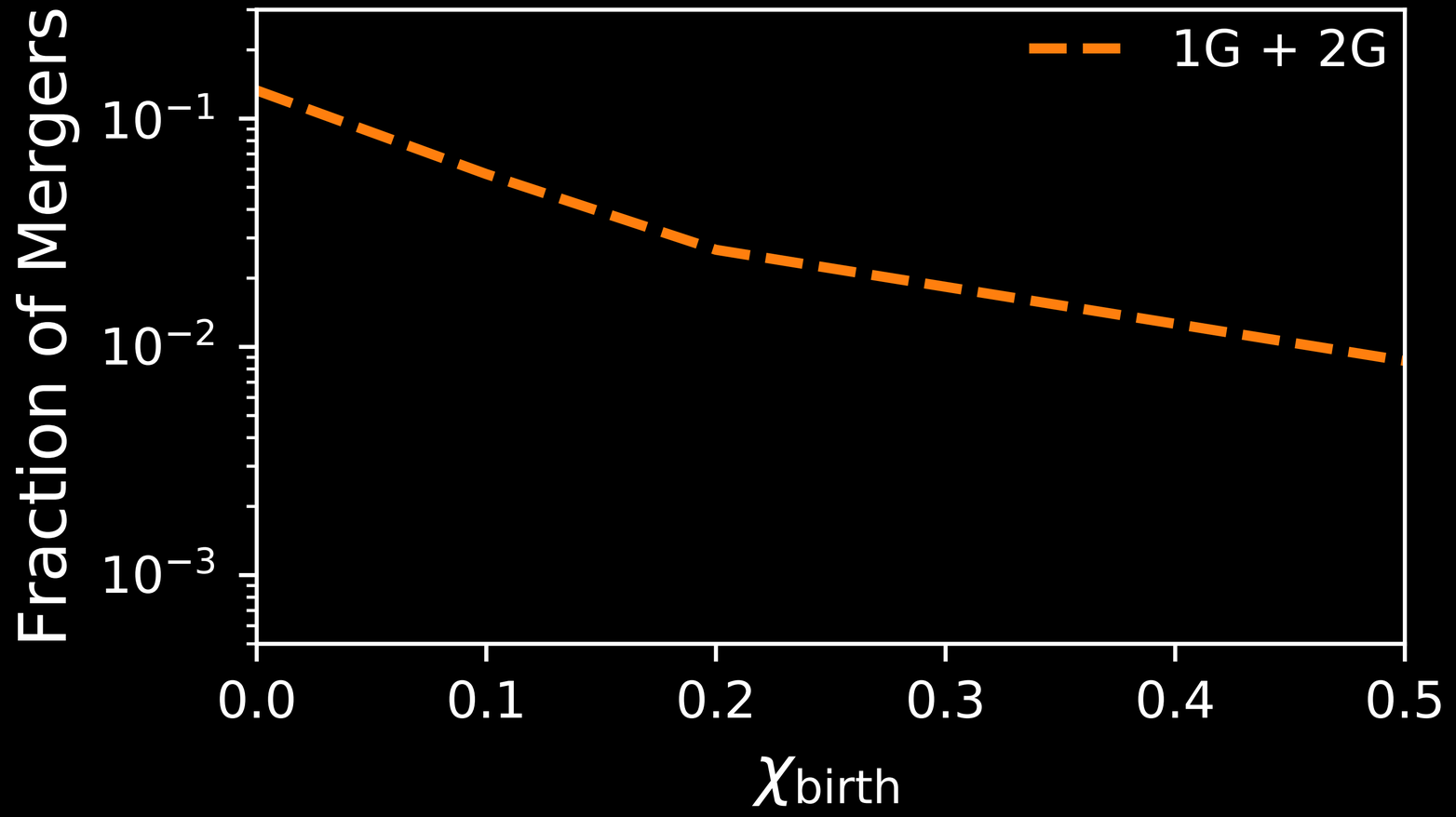

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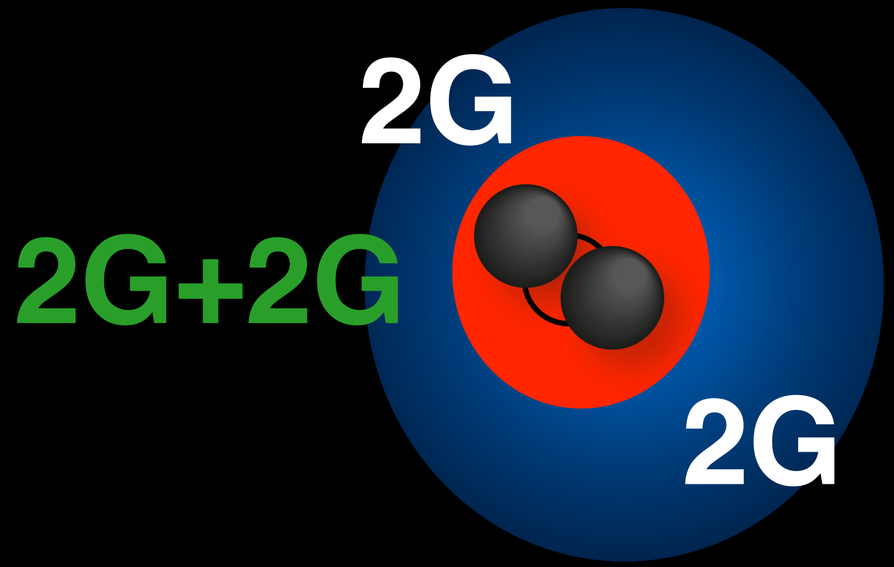


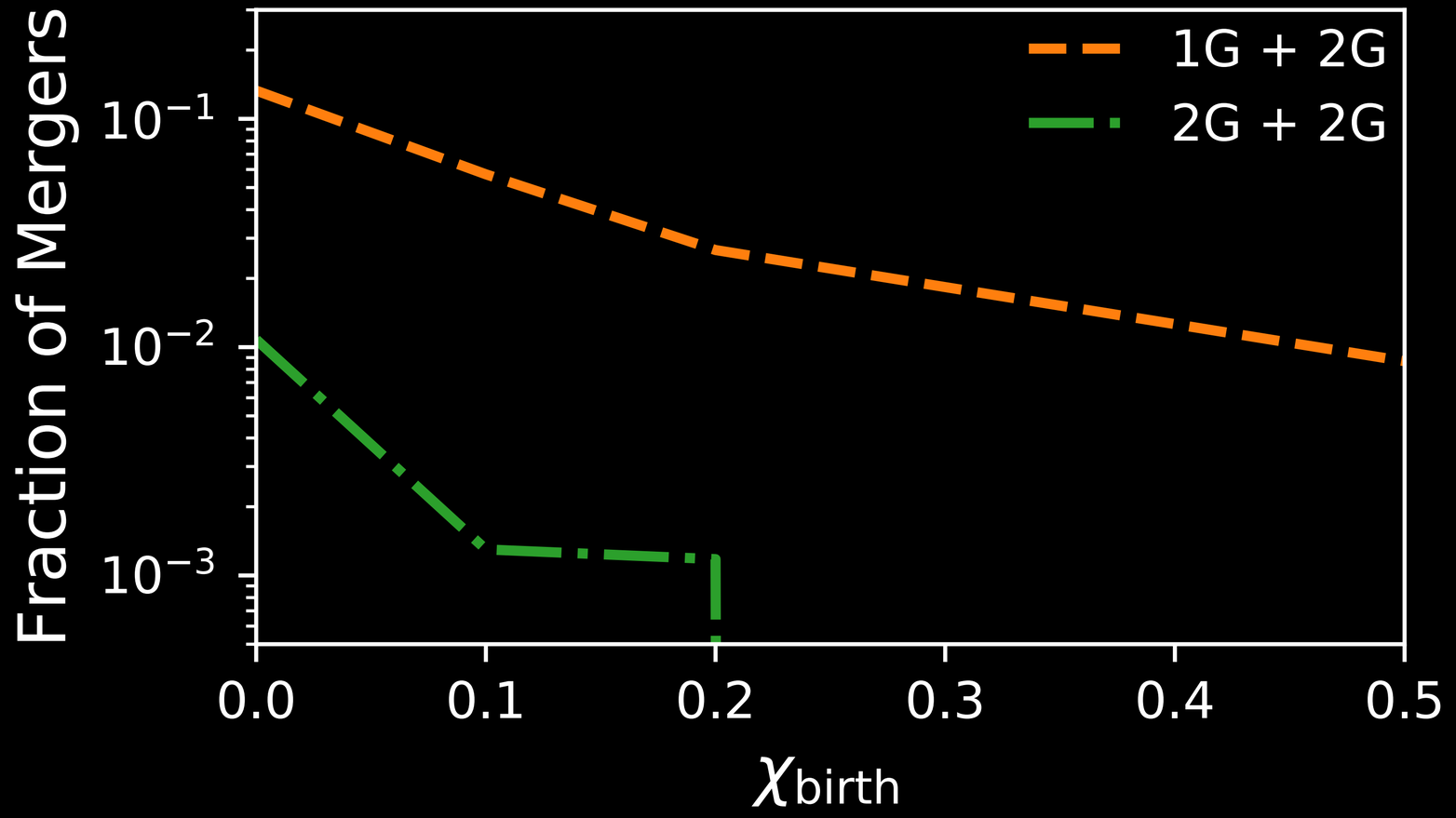

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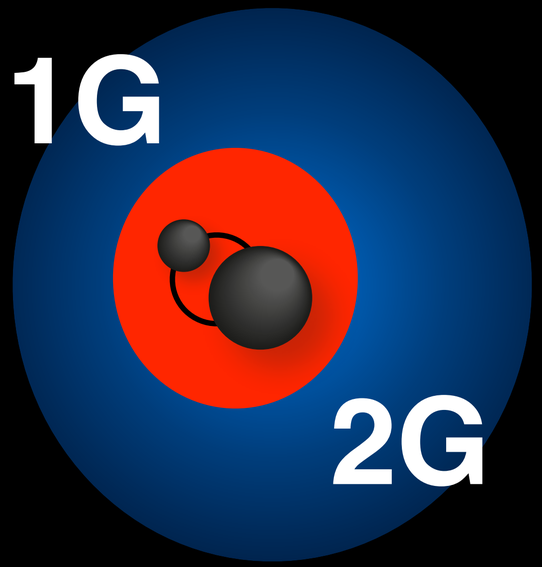


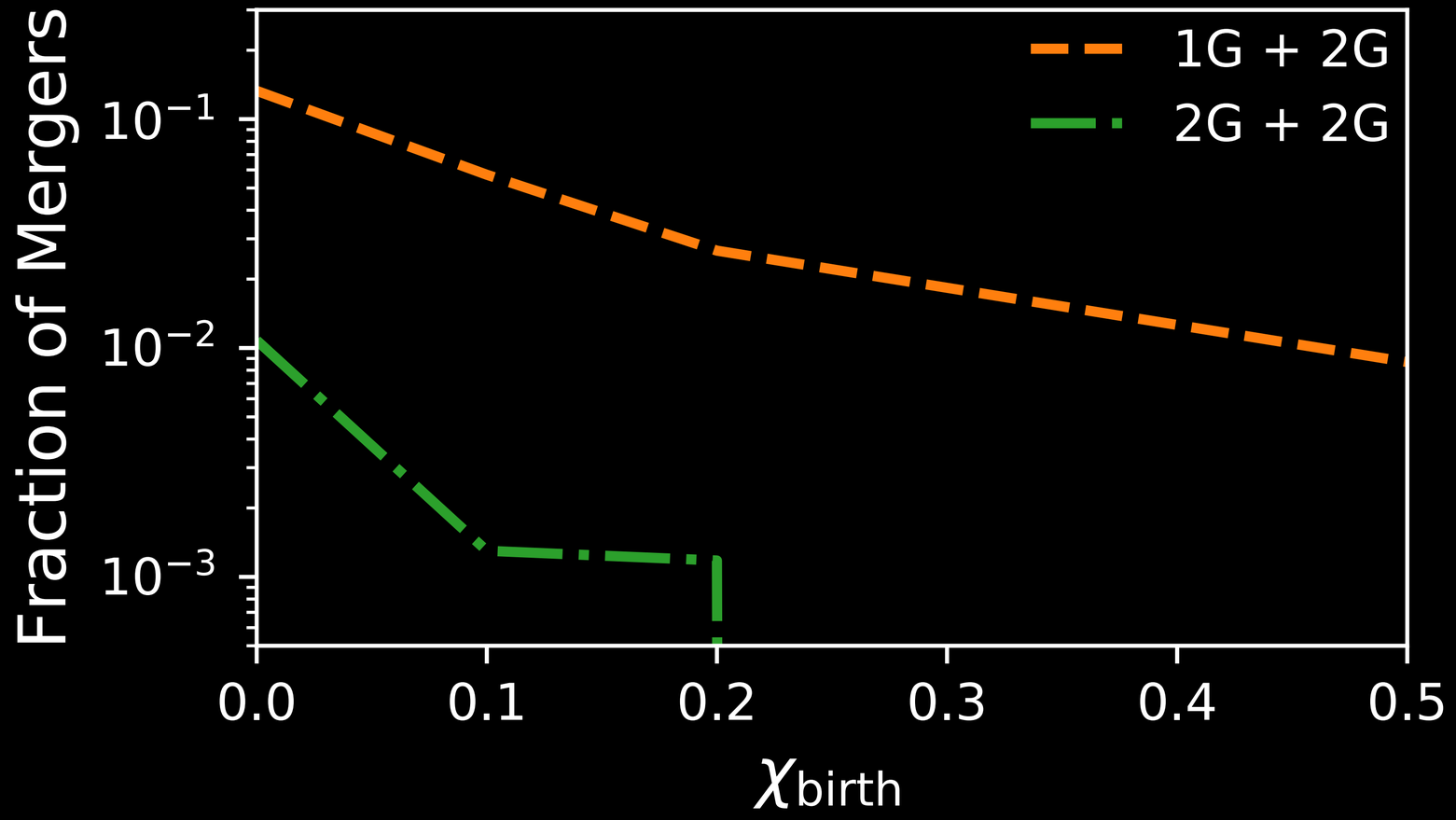

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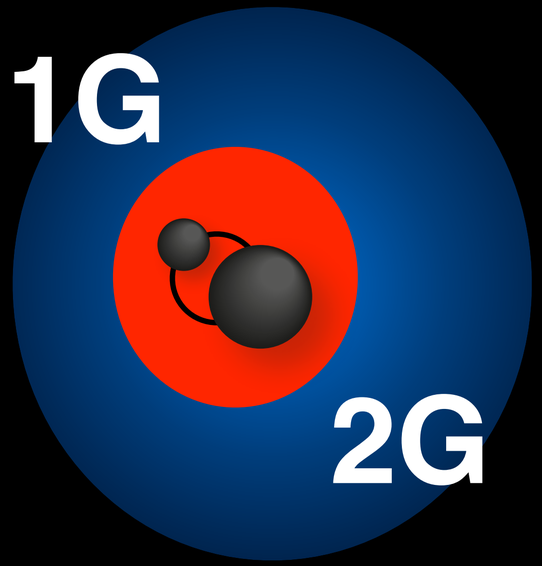


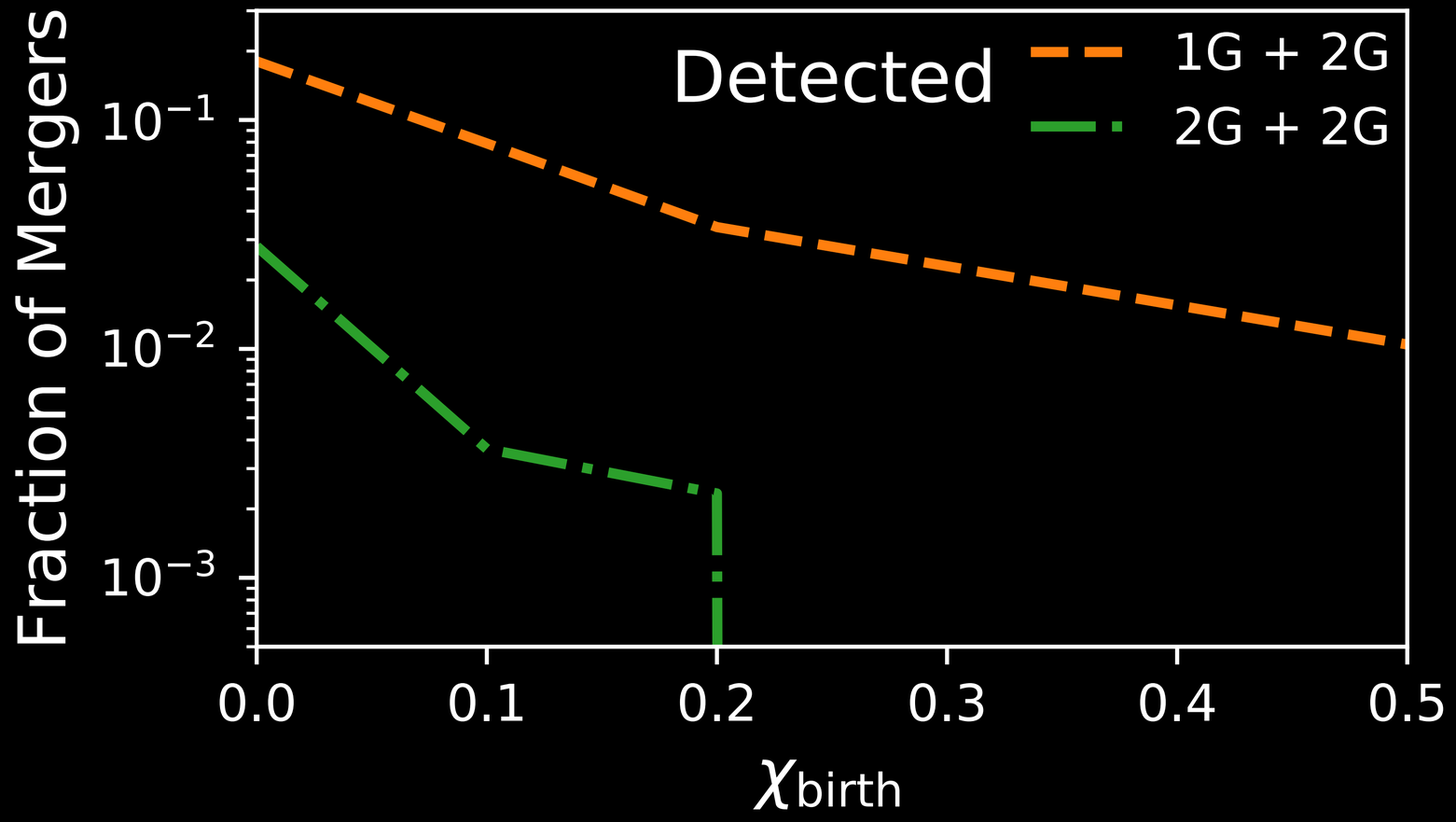

# Multiple Mergers

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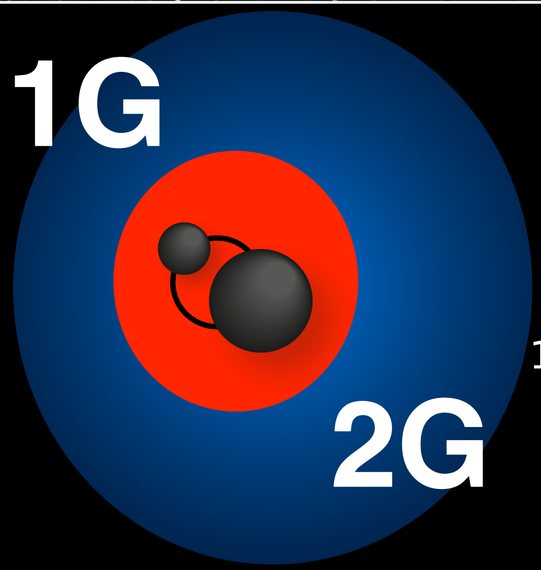
MIT KAVLI INSTITUTE




$\chi_{\rm birth} = 0.0$

Actual Distribution ($z < 1$)

Detected Distribution

All Mergers

$10^{-1}$

$10^{-2}$

$10^{-3}$

20 40 60 80 100 120 140 160

Total Mass ($M_\odot$)

20 40 60 80 100 120 140 160

Total Mass ($M_\odot$)

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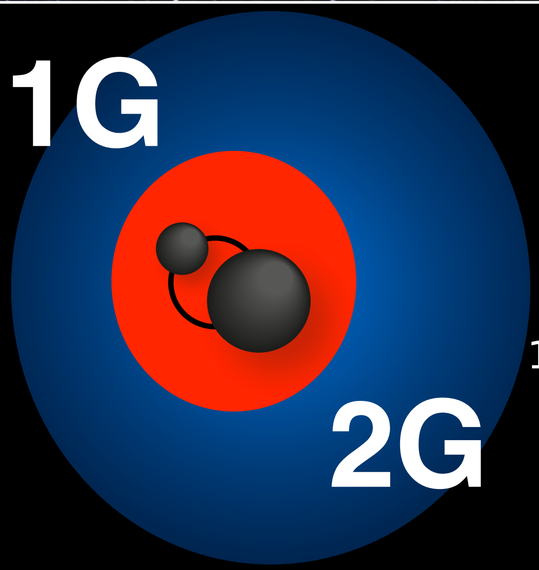


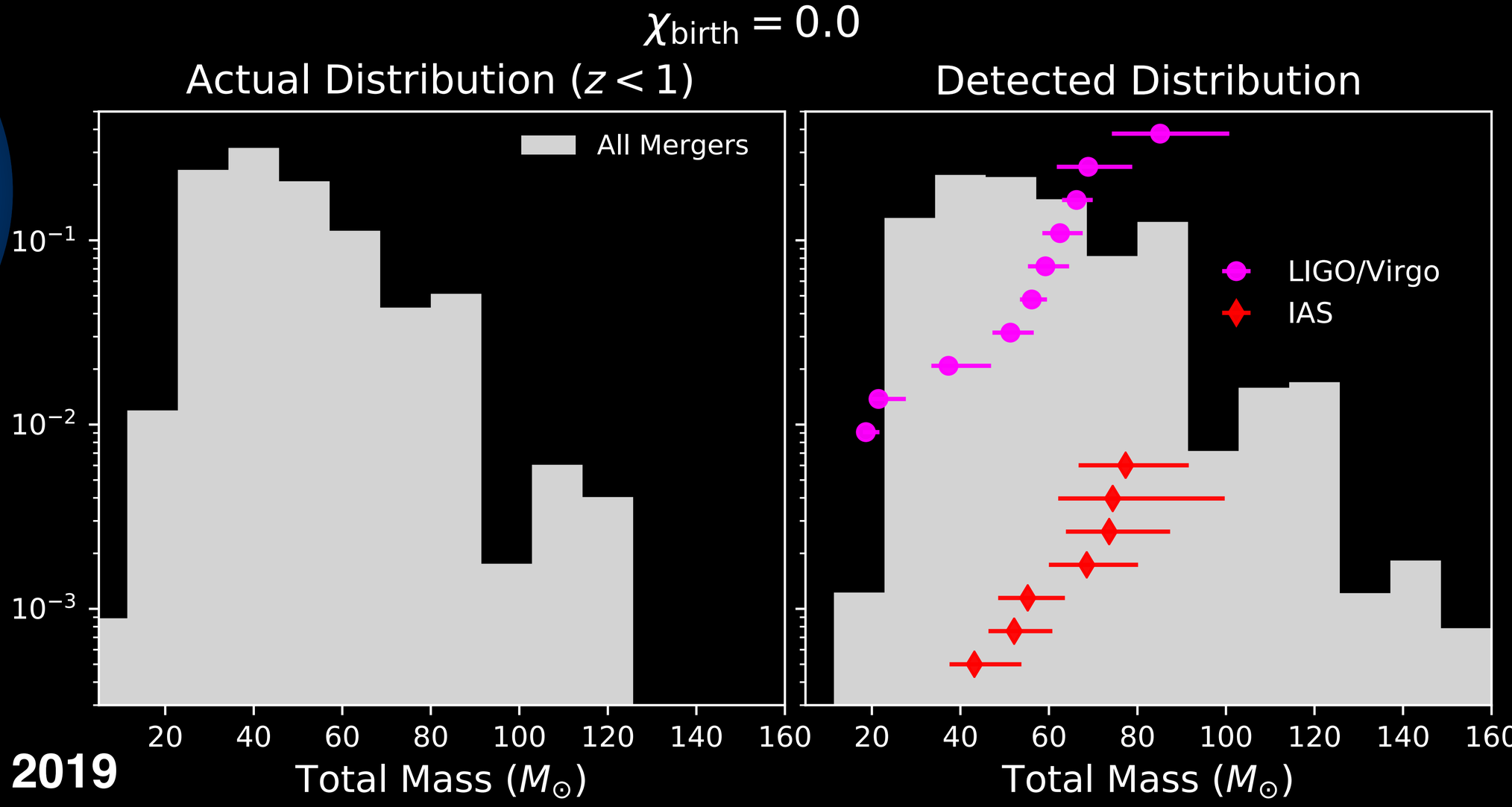


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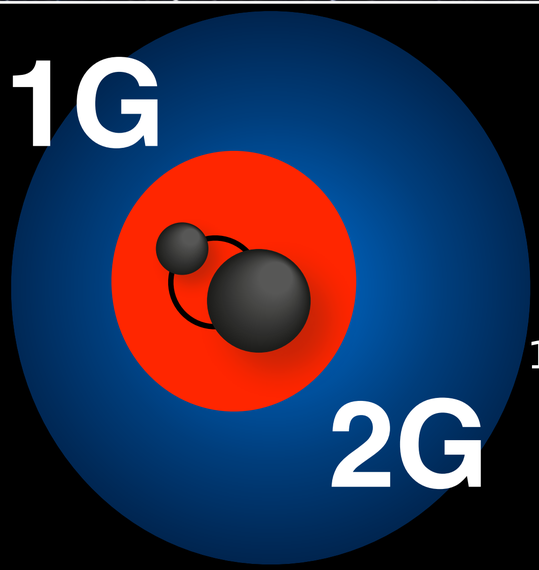


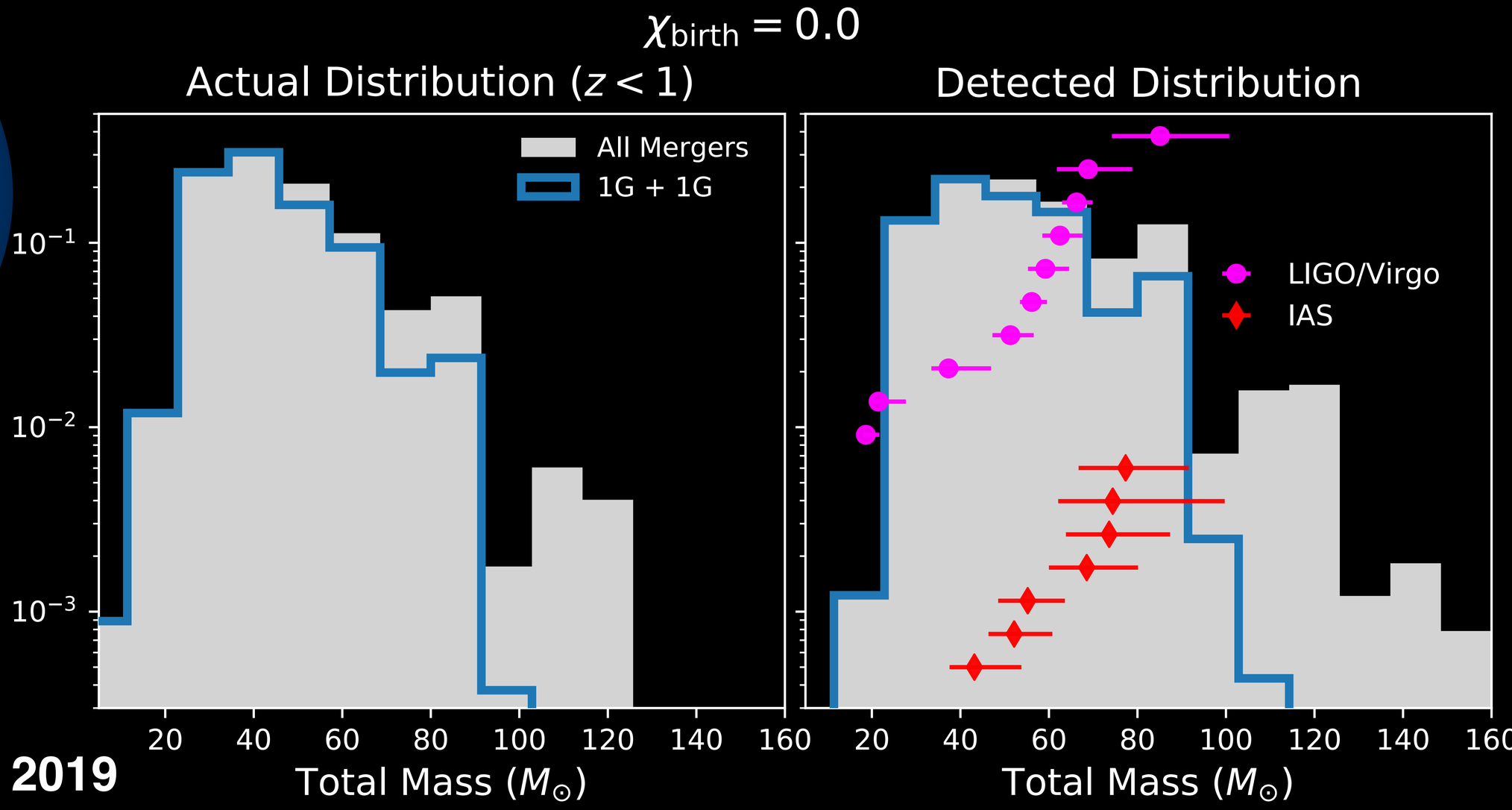


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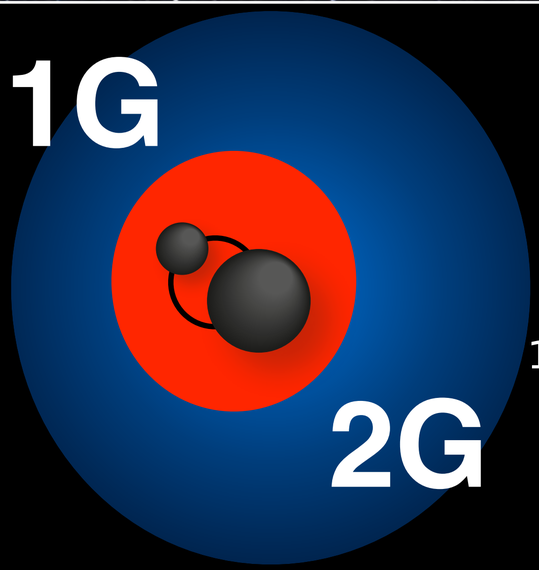
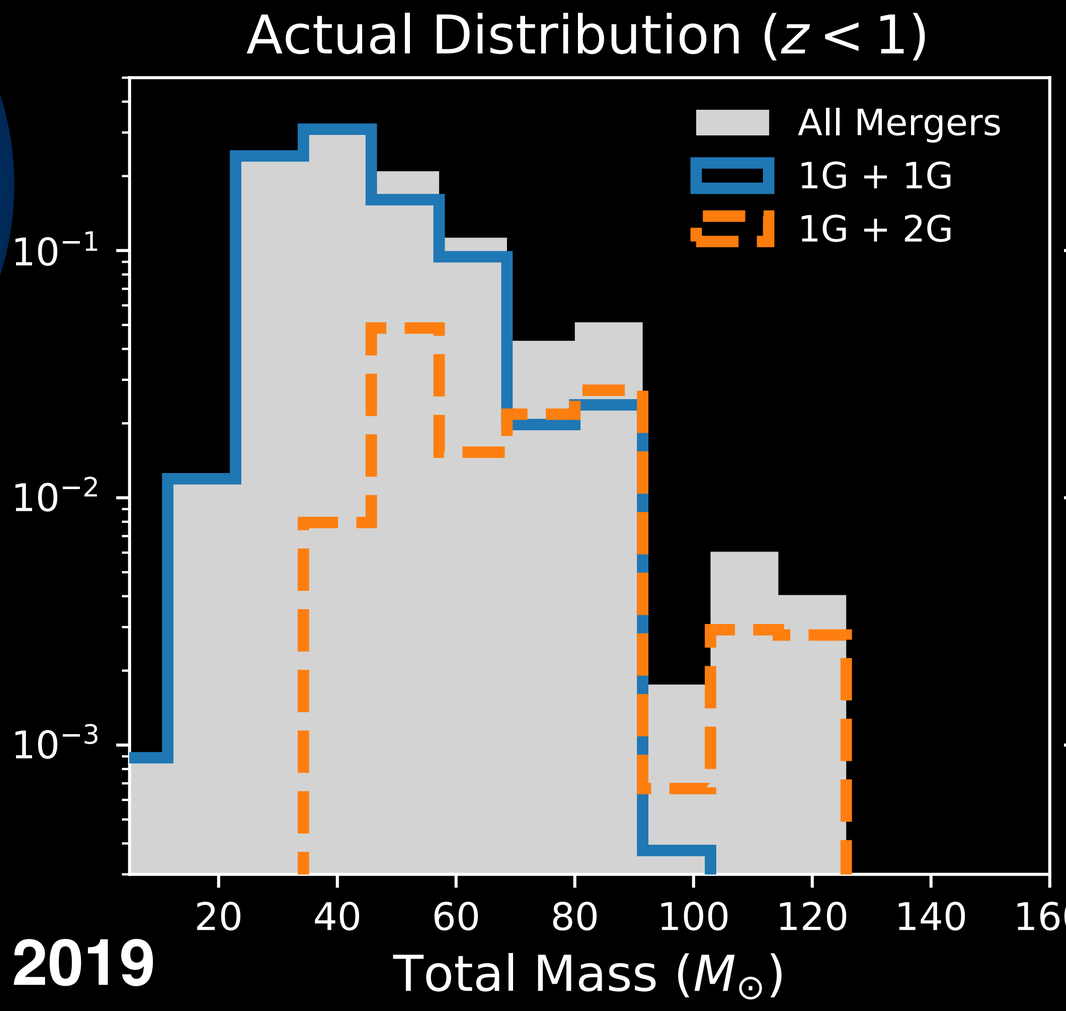
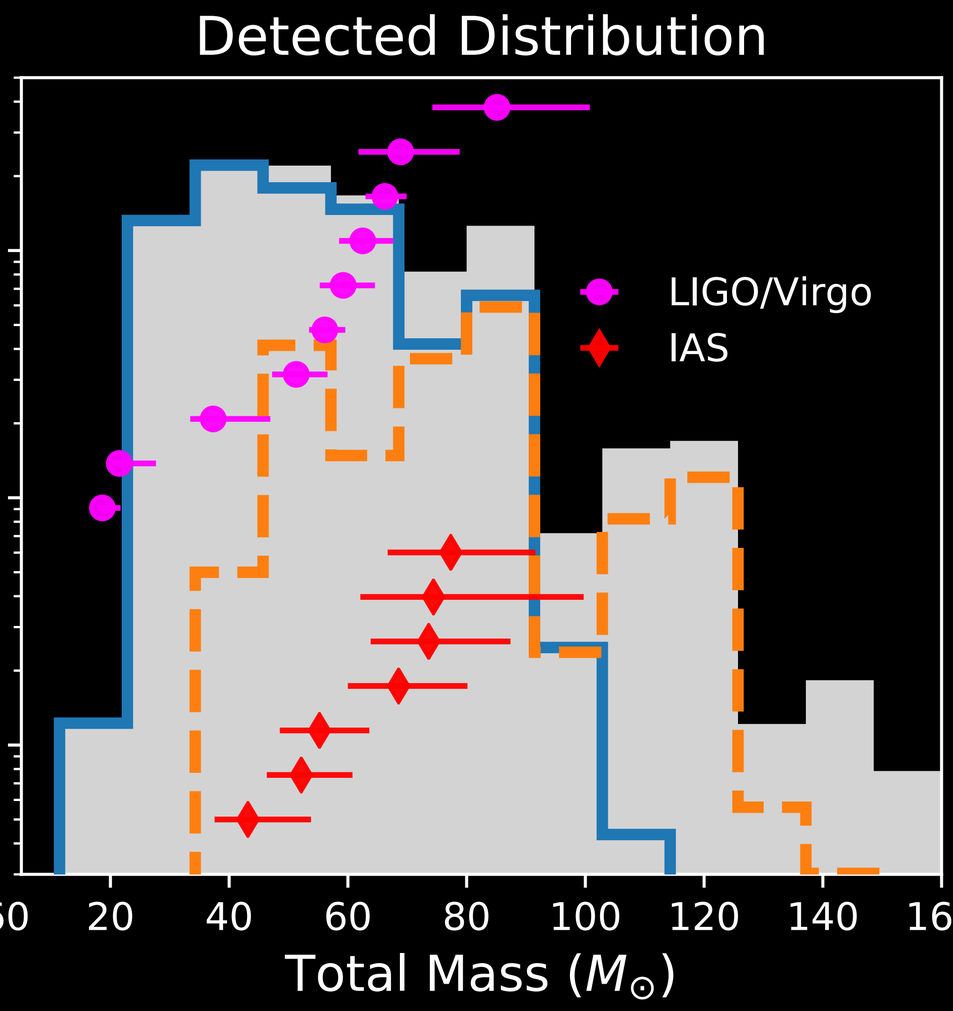



$\chi_{\rm birth} = 0.0$

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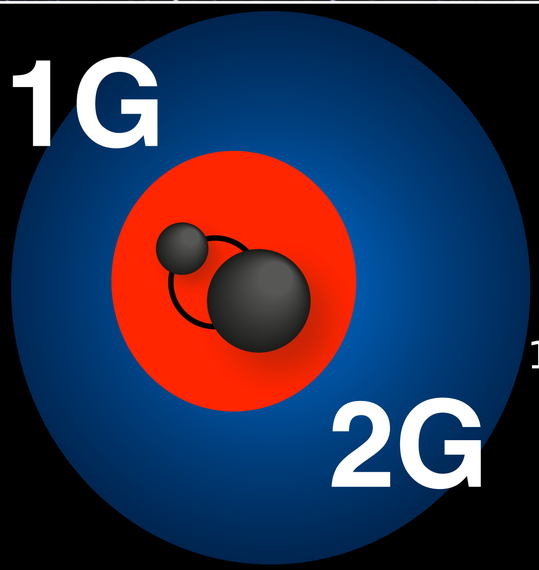


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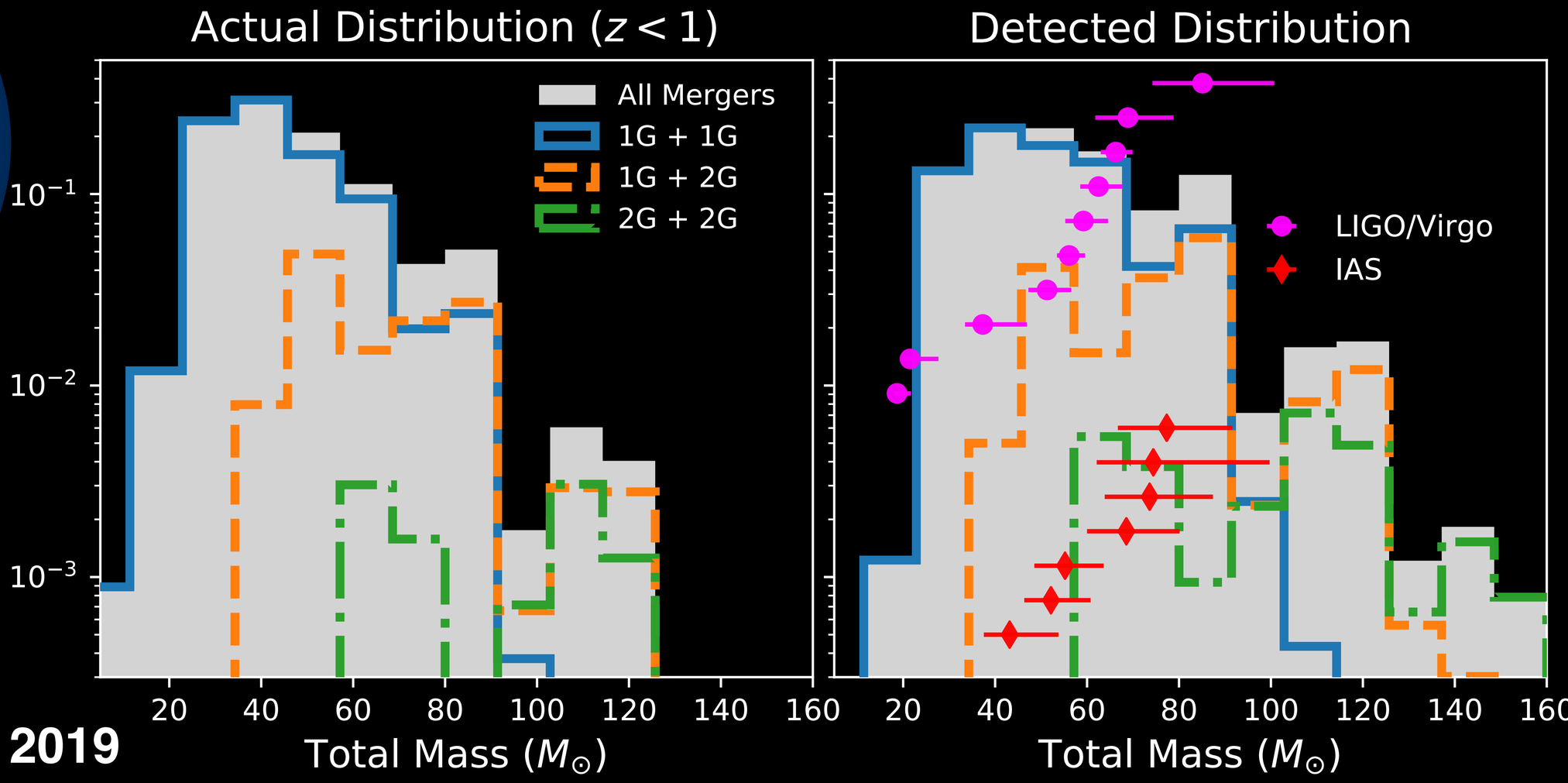


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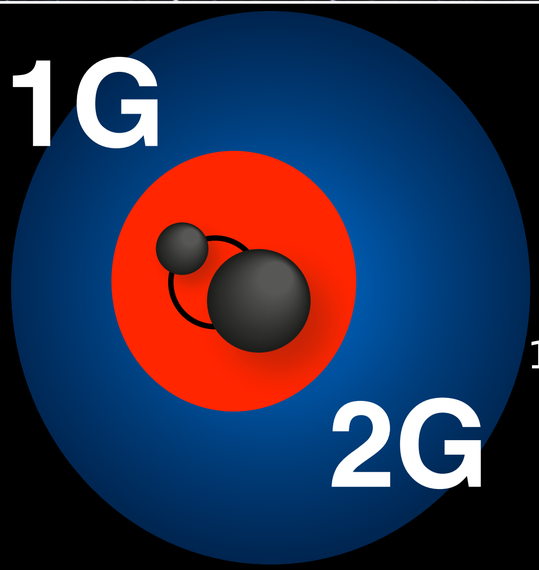
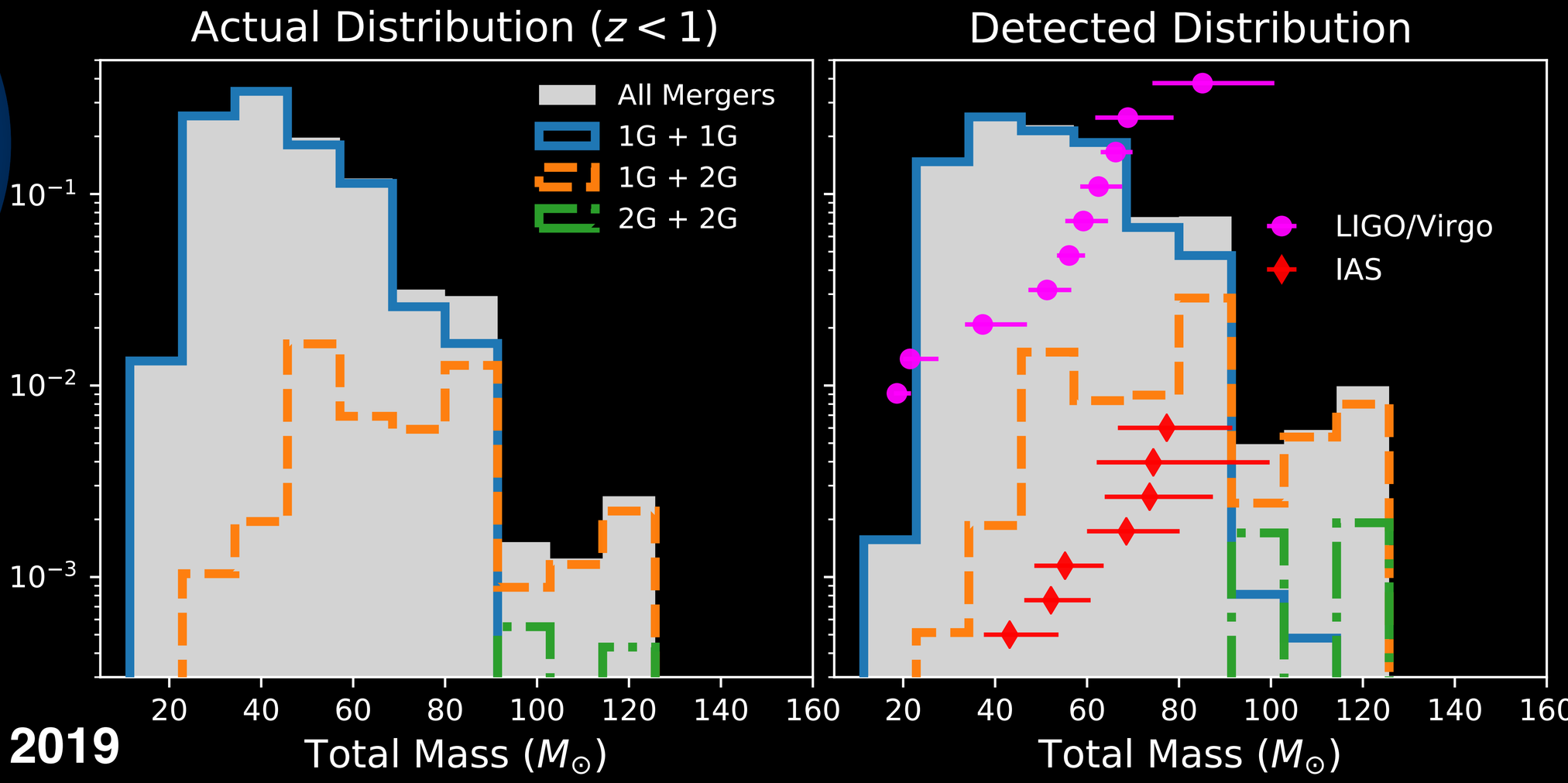



$\chi_{\rm birth} = 0.1$




**Rodriguez et al., 2019**
**PRD, 100, 043027**

# Multiple Mergers

CARL RODRIGUEZ
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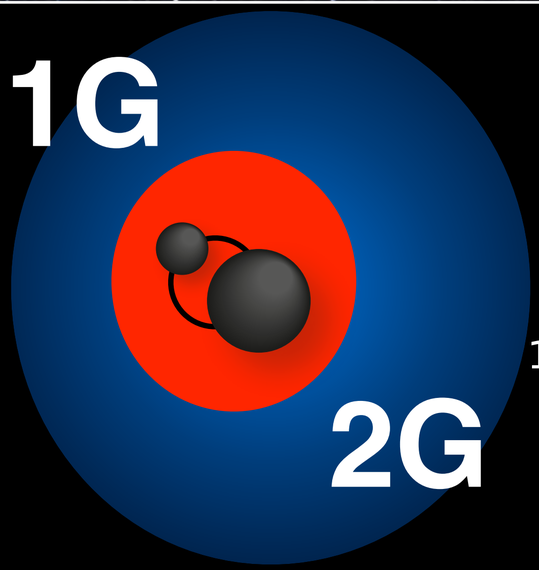
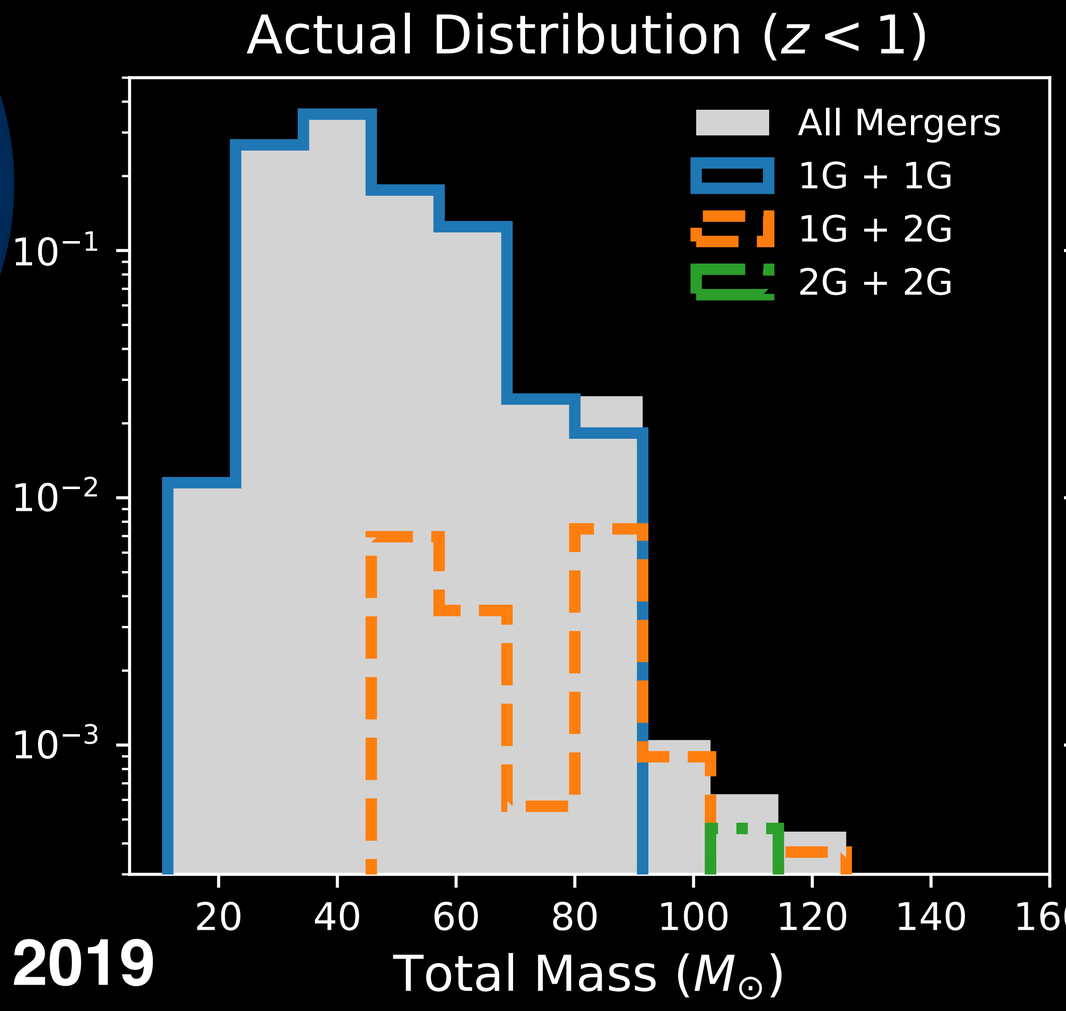
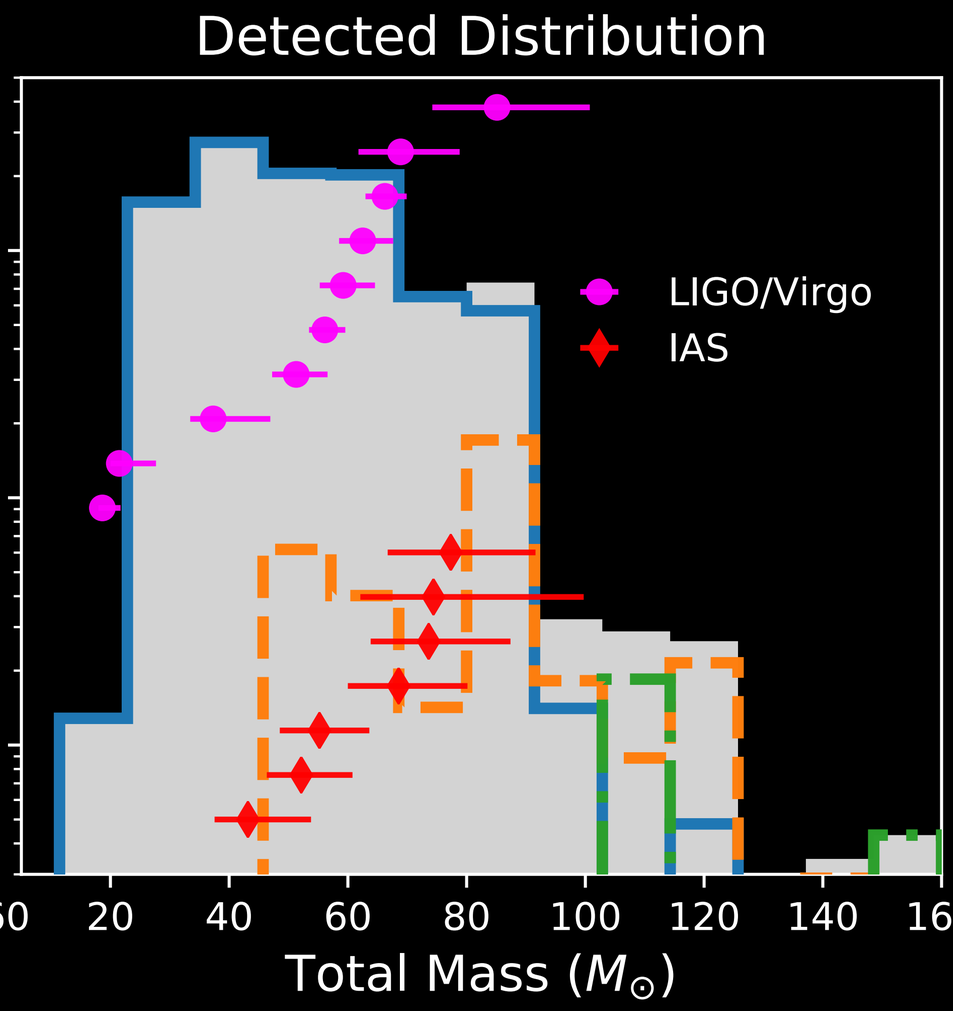
HARVARD & SMITHSONIAN




$\chi_{\rm birth} = 0.2$




**Rodriguez et al., 2019**
**PRD, 100, 043027**

# Multiple Mergers

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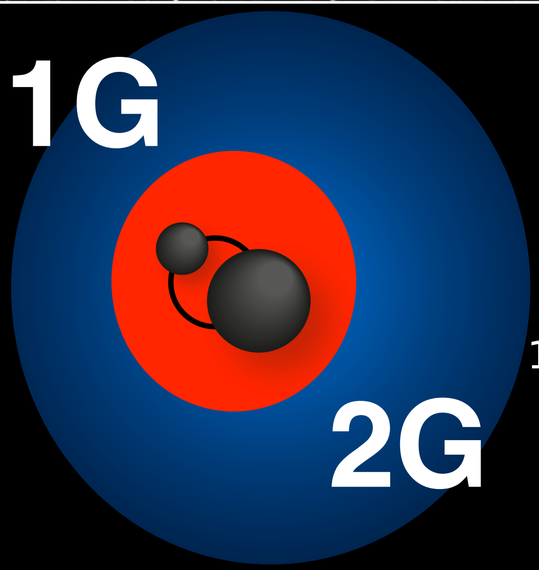
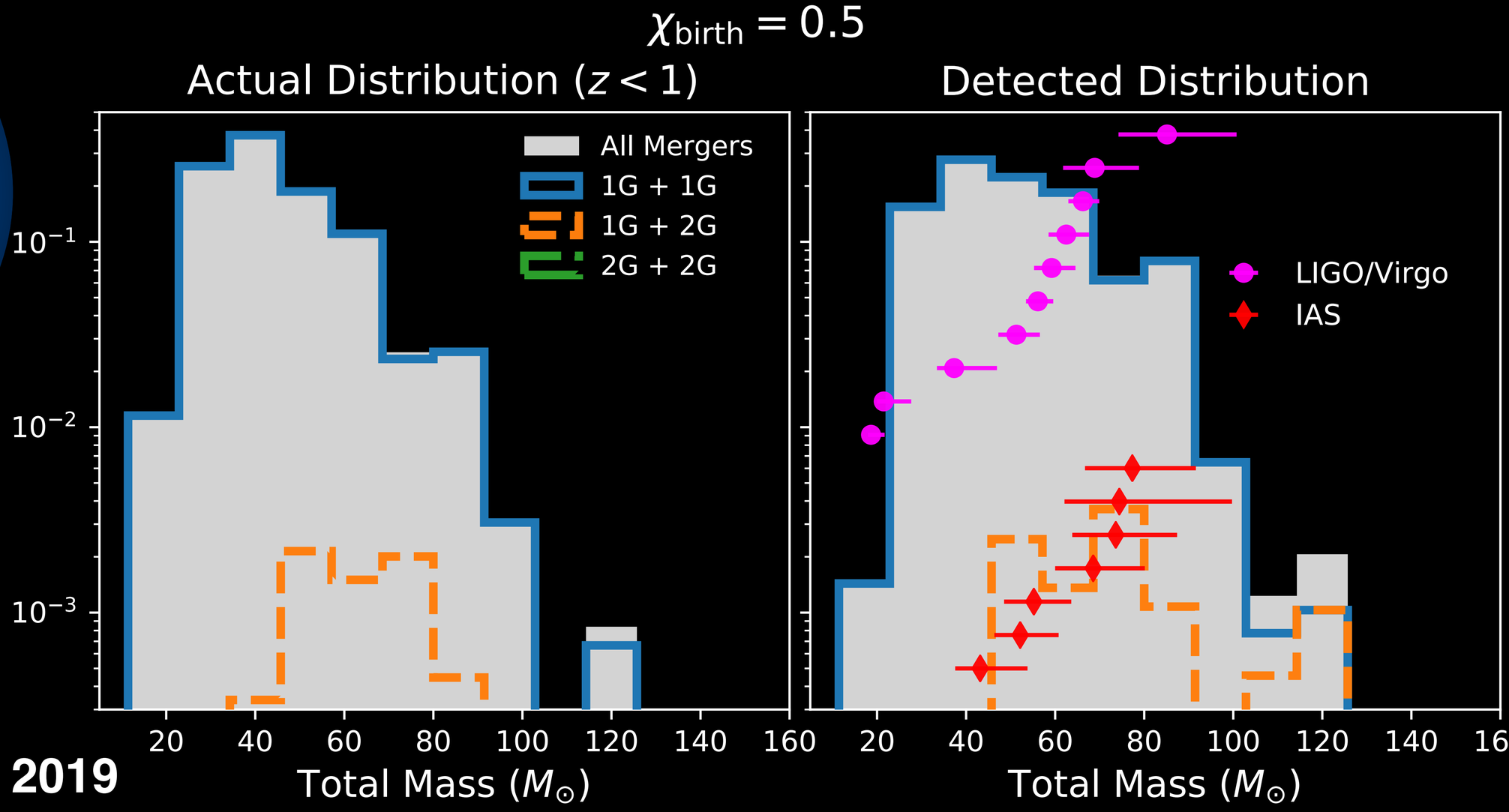
HARVARD & SMITHSONIAN




**Rodriguez et al., 2019**
**PRD, 100, 043027**

# Multiple Mergers

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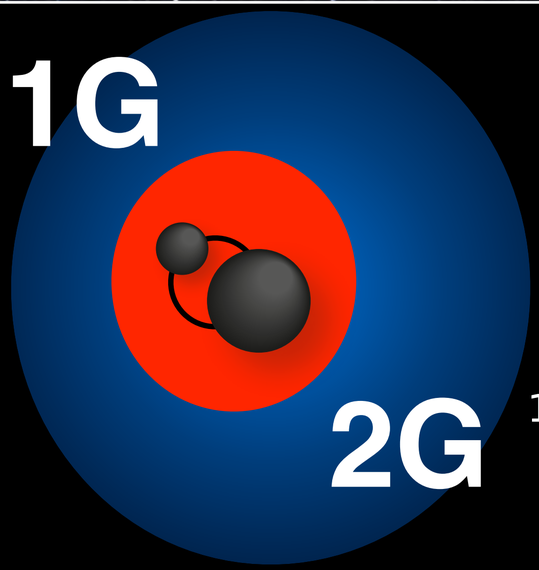
HARVARD & SMITHSONIAN

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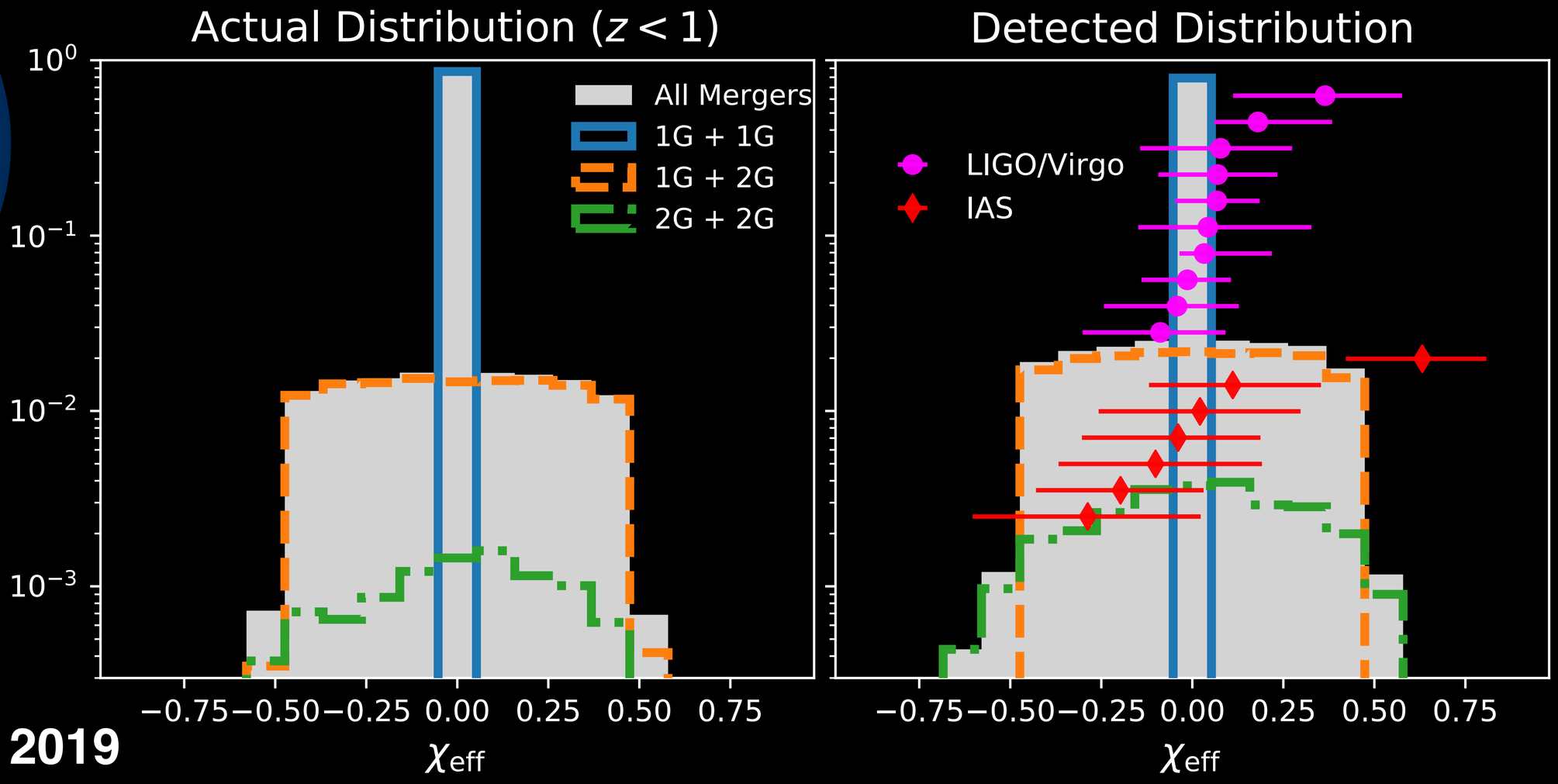


**Rodriguez et al., 2019**
**PRD, 100, 043027**

# Multiple Mergers

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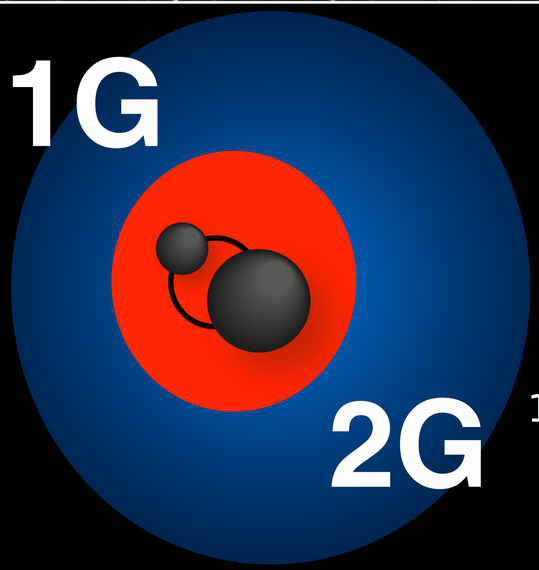
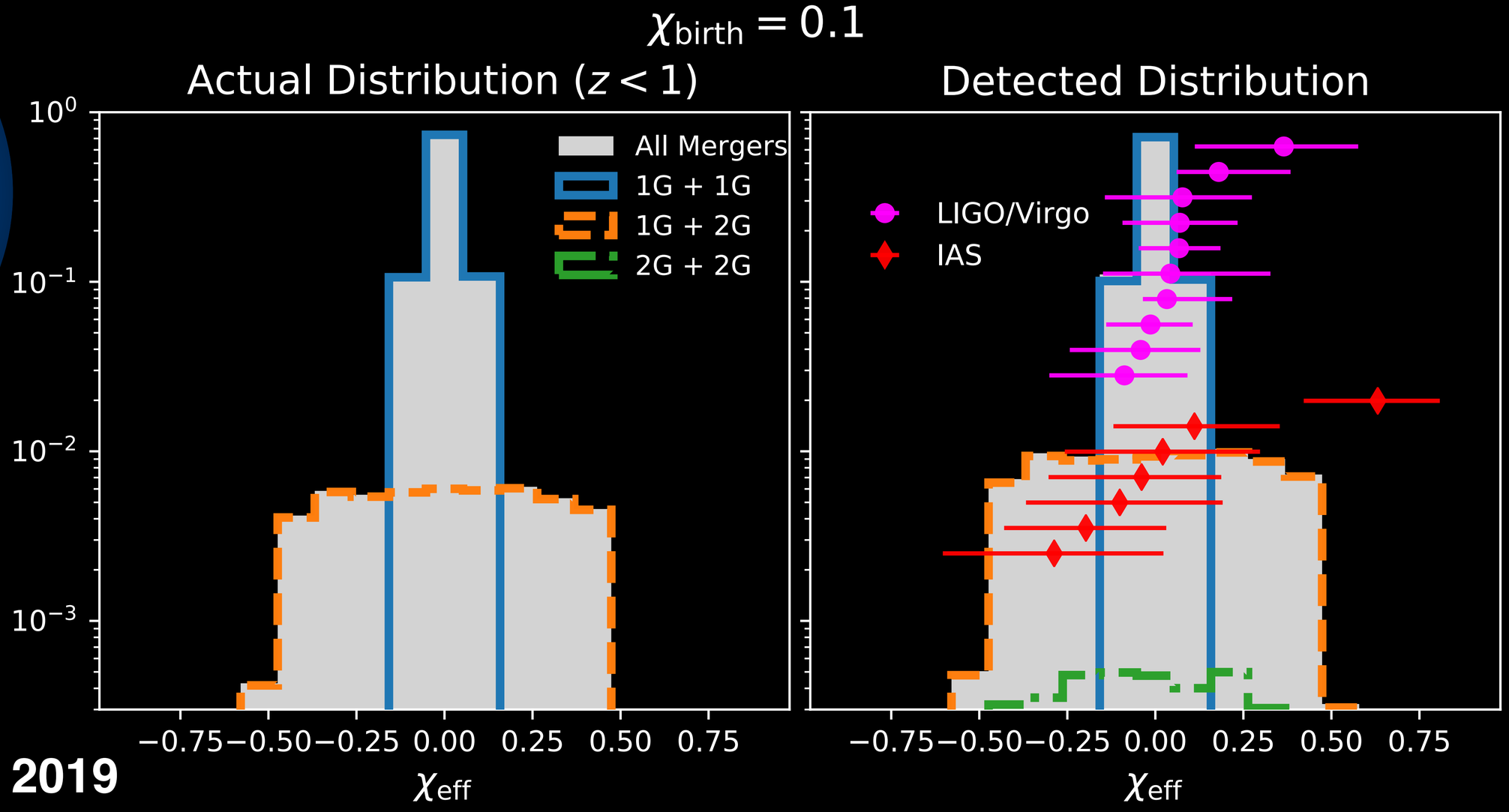
HARVARD & SMITHSONIAN




**Rodriguez et al., 2019**
**PRD, 100, 043027**

# Multiple Mergers

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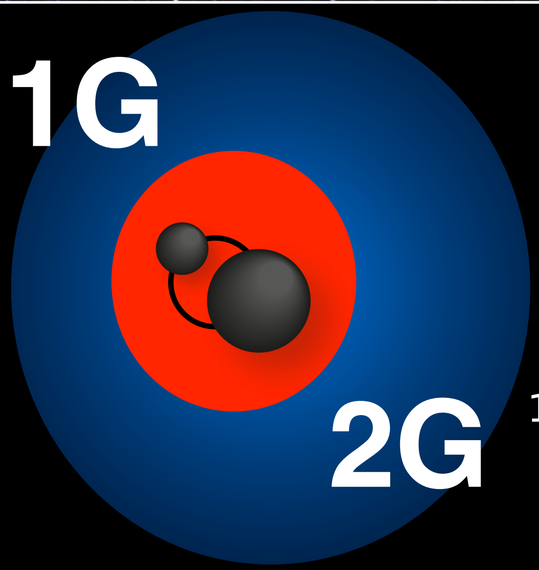
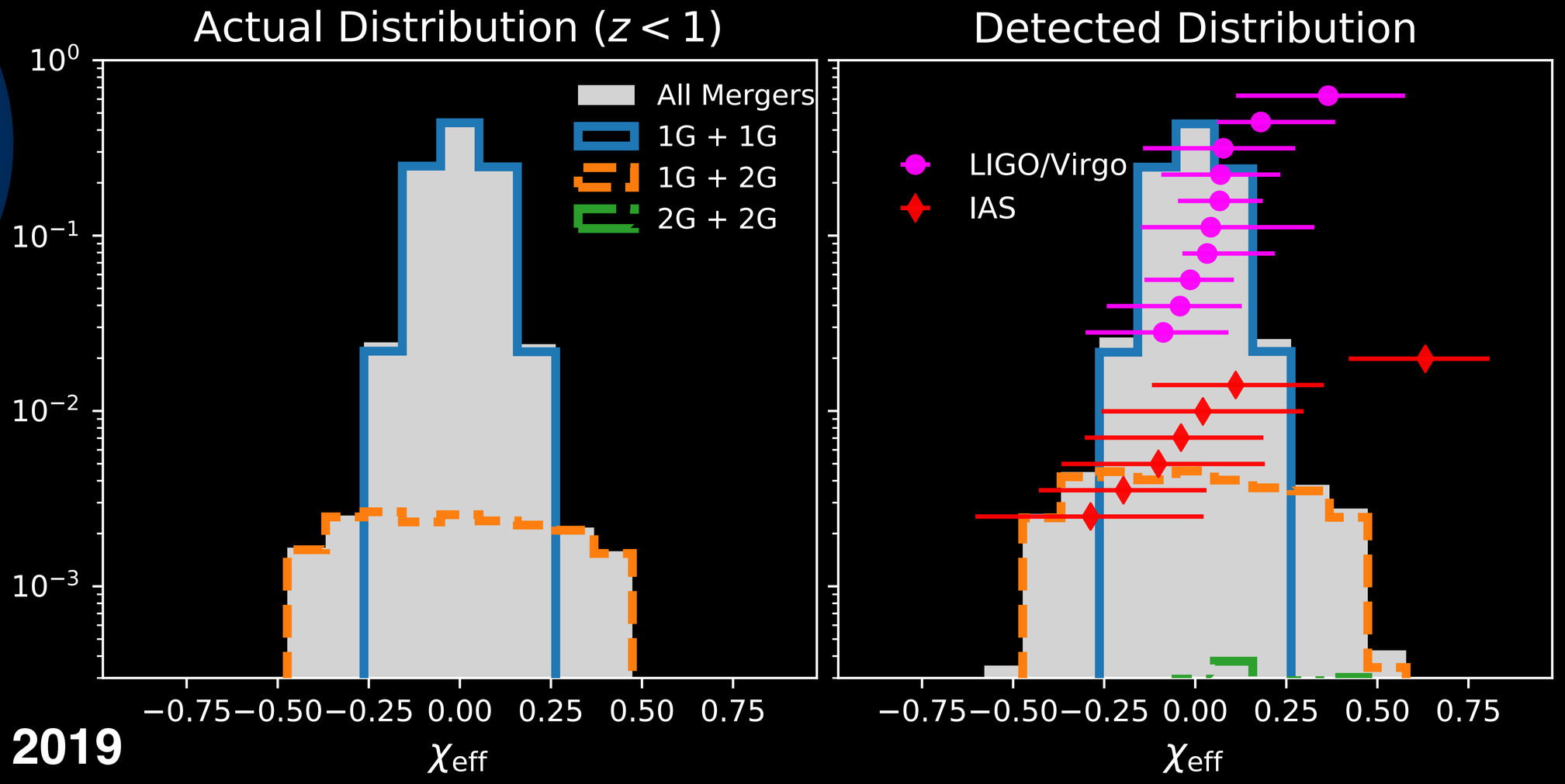
HARVARD & SMITHSONIAN




$\chi_{\rm birth} = 0.2$




**Rodriguez et al., 2019**
**PRD, 100, 043027**

# Multiple Mergers

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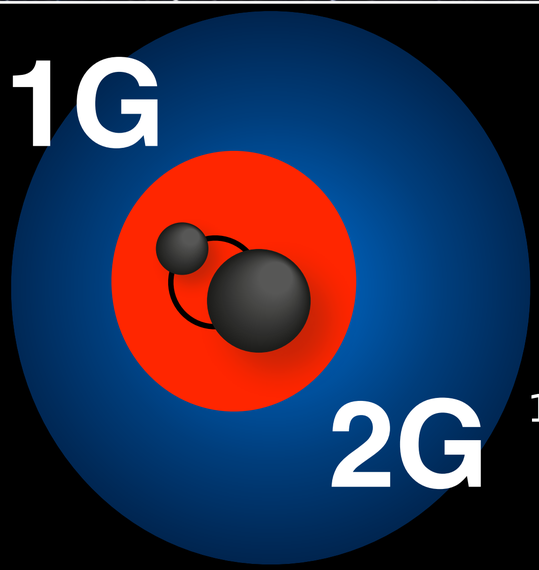
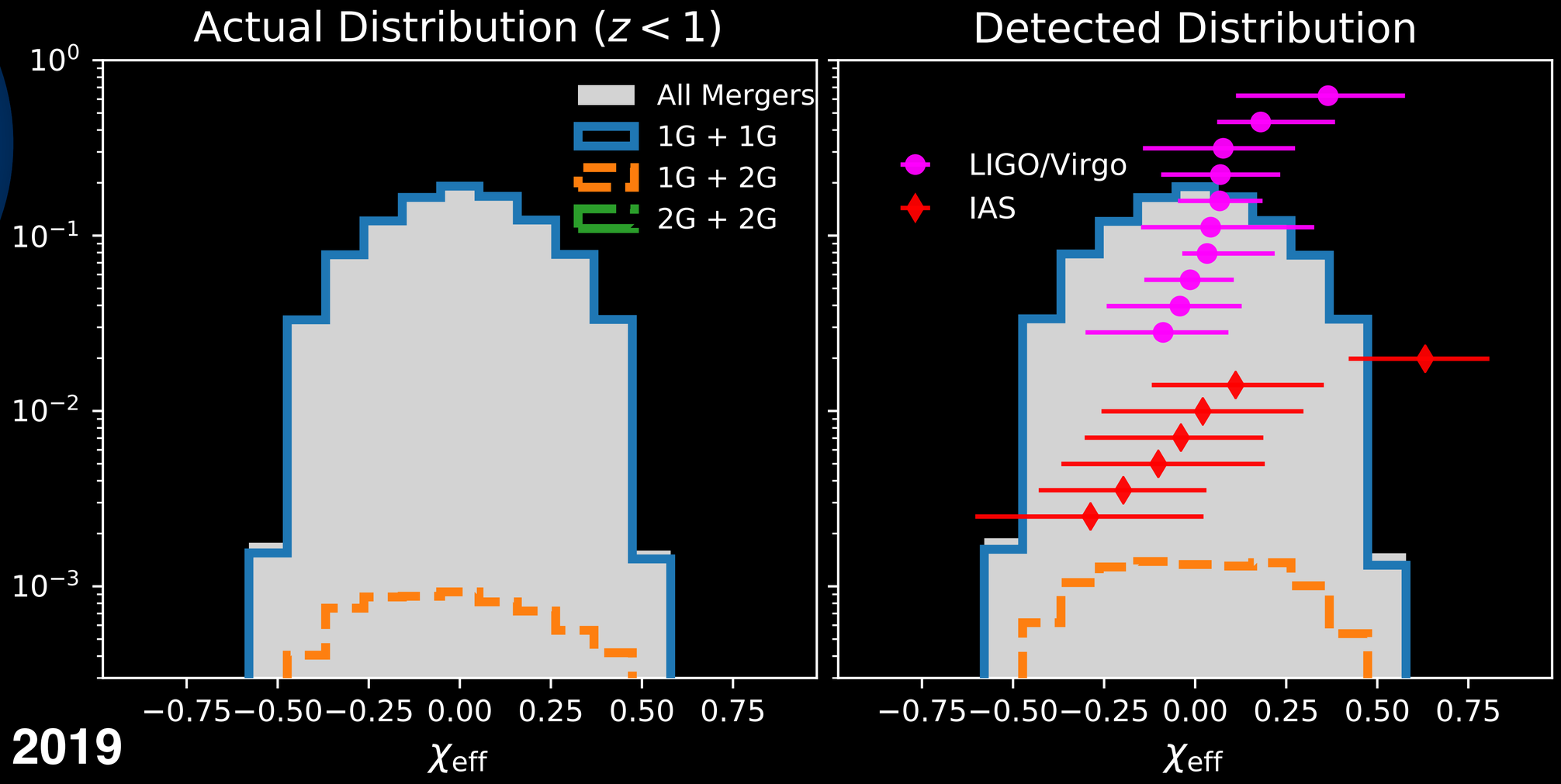
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN




$\chi_{\rm birth} = 0.5$




**Rodriguez et al., 2019**
**PRD, 100, 043027**

# Multiple Mergers

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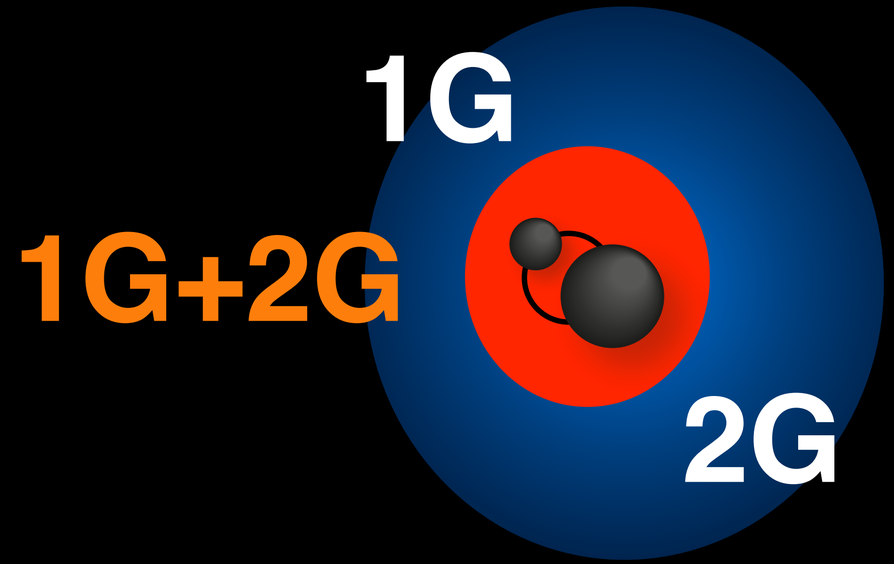
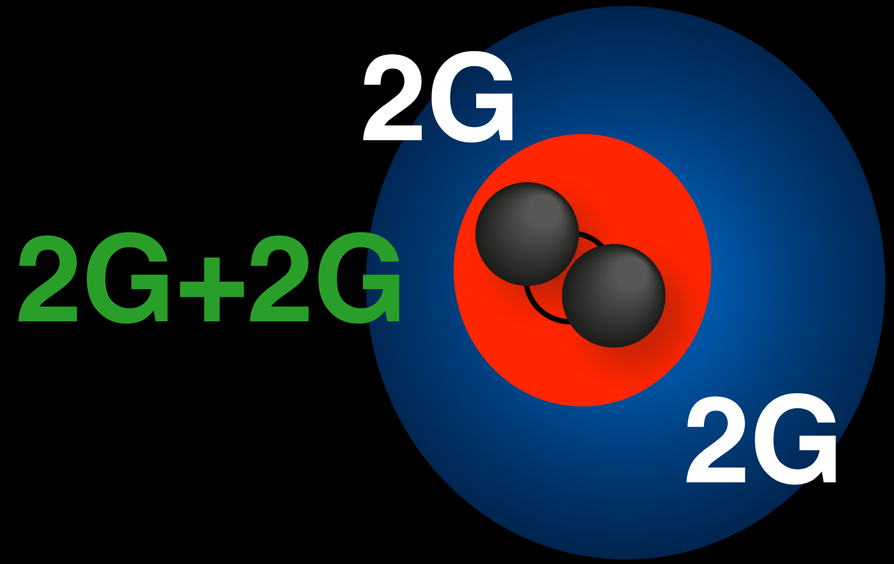
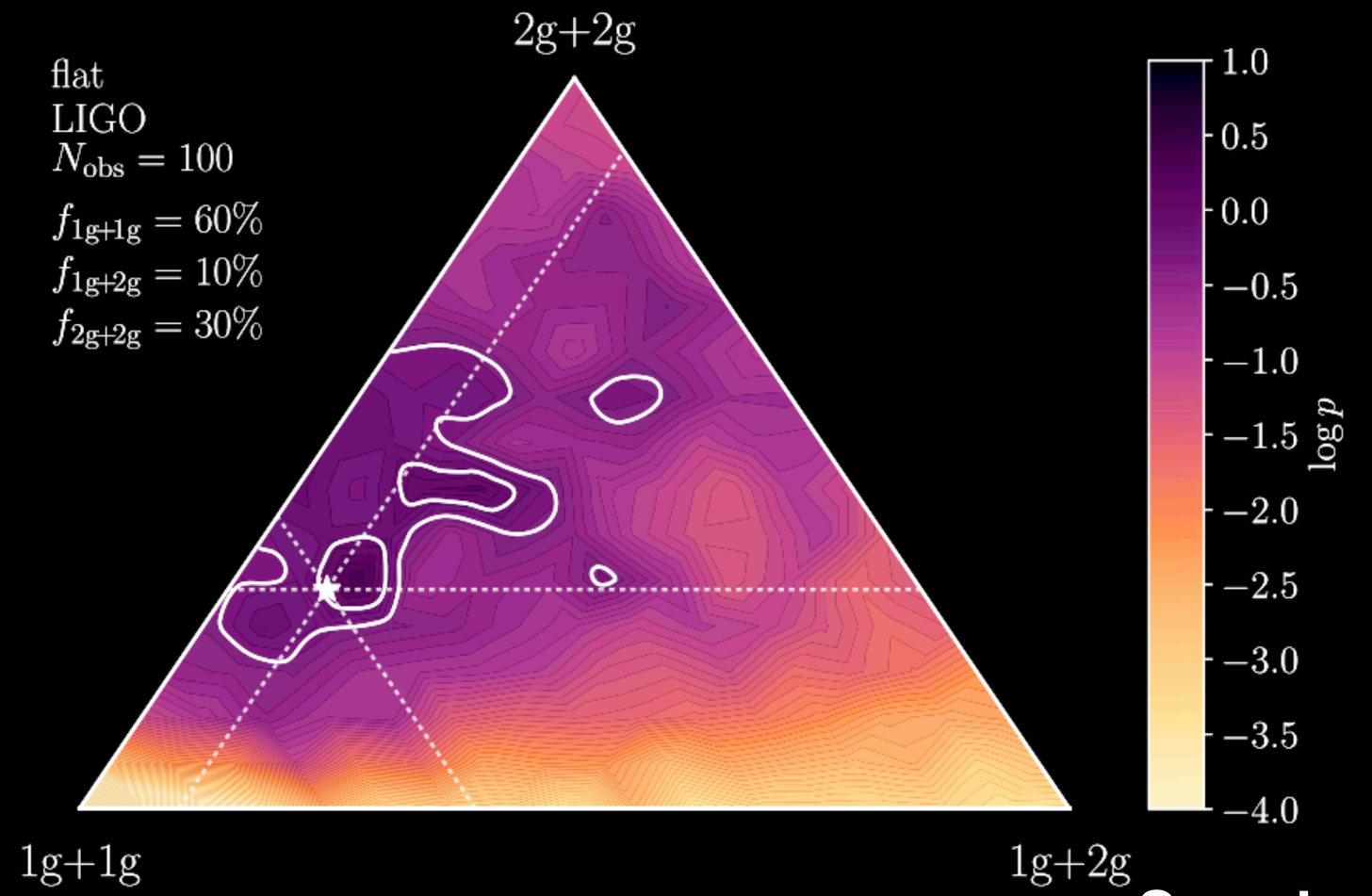
HARVARD & SMITHSONIAN




Gerosa & Berti 2017
PRD, 95, 124046

See also:
Fishbach, Holz, Farr 2017
ApJL, 840, L24

# Multiple Mergers

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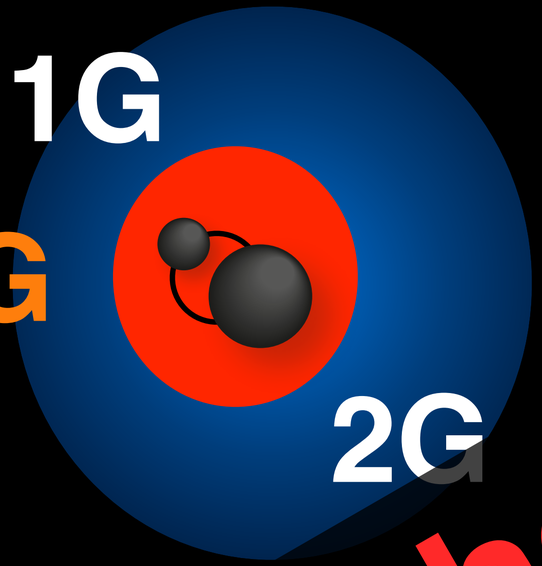
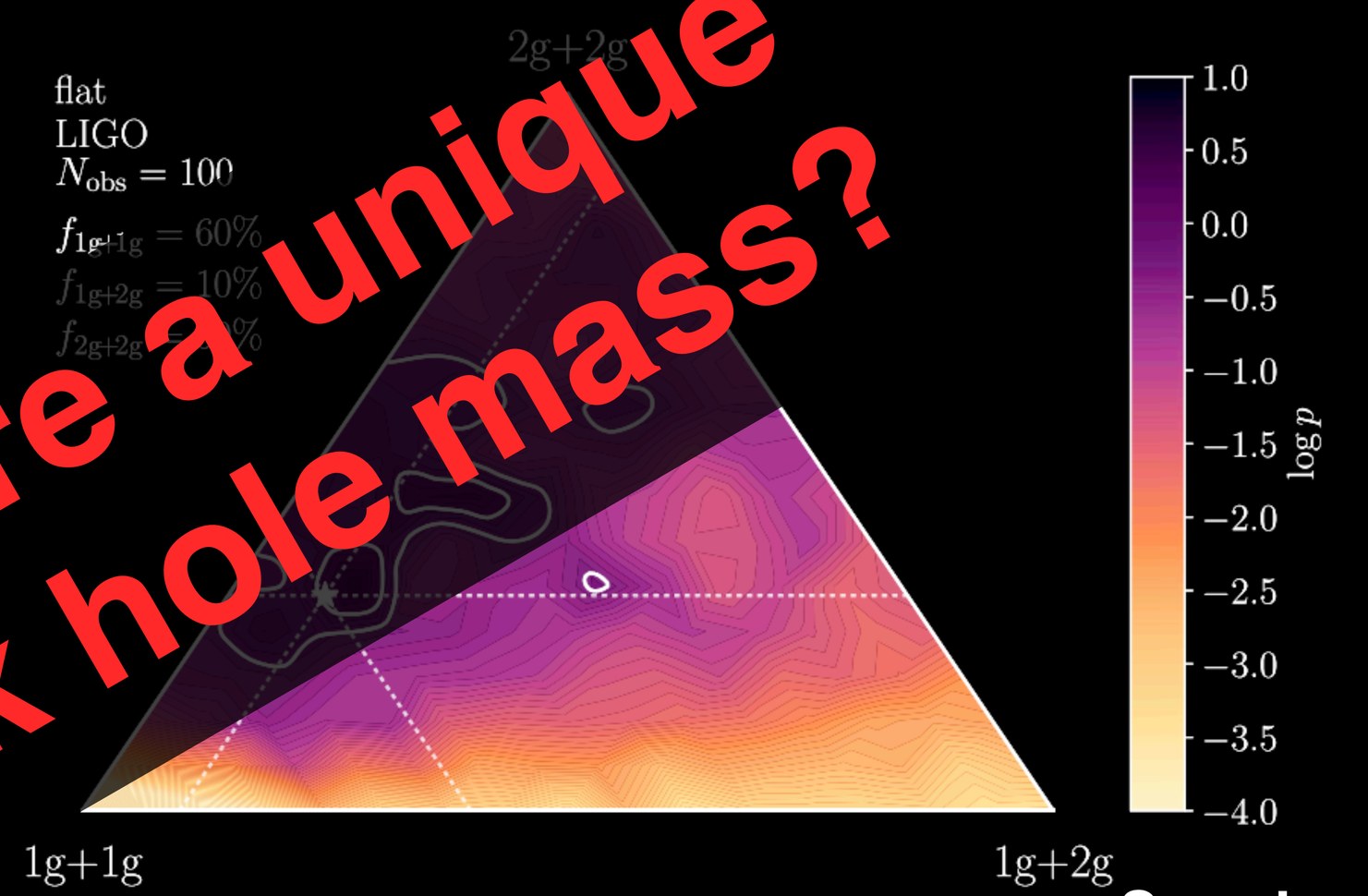
HARVARD & SMITHSONIAN





## Is there a unique black hole mass?




Gerosa & Berti 2017
PRD, 95, 124046

See also:
Fishbach, Holz, Farr 2017
ApJL, 840, L24

# Pulsational-Pair Instabilities

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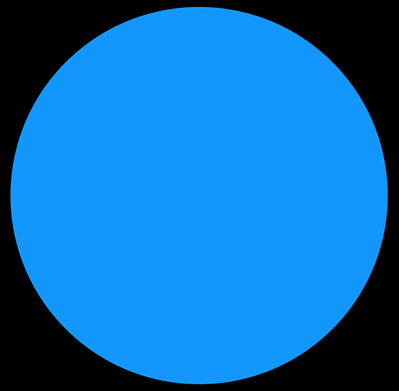
HARVARD & SMITHSONIAN

$\sim 150 M_\odot$



# Pulsational-Pair Instabilities

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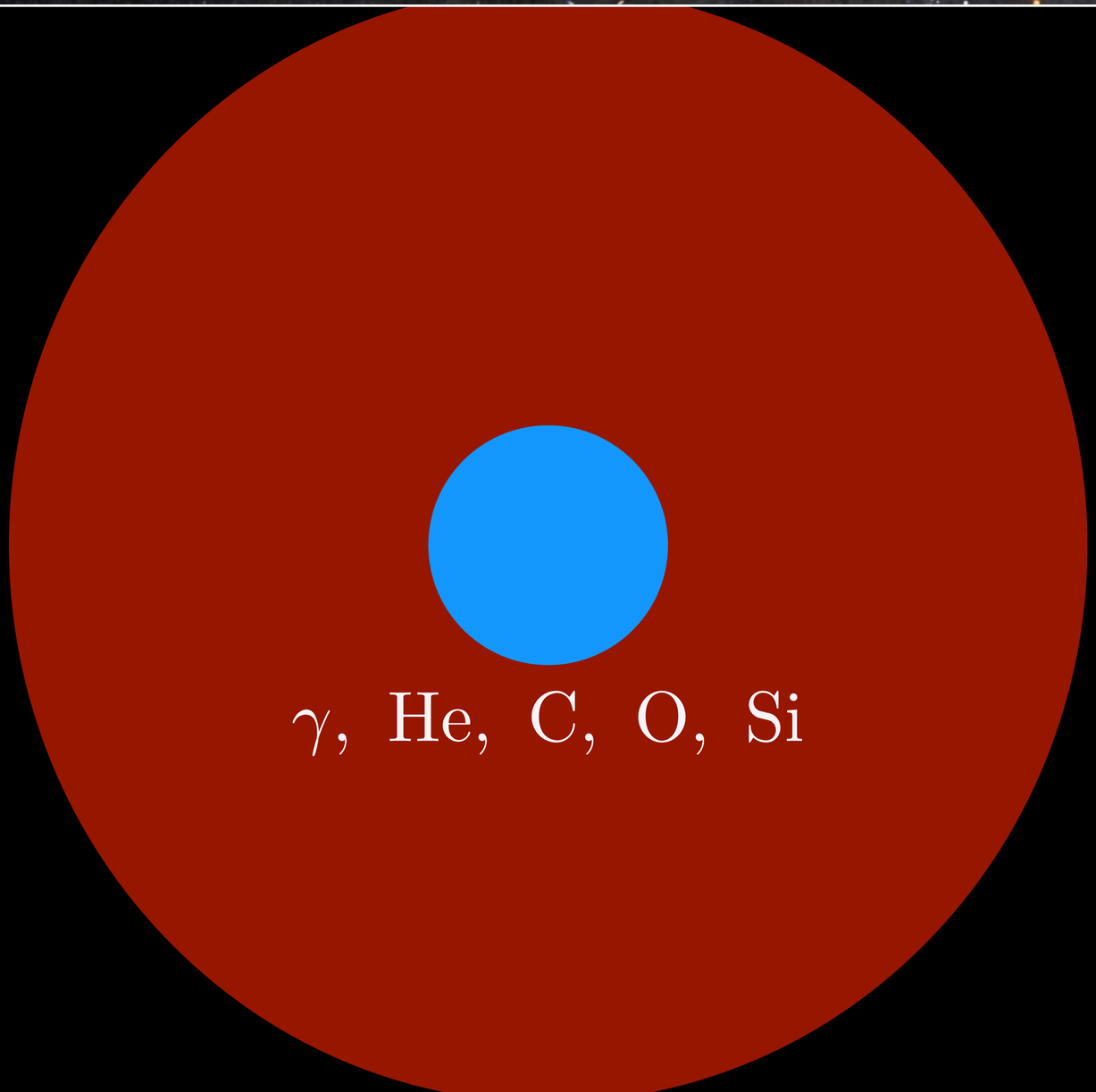
HARVARD & SMITHSONIAN



# Pulsational-Pair Instabilities

CARL RODRIGUEZ
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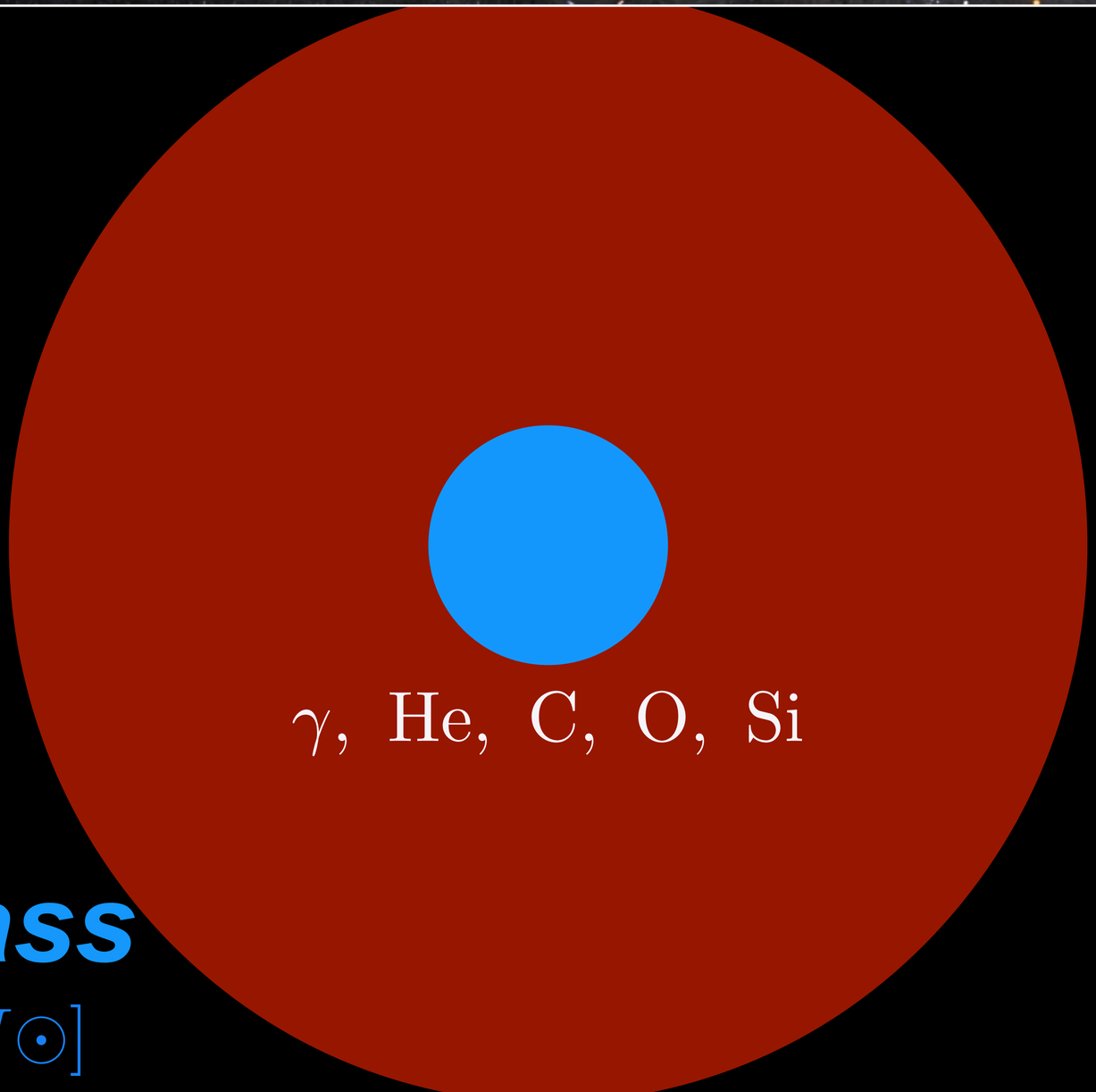
HARVARD & SMITHSONIAN




## He Core Mass

$M \in [40M_{\odot}, 65M\odot]$

# Pulsational-Pair Instabilities

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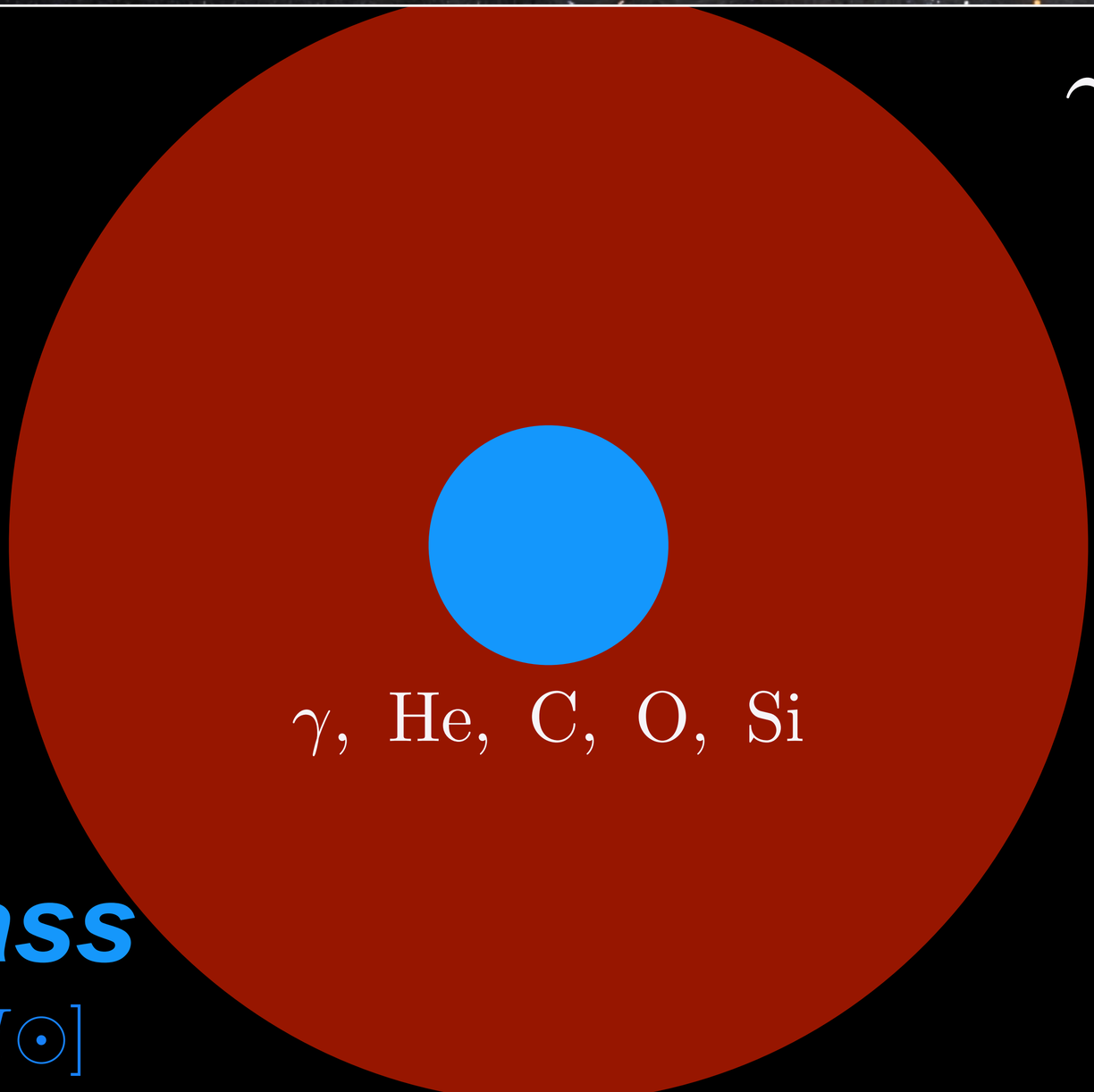
HARVARD & SMITHSONIAN

$$\gamma \rightarrow e^+ + e^-$$




## He Core Mass

$M \in [40M_\odot, 65M\odot]$

# Pulsational-Pair Instabilities

CARL RODRIGUEZ
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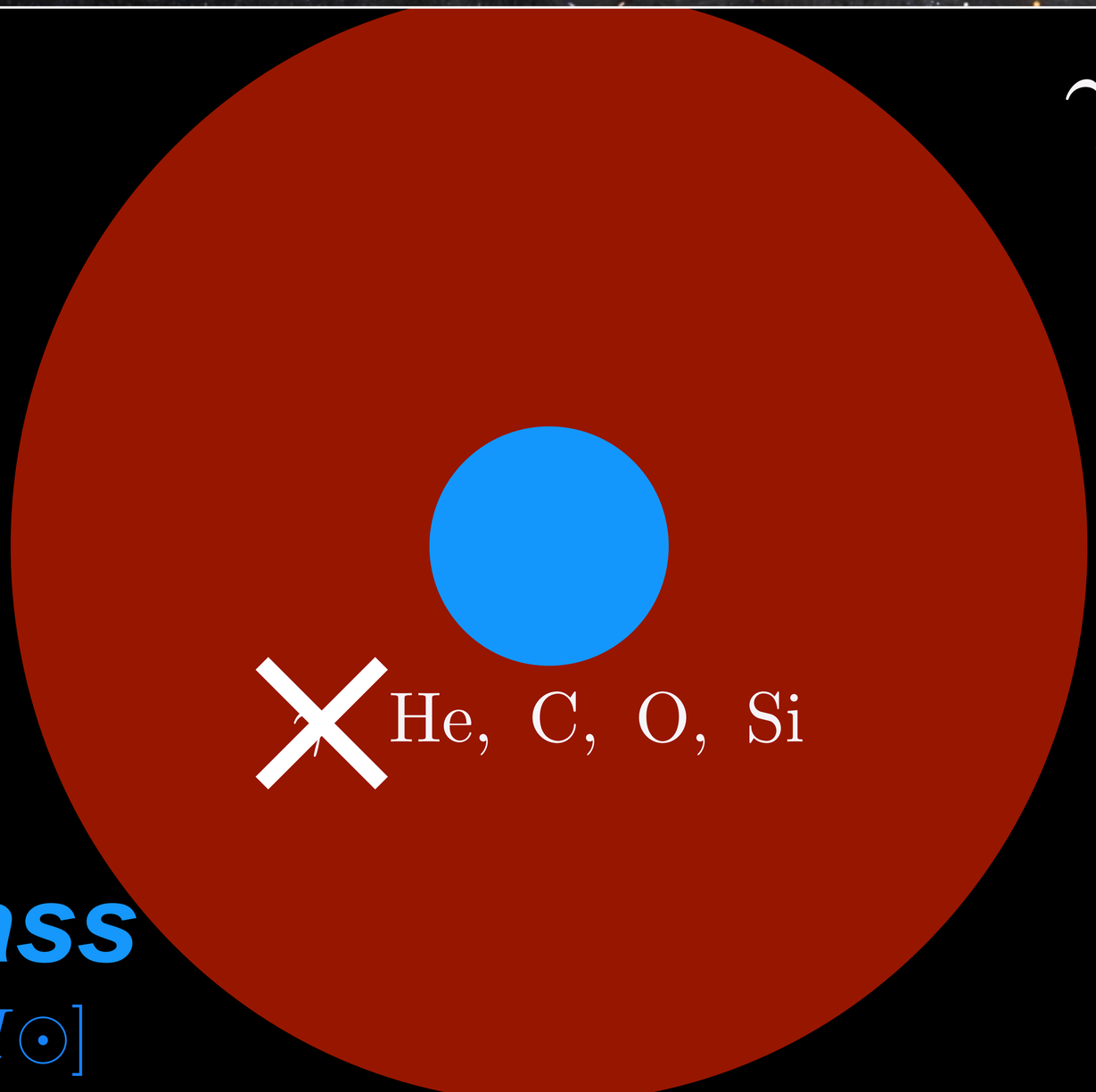
HARVARD & SMITHSONIAN

$$\gamma \rightarrow e^+ + e^-$$




## He Core Mass

$M \in [40M_\odot, 65M\odot]$

# Pulsational-Pair Instabilities

CARL RODRIGUEZ
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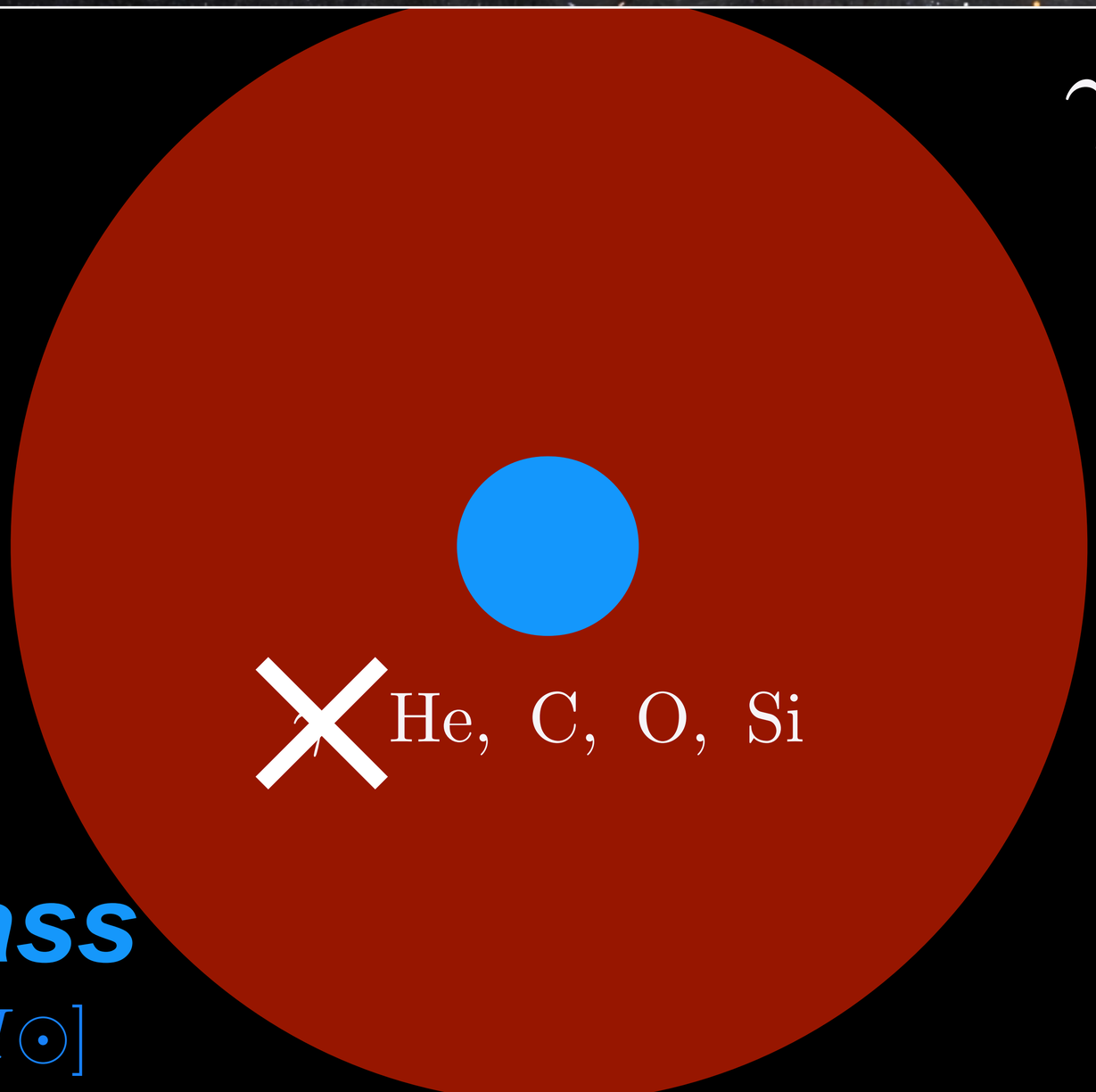
HARVARD & SMITHSONIAN

$$\gamma \rightarrow e^+ + e^-$$




## He Core Mass

$M \in [40M_\odot, 65M\odot]$

# Pulsational-Pair Instabilities

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HARVARD & SMITHSONIAN

$$\gamma \rightarrow e^+ + e^-$$

$$M_{\rm BH} \lesssim 45 M_\odot$$

## He Core Mass

$$M \in [40 M_\odot, 65 M \odot]$$

# Pulsational-Pair Instabilities

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$$\gamma \rightarrow e^+ + e^-$$


## He Core Mass

$M \in [65M_\odot, 135M\odot]$

# Pulsational-Pair Instabilities

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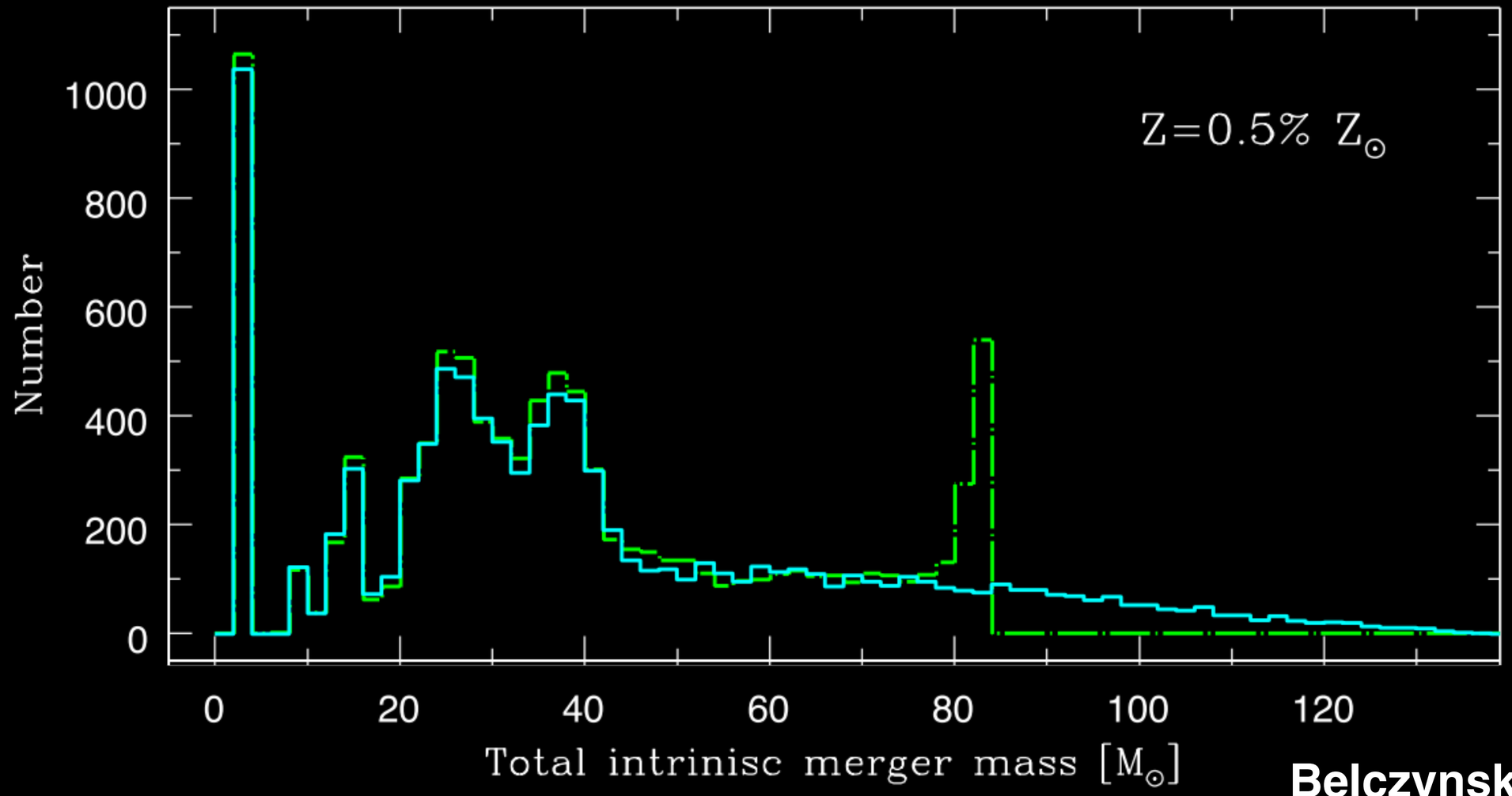
HARVARD & SMITHSONIAN




Belczynski et al., 2016
A&A, 594, A76

# Pulsational-Pair Instabilities

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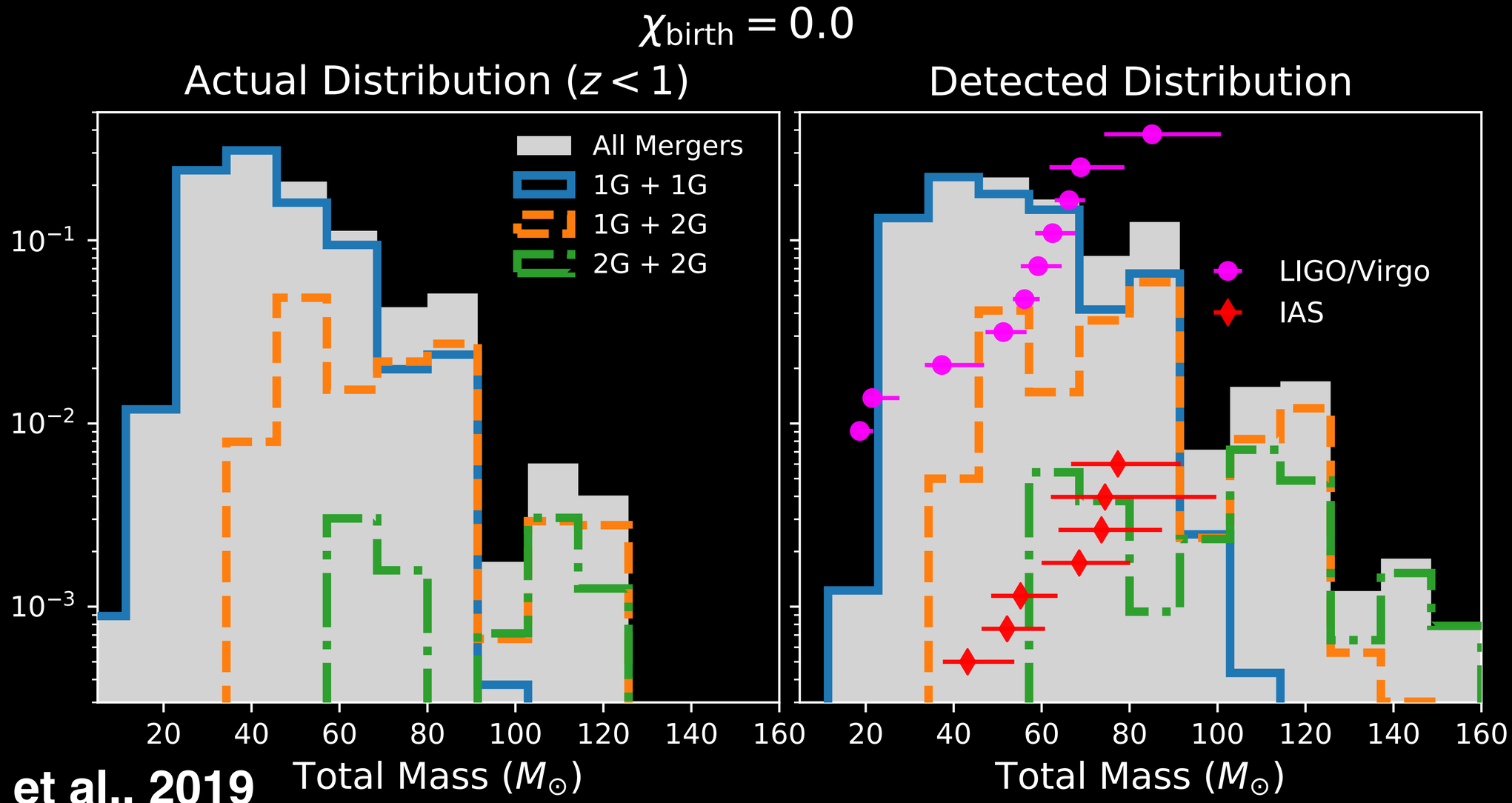
HARVARD & SMITHSONIAN




**Rodriguez et al., 2019**
**PRD, 100, 043027**

# Pulsational-Pair Instabilities

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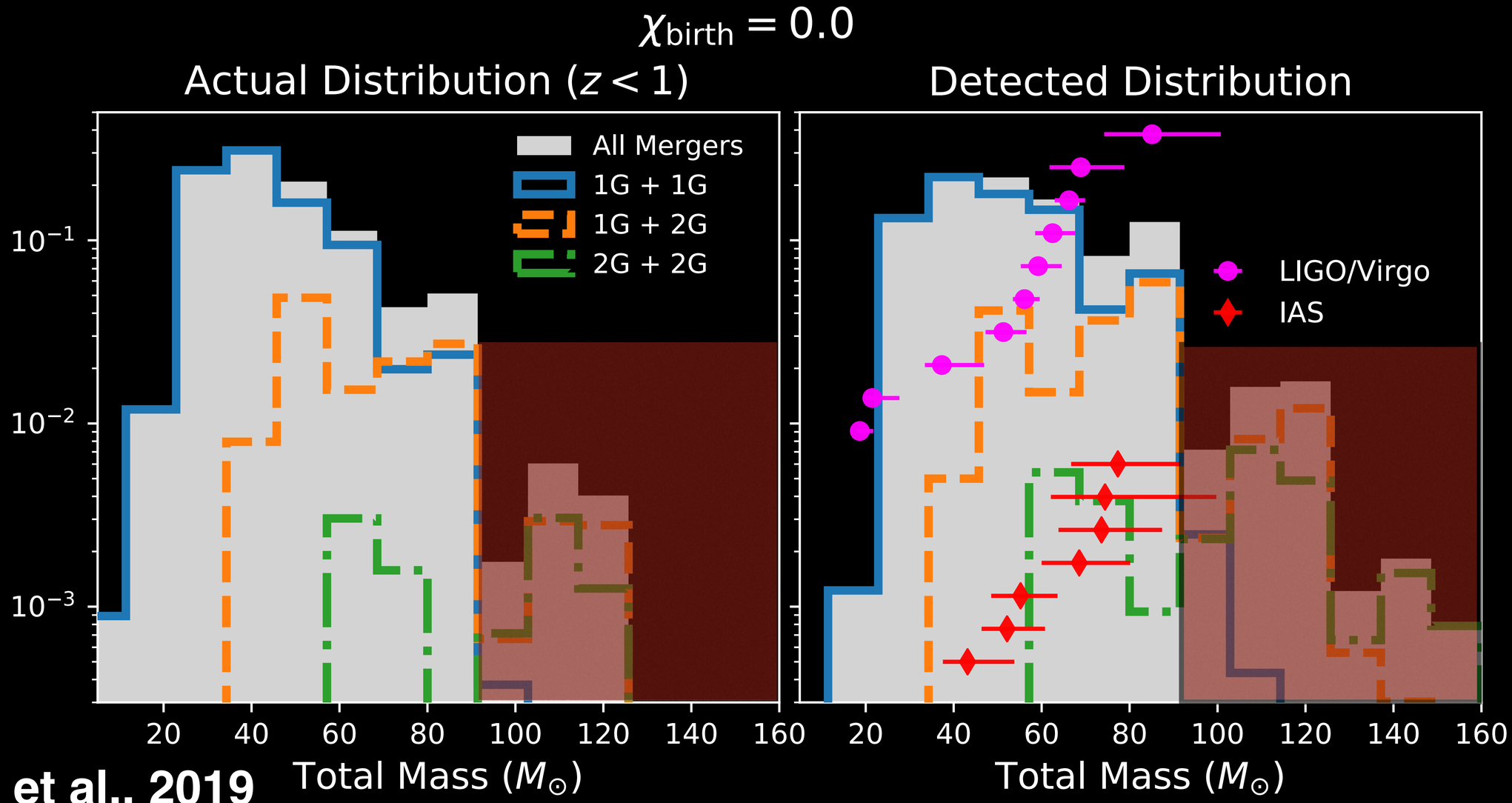
HARVARD & SMITHSONIAN




**Rodriguez et al., 2019**
**PRD, 100, 043027**

# Pulsational-Pair Instabilities

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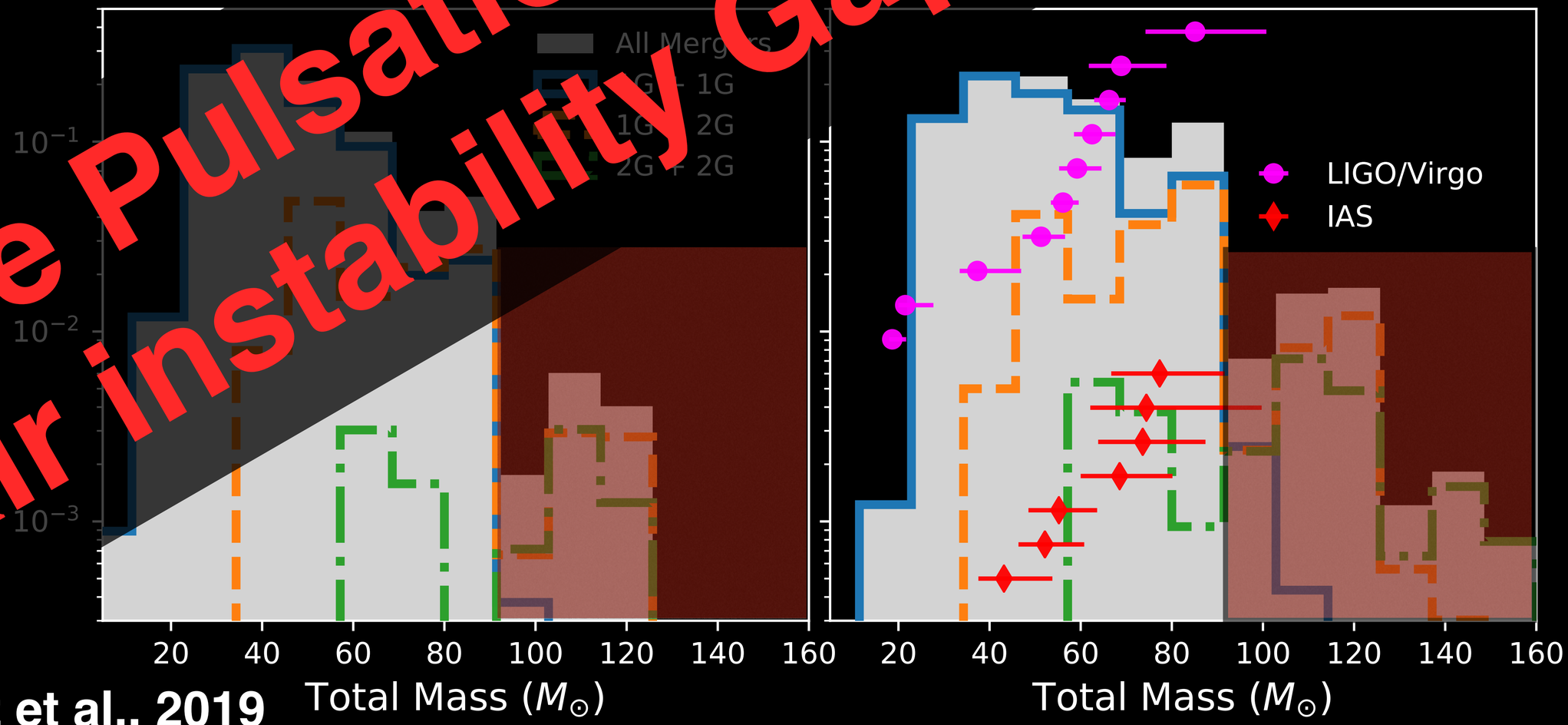
HARVARD & SMITHSONIAN




**The Pulsational-Pair instability Gap**

**Rodriguez et al., 2019**
**PRD, 100, 043027**

# Pulsational-Pair Instabilities

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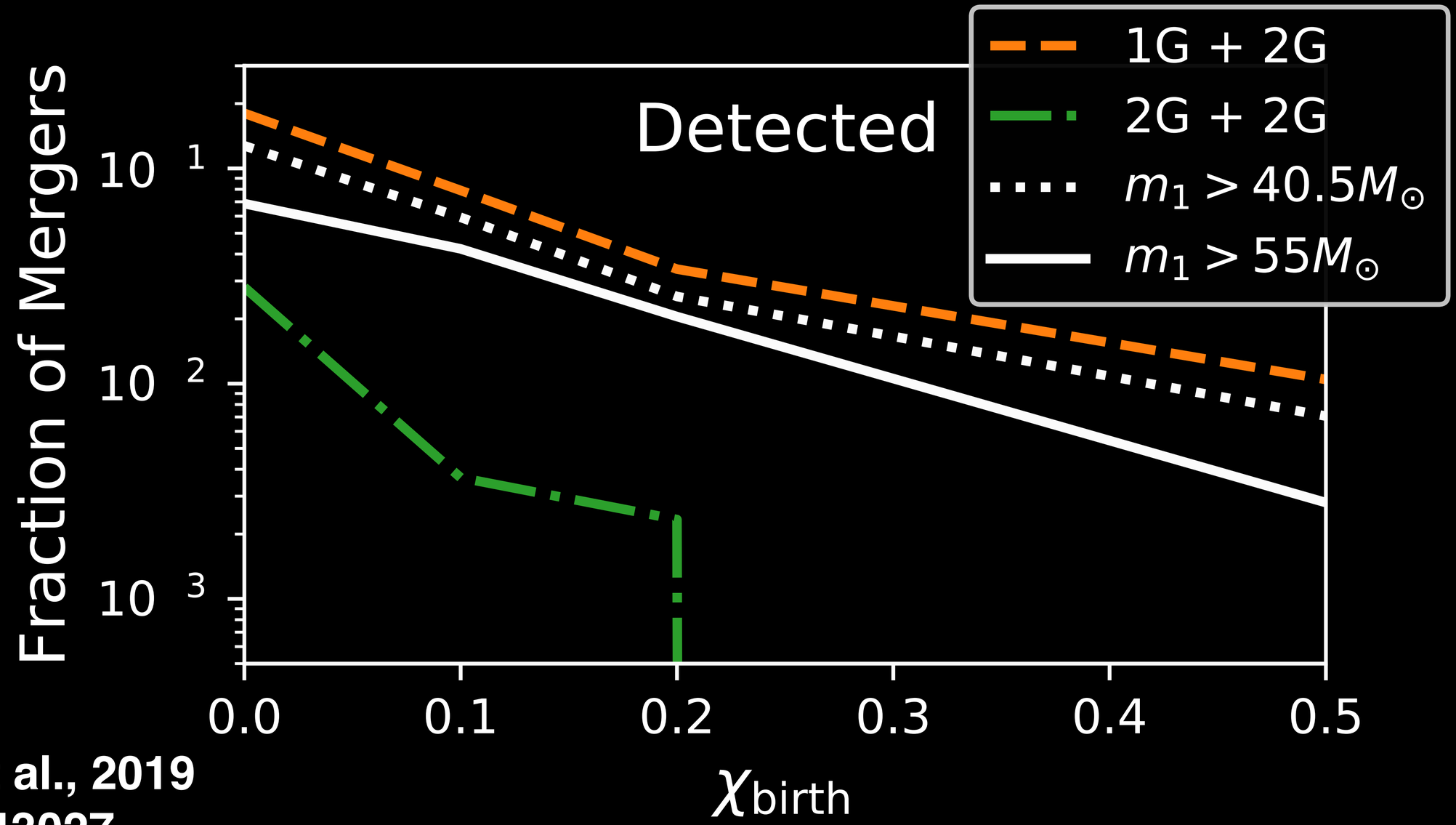
HARVARD & SMITHSONIAN




**Rodriguez et al., 2019**
**PRD, 100, 043027**

# *Pulsational-Pair Instabilities*

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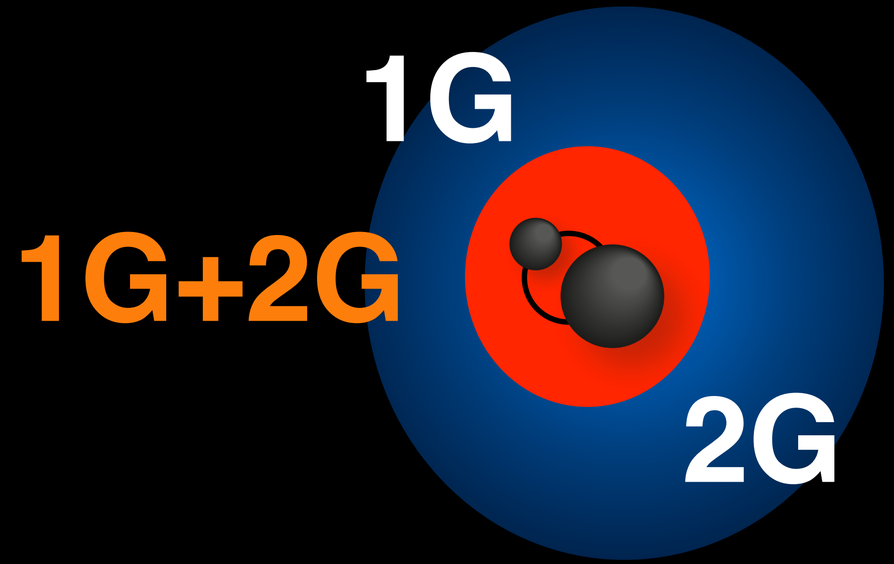
HARVARD & SMITHSONIAN




**Does this only come from a globular cluster?**

# *Pulsational-Pair Instabilities*

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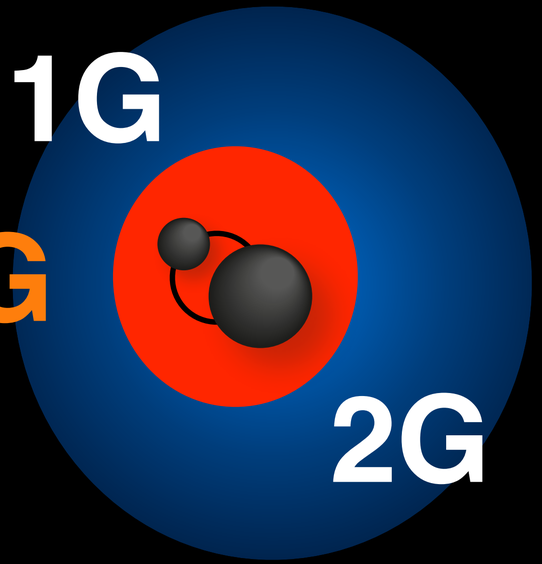
HARVARD & SMITHSONIAN




**Does this only come from a globular cluster?**

**....no**

# *Escape Speeds*

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HARVARD & SMITHSONIAN

~10-100 km/s

***GCs***

# Escape Speeds

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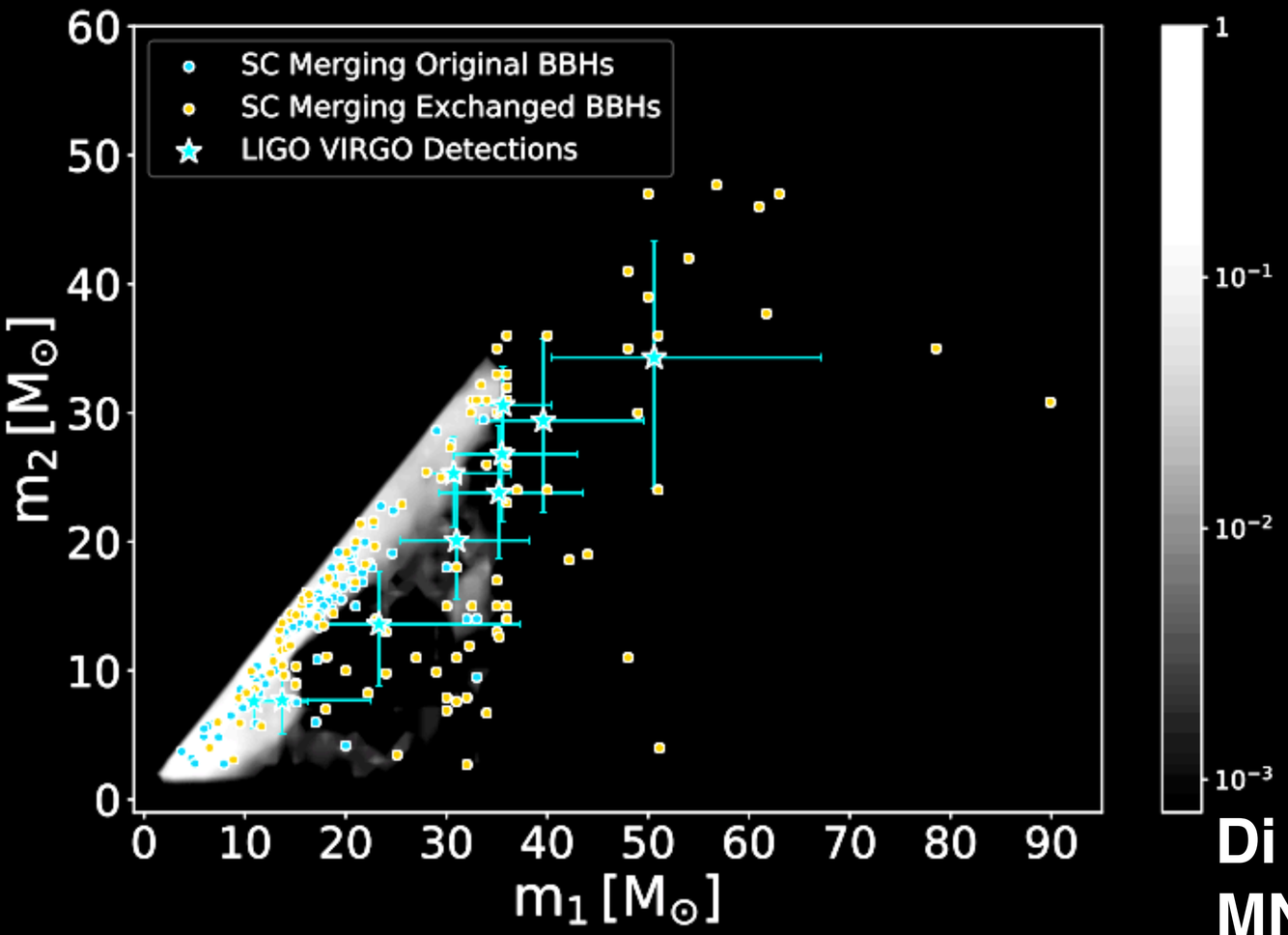
HARVARD & SMITHSONIAN

~1-10 km/s ~10-100 km/s

***Open Clusters***




**Di Carlo et al., MNRAS 487., 2, 2019**

# Escape Speeds

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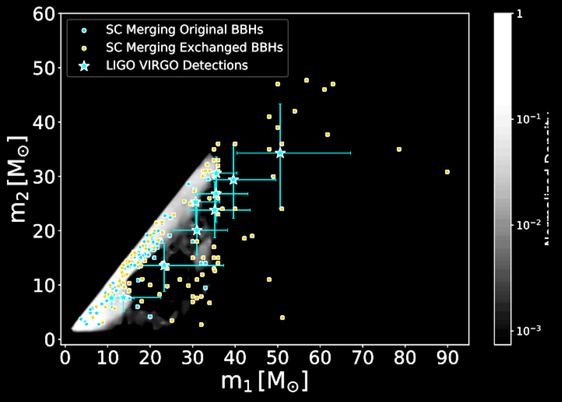
HARVARD & SMITHSONIAN

~1-10 km/s ~10-100 km/s

## Open Clusters




## GCs

**Di Carlo et al., MNRAS 487., 2, 2019**

# Escape Speeds

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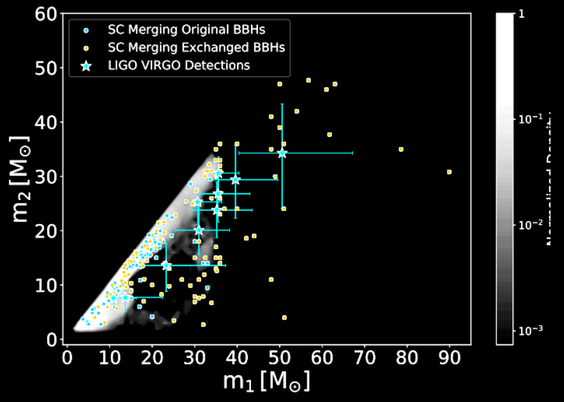
HARVARD & SMITHSONIAN

~1-10 km/s ~10-100 km/s ~100-1000 km/s

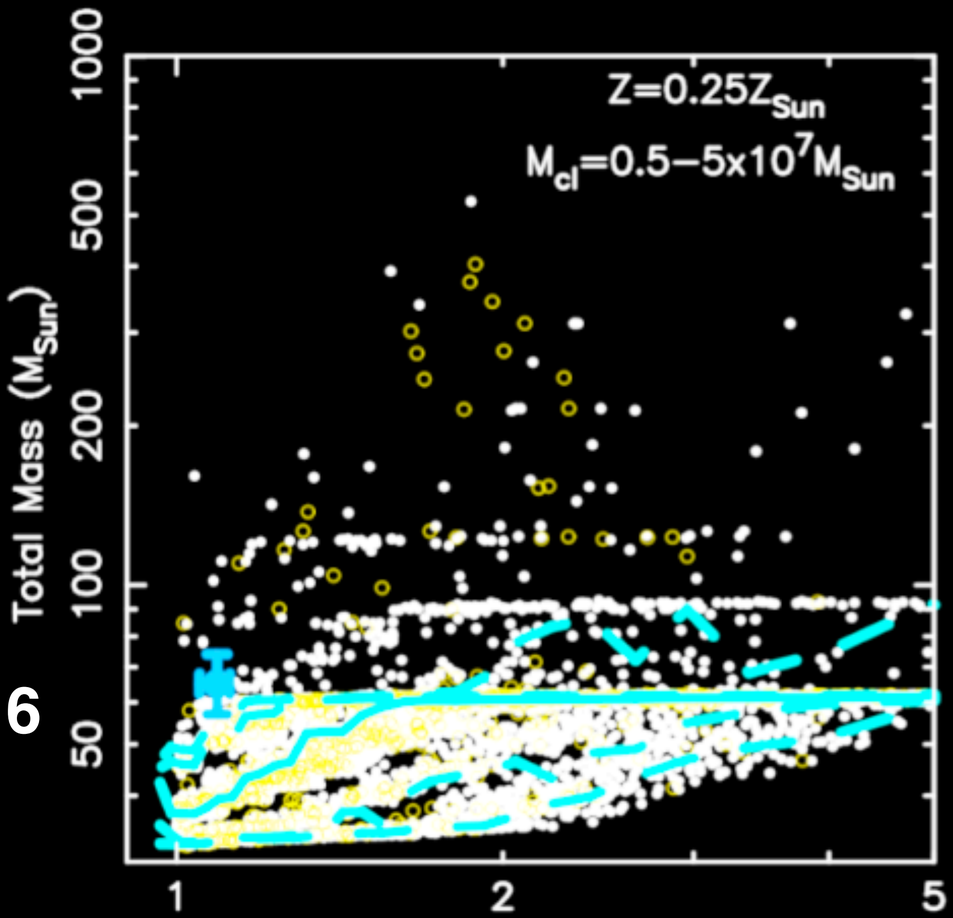
## Open Clusters




Di Carlo et al.,
MNRAS 487., 2, 2019

## GCs

## Nuclear Star Clusters




Antonini & Rasio 2016
ApJ, 831, 187

# Escape Speeds

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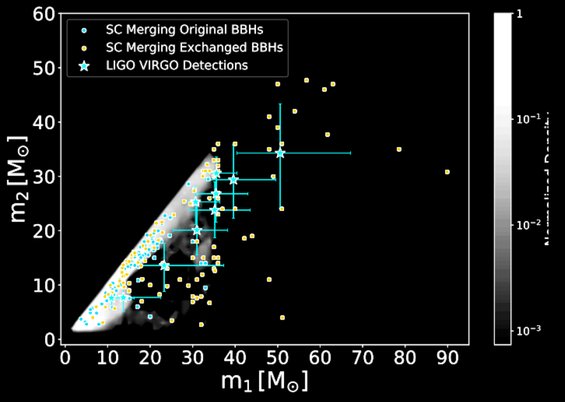
HARVARD & SMITHSONIAN

~1-10 km/s ~10-100 km/s ~100-1000 km/s ~1,000-10,000 km/s

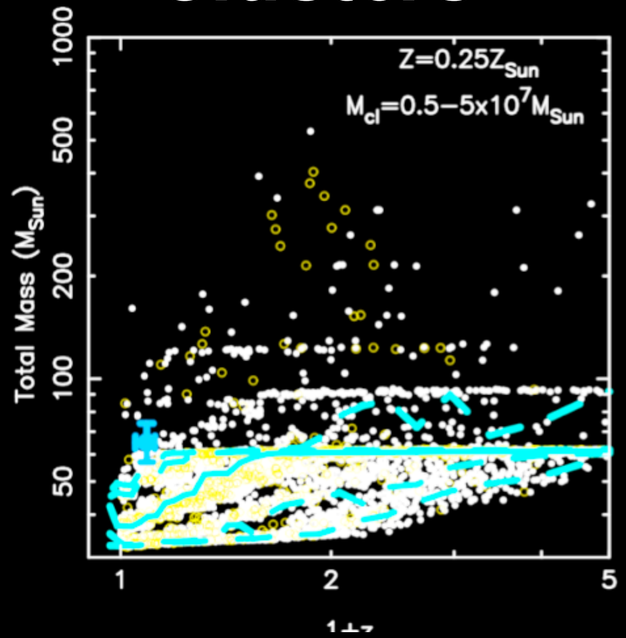
## Open Clusters




Di Carlo et al., MNRAS 487., 2, 2019

## GCs

## Nuclear Star Clusters




Antonini & Rasio 2016 ApJ, 831, 187

## AGN

# Active Galactic Nuclei

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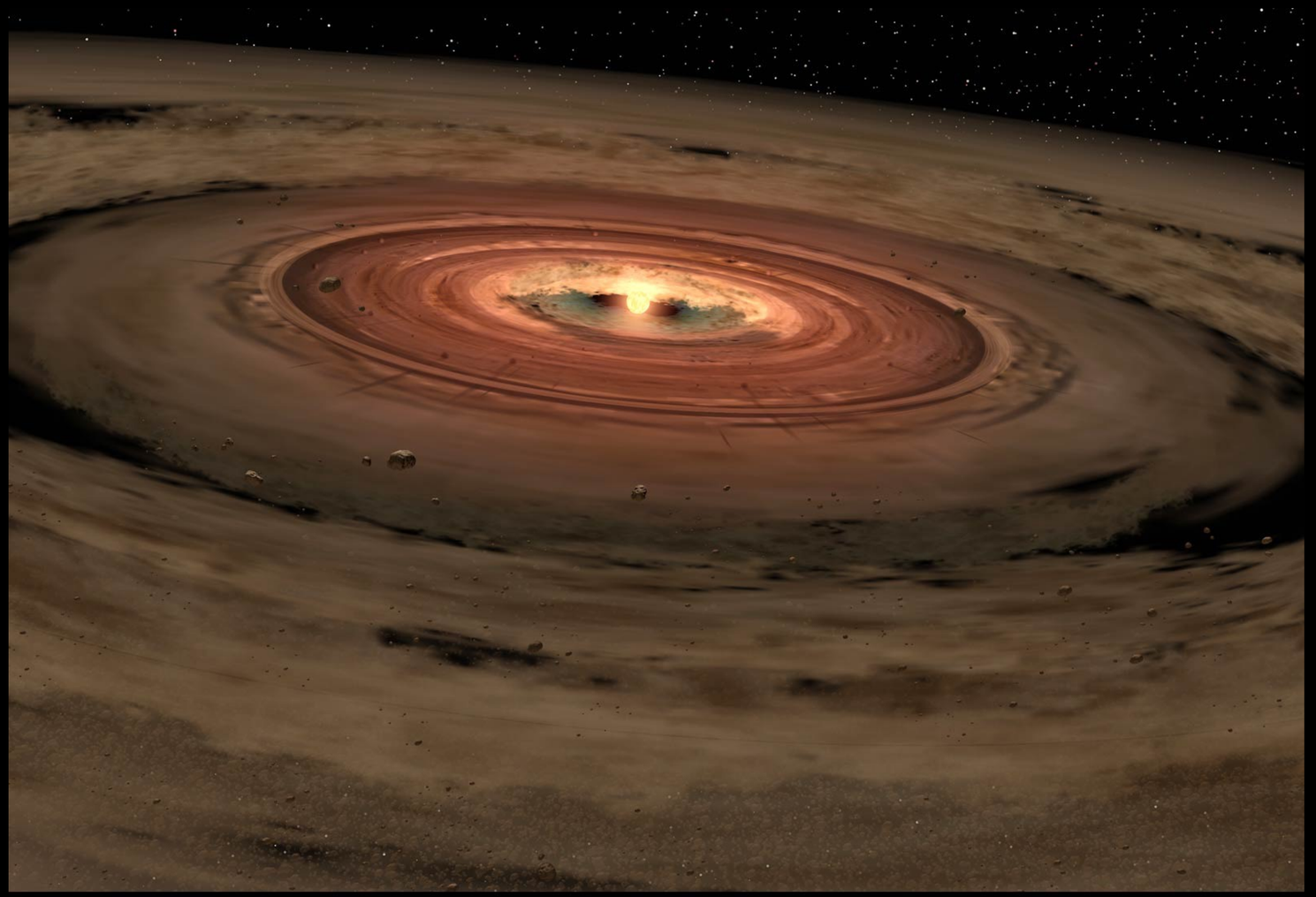
HARVARD & SMITHSONIAN



www.jpl.nasa.gov

# Active Galactic Nuclei

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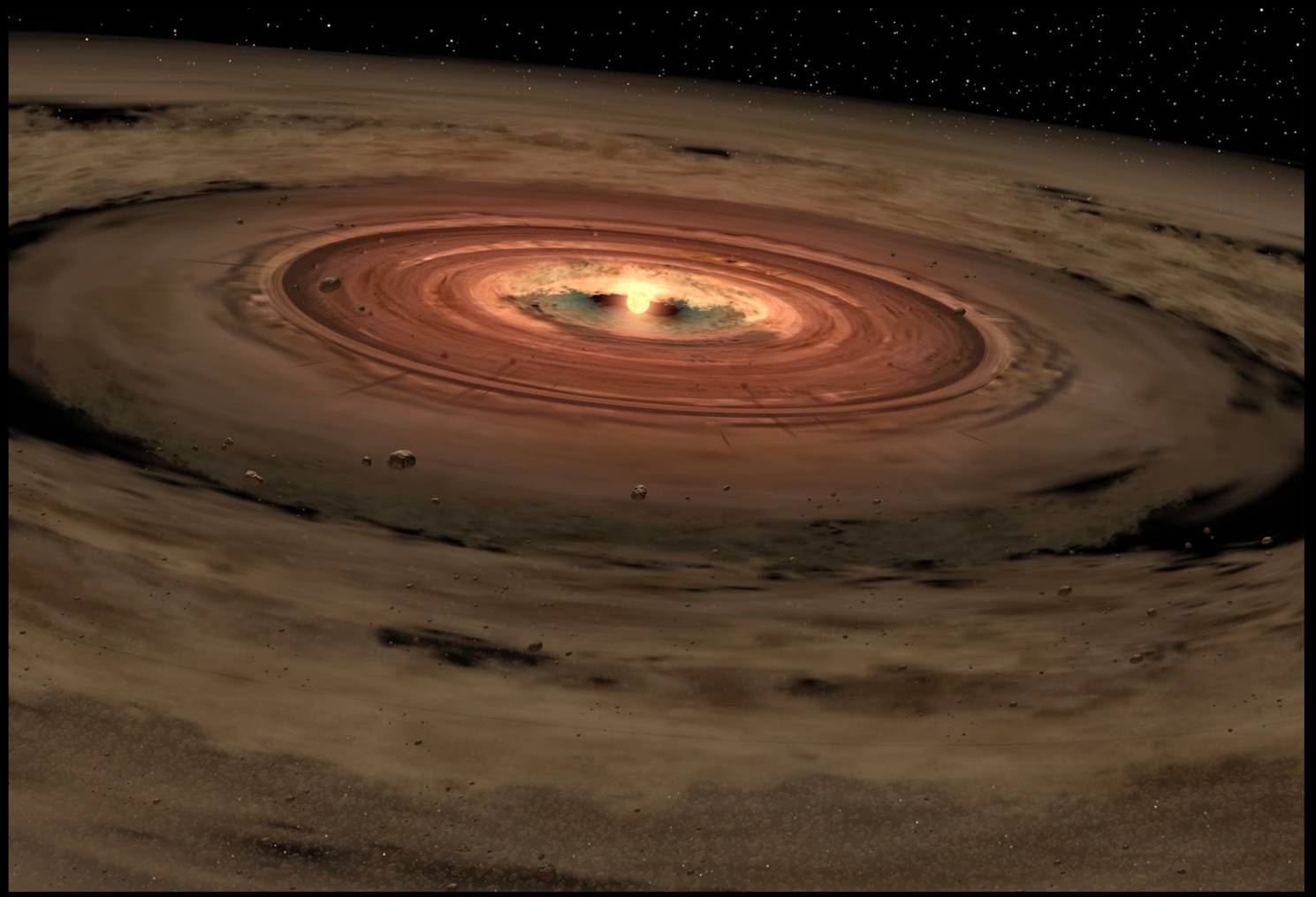
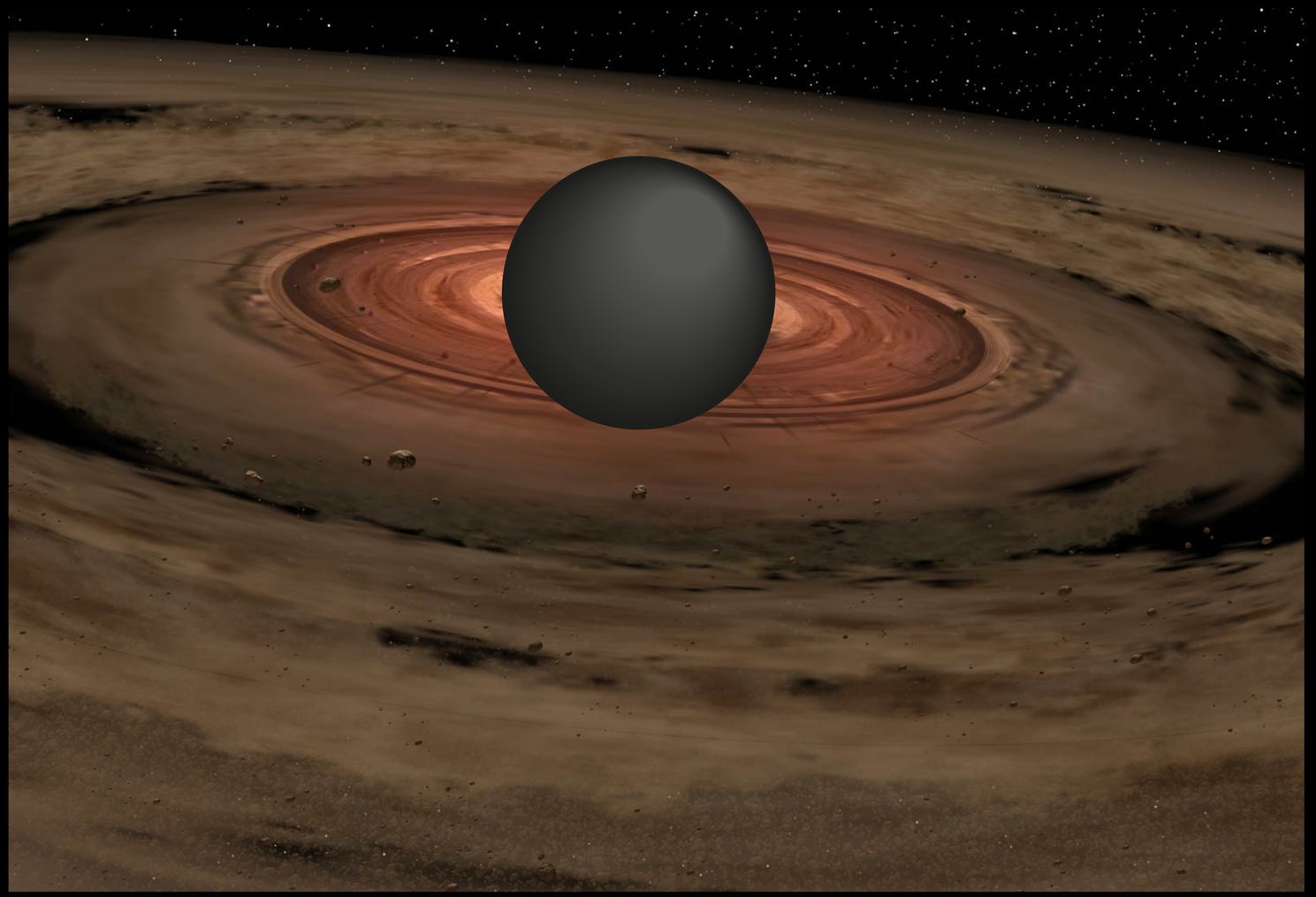
HARVARD & SMITHSONIAN



www.jpl.nasa.gov

$\times 10^6$



www.jpl.nasa.gov

$\times 10^6$

# Active Galactic Nuclei

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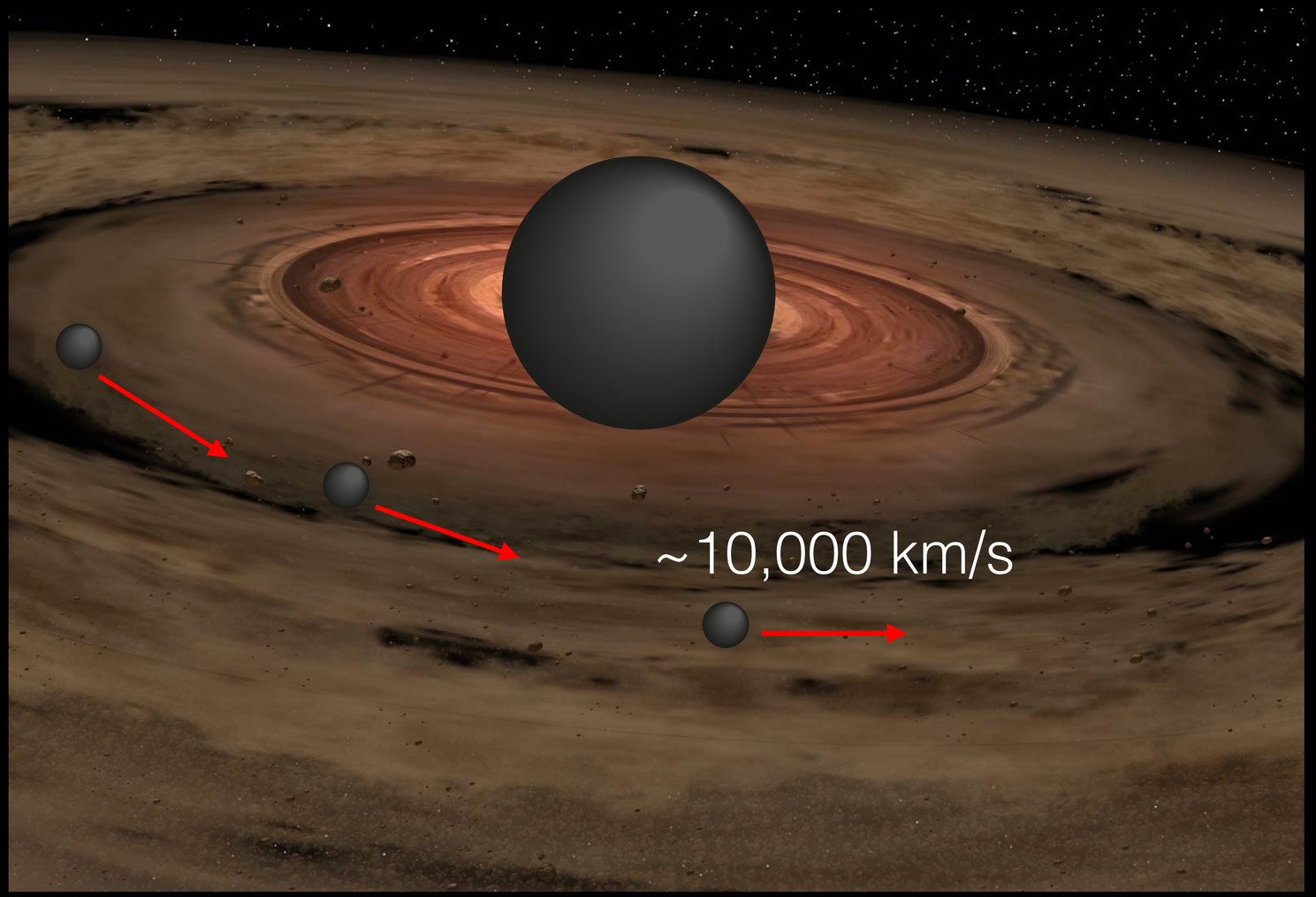
HARVARD & SMITHSONIAN




www.jpl.nasa.gov

$\times 10^6$

# Active Galactic Nuclei

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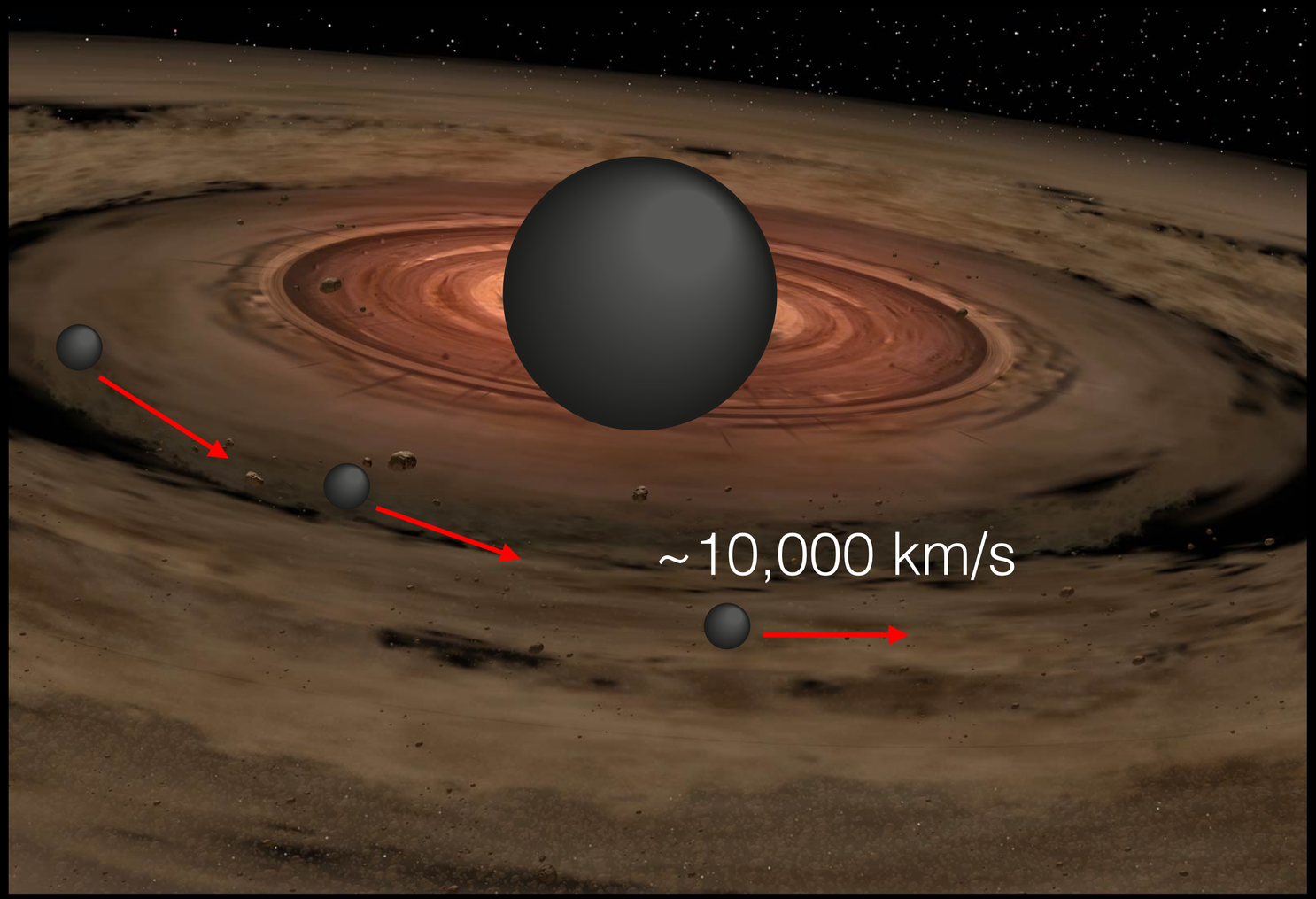
HARVARD & SMITHSONIAN




$\times 10^6$

**Stone, Metzger, Haiman, 2017 MNRAS 464, 946**

**Bartos, Kocsis, Haiman et al., 2017 ApJ, 835, 165**

**McKernan, Ford, Bellovary et al., 2018 ApJ, 866, 66**

**Secunda, Bellovary, Low et al., 2019 ApJ, 878, 85**

# Active Galactic Nuclei

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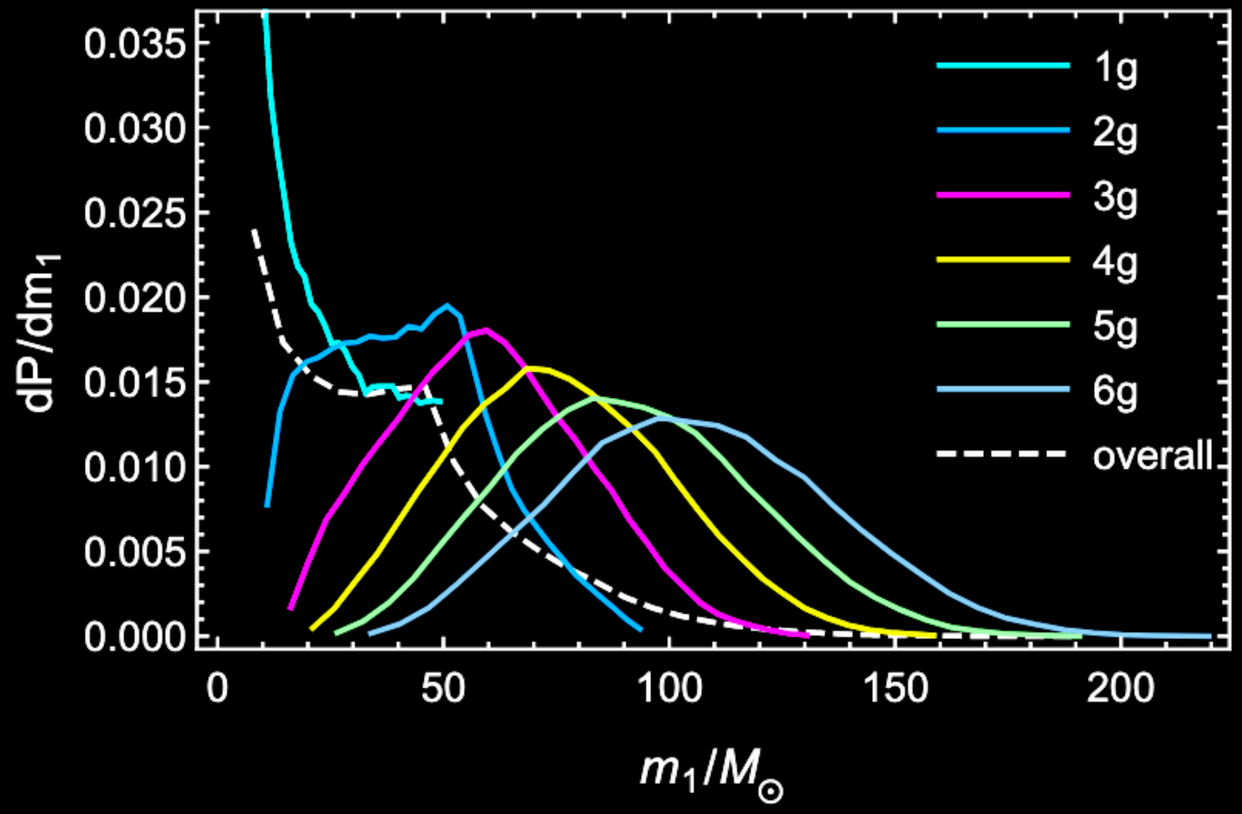
**Yang et al., 2019**
**PRL (in pres),**
**arXiv: 1906.09281**



# Active Galactic Nuclei

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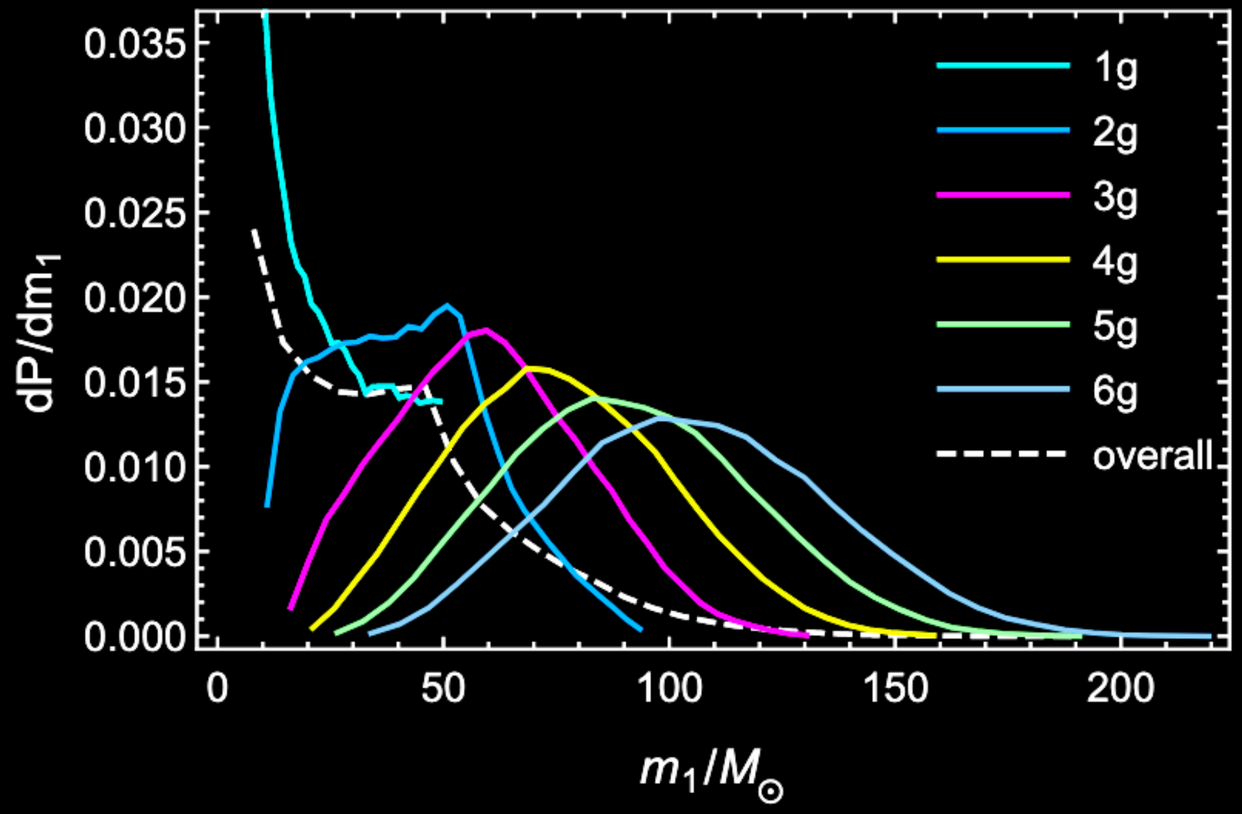
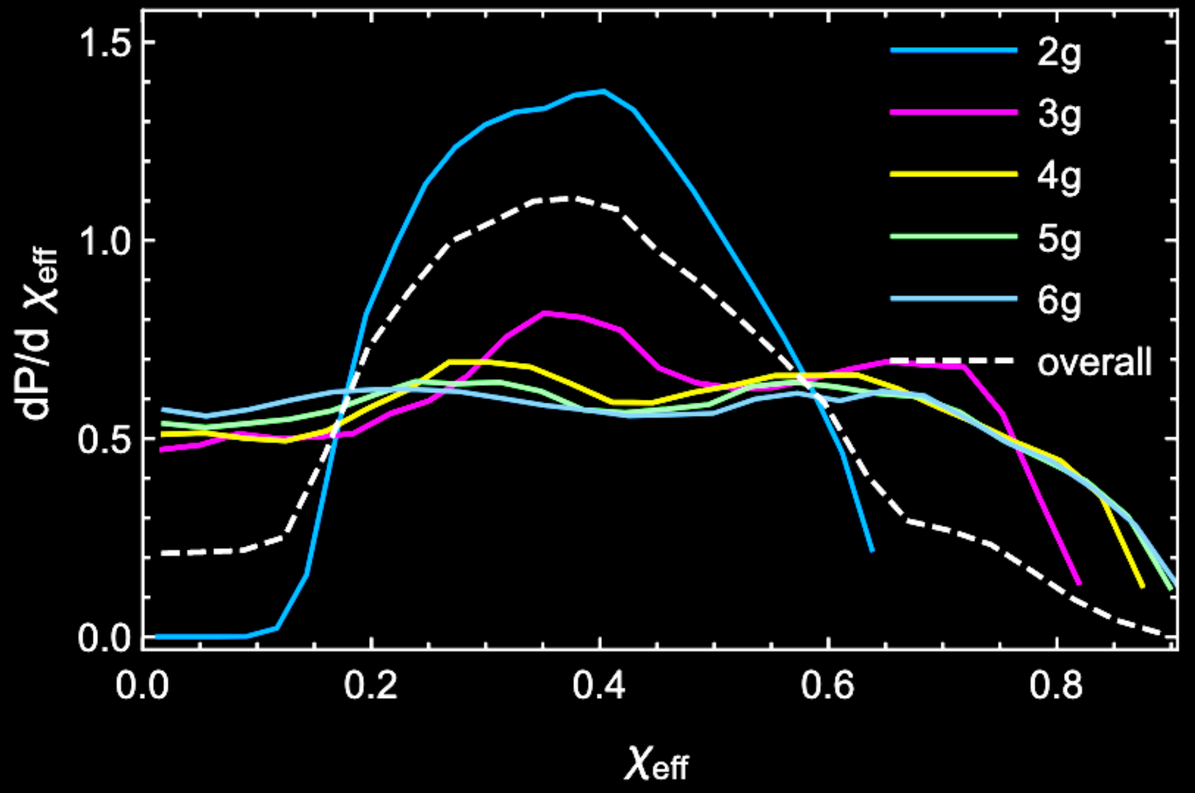
HARVARD & SMITHSONIAN

**Yang et al., 2019**
**PRL (in pres),**
**arXiv: 1906.09281**



# Dynamical Neutron Star Binaries?

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# Dynamical Neutron Star Binaries?

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**no**

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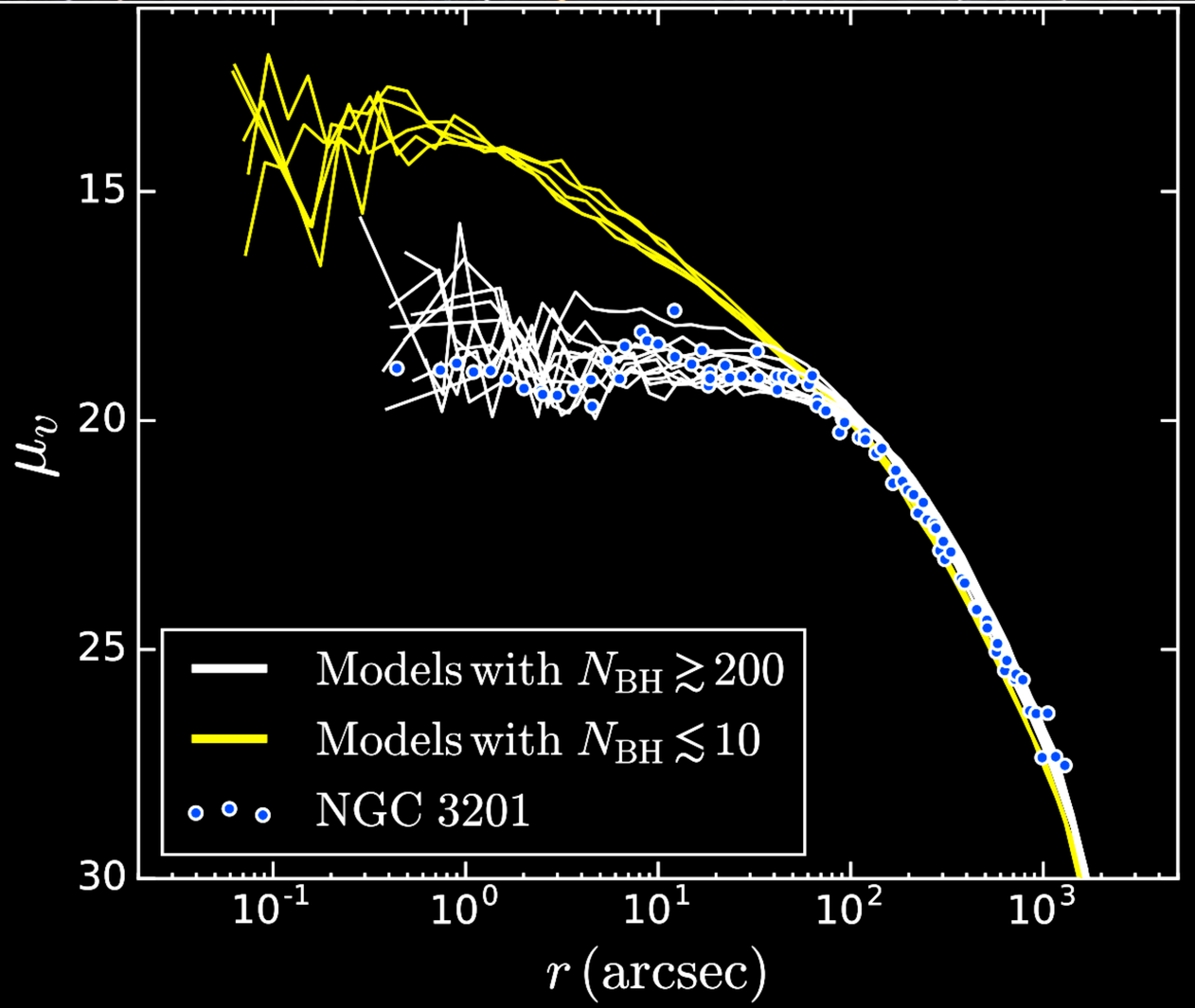
**NGC 3201**
**(ESO/MPG 2.2-m telescope)**




**Kremer, Ye, Chatterjee, Rodriguez, & Rasio**
**ApJL 855, L15 (2018)**

# Dynamical Neutron Star Binaries?

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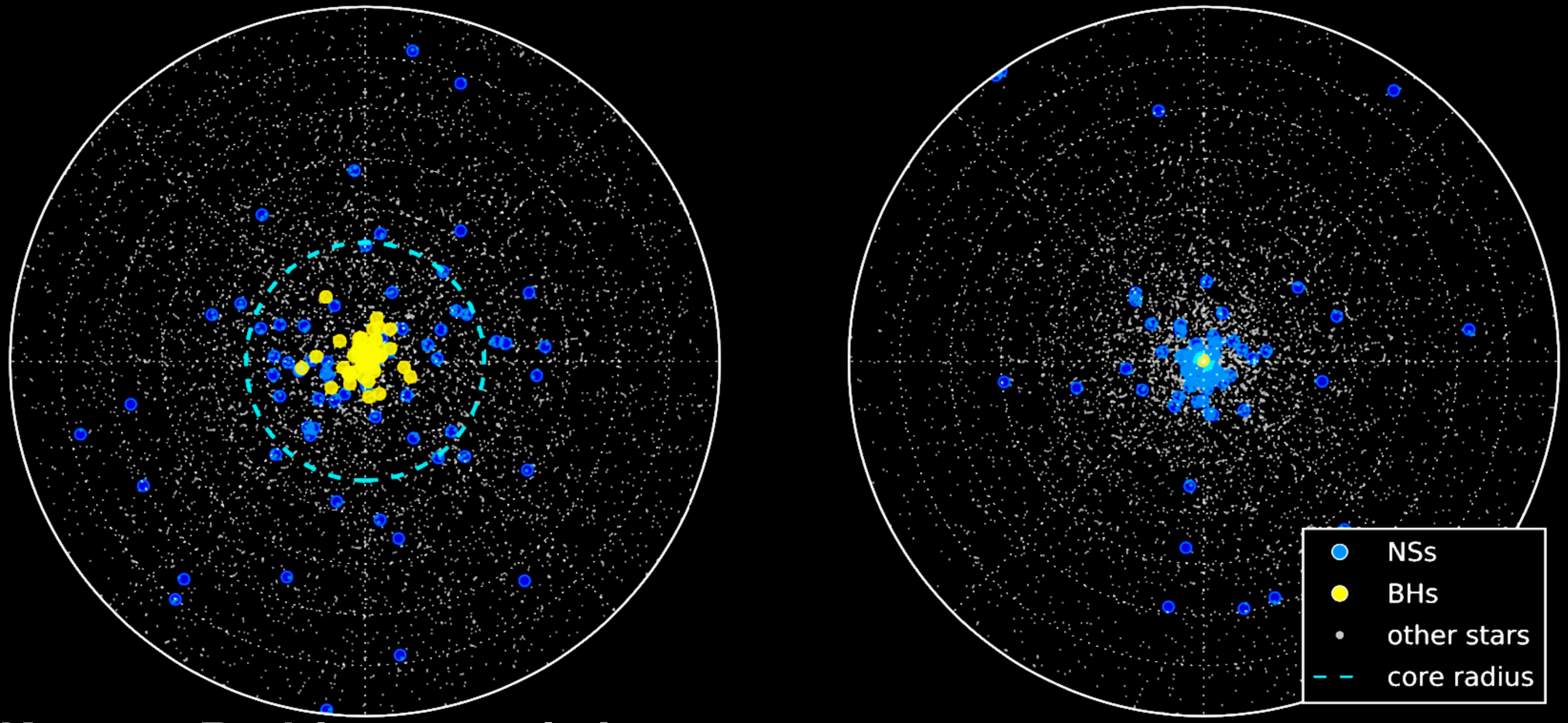
$\mathrm{non-core-collapsed},\ r_c = 2.35\,\mathrm{pc}$
$N_{BH} = 116,\ N_{NS} = 161$

$\mathrm{core-collapsed},\ r_c = 0.16\,\mathrm{pc}$
$N_{BH} = 1,\ N_{NS} = 283$




Ye, Fong, Kremer, Rodriguez et al., in prep

# Dynamical Neutron Star Binaries?

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HARVARD & SMITHSONIAN

$$\text{non} - \text{core} - \text{collapsed},\ r_c = 2.35\,\text{pc}$$
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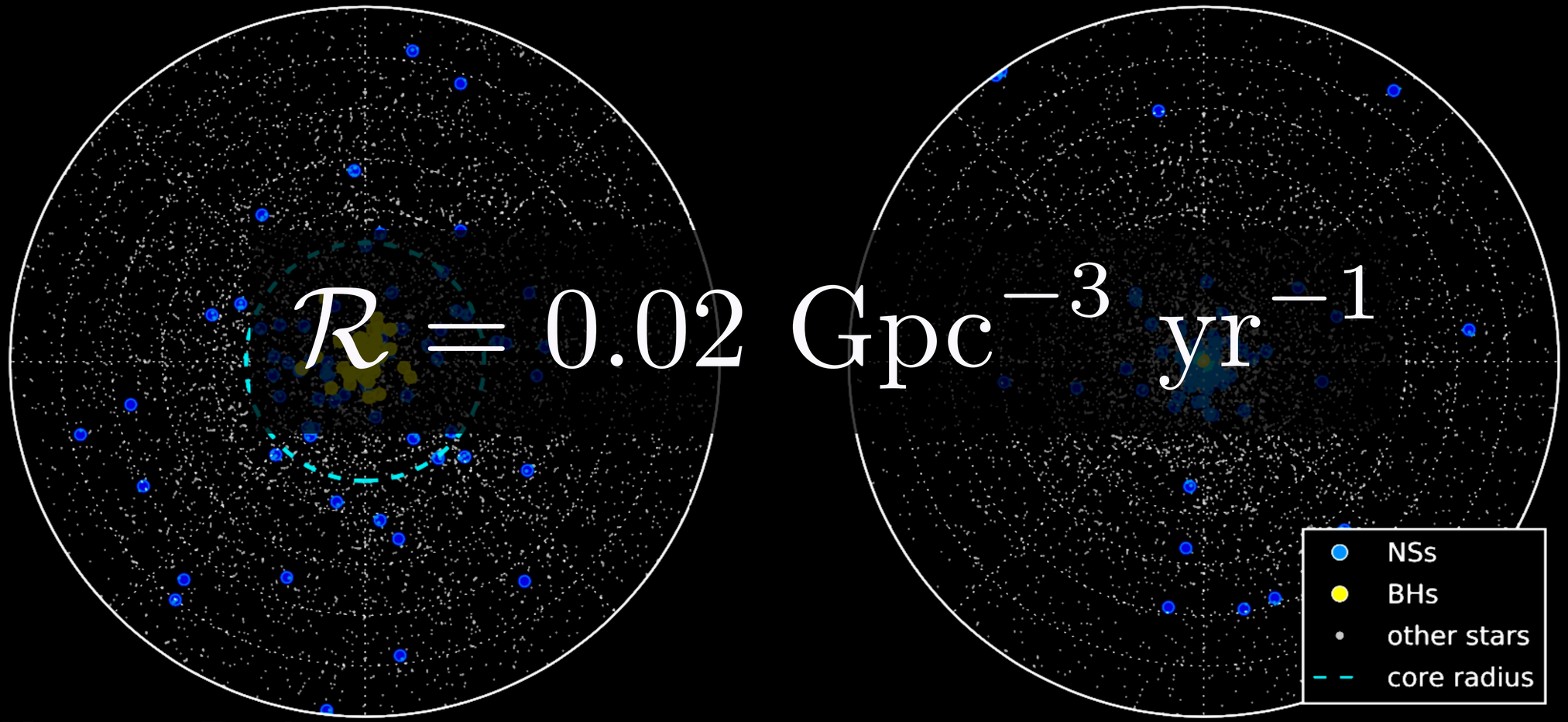


$$\mathcal{R} = 0.02\ \text{Gpc}^{-3}\ \text{yr}^{-1}$$

Ye, Fong, Kremer, Rodriguez et al., in prep