Title: Deciphering the Landscape of Binary Black Hole Formation Channels

Speakers: Michael Zevin

Series: Strong Gravity

Date: December 12, 2019 - 1:00 PM

URL: http://pirsa.org/19120053

Abstract: Merging compact objects encode a vast deal of information about their progenitor stellar systems, such as the types of galactic environments they were born in, the intricacies of stellar evolution the persisted throughout their lives, and the physics of the supernovae that marked their deaths. In this talk, I will highlight multiple open questions that can be illuminated through a combination of compact objects observations (via gravitational waves and/or electromagnetic radiation) and computational modeling of environments that lead to the formation of black holes and neutron stars. I first focus on how the growing catalog of black hole mergers observed by the LIGO/Virgo network can place constraints on binary black hole formation scenarios, both by uncovering gravitational-wave sources that have features specific to a subset of formation scenarios (such as spins that are anti-aligned from the orbital angular momentum, high masses that occupy the pair instability mass gap, and distinguishable eccentricities at merger) and through pairing Bayesian hierarchical inference with state-of-the-art astrophysical models. Next, I will show how various uncertain aspects of binary stellar evolution and supernova physics can be constrained by phenomena attributed to merging neutron stars, such as enigmatic r-process enrichment in globular clusters and the association between short gamma-ray bursts and their host galaxies.

Deciphering the Landscape
of compact binary formation channels

Mike Zevin - CIERA / Northwestern University

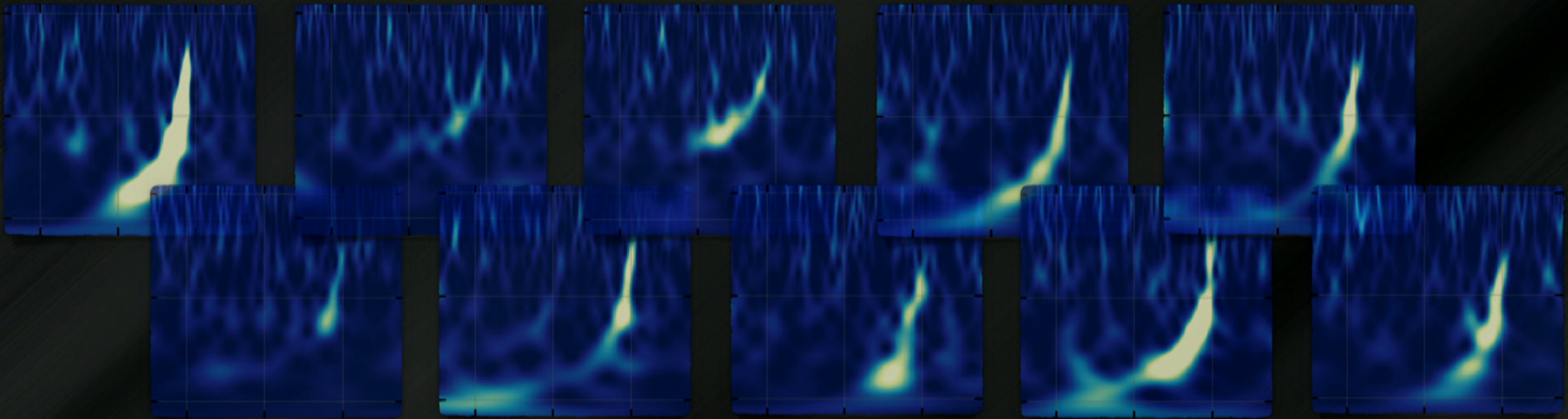
Scientific Advisor: Vicky Kalogera

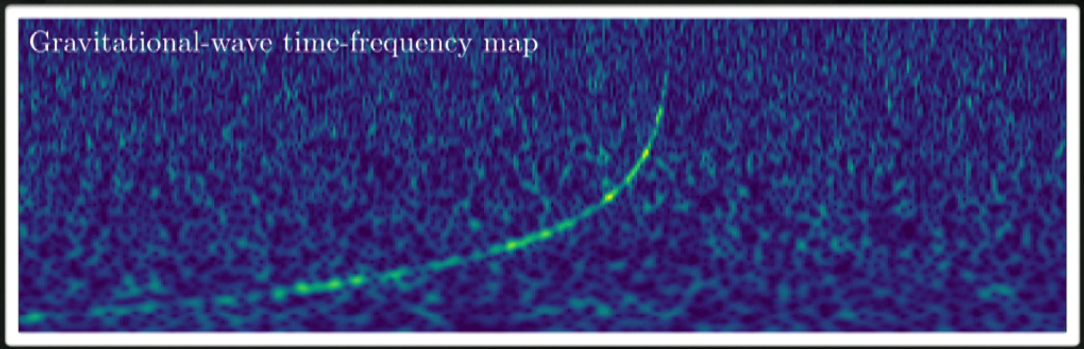
Collaborators:

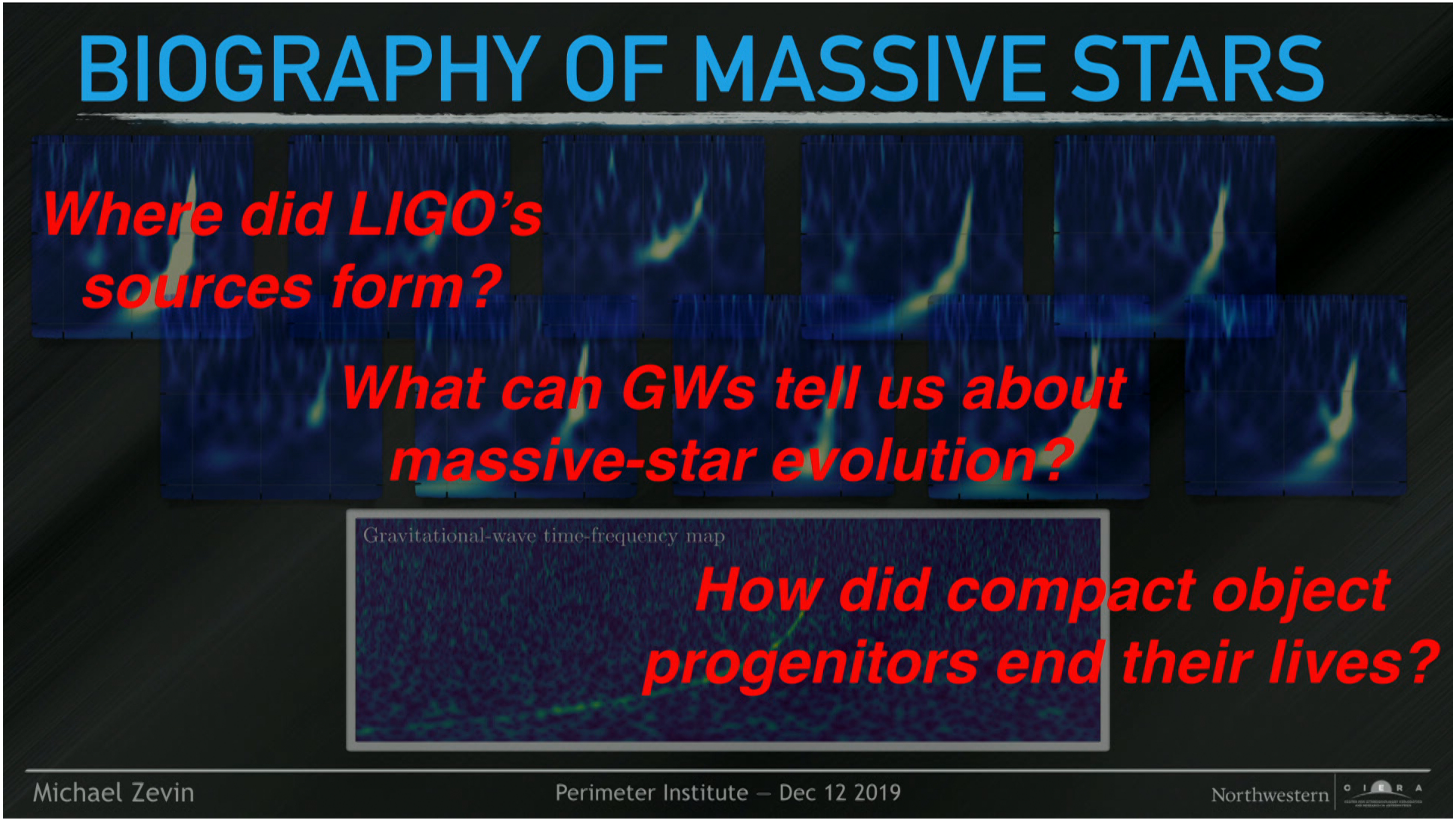
Christopher Berry (CIERA), Katie Breivik (CITA), Scotty Coughlin (CIERA), Wen-fai Fong (CIERA), Carl-Johan Haster (MIT), Luke Kelley (CIERA), Kyle Kremer (CIERA), Chris Pankow (CIERA), Enrico Ramirez-Ruiz (UCSC), Fred Rasio (CIERA), Carl Rodriguez (CfA), Johan Samsing (Princeton) Daniel Siegel (Perimeter), Benny Tsang (KITP)

Support:
NSF DGE-1007911

THE GROWING FAMILY



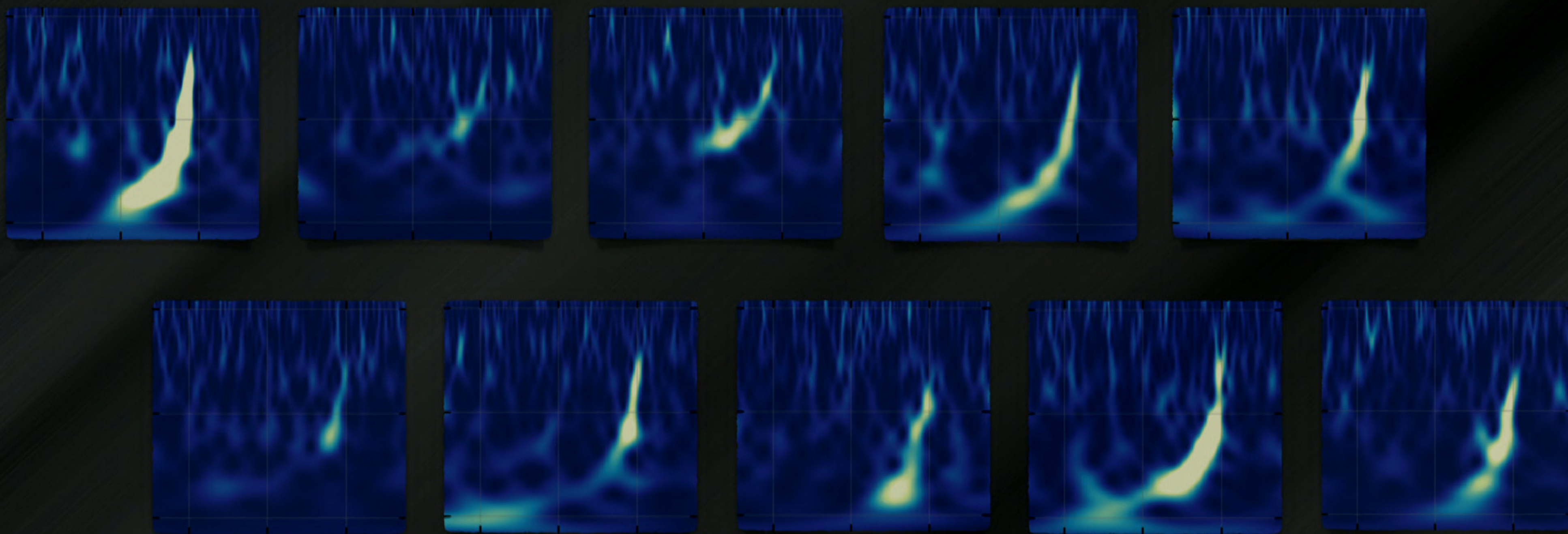



BIOGRAPHY OF MASSIVE STARS
Where did LIGO's sources form?
What can GWs tell us about massive-star evolution?
Gravitational-wave time-frequency map
How did compact object progenitors end their lives?
Michael Zevin
Perimeter Institute — Dec 12 2019
Northwestern
CIERA


BIOGRAPHY OF MASSIVE STARS
Whe
sou
ject
ives?
GraceDB |
gracedb.ligo.org/superevents/public/O3/
Incognito
S190408an
BBH (>99%)
April 8, 2019
18:18:02 UTC
GCN Circulars
Notices | VOE
1 per 1.1273e+10 years
S190412m
BBH (>99%)
April 12, 2019
05:30:44 UTC
GCN Circulars
Notices | VOE
1 per 1.883e+19 years
S190521r
BBH (>99%)
May 21, 2019
07:43:59 UTC
GCN Circulars
Notices | VOE
1 per 100.04 years
S190707q
BBH (>99%)
July 7, 2019
09:33:26 UTC
GCN Circulars
Notices | VOE
1 per 6018.9 years
S190828j
BBH (>99%)
Aug. 28, 2019
06:34:05 UTC
GCN Circulars
Notices | VOE
1 per 3.7395e+13 years
gracedb.ligo.org
Michael Zevin
Perimeter Institute — Dec 12 2019
Northwestern
CIERA


PART 1
Where and How
do LIGO’s black holes form?

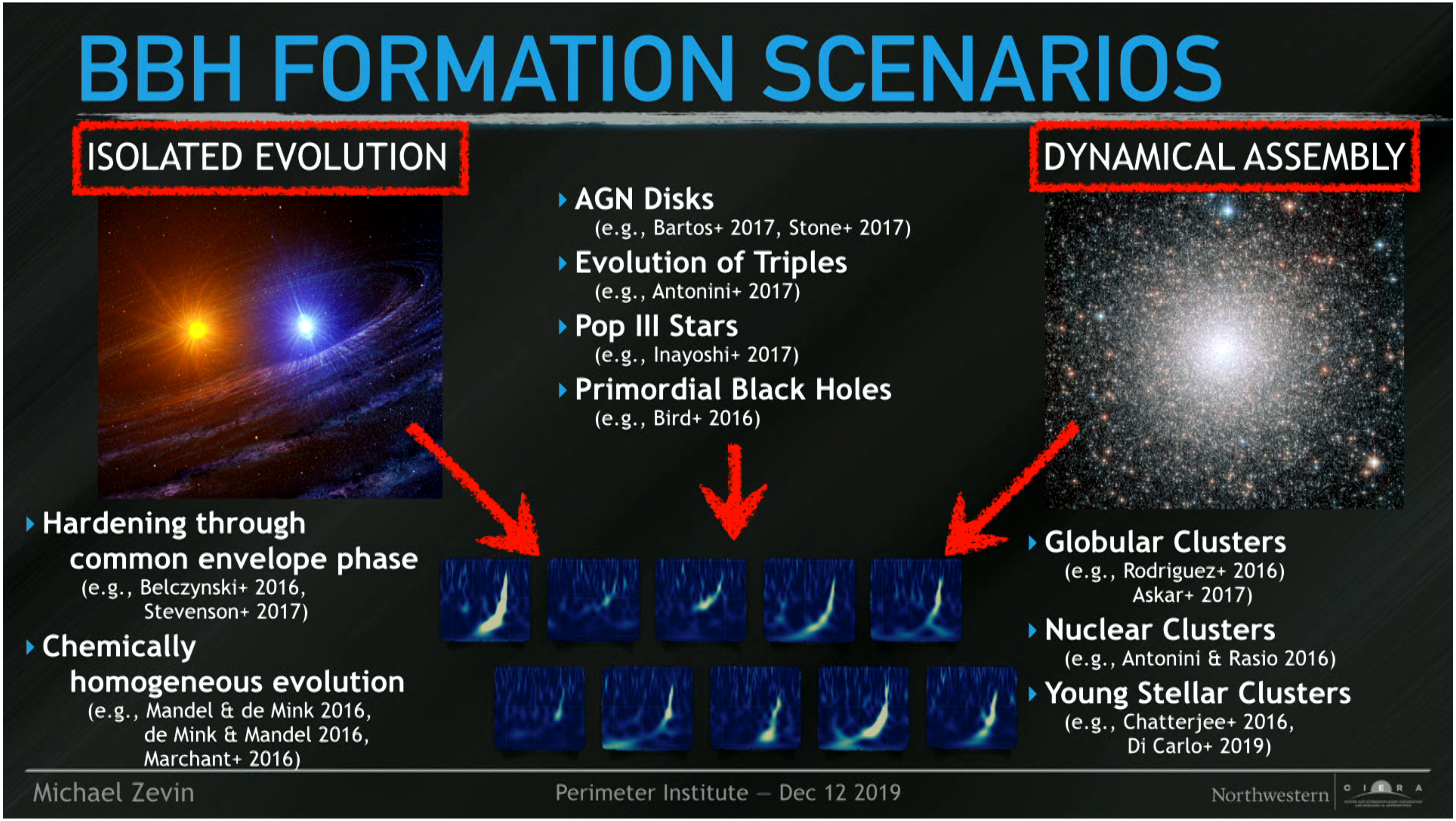
BBH FORMATION SCENARIOS



Michael Zevin

Perimeter Institute – Dec 12 2019

Northwestern

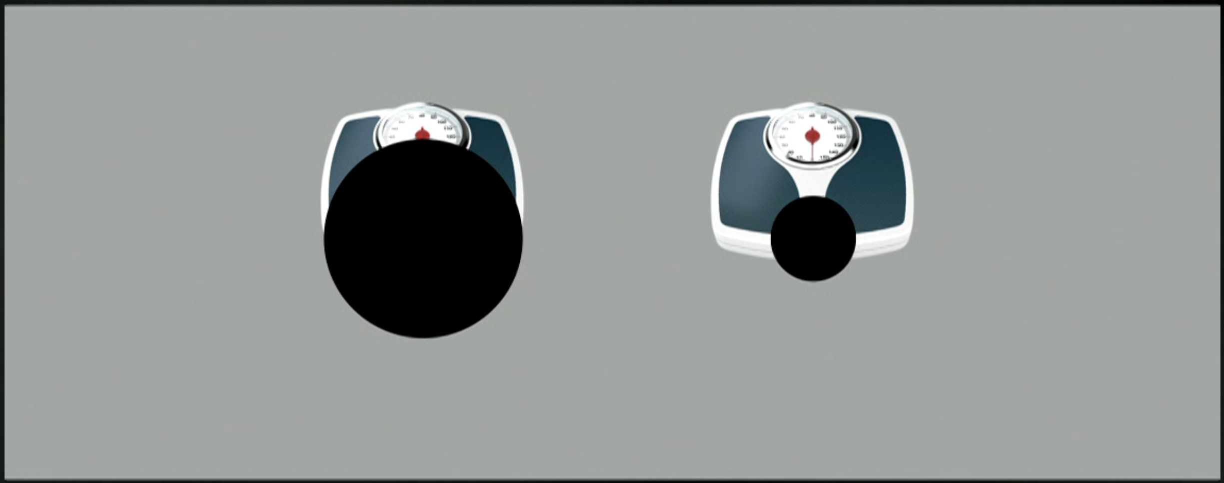


BBH FORMATION SCENARIOS
ISOLATED EVOLUTION
DYNAMICAL ASSEMBLY
AGN Disks
(e.g., Bartos+ 2017, Stone+ 2017)
Evolution of Triples
(e.g., Antonini+ 2017)
Pop III Stars
(e.g., Inayoshi+ 2017)
Primordial Black Holes
(e.g., Bird+ 2016)
Hardening through common envelope phase
(e.g., Belczynski+ 2016, Stevenson+ 2017)
Chemically homogeneous evolution
(e.g., Mandel & de Mink 2016, de Mink & Mandel 2016, Marchant+ 2016)
Globular Clusters
(e.g., Rodriguez+ 2016) Askar+ 2017)
Nuclear Clusters
(e.g., Antonini & Rasio 2016)
Young Stellar Clusters
(e.g., Chatterjee+ 2016, Di Carlo+ 2019)
Michael Zevin
Perimeter Institute — Dec 12 2019
Northwestern

What properties of black hole mergers are distinctive to a particular formation scenario?

masses?

mass ratios?



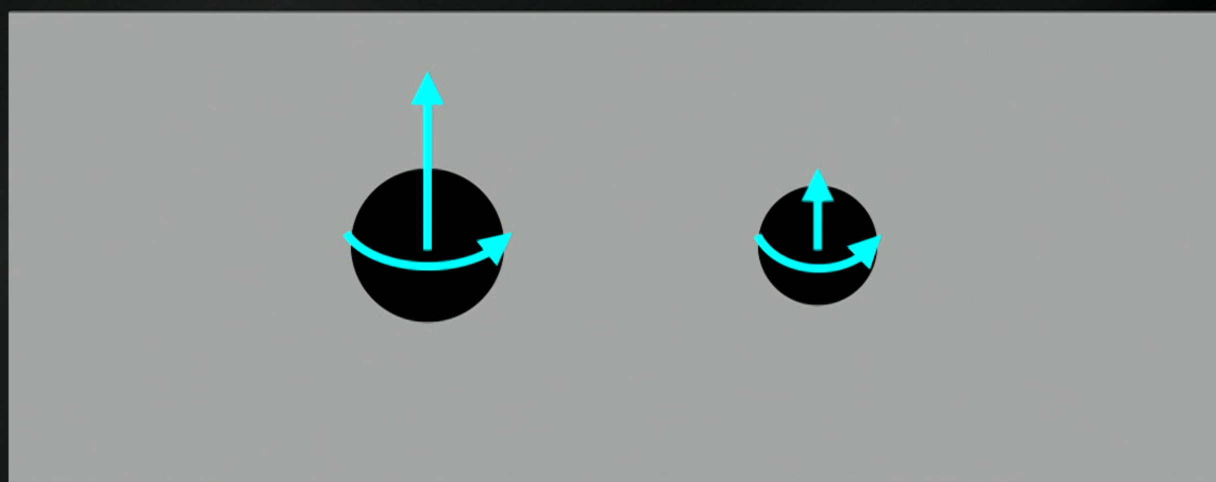
Michael Zevin   Perimeter Institute – Dec 12 2019   Northwestern | CIERA

What properties of black hole mergers are distinctive to a particular formation scenario?

masses?

spin magnitudes?

mass ratios?



Michael Zevin   Perimeter Institute — Dec 12 2019   Northwestern | CIERA

What properties of black hole mergers are distinctive to a particular formation scenario?

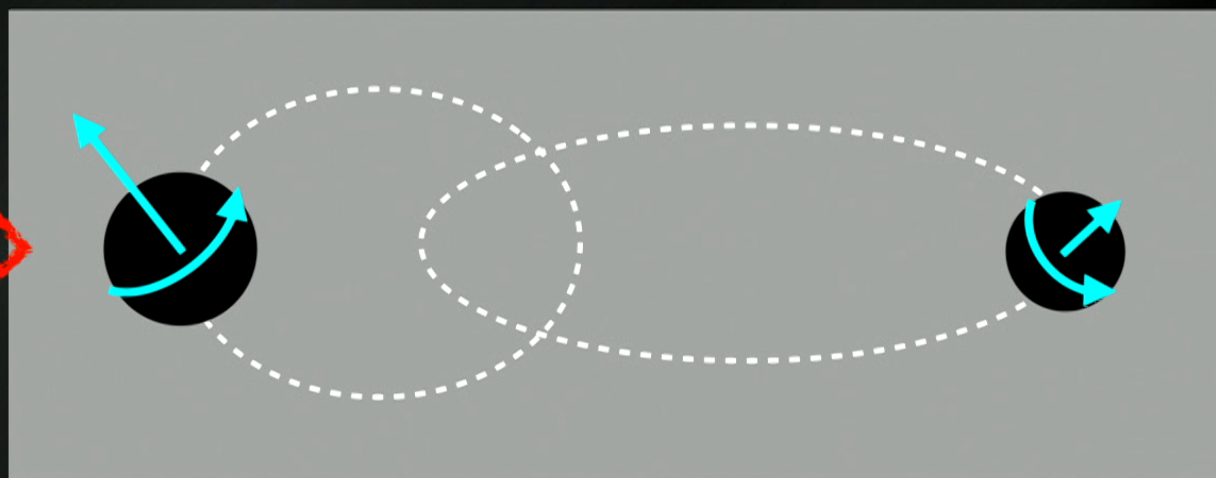
masses?

spin magnitudes?

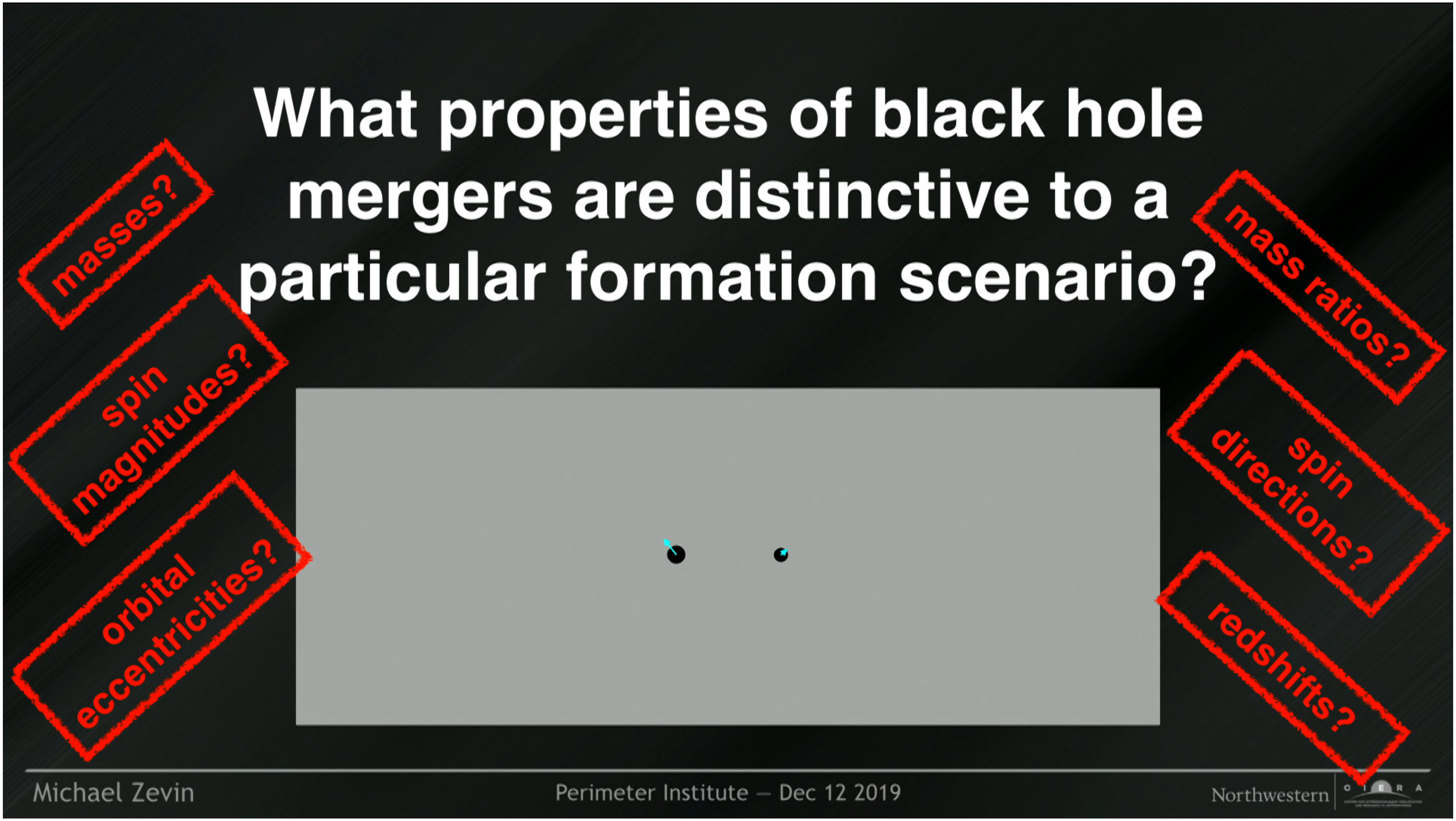
orbital eccentricities?

mass ratios?

spin directions?



Michael Zevin   Perimeter Institute – Dec 12 2019   Northwestern | CIERA


What properties of black hole mergers are distinctive to a particular formation scenario?
masses?
spin magnitudes?
orbital eccentricities?
mass ratios?
spin directions?
redshifts?
Michael Zevin
Perimeter Institute — Dec 12 2019
Northwestern
CIERA

What properties of black hole mergers are distinctive to a particular formation scenario?

masses?

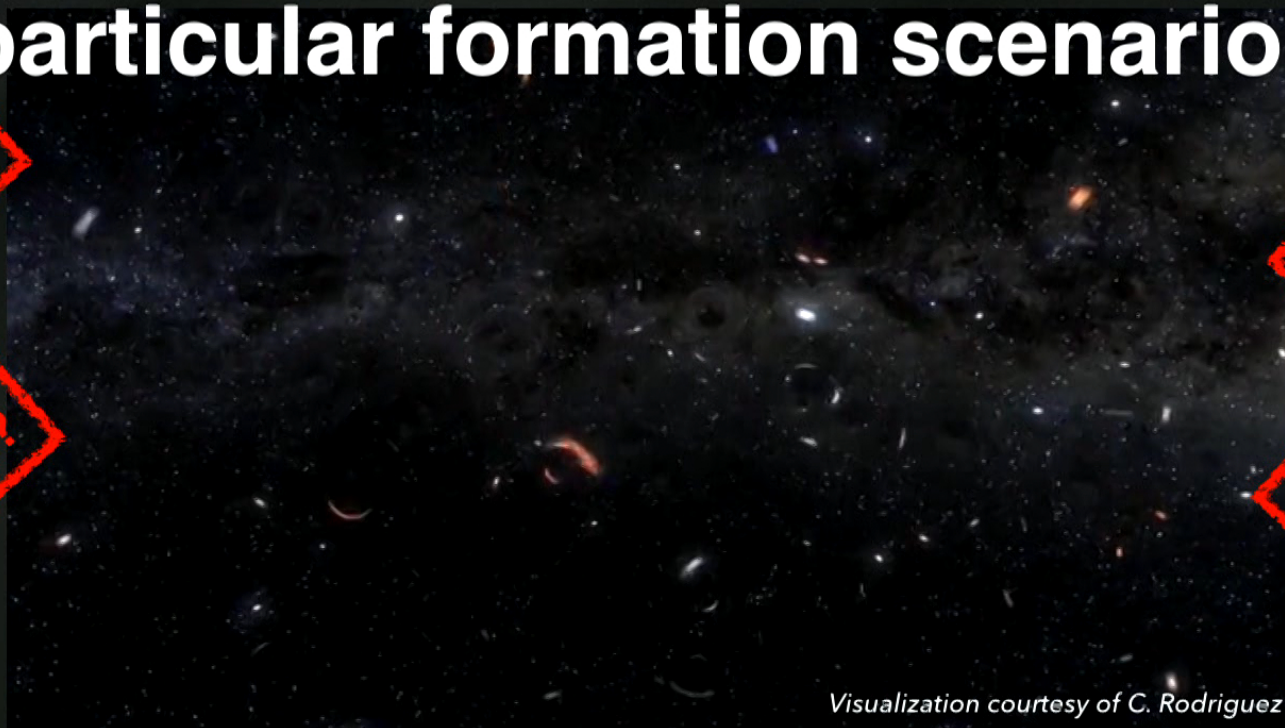
spin magnitudes?

orbital eccentricities?

mass ratios?

spin directions?

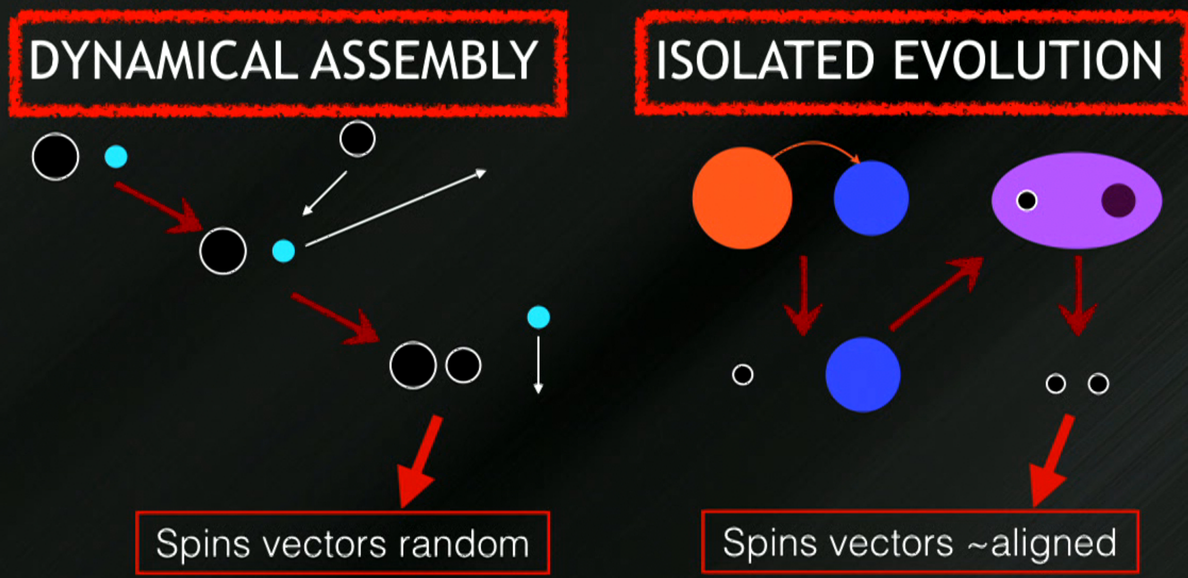
redshifts?

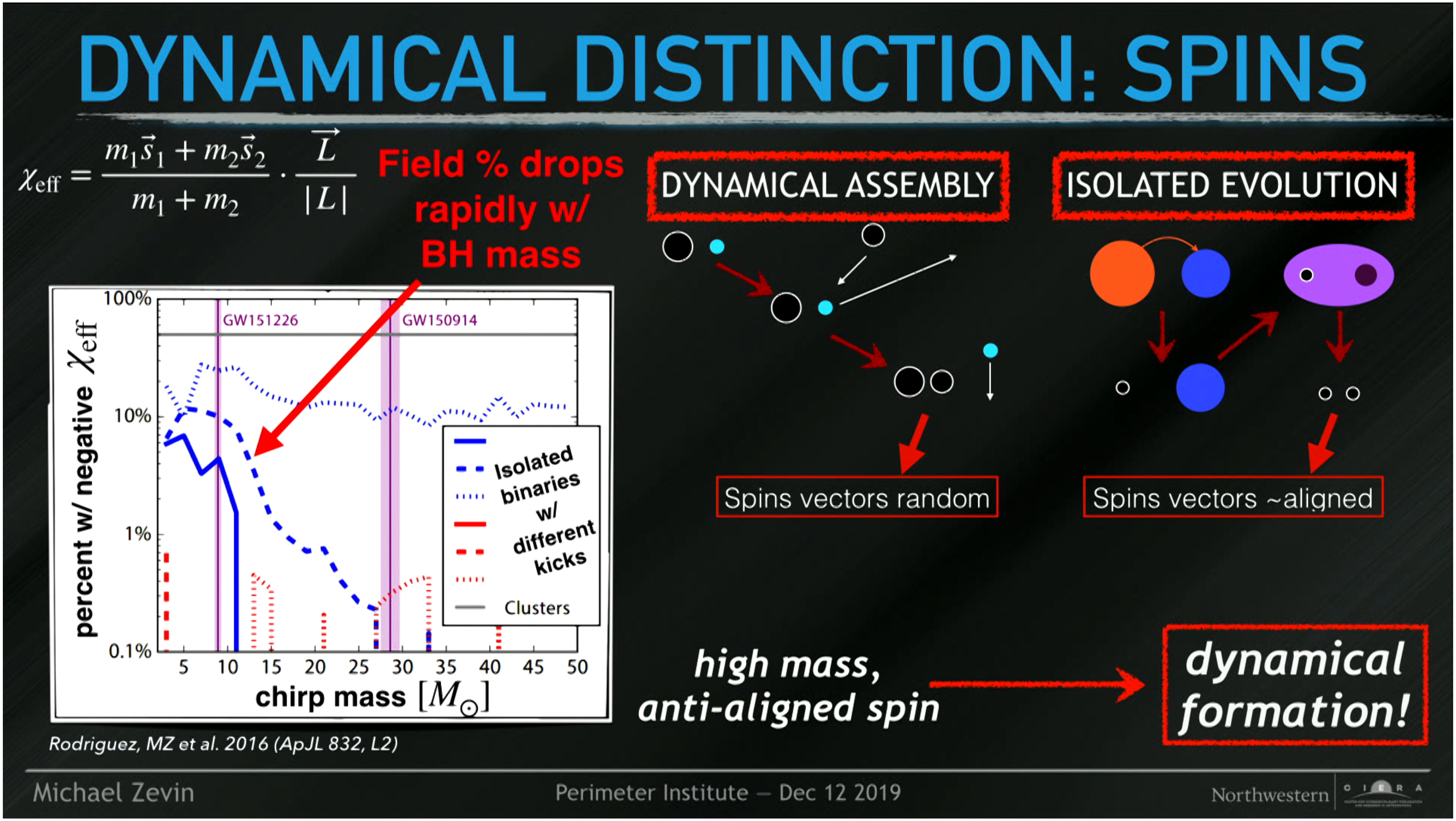


DYNAMICAL DISTINCTION: SPINS

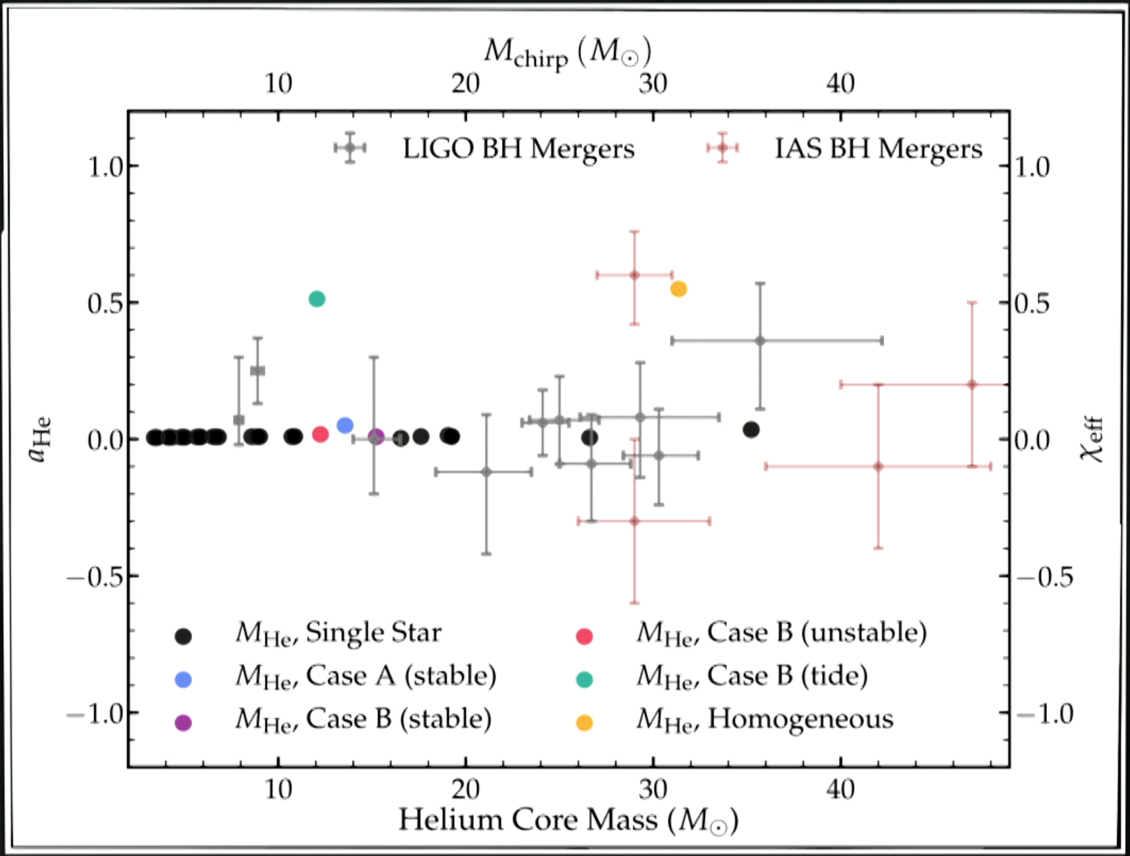
distinguishing spins between isolated and dynamical black holes

- Dynamically-assembled black holes form and evolve before meeting their final partners
  - ***relative spin orientations will be misaligned***
- Black holes from isolated binaries stay with their partners
  - ***retain memory of previous interactions***




DYNAMICAL DISTINCTION: SPINS
$\chi_{\rm eff} = \frac{m_1\vec{s}_1 + m_2\vec{s}_2}{m_1 + m_2} \cdot \frac{\vec{L}}{|L|}$
Field % drops rapidly w/ BH mass
100%
10%
1%
0.1%
percent w/ negative $\chi_{\rm eff}$
GW151226
GW150914
Isolated binaries w/ different kicks
Clusters
5 10 15 20 25 30 35 40 45 50
chirp mass $[M_\odot]$
Rodriguez, MZ et al. 2016 (ApJL 832, L2)
DYNAMICAL ASSEMBLY
ISOLATED EVOLUTION
Spins vectors random
Spins vectors ~aligned
high mass, anti-aligned spin
dynamical formation!
Michael Zevin
Perimeter Institute — Dec 12 2019
Northwestern
CIERA

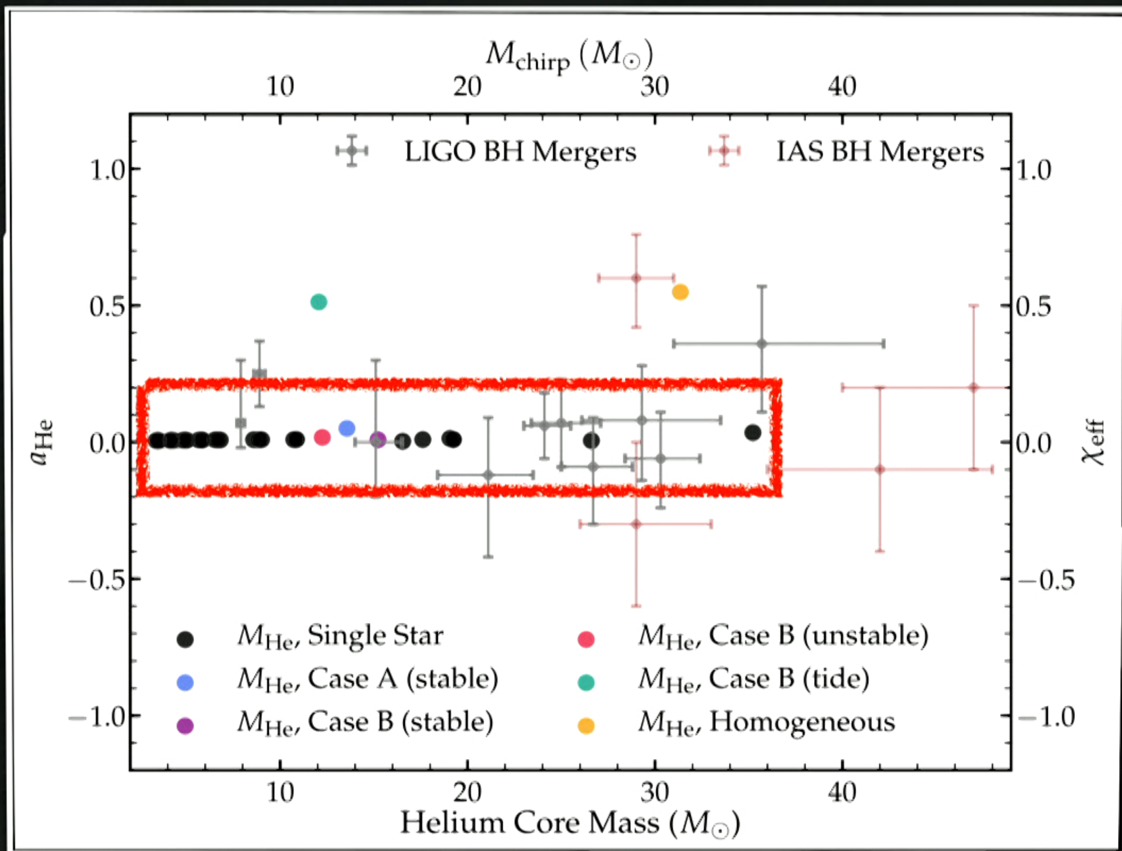
What if LIGO's black holes have low spins?



Fuller & Ma 2019 (ApJL 881, L1)

- Angular momentum transport in BH progenitors suggests efficient AM loss and ***low BH natal spins***
  Fuller & Ma 2019 (ApJL 881, L1)
- Since most BHs in clusters form as single stars or without significant binary interactions…

What if LIGO's black holes have low spins?

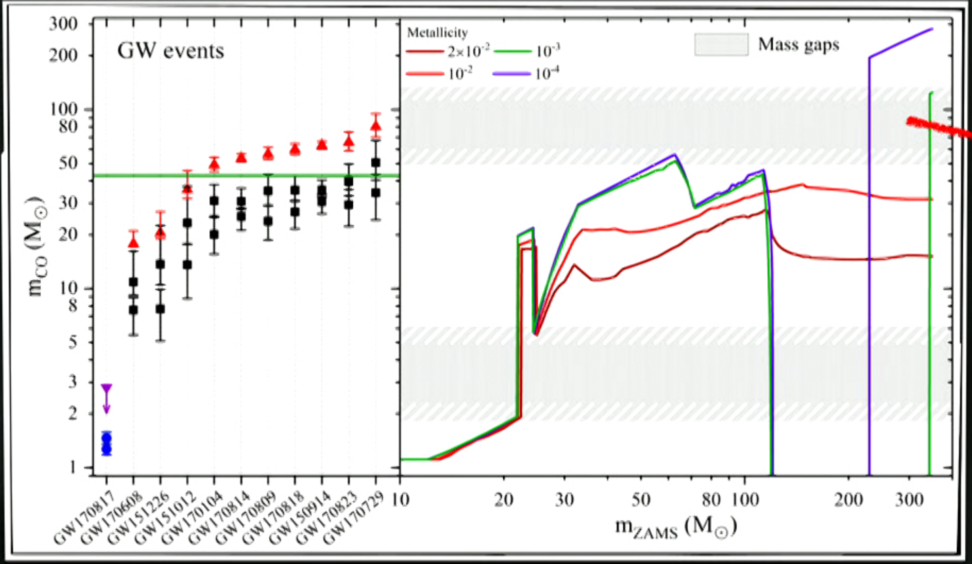


Fuller & Ma 2019 (ApJL 881, L1)

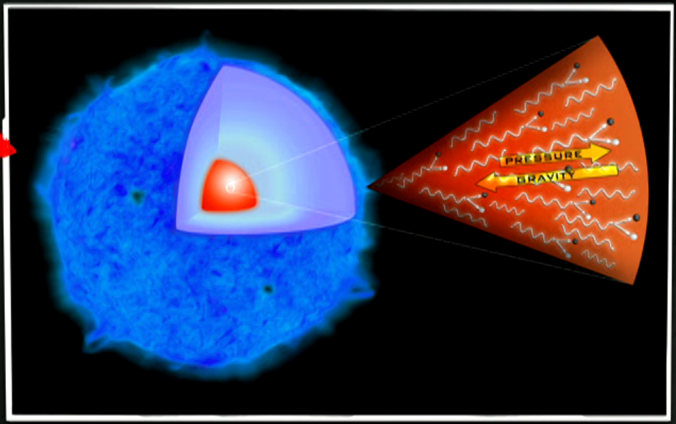
- Angular momentum transport in BH progenitors suggests efficient AM loss and ***low BH natal spins***
  Fuller & Ma 2019 (ApJL 881, L1)
- Since most BHs in clusters form as single stars or without significant binary interactions…

most black holes in clusters may have low natal spins!

THE "UPPER MASS GAP"



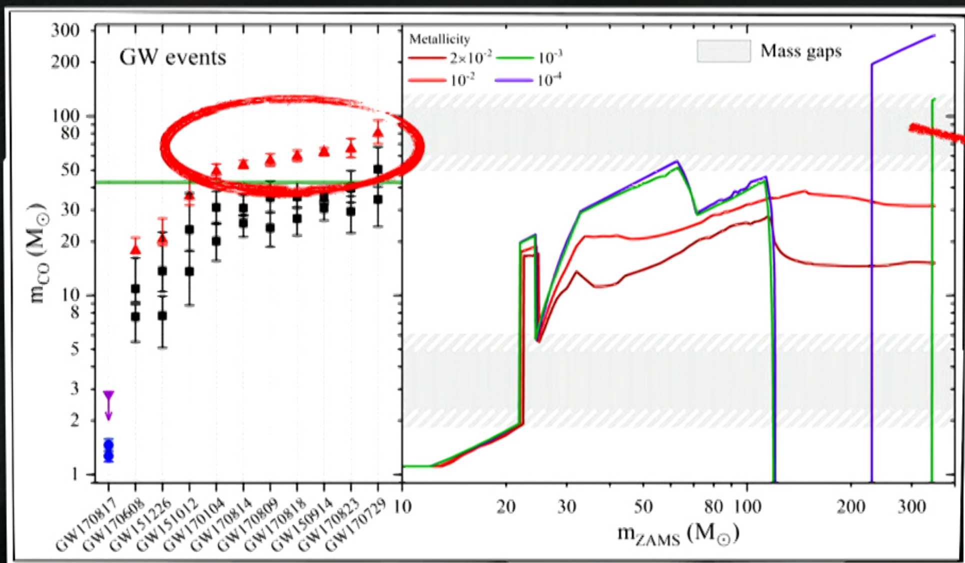
LVC 2019 (ApJL, in press)



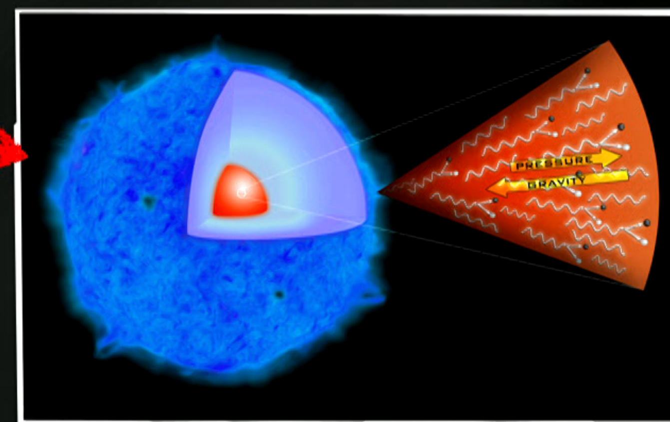
Wikipedia Commons

- In massive helium cores, conversion of photons to electron-positron pairs remove pressure support in the core, leading to ***pulsational pair instabilities*** or ***pair instability supernovae***
- Predict ***dearth of black holes with masses between*** $\sim 50 - 130\,M_\odot$ ***(e.g., Woosley 2017, ApJ 836, 2)***

THE "UPPER MASS GAP"



LVC 2019 (ApJL, in press)



Wikipedia Commons

- In massive helium cores, conversion of photons to electron-positron pairs remove pressure support in the core, leading to ***pulsational pair instabilities*** or ***pair instability supernovae***
- Predict ***dearth of black holes with masses between*** $\sim 50 - 130\,\mathrm{M}_\odot$ ***(e.g., Woosley 2017, ApJ 836, 2)***

GW RECOIL KICKS

can a merger product stay bound in a cluster?

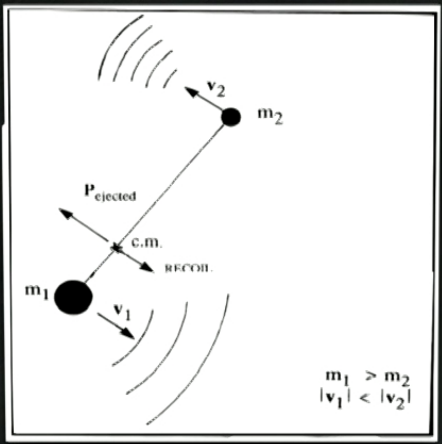


Figure from Wiseman 1992

- Merging compact binary systems receive a ***recoil kick***, due to anisotropies in GW emission
  e.g., Favata, Hughes, & Holz 2004 (ApJL 607, 1)
- Magnitude of recoil kick dependent on ***mass ratio*** and component ***spin magnitude***

GW RECOIL KICKS

can a merger product stay bound in a cluster?

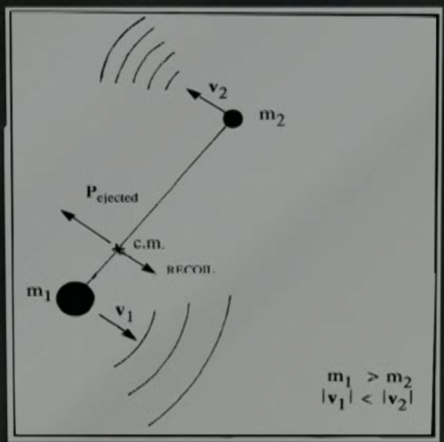
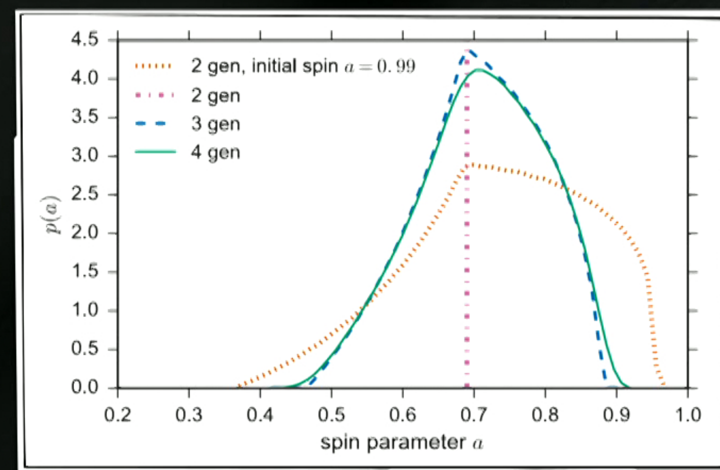


Figure from Wiseman 1992

- Merging compact binary systems receive a ***recoil kick***, due to anisotropies in GW emission
  - e.g., Favata, Hughes, & Holz 2004 (ApJL 607, 1)
- Magnitude of recoil kick dependent on ***mass ratio*** and component ***spin magnitude***



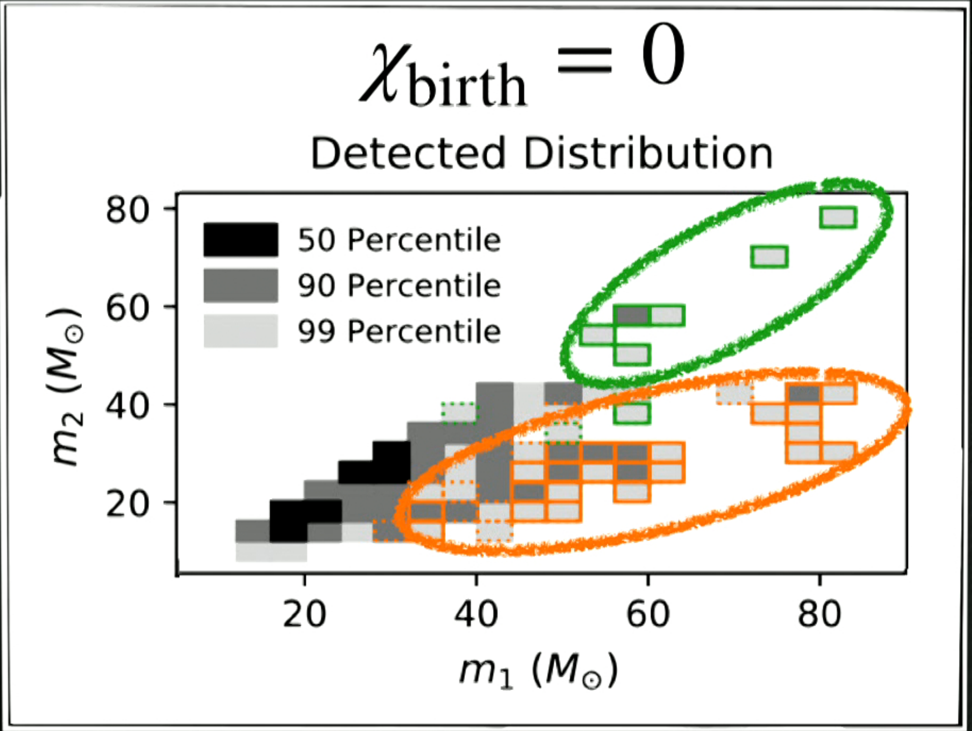
Fishbach, Holz, & Farr 2017 (ApJ 840, L24)

- If spin magnitudes for BBHs in clusters are low, the recoil kicks are suppressed
- Merger product can remain in the cluster, and merge as a ***highly spinning***, ***massive system***
  - e.g., Fishbach, Holz, & Farr (ApJL 840, L24), Gerosa & Berti (PRD 95, 124046)

DYNAMICAL DISTINCTION: MASSES

"hierarchical" black hole mergers & masses in the upper mass gap

- If black holes are born with low spins, ***merger products can remain in the cluster and go on to merge again***, either with a 1st-gen BH or another 2nd-gen BH
- These 2nd-generation black holes can ***occupy the PISN mass gap*** and ***have appreciable spins of $a \sim 0.7$***
- If natal spins are low, >20% of detectable mergers from globular clusters have a 2G black hole, with **7% having $M \gtrsim 55\,\mathrm{M}_\odot$**



Rodriguez, MZ et al. 2019 (PRD 100, 043027)

DYNAMICAL DISTINCTION: MASSES

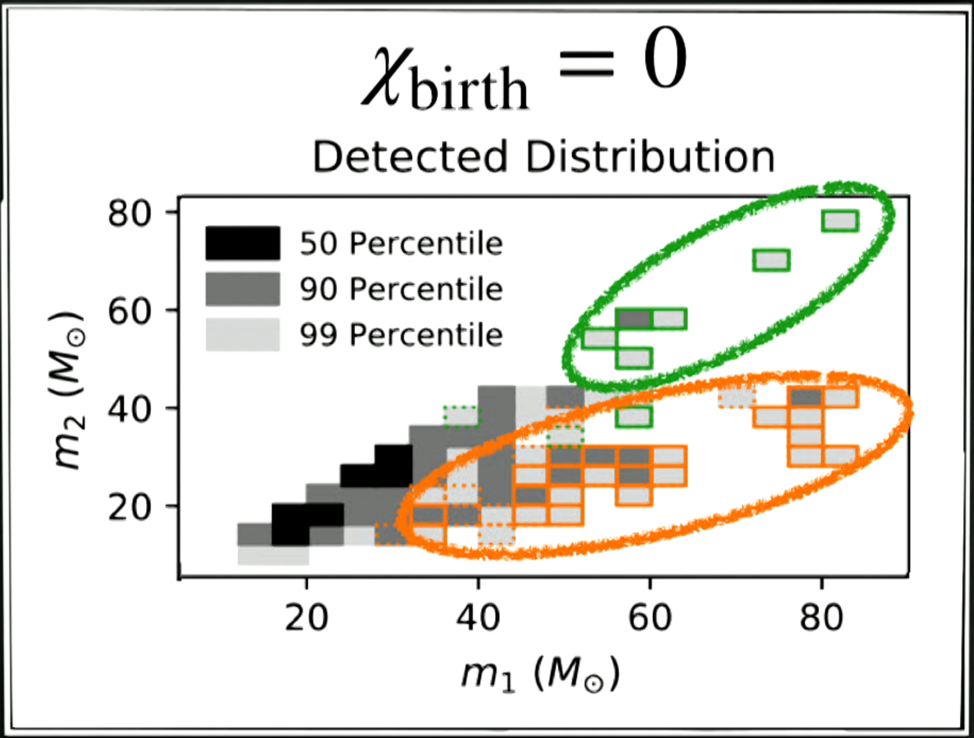
"hierarchical" black hole mergers & masses in the upper mass gap

Option A:

*Component BHs have **appreciable spins** and are not retained in the cluster after their first merger, but **a significant fraction have negative** $\chi_{\rm eff}$*

Option B:

Component BHs have **low (or no) natal spin**, but are more likely retained in the cluster after their first merger, leading to **second-generation mergers with high masses and component spins**

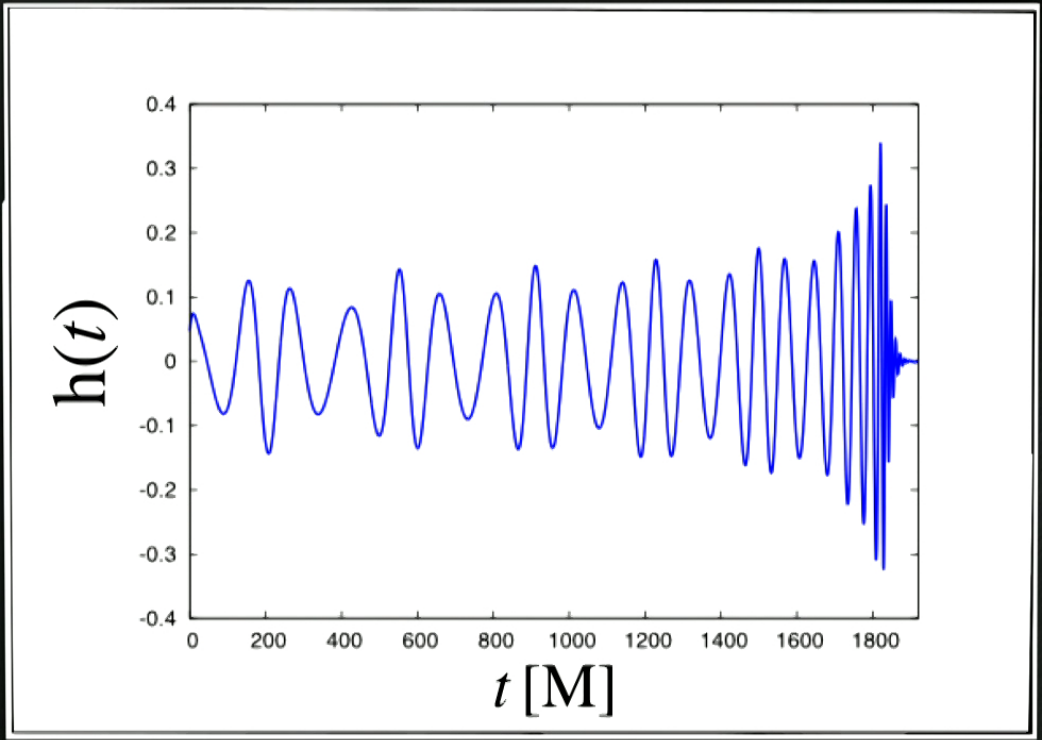


Rodriguez, MZ et al. 2019 (PRD 100, 043027)

What about eccentricity?

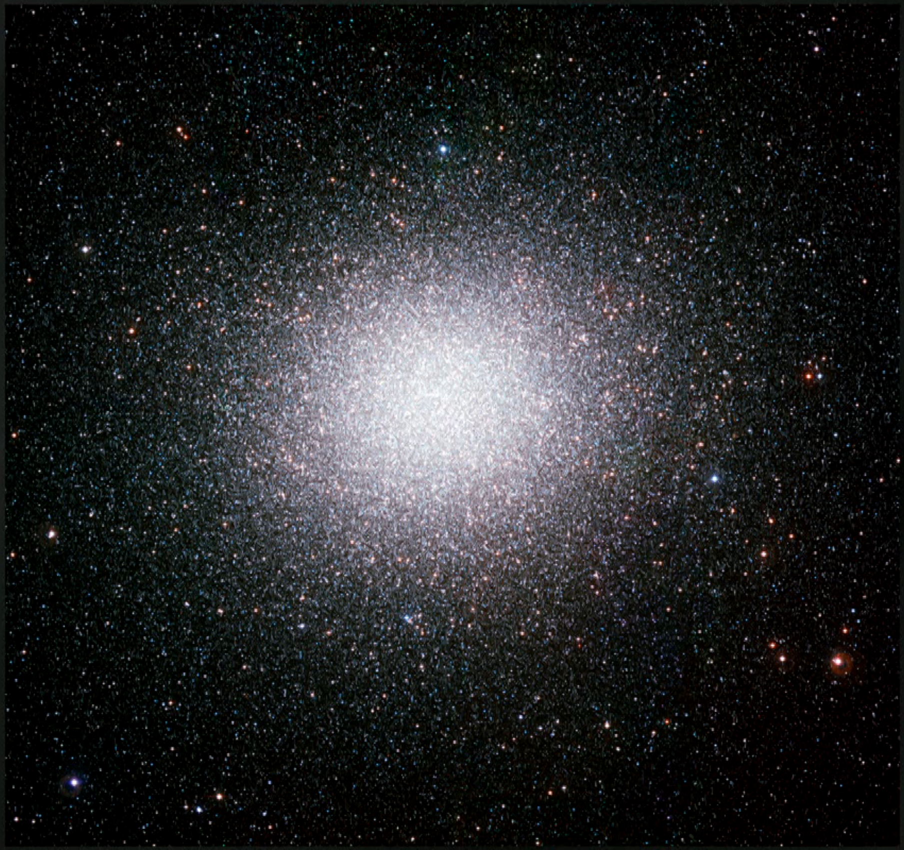
$$e \propto a^{19/12}$$

$$t_{\rm GW} \propto a^4(1 - e^2)^{7/2}$$



NCSA/XSEDE/E. Huerta

STRONG INTERACTIONS IN CLUSTERS



Michael Zevin

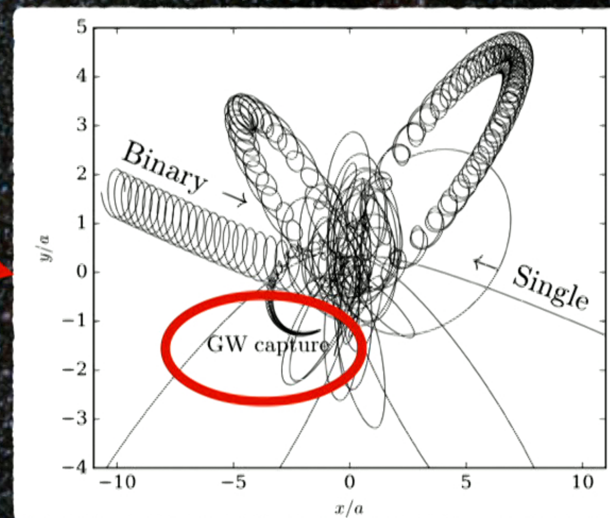
Perimeter Institute – Dec 12 2019

Northwestern

STRONG INTERACTIONS IN CLUSTERS

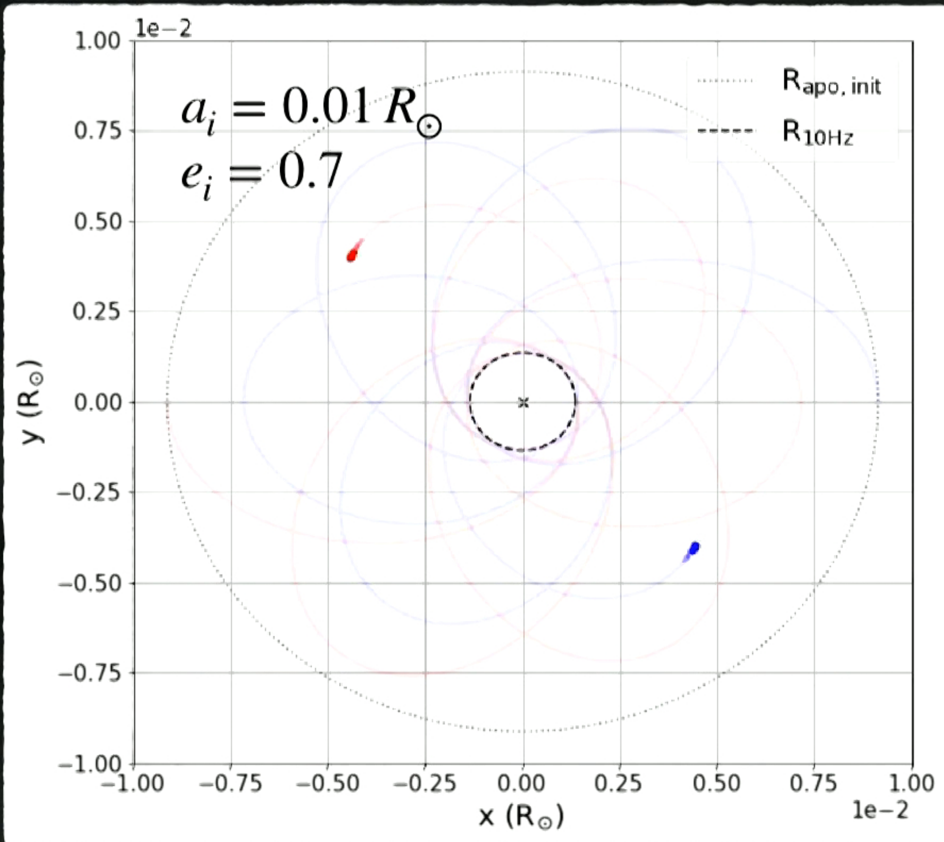
- Resonating interactions can facilitate highly relativistic close encounters…**which can result in rapid, highly-eccentric black hole mergers**

  see e.g., Samsing et al. 2014 (ApJ 784, 71); Samsing & Ramirez-Ruiz 2017 (ApJ 840, L14); Rodriguez et al. 2018 (PRL 120, 151101); D'Orazio & Samsing 2018 (MNRAS 481, 2775) MZ et al. 2019 (ApJ 871, 91)



Samsing et al. 2017 (PRD 97, 103014)

POST-NEWTONIAN DYNAMICS



$$\vec{F} = m(\vec{a}_{\mathrm{N}} + \vec{a}_{1\mathrm{PN}} + \vec{a}_{2\mathrm{PN}} + \vec{a}_{2.5\mathrm{PN}} + \ldots)$$

periapse precession

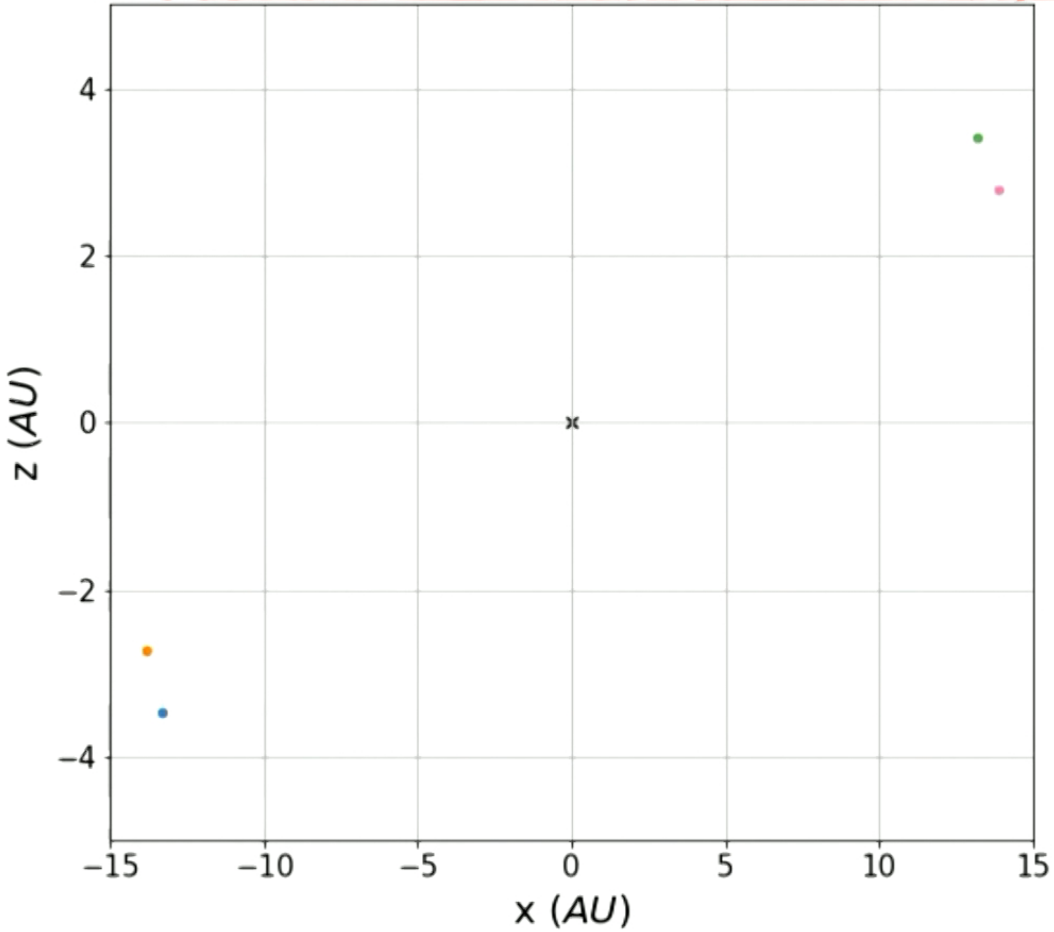
$$\underline{a}_2 = \frac{Gm_2}{r^2}\Big\{\underline{n}\Big[-v_1^2 - 2v_2^2 + 4v_1v_2 + \frac{3}{2}(nv_2)^2 + 5\Big(\frac{Gm_1}{r}\Big) + 4\Big(\frac{Gm_2}{r}\Big)\Big] + (\underline{v}_1 - \underline{v}_2)[4nv_1 - 3nv_2]\Big\}$$

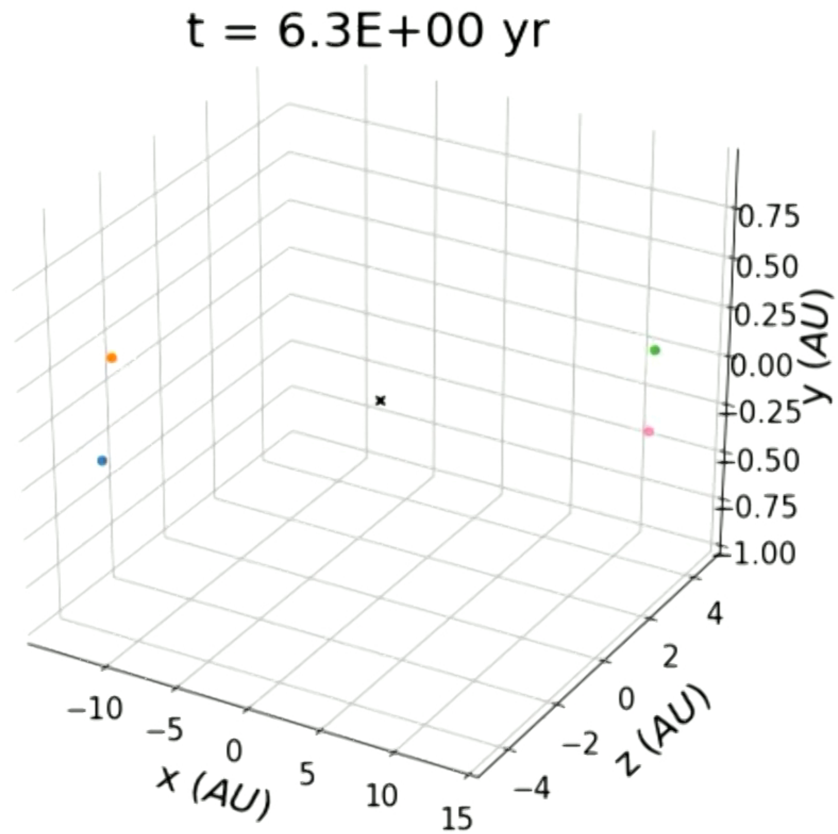
$$\begin{aligned}\underline{a}_4 = \frac{Gm_2}{r^2}\Big\{\underline{n}\Big[&-2v_2^4 + 4v_2^2(v_1v_2) - 2(v_1v_2)^2 \\ &+ \frac{3}{2}v_1^2(nv_2)^2 + \frac{9}{2}v_2^2(nv_2)^2 - 6(v_1v_2)(nv_2)^2 \\ &- \frac{15}{8}(nv_2)^4 + \Big(\frac{Gm_1}{r}\Big)\Big(-\frac{15}{4}v_1^2 + \frac{5}{4}v_2^2 - \frac{5}{2}v_1v_2 \\ &+ \frac{39}{2}(nv_1)^2 - 39(nv_1)(nv_2) + \frac{17}{2}(nv_2)^2\Big) \\ &+ \Big(\frac{Gm_2}{r}\Big)(4v_2^2 - 8v_1v_2 + 2(nv_1)^2 \\ &- 4(nv_1)(nv_2) - 6(nv_2)^2)\Big] \\ &+ (\underline{v}_1 - \underline{v}_2)\Big[v_1^2(nv_2) + 4v_2^2(nv_1) - 5v_2^2(nv_2) \\ &- 4(v_1v_2)(nv_1) + 4(v_1v_2)(nv_2) - 6(nv_1)(nv_2)^2 \\ &+ \frac{9}{2}(nv_2)^3 + \Big(\frac{Gm_1}{r}\Big)\Big(-\frac{63}{4}nv_1 + \frac{55}{4}nv_2\Big) \\ &+ \Big(\frac{Gm_2}{r}\Big)(-2nv_1 - 2nv_2)\Big]\Big\} \\ &+ \frac{G^3m_2}{r^4}\underline{n}\Big[-\frac{57}{4}m_1^2 - 9m_2^2 - \frac{69}{2}m_1m_2\Big],\end{aligned}$$

orbital decay (GWs)

$$\begin{aligned}\underline{a}_5 = \frac{4}{5}\frac{G^2m_1m_2}{r^3}\Big\{&(\underline{v}_1 - \underline{v}_2)\Big[-(\underline{v}_1 - \underline{v}_2)^2 + 2\Big(\frac{Gm_1}{r}\Big) - 8\Big(\frac{Gm_2}{r}\Big)\Big] \\ &+ \underline{n}(nv_1 - nv_2)\Big[3(\underline{v}_1 - \underline{v}_2)^2 - 6\Big(\frac{Gm_1}{r}\Big) + \frac{52}{3}\Big(\frac{Gm_2}{r}\Big)\Big]\Big\}\end{aligned}$$

“Resonating” binary-binary BH interaction leading to GW capture and inspiral

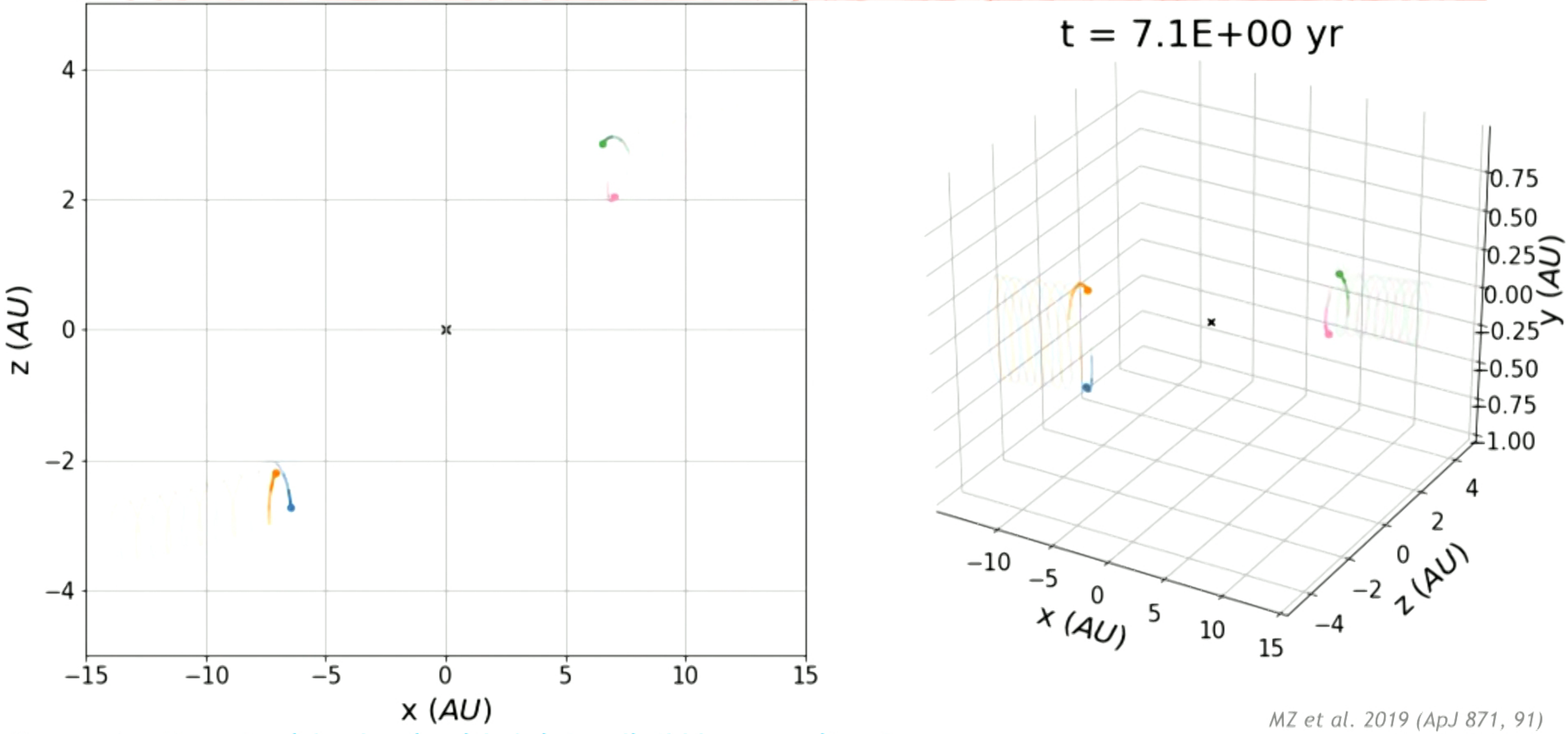




More animations at michaelzevin.github.io/media/bbh_progenitors/

MZ et al. 2019 (ApJ 871, 91)
arXiv: 1810:00901

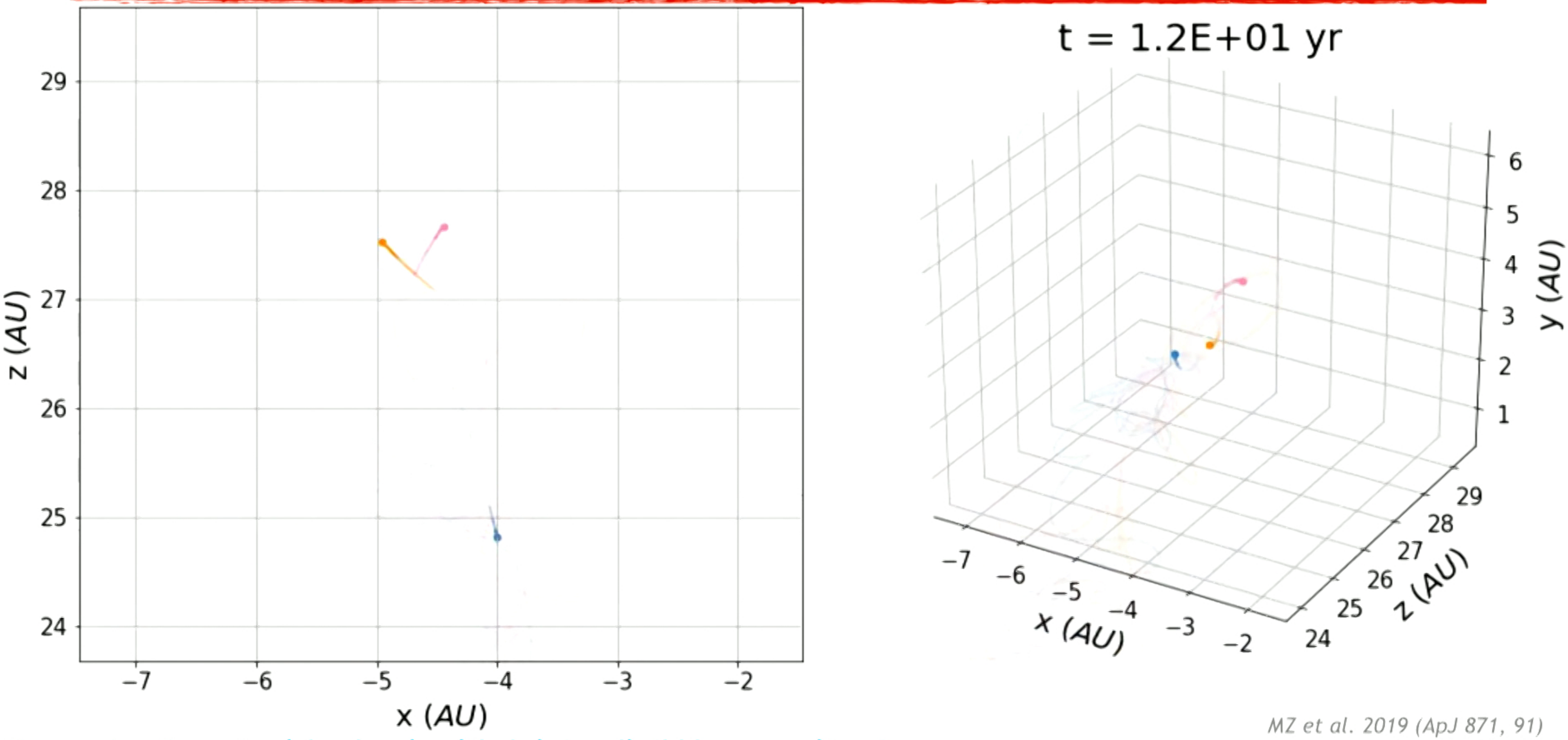
“Resonating” binary-binary BH interaction leading to GW capture and inspiral



MZ et al. 2019 (ApJ 871, 91)
arXiv: 1810:00901

More animations at michaelzevin.github.io/media/bbh_progenitors/

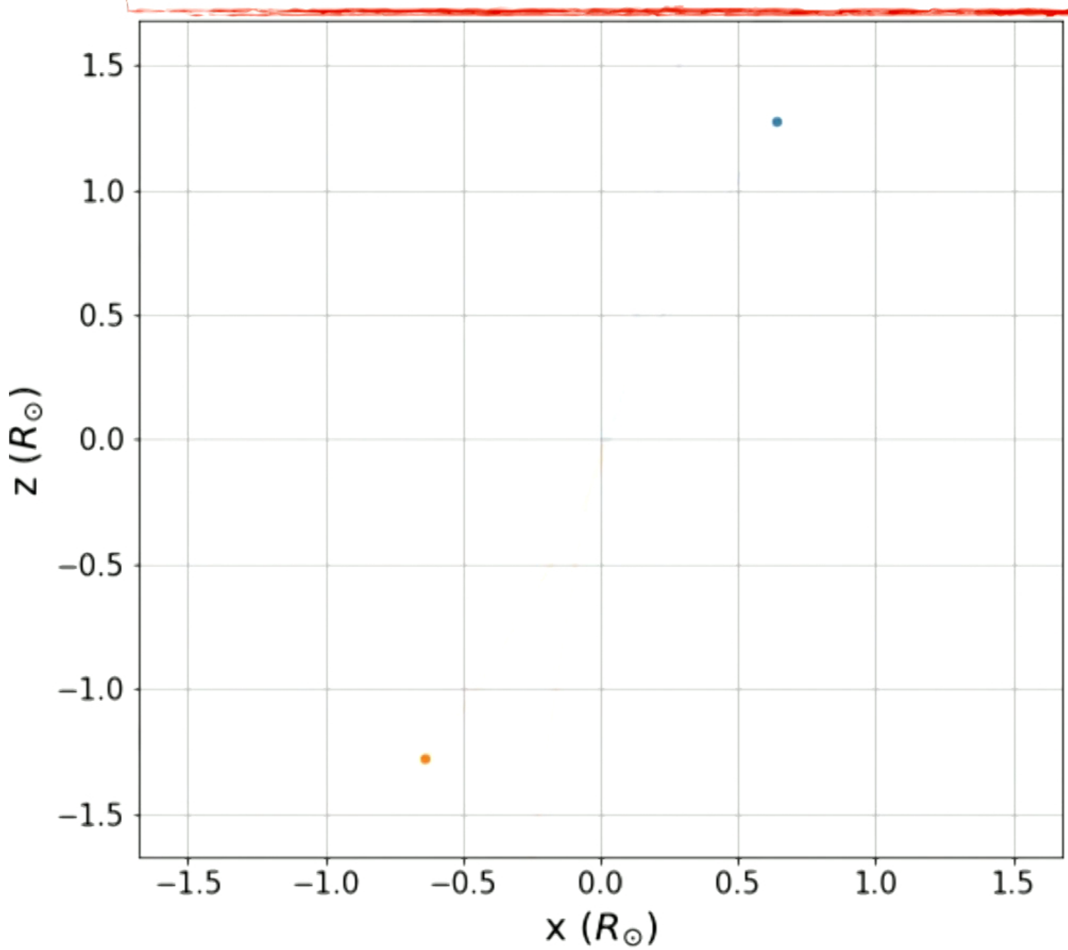
“Resonating” binary-binary BH interaction leading to GW capture and inspiral

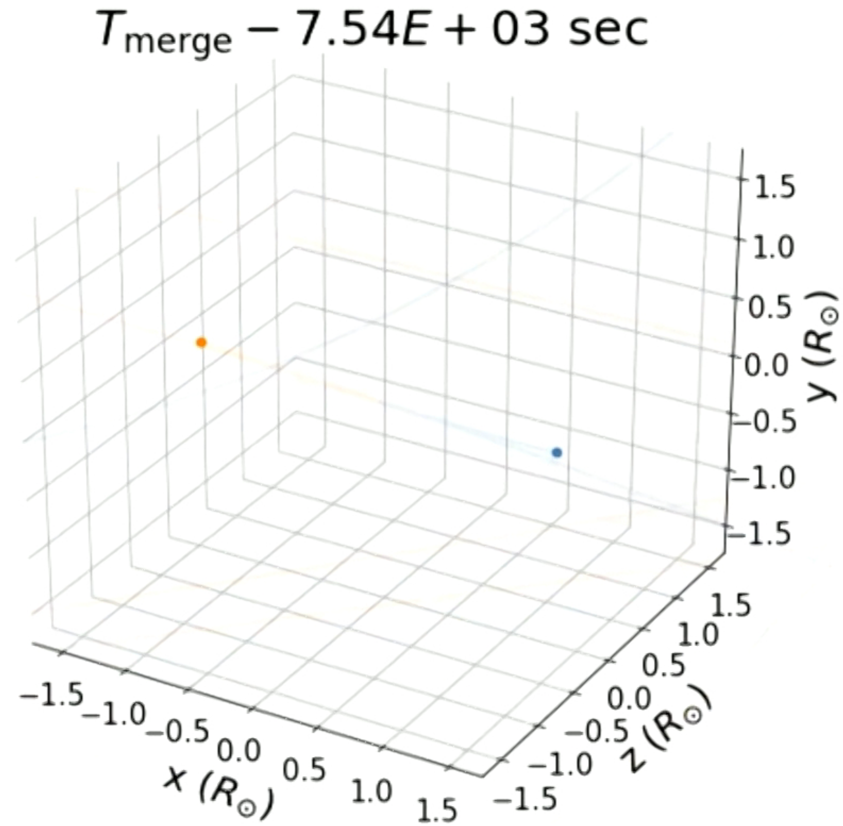


More animations at michaelzevin.github.io/media/bbh_progenitors/

MZ et al. 2019 (ApJ 871, 91)
arXiv: 1810:00901

"Resonating" binary-binary BH interaction leading to GW capture and inspiral

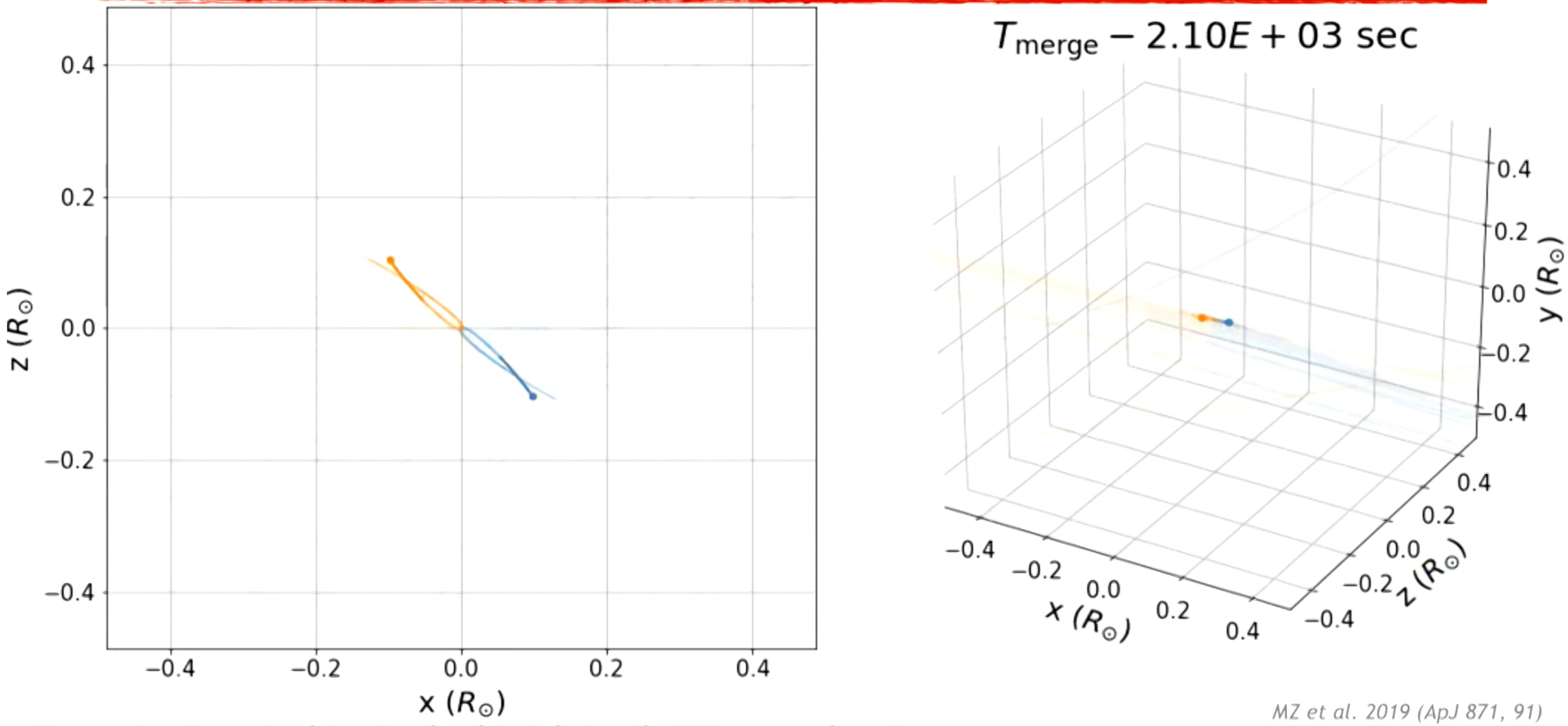




More animations at michaelzevin.github.io/media/bbh_progenitors/

MZ et al. 2019 (ApJ 871, 91)
arXiv: 1810:00901

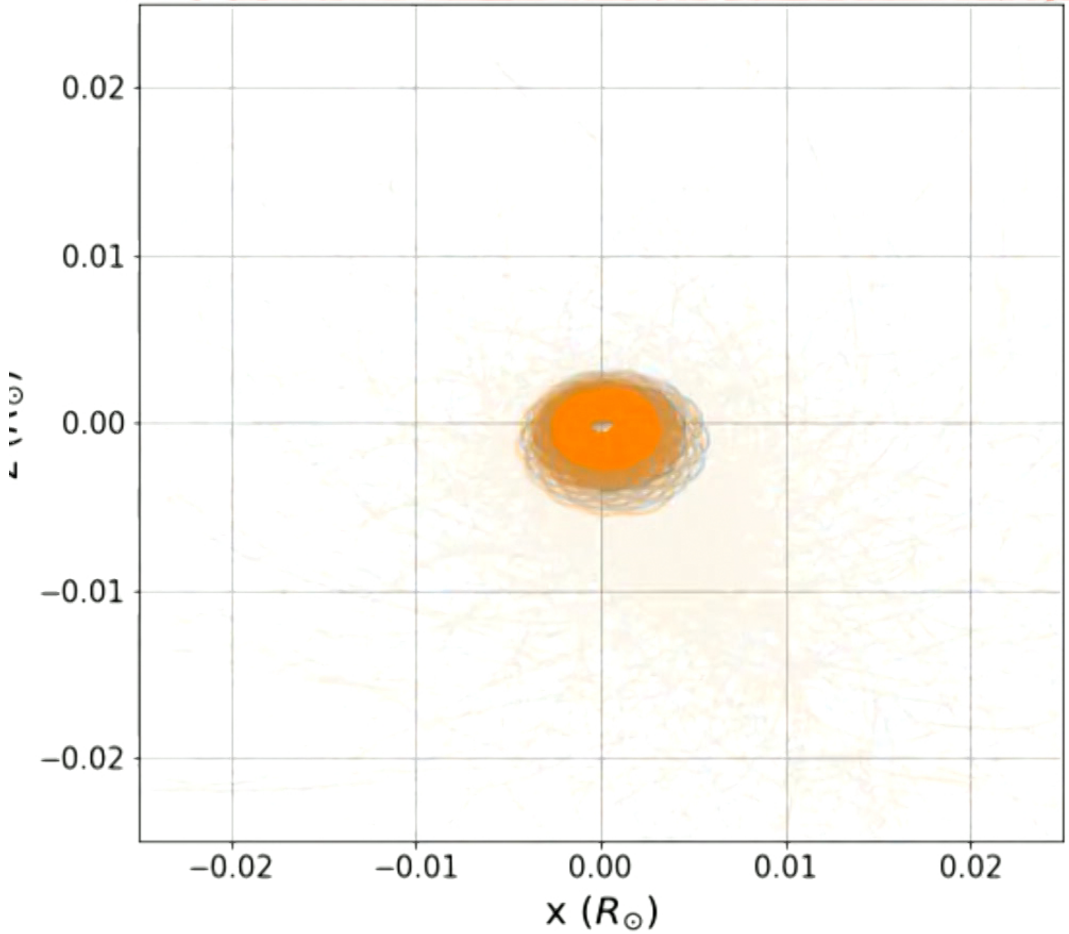
“Resonating” binary-binary BH interaction leading to GW capture and inspiral

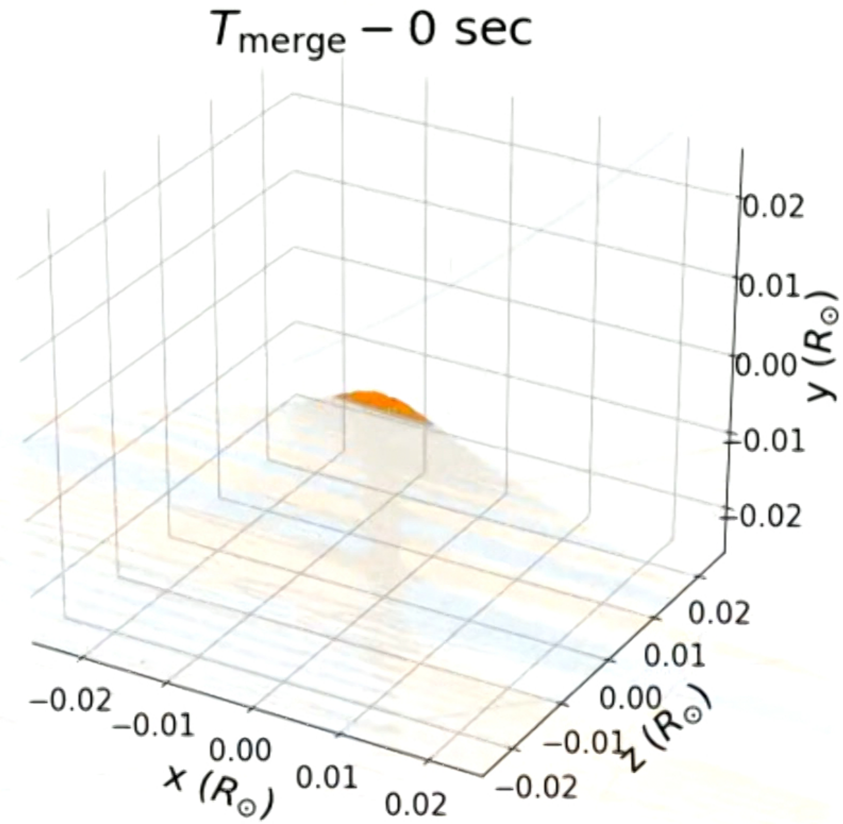


More animations at michaelzevin.github.io/media/bbh_progenitors/

MZ et al. 2019 (ApJ 871, 91)
arXiv: 1810:00901

"Resonating" binary-binary BH interaction leading to GW capture and inspiral



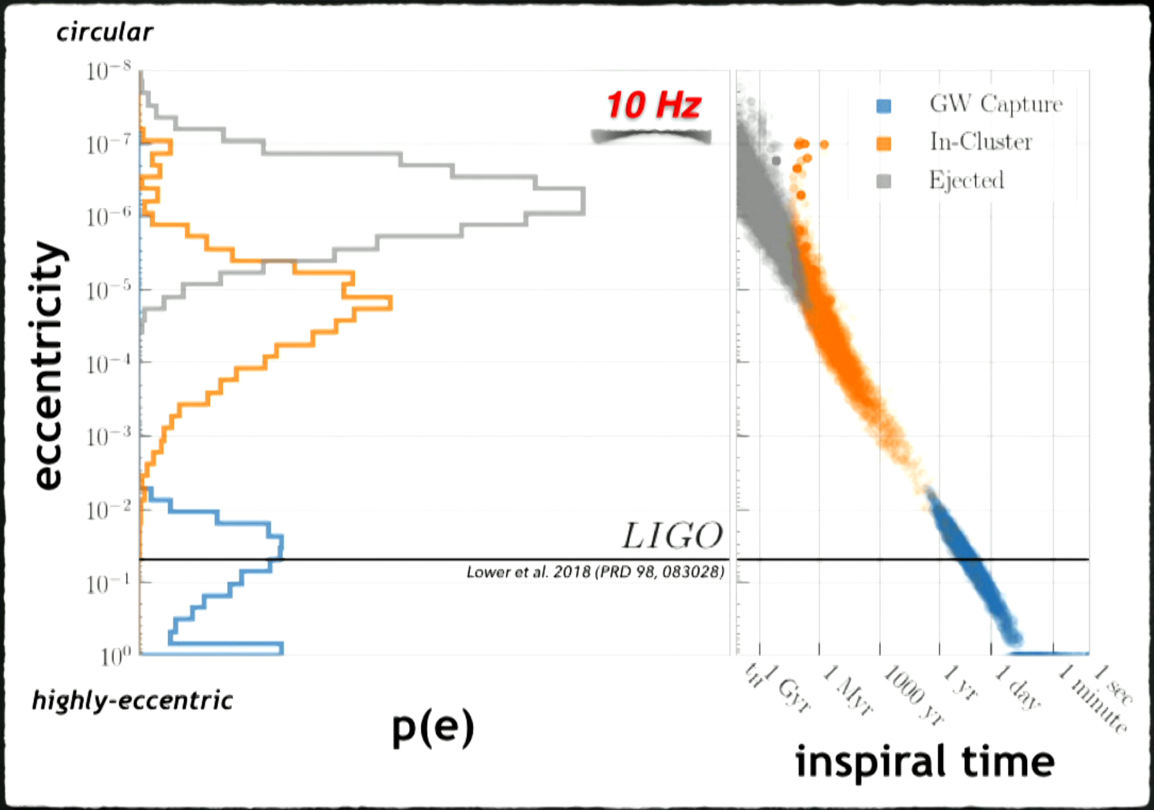


MZ et al. 2019 (ApJ 871, 91)
arXiv: 1810:00901

More animations at michaelzevin.github.io/media/bbh_progenitors/

DYNAMICAL DISTINCTION: ECCENTRICITY

- Three distinct populations of eccentric mergers from clusters: GW Captures, In-Cluster Mergers, and Ejected Mergers
- GW captures induced during resonant interaction maintain **appreciable eccentricities in the LIGO band**
- ~**10%** of mergers from GW captures, ~**50%** of which have measurable eccentricity

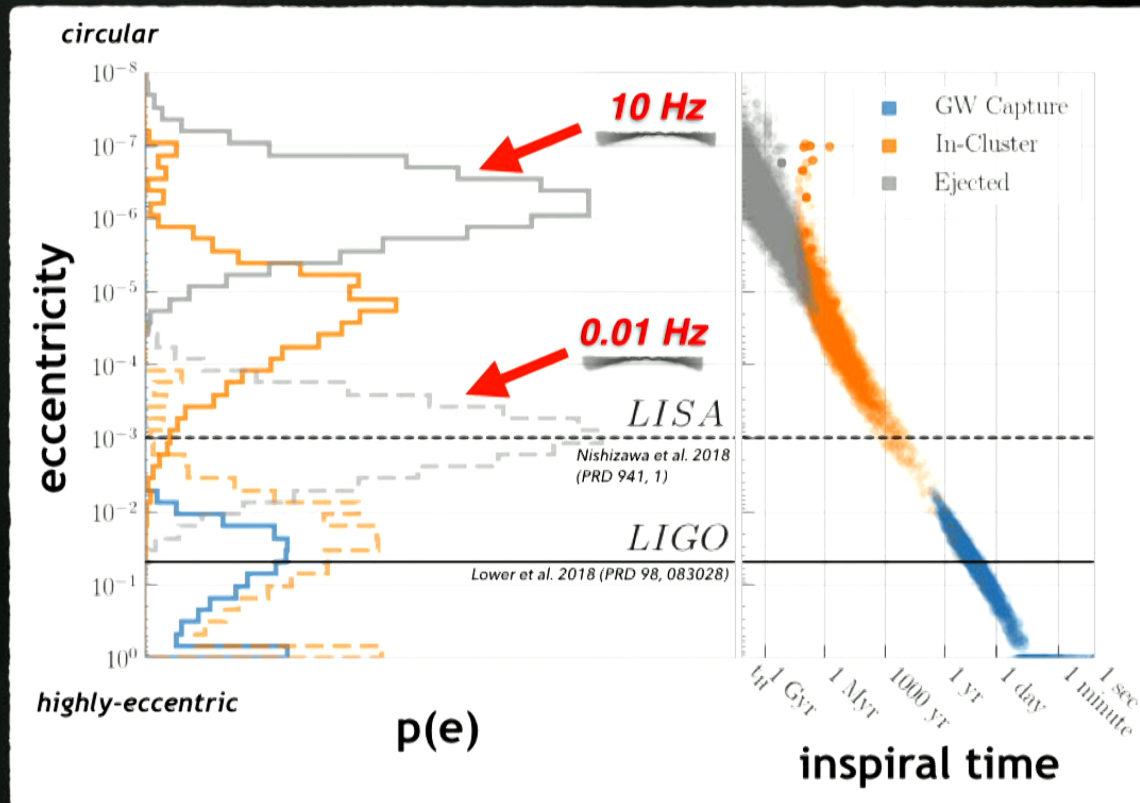


MZ et al. 2019 (ApJ 871, 91)
arXiv: 1810:00901

DYNAMICAL DISTINCTION: ECCENTRICITY

- Three distinct populations of eccentric mergers from clusters: GW Captures, In-Cluster Mergers, and Ejected Mergers
- GW captures induced during resonant interaction maintain **appreciable eccentricities in the LIGO band**
- ~**10%** of mergers from GW captures, ~**50%** of which have measurable eccentricity
- Post-encounter binaries that are ejected from cluster or merge before another encounter have eccentricities too low for LIGO to measure…

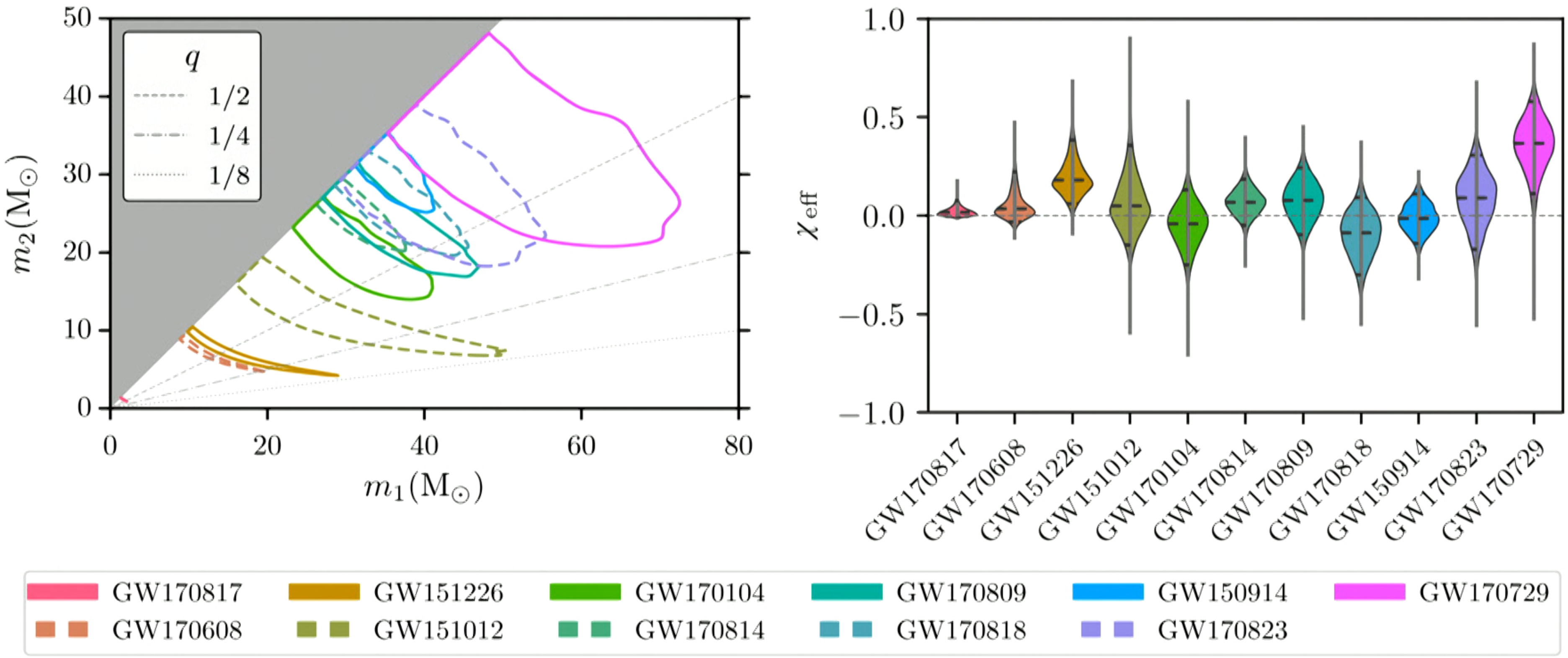
  but may be measurable by LISA!



see also Breivik et al. 2016 (ApJ 830, L18); Samsing & D'Orazio 2018 (MNRAS 5450, 5445); D'Orazio & Samsing 2018 (MNRAS 481, 2775); Kremer et al. 2019 (PRD 99, 063003)

MZ et al. 2019 (ApJ 871, 91) arXiv: 1810:00901

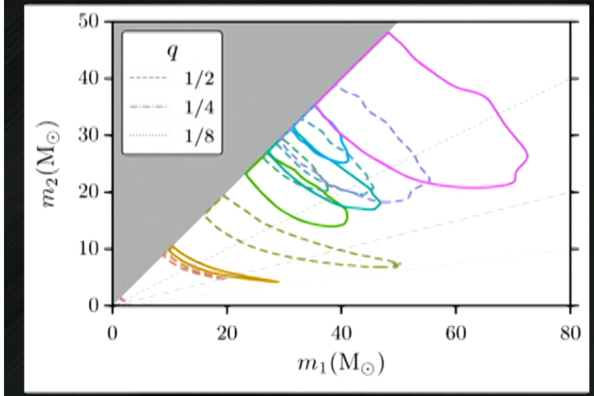
WHAT CAN WE DO WITH A POPULATION?



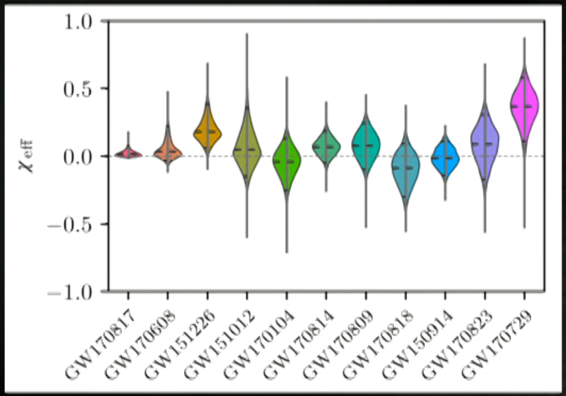
Michael Zevin Perimeter Institute – Dec 12 2019 Northwestern CIERA

WHAT CAN WE DO WITH A POPULATION?

masses



spins

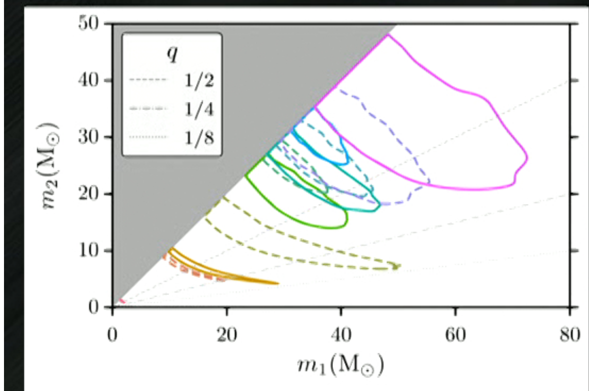


Michael Zevin   Perimeter Institute — Dec 12 2019   Northwestern | CIERA

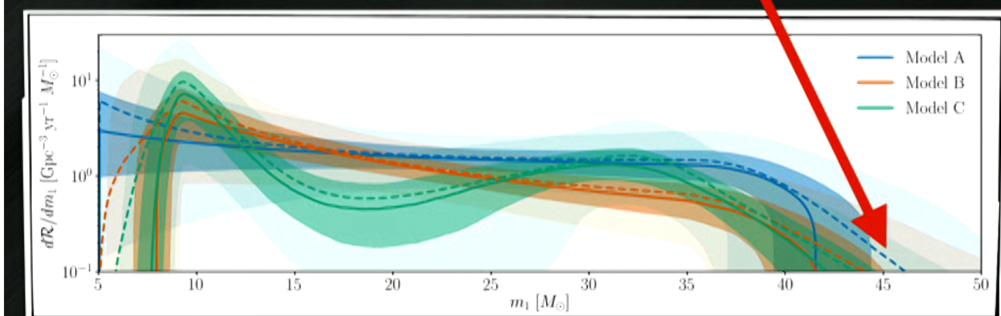
WHAT CAN WE DO WITH A POPULATION?

LVC 2019 (PRX 9, 031040)

masses

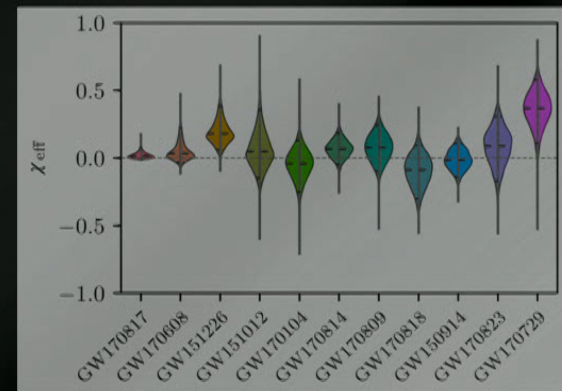


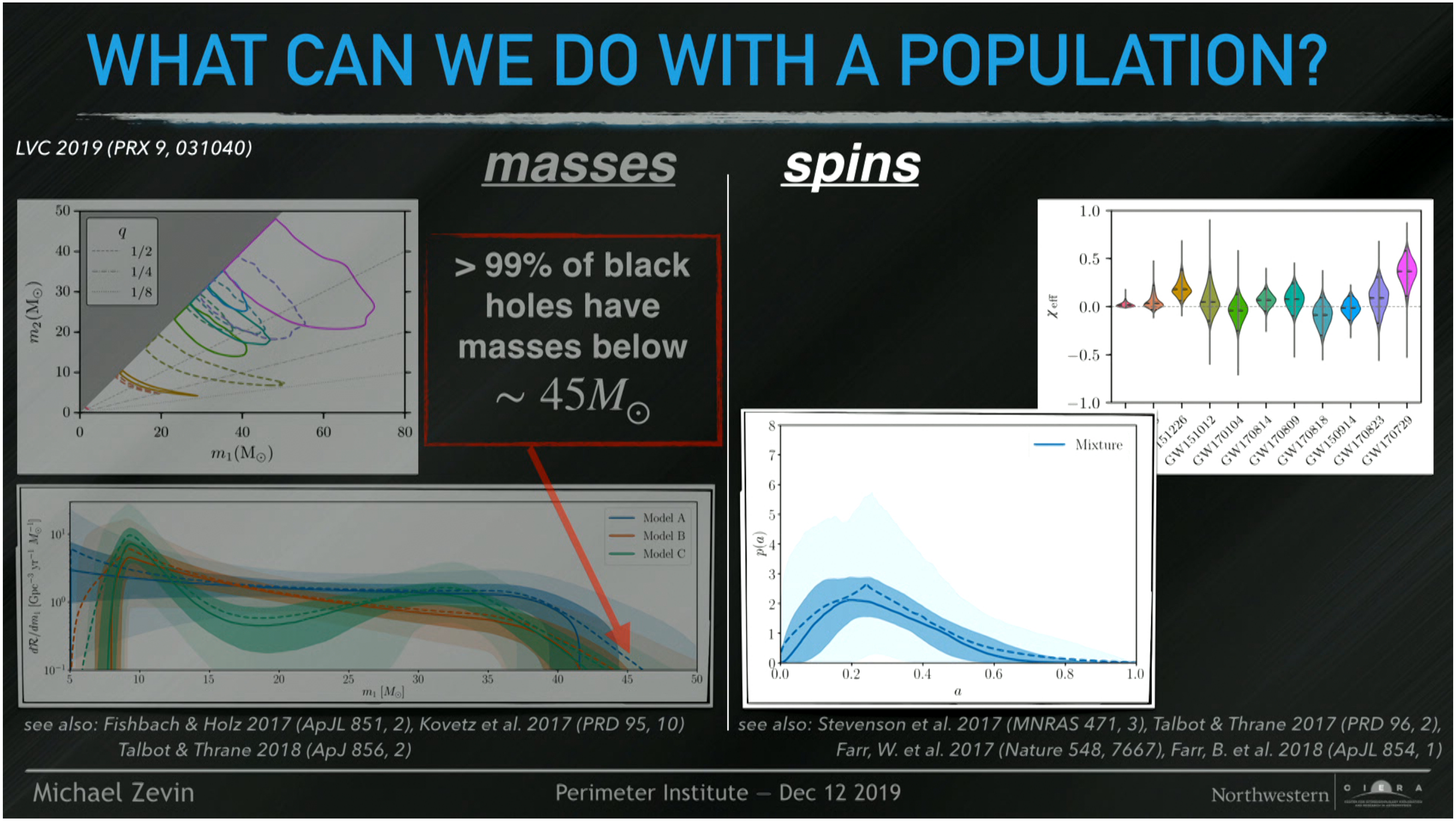
> 99% of black holes have masses below $\sim 45 M_\odot$



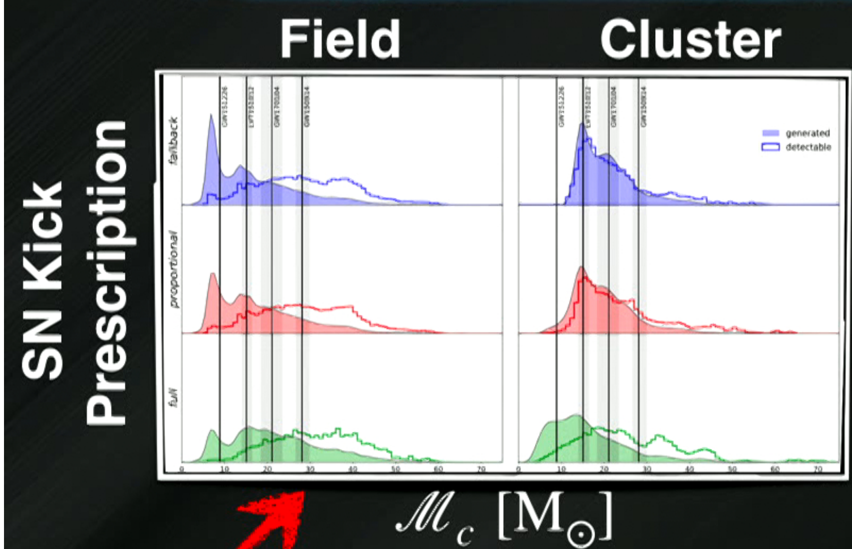
see also: Fishbach & Holz 2017 (ApJL 851, 2), Kovetz et al. 2017 (PRD 95, 10)
Talbot & Thrane 2018 (ApJ 856, 2)

spins




WHAT CAN WE DO WITH A POPULATION?
LVC 2019 (PRX 9, 031040)
masses
spins
> 99% of black holes have masses below
$\sim 45 M_\odot$
q
1/2
1/4
1/8
$m_2(\mathrm{M}_\odot)$
$m_1(\mathrm{M}_\odot)$
Model A
Model B
Model C
dR/dm_1 [Gpc^{-3} yr^{-1} $M_\odot^{-1}$]
m_1 [$M_\odot$]
χ_{eff}
GW151012
GW170104
GW170814
GW170809
GW170818
GW150914
GW170823
GW170729
Mixture
$p(a)$
a
see also: Fishbach & Holz 2017 (ApJL 851, 2), Kovetz et al. 2017 (PRD 95, 10)
Talbot & Thrane 2018 (ApJ 856, 2)
see also: Stevenson et al. 2017 (MNRAS 471, 3), Talbot & Thrane 2017 (PRD 96, 2),
Farr, W. et al. 2017 (Nature 548, 7667), Farr, B. et al. 2018 (ApJL 854, 1)
Michael Zevin
Perimeter Institute — Dec 12 2019
Northwestern
CIERA

CONSTRAINING FORMATION MODELS



BBH populations can be parameterized by...

- ***Branching ratios between channels***
  e.g. field vs. cluster vs. your favorite BBH channel
- ***Physical prescriptions***
  e.g. supernova kicks, common envelope efficiency, etc.

Bayesian hierarchical modeling

$$p(\Lambda\,|\,d) = \frac{\mathscr{L}(d\,|\,\Lambda)\pi(\Lambda)}{Z_\Lambda}$$

(hyper)posterior for $\Lambda = \{\vec{\beta}, \vec{\Theta}_{\rm pop}\}$

likelihood of data given model hyperparameters

Given N independent events...

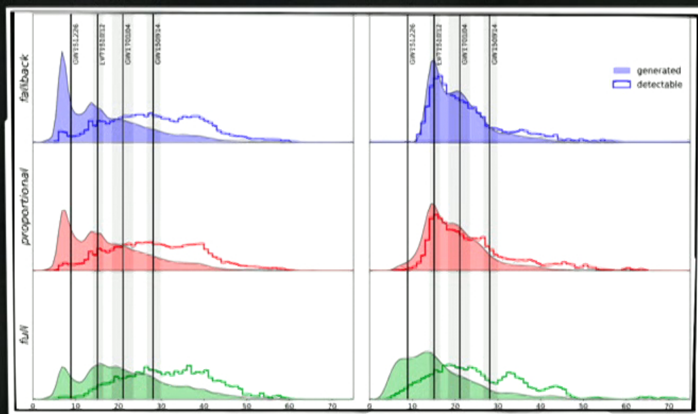
$$\mathscr{L}(\vec{d}\,|\,\Lambda) = \prod_i^N \int d\theta_i \mathscr{L}(d_i\,|\,\theta_i)\pi(\theta_i\,|\,\Lambda)$$

see e.g., Hogg et al. 2010 (arXiv 1008.4686), Mandel 2010 (PRD 81, 8)

BRANCHING RATIOS

Field **Cluster**

SN Kick Prescription

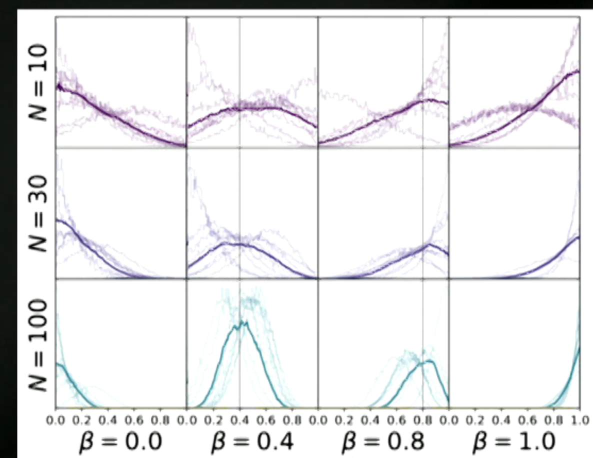


$\mathscr{M}_c$ [$M_\odot$]

GW observations

hierarchical modeling

$N_{\text{observations}}$



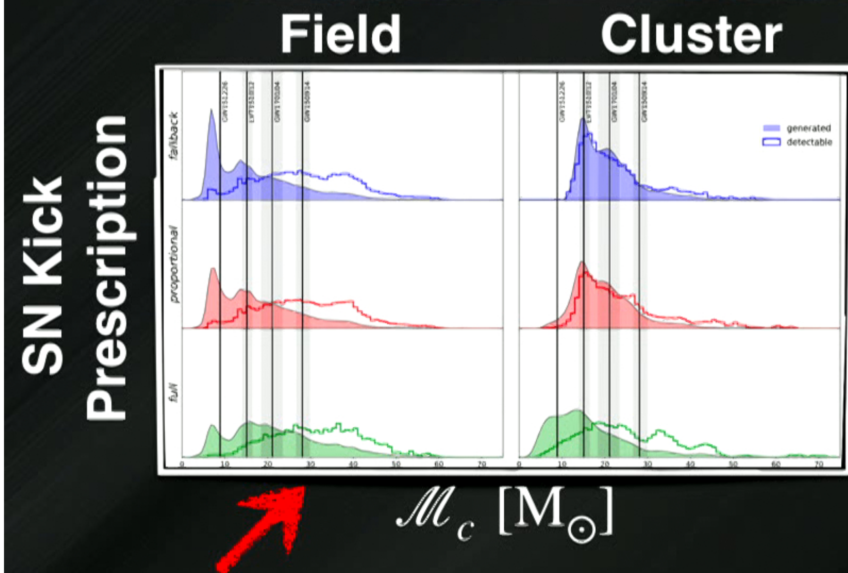
β : "Branching Ratio" $(N_{cluster}/N_{field})$

BBH populations can be parameterized by…

- ***Branching ratios between channels***
  - *e.g. field vs. cluster vs. your favorite BBH channel*
- ***Physical prescriptions***
  - *e.g. supernova kicks, common envelope efficiency, etc.*

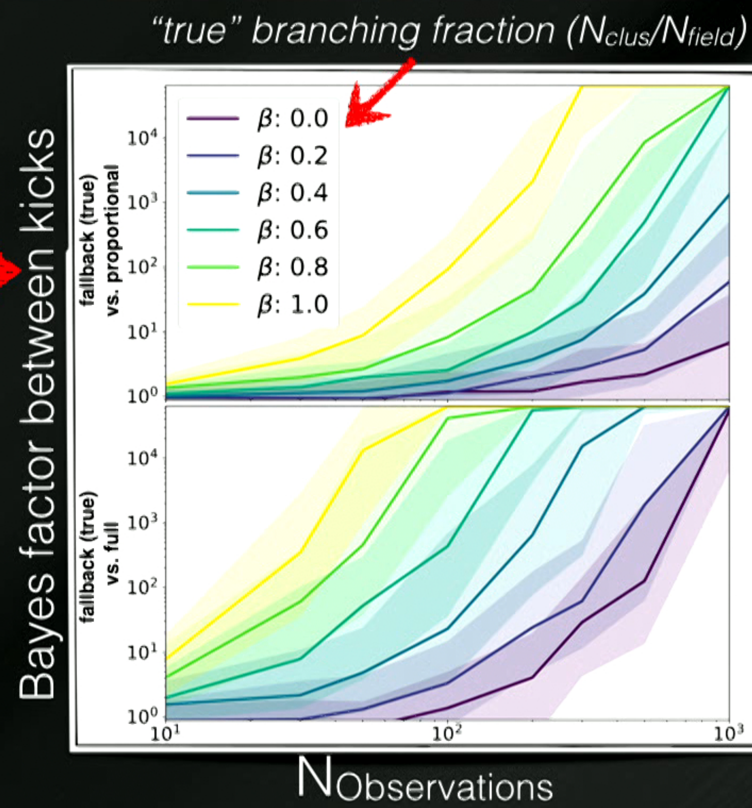
MZ et al. 2017 (ApJ 846, 82) arXiv: 1704.07379

PHYSICAL PRESCRIPTIONS



GW observations

hierarchical modeling



BBH populations can be parameterized by…

- ***Branching ratios between channels***
  - *e.g. field vs. cluster vs. your favorite BBH channel*
- ***Physical prescriptions***
  - *e.g. supernova kicks, common envelope efficiency, etc.*

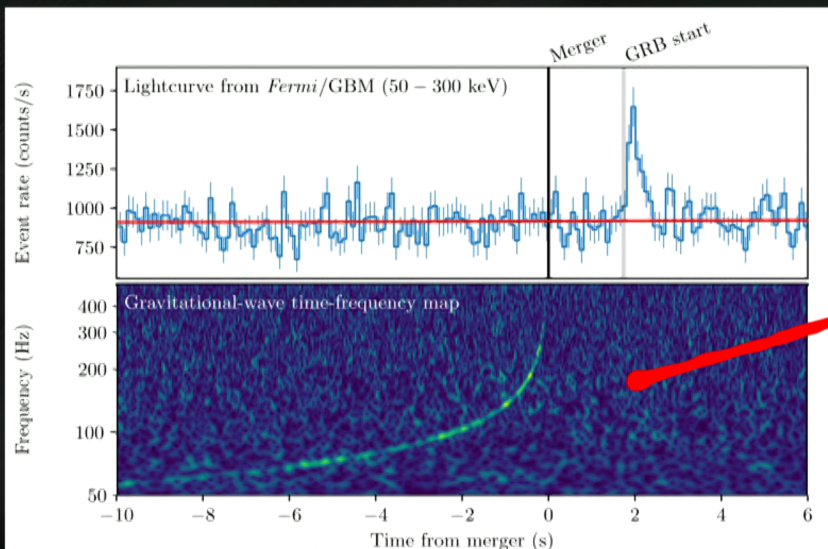
MZ et al. 2017 (ApJ 846, 82) arXiv: 1704.07379

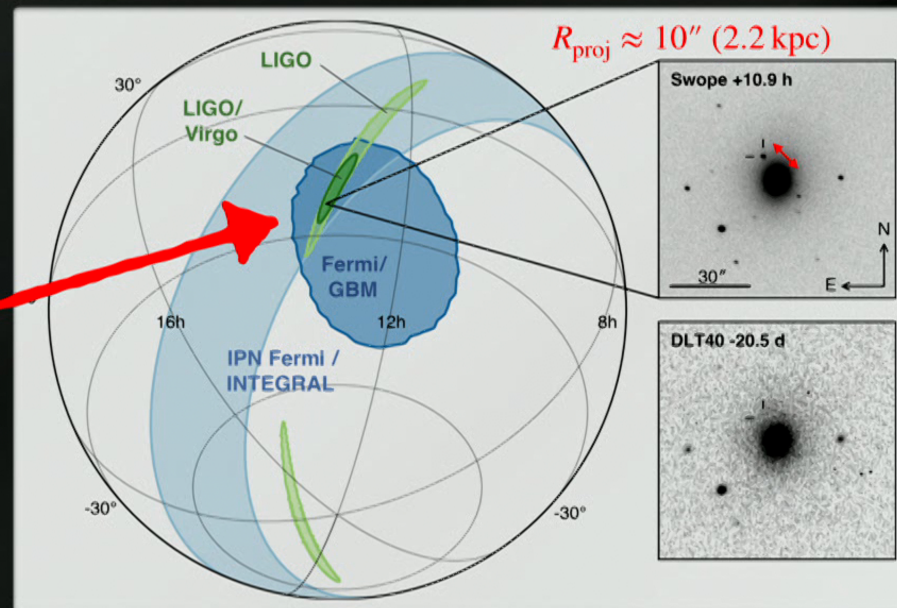
PART 2

Getting the Boot:

lonely GRBs, enigmatic r-process, and the birth of neutron stars

MULTIMESSENGER ASTRO F.T.W.





Abbott+ 2017 (ApJL 848, L12)

Strength of supernova kick?

Pre-supernova separation?

Mass loss in supernova?

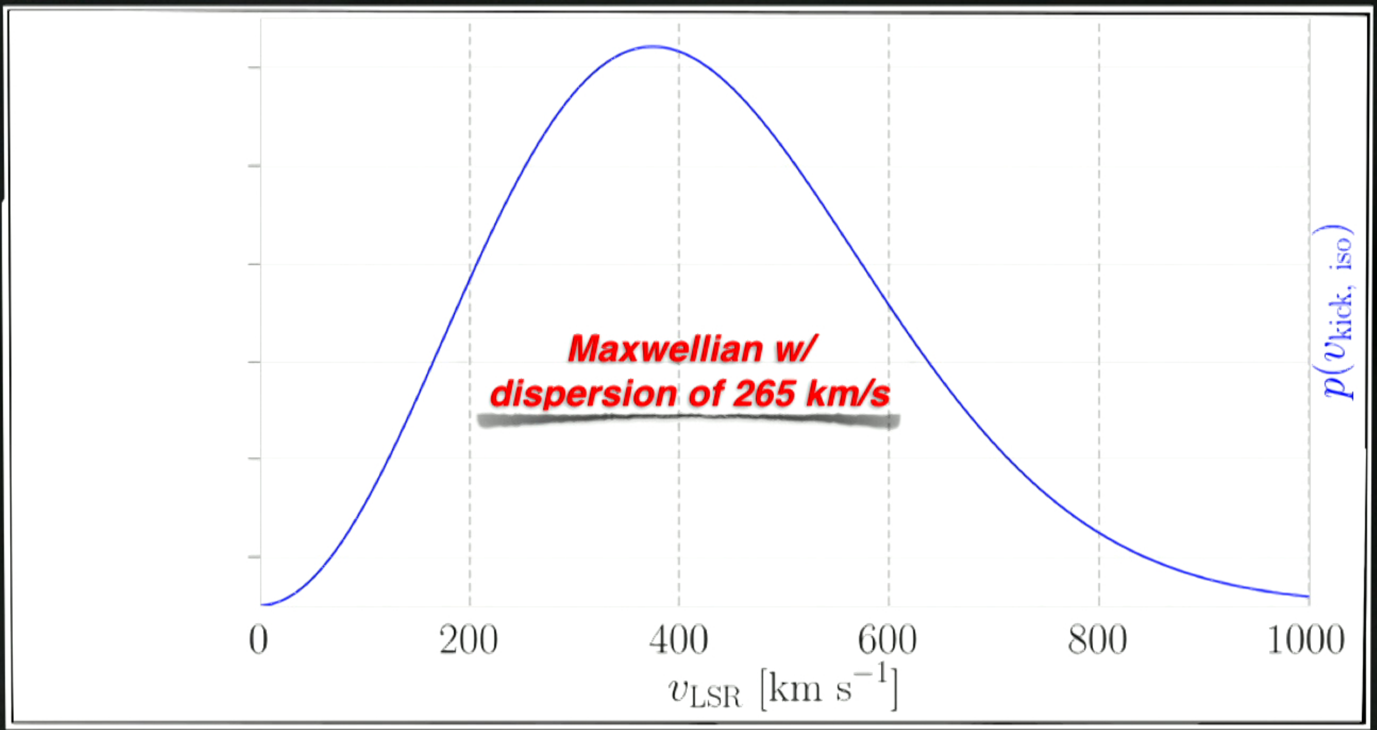
Birth location in host galaxy?

Michael Zevin

Perimeter Institute – Dec 12 2019

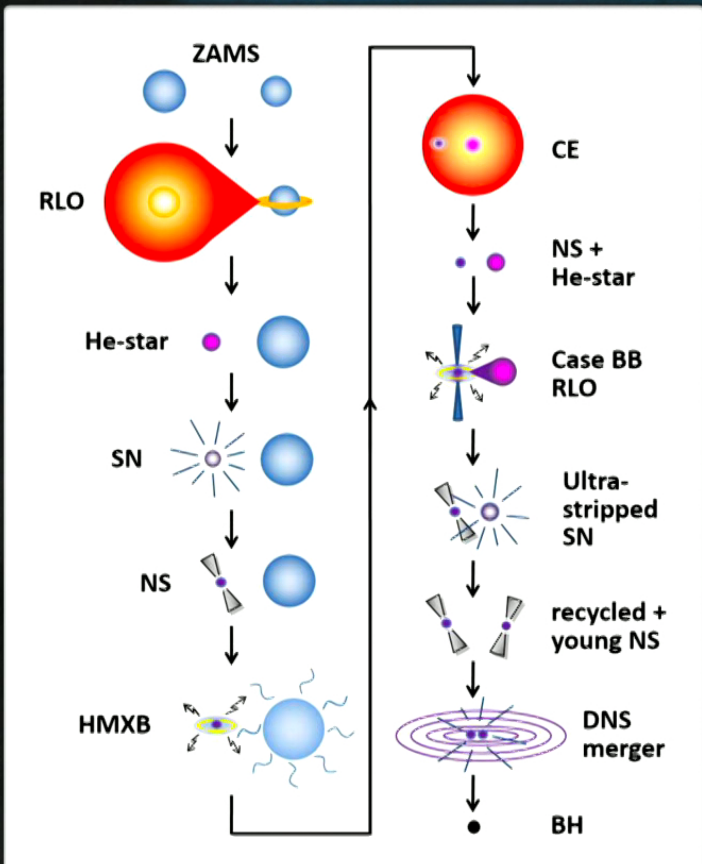
Northwestern

GALACTIC BINARY NEUTRON STARS

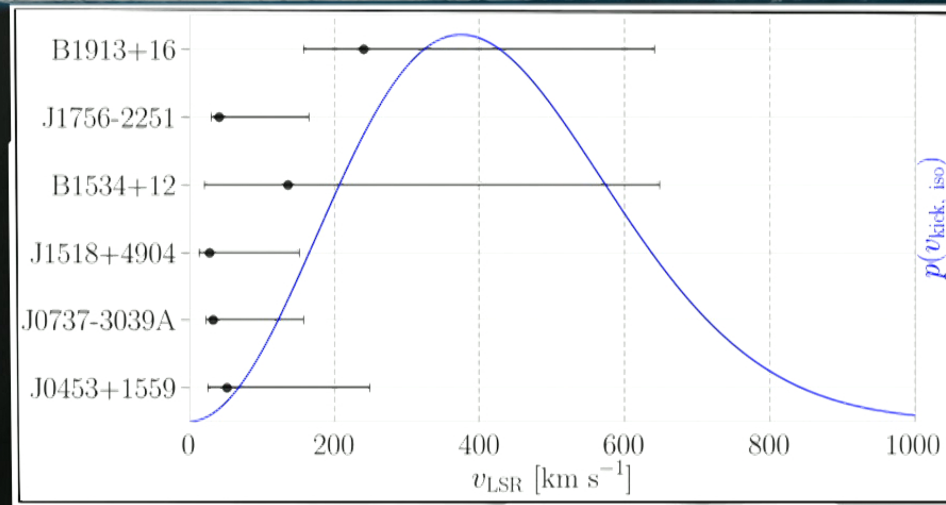


- Pulsars observed to be moving w.r.t. local standard of rest
  - get *kicked* at formation by asymmetries in supernova mechanism

GALACTIC BINARY NEUTRON STARS



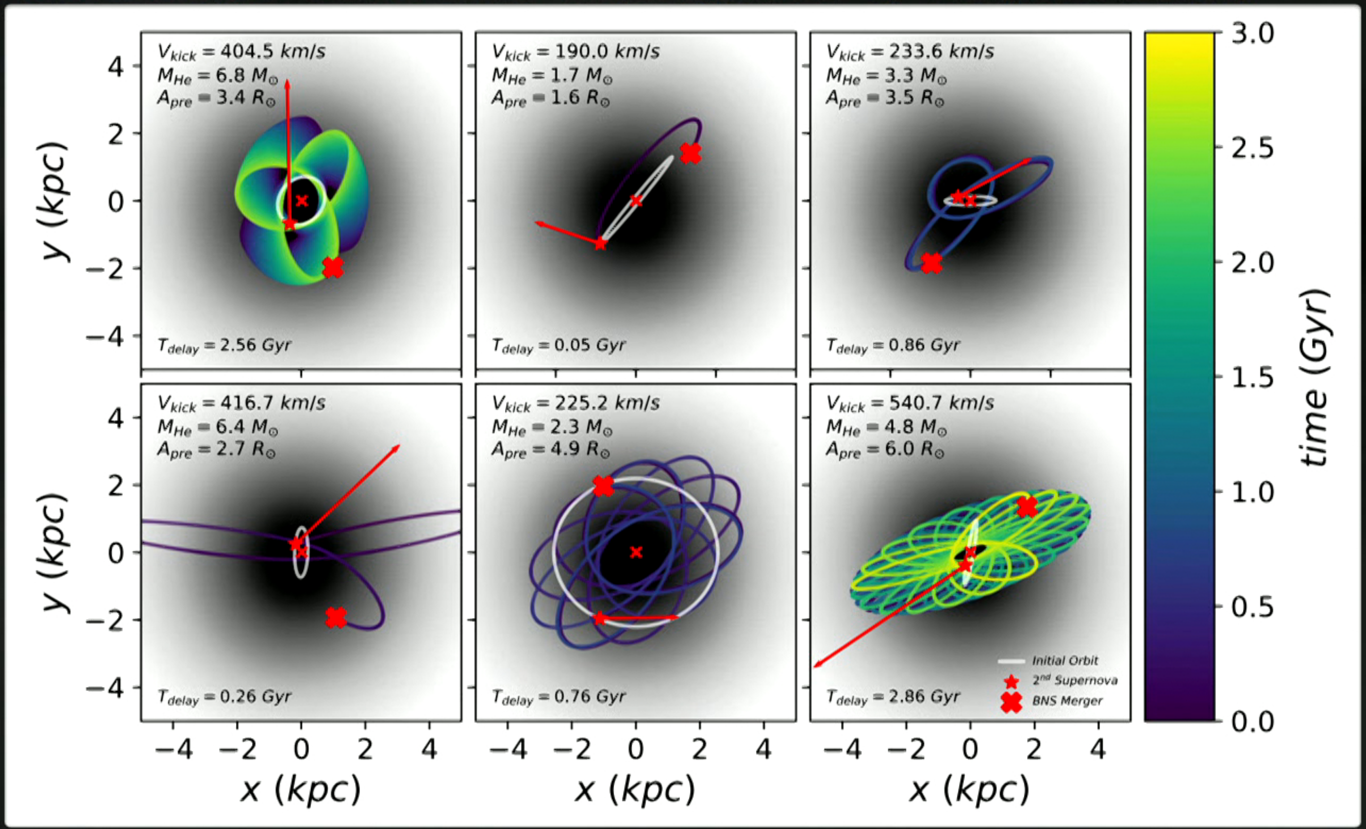
Tauris et al. 2017, ApJ 846, 170



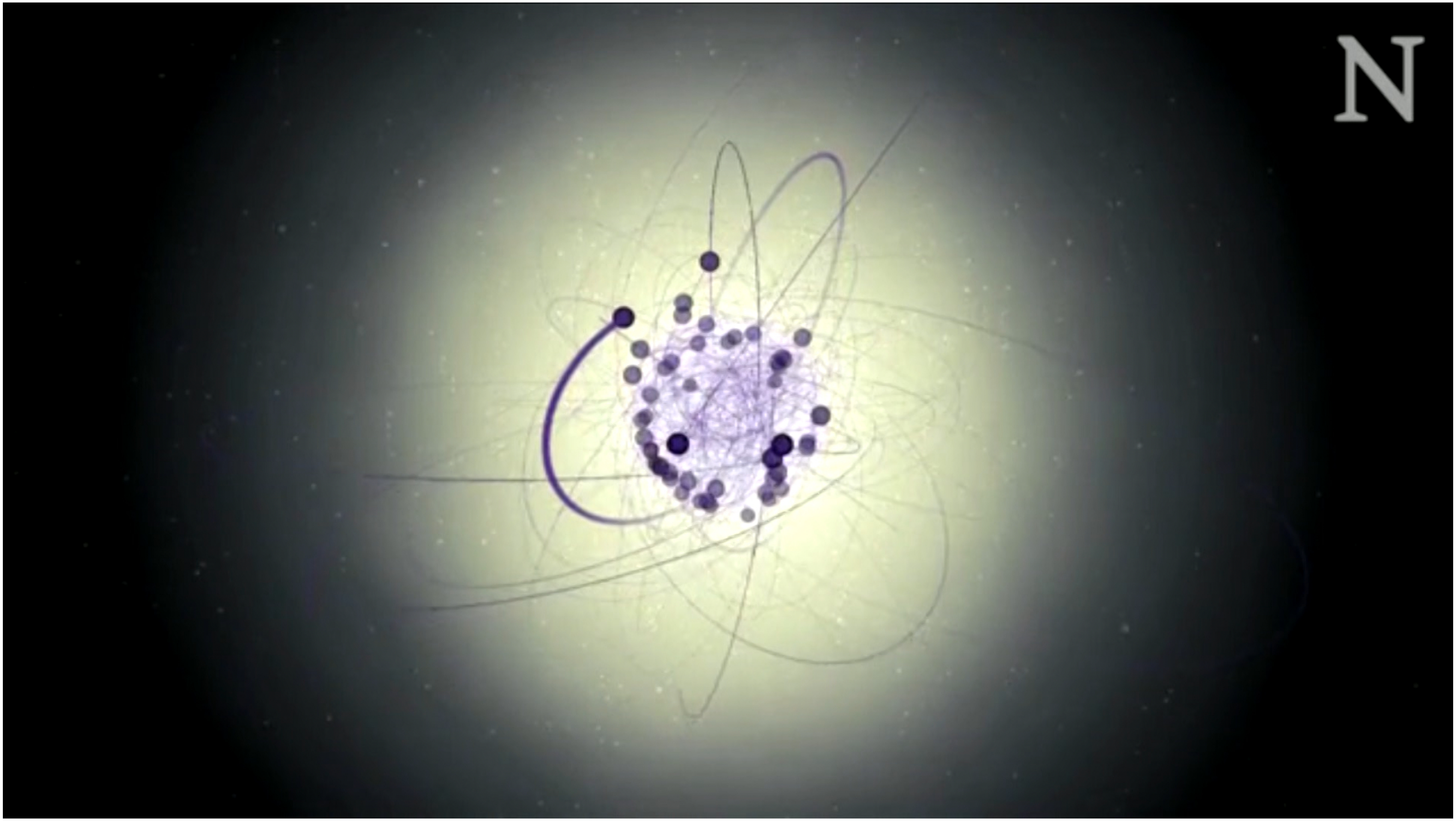
- Double neutron stars also moving w.r.t. local standard of rest, though ***mass loss in SN*** also affects motion
- Observed systems & theoretical considerations indicate LSR velocities ***smaller*** than those of isolated neutron stars…

GETTING THE BOOT

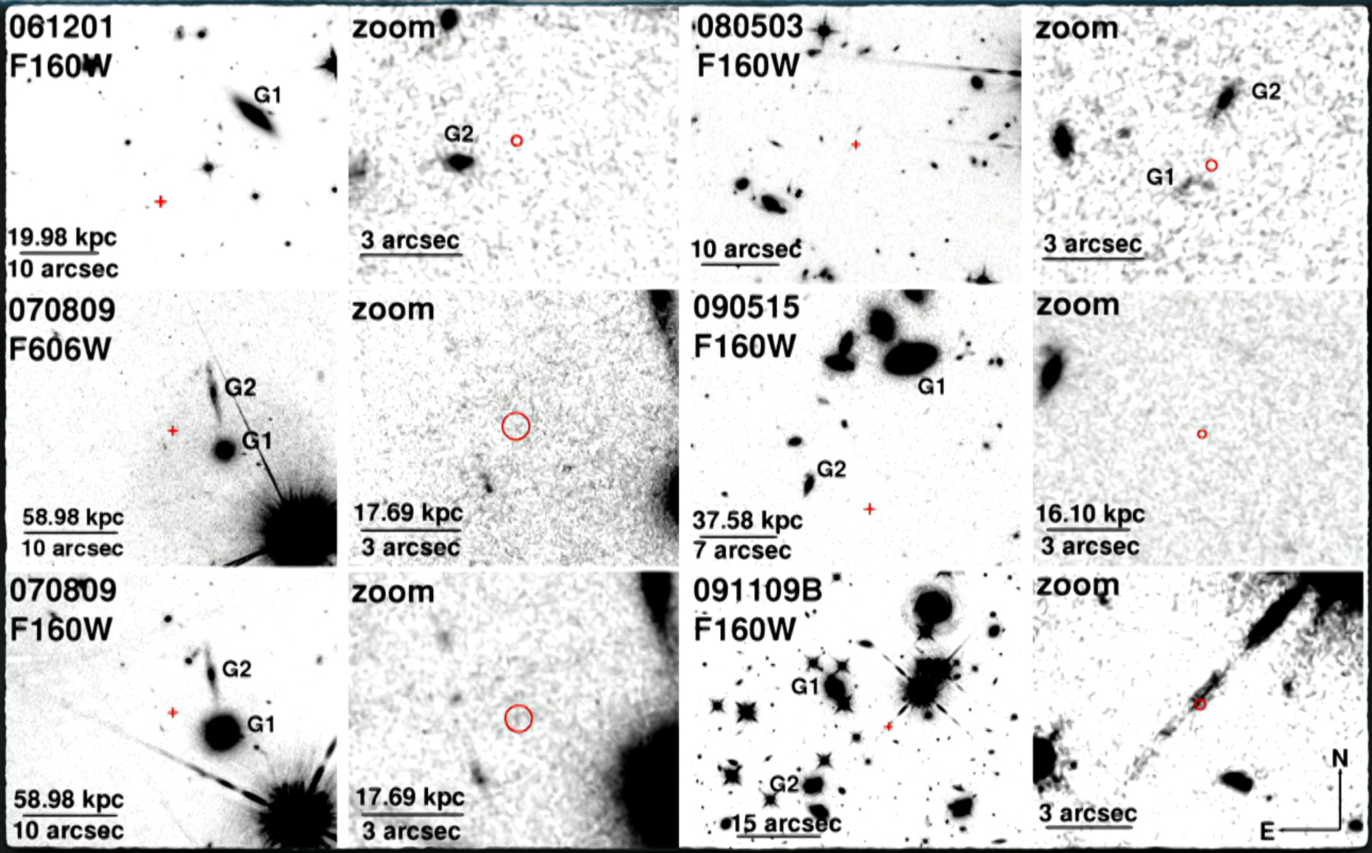
first multimessenger constraints on progenitor of compact binary



LVC 2017 (ApJL 850, L40)
arXiv: 1710.05838
MZ: Analysis lead & Paper lead



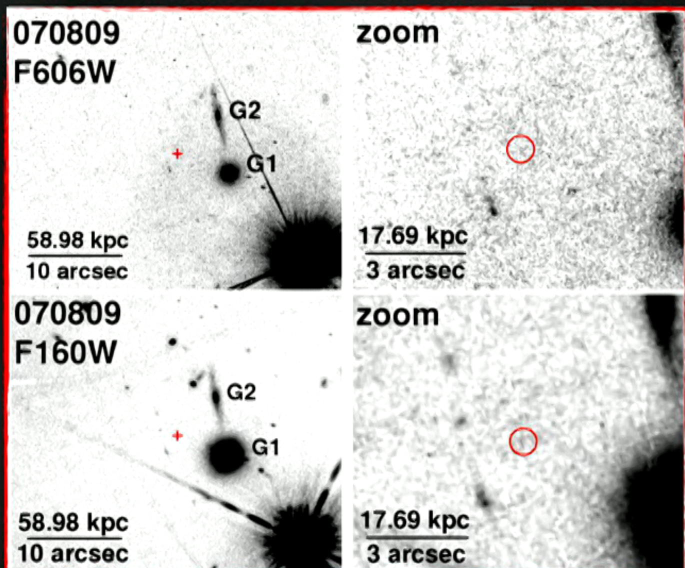
LOCATIONS OF SHORT GRBS

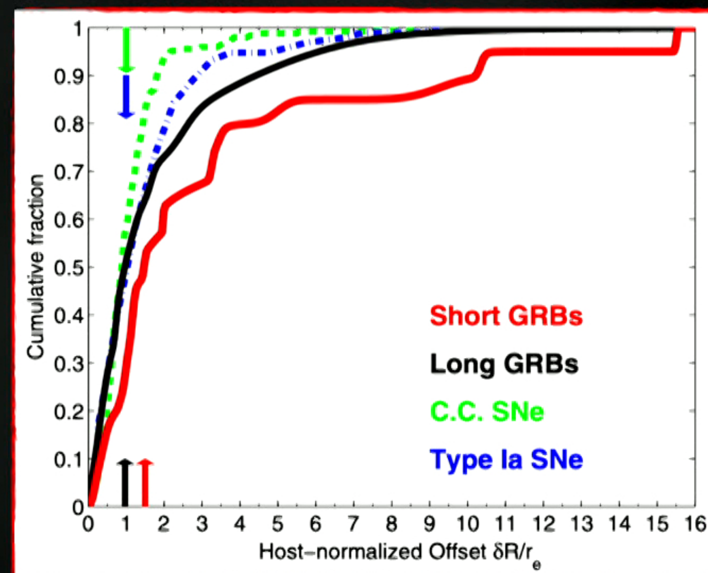


Fong & Berger 2013 (ApJ 776, 18)

LOCATIONS OF SHORT GRBS

- Many short GRBs found to be significantly offset from their host galaxies (>10s of half-light radii)
- Can we leverage these systems to *constrain progenitor population properties* and *better understand selection effects*?



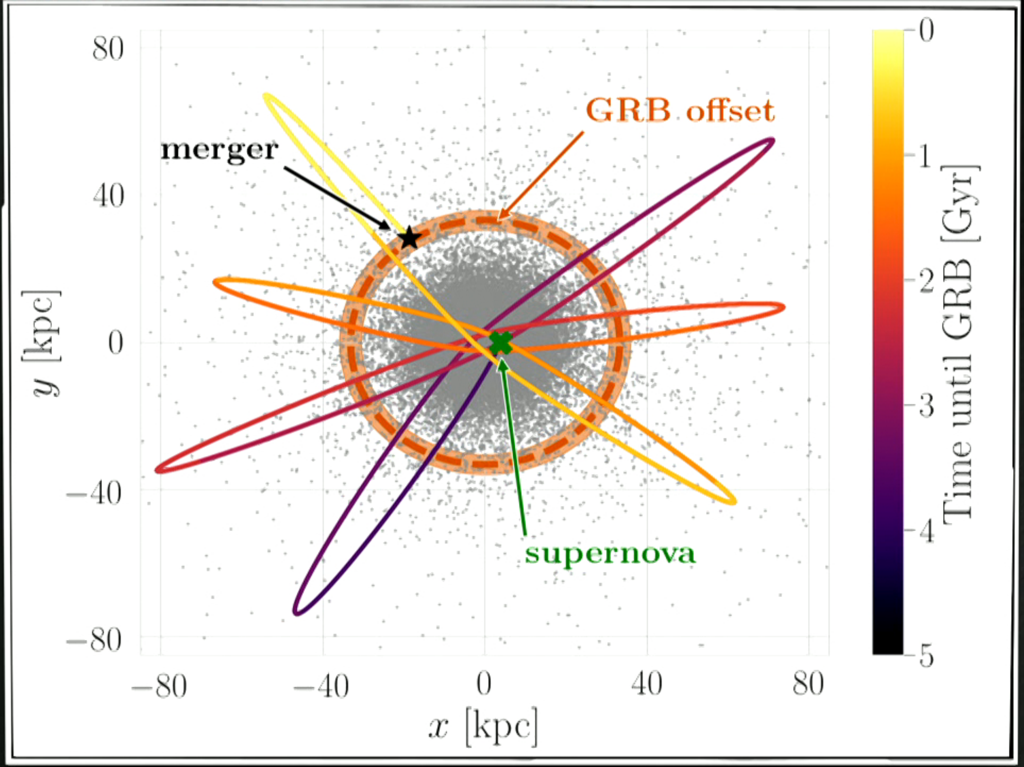


Fong & Berger 2013 (ApJ 776, 18)

CAN I KICK IT?

kinematically evolve double neutron stars to find GRB analogs

- Construct three-component, time-dependent galactic models using ***Galpy*** package
  (*Bovy et al. 2015, ApJS 216, 29*)
- Populate tracer particles in time according to star formation
- Distribute in star-forming disk and calculate pre-SN galactic motion
- Apply randomly-oriented systemic velocity & ***evolve***



MZ et al. 2019 (submitted)
arXiv: 1910.03598

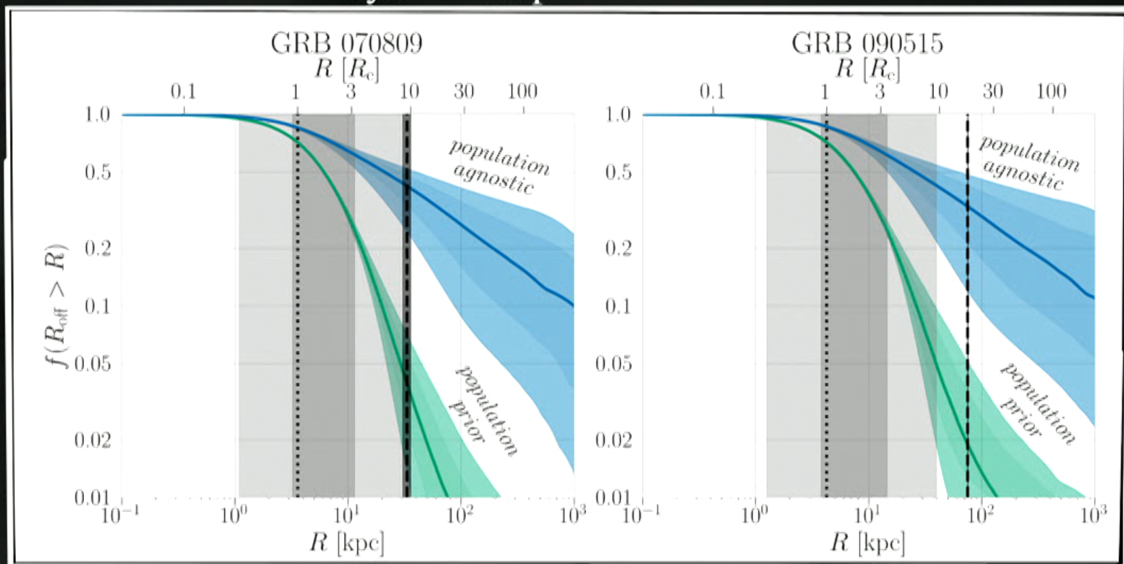
CAN I KICK IT?

https://cosmic-popsynth.github.io/

Breivik, Coughlin, **MZ** et al. 2019 (arXiv: 1911.00903)

pair with population modeling for progenitor constraints

- Tracers initialized using flat distribution of systemic velocities, inspiral time distribution following the galactic star formation
- Convolve with $V_{\rm sys} - t_{\rm insp}$ distribution from population of merging double neutron stars



MZ et al. 2019 (submitted)
arXiv: 1910.03598

COSMIC

- Binary population synthesis suite
- Efficient multidimensional sampling
- Python front-end, flexible, easy-to-use executables and ini files
- pip & conda installable
- Open source, version controlled

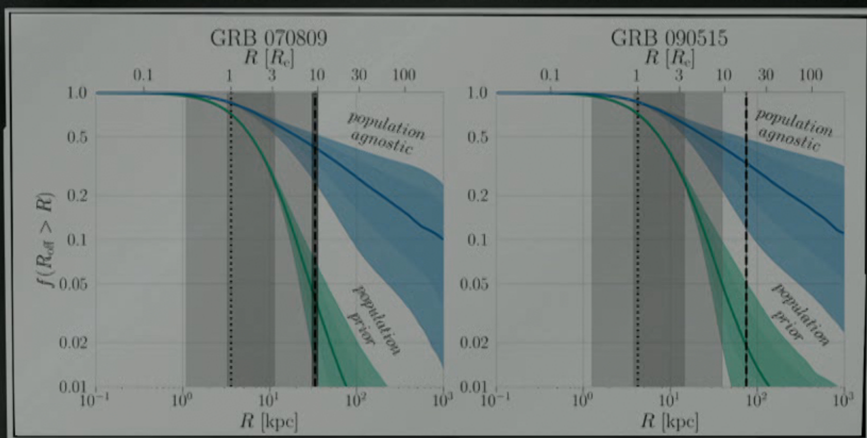
CAN I KICK IT?

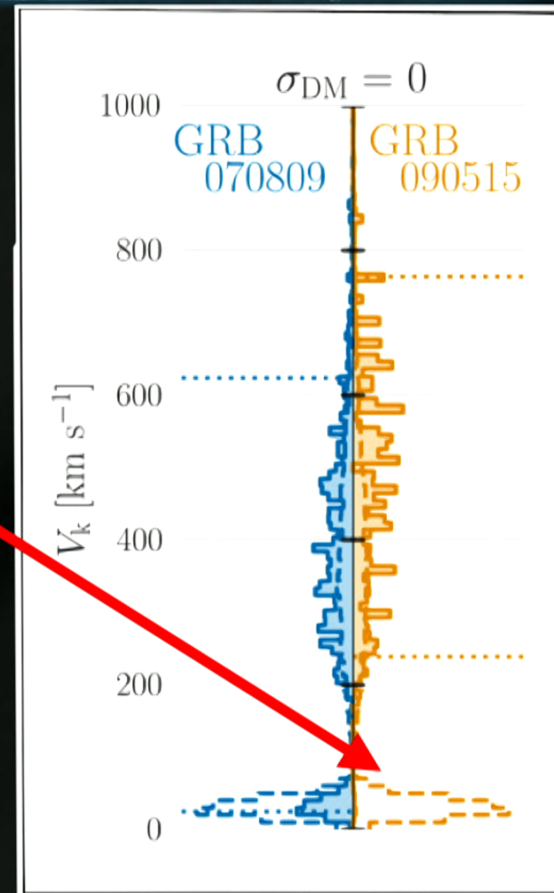
https://cosmic-popsynth.github.io/

Breivik, Coughlin, **MZ** et al. 2019 (arXiv: 1911.00903)

pair with population modeling for progenitor constraints

- Back out ***supernova natal kick*** necessary to explain GRB offset
- Both GRBs push to large natal kicks, with GRB070809 having $V_{\rm kick} \gtrsim 200\,{\rm km\,s^{-1}}$ at 98% confidence, ***regardless of stellar mass-halo mass relation!***

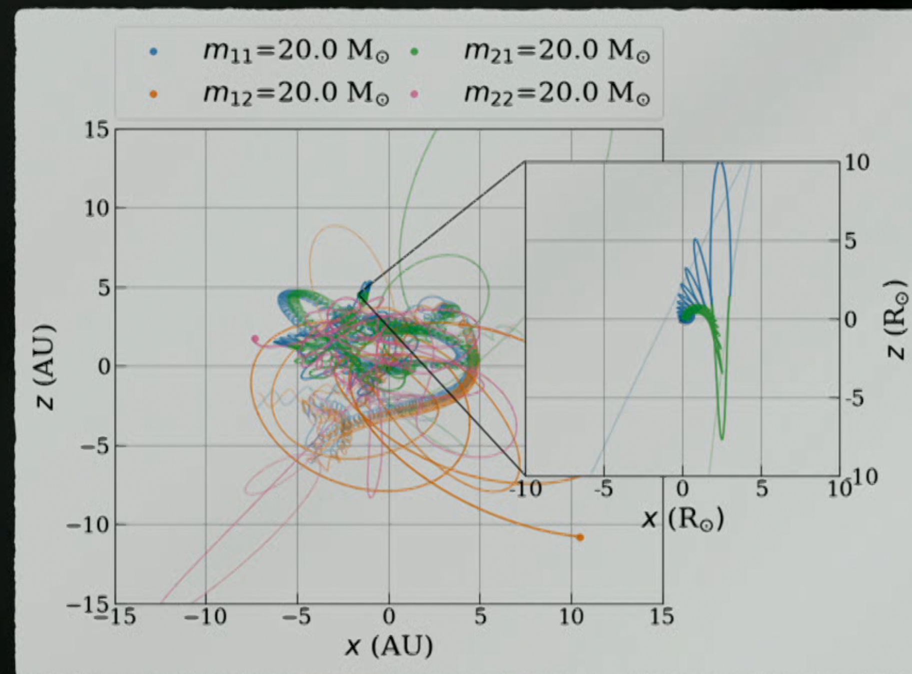




MZ et al. 2019 (submitted)
arXiv: 1910.03598

CONCLUSIONS

- Black hole mergers in globular clusters have distinctive characteristics, such as ***anti-aligned spins***, ***component masses in the pair instability gap***, and ***significant eccentricities***
- Dynamical channels naturally produce sources with ***eccentricities detectable by LIGO*** at a rate of ~0.5-1 $\mathrm{Gpc^{-3}\,yr^{-1}}$
- The growing population of BBHs mergers can ***constrain physical uncertainties binary stellar evolution*** and the ***contribution of formation channels to the total population***
- Host associations of neutron star mergers provide ***complementary constraints on DNS progenitors***, and show some GRBs required **natal kicks of** $\gtrsim 200\,\mathrm{km\,s^{-1}}$
- For BNS mergers to explain *r*-process enrichment in globular clusters, progenitors ***must proceed through Case BB mass transfer***
- Over the next few years, observations of compact binary mergers will unveil ***unprecedented information about stellar evolution!***



zevin@u.northwestern.edu

michaelzevin.github.io

@spacedontwait