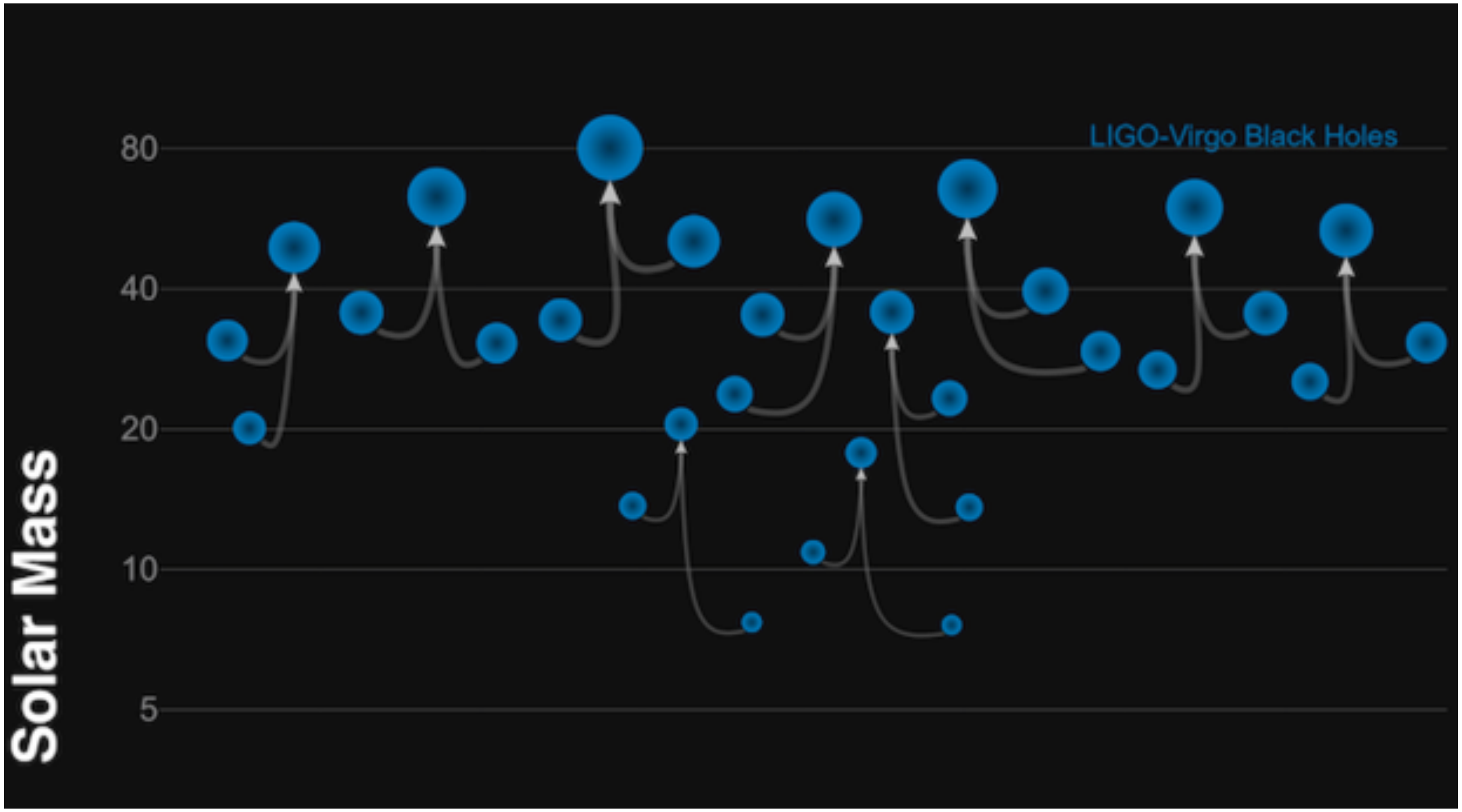
Formation of Merging BH Binaries

Dong Lai
Cornell University

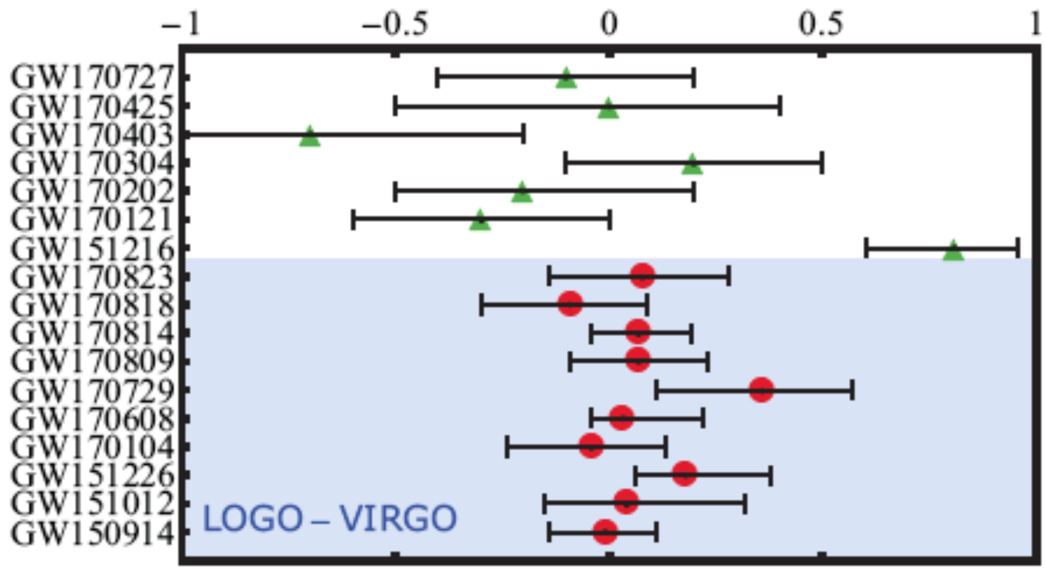
GRB and Multi-Messenger Conference, Nanjing, 5/14/2019



Gravitational waveform gives

$$M_1, M_2, \chi_{\rm eff}$$

$$\chi_{\rm eff} \equiv \frac{m_1 \boldsymbol{\chi}_1 + m_2 \boldsymbol{\chi}_2}{m_1 + m_2} \cdot \hat{\mathbf{L}}$$



Formation Channels of Merging BH Binaries

-- Isolated Binary Evolution

-- Dynamical Formation: several flavors (star clusters, triples…)

Formation Channels of Merging BH Binaries

-- Isolated Binary Evolution

-- Dynamical Formation: several flavors (star clusters, triples⋯)

How to distinguish different channels?

Formation Channels of Merging BH Binaries

-- Isolated Binary Evolution

-- Dynamical Formation: several flavors (star clusters, triples…)

How to distinguish different channels?

Rates (uncertain)?

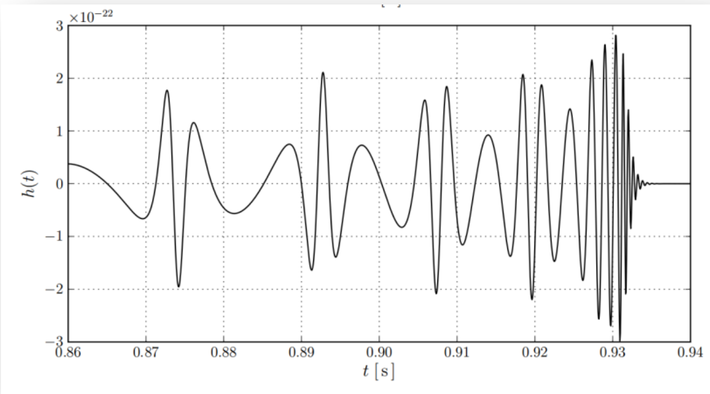
Formation Channels of Merging BH Binaries

-- Isolated Binary Evolution

-- Dynamical Formation: several flavors (star clusters, triples⋯)

How to distinguish different channels?

Rates (uncertain)?
Residual eccentricity when enter LIGO band (10Hz)



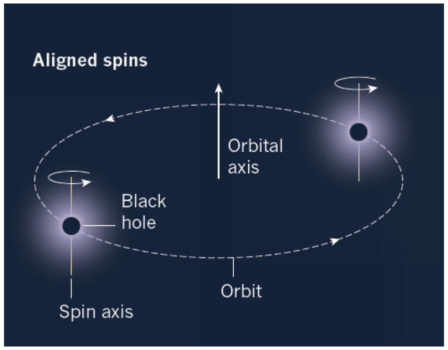
Formation Channels of Merging BH Binaries

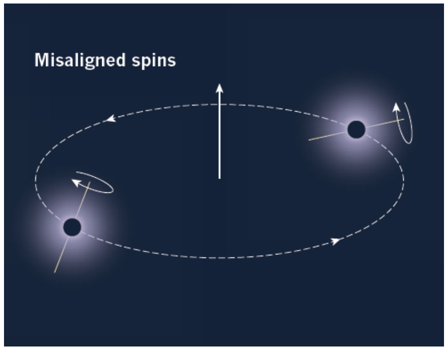
-- Isolated Binary Evolution

-- Dynamical Formation: several flavors (star clusters, triples…)

How to distinguish different channels?

Rates (uncertain)?
Residual eccentricity when enter LIGO band (10Hz)
Spin-orbit misalignmemt





Formation Channels of Merging BH Binaries

-- Isolated Binary Evolution

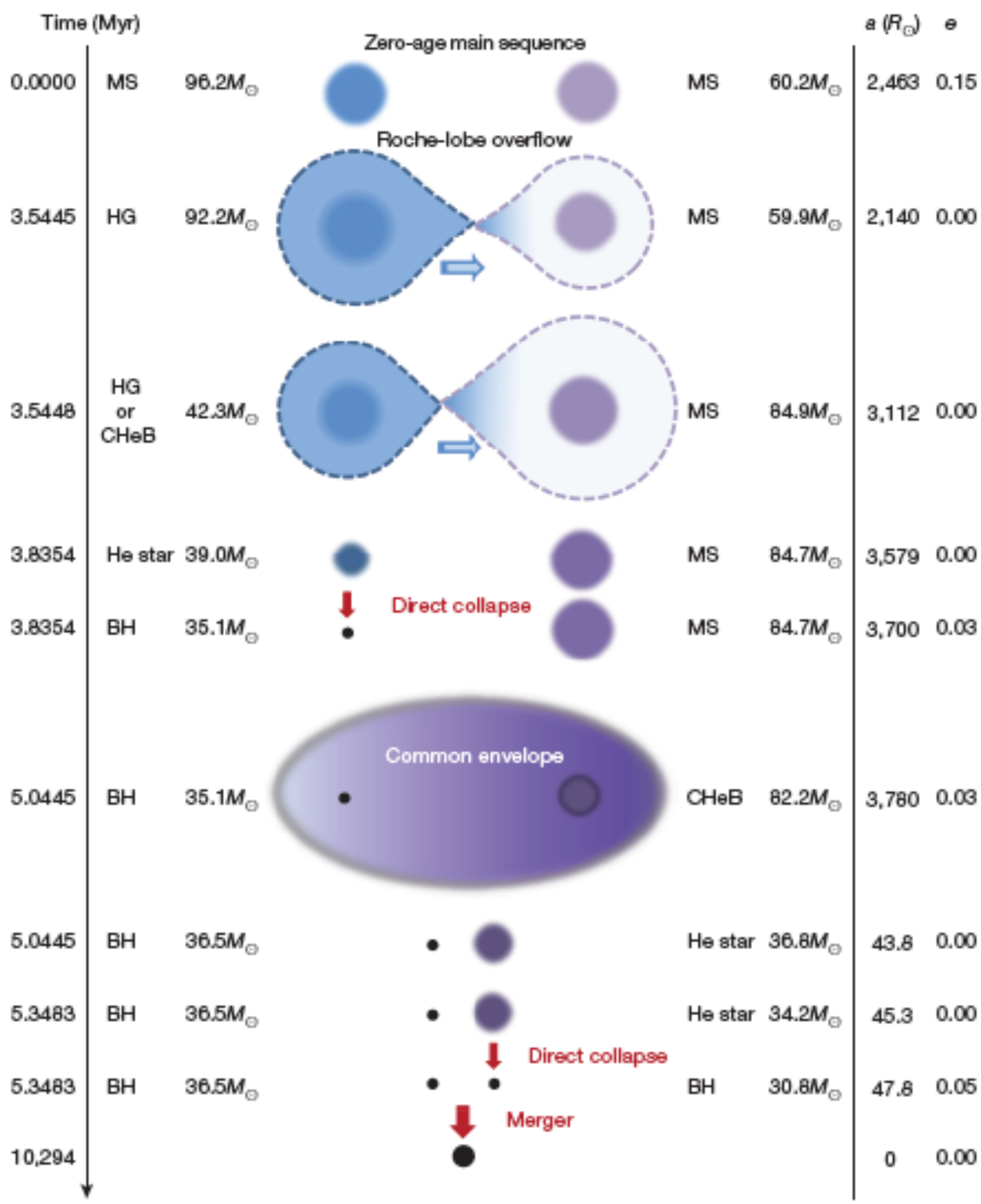
-- Dynamical Formation: several flavors (star clusters, triples…)

How to distinguish different channels?

Rates (uncertain)?
Residual eccentricity when enter LIGO band (10Hz)
Spin-orbit misalignmemt
EM counterparts ??

Standard Binary Evolution Channel:

many papers, uncertain physical ingredients



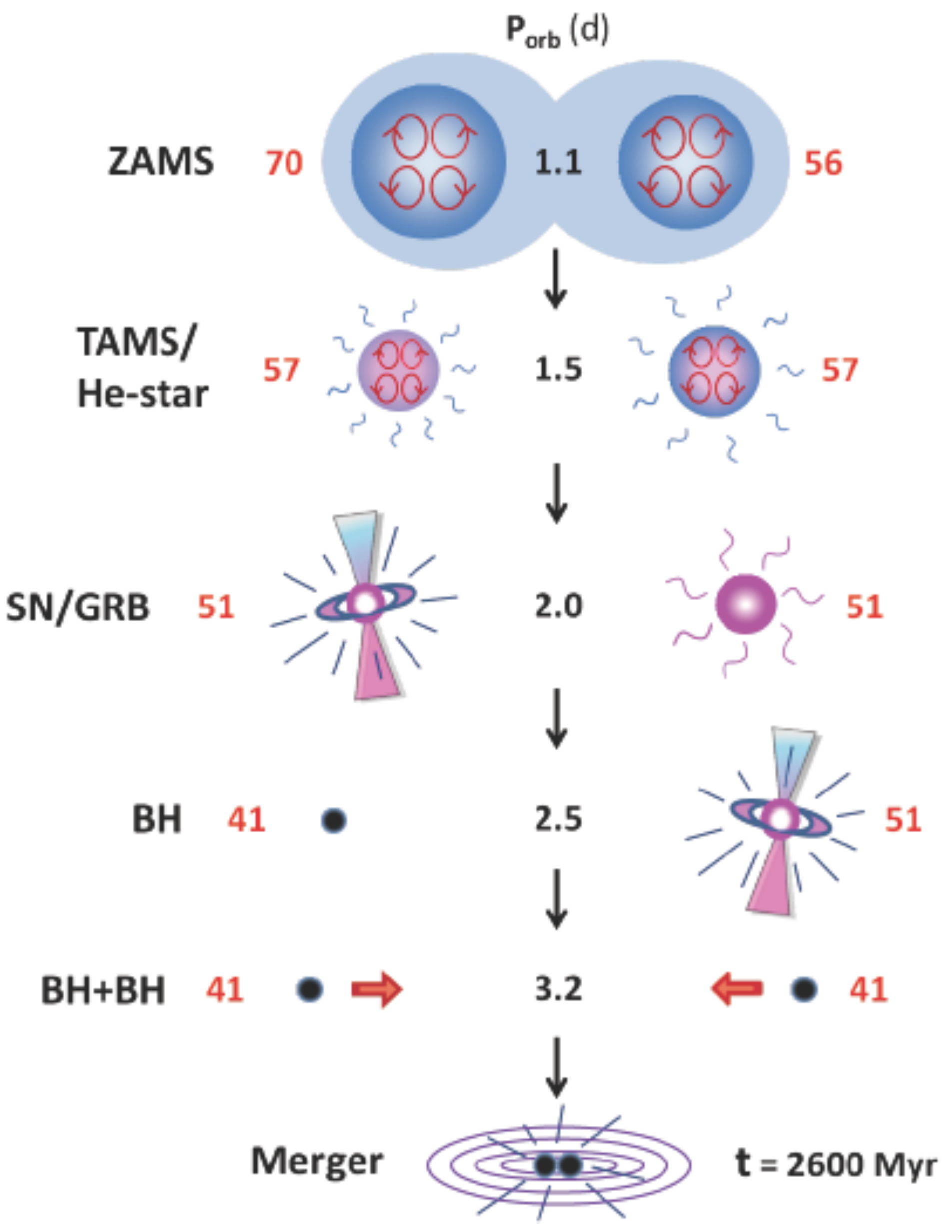
Produce

circular orbit at 10 Hz

aligned spin-orbit

Belczynski +16

Another flavor: Chemically Homogeneous Evolution

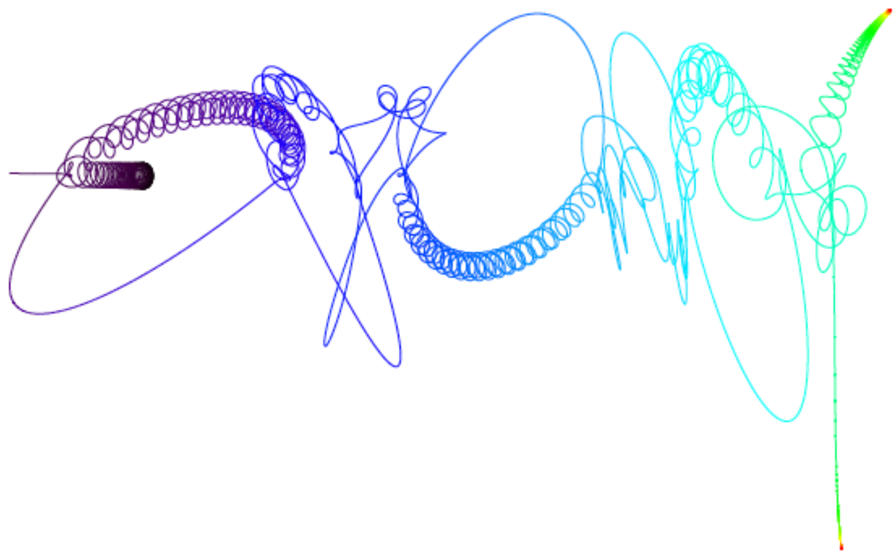


Marchant, Langer et al 2016

Dynamical Formation Channels

several flavors⋯

1. Dense clusters: binary-single scatterings ➔ tight binary



Samsing+14

Produce mostly circular orbit when enter LIGO band (10 Hz) ??

Expect random spin-orbit orientations

Portegies Zwart & McMillan 2000; Rodriguez et al.2015; Chatterjee et al.2017; Samsing et al. 2018; ⋯

Dynamical Formation Channels

several flavors⋯

1. Dense clusters: binary-single scatterings ➔ tight binary

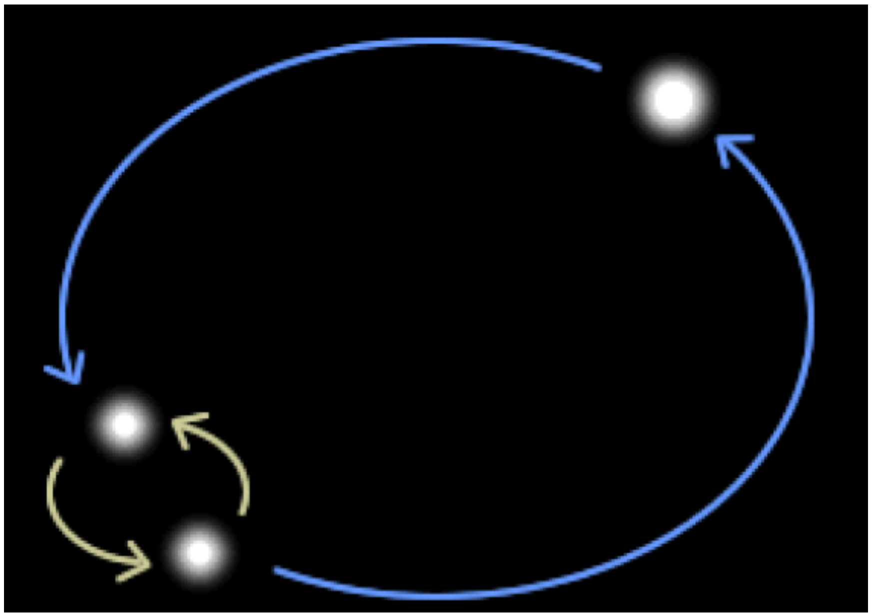
2. Tertiary-Induced Mergers:

Mergers induced by (gentle) perturbations from tertiary companion

stellar triples in galactic field, binary around SMBH

Tertiary-Induced Binary Mergers

merger window, residual eccentricity, spin-orbit misalignments



Liu & DL 2017,2018, 2019
Liu, DL & Wang 2019

Bin Liu (Cornell)

Previous/related works (in various contexts):

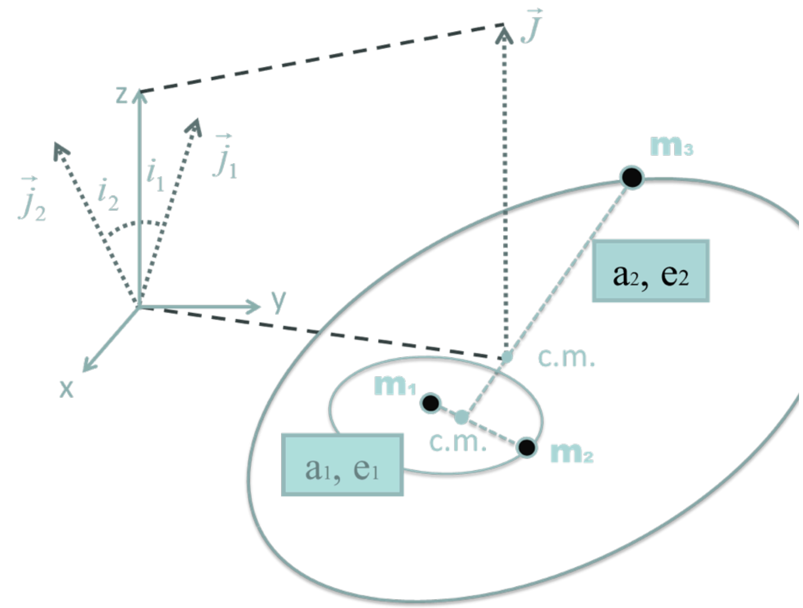
e.g. Blaes et al. 2002; Miller & Hamilton 2002; Wen 2003;
Thompson 2011; Antonini et al. 2012,2014,2017,
Silsbee & Tremaine 2017; Petrovich & Antonini 2017...

Lidov-Kozai oscillations

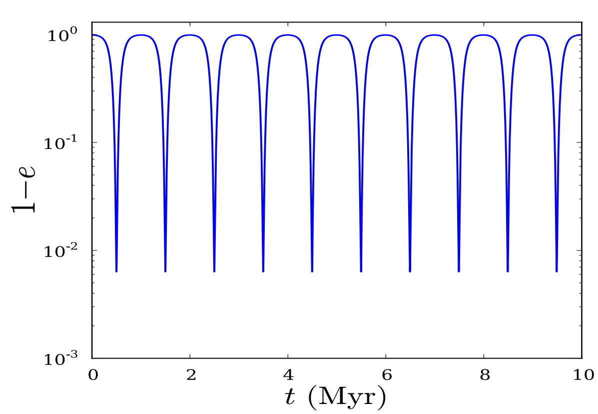
- **Inner binary + tertiary companion**

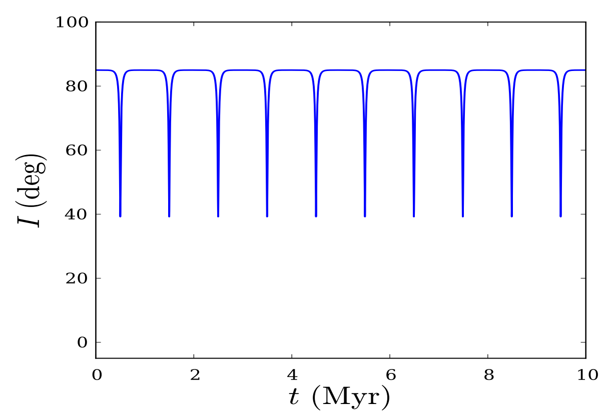
  --- Eccentricity and inclination oscillations induced if i > 40°

  --- If i large (85-90 degrees), get extremely large eccentricities (e > 0.99)

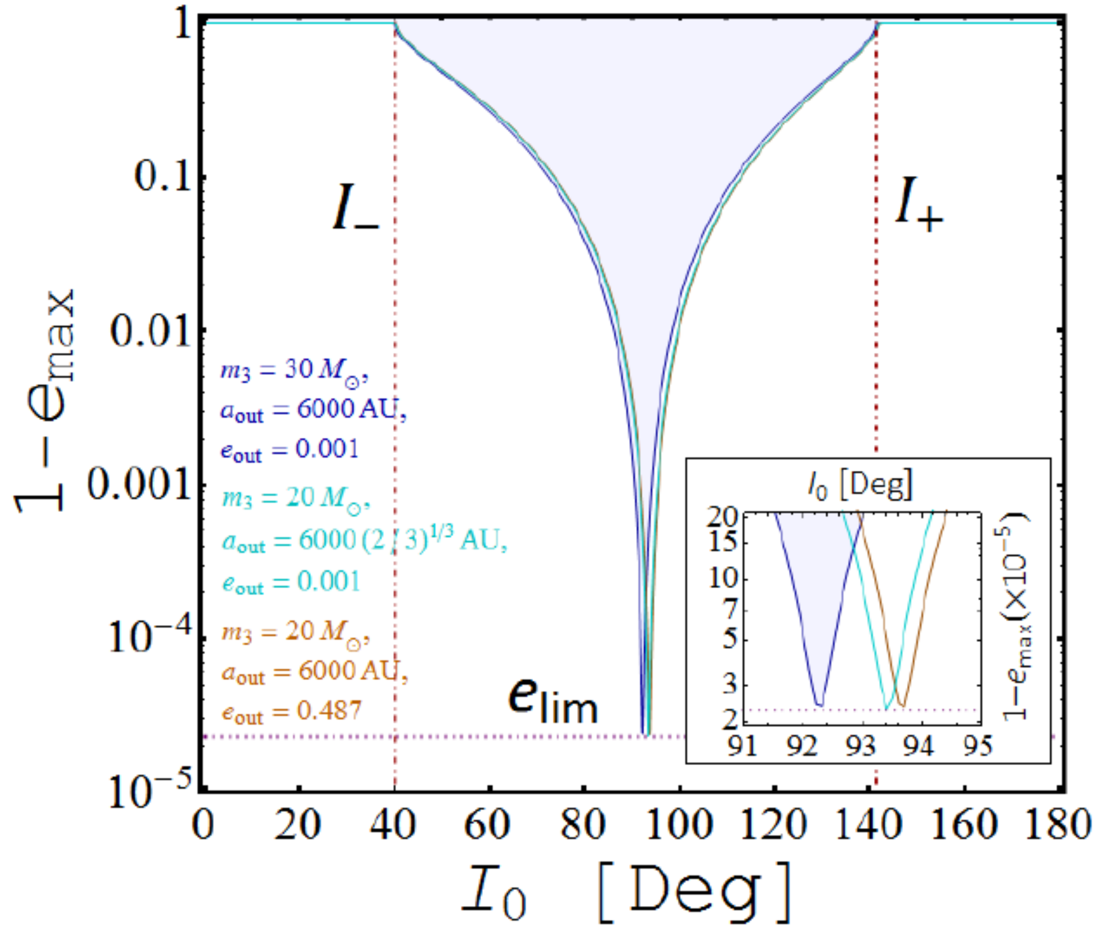


- **Orbital (secular) evolution**





Lidov-Kozai window for eccentricity excitation



quadrupole perturbation only

Eccentricity excitation depends on

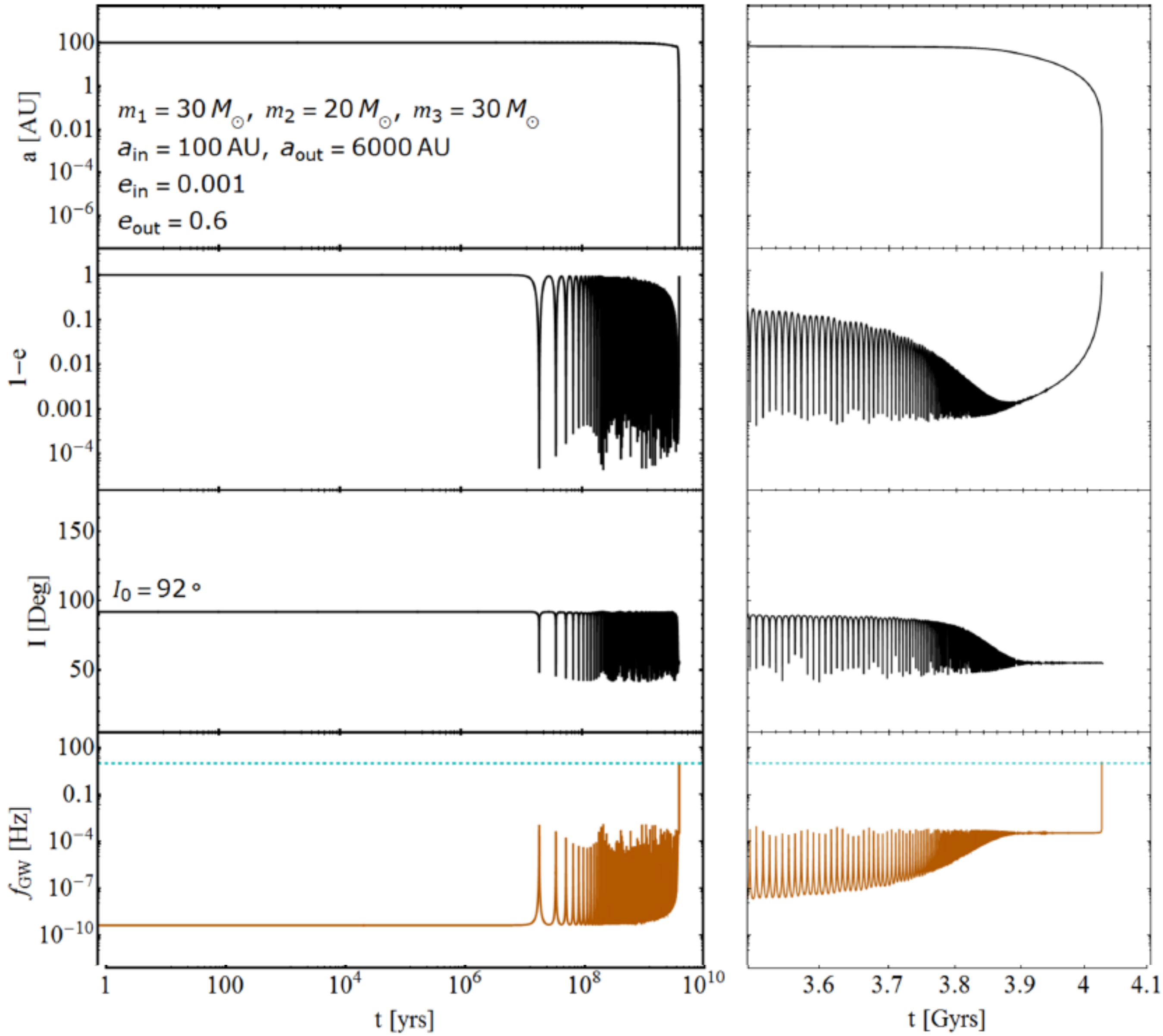
-- Initial mutual inclination

-- Competition between

LK driving $\propto \dfrac{m_3}{a_{out}^3}$

GR precession $\propto n_{in}\dfrac{m_{12}}{a_{in}}$

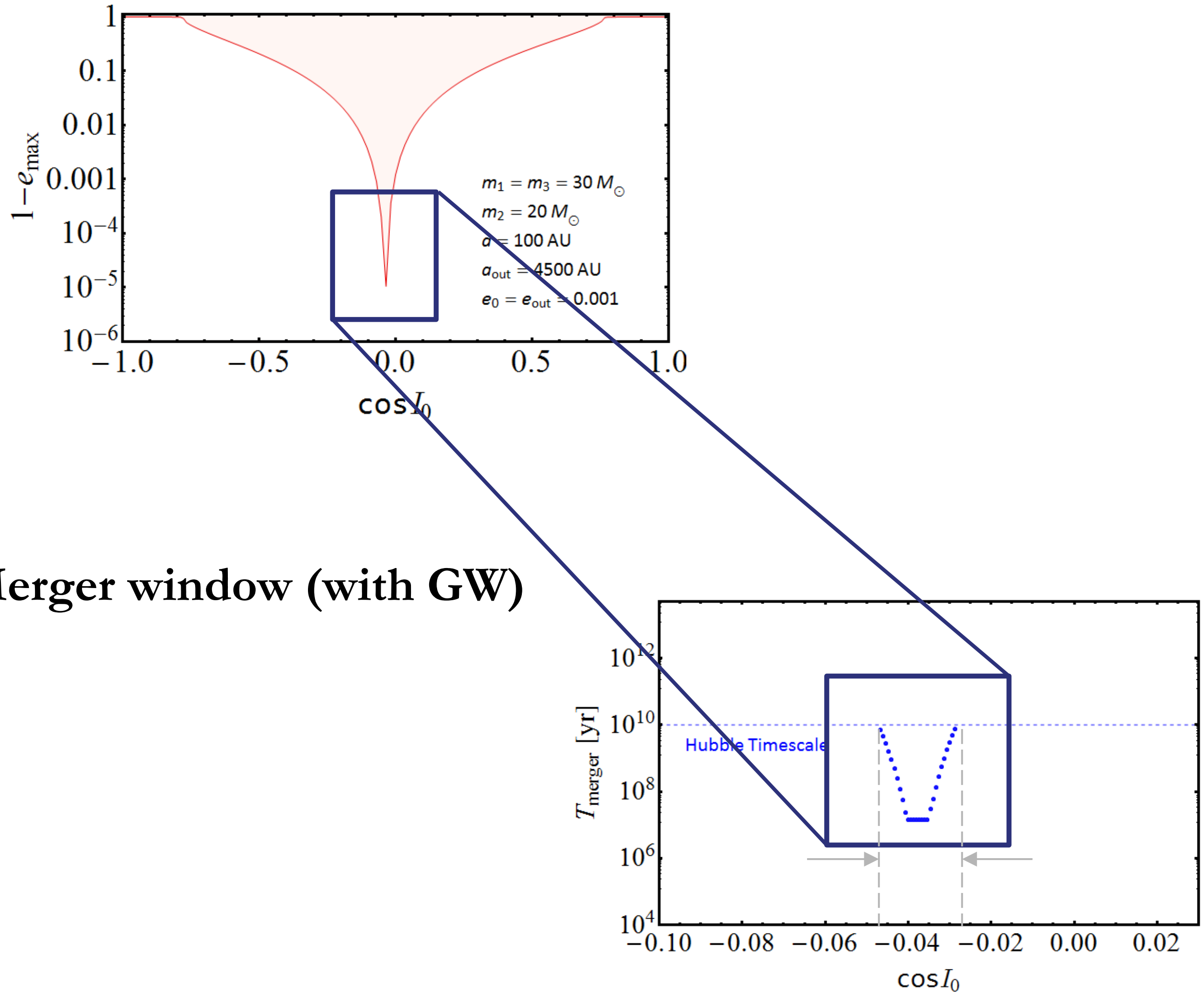
LK oscillation + Gravitation Radiation



Inclination window for merger

- e – excitation (no GW)

- Merger window (with GW)



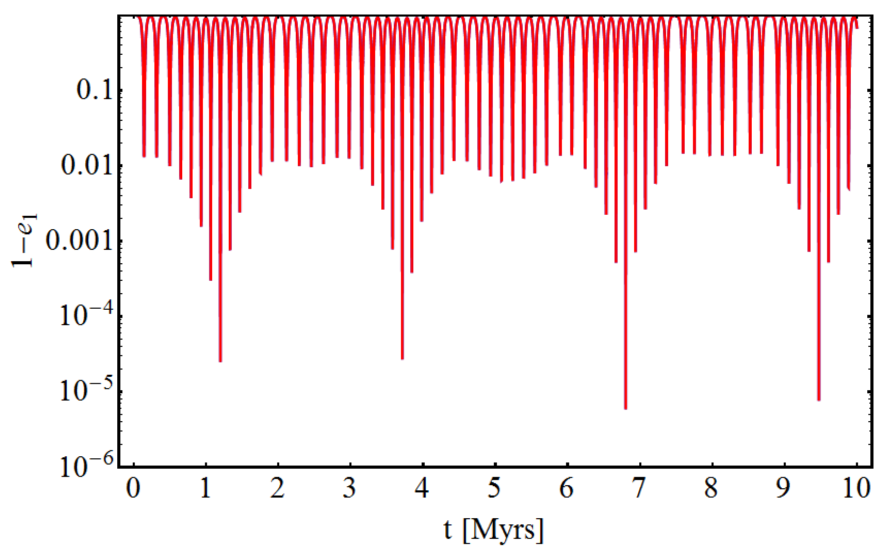
So far only “quadurpole” Lidov-Kozai···

LK driving rate $t_{\rm LK}^{-1} \propto \dfrac{m_3}{a_{\rm out}^3}$

Octupole effect

driving rate $\epsilon_{\rm oct}\, t_{\rm LK}^{-1}$

$$\varepsilon_{\rm oct} \equiv \frac{m_1 - m_2}{m_{12}} \left(\frac{a}{a_{\rm out}}\right) \frac{e_{\rm out}}{1 - e_{\rm out}^2}$$

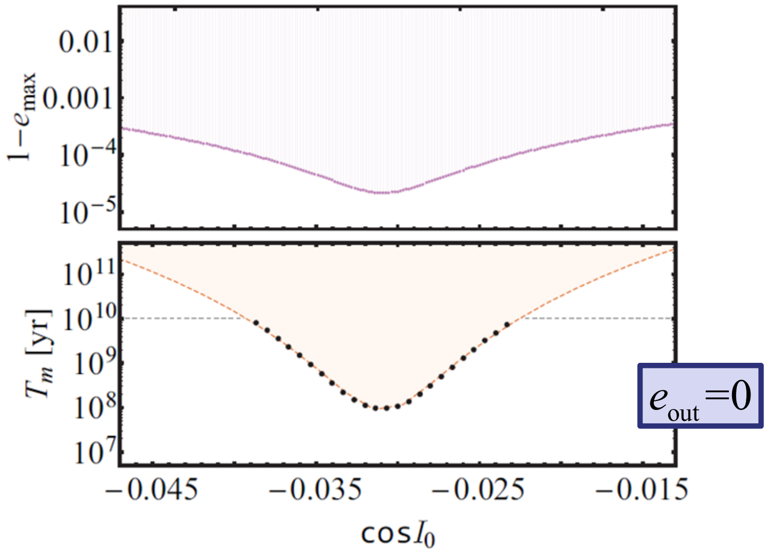


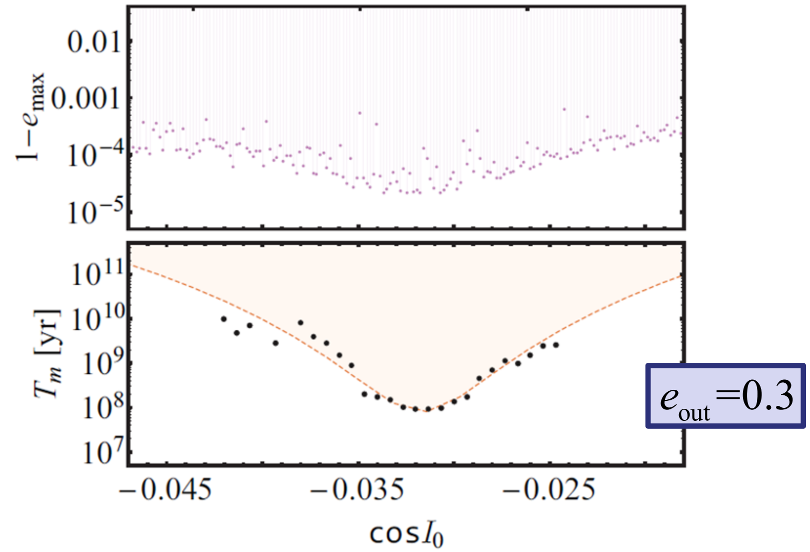
No longer “regular” LK oscillation

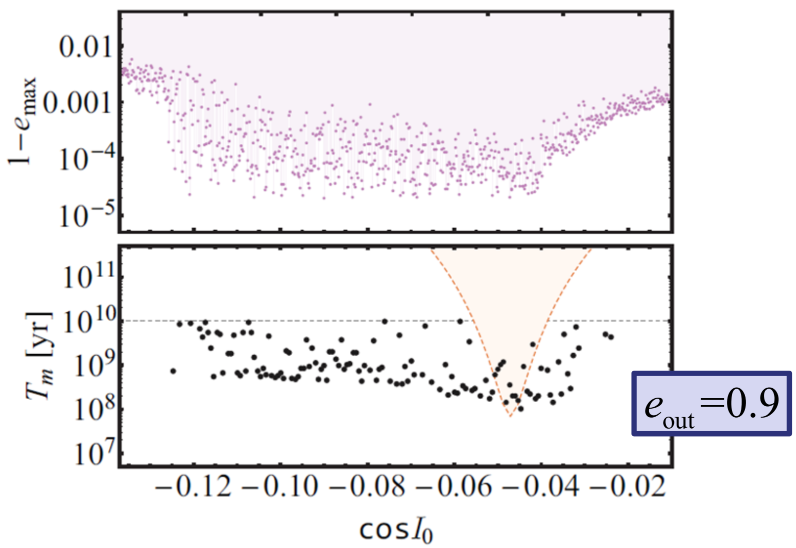
Inclination window for merger

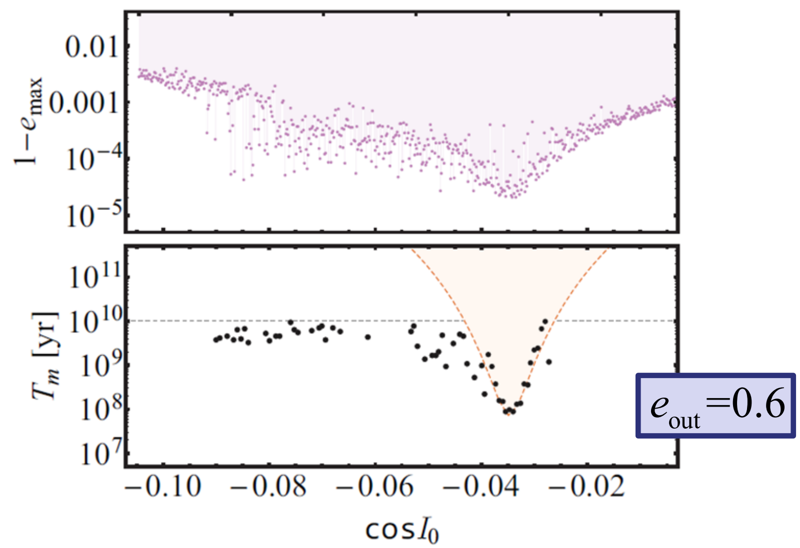
Fixed inner binary: $m_1=30M_\odot$, $m_2=20M_\odot$, $a_{in,0}=100AU$

Fixed $m_3/a_{\rm out}^3$ value

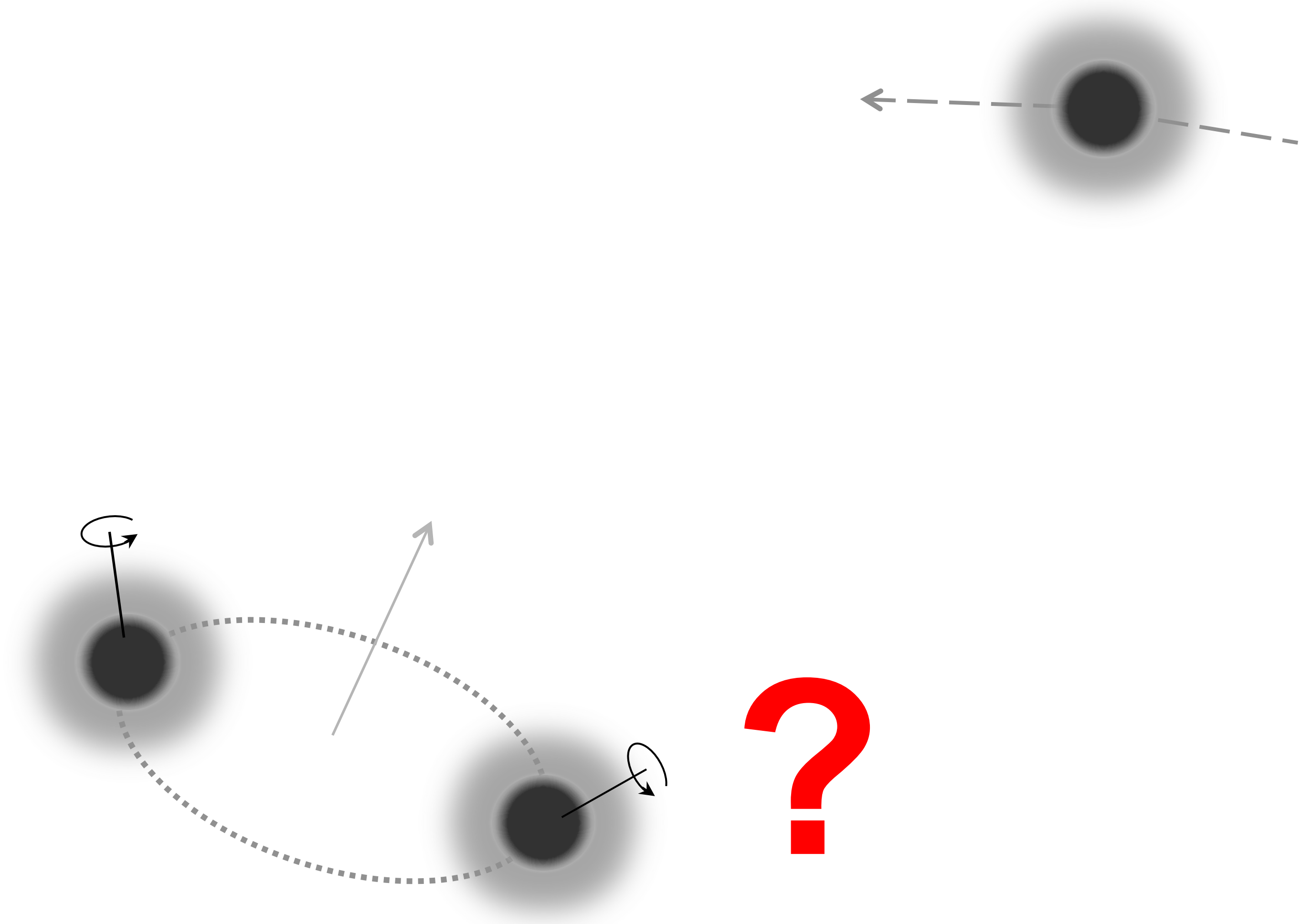




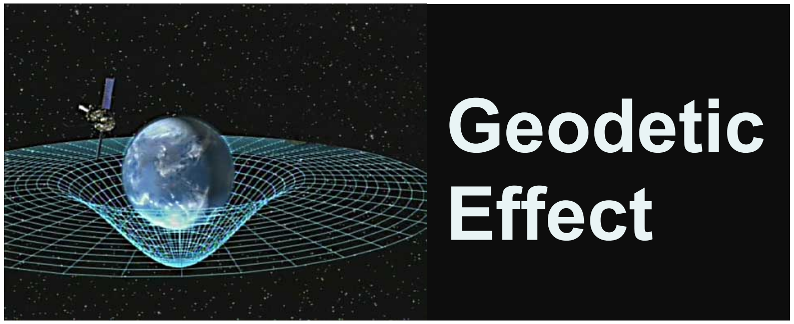




What about the BH Spin?

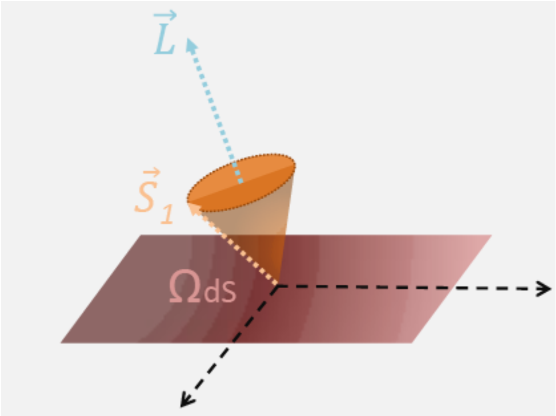


Spin-Orbit Coupling



The de Sitter precession of spin around the angular momentum axis of the binary

$$\frac{d\hat{S}_1}{dt} = \Omega_{dS}\hat{L} \times \hat{S}_1 \qquad \Omega_{dS} = \frac{3Gn\left(m_2 + \mu/3\right)}{2c^2 a\left(1-e^2\right)}$$

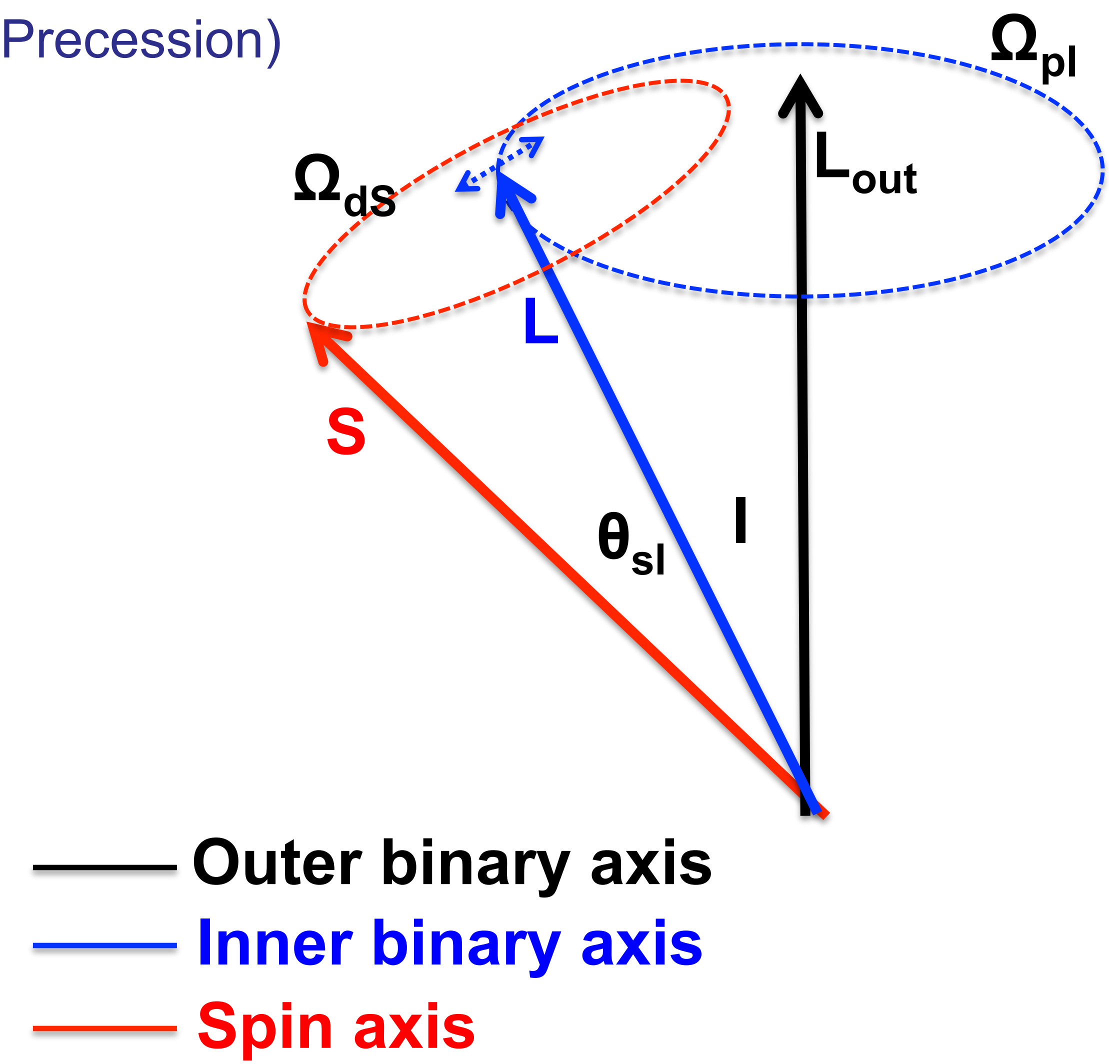


BH spin dynamics during LK oscillations

$$\frac{d\hat{\mathbf{S}}_1}{dt} = \Omega_{\mathrm{dS}}\hat{\mathbf{L}} \times \hat{\mathbf{S}}_1$$ (de Sitter Precession)

But **L** precesses and nutates during LK oscillations

$$\Omega_{\mathrm{pl}} \simeq \frac{3(1+e^2)}{t_{\mathrm{LK}}\sqrt{1-e^2}}|\sin 2I|$$



BH spin dynamics during LK oscillations

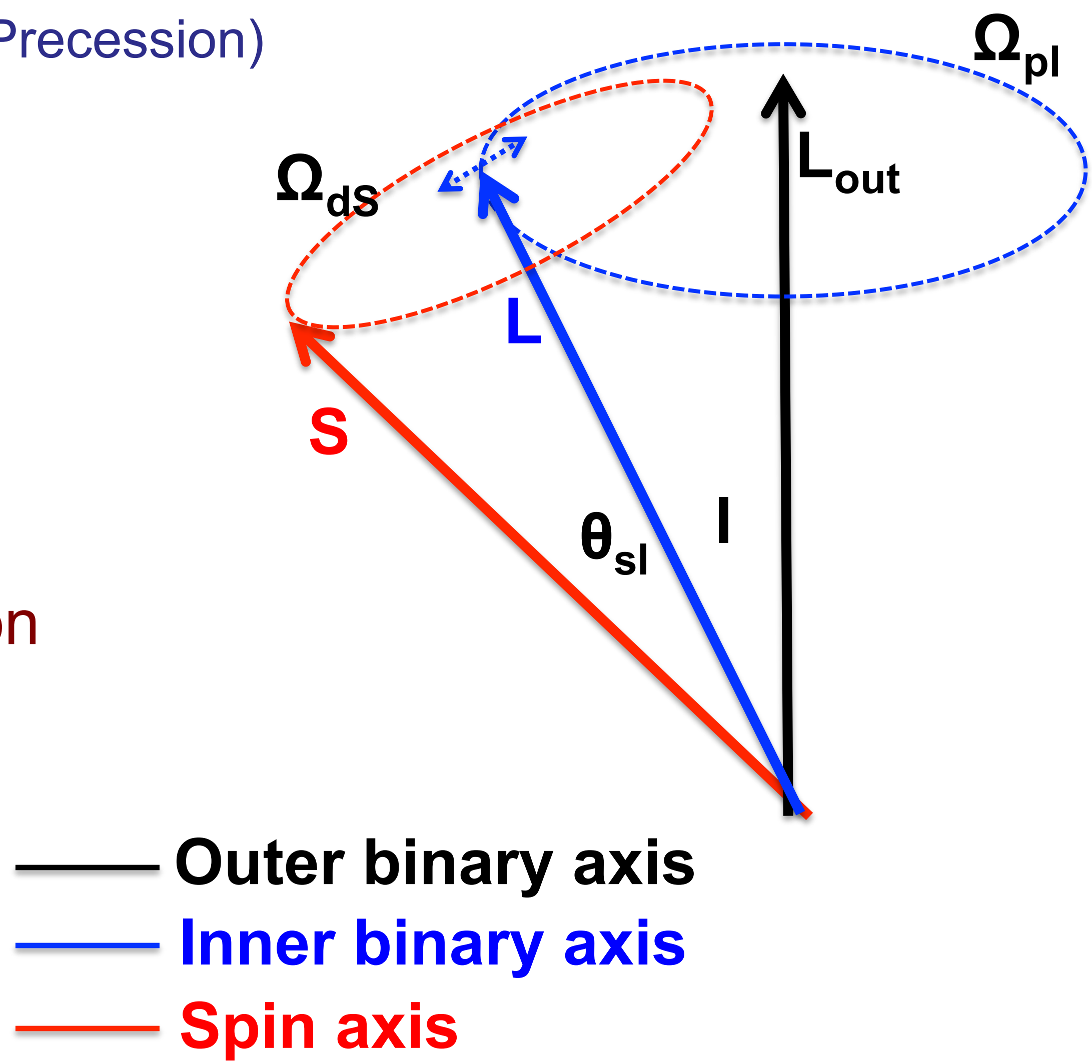
$$\frac{d\hat{\mathbf{S}}_1}{dt} = \Omega_{\rm dS}\hat{\mathbf{L}} \times \hat{\mathbf{S}}_1$$ (de Sitter Precession)

But **L** precesses and nutates during LK oscillations

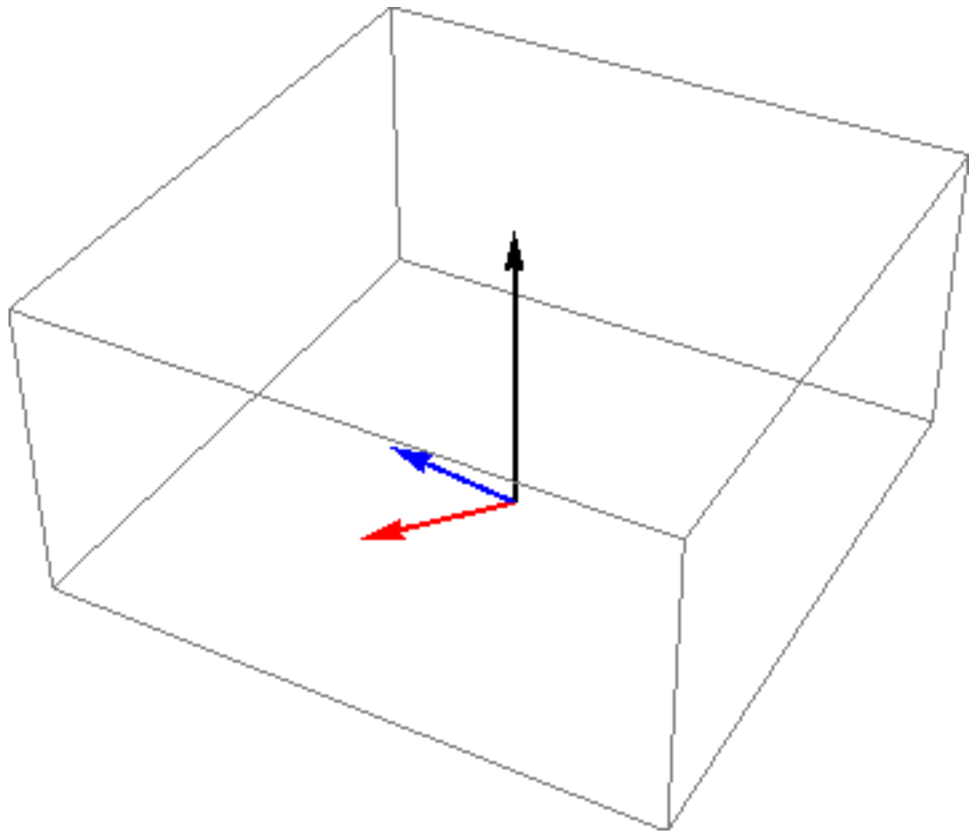
$$\Omega_{\rm pl} \simeq \frac{3(1+e^2)}{t_{\rm LK}\sqrt{1-e^2}}|\sin 2I|$$

Spin dynamics depends on

$$\Omega_{\rm dS} \text{ vs } \Omega_{\rm pl}$$

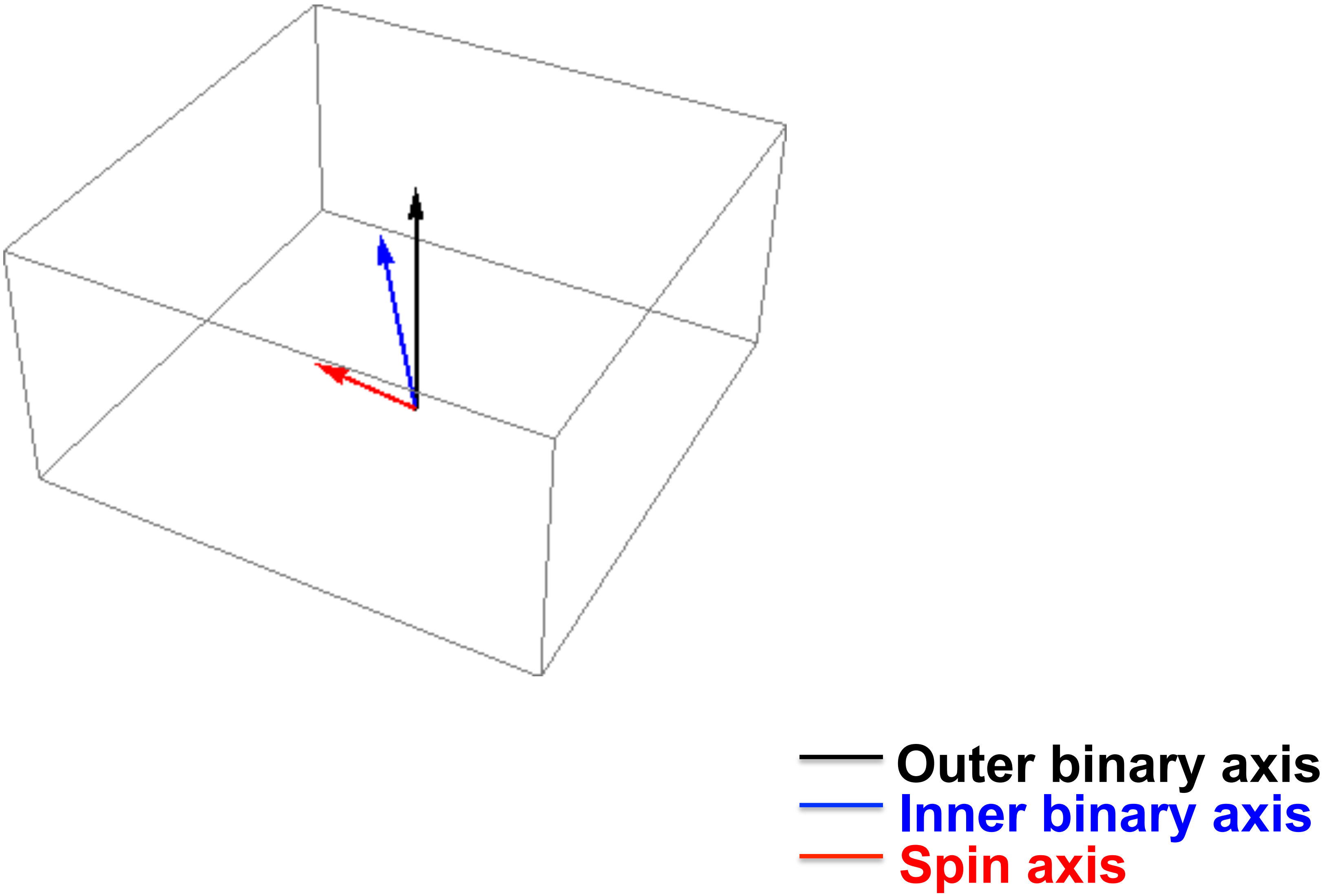


If $|\Omega_{dS}| >> |\Omega_{pl}|$:   S follows L adiabatically

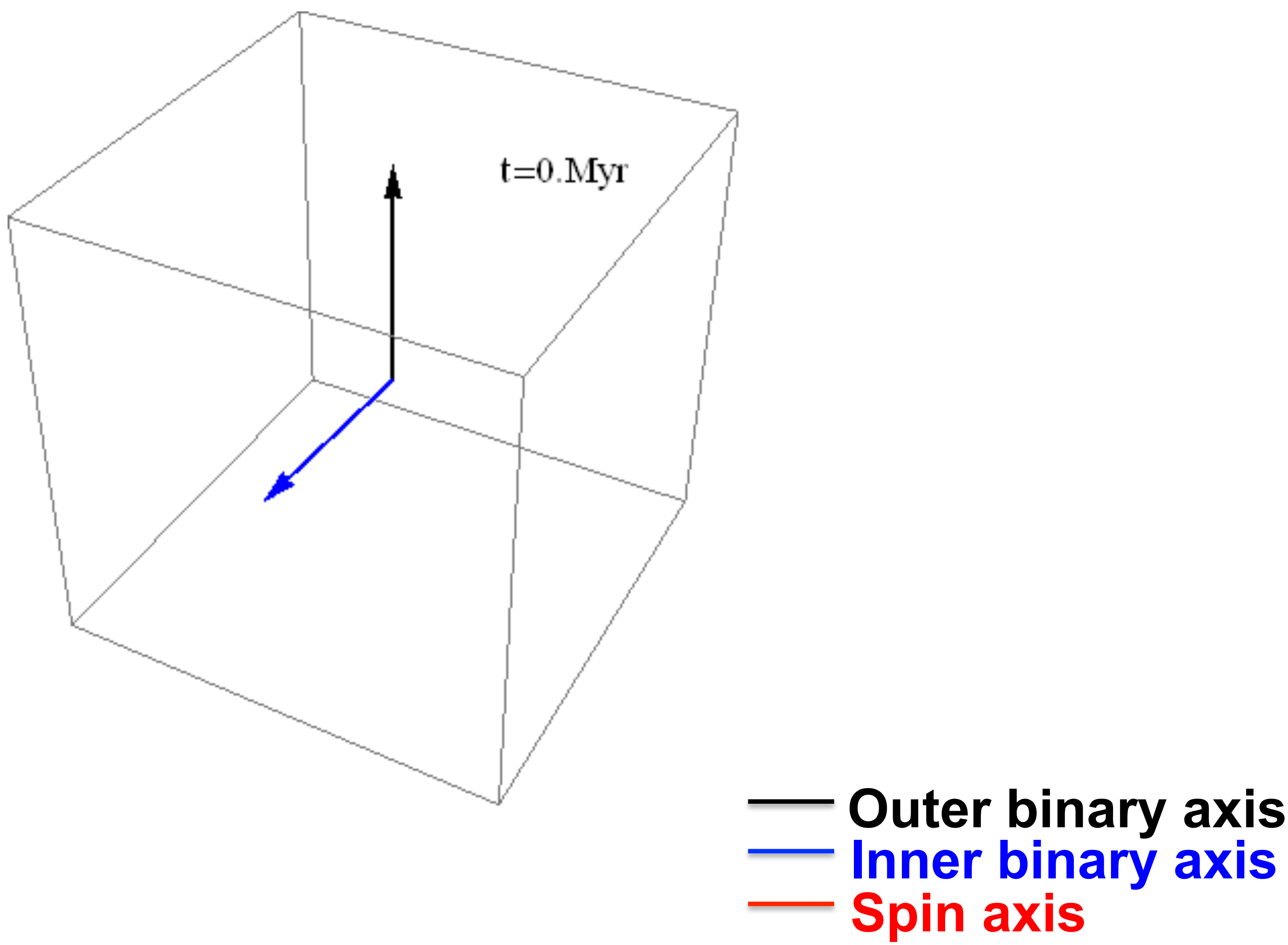


Outer binary axis
Inner binary axis
Spin axis

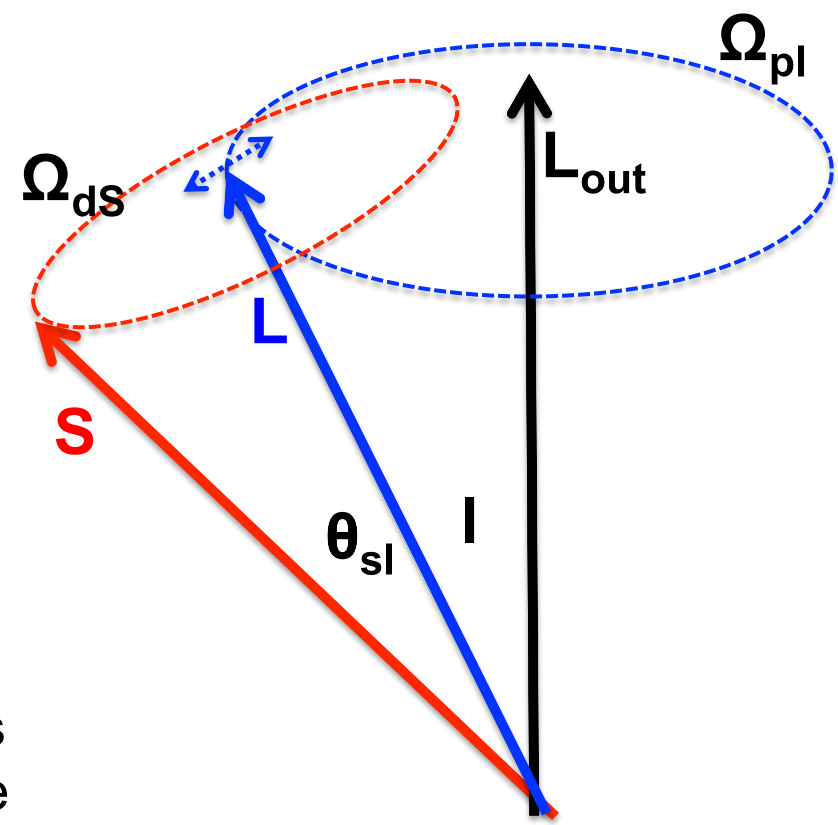
If $|\Omega_{dS}| << |\Omega_{pl}|$: Non-adiabatic



If $|\Omega_{dS}| \sim |\Omega_{pl}|$:

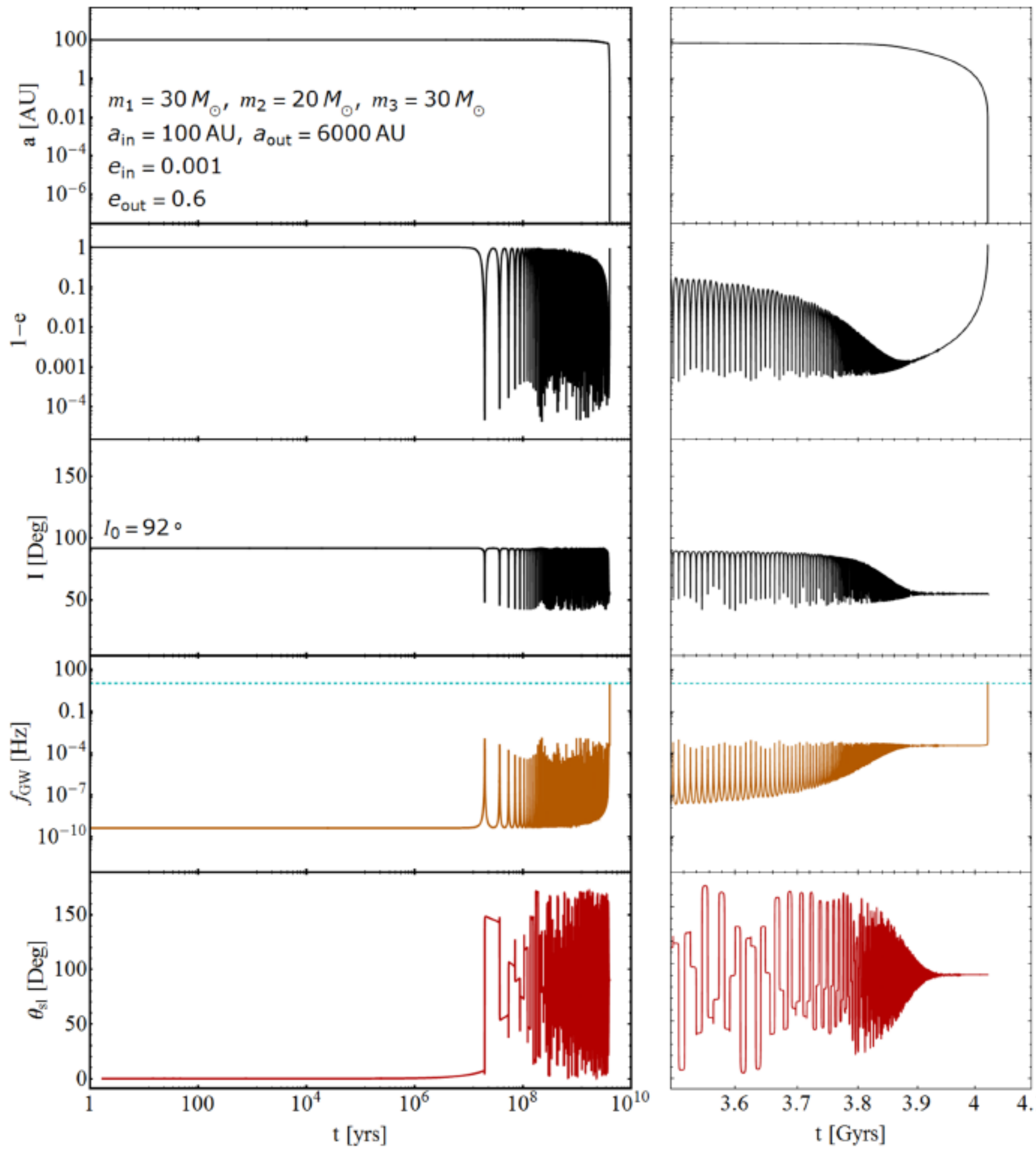


BH spin evolution in LK-induced orbital decay



$$\Omega_{\rm dS}/\Omega_{\rm pl}$$

changes from << 1 (non-adiabatic)
to >> 1 (adiabatic) as the orbit decays
➔ Final spin-orbit misalignment angle

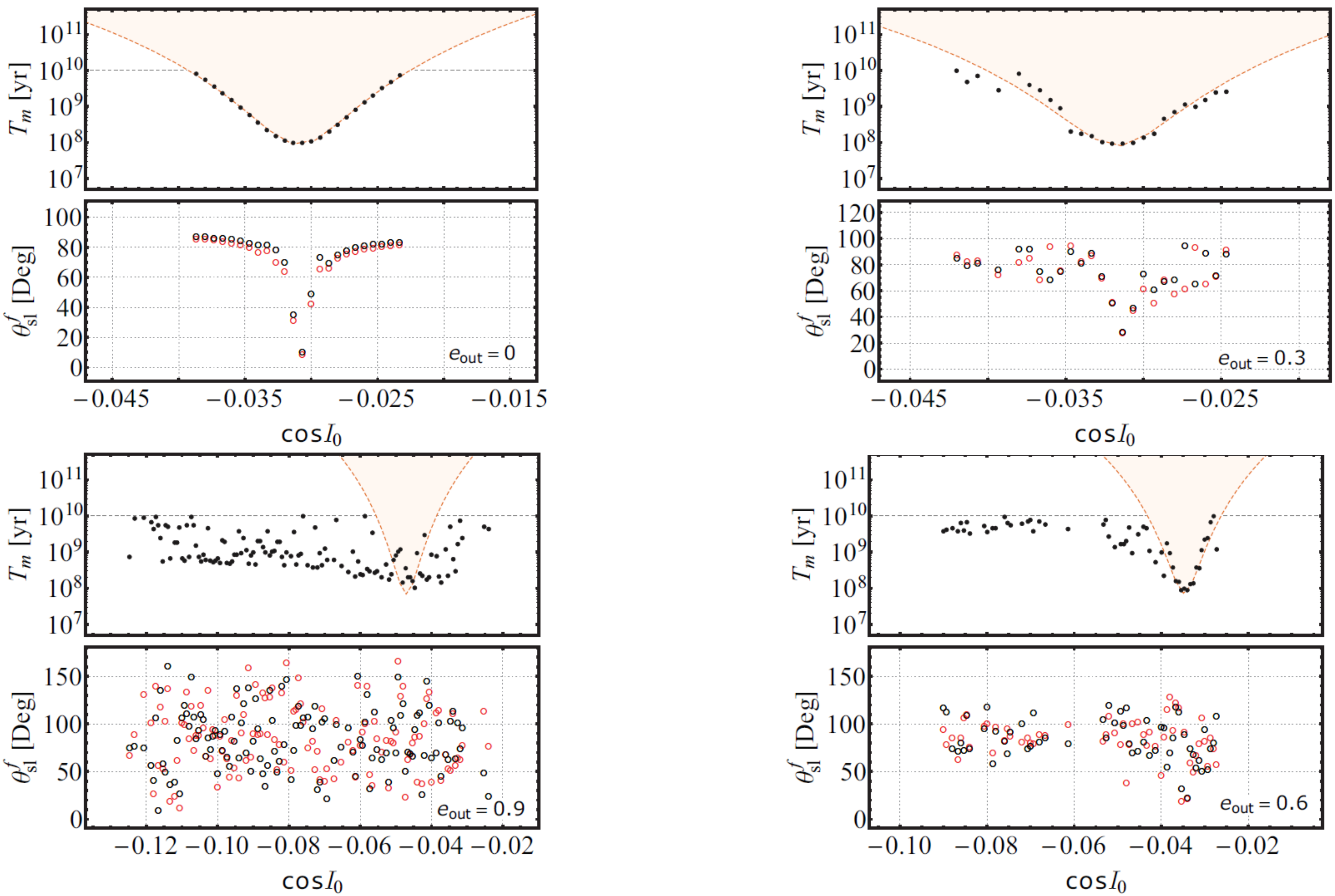


$m_1 = 30\,M_\odot,\ m_2 = 20\,M_\odot,\ m_3 = 30\,M_\odot$
$a_{in} = 100\,\mathrm{AU},\ a_{out} = 6000\,\mathrm{AU}$
$e_{in} = 0.001$
$e_{out} = 0.6$
$I_0 = 92\,^\circ$
a [AU]
1−e
I [Deg]
f_{GW} [Hz]
θ_{sl} [Deg]
t [yrs]
t [Gyrs]

Merger Window and Final Spin-Orbit Misalignments

Fixed inner binary: $m_1=30M_\odot$, $m_2=20M_\odot$, $a_{in,0}=100AU$

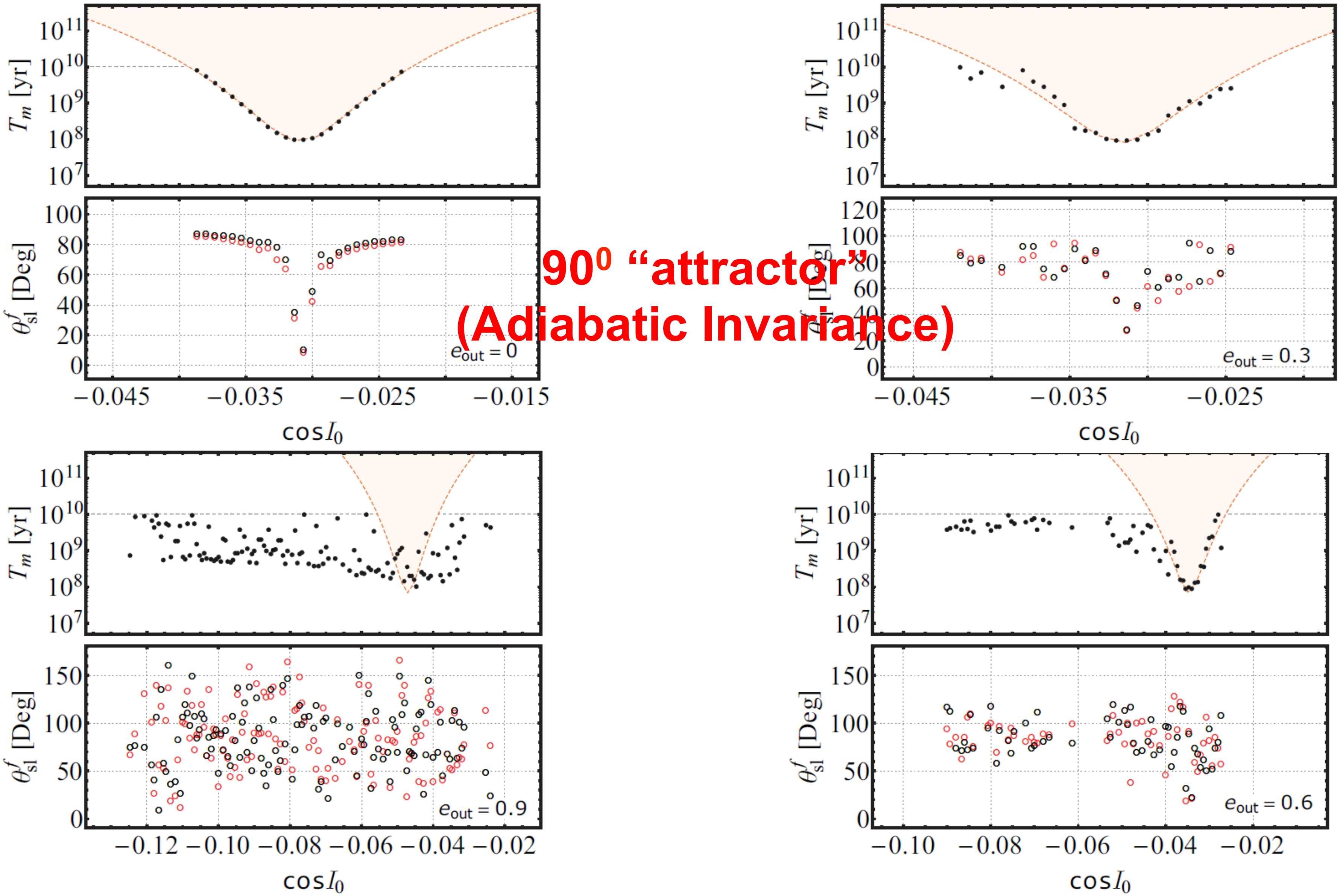
Fixed $m_3/a_{\rm out}^3$ value



Merger Window and Final Spin-Orbit Misalignments

Fixed inner binary: $m_1=30M_\odot$, $m_2=20M_\odot$, $a_{in,0}=100AU$

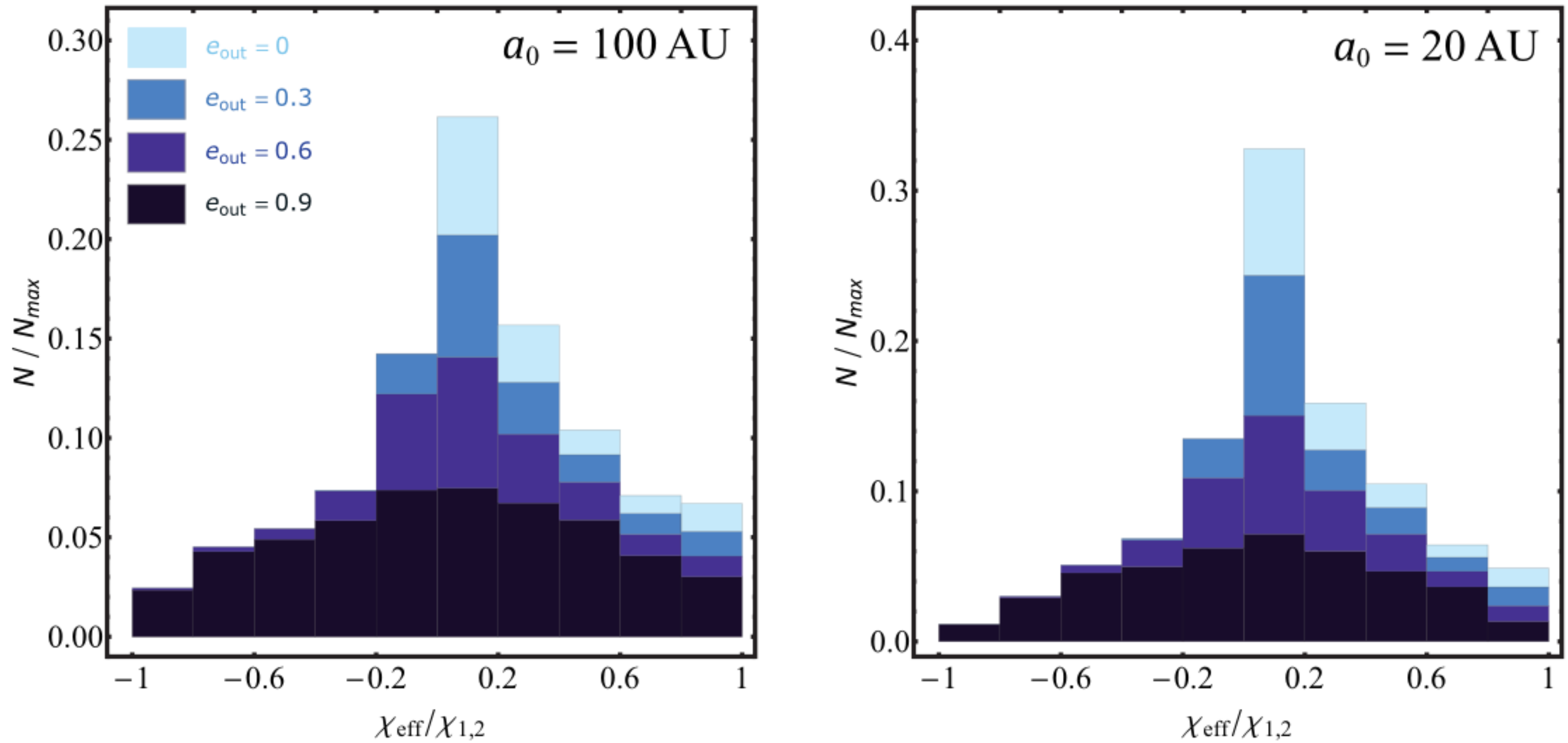
Fixed m_3/a_{out}^3 value



90^0 "attractor" (Adiabatic Invariance)

Effective Spin Distribution

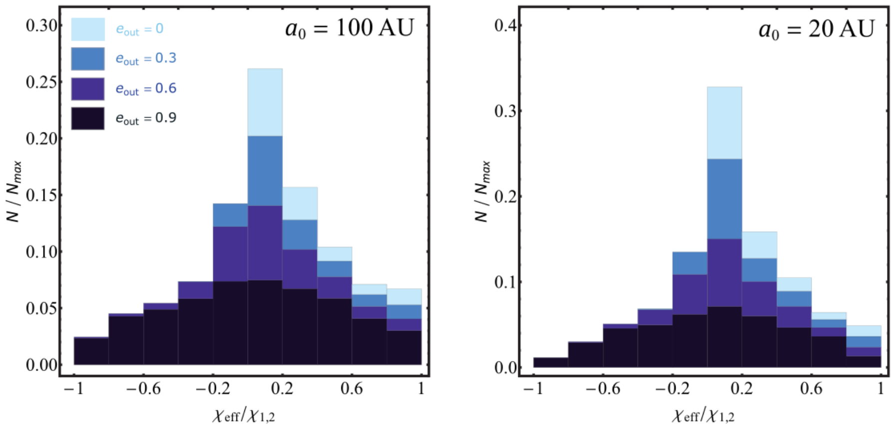
Effective spin parameter $\chi_{\rm eff} = \frac{m_1\chi_1 \cos\theta_{s_1 l} + m_2\chi_2 \cos\theta_{s_2 l}}{m_{12}}$



A unique signature of LK-induced mergers

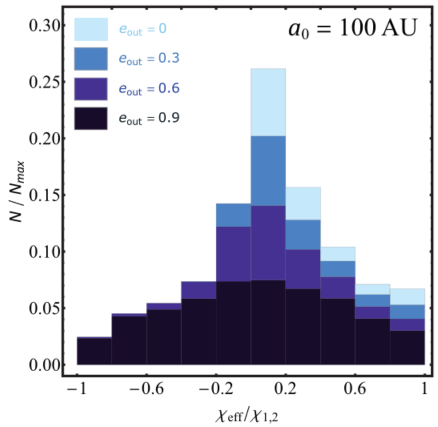
Effective Spin Distribution

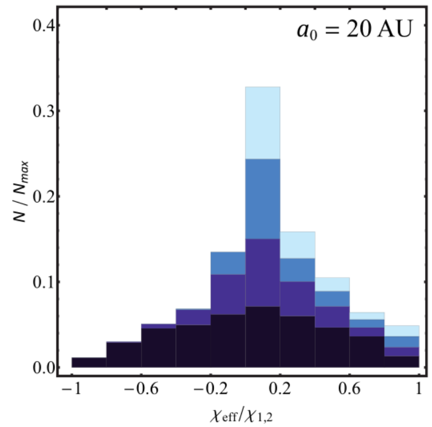
For “reasonable” initial binary/triple parameters (e_0=0, distant companions)



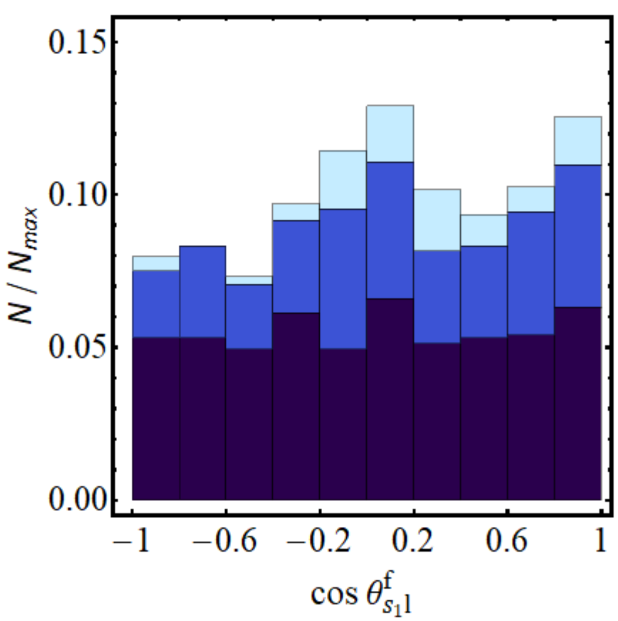
Effective Spin Distribution

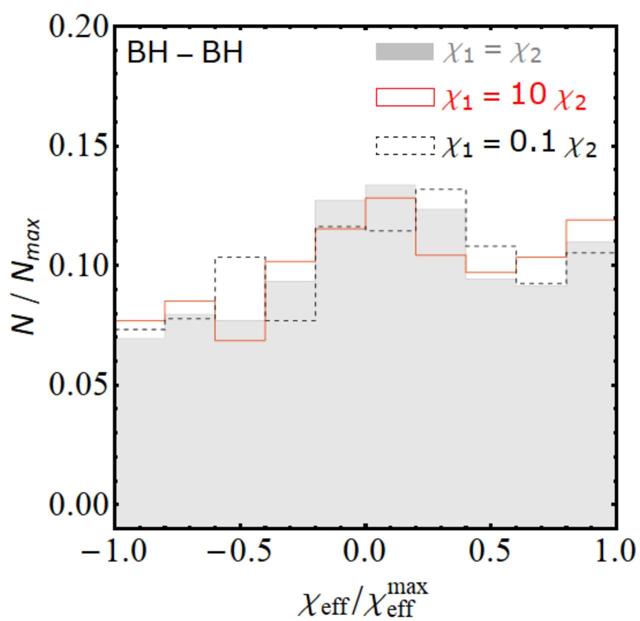
For “reasonable” initial binary/triple parameters (e_0=0, distant companions)





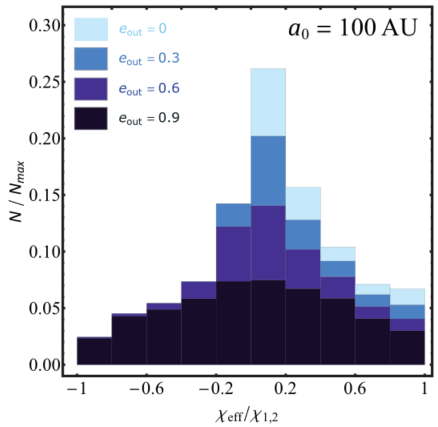
Consider ALL possible parameters

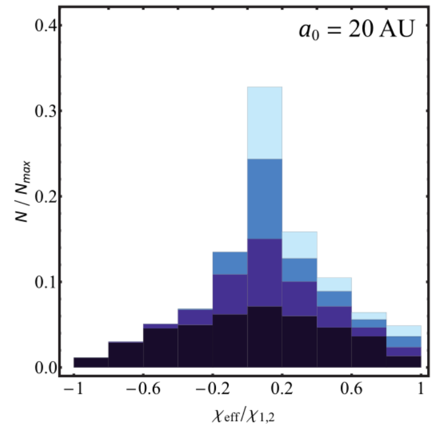


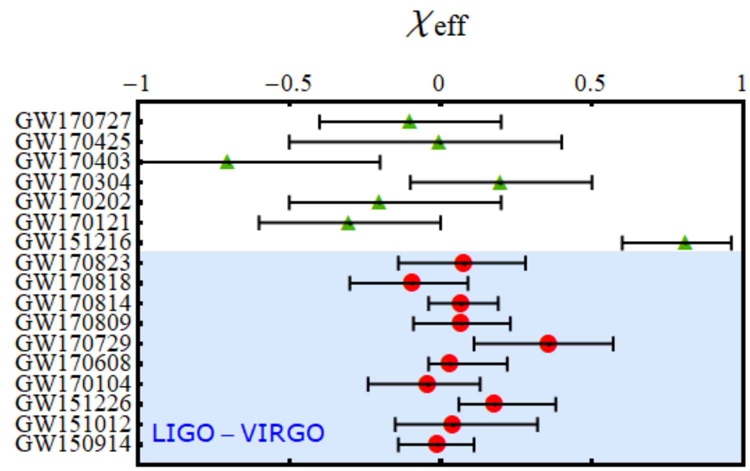


Effective Spin Distribution

For "reasonable" initial binary/triple parameters (e_0=0, distant companions)

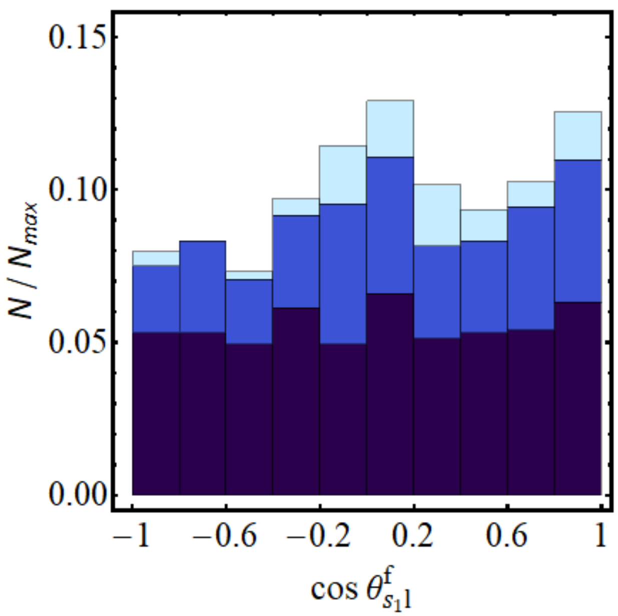


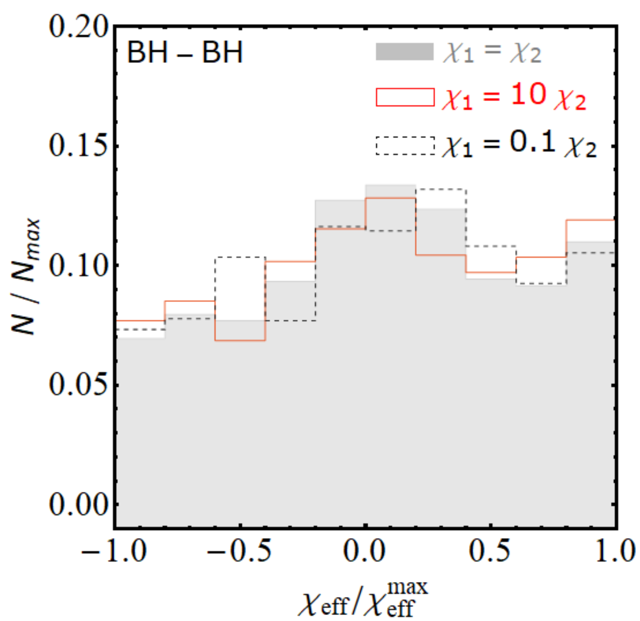




Observed so far

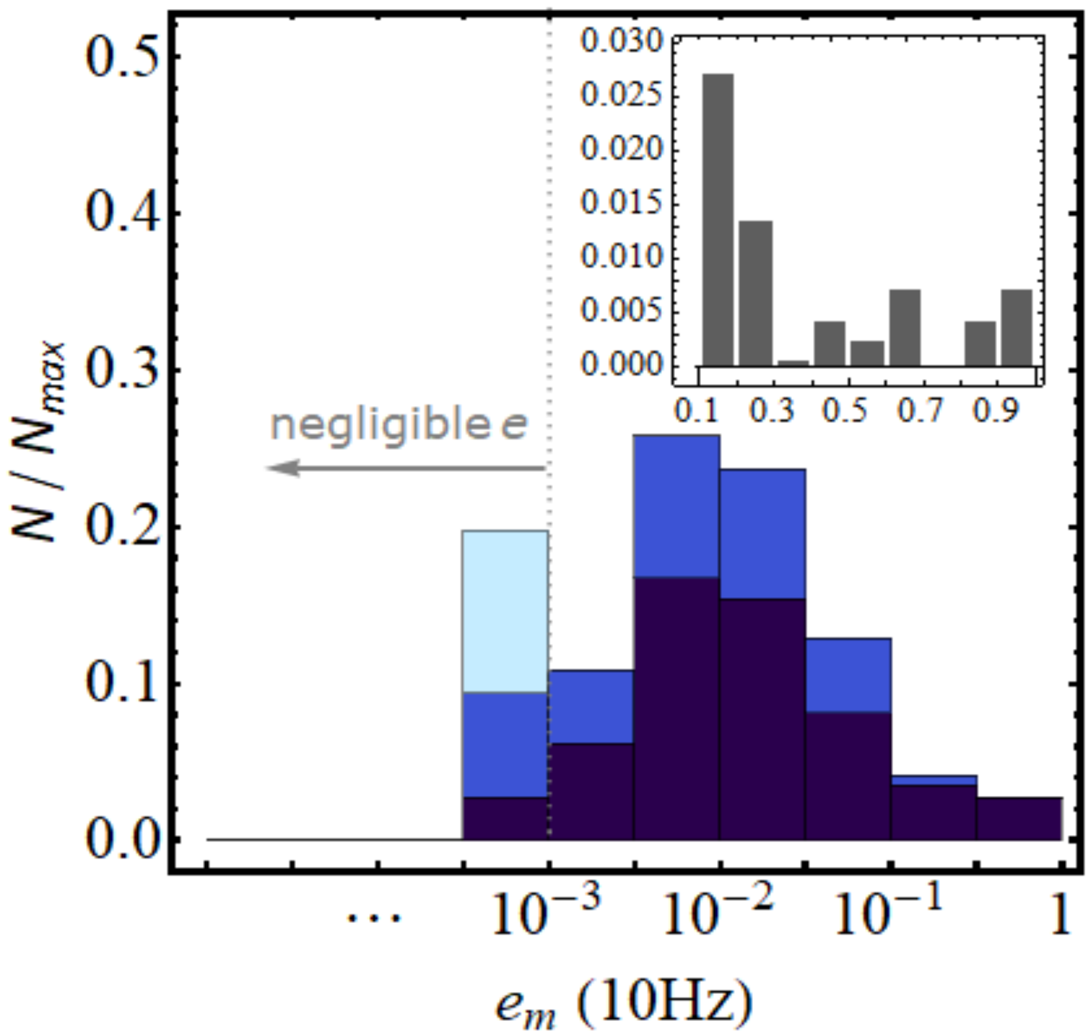
Consider ALL possible parameters





Residual Eccentricity (at 10 Hz)

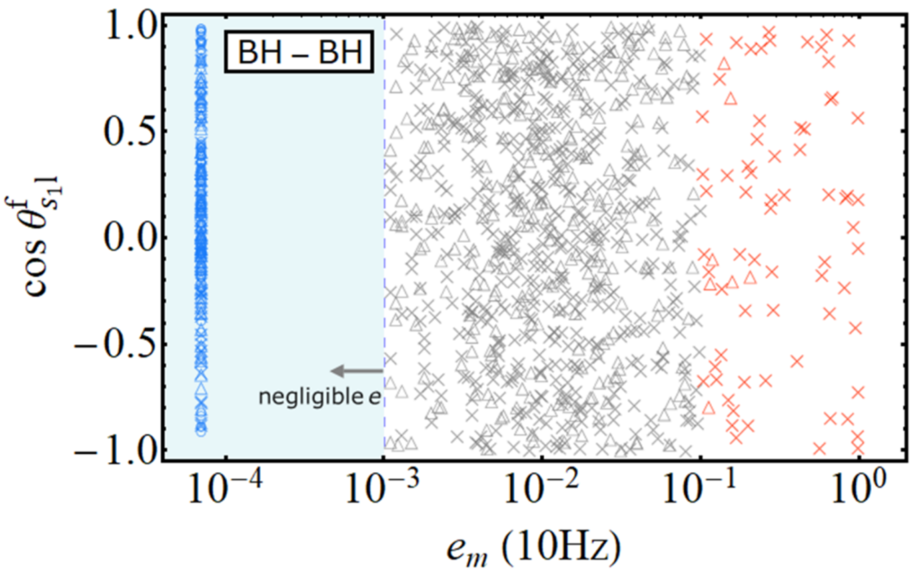
BH-BH mergers

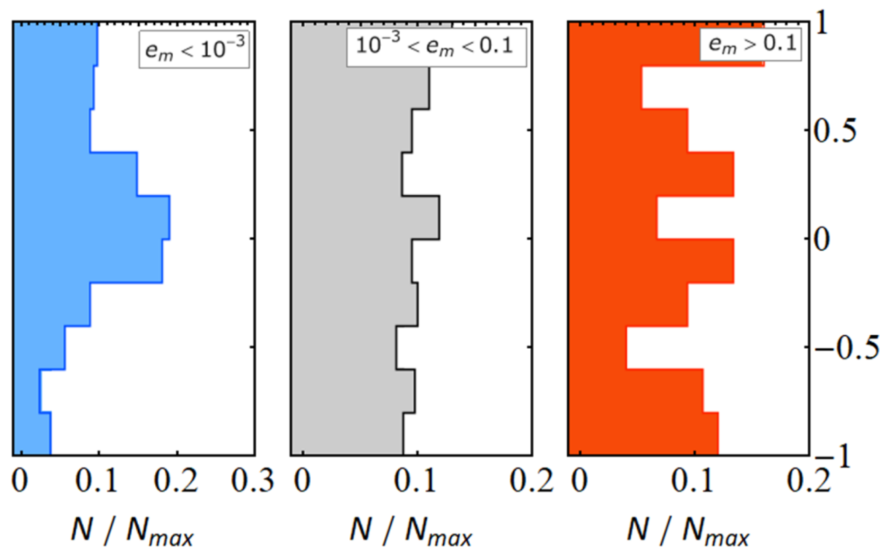


10% have $e_m > 0.1$

1% have $e_m > 0.9$

Residual eccentricity vs Spin-orbit Mislaignment





Circular Mergers ($e_m < 10^{-3}$) prefer $\theta^{f}_{sl} \sim 90°$

More eccentric Mergers has random θ^{f}_{sl}

Summary
Formation Channels of Merging BH Binaries

Standard isolated binary evolution channel:

uncertain physics (common envelope⋯)

➔ circular mergers (e_m=0)

aligned spin-orbit angle

Dynamical formation channels:

"clean" physics, but "environmental" uncertainties

1. Dense star clusters

➔ mostly circular mergers ?

expect random spin-orbit misalignments ?

2. Tertiary-induced mergers

Perturbations from outer companion → Lidov-Kozai

Spin-orbit coupling (de Sitter precession) important..

➔ 10% mergers have residual e>0.1 when entering LIGO band

Preference of 90^0 spin-orbit misalignment, especially for circular mergers

Rates? All potentially compatible⋯

LISA useful for probing dynamical formation

EM counterpart of BH Mergers

Standard binary evolution channel

Very likely to have gas around just after compact binary formation

e.g. incomplete common-envelope ejection ➔ circumbinary disk

Can disk survives the long binary inspiral phase?

If ~$0.01M_{sun}$ survives ➔ EM emission post-merger

(M_{tot} smaller, kick ➔ perturbed/dissipative disk)

Dynamical Formation: Clusters

No disk can survive multiple binary-single encounters ➔ No EM

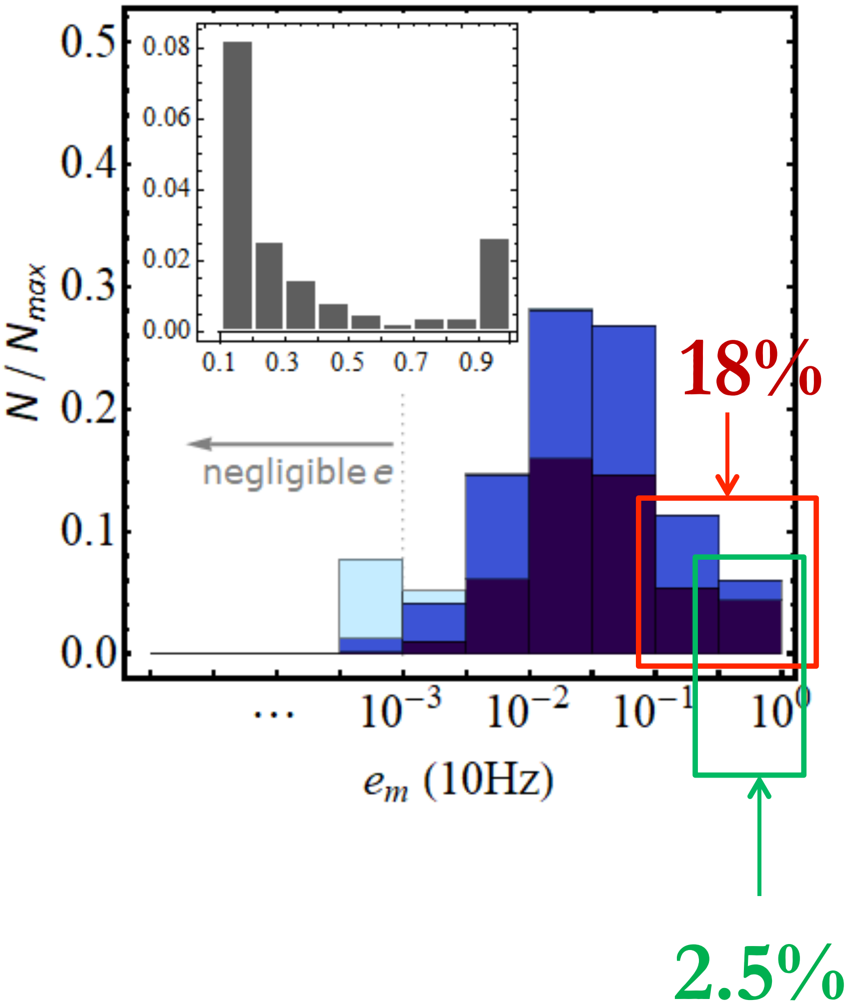
Dynamical Formation: Tertiary-induced in Triples

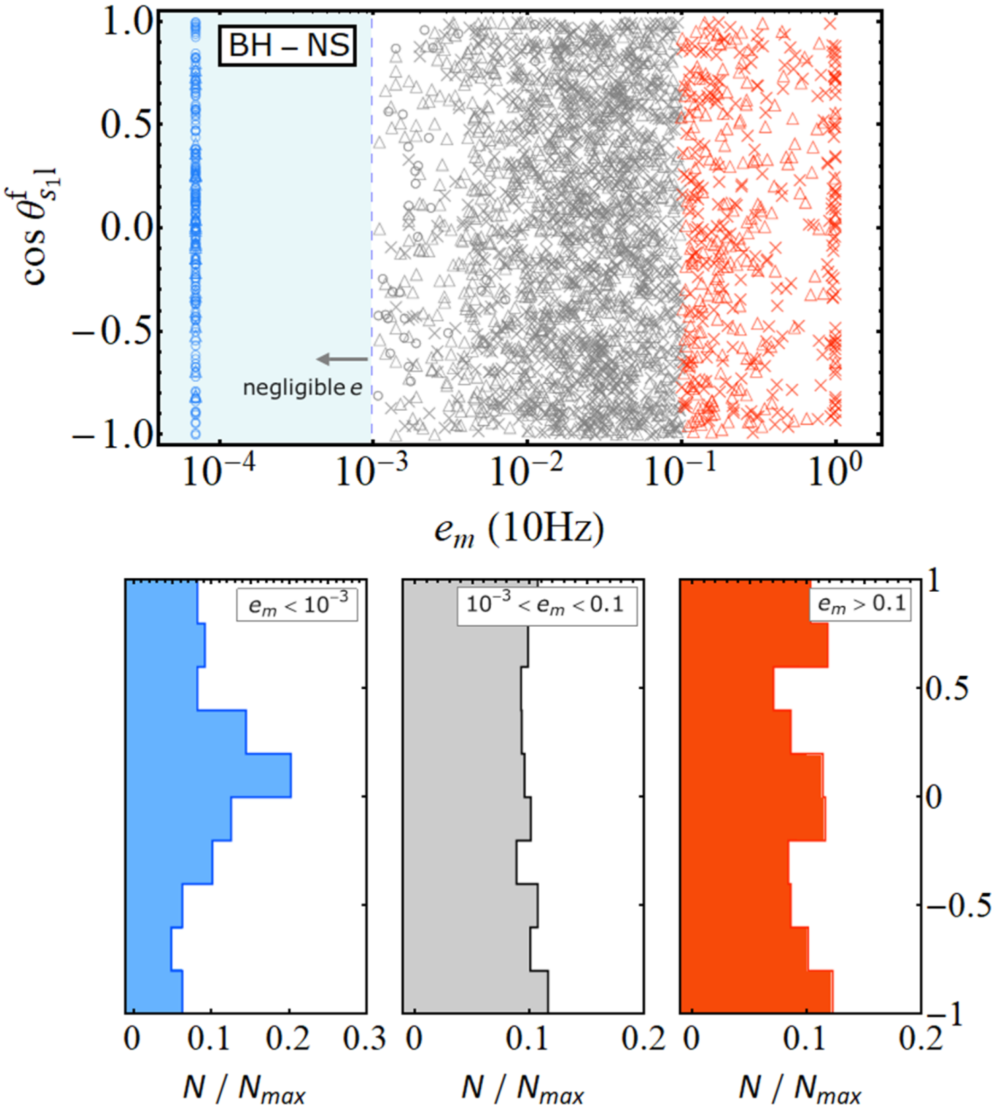
Original disk cannot survive

Mass transfer from tertiary star onto binary ➔ circumbinary disk ➔ EM radiation?

Thanks.

BH-NS Mergers





Spin Puzzle ?

$$\chi_{\rm eff} = \frac{m_1 \mathbf{a}_1 + m_2 \mathbf{a}_2}{m_1 + m_2} \cdot \hat{\mathbf{L}}$$

$$\begin{array}{ll}
\text{GW150914:} & -0.06^{+0.14}_{-0.14} \\
\text{GW151226:} & 0.21^{+0.2}_{-0.1} \\
\text{GW170104:} & -0.12^{+0.21}_{-0.3} \\
\text{GW170608:} & 0.07^{+0.23}_{-0.09} \\
\text{GW170814:} & 0.06^{+0.12}_{-0.12}
\end{array}$$

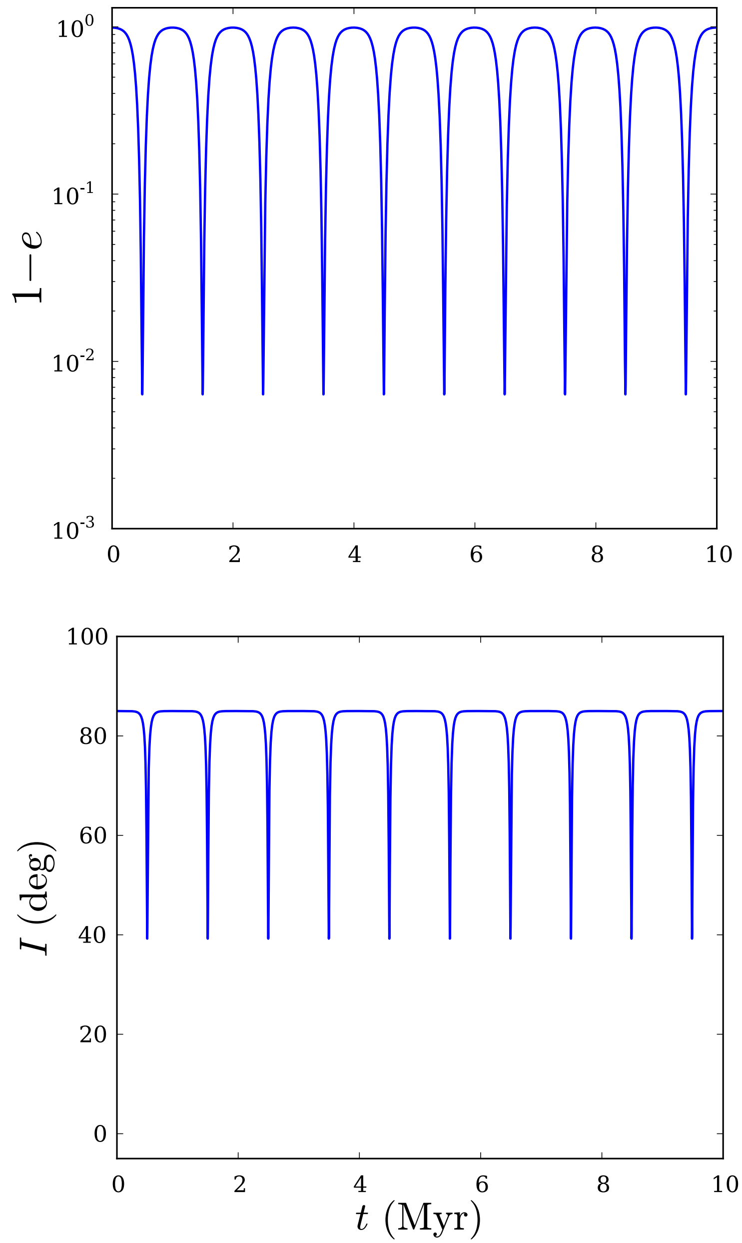
Eccentric mergers in LIGO band are probably rare…

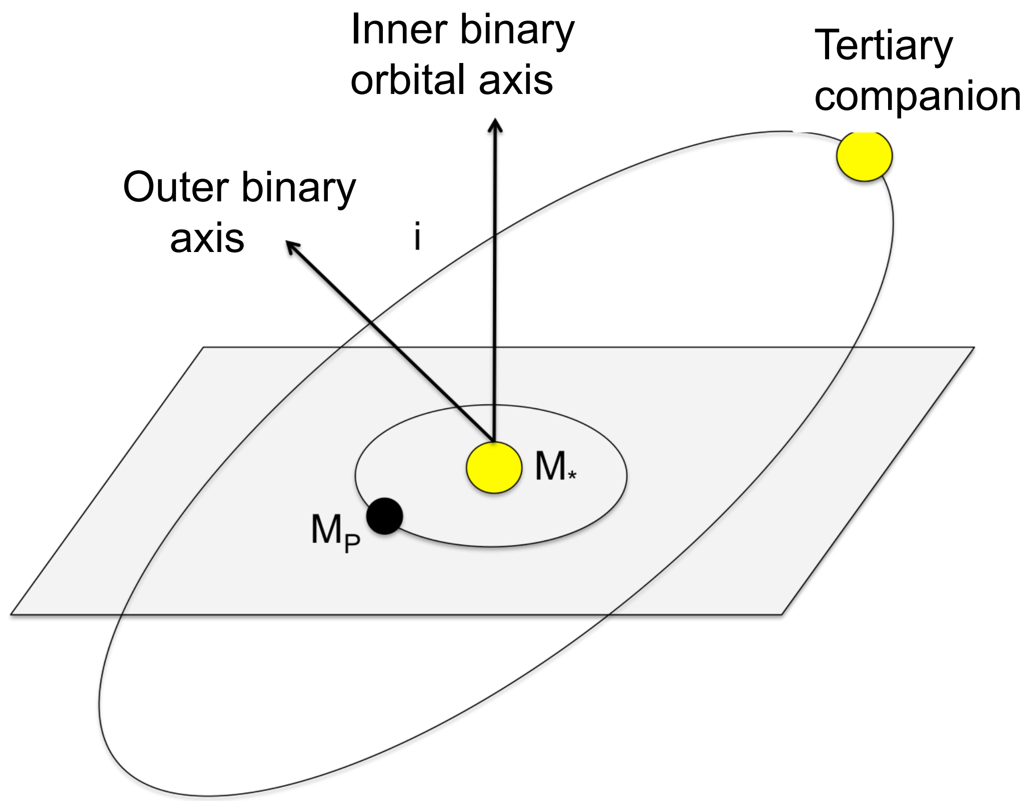
But **“high-e mergers” induced/enhanced by tertiary companion** (binary goes through high-e phase but has circularized when entering LIGO band) may not be rare (Competitive with normal binary evolution channel?)

Previous works:

e.g. Blaes et al. 2002; Miller & Hamilton 2002; Wen 2003; Thompson 2011; Antonini et al. 2014,2017, Silsbee & Tremaine 2017…

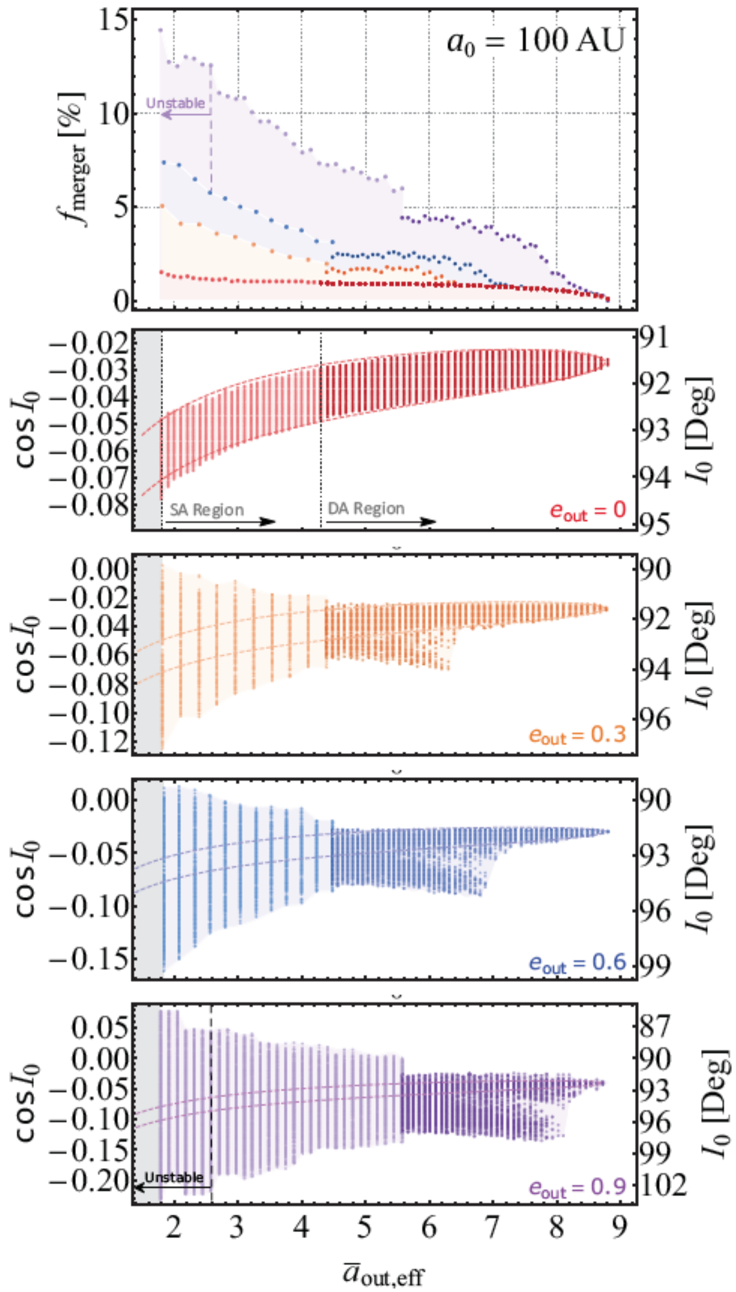
Recall: Lidov-Kozai Oscillations





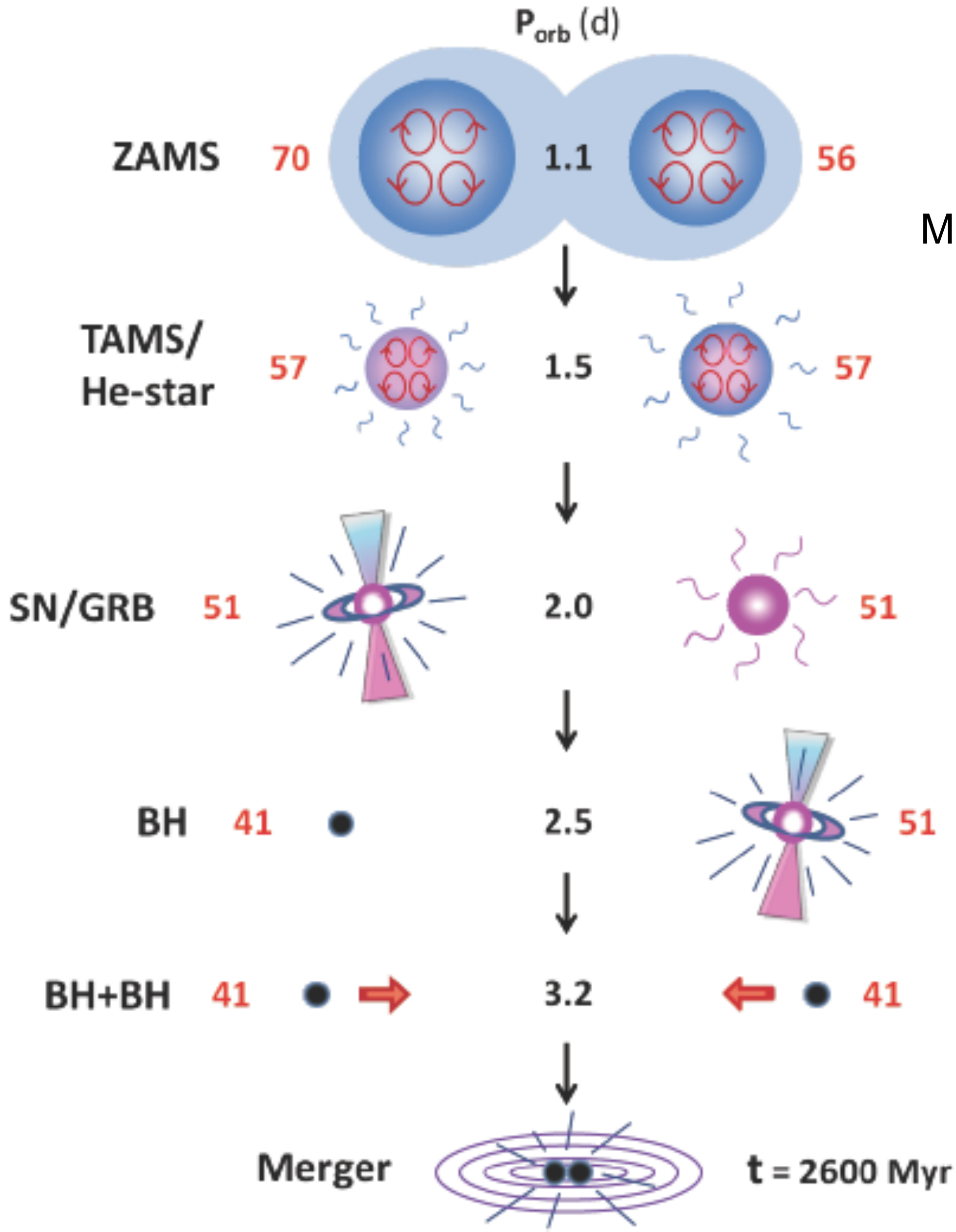
- Eccentricity and inclination oscillations induced if I > 40 degrees.
- If I large (85-90 degrees), get extremely large eccentricities (e > 0.99)

Merger Window and Merger Fraction

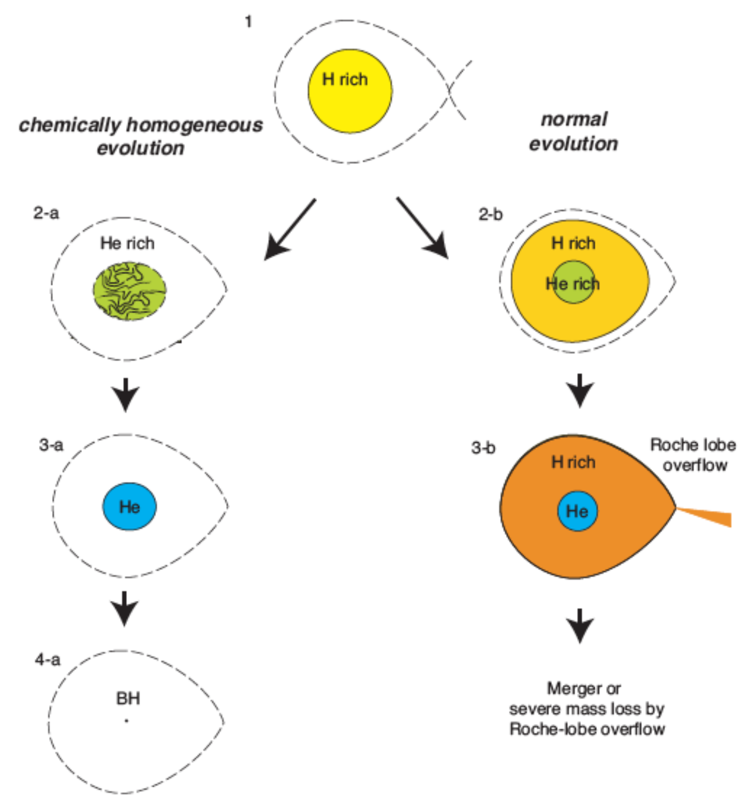


$$\bar{a}_{\rm out,eff} = \left(\frac{a_{\rm out}\sqrt{1-e_{\rm out}^2}}{1000{\rm AU}}\right)\left(\frac{m_3}{30M_\odot}\right)^{-1/3}$$

Chemically Homogeneous Evolution Channel



Marchant, Langer et al 2016



Mandel & de Mink 2016