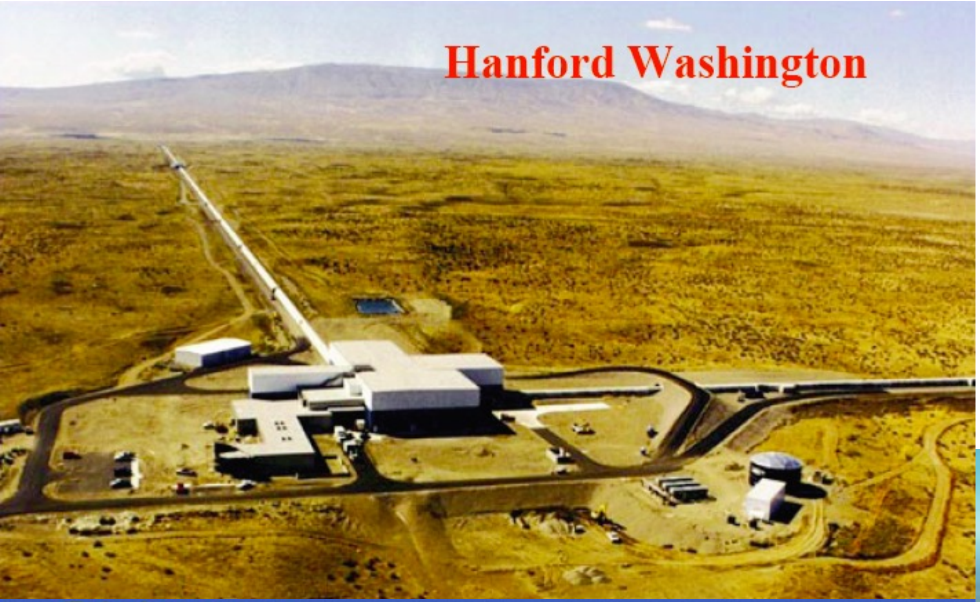
Formation of Merging Compact Binaries

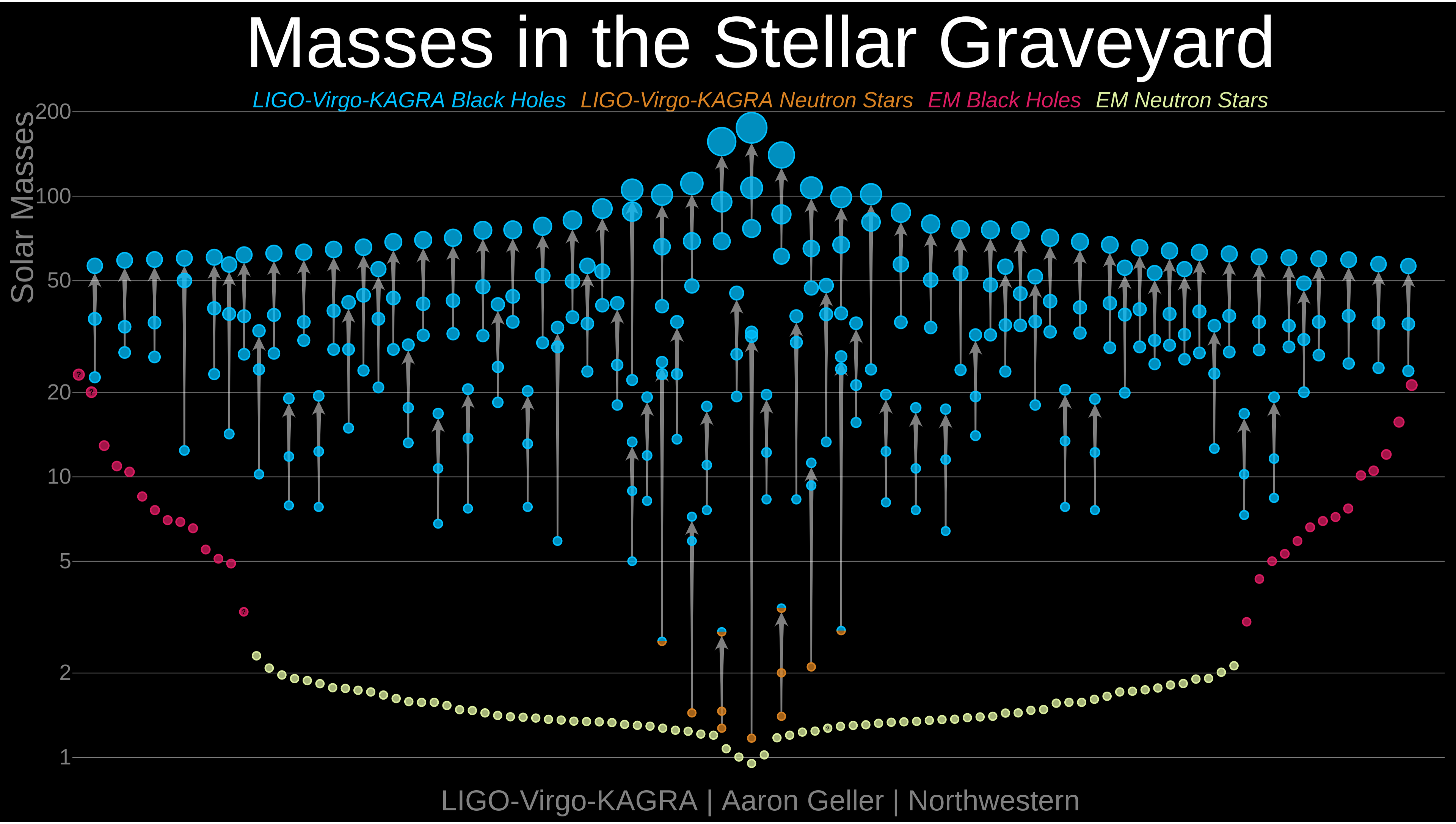
Dong Lai
Cornell University

Weizmann Institute of Sciences Colloquium 1/19/2023

Gravitational Wave Astronomy

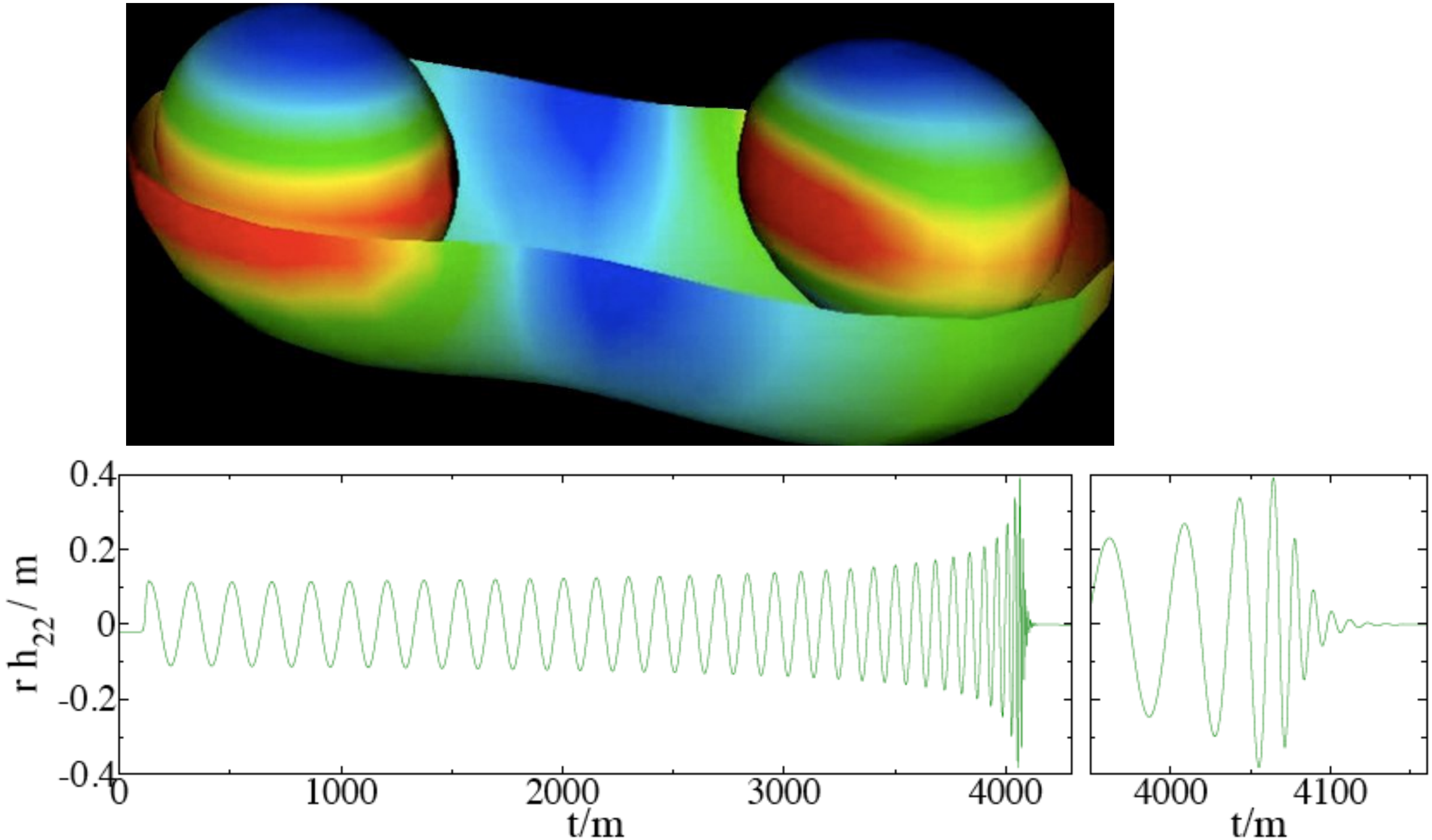


LIGO
VIRGO



GWTC-3: 90 merger events, with 2 NS/NS mergers, 3 NS/BH mergers

BH-BH Merger

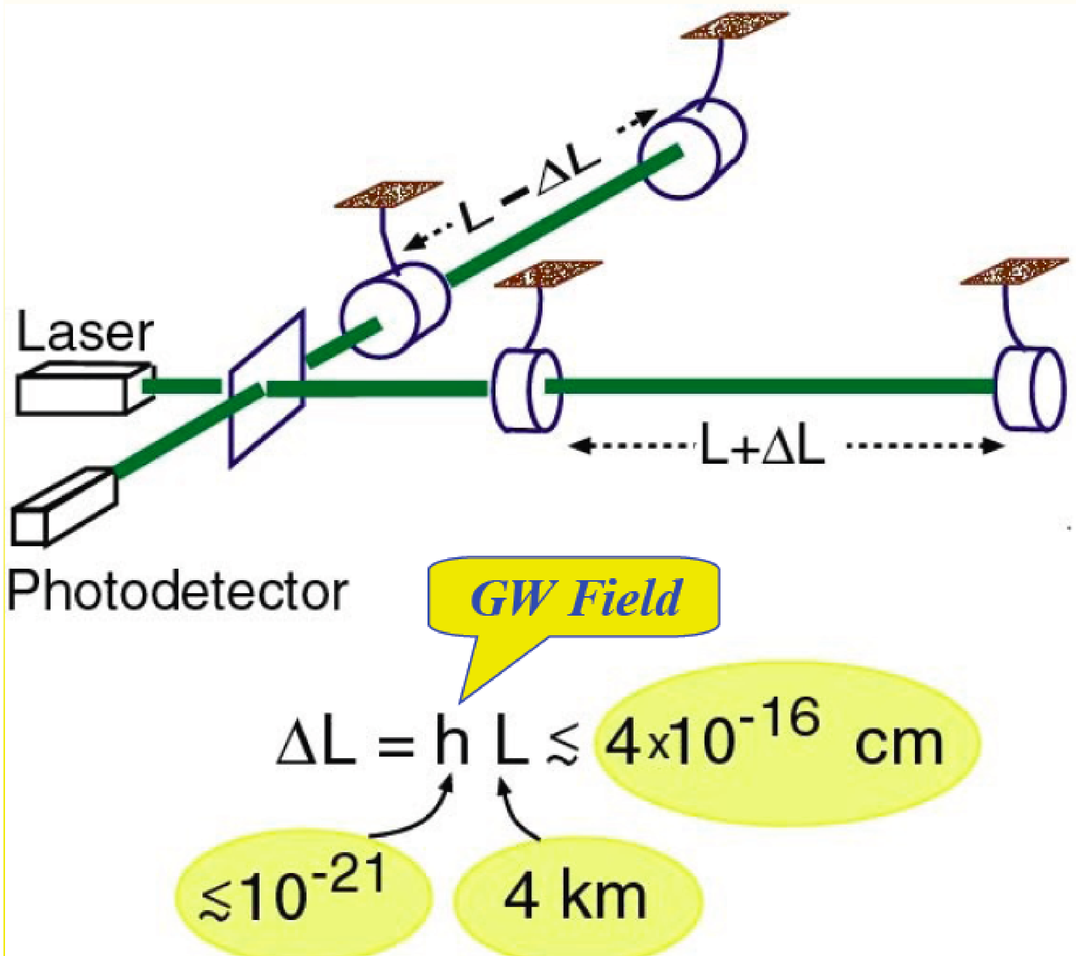


Cornell-Caltech collaboration

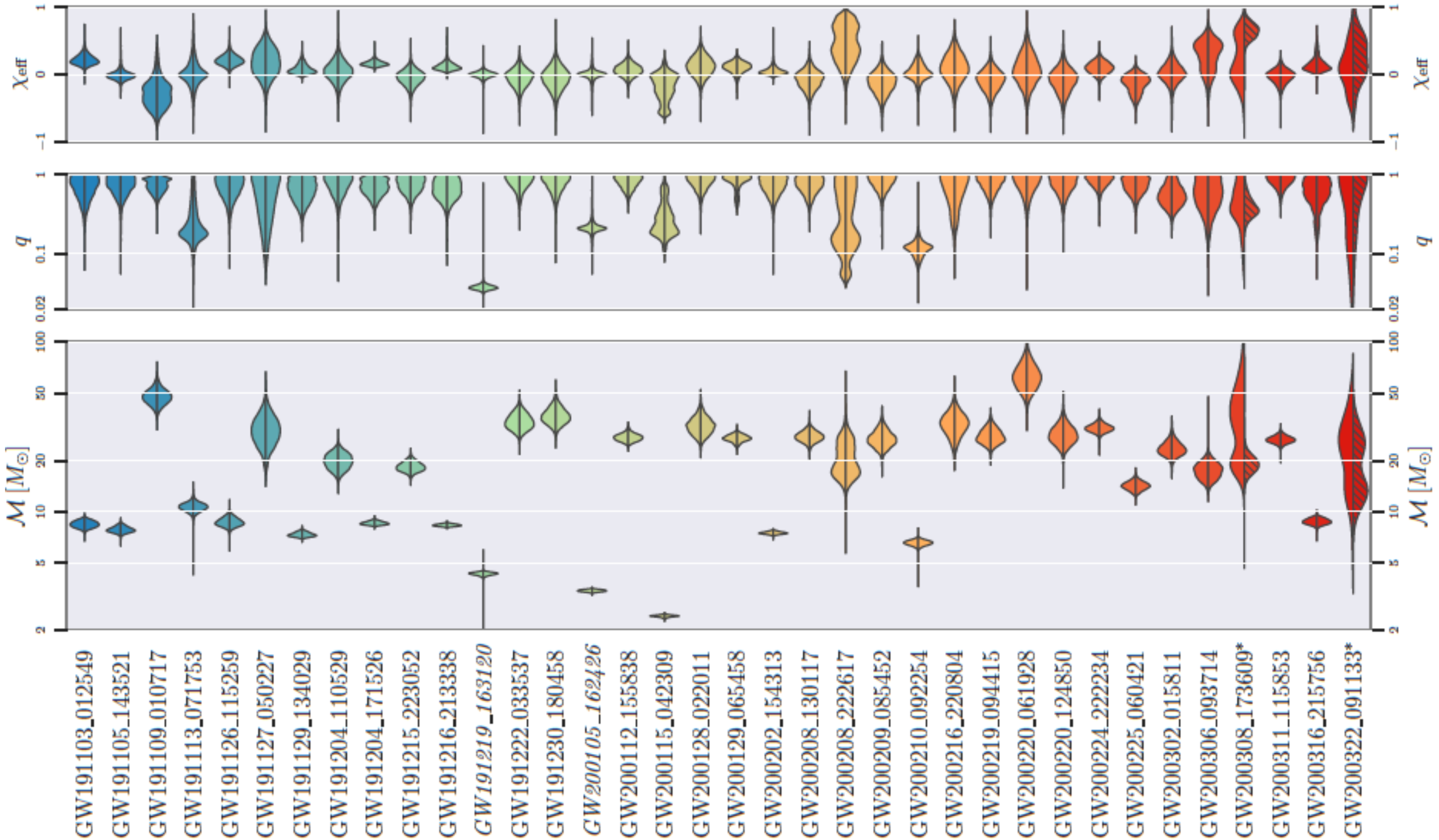
Gravitational Waves

- Warpage of Spacetime
- Generated by time-dependent quadrupoles
- Detector response to passage of GWs:

Laser Gravitational Wave Interferometer



Kip Thorne



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 of Merging BH Binaries

$$T_{\mathrm{m}} \approx \; 10^{10}\mathrm{yrs}\left(\frac{60M_{\odot}}{m_1+m_2}\right)^2\left(\frac{15M_{\odot}}{\mu}\right)\left(\frac{\mathbf{a_0}}{0.2\mathrm{AU}}\right)^{\mathbf{4}}\left(\mathbf{1}-\mathbf{e_0}^{\mathbf{2}}\right)^{7/2}$$

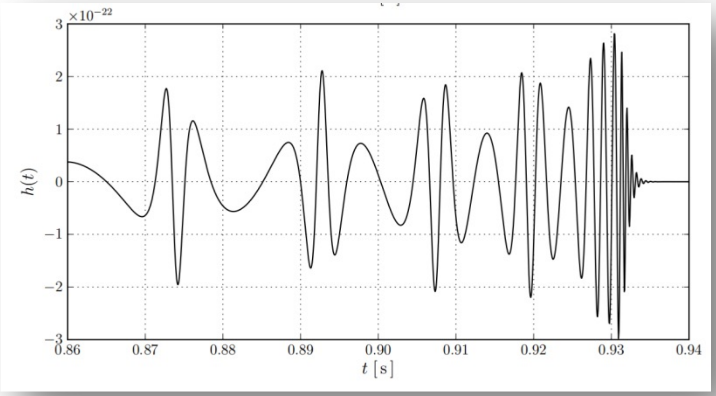
Formation Channels of Merging BH Binaries

-- Isolated Binary Evolution

-- Dynamical Formation:
several flavors: star clusters, triples (multiples), AGN disks

How to distinguish different channels?

Rates (uncertain)?
Masses and mass ratio
Residual eccentricity when enter LIGO band (10Hz) or lower-f band



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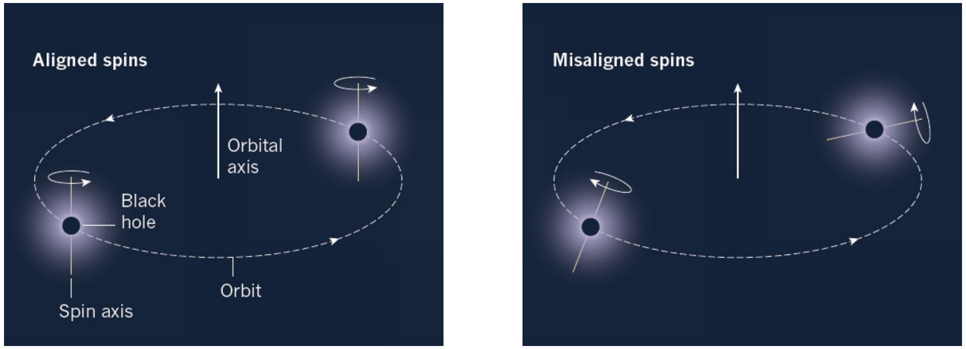
Spin-orbit misalignment



Formation Channels of Merging BH Binaries

-- Isolated Binary Evolution

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How to distinguish different channels?

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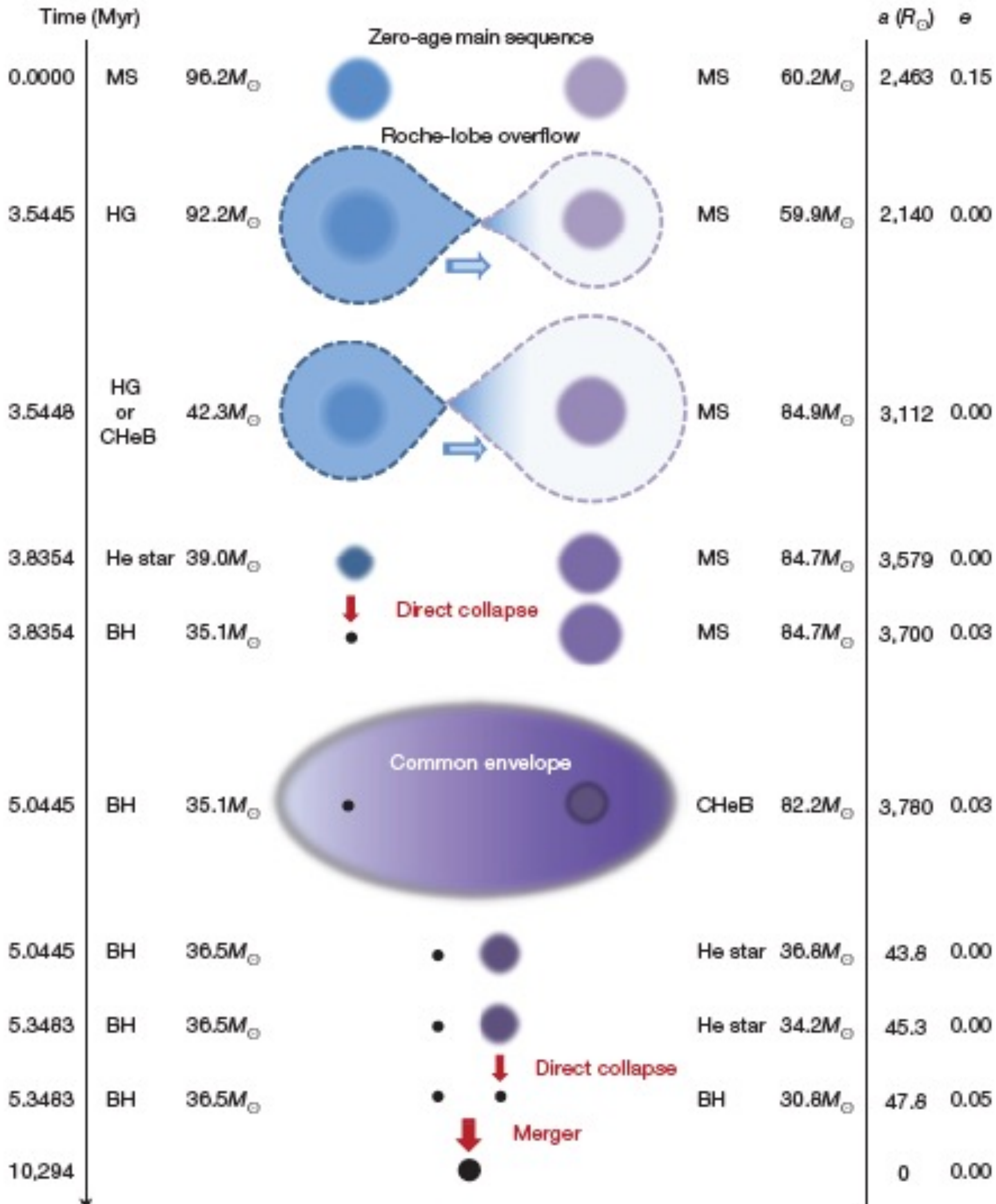
Residual eccentricity when enter LIGO band (10Hz) or lower-f band
Spin-orbit misalignment
EM coubterpart

Isolated Binary Evolution Channel: Standard



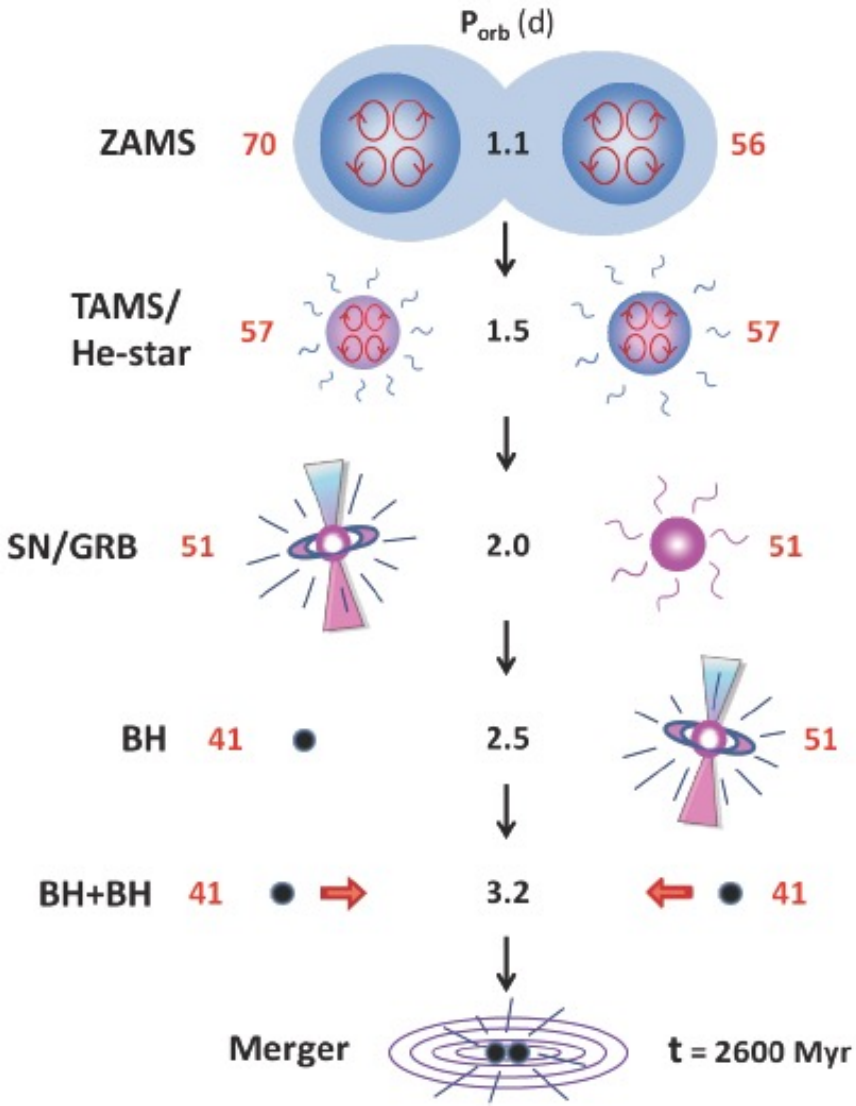
many papers, uncertain physical ingredients (e.g. common envelope)

Produce

circular orbit at 10 Hz
mostly aligned spin-orbit

Belczynski +16

Isolated Binary Evolution Channel:
Chemically homogeneous evolution



Produce

circular orbit at 10 Hz

mostly aligned spin-orbit

Merchant, Langer et al. 2016

Mandel & de Mink 2016

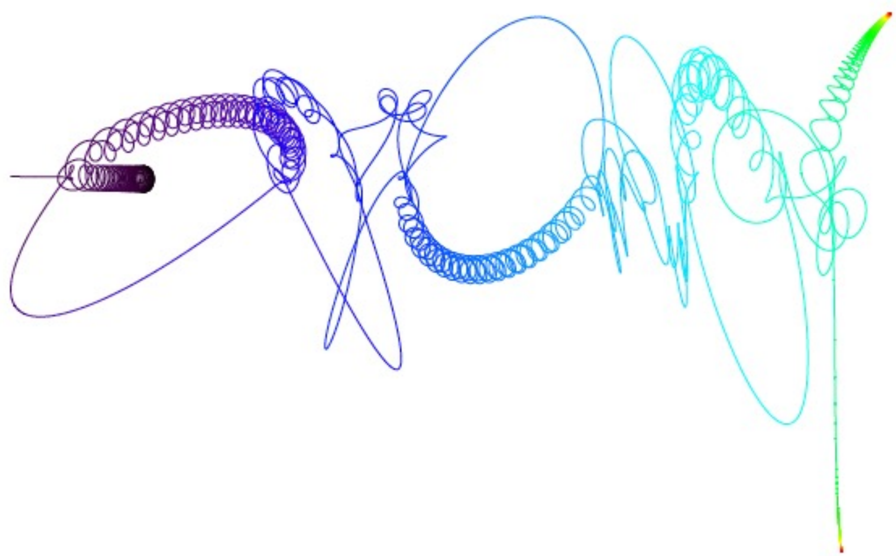
Dynamical Formation Channels

several flavors…

Dynamical Formation Channels

several flavors…

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



Samsing+14

Enough BHs in clusters? Kicks? GCs or Nuclear Star Clusters?

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**

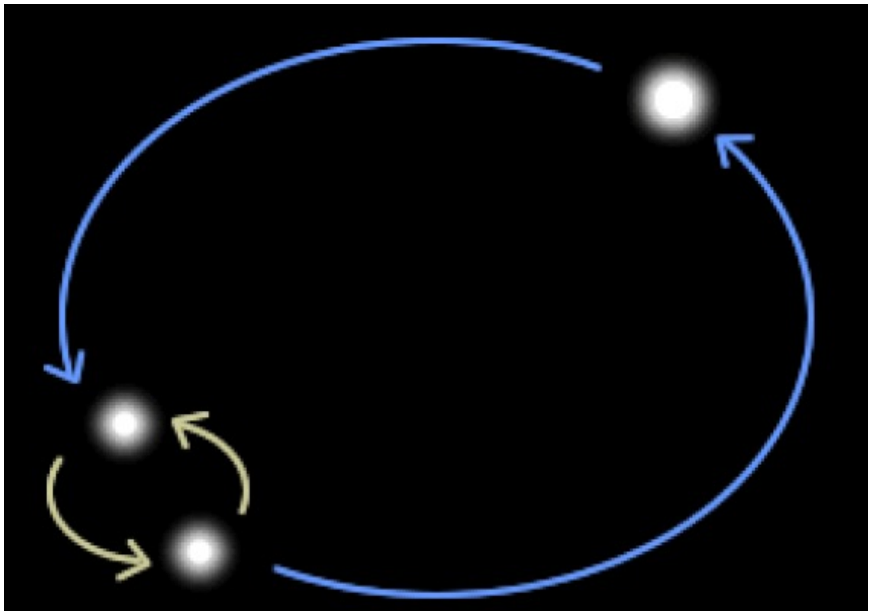
2. **Tertiary-Induced Mergers:**

   Mergers induced by (gentle) perturbations from tertiary companion

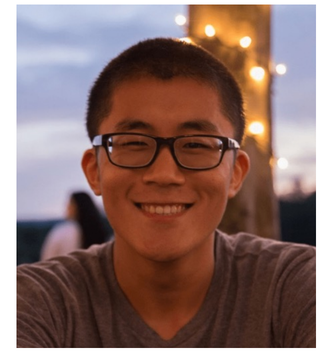
   stellar triples in galactic field, binary around SMBH

Tertiary-Induced Binary Mergers

merger window, mass ratio, GR effects, spin-orbit misalignments



Bin Liu
(Cornell→Niels Bohr Inst)



Yubo Su
(Cornell, Ph.D.22
→ Princeton)

Liu & DL 2017-2022
Su et al.2021a,b

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 Effect

Can perturbation from the Moon make Earth’s satellites fall?

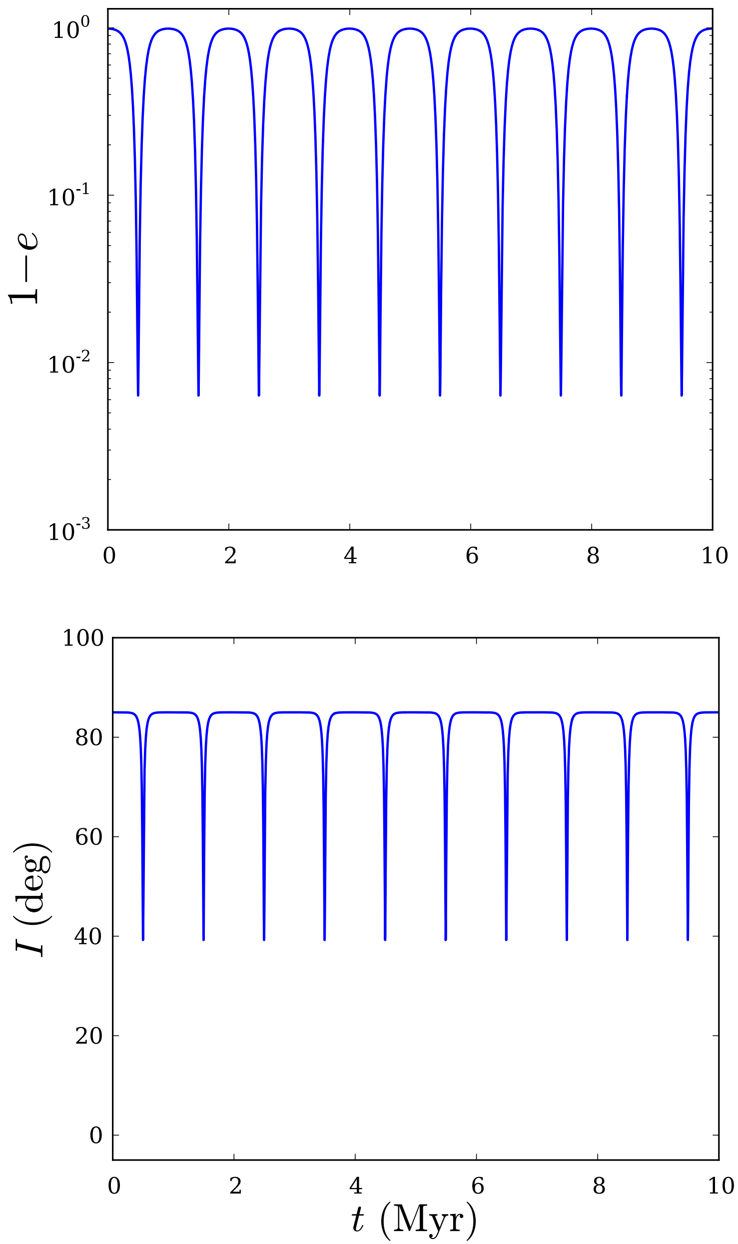
Planet. Space Sci., 1962, Vol. 9, pp. 719 to 759. Pergamon Press Ltd. Printed in Northern Ireland

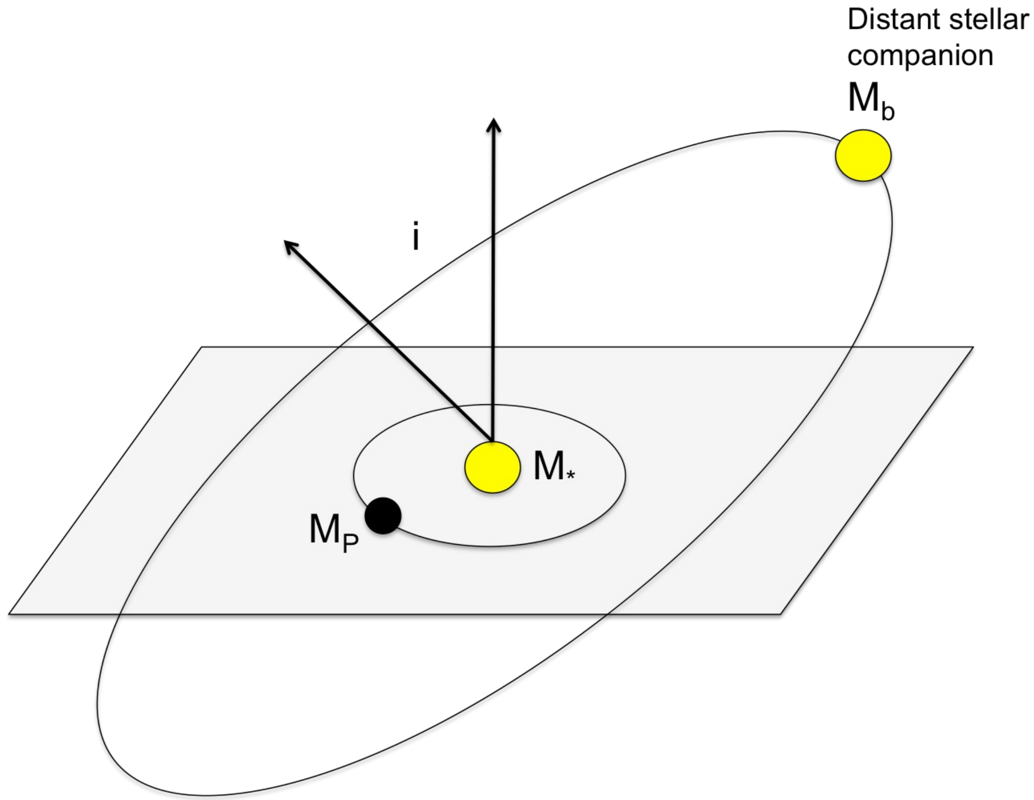
THE EVOLUTION OF ORBITS OF ARTIFICIAL SATELLITES OF PLANETS UNDER THE ACTION OF GRAVITATIONAL PERTURBATIONS OF EXTERNAL BODIES

M. L. LIDOV

Translated by H. F. Cleaves from *Iskusstvennye Sputniki Zemli*, No. 8, p. 5, 1961.

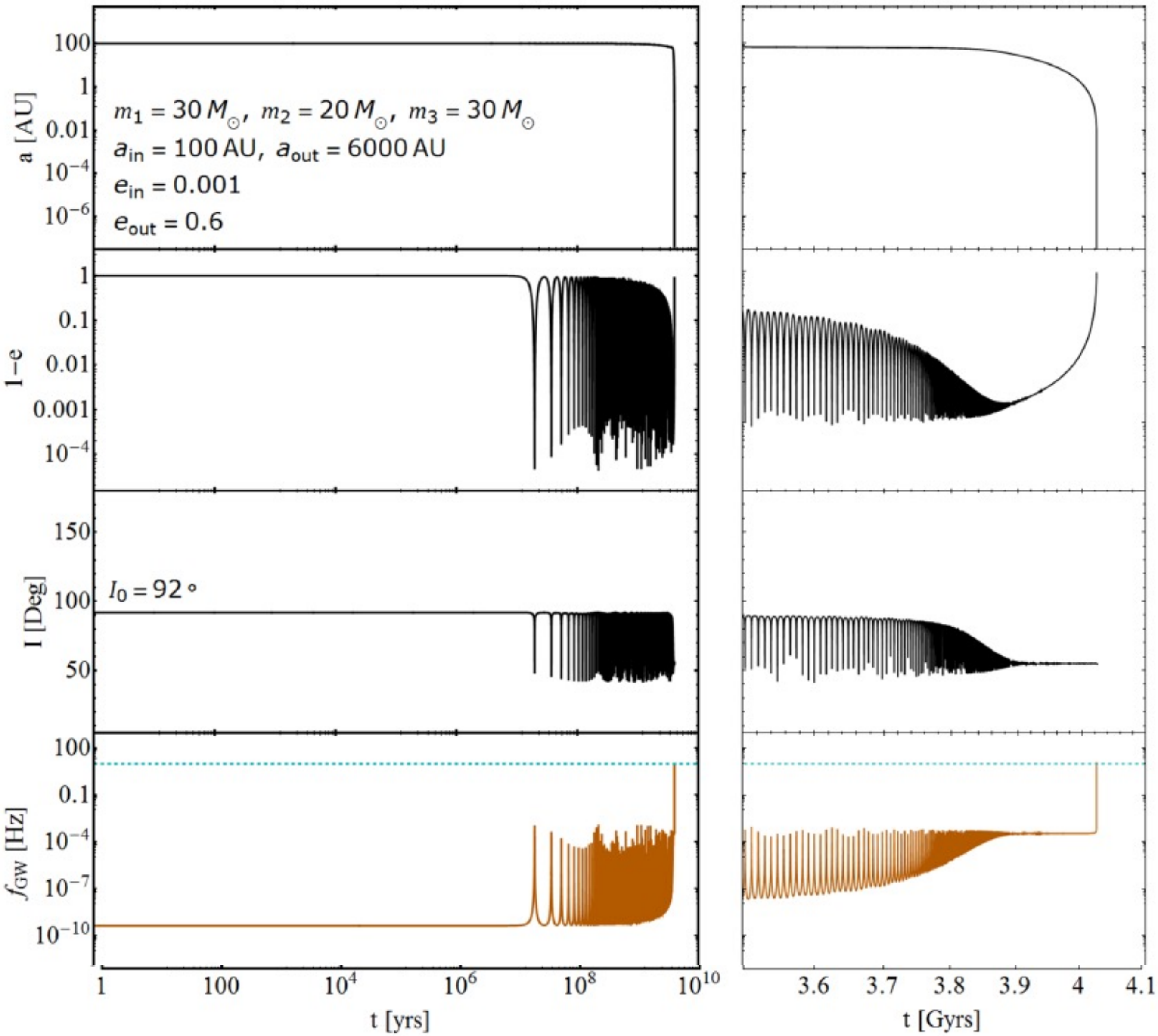
Lidov-Kozai Effect





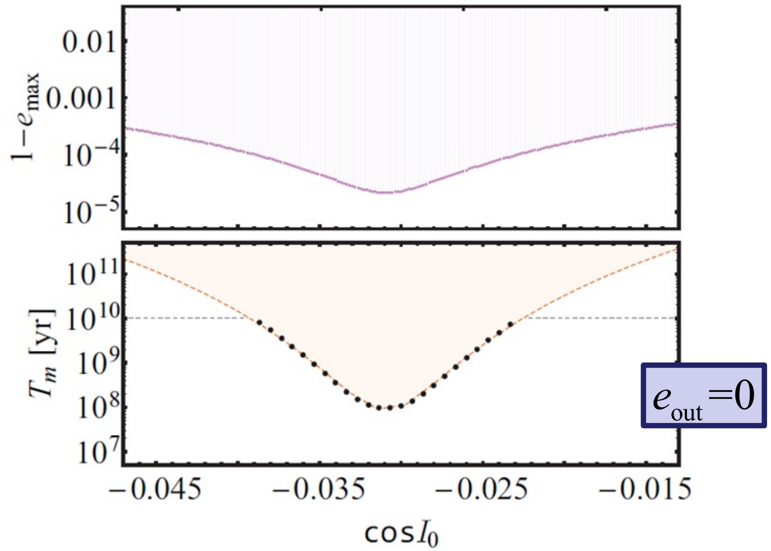
- Eccentricity and inclination oscillations induced if i > 40 degrees.
- If i large (85-90 degrees), get extremely large eccentricities (e > 0.99)

LK oscillation + Gravitation Radiation



Inclination window for merger

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



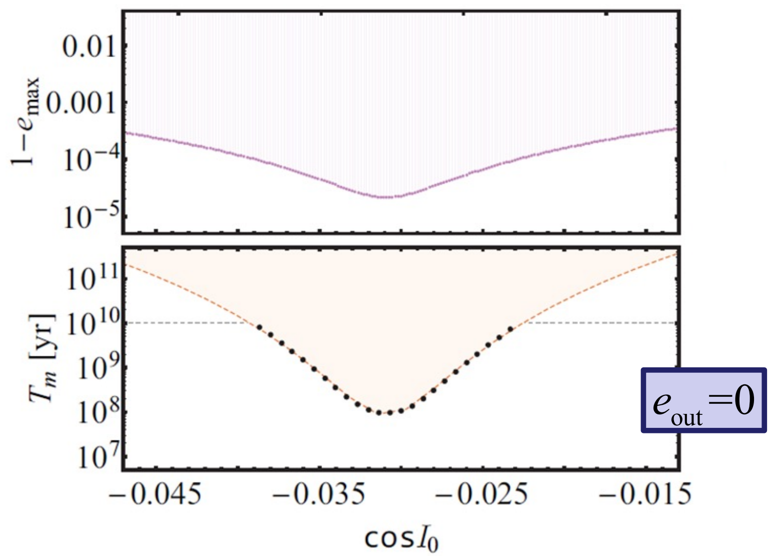
Fixed quadrupole strength $\frac{m_3}{a^3_{\mathrm{out,eff}}}$

Quadrupole LK:
e_{max} vs I_0 analytic:
LK driving compete with
GR apsidal precession

Merger window (almost)
analytic

Inclination window for merger

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



Fixed quadrupole strength $\frac{m_3}{a^3_{\rm out,eff}}$

Quadrupole LK:
e_{max} vs I_0 analytic:
LK driving compete with GR apsidal precession

Merger window (almost) analytic

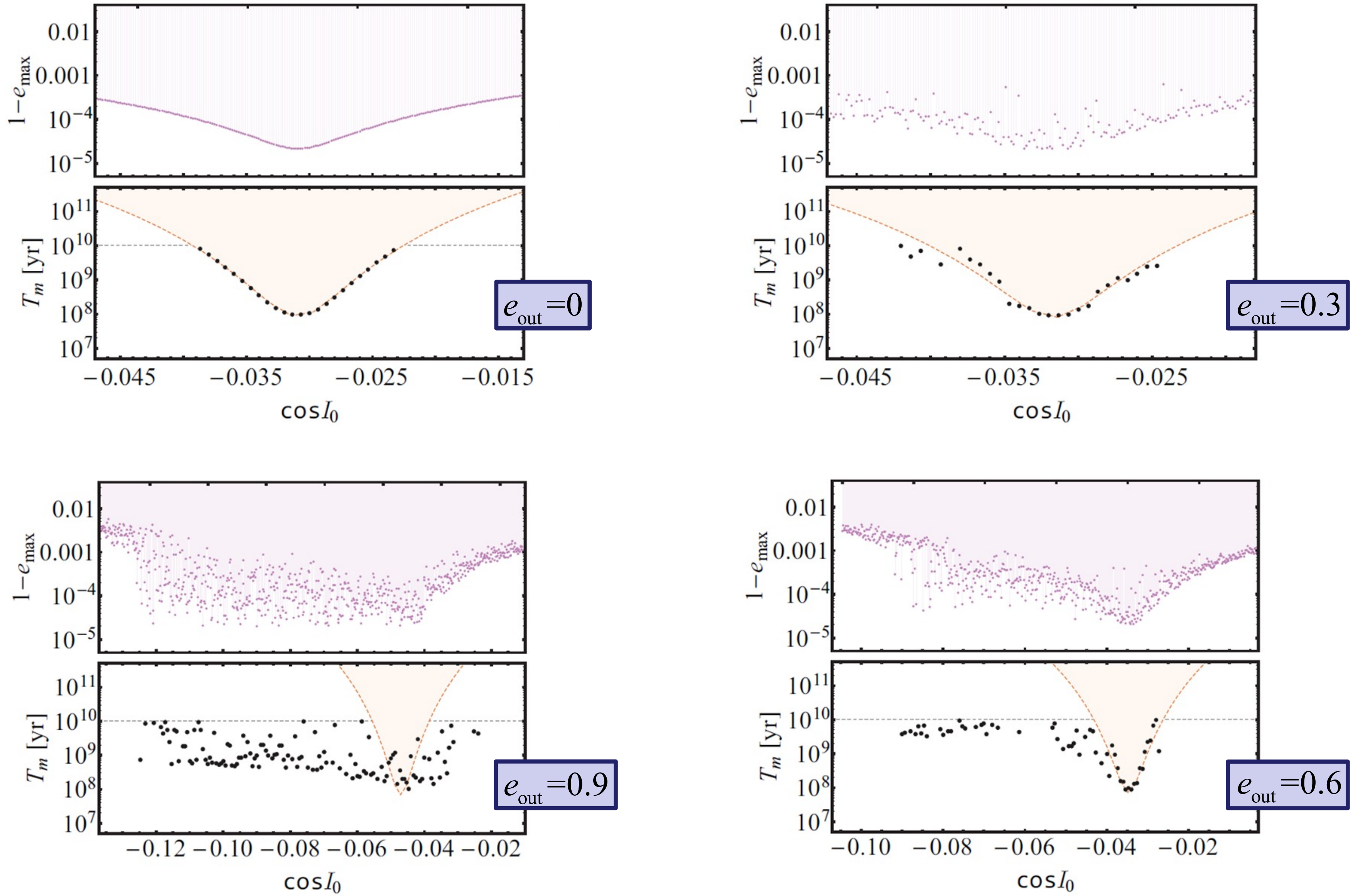
Octupole effect makes orbital evolution "chaotic":

$$\epsilon_{\rm oct} = \frac{m_1 - m_2}{m_1 + m_2}\frac{a}{a_{\rm out}}\frac{e_{\rm out}}{1-e^2_{\rm out}}$$

Inclination window for merger

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

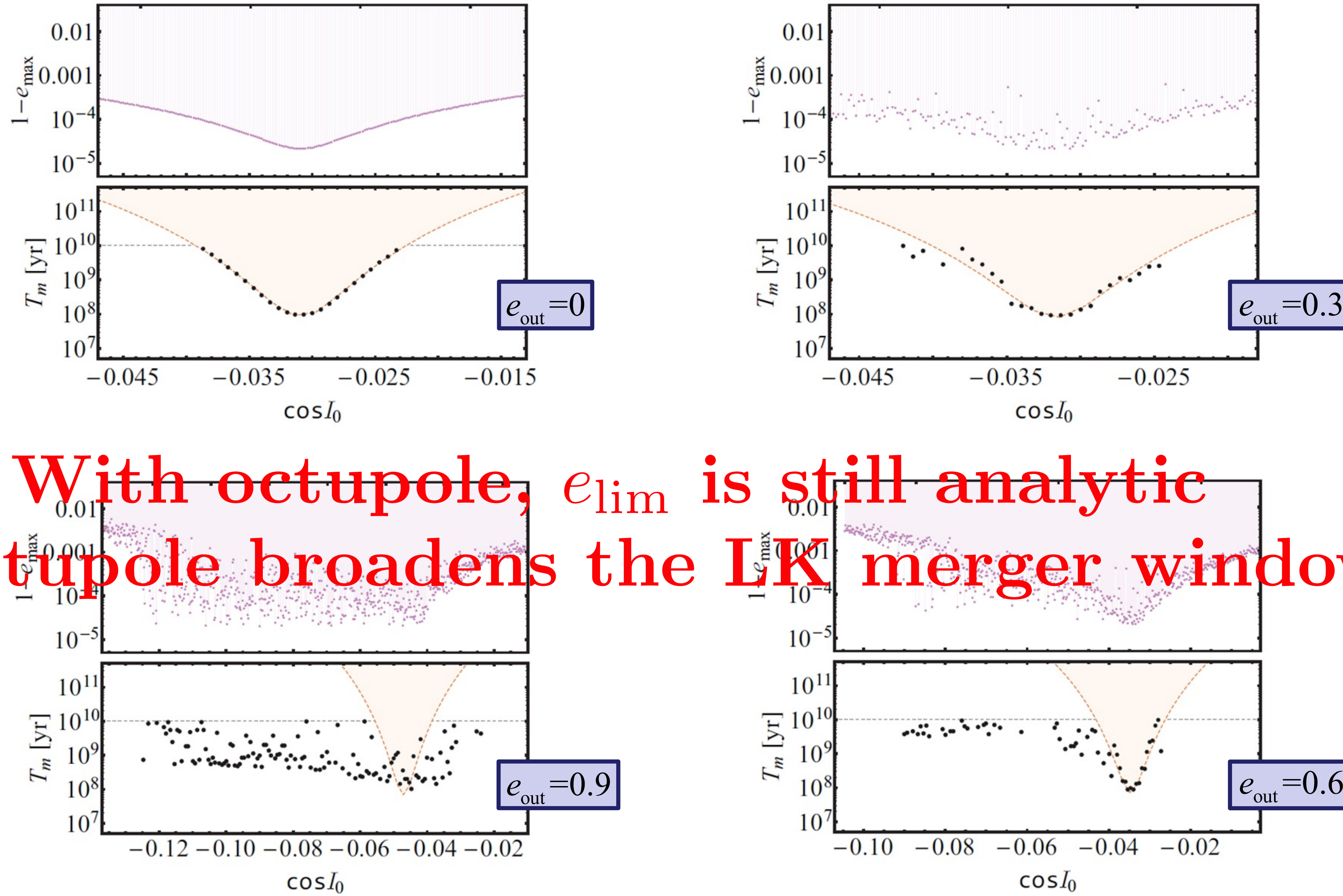
Fixed quadrupole strength $\frac{m_3}{a^3_{\mathrm{out,eff}}}$



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



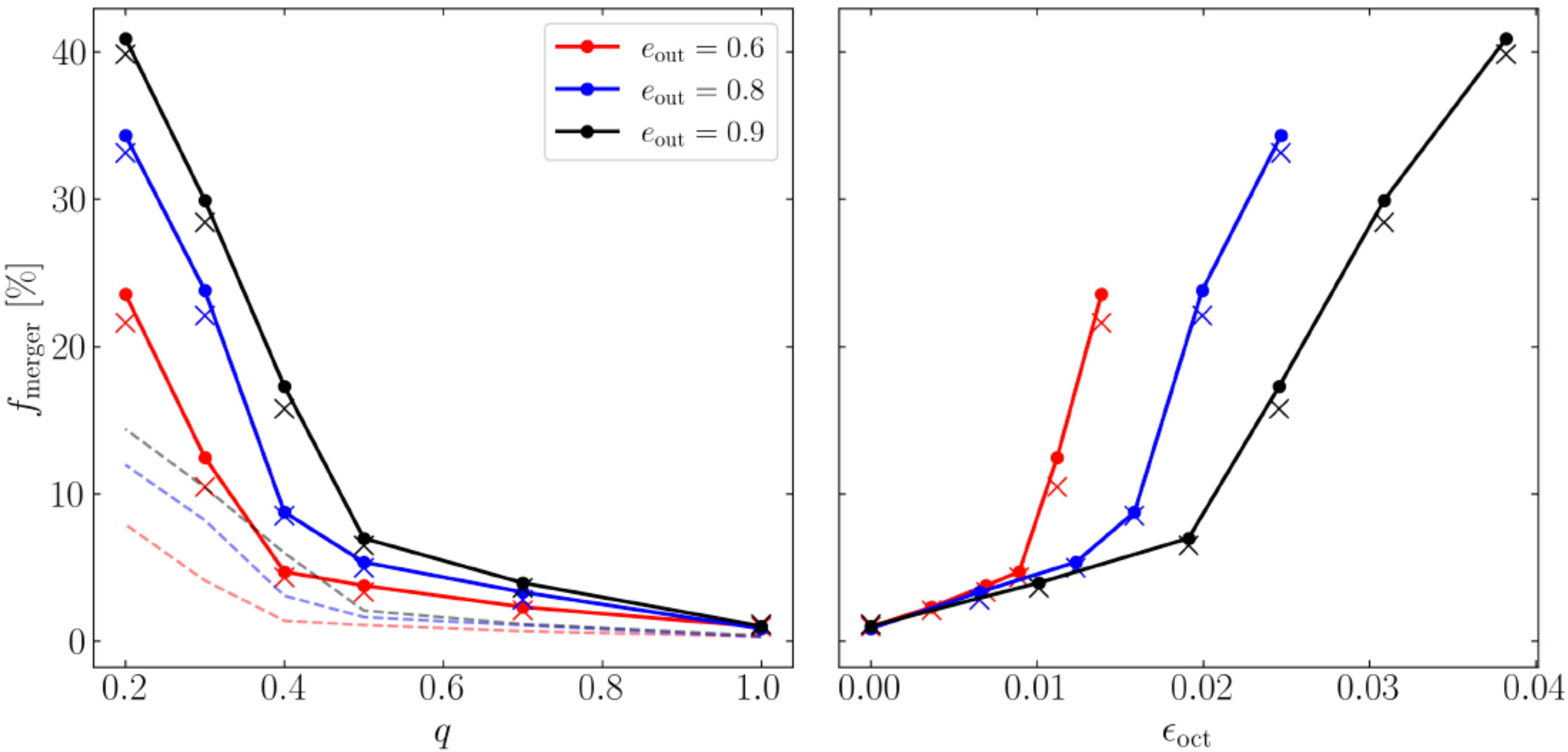
With octupole, $e_{\rm lim}$ is still analytic

Octupole broadens the LK merger window

Octupole effect depends on

$$\epsilon_{\rm oct} = \frac{m_1 - m_2}{m_1 + m_2} \frac{a}{a_{\rm out}} \frac{e_{\rm out}}{1 - e_{\rm out}^2}$$

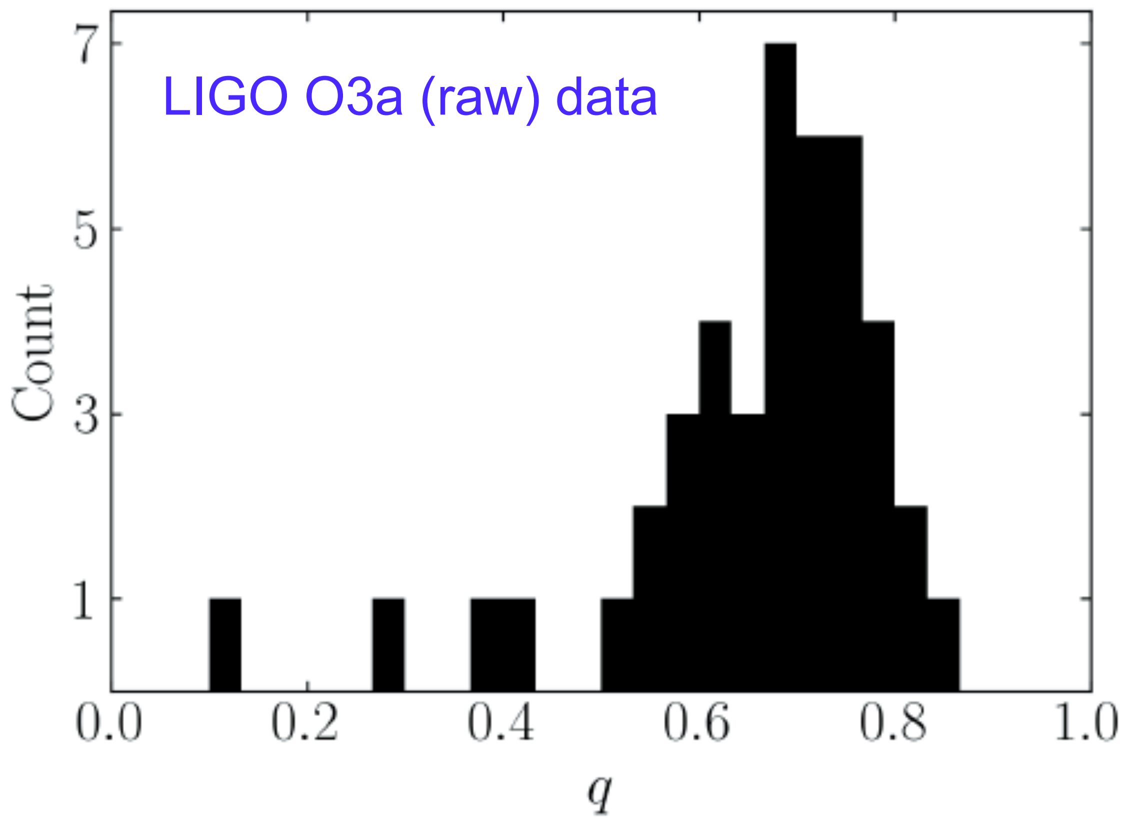
➔ Large $e_{\rm out}$ and/or small $q = m_2/m_1$ increases merger window



$a = 100$ AU, $a_{out,eff} = 3600$ AU, $m_{12} = 50 M_\odot$, $m_3 = 30 M_\odot$

Su et al. 2021

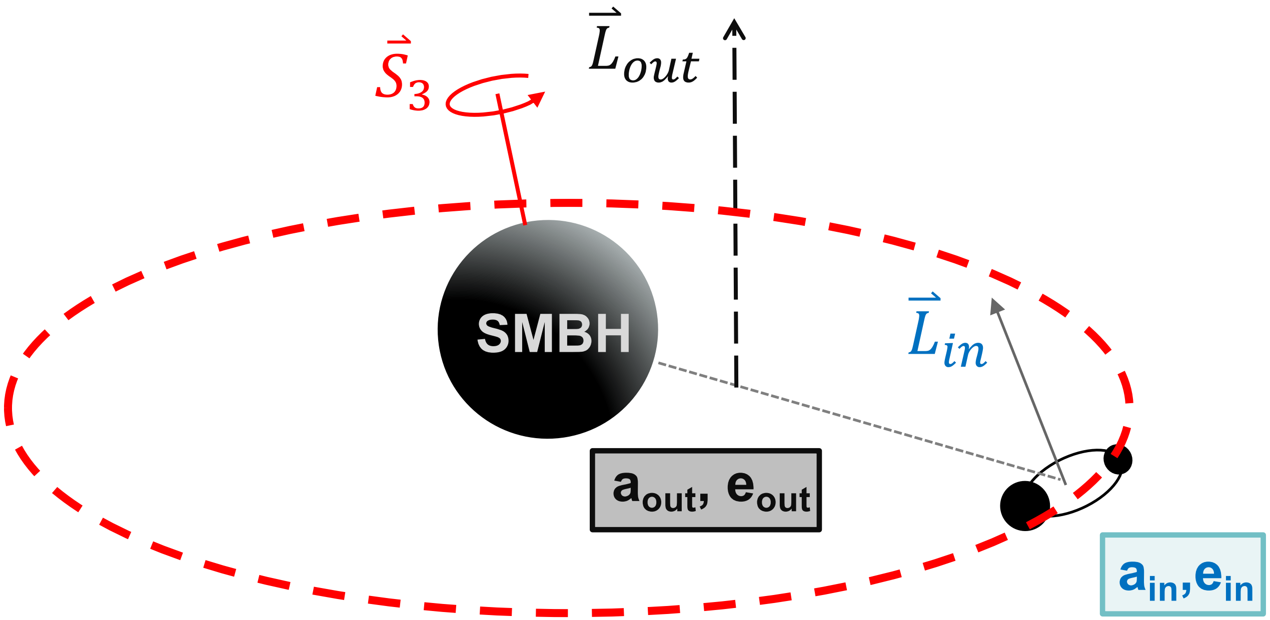
Is this compatible with the observed q-distribution of merging BH binaries?



-- Depends on the initial q-distribution of BH binaries.

-- Maybe incompatible with data if octupole effect is strong…

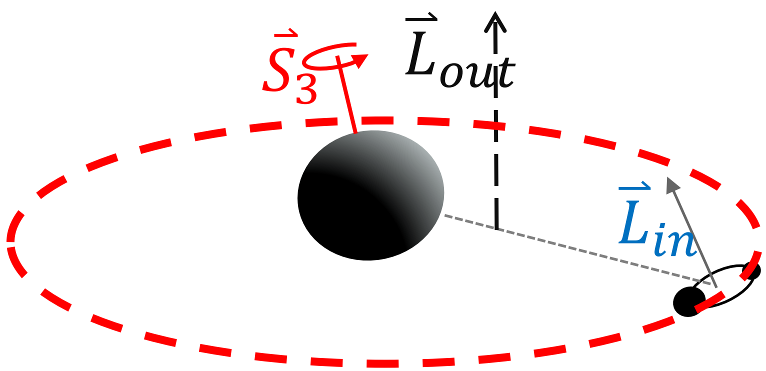
What happens if the tertiary is a Supermassive BH ?



Since $a_{out} \gg a$, octupole effect is negligible $\epsilon_{oct} = \frac{m_1 - m_2}{m_1 + m_2} \frac{a}{a_{out}} \frac{e_{out}}{1 - e_{out}^2}$

Relativistic Effects induced by the SMBH

Three leading-order GR effects (recognizing L_{in} behaves like a "spin")



Effect I: ***de-Sitter-like Precession of L_{in} around L_{out}***

--- 1.5 PN

$$\begin{cases} \left.\dfrac{d\mathbf{L}}{dt}\right|_{\mathrm{L_{in}L_{out}}} = \Omega^{(\mathrm{GR})}_{\mathrm{L_{in}L_{out}}} \hat{\mathbf{L}}_{\mathrm{out}} \times \mathbf{L}, \\ \left.\dfrac{d\mathbf{e}}{dt}\right|_{\mathrm{L_{in}L_{out}}} = \Omega^{(\mathrm{GR})}_{\mathrm{L_{in}L_{out}}} \hat{\mathbf{L}}_{\mathrm{out}} \times \mathbf{e}, \end{cases}$$

Effect II: ***Precession of L_{out} around S_3***

--- 1.5 PN

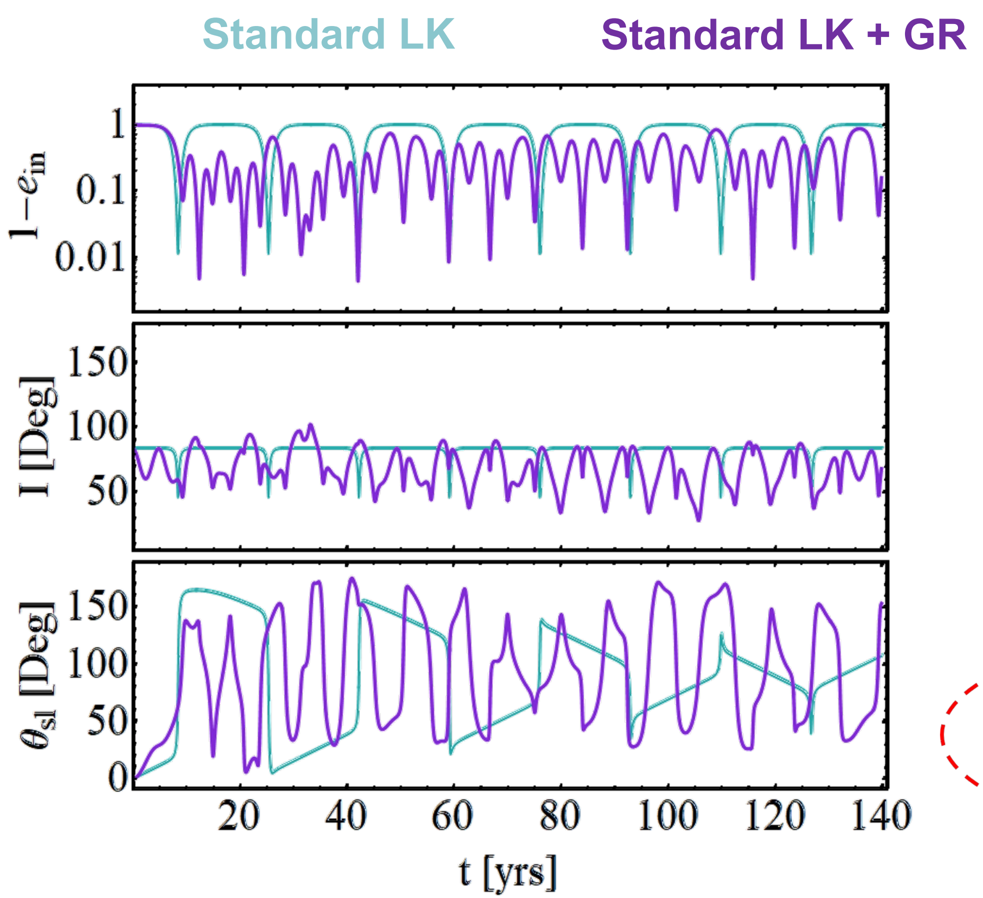
$$\begin{cases} \left.\dfrac{d\mathbf{L}_{\mathrm{out}}}{dt}\right|_{\mathrm{L_{out}S_3}} = \Omega_{\mathrm{L_{out}S_3}} \hat{\mathbf{S}}_3 \times \mathbf{L}_{\mathrm{out}}, \\ \left.\dfrac{d\mathbf{e}_{\mathrm{out}}}{dt}\right|_{\mathrm{L_{out}S_3}} = \Omega_{\mathrm{L_{out}S_3}} \hat{\mathbf{S}}_3 \times \mathbf{e}_{\mathrm{out}} \\ \qquad -3\Omega_{\mathrm{L_{out}S_3}} (\hat{\mathbf{L}}_{\mathrm{out}} \cdot \hat{\mathbf{S}}_3) \hat{\mathbf{L}}_{\mathrm{out}} \times \mathbf{e}_{\mathrm{out}} \end{cases}$$

Effect III: ***Lense-Thirring Precession of L_{in} around S_3***

--- 2 PN

$$\begin{cases} \left.\dfrac{d\mathbf{L}}{dt}\right|_{\mathrm{L_{in}S_3}} = \Omega_{\mathrm{L_{in}S_3}} \hat{\mathbf{S}}_3 \times \mathbf{L} \\ \qquad -3\Omega_{\mathrm{L_{in}S_3}} (\hat{\mathbf{L}}_{\mathrm{out}} \cdot \hat{\mathbf{S}}_3) \hat{\mathbf{L}}_{\mathrm{out}} \times \mathbf{L}, \\ \left.\dfrac{d\mathbf{e}}{dt}\right|_{\mathrm{L_{in}S_3}} = \Omega_{\mathrm{L_{in}S_3}} \hat{\mathbf{S}}_3 \times \mathbf{e} \\ \qquad -3\Omega_{\mathrm{L_{in}S_3}} (\hat{\mathbf{L}}_{\mathrm{out}} \cdot \hat{\mathbf{S}}_3) \hat{\mathbf{L}}_{\mathrm{out}} \times \mathbf{e}. \end{cases}$$

Evolution Example



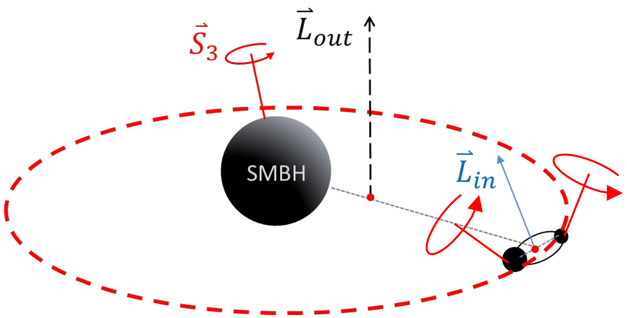
System Parameters:

$(m_1, m_2, m_3) = (30, 20, 2.3\times10^9)\ M_\odot$

$(a_{in,0}, a_{out}) = (0.1, 500)$ AU

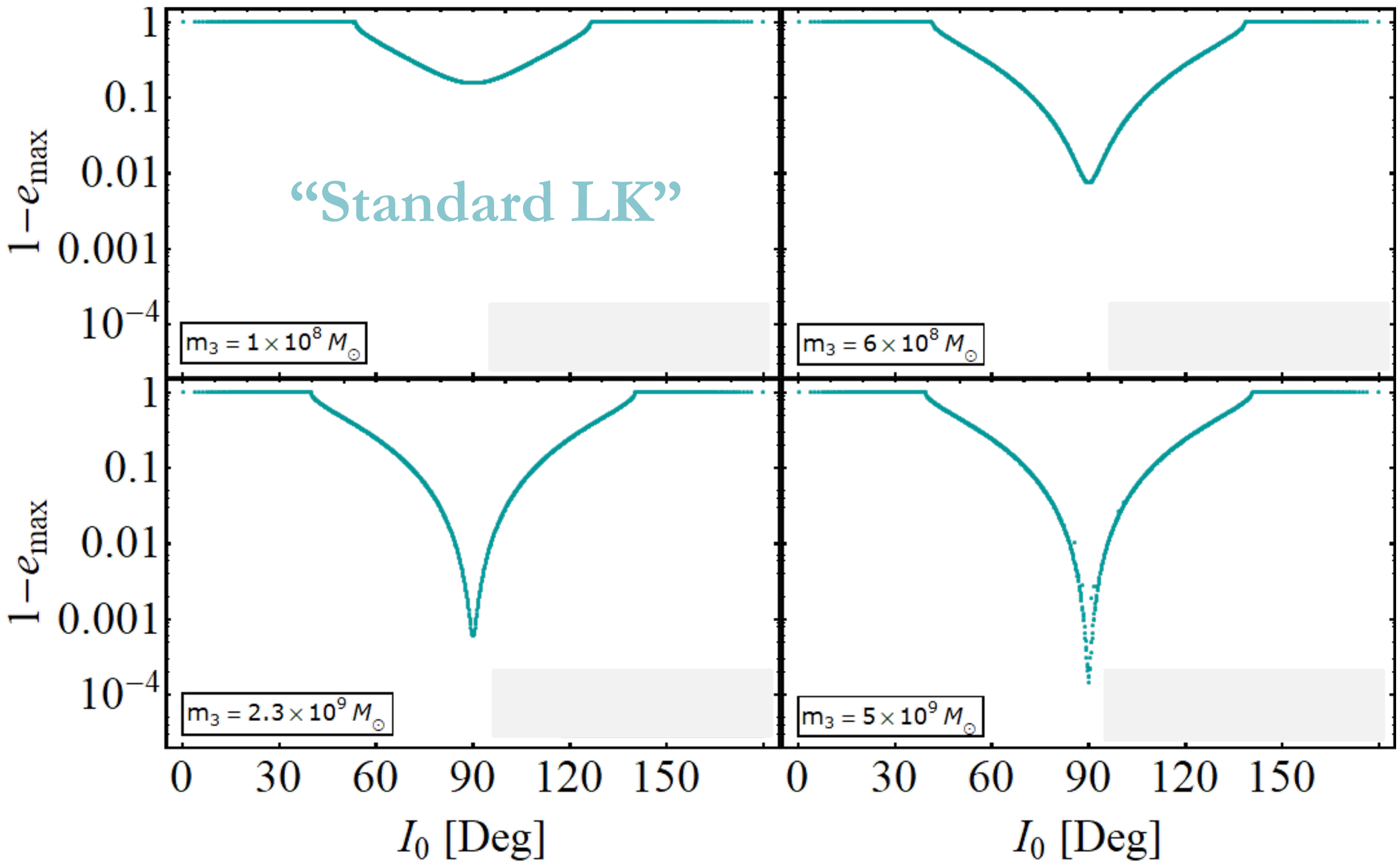
$(e_{in,0}, e_{out,0}) = 0.001$

$I_0 = 84^\circ$



Eccentricity Excitation

$(m_1, m_2) = (30, 20)\ M_\odot$; $(a_{in,0}, a_{out}) = (0.1, 500)$ AU ; Circular Orbits



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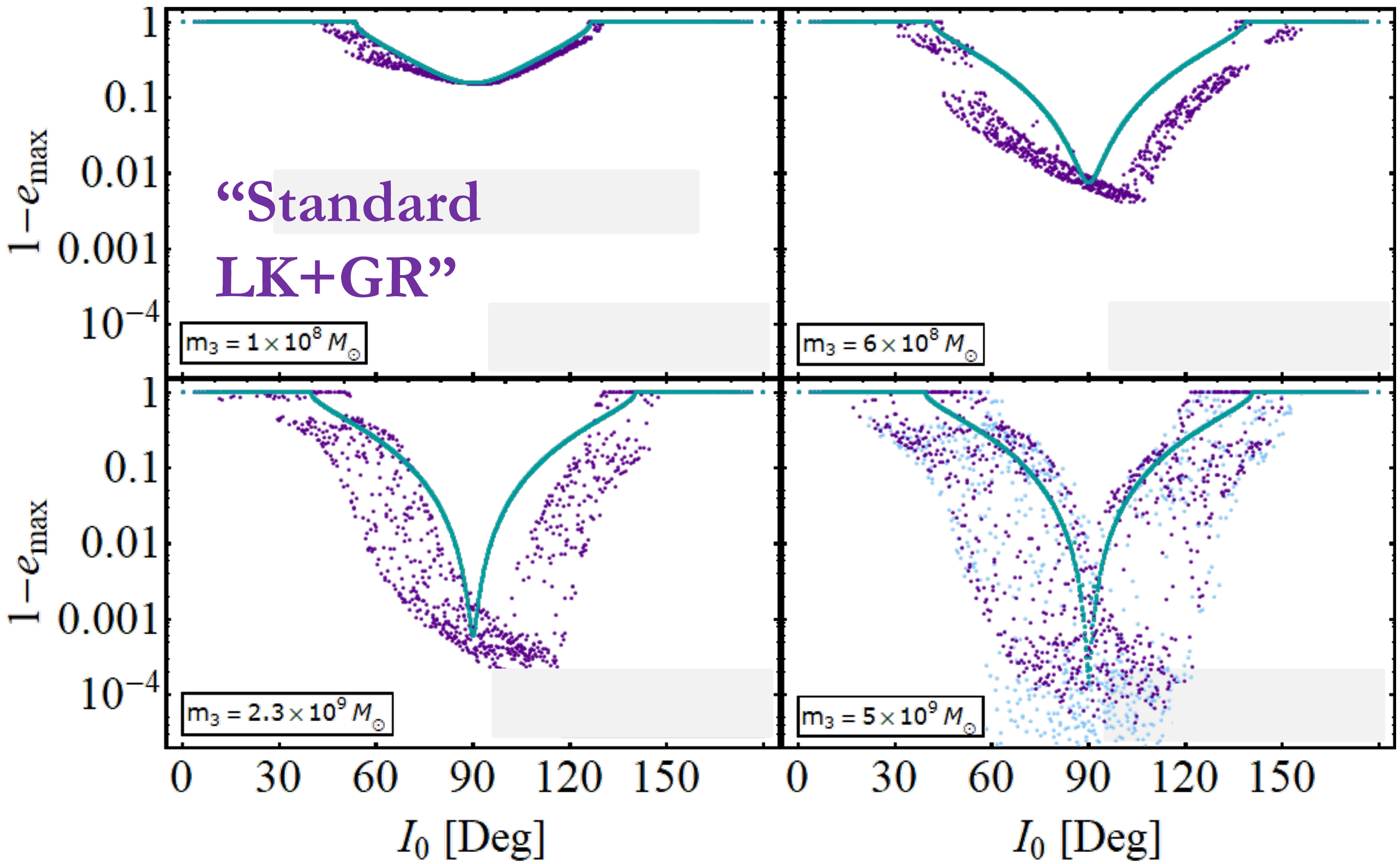
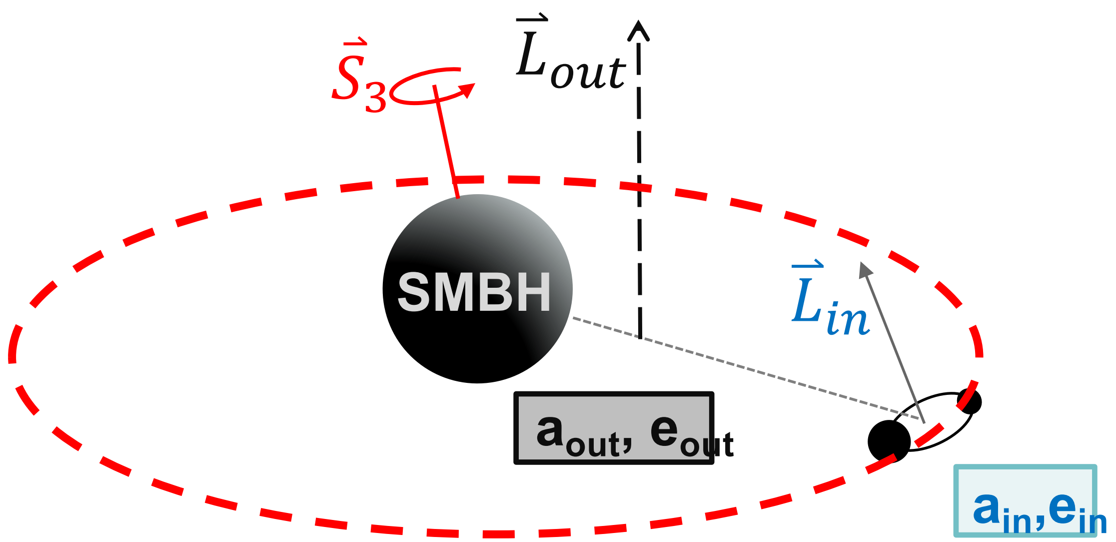


==> GR effects broaden the merger window

GR effects broaden Merger window: Why?

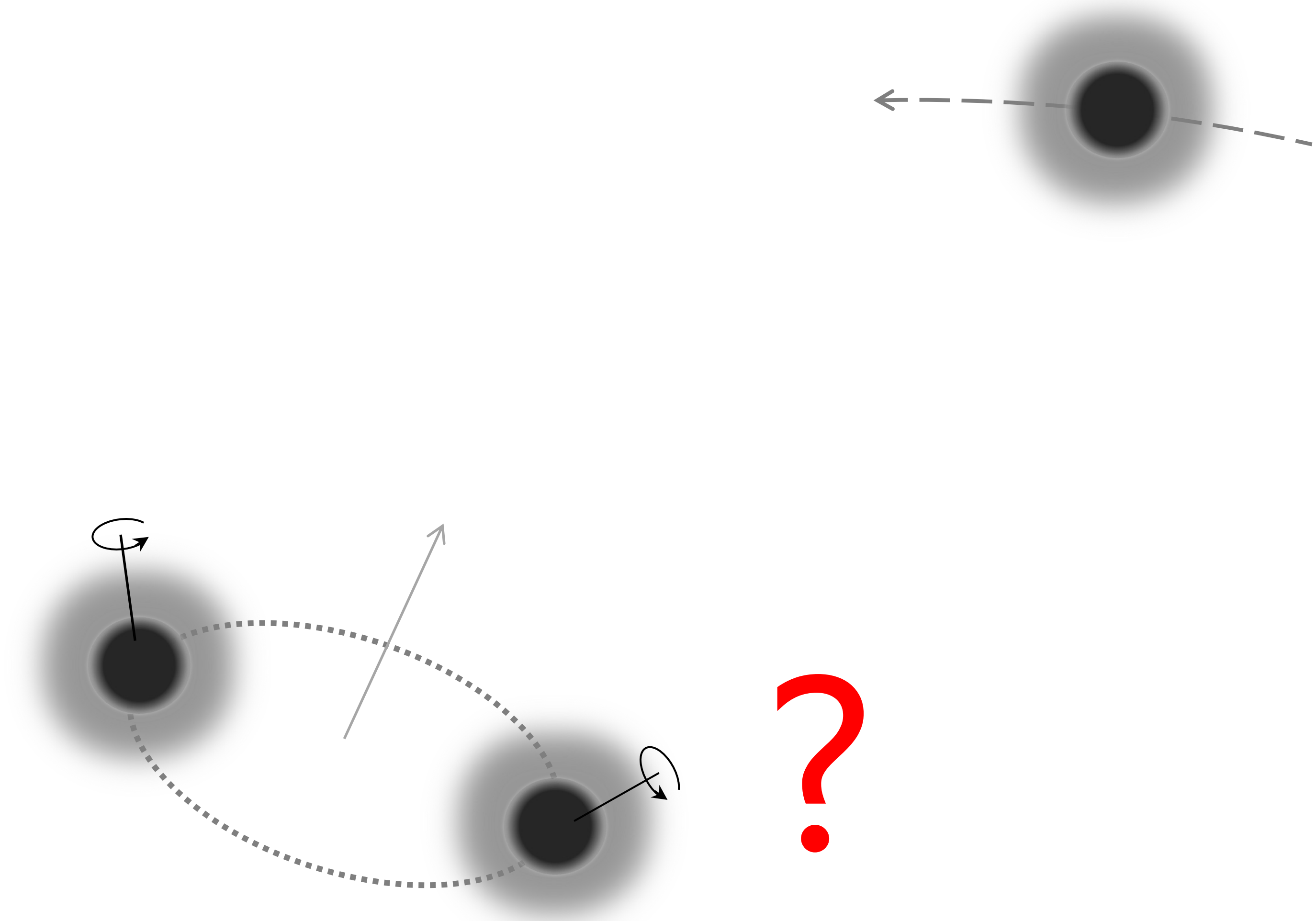
Inclination Resonance

$$\gamma \equiv \frac{\Omega_{\mathrm{L_{in}L_{out}}}}{\Omega_{\mathrm{L_{out}S_3}}} = \frac{\Omega^{(\mathrm{N})}_{\mathrm{L_{in}L_{out}}} + \Omega^{(\mathrm{GR})}_{\mathrm{L_{in}L_{out}}}}{\Omega_{\mathrm{L_{out}S_3}}}$$



Mutual inclination is excited when the two precession rates are equal

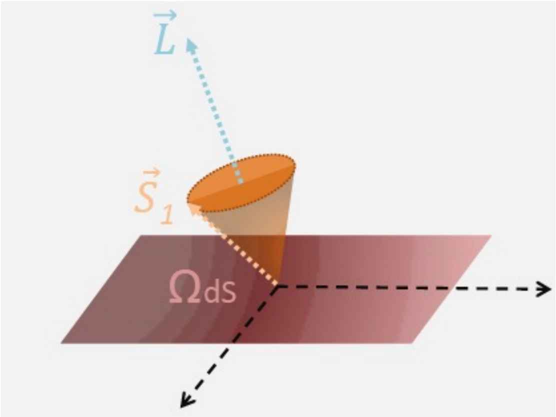
What about the BH Spins of merging BHs?



Spin-Orbit Coupling

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

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



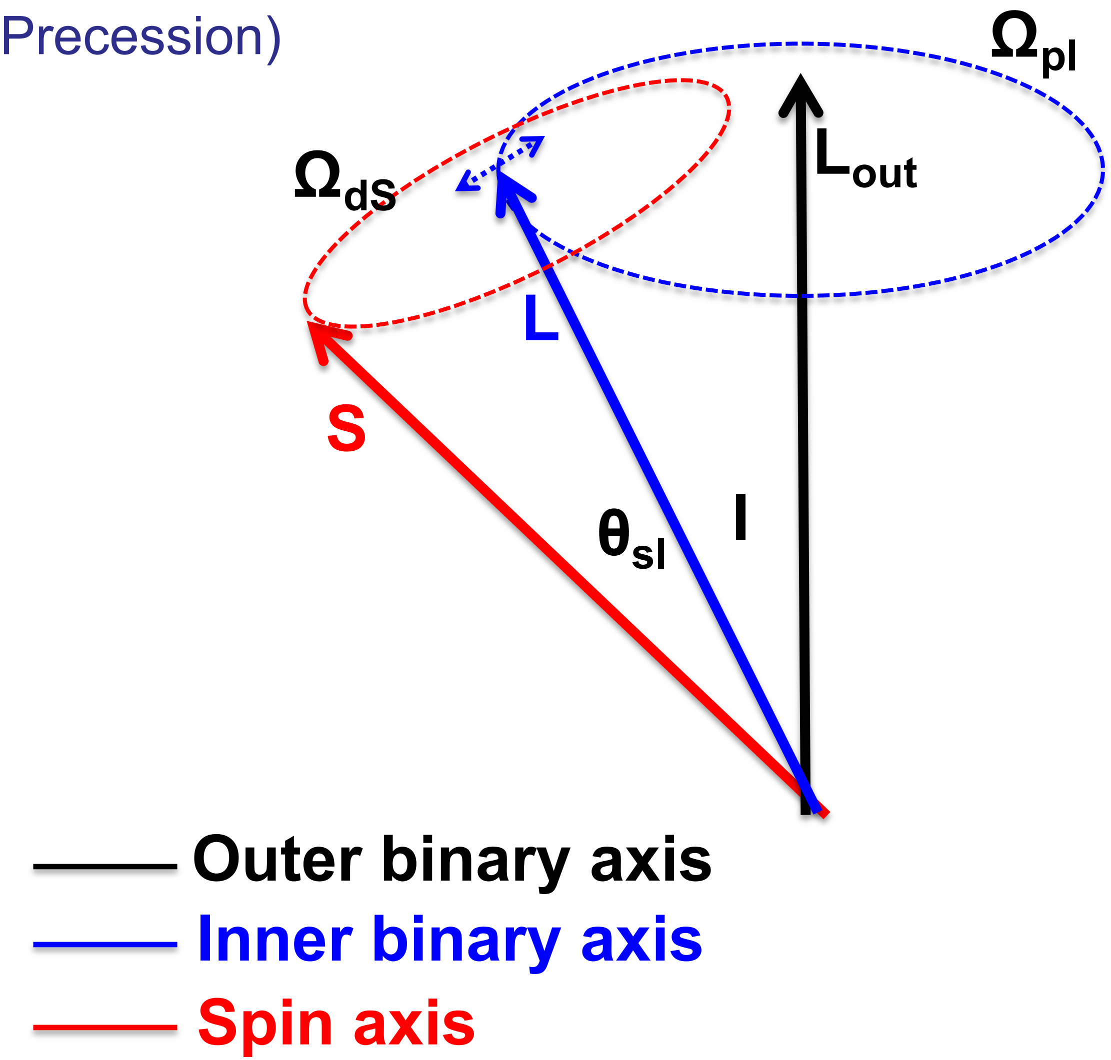
BH spin dynamics during LK oscillations

$$\frac{d\hat{\mathbf{S}}_1}{dt} = \Omega_{\rm dS}\hat{\mathbf{L}} \times \hat{\mathbf{S}}_1$$

(de Sitter Precession)

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

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



BH spin dynamics during LK oscillations

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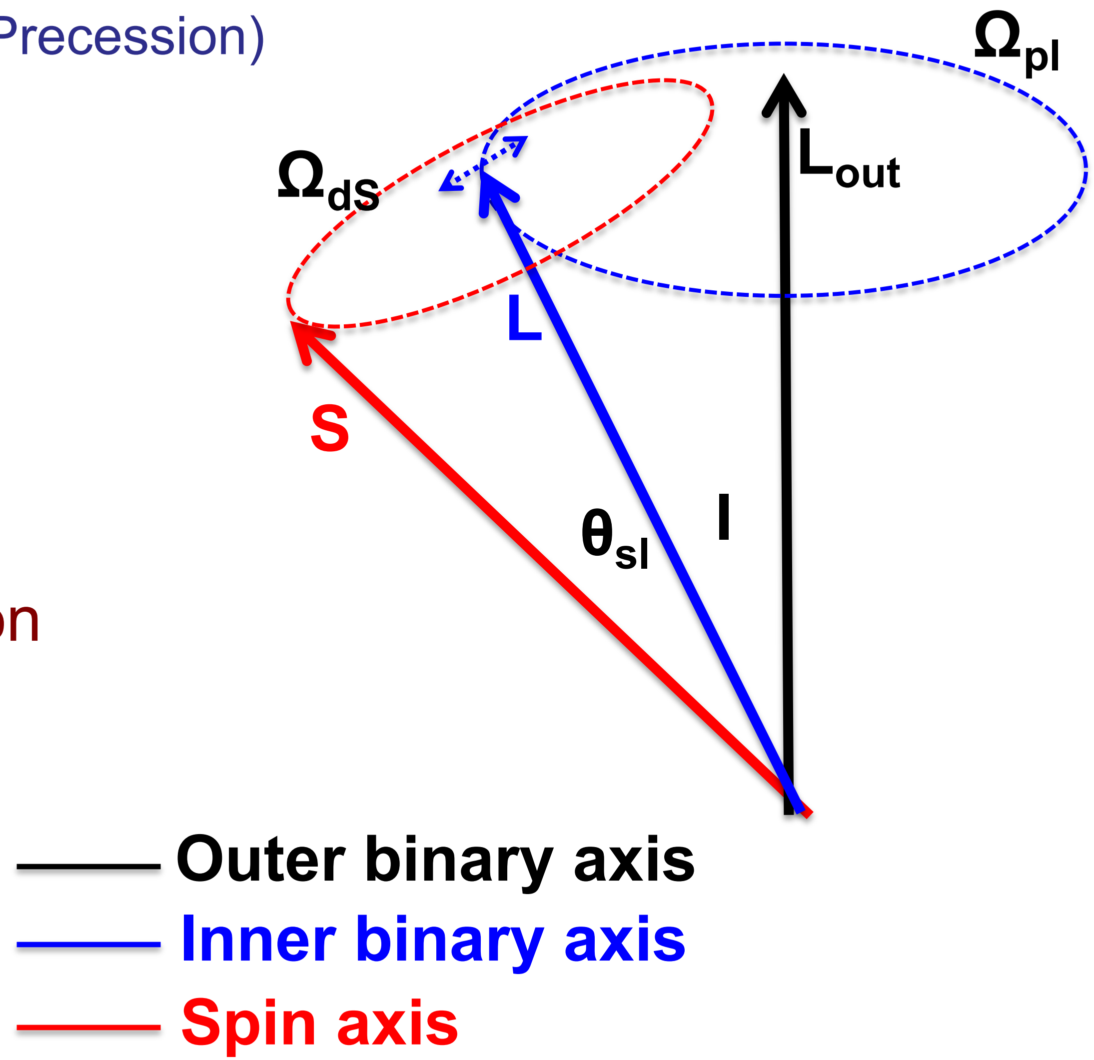
But **L** precesses and nutates during LK oscillations

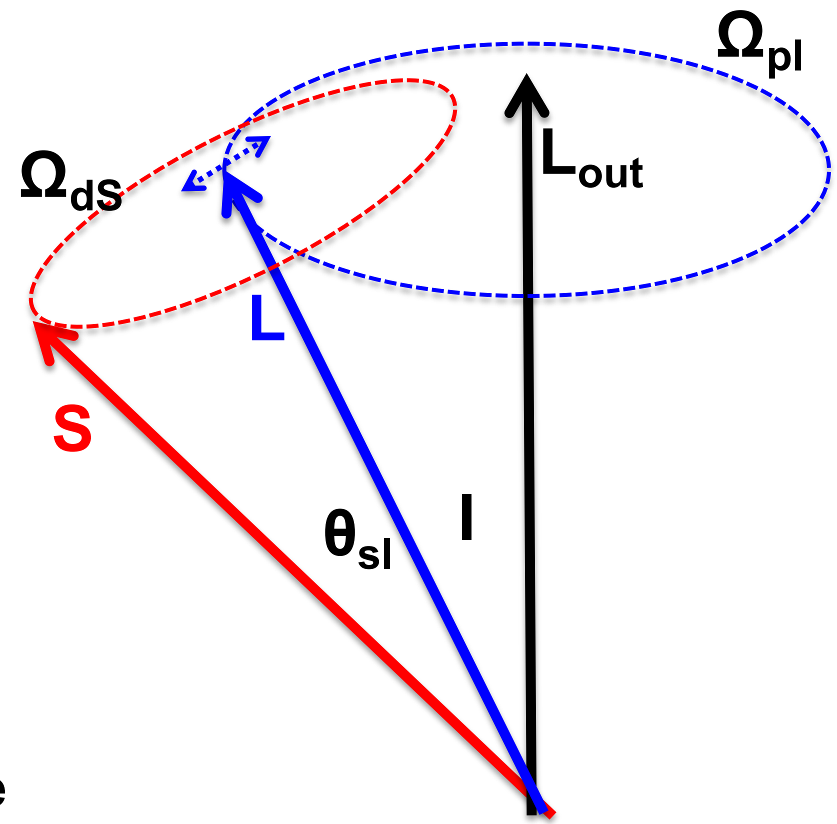
$$\Omega_{\rm pl} \simeq \frac{3(1+e^2)}{t_{\rm LK}\sqrt{1-e^2}}|\sin 2I|$$

Spin dynamics depends on

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

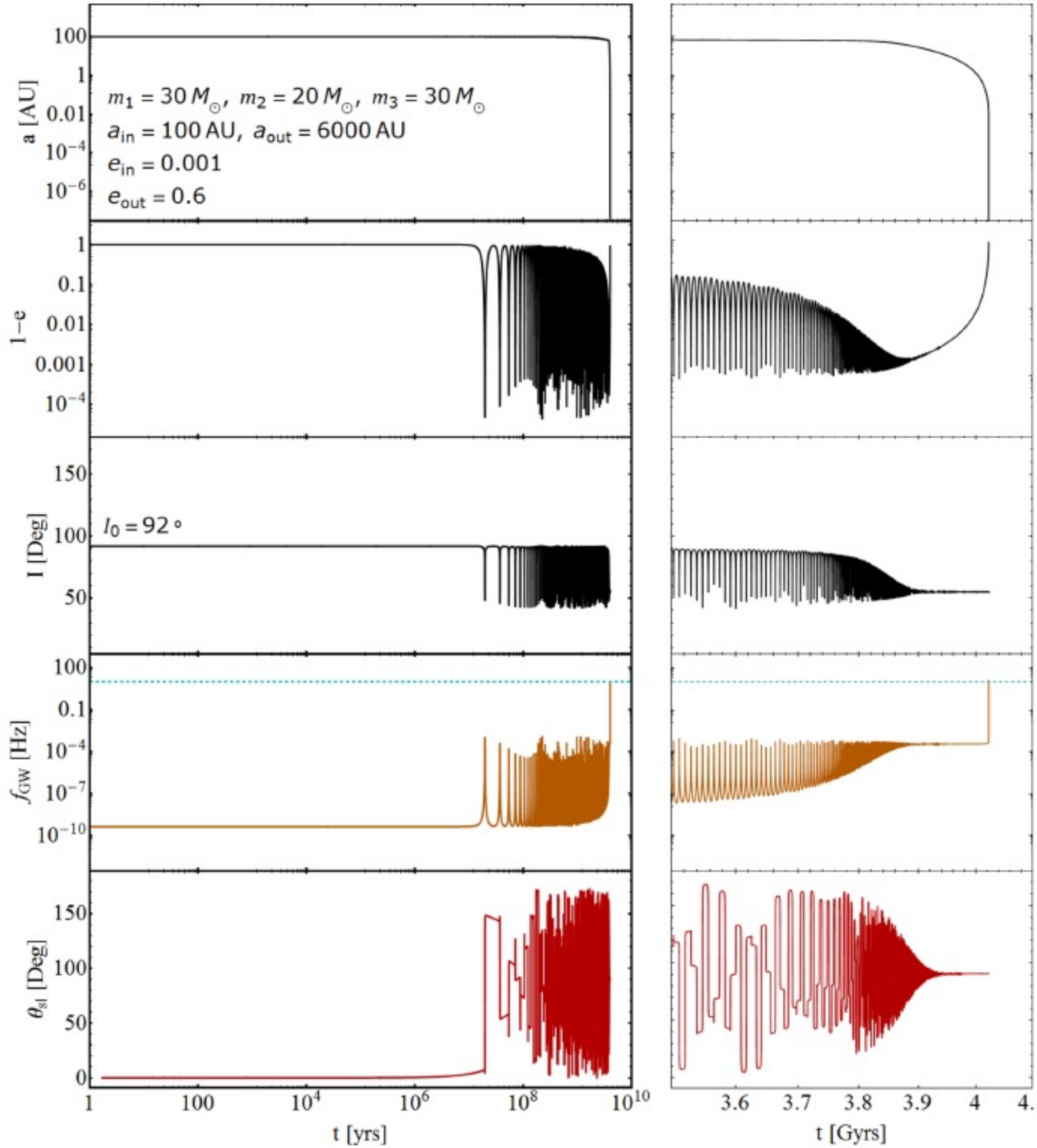


BH spin evolution in LK-induced orbital decay



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

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

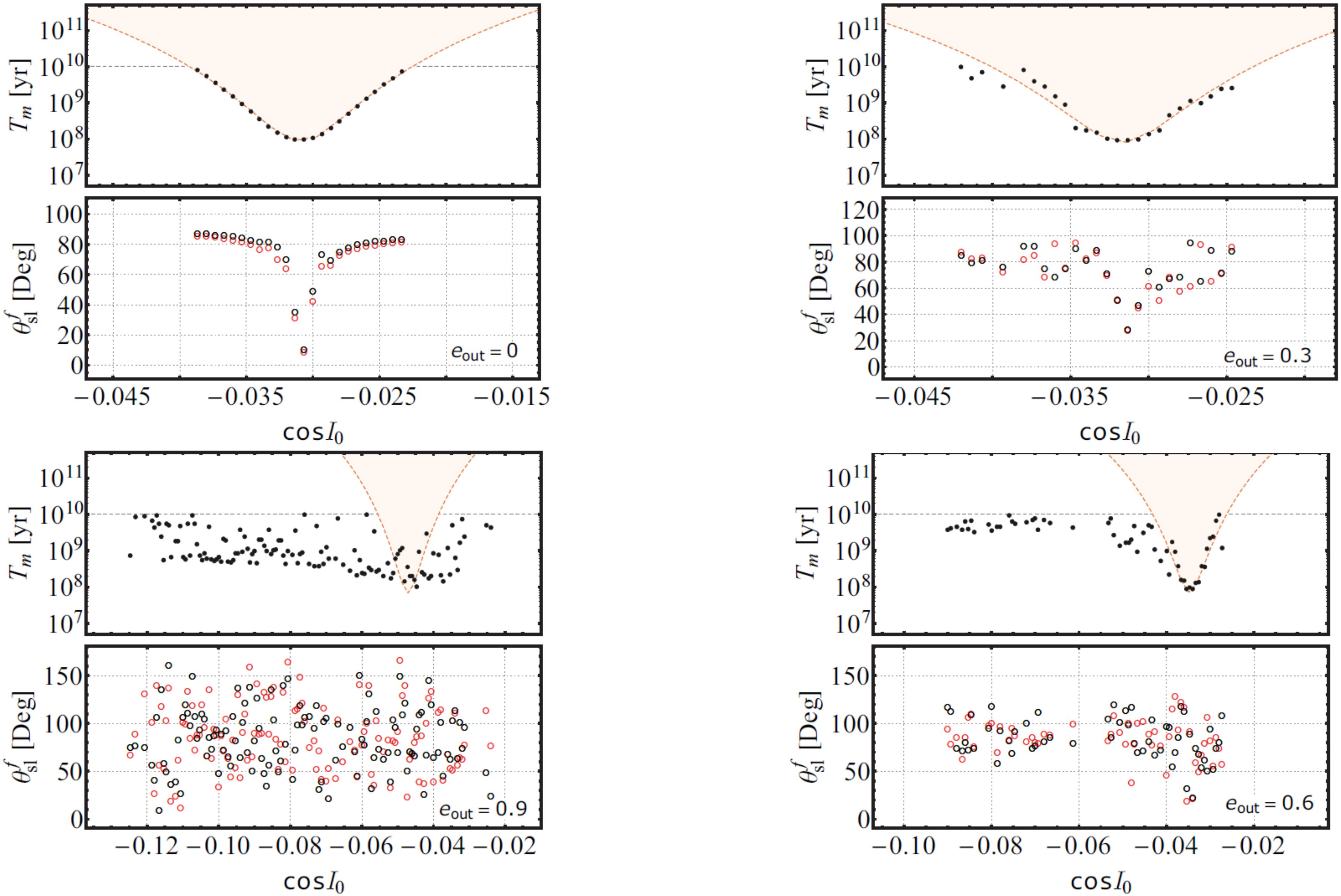


$m_1 = 30\,M_\odot,\ m_2 = 20\,M_\odot,\ m_3 = 30\,M_\odot$
$a_{\rm in} = 100\,{\rm AU},\ a_{\rm out} = 6000\,{\rm AU}$
$e_{\rm in} = 0.001$
$e_{\rm out} = 0.6$
$I_0 = 92\circ$
a [AU]
1−e
I [Deg]
$f_{\rm GW}$ [Hz]
$\theta_{\rm sl}$ [Deg]
t [yrs]
t [Gyrs]

Merger Window and Final Spin-Orbit Misalignments

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

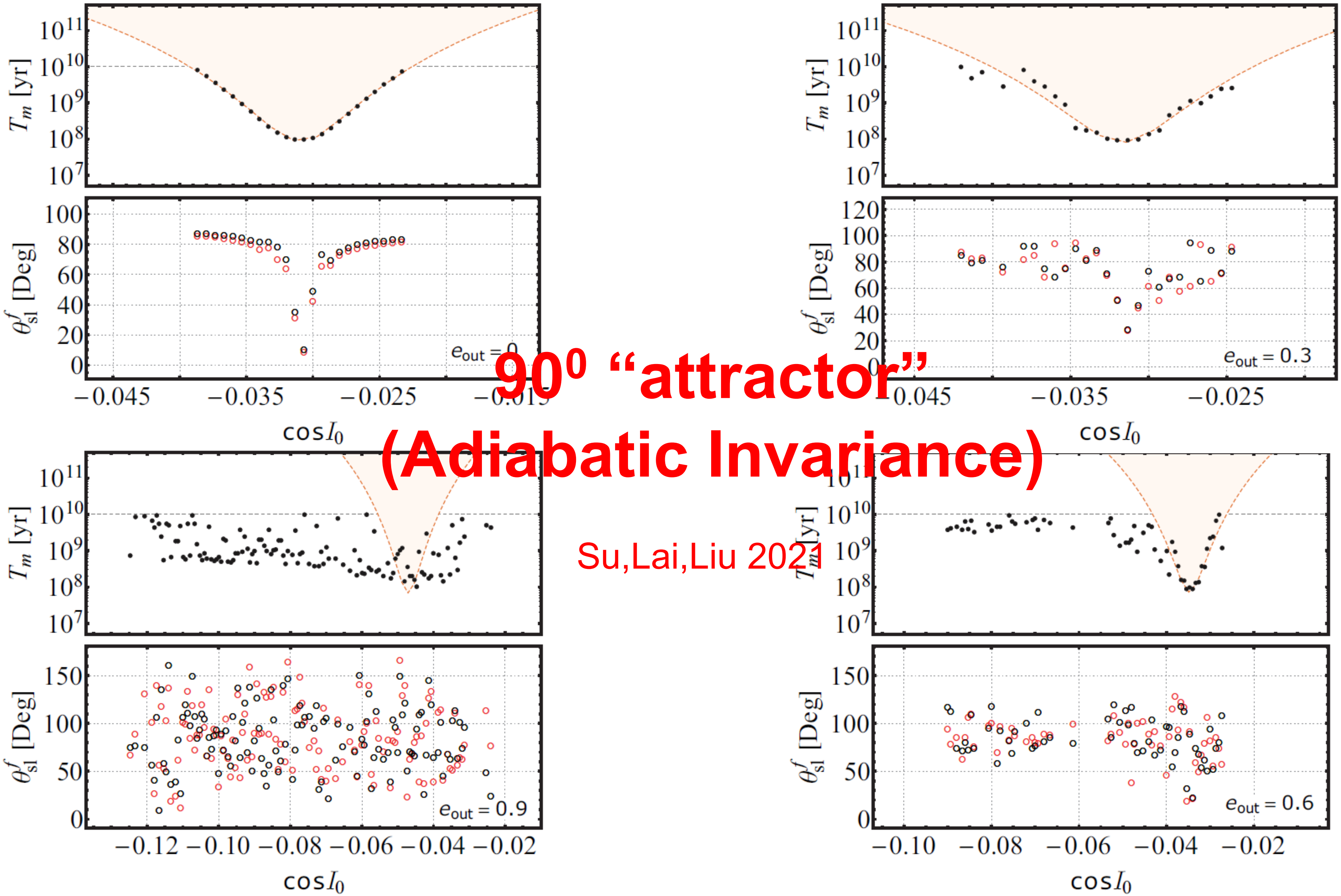
Fixed $m_3/a_{\rm out}^3$ value



Merger Window and Final Spin-Orbit Misalignments

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

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



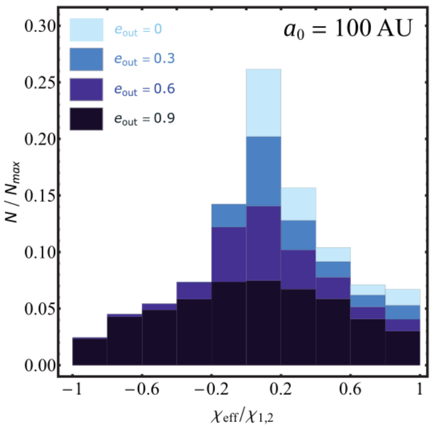
90^0 "attractor"

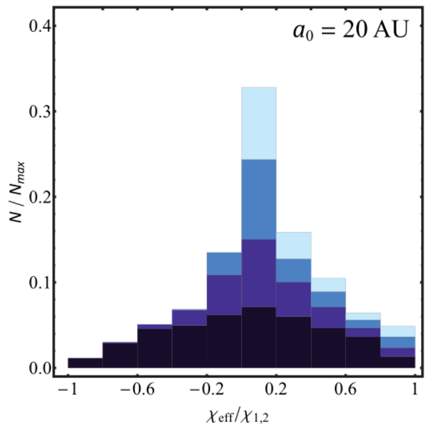
(Adiabatic Invariance)

Su,Lai,Liu 2021

Effective Spin Distribution

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





Effective Spin Distribution

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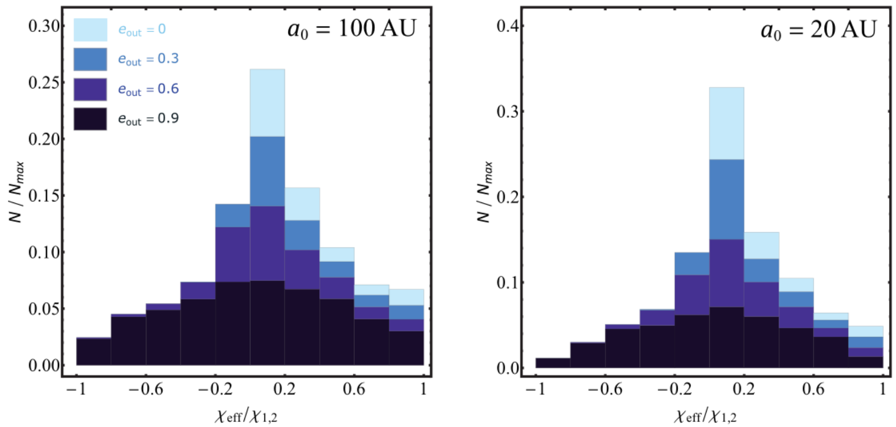
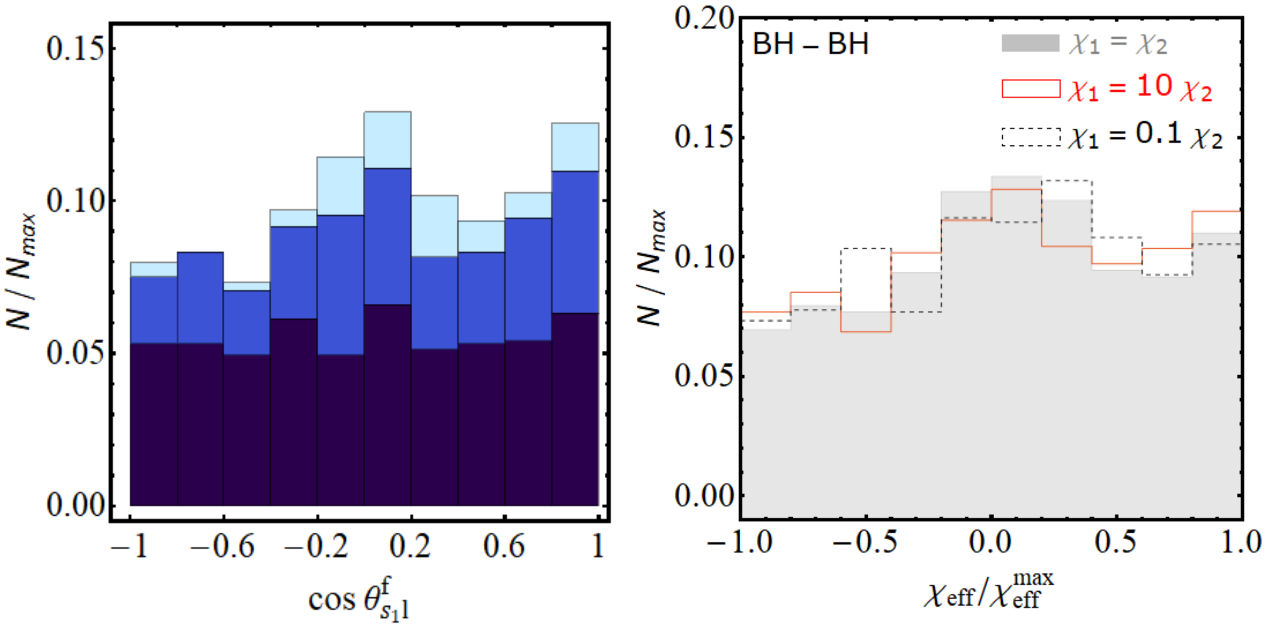
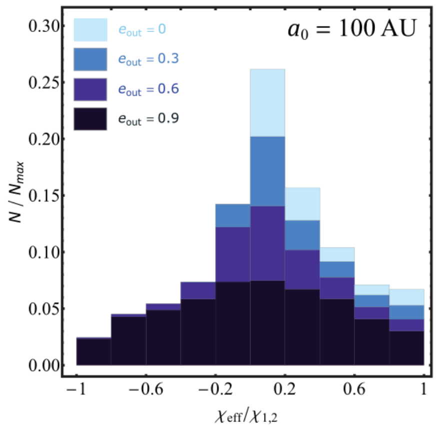


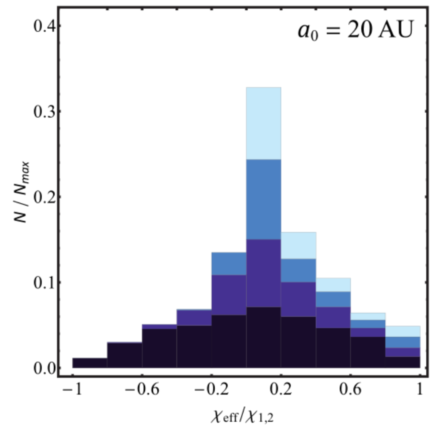
Consider ALL possible parameters

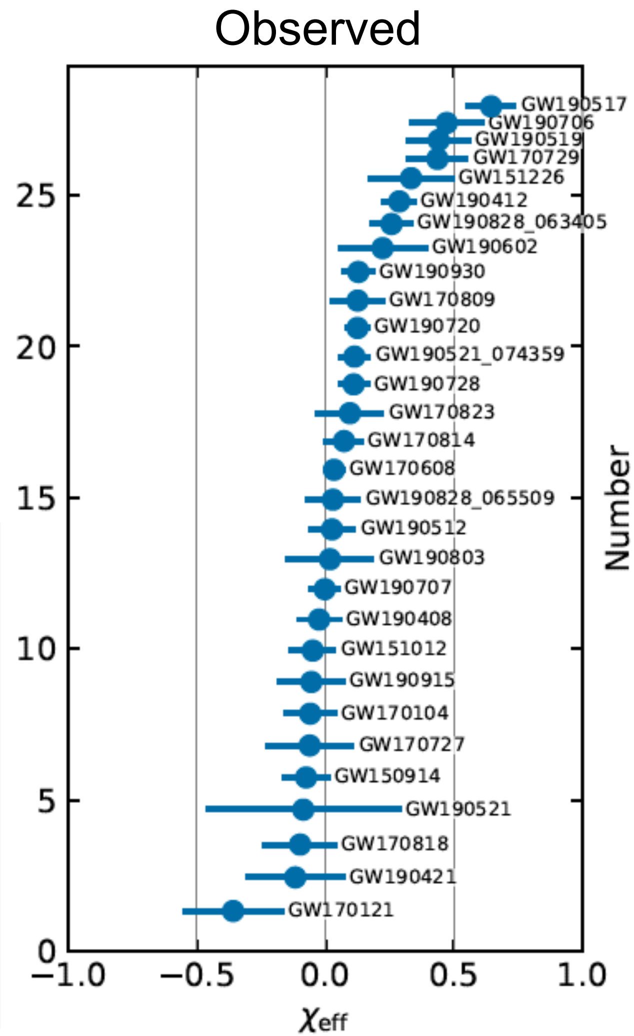


Effective Spin Distribution

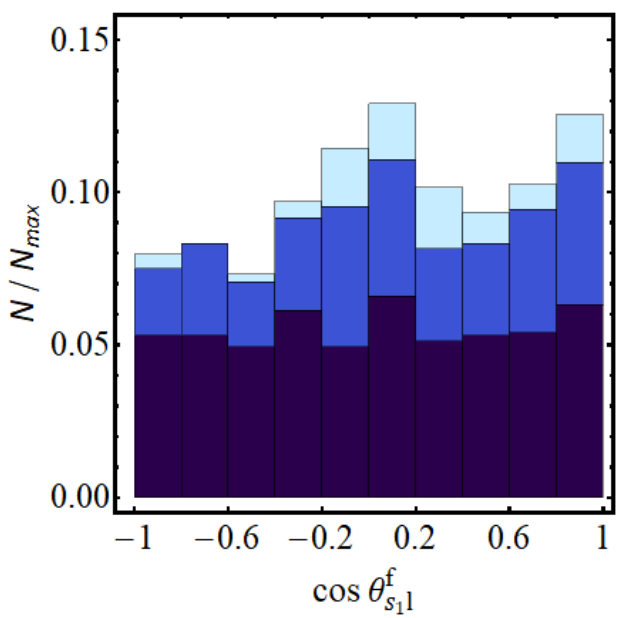
For “some” initial binary/triple parameters (e_0=0, distant companions)

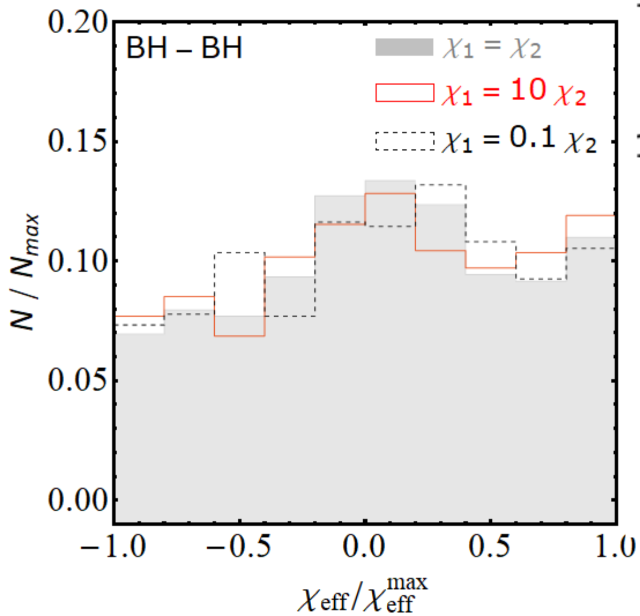






Consider ALL possible parameters

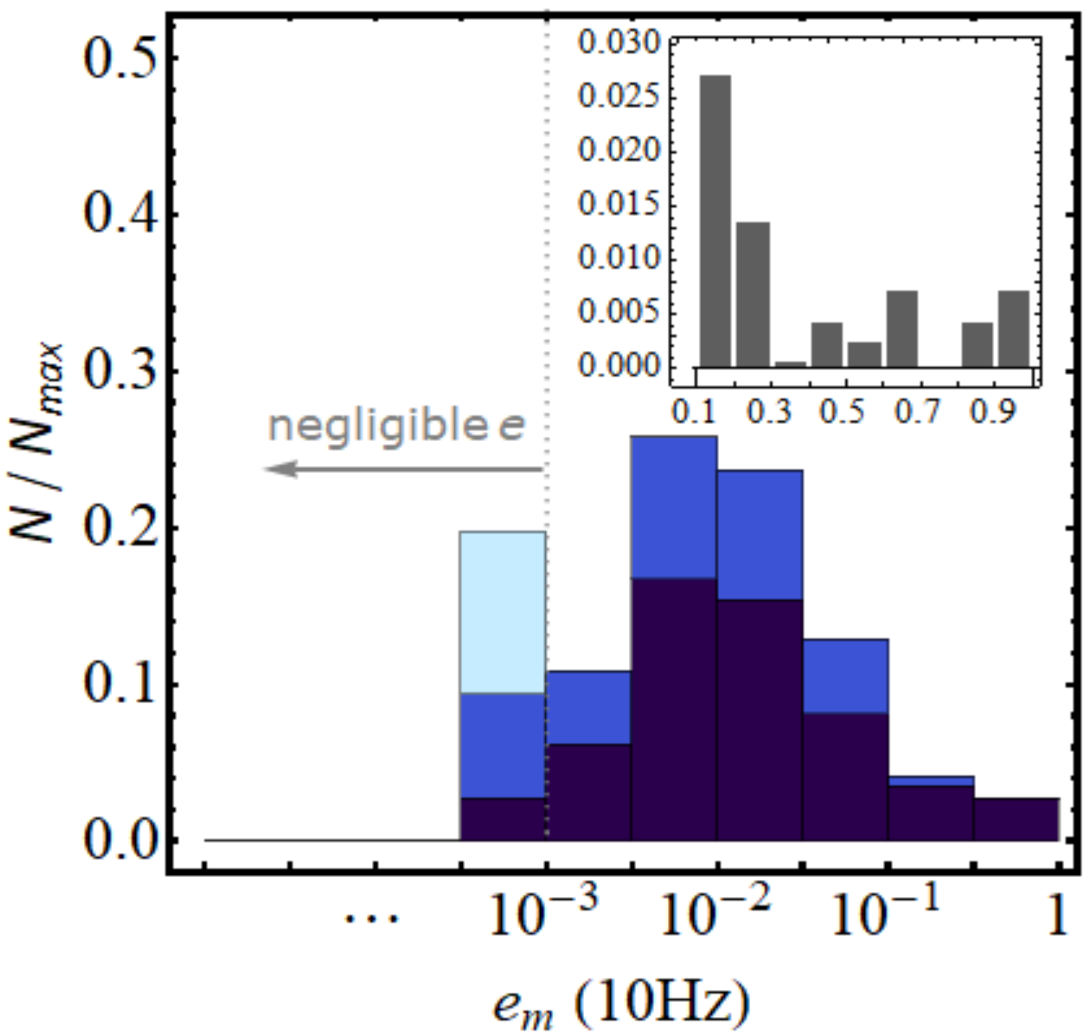




Roulet…Zackay…2021

Residual Eccentricity (at 10 Hz)

BH-BH mergers



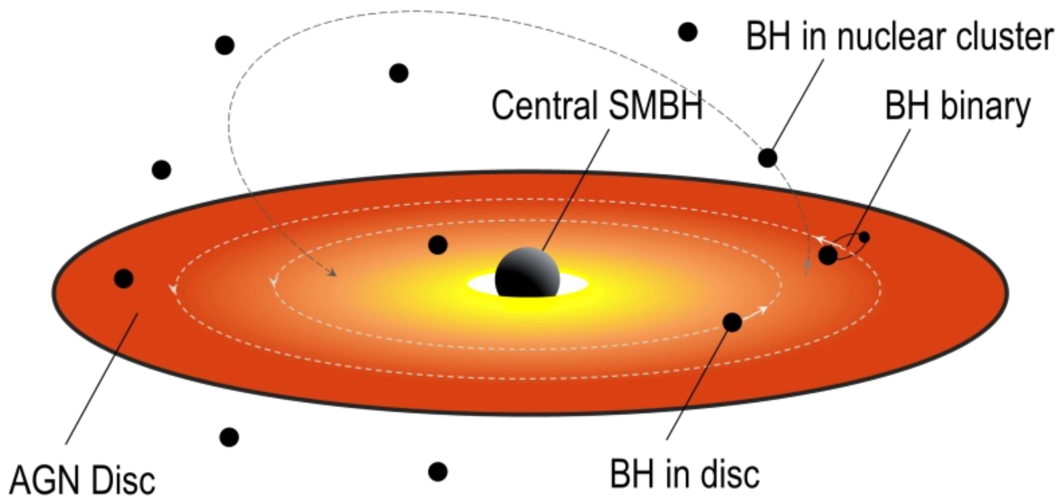
Very approximately

10% have $e_m > 0.1$

1% have $e_m > 0.9$

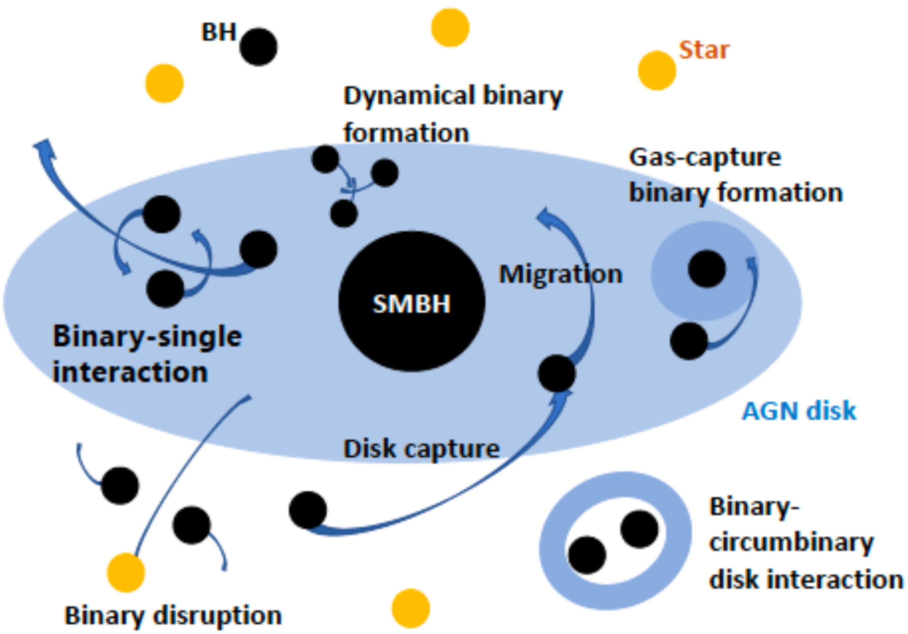
LISA/Taiji/Tianqin
would be very useful

Binary BH Mergers in AGN disks



Bellovary+16, Bartos+16, Stone+17, McKernan+18, Secunda+18, Yang+19, Tagawa+20, etc

Where do BH binaries in AGN disks come from?



Tagawa, Haiman, Kocsis 2020

See also Bartos+17; Stone+17; ….

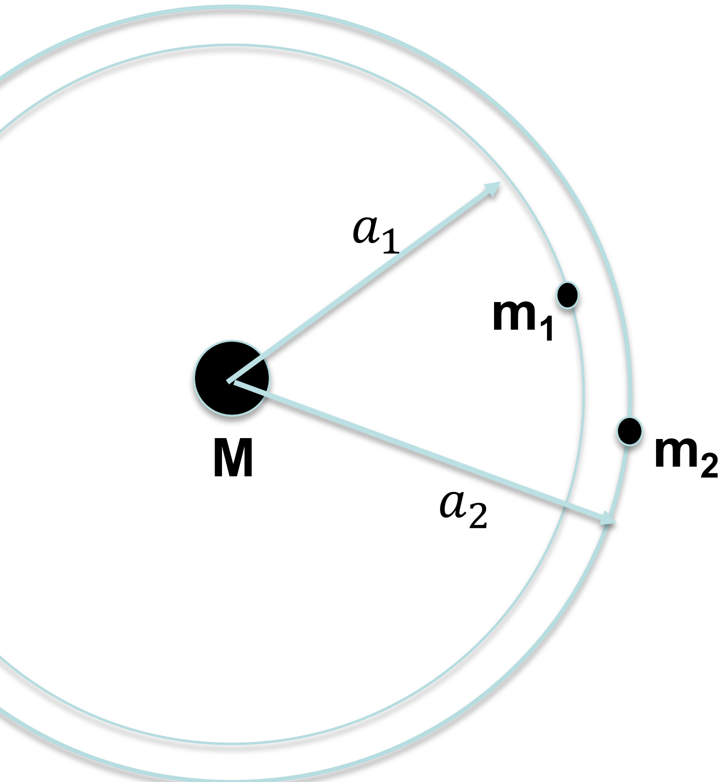
1. Binaries form in disks via GI (~pc)
2. Binaries in nuclear clusters get captured in disks
3. Single BHs in AGN disks get captured in binaries

Long-Term Evolution of Tightly-Packed Stellar BHs in AGN Disks: Formation of Merging BH Binaries via Close Encounters

Jiaru Li, Lai, Rodet 2023

Jiaru Li
(Cornell Ph.D. 2023)

The Problem:



Two BHs (m_1, m_2) on closely-packed, nearly circular, nearly-coplanar orbits around a SMBH (M)
(e.g. brought together by migration in AGN disks)

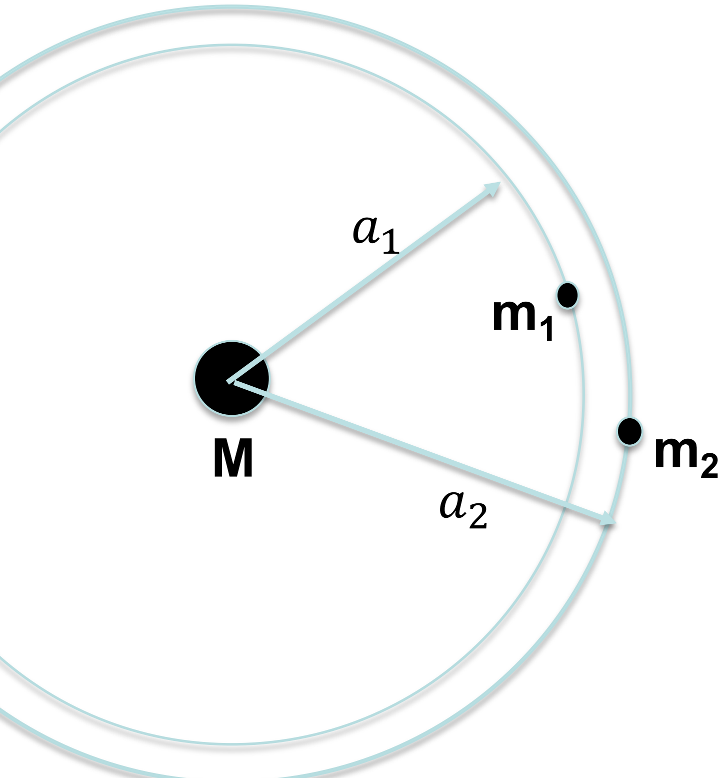
When $a_2 - a_1 \lesssim 3.46 R_{\rm H}$

$$R_{\rm H} = a_1 \left(\frac{m_{12}}{3M}\right)^{1/3}, \quad m_{12} = m_1 + m_2$$

orbits are dynamically unstable.

What happens to the two BHs?

Neglect gas effect for now…



Two planets in unstable orbits around a star:

Three outcomes:

1. Ejection of lower-mass planet
2. Planet-planet collision
3. Injection into the the near vicinity of star

Two BHs in unstable orbits around a SMBH:

Since $M/m_{12} \sim 10^6 \gg 1$
Ejection and injection are not possible
(takes many orbits > Hubble time)

Since $\frac{GMm_{1,2}}{a} \gg \frac{Gm_1 m_2}{a}, \frac{Gm_1 m_2}{R_H}$

➔ The two BHs undergo “chaotic” motion, experience recurring closer encounters (separation < R_H)

For VERY close encounter:

GW emission $$\Delta E_{\rm GW} \sim \frac{\mu^2 m_{12}^{5/2}}{r_{\rm rel}^{7/2}} \gtrsim \frac{G m_1 m_2}{R_{\rm H}}$$

$$\Longrightarrow \quad \frac{r_{\rm rel}}{R_{\rm H}} \lesssim 10^{-4} \left(\frac{4\mu}{m_{12}}\right)^{2/7} \left(\frac{10^6 m_{12}}{M}\right)^{10/21} \left(\frac{a_1}{100M}\right)^{-5/7}$$

Capture radius for forming “permanent” binary due to GW bremsstrahlung

What is the capture rate?

For a typical "SMBH + 2 BHs" system (in unstable orbits), what is the cumulative capture rate to form real bound binary?

(1) Close encounter (CE0) rate

(2) $P(< r_{\rm cap}) \simeq \dfrac{r_{\rm cap}}{R_{\rm H}}$

$$\langle N_{\rm cap}(t)\rangle \simeq 6 \times 10^{-5} \left(\frac{t}{P_1}\right)^{0.52} \left(\frac{r_{\rm cap}}{10^{-4} R_{\rm H}}\right)$$

It takes $10^8 P_1$ (on average) for two BHs to capture into bound merging binary

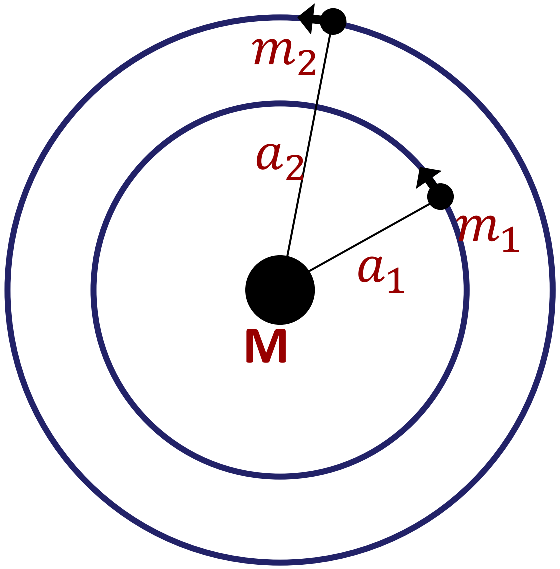
Captured BH binary as GW source

$$f_{\rm cap} \simeq (1.4\,{\rm Hz}) \left(\frac{4\mu}{m_{12}}\right)^{-3/7} \left(\frac{M}{10^8 M_\odot}\right)^{-2/7} \left(\frac{m_{12}}{100 M_\odot}\right)^{-5/7} \left(\frac{a_1}{100M}\right)^{-3/7}$$

Once capture, it will take a few orbits to merge
it enters LIGO band with $e \gtrsim 0.5$

This mechanism always produce very eccentric mergers
(not typical/most LIGO events)

Formation of BH binaries: Gas effects
hydrodynamics simulations

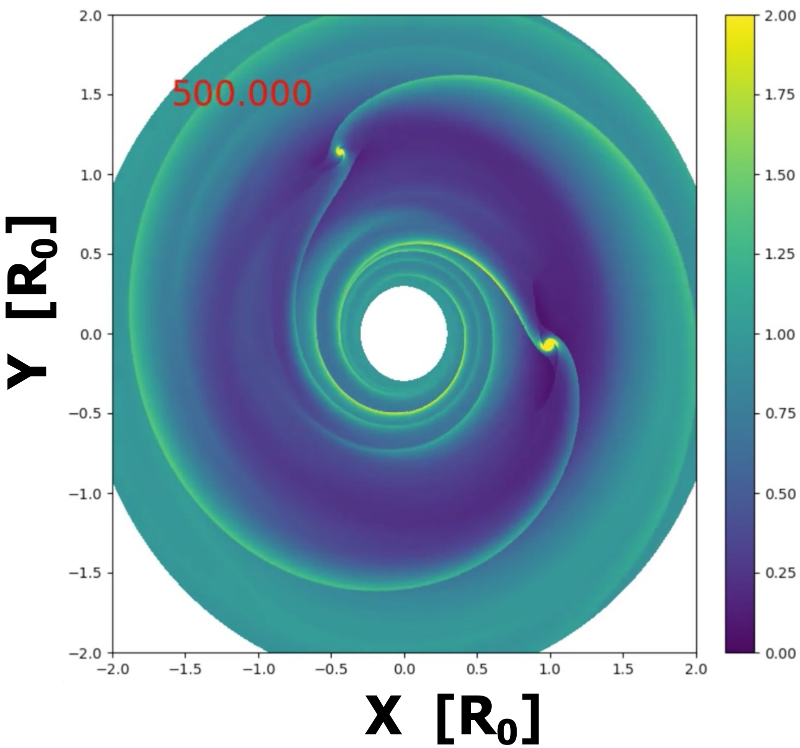


- Initial condition:

$$a_2 - a_1 = 2R_{\mathrm{H}}$$

Jiaru Li + 2023
(with Hui Li's group at LANL)

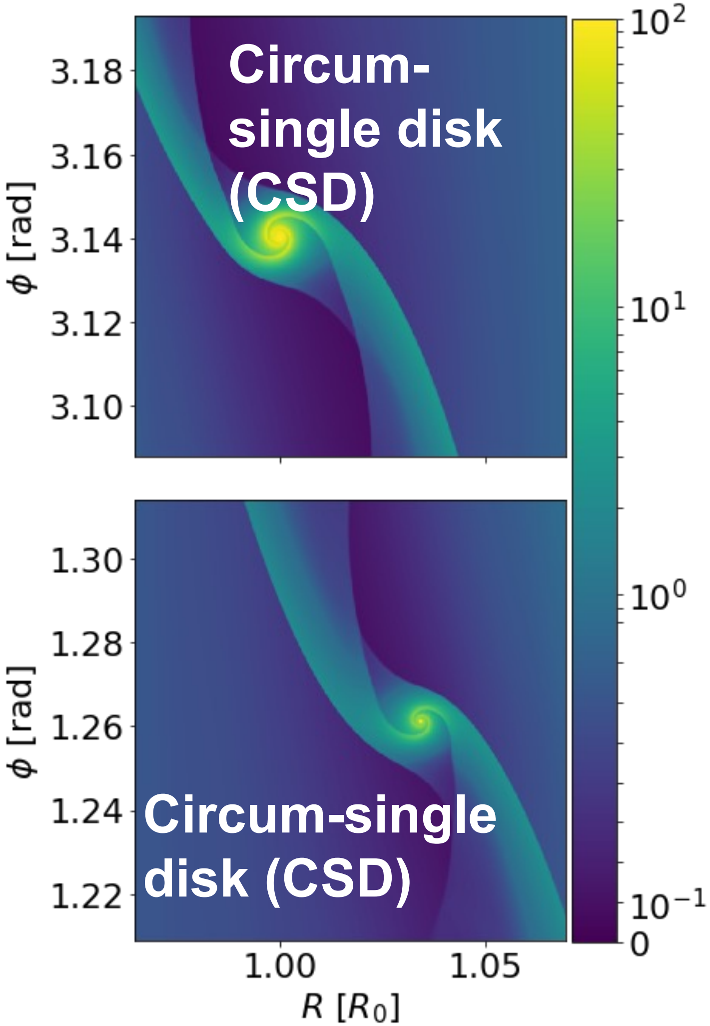
Formation of BH binaries: Gas effects
hydrodynamics simulations



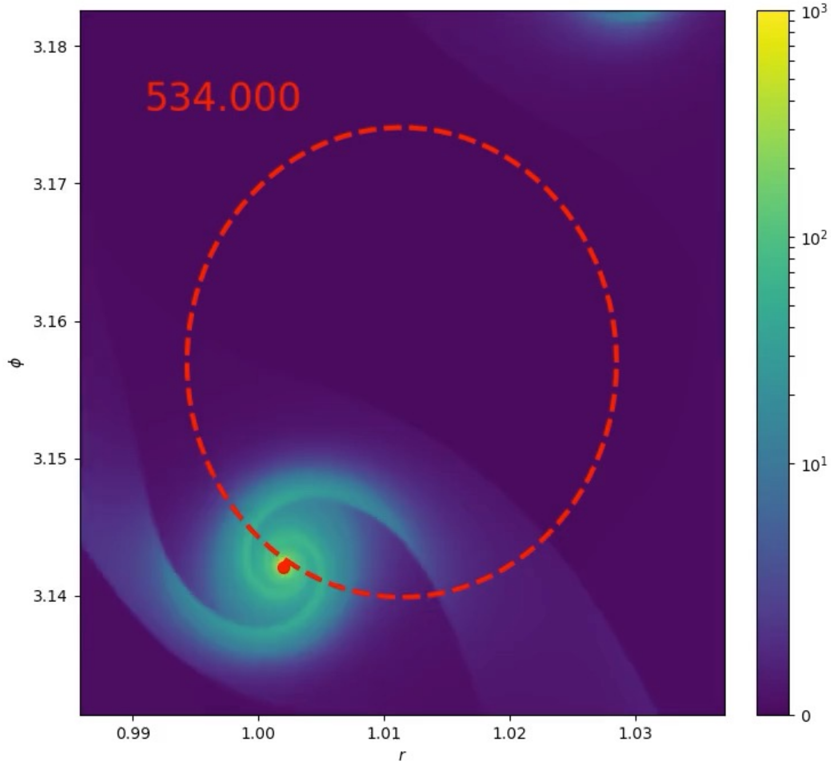
- Initial condition:

$$a_2 - a_1 = 2R_{\mathrm{H}}$$

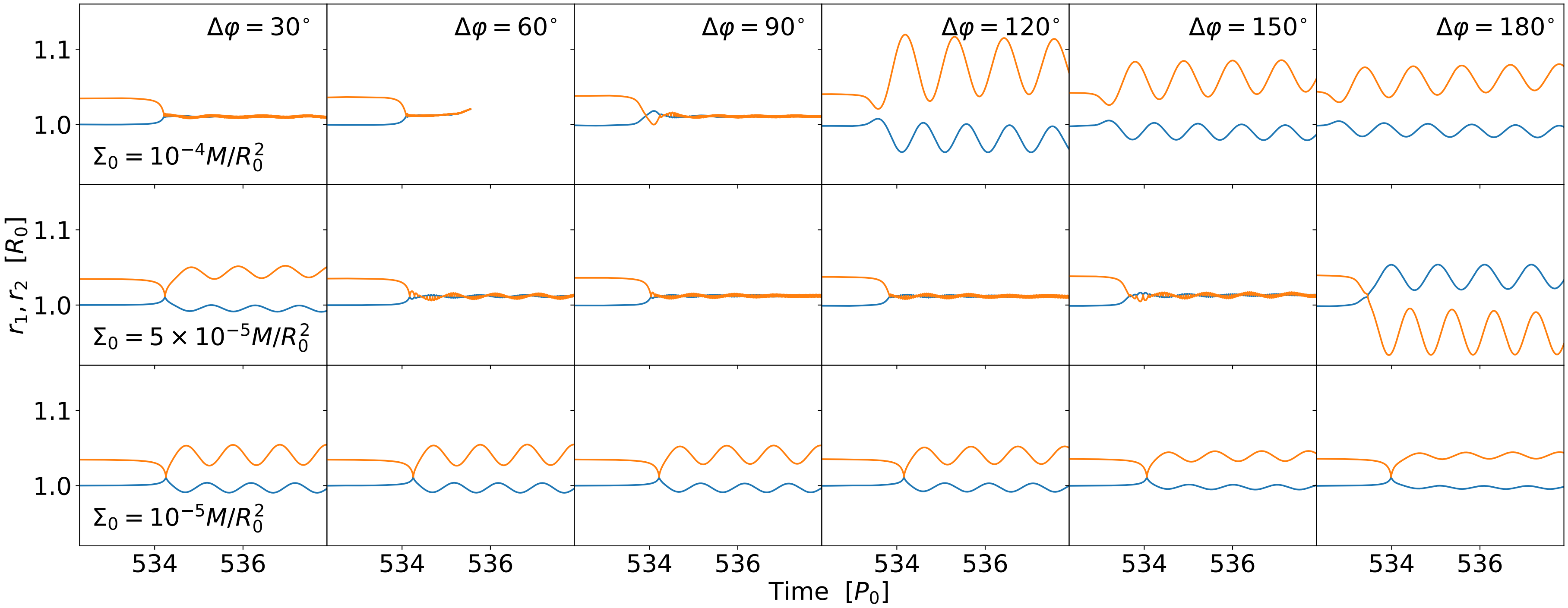
- Simulation setup:
  - $M_{\mathrm{SMBH}} = 1, \ m_1 = 10^{-5}, \ m_2 = 5\times10^{-6}$
  - Thin disk $H/R = 0.01$, low viscosity $\alpha = 0.01$.
  - Isothermal disk.
  - High resolution with 50→100 grid cells per R_{H}, where $R_{\mathrm{H}} = 0.017R_0$



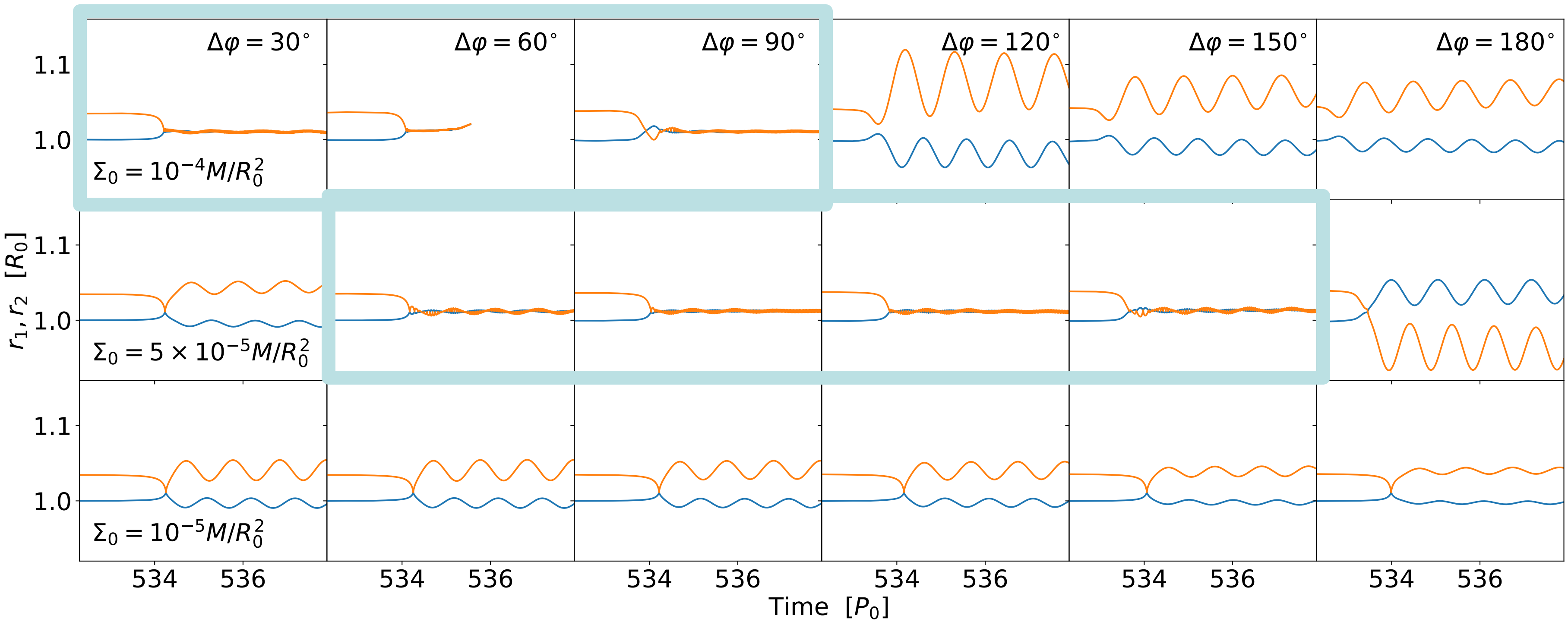
Formation of a binary



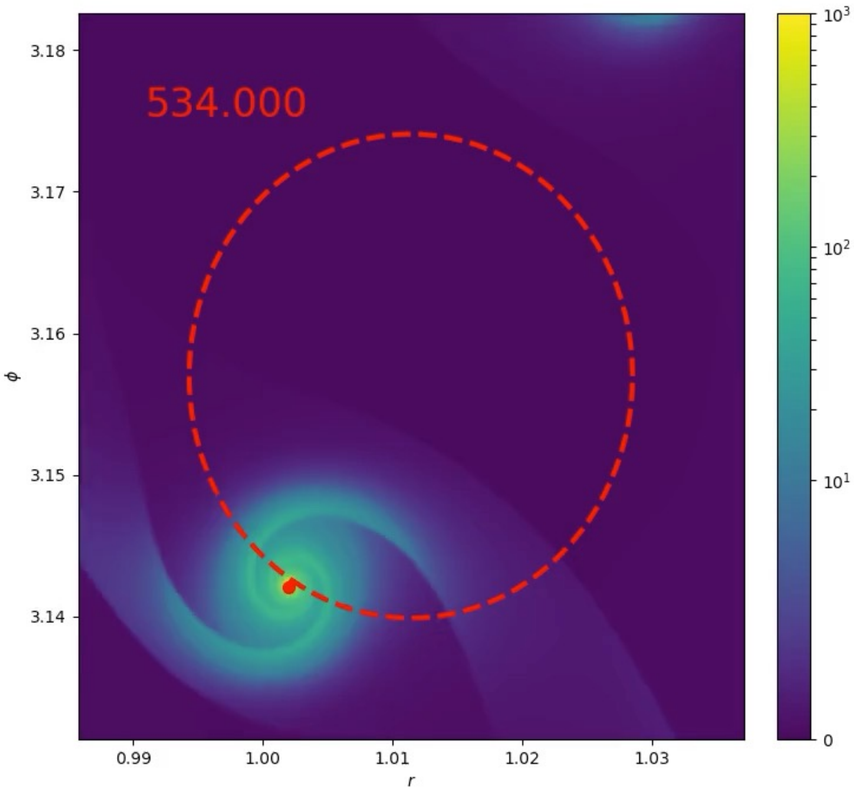
Simulation outcomes

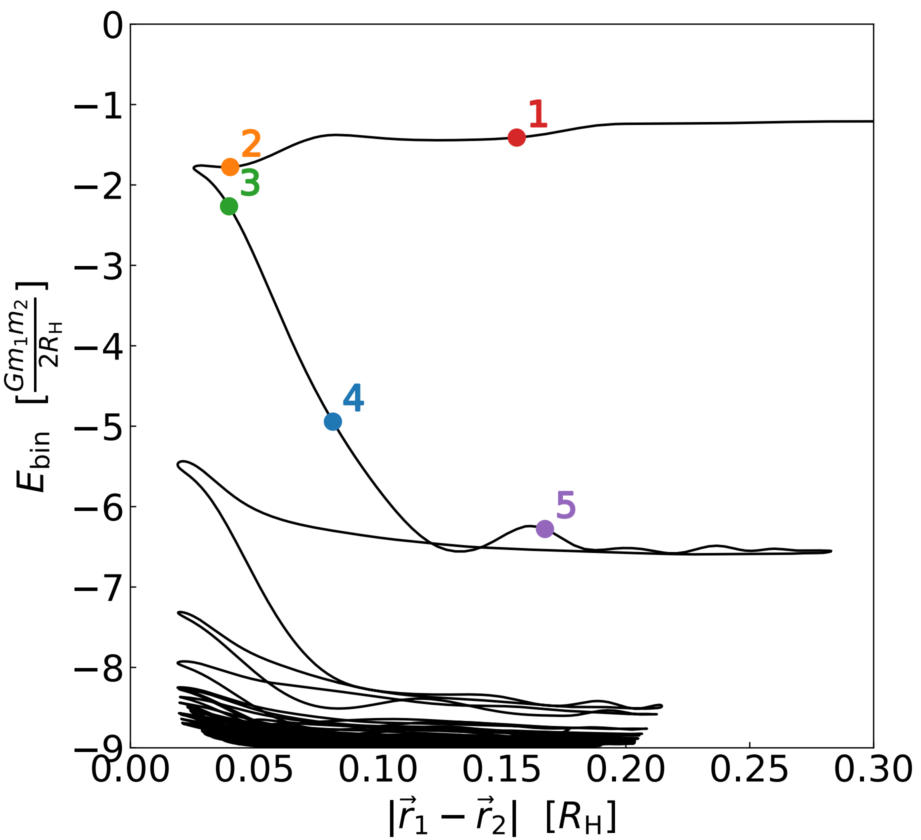


Simulation outcomes



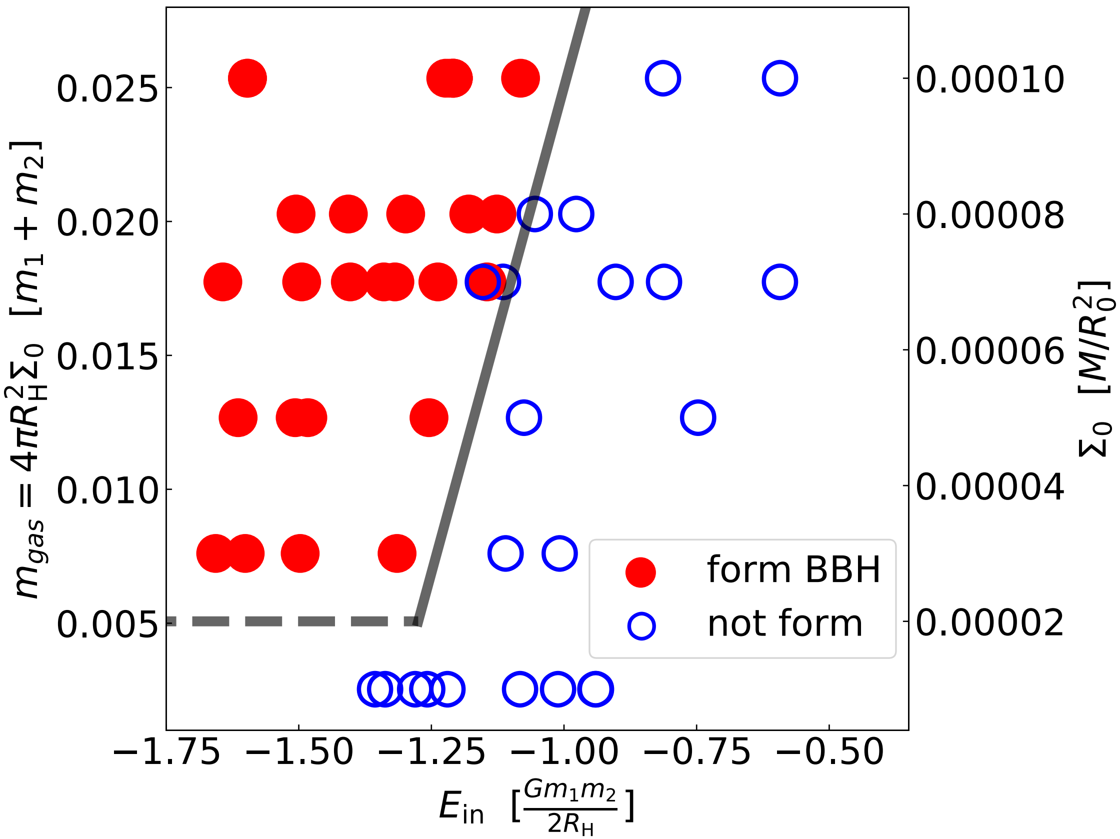
Analysis: formation mechanism -- a departure drag





$$\boldsymbol{E}_{\mathbf{bin}} = \frac{1}{2}\mu v_{\rm rel}^2 - \frac{Gm_1m_2}{r_{\rm rel}}$$

Analysis: criteria for binary formation



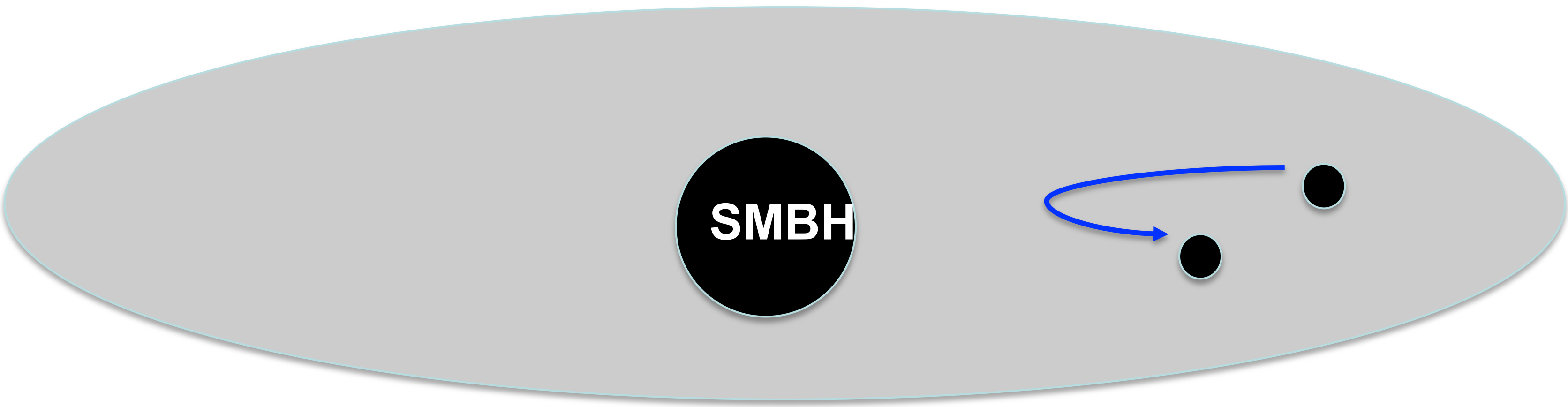
Forming binary requires:

- sufficiently large gas mass
- sufficiently small initial binary energy

$\boldsymbol{E}_{\mathbf{in}} := \frac{1}{2}\mu v_{\rm rel}^2 - \frac{Gm_1m_2}{r_{\rm rel}}$ when $r_{\rm rel} = 0.3R_{\rm H}$

Hydrodynamical interaction of Binary in ANG Disk

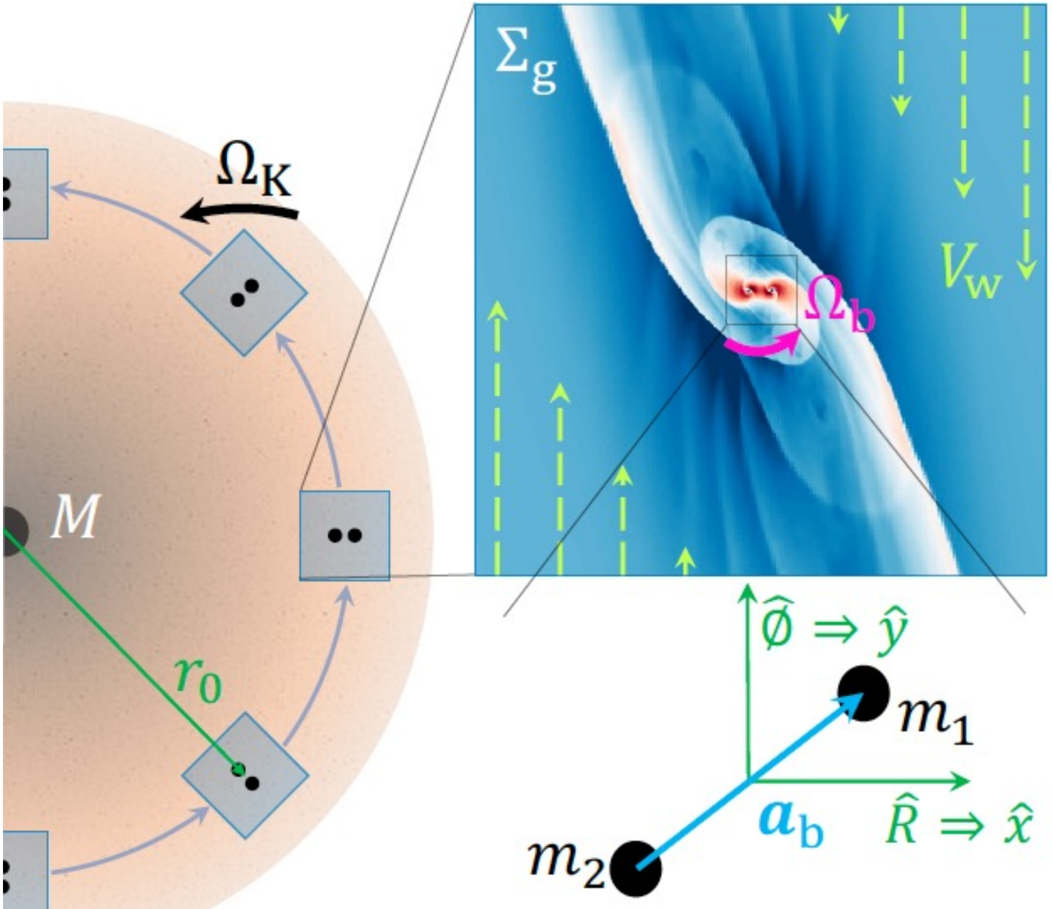
Assume a pre-existing binary



Local simulations of binary in disk

R.Li & Lai 2022,2023

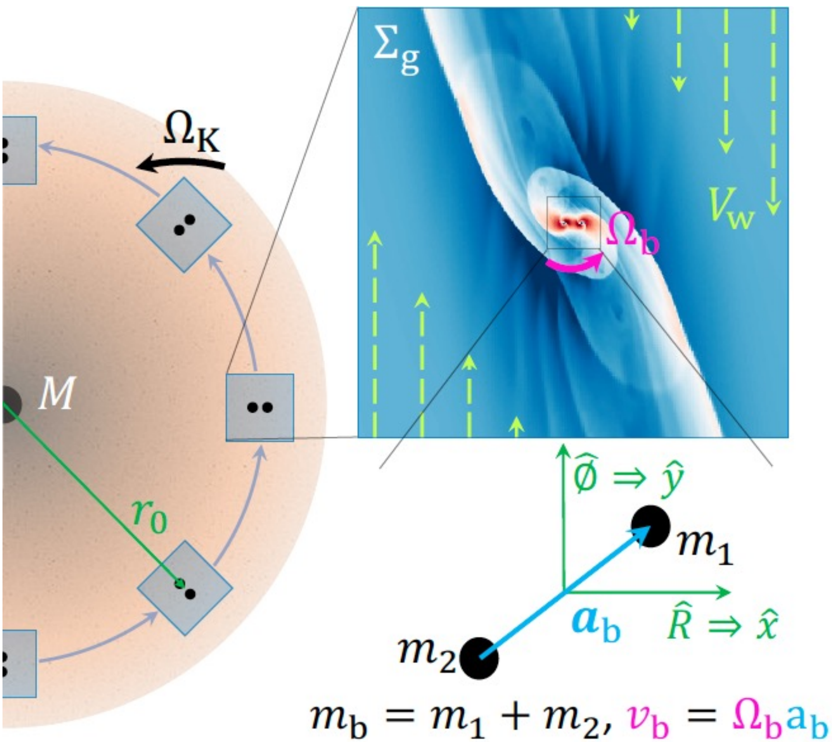
Dr. Rixin Li
(Cornell)



$$m_b = m_1 + m_2,\ v_b = \Omega_b a_b$$

Local shearing box
(not "local wind tunnel box" used by Kaaz et al. 2021)

ATHENA
Mesh refinement
Resolution: a_b ~250 cells
zero softening in gravity



Length scales of the problem:

$$a_b, \quad R_B \sim \frac{Gm_b}{c_\infty^2}, \quad R_H \sim r_0 \left(\frac{m_b}{M}\right)^{1/3}, \quad H$$

Velocity scales of the problem:

$$v_b, \quad c_\infty, \quad V_{\rm shear}$$

➔ Dimensionless ratios:

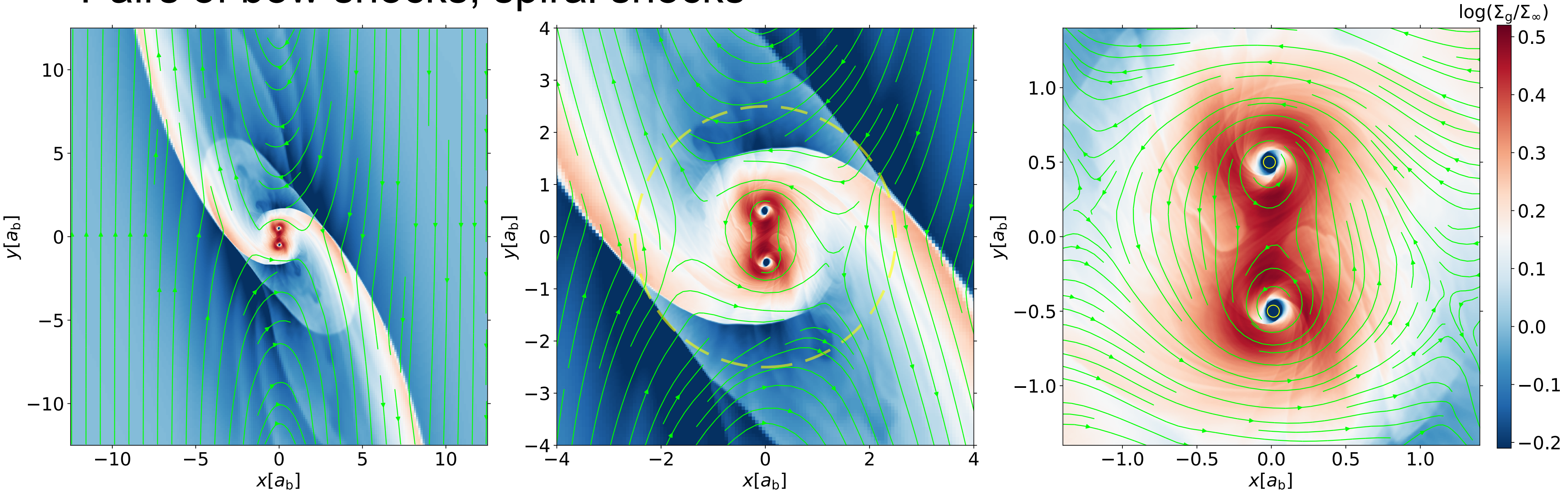
$$\frac{q}{h^3}, \quad \frac{R_H}{a_b} \equiv \lambda$$

where $q = m_b/M$, $h = H/r_0$

$$m_2/m_1, \quad e_b, \quad \text{EOS} \ \ (\text{e.g.} \ \ \gamma \text{ law})$$

Example of flow structure

Pairs of bow shocks, spiral shocks



BH = absorbing sphere: sink radius: $r_{\rm sink} = 0.04\, a_{\rm b} \simeq 10$ cells ➔ $\dot{m}_b$

Force on each BH: from gravity + accretion + pressure

➔ Torque on binary, energy transfer rate ➔ $\dot{a}_b, \quad \dot{e}_b$

Some ''Typical'' Results:

$\langle \dot{m}_b \rangle$ **: can be << Bondi-Hoyle-Lyttleton rate (even including shear)**
depends on sink radius (for non-viscous flow)

$$\ell_0 = \frac{\langle \dot{L}_\mathrm{b} \rangle}{\langle \dot{m}_\mathrm{b} \rangle} = -0.23\, v_\mathrm{b} a_\mathrm{b}$$

$$\frac{\langle \dot{a}_\mathrm{b} \rangle}{a_\mathrm{b}} = -4.81 \frac{\langle \dot{m}_\mathrm{b} \rangle}{m_\mathrm{b}}$$

$$m_2/m_1 = 1, \quad e_b = 0$$

$$q/h^3 \sim 1, \quad \lambda = 5, \quad \gamma = 5/3$$

Orbital evolution is always accompanied by accretion

Summary
Formation Channels of Merging BH Binaries

Standard isolated binary evolution channel:

uncertain physics (common envelope…)

➔ circular mergers (e_m=0), mostly 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

Octupole effect → mass ratio dependence

Binary mergers around SMBH: GR effects important

Spin-orbit misalignment

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

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

3. BH Mergers in AGN disks

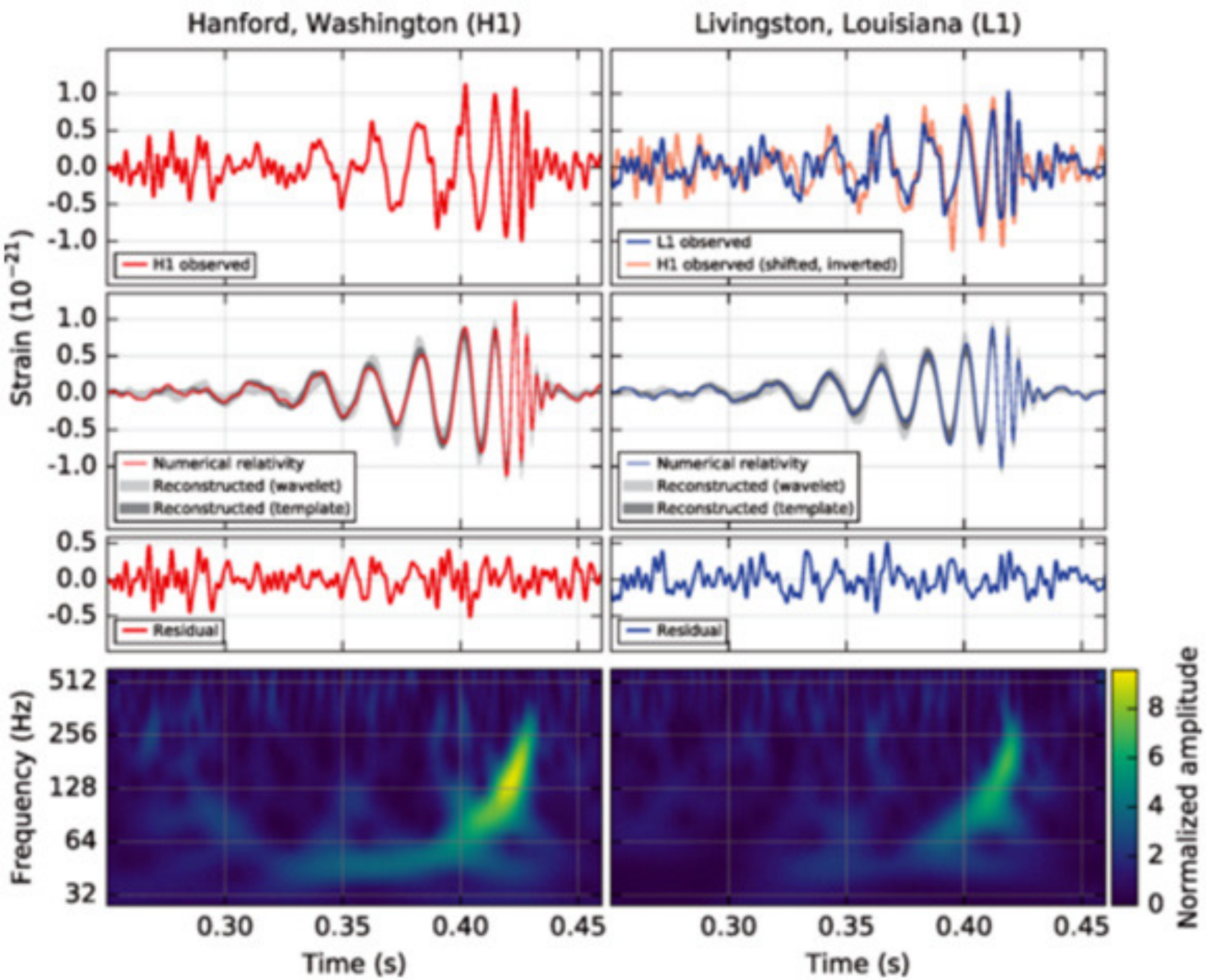
GW capture → very eccentric mergers

gas assisted mergers?

Rates? All potentially can play a role

LISA/Taiji/Tianqin useful for probing dynamical formation

LIGO's First Merging Binary Black Holes: GW150914



Binary Dynamics Near a Supermassive BH

'Environmental' effects

- **Binary Evaporation**

  e.g., Binney & Tremaine 2008; Perets 2009

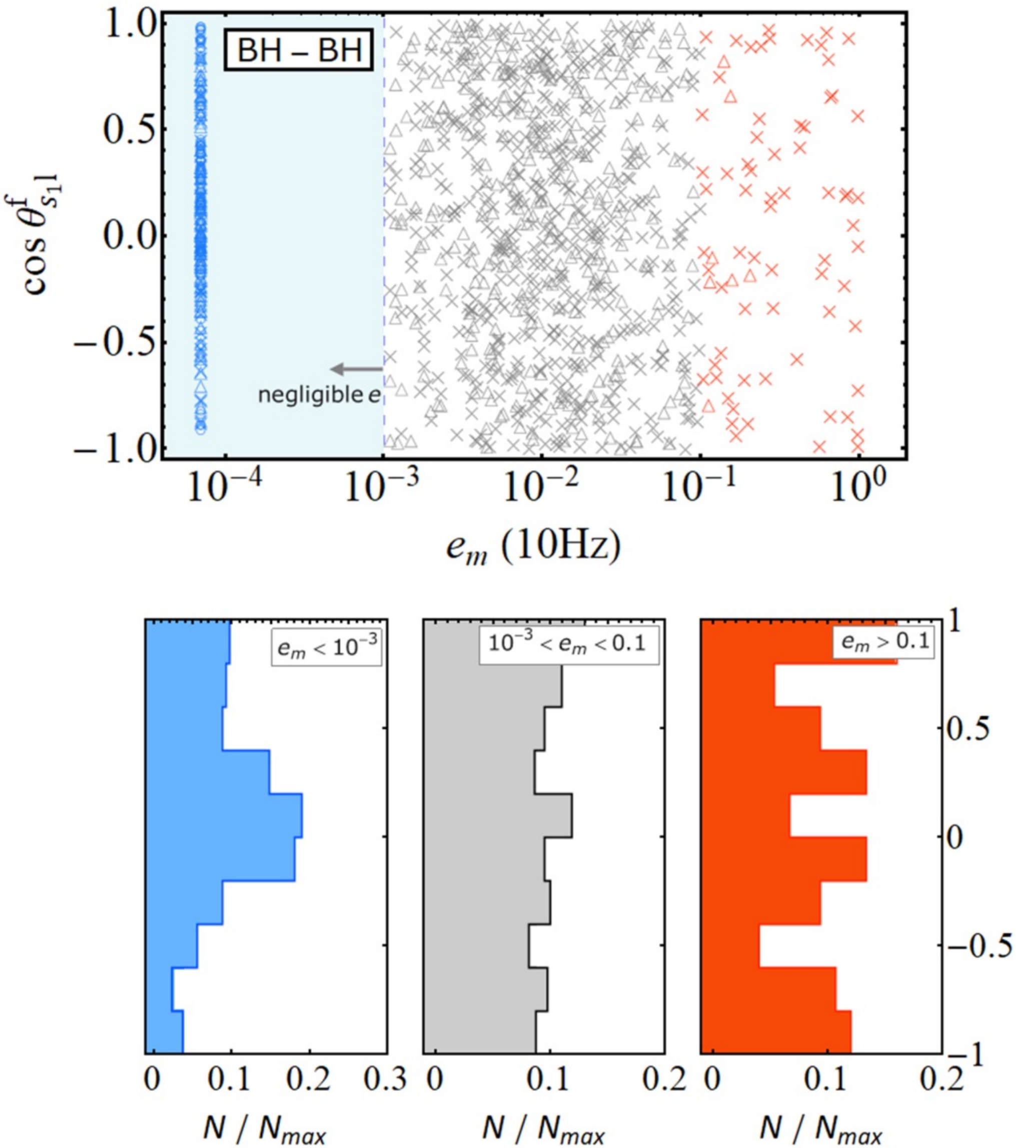
- **Resonant Relaxation**

  e.g., Rauch & Tremaine 1996; Perets et al. 2009; Kocsis & Tremaine 2011; Hamers et al. 2018;

- **Non-spherical Cluster**

  e.g., Petrovich & Antonini 2017; Hamilton & Rafikov 2019a/2019b/2020

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}