Title: Dynamical Formation of Merging Compact Binaries

Speakers: Dong Lai

Series: Colloquium

Date: January 17, 2024 - 2:00 PM

URL: https://pirsa.org/24010077

Abstract: The recent breakthrough in the detection of gravitational waves (GWs) from merging black hole (BH) and neutron star (NS) binaries by advanced LIGO/Virgo has generated renewed interest in understanding the formation mechanisms of merging compact binaries, from the evolution of massive stellar binaries and triples in the galactic fields, dynamical interactions in dense star clusters to binary mergers in AGN disks. I will review different aspects of the dynamical formation channels, and discuss how observations of spin-orbit misalignments, eccentricities, masses and mass ratios in a sample of merging binaries by aLIGO can constrain these formation channels. The important roles of space-borne gravitational wave detectors will also be discussed.

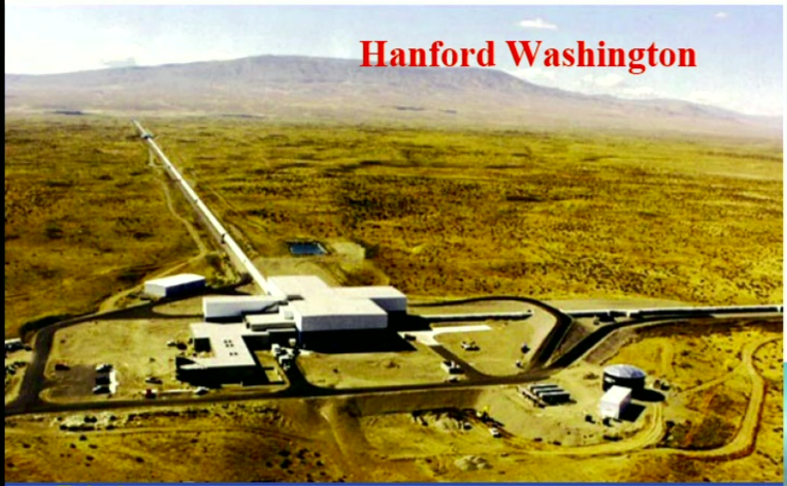
Zoom link

Dynamical Formation of Merging Black-Hole Binaries

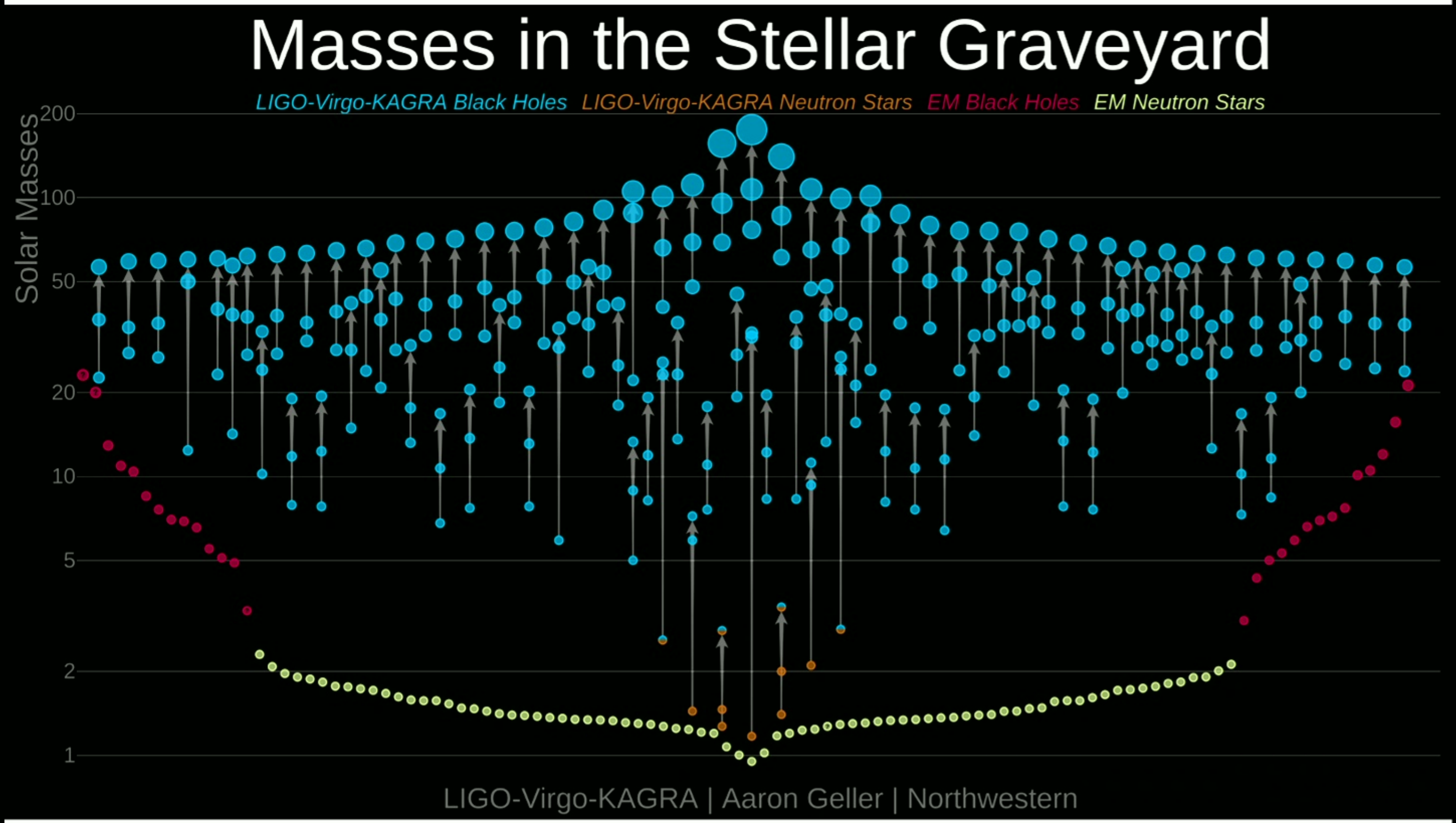
Dong Lai
Cornell University
& T-D Lee Institute (Shanghai)

Perimeter Institute Colloquium, 2/17/2024

The New Era of Gravitational Wave Astronomy

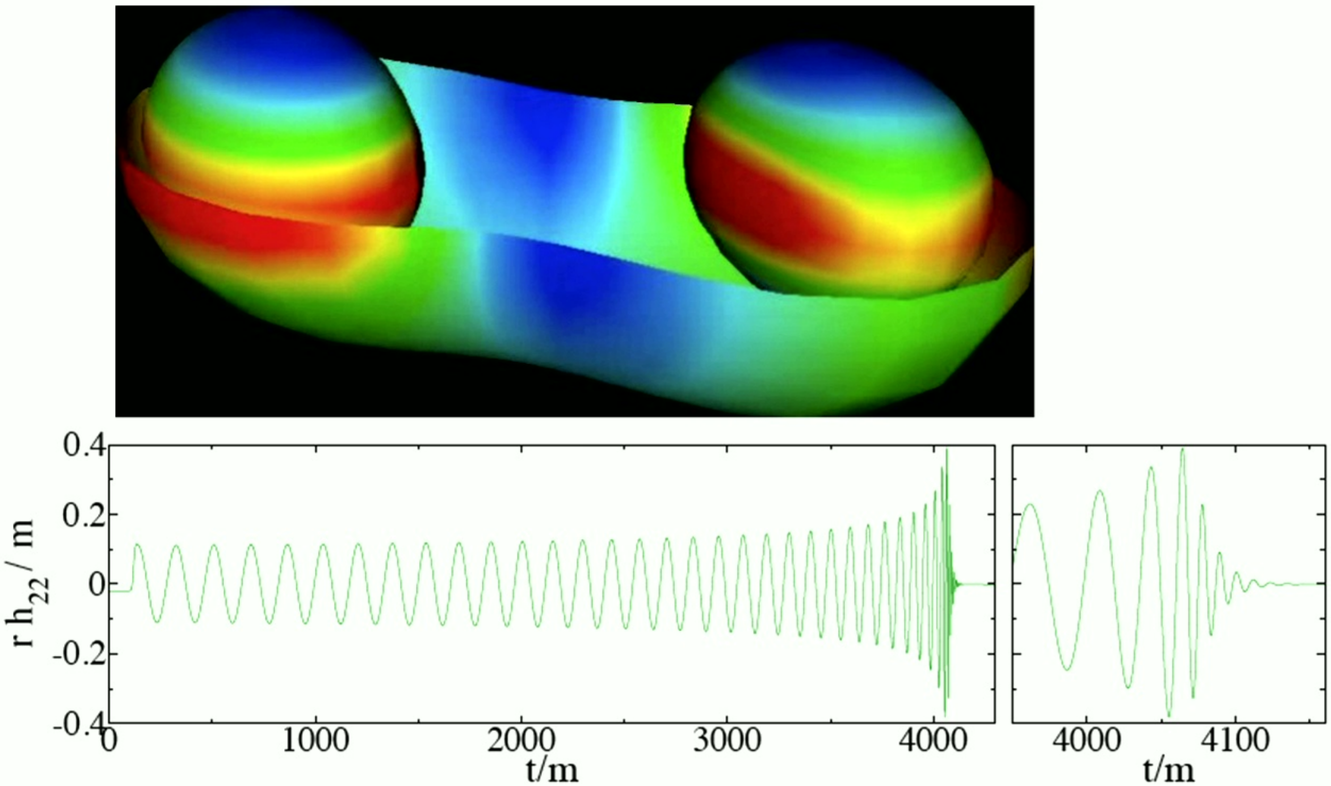


LIGO
VIRGO

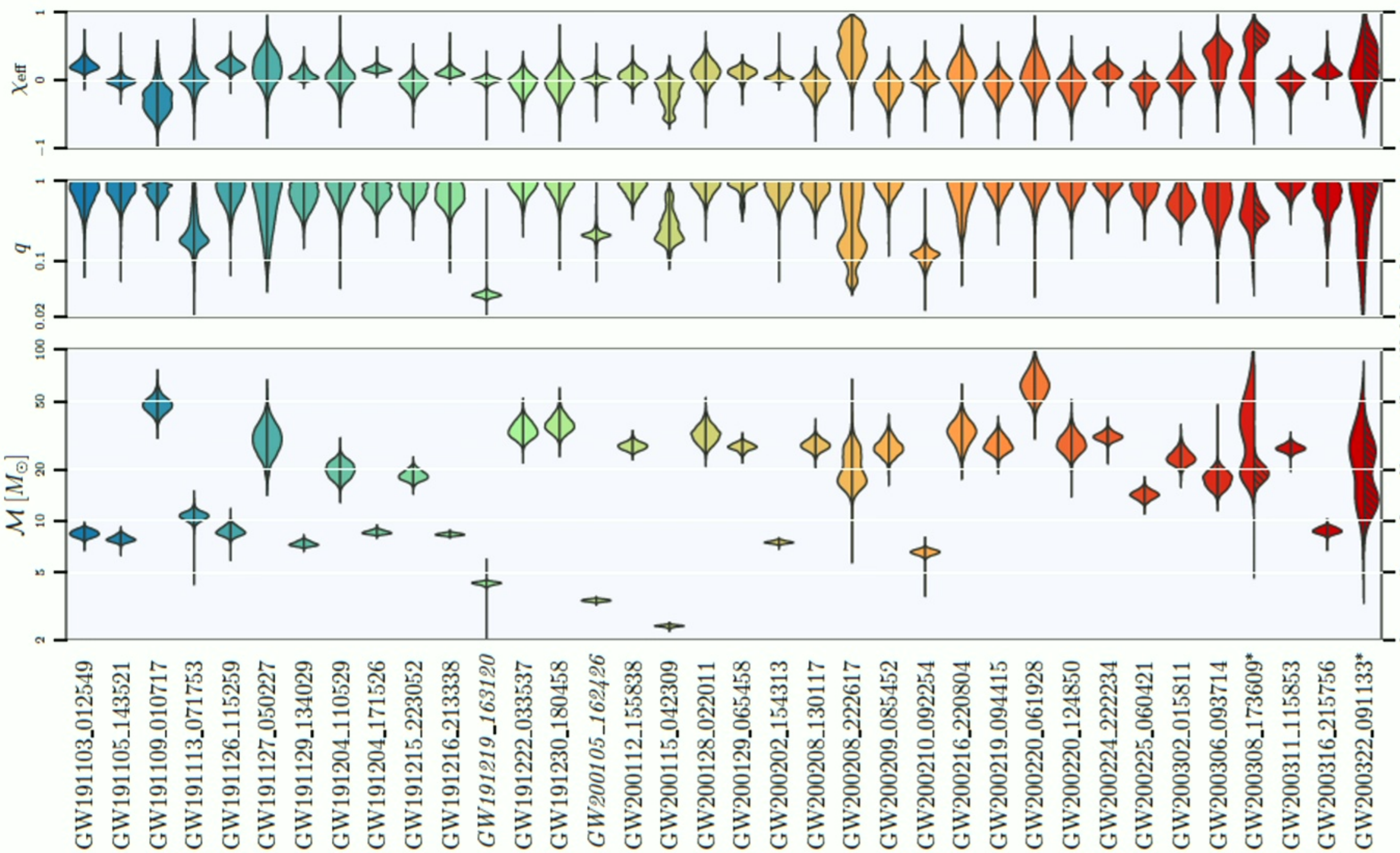


GWTC-3: 90 merger events, with 2 NS/NS mergers, 3 NS/BH mergers

BH-BH Merger



Cornell-Caltech collaboration



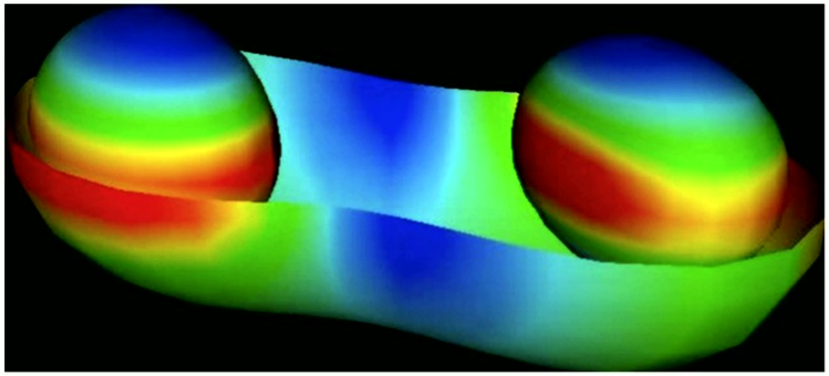
Gravitational waveform gives $M_1, M_2, \chi_{\rm eff}$

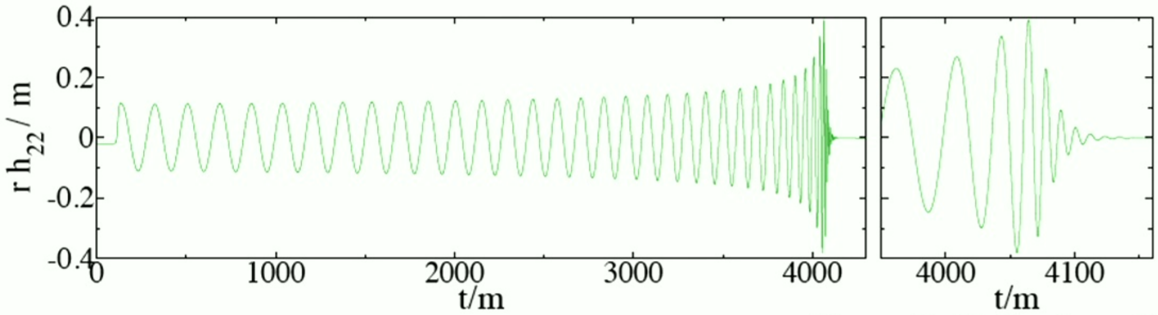
$$\chi_{\rm eff} \equiv \frac{m_1 \boldsymbol{\chi}_1 + m_2 \boldsymbol{\chi}_2}{m_1 + m_2} \cdot \hat{\mathbf{L}}$$

What to do with these GW detections?

1. Test gravity theory in nonlinear regime:

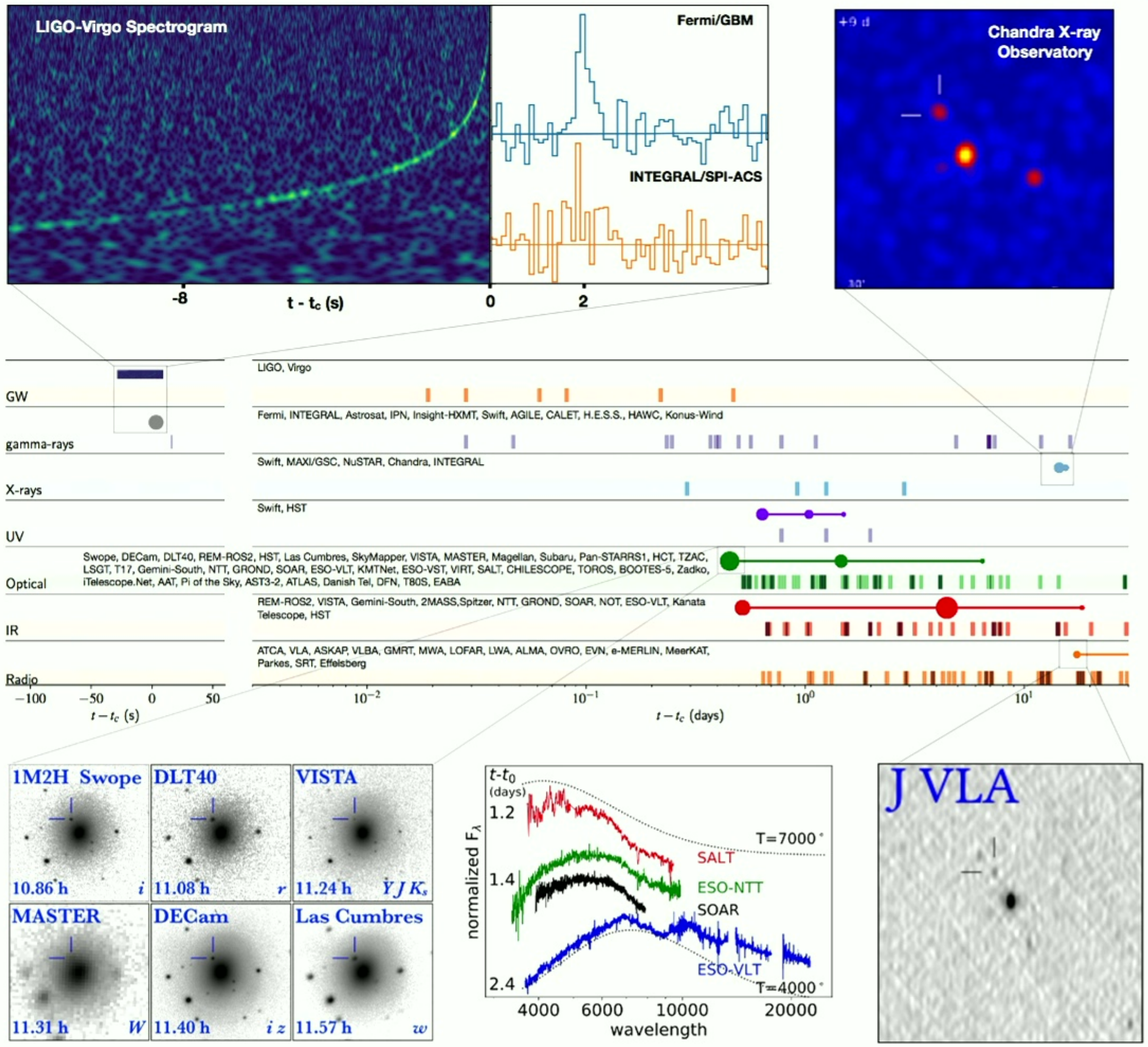
   so far, GR works "perfectly"





Cornell-Caltech collaboration

LIGO's first NS Binaries: GW170817 / AT2017gfo



What to do with these GW detections?

1. Test gravity theory in nonlinear regime
2. Study dense nuclear matter and nucleosynthesis
3. Astrophysics

Formation of Merging BH Binaries

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

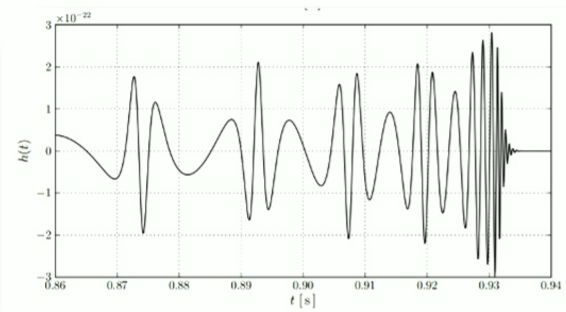
Formation Channels of Merging BH Binaries

-- 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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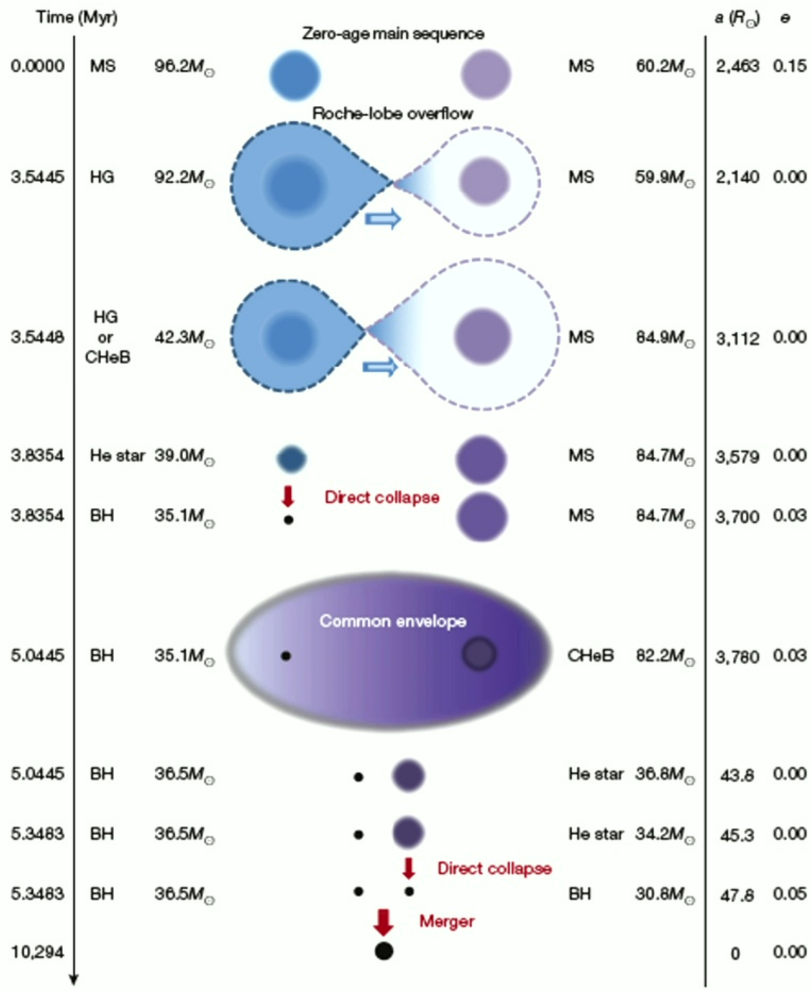
How to distinguish different channels?

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

Isolated Binary Evolution Channel: Standard



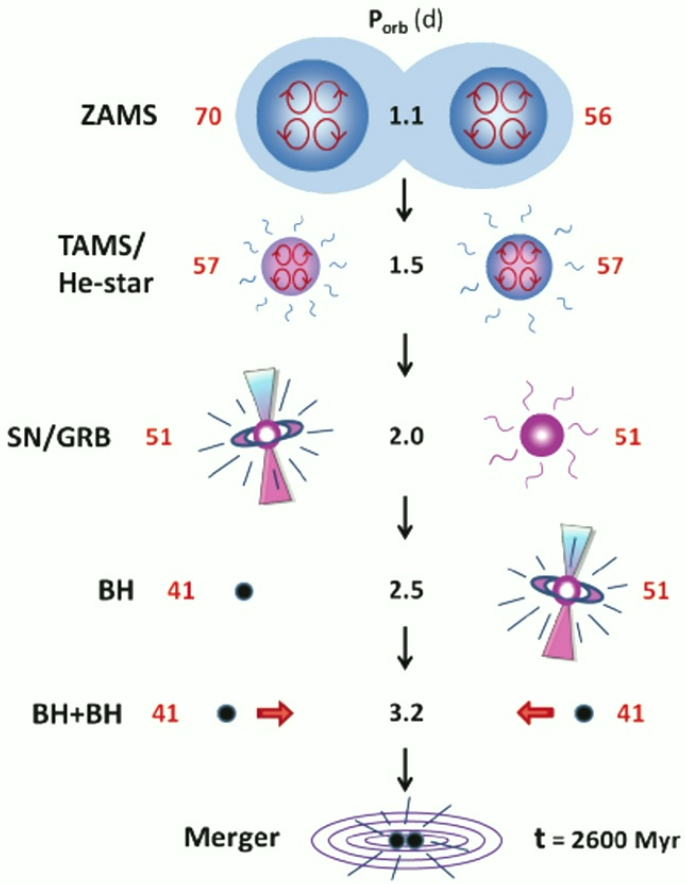
many papers, uncertain physical ingredients (e.g. common envelope)

Produce

circular orbit at 10 Hz
mostly aligned spin-orbit

Belczynski +16

Isolated Binary Evolution Channel:
Chemically homogeneous evolution



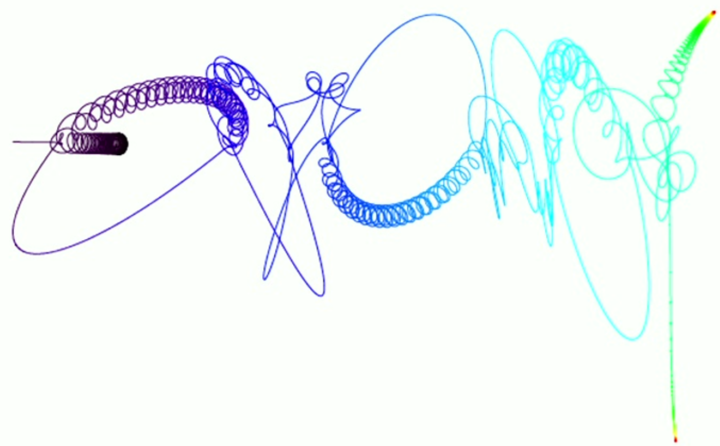
Produce
- **circular orbit at 10 Hz**
- **mostly aligned spin-orbit**

Merchant, Langer et al. 2016
Mandel & de Mink 2016

Dynamical Formation Channels

several flavors…

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

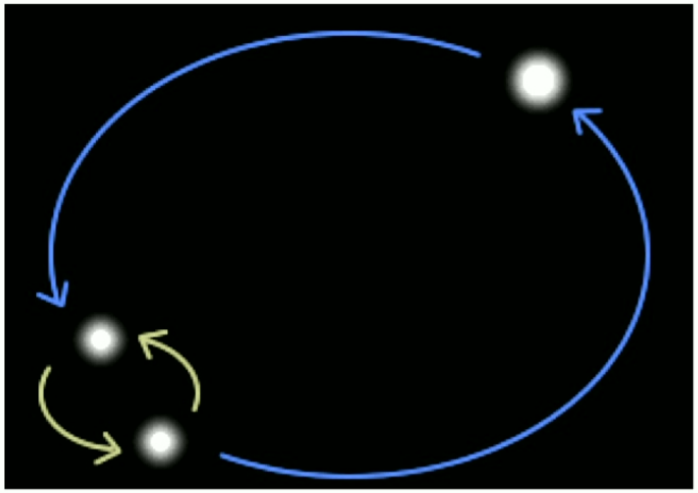
several flavors…

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
→ Zhejiang U.)

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...

Summary of Tertiary-Induced Mergers
Some implications/predictions:

1. Residual eccentricity at 10 Hz: a few % have e ~0.1-0.2

2. Broad spin-orbit angles, peak around 90 degrees

3. In galactic field (induced by another star):
   unequal-mass mergers are more likely (other factors being equal)
   maybe constrained by LIGO data

4. In nuclear star cluster (induced by SMBH):
   SMBH spin affects the LK dynamics: prefer high SMBH spin

Liu & Lai 2017-2022
Liu, Lai, Wang 2019a,b
Su & DL 2021a,b

Lidov-Kozai Effect

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

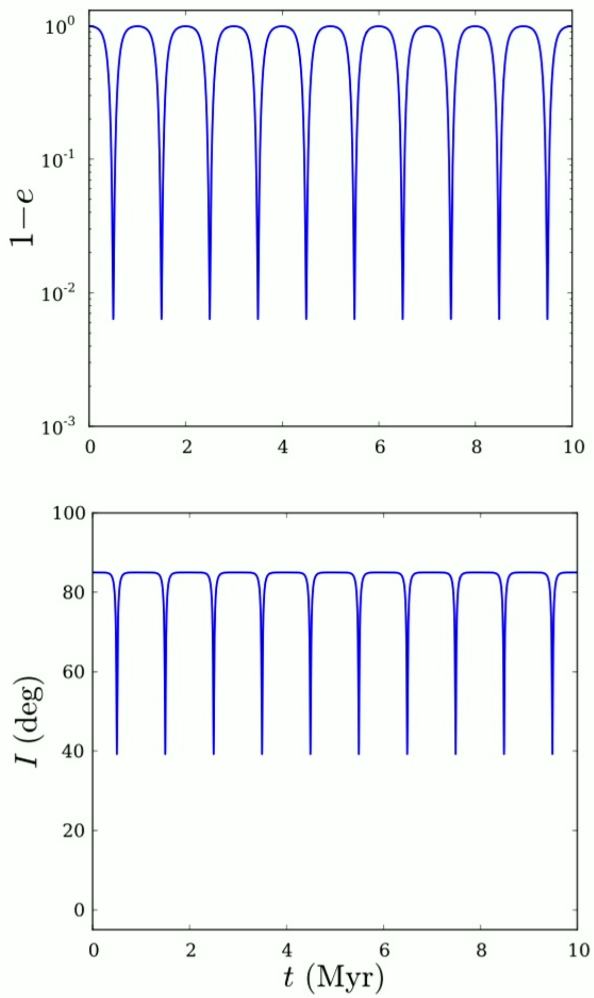
Planet. Space Sci., 1962, Vol. 9, pp. 719 to 759. Pergamon Press Ltd. Printed in Northern Ireland

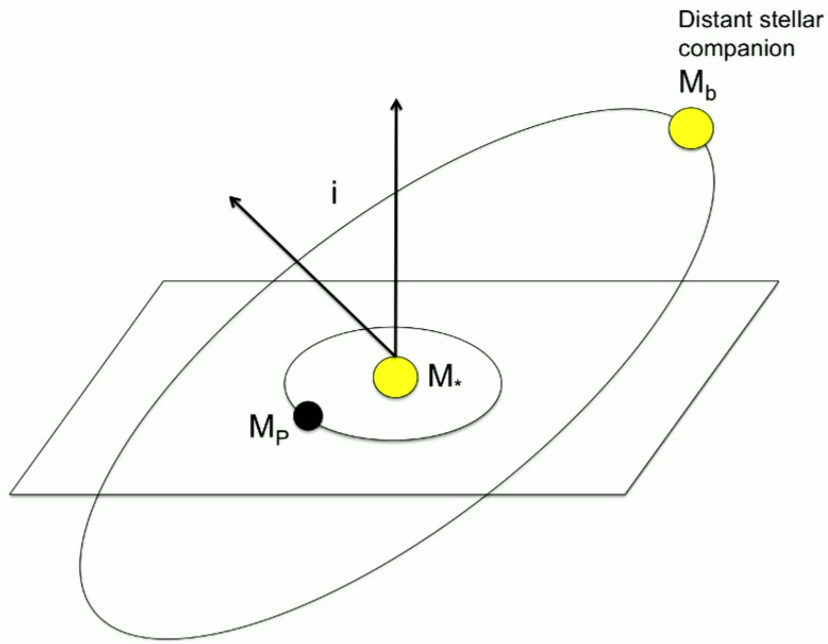
THE EVOLUTION OF ORBITS OF ARTIFICIAL SATELLITES OF PLANETS UNDER THE ACTION OF GRAVITATIONAL PERTURBATIONS OF EXTERNAL BODIES

M. L. LIDOV

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

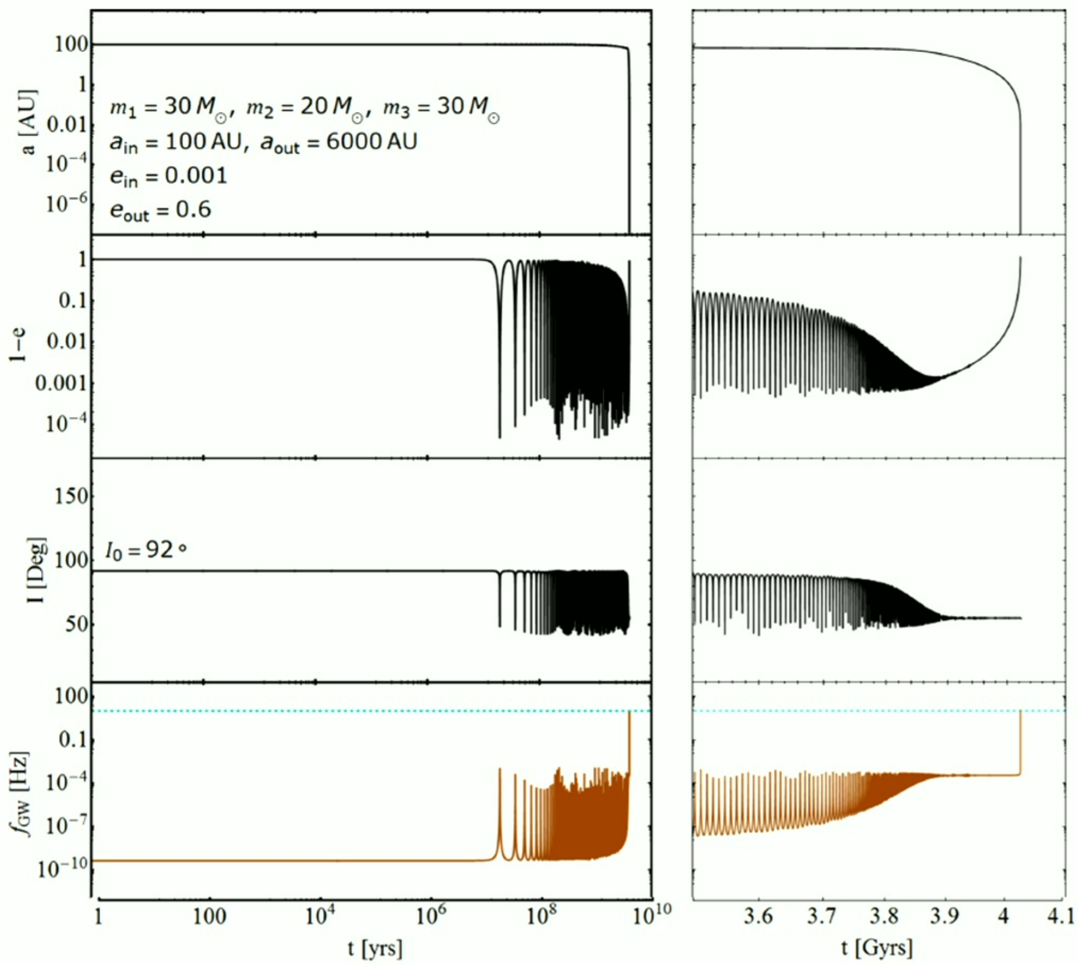
Lidov-Kozai Effect





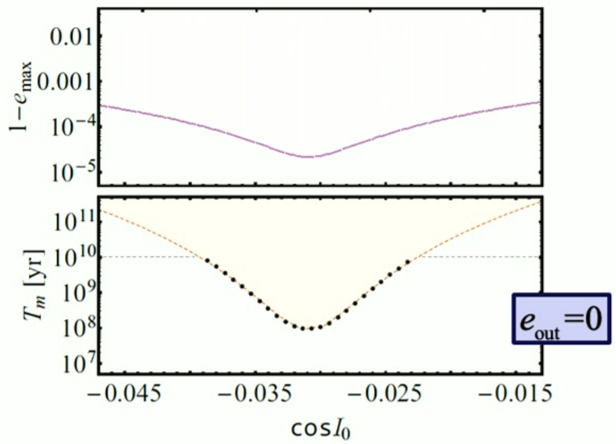
- Eccentricity and inclination oscillations induced if i > 40 degrees.
- If i large (85-90 degrees), get extremely large eccentricities (e > 0.99)

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

Octupole effect makes orbital evolution “chaotic”:

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

Inclination window for merger

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

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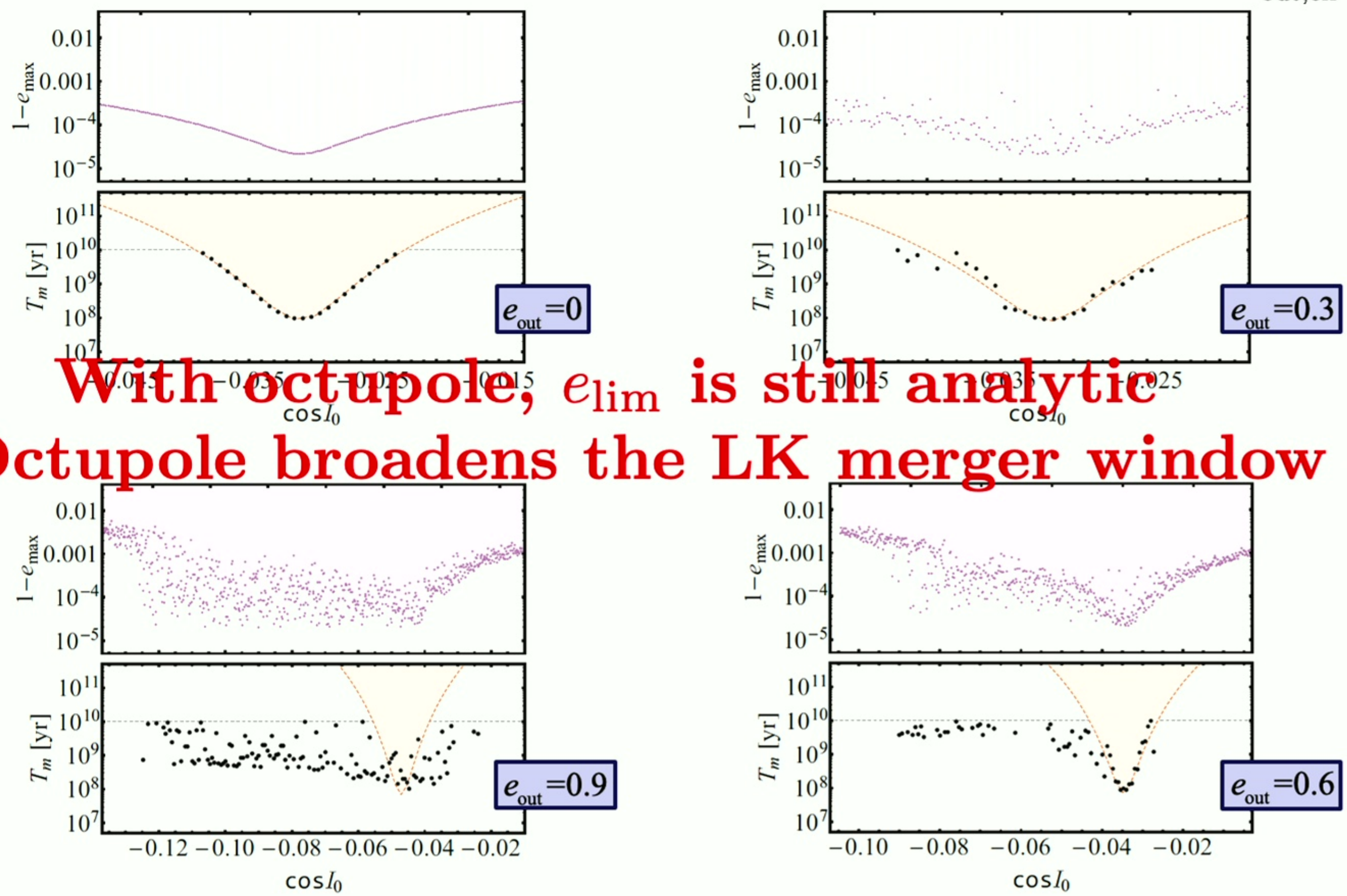


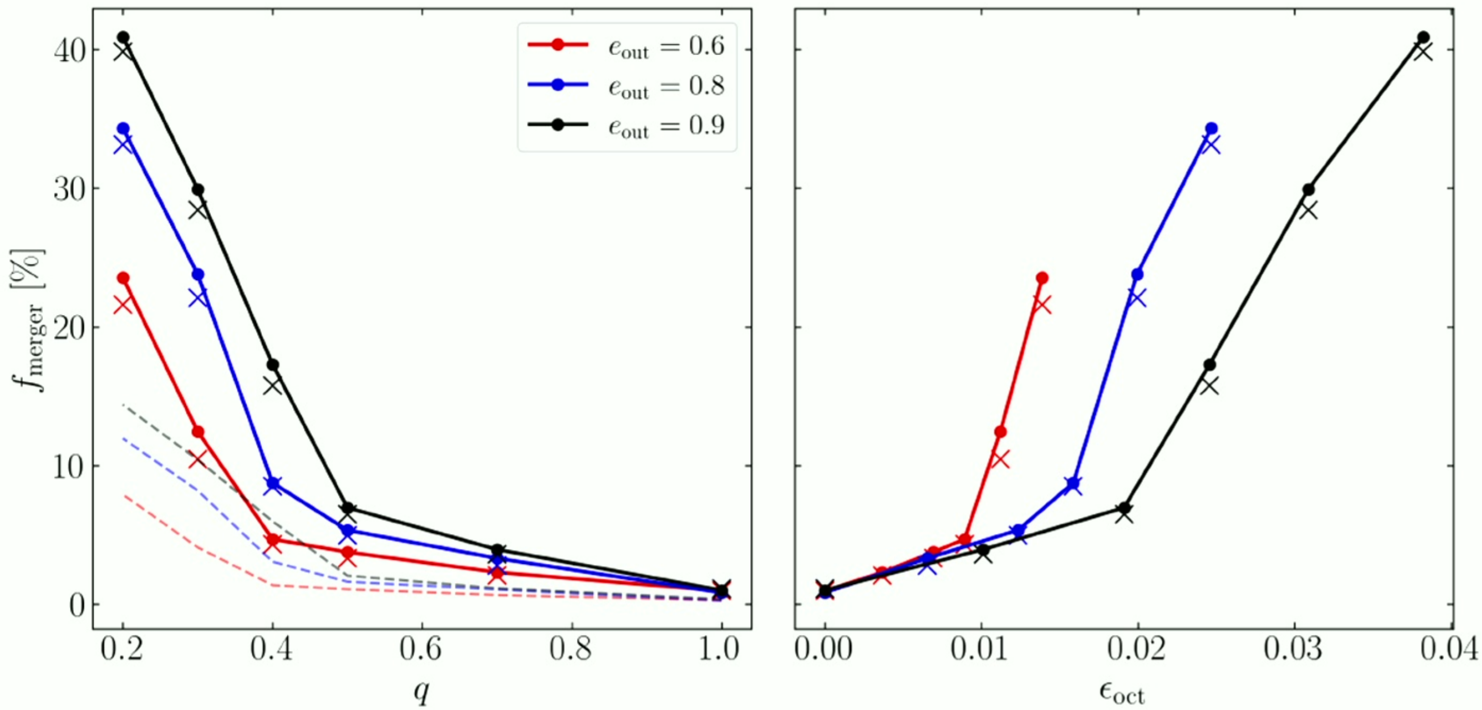
With octupole, $e_{\rm lim}$ is still analytic

Octupole broadens the LK merger window

Octupole effect depends on

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

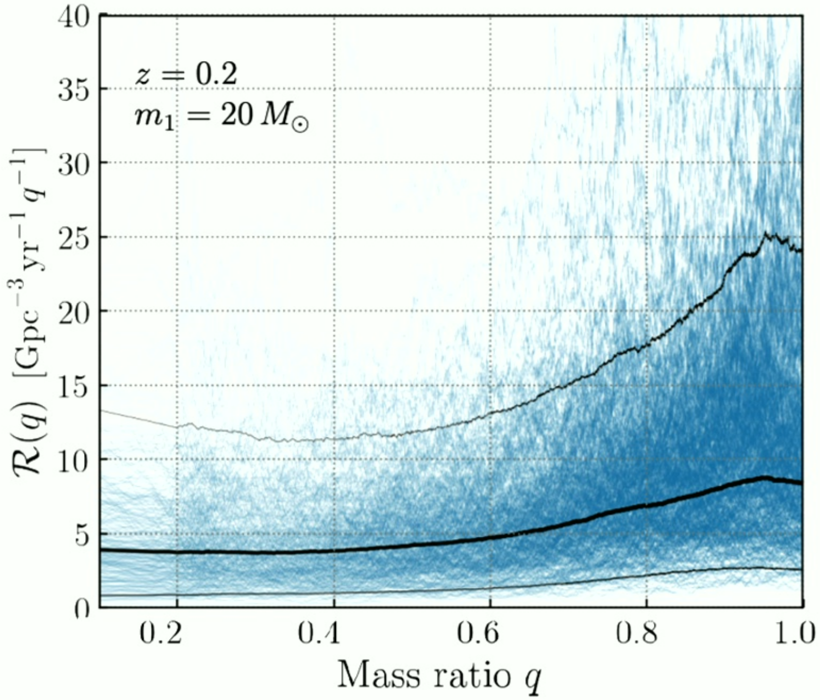
➔ Large $e_{\rm out}$ and/or small $q = m_2/m_1$ increases merger window



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

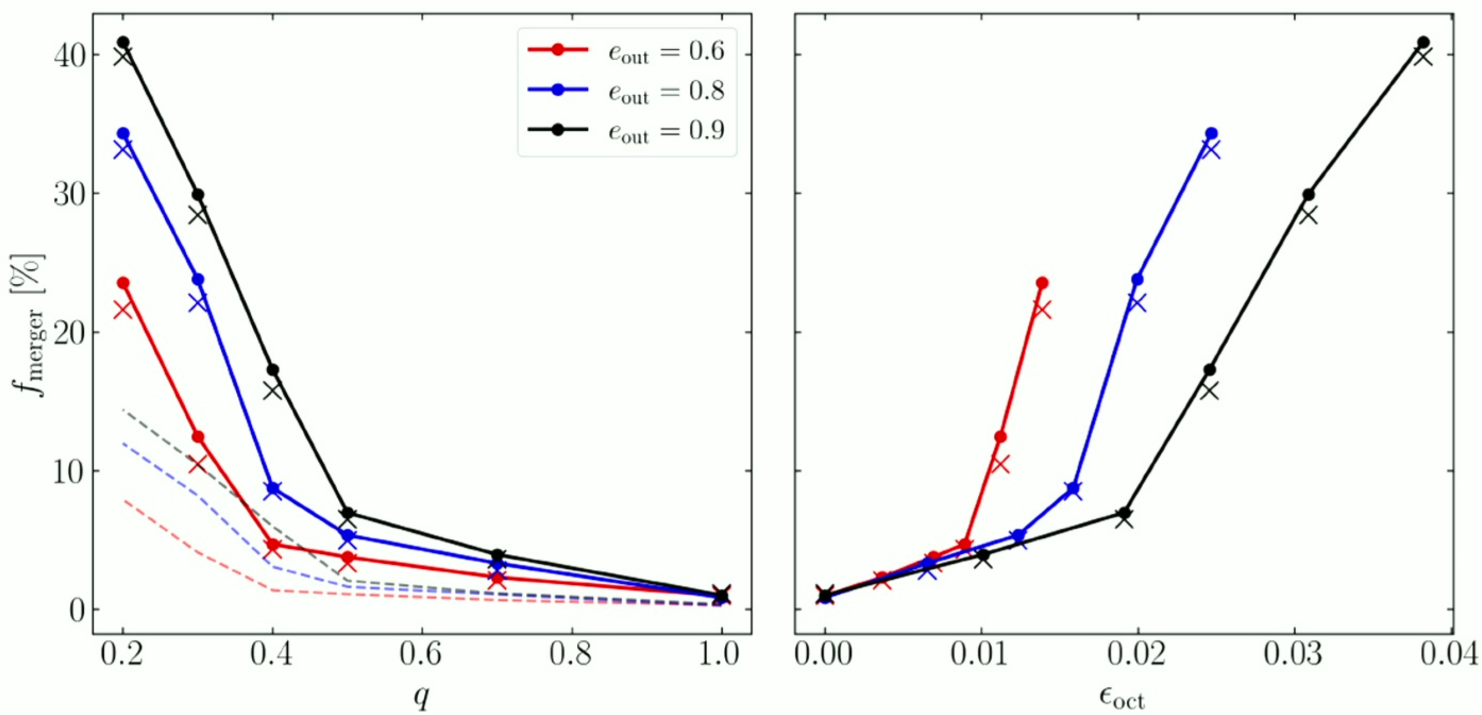
Su et al. 2021

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



Callister & Farr 2023

-- Maybe incompatible with data if octupole effect is strong
-- Depends on the initial q-distribution of BH binaries.



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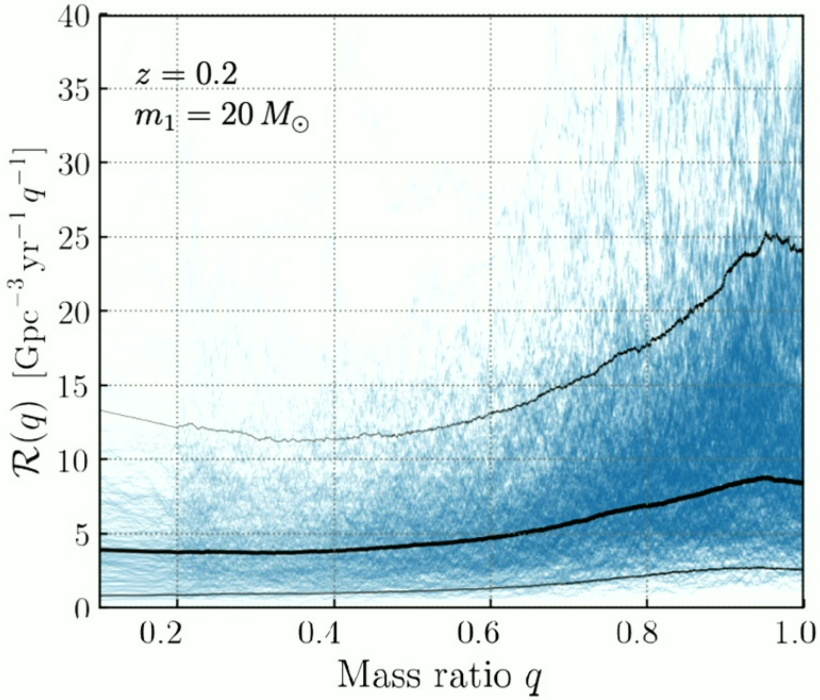

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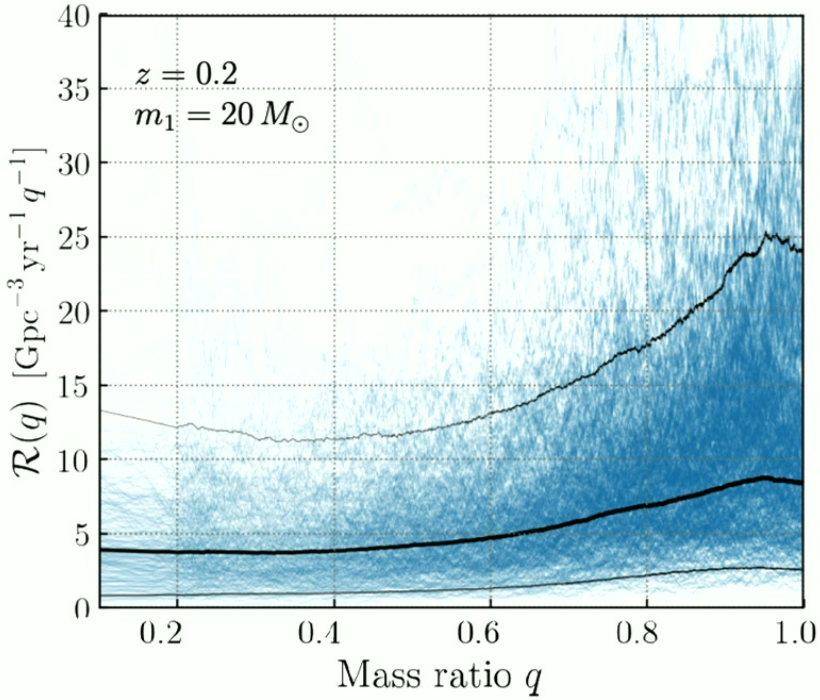

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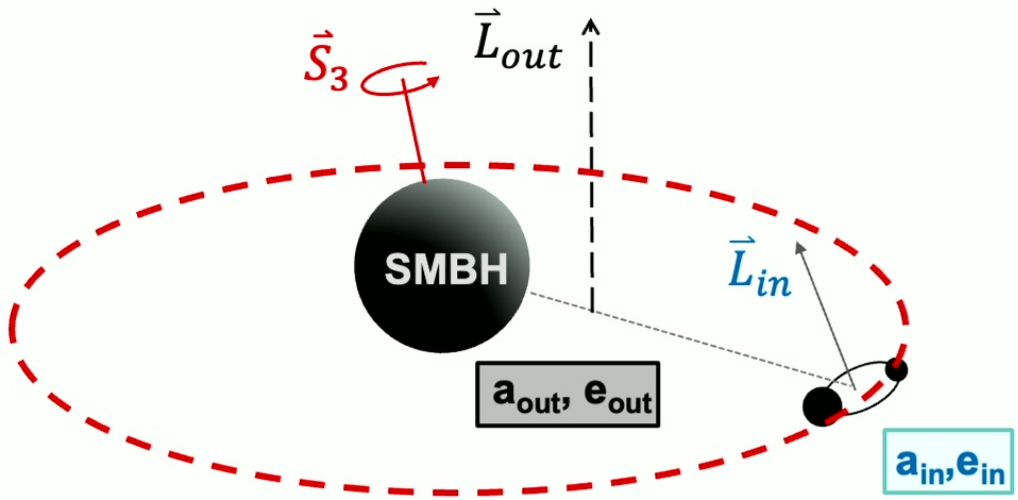
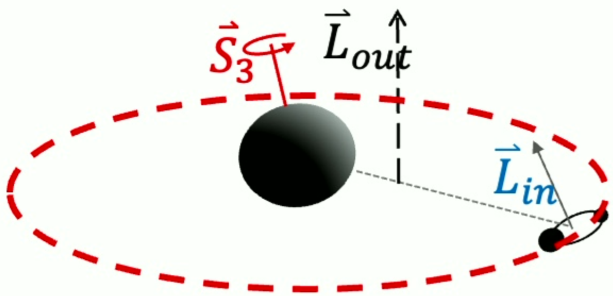
What happens if the tertiary is a Supermassive BH ?



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

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

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

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

--- 1.5 PN

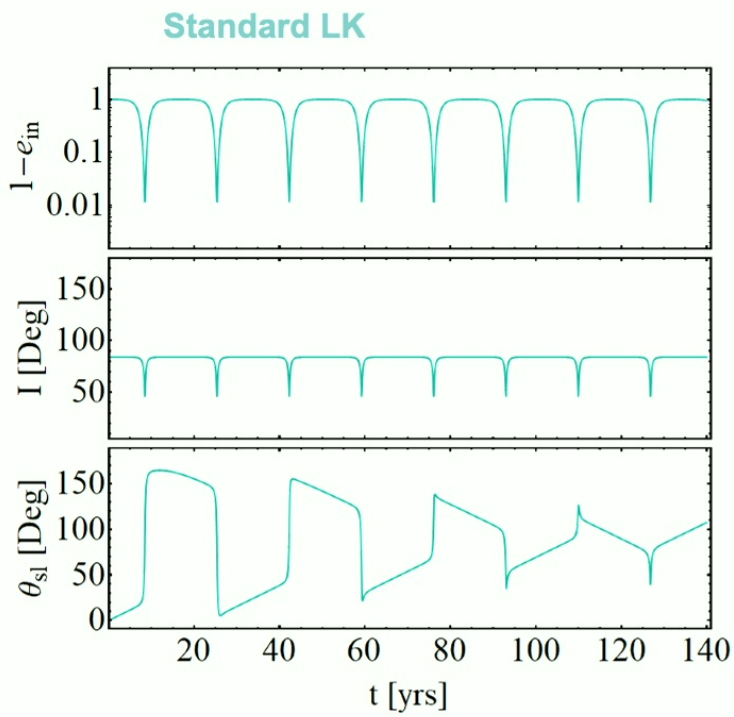
$$\begin{cases} \left.\frac{d\mathbf{L}_{\mathrm{out}}}{dt}\right|_{\mathrm{L_{out}S_3}} = \Omega_{\mathrm{L_{out}S_3}} \hat{\mathbf{S}}_3 \times \mathbf{L}_{\mathrm{out}}, \\ \left.\frac{d\mathbf{e}_{\mathrm{out}}}{dt}\right|_{\mathrm{L_{out}S_3}} = \Omega_{\mathrm{L_{out}S_3}} \hat{\mathbf{S}}_3 \times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

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

--- 2 PN

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

Evolution Example



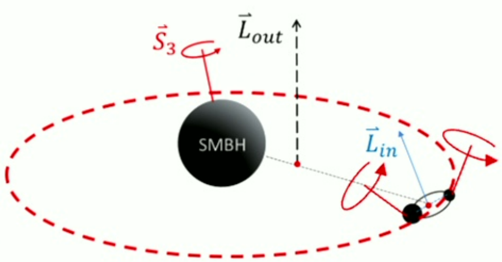
System Parameters:

$(m_1, m_2, m_3) = (30, 20, 2.3 \times 10^9)\ M_\odot$

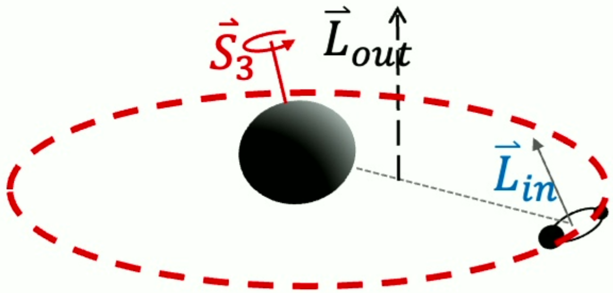
$(a_{in,0}, a_{out}) = (0.1, 500)$ AU

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

$I_0 = 84^\circ$



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



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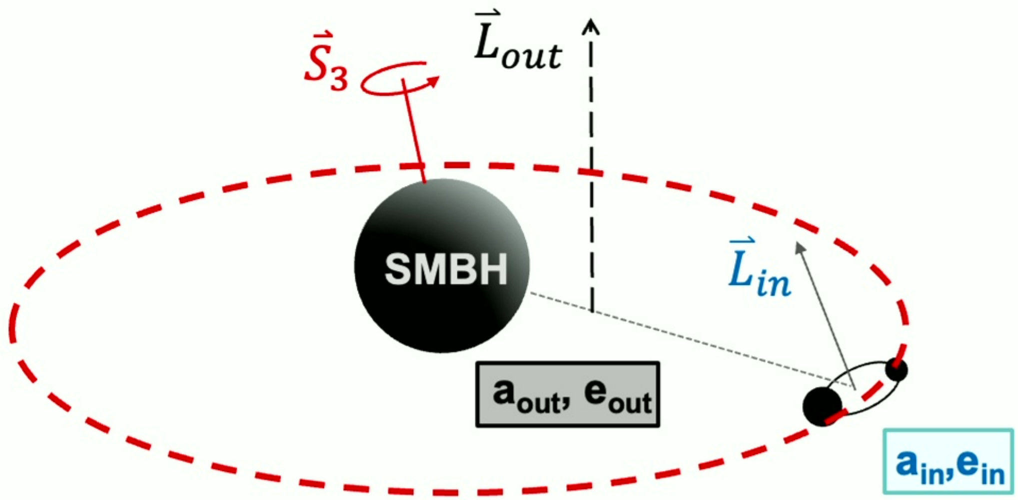

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Relativistic Effects induced by the SMBH

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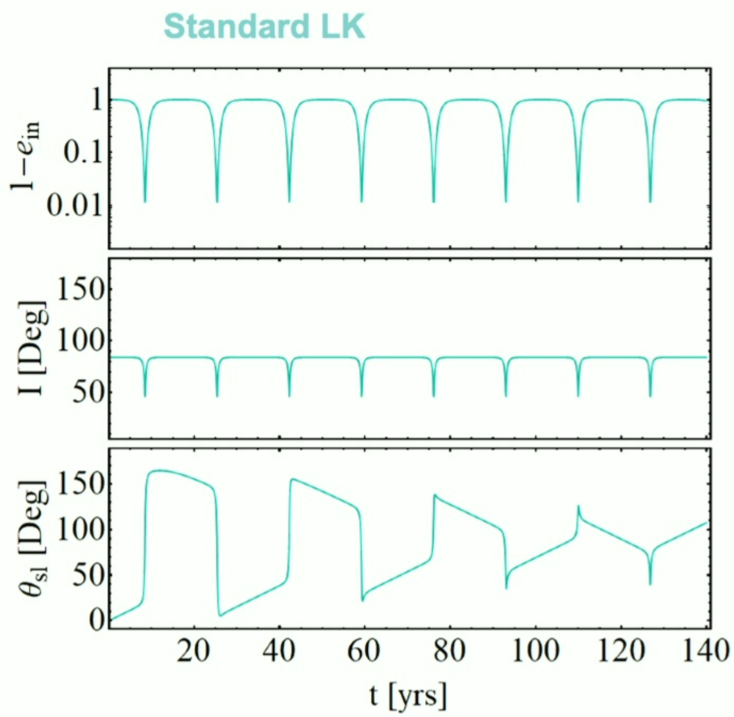

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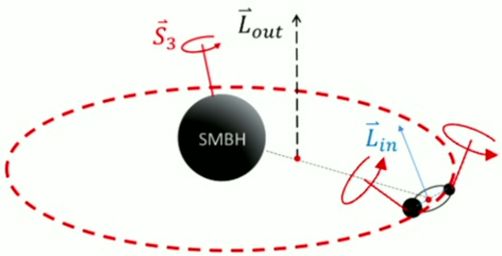
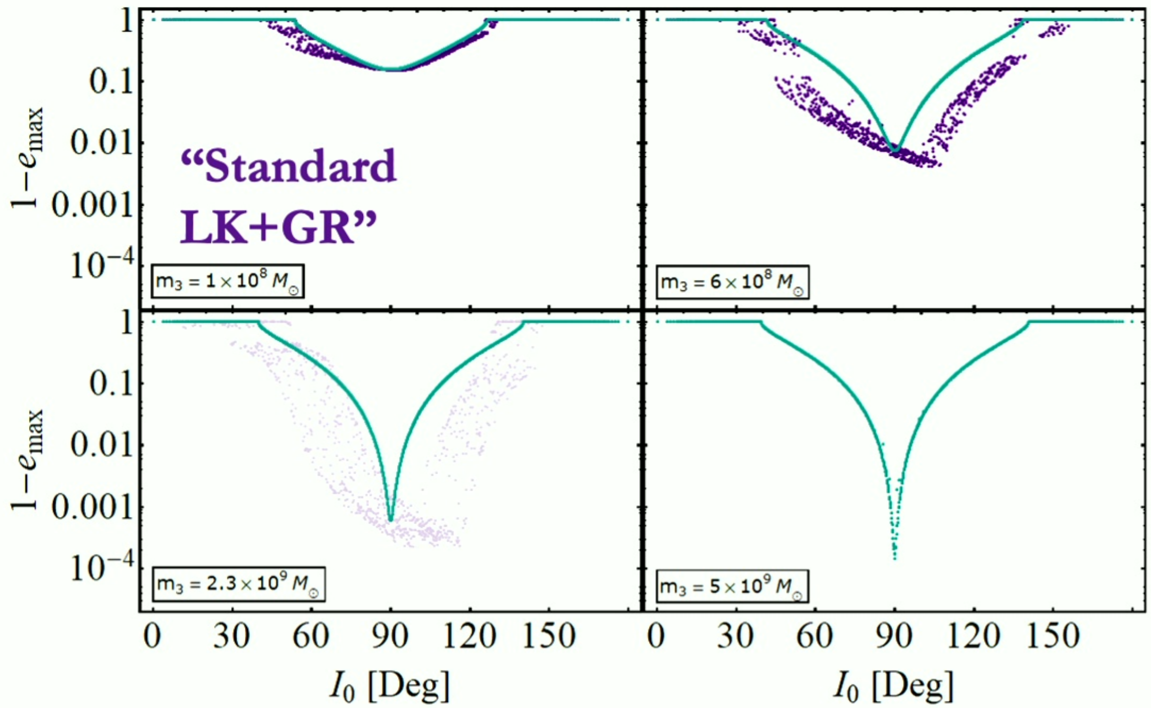


Eccentricity Excitation

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



==> GR effects broaden the merger window

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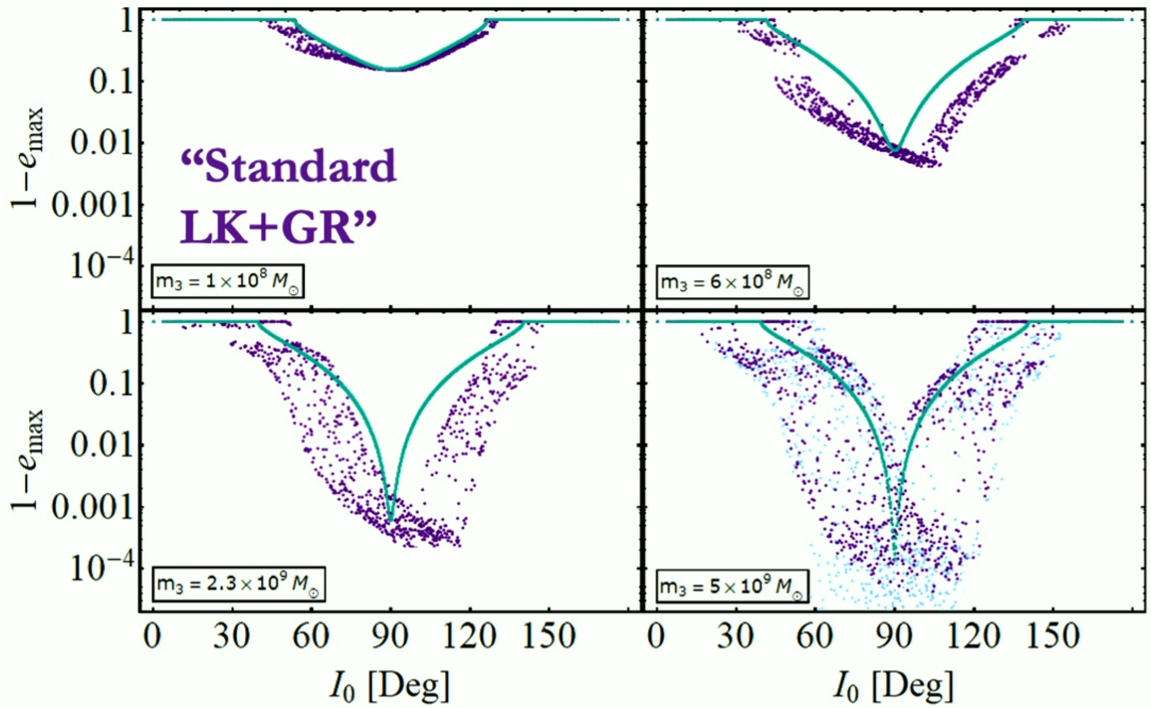
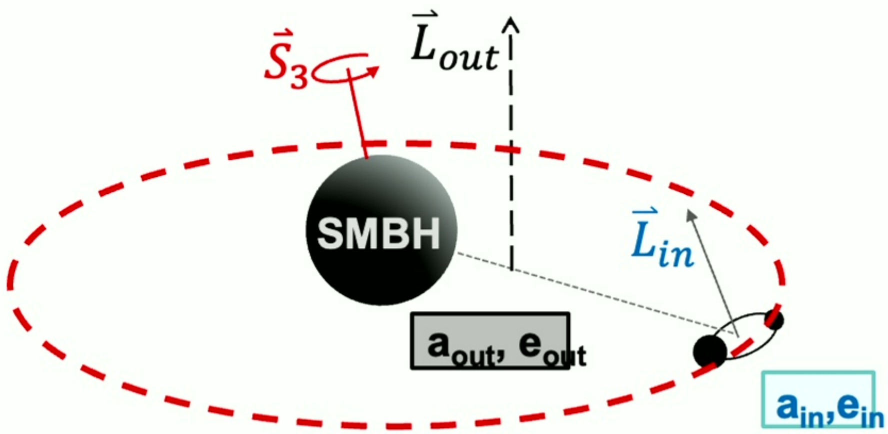


==> GR effects broaden the merger window

GR effects broaden Merger window: Why?

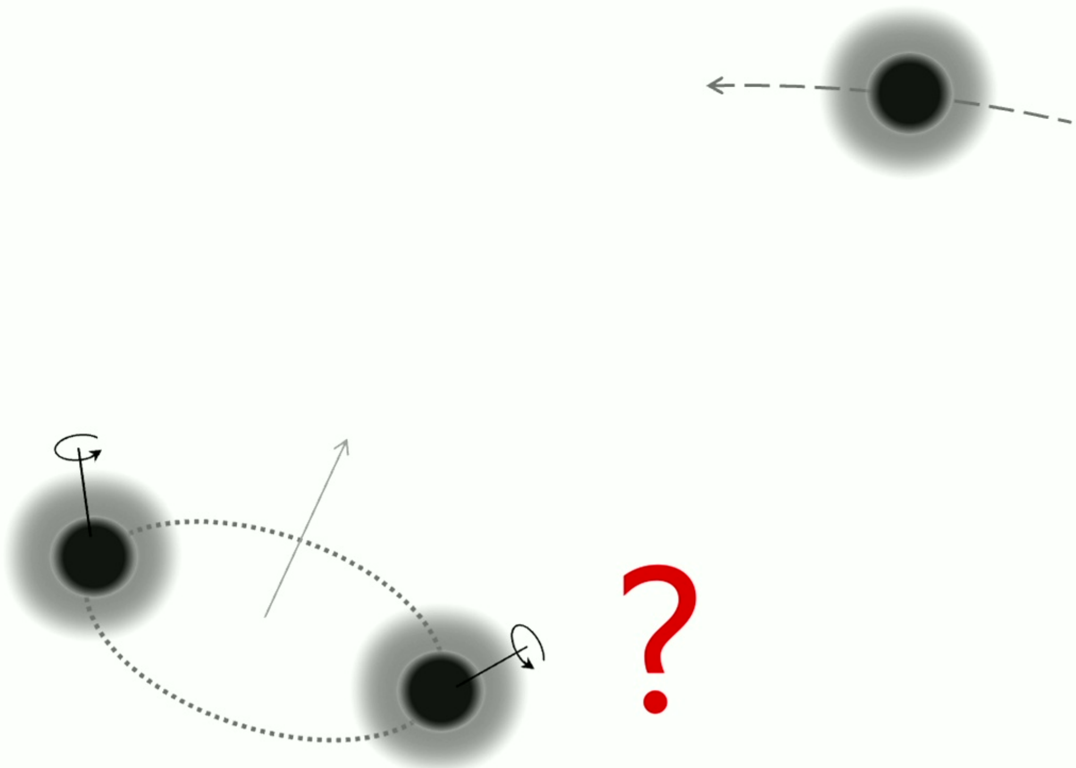
Inclination Resonance

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



Mutual inclination is excited when the two precession rates are equal

What about the BH Spins of merging BHs?



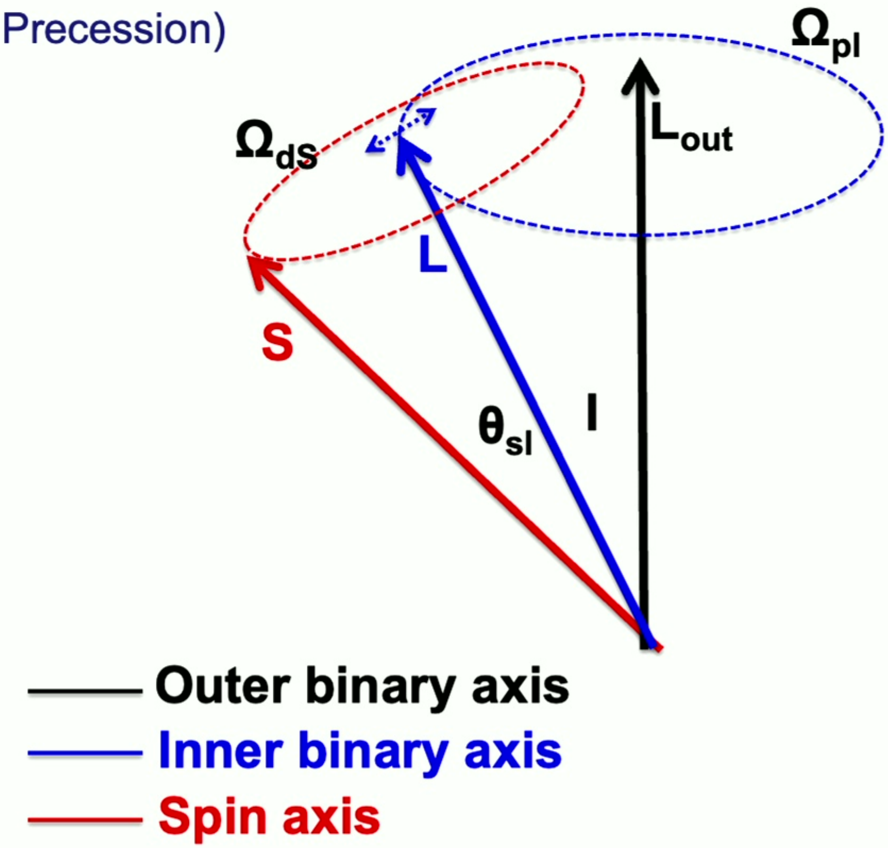
BH spin dynamics during LK oscillations

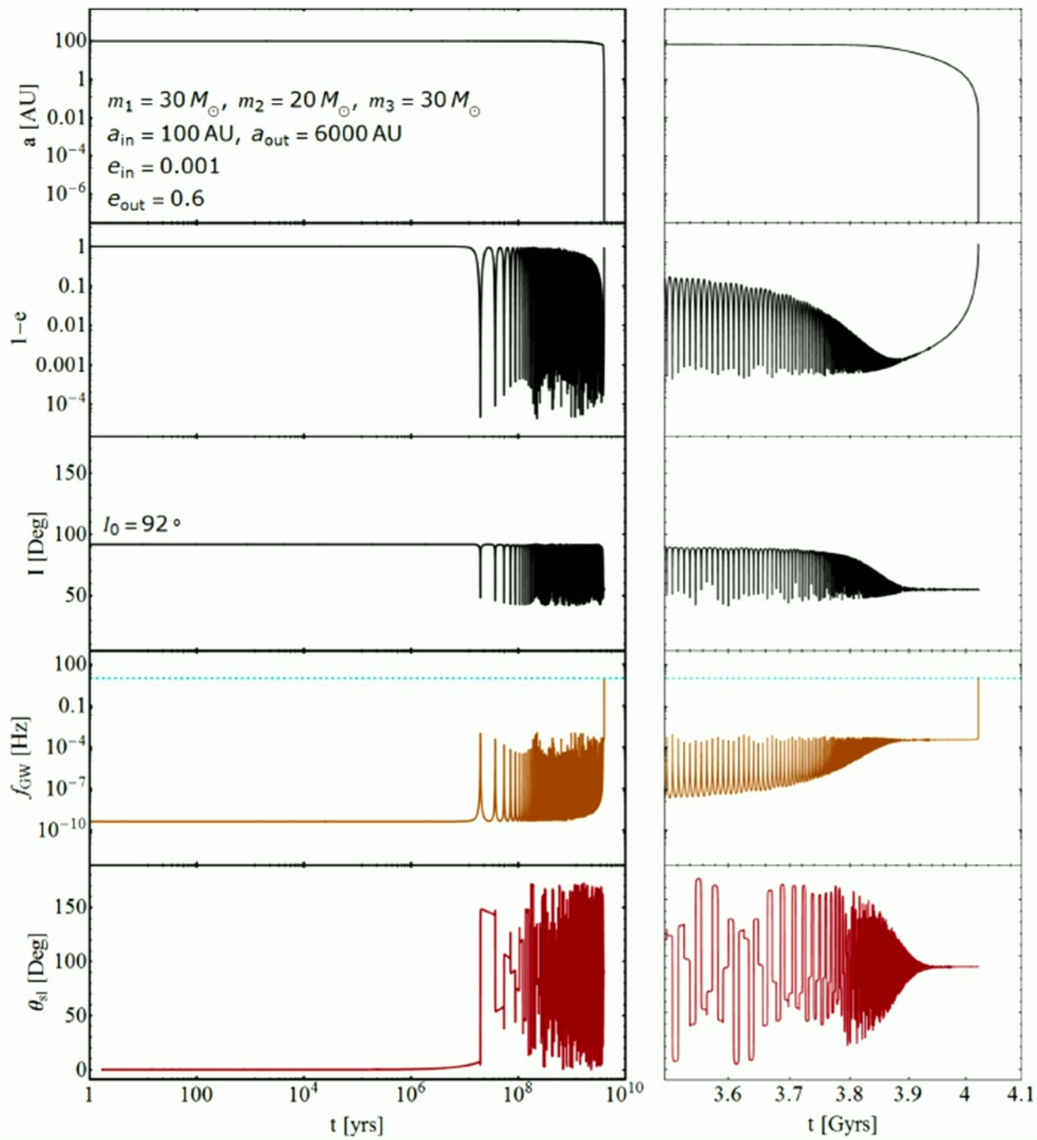
$$\frac{d\hat{\mathbf{S}}_1}{dt} = \Omega_{\rm dS}\hat{\mathbf{L}} \times \hat{\mathbf{S}}_1$$ (de Sitter Precession)

$$\Omega_{dS} = \frac{3Gn\left(m_2 + \mu/3\right)}{2c^2 a\left(1-e^2\right)}$$

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

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



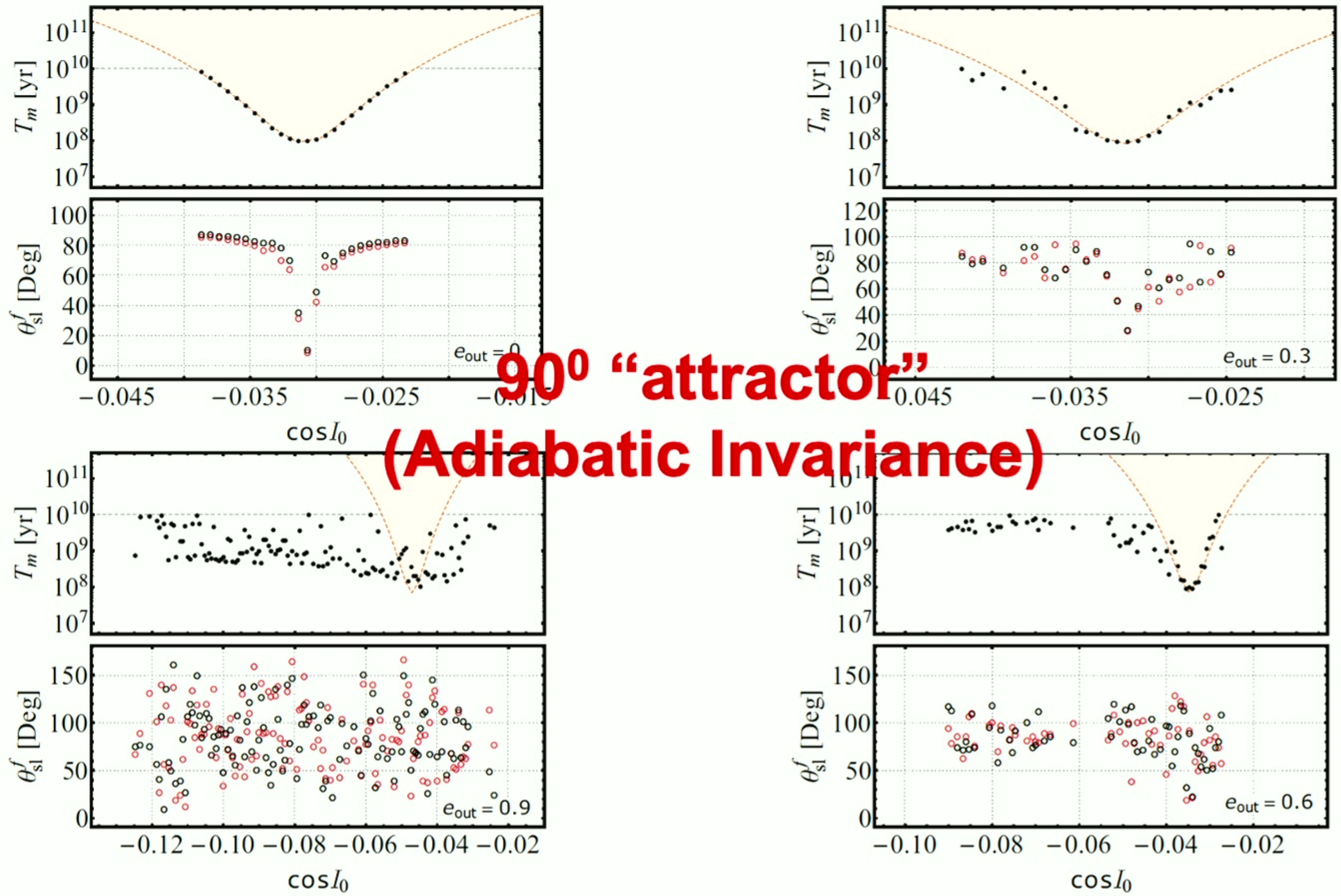


$m_1 = 30\,M_\odot,\ m_2 = 20\,M_\odot,\ m_3 = 30\,M_\odot$
$a_{in} = 100\,AU,\ a_{out} = 6000\,AU$
$e_{in} = 0.001$
$e_{out} = 0.6$
$I_0 = 92°$
a [AU]
1−e
I [Deg]
f_{GW} [Hz]
θ_{sl} [Deg]
t [yrs]
t [Gyrs]

Merger Window and Final Spin-Orbit Misalignments

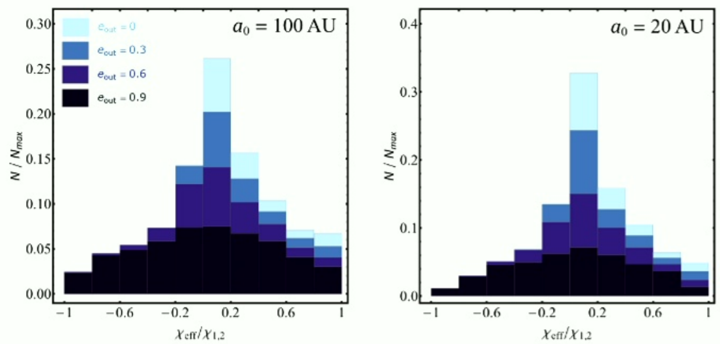
Fixed inner binary: $m_1=30M_\odot$, $m_2=20M_\odot$, $a_{in,0}=100AU$

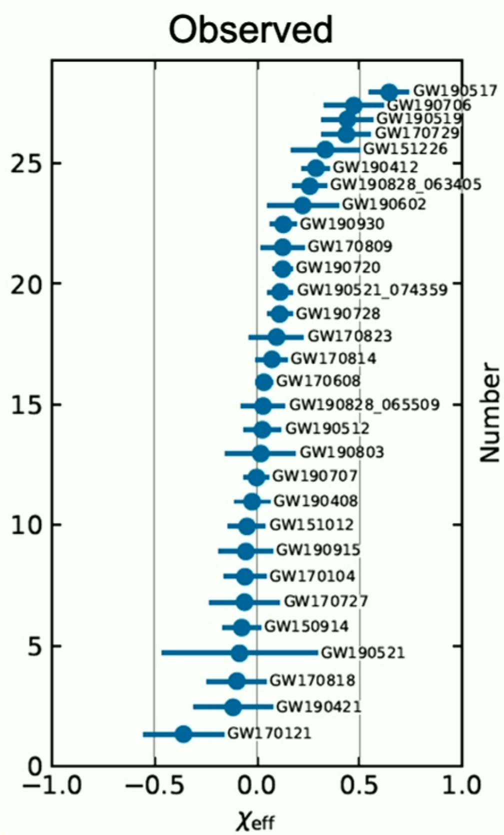
Fixed m_3/a_{out}^3 value



Effective Spin Distribution

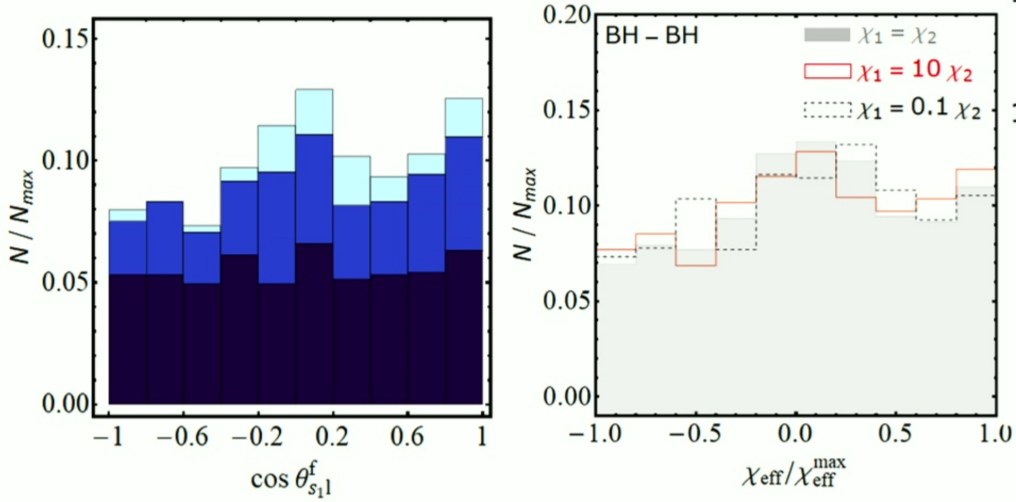
For "some" initial binary/triple parameters (e_0=0, distant companions)





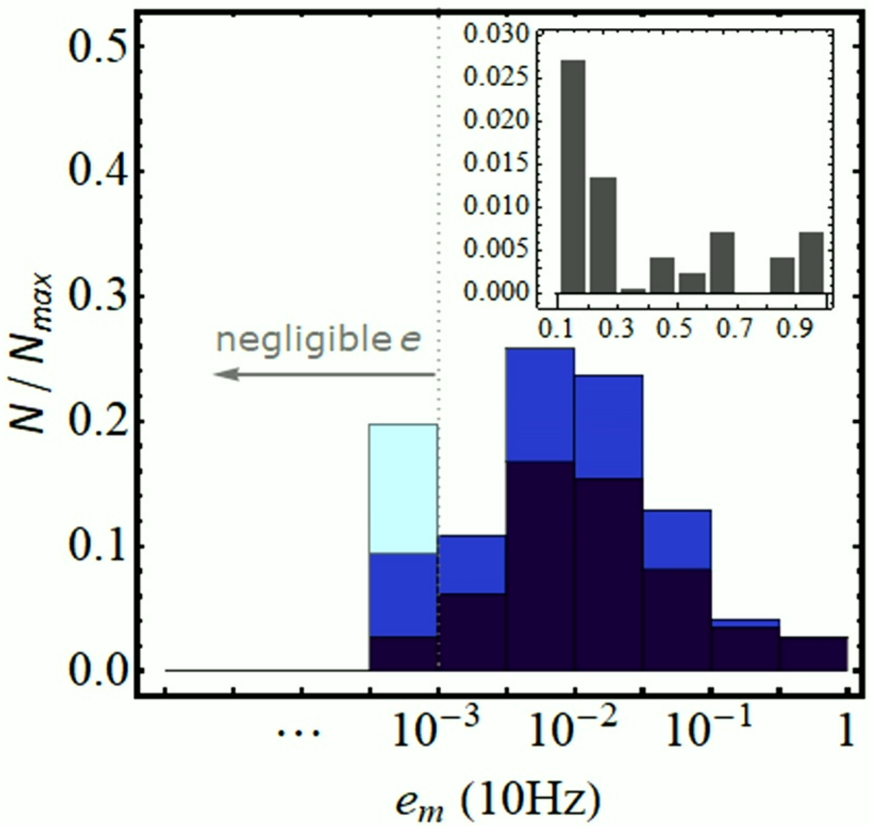
Roulet et al. 2021

Consider ALL possible parameters



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

Summary of Tertiary-Induced Mergers
Some implications/predictions:

1. Residual eccentricity at 10 Hz: a few % have e ~0.1-0.2

2. Broad spin-orbit angles, peak around 90 degrees

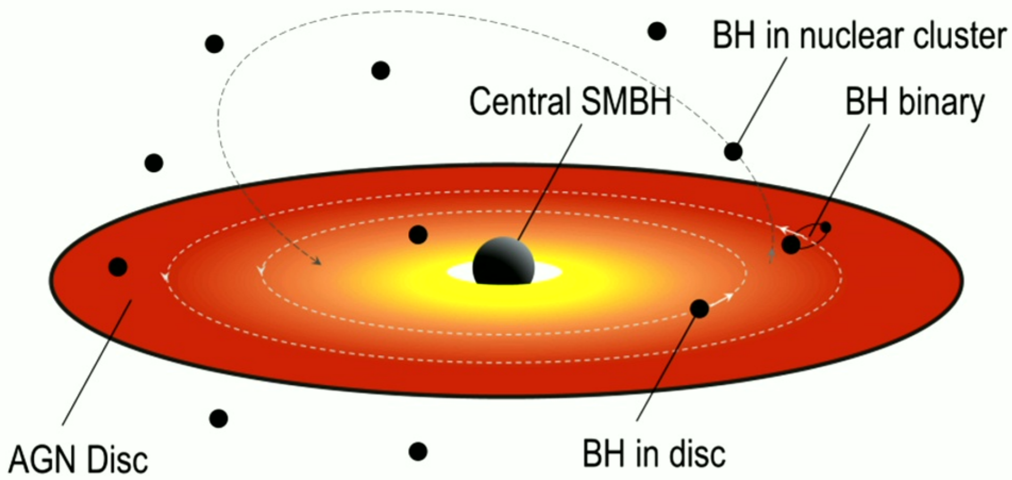
3. In galactic field (induced by another star):
   unequal-mass mergers are more likely (other factors being equal)
   maybe constrained by LIGO data

4. In nuclear star cluster (induced by SMBH):
   SMBH spin affects the LK dynamics: prefer high SMBH spin

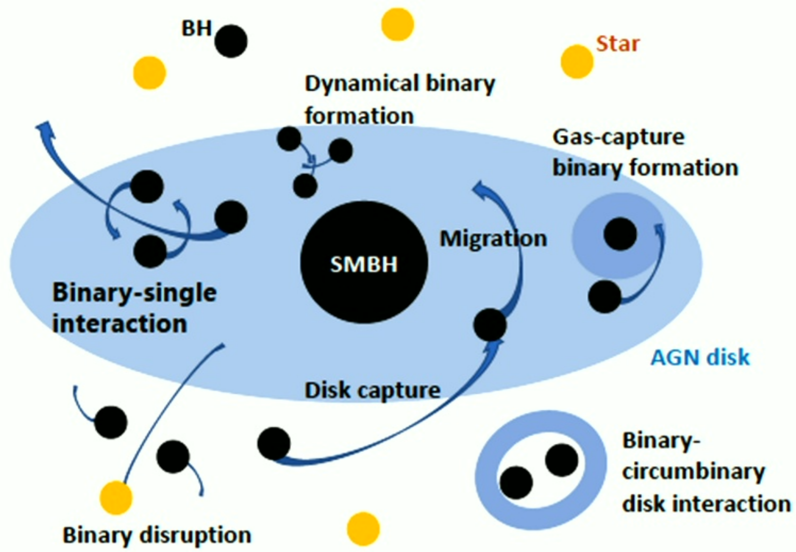
Liu & Lai 2017-2022
Liu, Lai, Wang 2019a,b
Su & DL 2021a,b

Dynamical Formation Channel:

3. Binary BH Mergers in AGN (Active Galactic Nuclei) disks



Dynamical Formation Channel:
3. Binary BH Mergers in AGN (Active Galactic Nuclei) disks



Tagawa+20

Several merger scenarios…

Previous works: Bellovary+16, Bartos+16, Stone+17, McKernan+18, Secunda+18, Yang+19, Tagawa+20…

AGN channel merger scenarios:

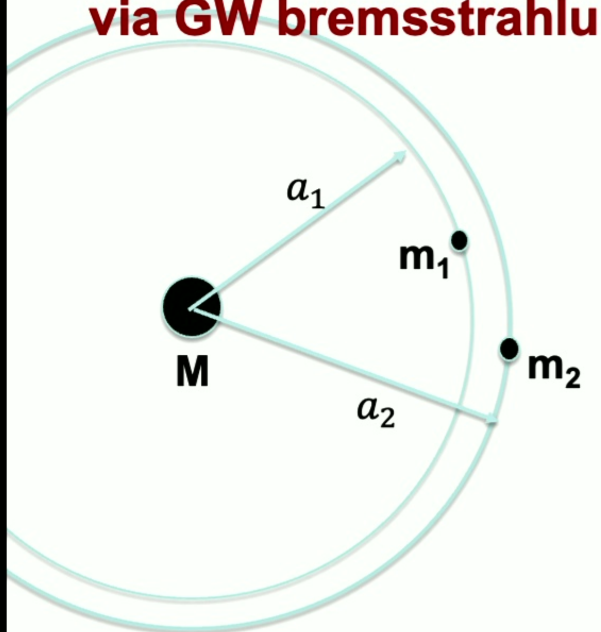
(leading to different "predictions")

-- Gas-free (essentially) mergers

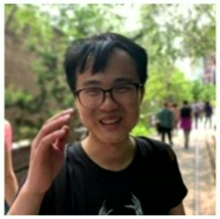
AGN disk helps to bring BHs to a plane…

-- Gas-assisted mergers

Gas-free single-single "collision"
via GW bremsstrahlung



Li, Lai & Rodet 2022
Also: Rom, Sari & Lai 2024



Jiaru Li, Cornell Ph.D.23
➔ Northwestern

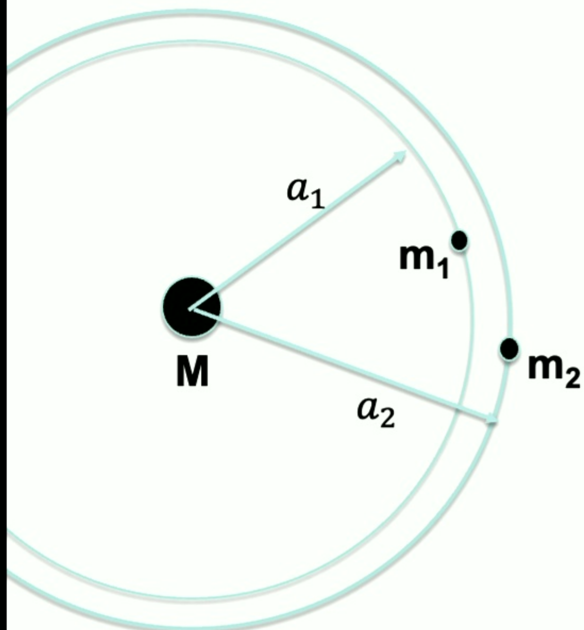
Two BHs (m_1, m_2) on closely-packed, nearly circular, nearly-coplanar orbits around a SMBH (M) (e.g. brought together by migration in AGN disks

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?



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 $\frac{GMm_{1,2}}{a} \gg \frac{Gm_1m_2}{a}, \frac{Gm_1m_2}{R_{\rm H}}$

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

For VERY close encounter:

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

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

Capture radius for forming "permanent" binary due to GW bremsstrahlung

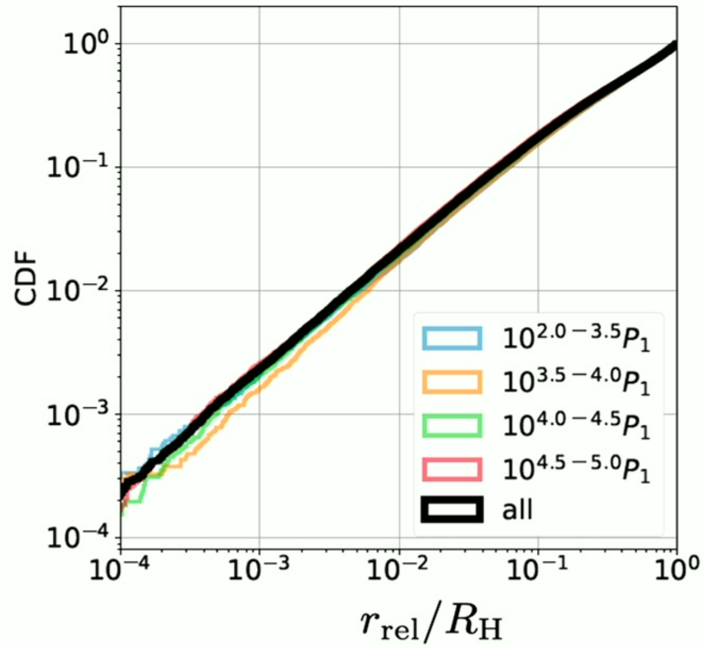
How likely/often does this happen?
(loss cone problem…)

Probability of very close encounters (with separation $< r_{\rm rel} \ll R_{\rm H}$)

$$P(< r_{\rm rel}) \simeq \frac{r_{\rm rel}}{R_{\rm H}}$$

$$\Longleftrightarrow \quad \frac{\mathrm{d}P}{\mathrm{d}\,l_{\rm rel}} \propto l_{\rm rel}$$

$$l_{\rm rel} \simeq \sqrt{2m_{12}r_{\rm rel}}$$



Two BHs get captured into a (very eccentric) binary
via GW bremsstrahlung

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

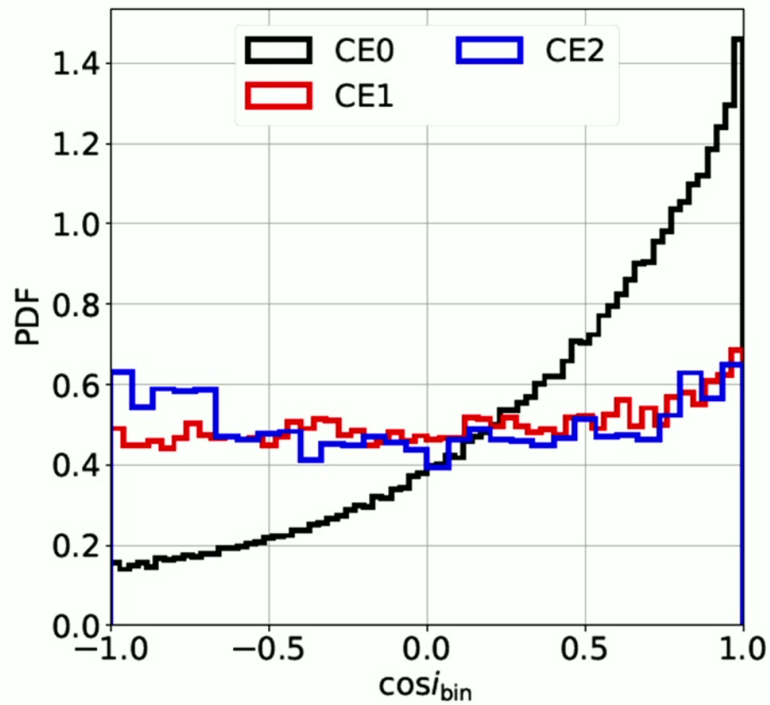
Once captured, it will take a few orbital period to merge
it enters LIGO band with $e \gtrsim 0.1$

This mechanism always produces eccentric mergers

Li, Lai & Rodet 2022
Rom, Sari & Lai 2024

Broad (~isotropic) orientations of binary orbit wrt AGN disk

➔ broad spin-orbit angles

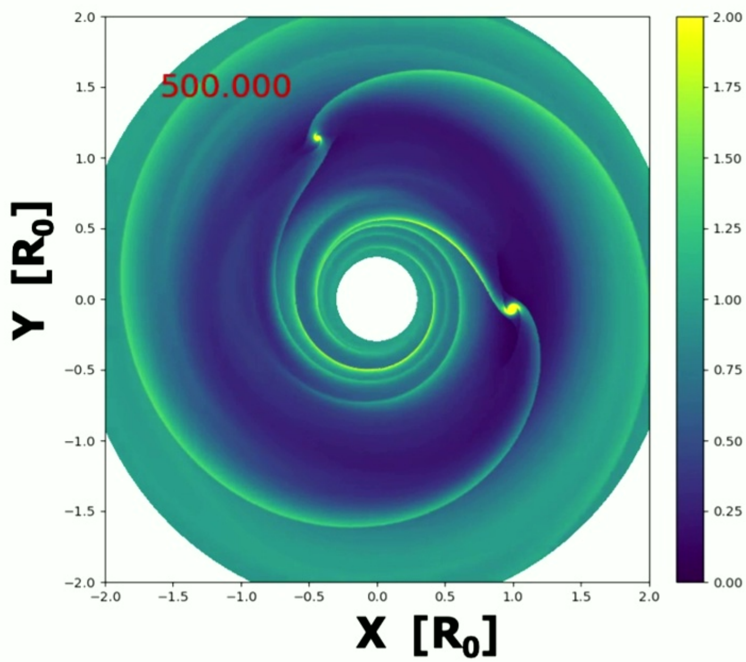


Blue: close encounters with separation < $10^{-2} R_H$

Note: Non-zero initial mutual inclination makes a hugh difference.
(mutual inclination grows to R_H/a)

Gas Effects: Formation of BH binaries
hydrodynamics simulations

Jiaru Li … Hui Li's LANL group… 2023

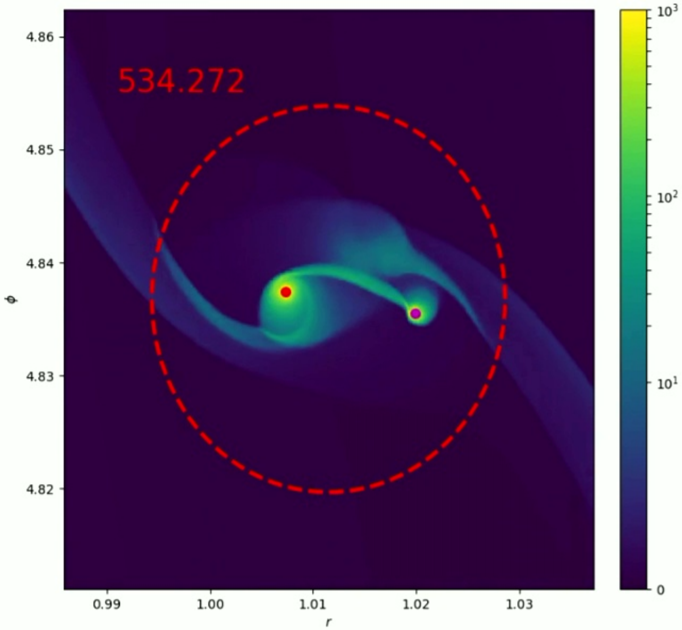


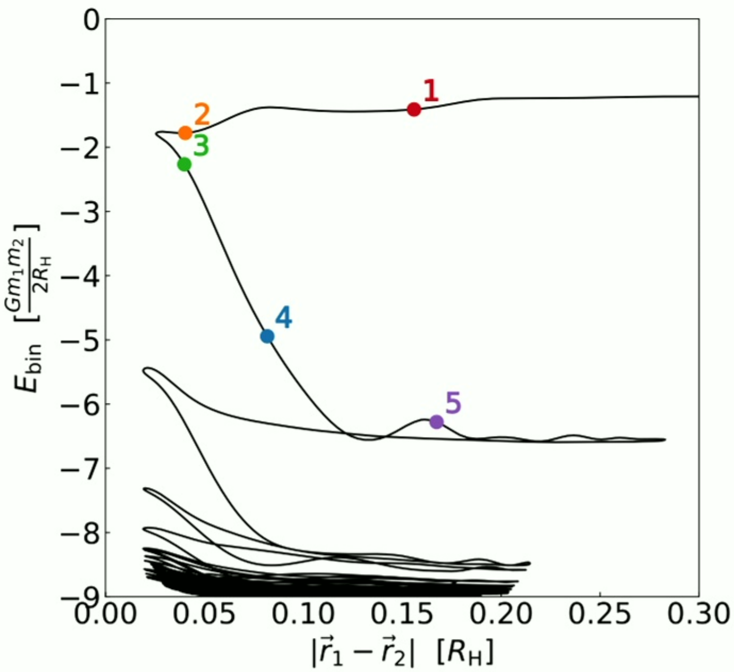
- Initial condition:

$$\boldsymbol{a_2 - a_1 = 2R_H}$$

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

Analysis: formation mechanism – “departure” drag

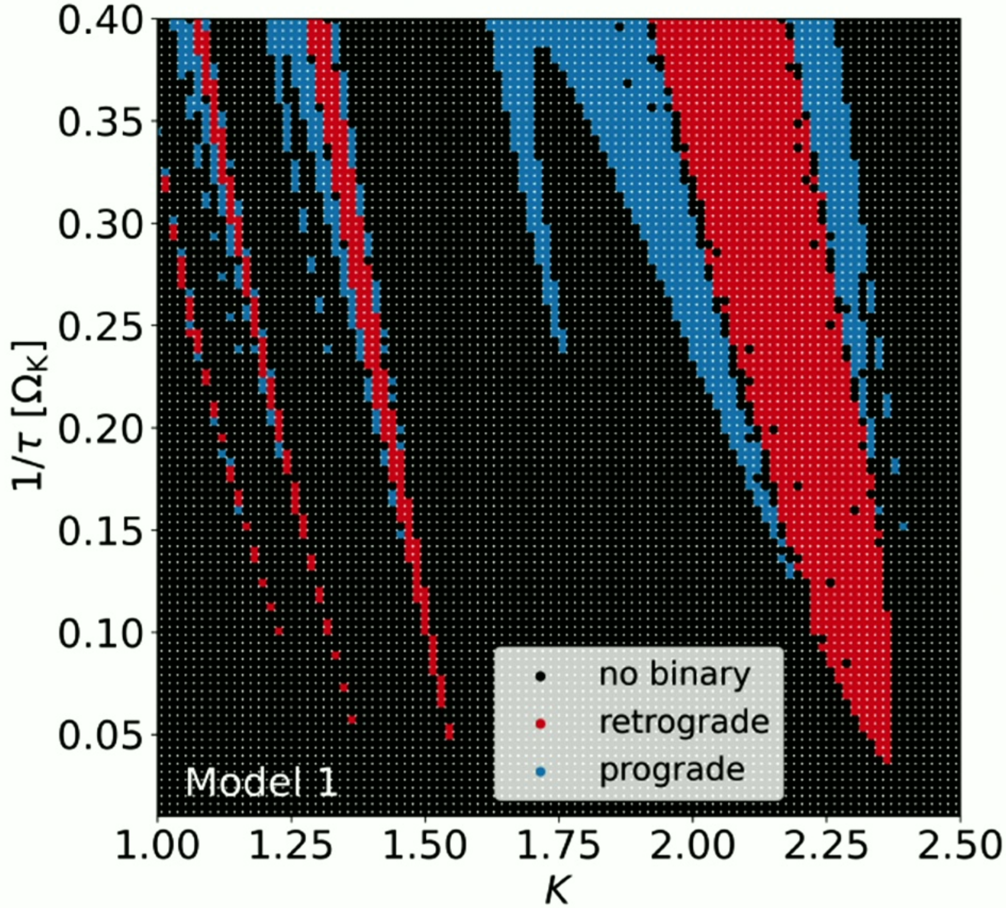




$$\boldsymbol{E}_{\mathbf{bin}} = \frac{1}{2}\mu v_{\mathrm{rel}}^2 - \frac{Gm_1m_2}{r_{\mathrm{rel}}}$$

Gas-assisted binary formation: model calculation

Gas drag on each BH: $\mathbf{F}_{\rm drag} = -m\,\dfrac{\mathbf{v}-\mathbf{v}_K}{\tau}$



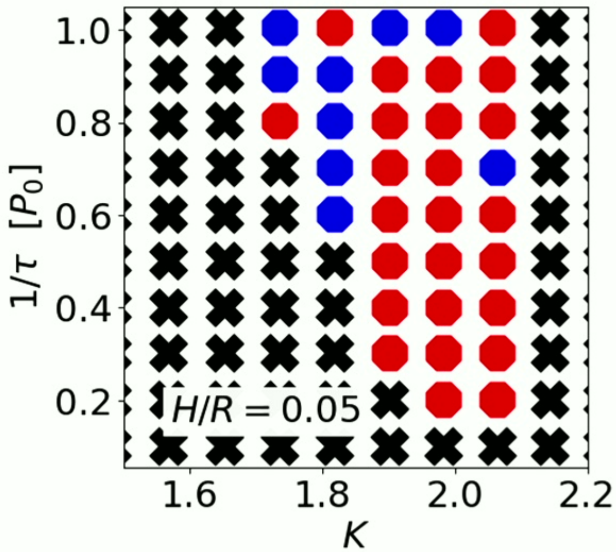
Initial condition:
$a_2 - a_1 = K R_{\rm H}$

Qian, Jiaru Li & Lai 2024

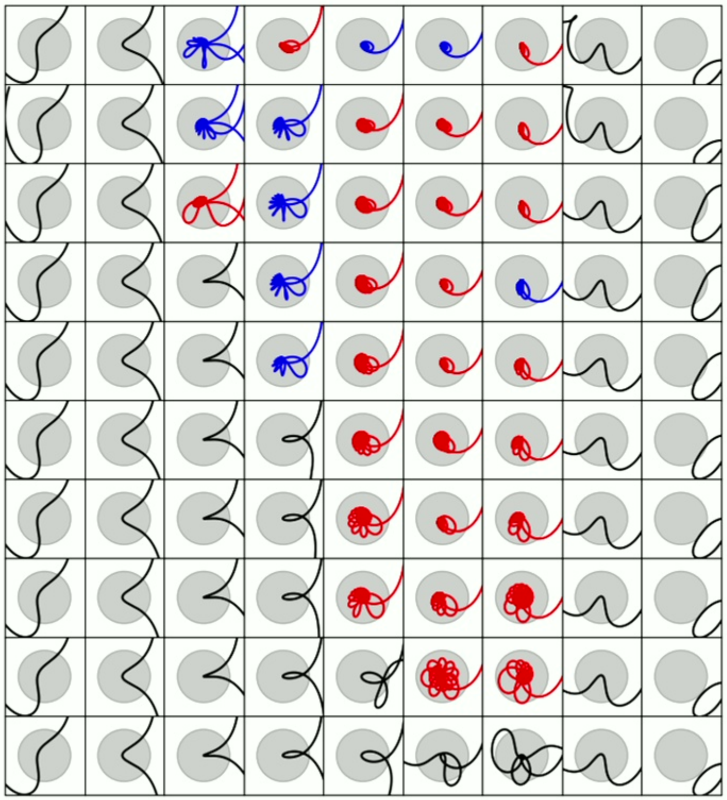
Kecheng (Sephon) Qian
(Cornell '24)

2D Hydro simulation survey:

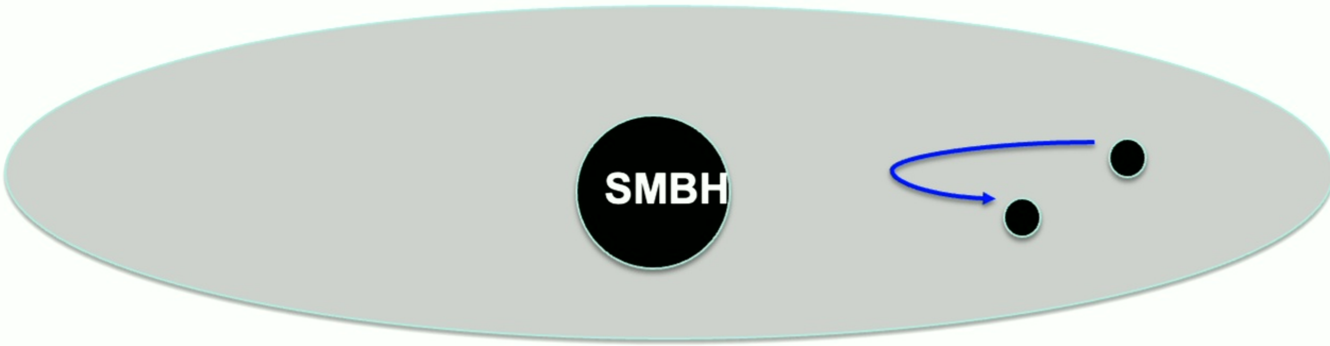
Jiaru Li et al, 2024 (in prep)



Relative trajectories of the BHs ⇒



Gas effects: embedded Binary in AGN Disk



Baruteau et al. 2011
Y.Li,… H.Li… 2021
Dempsey, H.Li… 2023
R.Li & DL 2022,23,24

Recap: Embedded binaries in gas disks

Prograde binaries:

Orbital decay or expansion? Depends on gas thermodynamics, viscosity, size of accretor…

Retrograde binaries:

Always orbital decay

In general, orbital evolution of the binary is much faster than migration of the center of mass of binary in AGN disk.

Binary BH Mergers and EM Counterparts?

ZTF19abanrhr: Graham et al 2020

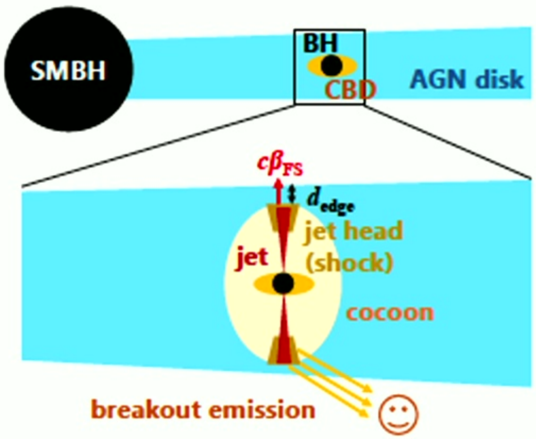
Optical flare L~10^{45} erg/s, duration ~ 1month, in AGN J124942

Associated with GW190521? (within 18 days)

6 similar ZTF flares reported: Graham et al. 2022

GRB (Fermi) (10^{49}erg/s, ~1s) associated with GW150914 ?? (Connaughton+16)

GRB associated with LVT151012 ?? (Bagily+16)



Tagawa+2023

Summary
Formation 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

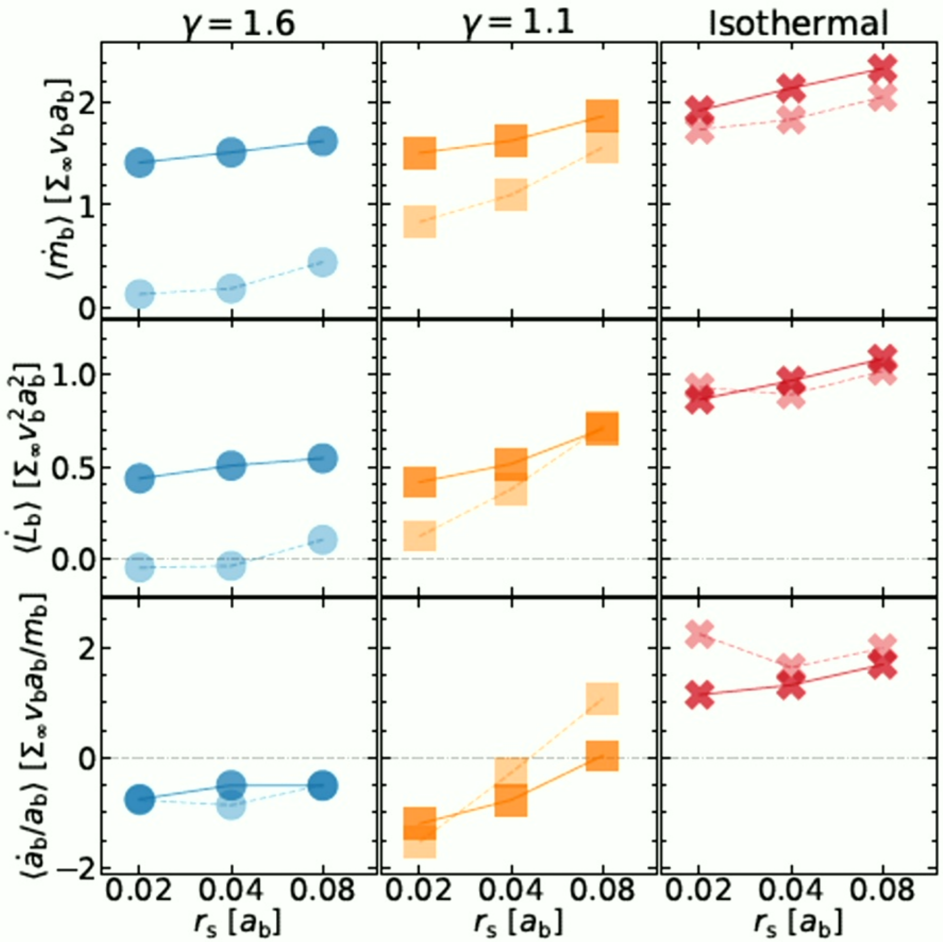
   Perturbations from outer companion → Lidov-Kozai
   Octupole effect → mass ratio dependence
   Binary mergers around SMBH: GR effects important
   Spin-orbit misalignment

➔ a few % 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

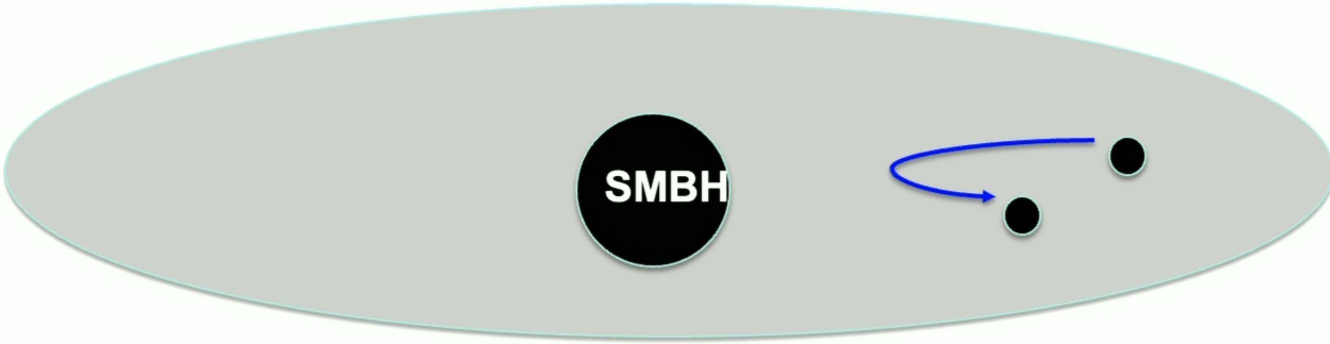
   GW capture → very eccentric mergers
   gas assisted mergers? More works to be done…

Rates? All potentially can play a role
LISA/Taiji/Tianqin useful for probing dynamical formation



Solid line: alpha=0.1
Dashed line: alpha=0

Gas effects: embedded Binary in AGN Disk



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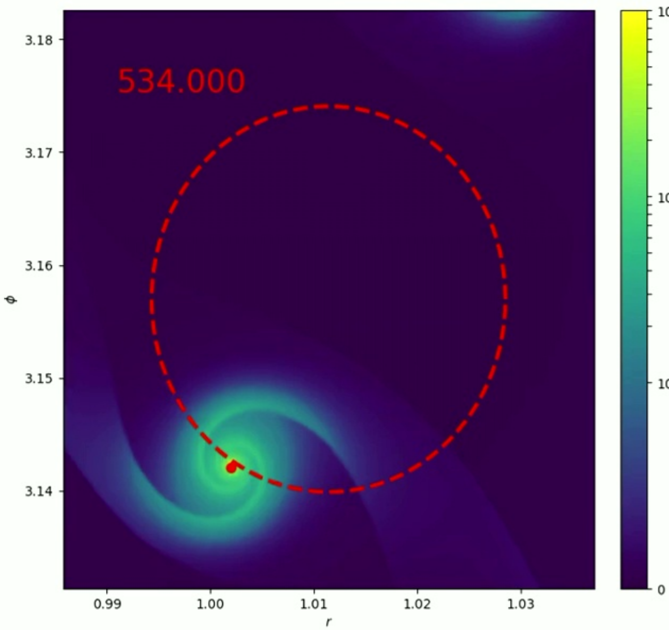

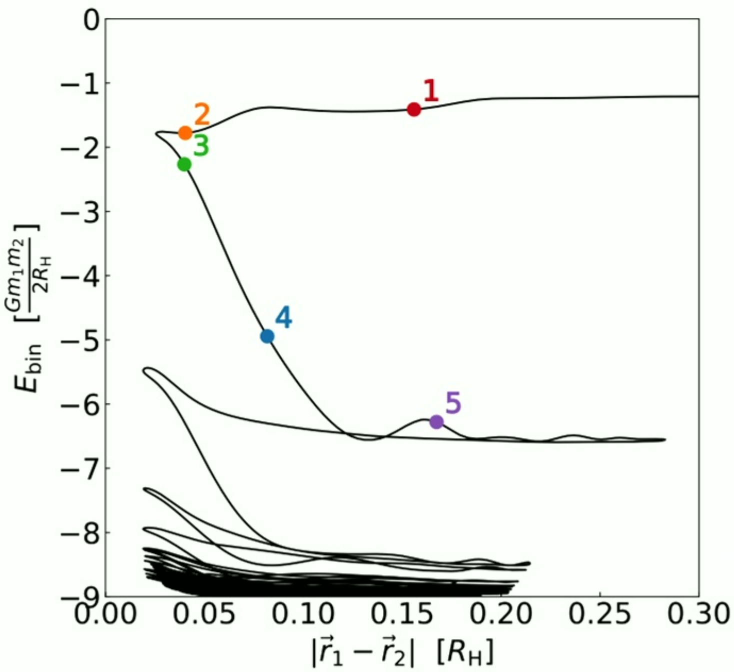

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