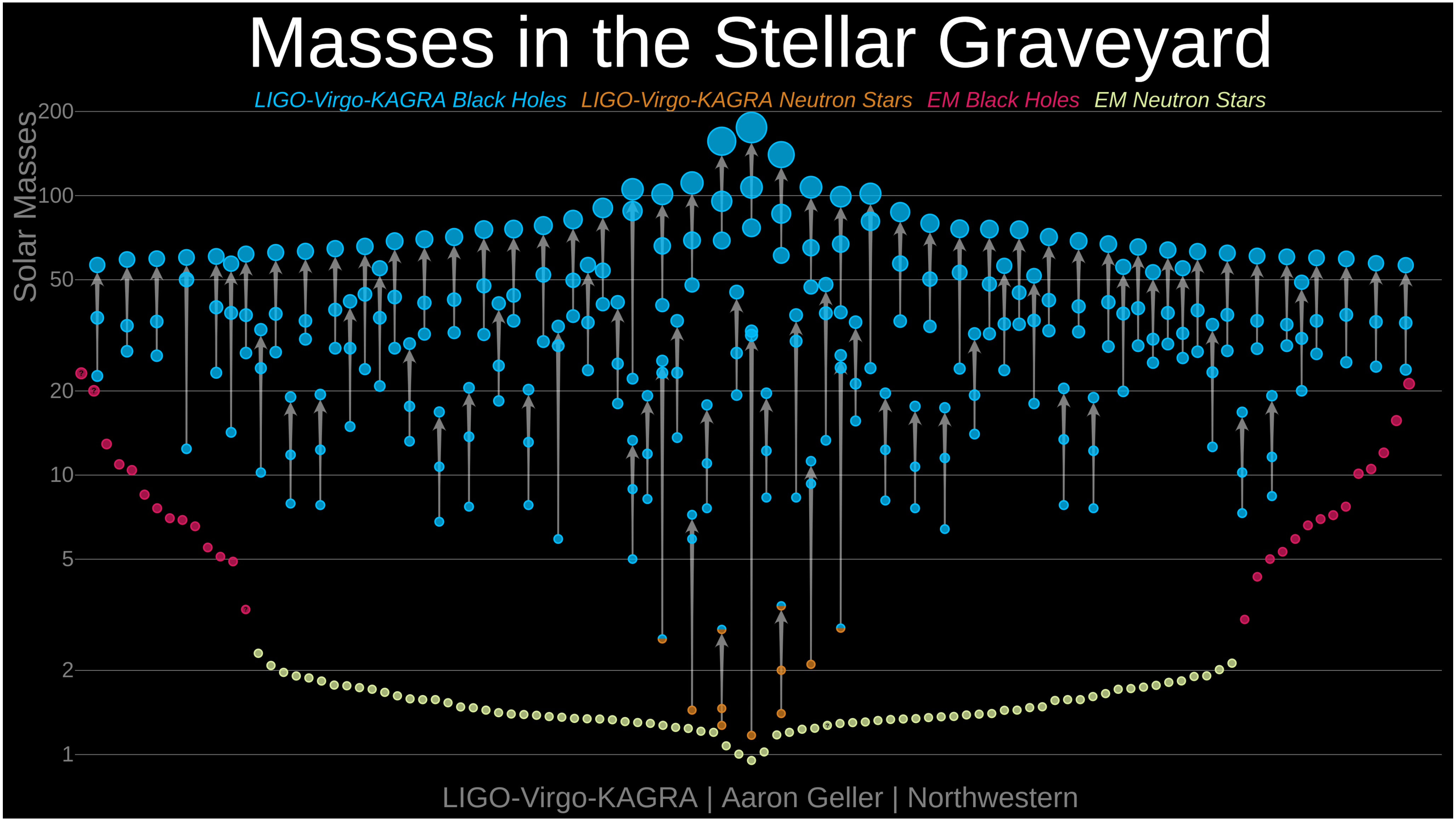
Dynamical Formation of Merging Black-Hole Binaries

(a planetary dynamics talk disguised as a BH talk)

Dong Lai

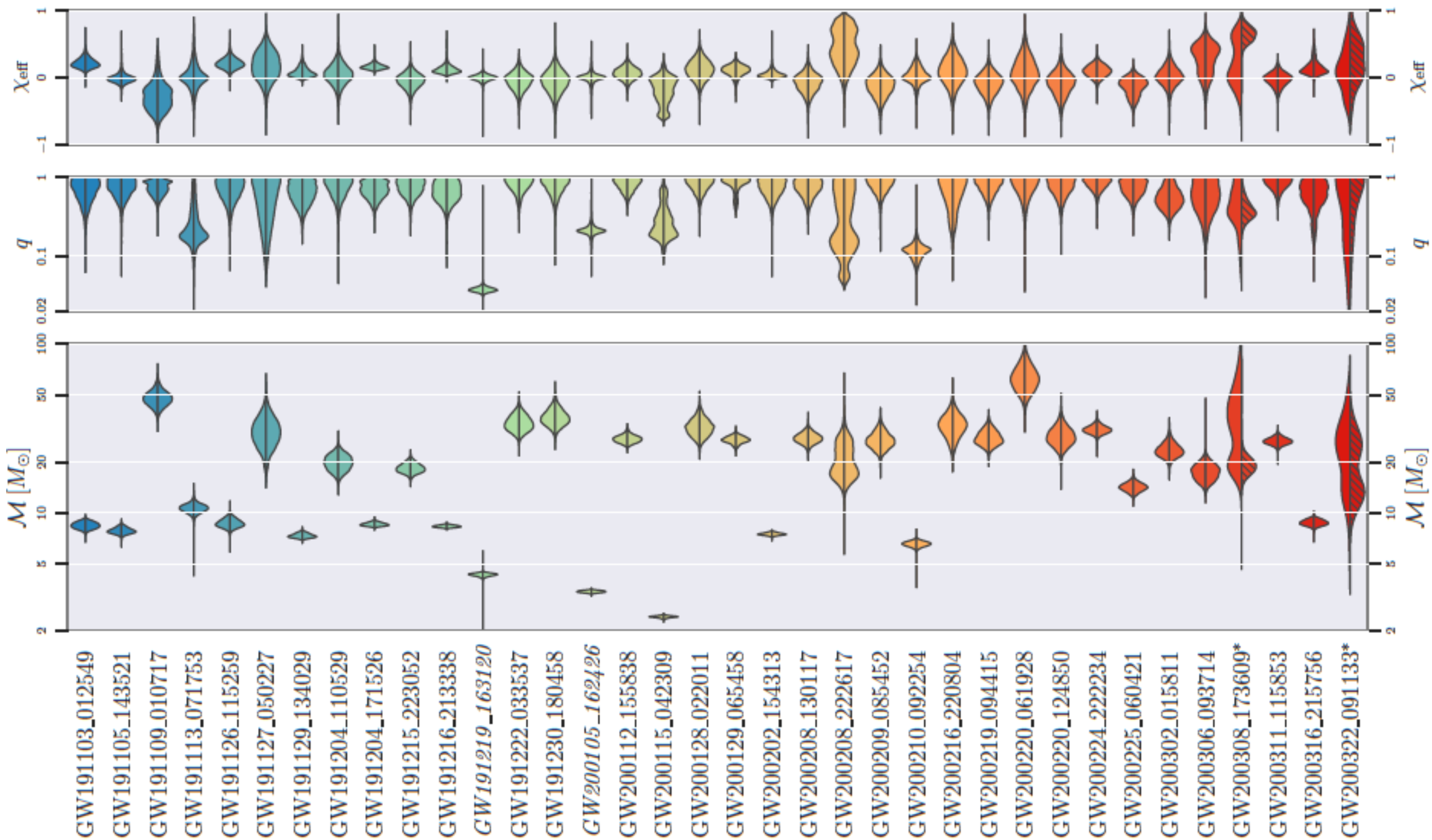
Brouwer Award Lecture, 56th AAS-DDA annual meeting, Atlanta, 5/20/2025



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

Observation Run 4 (O4)

100+ candidates



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?

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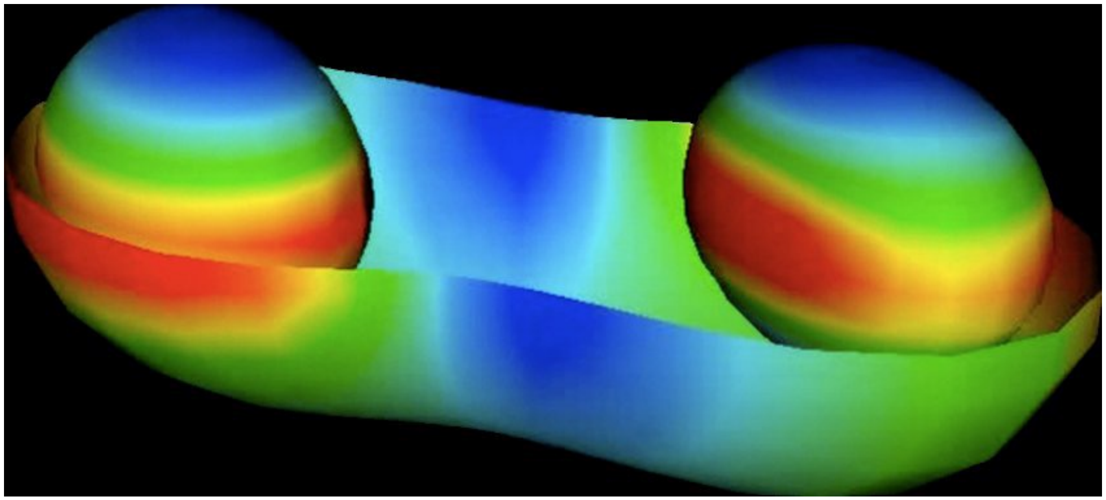
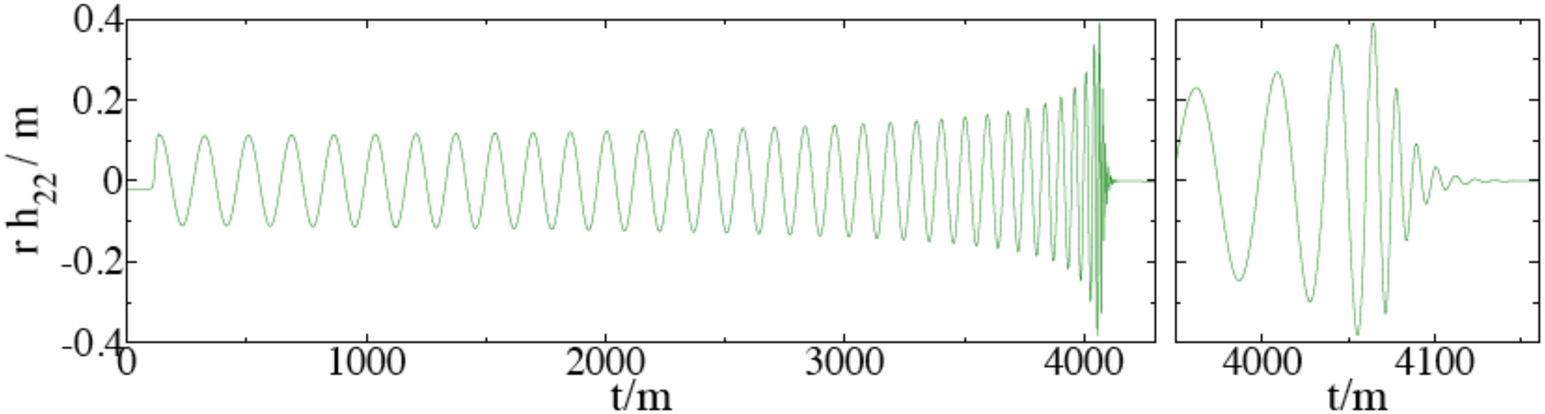
1. Test gravity theory in nonlinear regime:

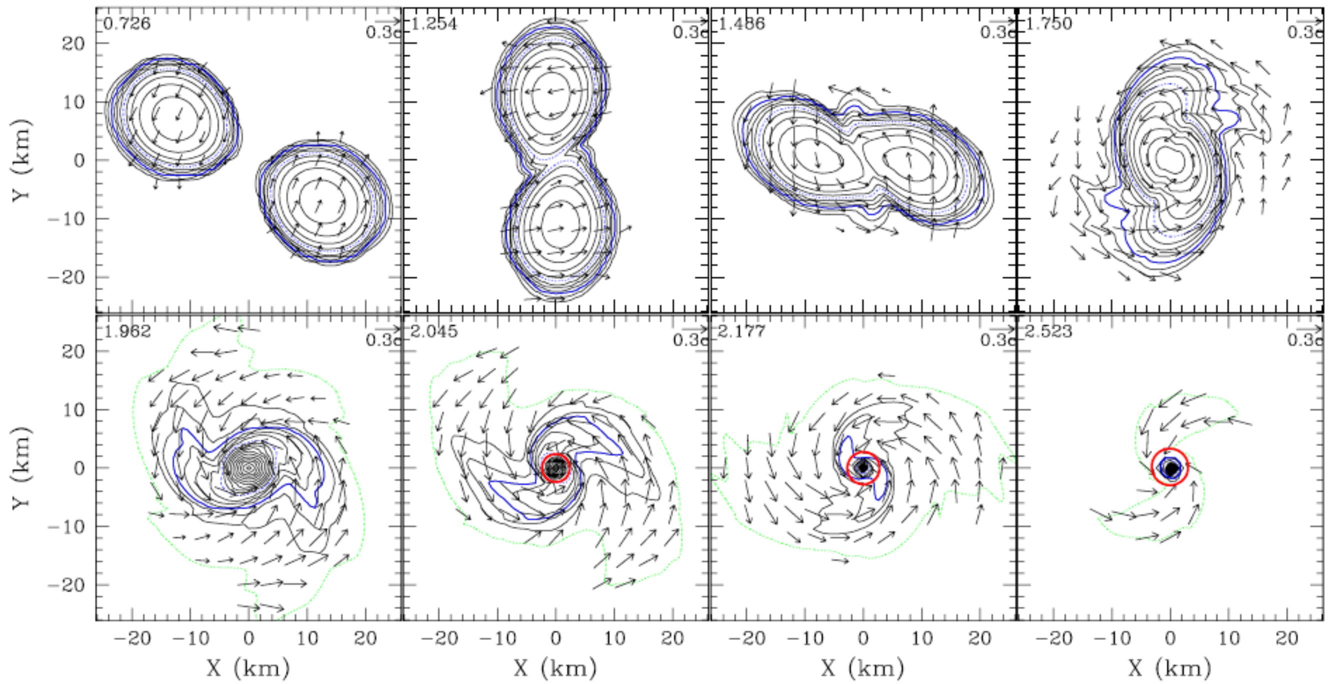




Cornell-Caltech collaboration

What to do with these GW detections?

1. Test gravity theory in nonlinear regime
2. Study dense nuclear matter



Shibata et al.

What to do with these GW detections?

1. Test gravity theory in nonlinear regime

2. Study dense nuclear matter

Inspiral phase:

Tidal/spin deformation (quasi-static tide) well-understood (since 1990s): many papers…

Resonant tide (excitation of g-mode etc) ? e.g. Lai 1994; Yu et al 2024…

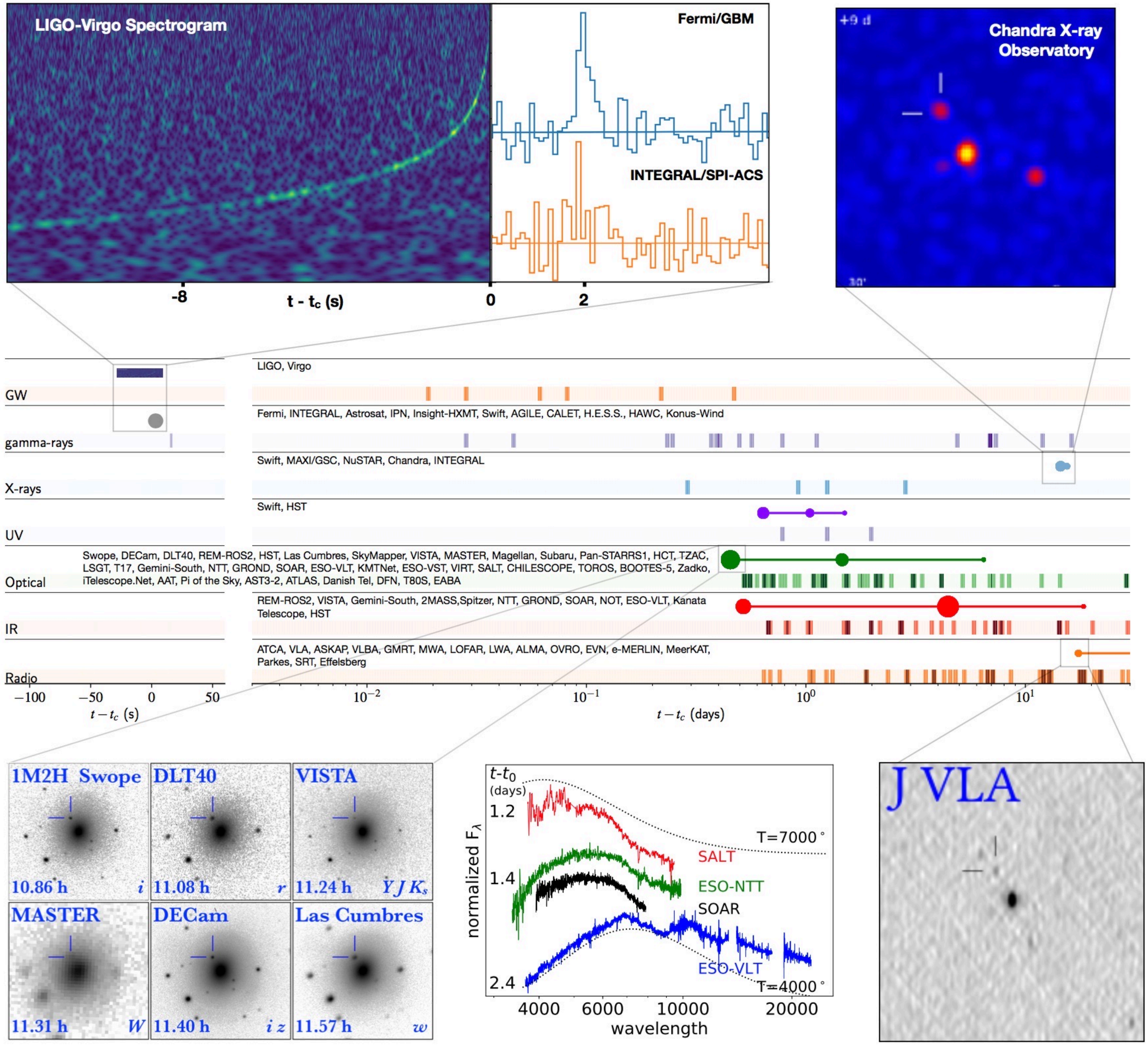
Merger waveform:

Remnant NS (hyper-massive or supermassive) or BH ?

What to do with these GW detections?

1. Test gravity theory in nonlinear regime
2. Study dense nuclear matter
3. Nucleosynthesis & EM counterparts

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
3. Nucleosynthesis & EM counterparts
4. Astrophysics of BH binary formation

Formation of Merging BH Binaries

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

Final AU problem…

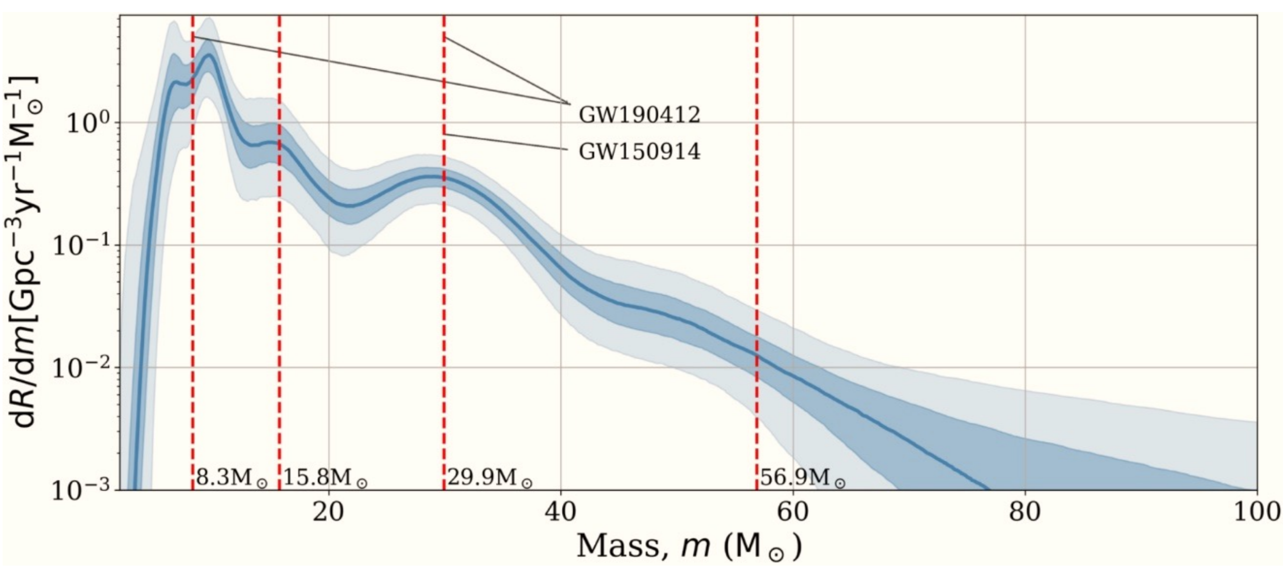
Formation Channels of Merging BH Binaries

-- Isolated Binary Evolution

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

How to distinguish different channels?

Rates (uncertain)?
Masses and mass ratio



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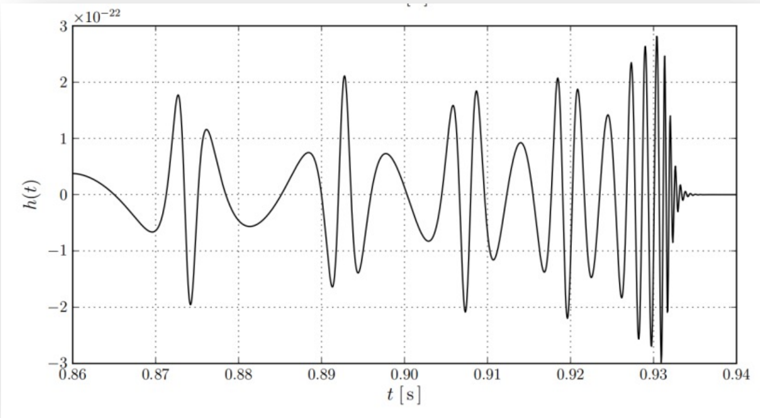

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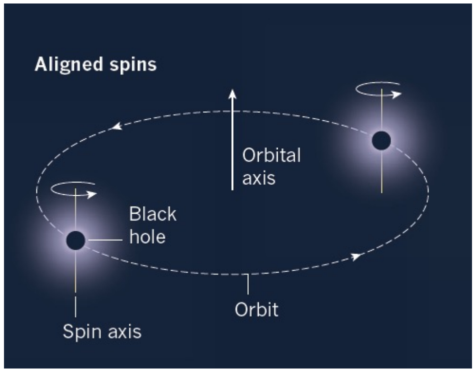

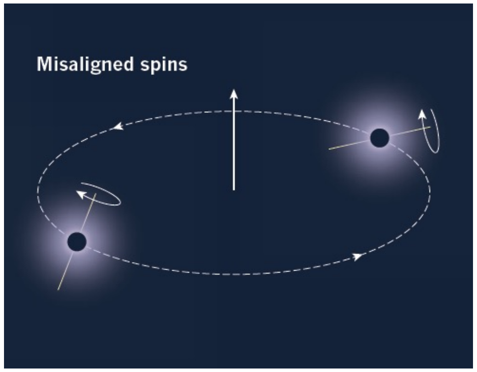

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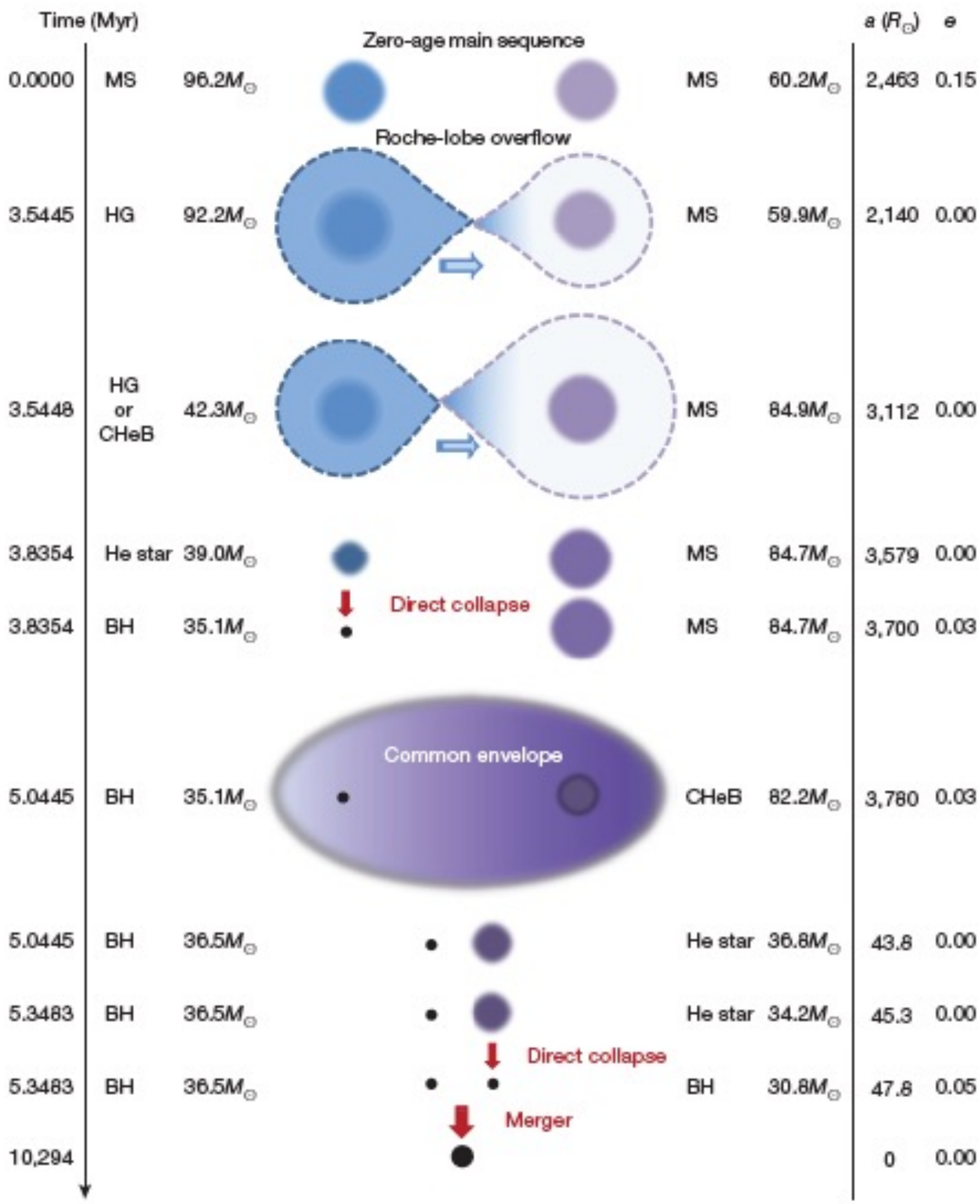
Spin-orbit misalignment
EM counterpart

Isolated Binary Evolution Channel: Standard



many papers, uncertain physical ingredients (e.g. common envelope; Gaia BH1,2,3 ??)

Produce

circular orbit at 10 Hz
mostly aligned spin-orbit

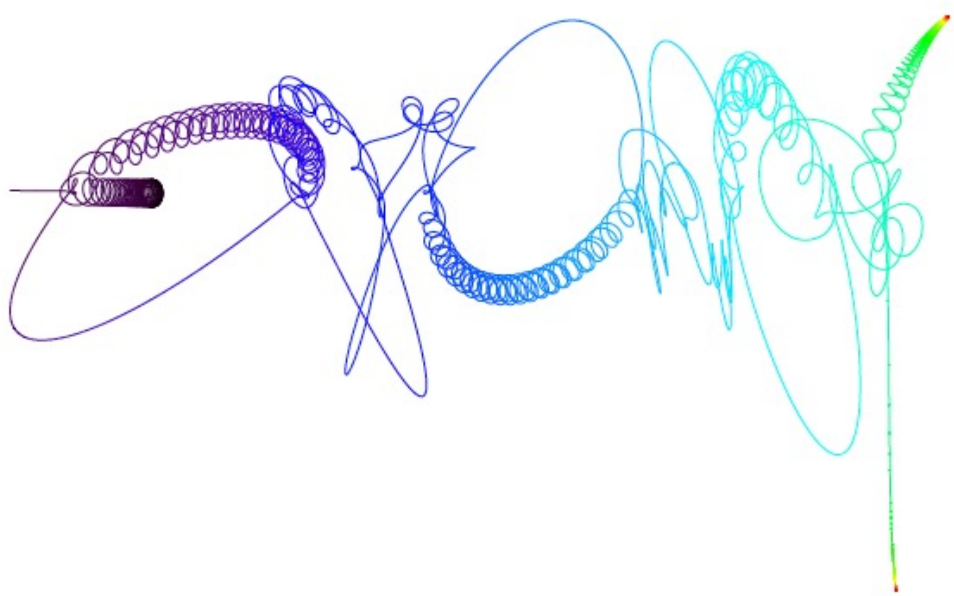
Belczynski +16

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 (via Lidov-Kozai or other secular resonance effects)

   stellar triples in galactic field, binary around SMBH

Lidov-Kozai Effect

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

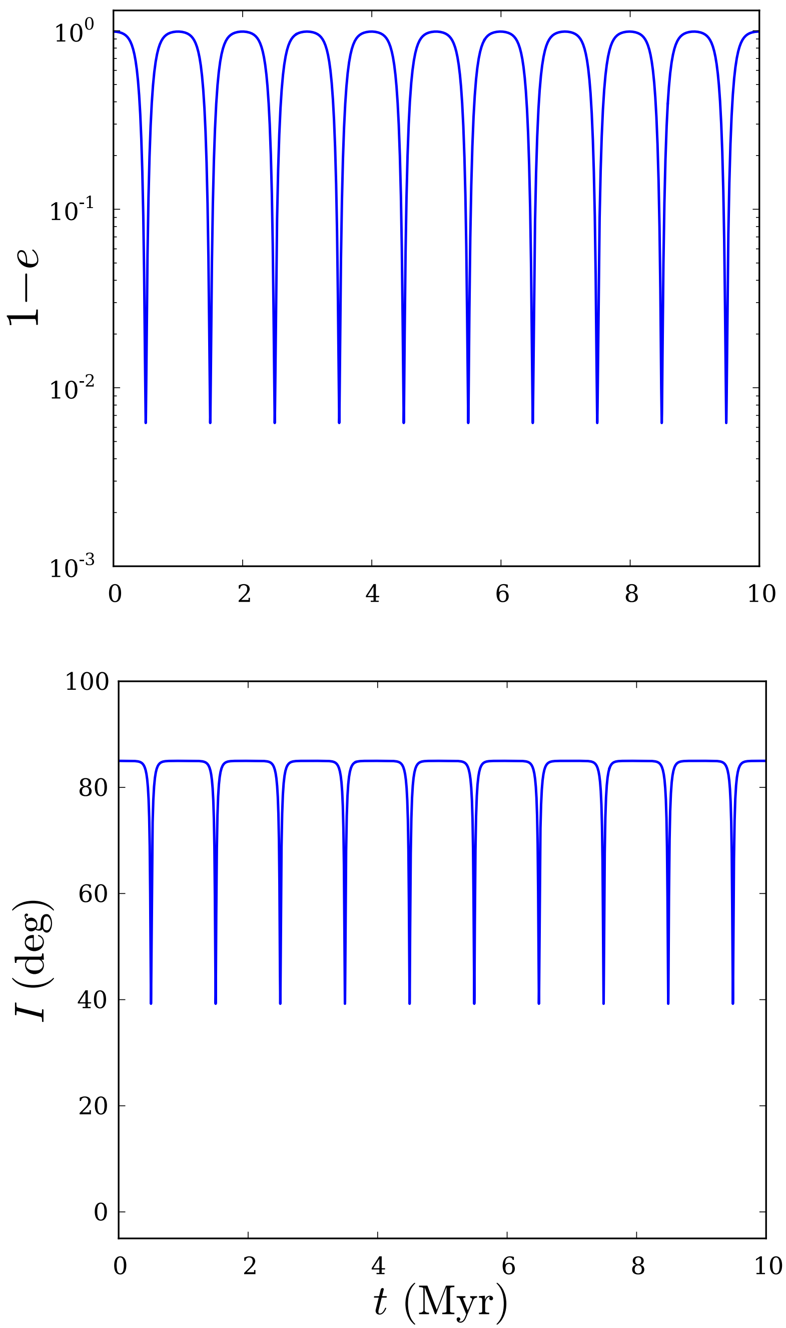
Planet. Space Sci., 1962, Vol. 9, pp. 719 to 759. Pergamon Press Ltd. Printed in Northern Ireland

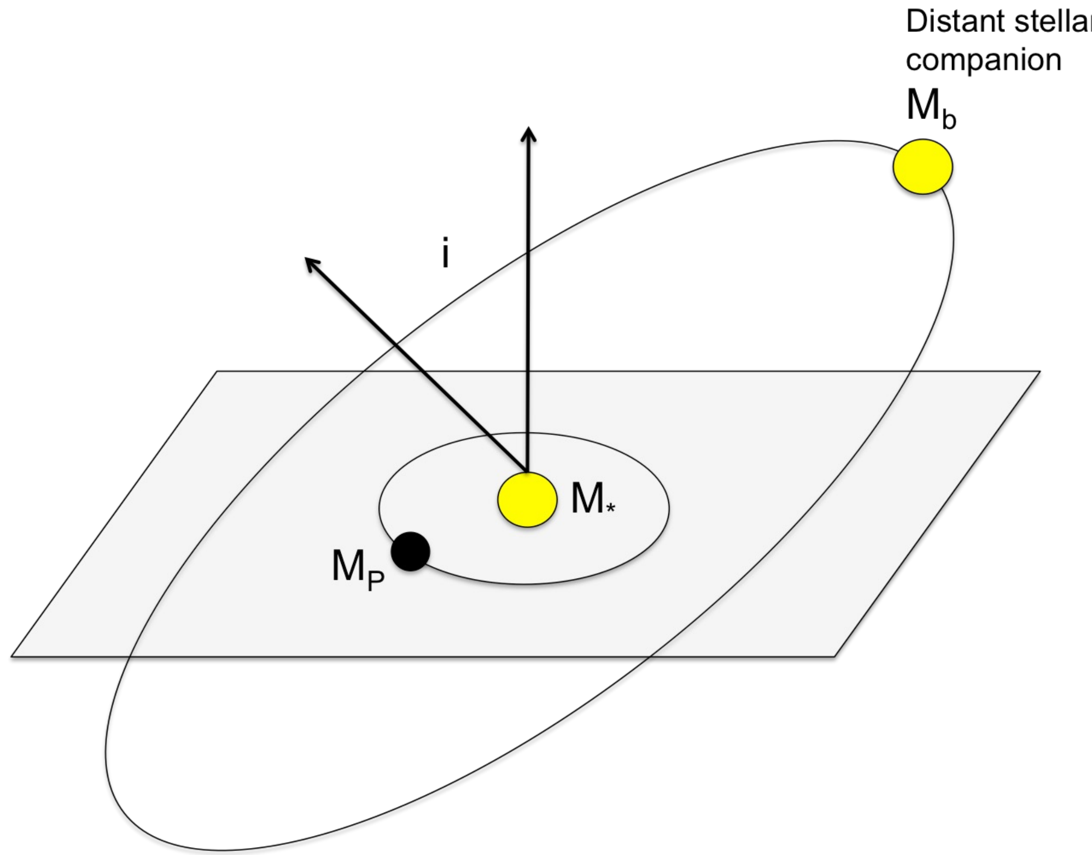
THE EVOLUTION OF ORBITS OF ARTIFICIAL SATELLITES OF PLANETS UNDER THE ACTION OF GRAVITATIONAL PERTURBATIONS OF EXTERNAL BODIES

M. L. LIDOV

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

Lidov-Kozai Effect

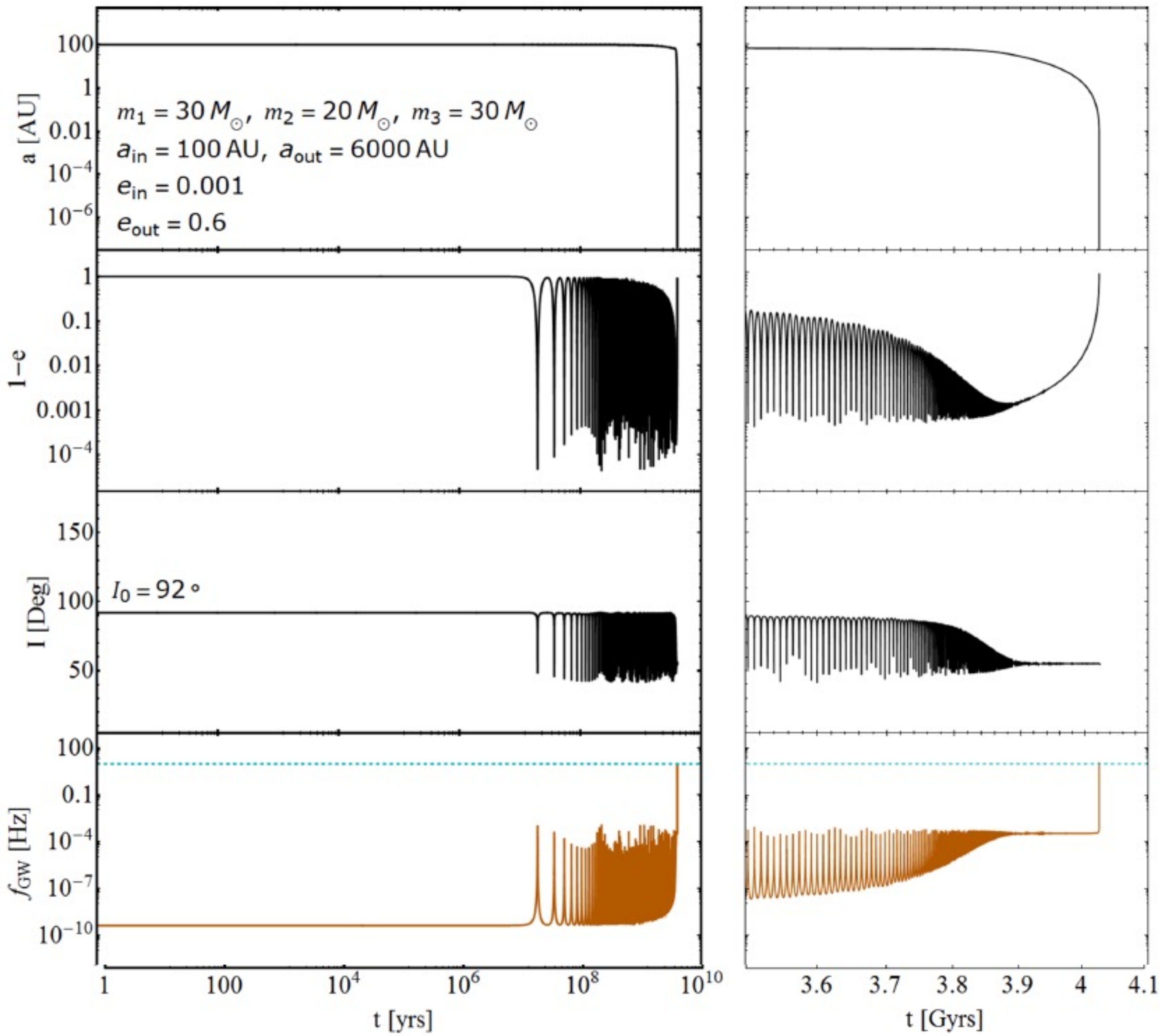




- Eccentricity and inclination oscillations induced if i > 40 degrees.
- If i large (depending on octupole strength), get extremely large eccentricities (e > 0.99)

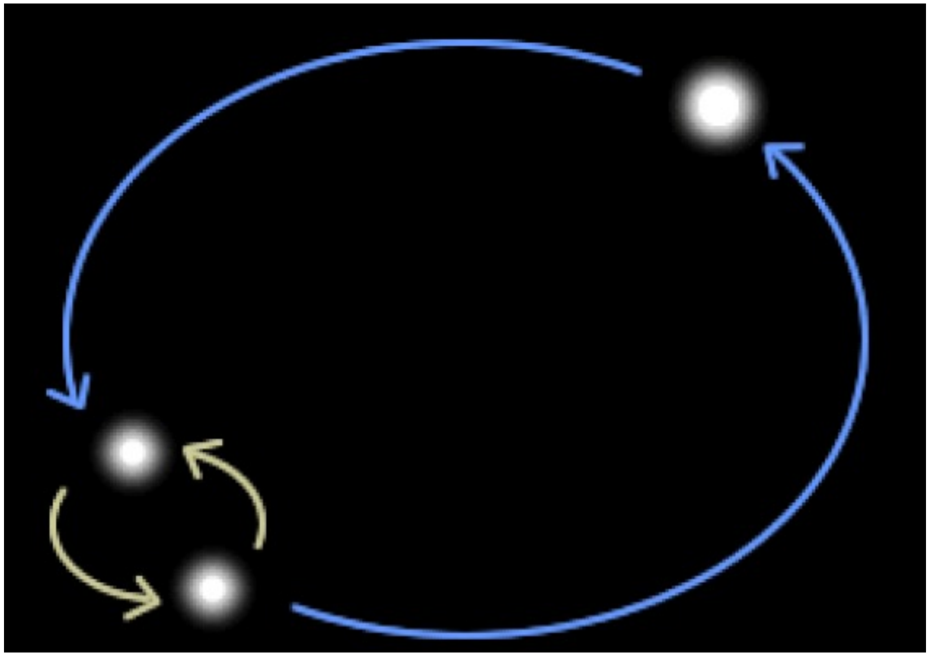
See Naoz (2016) review

LK oscillation + Gravitation Radiation

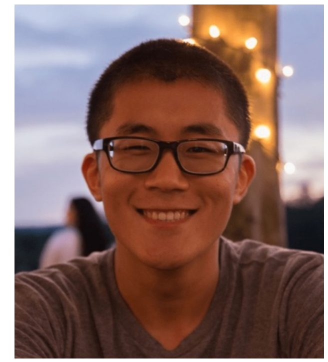


Tertiary-Induced Binary Mergers

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 2017-2023
Su et al.2021a,b; Su+2024

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....
Note: Related/general effects of galatic tidal potential
Hamilton & Rafikov 2019-2021 (a la Heisler-Tremaine)

Summary of Tertiary-Induced Mergers

Some general "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 enhances the LK merger fraction;
   Galactic tidal potential (e.g. Petrovich & Antonini 2017; Hamilton & Rafikov)
   Synergy between galactic tide and stellar flybys (Winter-Granic+2024)

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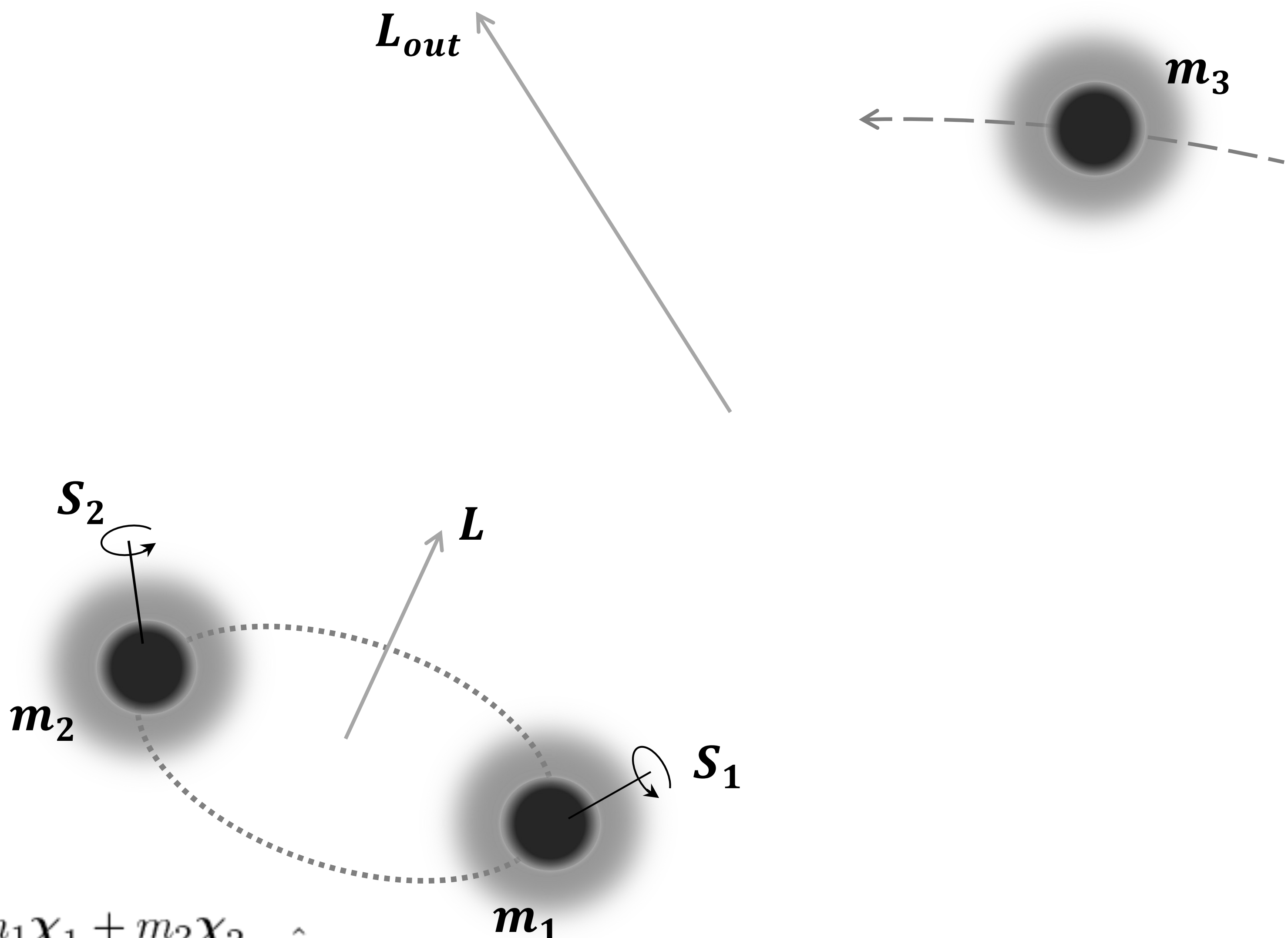
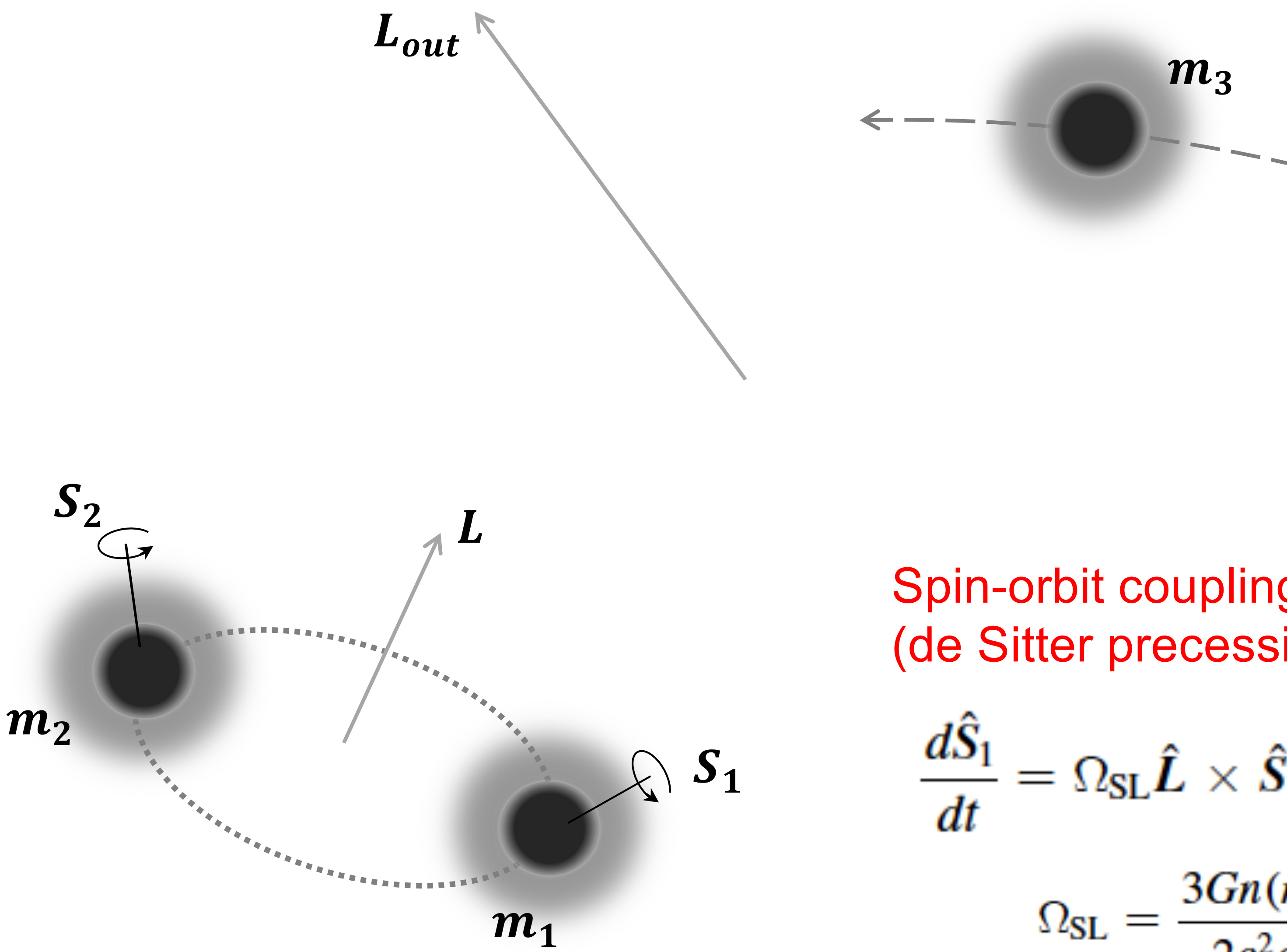
How does BH spin axis evolve ?



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

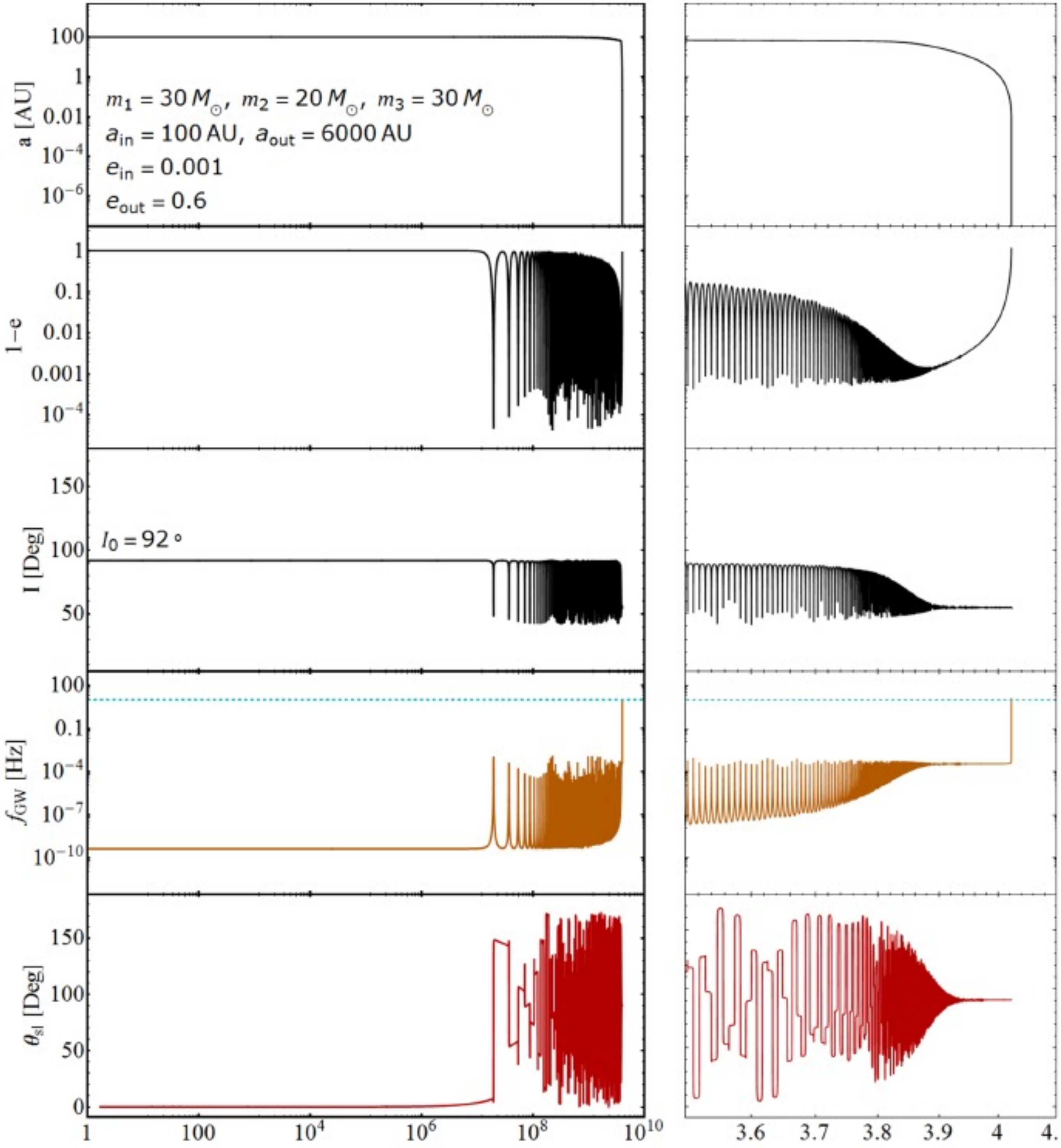
How does BH spin axis evolve ?



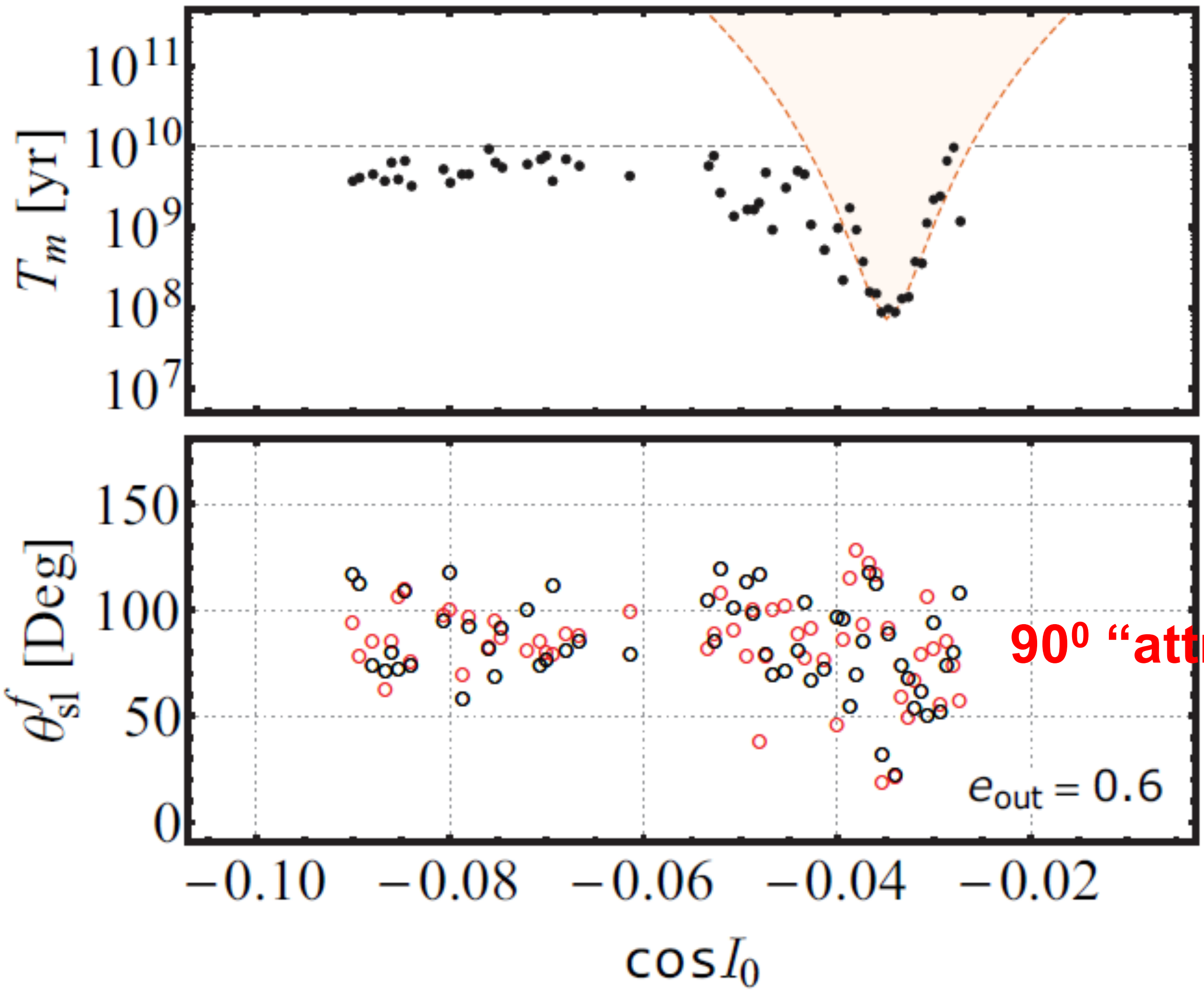
Spin-orbit coupling
(de Sitter precession):

$$\frac{d\hat{S}_1}{dt} = \Omega_{SL}\hat{\boldsymbol{L}} \times \hat{\boldsymbol{S}}_1,$$

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



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



90^0 "attractor"

Liu & Lai 2018

BH spin dynamics during LK oscillations

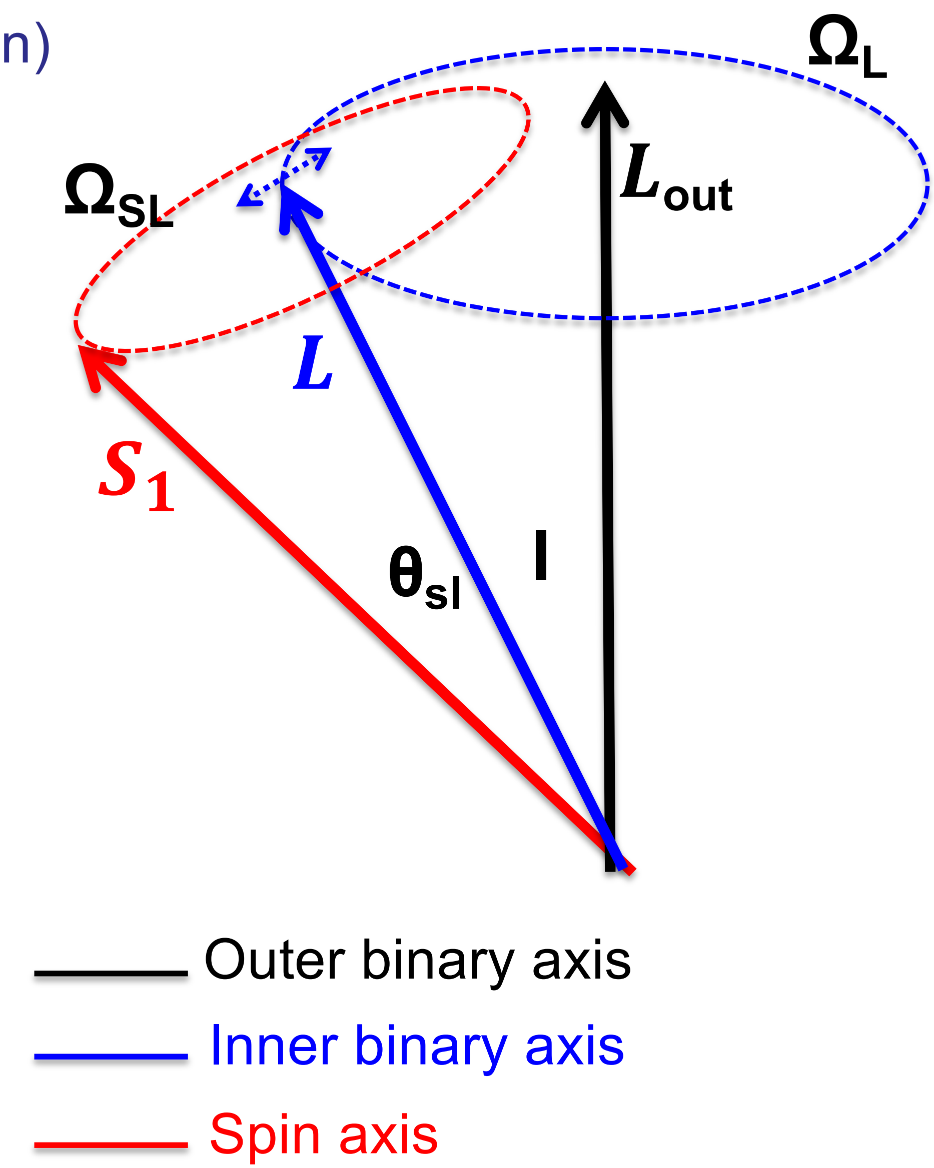
$$\frac{d\hat{S}_1}{dt} = \Omega_{SL}\hat{L} \times \hat{S}_1$$ (de Sitter Precession)

$$\Omega_{SL} = \frac{3Gn(m_2 + \mu/3)}{2c^2 a(1 - e^2)} \propto a^{-5/2}$$

But $\boldsymbol{L}$ precesses and nutates around $\boldsymbol{L}_{out}$

$$\Omega_L \sim \frac{1}{t_{LK}} \times f(e, I)$$

$$\frac{1}{t_{LK}} = n \frac{m_3}{m_{12}} \left(\frac{a}{a_{out}}\right)^3 \propto a^{3/2}$$



In the frame co-rotating with $\boldsymbol{L}$

$$\left(\frac{\mathrm{d}\hat{\mathbf{S}}_1}{\mathrm{d}t}\right)_{\mathrm{rot}} = \boldsymbol{\Omega}_e \times \hat{\mathbf{S}}_1$$

$$\boldsymbol{\Omega}_{\mathrm{e}} \equiv \Omega_{\mathrm{L}} \hat{\mathbf{L}}_{\mathrm{out}} + \Omega_{\mathrm{SL}} \hat{\mathbf{L}}$$

Ω_L and Ω_{SL} both vary (a, e, I)

Over orbital decay timescale ($\gg t_{LK}$), LK oscillation of e and I can "average" out…

$$\bar{\Omega}_{\mathrm{SL}} \propto a^{-5/2}, \quad \bar{\Omega}_L \propto a^{3/2}$$

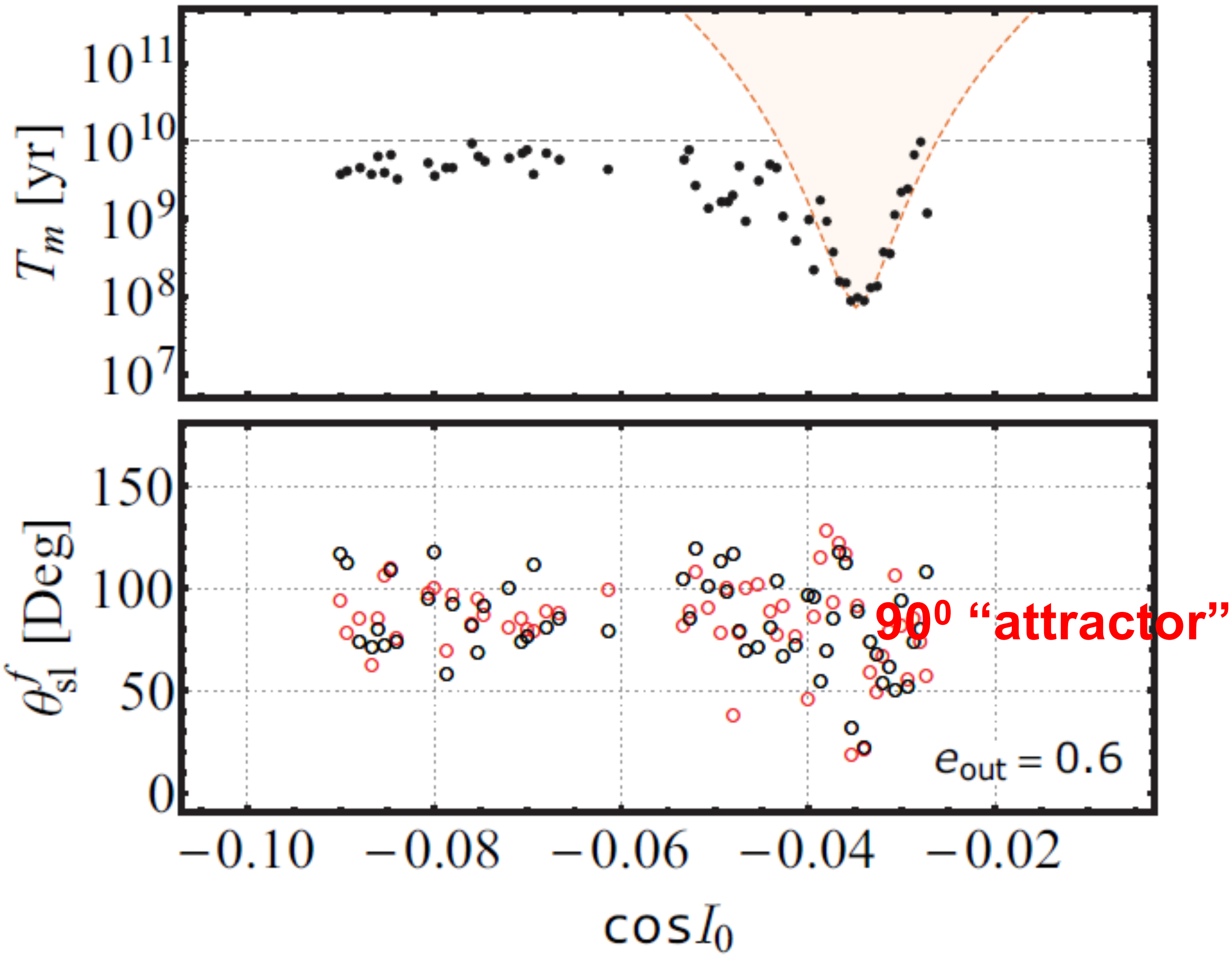
➔ $\mathbf{S}_1$ processes rapidly around $\boldsymbol{\Omega}_e$, which is slowly varying

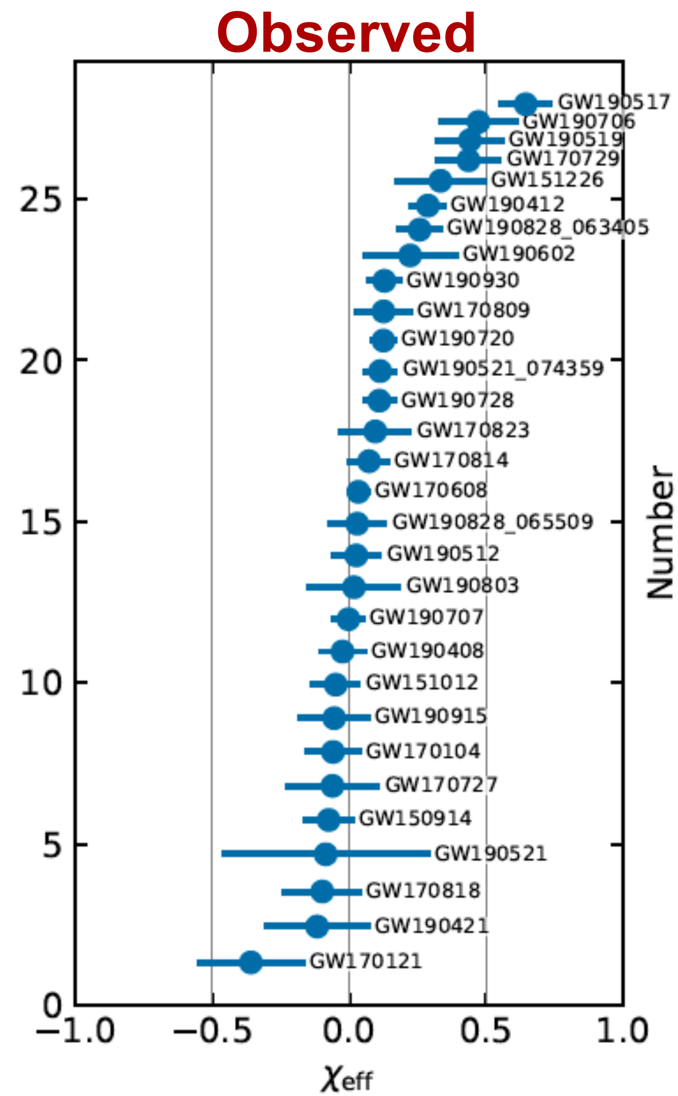
➔ θ_{Se} (the angle between $\mathbf{S}_1$ and $\boldsymbol{\Omega}_e$) is adiabatic invariant

Initial (large a): $\bar{\Omega}_L \gg \bar{\Omega}_{\mathrm{SL}} \Longrightarrow \boldsymbol{\Omega}_e \propto \hat{\mathbf{L}}_{\mathrm{out}}$

Final (small a): $\bar{\Omega}_L \ll \bar{\Omega}_{\mathrm{SL}} \Longrightarrow \boldsymbol{\Omega}_e \propto \hat{\mathbf{L}}$

Su, Lai & Liu 2021; Su 2025



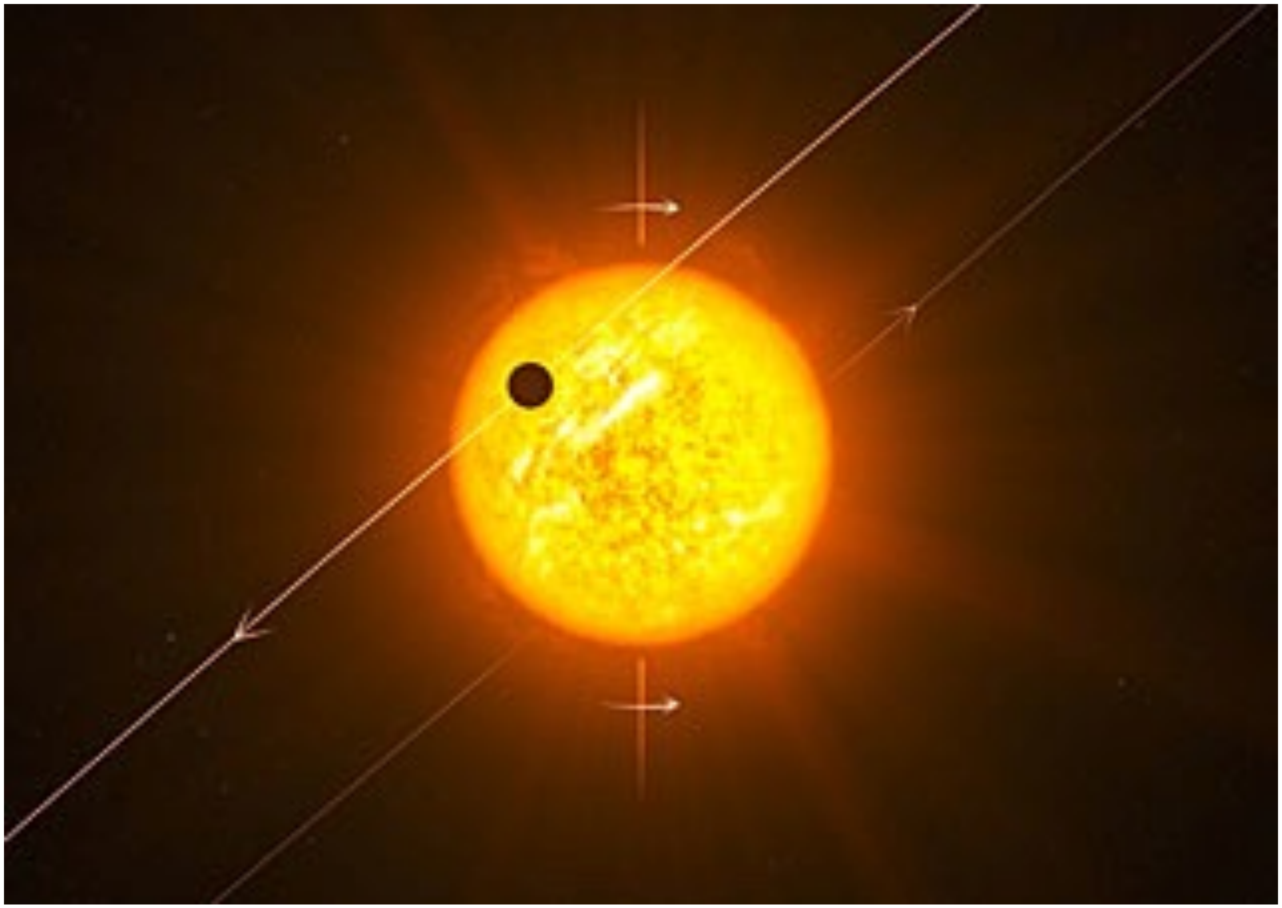


Liu & Lai 2018

$$\chi_{\rm eff} \equiv \frac{m_1\chi_1 + m_2\chi_2}{m_1 + m_2} \cdot \hat{\mathbf{L}}$$

Digression:

Stellar Obliquity (S-L misalignment) of Hot Jupiter Systems



One of the ways of forming Hot Jupiters: Tertiary-induced high-e migration

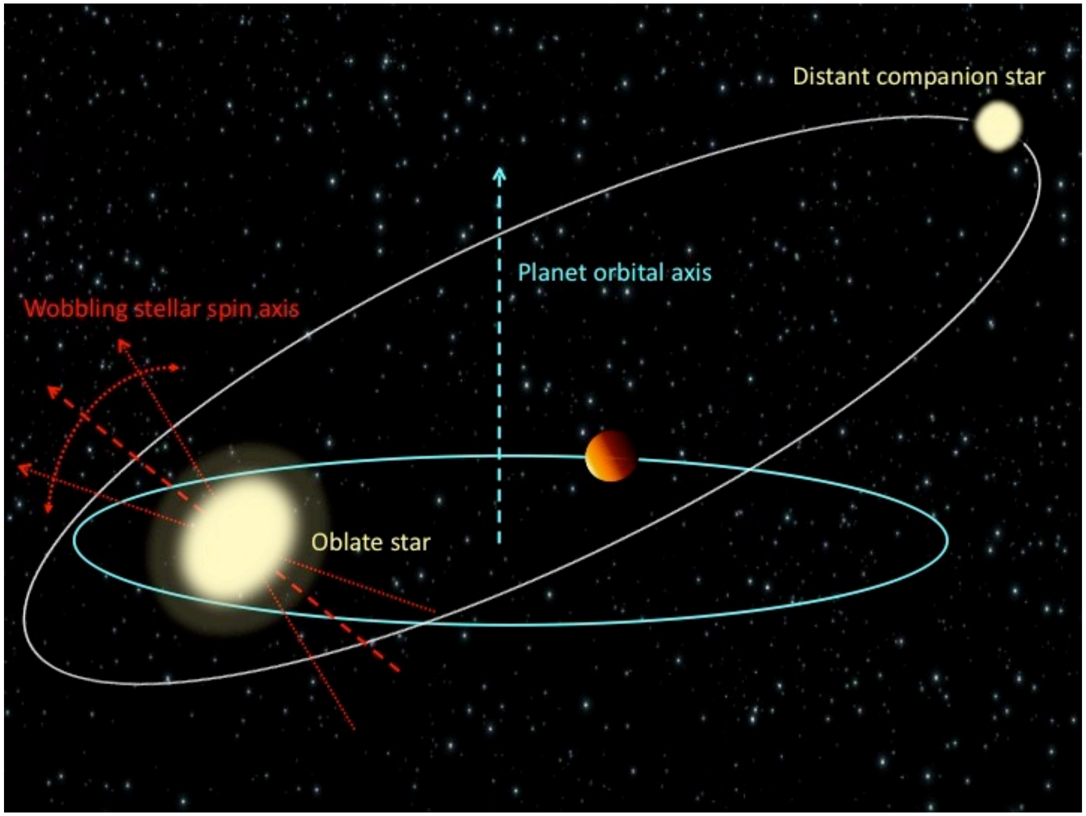
- Planet forms at ~ a few AU

- Interaction with companion (other star or planets) pumps planet into high-e orbit (e.g. Lidov-Kozai)

- Tidal dissipation in planet during high-e phases causes orbital decay

➔ Combined effects can result in planets in ~ few days orbit

What happens to stellar spin axis as the planet undergoes Lidov-Kozai Oscillations ?



Star rotates ➔ oblate
➔ S precesses around L

$$\Omega_{\rm SL} \propto -\frac{\Omega_\star m_p}{a^3(1-e^2)^{3/2}}\cos\theta_{\rm sl}$$

Stellar spin dynamics during LK oscillations

$$\frac{d\hat{\mathbf{S}}}{dt} = \Omega_{\rm SL}\hat{\mathbf{L}} \times \hat{\mathbf{S}}$$ (Newtonian Precession)

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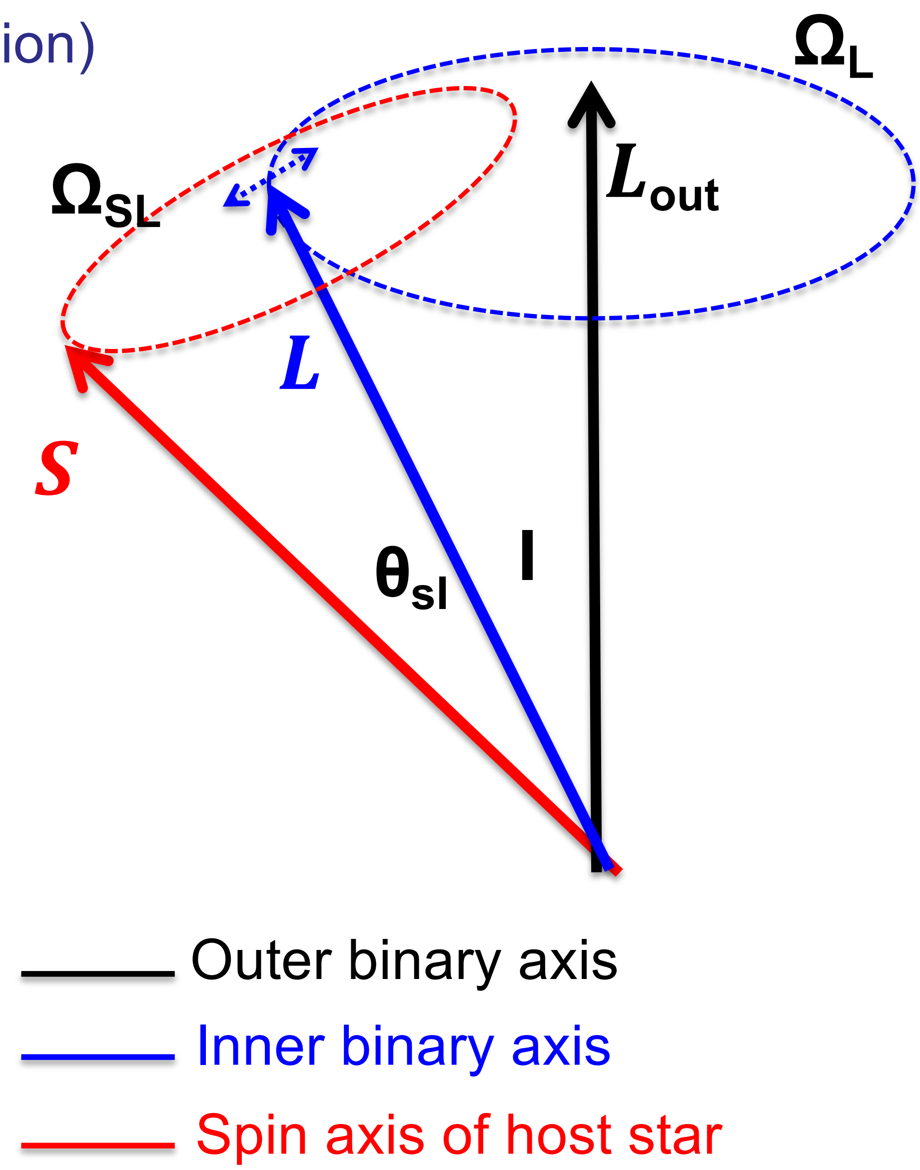
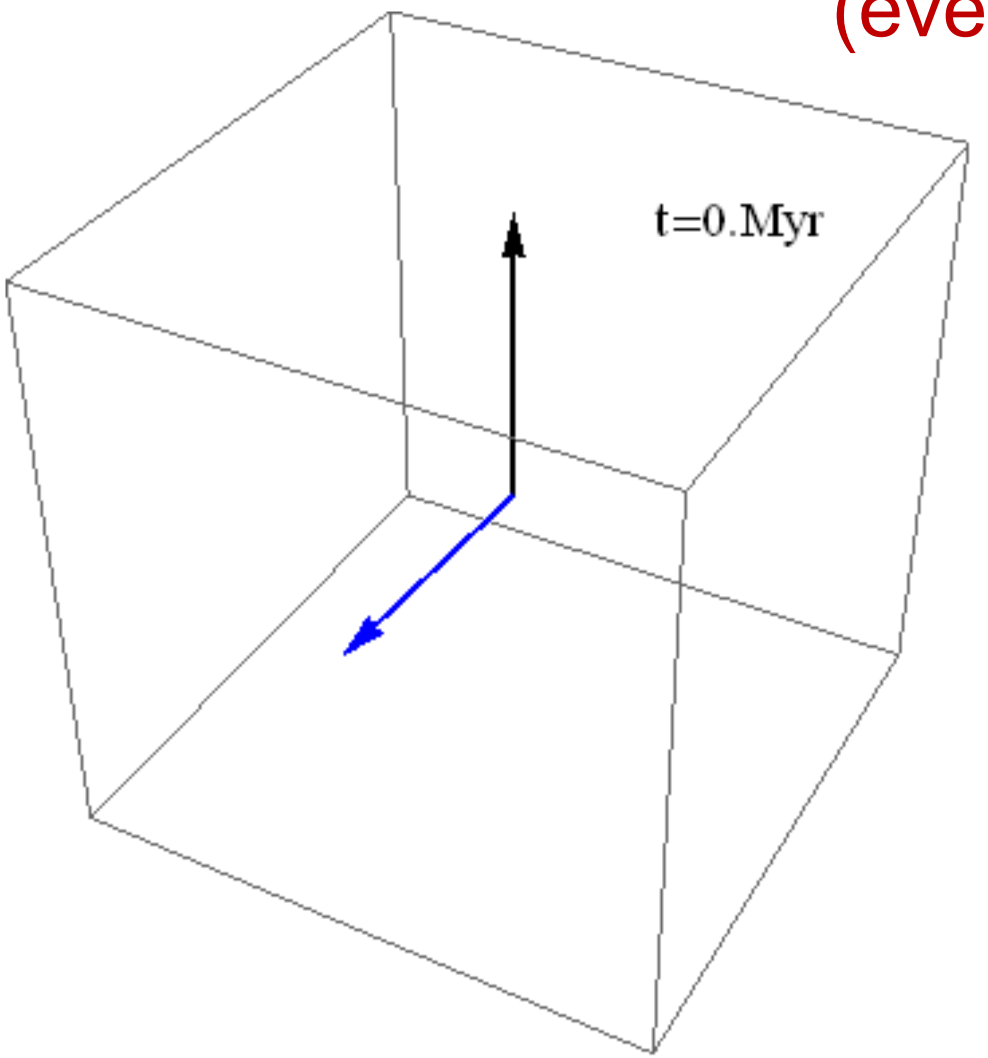


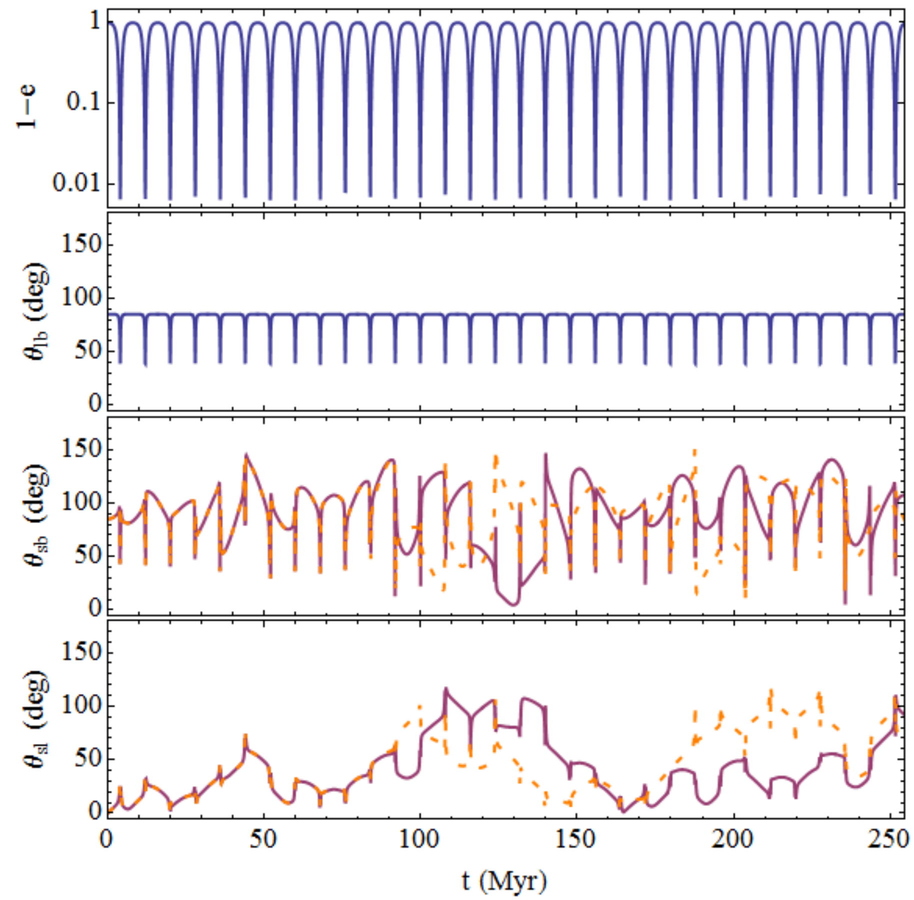
Spin evolution can be chaotic (even when the orbit is regular)



Outer binary axis

Planet orbital axis

Stellar spin axis



Storch, Anderson & Lai 2014
Anderson, Storch & Lai 2016

BH spin:

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Stellar Spin:

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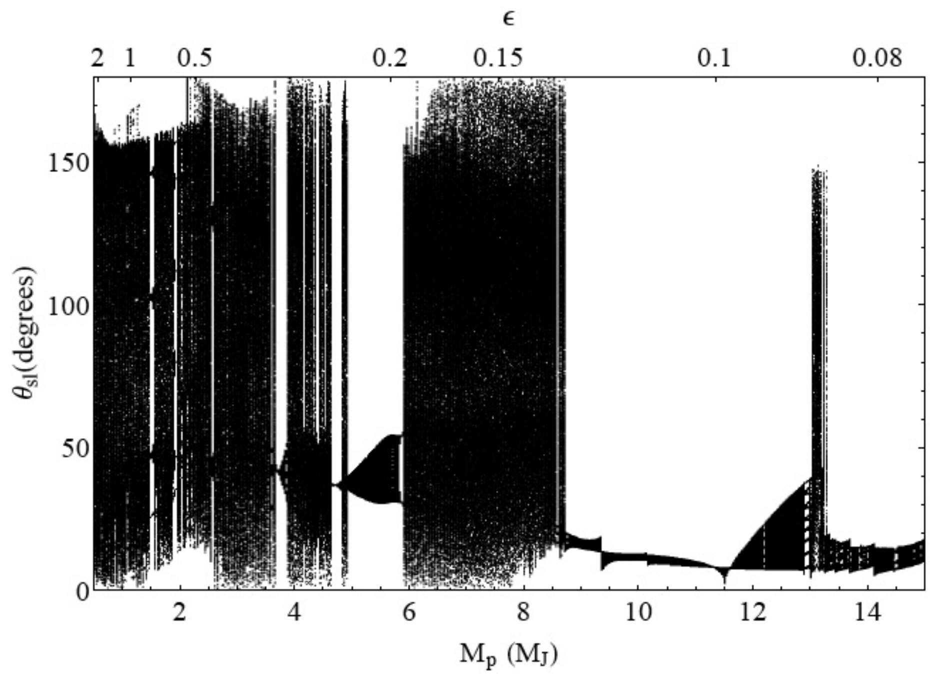
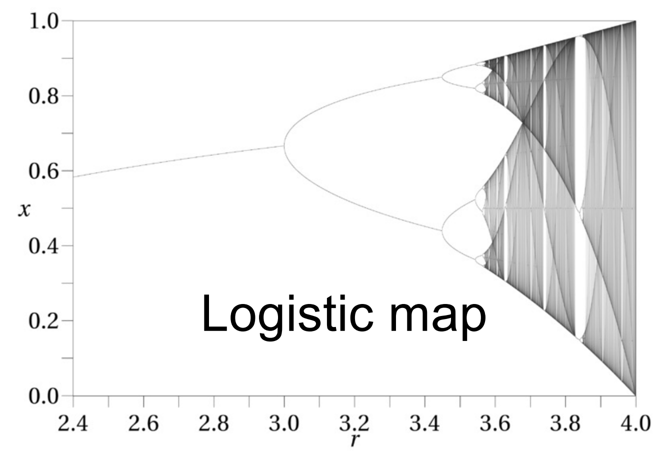
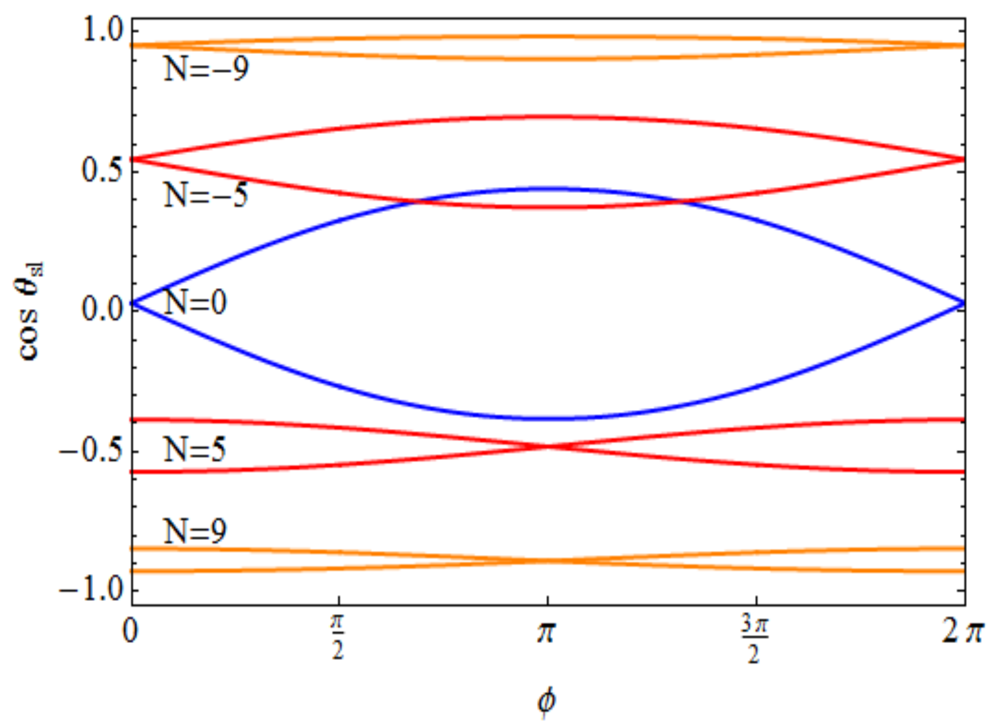
Theory of Spin Chaos during Lidov-Kozai



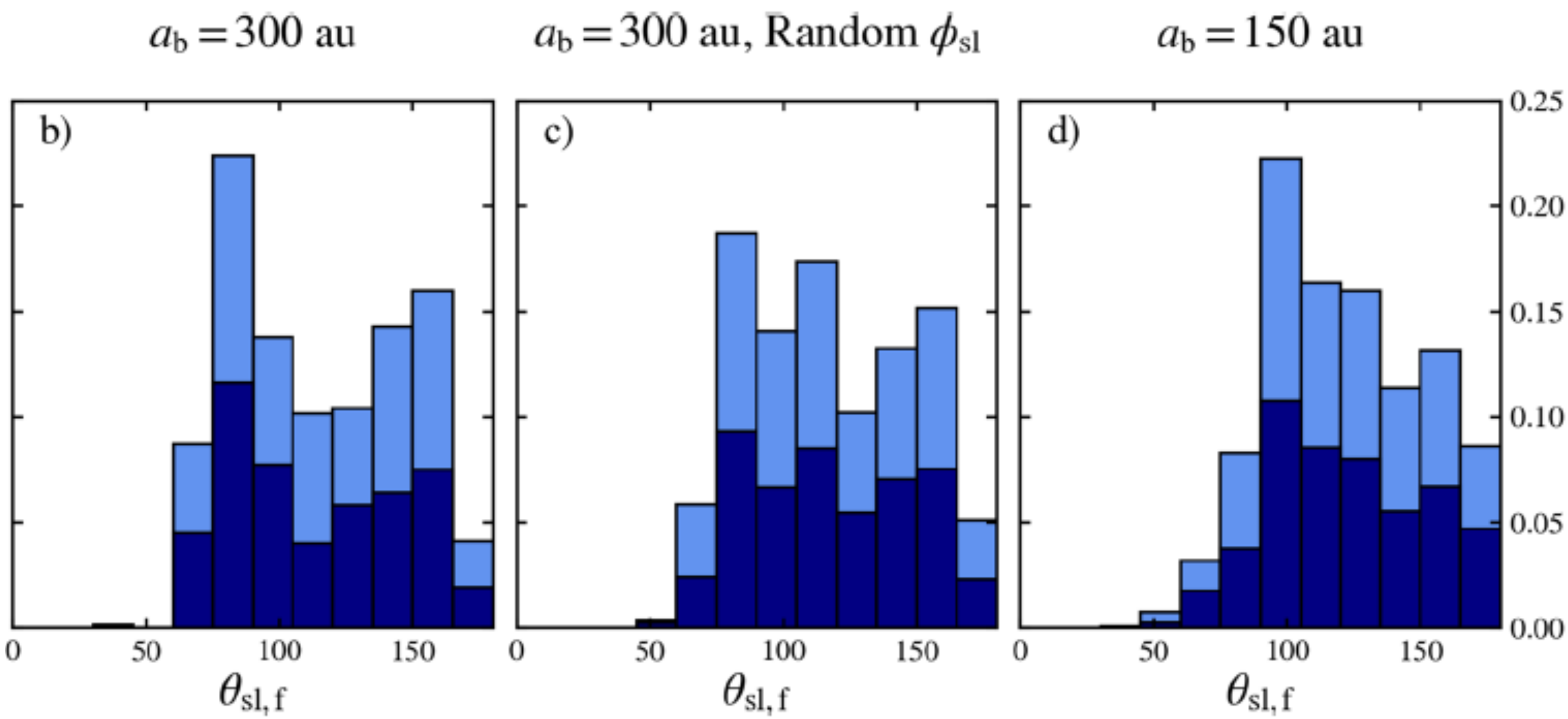




Chaos arises from overlapping resonances (Chirikov criterion)

Storch & Lai 2015,2017

Population synthesis of Lidov-Kozai high-e migration
“Predicted” S-L angle Distribution
(including star-disk-binary interaction prior to LK phase)



Vick, Su & Lai (2023)

Michelle Vick
(Cornell PhD 20→Brown)

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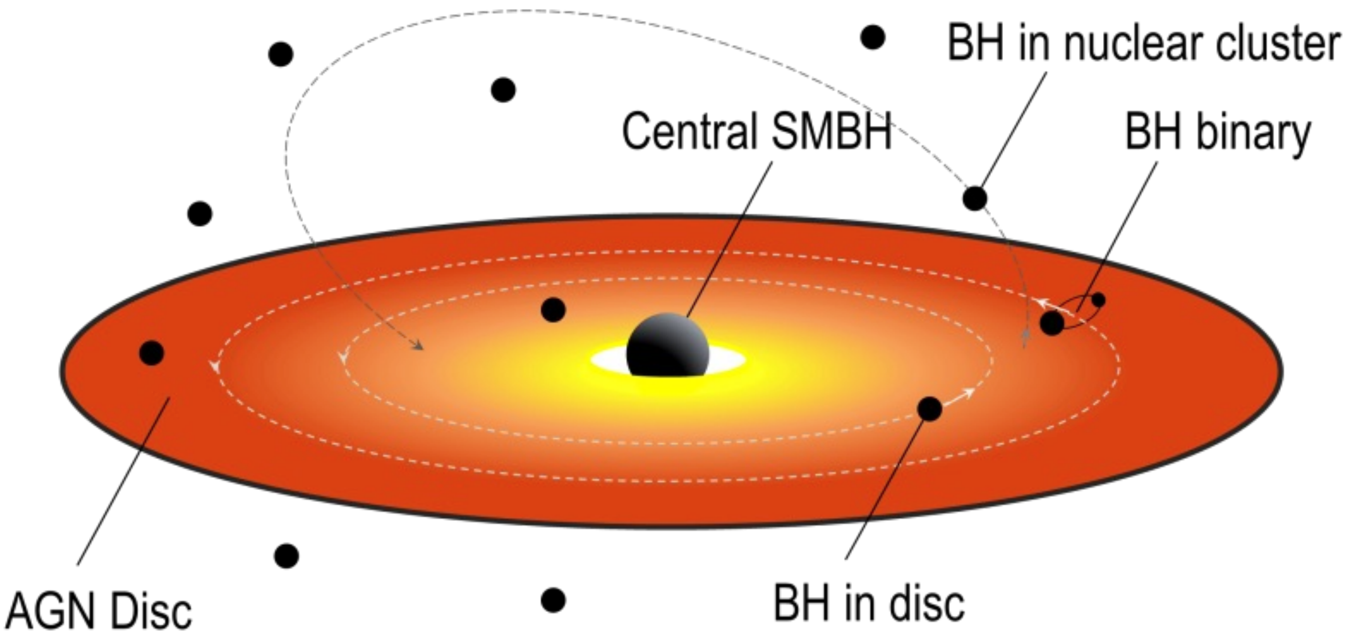
Dynamical Formation Channel:

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



Empirical evidence for massive stars (-> stellar mass BHs) in AGN disks

Galactic Center:

0.04-0.5 pc: OB/WR stars in disk

Broad emission lines of AGN

==> metal rich (independent of redshift)

Dynamical Formation Channel:

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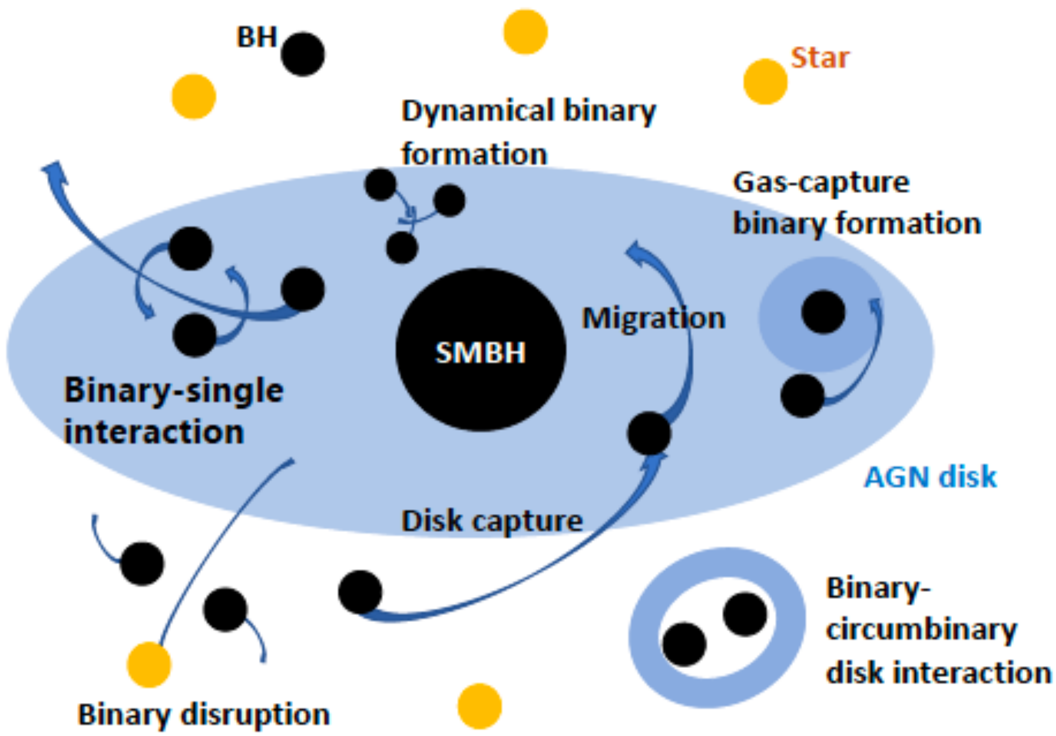


Tagawa+20

Several merger scenarios…

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

AGN channel merger scenarios:

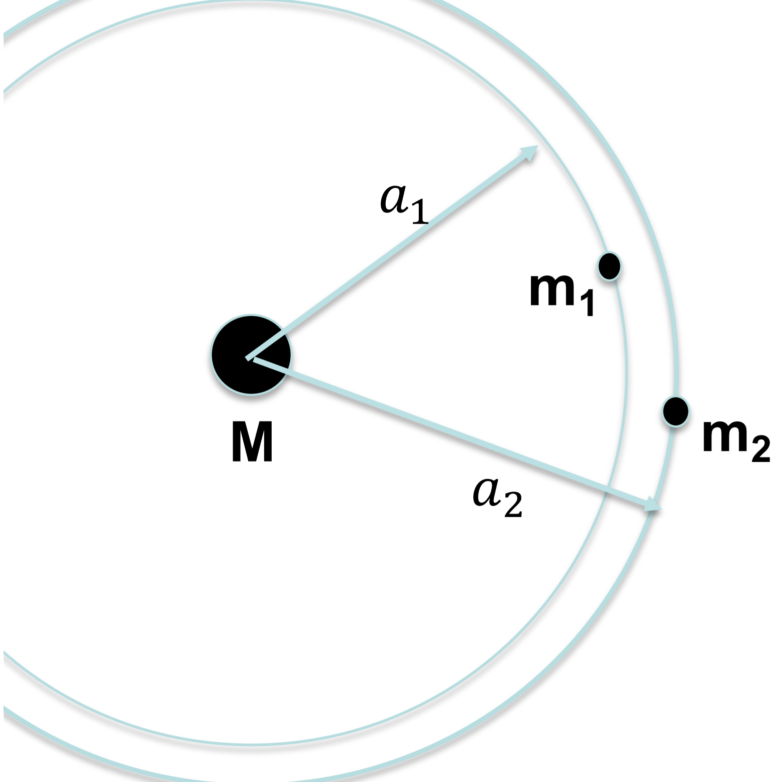
(leading to different "predictions")

-- 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

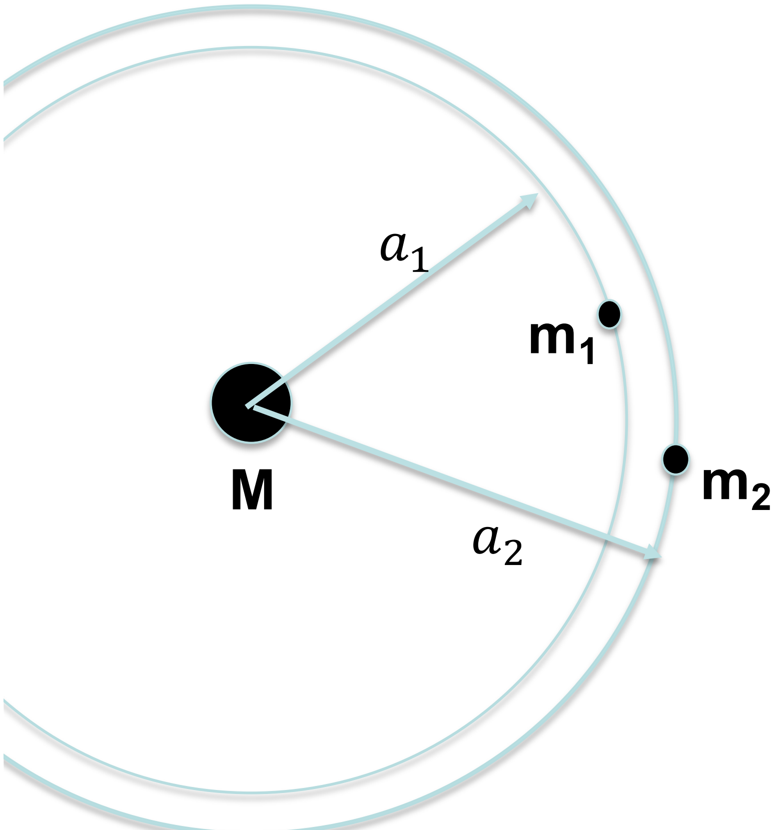
Jiaru Li, Cornell Ph.D.23
➔ Northwestern

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

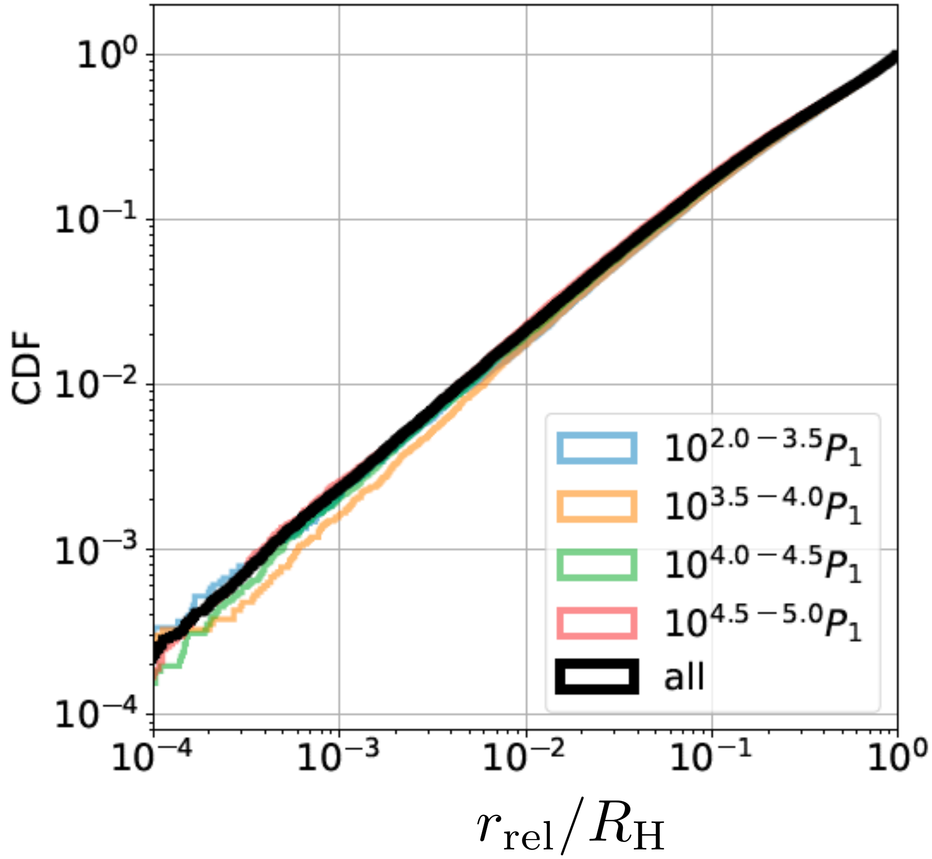
How likely/often does this happen?
("loss cone" problem…)

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

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

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

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



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

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

Once captured, it will take a few orbital period to merge

it enters LIGO band with $e \gtrsim 0.1$

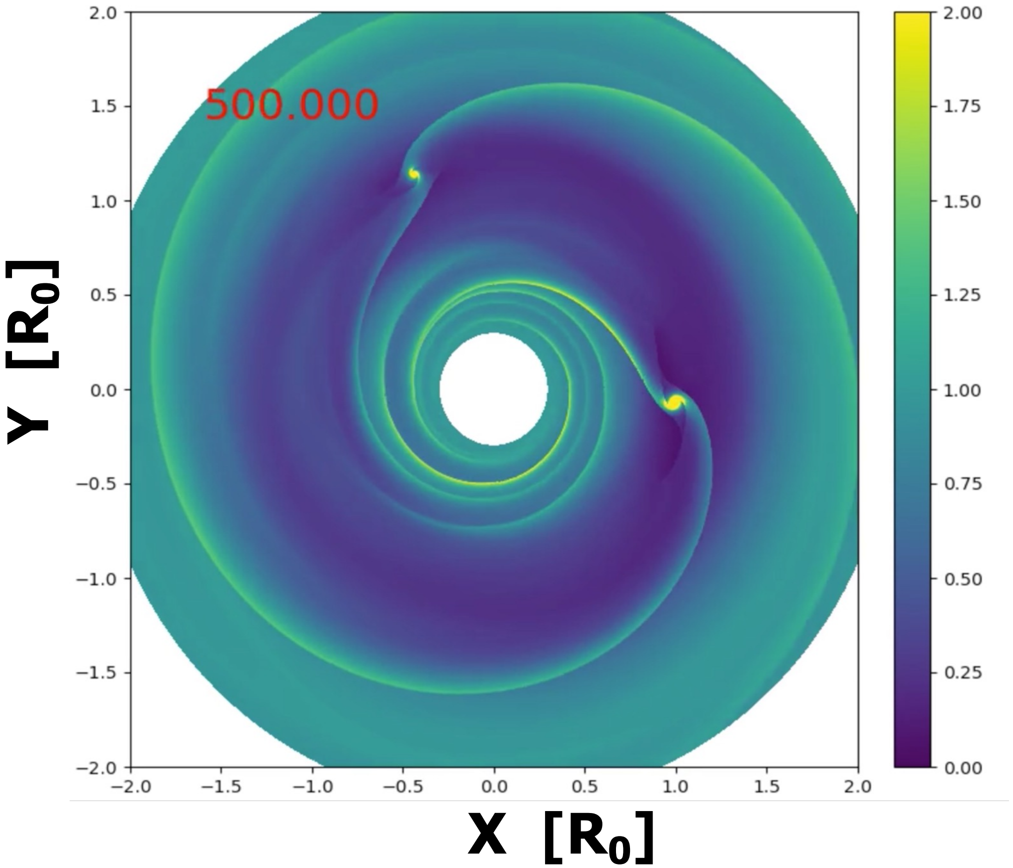
This mechanism always produces eccentric mergers

Li, Lai & Rodet 2022

Rom, Sari & Lai 2024

Gas Effects: Formation of BH binaries
hydrodynamics simulations

Jiaru Li … Hui Li's LANL group… 2023,2025

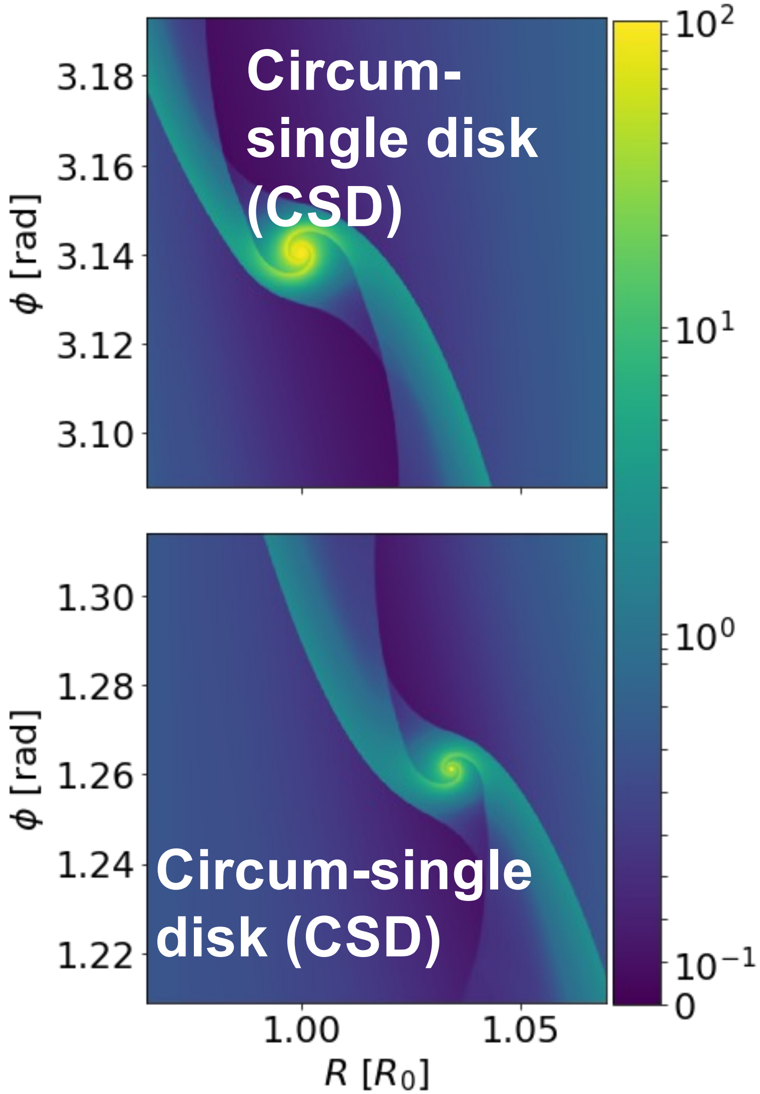


- Initial condition:

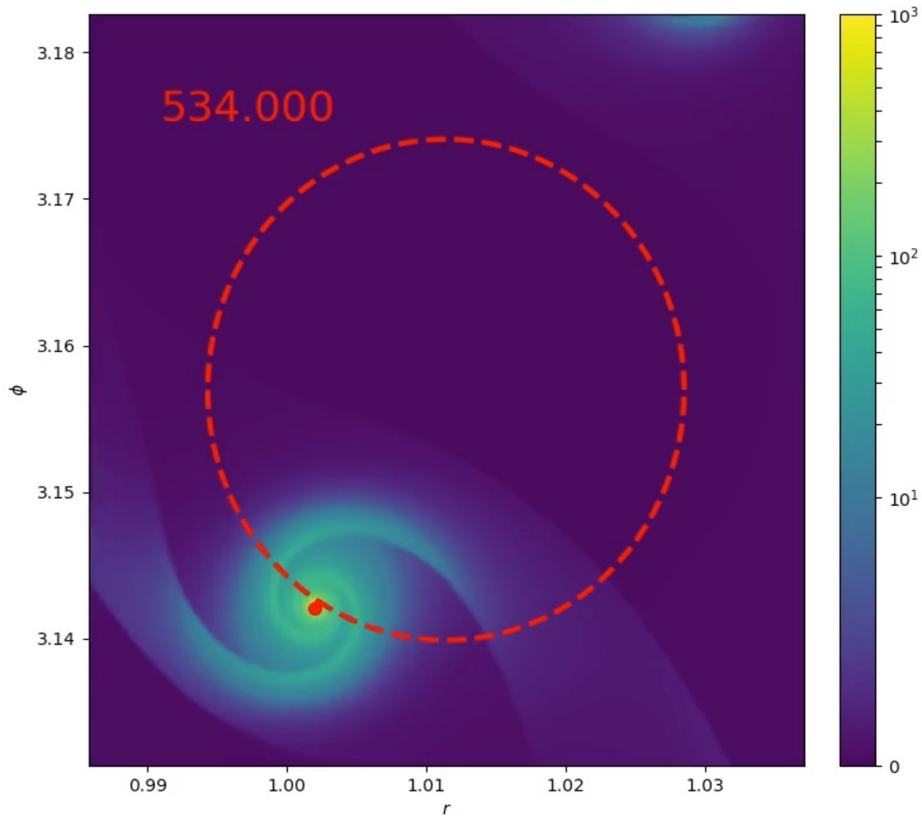
$$a_2 - a_1 = 2R_\mathrm{H}$$

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

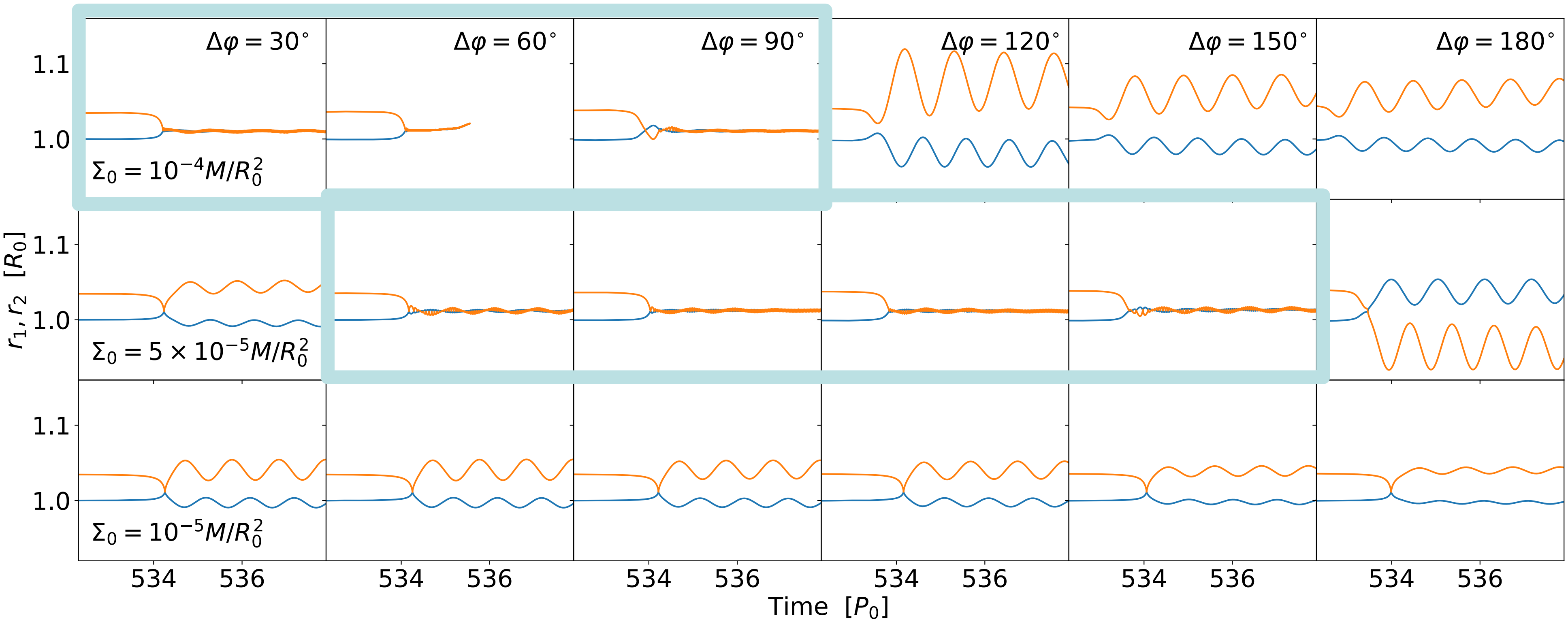
See also Rowan et al. 2023,24;
Whitehead et al 2024



Formation of a binary



Outcomes: depend on gas density, initial $a_2 - a_1 = K R_{\mathrm{H}}$ and orbital phase

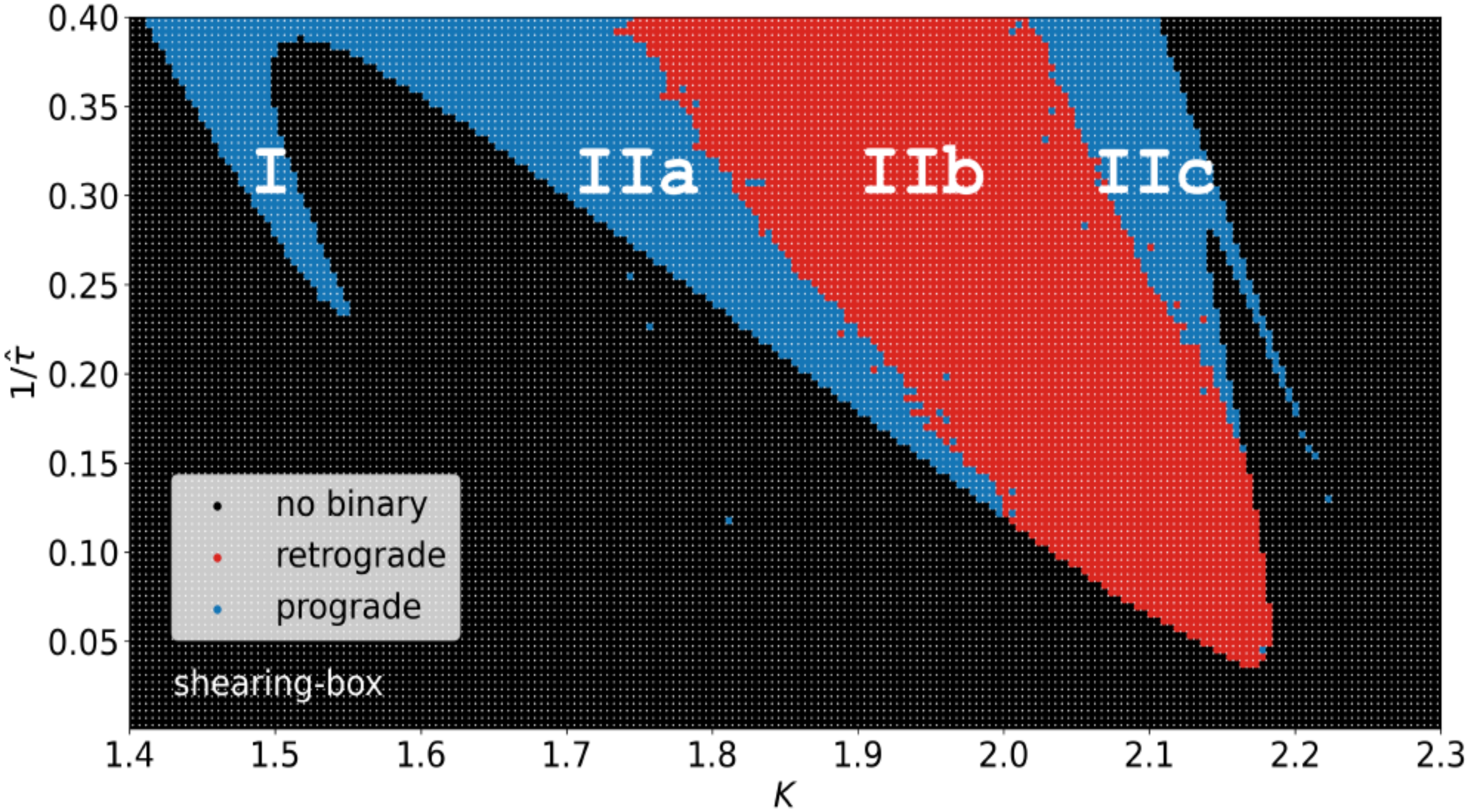


Gas-assisted binary formation: Toy model calculation

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

Gas-assisted binary formation: Toy model calculation

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



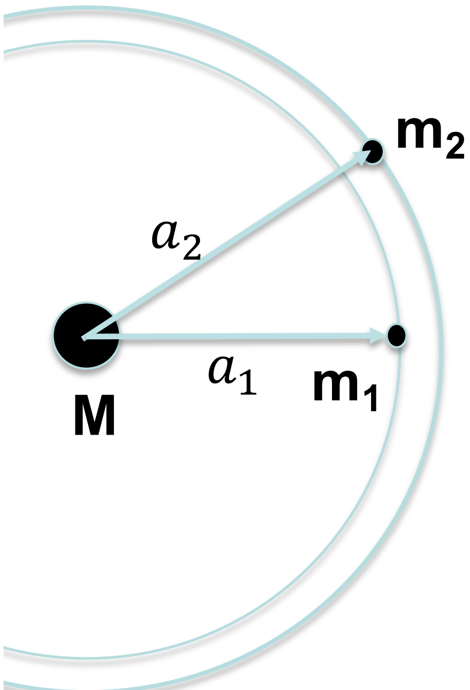
Initial condition:

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

Qian, Jiaru Li & DL 2024

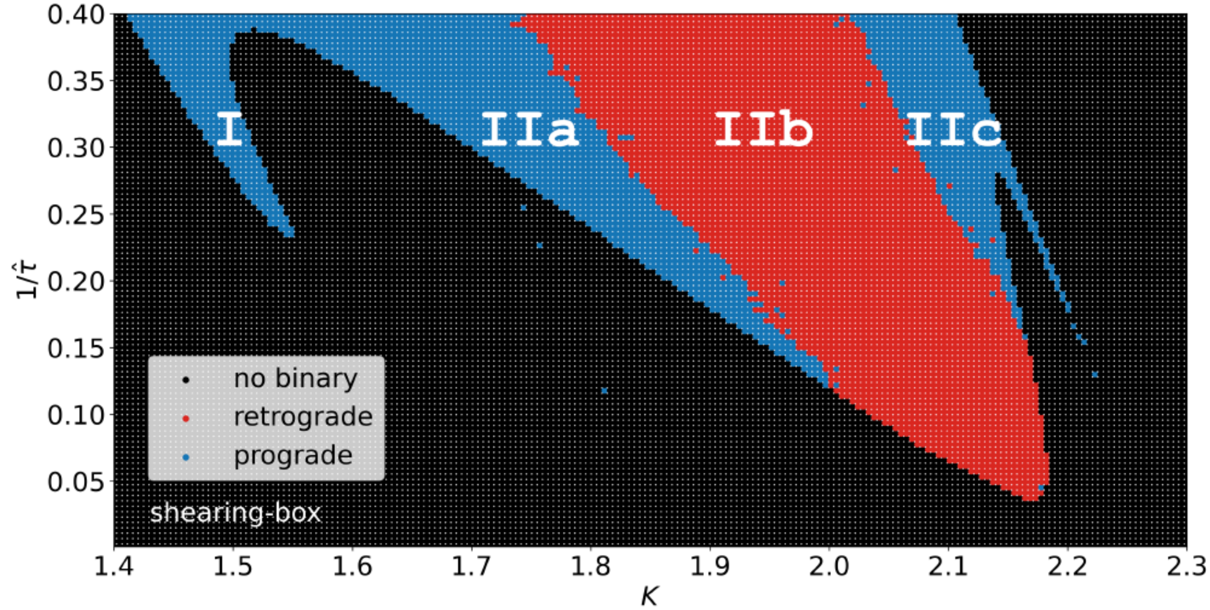
Kecheng (Stephon) Qian
(Cornell ’24 -> UC Berkeley)

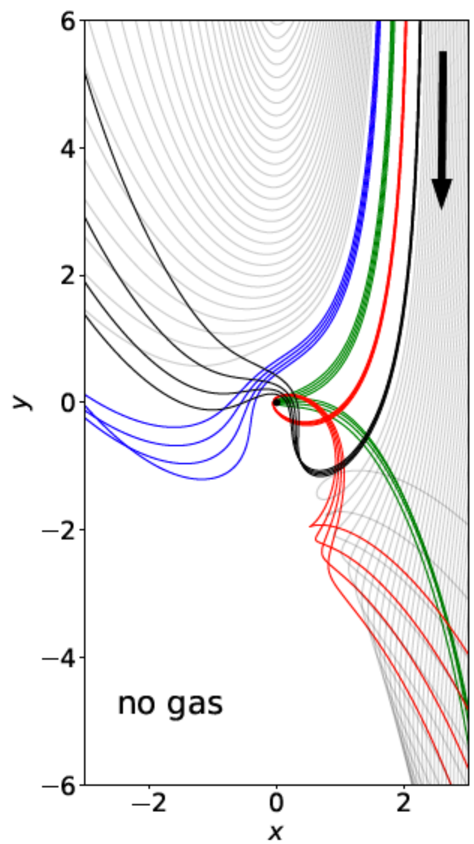
See also
Tjarda Boekholt et al. 2023
Mark Dodici & Tremaine 2024

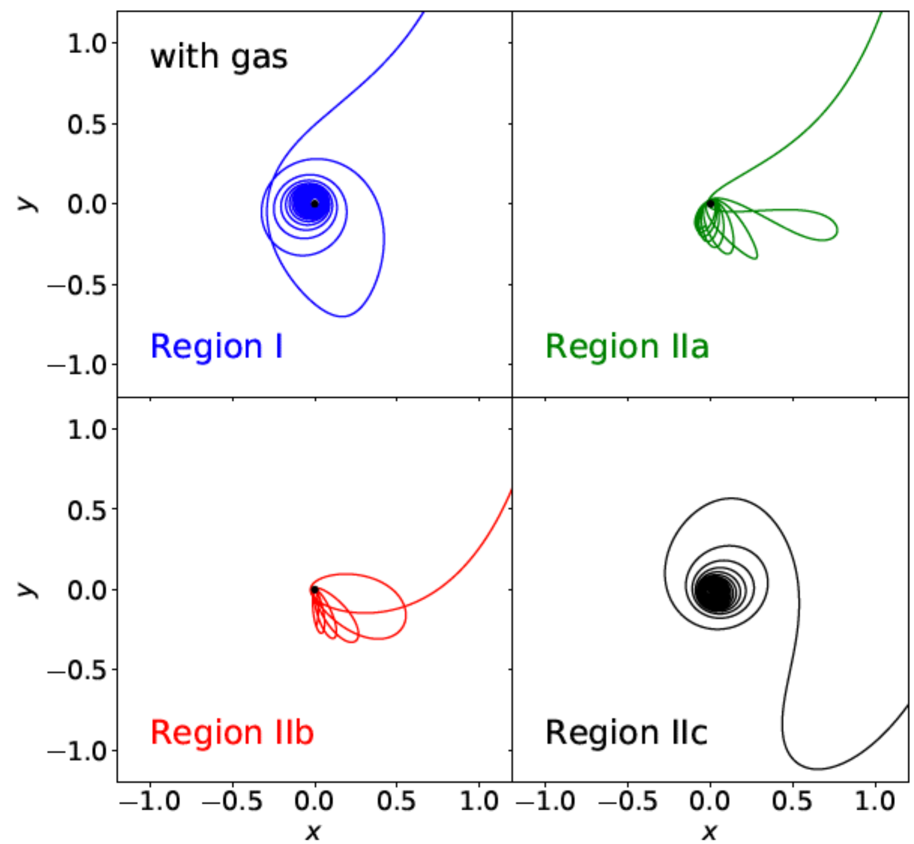


$$a_2 - a_1 = K R_{\mathrm{H}}$$

See Petit & Helon 1986
“Satellite Encounters”

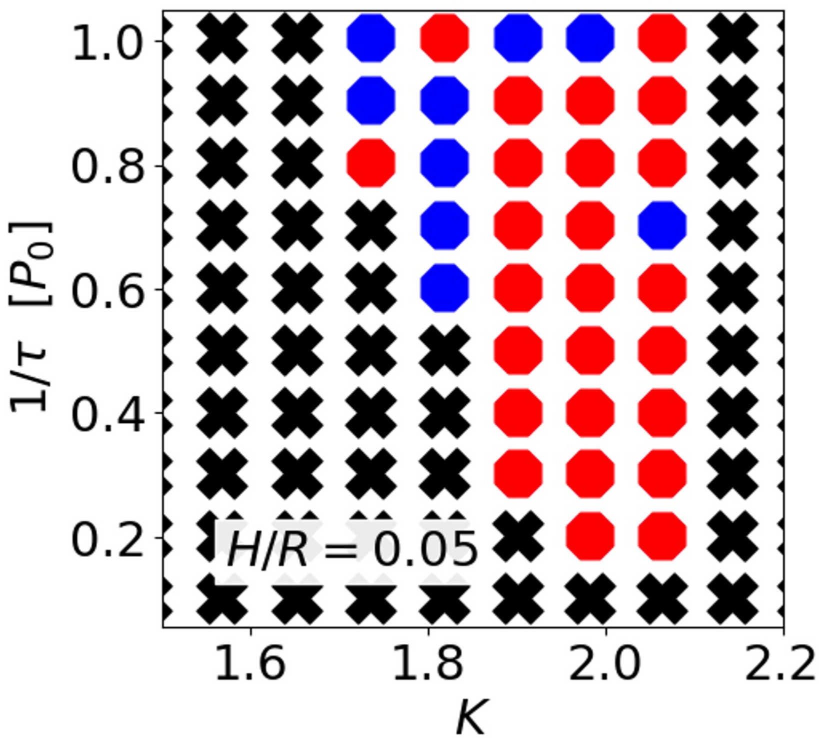




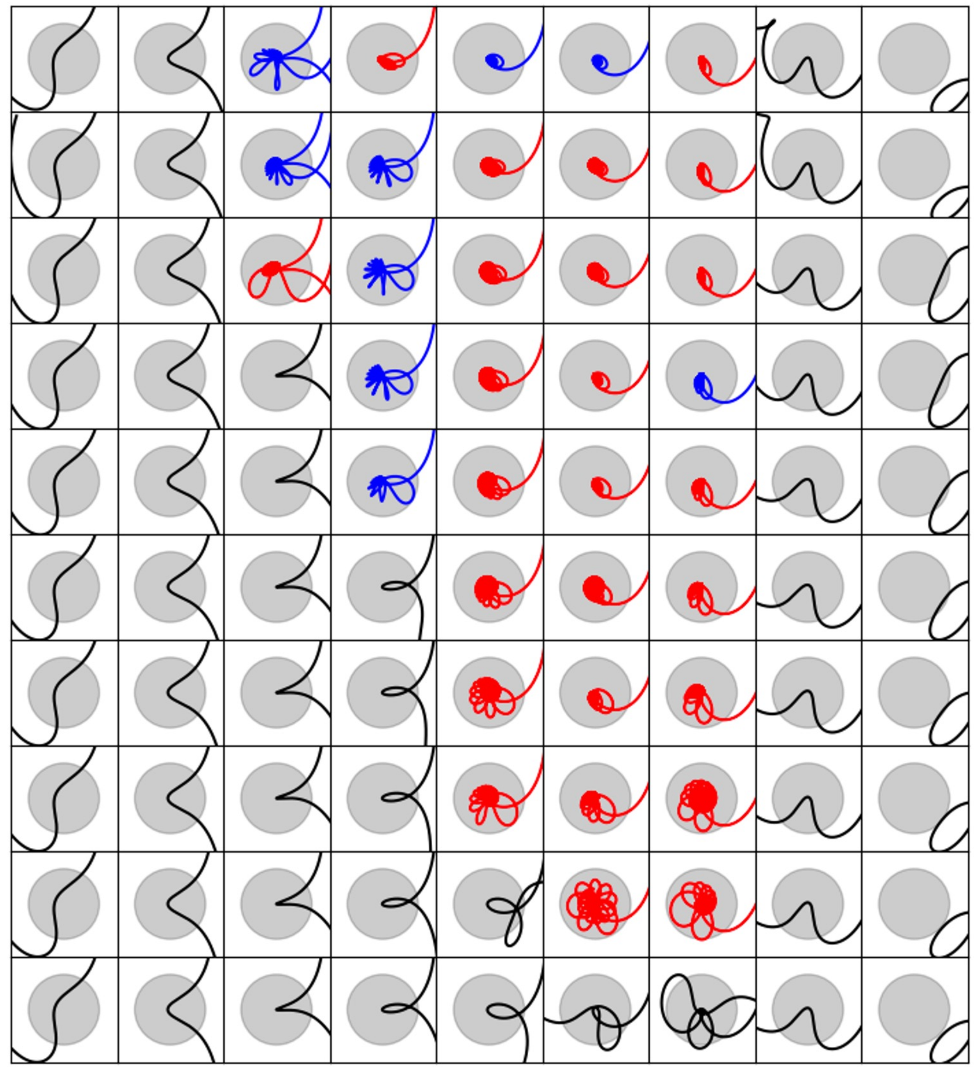


2D Hydro simulation survey:

Jiaru Li et al, 2025 (in prep)



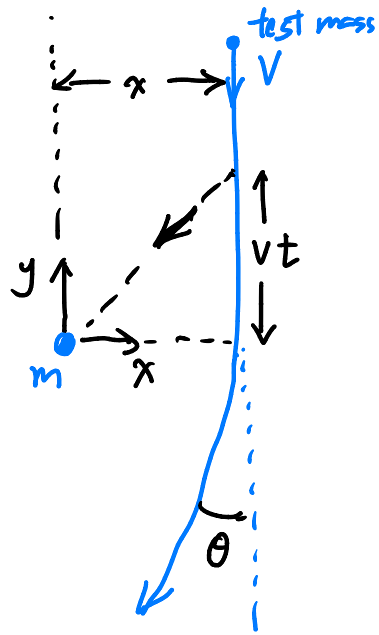
Relative trajectories of the BHs ⇒



Capture happens only for $1.7 \lesssim K \lesssim 2.1$ **Why?** →

Digression:

Two-body encounter

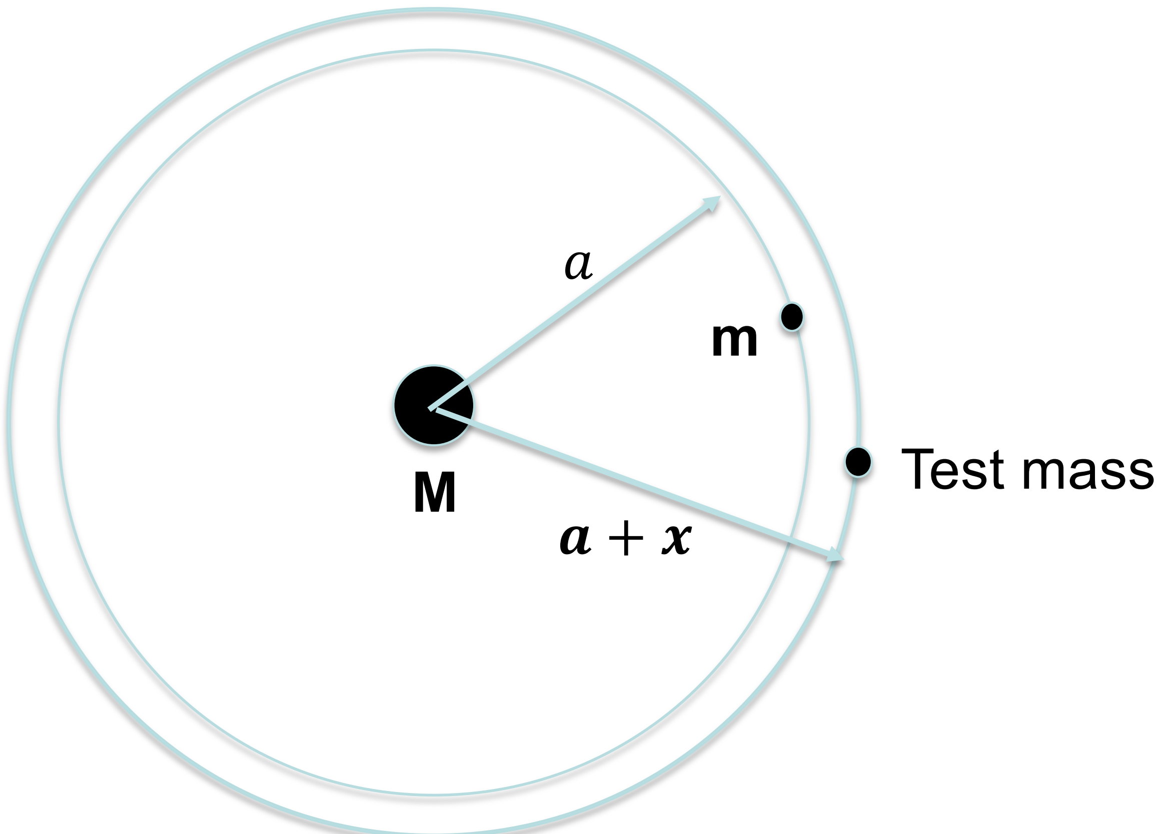


Impulse approximation

$$\Delta P_x \simeq - Gm \int_{-\infty}^{+\infty} \frac{x\,dt}{(x^2 + v^2 t^2)^{3/2}}$$

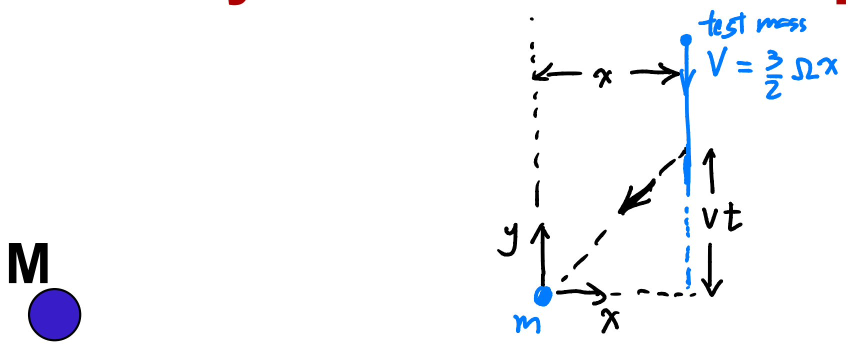
$$= - \frac{2Gm}{xv}$$

Deflection angle $\theta \simeq \dfrac{2Gm}{xv^2}$



a
m
M
$a + x$
Test mass

Two-body encounter in the presence of M



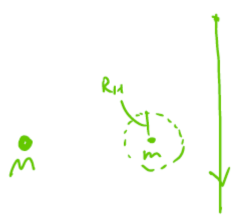
ΔJ = loss of angular momentum by the test mass due to m's gravity from ∞ to the point of the closest approach

Impulse approximation

$$\Delta J = \int_{-\infty}^{0} dt \; a\,|f_y|$$

$$= \frac{Gma}{x^2}\,\frac{2}{3\Omega}$$

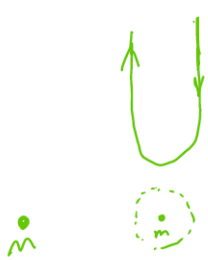
Depending on x, there are 3 outcomes



* If $\Delta J(x) < \sqrt{GM(a+x)} - \sqrt{GM(a+R_H)} \simeq \sqrt{GMa}\,\frac{x-R_H}{2a}$

  $\iff x > 2R_H$

  the particle loses little AM and will always stay outside R_H



* If $\Delta J(x) > \sqrt{GM(a+x)} - \sqrt{GMa} \simeq \sqrt{GMa}\,\frac{x}{2a}$

  $\iff x \lesssim 1.6\,R_H$

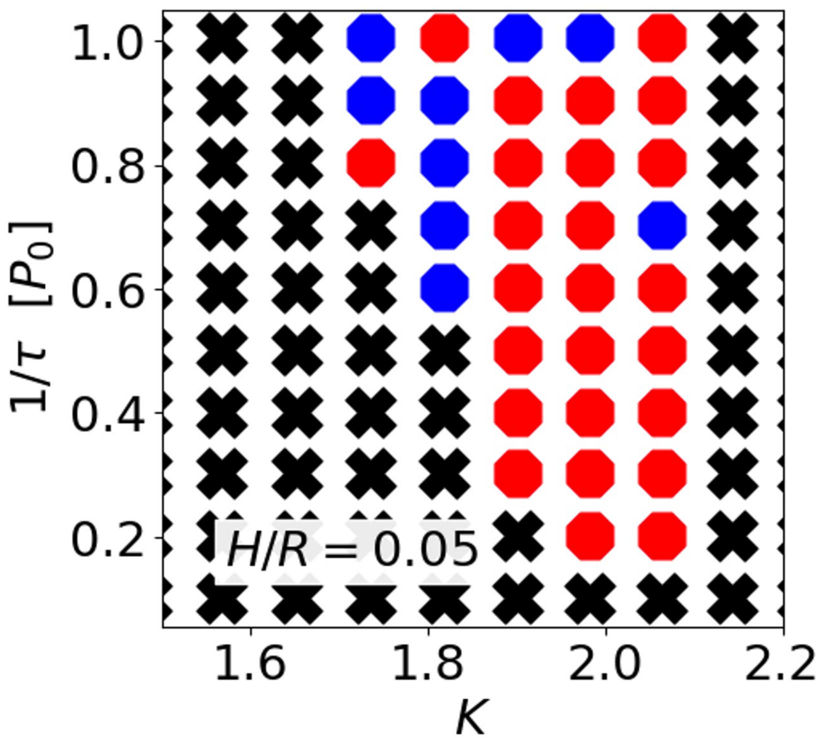
  the particle loses enough AM to be pushed into the $x<0$ region

  $\Rightarrow$ horseshoe orbit

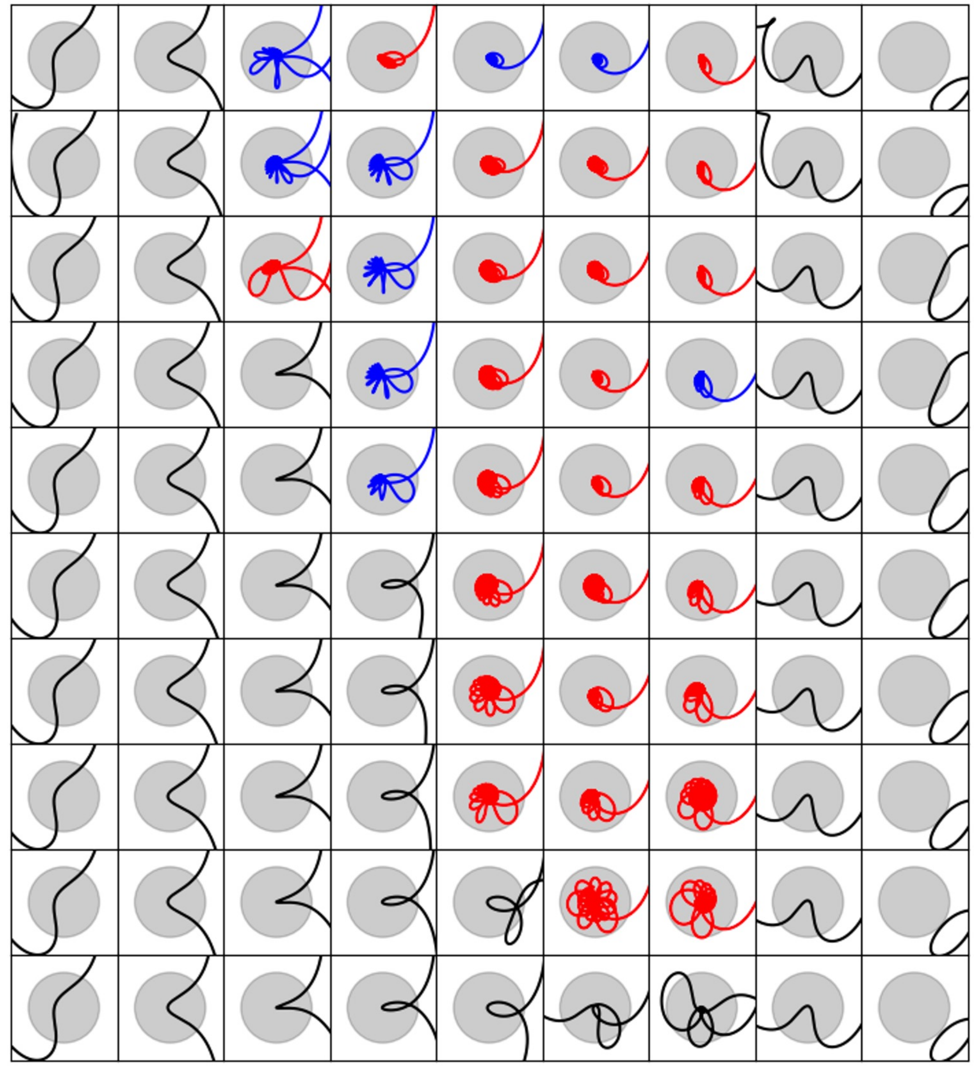
* If $1.6\,R_H \lesssim x \lesssim 2\,R_H$, the particle collides with Hill sphere.

2D Hydro simulation survey:

Jiaru Li et al, 2025 (in prep)

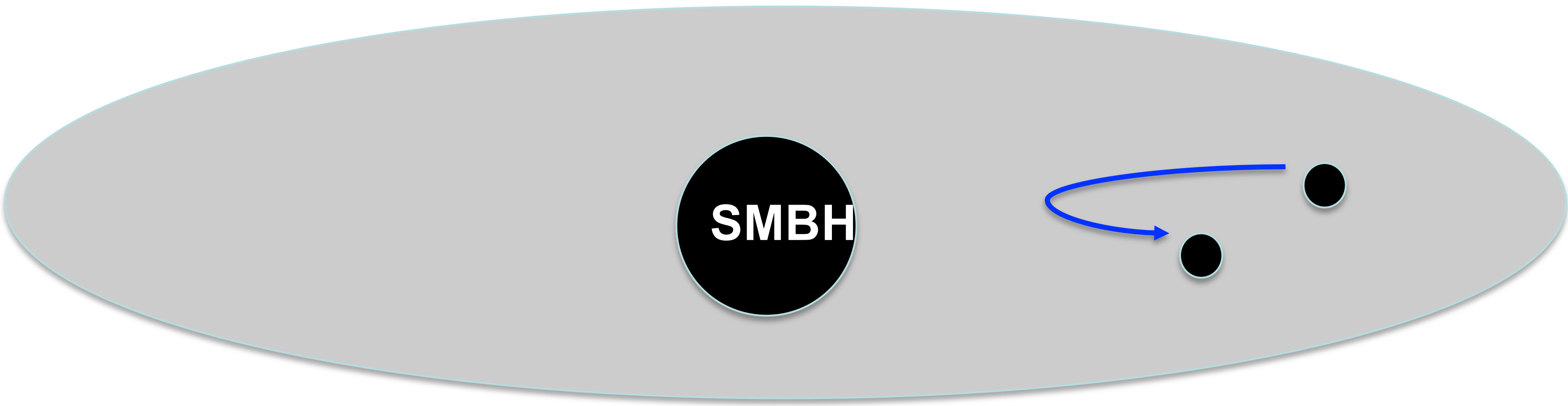


Relative trajectories of the BHs ⇒



Capture happens only for $1.7 \lesssim K \lesssim 2.1$

Gas effects: Embedded Binary in AGN Disk

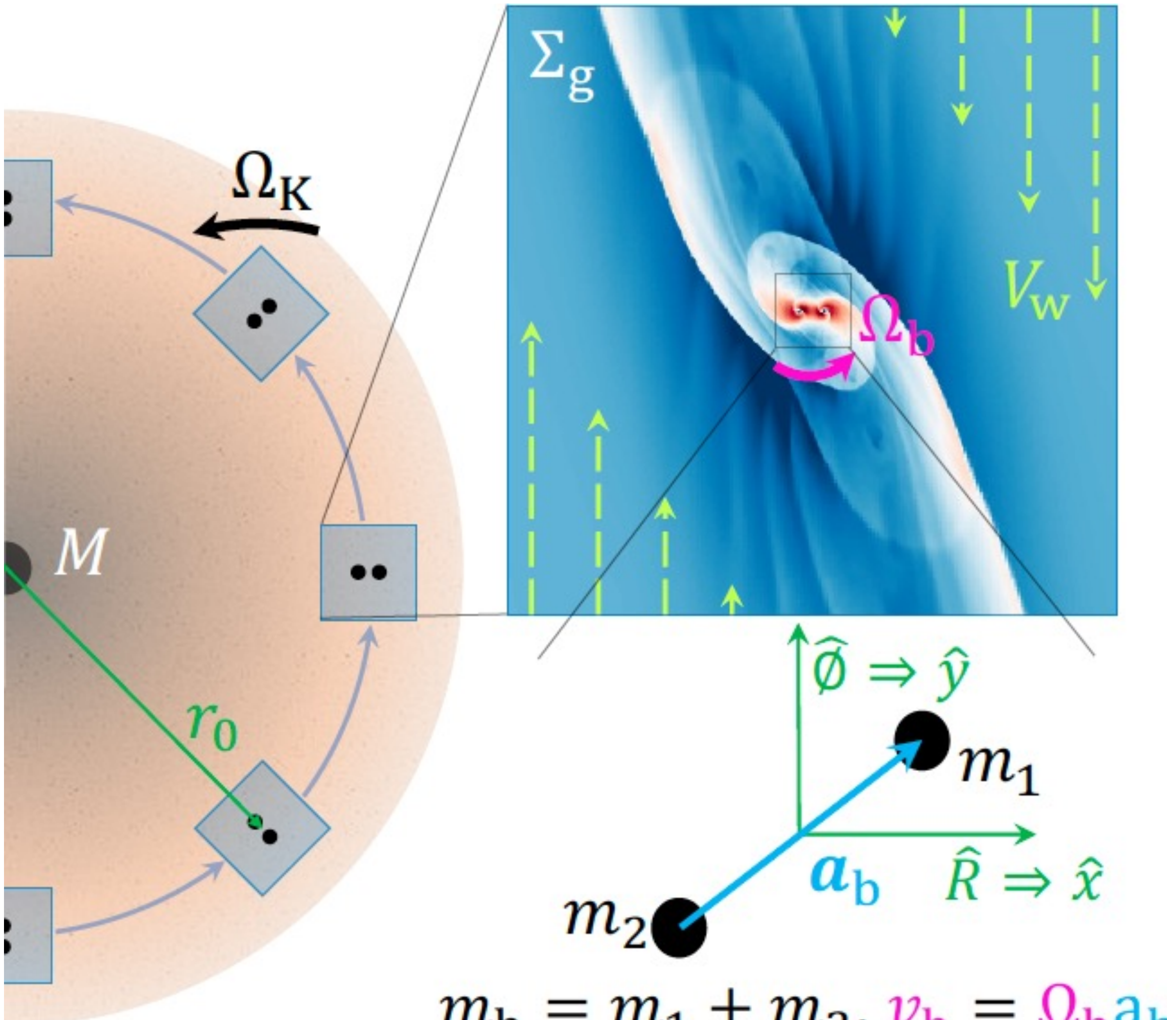


Baruteau et al. 2011
Y.Li,… H.Li… 2021
Dempsey, H.Li… 2023
R.Li & DL 2022,23,24

Local simulations of binary in disk

R.Li & Lai 2022,2023,2024

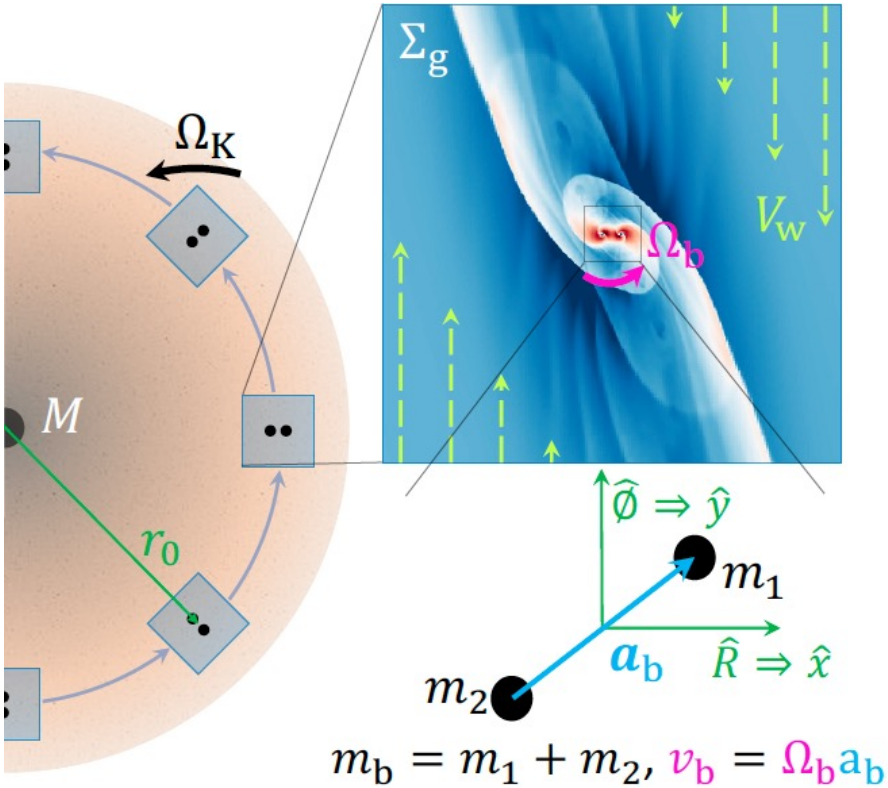
Dr. Rixin Li
(Cornell -> Berkeley)



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

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:

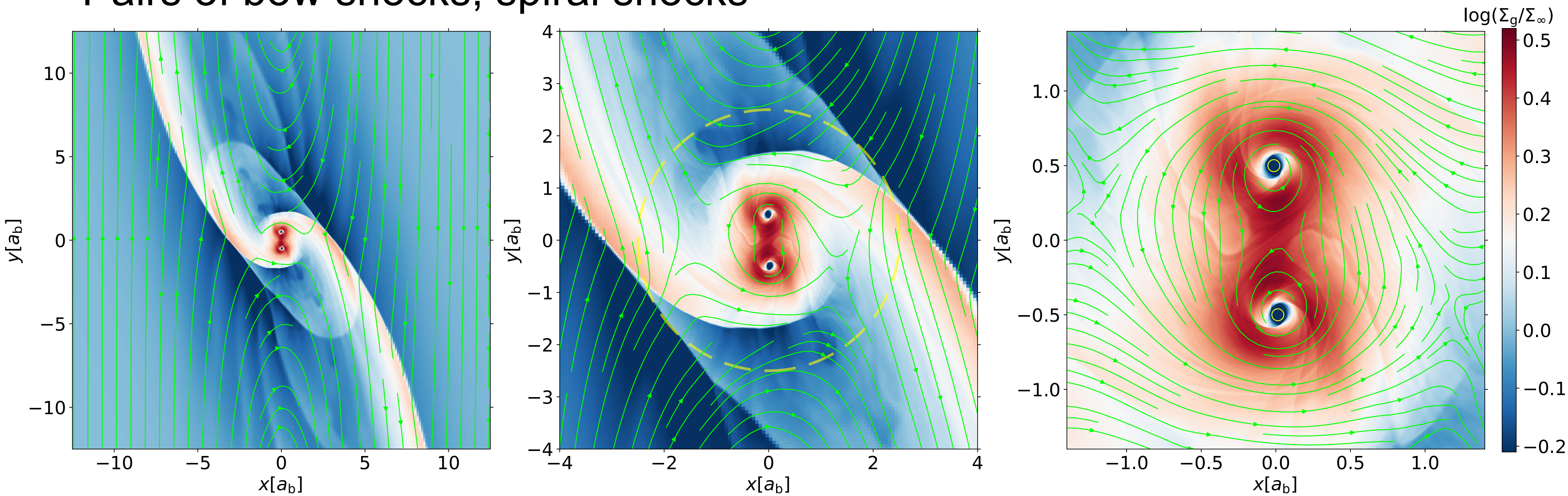
$$\frac{q}{h^3}, \quad \frac{R_H}{a_b} \equiv \lambda$$

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

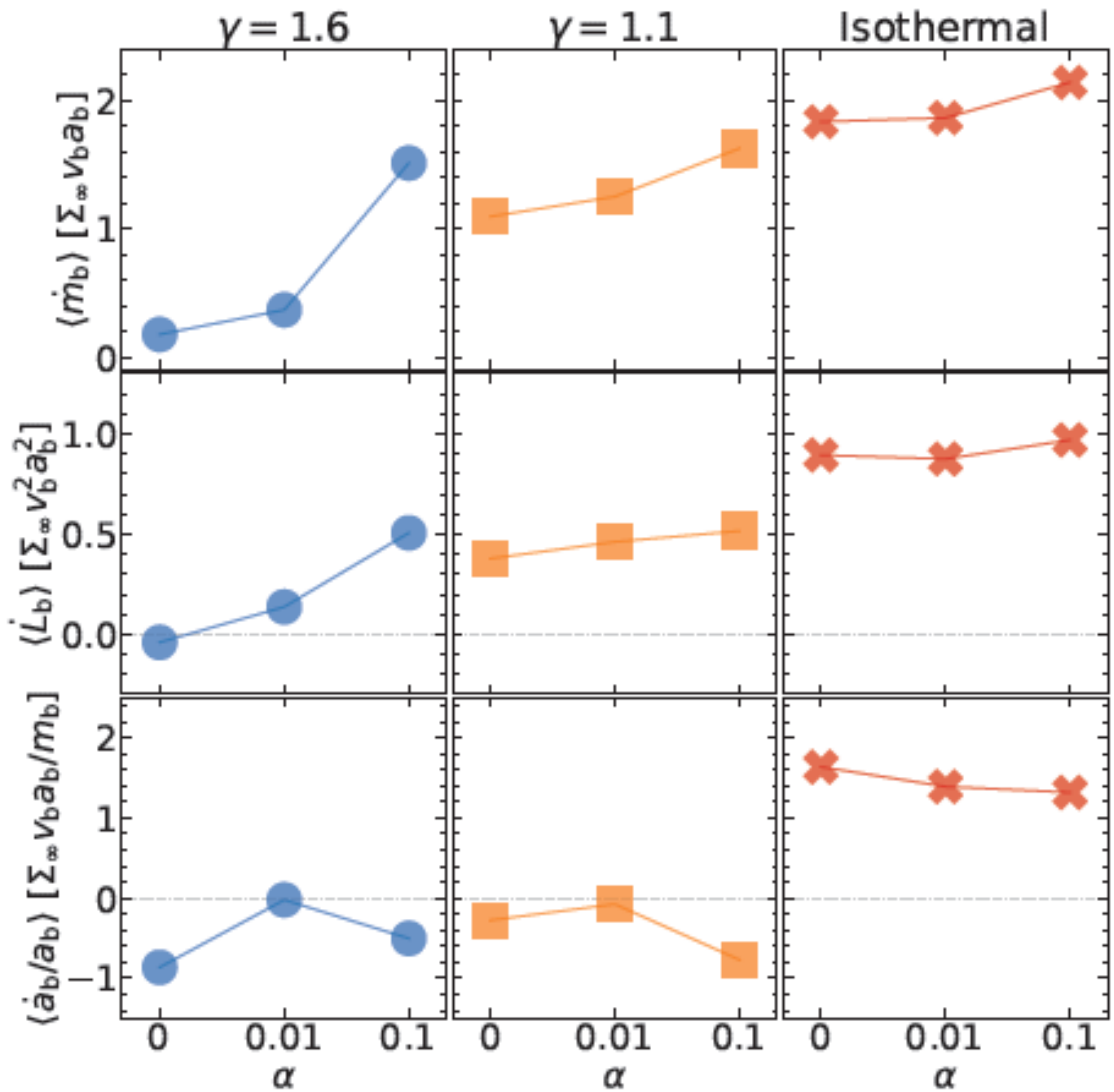
Pairs of bow shocks, spiral shocks



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

Force on each BH: from gravity + accretion + pressure

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



Rixin Li & DL 2024

$$\frac{m_1}{m_2}=1,\ e_b=0,\ \frac{R_{\rm H}}{H}=\left(\frac{q}{h^3}\right)^{1/3}=3^{1/3},\ \frac{R_{\rm H}}{a_{\rm b}}=5$$

prograde

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.

Take-Home Messages

Formation Channels of Merging BH Binaries:

Isolated binary evolution: ”standard model”

Dynamical formation channels:

1. Dense star clusters
2. Tertiary-induced mergers
3. BH Mergers in AGN disks

All can contribute: Rates, branching ratios uncertain… “smoking guns”?

More detections (aLIGO, ET), LISA useful for probing dynamical formation

Planetary dynamics applied to new/different regimes

e.g.

-- Spin-orbit coupling: GR vs Newtonian gives different spin obliquities

-- BH-BH scatterings around SMBH vs planet-planet scatterings

Loss cone via GW bremsstrahlung

-- Binary capture vs pebble accretion…

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Shanghai, China | December 8-12, 2025

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