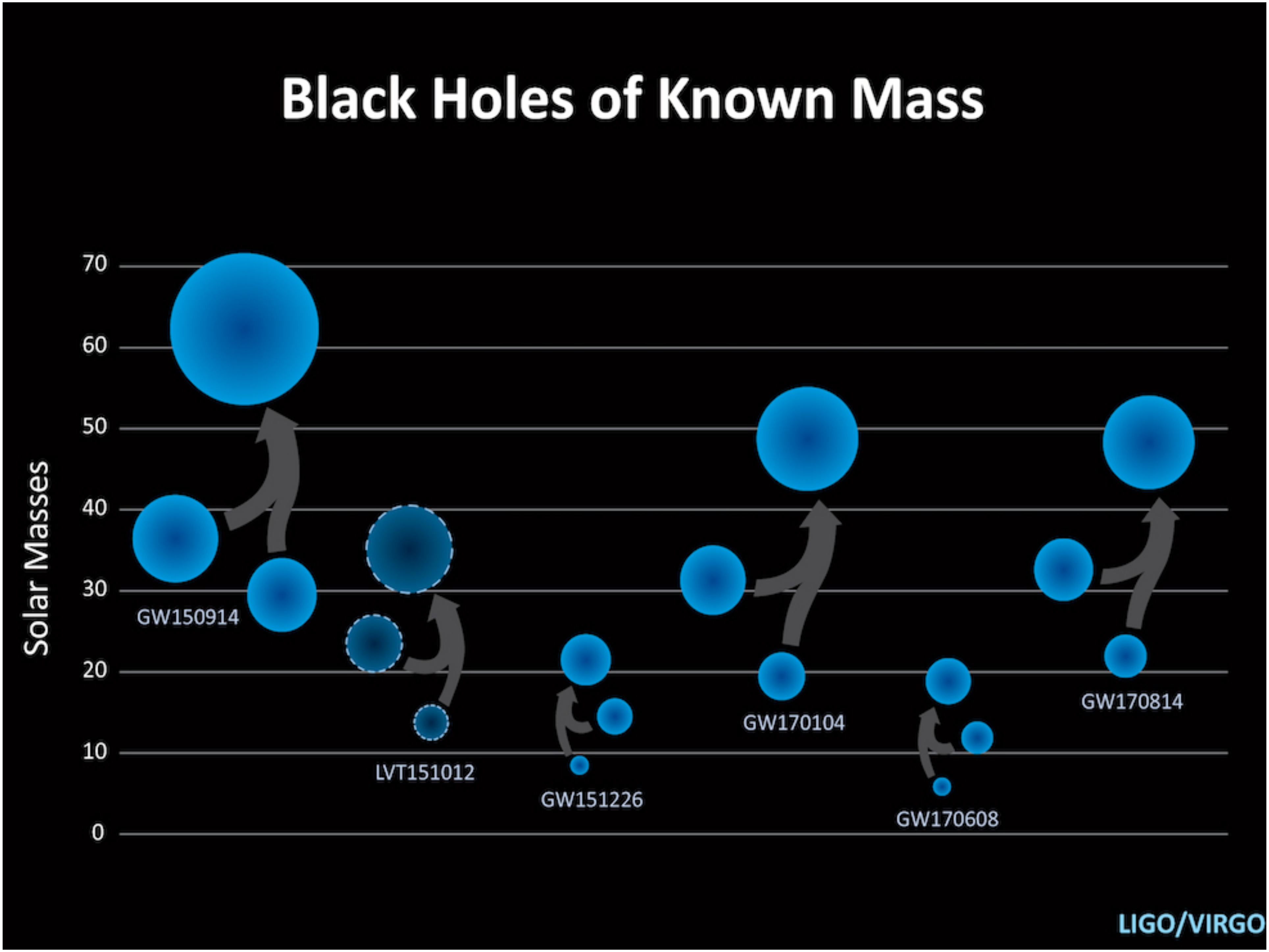
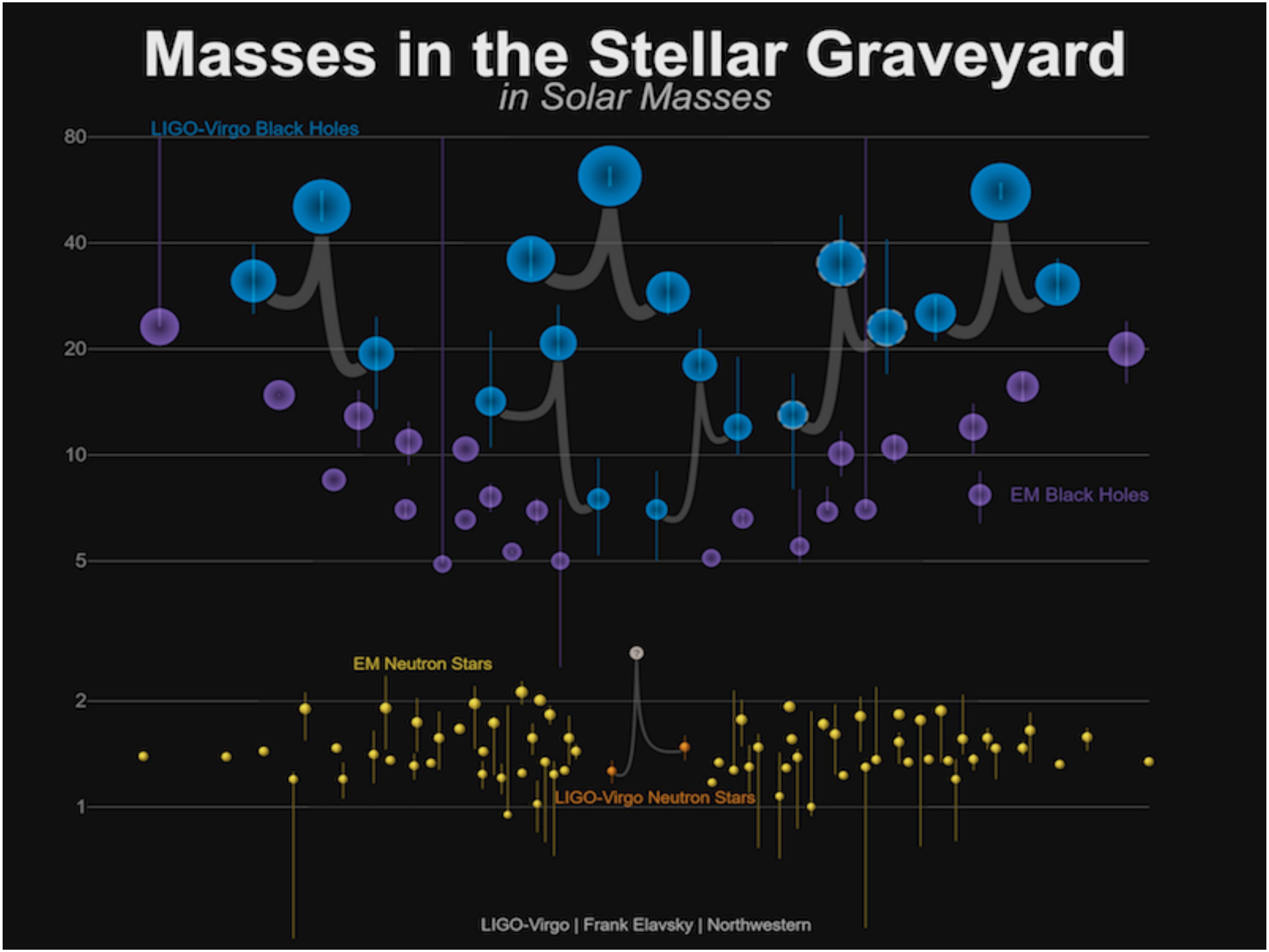
LIGO Results/Surprises?

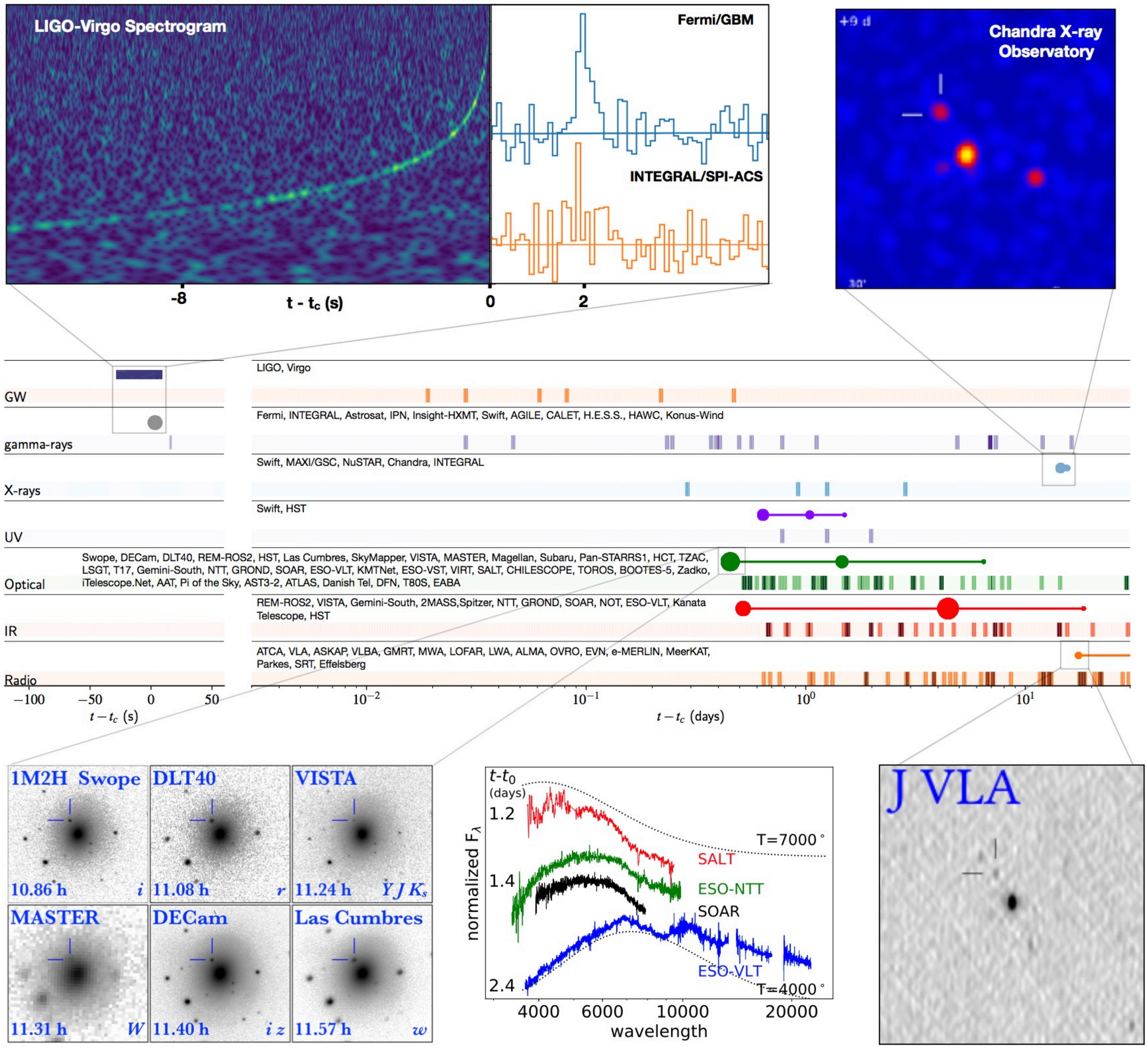
Dong Lai
Cornell University

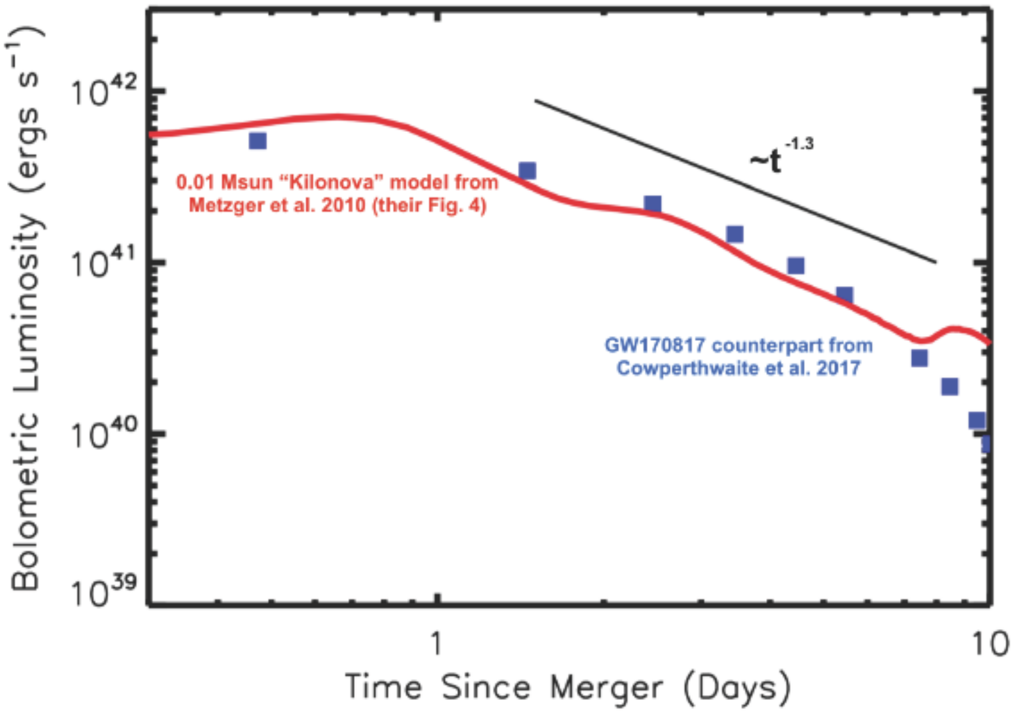
“Exploding Universe” Workshop, TDLI, 5/28/2018

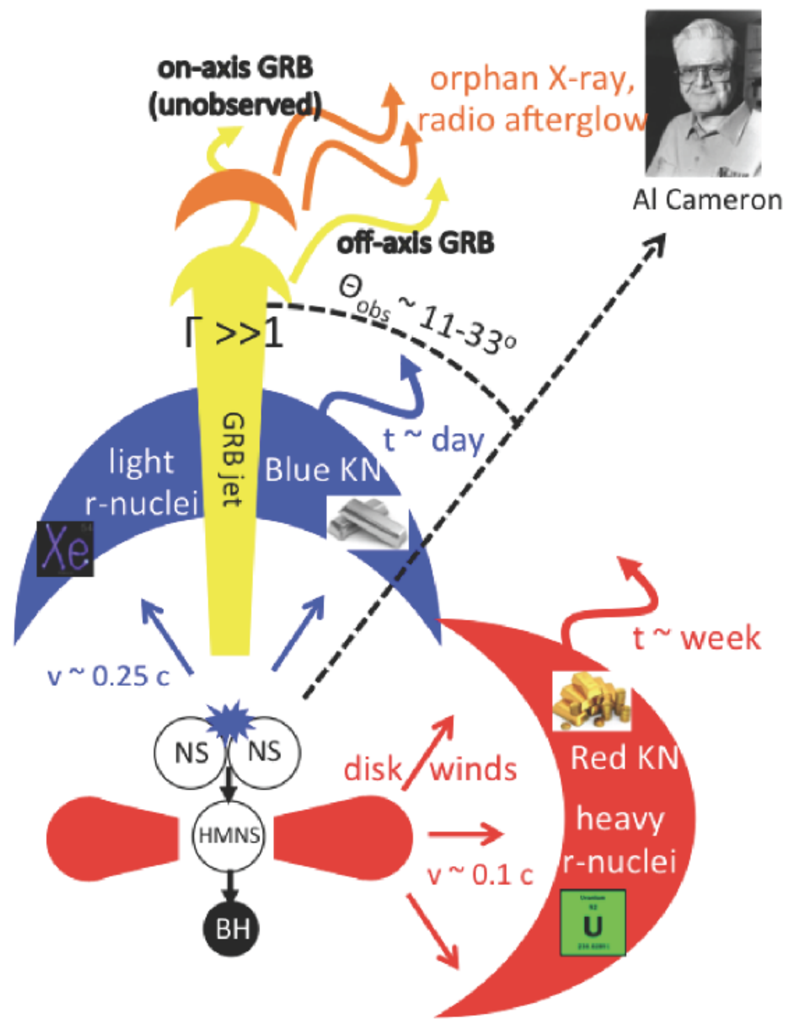

Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814
LIGO/VIRGO


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
2
1
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

GW170817 / AT2017gfo







Metzger 2017

LIGO Surprises?

1. Tidal Resonances → NS EOS

2. Dynamical Formation of BH Binaries and Spin-Orbit Misalignments

Dong Lai

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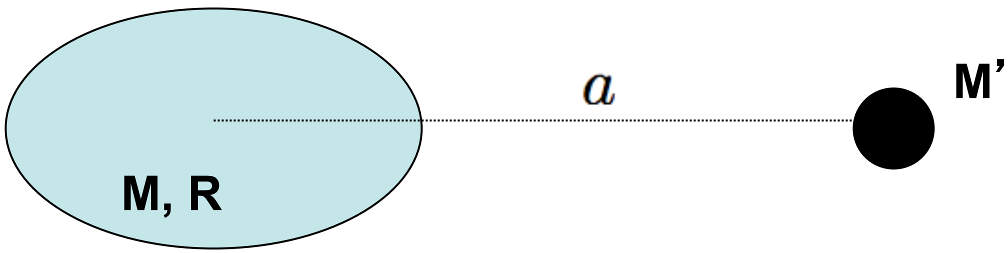
Tides in Merging NS Binaries

➔ Probe NS EOS

-- Quasi-Equilibrium tides

-- Resonant (Dynamical) tides

"Quasi-Equilibrium" Tide (F-mode Distortion)



$$V = -\frac{MM'}{a} - \mathcal{O}\left(k_2 \frac{M'^2 R^5}{a^6}\right)$$

$k_2 =$ Love number

$$d\Phi = d\Phi^{(0)}\left[1 - \mathcal{O}\left(\frac{k_2 M' R^5}{M a^5}\right)\right]$$

(GW Phase Shift)

➔ **Important only at small separation (just prior to merger)**

(Kochenek; Bildsten & Cutler; Lai, Rasio & Shaipro, etc 1990s)

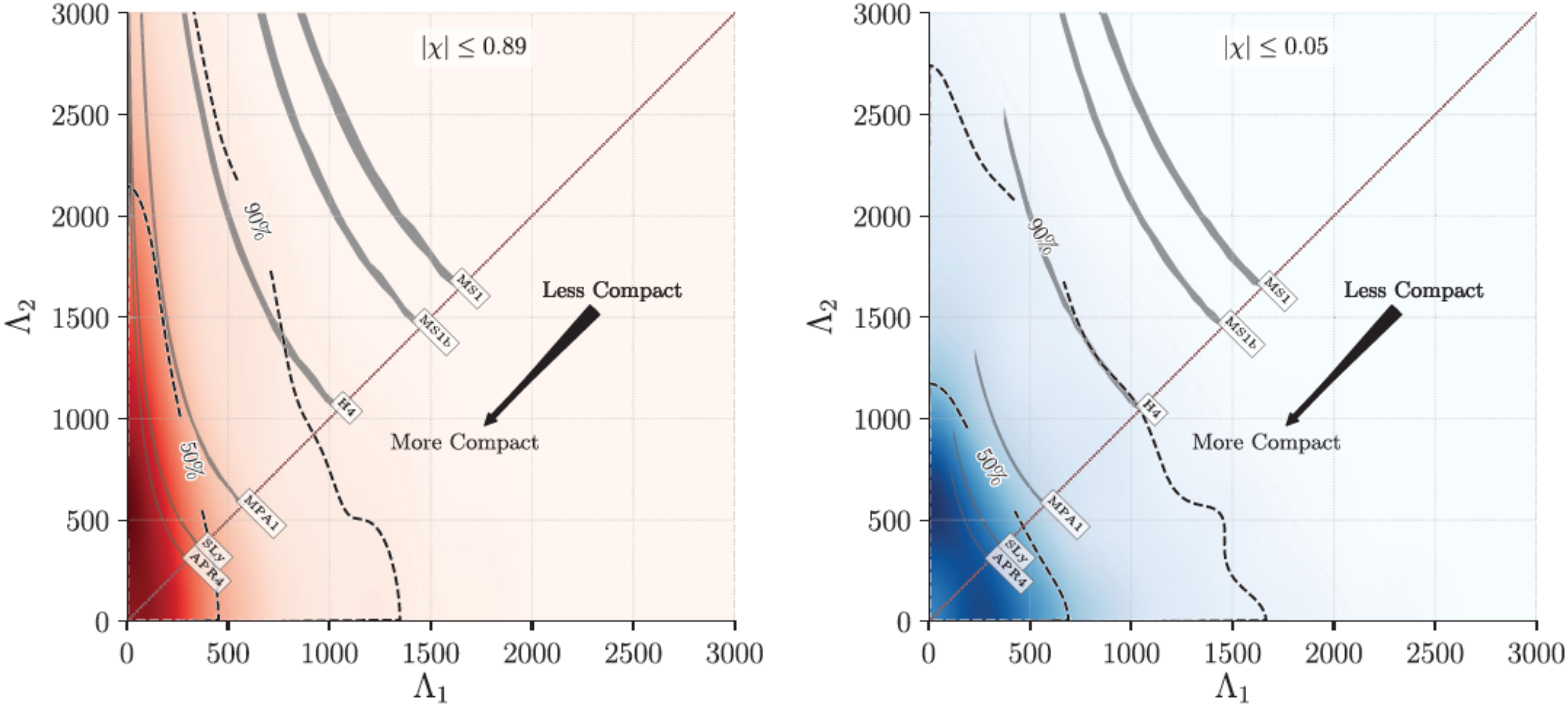
Numerical GR Quasi-equilibrium NS binary sequence

(Baumgarte, Shapiro, Teukolsky, Shibata, Meudon group, etc. 1990s--200x)

Recent (semi-analytic) GR calculation of tidal effect

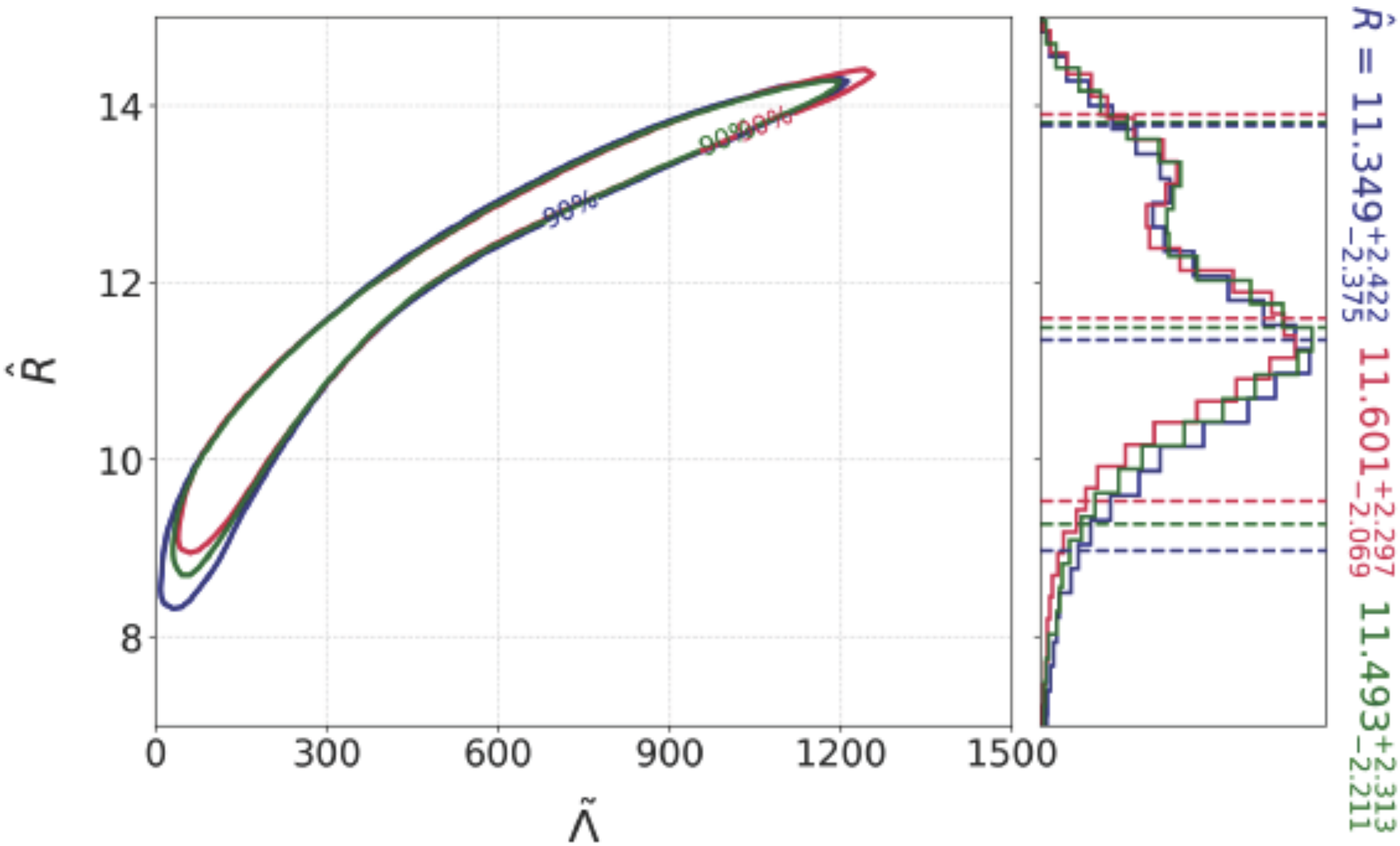
(Hinderer, Flanagan, Poisson, Damour, Penner, Andersson, Jones, etc., 2008+)

GW170817:



$$\Lambda_2^{(i)} = \frac{2}{3} k_2^{(i)} \left[\left(\frac{c^2}{G} \right) \left(\frac{R_i}{M_i} \right) \right]^5$$

GW170817:



De, Finstad, Lattimer et al. 2018

Resonant Tides:
Excitations of Internal Modes

NS has low-frequency oscillation modes:

g-modes (~100 Hz)
inertial modes (incl. r-modes)

Resonance: $$\sigma_\alpha = m\Omega_{\rm orb}, \quad m = 2, 3, \cdots$$

Rosonant tidal excitations of NS modes during inspiral

➔ transfer orbital energy to NS
➔ GW phase shift

Resonant Excitations of NS Oscillations During Inspiral

$$\Delta\Phi \propto \frac{(Q_{\alpha,lm})^2}{\epsilon_\alpha \sigma_\alpha}, \quad Q_{\alpha,lm} = \int d^3x \, (\delta\rho_\alpha)^\star \, r^l Y_{lm}$$

Non-rotating NS:

G-mode (Reisenegger & Goldreich 94; DL 94; Shibata 94)

Rotating NS:

G-mode, F-mode, R-mode (Ho & DL 99)

Inertial modes (DL & Wu 06)

R-mode (excited by gravitomagnetic force; Racine & Flanagan 06)

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G-mode, F-mode, R-mode (Ho & DL 99)
Inertial modes (DL & Wu 06)
R-mode (excited by gravitomagnetic force; Racine & Flanagan 06)

Recent works:

- Superfluid NSs: Yu & Weinberg 2017
- Gravity-inertial modes, scalings (parameterized EOS): Xu & DL 2017

Wenrui Xu
(Cornell → Princeton)

G-modes

crustal density continuities
thermal stratification
stable composition stratification of core: symmetry energy, superfluidity

Parameterize the uncertainties:

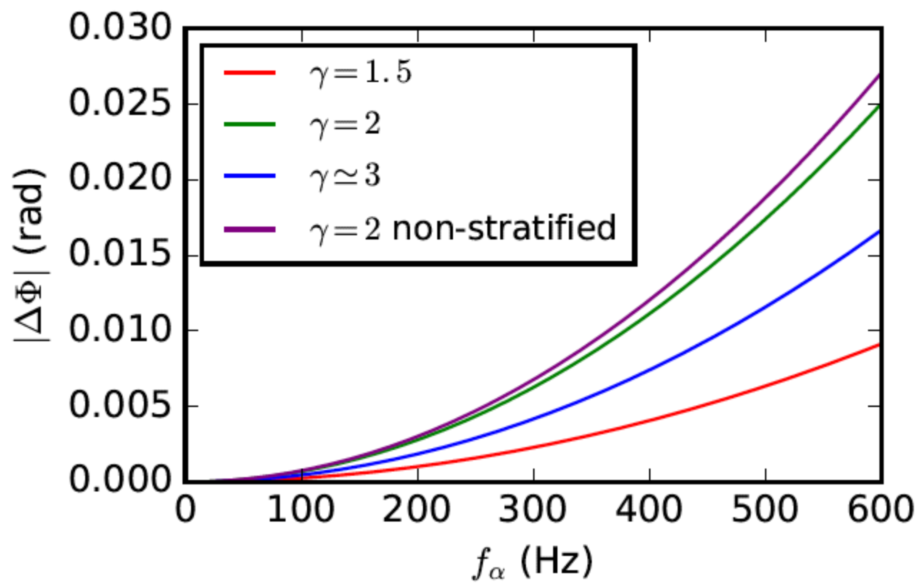
$P \propto \rho^\gamma, \quad \Gamma = (\partial \ln P / \partial \ln \rho)_{\rm ad}$

$$\omega_\alpha \propto (\Gamma - \gamma)^{1/2} M^{1/2} R^{-3/2}$$

$$Q_{\alpha,2m} \propto \Gamma - \gamma,$$

$$\Delta\Phi = -0.060 \left(\frac{R_{10}^8}{M_{1.4}^6}\right) \frac{2}{q(1+q)} \left(\frac{f_\alpha}{100\,{\rm Hz}}\right)^2 \times \left(\frac{\bar{f}_\alpha}{100\,{\rm Hz}}\right)^{-4} \left(\frac{\bar{Q}_{\alpha,22}}{10^{-3}}\right)^2,$$

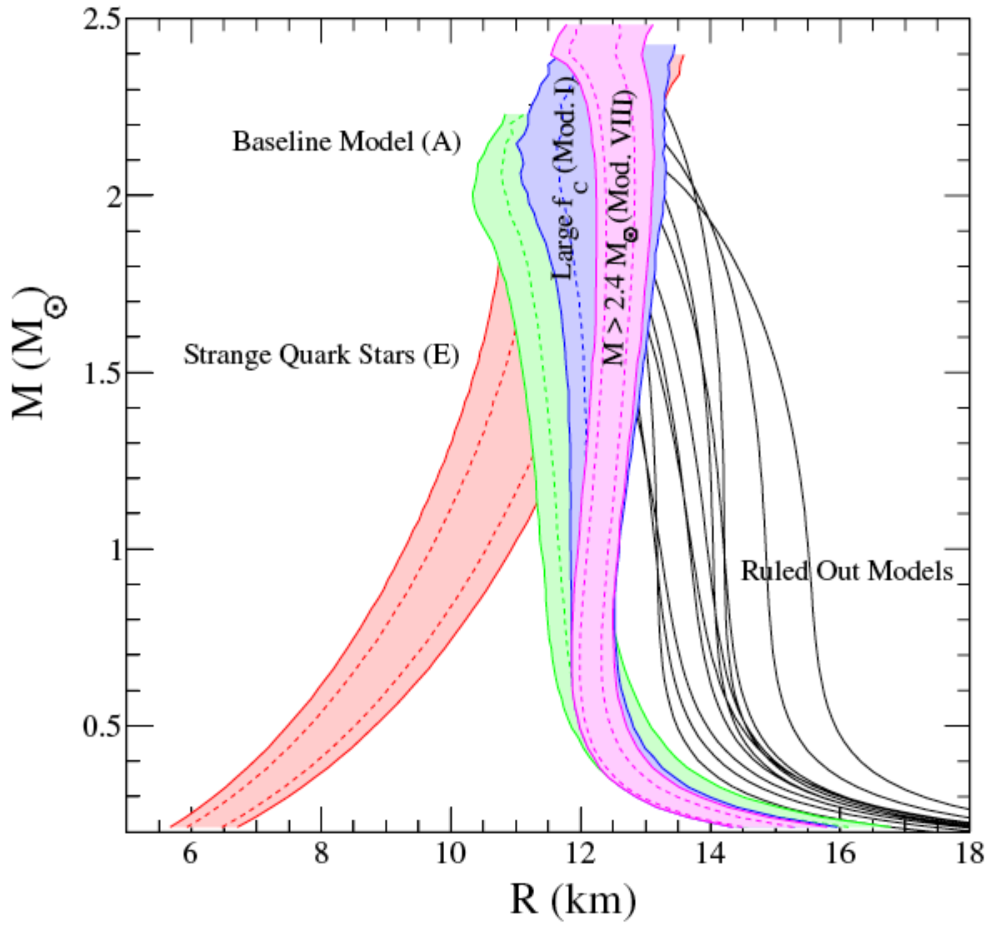
Xu & DL 17



Note: $M = 1.2 M_\odot$, $R = 13$ km NS

➔ x 21 Important !

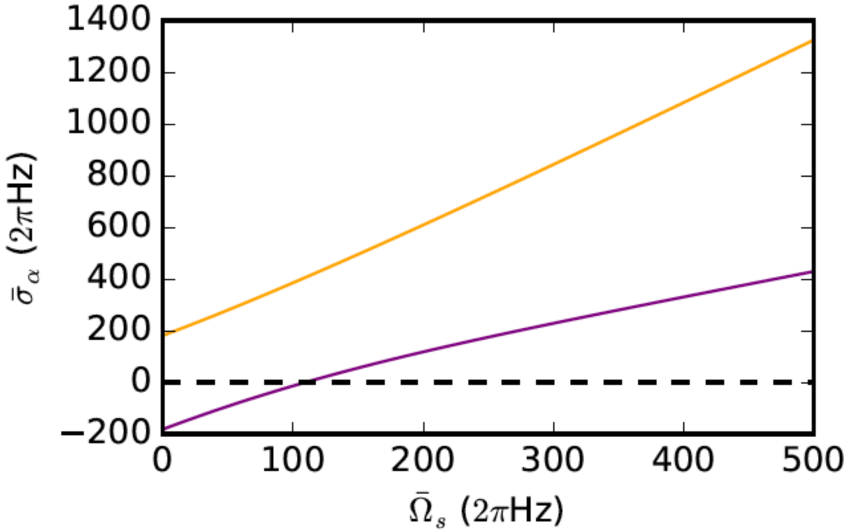
NS Mass-Radius



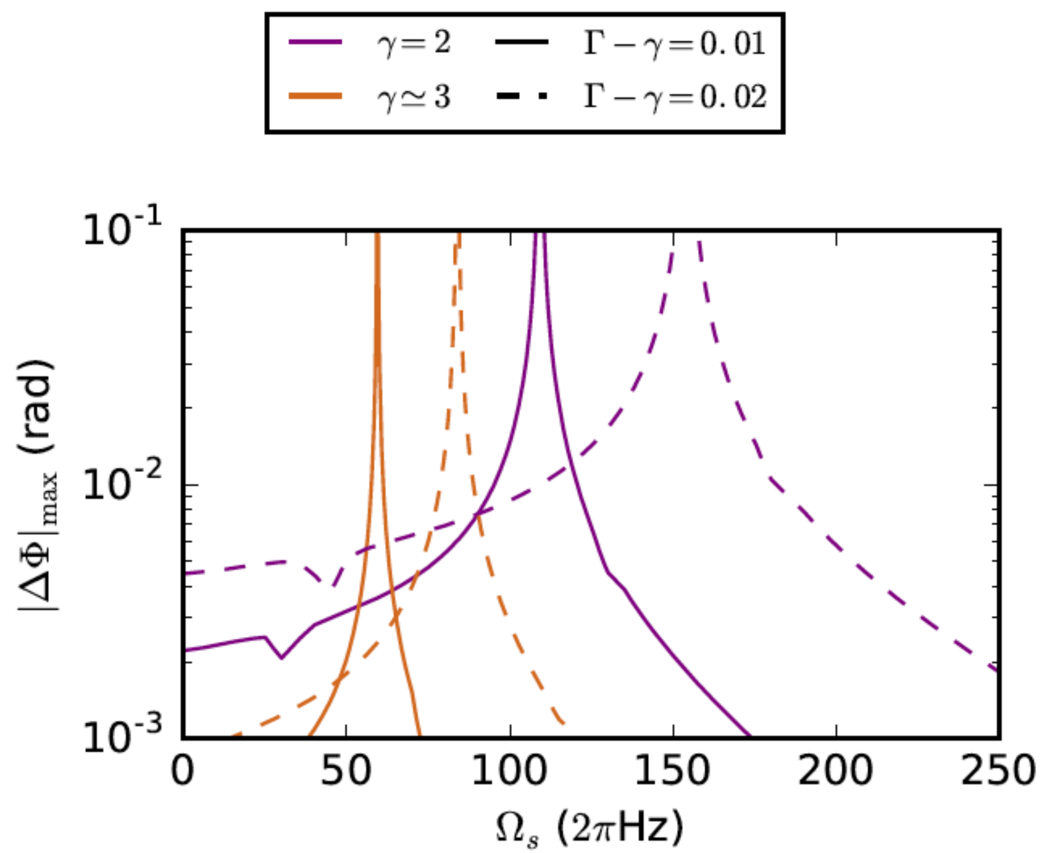
Measured NS mass: 1.17–2.0 Solar mass

Steiner et al 2013

With rotation: Inertial-Gravity Modes



Rotation can reduce (retrograde) g-mode $|\sigma_\alpha|$, thus increase $|\Delta\Phi|$



Xu & DL 2017

Resonant excitation of F-modes?

Very strong … possible with **very rapid rotations**

Wynn Ho & DL 1999

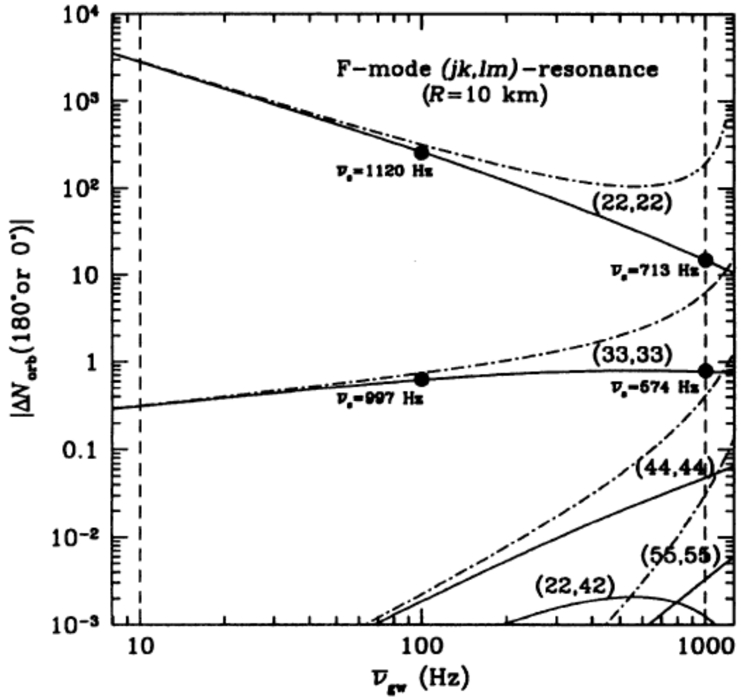


Figure 2. Orbital cycle change $|(\Delta N_{\rm orb})_{jk,lm}|$, with $M = 1.4\,\mathrm{M}_\odot$, $R = 10\,\mathrm{km}$, $q = 1$, as a function of the normalized gravitational wave frequency, $\bar{\nu}_{\rm gw} = \nu_{\rm gw} M_{1.4}^{-1/2} R_{10}^{3/2} = (2/m)|\nu_\alpha| M_{1.4}^{-1/2} R_{10}^{3/2}$, for the f-mode (jk,lm)-resonance. The labels in the figure give the values of (jk,lm). The solid lines are for the $\omega_\alpha^{(r)} > 0$ and $\omega_\alpha > 0$ (spin-retrograde) stable modes with $(\Delta N_{\rm orb})_{jk,lm}(180°) < 0$. The dot-dashed lines are for the $\omega_\alpha^{(r)} > 0$ and $\omega_\alpha < 0$ (spin-prograde) unstable modes with $(\Delta N_{\rm orb})_{jk,lm}(0°) > 0$. Note

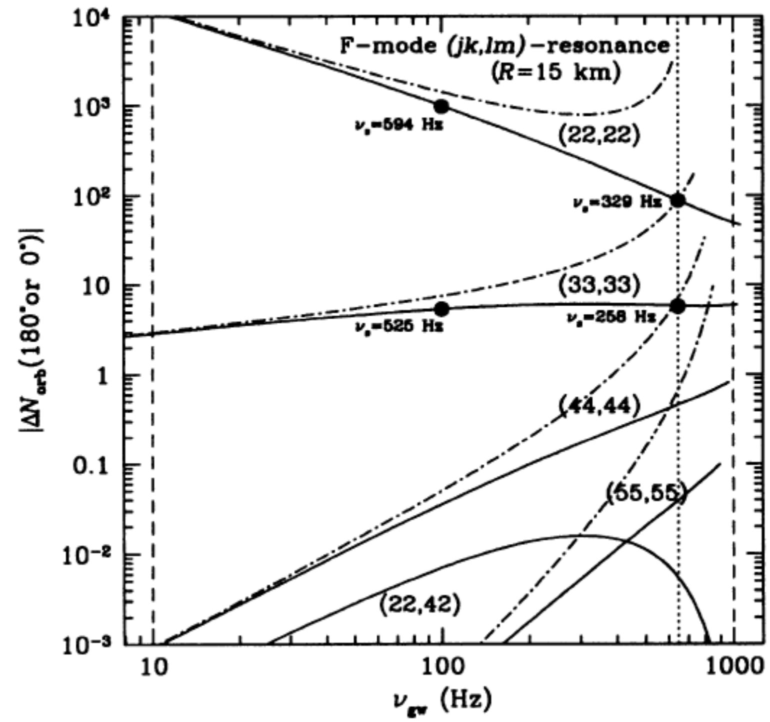


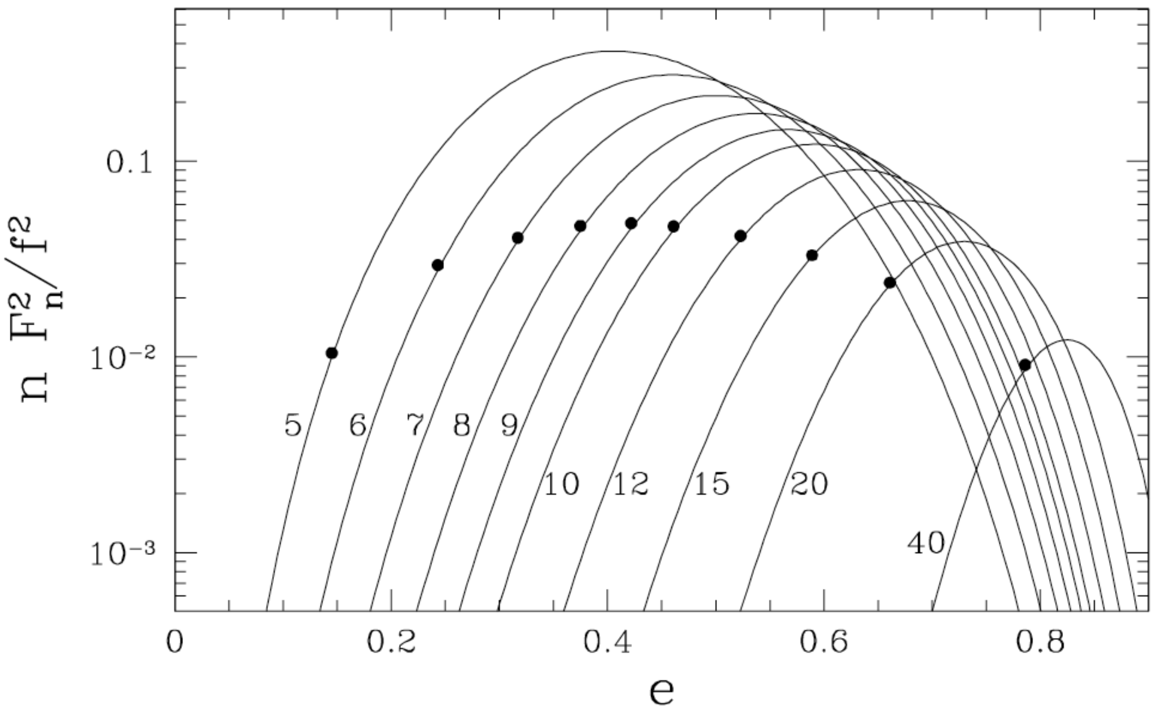
Figure 4. Orbital cycle change $|(\Delta N_{\rm orb})_{jk,lm}|$, with $M = 1.4\,\mathrm{M}_\odot$, $R = 15\,\mathrm{km}$, $q = 1$, as a function of the gravitational wave frequency, $\nu_{\rm gw} = (2/m)|\nu_\alpha|$, for the f-mode (jk,lm)-resonance. The labels in the figure give the values of (jk,lm). The solid lines are for the $\omega_\alpha^{(r)} > 0$ and $\omega_\alpha > 0$ (spin-retrograde) stable modes with $(\Delta N_{\rm orb})_{jk,lm}(180°) < 0$. The dot-dashed lines are for the $\omega_\alpha^{(r)} > 0$ and $\omega_\alpha < 0$ (spin-prograde) unstable modes with

Resonant excitation of F-modes?

Eccentric Mergers

Resonance occurs: $\sigma_\alpha = n\Omega_{\rm orb}$ (even for $l = m = 2$ tides)

$$\Delta\Phi = -\frac{151}{q(1+q)}\left(\frac{R}{5M}\right)^5\left(\frac{\hat{Q}_\alpha}{\hat{\sigma}_\alpha}\right)^2\left(\frac{nF_n^2(e)}{f(e)}\right)$$



DL & Chernoff 2018

Summary I:

Resonant tidal excitation of modes occurs at low frequency (< 100 Hz).
If strong, would provide a unique probe of EOS**:**

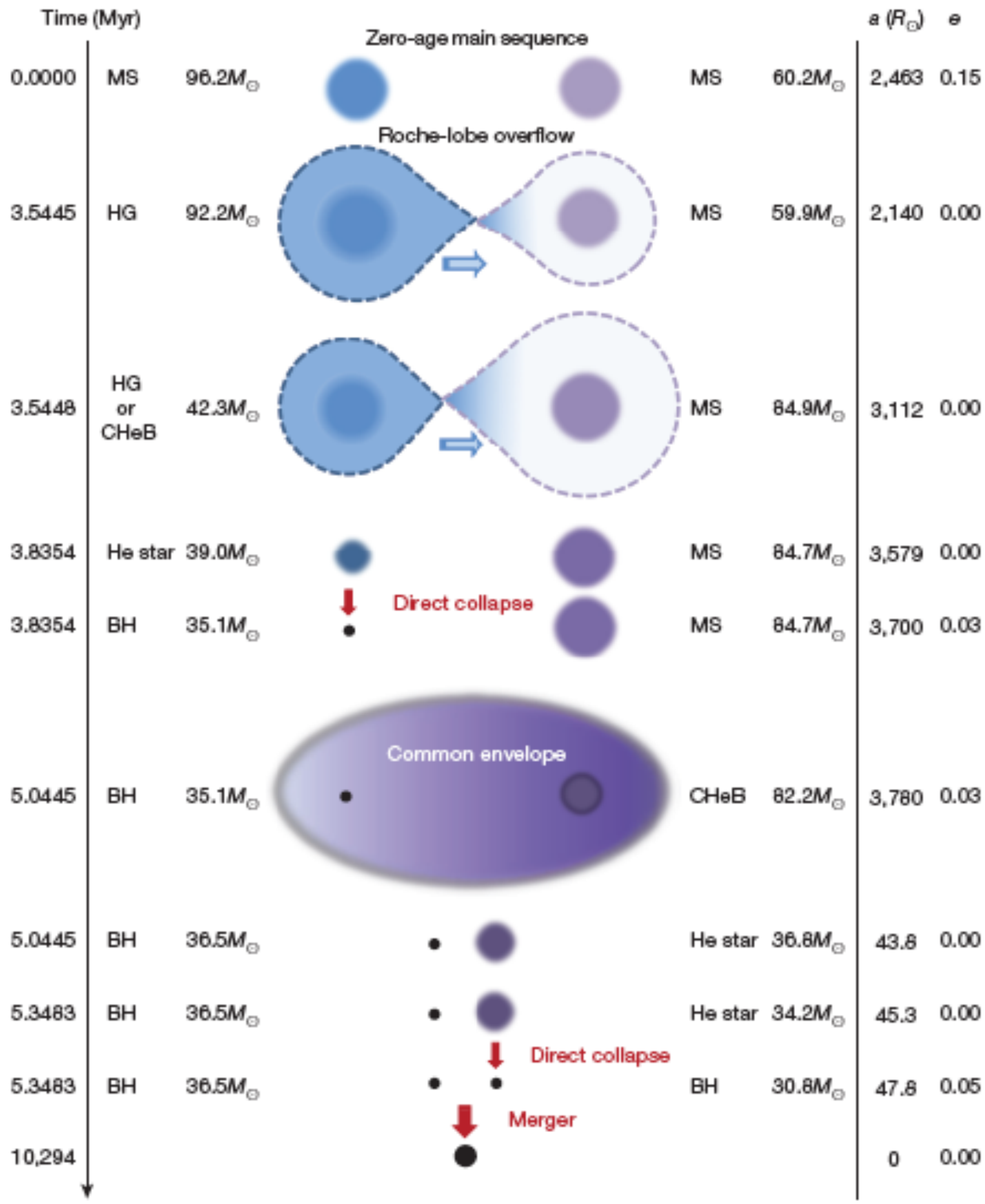
-- g-modes: Important for low-M, large-R NSs
-- rotation enhances resonance.
-- f-mode resonance: Important for very rapid rotation

Note: Resonant tides are certainly important for WD binaries (or WD-NS, WD-BH): LISA band
Also for 1-10 Hz band (Cosmic Explorer, Einstein Telescope)

Formation Channels of Black Hole Binaries

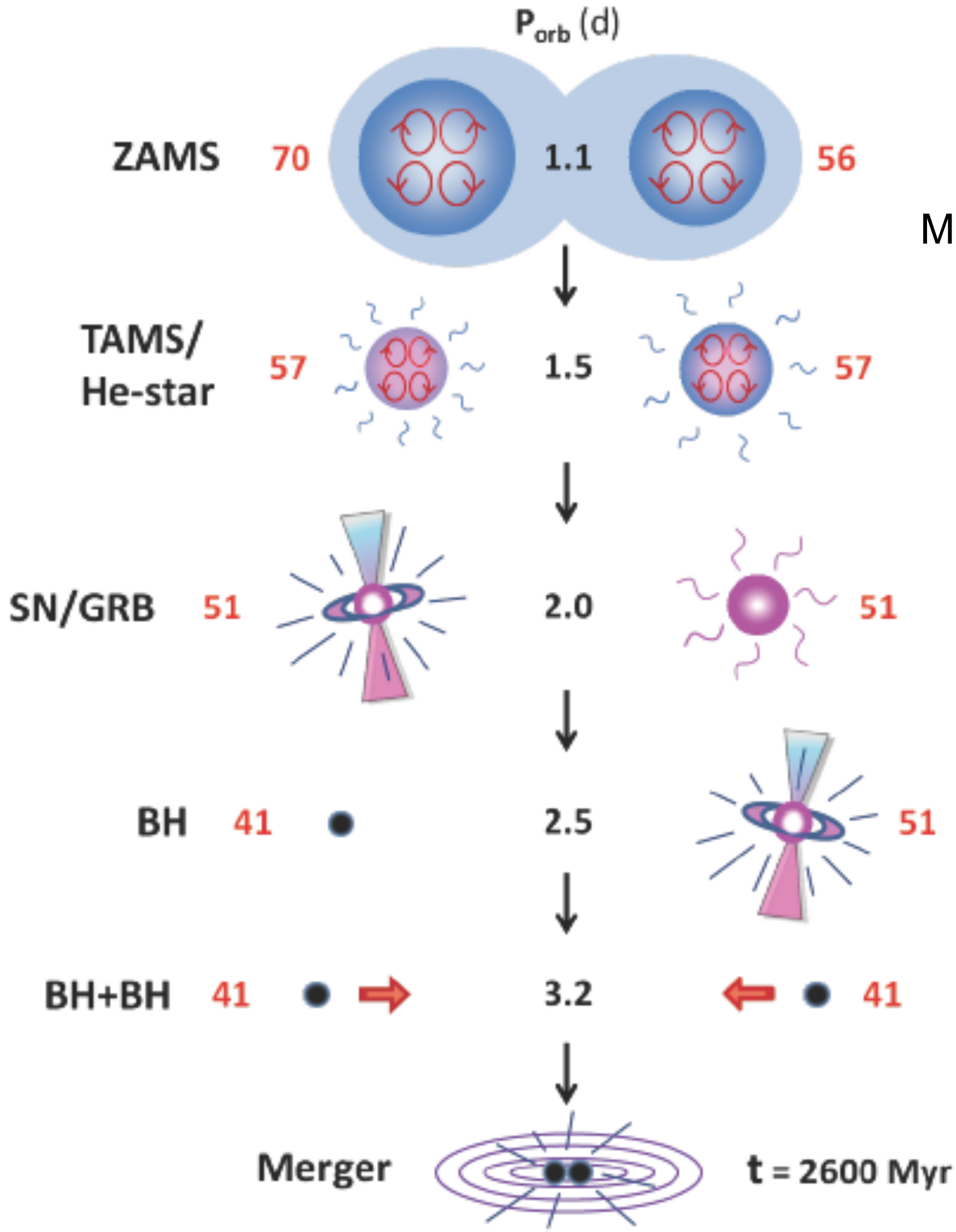
A large and important topics…
LIGO O3 may have ~1 BH binary events per week !

Standard Binary Evolution Channel:

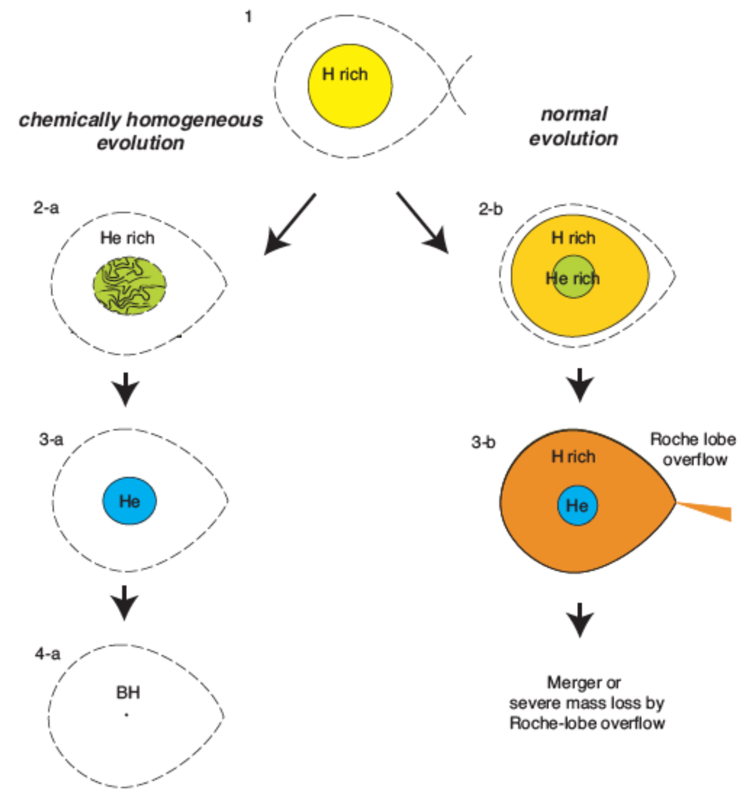


Belczynski +16

Chemically Homogeneous Evolution Channel



Marchant, Langer et al 2016

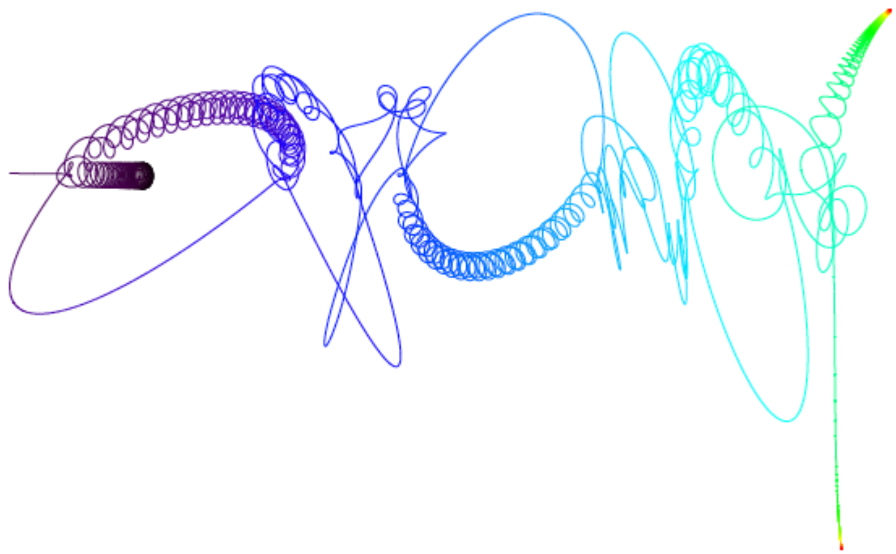


Mandel & de Mink 2016

Dynamical Formation Channels

many flavors, many papers …

-- Binary + single scatterings dense clusters ➔ Tight binary



Samsing+14

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-- Binary mergers induced by external companion (SMBH, stellar triple)

Dynamical Formation Channels

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➔ Eccentric mergers in LIGO band

e.g., Silsbee & Tremaine (2017) claim a few % of no-so hierarchical triples that lead to merger will enter LIGO band with $e>0.999$

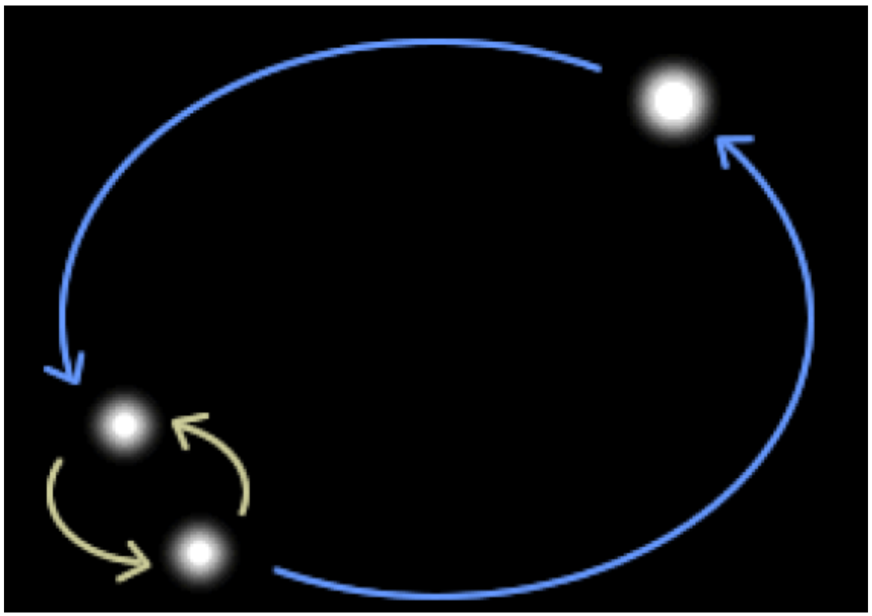
Eccentric mergers in LIGO band are probably rare…

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:

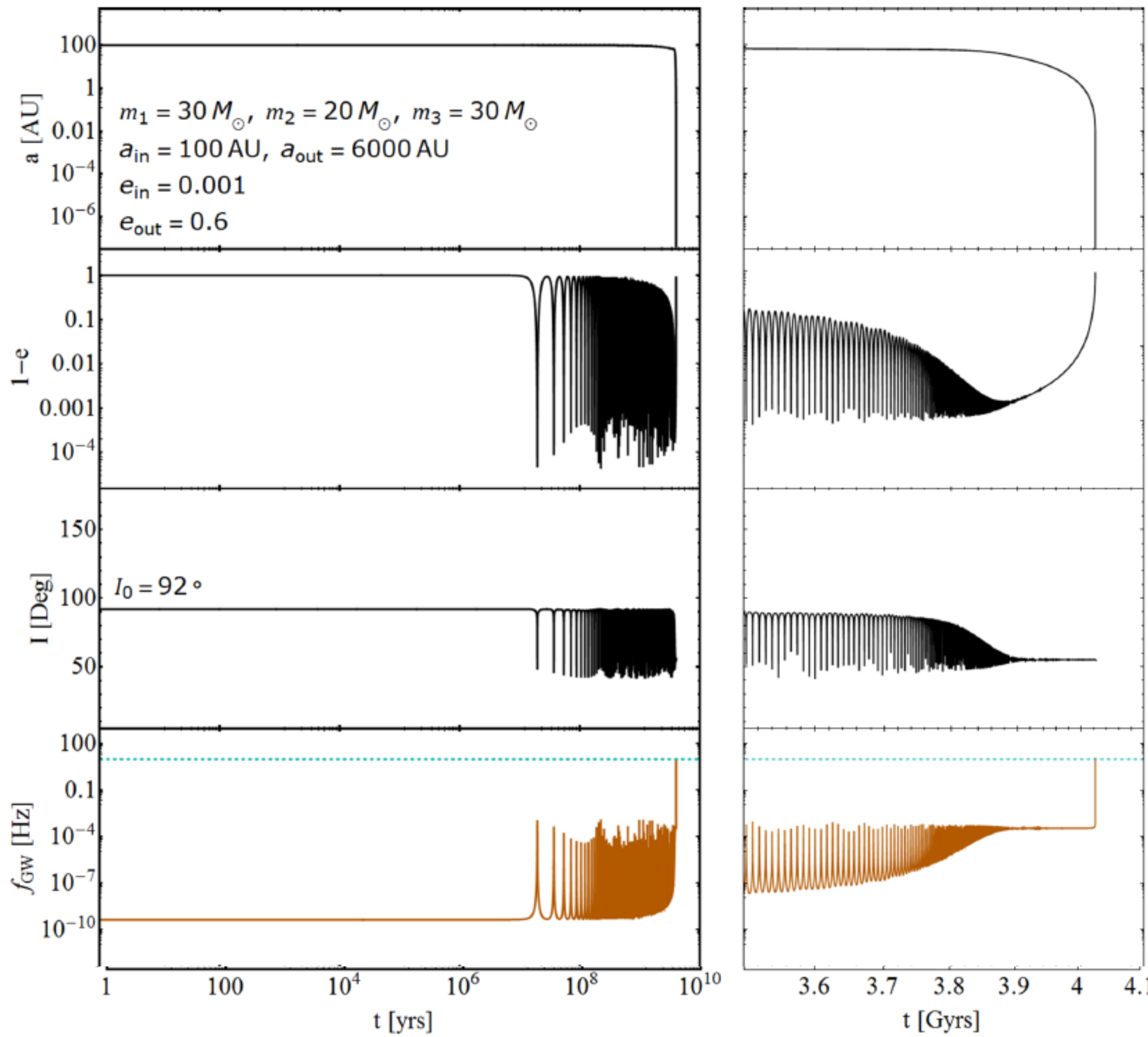
e.g. Blaes et al. 2002; Miller & Hamilton 2002; Wen 2003; Thompson 2011; Antonini et al. 2014,2017, Silsbee & Tremaine 2017…

Binary Mergers Induced by Tertiary Companions and Spin-Orbit Misalignments



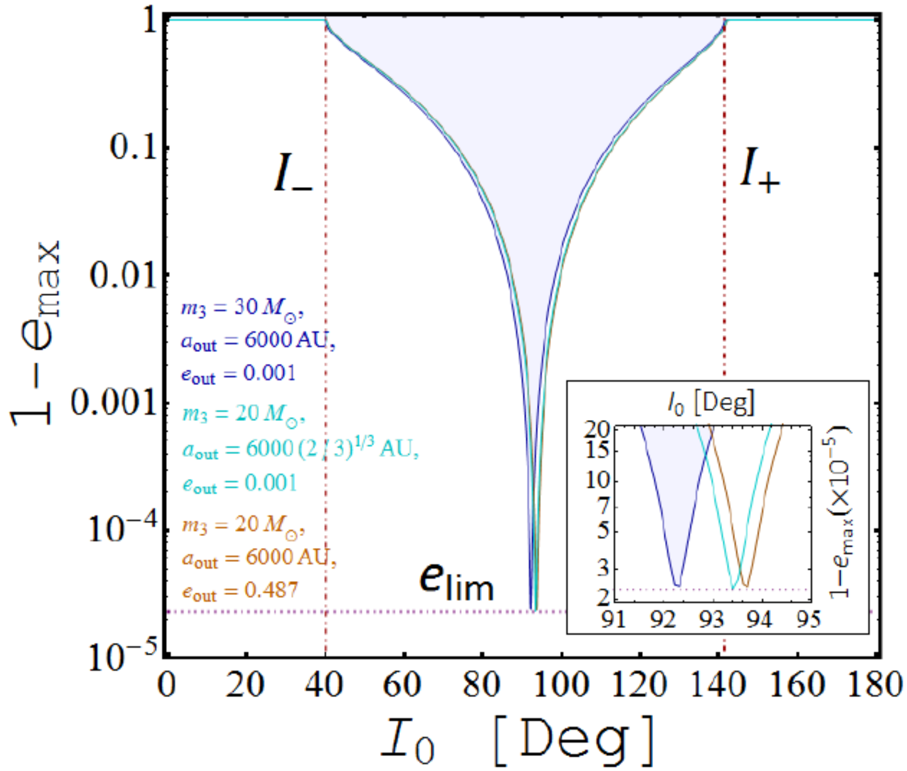
B.Liu & DL 2017,2018

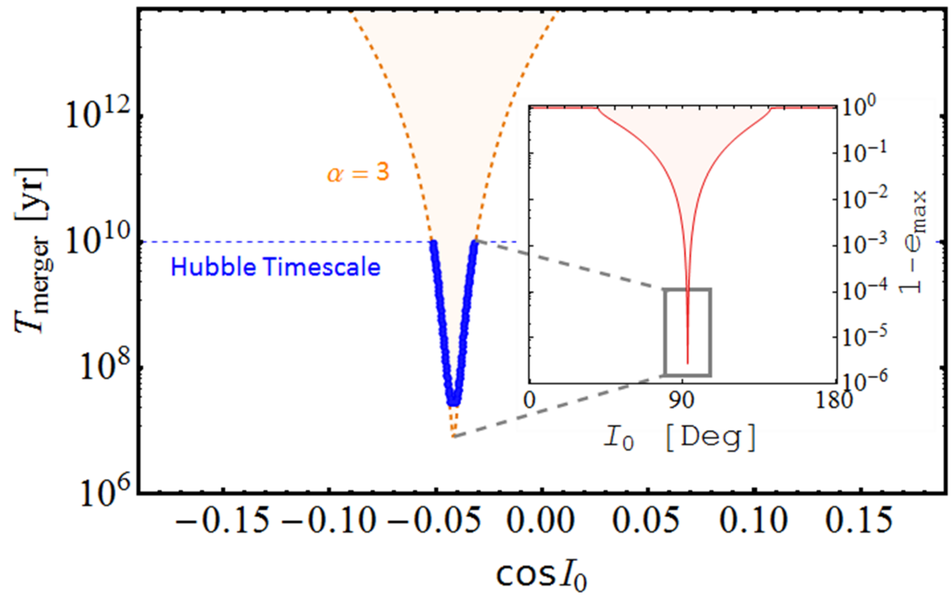
Bin Liu (SHAO, Cornell)



Lidov-Kozai oscillations

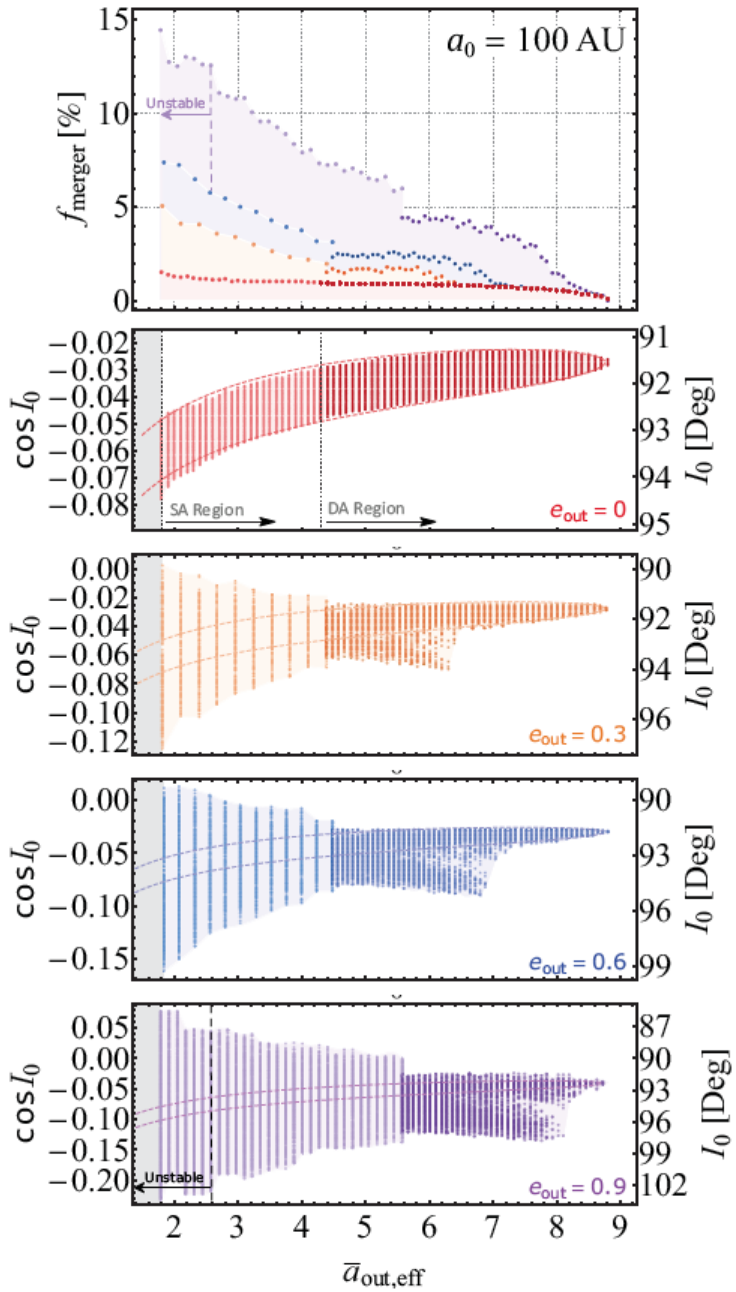
Inclination Window for Merger





Many old/new semi-analytic expressions are summazried/derived in B.Liu & DL 2018, arXiv1805.03202

Merger Window and Merger Fraction



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

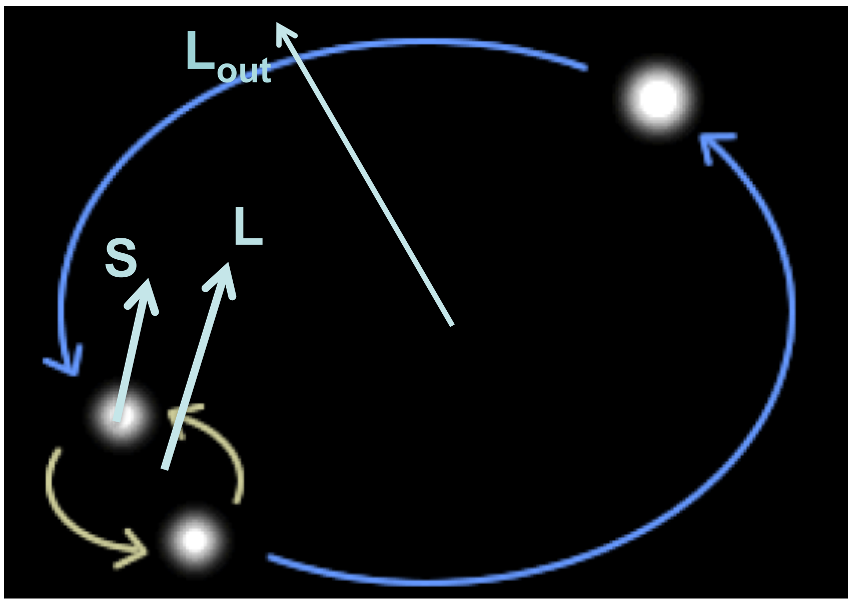
Spin Puzzle ?

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

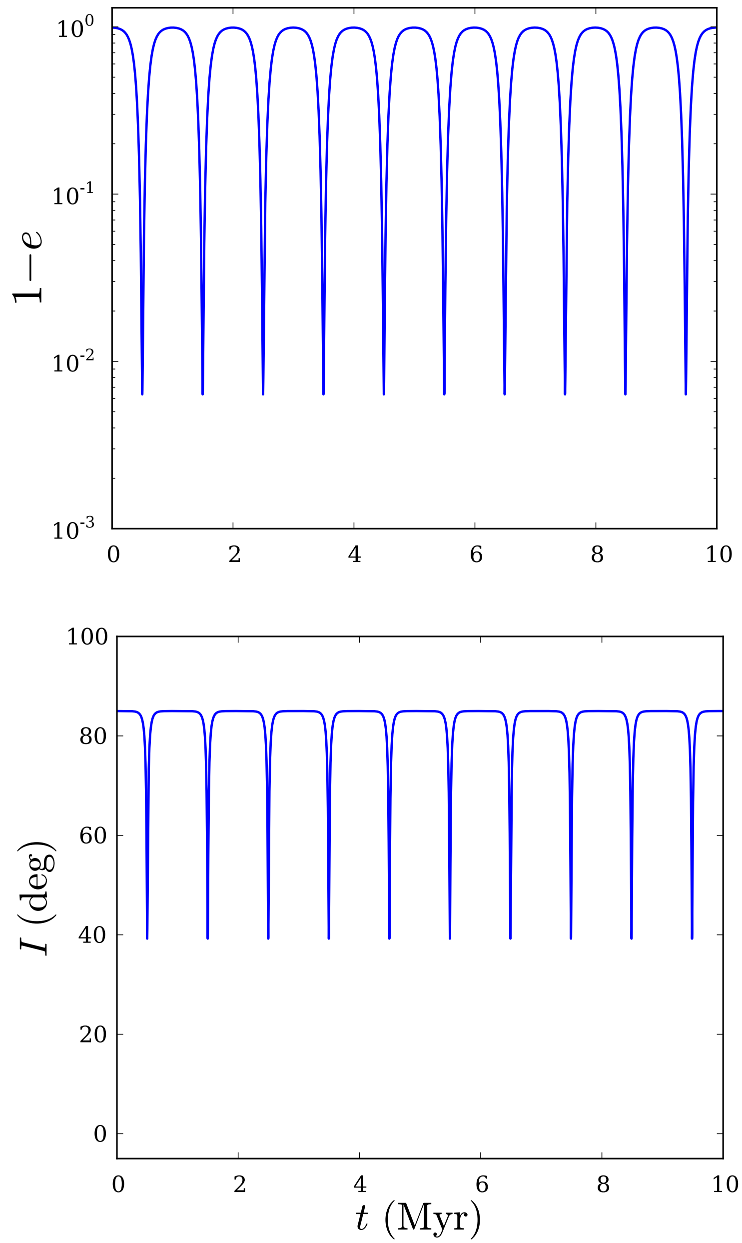
$$\begin{array}{ll}
\text{GW150914:} & -0.06^{+0.14}_{-0.14} \\
\text{GW151226:} & 0.21^{+0.2}_{-0.1} \\
\text{GW170104:} & -0.12^{+0.21}_{-0.3} \\
\text{GW170608:} & 0.07^{+0.23}_{-0.09} \\
\text{GW170814:} & 0.06^{+0.12}_{-0.12}
\end{array}$$

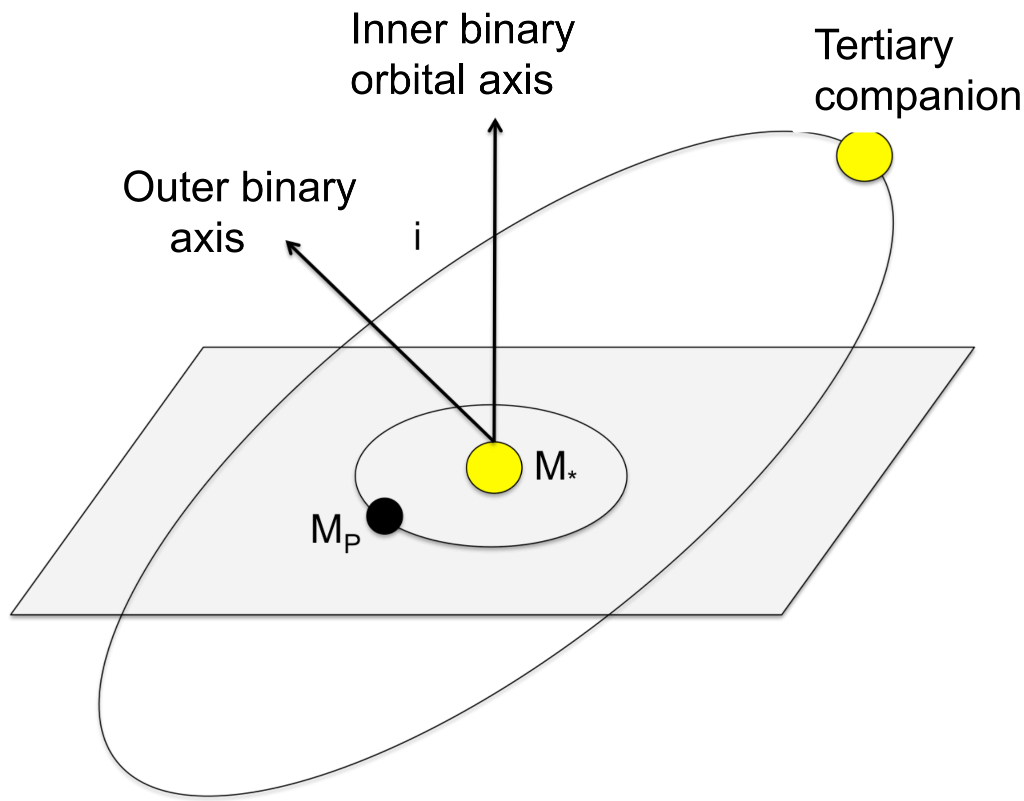
Spin-Orbit Misalignments in Merging Binaries with Tertiary Companions

Bin Liu & DL 2017, 2018

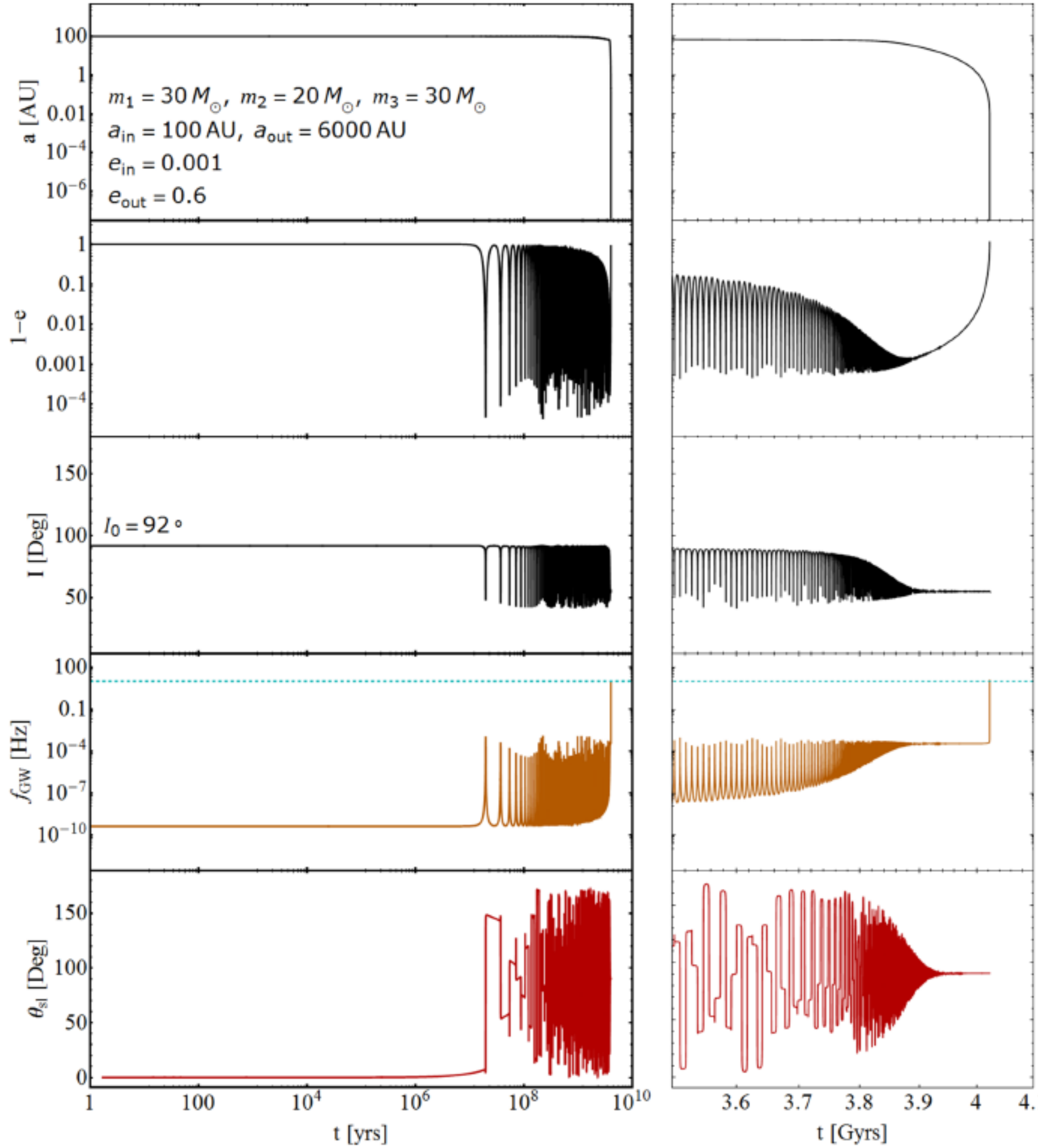


Lidov-Kozai Oscillations





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

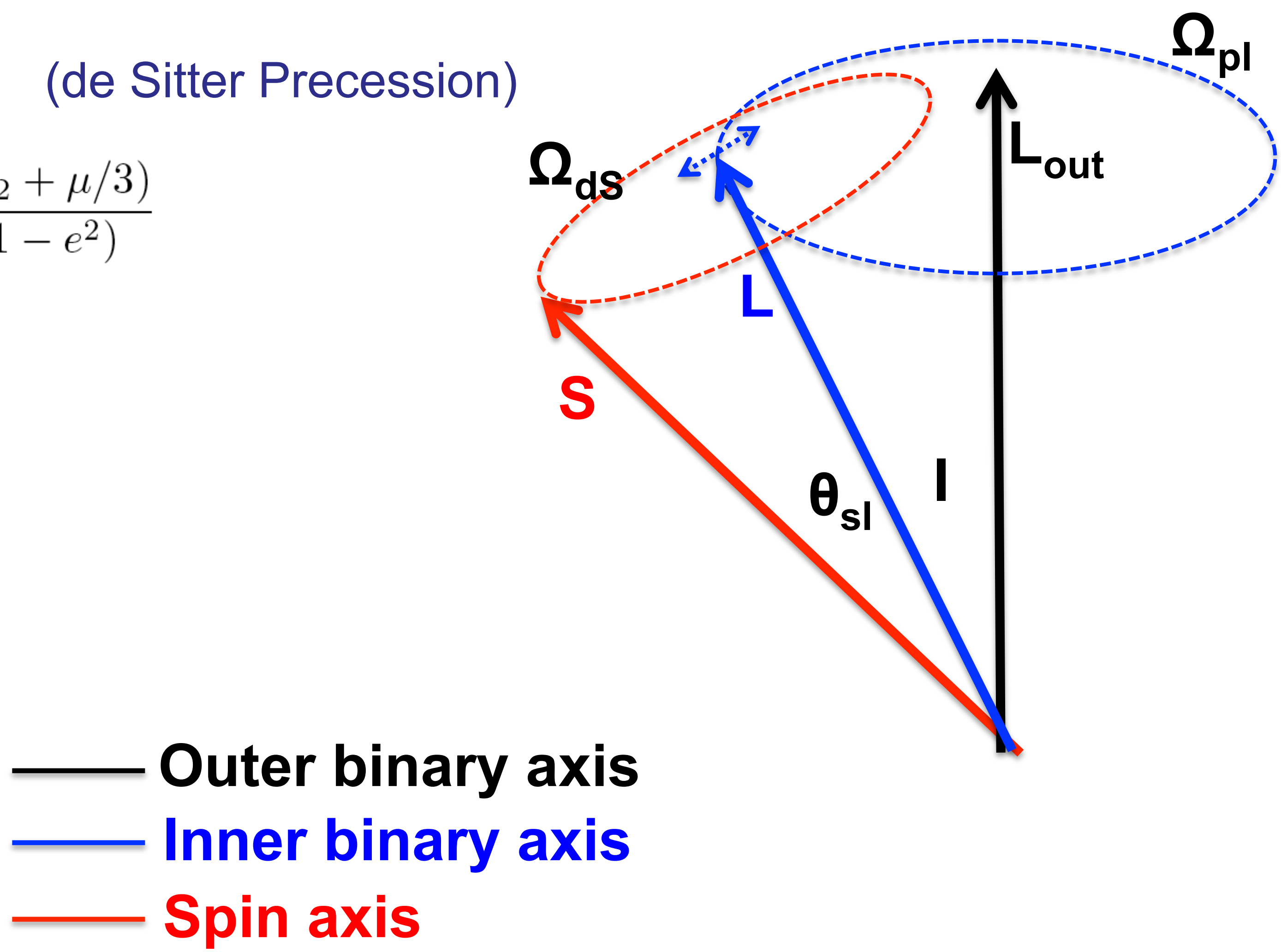


$m_1 = 30\,M_\odot,\ m_2 = 20\,M_\odot,\ m_3 = 30\,M_\odot$
$a_{in} = 100$ AU, $a_{out} = 6000$ AU
$e_{in} = 0.001$
$e_{out} = 0.6$
$I_0 = 92^\circ$
a [AU]
1−e
I [Deg]
f_{GW} [Hz]
θ_{sl} [Deg]
t [yrs]
t [Gyrs]

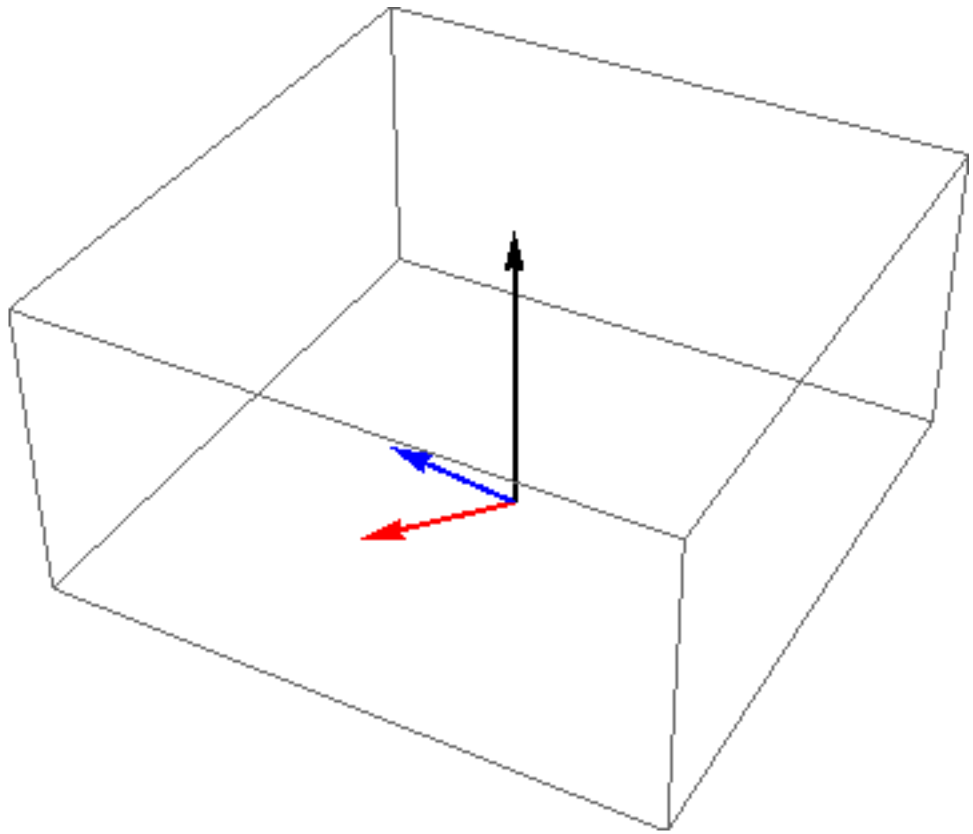
BH Spin Dynamics

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

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

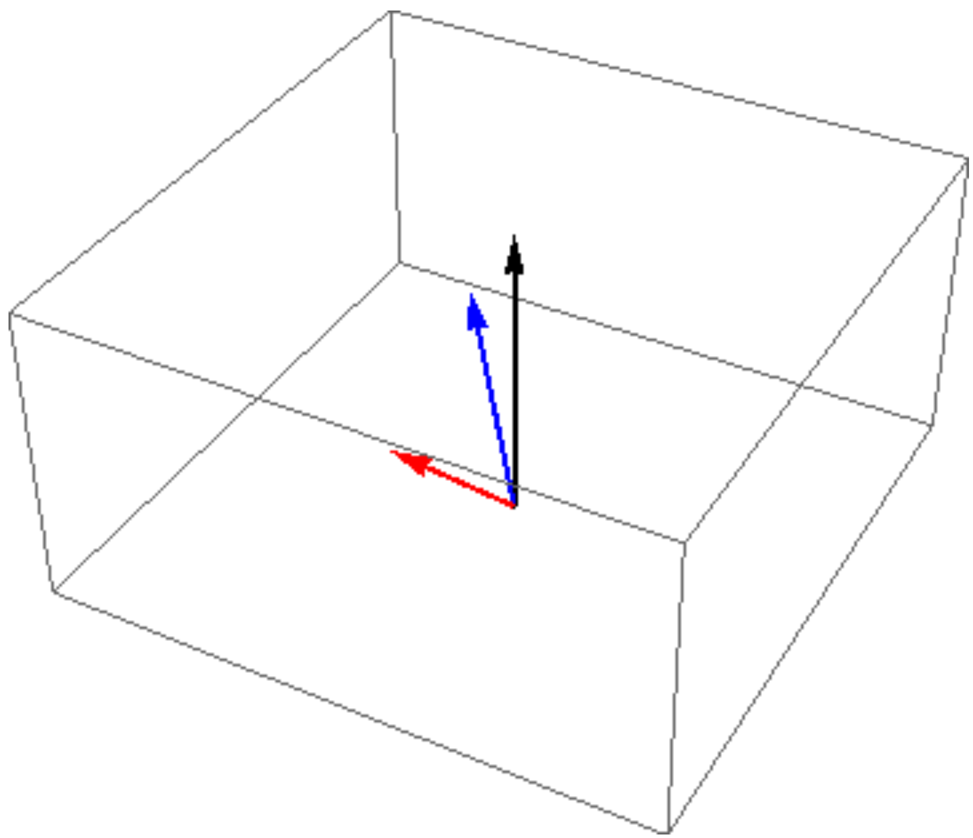


If $|\Omega_{dS}| >> |\Omega_{pl}|$: S follows L adiabatically



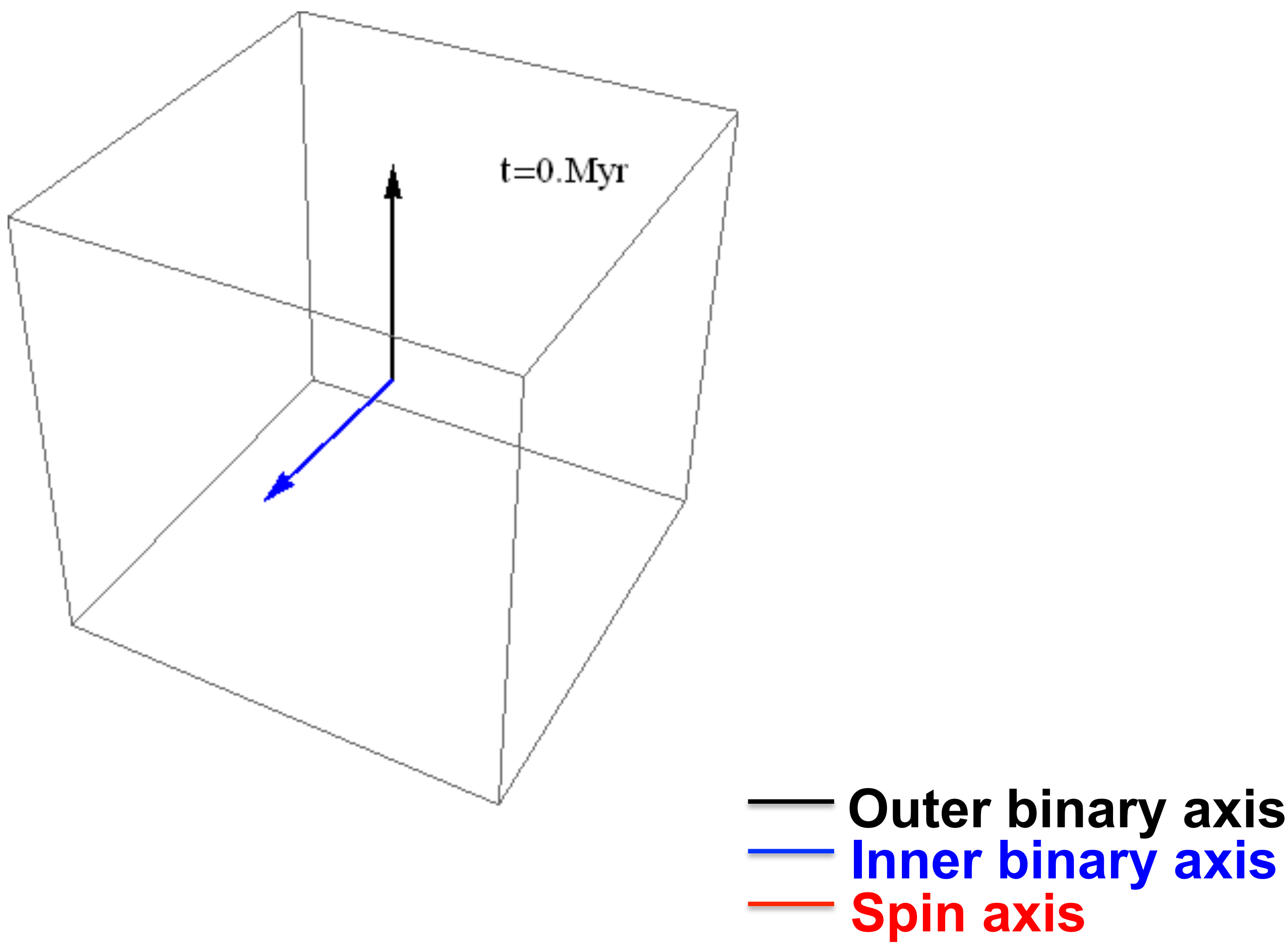
Outer binary axis
Inner binary axis
Spin axis

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

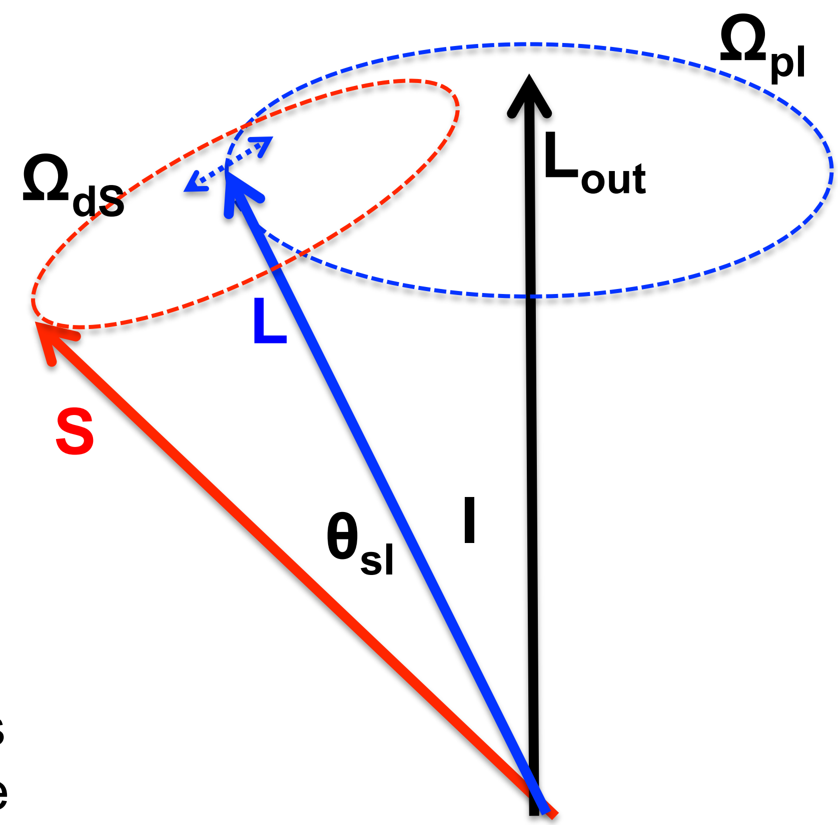


Outer binary axis
Inner binary axis
Spin axis

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



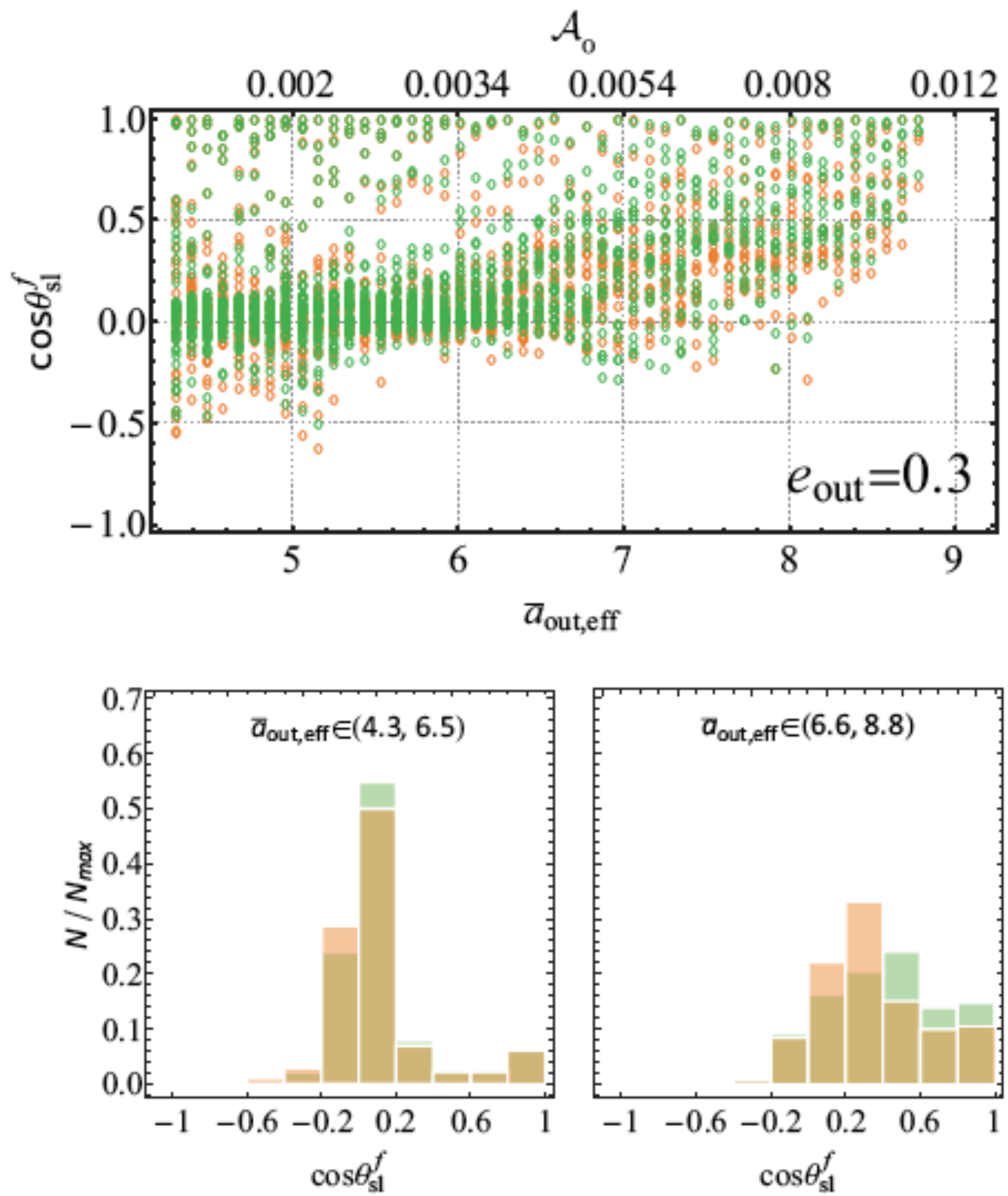
BH Spin Evolution



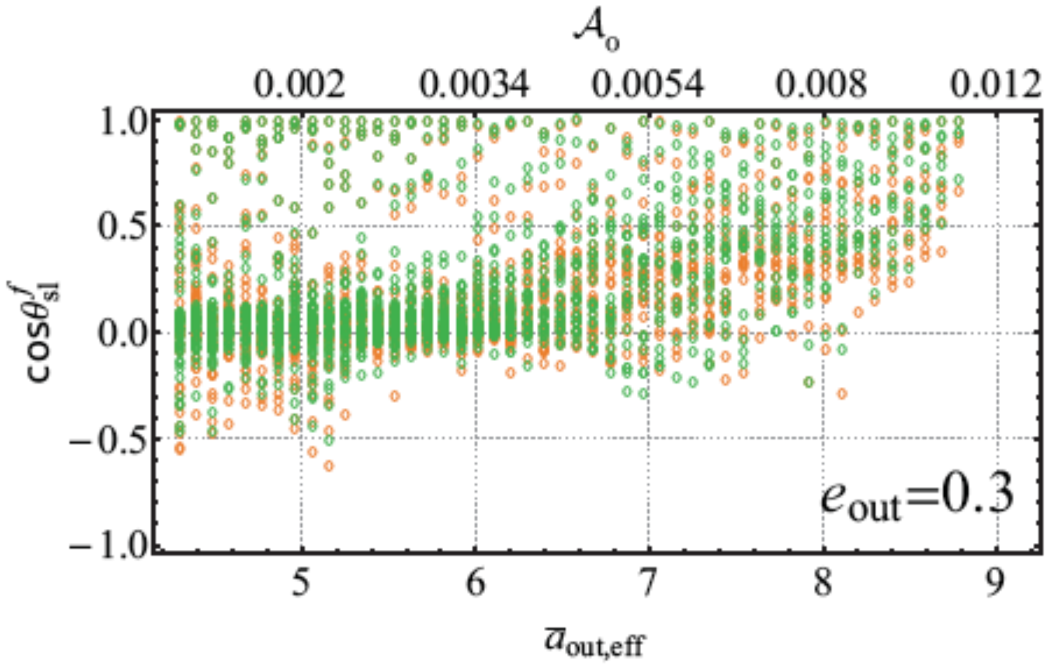
$$\Omega_{\rm dS}/\Omega_{\rm pl}$$

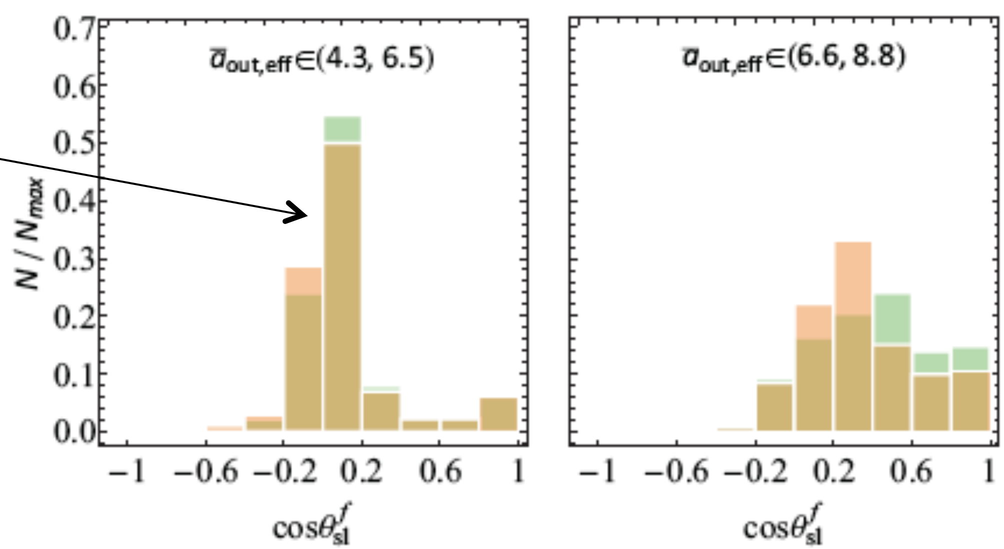
changes from << 1 (non-adiabatic)
to >> 1 (adiabatic) as the orbit decays
➔ Final spin-orbit misalignment angle

Final Spin-Orbit Misalignment Distribution (starting from alignment)



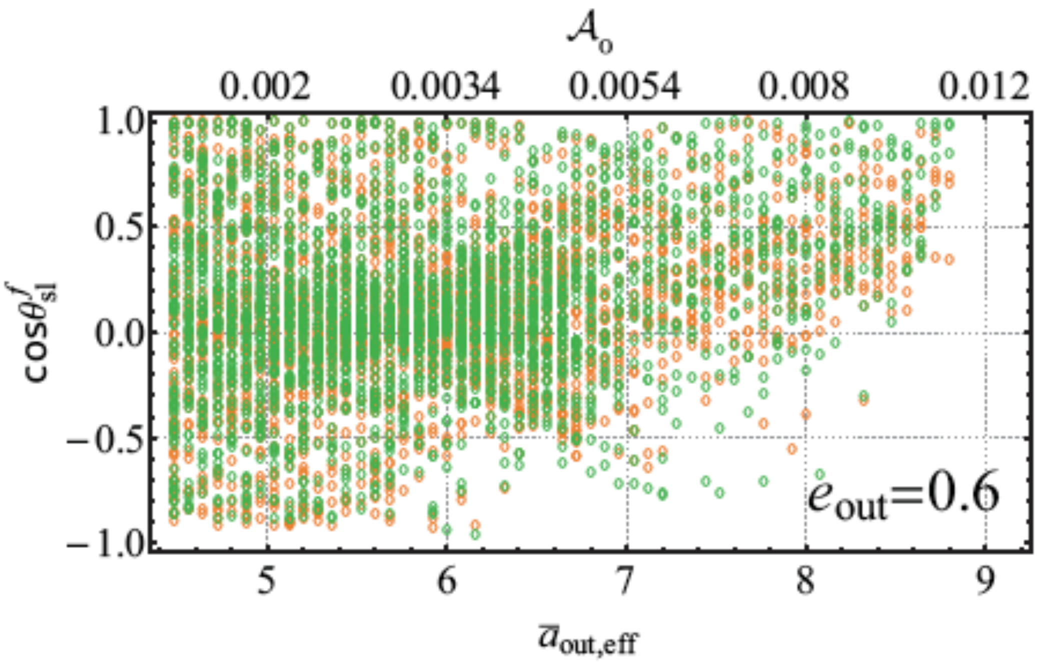
Final Spin-Orbit Misalignment Distribution (starting from alignment)

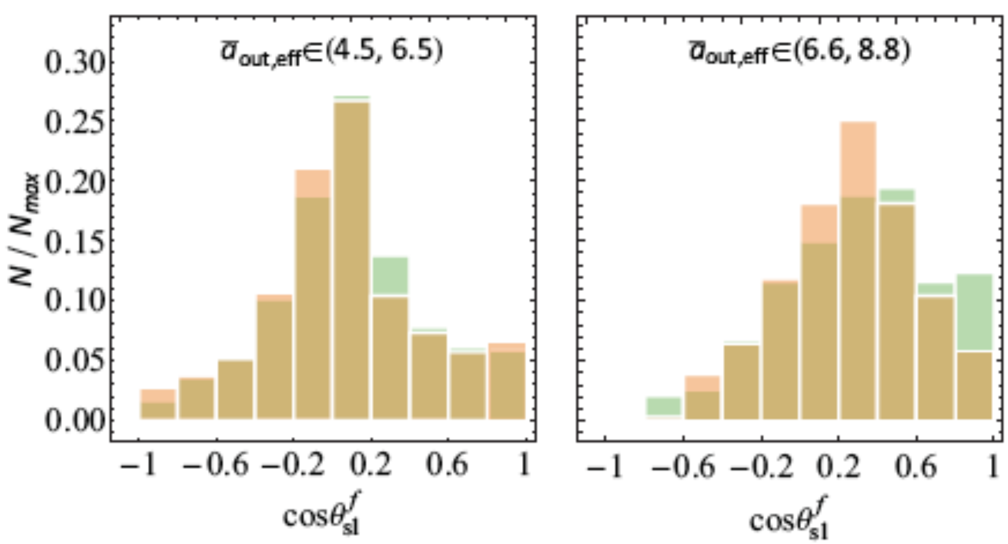




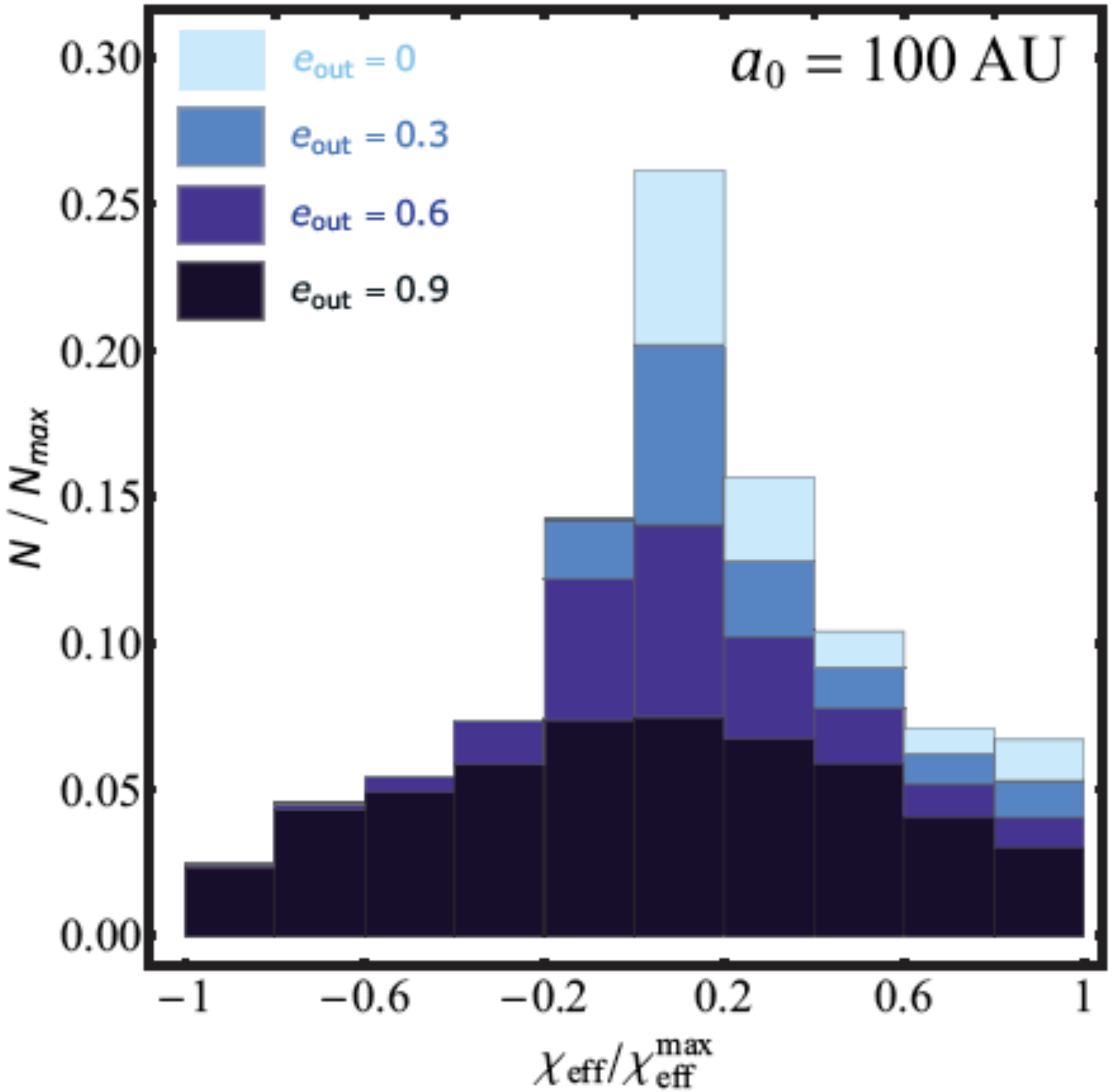
90 degree Attractor ("adiabatic Invariance")

Final Spin-Orbit Misalignment Distribution (starting from alignment)

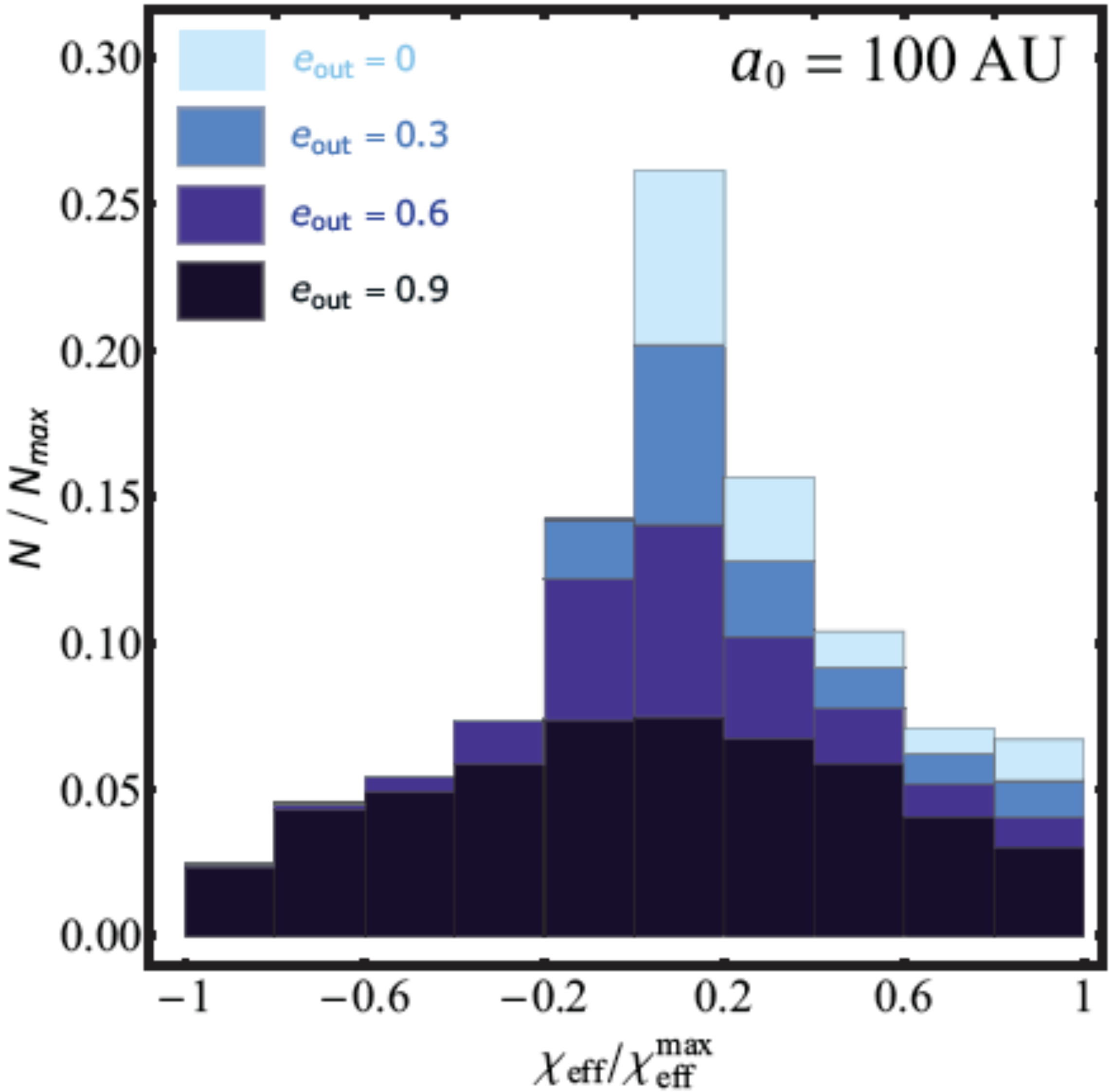




Distribution of $$\chi_{\rm eff} = \frac{m_1\mathbf{a}_1 + m_2\mathbf{a}_2}{m_1+m_2}\cdot\hat{\mathbf{L}}$$



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



A unique signature of LK-induced mergers

Summary

Resonant tidal excitation of modes (<100 Hz) would probe EOS:

Probably not important unless Nature is kind:

-- g-modes: small M, large R

-- rotation enhances resonance.

-- f-mode resonance: very rapid rotation, eccentric merger.

Dynamically Induced BH mergers may be common: many flavors...

Binary mergers induced by tertiary companions in triples

may compete with standard channel ??

Non-trivial spin-orbit misalignments in binary mergers with external companions

Thanks.

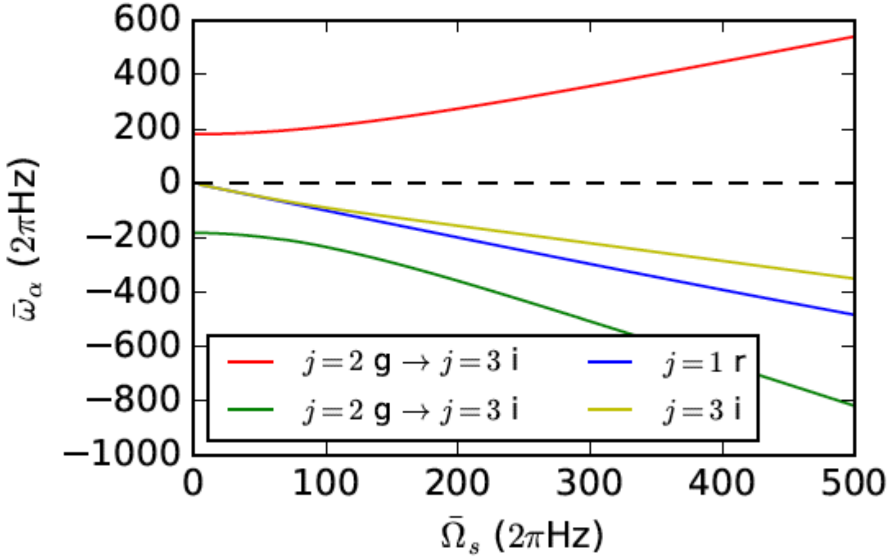
“Quasi-Equilibrium” Tide (F-mode Distortion)

“dynamical correction” to equilibrium tide:

$$d\Phi = d\Phi^{(0)} \left[1 - \mathcal{O}\left(\frac{k_2 M' R^5}{M a^5} \right) \frac{1}{1 - 4\Omega^2/\omega_{\rm f}^2} \right]$$

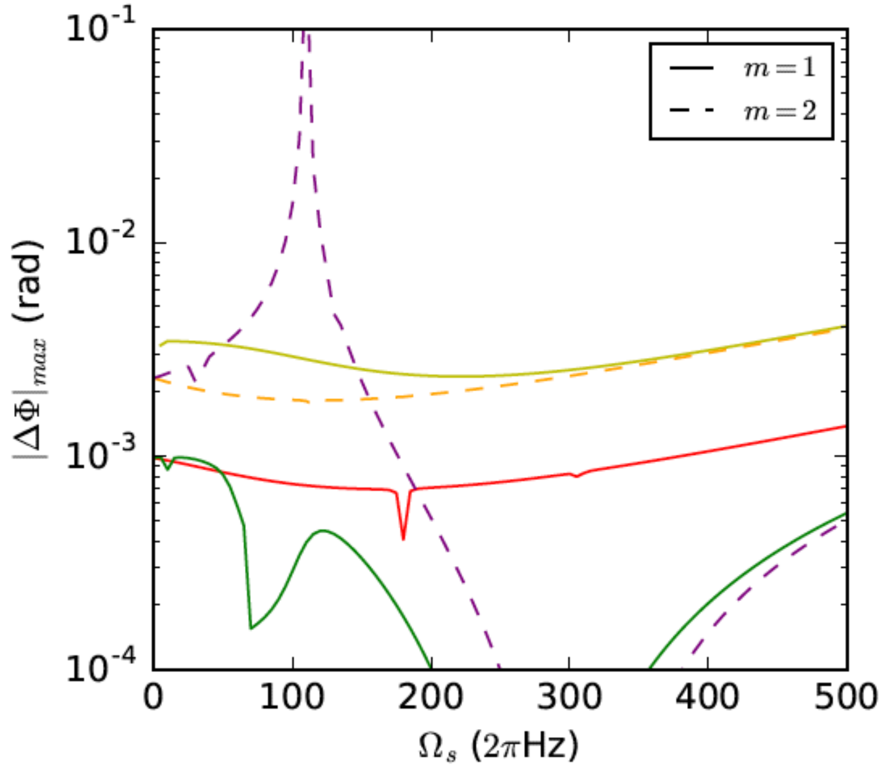
$$\text{where } \omega_{\rm tide} = 2(\Omega - \Omega_s) \simeq 2\Omega$$

With rotation: Many other inertial modes
(modified by stratification)



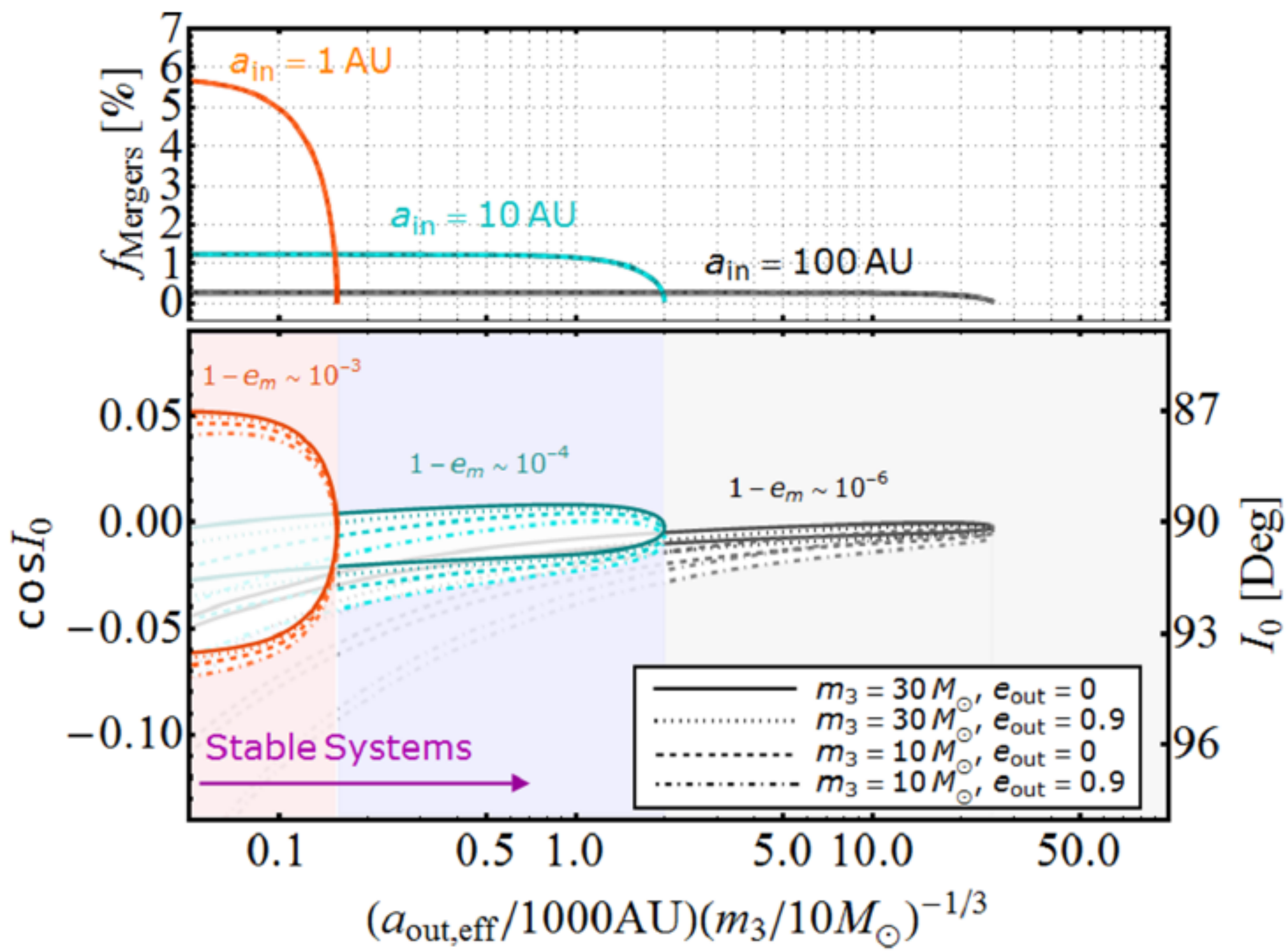
Not as important…

Xu & DL 2017



Merger Window and Merger Fraction

NS-NS binary with a tertiary



$$a_{\rm out,eff} = a_{\rm out}\sqrt{1 - e_{\rm out}^2}$$