Bread & Butter Astrophysics with Gravitational Wave events

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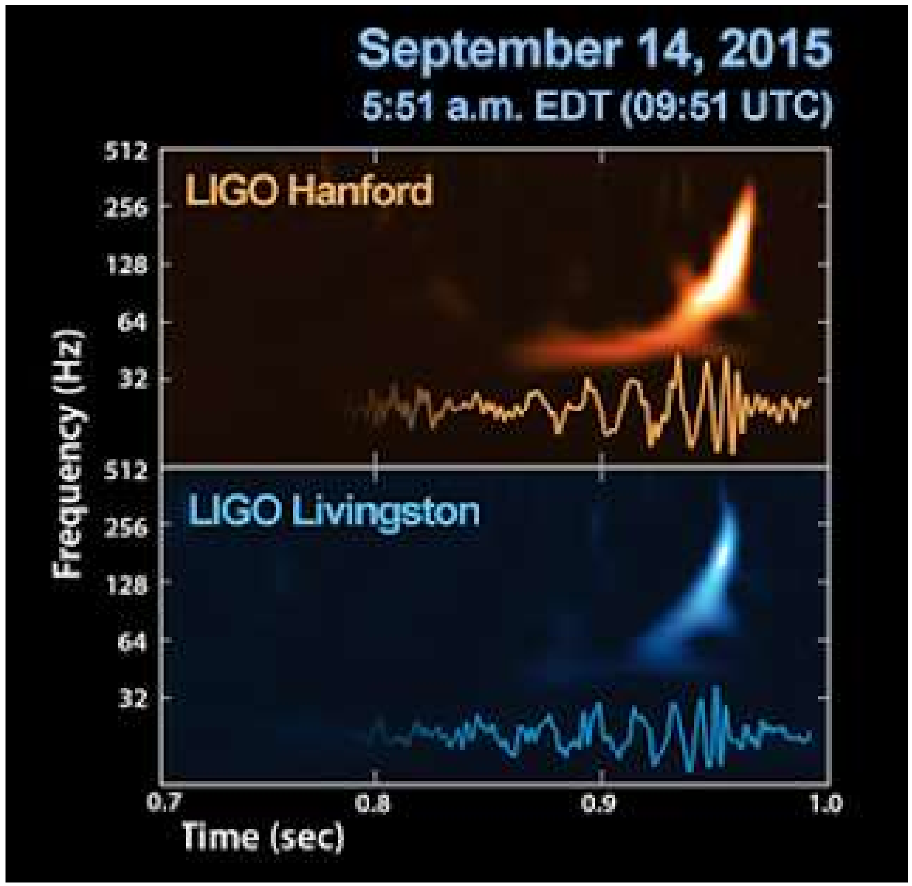
What I’m going to tell you

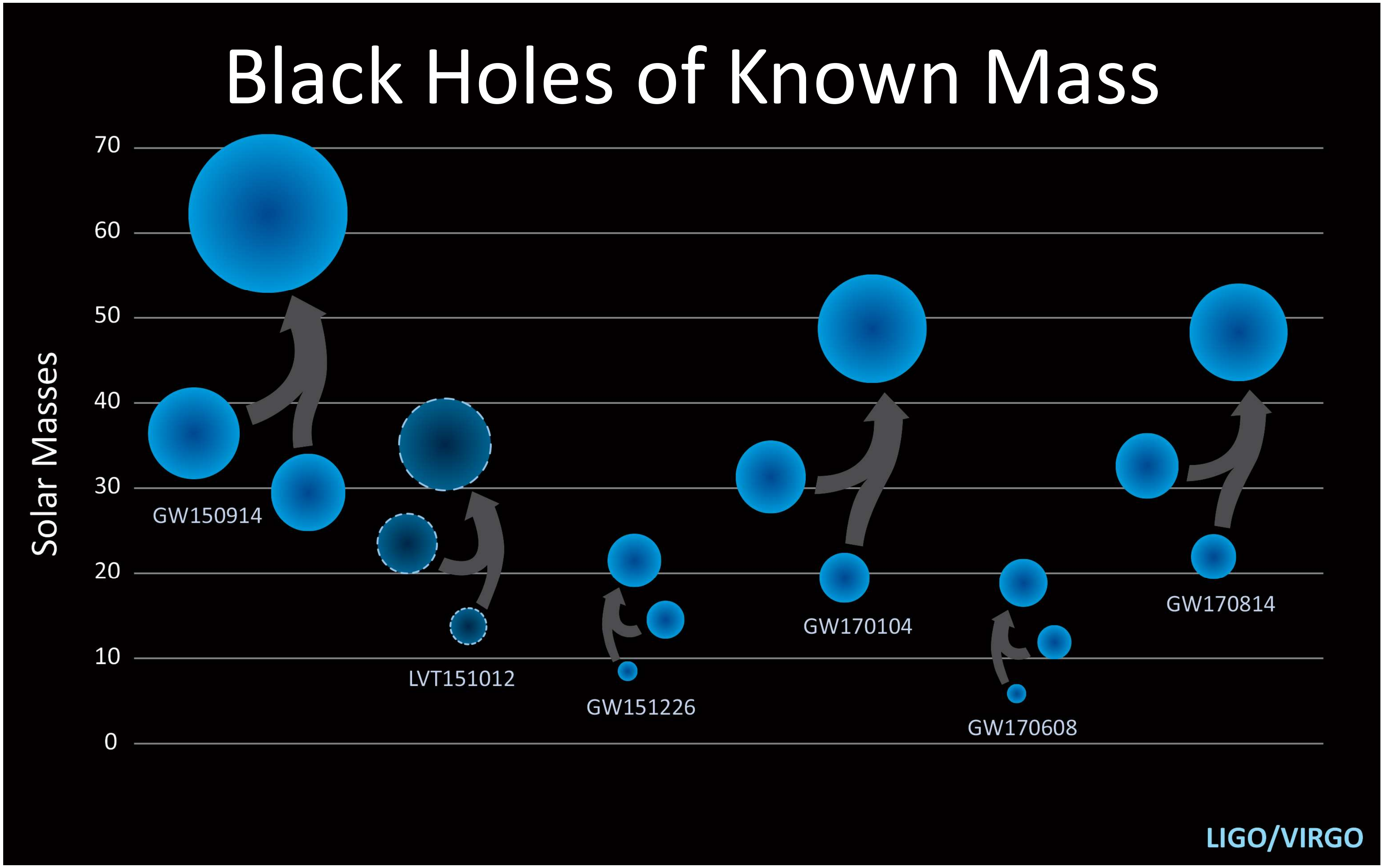
- What is ‘bread & butter astrophysics’?
- What are gravitational wave events?
  - How can we produce LIGO events?
- What have we learned?
- Looking to the future

Astrophysics: Two Questions

- Are we alone?
- How did we get here?
  - Where do elements come from?
  - How do planets form?
  - How do stars form, live & die?
  - How do galaxies form, live & die?

Gravitational Wave Events





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

What we know

- LIGO: 5.9 BH-BH mergers
  - Inferred rate: 12-213 Gpc^{-3} yr^{-1}
    - SNe rate: 10^5 Gpc^{-3} yr^{-1}
  - Masses: large compared to MW BHs
  - Spins: not maximal, not all aligned

Plain vanilla astrophysics models

- Field binaries
  - But rates, masses, spins
- Dynamics in clusters
  - Including nuclear star clusters (NSCs)
- AGN disks
  - NSCs with gas (McKernan, Ford, Kocsis, Lyra & Winter 2014)

A cartoon AGN

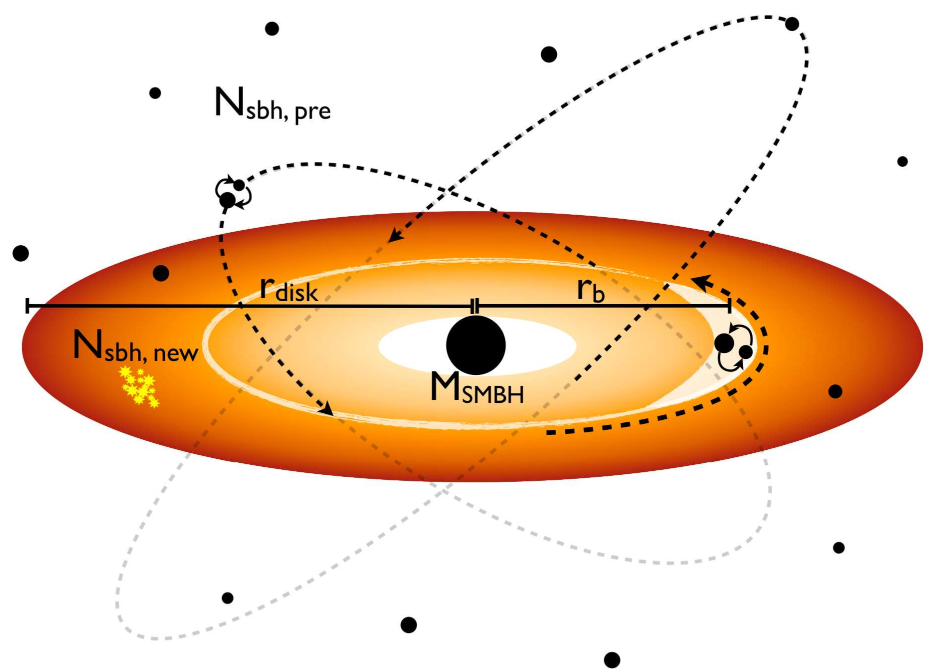


Image credit: O'Dowd

A Parameterized Rate Equation

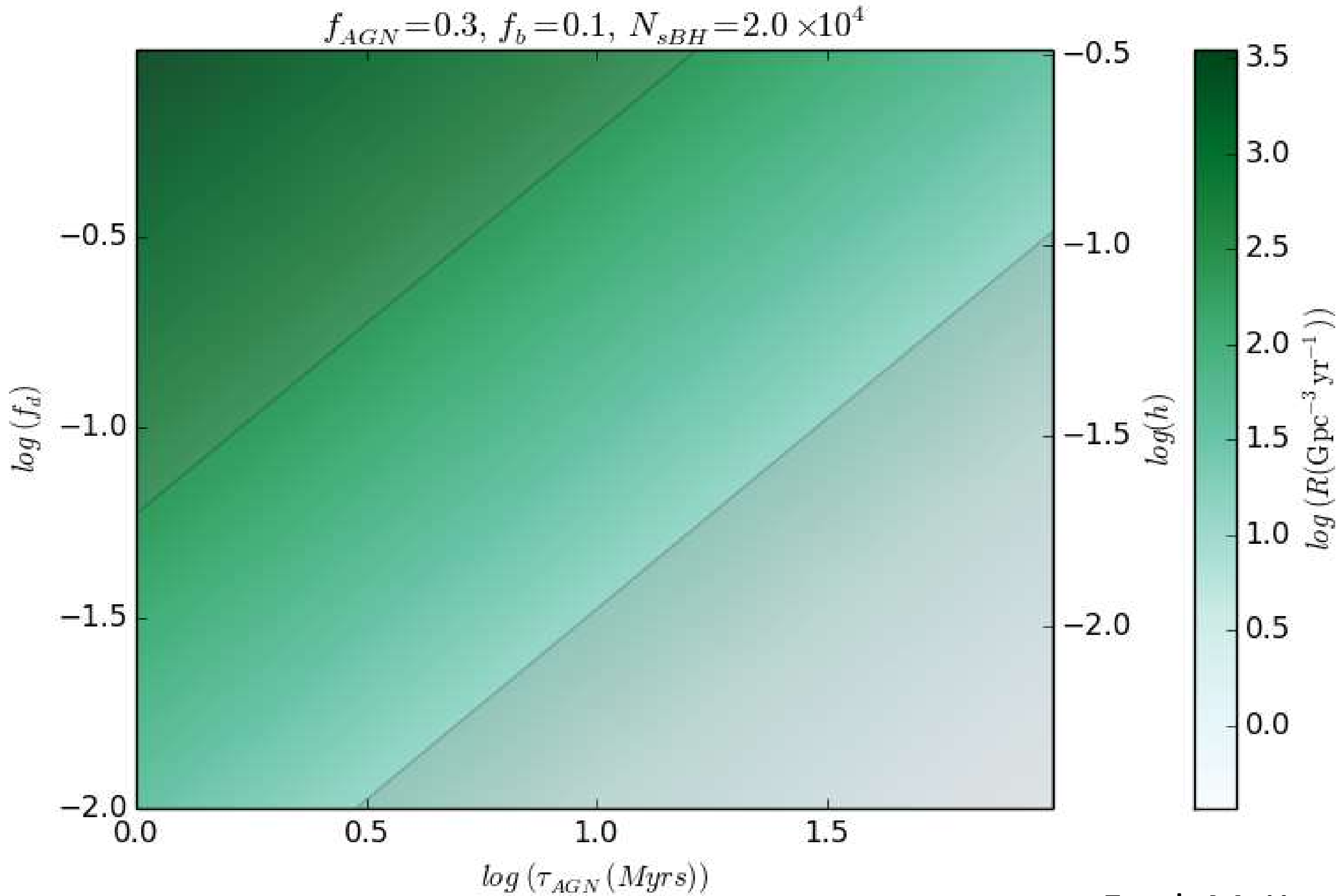
$$\mathcal{R}_A = \frac{N_{GN} N_{sBH} f_{AGN} f_d f_b \epsilon}{\tau_{AGN}}$$

McKernan, Ford + 2018 ApJ accepted
arXiv:1702.07818

Rate Values

Parameter	Lower	Upper
$N^{a}_{GN}(\mathrm{Mpc}^{-3})$	4×10^{-3}	10^{-2}
$N^{b}_{BH}(\mathrm{pc}^{-3})$	10^{3}	10^{6}
f^{c}_{AGN}	0.01	0.3
f_b	0.01	0.2
f^{d}_{d}	0.01	0.7
$\tau_{AGN}(\mathrm{Myr})$	1	100
ϵ	0.5	2
$\mathcal{R}(\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1})$	10^{-4}	10^{4}

McKernan, Ford + 2018 ApJ accepted



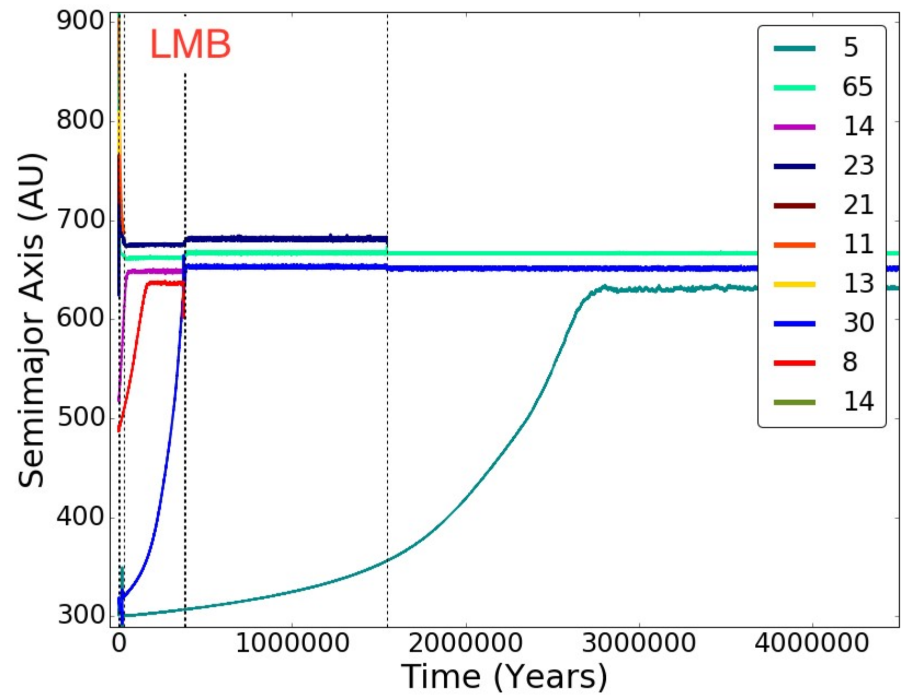
Ford, McKernan+ in prep

What astrophysics have we learned?

- Most LINERs are not super-Eddington ADAFs
  - AGN disks are not (typically) very fat
- Stellar mass BH in NSCs are not maximally packed
- AGN lifetimes are not very short

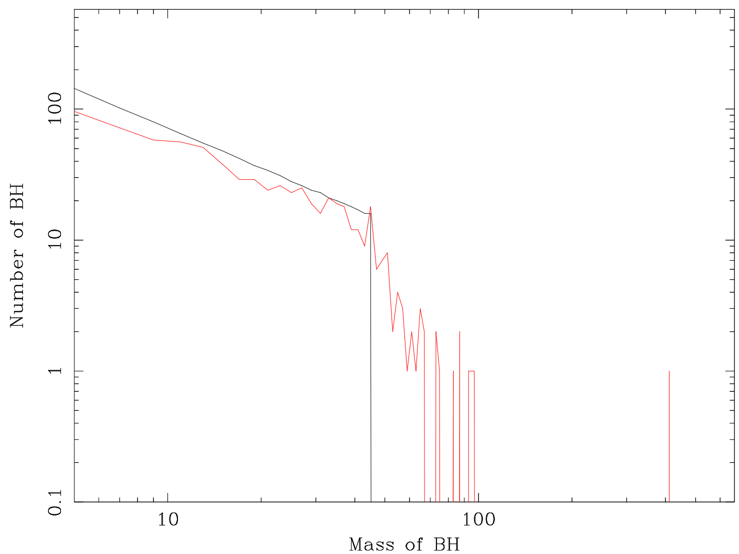
Can we build more complex models?

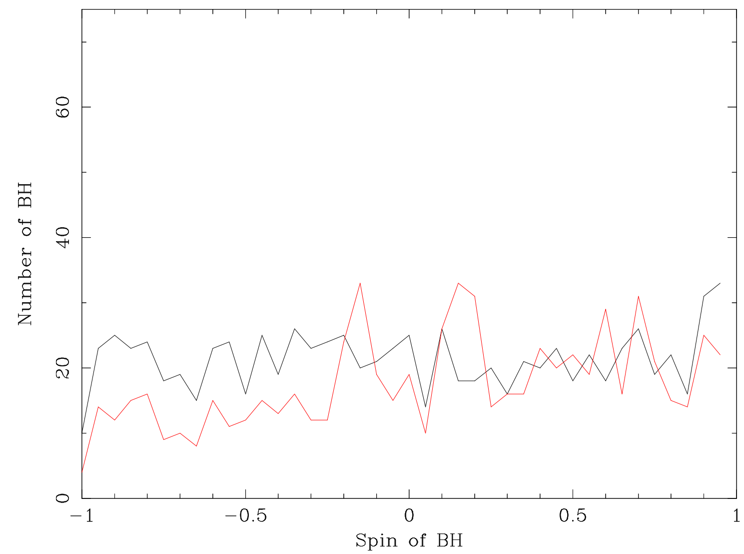
- N-body sims:



Secunda, Bellovary, MacLow, Ford, McKernan++ 2018

Probabilistic sims: Mass & Spin



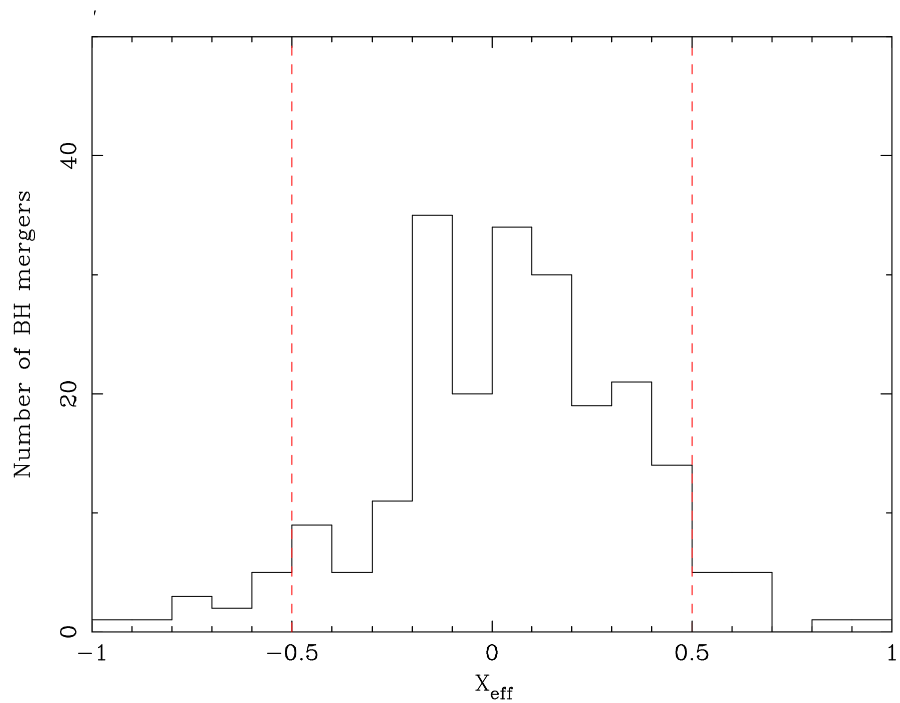


McKernan, Ford, O'Shaughnessy, Wysocki in prep

Spin

$$\vec{\chi}_{\text{eff}} = \frac{M_1\vec{S}_1 + M_2\vec{S}_2}{M_1 + M_2} \bullet \vec{L}_b.$$

χ_{eff}



McKernan, Ford, O'Shaughnessy, Wysocki in prep

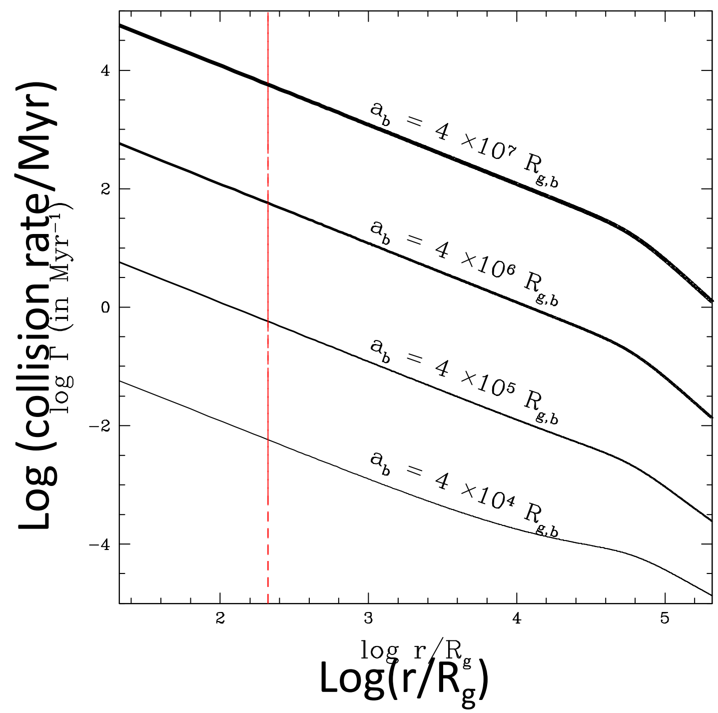
The Future

- LIGO/VIRGO statistics
  - Spin, mass statistics
  - Need O(100) events to limit AGN contribution
- LISA will find (or not) SMBH-IMBH binaries
- JWST will look at AGN too
  - Guaranteed Time Observing

What you should remember

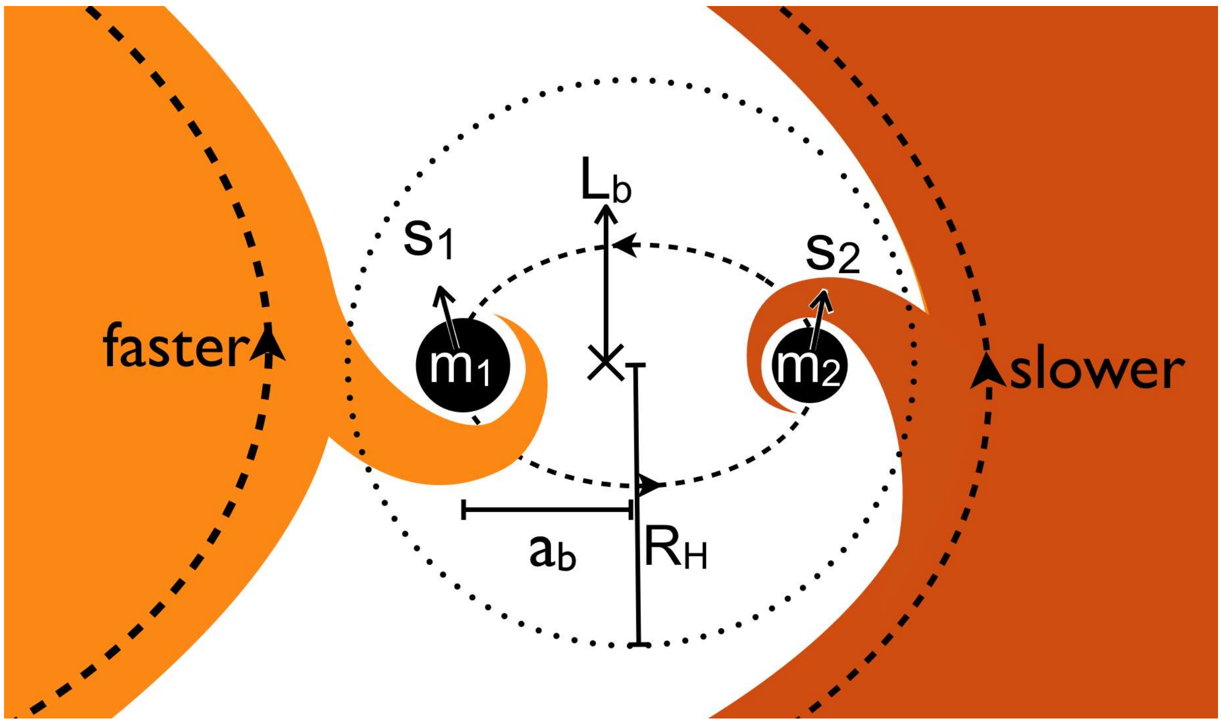
- GW events don’t just do GR
- Zero AGN contribution is most interesting!
- Modeling efforts ongoing
- Statistics in the near future
- Many missions in 10-20 year timeframe

Collisions in NSCs



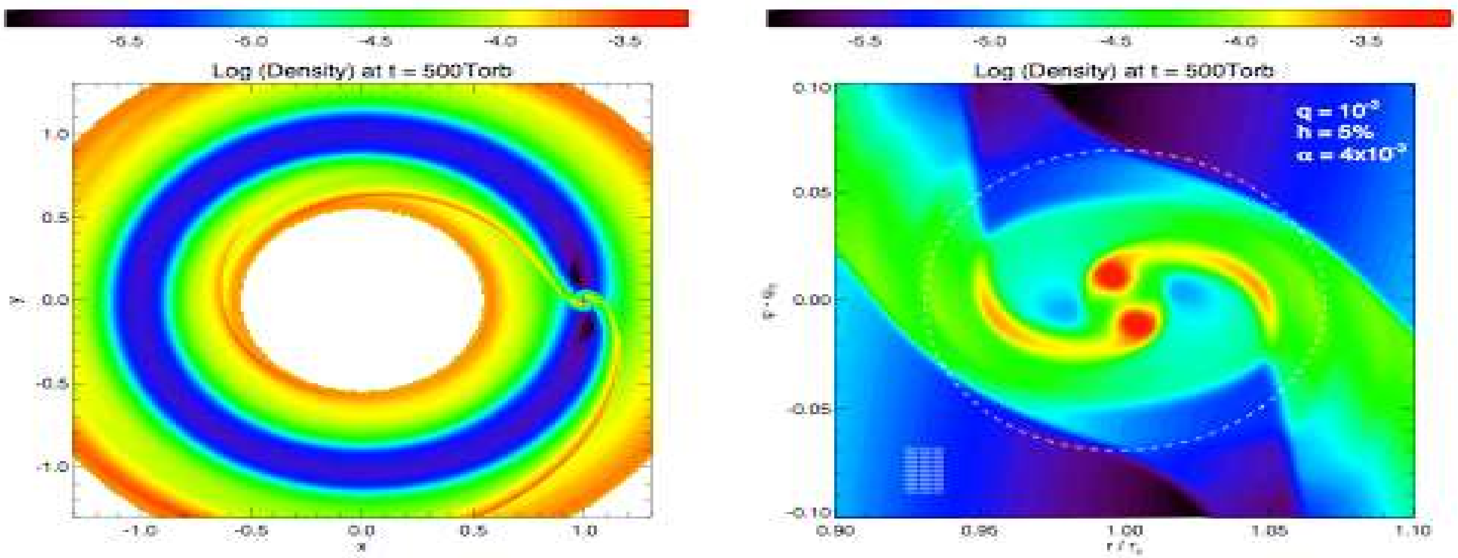
Leigh, Geller, McKernan, Ford + 2018

Binary merger timescales in disk?



$$R_H = r_b (q/3)^{1/3}$$

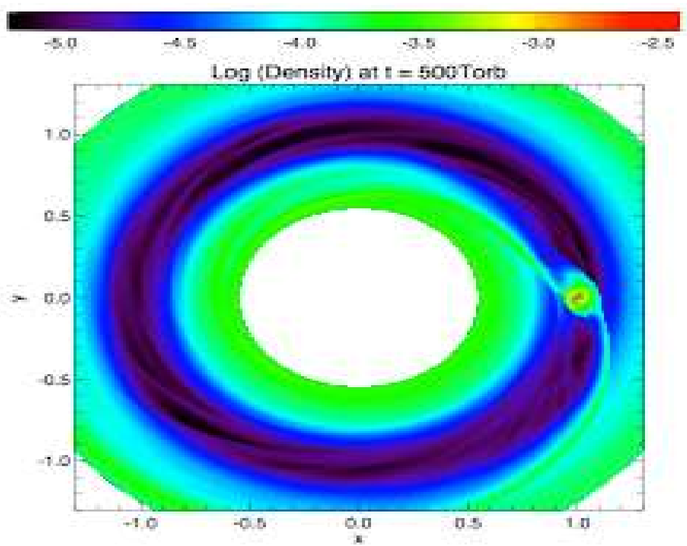
Wakes within Hill sphere harden binary

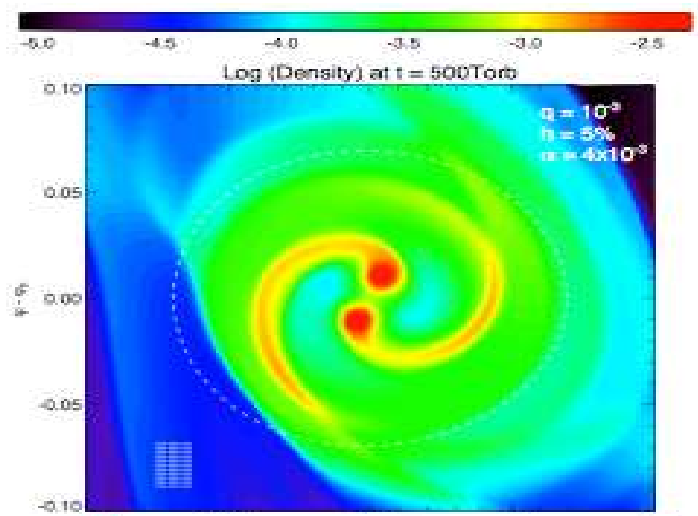


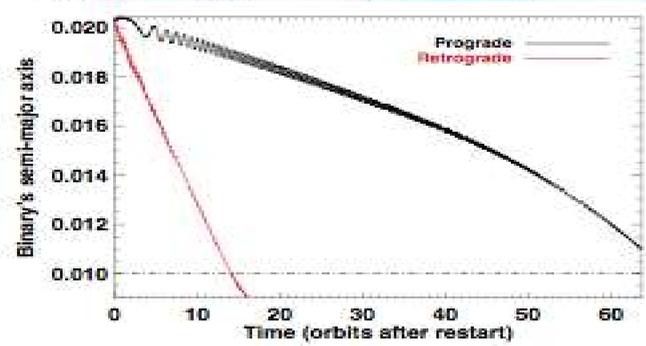
Baruteau+11

- $a_b \rightarrow a_b/2$ in only $\sim 10^3\ T_{orb,bin}$

Retrograde binaries harden faster





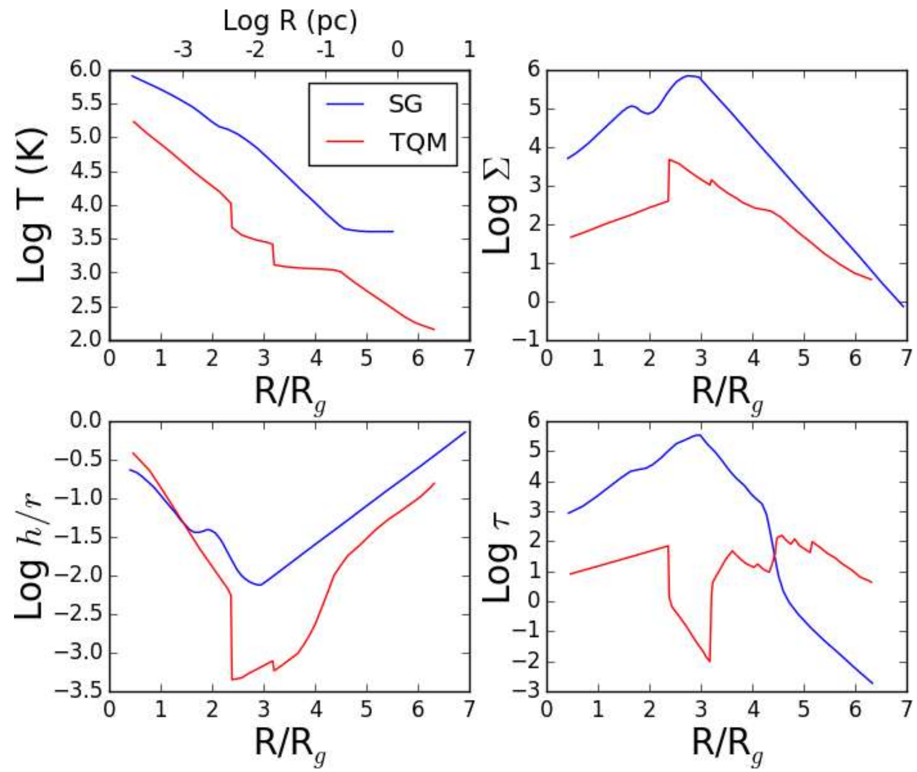


Baruteau+11

- $a_b \longrightarrow a_b/2$ in only ~200 $T_{orb,bin}$

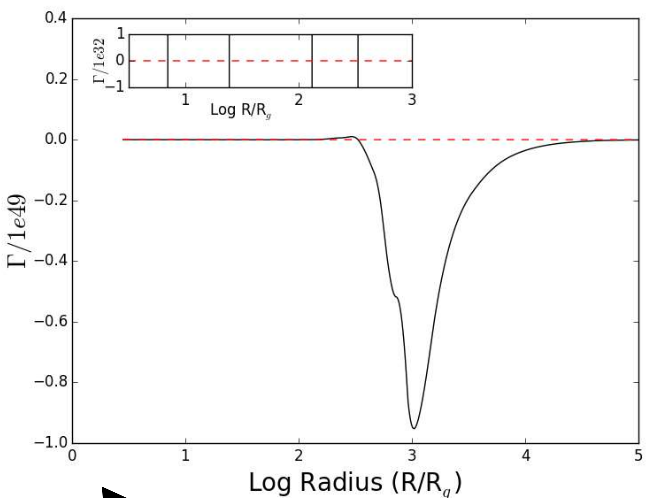
Look for Hernandez, Lyra++ 2019

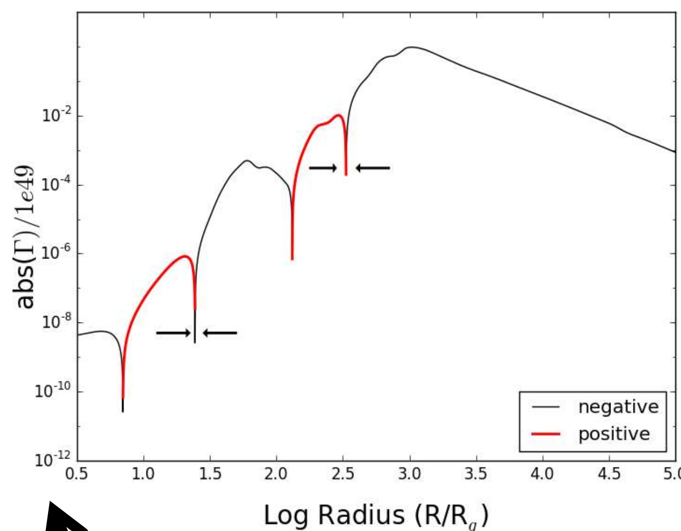
AGN disk models



Sirko & Goodman 2003 Thompson, Quataert & Murray 2005

Migration traps in S&G model





Linear scale

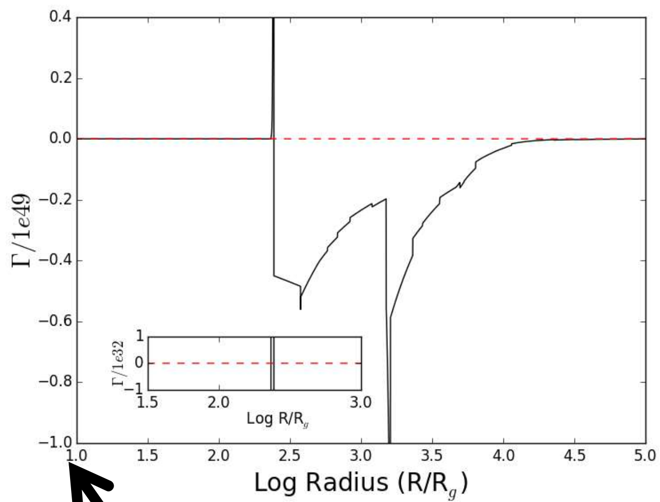
Log scale

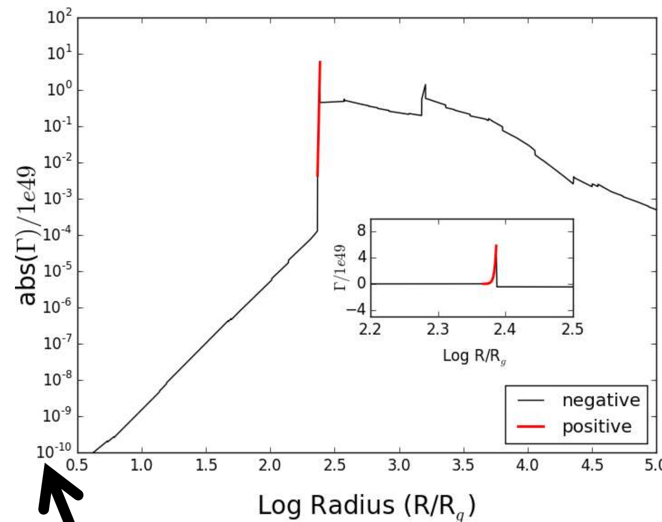
Bellovary, MacLow, McKernan & Ford 2016

24.5 and 331 R_g

Sirko & Goodman 2003 disk model: TWO TRAPS

Migration traps in TQM model





Bellovary, MacLow, McKernan & Ford 2016

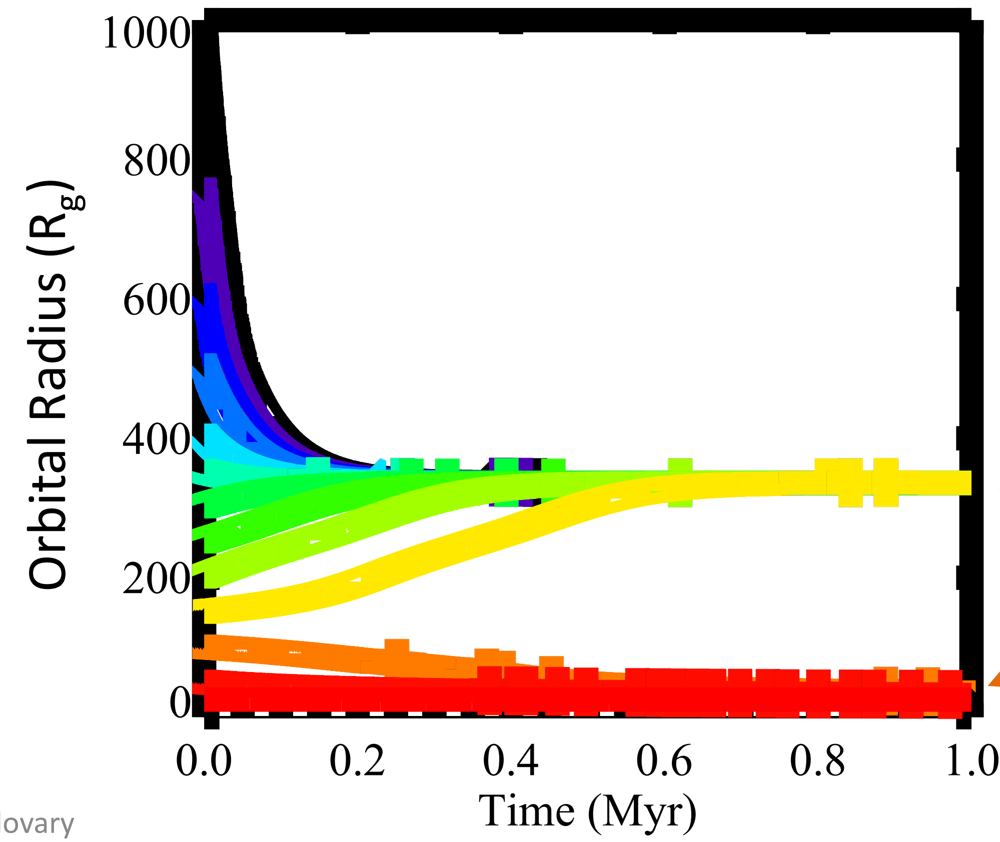
Linear scale

Log scale

Thompson Quataert & Murray 2005 disk model: ONE TRAP

245 R_g

Migration of a single object



- One 30 $M_\odot$ BH
- Different starting radii
- $M_{SMBH} = 10^8 M_\odot$

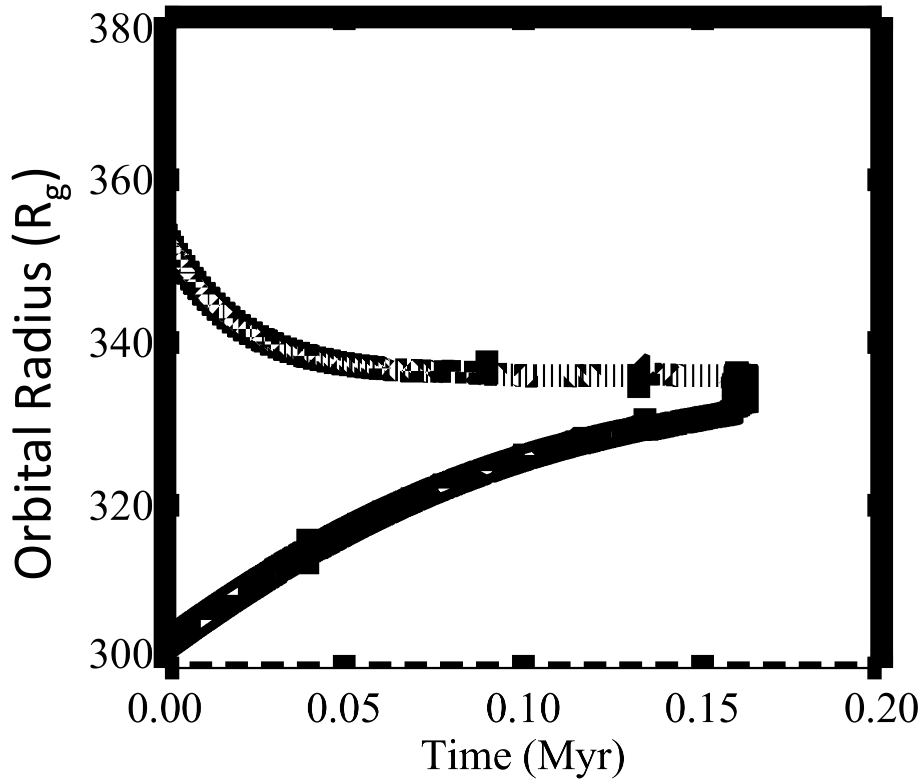
Predicted traps:
331 R_g
25 R_g

@j_bellovary

Secunda, Bellovary, Ford++ in prep

Migration and merger of two objects

- 50 $M_\odot$ BH and 30 $M_\odot$ BH
- Form a binary upon reaching trap



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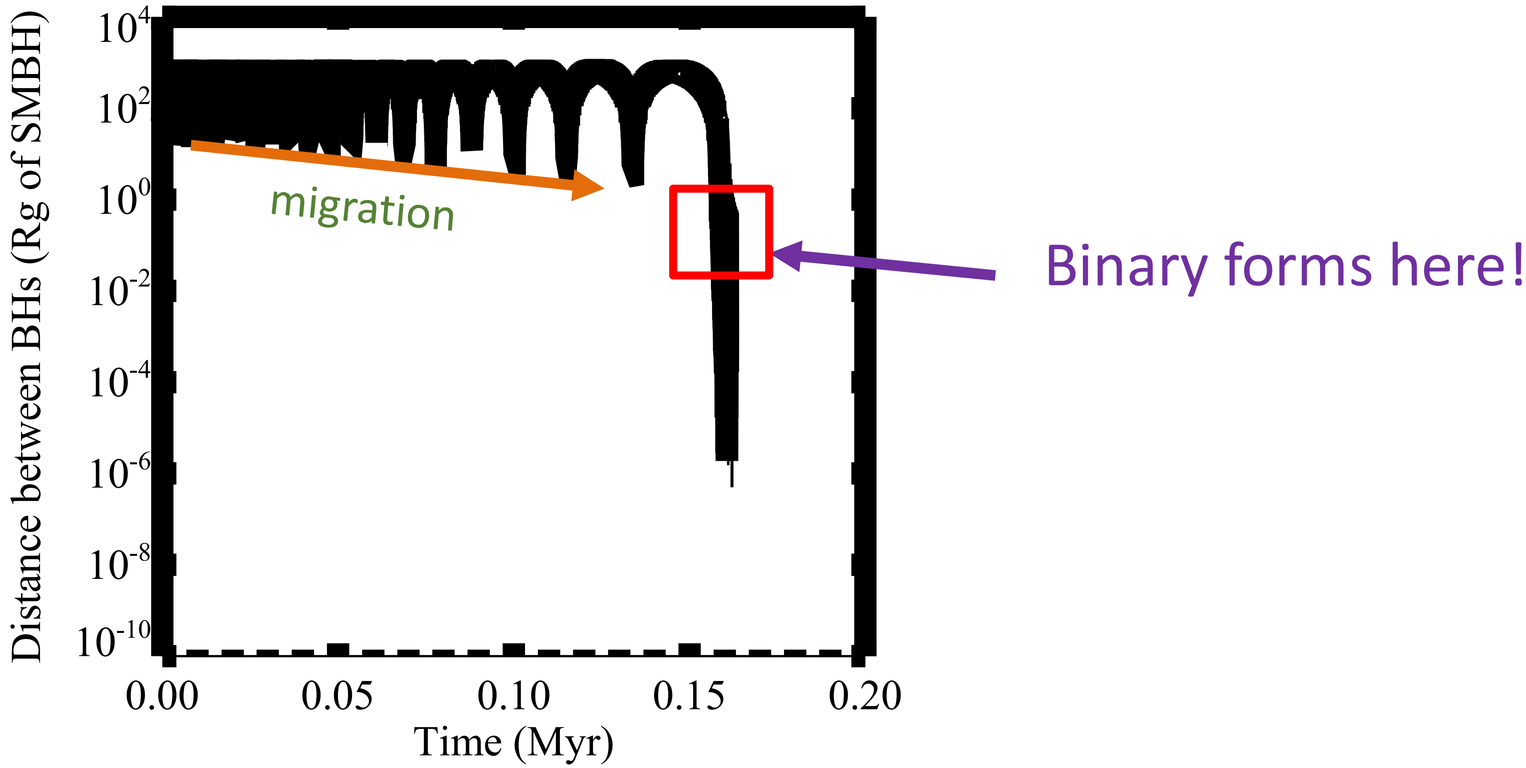
Binary Details: formation



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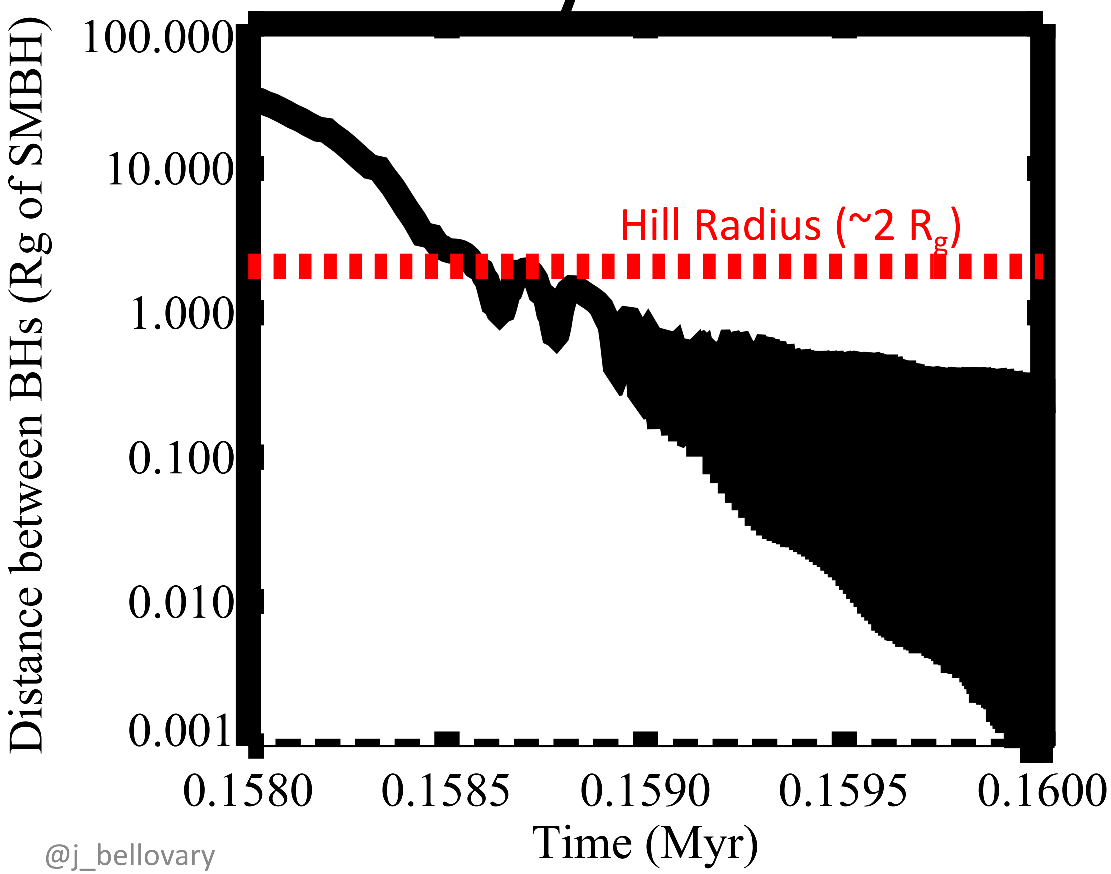
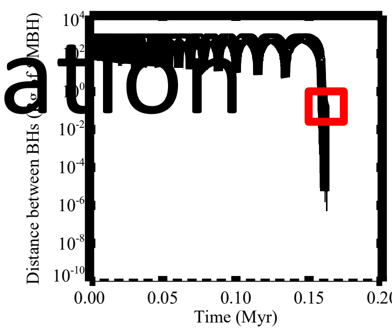
Binary Details: formation





Binary forms, orbit becomes eccentric

Gas torques tug and perturb the orbit

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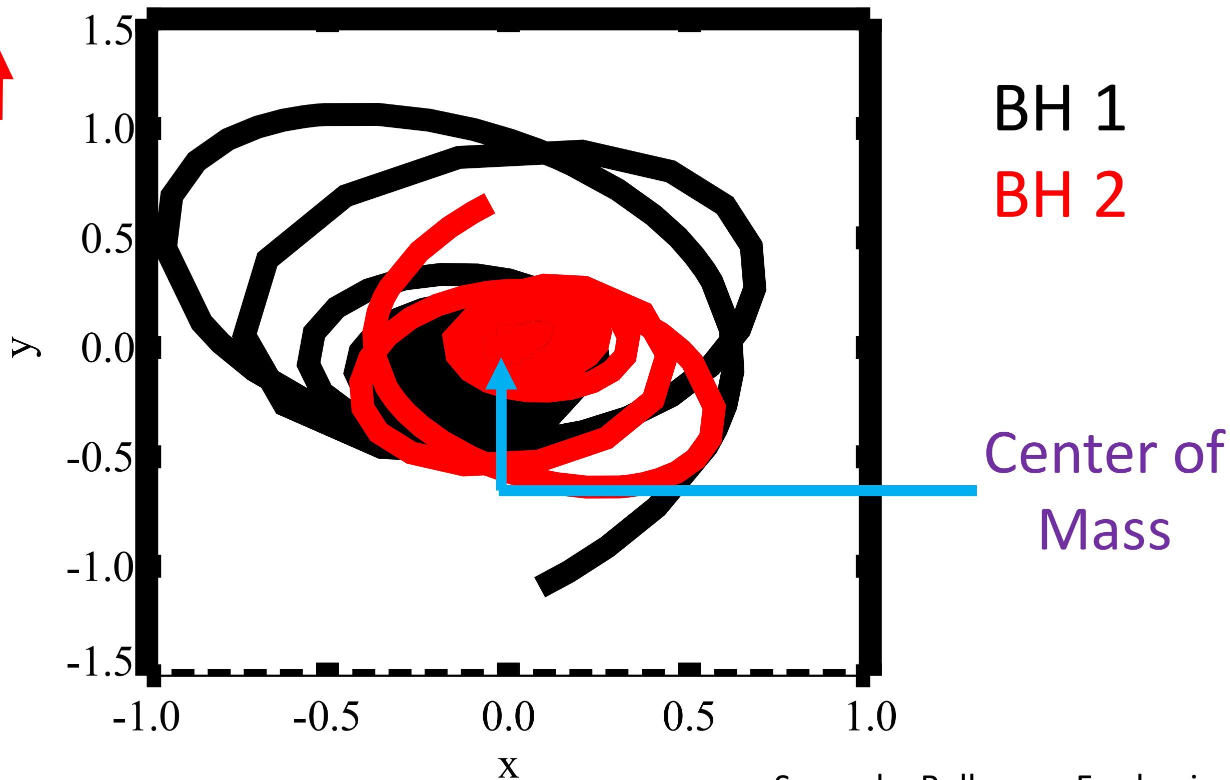
Binary Details: center of mass frame

Orbital eccentricity ↑

Orbital energy lost to gas (which we do not track)

Eventually plunging orbits cause merger



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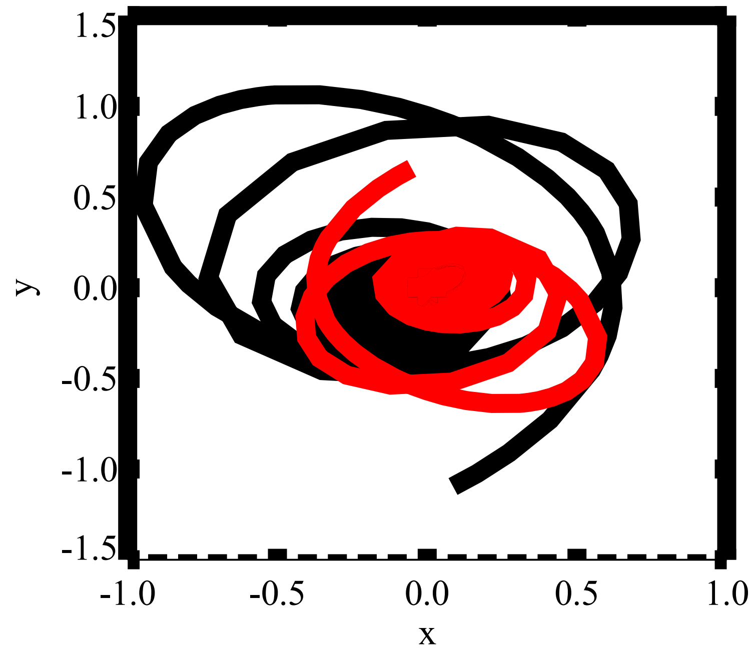
Secunda, Bellovary, Ford++ in prep

Worst Case scenario!

- Physics not included*:
  - Gas drag
  - GW energy losses

Both will speed up the merger!



*among many many other effects

@j_bellovary

Hey, what about Stone+ and Bartos+ 2017?

- One number
  - many implicit assumptions
- Razor thin disks
  - definitely wrong
- Implicitly long AGN lifetime
  - poorly constrained

Naive timescale argument

- Average rate of sBH merger across all GN

  R =

Naive timescale argument

- Average rate of sBH merger across all GN

  $R = N_{sbh}$

Naive timescale argument

- Average rate of sBH merger across all GN

  $R = N_{sbh}\ f_b$

Naive timescale argument

- Average rate of sBH merger across all GN

$$R = \frac{N_{sbh}\, f_b}{t_b}$$

Naive timescale argument

- Average rate of sBH merger across all GN

$$R = \frac{N_{sbh}\, f_b\, n_{GN}}{t_b}$$

Naive timescale argument

- Average rate of sBH merger across all GN

$$R = \frac{N_{sbh,Q}\, f_{b,Q}\, n_{GN}}{t_{b,Q}} + \frac{N_{sbh,A}\, f_{b,A}\, f_{AGN}\, n_{GN}}{t_{b,A}}$$

Naive timescale argument

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$$R = \frac{N_{sbh,Q}\, f_{b,Q}\, n_{GN}}{t_{b,Q}} + \frac{N_{sbh,A}\, f_{b,A}\, f_{AGN}\, n_{GN}}{t_{b,A}}$$

Assume:

$N_{sbh,Q} = N_{sbh,A}$

Naive timescale argument

- Average rate of sBH merger across all GN

$$R = \frac{N_{sbh,Q}\, f_{b,Q}\, n_{GN}}{t_{b,Q}} + \frac{N_{sbh,A}\, f_{b,A}\, f_{AGN}\, n_{GN}}{t_{b,A}}$$

Assume:

$N_{sbh,Q} = N_{sbh,A}$

$f_{b,Q} = f_{b,A}$