LIGO sources in AGN disks

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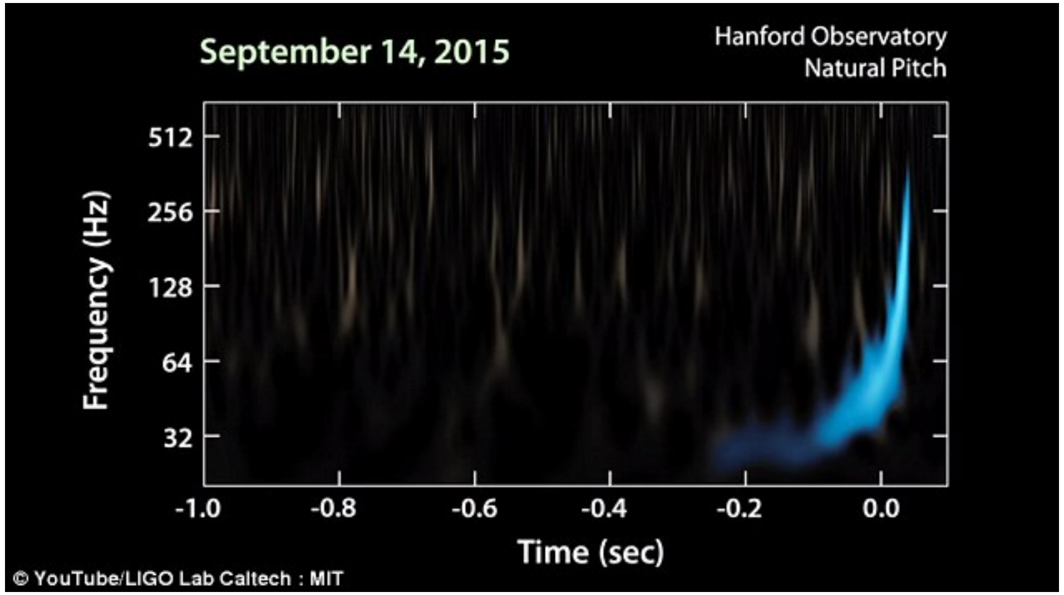
Budapest, June 14rd, 2017

Motivation



LIGO BH Masses:

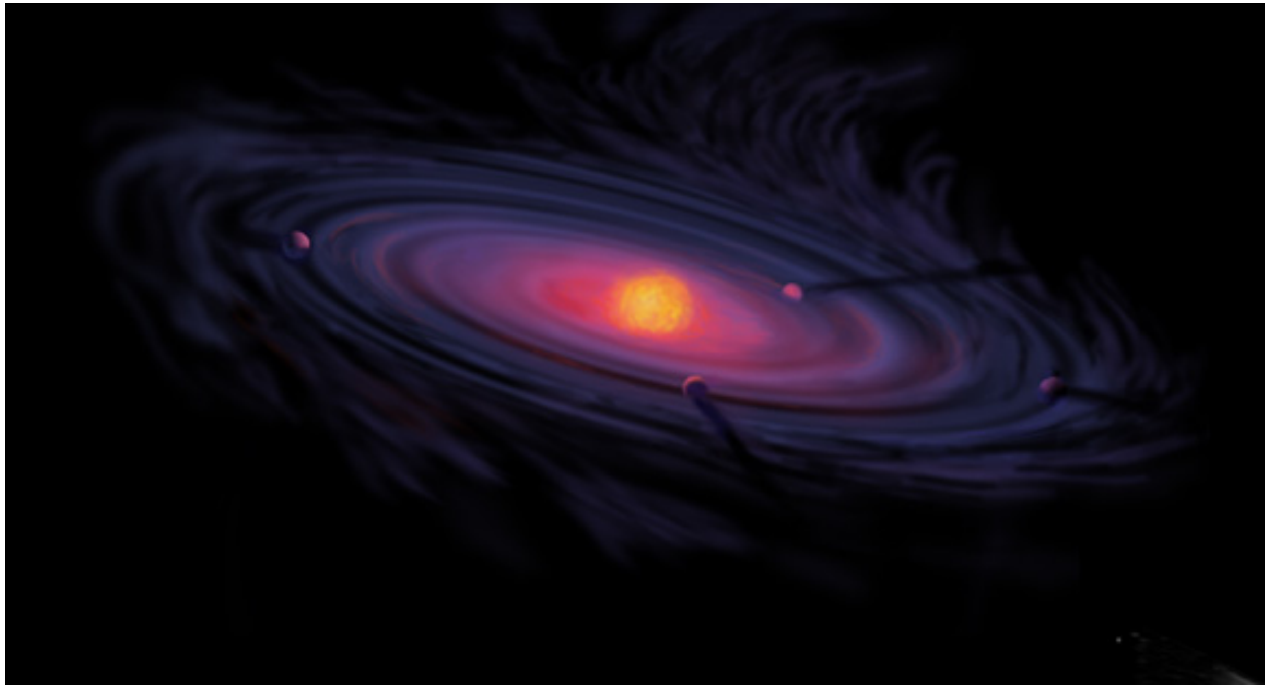
GW150914: 36 and 29 $M_\odot$
LVT151012: 23 and 13 $M_\odot$
GW151226: 14 and 7 $M_\odot$
GW170104: 31 and 19 $M_\odot$

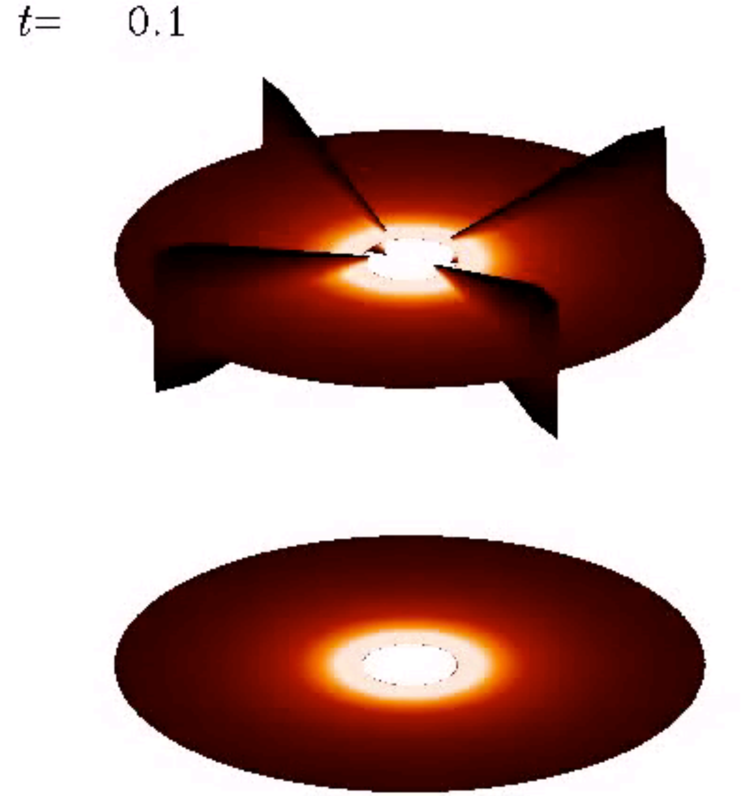
Large masses + misaligned spins challenge stellar evolution-based BH-BH merger theories

We need a new theory!

Diversion: Let's talk about planets

Planets impact the gas dynamics in their parental disk

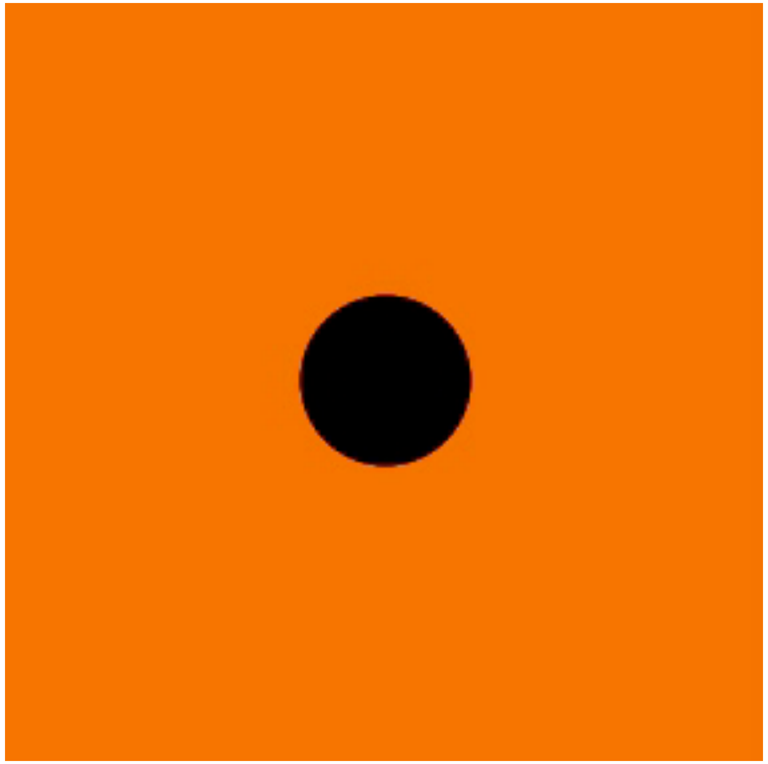




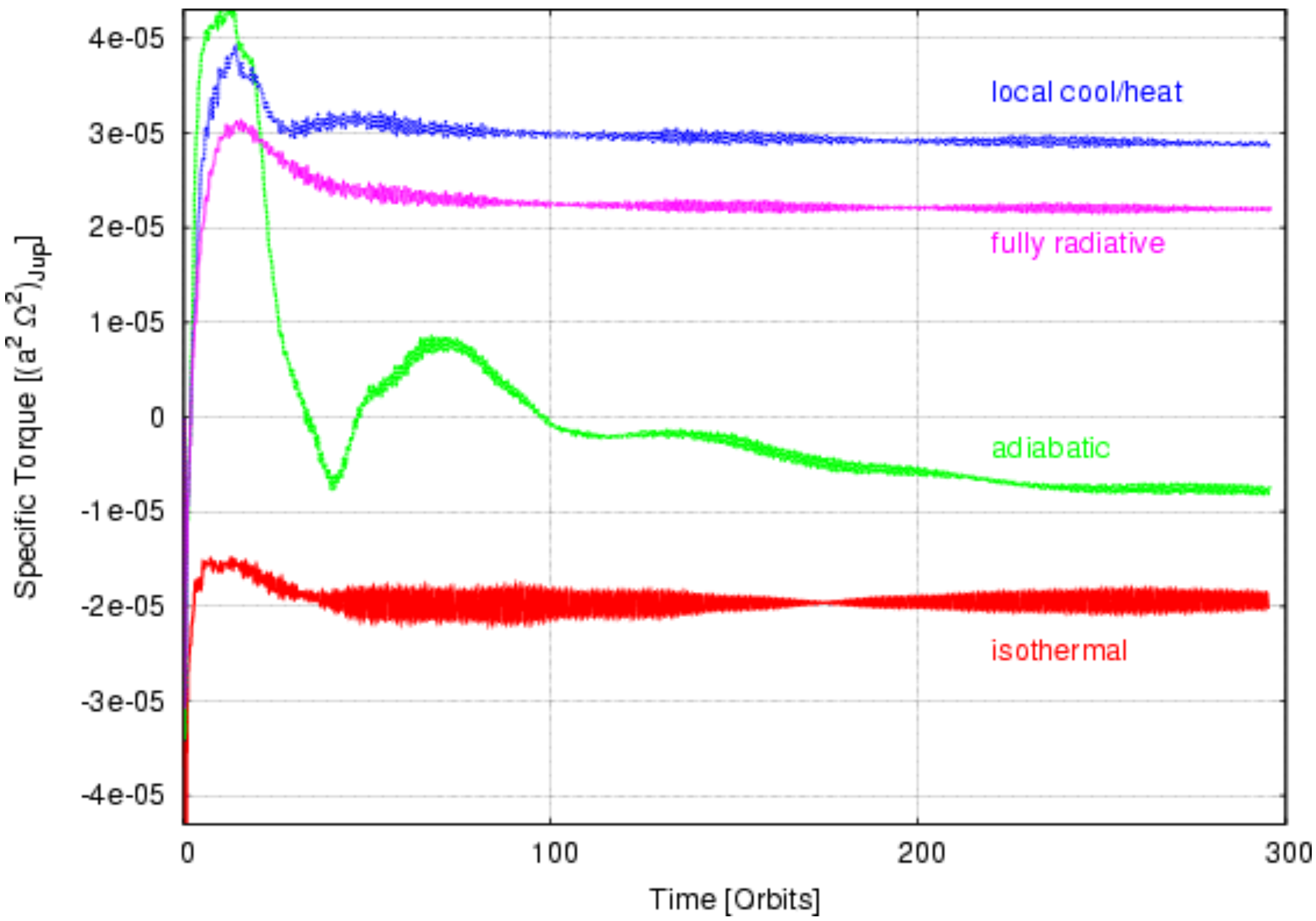
(Lyra 2009)

Diversion: Let’s talk about planets

Planet-disk interaction leads to angular momentum exchange (migration)



Migration – Thermodynamics matter



Rule of thumb: ***Migration is***

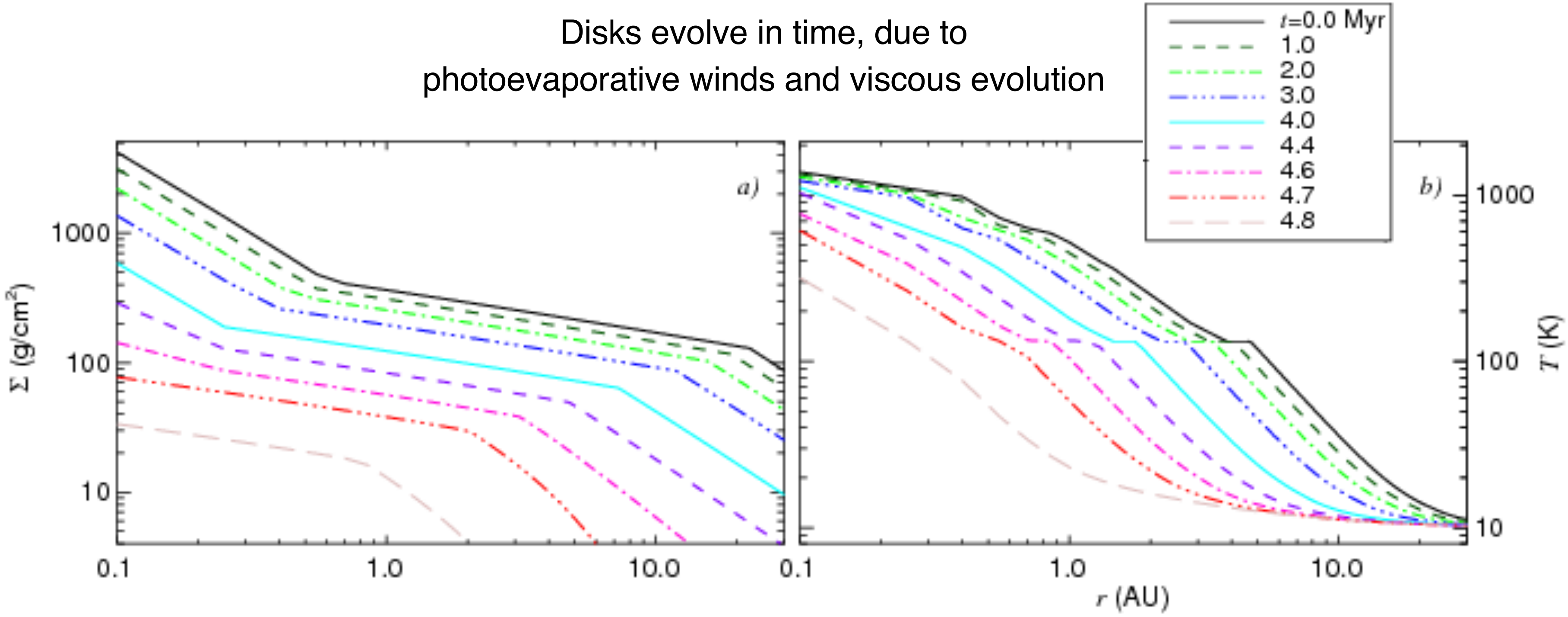
outwards in
steep temperature gradients,

inwards in
isothermal regions.

Paardekooper & Mellema (2006)
Kley & Crida (2008)

Disk Evolution

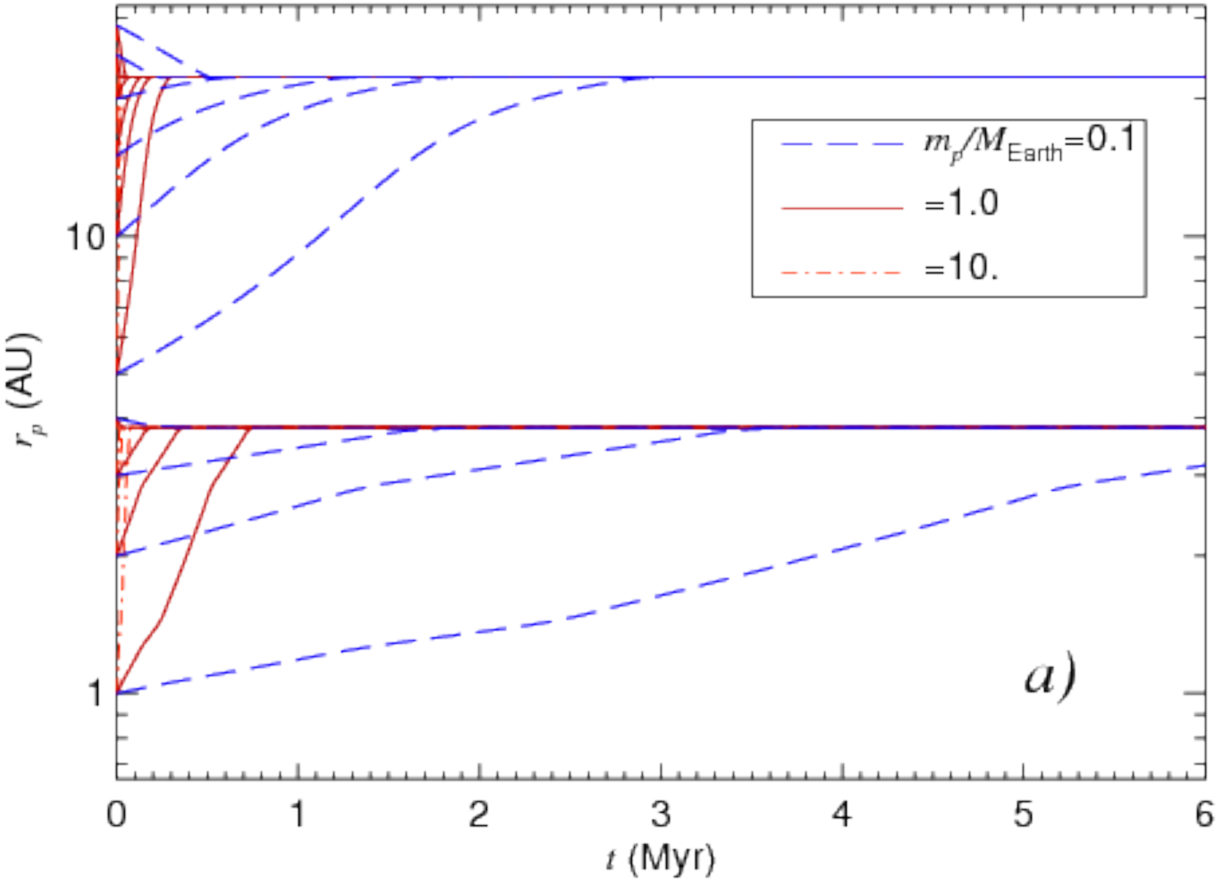
Disks evolve in time, due to
photoevaporative winds and viscous evolution



Lyra, Paardekooper, & Mac Low (2010)

Migration Traps

Planet-disk interaction leads to **angular momentum exchange**



Lyra, Paardekooper, & Mac Low (2010)

Rule of thumb: ***Migration is***

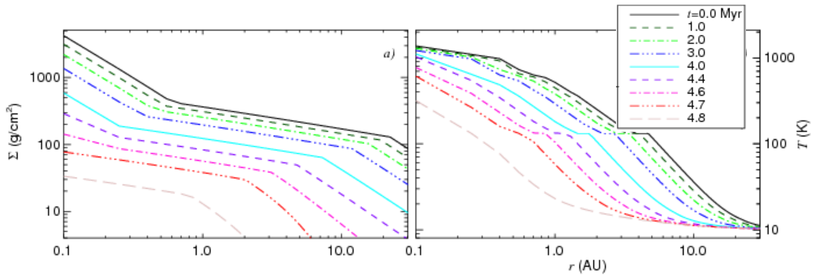
outwards in
steep temperature gradients,

inwards in
isothermal regions.

Planet traps where migration is
convergent
(τ=0, $d\tau/dr < 0$).

Migration in Evolutionary Models

Disks evolve in time, due to
photoevaporative winds and viscous evolution



Single planets in a planetary trap evolve in lockstep with the gas at the accretion timescale.

At some point, the **disk becomes too thin** to drive accretion. The **planet decouples** and is **released** in a safe orbit.

Rule of thumb: ***Migration is***

outwards in
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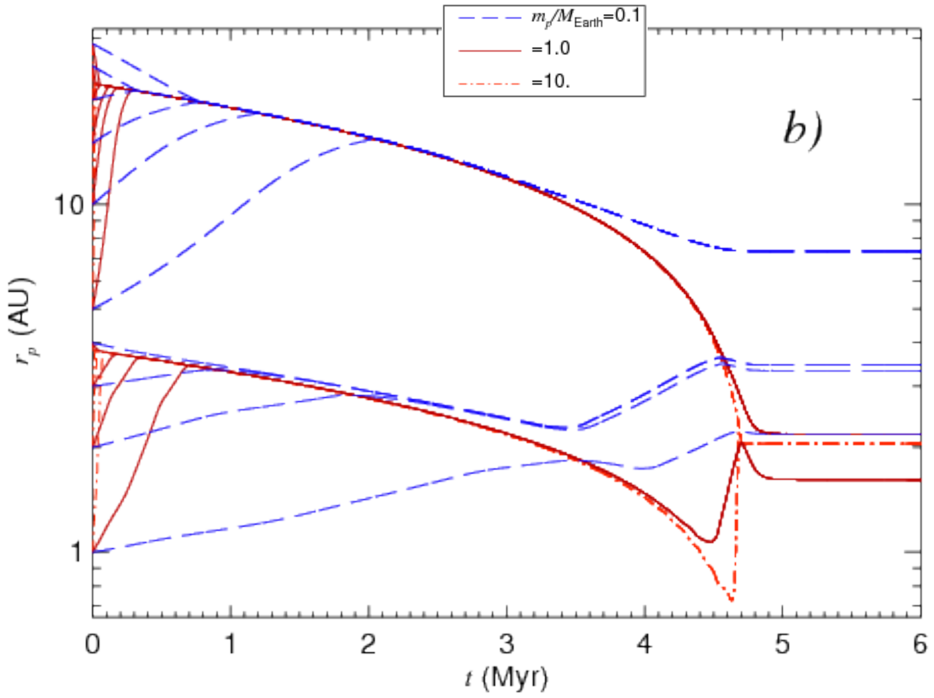
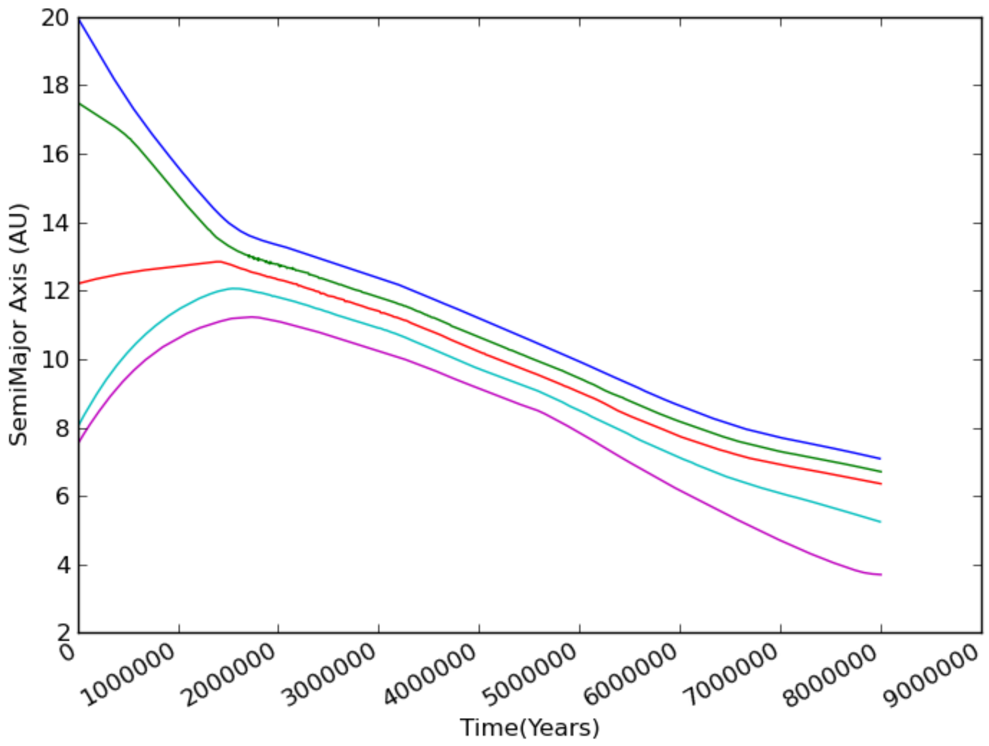
isothermal regions.



Lyra, Paardekooper, & Mac Low (2010)

Resonance Trapping



Migration in resonance !

Sandor, Lyra & Dullemond (2011)

Growing larger stuff in migration traps

Resonance trapping

FORMATION OF PLANETARY CORES AT TYPE I MIGRATION TRAPS

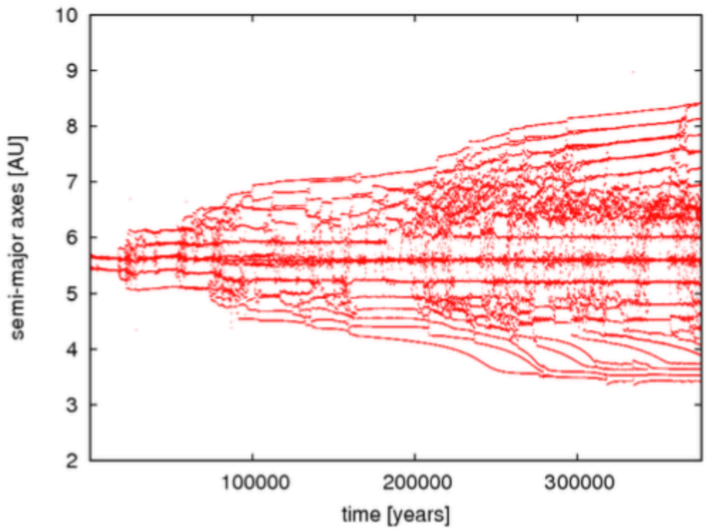
Zsolt Sándor[1], Wladimir Lyra[2], and Cornelis P. Dullemond[1,3]

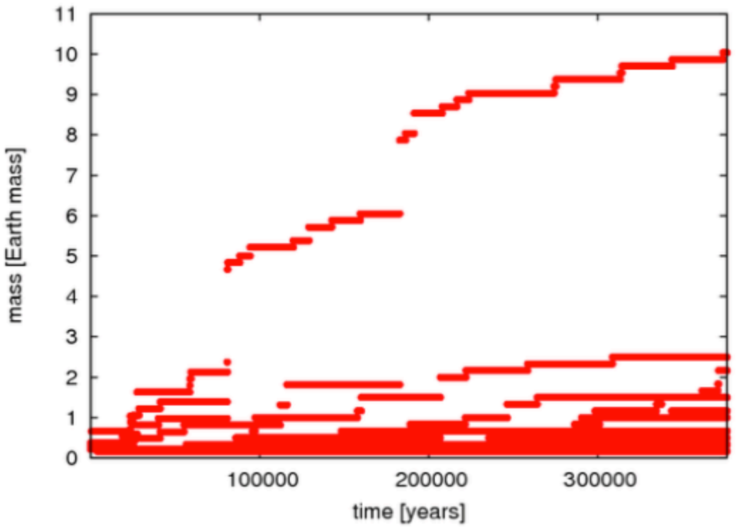
Draft version January 6, 2011

ABSTRACT

One of the longstanding unsolved problems of planet formation is how solid bodies of a few decimeters in size can "stick" to form large planetesimals. This is known as the "meter size barrier". In recent years it has become increasingly clear that some form of "particle trapping" must have played a role in overcoming the meter size barrier. Particles can be trapped in long-lived local pressure maxima, such as those in anticyclonic vortices, zonal flows or those believed to occur near ice lines or at dead zone boundaries. Such pressure traps are the ideal sites for the formation of planetesimals and small planetary embryos. Moreover, they likely produce large quantities of such bodies in a small region, making it likely that subsequent N-body evolution may lead to even larger planetary embryos. The goal of this Letter is to show that this indeed happens, and to study how efficient it is. In particular, we wish to find out if rocky/icy bodies as large as 10 $M_\oplus$ can form within 1 Myr, since such bodies are the precursors of gas giant planets in the core accretion scenario.

Subject headings: planets and satellites: formation — protoplanetary disks — planet-disk interactions — methods: numerical





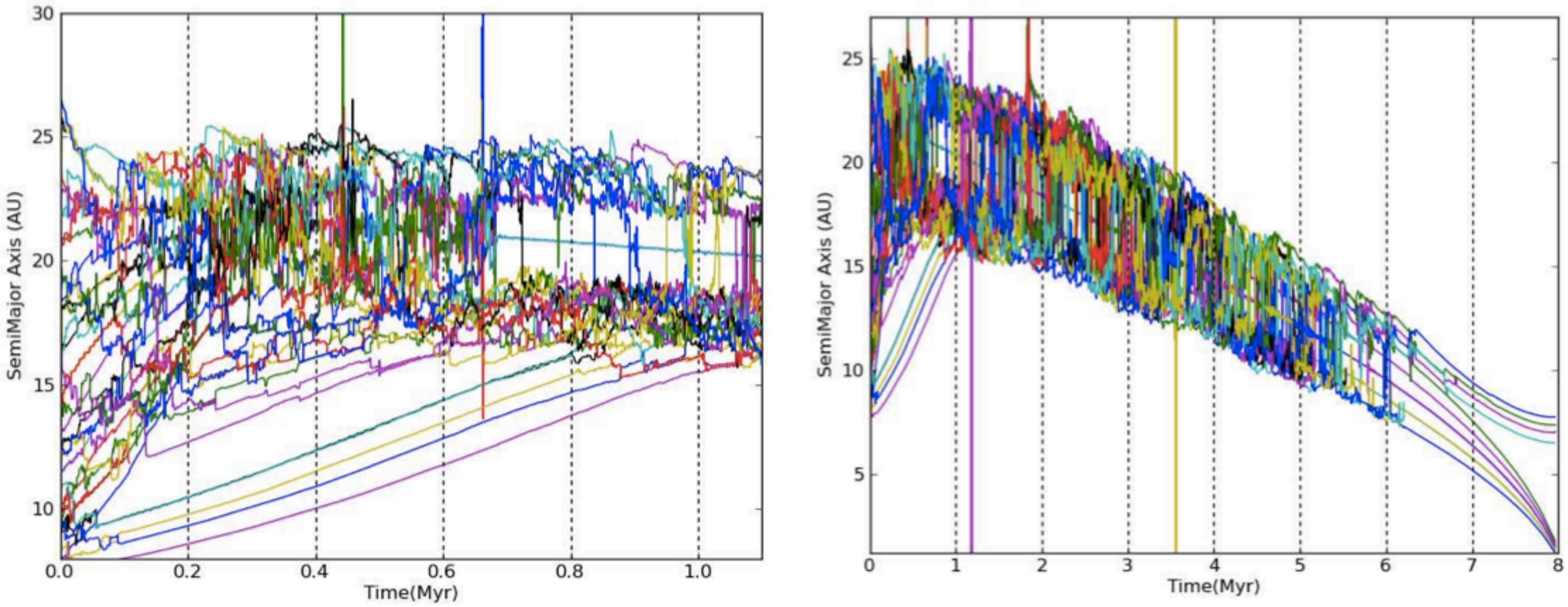
Mars-mass protoplanets added at migration trap

Resonance broken by N-body interaction, that disturbs the resonance

Sandor, Lyra & Dullemond (2011)

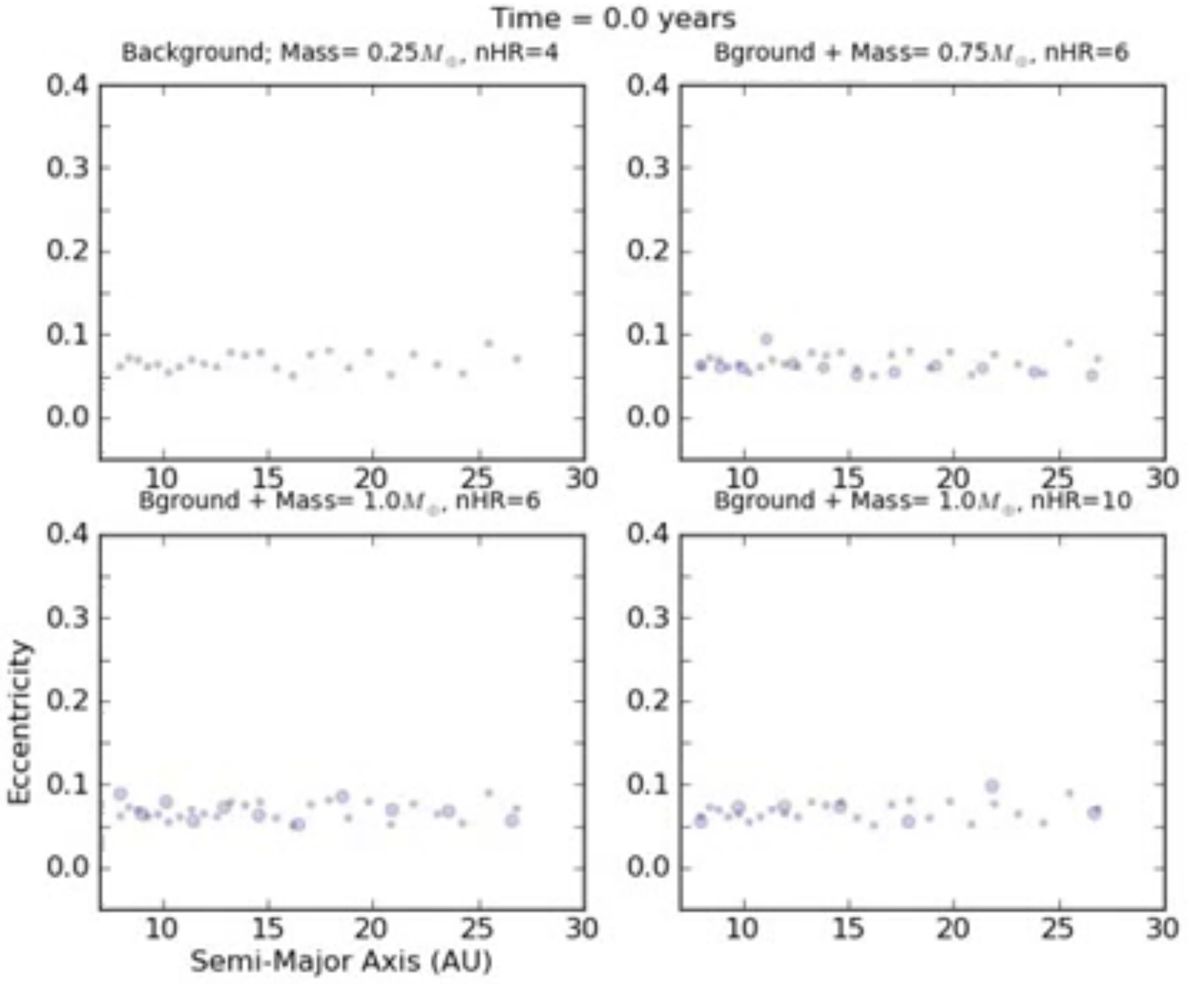
Orbital migration of interacting planets in a radiative evolutionary model

Combines
migration + N-body + photoevaporation + turbulence
modelled as stochastic forcing
(Laughlin et al. 2004, Ogihara et al. 2007)



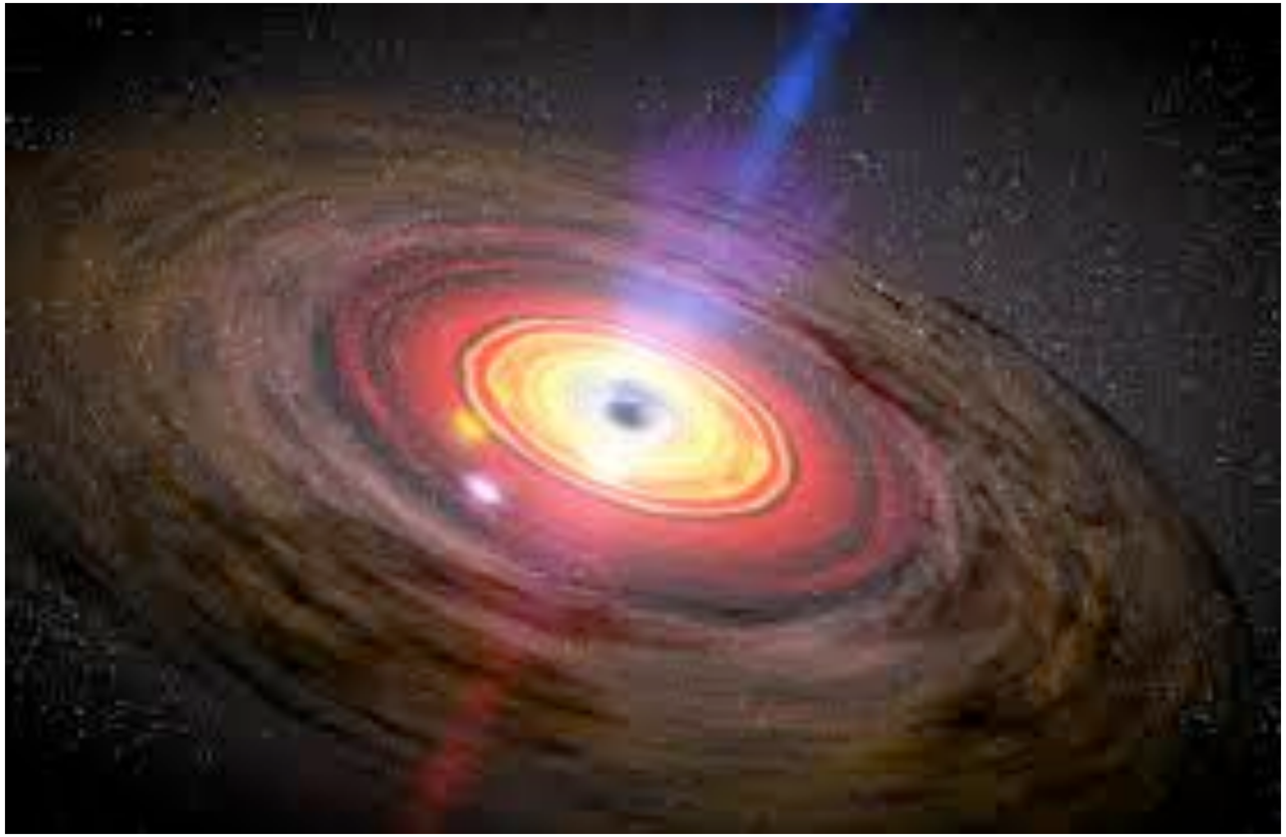
Horn, Lyra, Mac Low & Sándor (2012)

Orbital migration of interacting planets in a radiative evolutionary model



Horn, Lyra, Mac Low & Sándor (2012)

Back to black holes, and migration traps



- Protoplanets → stellar mass black holes
- Protoplanetary disk → SMBH accretion disk
- Black holes can migrate too!

→ MIGRATION TRAPS

Result → lots of black hole mergers, making bigger and bigger black holes?!

McKernan+ 12

Torque calculation:

- Surface density gradient $\alpha = -\frac{\partial \ln \Sigma}{\partial \ln r}$
- Temperature gradient $\beta = -\frac{\partial \ln T}{\partial \ln r}$
- Entropy gradient $\xi = \beta - (\gamma - 1)\alpha$
- Scale height *h/r*
- Optical depth τ

Paardekooper+ 10

Torque calculation:

- Surface density gradient $\alpha = -\frac{\partial \ln \Sigma}{\partial \ln r}$
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- Scale height h/r
- Optical depth τ

Total torque:

$$\Gamma = \frac{\Gamma_{ad}\Theta^2 + \Gamma_{iso}}{(\Theta + 1)^2}$$

Torques:

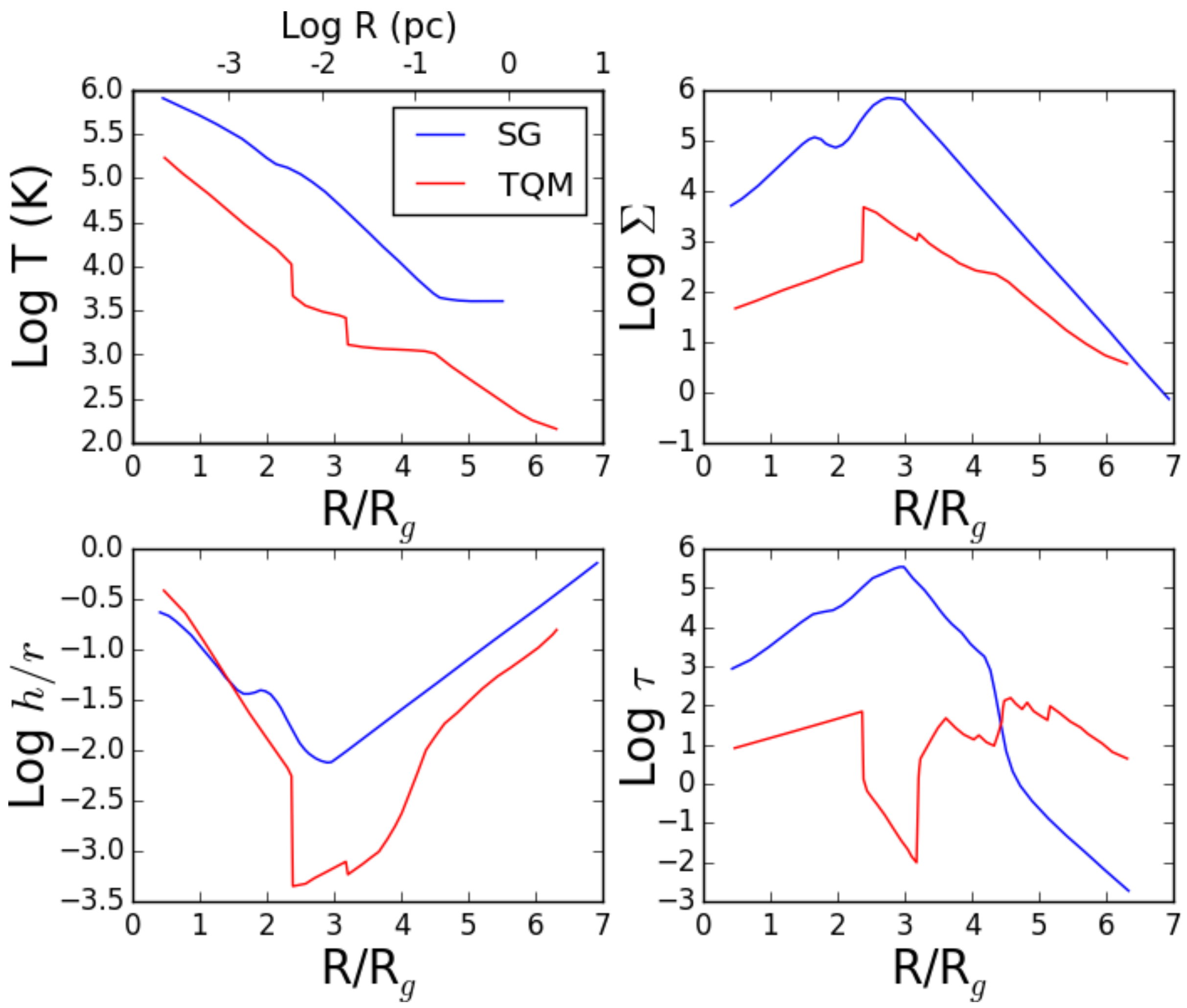
$$\gamma\Gamma_{ad}/\Gamma_0 = -0.85 - \alpha - 1.7\beta + 7.9\xi/\gamma$$

$$\Gamma_{iso}/\Gamma_0 = -0.85 - \alpha - 0.9\beta$$

$\Theta = t_{rad}/t_{dyn}$

Paardekooper+ 10
Lyra+ 10

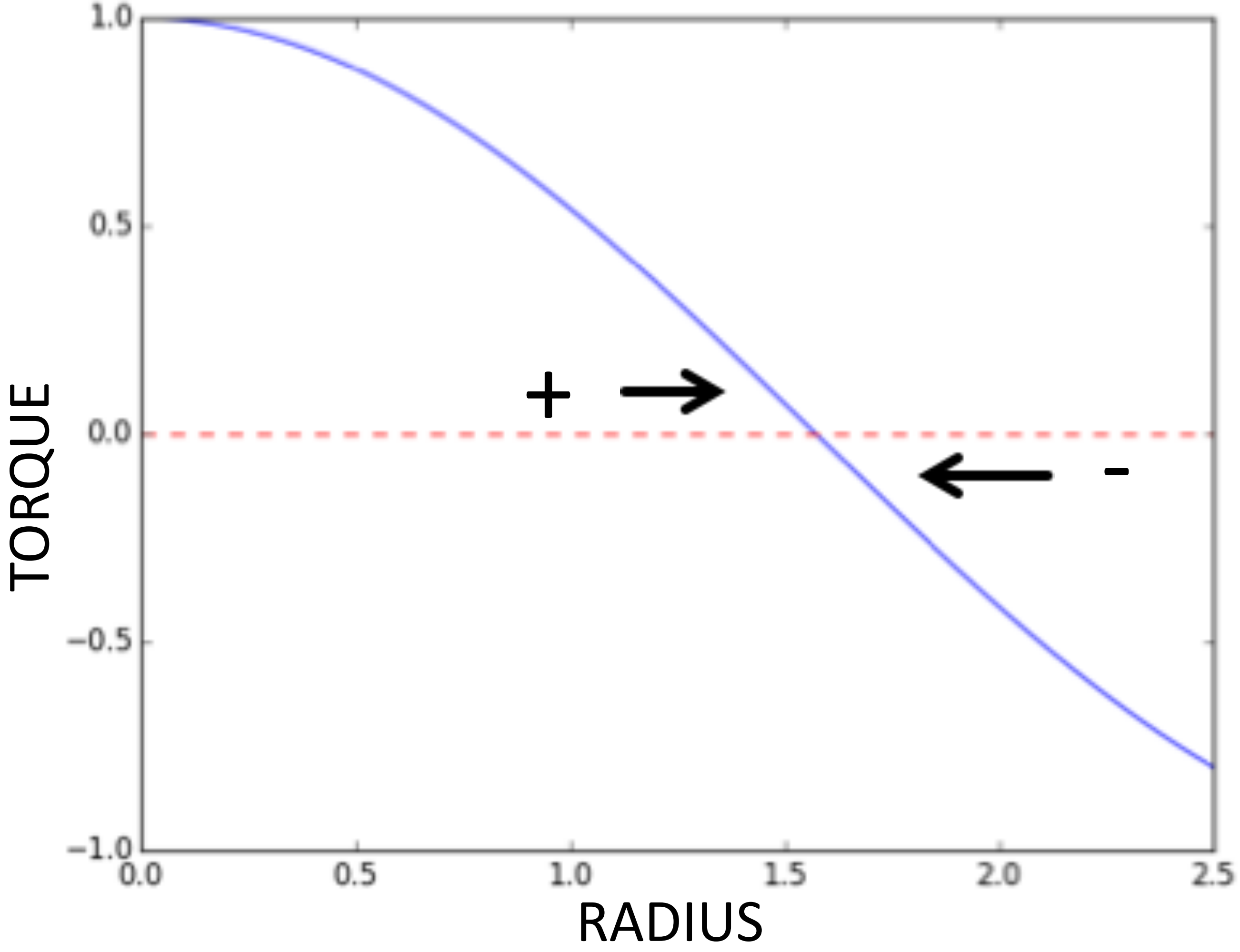
AGN disk models



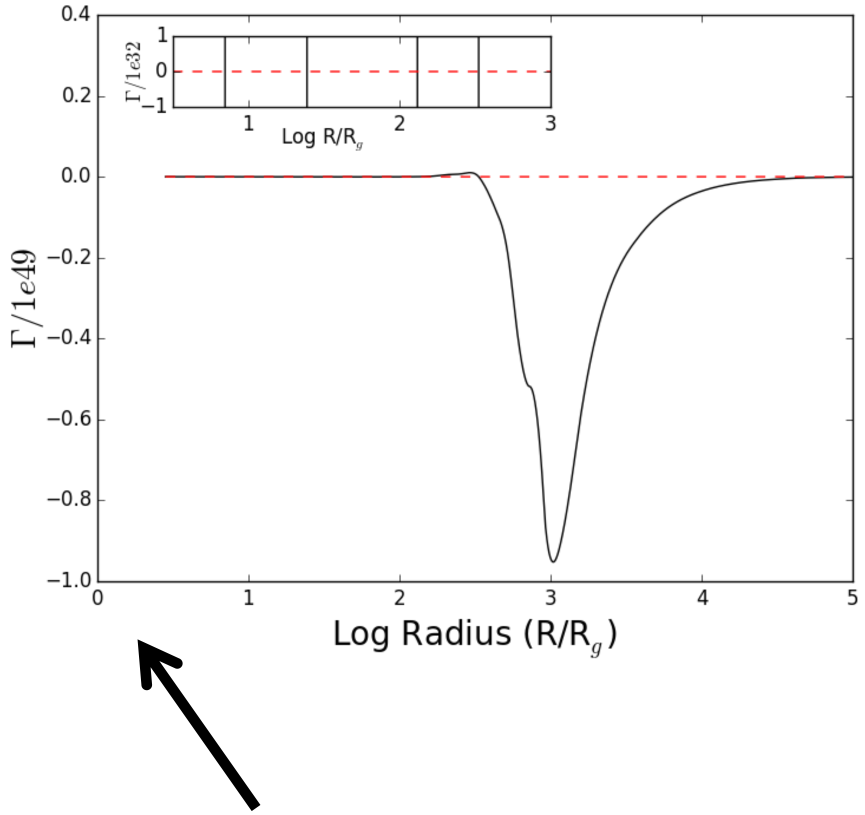
Sirko & Goodman 2003

Thompson, Quataert & Murray 2005

Migration Traps: a simple example



Migration traps in S&G model



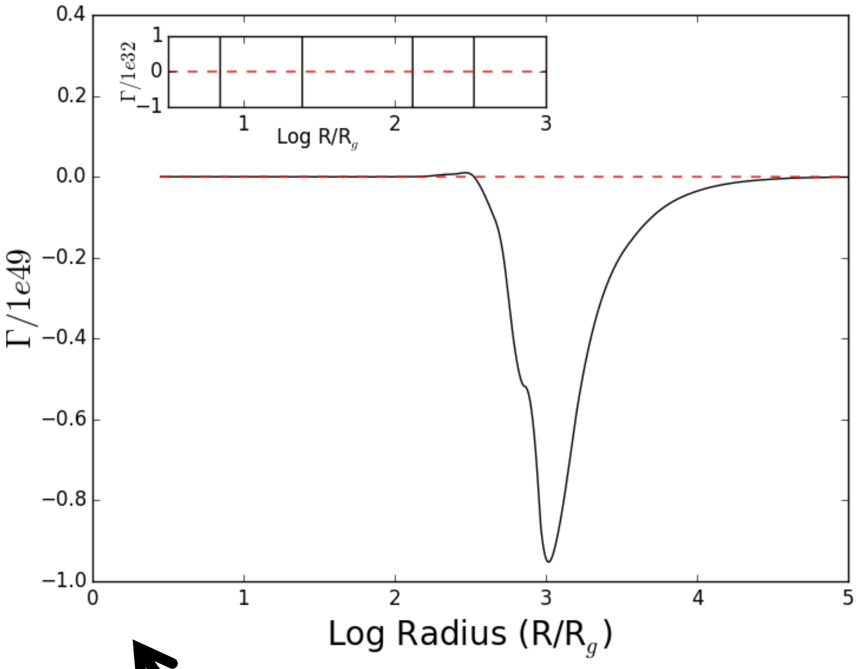
Linear scale

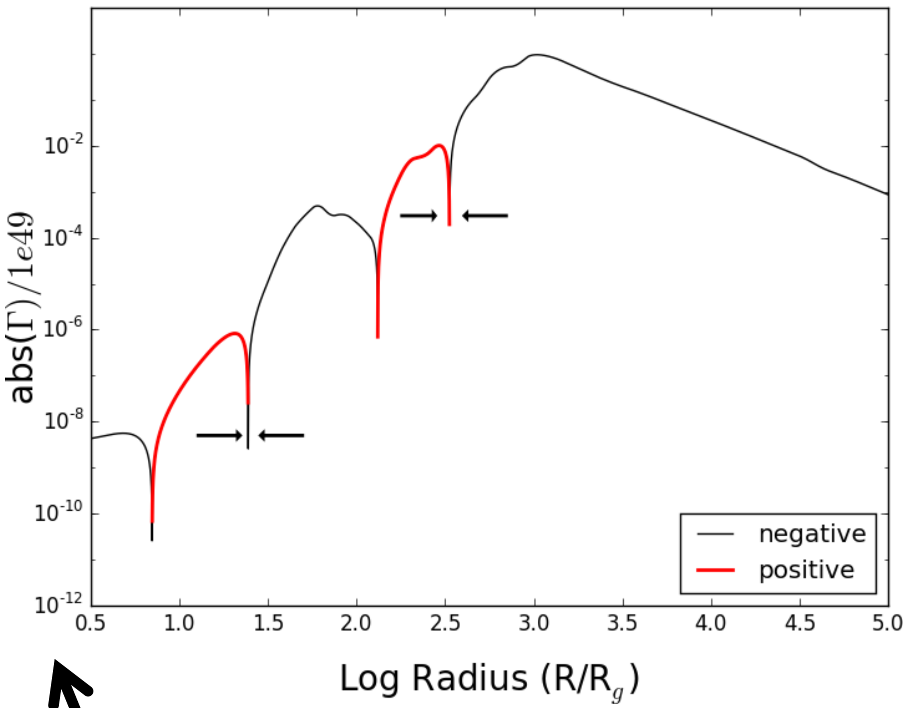
Bellovary et al 2016

24.5 and 331 R_g

Sirko & Goodman 2003 disk model: TWO TRAPS

Migration traps in S&G model





Linear scale

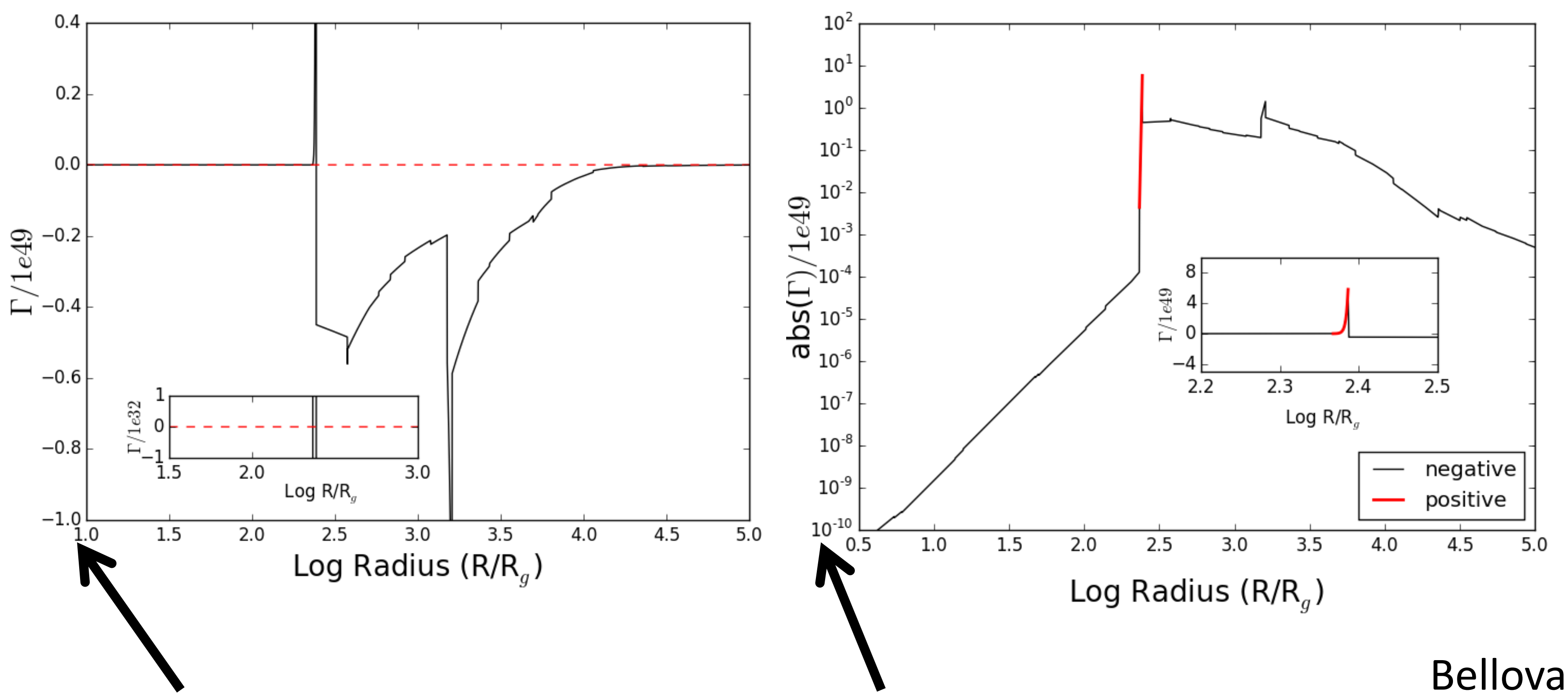
Log scale

Bellovary et al 2016

24.5 and 331 R_g

Sirko & Goodman 2003 disk model: TWO TRAPS

Migration traps in TQM model



Linear scale

Log scale

Bellovary et al 2016

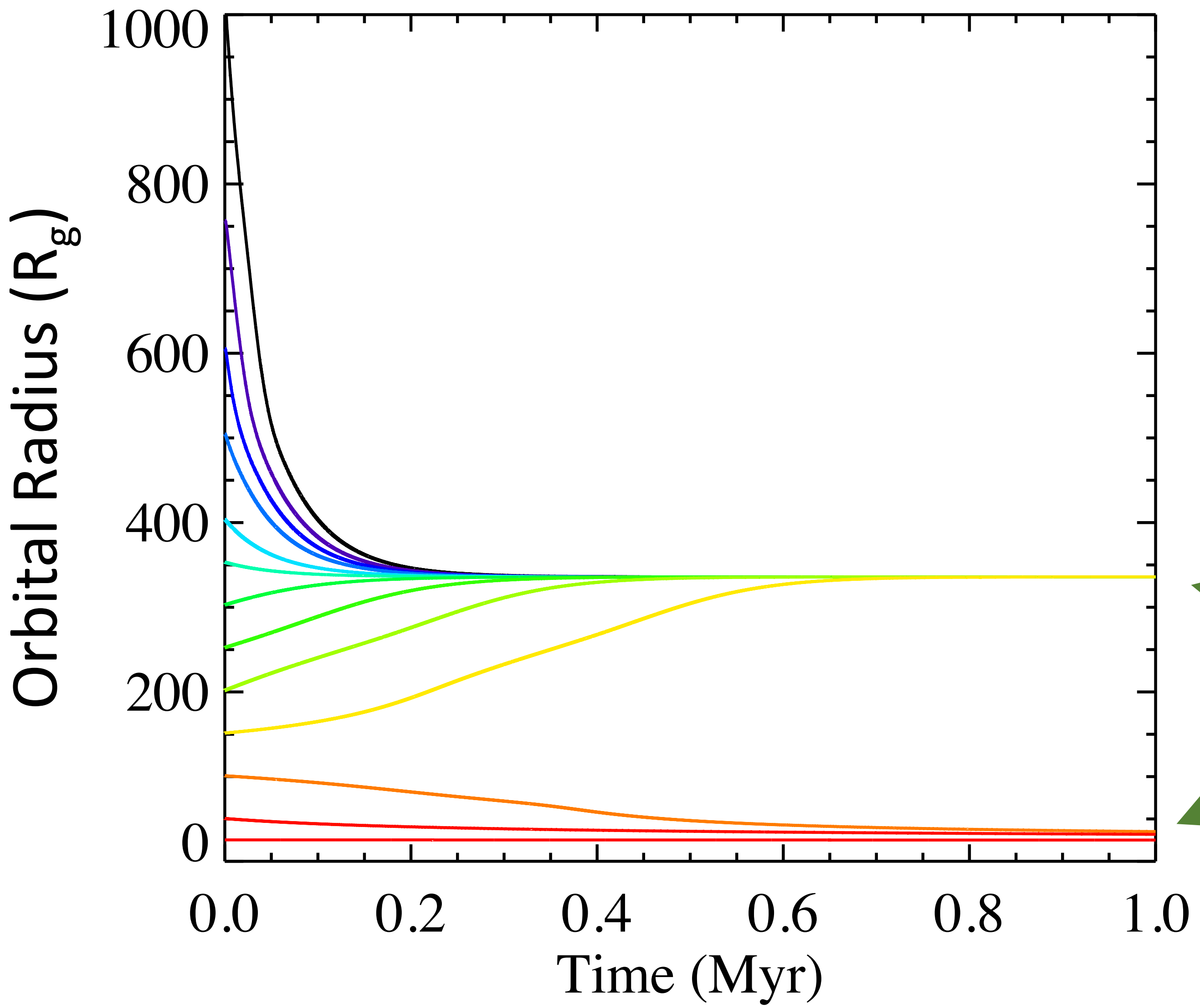
Thompson Quataert & Murray 2005 disk model: ONE TRAP

245 R_g

Traps (maybe) exist. What next?

- 3-D N-body modeling of migrating BHs
- 1-D static disk based on Sirko & Goodman 2003
- Examine migration of single and multiple objects

Migration of a single object



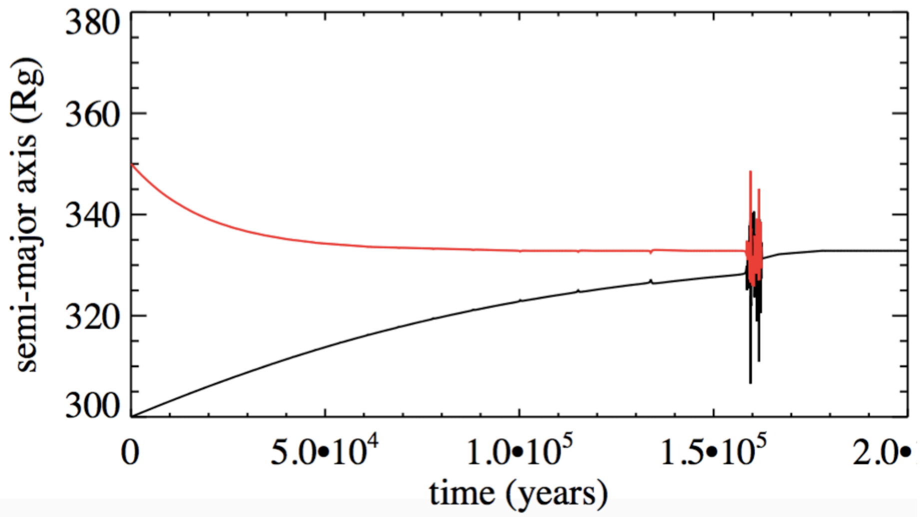
- One 30 $M_\odot$ BH
- Different starting radii
- $M_{SMBH} = 10^8 M_\odot$

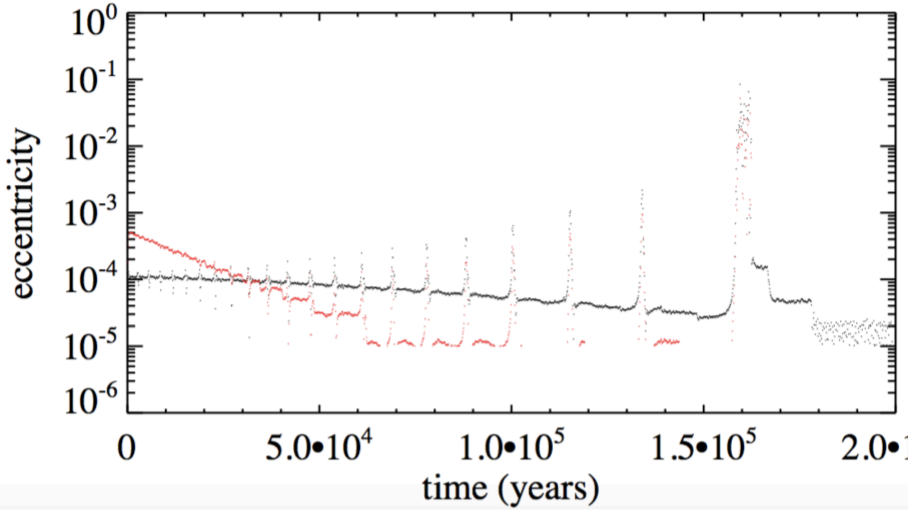
Predicted traps:
331 R_g
25 R_g

Bellovary et al. in prep

Migration and merger of two objects

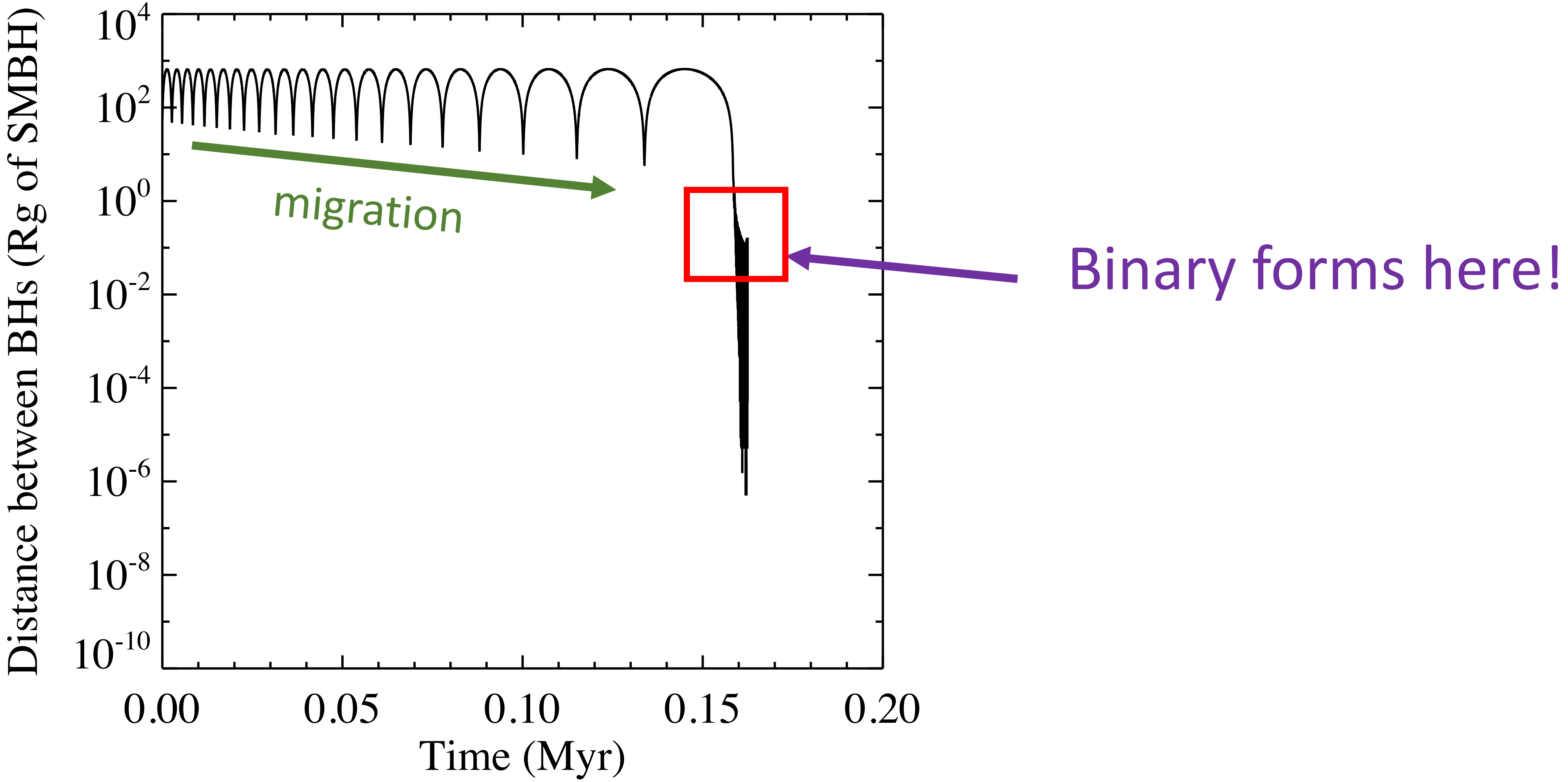
- 50 $M_\odot$ BH and 30 $M_\odot$ BH
- Form a binary upon reaching trap



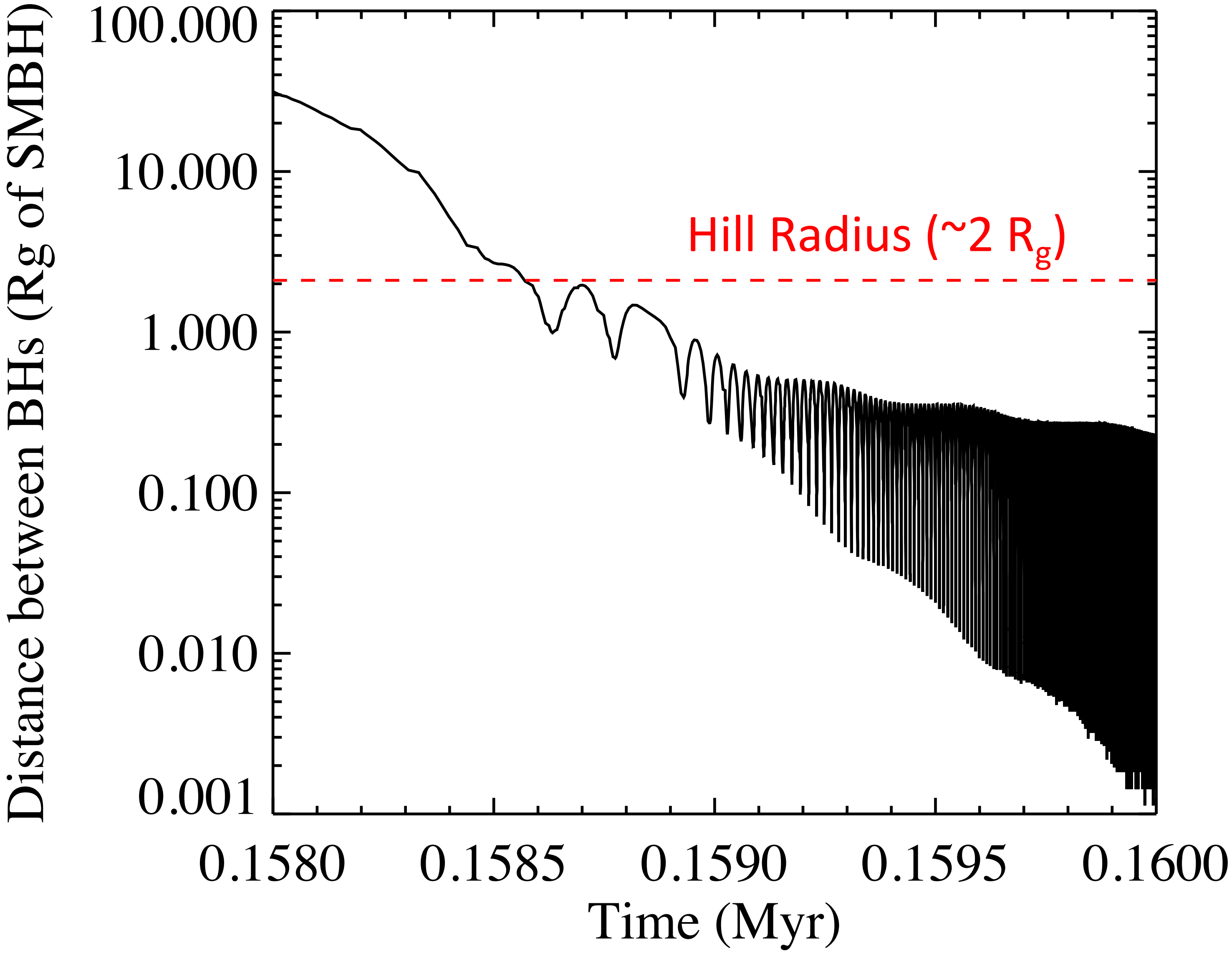


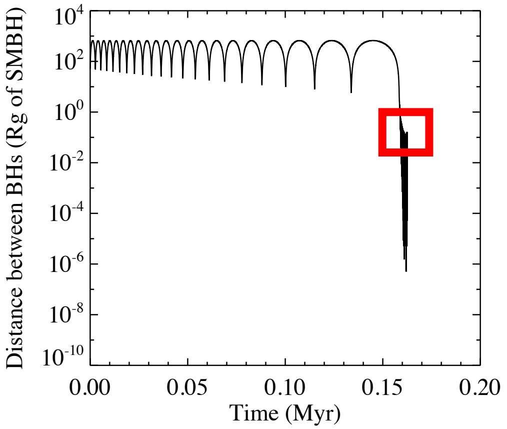
Bellovary et al. in prep

Binary Details: formation



Binary Details: formation





Binary forms, orbit becomes eccentric

Gas torques tug and perturb the orbit

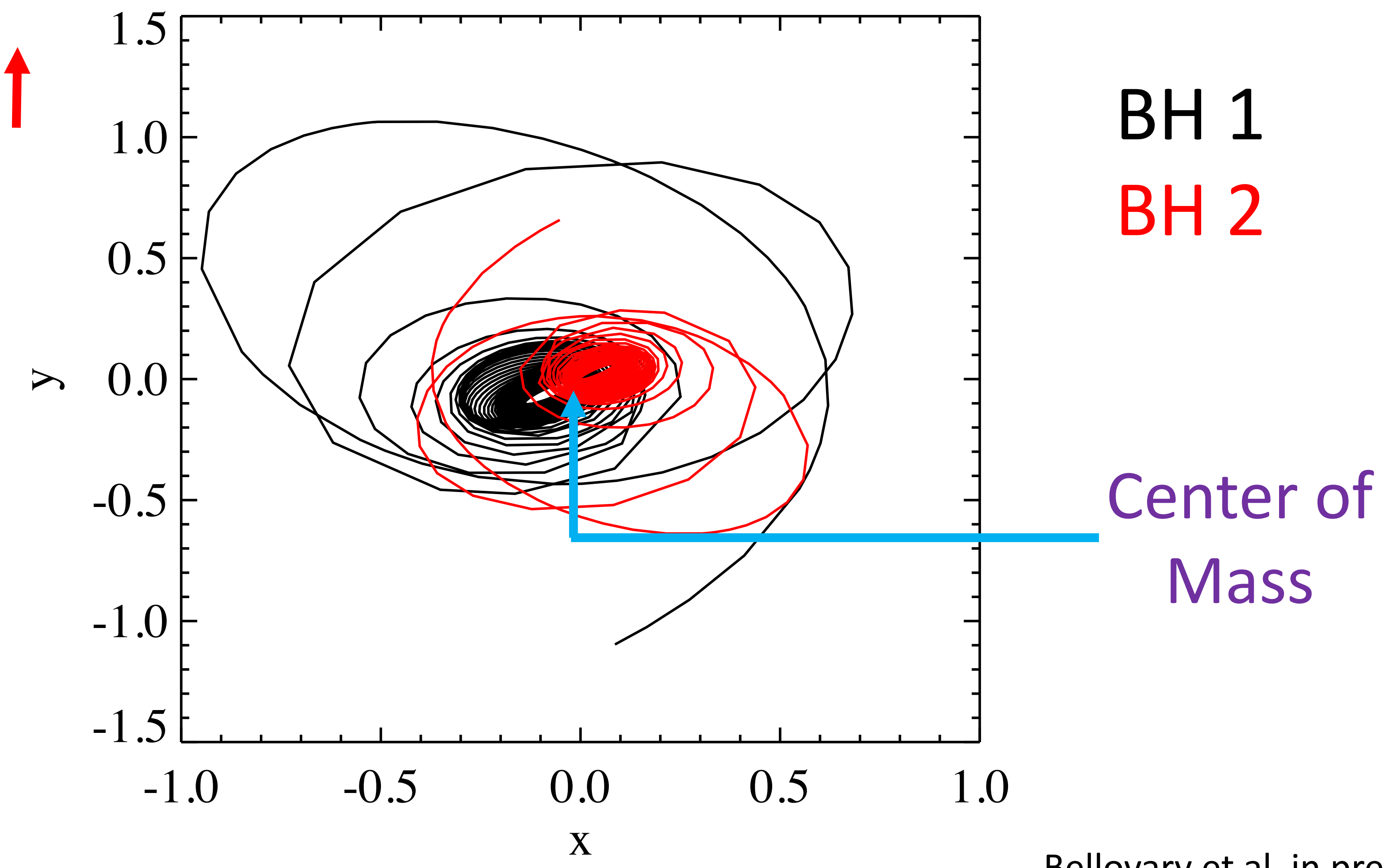
Bellovary et al. in prep

Binary Details: center of mass frame

Orbital eccentricity ↑

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

Eventually plunging orbits cause merger

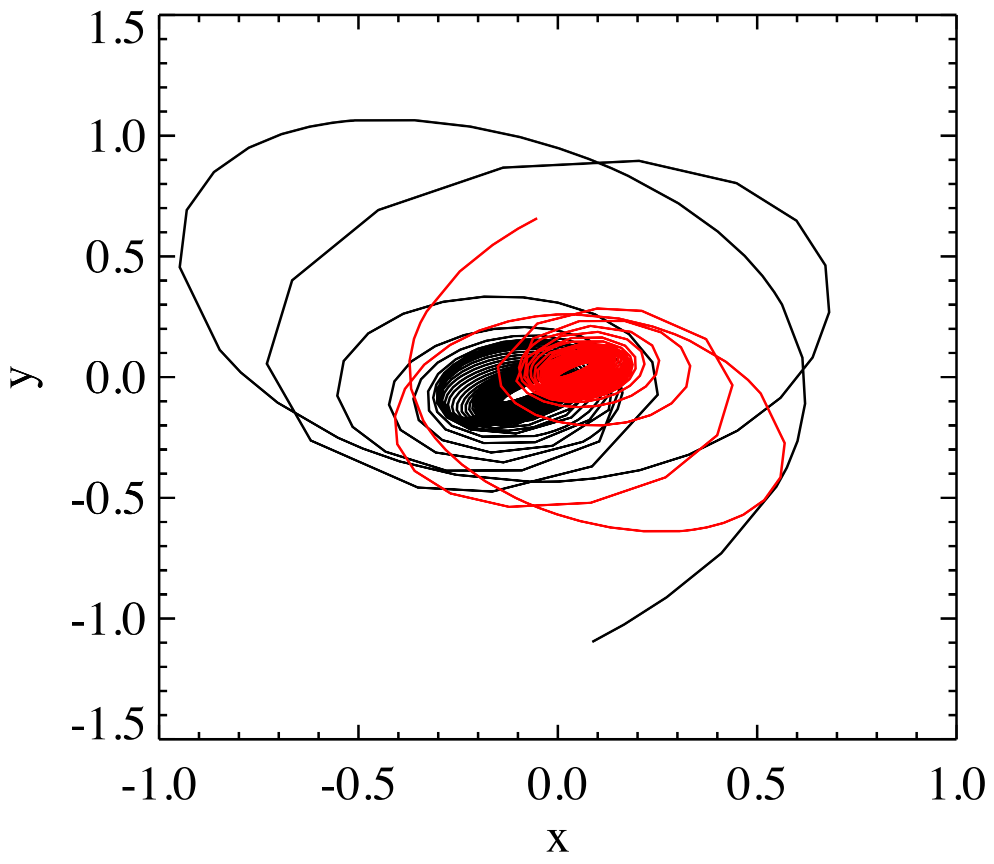


Bellovary et al. in prep

Worst Case scenario!

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

Both will speed up the merger!

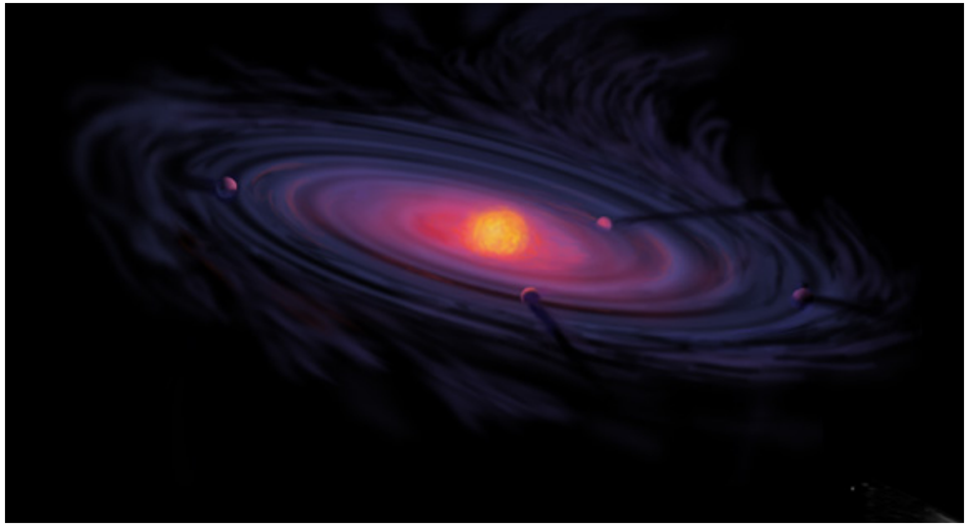


*among many many other effects

GW Implications

- LIGO: Provides explanation for large masses
- LISA: runaway growth in disk creates an IMBH (10^2-10^3 $M_\odot$), if merge with SMBH we get an EMRI
- EM Counterparts… the AGN wins (but! target next searches on AGN instead of galaxies for improved efficiency!)

In Summary



- Migration traps may exist in AGN disks
- Compact objects can grow and merge quickly in the traps (LIGO sources)
- Growth can result in IMBH!

The Future

- N > 2 bodies
- Actual hydro simulations
- Modify torque prescription to include retrograde orbiters, multiple orbiters , feedback from BH accretion, ++