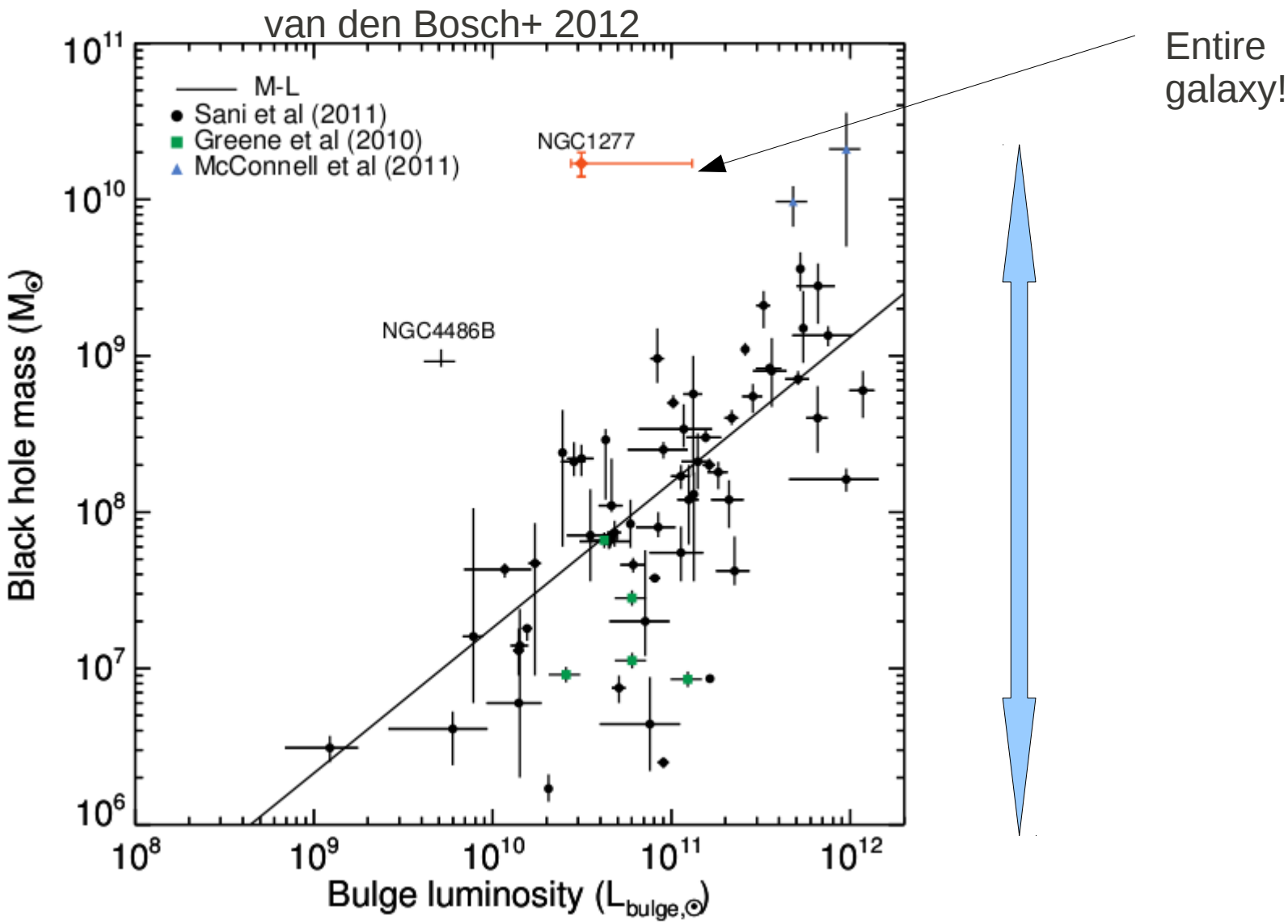
Observational Signatures of Merging Black Holes (in galactic nuclei)

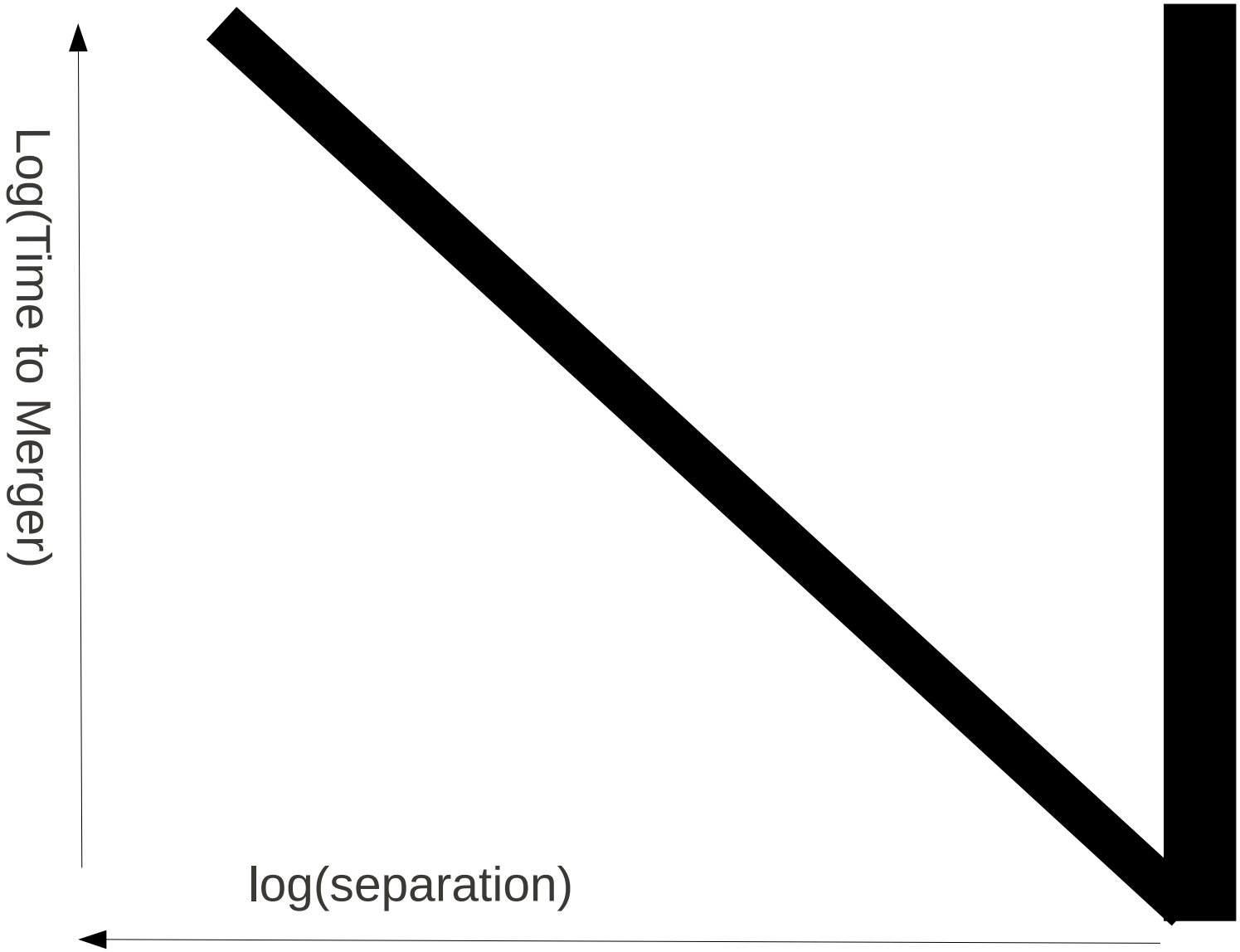
E. Sterl Phinney

Caltech

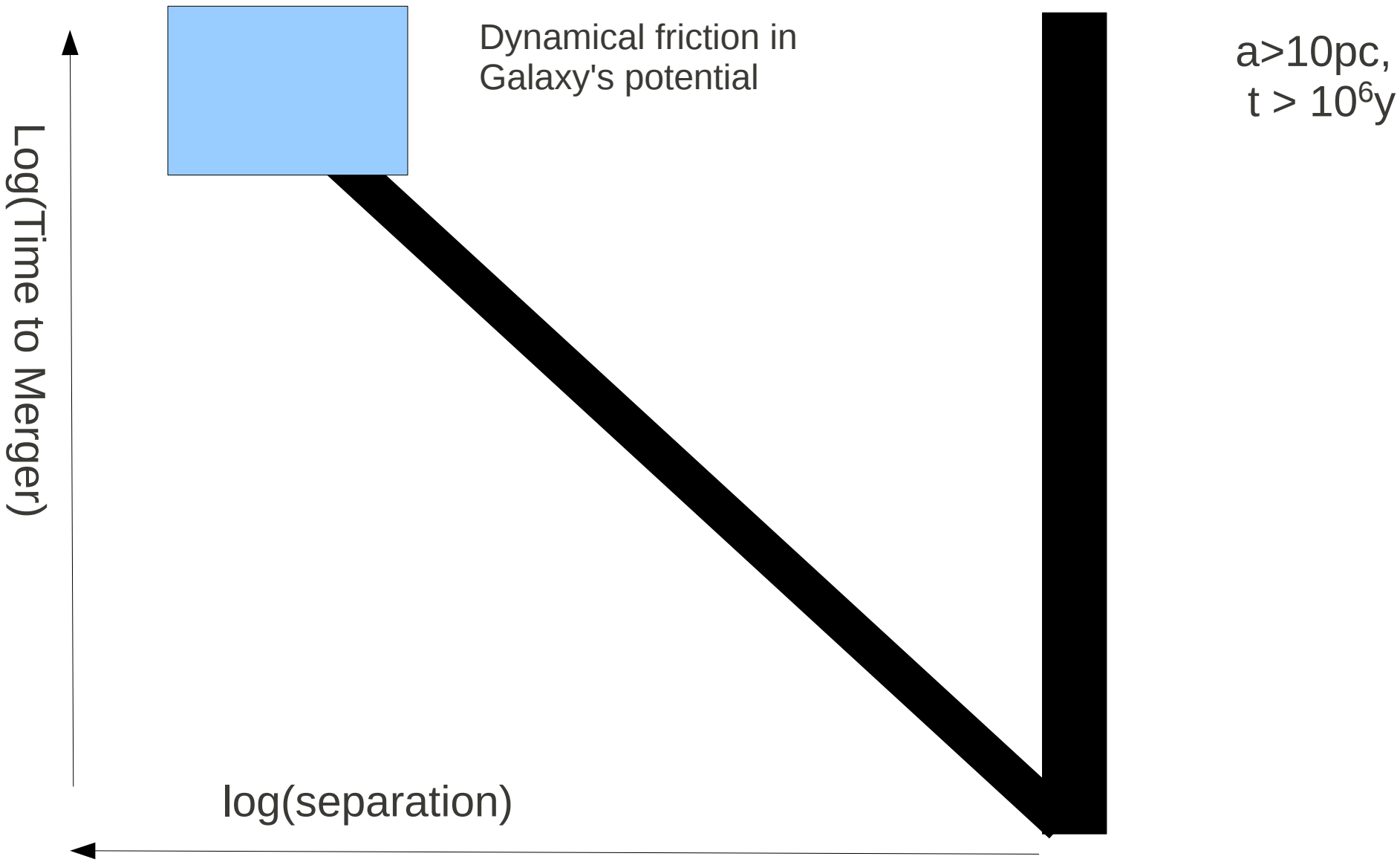
Dynamical masses of nuclear BH



Phases of Black Hole merger



Phases of Black Hole merger (10^8Msun, q=0.5)



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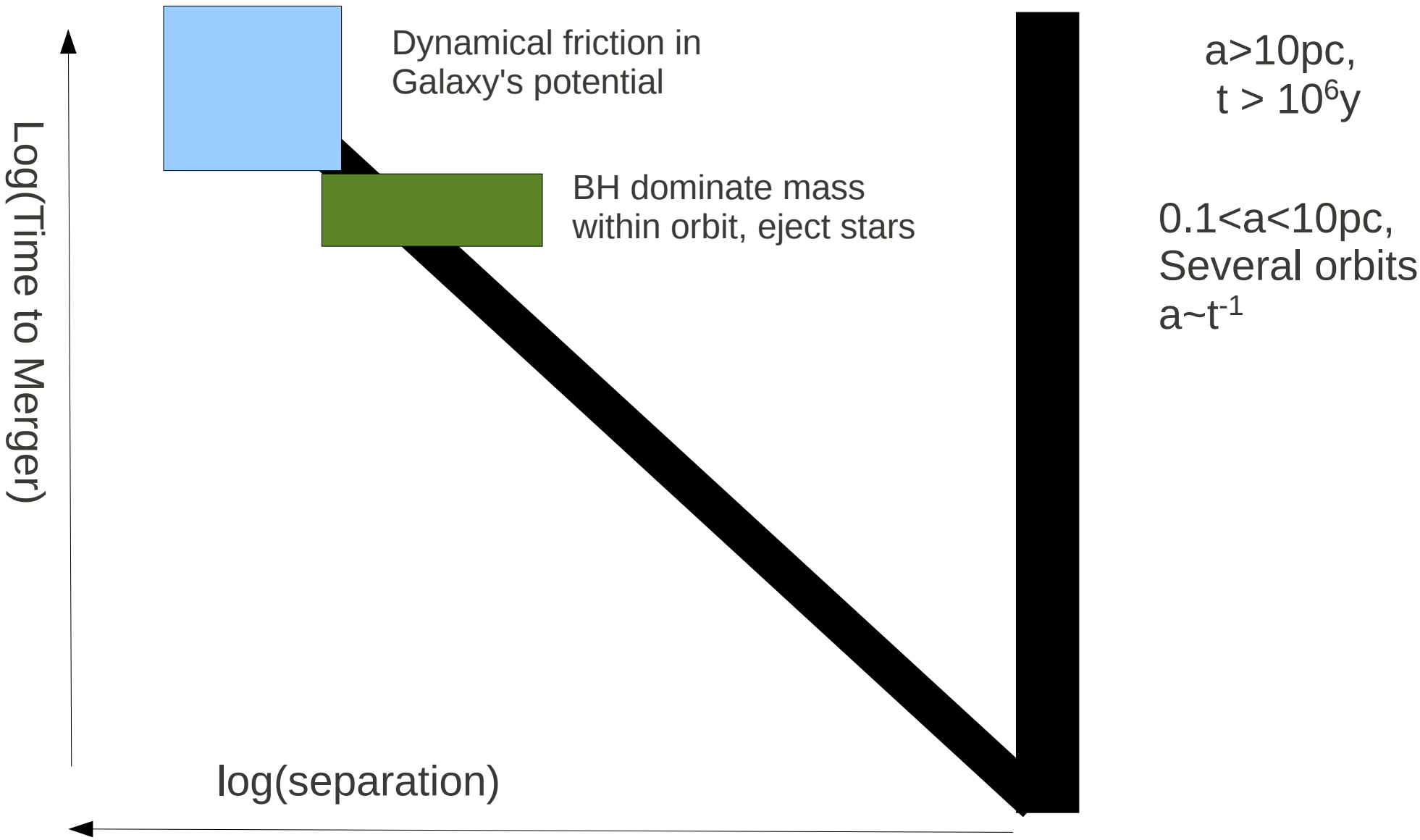

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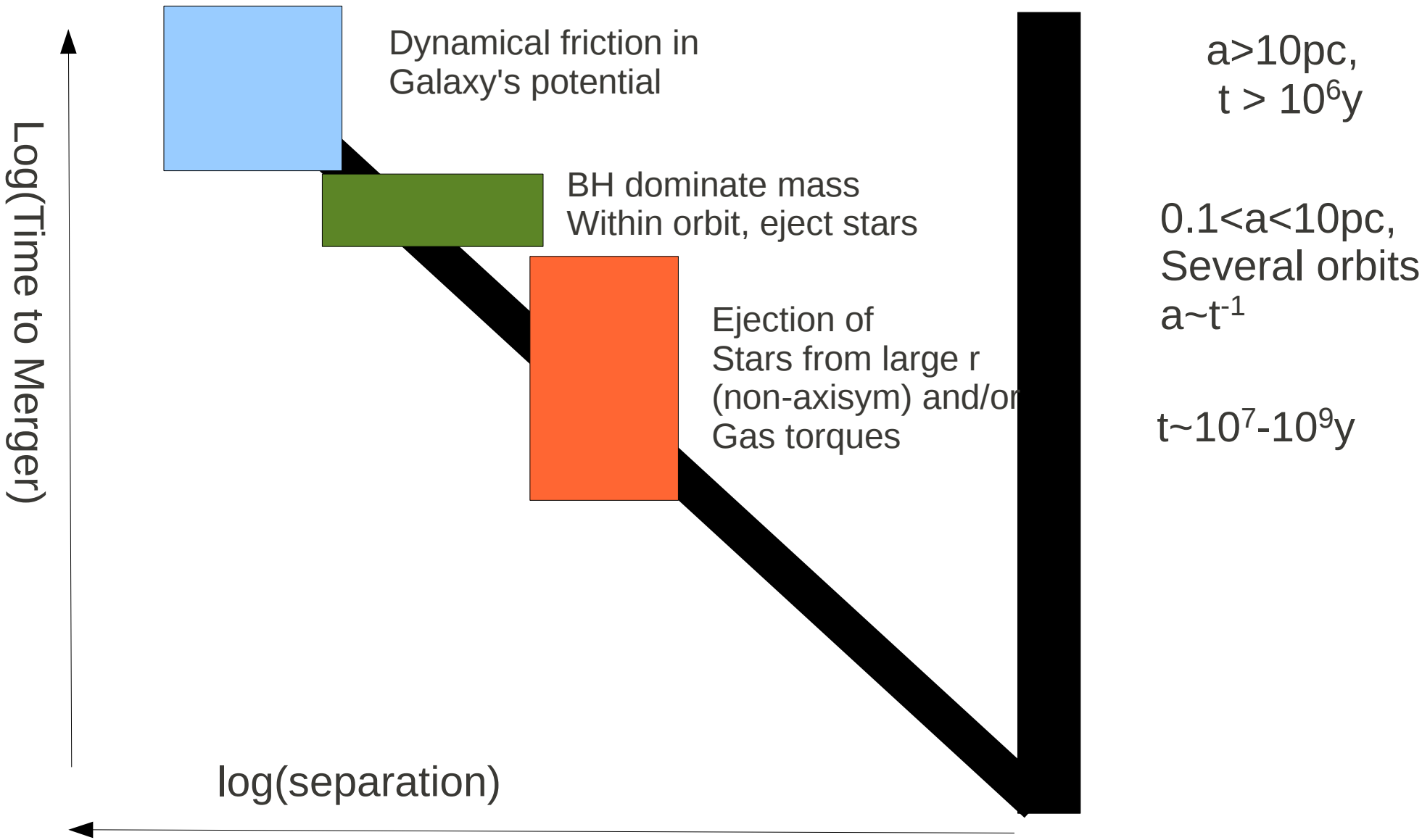

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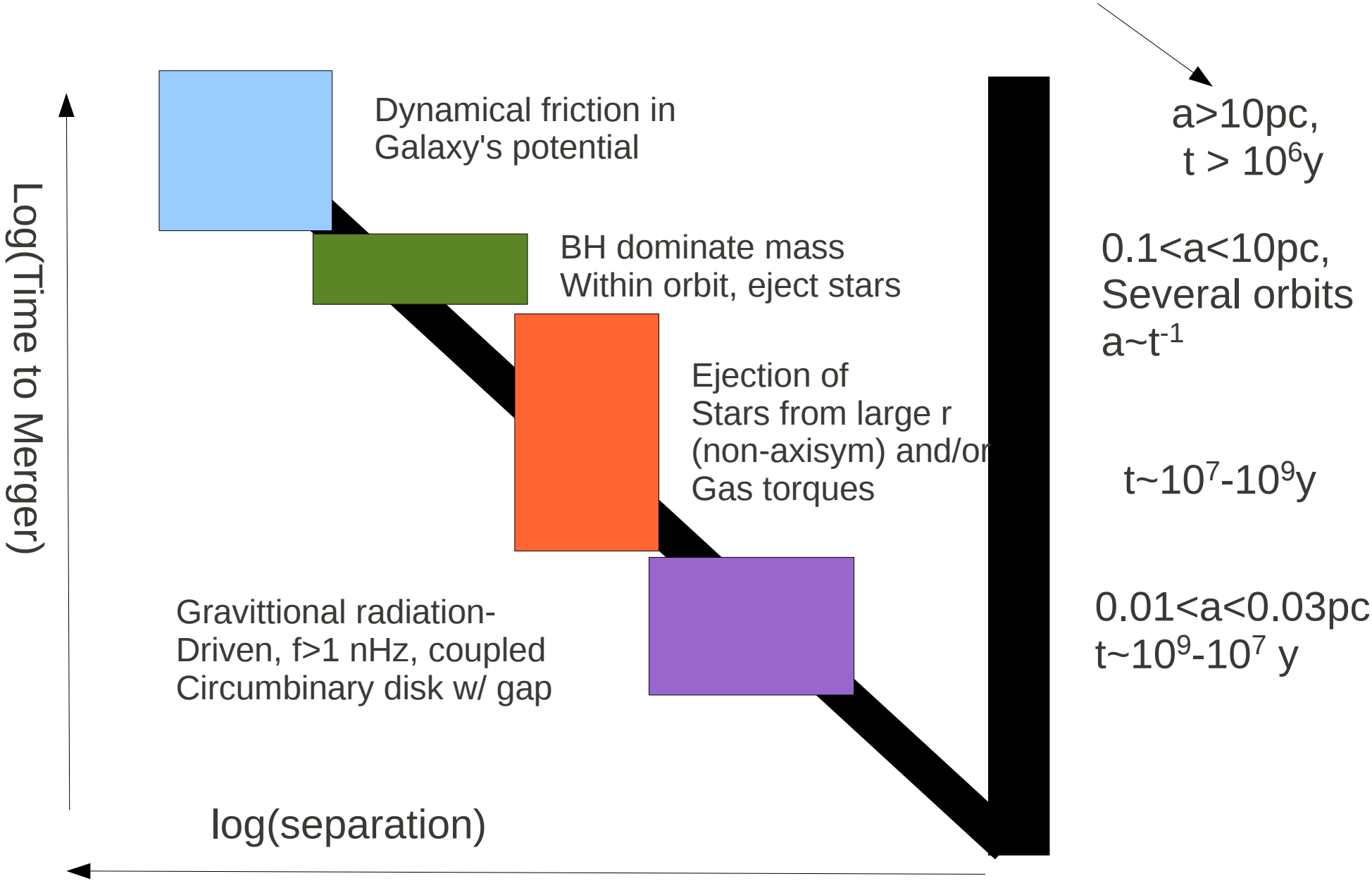
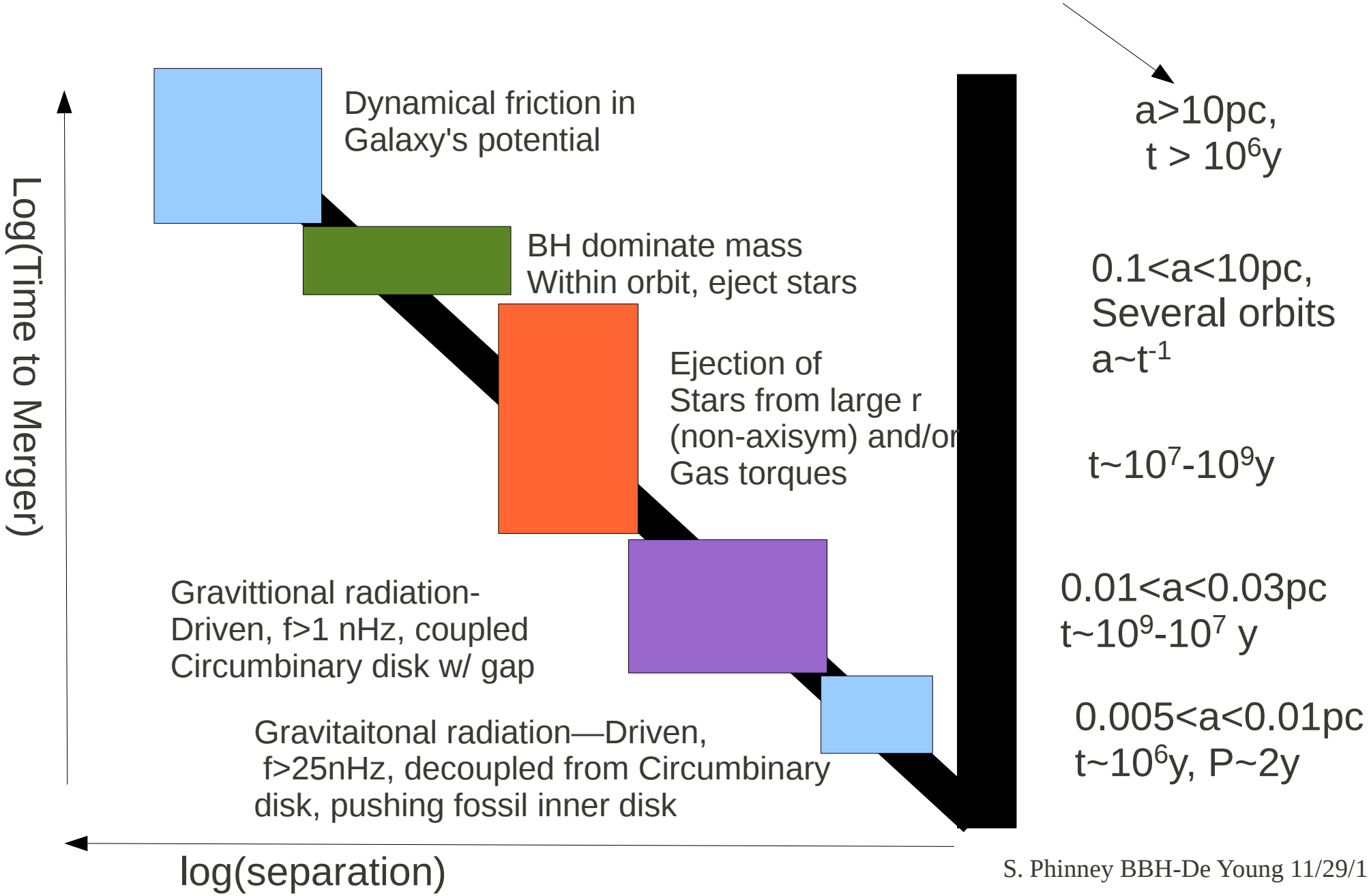
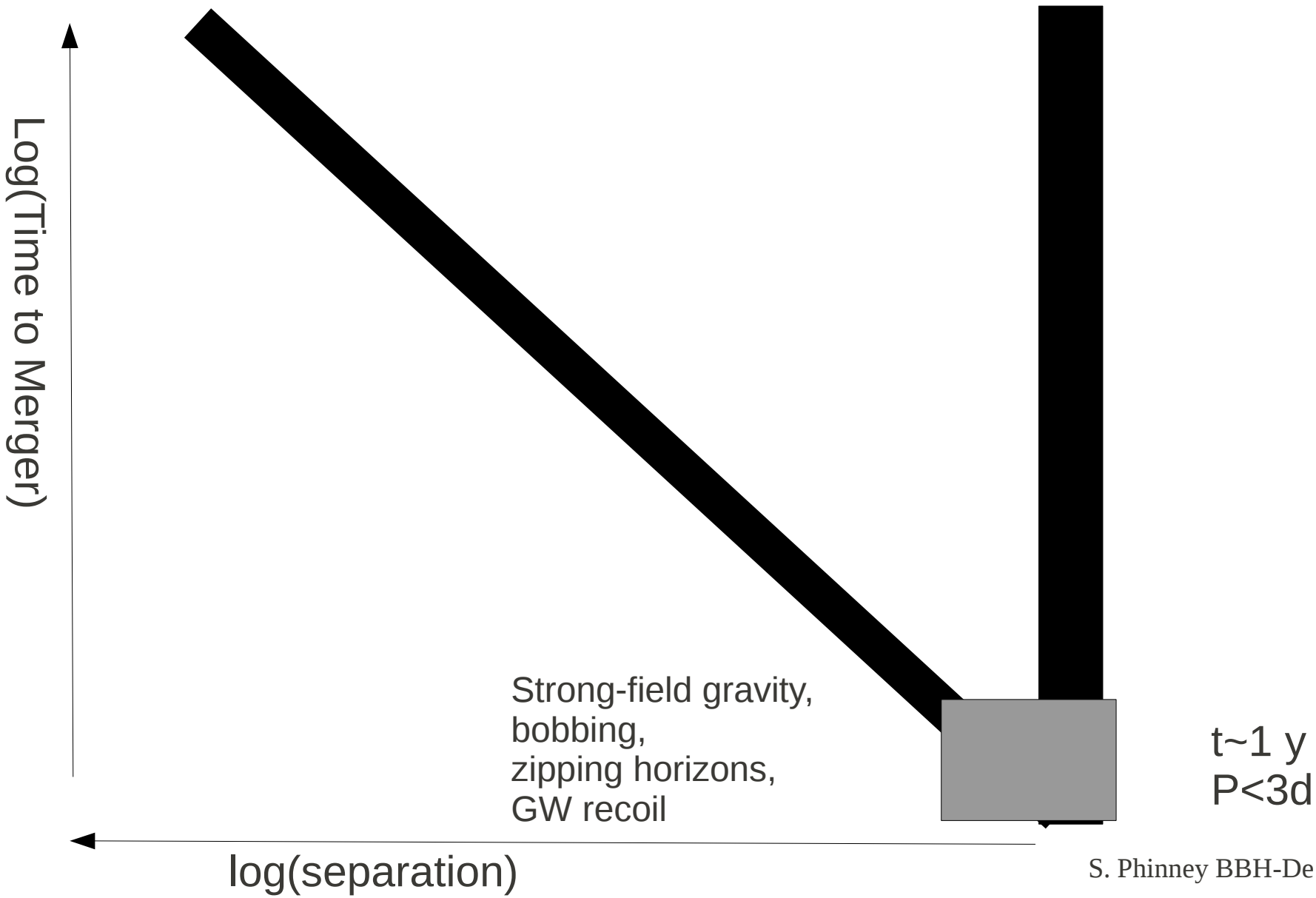


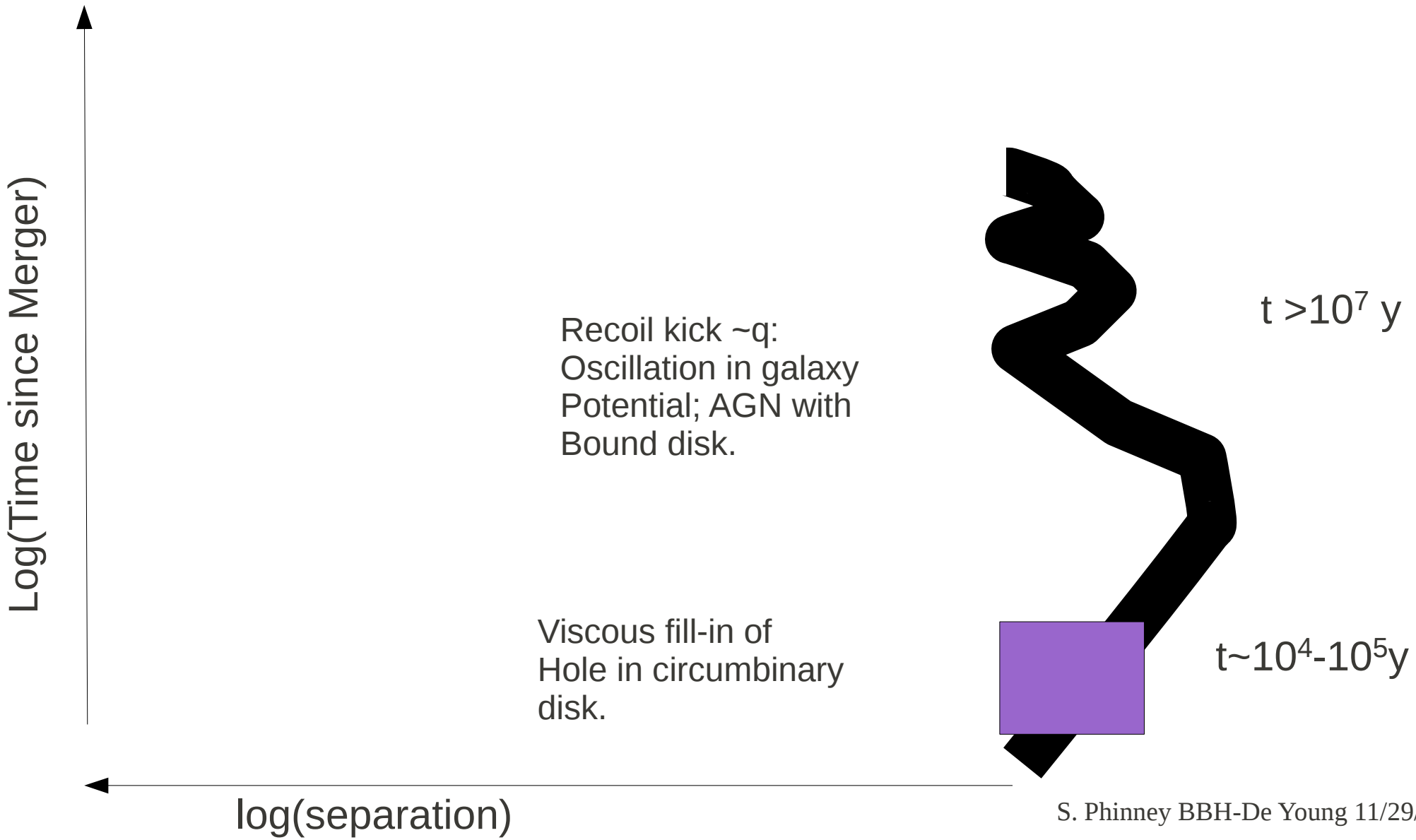
Phases of Black Hole merger (10^8Msun, q=0.5)



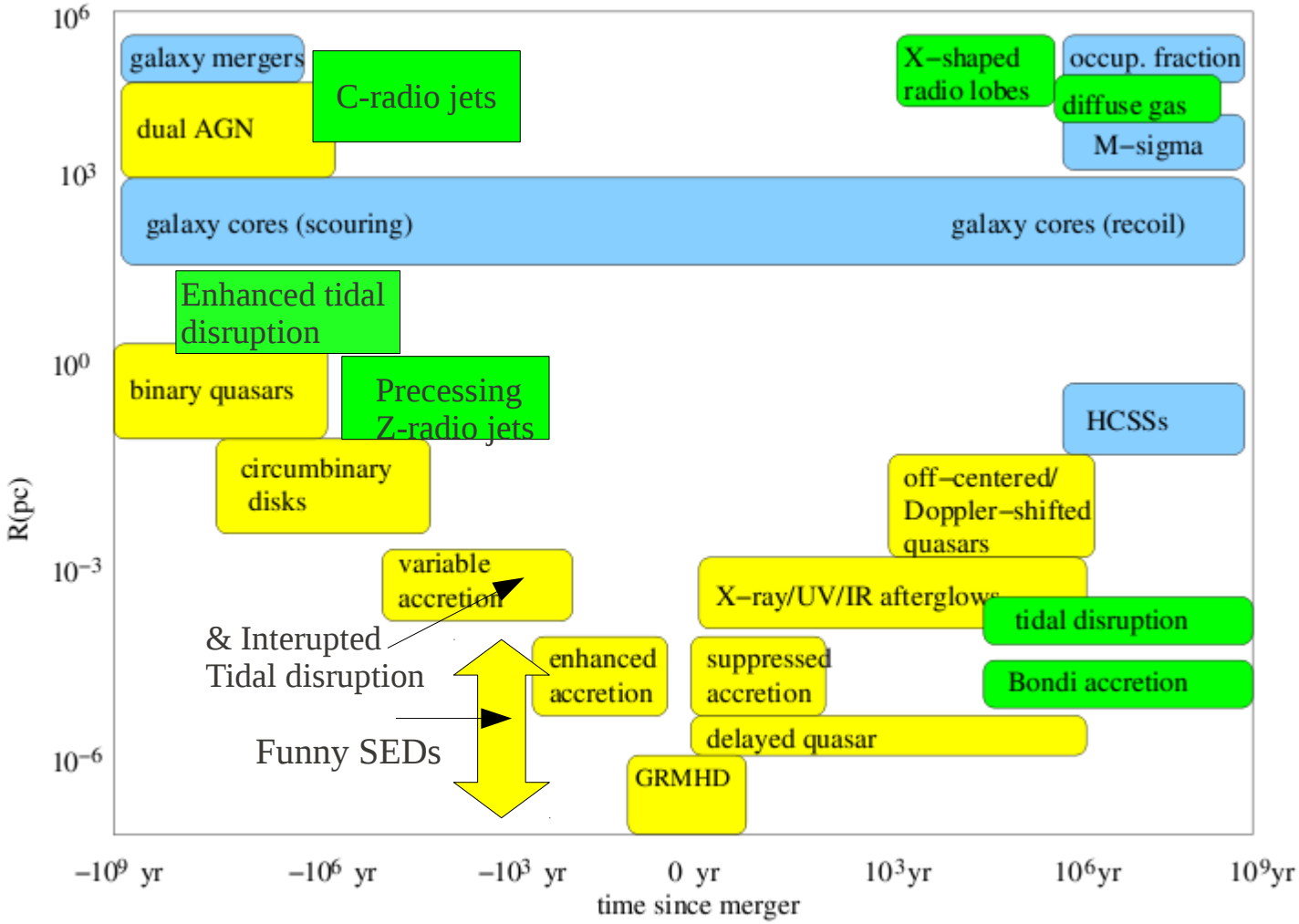
Phases of Black Hole merger (10^8Msun, q=0.5)



Post-merger Evolution Black Hole(10^8Msun, q=0.5)



Grand survey of merger signatures



Phinney additions to Schnittman 1010.3250

Theorist

- We've given you dozens of clear, unambiguous ways to identify merging BH at all pre and post-merger phases. What's the problem with you slowpokes? Why do you keep announcing discoveries, then shooting them down?

Theorist

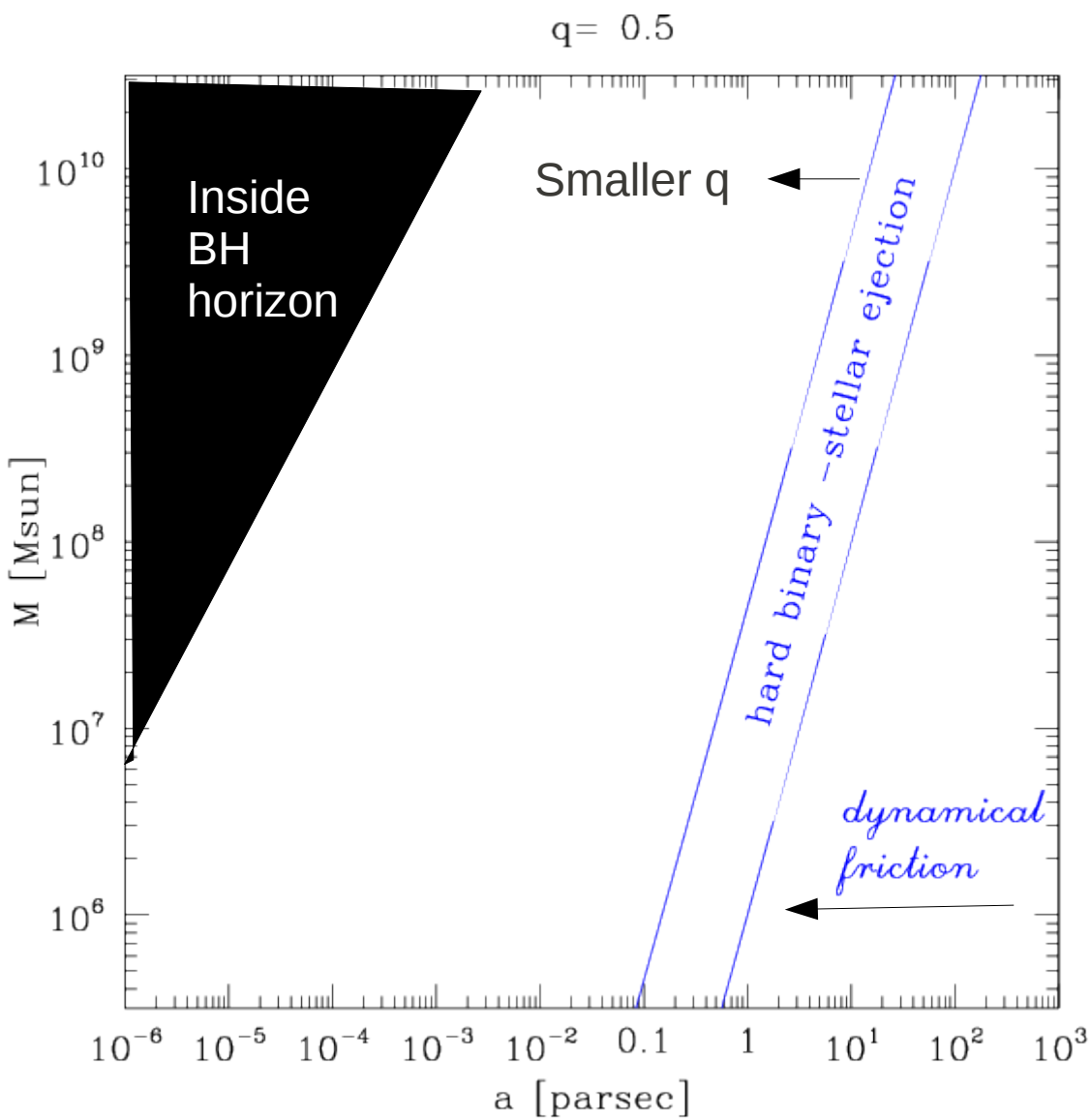
- We've given you dozens of clear, unambiguous ways to identify merging BH at all pre and post-merger phases. What's the problem with you slowpokes? And why do you keep announcing discoveries, then shooting them down?

Observer

- (laughing uncontrollably) Clear? Unambiguous? Have you looked at all the weird spectral and photometric variability of galactic nuclei? And anyway, you guys keep contradicting each other!

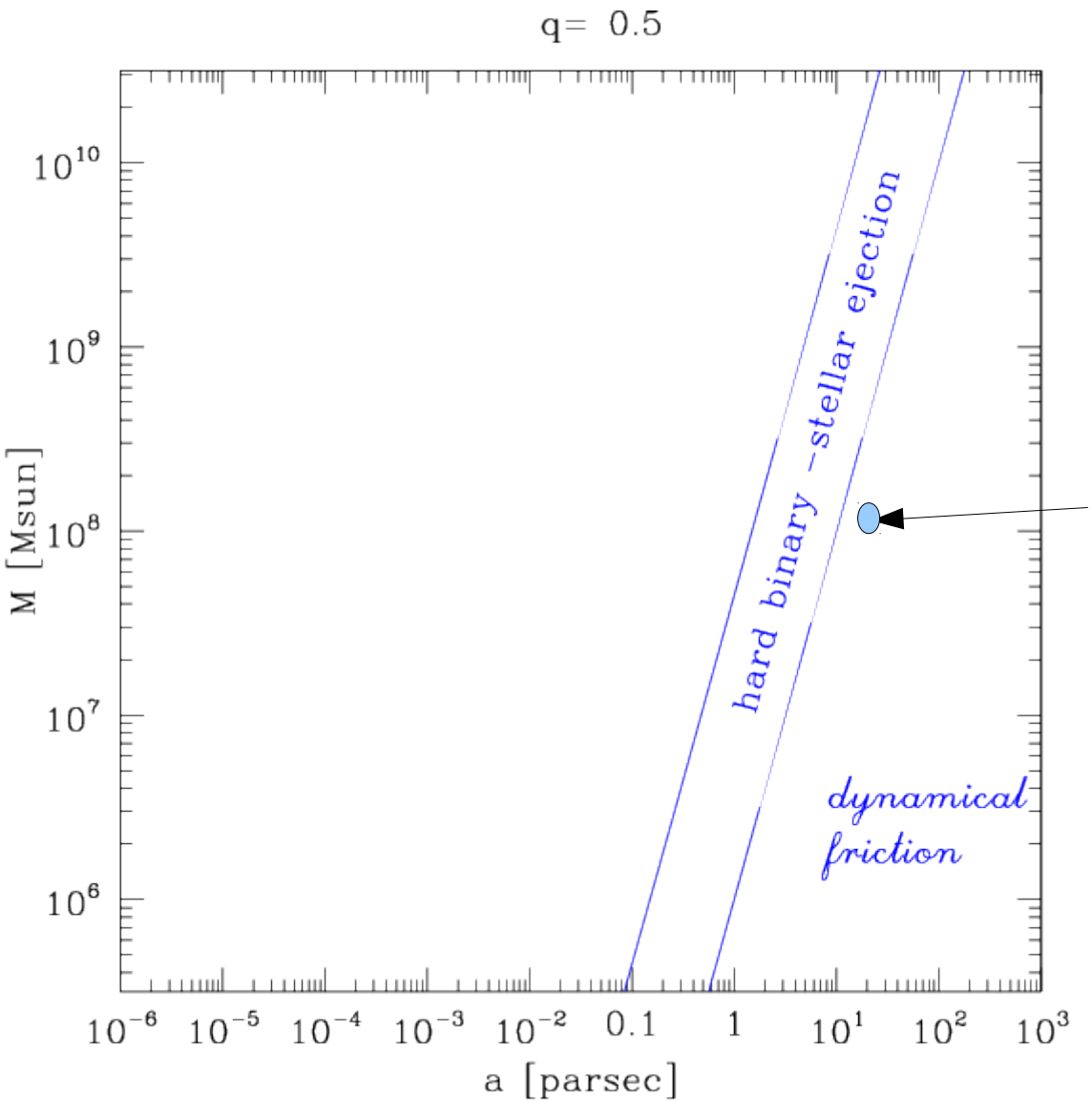
$a_h = G\mu/(4\sigma^2)$ $r_i = GM/\sigma^2$

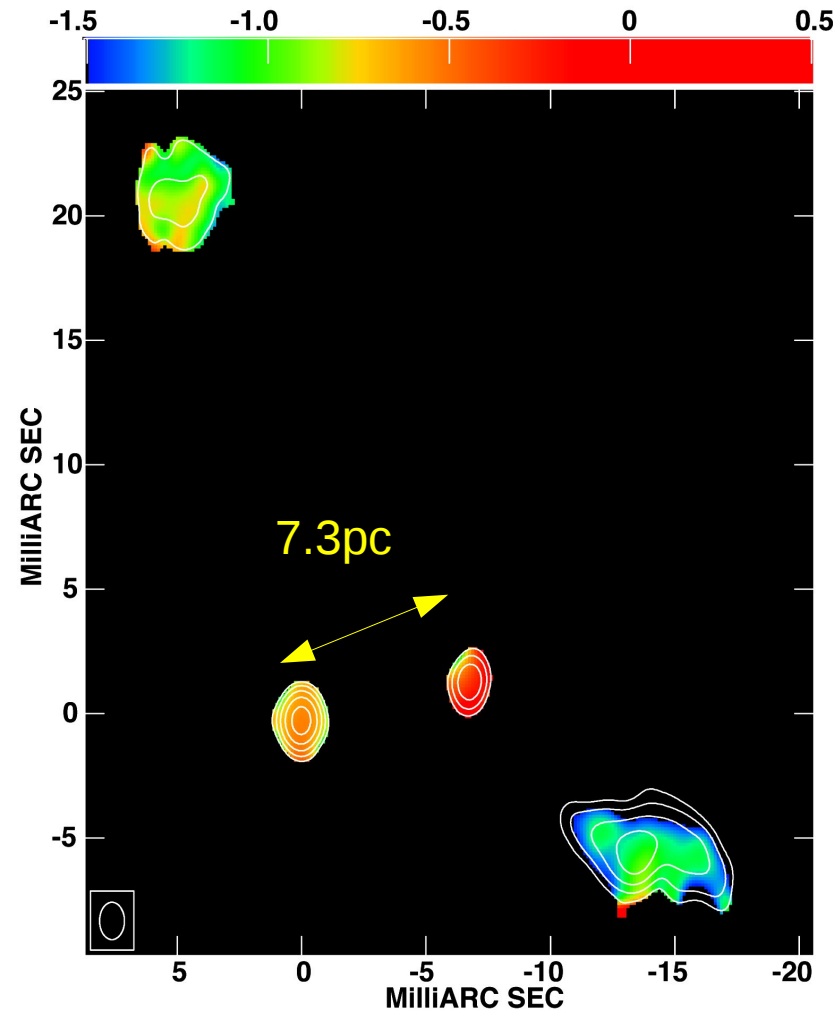
q=m/M



Binary binding energy= intial stellar cusp binding	BH potential Dominates stars
20pc	300pc
1pc	10pc
0.08pc	0.9pc

Orbital periods
~1000-100,000 y
eccentric





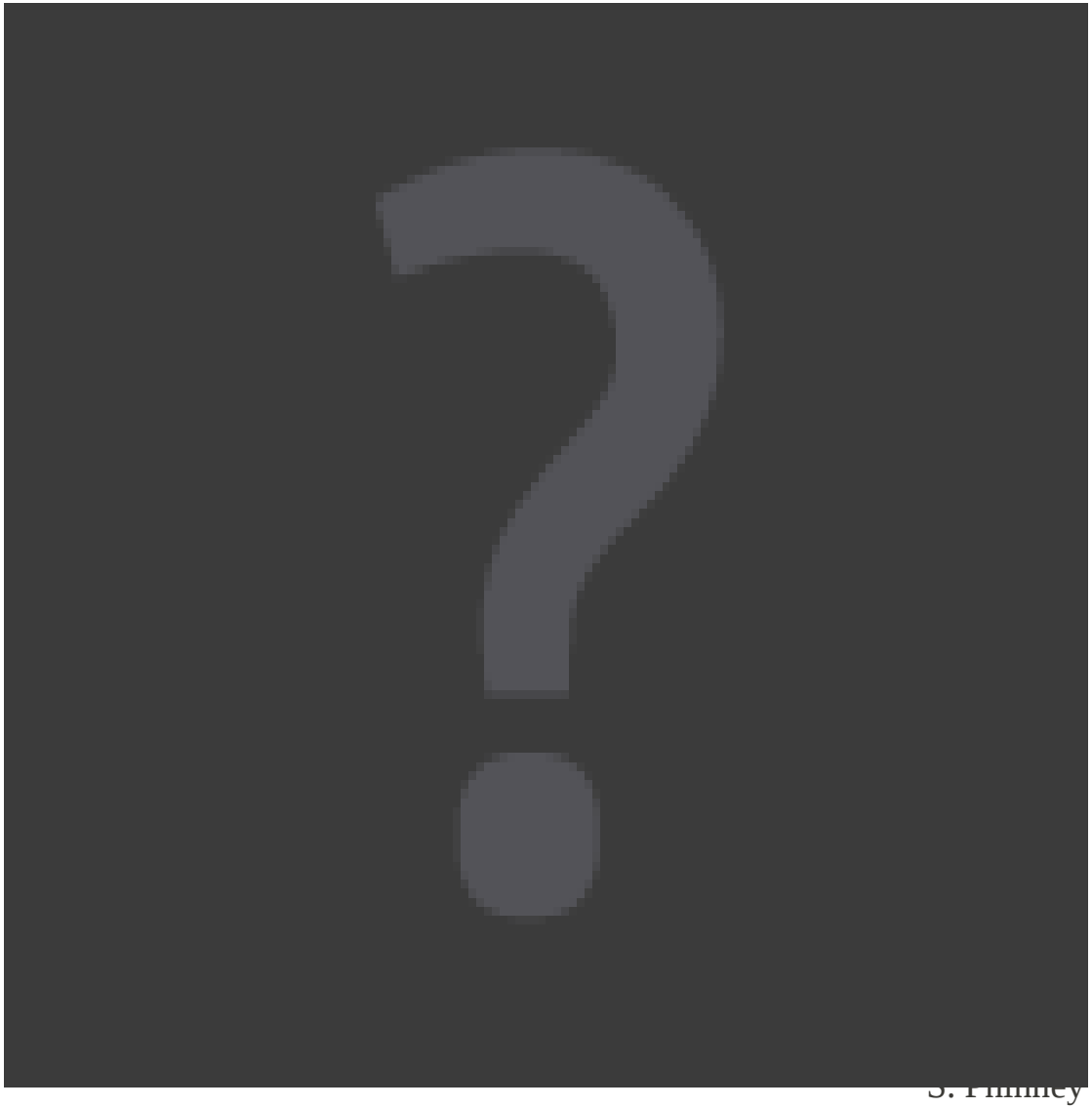
$M \sim 10^8 M_{sun}$, $P_{orb} \sim 10^5$ y. $a \sim 5a_h$

0402+379, Rodriguez et al Astro-ph/0604042. See also Burke-Spolaor 1008.4382 Only 1:3114

A new way to find BBH entering the final parsec (in the stellar ejection phase)

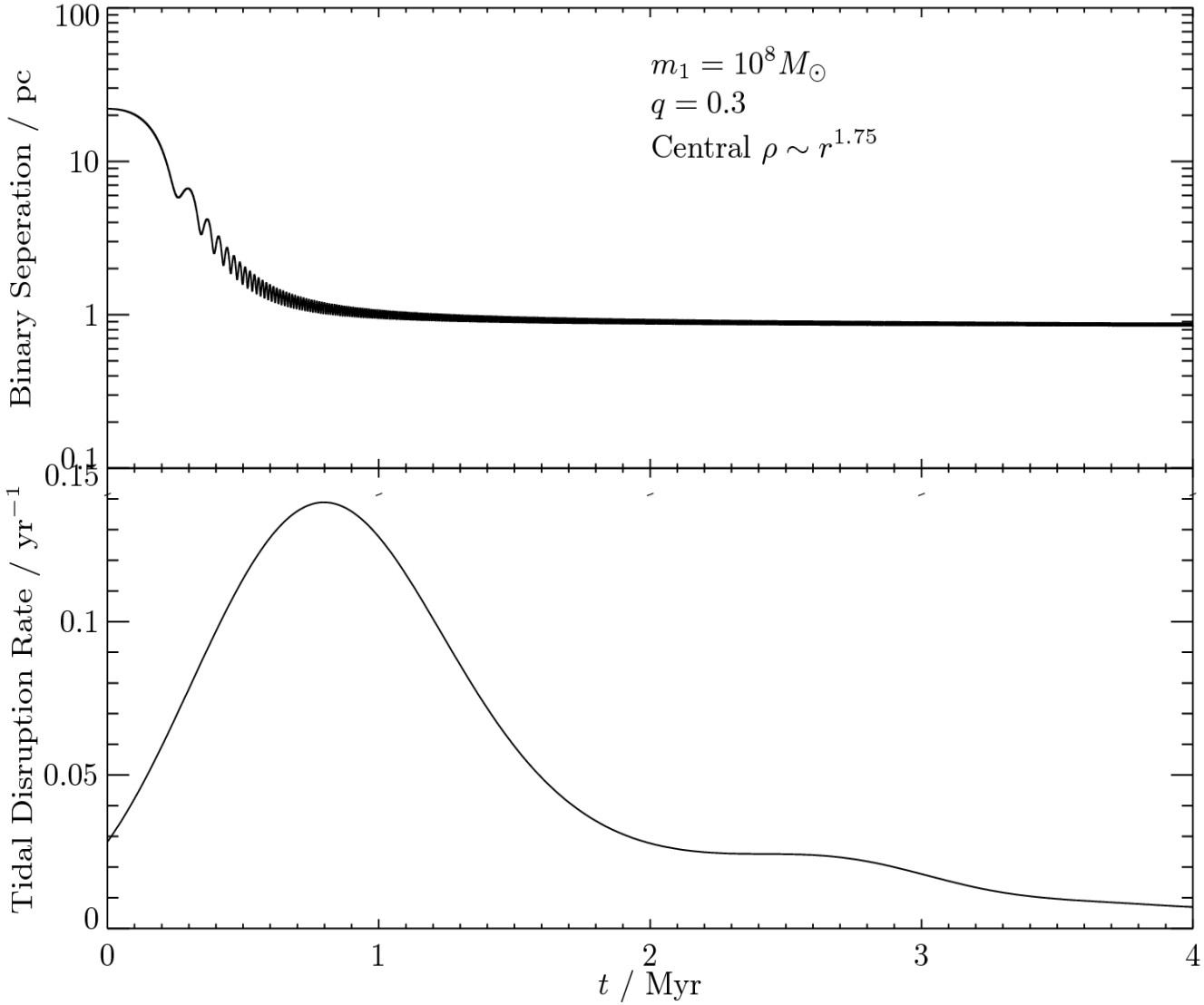
Stars are not point masses for <10^8Msun BH:

Tidal disruption Rate enhanced by X1000 during Stellar ejection phase

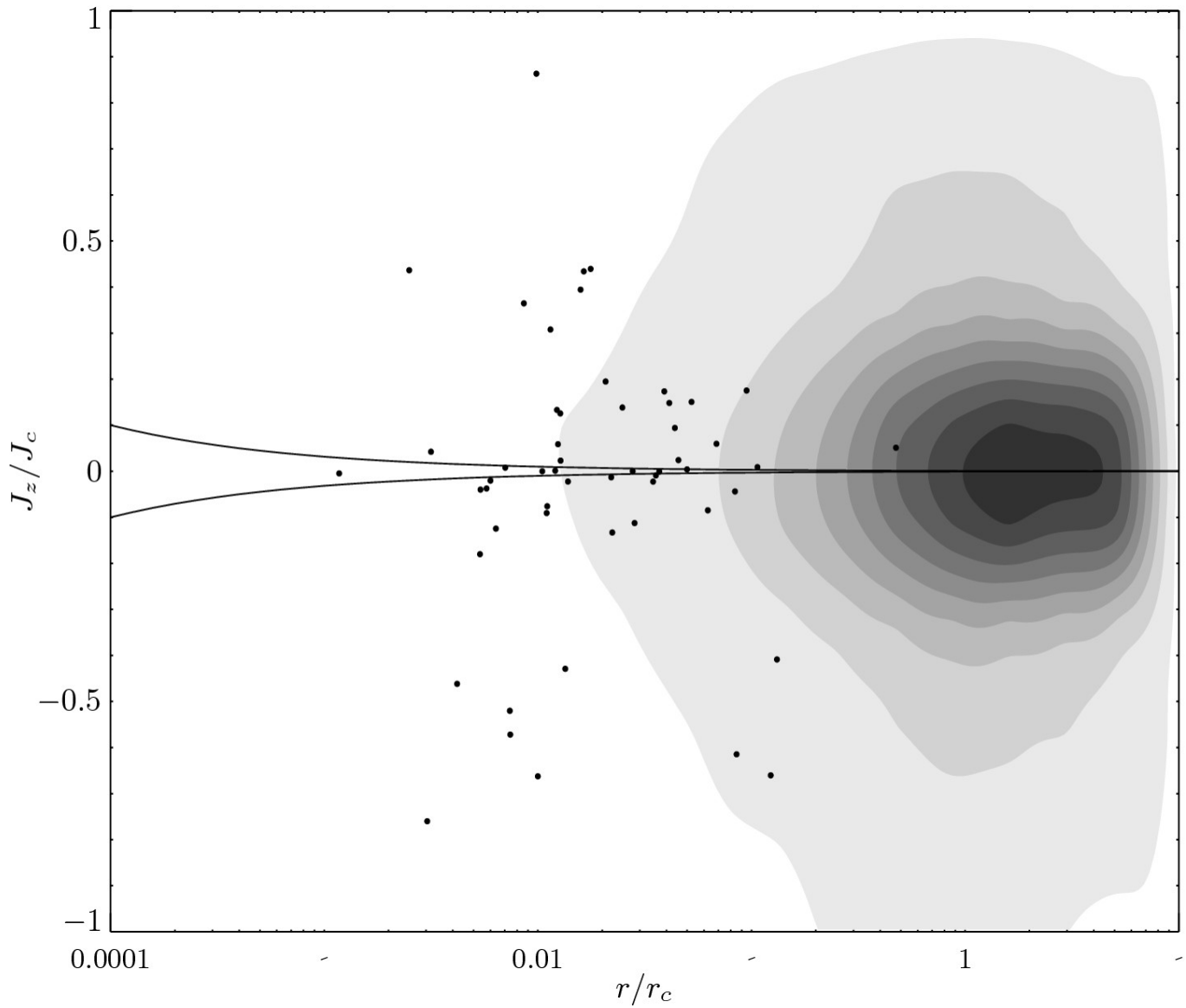


Wegg&Bode ArXiv: 1011.5874

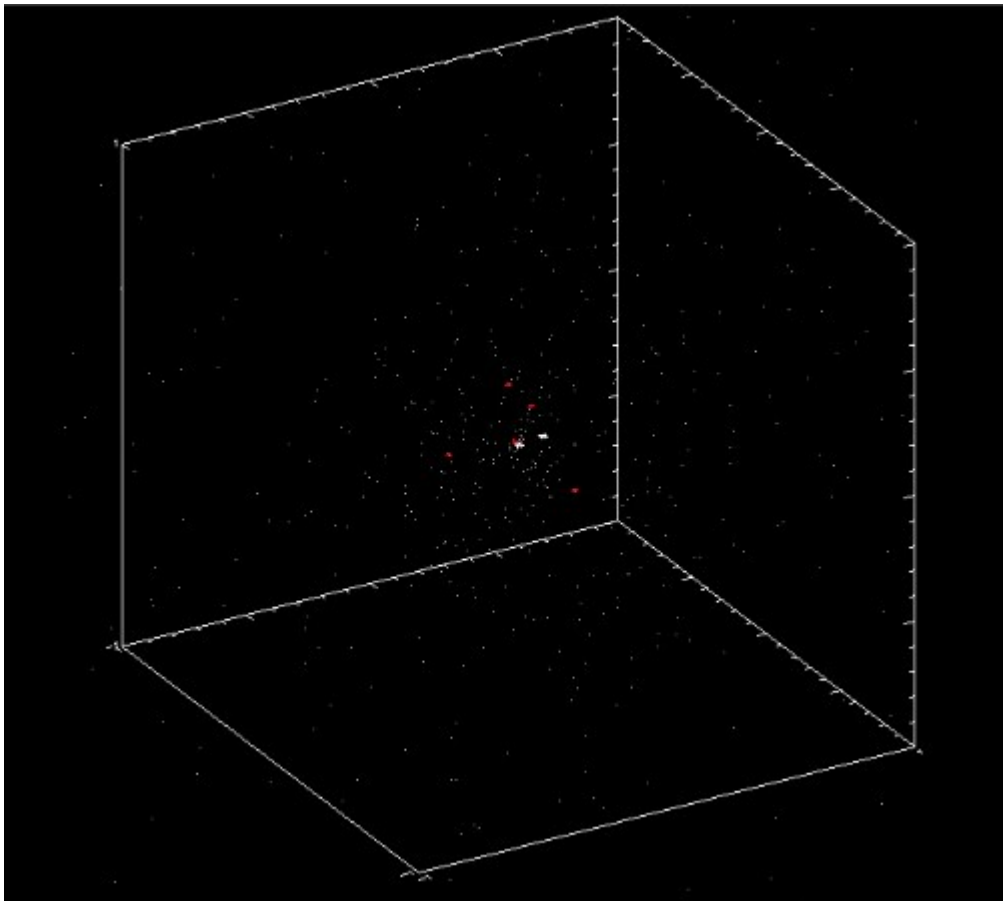
(see also Ivanov+ 2005 Chen+ 2009, But those not Self-consistent, overoptimistic)


$m_1 = 10^8 M_\odot$
$q = 0.3$
Central $\rho \sim r^{1.75}$
Binary Seperation / pc
100
10
1
0.1
Tidal Disruption Rate / yr^{-1}
0.15
0.1
0.05
0
0
1
2
3
4
t / Myr

1/7 yrs!



Tidal Captures not primarily in Kozai wedge. Most are just complicated 3-body orbits.

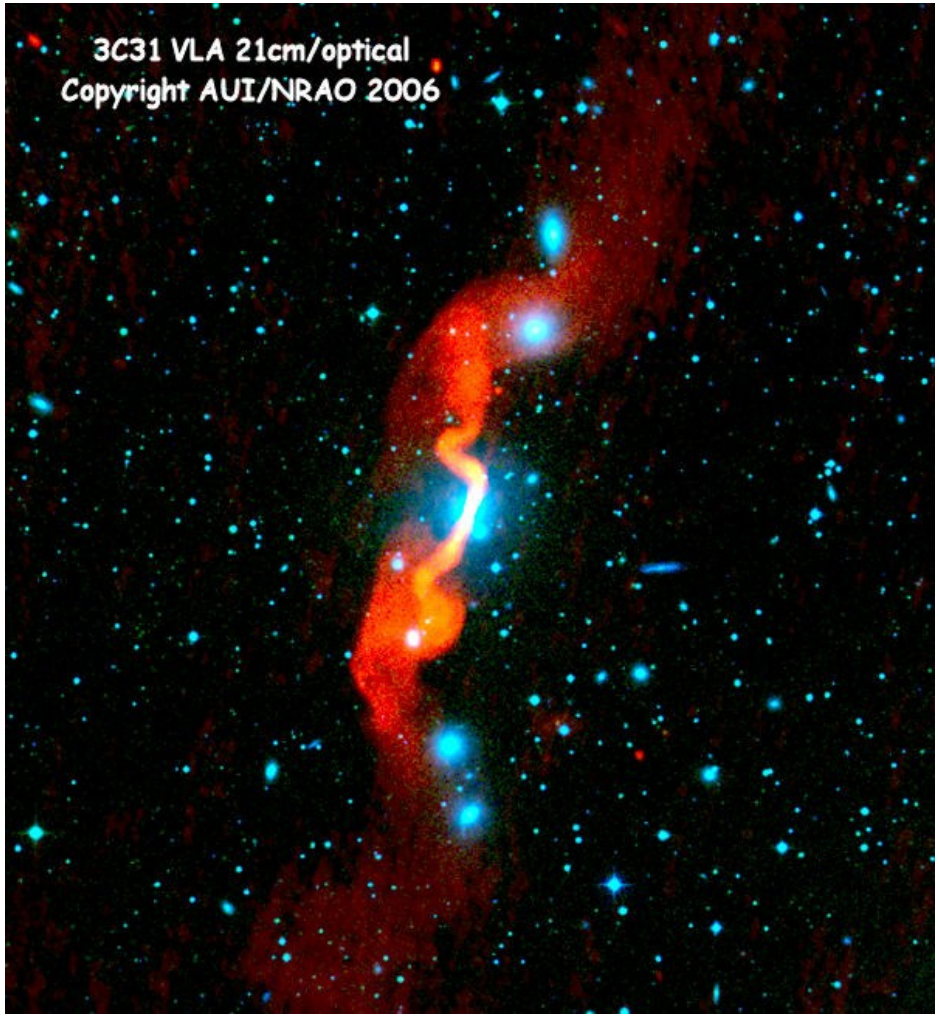


10-50% of all tidal disruptions in the Universe should be from this binary phase.

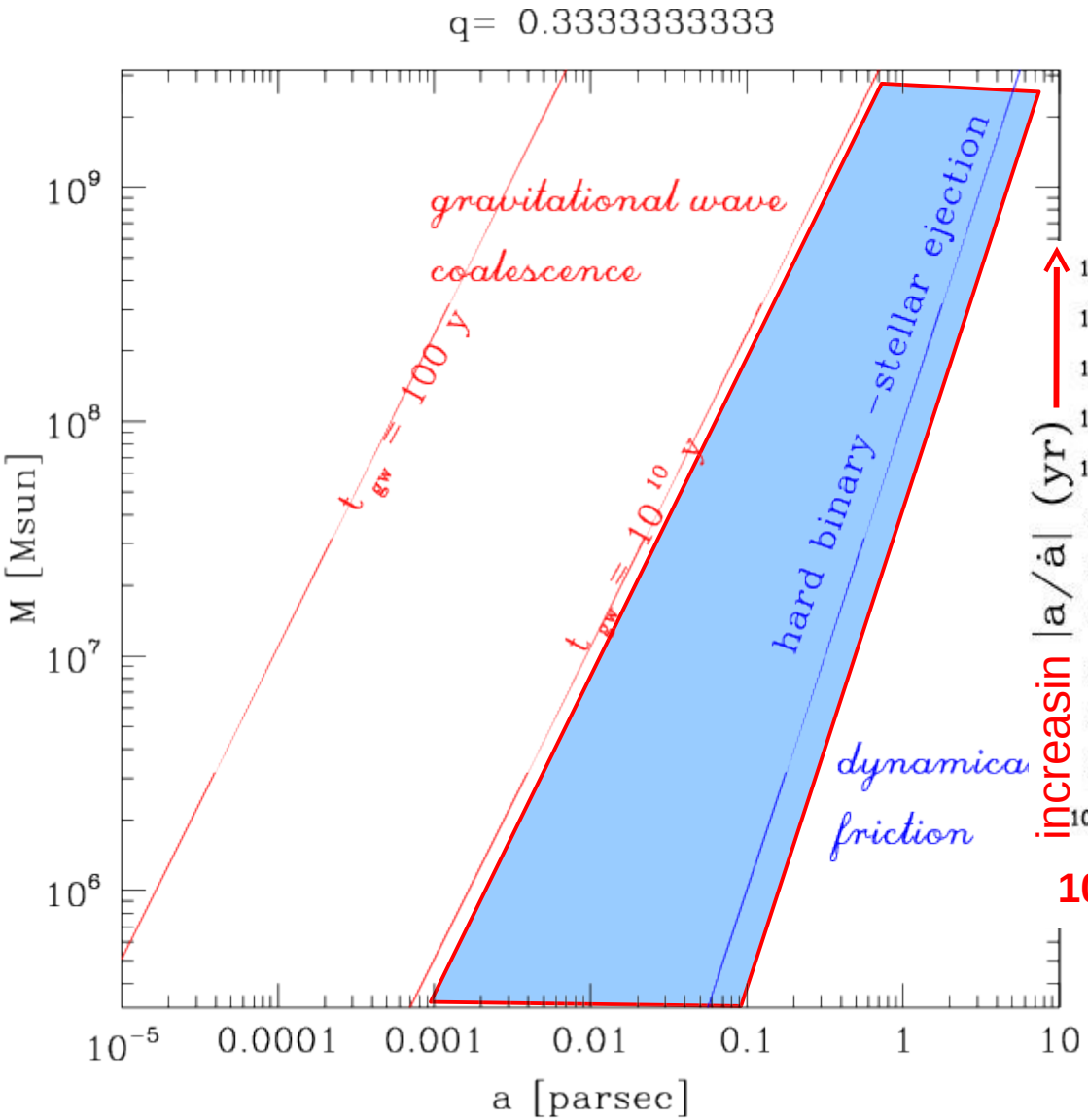
So if monitor galaxies with known tidal disruptions for a decade, those that repeat will, with 99% probability, be BBHs in the Stellar ejection phase!

Other ways to identify BBH stellar ejection phase

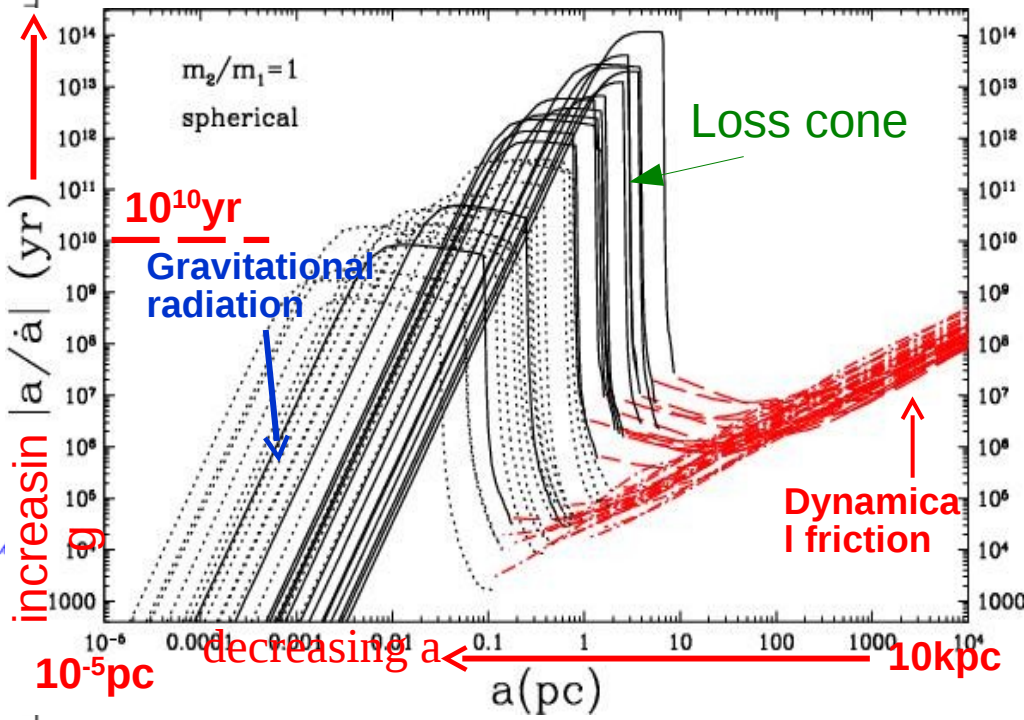
- C-symmetry FR I (slow, entrained -cf De Young) jets
- Hypervelocity stars (but can also be from binary stars+ single BH)
- (Fossil) “core” cuspless stellar distributions



The final parsec problem



Yu 2002



Begelman, Blandford & Rees 1980

Getting through the final parsec

Stellar ejection finishes after binary hardens

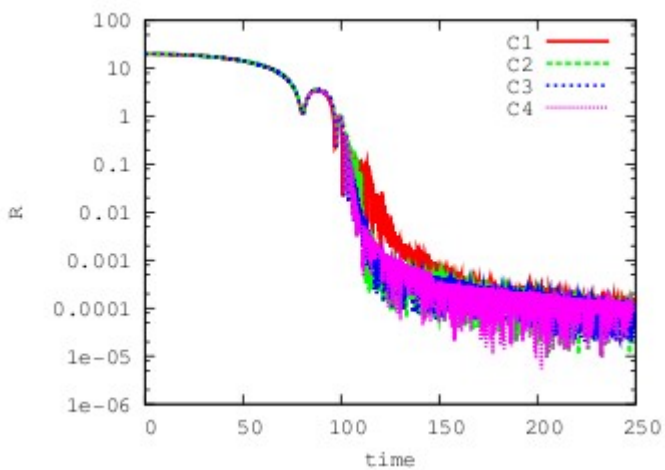
- Spherical core: loss cone emptied.
- Slow refilling by 2body relaxation

- Enhanced relaxation due to massive bodies (GMCs etc) -Peretz & Alexander 2008
- Triaxiality: from merger-induced bar: no loss cone -centrophilic orbits (Berentzen+ 2009 arXiv:0812.2756; Khan+ arXiv:1103.0272; Merritt talk)
- Gas migration (needs Mgas> Mbh)

Problem?

Triaxial?: no problem

Kahn+ arXiv 1103.0272
tmerg<1Gyr

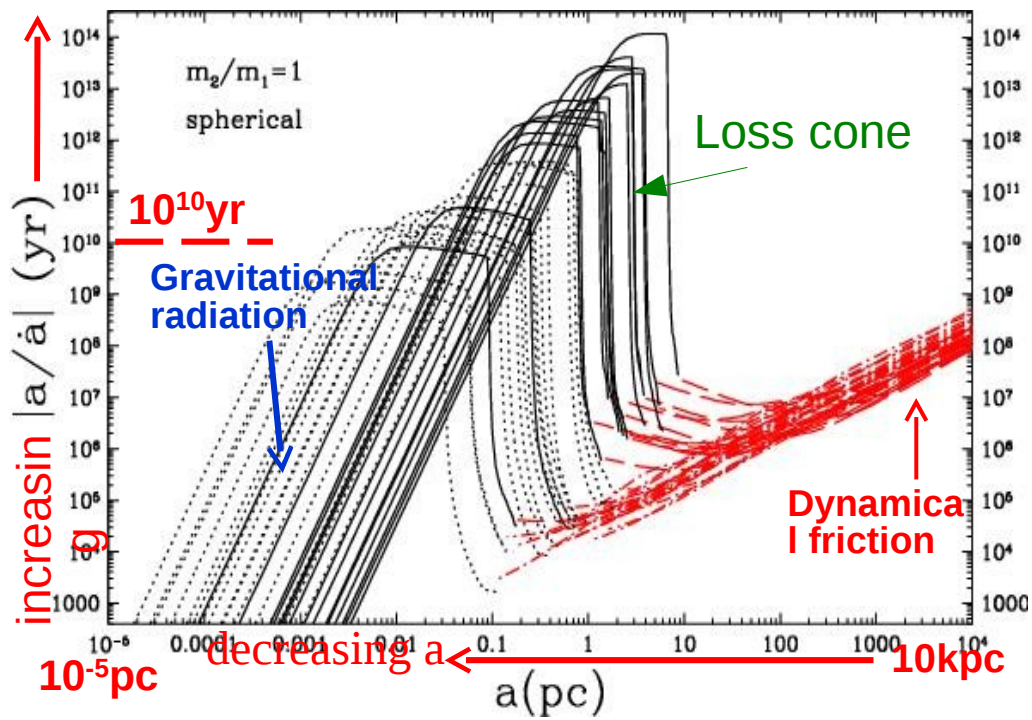


Note: orbit doesn't circularize

Axisymmetric: problem

tmerg>10Gyr

Yu 2002



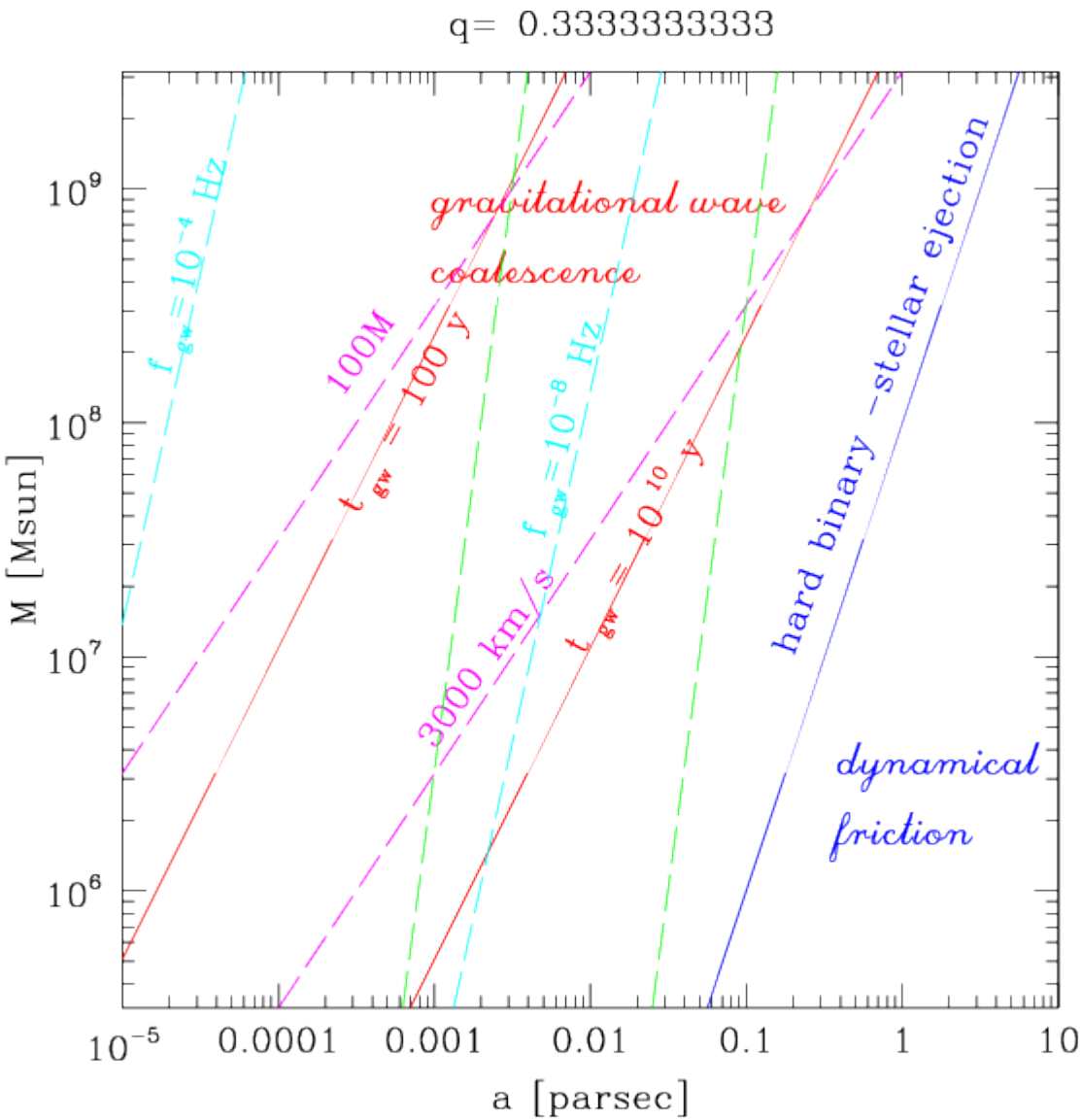
Gas-driven migration?

Depends on circumbinary gas mass, radial distribution (i.e. past binary history), 1D vs 3D gaps/orbits, disk thermal equlib (thickness), star Formation due to self-gravitating instability at high disk mass...

- Doesn't solve:
- Lodato+ 2009
- Chang+ 2010

- Does solve
- Armitage & Natarajan 2002, 2005
- Cuadra+ 2009
- Kocsis+ arXiv 1205.5268

Looking for post-final parsec sources

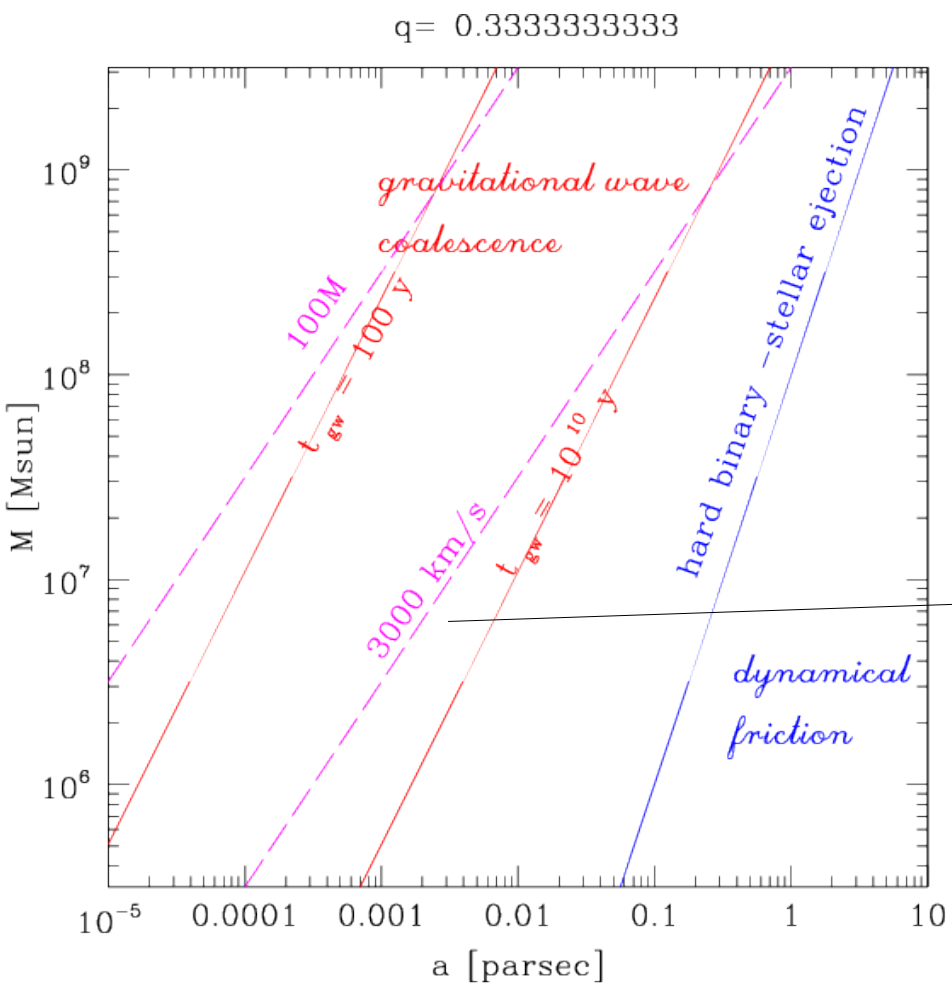


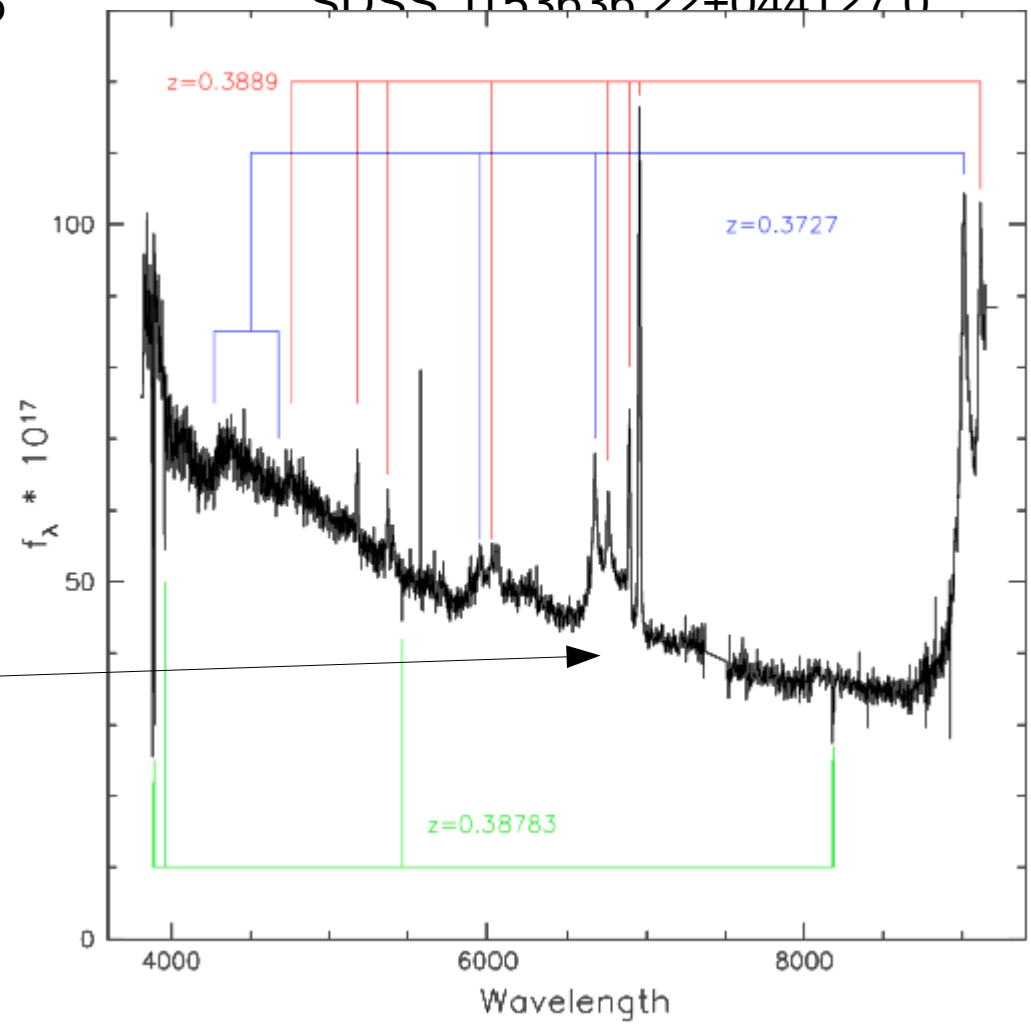
Ways to find
Binaries
In GW stage

Offset/doubled emission lines

Boroson & Lauer
arXiv:0901.3779
SDSS J153636.22+044127.0

cf similar systems Gaskell 1986



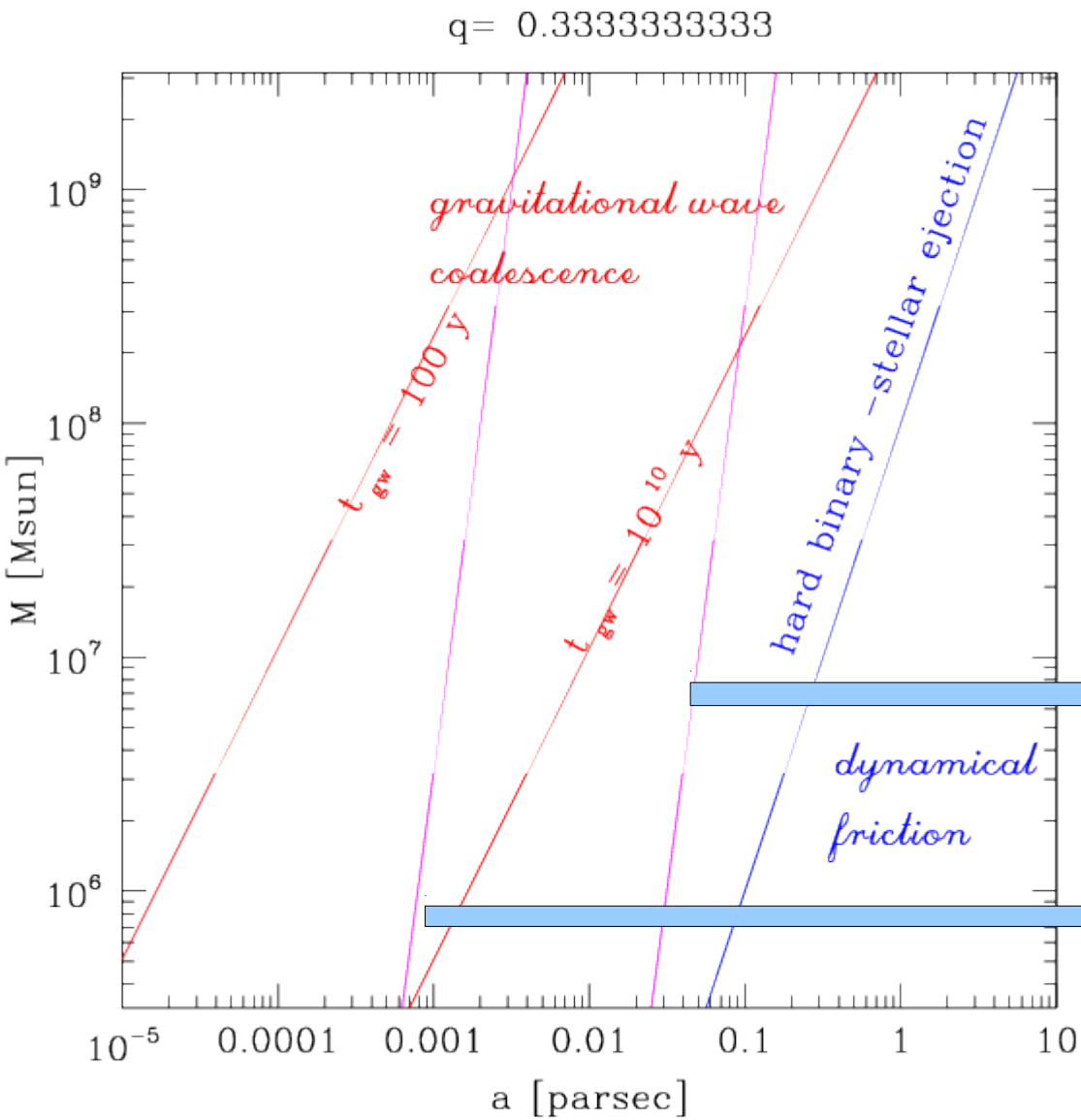


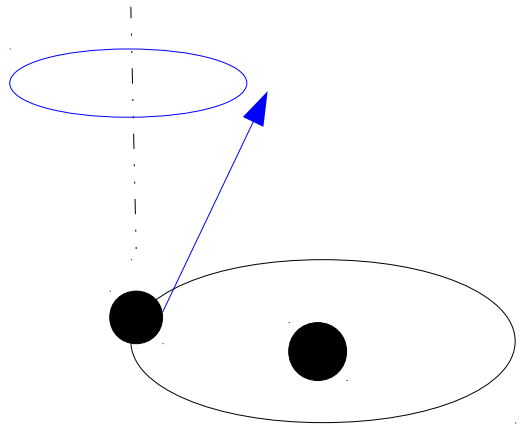
red: broad+narrow lines
blue: broad only
some abs at intermediate vel.

dV=3500km/s
P_{orb}=100y
10^9+10^7 Msun

Cf Loeb 0909.0261, Shen+Loeb 2010:
Not double -dispersion too high!

(Geodetic) spin precession





$T_{prec}=10^7$y

$T_{prec}=10^3$y

S-shaped radio sources?

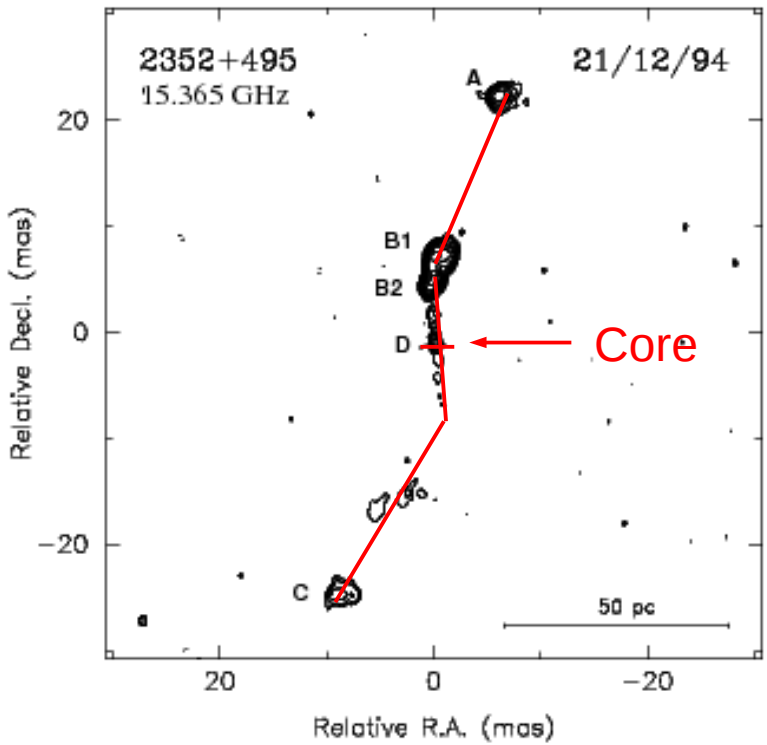


Figure 3. The naturally weighted 15 GHz VLBI image of 2352+495. Contours are drawn at −0.75, 0.75, 1.5, 3, 6, ..., 96 mJy/beam. The synthesized beam is drawn in the lower left-hand corner and has dimensions 0.91 × 0.67 mas in p. a. −3°. We identify component D as the core and components A and C as hot spots.

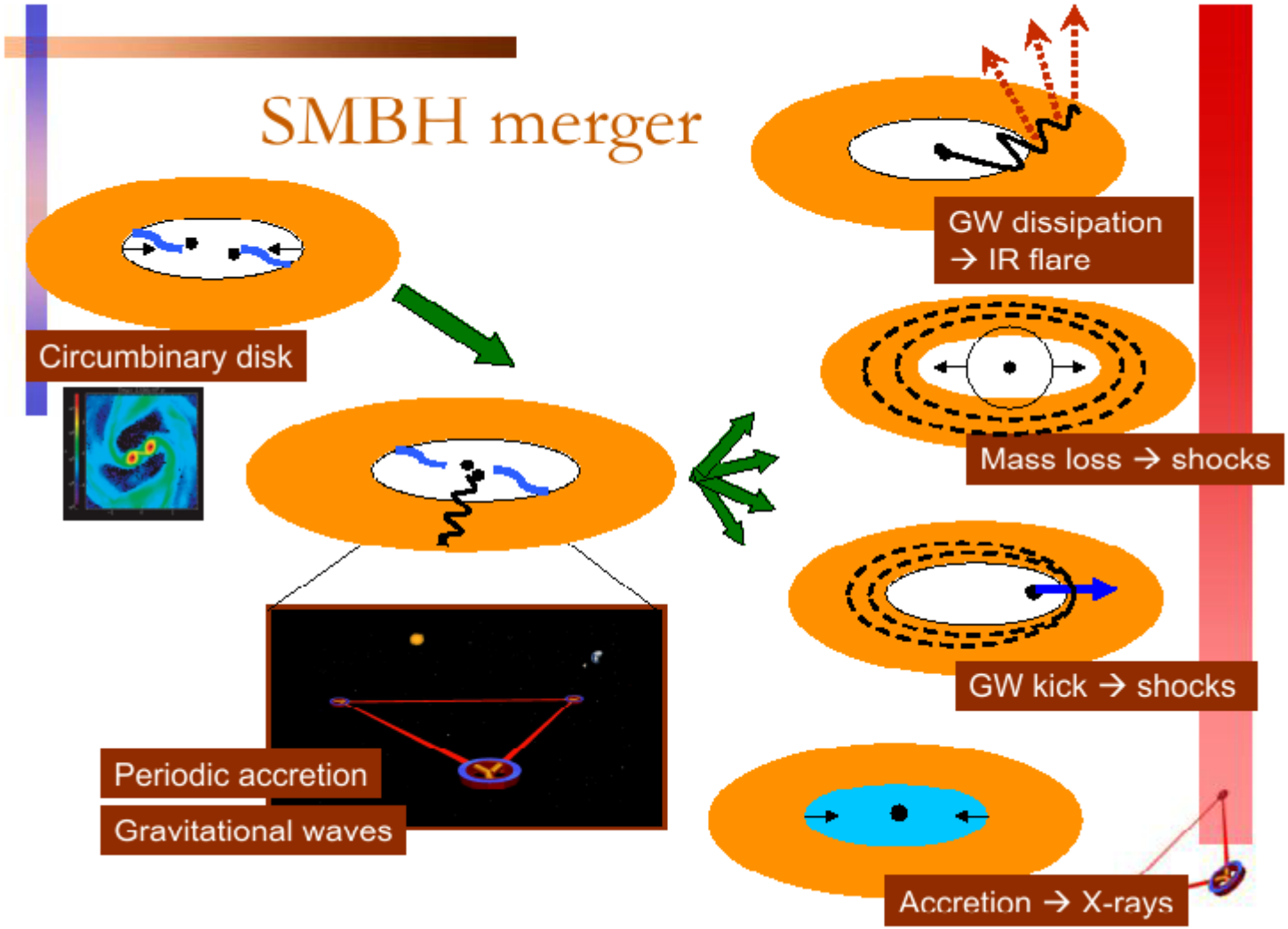
S-shaped radio Sources: BH spin precession due to geodetic precession In BBH binary? Begelman, Blandford & Rees 1980.

VLBI systems Tprec~1000-10,000y

But could be disk precession also. (cf SS433, Roos 1988)

$$P_{prec,i} = 6\times10^{6}(a/0.1\mathrm{pc})^{5/2} M_8^{1/2}(m_i 10^8 M_{sun}/m_1 m_2)\,\mathrm{y}$$

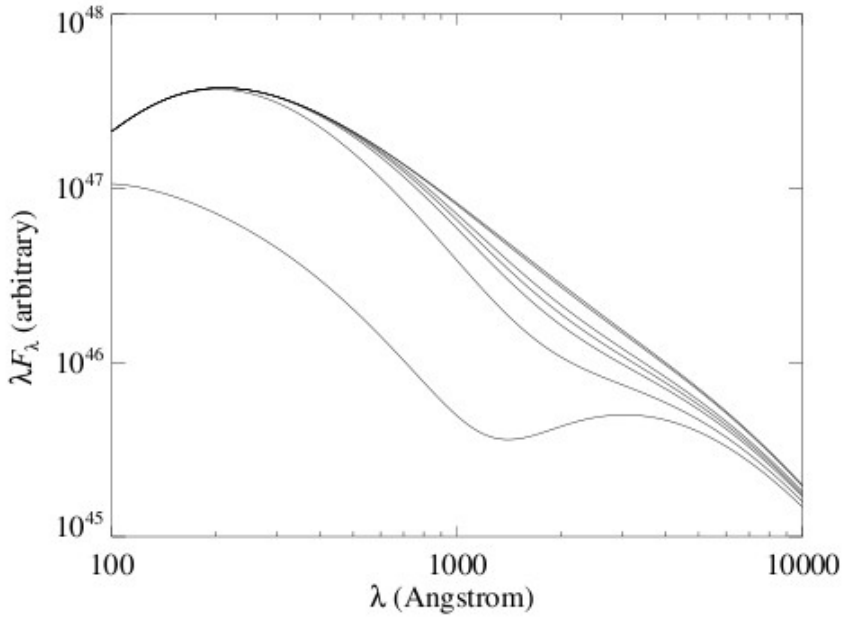
Manifestations during the GW-dominated phase of inspiral



Funny AGN spectra from circumbinary disk gaps before merger

- Milosavljevic & Phinney 2005
- Lodato+ 2009
- Gultekin+Miller 1207.0296
- Tanaka+ 1107.2937

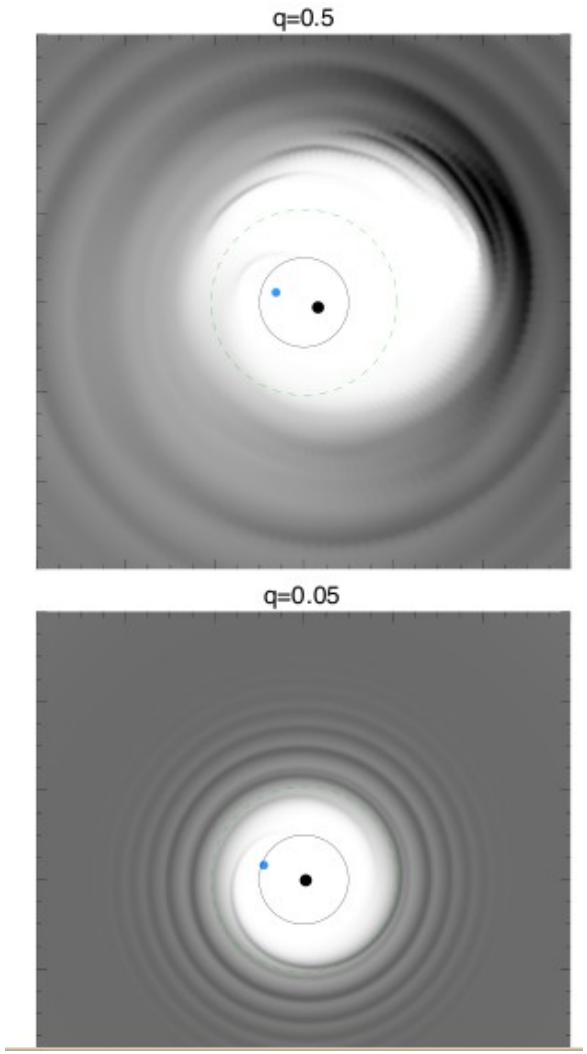
1E8Msun, at decoupling r=1000M, h/r=0.01, w/h=0,10,60..180



Beware of silicate 2000Angstrom dust features!

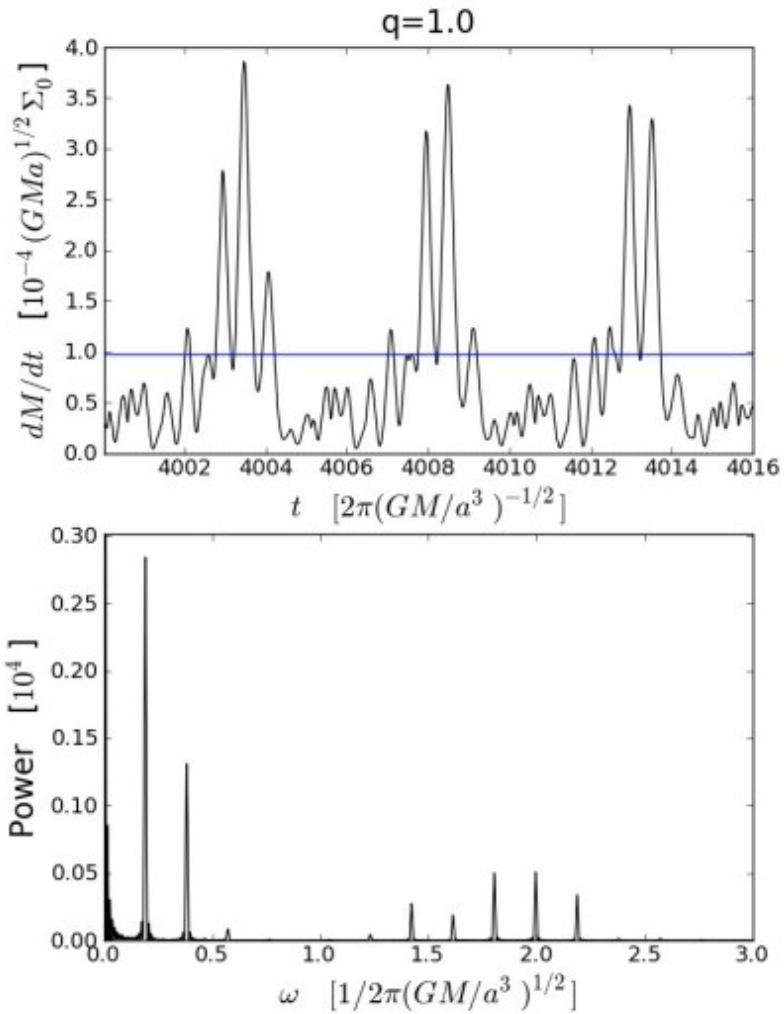
How complete is the gap? Do the BH accrete from the circumbinary disk

- Noble+ 1204.1073: 3D MHD disk, gap open, but accretion only halved
- D'Orazio+ 1210.0536 2D alpha disk: accretion reduced by 5, q>0.05, accretion modulated: compare analytic:
- Kocsis+ 1205.5268; Lodato+0906.0737

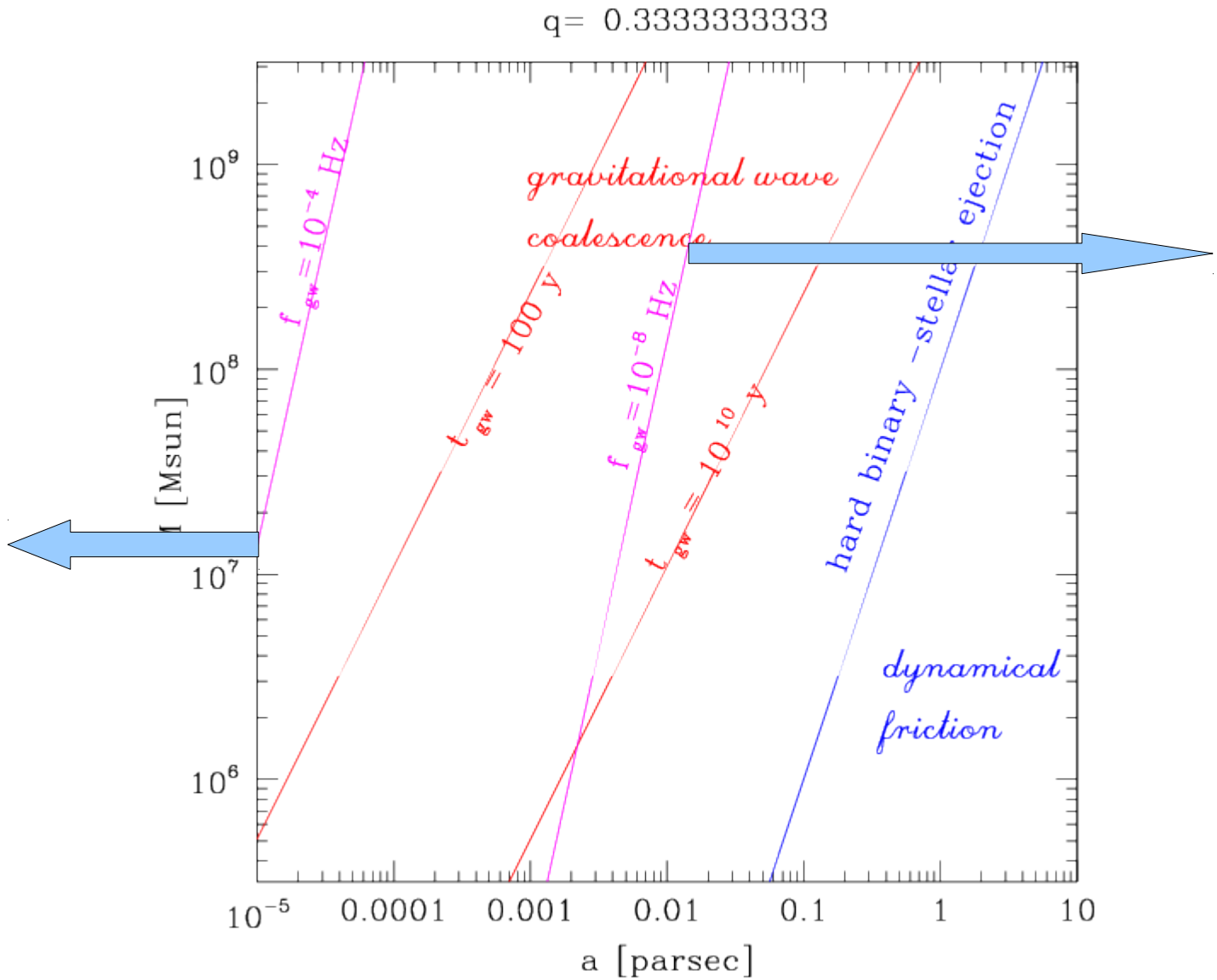


Periodic Accretion from Gap

- Noble+ 1204.1073: 3D MHD disk, gap open, but accretion only halved
- D'Orazio+ 1210.0536 2D alpha disk: accretion reduced by 5, q>0.05, accretion modulated
- Hasayaki+ 1211.5137 misaligned circumbinary disk: circular 2 bursts per orbit (plane crossing), 1 per orbit if eccentric.
- Note: orbital period at disk decoupling (viscous time = gw time) is ~ $3M_8$ y. So interesting only for low-mass holes



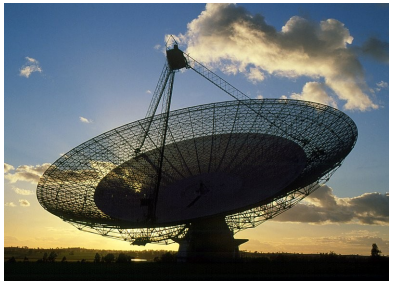
Gravitational Waves: in PSR timing band



LISA

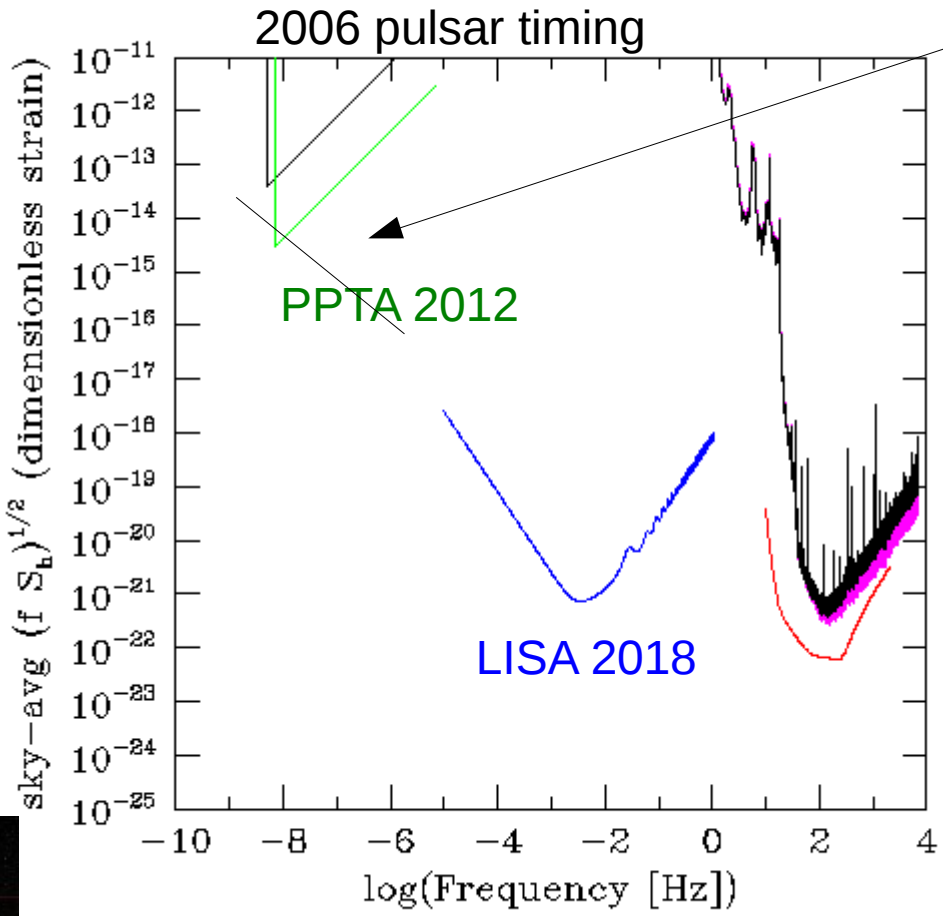
Pulsar Timing

Gravitational wave detector sensitivity



Parkes

Predicted amplitude
Dominated by massive
108-109Msun BH.

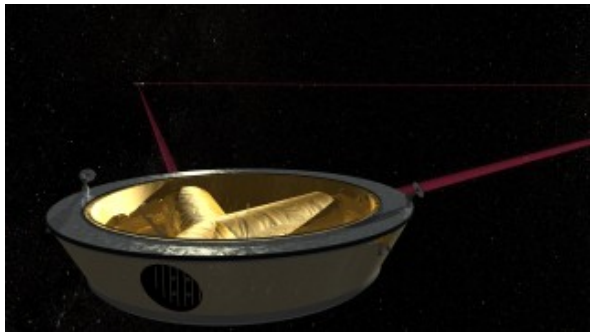


LIGO 2007 S5 run

enhanced LIGO 2009

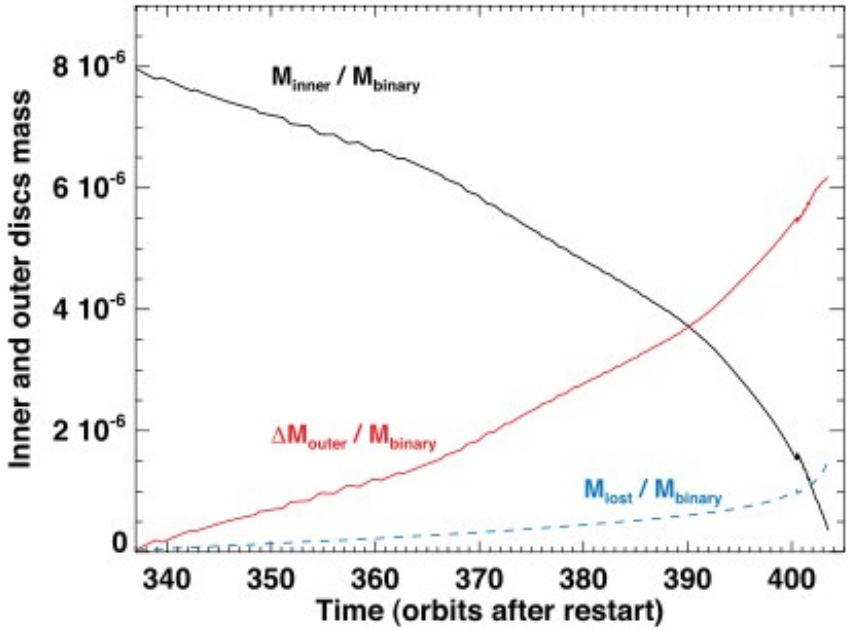
Advanced LIGO 2014

LISA Pathfinder 2011
LISA 2018?



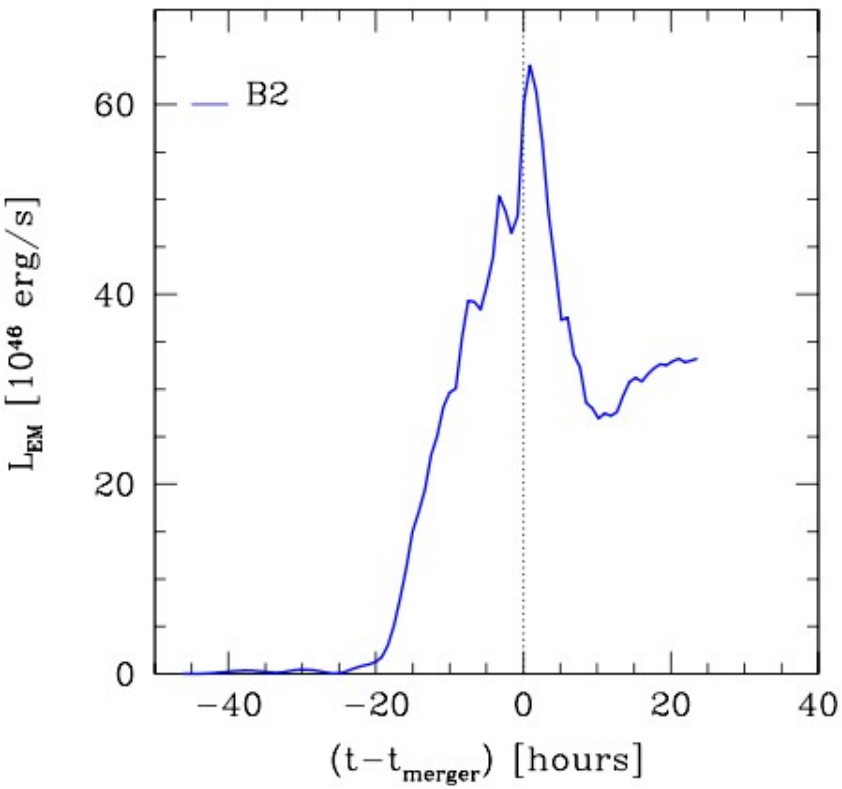
Burst from fossil disk driven in during decoupled phase

- Chang et al 0906.0825
  L~ t(to merger)$^{-5/4}$.
- But Hayasaki 1009.0157
  -can become radiatively inefficient
- Fossil disk may not exist due to gas escape on horseshoe orbits: Baruteau+ 1203.4085



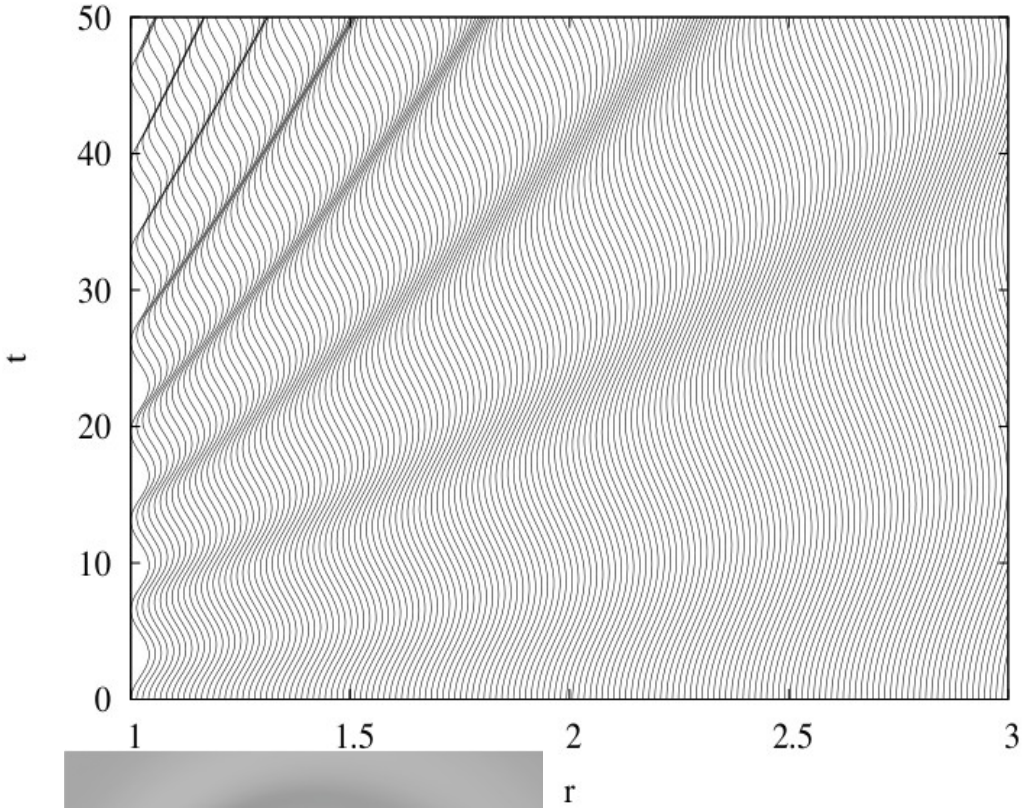
Final jet produced by compression of fossil disk

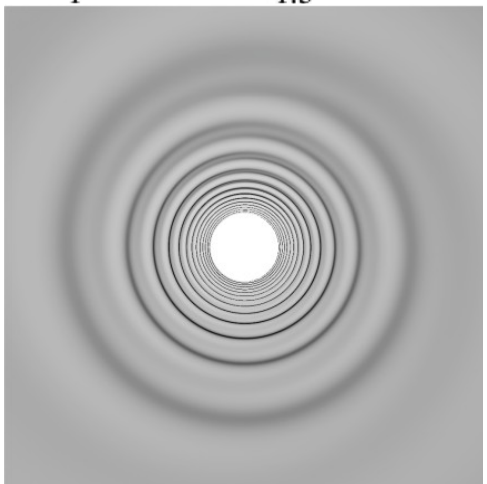
- Giacomazzo+ 1203.6108 MHD: B frozen in disk amplifed by binary torque compression, so L(jet) increased by 10^4.
- (earlier force-free have no flux freezing, so no amplification of B).



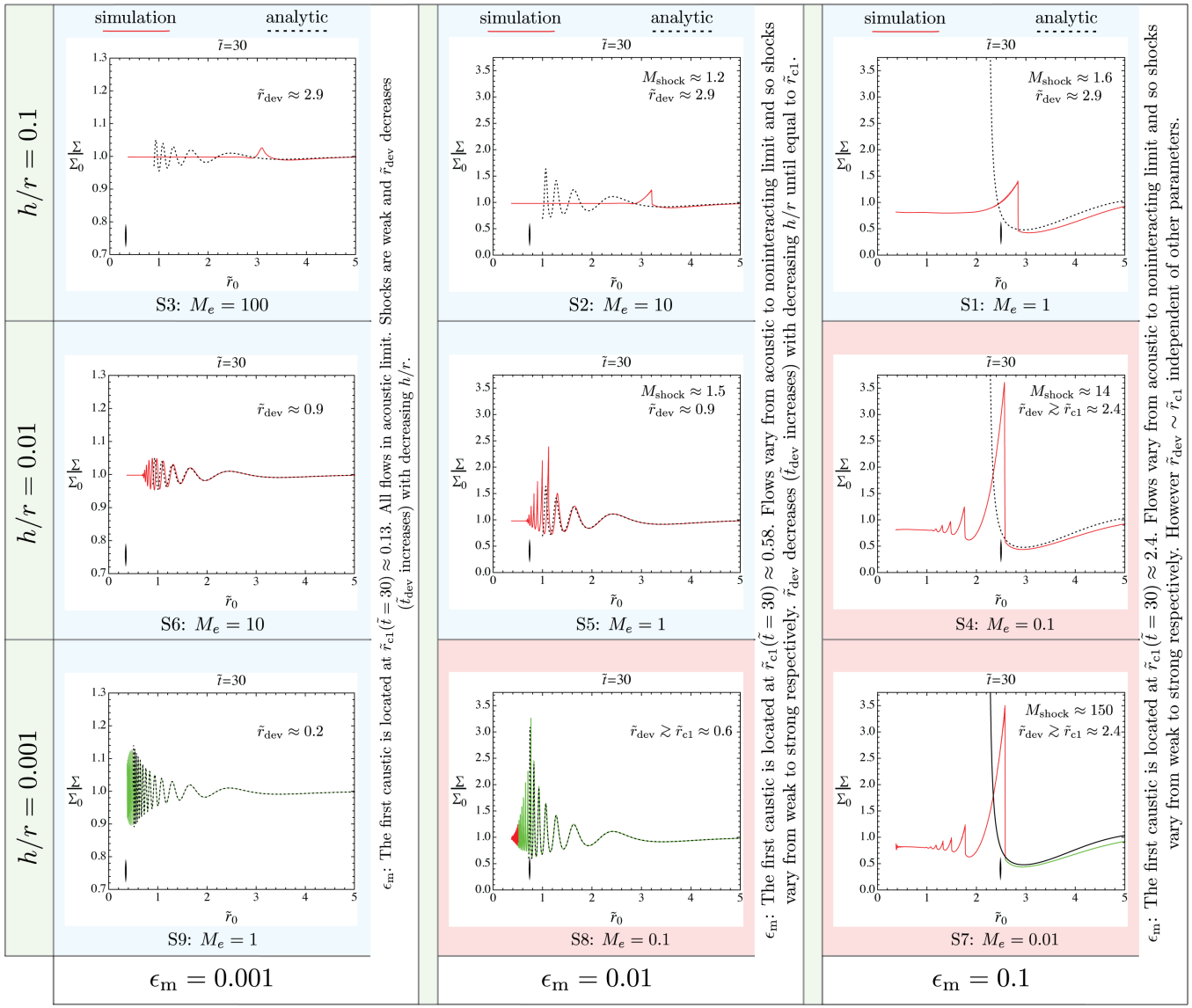
Response of decoupled circumbinray disk to GW mass loss+kick

- Penna & Phinney 2006, Krolik 0912.5711, Bode PhD 2011, Bode+Phinney 2012, Rosotti+ 1206.2647
- Gravitational radiation removes mass-energy: circular orbits become eccentric, all in phase initially. Dominates inner disk
- Kick also makes orbits eccentric (parabolic far enough out), but with initial phase m=1 varying.





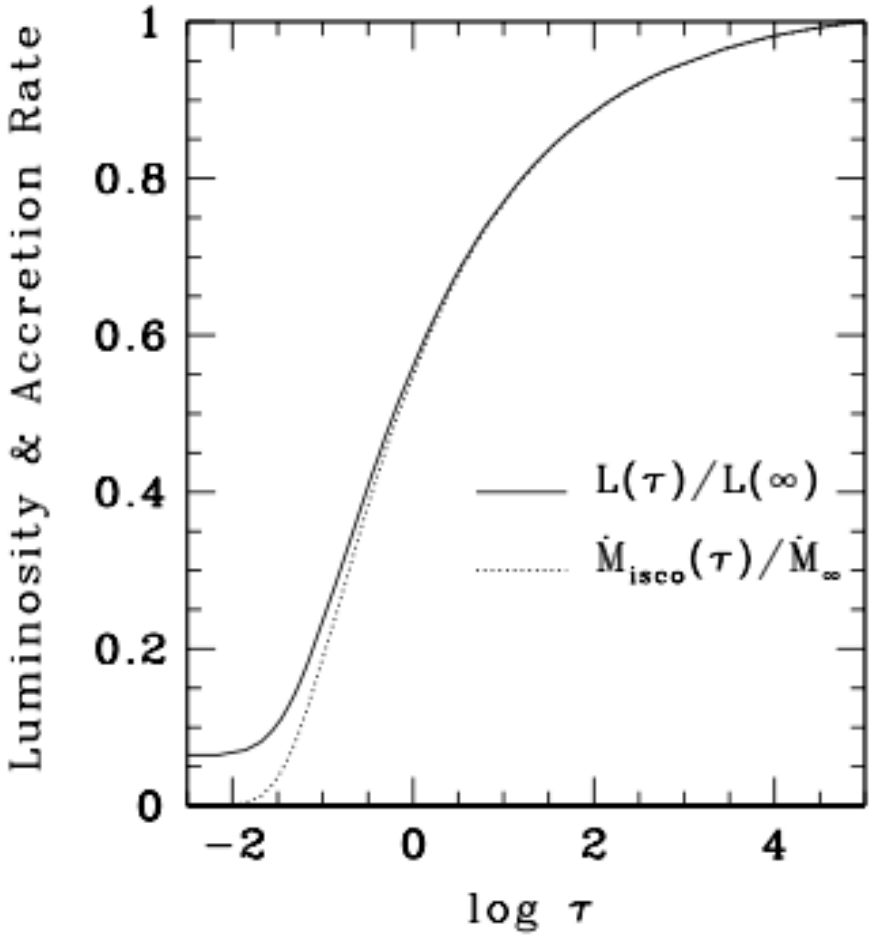
Disk response diagnostic of disk thickness and vertical structure



Bode PhD 2011
Bode+Phinney 2012

Post-merger fill-in of disk

- Milosavljevic & Phinney 2005
- Shapiro 0912.2345
- Liu+Shapiro 1011.0002
- Farris+ 1105.2021
- Takamitsu 1004.5411 -could be 100 all sky sources brightening 10%/yr in soft X



Long after the merger

- If q~0.5, rapidly spinning Bhs with spins not aligned with orbital angular momentum, can get kicks of 1000's of km/s -cf Lousto 1201.1923. For small <0.1, spins a/M<0.5, or aligned, only <100's of km/s.
- Ejected BH carries inner accretion disk and stars -enough disk to power for Myr. Non-nuclear quasars, offset BLRs... cf. Komossa 1202.1977 review.
- Change in loss cone can initially enhance, then reduce tidal disruption rate: Stone&Loeb 1004.4833, Li+ 1201.3407
- Blecha+ 1009.4940. When recoiling black hole out of nucleus, enhances nuclear star formation.

X-shaped radio sources -merger-induced BH spin change?

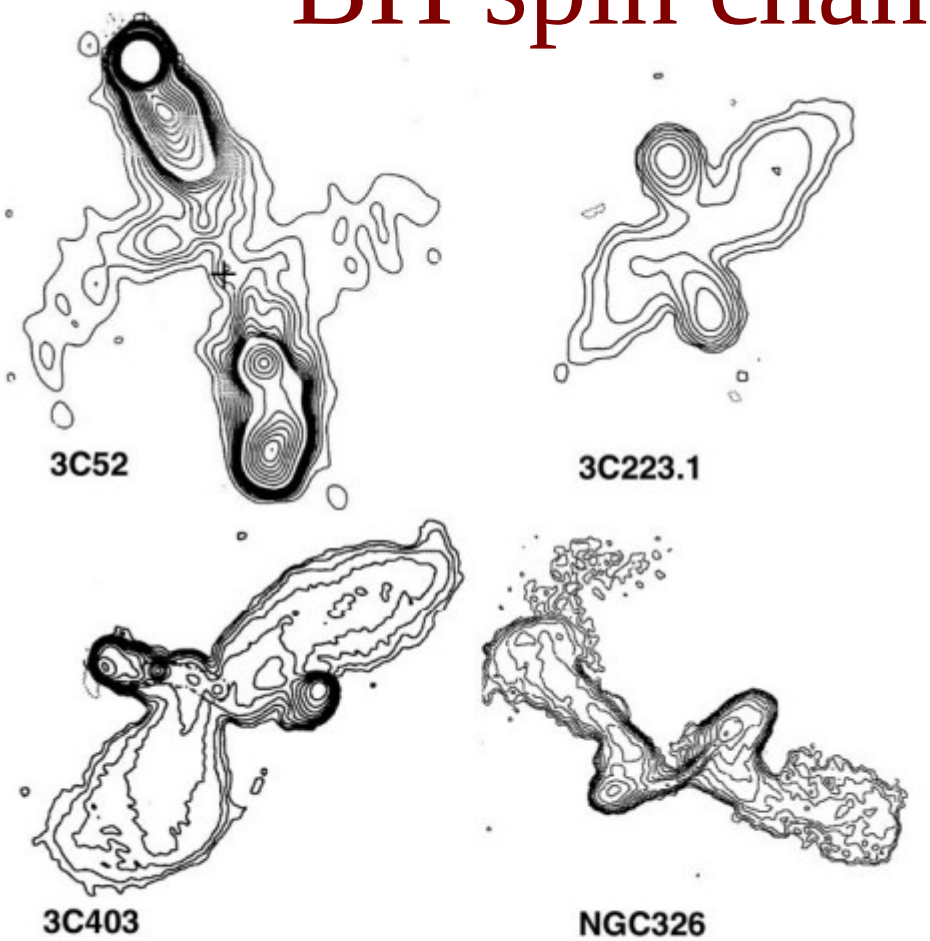
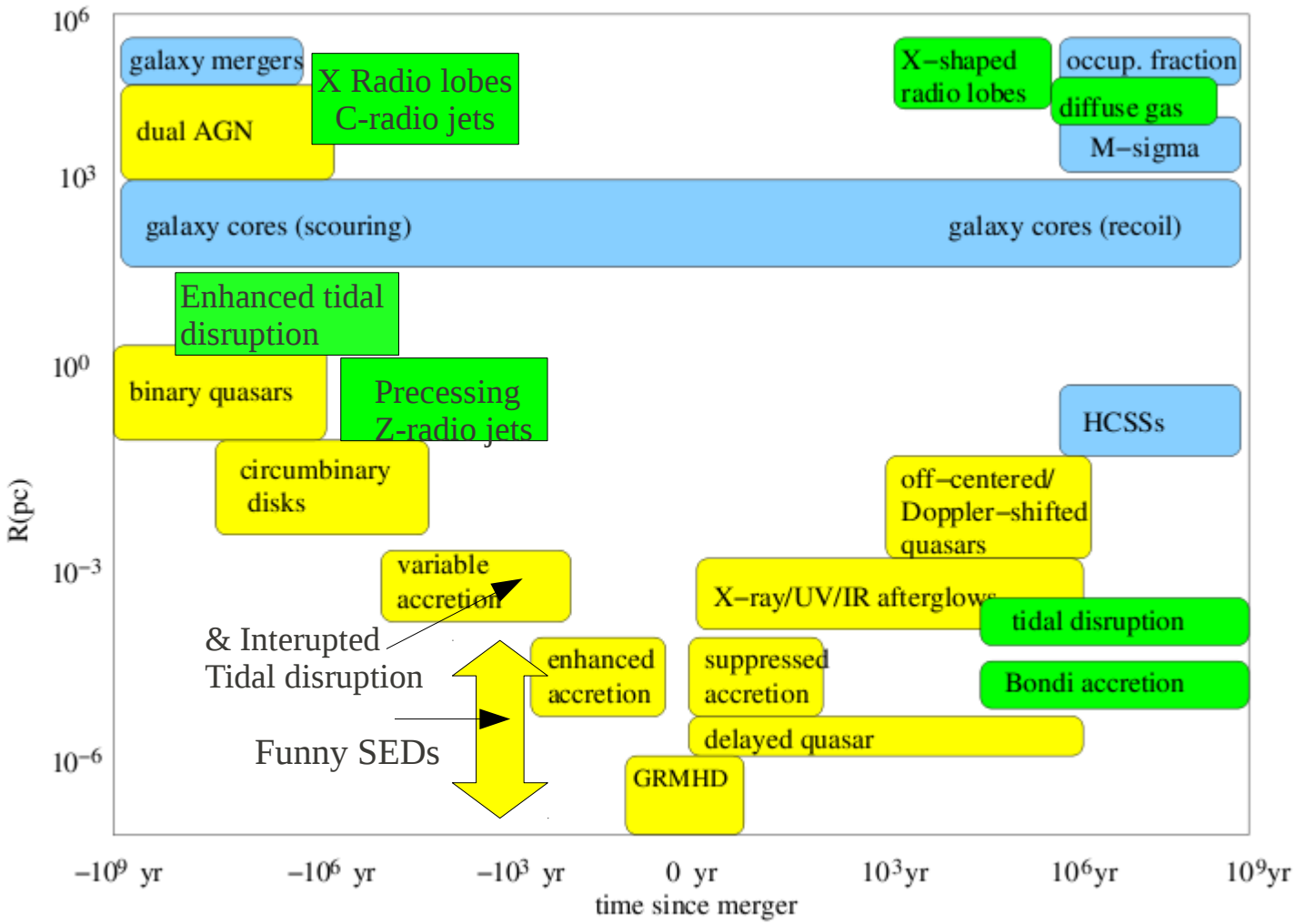


Fig. 2. A composite of four clear examples of the X-shape morphology. VLA radio observations of 3C52 (*28*), 3C223.1 (*29*), 3C403 (*29*), and NGC 326 (*12*).

Ekers & Merritt 2002
X-type radio sources:
Spin, hence disk reorientation
After BBH merger?

But see Saripalli & Subrahmanyan 2009:
Wing correlation with galaxy minor axis
suggests wings are just redirected jet backflow in most cases.

Grand survey of merger signatures



Modified after Schnittman 1010.3250