Black Hole Coalescence: The Gravitational Wave Driven Phase

Jeremy Schnittman

NASA Goddard

UM Black Holes
Augest 24, 2011

Motivation

Observing supermassive black hole mergers will teach us about

- Relativity
- High-energy Astrophysics
- Radiation Hydrodynamics
- Cosmology
- Galaxy Formation and Evolution
- Stellar Evolution
- Dark Matter

Motivation

Observing supermassive black hole mergers will teach us about

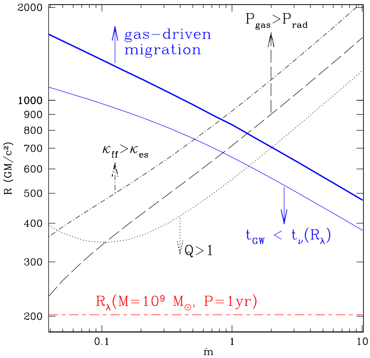
- Relativity
- High-energy Astrophysics
- Radiation Hydrodynamics
- Cosmology
- Galaxy Formation and Evolution
- Stellar Evolution
- Dark Matter

Time scales

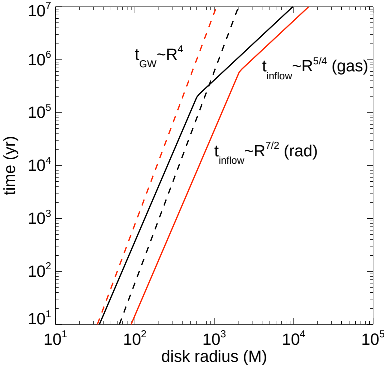
"final parsec" problem (maybe) not such a big problem after all

- triaxial galaxies e.g., Merritt & Poon 04, Preto+ 11
- massive perturbers Perets & Alexander 08
- high eccentricities Quinlan 96, Preto+ 11
- circumbinary gas disk Callegari, Cuadra, Dotti, Van Wassenhove, ...

Time scales, con't



Tanaka+ 11

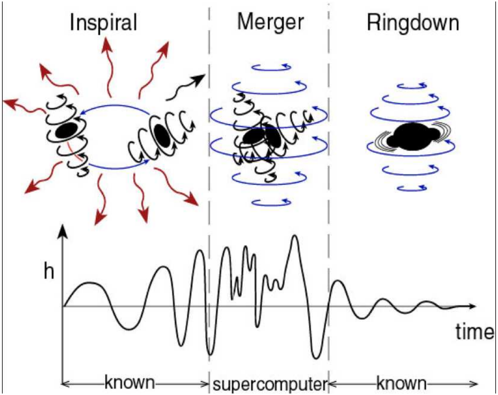


JS & Krolik 08

Time scales, con't

vaccuum binary merger is basically a solved problem

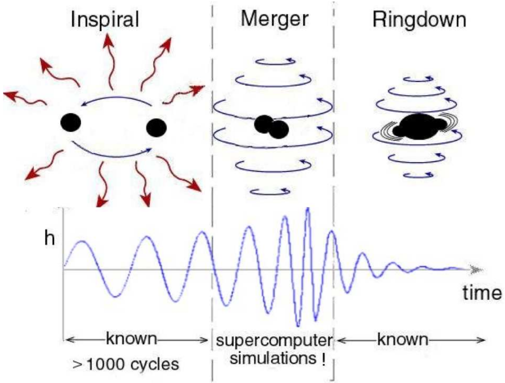
$t < 2005$: "Kip diagram"



Time scales, con't

vaccuum binary merger is basically a solved problem

$t > 2005$: "Joan diagram"



EM counterparts – What do we know?

- galaxy mergers + ubiquitous SMBHs
- remarkably few AGN pairs, no triples
- phases of BH binary evolution
  - stellar dynamical friction
  - gas dynamical friction
  - GW loss
- post-Newtonian + numerical relativity
- kick formula for known masses, spins

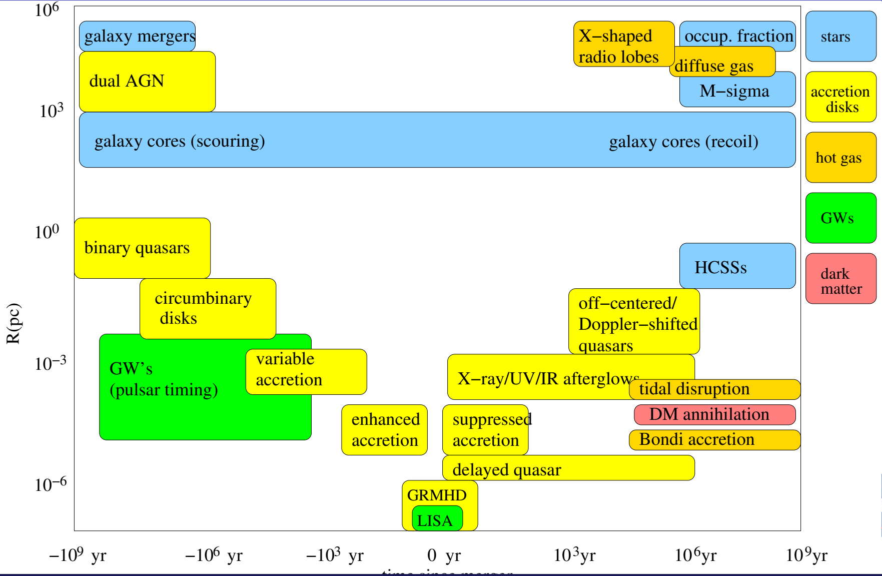
EM counterparts – What do we need to know?

- galaxy merger rates (dependence on masses, mass ratio, gas fraction, etc.)
- BH parameters
  - BH masses
  - BH spins: amplitude and orientation
- BH environment prior to merger
  - quantity and quality of gas
  - stellar distribution and age/metallicity
  - properties of circumbinary disk

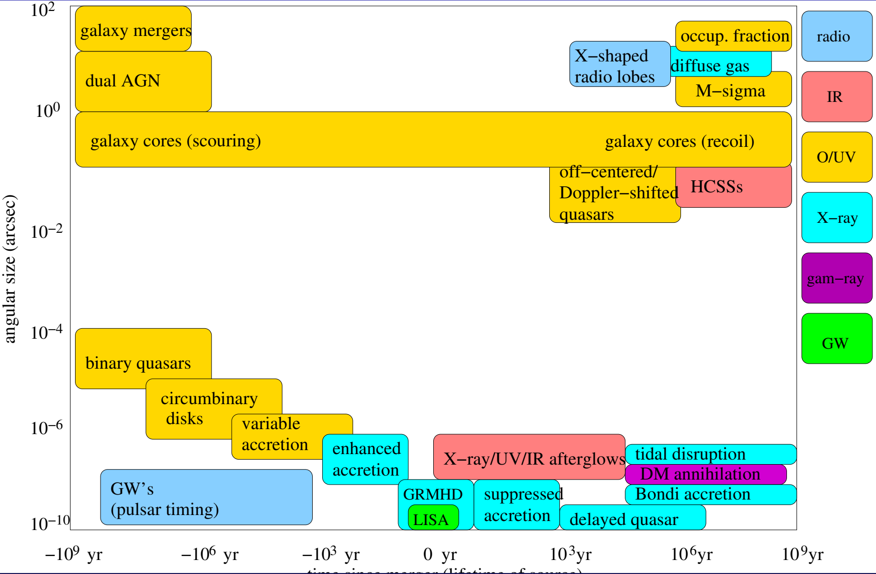
What we will learn

- galaxy environs: gas vs stars
- high-velocity end of kick distribution
- time delay between galaxy, BH merger
- w/ PTA: merger rates for $M \gtrsim 10^8 M_\odot$, $z \lesssim 1$
- w/ LISA: rates, masses, spins for $M \lesssim 10^{6-7} M_\odot$, $z \lesssim \infty$
- L_D vs z out to $z \sim 1$
- w/ LIGO: rates, masses, spins for $M \lesssim 10^2 M_\odot$, $z \lesssim 0.3$

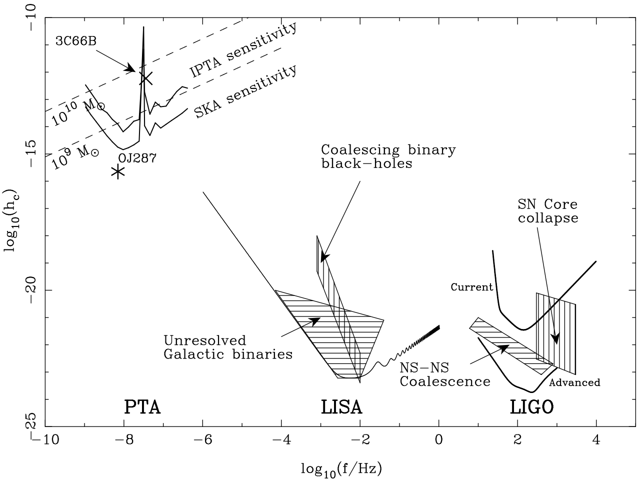
Diversity of Sources (theorist)



Diversity of Sources (observer)

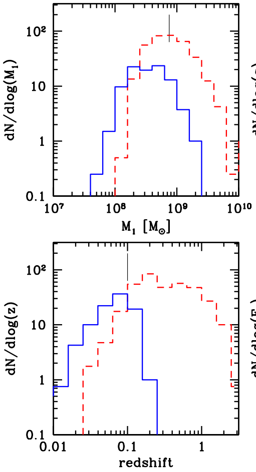


Pulsar timing arrays



Hobbs+ 10

PTA sources



Sesana+ 11

Future wide-field surveys

- LOFAR → SKA
- PanSTARRS → LSST
- eROSITA → WFXT/LOBSTER
- UKIDSS → ?

all need massive efforts at automated, real-time data analysis and coordination

GW counterparts

Analytic

Shields & Bonning (2008)
JS & Krolik (2008)
Lippai et al. (2008)
Kocsis & Loeb (2008)
Krolik (2010)
Chang et al. (2009)
Tanaka & Menou (2010)
Haiman et al. (2010)
Shapiro (2010)

Newtonian hydro

Armitage & Natarajan (2002)
Hayasaki et al. (2008)
MacFadyen & Milos. (2008)
O'Neill et al. (2009)
Corrales et al. (2009)
Rossi et al. (2010)
Anderson et al. (2010)

Relativistic hydro

Palenzuela et al. (2009)
Bode et al. (2009)
van Meter et al. (2010)
Farris et al. (2010)
Megevand et al. (2009)
Palenzuela et al. (2010)
Mosta et al. (2010)
Zanotti et al. (2010)

Astro 2010 white papers

Bloom et al. (2009)
Demorest et al. (2009)
Jenet et al. (2009)
Madau et al. (2009)
Miller et al. (2009)
Nandra et al. (2009)
Owen (2009)
Phinney (2009)
Prince (2009)
Schutz et al. (2009)
Stamatikos et al. (2009)

NS mergers:

Rasio & Shapiro (1992)
Rasio & Shapiro (1994)
Zhuge et al. (1994)
Ruffert et al. (1996)
Janka et al. (1999)
Faber & Rasio (2000)
Faber & Rasio (2001)
Shibata et al. (2003)
Anderson et al. (2008ab)
...

Even small amount of gas leads to bright EM signal

energy content of gas dominated by gravitational potential:

$$E_{\rm gas} \sim \epsilon \Sigma R^2 \qquad (\epsilon \approx 0.01 - 0.1)$$

cooling time for optically thick gas:

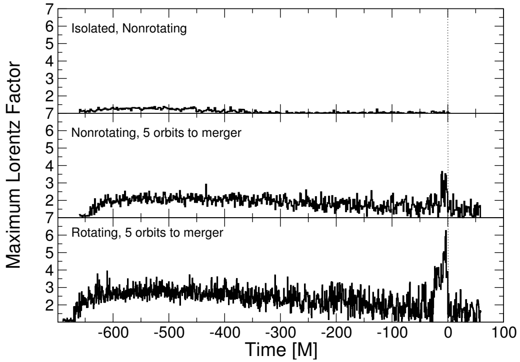
$$t_{\rm cool} = \frac{\tau h}{c} \sim \epsilon^{1/2} \Sigma R^{3/2},$$

giving "universal" luminosity:

$$\frac{dL}{d \ln R} \approx \epsilon^{1/2} R^{1/2} L_{\rm Edd} \sim 10^{44}\, M_6\, {\rm erg/s}$$

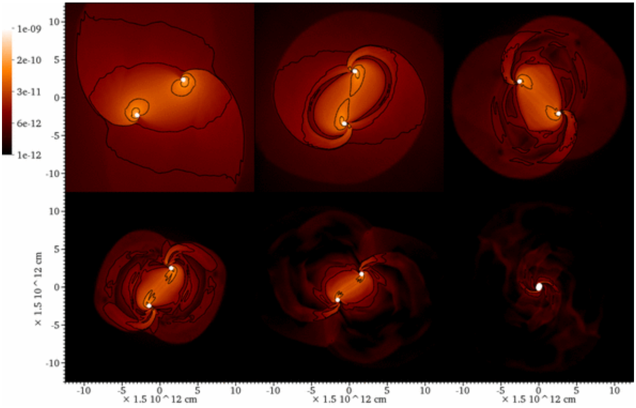
Krolik (2010)

Test particle simulations ⇒ ultra-relativistic flows



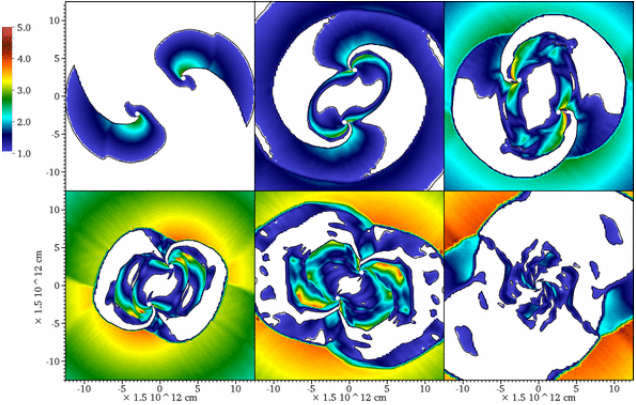
van Meter et al.(2010)

Hydro plus NR ⇒ strong shocks, heating



Bode et al.(2010)

Hydro plus NR ⇒ strong shocks, heating



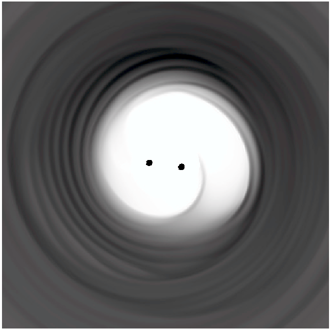
Bode et al.(2010)

but just one question...

...will there be any gas?

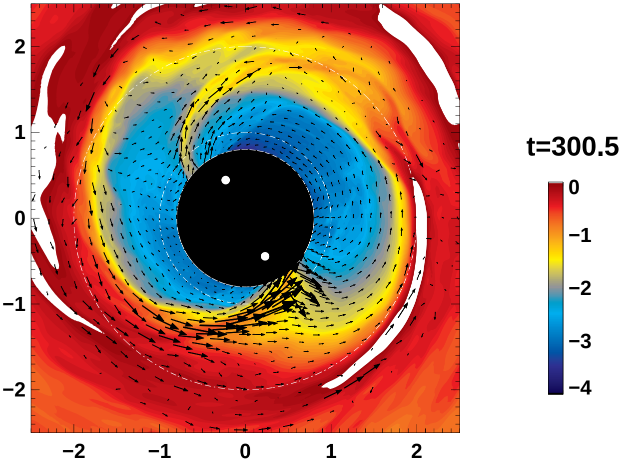
circumbinary disk clears out a gap around the BHs:

MacFadyen & Milosavljevic (2008)



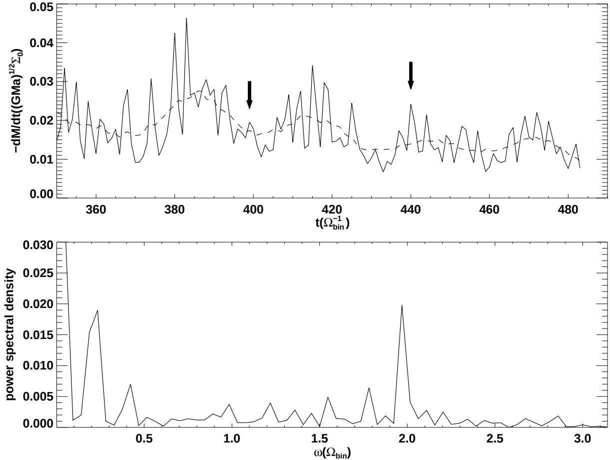
after disk decouples ($t_{\mathrm{GW}} < t_{\mathrm{inflow}}$), could be even less gas

Need grid-based 3D MHD simulations



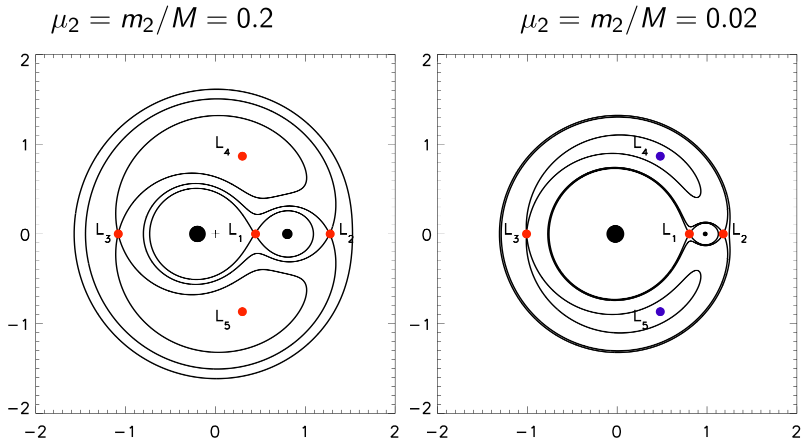
Shi, Krolik, & Lubow (2011)

Clear periodic accretion



Shi, Krolik, & Lubow (2011)

Classical Lagrange points in restricted 3-body problem



$\mu_{\rm crit} \approx 0.0385$

JS 2010

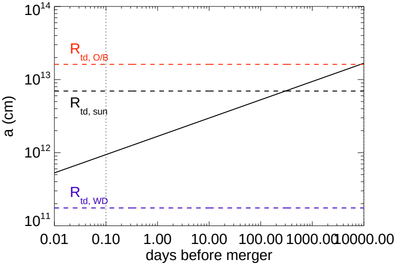
Applications

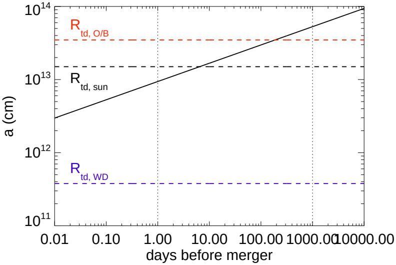
- formation mechanisms:
  - tidal capture of GC+IMBH
  - supermassive star formation in accretion disk
  - gas leaking from circumbinary disk
  - IMBH+MS star
- observables:
  - tidal disruption events
  - *hyper*-velocity stars
  - enhanced star formation
  - highly-shifted emission lines
  - accretion burst prior to merger
  - effect on gravitational waveforms

Tidal disruption of stars during inspiral

$$R_{\mathrm{td},*} = 2R_* \left(\frac{M_{\mathrm{BH}}}{M_*}\right)^{1/3}$$

$M_1 = 10^6 M_\odot,\ \mu_2 = 1/50$ $\qquad$ $M_1 = 10^7 M_\odot,\ \mu_2 = 1/50$





What do we do next—theory

- cosmological N-body plus hydro
- high-resolution N-body simulations of galactic nuclei
- Newtonian regime: grid-based code vs. geodesics/SPH
- good initial conditions for circumbinary disk
- full NR+MHD
- radiation post-processing

What do we do next—observations

- dual AGN: HST imaging, field integral spectroscopy
- binary AGN: SDSS + long-term spectroscopic followups
- pulsar timing: more pulsars, ~ 10 ns resolution
- afterglows: wide-field multi-band surveys
- cores/star clusters: HST imaging + hires spectra
- LISA counterparts/precursors: wide-field time domain surveys (Pan-STARRS, LSST, MAXI, WFXT, etc.)

Summary/Conclusions

EM signatures of BH mergers are valuable as:

- Probes of strong-field GR (mass loss, kicks)
- Probes of accretion disk properties
- Cosmological observations
  - $M_{\rm BH}$, $M_{\rm bulge}$, $\sigma_{\rm bulge}$ relationships
  - galaxy formation and evolution
  - SMBH growth (mergers vs. accretion)
  - mass/spin distribution functions
- PTA counterparts
  - nearby, massive, bright
  - extensive follow-up on human timescales
- LISA counterparts
  - distance ladder in a single step
  - luminosity-redshift to $\lesssim 1\%$
- LIGO counterparts: GW confirmation

Discussion Questions

is there gas?

can we see it?