Black Hole Coalescence: The Gravitational Wave Driven Phase

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UM Black Holes

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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
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  Hydrodynamics
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“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

\[ P_{\text{gas}} > P_{\text{rad}} \]

\[ \kappa_{\text{ff}} > \kappa_{\text{es}} \]

\[ t_{\text{GW}} < t_{\nu}(R_\lambda) \]

\[ R_\lambda(M=10^9 \text{ M}_\odot, P=1\text{ yr}) \]

Tanaka+ 11

\[ t_{\text{GW}} \sim R^4 \]

\[ t_{\text{inflow}} \sim R^{5/4} \text{ (gas)} \]

\[ t_{\text{inflow}} \sim R^{7/2} \text{ (rad)} \]

JS & Krolik 08
Time scales, con’t

vacuum binary merger is basically a solved problem

$t < 2005$: “Kip diagram”
vaccuum binary merger is basically a solved problem after 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)

- Galaxy mergers
- Dual AGN
- Galaxy cores (scouring)
- Circumbinary disks
- GW’s (pulsar timing)
- Variable accretion
- Enhanced accretion
- X-shaped radio lobes
- Off-centered/Doppler-shifted quasars
- Suppressed accretion
- X-ray/UV/IR afterglow
- Tidal disruption
- DM annihilation
- Bondi accretion
- Delayed quasar
- GRMHD
- LISA
- HCSSs
- Diffuse gas
- Occup. fraction
- M–sigma
- Accretion disks
- Stars
- Hot gas
- GWs
- Dark matter
- Dual AGN
- Binary quasars
- Accretion disks
- Dark matter
- Stars
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- Stars
- Hot gas
- GWs
- LISA
- GRMHD

Time since merger:
- $10^{-9}$ yr
- $10^{-6}$ yr
- $10^{-3}$ yr
- 0 yr
- $10^{3}$ yr
- $10^{6}$ yr
- $10^{9}$ yr
Diversity of Sources (observer)

- **galaxy mergers**
- **dual AGN**
- **galaxy cores (scouring)**
- **galaxy cores (recoil)**
- **off-centered/Doppler-shifted quasars**
- **HCSSs**
- **X–shaped radio lobes**
- **diffuse gas**
- **M–sigma**
- **tidal disruption**
- **DM annihilation**
- **Bondi accretion**
- **GW’s (pulsar timing)**
- **circumbinary disks**
- **variable accretion**
- **enhanced accretion**
- **X–ray/UV/IR afterglows**
- **GW’s**
- **GRMHD**
- **LISA**
- **suppressed accretion**
- **delayed quasar**
- **radio**
- **IR**
- **O/UV**
- **X–ray**
- **gam–ray**
- **GW**
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

<table>
<thead>
<tr>
<th>Analytic</th>
<th>Newtonian hydro</th>
<th>Relativistic hydro</th>
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<tbody>
<tr>
<td>Shapiro (2010)</td>
<td></td>
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Astro 2010 white papers

| Bloom et al. (2009)               | Phinney (2009)                         | NS mergers:                              |
| Miller et al. (2009)              |                                        | Ruffert et al. (1996)                   |

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Even small amount of gas leads to bright EM signal

energy content of gas dominated by gravitational potential:

\[ E_{\text{gas}} \sim \epsilon \Sigma R^2 \quad (\epsilon \approx 0.01 \text{ -- } 0.1) \]

cooling time for optically thick gas:

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

giving “universal” luminosity:

\[ \frac{dL}{d \ln R} \approx \epsilon^{1/2} R^{1/2} L_{\text{Edd}} \sim 10^{44} M_6 \text{ erg/s} \]

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:

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

MacFadyen & Milosavljevic (2008)
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

\[ \mu_2 = m_2/M = 0.2 \]

\[ \mu_2 = m_2/M = 0.02 \]

\[ \mu_{\text{crit}} \approx 0.0385 \]

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

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

\[ M_1 = 10^6 M_\odot, \mu_2 = 1/50 \]

\[ M_1 = 10^7 M_\odot, \mu_2 = 1/50 \]
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, $\sim 10$ 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
  - $M_{\text{BH}}, M_{\text{bulge}}, \sigma_{\text{bulge}}$ 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?