Black Hole Growth in Mergers: Predictions from Simulations

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BASS Workshop
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SMBH/galaxy co-evolution: the merger-driven paradigm

- Simultaneous growth of galaxy bulges and SMBHs
- (Self-)regulation of growth via stellar and AGN feedback
- Formation of SMBH pairs, mergers and recoils
Most AGN are not found in major mergers (ex: ~4% of SDSS AGN)

Not all (major) mergers trigger AGN

Many surveys find lack of connection between mergers & AGN (e.g., Cisternas et al. 2011, Kocevski et al. 2012, Simmons et al. 2012, Villforth et al. 2014, Rosario et al. 2015)

Major mergers do appear to trigger the most luminous AGN —> critical (dominant?) mode of BH growth

Selection effects are critically important, esp. merger stage, AGN luminosity, obscuration, & redshift

(Liu et al. 2011)
The merger-driven paradigm: where does it apply?

What triggers most AGN?

How did massive SMBHs (and stellar bulges) get their mass?

—> must consider selection effects
Modeling BH & galaxy evolution in the Illustris cosmological simulations

credit: M. Vogelsberger & the Illustris Collaboration

<table>
<thead>
<tr>
<th>redshift</th>
<th>4.24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time since the Big Bang</td>
<td>1.5 billion years</td>
</tr>
<tr>
<td>stellar mass</td>
<td>1.5 billion solar masses</td>
</tr>
</tbody>
</table>
Modeling BH & galaxy evolution with isolated merger simulations + dust radiative transfer

Merger simulation
t=0.06 Gyr
BH accretion in Illustris

All BHs

Sijacki et al 2014

Merging BHs

Blecha et al 2016
Accretion rates of merging BHs in Illustris vs TNG

Thomas et al. in prep.

Use observations to constrain feedback models?
Mergers trigger *luminous AGN* (especially at high redshift)

Edd ratio evolution during mergers in IllustrisTNG

Empirical $f_{\text{Edd}}$ & $L_{\text{bol}}$ measurements: bridge gap b/t sims & observations

Thomas et al. in prep.
(Late-stage) mergers trigger **luminous AGN**

![Graph](image1)

**Koss et al. 2012**

![Graph](image2)

**Fan et al. 2016**

![Graph](image3)

**Goulding et al. 2017**

**AGN fraction**

**Stellar mass (log $M_{\odot}$)**
(Late-stage) mergers trigger obscured, luminous AGN

\[ L_{\text{AGN}} > 10^{44} \text{ erg s}^{-1} \]

\[ N_H [\text{cm}^{-2}] \]

\[ t(\text{post-merger}) \text{ [Myr]} \]

\[ \text{projected sep. [kpc]} \]

Kocevski et al. 2015

Ricci et al. 2017a
(Late-stage) mergers trigger obscured, luminous AGN

Follow-up of Swift-BAT AGN:

SDSS/Kitt Keck AO mock HST @ z=1

Koss, LB et al. 2018 in review
Merger simulation
$t=1.23\ \text{Gyr}$
(Late-stage) mergers trigger obscured, luminous AGN

LB et al. 2018
Virtually all luminous quasars are selected via mid-IR colors.

Nearly 1/2 of moderate-luminosity AGN missed with common selection criteria.

More lenient cuts: much higher completeness (for $z < 0.5$), and very high reliability (for $z < 1$).

In mergers, starbursts with red mid-IR colors is accompanied by an AGN $\rightarrow$ no “true” contamination by SF.
Redshift evolution of WISE mid-IR color in mergers

![Graphs showing redshift evolution of WISE mid-IR color in mergers for different AGN luminosities.](image)
2-10 keV X-ray vs MIR AGN lifetimes

Newsome et al. in prep

Next steps: compare different sub-grid torus models (incl. evolution-dependent?), compare with observations
Uncovering dual nuclei in mid-IR selected AGN

Simulated WISE dual AGN:

Candidate WISE dual AGN:

SDSS

Chandra (ACIS-S 0.3-8.0 keV)

Satyapal et al. 2017
SMBH binary evolution

- Galaxy inspiral phase
- Dual SMBH inspiral phase
- Bound SMBH binary phase
- GW-dominated phase
- Dynamical Friction
- Stellar “loss cone” scattering
- Viscous gas disk drag
What happens in the BH binary phase?

Open questions:

• How long do SMBHBs take to inspiral & merge? do they merge?

• Do they accrete through all/some of that phase or not? If so, how can we find their signatures?
Modeling BH binary inspiral timescales

Kelley, LB, & Hernquist 2017a

DF: Dynamical Friction
LC: “Loss-Cone” Stellar Scattering
VD: Viscous Disk drag
GW: Gravitational wave emission
Modeling BH binary inspiral timescales

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Kelley, LB, & Hernquist 2017a
nHz GW background & BH coalescing fraction

Detecting GWs with Pulsar Timing Arrays:

- **GWB strain amplitude** depends weakly on host galaxy
- Pulsar timing arrays: **95% detection probability** of GWB in <10yr (Kelley, LB et al 2017b)
- **Coalescing fraction** varies widely; long lifetimes common
  - Important for **LISA** merger rates
  - need **EM constraints** on BHs in mergers!

*Kelley, LB, & Hernquist 2017a*
GW + EM constraints on SMBH binaries

**parsec-scale binary**

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**Rodriguez et al. 2006**
(See also: Burke-Spolaor 2011)

**milliparsec-scale binary candidates**

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**Eracleous et al. 2012**

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**Liu et al. 2015**

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**Sesana et al. 2017**

$\rightarrow$ future constraints from PTAs + LSST?
EM signatures of SMBH binaries

- Relativistic Doppler boost
- Hydrodynamic variability
- Disambiguation of variability?
- Dilution?
- Obscuration?

Farris et al 2015

Charisi et al 2018

Tang et al 2017

Charisi et al 2018
Predictions for detectable EM variability of SMBHBs from Illustris

• Kelley et al 2018 predict ~ 0.2 Doppler and 5 hydrodynamic binaries identifiable in CRTS

• 20 and 100 identifiable in 5-yr LSST
Modeling LISA event rates
Modeling LISA event rates

5yr observation time
10^4 MC realizations
1 Gyr inspiral delay
2.5x10^6 km arms

- 40% have at least 1 BH < 10^6 M☉
- 7% have both BHs < 10^6 M☉
- These would be excluded with standard mass cuts
- Currently implementing with Kelley et al. inspiral models

Michael Katz et al. in prep
BH Spin Evolution
(see talk by Mohammad Sayeb)

Gas-driven

GR precession

Roedig et al 2012
BH Spin Evolution
(see talk by Mohammad Sayeb)

- Gas-driven
- GR precession

Gravitational-wave recoil

Precessing LISA waveforms

- Precessing binary black hole inspiral waveform, \( m_1 = 0.5, m_2 = 5 \) solar masses;
  - \( i_1 = 0, i_2 = 0.99 \) (Kerr dimensionless spin parameter);
  - spin2 initially misaligned from initial orbital angular momentum by 60 degrees;
  - detector direction 140 degrees away from initial orbital angular momentum;
  - initial frequency is 2 \( f_{\text{orb}} = 40 \) Hz ending frequency is 2 \( f_{\text{orb}} = 4252 \) Hz.

soundsofspacetime.org
**Observability of recoiling AGN:** predictions from the Illustris simulations

- **Gas dynamics** aligns spins (lower $v_{\text{kick}}$), suppresses recoil trajectories
- Models + SDSS spectra suggest **some spin alignment occurs**
- Still predict **hundreds** of spatial offsets in large surveys
- **Time domain surveys** (Pan-STARRS, LSST) uniquely capable of finding recoils (see Kumar et al. 2015)
BASS observations vs. simulations: possible synergies

- BH masses, Edd ratios, multi-wavelength SED bolometric corrections — connection with simulations
- Comparison b/t X-ray and IR: constrain torus models / covering fractions
- Use EM observations of dual AGN / AGN in mergers to constrain BH inspiral models — critical for GW predictions!
- Searches for offset AGN
- TNG50 - dwarf galaxies, higher res modeling of merger dynamics, galaxy structure, feedback
- Future cosmological simulations: lower mass BH seeds — compare with local low-mass analogs
- Use high-res observations to constrain feedback models in sims
- Other ideas?