The Known Unknowns: predicting the landscape of LISA black hole sources

Kelly Holley-Bockelmann
Vanderbilt University and Fisk University
k.holley@vanderbilt.edu
Why can’t we predict a (robust) SMBH merger event rate?
Step 0: measure a black hole mass

Step 1: relate BH mass to host galaxy

Step 2: find evidence of binary black holes

Step 3: measure galaxy merger rate to constrain SMBH merger rate

Step 4: Sow SMBH seeds

Step 5: Model SMBH growth

Step 6: Model SMBH merger dynamics to get merger timescales

Step 7: Find the strain, SNR for each merger
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A Supermassive Black Hole for ‘Every’ Galaxy

Gultekin et al 2009 -- see also Gebhardt et al 2000; Ferrarese & Merritt 2000; McConnell+Ma 2013...

\[ R_{\text{sch}} = 2 \frac{G M}{c^2} = O(10^{-6}) \text{ pc} \]

\[ R_{\text{infl}} = \frac{G M}{\sigma^2} = O(10^0) \text{ pc} \]

\[ R_e = O(10^3) \text{ pc} \]

Ghez group, UCLA
Rule-breaker: Unassuming galaxy with 17 billion solar mass black hole!

van den Bosch et al. 2012
Rule-breaker: Unassuming galaxy with 17 billion solar mass black hole!
Heinze 2-10 is dwarf with a million solar mass black hole and there are SMBHs in bulgeless galaxies,

Reines et al. 2011
Sommers et al. 2012
Satyapal et al. 2014
...and in low surface brightness galaxies, like Malin 1...

Warning: viral masses — assume line width maps to velocity for Keplerian motion

$3 \times 10^6 \, M_{\odot}$ black hole here

Subramanian et al. 2015
Evidence of an intermediate mass black hole --- in the outskirts of a galaxy

$>500 \, M_\odot$, with stellar shroud!

Farrell et al. 2009; 2012
Newly discovered dark star clusters may contain IMBHs

Taylor et al. 2015; Bovill et al. 2016
Step 0: measure a black hole mass

Step 1: relate BH mass to host galaxy

**Step 2: find evidence of binary black holes**
See Dotti et al. 2012!

Step 3: measure galaxy merger rate to constrain SMBH merger rate

Step 4: Sow SMBH seeds (see Rossi and Latif talks!)

Step 5: Model SMBH growth

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Step 7: Find the strain, SNR for each merger
While there are certainly dual AGN,
Pan-Starrs PSO J334.2028+01.4075 — Periodicity caused by 542 +/- 15 day orbit of a 10^10 solar mass binary at 0.05 < q < 0.25 @ z=2.06 — separation of ~10 R_s!!

Liu et al. 2015
Pan-Starrs PSO J334.2028+01.4075 — Periodicity caused by 542+/− 15 day orbit of a $10^{10}$ solar mass binary at $0.05 < q < 0.25$ @ $z=2.06$ — separation of ~10 R$_s$!!

Liu et al. 2015

Not seen in the Catalina Real-time Transit Survey Graham et al. 2015
VLBI search OF ~3100 AGN, only 1 found to be consistent with a BBH

Burke-Spolaor 2011

Stay tuned! Time-domain astronomy will help here…
Sample bias can offset the normalization of SMBH relations.

Dynamical mass estimates themselves are uncertain by factors of 3-10 by including dark matter and galaxy shape.
Orientation changes the measurement of velocity dispersion, too

Bellovary, KHB, et al. 2014
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To build a massive black hole seed, you must battle fragmentation!

Once halo is polluted with metals, they really dominate cooling!
Lyman-Werner radiation from the first stars and black holes can dissociate H₂
Low mass halos bathed in Lyman-Werner Flux can form Direct Collapse BHs

$10^5 - 10^6$ solar masses

adapted from Zackrisson et al. 2012
Rare SMBH birthplaces in a uniform UV background

See also Agarwal et al. 2013; Akutalp et al. 2014
Cosmological Hydrodynamical Simulations of Direct Collapse Black Hole Formation

Dunn, KHB, Bellovary, Christensen
Surprises so far — several Direct Collapse Black Holes can form in a single halo

...and seeds can form in ‘high’ metallicity halos, too!
Step 0: measure a black hole mass

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Step 5: Use number of galaxy mergers to find the rate of SMBH mergers

Step 6: Find the strain, SNR for each merger
Most of the early SMBH growth is not from gas... ...and the gas that does fuel the SMBH is not from galaxy mergers

Sanchez, Bellovary and KHB 2016
We simulated the growth of MW-like SMBHs using cosmological N-body simulations

Massive central

Slowly sinking

Ejected
Light SMBHs (like our own) don’t assemble from equal mass (or even nearly equal mass) mergers after the dark ages, there are few major mergers.
Assembling a MW SMBH results in dozens of resolvable sources, mostly IMRIs, scaling to the universe, ~ 500 sources with SNR>30 for a 5 year mission.
Dwarf galaxies may also have central black holes.

This leads to a second class of IMRI.

Warning: BH growth depends on the hydrodynamic code

BHs grow less, take longer to merge

Gabor et al. 2015
Warning: BH growth depends on a feedback recipe

(!) box
Habouzit et al
2016
see also Dubois
2015
Warning: Over-zealous AGN feedback stifles BH growth (and star formation, too)

Volgelsburger et al. 2014
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Galaxy mergers sink black holes though dynamical friction

Separation: \(O(10^5)\) pc

Timescale: \(O(10^8)\) yr
Next: black holes sink closer via 3-body scattering.

Quinlan 1997; Sesana et al 2006, 2007

\[ a_h \equiv \frac{G \mu_r}{4 \sigma^2} \sim \frac{1}{4} \frac{q}{(1 + q)^2} r_h, \]

\( O(10) \) pc

\( > O(10^{10}) \) yr!**

**in a static spherical galaxy with permanent ejections and no resonances
The final parsec problem -- refilling a spherical loss cone takes $> t_{\text{Hub}}$.


$$a_h := \frac{G \mu_r}{4 \sigma^2} \sim \frac{1}{4} \frac{q}{(1 + q)^2} r_h,$$

$O(10)$ pc

**in a static spherical galaxy with permanent ejections and no resonances**
Final Parsec Problem? Not a problem for a non-spherical galaxy!

Expect $10^8 \, M_\odot$ Binary BHs to take less than 3 Gyr to coalesce in an equilibrium axisymmetric galaxy

Supported by NSF CAREER award and NSF MRI for GPU cluster
Axisymmetric galaxies have low angular momentum orbits that overfill the loss cone.

\[ \text{Li, KHB+Khan 2015} \]

\[ \sim 60\% \text{ of the stars within the inner 100 pc are saucers} \]
Now, let’s add rotation — and the black hole orbit shrinks faster.

Direct N-body code with GPU acceleration and 2.5 PN terms included.
Black holes *can* merge quickly…or not.

<table>
<thead>
<tr>
<th>galaxy type</th>
<th>black hole merger timescale</th>
<th>eccentricity in the gw regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>spherical</td>
<td>&gt; 15 Gyr</td>
<td>N/A</td>
</tr>
<tr>
<td>axisymmetric (c/a=0.75)</td>
<td>3 Gyr (t_{Hub}@z~0.4)</td>
<td>0.1</td>
</tr>
<tr>
<td>axisymmetric, rotating</td>
<td>1 Gyr</td>
<td>0.1</td>
</tr>
<tr>
<td>axisymmetric, counterrotating</td>
<td>100 Myr</td>
<td>~1</td>
</tr>
<tr>
<td>triaxial</td>
<td>O(10) Myr</td>
<td>large</td>
</tr>
<tr>
<td>Gas-Rich</td>
<td>10 Myr — 1 Gyr</td>
<td>~0.0</td>
</tr>
</tbody>
</table>
Latest advance: BBH merger in a cosmological volume — 10 Myr!

merger caused not by gas — by new star formation

Khan et al. 2016
~few Gyr SMBH merger times interestingly long -- subparsec dual BHs abound? Triple black holes less rare?

Need to add realistic merger times to semi-analytic models and simulations to help predictions for PTA, BH growth, circumbinary disk observational signals, and so much

*We need to calculate merger timescales for a realistic suite of galaxy models/interactions.*
Why can’t we predict an accurate SMBH merger rate?

We need to get robust SMBH masses.

We need to know the real SMBH-galaxy correlation.

We don’t know how black holes are born.

We don’t understand SMBH accretion and feedback (including secular mass growth from, e.g., stellar plunges).

We need to include accurate SMBH.
For more information:  P.S. Please cite generously!

KHB, Khan, Li 2015
Li, KHB, Khan, 2015
Khan, KHB, et al 2013
Bellovary et al. 2013
Sinha + HB 2012
HB, Wise + Sinha 2012
Palladino, HB, Morrison, Durrell, Ciardullo, Feldmeier, Wade, Kirkpatrick, Lowrance, 2012
Lang, HB, Bogdanovic, Sesana, Amaro-Seoane, Sinha, 2013
Micic, HB + Sigurdsson 2011
**HB, Micic, Sigurdsson + Rubbo 2010**
Micic, HB + Sigurdsson 2008
Micic, HB, Sigurdsson et Al 2007
Rogue Black Holes sit in the outer halo

see also Micic, KHB 2007, Bellovary et al. 2011

Slowly sinking