Supermassive black-hole binaries as gravitational-wave sources

“The disc migration issue: from protoplanets to supermassive black holes”
Cambridge, 22-24 May 2017
The status of LISA (2015-17 developments)

Massive BH mergers as GW sources for LISA:
- Event rates & parameter estimation
- Effect of BH spins
- High-redshift seeds and “delays” between galaxy and BH mergers

Massive BH binaries as PTA sources: environmental effects and synergies with LISA
Existing GW detectors

Pulsar Timing Arrays
Frequency windows

Figure from Moore, Cole and Berry 2015
The status of LISA

- ESA selected the “Cosmic Vision” L3 launch slot (2034) for theme “The Gravitational Universe”

- LISA Pathfinder mission a success (surprisingly stable)

- LISA design/mission not selected yet, options have been analyzed by Gravitational Wave Advisory Team (GOAT) collaboration with LISA consortium

2. Tamanini, Caprini, EB, Sesana, Klein, Petiteau, JCAP 04 (2016) 002: standard sirens
5. EB, Yunes and Chamberlain, PRL 116, 241104 (2016): multiband, tests of GR

- ESA call for mission adoption in Jan 2017, then industrial production (~10 yrs) which will make mission possible in ~2030 (?)
LISA configuration proposed to ESA, Jan 2017

6 links, 2.5 Gm arms, nominal 4 yr duration, up to 10 yr
Why massive BH merge

Figure from De Lucia & Blaizot 2007

Ferrarese & Merritt 2000
Gebhardt et al. 2000,
Gültekin et al (2009)

EB 2012
Figure credits: Lucy Ward
What links large and small scale?

Small to large: BH jets or disk winds transfer kinetic energy to the galaxy and keep it “hot”, quenching star formation (“AGN feedback”). Needed to reconcile ΛCDM bottom-up structure formation with observed “downsizing” of cosmic galaxies.

Disk of dust and gas around the massive BH in NGC 7052

Large to small: galaxies provide fuel to BHs to grow (“accretion”)
NSC: masses up to $\sim 10^7 M_{\odot}$, $r \sim pc$

BH binaries eject stars by slingshot effect and through remnant’s recoil ("erosion")

Erosion by BH binaries crucial to reproduce NSC scaling relations

$$M_{ej} \approx 0.7 q^{0.2} M_{bin} + 0.5 M_{bin} \ln \left( \frac{a_h}{a_{gr}} \right) + 5 M_{bin} \left( \frac{V_{kick}}{V_{esc}} \right)^{1.75} ,$$

Antonini, EB & Silk (2015)
Evolution of massive BHs difficult to predict because co-evolution with galaxies (c.f. $M-\sigma$ relation, accretion, jets, feedback, etc)

Purely numerical simulations impossible due to sheer separation of scales ($10^{-6}$ pc to Mpc) and dissipative/nonlinear processes at sub-grid scales

Semi-analytical model (EB 2012) with 7 free parameters, calibrated vs data at $z = 0$ and $z > 0$ (e.g. BH luminosity & mass function, stellar/baryonic mass function, SF history, $M-\sigma$ relation, etc)

EB 2012
Massive BH model’s uncertainties

- Seed model: light seeds from PopIII stars (~100 $M_{\text{sun}}$) vs heavy seeds from instabilities of protogalactic disks (~$10^5 M_{\text{sun}}$)

- No delays between galaxy and BH mergers, or delays depending on environment/presence of gas:
  - 3-body interactions with stars on timescales of 1-10 Gyr
  - Gas-driven migration on timescales $\gtrsim 10$ Myr
  - Triple massive BH systems on timescales of 0.1-1 Gyr

From Klein EB et al 2015
Model predictions

PopIII=light seeds, delays

Q3-d= heavy seeds, delays

Q3-nod= heavy seeds, no delays
Model predictions

PopIII=light seeds, delays

Q3-d= heavy seeds, delays

Q3-nod= heavy seeds, no delays
Detection rates

PopIII

Q3-d

Q3-nod
The effect of BH spins: frame-dragging in isolated BHs

- Mass behaves qualitatively like in Newtonian gravity
- Spin affects motion around BHs (“frame dragging”):

  - Innermost Stable Circular Orbit (i.e. inner edge of thin disks)
  - Efficiency of EM emission from thin disks

42% for $a=1$, 32% for $a=0.998!$
The effect of BH spins: frame-dragging in binaries

Spin-orbit coupling or “hang-up” effect: for large spins aligned with L, effective ISCO moves inward ...

Figures from Lousto, Campanelli & Zlochower (2006)
The effect of BH spins: frame-dragging in binaries

... and GW “efficiency” gets larger

Spins strongly affect GW signals!

Figure from EB, Morozova & Rezzolla (2012)
The effect of BH spins on the waveforms

- GW amplitude at merger increases with spins (because ISCO moves inward for larger spins)
- Spin precesses around total angular momentum $J = L + S_1 + S_2$
- Precession-induced modulations observable with GW detectors:
  - Increase SNR and improve measurements of binary parameters (e.g. luminosity distance and sky localization)
  - Allow measurements of angle between spins

EOB waveforms for BH binary with mass ratio 1:6 and spins 0.6 and 0.8, from Pan et al (2013)
The Bardeen Petterson effect
(c.f. also Massimo Dotti’s talk)

- Coupling between BH spin $S$ and angular momentum $L$ of misaligned accretion disk + dissipation
- Either aligns or anti-aligns $S$ and $L$ in $\sim 10^5$ yrs (for MBHs) $\ll$ accretion timescale
- Anti-alignment only if disk carries little angular momentum ($L < 2S$) and is initially counterrotating

$L > 2S$

$L \ll 2S$
Errors on individual masses/spins

red = popIII, orange = Q3-d, green = Q3-nod
thick = six links (L6), thin = four links (L4)

Relative loss relative to NGO (N2A1MkL4)

Provides information about
properties of BH accretion and
BH mass history

From
Klein EB et al
2015
Errors on spin inclinations and final spin

From Klein EB et al 2015

red = popIII, orange = Q3-d, green = Q3-nod
thick = six links (L6), thin = four links (L4)

Relative loss relative to NGO (N2A1MkL4)

Provides information about interactions with gas (Bardeen-Petterson effect) and ringdown tests of GR
Cosmography ("standard sirens") and probes of massive BH formation

From Klein EB et al 2015

red = popIII, orange = Q3-d, green = Q3-nod
thick = six links (L6), thin = four links (L4)

Relative loss relative to NGO (N2A1MkL4)
GWs provide measurement of luminosity distance (though degraded by weak lensing) but not redshift

In order to do cosmography in a non-statistical way, we need redshift

Electromagnetic (spectroscopic or photometric) redshift measurement needs presence of gas, e.g. radio jet+ follow-up optical emission

From Tamanini et al 2016
What can we learn from PTA limits?

Why are we seeing nothing?

Predictions assume:
- GW driven binaries
- Circular orbits
- Efficient formation of bound massive BH binaries after galaxy mergers
- $M-\sigma$ relation

Loopholes:
- Binaries may merge faster than expected based on GW emission alone (hence less time in band)
- Eccentric binaries (more power at high frequencies) due e.g. to strong environmental effects/triple systems
- Last pc problem (binaries stall)
- $M-\sigma$ relation may be biased

Figure courtesy of A. Sesana
What can we learn from PTA limits?

- PTAs sensitive to massive BH mergers like LISA, but larger masses
- Agreement among theoretical models of target massive BH population

EB 2012 vs Illustris

Figure courtesy A. Sesana
The nightmare scenario, aka the final-pc problem

- What if binaries stall at separations $\gtrapprox$ hardening radius? (i.e. no loss cone replenishment and 3-body interactions with stars become inefficient)

- Model A: all binaries stall 13 Gyr before merger ($a = a_{GW}$)
  Model B: all binaries stall at $a = \max(a_h, a_{GW})$
  Model C: all binaries stall at $a = a_h$

- In model C, binaries with $q \lesssim 1.e-3$ merge in a Hubble time because $a_h < a_{GW}$

50 pulsars with timing accuracy of 30 ns and 10 yrs observation time (Dvorkin & EB 2017)

cf Irina Dvorkin's talk
The nightmare scenario, aka the final-pc problem

SNR, timing accuracy = 30 ns

Model A

Model B

Model C
The nightmare scenario, aka the final-pc problem

If long delays, triple systems will naturally form as a result of later galaxy mergers, which will favour mergers via Kozai–Lidov resonances (periodic exchange between eccentricity and orbital inclination).

\[ t_{KL} \approx \frac{a_{out}^3(1-e_{out}^2)^{3/2}\sqrt{m_1+m_2}}{G^{1/2}a_{in}^{3/2}m_3} \approx 2 \times 10^6 \text{ yrs}, \]

\[ m_1 = m_2 = m_3 = 10^8 \text{ M}_\odot, \ a_{in} = 1 \text{ pc}, \ a_{out} = 10 \text{ pc and } e_{out} = 0. \]

PN 3-body simulation in a stellar environment, with \( m_1=1.\text{e}8 \text{ Msun}, \ m_2=3.\text{e}7 \text{ Msun}, \ m_3=5.\text{e}7 \text{ Msun} \) (Bonetti, Haardt, Sesana & EB 2016)
How many triple-induced mergers?

red: $M_{\text{tot}} < 10^4 \, M_{\odot}$; blue: $10^4 < M_{\text{tot}} < 10^8 \, M_{\odot}$; green: $M_{\text{tot}} > 10^8 \, M_{\odot}$

What if delays are infinite (nightmare scenario)?

Preliminary!
Conclusions

LISA main science goal is to reconstruct cosmological merger history of massive BHs, achievable with not-too-descoped configurations (6 links, 2.5 Gm arms, >4 yrs mission)

Uncertainties about seed model and delays (final-parsec problem) but we expect tens to hundreds of detections

Synergies with PTAs experiments

LISA’s science goal best ESA’s decision on final design by 2017 so as to allow launch in ~2034 or before
Thank you!