Deciphering the Astrophysics behind the Discovery

MONICA COLPI
Department of Physics G. Occhialini
University of Milano Bicocca, Italy

9-12 October 2018
**HERE IS THE BEAUTY!**

**THE MERGER OF TWO PURELY GEOMETRICAL OBJECTS**

\[
3.6^{+0.5}_{-0.4} \times 10^{56} \text{ erg/s}
\]

\[
3.0^{+0.5}_{-0.5} M_\odot c^2
\]

The LIGO and VIRGO Scientific Collaboration
BLACK HOLE COALESCENCE - UNIVERSALITY - SIMPLICITY

initial state

external parameters

final state

\[ m_{BH,1}, m_{BH,2}, q = m_{BH,1}/m_{BH,2}, S_{BH,1}, S_{BH,2} \]

spins and mass ratio can vary widely in LISA sources

distance, sky position, orientation of the orbit, polarization \[ \Phi, t_{coal} \]

\[ M_{BH,f}, S_{BH,f} \]

15-dimensional parameter space

BLACK HOLE COALESCENCE - HYDROGEN ATOM (classical!!)
\( (10^6, 10^6) \, M_\odot \quad 10^4 \, M_\odot c^2 \)

THE COALESCENCE OF MASSIVE BLACK HOLES

\[
f_{\text{gw}} = \frac{1}{\pi} \left( \frac{GM}{a} \right)^{1/2}
\]

\[
f_{\text{coal}} = \frac{1}{(\pi 6^{3/2})} \frac{c^3}{GM}
\]

\[
t_\odot = \frac{GM}{c^3}
\]

\[
f_\odot = \frac{c^3}{GM}
\]
What is the origin of the supermassive black holes and how fast do they grow?

Do “seed black holes” exist?
Black Holes - Universe

hidden universe of black holes yet unexplored

Start (mass distribution)

sBHs

GW150914

RGG118

SgR A*

J0100+2802

QSOs

z \sim 7

SEEDS

J2150-0551

M/M_\odot

a fil rouge (only stars make black holes) ? genetic divide?
Black Holes in the High Redshift Universe - POP III relics - “LIGHT SEEDS”

$10^2 < \frac{m_{\text{BH}*}}{M_{\odot}} < 300$

$Z \lesssim 10^{-4}$

do they pair in close binaries in situ?
Black Holes - new, yet unseen objects - “HEAVY SEEDS”

$$T_{GR} = 4 \times 10^9 \left( \frac{M}{10^4} \right) \, \text{K}$$

$$\rho_{GR} = 2 \times 10^4 \left( \frac{M}{10^4} \right)^{7/2} \, \text{gr cm}^{-3}$$

Direct monolithic collapse of Pop III supermassive stars in atomic cooling halos illuminated by UV radiation

**References:**
- Agarwal 2018
- Haemmerlé+2018
- Schleicher+2013
- Hosokawa+2913
- Pezzulli_2016
- Omukai 2001
Black Holes: collisional runaway of stars, Pop II clusters @z~10

Formation of runaway stars in the stellar clusters

\[ m_{\text{runaway-stars}} \approx 10^{3-4} M_\odot \]

\[ z \approx 7 \]

GW150914, RGG118, SgR A*, J0100+2802

Katz 2018
Devecchi + 2012
Schleicher+2018
• LISA

1 AU (150 million km)

Earth

2.5 million km

19 – 23°

60°
\[ M_{\text{chirp}}^{\text{obs}} = (1 + z) M_{\text{chirp}} \text{source} \]
- LISA horizon extends deep into the epoch of formation of the earliest black holes
- LISA traces the black hole cosmic swift drift to higher masses through accretion & mergers - low mass tail of the supermassive black holes
- spin and mass measurements are carried on with high precision
MOCK DATA

- cosmic dawn
- reionization epoch
- cosmic high noon

- GRBs
- Galaxy
- QSO
- AGN

- Mock data
- Contour lines of constant SNR

q = 0.2

- MW BH
- "Seed" black holes

M_{rest-frame} (M_\odot)

- 10^1
- 10^2
- 10^3
- 10^4
- 10^5
- 10^6
- 10^7
- 10^8
- 10^9

- 1
- 2
- 3
- 4
- 5
- 6

- 0.1
- 0.2
- 0.3
- 0.4
- 0.5
- 0.6

- 1
- 2
- 3
- 4
- 5
- 6
How to interpret this MOCK DATA file?

- DOMINATED BY THE DEGENERACY OF MODELS
- REAL HEAVY SEEDS?
- LIGHT SEEDS (POP III) + ACCRETION?
- RUNAWAY STELLAR COLLISIONS?

ET + LISA can break this degeneracy
Black holes forming in pristine halos and pairing during halo-halo mergers
“cosmologically-driven mergers”
NO DELAY is included here
mass and spin are modeled by accretion and merger

- Spin increases from 0 to 1 after accreting (for prograde accretion) \( \sqrt{6} M_{\text{BH,initial}} \)
- Spin decrease from 1 to 0 after accreting (for retro-grade accretion) \( \sqrt{3/2} M_{\text{BH,initial}} \)
- Accretion torques lead to fast re-orientation of BH (disc-spin alignment)
- Isotropic versus coherent accretion shape the spins in relation to the environment and feeding process
- Mergers make two coalescing black hole spin up to 0.6578
\[
\frac{dM_{\text{BH}}}{dt} = (1 - \eta)M \frac{\dot{c}}{c} = (1 - \eta)\left( \frac{f_{\text{Edd}}}{\eta} \right) \frac{M_{\text{BH}}}{\tau_S},
\]

\[
\tau_S = 45\varepsilon_{0.1} \text{ Myrs}
\]

\[
\frac{dJ_{\text{BH}}}{dt} = \dot{M} \frac{GM_{\text{BH}}}{c} \Lambda_{\text{isco}} \hat{l}(R_{\text{isco}}) + \frac{4\pi G}{c^2} \int_{\text{disk}} \frac{L \times J_{\text{BH}}}{R^2} dR,
\]

\[
J_{\text{disk}}/J_{\text{BH}}
\]

\[
\tau_{\text{warp}} < \tau_{\text{al}} < \tau_{\text{acc}} < \tau_{M_{\text{BH}}} \sim \tau_{\text{spin}}.
\]
BH accretes a few times its initial mass (`accretion episode mass`es). The spin modulus decreases because over a single the transition between phases I and II occurs at smaller BH

...of anisotropy parameter

Figure 6. Evolution of the BH spin magnitude shows the evolution of the BH spin... `M_\text{BH} [M_\odot]`.

LISA black holes might be highly spinning regardless the accretion mode

Dotti, Colpi+ 2013
Sesana+ 2015
Tendency to align with the angular momentum of the circum-nuclear disc
cosmic dawn

reionization epoch

cosmic high noon

MOCK DATA

CONTOUR LINES OF CONSTANT SNR

MOCK DATA

GRBs

Galaxy

QSO

"seed" black holes

MW BH

AGN
cosmic dawn

reionization epoch

cosmic high noon

LOW REDSHIFT EVENTS
the scale of gravitational-wave-driven inspiral is minuscule compared to galactic dimensions

delays between formation of the binary and coalescence

\[ t_{\text{coal}} = \frac{5}{256} \frac{c^5}{G^3} \mathcal{G}(e)(1 - e^2)^{7/2} \frac{a^4}{\nu M_B^3} \]

<table>
<thead>
<tr>
<th>( z = 15 )</th>
<th>( \nu^{1/4} 2.5 \times 10^4 , R_G )</th>
<th>( \nu^{1/4} 1.4 \times 10^4 , R_G )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{\text{cosmic}} = 0.27 , \text{Gyr} )</td>
<td>0.25 mparsec</td>
<td>1.4 mparsec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( z = 3 )</th>
<th>( \nu^{1/4} 4 \times 10^4 , R_G )</th>
<th>( \nu^{1/4} 4.8 \times 10^4 , R_G )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{\text{cosmic}} = 2.16 , \text{Gyr} )</td>
<td>0.4 mparsec</td>
<td>5 mparsec</td>
</tr>
</tbody>
</table>

\[ a \propto \nu^{1/4} M^{3/4} \]
THE LONG JOURNEY TRAVELLED BY MASSIVE BLACK HOLES IN MAJOR MERGERS (1:4)

II. BINARY FORMATION & HARDENING

III. GW DOMAIN

I. PAIRING

HUBBLE TIME

log \left( \frac{t}{t_H} \right)

0.001 pc

1 pc

micro-pc

migration in a gaseous disc

merger of host galaxies on 10-100 kpc scales

1-10 kpc

scattering off single stars

1 Gyr
black hole dynamics in massive circum-nuclear gas discs on \(\sim (100 - 1)\)pc

\[
M_{\text{disc}} = 10^8 M_\odot \\
M_{\text{BH,1}} = 10^7 M_\odot \\
M_{\text{BH,2}} = 5 \times 10^5 M_\odot
\]

Fiacconi+2013, Souza Lima+2016, Tamburello+2016
• fragmentation from inside out occurs on a timescale smaller than the orbital decay time
• dense gaseous clumps form, interact, merge to form fewer and larger clump, and migrate to the centre
• clumps can have masses comparable or larger than the black hole masses
• high density contrast leading to a completely different dynamics

Souza Lima+2016, del Valle+2015, Fiacconi+2013
The shortest timescales for the orbit of the secondary BH to fall under the one-pc scale separation from the central BH are observed in the adiabatic runs (top panel). Almost all the other runs that include gas cooling lead to prolonged, if present, orbital decay. The exception is run CSFSN (bottom panel), in which an encounter between the secondary BH and an overdense region of gas caused a relatively short decay time. Run CSFSNBF was stopped before 60 Myr due to computational limitations.

The diffuse background gas is also affected by torques, which produce a global inward flux of mass and make the CND more centrally concentrated. This reflects the nature of self-gravity, which can be described by an effective viscosity acting throughout the disk even in absence of fragmentation (Lin & Pringle 1987).

In run NAC (see Table 1), within 10 Myr, the inner 25-pc region goes from enclosing less than 20% of the total mass of the disk and being smooth to having more than 50% of the total disk mass in 3 clumps, one of about $3.19 \times 10^7 M_\odot$ enclosing the primary BH, another one of about $1.88 \times 10^7 M_\odot$ (heavier than the primary BH itself) at a distance of about 8 pc center to center (each have a radius larger than 1.5 pc), and the third one of about $6.7 \times 10^6 M_\odot$, still much heavier than the secondary BH, with respective densities $\sim 1.5 \times 10^8$, $\sim 5 \times 10^8$ (during this time, the secondary BH is always outside this inner region; see Figure 1).

Figure 6 shows the distribution of clump masses at different times (0.5–5 Myr) normalized to the mass of the secondary BH, which is almost constant during this time range in the runs shown in the figure (NAC, CSFSN, and CSFSNBF; see Table 1). In run NAC, especially after 3–5 Myr, there are more than 10 clumps with masses from commensurate to ten times more massive than the secondary BH. As discussed in Fiacconi et al. (2013) and Roškar et al. (2015), clumps with masses comparable to or larger than the mass of the secondary BH can have a dramatic effect on the latter, with direct hits or even repeated softer perturbations. At the same time, Figure 6 shows that most of the clumps have masses about the same or less than the secondary BH, namely close to or

- increase in the sinking time
- no-circularization
- scattering off the disc plane - postponed merger
- rare cases in which the secondary black hole is drag inside a clump rapidly to the centre
- spread in the delay times (stochastic dynamics): 2–100 Myrs
type II migration in a circum-binary disc

- black holes deposit orbital angular momentum exciting both leading and trailing spiral waves opening a gap of twice the size of the binary separation

Courtesy by Zoltan Haiman +2017

Kocsis+ 2007,2012; MacFadyen+2008; Roedig et al. 2011,12,14; D’Orazio et al. 2013; Farris et al. 2015; Dunhill et al. 2015; Tang et al. 2017; Maureira-Fredes 2018; Dotti+2015
• turbulence and gravitational torques maintain the contact between the disc and the black hole
• the two black holes “migrate” inwards
• the gap “follows” the binary
• mini discs and not empty cavity
Fig. 10 Residence time $t_{\text{res}}$ of equal-mass black hole binaries, embedded in a steady circum-binary disc, as a function of the black hole separation (in units of $2GM/c^2$), as computed in Ref. 1. The top $x$-axis label refers to the Keplerian relative orbital velocity of the black holes in the binaries. The four curves correspond to binaries with total masses of $10^3M_\odot$, $10^5M_\odot$, $10^7M_\odot$, and $10^9M_\odot$ as labeled. The large dots denote the critical radius beyond which the assumed circum-binary Keplerian disc is unstable to fragmentation. Similarly, triangles denote radii beyond which the disc may be susceptible to ionisation instabilities (the gas temperature falls below $10^4K$). In each case, blue/red colors indicate whether the disc mass enclosed within the binary's orbit is larger/smaller than the black hole mass $M_\bullet$. The dotted/dashed/solid portion of each curve indicates the outer/middle/inner disc region.

Note that in the disc-dominated regime (blue segments) the binary residence time is $\sim 10^9$ yr, while it decreases below $\sim 10^7$ yr for all binaries, i.e. independent of their mass, at the entrance in the stable region of a circum-binary disc (red dots). Courtesy of Ref. 1.

Despite these studies, we are nonetheless far from having a reliable estimate of the migration timescale in circum-binary discs under a variety of conditions, given the rich physics involved.

6 Gap opening and/or maintenance of the inner cavity around massive black holes have been seen in numerous numerical simulations of both Keplerian and self-gravitating circum-binary discs. But interestingly, recent 2D and 3D simulations have demonstrated that the binary+disc system contains as many as three discs and that these discs may persist being constantly fed by gas flowing through the gap. The three...
electromagnetic counterparts

- DUAL AGN (NGC6240)
- BINARY AGN long search for and still under search
- EM-counterpart @ coalescence -kseconds prior merging

\[ \Delta \Omega \approx 0.5 \text{deg}^2 \rho_3^{-7/4} \]

\[ \rho_3 \rightarrow \text{SNR} = 10^3 \]
Summary

- The gravitational universe promises many new discoveries
- New way of observing black holes: binary and GW signal
- Study of the EM signature of a binary coalescence events
- Search for strategies to recognize these transient events
- Search for synergies with Athen
- ... please join the effort
- ............ please join the effort in understanding the dynamics critical for assessing the rate and the binary black holes mass spectrum
black hole dynamics is a very complex problem

presence of a massive **stellar cusp** leads to swift coalescence (z-dependent? wait until z~4-5?)

presence of large inflows of gas produce scatter in the delay times

setting the “clock” is both a cosmological and local problem

it is still difficult to quantify the level of broadening of the time delay distribution in the formation of ET-LISA coalescing binary black holes: 10 Myrs - 4 Gyrs
ANCILLARY SLIDES
portrait of an isolated gas-rich major (1:4) merger

Clock: time "zero"

70x70 kpc box
1:4 merger between two disc galaxies
gas fraction 30%

Capelo+2014

$M_{BH,\text{primary}} = 3 \times 10^6 \, M_\odot$
$M_{\text{halo}} = 2.2 \times 10^{11} \, M_\odot$; $M_{\text{bulge}} = 2 \times 10^9 \, M_\odot$
$M_{\text{disc,}*, \text{gas}} = 6 \times 10^9 \, M_\odot$; $M_{\text{disc,} \text{gas}} = 3 \times 10^9 \, M_\odot$
black hole dynamics is a very complex problem

presence of a massive stellar cusp leads to swift coalescence (z-dependent? wait until z~4-5?)

presence of large inflows of gas produce scatter in the delay times

setting the “clock” is both a cosmological and local problem

it is still difficult to quantify the level of broadening of the time delay distribution in the formation of ET-LISA coalescing binary black holes: 10 Myrs - 4 Gyrs
primary black hole

secondary black hole

Capelo+2014
portrait of a cosmological merger

$M_{1,\text{halo}} \lessapprox 10^{13} M_\odot$ at $z = 0$

Figure 1. Group environment of the galaxy merger. The left panel shows a mock UVJ photometric image of the merger, and the red and blue dots mark the position of the primary and secondary BH, respectively. Lengths are in physical coordinates.

Figure 2. From left to right: time evolution of the galaxy merger after the beginning of the re-sampled, higher-resolution simulation. Each panel shows a mock UVJ photometric image of the merger, and the red and blue dots mark the position of the primary and secondary BH, respectively. Lengths are in physical coordinates.

- first ab initio simulation of a galaxy group @ z=3.5 from Argo cosmological simulation
- identification of the two main spirals undergoing a major merger (1:3.6 mass ratio) on a nearly parabolic orbit with co-rotating stellar discs inclined by 67 degrees
- gas fractions of about 10%
- splitting procedure to attain a force resolution of 5 pc - Direct N-Body code (mass resolution 6000 gas, 10,000 stars, 100,000 dark matter)

\begin{align*}
m_{1,\text{BH}} & = 10^8 M_\odot \\
m_{2,\text{BH}} & = 3 \times 10^7 M_\odot \\
M_{2,*} & \sim 10^{10} M_\odot \\
M_{1,*} & \sim 3.6 \times 10^{10} M_\odot \\
M_{\text{halo}} & \sim 10^{13} M_\odot \quad @ \quad z = 0
\end{align*}

Khan, Mayer, Fiacconi 2016
II. (a) pairing phase

- gas inflows in the inner 500 pc from cosmological streams are conducive to intense bursts of star formation around the secondary black hole
- the black holes are surrounded by a stellar cusp which enhances their “effective mass” - the orbital decay is governed by dynamical friction of the stellar cusps

Effective black hole mass enhanced by an episode of star formation
nuclear inflows of gas and episodes of star formation in the vicinity of the black holes are instrumental in creating the conditions for rapid pairing as they enhance the effective mass of the black hole and thus the dynamical friction drag

provide the reservoir of stars for the **slingshot mechanism** to become effective in the triaxial potential of the new galaxy

stars are “key players” for the merger to stay on clock with the **“help” of gas:** having a higher degree of dissipation/ability to lose angular momentum gaseous stream lead to formation of stellar cusps

just a single simulation with “massive” black holes