Influence of **dynamics** and **metallicity** on the formation and evolution of **black-hole binaries** in **star clusters**

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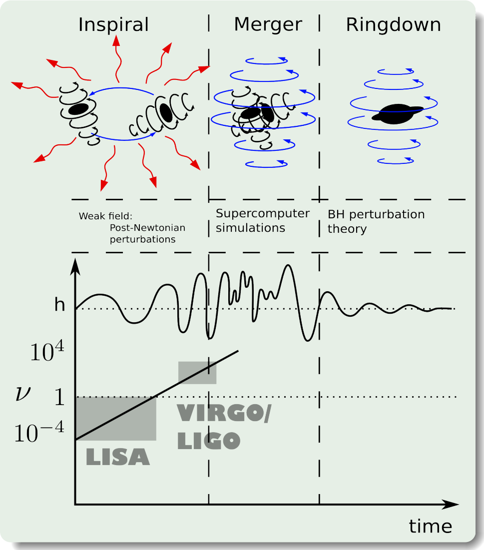
Gravasco, W2 workshop
Paris, 2013-11-08

Outline

Why DCOBs?

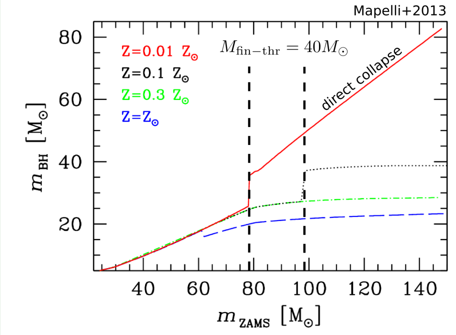
- DCO binaries during inspiral and merger events produce **GWs** we could observe in the near future
- Simulations provide theoretical **models** to interpret Advanced **Virgo/LIGO** upcoming data
- Key quantities:
  - **Number** of DCOBs
  - BH **mass** spectrum
  - Binary **orbital properties**



Why stellar evolution and metallicity (Z)?

- Massive stars **lose mass** by stellar winds
- Winds efficiency **depends** on **metallicity**
- Stars with $M_{\rm fin} \geq 40 M_{\odot}$ are expected to collapse to a BH **without SN explosion**

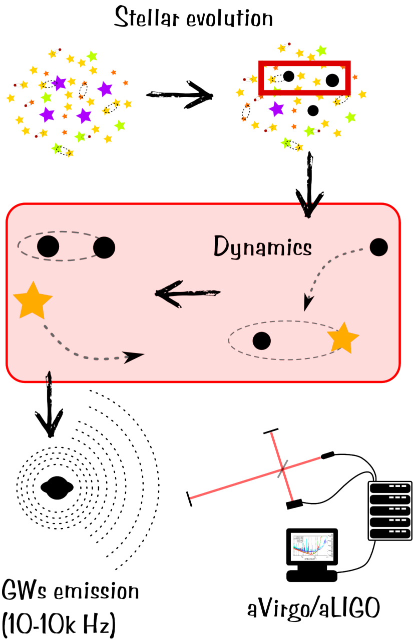
  (Fryer 1999, Fryer&Kalogera 2001)
- BHs formed from direct collapse are **more massive** than BHs formed from SN
- Metal-poor stars lose less mass by stellar winds $\Rightarrow$ more likely to collapse to BH directly



Why dynamics? Why YSCs?

- **YSCs** are **birthplace** for $> 80\%$ of stars in the local universe (Lada&Lada, 2003)
- (Collisional) YSCs are
  - young (< 100 Myr)
  - relatively massive ($10^3 - 10^7 M_\odot$),
  - dense ($10^3 - 10^6 \star / pc^3$)

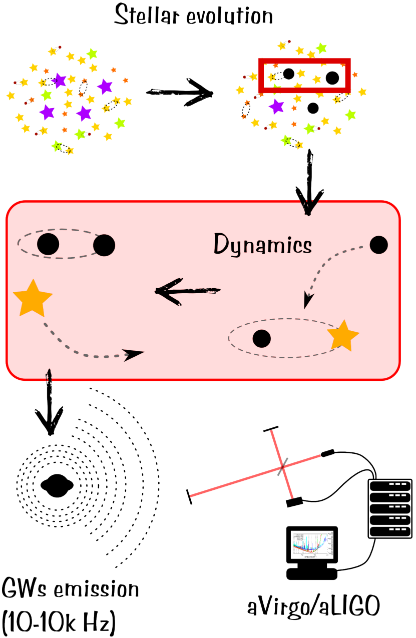
  groups of stars
- YSCs are sites of **intense dynamical activity**: central $t_{\rm relax} < 10$ Myr



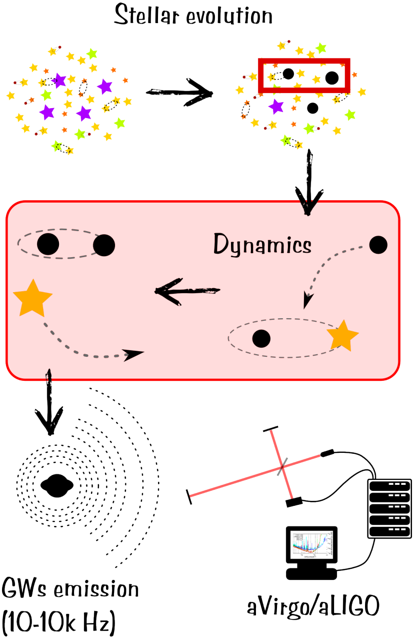
Why dynamics? Why YSCs?

- Focus on **3-body encounters**: close encounters between a single object and a binary
- If kinetic energy is tranferred from the binary to the single object $\Rightarrow$ SMA decrease (**hardening**)
- **"Hard" binary**: $\frac{Gm_1m_2}{a} \geq \frac{1}{2}\langle m\rangle\sigma^2$
- Hard binaries tend to become harder, soft binaries tend to become softer as effect of three-body encounters

  (Heggie 1975)
- If $m_{\rm single} \geq m_2 \Rightarrow$ the single star can take the place of one of the stars in the binary $\Rightarrow$ **exchange**



Why dynamics? Why YSCs?



- **Dynamics** enhances the formation of hard compact-object binaries (exhanges also produces very high eccentricity binaries)
- Key processes:
  - **mass segregation**
  - 3-body **exchanges**
  - **hardening**

Tools

- 200 N-body realizations of the same cluster for each $Z = 0.01, 0.1, 1Z_\odot$
- **StarLab**: Kira (GPU) + SeBa (CPU)
  (Portegies Zwart et al. 2001)
- Our simulations combines **dynamics + up-to-date recipes for Z-dependent stellar evolution**
- Custom recipes:
  - accurate **metallicity-dependent** stellar evolution (Hurley et al. 2000) and stellar winds (Vink et al. 2001; Vink & de Koter 2005; Belczynski et al. 2010)
  - the possibility of massive BHs formation by **direct collapse** (Fryer et al. 2012; Mapelli et al. 2013)

600 simulations

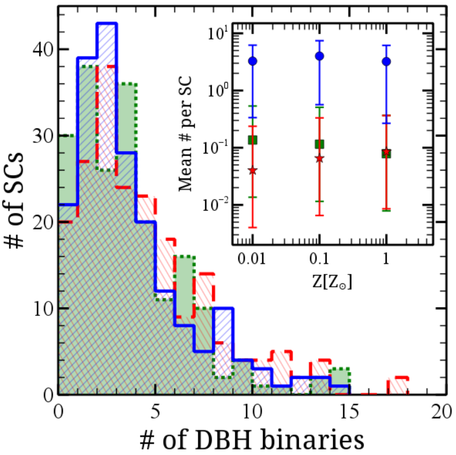
Parameter	Value
W_0	5
N_*	5500
$M_{\rm tot}$	$\sim 3500 M_\odot$
$r_{\rm c}$ [pc]	0.4
$c = r_{\rm t}/r_{\rm c}$	1.03
IMF	Kroupa (2001)
$m_{\rm min}$ [$M_\odot$]	0.1
$m_{\rm max}$ [$M_\odot$]	150
$f_{\rm PB}$	0.1
Z [$Z_\odot$]	0.01, 0.1, 1
Sim. time	100 Myr

MW typical, e.g. Orion Nebula Cluster

DCOB population

- DBH distribution
- Mean number of DBHs: ~ 3
- Max number of DBHs: 18
- # NS $\sim$ 4 # BH but
- # DBH $\sim$ 10 # DNS due to **dynamics**
- Negligible **dependence on Z**, but... (see after)

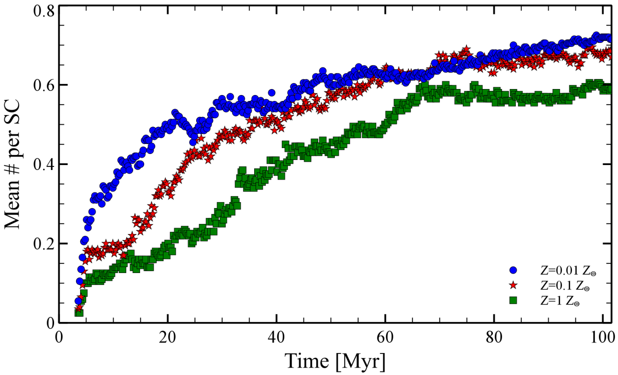
Ziosi et al., in prep



DBH population in time

Low-Z case vs higher metallicities:

- Build up the DBH population **before** high-Z case
- Higher DBH mass allowed ⇒ **earlier** DBHBs **formation**
- **But** mean # and mean # in time of DBHs do not agree
- Higher DBH mass allowed ⇒ more stable binaries & **longer lifetime**



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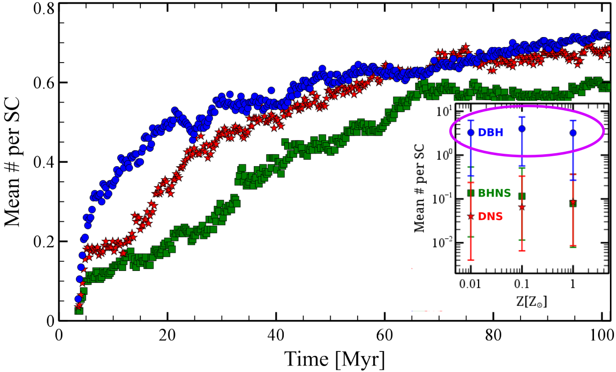

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Exchanges & mean DCOB life time

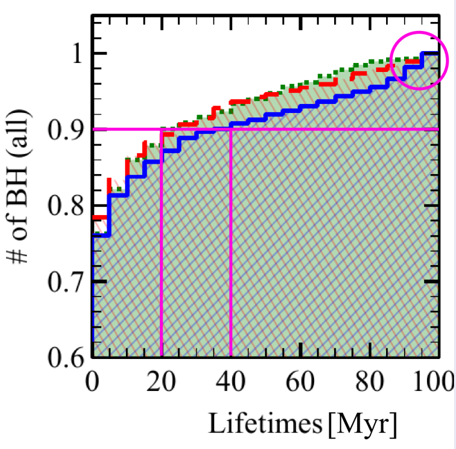
- Z=0.01 $Z_\odot$ DBHBs live longer than at higher Z **but** the avg number of exchanges is similar
- Z=0.1, 1 $Z_\odot$ DBHBs tend to **break-up**
- DNS are 10 times less numerous but are much **more stable**

Avg exchanges per CO and Z

Type	$0.01Z_\odot$	$0.1\ Z_\odot$	$Z_\odot$
DBH	9.92	9.91	10.14
DNS	0.00	0.5	0.26

- **97%** of all the DBHBs come from **exchanges**

Distribution of DBHBs lifetimes



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Orbital properties

- Distribution of orbital parameters at minimum semi-major axis
- Critical for **coalescence** times and mergers **detection**
- SMA and period span a **wide range**
- Eccentricity follows the **thermal distribution** $f(e) \propto 2e$ but
- excess in $e \sim 0$: **GW** and tidal **circularization**
- **DNS** (grey) are 10 times less numerous but have small SMA and short periods

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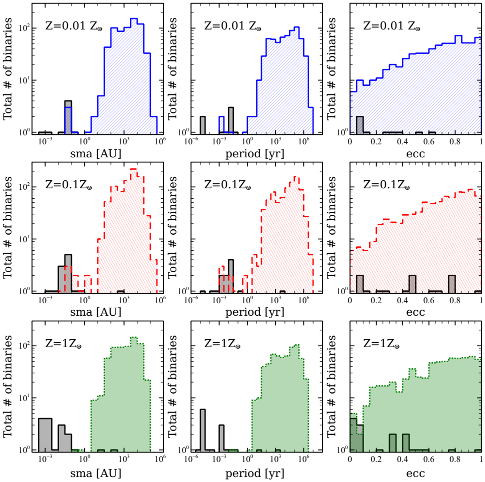

Masses

- High BH masses because of **direct collapse** at low metallicity
- **Chirp mass** $m_{\mathrm{chirp}} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$
- Why chirp mass:
  - $\nu_{\mathrm{GW}} \propto m_{\mathrm{chirp}}^{-5/8}$, $h_{\mathrm{GW}} \propto m_{\mathrm{chirp}}^{5/3}$
  - So from observations we can reconstruct m_{chirp}
  - In our model m_{chirp} strongly depends on Z
    $\Rightarrow$ Z-dependent BH mass model test
- **But**: in black chirp mass distribution of the best merger-candidates

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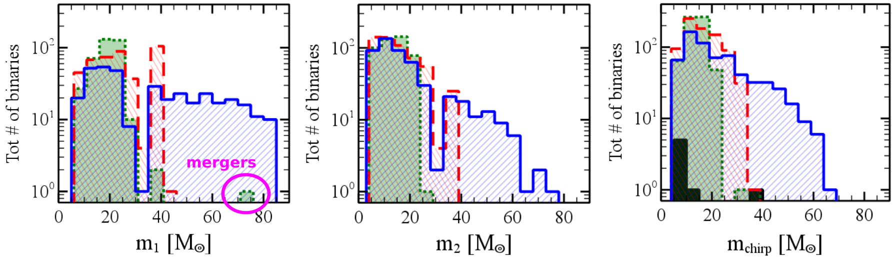

Coalescence times

- Time to reach **SMA=0** considering only **GW emission**
- $t_{GW} \propto \frac{a^4(1-e^2)^{7/2}}{m_1 m_2 m_{\rm tot}}$ (Peters, 1964)
- GW emission: **SMA shrink** and **orbit circularization**
- **Dynamical outlier**: signal **detectability** depends on e
- 7 DBHs with $t_{\rm GW} < 13$ Gyr (0 for $Z = Z_\odot$)
- 17 DNSs with $t_{\rm GW} < 13$ Gyr, 11 DNS mergers during the simulations

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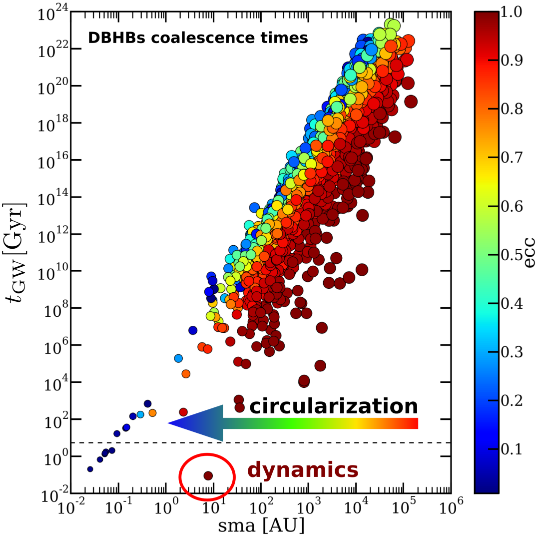

Conclusions

- **DCOBs** during mergers **emits GWs** likely to be detected in the near future
- **Metallicity** is important:
  - **Heavier BHs** form at low Z
  - They tend to form DBHBs at **early times**
  - and these binaries are **more stable** ⇒ BHBs lifetimes are longer at low Z
- **Dynamics** is important
  - Dynamics enhances the formation of DCOBs: **97% of DBHBs** come **from exchanges**
  - Dynamics **hardens** binaries and can modify the **eccentricity** ⇒ increase **detection probability**
- **DNSBs** are 10 times less numerous but **are harder**
  - Fewer exchanges and shorter coalescence times than DBHBs
  - **Selection** effect

Thank you