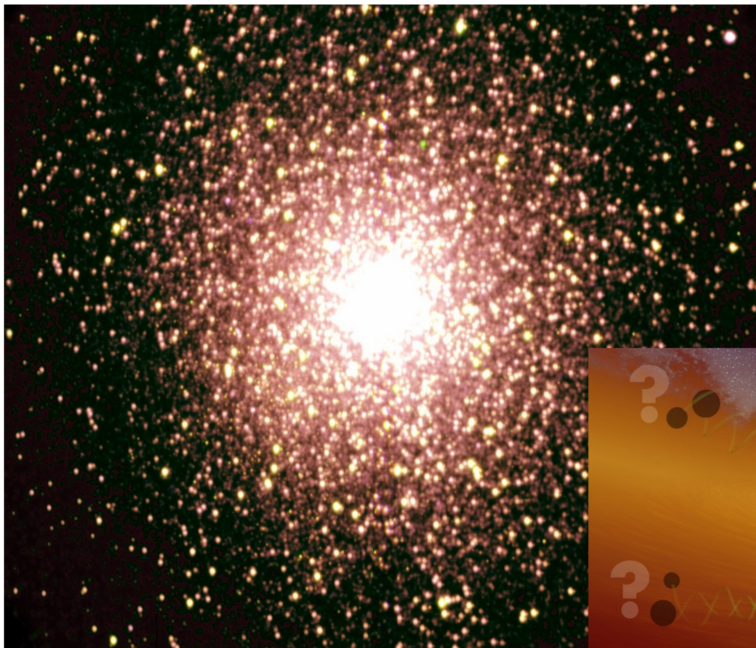
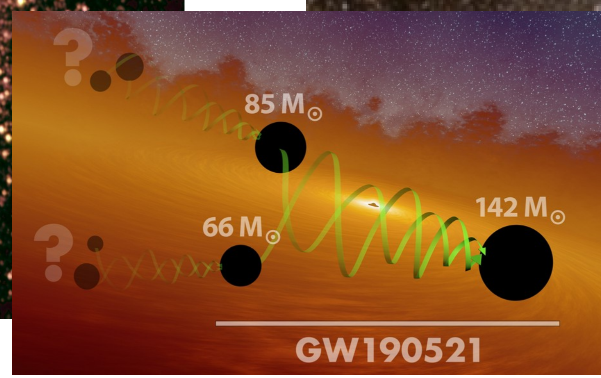
Binary black holes originating from Globular Clusters as sources of Gravitational Waves





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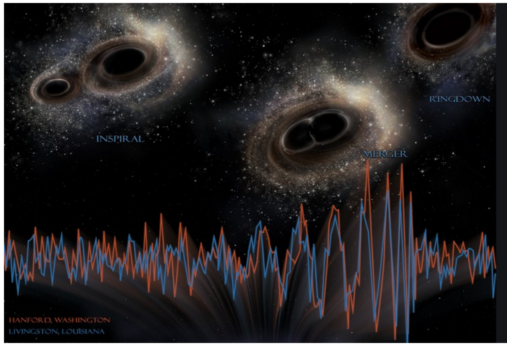
M. Szkudlarek, K. Maliszewski, M.Giersz, A. Askar, T.Bulik

INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY

FNP
Foundation for Polish Science

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

Gravitational Waves Astronomy

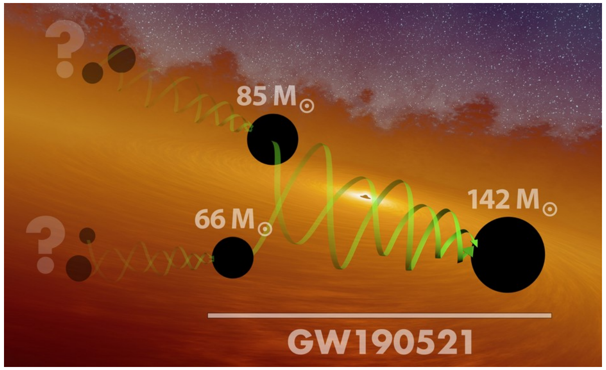


- Advanced LIGO-Virgo (observation:O1,O2,O3a,b)-> breakthrough discoveries
- - 2015 - **GW150914** - 1st detection of gravitational waves from binary black hole merger

  29 Msol+36Mso -> 62 Msol the brightest source ever observed (evidence of massive BH)

$$L_{GW} = 200^{+30}_{-20} \mathrm{M}_{\odot} s^{-1} = 3.6^{+0.5}_{-0.4} \times 10^{56} \mathrm{erg\ s}^{-1}$$

→ Nobel Prize in Physics 2017 R. Weiss, B. Barish, K. Thorne from Ligo-VIRGO collaboration *„For decisive contributions to the LIGO detector and the observation of gravitational waves"*

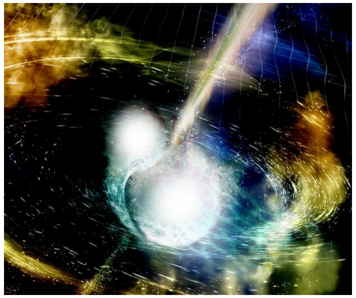


- 2017 – **GW170817** - the 1st observation of a binary neutron star merger

with GW and EM observatories → **the era of multimessenger astronomy**

- - 2019 - **GW190521** the 1st Intermediate Mass Black Hole (IMBH) of 142 Msol
- **Up to now we have confirmed 90 mergers: 84 ? BBH, 2 BNS, (3-4 ?) BH-NS**

Recent Gravitational-Wave Transient Catalog: GWTC-3



→ important results for astrophysics, cosmology and fundamental physics

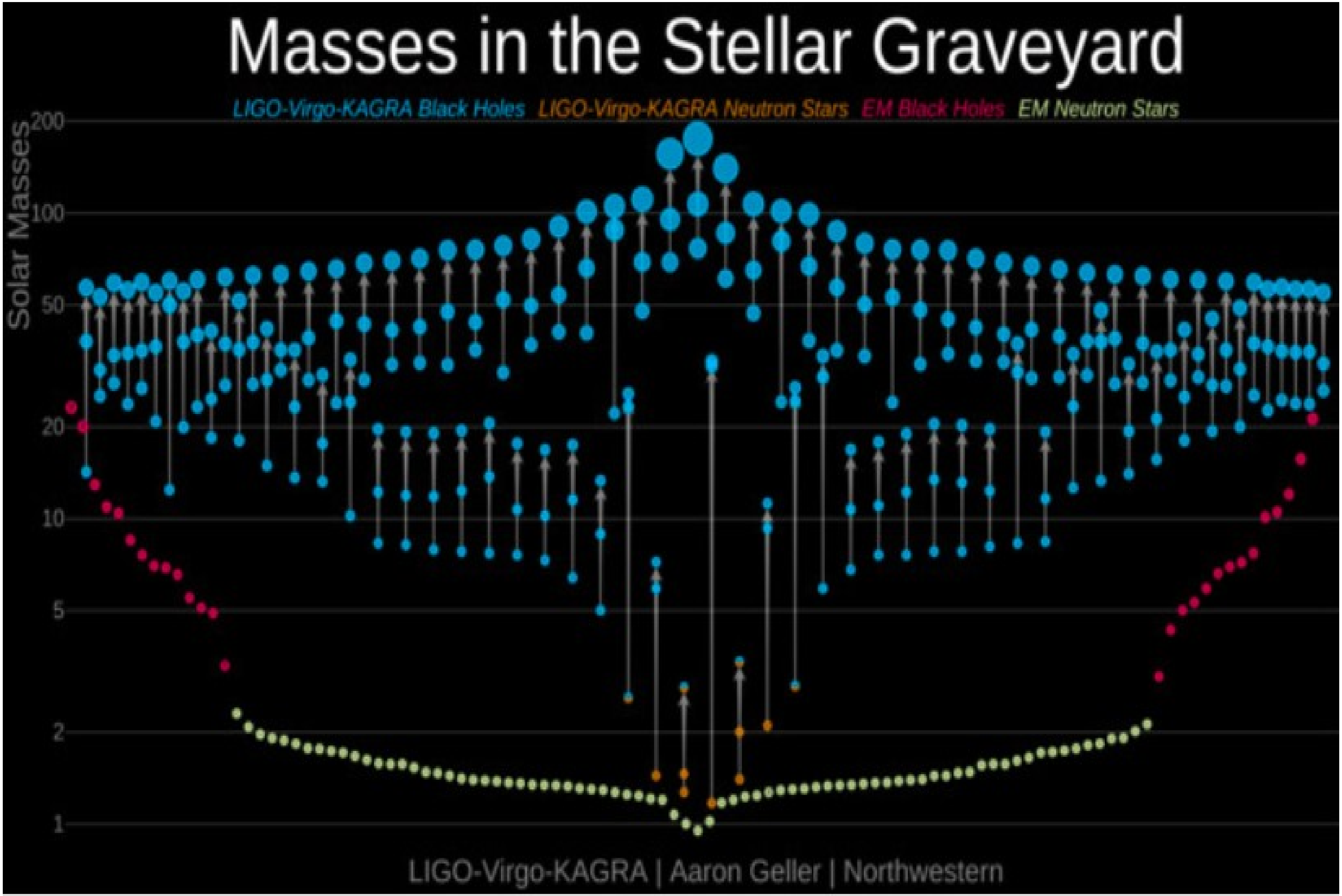
- **Expect a lot of discoveries in near future**

  - Ligo-Virgo-Kagra O4,O5 and final Observational run with Ligo-India

  - 3rd generation detectors: Einstein Telescope, Cosmic Explorer, Space mission: LISA, DECIGO..

- **What is the observed BBH origin ?** isolated binary evolution, **dynamical formation in dense stellar environments (**Open Clusters,**Globular Clusters,** Nuclear Star Clusters**),** priomordial ? **what are the distinctive signatures of BBH from GC ? masses, rates, eccentricities,spins..**

90 Gravitational Waves detections (GWTC-3) + Black Holes and Neutron Stars previously constrained through electromagnetic observations



Evidence of Intermediate Mass Black Holes (IMBH, 10^2 – 10^5 Msol)

GW190521,GW190426_190642,GW190403_051519, GW200220_061928

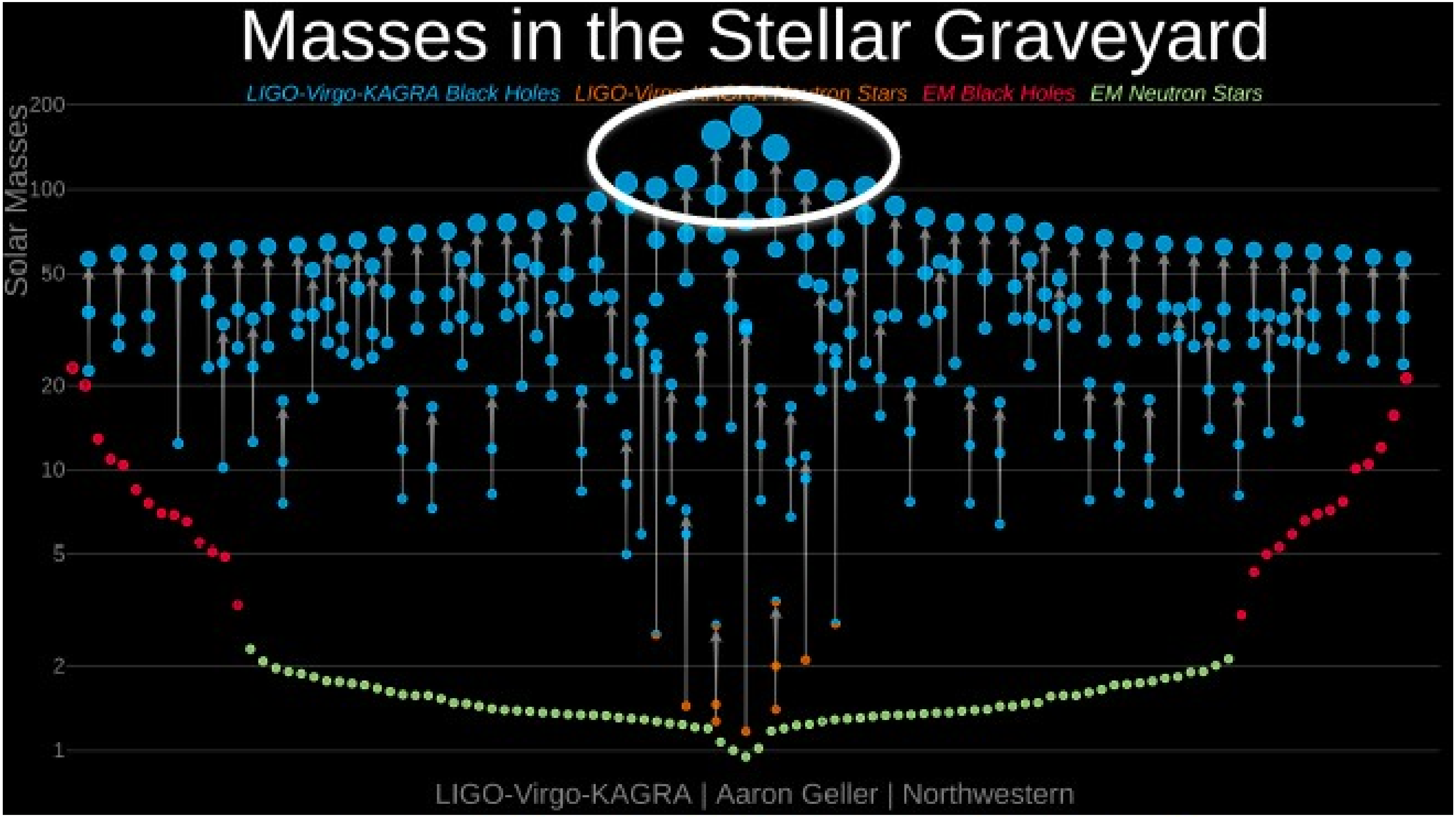
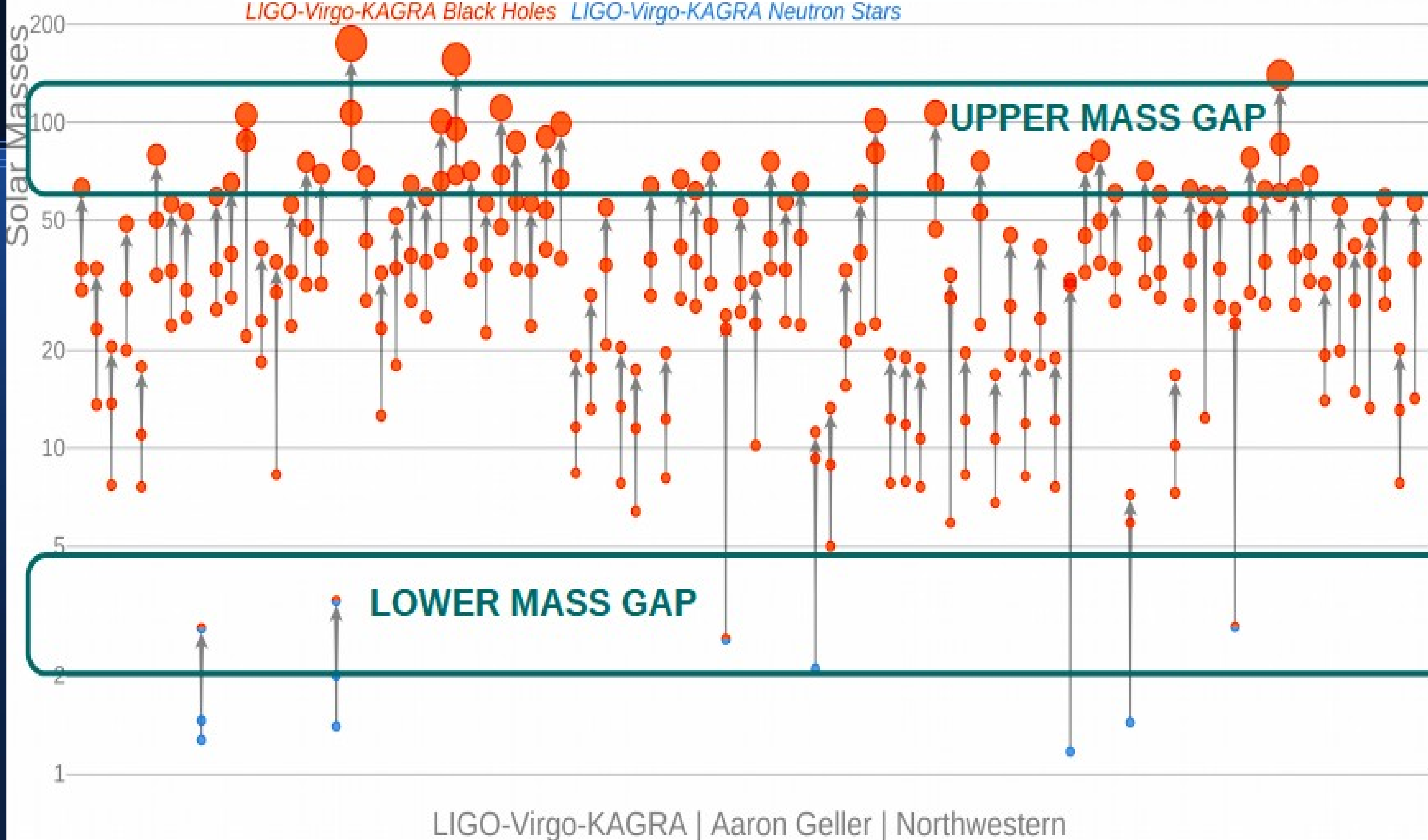


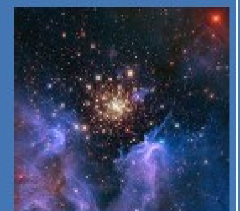
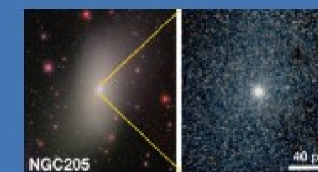
Image Credit: LIGO-Virgo-KAGRA/Northwestern Univ./Aaron Geller

Pair and pulsational pair instability supernovae prevent formation of black holes with masses in the range: $\sim 50^{+20}_{-10} - 120\ M_\odot$



Abbott et al. 2022, GWTC-3

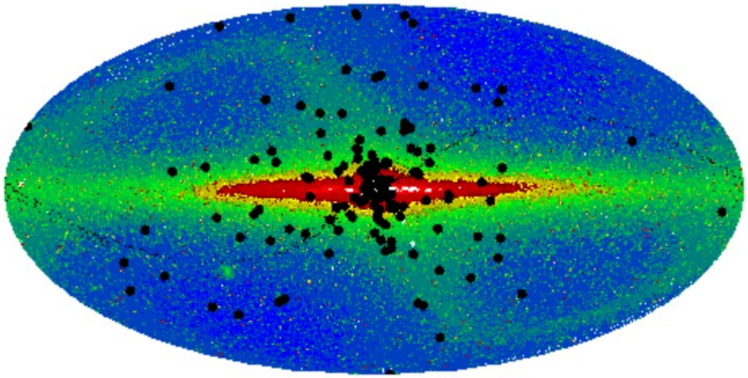
Credit: A. Askar

	Open Clusters & Young Massive Clusters		Globular Clusters	Nuclear Star Clusters
				
Mass	$100 - 1000\ M_\odot$	$10^4 - 10^5\ M_\odot$	$10^4 - 10^6\ M_\odot$	$10^5 - 10^8\ M_\odot$
Radius	$\sim 1 - 10$ pc	$\sim 1 - 5$ pc	$\sim 10 - 30$ pc	$\sim 1 - 10$ pc
Central Density	$\lesssim 10^3\ M_\odot\ pc^{-3}$	$\gtrsim 10^4\ M_\odot\ pc^{-3}$	$\gtrsim 10^5\ M_\odot\ pc^{-3}$	$10^5 - 10^7\ M_\odot\ pc^{-3}$
Ages	~ 1 Myr to few Gyr	$\sim 10 - 100$ Myr	$\gtrsim 5 - 13$ Gyr	Age Spread
Local Merger Rates for Binary Black Holes	$\sim 50 - 100\ Gpc^{-3}\ yr^{-1}$		$\sim 5 - 15\ Gpc^{-3}\ yr^{-1}$	$\sim 1 - 10\ Gpc^{-3}\ yr^{-1}$
Useful Papers	Portegies Zwart & McMillan (2002), Banerjee et al. (2010), Mapelli et al. (2013), Ziosi et al. (2014), Goswami et al. (2014), Banerjee (2017; 2018; 2020; 2021), Fuji et al. (2017), Di Carlo et al. (2019; 2020;2021), Rastello et al. (2019; 2020; 2021), Kumamoto et al. (2019; 2020; 2021), Kremer et al. (2020), Martinez et al. (2020), Santoliquido et al. (2020), González et al. (2021), Rizzuto et al. (2021; 2022), Dall'Amico (2021), Fragione & Banerjee (2021); Bouffanais (2019), Britt et al. (2021), Trani et al. (2021; 2022), Mapelli et al. (2020; 2021; 2022)		Portegies Zwart & McMillan (2000), Miller & Hamilton (2002), M. Benacquista (2002), O'Leary et al. (2006; 2007), Sadowski et al. (2008), Moody & Sigurdsson (2009), Downing et al. (2010; 2011), Morscher et al. (2013), Bae et al. (2014), Rodriguez et al. (2016; 2017; 2018; 2019; 2020, 2021), Askar et al. (2017), Park et al. (2017), Chatterjee et al. (2017), Zevin et al. (2017; 2019), Samsing et al. (2017; 2018; 2019; 2020), Hong et al. (2018), Fragione & Kocsis (2018), Choksi et al. (2019), Arca Sedda et al. (2020), Antonini & Gieles (2020), Kremer et al. (2020), Samsing & Hotokezaka (2020); Mapelli et al. (2020; 2021; 2022)	Miller & Lauburg (2009), O'Leary et al. (2009), Miller & Davies (2012), McKernan (2012), Antonini et al. (2014;2016;2019), Antonini & Rasio (2016), Stone et al. (2017) Bartos et al (2017), Rodriguez & Antonini (2018), Arca Sedda et al. (2018;2020) Fragione et al. (2019), Hoang et al. (2018; 2019), Leigh et al. (2018), Arca-Sedda & Gualandris (2018), Yang et al. (2019), Rasskazov et al. (2019), Gerosa & Berti (2019), Arca Sedda (2020), Fragione & Silk (2020), Mapelli et al. (2022), Palmese & Conselice (2021), Fragione et al. (2022)

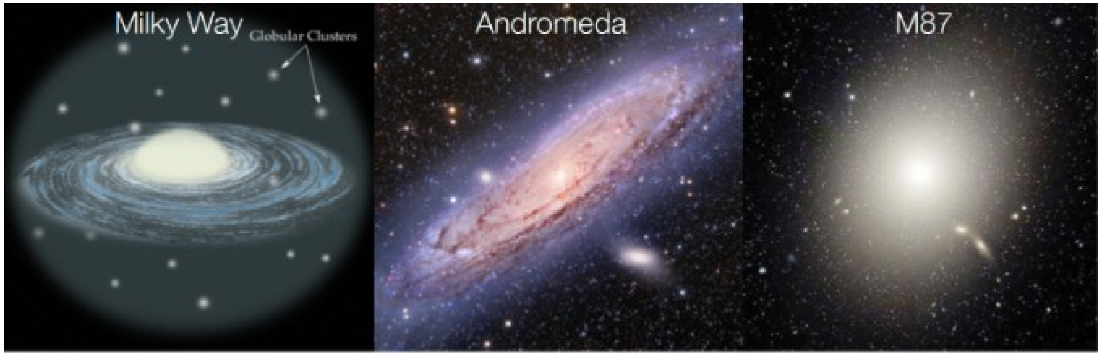
Globular Clusters

NGC 104 aka 47 Tucanae

- Spherical and very dense collections of stars (10^5-10^6) that orbit a galactic core as satellites. More than 60 000 extragalactic Globular Cluster (GC) observed .
- Old stellar systems -12 billion years old
- Most of stars are old Population II (metal-poor) stars
- Stars are clumped closely together, especially near the centre of the cluster --> close dynamical interactions → tight binary systems containing compact objects
- Central Densities: $10^3 - 10^6$ M⊙/ pc^3
- Intermediate Mass Black Hole ($10^2 - 10^5$ $M_\odot$) can be formed in 30 % GC (e.g. Giersz et al. 2015, Hong et al. 2020)



Credit: M. Benacquista & Downing, 2011, the distribution of 157 GC in the Milky Way from Hariss catalog



~200 GCs ~500 GCs ~15 000 GCs

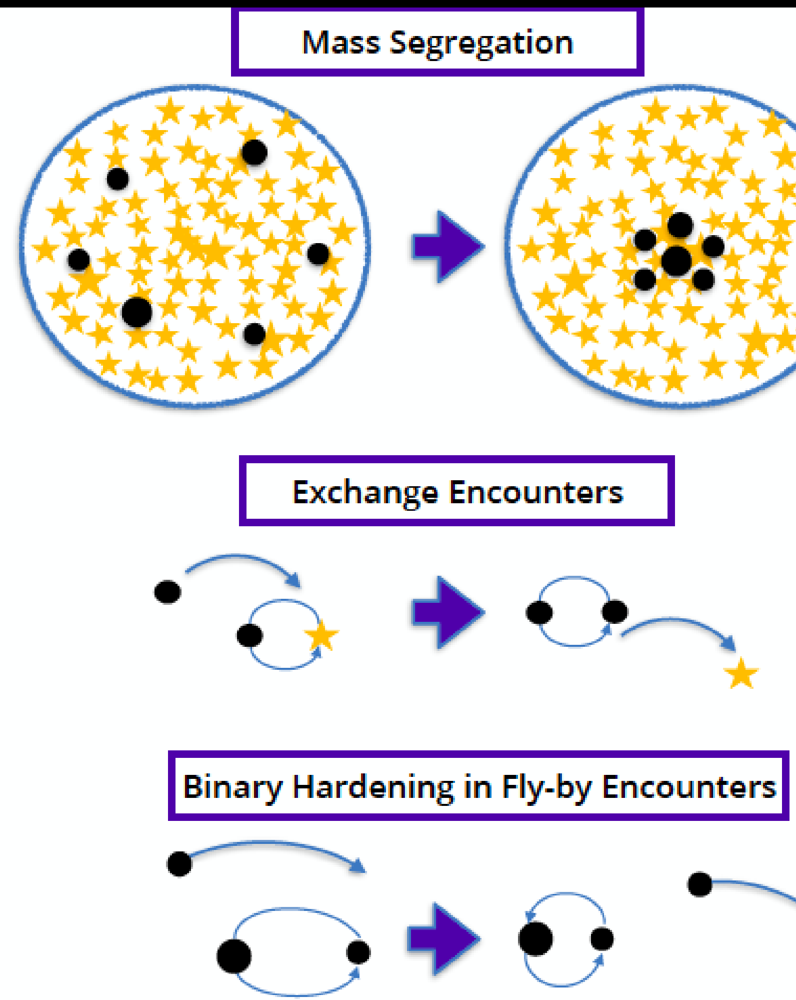
Credit: A. Askar

- Black holes segregate to the center of the cluster → interact with each other and surrounding stars

- 3 and 4-body close dynamical interactions involving black holes
  - **Formation of binary black holes through exchange encounters**
  - Mergers can also occur during these interactions (Samsing 2018, Samsing, Askar, Giersz 2018, Rodriguez et al. 2018 a,b, Zevin 2018)

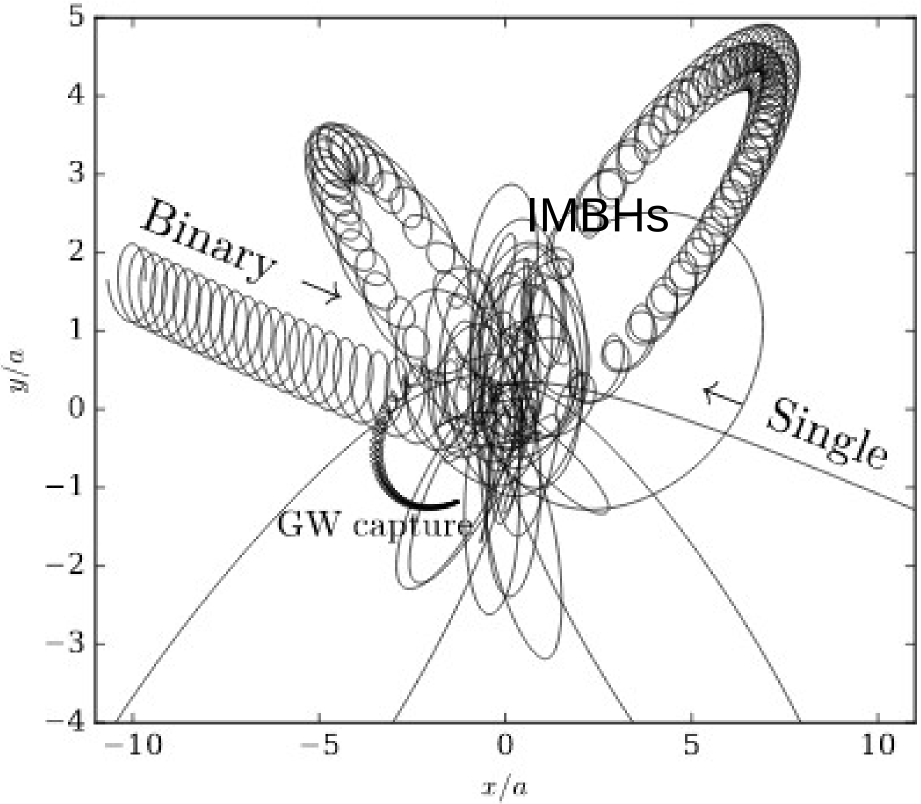
- Hardening of binary black holes through interactions → binary becomes 'useful' → can merge due to gravitational wave radiation within a Hubble time

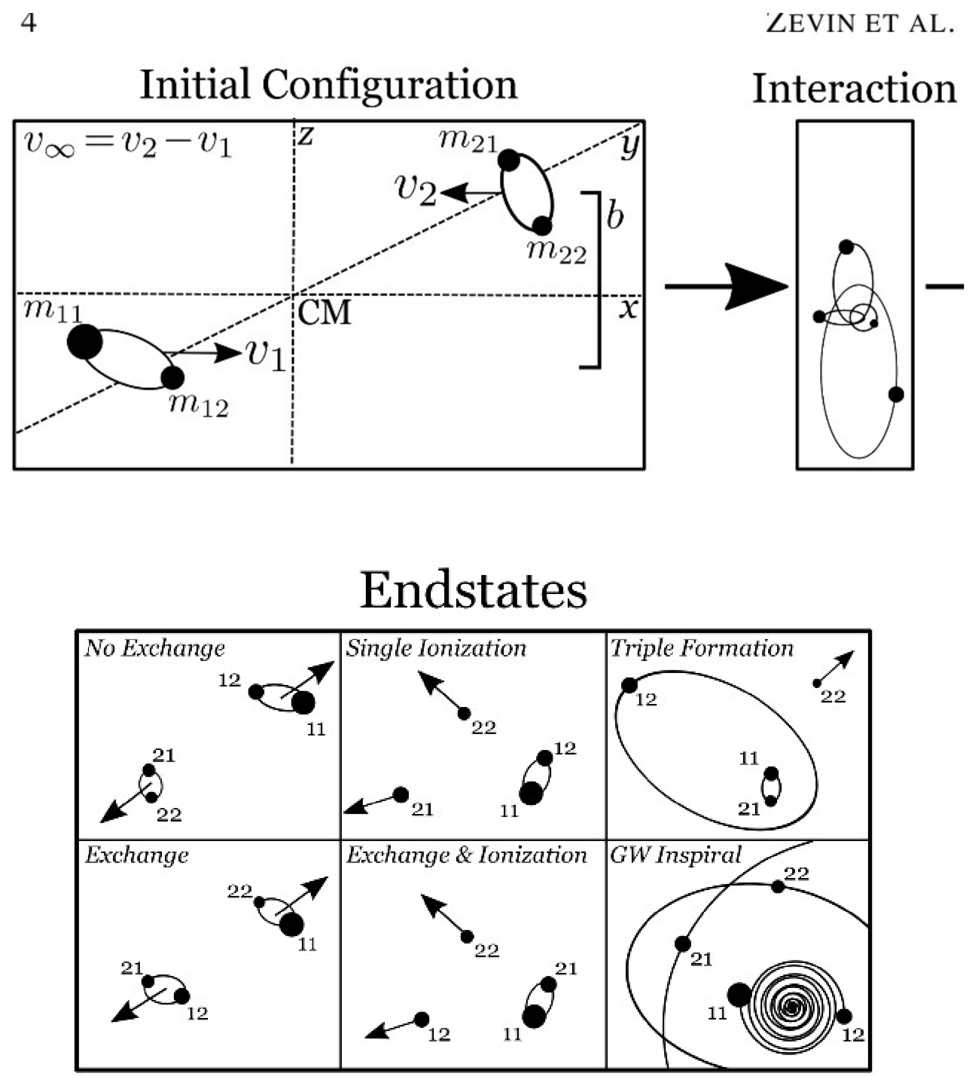
$$\tau_{\rm gr} \simeq 10^{10} yr \left(\frac{a_{\rm bin}}{3.3R_{\odot}}\right)^4 \frac{1}{(m_1+m_2)m_1 m_2} \cdot \left(1-e^2\right)^{7/2}$$ (Peters 1964)



Many eccentric binaries from 3 and 4 body interactions when PN corrections to the equations of motion were included

left 3-body interactions (J.Samsing, 2018),
right 4-body M. Zevin et al. 2019





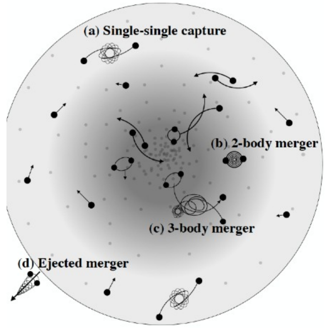
MOCCA code to simulate Globular Clusters

- We use the MOCCA (MOnte Carlo Cluster simulAtor) code developed by Mirek Giersz, Henon (1971), Stodolkiewicz (1982), Abbas et al. (2016, 2017). Similar to the code used by the Northwestern group (Rodriguez et al.)
- Well tested, allows to investigate individual interactions, while ensuring that the evolution of cluster is accurate and computationally efficient.
- BIGSURVEY ~1000 MOCCA models, range of metallicities and sizes to match the population of GCs in the Milky Way
- The initial conditions for these models models cover a wide range of the parameter space (different initial masses, densities, primordial binary fraction, metallicities).
- Matches Milky Way but is not a fit. Many degeneracies.

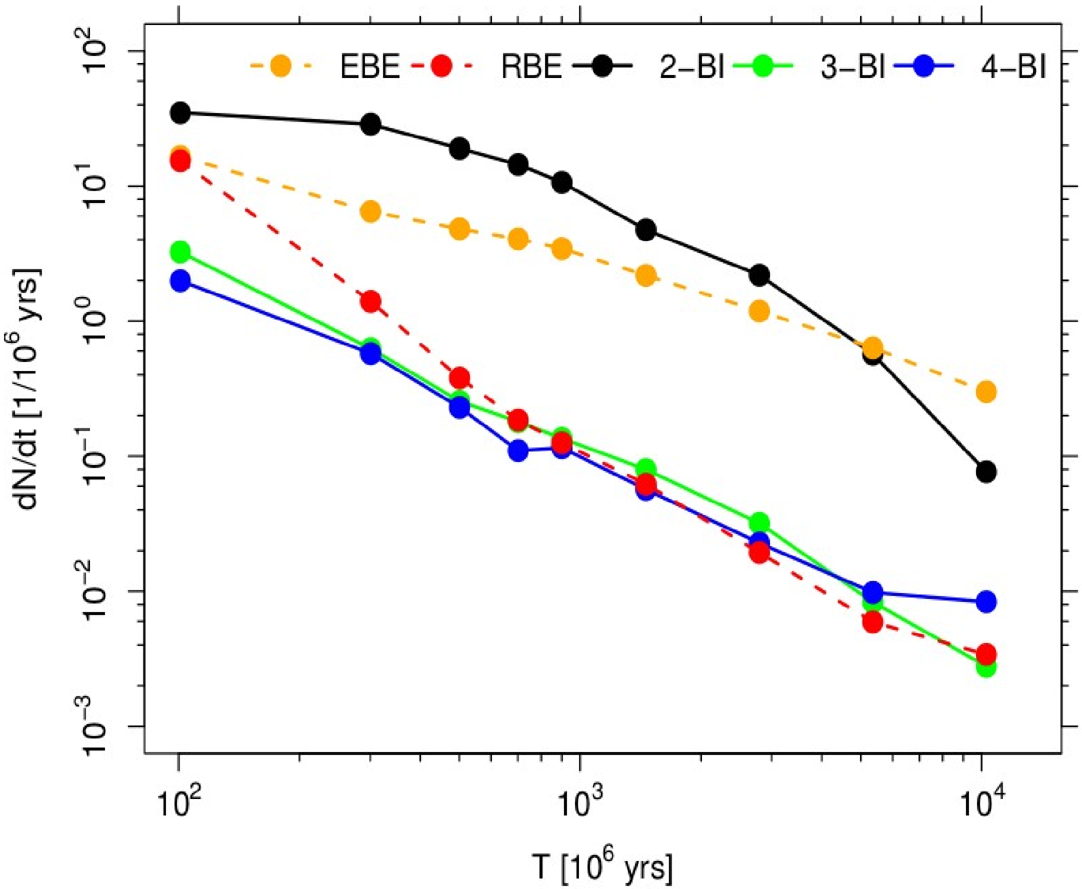
Merging BBHs and Colliding BHs From Globular Clusters

Number of merging BH binaries or colliding BH within Hubble time per unit time (1 Myr) as a function of merger time for black holes (Szkudlarek,Rosinska,Askar,Giersz,Bulik,2017)

Five different interactions, which can lead to the emission of **chirp** signal (dashed lines) due to the coalescence of two BHs in a binary system or a **burst GW signal** (solid lines) due to the collision of two BHs in 2-,3-,4-body interactions



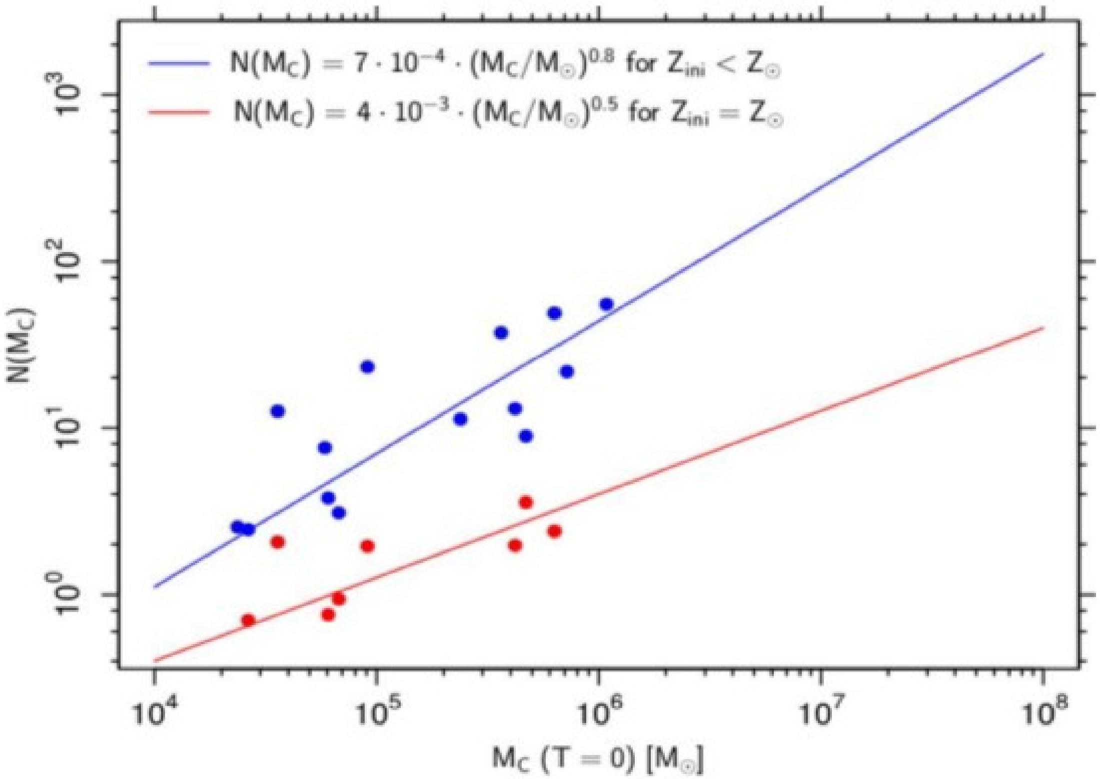
Samsing et al. 2019



- **Coalescing BBH** – via GW emission -a chirp signal/burst signal
  - EBE -Ejected Binary Evolution
  - RBE – Retained Binary Evolution
- **Colliding 2 BHs** – a burst signal due to dynamical
  - 2-BI - 2 Body Interaction,
  - 3-BI - 3 Body Interactions (binary+single star)
  - 4-BI - 4 Body Interactions (binary+binary)

BBHs mergers (with m< 100 Msun) dependence on the initial cluster mass

- Analysis (cont) & Results



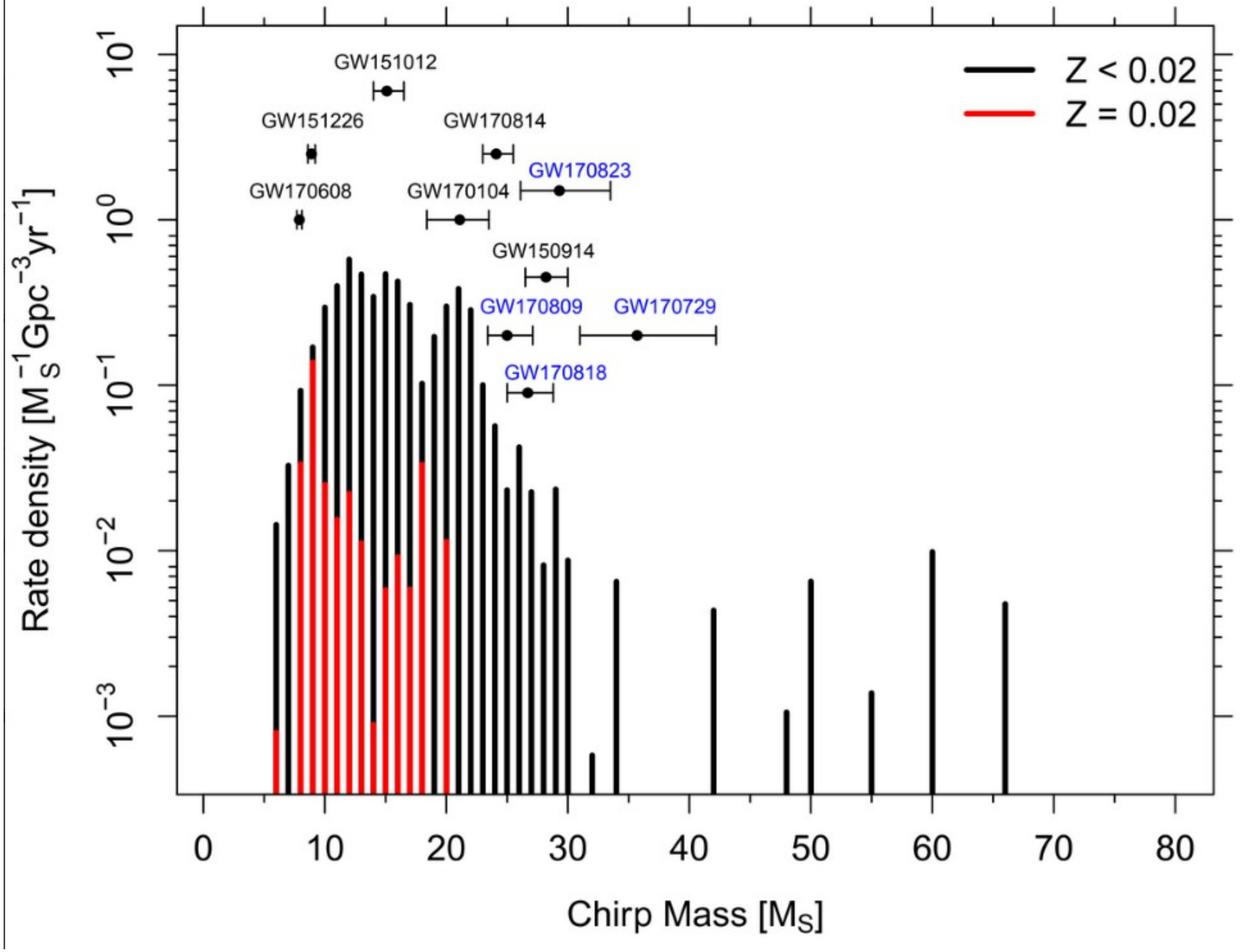
Normalized number of BBHs as a function of initial cluster mass M_c with fitted function $N(M_c)$ (BBH production efficiency).

- Normalization function:

$$N(M_c) = \frac{n}{n_s \cdot M_c / 10^6\,\mathrm{M}_\odot}$$

- $Z < 0.02$ – 17 269 merger events
  $Z = 0.02$ – 865 mergers
- Regardless of the metallicity, if the mass of a GC model is large, then the number of merging BBHs is higher.
- Low-metallicity clusters have a greater ratio of producing merging BBHs compared to higher metallicity cluster models.
- If clusters have larger initial masses then they will produce more merging BBHs.

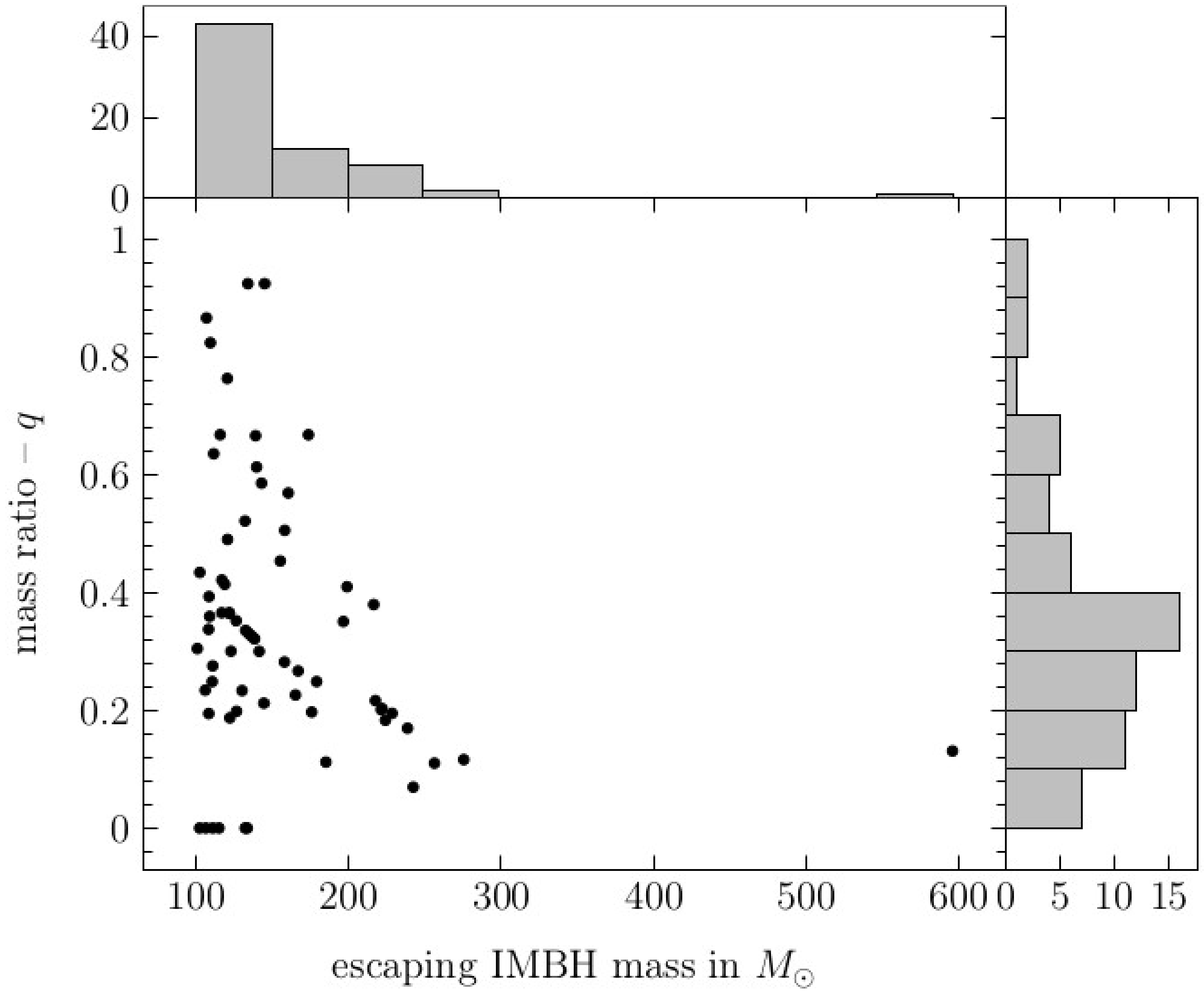
Local merger rate density for escaping BBH



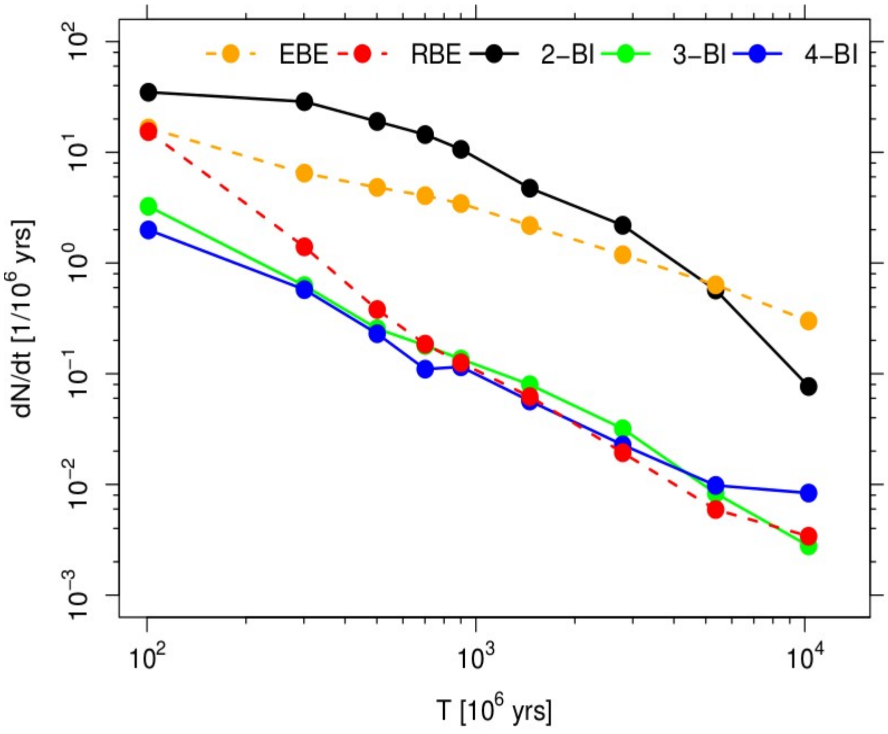
Masses of escaping IMBHs – maximum at 100-140 Msol

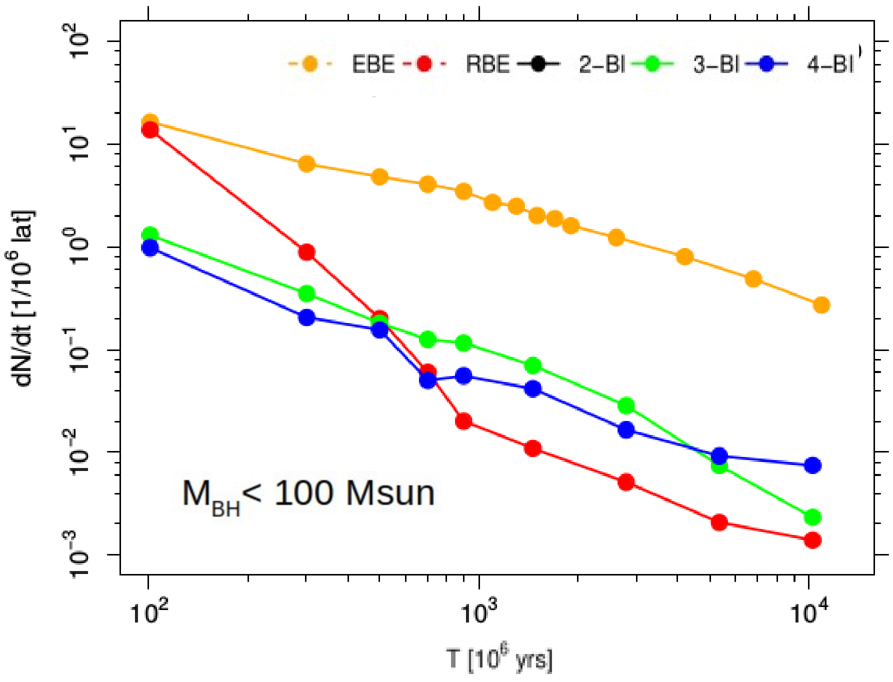
The majority of IMBHs is in BBHs and escapes within first 500 Myrs of the cluster evolution

Maliszewski,Giersz,Gondek-Rosinska,Askar,Hypki 2022



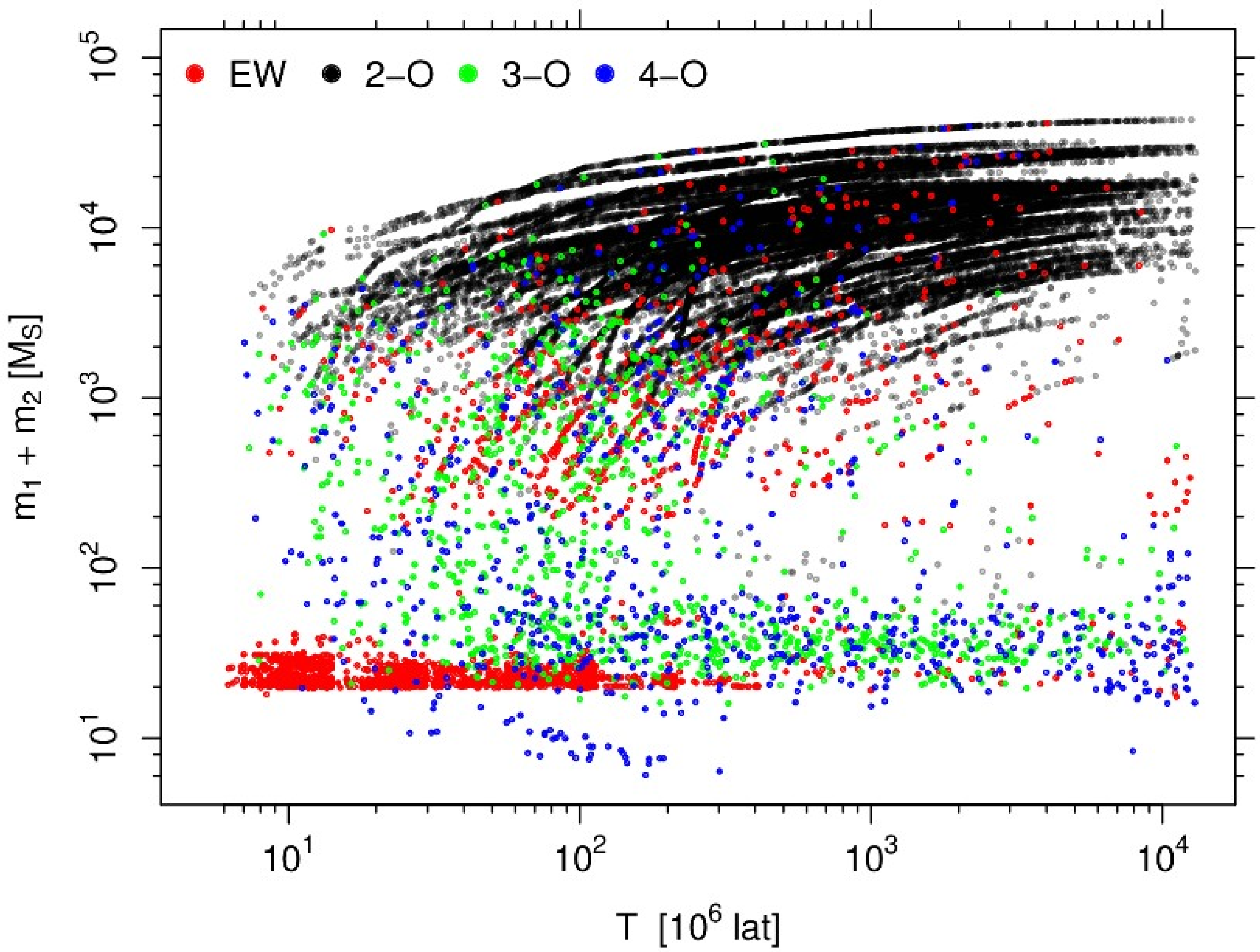
The impact of Intermediate Mass Black Hole on BH-BH collisions and mergers rate



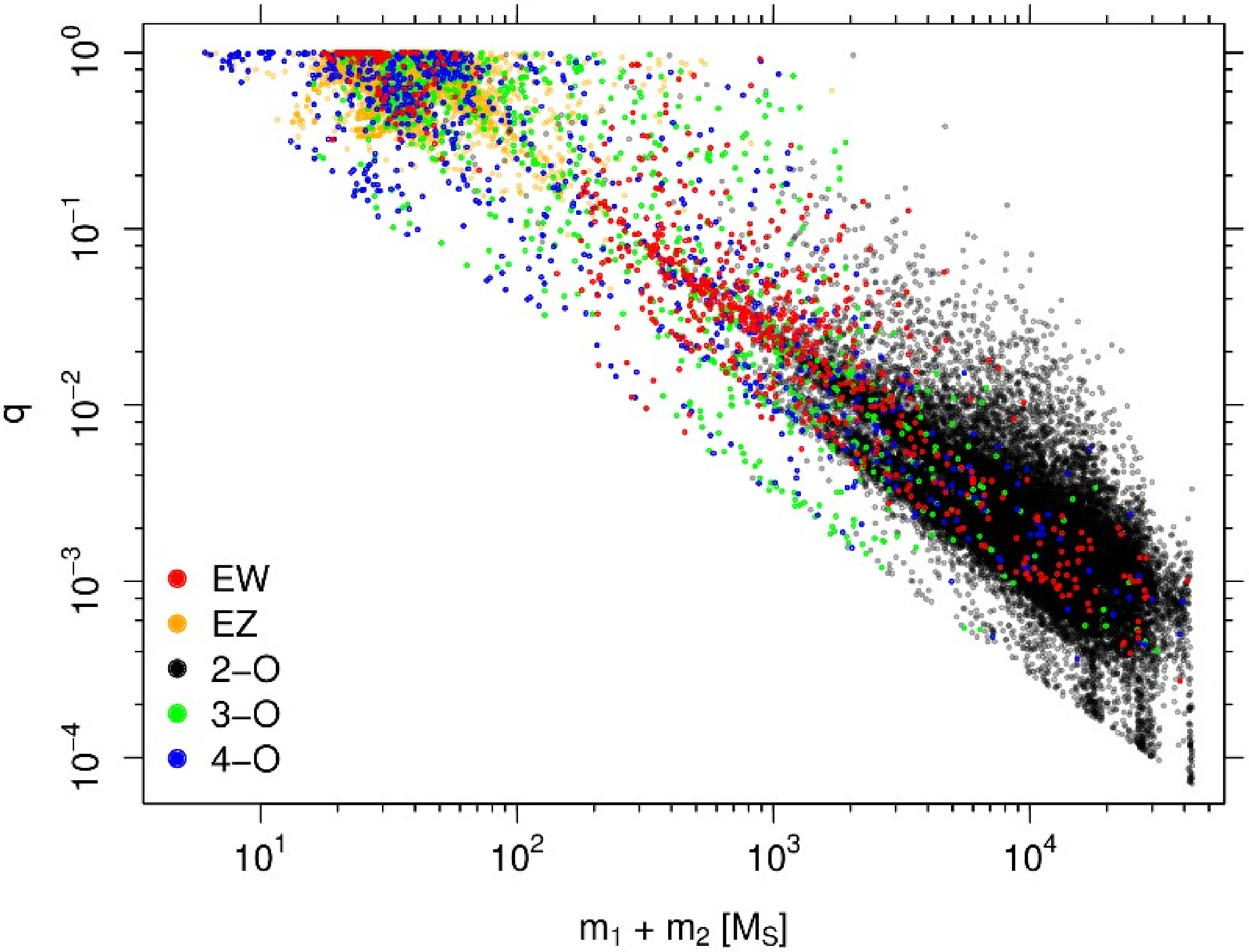


Intermediate Mass Black Hole inside GC

30 % of globular cluster models contain IMBHs, 100-10000 Msol (Giersz et al. 2015). One of formation scenario: built up IMBH mass mainly due to: BH-BH collisions and the formation of massive stars through collisions in the early stages of the GC's evolution.

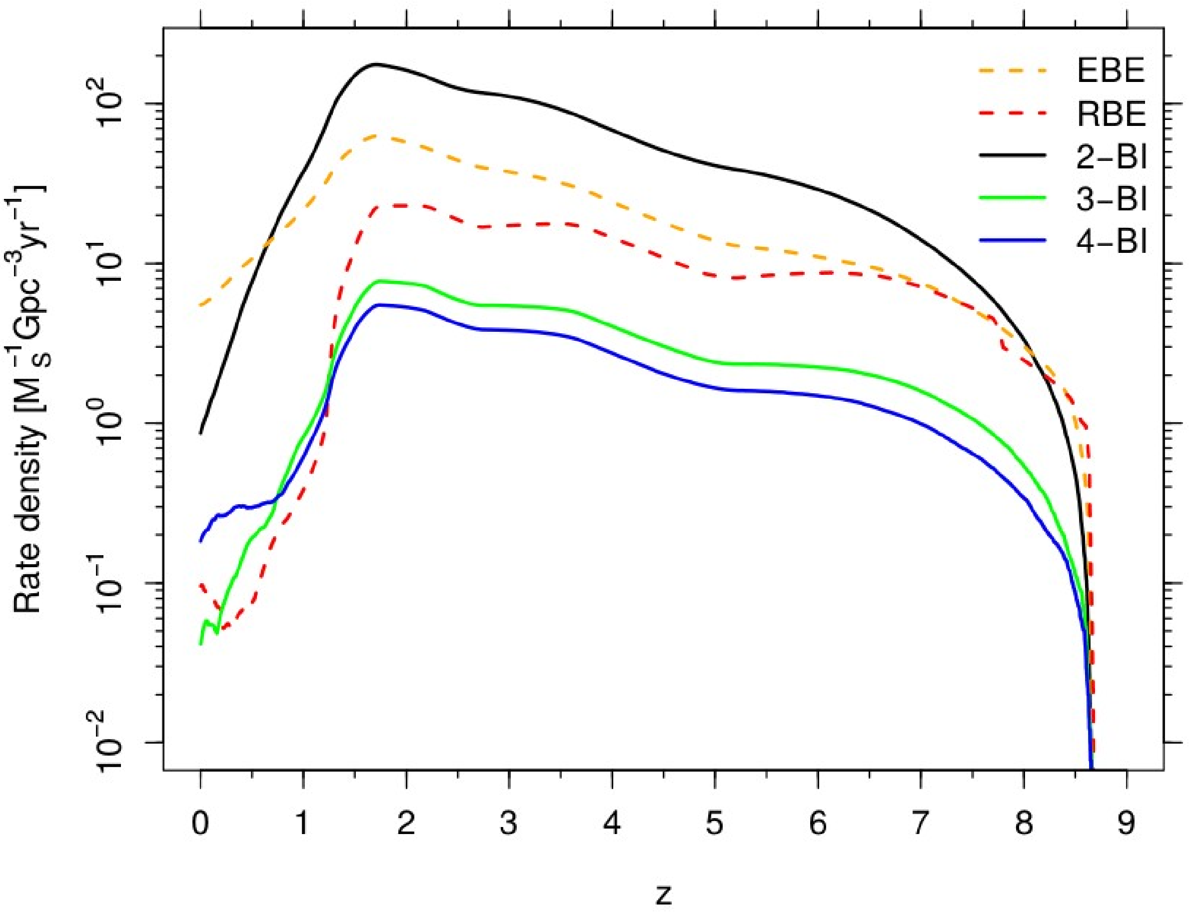


Mass ratio for merging and colliding BHs in GC

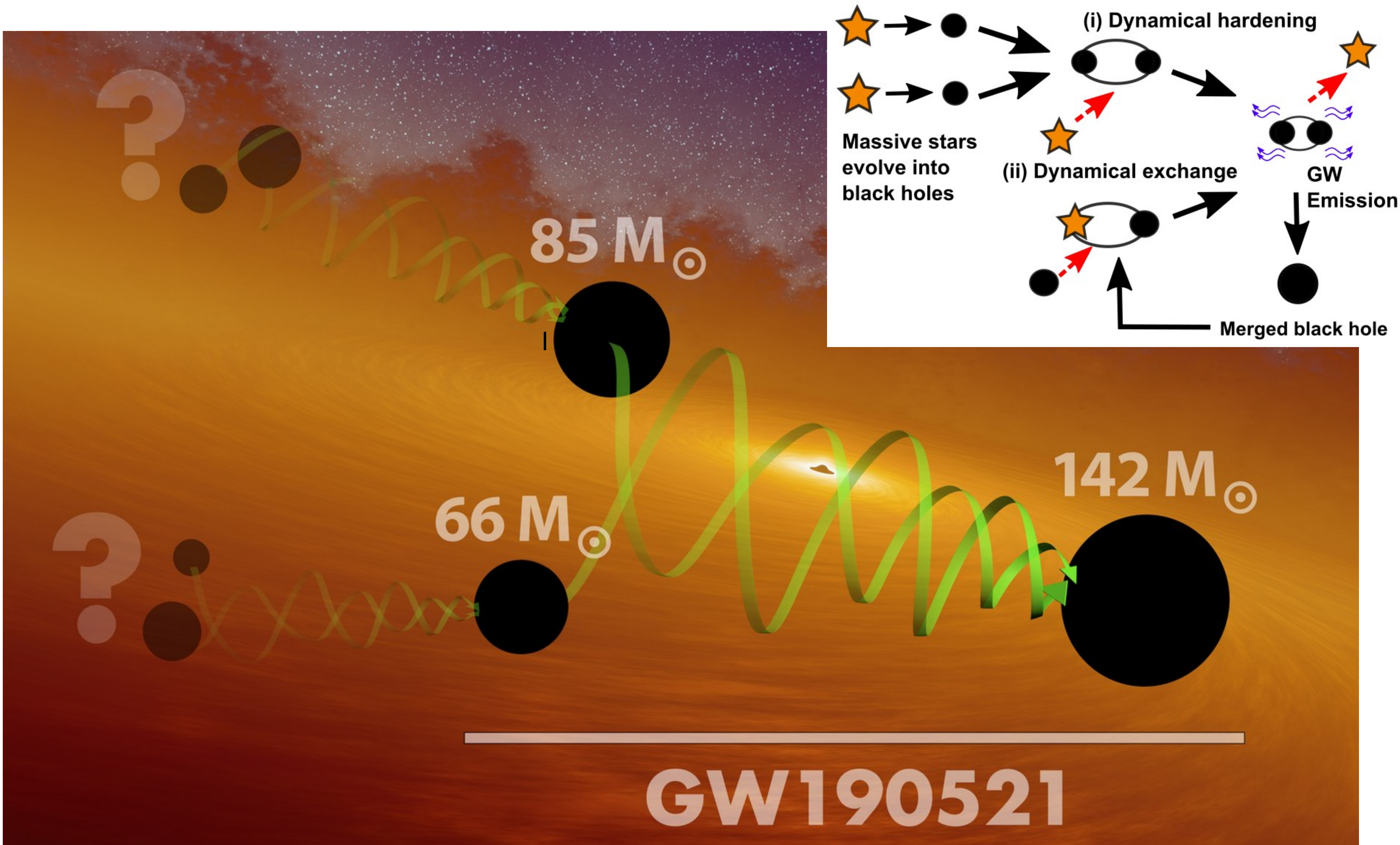


Rate density for BBH mergers and collisions as a function of redshift

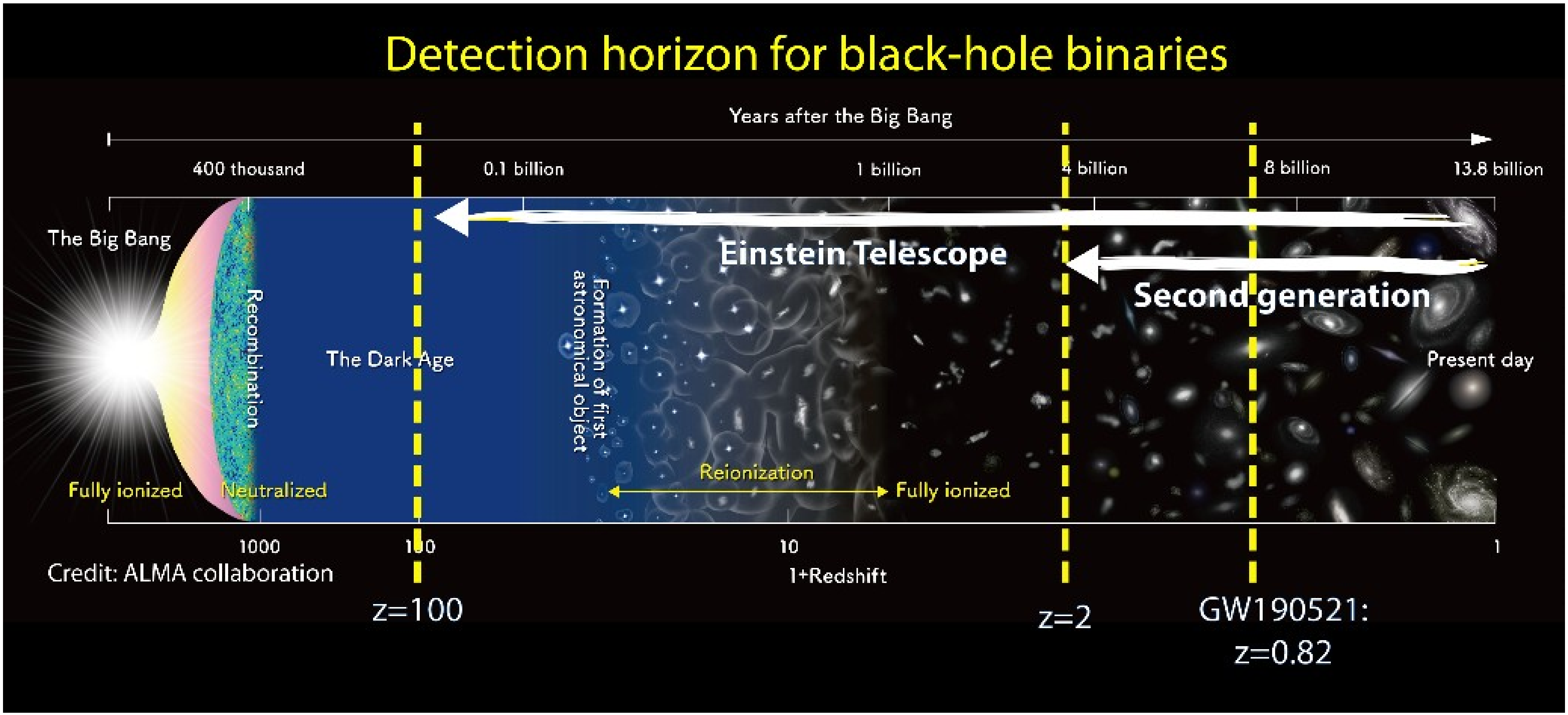
30 % of globular cluster models contain IMBHs, 100-10000 Msol (Giersz et al. 2015). One of formation scenario: built up BH mass due to dynamical interactions and mass transfer in binaries



The 1st Intermediate Mass Black Hole detected by LVK (hierarchical mergers ?)



Einstein Teleskop (1Hz-10 kHz) will observe all BH-IMBH in Universe



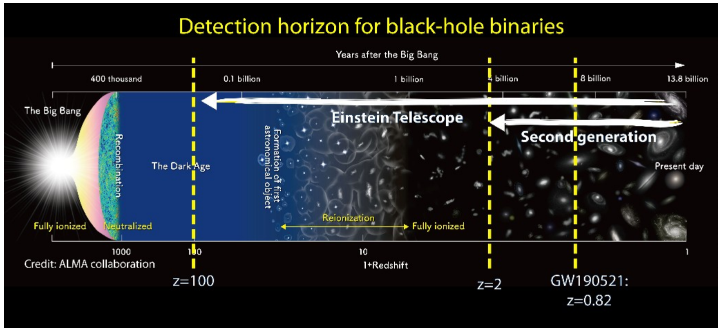
Summary

- We have explored mergers and collisions of BBHs from ~1000 GC using well tested MOCCA code.
- The dominant contribution to mergers is from ejected BBH and low metalicity models
- The Intermediate Mass Black Hole (10^2-10^5 Msol) is formed in 30 % GC models (hierarchical mergers) →

  Inside GC- many BH-BH collisions (indication of existance of IMBH)

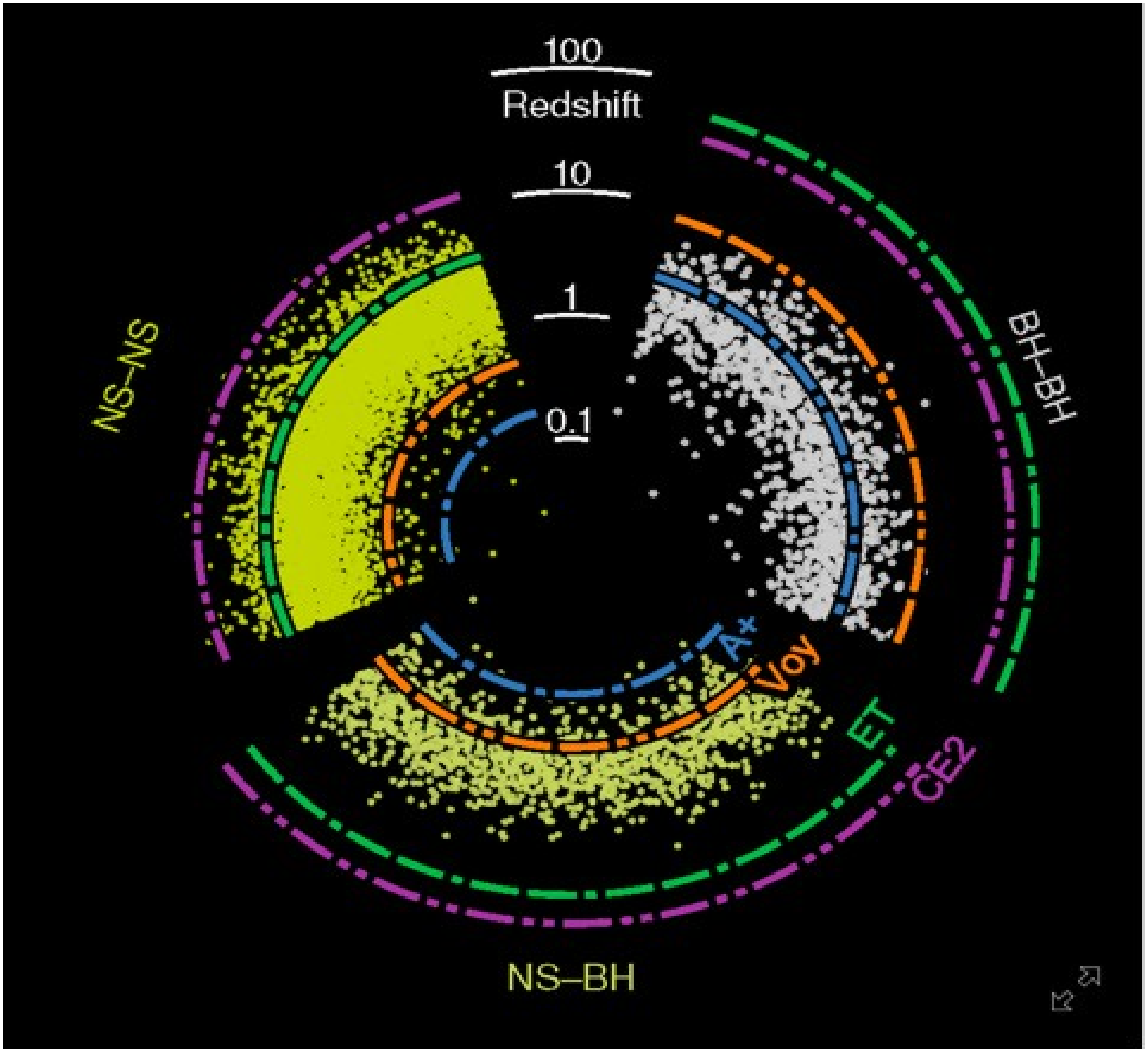
  Ejected BBH -the majority of escaping IMBHs has masses 100-200 Msol and merge in binary systems with a BH (1% of ejected BBH). They escape within first 500 Myrs of the cluster evolution.
- The local merger rate density of **escaping** BBH from globular cluster for masses of BH < 100 Msol is 5.4-15 Gpc^{-3} yr^{-1} (Abbas,Szkudlarek,Rosinska,Giersz,Bulik 2017), 0.7 Gpc^{-3} yr^{-1} for BH-IMBH (Maliszewski, Giersz, Rosinska et al. 2022)
- Mass distribution of BBH consistent with

  LVK observations



- Expect a lot of discoveries in near future !!!

Ligo-Virgo-Kagra Conference
2-5.09.2019,CNK, Warsaw
Astronarium 84 na youtube



Evan Hall and Salvatore Vitale/Massachusetts Institute of Technology

EXTRA SLIDES

Dynamical origin ?

Pair and pulsational pair instability supernovae prevent formation o
holes with masses in the range: $\sim 50^{+20}_{-10} - 120\ M_\odot$ (talk by *Michela Mapelli*

- LVK Observations of massive stellar-mass black holes:

LVK Merger Event	Primary Mass $[M_\odot]$	Secondary Mass $[M_\odot]$	Effective Spin $\chi_{\rm eff}$	Luminosity Distance (Gpc)	Redshift (z)
GW190521_030229	$95.3^{+28.7}_{-18.9}$	$69^{+22.7}_{-23.1}$	$0.03^{+0.32}_{-0.39}$	$6.1^{+4.9}_{-3.1}$	$0.64^{+0.28}_{-0.28}$
GW190403_051519	$88^{+28.2}_{-32.9}$	$22.1^{+23.8}_{-9.0}$	$0.70^{+0.15}_{-0.27}$	$8.00^{+5.99}_{-3.99}$	$1.14^{+0.64}_{-0.49}$
GW190426_190642	$106.9^{+41.6}_{-25.2}$	$76.6^{+26.2}_{-33.6}$	$0.19^{+0.43}_{-0.40}$	$4.35^{+3.35}_{-2.15}$	$0.70^{+0.41}_{-0.30}$
GW200220_061928	87^{+40}_{-23}	61^{+26}_{-25}	$0.06^{+0.40}_{-0.38}$	$6.1^{+4.9}_{-3.1}$	$1.14^{+0.64}_{-0.49}$

Population of merging compact binaries (GWTC-3)
Rates

Multiple models
consistent with same rates

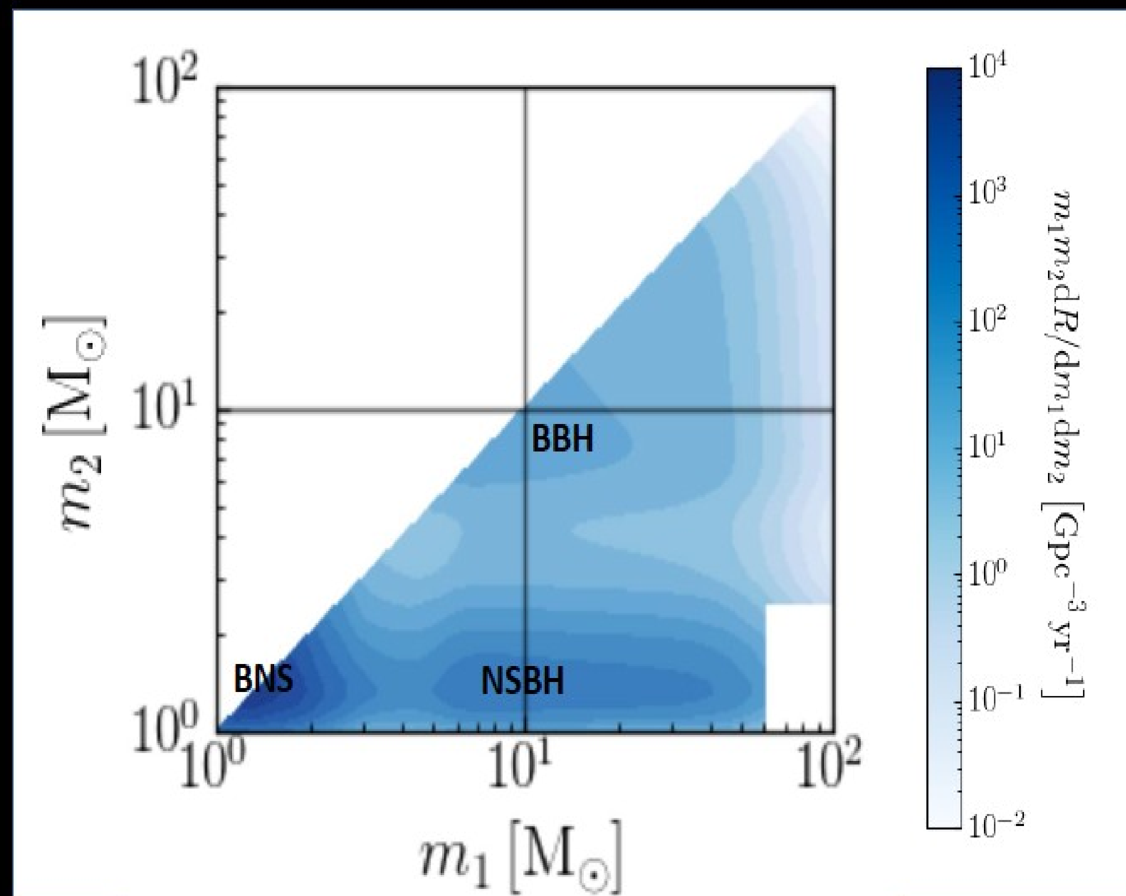
$$\mathcal{R}_{\rm total} = 470^{+830}_{-300}\ {\rm Gpc^{-3}\,yr^{-1}}$$

$$\mathcal{R}_{\rm BNS} = 250^{+640}_{-200}\ {\rm Gpc^{-3}\,yr^{-1}}$$

$$\mathcal{R}_{\rm NSBH} = 170^{+150}_{-89}\ {\rm Gpc^{-3}\,yr^{-1}}$$

$$\mathcal{R}_{\rm BBH} = 22^{+9}_{-6}\ {\rm Gpc^{-3}\,yr^{-1}}$$

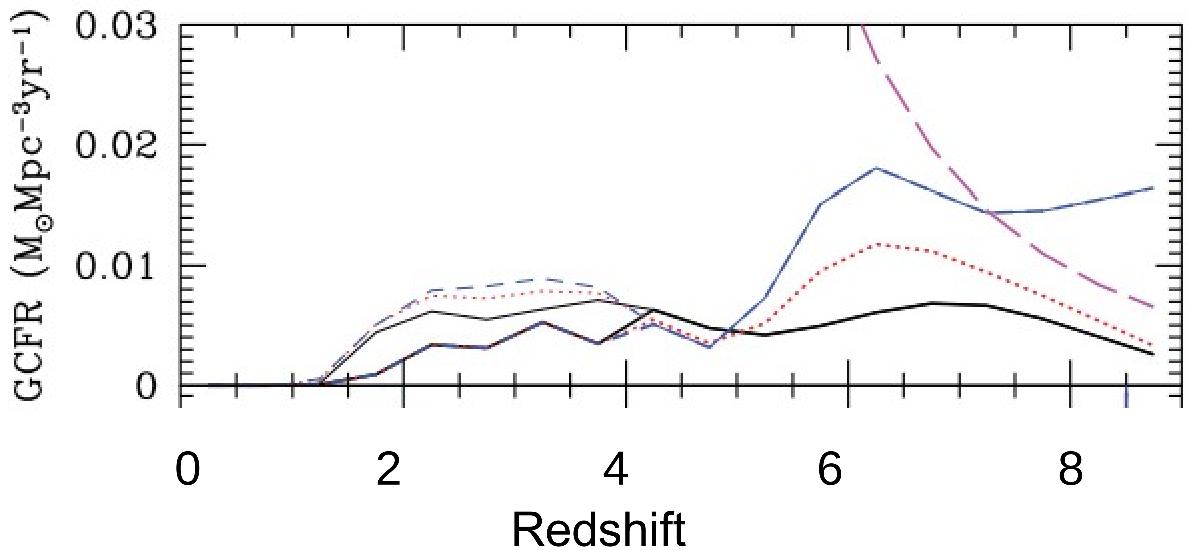
From Abbott et al, "Population of merging compact binaries inferred using gravitational waves through GWTC-3" arXiv:2111.03634



Merger rates in clusters

- Globular Cluster   formation rate

Katz & Ricotti 2013

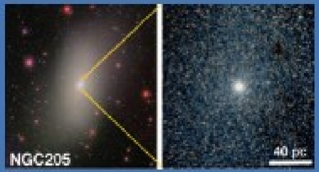


- GC mass composition
- GC metallicity
- The local merger rate (Abbas,Szkudlarek, GR, Bulik, Giersz 2017)

  - 5.4 Gpc^-3 yr^{-1} up to 30 Gpc^-3 yr^{-1} if we include GC with 10^7 Msol

- Systematic uncertainties to be understood

Credit: A. Askar

	Open Clusters & Young Massive Clusters		Globular Clusters	Nuclear Star Clusters
				
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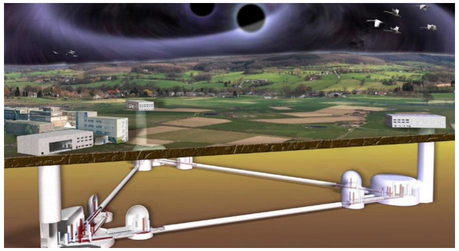
Ages	~ 1 Myr to few Gyr	$\sim 10 - 100$ Myr	$\gtrsim 5 - 13$ Gyr	Age Spread
Local Merger Rates for Binary Black Holes	$\sim 50 - 100\ Gpc^{-3}\ yr^{-1}$		$\sim 5 - 15\ Gpc^{-3}\ yr^{-1}$	$\sim 1 - 10\ Gpc^{-3}\ yr^{-1}$
Useful Papers	Portegies Zwart & McMillan (2002), Banerjee et al. (2010), Mapelli et al. (2013), Ziosi et al. (2014), Goswami et al. (2014), Banerjee (2017; 2018; 2020; 2021), Fuji et al. (2017), Di Carlo et al. (2019; 2020;2021), Rastello et al. (2019; 2020; 2021), Kumamoto et al. (2019; 2020; 2021), Kremer et al. (2020), Martinez et al. (2020), Santoliquido et al. (2020), González et al. (2021), Rizzuto et al. (2021; 2022), Dall'Amico (2021), Fragione & Banerjee (2021); Bouffanais (2019), Britt et al. (2021), Trani et al. (2021; 2022), Mapelli et al. (2020; 2021; 2022)		Portegies Zwart & McMillan (2000), Miller & Hamilton (2002), M. Benacquista (2002), O'Leary et al. (2006; 2007), Sadowski et al. (2008), Moody & Sigurdsson (2009), Downing et al. (2010; 2011), Morscher et al. (2013), Bae et al. (2014), Rodriguez et al. (2016; 2017; 2018; 2019; 2020, 2021), Askar et al. (2017), Park et al. (2017), Chatterjee et al. (2017), Zevin et al. (2017; 2019), Samsing et al. (2017; 2018; 2019; 2020), Hong et al. (2018), Fragione & Kocsis (2018), Choksi et al. (2019), Arca Sedda et al. (2020), Antonini & Gieles (2020), Kremer et al. (2020), Samsing & Hotokezaka (2020); Mapelli et al. (2020; 2021; 2022)	Miller & Lauburg (2009), O'Leary et al. (2009), Miller & Davies (2012), McKernan (2012), Antonini et al. (2014;2016;2019), Antonini & Rasio (2016), Stone et al. (2017) Bartos et al (2017), Rodriguez & Antonini (2018), Arca Sedda et al. (2018;2020) Fragione et al. (2019), Hoang et al. (2018; 2019), Leigh et al. (2018), Arca-Sedda & Gualandris (2018), Yang et al. (2019), Rasskazov et al. (2019), Gerosa & Berti (2019), Arca Sedda (2020), Fragione & Silk (2020), Mapelli et al. (2022), Palmese & Conselice (2021), Fragione et al. (2022)

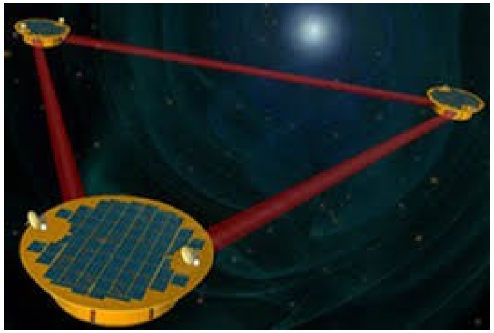
Detektory 3ciej generacji (>2030)



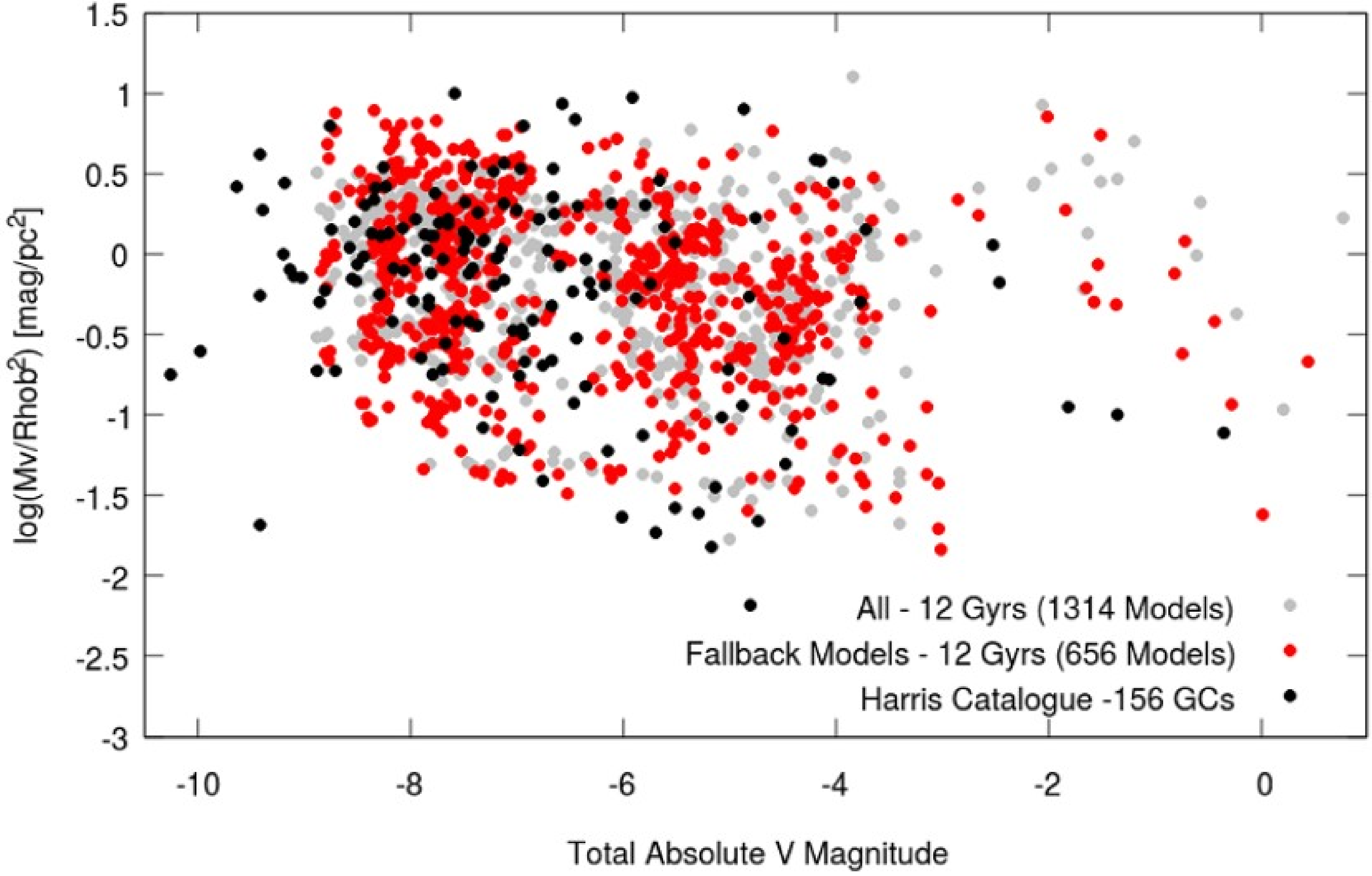
-Einstein Telescope (Europa) ~2035
triangle 10 km

-Cosmic Explorer (USA) ~ 2045
40 km

- LISA (space detector) ~2034



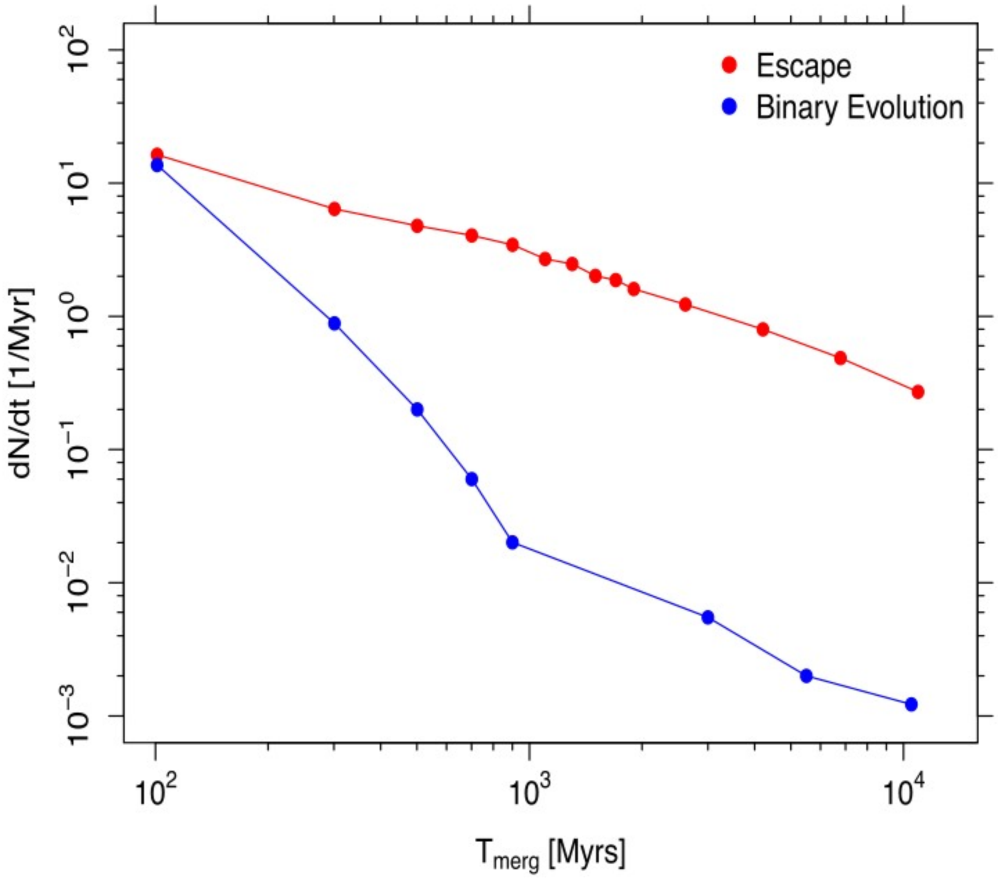
Mocca globular clusters models at 12 Gyrs and Galactic GCs



Cluster Absolute Magnitude vs Average Surface Brightness Inside Half Light Radius

BBH Mergers due GW radiation from Globular Clusters

Number of merging BBH binaries within Hubble time per unit time (1 Myr) as a function of merger time for black holes with $M_{BH} < 100 M_{sun}$
BBH in GC: 3 000; BBH ejected from GC ~15 000,

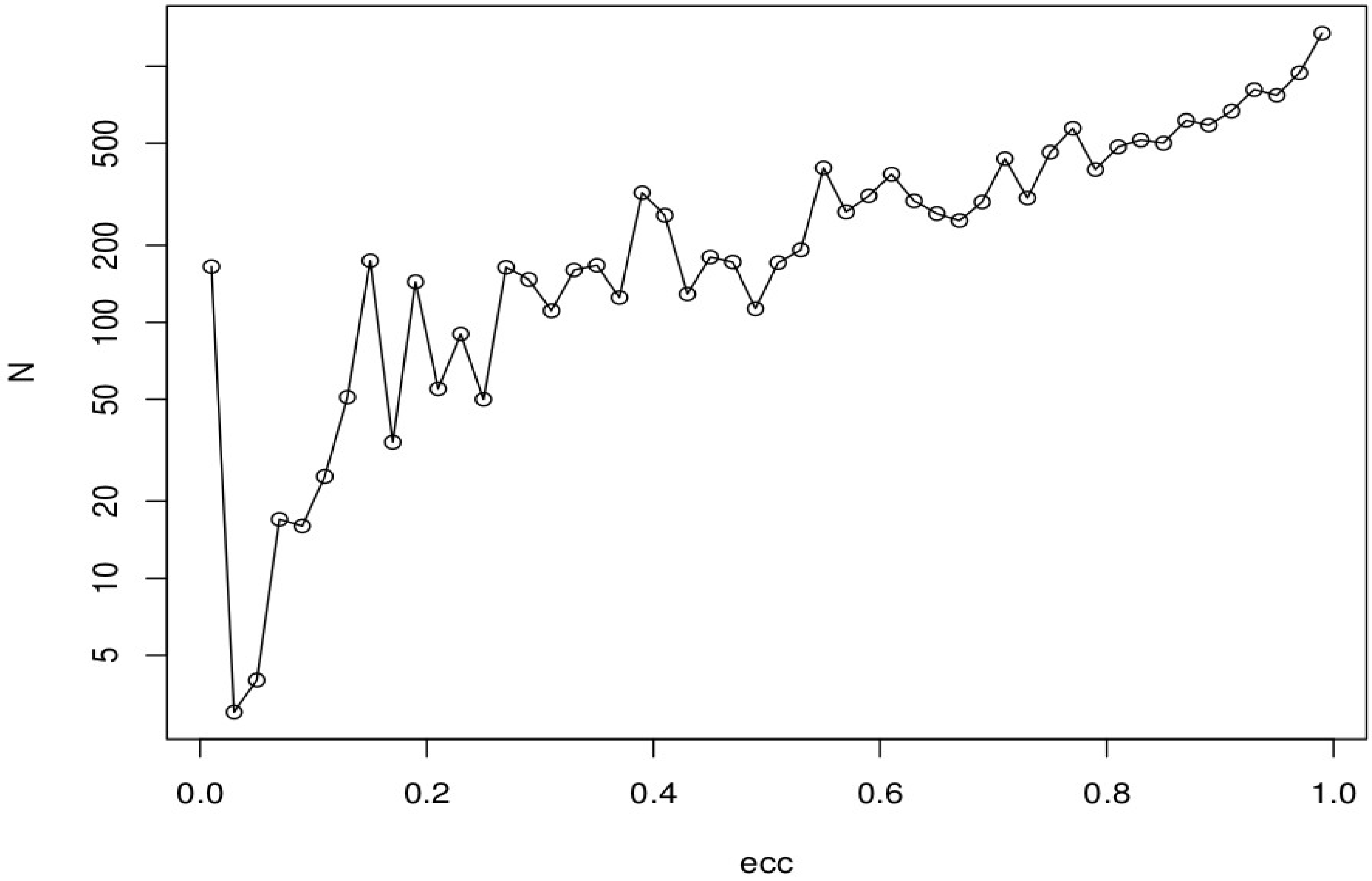


- Path to BBH mergers

  - escaping binaries (dominating)

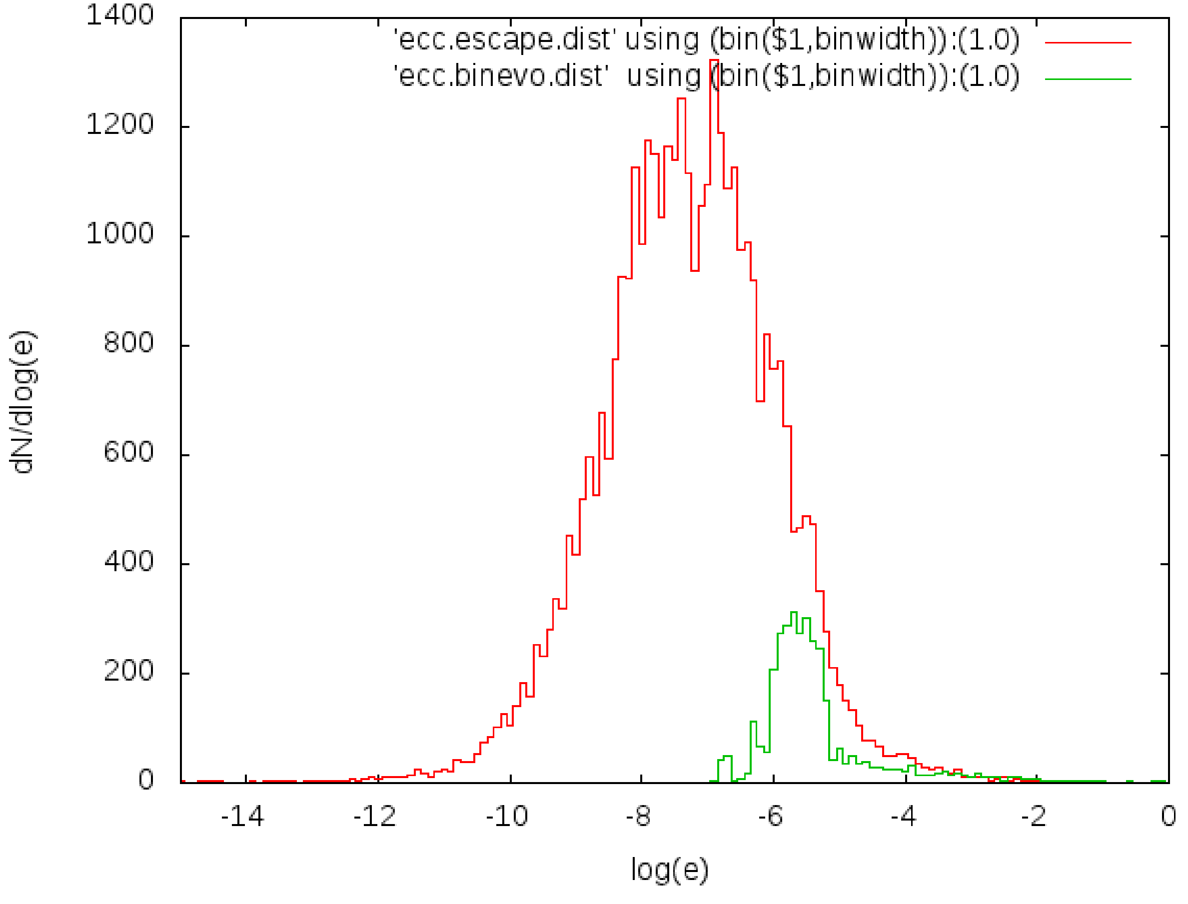
  -binary evolution inside GC

Eccentricity of BBH at ejection



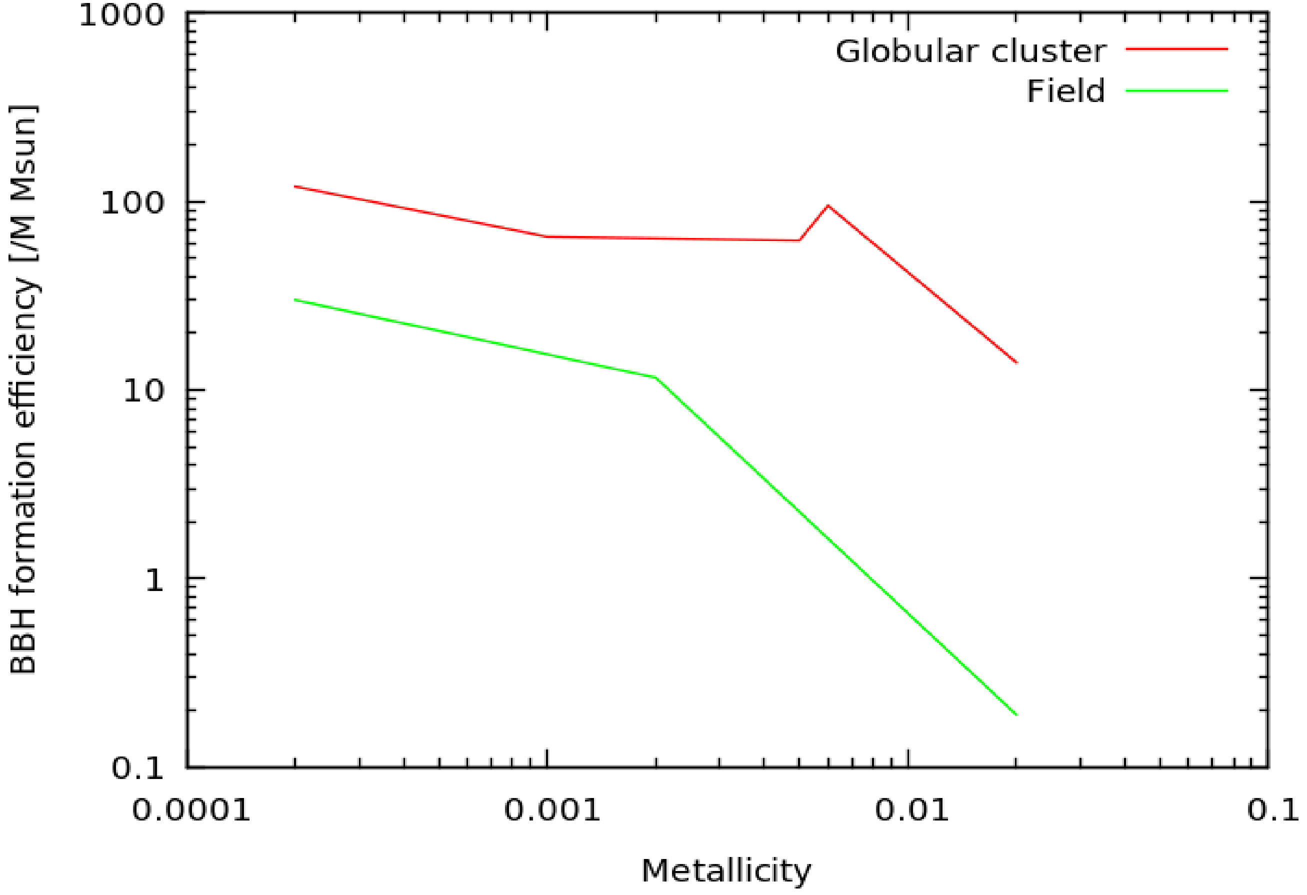
Eccentricities of coalescing BBH at 10 Hz

...but 3-body interactions (see J.Samsing papers)



BBH production efficiency:GC vs Field

Number of merging BBH binaries per 10^6 solar masses of stars.
Field data from Belczynski et al 2016



Summary of simulations

Metallicity	Total mass [10^6 Msun]	Mass range of clusters [10^6 Msun]	Number of models	Number of BHBH mergers
0.02	51.7	0.024-0.61	258	735
0.006	19.6	0.63	31	1857
0.005	49.4	0.024-0.61	243	3042
0.001	141	0.02-1.08	423	9169
0.0002	18.9	0.63	30	2276

Table : About 2000 models. BH and NS kicks are the same, 265 km/s, except the case of mass fallback Belczynski et al.(2002). Two segment IMF (Kroupa 2001) was used for all models, with $M_{min} = 0.08 M_\odot$ and $M_{max} = 100.0 M_\odot$. If the binary fraction, f_b, is equal to 0.95 then binary parameters are chosen according to Kroupa (1995) (eigenevolution, mass feeding algorithm), otherwise eccentricity distribution is thermal, mass ratio distribution is uniform and semi-major distribution is uniform in logarithm, between $2(R_1 + R_2)$ and 100 AU. R_t - tidal radius, R_h - half-mass radius, W_0 - King model parameter, Z - cluster metallicity. For each initial number of objects different combinations of parameters are used to generate the initial model. The number of models with different metallicities are as follows: 63, 831, 487, 64 and 503 for Z = 0.0002, 0.001, 0.005, 0.006 and 0.02, respectively.

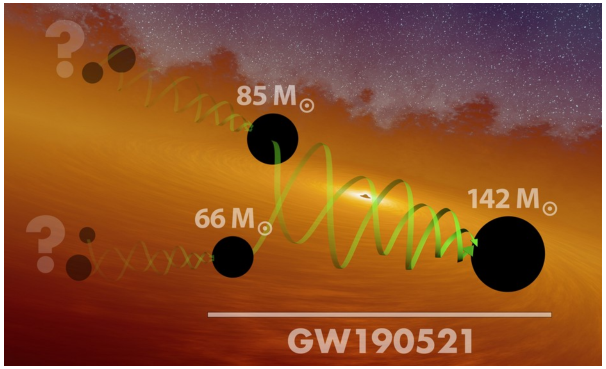
Observations of coalescing BBH

- 2015 – GW150914 - 1st detection of gravitational waves by LIGO - the "brightest" source ever observed

$$L_{GW} = 200^{+30}_{-20} \mathrm{M}_\odot s^{-1} = 3.6^{+0.5}_{-0.4} \times 10^{56} \mathrm{erg\ s}^{-1}$$

- 2021 GWTC-2.1 t**he Virgo-Ligo catalog paper** ~ 50 coalescing black hole binaries (BBH)
  O3a, 6 months in 2019 ~40 BBH !

- **Intermediate Mass Black Holes** (IMBH) in 3 Virgo-LIGO systems:



- **GW190521 → 142 Msol**
- **GW190403_051519 → 105 Msol**
- **GW190426_190642** $106.9^{+41.6}_{-25.2}$ $76.6^{+26.2}_{-33.6}$ → **175 Msol**

- **Expect a lot of discoveries in near future by**
  Advanced LIGO/VIRGO + Kagra detectors + 3rd generation detectors!!!

→ Observation evidence that BBHs merge within Hubble time

→ Evidence for massive stellar BHs with masses higher than 30 solar masses

(their formation requires an origin from low metalicity environments e.g.Belczynski et al. 2010, 2016)