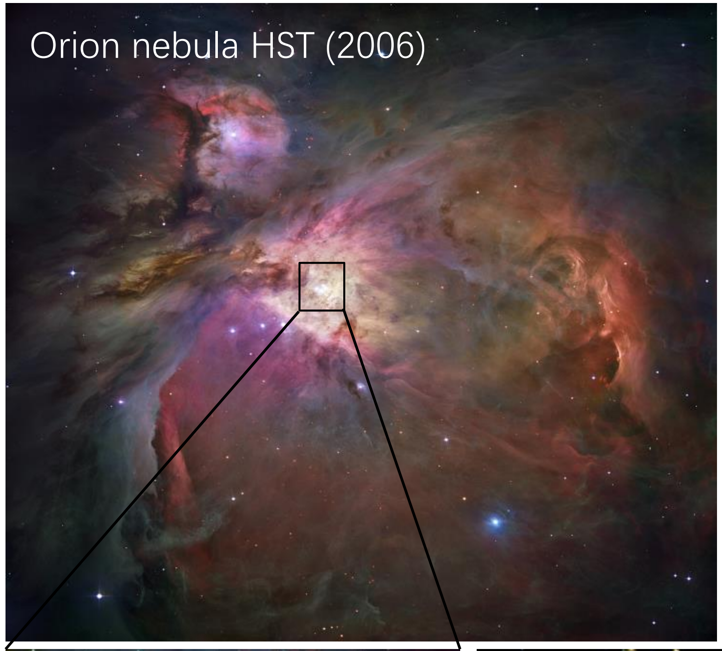
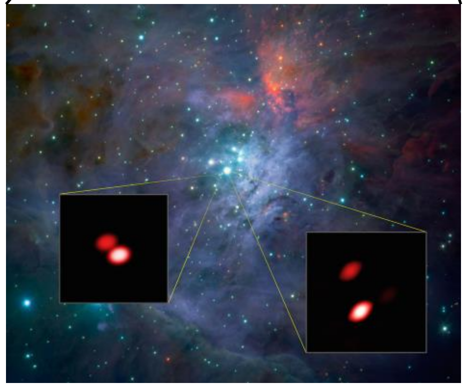
Gravitational waves link to the formation and evolution of star clusters

Long Wang (Associate professor, SYSU)

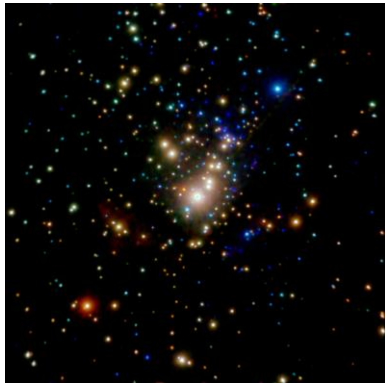
TianQin Astrophysics Workshop 2022/8/22-24

Star formation in star clusters

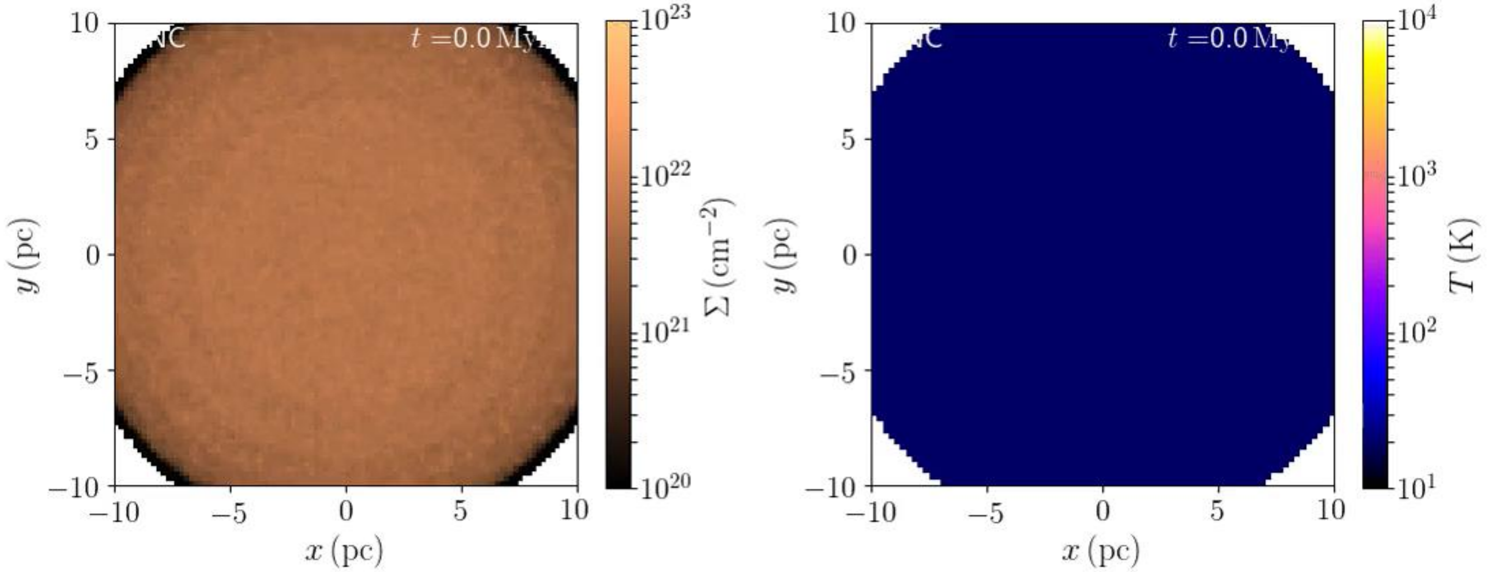




First Light For Future Black Hole Probe | ESO
GRAVITY, VLTI, ESO (2016)



Chandra X-ray
NASA/CXC/Penn State/E.Feigelson & K.Getman et al. 2017

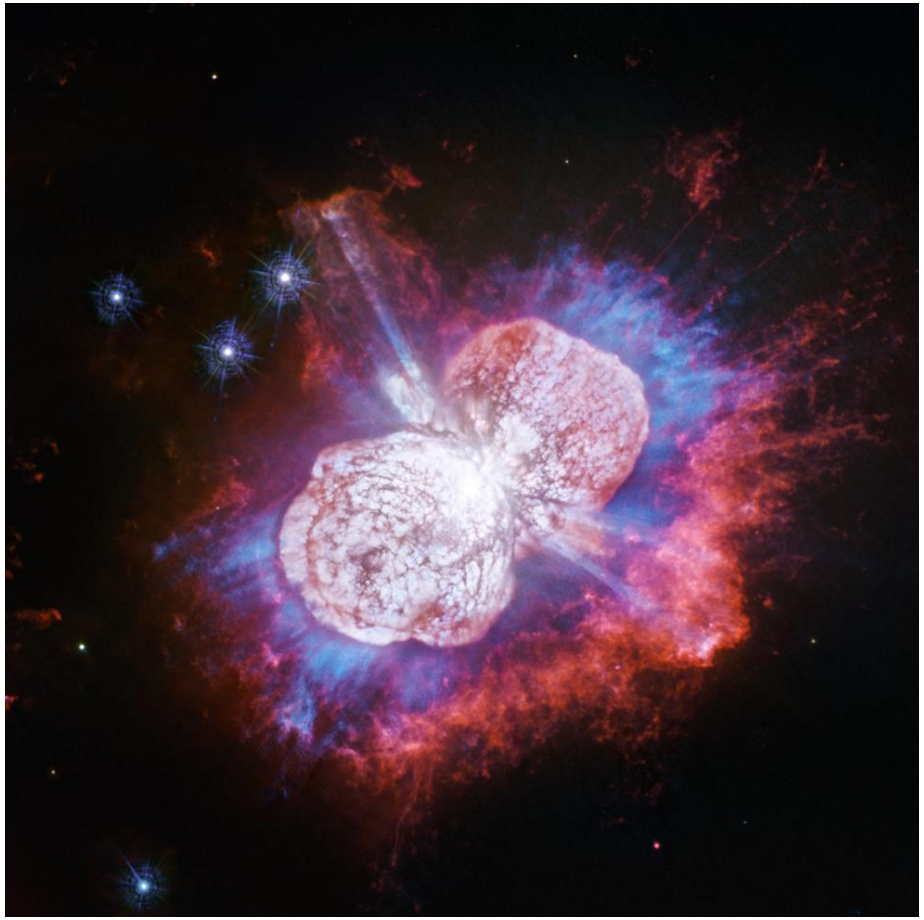


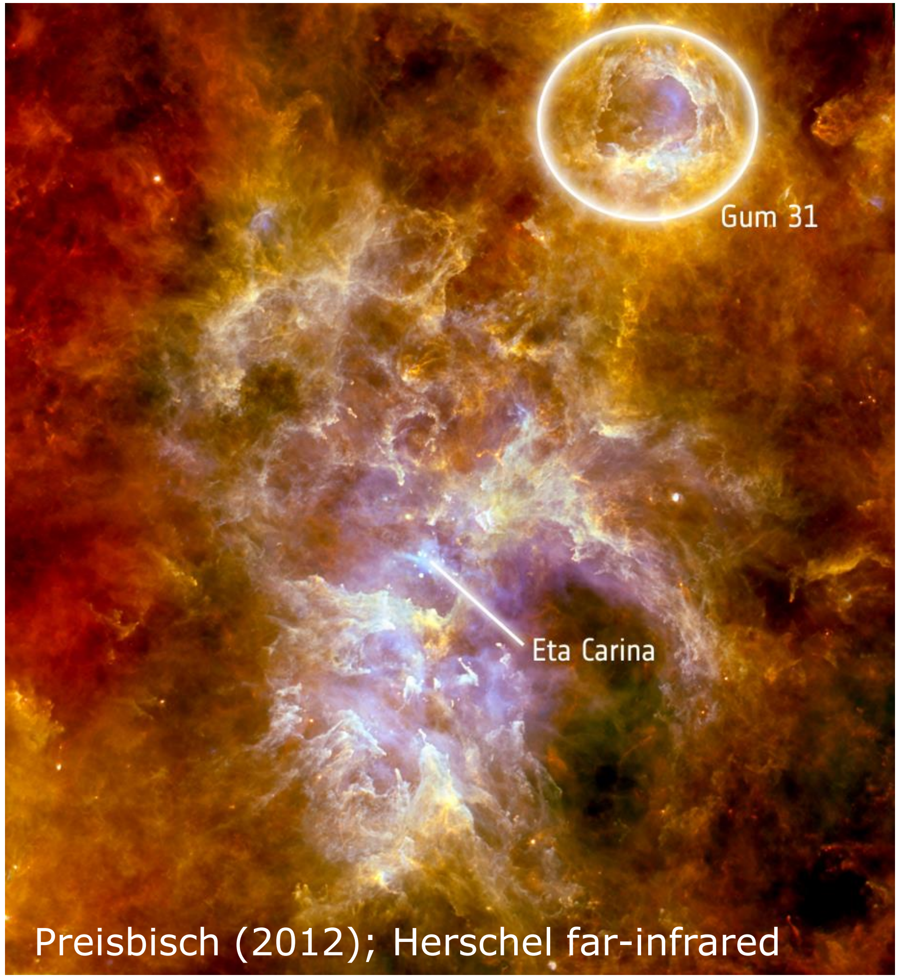
Asura-bridge + PeTar, SIRIUS project (Fujii et al. 2021a,b 2022a,b)

Star formation and evolution are one fundamental problem

- Star form together in giant molecular cloud
- Massive stars have strong feedback to star formation

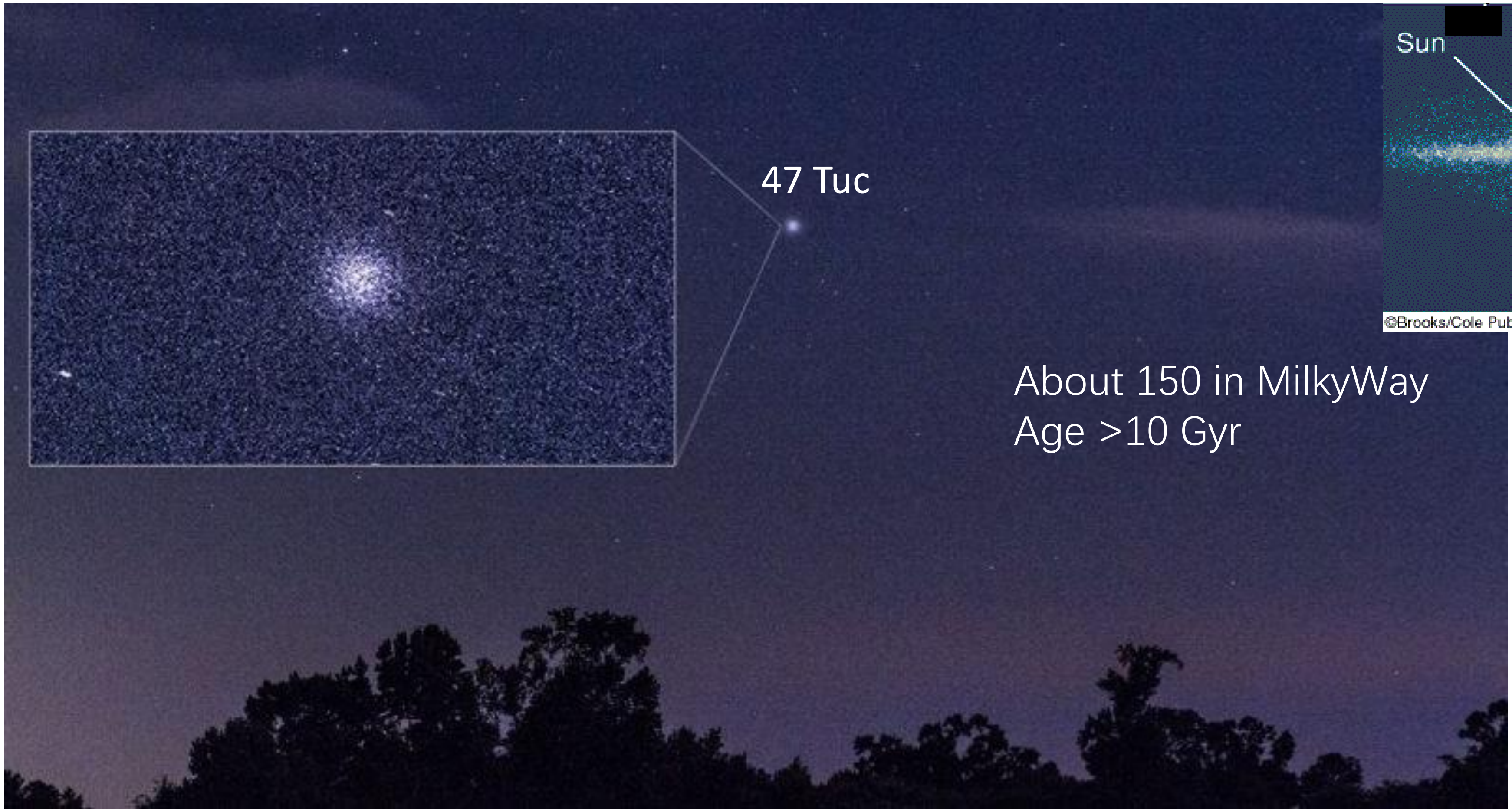
Ionization, wind and supernovae Feedback from massive stars



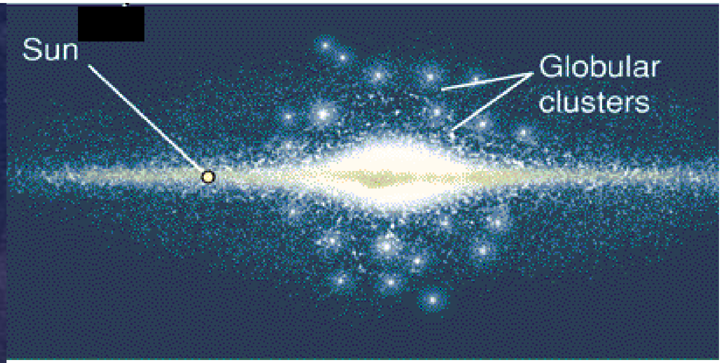


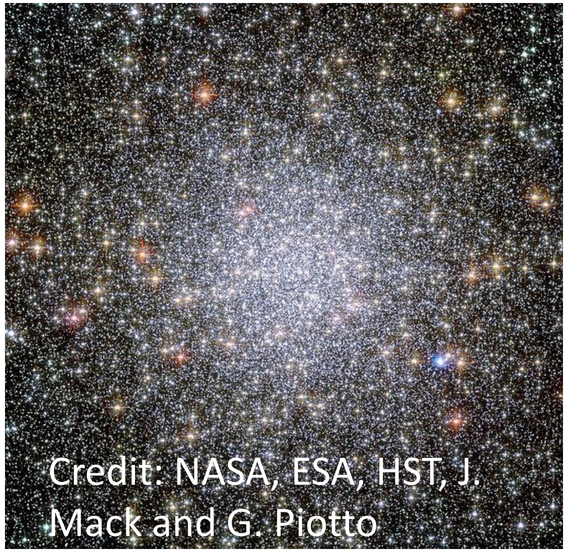
Preisbisch (2012); Herschel far-infrared

Massive old globular clusters (GCs)

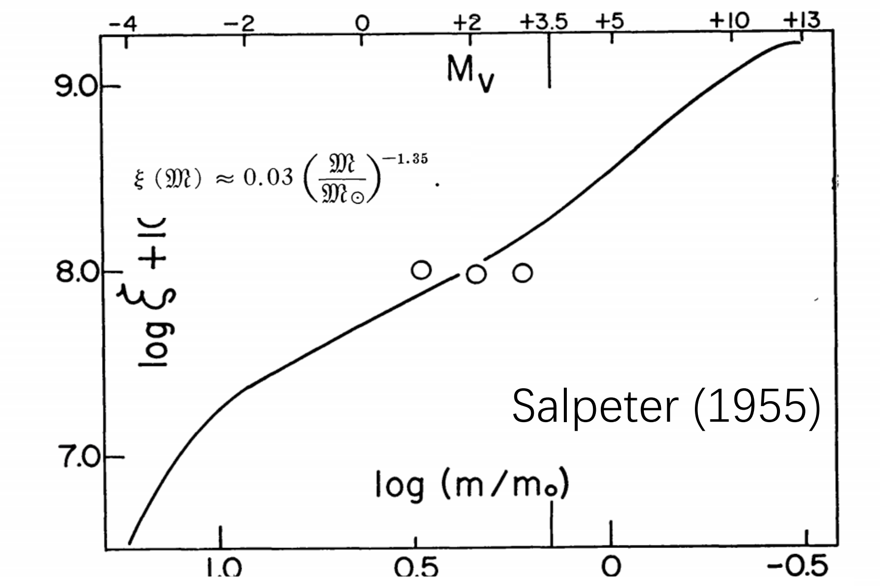


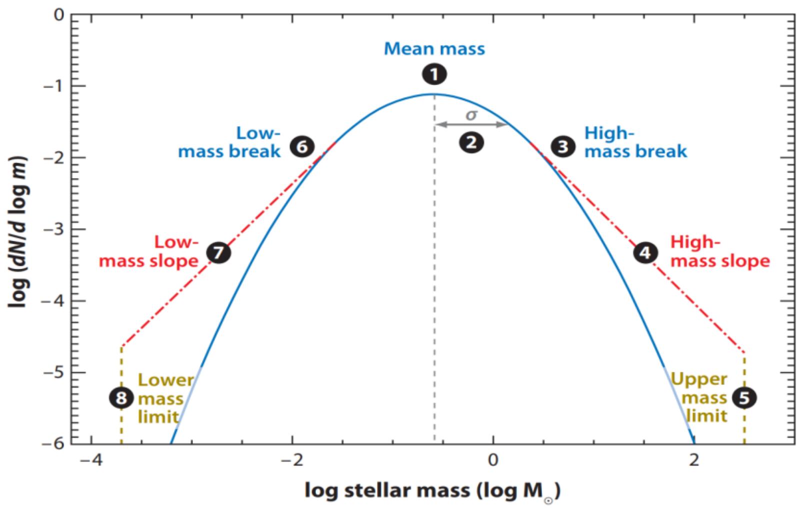
About 150 in MilkyWay
Age >10 Gyr

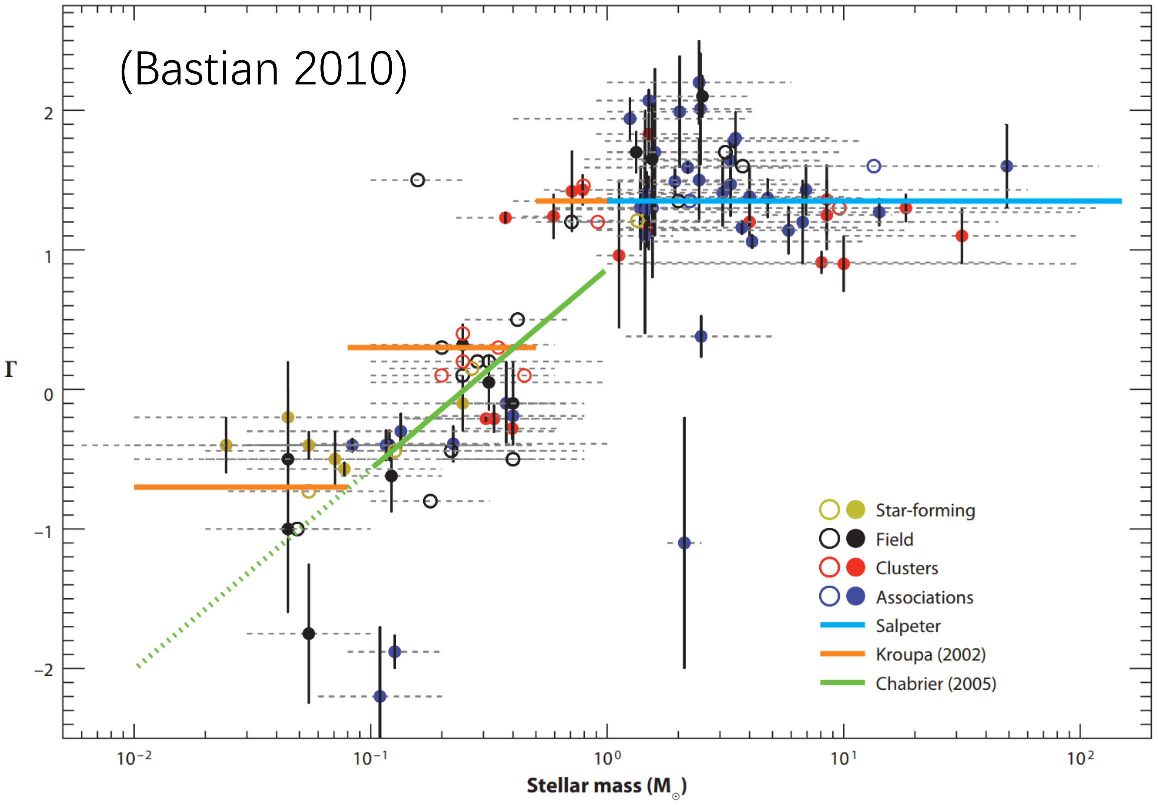




Initial mass function (IMF)







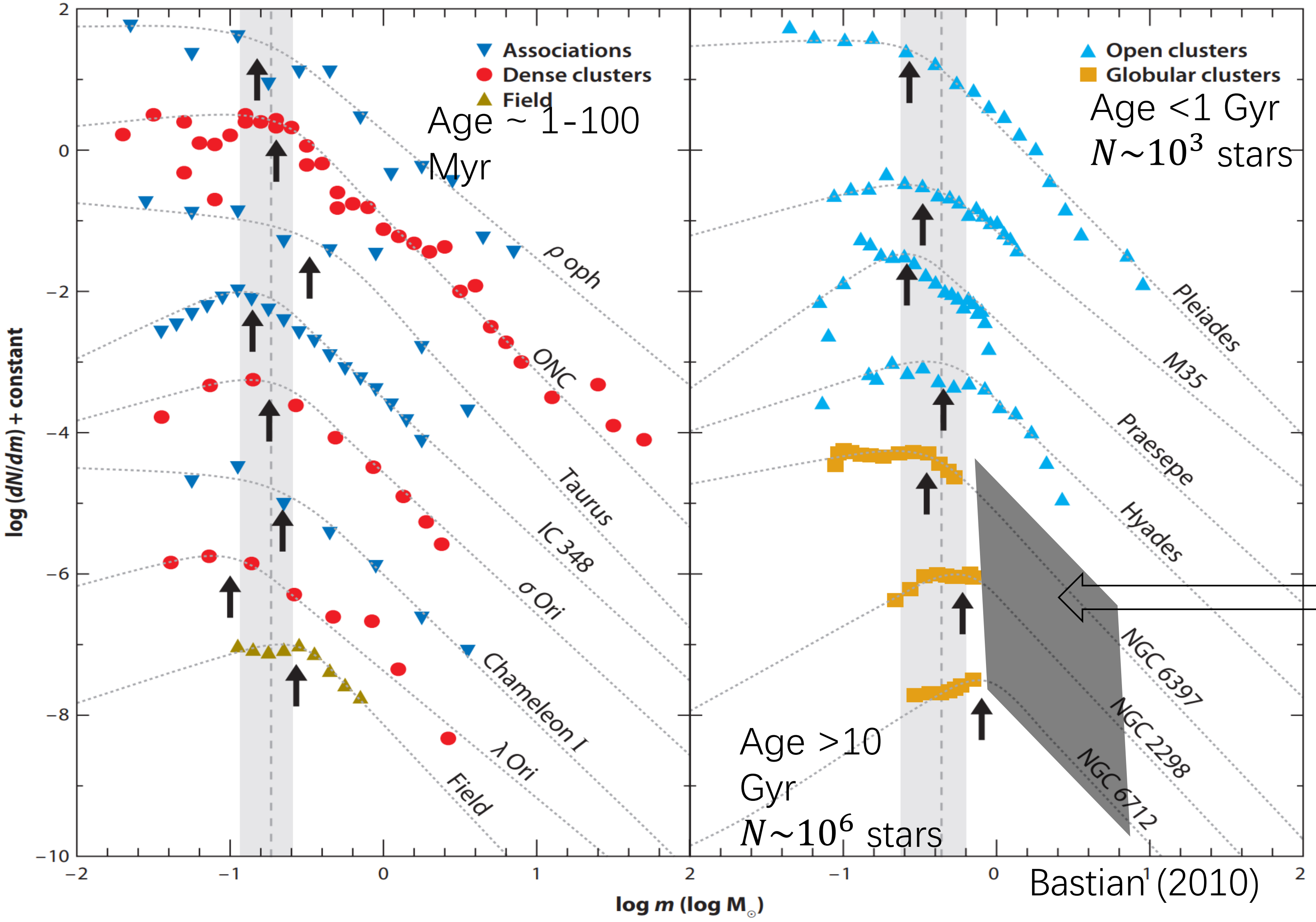
$$\Phi(\log m) = dN/d\log m \propto m^{-\Gamma},$$

The power index of IMF measured from solar neighbor star forming regions

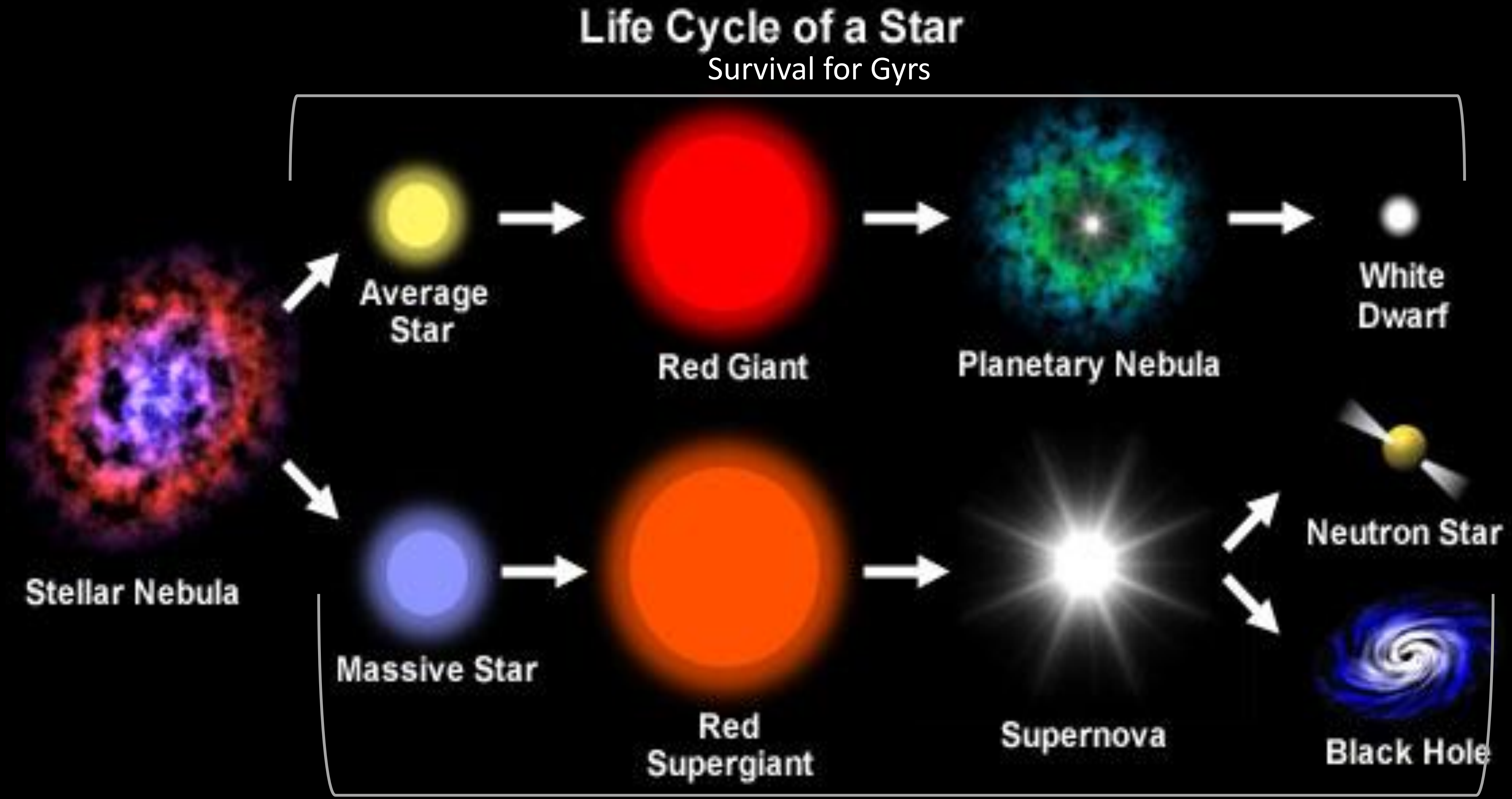
Is IMF universal?

- Most previous assume IMF universal
  - Cosmologic evolution
  - Galaxy formation
  - Stellar mass determination for distant star clusters
  - Modelling star formation and cluster evolution

IMF from different stellar systems



Cannot obtain from EM observaition

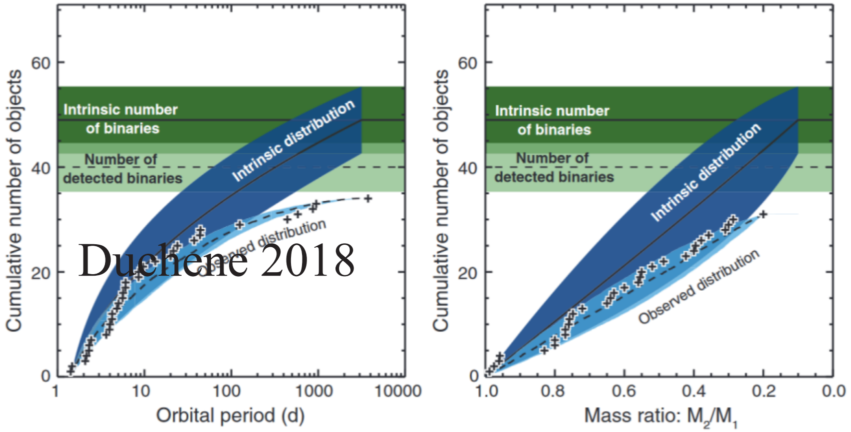


Only <100 Myr for massive stars

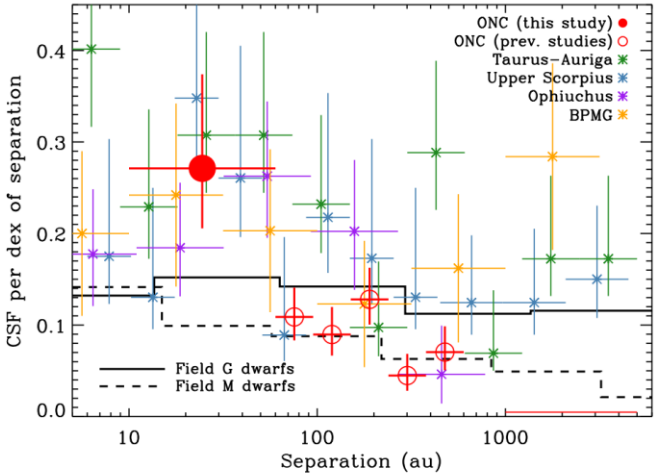
credit: NASA

Universal properties of primordial binaries?

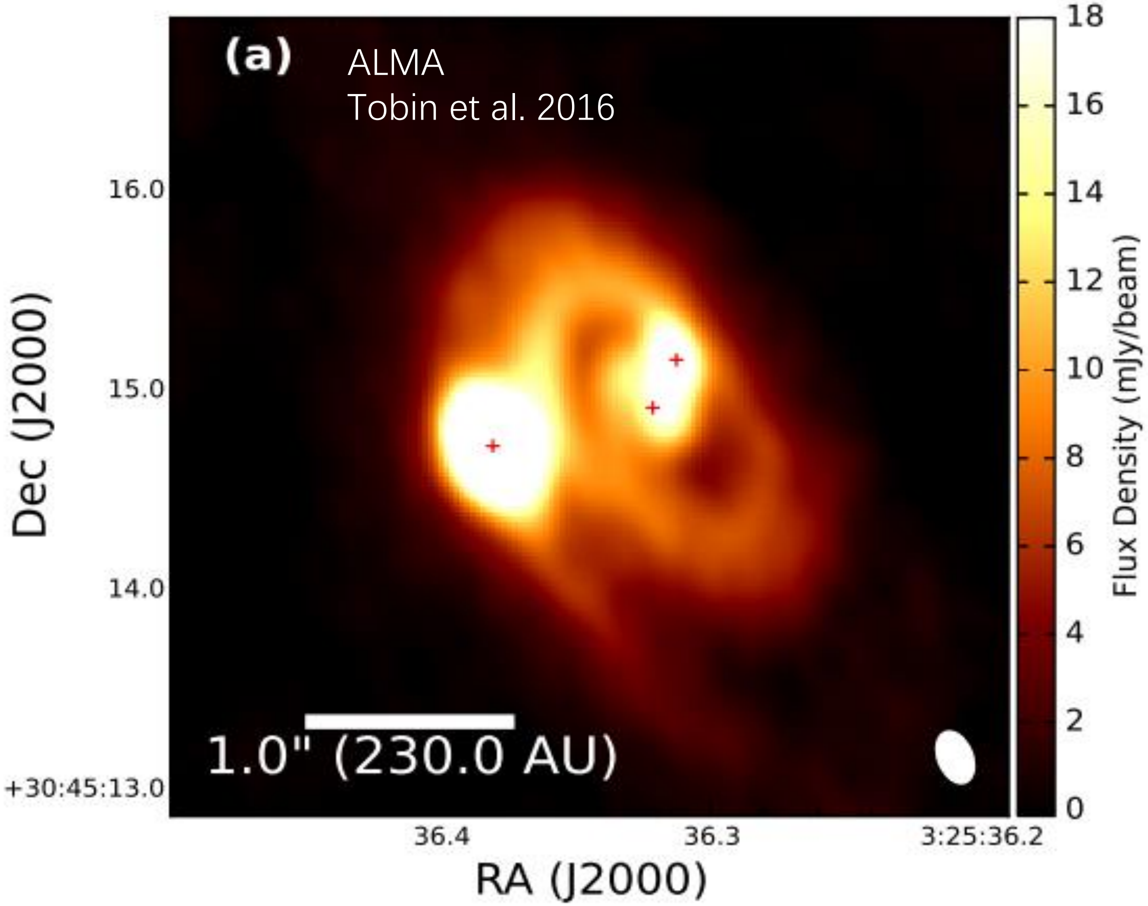
- Young star clusters have almost 100% primordial binary of OB stars (Sana 2012)

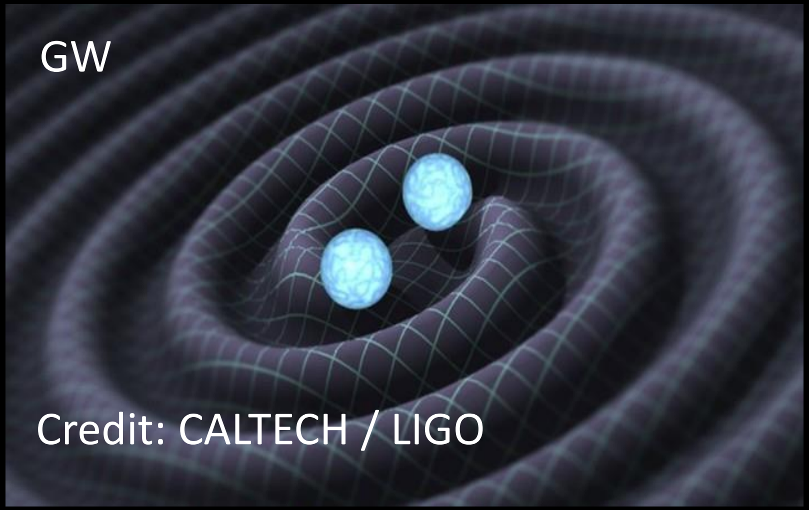


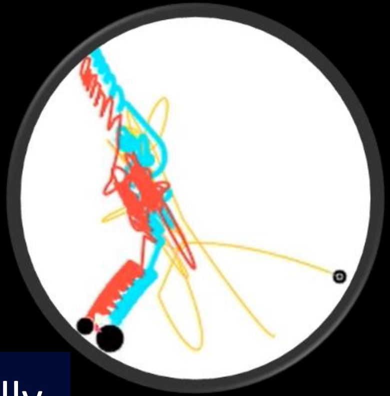
- Binary fraction of low-mass stars:

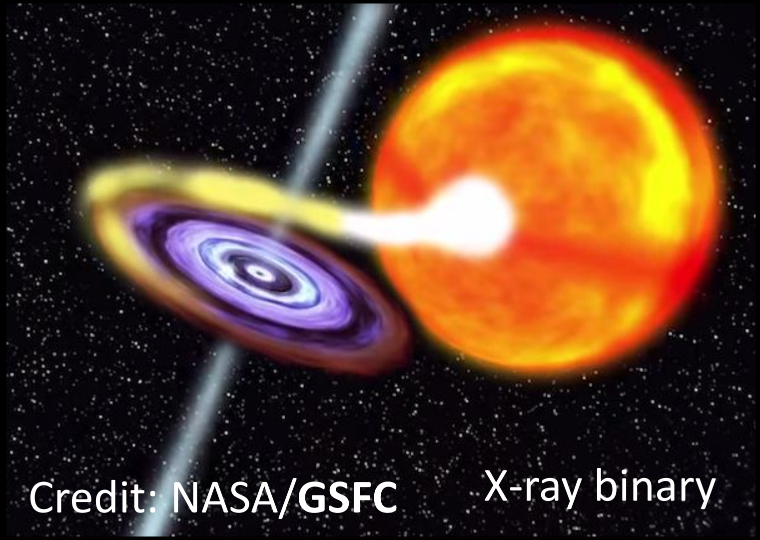


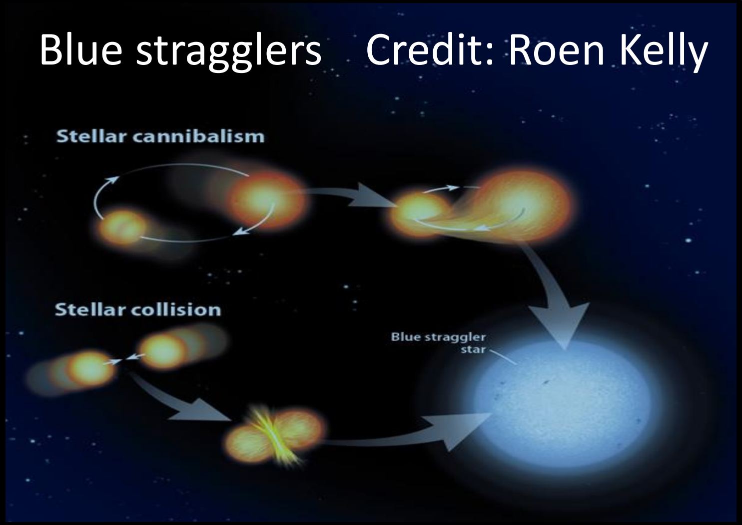
Hierarchical triple systems




GW
Credit: CALTECH / LIGO




Credit: NASA/**GSFC**
X-ray binary


Blue stragglers
Credit: Roen Kelly
Stellar cannibalism
Stellar collision
Blue straggler star

BBH mergers strongly depend on IMF

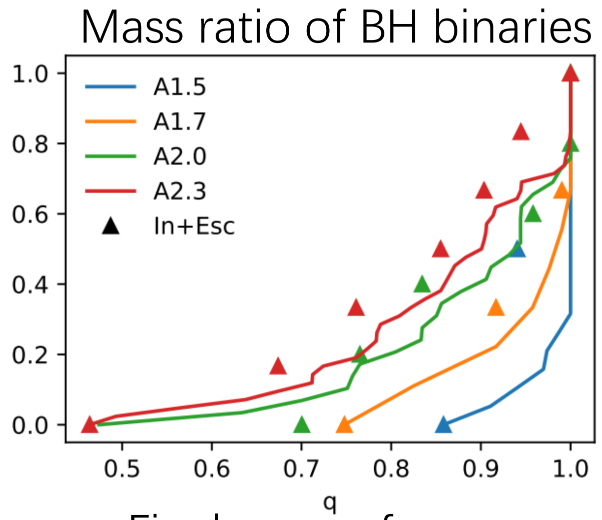
- Multiple component IMF (Kroupa 2001)

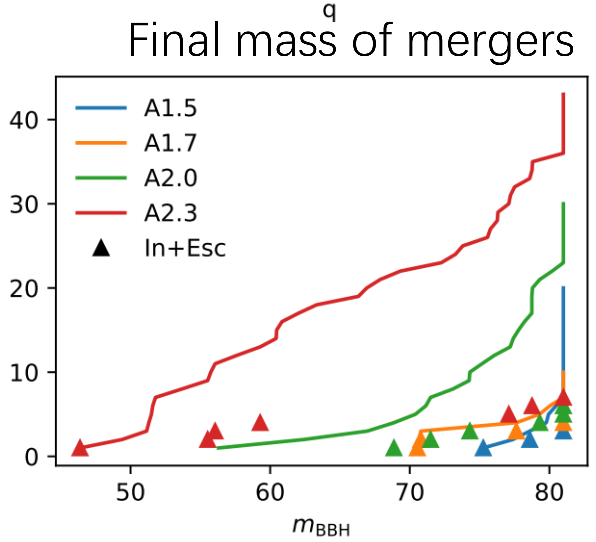
$$0.08 < m \leq 0.5\, M_\odot \quad \alpha_1 = -1.3$$
$$0.5 < m \leq 1 M_\odot \quad \alpha_2 = -2.3$$
$$1 < m < 150 M_\odot \quad \alpha_3 = -2.3$$

- Vary Γ of IMF from Kroupa (2001)

Γ	**0.5**	**0.7**	**1.0**	**1.3**
M_{BH}/M	55%	38%	18%	7%

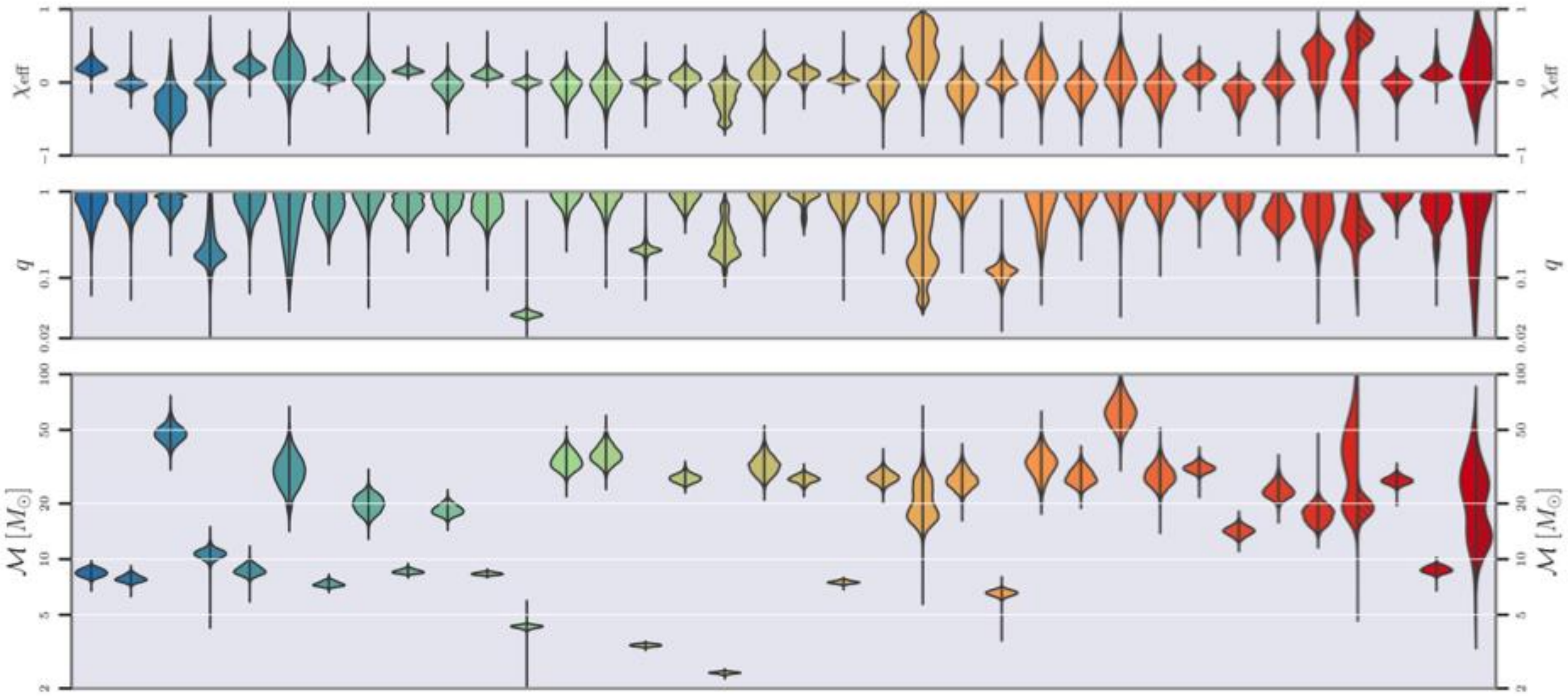
- $Z = 0.001$ Wang et al. 2021
- Better statistic data of GW events may help to constrain IMF in the future





Gravitational waves from LVK observation

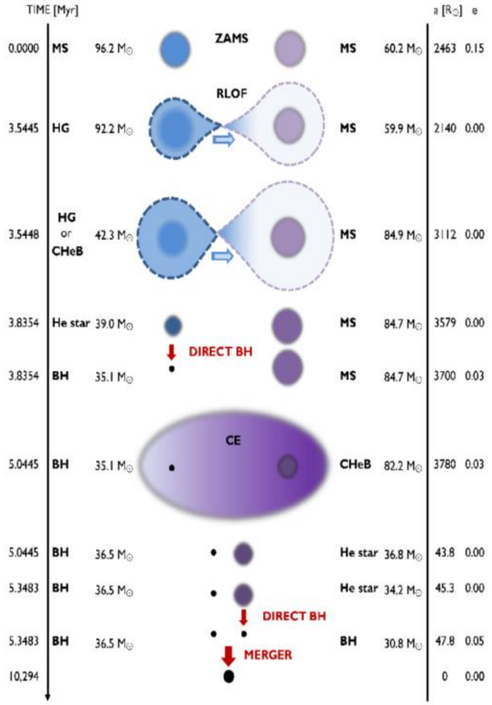
LIGO-Virgo-KAGRA release
new catalog from 3rd observing run



Gravitational waves (GWs) from binary black hole (BBH) mergers

Stellar-evolution channel

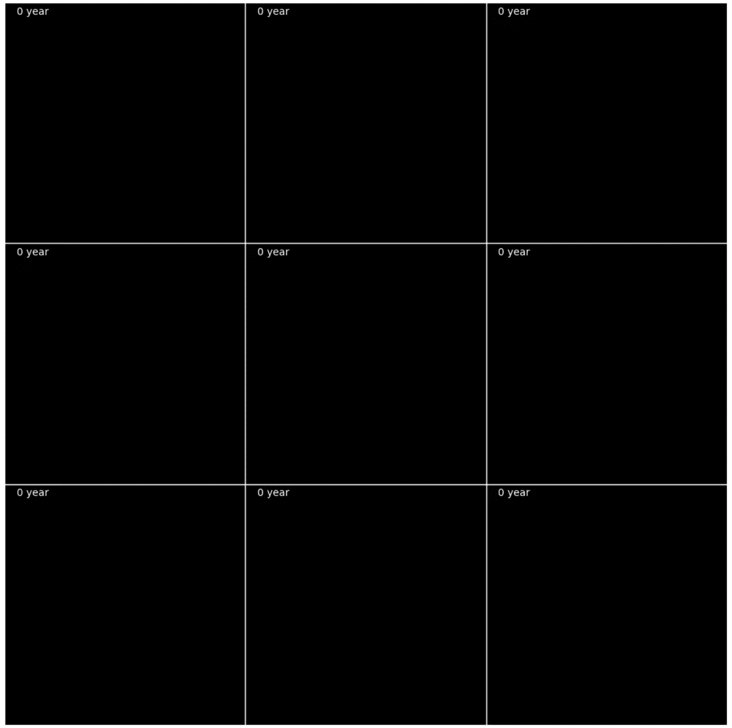
- **common envelope**, *e.g., Giacobbo 2018; Belczynski, 2020*
- ***stable mass transfer***, *e.g., Kinugawa 2014, Tanikawa 2020*



Highly uncertain, require fine tuning

Dynamical channel

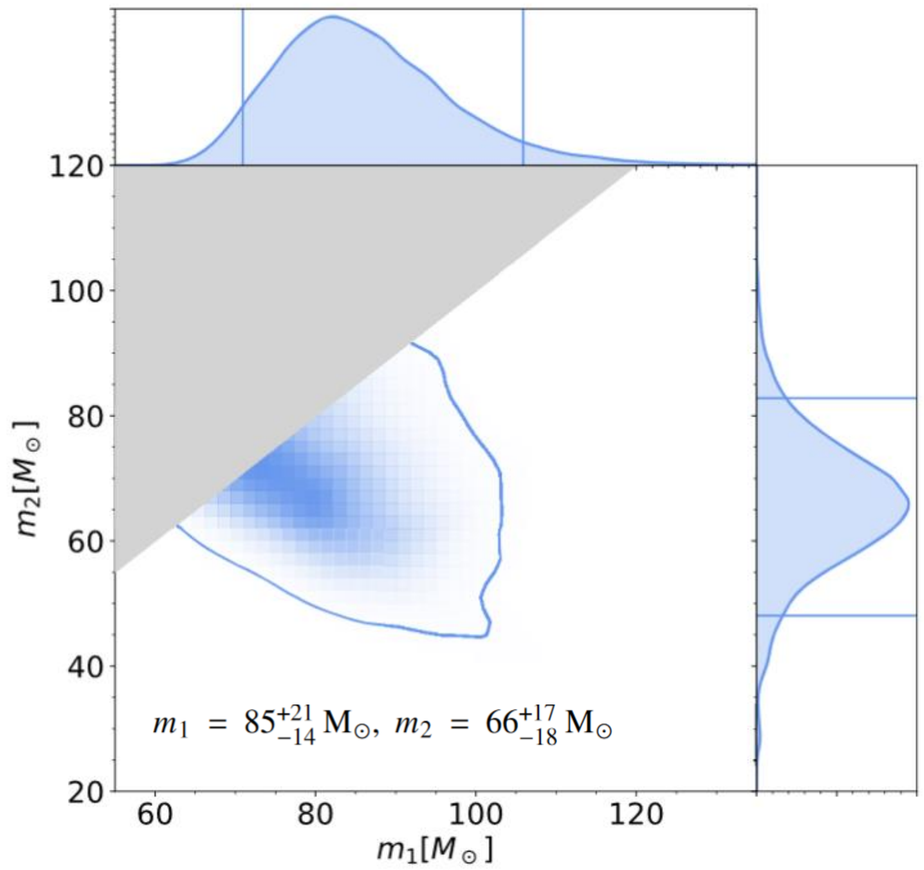
- **globular clusters**, *e.g., Portegies Zwart 2020, Tanikawa 2013, Rodriguez 2016; Askar 2017; Fujii 2017*
- **open clusters**, *e.g., Di Carlo 2019; Kumamoto 2019*
- **galactic center**, *e.g., O'Leary 2009, Antonini 2019*



Purely dynamics

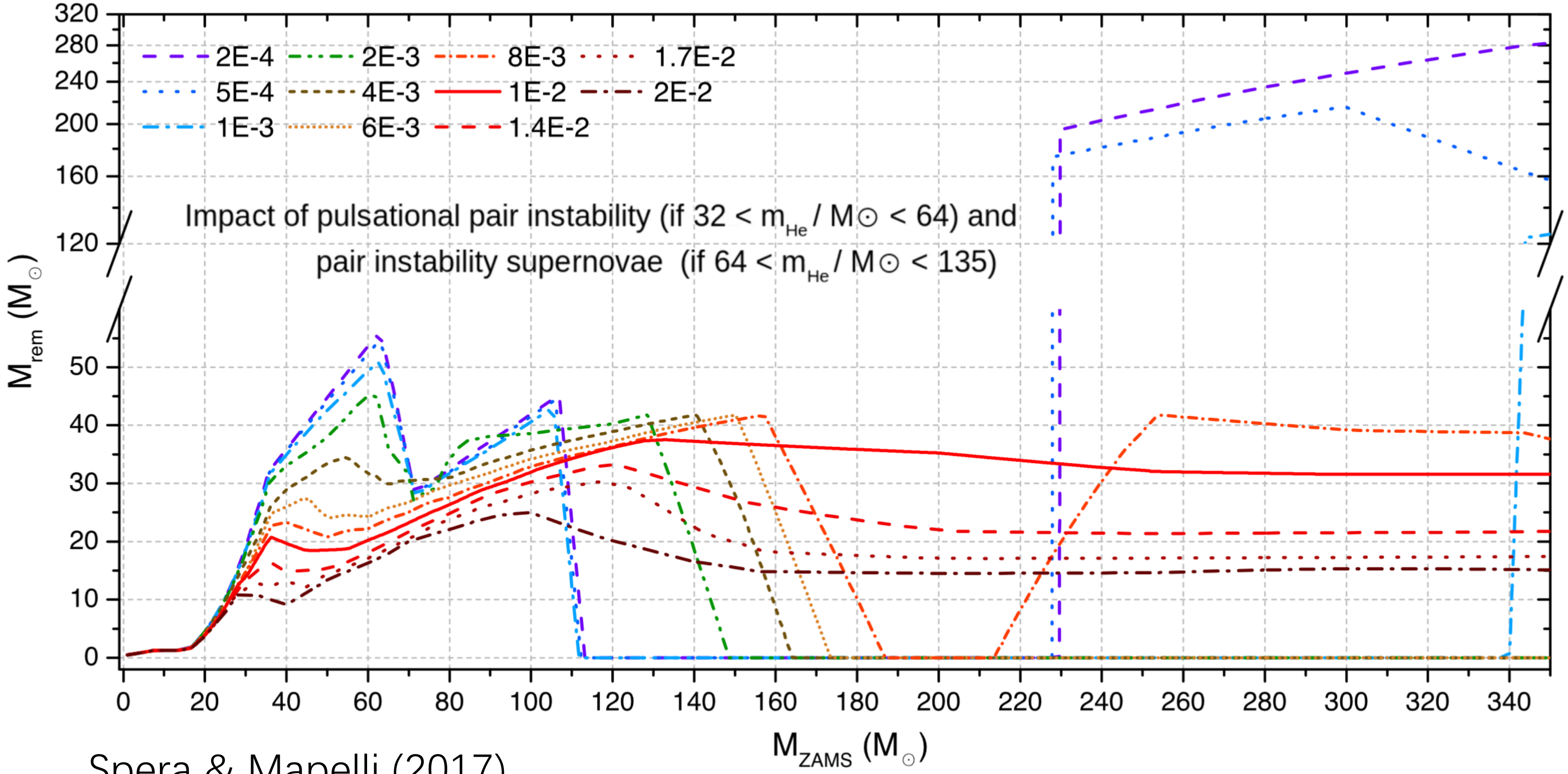
GW190521

A Binary Black Hole Merger with a Total Mass of $150\ M_{\odot}$



LIGO/VIRGO (Abbott et al. 2020)

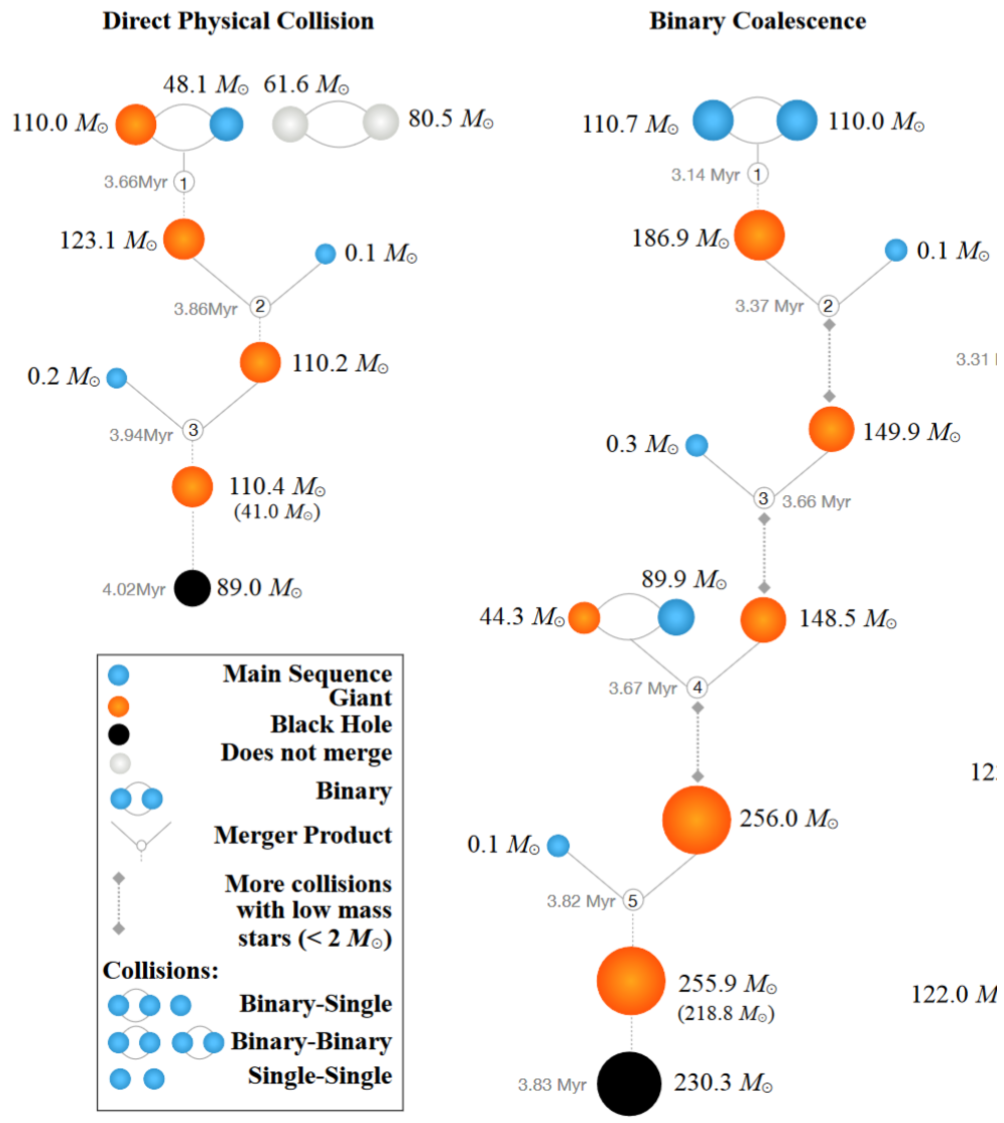
Pair-instability mass gap of BHs



Spera & Mapelli (2017)

Pair-instability BBH mergers

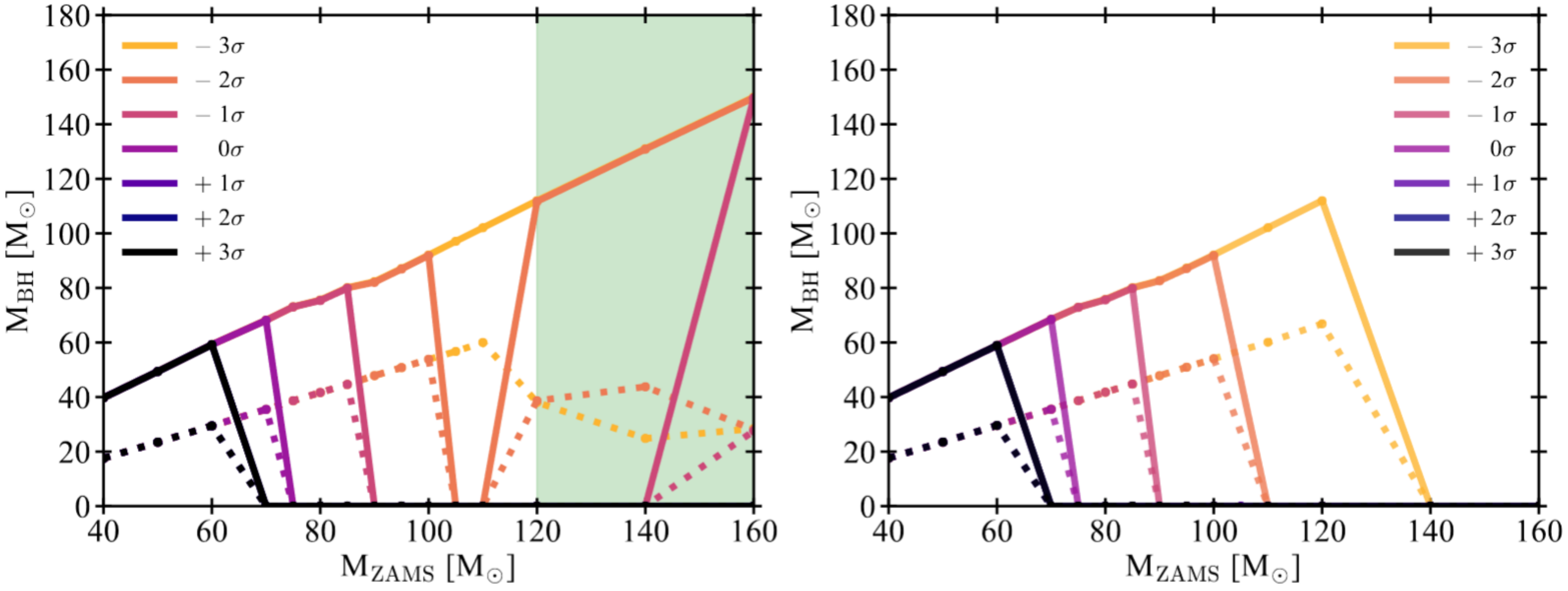
Binary stellar evolution may generate pair-instability BH



González et al. 2021

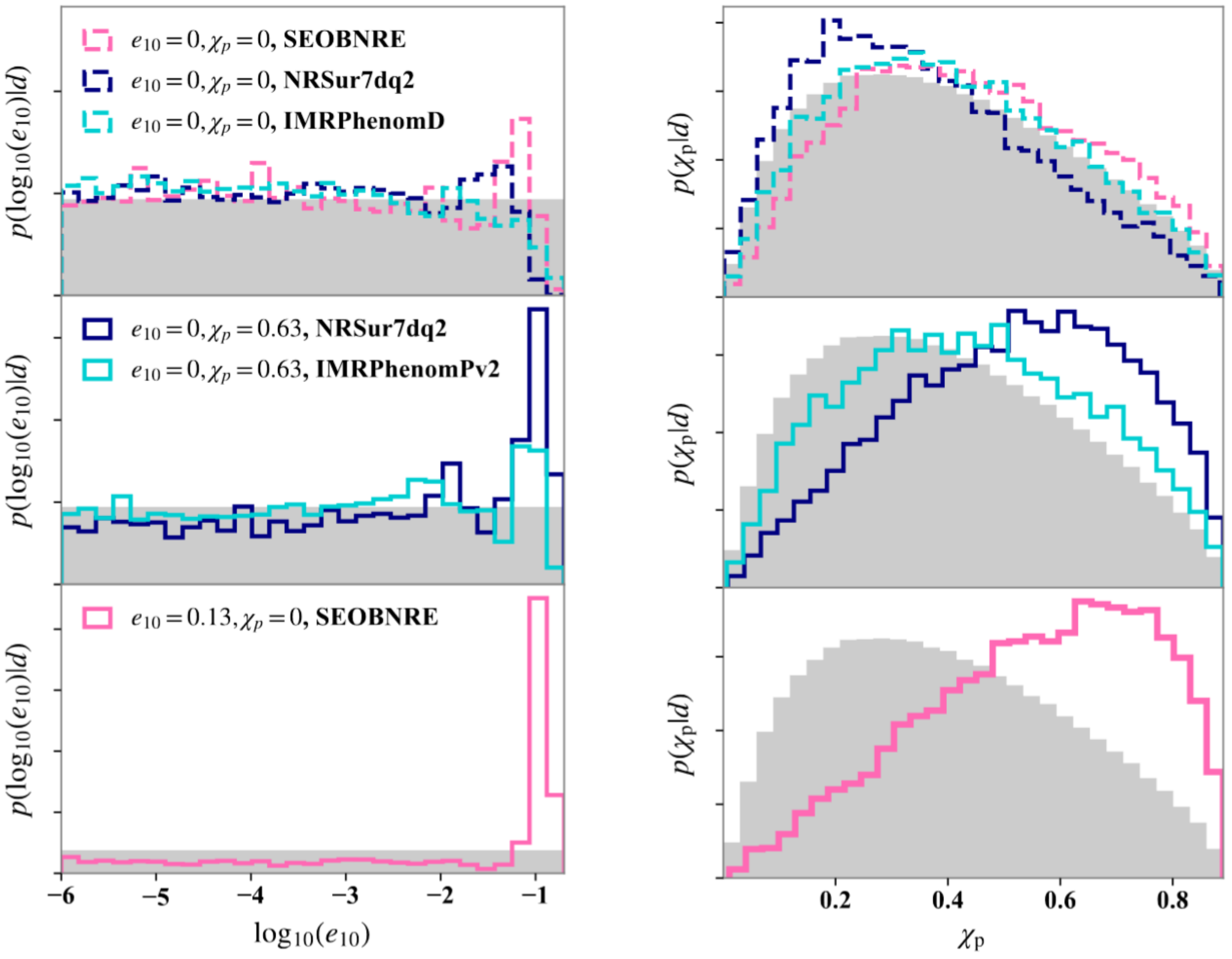
Pair-instability BBH mergers

Impact of stellar evolution models (Costa et al. 2021)

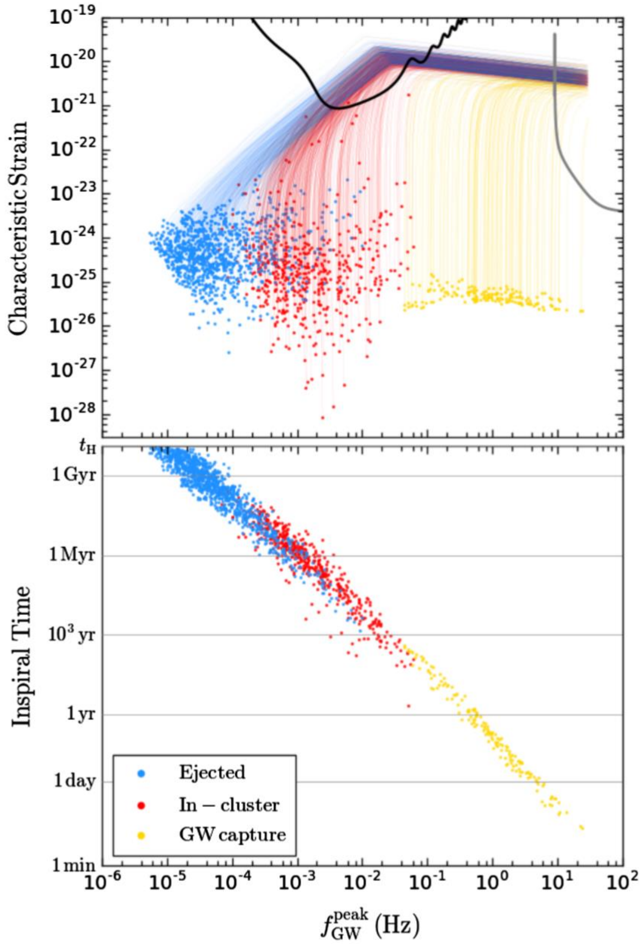


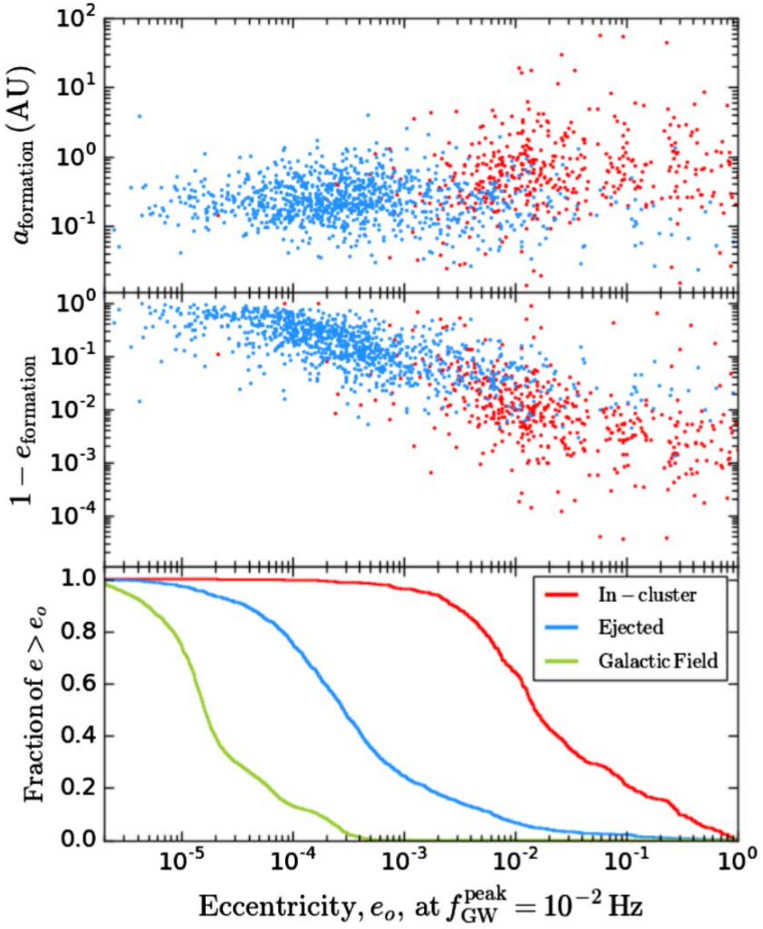
GW190521 orbital parameters

- (Romero-Shaw et al. 2020)



Better constraint on eccentricities via space-borne GW detectors



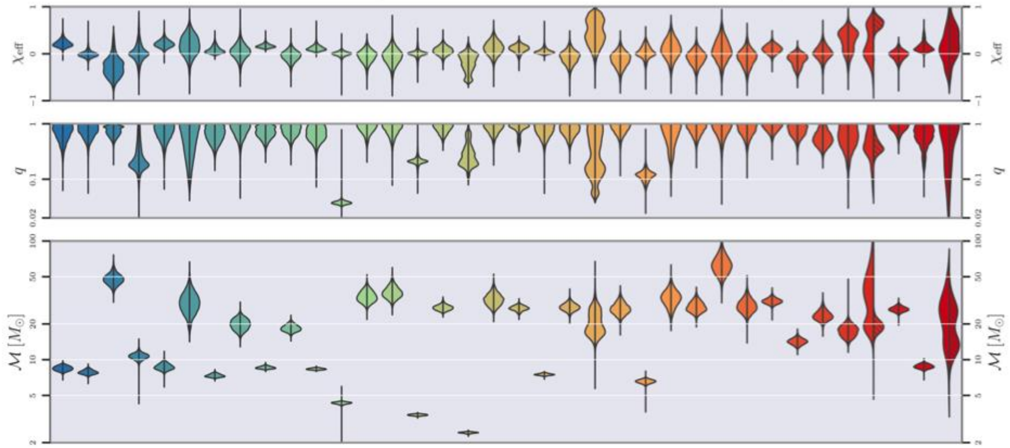


Kremer et al. 2019

Missing intermediate-mass black holes (IMBHs)

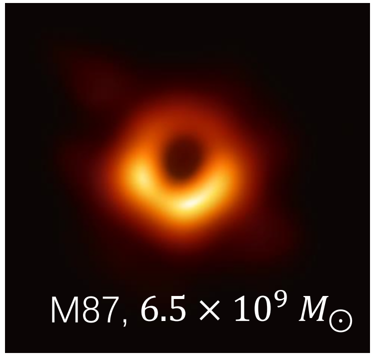
Stellar mass black holes

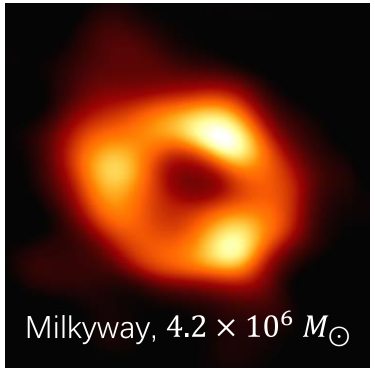
LIGO-Virgo-KAGRA release
new catalog from 3rd observing run



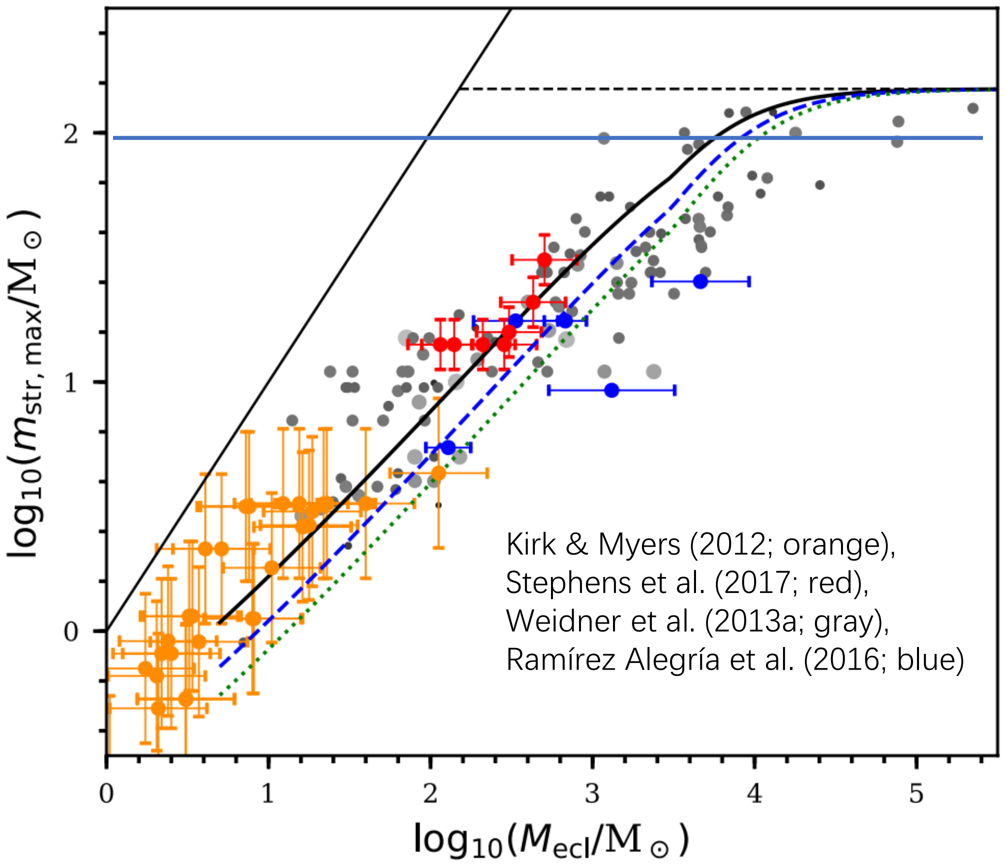
Supermassive black hole

(Event horizon telescope, 2019, 2022)





Maximum mass of a star during star formation



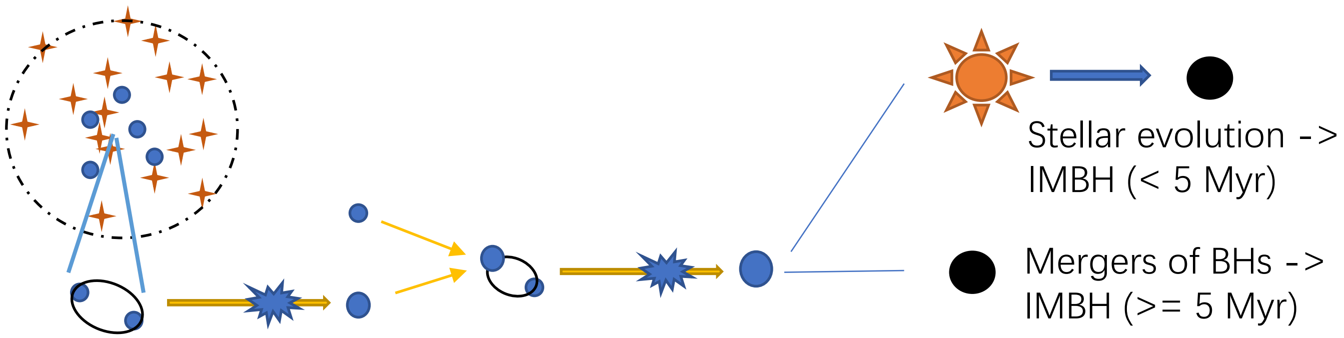
$\sim 150\ M_\odot$

Pair-instability mass gap of BH

Yan et al. 2017

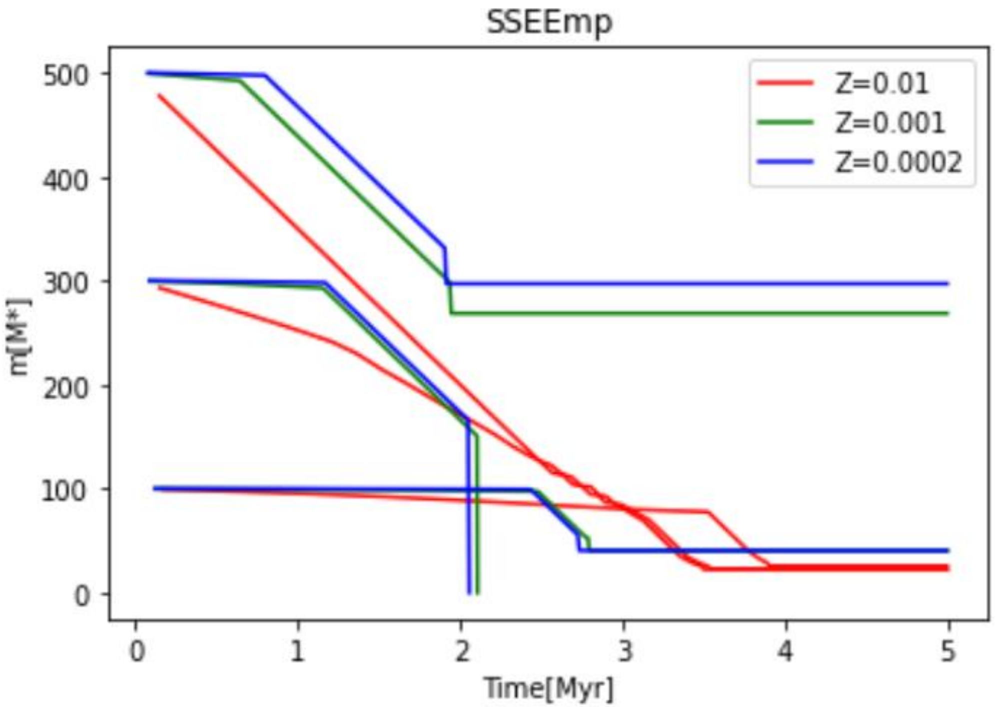
Formation of IMBHs in dense star clusters

- Hierarchical mergers of massive stars / stellar mass BHs
  - (e.g. Taniguchi et al. 2000, Miller & Hamilton 2002; Mouri & Taniguchi 2002; Gültekin et al. 2004; Portegies Zwart et al. 2002, 2004, 2006, Freitag et al. 2006; Giersz et al. 2015; Antonini et al. 2018; Kroupa et al. 2020; Rizzuto et al. 2021; Mapelli et al. 2021, 2022; Kremer et al. 2020; González et al. 2021; Wang et al. 2022)
- Young massive clusters, GCs and nuclear star clusters

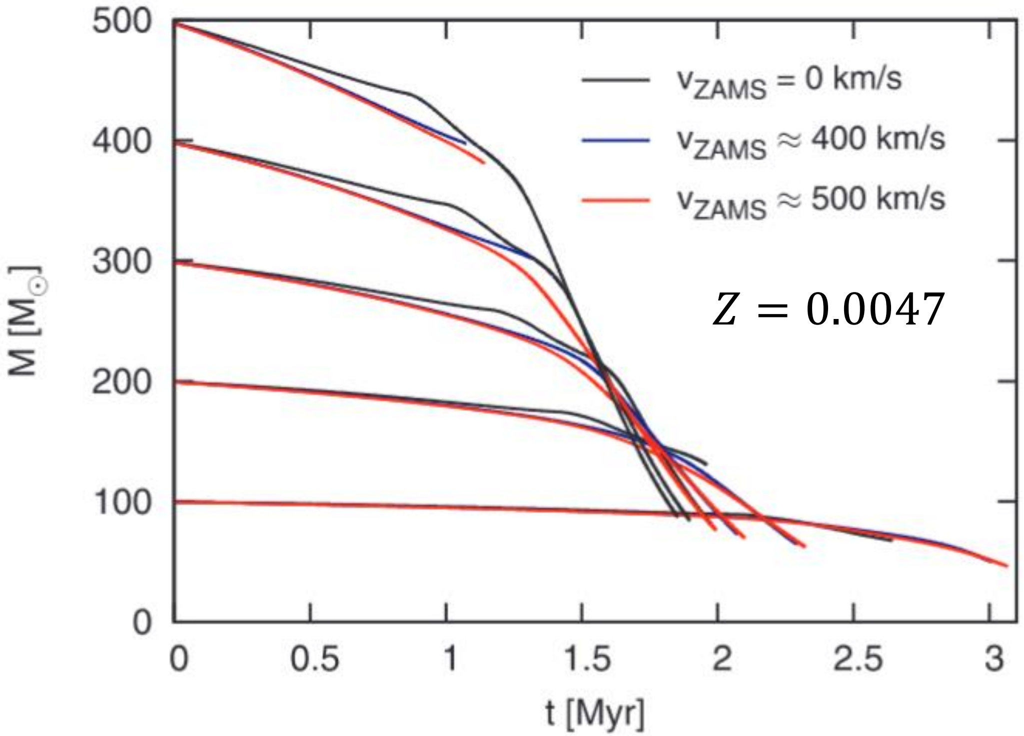


Wind mass loss of massive stars

Crucial condition: hierarchical mergers must occur within a short period (<2 Myr) to grow up very massive stars



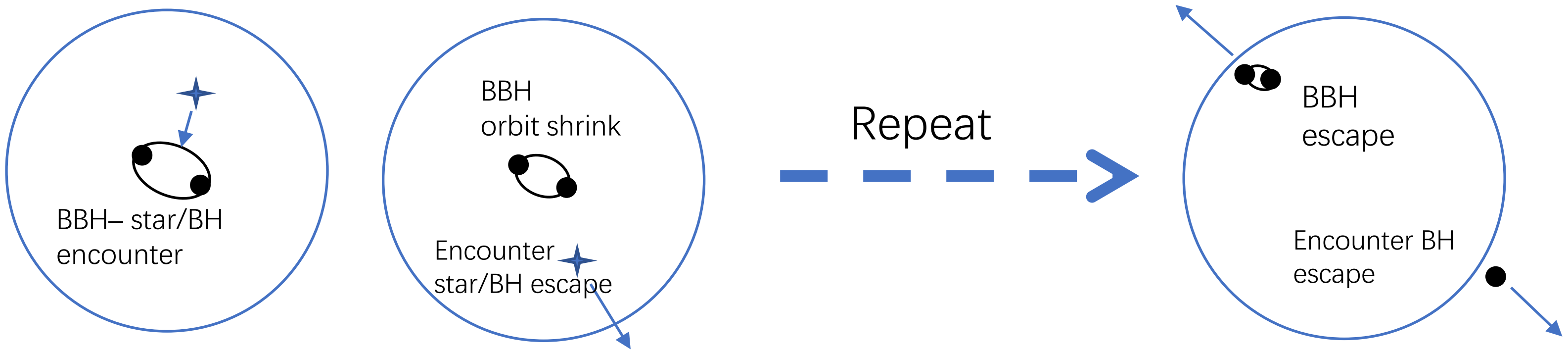
SSEEmp code
(Tanikawa et al. 2020)

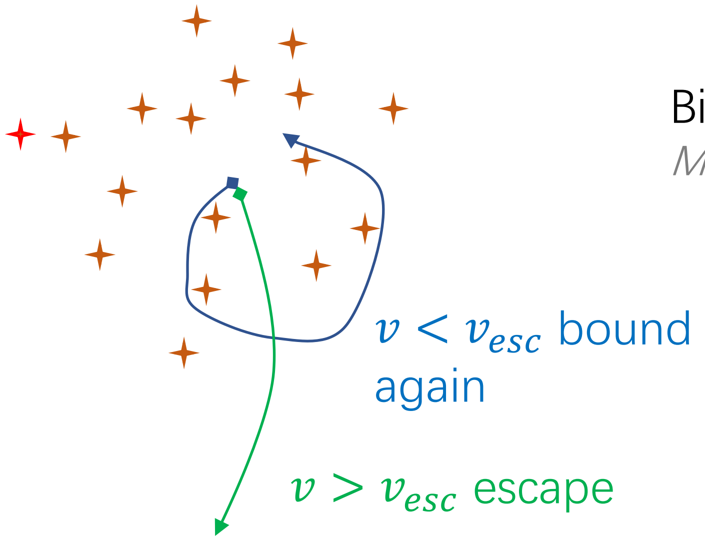


With rotation (Köhler 2015)

IMBH form from BBH mergers

Crucial condition: gravitational potential should be strong enough to keep BBH mergers



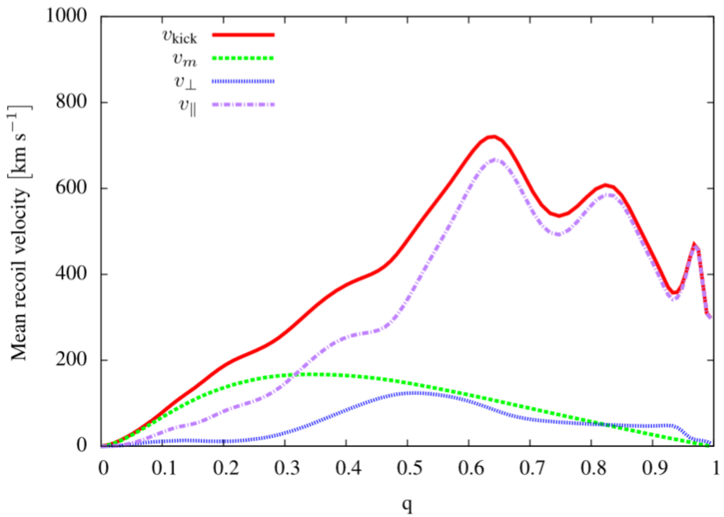


Binary ejection criterion

Miller & Hamilton 2002; Mapelli et al. 2021

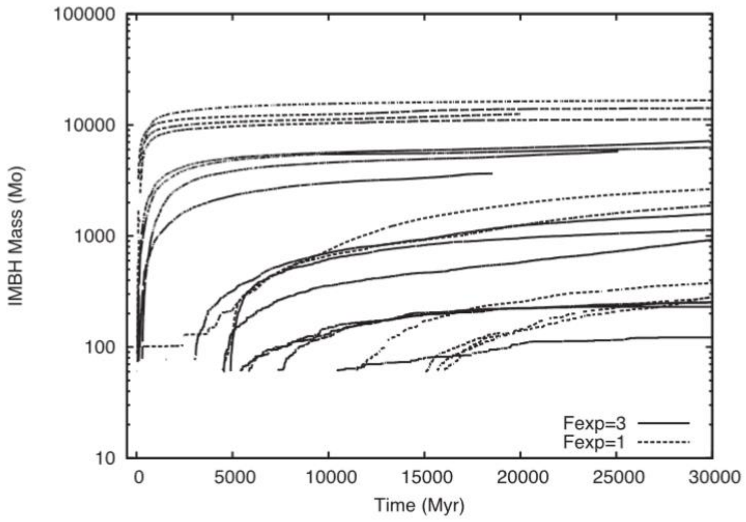
$$a_{ej} \propto \frac{\langle m \rangle^2 m_1 m_2}{(m_1 + m_2)^3 v_{esc}^2}$$

GW recoil (Morawski et al. 2018)

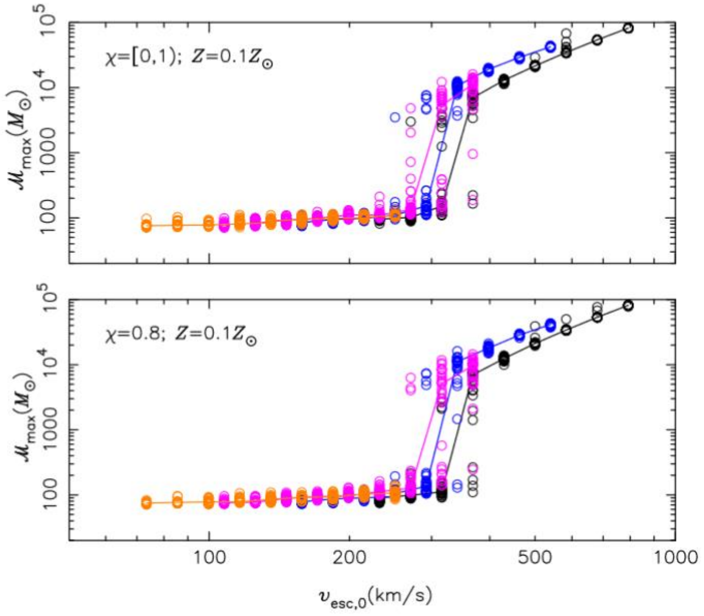


IMBHs form in GCs, UCDs and NSCs

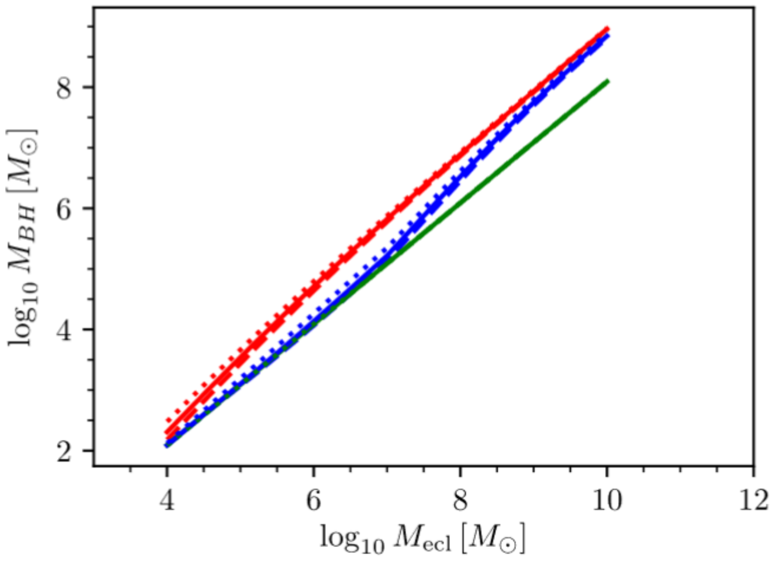
Monte-Carlo simulations of GCs (MOCCA, Giersz 2015)



Analytic model of NSCs (Antonini et al. 2019)



Analytic model of UCDs (Kroupa et al. 2020)

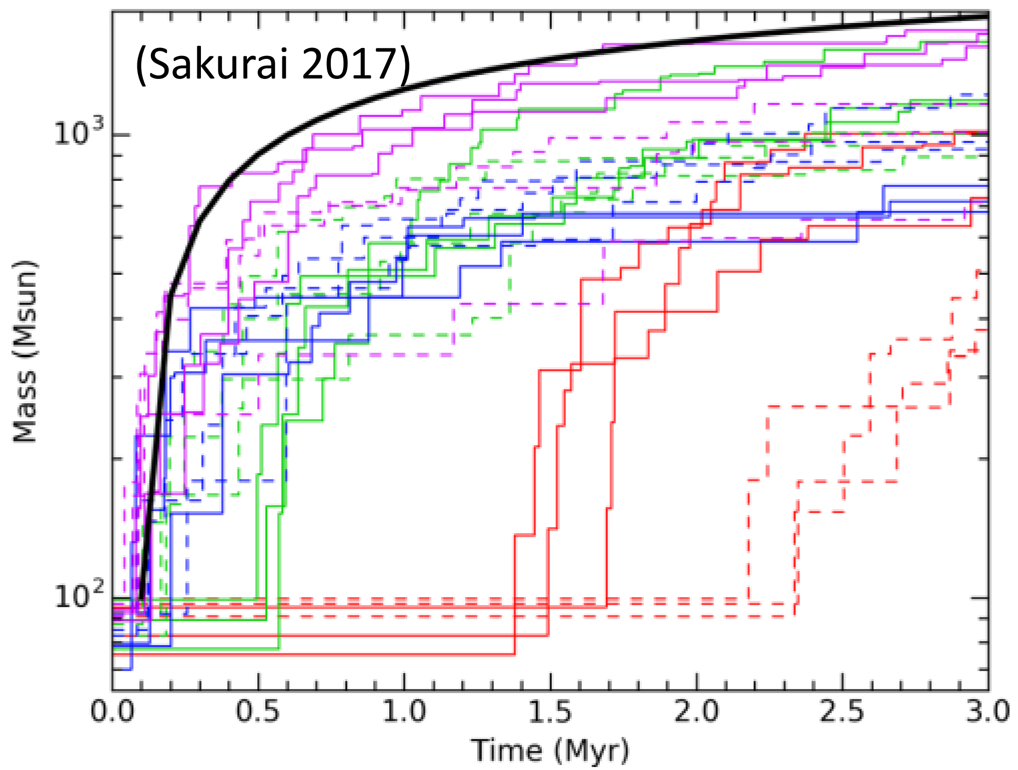


IMBH in Population III (Pop3) star clusters

- Formation of very massive stars (VMSs) via multiple mergers in Pop3 star clusters

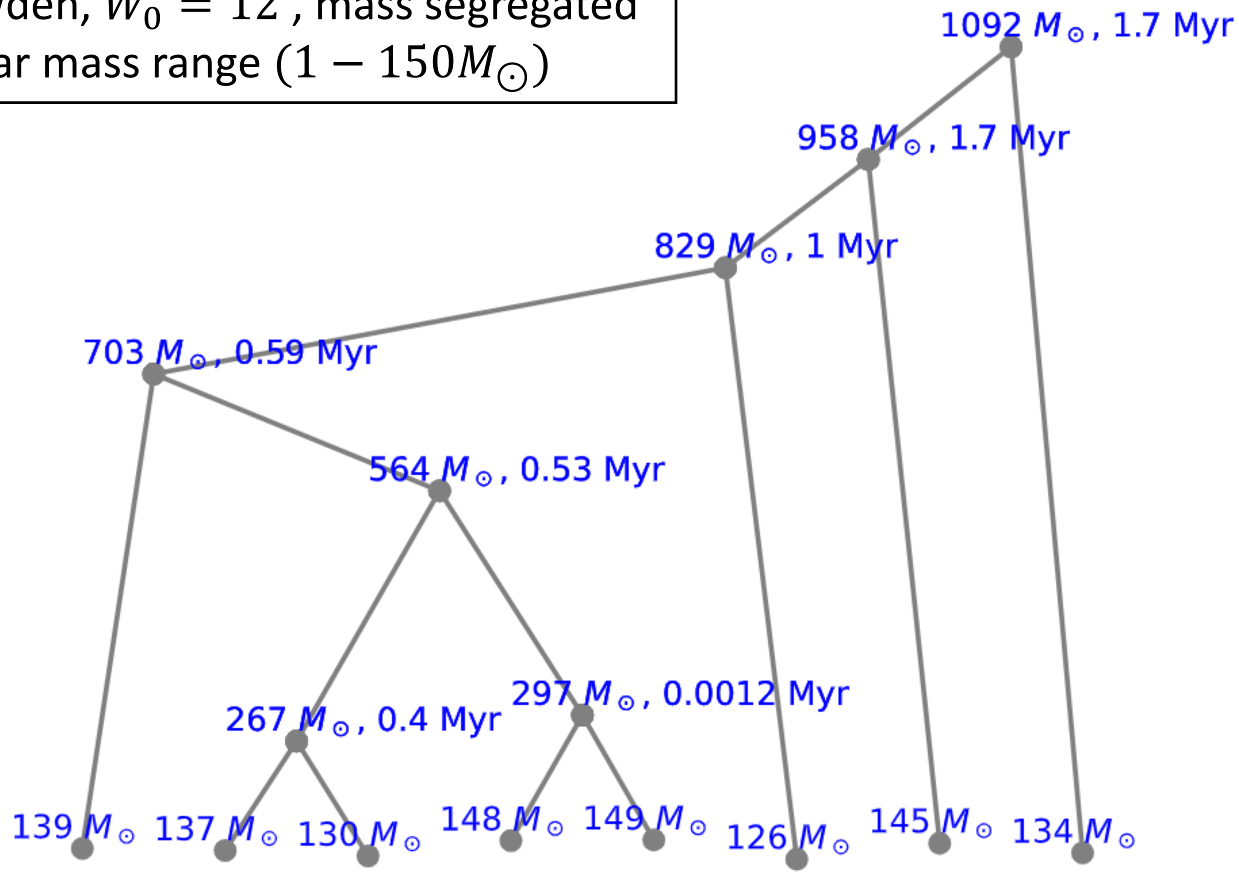
- Cosmological galaxy formation
  -> star cluster formation
  -> star cluster dynamics

- Time-consuming computing
  Stop at early time (a few Myr)

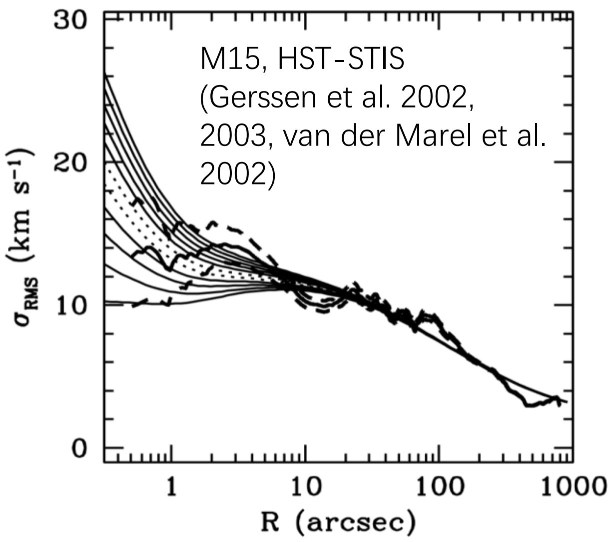


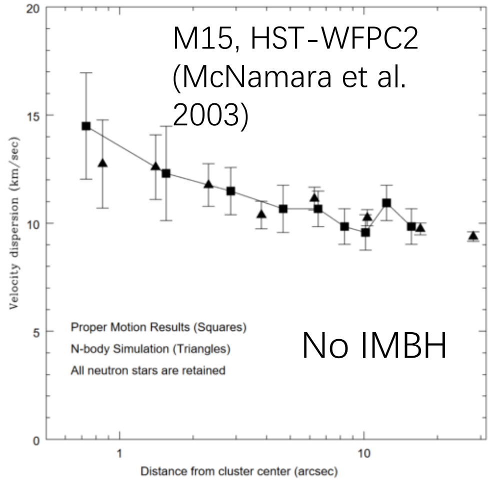
Hierarchical mergers of stars

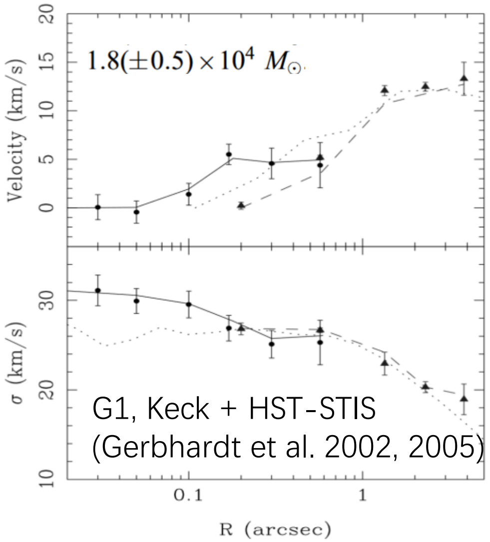
NFWden, $W_0 = 12$, mass segregated
stellar mass range $(1 - 150 M_{\odot})$

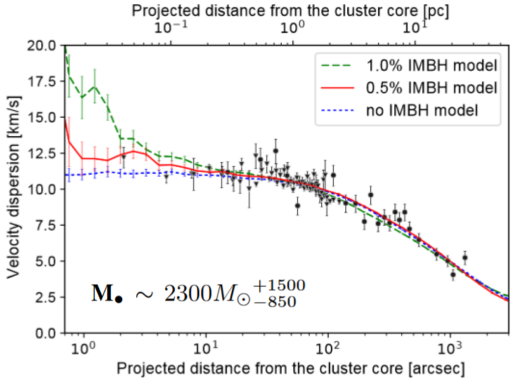


Search IMBH in GCs using velocity dispersion

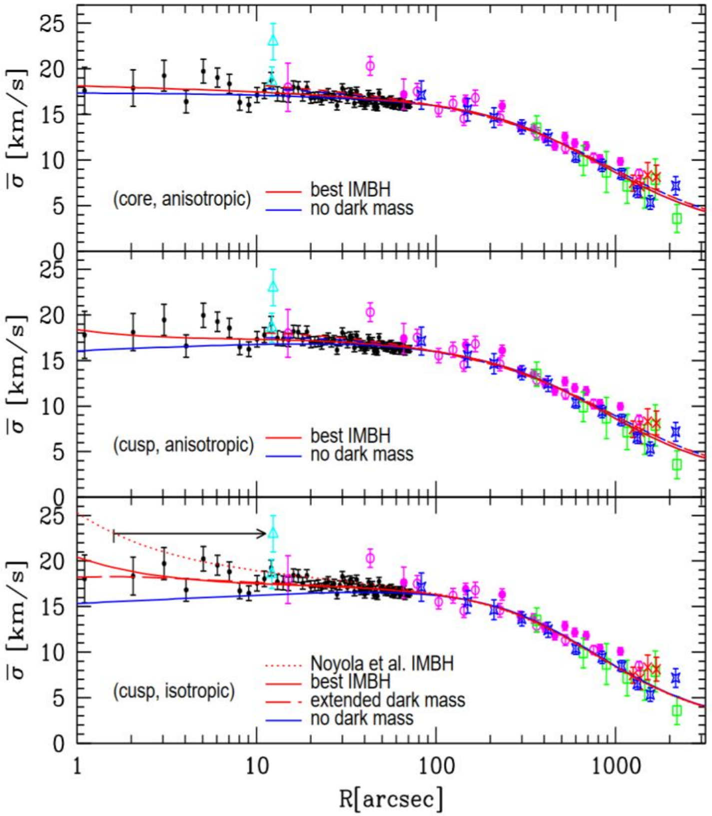








47 Tuc, Pulsar- Parkes radio telescope
(Kızıltan et al. 2017)

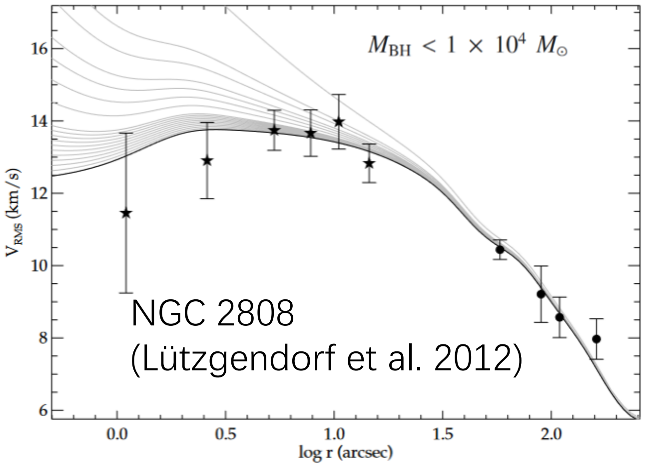


ω-Cen, Gemini GMOS-IFU, HST-ACS
(Noyola et al. 2008, Anderson & van der Marel 2010a,b)

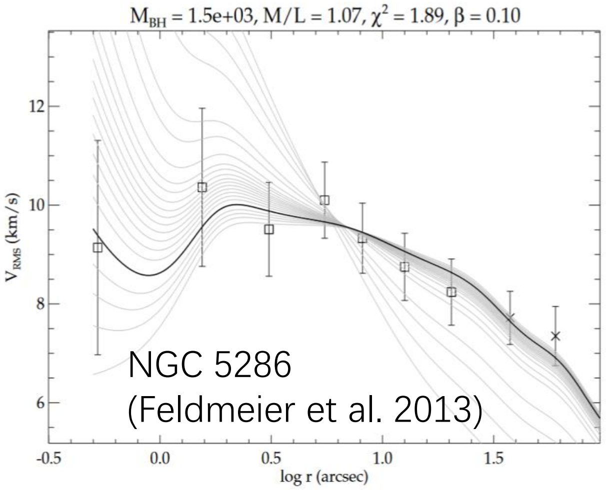
Search IMBH in GCs using velocity dispersion

Integral field units (IFU)   VLT/FLAMES, HST-ACS

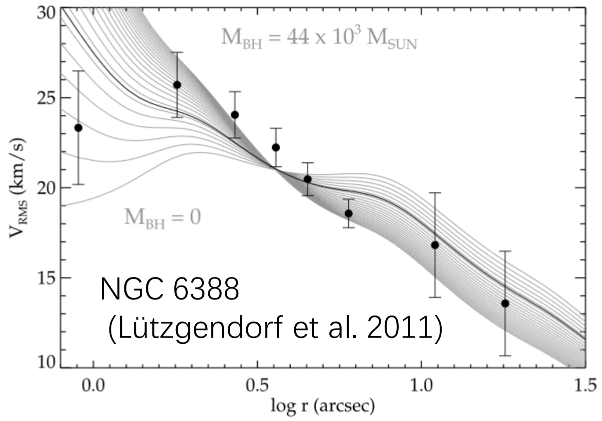
$\mathrm{M_{BH}} \sim 10^3 M_\odot$ (Lützgendorf et al. 2013)



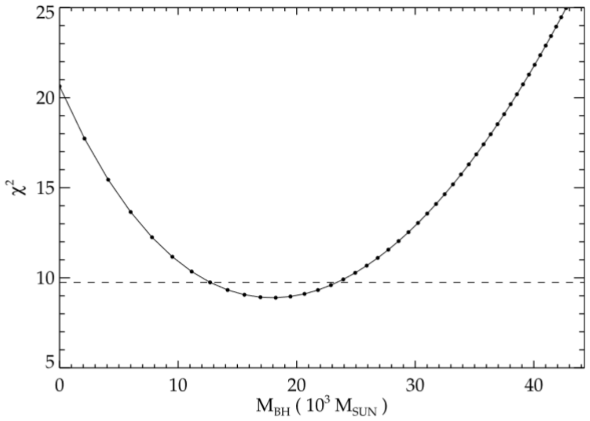
NGC 2808
(Lützgendorf et al. 2012)

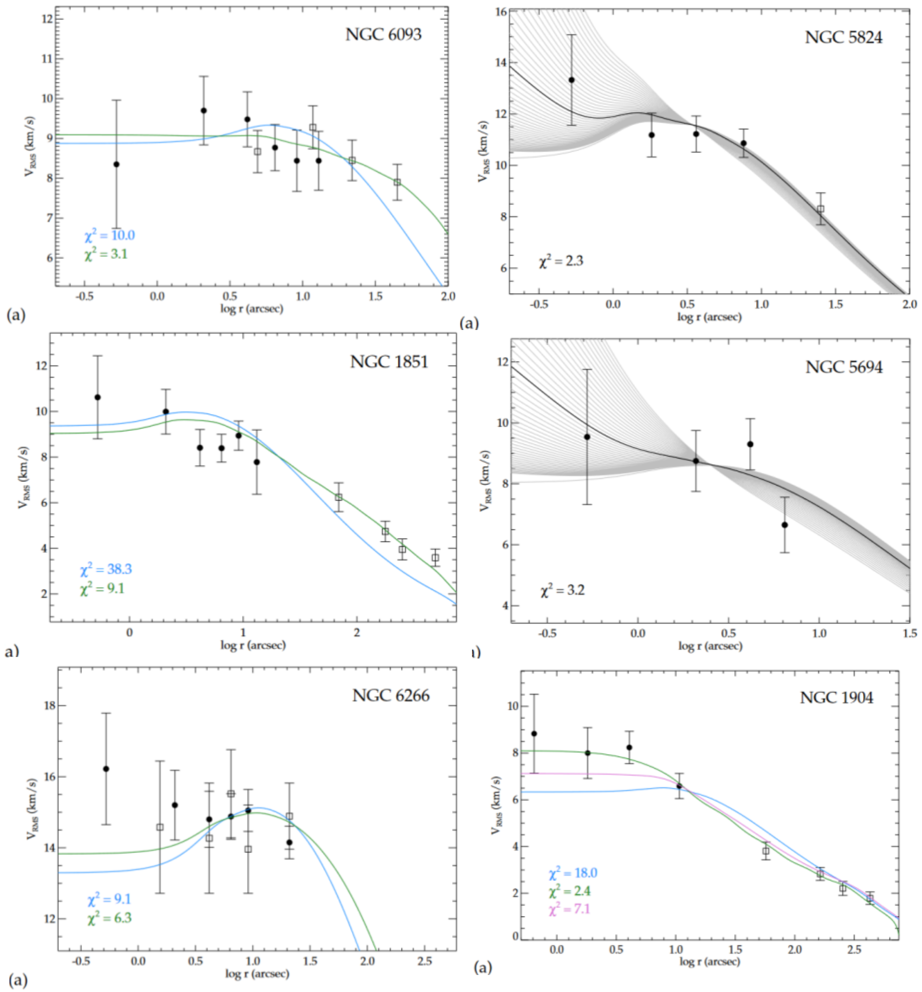


NGC 5286
(Feldmeier et al. 2013)



NGC 6388
(Lützgendorf et al. 2011)

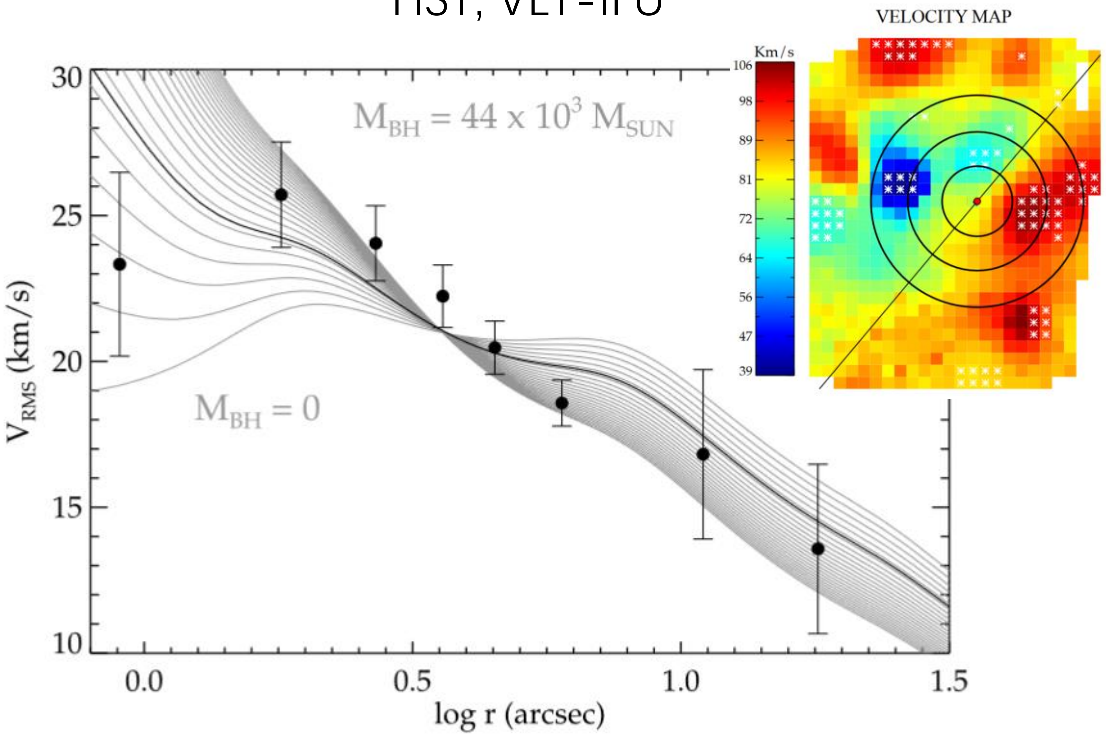




Challenge of searching IMBH in GCs

Large observational uncertainty

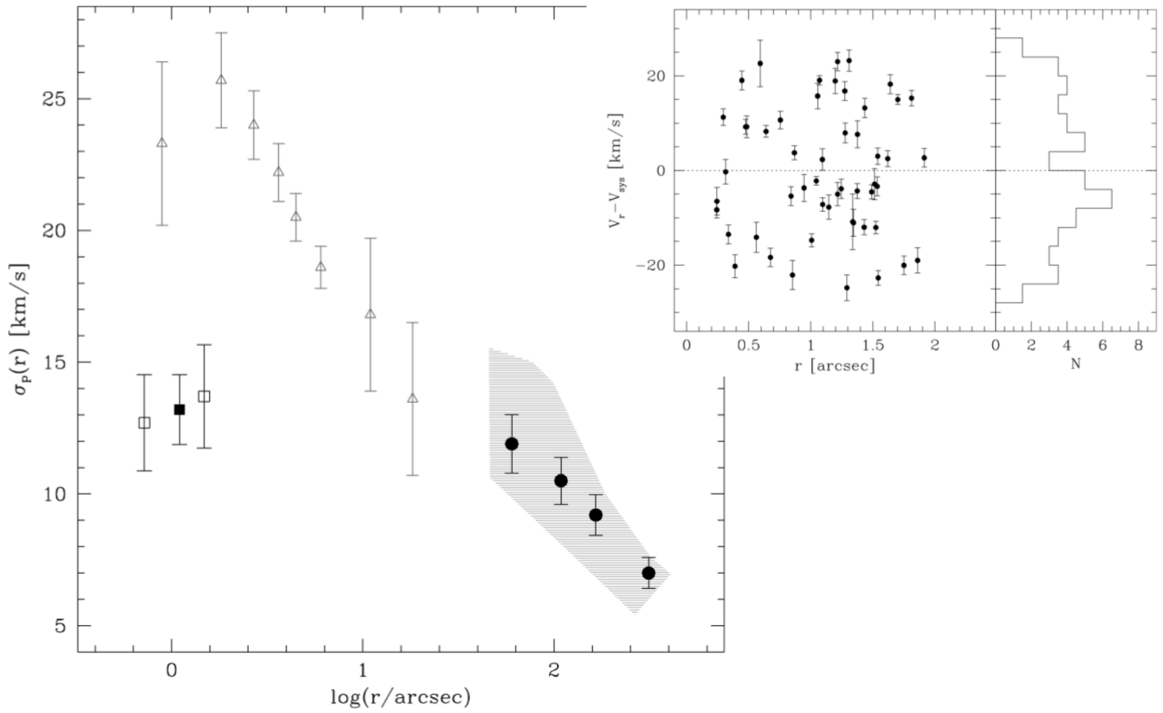
HST, VLT-IFU



NGC 6388 (Lützgendorf et al. 2011)

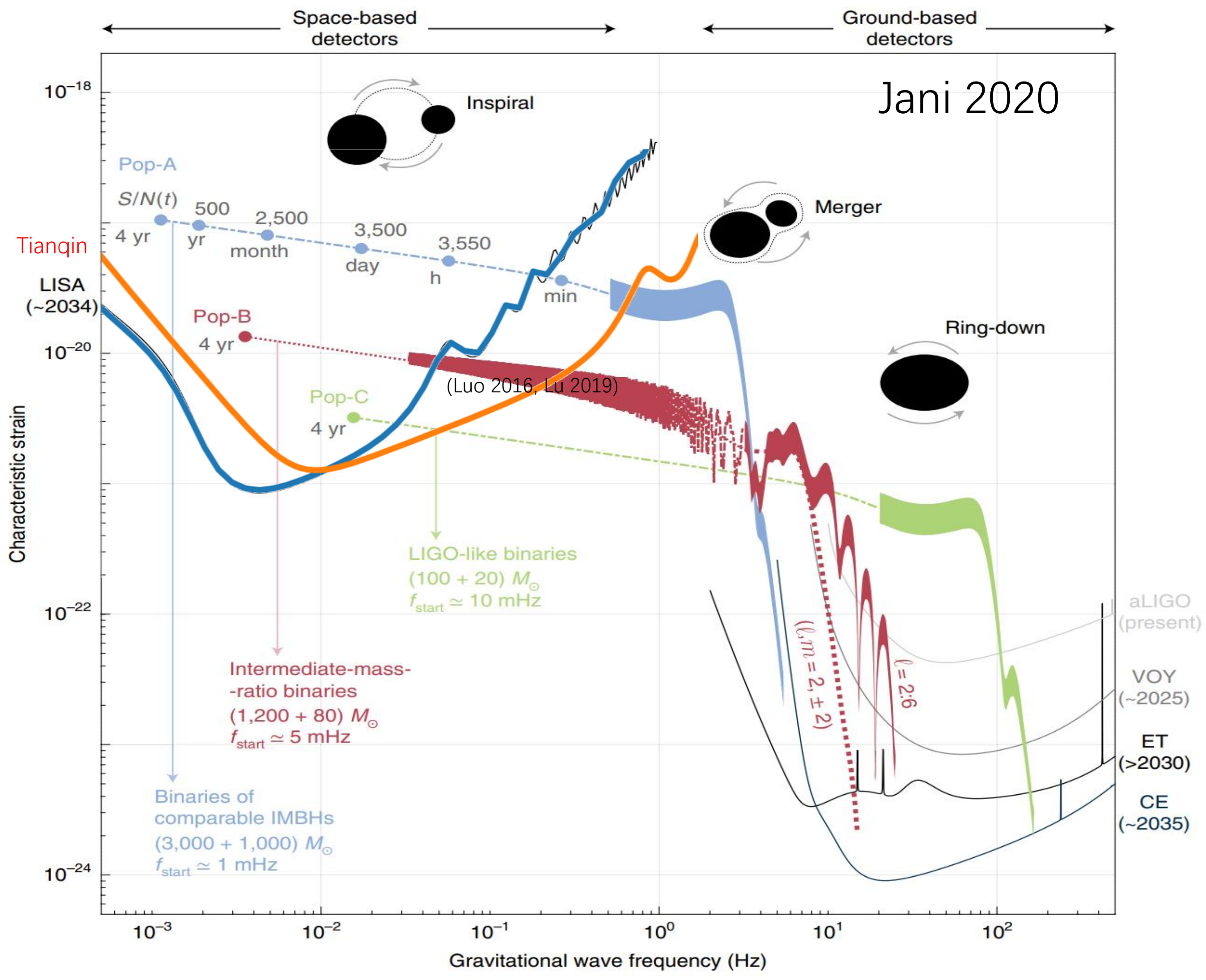
SINFONI, VLT-UT4

52 targets



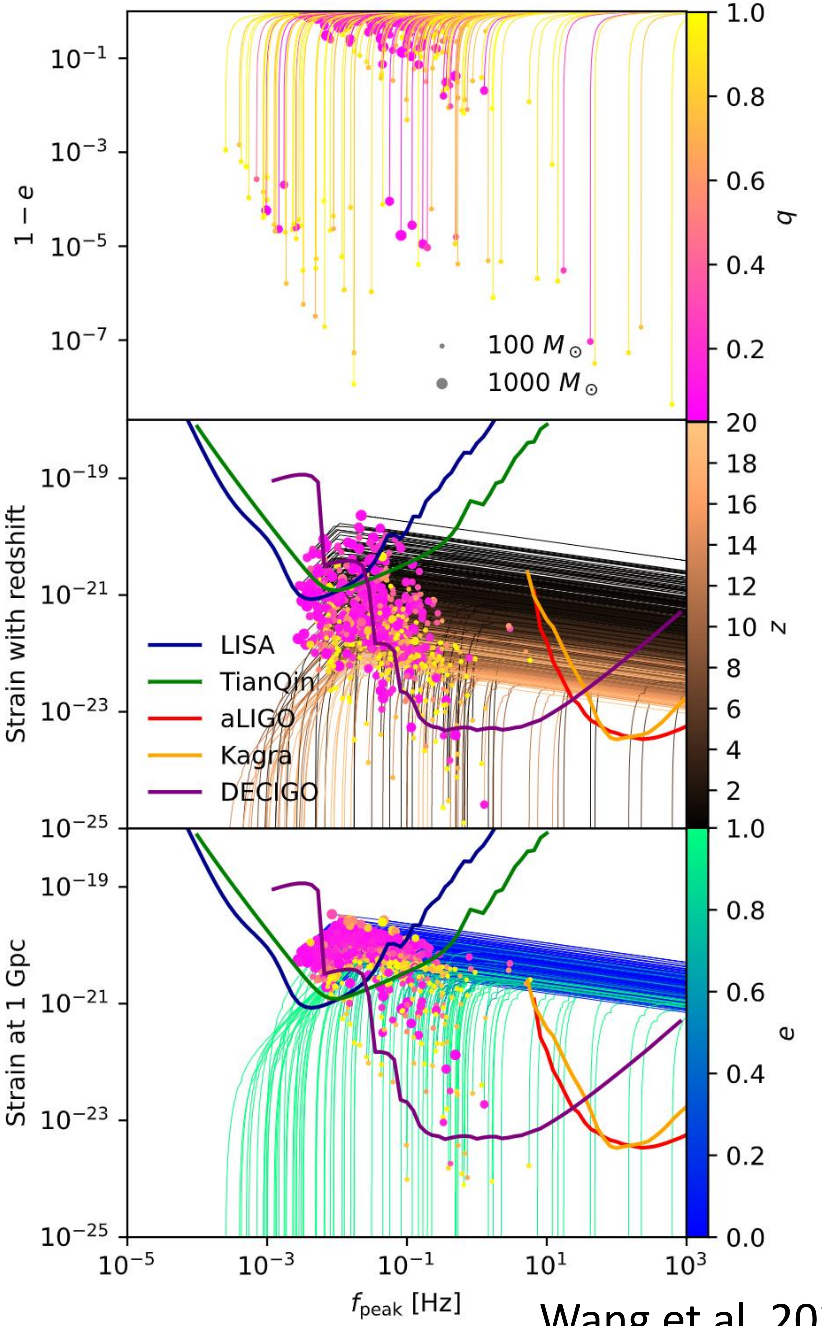
NGC 6388 (Lanzoni 2013)

Multiband GW detections of IMBHs



Gravitational wave signals from IMBH-BH mergers in Pop3 star clusters

- Secular orbital evolution of a, e using Peters (1964)
- Characteristic strain formula from Kremer et al. (2019)



Wang et al. 2022

IMBH-BH merger rate

- **Pop3 total stellar mass**
  - From z = 10 – 20 is about $3.2 \times 10^4 M_\odot\ \mathrm{Mpc}^{-3}$ (Skinner & Wise 2020; Tanikawa et al. 2022)
  - Upper limit is about $2 \times 10^5 M_\odot\ \mathrm{Mpc}^{-3}$ inferred by re-ionization history (Inayoshi et al. 2021)
- **Average merger rate:**
  - $M = 2 \times 10^5 M_\odot$ star cluster: 5 mergers/12 Gyr
  - A high rate: $0.1 - 0.8\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$
  - Most occur at $z > 6$
- **Pair-instability BH merger rate:**
  - $0.01 – 0.15\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$
  - Can explain GW190521-like mergers

Summary

- GWs may bring the possibility to constrain the IMF and primordial binary properties of massive stars from old star clusters.
- Distinguish formation channels (binary stellar evolution and dynamical channels) using eccentricities from space-borne detections
- Detecting the IMBH-BH mergers from density