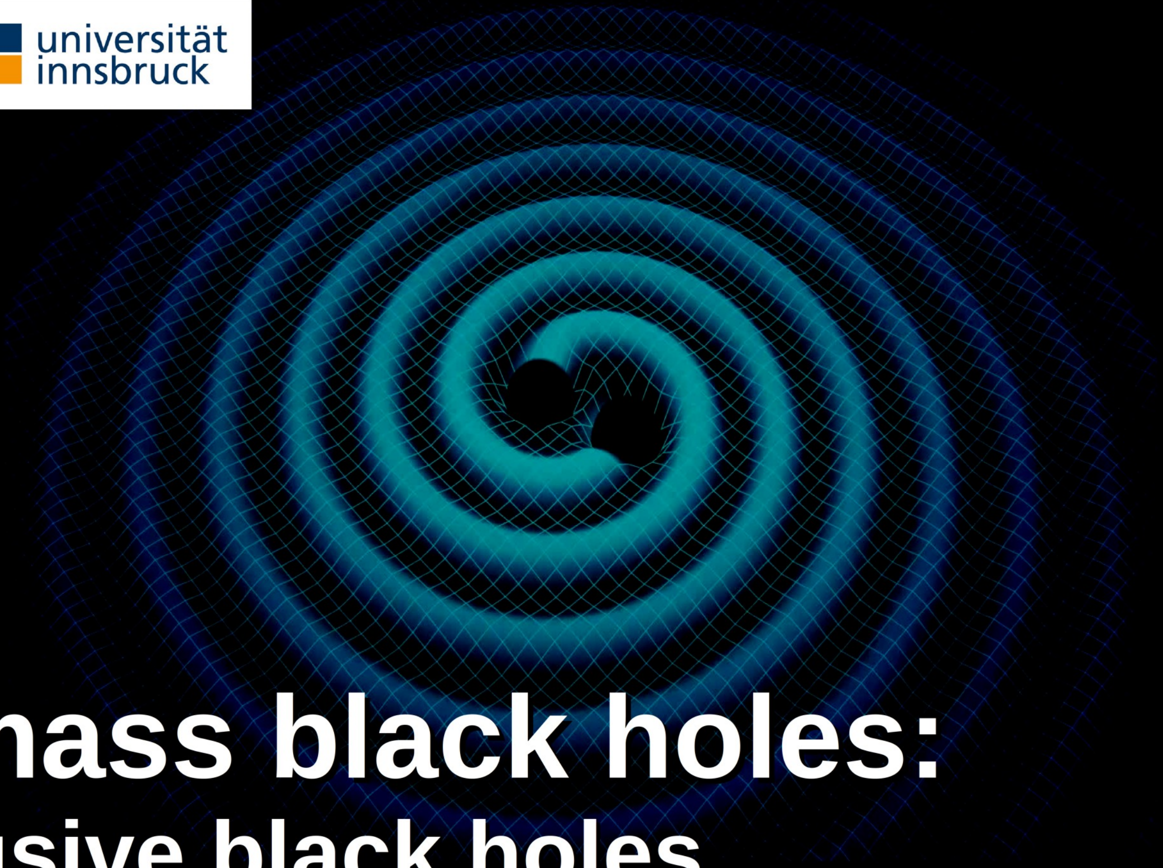
Michela Mapelli

University of Innsbruck

INAF – Padova



Intermediate-mass black holes:
the most elusive black holes

Collaborators: Alessandro Ballone, Nicola Giacobbo, Mario Spera, Alessandro A. Trani, Sandro Bressan, Tom O. Kimpson, Ugo N. Di Carlo

9th FERO meeting, May 23rd 2018

OUTLINE:

1. The mass gap of black holes (BHs)
2. Formation channels of intermediate-mass black holes (IMBHs)
3. Dynamics of IMBHs in star clusters and galactic nuclei
4. Gravitational waves from IMBHs?
5. Conclusions

1. The mass gap of black holes (BHs)

"*Natura non facit saltus*", Gottfried Leibniz
from an ancient Greek & Latin motto

1. The mass gap of black holes (BHs)

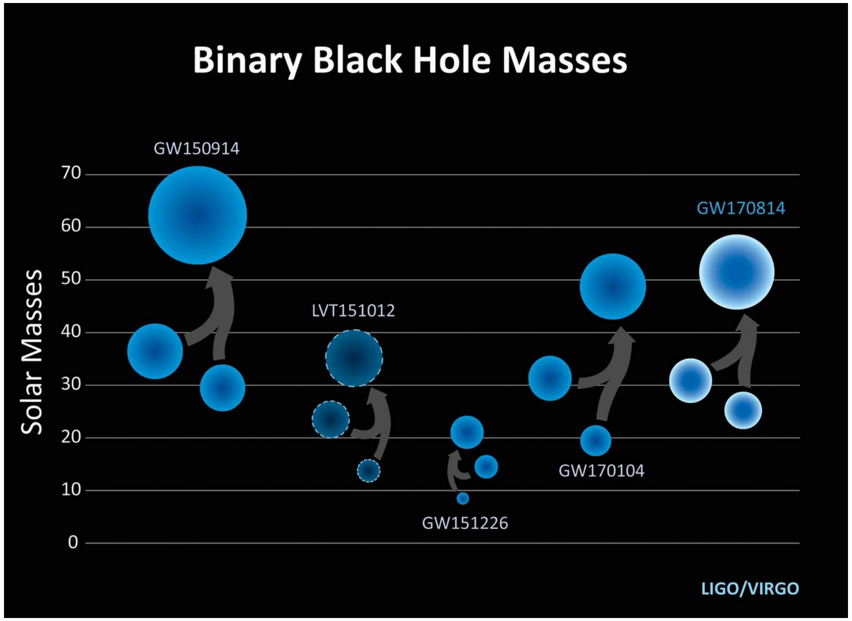
"*Natura non facit saltus*", Gottfried Leibniz

Supermassive BHs (SMBHs) > 10^5 M⊙

?

IMBHs?

Intermediate-mass BHs (IMBHs) ~ 100 – 10^5 M⊙



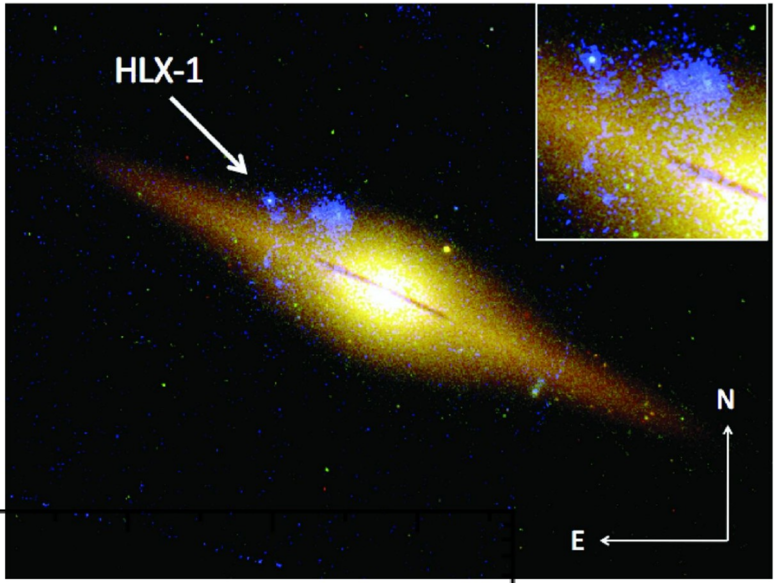
Stellar BHs < 100 M⊙

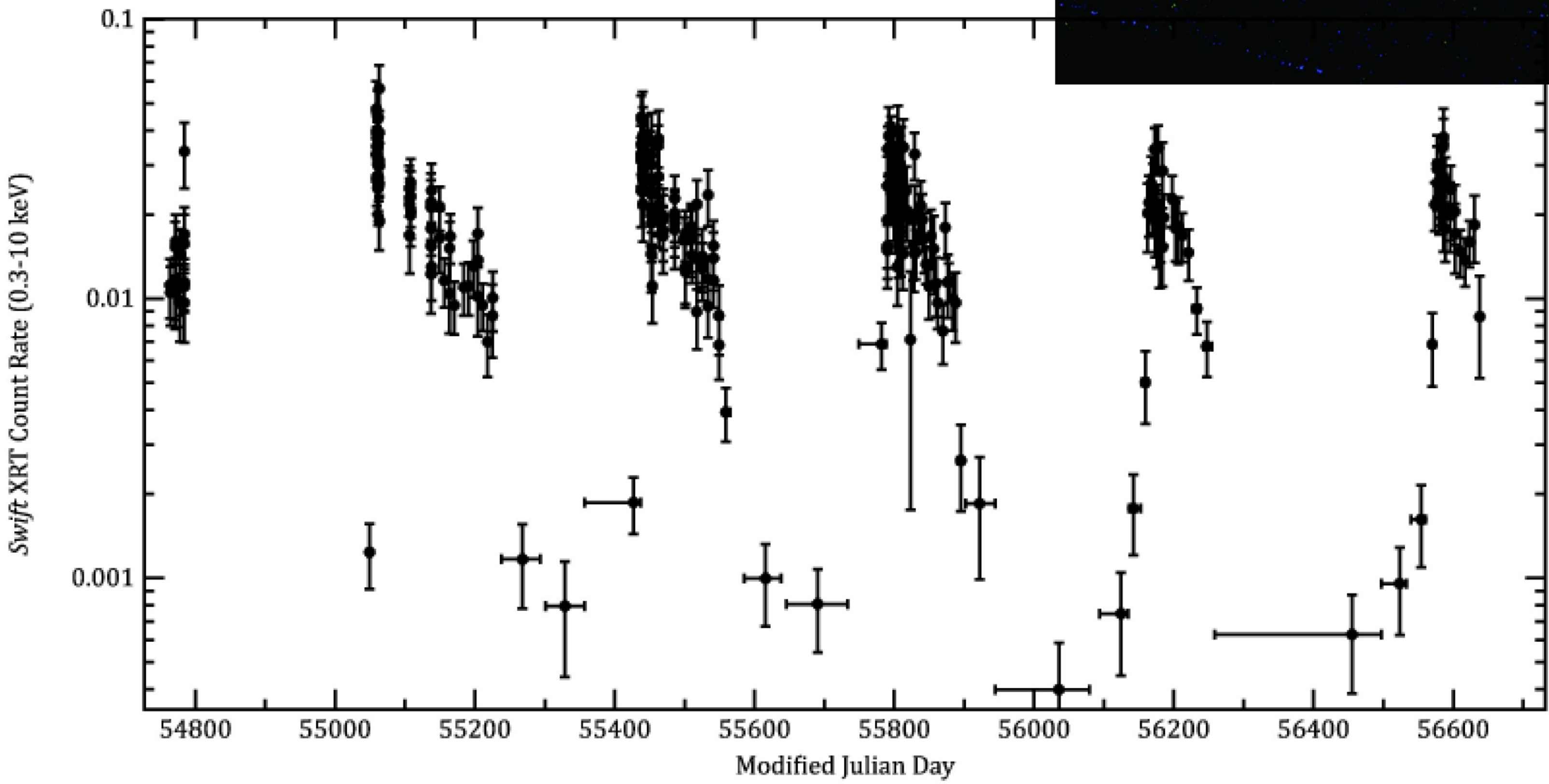
1. The mass gap of black holes (BHs)

Scanty observations:

1. HLX-1 in ESO 243 – 49 (Farrell+ 2009)

MM, Annibali+ 2013





Webb+ 2014

1. The mass gap of black holes (BHs)

Scanty observations:

1. **HLX-1 in ESO 243 – 49 (Farrell+ 2009)**

2. **Globular clusters**

ω Centauri

Noyola et al. (2010)

radial velocity (VLT-FLAMES spectra)
+ <u>isotropic</u> dynamical models
→ 4.7 +/- 1.0 x 10^4 M⊙

Anderson & van der Marel (2010)

photometry and proper motions (HST)
→ no evidence for IMBHs

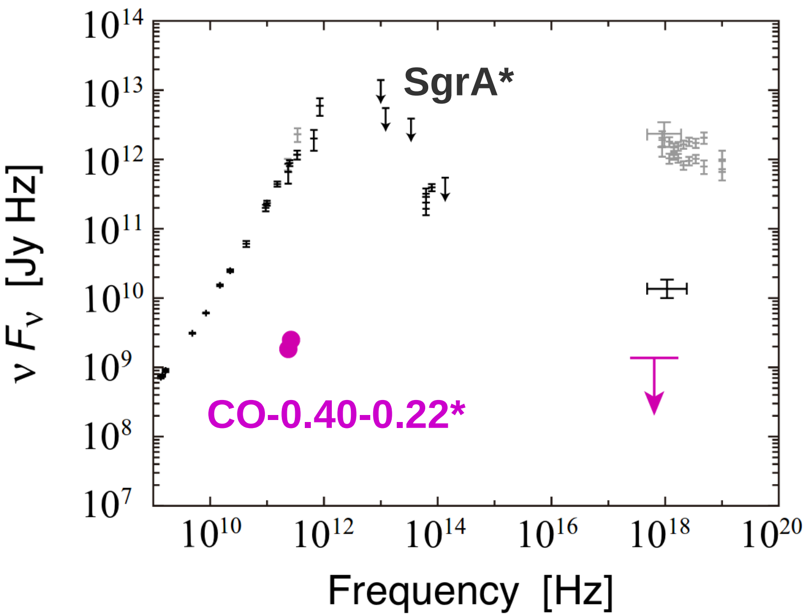
1. The mass gap of black holes (BHs)

Scanty observations:

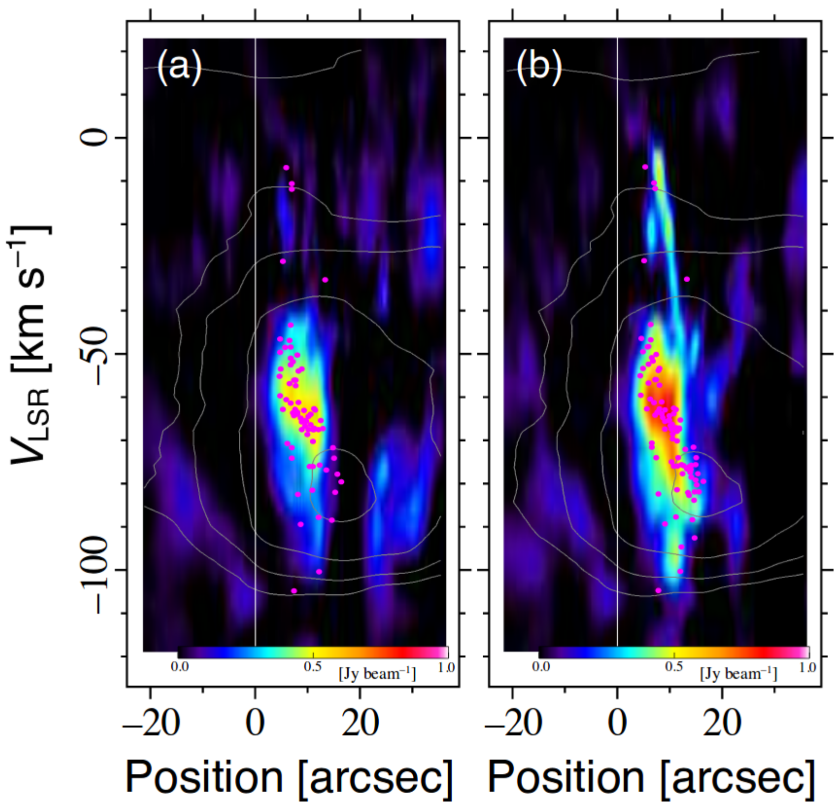
1. **HLX-1 in ESO 243 – 49 (Farrell+ 2009)**

2. **Globular clusters**

3. **CO-0.40-0.22* (Tanaka et al. 2014; Oka et al. 2016, 2017)**



Oka et al. 2017, ALMA data



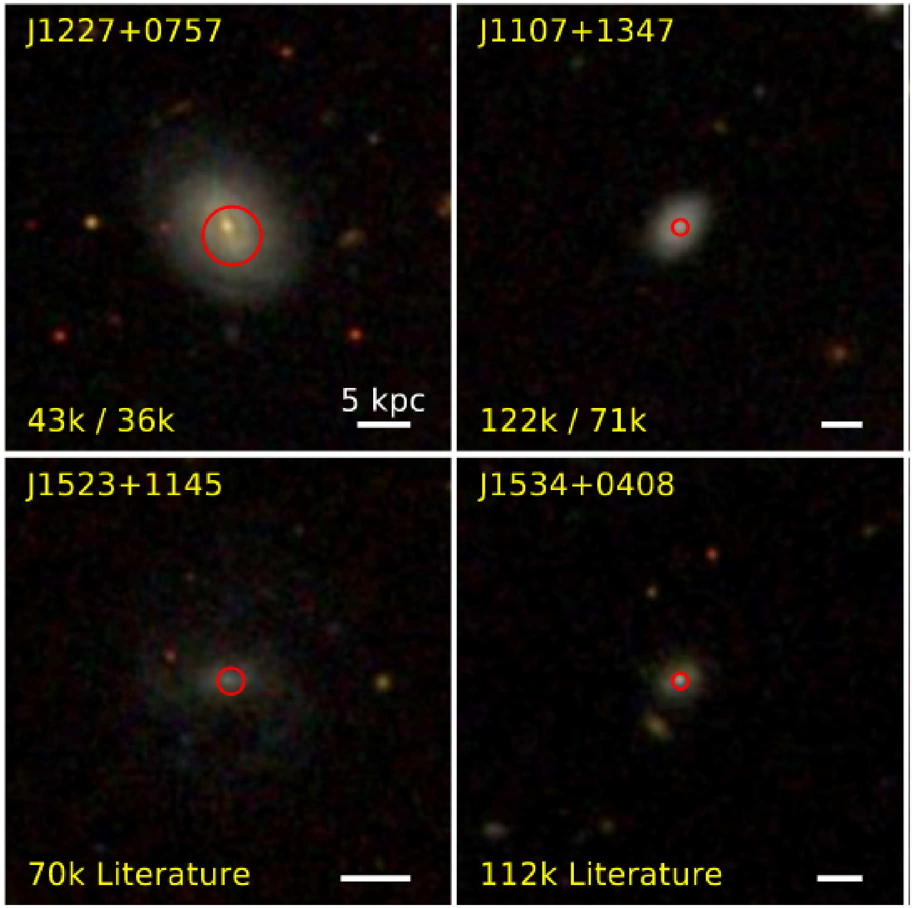
~ 40 M⊙ molecular cloud with large velocity spread (~ 50 km/s) close to a point-like source interpreted as disrupted by ~ 10^{4-5} M⊙ IMBH

1. The mass gap of black holes (BHs)

Scanty observations:

1. **HLX-1 in ESO 243 – 49 (Farrell+ 2009)**
2. **Globular clusters**
3. **CO-0.40-0.22* (Tanaka et al. 2014; Oka et al. 2016, 2017)**
4. **Low-luminosity AGNs (e.g. Green & Ho 2005; Dong+ 2007; Reines+ 2013; Baldassarre+ 2015 Chilingarian+ 2018)**

Chilingarian+ 2018



*** ~ 10 candidates in dwarf galaxies from optical SDSS spectra**

*** only high-mass IMBHs 30'000 – 200'000 M⊙**

WHAT ARE THE FORMATION CHANNELS of IMBHs?

i. **Collapse of very massive metal-poor stars**

ii. **Runaway collisions in star clusters**

iii. **Repeated mergers in star clusters**

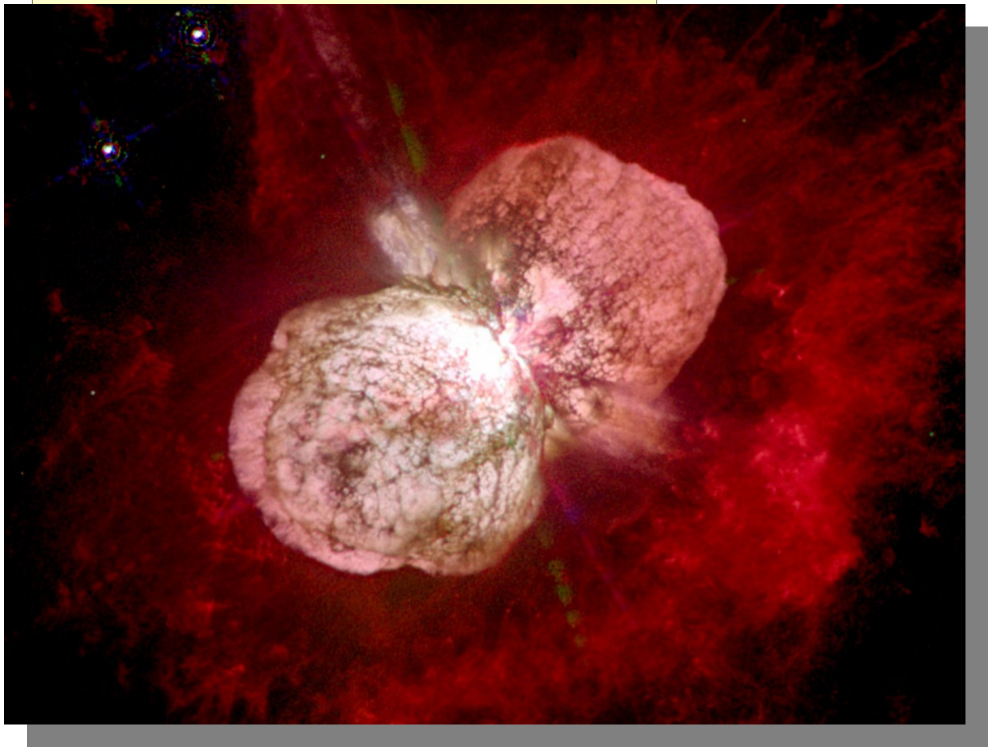
} **DYNAMICS NEEDED**

iv. **Failed supermassive BHs**

2. Formation channels of IMBHs: collapse of very massive stars

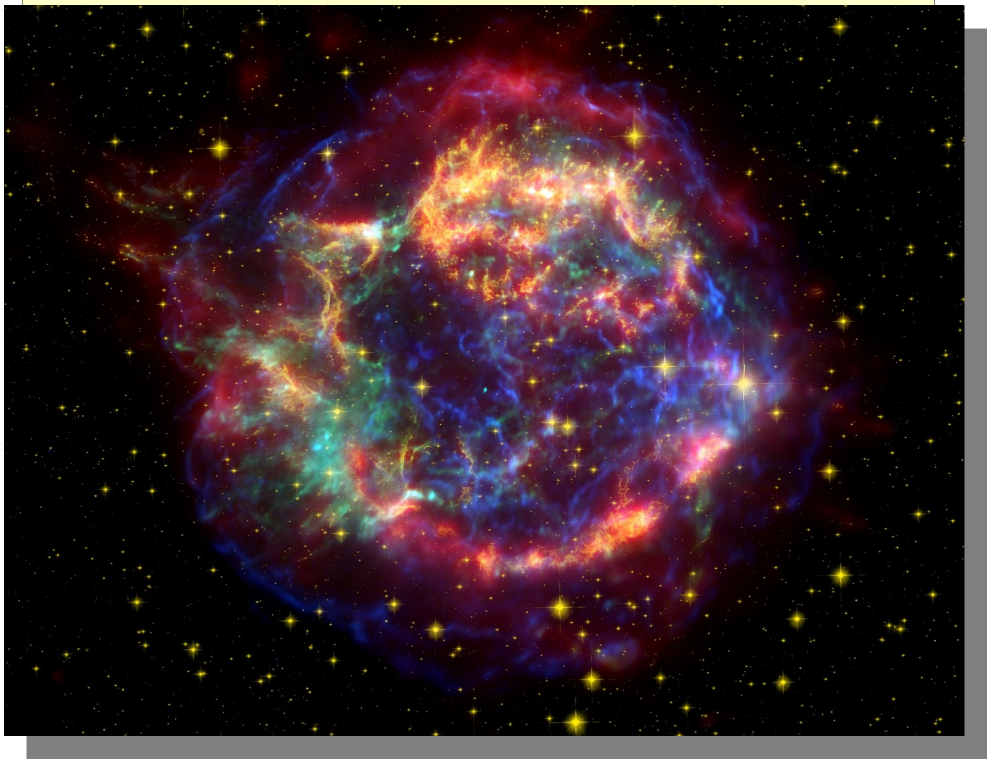
What are the main physical ingredients for the formation of stellar BHs?

STELLAR WINDS



Winds ejected by Eta Carinae (HST, credits: NASA)

SUPERNOVA (SN) EXPLOSIONS



Chandra + HST + Spitzer image of the SN remnant Cassiopeia A

2. Formation channels of IMBHs: collapse of very massive stars

Massive stars lose mass by stellar winds

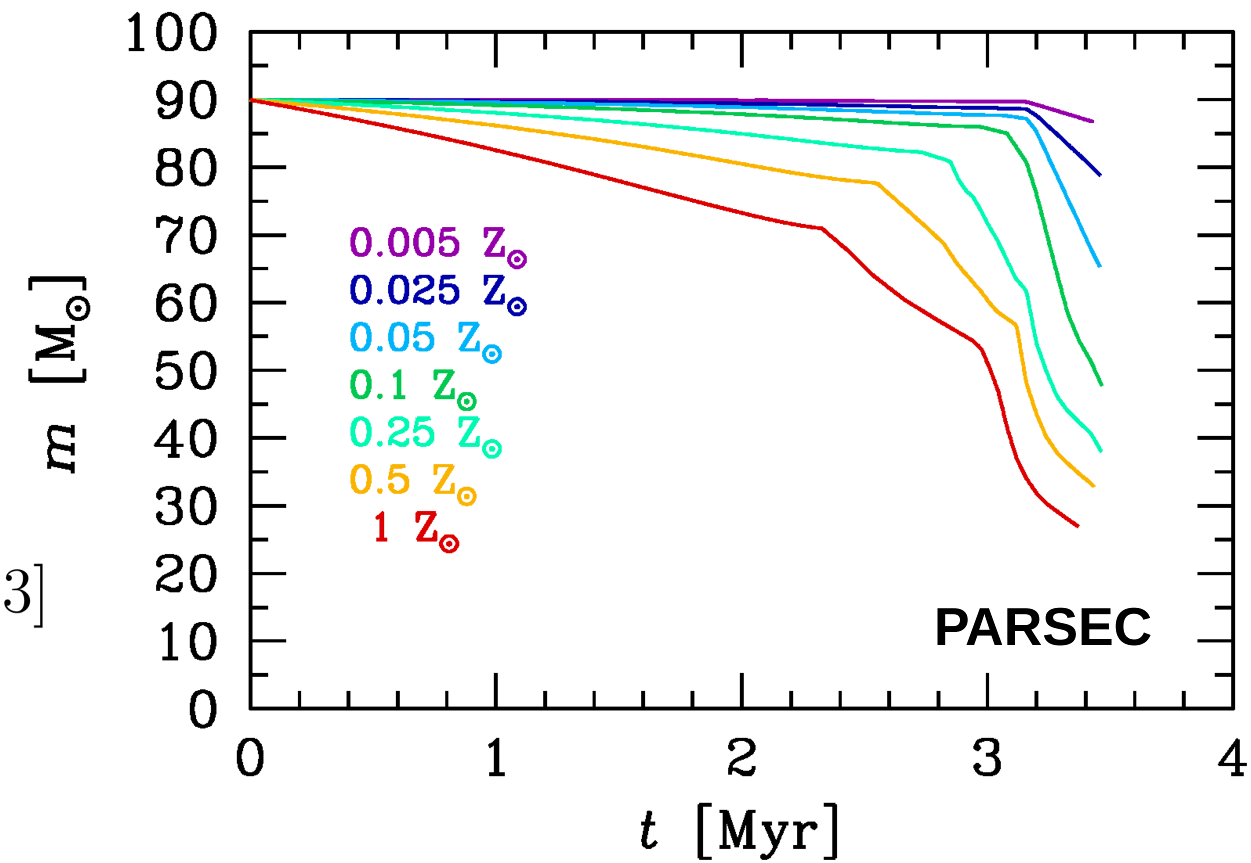
- **Winds depend on metallicity**
  (e.g. Vink+ 2001; Vink & de Koter 2005; Vink+ 2011)
- **Winds depend on Eddington ratio**
  (e.g. Graefener & Hamann 2008; Vink+ 2011; Vink 2016)

$$\dot{M} \propto Z^{\alpha}$$

$$\alpha = 0.85 \quad [\text{if } \Gamma < 2/3]$$

$$\alpha = 2.45 - 2.4\,\Gamma \quad [\text{if } \Gamma > 2/3]$$

$$\Gamma = \frac{L_*}{L_{\rm Edd}}$$

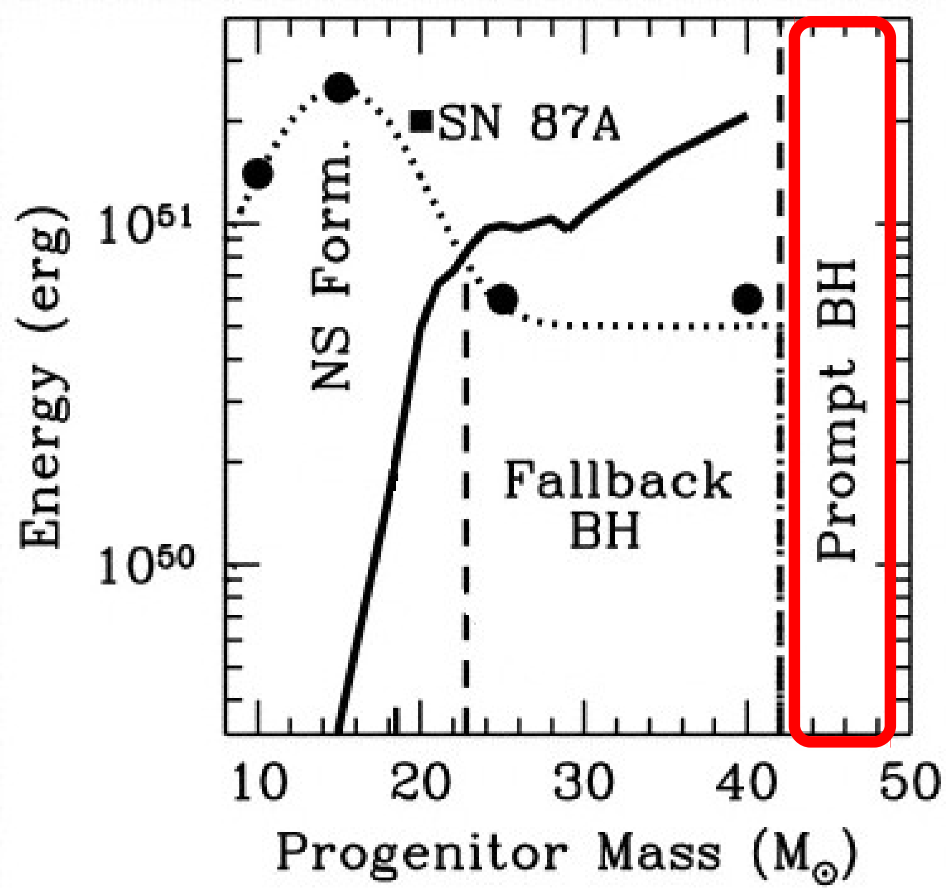


Tang, Bressan+ 2014; Chen, Bressan+ 2015

2. Formation channels of IMBHs: collapse of very massive stars

* Physics of core-collapse SNe is <u>uncertain</u>
 (Fryer et al. 2012; Ugliano et al. 2012; Janka 2012; Sukhbold & Woosley 2014)

Fryer & Kalogera 2001

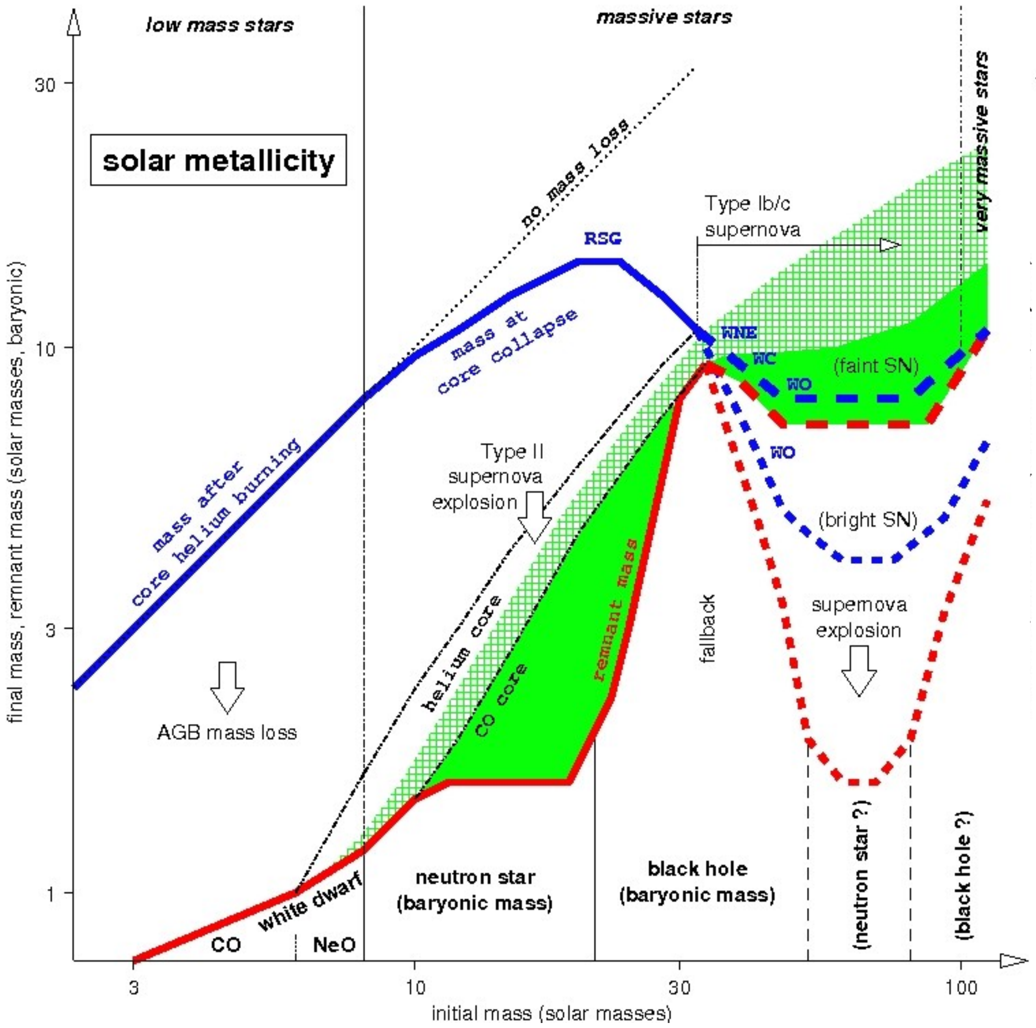


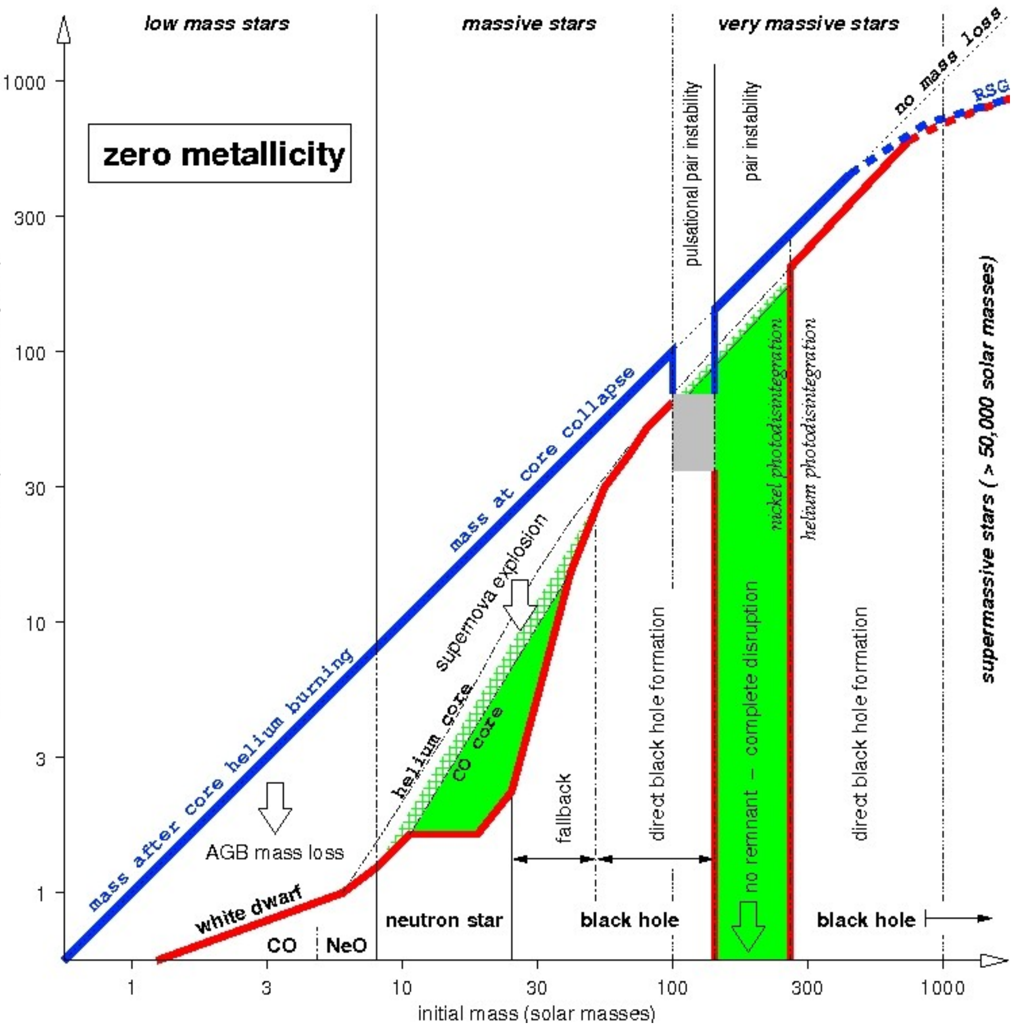
* If mass bound before onset of SN is sufficiently large, star can avoid SN and <u>directly collapse to BH</u>
 (Fryer 1999; Fryer & Kalogera 2001; Heger+ 2003; MM, Colpi & Zampieri 2009)

* If direct collapse, remnant mass is larger

* Since metal-poor stars have larger pre-SN masses, they are more likely to directly collapse, producing more massive BHs
 (MM, Colpi & Zampieri 2009; Belczynski et al. 2010; Fryer et al. 2012)

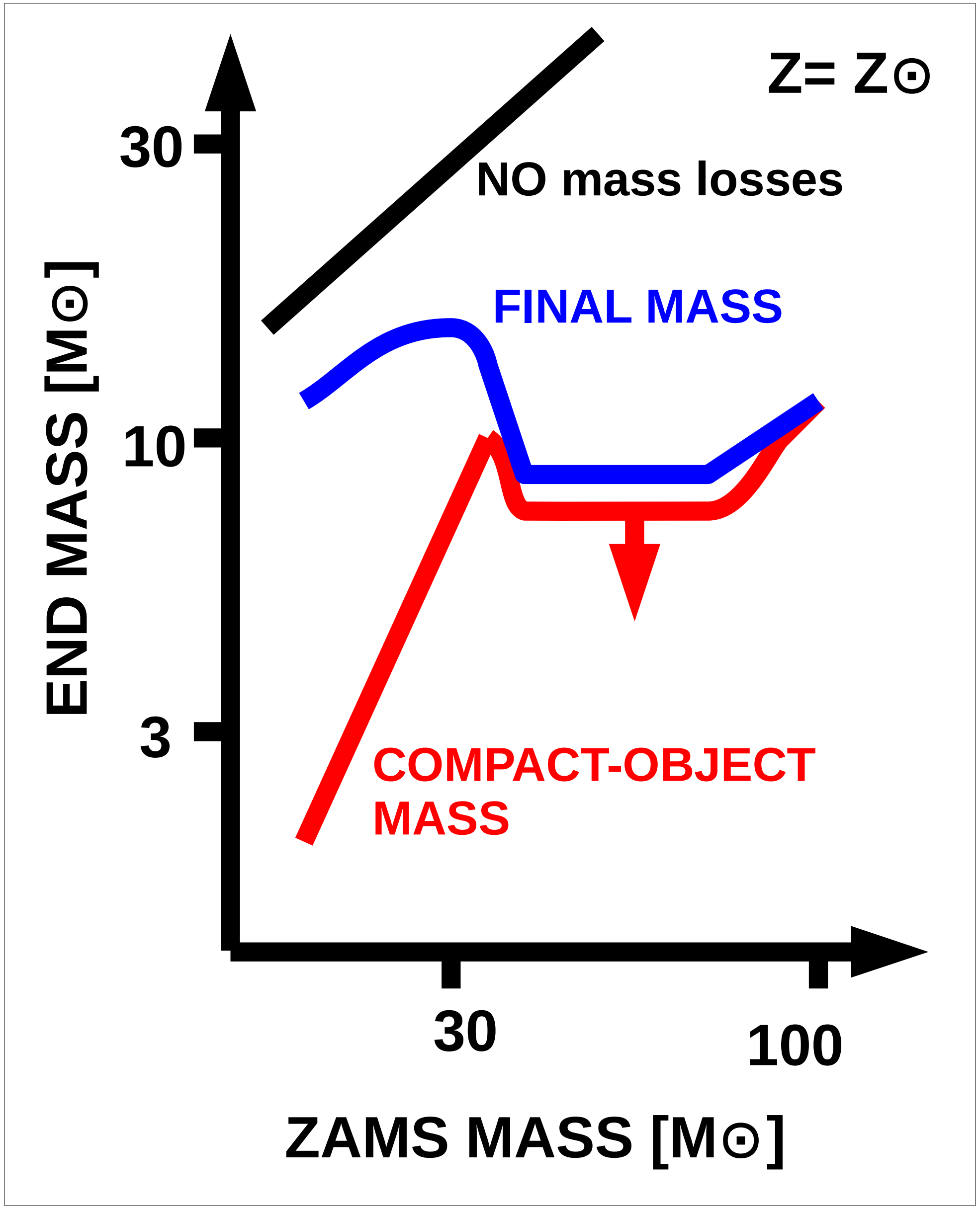
2. Formation channels of IMBHs: collapse of very massive stars

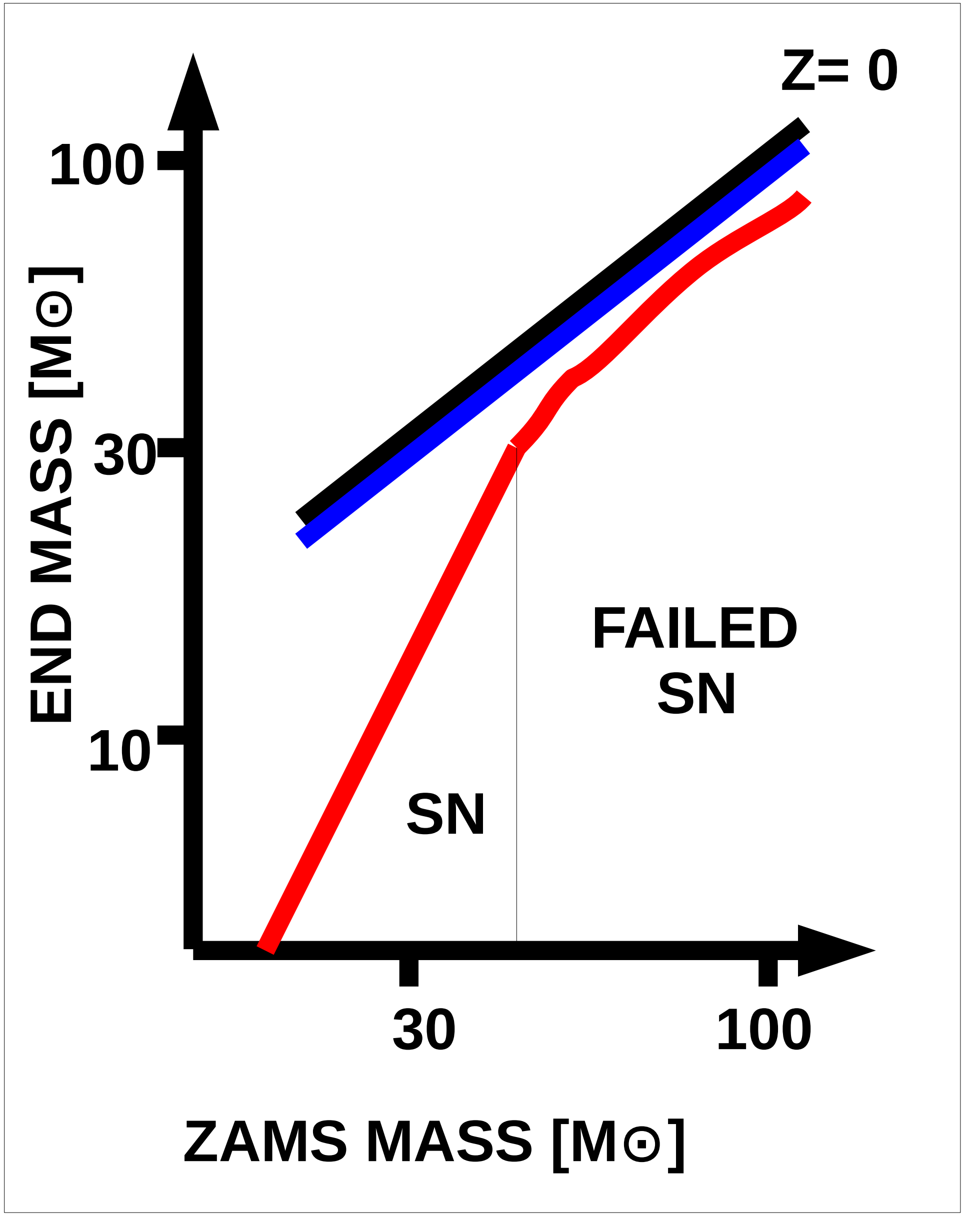




Heger et al. (2003)

2. Formation channels of IMBHs: collapse of very massive stars

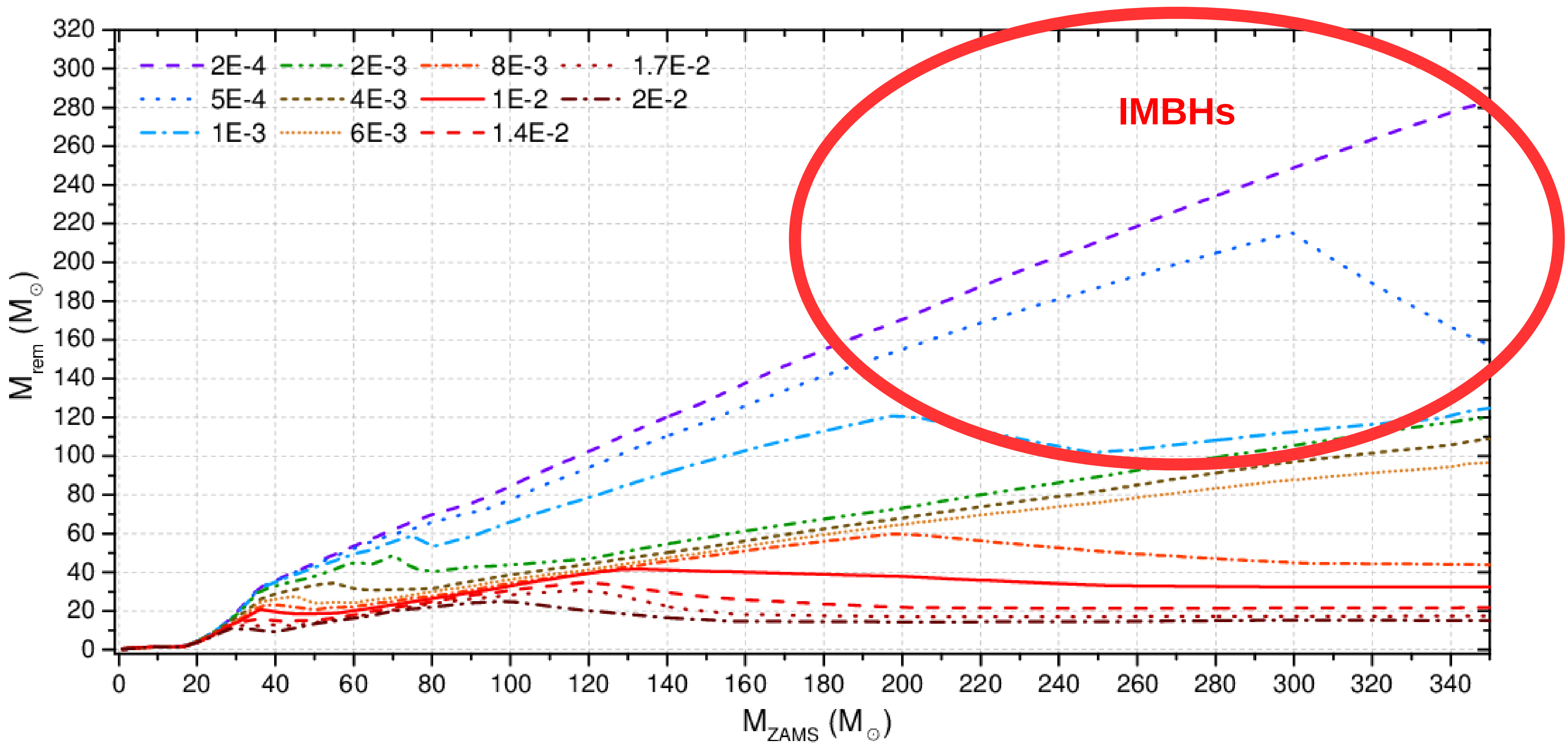




My cartoon from Heger et al. (2003)

2. Formation channels of IMBHs: collapse of very massive stars

What happens for intermediate metallicities?

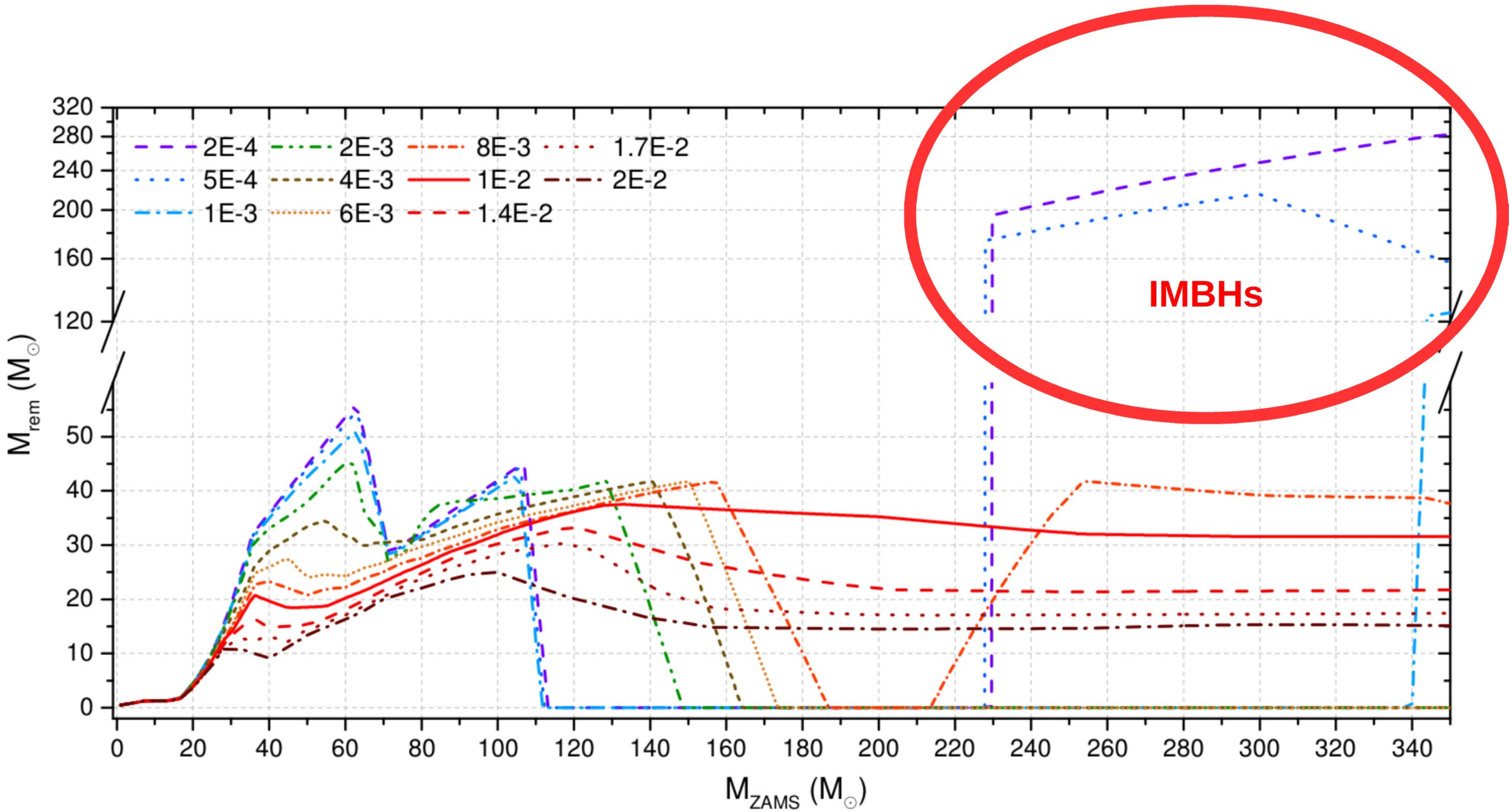


Spera & MM 2017
(PISN formalism based on Woosley 2017)

See also MM+ 2009, 2010; Belczynski+ 2010; Fryer+ 2012; MM+ 2013, 2014; Spera+ 2015

2. Formation channels of IMBHs: collapse of very massive stars

Role of pulsational pair-instability and pair-instability supernovae



Spera & MM 2017
(PISN formalism based on Woosley 2017)

See also MM+ 2009, 2010; Belczynski+ 2010; Fryer+ 2012; MM+ 2013, 2014; Spera+ 2015

2. Formation channels of IMBHs: dynamical channels

DYNAMICS is IMPORTANT ONLY IF **$n > 10^3$ stars pc^{-3}**

i.e. only in dense star clusters

but massive stars (compact-object progenitors) form in star clusters

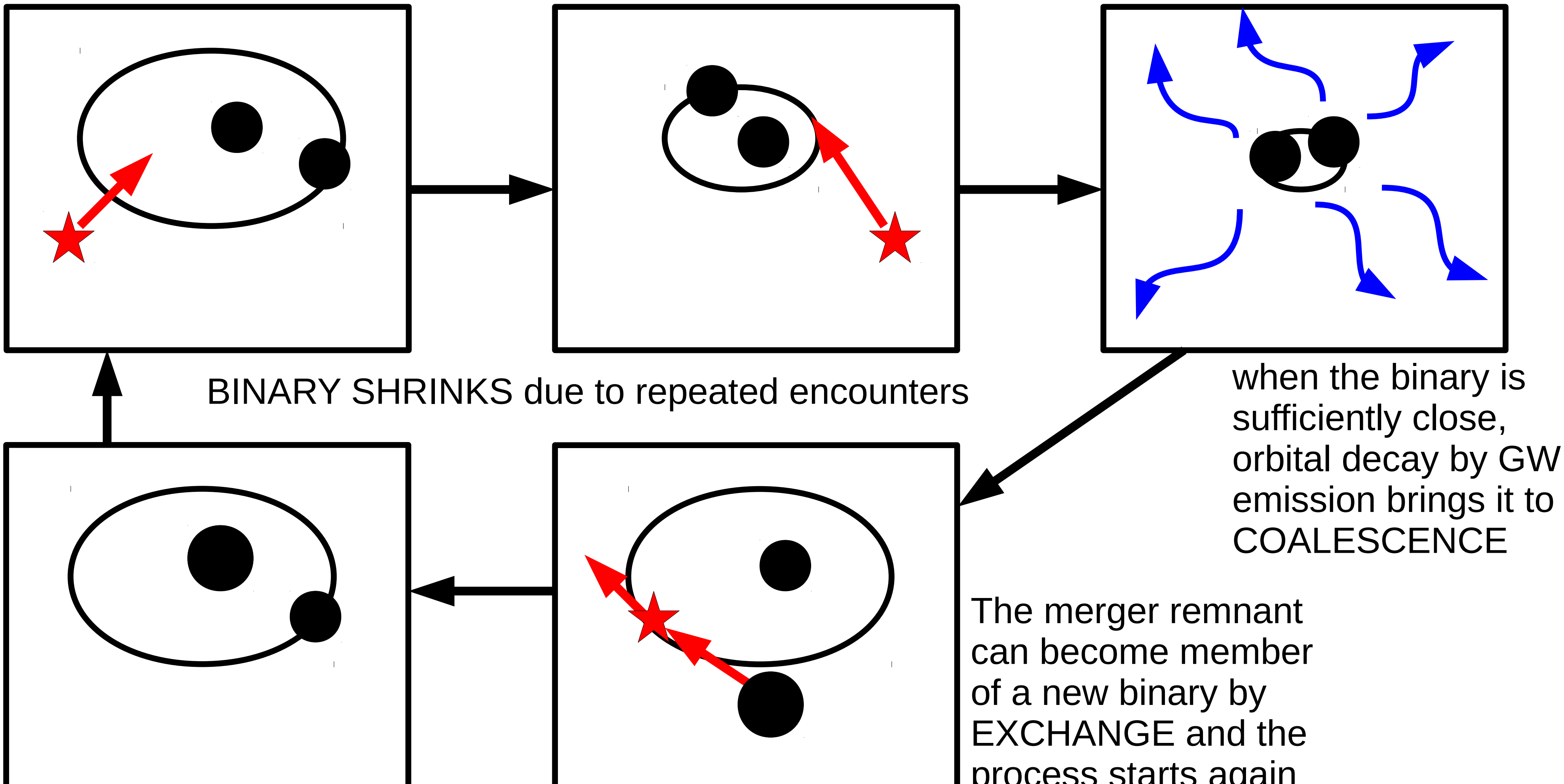
***(Lada & Lada 2003; Weidner & Kroupa 2006; Weidner, Kroupa & Bonnell 2010; Gvaramadze et al. 2012; see Portegies Zwart+ 2010 for a review*)**

**R136
in the LMC**

2. Formation channels of IMBHs: repeated mergers

Formalism by Miller & Hamilton (2002)

In a old cluster stellar BHs can grow in mass because of repeated mergers with the companion triggered by 3-body encounters

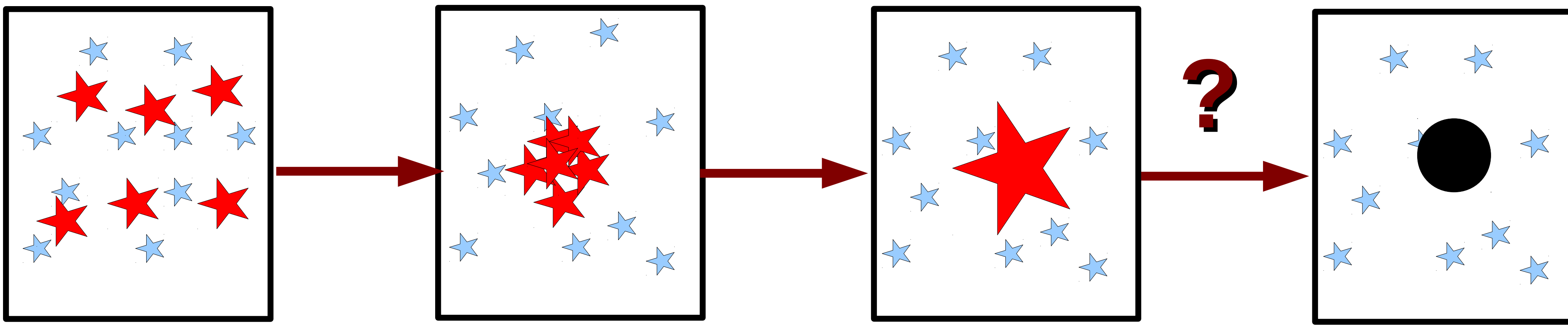


2. Formation channels of IMBHs: runaway collisions

Mass segregation fast in young star clusters:

$$t_{\rm DF}(25M_\odot) \sim 2{\rm Myr}\left(\frac{t_{\rm rlx}}{50{\rm Myr}}\right) < t_{\rm SN}$$

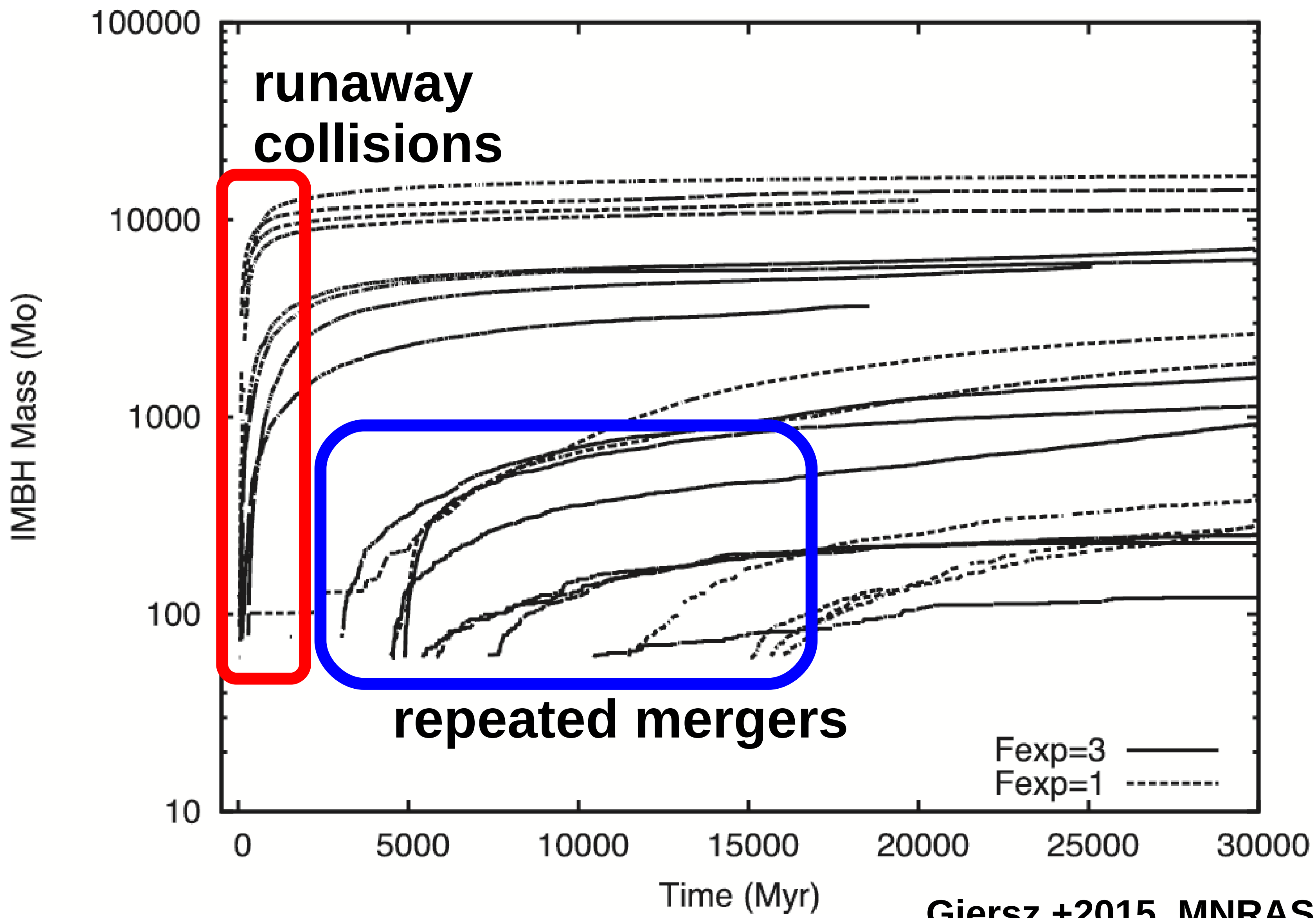
Massive stars segregate to the centre where collide with each other



Super-massive star forms and possibly collapses to IMBH

Colgate 1967, ApJ, 150, 163; Sanders 1970, ApJ, 162, 791; Portegies Zwart+ 1999, A&A, 348, 117; **Portegies Zwart & McMillan 2002, ApJ, 576, 899; Portegies Zwart+ 2004, Nature, 428, 724***; Gurkan+ 2006, ApJ, 640, L39; Freitag+ 2006, MNRAS, 368, 141; Giersz+ 2015, MNRAS, 454, 3150; MM 2016, MNRAS, 459, 3432 and many many others*

2. Formation channels of IMBHs: dynamical channels



Giersz +2015, MNRAS, 454, 3150

PROBLEMS of dynamical channels:

REPEATED MERGERs:

1. dynamical kicks eject binary before becomes IMBH (Miller & Hamilton 2002)

2. gravitational-wave kicks eject binary before becomes IMBH (Holley-Bockelmann+ 2008)

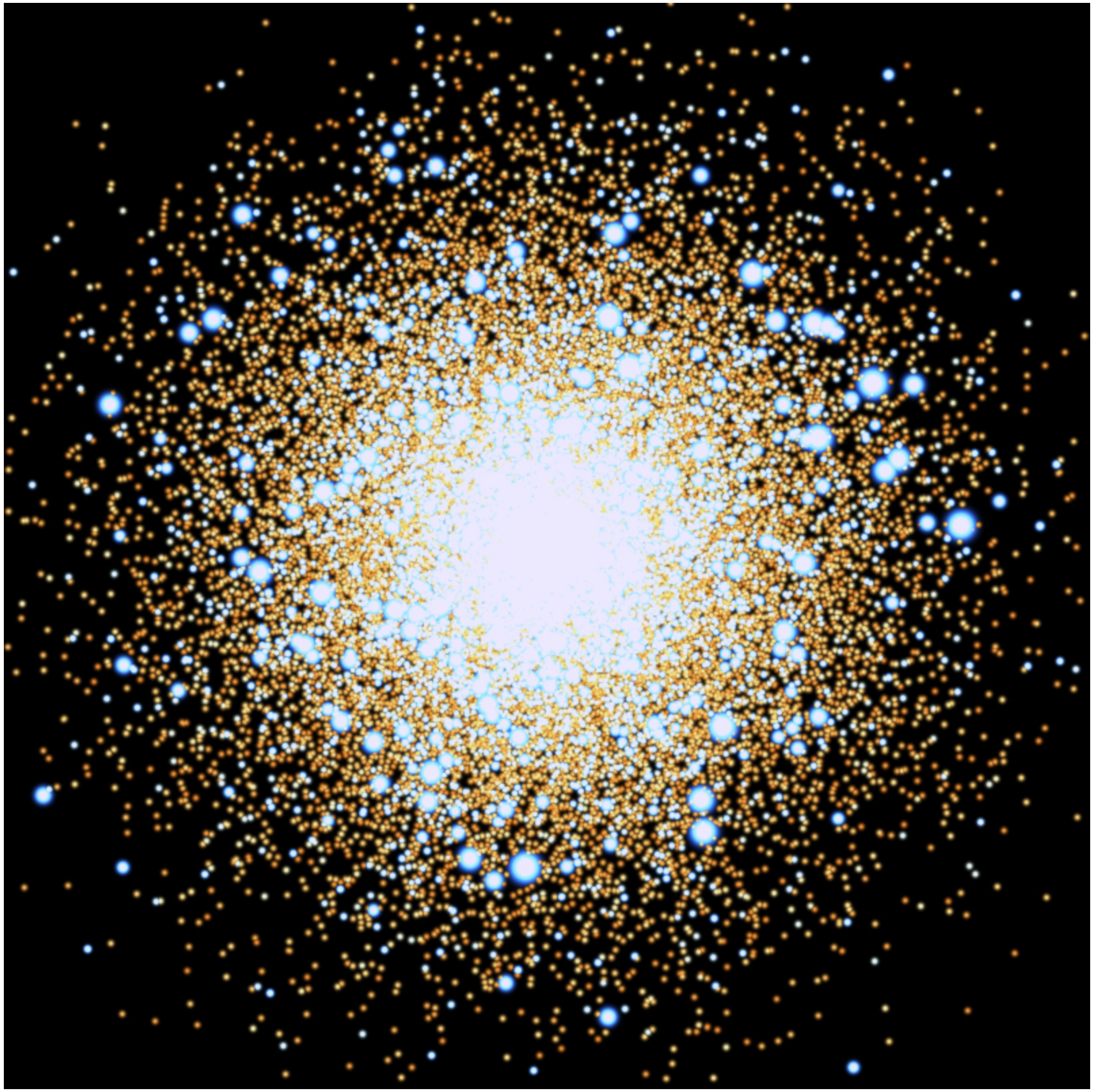
RUNAWAY COLLISIONs:

1. mass loss during collisions (Gaburov+ 2010)

2. mass loss due to stellar evolution (Glebbeek+ 2009; MM 2016) and SN (Portegies Zwart & van den Heuvel 2007; MM 2016)

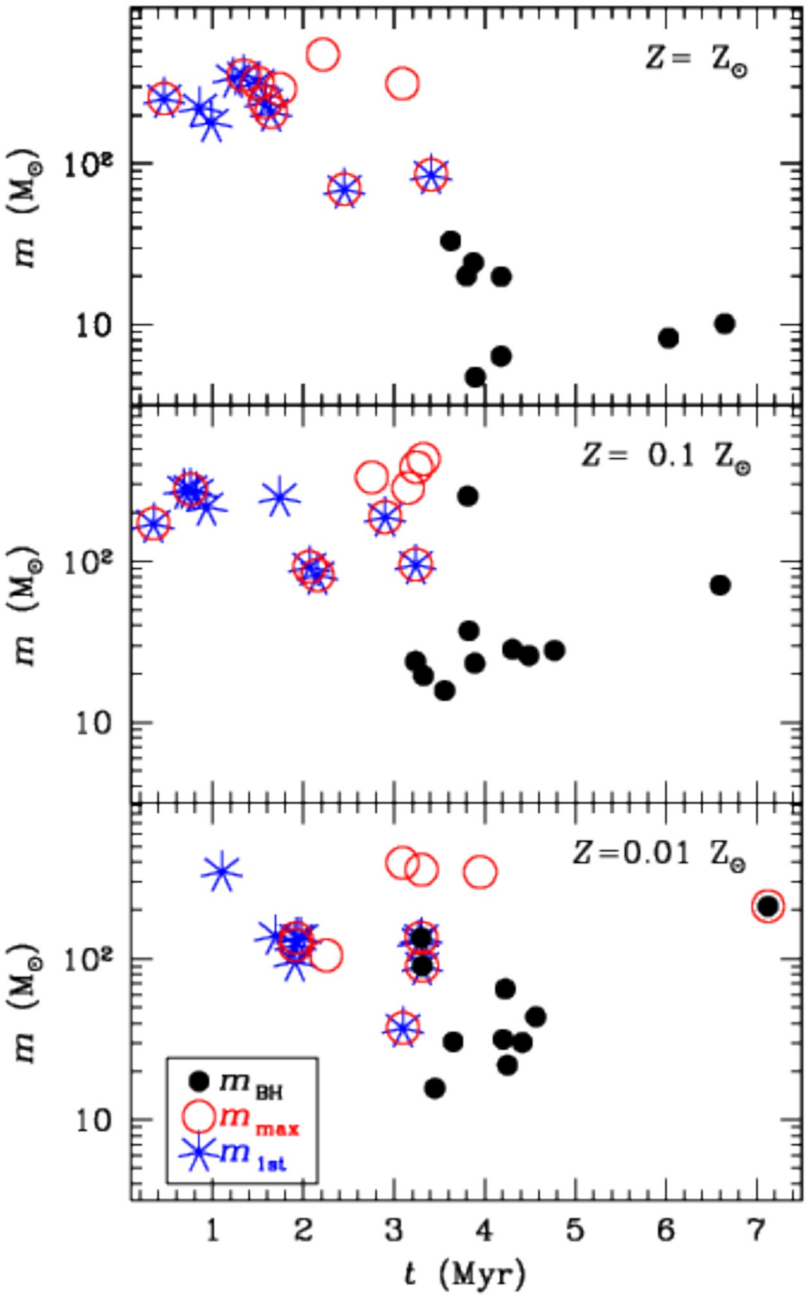
2. Formation channels of IMBHs: runaway collisions

N-body simulations with star evolution



MM 2016, MNRAS, 459, 3432

2. Formation channels of IMBHs: runaway collisions



N-body simulations with star evolution

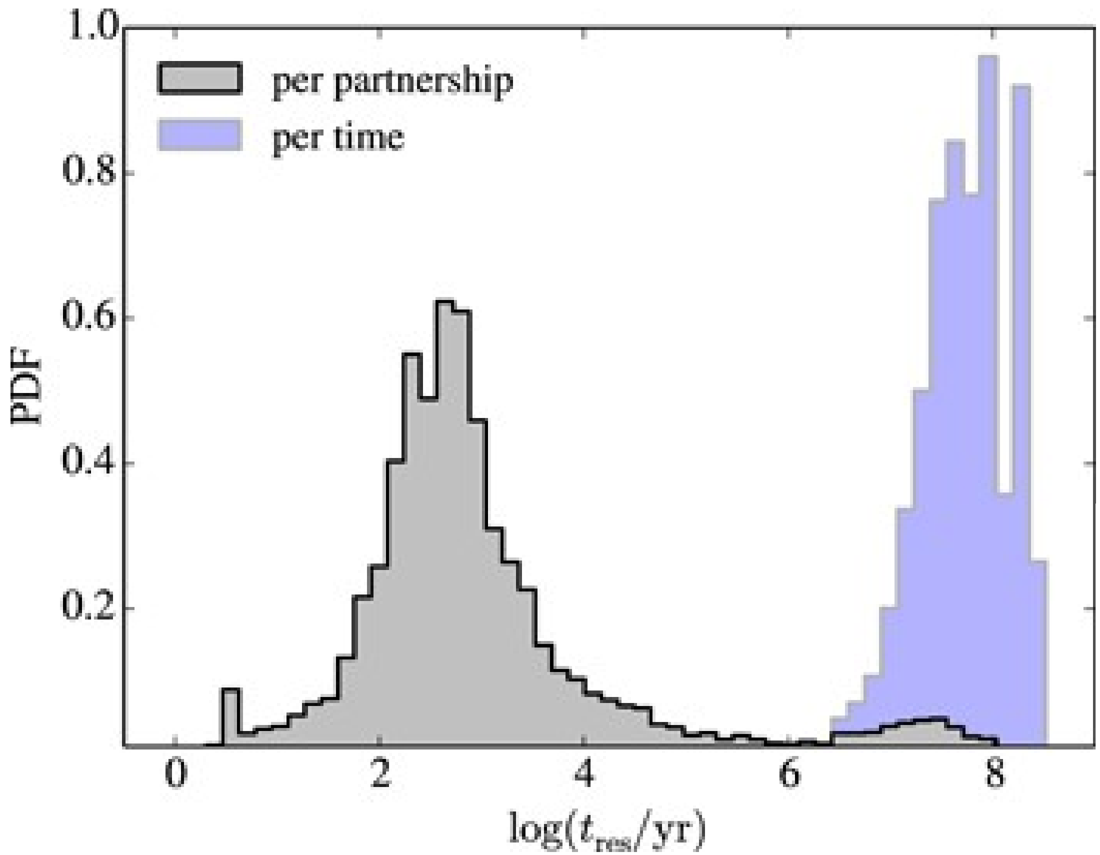
*** no intermediate-mass BHs (IMBHs) at Z⊙ because stellar winds are too strong**

*** 10% BHs in the IMBH regime (>100 M⊙) at Z = 0.01 – 0.1 Z⊙ but with optimistic assumptions**

MM 2016, MNRAS, 459, 3432

3. Dynamics of IMBHs in globular clusters

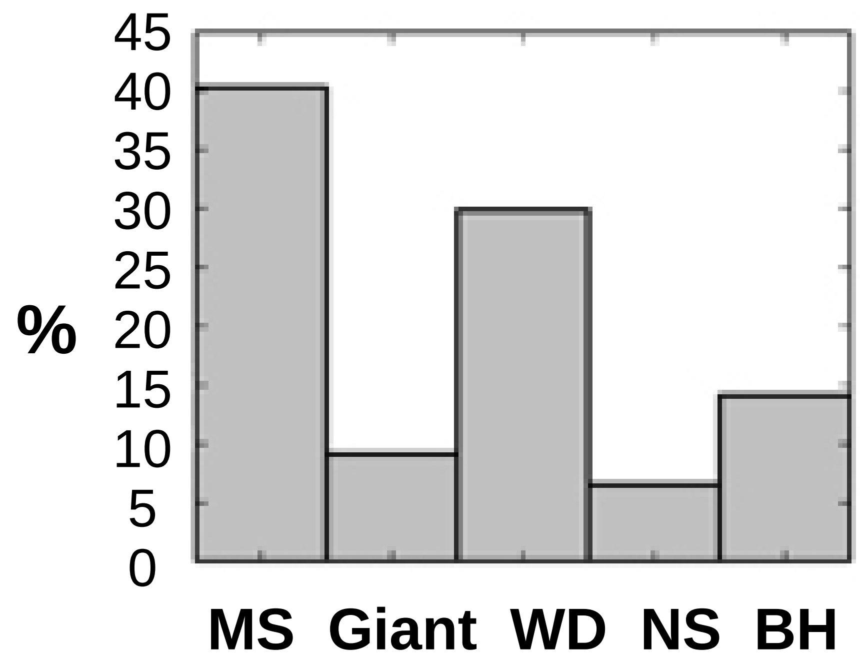
Patruno+ (2005); Blecha+ (2006); MM+ (2011, 2016); MacLeod+ (2016)



MacLeod+ (2016)

An IMBH in a globular cluster spends most of the time with a companion (~ 10^8 yr)

but this companion changes often (~ 1000 yr)



Companions are ~ 50% stars
~ 50% compact objects

Expected tidal disruptions and IMRIs

4. Dynamics of IMBHs in galactic nuclei

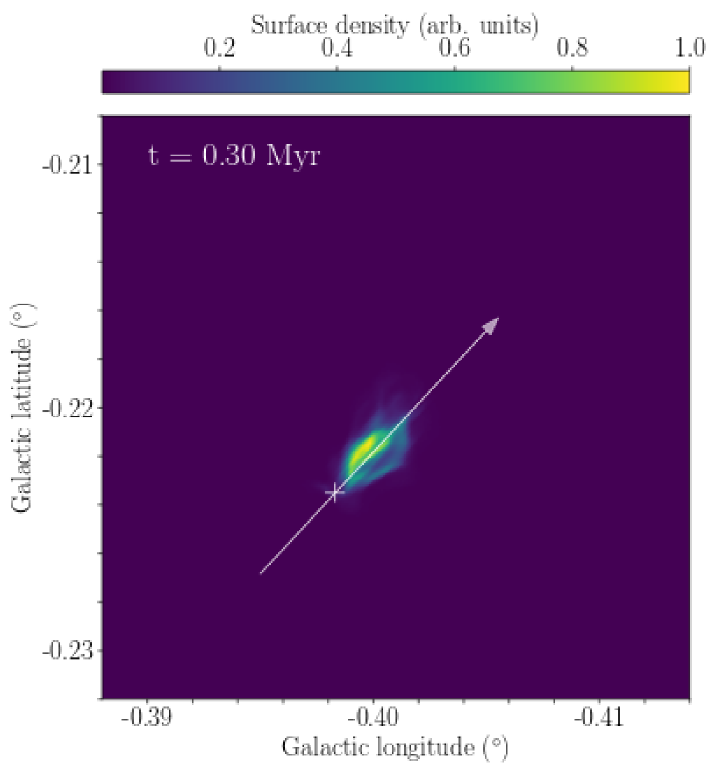
IMBHs meeting molecular clouds in galactic nuclei:

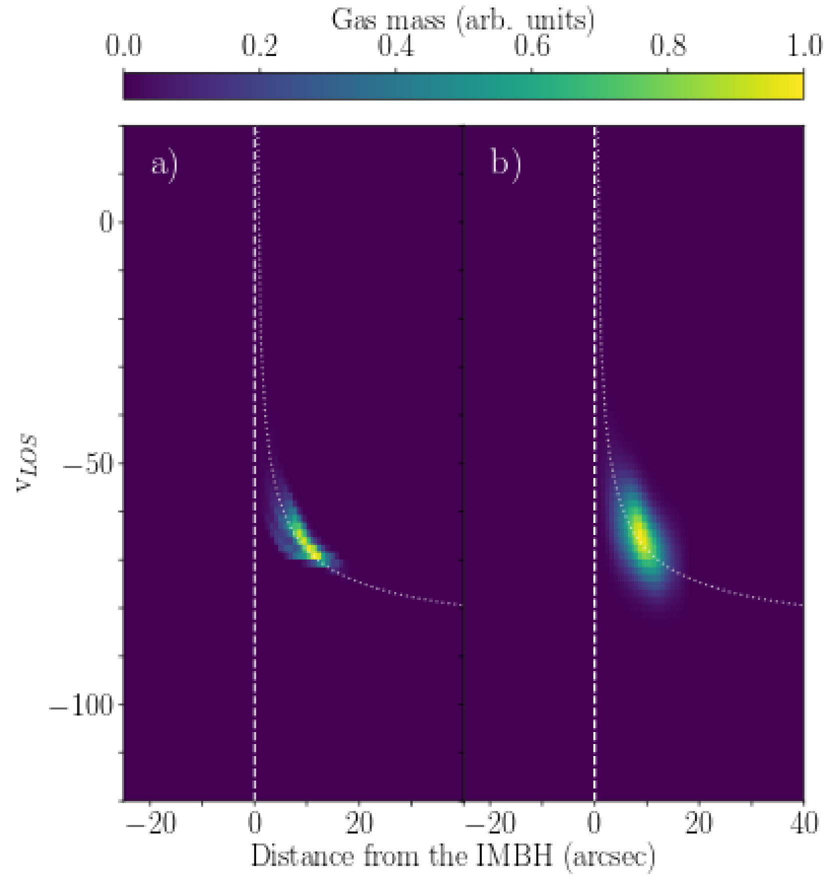
- **accrete**
- **disrupt molecular clouds**

} **see CO-0.40-0.22* (Oka et al. 2017)**

Theoretical constraints from hydro simulations:

IMBH mass > few x 10^4 M⊙

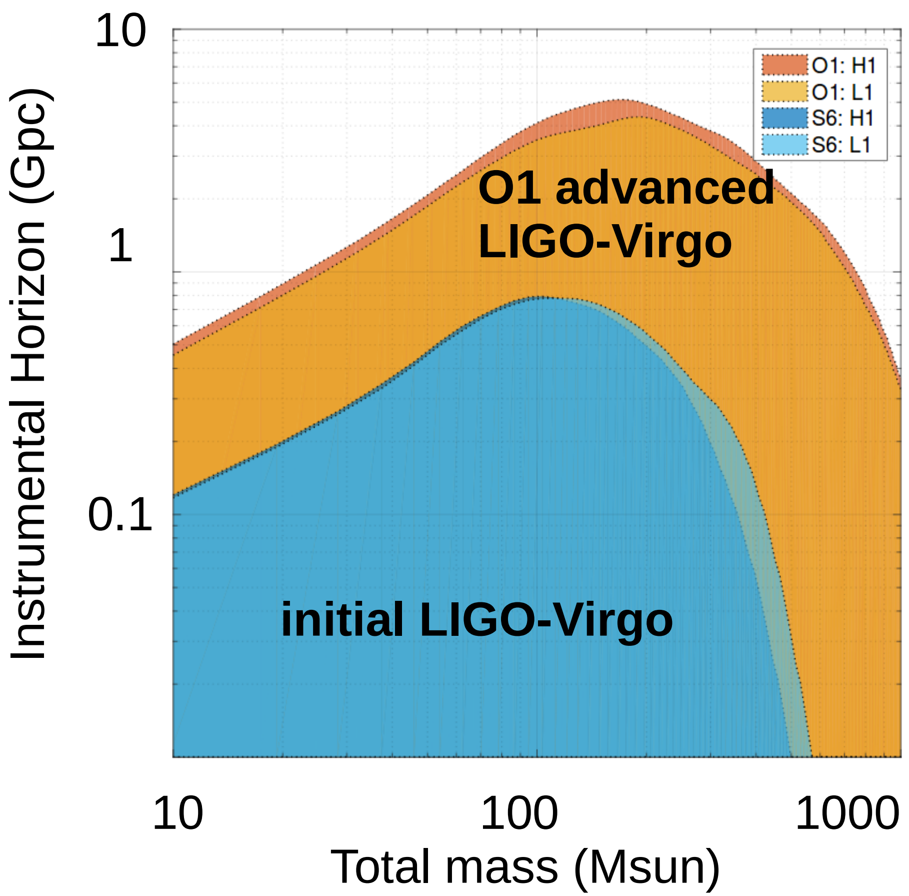


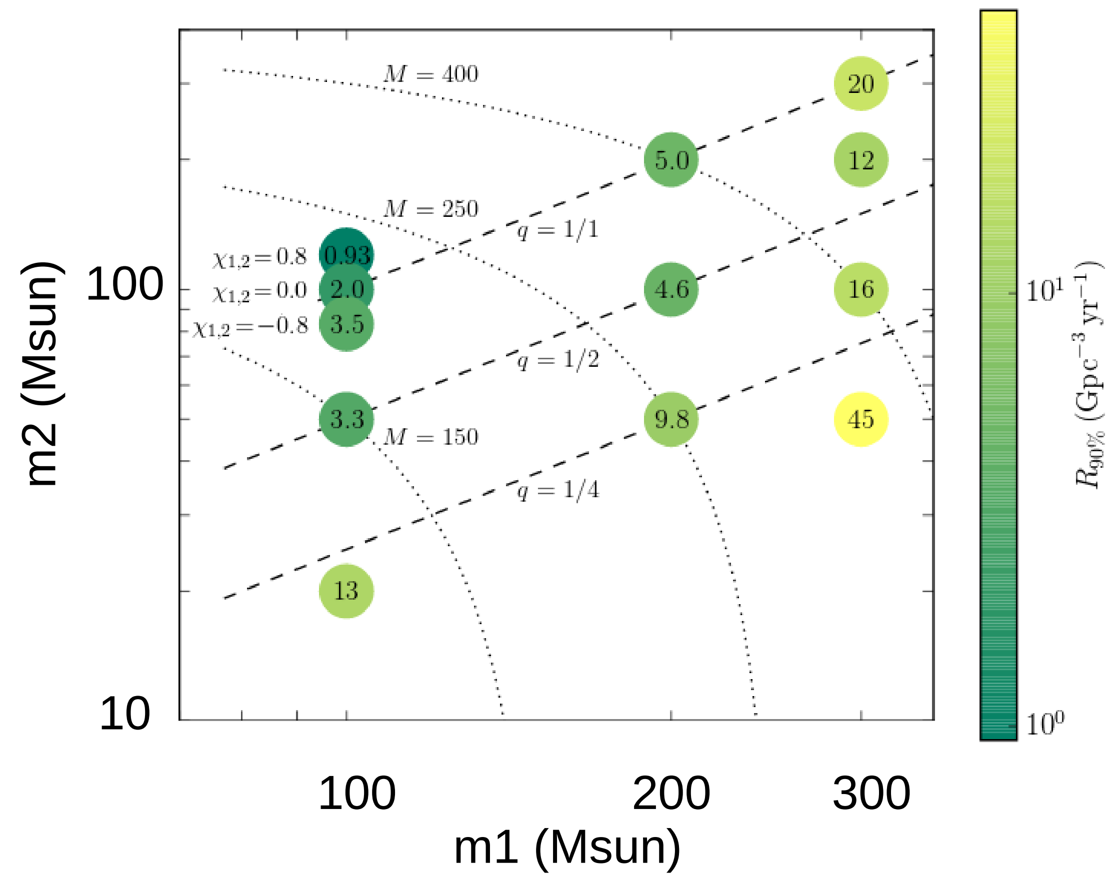


(Ballone & MM 2018)

4. Gravitational waves from IMBHs

LIGO – Virgo upper limit ~ 0.93 $Gpc^{-3}\ yr^{-1}$
for IMBH mass = 100 M⊙ and aligned spins





Abbott et al. 2017, https://arxiv.org/pdf/1704.04628.pdf

5. Conclusions

* **IMBHs bridge the mass gap between stellar BHs and SMBHs but no observational evidence**
(e.g. Farrell+ 2009; Noyola+ 2010; Anderson & van der Marel 2010; Oka+ 2016, 2017)

* **Several mechanisms have been proposed to form IMBHs:**
  - **direct collapse of massive metal-poor stars**
  (e.g. Heger et al. 2003; Spera & Mapelli 2017)
  - **repeated mergers in globular clusters**
  (e.g. Miller & Hamilton 2002; Giersz et al. 2015)
  - **runaway collisions in star clusters**
  (e.g. Colgate 1967; Portegies Zwart et al. 2004; MM 2016)

* **IMBHs in star clusters are expected to efficiently acquire companions**
(e.g. MacLeod+ 2016)

* **IMBHs in galactic nuclei can disrupt molecular clouds and accrete**
(e.g. Ballone & MM 2018)

* **LIGO-Virgo have not found any IMBH mergers in O1:**
upper limit for 100 $M_\odot$ IMBHs: 0.93 Gpc^{-3} yr^{-1}
(Abbott+ 2017)