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Constraints on the intermediate-mass black hole population from GW events

Main collaborators:

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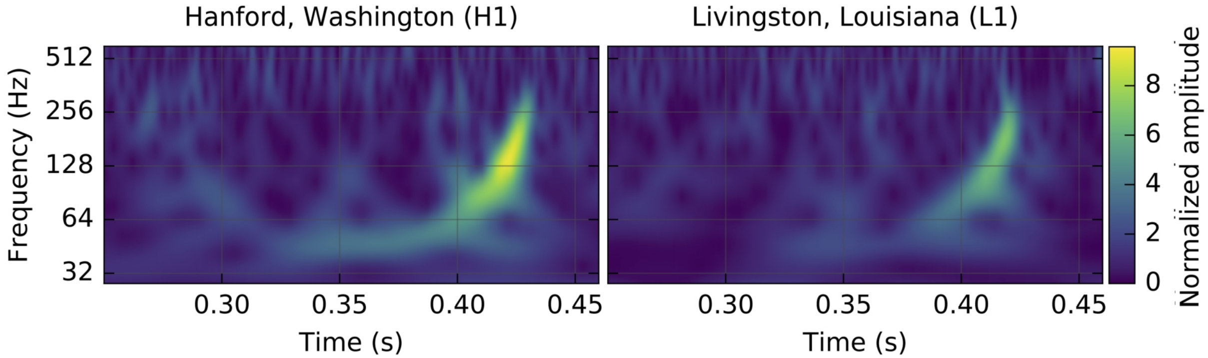
FERO 10, Toulouse March 30th 2022

OUTLINE:

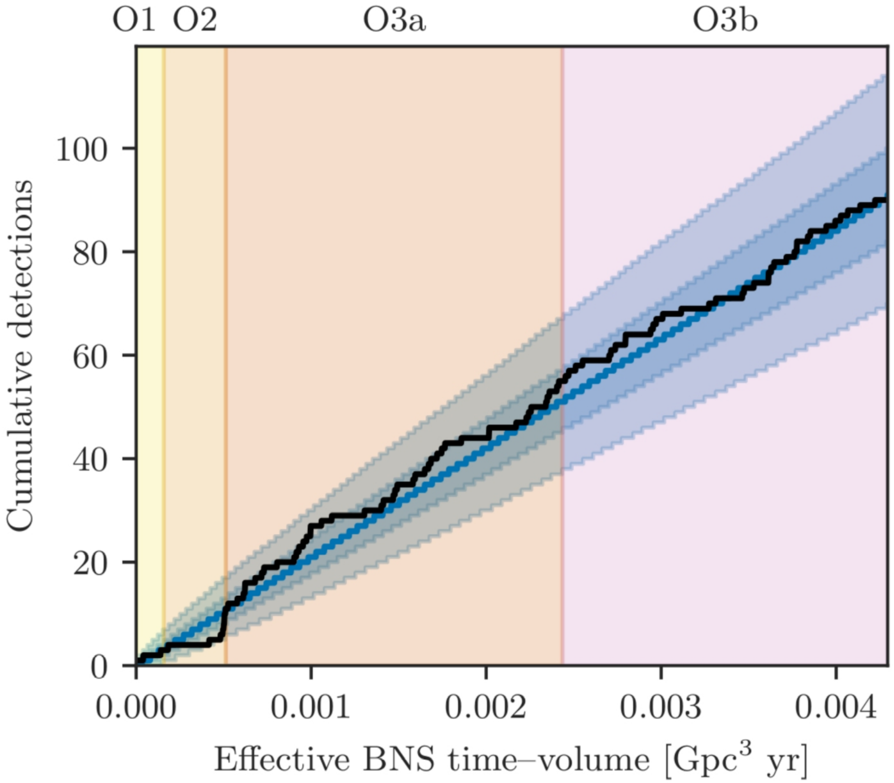
1. Lessons learned from gravitational waves (GWs)
2. Formation channels of intermediate-mass black holes (IMBHs)
3. Future GW detectors
4. Conclusions

1. Lessons learned from GW detections

GW150914: the first binary black hole (BBH)



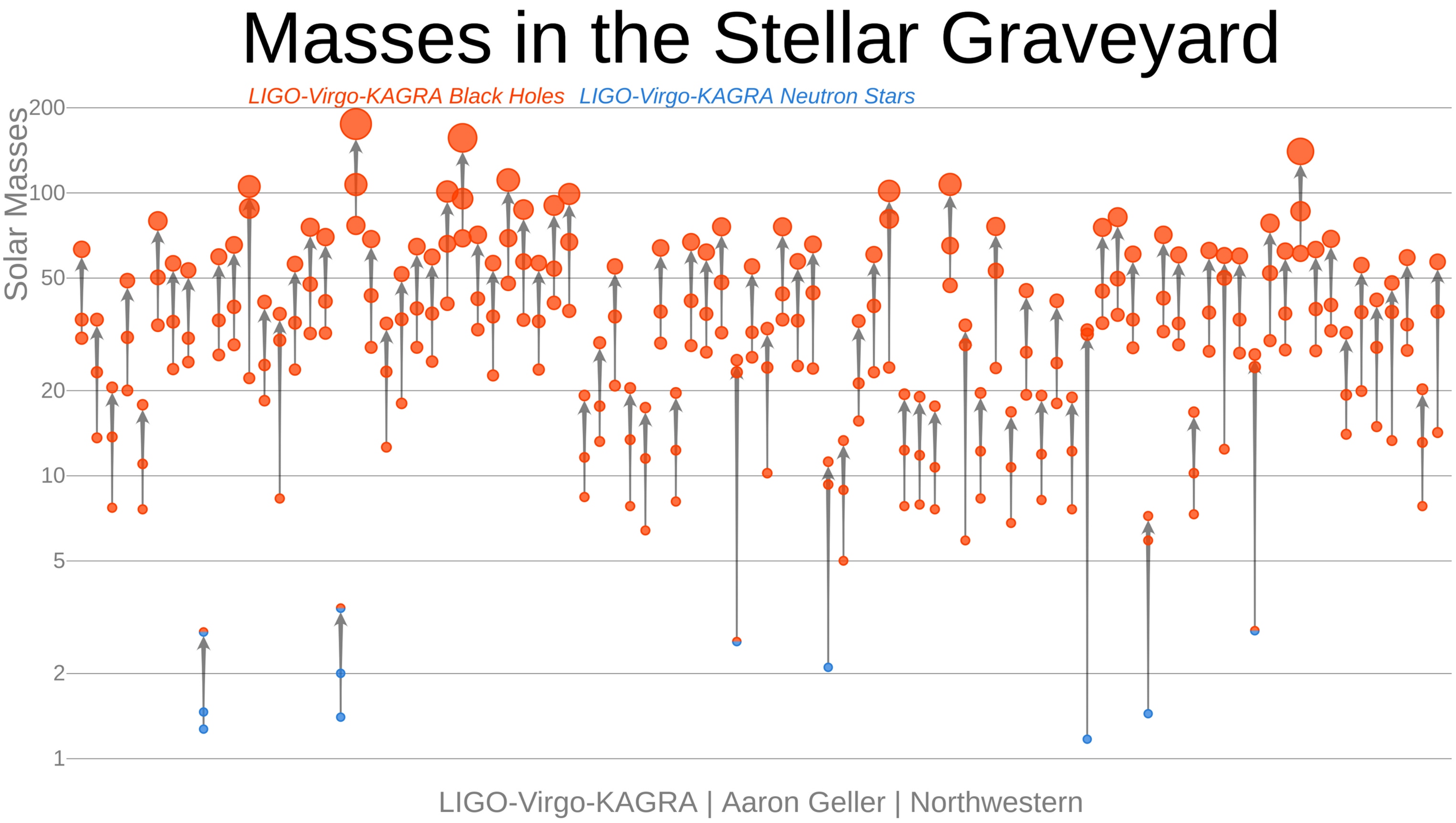
Abbott et al. 2016, PhRvL, 116, 1102



O1 + O2 + O3:

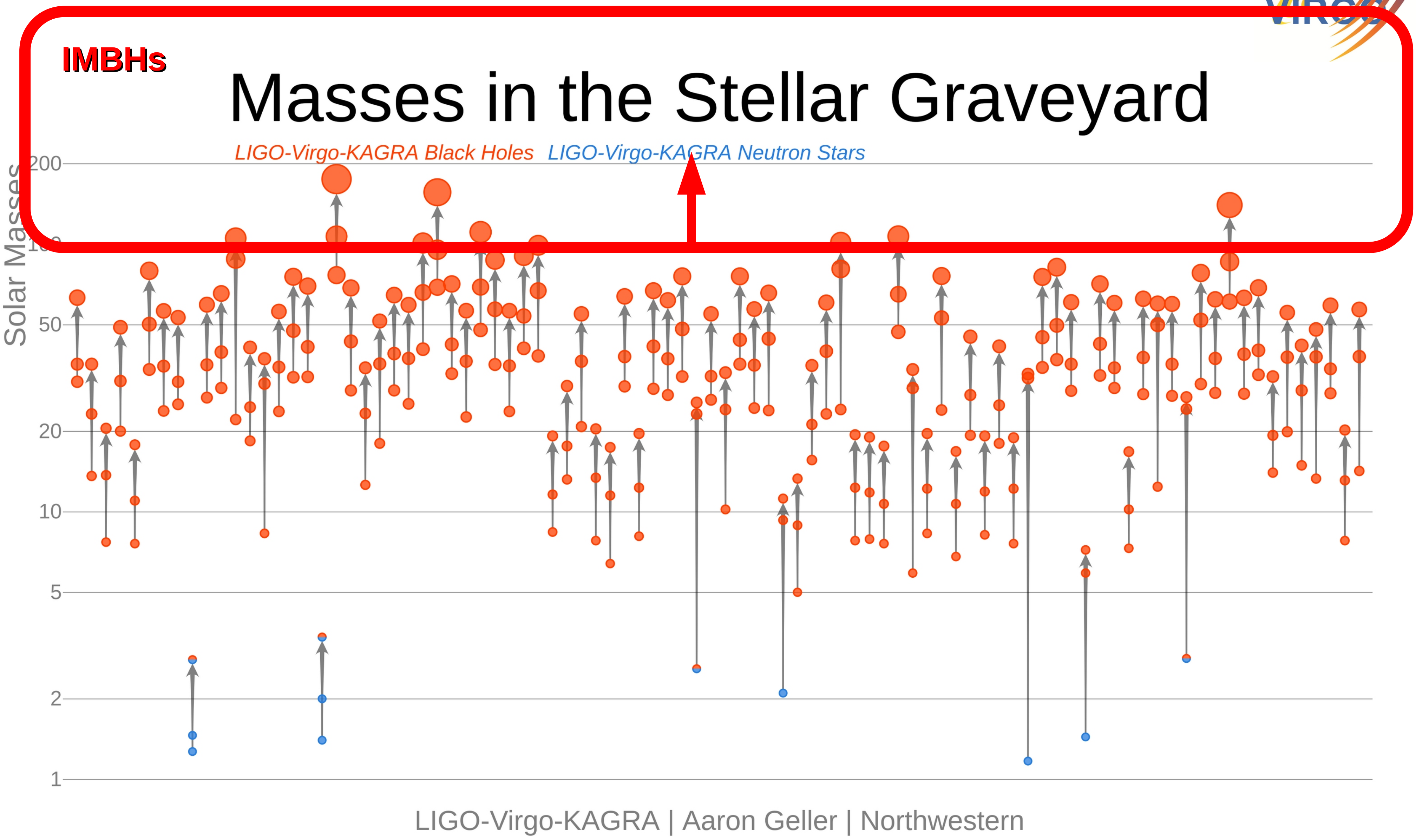
90 GW event candidates
most of them BBHs

(Abbott et al. 2021, GWTC-2;
Abbott et al. 2022, GWTC-2.1;
Abbott et al. 2022, GWTC-3)



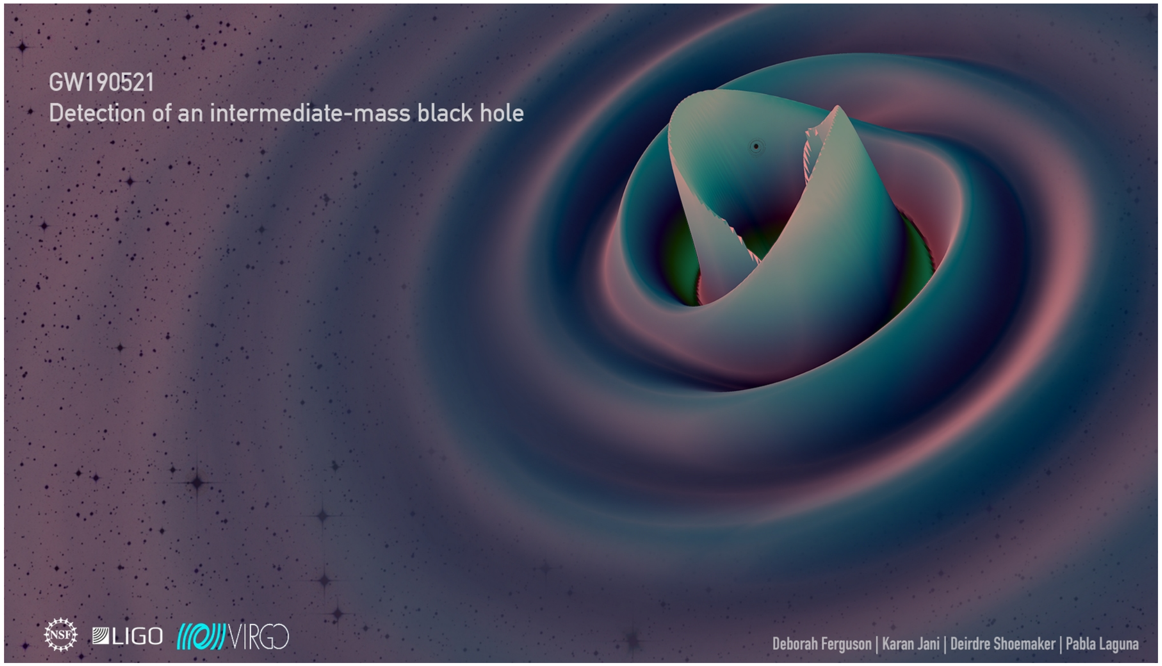
Abbott et al. 2022, GWTC-3

1. Lessons learned from GW detections



Abbott et al. 2022, GWTC-3

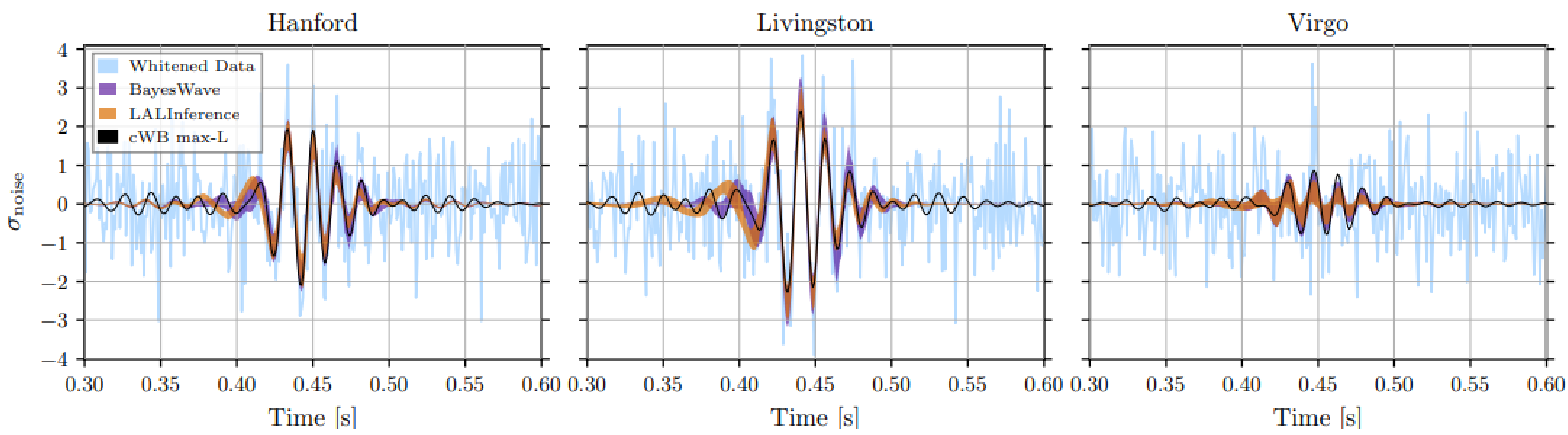
1. Lessons learned from GW detections: GW190521



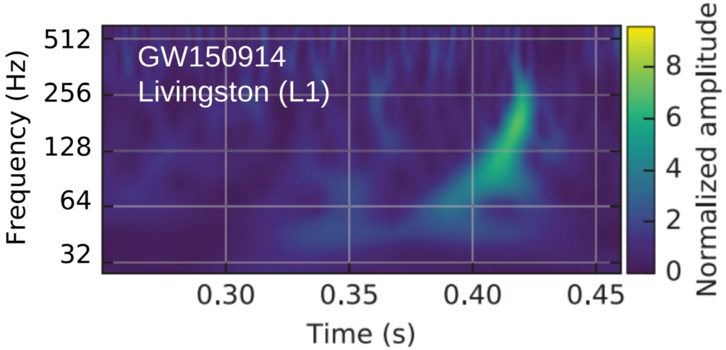
Discovery paper -
Phys. Rev. Lett. 125, 101102 (2020)
https://dcc.ligo.org/LIGO-P2000020/public

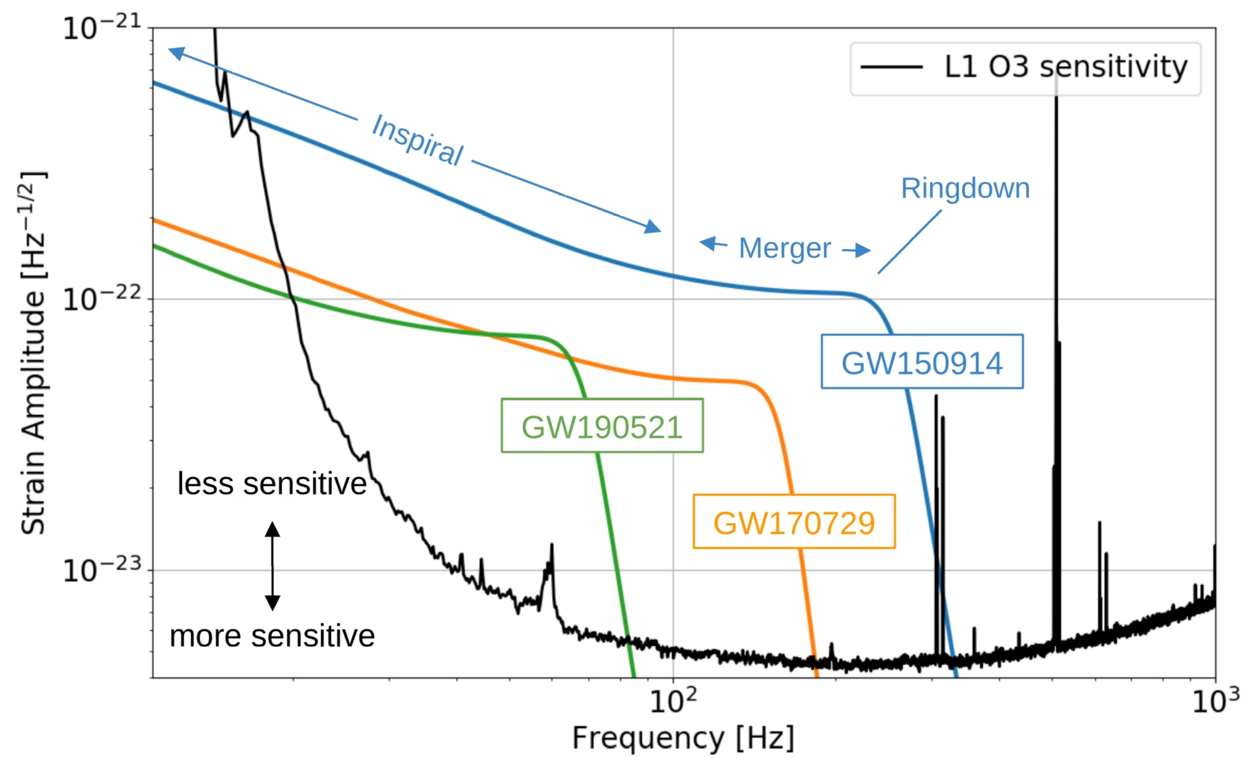
(Astro)physical implications -
Astrophys. J. Lett. 900, L13 (2020)
https://dcc.ligo.org/LIGO-P2000021/public

Data release -
https://dcc.ligo.org/LIGO-P2000158/public

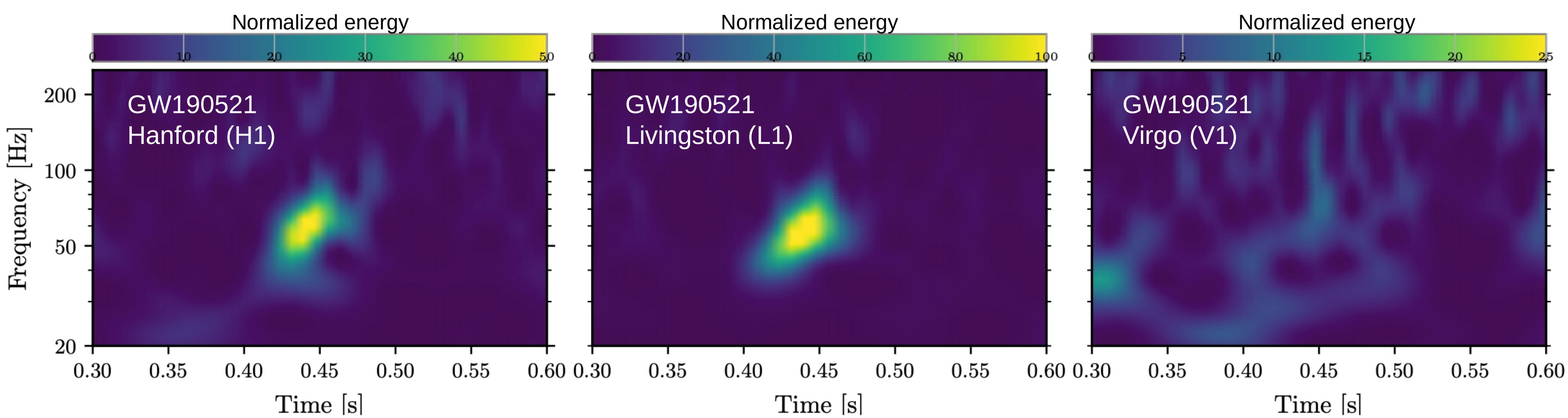


1. Lessons learned from GW detections: GW190521

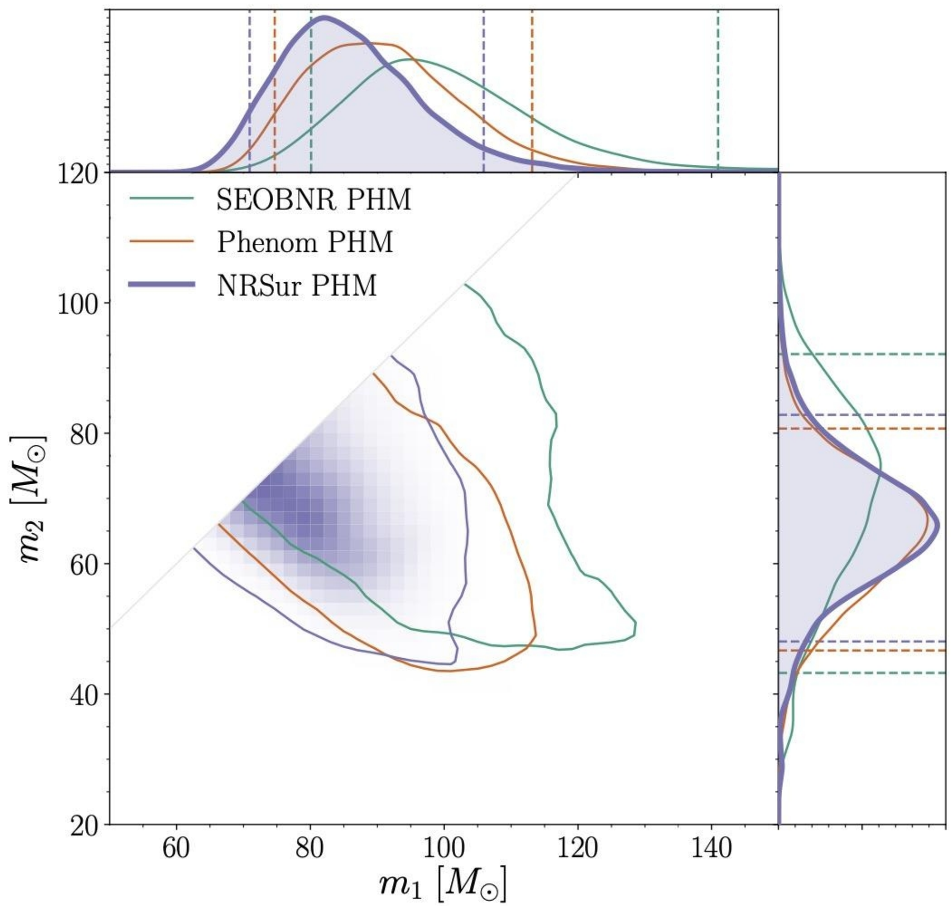


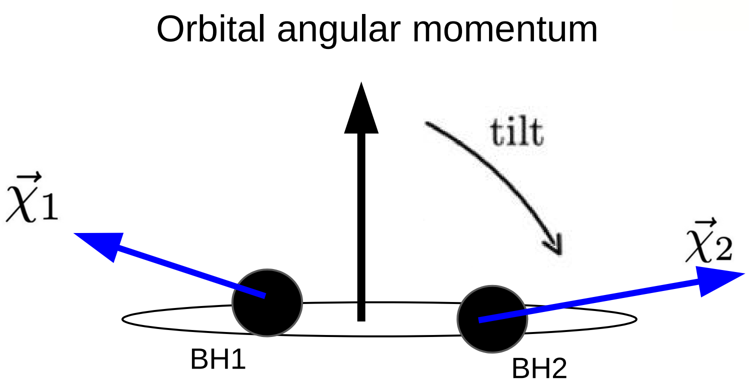


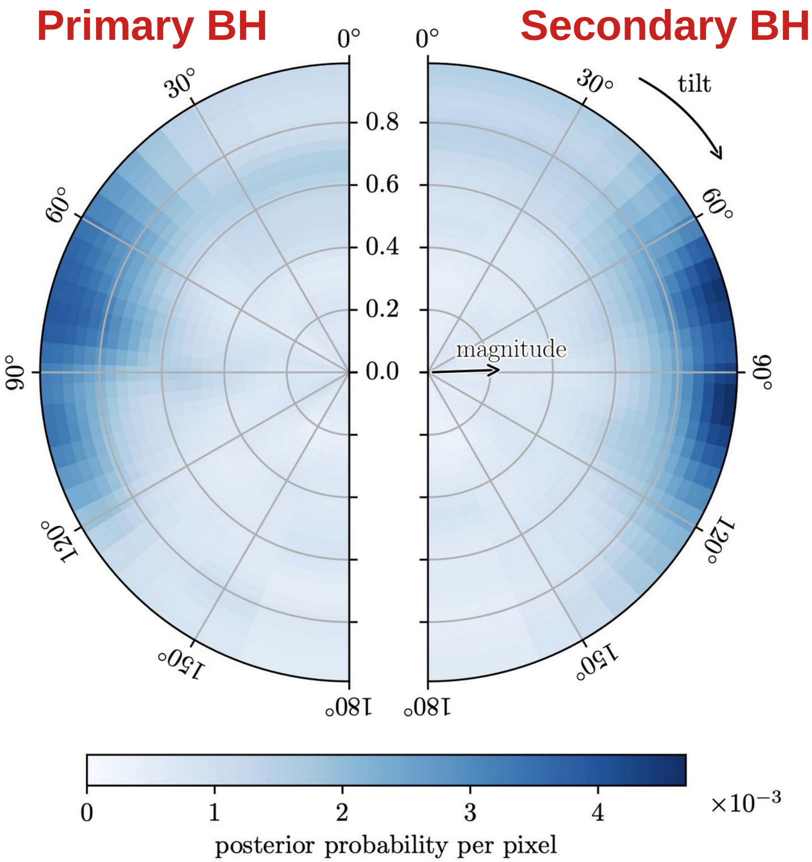
wrt smaller BBHs, the event looks like a BANG: no inspiral, only merger



1. Lessons learned from GW detections: GW190521



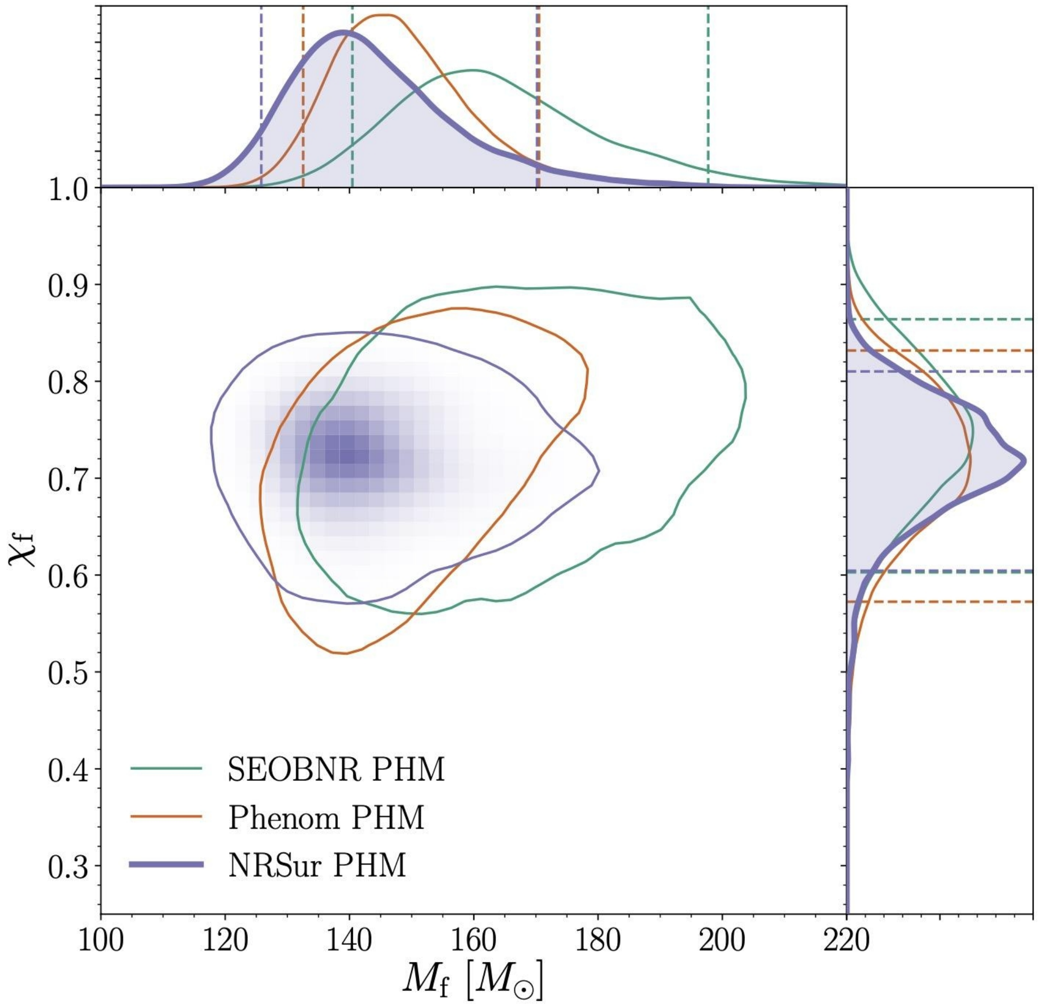




Spin magnitudes:

$$\chi_1 = 0.69^{+0.27}_{-0.62} \qquad \chi_2 = 0.73^{+0.24}_{-0.64}$$

1. Lessons learned from GW detections: GW190521



- Final BH MASS

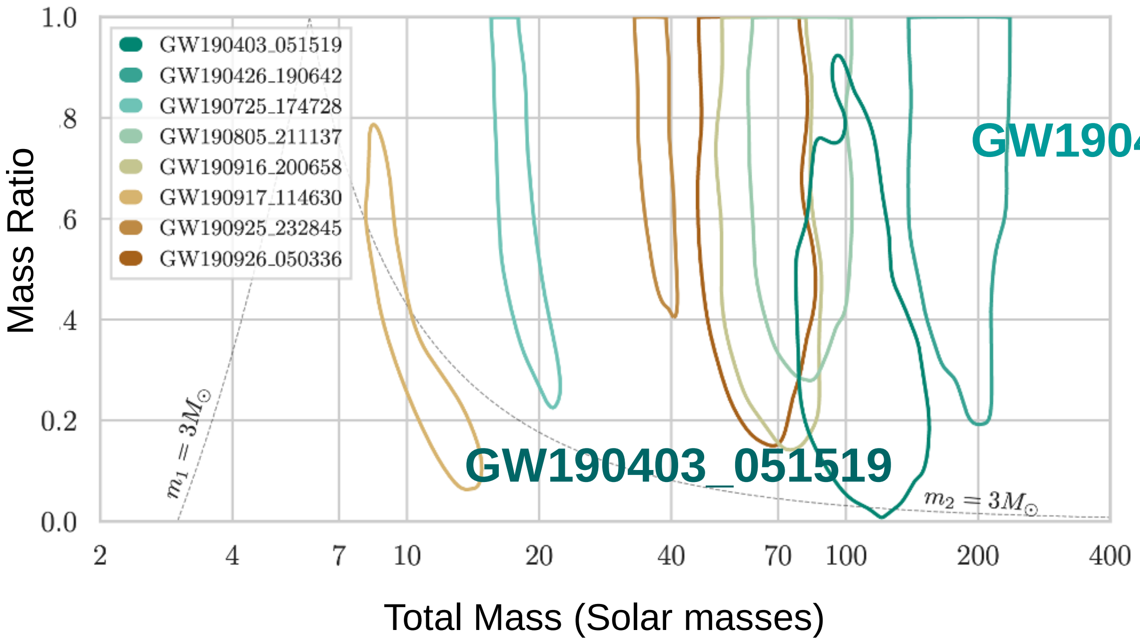
$$M_f = 142^{+28}_{-16} M_\odot$$

$$E_{GW} \sim 8 M_\odot c^2 \sim 10^{55} erg$$

- No support for $M_f < 100 M_\odot$
- Most massive BH observed via GWs
- **First conclusive observation of an intermediate-mass black hole with GWs**
- Final spin

$$\chi_f = 0.72^{+0.09}_{-0.12}$$

1. Lessons learned from GW detections: the other candidates



PROBLEMS:

* low SNR
* low probability of astro. origin

Other IMBH candidates:

GW190426_190642 (O3a)
GW200220_061928 (O3b)

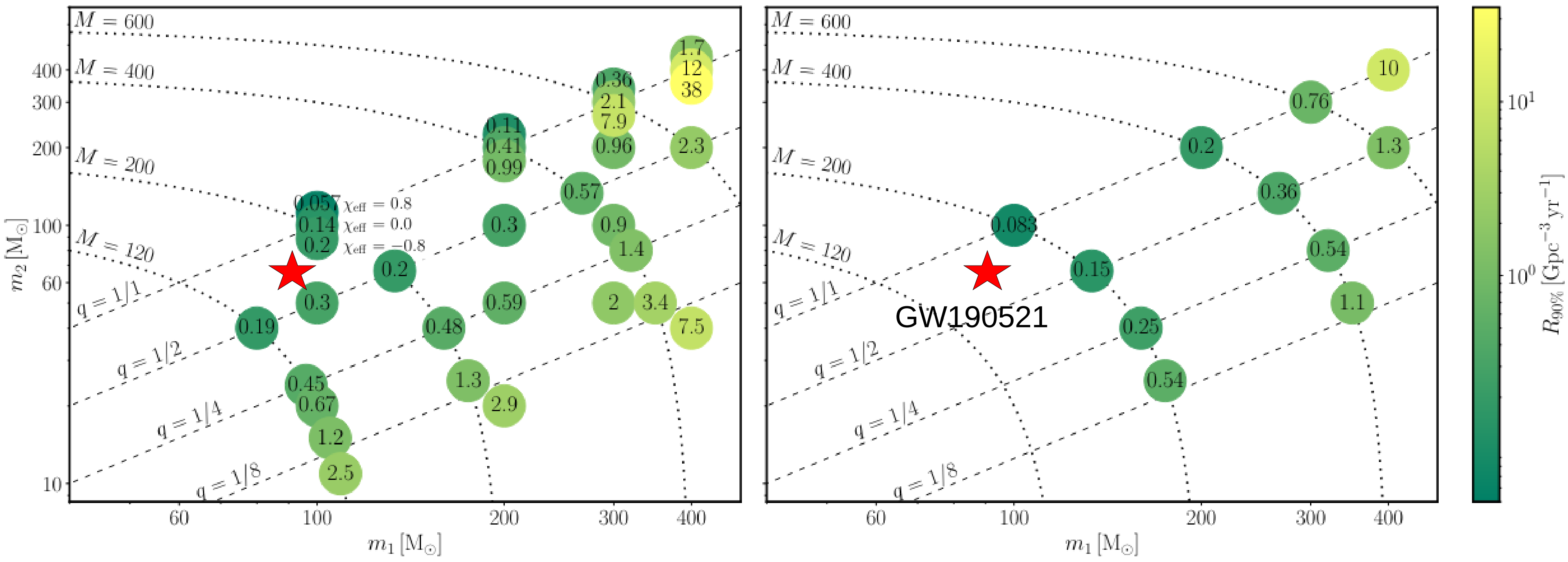
+ maybe **GW190403_051519** (O3a)

* low mass ratio
* large spin (χ_1 ~ 0.9) aligned with orbital angular momentum

(Abbott et al. 2022, GWTC-2.1; Abbott et al. 2022, GWTC-3)

1. Lessons learned from GW detections: rates

$\chi_p = 0.0$ $\chi_p = 0.42$



90% upper limit on IMBH rate from LVC

Best constraints on 200 + 200 M⊙ and effective aligned spin $\chi_{eff} = 0.8$

$$R_{90\%} = 0.056\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}\ \text{(90\% confidence)}$$

Merger rate density of BBHs similar to GW190521 $R = 0.08\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

2. Formation channels of IMBHs

1. (Very) massive & metal – poor star collapse

2. Hierarchical merger

Dynamics

3. Star – star collision

2. Formation channels of IMBHs: massive star collapse

MASSIVE STARS lose mass by stellar WINDS

Stellar winds depend on metallicity & stellar luminosity
(e.g. Vink et al. 2001; Graefener & Hamann 2008; Vink et al. 2011)

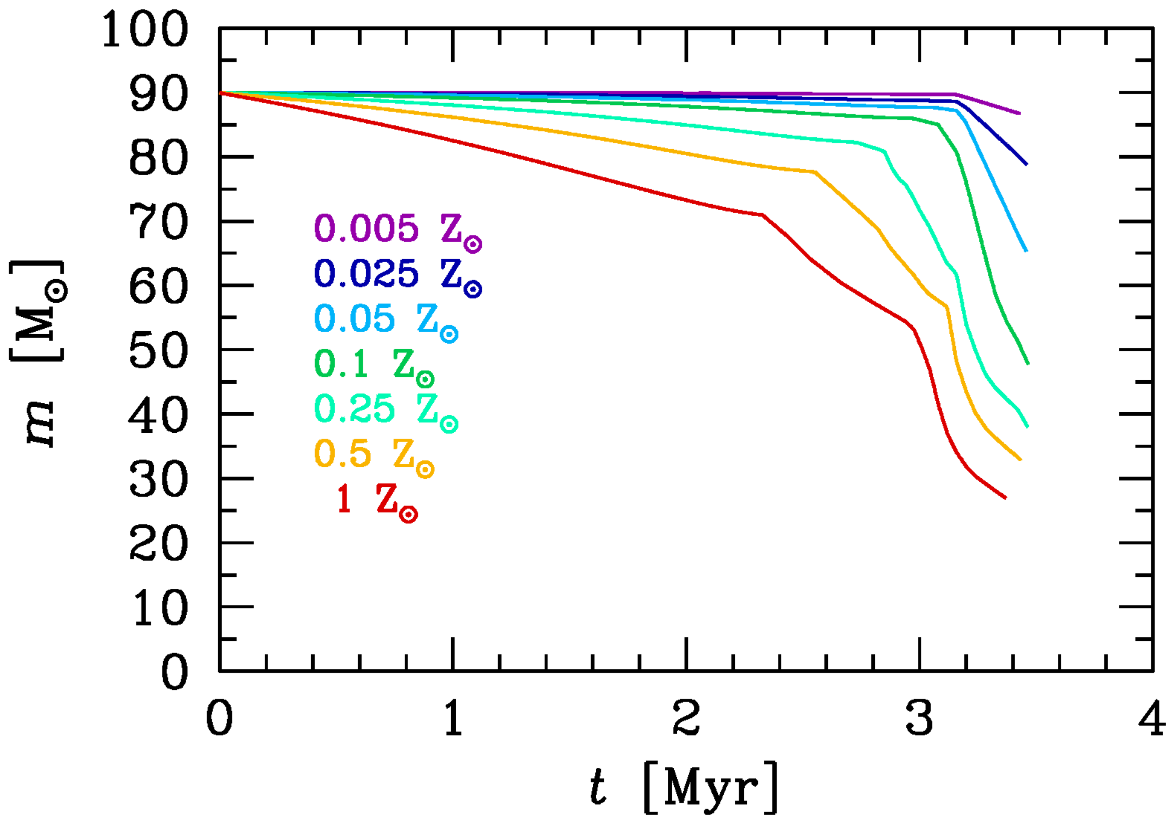
$$\dot{M} \propto Z^{\alpha}$$

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

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

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

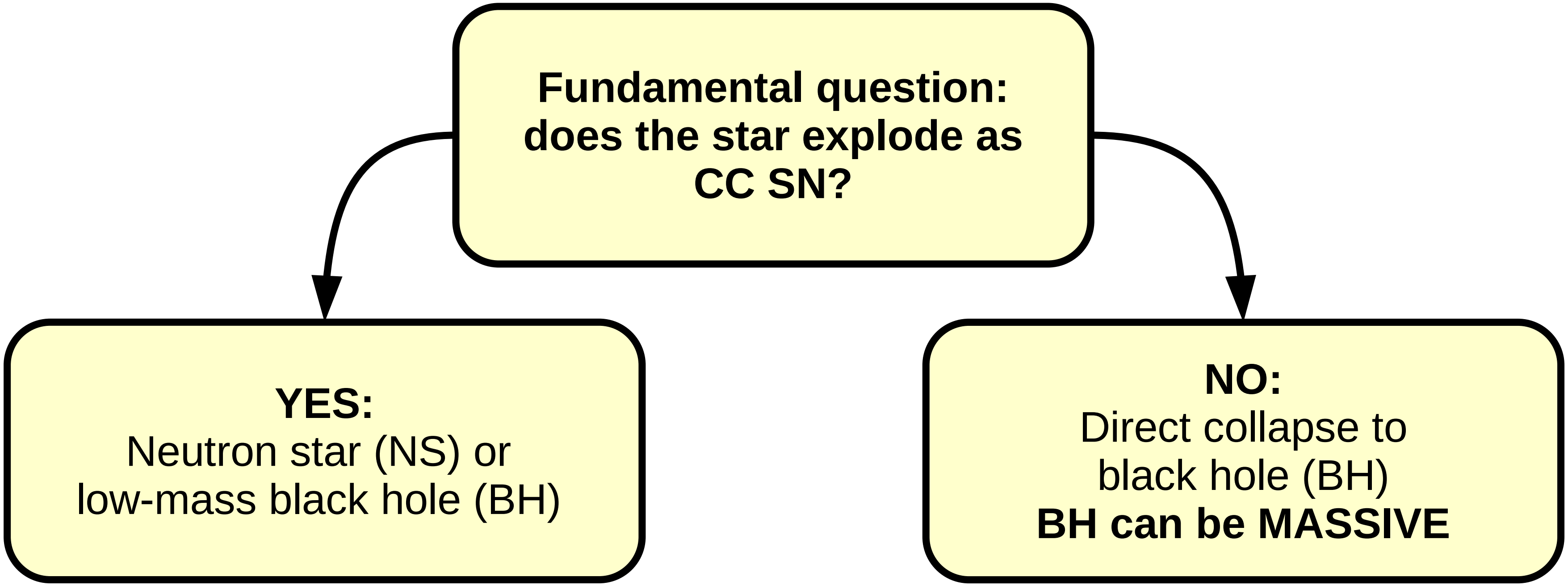
Chen, Bressan et al. (2015)



Massive metal-poor stars end their life with higher mass than metal-rich ones

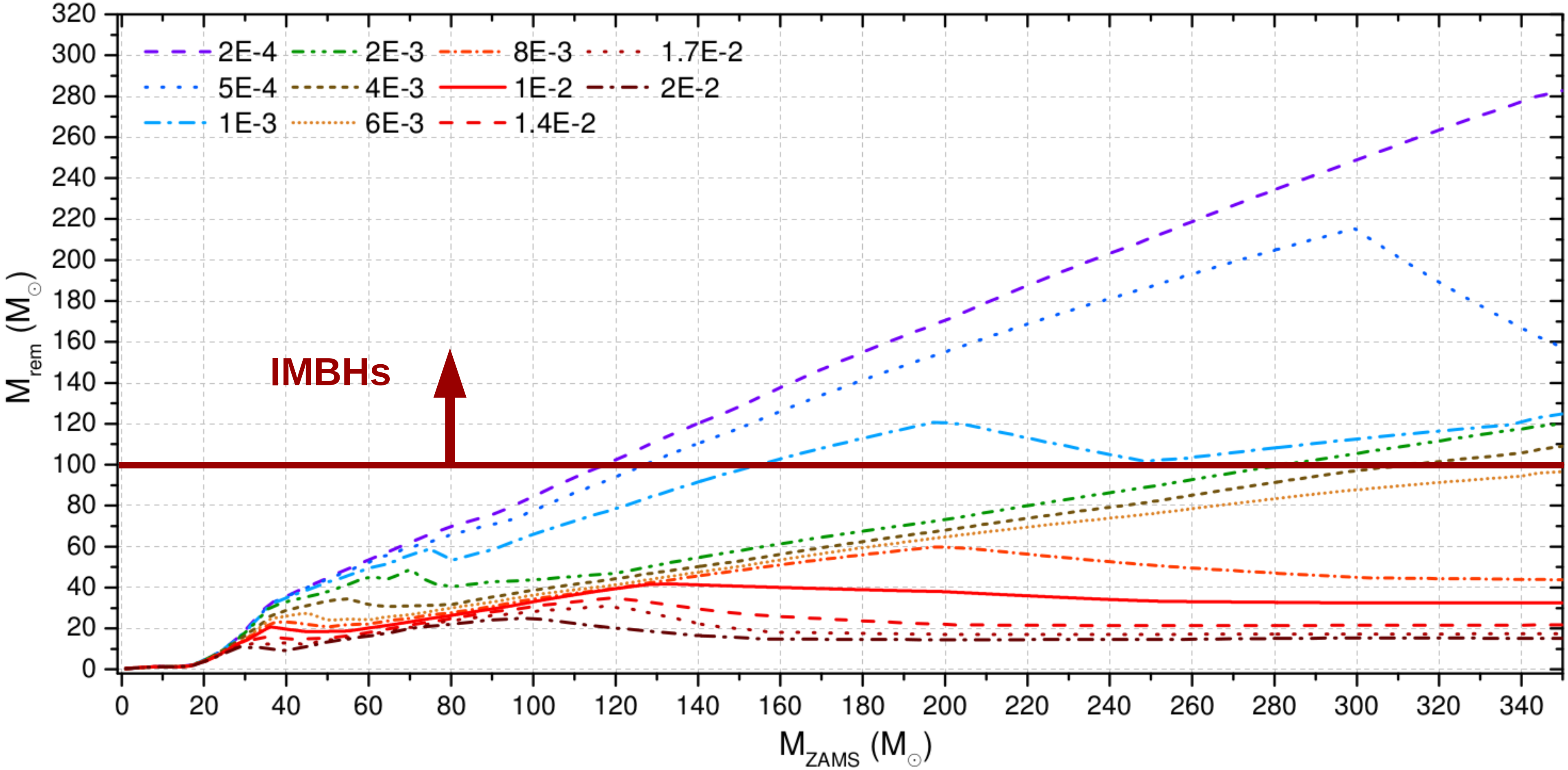
2. Formation channels of IMBHs: massive star collapse

CORE – COLLAPSE SUPERNOVA (CC SN) / DIRECT COLLAPSE:



Since metal-poor stars have larger pre-supernova masses, they are more likely to directly collapse, producing more massive BHs
(Heger et al. 2003; MM et al. 2009, 2010, 2013; Belczynski et al. 2010; Fryer et al. 2012)

2. Formation channels of IMBHs: massive star collapse



Spera & MM (2017)

2. Formation channels of IMBHs: massive star collapse

$$\Gamma = \left(\frac{\partial \ln P}{\partial \ln \rho} \right)_{\mathrm{ad}}$$

Very massive metal poor stars
efficiently produce gamma-ray (~1 MeV) photons at the end of carbon burning

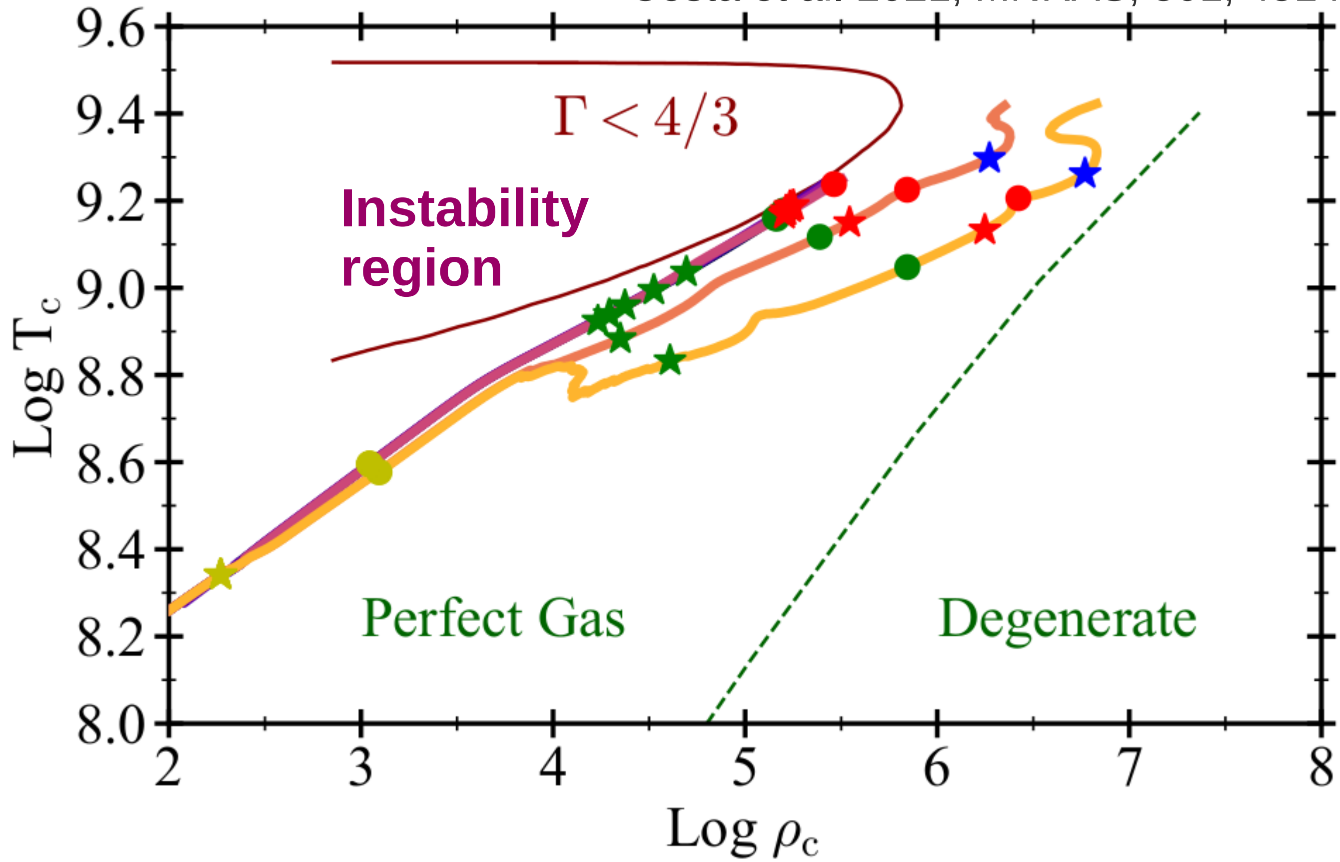
Leading to formation of **electron-positron pairs**

Missing photon pressure triggers instability:

PAIR INSTABILITY

* contraction of stellar core
* premature ignition of neon, oxygen, silicon

Costa et al. 2021, MNRAS, 501, 4514

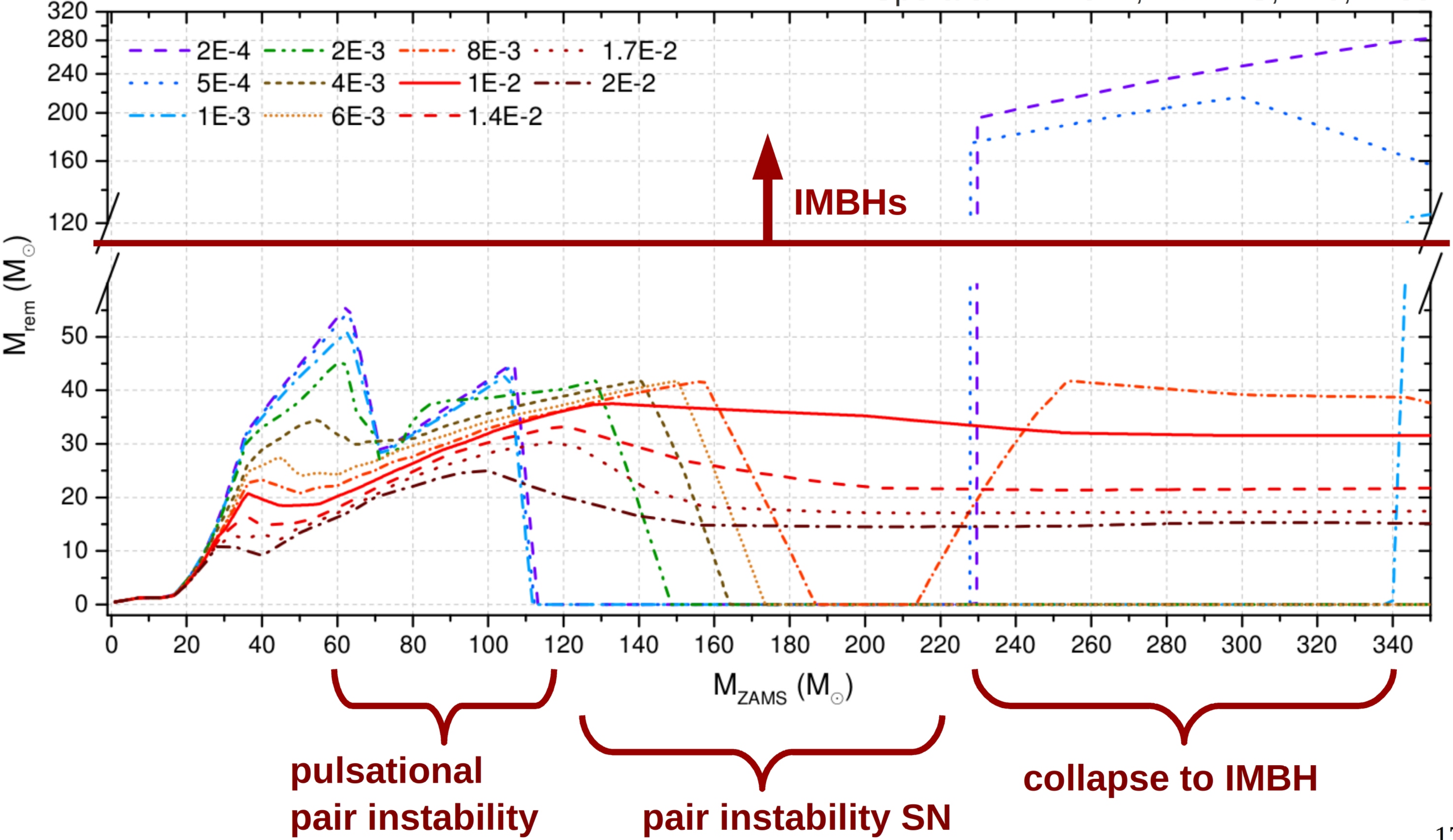


Stars (Circles): beginning (end) of helium, carbon, neon, and oxygen burning

2. Formation channels of IMBHs: massive star collapse

Impact of pulsational pair instability (if $32 < m_{He} / M_\odot < 64$) and
pair instability supernovae (if $64 < m_{He} / M_\odot < 135$)

Spera & MM 2017, MNRAS, 470, 4739



2. Formation channels of IMBHs: dynamical

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

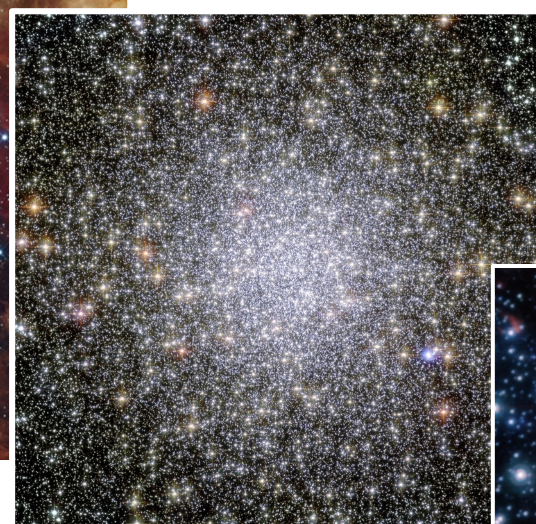
i.e. only in dense star clusters

but massive stars (BH progenitors) form in star clusters

(Lada & Lada 2003; Weidner & Kroupa 2006; Weidner, Kroupa & Bonnell 2010; Gvaramadze et al. 2012; Portegies Zwart et al. 2010)

R136, credit: NASA

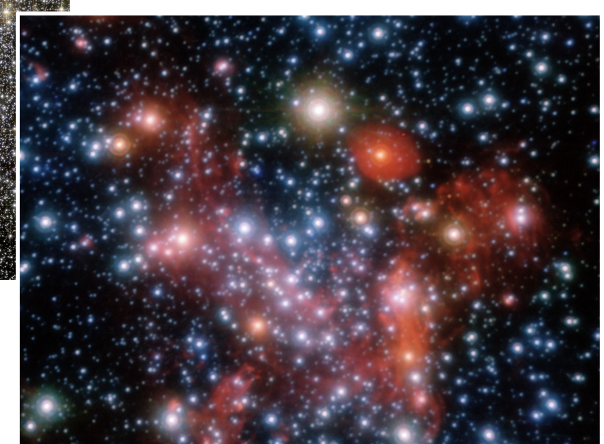
Young star clusters



47 Tucanae, credit: NASA/ESA/HST

Globular clusters

Nuclear star clusters

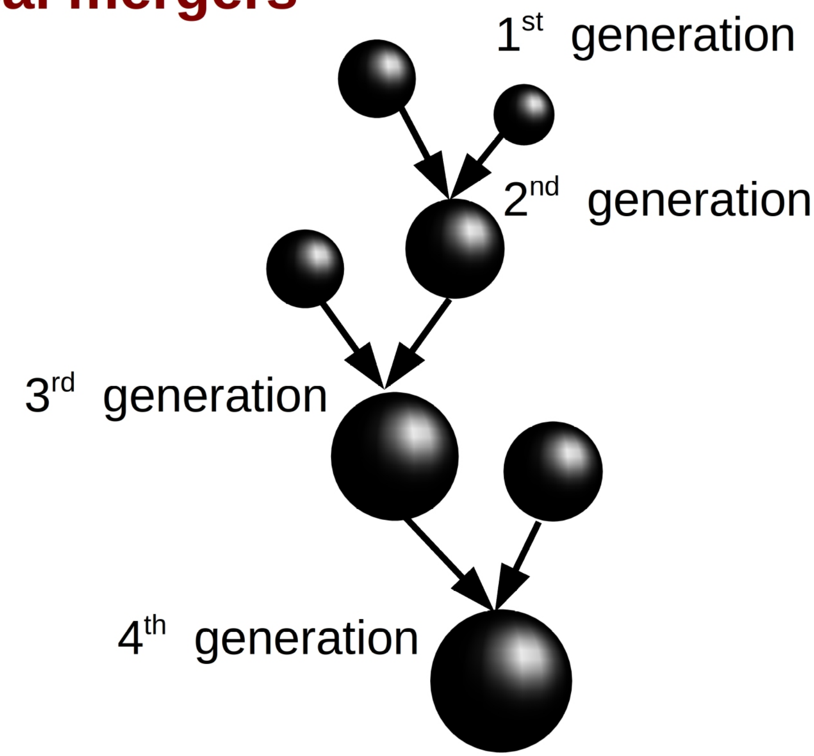


Credit: ESO, Gillessen et al.

2. Formation channels of IMBHs: hierarchical mergers

Possible only in star clusters: the merger remnant can pair up by dynamical exchange
(e.g. Miller & Hamilton 2002)

RELATIVISTIC KICK up to few x 1000 km/s
(e.g. Campanelli et al. 2007)
→ the merger product might be ejected



R136, credits: NASA

Young star clusters:
Escape velocity:
few km/s

47 Tucanae, credits: NASA/ESA/HST

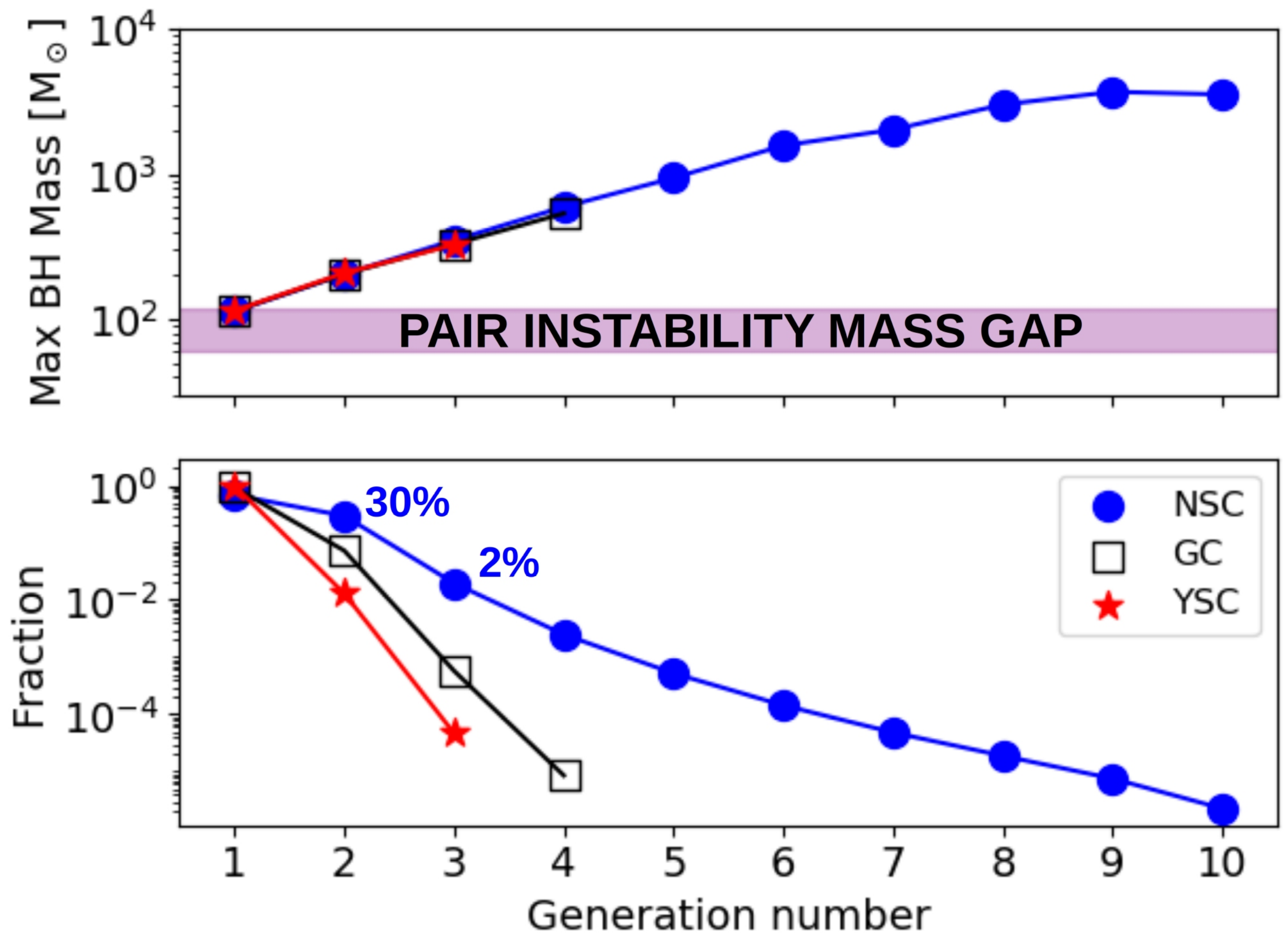
Globular clusters:
Escape velocity:
few ten km/s

Credits: ESO, Gillessen et al.

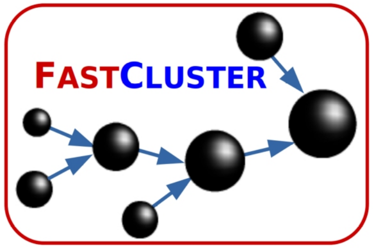
Nuclear clusters:
Escape velocity:
~ hundred km/s

WHAT KIND OF BH MASS DO WE EXPECT?

2. Formation channels of IMBHs: hierarchical mergers



MM et al. 2021, MNRAS, 505, 339



* Up to 10 generations in nuclear star clusters

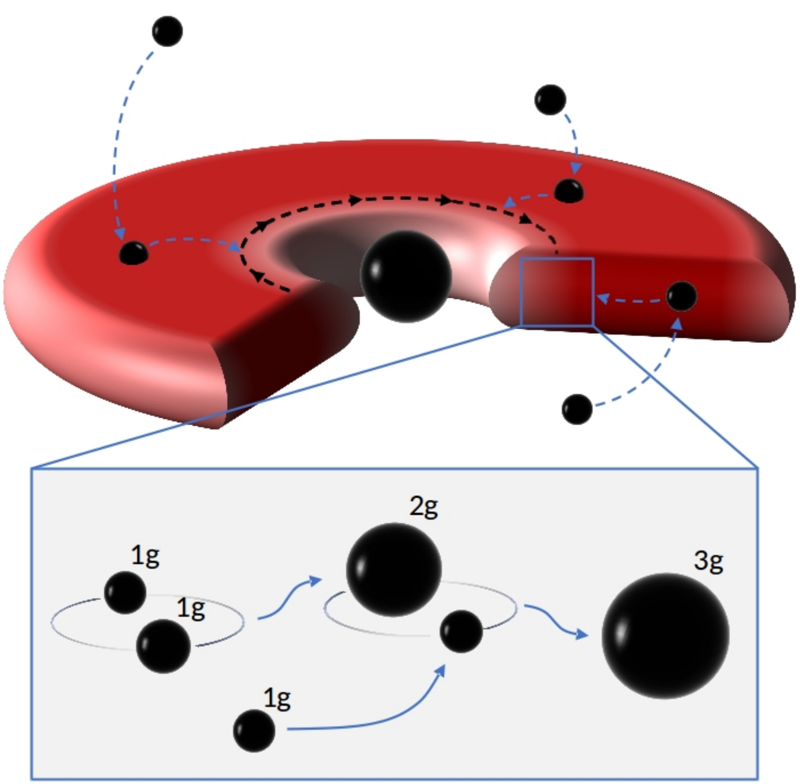
* IMBHs form efficiently in nuclear star clusters

* Most hierarchical mergers are 2^{nd} generation

dynamics population code FASTCLUSTER:
open-source version available at this link

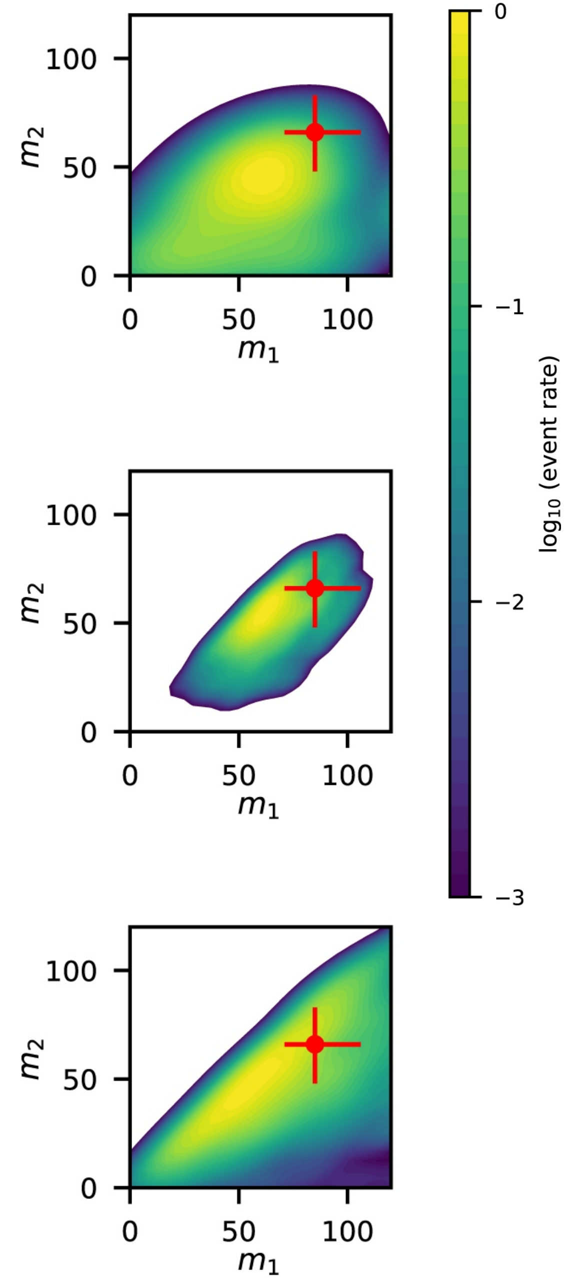
2. Formation channels of IMBHs: hierarchical mergers in AGN disks

Torques in the dense gas disk of an AGN favour pairing and merger of BBHs



Credit: Imre Bartos

See also Bartos et al. 2017; McKernan et al. 2012, 2018; Secunda et al. 2019; Yang et al. 2019, 2020; Samsing et al. 2020; Tagawa et al. 2020 and many others



● GW190521

Low-mass first gen (<15 M⊙) but > 4 generations

High-mass first gen (<45 M⊙) up to 2[nd] generations

First generation but super-Eddington accretion

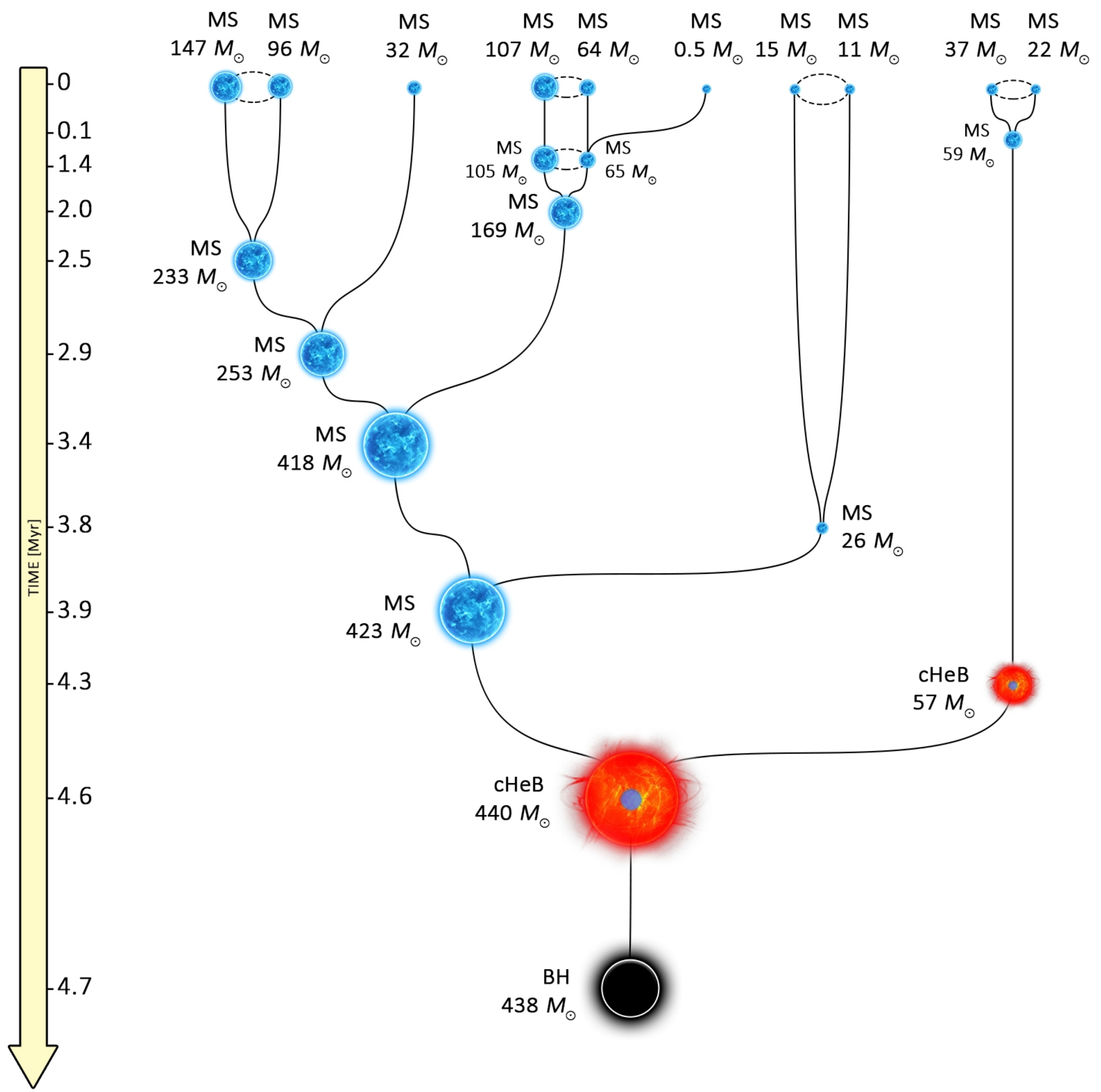
Tagawa et al. 2021,ApJ, 908, 194

2. Formation channels of IMBHs: star – star collisions

Dynamical friction brings massive stars to cluster's core

If dynamical friction timescale shorter than massive star lifetime, massive stars collide and form a super-massive star (>100 M⊙)

Portegies Zwart et al. 2004, Nat, 428, 724

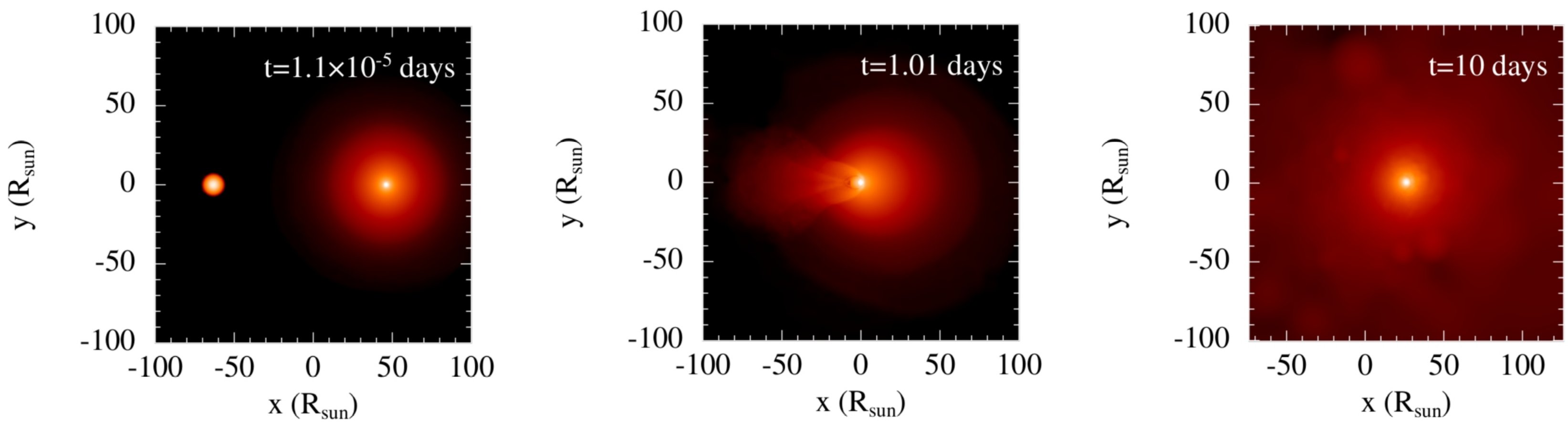


Di Carlo, MM et al. 2021, MNRAS, 507, 5132

2. Formation channels of IMBHs: star – star collisions

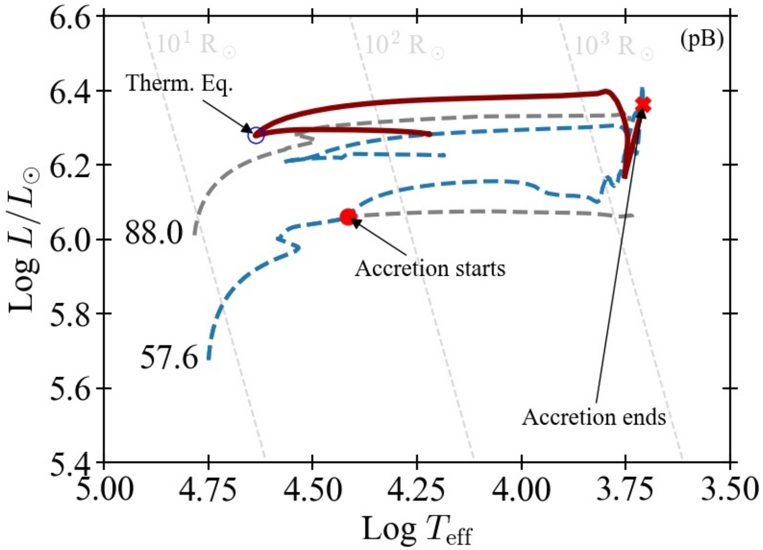
PROBLEMS: 1. mass loss during collision → needs hydro-dynamical simulations

2. mass loss by stellar winds → needs accurate star evolution calculations



Max 12% mass loss during head-on star – star collision

(Ballone et al., subm.)



If star is metal-poor (<0.1 Z☉), stellar winds after collision < 1 M☉

→ Massive black hole can form

(Costa et al., subm.)

2. Formation channels of IMBHs: theory vs observations

	LVK IMBHs (GW190521 remnant)	Massive Star Collapse	Hierarchical Merger	Hierarchical Merger (AGN disk)	Star – Star collision
Mass ($M_\odot$)	142 (+28,-16)	120 – 300 (depends on max star mass)	100 – 10'000?	100 – ?	100 – 500 ?
Spin	0.72(+0.09,-0.12)	???? (depends on ang. mom. transport)	~0.7 – 0.9 (from NR)	~0.7 – 0.9 (from NR)	???? (depends on ang. mom. transport)

- The remnant of GW190521 is a HIERARCHICAL MERGER
& its properties agree with expectations

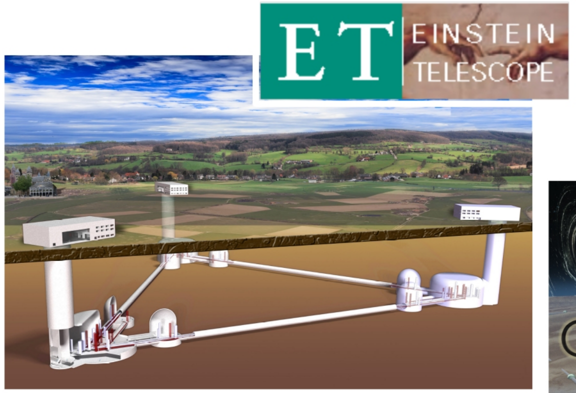
- Will GW190521 merge again?
We do not know its recoil velocity and location

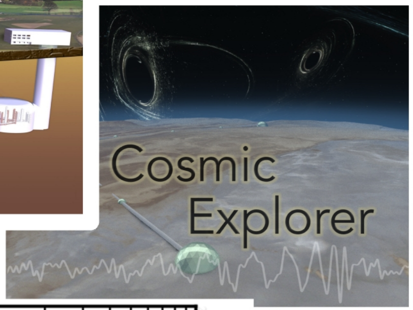
- Can we observe other IMBH channels with LVK?
In principle yes, but limitation at low frequencies

3. Future GW detectors: The Einstein Telescope (2035)

Einstein Telescope (ET) and Cosmic Explorer will observe BBH mergers up to z ~ 30 (~100 Myr after Big Bang)

ET first "light": 2035 (expected)

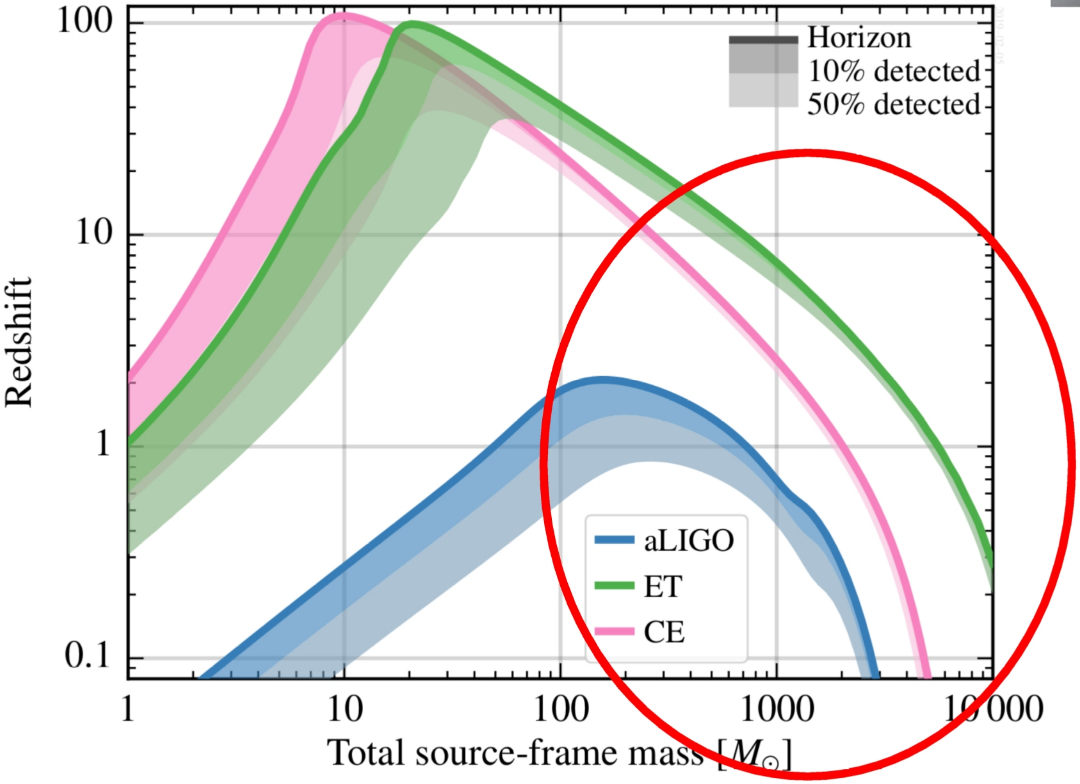




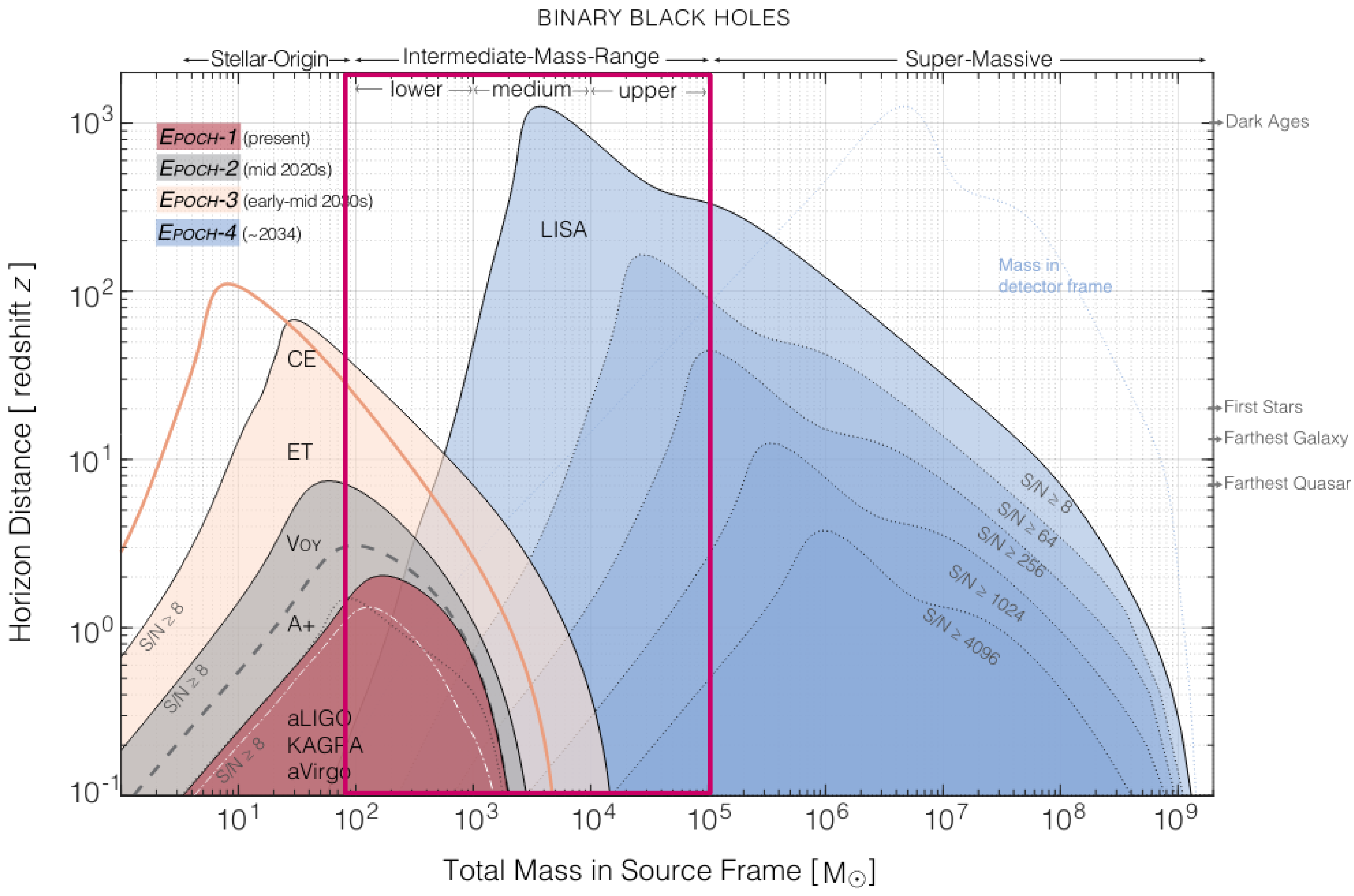
Join the Einstein Telescope's Observation Science Board (link)

→ 2023: first blue book of ET science case

→ by 2035: build an active and inclusive scientific community ready to exploit ET data



3. Future GW detectors: LISA (2037)



Jani, Shoemaker & Cutler 2020, NatAs, 4, 260

www.demoblack.com

4. Conclusions

* The remnant of GW190521 (mass ~ 142 $M_\odot$, spin ~ 0.72)
is the first IMBH observed with GWs (Abbott et al. 2020a, 2020b)

* Other candidates (GW190403, GW190426, GW200220) with much lower SNR
(Abbott et al. 2022, GWTC-2.1; Abbott et al. 2022, GWTC-3)

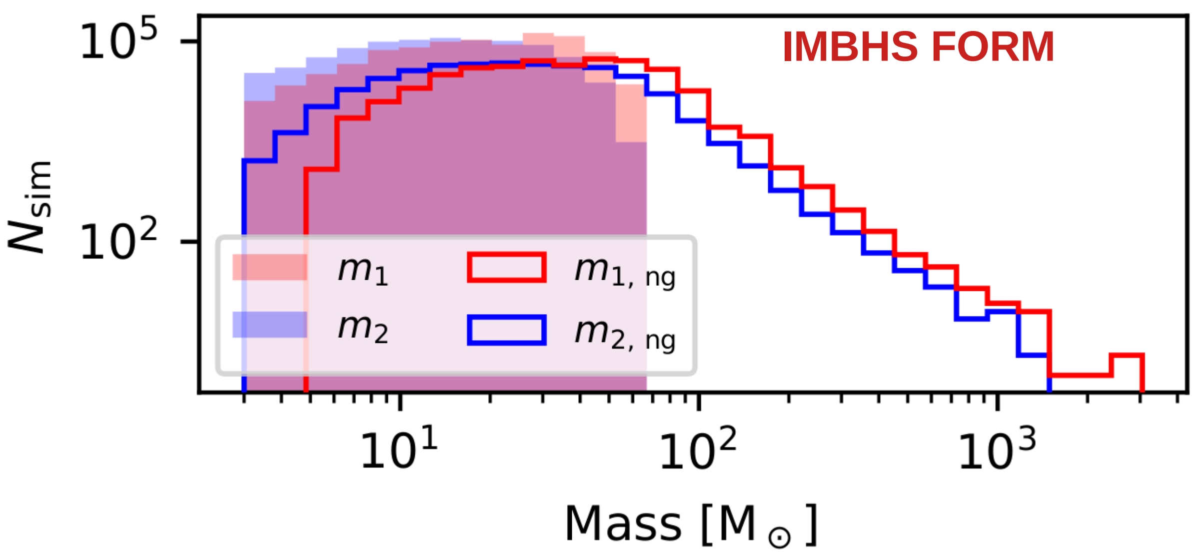
→ **GW detectors can be used to study IMBHs**

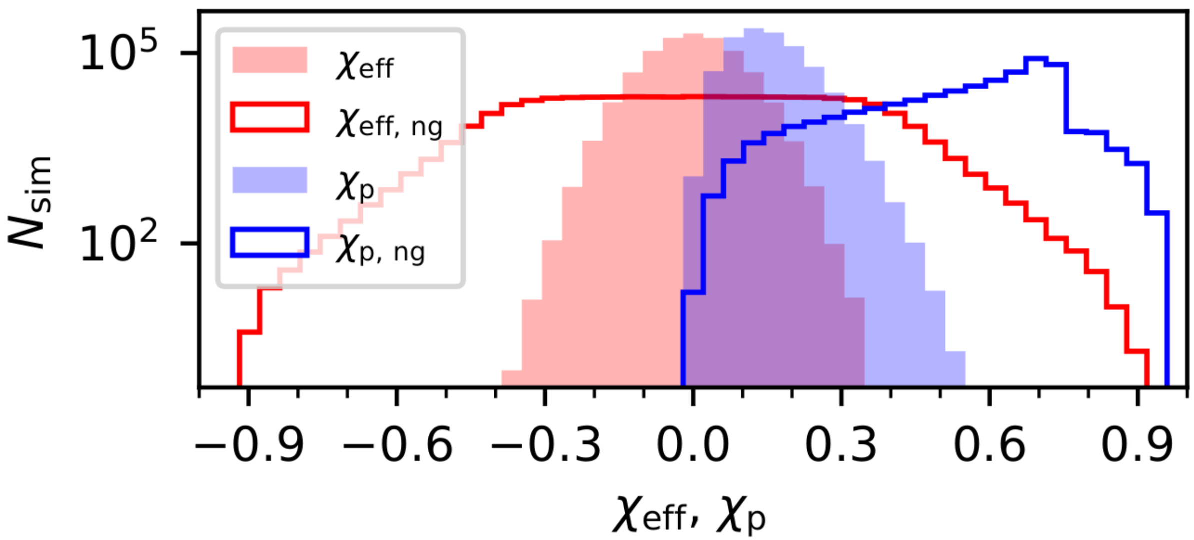
***** Theoretical channels still uncertain:
- collapse of massive metal-poor star (mass >100 $M_\odot$, spin unknown)
- **hierarchical merger (100 – 10^4 $M_\odot$, spin ~ 0.7 – 0.9)**
- hierachical merger in AGN disk (>100 $M_\odot$, spin ~ 0.7 – 0.9)
- star – star collision (100 – 500 $M_\odot$, spin unkwnon)

*** The future is loud:**
Einstein Telescope, Cosmic Explorer and LISA will observe IMBHs possibly with multi-band detections

THANK YOU

2. Formation channels of IMBHs: hierarchical mergers





MM et al. 2021, MNRAS, 505, 339

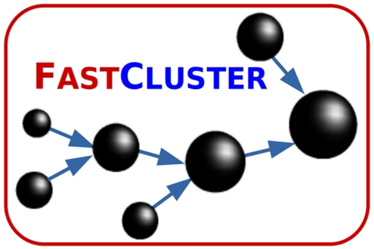
MM et al. 2022, MNRAS, 511, 5797

Filled histograms: first generation BBH mergers

Unfilled histograms: 2nd or Nth generation BBH mergers

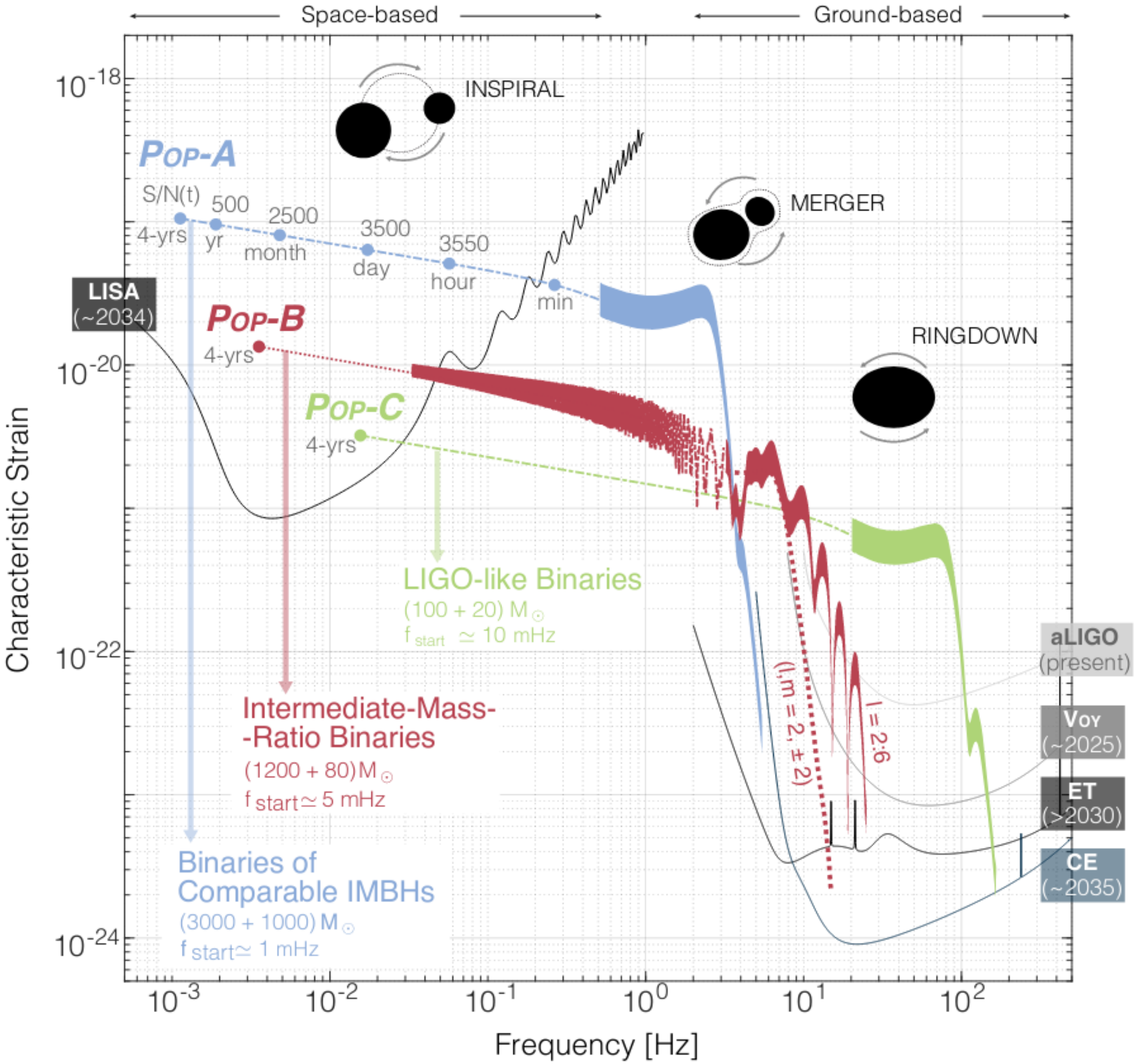
χ_{eff} → measuring spin components **aligned with orbital angular momentum**

χ_p → measuring spin components **in the orbital plane**



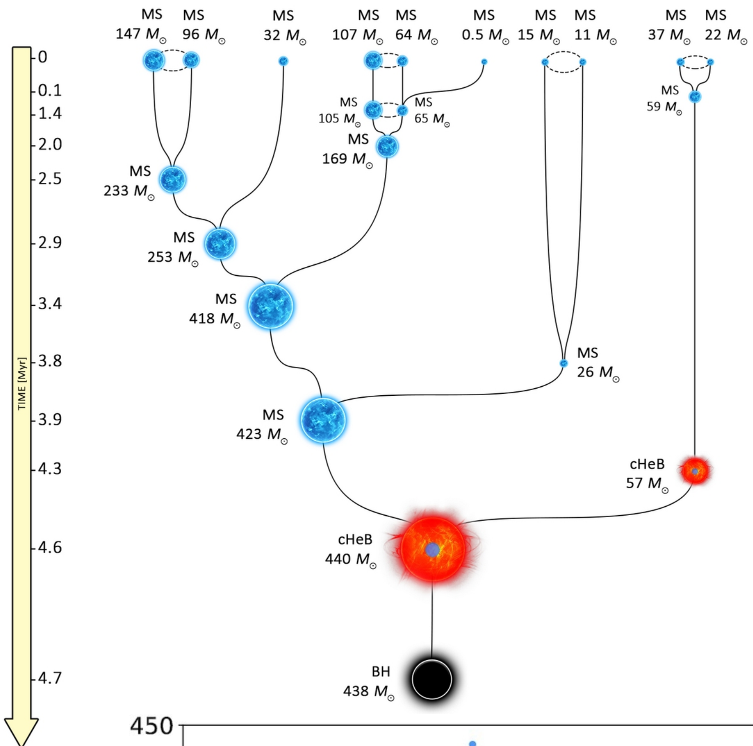
dynamics population code FASTCLUSTER:
open-source version available at this link

4. Evolution across cosmic time: which IMBH binaries?



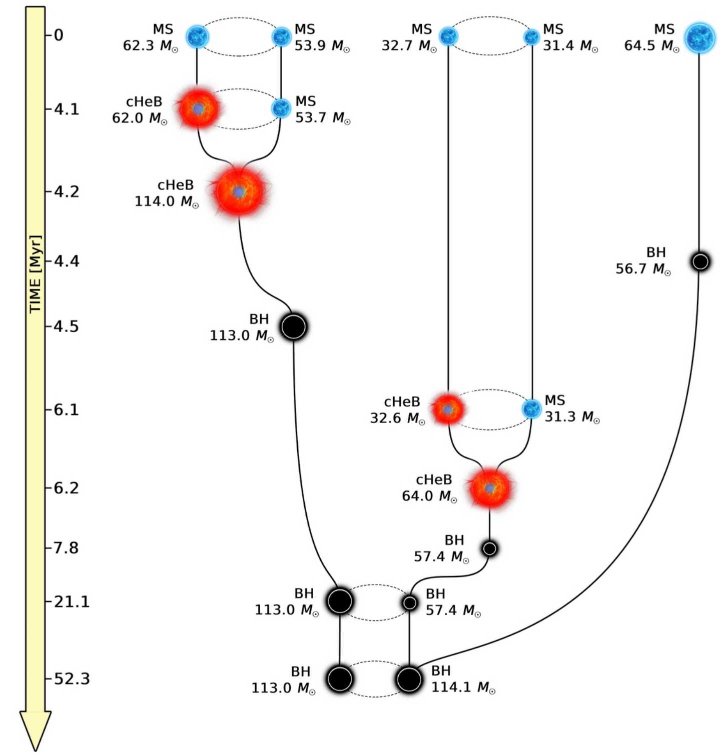
Jani, Shoemaker & Cutler 2020, NatAs, 4, 260

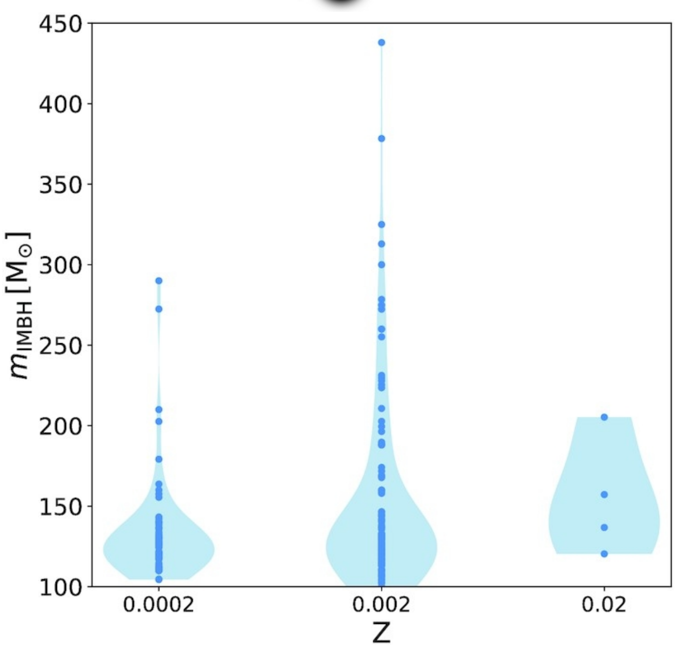
3. Formation channels of IMBHs: star – star collisions



The most massive IMBH
(~ 440 M⊙)

A binary IMBH
(~ 110 + 110 M⊙)

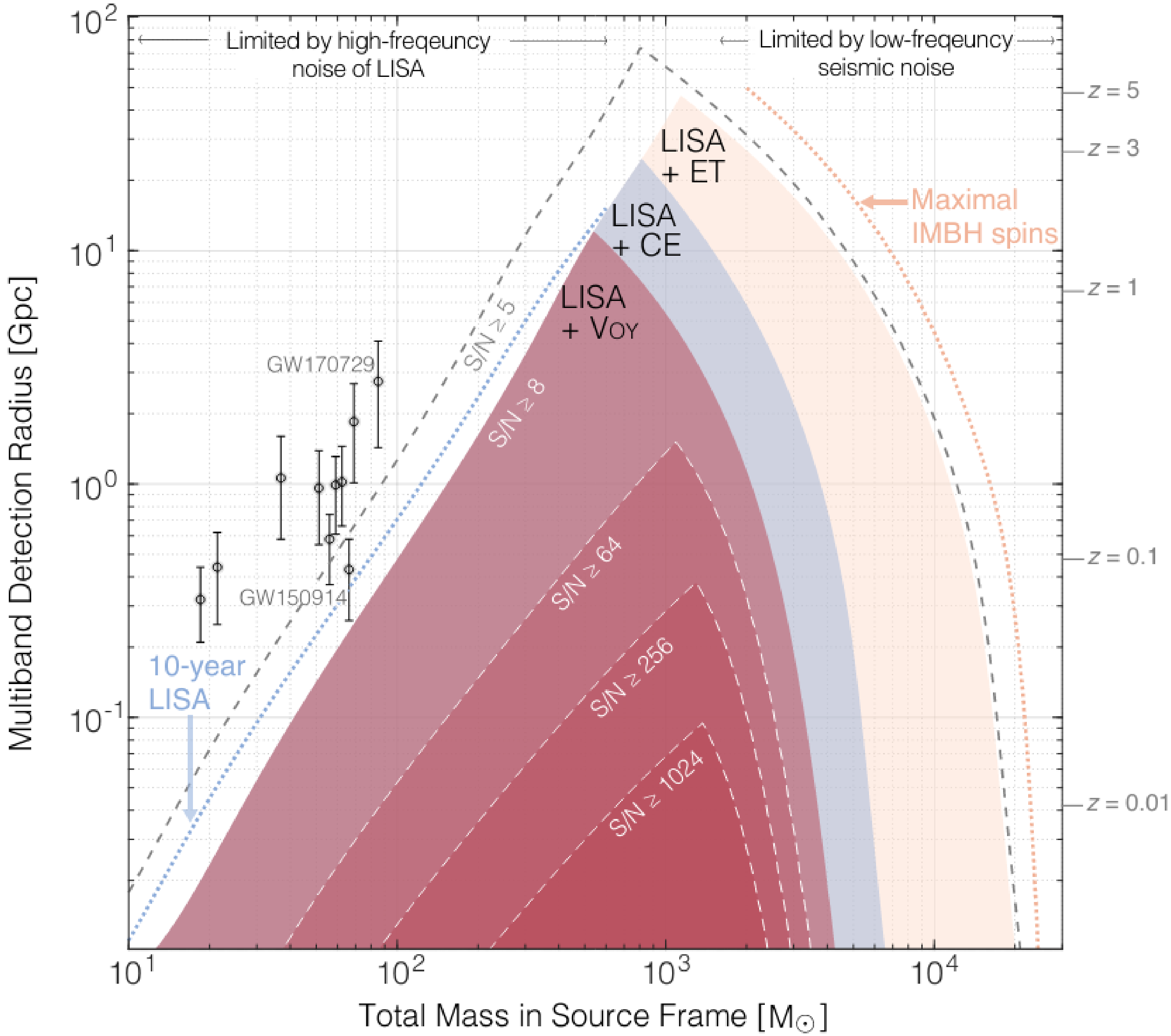




0.15% of clusters host an IMBH at Z = 0.02
VS
2 – 4 % at Z = 0.0002 – 0.002

Di Carlo, MM et al. 2021, MNRAS, 507, 5132

4. Evolution across cosmic time: will we do multi-band GW astronomy?



Jani, Shoemaker & Cutler 2020, NatAs, 4, 260