First binary BH coalescences

Kohei Inayoshi

**Kavli Institute for Astronomy and Astrophysics,
Peking University (KIAA/PKU)**

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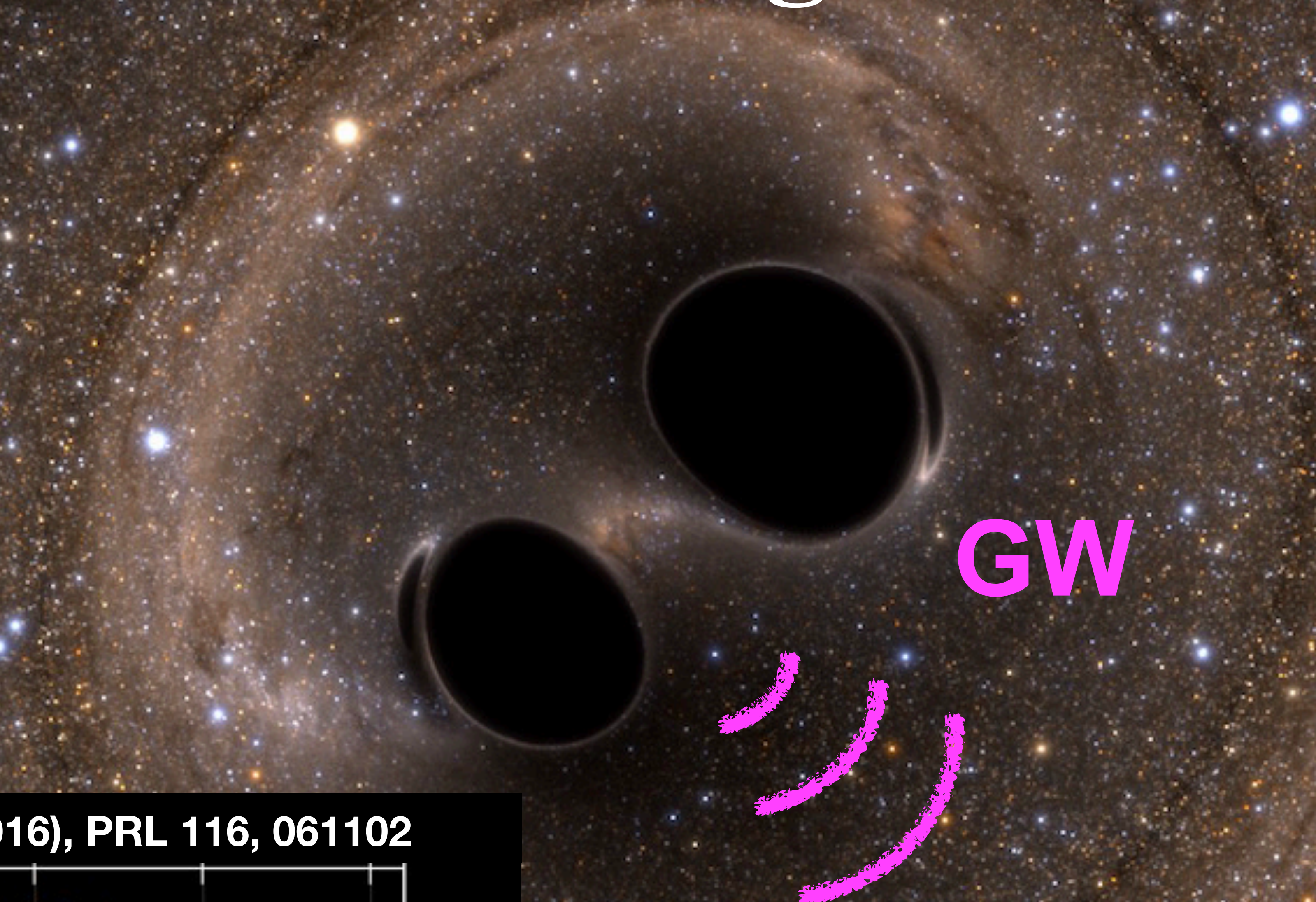
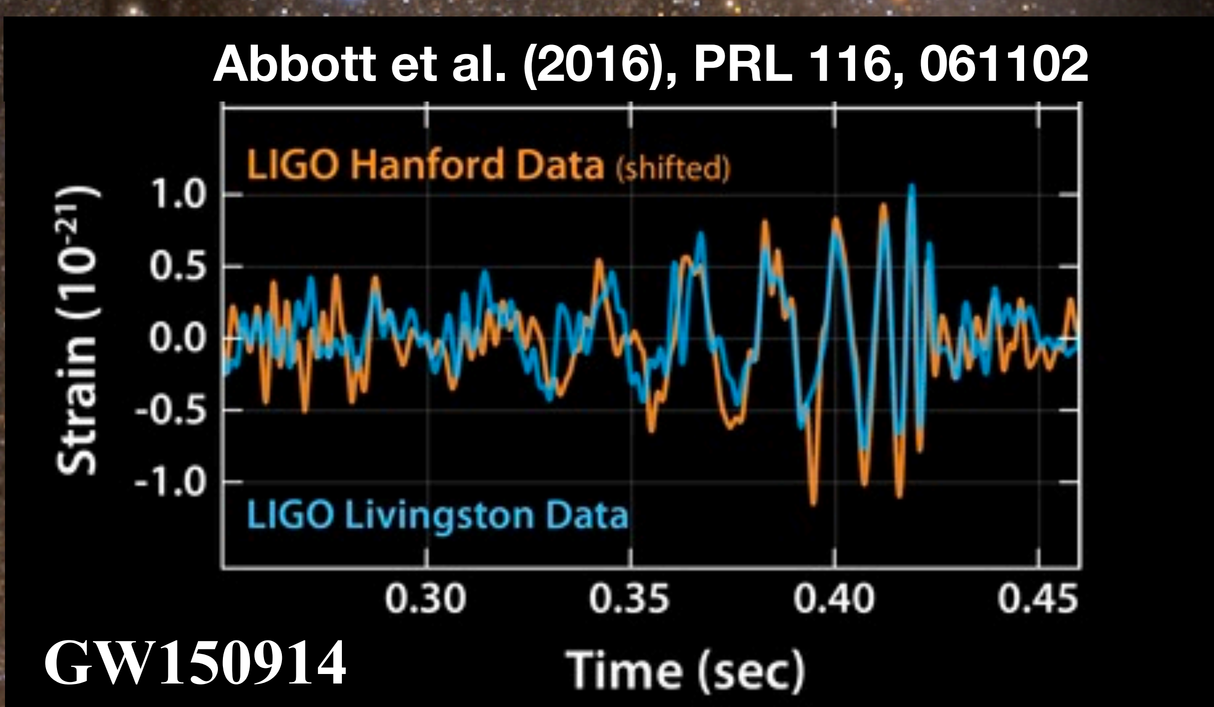
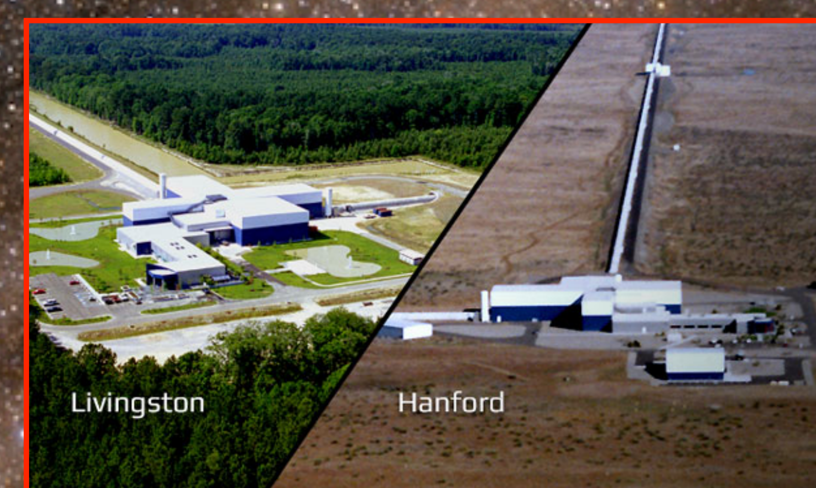
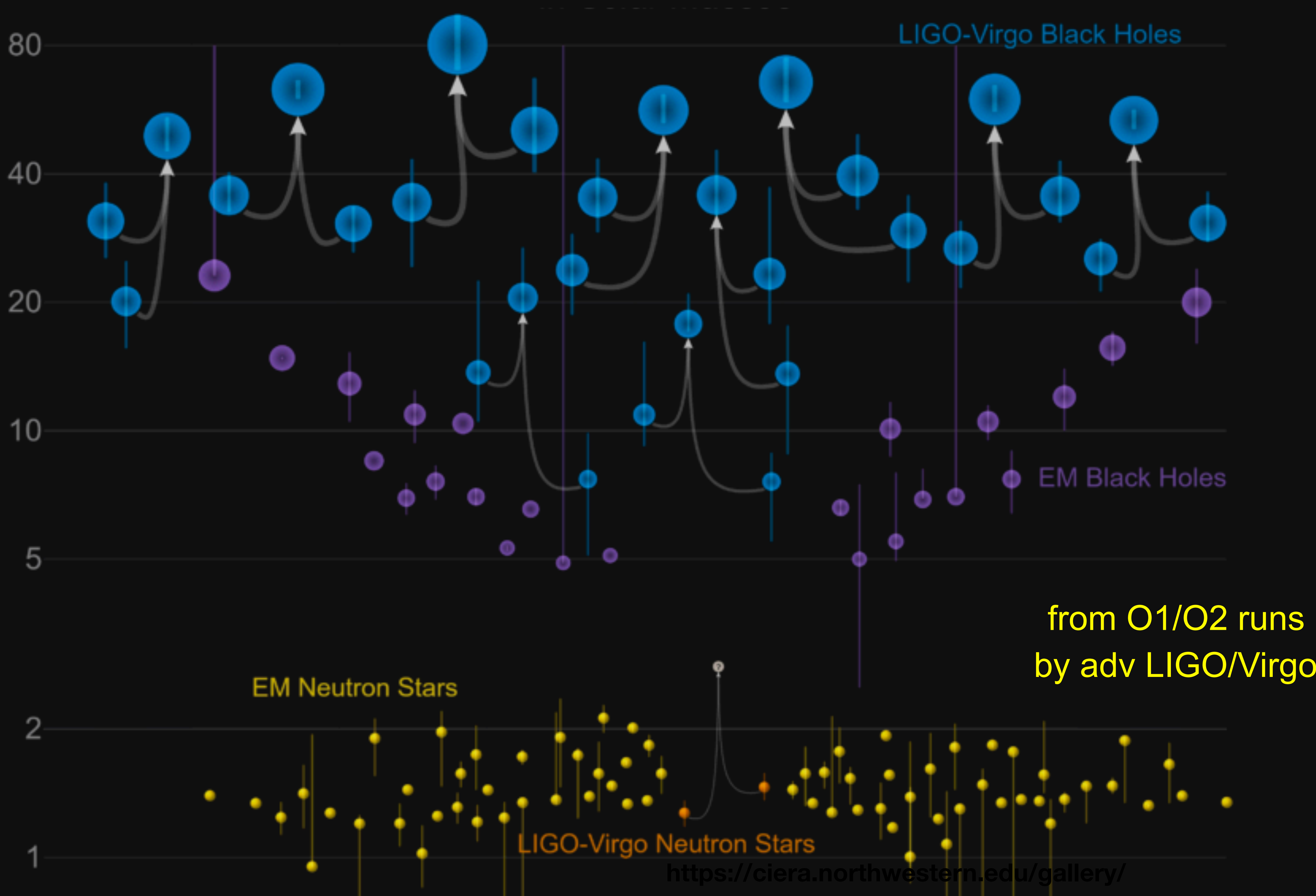
GW from colliding black holes







GW events from merging BBHs



Compact binary mergers (O1/O2)

LIGO/Virgo collaboration (arXiv:1811.12907)

	Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	χ_{eff}	$M_{\mathrm{f}}/\mathrm{M}_\odot$	d_L/Mpc	z
BH-BH	GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$
BH-BH	GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$
BH-BH	GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$
BH-BH	GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$
BH-BH	GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$
BH-BH	GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$
BH-BH	GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$
BH-BH	GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$
NS-NS	GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$
BH-BH	GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	[illegible]	[illegible]	[illegible]
BH-BH	GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	[illegible]	[illegible]	[illegible]

HLV (O3): 22 more BH-BH c

More detections!
Venumadhav's talk

- **heavy** binary BHs: $19 \lesssim M_{\mathrm{tot}}/M_\odot \lesssim 85$
- no significant spin alignment (positive for two BBHs)
- merger rate: $R = 52.9^{+55.6}_{-27.0}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ @ local universe

Formation channels

- **isolated field massive binaries**

  (e.g., Dominik+ 2013; Belczynski+ 2016; Kinugawa+ 2014, 2016; Inayoshi+ 2017; Mapelli+ 2017)

  - binary formation in **low-metallicity** gas
  - interaction btw two **PopII** stars ($Z < 0.1\, Z_{sun}$)
  - aligned spin is expected ($\chi_{\rm eff} \gtrsim 0$)

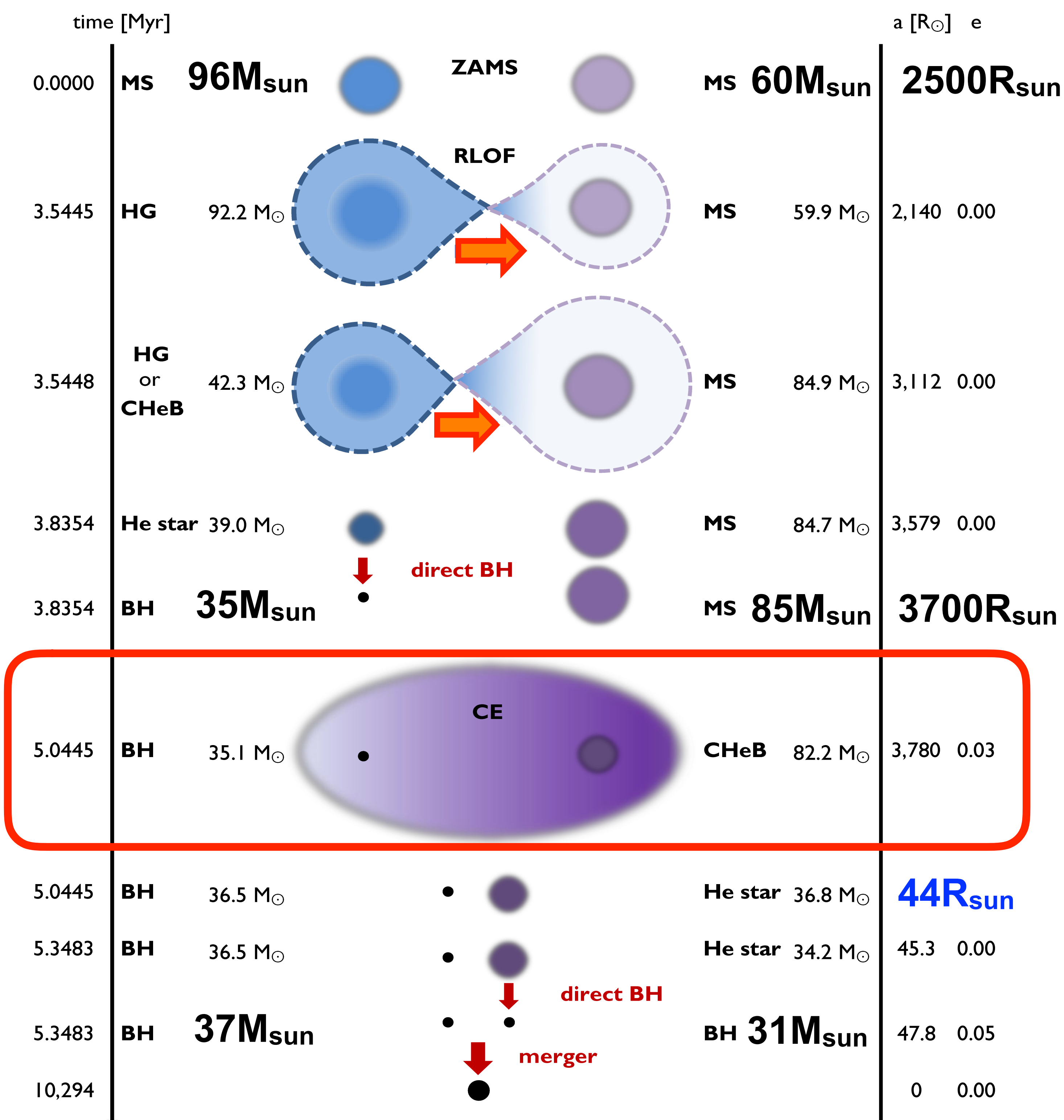
Rodriguez's & Samsing's talk

- **dynamical formation in dense clusters**

  (e.g., Portegies Zwart 2000, O'Leary, Meiron & Kocsis 2009, Rodriguez+ 2016, Antonini+ 2016)

  - mass segregation, 3-body interaction
  - eccentric binaries (Kozai-Lidov)
  - uniform $\chi_{\rm eff}$-distribution is expected

PopII-BBH formation (~0.1Z_{sun})



stable mass transfer

1st BH!

common envelope phase (uncertain!)

2nd BH!

Belczynski et al. (2016)

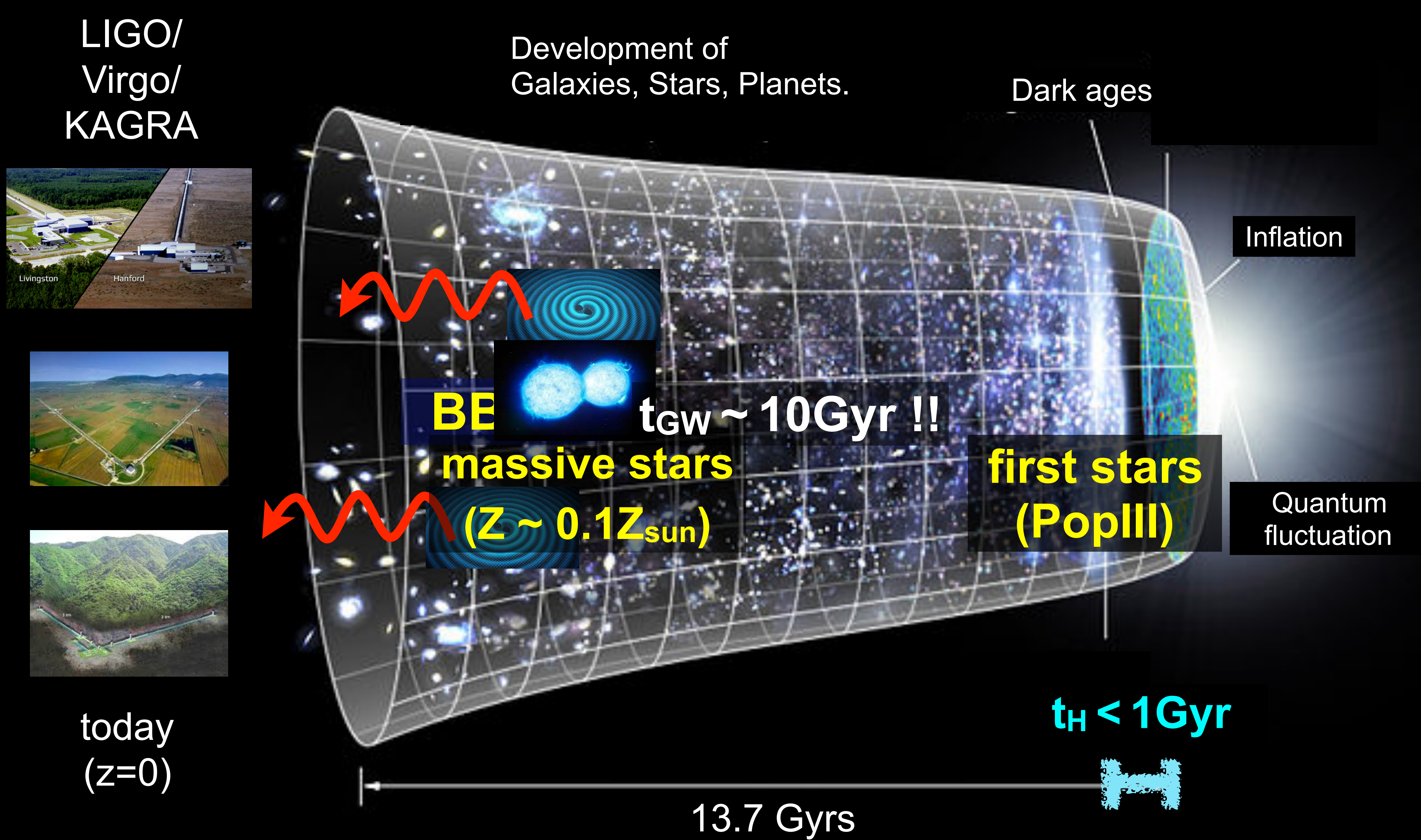
1. The origin of stellar-mass BBHs

~ First massive stars ~

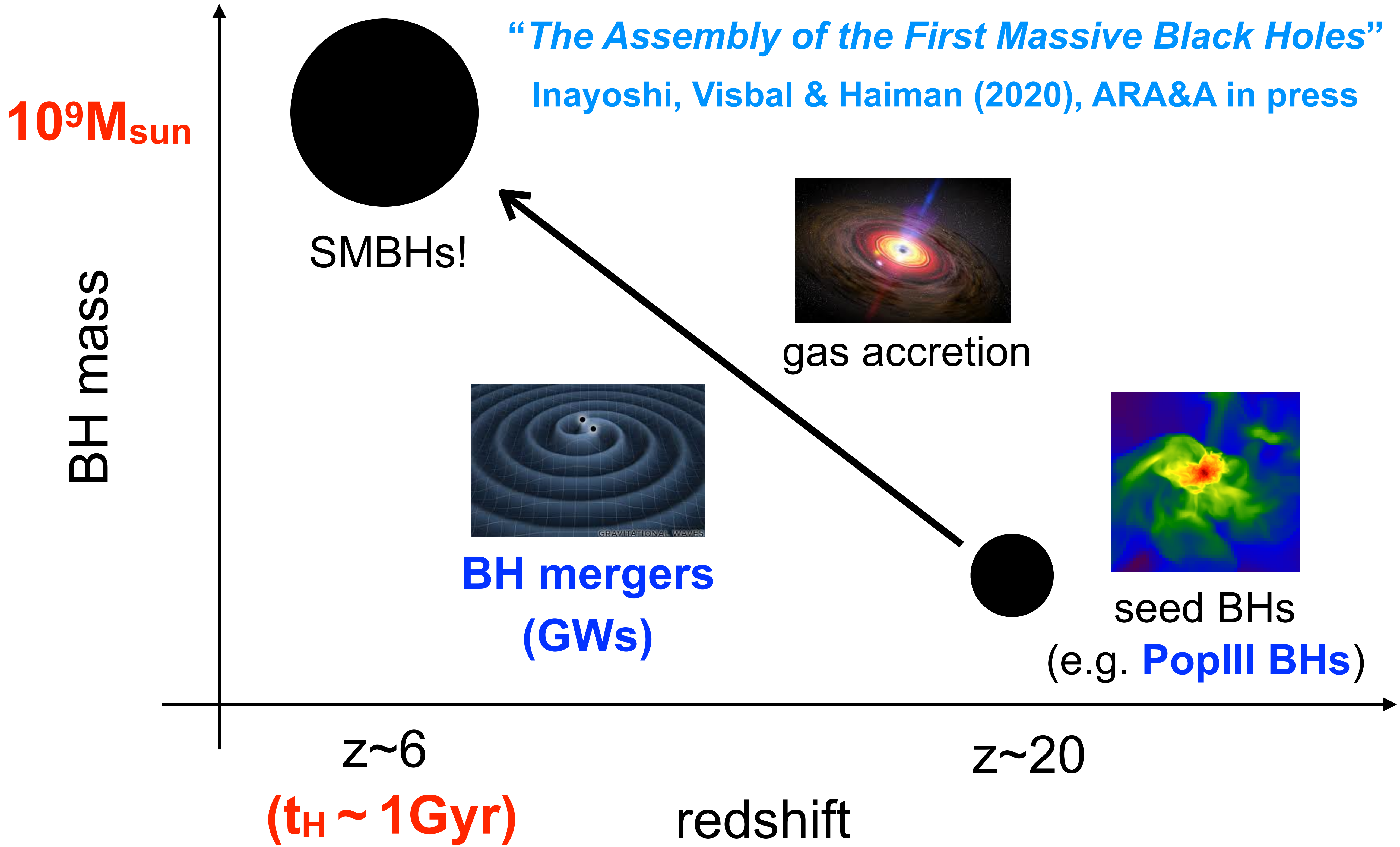
Kinugawa, Inayoshi & Hotokezaka et al. (2014) MNRAS 442, 2963

Inayoshi, Hirai, Kinugawa & Hotokezaka (2017) MNRAS 468, 5020

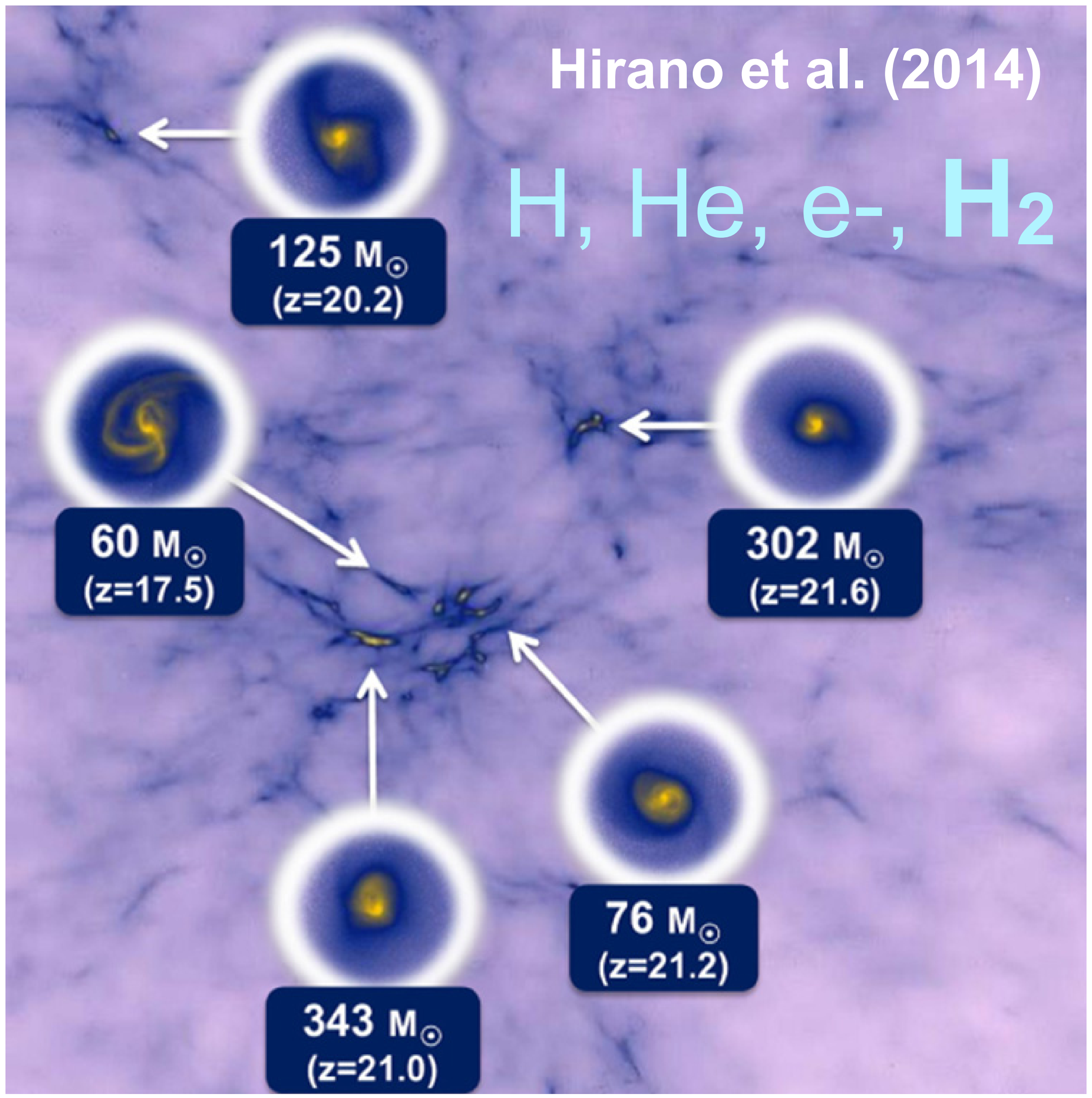
low metallicity ≈ high redshift

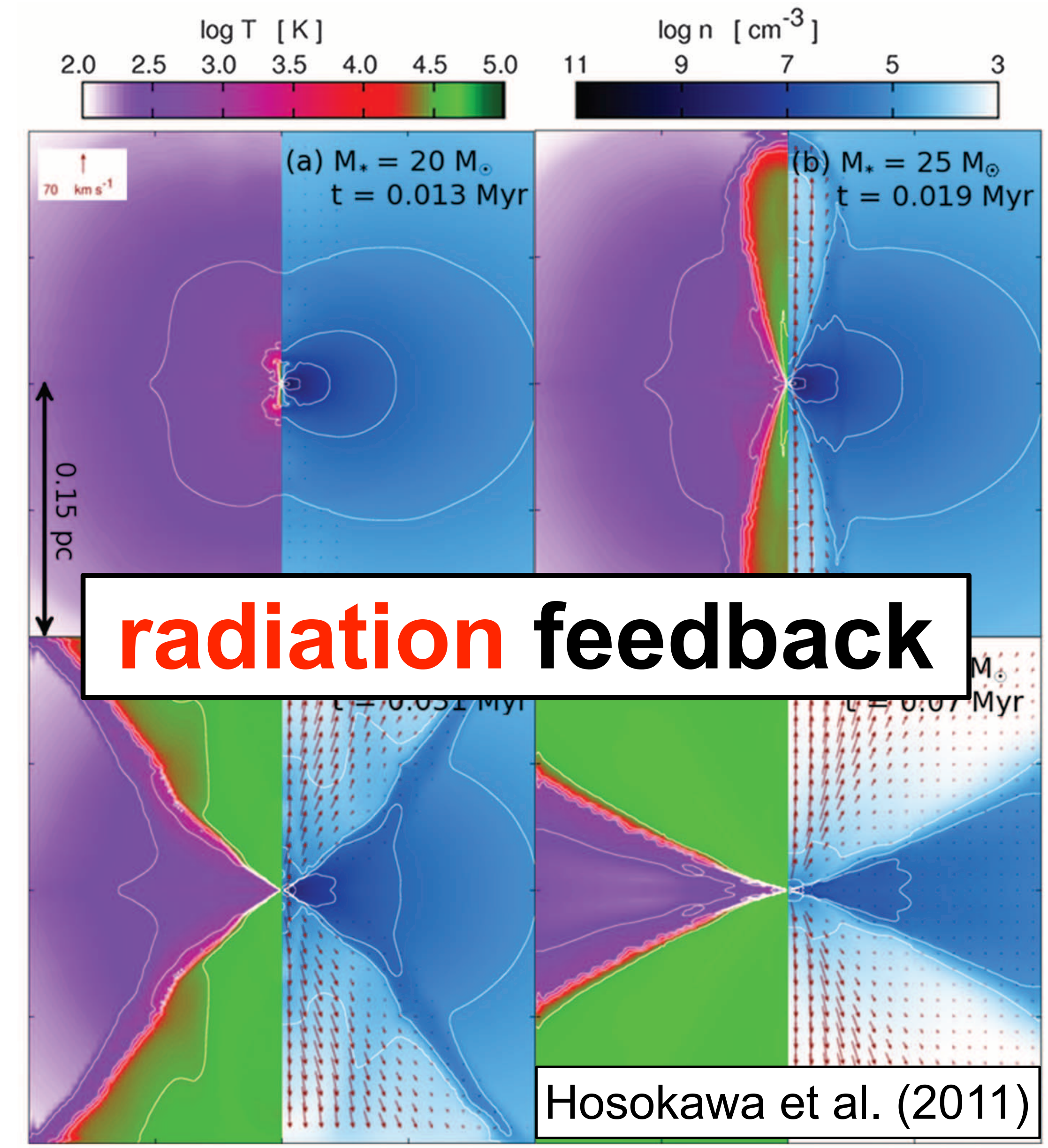


Formation of SMBHs at high-z



Formation of First Stars

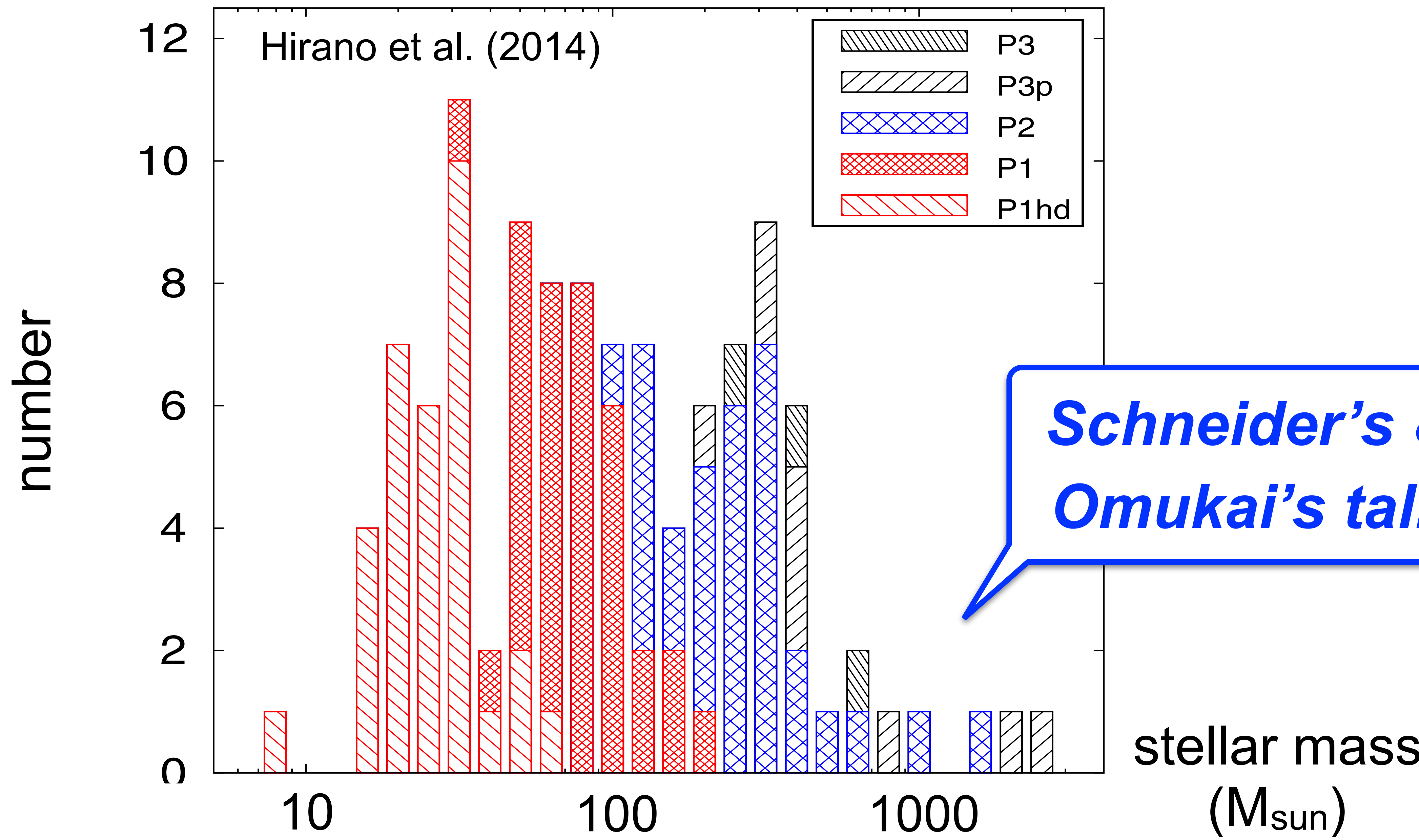




Collapse of metal-free, warm gas clouds (Z~0):

$\mathbf{M_{gas} \sim 10^3 M_{sun}}$ ➡ $\mathbf{M_* \sim 100\ M_{sun}}$

PopIII stellar IMF

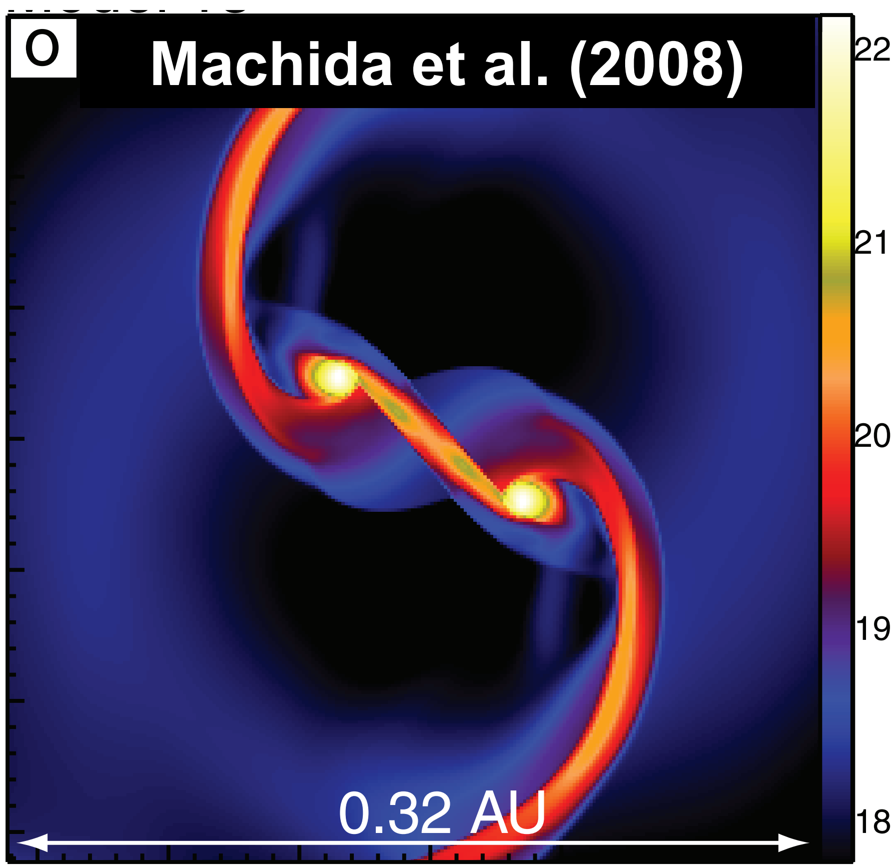


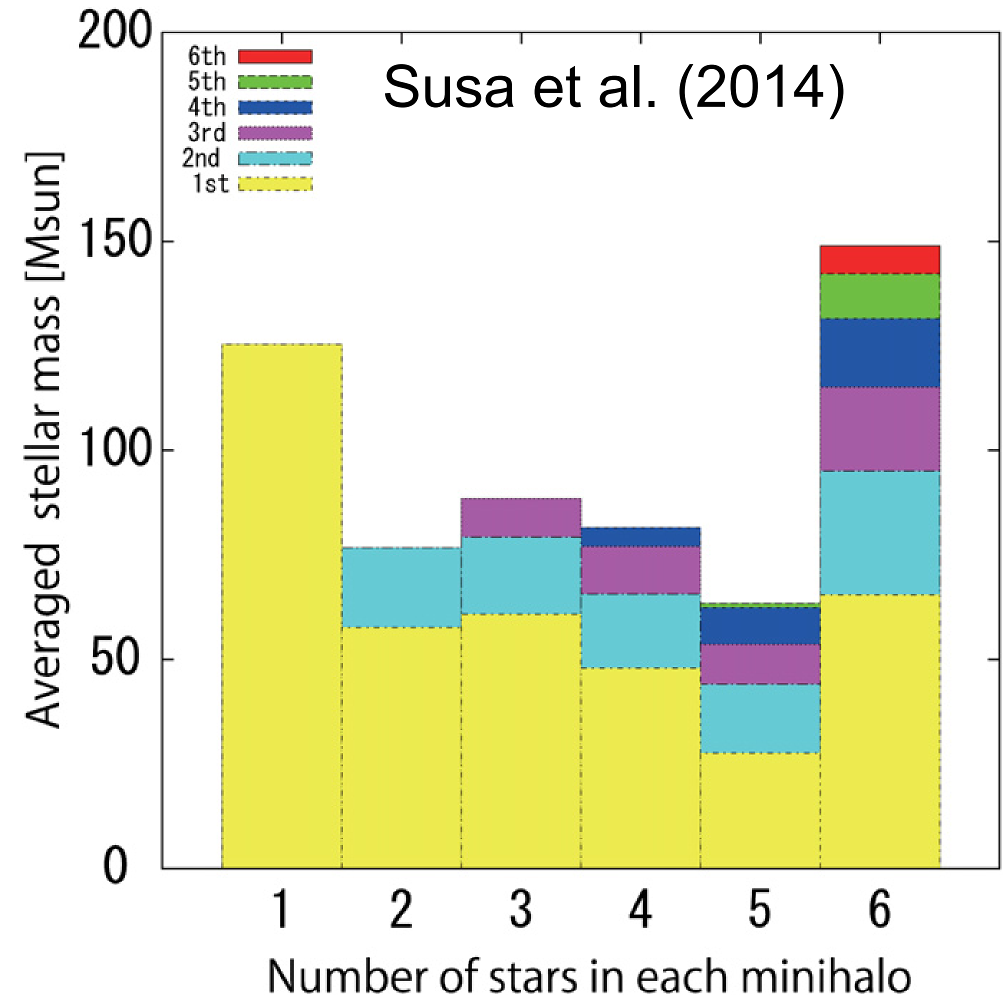
Schneider's & Omukai's talk

PopIII IMF : **top-heavy** (~100M_{sun})

PopIII binary formation

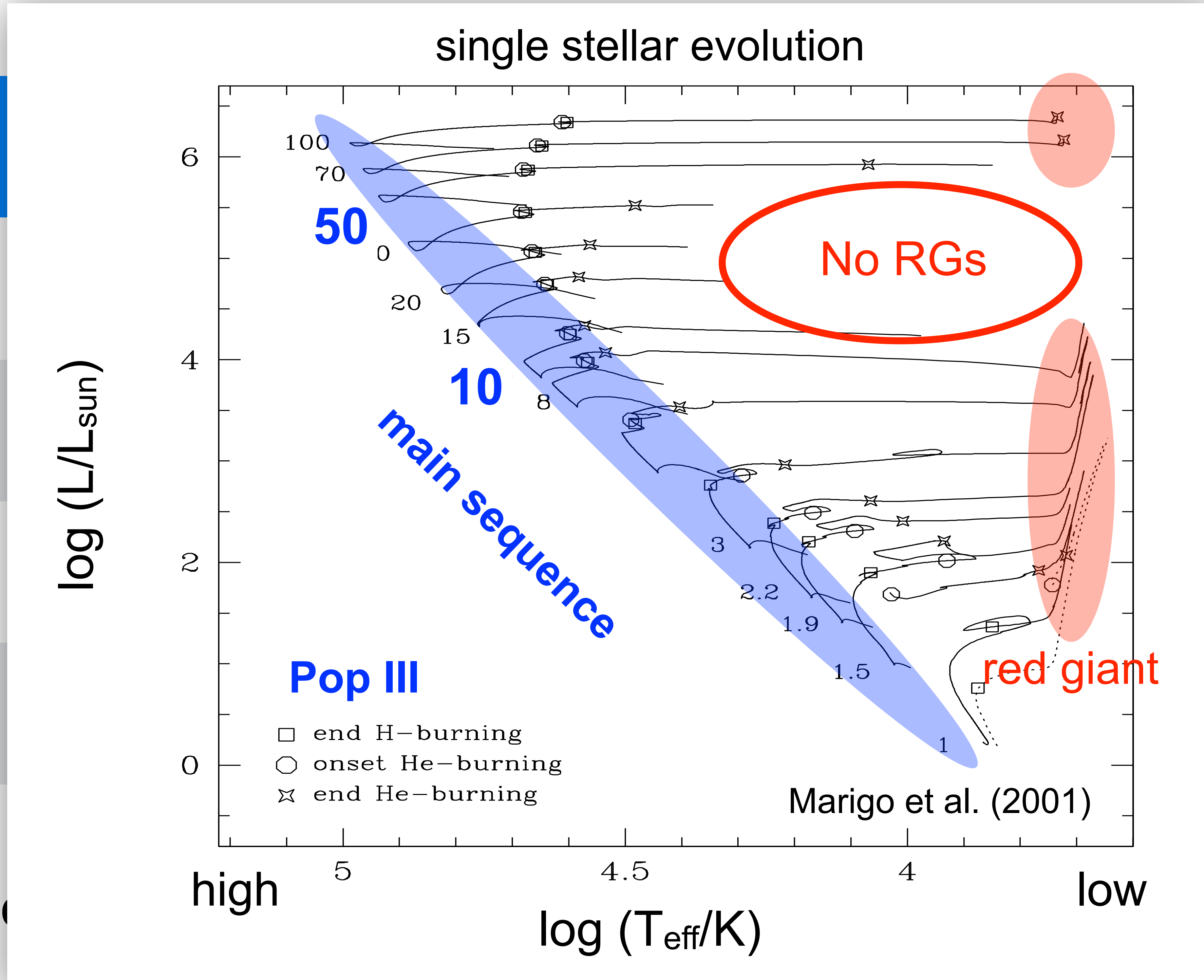
Turk et al. (2009); Stacy et al. (2013,2016), Susa et al. (2013), Hosokawa et al. (2016)



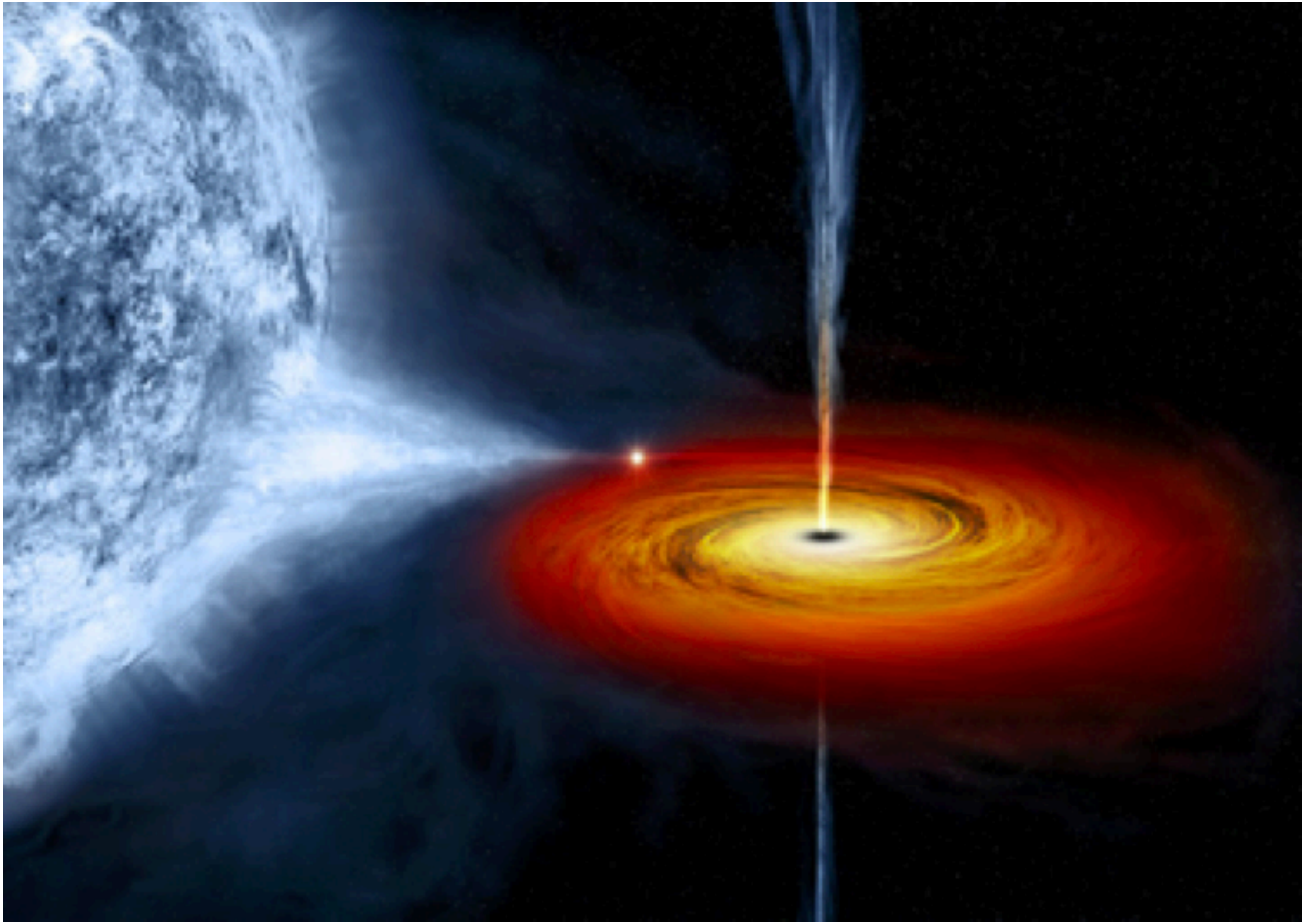


- Binary formation due to disk fragmentation
- high binary fraction (f_{bin}~60% @MW)

Pop II vs. Pop III



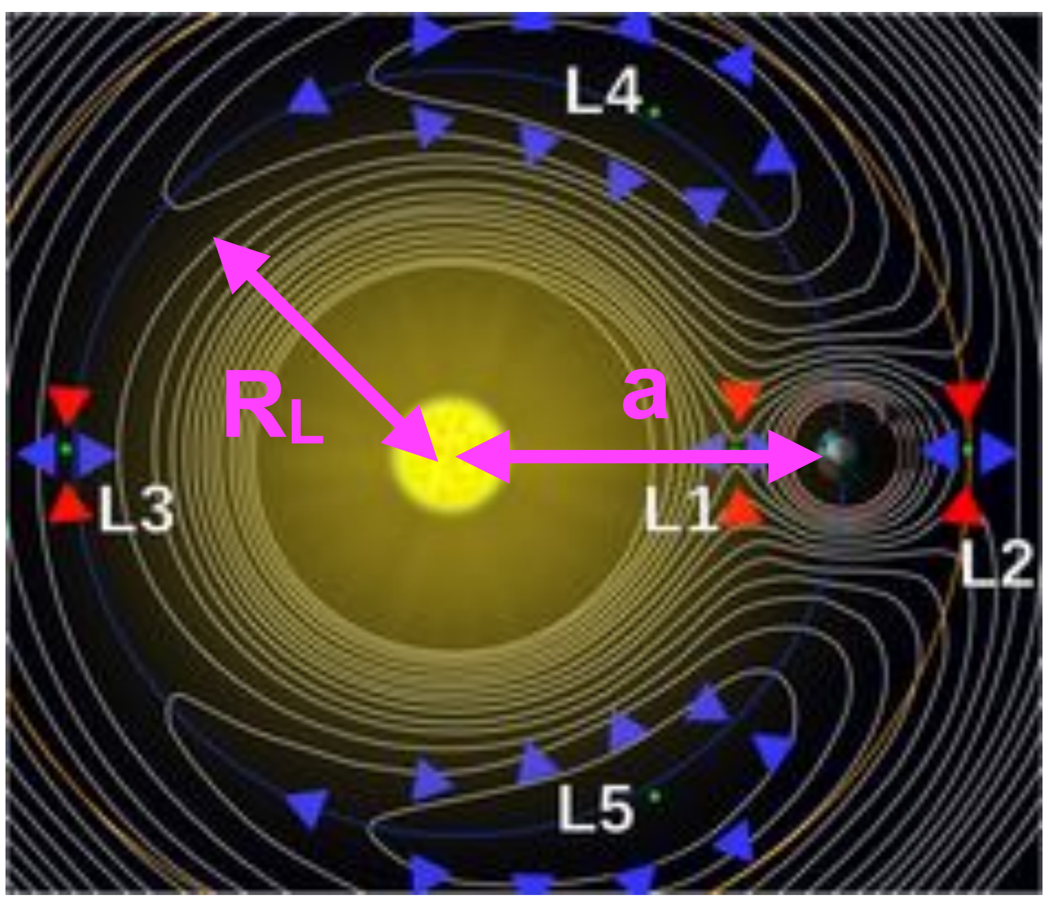
Binary evolution

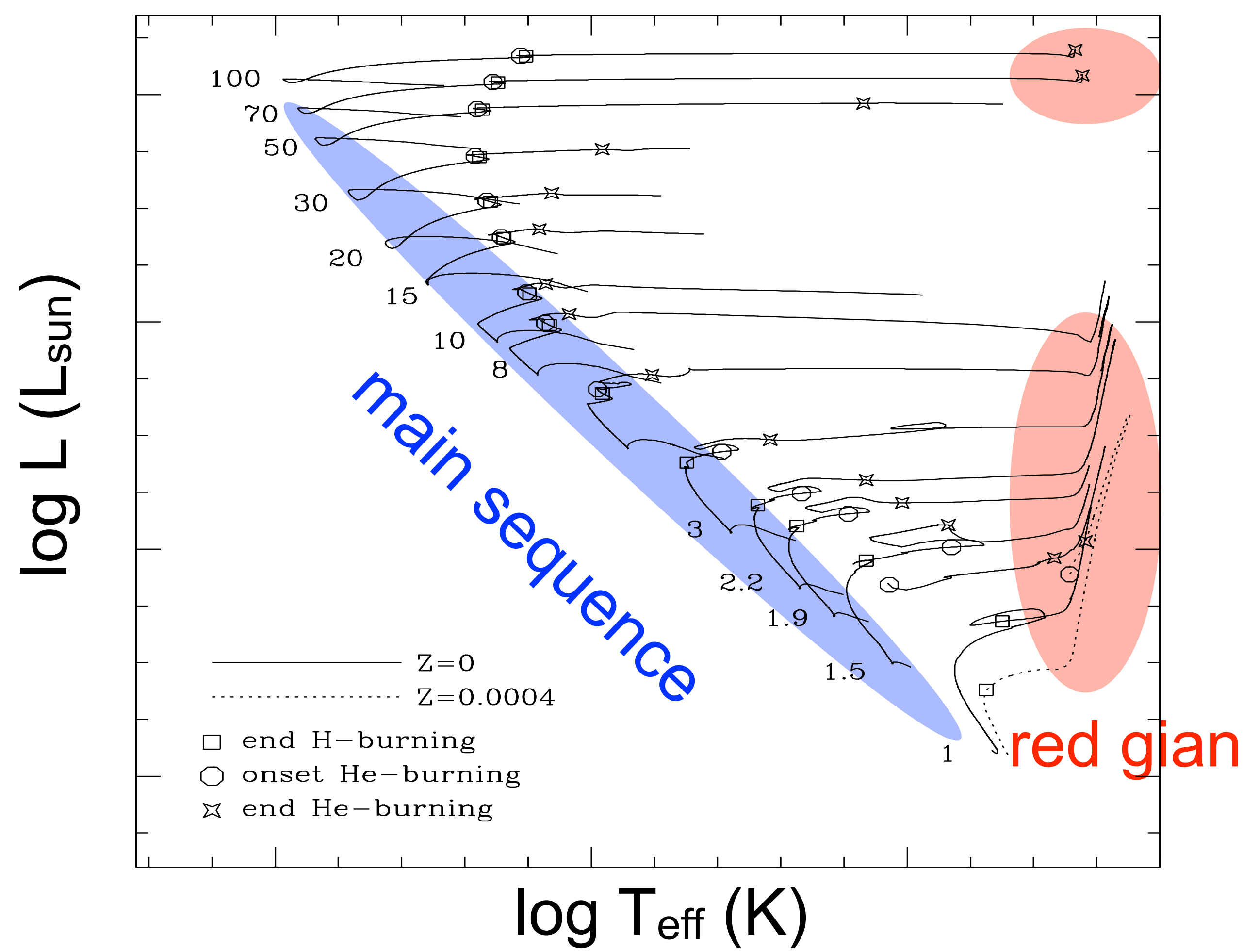


Binary structure evolution

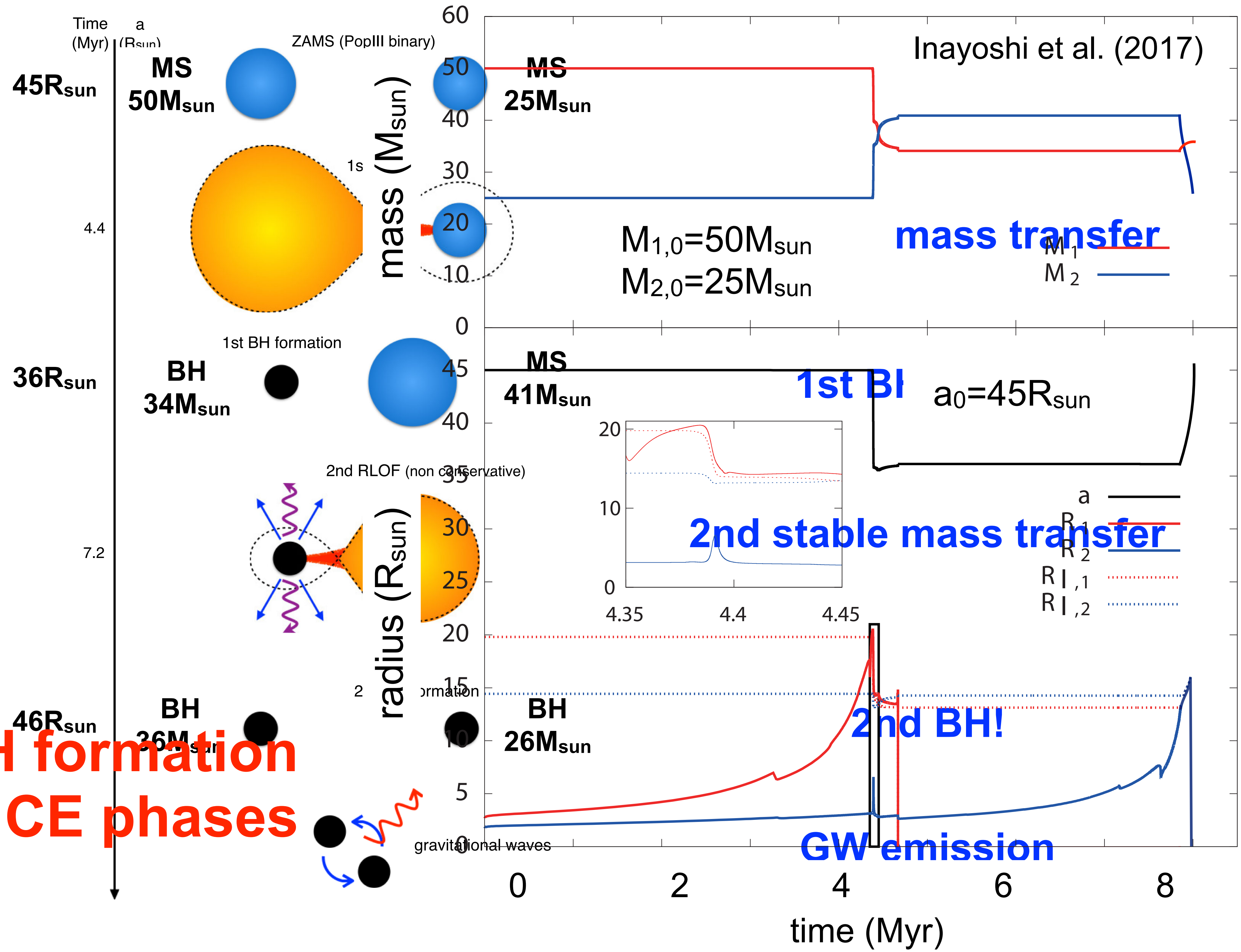
MESA : stellar structure evolution code (Paxton et al. 2011)

binary interaction + **single stellar evolution**



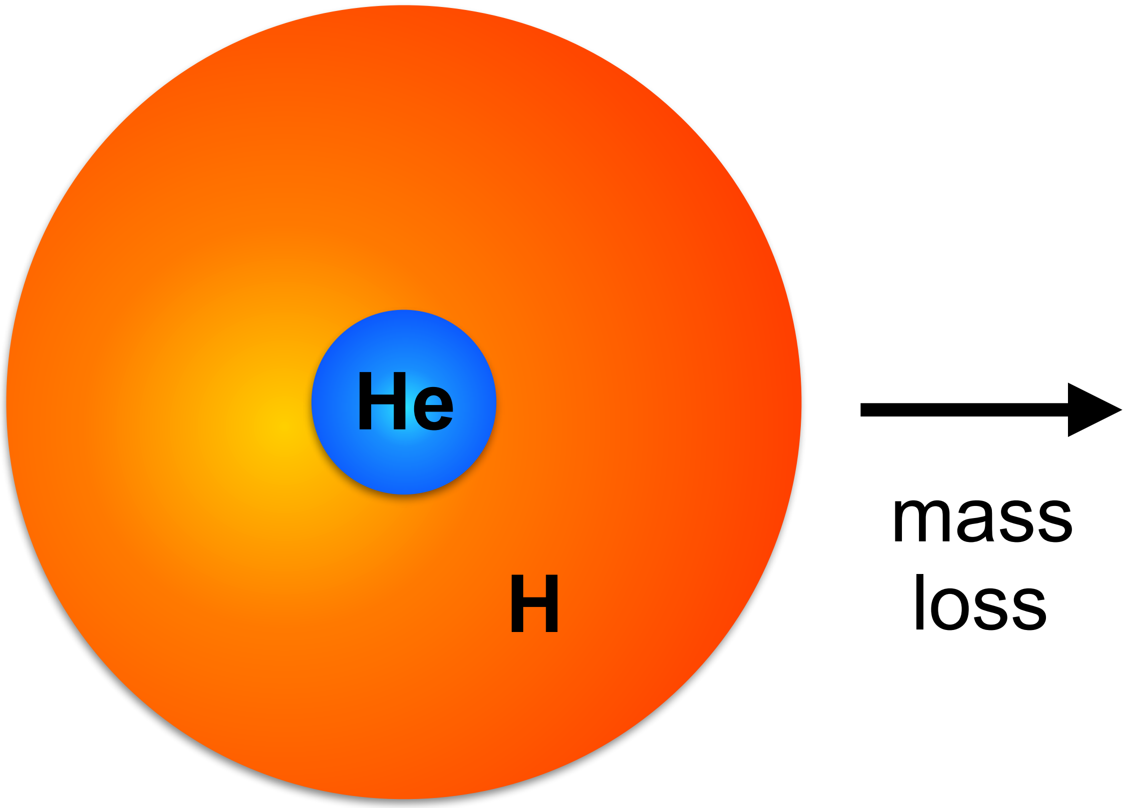


PopIII-BBH formation (Z=0)



BBH formation w/o CE phases

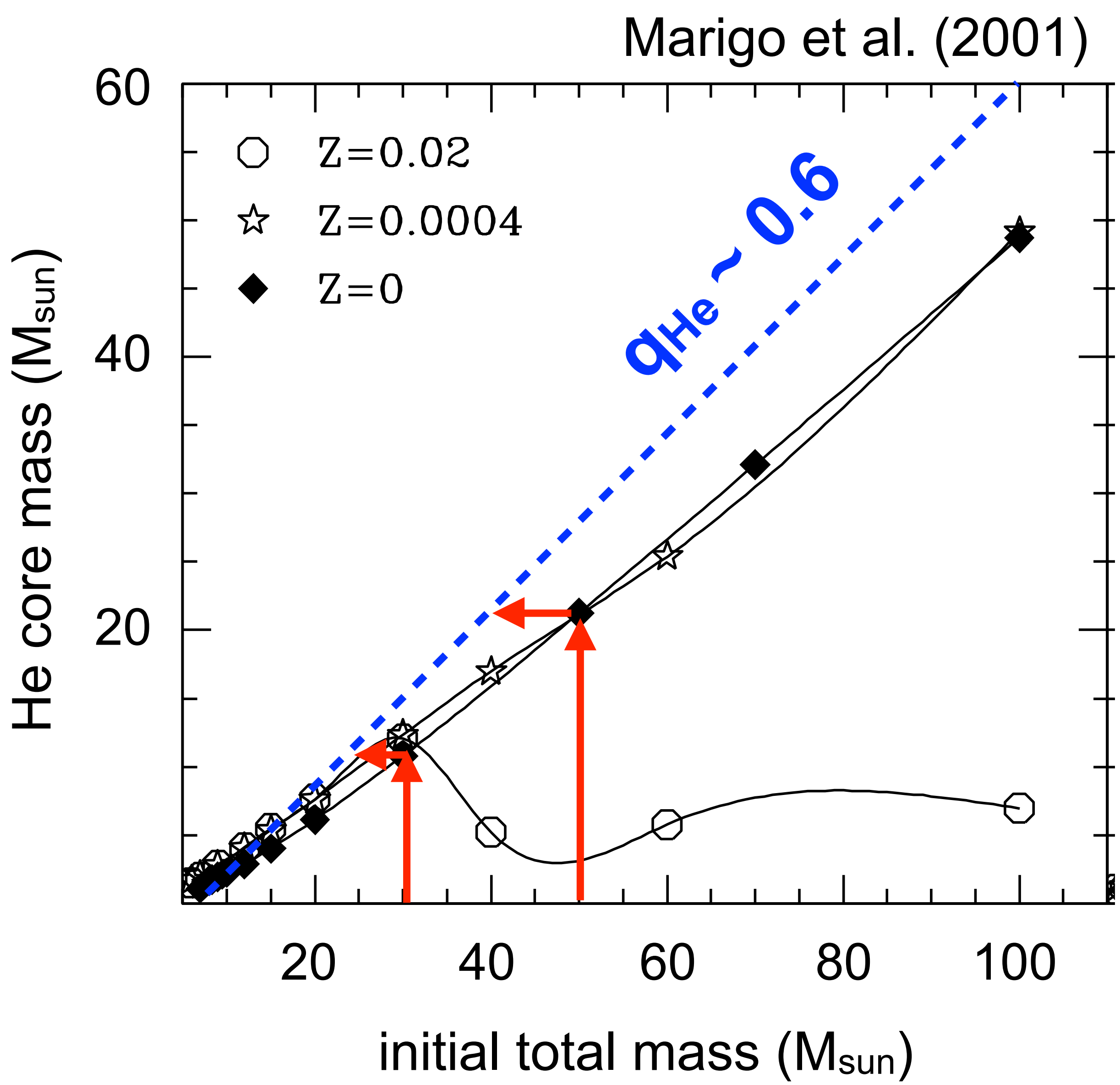
Termination of stable MT



1. mass loss by MT
2. the mass ratio of He core to the total mass increases
3. reach the critical ratio

$$\mathbf{q_{He} \sim 0.6}$$

Termination of stable MT



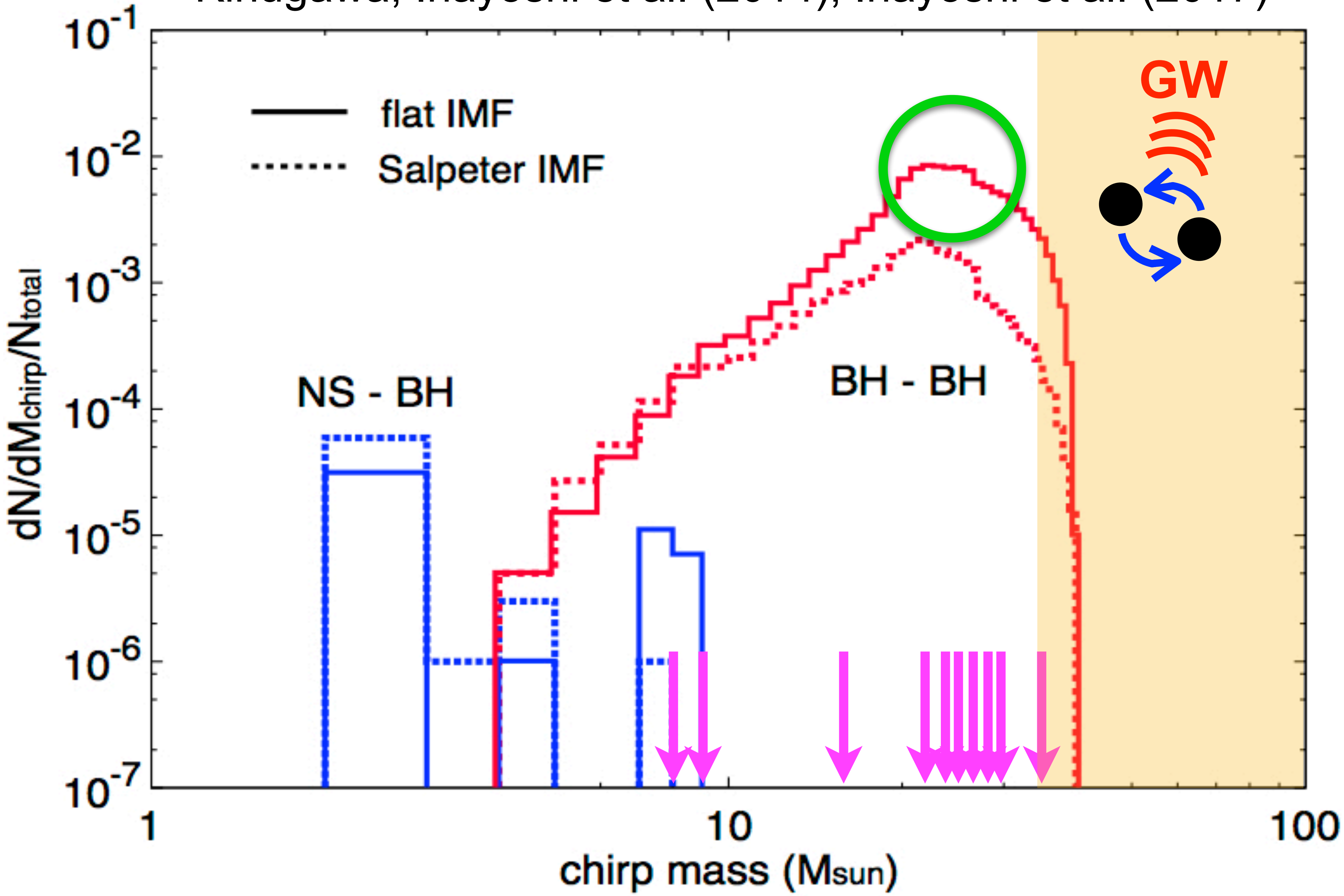
1. mass loss by MT
2. the mass ratio of He core to the total mass increases
3. reach the critical ratio

$q_{He} \sim 0.6$

Typical mass of BHs in PopIII binaries **~ 30M_{sun}**

Mergers of PopIII BBHs

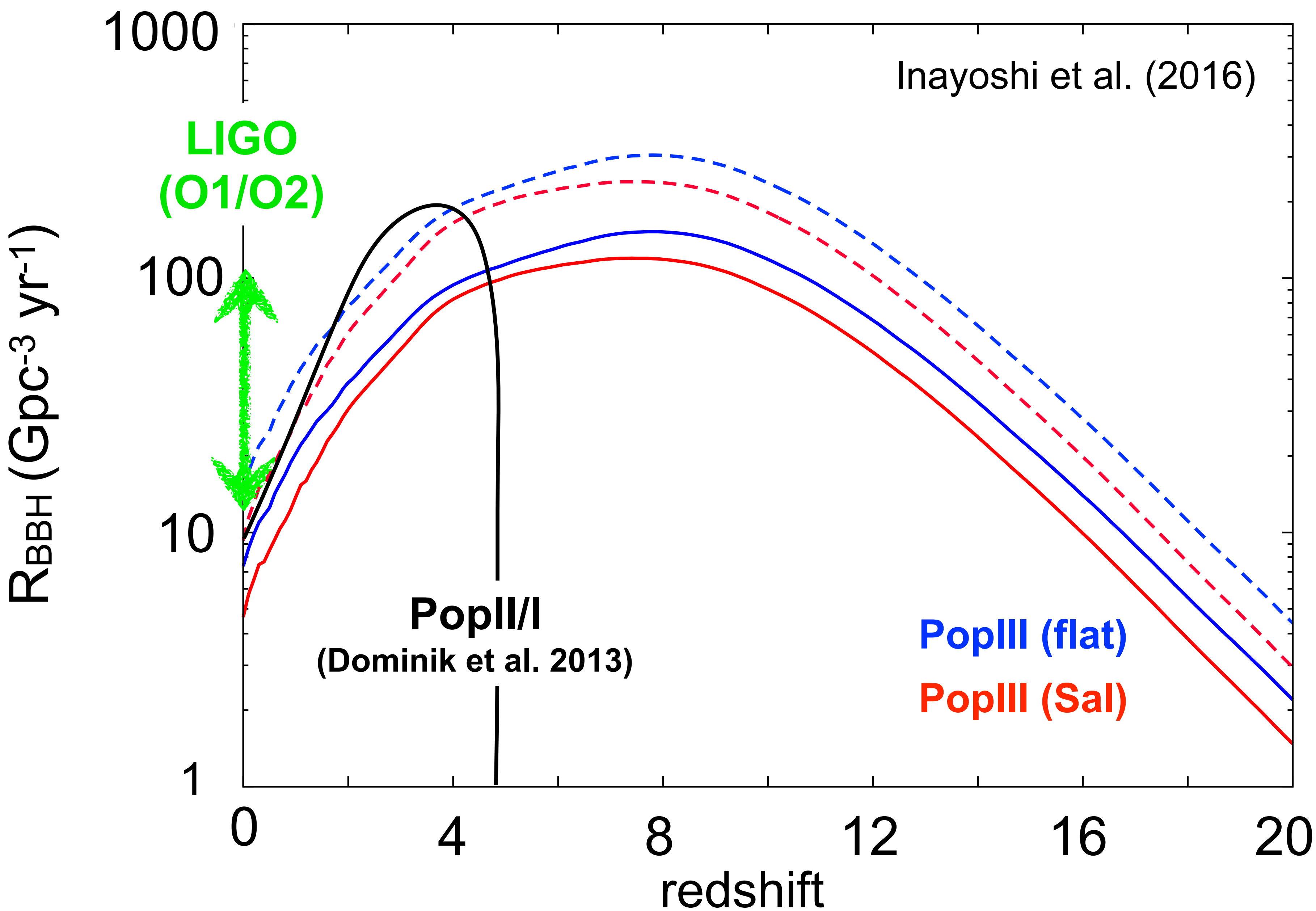
Kinugawa, Inayoshi et al. (2014); Inayoshi et al. (2017)



Typical mass of merging Pop BBHs ~ **30+30M$_{sun}$**

(high-mass end depends on CE model…)

PopIII BBH merging rate

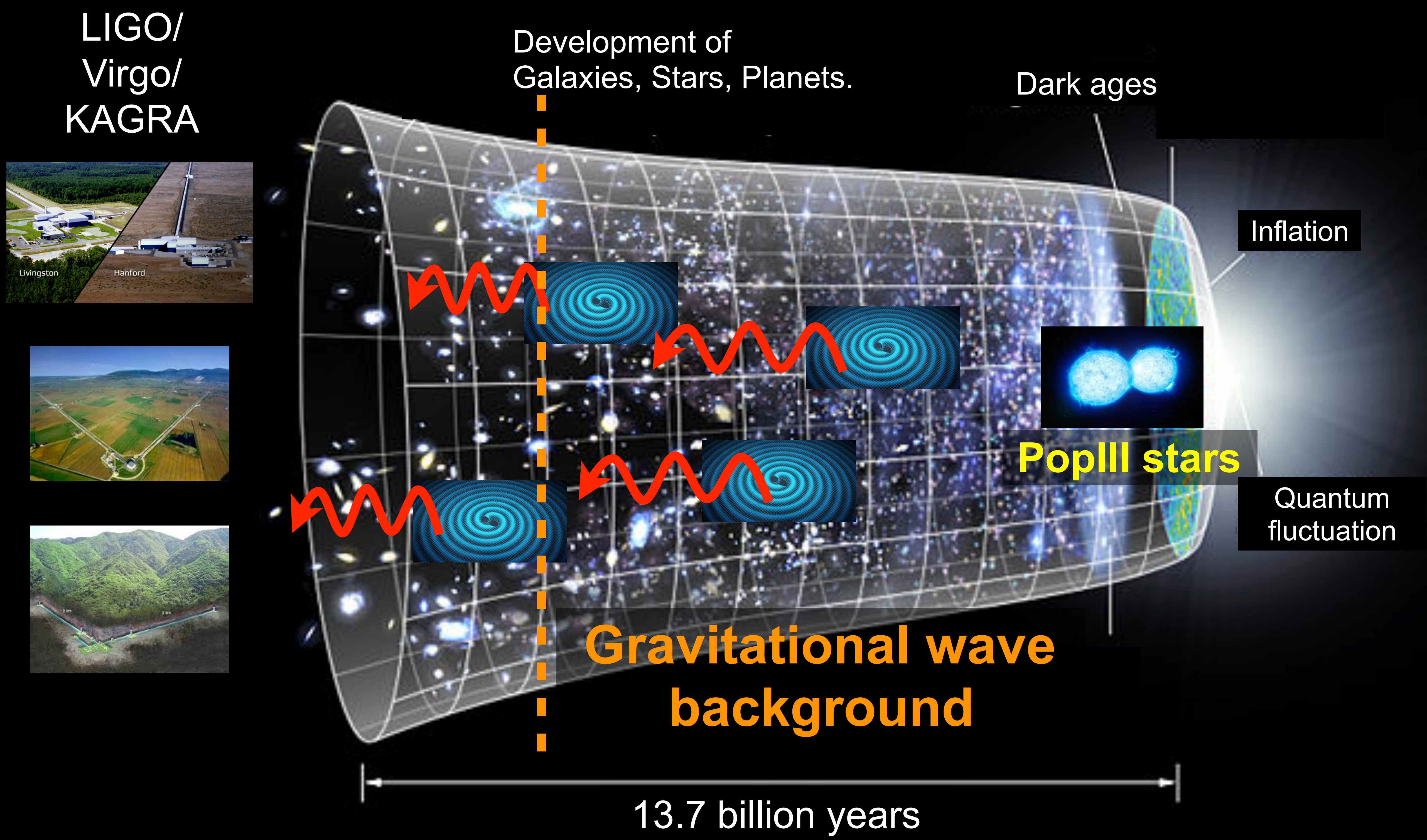


High merger rates of remnant PopIII BBHs in the local universe: **R_{BBH} ~ O(10) Gpc^{-3} yr^{-1}**

2. Stochastic GW background from high-z & massive BBHs

Inayoshi, Kashiyama, Visbal & Haiman (2016) MNRAS 461, 2722

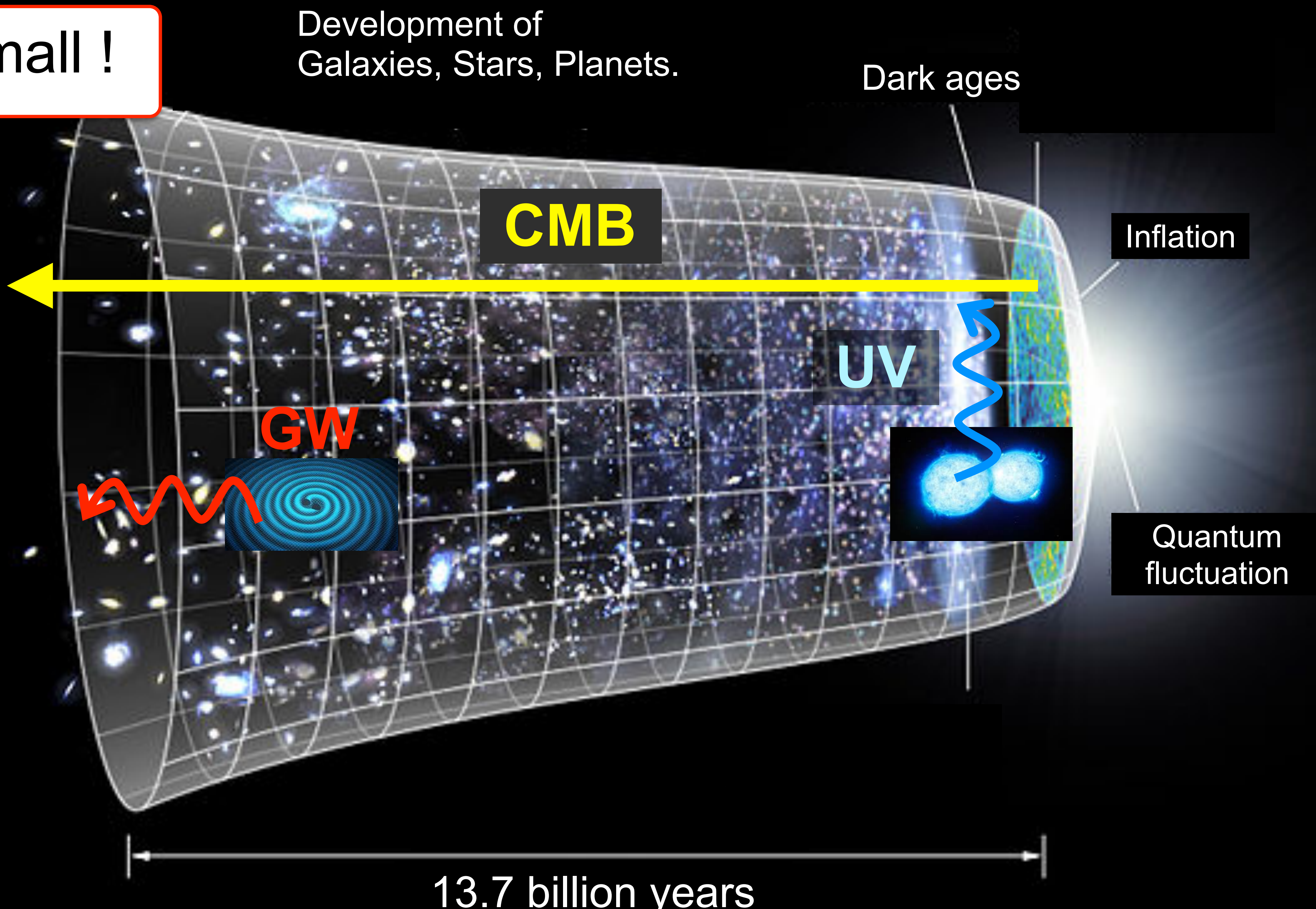
First binary BH mergers



Relation between GWB & CMB

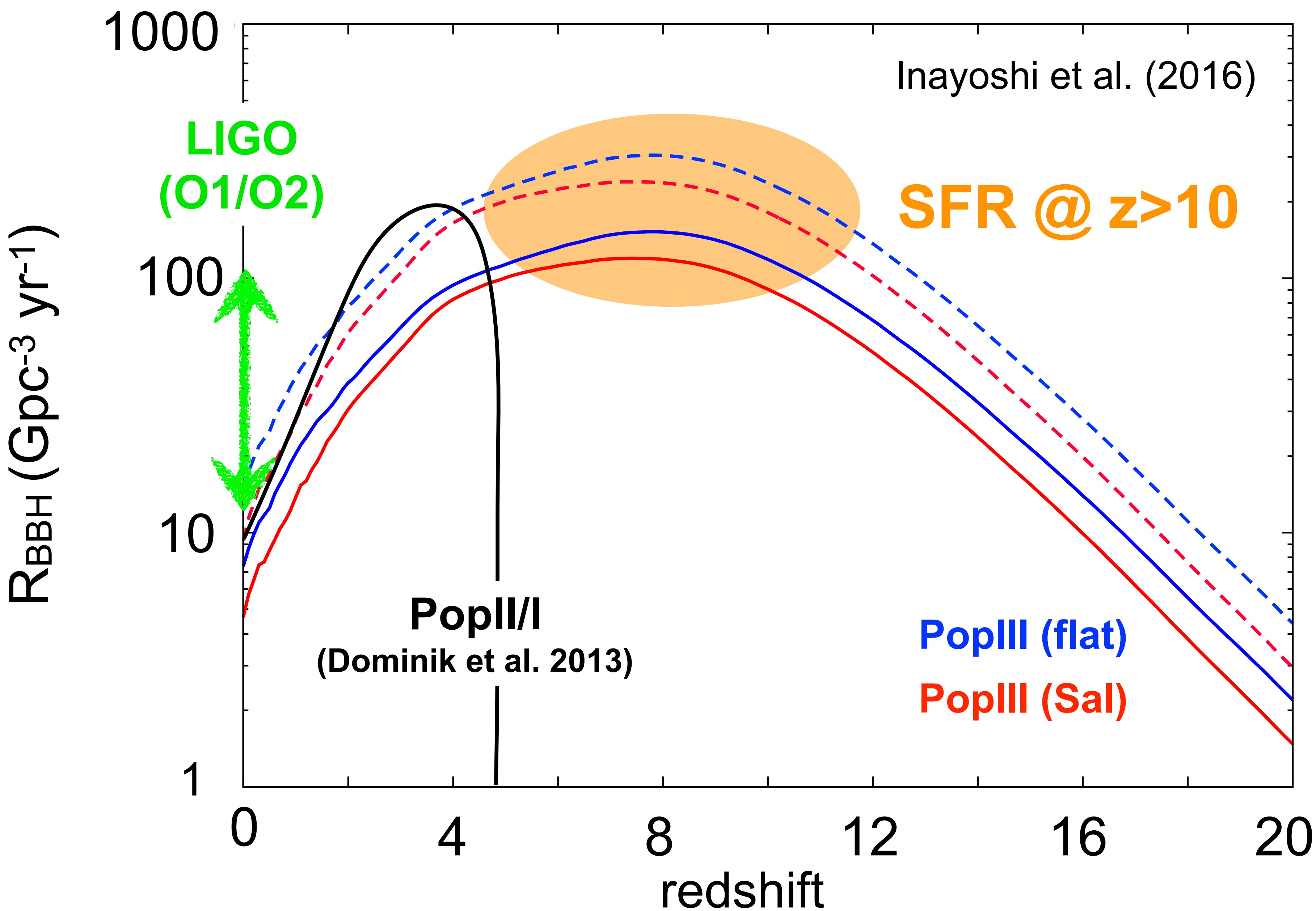
τ_e is small !

Planck



LIGO/Virgo/KAGRA

PopIII BBH merging rate



More BBH mergers in the early universe

R_{BBH} > 100 Gpc^{-3} yr^{-1}

Gravitational wave backgrounds

- GWB energy density (Phinney 2001)

$$\rho_c c^2 \Omega_{gw}(f) = \int_{z_{min}}^{\infty} \frac{R_{BBH}}{1+z} \frac{dt}{dz} \left(f_r \frac{dE_{gw}}{df_r} \right) \Bigg|_{f_r = f(1+z)} dz$$

merging rate

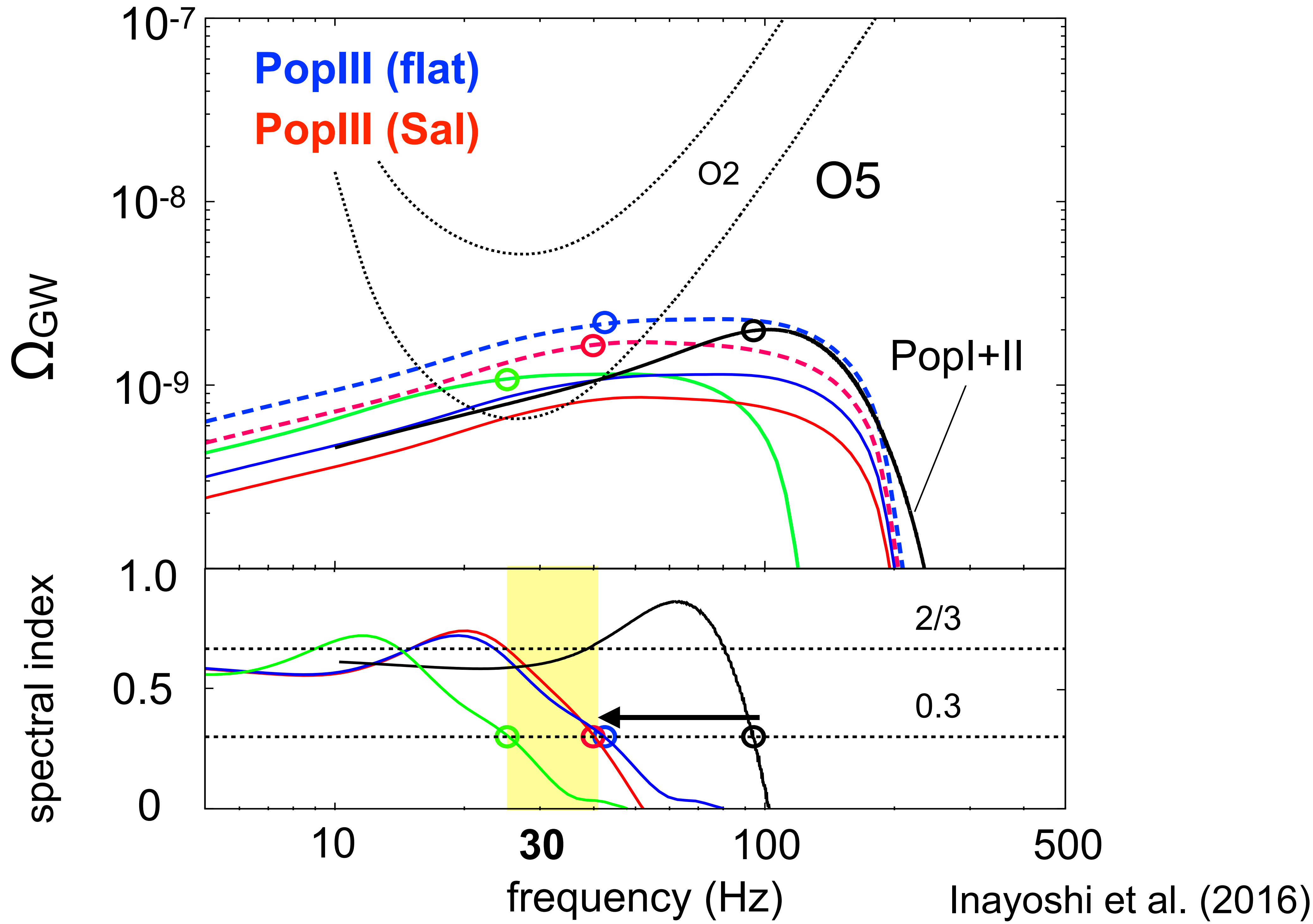
GW spectrum from each BBH

$$\frac{dE_{gw}}{df_r} = \frac{(\pi G)^{2/3} M_{chirp}^{5/3}}{3} \begin{cases} f_r^{-1/3} \mathscr{F}_{PN} & f_r < f_1, \\ \omega_m f_r^{2/3} \mathscr{G}_{PN} & f_1 \le f_r < f_2, \\ \frac{\omega_r \sigma^4 f_r^2}{[\sigma^2 + 4(f_r - f_2)^2]^2} & f_2 \le f_r < f_3, \end{cases}$$

if GW emission due to inspiral phases dominates,

$$\Omega_{gw}(f) \propto f^{2/3}$$ power-law index ~**2/3**

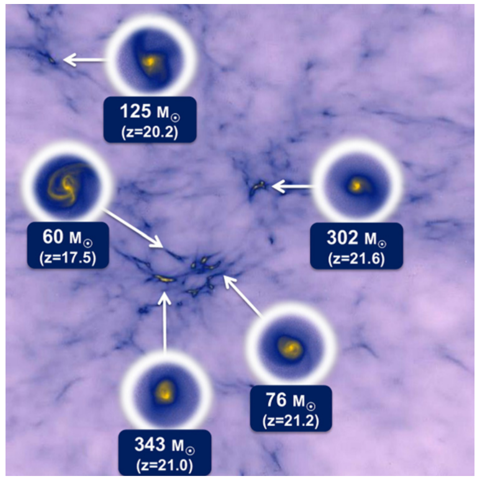
Pop-III GW background

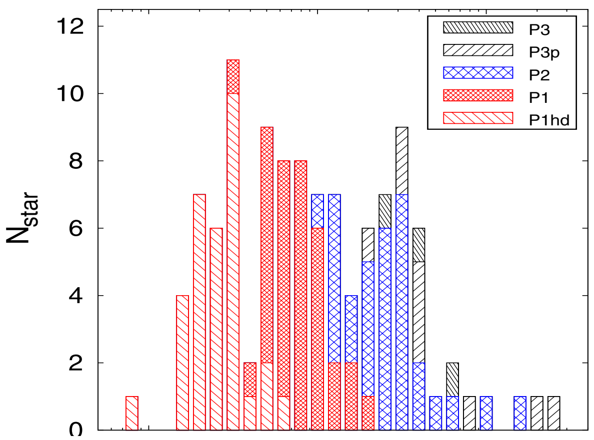


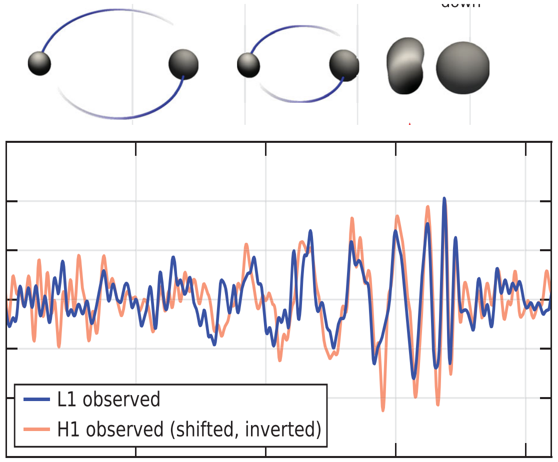
Smoking-gun signature for **high-z & heavy** BBH population

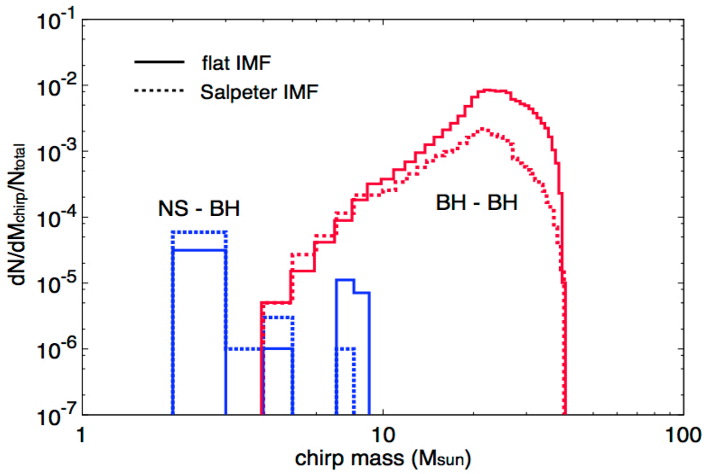
Summary

- Star formation in low-metallicity environments is required to form massive BBHs
- Pop III stars (Z~0) are expected to be born as massive stars with ~10-100M_{sun} in a binary
- Pop III binaries could result in BBHs with **30+30** M_{sun} via stable mass transfer (w/o uncertain CE process)
- GWB produced from high-z & massive BBH population could be distinguishable from other sources









KIAA / PKU

25 faculties
22 postdocs
80 PhD students

KIAA / PKU

- **KIAA fellowships** (all fields)

  https://jobregister.aas.org/ad/de436c12

- **BHOLE** postdoc researchers

  (SMBH, galaxies and coevolution, high-z)

  https://jobregister.aas.org/ad/930735dc

- **PKING** postdoc researchers

  (**Gravitational Astrophysics**, Interstellar Medium, Sky-Survey Science)

  https://jobregister.aas.org/ad/0bb38802

- Kavli Astrophysics Postdoctoral Fellowship (KIAA-IMPU)

  https://jobregister.aas.org/ad/3cbd55c3

Thank you !!