Implications from GW190814

Wenbin Lu
(for Ay215)

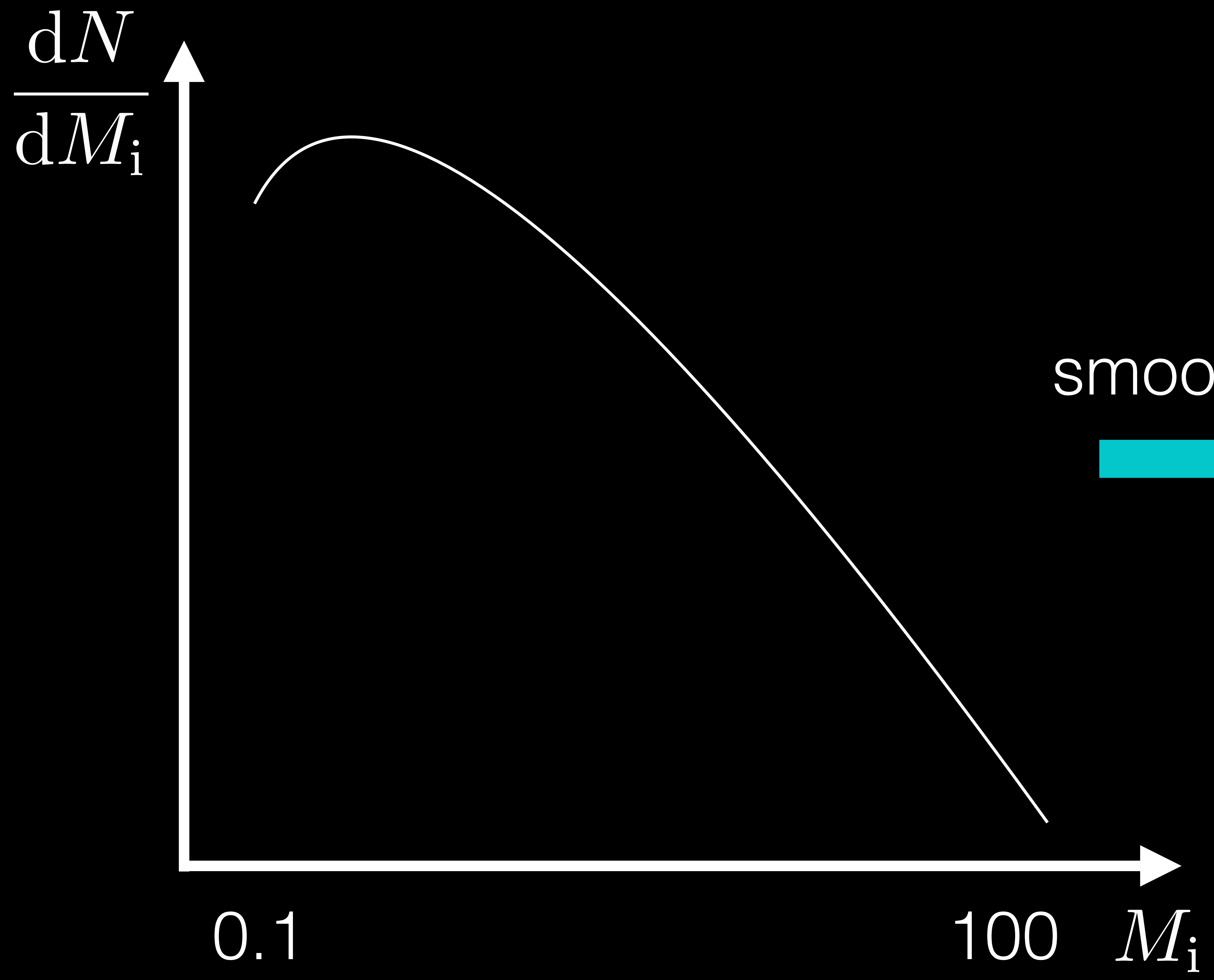
Outline

- ⋆ Lower-Mass Gap (LMG)
- ⋆ Observations of GW190814
- ⋆ Nature of 2.6 Msun object
- ⋆ My favorite model (& others)

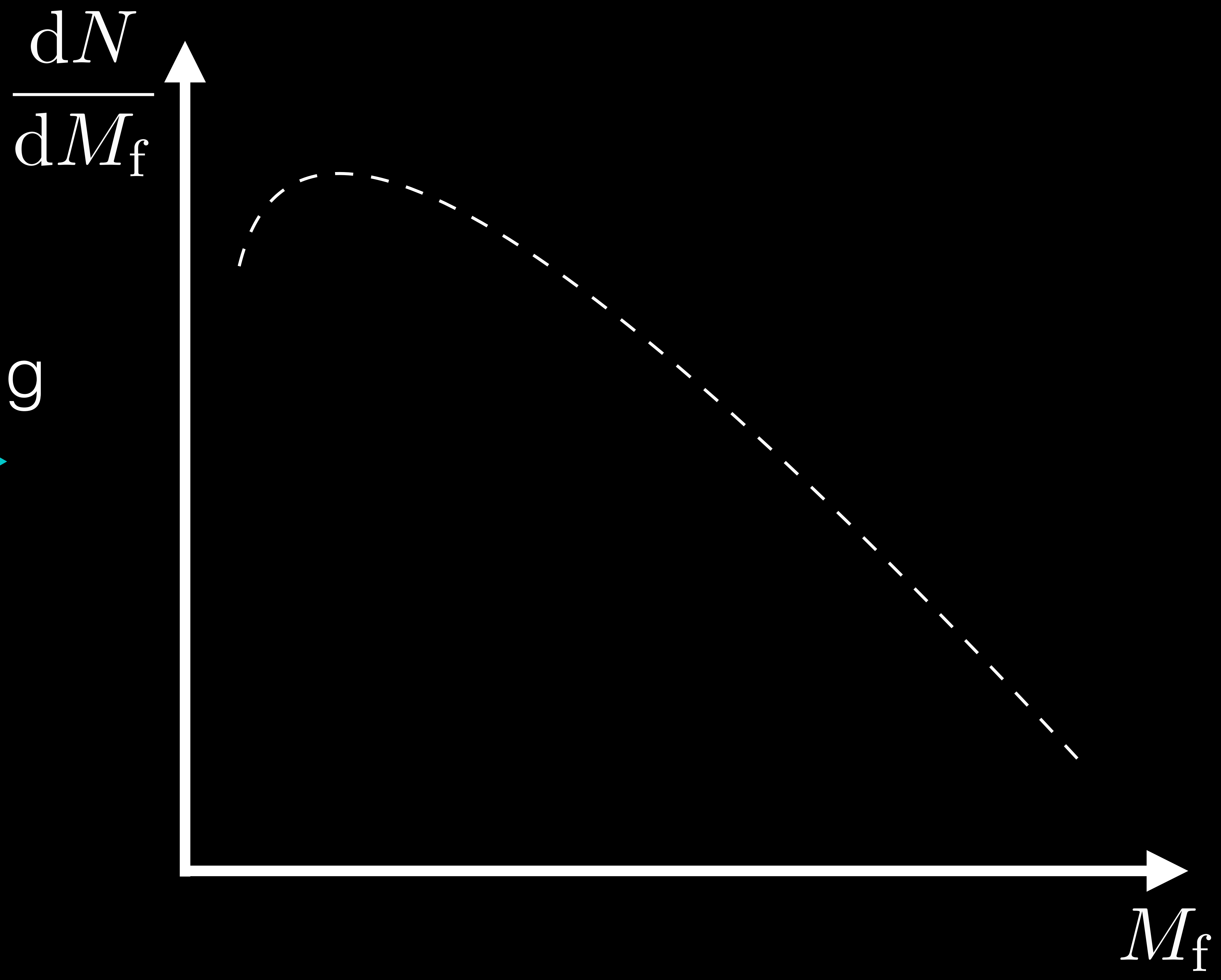
Initial-Final Mass Relation

single: $M_{\rm f} = f_{\rm sig}(M_{\rm i}, Z)$ **binary:** $M_{\rm f} = f_{\rm bin}(M_{\rm i}, Z, q_{\rm i})$

If *Nature* always makes smooth functions, then $\mathrm{d}N/\mathrm{d}M_{\rm f}$ should be smooth



smooth mapping



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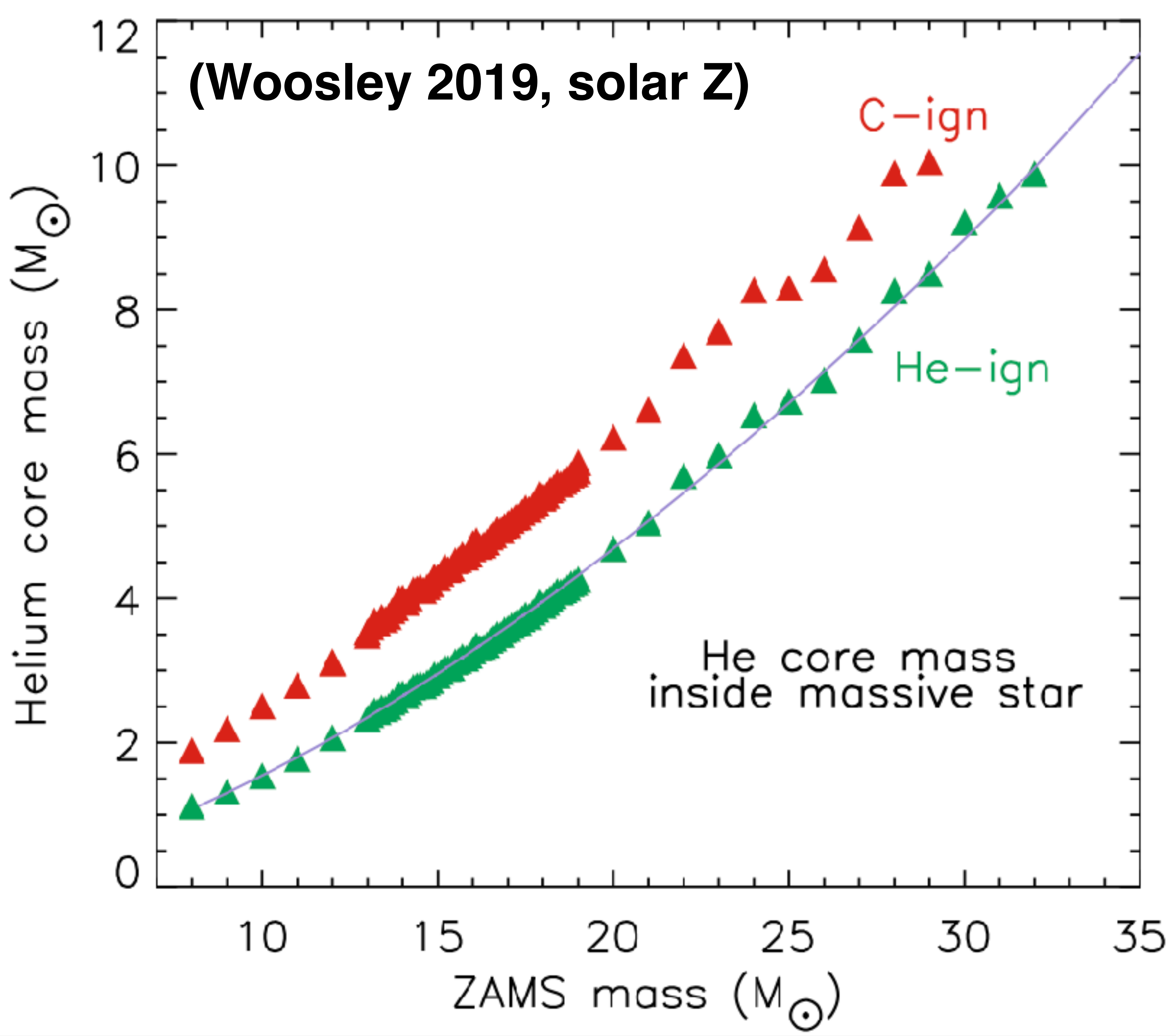
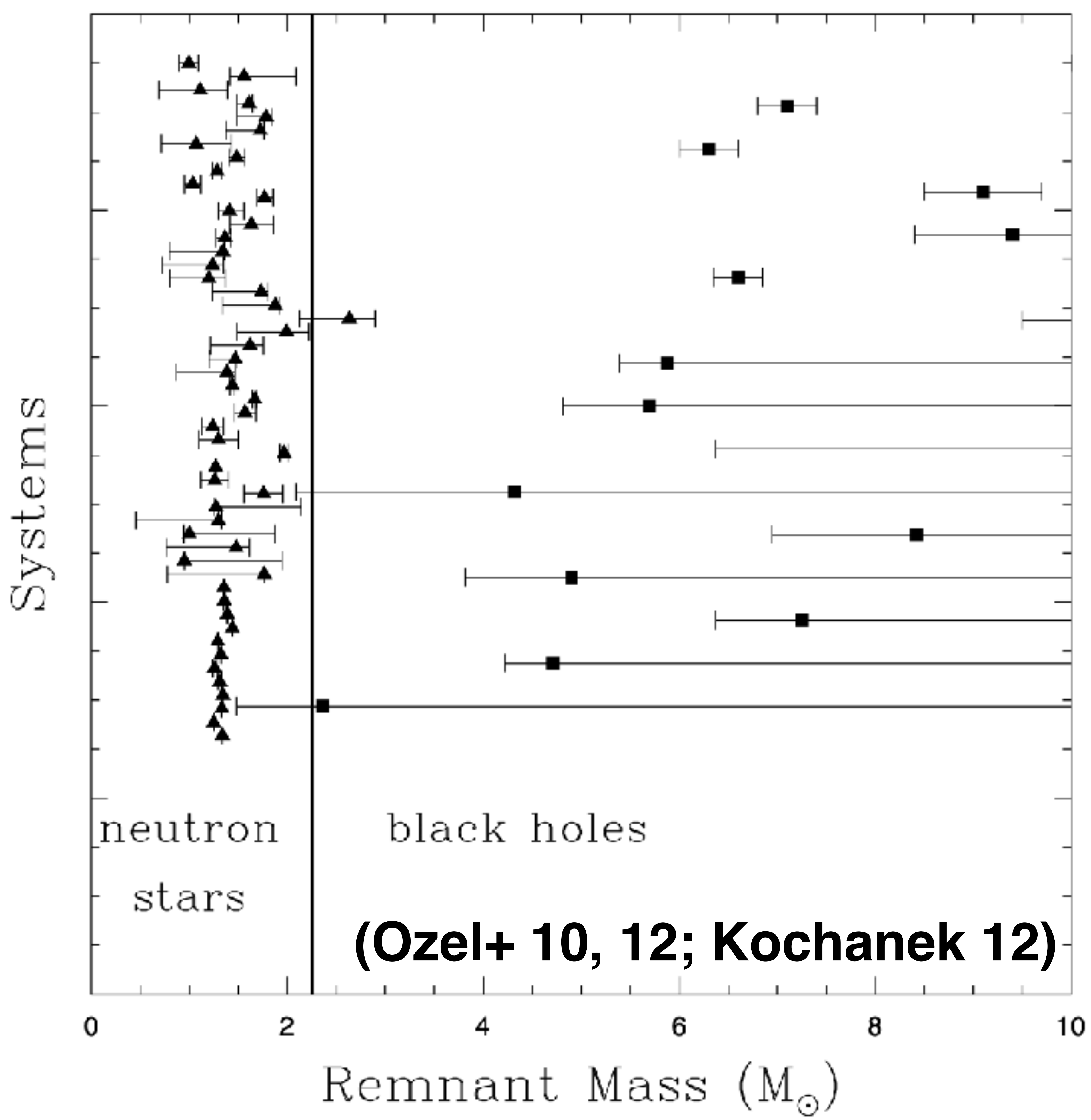


core collapse



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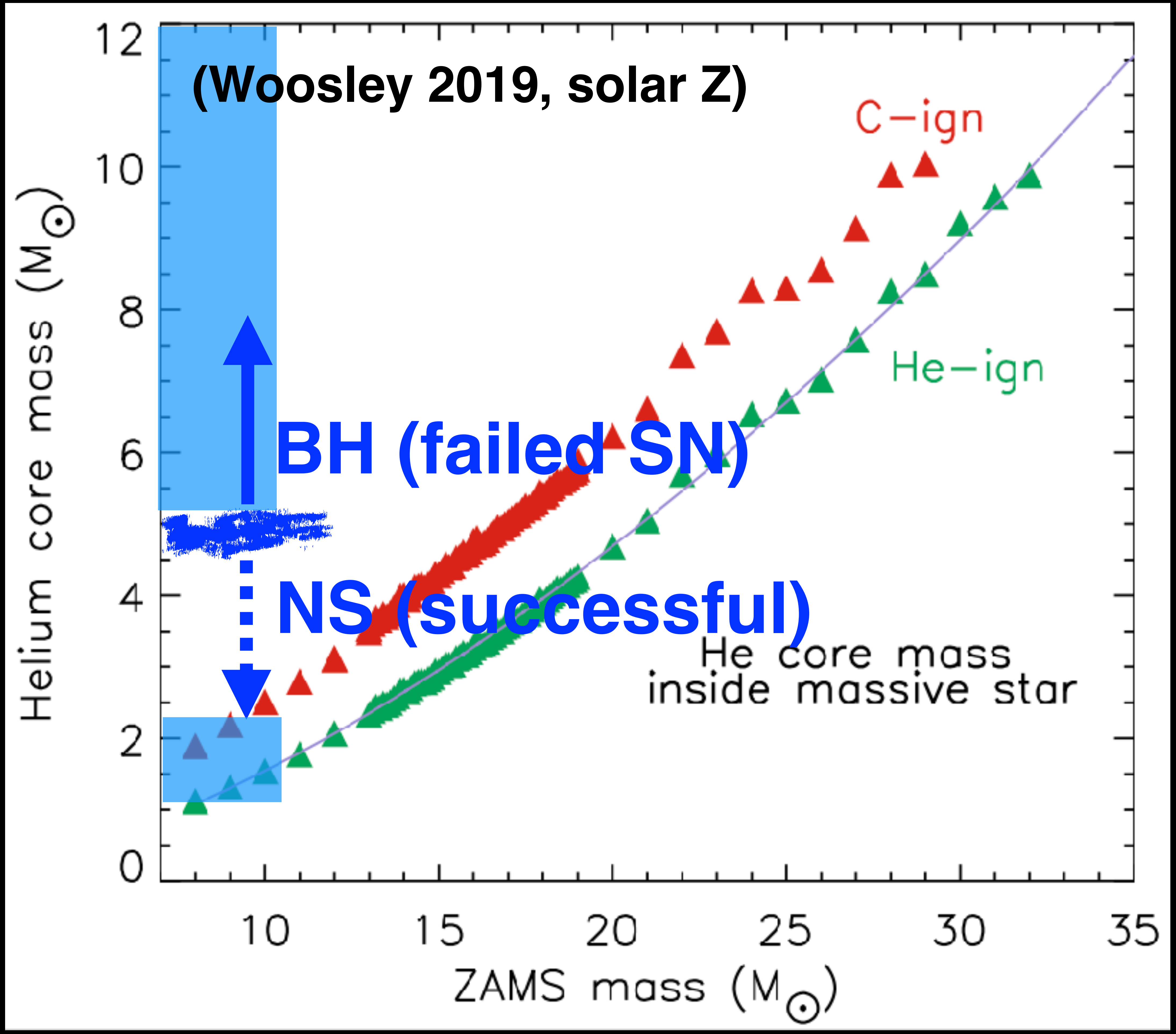

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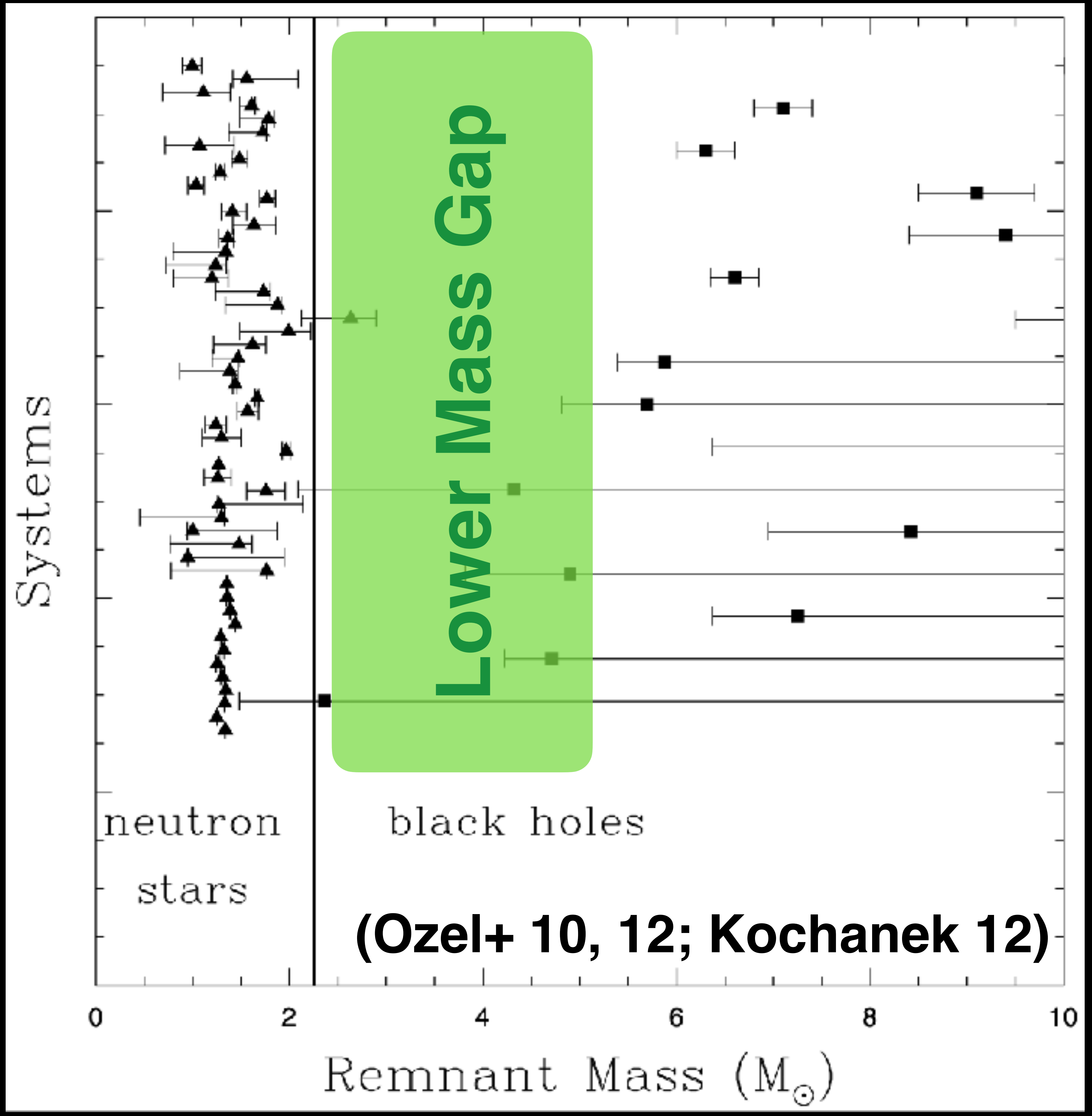

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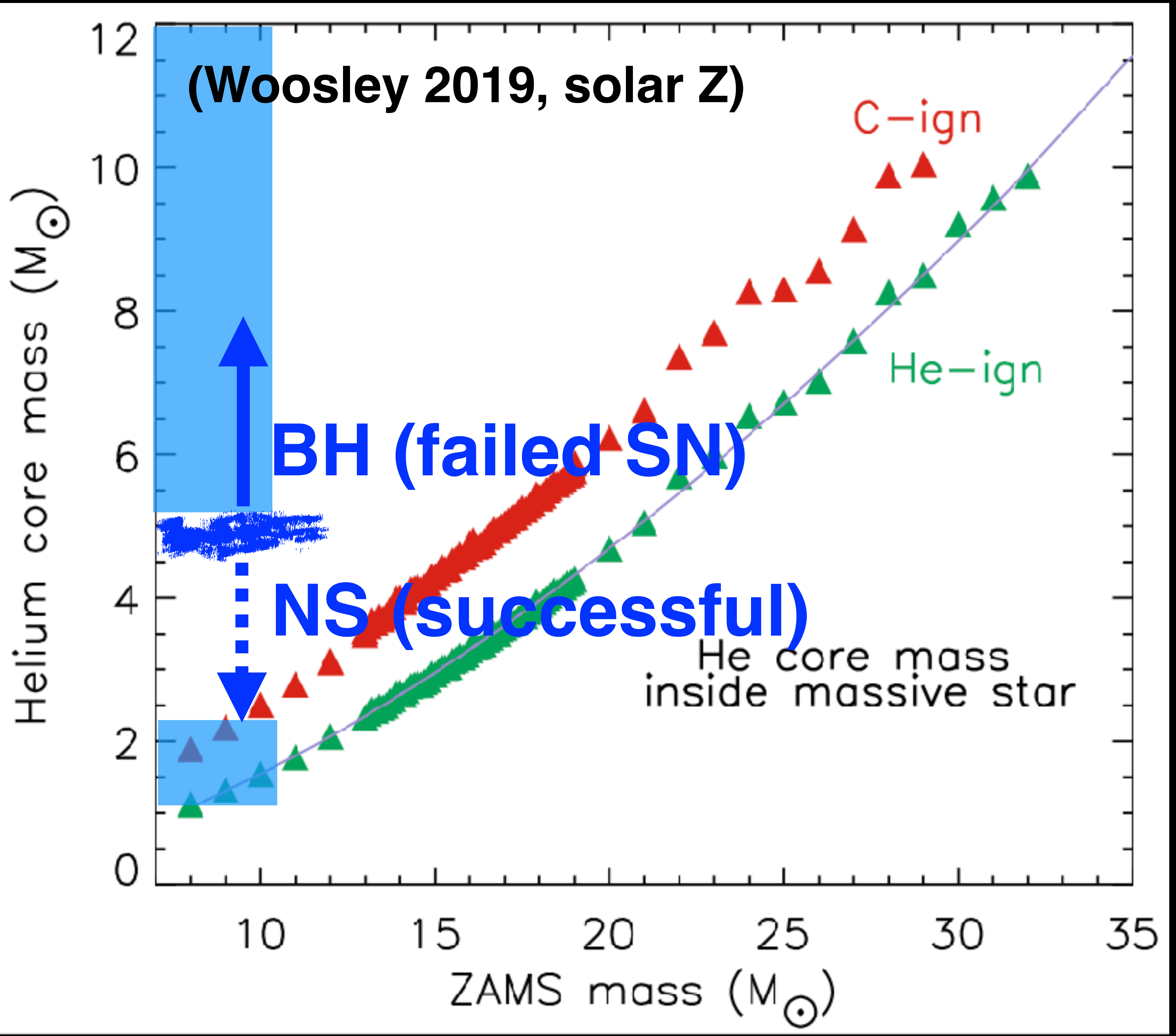

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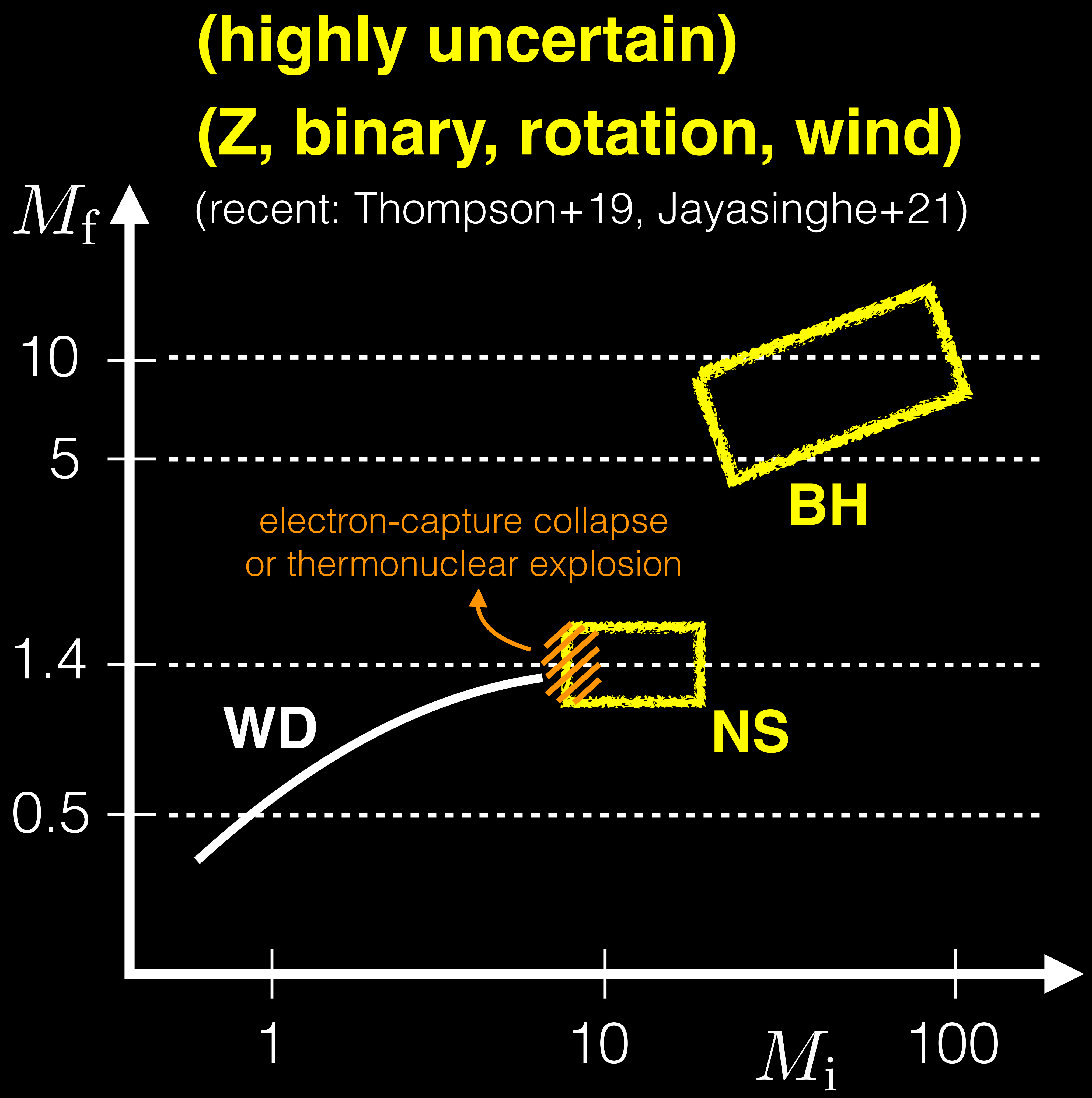

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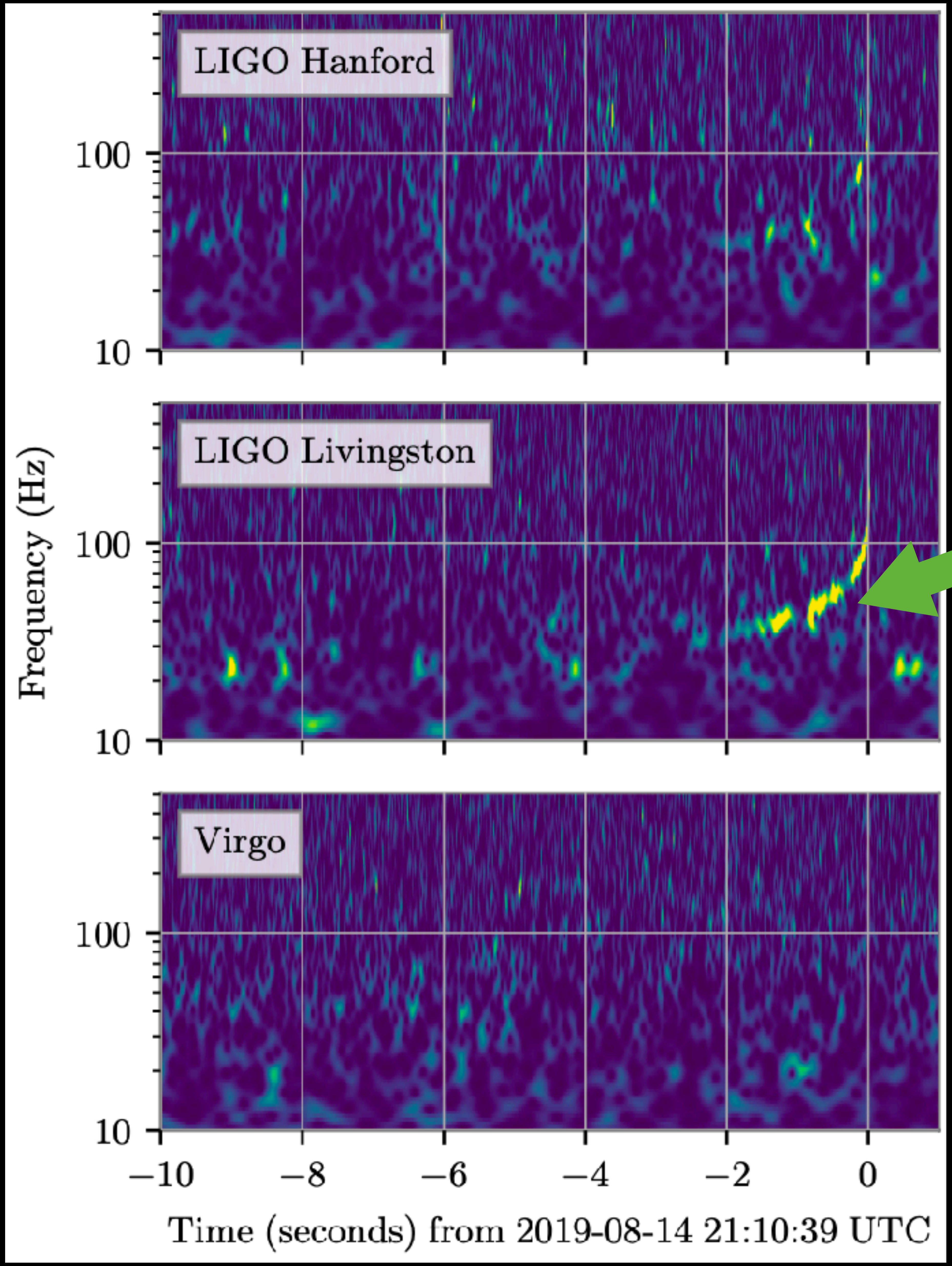
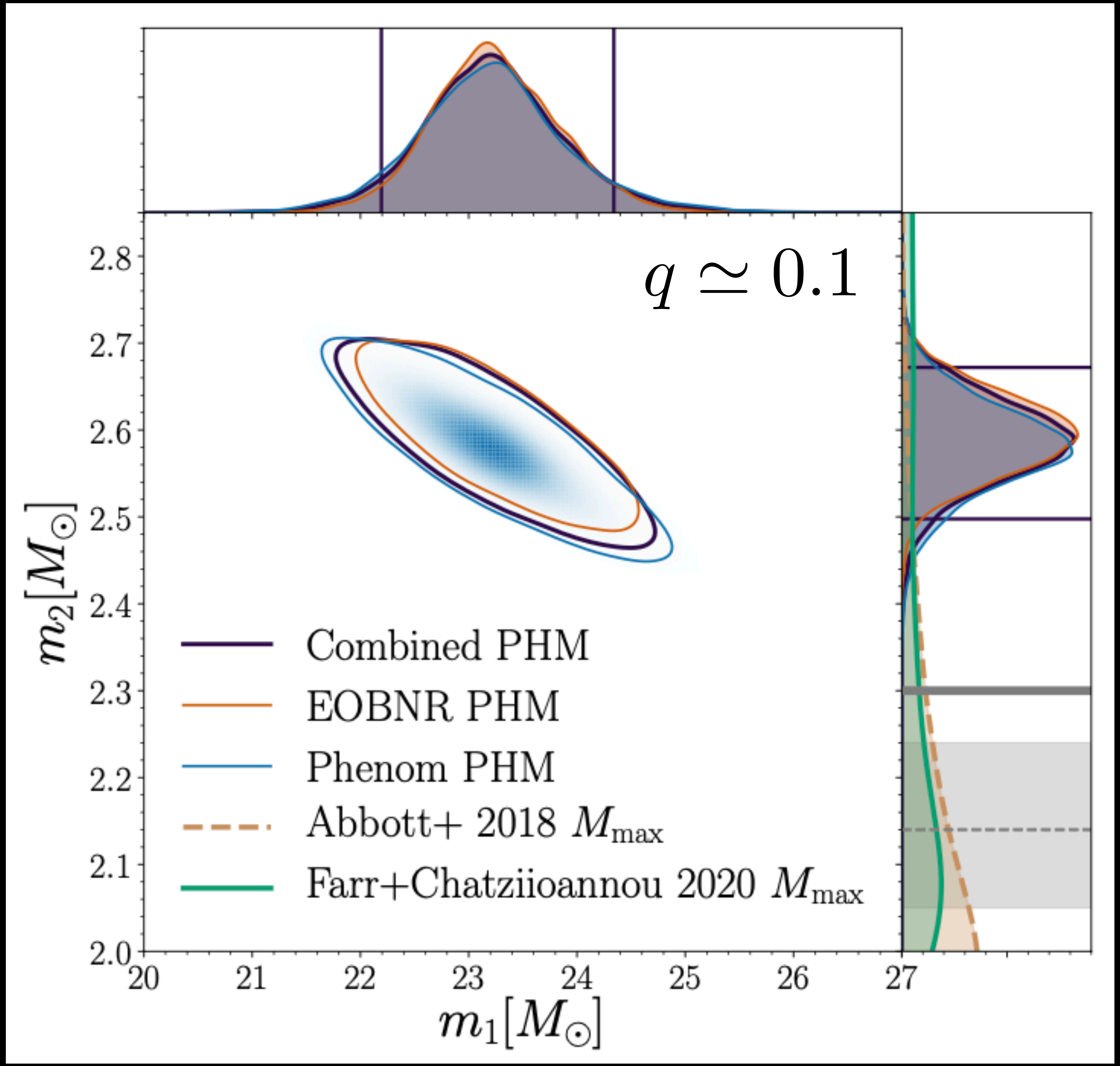
EMRI-like Event: GW190814

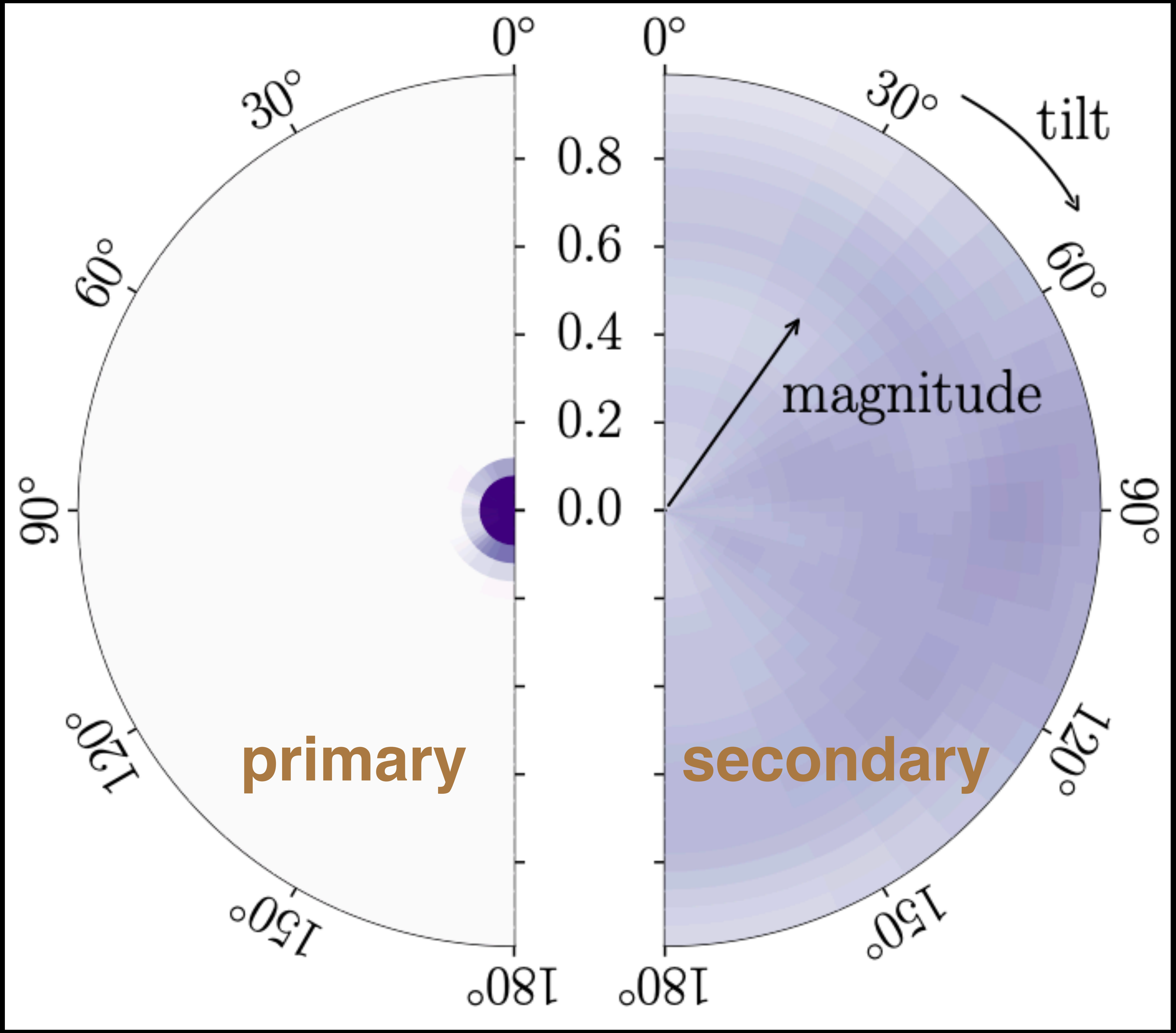


Abbott+20

$N \sim 50$



Spin Constraints



Long inspiral

Accurate phase evolution

$$\boxed{|\chi_{\text{eff}}| \lesssim 0.06}$$

Lack of Lens-Thirring precession

$$\boxed{\chi_{\text{p}} = 0.04^{+0.04}_{-0.03}}$$

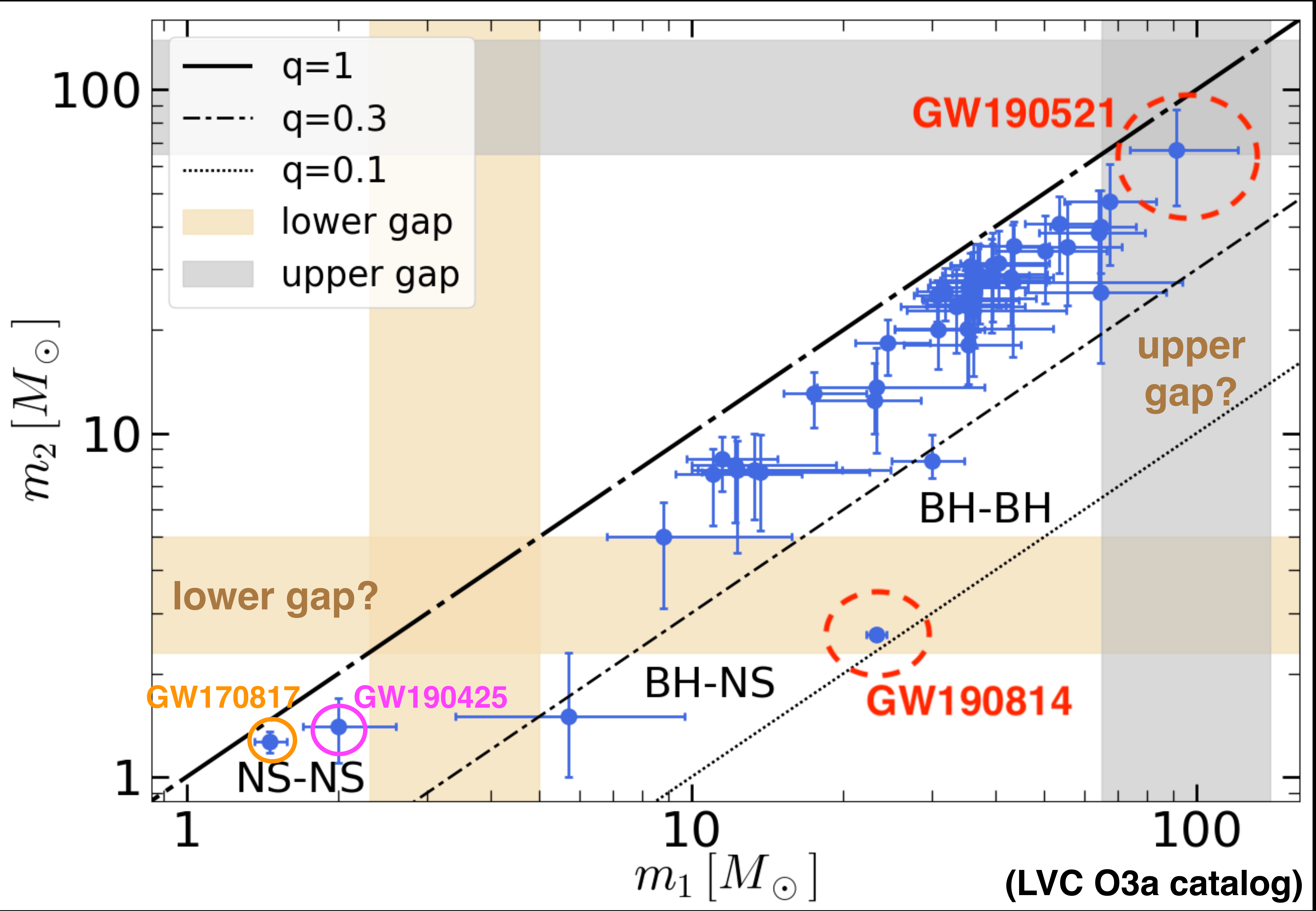
$$\chi_{\text{eff}} = \frac{\chi_{1\|} + q\,\chi_{2\|}}{1+q}$$

$$\chi_{\text{p}} = \max\left(\chi_{1\perp},\ q^3\frac{4+3q}{4q+3}\chi_{2\perp}\right)$$

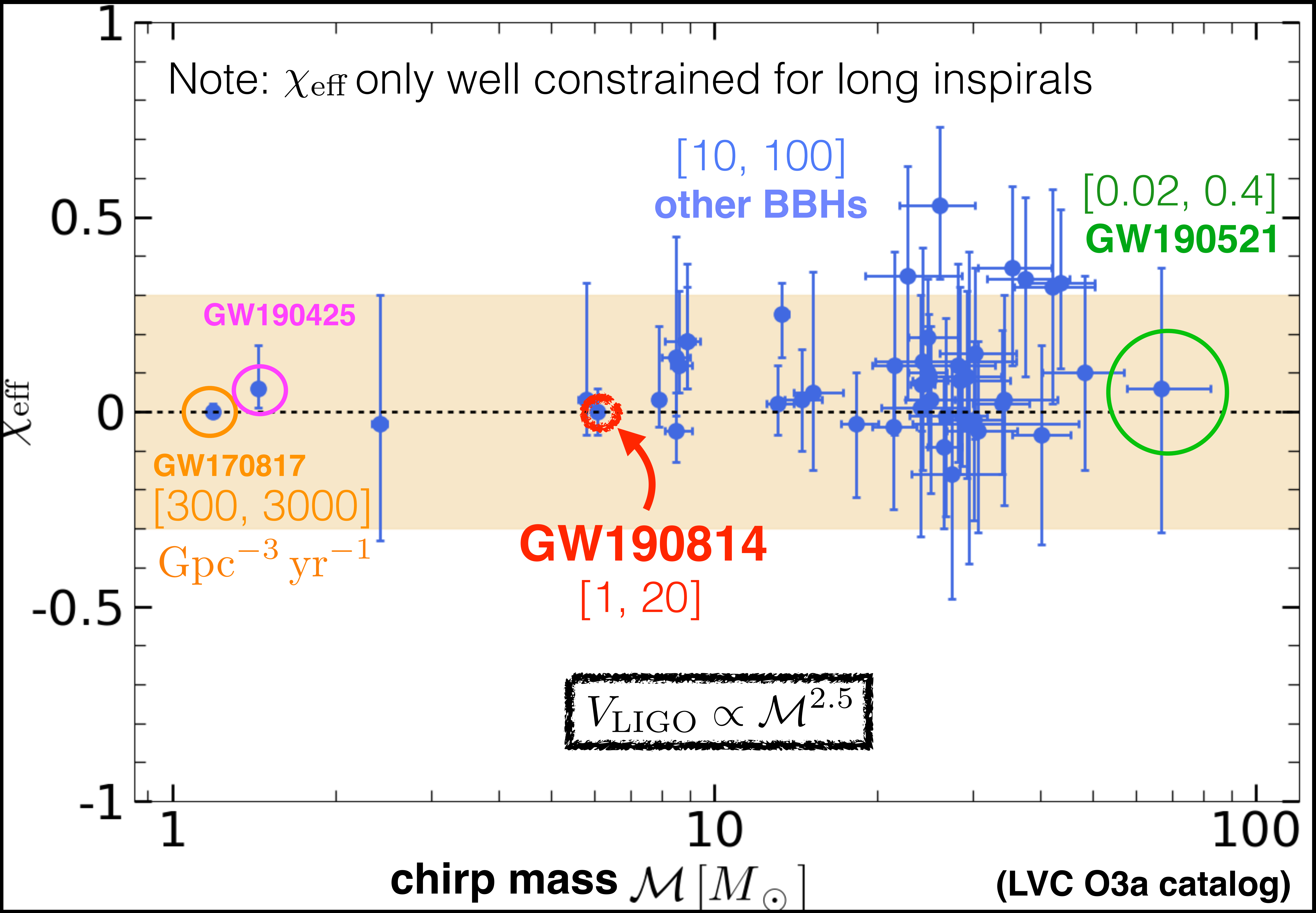

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
Upper-Mass Gap
LIGO-Virgo Black Holes
Not in Galactic XRBs
EM Black Holes
Lower-Mass Gap
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
likely low Z
successful SNe?
LIGO-Virgo Black Holes
EM Black Holes
GW190814
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern



q=1
q=0.3
q=0.1
lower gap
upper gap
GW190521
upper gap?
lower gap?
BH-BH
BH-NS
NS-NS
GW170817
GW190425
GW190814
100
10
1
$m_2\,[M_\odot]$
$m_1\,[M_\odot]$
(LVC O3a catalog)



Note: $\chi_{\rm eff}$ only well constrained for long inspirals
[10, 100]
other BBHs
[0.02, 0.4]
GW190521
GW190425
GW170817
[300, 3000]
$\rm Gpc^{-3}\,yr^{-1}$
GW190814
[1, 20]
$V_{\rm LIGO} \propto \mathcal{M}^{2.5}$
$\chi_{\rm eff}$
1
0.5
0
-0.5
-1
1
10
100
chirp mass $\mathcal{M}\,[M_\odot]$
(LVC O3a catalog)

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Nature of the Secondary

- Clue from GW170817 $M_{\rm tot} = 2.73^{+0.04}_{-0.01} M_\odot$

Mass loss during bNS merger:

$(\Delta m \lesssim 0.2 M_\odot)$

- GW radiation

  $0.05 \sim 0.1 M_\odot$

- Neutrino loss

  $\lesssim 0.1 M_\odot$

- Baryonic ejecta

  $0.03 \sim 0.2 M_\odot$

- Spin down

  $\lesssim 0.03 M_\odot$

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KNe and afterglow studies suggest:

$E_{\rm rad} \sim 10^{48}\,{\rm erg}$ $\quad E_{\rm k} \lesssim 10^{51}\,{\rm erg}$

missing ↓ $E_{\rm rot} \sim 10^{52.5}$–$10^{53}\,{\rm erg}$

Almost certainly made a BH

$m \sim 2.6 M_\odot$ $\quad \chi \sim 0.7$

with rotation ↓ $m_{\rm max} \simeq 1.2 m_{\rm TOV}$

$m_{\rm TOV} \lesssim 2.2 M_\odot$

(~Chandrasekhar mass for NS)

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$m_{\rm TOV} \lesssim 2.2 M_\odot$

(~Chandrasekhar mass for NS)

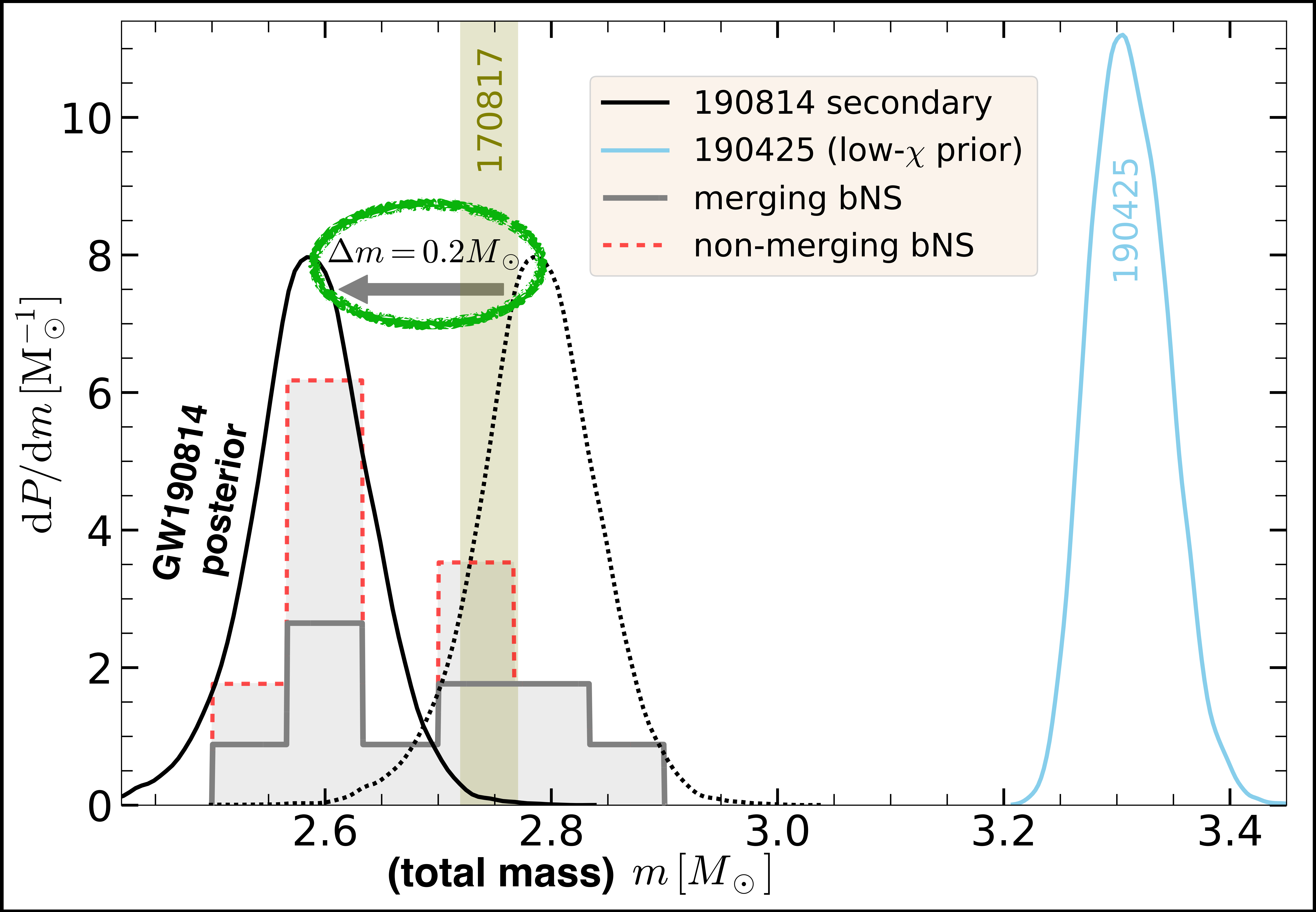
- GW190814 secondary

$m = 2.6 \pm 0.1 M_\odot \gg m_{\rm TOV}$

spin down to $\chi \ll 1$ after $t_{\rm GW}$

$\Rightarrow$ $\boxed{\text{BH}}$

Mass Consistent with BNS Merger Product



Mass loss during merger:

$(\Delta m \lesssim 0.2 M_\odot)$

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- **Neutrino loss** $\lesssim 0.1 M_\odot$
- **Baryonic ejecta** $0.03 \sim 0.2 M_\odot$
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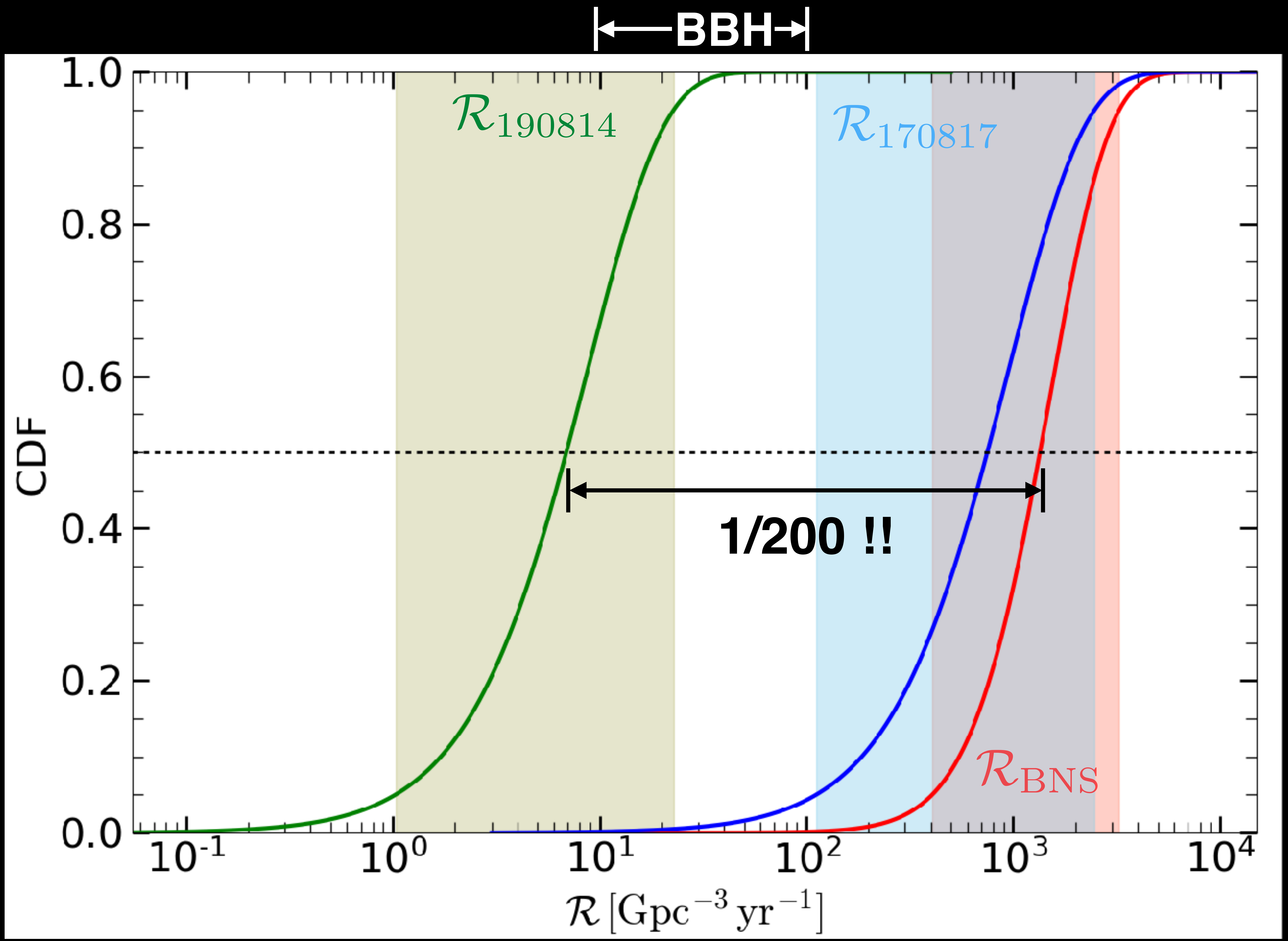
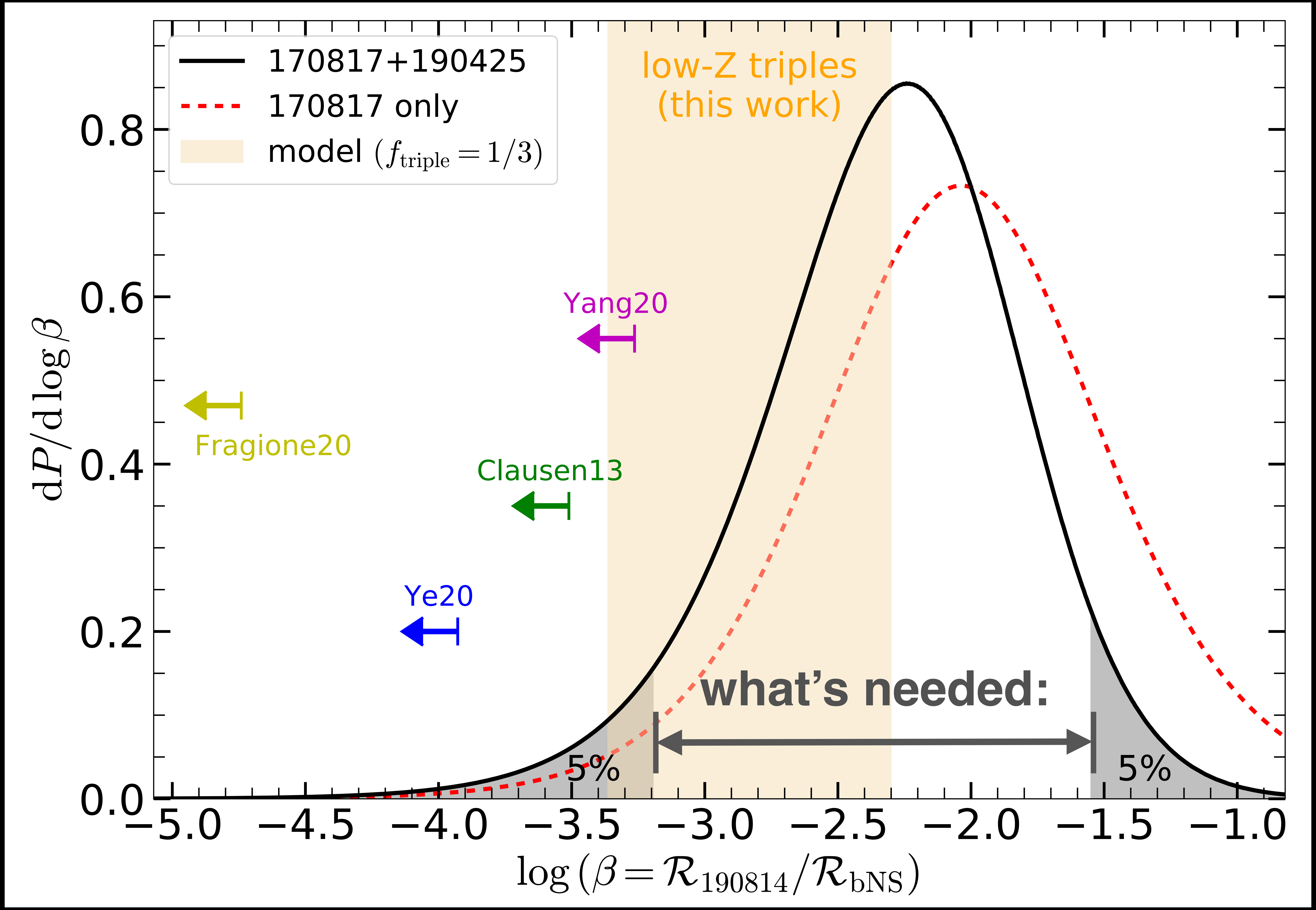
Volumetric Rates (z ~ 0)



Only a small fraction of BNS mergers need to participate 2G merger!

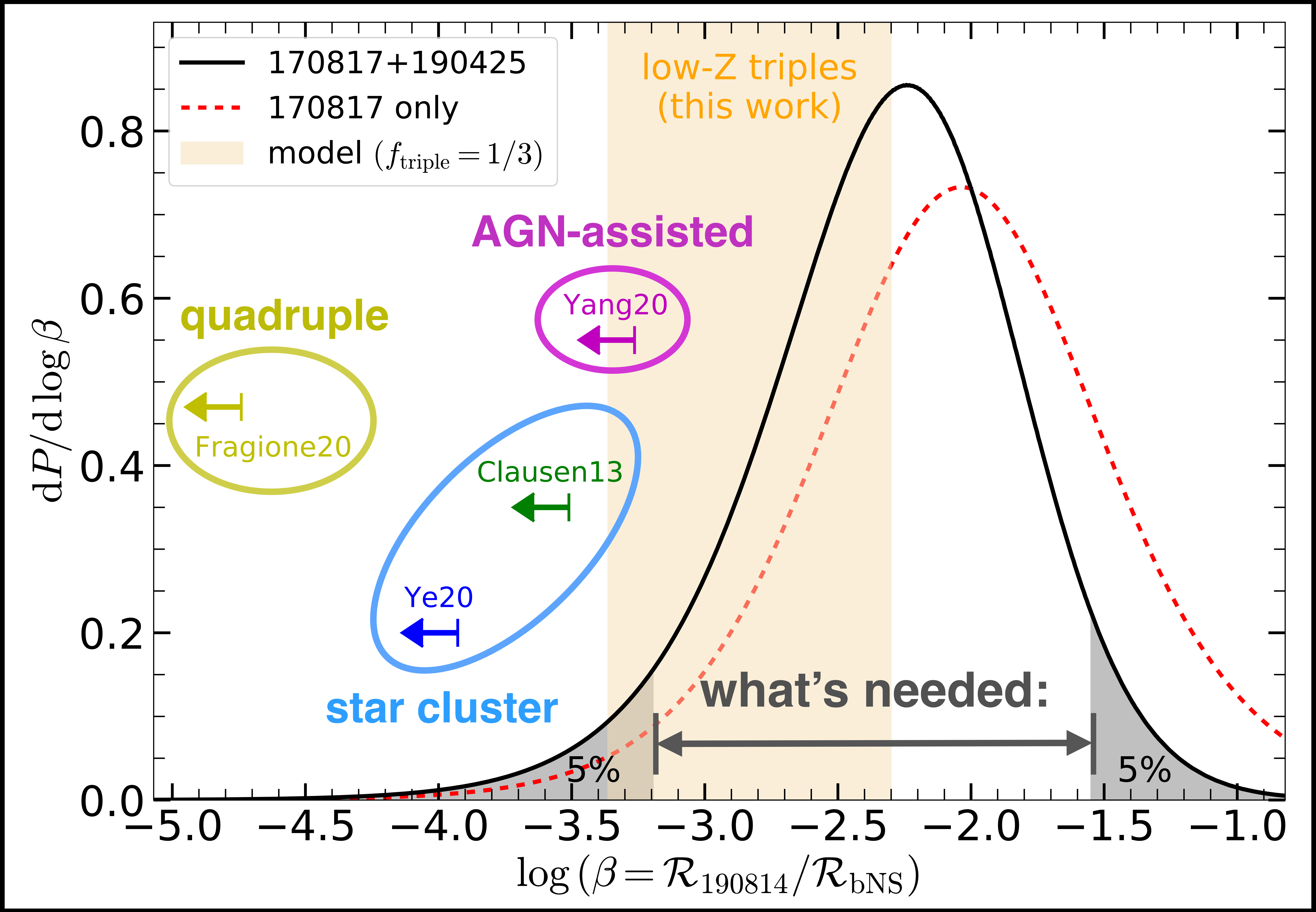
Rate Ratio



$0.064\% \lesssim \beta \lesssim 2.8\%$

(90% C.L.)

Rate Ratio



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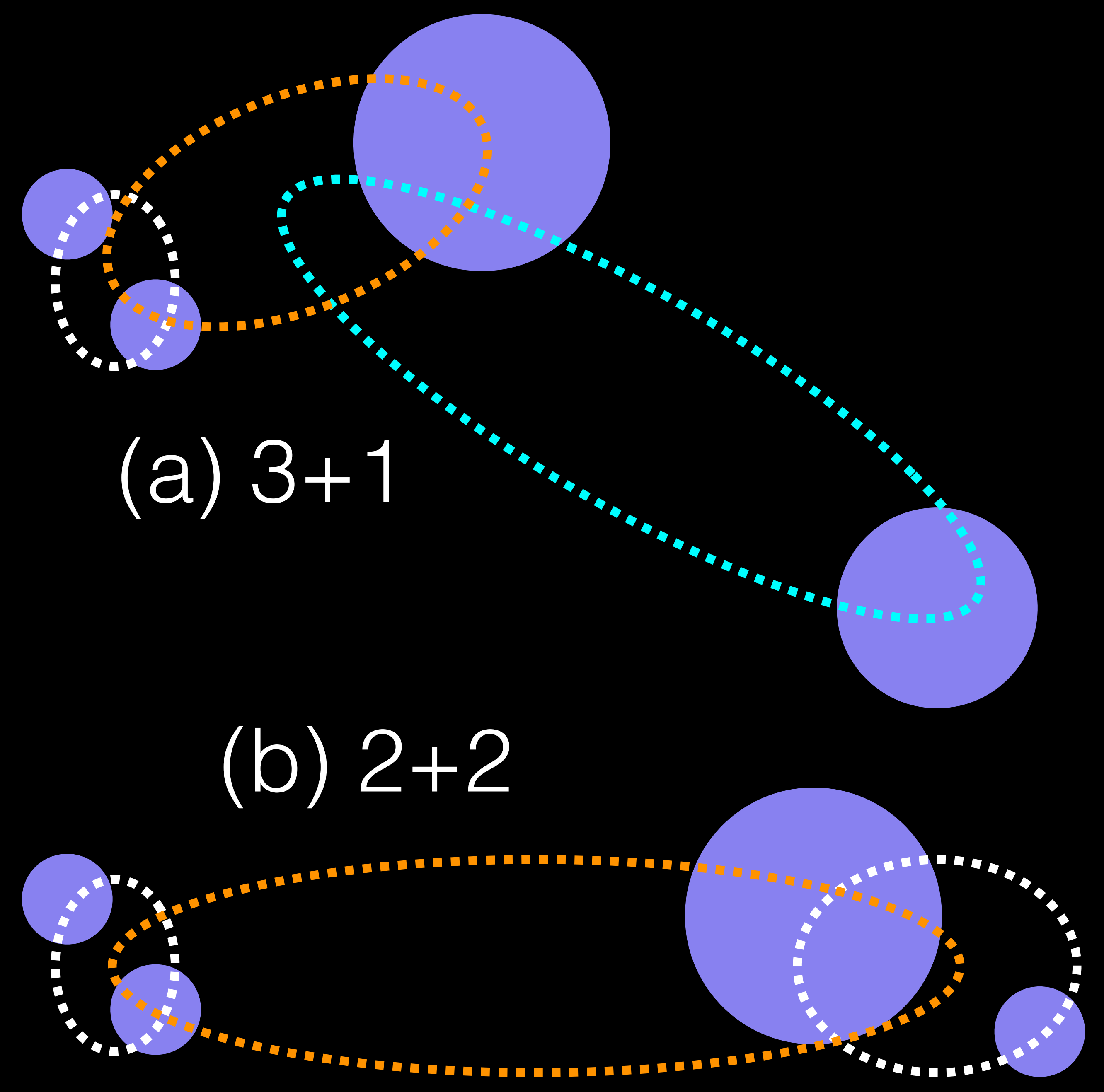
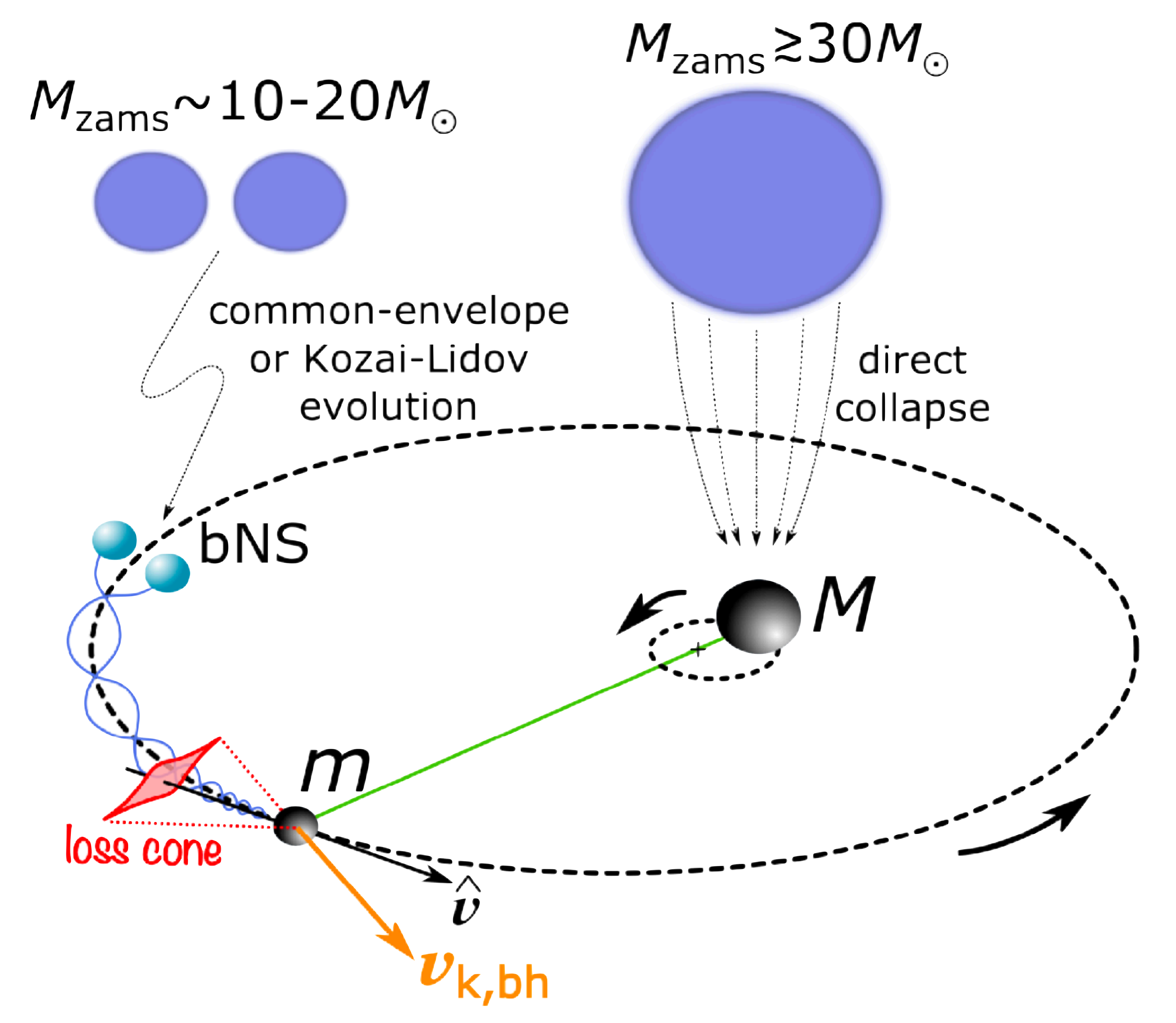
For instance,

- ★ **quadruple scenarios**



A Triple Model?



Kick on BNS merger remnant

$(\text{mass ratio } 0.8 \lesssim q < 1)$

- ⋆ **GW** $v_{k,GW} \lesssim 30\,\mathrm{km/s}$
- ⋆ **Neutrinos** $v_{k,\nu\bar{\nu}} \lesssim 100\,\mathrm{km/s}$
- ⋆ **Dynamical Ejecta**

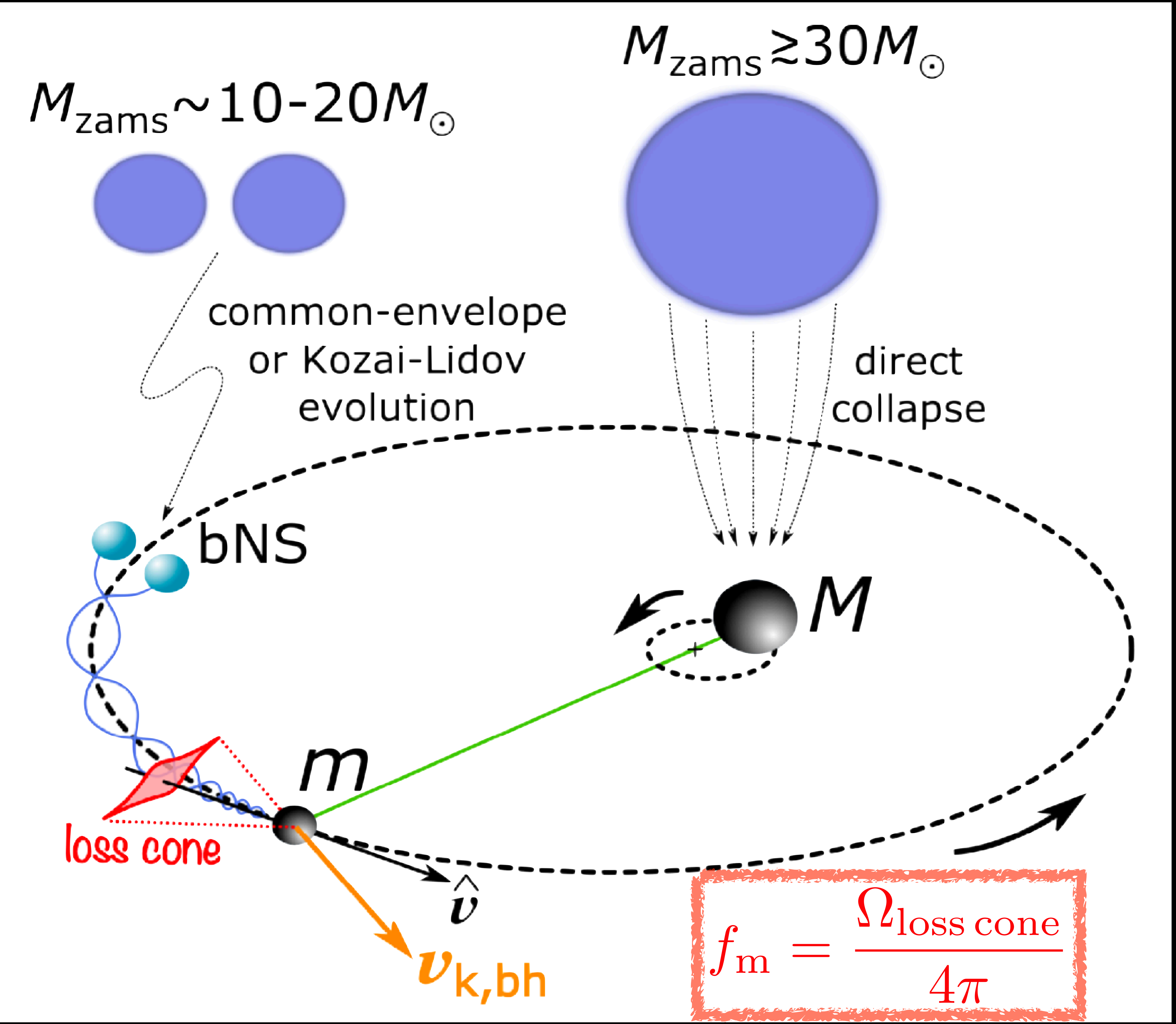
$v_{k,ej} \sim 30 \text{ to } 150\,\mathrm{km/s}$

(highly uncertain)

$\boxed{v_{k,bh} \sim 100\,\mathrm{km/s}}$

comparable to orbital speed for $a \sim 1\,\mathrm{AU}$

A Triple Model?



$$\boxed{0.064\% \lesssim \beta \equiv \frac{\mathcal{R}_{190814}}{\mathcal{R}_{\rm bns}} \lesssim 2.8\%}$$

- A fraction $f_{\rm triple}$ of BNS mergers have a tertiary BH
- 2G-merger probability $f_{\rm m}$

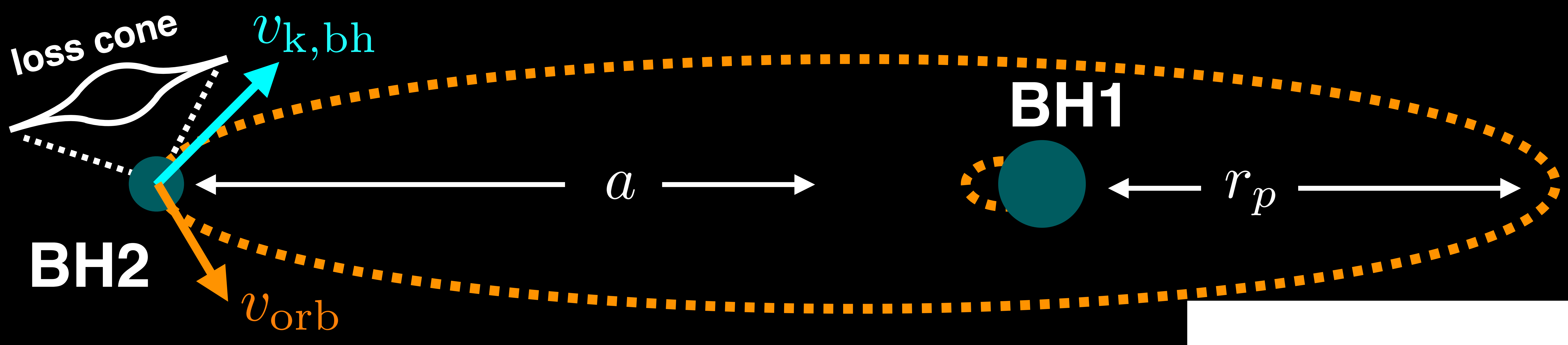
$$\boxed{\beta = f_{\rm triple} f_{\rm m}}$$

if $f_{\rm triple} = 1/3$

what's needed:

$$0.2\% \lesssim f_{\rm m} \lesssim 8\%$$

Average Over $\vec{v}_{\rm k,bh}$ & Orbital Phase



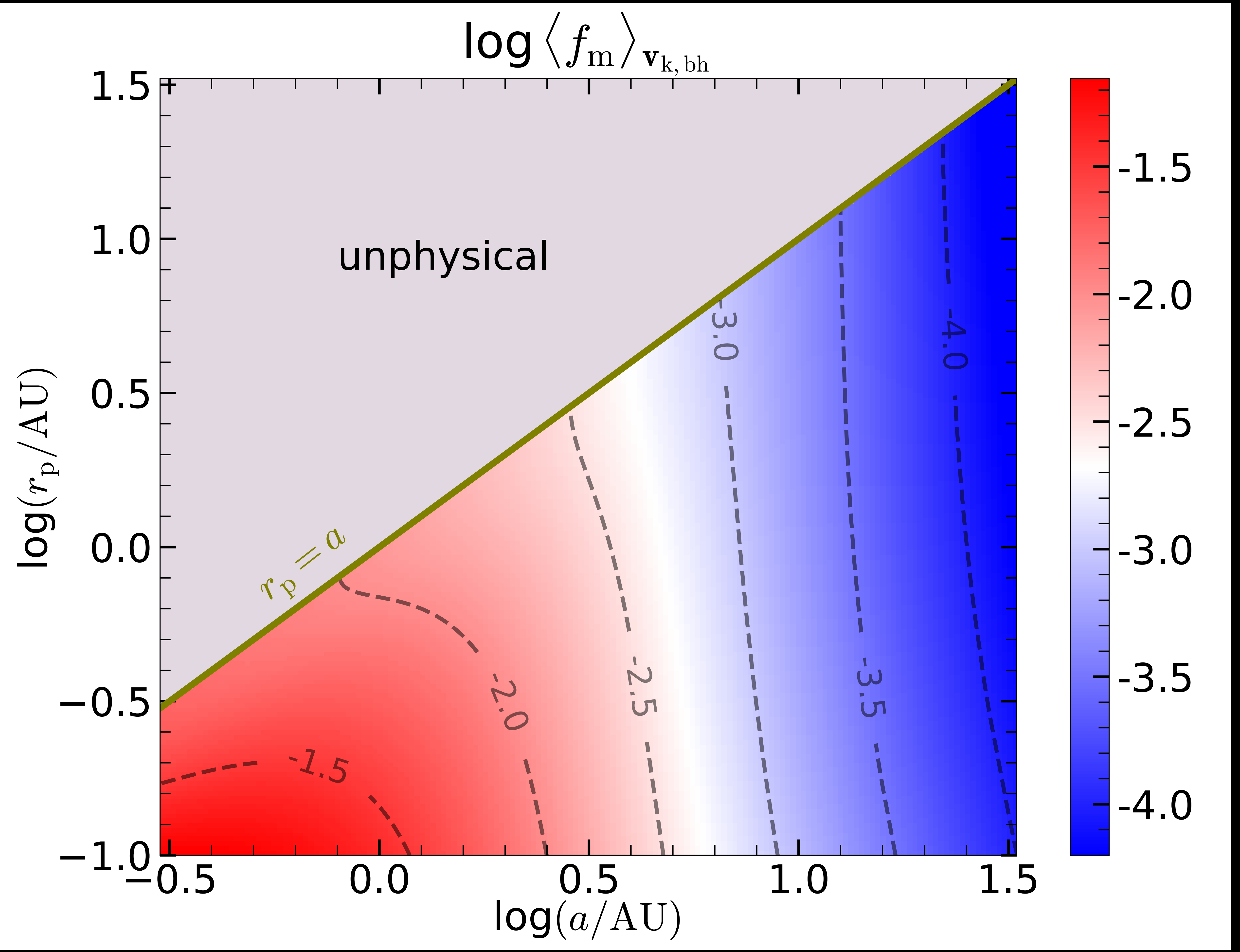
(outer orbit slightly eccentric before BNS merger)

- **magnitude**: log-normal $P(\log v_{\rm k,bh}[{\rm km/s}])$

  $\mu = 2 \ ({\rm or}\ 100\,{\rm km\,s^{-1}}) \quad \sigma = 0.3$

- **direction**: isotropic

$\boxed{\text{For } a \sim 1\,{\rm AU},\ \langle f_{\rm m}\rangle_{v_{\rm k,bh}} \sim 1\%}$

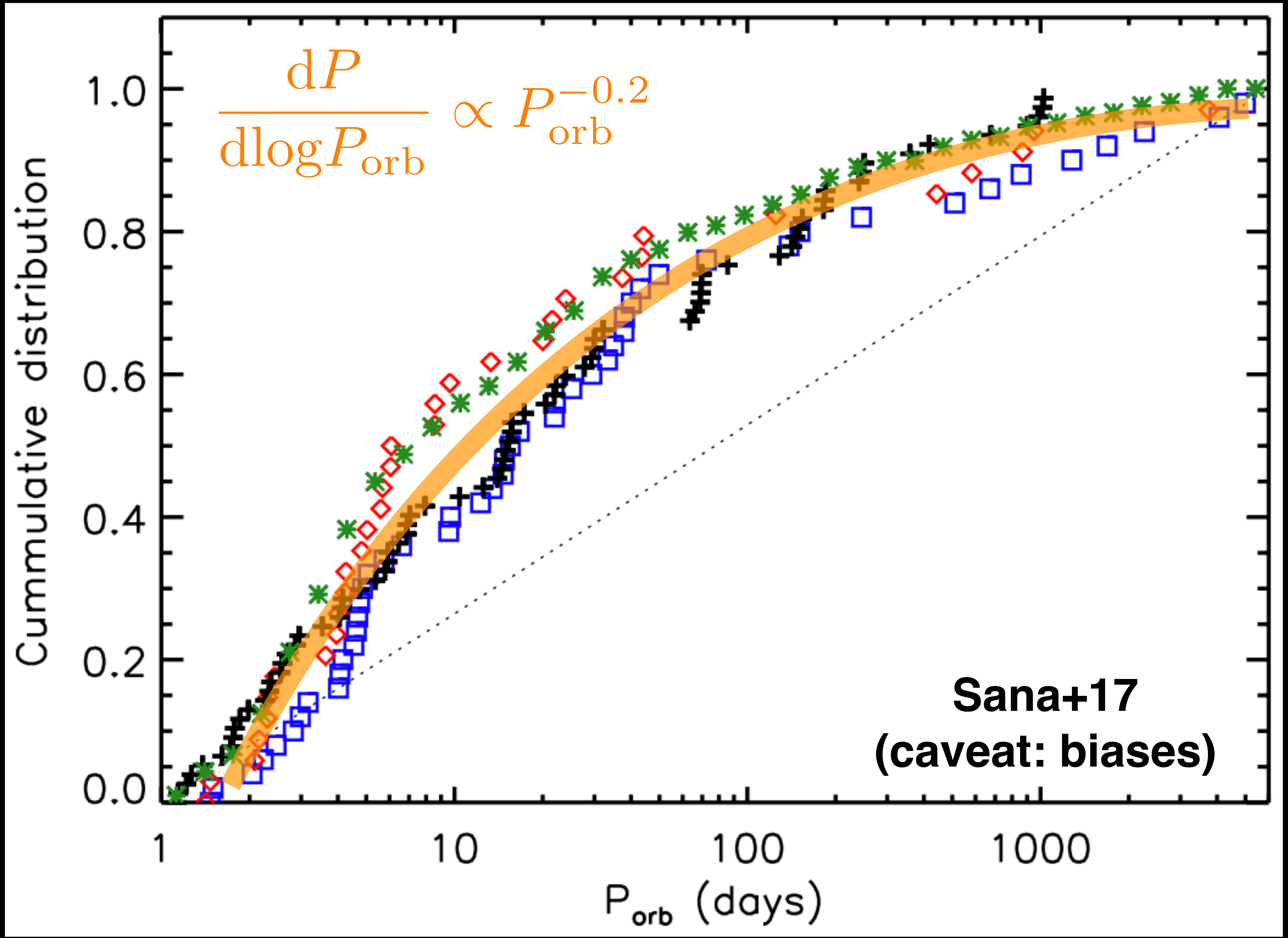


Average Over SMA a

Power-law distribution $\dfrac{\mathrm{d}P}{\mathrm{d}\log a} \propto a^{-p} \quad (a \gtrsim a_{\min})$

(caveat: orbital migration)

- **PL index**: $p \simeq 0.3$**?**
- **min SMA:**



Average Over SMA a

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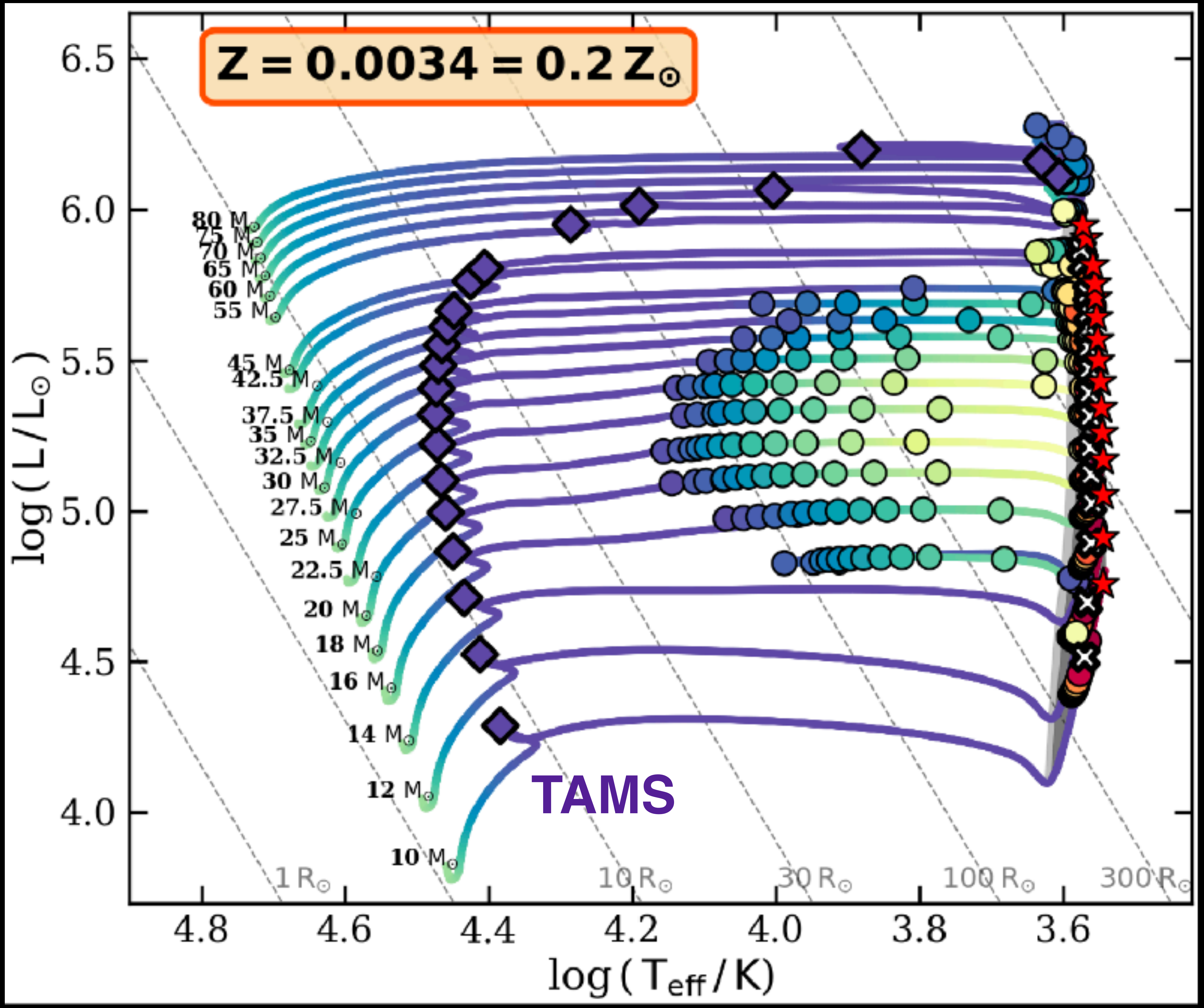
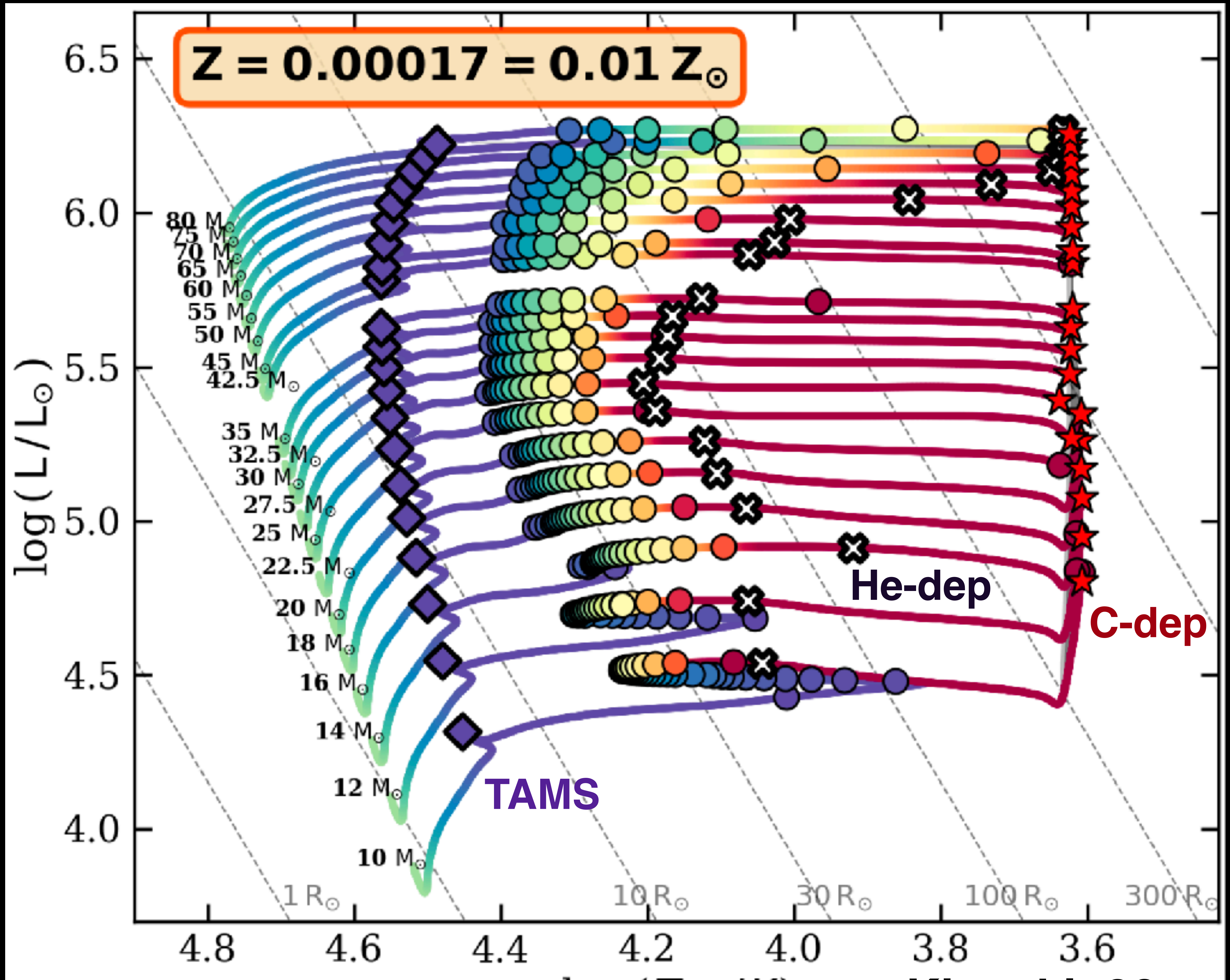
- ⋆ **PL index**: $p \simeq 0.3$**?**
- ⋆ **min SMA**: $3 \times 20 R_\odot \simeq 0.3\,\mathrm{AU}$





Klencki+20

2G Merger Fraction (%)

$a_{\min}$	p	$\bar{v}_{\mathrm{k,bh}}\,[\mathrm{km/s}]$		
		50	100	150
0.3 AU	0	**0.16**	**0.43**	**0.58**
	0.3	**0.22**	**0.70**	**0.97**
	2/3	**0.28**	**1.0**	**1.4**
1 AU	0	**0.12**	**0.18**	**0.17**
	0.3	**0.16**	**0.28**	**0.27**
	2/3	**0.21**	**0.39**	**0.39**

predictions

$$\boxed{0.064\% \lesssim \beta \equiv \frac{\mathcal{R}_{190814}}{\mathcal{R}_{\mathrm{bns}}} \lesssim 2.8\%}$$

- ⋆ **A fraction f_{triple} of BNS mergers have a tertiary BH**
- ⋆ **2G-merger probability f_{m}**

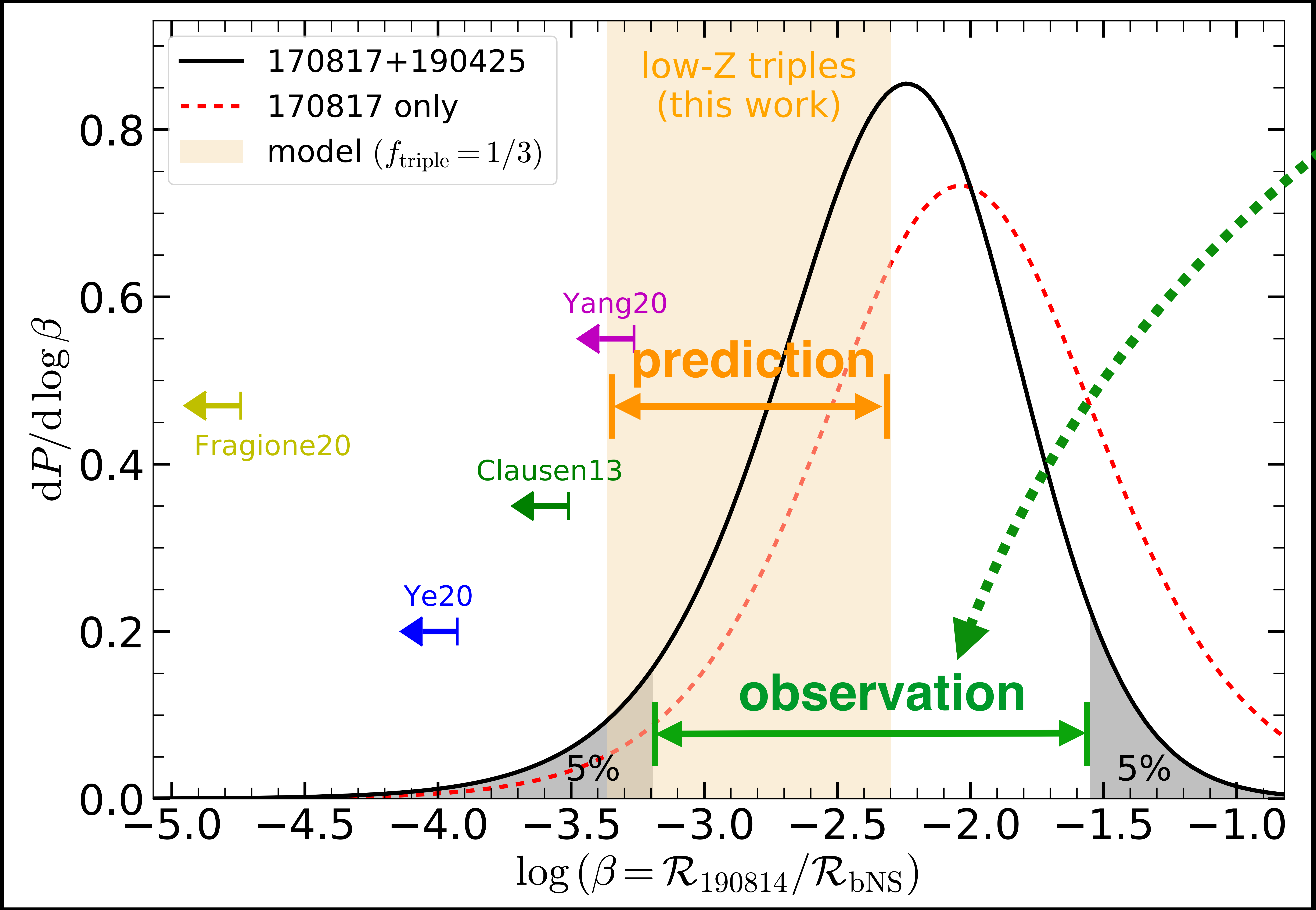
$$\boxed{\beta = f_{\mathrm{triple}} f_{\mathrm{m}}}$$

if $f_{\mathrm{triple}} = 1/3$

what's needed:

$$0.2\% \lesssim f_{\mathrm{m}} \lesssim 8\%$$

2G Merger Fraction (%)



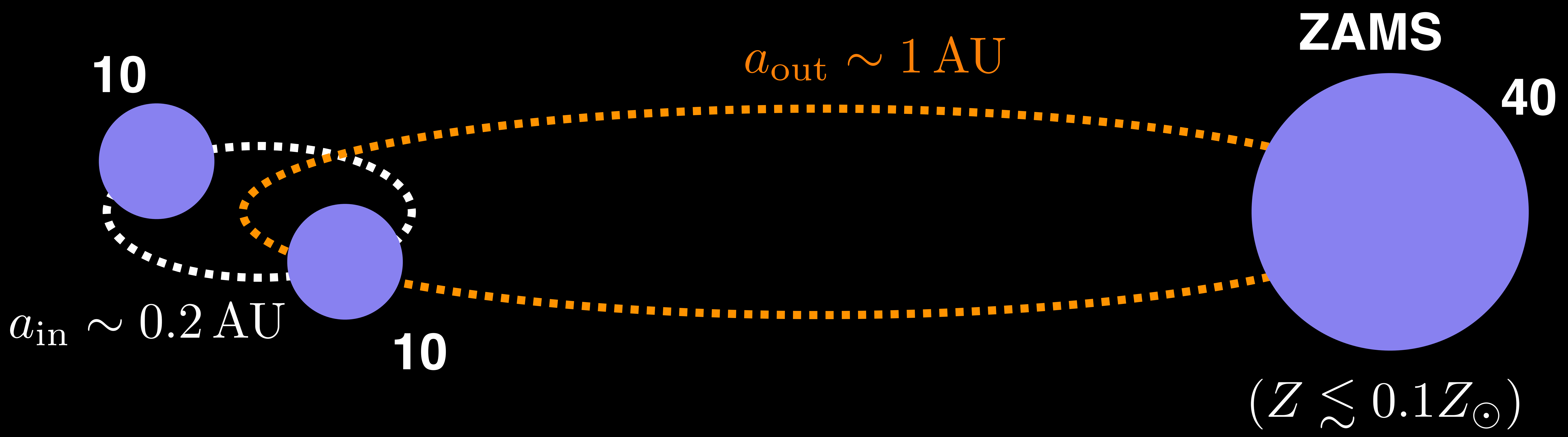
$$\boxed{0.064\% \lesssim \beta \equiv \frac{\mathcal{R}_{190814}}{\mathcal{R}_{\rm bns}} \lesssim 2.8\%}$$

- ⋆ **A fraction $f_{\rm triple}$ of BNS mergers have a tertiary BH**
- ⋆ **2G-merger probability $f_{\rm m}$**

$$\boxed{\beta = f_{\rm triple} f_{\rm m}}$$

Q: Is large $f_{\rm triple}$ allowed??

A Practical Triple Model



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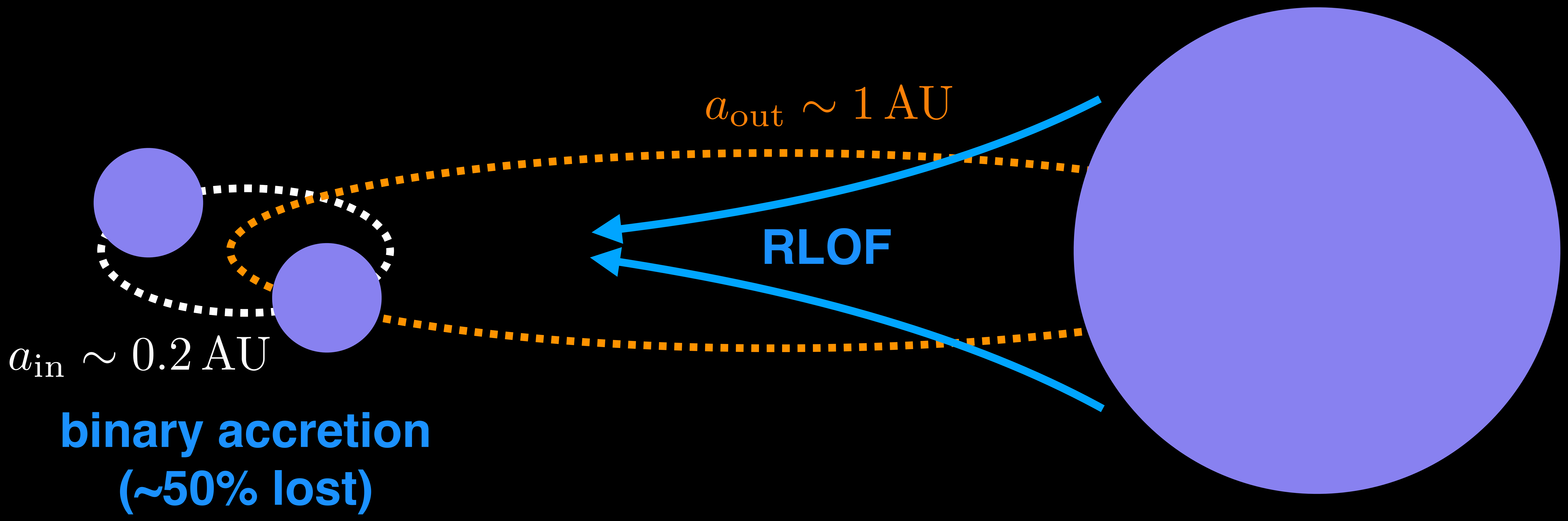

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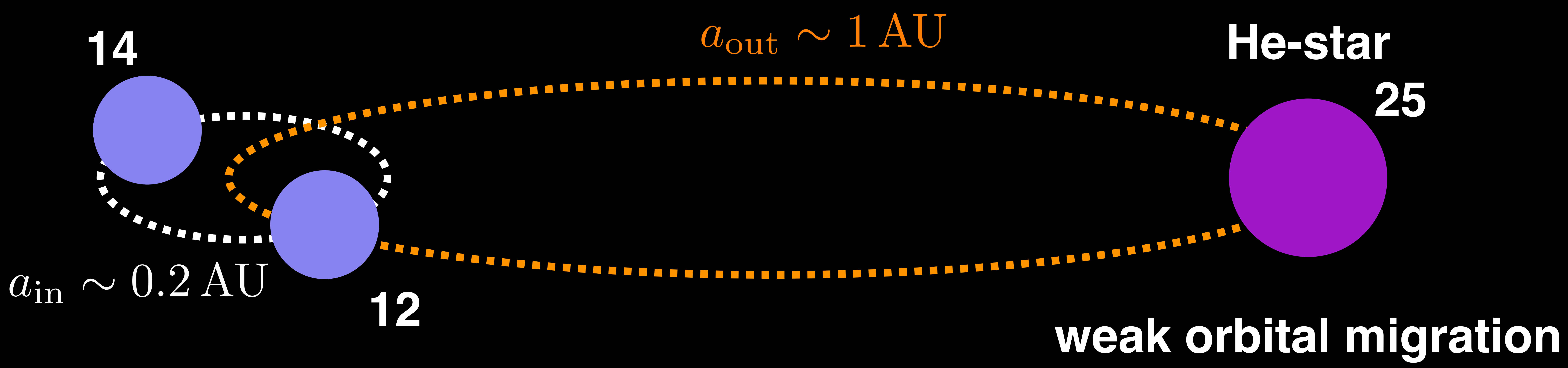

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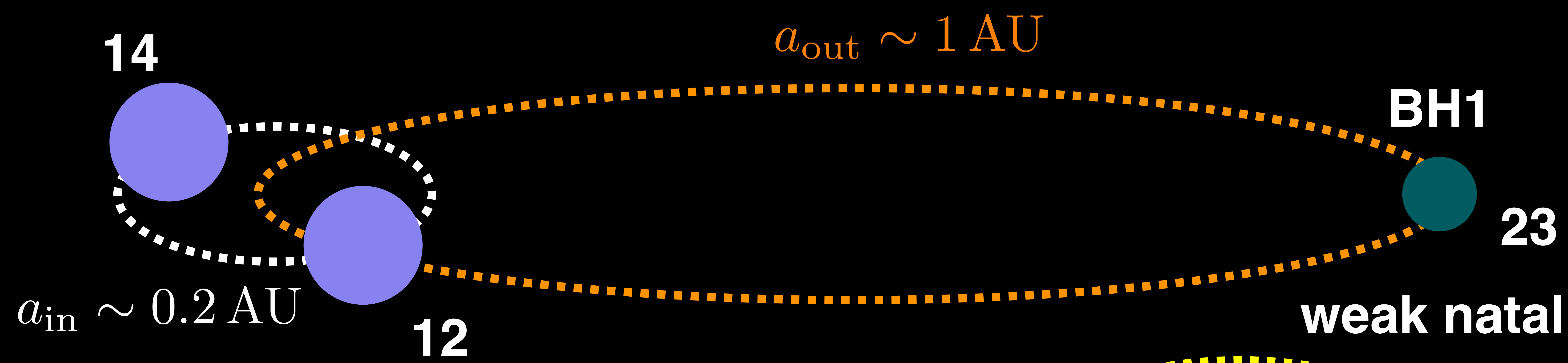
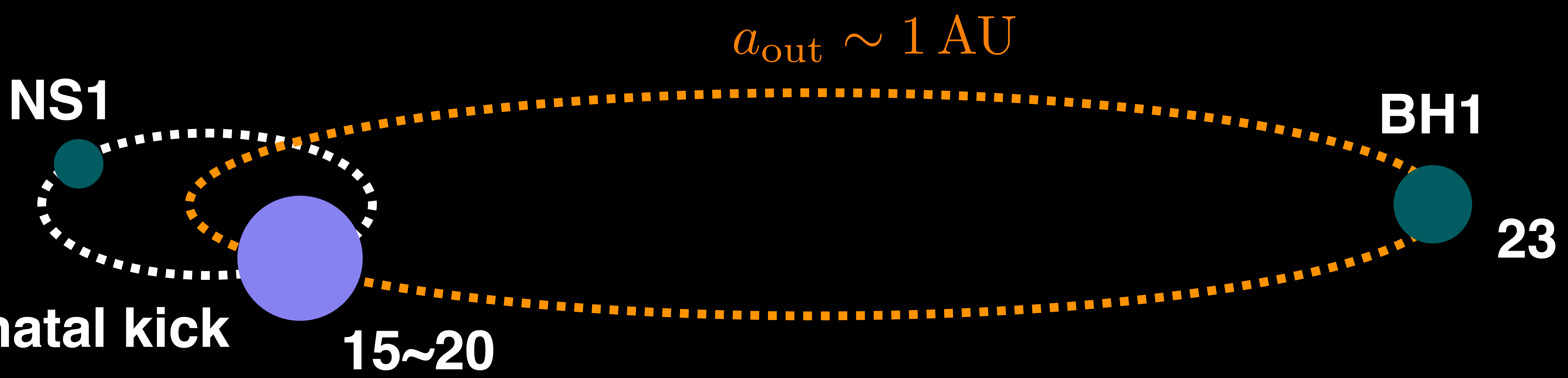


weak natal kick

$v_{\mathrm{k}} \sim 20\,\mathrm{km/s} \ll \mathrm{v}_{\mathrm{orb}} \sim 100\,\mathrm{km/s}$

A Practical Triple Model



strong natal kick

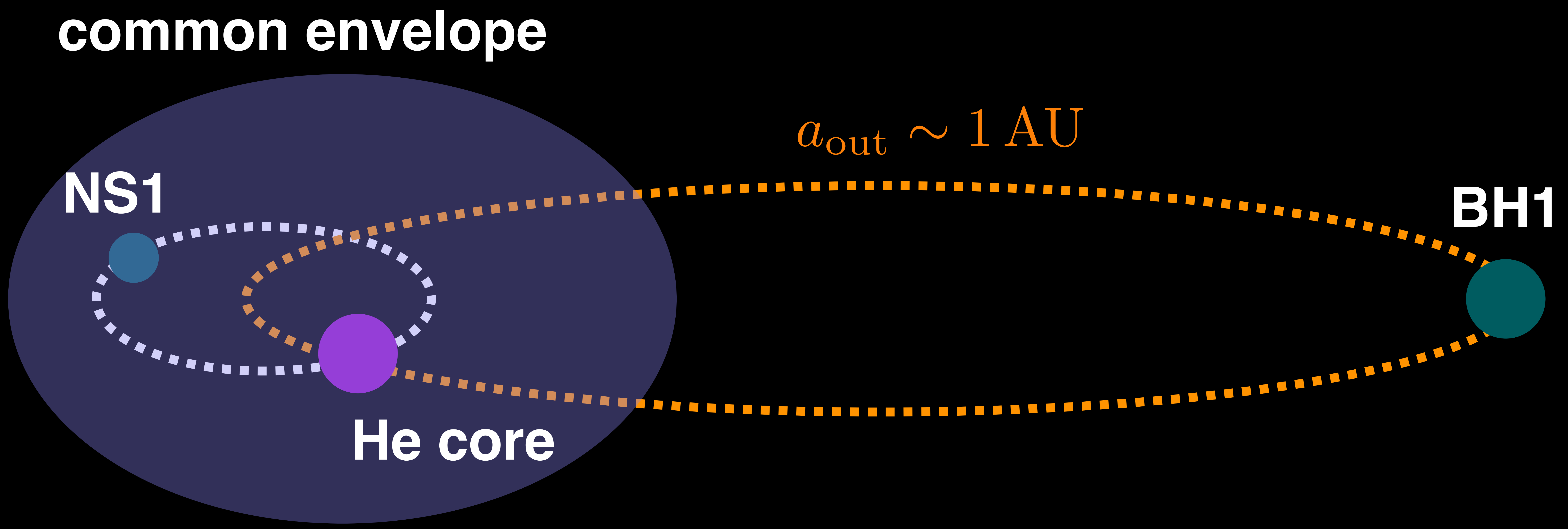
$$v_{\rm k} \sim 300\,\mathrm{km/s} \sim \mathrm{v_{orb,in}}$$

⬇

binary center-of-mass kick

$$v_{\rm k,b} \lesssim 30\,\mathrm{km/s} \ll \mathrm{v_{orb}} \sim 100\,\mathrm{km/s}$$

A Practical Triple Model



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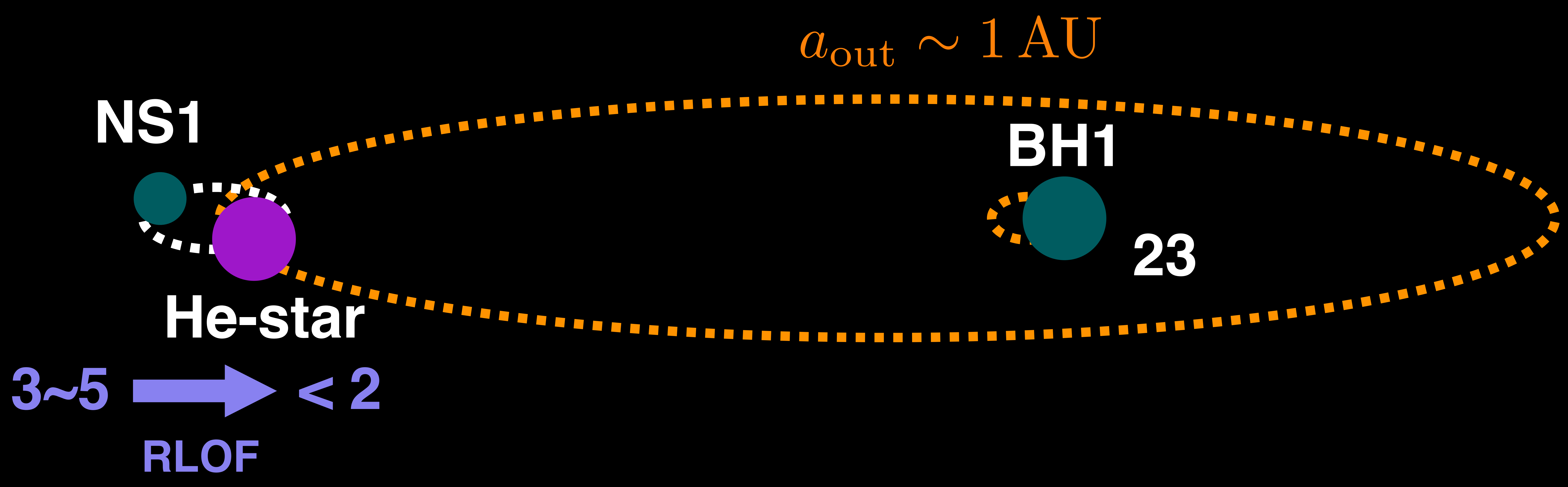

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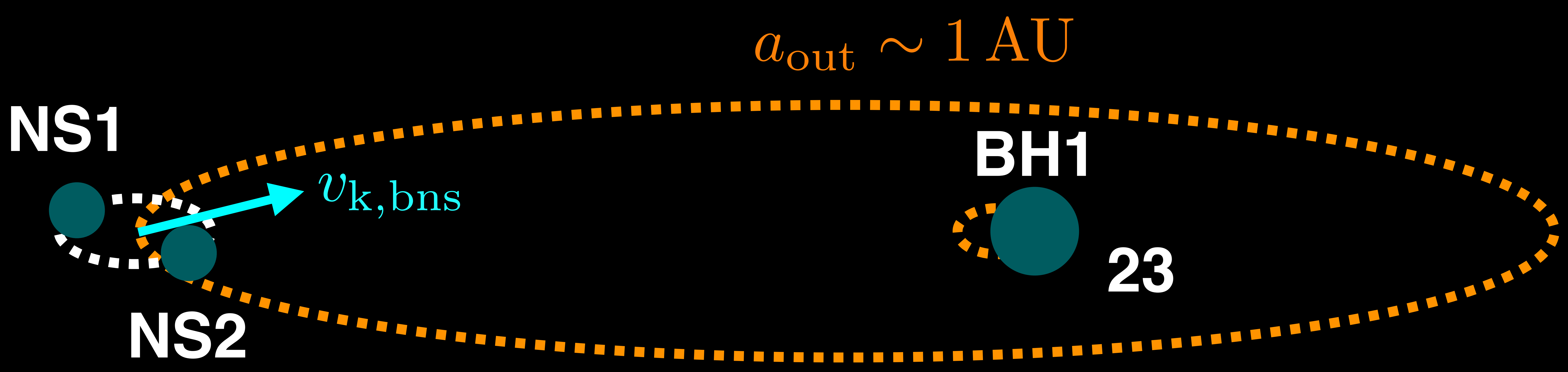


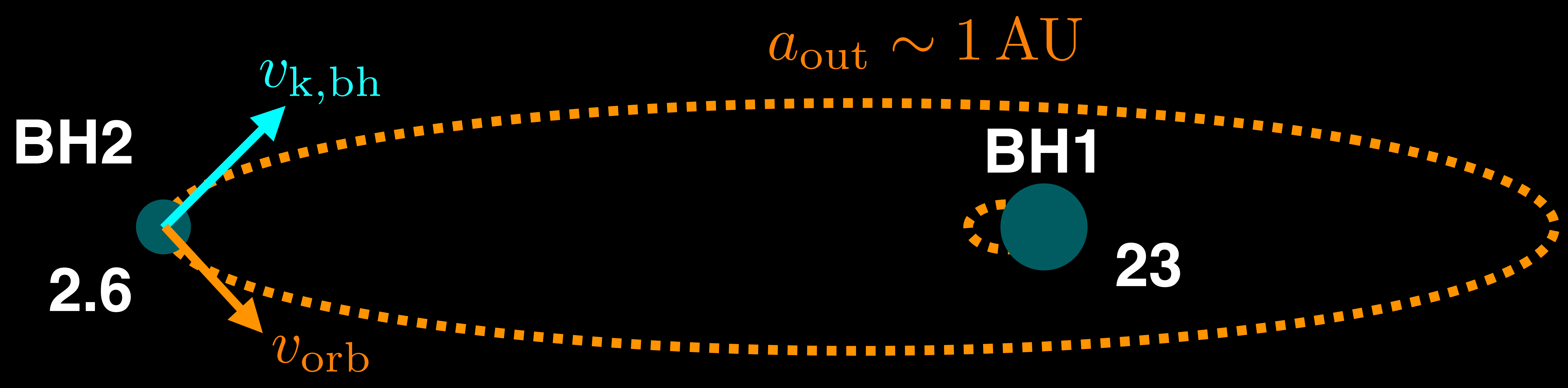
natal kick (ultra-striped SN)

$$v_{\rm k} \lesssim 50\,{\rm km/s}$$

binary center-of-mass kick

$v_{\rm k,bns} \lesssim 25\,{\rm km/s} \ll v_{\rm orb} \sim 100\,{\rm km/s}$ **outer orbit mildly affected**

A Practical Triple Model



merger kick

$v_{\mathrm{k,bh}} \sim 100\,\mathrm{km/s} \sim \mathrm{v_{orb}}$ ➡ **outer orbit strongly perturbed**

Q: Is Large $f_{\rm triple}$ Allowed?

Observation: none of the ~20 Galactic BNS systems are in triples!

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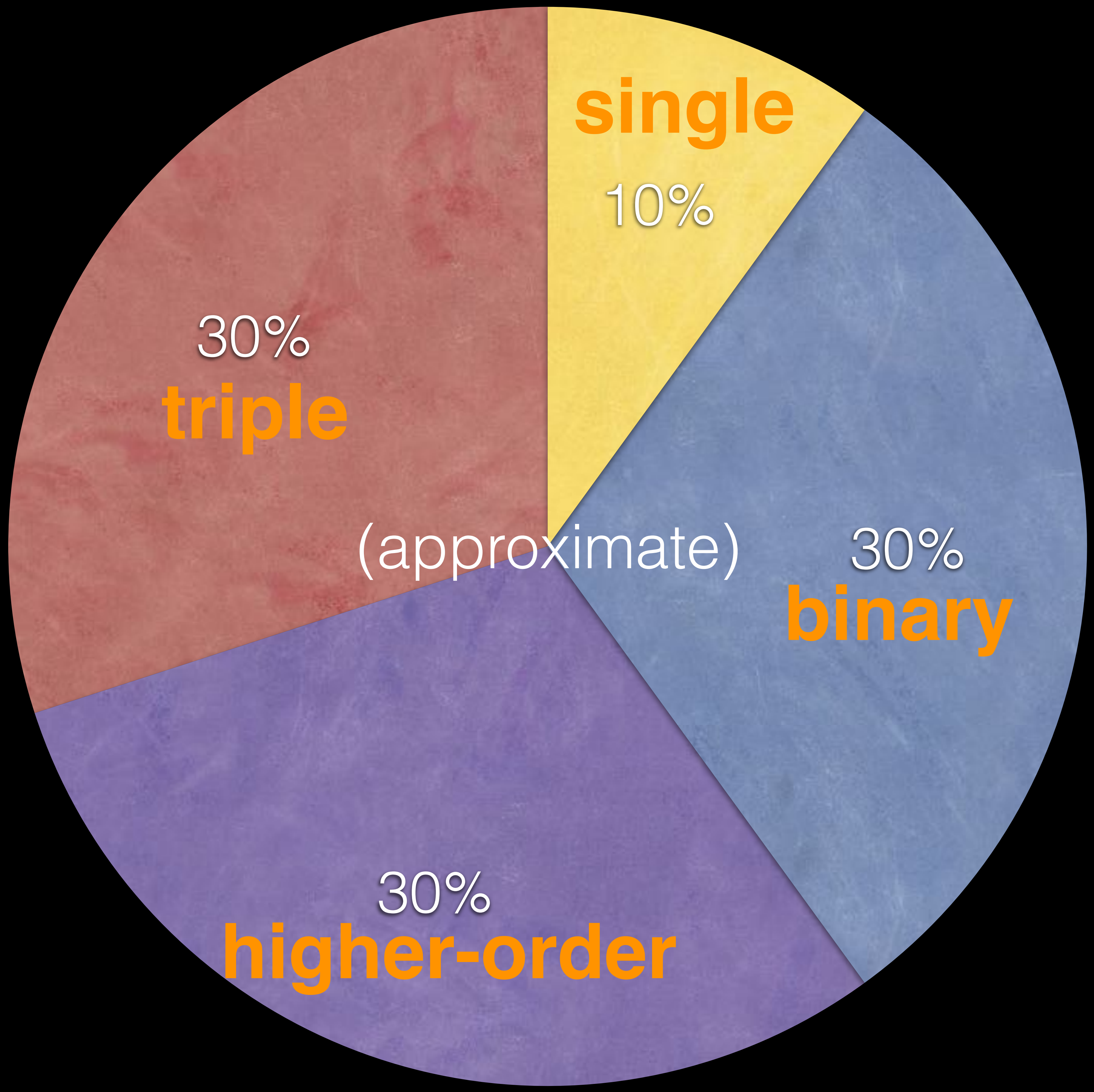


Massive Stars (Moe & Di Stefano 2017)

~2/3 of them must have lost the tertiary

High-Z

envelope expansion

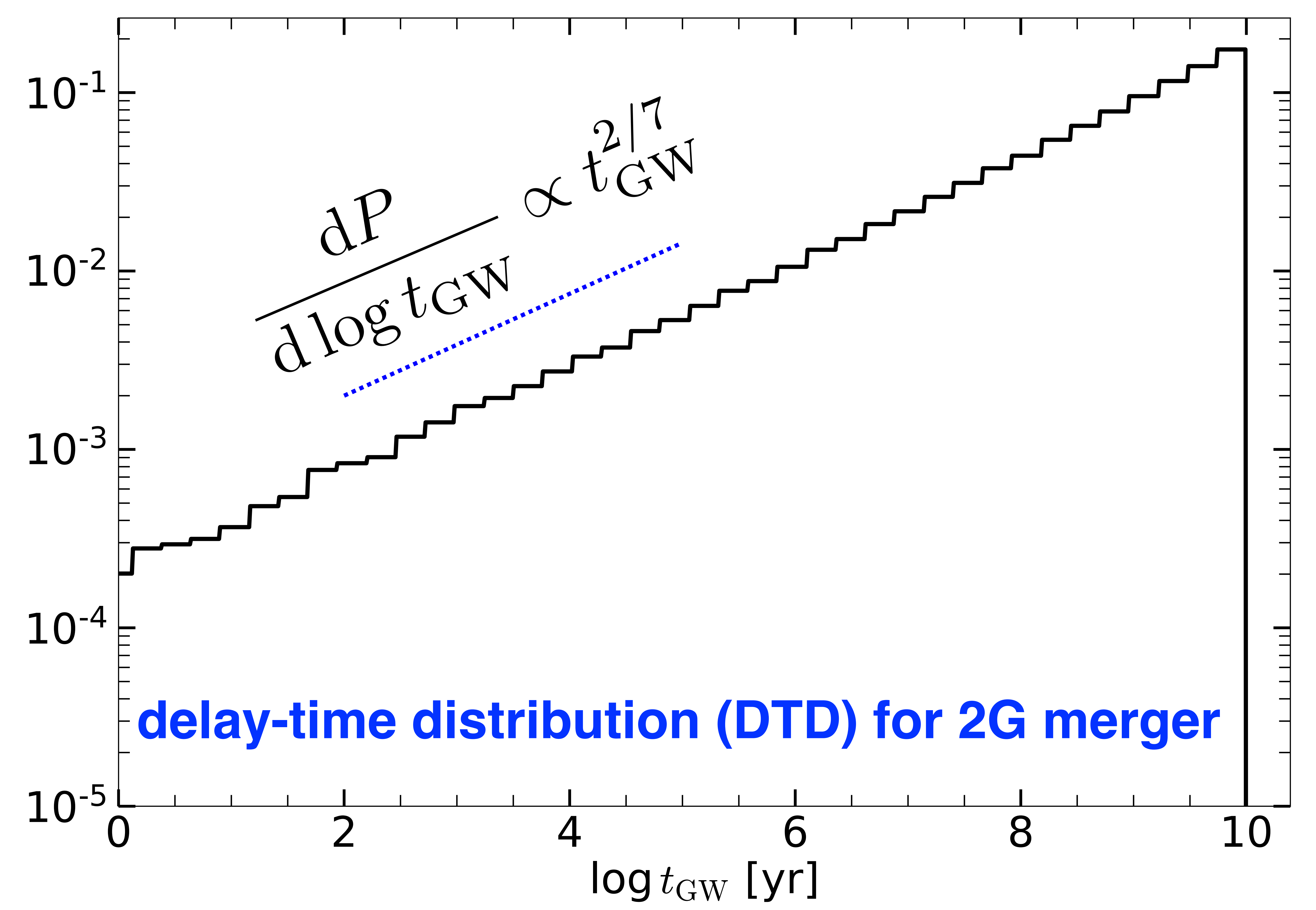
wind mass loss

wider separation
lower mass compact objects
faster natal kicks

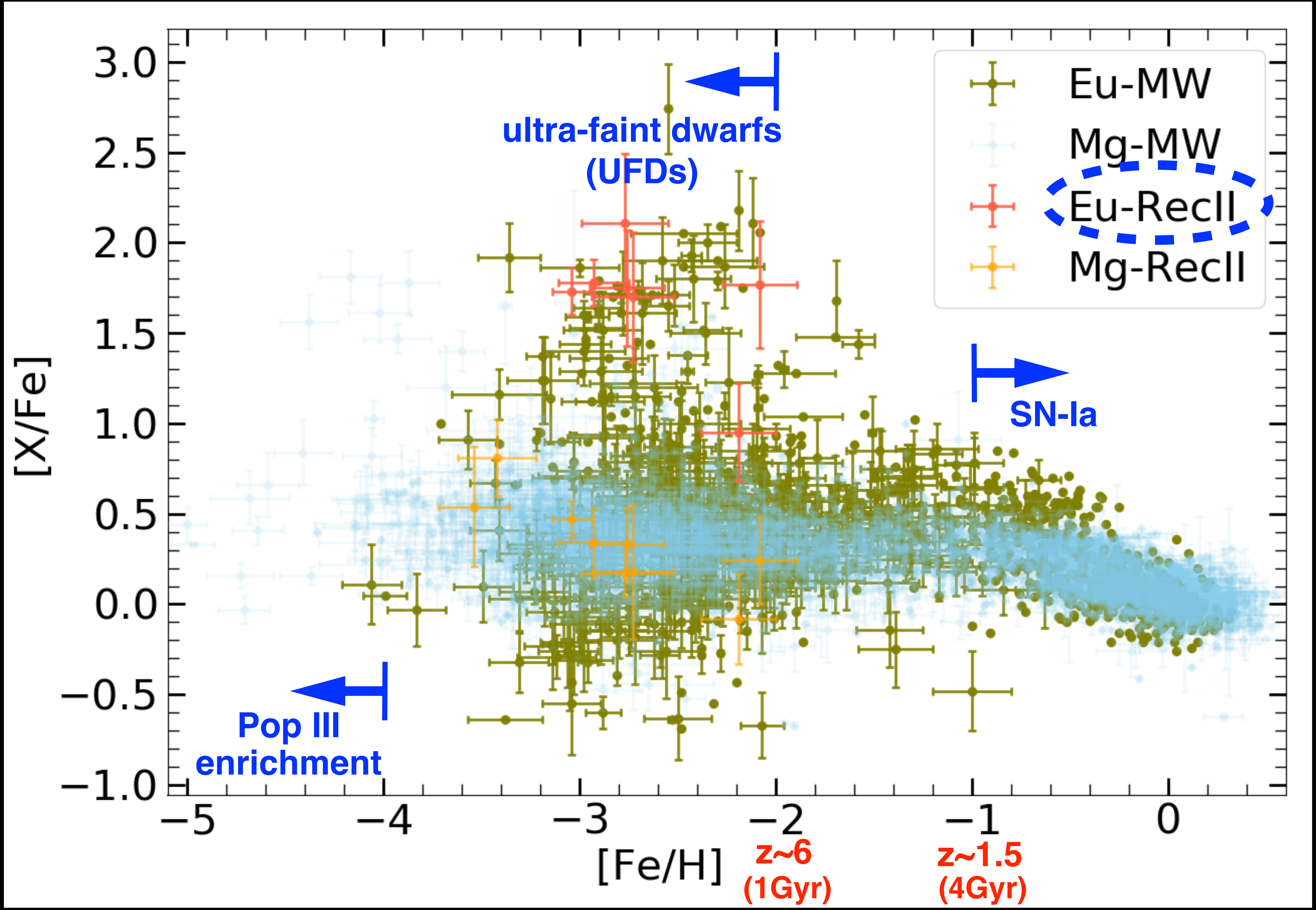
Q: Is Large $f_{\rm triple}$ Allowed?

Observation: none of the ~20 Galactic BNS systems are in triples!

Solution: **low-Z triples** in the early Universe (Initially suggested by Shri)



BNS mergers many Gyr ago



r-process enrichment history

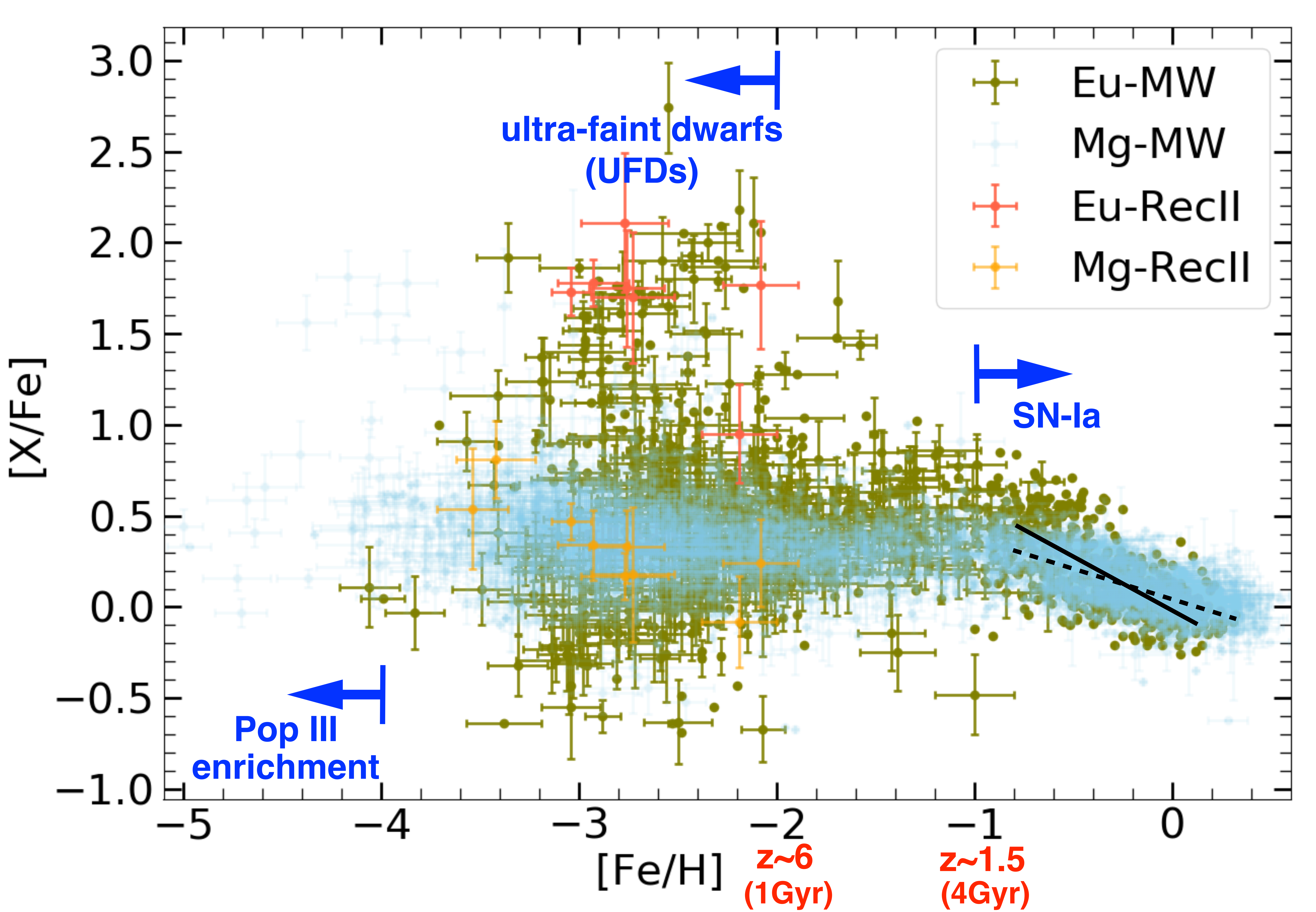
(A)

UFD enrichment

(i) Rapid (<Gyr) BNS mergers

(ii) Triples help retain BNS

Some BNS mergers > 6 Gyrs ago



r-process enrichment history

(B)

$\mathcal{R}_{\rm bns}$ **decreases faster than** $\mathcal{R}_{\rm Ia}$

DTD steeper than t^{-1}

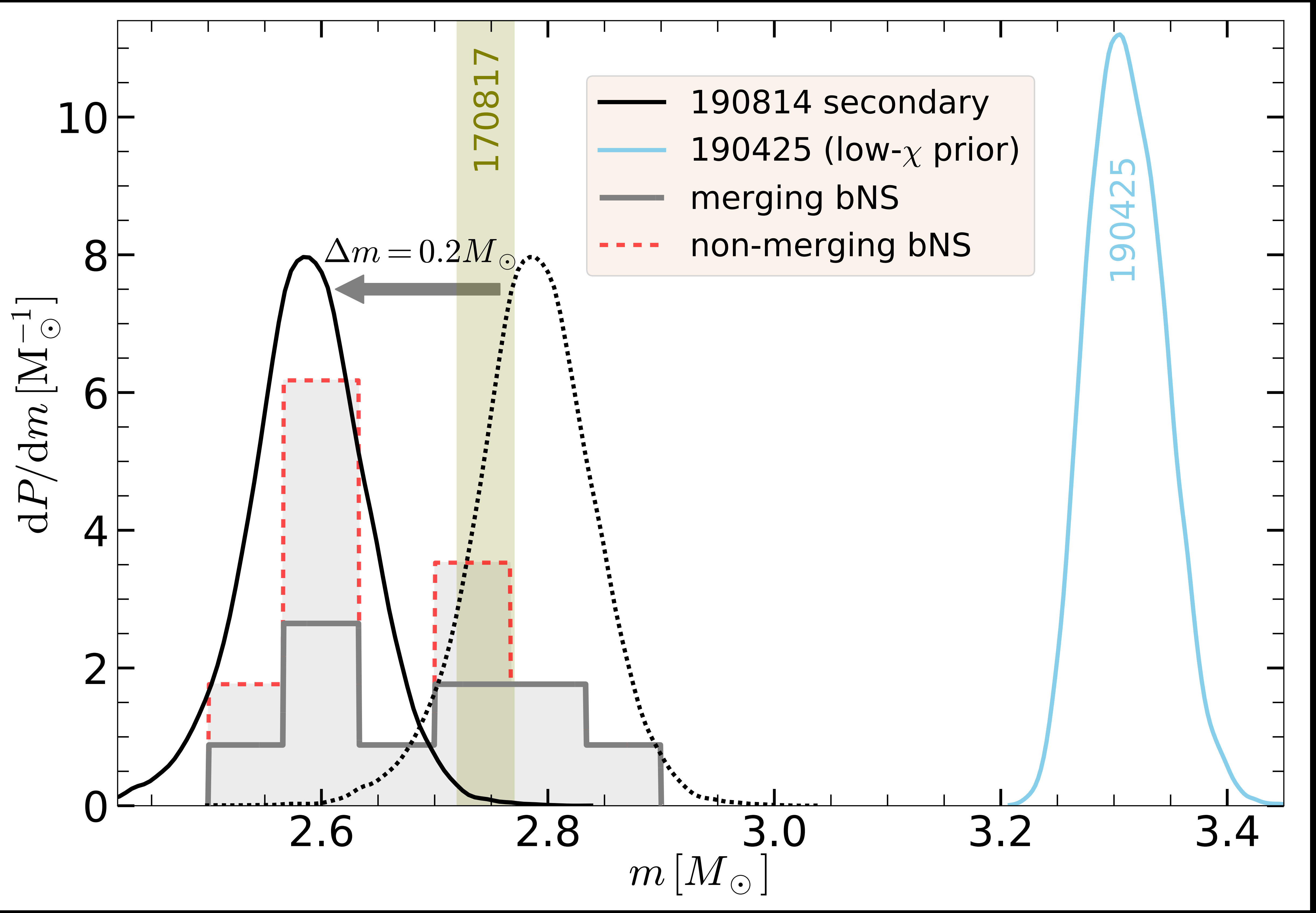
Large fraction of BNS mergers occurred many Gyrs ago

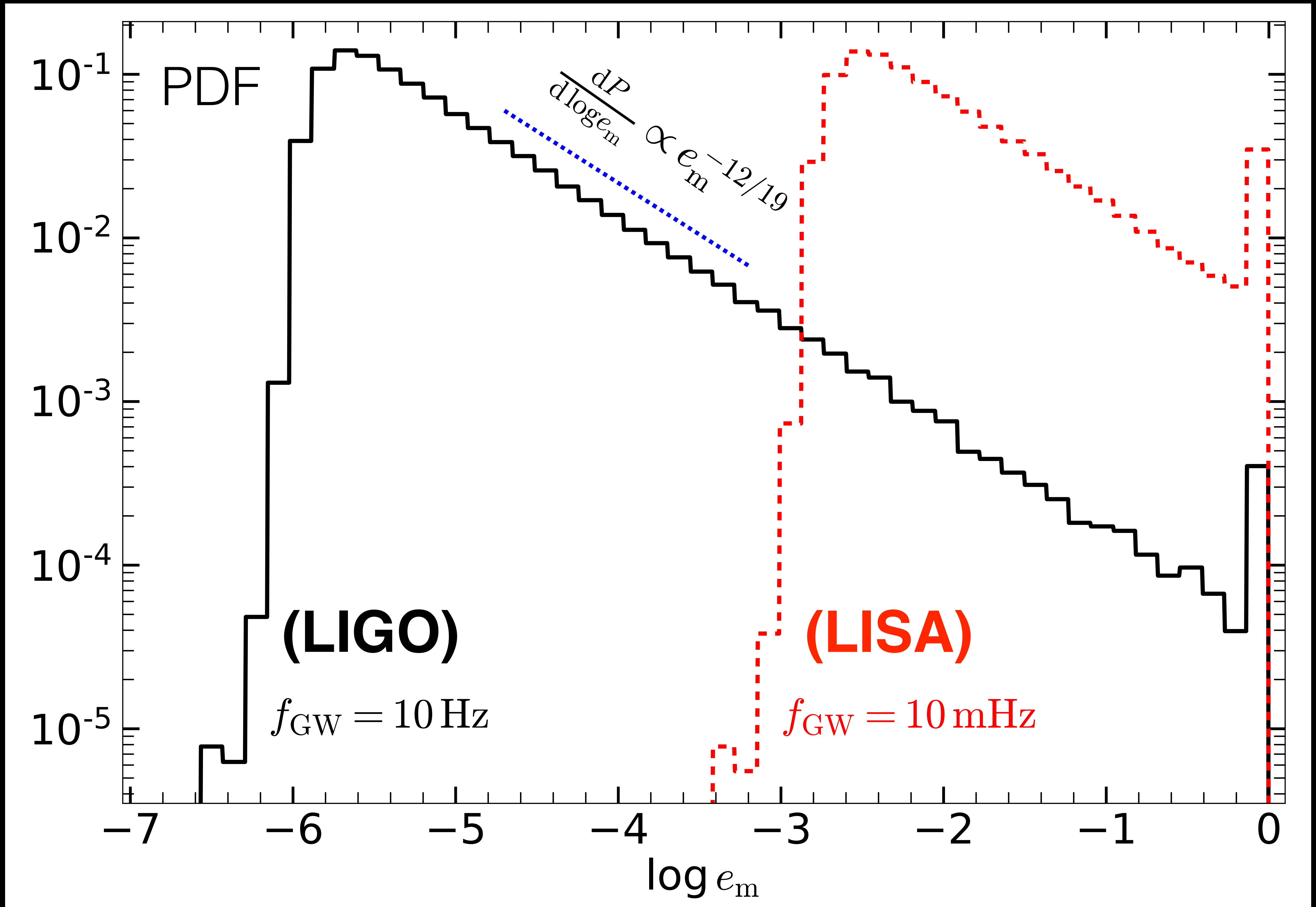
Predictions

GW190814-like Future Events

- **Spin** of secondary: **0.6 ~ 0.7**
- **Mass** of secondary: **2.5 ~ 2.8 (but up to 3.4)**
- **Eccentricity**: $e \sim 10^{-2.5}$ in LISA band

- 10^5 **triple BNS** in the Milky Way
- **GW phase perturbation** by tertiary in BNS mergers





Summary

- GW190814 consistent with 2G merger from low-Z triple
- Key is the merger kick on remnant BH $v_{\rm k,bh} \sim 100\,{\rm km/s}$
- Requires $f_{\rm triple} \gtrsim 10\%$ of BNS mergers to have a BH tertiary
- Many testable predictions
- (Study low-Z triples!!)

Fin