~Find the Gap~

New Physics and the Black Hole Mass Gap

Samuel D. McDermott

work with Djuna Croon + Jeremy Sakstein: PotDU & 2007.00650 [hep-ph], PRD & 2007.07889 [gr-qc]

&/+ Maria Straight and Eric Baxter: PRL & 2009.01213 [gr-qc]

&/+ Eric Baxter: ApJL & 2104.02685 [astro-ph.CO]

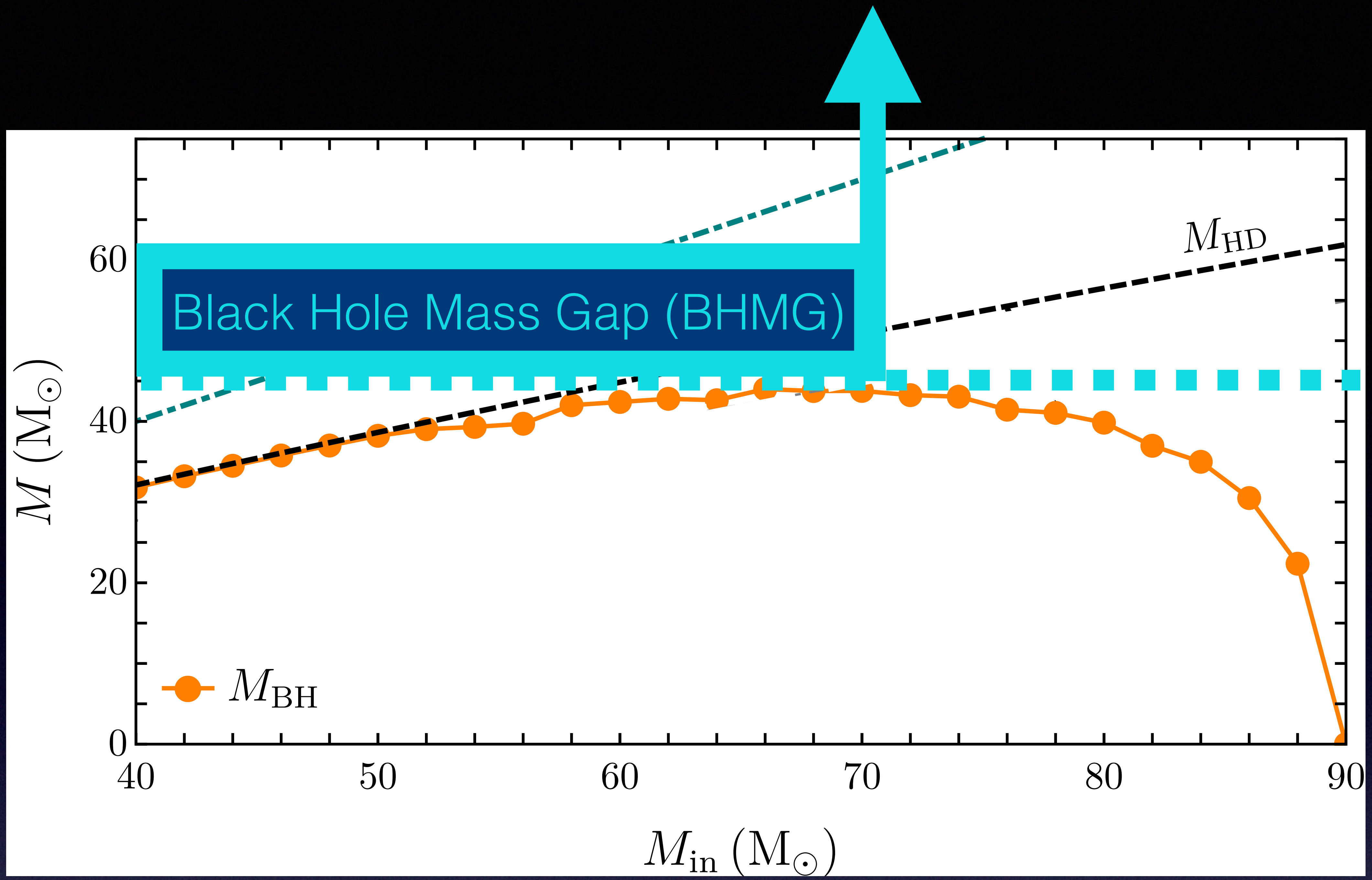
+ code development in progress (email me for updates/release info)

Fermilab

sammcd00@fnal.gov

Sam McDermott

"Find the Gap" 2104.02685/ApJL



$$\frac{dN^{(1g)}}{dM_{BH}} \sim \int d\theta \frac{dN_*}{dM_*}\frac{1}{dM_{BH}(\theta)/dM_*}$$

$$p\left(m_1, m_2 \mid \vec{\theta}\right) \propto \frac{dN^{(1g)}}{dM_{BH}} + \lambda \frac{dN^{(2g)}}{dM_{BH}}$$

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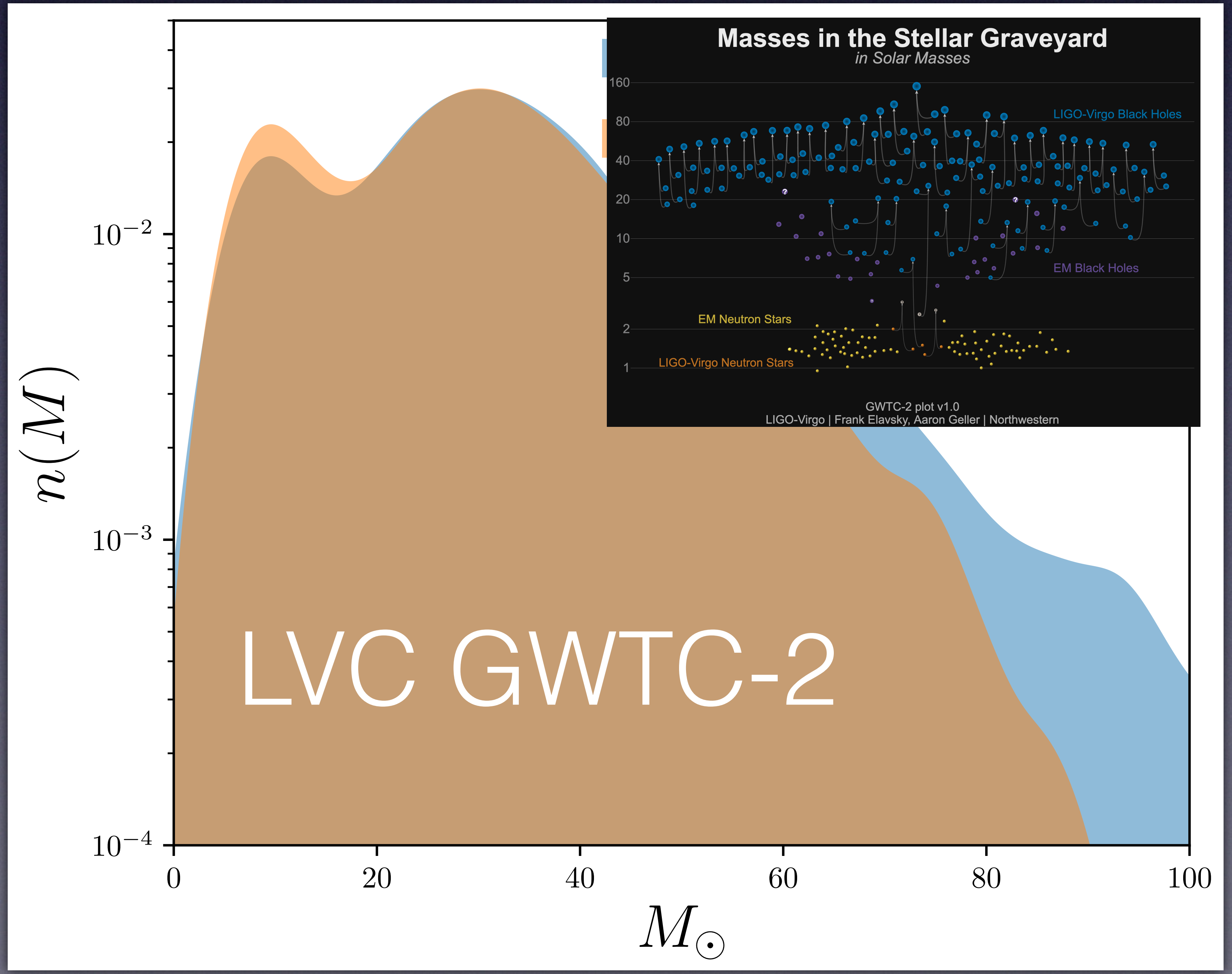

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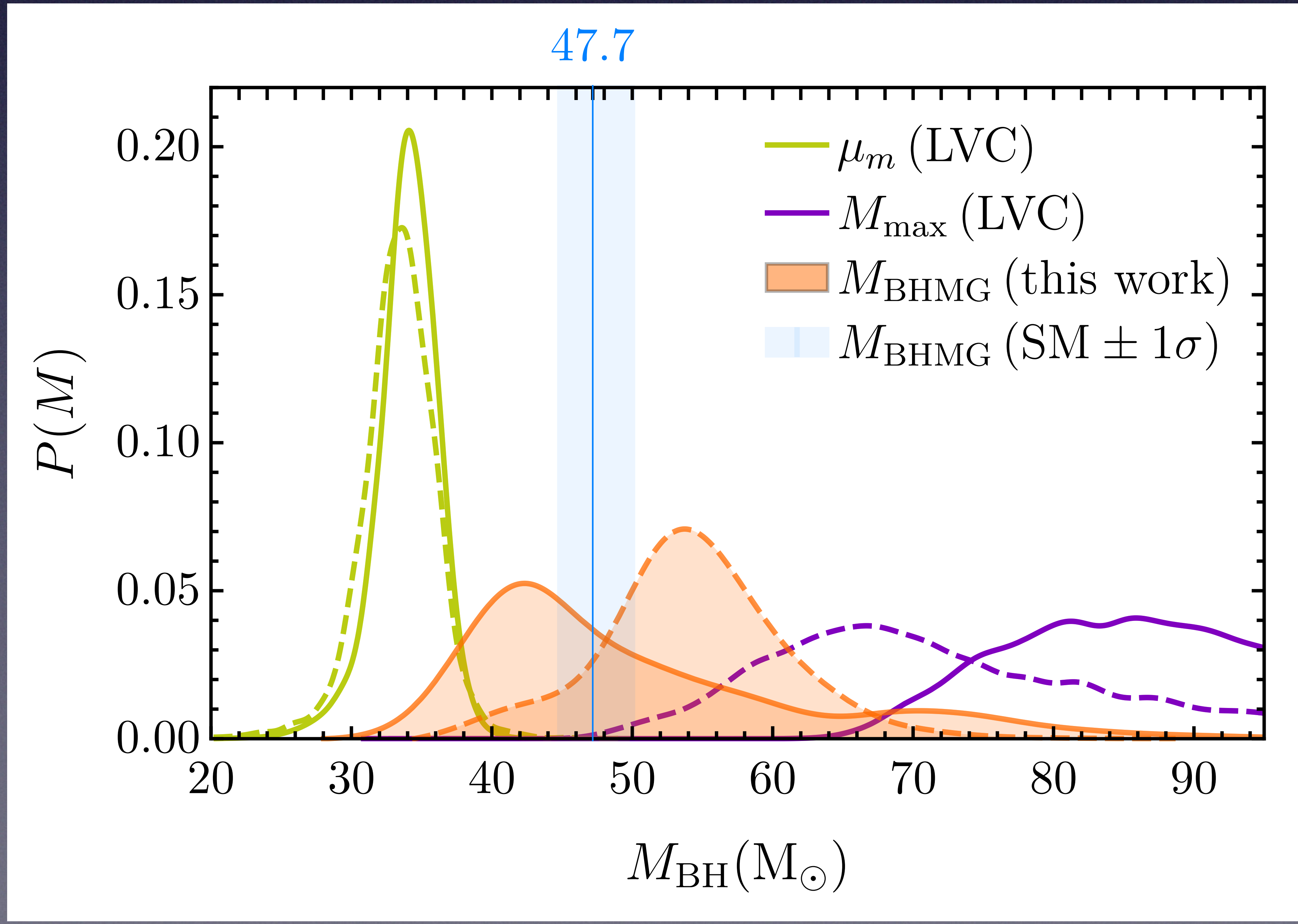

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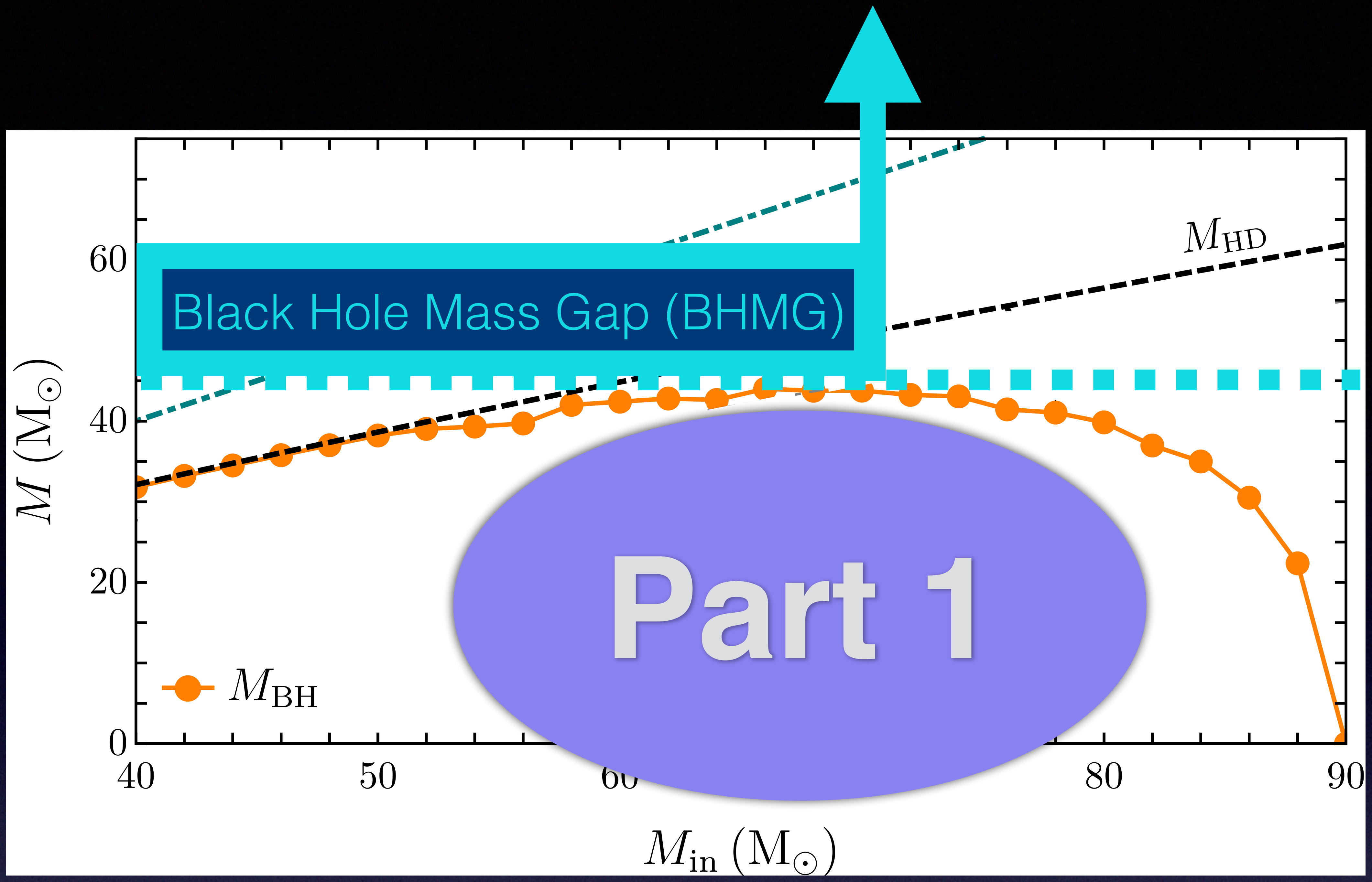

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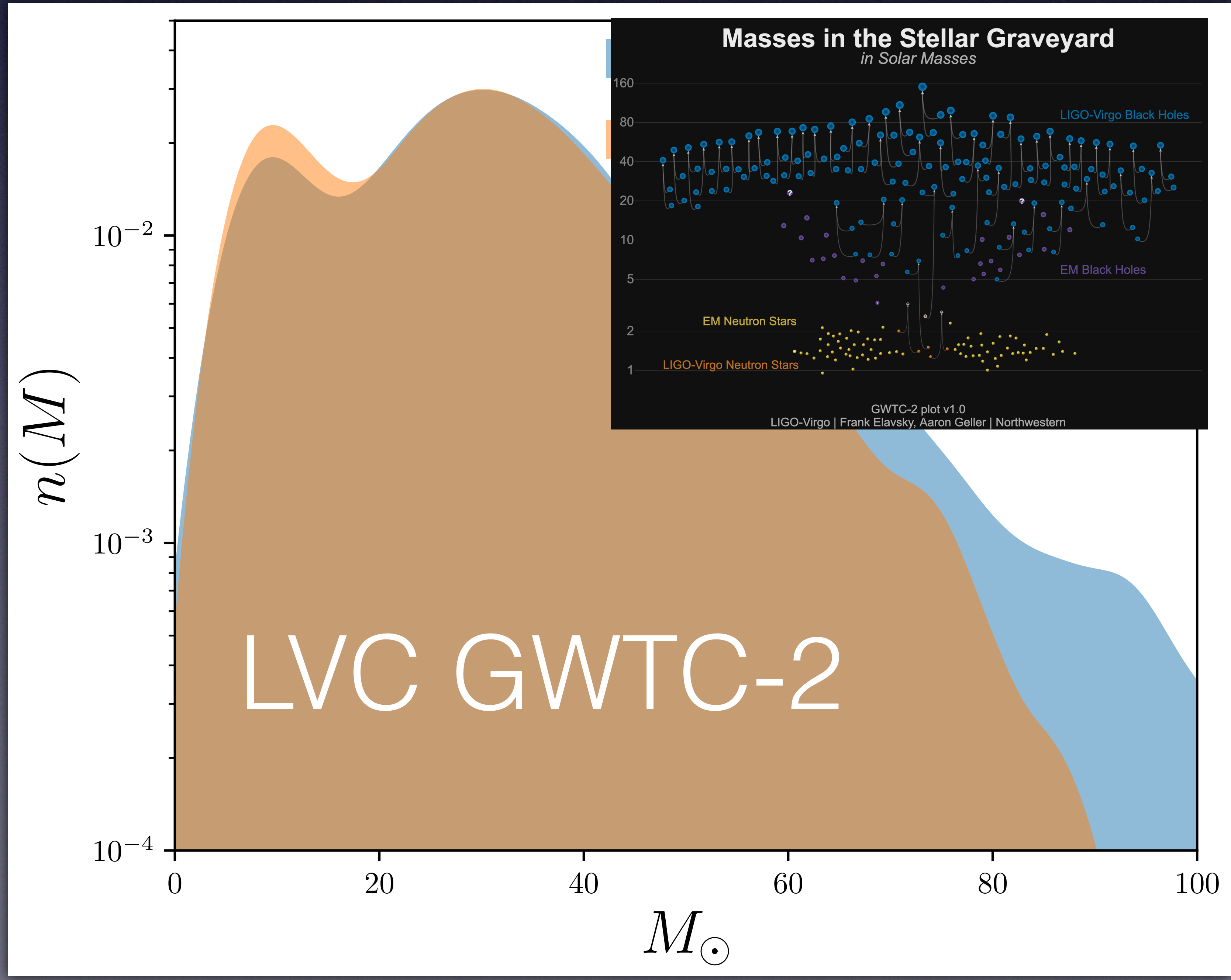

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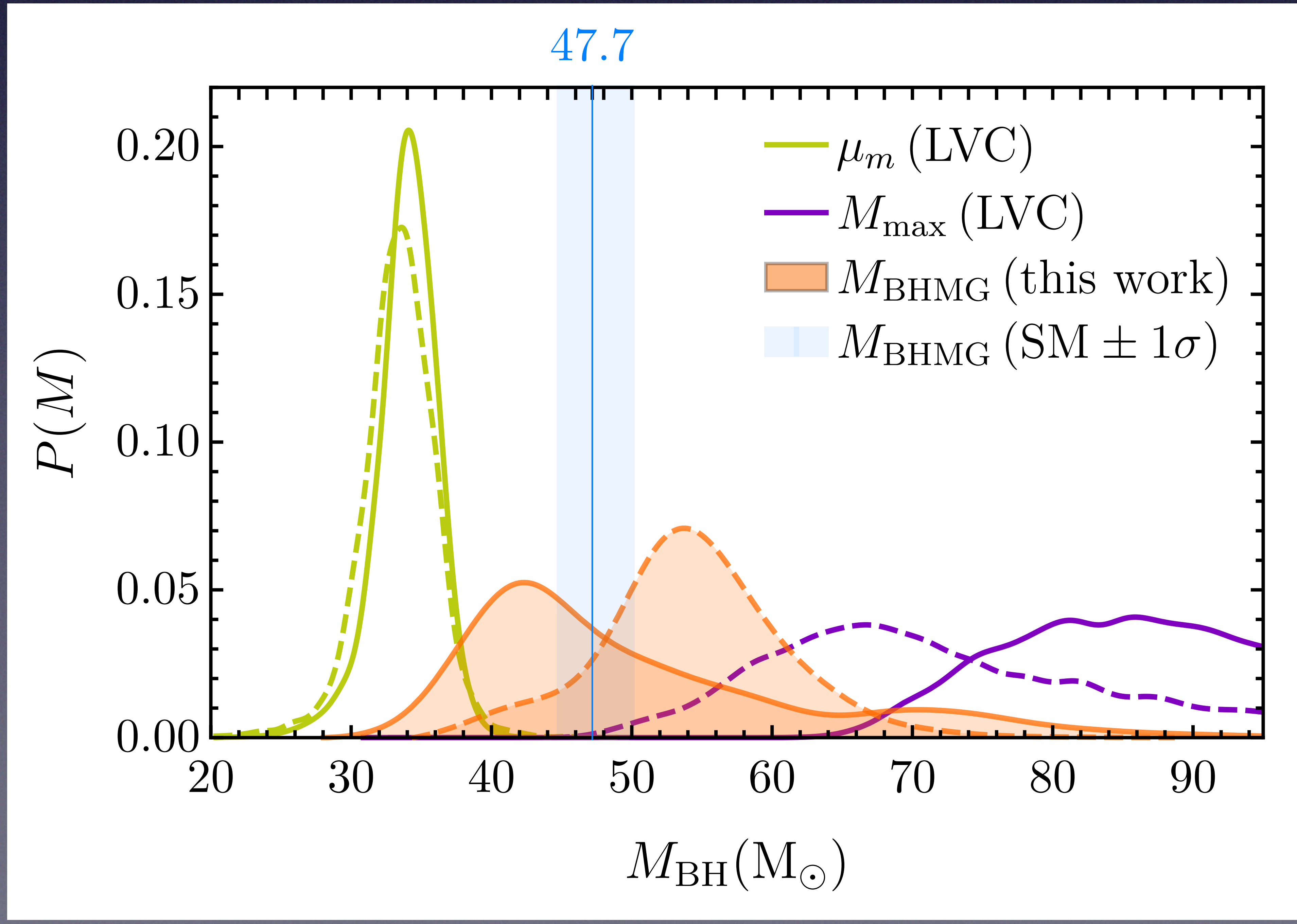

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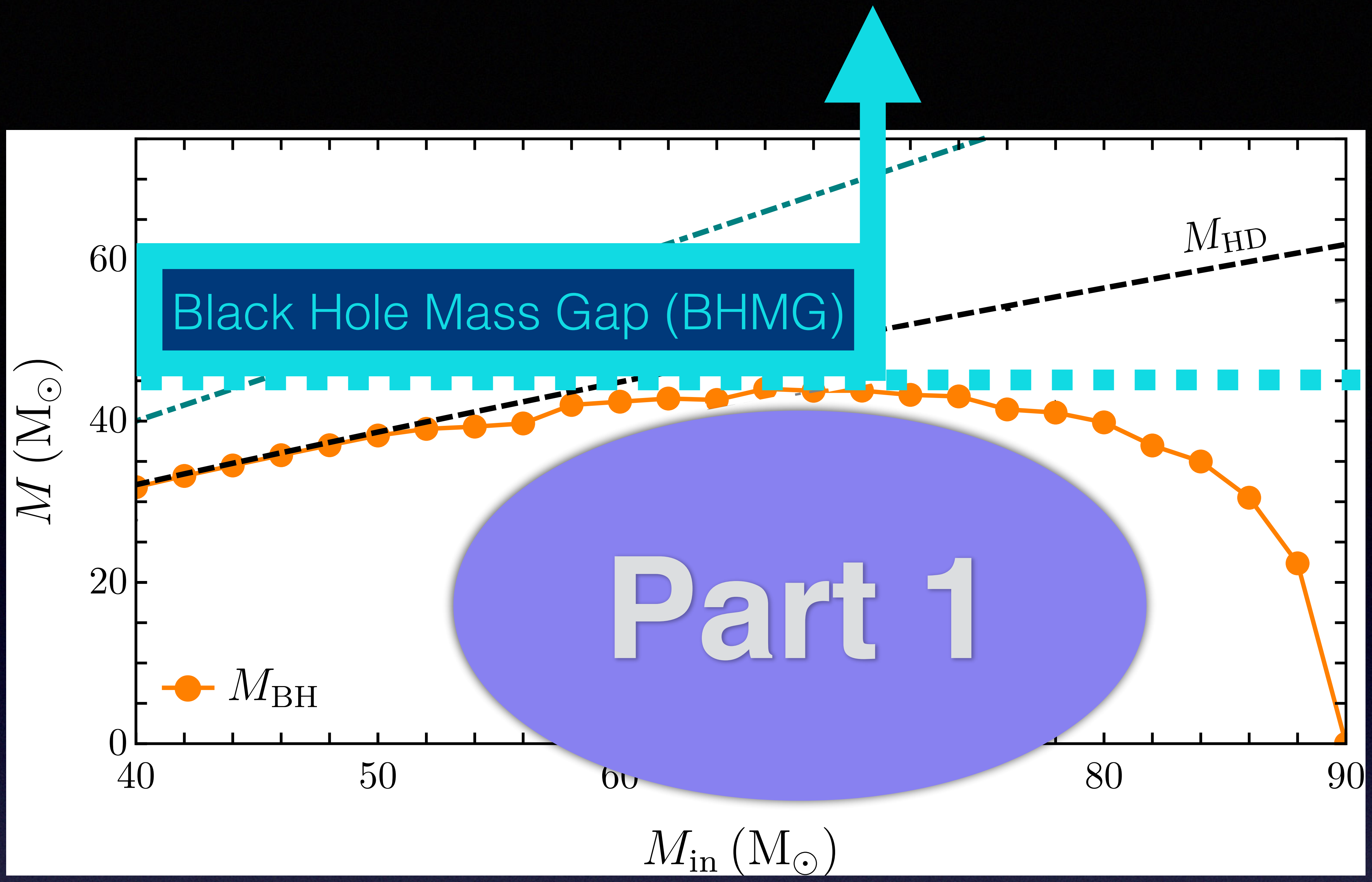

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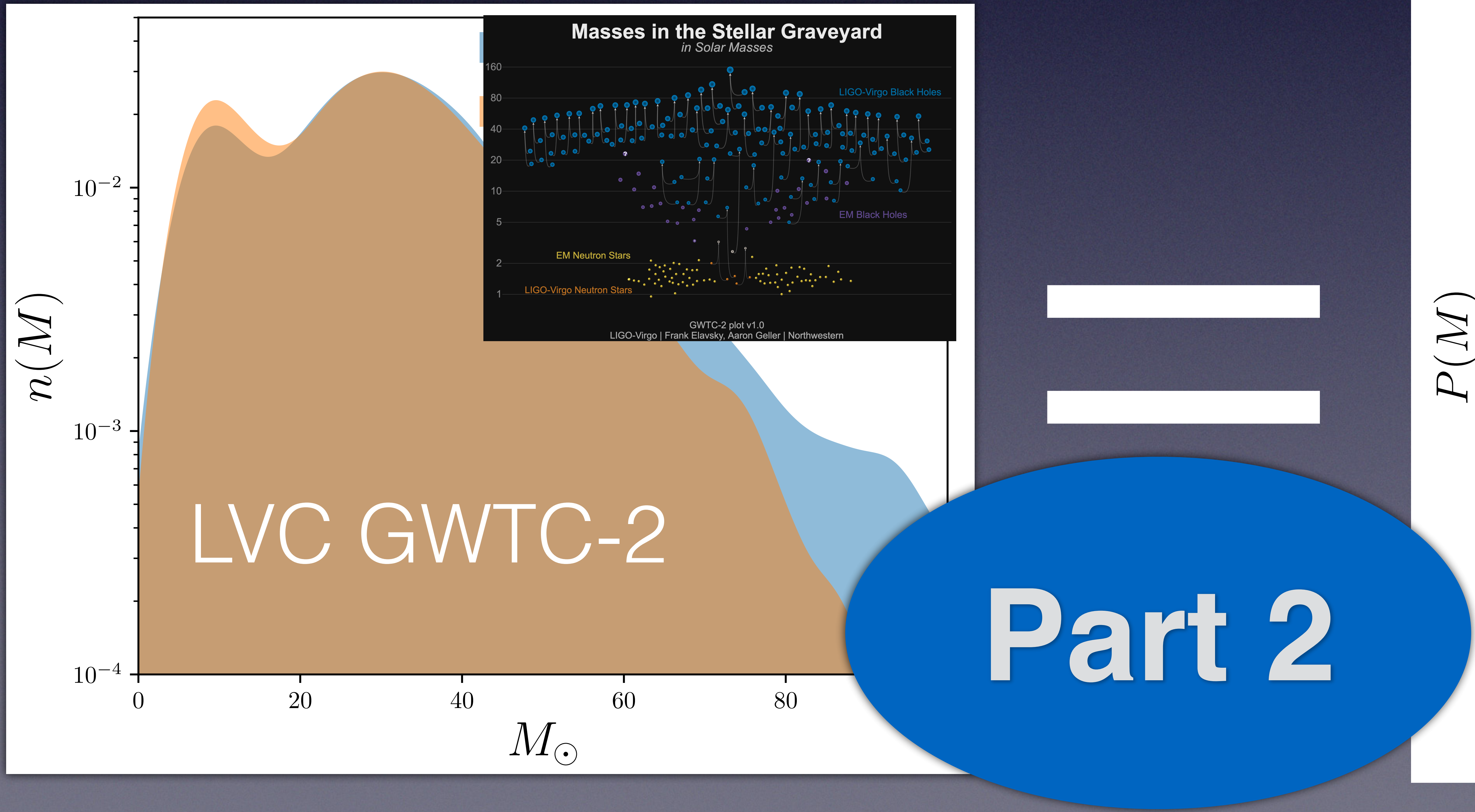

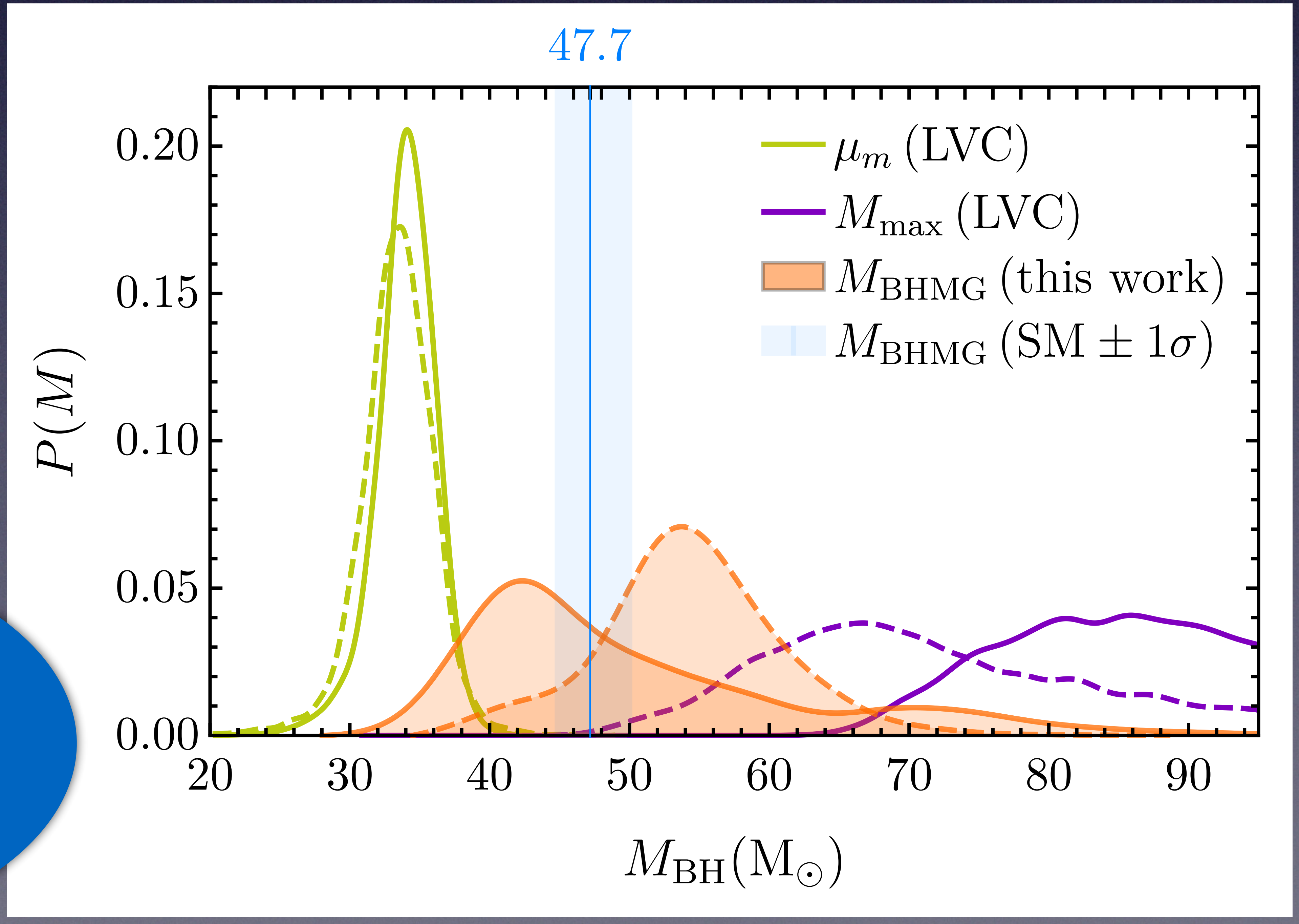

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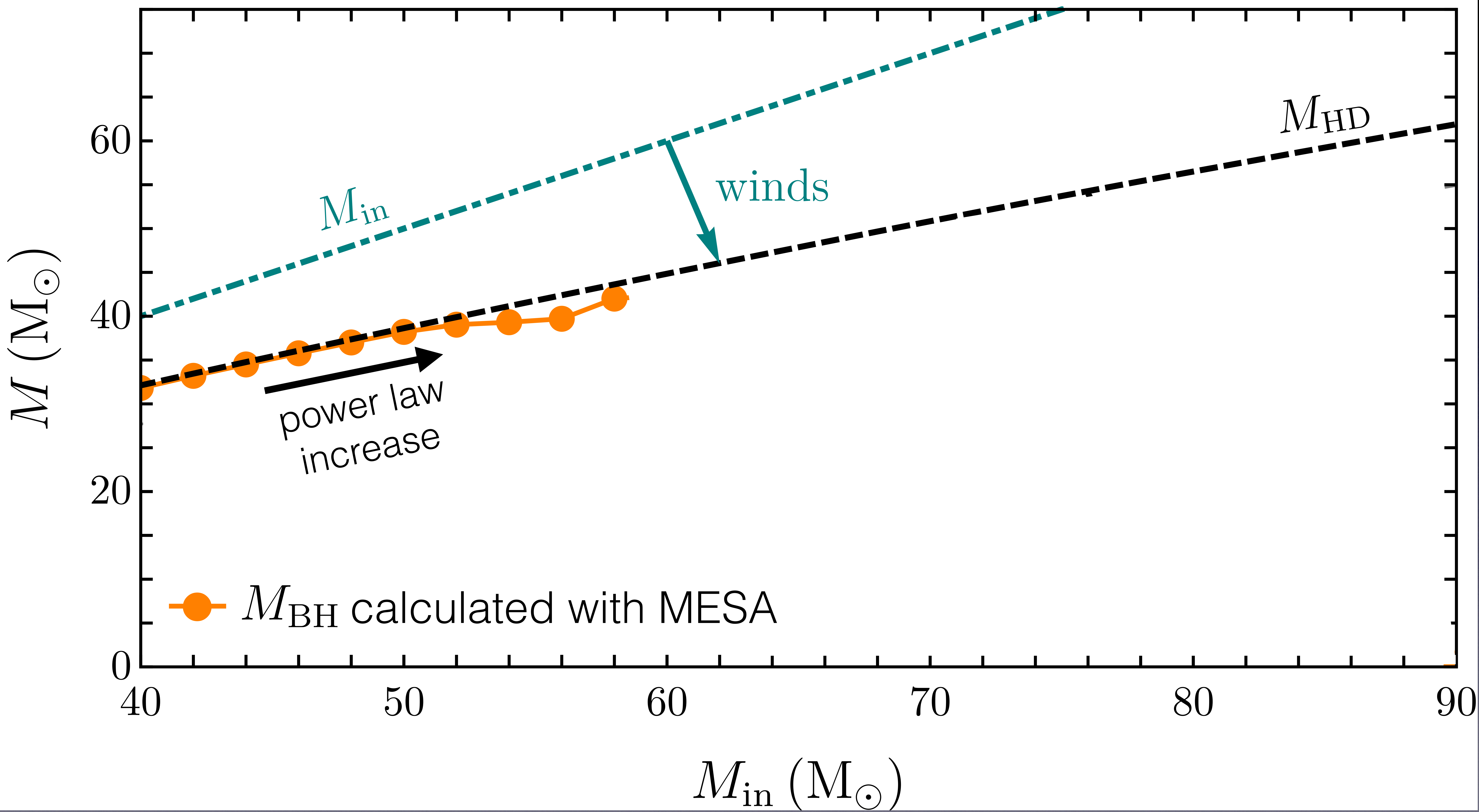
PRD & 2007.07889



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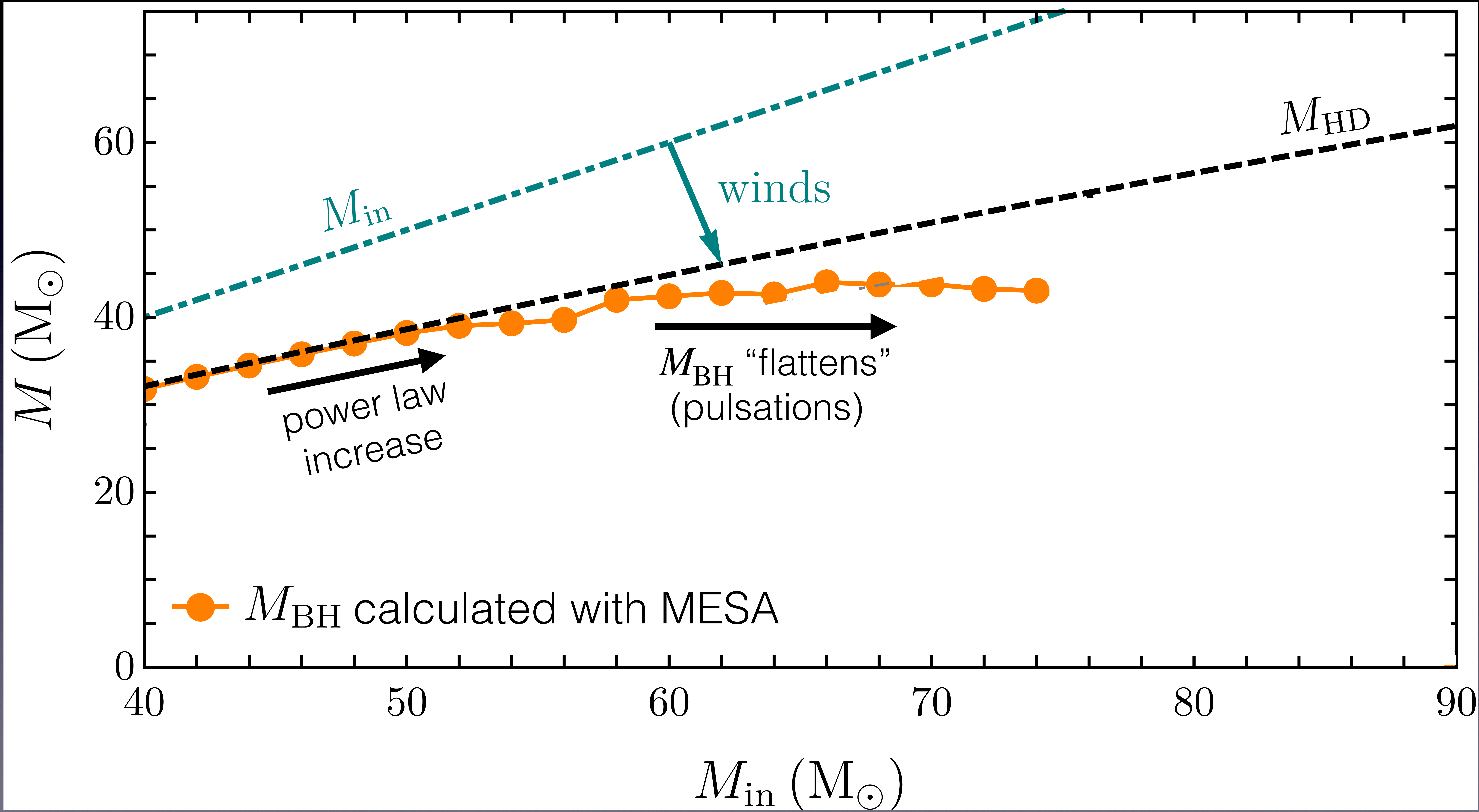

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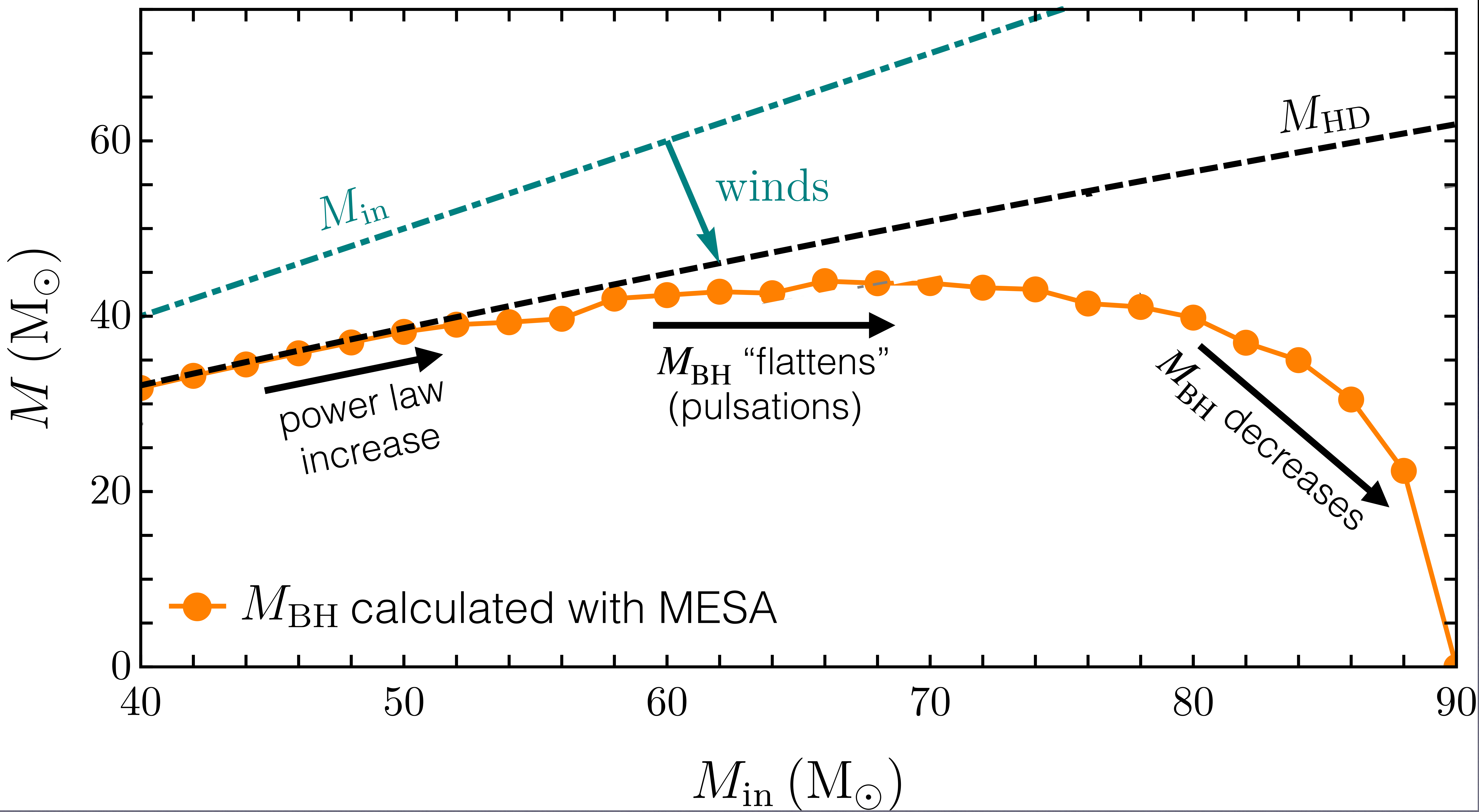

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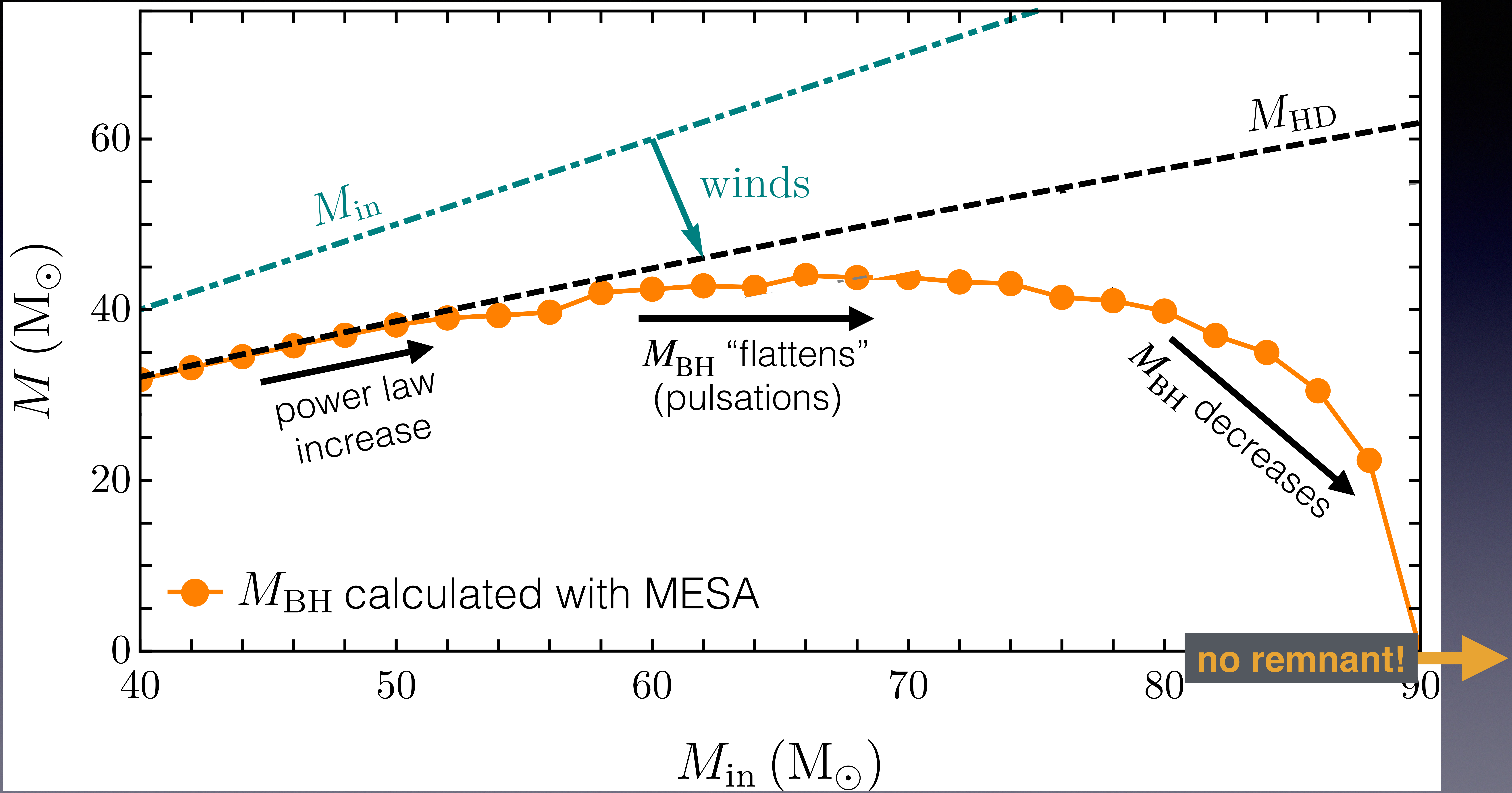

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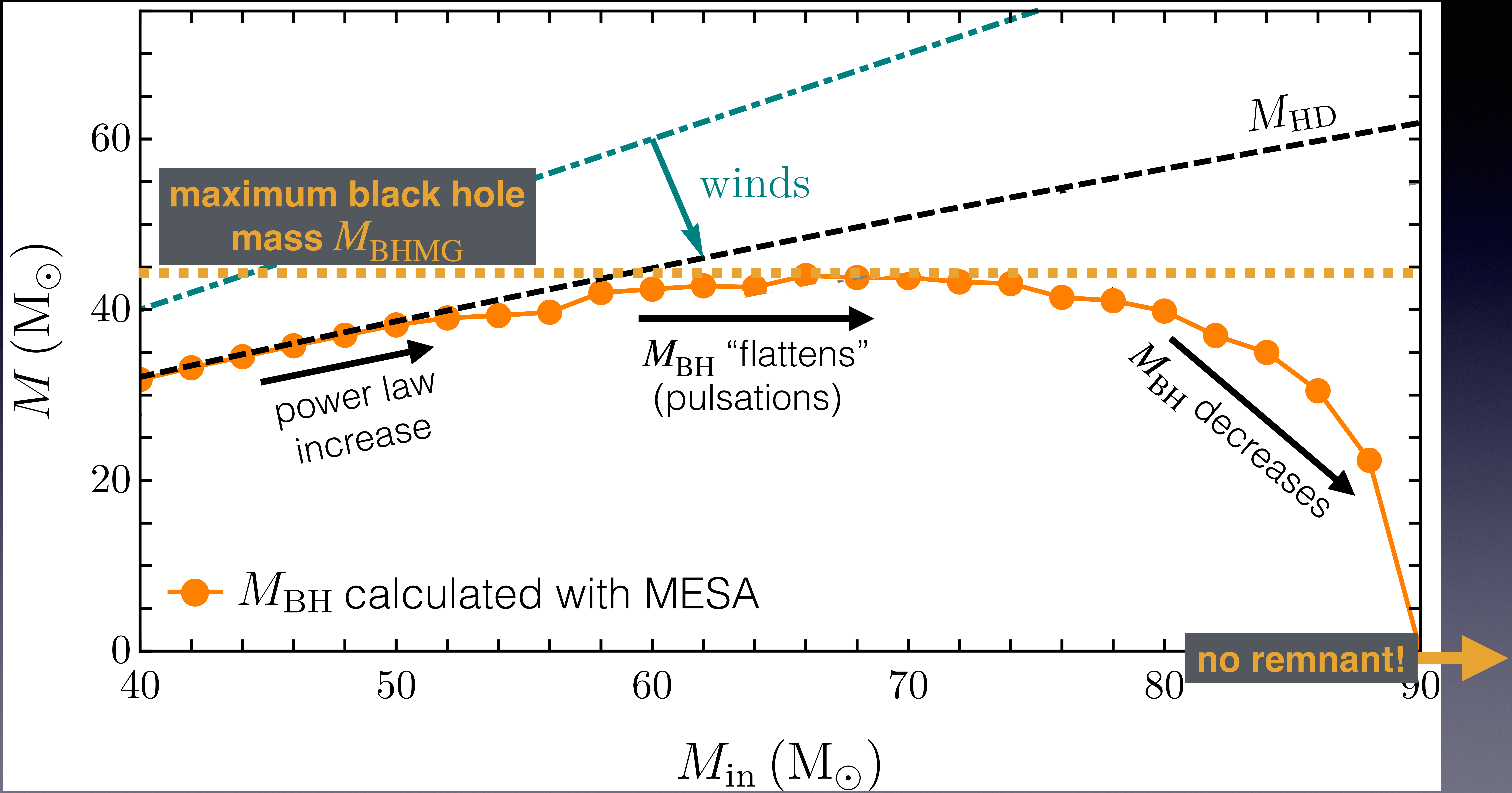

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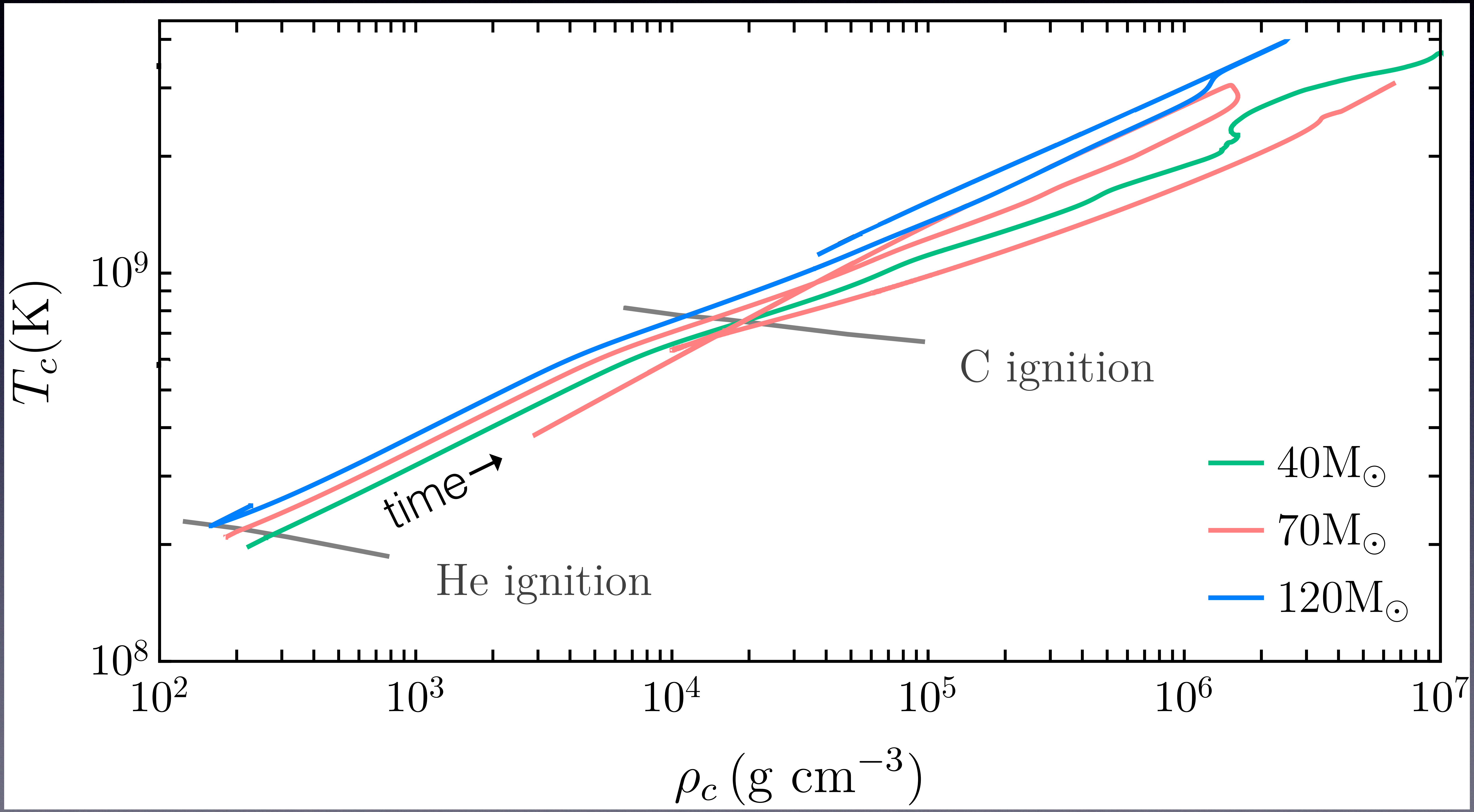
Evolution* of Pop III Stars



*MESA v12778 Paxton et al, arXiv:1710.08424 [astro-ph.SR]

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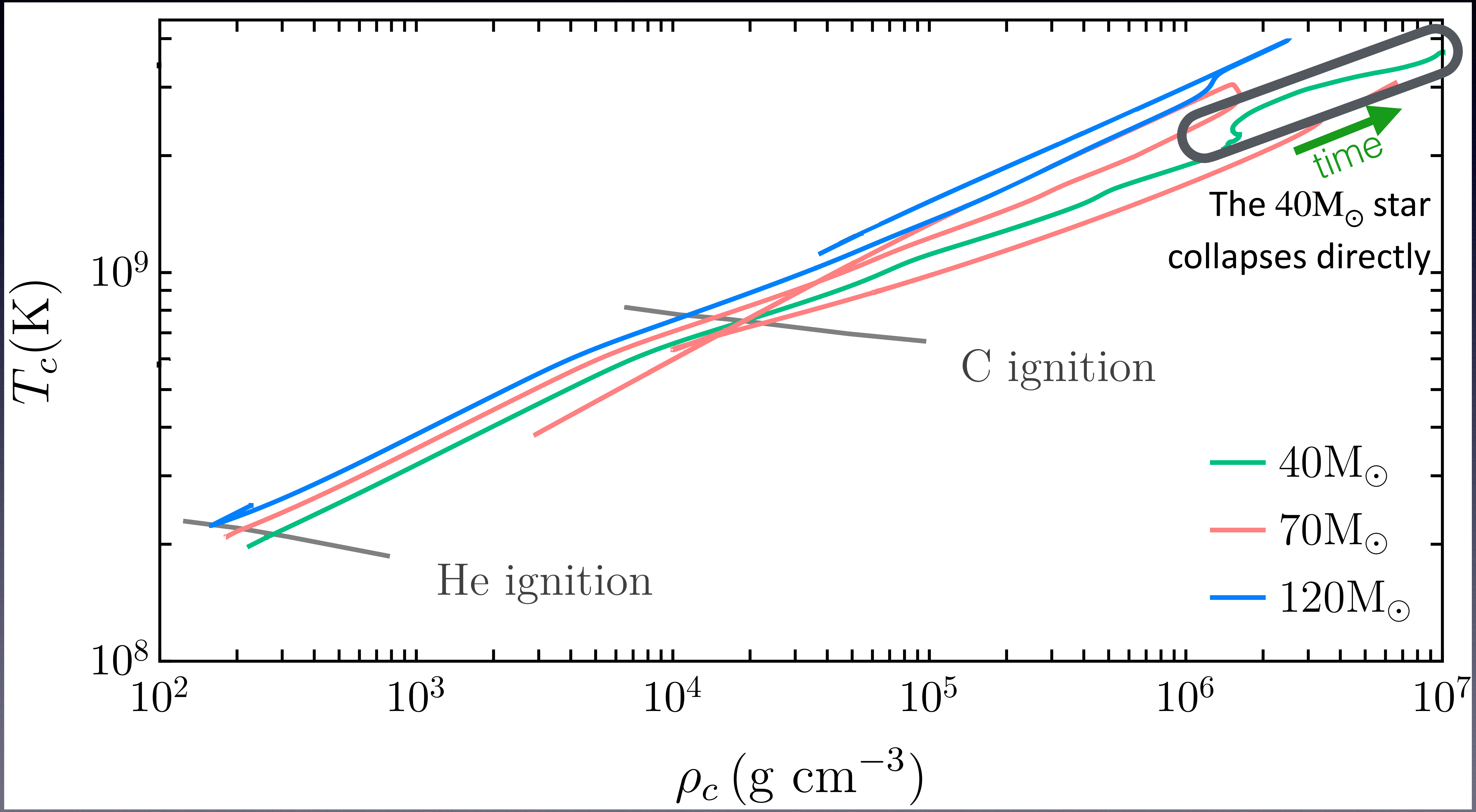

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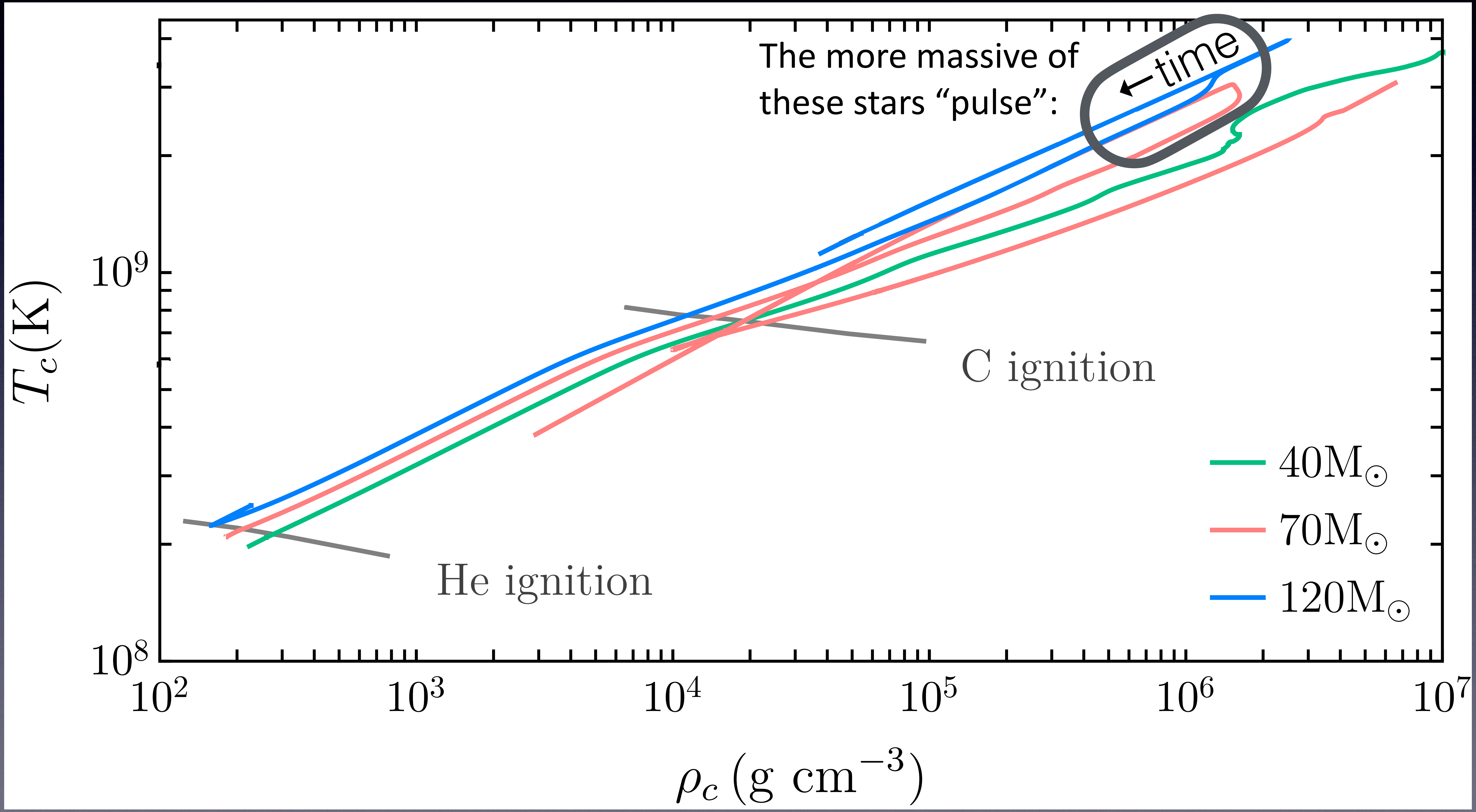

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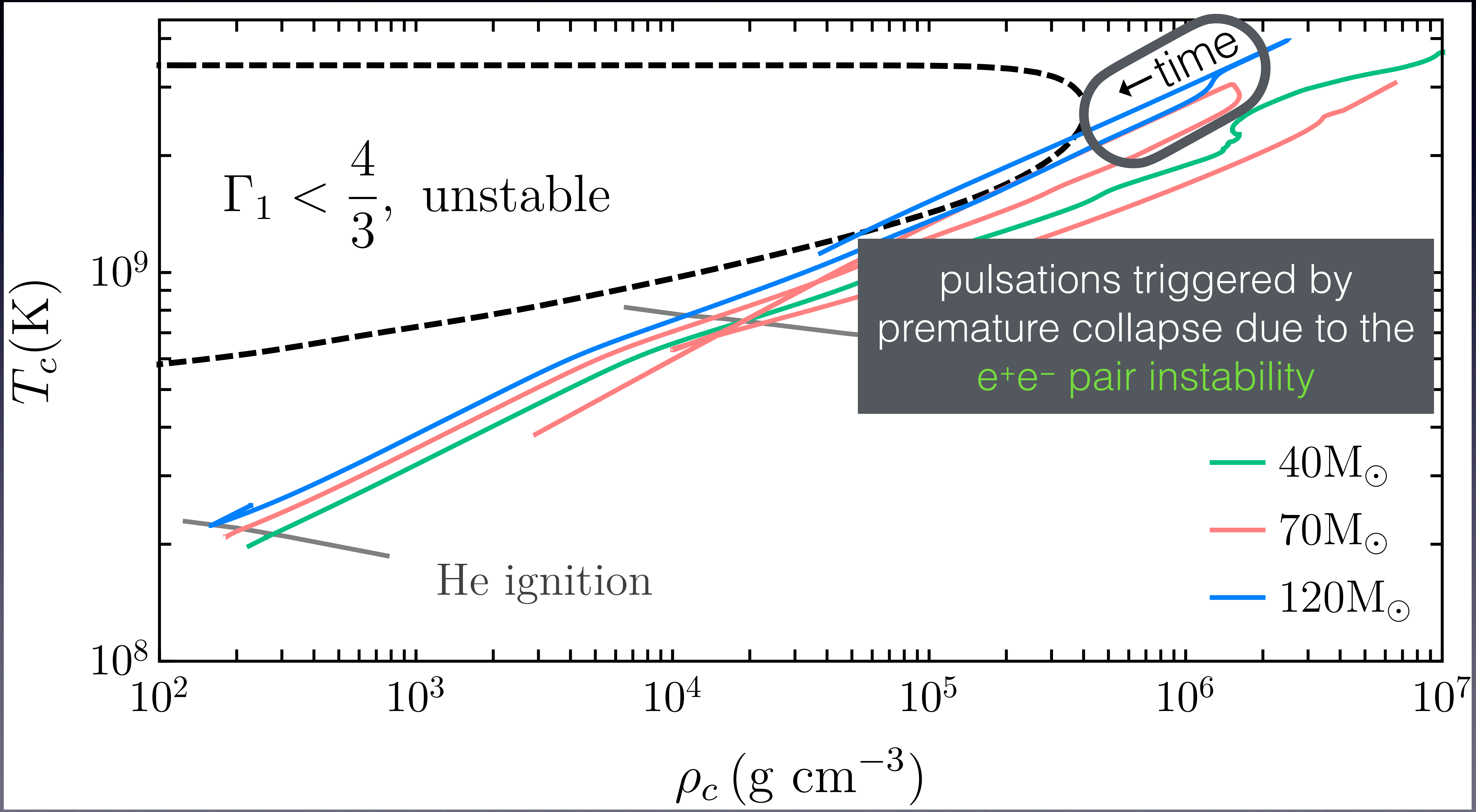
(Pulsational) Pair Instability



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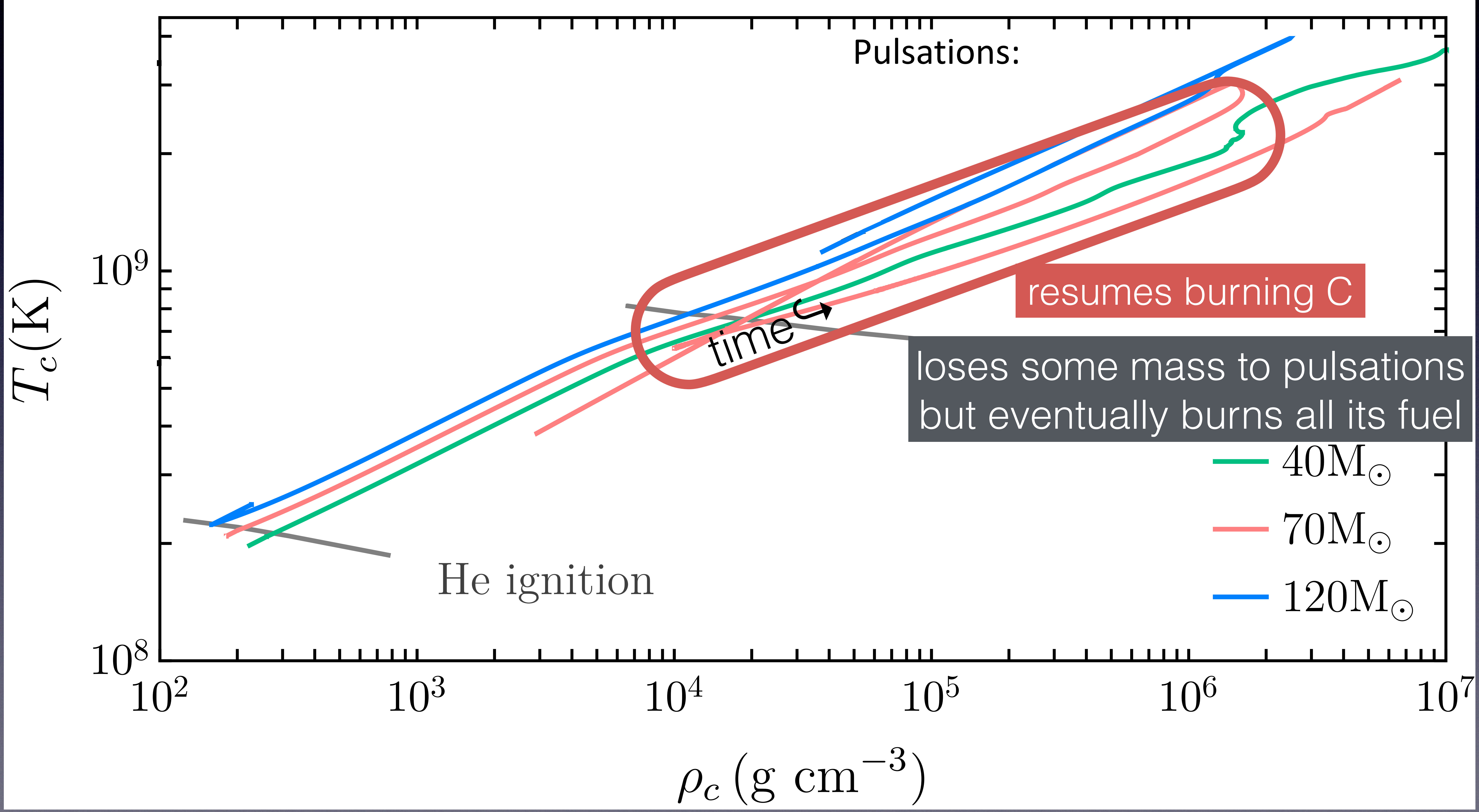
Outcome of Pulsations



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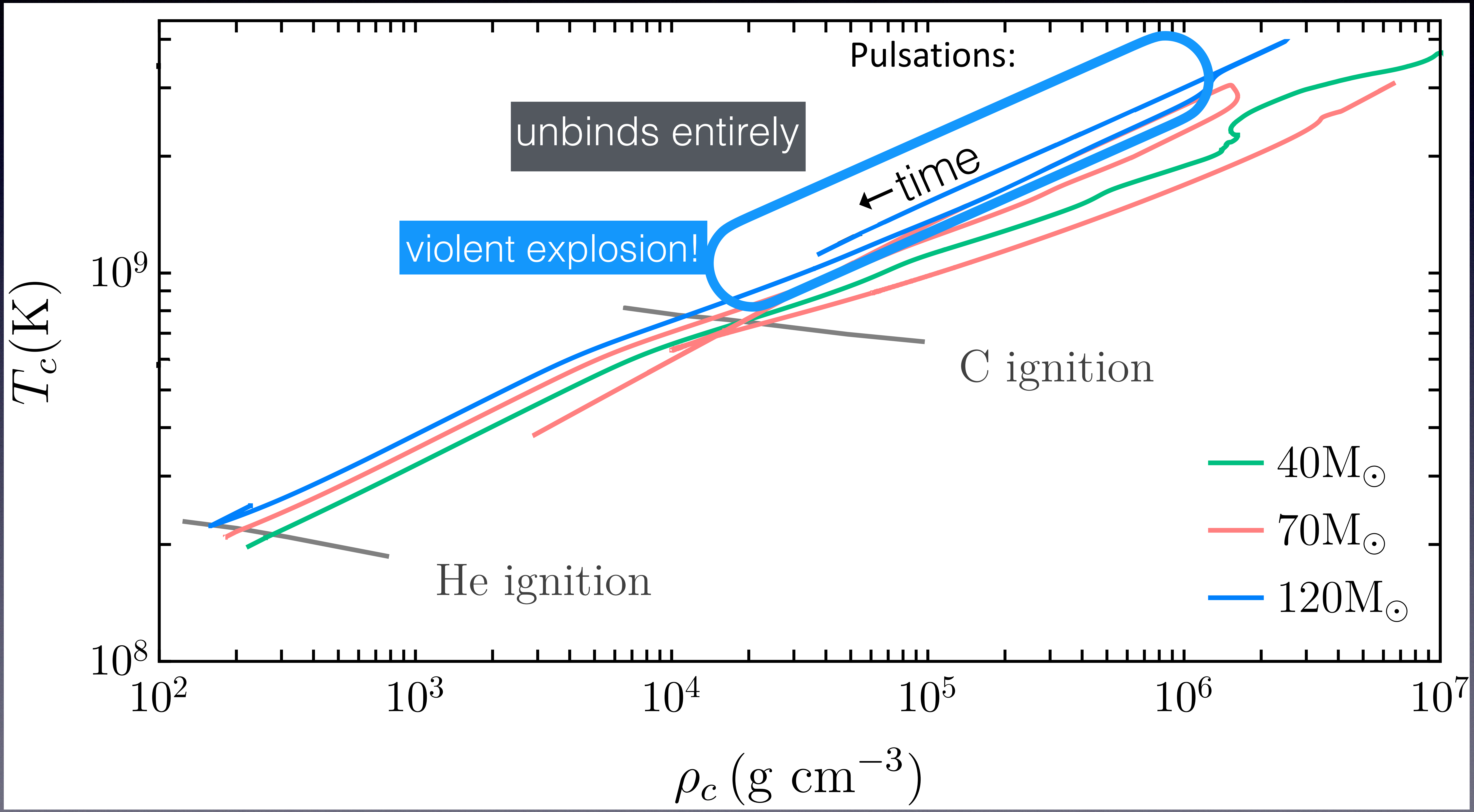

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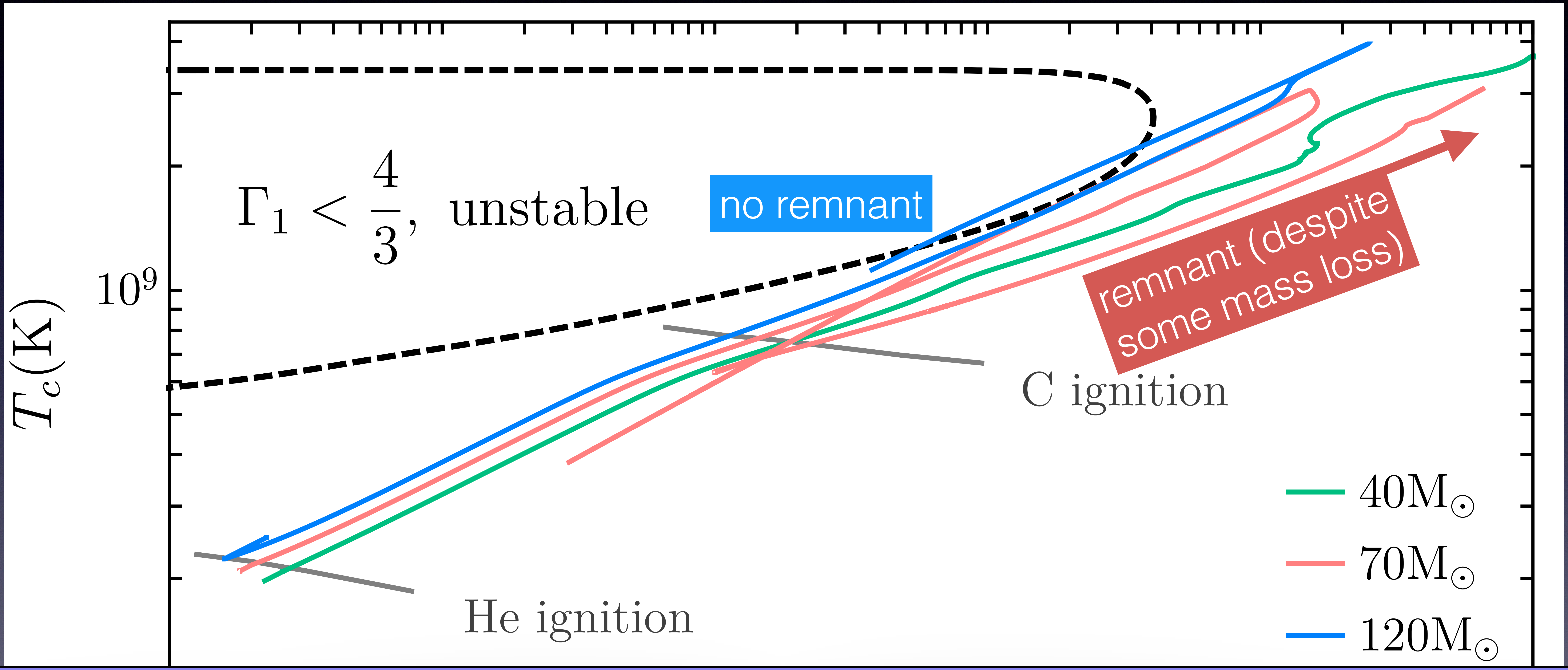

$70M_\odot \lesssim M_{in} \lesssim 100M_\odot$ — pulsational pair instability supernova (PPISN)

vs

$100M_\odot \lesssim M_{in} \lesssim 250M_\odot$ — pair instability supernova (PISN)

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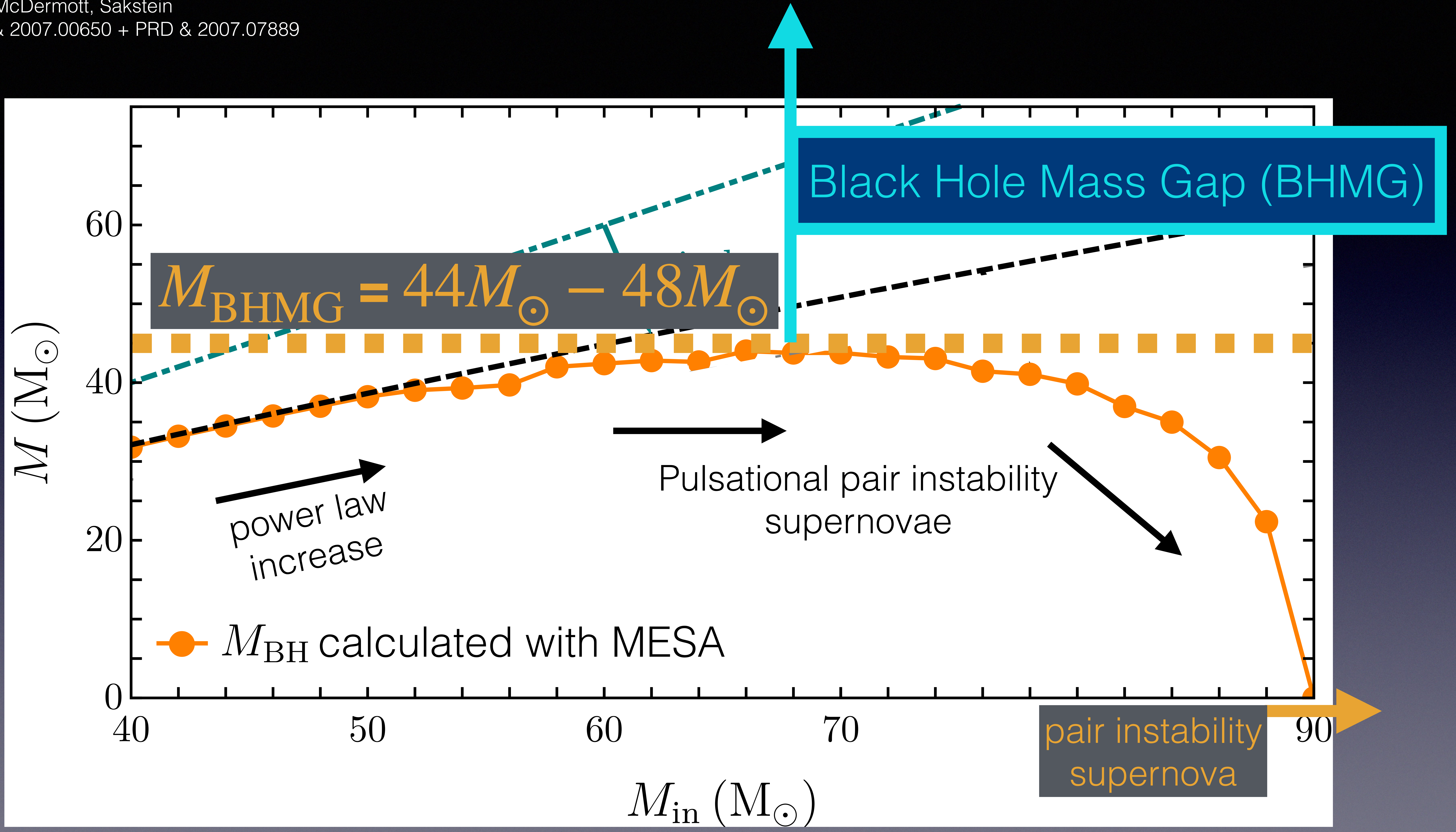
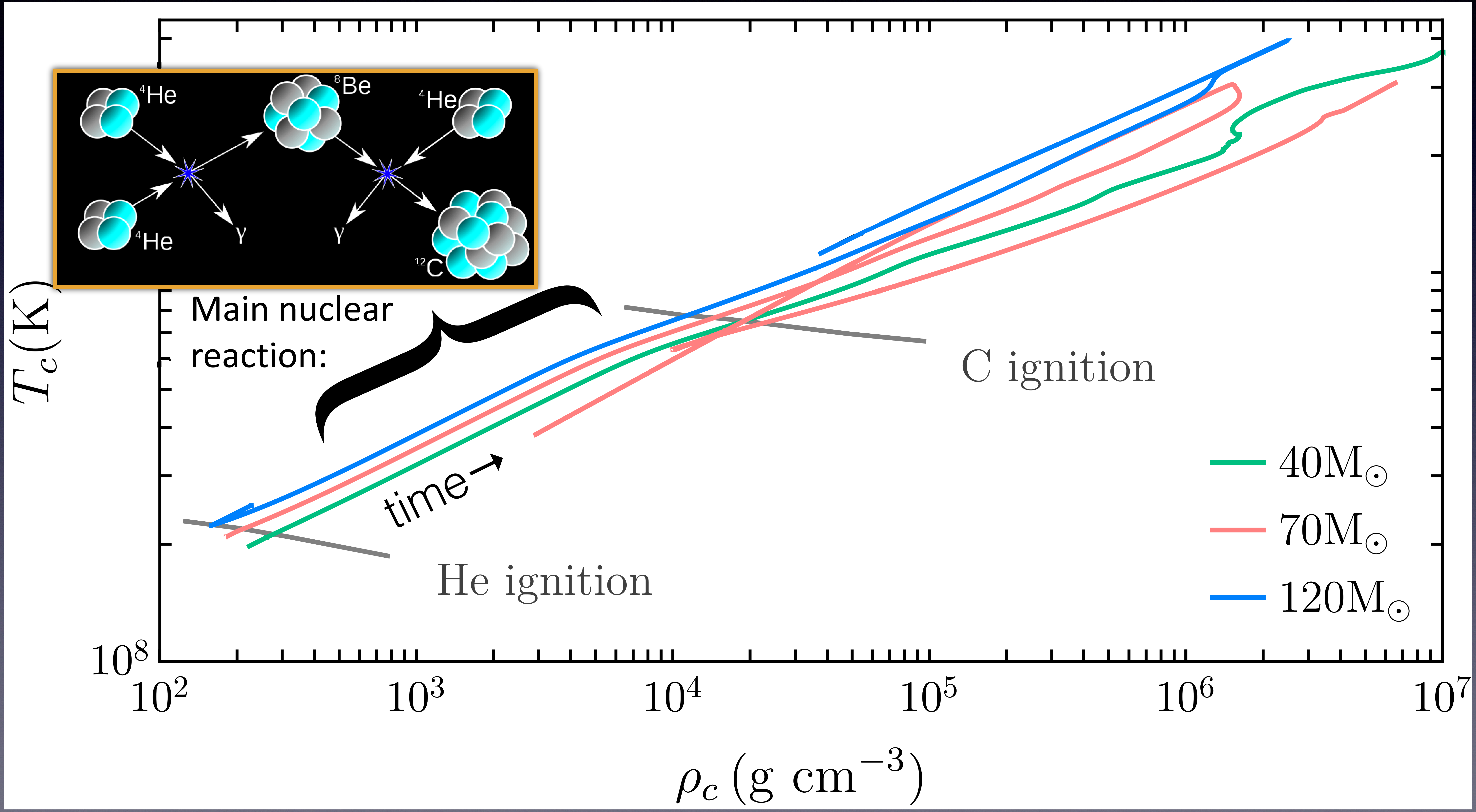


Can we Change the BHMG?

- New light degree(s) of freedom are **produced in the core** of a massive star during helium burning
- This additional loss channel causes the star to **consume fuel more quickly** and **end helium burning earlier**
- This **reduces** the amount of **^{16}O** available **during pulsations**
- Explosions are less violent $\Longrightarrow$ mass loss is less pronounced $\Longrightarrow$ a **heavier black hole**

Reactions in Pop III Stars



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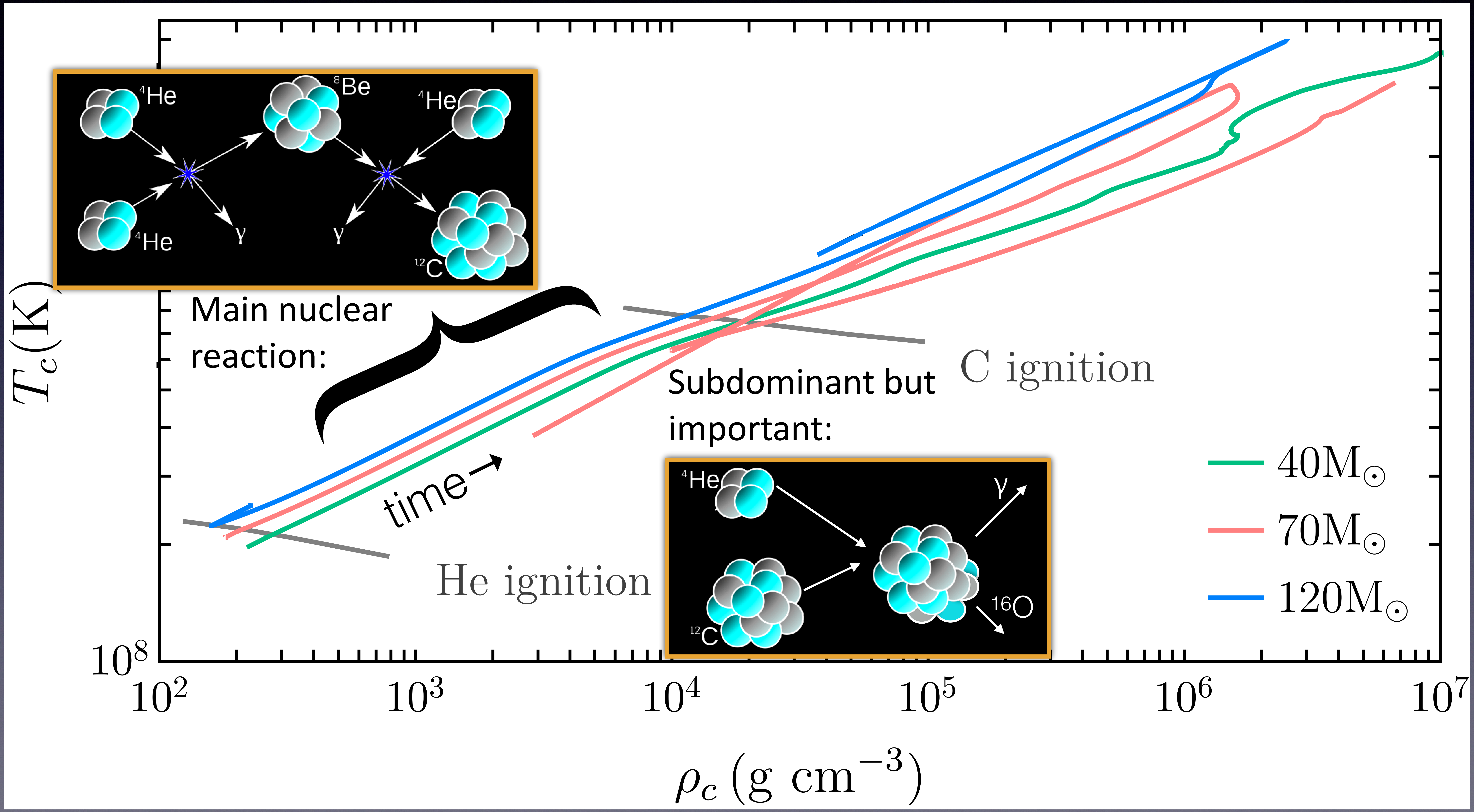

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Losses to Light Particles

- Electrophilic axion: $$\mathcal{Q}_{\rm sC} = \frac{40\,\zeta_6 \alpha_{\rm EM} g_{ae}^2}{\pi^2}\frac{Y_e T^6}{m_N m_e^4} F_{\rm deg} \simeq 33\,\frac{\rm erg}{\rm g\cdot s}\alpha_{26}\, Y_e\, T_8^6\, F_{\rm deg}$$

$$T_8 \equiv \frac{T}{10^8{\rm K}}$$

- Photophilic axion: $$\mathcal{Q}_{a\gamma} = \frac{g_{a\gamma}^2 T^7}{4\pi^2\rho}\left(\frac{k_S}{2T}\right)^2 f\left[\left(\frac{k_S}{2T}\right)^2\right] \simeq 283.16\frac{\rm erg}{\rm g\cdot s} g_{10}^2\, T_8^4$$

$$\left(\frac{k_S}{2T}\right)^2 = 0.166\frac{\rho_3}{T_8^3}\sum_j Y_j Z_j^2$$

- Dark photon: $$\mathcal{Q}_{A'} = \frac{\epsilon^2 m_{A'}^2}{4\pi\rho}\frac{\omega_p^3}{e^{\omega_p/T}-1} \simeq 1800\frac{\rm erg}{\rm g\cdot s}\frac{Z}{A}\left(\frac{\epsilon}{10^{-7}}\frac{m_{A'}}{\rm meV}\right)^2 T_8$$

$$\omega_p^2 \simeq \frac{4\pi\alpha_{\rm EM} n_e}{m_e} \simeq (654{\rm eV})^2\frac{Z}{A}\rho_3$$

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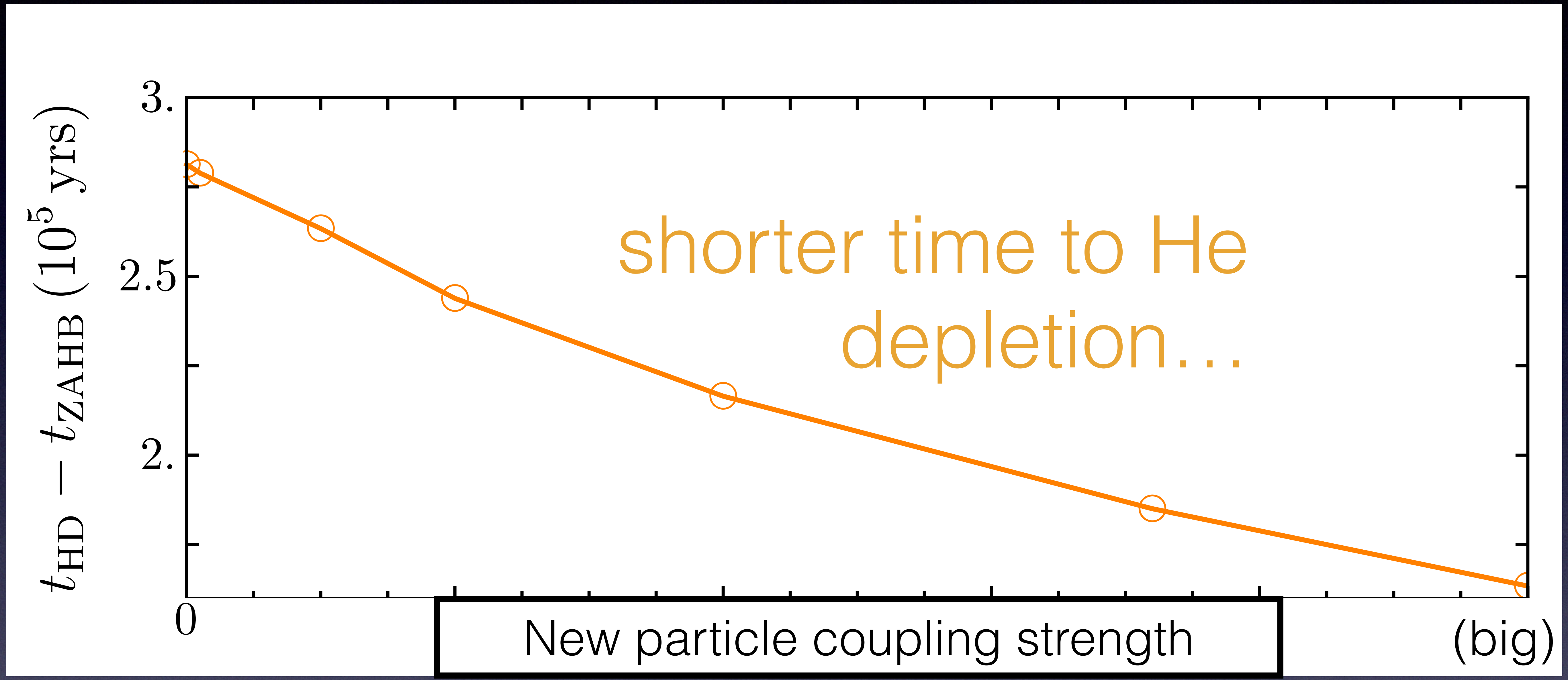
Implications for Oxygen Production



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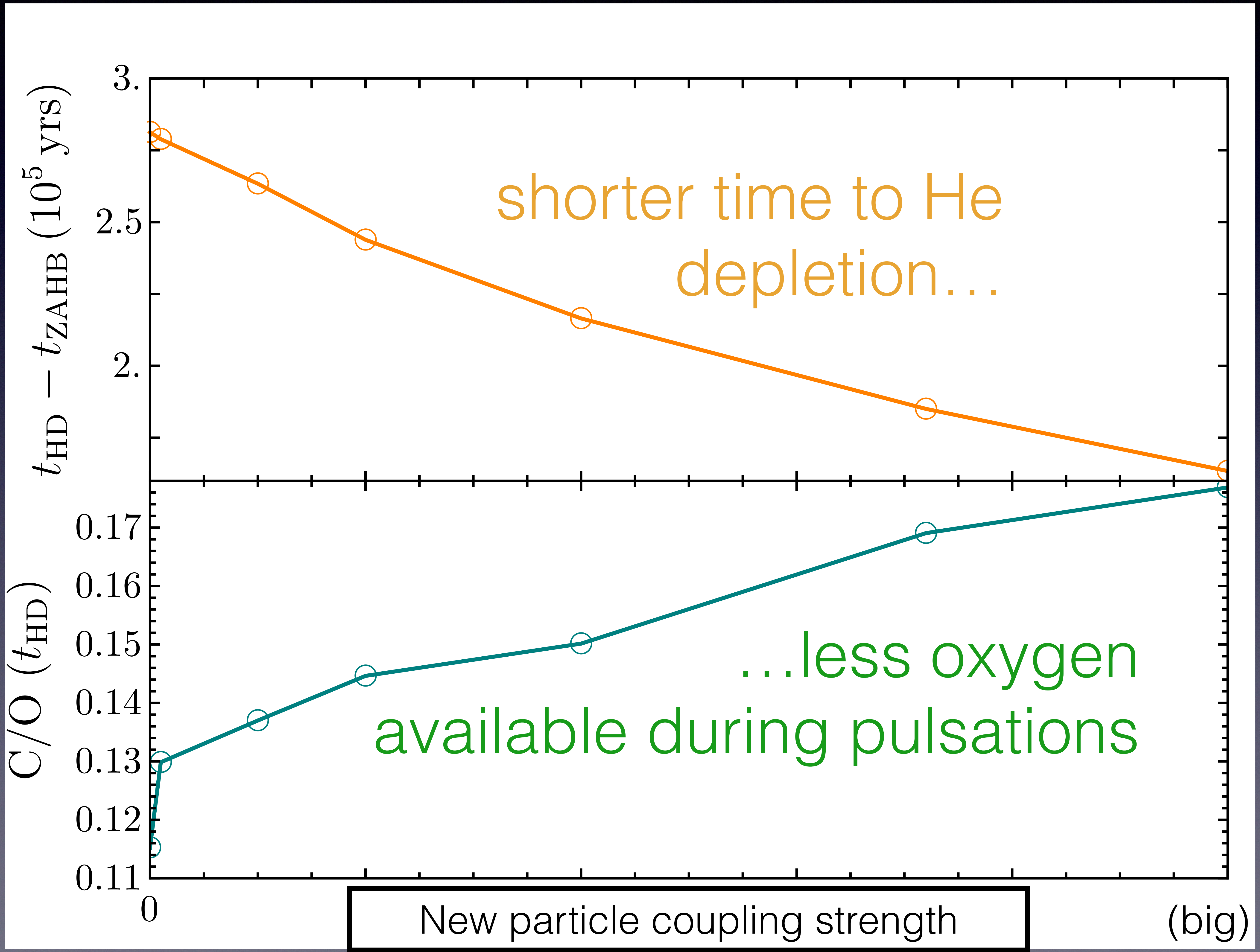

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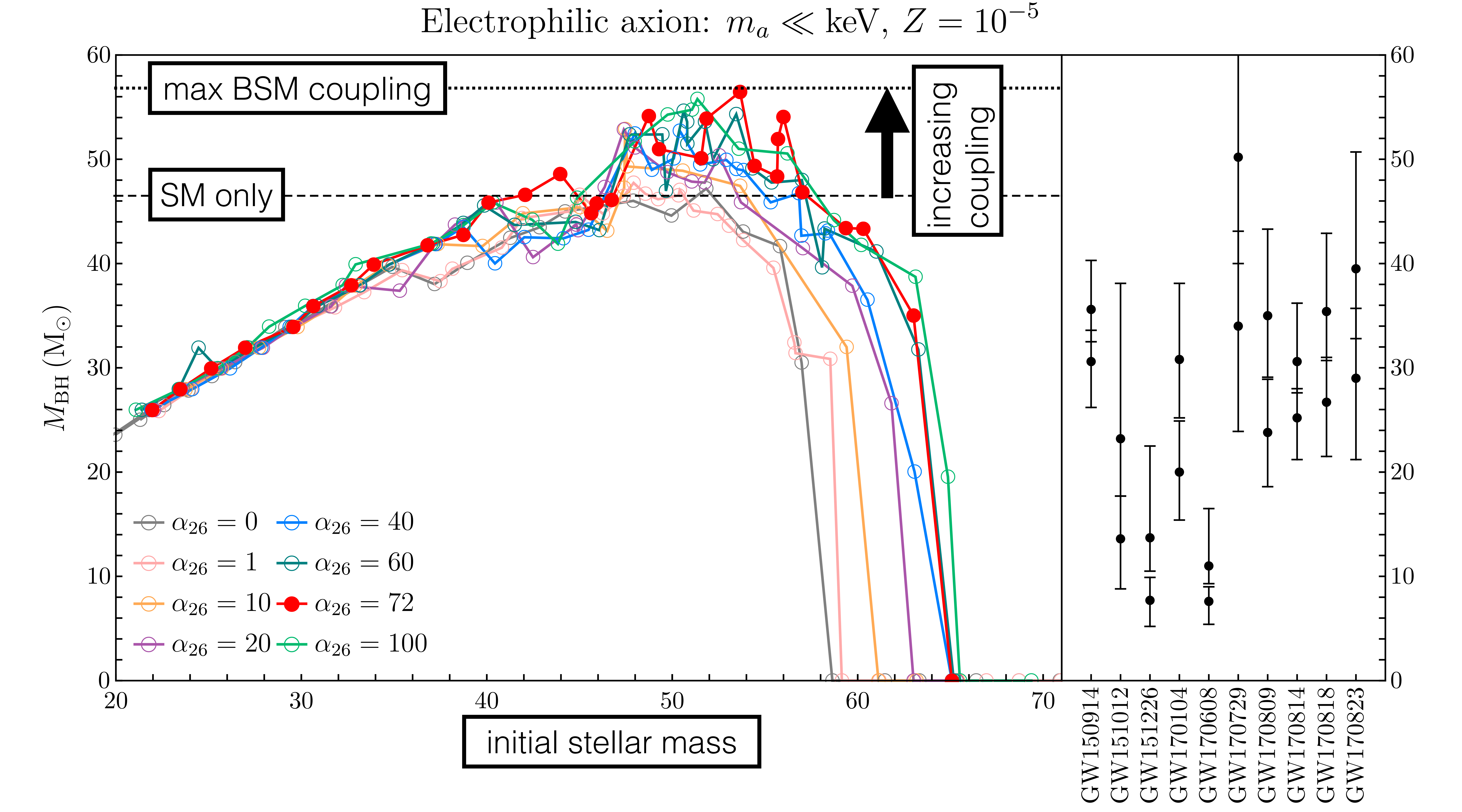
Implications for Black Hole Masses



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- Photophilic axion:
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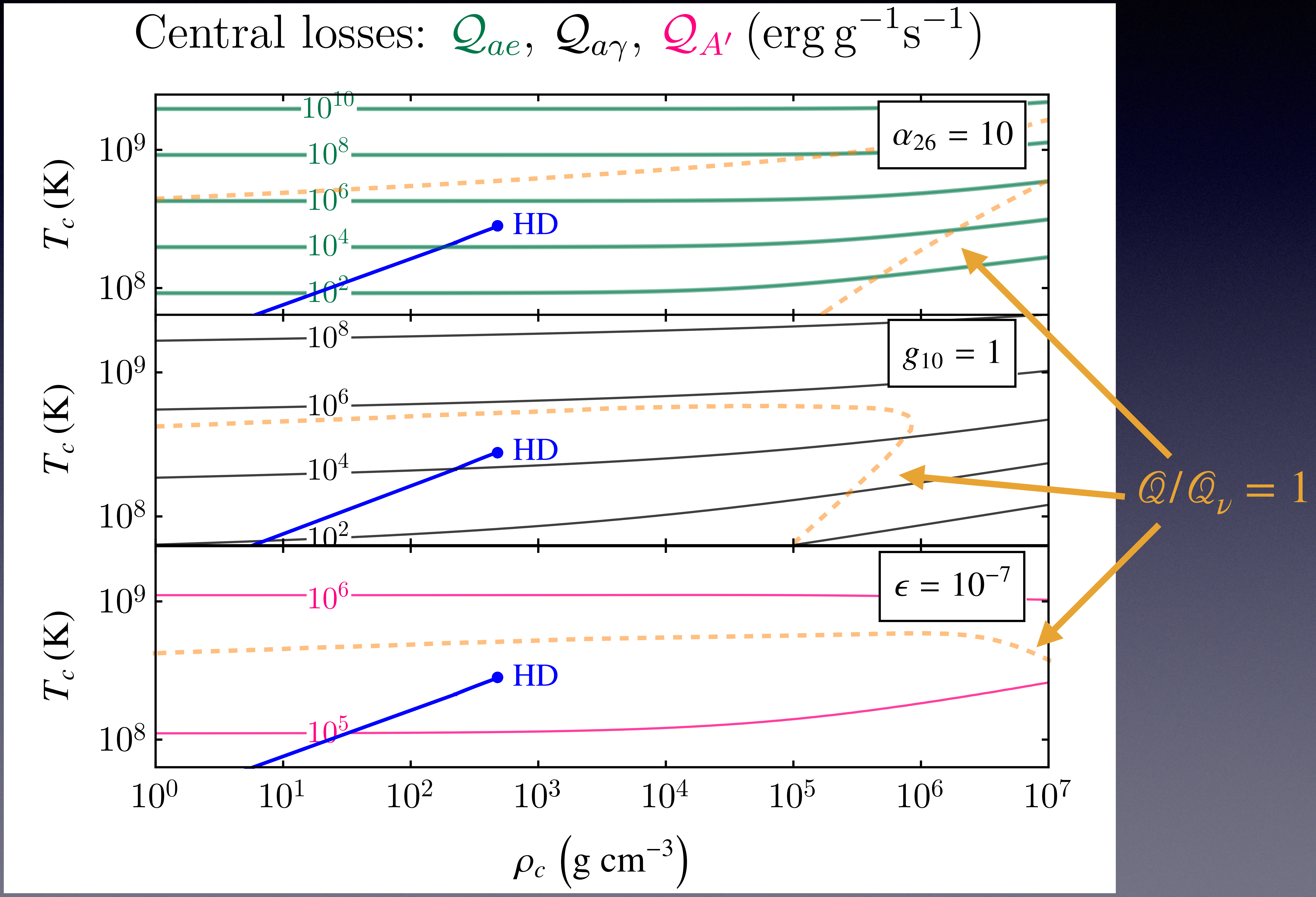

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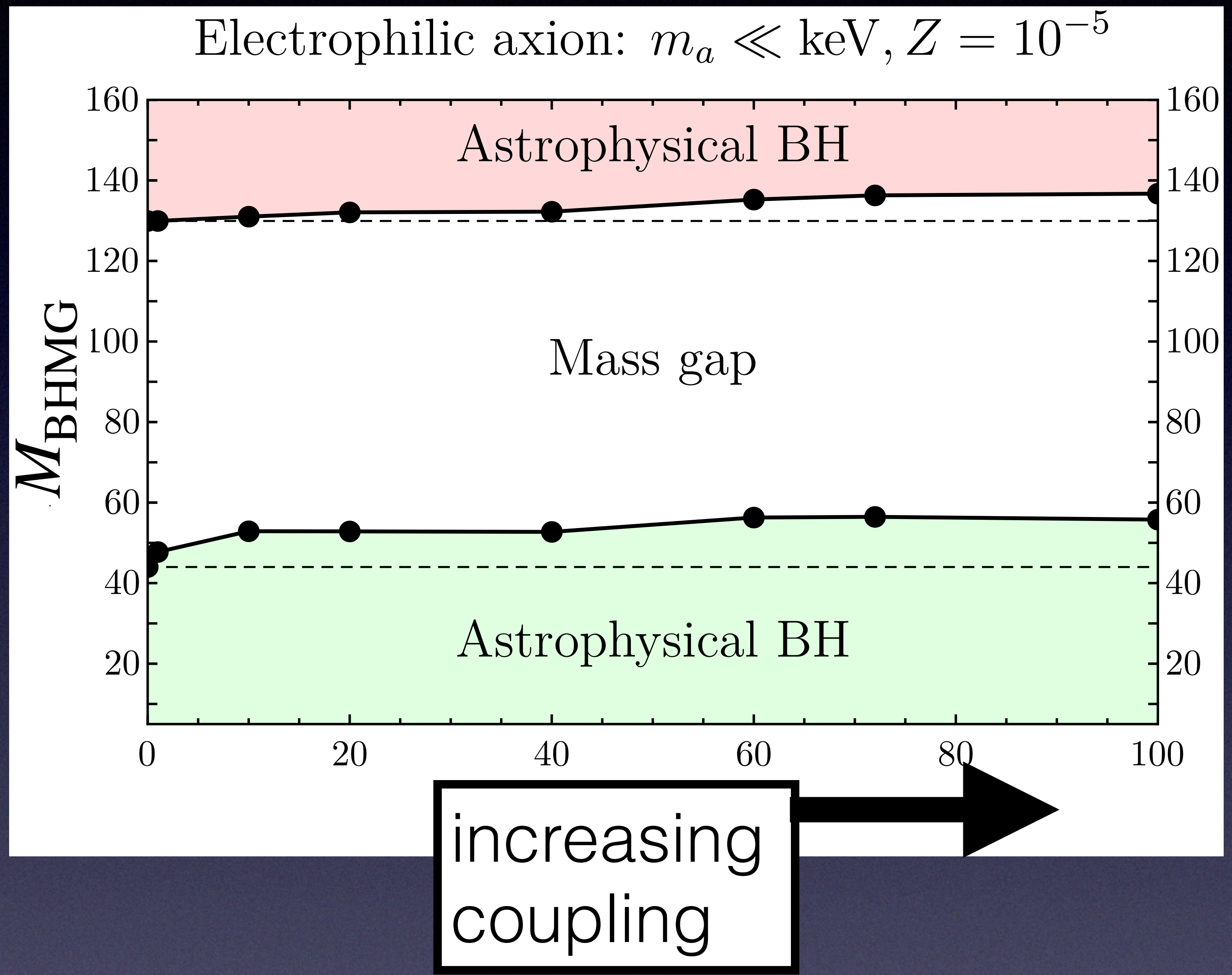

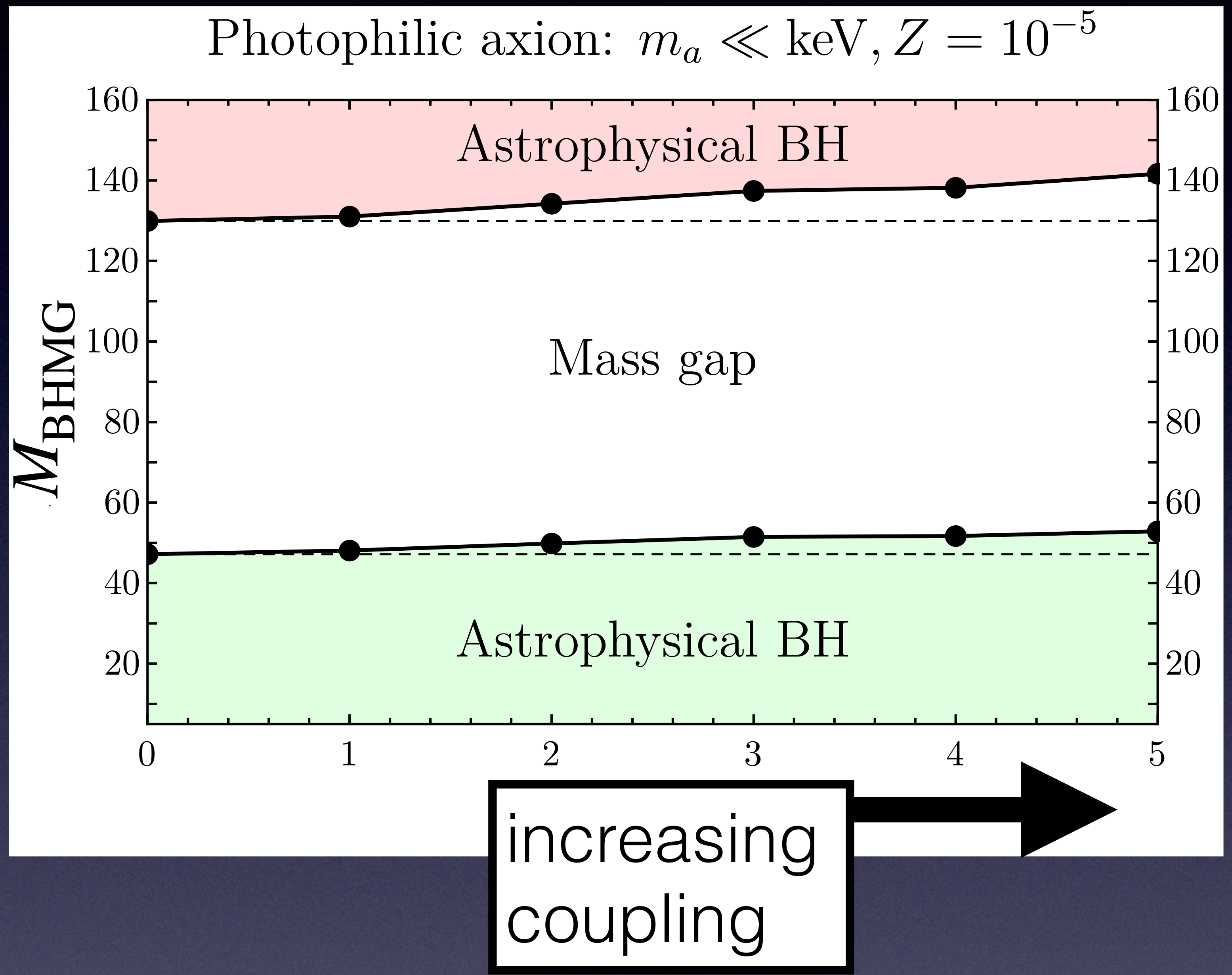

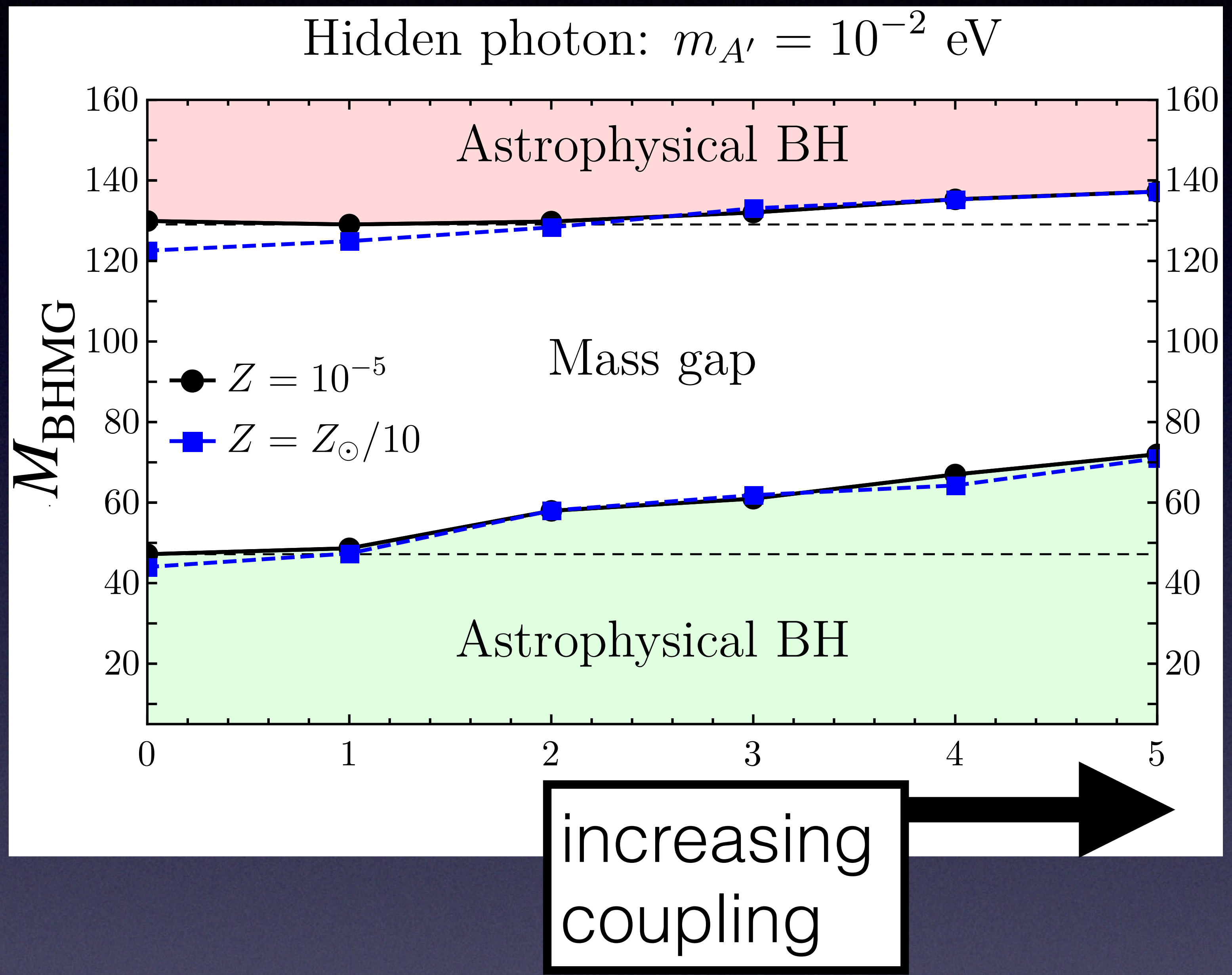

larger coupling to new physics $\Longrightarrow$ larger black hole mass

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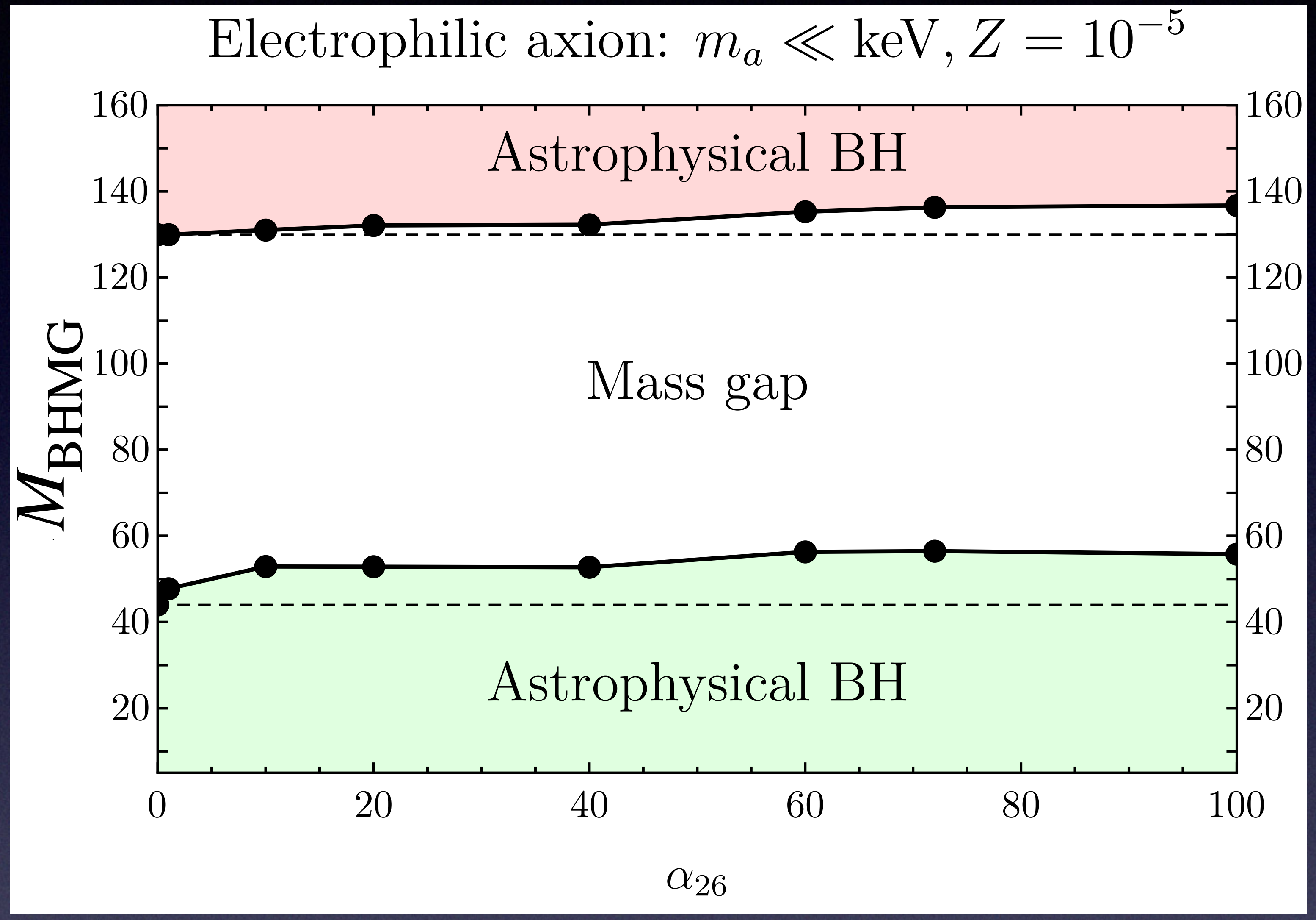

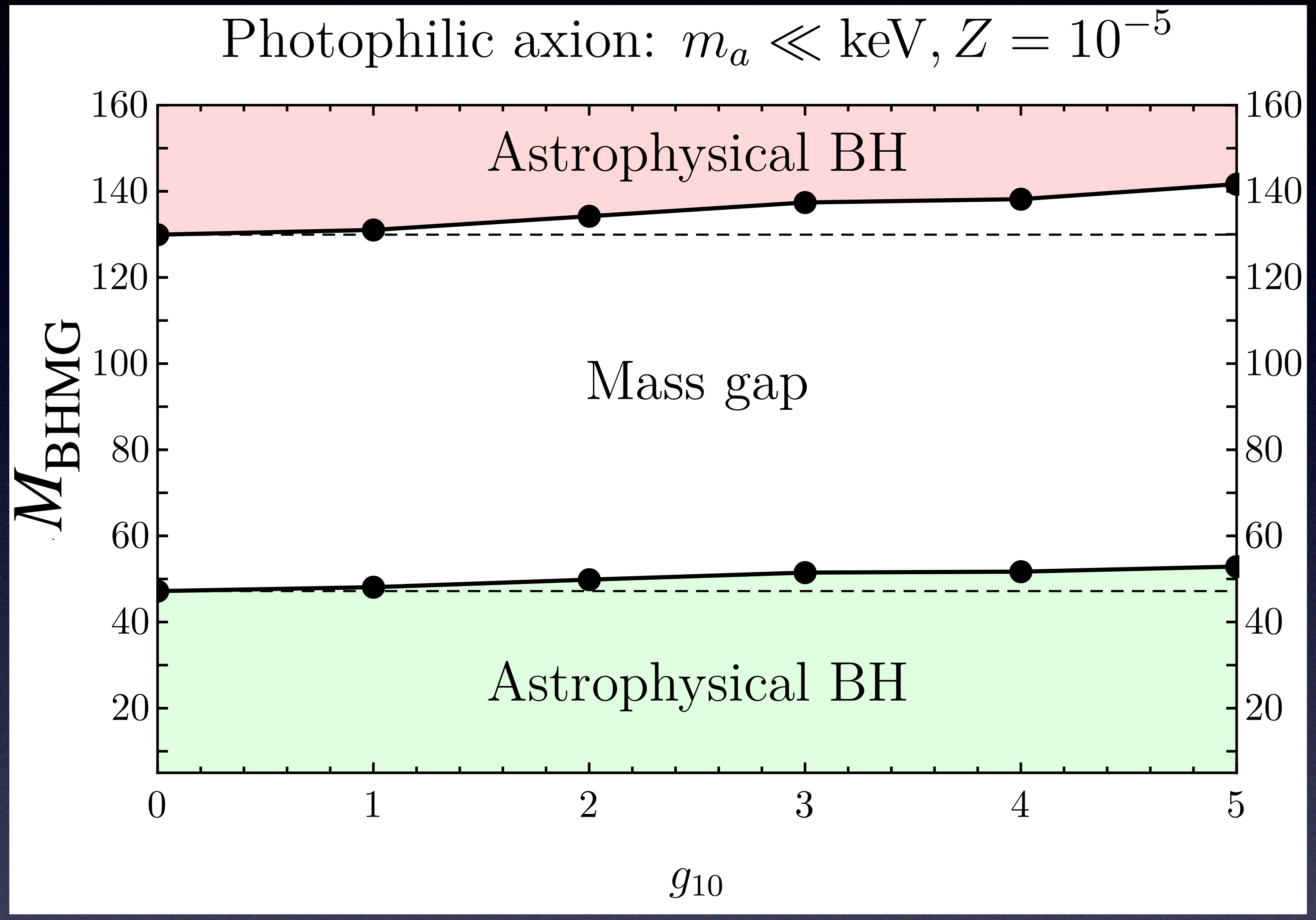

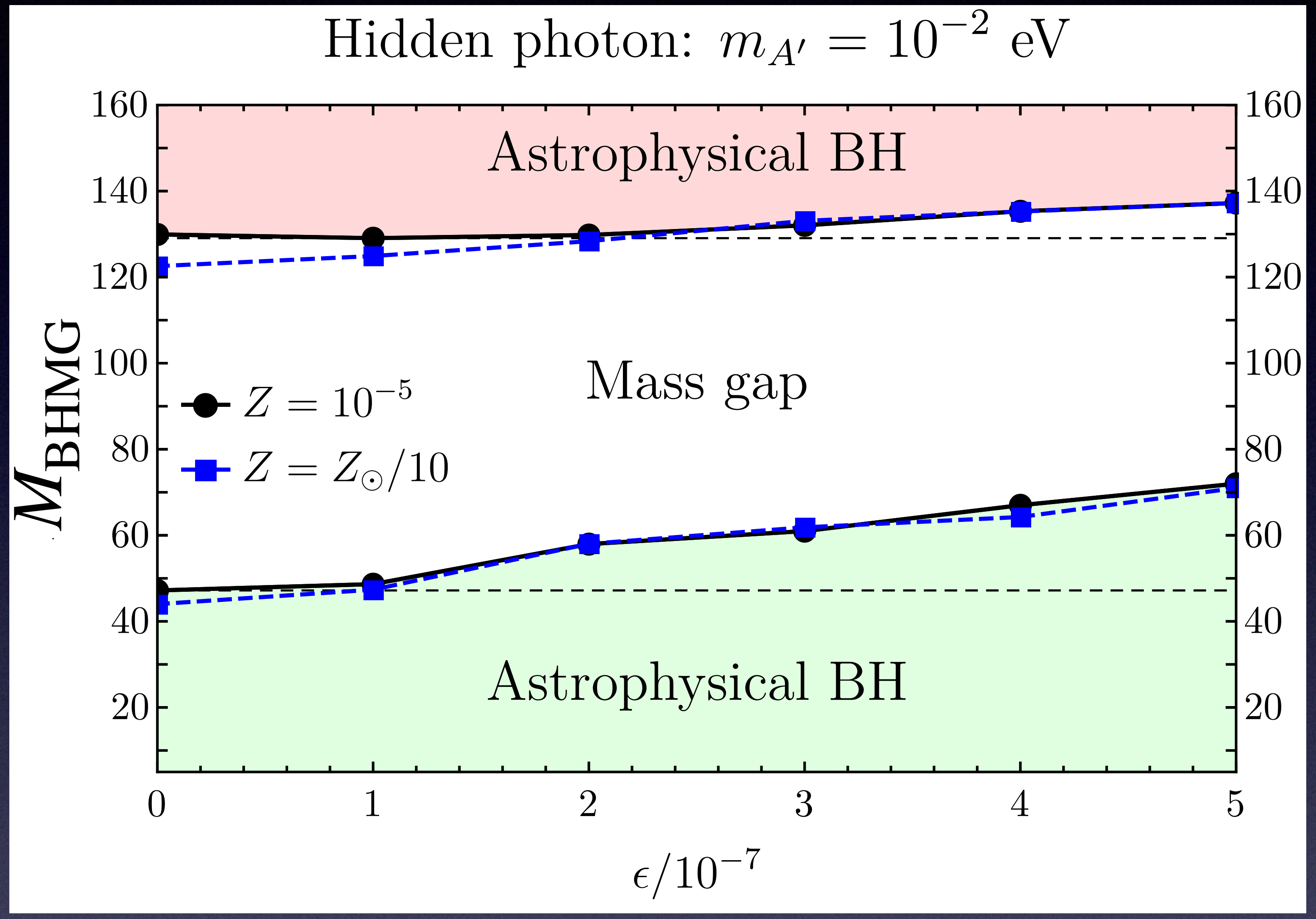

0 —— 35

g_{13}

larger coupling to new physics $\Longrightarrow$ larger black hole mass

But… Limits!

Claimed constraints from other stellar systems are in "tension"

- Capozzi & Raffelt 2007.03694: "The evolution of a low-mass star as it ascends the red-giant branch (RGB) is driven by the growing mass and shrinking size of its degenerate core until helium ignites and the core quickly expands" $\Longrightarrow \alpha_{26} \leq 0.2$
- CAST excludes $g_{10} \leq 0.7$ up to $m_a \sim 0.02$ eV, weakening linearly at larger m_a; helioseismology requires $g_{10} \leq 4$ (Vinyoles et al., 1501.01639)
- Exceeding the luminosity of photons from the sun unacceptably changes the ^{8}B neutrino flux, limiting $\epsilon m_{A'}/\mathrm{meV} \lesssim 10^{-9}$ (An et al., 1302.3884; Redondo and Raffelt 1305.2920)

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Solar bound only $\alpha_{26} \leq 4200$ (Redondo 1310.0823)

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Di Luzio, et al., 2006.12487 & PRL

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• *R-parameter.* After He ignition the RG core expands and its density decreases by two orders of magnitude. The star migrates to the HB and remains supported by He burning in a non-degenerate core. The ratio $R = N_{\mathrm{HB}}/N_{\mathrm{RGB}}$ between the number of stars in in globular clusters in the HB and in the upper portion of the RGB directly measures the duration of He burning in the HB phase. The value $R = 1.39 \pm 0.03$ was obtained in Ref. [26] from the analysis of 39 clusters. The duration of the HB phase can be affected by g_{ae}-related processes both directly and indirectly. If g_{ae} is sufficiently large, axion emission would directly produce extra cooling of the He core. The star self-regulates by slightly contracting, the core temperature increases speeding up the He burning rate. Once the He fuel is exhausted, the star turns into a WD. The indirect effect is related to the growth of the degenerate He core during the RGB phase previously discussed. HB stars would unavoidably inherit a more massive core from the parent RGs, resulting in an increased He burning rate to contrast the larger gravitational pull, and shortening further the duration of the HB phase. Note that the indirect effect of g_{ae} is so important that for $g_{e13} \sim 15$ it would suffice to depopulate almost completely the HB in the Color-Magnitude Diagram (CMD) ($R \approx 0$). Cooling of HB stars can also

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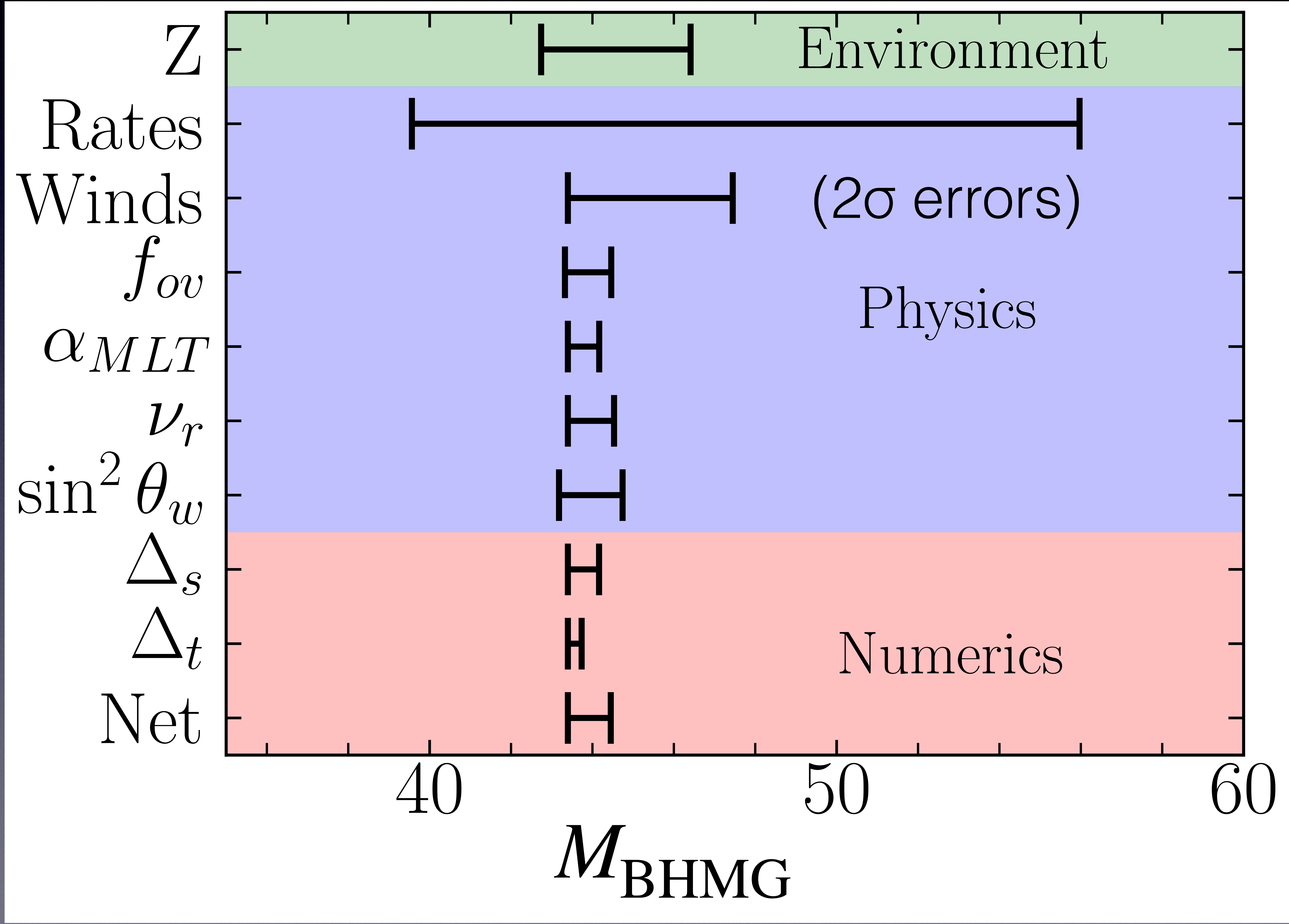
Not true! (we simulated this)

SM Uncertainties



also rare events:

- pre-/post-collapse merger
- accretion after formation
- retention of H envelope
- binarity
- rotation
- …

Farmer et al., 1910.12874

Surprisingly Massive: SM vs BSM

SM physics

- $M_{\rm BHMG}$ is at the value predicted by the SM-only calculation*

*unless ~5σ deviations from nuclear rates or major differences in stellar physics wrt to MESA

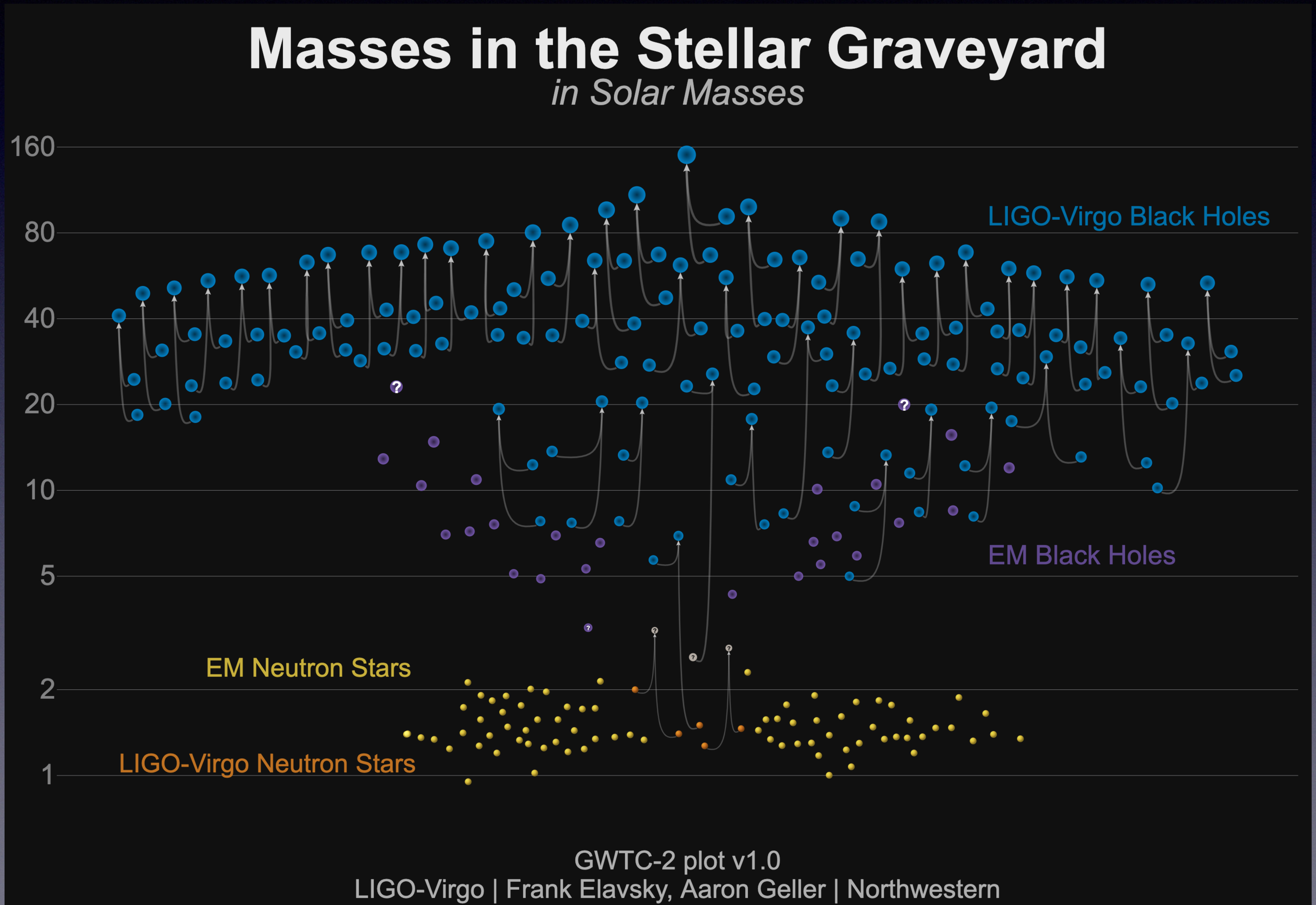
- Continuous distribution of $M_{\rm BH}$ up to **expected value of $M_{\rm BHMG}$** due to isolated stars, plus **rare excursions** to $M_{\rm BH} > M_{\rm BHMG}$ ("pollutants")

BSM physics

- $M_{\rm BHMG}$ is **not** as expected from SM-only calculation: objects "in the (SM) mass gap" form from isolated evolution, no rare process required

- Implies a continuous distribution of BH masses up to a **new, higher value of $M_{\rm BHMG}$**

LIGO Observations: Oct 2020



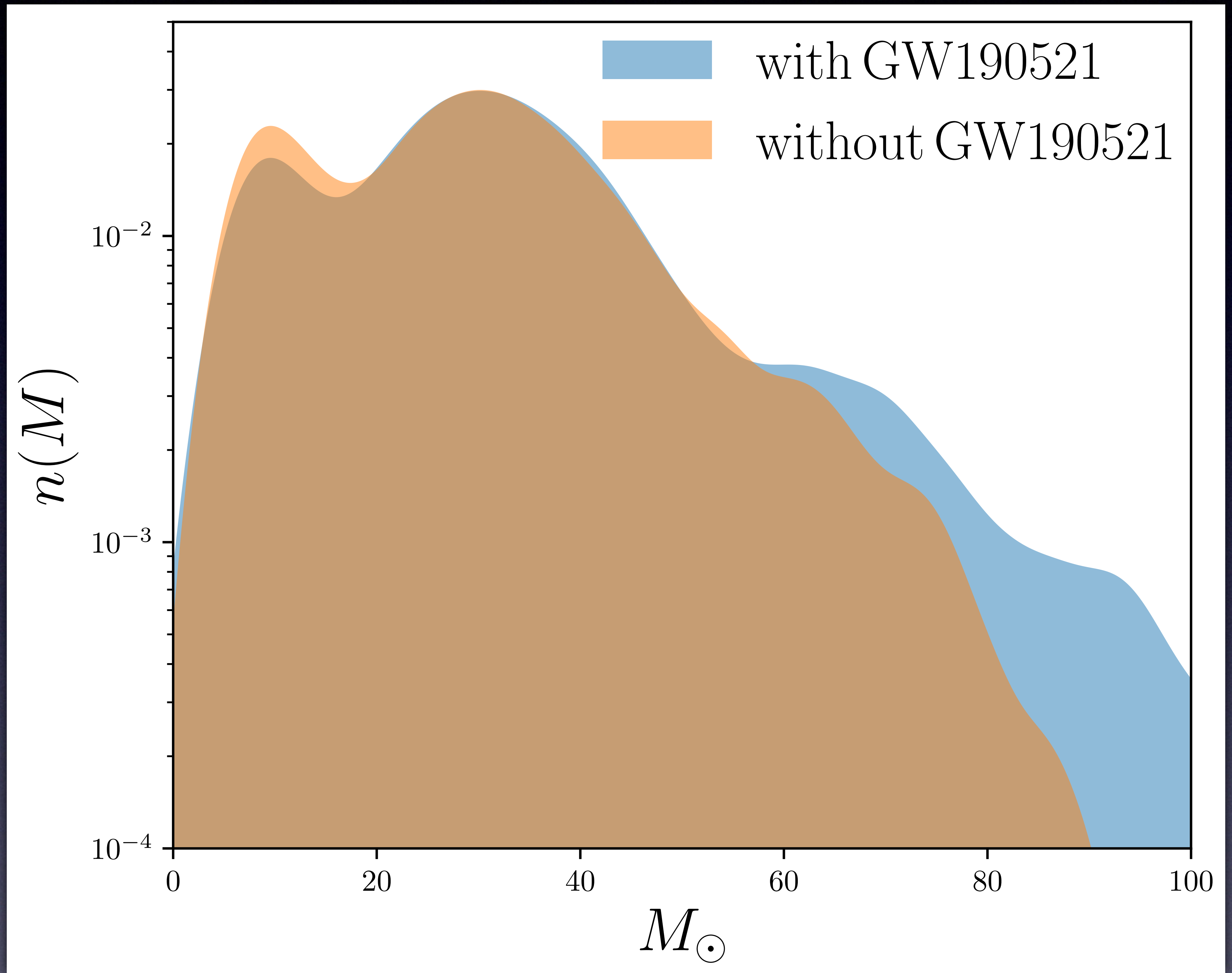
Black Hole Population Statistics

Black Hole Population Statistics

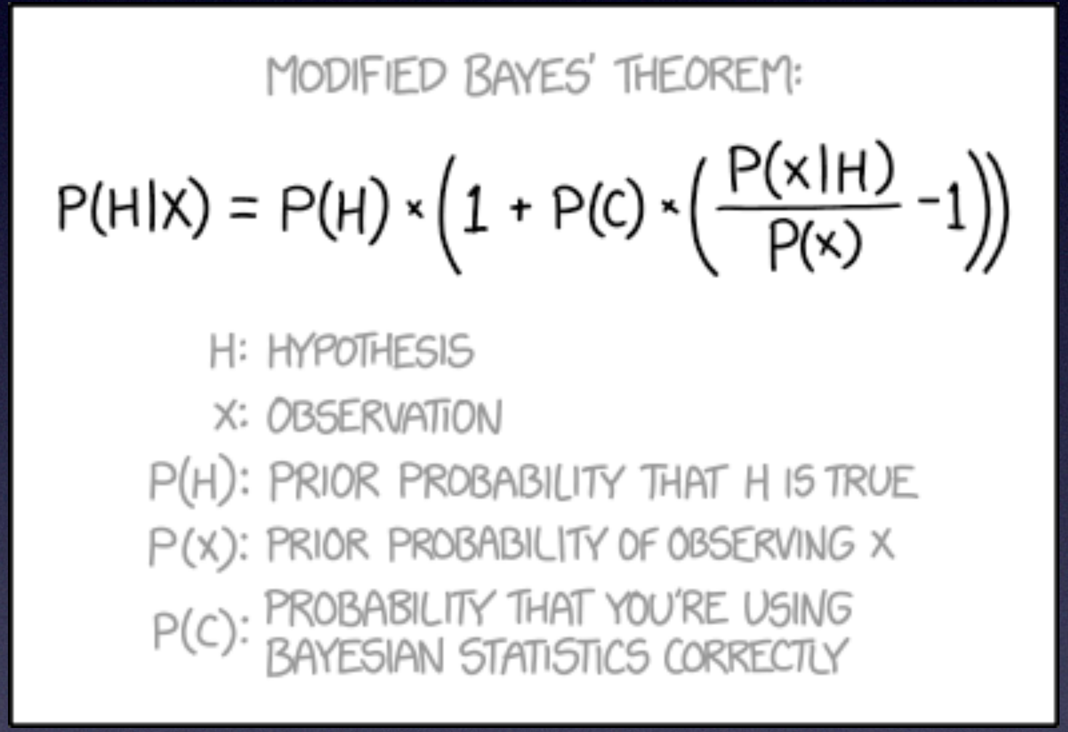
$$p\left(m_1, m_2 \mid \vec{\theta}\right) \propto \frac{dN^{(1g)}}{dM_{BH}} + \lambda \frac{dN^{(2g)}}{dM_{BH}}$$

BHs formed from isolated stellar evolution

"pollutants" (λ<1)



Baxter, Croon, SDM, Sakstein
ApJL & 2104.02685



xkcd.com/2059/

Black Hole Population Statistics

$$p\left(m_1, m_2 \mid \vec{\theta}\right) \propto \frac{dN^{(1g)}}{dM_{BH}} + \lambda \frac{dN^{(2g)}}{dM_{BH}}$$

BHs formed from isolated stellar evolution

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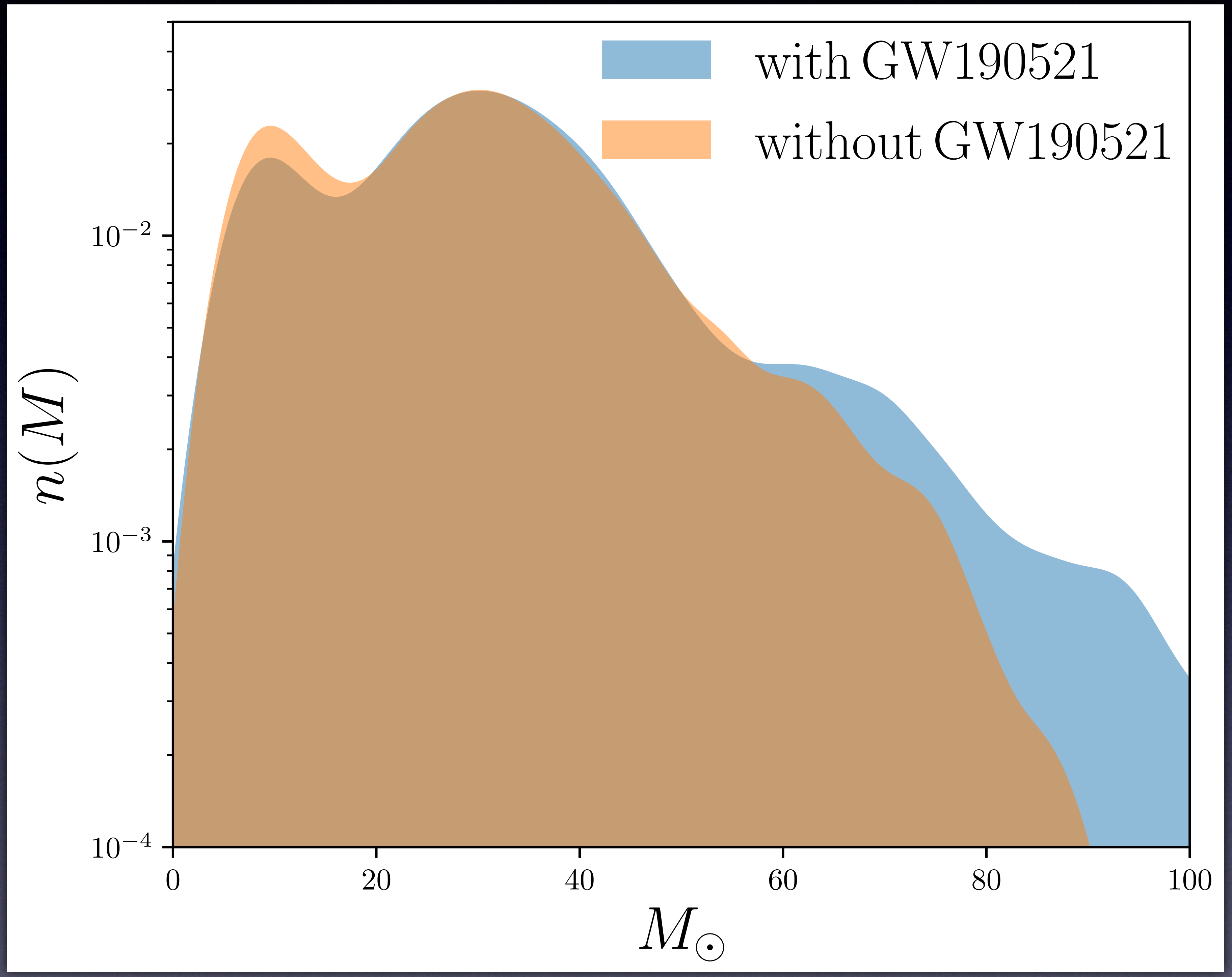

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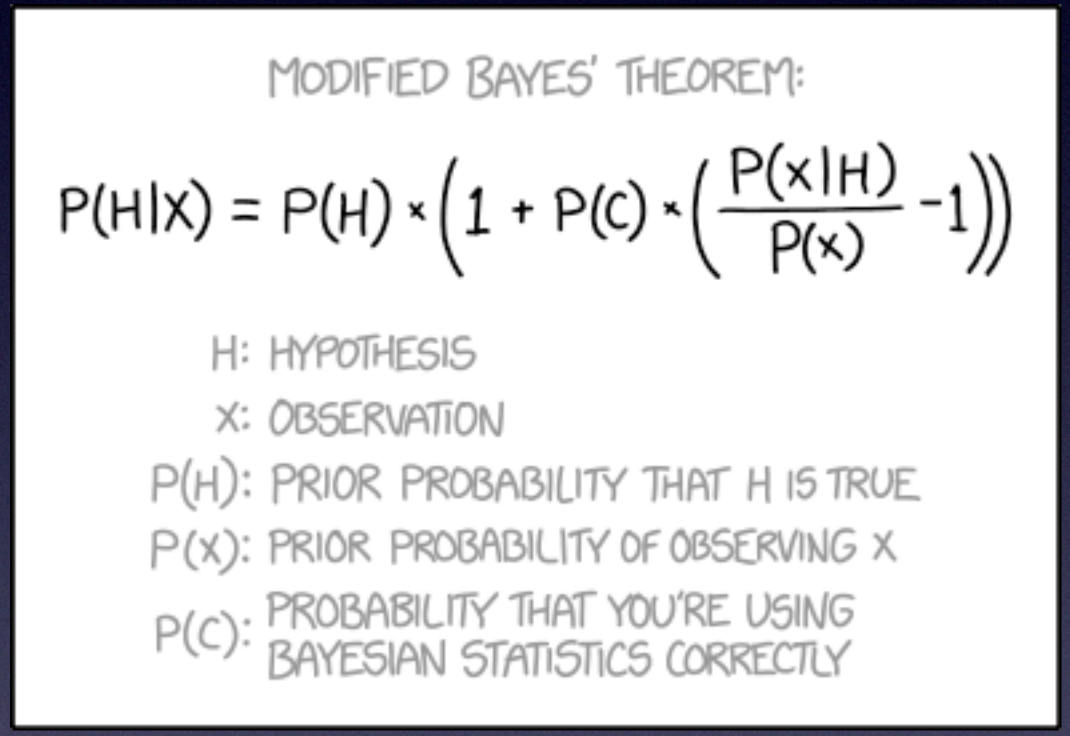


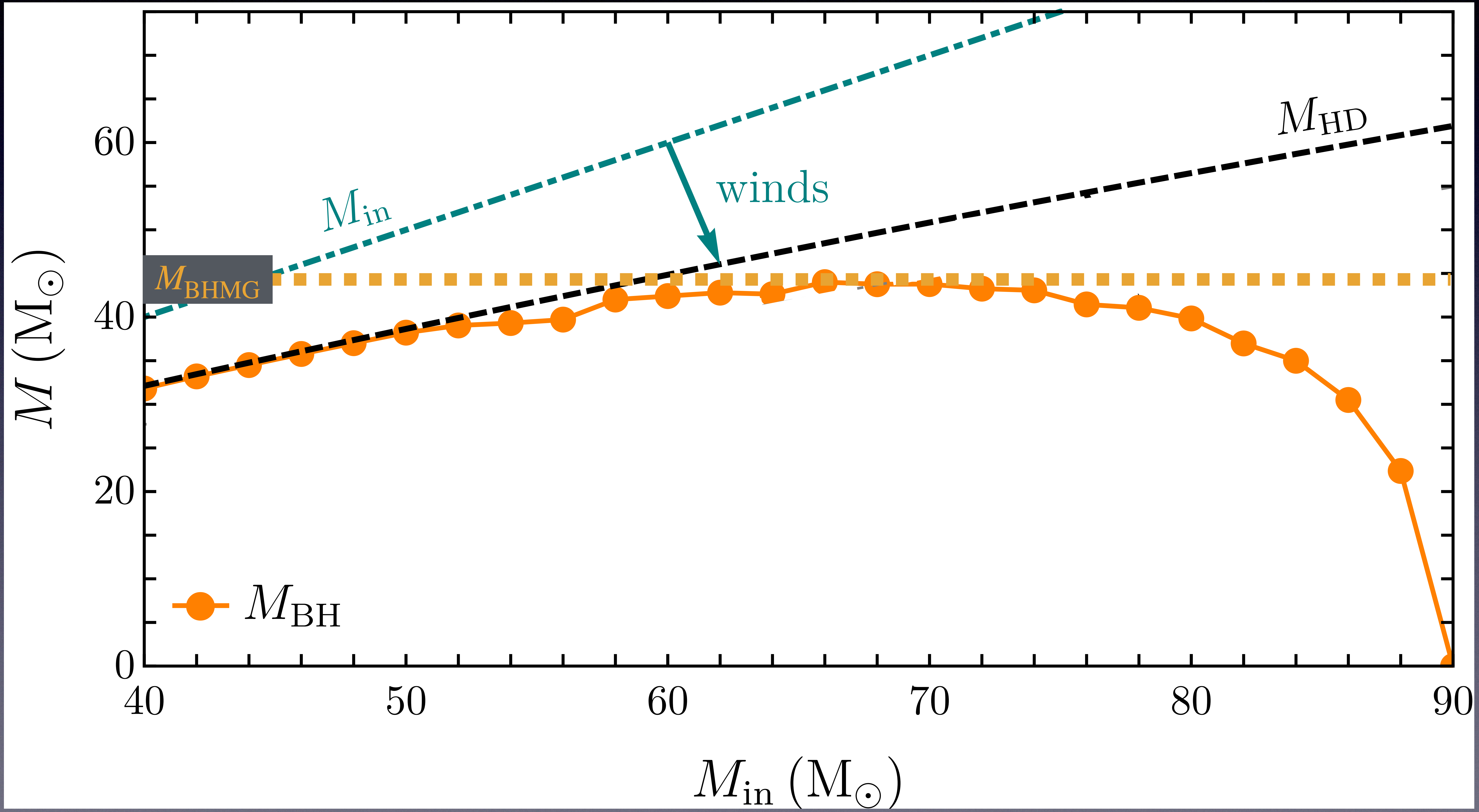
xkcd.com/2059/

$$\frac{dN^{(1g)}}{dM_{BH}} \sim \int d\vec{\alpha}\, \frac{dN_*}{dM_*} \frac{1}{dM_{BH}(\vec{\alpha})/dM_*}$$

this is exactly what we get from MESA!

Croon, McDermott, Sakstein PRD & 2007.07889
&/+ Baxter ApJL & 2104.02685

$dM_{\rm BH}/dM_*$



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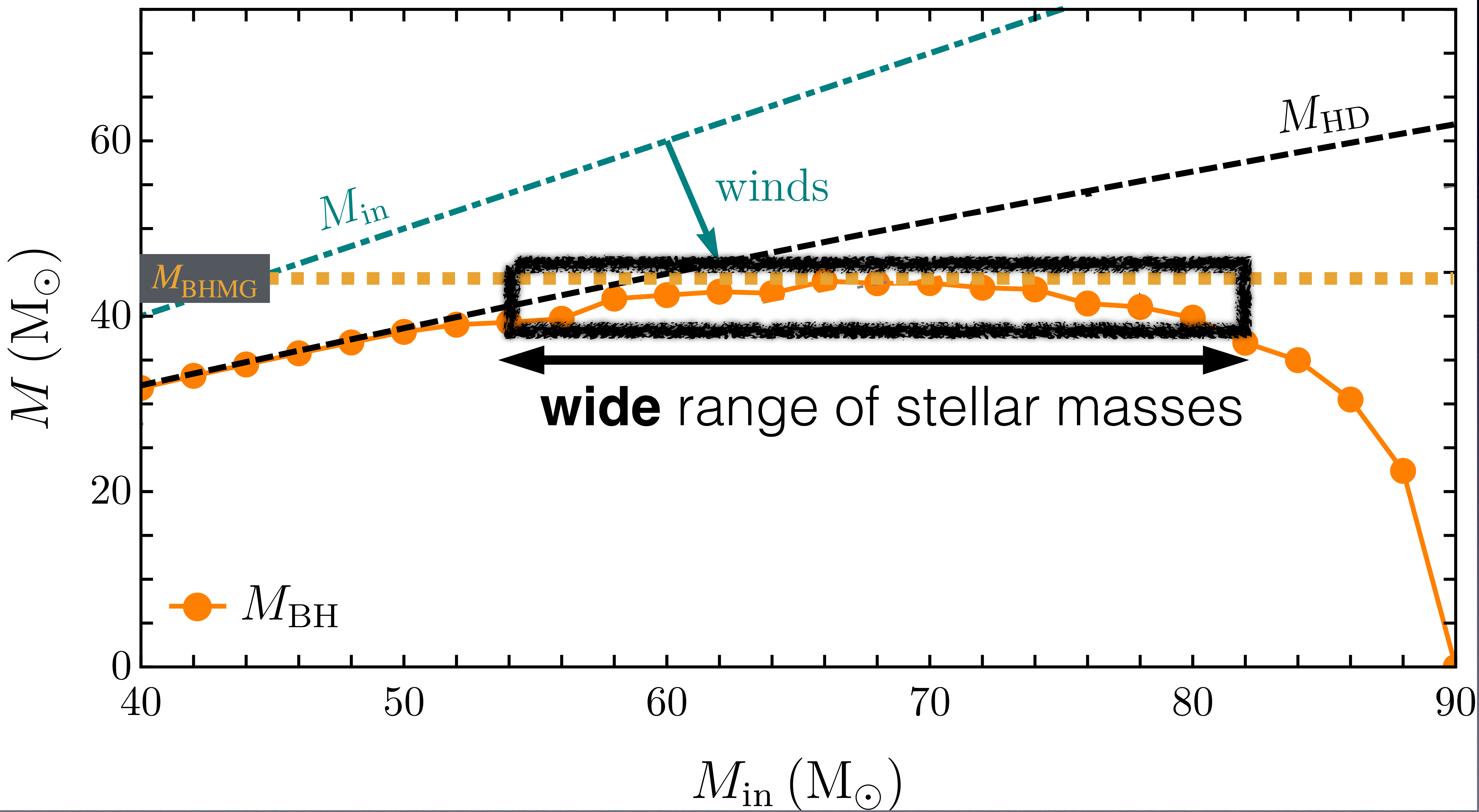
$dM_{\rm BH}/dM_*$



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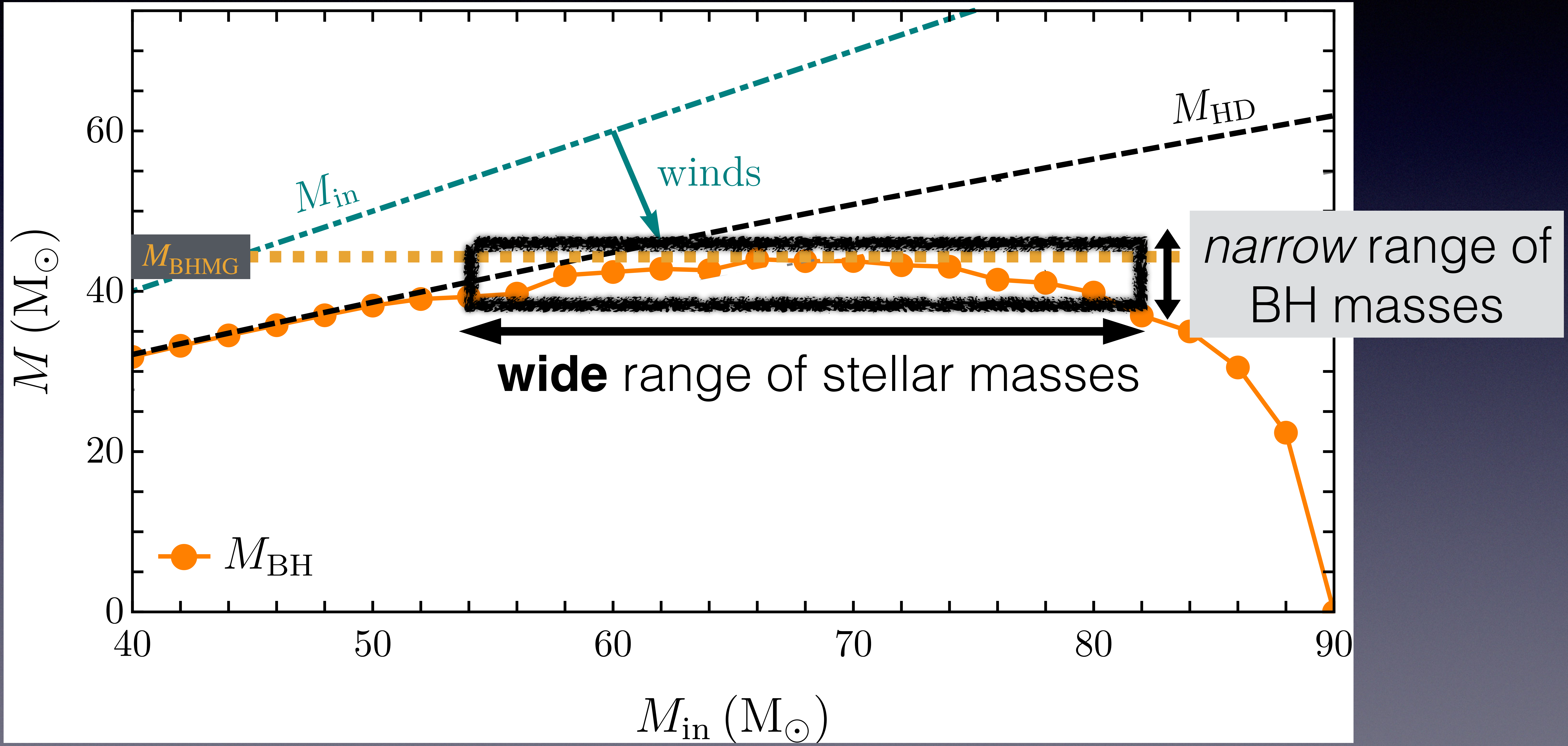
dM_{BH}/dM_*



Croon, McDermott, Sakstein PRD & 2007.07889
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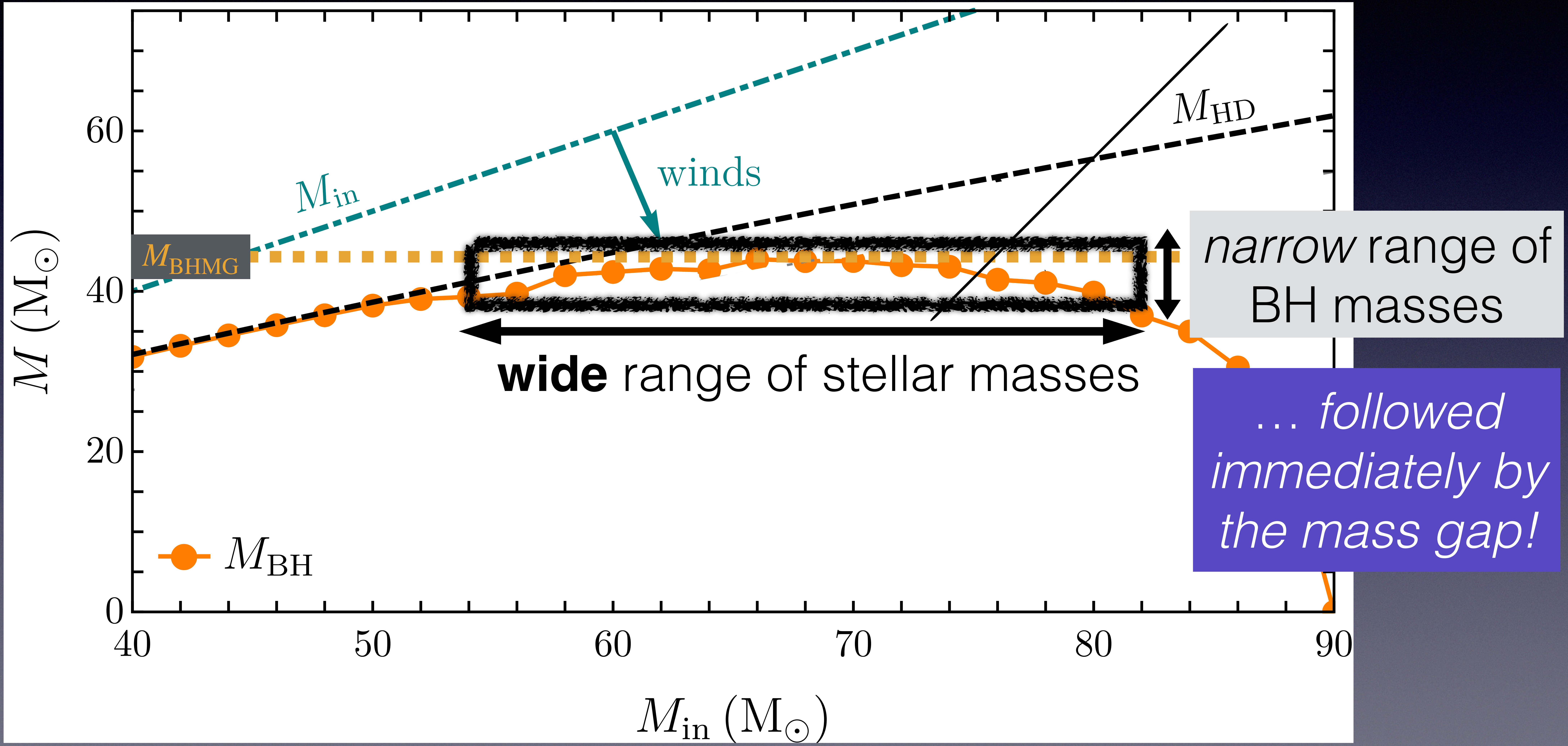
dM_{BH}/dM_*



Black Hole Population Statistics

after GWTC-2

$$p\left(m_1, m_2 \mid \vec{\theta}\right) \propto \frac{dN^{(1g)}}{dM_{BH}} + \lambda \frac{dN^{(2g)}}{dM_{BH}}$$

Baxter, Croon, SDM, Sakstein
ApJL + 2104.02685

flexible fitting function with a sharp peak followed by a gap:

$$\frac{dN_{BH}^{(1g)}}{dM_{BH}} \propto \left[1 + 2a^2\sqrt{\frac{M_{BH}}{M_{BHMG}}}\left(1 - \frac{M_{BH}}{M_{BHMG}}\right)^{a-1}\right]\Theta(M_{BHMG} - M_{BH})$$

Black Hole Population Statistics

after GWTC-2

$$p\left(m_1, m_2 \mid \overrightarrow{\theta}\right) \propto \frac{dN^{(1\mathrm{g})}}{dM_{\mathrm{BH}}} + \lambda \frac{dN^{(2\mathrm{g})}}{dM_{\mathrm{BH}}}$$

Baxter, Croon, SDM, Sakstein
ApJL + 2104.02685

flexible fitting function with a sharp peak followed by a gap:

$$\frac{dN^{(1\mathrm{g})}_{\mathrm{BH}}}{dM_{\mathrm{BH}}} \propto \left[1 + 2a^2 \sqrt{\frac{M_{\mathrm{BH}}}{M_{\mathrm{BHMG}}}} \left(1 - \frac{M_{\mathrm{BH}}}{M_{\mathrm{BHMG}}}\right)^{a-1}\right] \Theta(M_{\mathrm{BHMG}} - M_{\mathrm{BH}})$$

$$\frac{dN^{(2\mathrm{g})}}{dM_{\mathrm{BH}}} \sim \int dM_a \frac{dN^{(1\mathrm{g})}(M_a)}{dM_a} \frac{dN^{(1\mathrm{g})}(M_{\mathrm{BH}} - M_a)}{dM_a}$$

Black Hole Population Statistics

examples...

after GWTC

flexible fitting func

$$\frac{dN^{(1g)}_{BH}}{dM_{BH}} \propto \Bigg[1 + 2a \quad M_{BH})$$

$dN^{(1g)}$ $dN^{(2g)}$

Baxter, Croon, SDM, Sakstein
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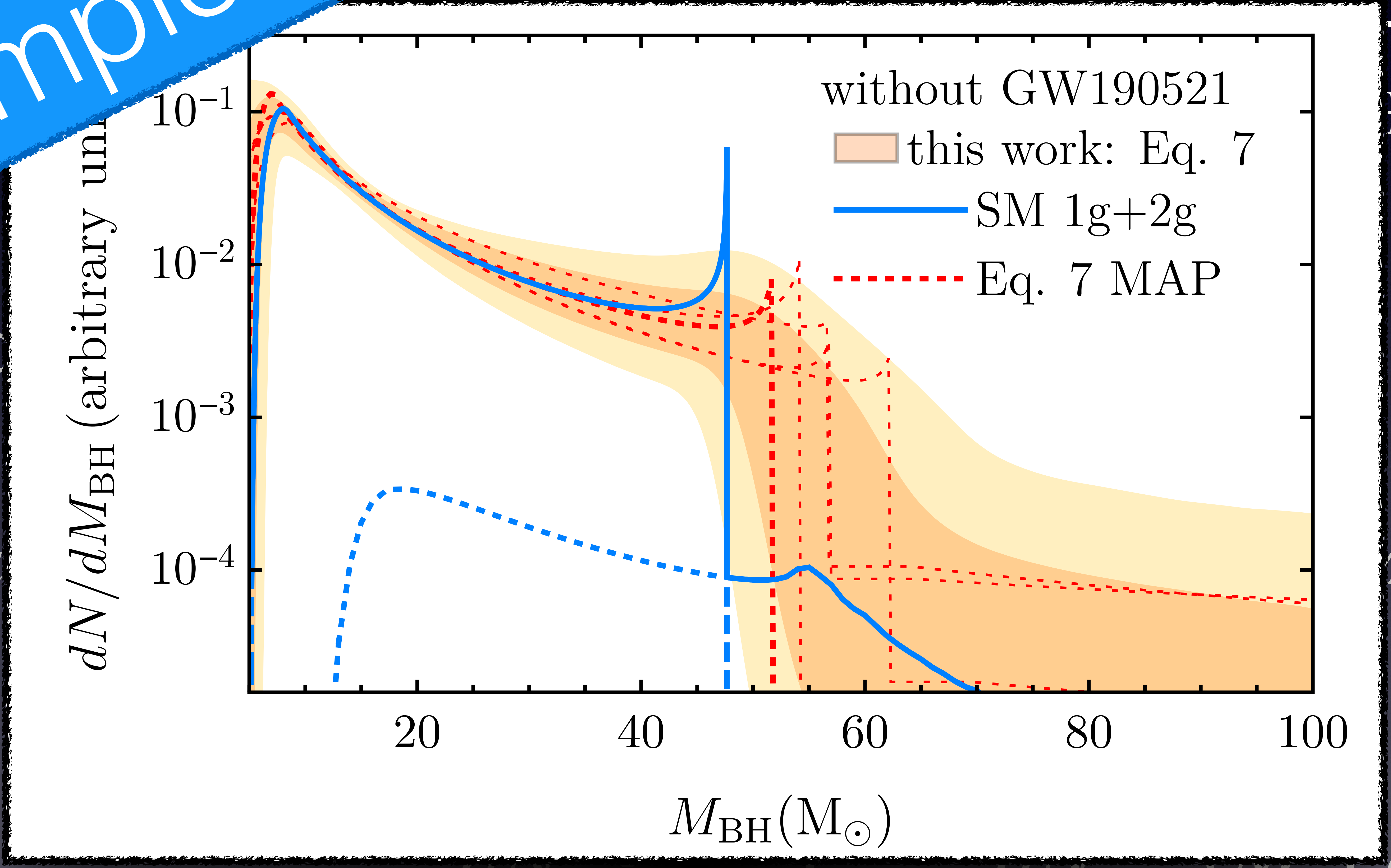


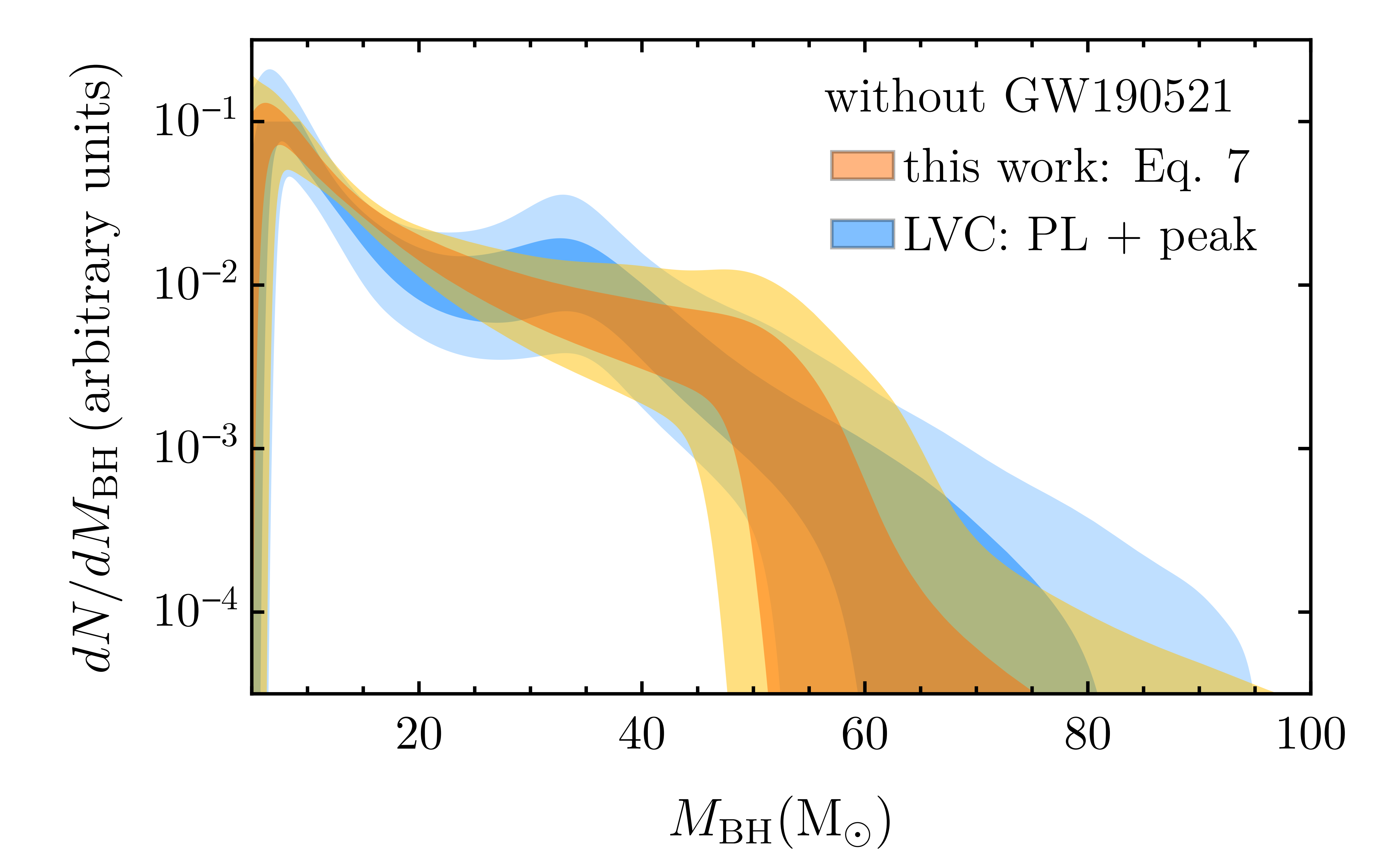
$$\frac{dN}{dM_{BH}} \sim \int dM_a \frac{dN}{dM_a}(M_a) \frac{dN^{(1g)}(M_{BH} - M_a)}{dM_a}$$

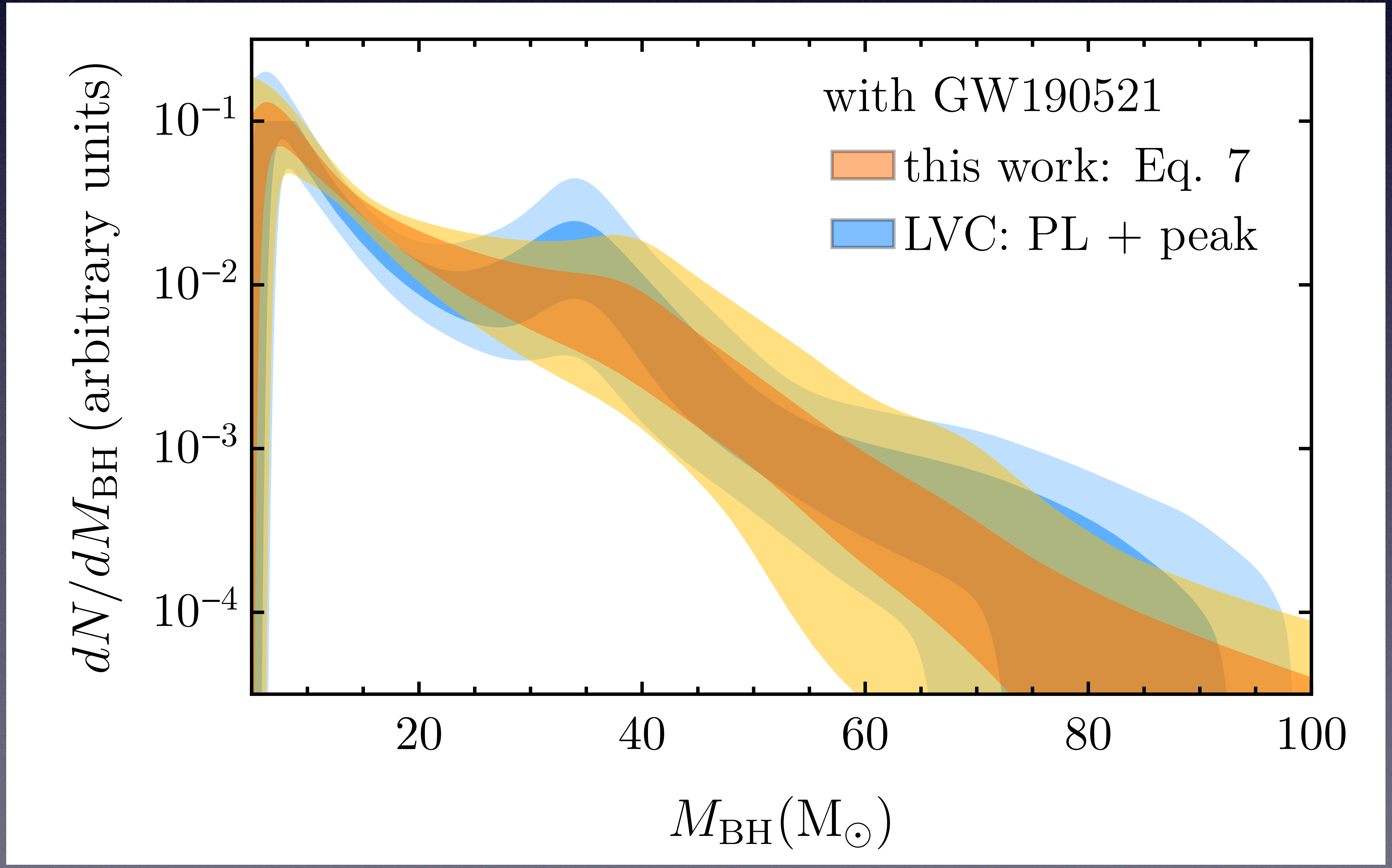
Black Hole Population Statistics

after GWTC-2

$$p\left(m_1, m_2 \mid \vec{\theta}\right) \propto \frac{dN^{(1g)}}{dM_{BH}} + \lambda \frac{dN^{(2g)}}{dM_{BH}}$$

Baxter, Croon, SDM, Sakstein
ApJL + 2104.02685v2





Black Hole Population Statistics

after GWTC-2

$$p\left(m_1, m_2 \mid \vec{\theta}\right) \propto \frac{dN^{(1\mathrm{g})}}{dM_{\mathrm{BH}}} + \lambda \frac{dN^{(2\mathrm{g})}}{dM_{\mathrm{BH}}}$$

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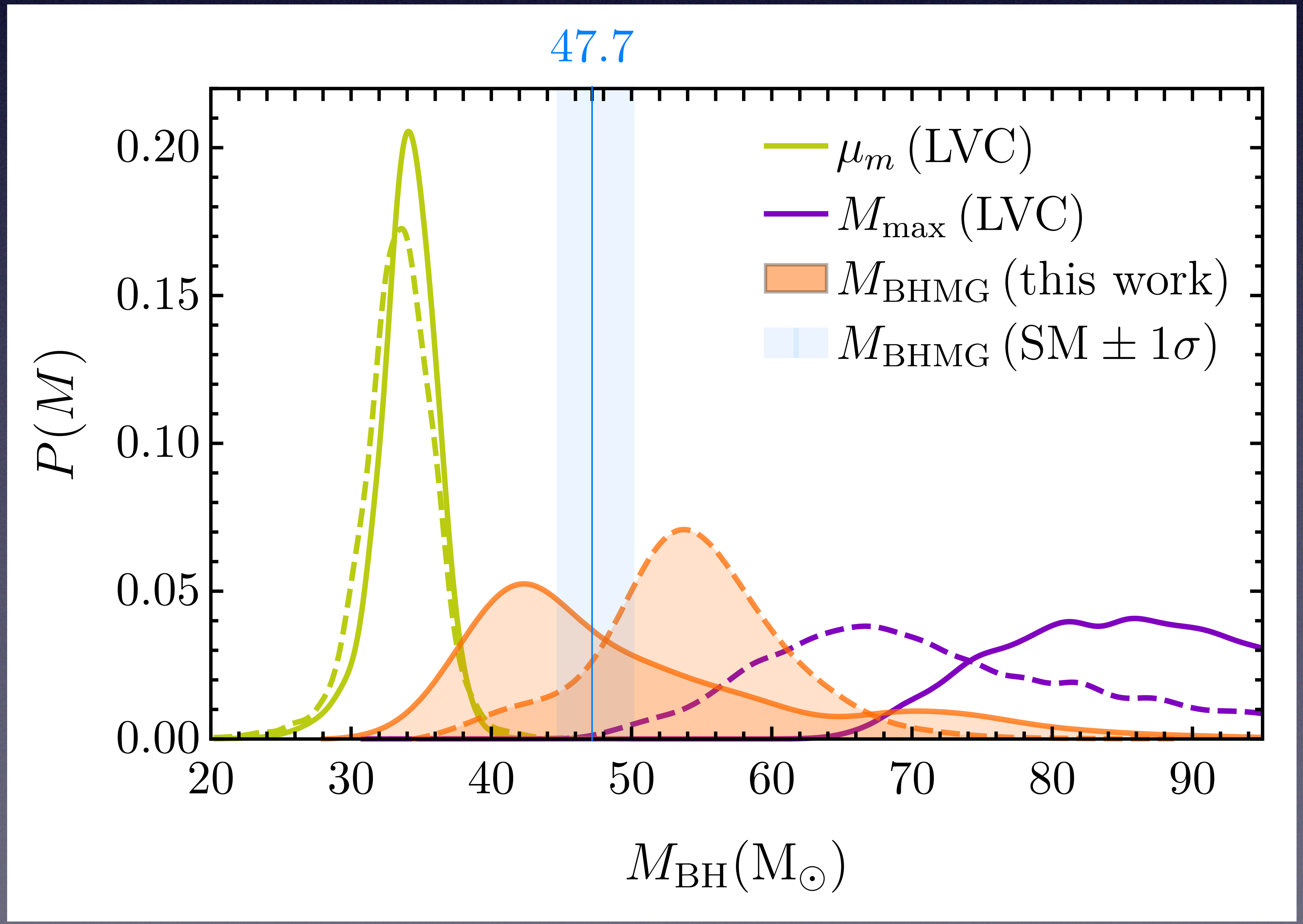

Conclusions

xkcd.com/1022/

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xkcd.com/1022/

- LIGO is in the middle of its "discovery bump" — we are learning so much more about the Universe all the time!
- Physically motivated mass functions will soon reveal intimate details of the black hole creation mechanism
- The future is exciting!

Thanks!

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