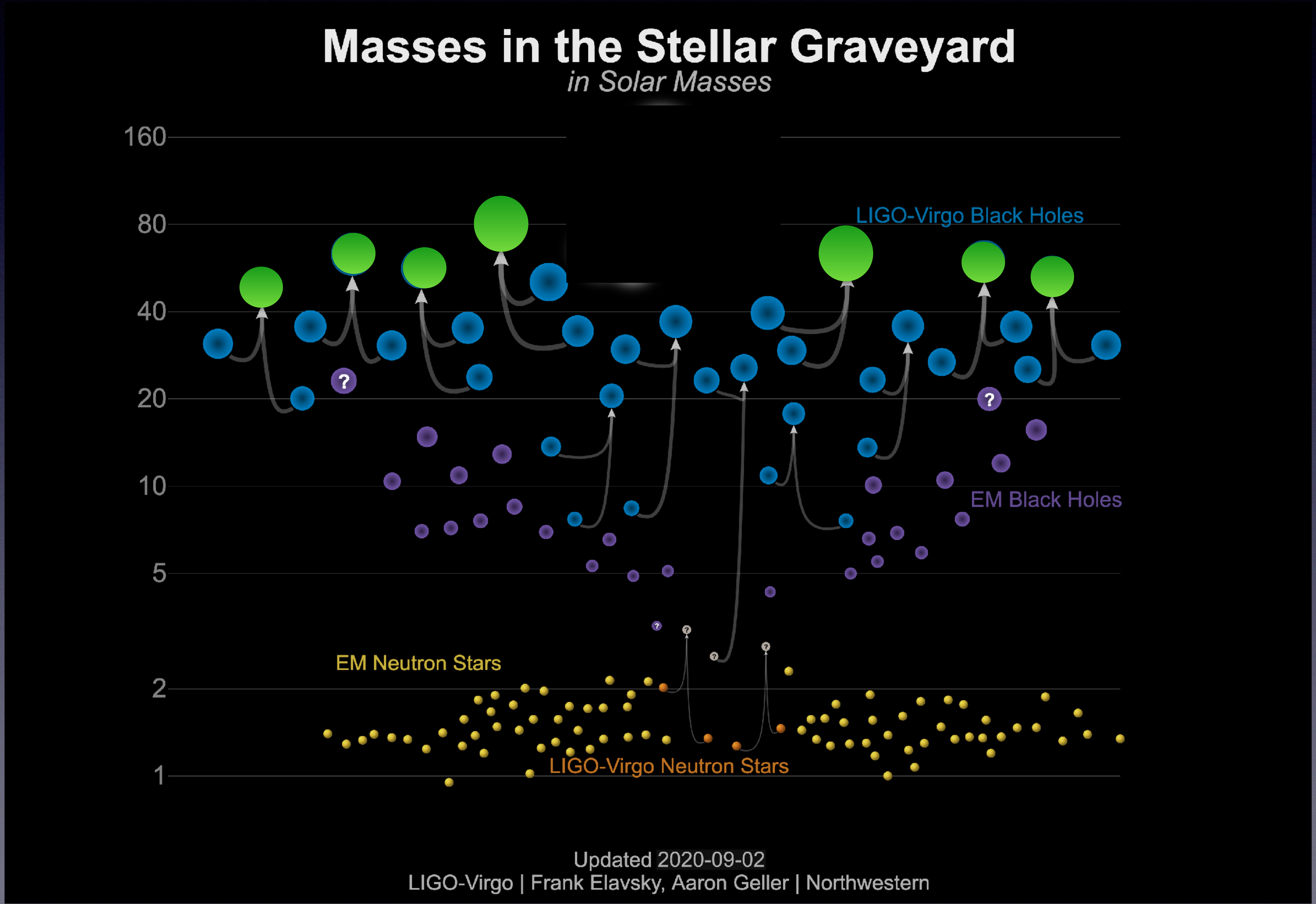
New Physics and the Black Hole Mass Gap

Samuel D. McDermott, Fermilab (6th Floor)

Work with Djuna Croon + Jeremy Sakstein: 2007.00650 [hep-ph], 2007.07889 [gr-qc]

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

LIGO Observations: O1+O2



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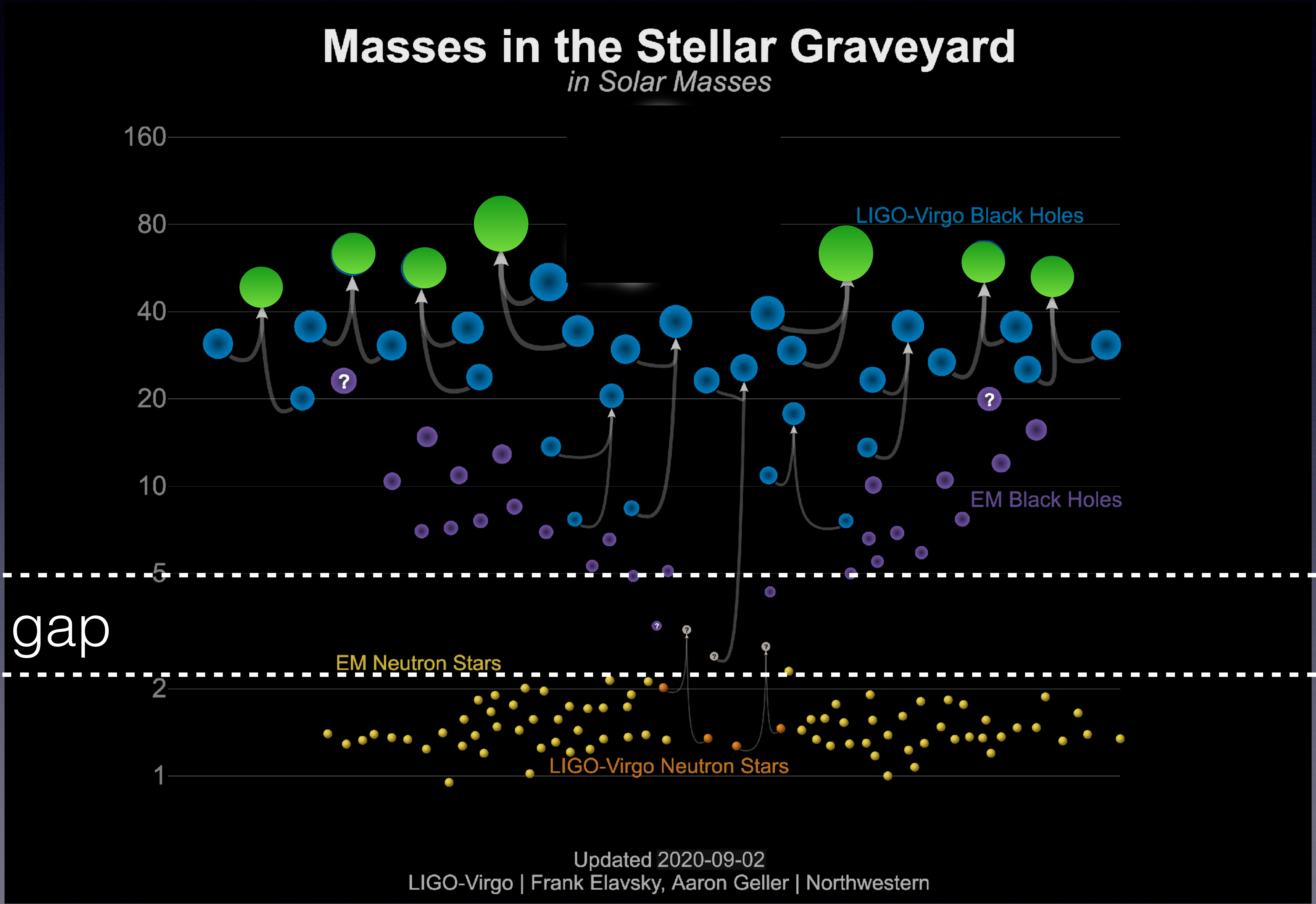
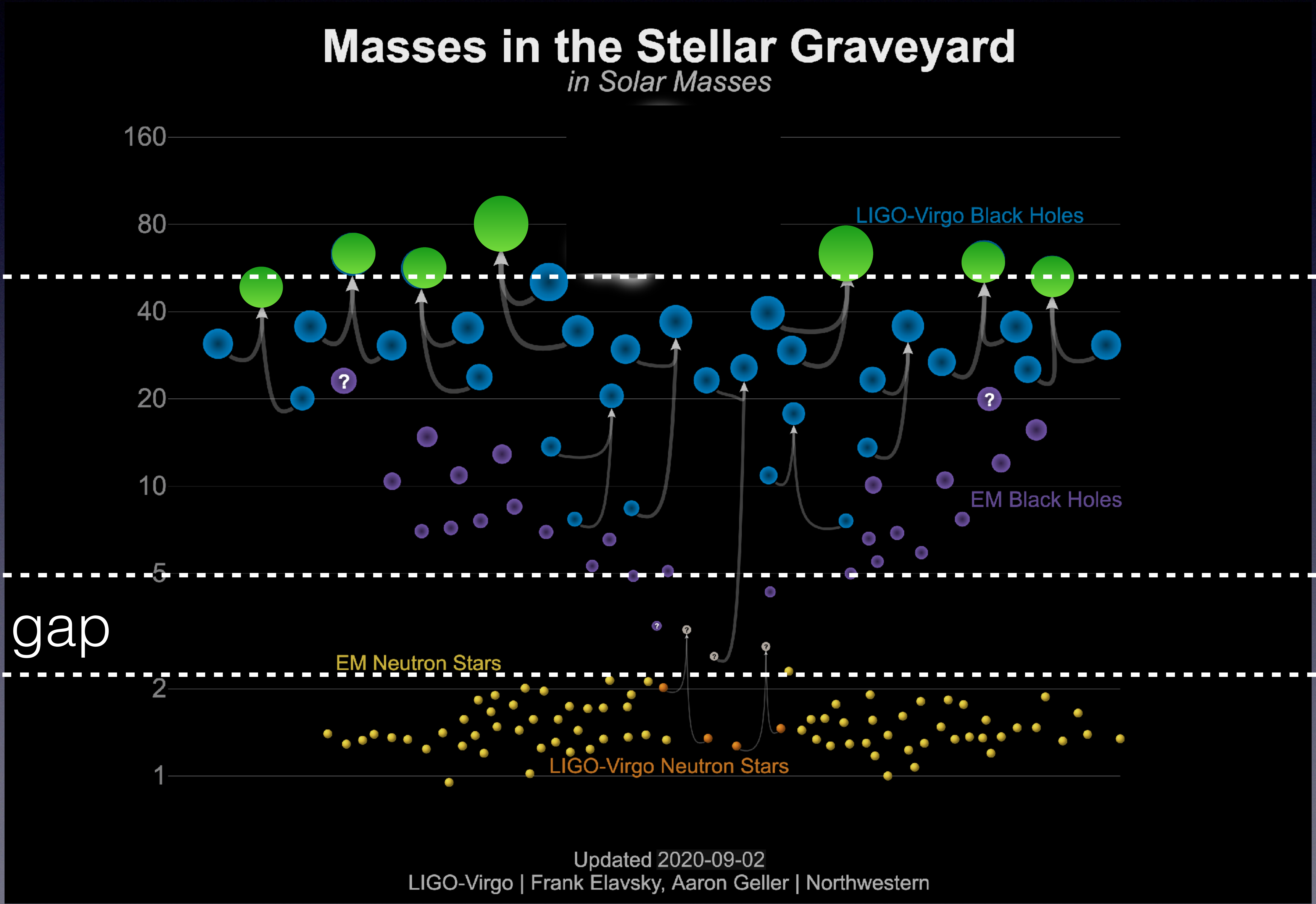


“lower” mass gap

LIGO Observations: O1+O2

“Black hole mass ceiling”

“lower” mass gap



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“upper” mass gap

“Black hole mass ceiling”

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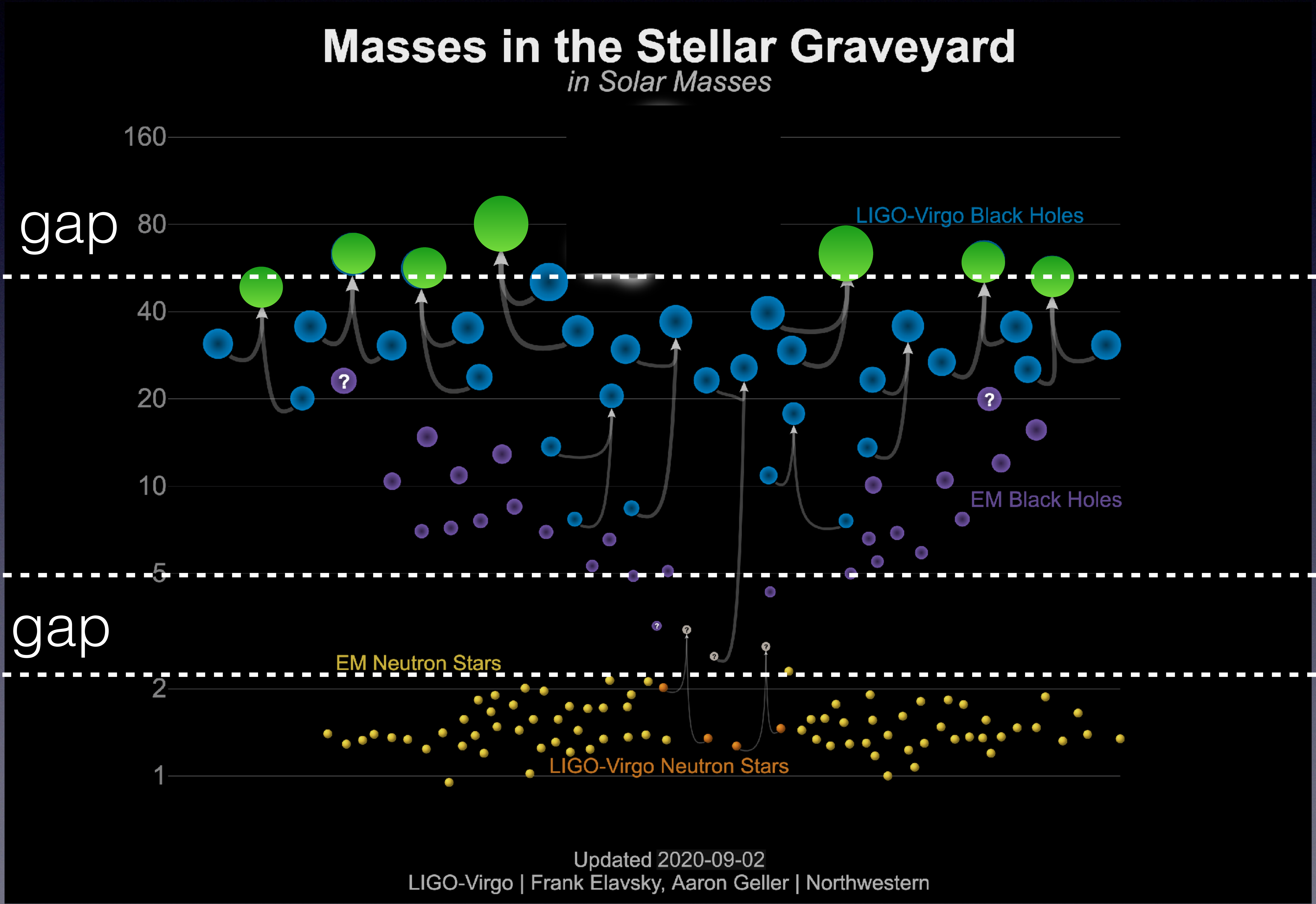
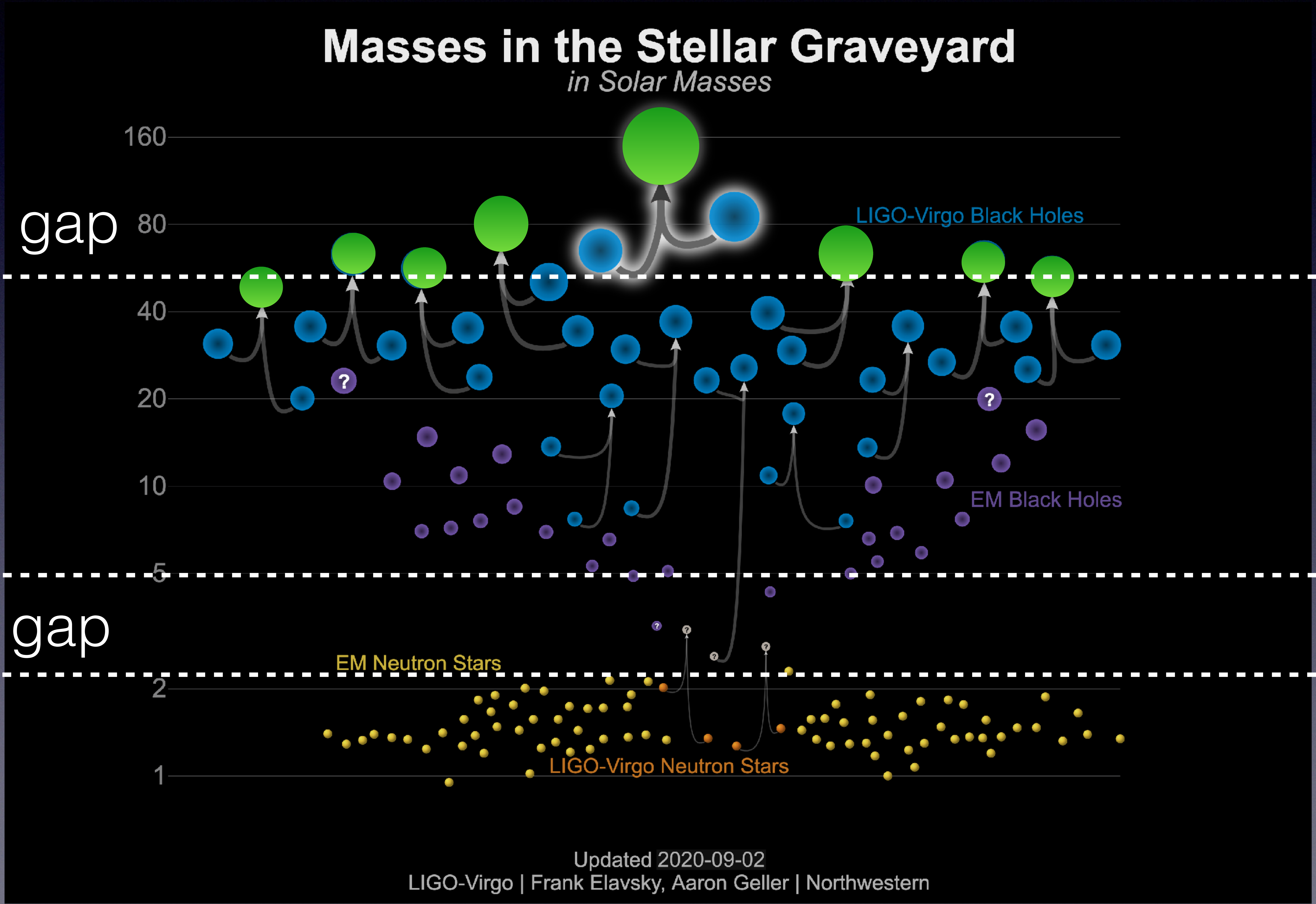


LIGO Observations: O1+O2

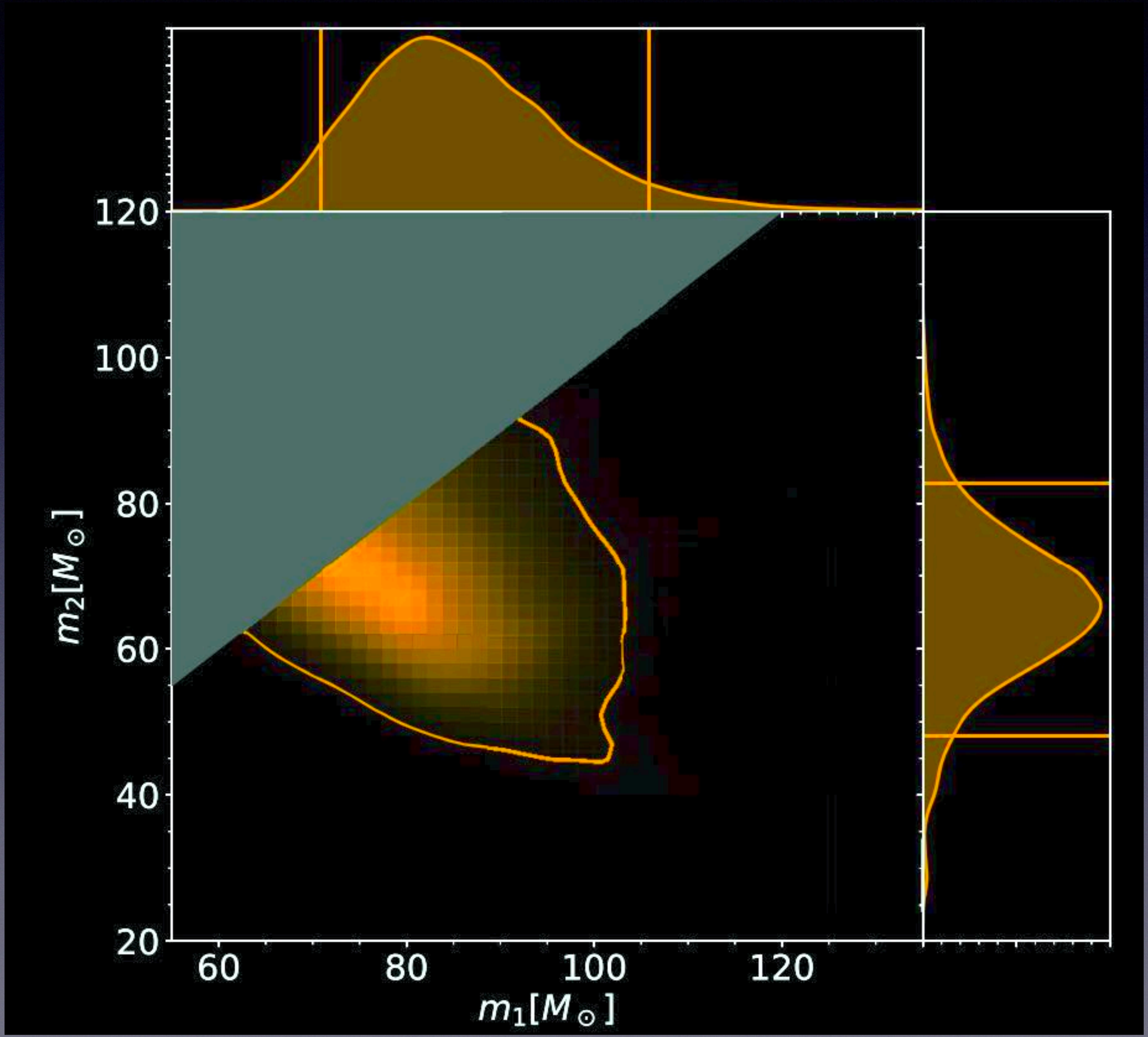
"upper" mass gap

"Black hole mass ceiling"

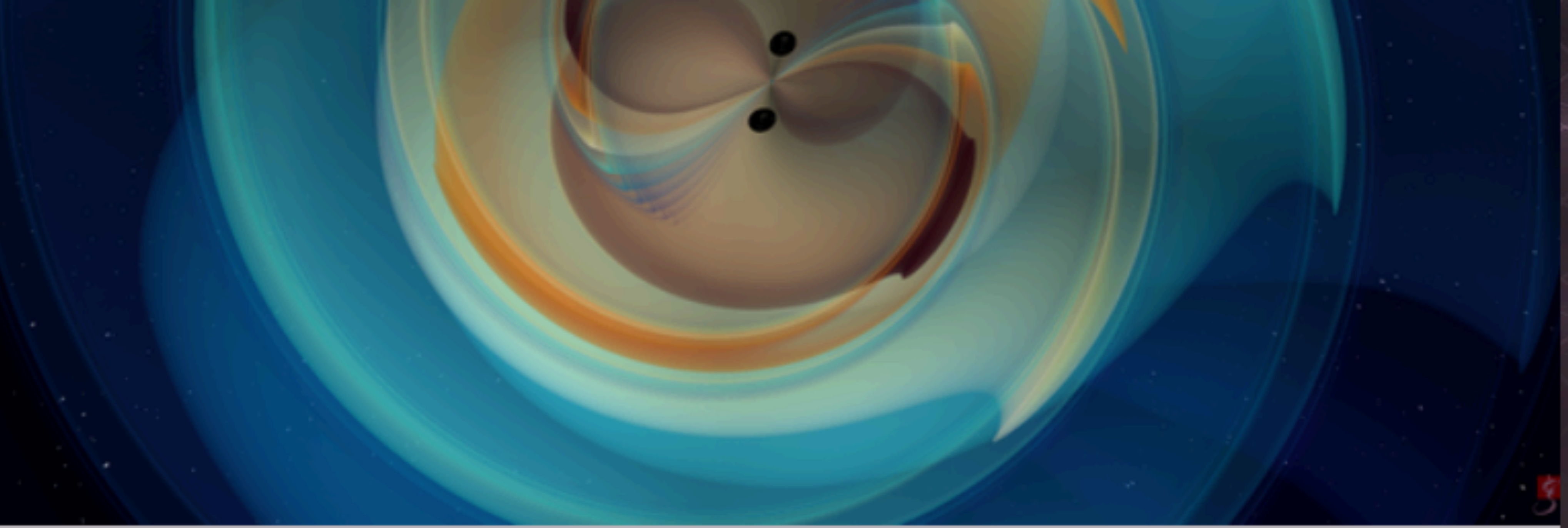
"lower" mass gap



GW190521



From R. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. 125, 101102 (2020).



A still image from a numerical simulation of two black holes that inspiral and merge, emitting gravitational waves. The black holes have large and nearly equal masses, with one only 3% more massive than the other. The simulated gravitational wave signal is consistent with the GW190521 observation made by the LIGO and Virgo. (Credit: N. Fischer, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes (SXS) Collaboration)

https://www.ligo.caltech.edu/news/ligo20200902

W19052

A "bang" in LIGO and Virgo detectors signals most massive gravitational-wave source yet

News Release • September 2, 2020

A binary black hole merger likely produced grav
to the energy of eight suns.

FORBES.COM

LIGO's Biggest Mass Merger Ever Foretells A Black Hole Revolution

From R. Abbott et al. (LIGO Scienti... laboration),
Phys. Rev. Lett. 125, 101102 (2020

Astronomers dete
black hole for the

BY SOPHIE LEWIS
SEPTEMBER 3, 2020 / 7:03 AM / CBS NEWS

The New York Times

These Black Holes Shouldn't Exist, but There They Are

Black holes: Cosmic signal rattles after 7 billion years

By Jonathan Amos
BBC Science Correspondent

NewScientist IDEEËN DIE DE WERELD VERANDEREN
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Zwaartekrachtsgolven van 'te zware' zwart gaten waargenomen

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LIGO and Virgo Capture Their Most Massive Black Holes Yet

ars TECHNICA

CHIRP, CHIRP, BANG, BANG —

Meet GW190521—a black-hole merger for the record books

It's the most massive, distant, and energetic black-hole merger yet.

JENNIFER OUELLETTE - 9/2/2020, 11:54 AM

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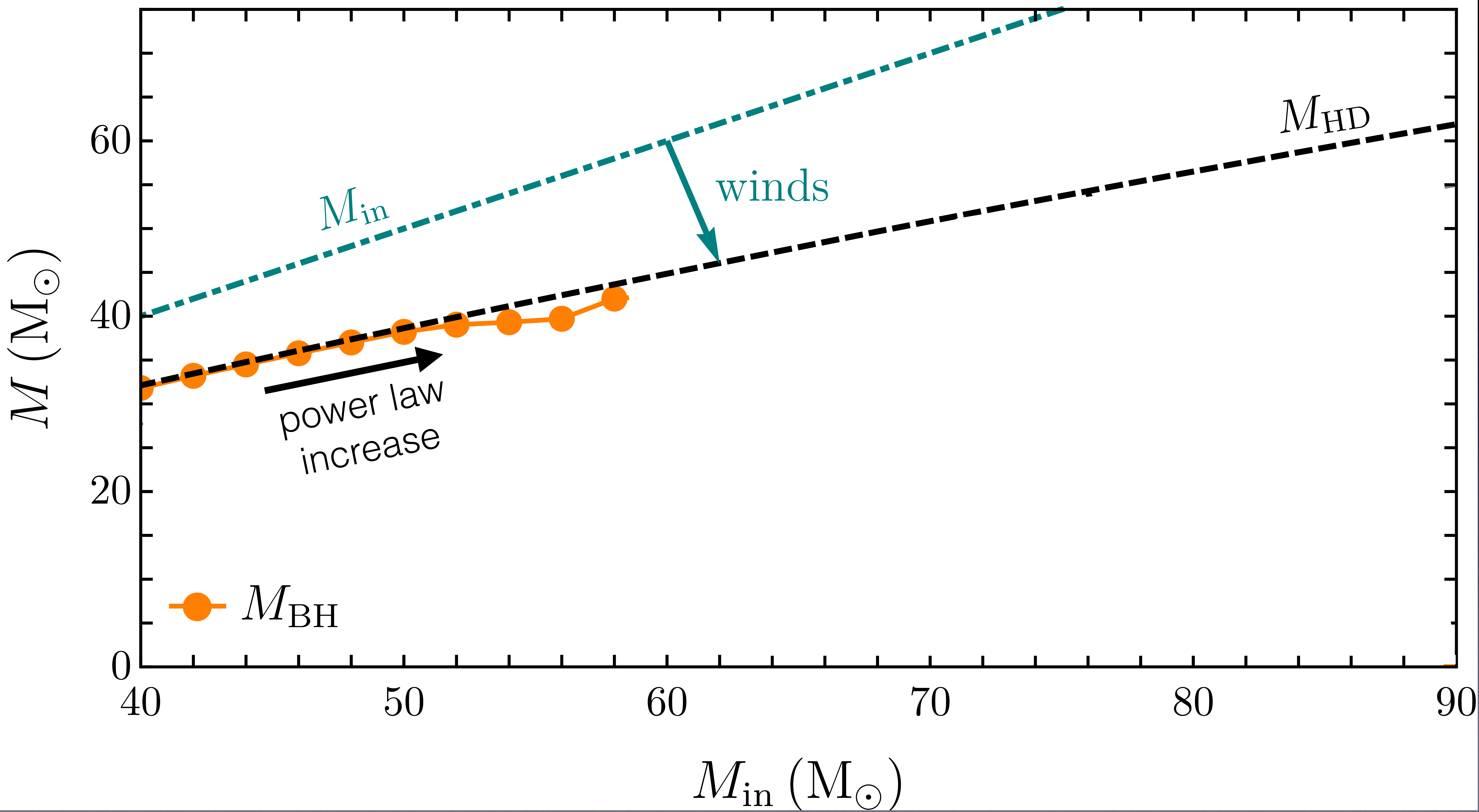
2007.07889



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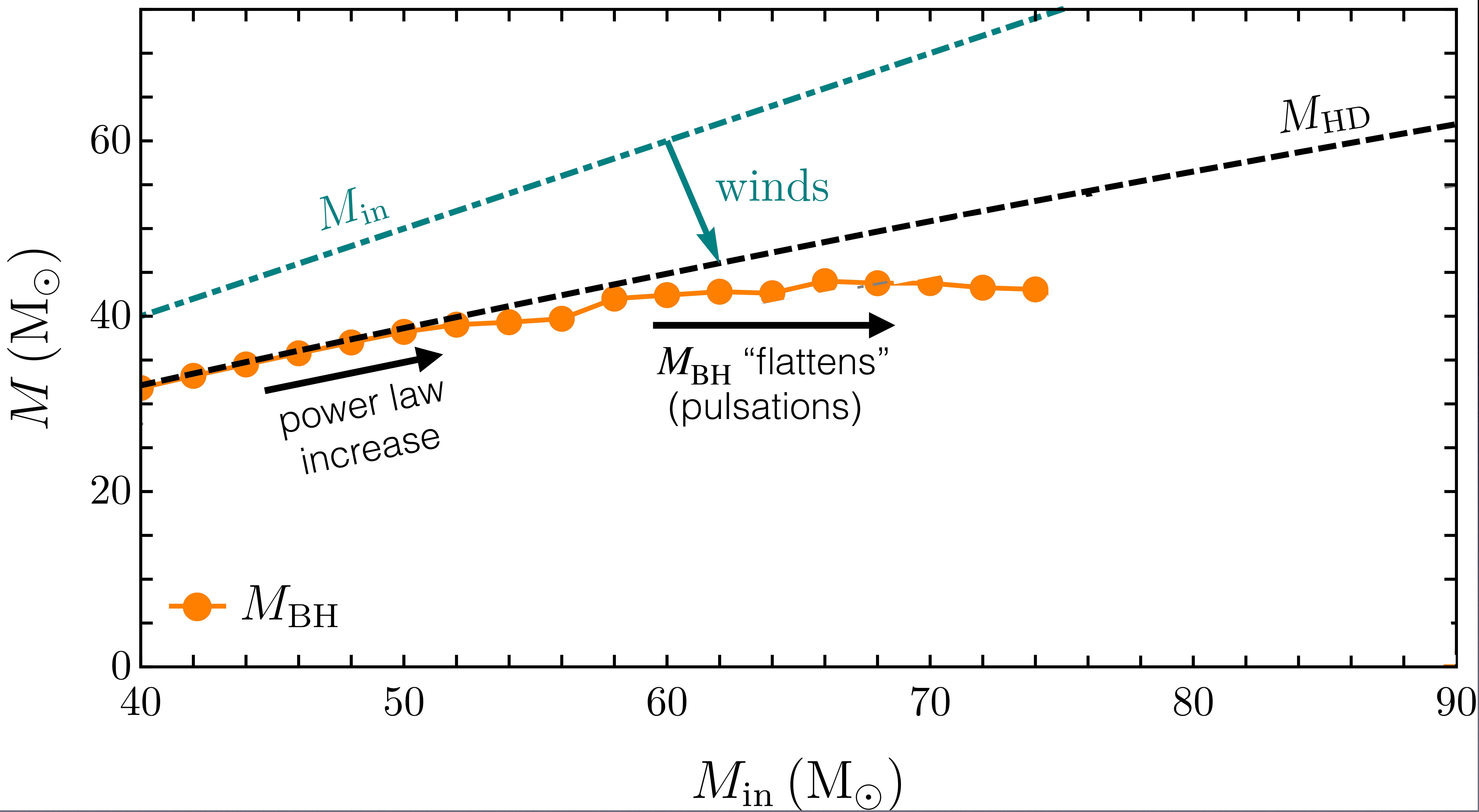

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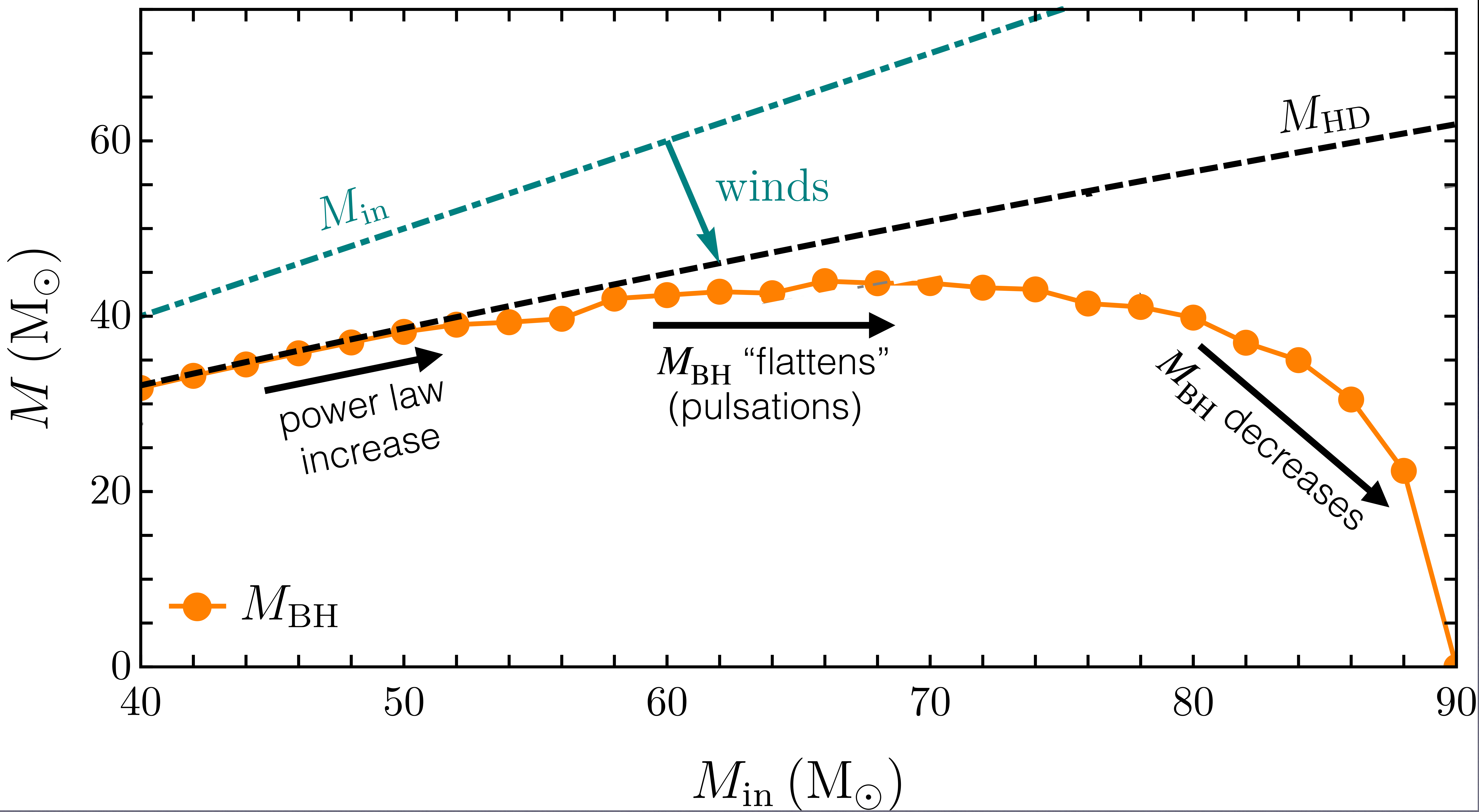

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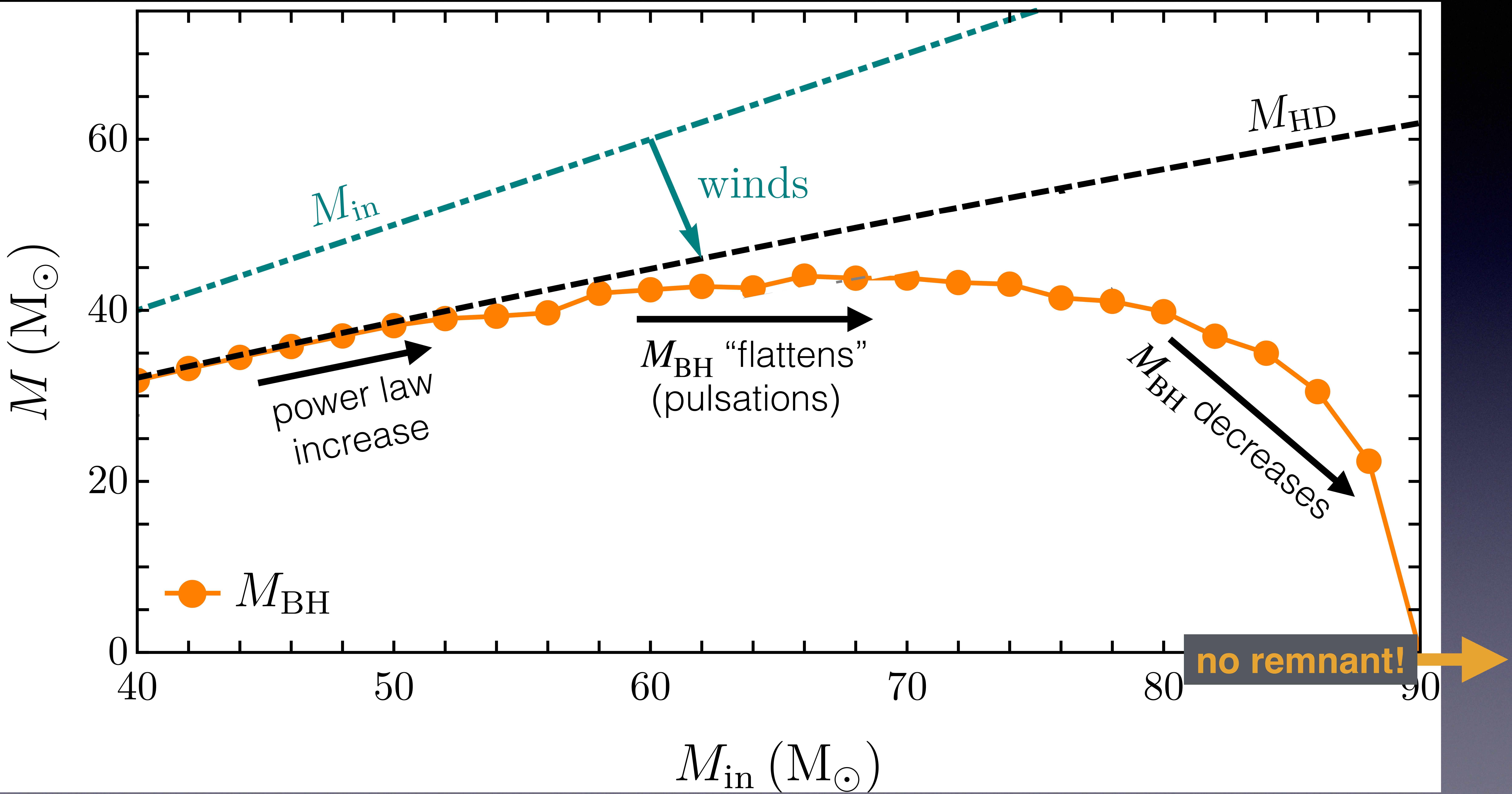

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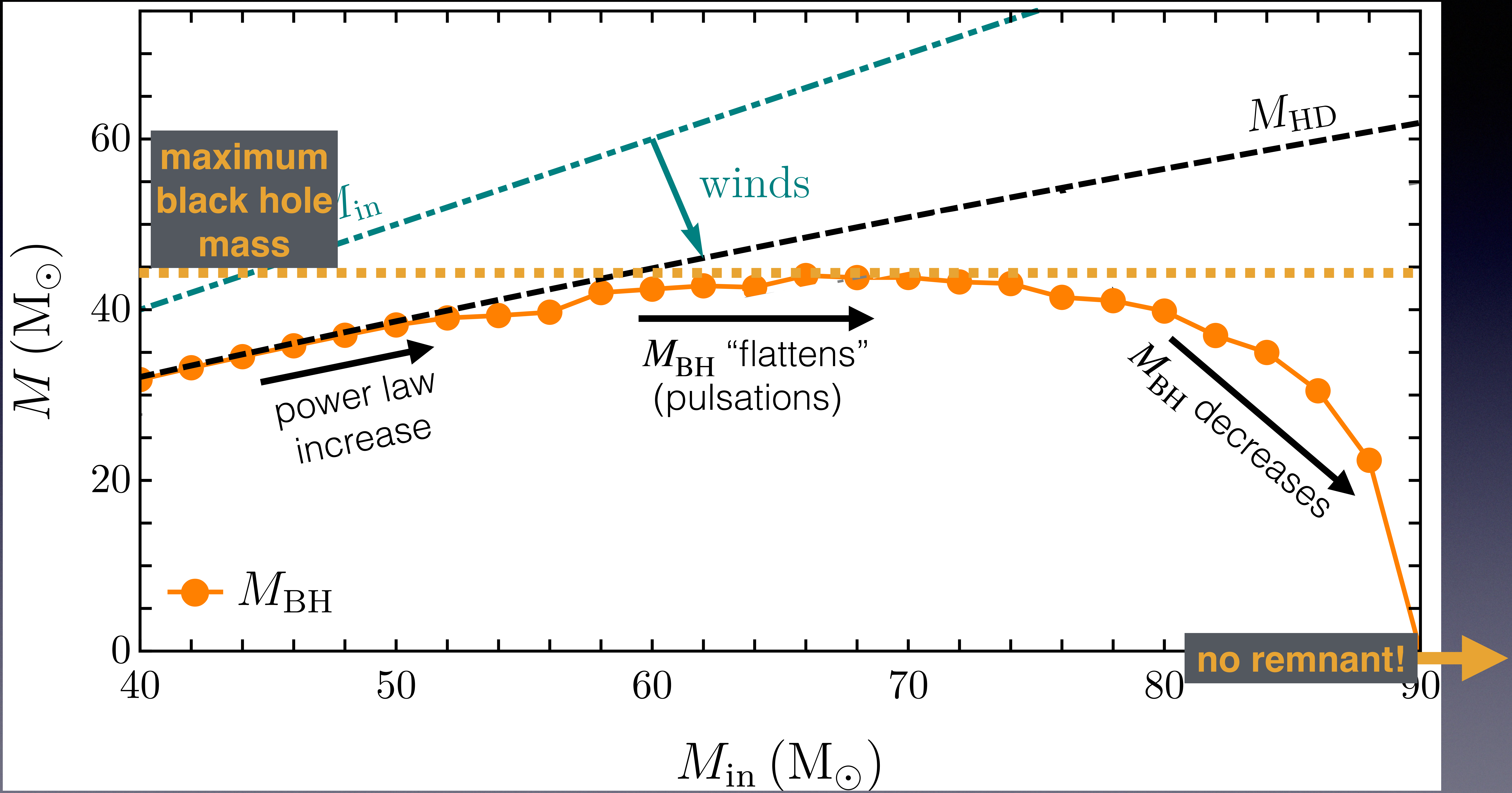

Outline

1. Physics of the pair instability mechanism
2. Beyond-the-Standard-Model explanations of GW190521
3. Standard Model explanations of GW190521
4. Future prospects

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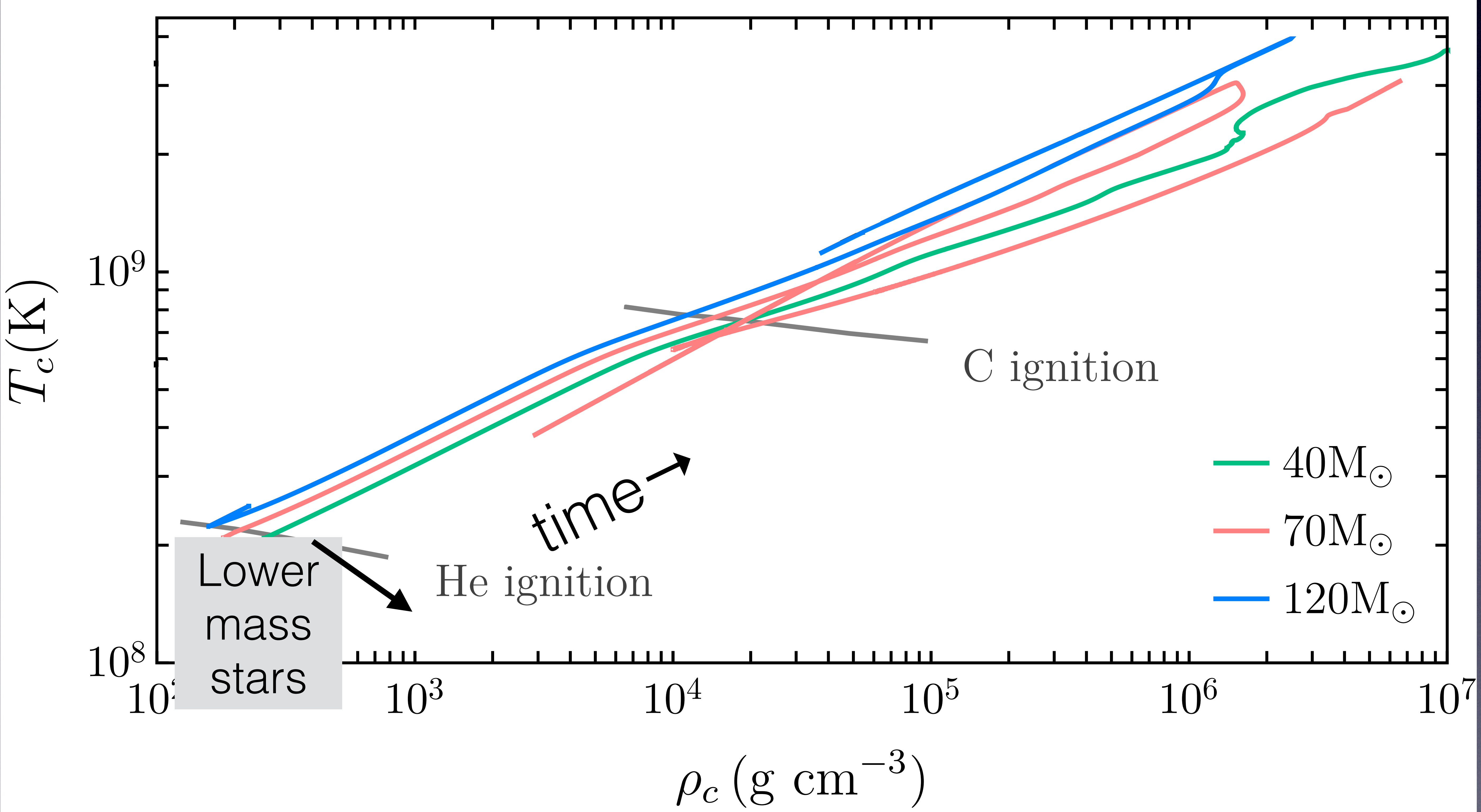
2007.00650 + 2007.07889

Evolution of Pop III Stars

- Simulate stars with `MESA v12778*` starting from the zero-age helium branch through pulsations
- Final BH mass is the material gravitationally bound to the core after hydostratic equil-ibrium is regained (following pulsations)



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

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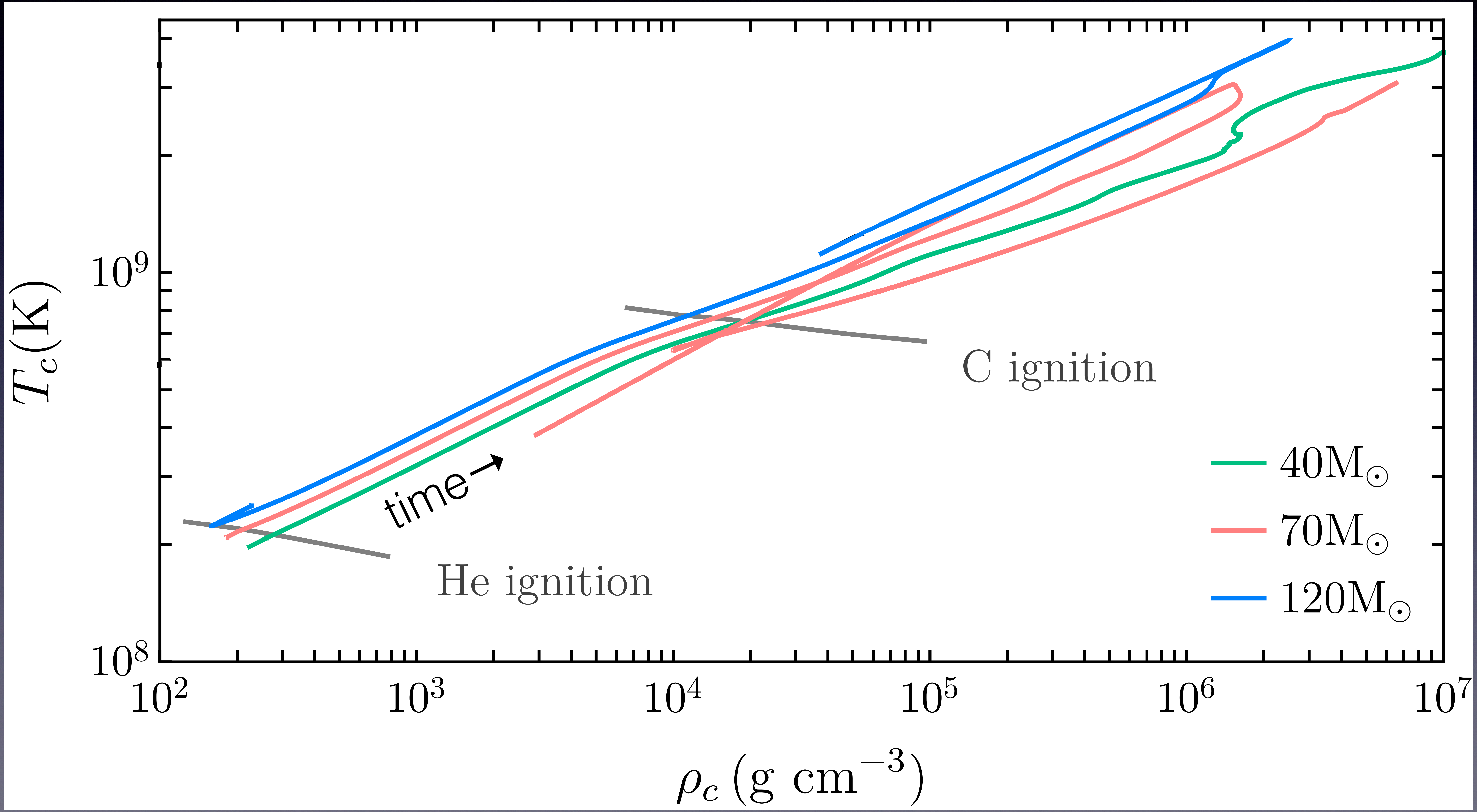
Evolution* of Pop III Stars



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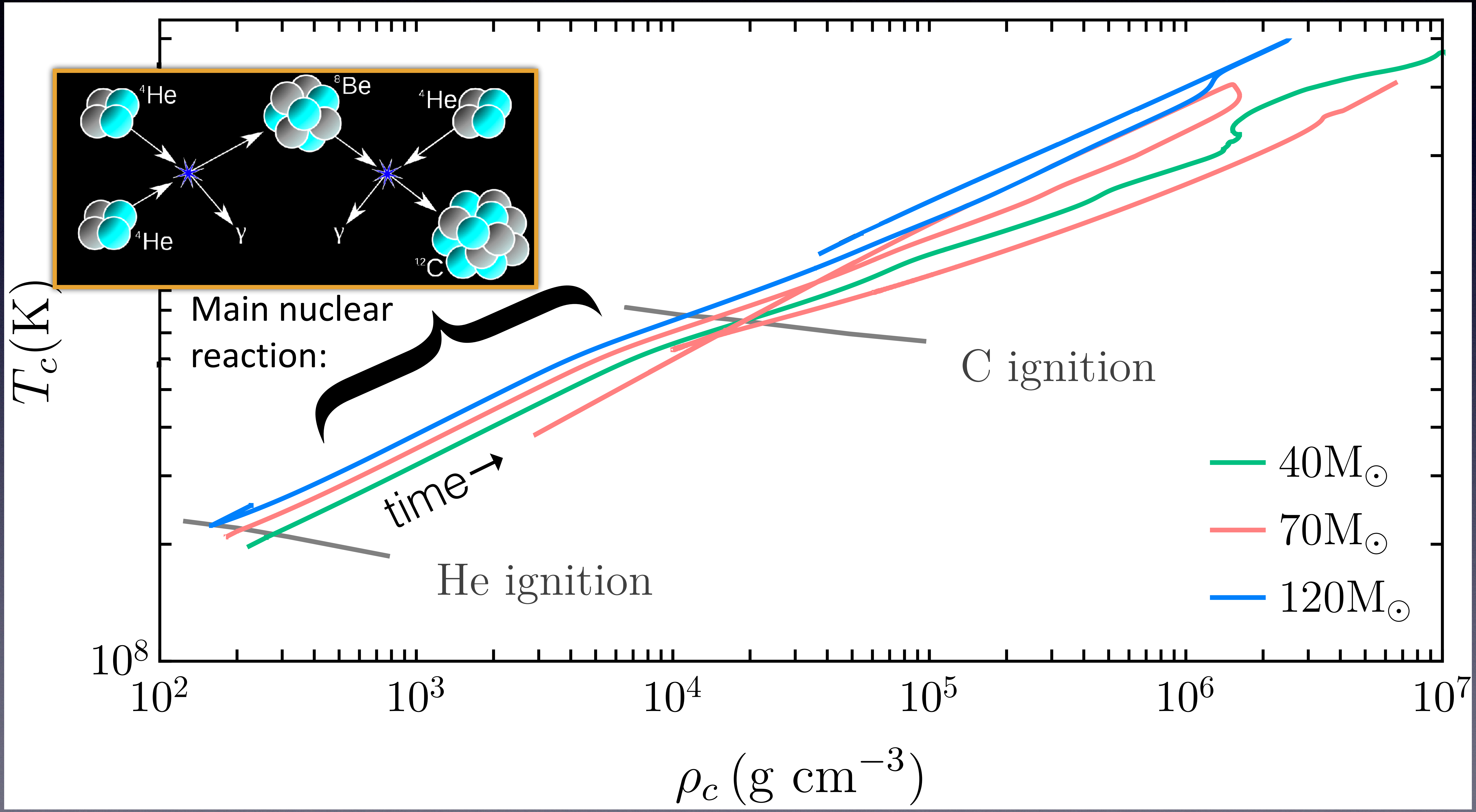

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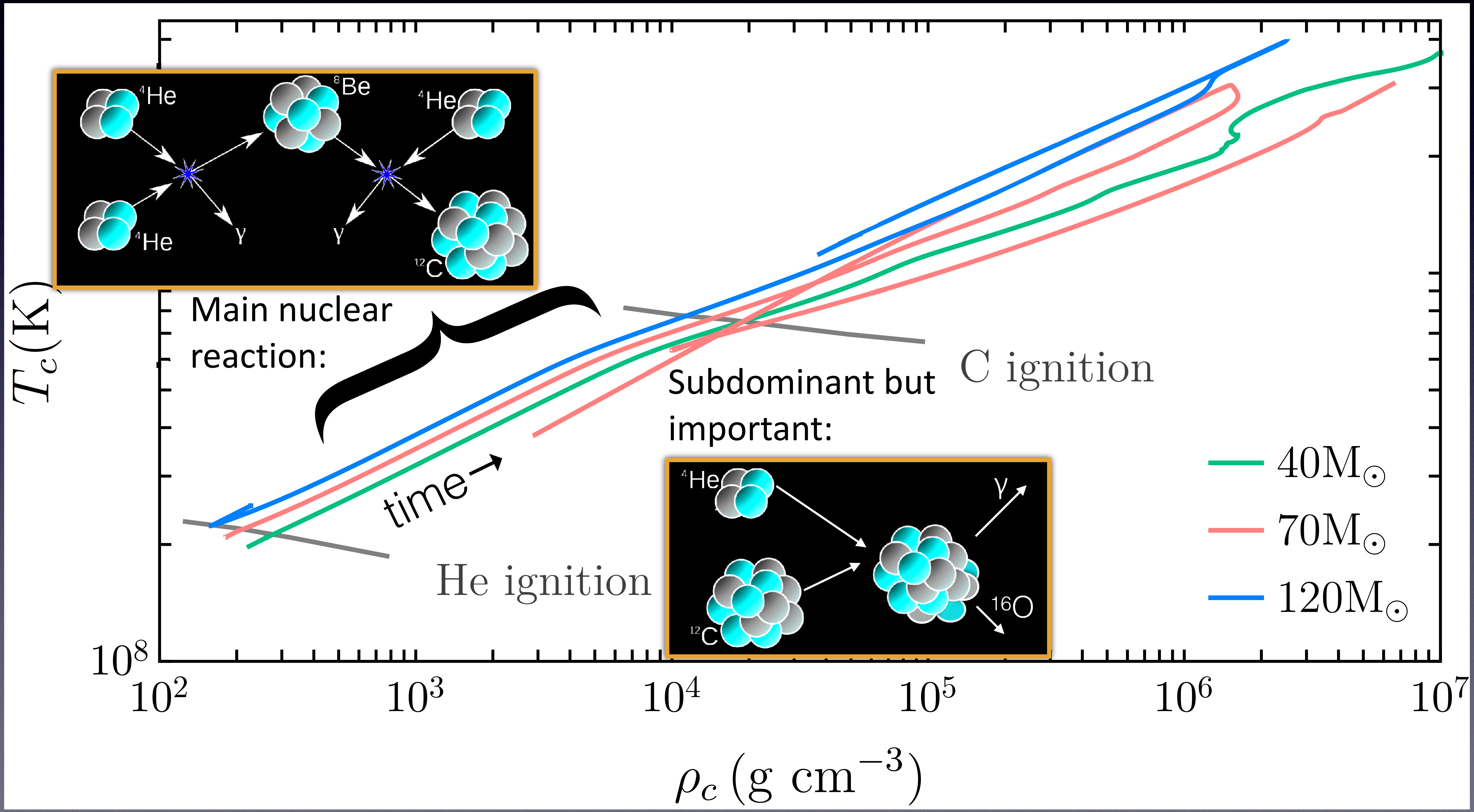

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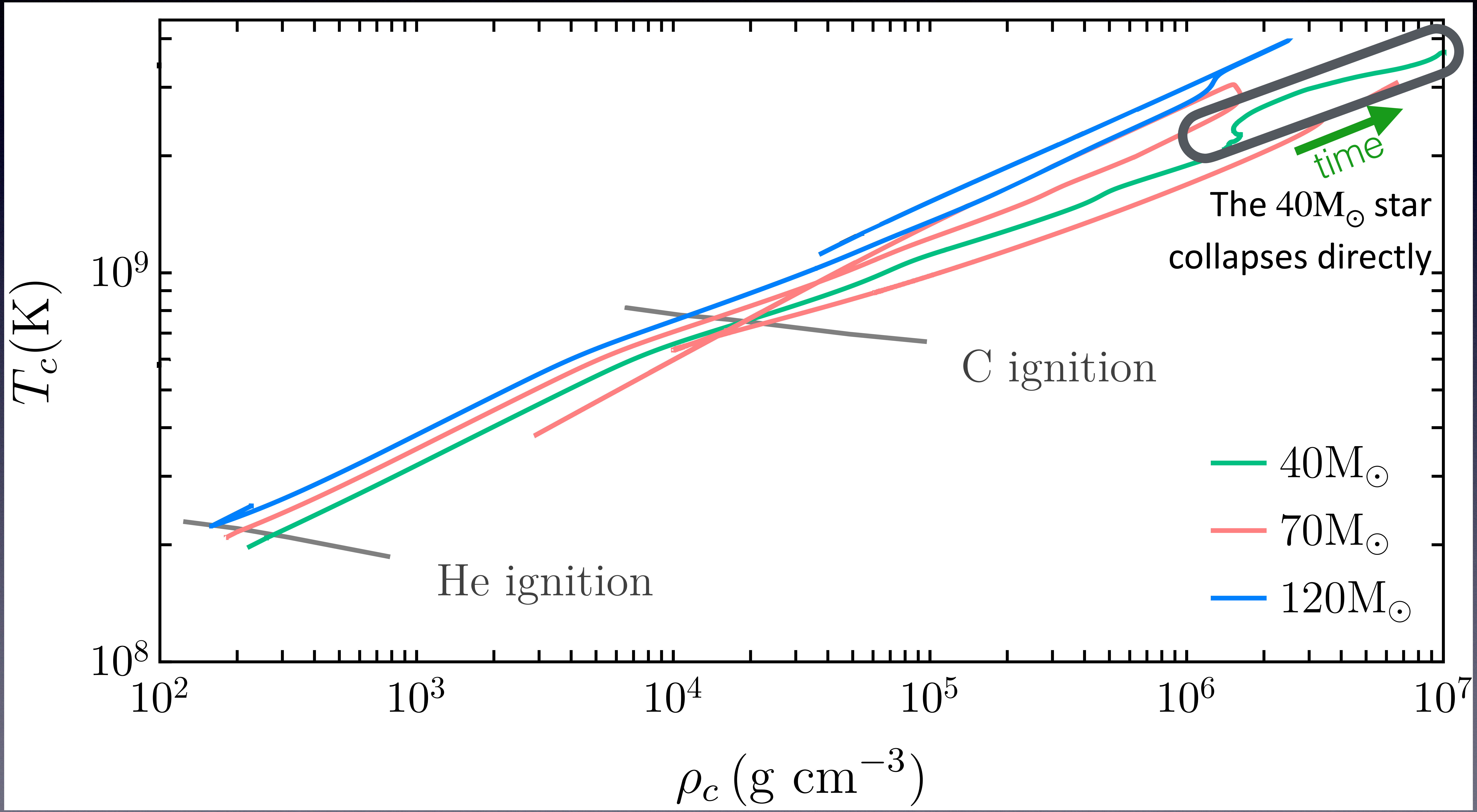

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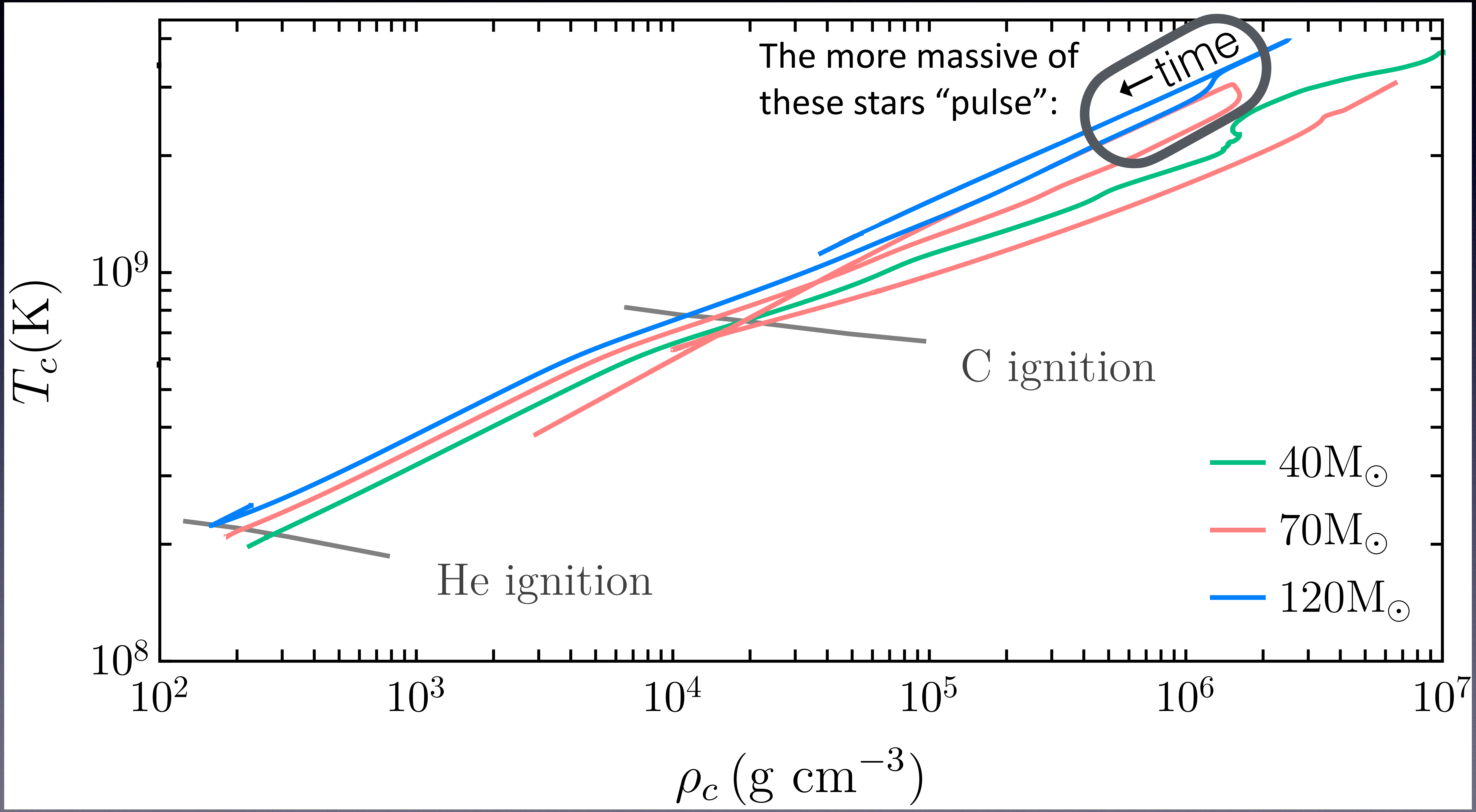

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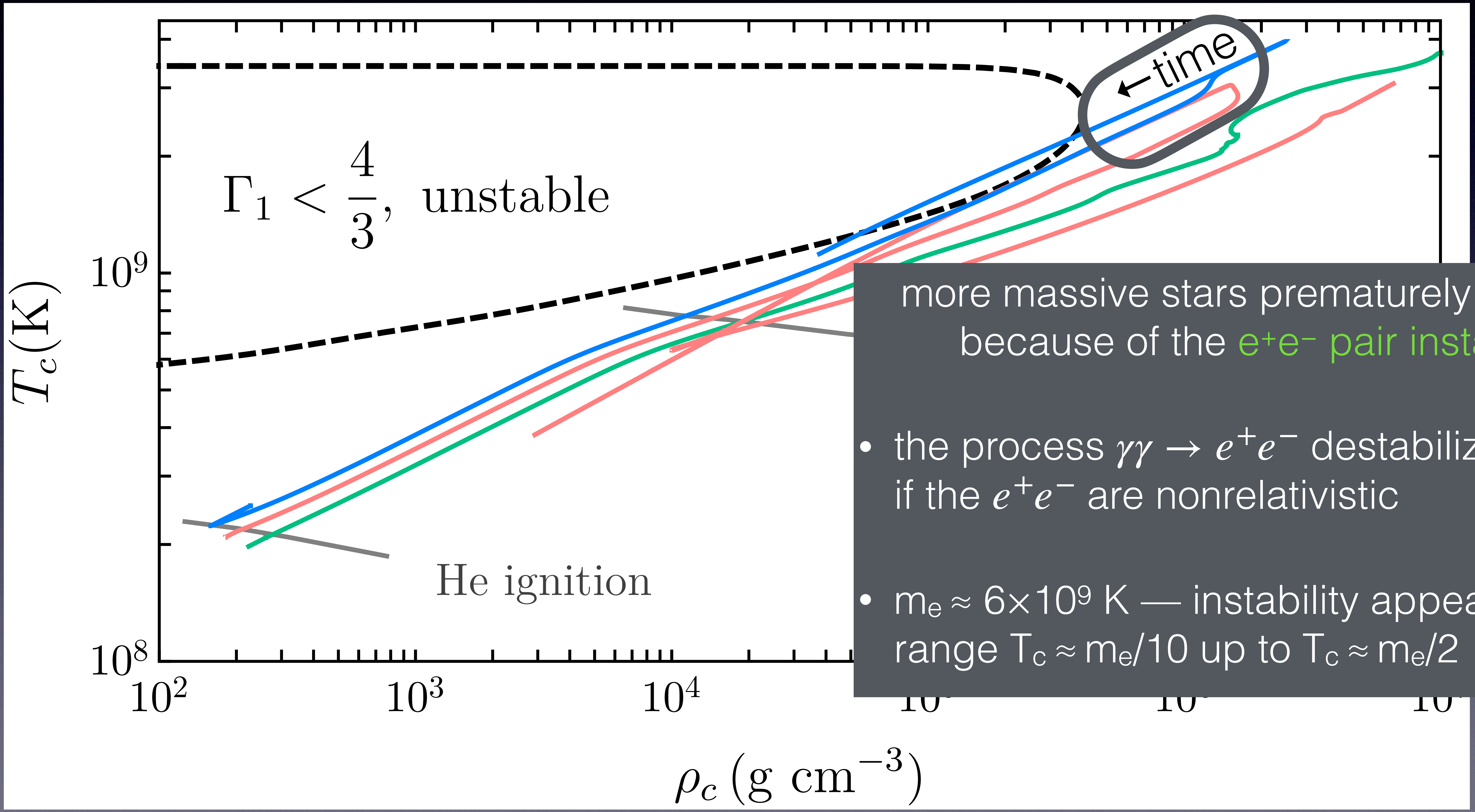
(Pulsational) Pair Instability



more massive stars prematurely collapse because of the e^+e^- pair instability

- the process $\gamma\gamma \to e^+e^-$ destabilizes the star if the e^+e^- are nonrelativistic
- $m_e \approx 6\times10^9$ K — instability appears in the range $T_c \approx m_e/10$ up to $T_c \approx m_e/2$

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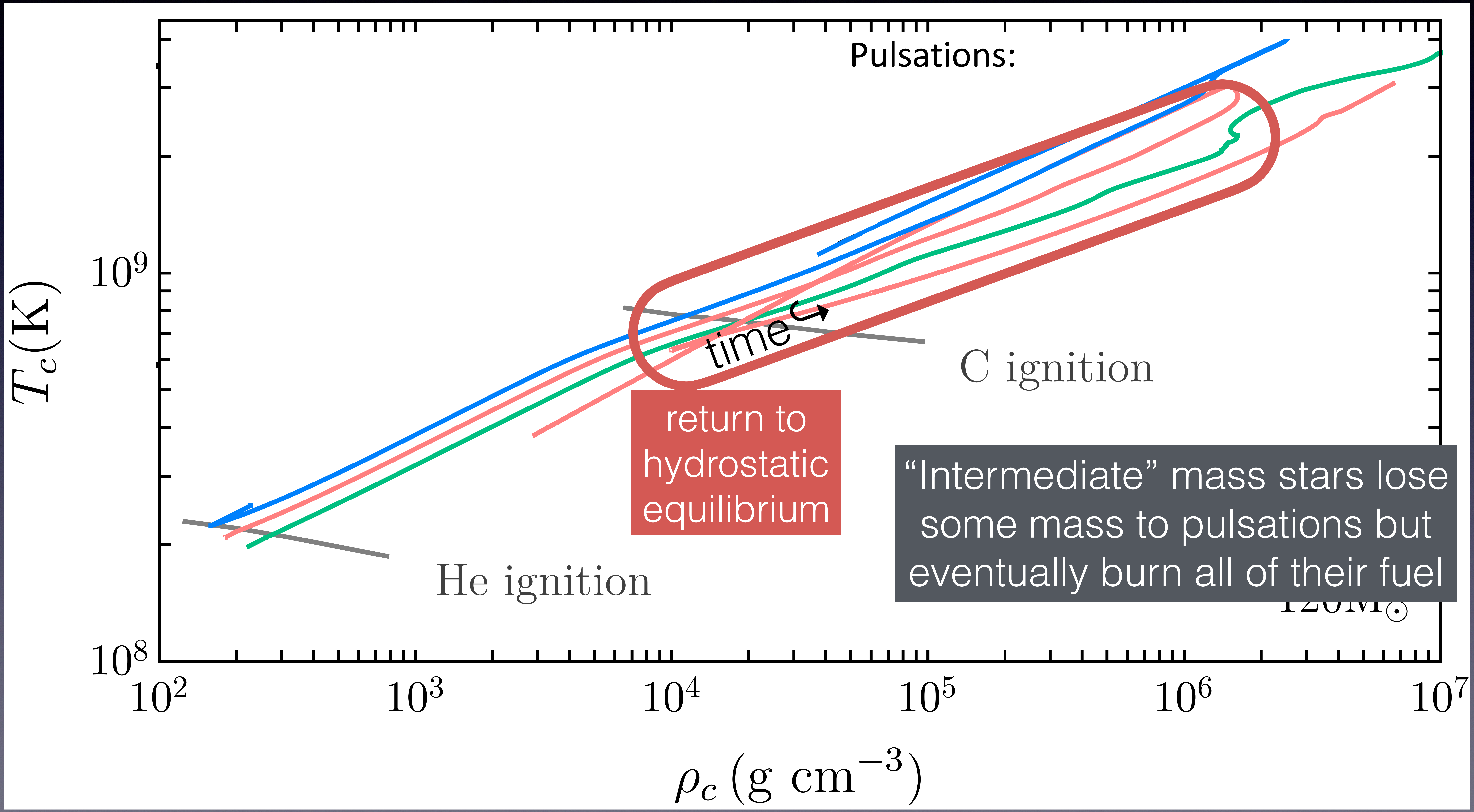
Outcome of Pulsations



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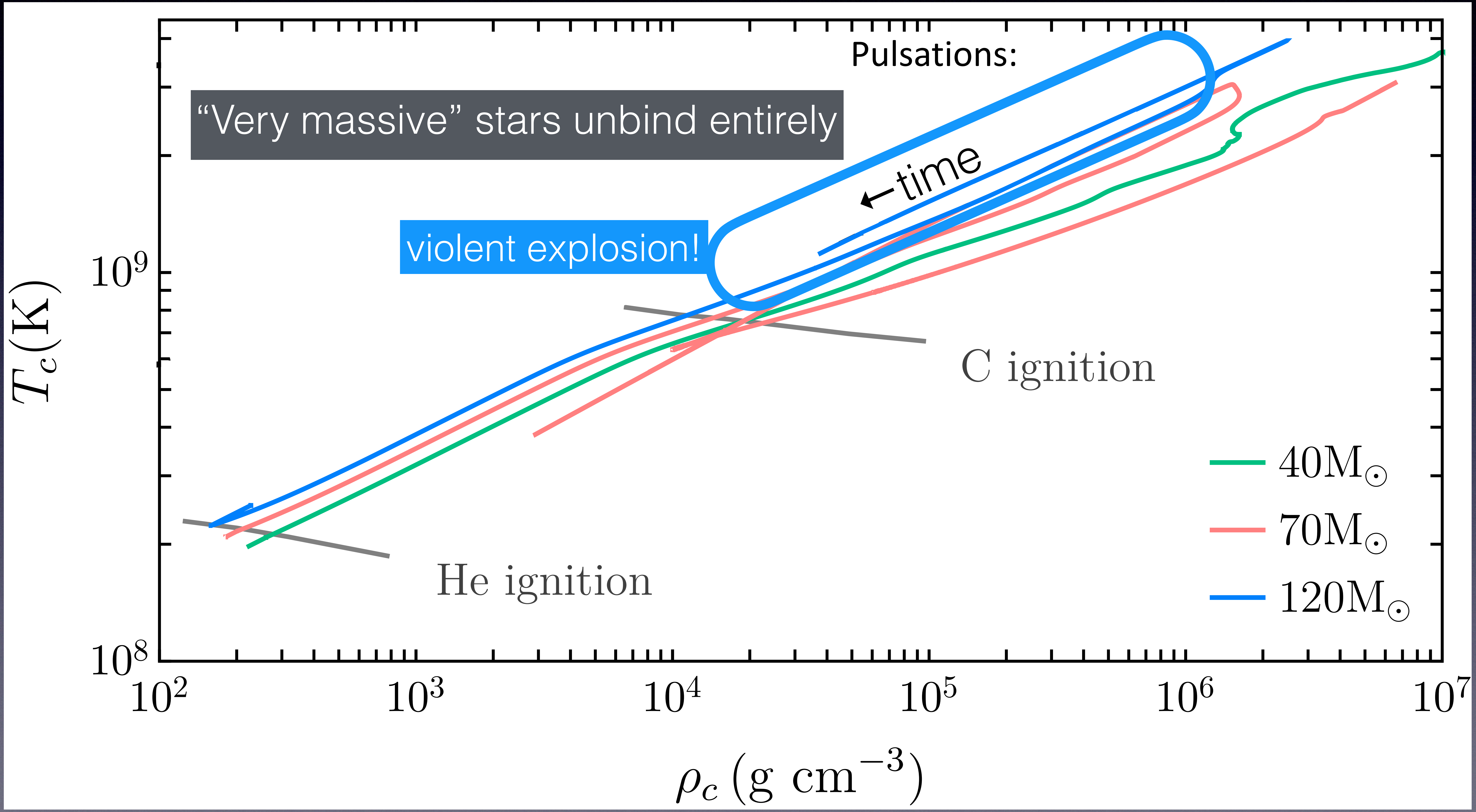

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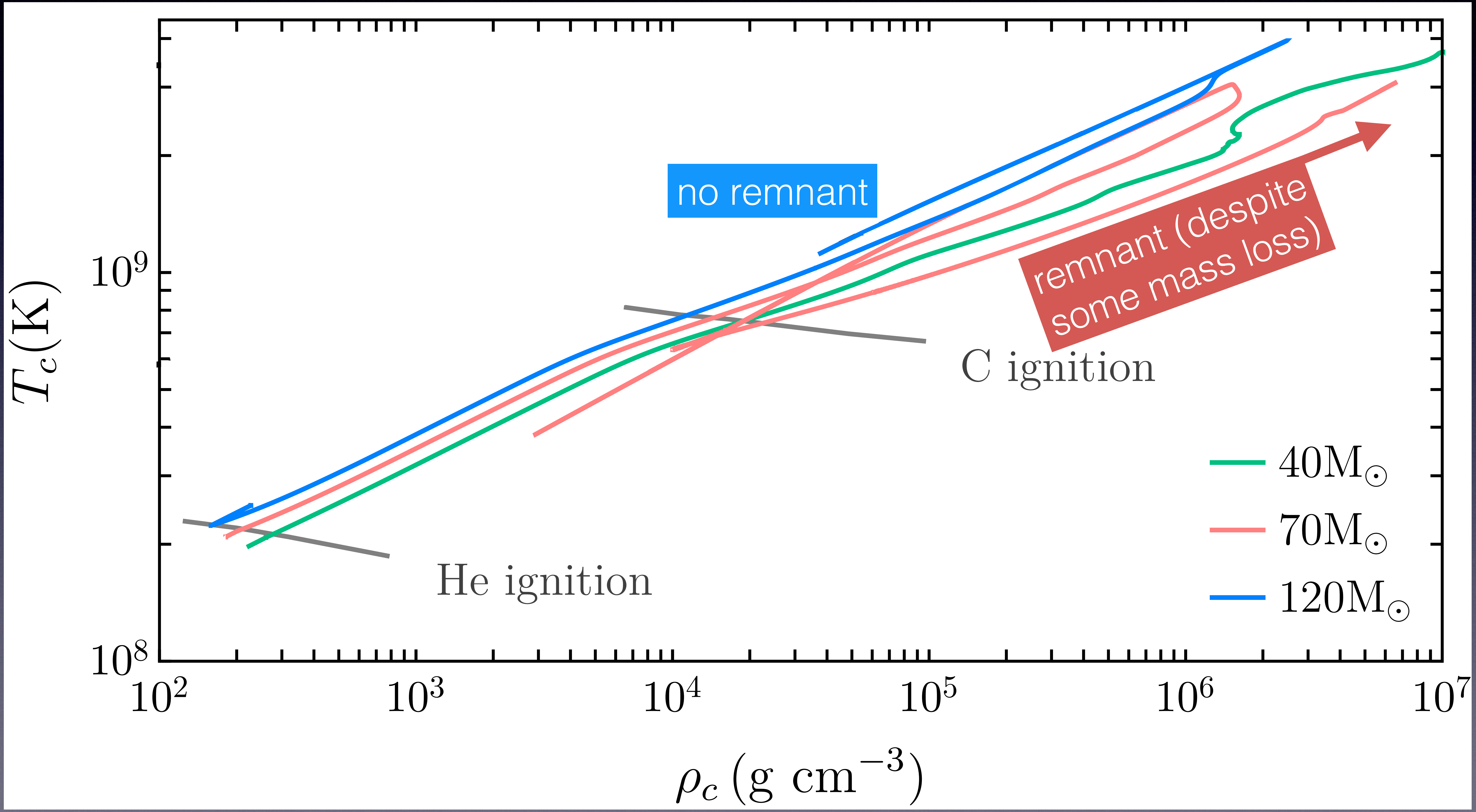

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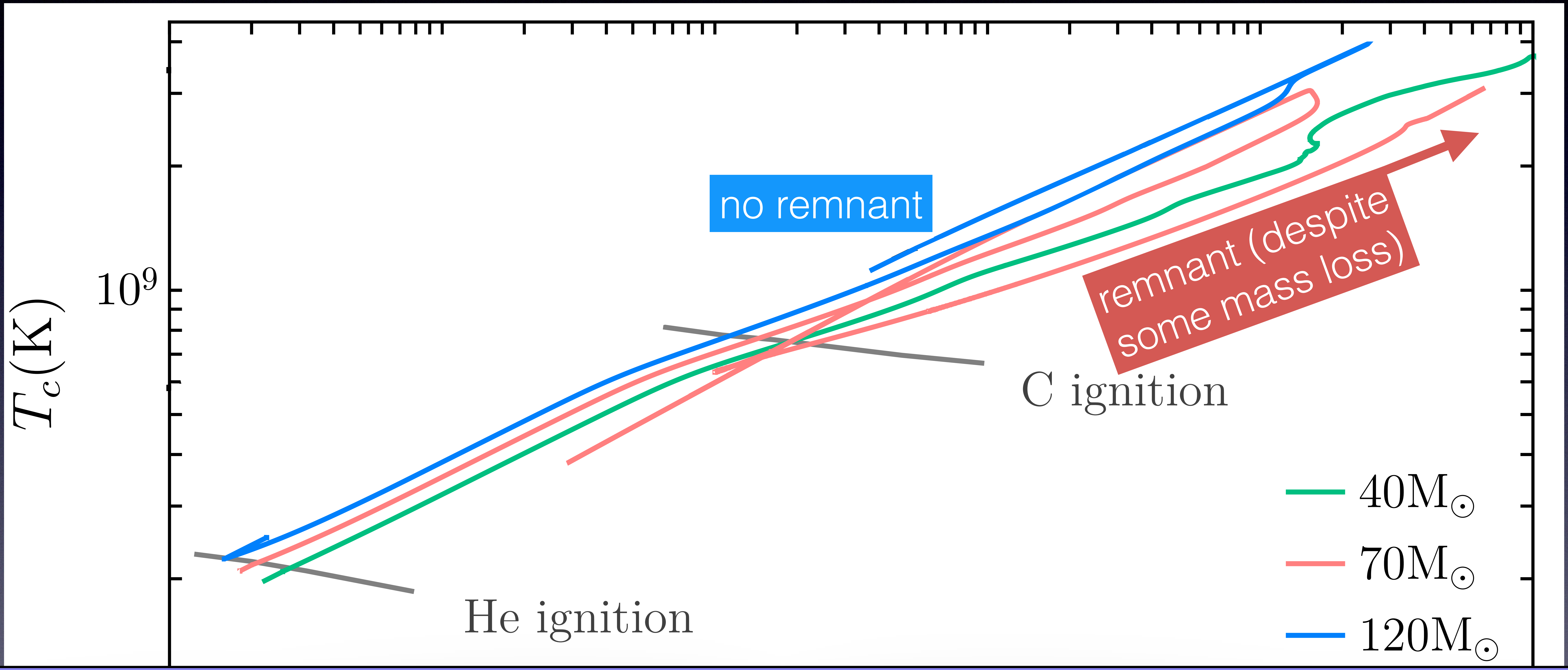

$70\mathrm{M}_\odot \lesssim M_{\rm in} \lesssim 100\mathrm{M}_\odot$ — pulsational pair instability supernova (PPISN)

vs

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

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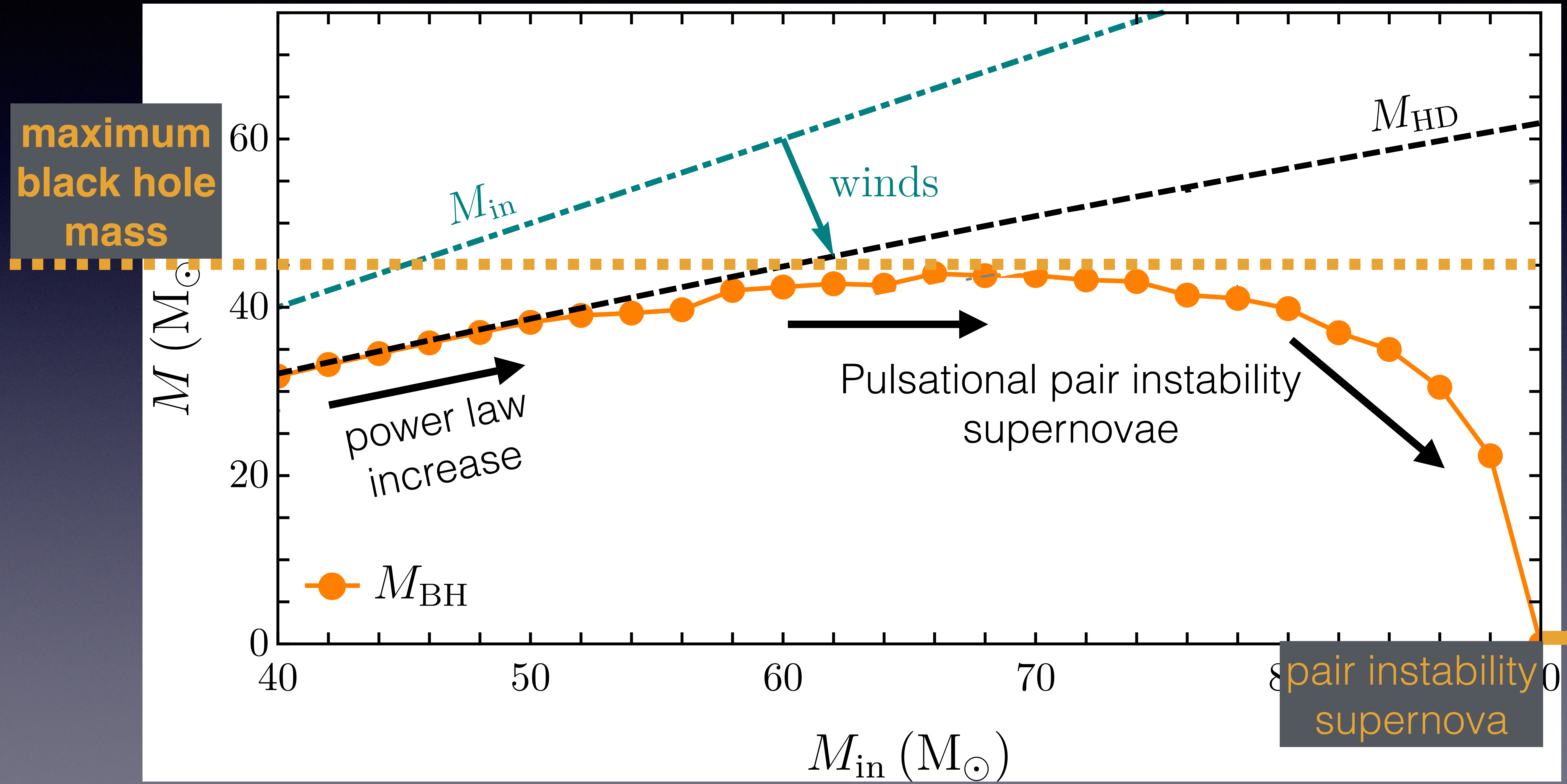

Black Hole Mass Gap (BHMG)

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Recipe for Changing 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**

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Models of Light BSM Physics

- Electrophilic axion: $\mathcal{L}_{ae} \supset -i g_{ae} \bar{\psi}_e \gamma_5 \psi_e a, \qquad \alpha_{26} = 10^{26} g_{ae}^2 / 4\pi$

- Photophilic axion: $\mathcal{L}_{a\gamma} \supset -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}, \qquad g_{10} = g_{a\gamma} \times 10^{10} \mathrm{GeV}$

- Dark photon: $\mathcal{L}_{A'} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu$

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- Ph $0^{10}\mathrm{GeV}$

additional models:

Sakstein, Croon, McDermott, Straight, Baxter
2009.01213

Neutrino dipole moment: $\mathcal{L}_\nu \supset \frac{\mu_\nu}{2}\bar{\nu}\sigma_{\alpha\beta}\nu F^{\alpha\beta}$

Large extra dimensions: $\mathcal{L}_{\mathrm{LED}} \supset -2\sqrt{\pi}M_{\mathrm{Pl}}^{-1}\int d^4x\, h^{\mu\nu,(n)}T_{\mu\nu}$

Modified gravity*: $G = G_{\mathrm{N}}(1 + \Delta G/G_{\mathrm{N}})$ "Dramatic violations of the equivalence principle outside of the Milky Way"

- Dark photon: $\mathcal{L}_{A'} \supset -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m^2_{A'}}{2}A'_\mu A'^\mu$

*see also
Straight, Sakstein, Baxter
2009.10716

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Losses to Light Particles

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

  $T_8 \equiv \dfrac{T}{10^8\mathrm{K}}$

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

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

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

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

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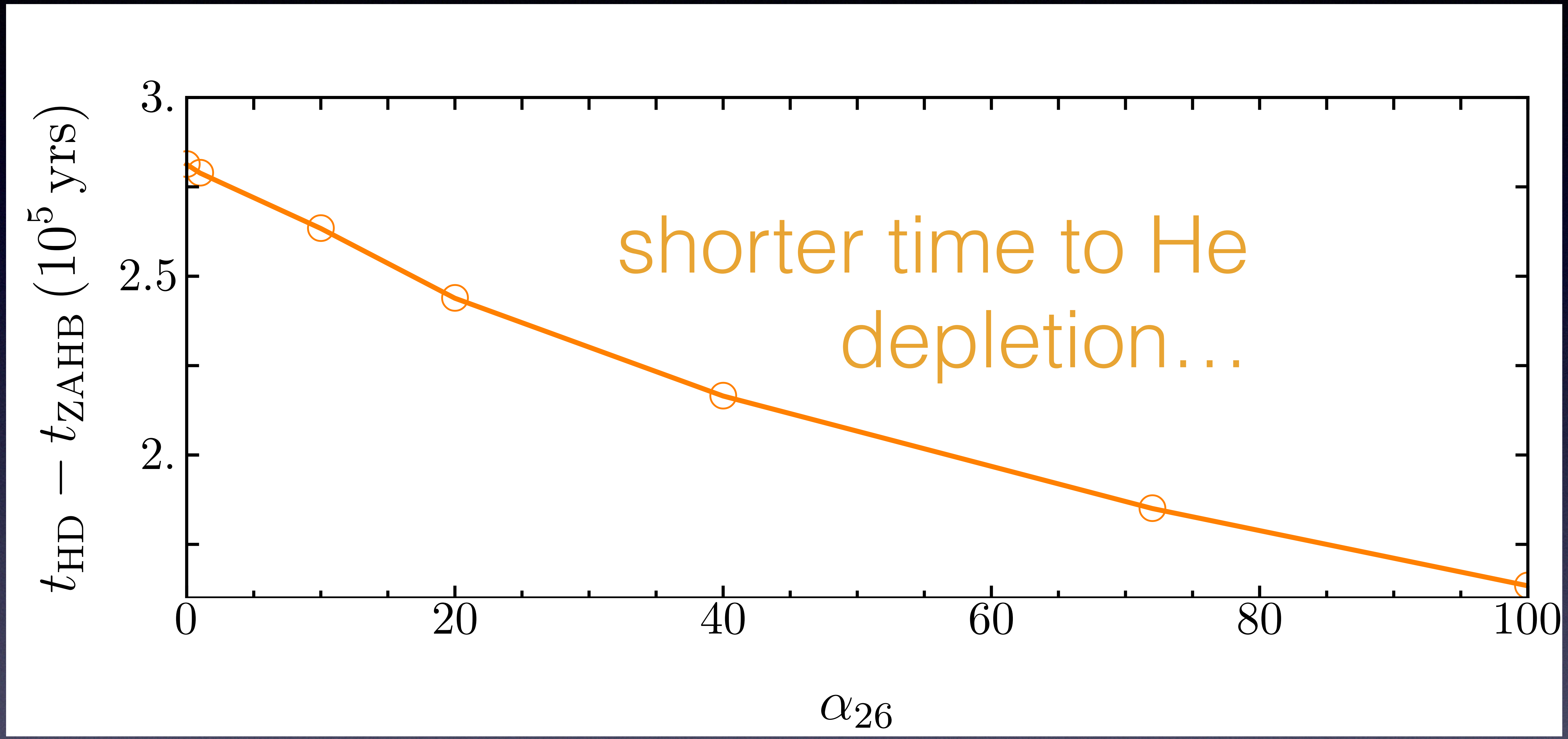
Implications for Oxygen Production



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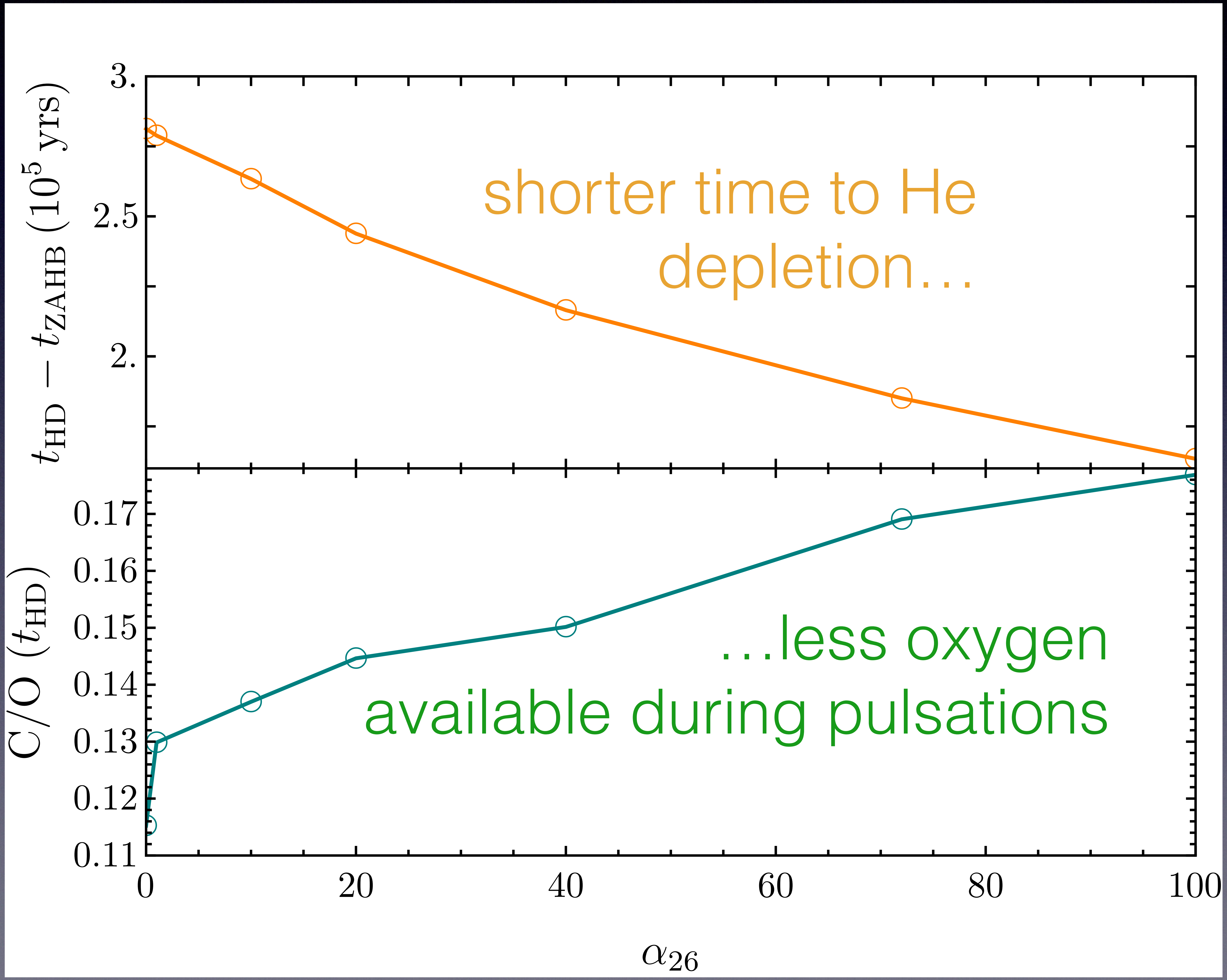

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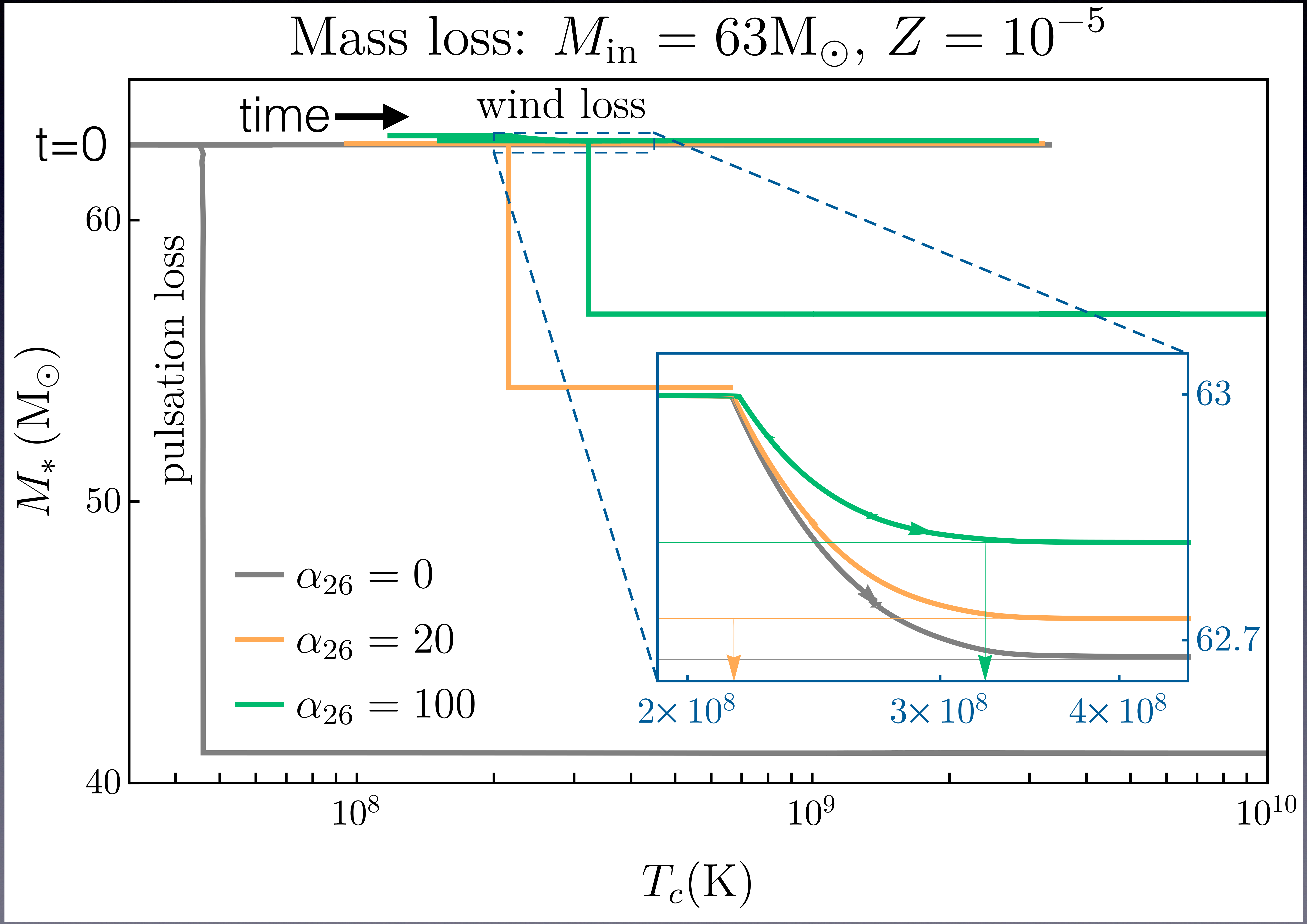

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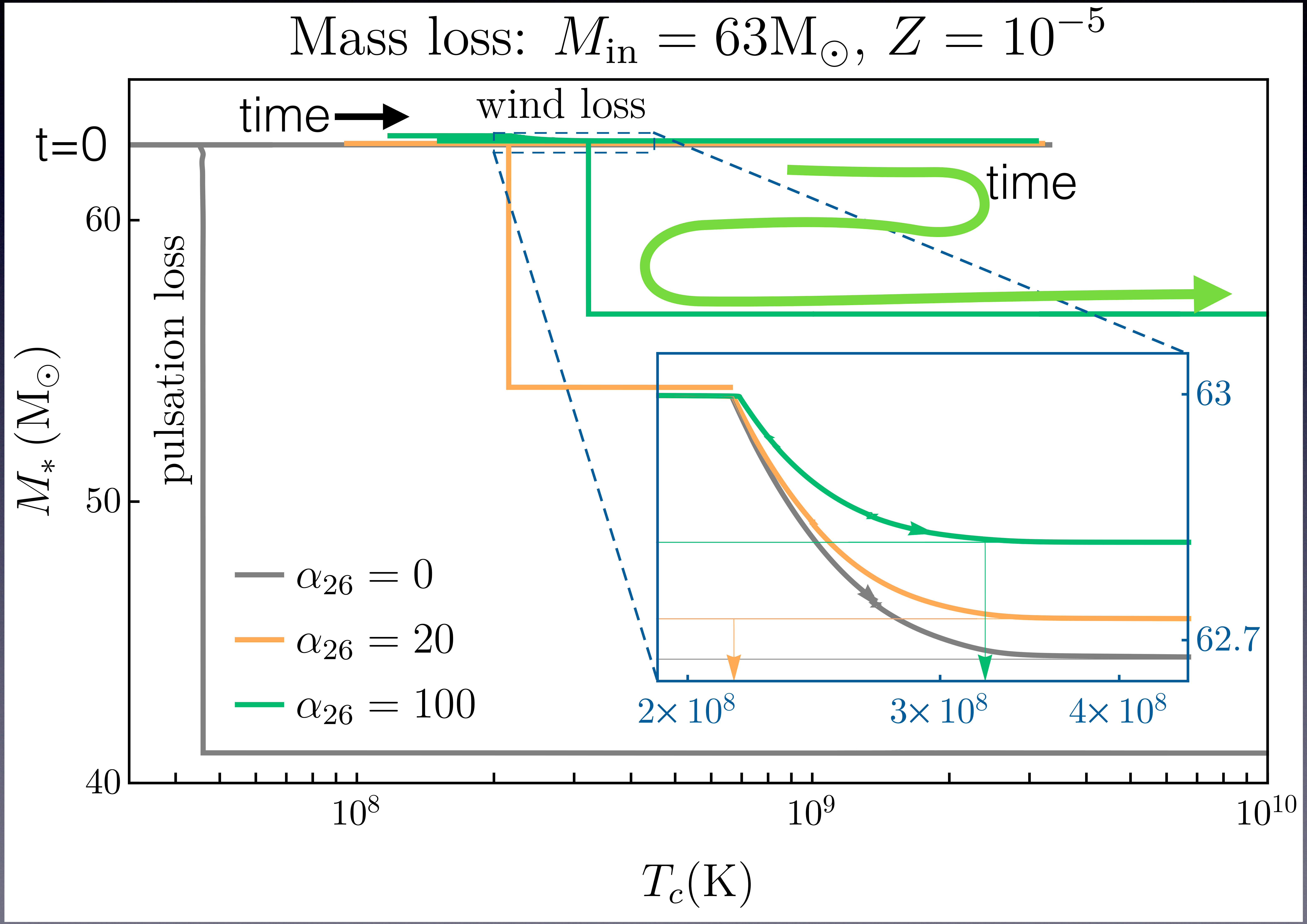

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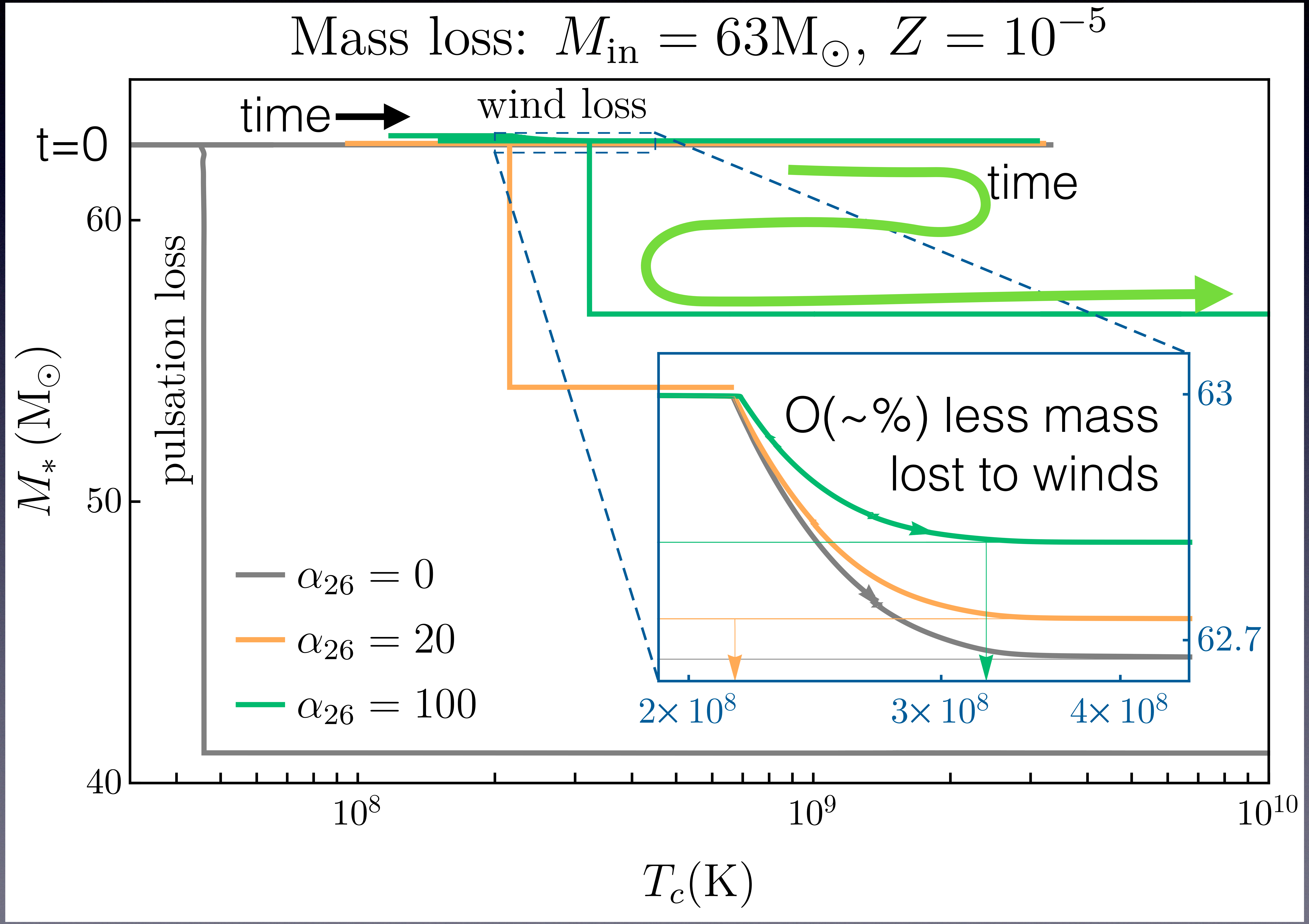

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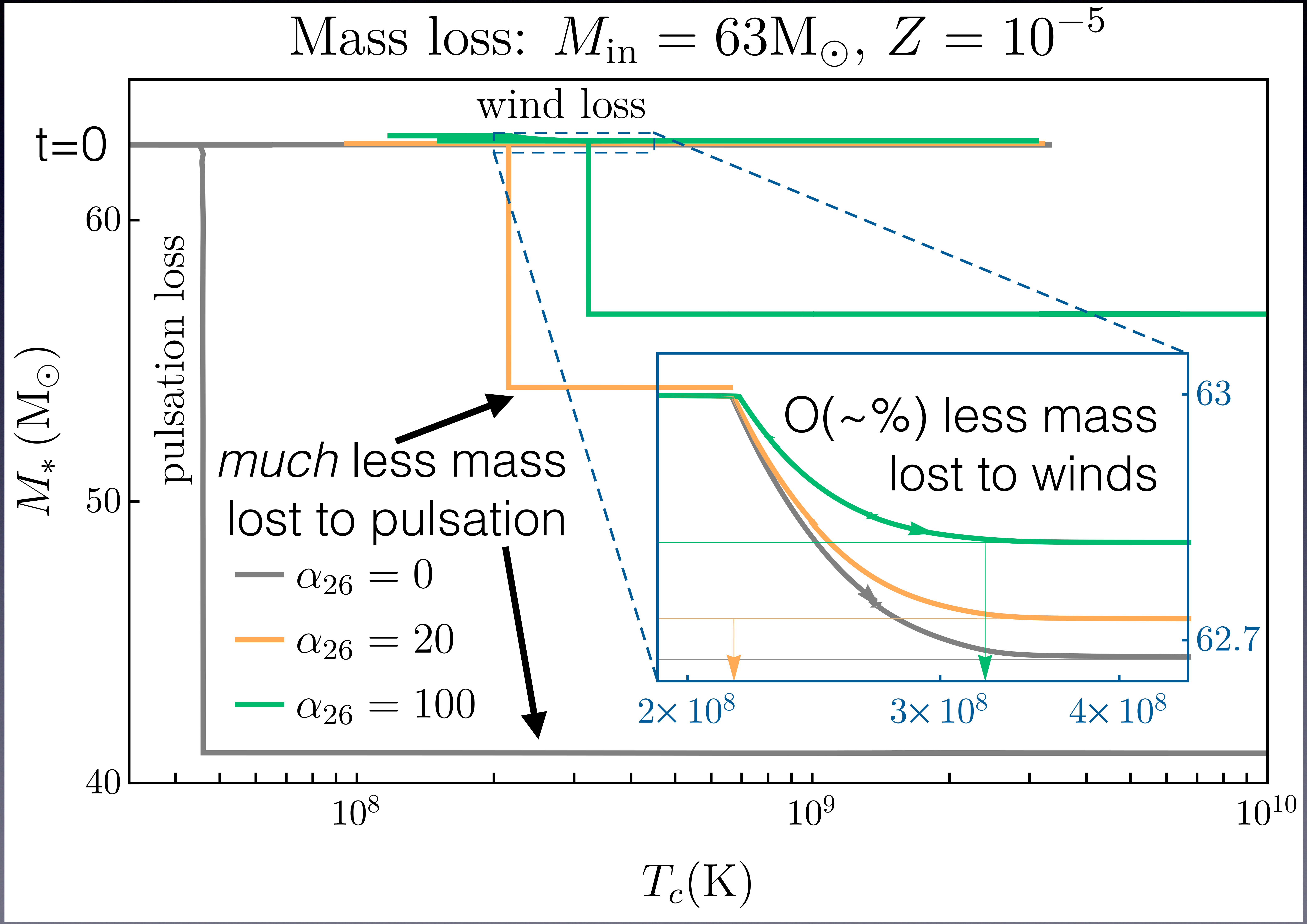

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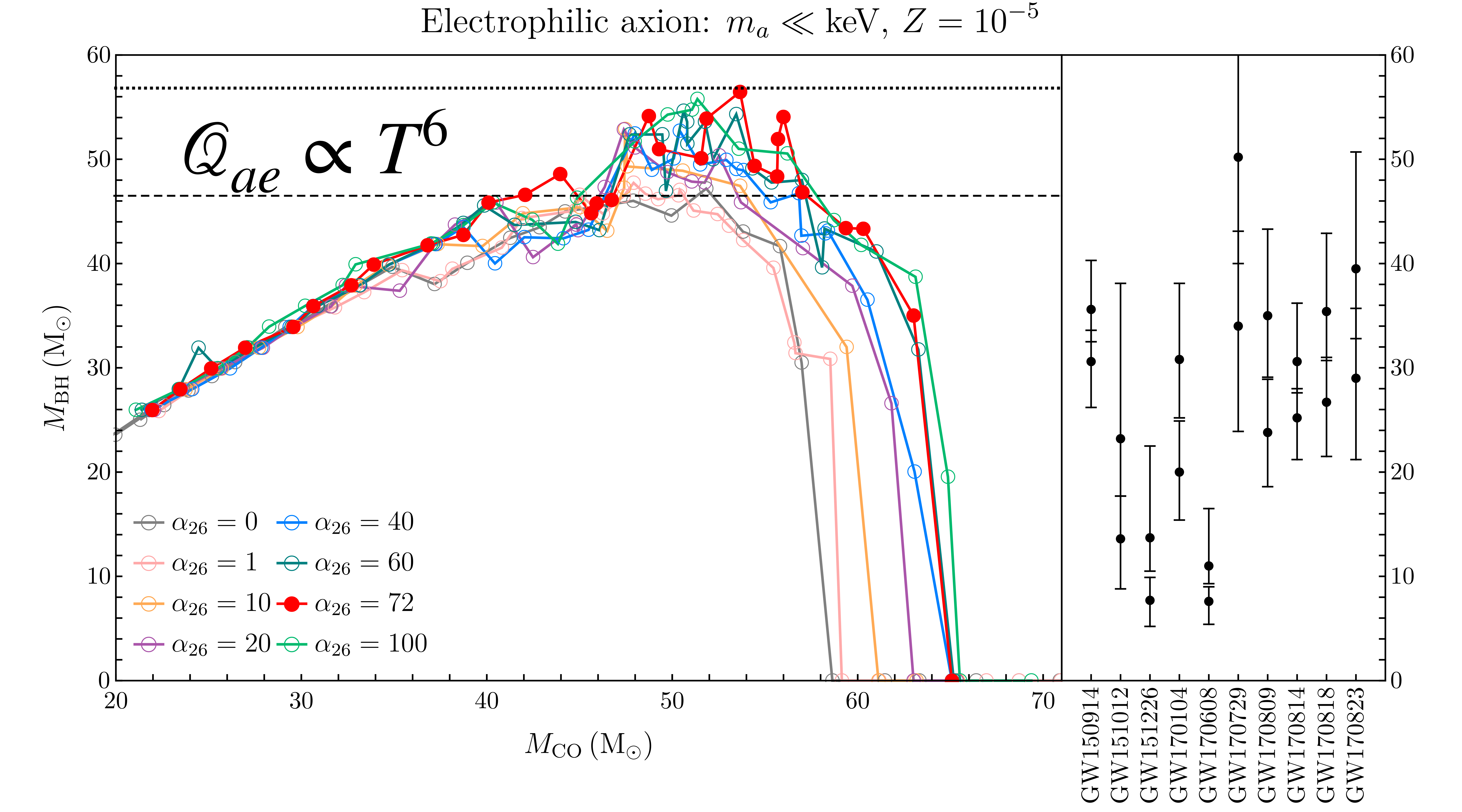
Implications for Black Hole Masses



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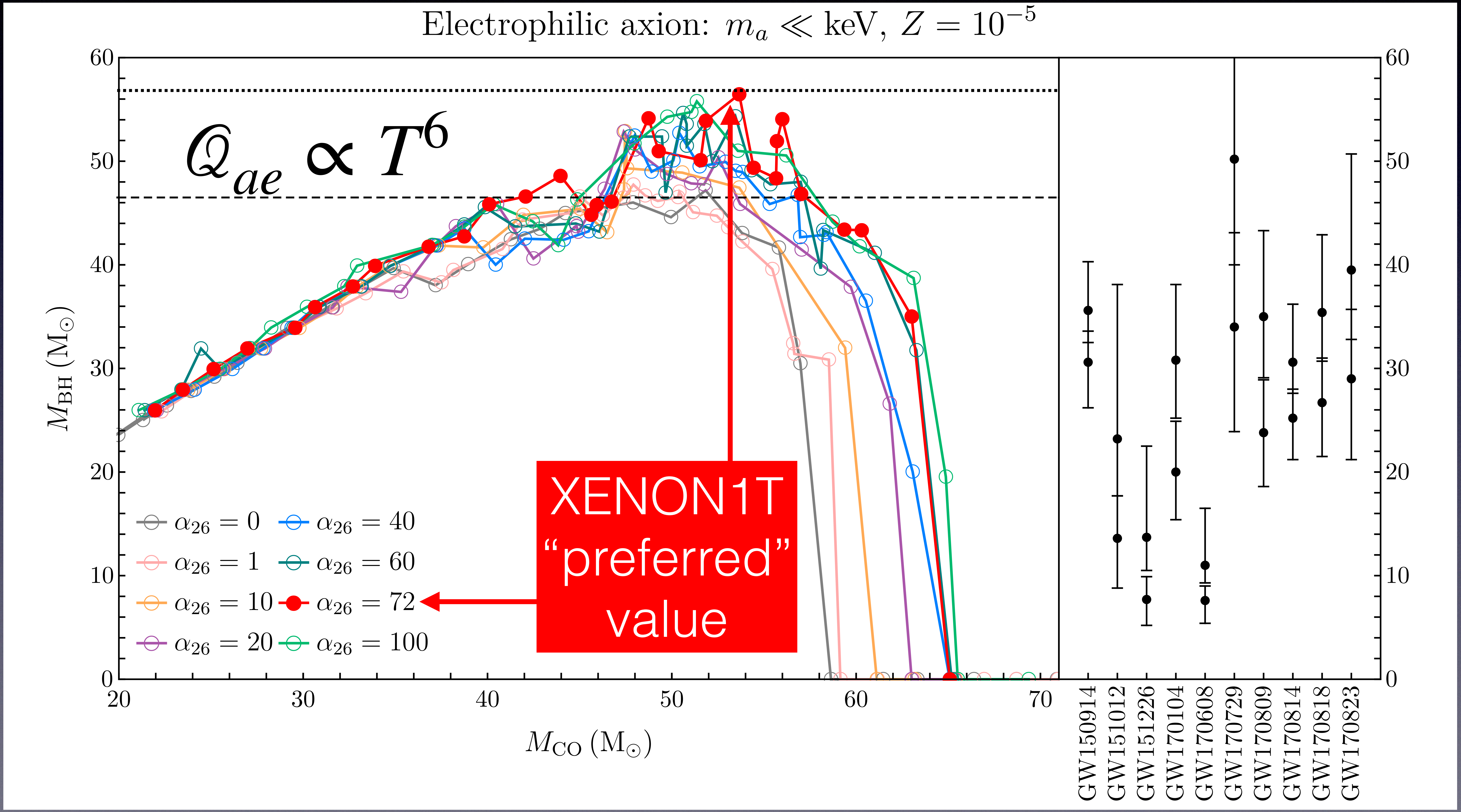

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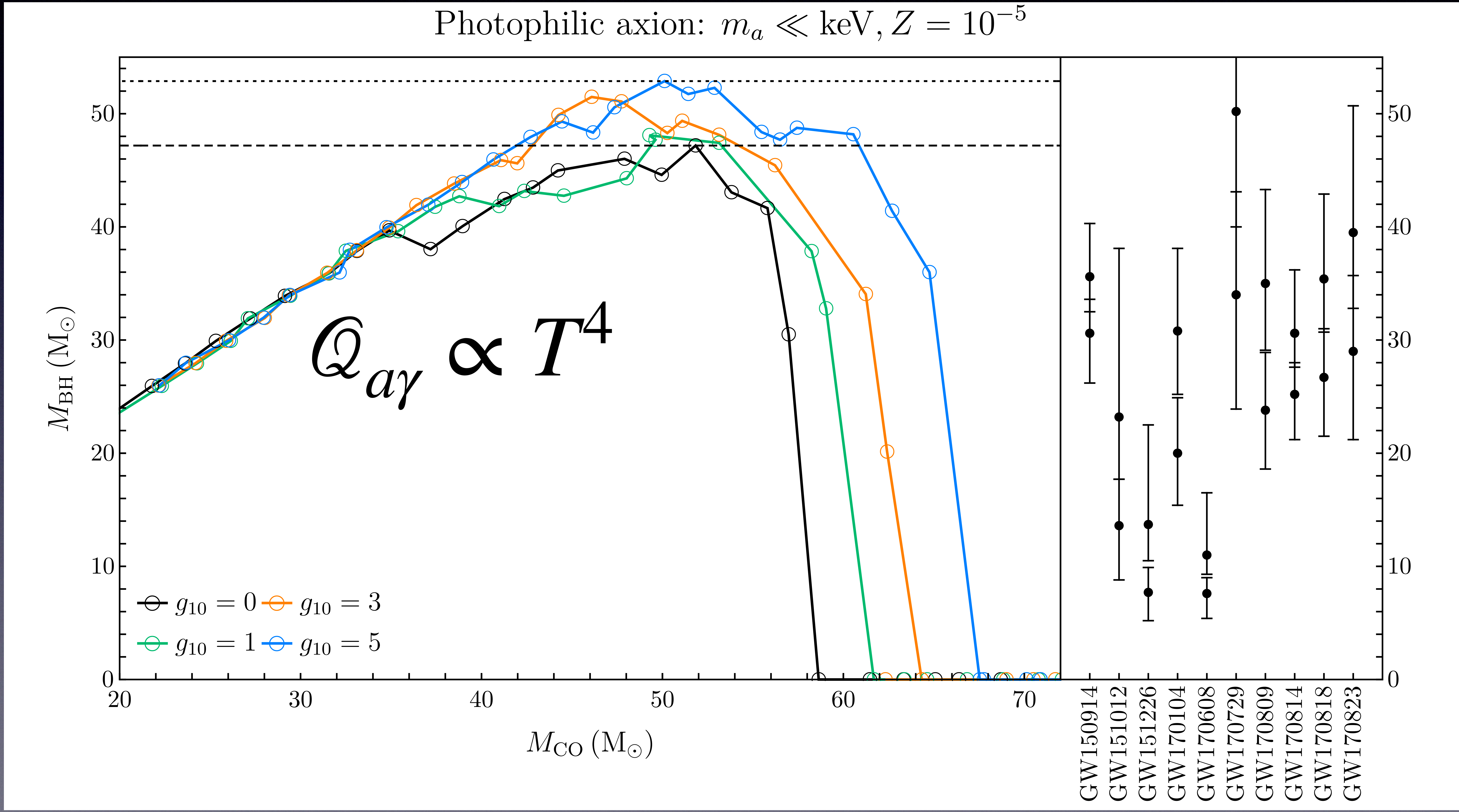

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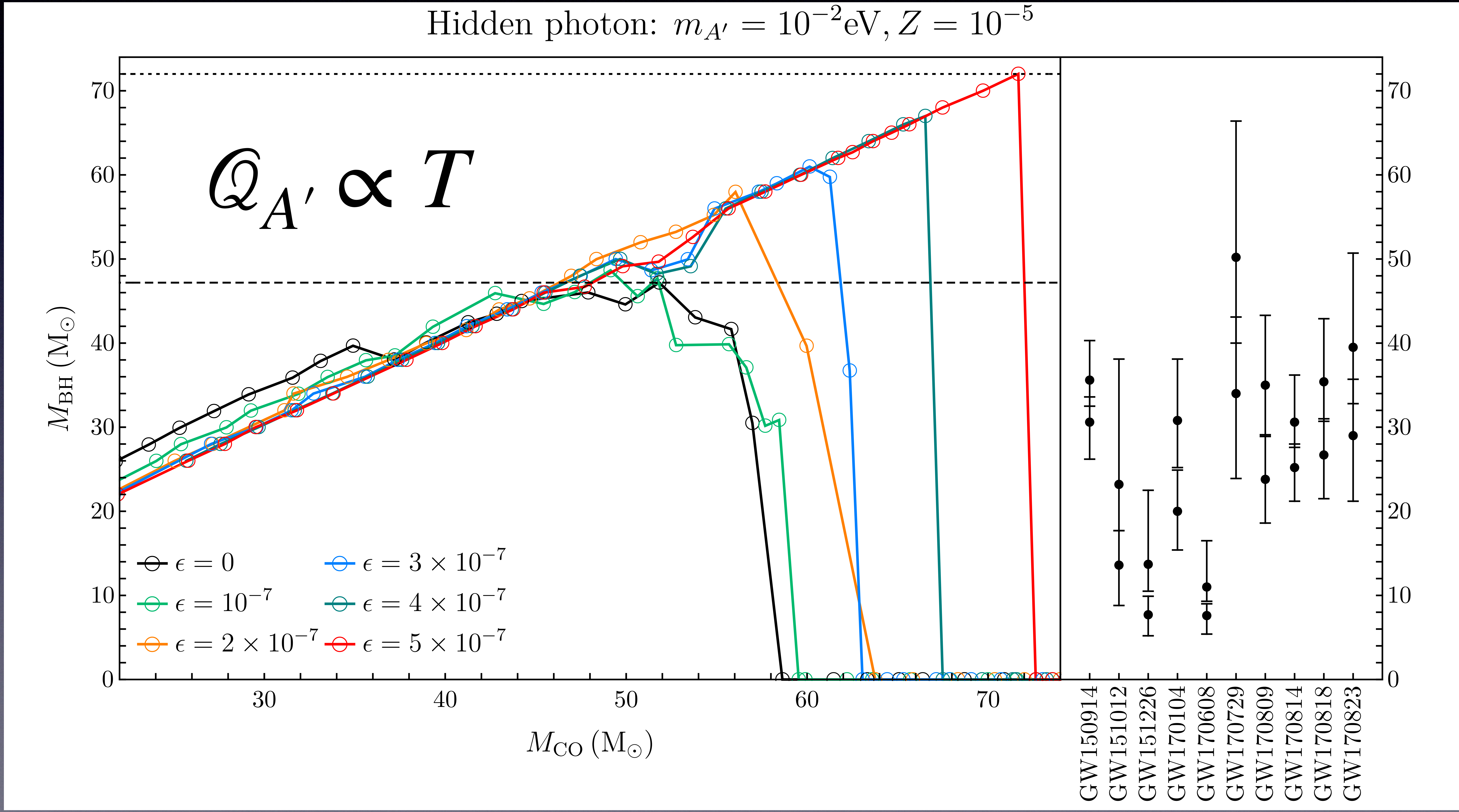

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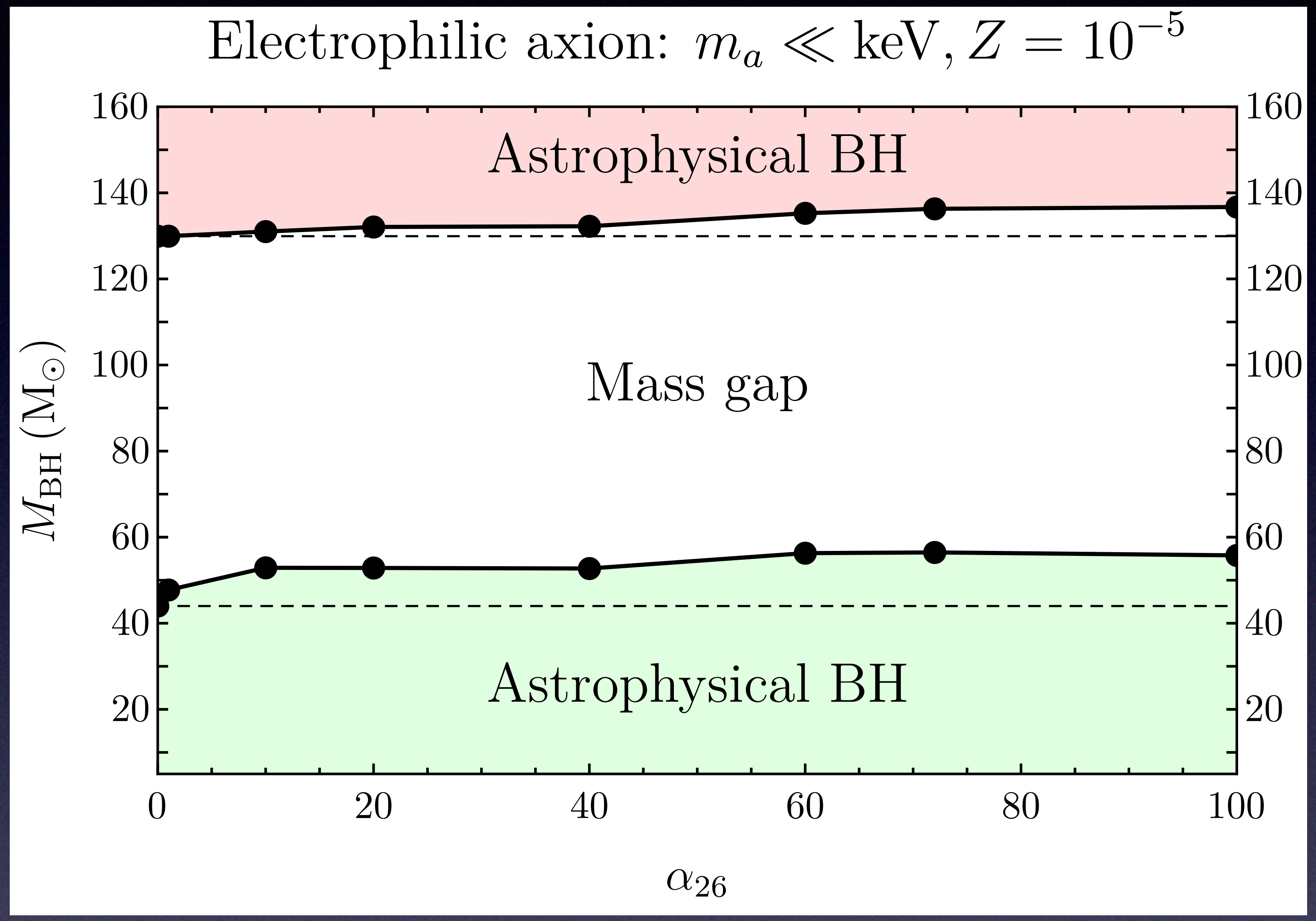

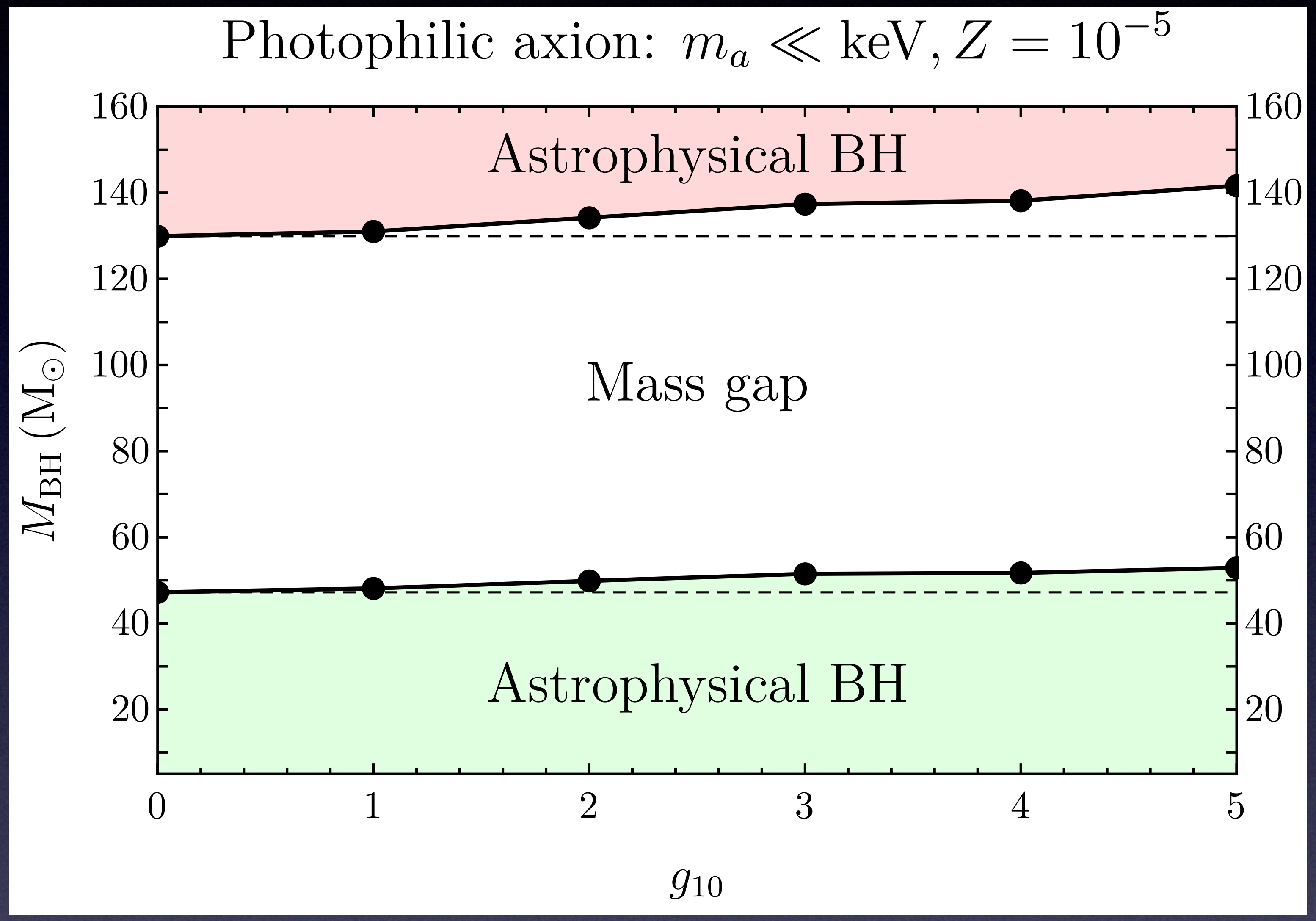

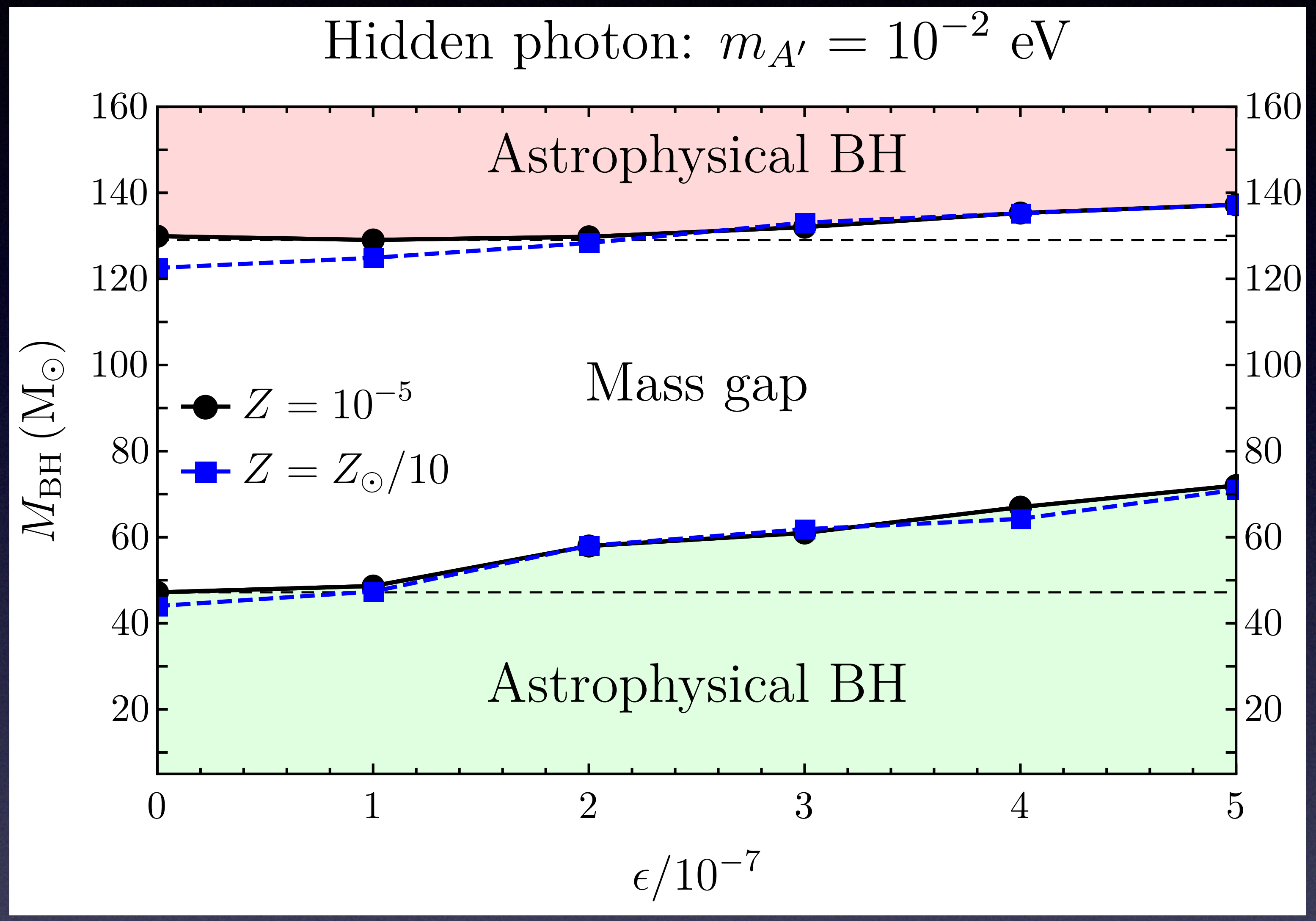

larger coupling to new physics $\Longrightarrow$ larger black hole mass

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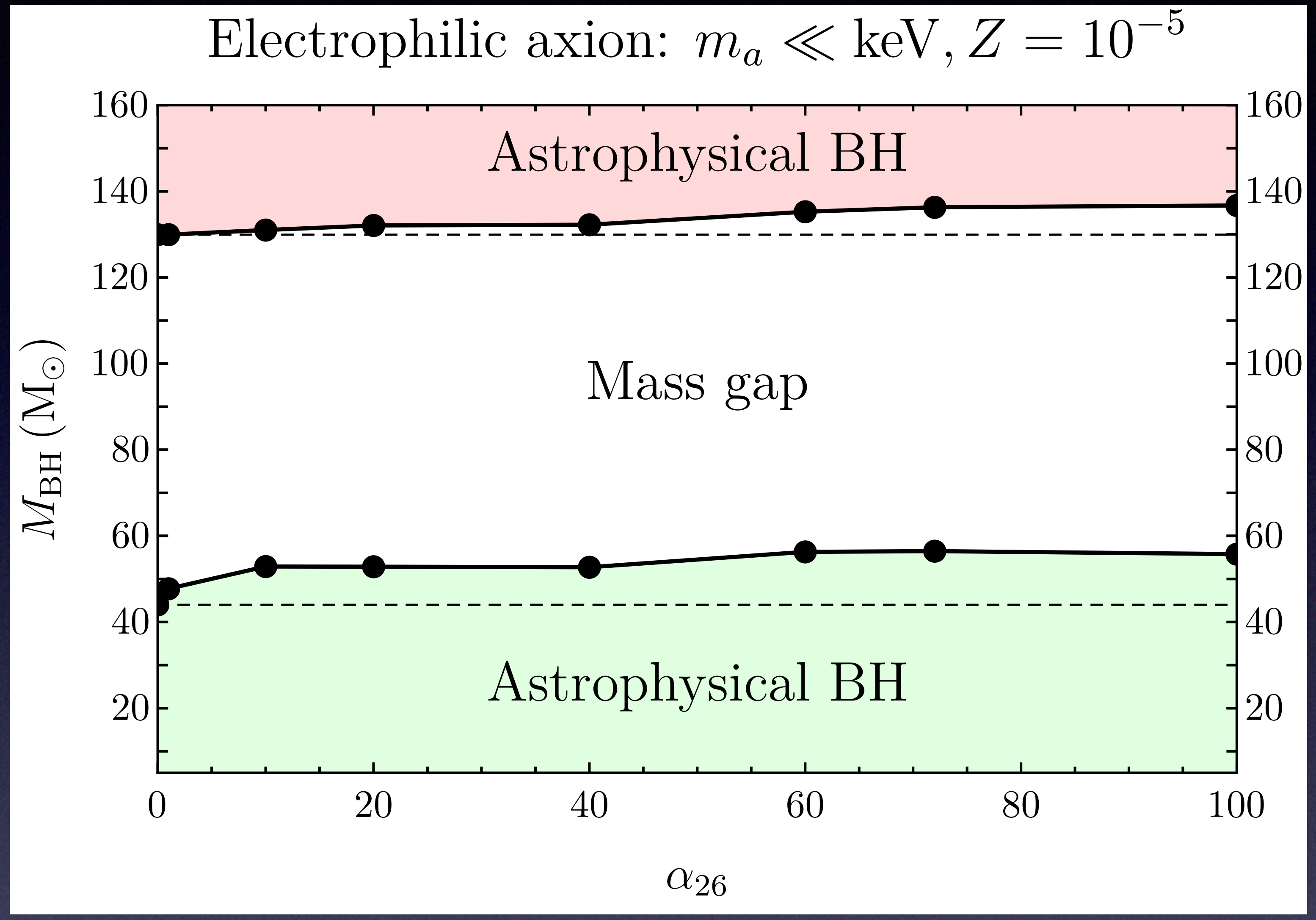

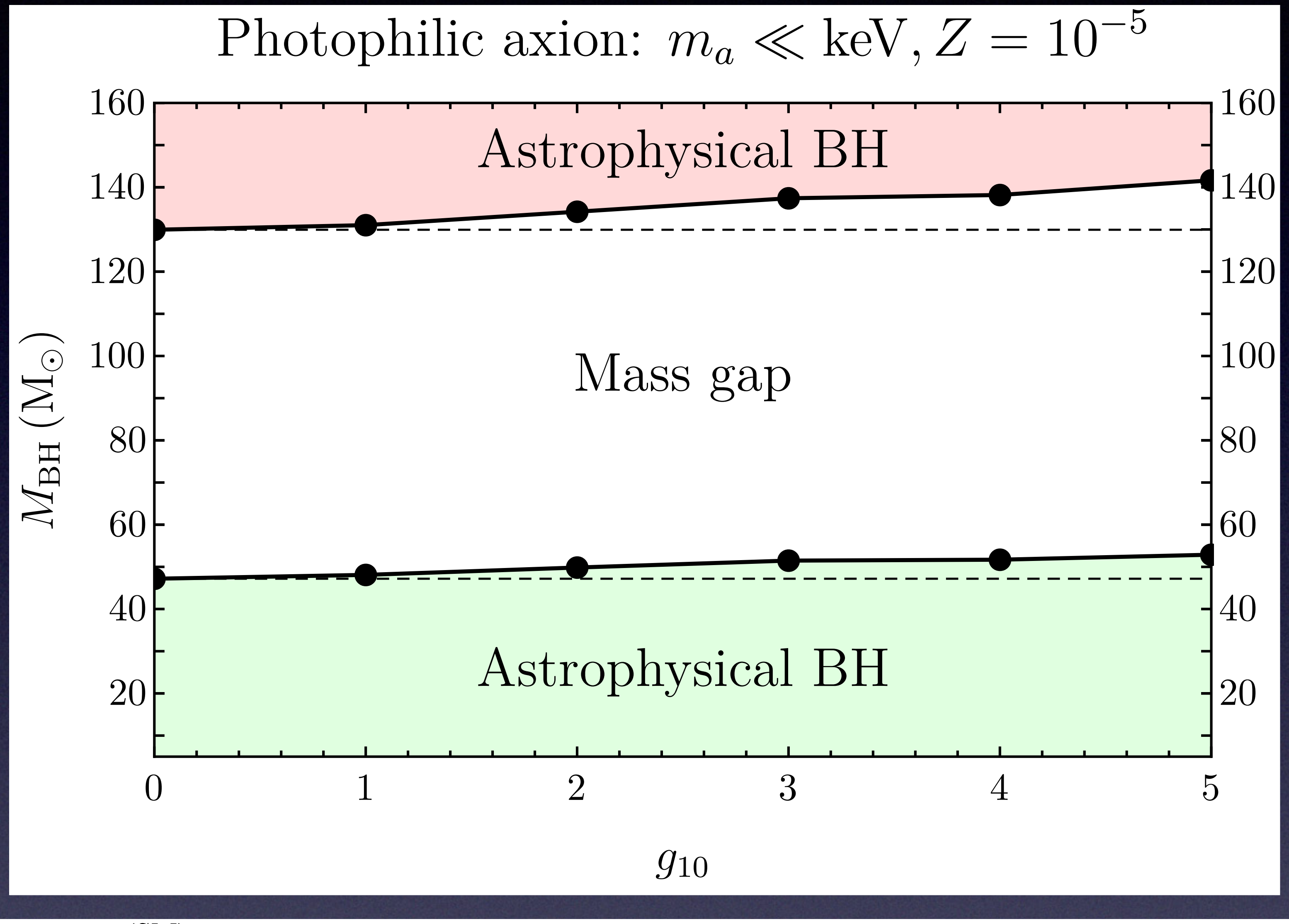

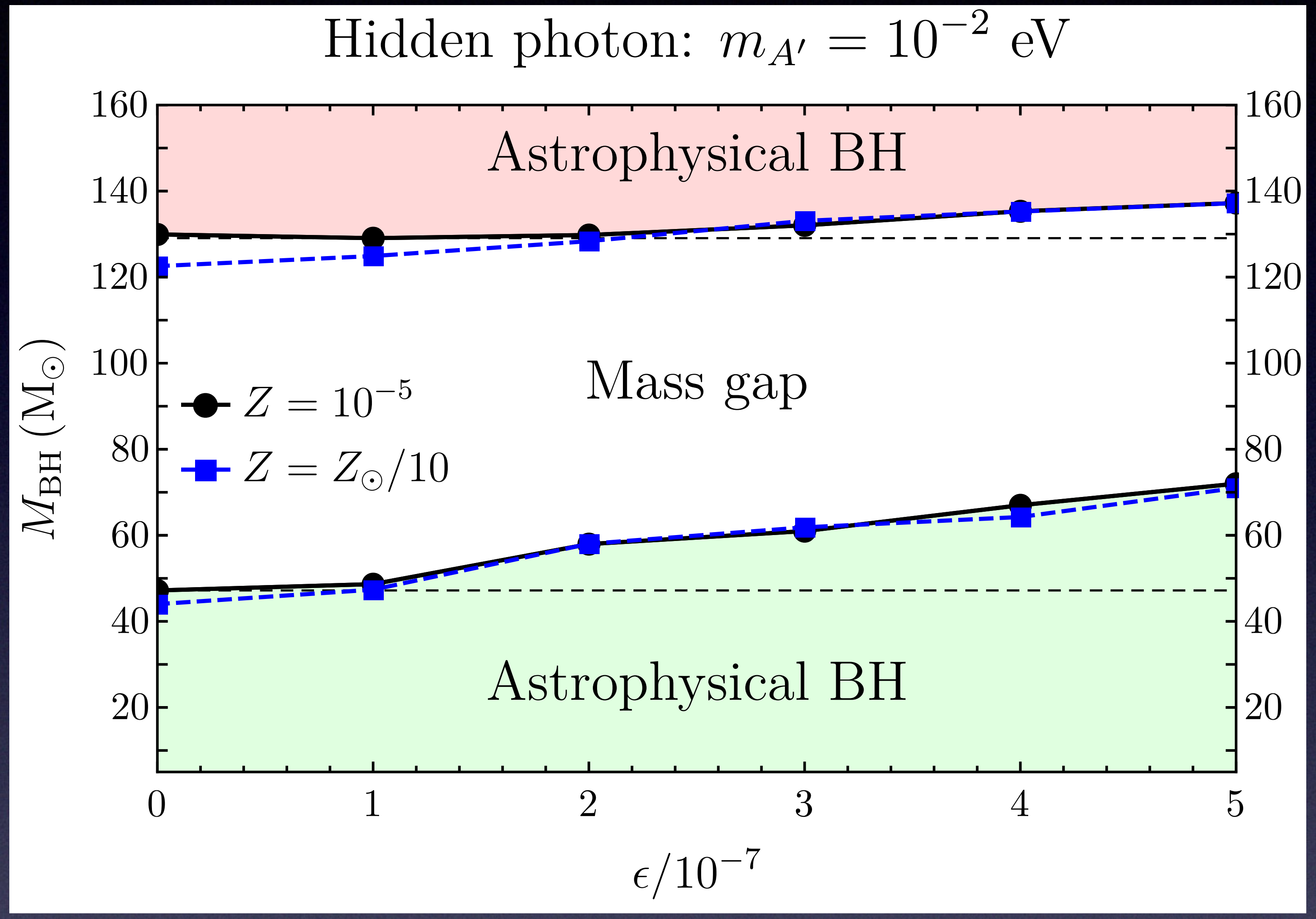

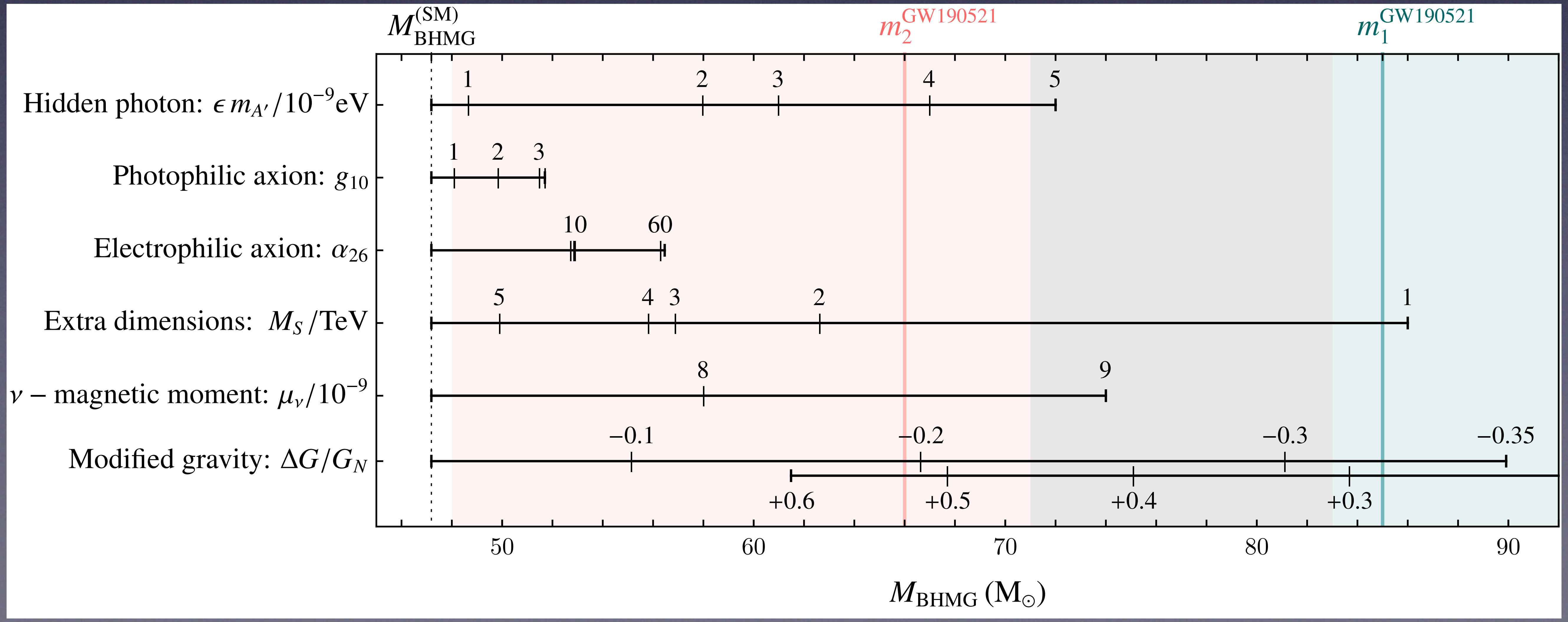

Sakstein, Croon, SDM, Straight, Baxter
2009.01213

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” $\implies \alpha_{26} \leq 0.2$
- 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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the Sun is pretty well (though as yet imperfectly) understood

But… Limits!

Claimed cor these stars have uncertainties (mixing, structure) and unexplored parameter degeneracies (age, metallicity; distance, reddening)

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- 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)

the Sun is pretty well (though as yet imperfectly) understood

But… Limits!

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

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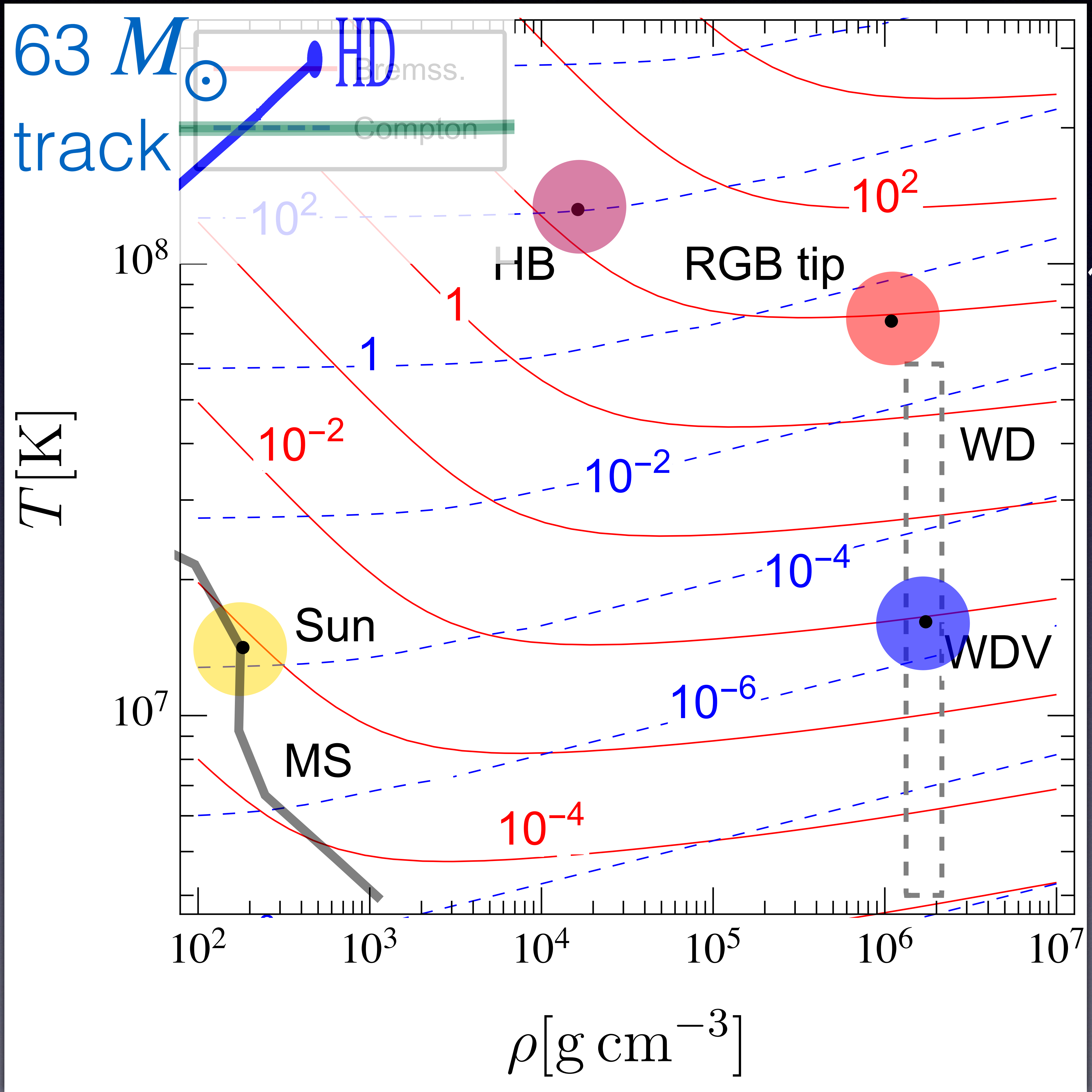
Also: different characteristic T_c



~ 10 keV

New Physics: Summary

- New light particles can shorten helium burning, reduce the amount of oxygen, and increase the black hole mass
- The picture (including effects on other stars) is not perfectly tidy as degeneracies / observational uncertainties are underexplored
- Constraints on hidden photon, photophilic axion, and neutrino dipole moment seem robust; electrophilic axion potentially less so
- Model building routes to skirt bounds?

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Lots of room remains for better understanding!

Outline

1. Physics of the pair instability mechanism
2. Beyond-the-Standard-Model explanations of GW190521
3. Standard Model explanations of GW190521
4. Future prospects

Three Routes for SM Explanations

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The Stellar Merger Scenario for Black Holes in the Pair-instability Gap

M. Renzo,[1,2] M. Cantiello,[1,3] B. D. Metzger,[2,1] and Y.-F. Jiang (姜燕飞)[1]

[1] *Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*
[2] *Department of Physics, Columbia University, New York, NY 10027, USA*
[3] *Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*

2010.00705

akin to luminous blue variable (LBV) eruptions are expected. An energetic estimate of the amount of mass loss neglecting the back-reaction of the star suggests that the total amount of mass that can be removed at low metallicity is $\lesssim 1\,M_\odot$. This is small enough that at core-collapse our models are retaining sufficient mass to form black holes in the pair-instability gap similar to the recent ones detected by LIGO/Virgo. However, mass loss at the time of merger and the neutrino-driven mass loss at core collapse still need to be quantified for these models in order to confirm the viability of this scenario.

Three Routes for SM Explanations

1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN → make pulsations less effective
3. Increase the mass *after* PPISN

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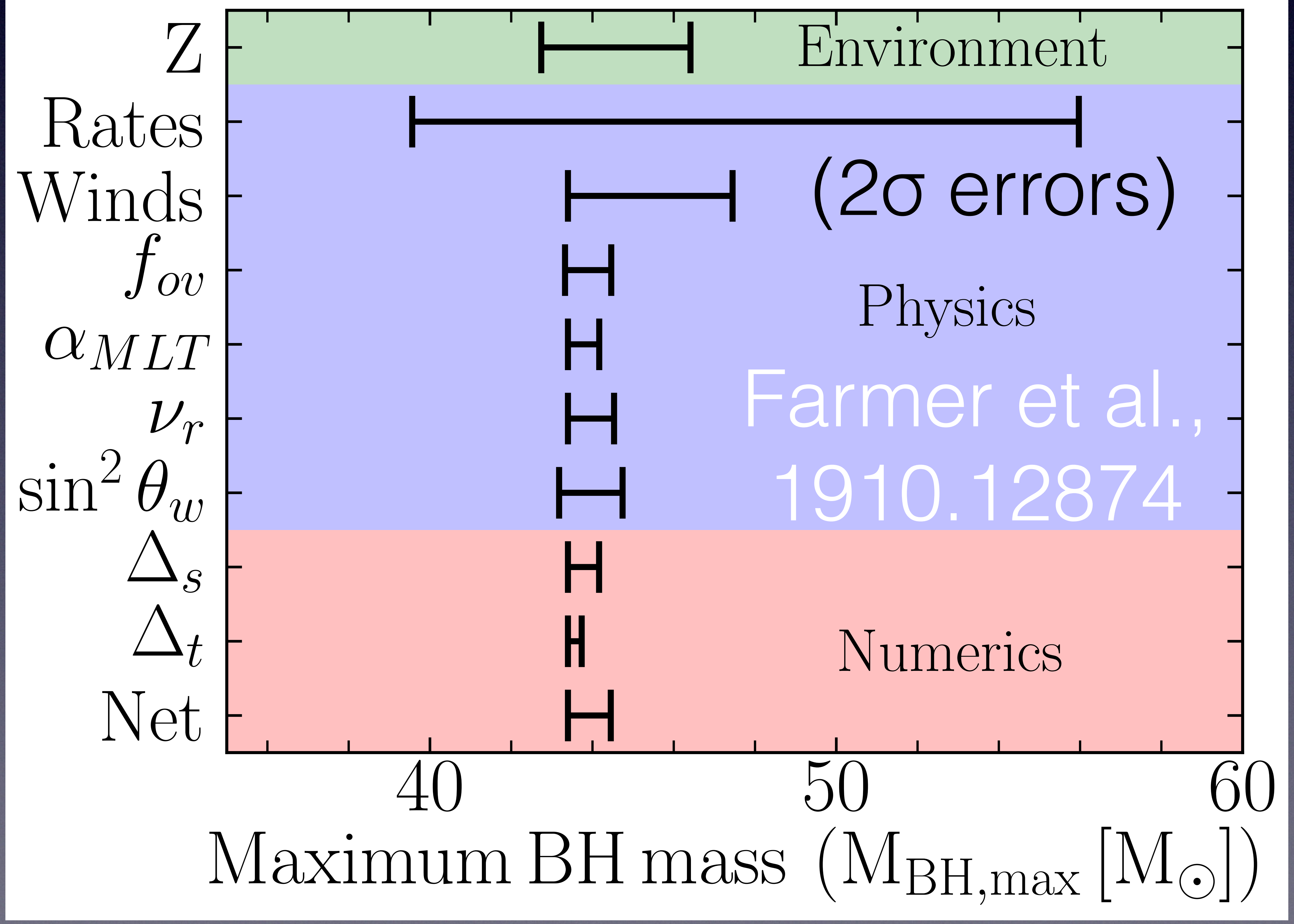

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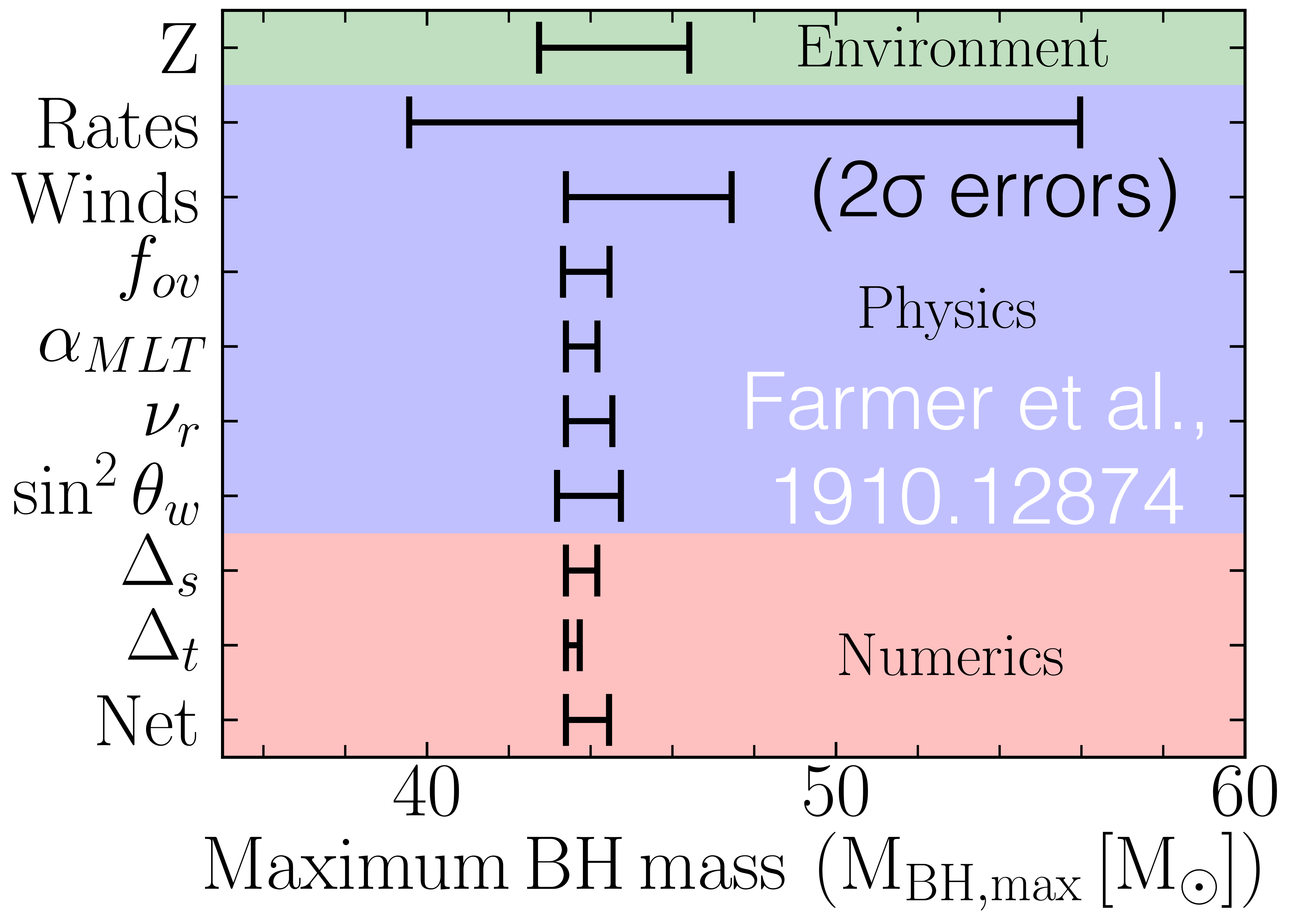
“rates” error bar dominated by rate of $^{12}C(\alpha,\gamma)^{16}O$



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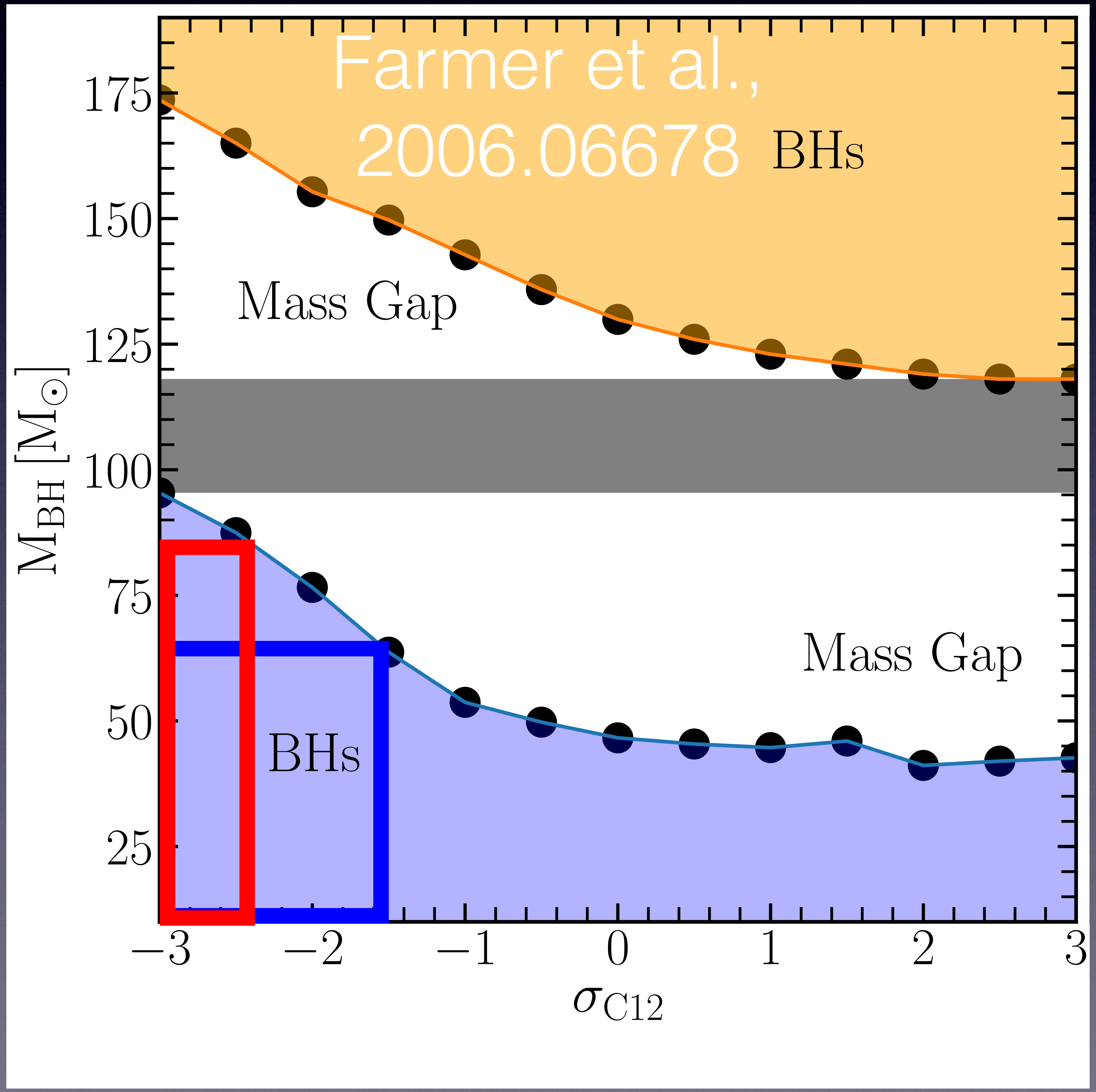
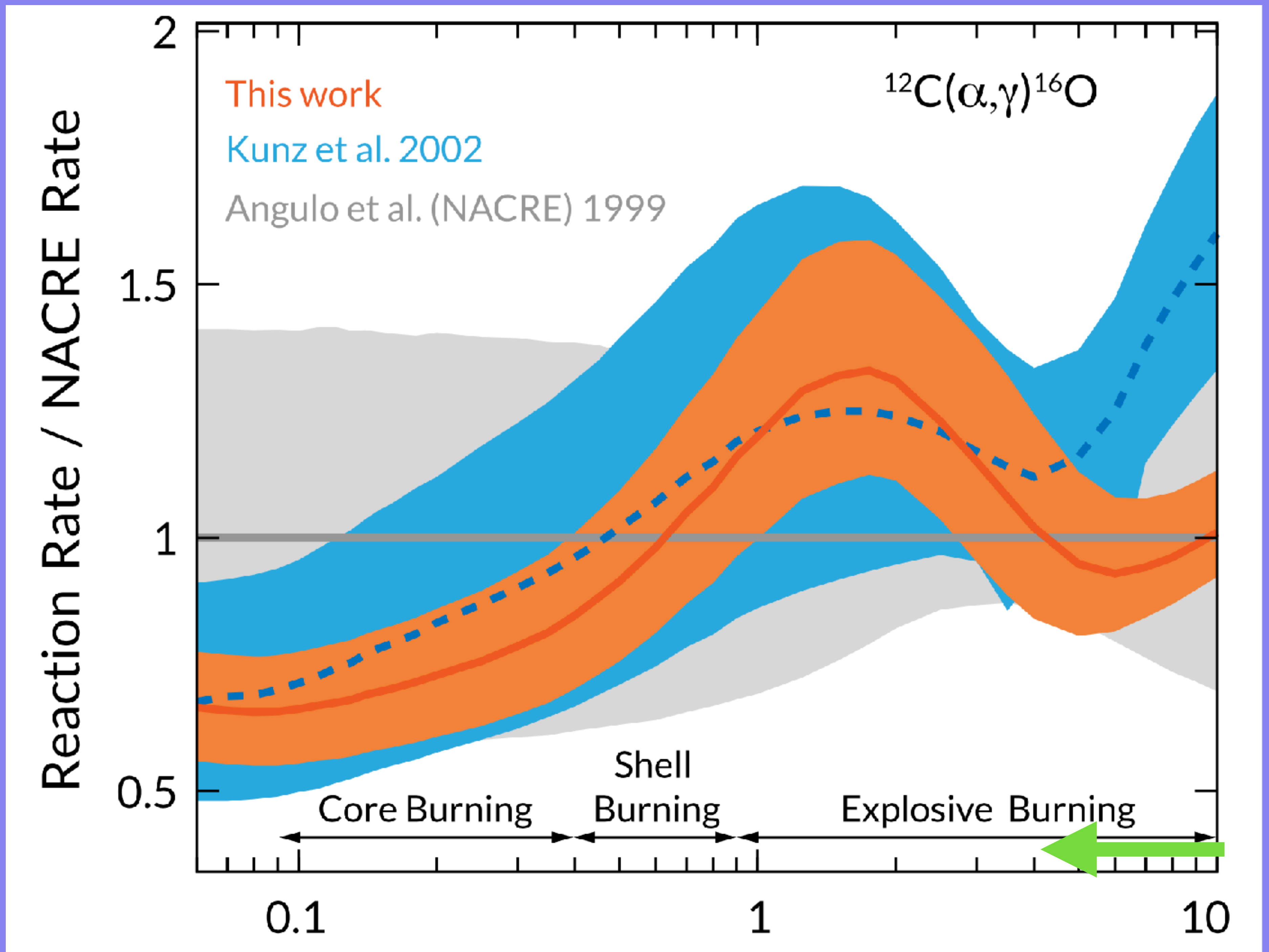


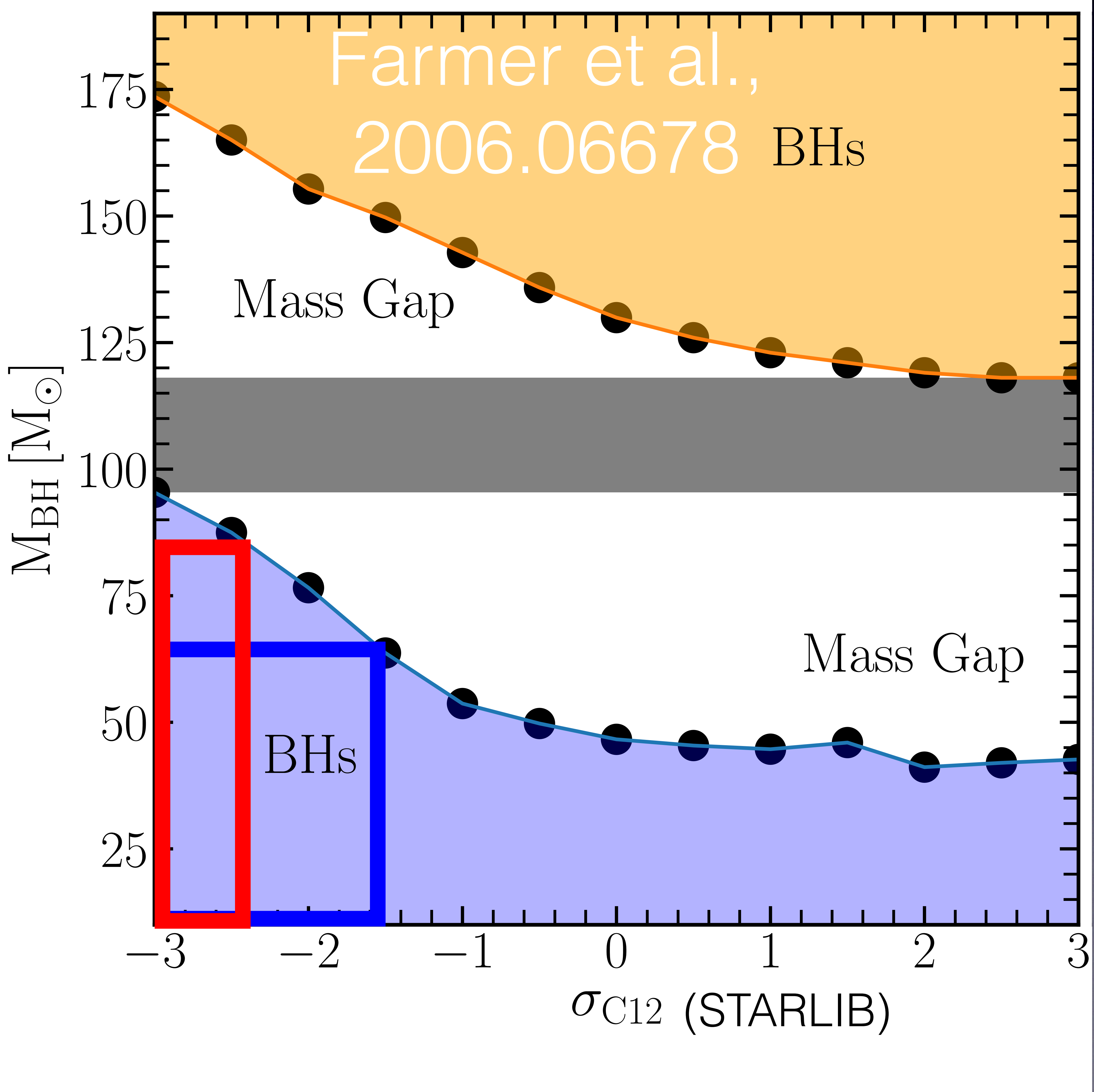
Three Routes for SM Explanations

Update: deBoer et al. 2017

R. J. deBoer, J. Görres, M. Wiescher, R.E. Azuma, A. Best, C. R. Brune, C.E. Fields, S. Jones, M. Pignatari, D. Sayre, K. Smith, F.X. Timmes, and E. Uberseder
Rev. Mod. Phys. **89**, 035007 – Published 7 September 2017



we find $48^{+3.6}_{-1} M_\odot$ (vs. $48^{+7}_{-2} M_\odot$)



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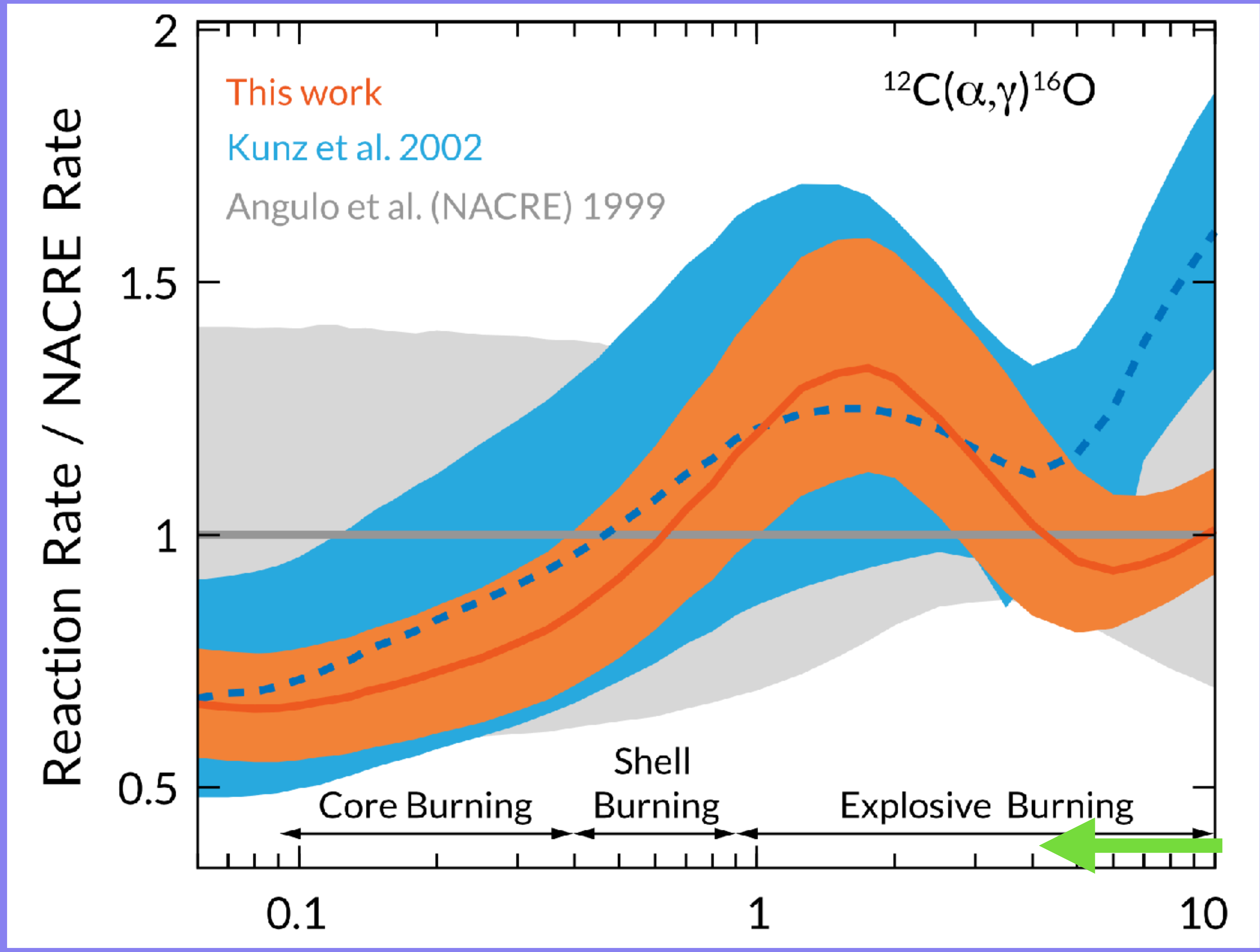

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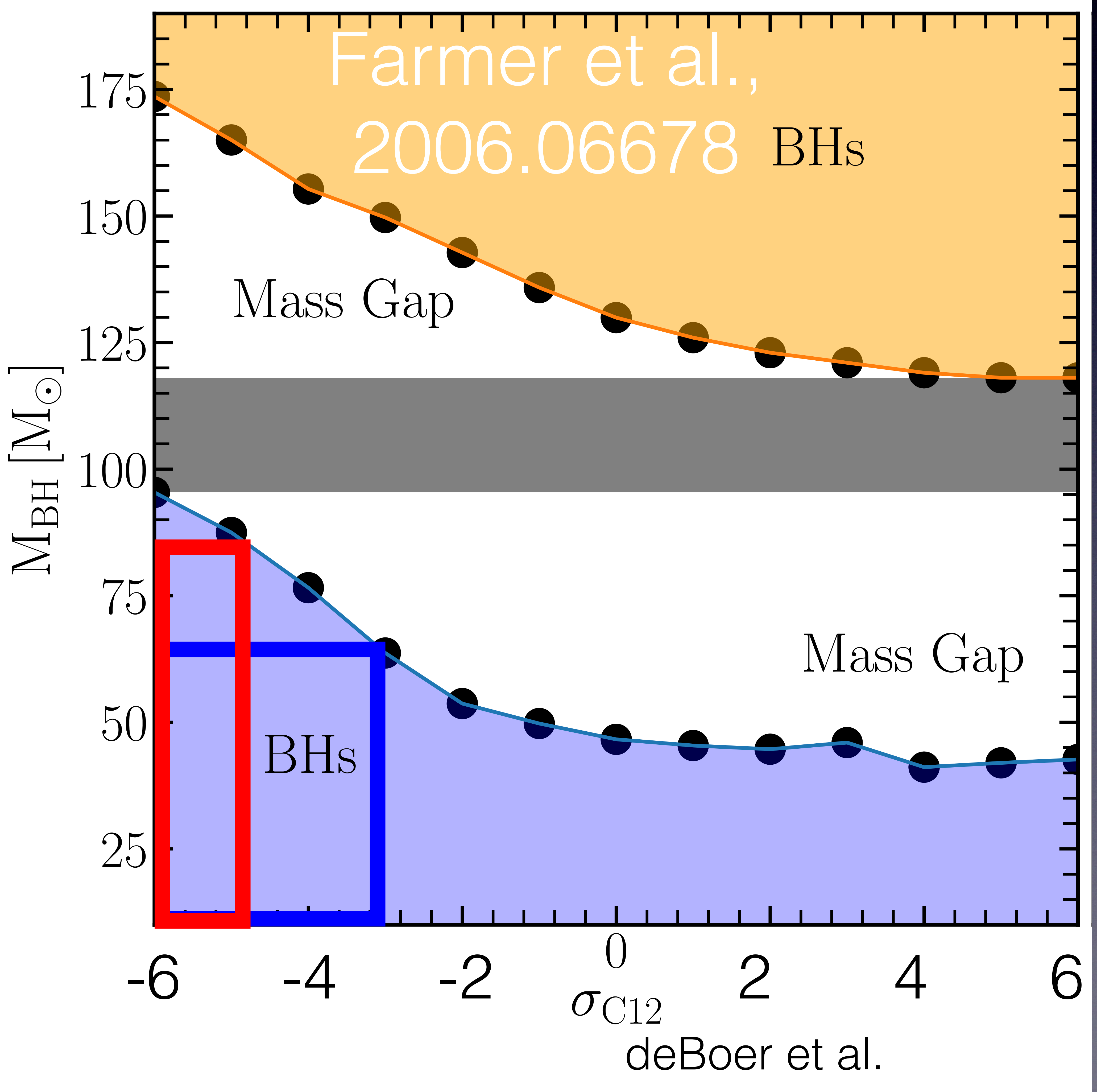

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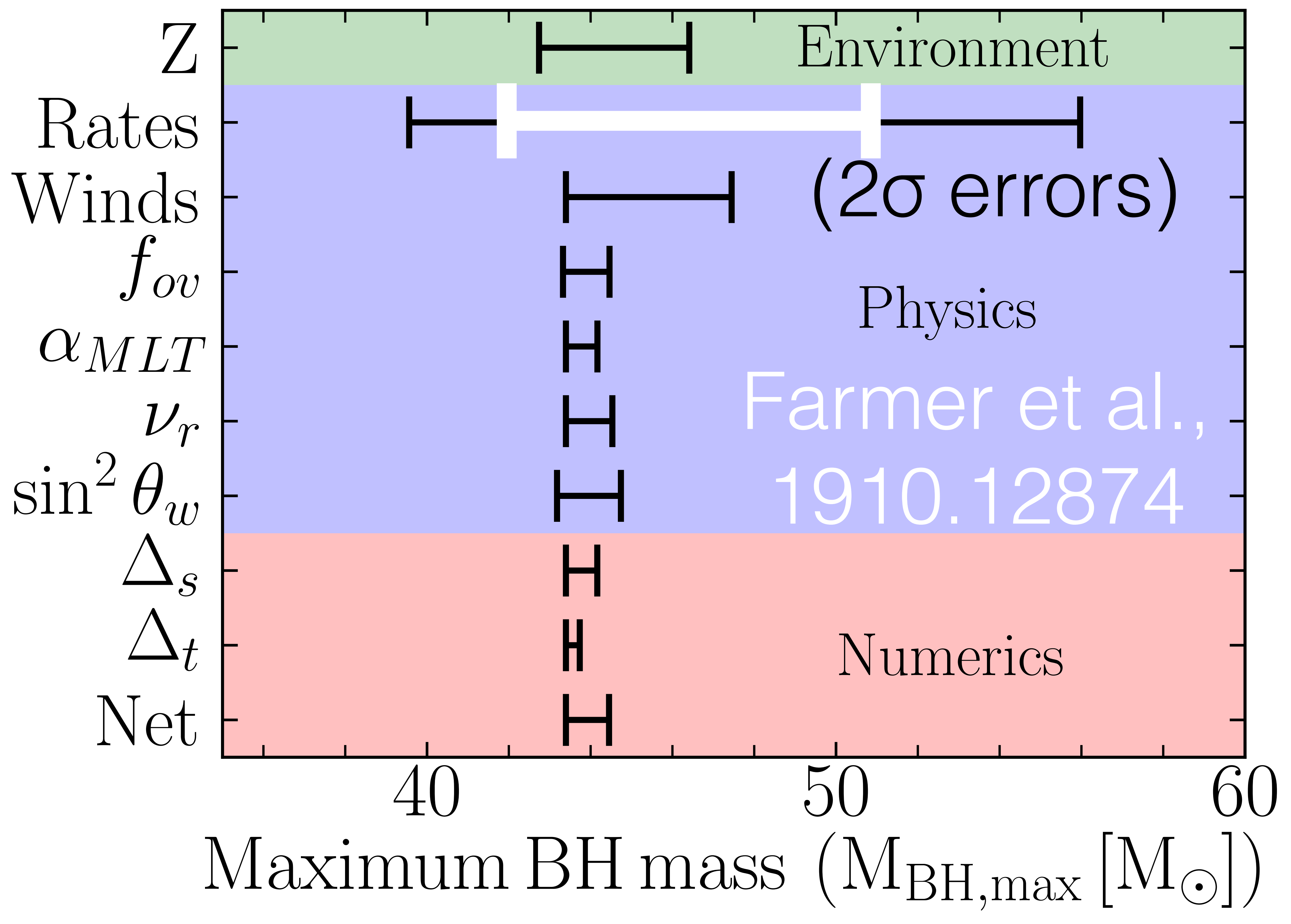
approximate deBoer et al. error bar for $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$



Farmer et al., 1910.12874

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N^{th} gen - N^{th} gen mergers,
accretion in nuclear star cluster,
…

Three Routes for SM Explanations

van Son et al., 2004.05187

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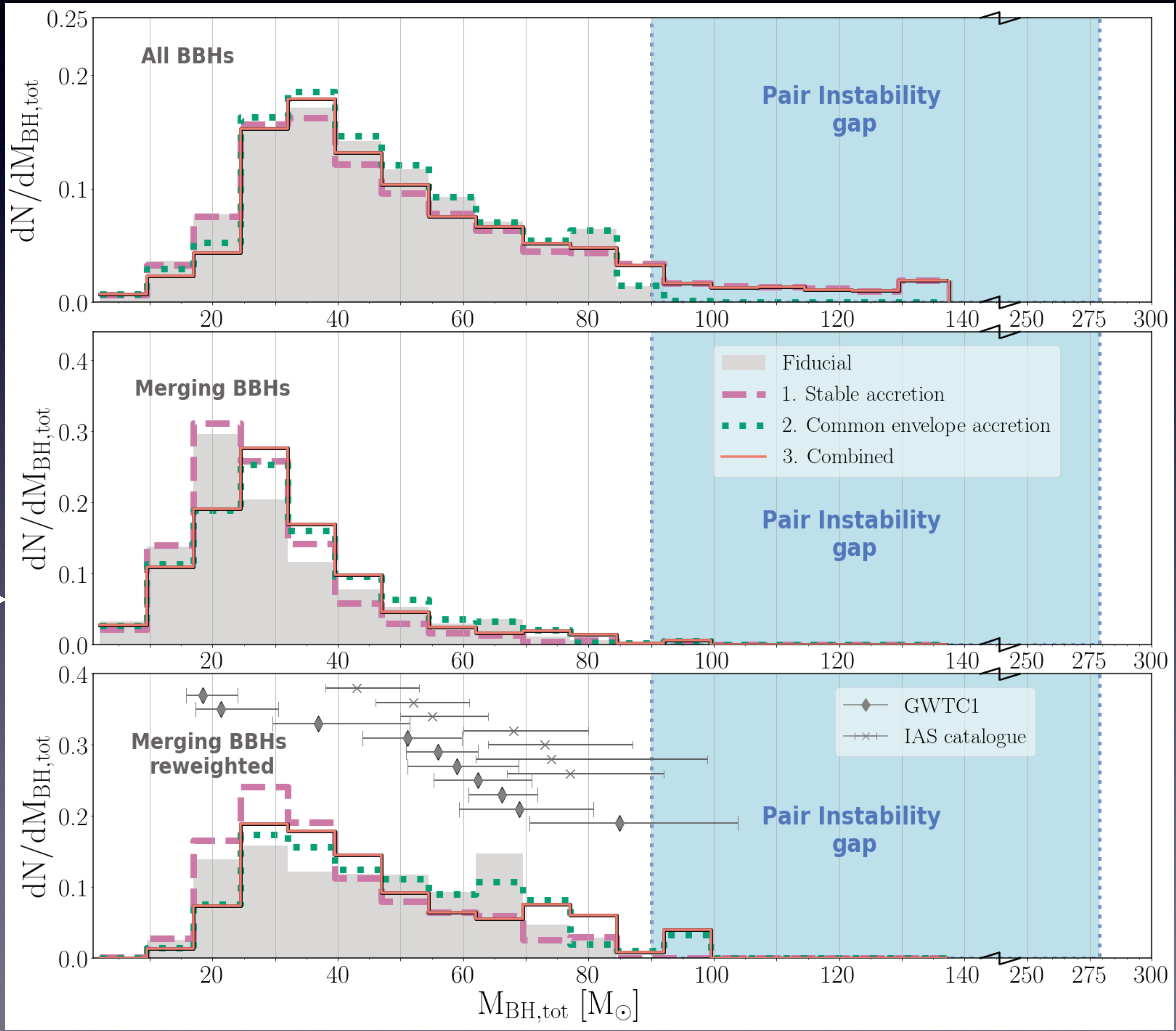

SM Explanations: Summary

- There **“definitely may be”** paths to making BHs with masses $M \gtrsim 50\mathrm{M}_\odot$ through SM mechanisms alone

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- Reliant on very uncertain SM ((g)astro)physics:
  - nonequilibrium stellar dynamics: how do stars merge / mix? what happens to the new core and envelope?
  - stellar populations: how do binary systems evolve? what are viable pathways for multiple mergers?
  - nuclear physics: how does ^{12}C capture ^{4}He?

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  - stellar populations: how do binary systems evolve? what are viable pathways for multiple mergers?
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If these are responsible for GW190521, we have witnessed a **rare event** (not every star or black hole experiences a merger)

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GW190521: BSM vs SM explanations

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- “Location” of the mass gap is the SM-only calculation prediction*

*unless ~5σ deviations from nuclear rates

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BSM physics

- "Location" of the mass gap is **not** as expected from SM-only calculation: objects "in the (SM) mass gap" form from isolated evolution, no mergers required

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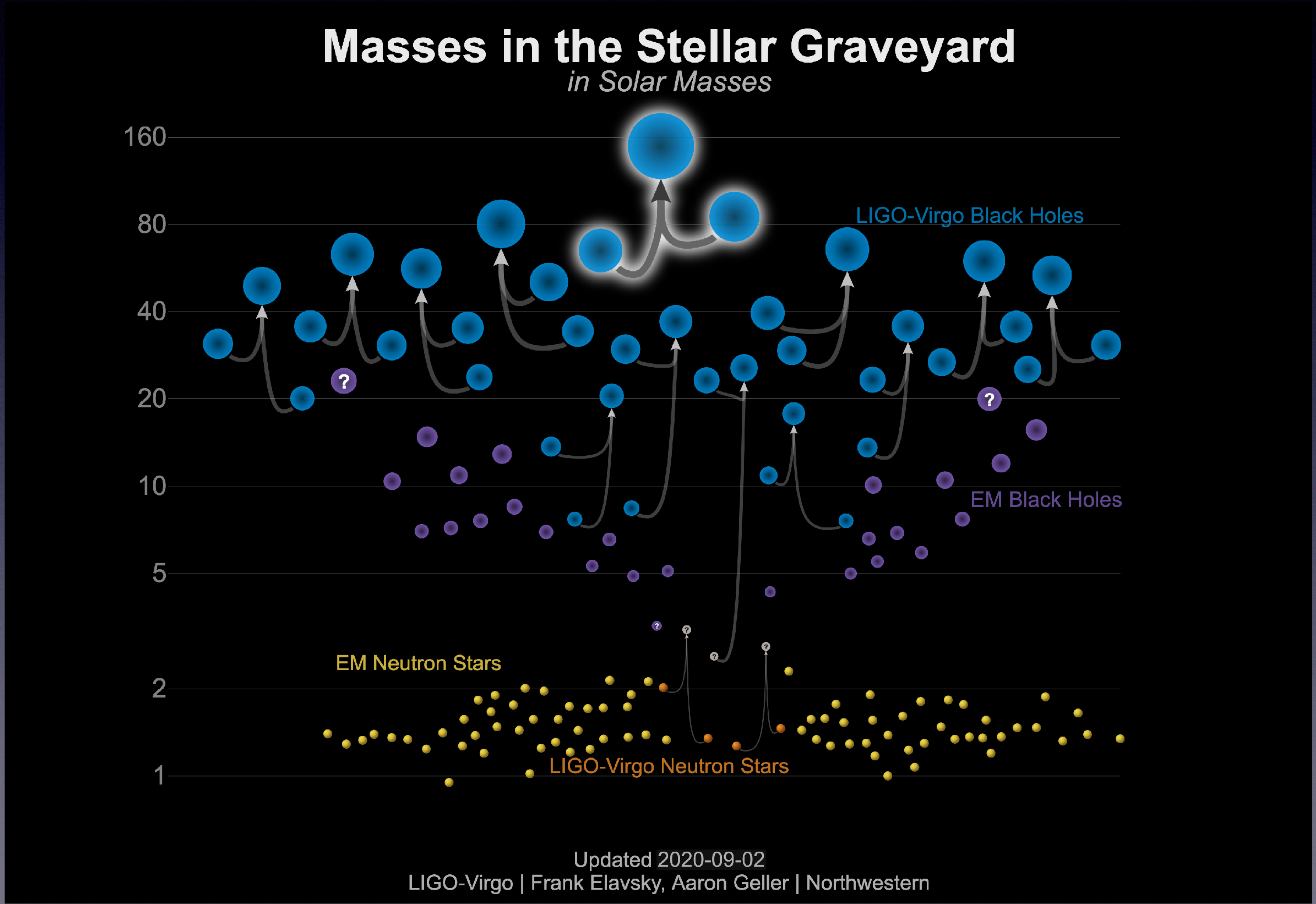
BSM physics

- “Location” of the mass gap is **not** as expected from SM-only calculation: objects “in the (SM) mass gap” form from isolated evolution, no mergers required

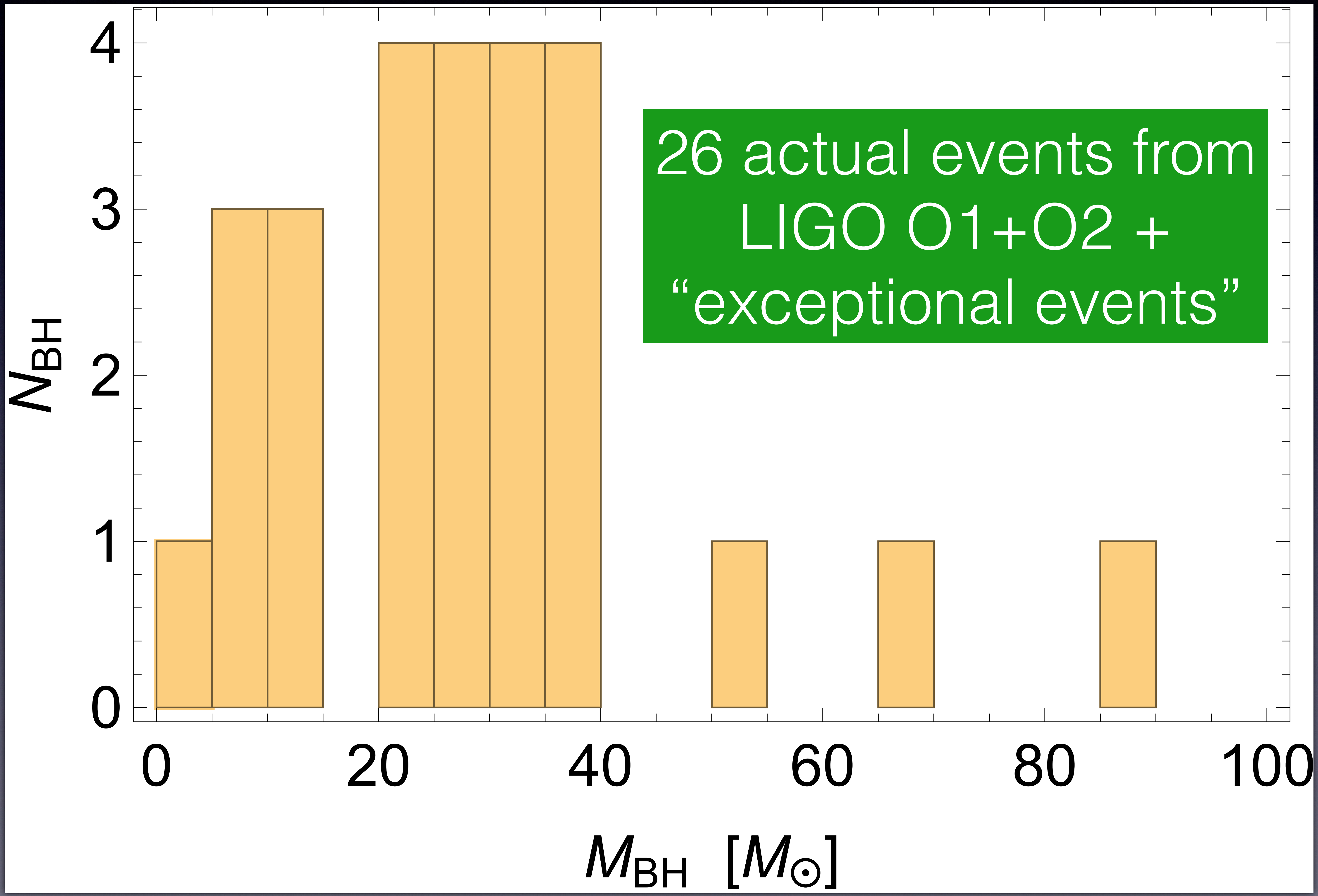
- Implies a **continuous**† distribution of BH masses up to a new, higher value of $M_{\rm BH}$

† caveat to be discussed shortly

LIGO Observations: O1+O2



Black Hole Population Statistics



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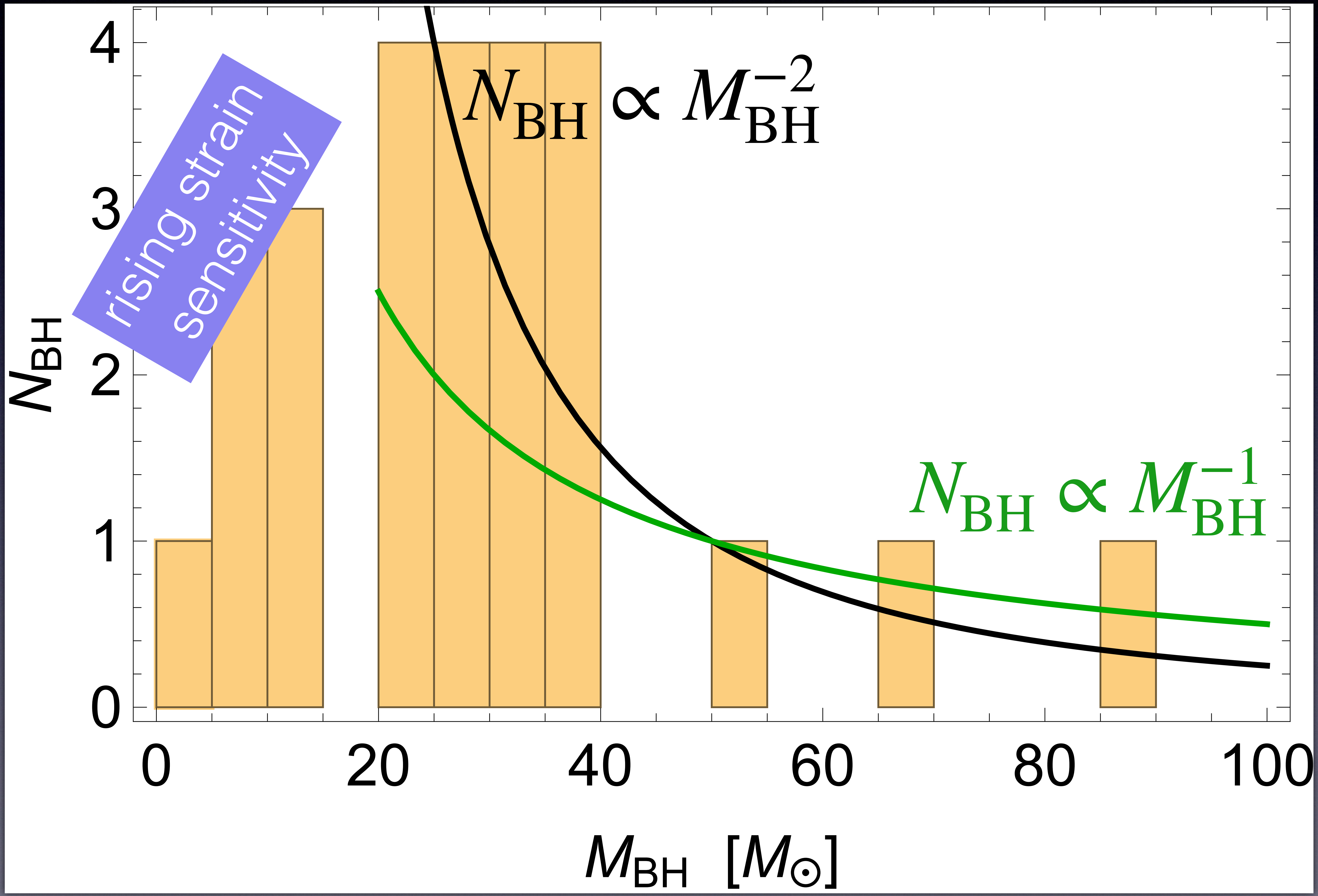

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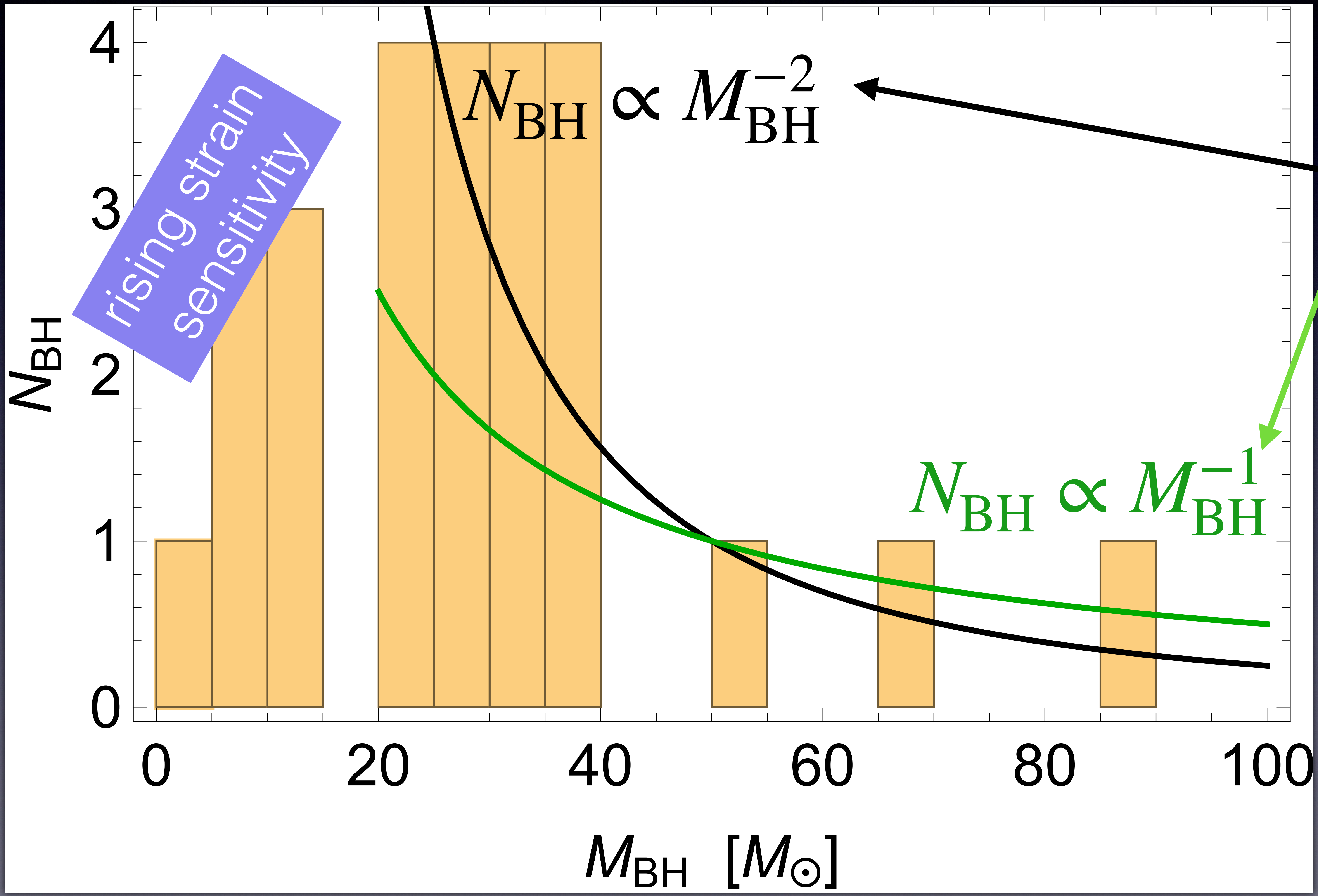
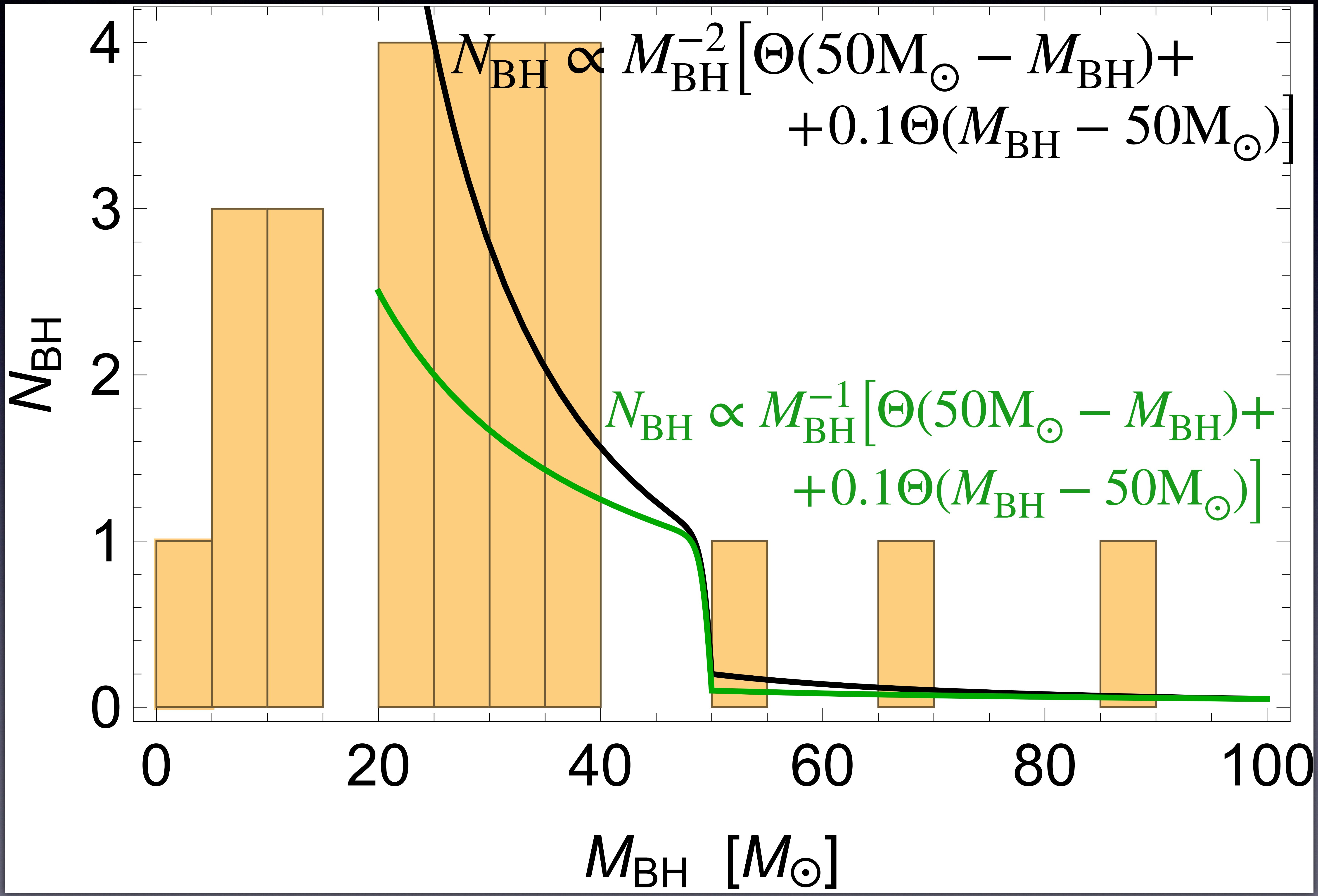


inherited from a stellar IMF

Black Hole Population Statistics



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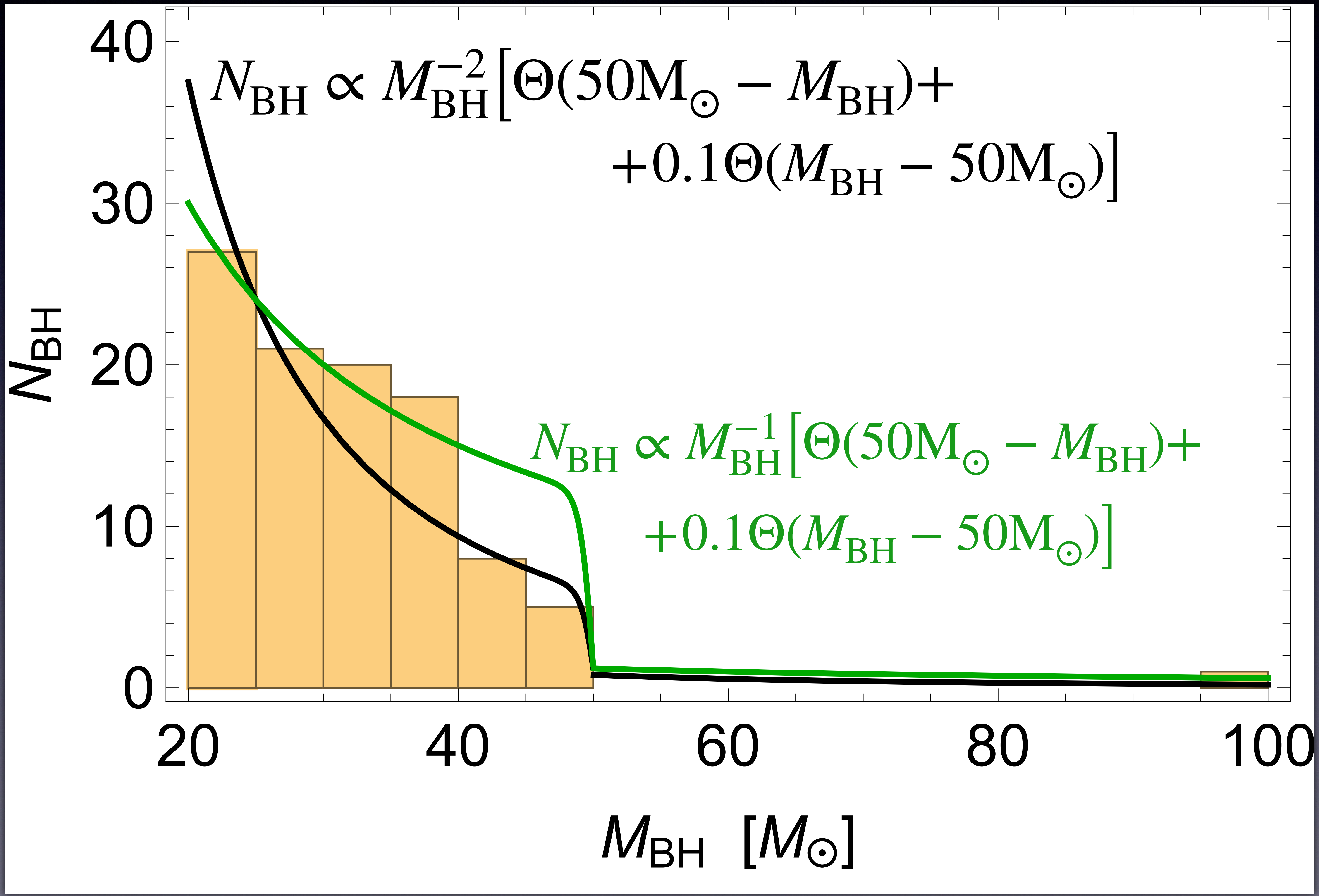

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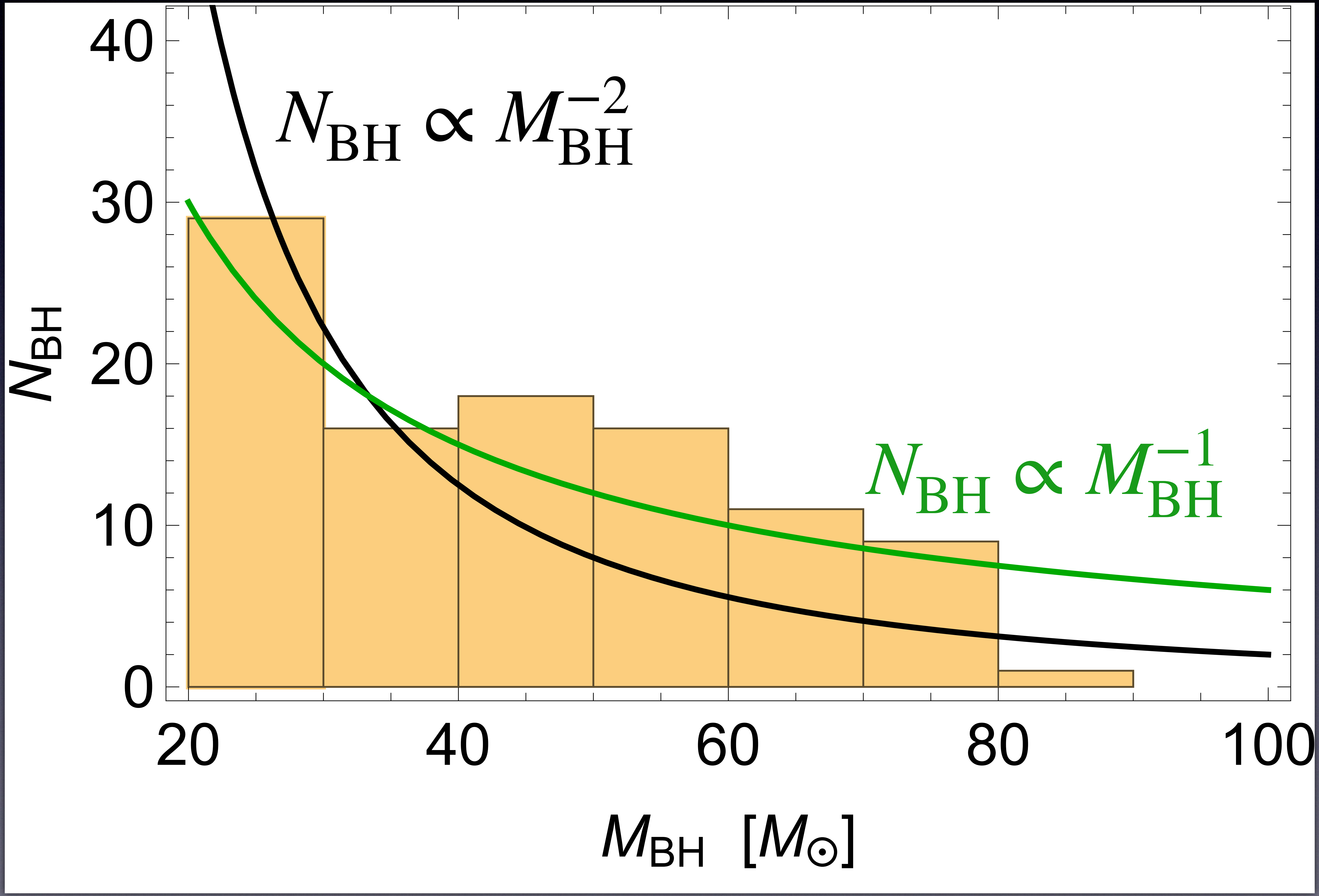
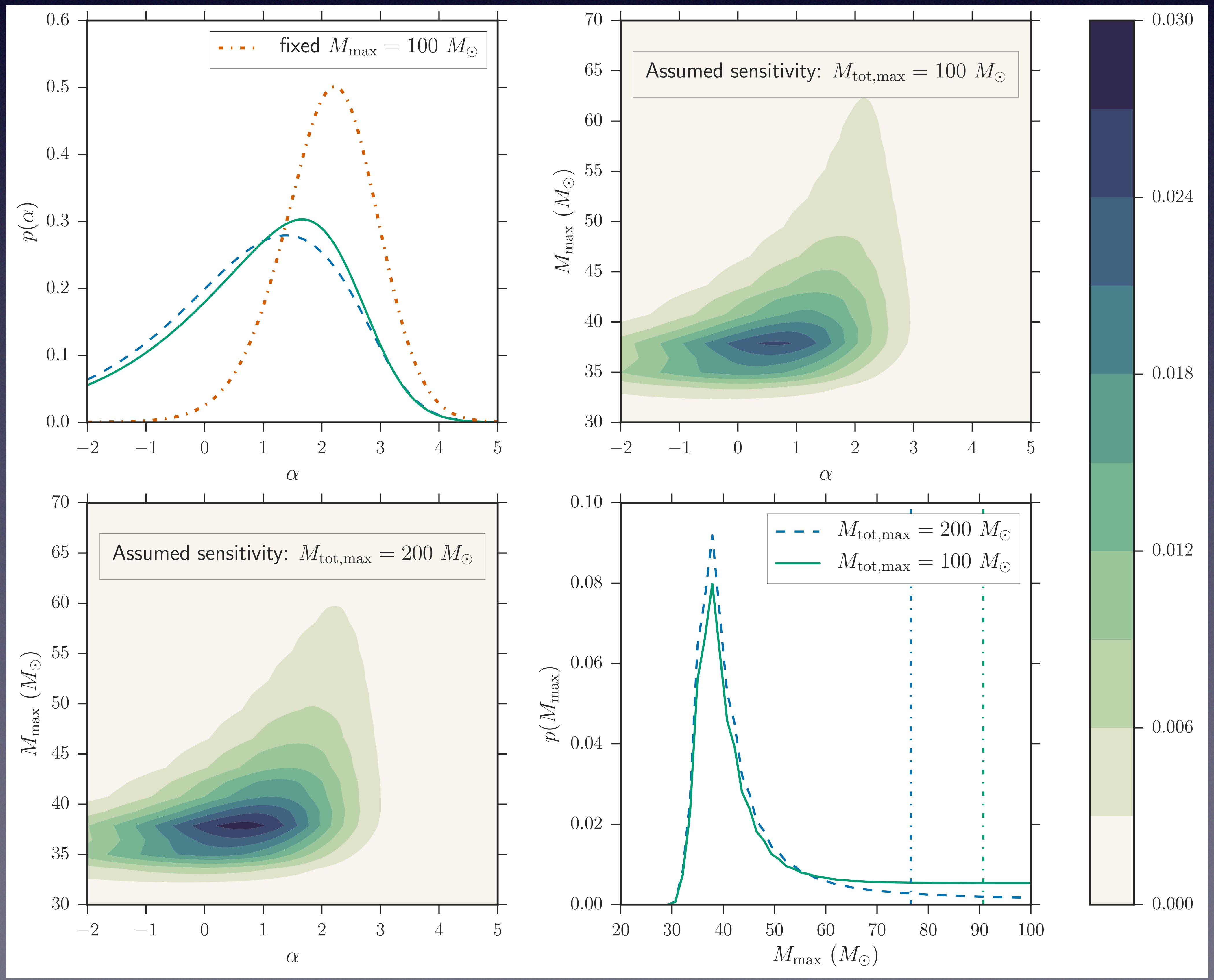


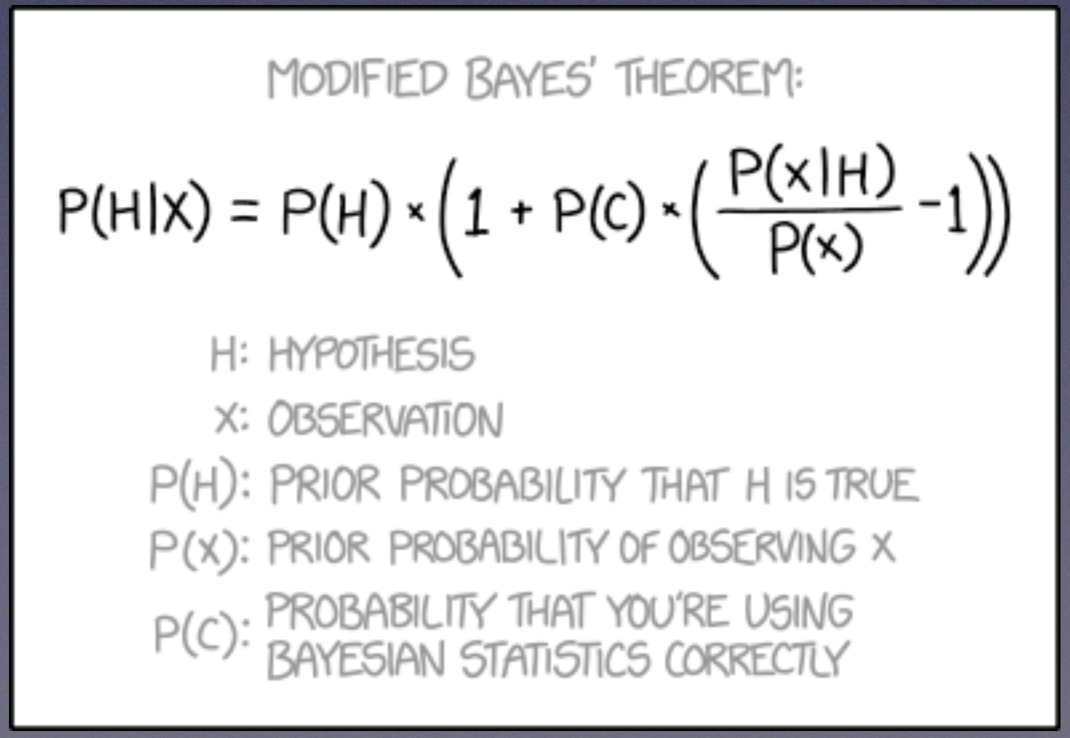
Black Hole Population Statistics

$$p\left(m_1, m_2 \mid \alpha, M_{\mathrm{max}}\right) \propto \frac{m_1^{-\alpha}\, \mathscr{H}(M_{\mathrm{max}} - m_1)}{\min(m_1, M_{\mathrm{tot,max}} - m_1) - M_{\mathrm{min}}}$$

First four LIGO detections:

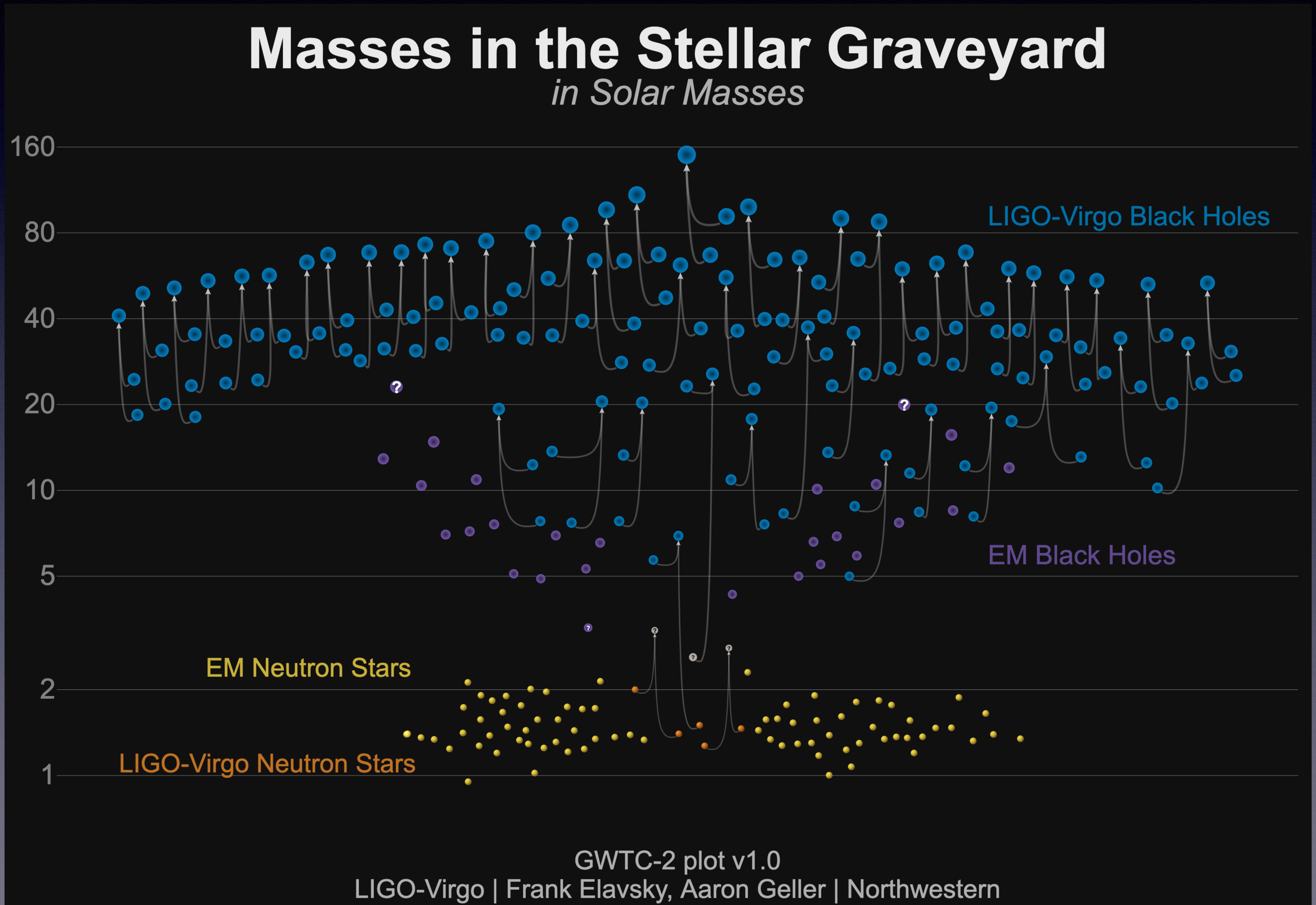


Fishbach & Holz, 1709.08584

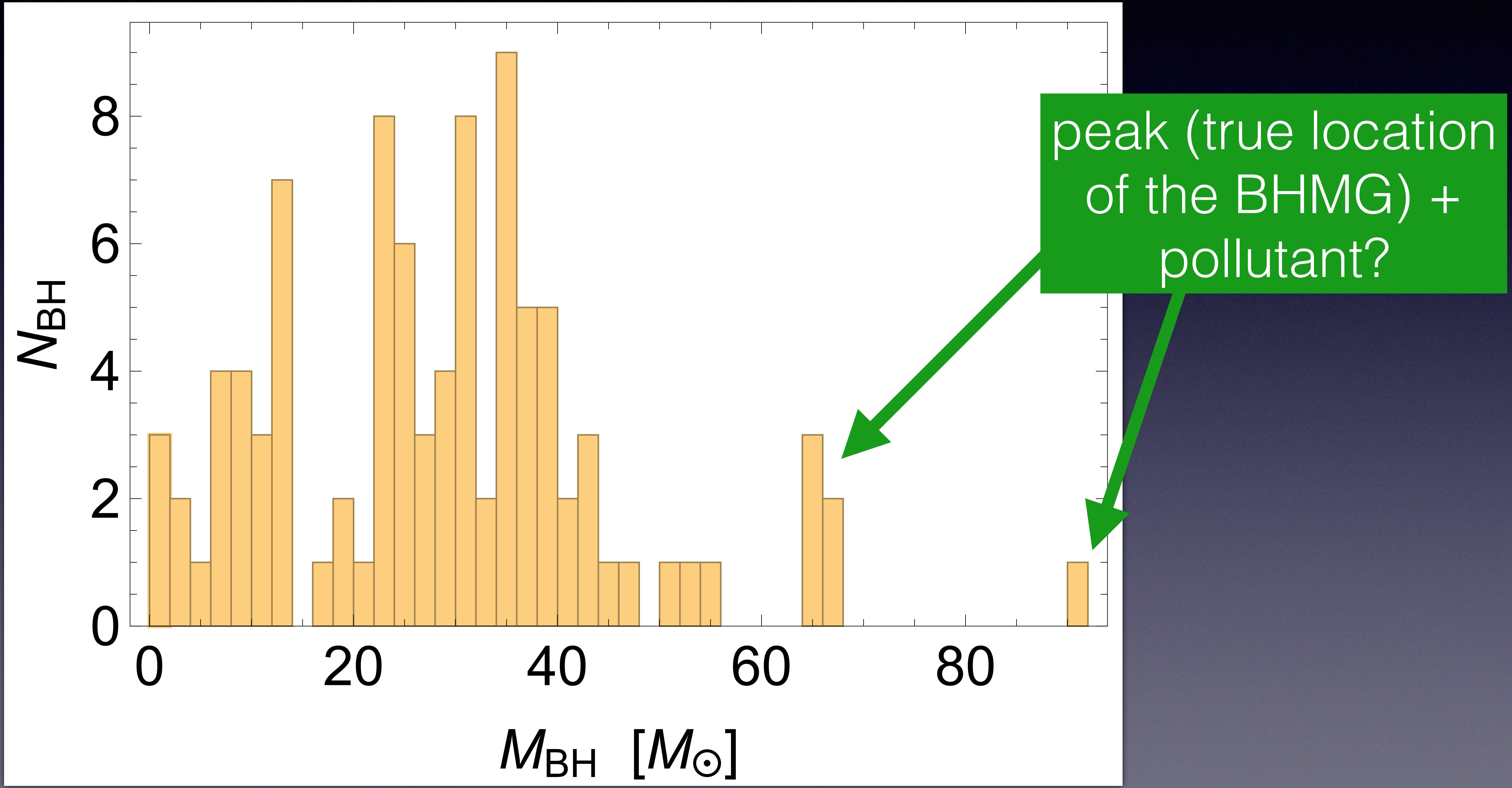


xkcd.com/2059/

LIGO Observations: O1+O2+O3a



Black Hole Population Statistics



Conclusions

xkcd.com/1022/

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xkcd.com/1022/

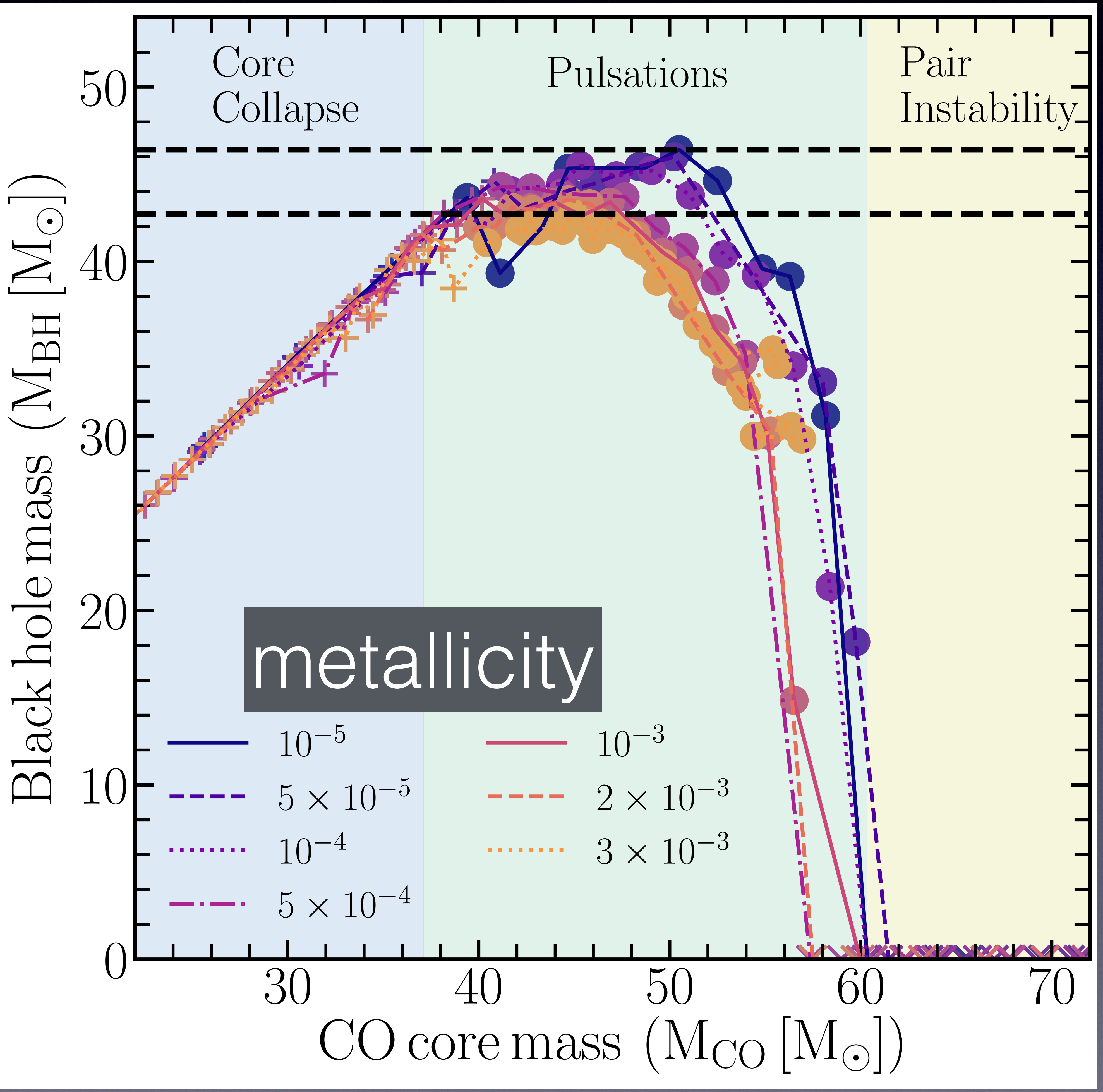
- LIGO is in the middle of its "discovery bump" — we are learning so much more about the Universe all the time!
- GW190521 provides rich fodder for new ideas and tests of both SM and BSM physics
- The future is exciting!

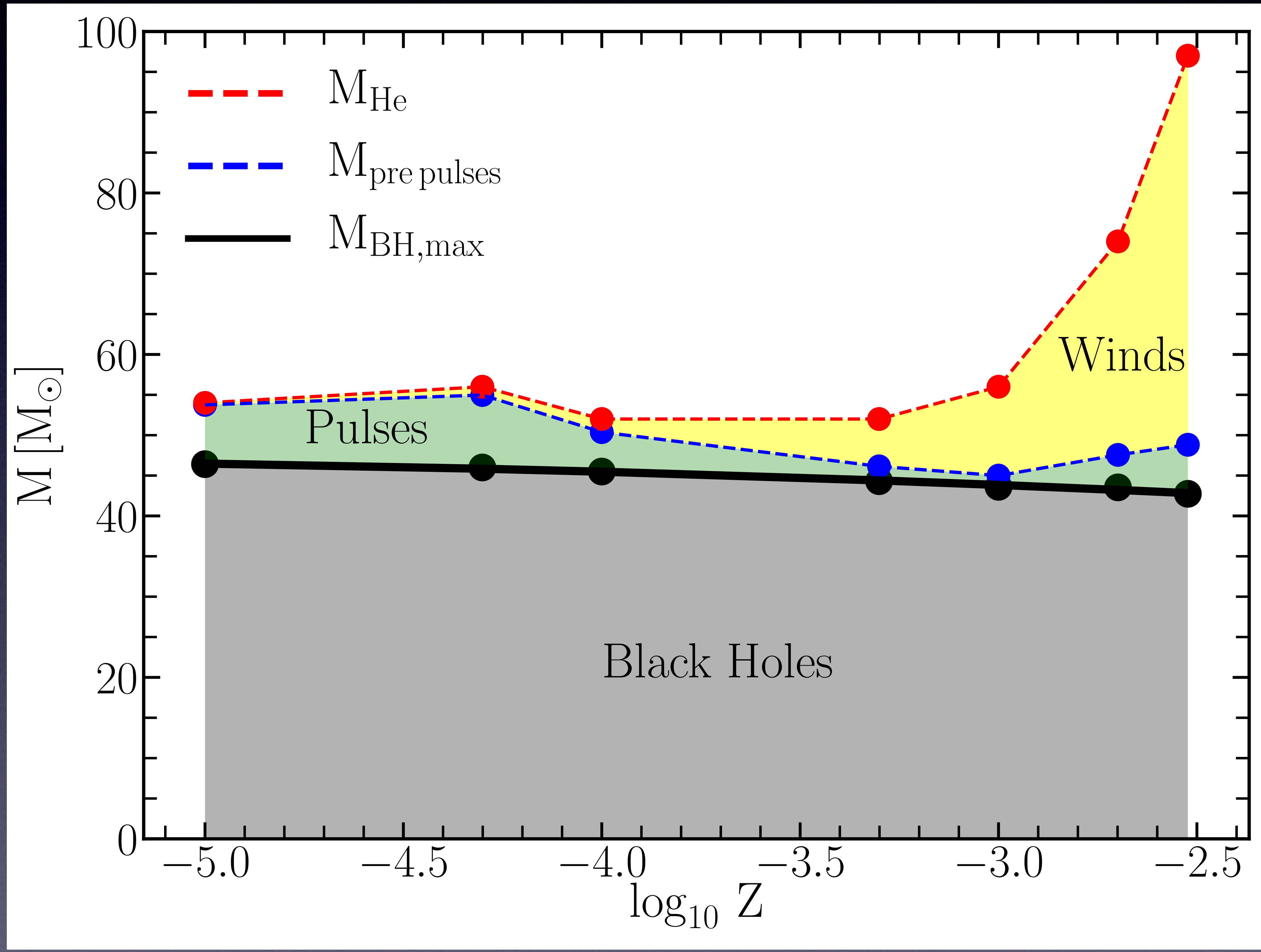
Thanks!

sammcd00@fnal.gov

home.fnal.gov/~sammcd00/

Environmental Variation





Farmer et al., 1910.12874 ApJ 887 53F

SM prediction: $M_{BH} < 48\ M_\odot$

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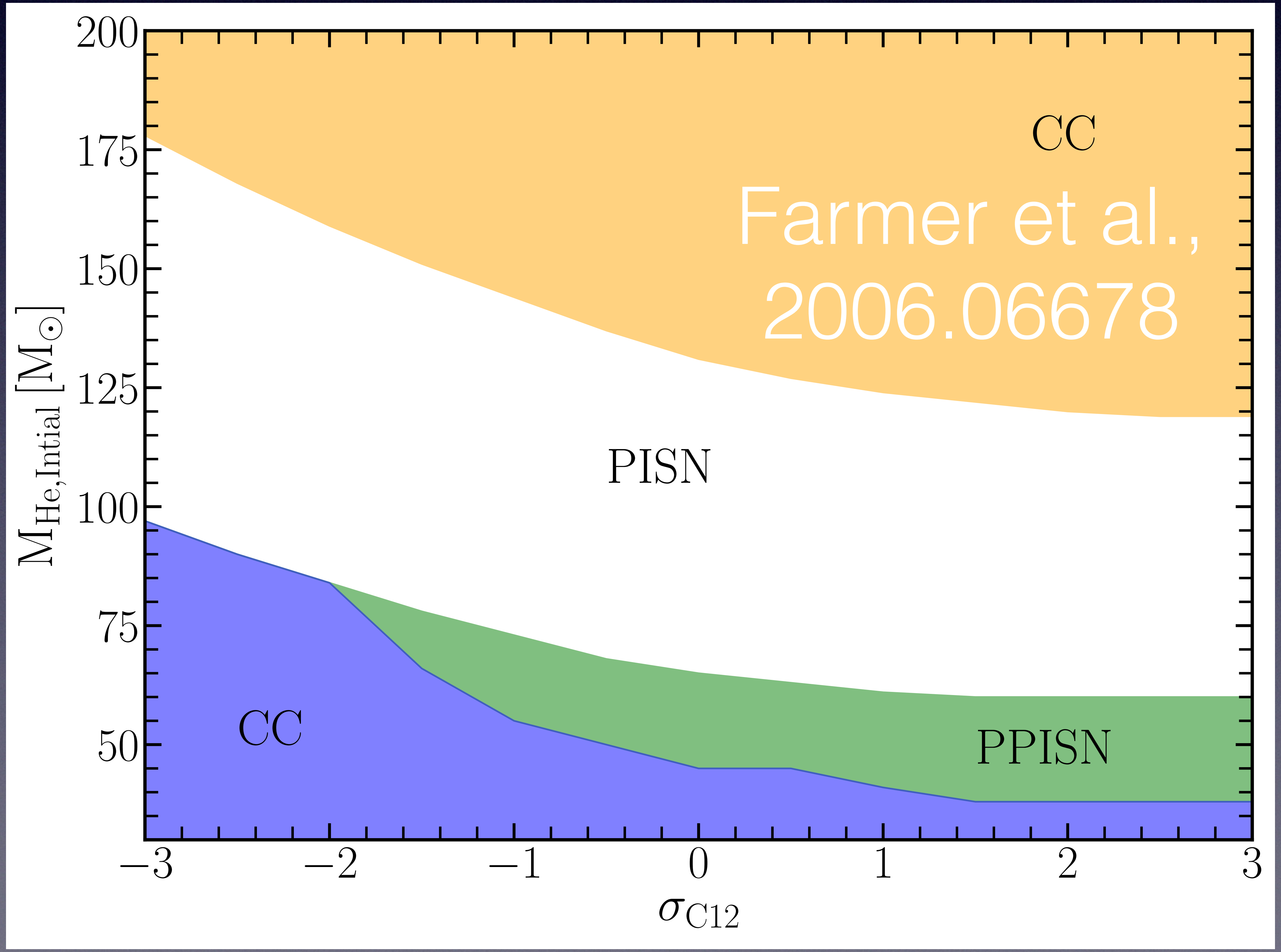

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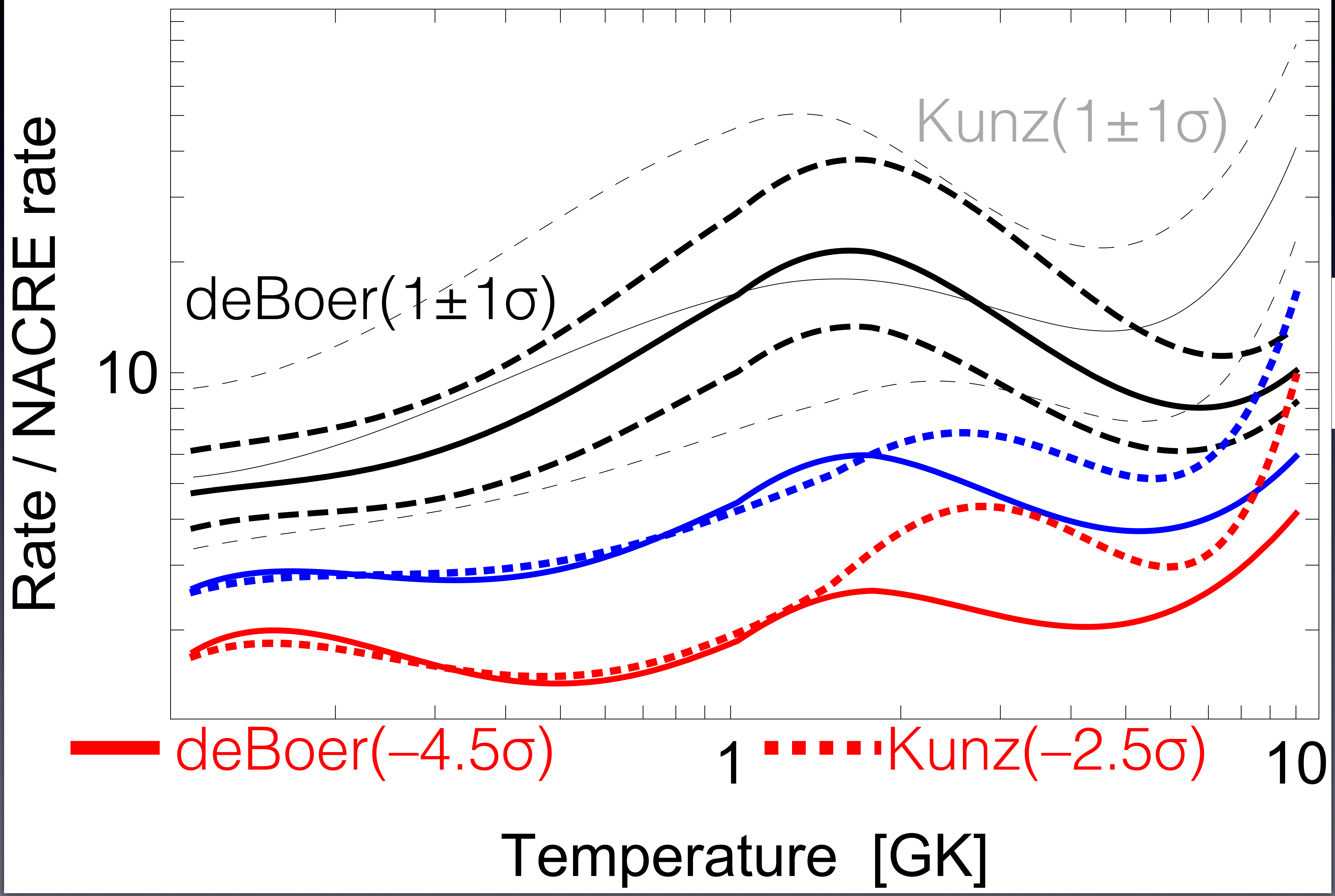
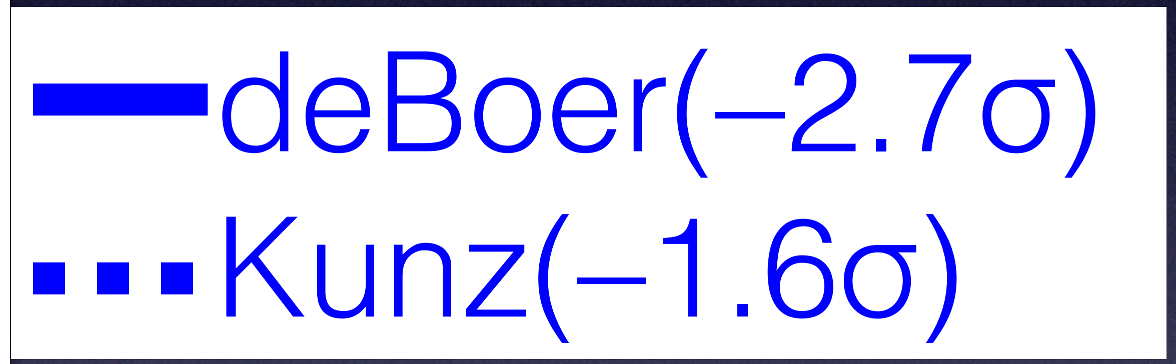
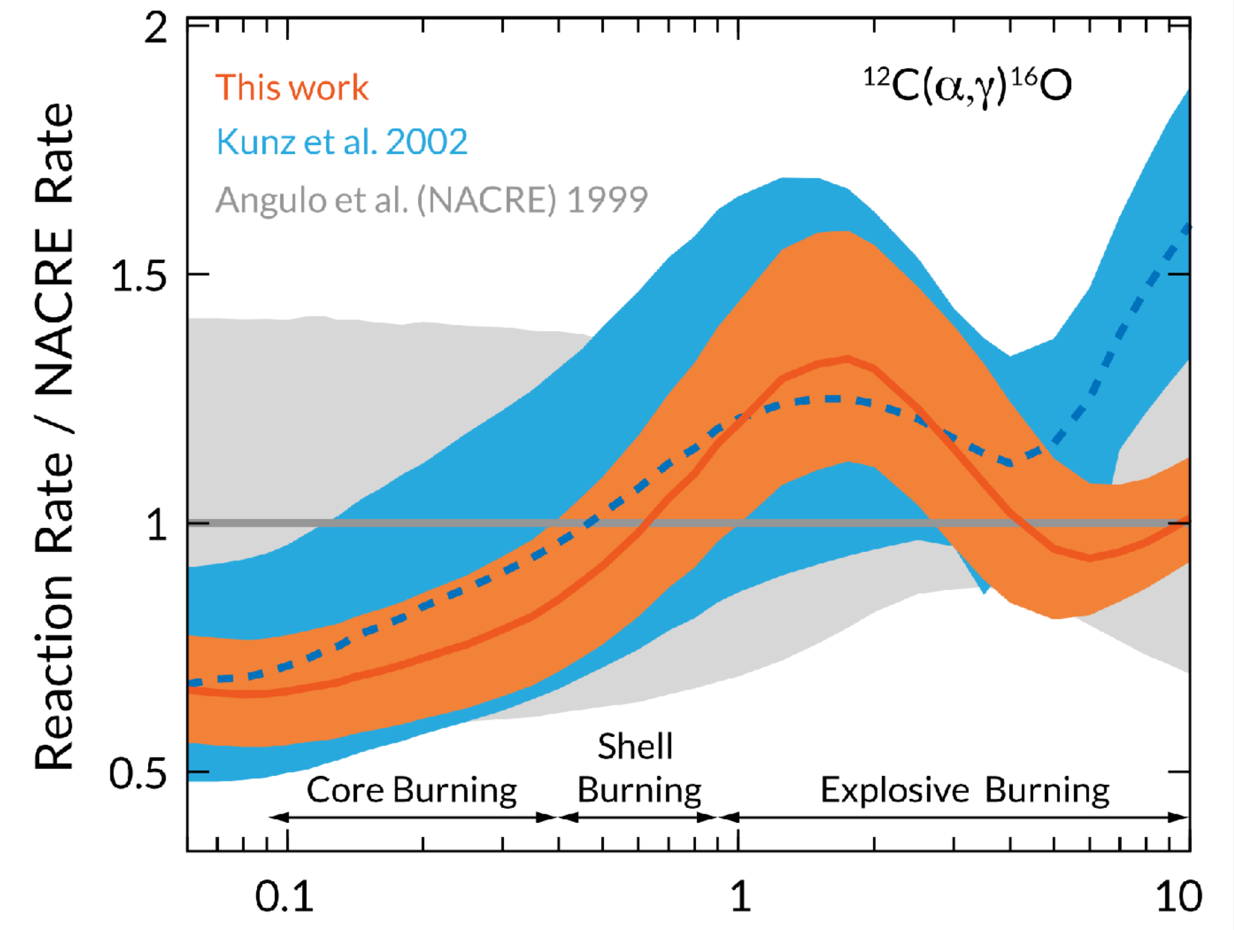
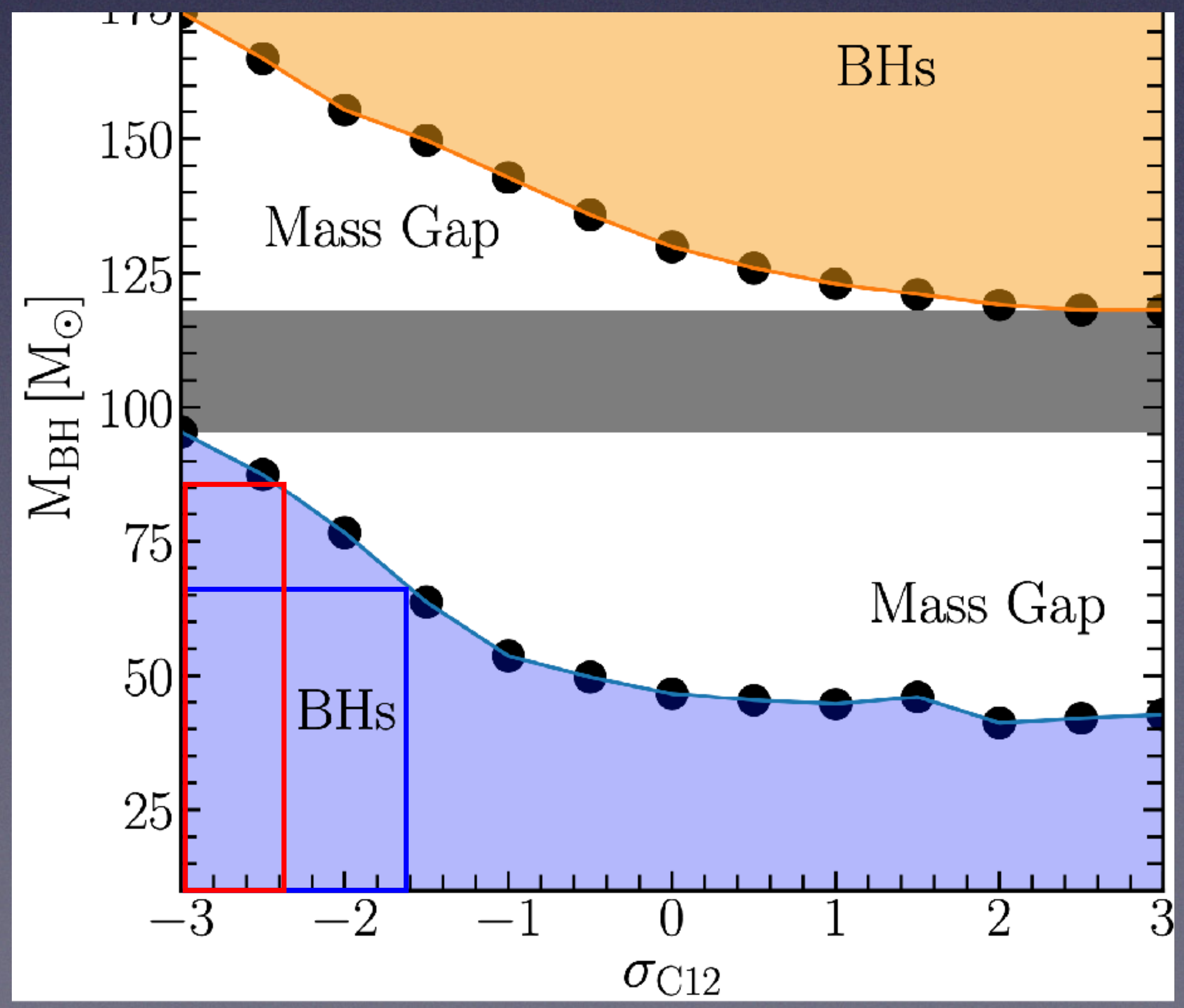
$^{12}C(\alpha,\gamma)^{16}O$ rates









Croon, McDermott, Sakstein
2007.00650 + 2007.07889

Losses to Light Particles

- Electrophilic axion: $$\mathcal{Q}_{\mathrm{sC}} = \frac{40\,\zeta_6 \alpha_{\mathrm{EM}} g_{ae}^2}{\pi^2} \frac{Y_e T^6}{m_N m_e^4} F_{\mathrm{deg}} \simeq 33 \frac{\mathrm{erg}}{\mathrm{g \cdot s}} \alpha_{26} Y_e T_8^6 F_{\mathrm{deg}}$$
  $$T_8 \equiv \frac{T}{10^8 \mathrm{K}}$$
- Photophilic axion: $$\mathcal{Q}_{a\gamma} = \frac{g_{a\gamma}^2 T^7}{4\pi^2 \rho} \left(\frac{k_S}{2T}\right)^2 f\left[\left(\frac{k_S}{2T}\right)^2\right] \simeq 283.16 \frac{\mathrm{erg}}{\mathrm{g \cdot s}} g_{10}^2 T_8^4$$
  $$\left(\frac{k_S}{2T}\right)^2 = 0.166 \frac{\rho_3}{T_8^3} \sum_j Y_j Z_j^2$$
- Dark photon: $$\mathcal{Q}_{A'} = \frac{\epsilon^2 m_{A'}^2}{4\pi\rho} \frac{\omega_p^3}{e^{\omega_p/T} - 1} \simeq 1800 \frac{\mathrm{erg}}{\mathrm{g \cdot s}} \frac{Z}{A} \left(\frac{\epsilon}{10^{-7}} \frac{m_{A'}}{\mathrm{meV}}\right)^2 T_8$$
  $$\omega_p^2 \simeq \frac{4\pi\alpha_{\mathrm{EM}} n_e}{m_e} \simeq (654\mathrm{eV})^2 \frac{Z}{A} \rho_3$$

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