New Physics and the Black Hole Mass Gap

Samuel D. McDermott

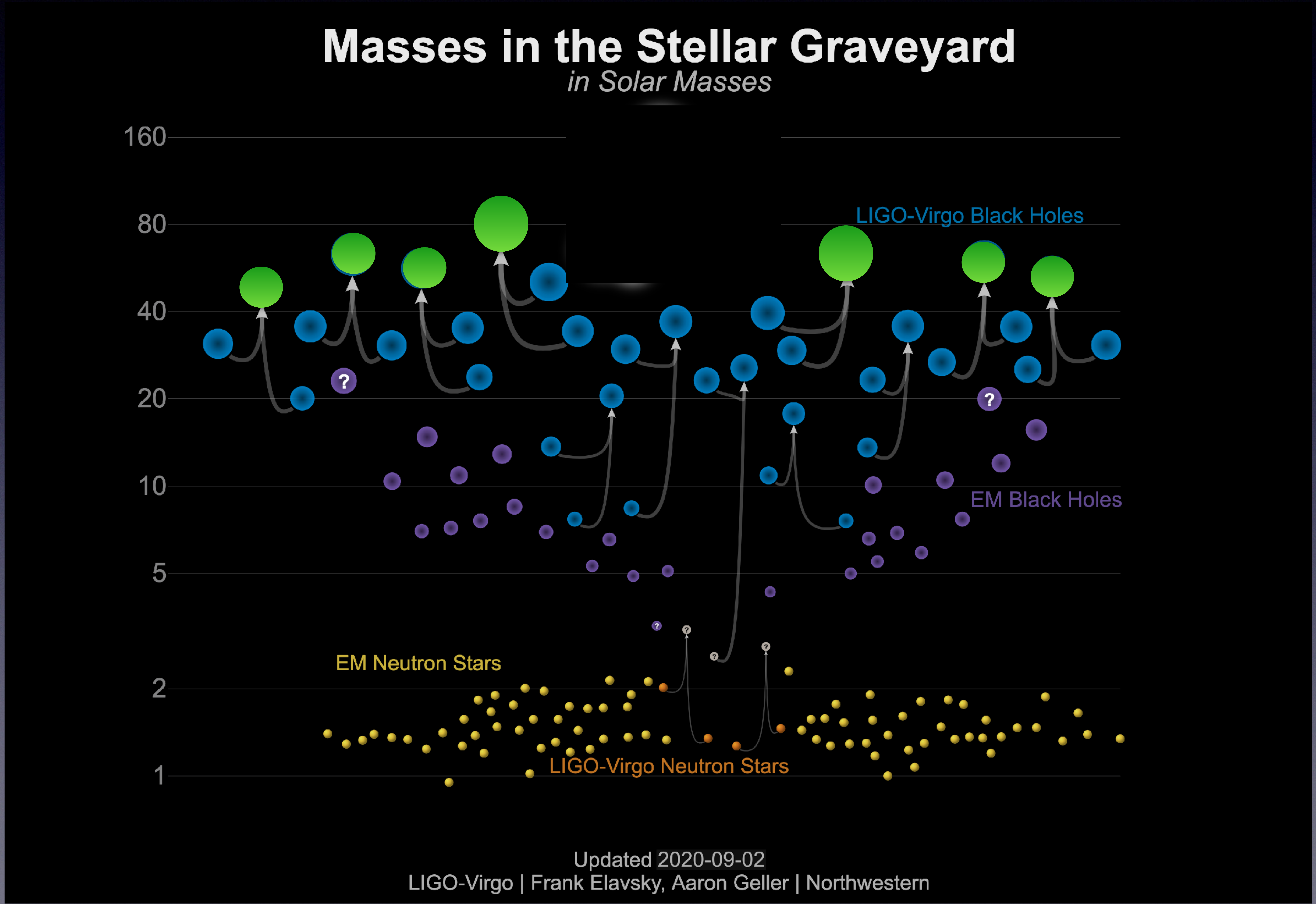
Work with Djuna Croon + Jeremy Sakstein: 2007.00650 [hep-ph], 2007.07889 [gr-qc]

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

&/+ Eric Baxter: 2104.abcde [astro-ph.??]

Fermilab

LIGO Observations: O1+O2

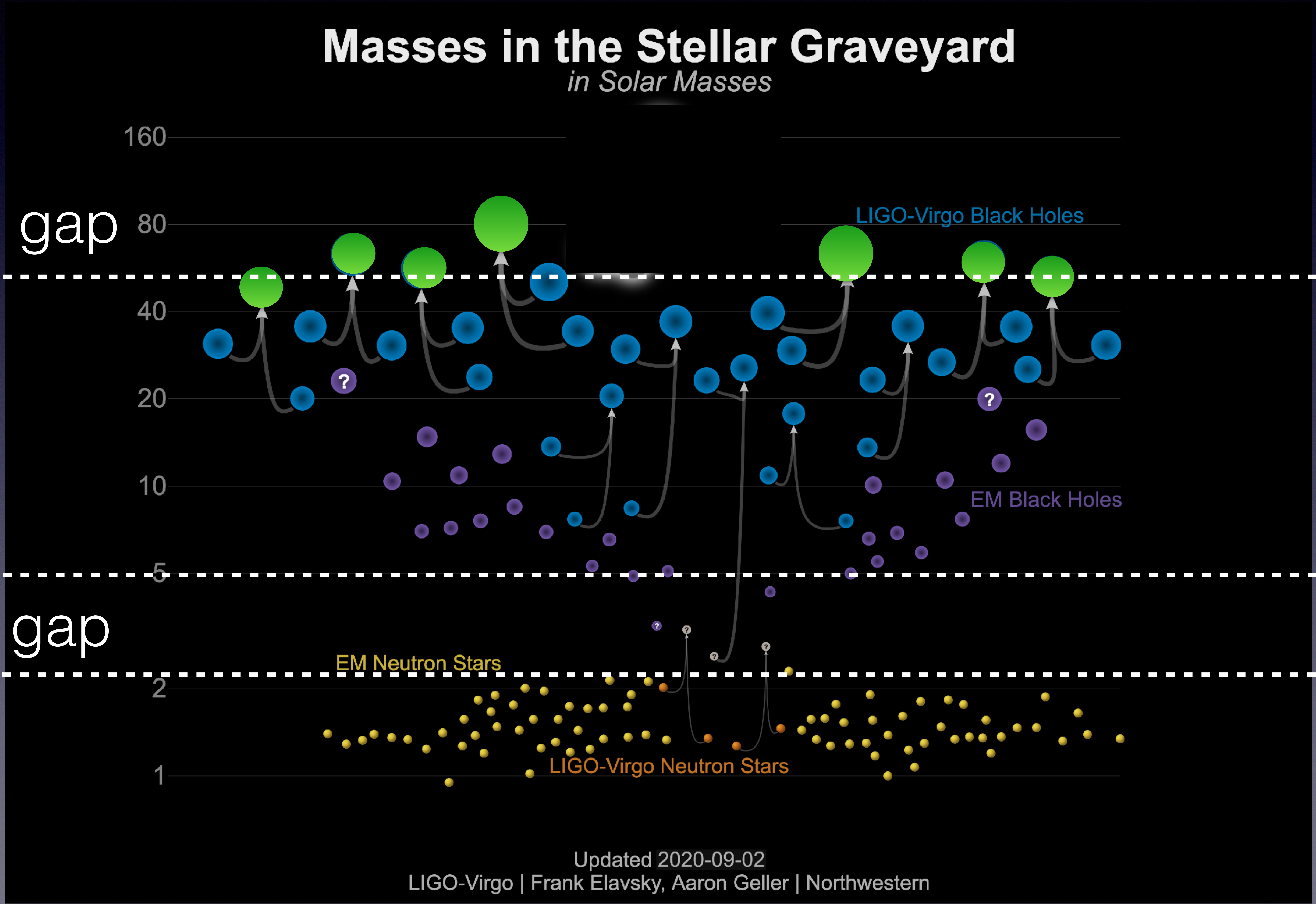


LIGO Observations: O1+O2

"upper" mass gap

"Black hole mass ceiling"

"lower" mass gap

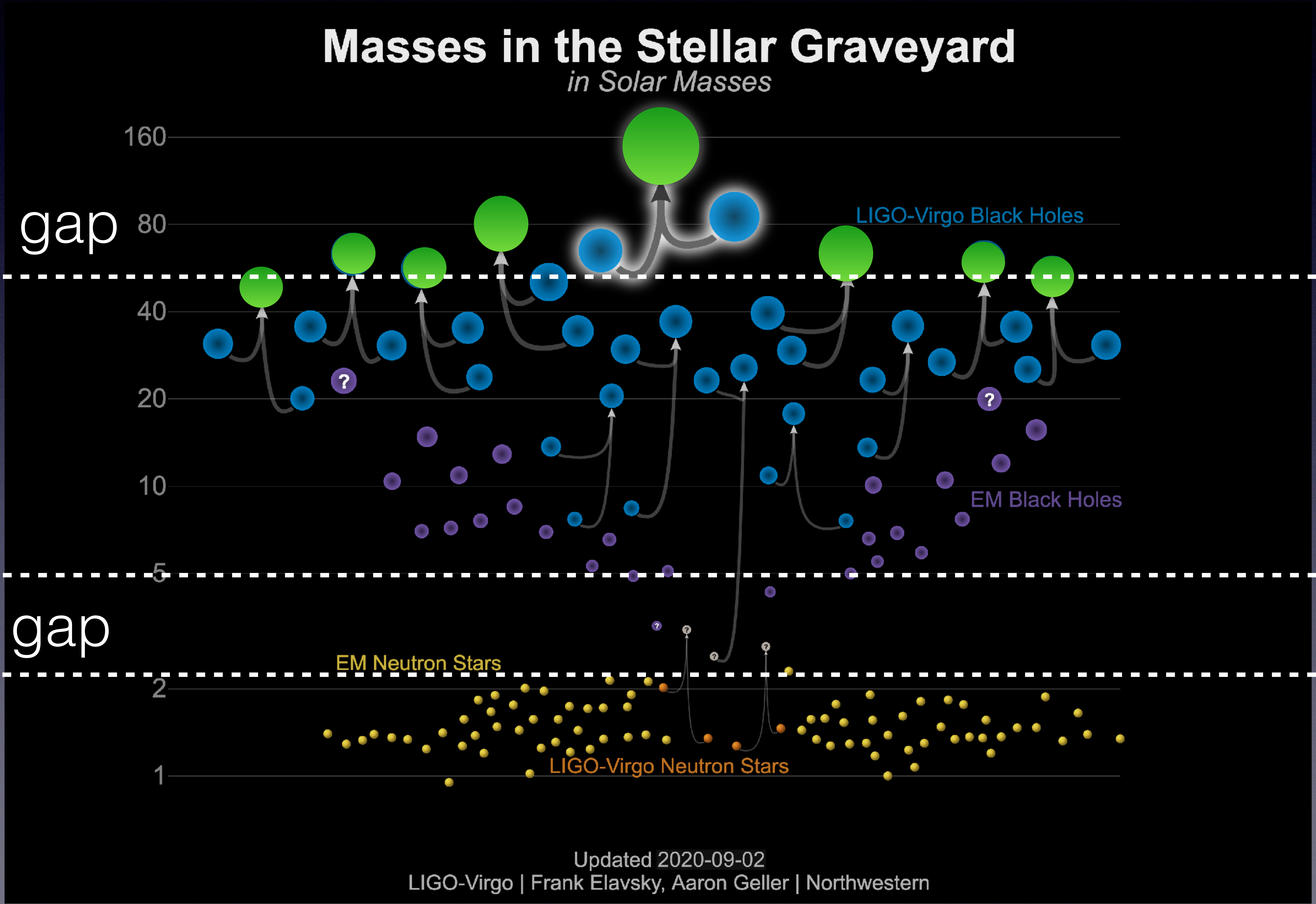


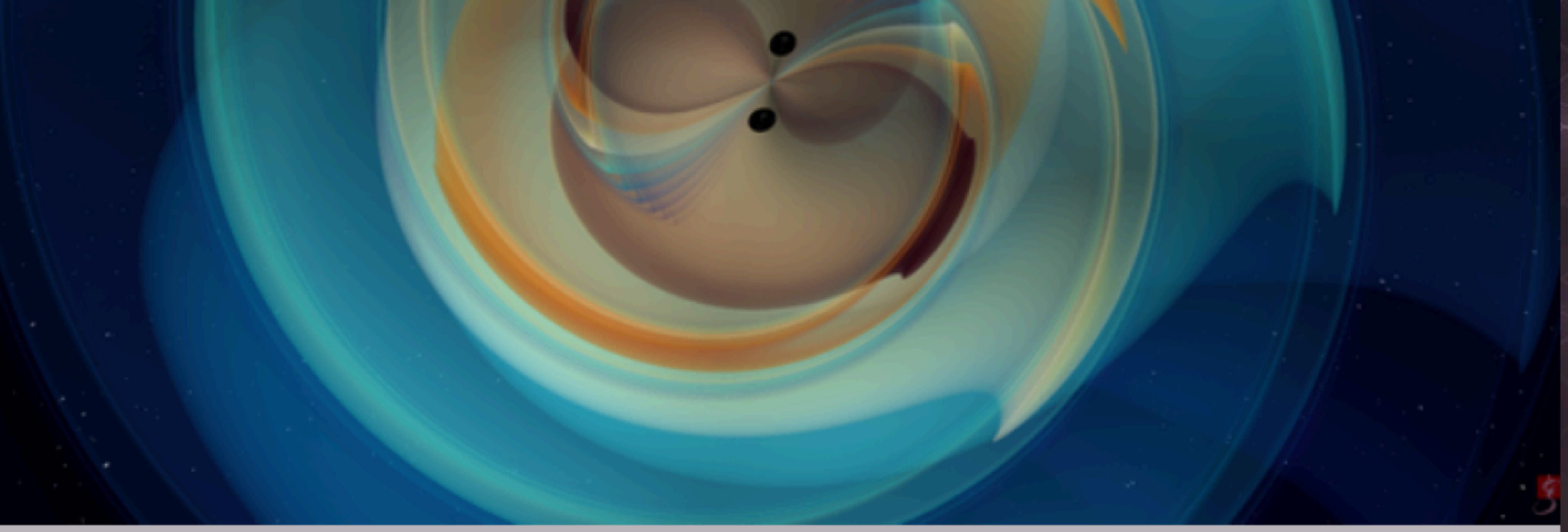
LIGO Observations: O1+O2

“upper” mass gap

“Black hole mass ceiling”

“lower” mass gap





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

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.

ervations

es in the Stellar Grave
in Solar Masses

FORBES.COM

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

lack Holes

"Bla
mass

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

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NewScientist
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Latest Issues SCIENTIFIC AMERICAN 175 Cart 0

LIGO and Virgo Capture Their Most Massive Black Holes Yet

ars TECHNICA

CHIRP, CHIRP, BANG, BANG —

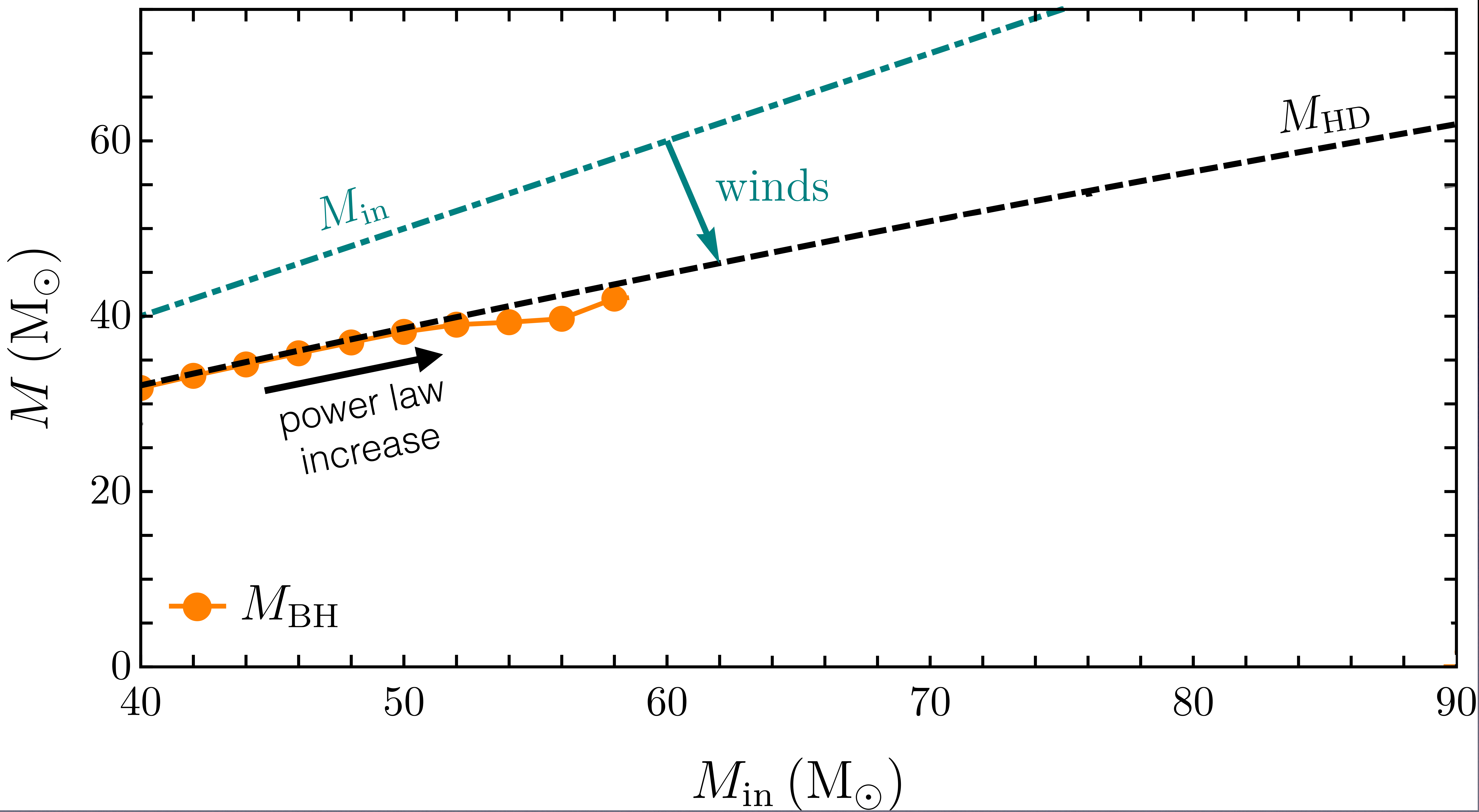
Meet GW190521—a black-hole merger for the record books

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

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

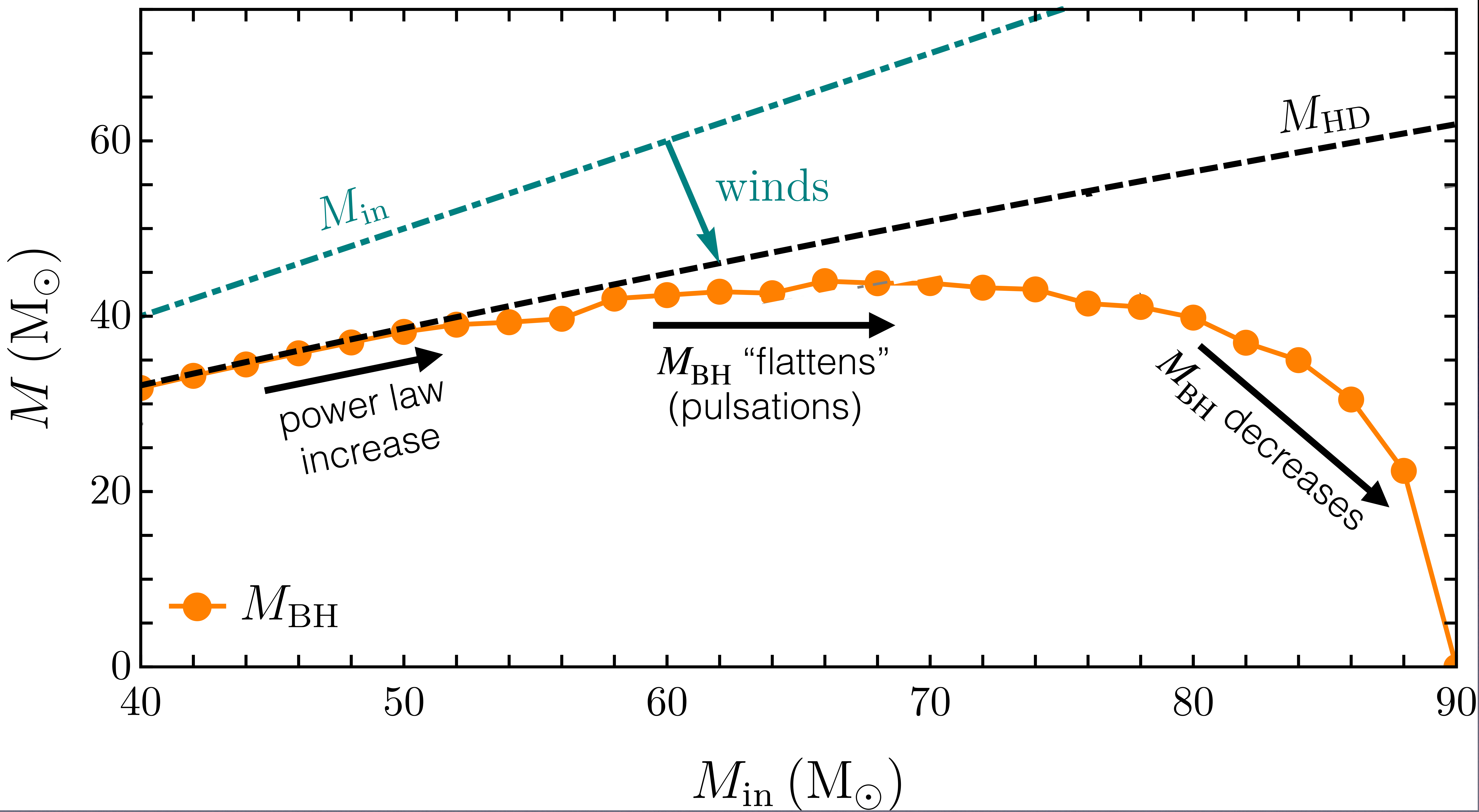
From R. Abbott et al. (LIGO Scienti... laboration),
Phys. Rev. Lett. 125, 101102 (2020

Croon, McDermott, Sakstein
2007.07889

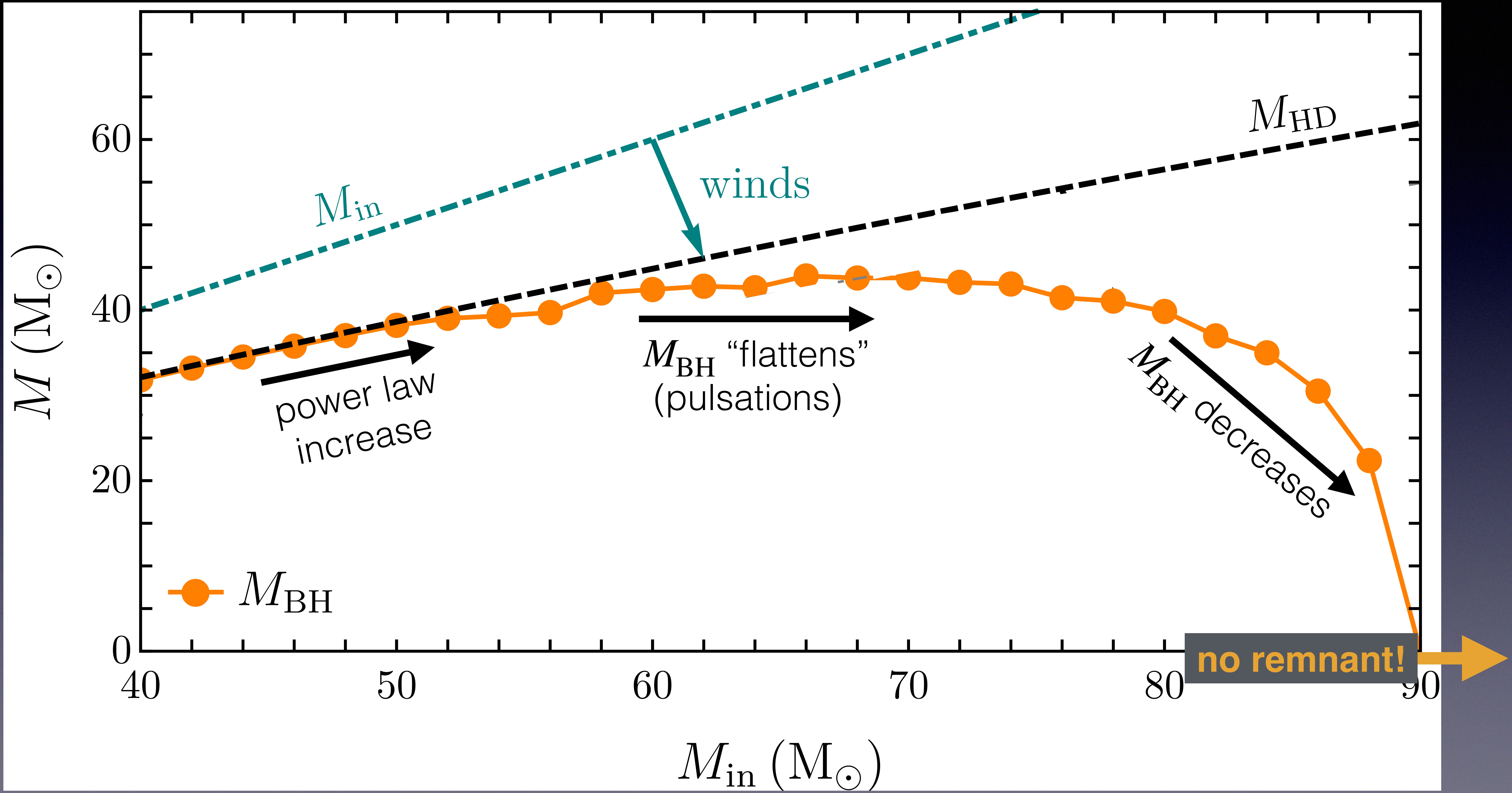



Croon, McDermott, Sakstein
2007.07889
$M_{\rm in}$
winds
$M_{\rm HD}$
$M_{\rm BH}$ "flattens"
(pulsations)
power law
increase
$M_{\rm BH}$
M ($M_\odot$)
$M_{\rm in}$ ($M_\odot$)
0
20
40
60
40
50
60
70
80
90

Croon, McDermott, Sakstein
2007.07889



Croon, McDermott, Sakstein
2007.07889



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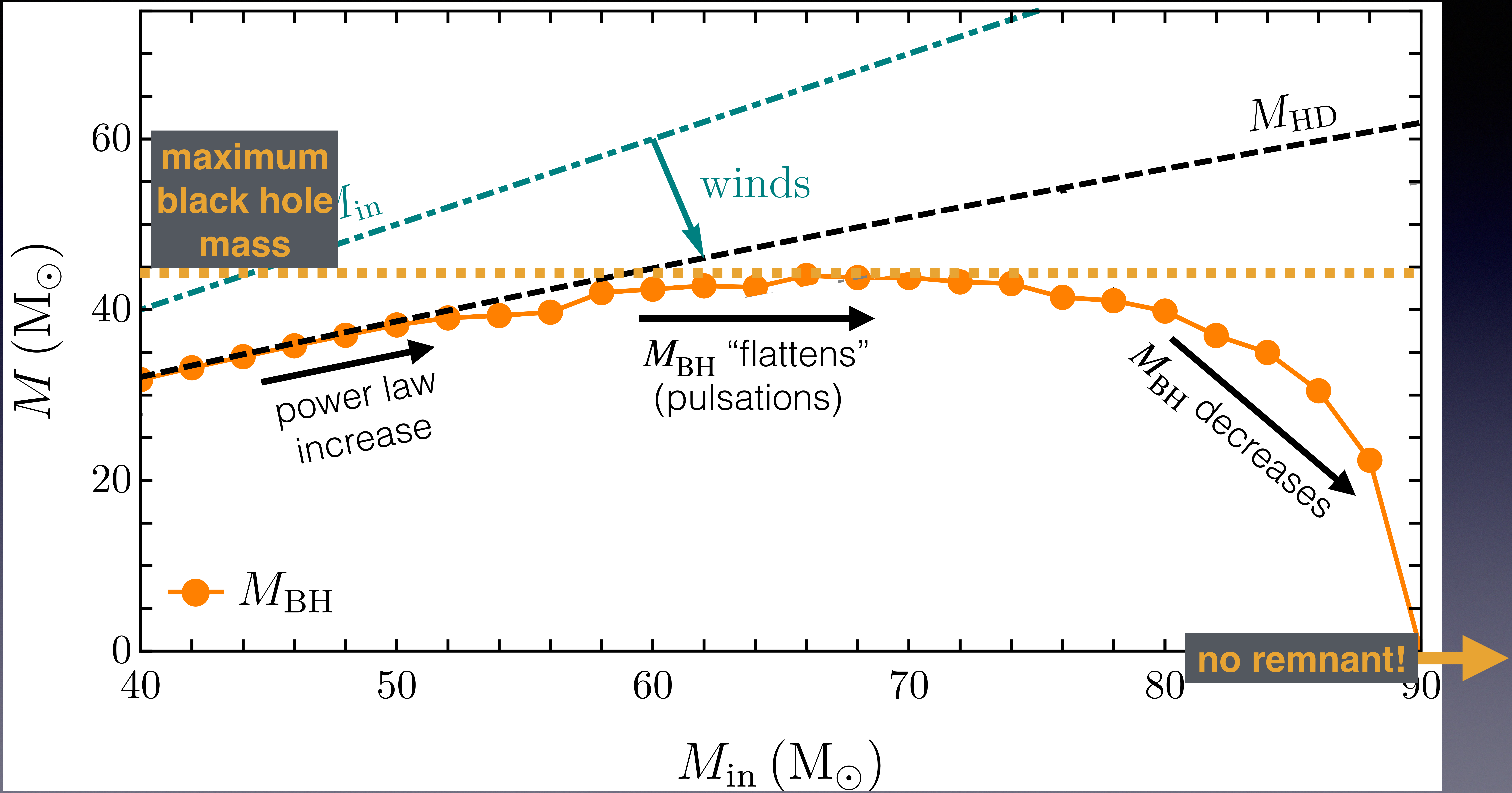
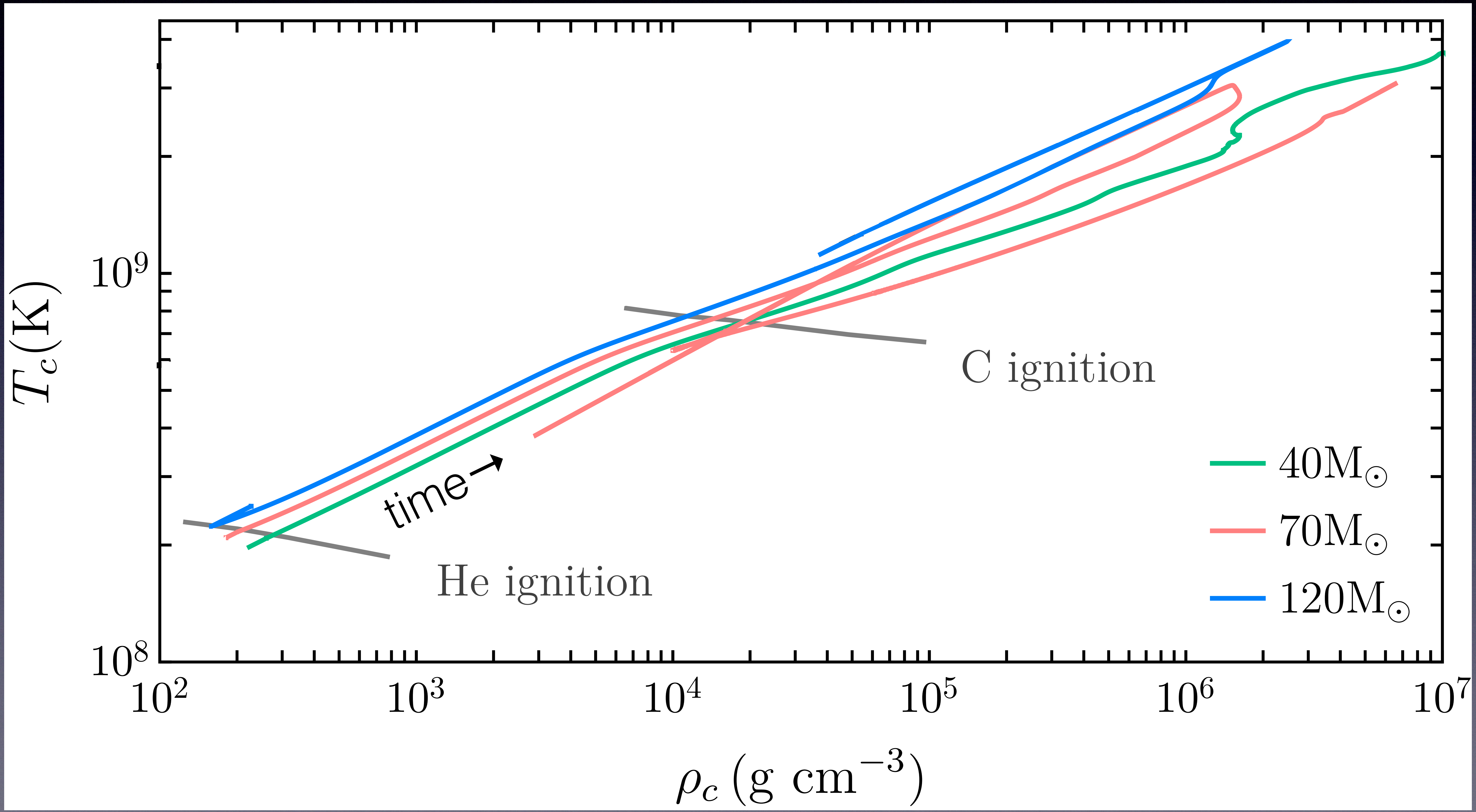


Croon, McDermott, Sakstein
2007.00650 + 2007.07889

Evolution* of Pop III Stars



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

Croon, McDermott, Sakstein
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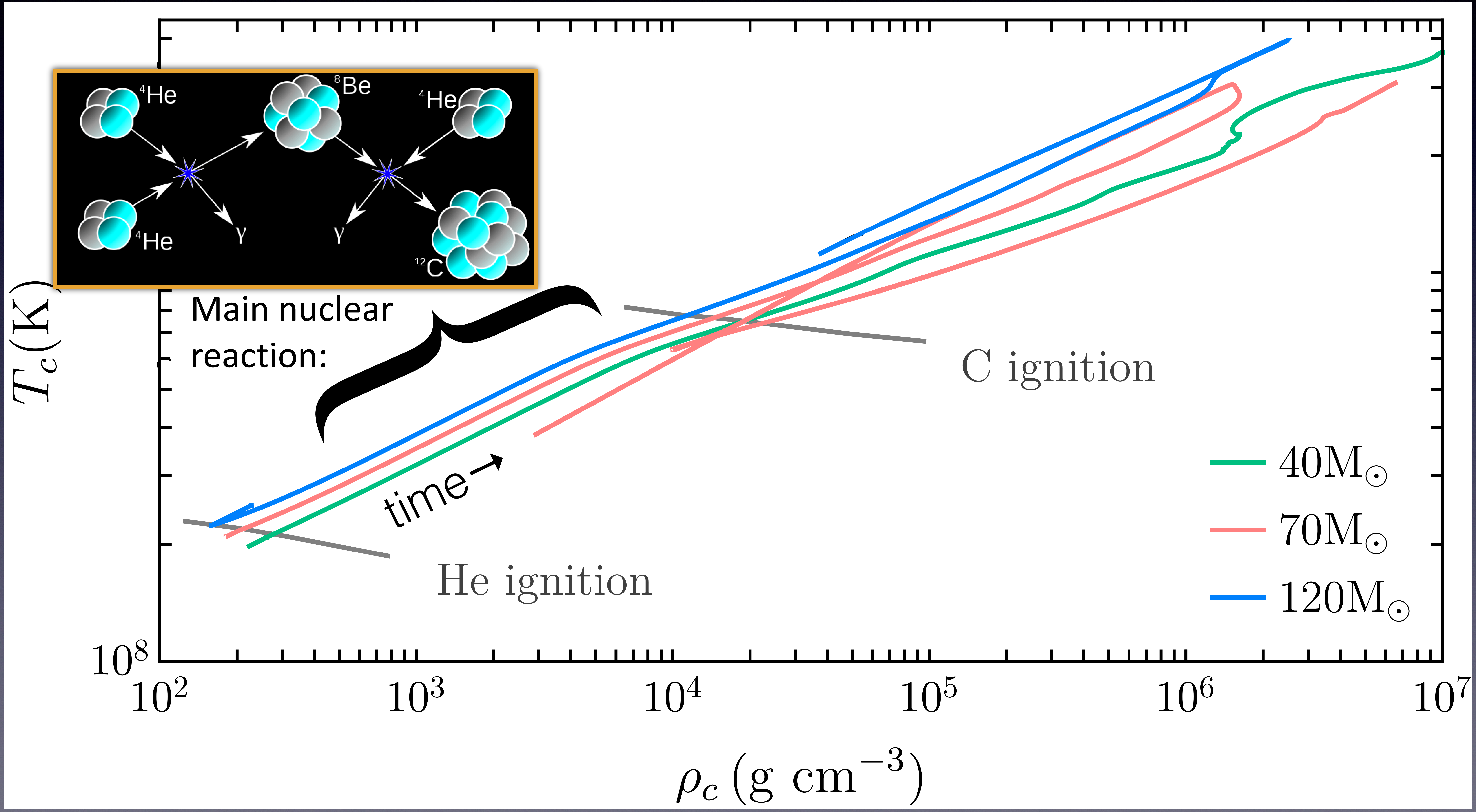

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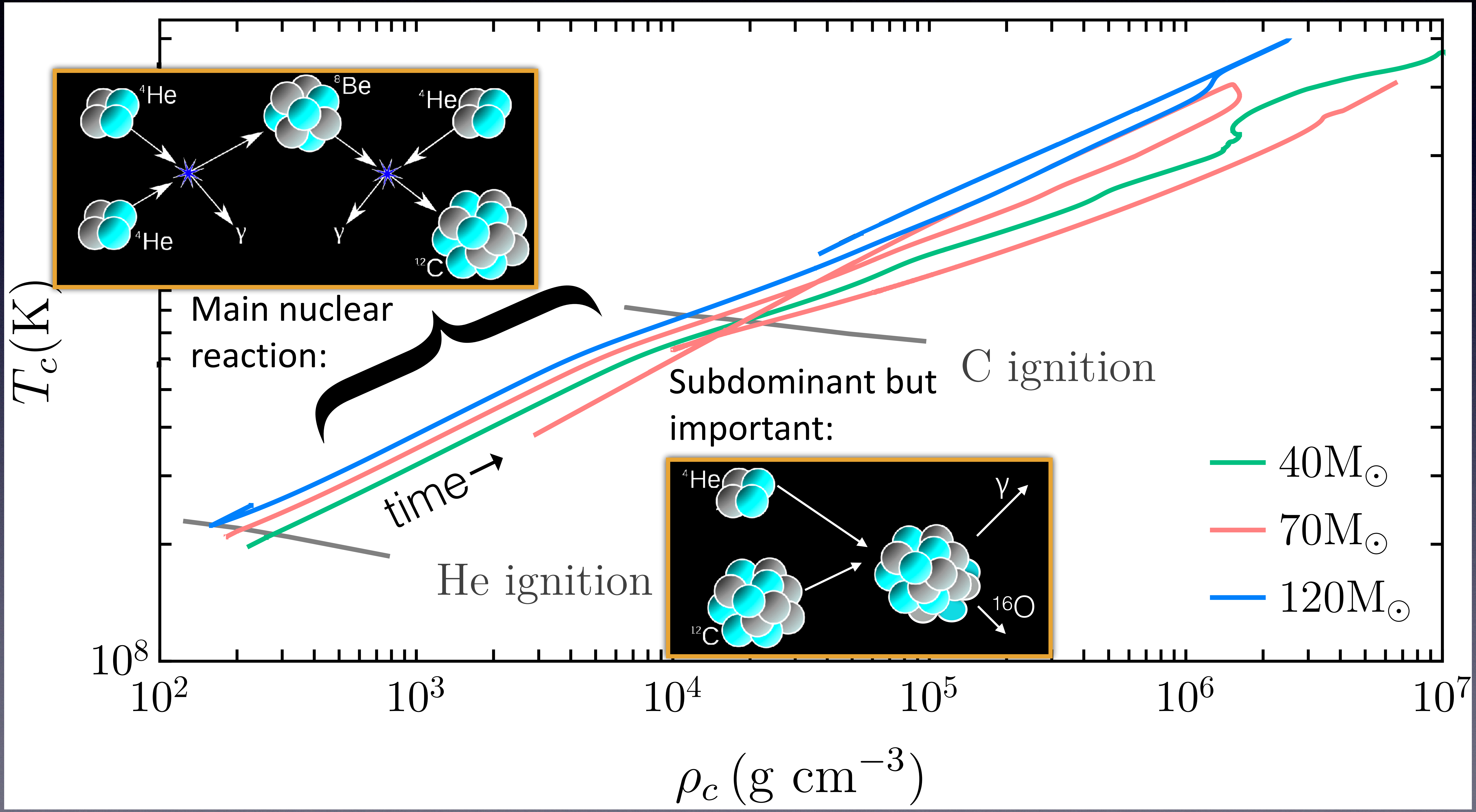

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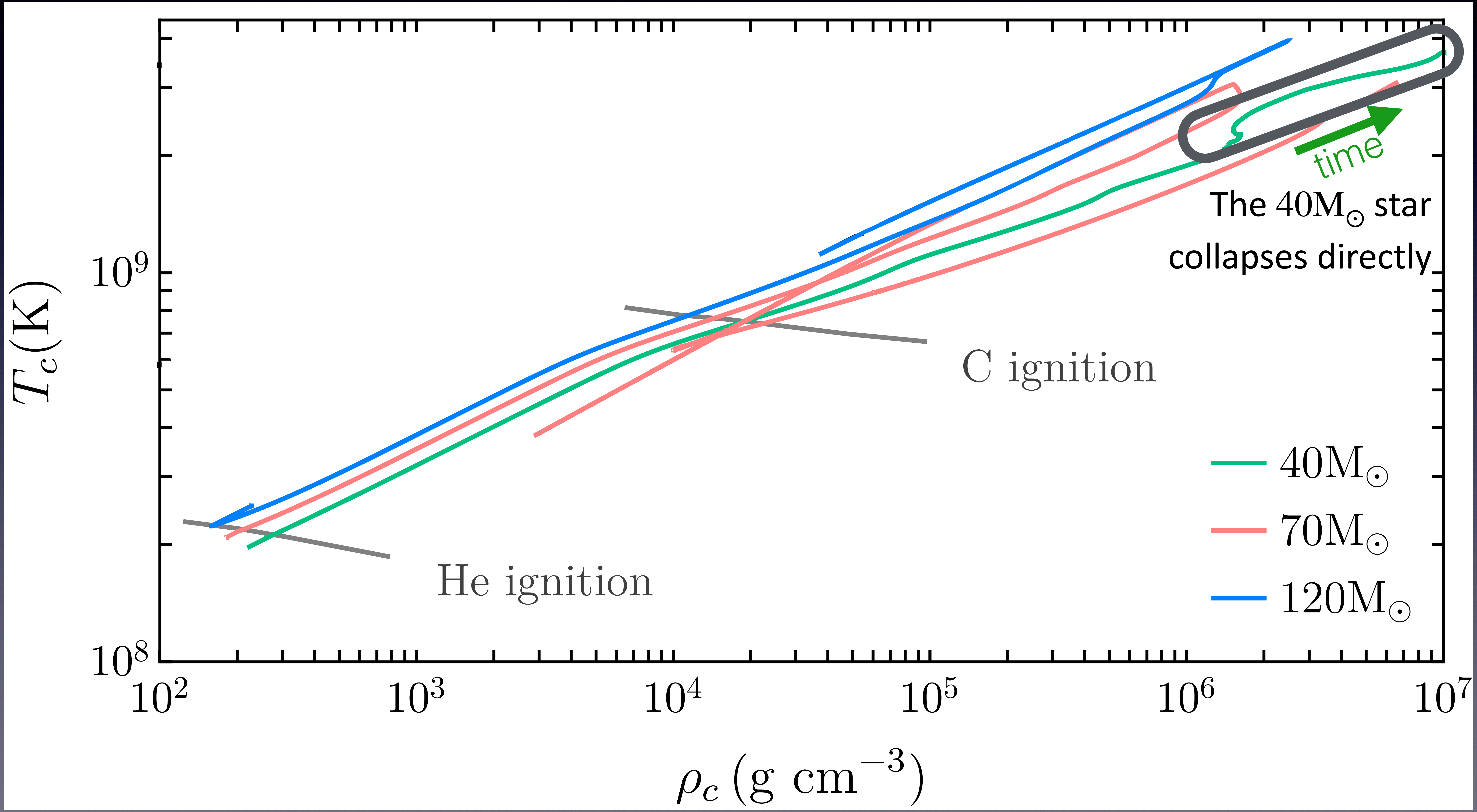

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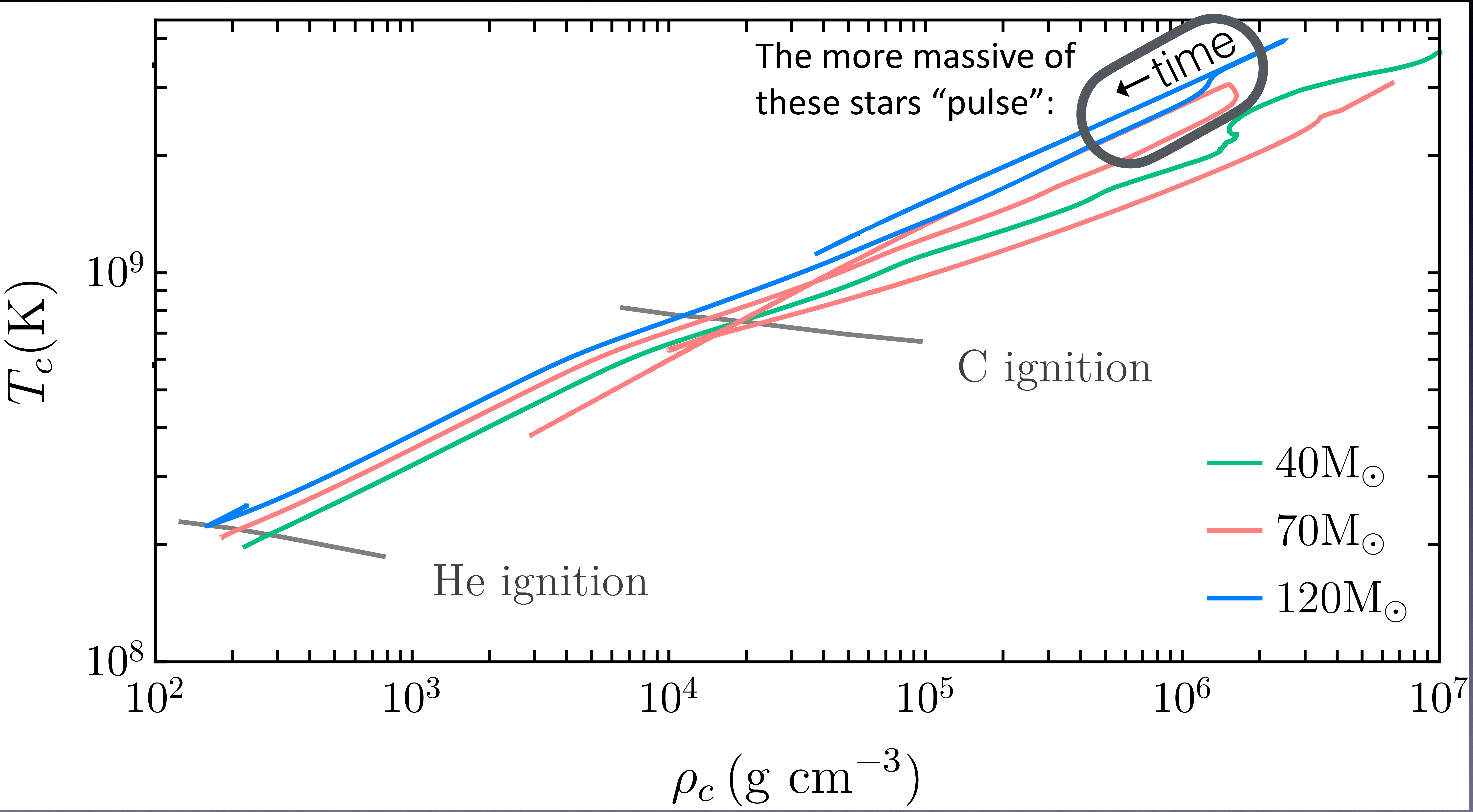

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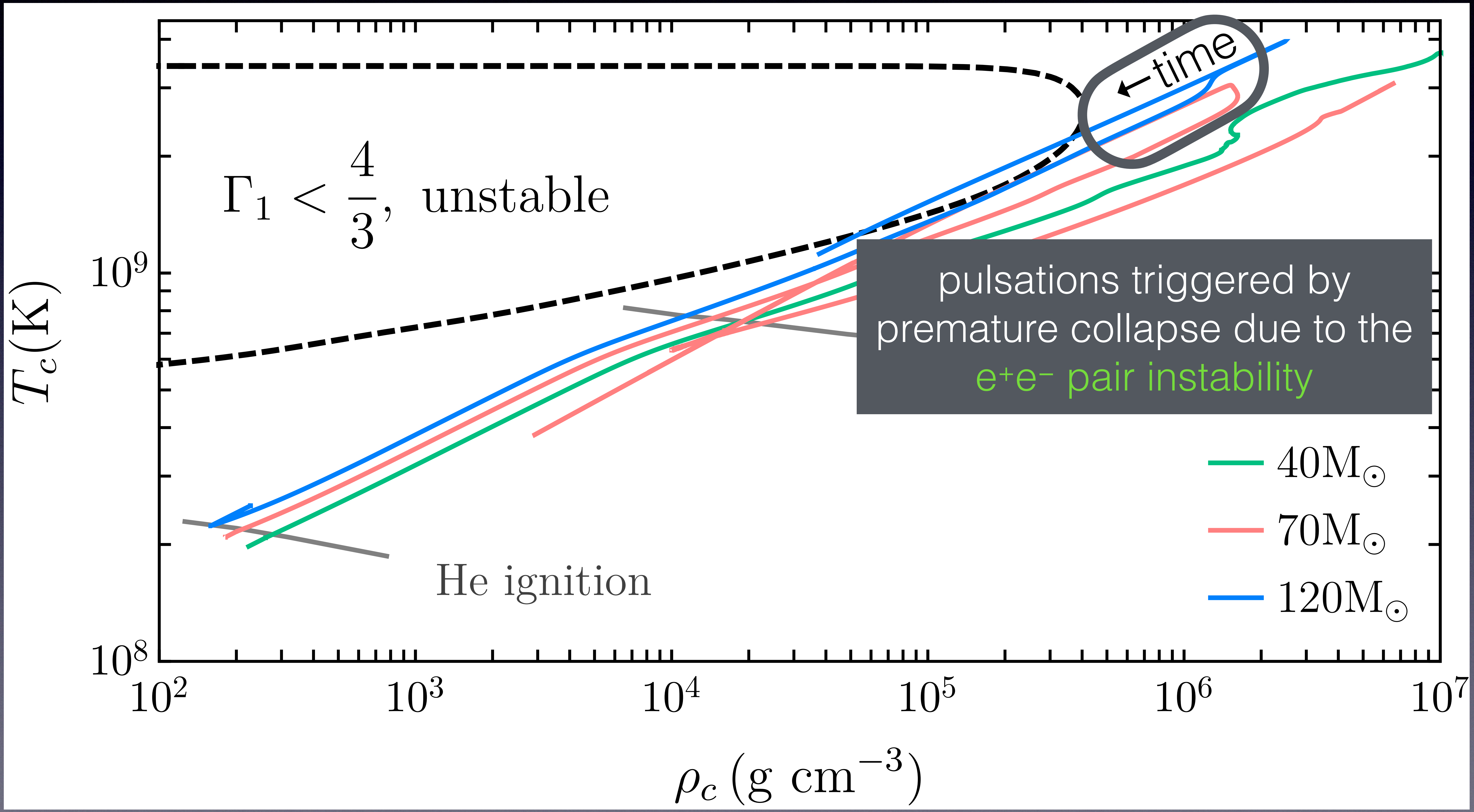
(Pulsational) Pair Instability



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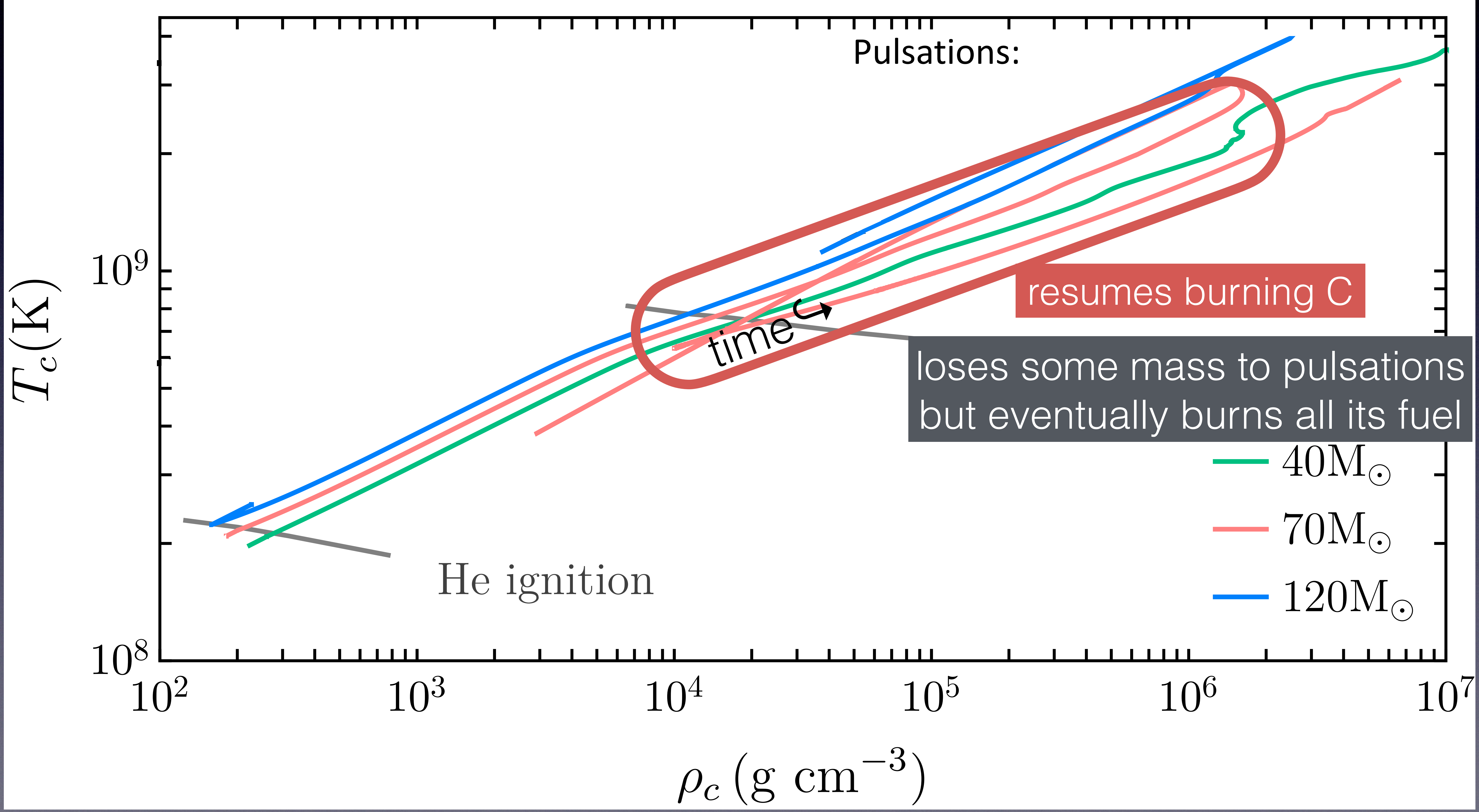
Outcome of Pulsations



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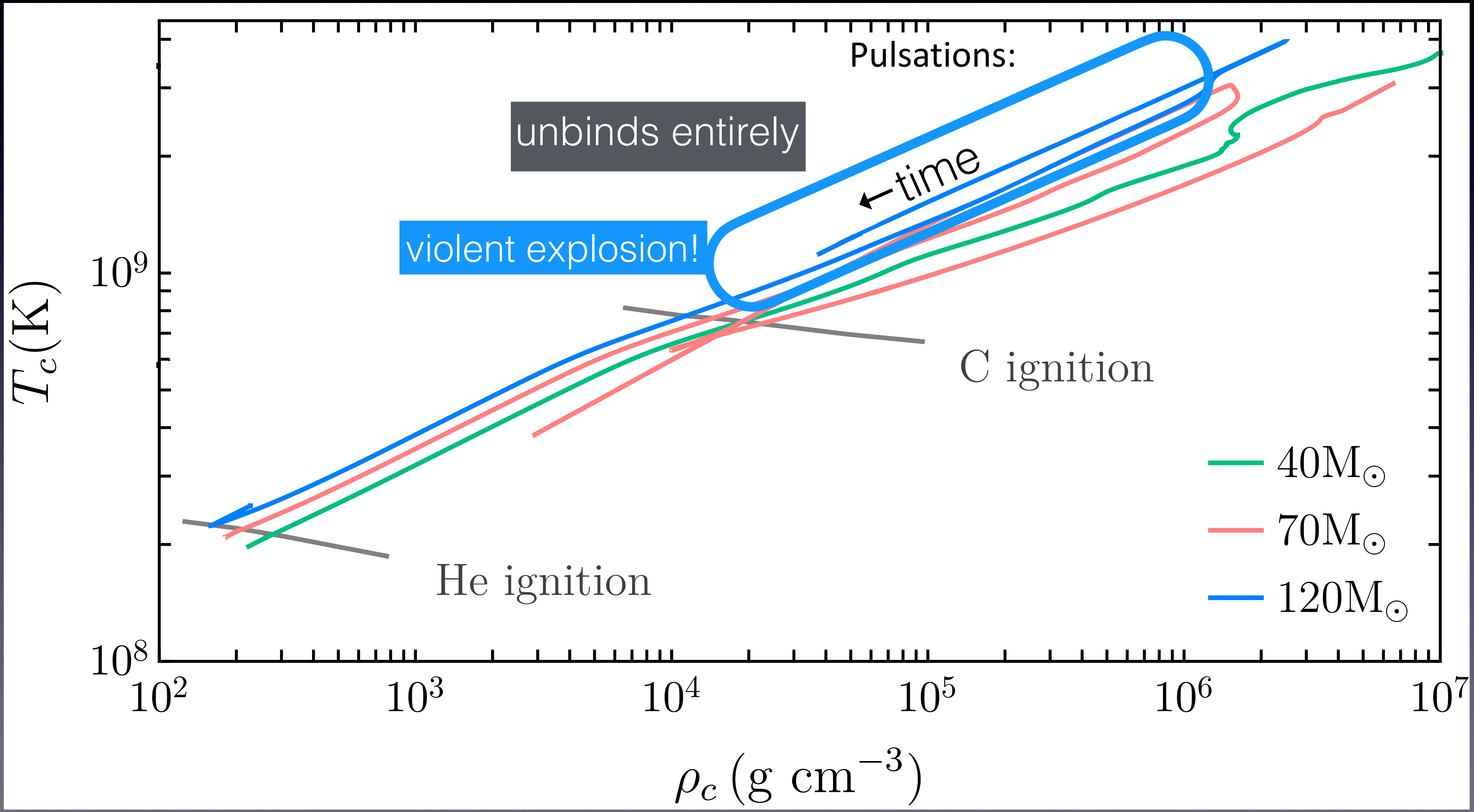

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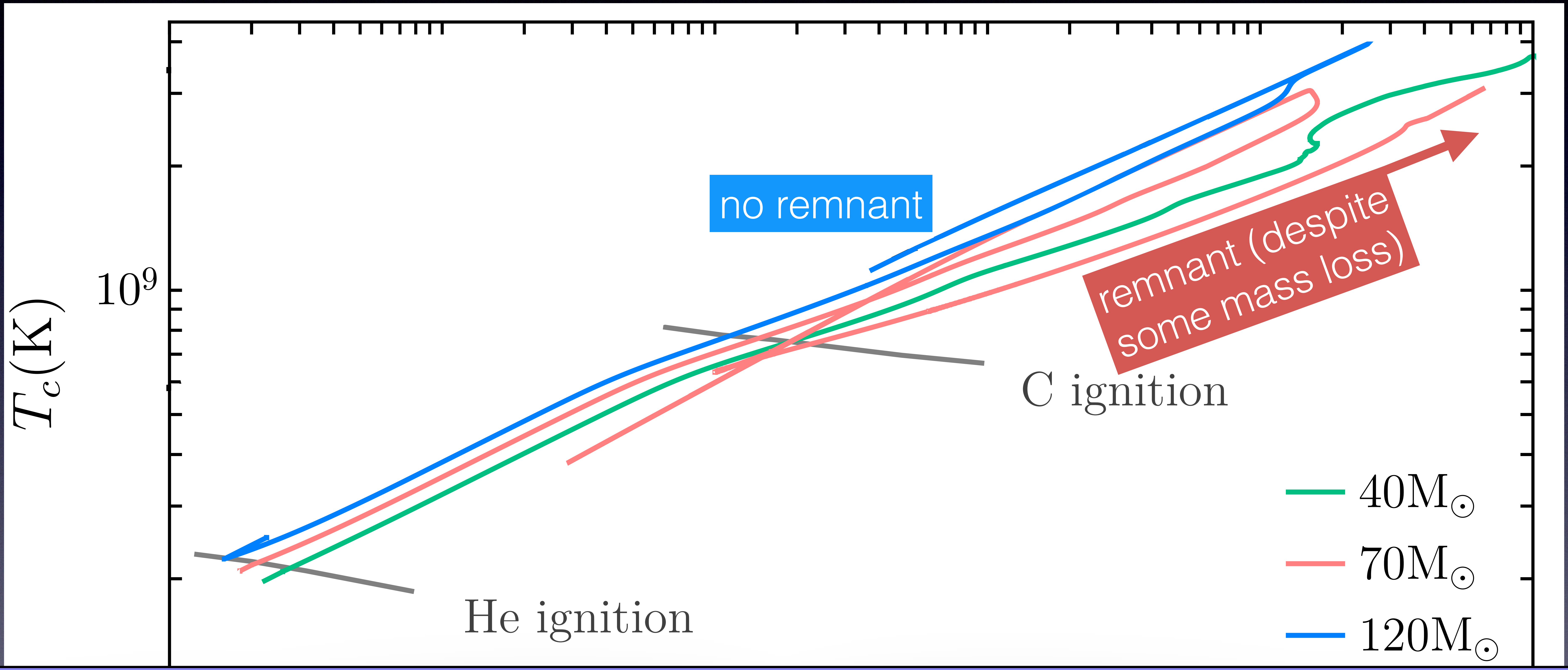
Outcome of Pulsations

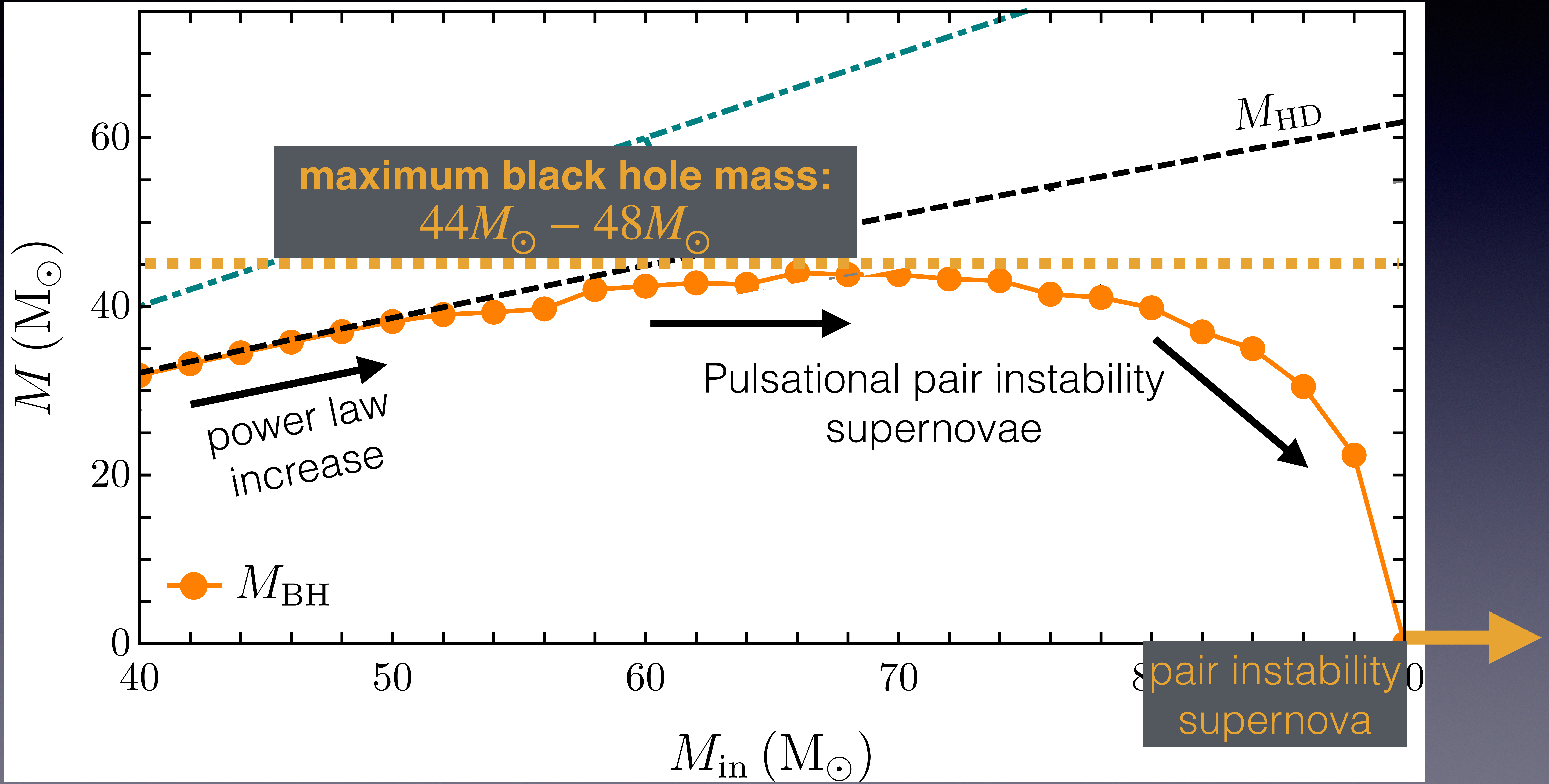


$70\mathrm{M}_\odot \lesssim M_{\mathrm{in}} \lesssim 100\mathrm{M}_\odot$ — pulsational pair instability supernova (PPISN)

vs

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

Croon, McDermott, Sakstein
2007.07889



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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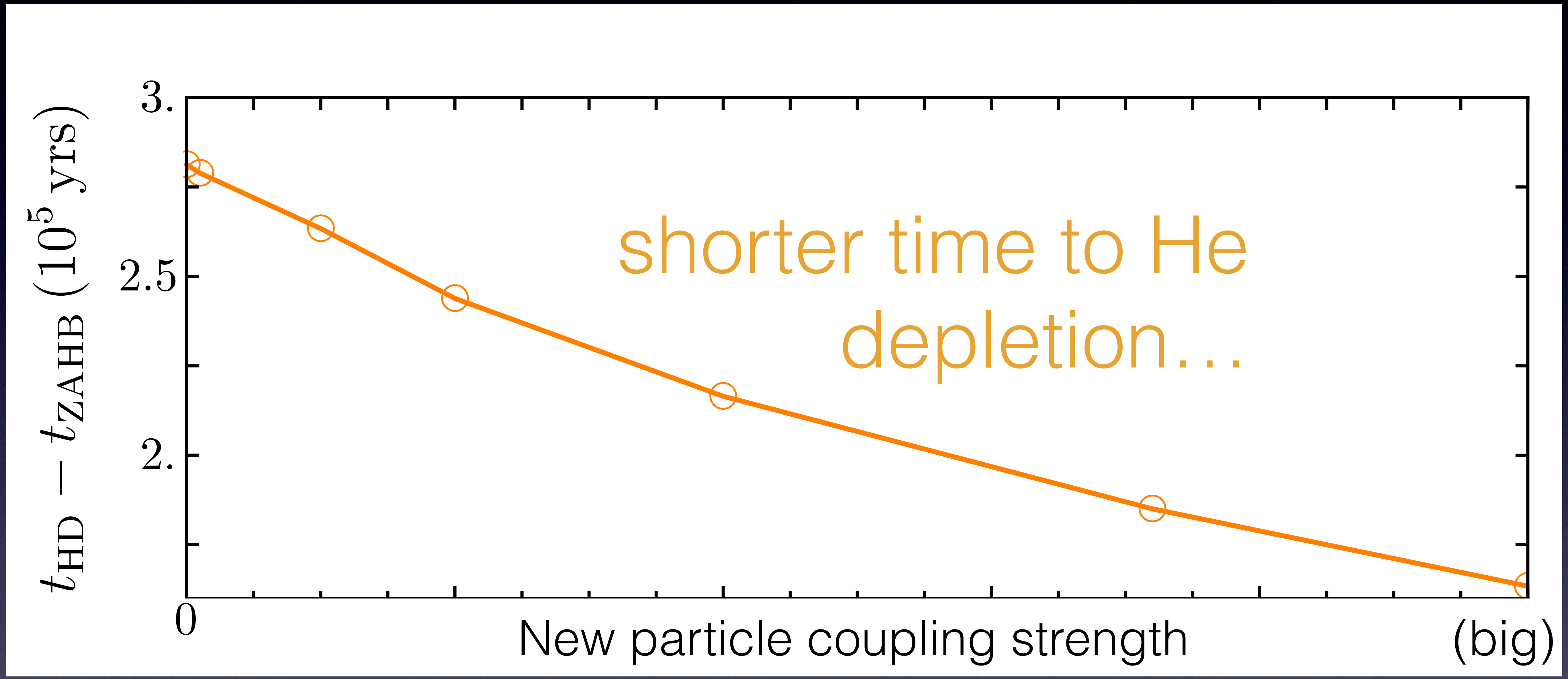
Implications for Oxygen Production



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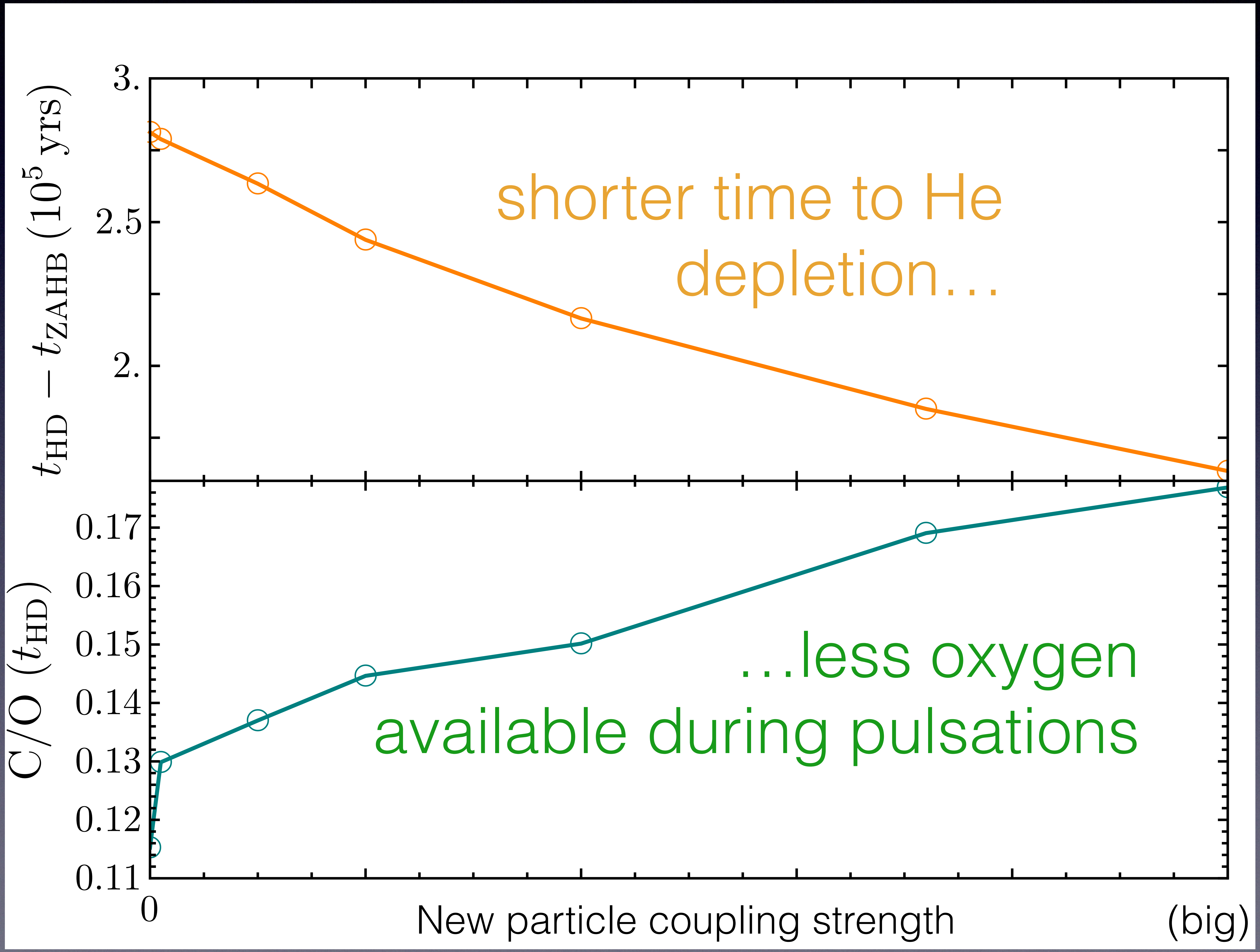

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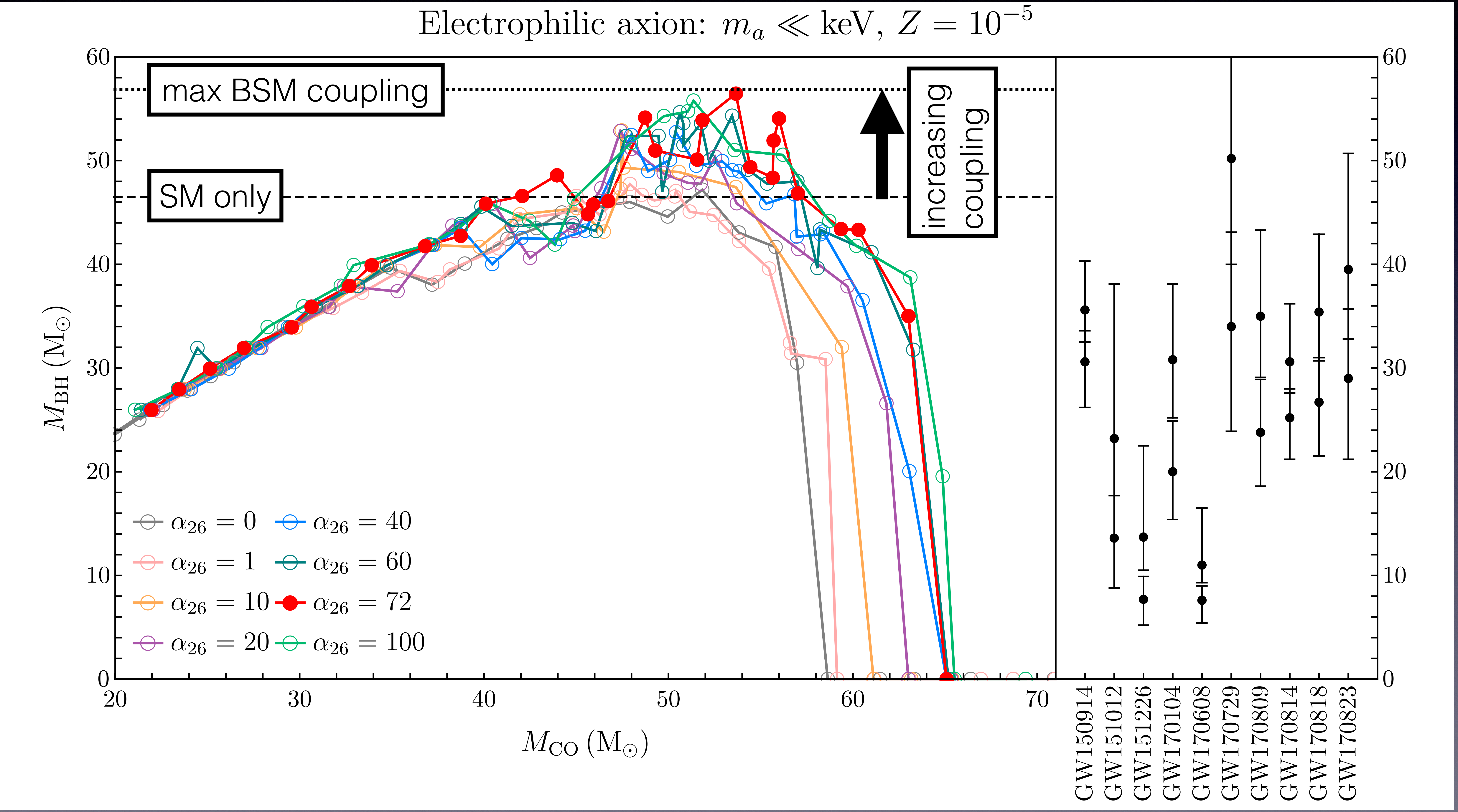
Implications for Black Hole Masses



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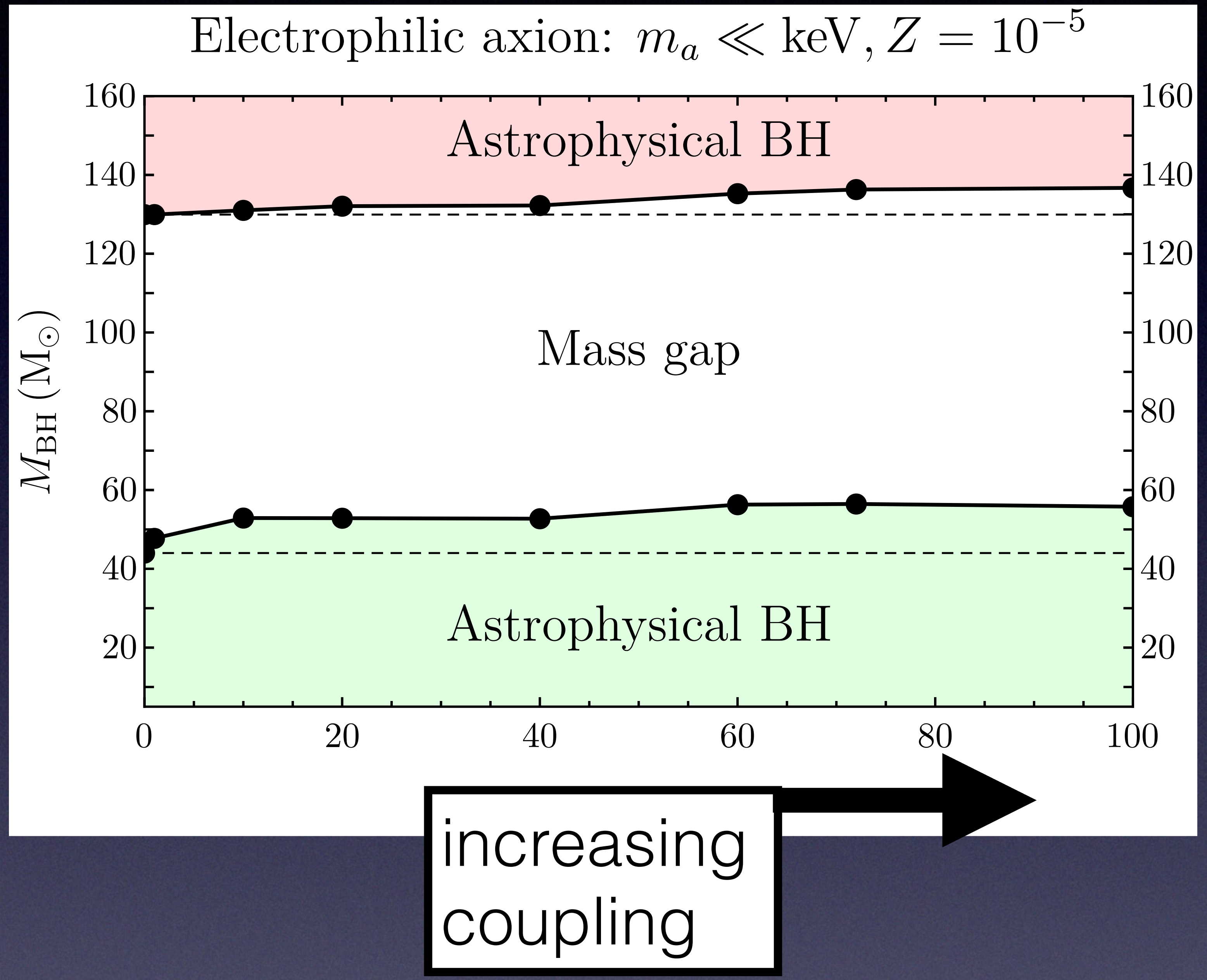
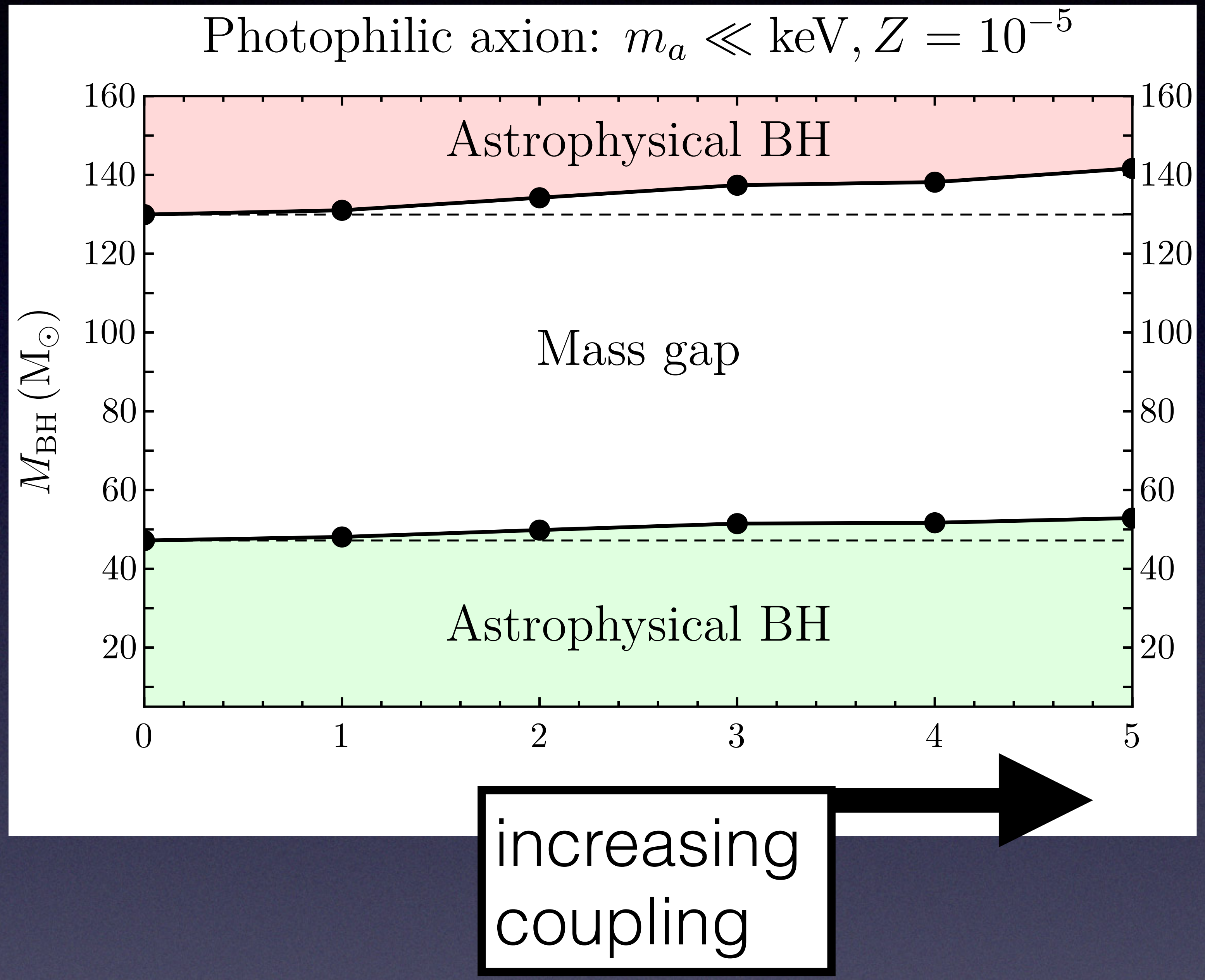
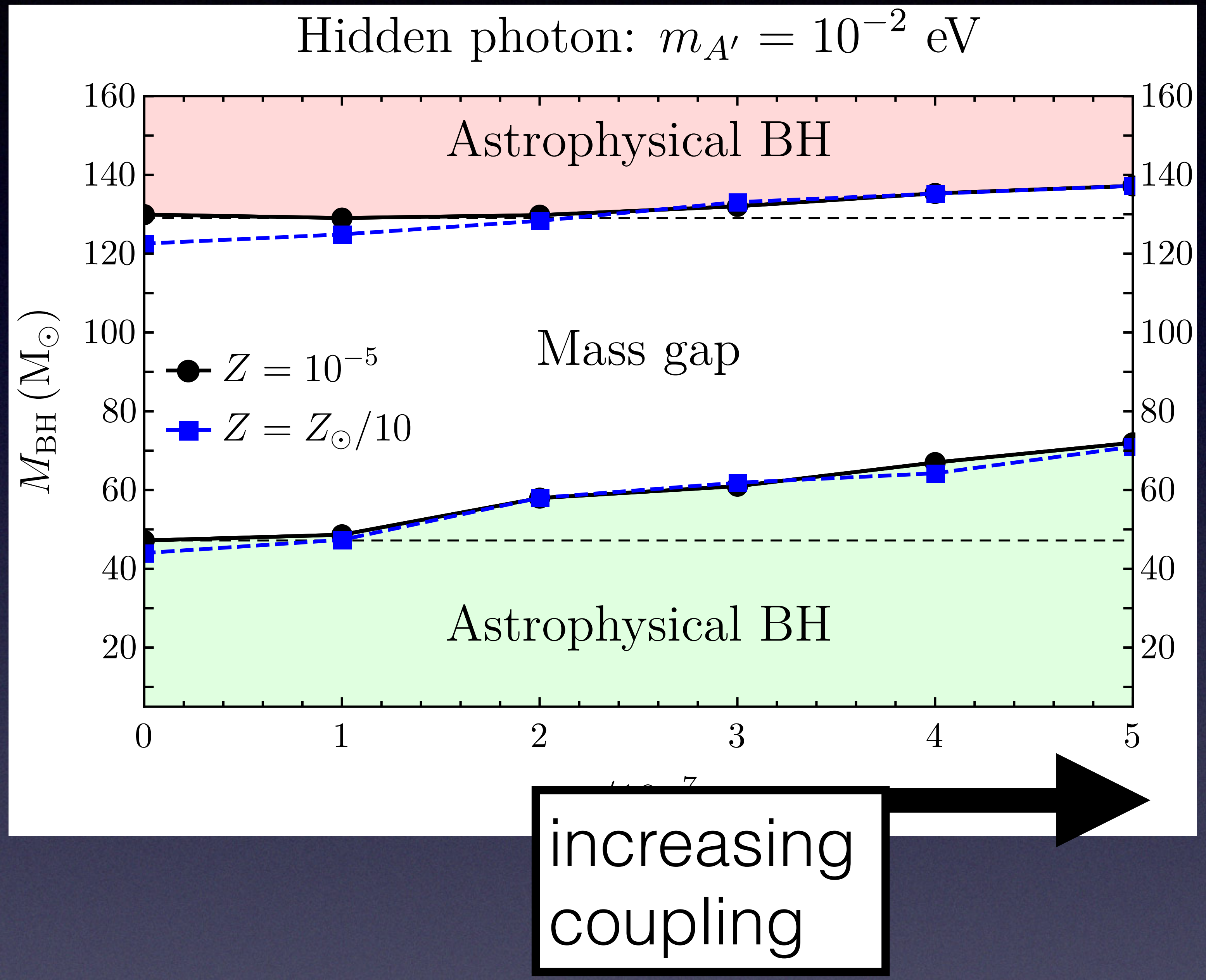
Implications for Black Hole Masses







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

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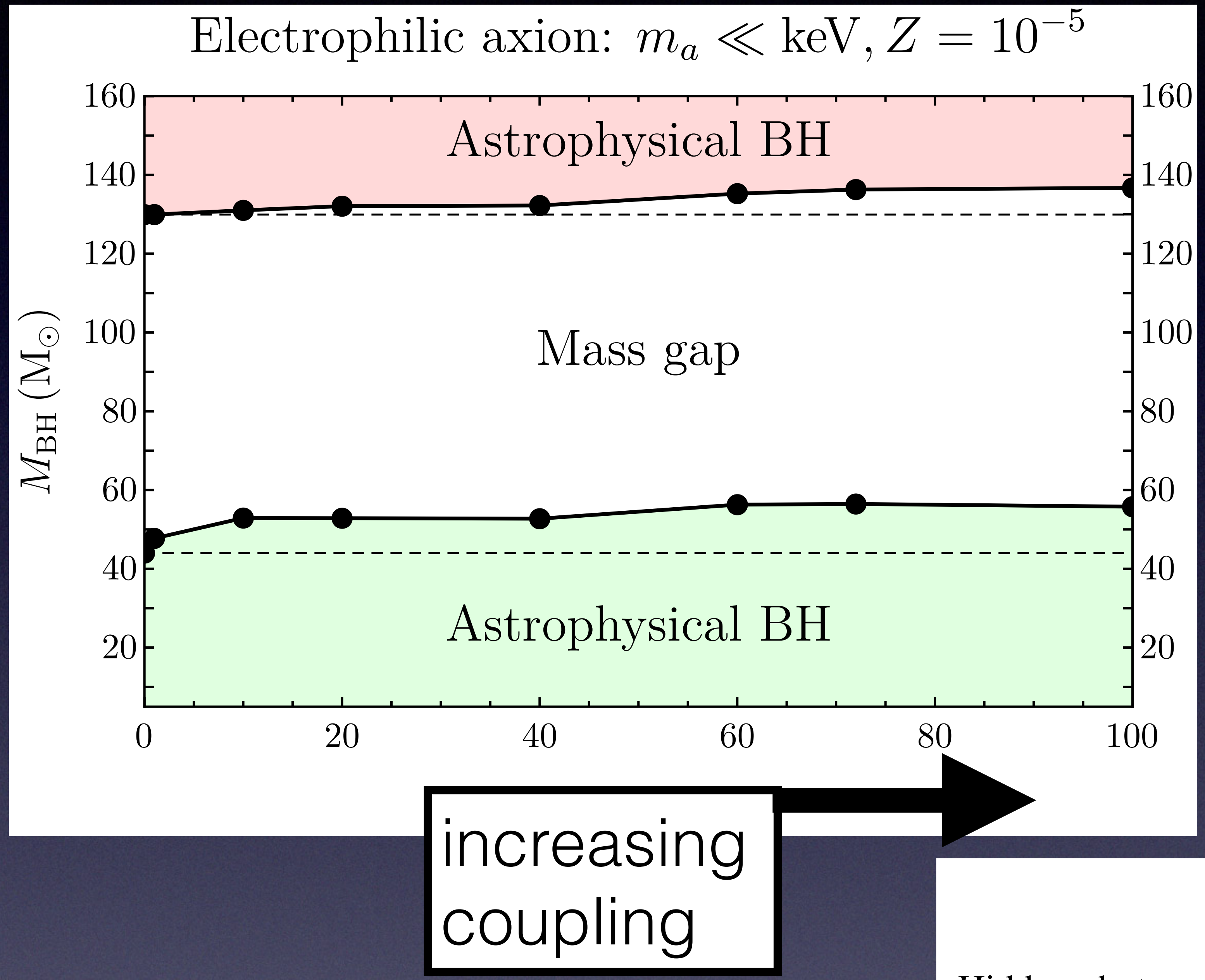
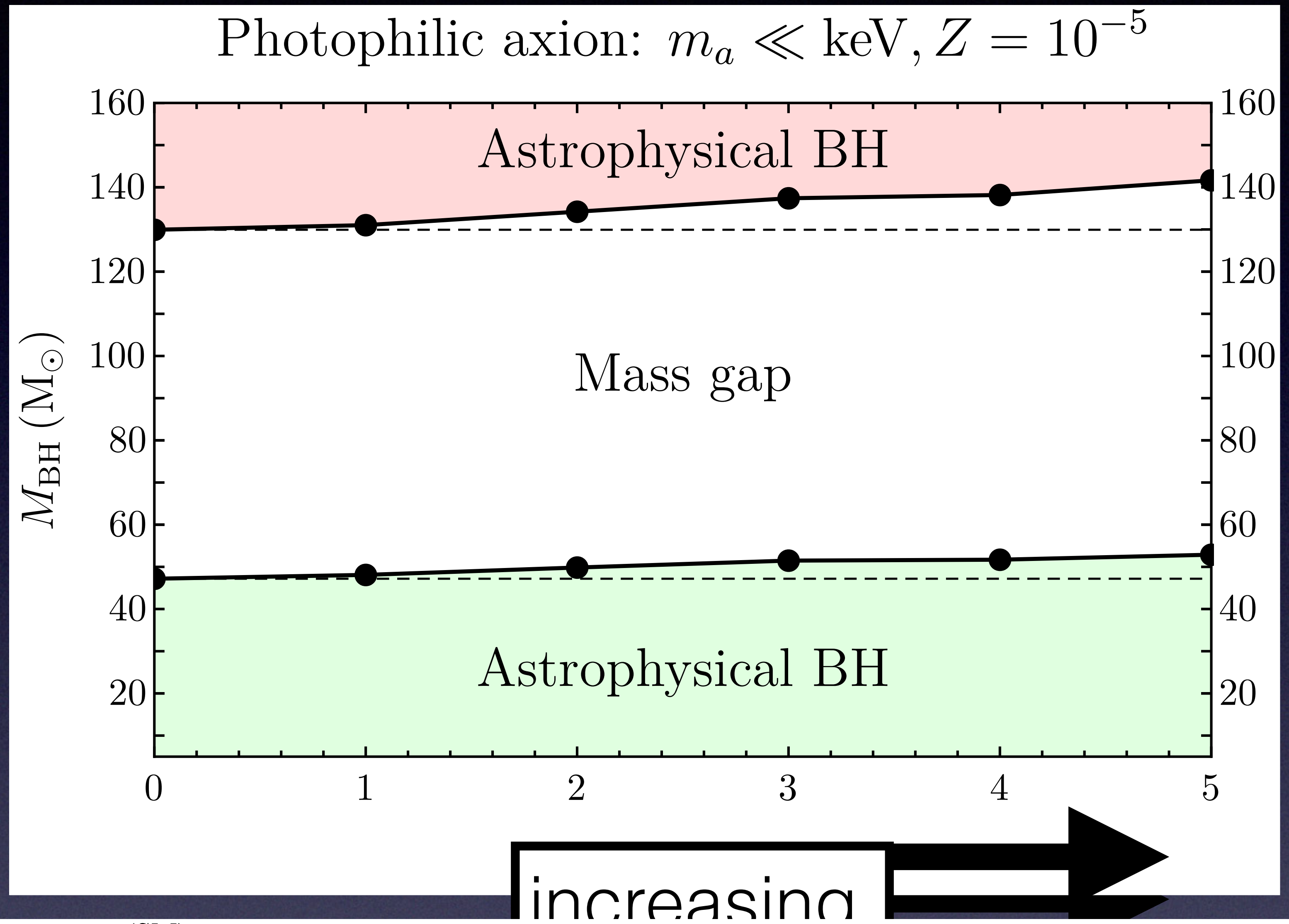
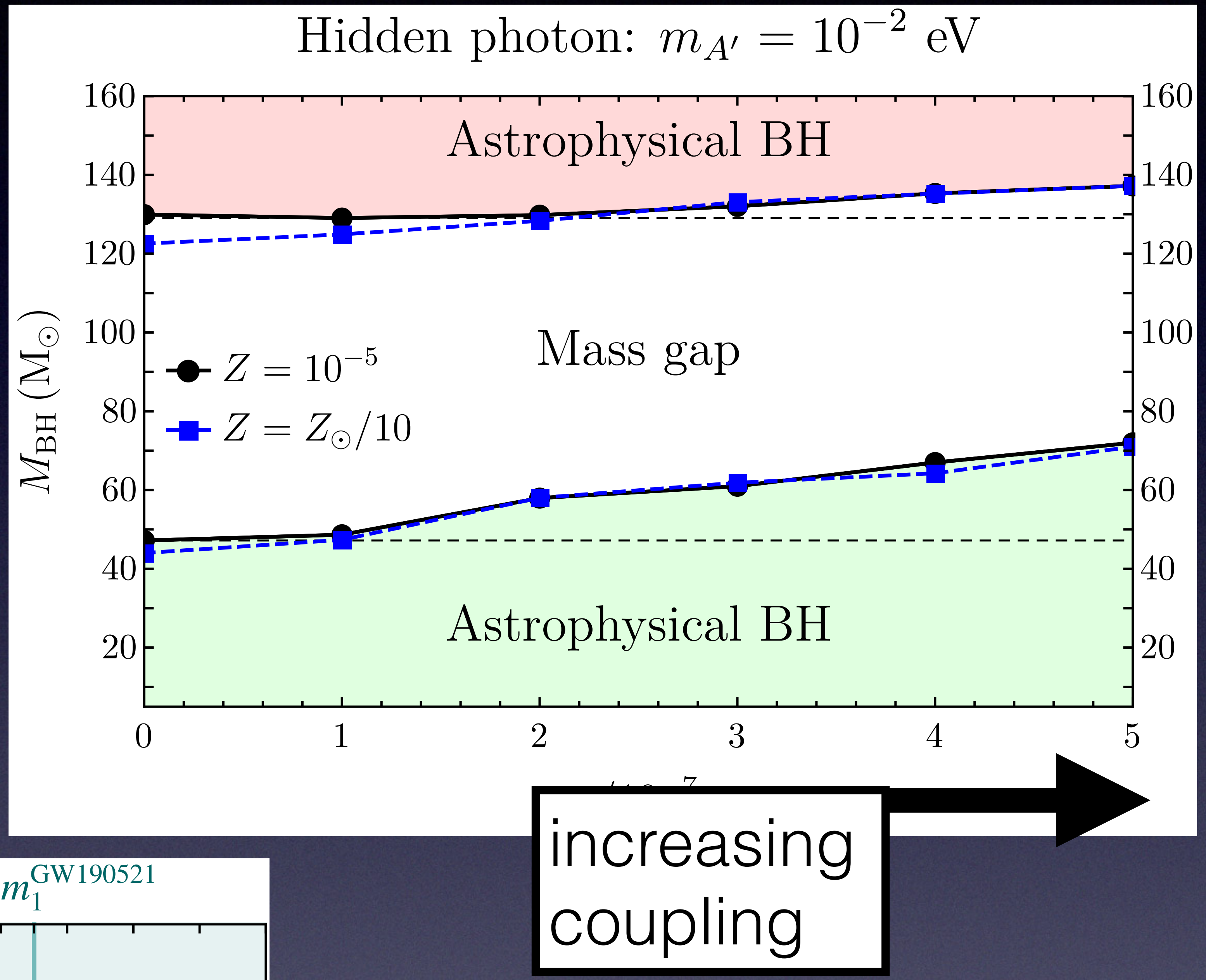
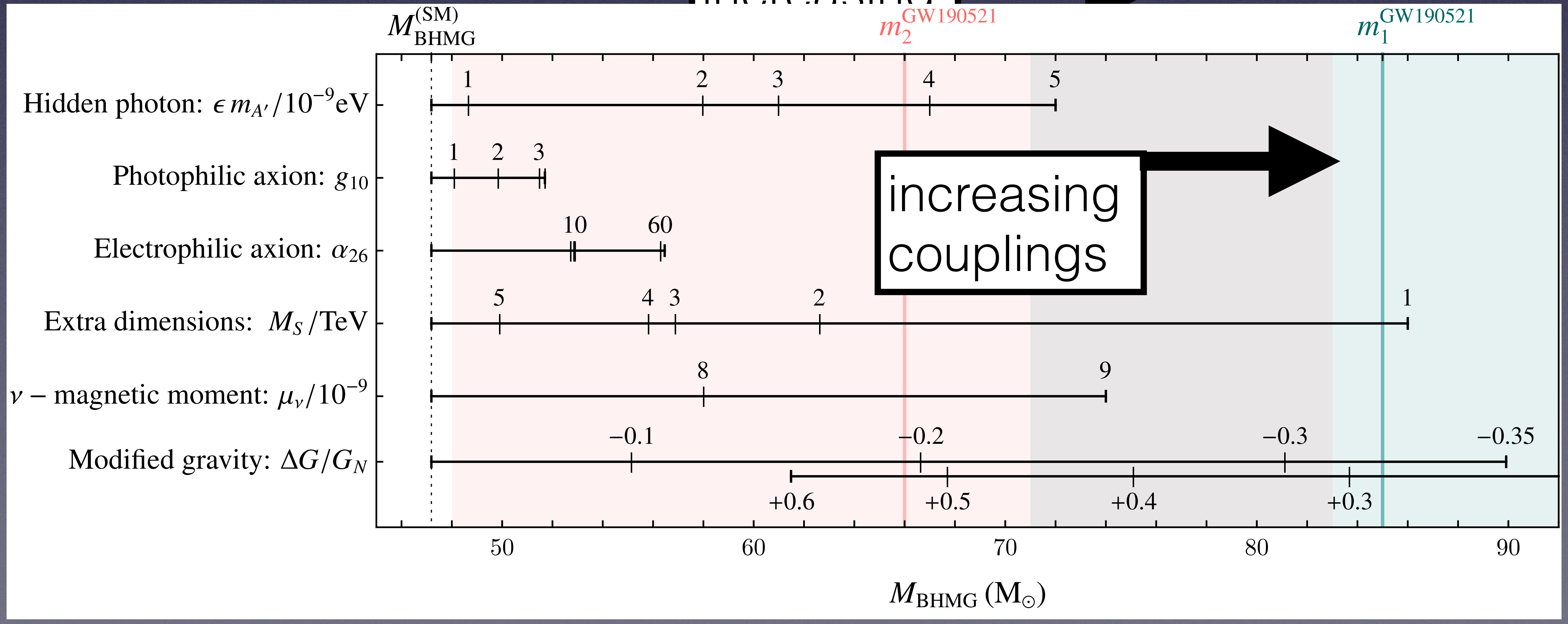
Implications for Black Hole Masses



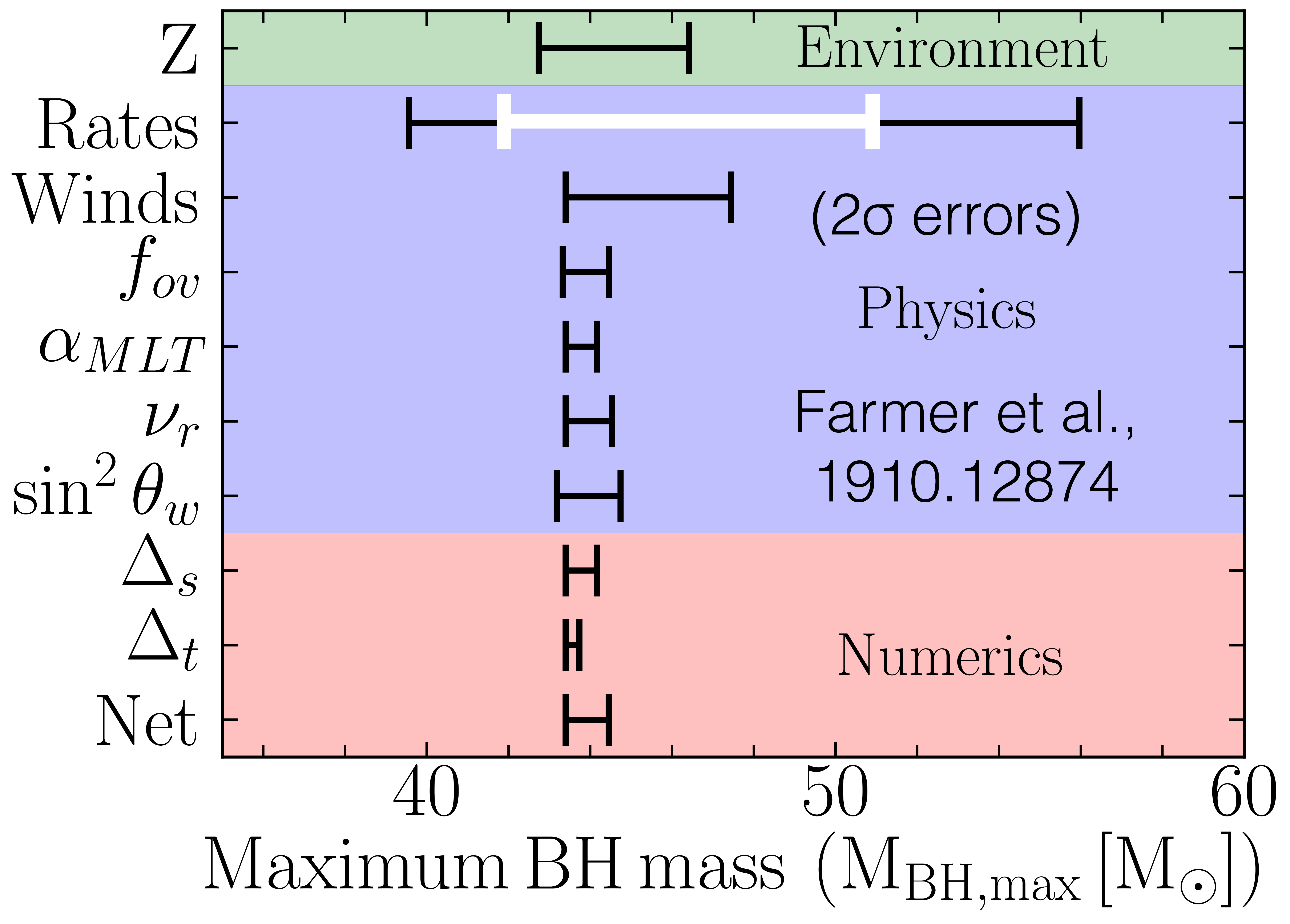






Sakstein, Croon, SDM, Straight, Baxter
2009.01213

SM Uncertainties



"Rates" mainly $^{12}C(\alpha,\gamma)^{16}O$

R. J. deBoer, et al. Rev. Mod. Phys. **89**, 035007 – 2017

also rare events:

- pre- & post-collapse mergers
- accretion after formation
- binarity
- rotation
- …

Surprisingly Massive: SM vs BSM

SM physics

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

*unless ~5σ deviations from nuclear rates

- Systems with no mergers give a continuous distribution of $M_{\rm BH}$ up to **expected** value of the gap plus **rare** excursions to higher masses that "pollute" the gap

BSM physics

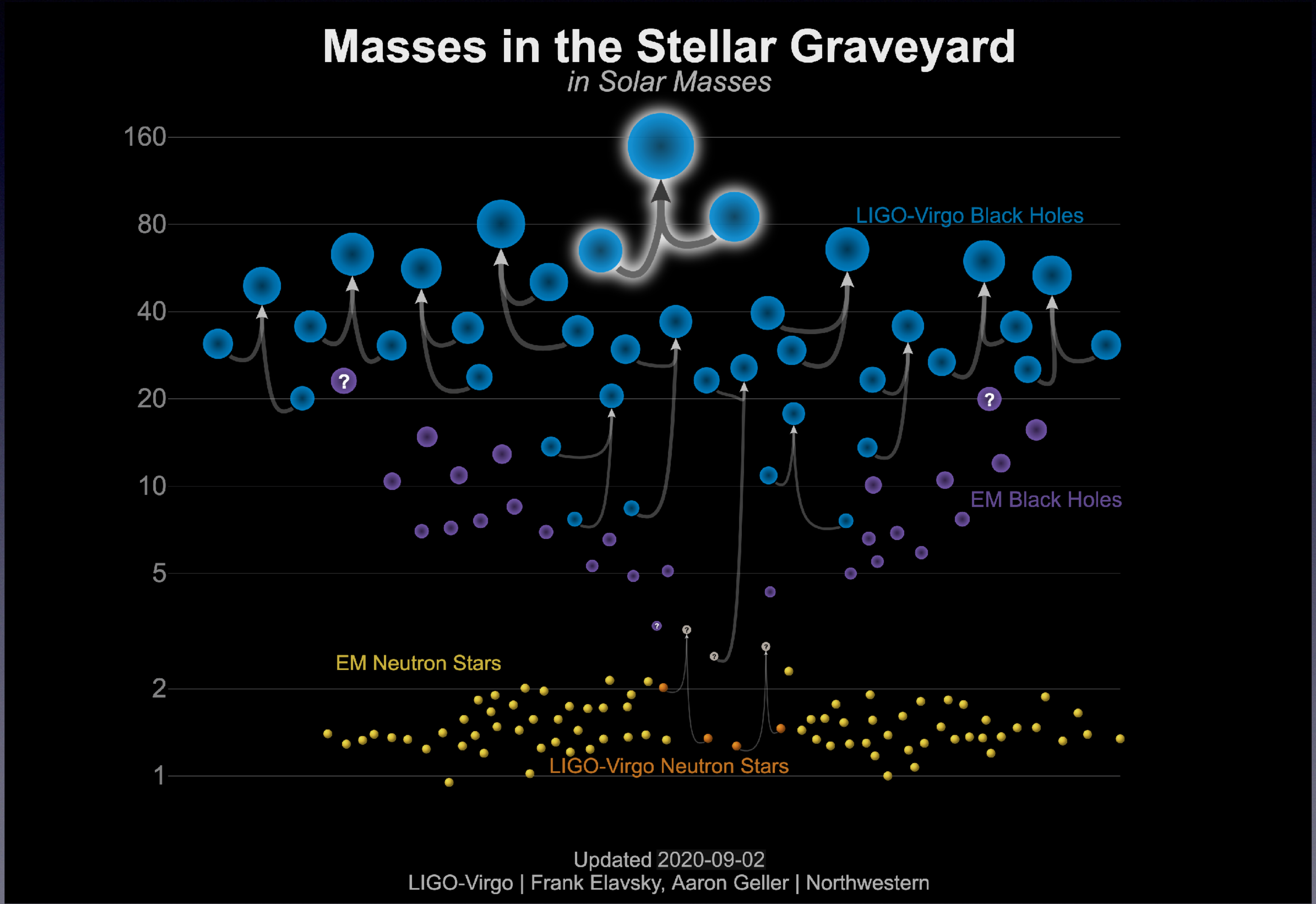
- "Location" of the mass gap is **not** as expected from SM-only calculation: objects "in the (SM) mass gap" form from isolated evolution, no mergers required

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

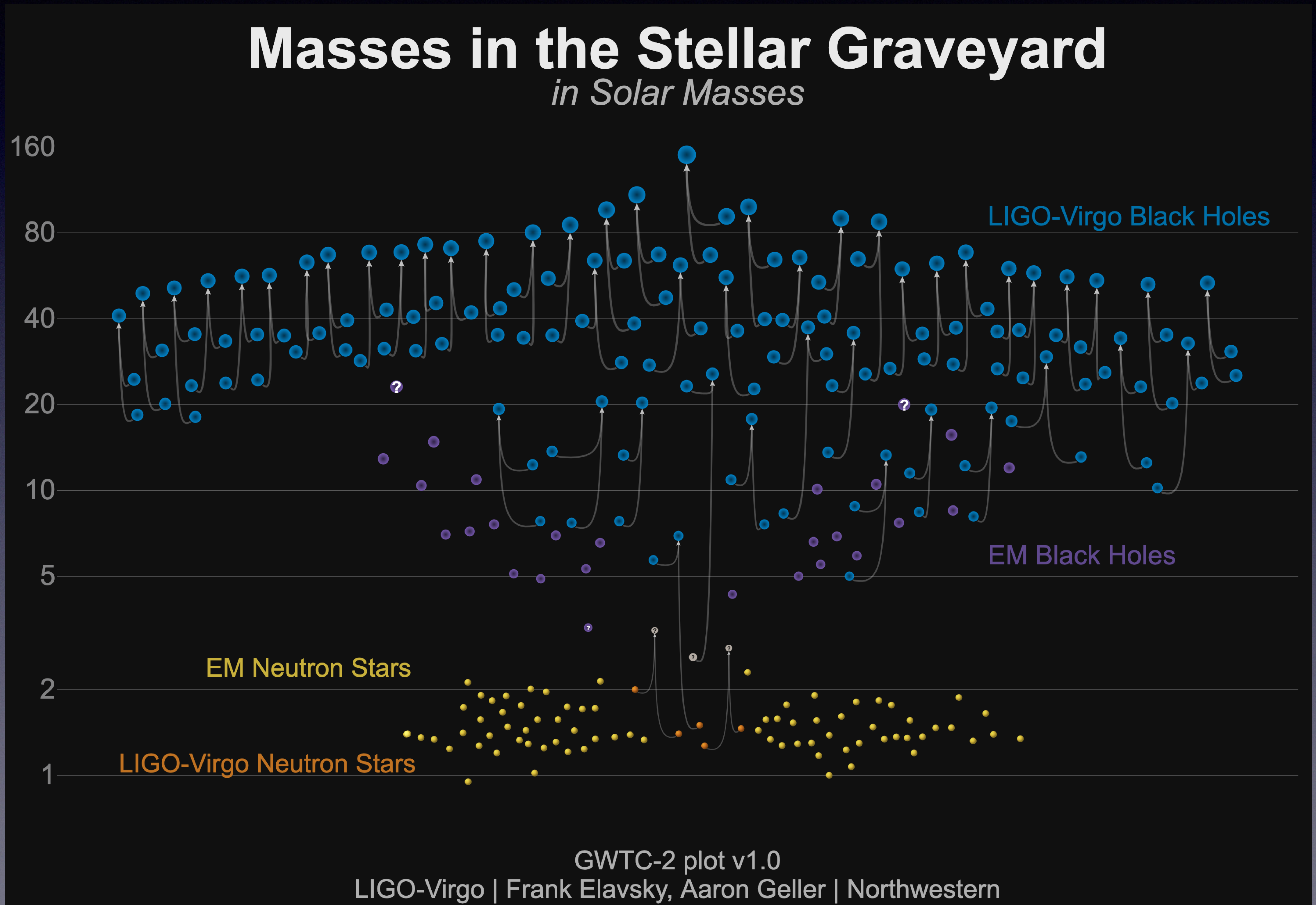
† plus higher-gen BH mergers

The Future

LIGO Observations: Sept 2020



LIGO Observations: Oct 2020



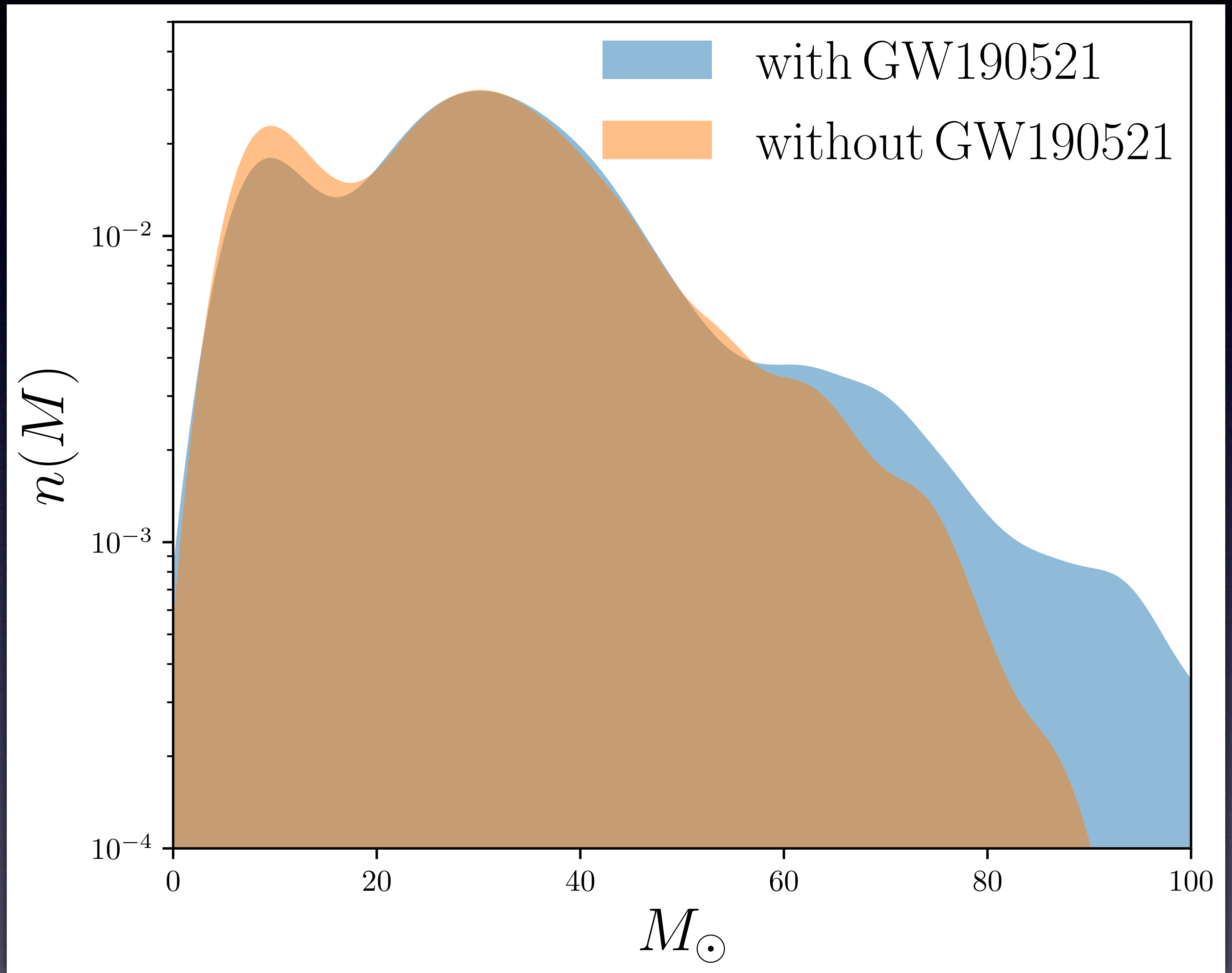
Black Hole Population Statistics

Black Hole Population Statistics

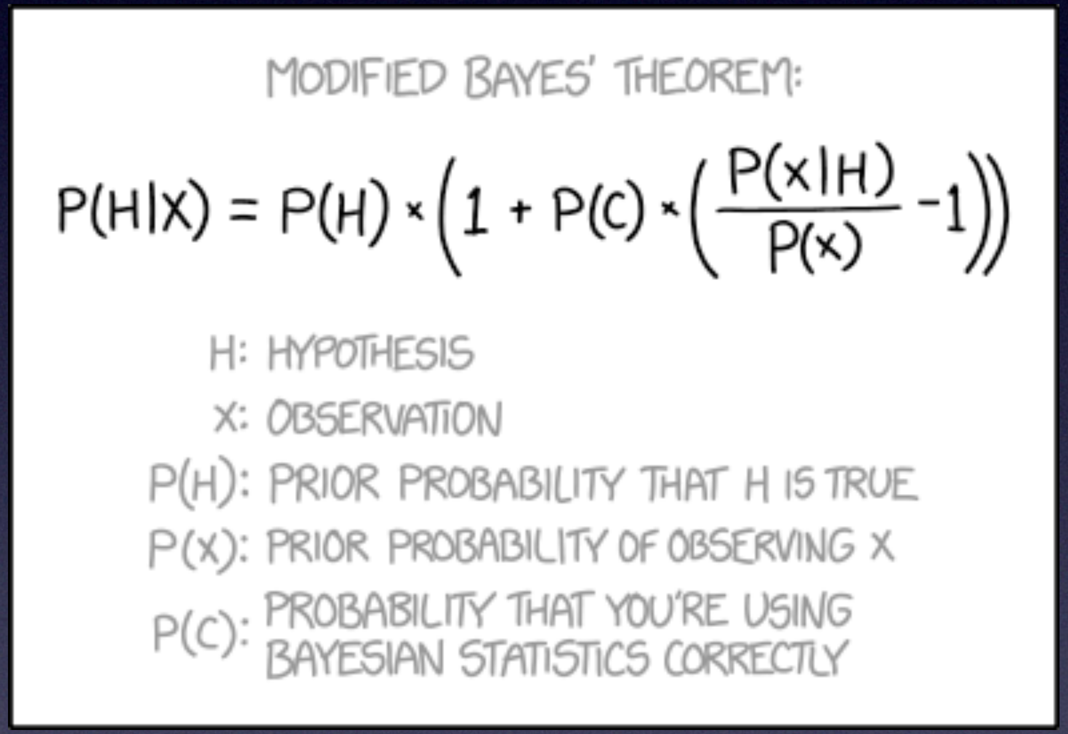
$$p\left(m_1, m_2 \mid \alpha, M_{\max}\right) \propto \frac{dN^{(1g)}}{dM_{BH}} + \lambda \frac{dN^{(2g)}}{dM_{BH}}$$

BHs formed from isolated stellar evolution

“pollutants” (λ<1)



Baxter, Croon, SDM, Sakstein
arXiv:2104.abcde



xkcd.com/2059/

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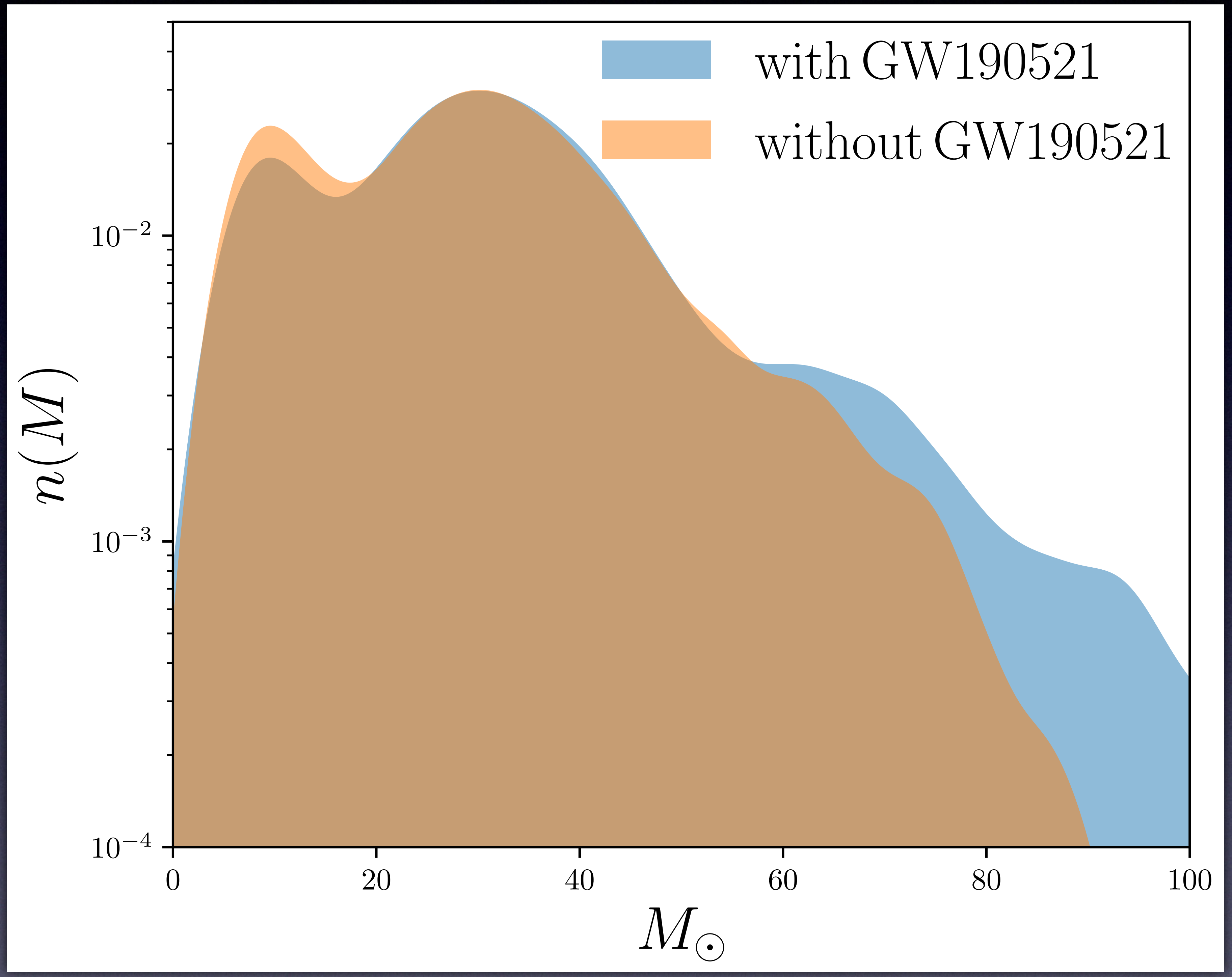

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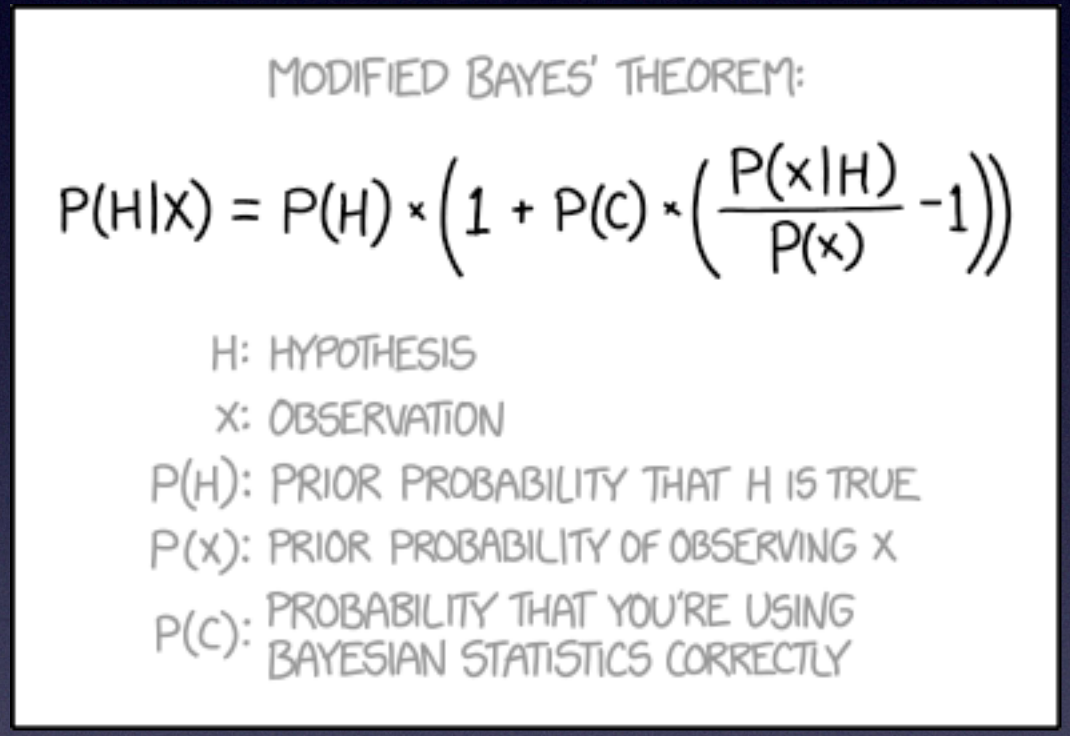


xkcd.com/2059/

this is exactly what we get from MESA!

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

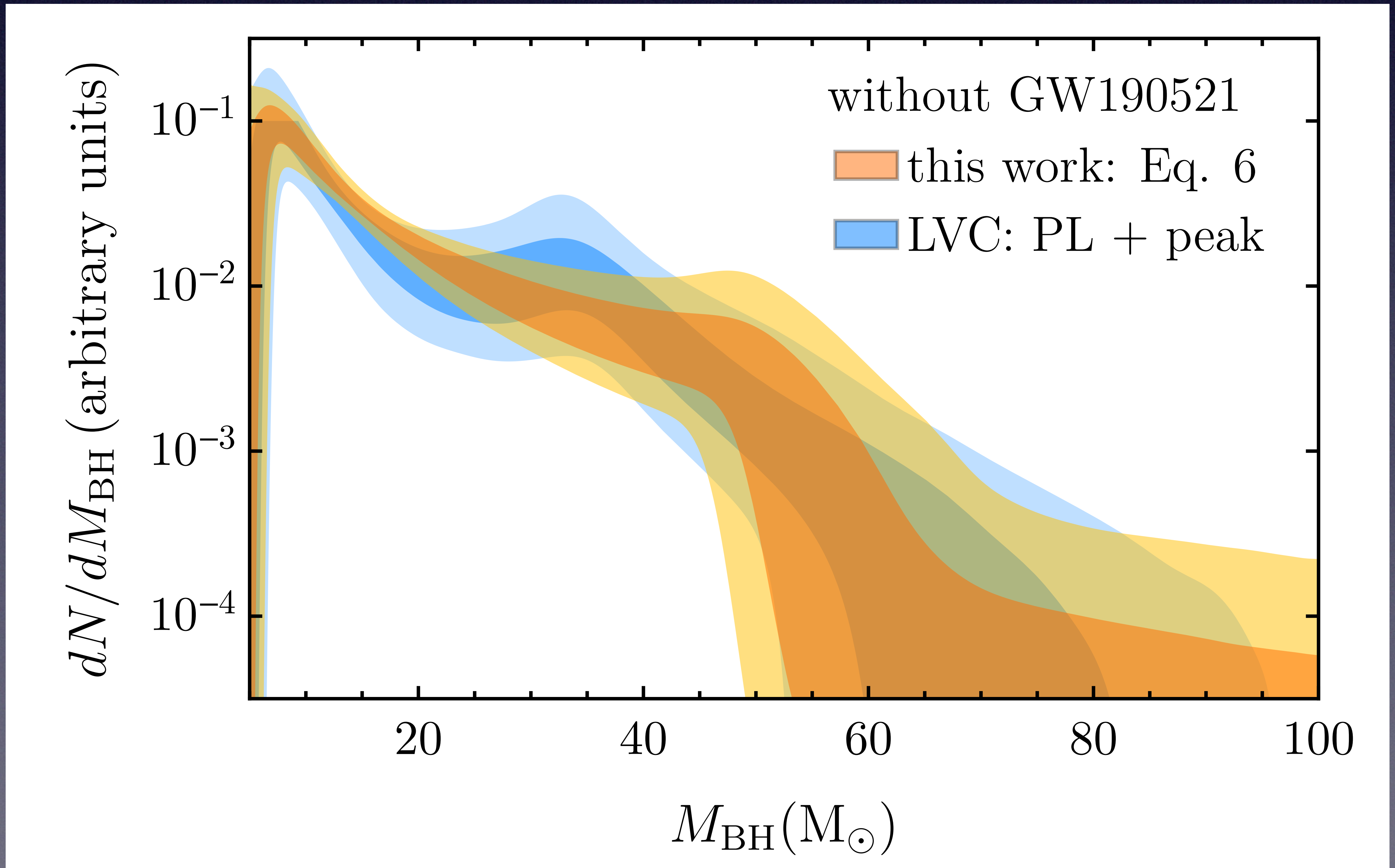
$$\frac{dN^{(2g)}}{dM_{BH}} \sim \int dM_a \frac{dN^{(1g)}(M_a)}{dM_a} \frac{dN^{(1g)}(M_{BH} - M_a)}{dM_a}$$

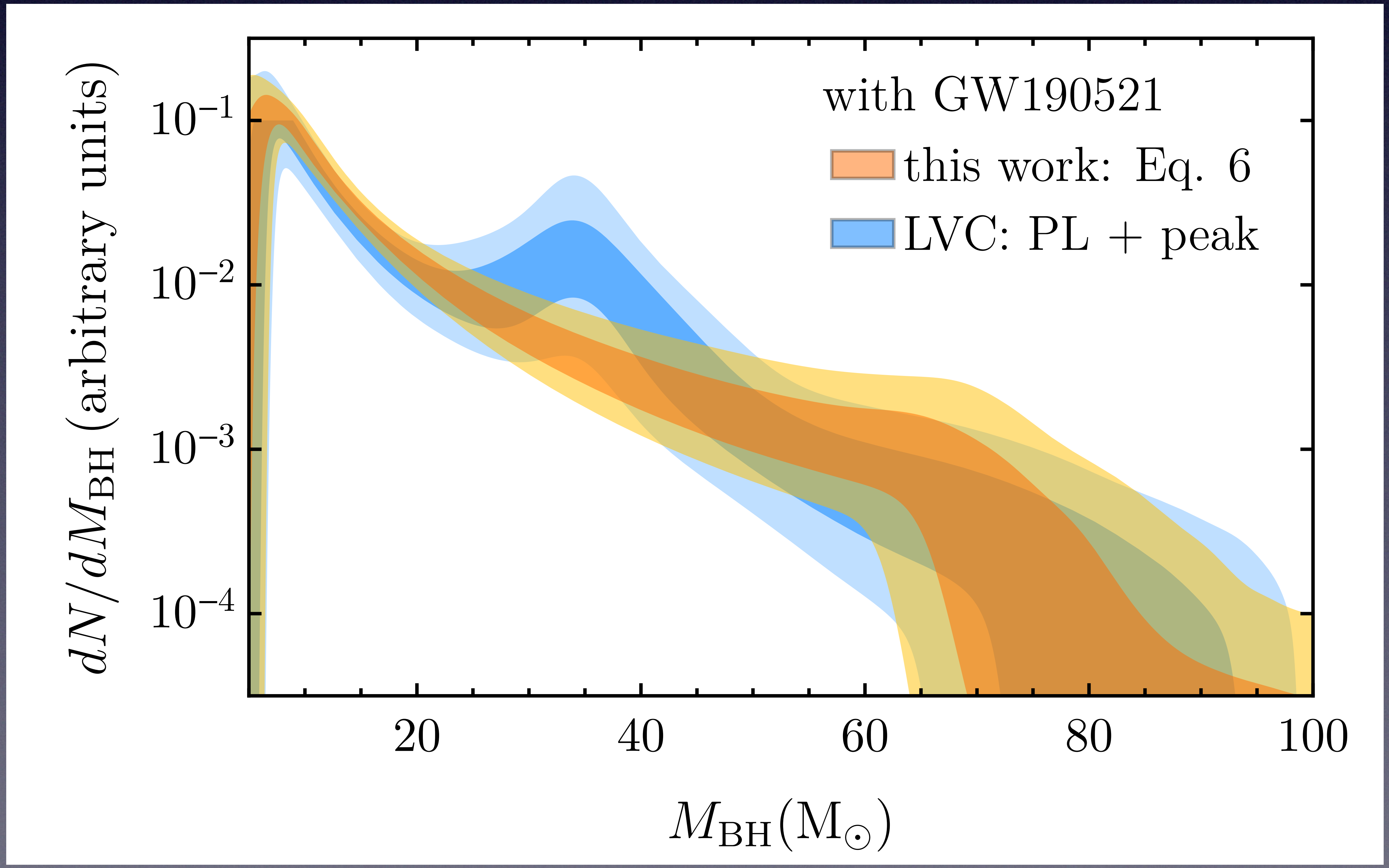
Black Hole Population Statistics

after GWTC-2

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

Baxter, Croon, SDM, Sakstein arXiv:2104.abcde





Conclusions

xkcd.com/1022/

Conclusions

xkcd.com/1022/

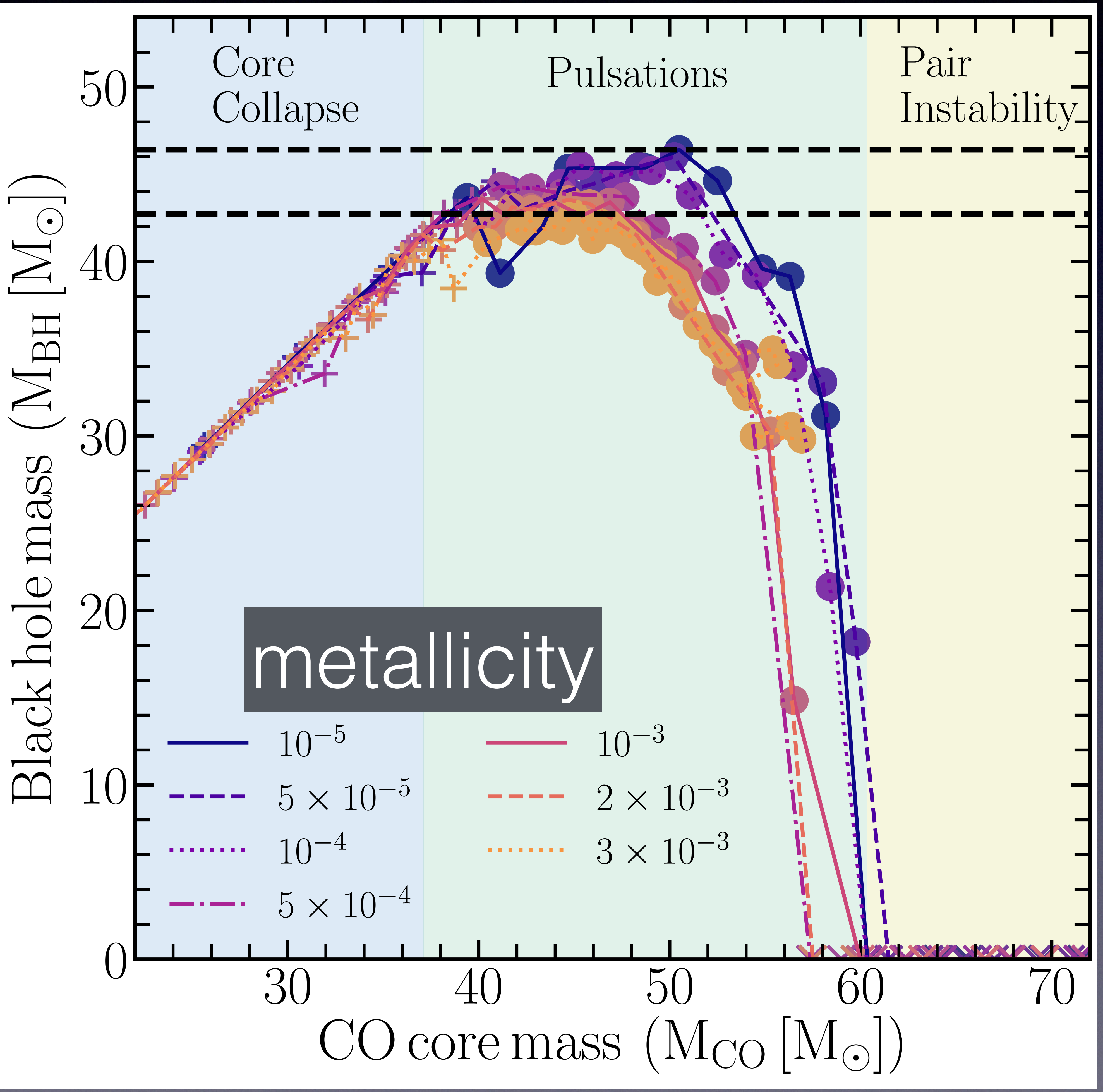
- LIGO is in the middle of its "discovery bump" — we are learning so much more about the Universe all the time!
- GW190521 provides rich fodder for new ideas and tests of both SM and BSM physics
- The future is exciting!

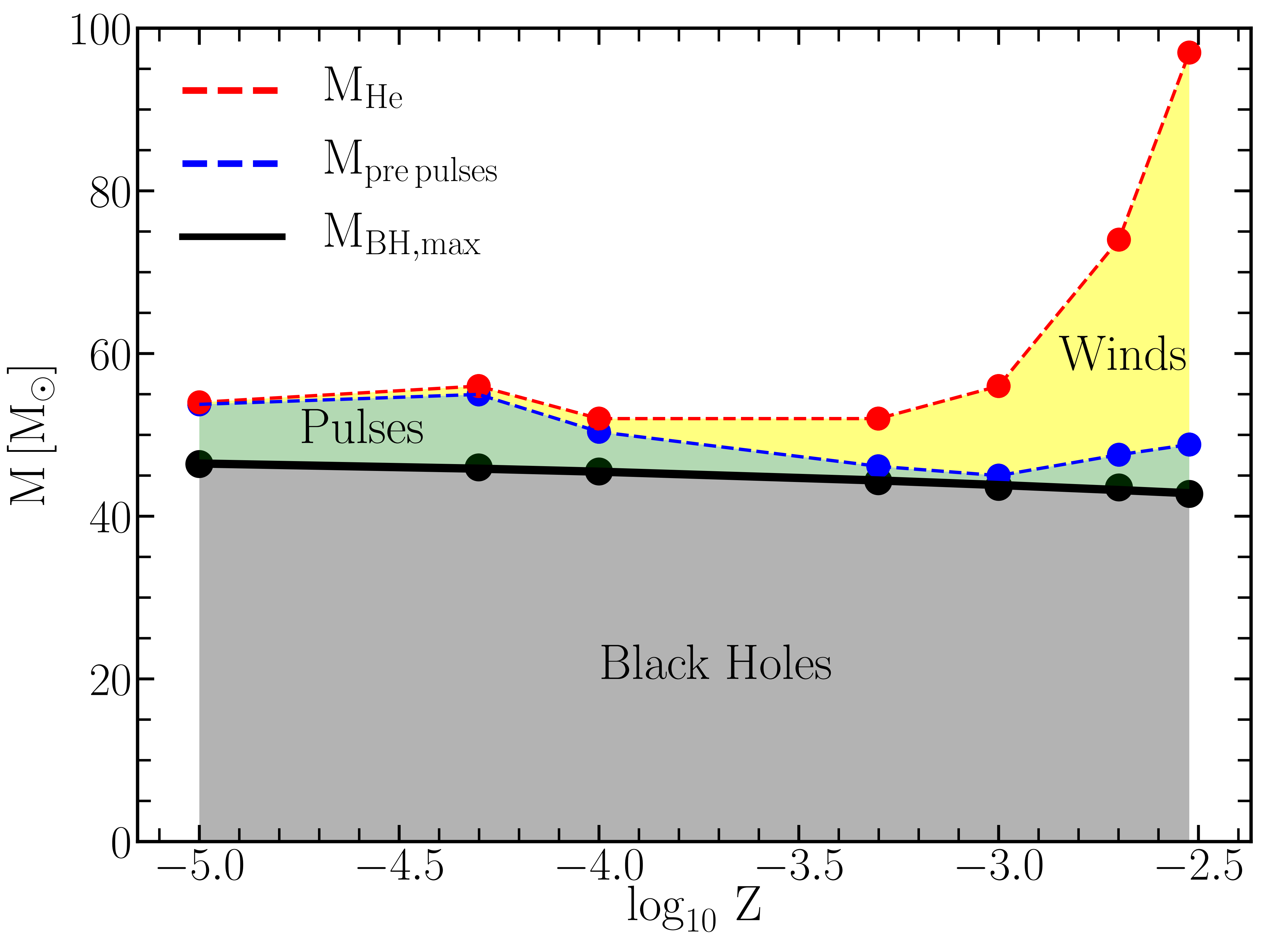
Thanks!

sammcd00@fnal.gov

home.fnal.gov/~sammcd00/

Environmental Variation



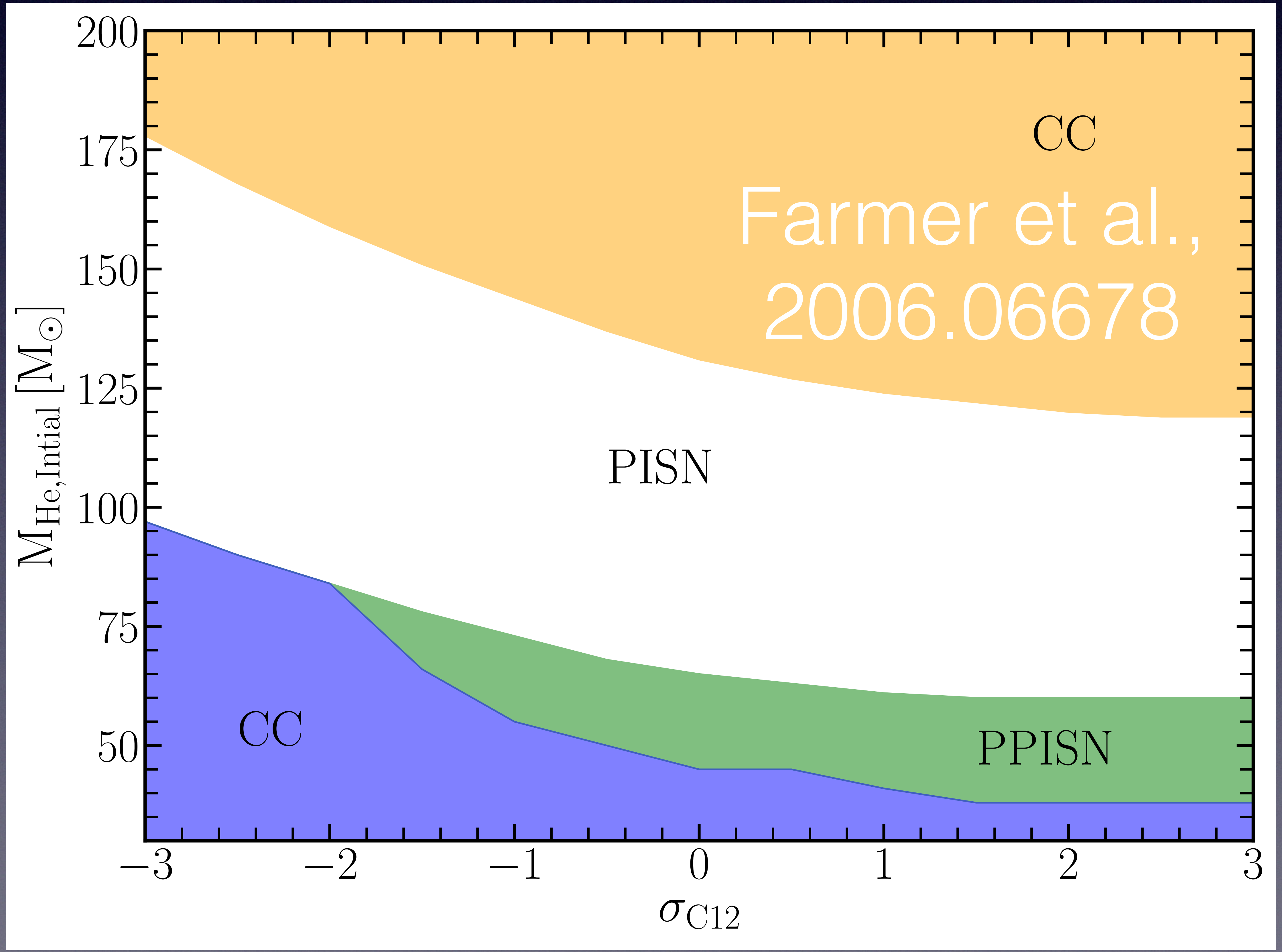


Farmer et al., 1910.12874 ApJ 887 53F

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

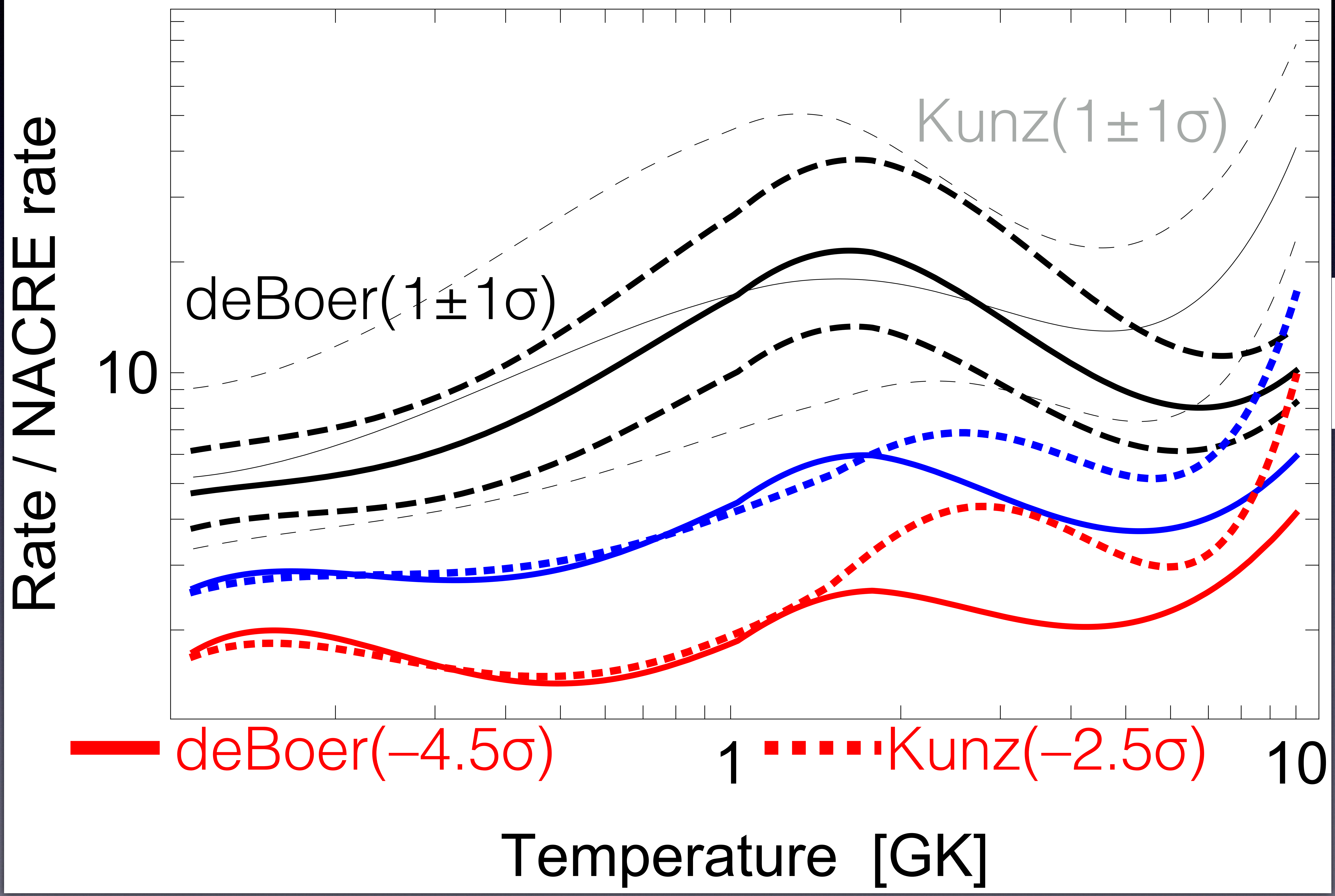
Three Routes for SM Explanations

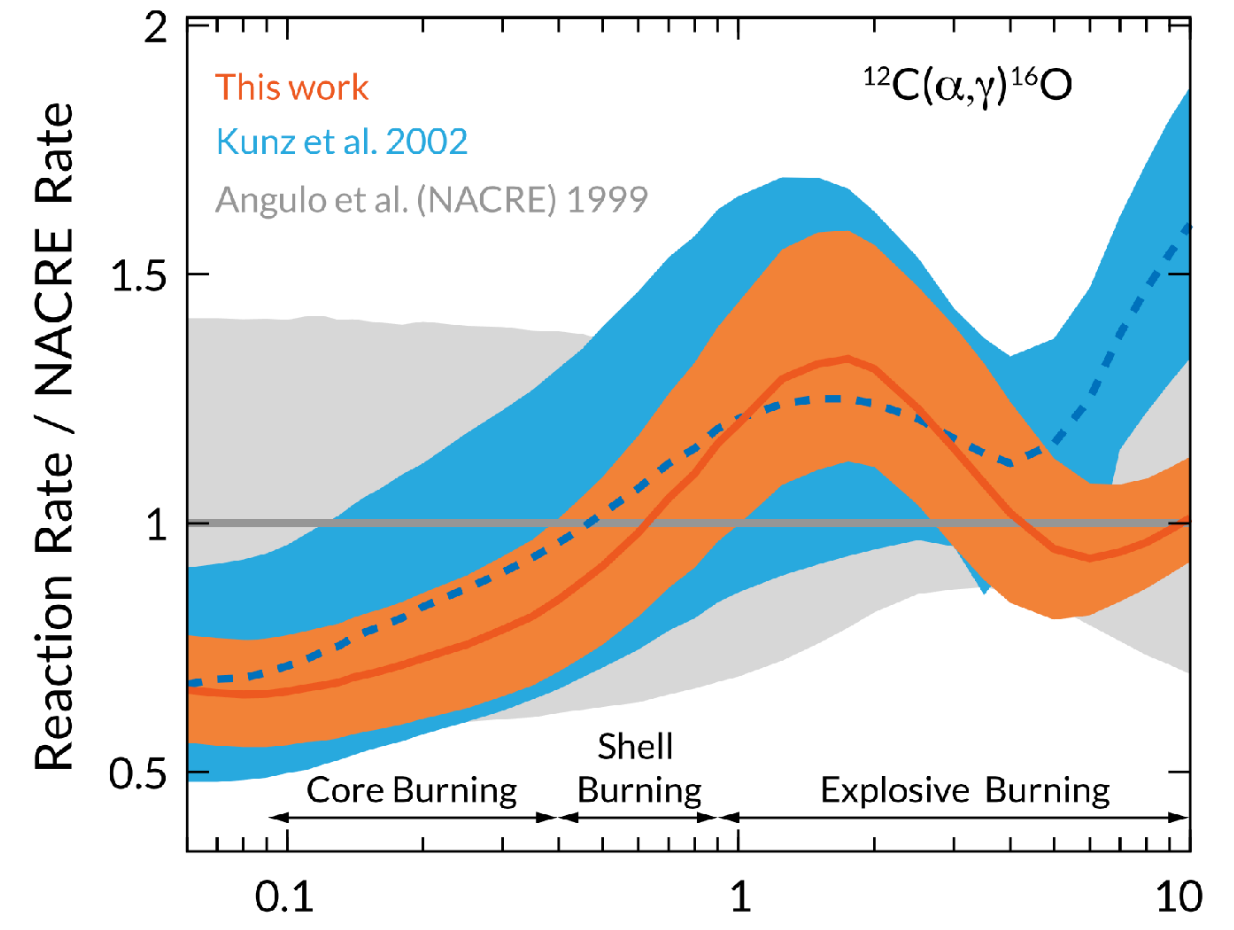
1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN →
3. Increase the mass *after* PPISN

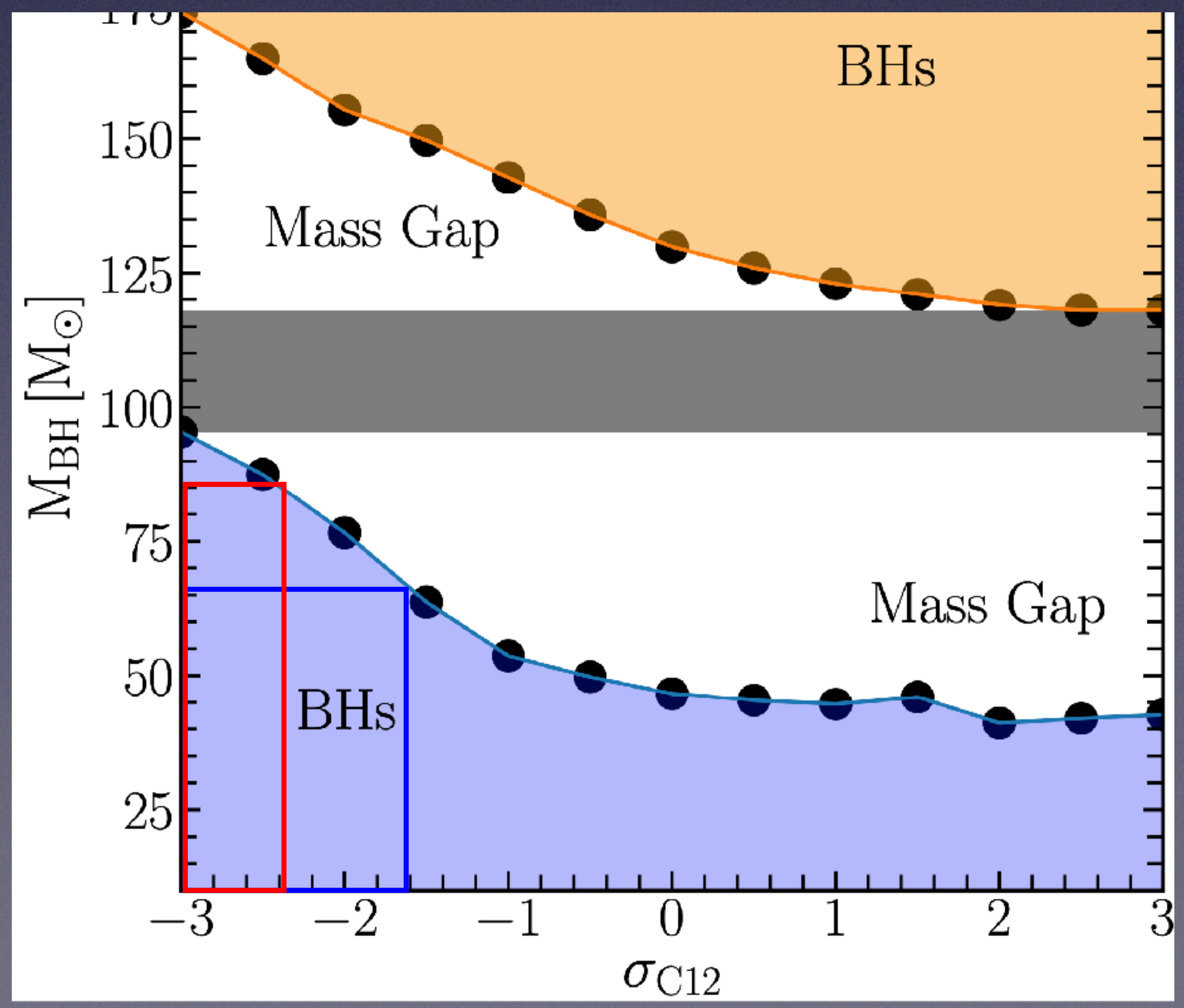


$^{12}C(\alpha,\gamma)^{16}O$ rates

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

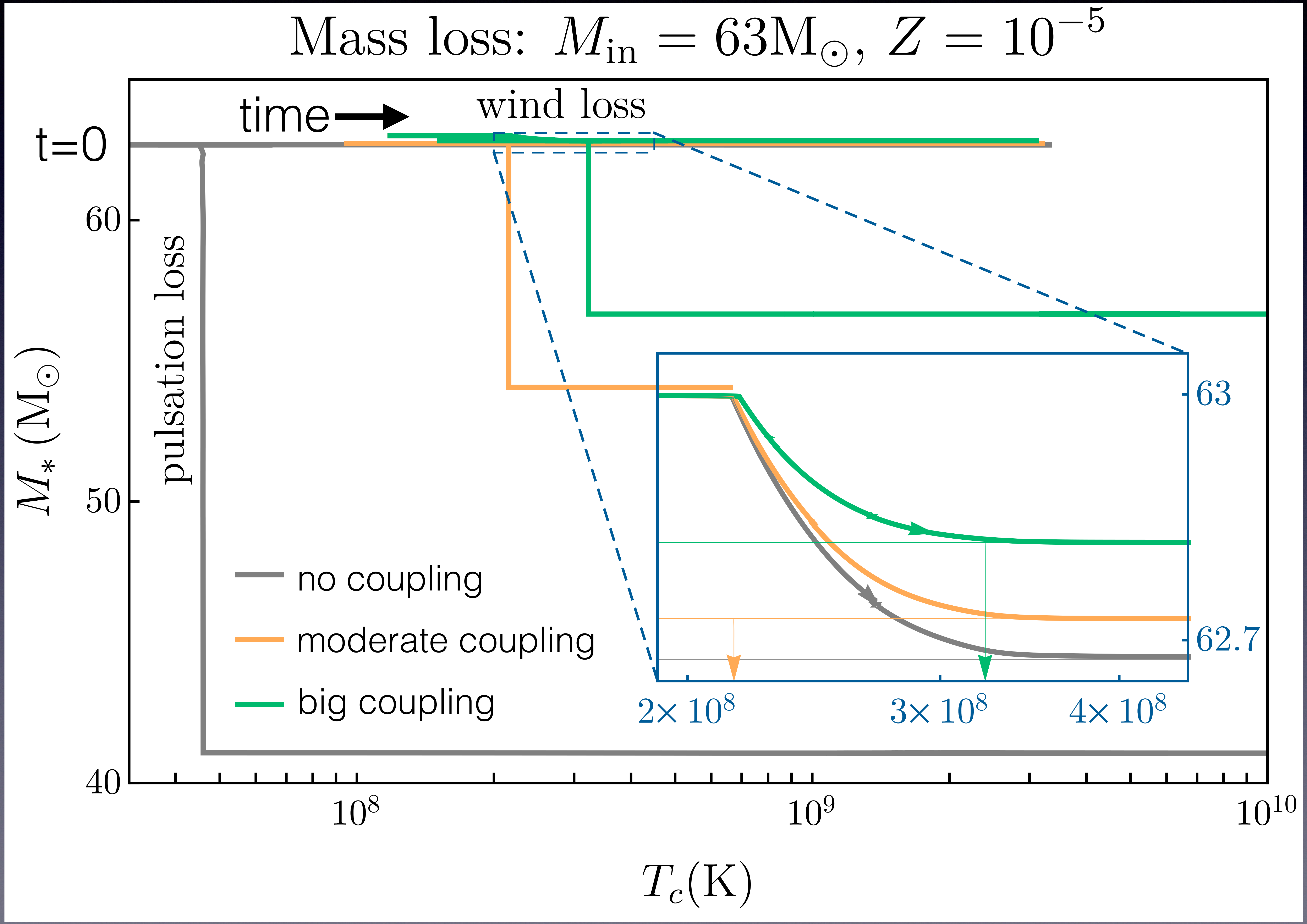






Croon, McDermott, Sakstein
2007.00650 + 2007.07889

Implications for Pulsations



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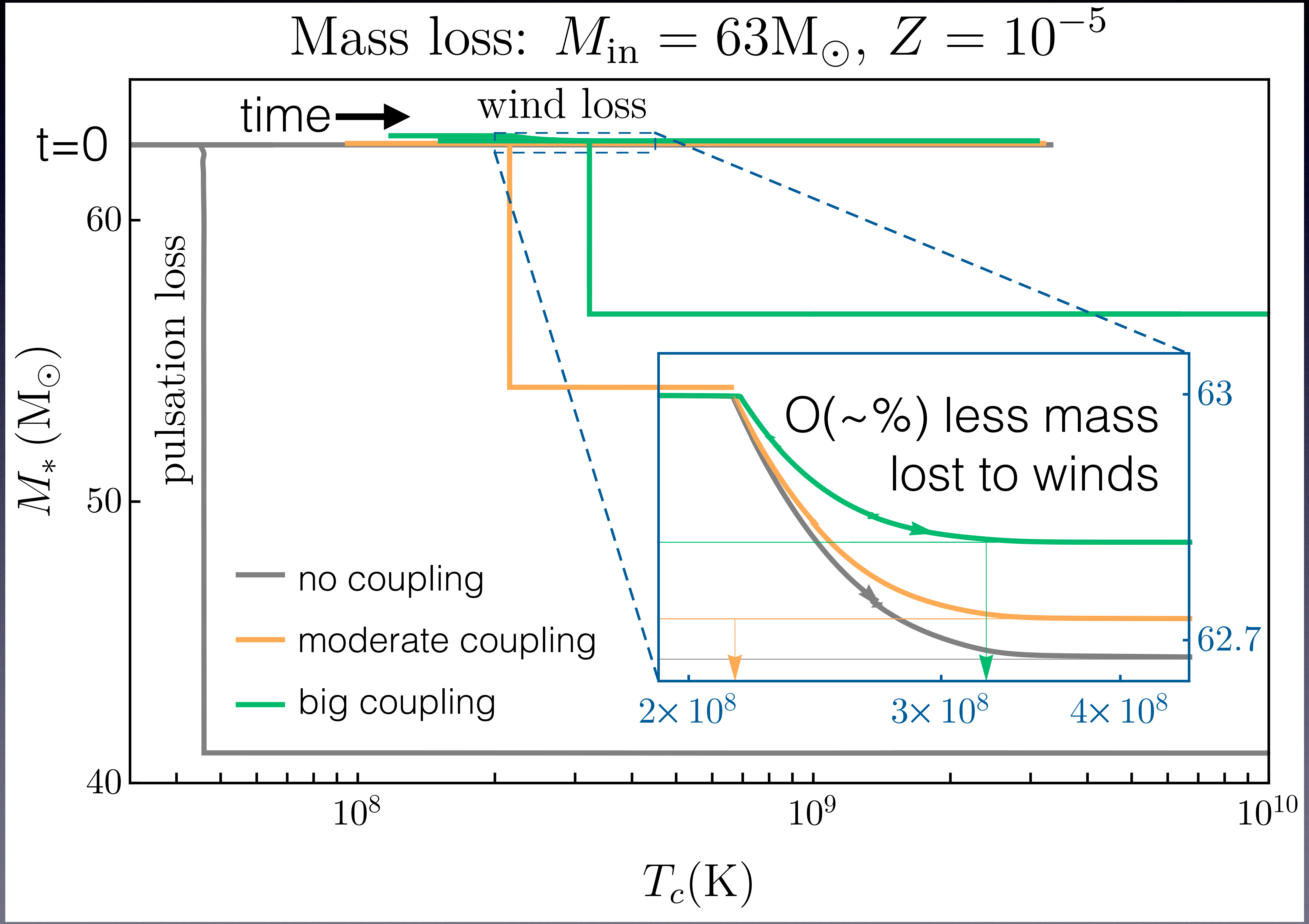

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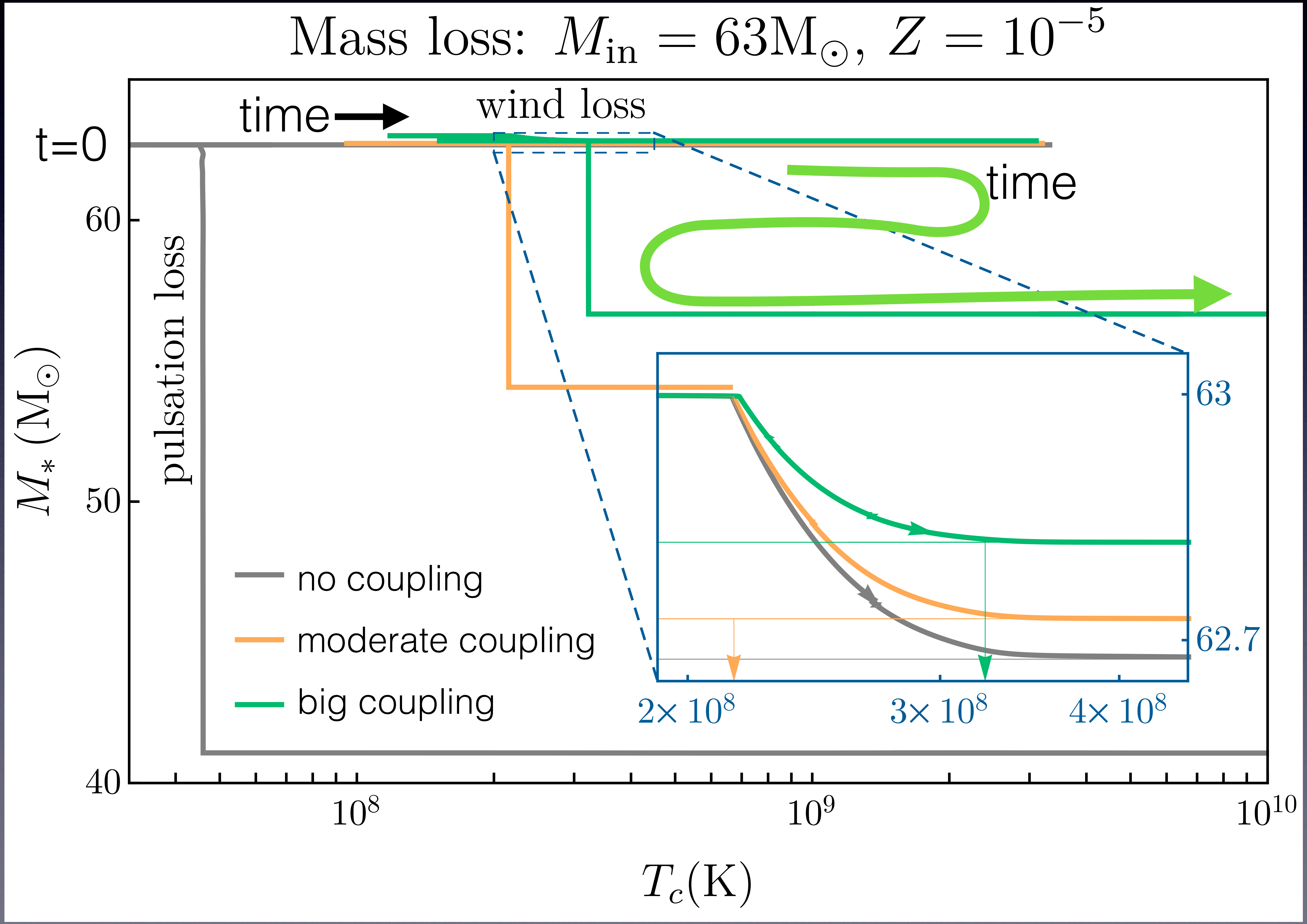

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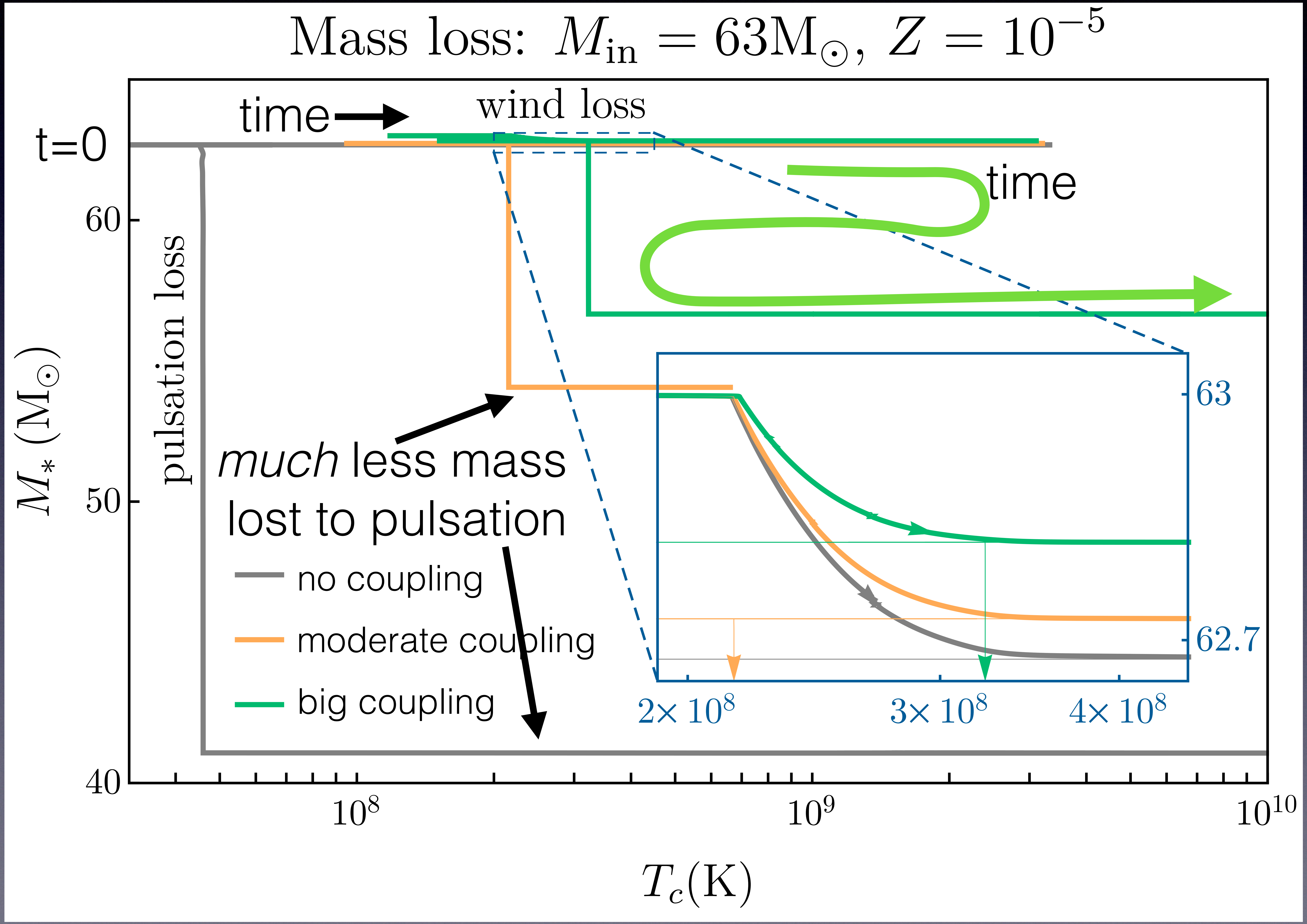

Croon, McDermott, Sakstein
2007.00650 + 2007.07889

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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2007.00650 + 2007.07889

Losses to Light Particles

- Electrophilic axion:
- Photophilic axion:
- Dark photon: