Beyond the Standard Model Explanations of GW190521

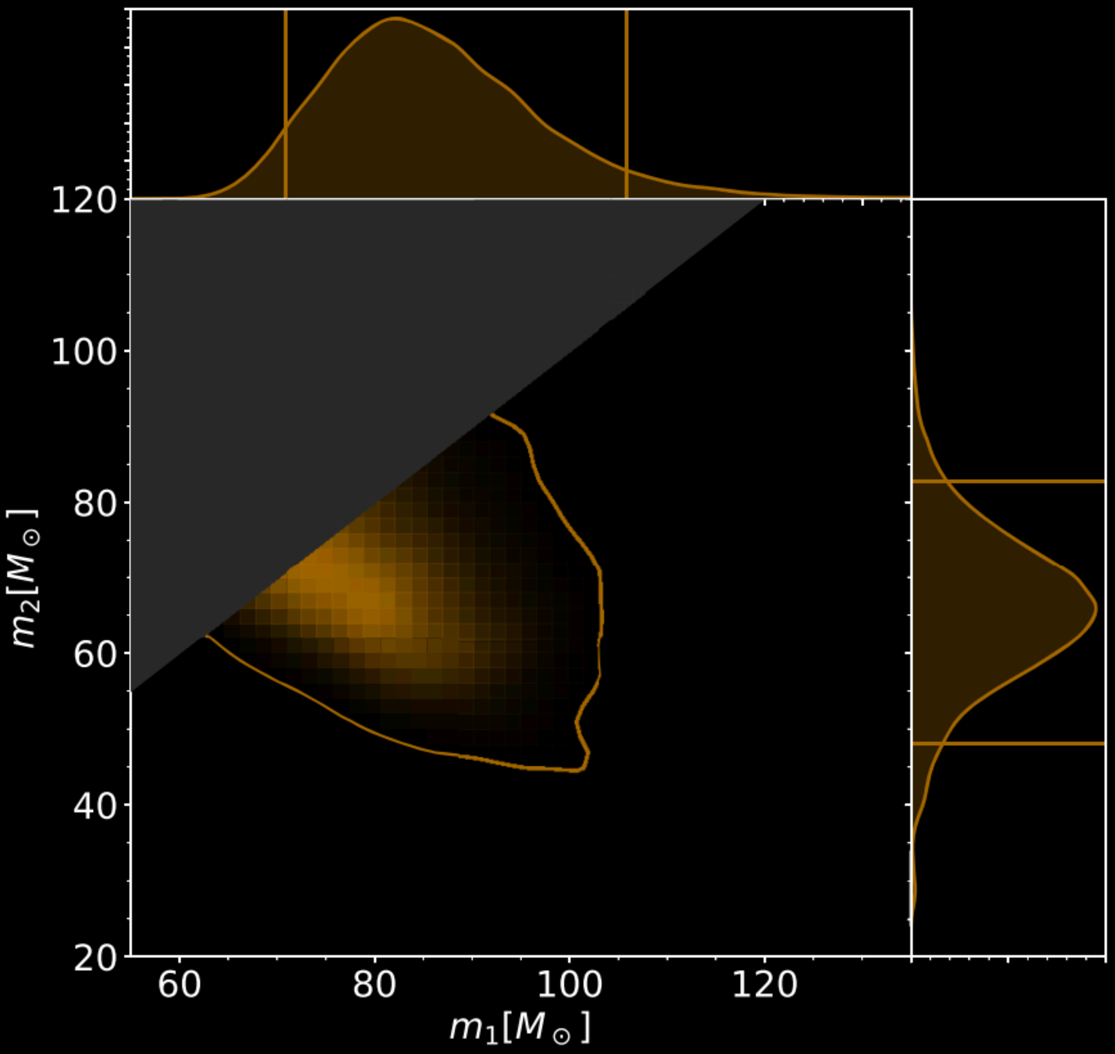
Jeremy Sakstein (University of Hawai’i)

Action Dark Energy, October 2020

sakstein@hawaii.edu | jeremysakstein.com

Slide credit: Djuna Croon

GW190521



LIGO/Virgo's biggest discovery yet: the *impossible* black holes

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

GW190521

The New York Times

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

SCIENCE&VIE

Un trou noir d'une masse inédite a fait vibrer les détecteurs

Astrono
black h

LIGO and Virgo Capture Their Most Massive Black Holes Yet

after 7 billion years

By Jonathan Amos
BBC Science Correspondent

LIGO/Virgo's biggest discovery yet: the *impossible* black holes

- What is the black hole mass gap?
- Why haven’t I heard of it?
- Why should I care?

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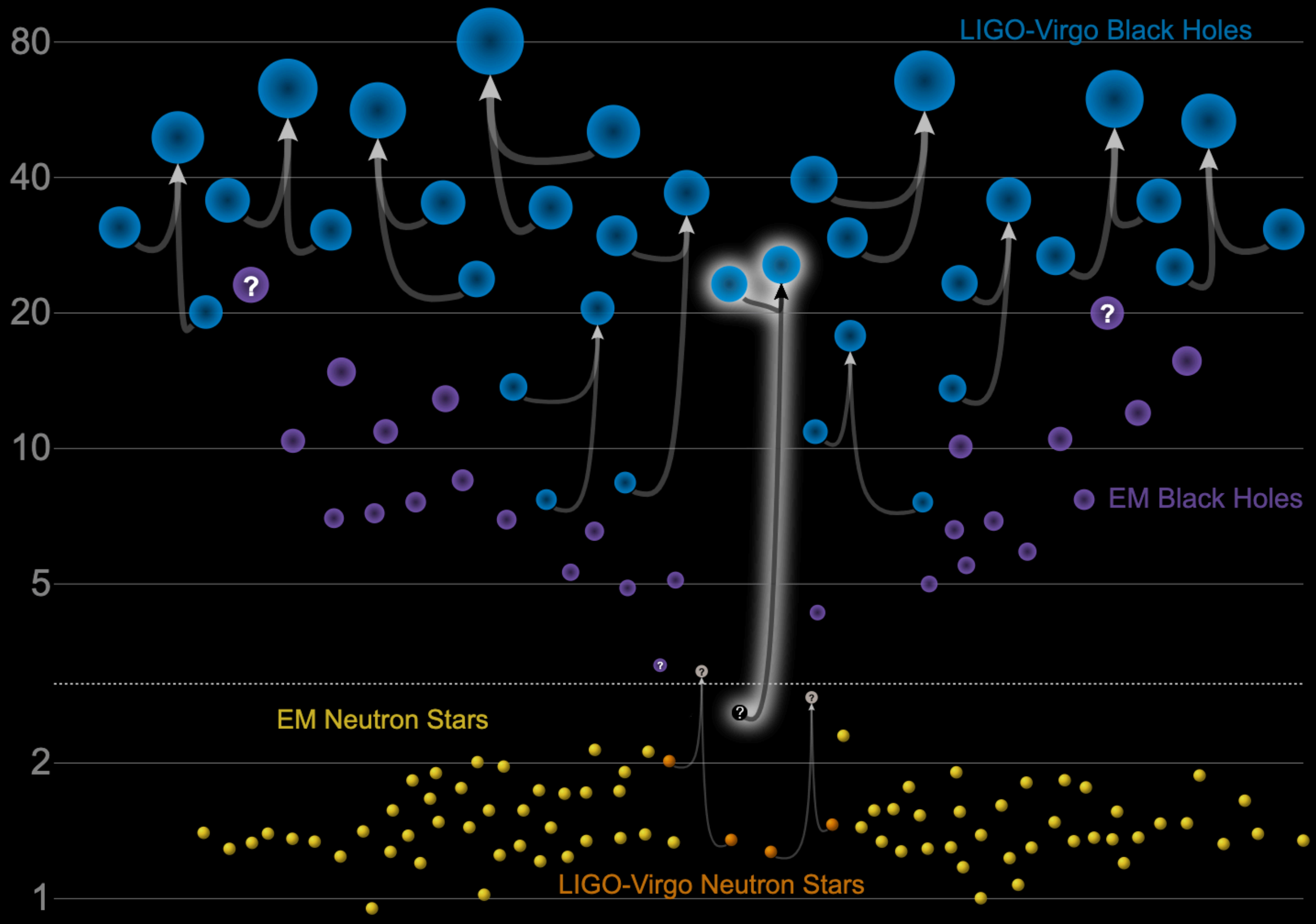
Binary mergers in LIGO/Virgo O1+O2

"The Stellar Graveyard"



Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

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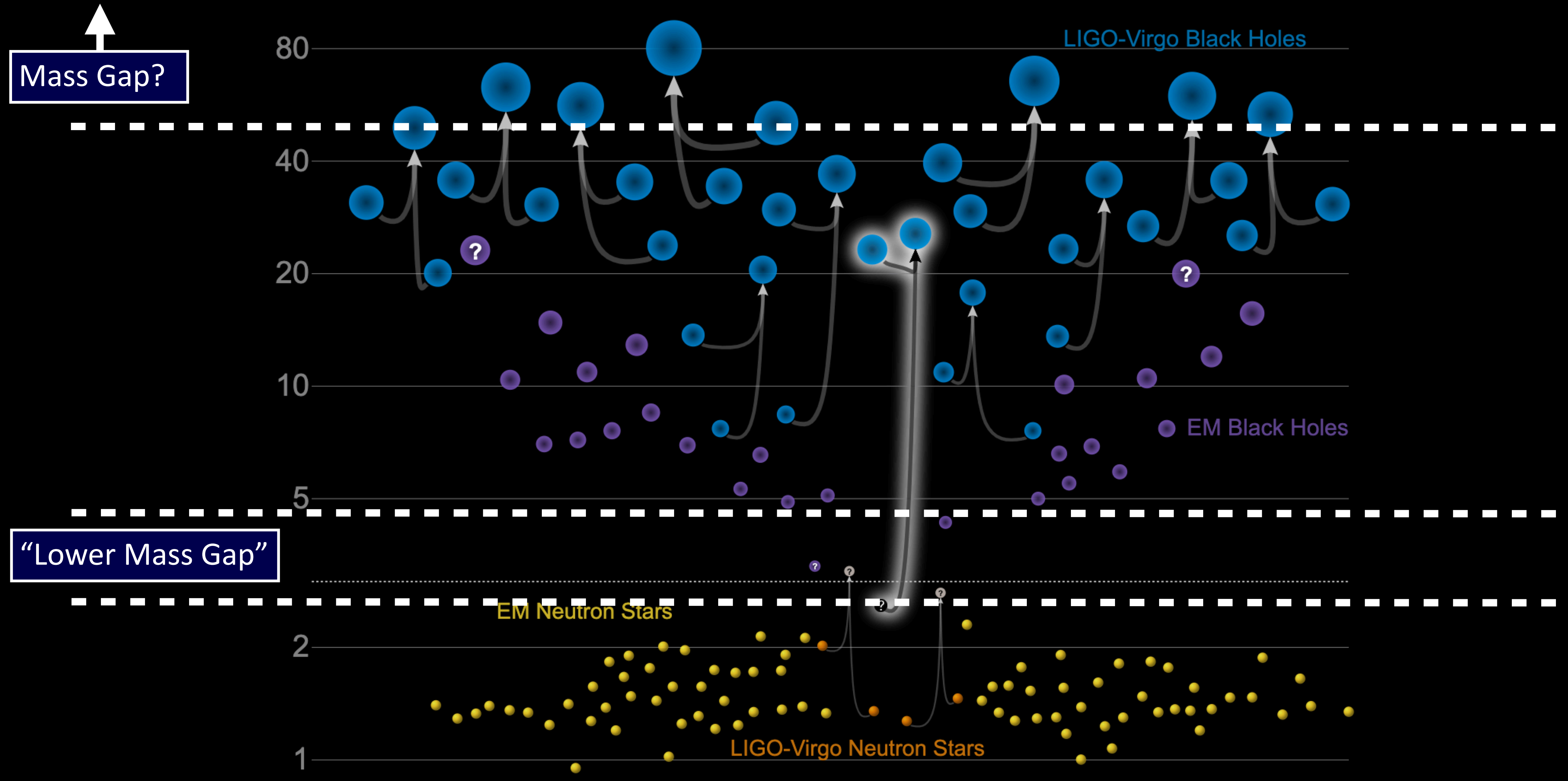

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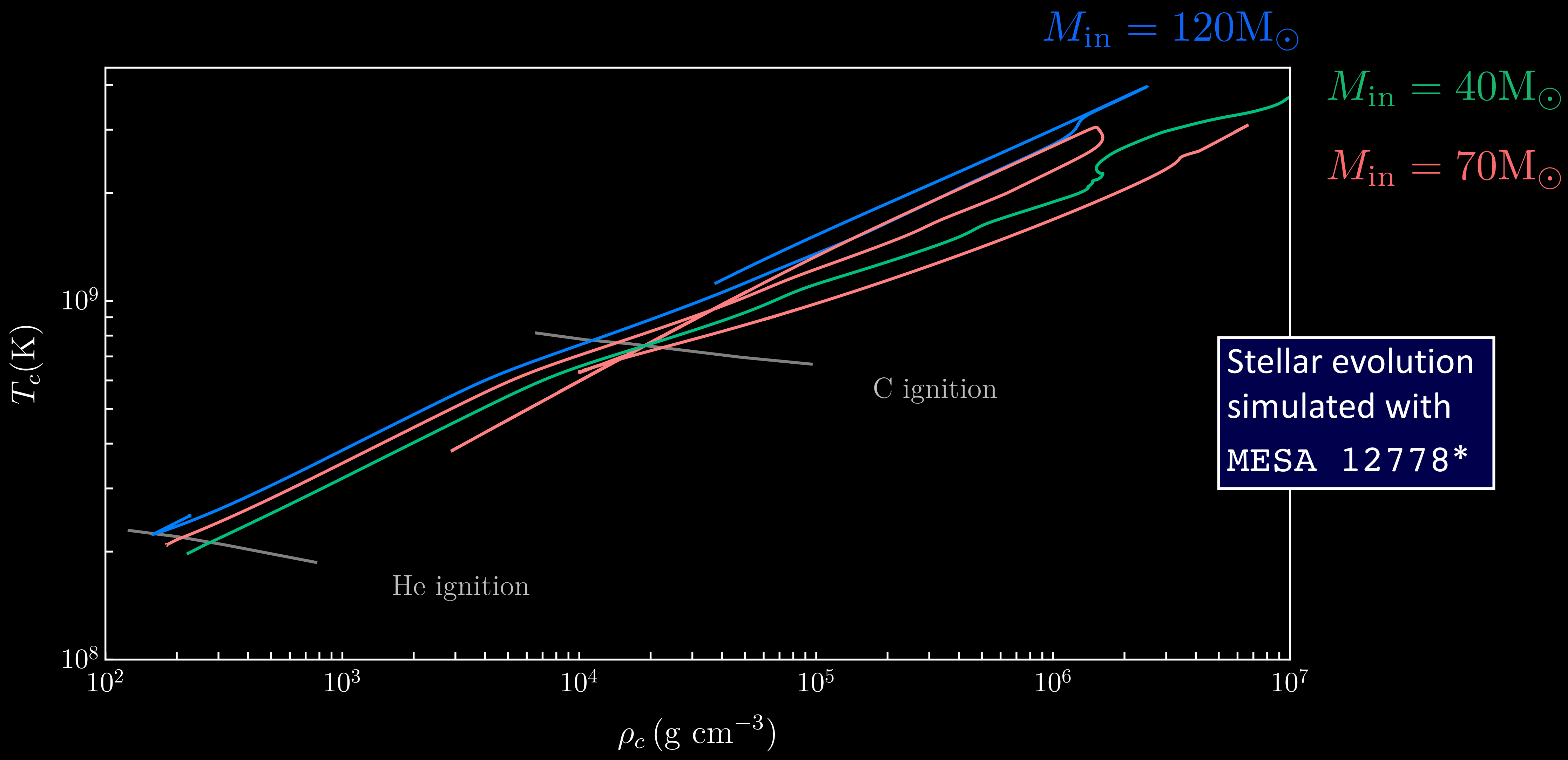
What populates the stellar graveyard?

- In the LIGO/Virgo mass range: remnants of heavy, low-metallicity population-III stars
  - Primarily made of hydrogen (H) and helium (He)
  - Would have existed for $z \gtrsim 6, M \sim 20 - 130\,\mathrm{M}_\odot$
  - Have not been directly observed yet (JWST target)

- Collapsed into black holes in core-collapse supernova explosions. *(Or did they?)*
- We study their evolution from the Zero-Age Helium Branch (ZAHB)

Evolution of old population-III stars



Stellar evolution simulated with `MESA 12778*`

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

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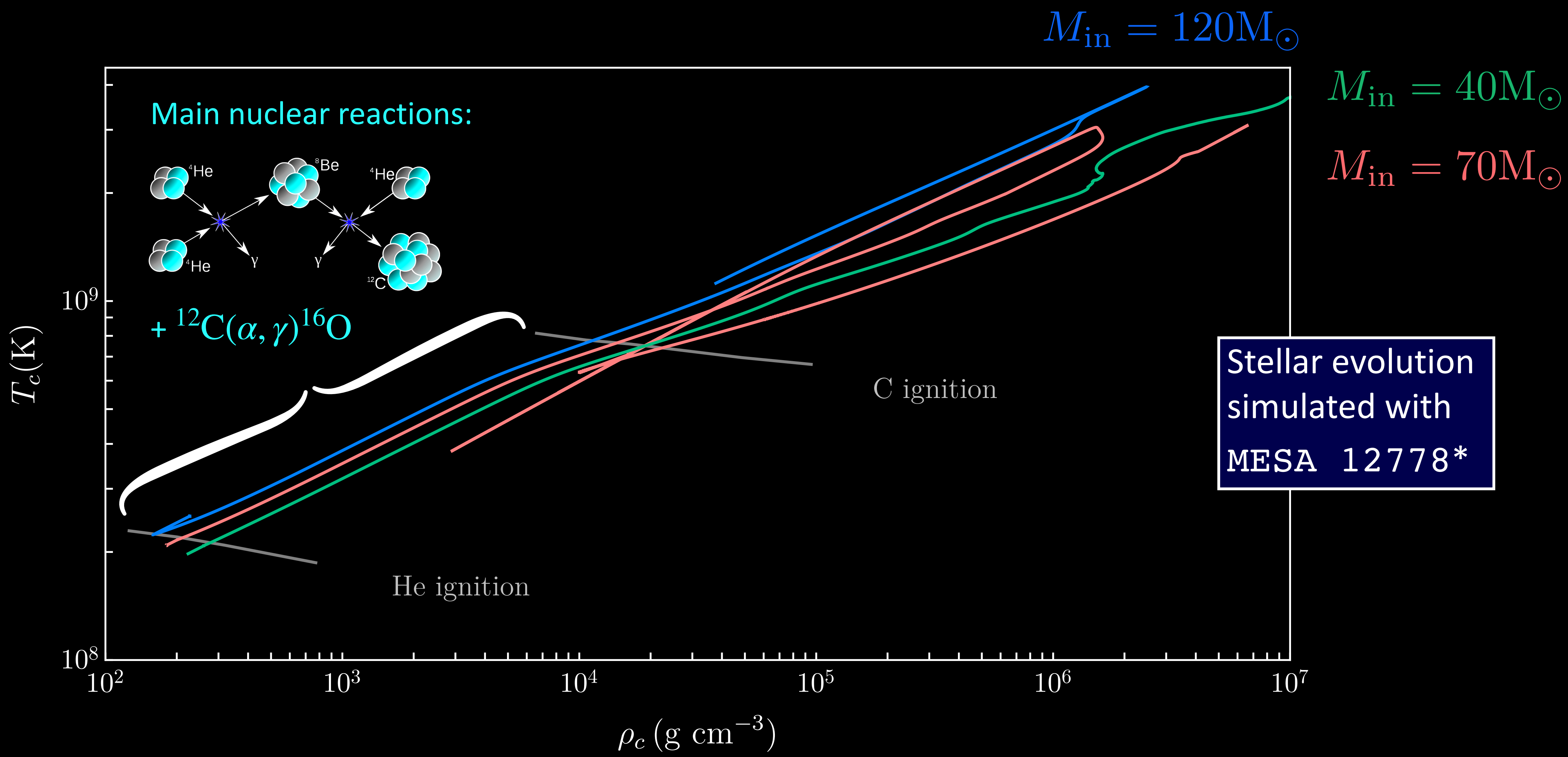

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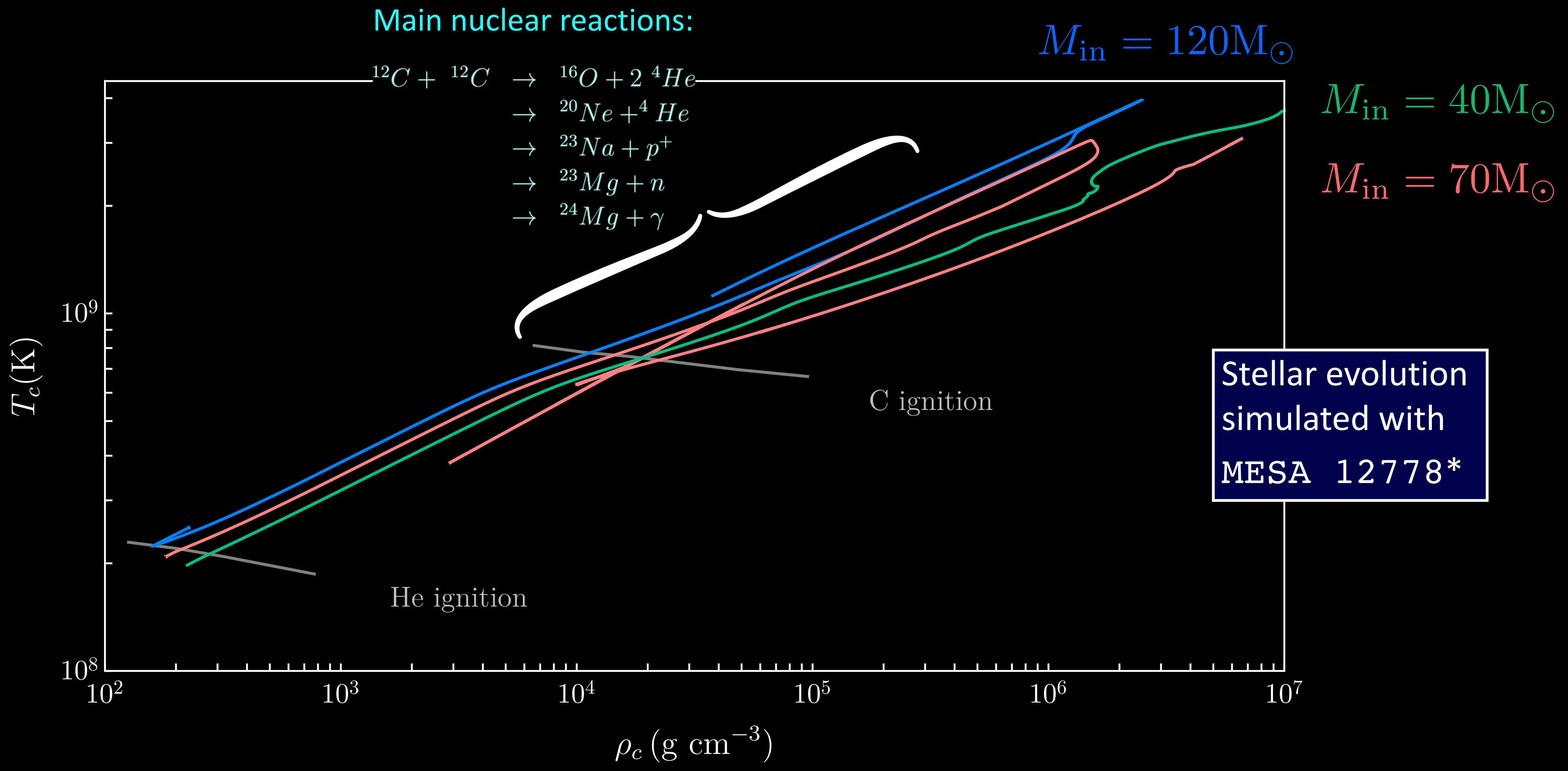

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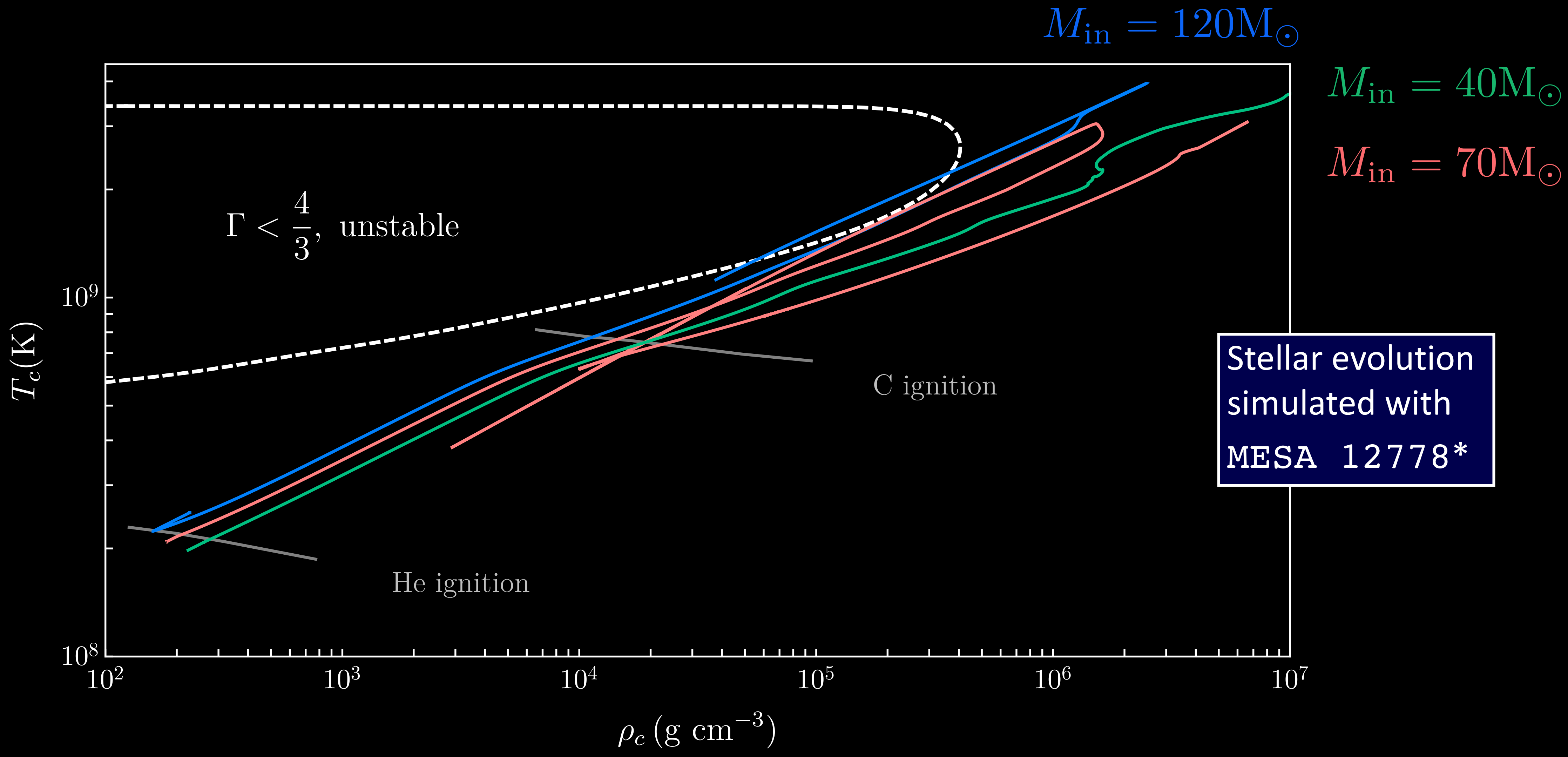

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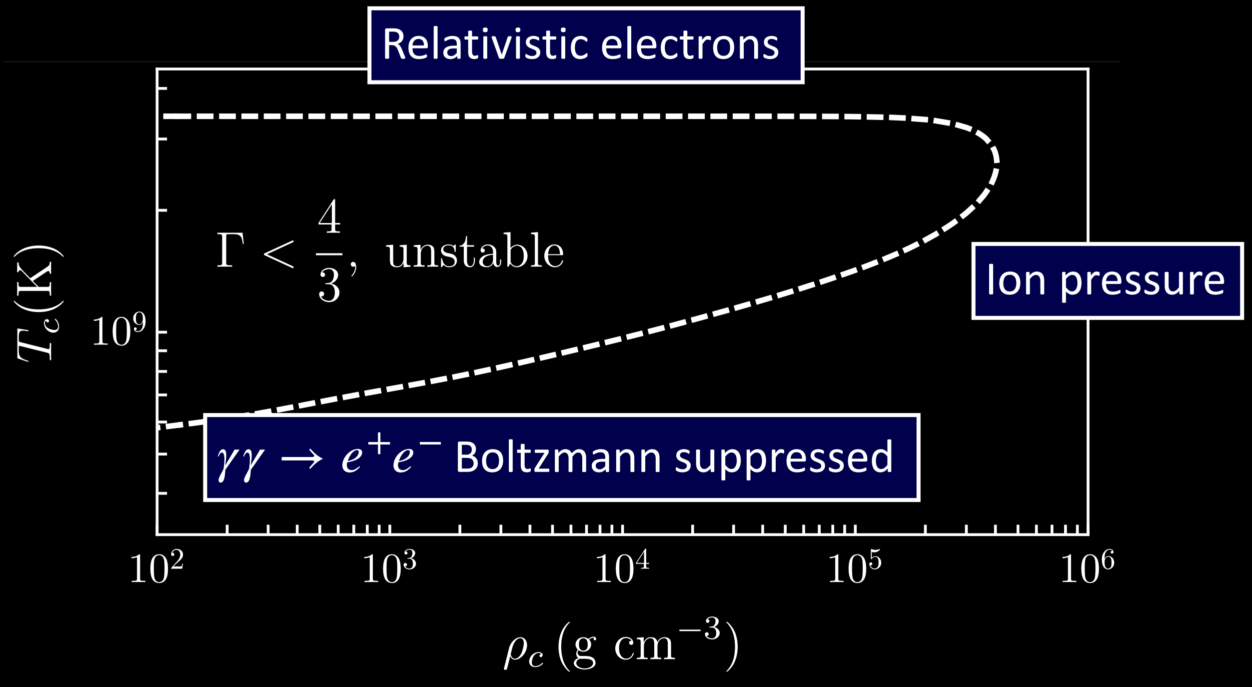
Pair-instability

- The high temperatures of the pop-III stars lead to electron-positron pair creation in the thermal plasma via $\gamma\gamma \to e^+e^-$ $(2m_e \simeq 10^{10}\mathrm{K})$

- Stars supported by radiation pressure $\Gamma = \left(\partial P / \partial \rho\right)_s \approx 4/3$

- Instability occurs for $\Gamma < 4/3$
  - Non-relativistic electrons destabilize the star
  - Rapid thermonuclear burning of $^{16}\mathrm{O}$ follows



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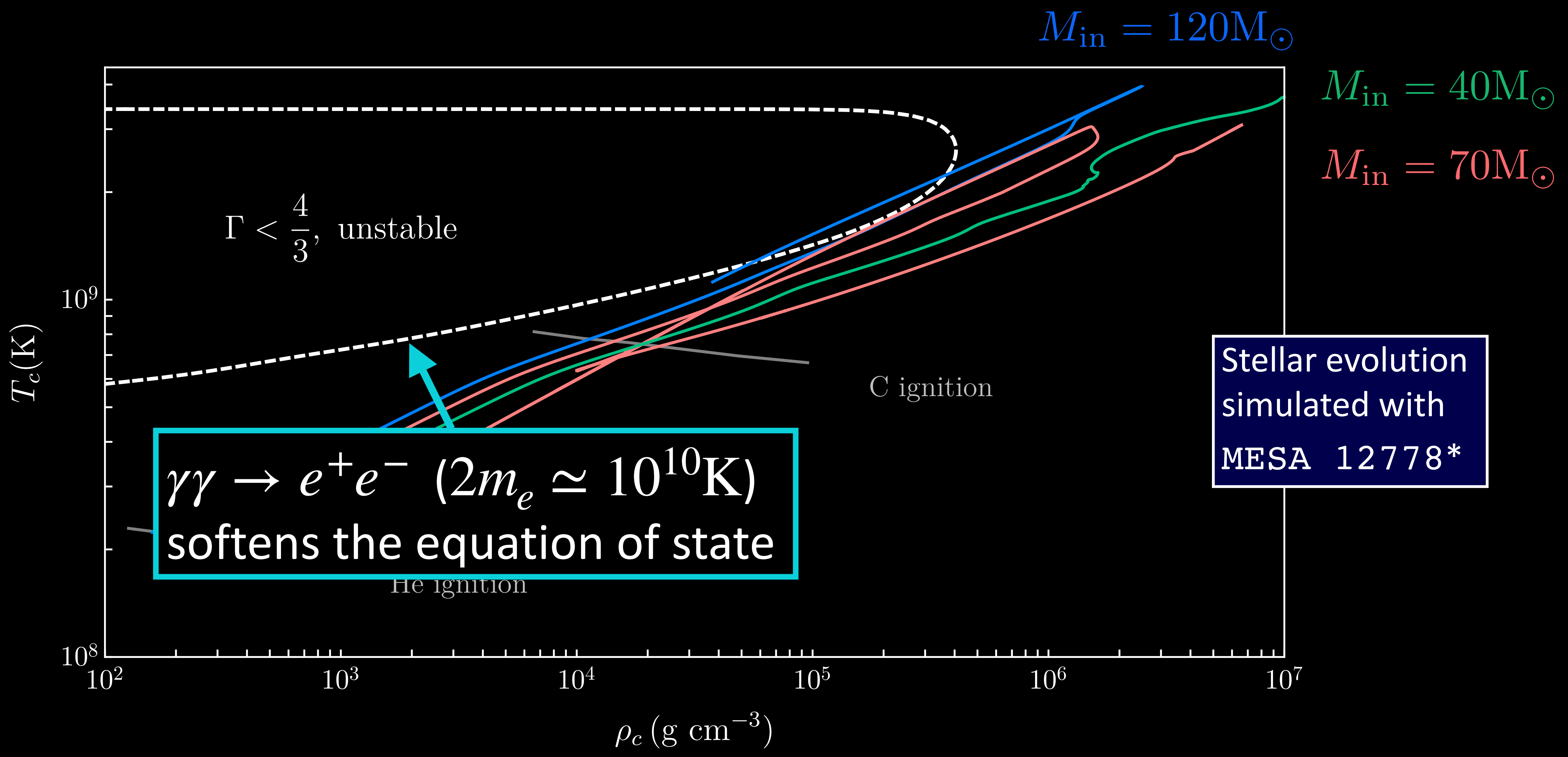

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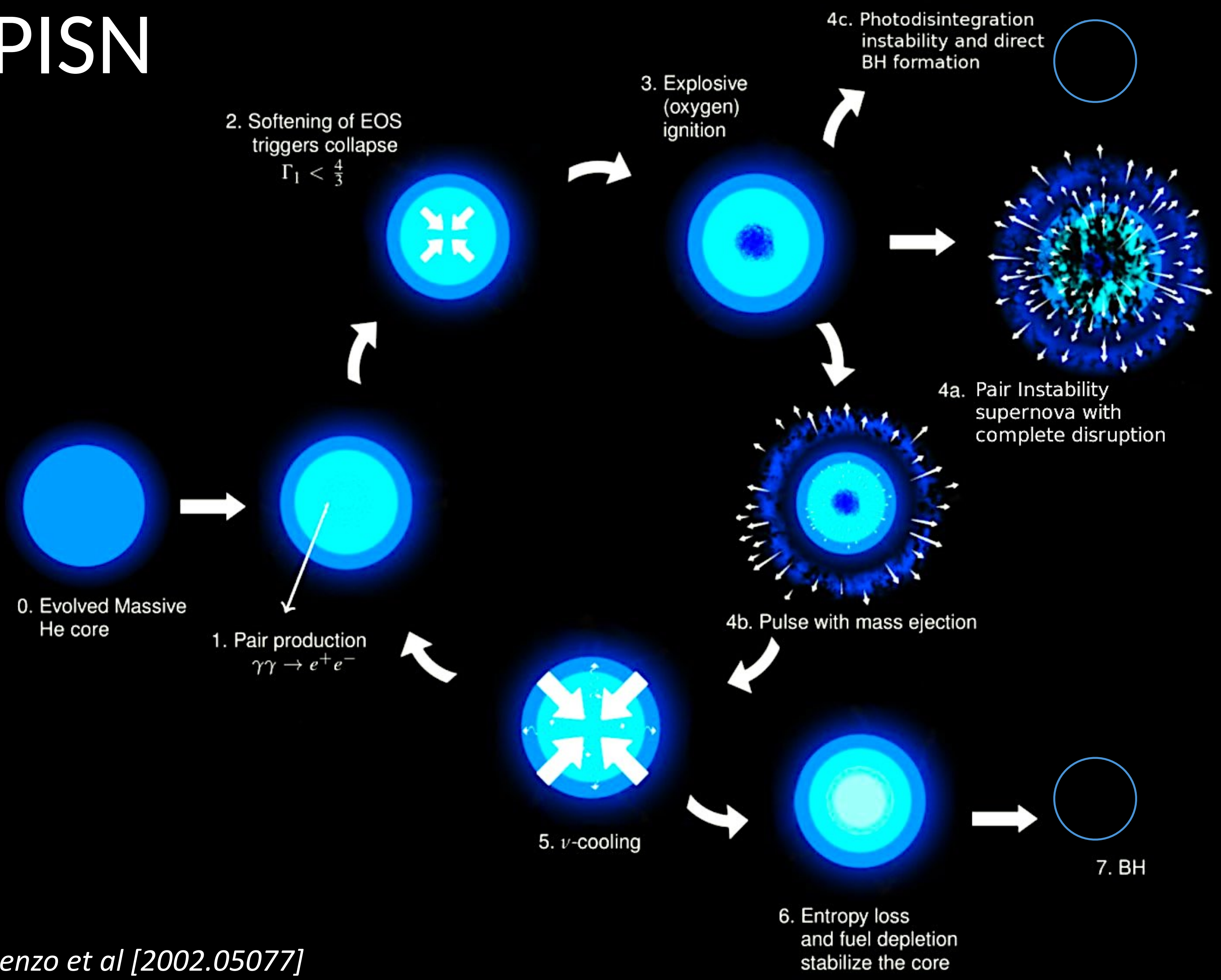


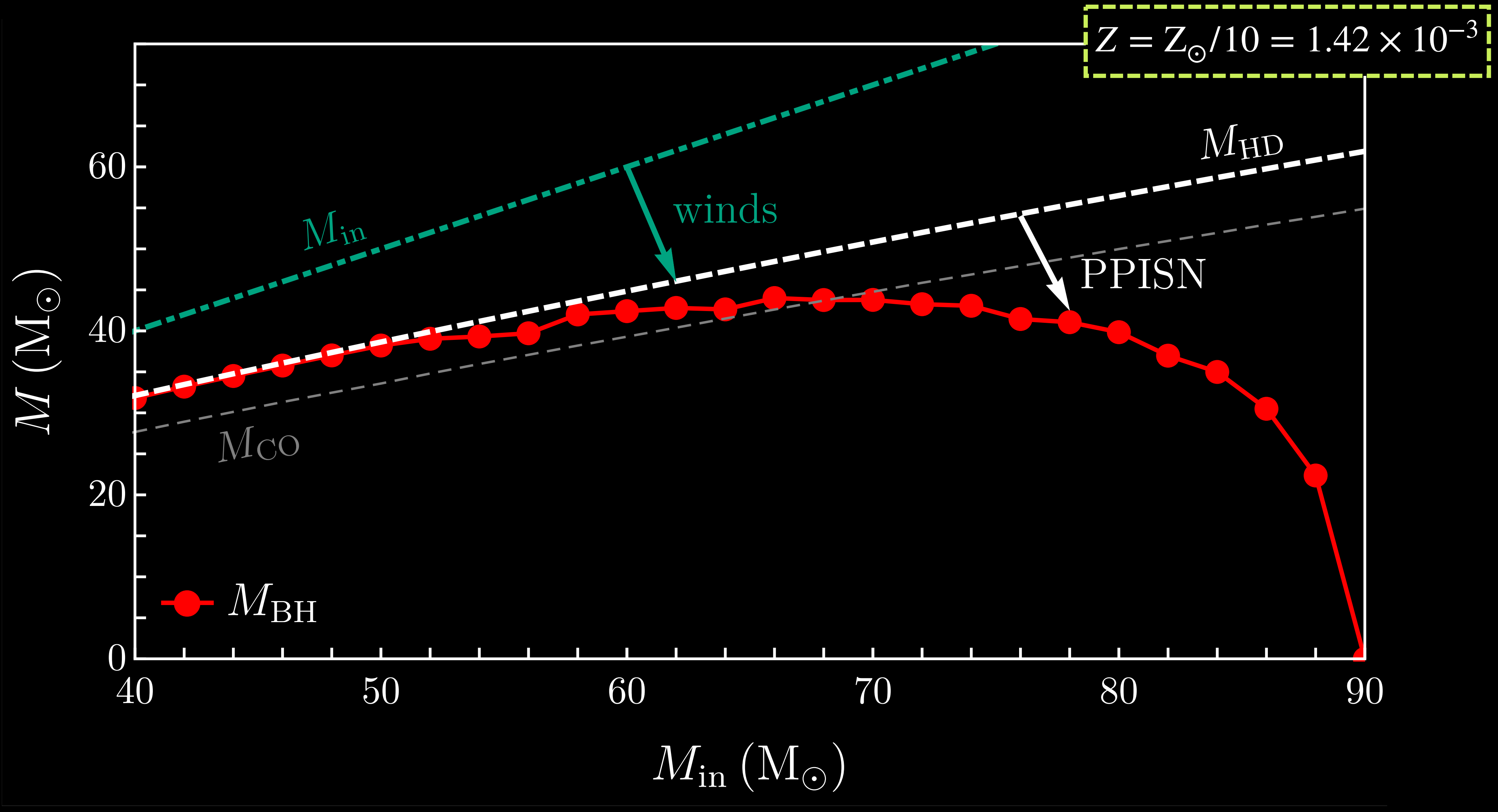
Extremely massive stars ($M_{\rm in} > 200\,{\rm M}_\odot$)

Very, very massive stars ($M_{\rm in} > 90\,{\rm M}_\odot$)

Very massive stars ($M_{\rm in} > 50\,{\rm M}_\odot$)

Adapted from Renzo et al [2002.05077]

Pair-instability and the BHMG

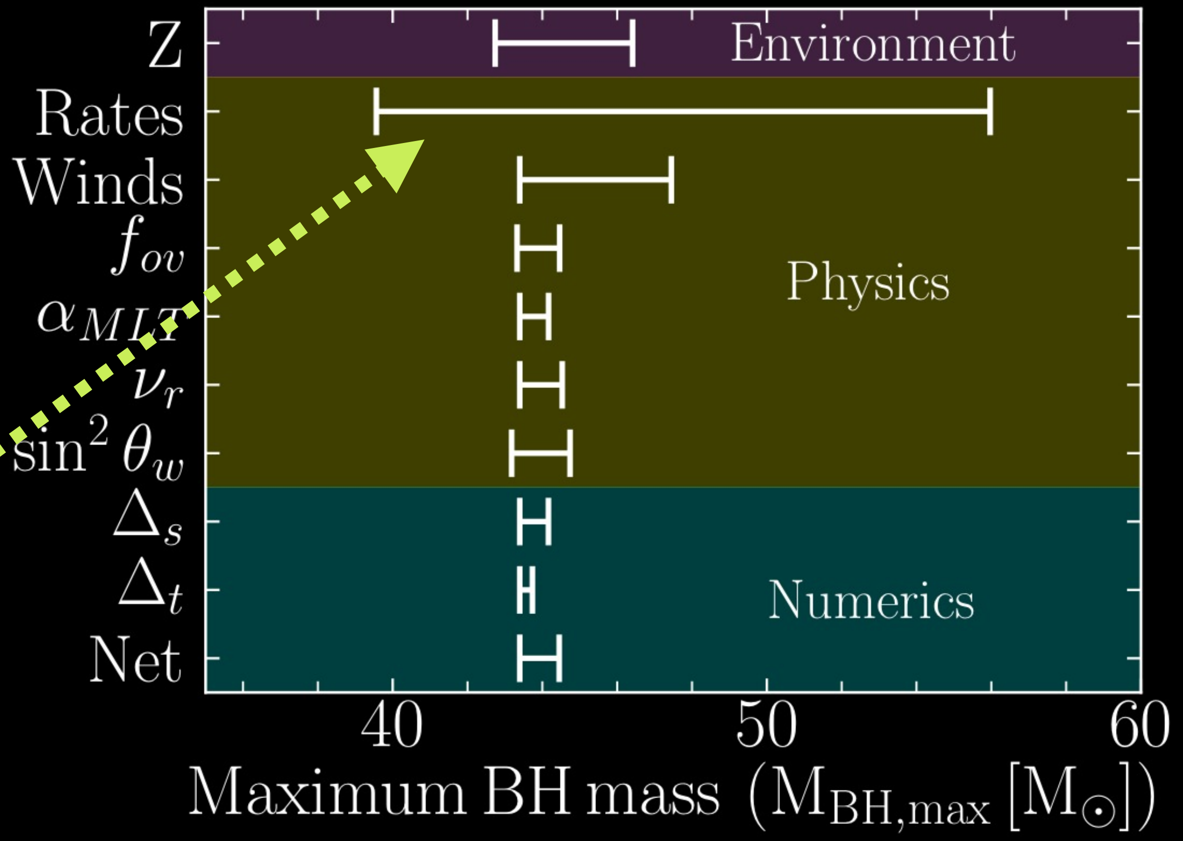


Croon, McDermott, JS arXiv:2007.00650 [hep-ph]

Known physics dependence of the BHMG

- Astrophysical + nuclear + numerical uncertainties
- Most important uncertainty: $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ rate
- Using updated deBoer et al rate, BHMG found at $51^{+0}_{-4}\,\mathrm{M}_{\odot}$

deBoer et al arXiv:1709.03144 [hep-ex]
Farmer, Renzo, de Mink, Fishbach, Justham arXiv:2006.06678 [astro-ph.SR]



Farmer, Renzo, de Mink, Marchant, Justham arXiv:1910.12874 [astro-ph.SR]

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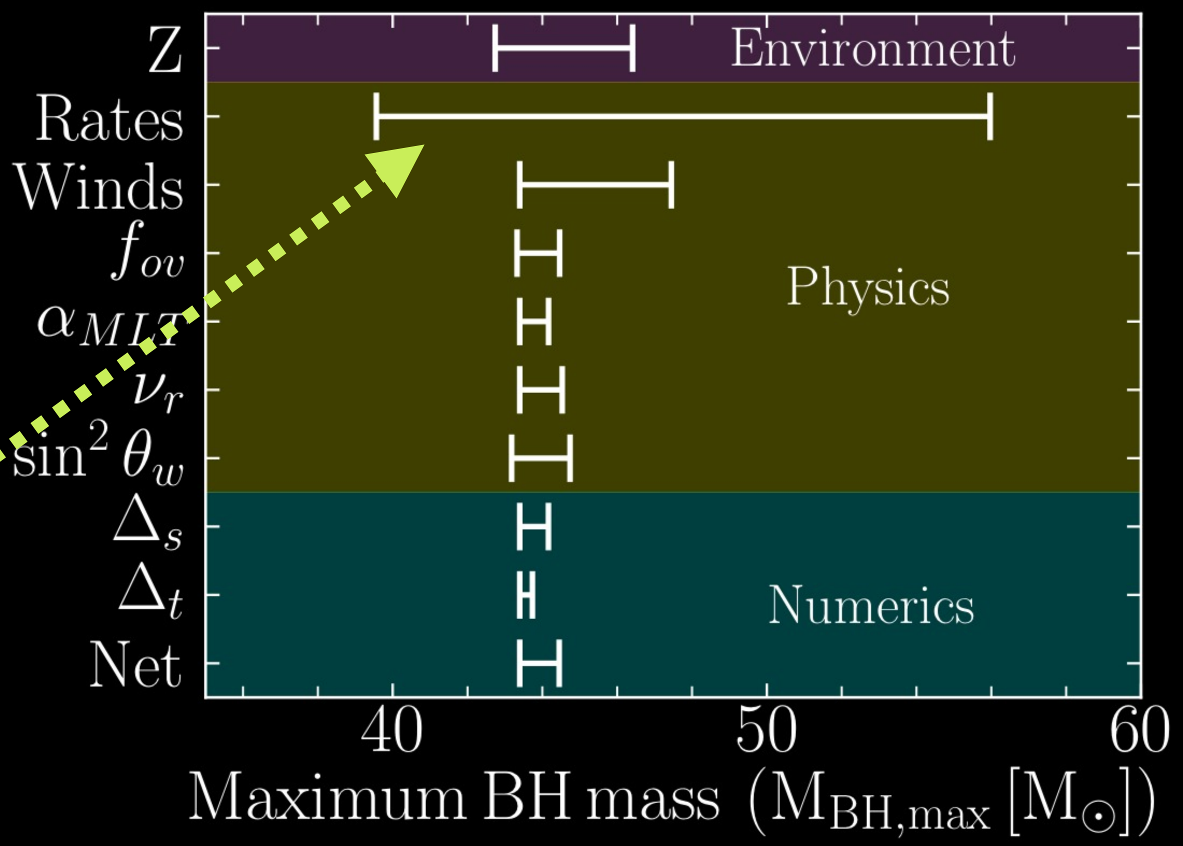

Farmer, Renzo, de Mink, Marchant, Justham arXiv:1910.12874 [astro-ph.SR]

But GW190521?!

What about new physics?

Croon, McDermott, JS arXiv:2007.00650 [hep-ph]

Croon, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

JS, Croon, McDermott, JS, Baxter arXiv:2009.01213 [gr-qc]

Straight, JS, Baxter 2009.10716 [gr-qc]

Croon, McDermott, JS arXiv:2007.00650 [hep-ph]

Croon, McDermott, JS arXiv:2007.07889 [gr-qc]

The BHMG and new physics

- Scenario 1: new, light particles coupled to material in the star introduce new loss channels

- Case studies:
  - the electrophilic axion $\mathscr{L}_{ae} = -ig_{ae}\bar{\psi}_e\gamma_5\psi_e a$ (will also work with $\alpha_{26} \equiv 10^{26}g_{ae}^2/4\pi$ for convenience)*
  - the photophilic axion $\mathscr{L}_{a\gamma} = -\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\widetilde{F}^{\mu\nu}$ (will also define $g_{10} \equiv 10^{10}g_{a\gamma}$ GeV)
  - the hidden photon $\mathscr{L}_{A'\gamma} = -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu$

*Interesting in light of the XENON1T excess, arXiv:2006.09721 [hep-ex]

Croon, McDermott, JS arXiv:2007.00650 [hep-ph]

Croon, McDermott, JS arXiv:2007.07889 [gr-qc]

The BHMG and new physics

- Scenario 1: new, light particles coupled to material in the star introduce new loss channels

Extra scenarios: large extra dimensions ($d = 4 + 2$) and neutrino magnetic moment work through essentially the same mechanism

- Case studies:
  - the electrophilic axion $\mathscr{L}_{ae} = -\imath g_{ae}\psi_e\gamma_5\psi_e a$ (will also work with $\alpha_{26} \equiv 10^{26}g_{ae}^2/4\pi$ for convenience)*
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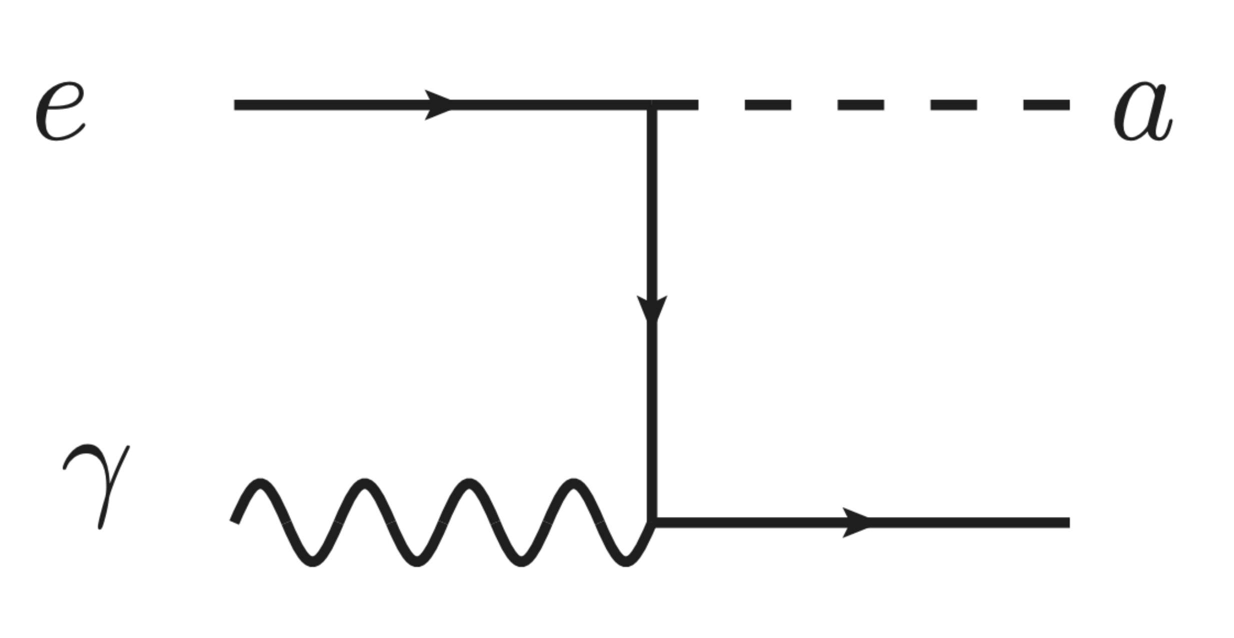
Croon, McDermott, JS arXiv:2007.00650 [hep-ph]

Energy loss due to electrophilic axions

- Semi-Compton scattering, $e + \gamma \to e + a$:

$$\mathcal{Q}_{\rm sC} = \frac{40\,\zeta_6 \alpha_{\rm EM} g_{ae}^2}{\pi^2} \frac{Y_e T^6}{m_N m_e^4} \simeq 33\,\alpha_{26}\,Y_e\,T_8^6\,F_{\rm deg}\,\frac{\rm erg}{\rm g \cdot s} \qquad \left(T_8 \equiv \frac{T}{10^8 \rm K}\right)$$

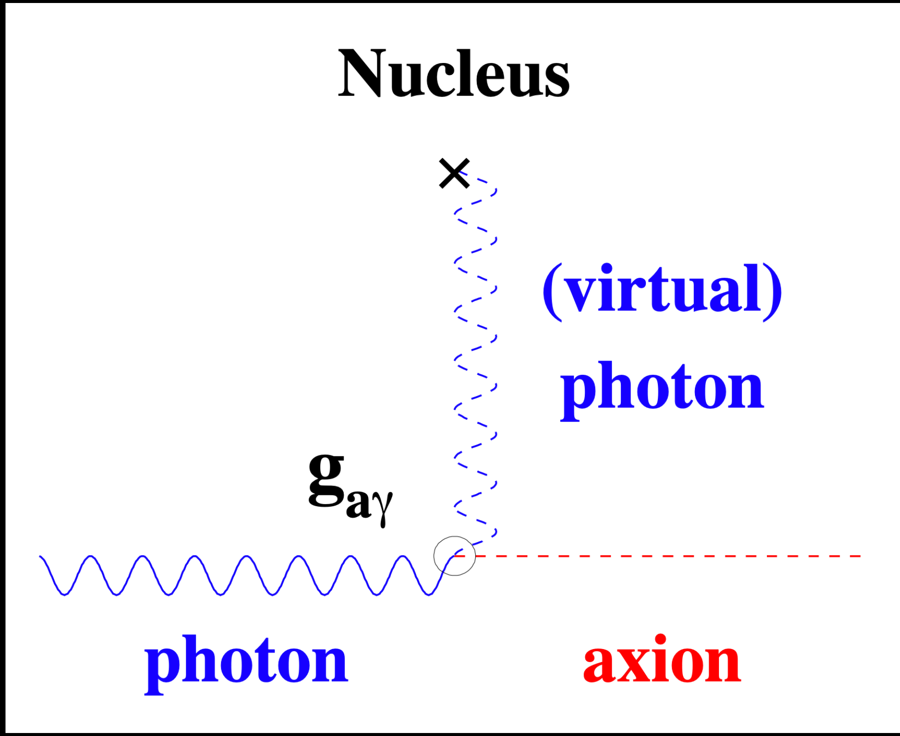


Energy loss due to photophilic axions

- Primakov effect $(Z, A) + \gamma \to (Z, A) + a$

$$\mathcal{Q}_{a\gamma} = \frac{g_{a\gamma}^2 T^7}{4\pi^2 \rho}\left(\frac{k_S}{2T}\right)^2 f[(k_S/2T)^2] \simeq 283.16 \frac{\text{erg}}{\text{g}\cdot\text{s}} g_{10}^2 T_8^7 \rho_3^{-1}\left(\frac{k_S}{2T}\right)^2 f[(k_S/2T)^2]$$

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



Croon, McDermott, JS arXiv:2007.07889 [gr-qc]

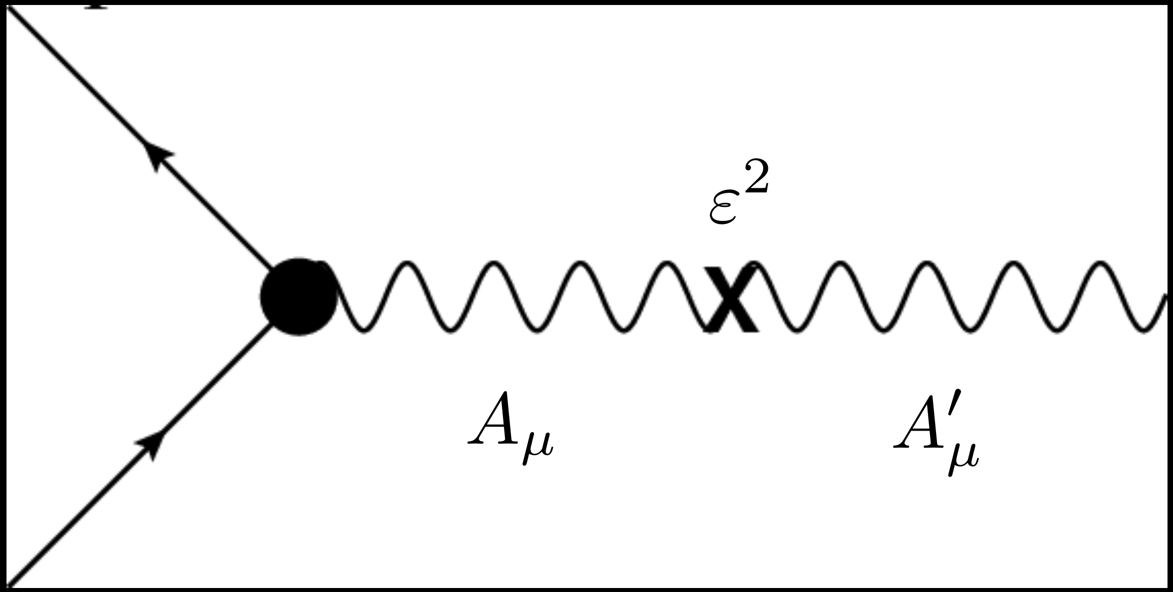
Energy loss due to hidden photons

- Plasma production, dominated by longitudinal modes (in a non-relativistic plasma)

$$\mathcal{Q}_{A'} = \frac{\epsilon^2 m_{A'}^2}{4\pi\rho}\frac{\omega_p^3}{e^{\omega_p/T}-1} \simeq \frac{\epsilon^2 m_{A'}^2}{4\pi}\frac{\omega_p^2 T}{\rho} \simeq 1.8\times 10^3 \frac{\text{erg}}{\text{g}\cdot\text{s}}\frac{Z}{A}T_8\left(\frac{\epsilon}{10^{-7}}\frac{m_{A'}}{\text{meV}}\right)^2$$

Where photons have plasma mass

$$\omega_p \simeq \sqrt{\frac{4\pi\alpha_{\text{EM}} n_e}{m_e}} \simeq 654\text{eV}\sqrt{\frac{Z}{A}\rho_3}$$



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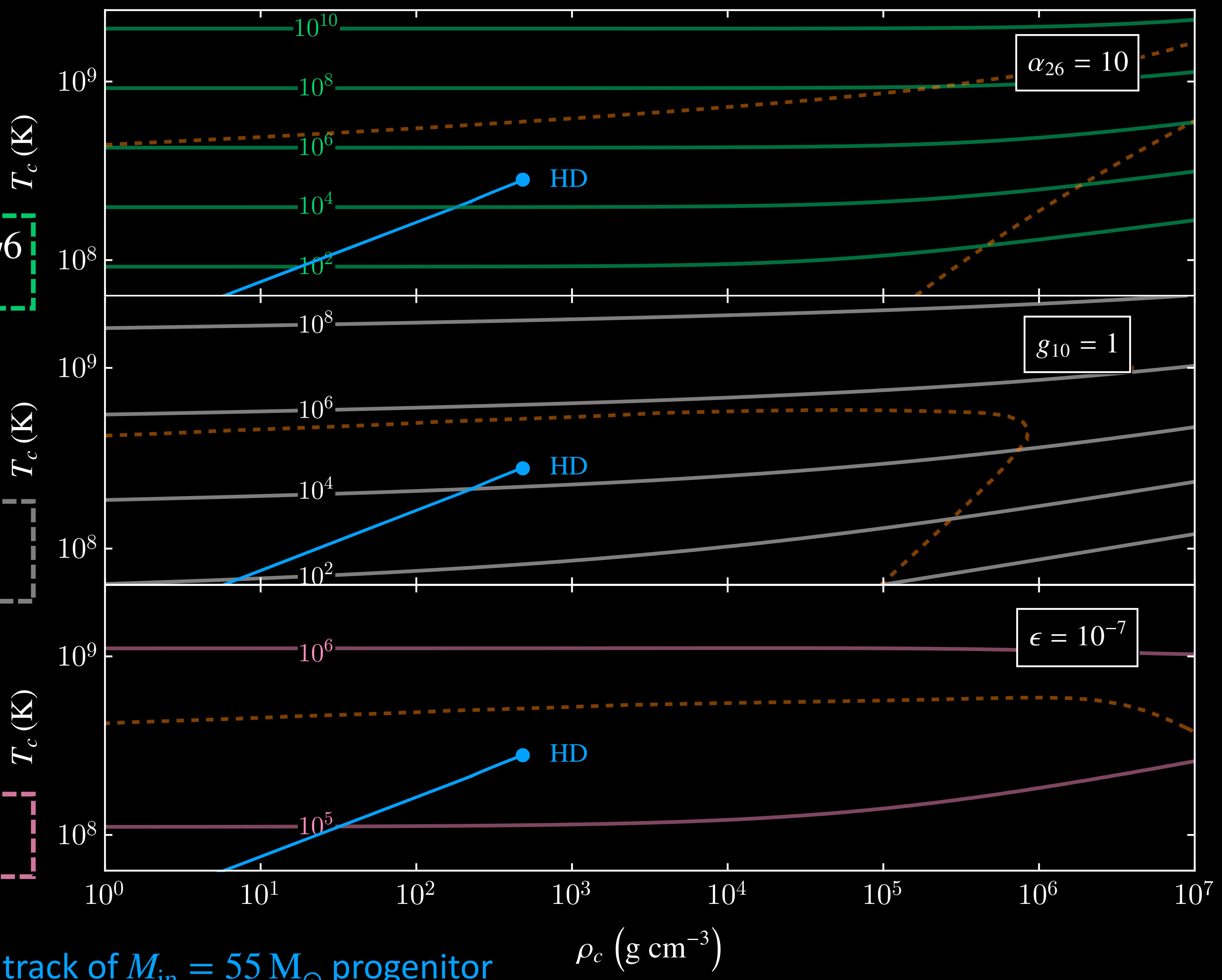
Loss rates

Electrophilic axion: $Q_{ae} \propto T^6$

Photophilic axion: $Q_{a\gamma} \propto T^4$

Hidden photon: $Q_{A'} \propto T$

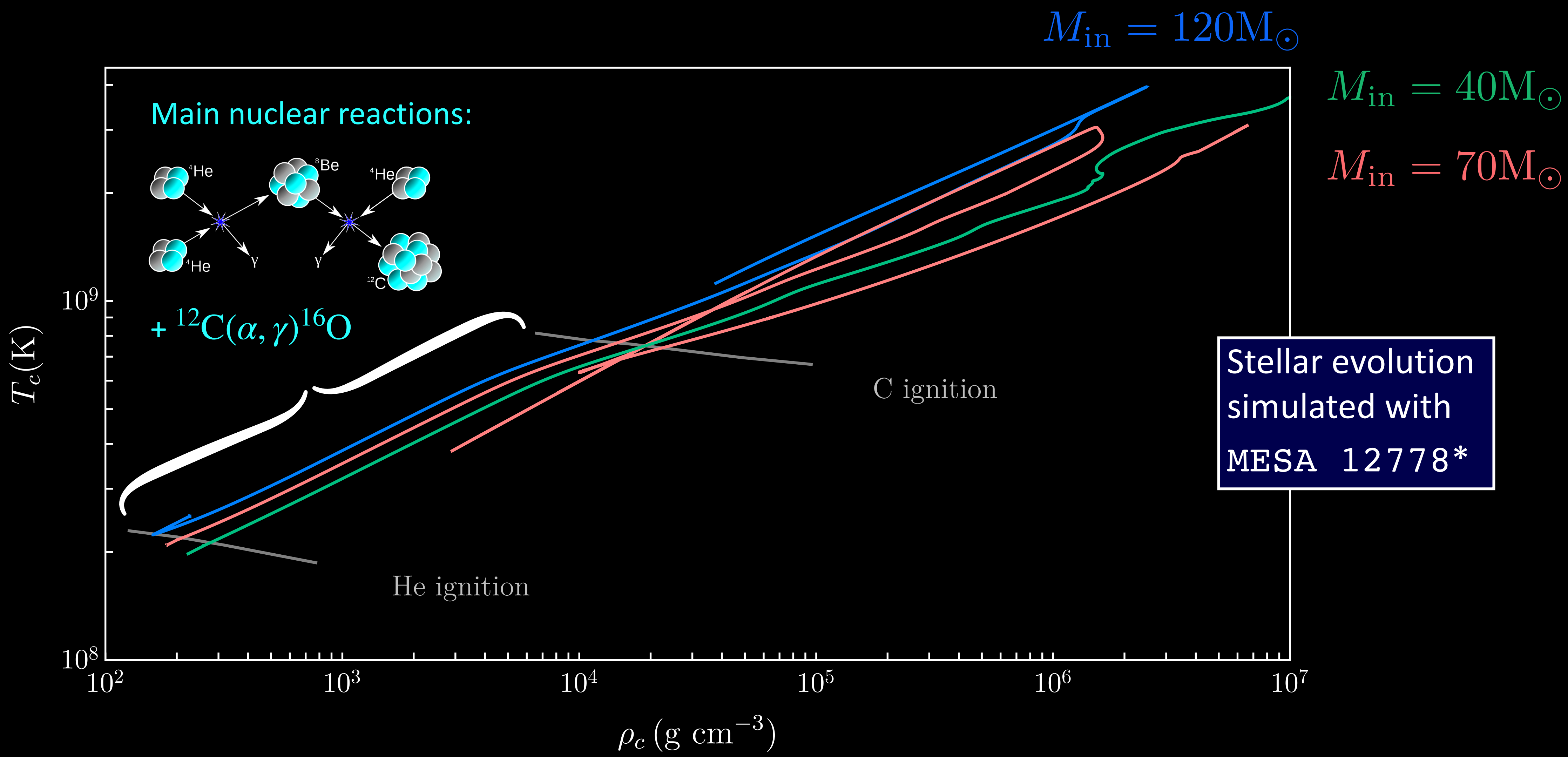
Central losses: Q_{ae}, $Q_{a\gamma}$, $Q_{A'}$ (erg g^{-1}s^{-1})



Example track of $M_{\rm in} = 55\ {\rm M}_\odot$ progenitor

Croon, McDermott, JS arXiv:2007.07889 [gr-qc]

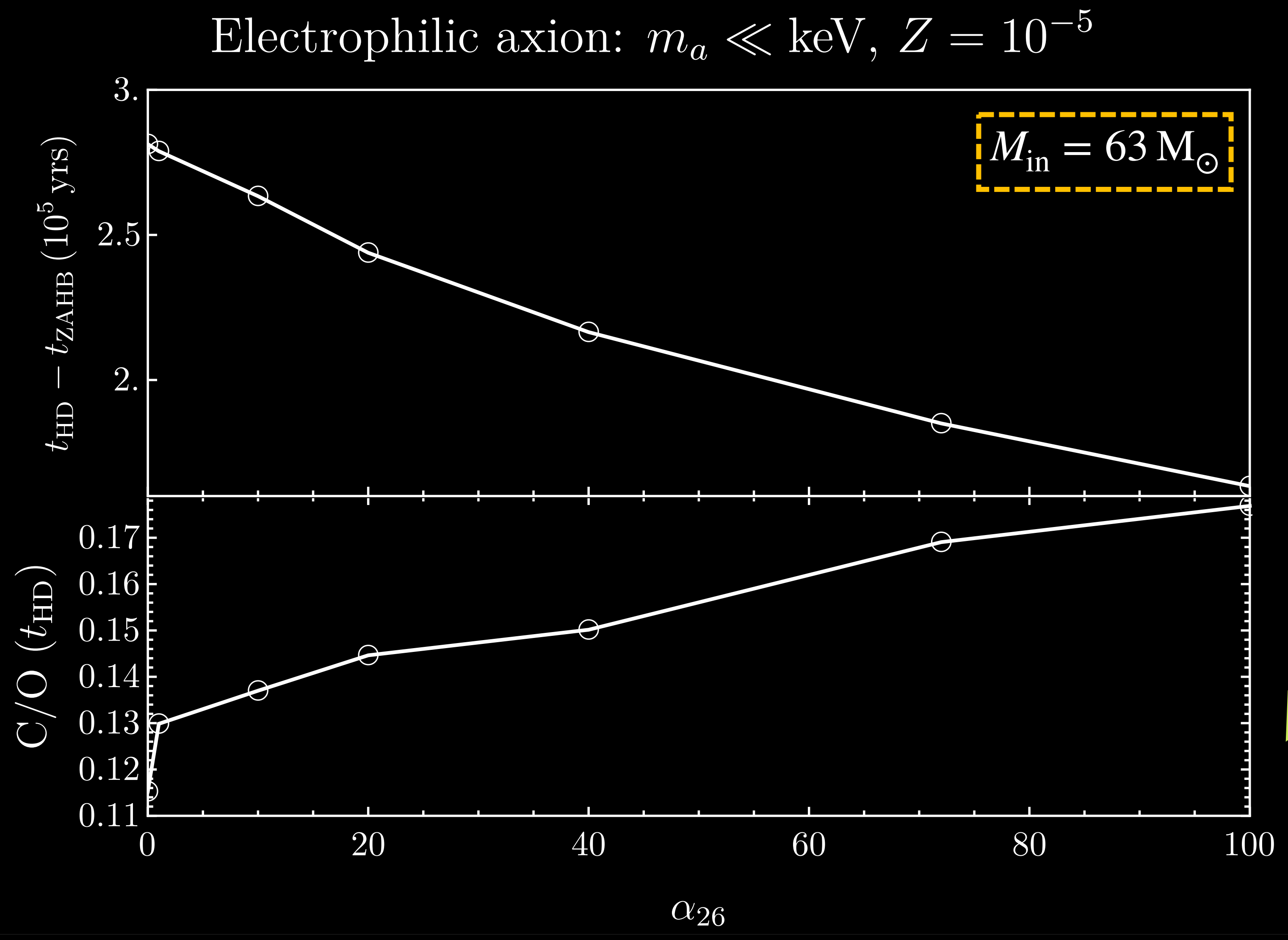
Evolution of old population-III stars



Stellar evolution simulated with MESA 12778*

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

What does the extra energy loss do?



Greater energy losses lead to *shorter He-burning phases*

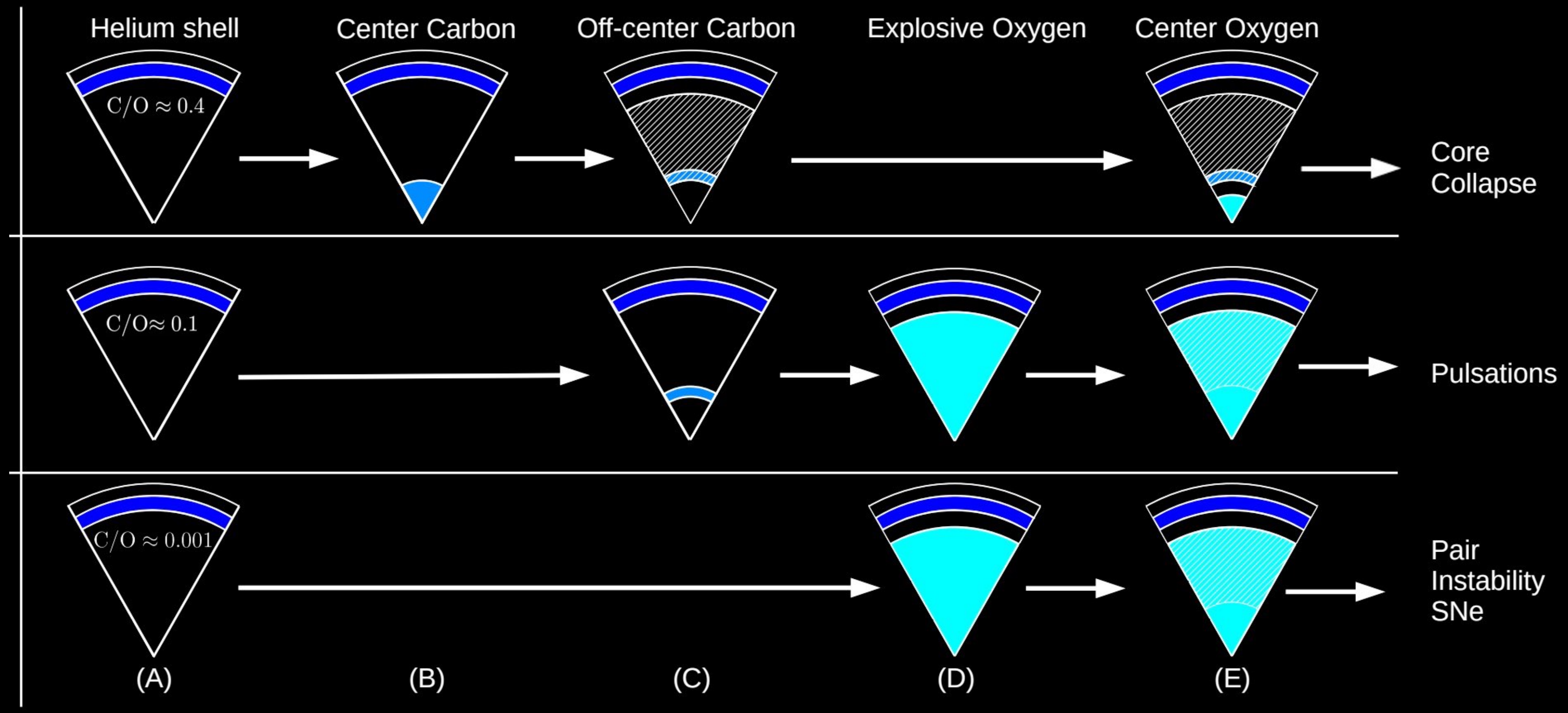
Extra dissipation scales linearly with α_{26}

Less time for $^{12}C(\alpha,\gamma)^{16}O$: *C/O is larger* at the time of helium depletion (HD)

The BHMG and new physics

Helium burning
Carbon burning
Oxygen burning

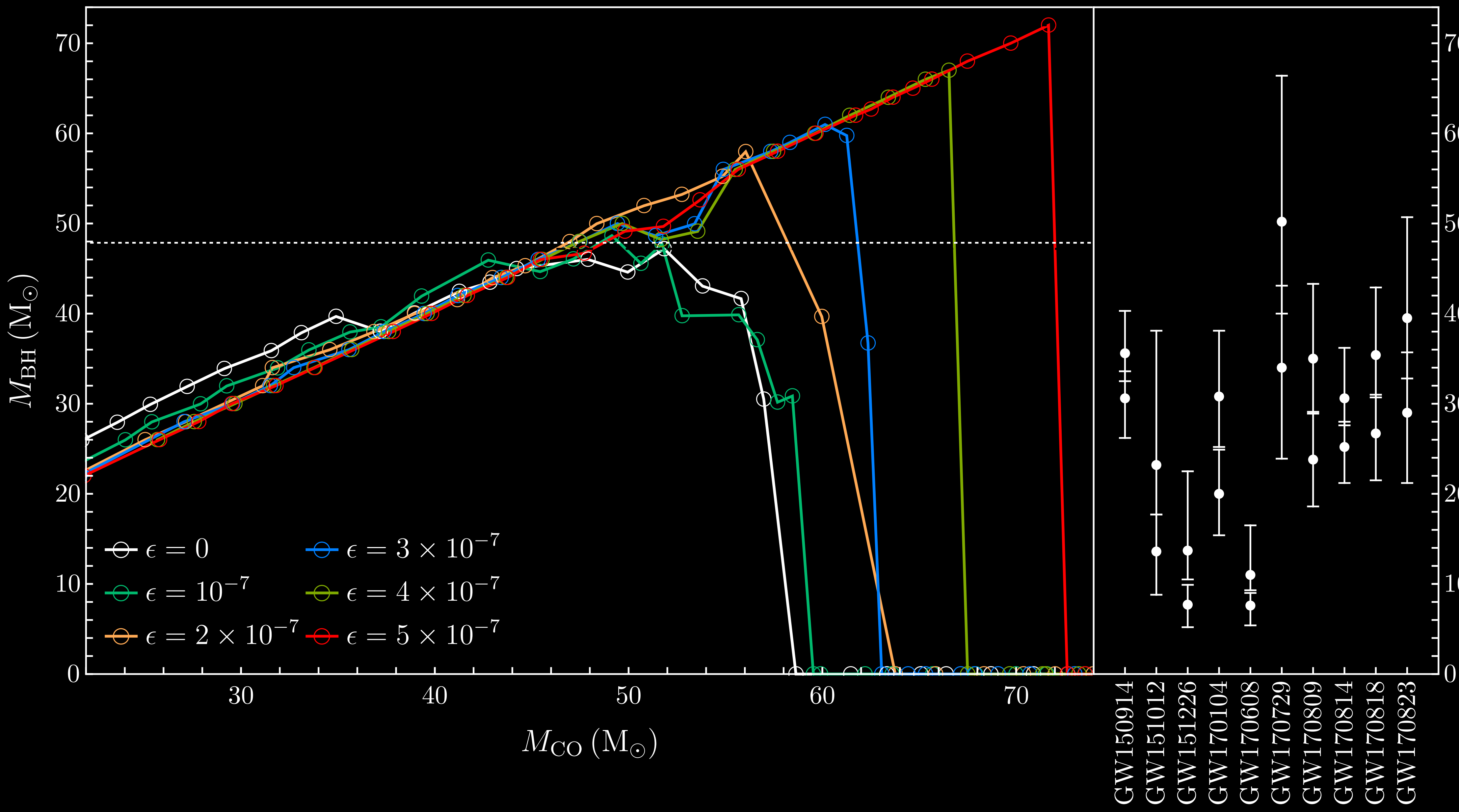
Enhanced losses, larger C/O at HD →



Adapted from Farmer, Renzo, de Mink, Fishbach, Justham [2006.06678]

Enhanced losses → greater progenitors collapse → larger black holes

Hidden photon: $m_{A'} = 10^{-2}$eV, $Z = 10^{-5}$



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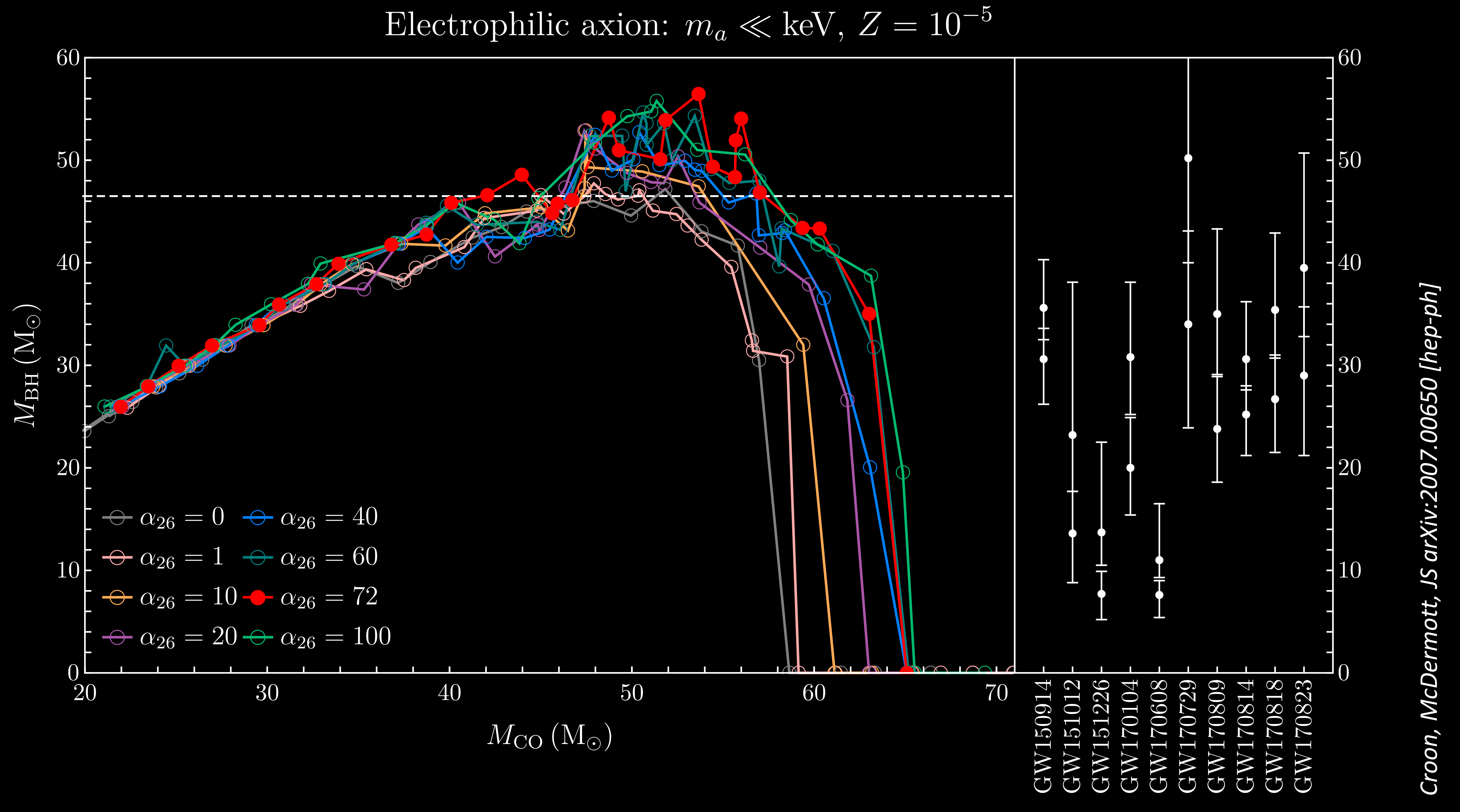
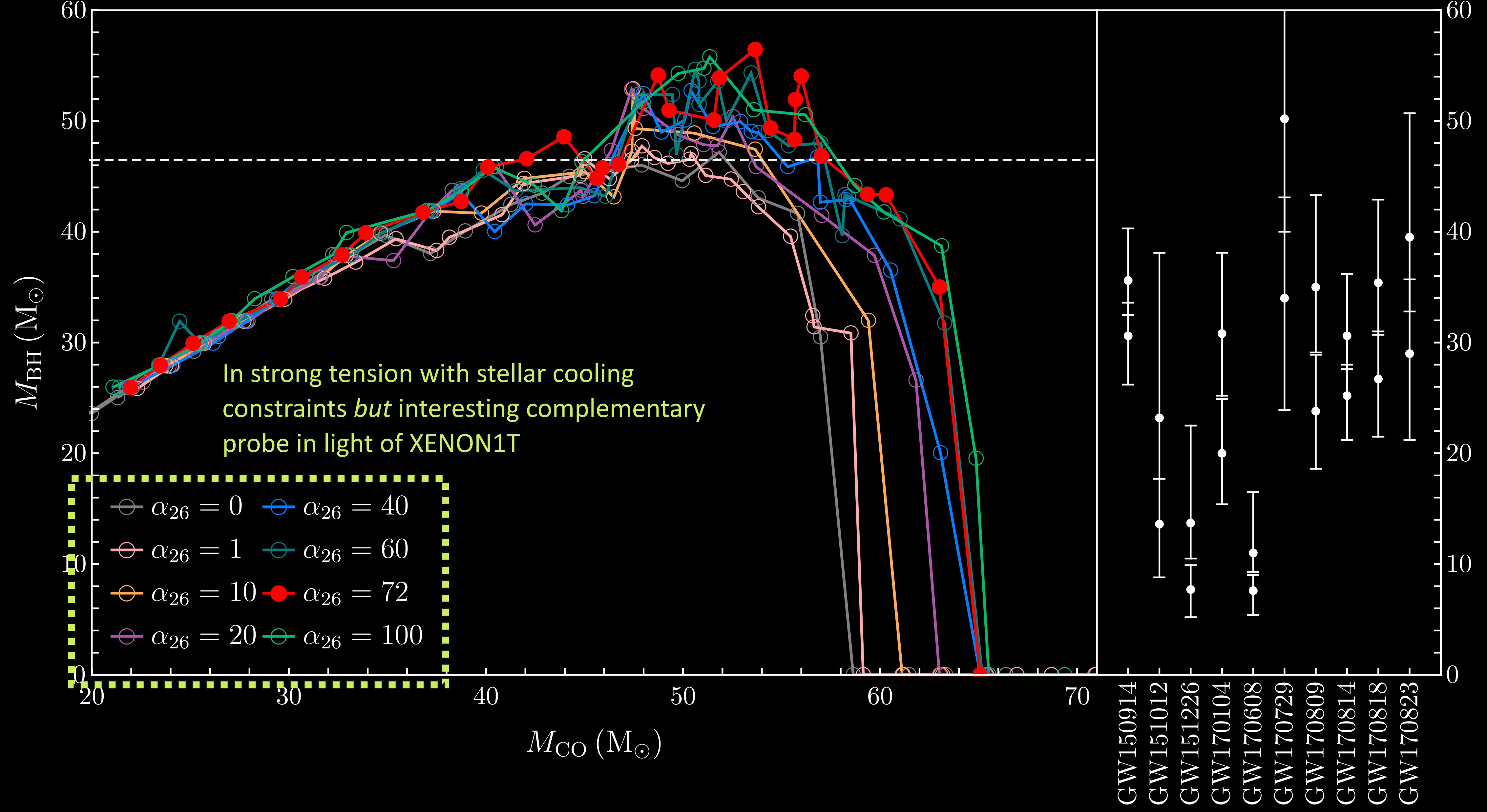

Electrophilic axion: $m_a \ll$ keV, $Z = 10^{-5}$
$M_{\rm BH}$ ($M_\odot$)
$M_{\rm CO}$ ($M_\odot$)
$\alpha_{26} = 0$
$\alpha_{26} = 1$
$\alpha_{26} = 10$
$\alpha_{26} = 20$
$\alpha_{26} = 40$
$\alpha_{26} = 60$
$\alpha_{26} = 72$
$\alpha_{26} = 100$
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
Croon, McDermott, JS arXiv:2007.00650 [hep-ph]

Electrophilic axion: $m_a \ll \text{keV},\ Z = 10^{-5}$



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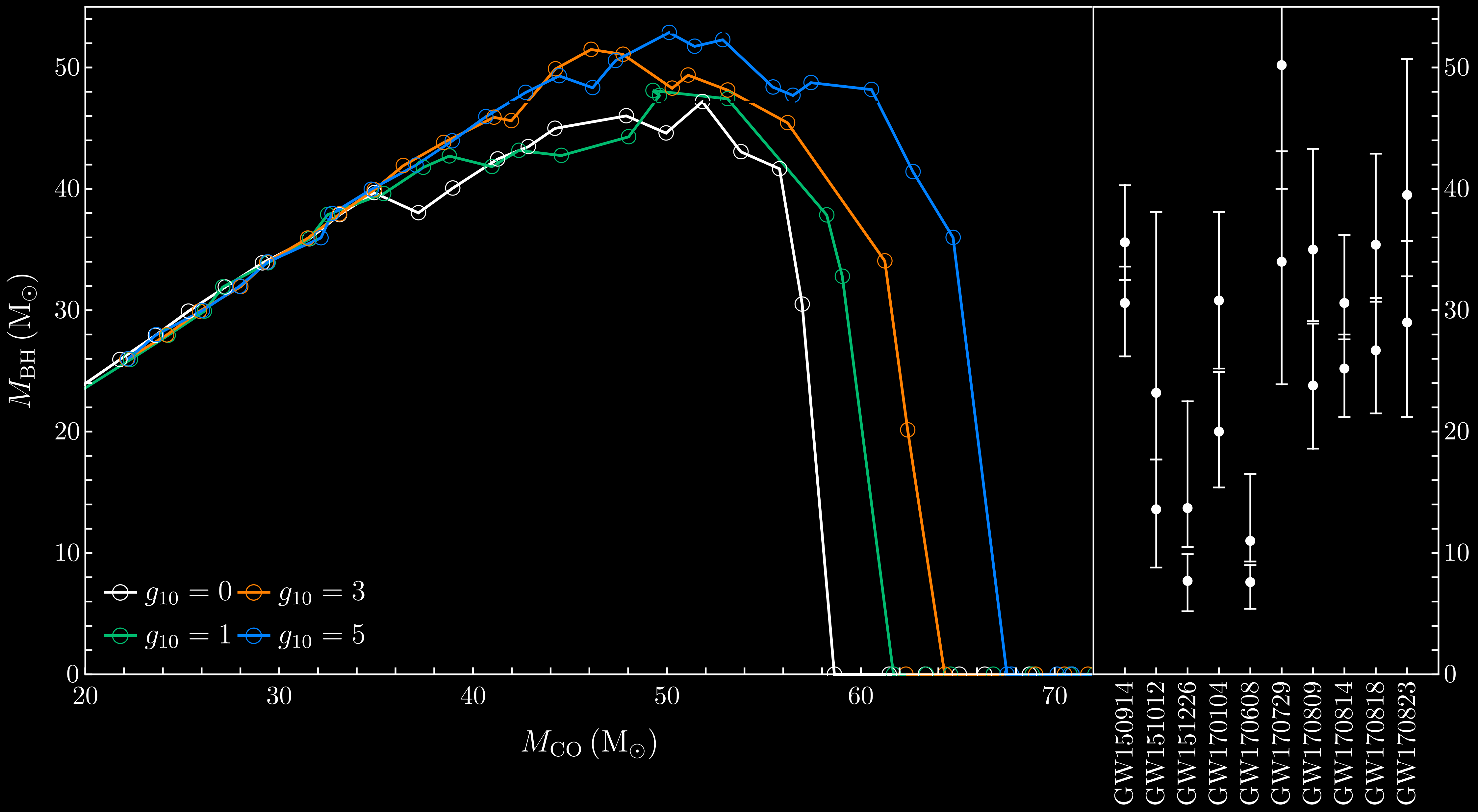

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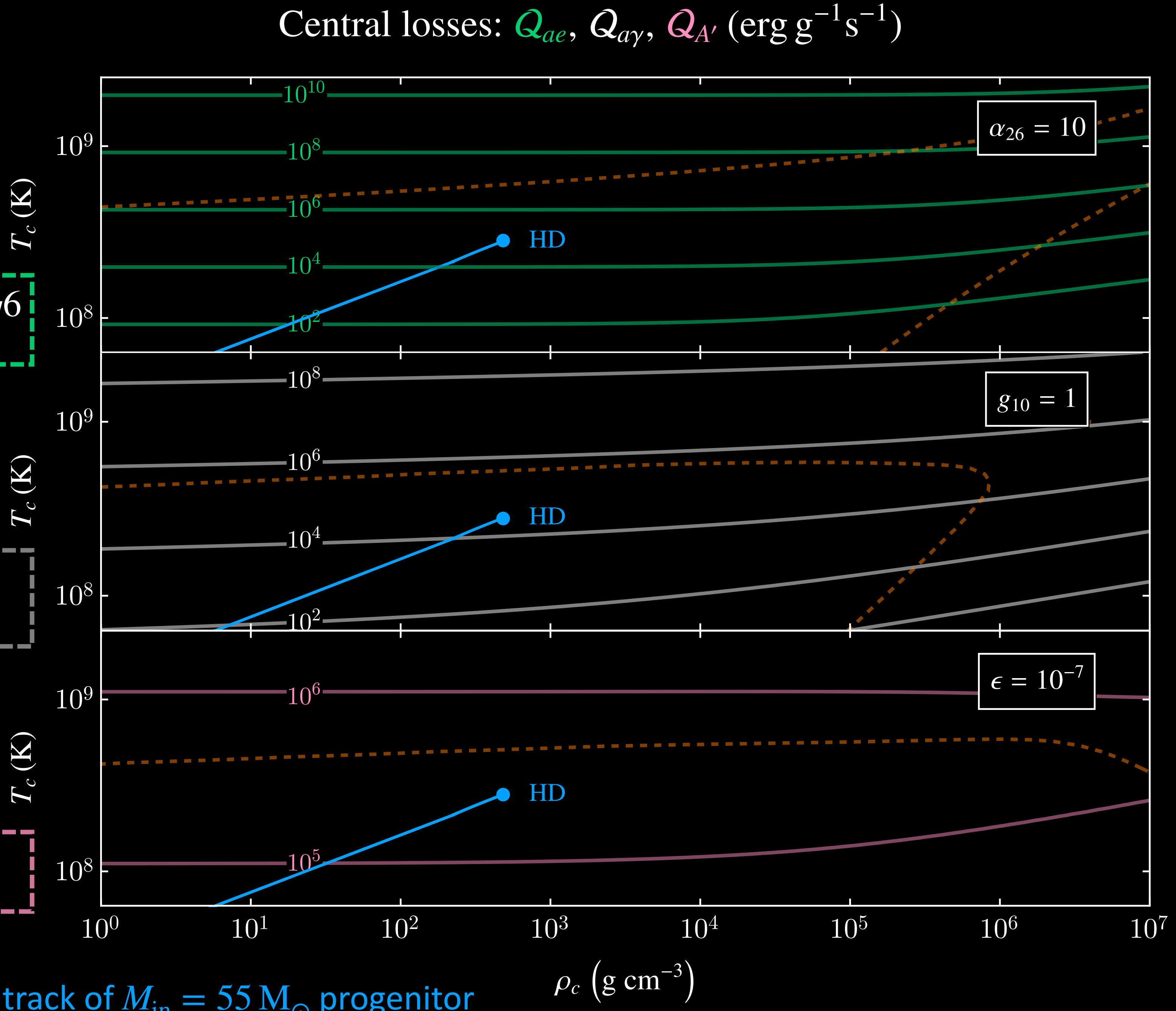

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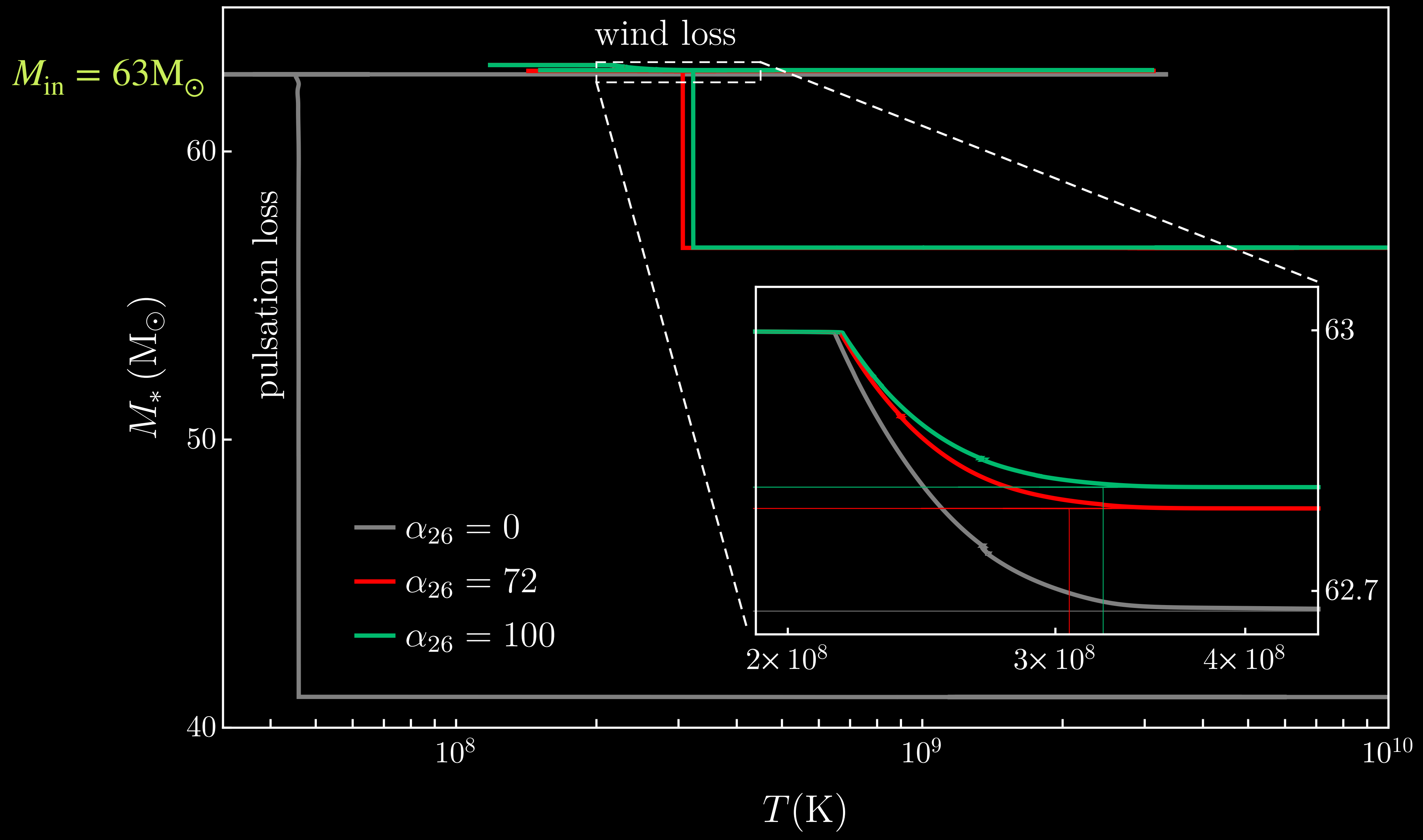
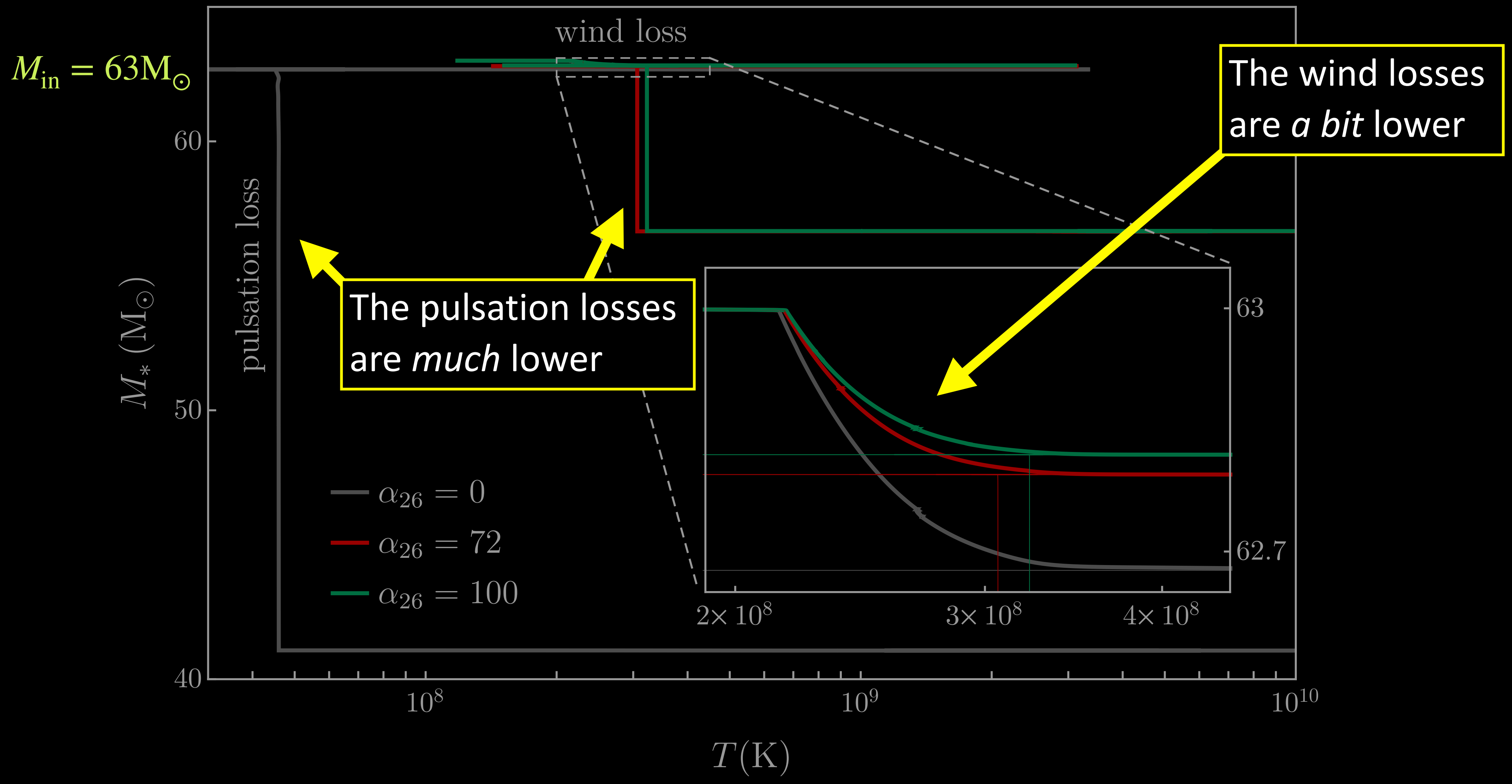
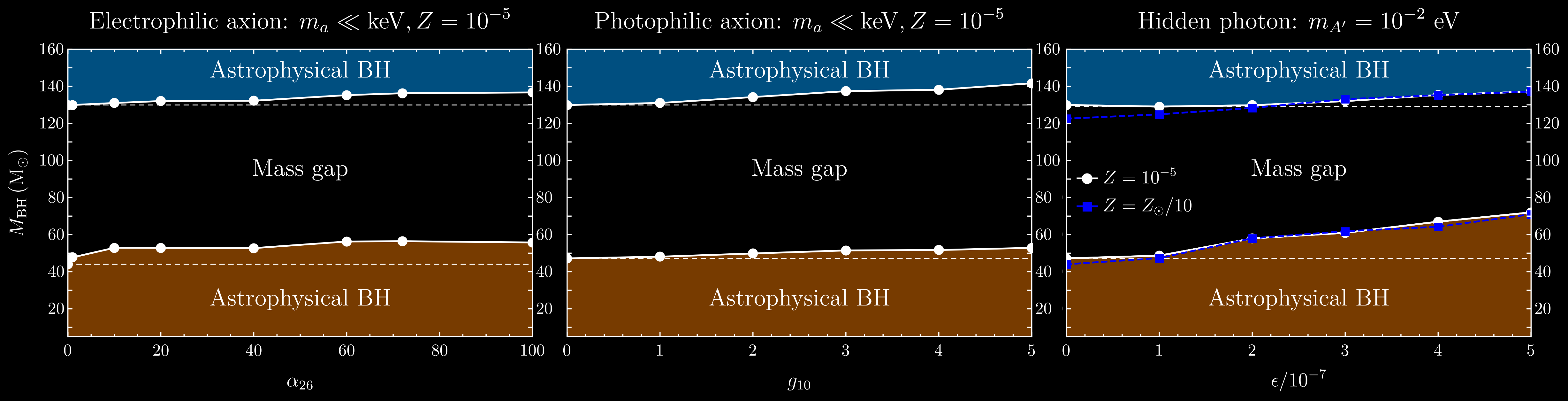
Implications of enhanced losses



Implications of enhanced losses



New physics and the black hole mass gap



$\mathcal{Q}_{ae} \propto T^6$

$\mathcal{Q}_{a\gamma} \propto T^4$

$\mathcal{Q}_{A'} \propto T$

Potentially large shifts of the mass gap!

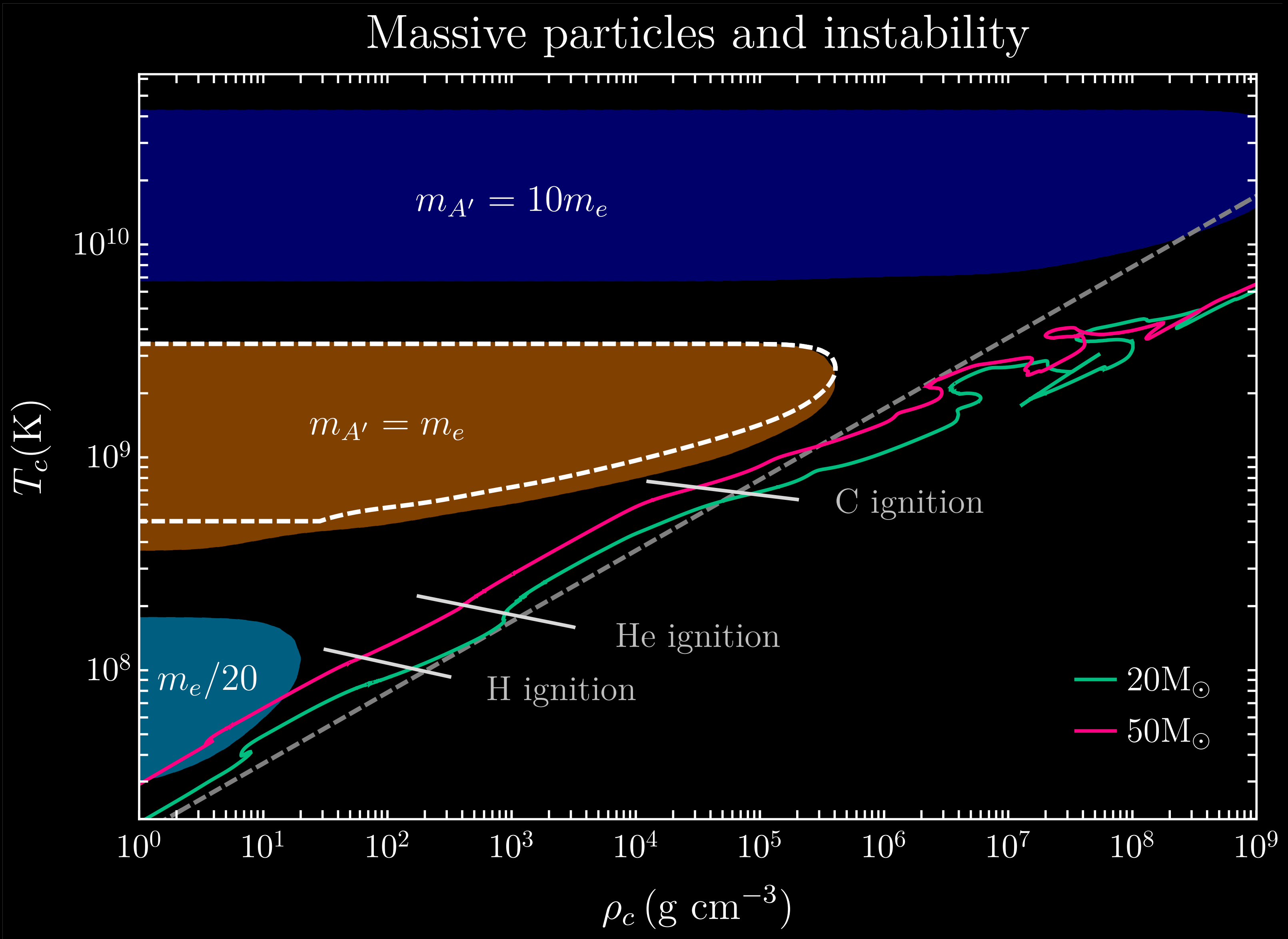
Croon, McDermott, JS arXiv:2007.07889 [gr-qc]

Heavier degrees of freedom?

Heavier degrees of freedom may instead be thermalized in the core

Then, they may give rise to an instability in the same way that electron-positron pairs do

Equilibration time (vector):
$t_{A'} \simeq \Gamma_{A'}^{-1} \simeq \left(\epsilon^2 \sigma_T n_e e^{-m_{A'}/T_c}\right)^{-1}$
so for $\epsilon = 3 \times 10^{-12}$, we find $t_{A'} \simeq 10^5$ years, a timescale similar to the lifetime of helium burning



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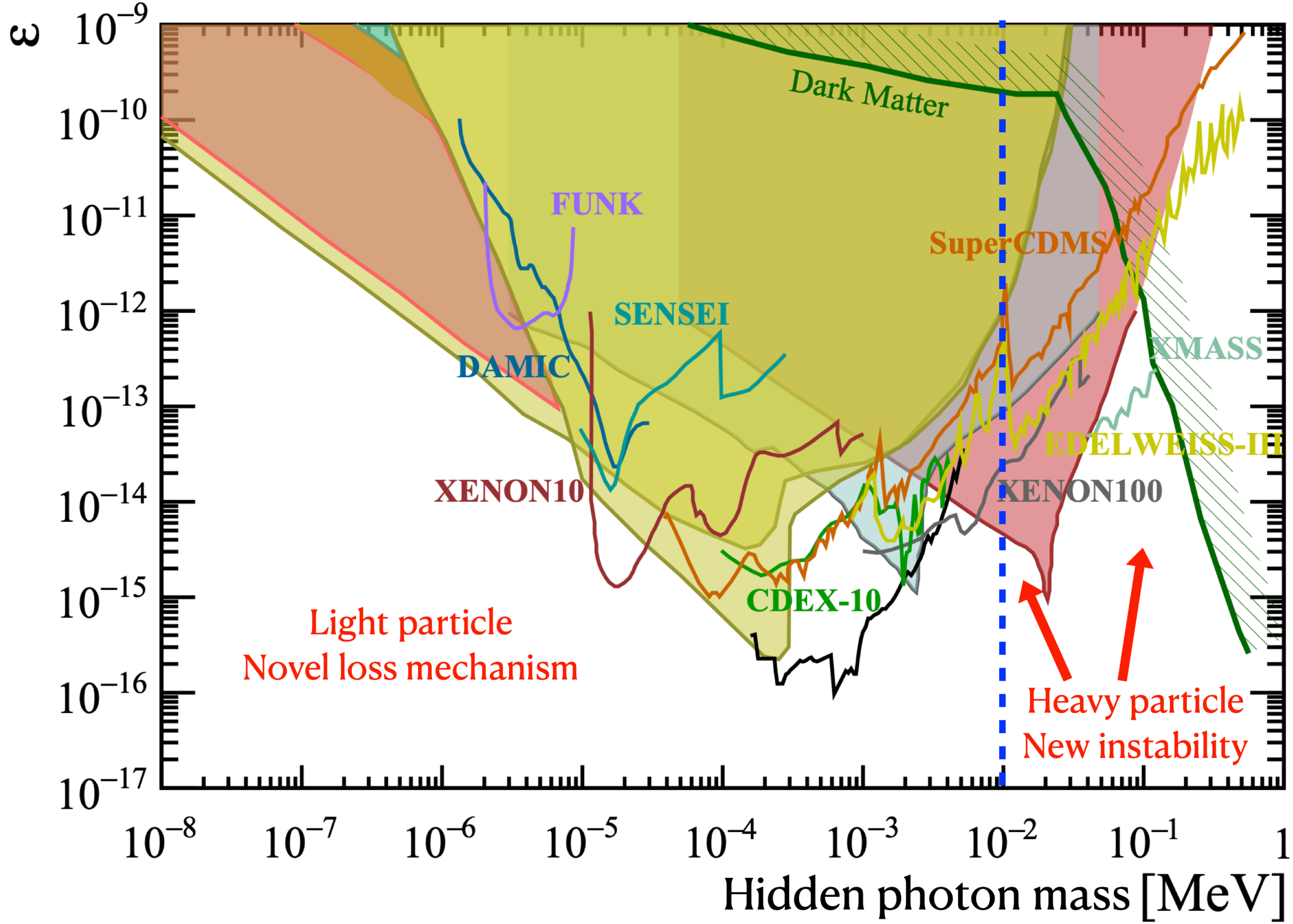

ε
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
Dark Matter
FUNK
SENSEI
DAMIC
XENON10
SuperCDMS
XMASS
EDELWEISS-III
XENON100
CDEX-10
Light particle
Novel loss mechanism
Heavy particle
New instability
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Hidden photon mass [MeV]

The BHMG and new physics

Sakstein, DC, McDermott, Straight, Baxter arXiv:2009.01213 [gr-qc]

Straight, JS, Baxter 2009.10716 [gr-qc]

- Scenario 2: screened modified gravity (MG)
- Cosmic acceleration may be driven by large scale modifications of gravity
- Theories need to include screening mechanisms to satisfy solar system bounds
- Examples: chameleon, DHOST, dark matter—baryon interactions

The BHMG and new physics

Sakstein, DC, McDermott, Straight, Baxter arXiv:2009.01213 [gr-qc]

Straight, JS, Baxter 2009.10716 [gr-qc]

- Scenario 2: screened modified gravity (MG)
- Unscreened galaxies: $F = \left(1 + \frac{\Delta G}{G_{\mathrm{N}}}\right)\frac{G_{\mathrm{N}} M}{r^2}$

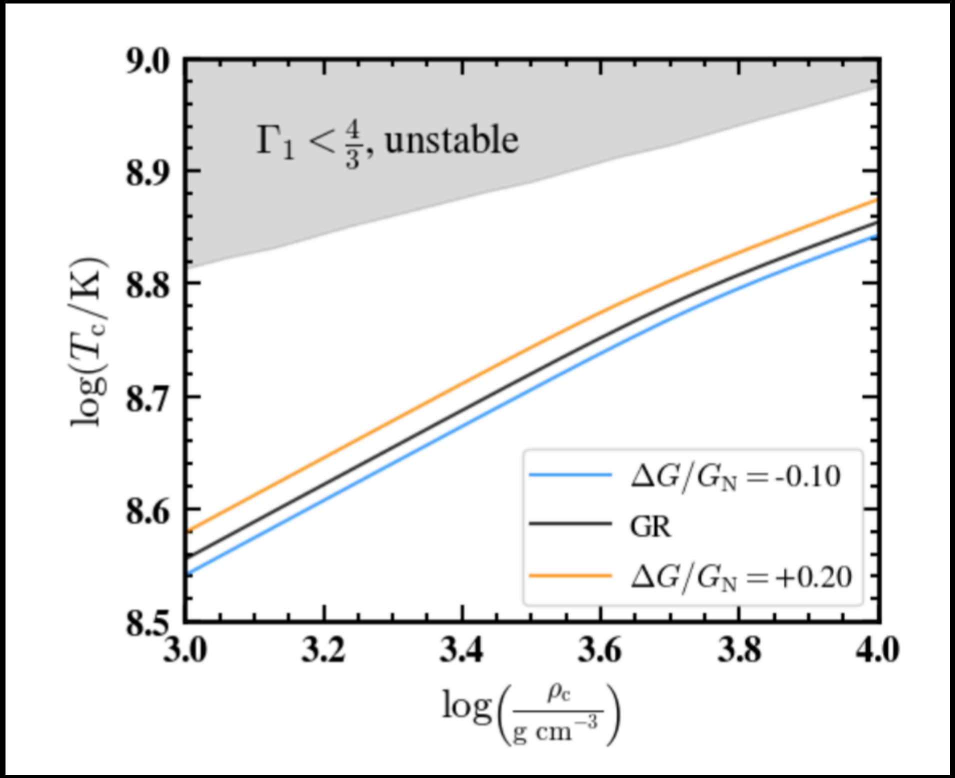
Environment-dependent
Value depends on galaxy, level of screening, and theory
=0 in screened galaxies

- Screening of galaxies depends on theory
- Need screening maps to determine screening level
- Extra complication that is the subject of ongoing work

Straight, JS, Baxter 2009.10716 [gr-qc]

The BHMG and new physics

- Scenario 2: screened modified gravity (MG)
- Increased local strength of gravity → need larger pressure gradient to maintain hydrostatic equilibrium → larger core temperature at fixed density
- Pair instability is exacerbated
  →Lighter black holes
- Decreased local strength of gravity works in reverse
  → Heavier black holes



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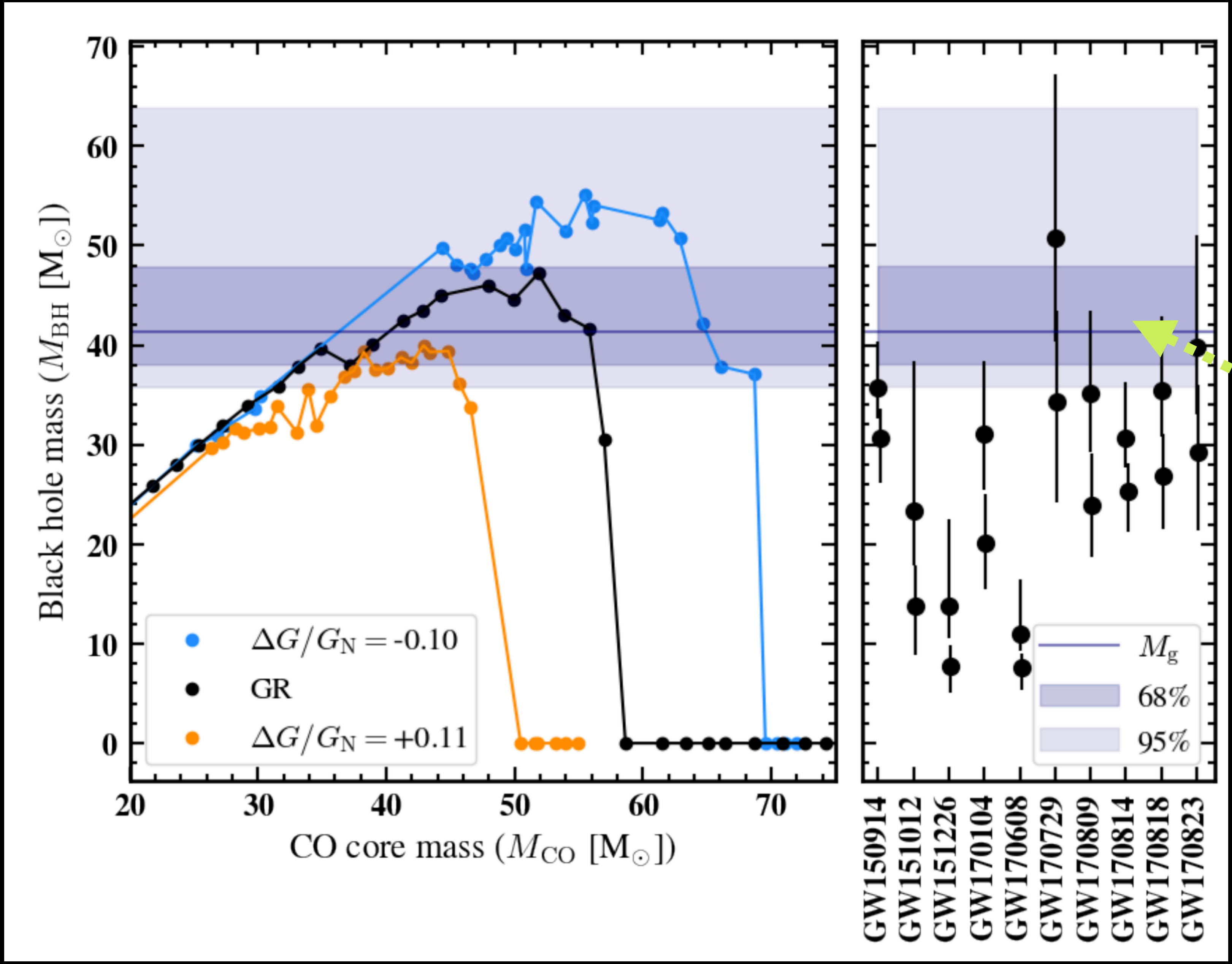
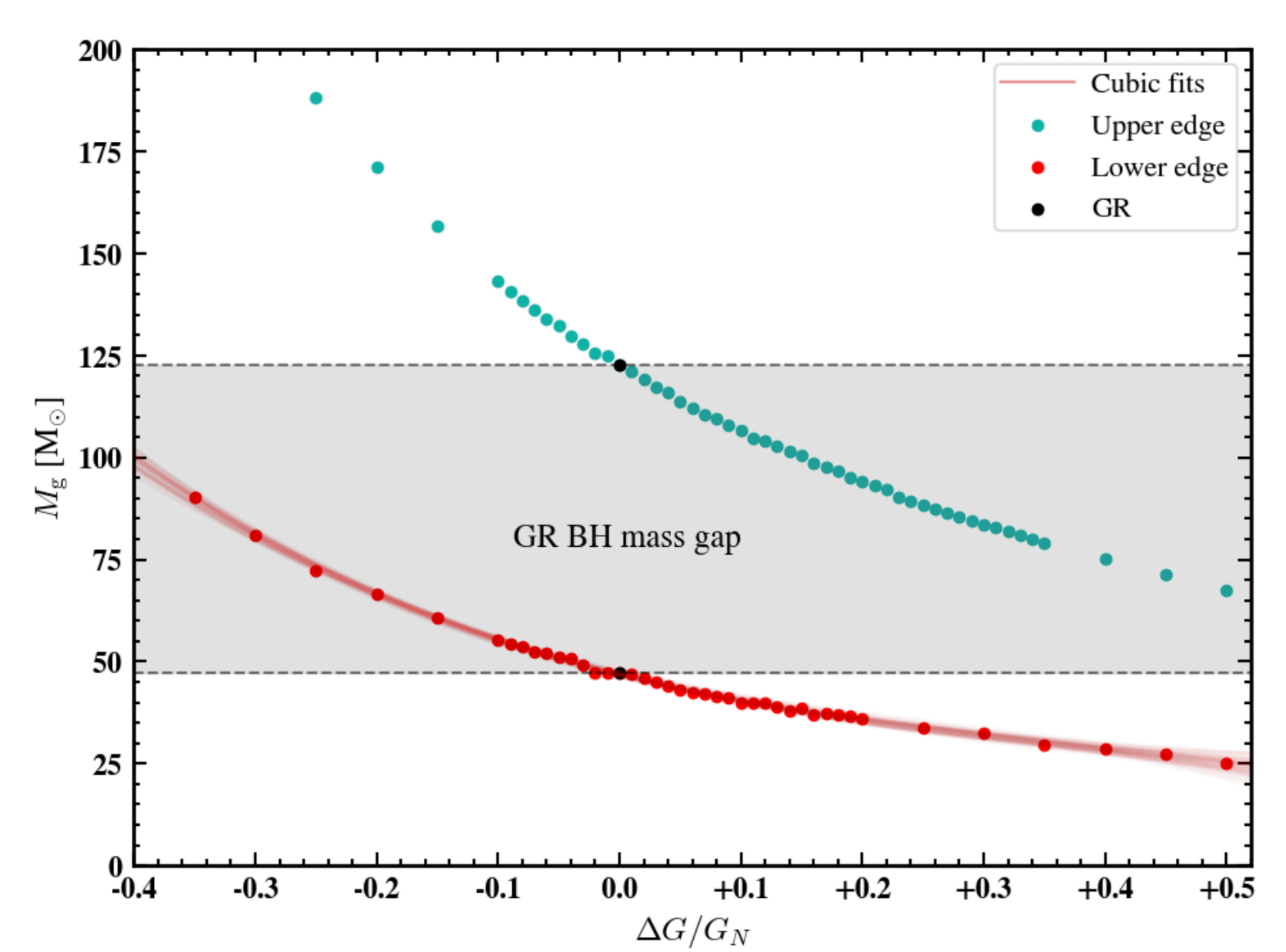


LIGO/Virgo confidence regions for the location of the BHMG

Straight, JS, Baxter 2009.10716 [gr-qc]

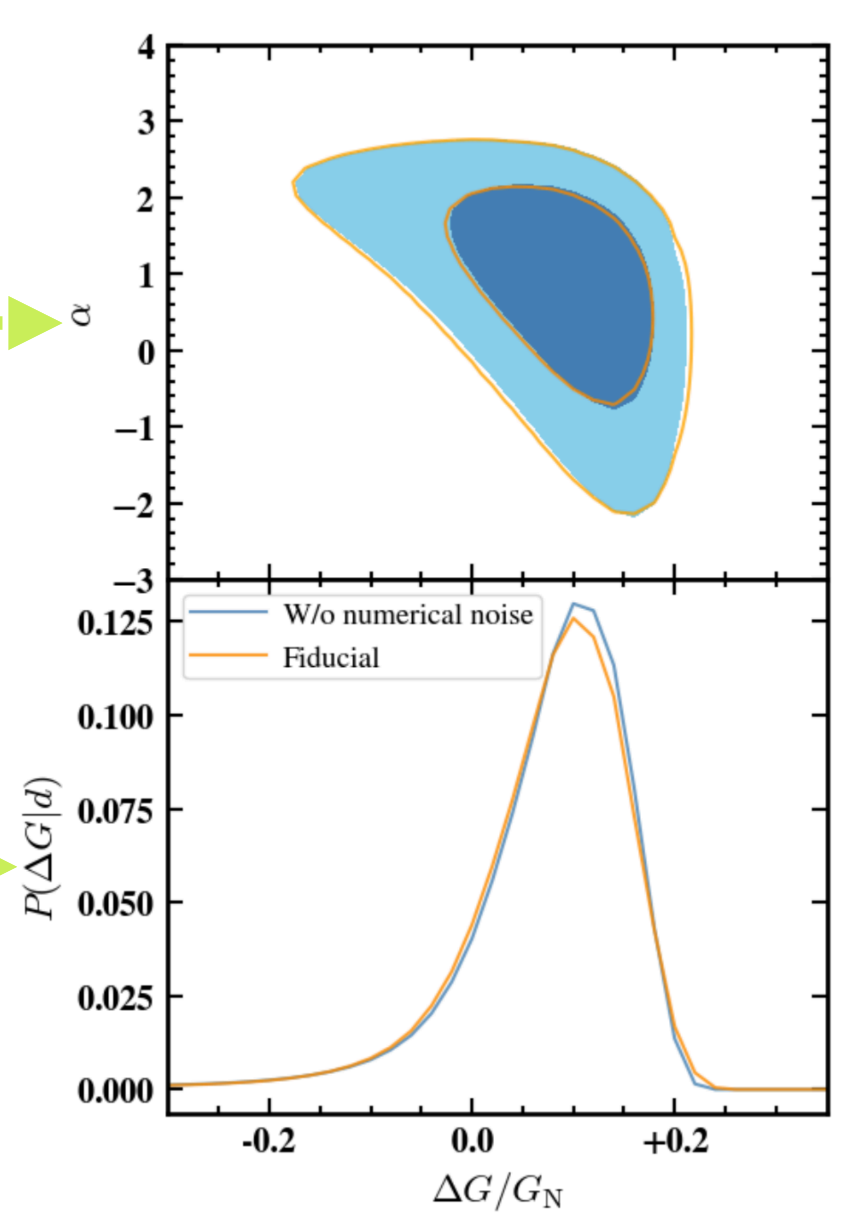


A new test of the strong equivalence principle

- Change G in stars but note black holes (no-hair theorem)
- BHMG changes but waveform doesn't
- Compare mass gap prediction with LIGO/ Virgo data
- 7% bound: $\frac{\Delta G}{G_N} = 0.1^{+0.04}_{-0.1}$

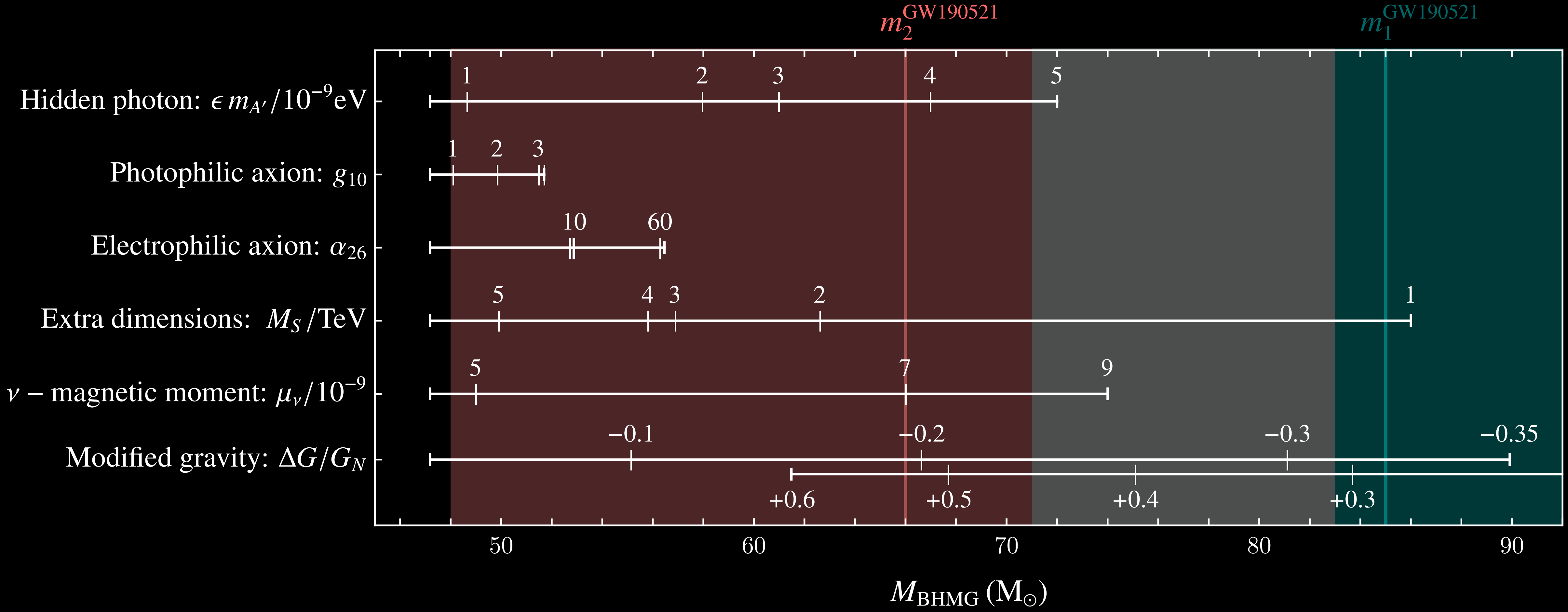
Slope of the IMF

Marginalized results using first 10 detections



GW190521, the impossible black holes

... and Beyond the Standard Model physics

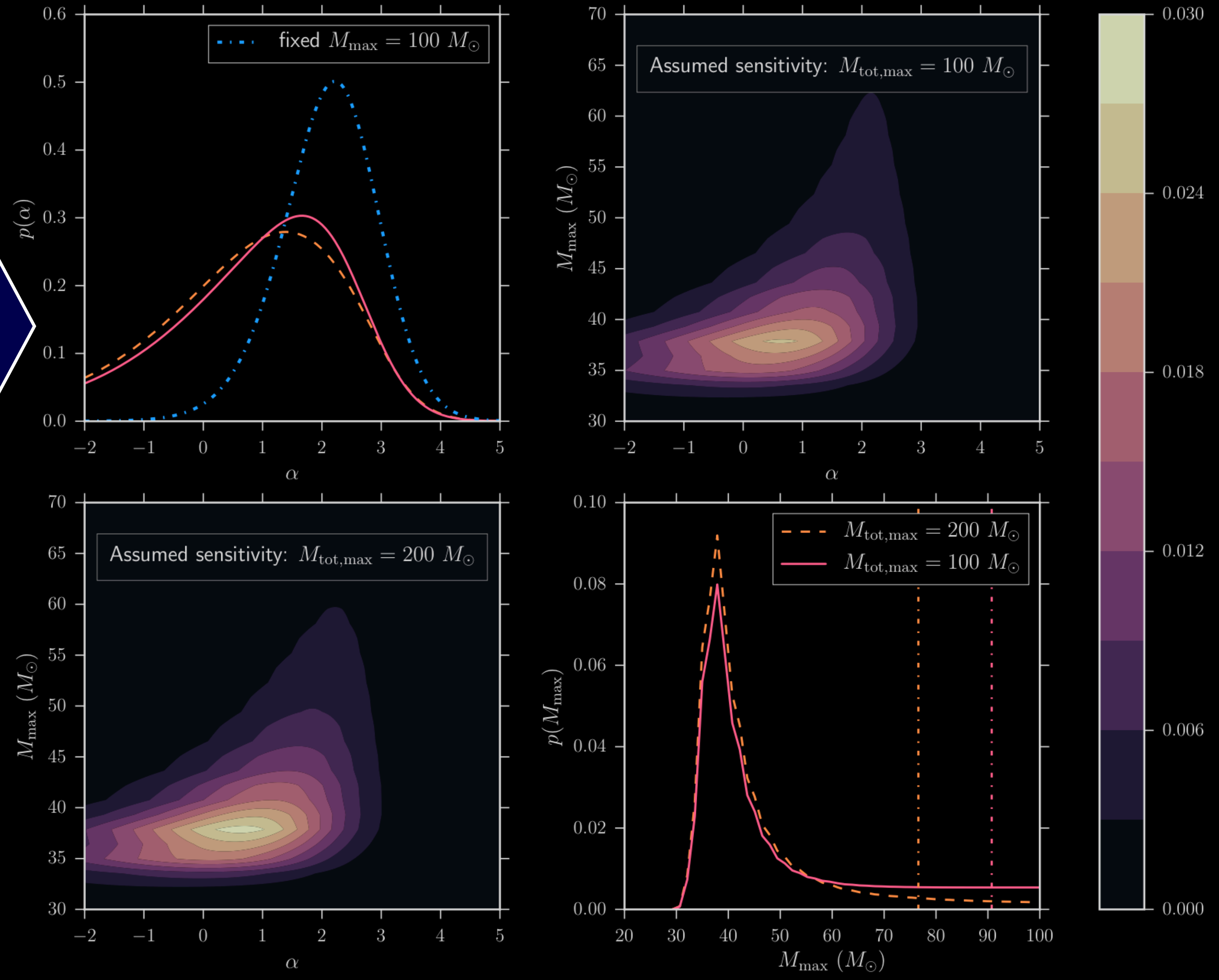


JS, Croon, McDermott, Straight, Baxter arXiv:2009.01213 [gr-qc]

Looking ahead…

Posterior PDFs using the first 4 BBH mergers, and assuming a power law mass distribution, $p(m_1\,|\,\alpha) \propto m_1^{-\alpha}$

With the complete O3 data set (and beyond), the field of *black hole population studies* will really take off!



from Fishbach & Holz, arXiv:1709.08584 [astro.ph]

To conclude,

- Gravitational waves offer an exciting new opportunity to study open questions in particle astrophysics and cosmology

- Binary mergers allow for black hole population studies

- The black hole mass gap is an exciting probe of new physics, which will come into focus in the next few years

- GW190521 constitutes an intriguing puzzle which could be (partially) explained by BSM physics

Thank you!

sakstein@hawaii.edu | jeremysakstein.com

Slide credit: Djuna Croon

Large black hole in LB-1?

- Last year, a $70\,\mathrm{M}_{\odot}$ black hole was reported in a binary with a high-metallicity smaller star (from the radial velocity variability of the $H\alpha$ emission line, suggesting an accretion disk)
- It was suggested (1911.12357) that it was formed due to the core-collapse of a high metallicity progenitor with reduced stellar winds
- However, those simulations did not include pulsations (they were stopped at carbon burning)
- The observation has since also been disputed (1912.04185 and 1912.03599) - apparent shifts instead originate from shifts in the luminous star's $H\alpha$ absorption line