New physics and the Black Hole Mass Gap

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IPPP seminar, December 2020

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GW190521

The New York Times

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

Astronomers detect super-rare type of black hole for the first time

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

NewScientist
IDEEËN DIE DE WERELD VERANDEREN

BLOGS DOSSIERS RECENSIES MAGAZINE AGENDA

Zwaartekrachtsgolven van 'te zware' zwarte gaten waargenomen

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

Latest Issues

SCIENTIFIC AMERICAN 175

LIGO and Virgo Capture Their Most Massive Black Holes Yet

Black holes: Cosmic signal rattles Earth after 7 billion years

By Jonathan Amos
BBC Science Correspondent

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

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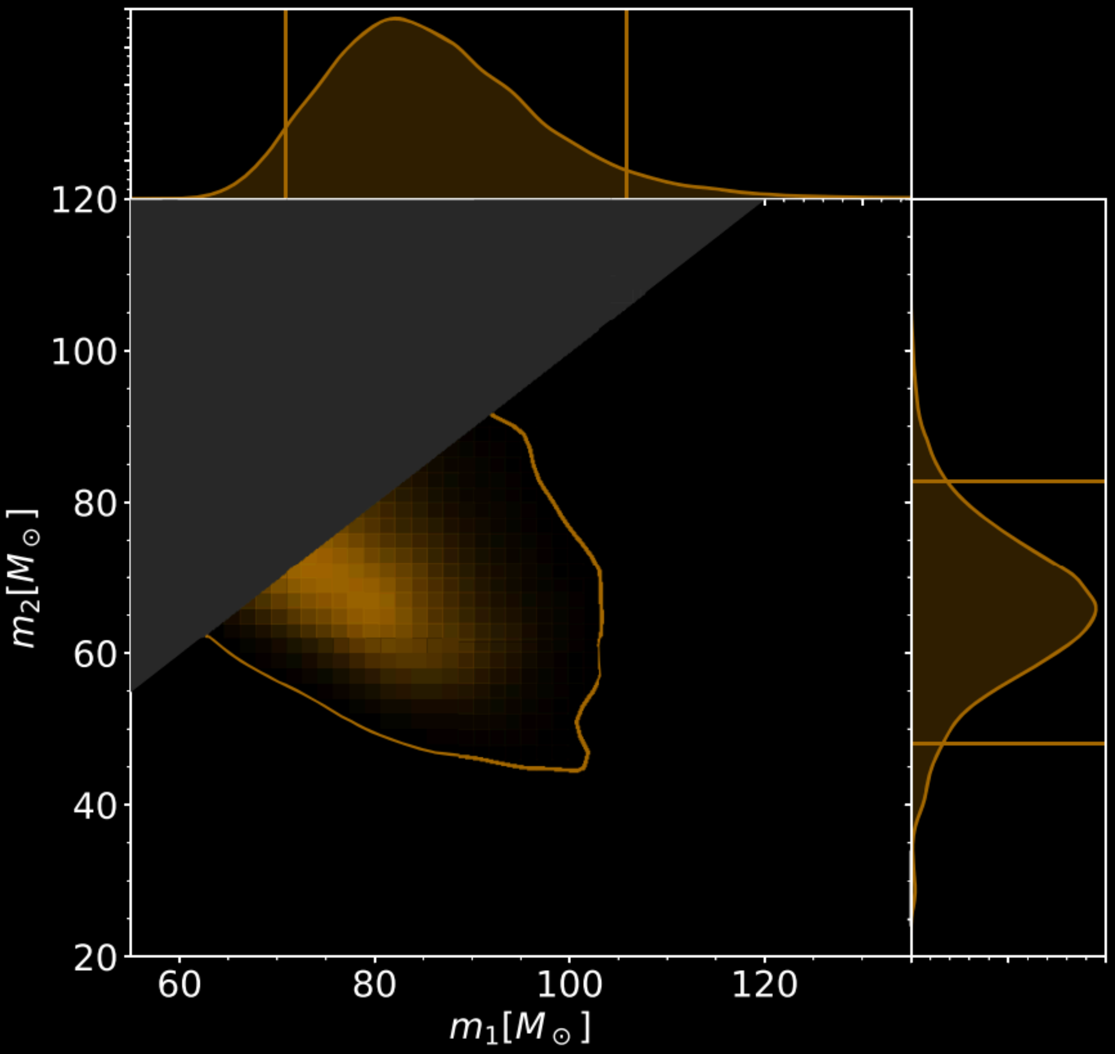

LIGO/Virgo's biggest discovery yet: the *impossible* black holes

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

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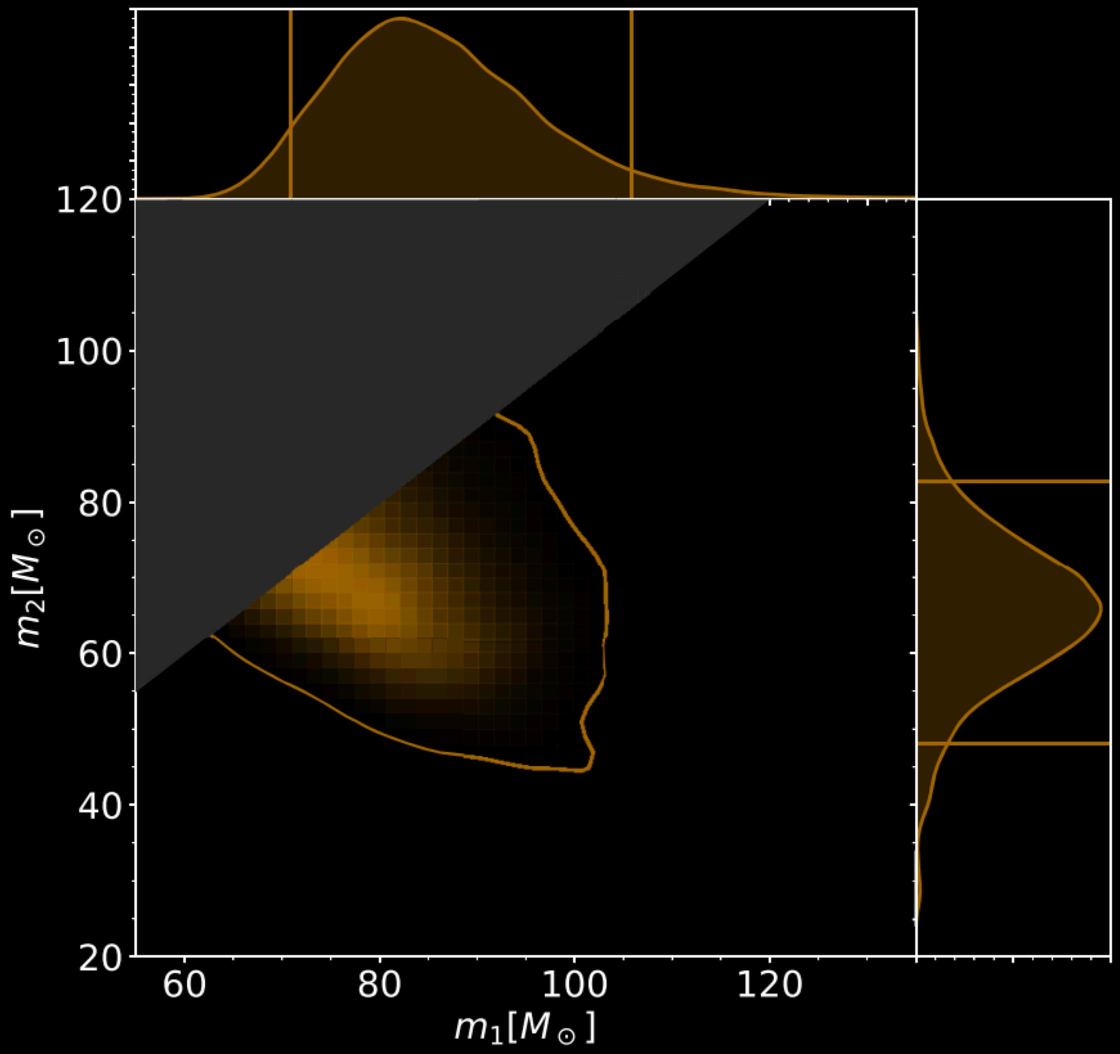


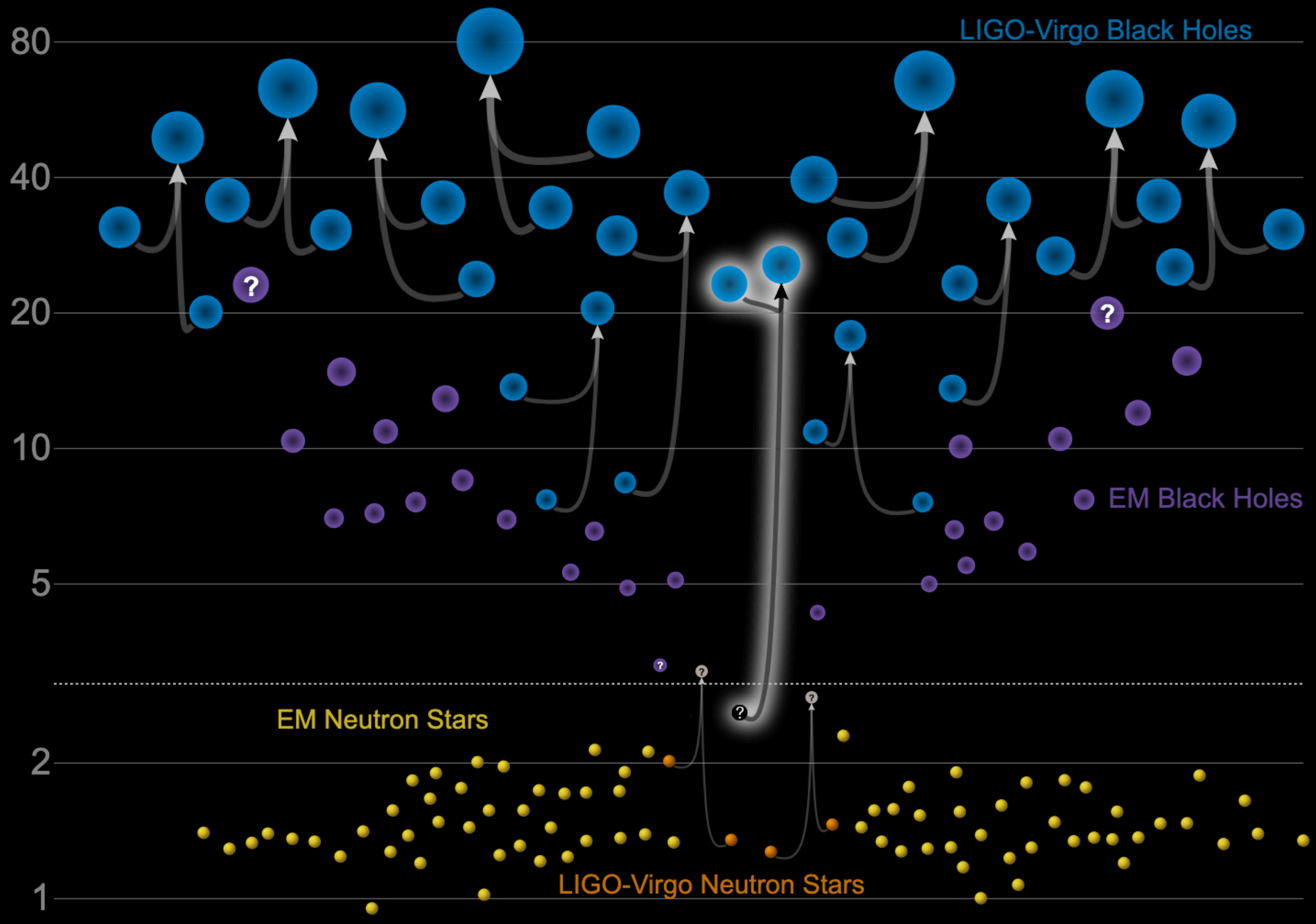
LIGO/Virgo's biggest discovery yet: the *impossible* black holes

… let's wind back a bit

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

Binary mergers in LIGO/Virgo O1+O2

"The Stellar Graveyard"



Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

Binary mergers in LIGO/Virgo O1+O2

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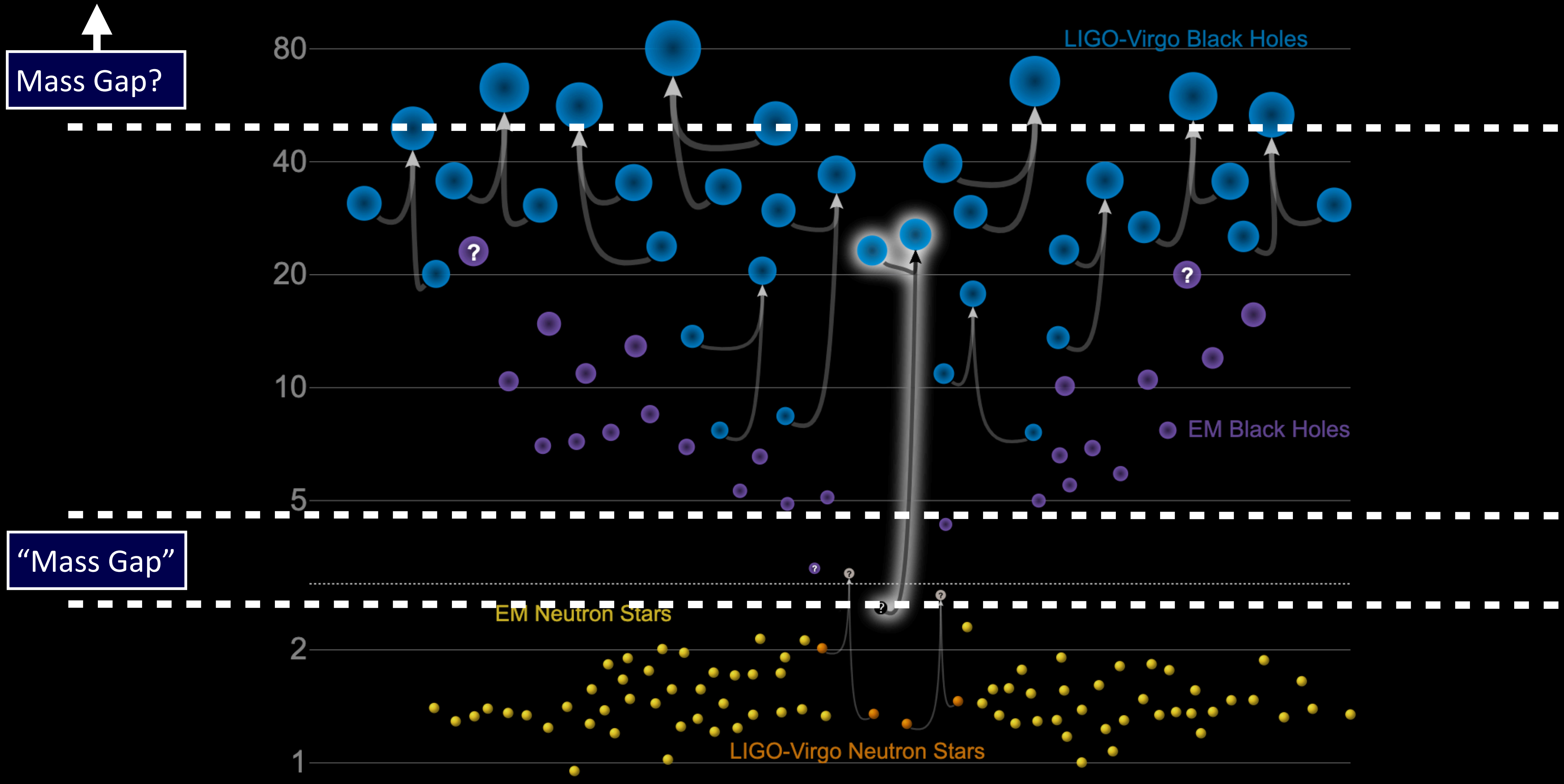

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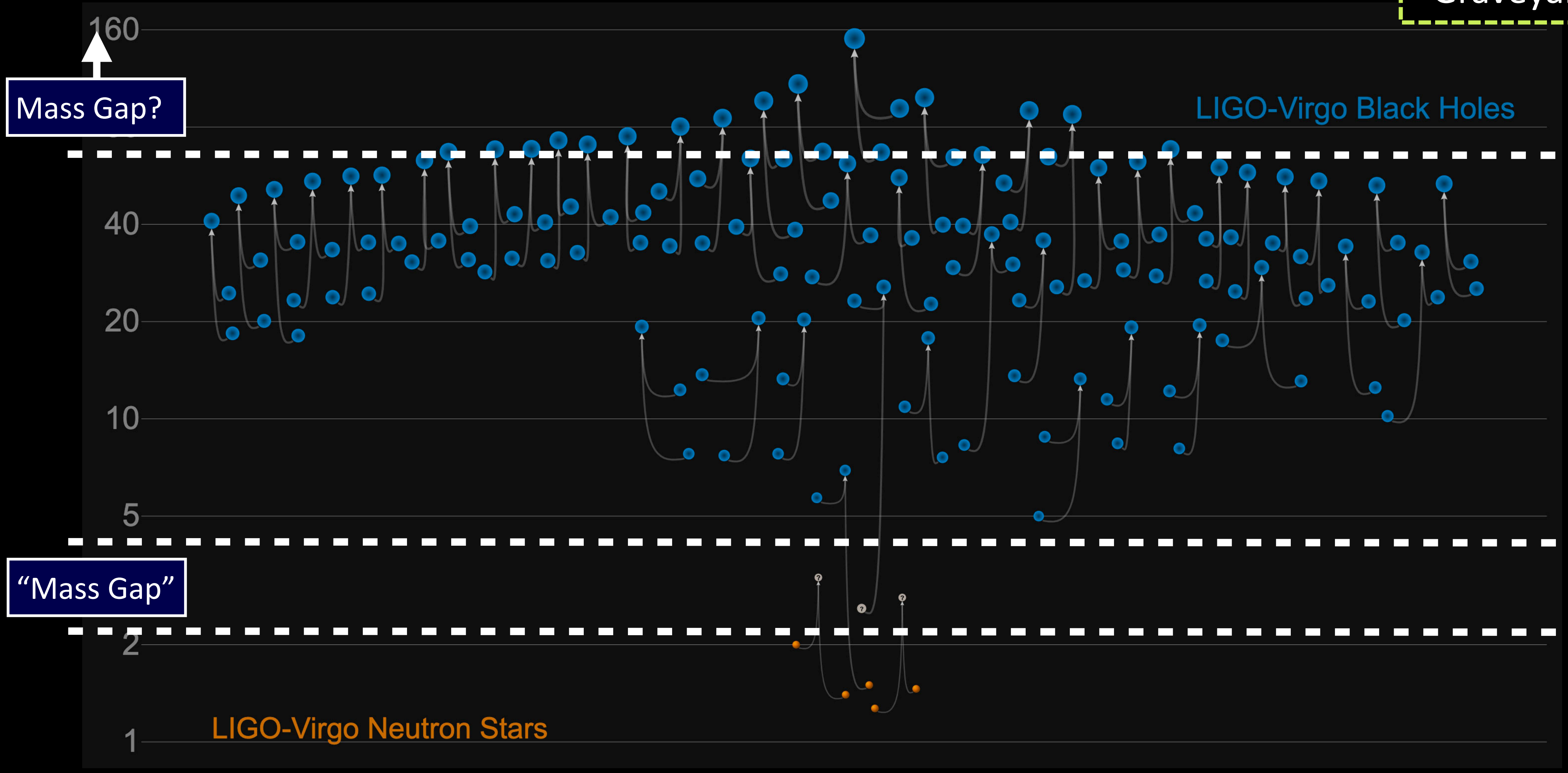
Binary mergers in LIGO/Virgo O3a

“The Stellar Graveyard”



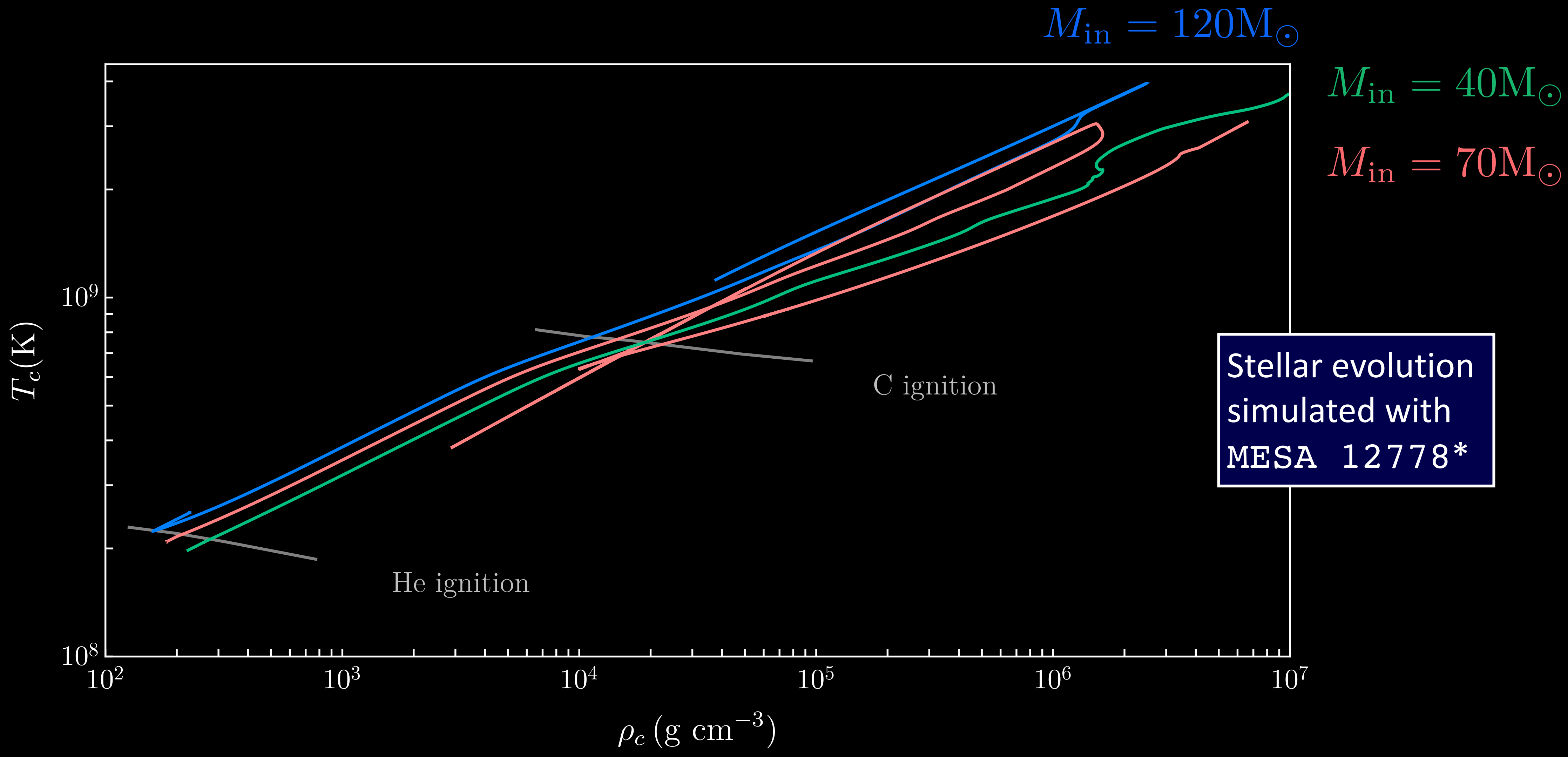
Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

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)

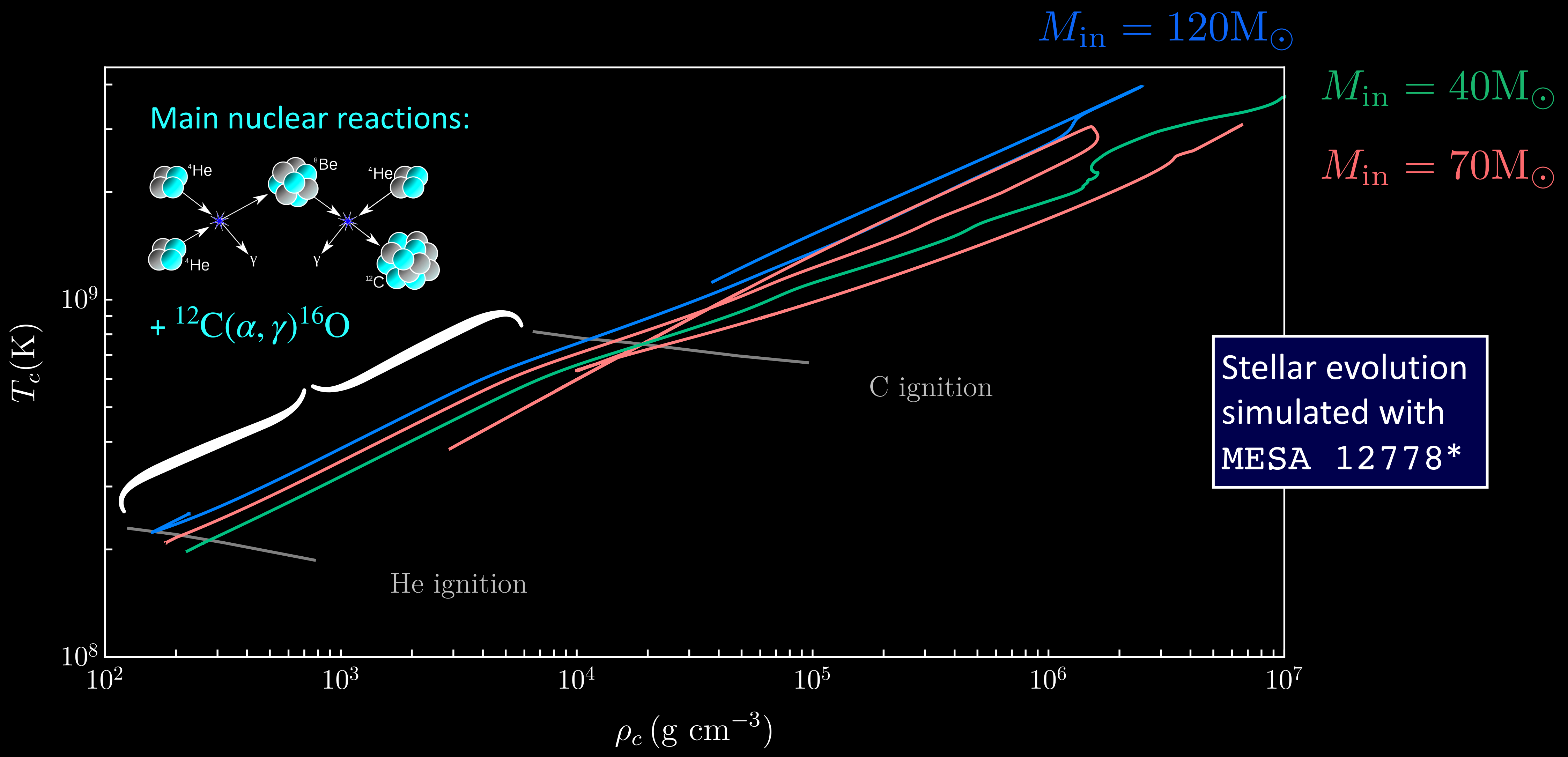
Evolution of old population-III stars



Stellar evolution simulated with `MESA 12778*`

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

Evolution of old population-III stars



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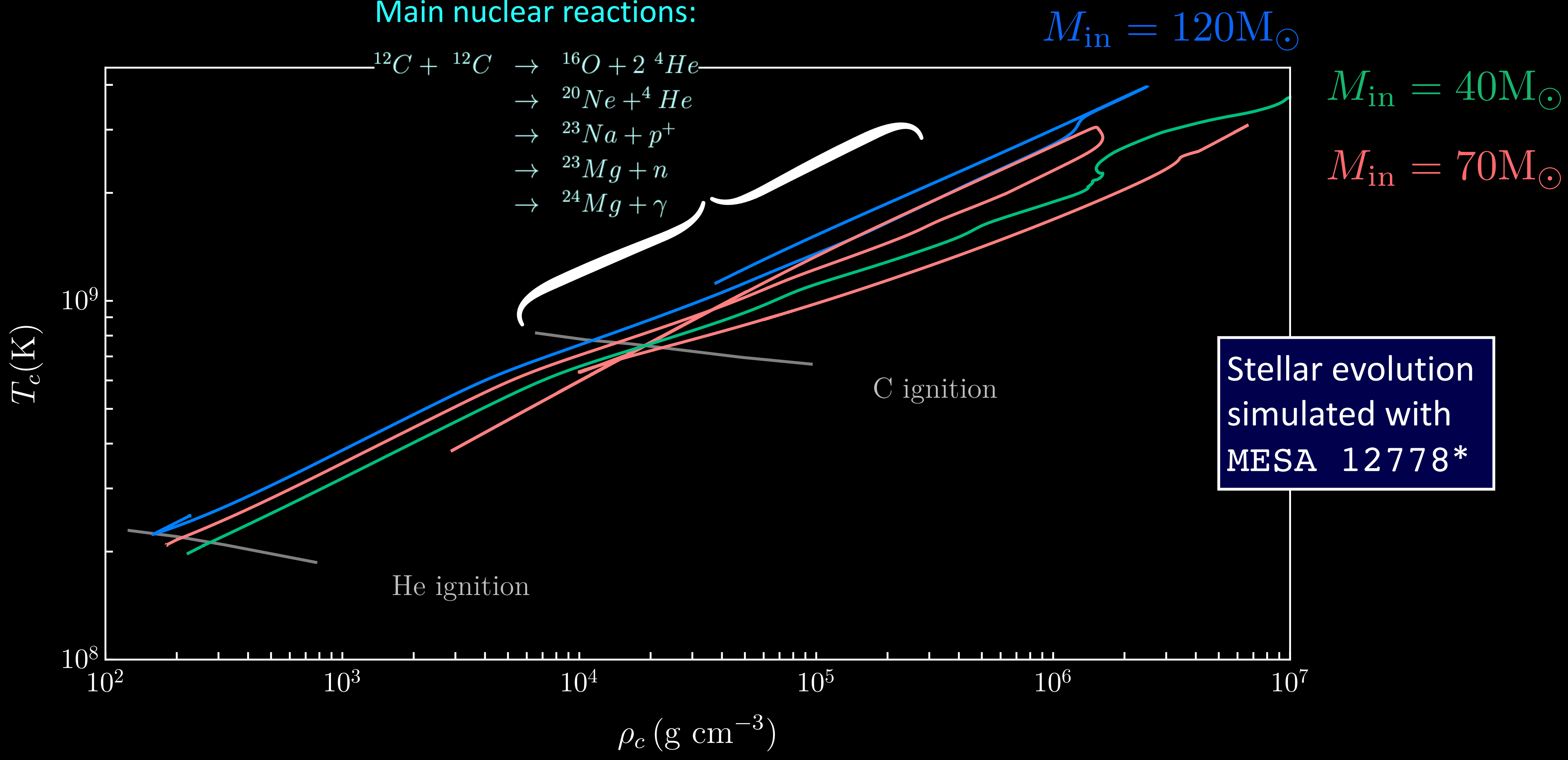

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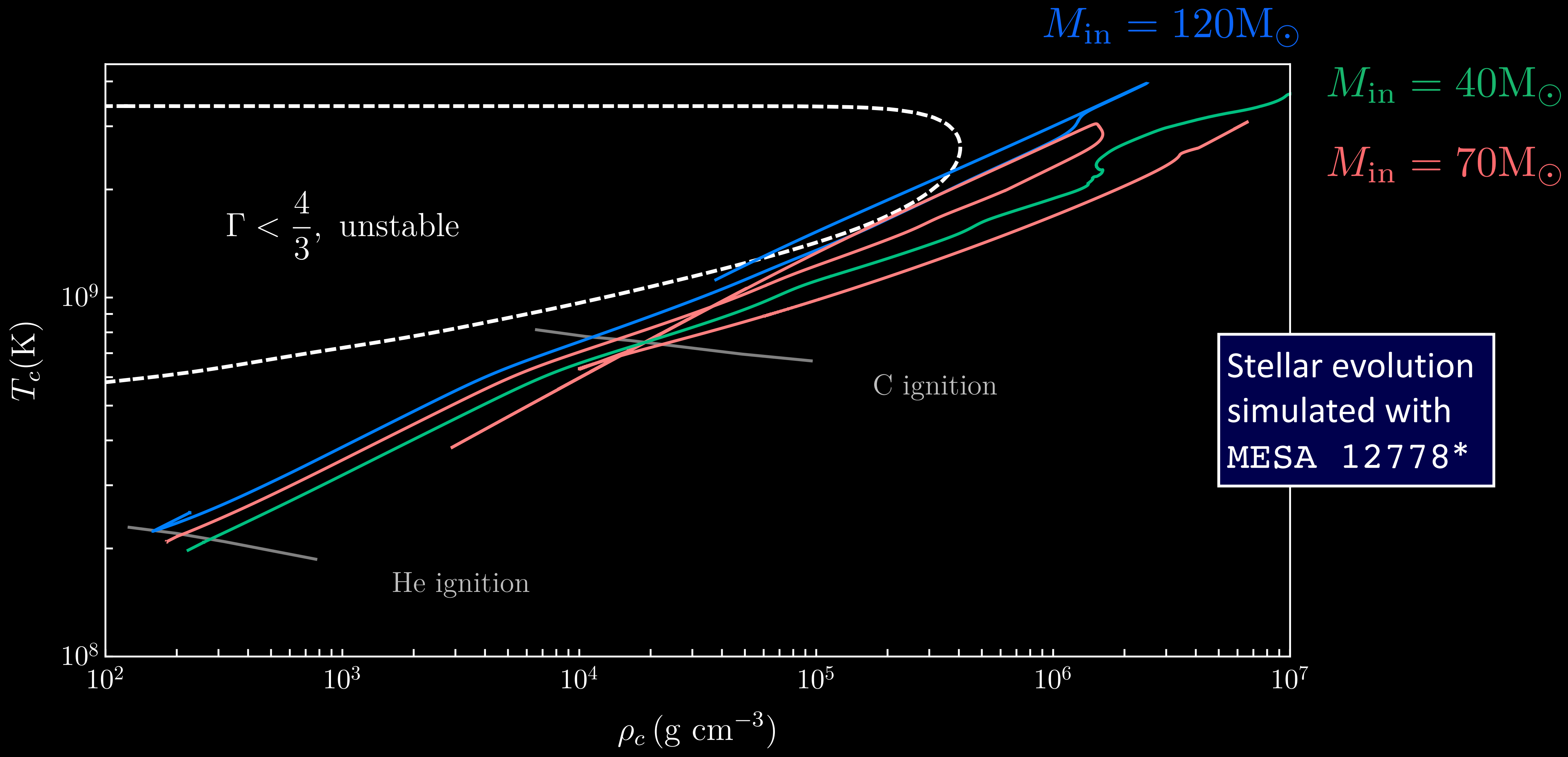


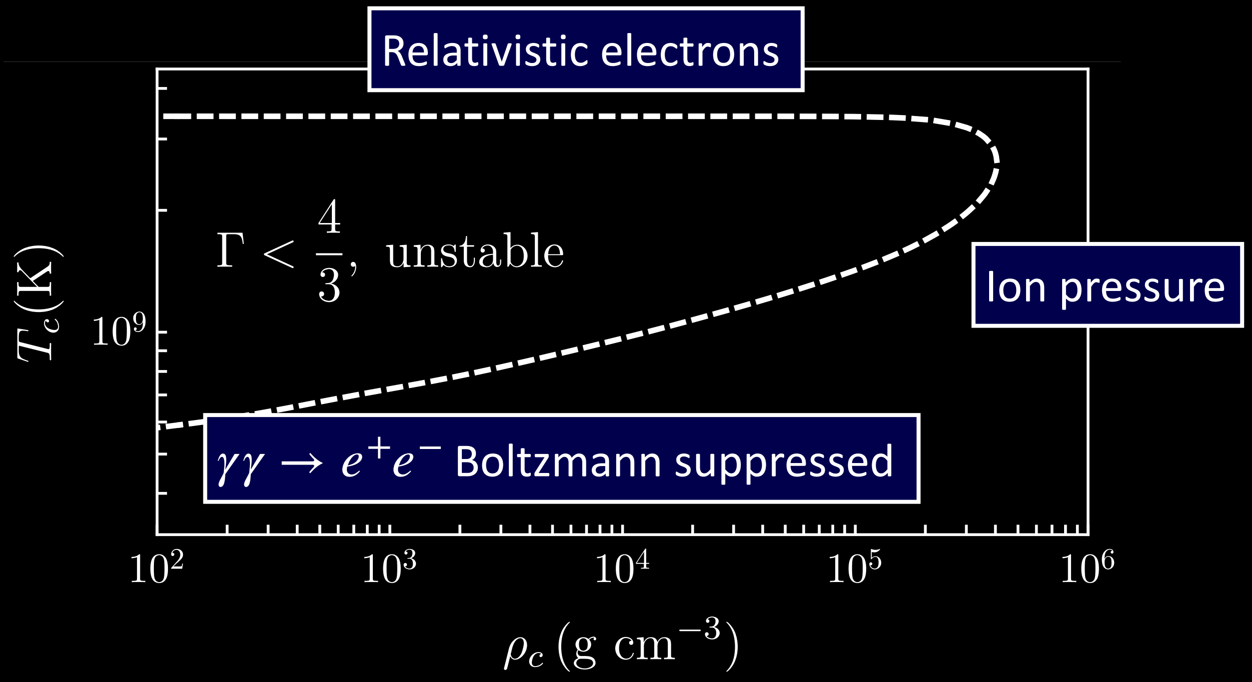
Stellar evolution simulated with `MESA 12778*`

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

Pair-instability

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

- 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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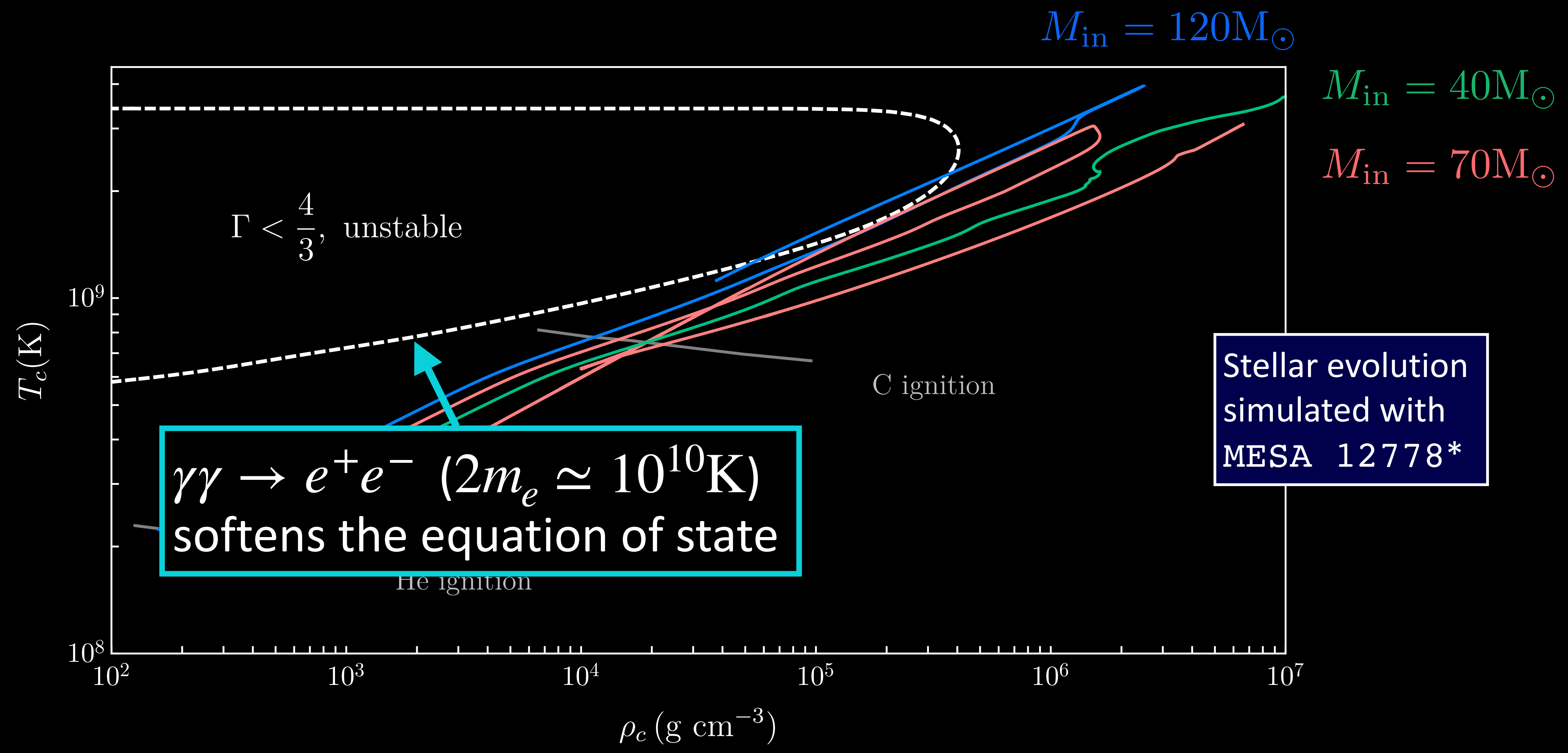

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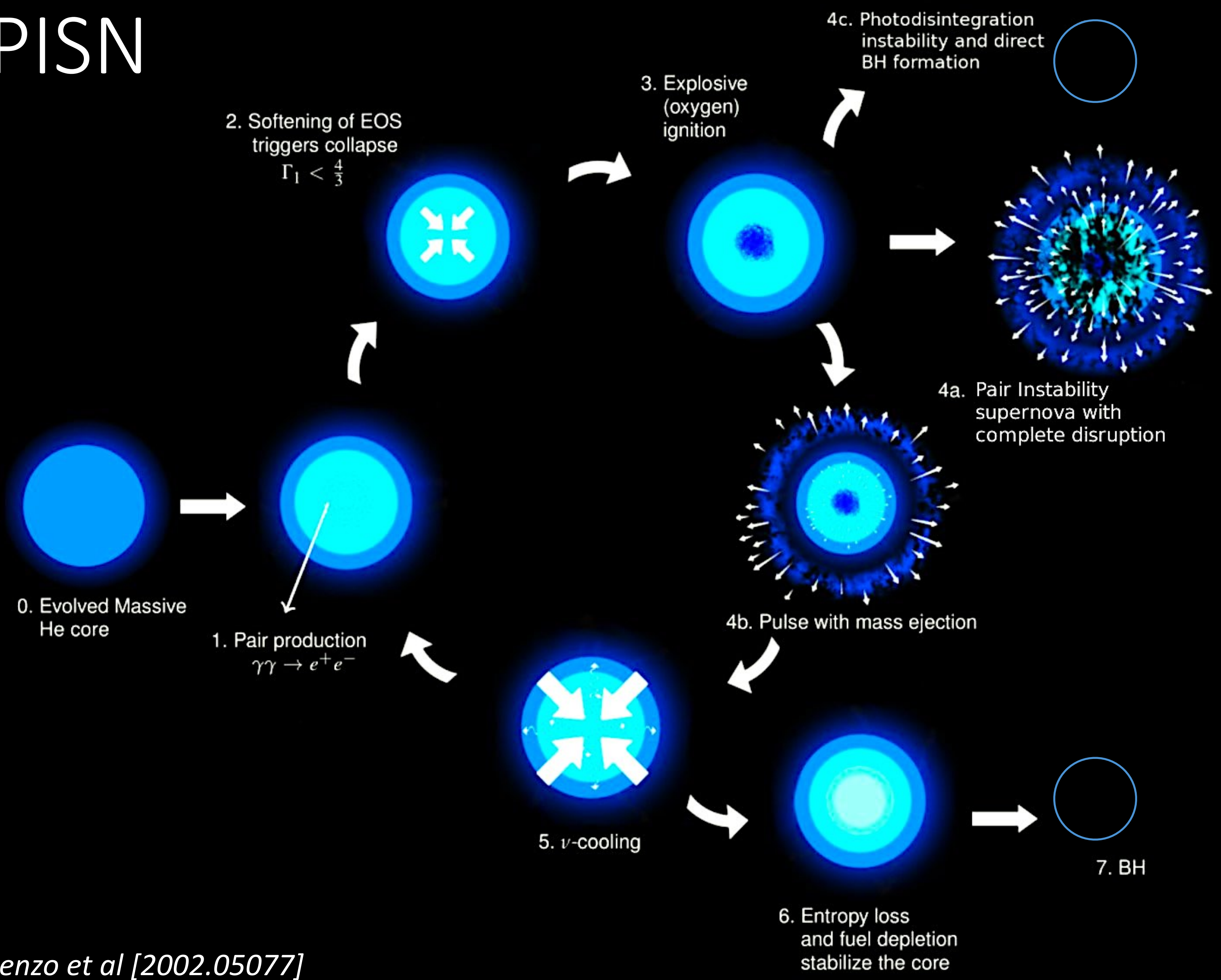
(P)PISN



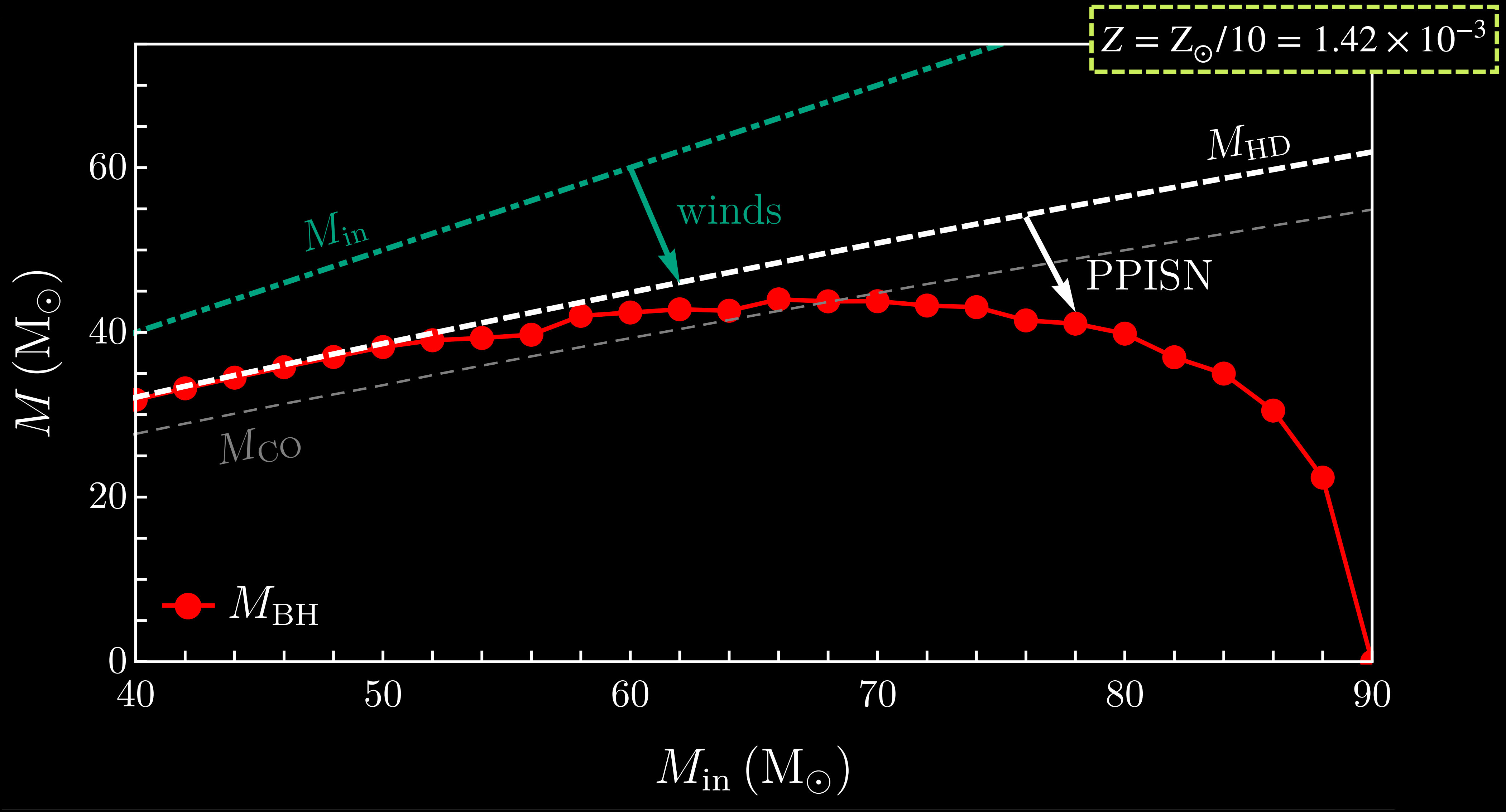
Extremely massive stars ($M_{\rm in} > 200\,{\rm M}_\odot$)

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



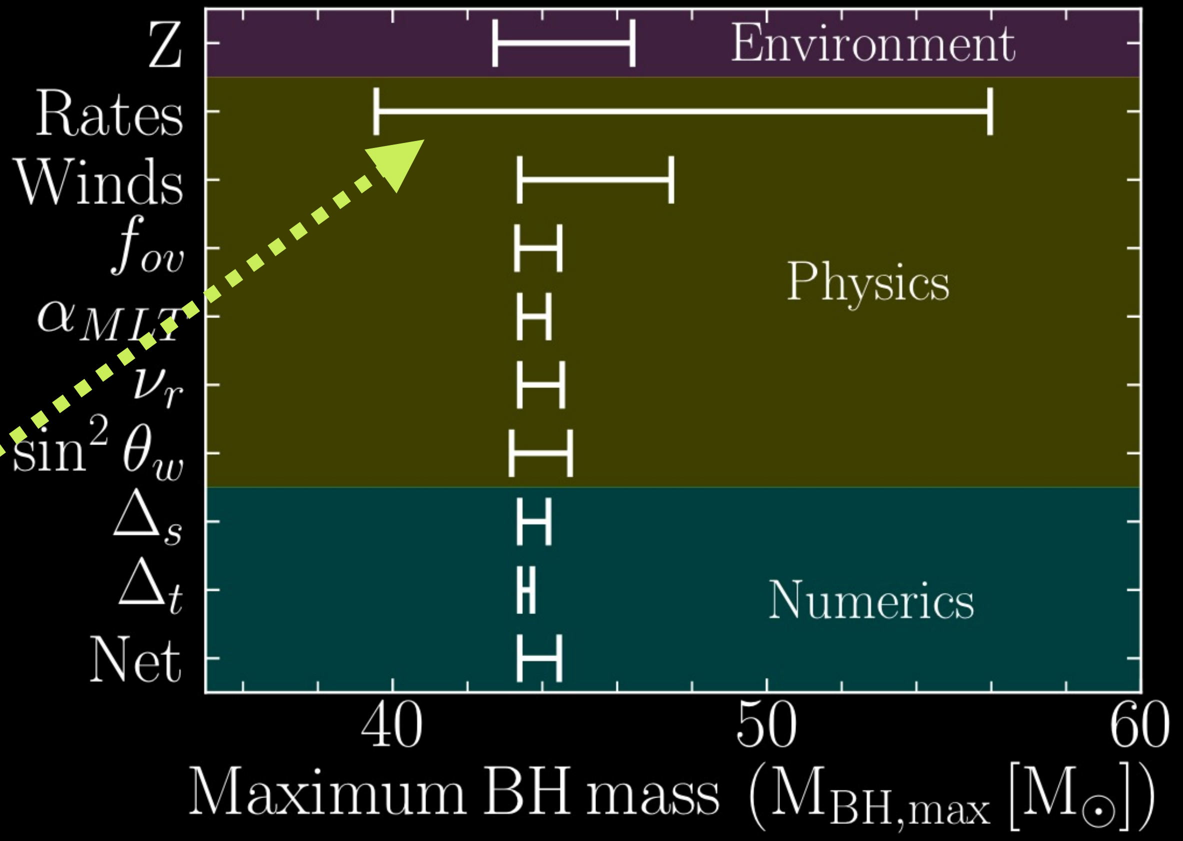
DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

Known physics dependence of the BHMG

- Astrophysical + nuclear + numerical uncertainties

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

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]

What about new physics?

DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

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

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

Several other works in progress…

DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

DC, McDermott, Sakstein 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 $g_{10} \equiv 10^{10}g_{a\gamma}\,\mathrm{GeV}$)
  - the hidden photon $\mathscr{L}_{A'\gamma} = -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m_{A'}^2}{2}A_\mu A^\mu$ (and define nothing)

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

DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

DC, McDermott, Sakstein 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 $\mathscr{L}_{ae} = -ig_{ae}\bar{\psi}_e\gamma_5\psi_e a$ (will also work with $\alpha_{26} \equiv 10^{26}g_{ae}^2/4\pi$ for convenience)*
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*Interesting in light of the XENON1T excess, arXiv:2006.09721 [hep-ex]

Energy loss due to electrophilic axions

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

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

$$F_{\rm deg} = \frac{2}{n_e}\int \frac{d^3\mathbf{p}}{(2\pi)^3} f_{e^-}(1-f_{e^-}),$$ where f_{e^-} is the Fermi-Dirac distribution

- Bremsstrahlung, $e+(Z,A) \to e+(Z,A)+a$:

$$\mathcal{Q}_{b,\rm ND} = \frac{32}{45}\frac{\alpha_{\rm EM}^2 g_{ae}^2 \rho T^{5/2}}{\sqrt{\frac{\pi^3}{2}m_N^2 m_e^{7/2}}} F_{b,\rm ND} \simeq 582\,\alpha_{26}\,\rho_6\, T_8^{5/2}\, F_{b,\rm ND}\,\frac{\rm erg}{\rm g\cdot s} \qquad \left(\rho_6 \equiv \frac{\rho}{10^6{\rm g\,cm^{-3}}}\right)$$

$$\mathcal{Q}_{b,\rm D} = \frac{\pi}{60}\frac{Z^2}{A}\frac{\alpha_{\rm EM}^2 g_{ae}^2 T^4}{m_N m_e^2} F_{b,\rm D} \simeq 10.8\,\alpha_{26}\, T_8^4\, F_{b,\rm D}\,\frac{\rm erg}{\rm g\cdot s}$$

DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

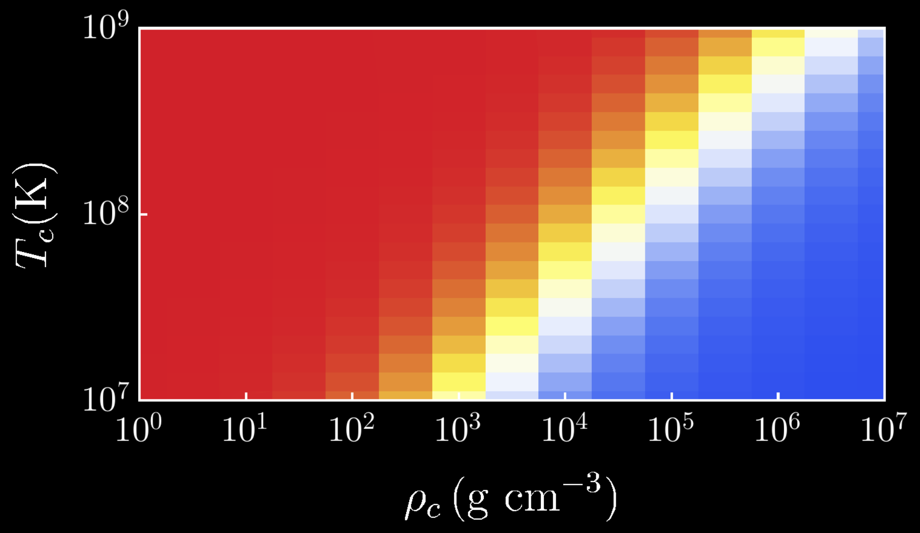
Energy loss due to electrophilic axions

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

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

$$F_{\rm deg} = \frac{2}{n_e} \int \frac{d^3\mathbf{p}}{(2\pi)^3} f_{e^-}(1 - f_{e^-}),$$ where f_{e^-} is the Fermi-Dirac distribution

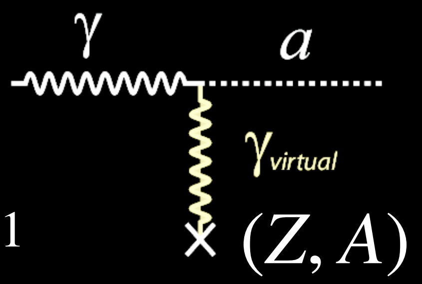
$0 < F_{\rm deg} < 1$



Semi-Compton emission dominates throughout the Helium burning phase

Energy loss due to photophilic axions

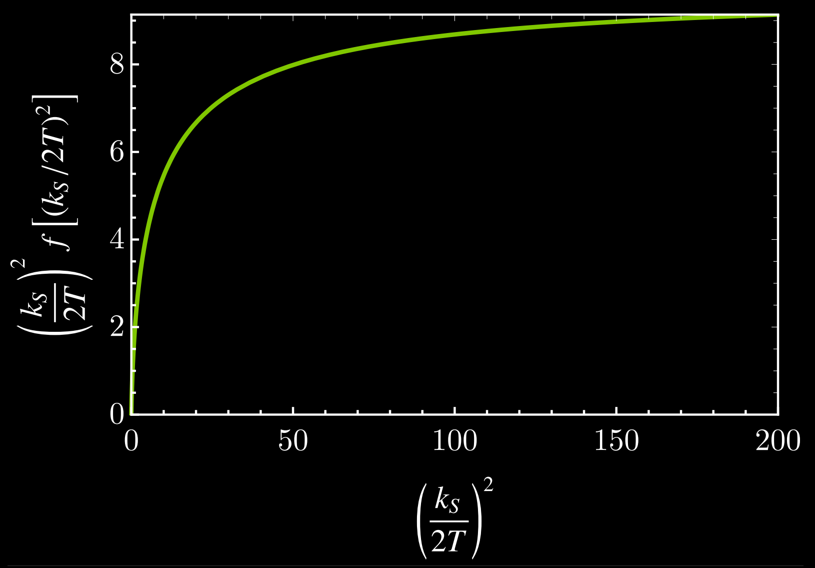
- Primakov effect $(Z, A) + \gamma \to (Z, A) + a$



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

$$\times \underbrace{\left(\frac{k_S}{2T}\right)^2 f\left[\left(k_S/2T\right)^2\right]}, \text{ where } \left(\frac{k_S}{2T}\right)^2 = 0.166 \frac{\rho_3}{T_8^3} \sum_j Y_j Z_j^2$$

Screened at high T and low ρ



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

Energy loss due to hidden photons

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

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

In the limit $\omega_p \ll T$

- Where photons have plasma mass $\omega_p \simeq \sqrt{\frac{4\pi\alpha_{\text{EM}} n_e}{m_e}} \simeq 654\text{eV}\sqrt{\frac{Z}{A}\rho_3}$

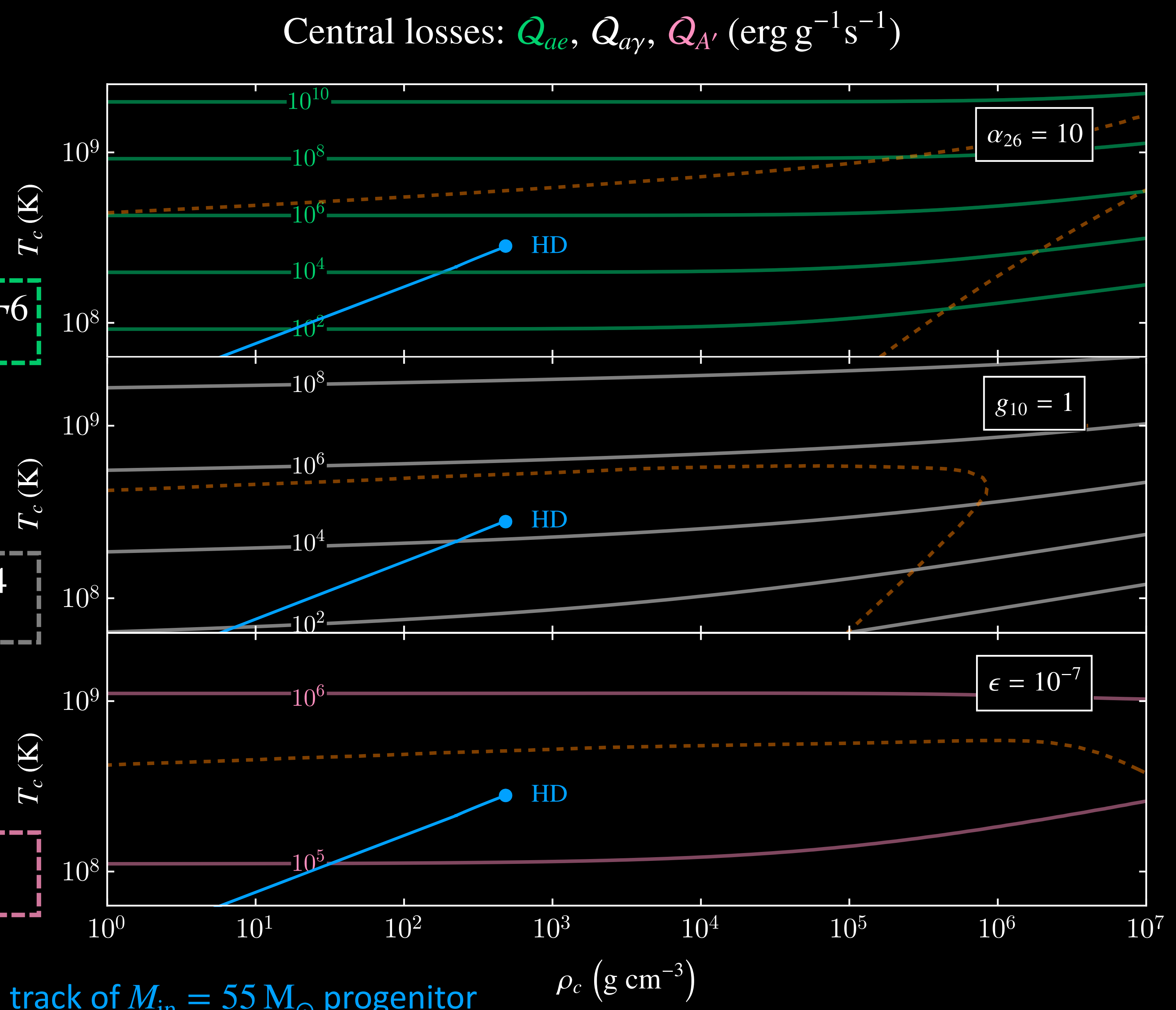
DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

Loss rates

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

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

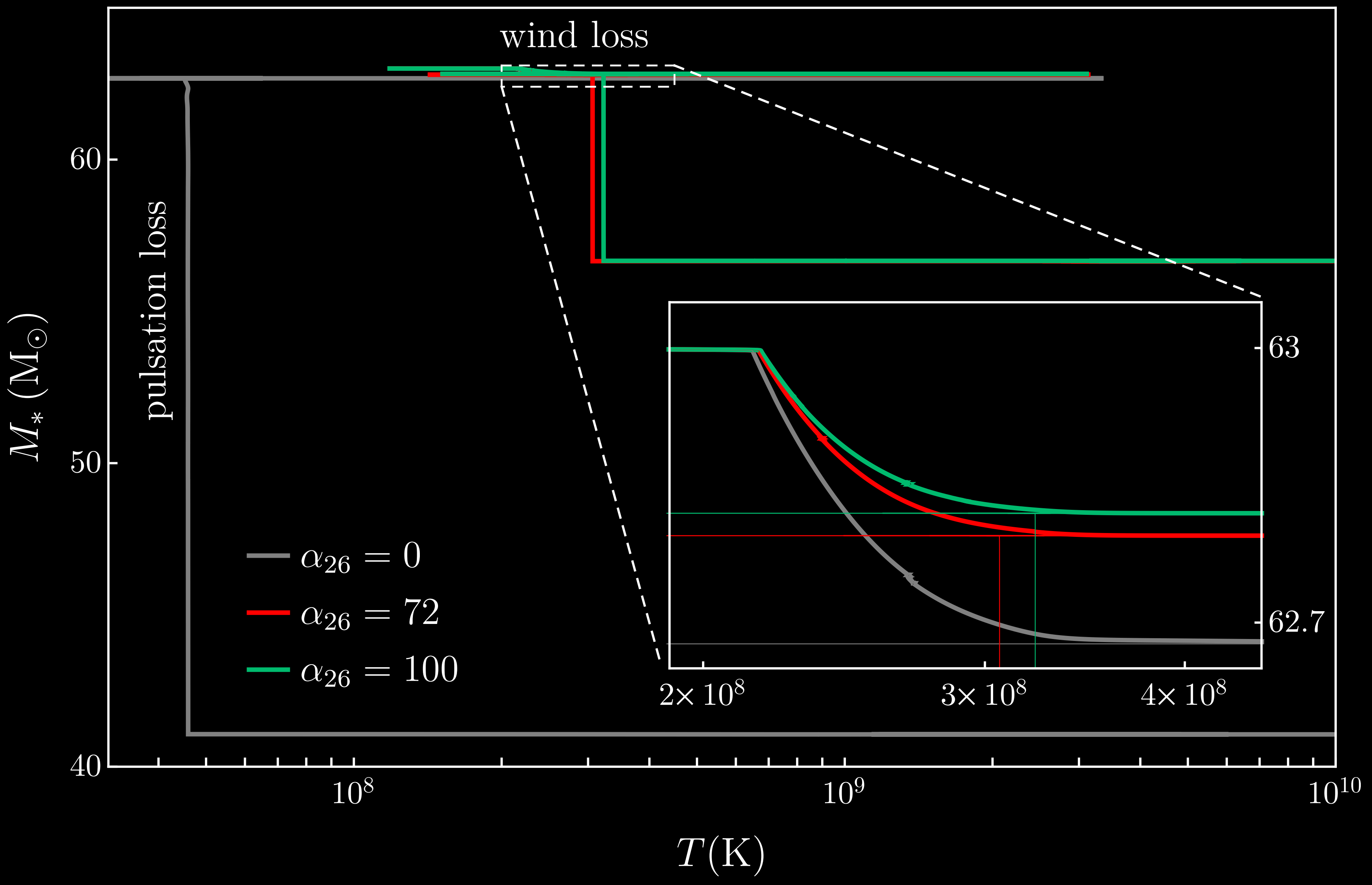
Hidden photon: $Q_{A'} \propto T$



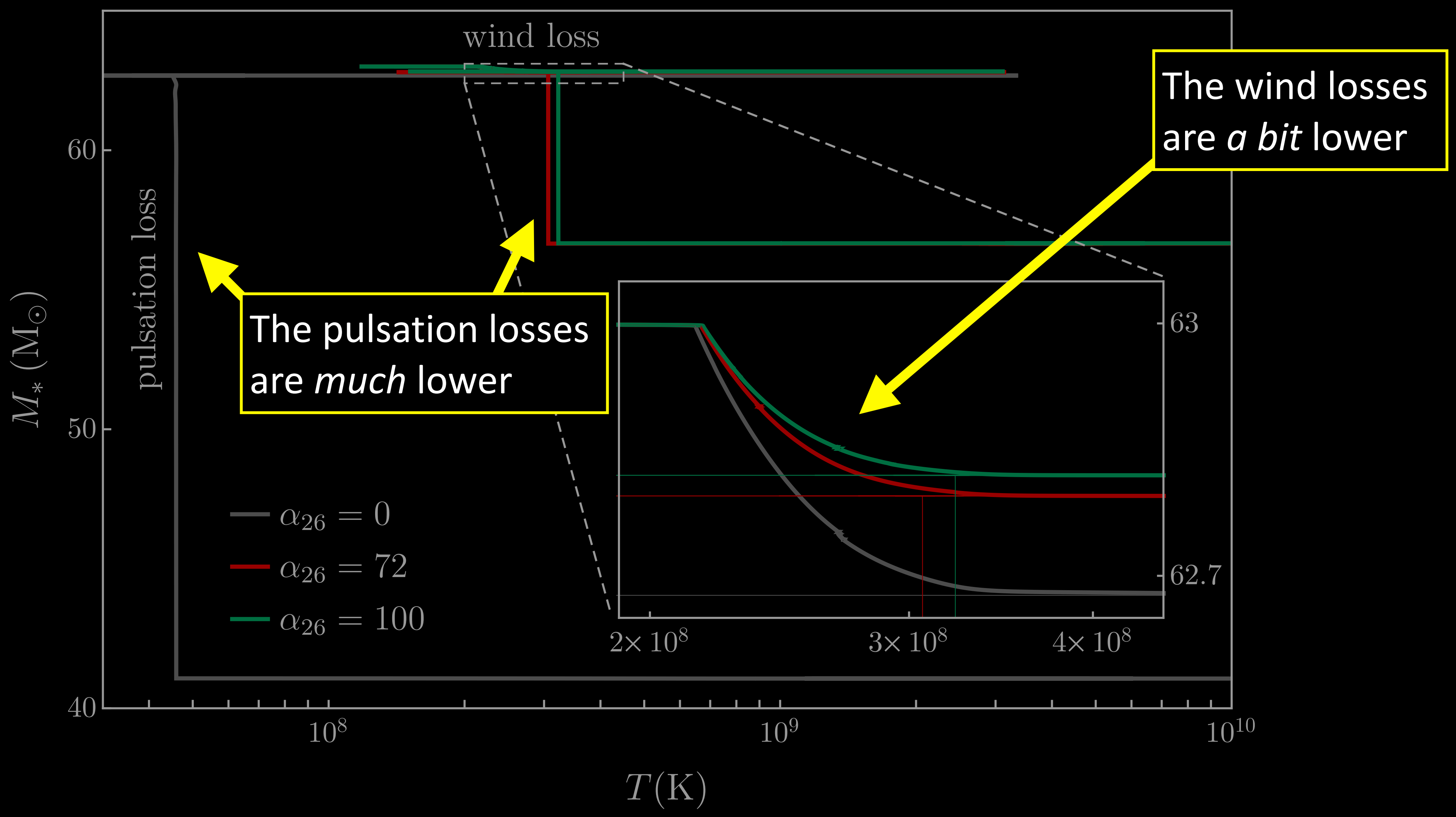
Example track of $M_{\rm in} = 55\,\mathrm{M}_\odot$ progenitor

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

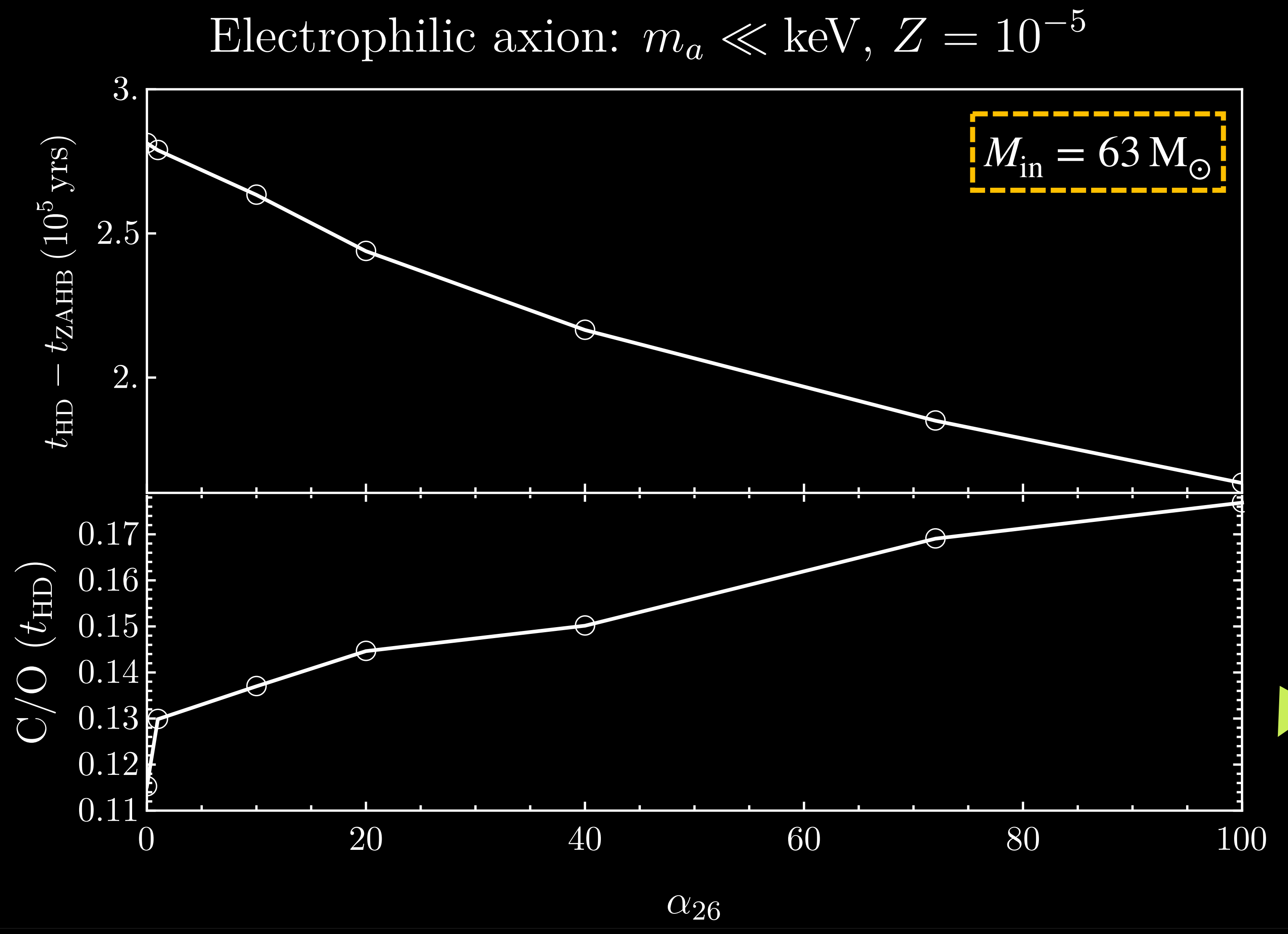
Implications of enhanced losses



Implications of enhanced losses



What does the extra energy loss do?

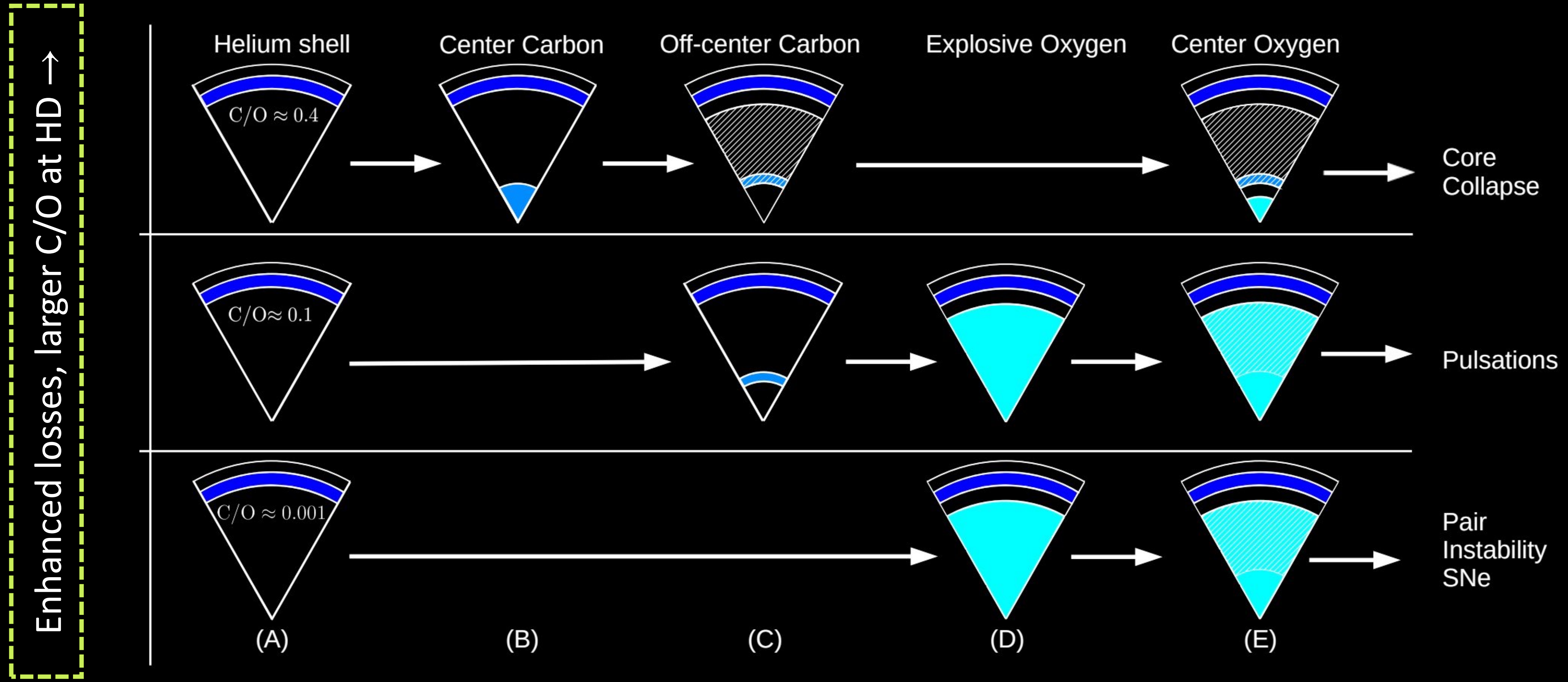


Greater energy losses lead to *shorter He-burning phases*

Extra dissipation scales linearly with α_{26}

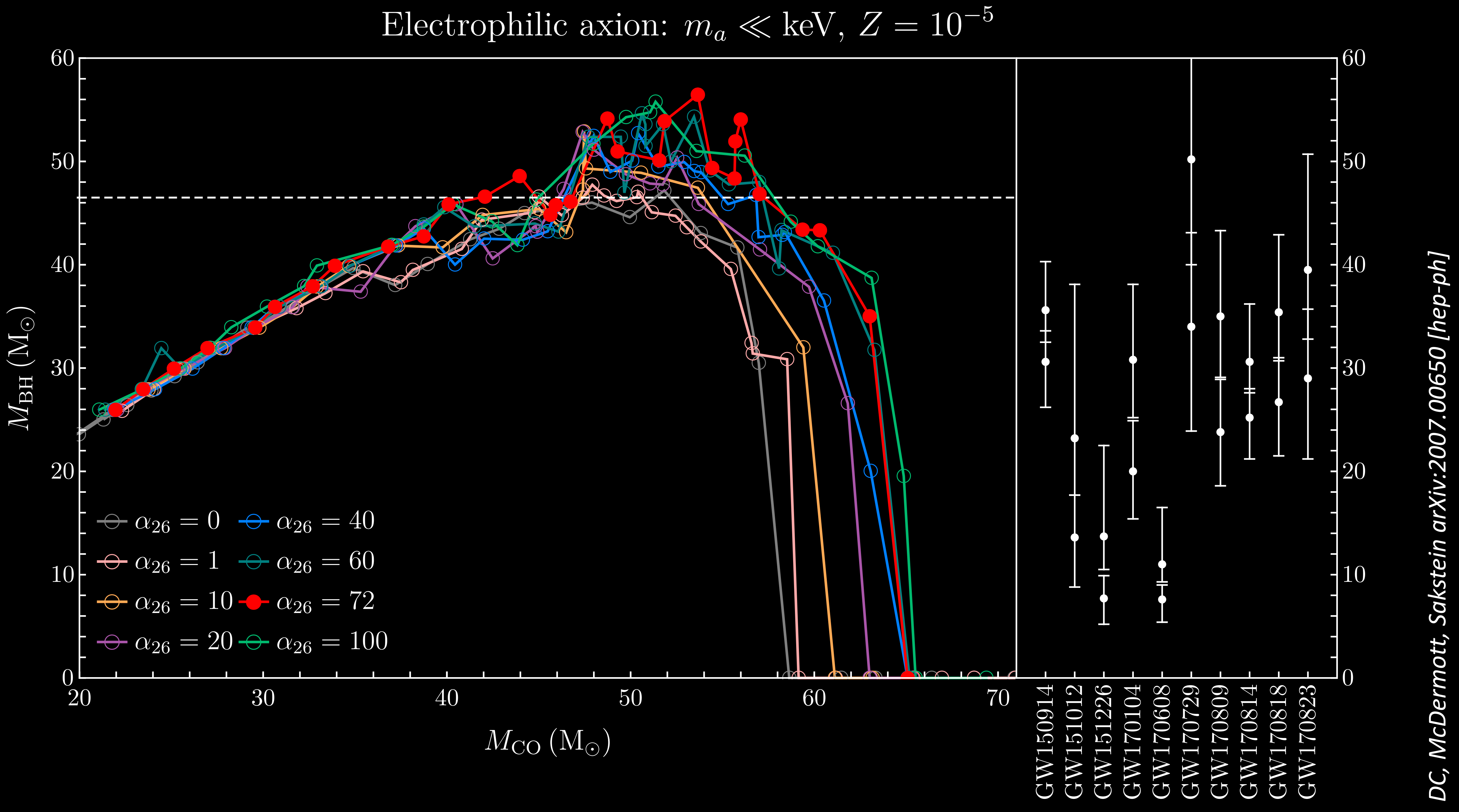
Less time for $^{12}{\rm C}(\alpha,\gamma)^{16}{\rm O}$: *C/O is larger* at the time of helium depletion (HD)

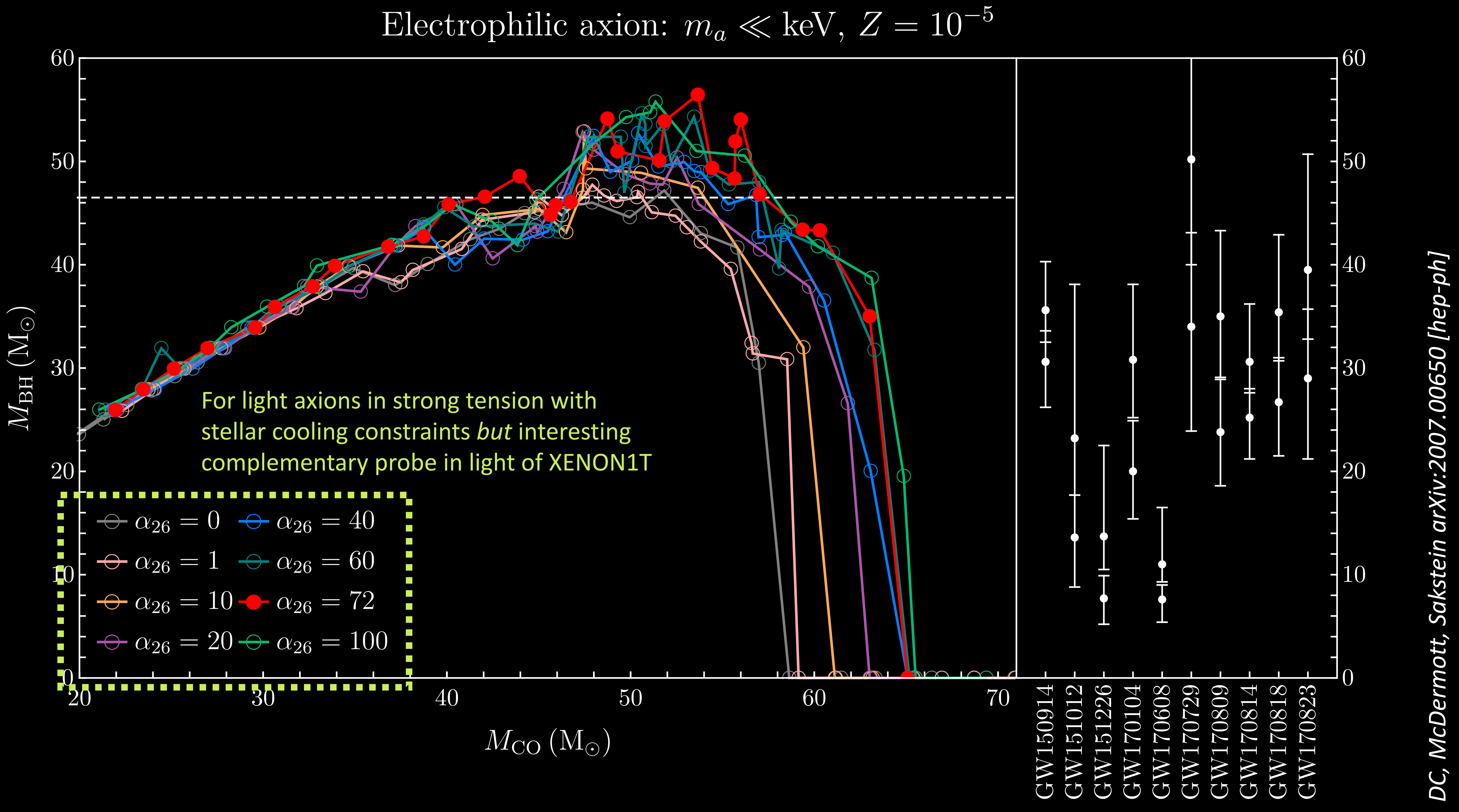
The BHMG and new physics



Enhanced losses → greater progenitors collapse → larger black holes

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


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
DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]



Electrophilic axion: $m_a \ll \text{keV},\ Z = 10^{-5}$
$M_{\rm BH}\,(M_\odot)$
$M_{\rm CO}\,(M_\odot)$
For light axions in strong tension with stellar cooling constraints *but* interesting complementary probe in light of XENON1T
$\alpha_{26} = 0$
$\alpha_{26} = 1$
$\alpha_{26} = 10$
$\alpha_{26} = 20$
$\alpha_{26} = 40$
$\alpha_{26} = 60$
$\alpha_{26} = 72$
$\alpha_{26} = 100$
GW150914
GW151012
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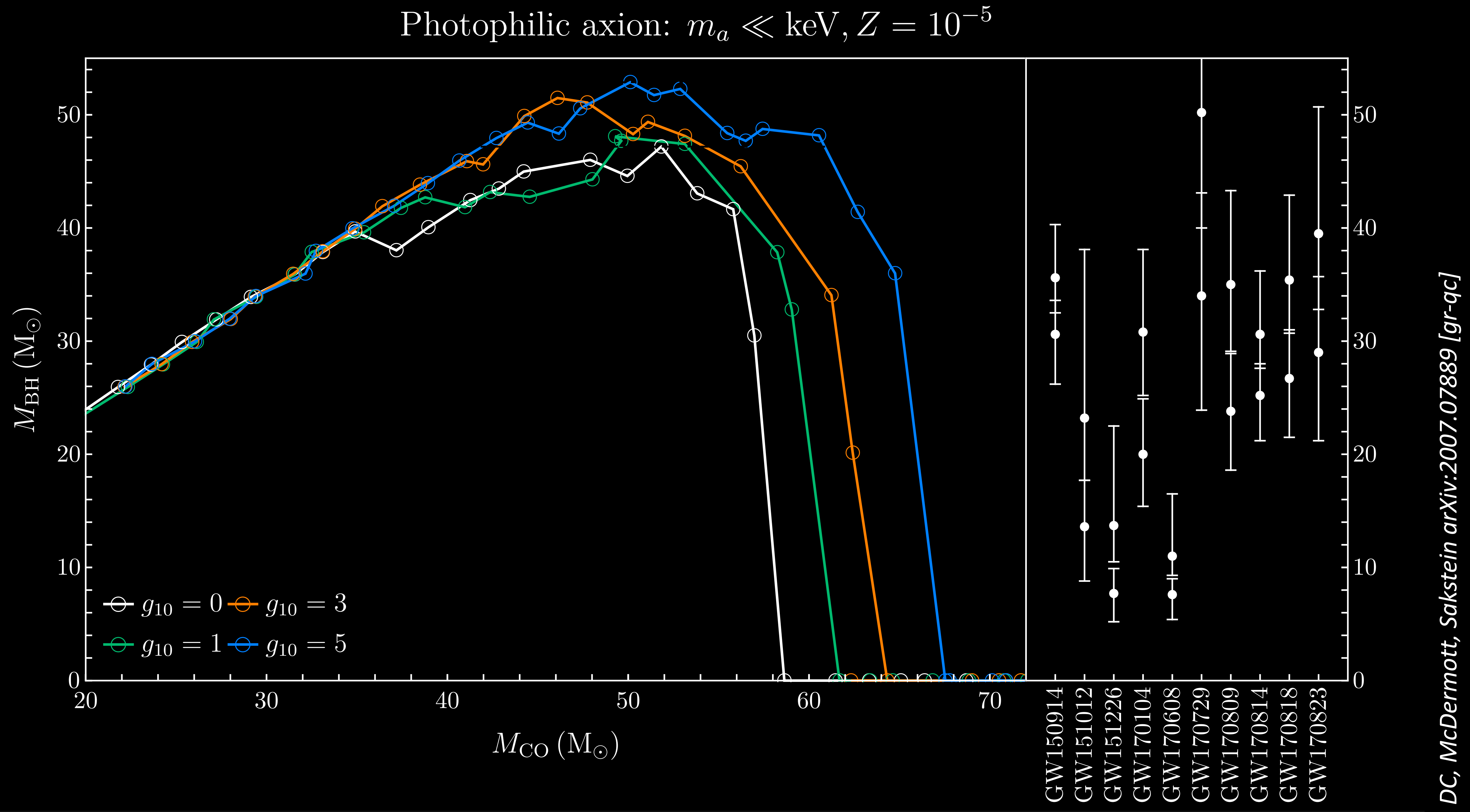
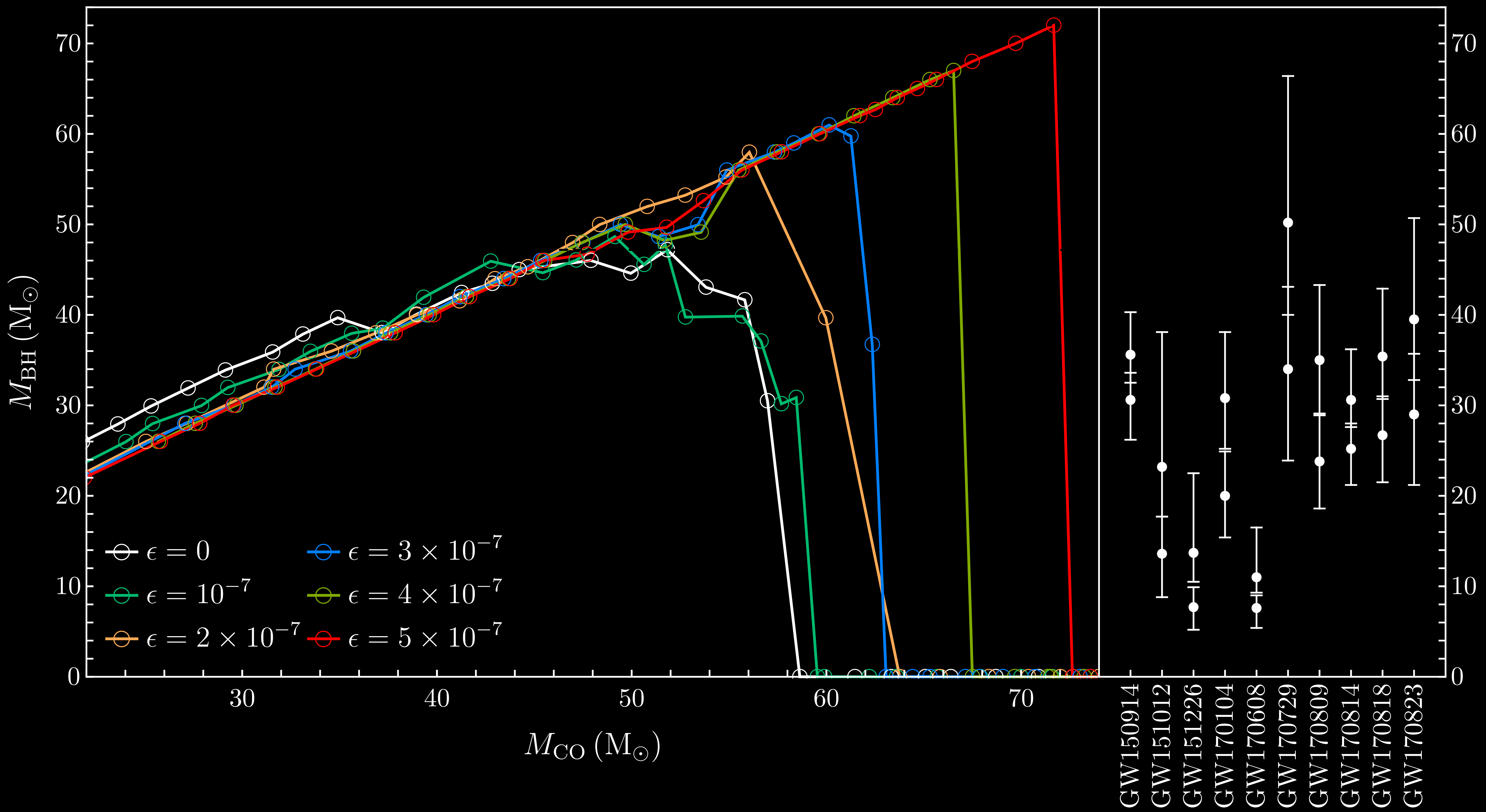


Photophilic axion: $m_a \ll \text{keV}, Z = 10^{-5}$
$M_{\rm BH}$ ($M_\odot$)
$M_{\rm CO}$ ($M_\odot$)
$g_{10} = 0$
$g_{10} = 3$
$g_{10} = 1$
$g_{10} = 5$
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

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



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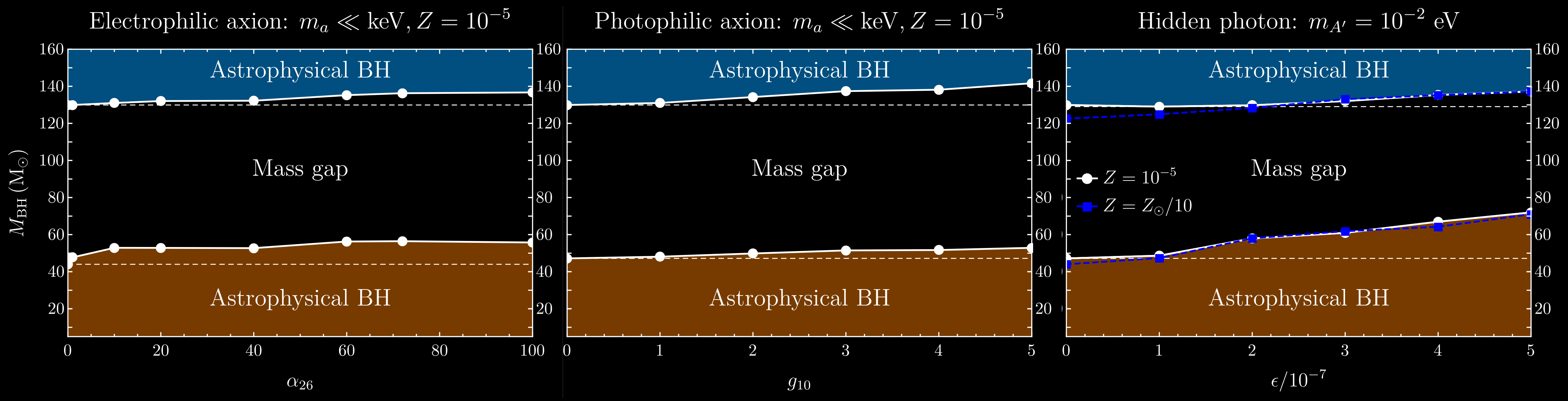
New physics and the black hole mass gap



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

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

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

Potentially large shifts of the mass gap!

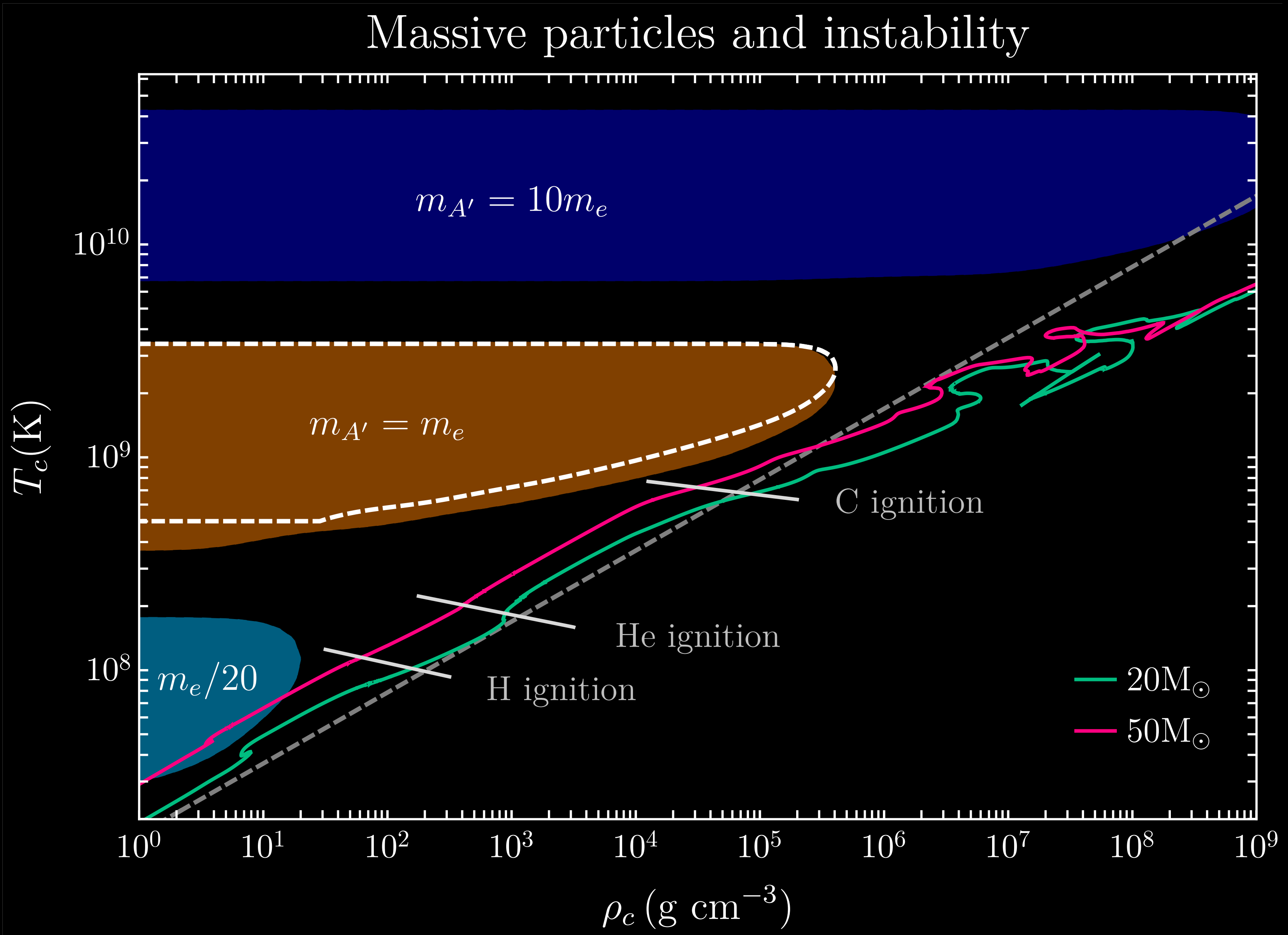
DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

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

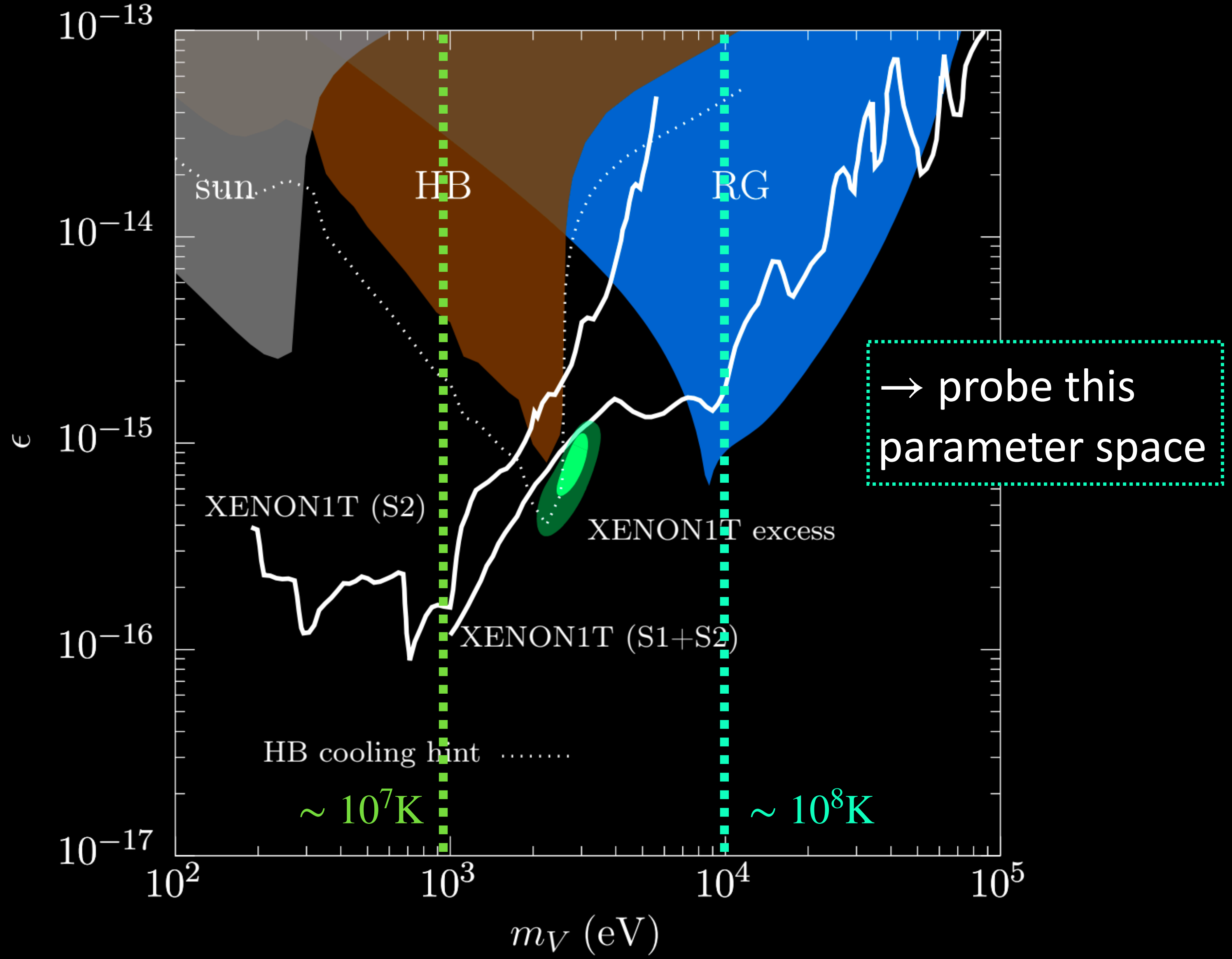
Equilibration time (vector):
$t_{A'} \simeq \Gamma_{A'}^{-1} \simeq \left(\epsilon^2 \sigma_T n_e e^{-m_{A'}/T_c}\right)^{-1}$
so for $\epsilon = 3 \times 10^{-12}$, we find $t_{A'} \simeq 10^5$ years, a timescale similar to the lifetime of helium burning



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

Heavier degrees of freedom?

DC, McDermott, Sakstein,
work in progress



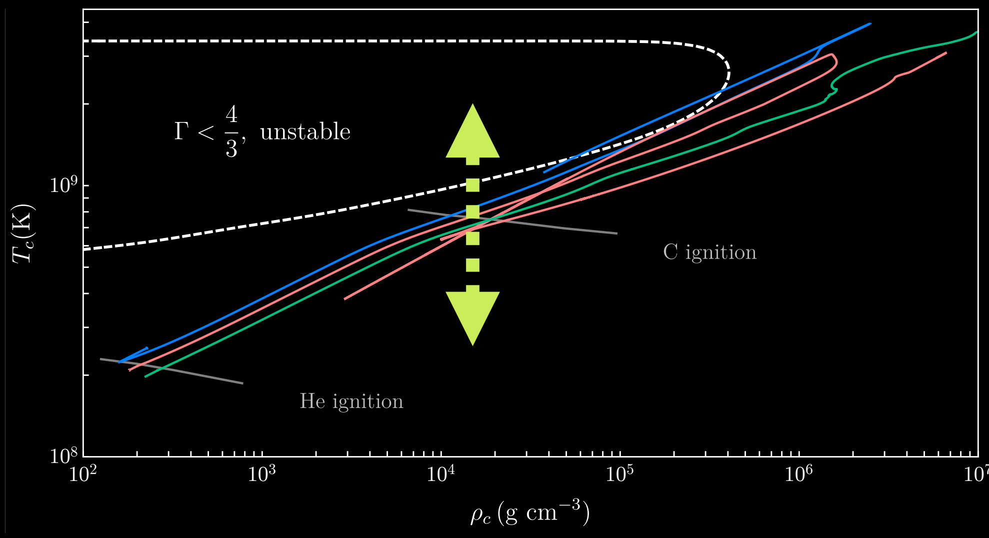
Adapted from Ann, Pospelov, Pradler, Ritz arXiv:2006.13929 [hep-ph]

Other scenarios

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

Straight, Sakstein, Baxter, arXiv: 2009.10716 [gr-qc]

- 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

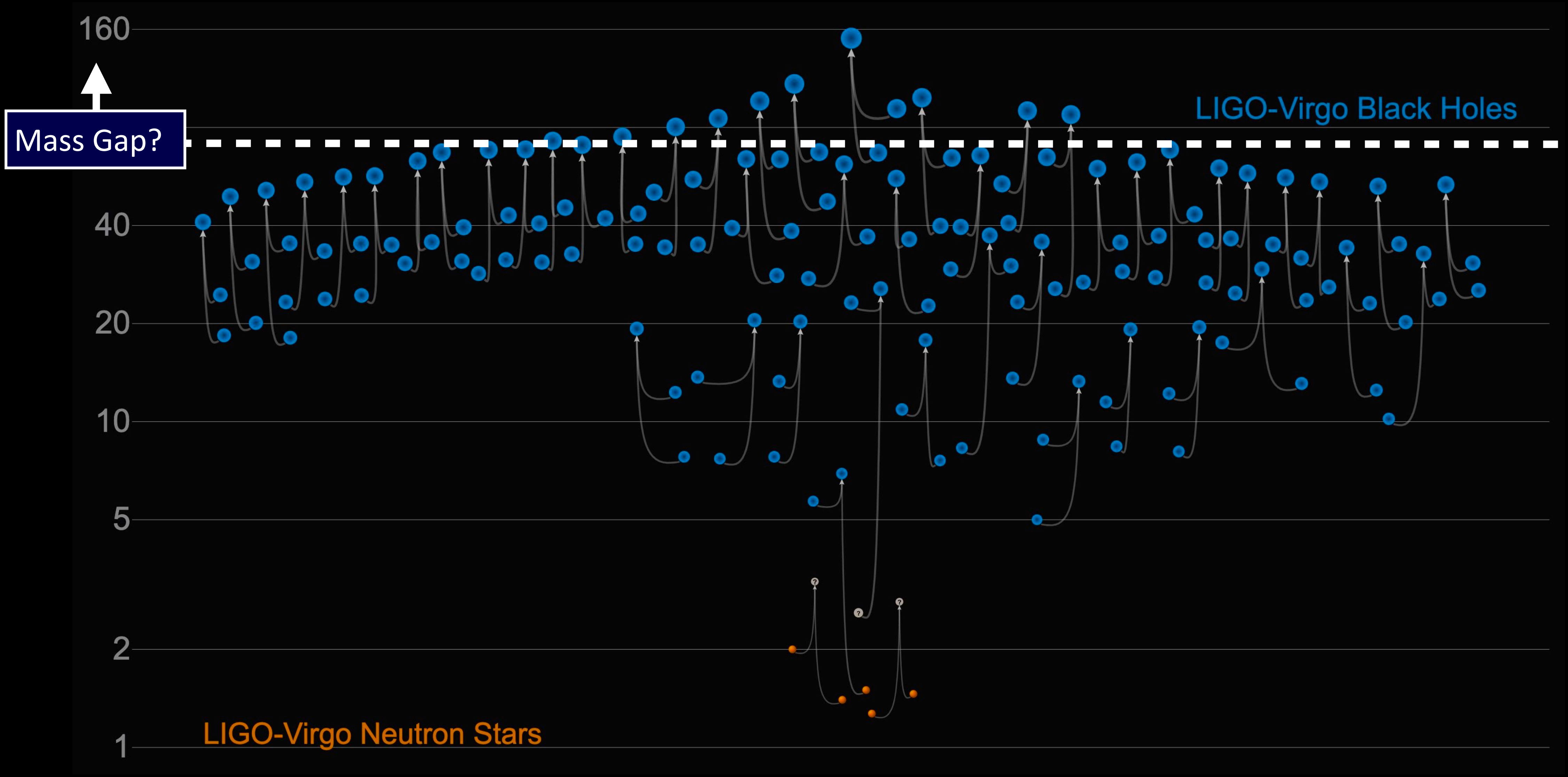


- Dark matter annihilation
  - Extra source of energy

Ziegler, Freese arXiv:2010.00254 [astro-ph]

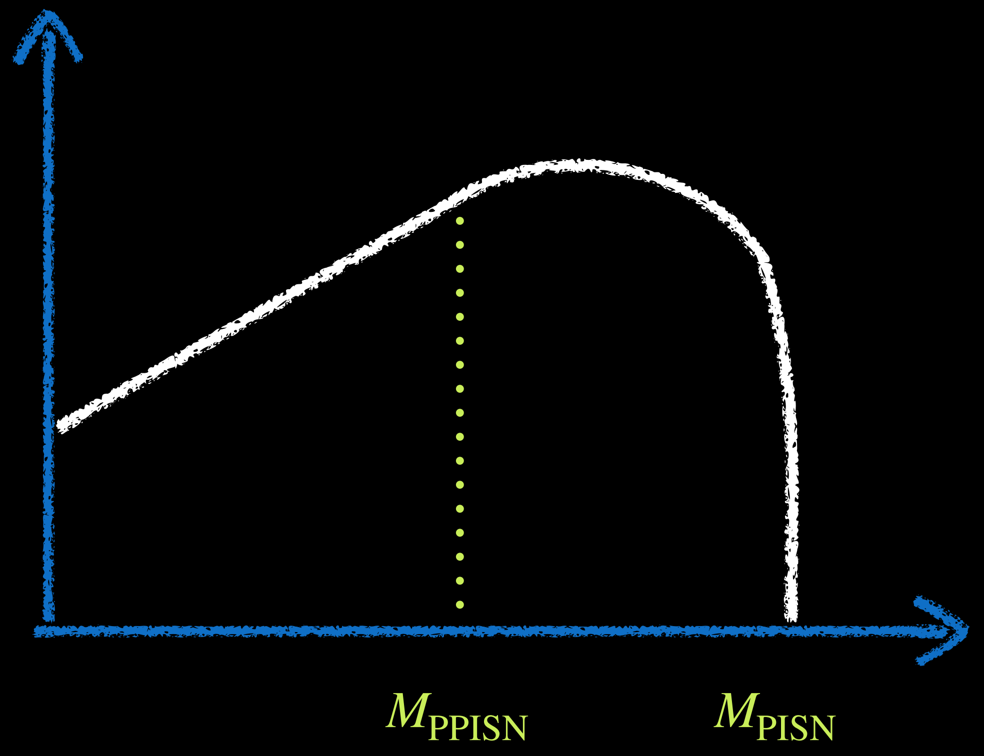
DC, McDermott, Sakstein, work in progress

Now, what about LIGO/Virgo O3a (and beyond)?



Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

Now, what about LIGO/Virgo O3a (and beyond)?



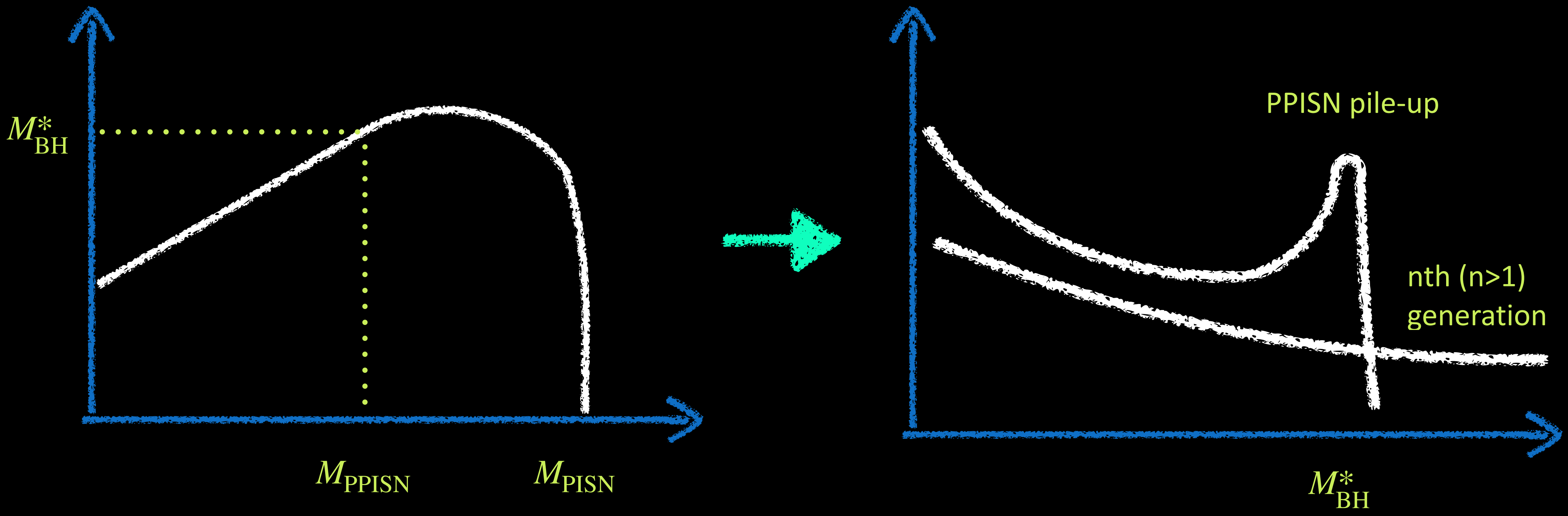
As we have seen, BSM scenarios may affect both $M_{\rm PPISN}$ and $M_{\rm PISN}$

Given a prediction for the onset of $M_{\rm PPISN}$ and $M_{\rm PISN}$, what BH mass distribution would be expected?

How does that compare to the data?

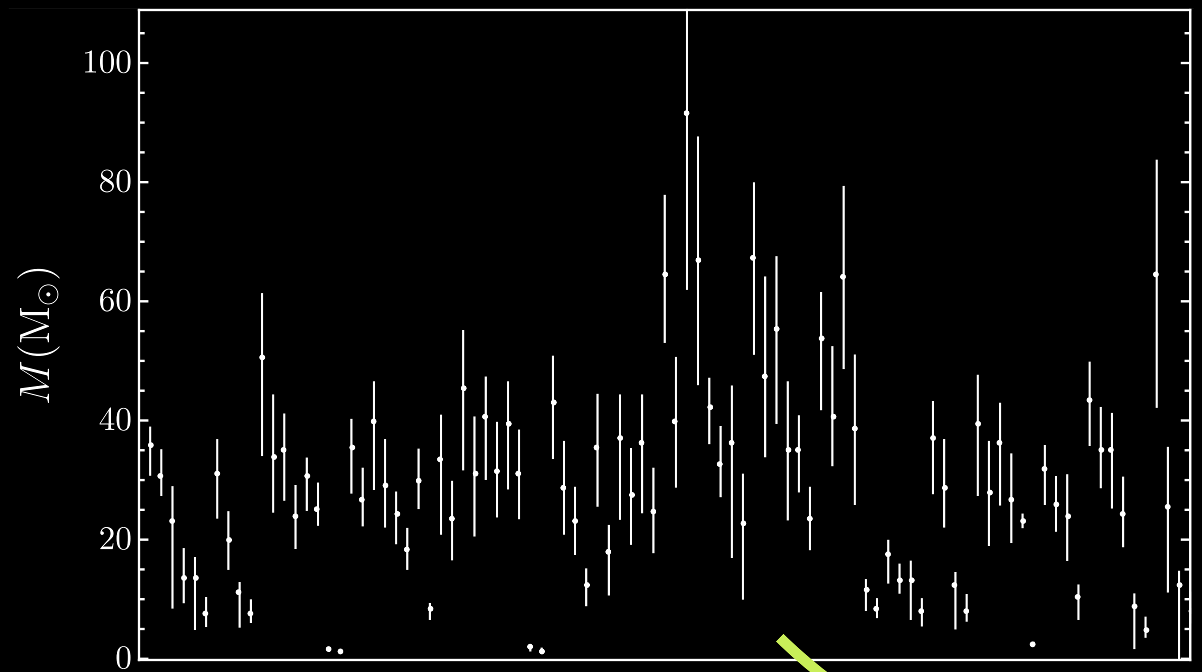
Baxter, DC, McDermott, Sakstein, work in progress

Now, what about LIGO/Virgo O3a (and beyond)?

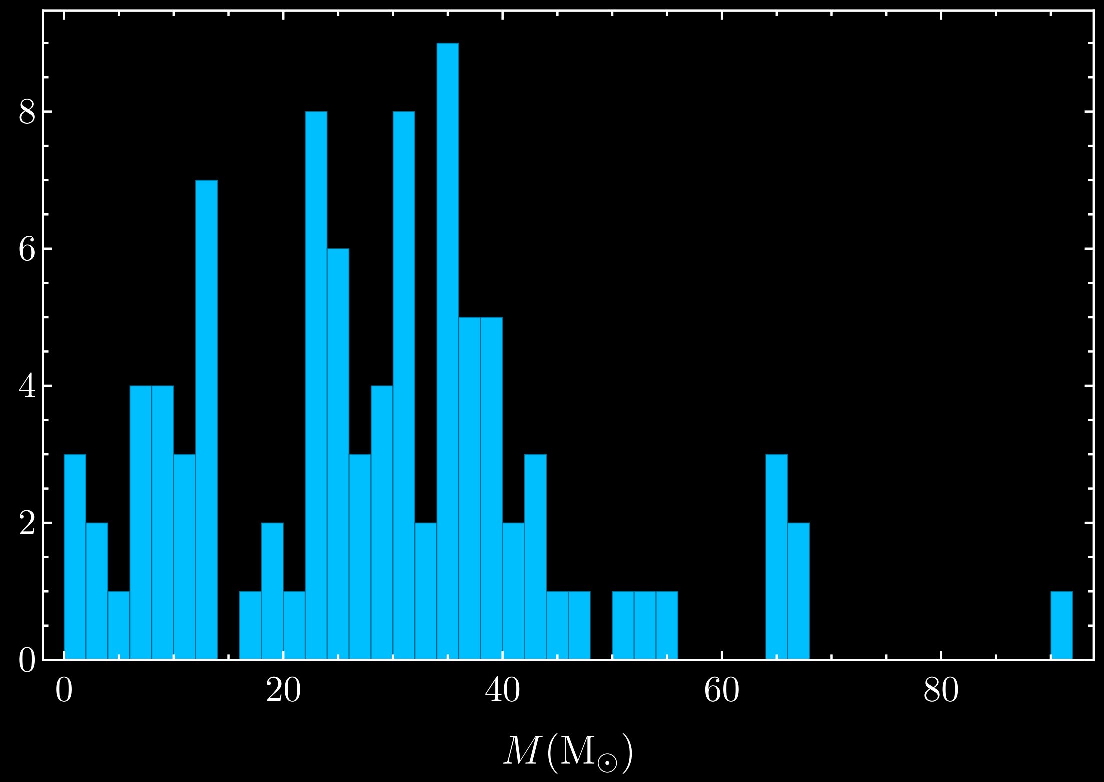


+ Initial mass function
+ Effective detector volume

Binary mergers in LIGO/Virgo O3a



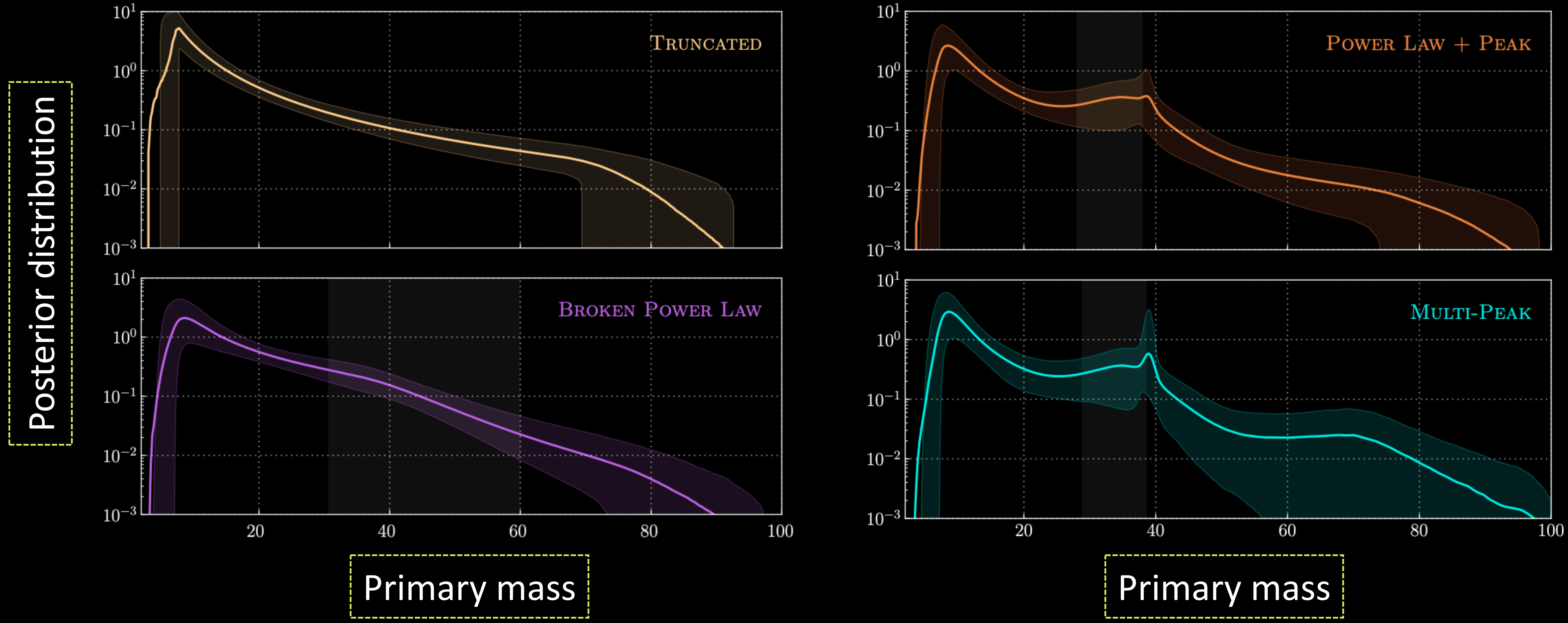
In the case of PPISN: expect a peak and then a truncation; in the case of PISN only: just a truncation



Spin alignment and mass ratio can serve as further evidence for the binary's environment/merger history

Baxter, DC, McDermott, Sakstein, work in progress

Binary mergers in LIGO/Virgo O3a



Adapted from LIGO-Virgo, arXiv: 2010.14533 [astro-ph.HE]

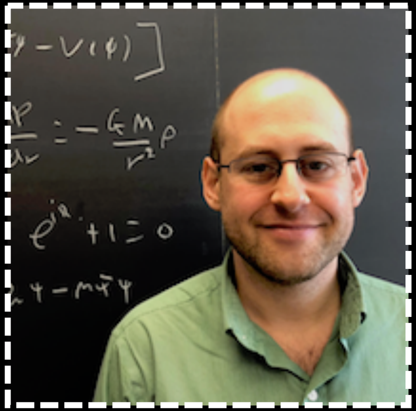
To conclude,

- 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!

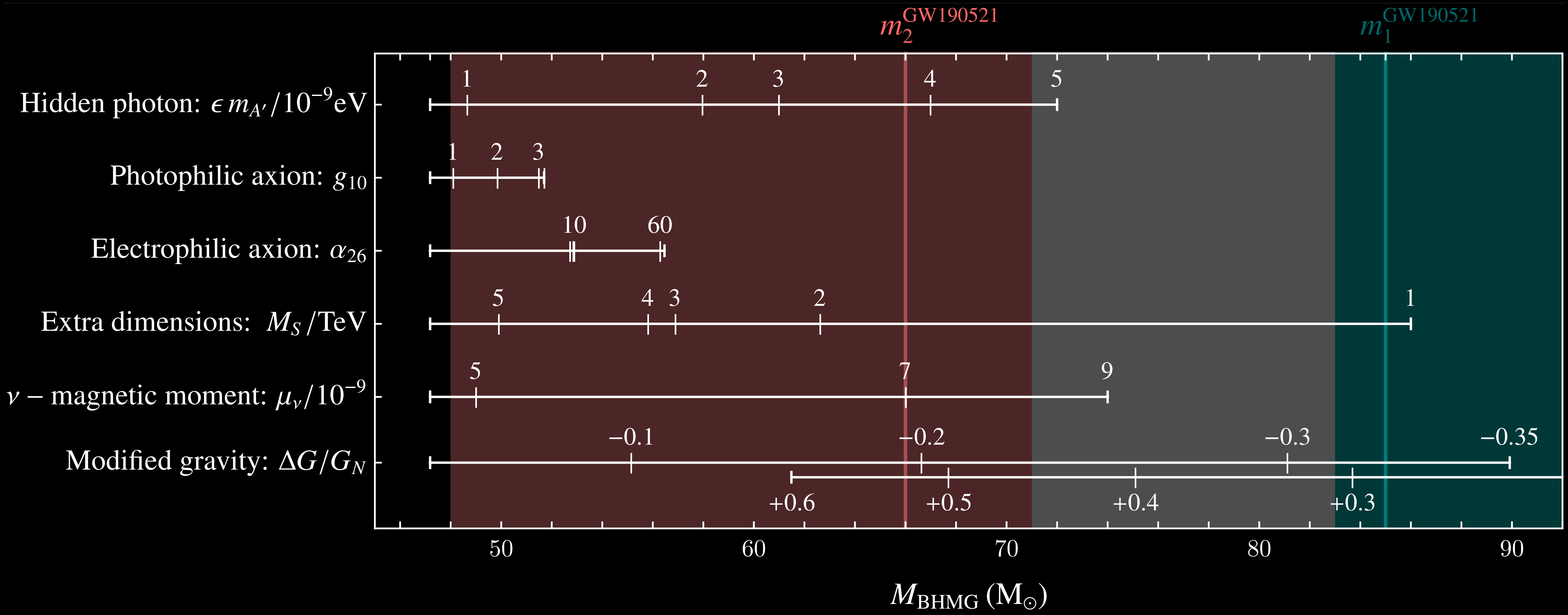
…ask me anything you like!

dcroon@triumf.ca | djunacroon.com

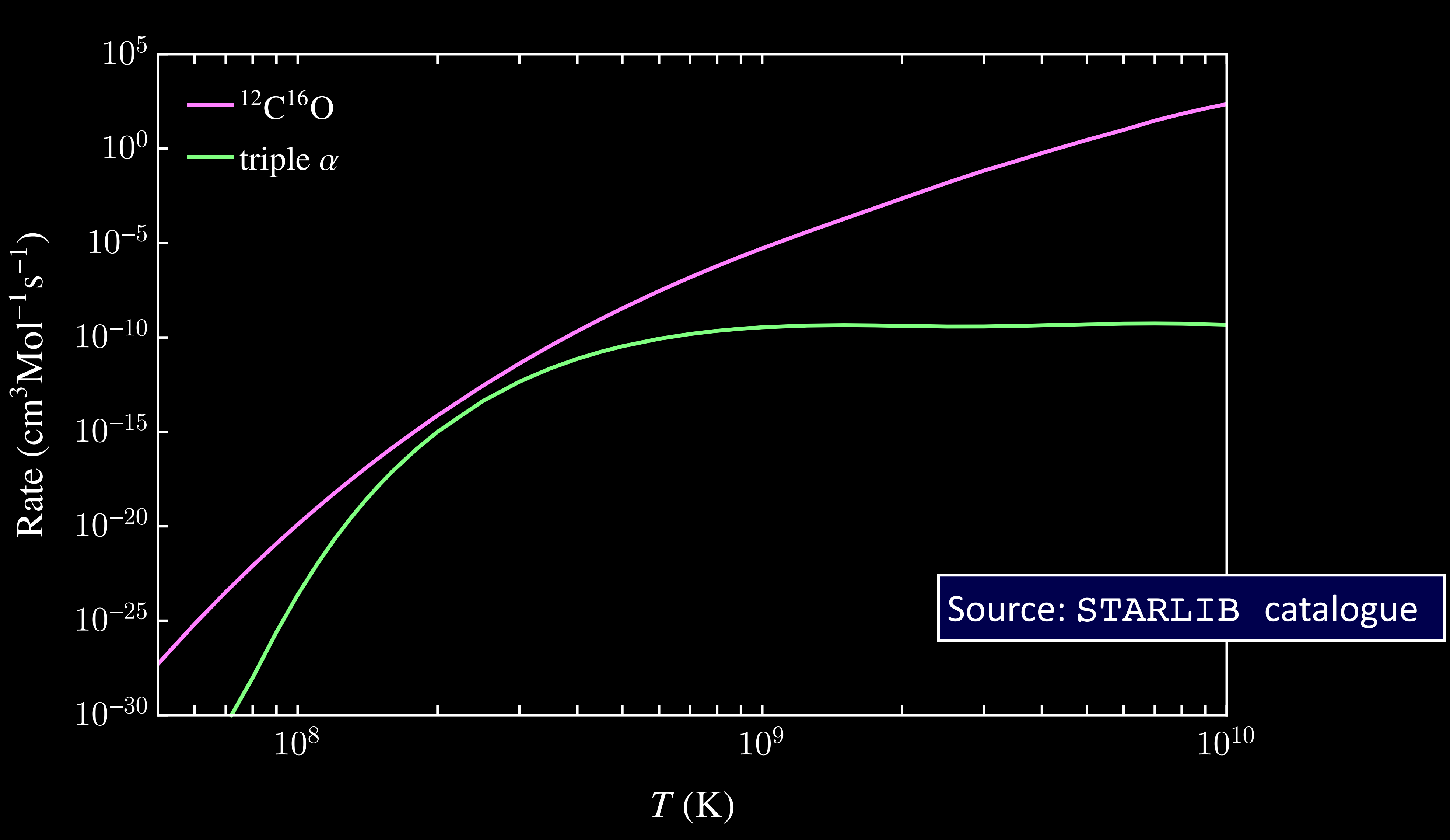
GW190521, the impossible black holes

… and Beyond the Standard Model physics

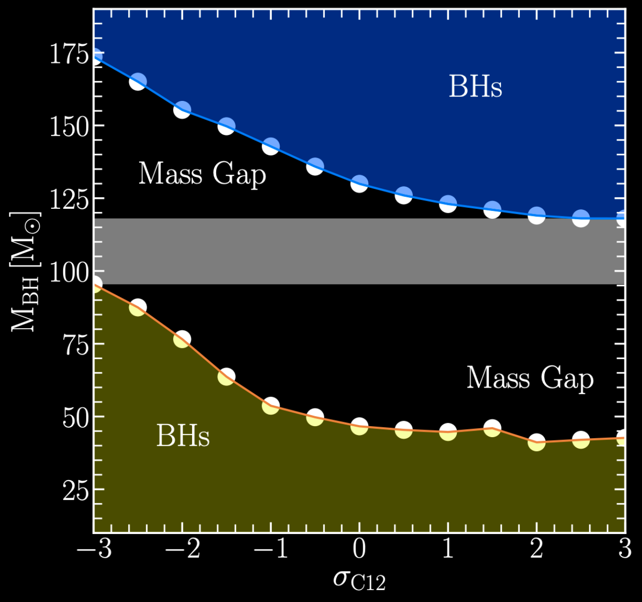


Sakstein, DC, McDermott, Straight, Baxter arXiv:2009.01213 [gr-qc]

Helium burning rates as a function of T

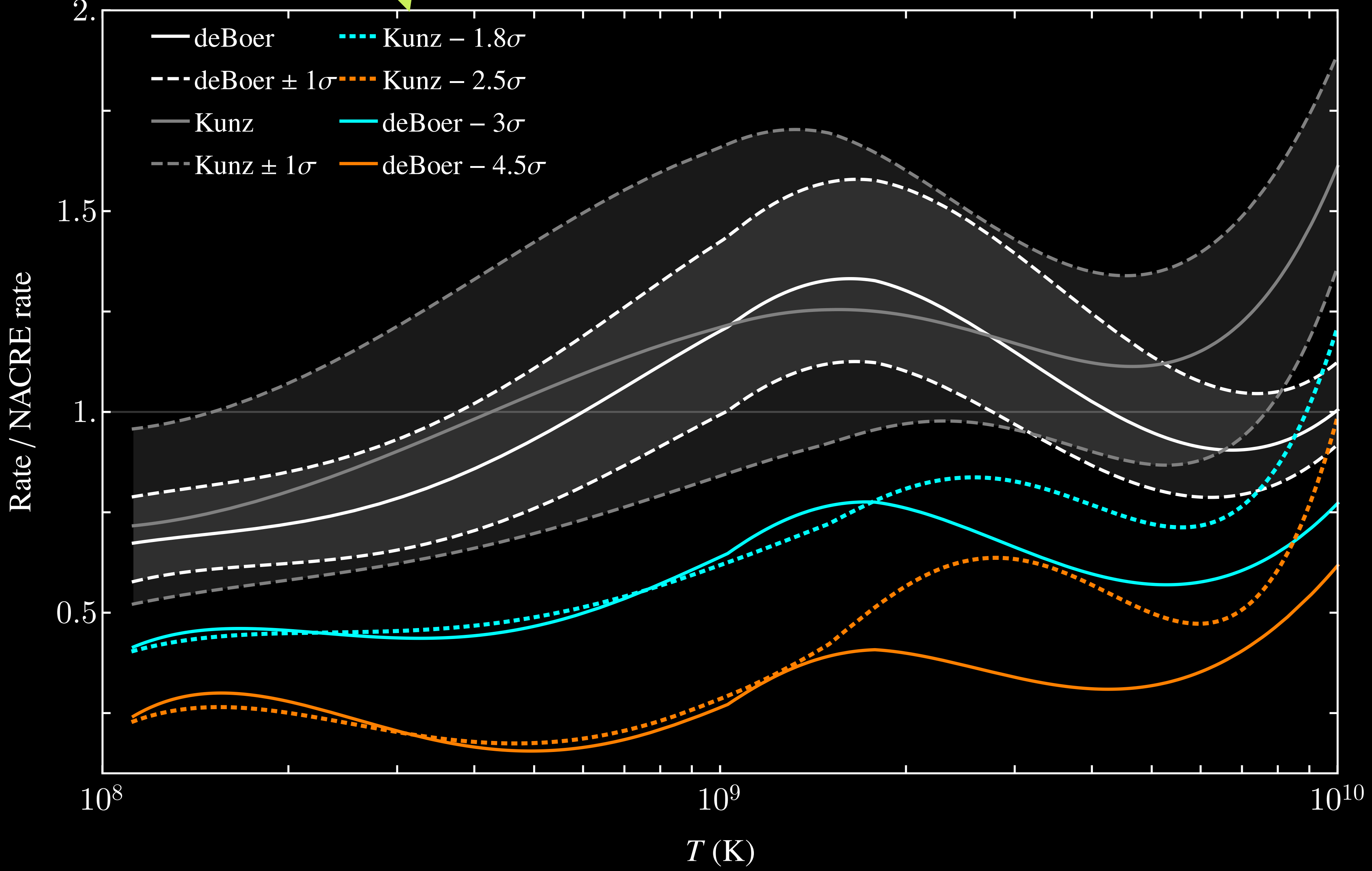


Farmer, Renzo, de Mink, Fishbach, Justham arXiv:2006.06678 [astro-ph.SR]



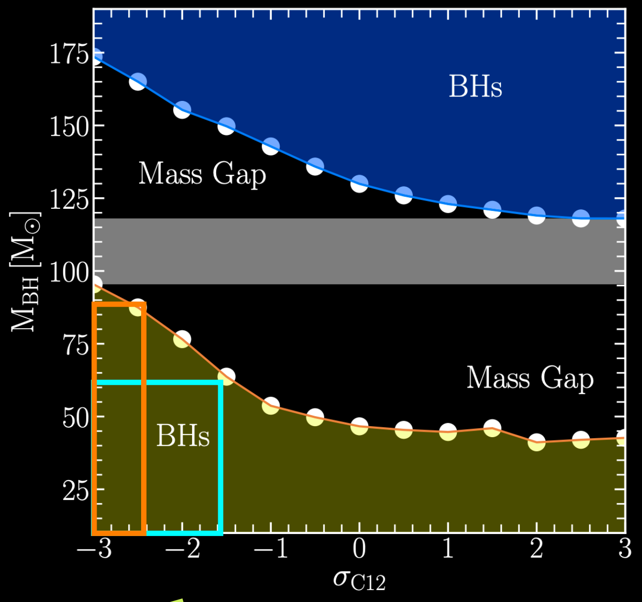
(Kunz is currently used in STARLIB)

Fitting GW190521 masses m_1 and m_2

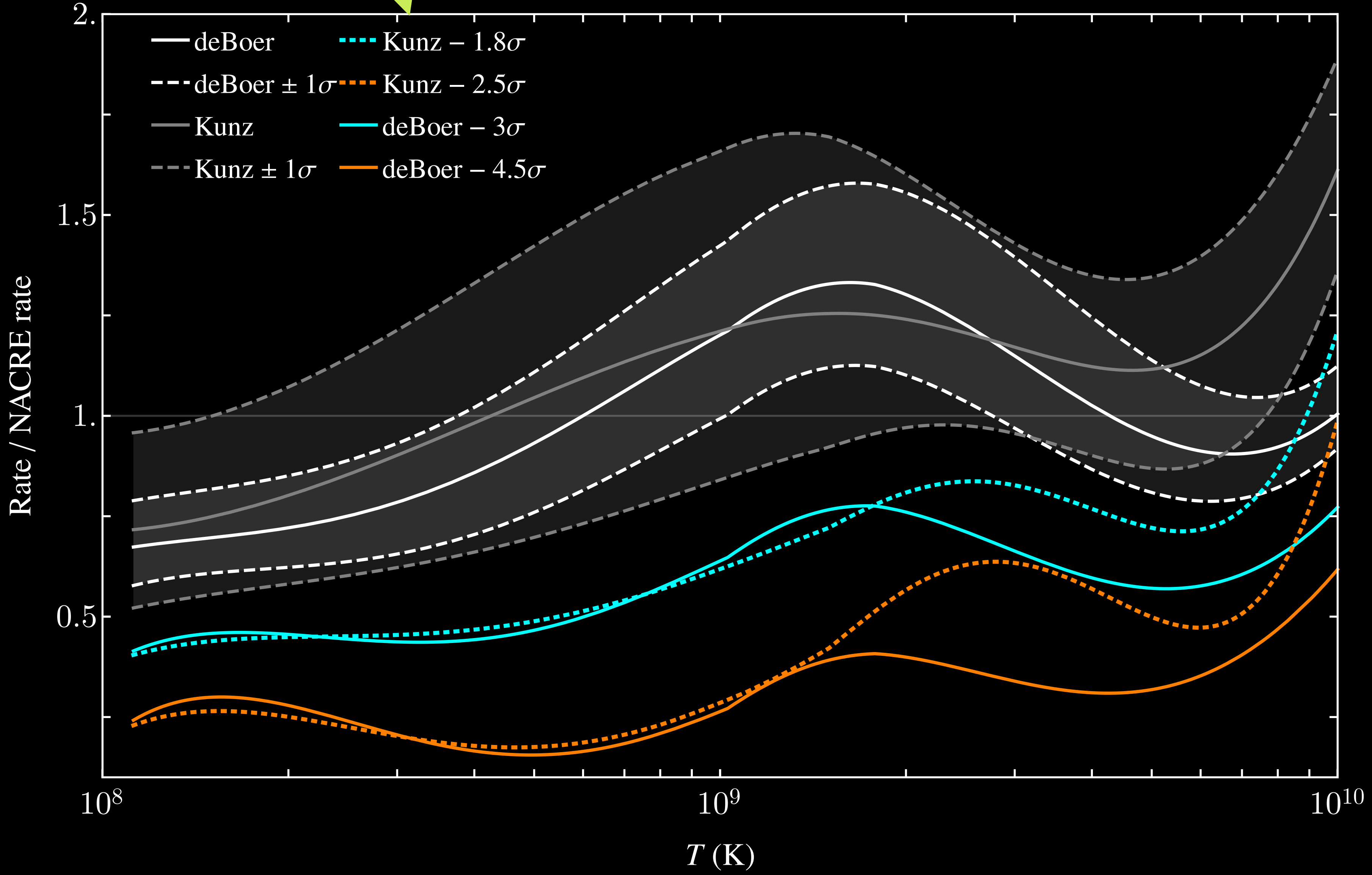


Farmer, Renzo, de Mink, Fishbach, Justham arXiv:2006.06678 [astro-ph.SR]

(Kunz is currently used in `STARLIB`)



Fitting GW190521 masses m_1 and m_2



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

Binary merger events ($M_1 \approx M_2$)

- >50 LIGO/Virgo observations
  - 2017 Nobel Prize in Physics

- *Can be used to learn about new physics in various ways*

- Most GW radiation from the inspiral phase, ending in $f_{\rm ISCO}$

- Solvable in a (v/c) expansion

  → Weak gravity, small velocity

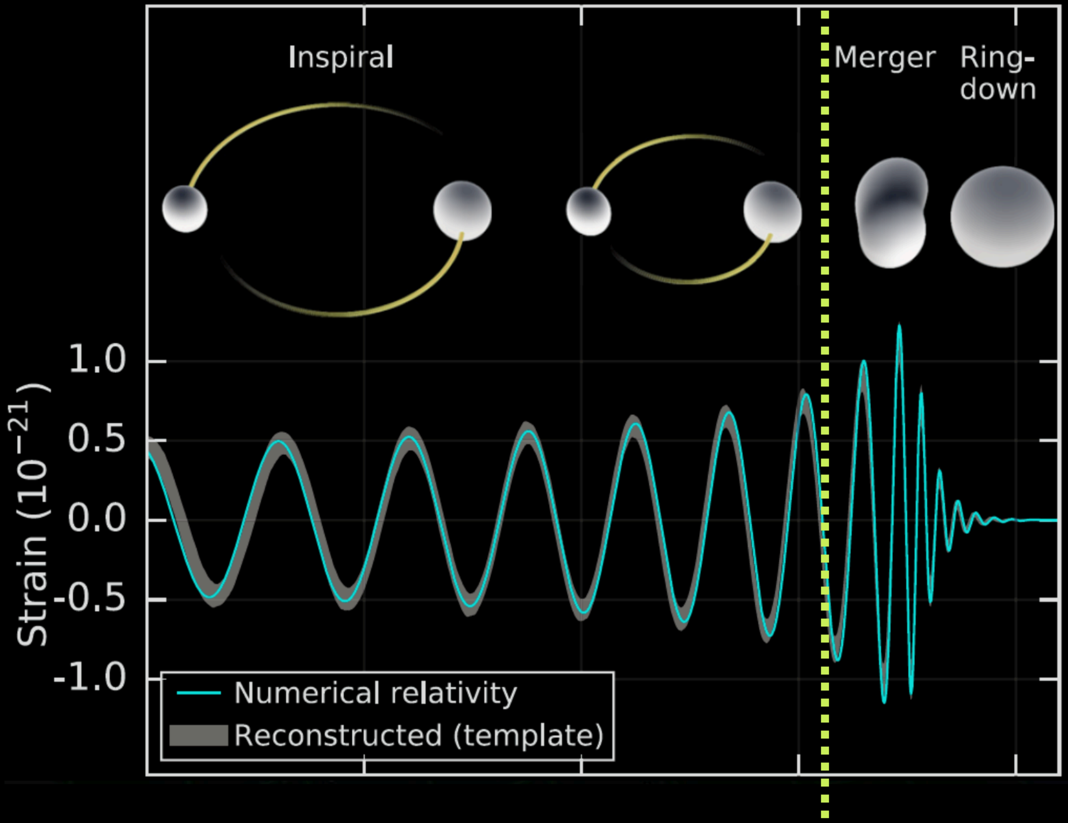


Image credit: LIGO collaboration

$$f_{\rm ISCO} = \frac{C_*^{3/2}}{3^{3/2}\,\pi\, G_N (M_1 + M_2)}$$

Compact object merger sensitivity

- Best detection prospects for

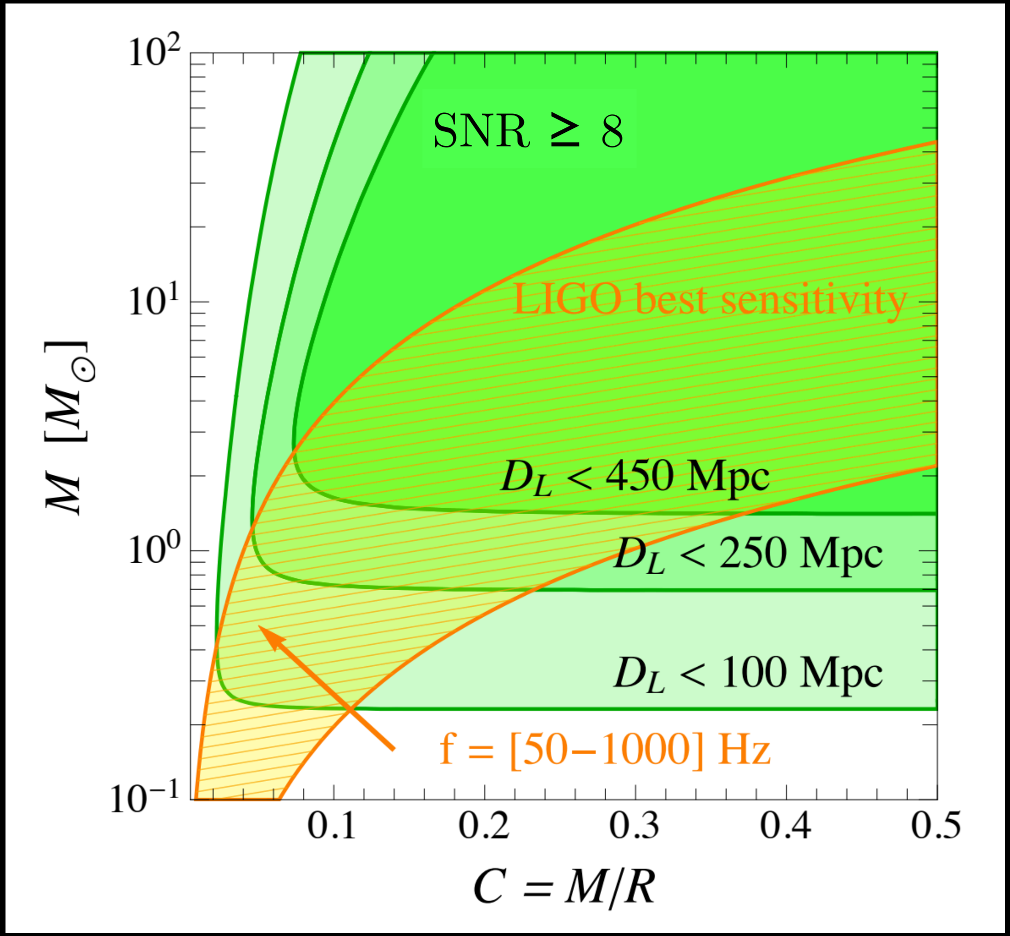
$$f_{\rm min} < f_{\rm peak} \sim f_{\rm ISCO} < f_{\rm max}$$

- Defines an CO sensitivity band

$$f_{\rm ISCO} = \frac{C_*^{3/2}}{3^{3/2}\,\pi\, G_N (M_1 + M_2)} \qquad C_* = \frac{G_N M_*}{R_*}$$

$$C_\odot = 2 \times 10^{-6} \qquad C_{\rm BH} = 0.5$$
$$C_\oplus = 7 \times 10^{-10} \qquad C_{\rm NS} \sim 0.1$$

- Sensitivity determined by masses, compactness and luminosity distance



Giudice, McCullough, Urbano [JCAP, 1605.01209]

What can we learn from the inspiral waveform?*

A lot, for example,

1. Component masses
2. Tidal effects → equation of state
3. Dynamical friction → environmental effects
4. Long-range (dark) forces → BSM effects
5. Extra dissipation channels → BSM effects
6. Redshift distribution of events → age of objects
7. “Hair”: multipolar metric deviations (EMRIs) → tests of GR

Hints of mass-gap mergers:
- GW190814 → downgraded mass gap probability <1% → publication June ‘20
- GW190924 (24 September ‘19)
- GW190930 (30 September ’19)

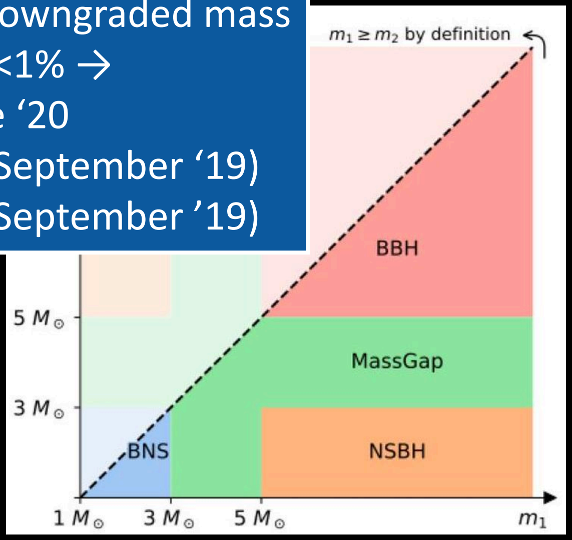


Image credit: LIGO collaboration

So what about new physics? May show up in various ways, I will give a (unabashedly biased) selection of examples

**Further information could come (for example) from multi-messenger signals (or absence thereof), or post-merger quasi-normal modes or “echoes”*