New physics and the Black Hole Mass Gap

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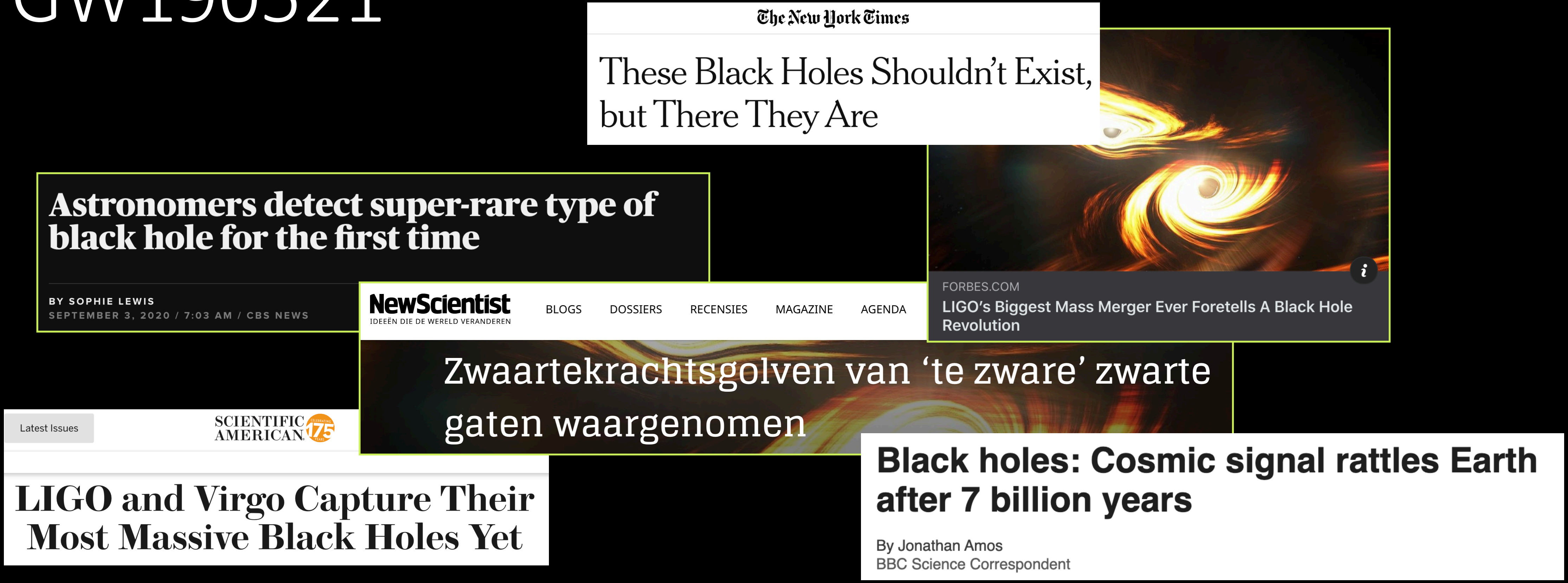
GW190521



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

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

NewScientist
IDEEËN DIE DE WERELD VERANDEREN

Zwaartekrachtsgolven van 'te zware' zwarte gaten waargenomen

SCIENTIFIC AMERICAN

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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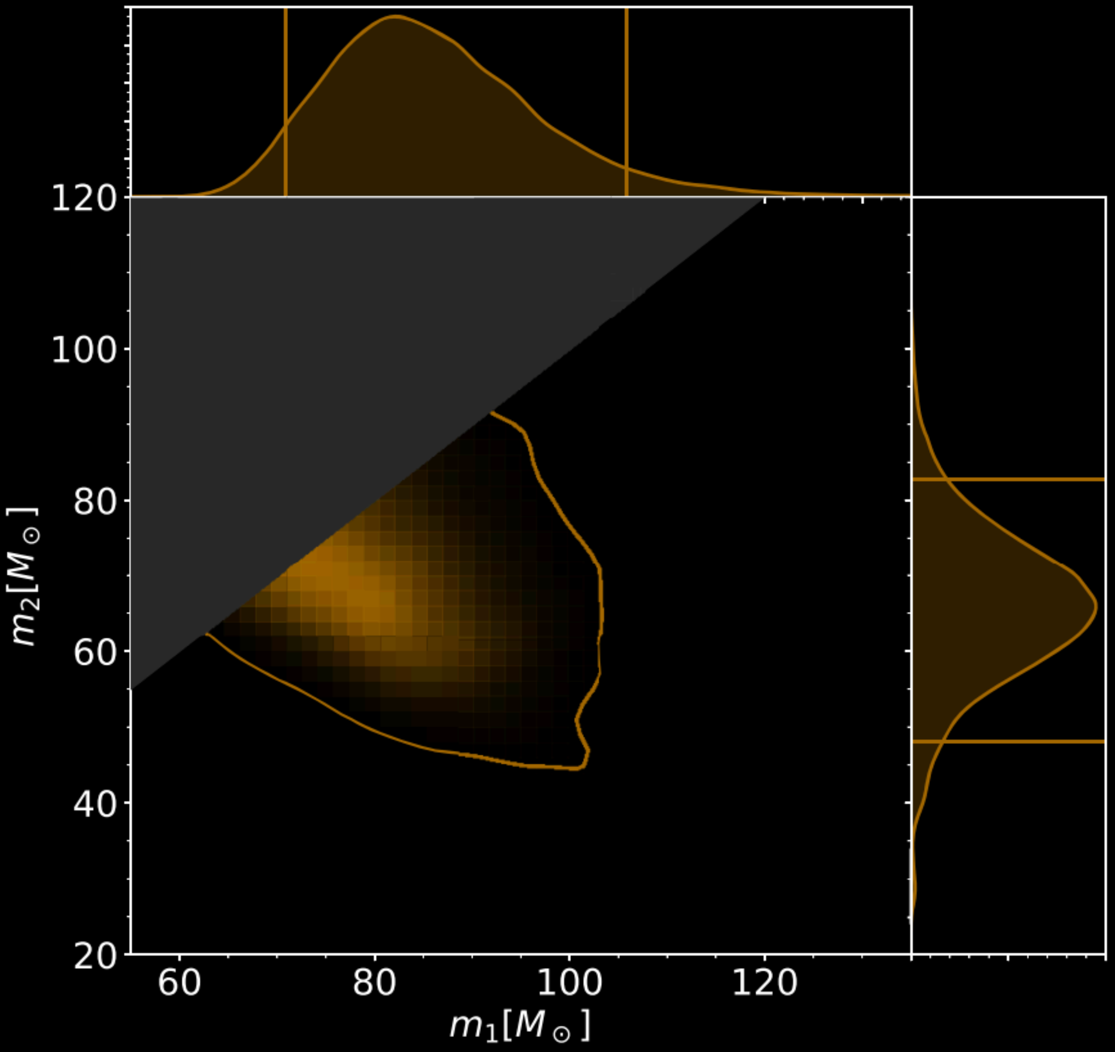

LIGO/Virgo's biggest discovery yet: the *impossible* black holes

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

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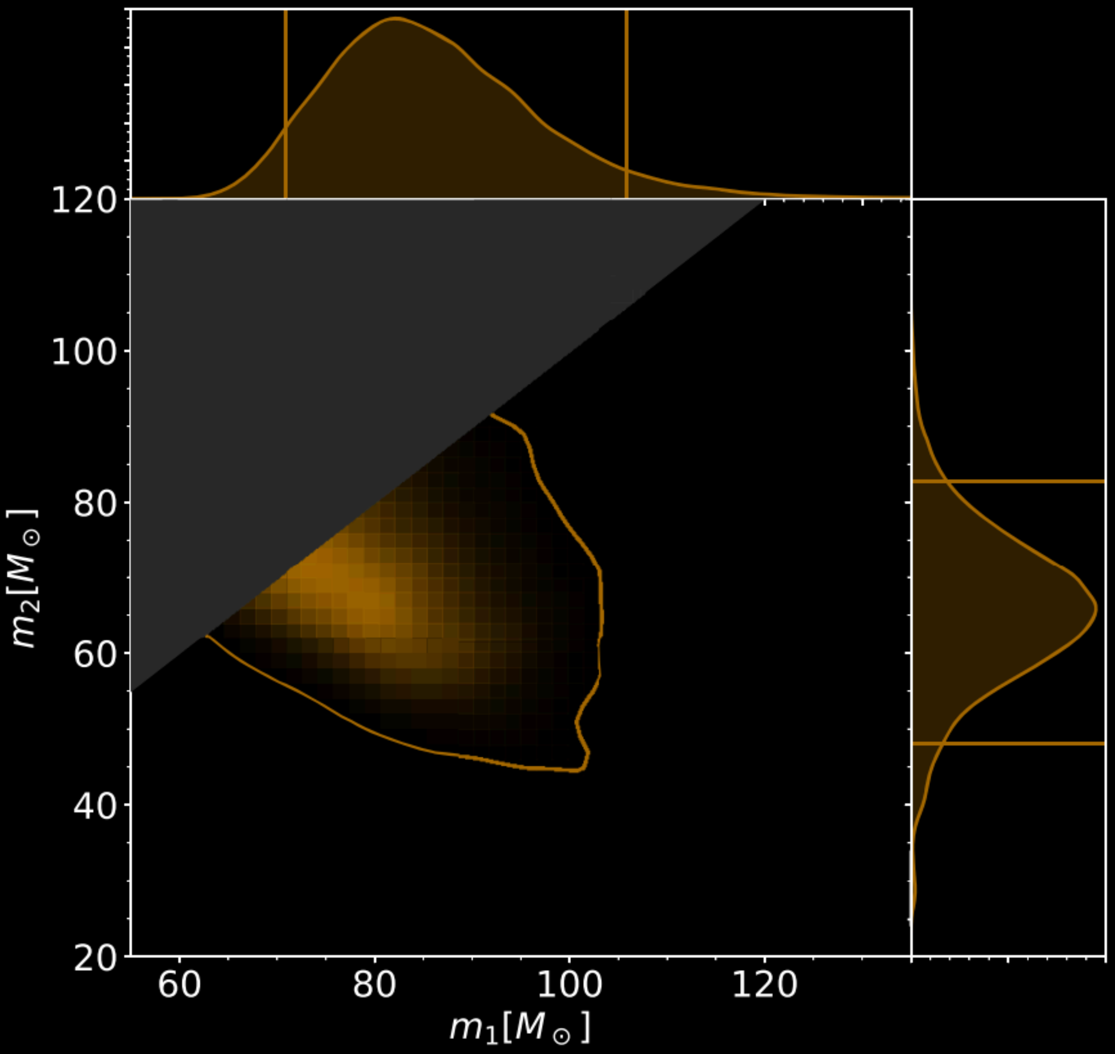


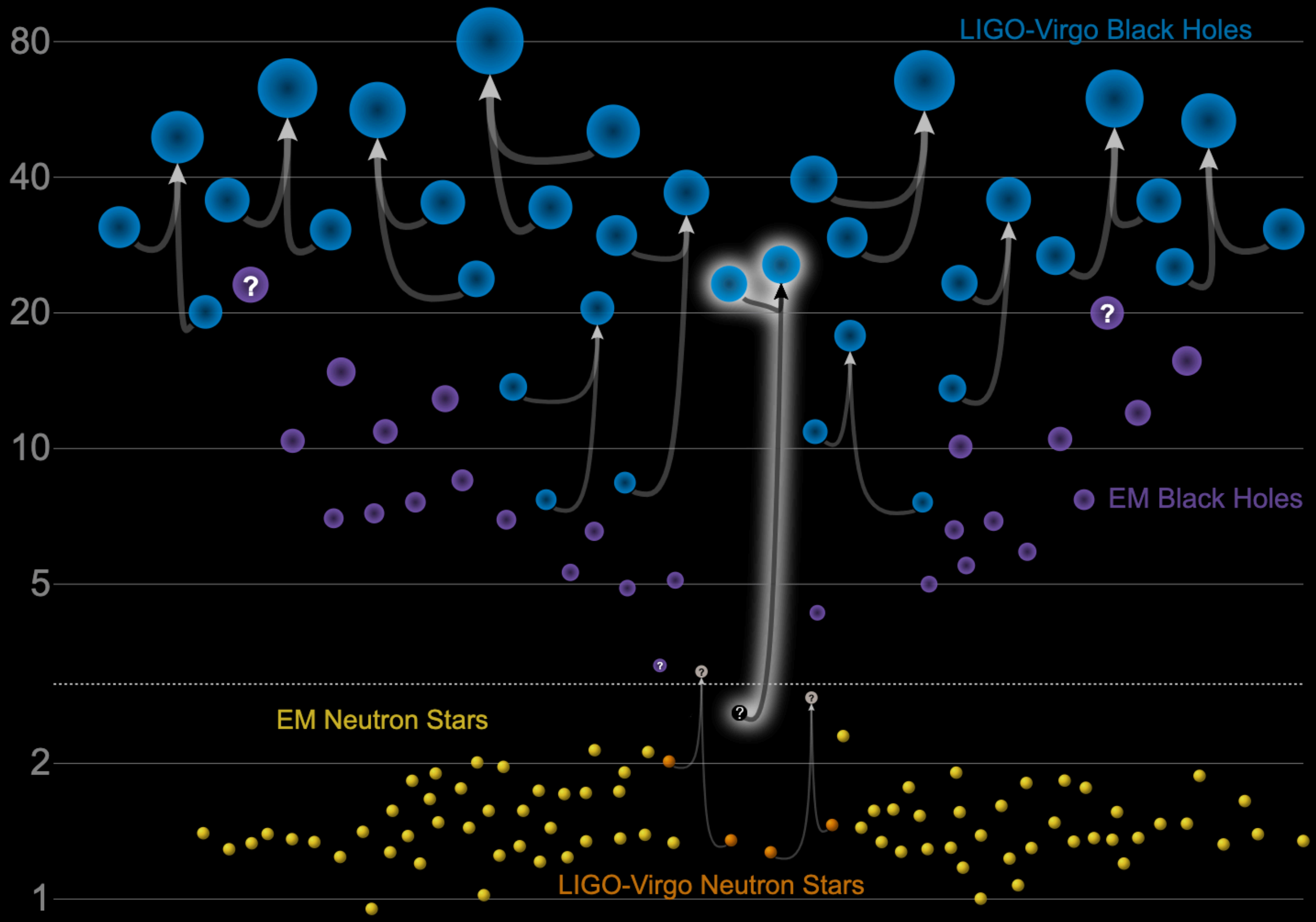
From R. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. 125, 101102 (2020).

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

… let’s wind back a bit

Binary mergers in LIGO/Virgo O1+O2

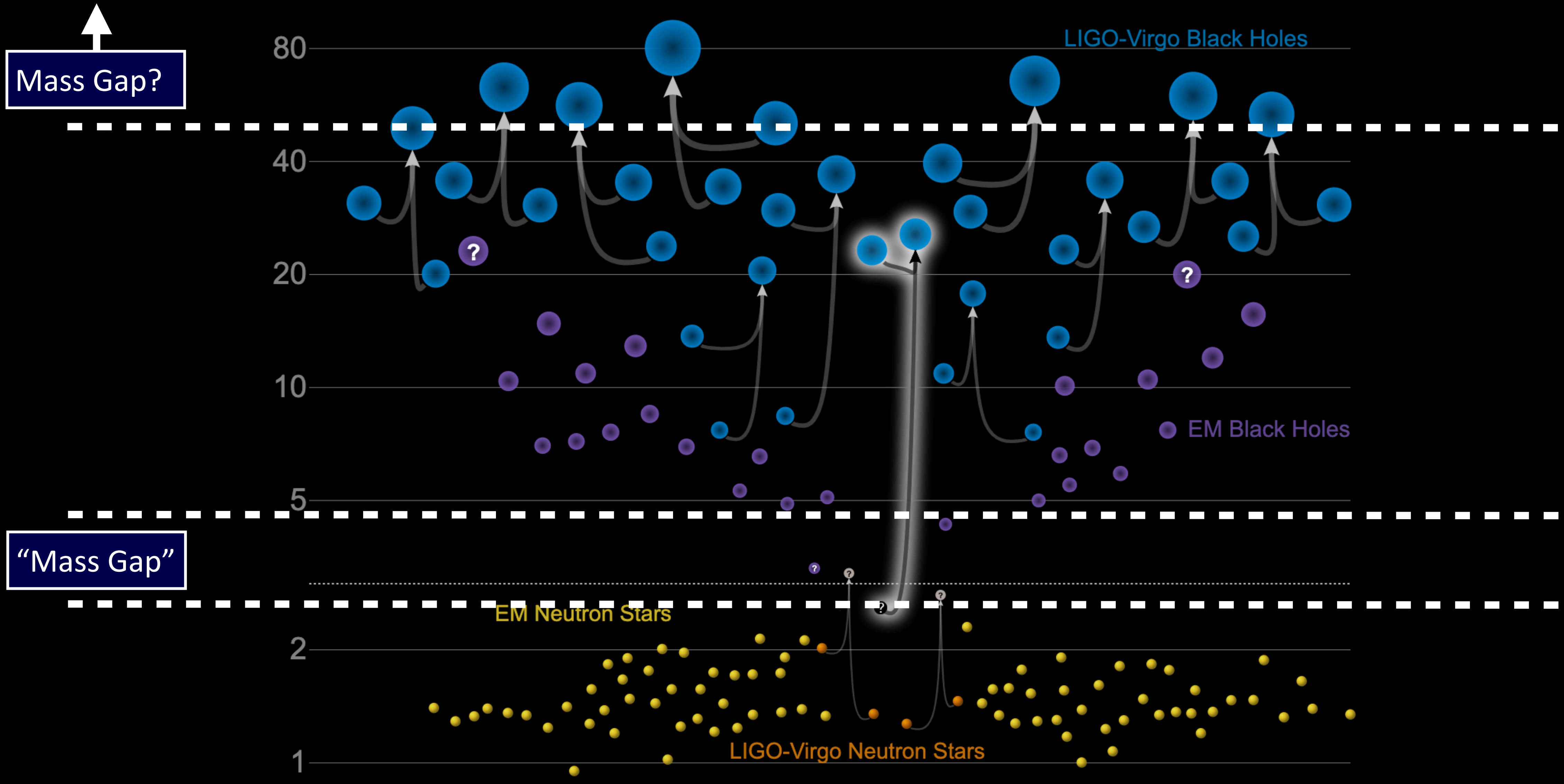
“The Stellar Graveyard”



Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

Binary mergers in LIGO/Virgo O1+O2

“The Stellar Graveyard”



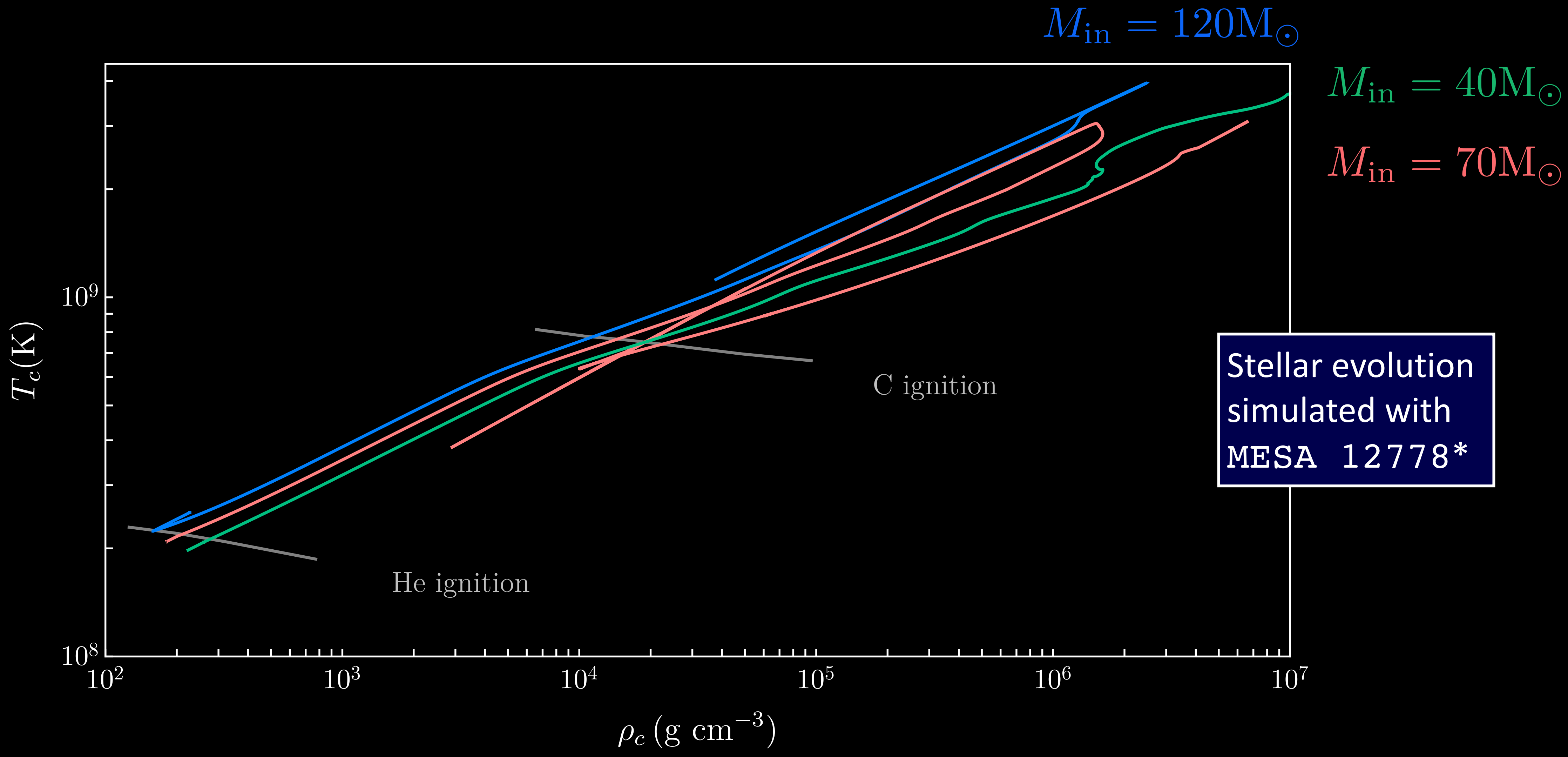
Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

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*`

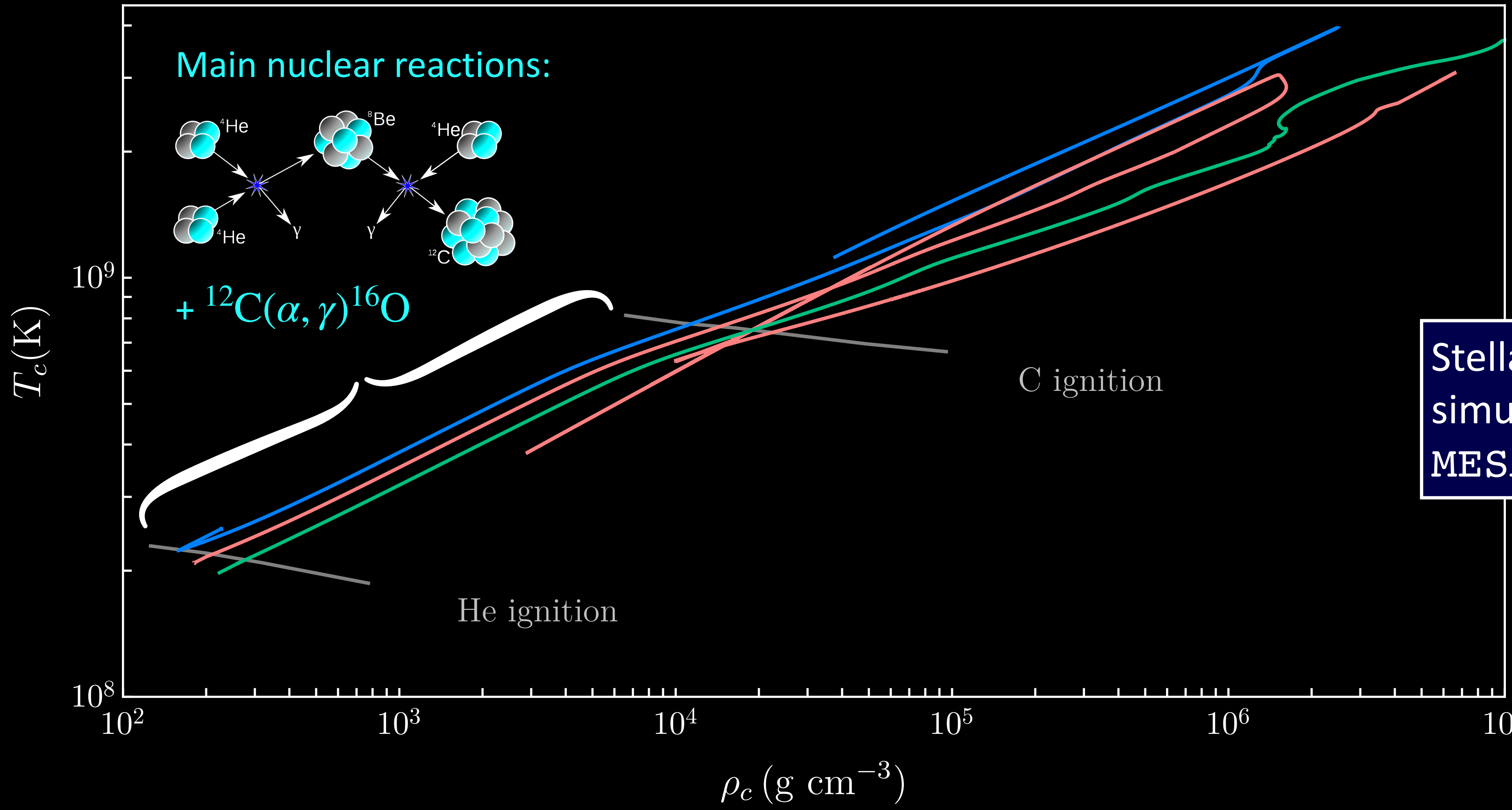
**Paxton et al, arXiv:1710.08424 [astro-ph.SR]*

Evolution of old population-III stars

$M_{\rm in} = 120 M_\odot$

$M_{\rm in} = 40 M_\odot$

$M_{\rm in} = 70 M_\odot$



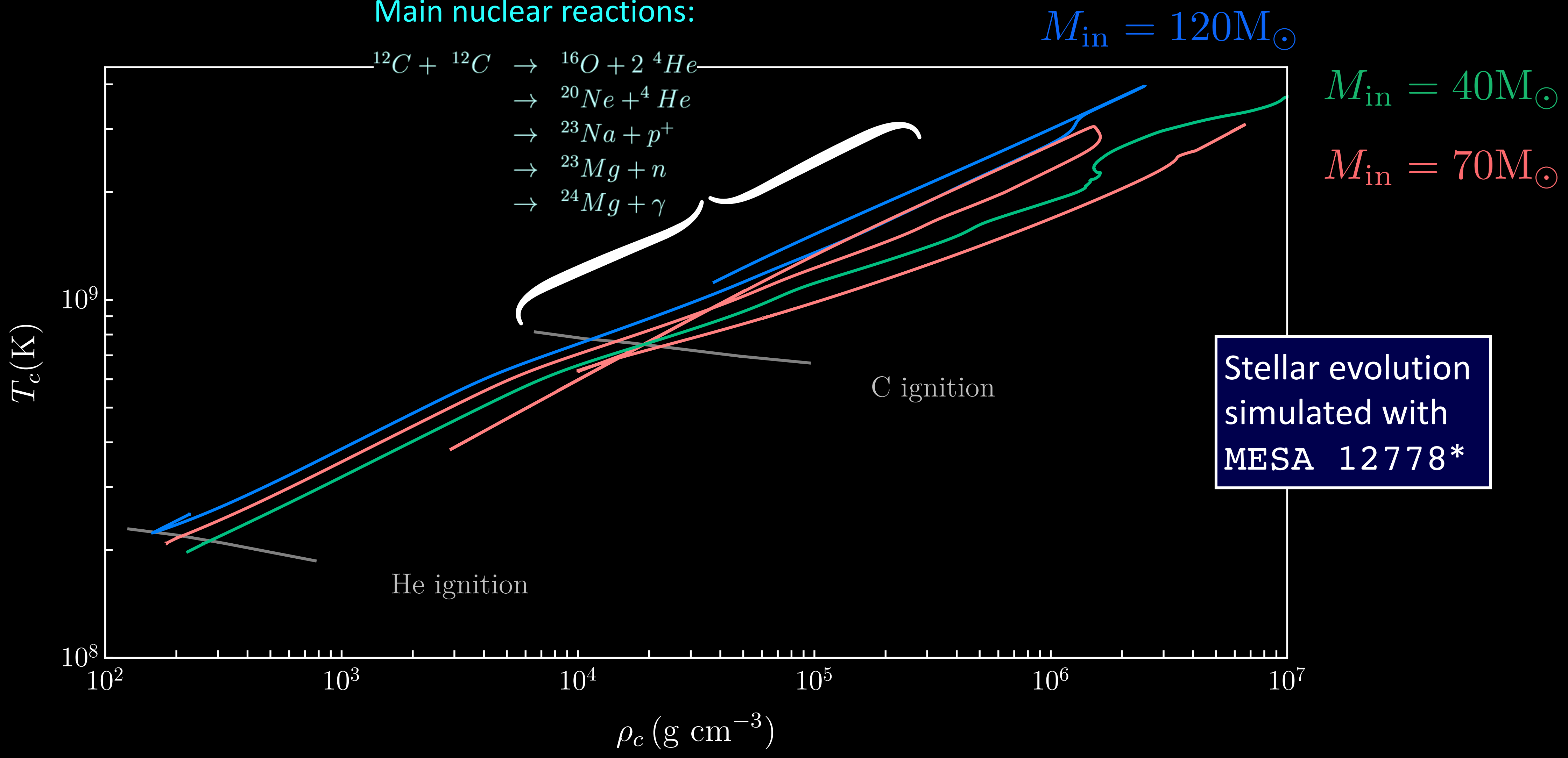
Stellar evolution simulated with
`MESA 12778*`

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

Evolution of old population-III stars

Main nuclear reactions:

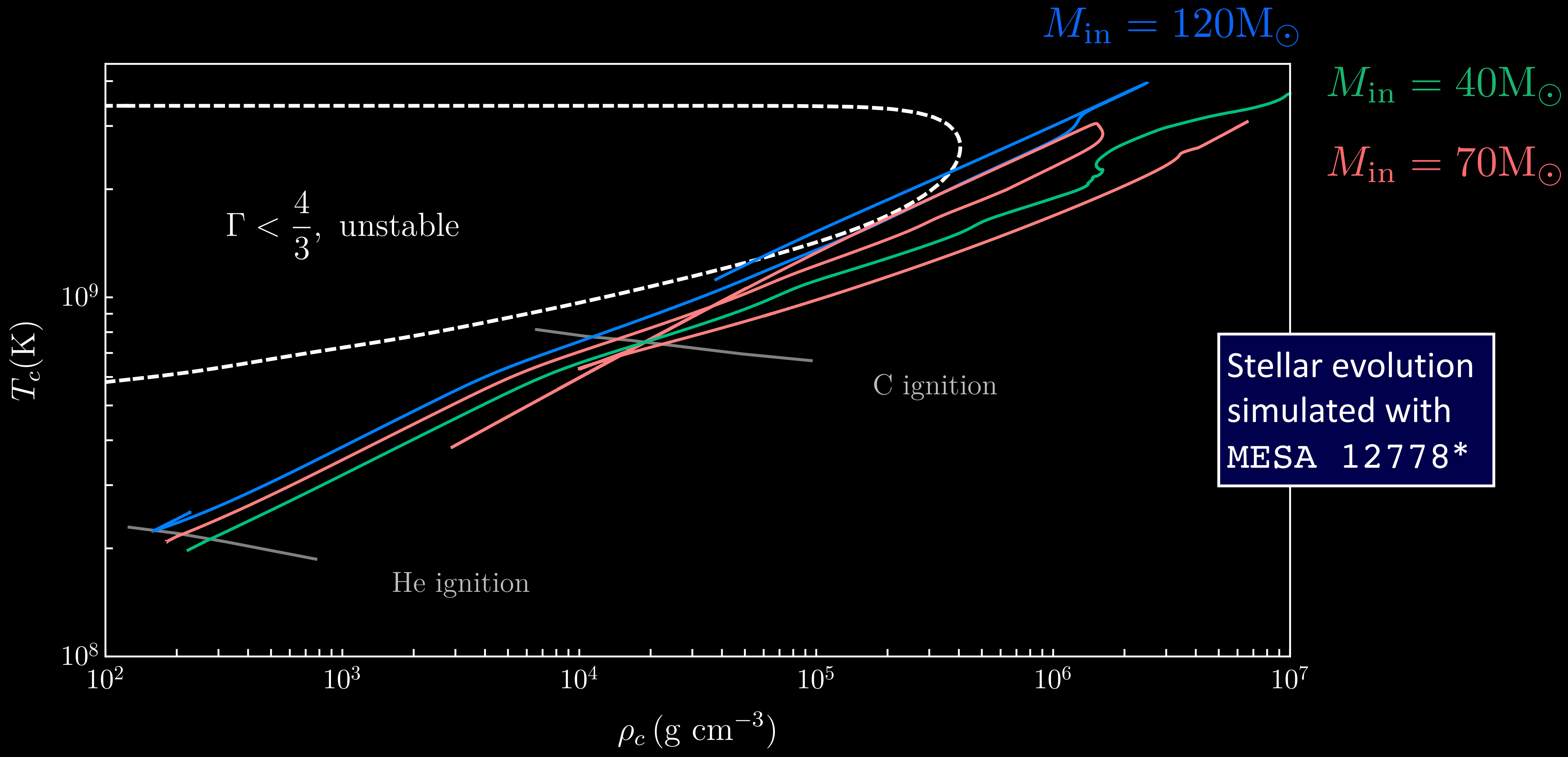
$$
\begin{aligned}
{}^{12}C + {}^{12}C &\rightarrow {}^{16}O + 2\,{}^{4}He \\
&\rightarrow {}^{20}Ne + {}^{4}He \\
&\rightarrow {}^{23}Na + p^{+} \\
&\rightarrow {}^{23}Mg + n \\
&\rightarrow {}^{24}Mg + \gamma
\end{aligned}
$$



Stellar evolution simulated with `MESA 12778`*

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

Evolution of old population-III stars



Stellar evolution simulated with `MESA 12778*`

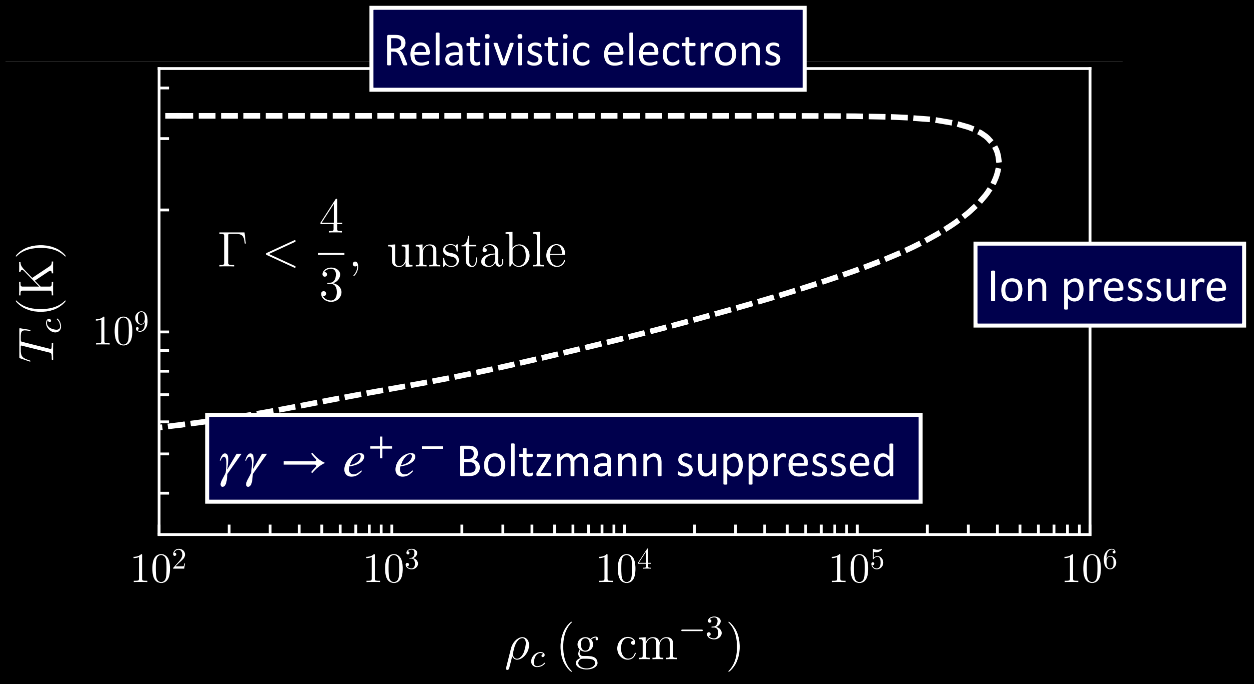
**Paxton et al, arXiv:1710.08424 [astro-ph.SR]*

Pair-instability

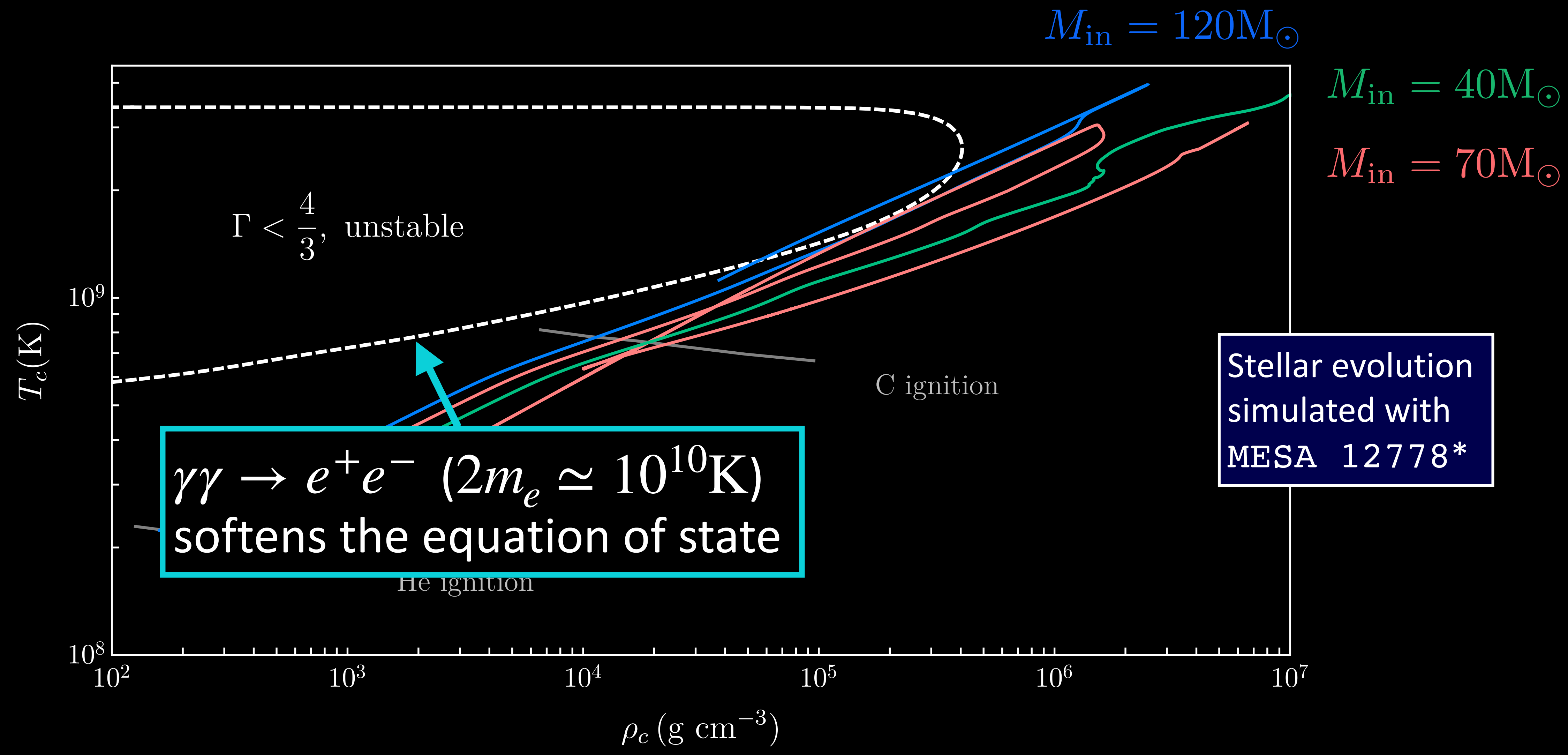
- The high temperatures of the pop-III stars lead to electron-positron pair creation in the thermal plasma via $\gamma\gamma \rightarrow e^+e^-$ $(2m_e \simeq 10^{10}\mathrm{K})$

- 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



Evolution of old population-III stars



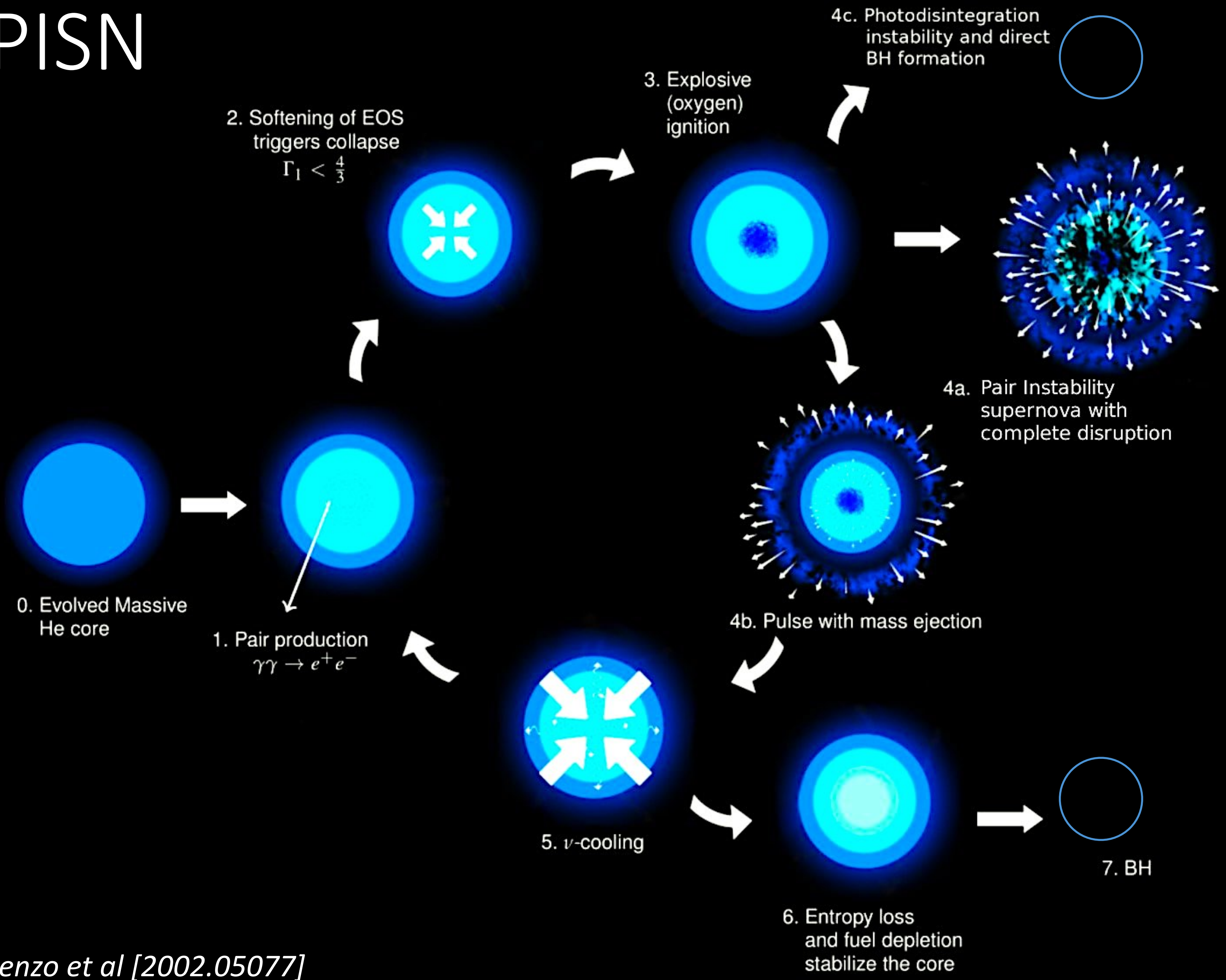
$\gamma\gamma \to e^+e^-$ $(2m_e \simeq 10^{10}\text{K})$

softens the equation of state

Stellar evolution simulated with `MESA 12778*`

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

(P)PISN



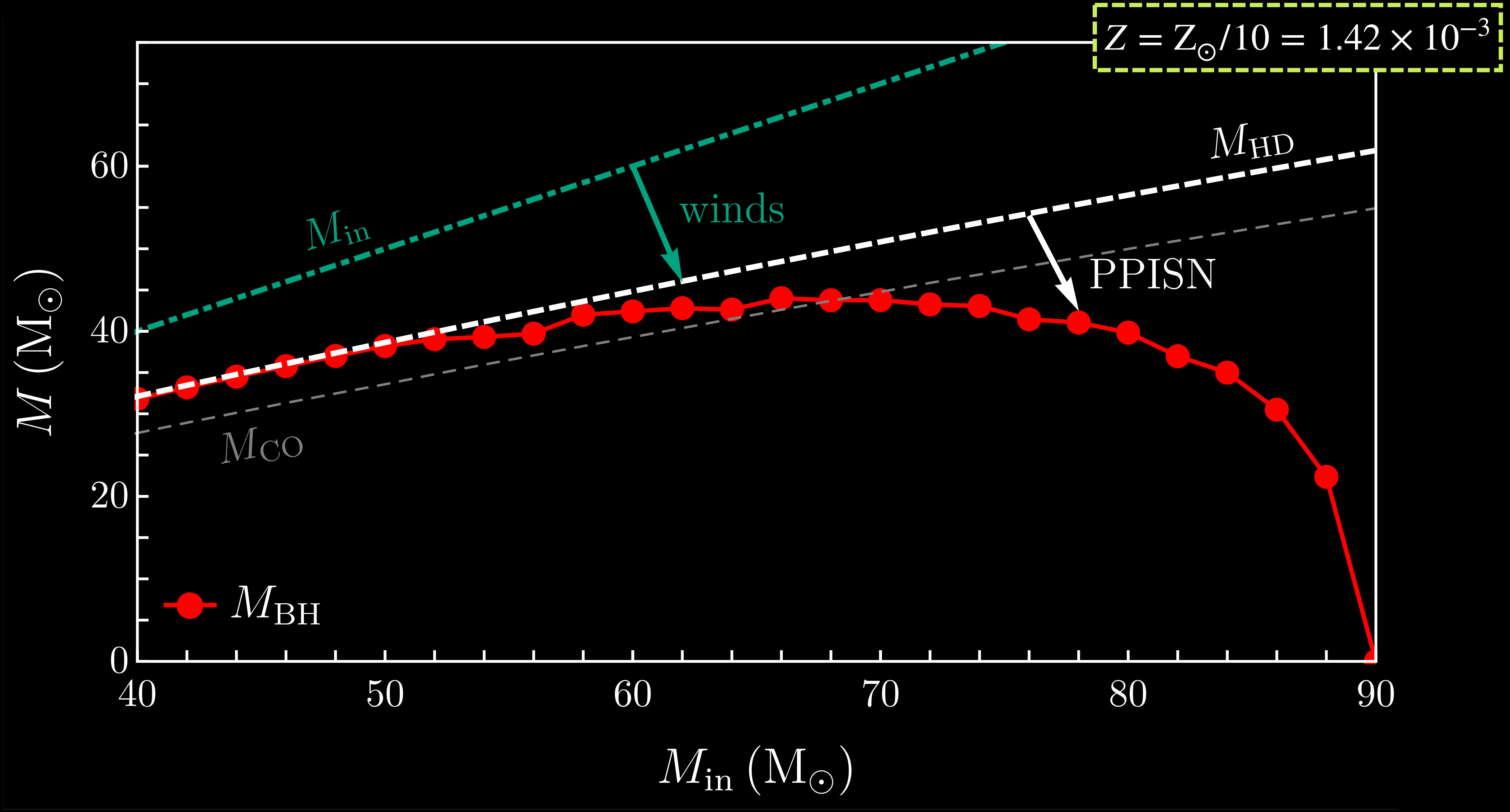
Extremely massive stars ($M_{\rm in} > 200\,{\rm M}_\odot$)

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

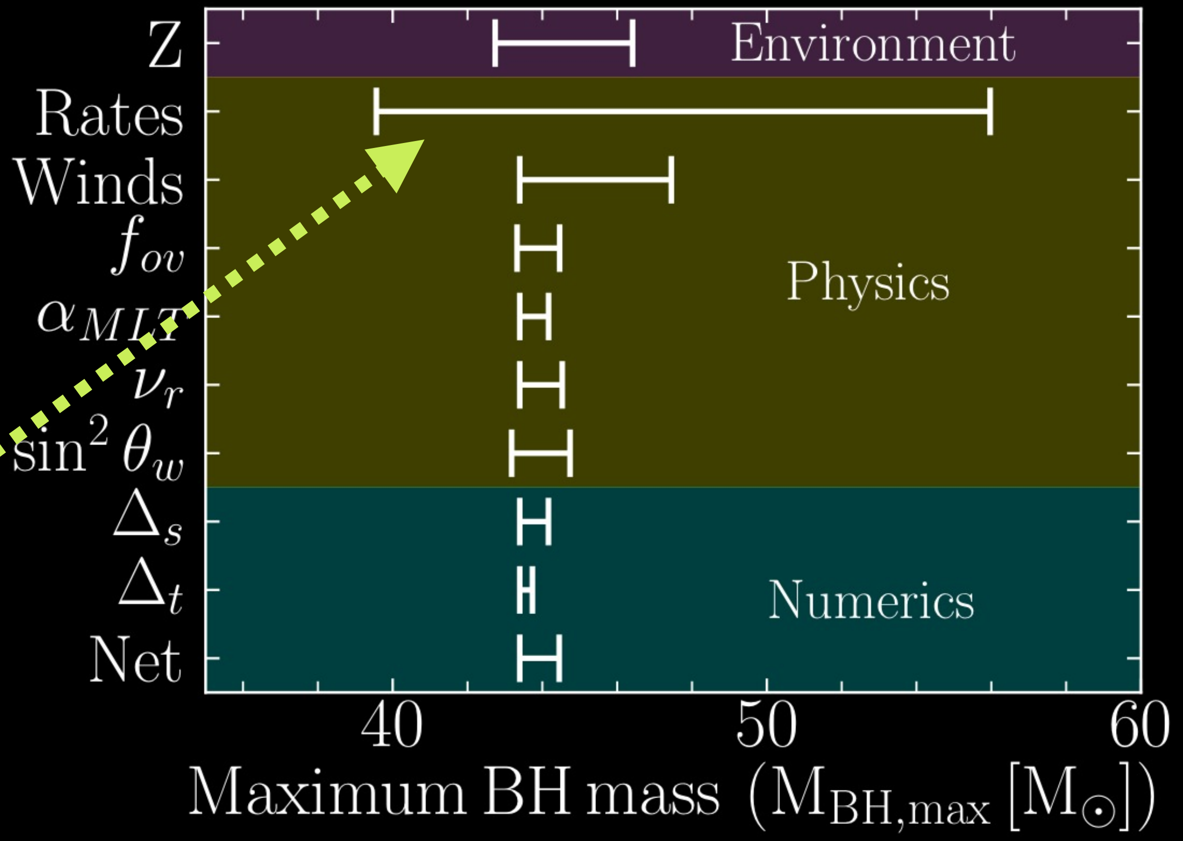


DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

Known physics dependence of the BHMG

- Astrophysical + nuclear + numerical uncertainties
- Most important uncertainty: $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ 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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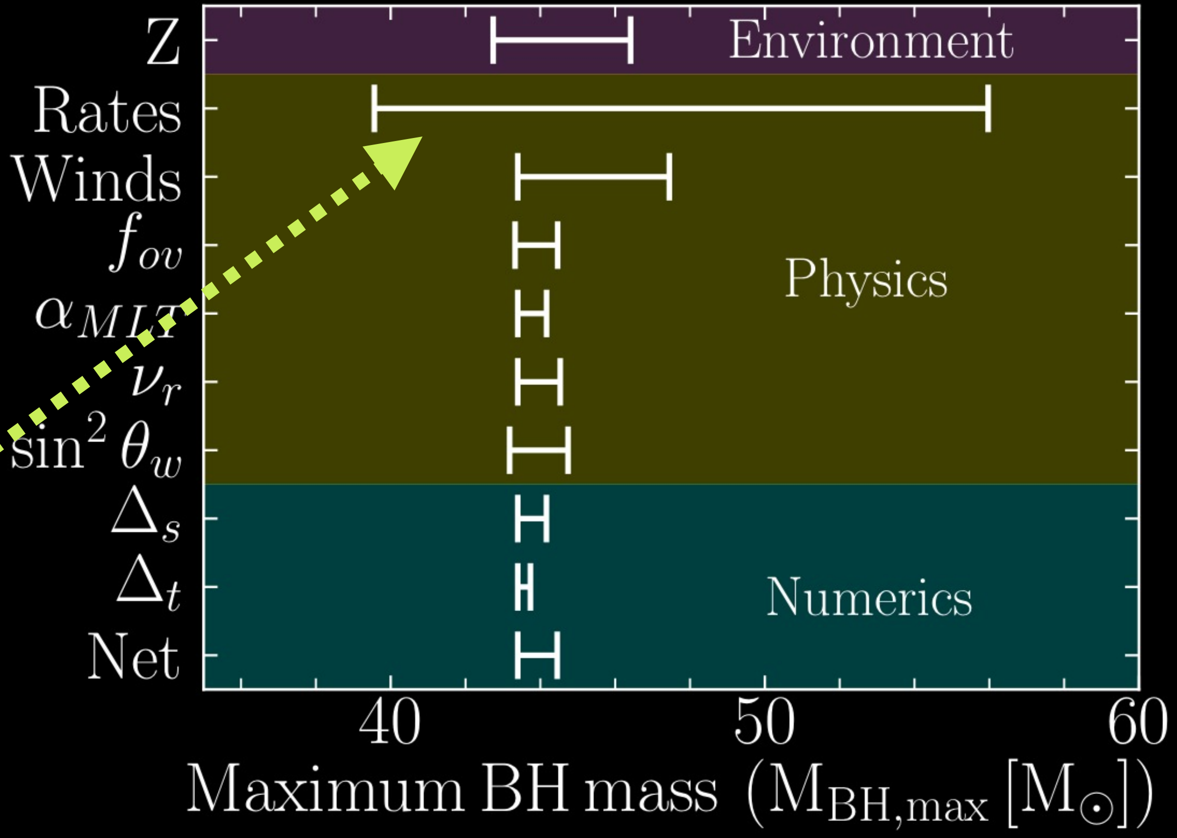
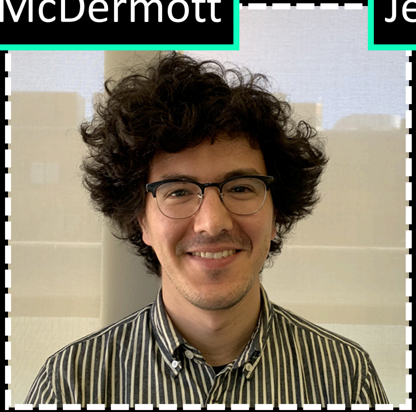


Farmer, Renzo, de Mink, Marchant, Justham arXiv:1910.12874 [astro-ph.SR]

But GW190521?!

What about new physics?


Sam McDermott


Jeremy Sakstein


Eric Baxter


Maria Straight

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]

The BHMG and new physics

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

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

- 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]*

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

Energy loss due to electrophilic axions

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

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

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

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

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

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

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

Energy loss due to electrophilic axions

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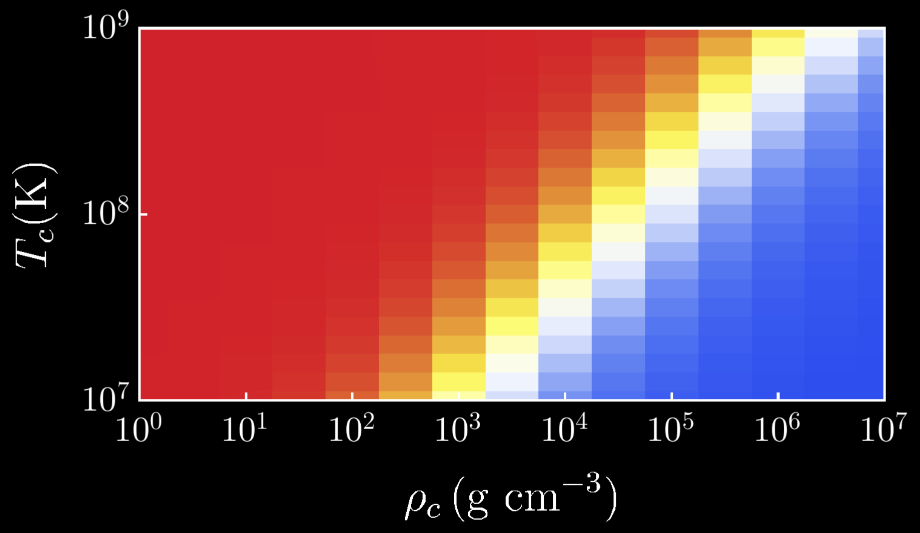
$$F_{\mathrm{deg}} = \frac{2}{n_e}\int \frac{d^3\mathbf{p}}{(2\pi)^3} f_{e^-}(1-f_{e^-}),$$ where f_{e^-} is the Fermi-Dirac distribution

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



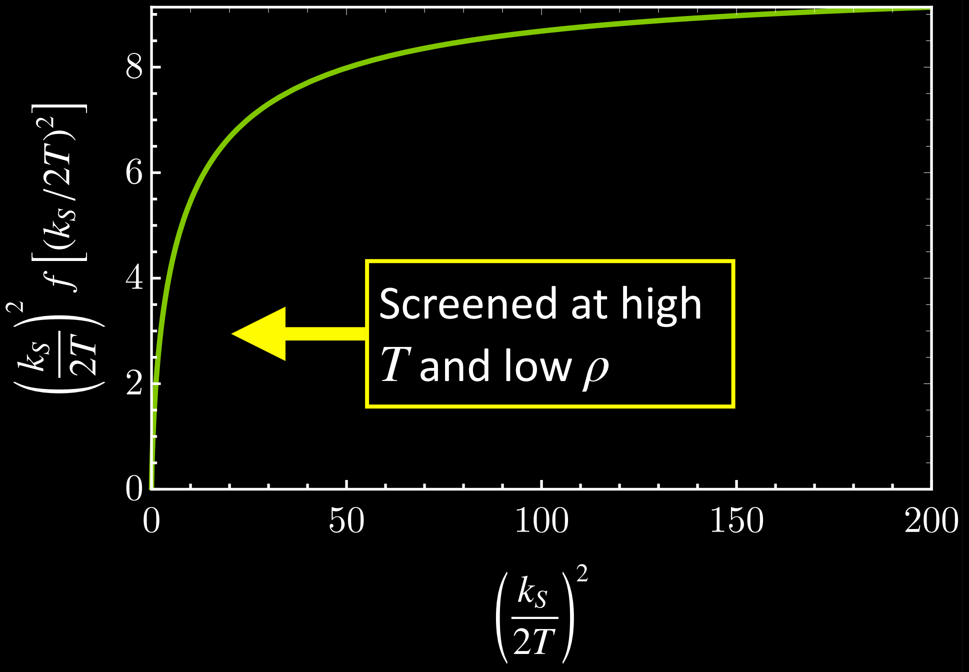
Semi-Compton emission dominates throughout the Helium burning phase

Energy loss due to photophilic axions

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

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

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



Screened at high T and low ρ

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

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)

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

In the limit $\omega_p \ll T$

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

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

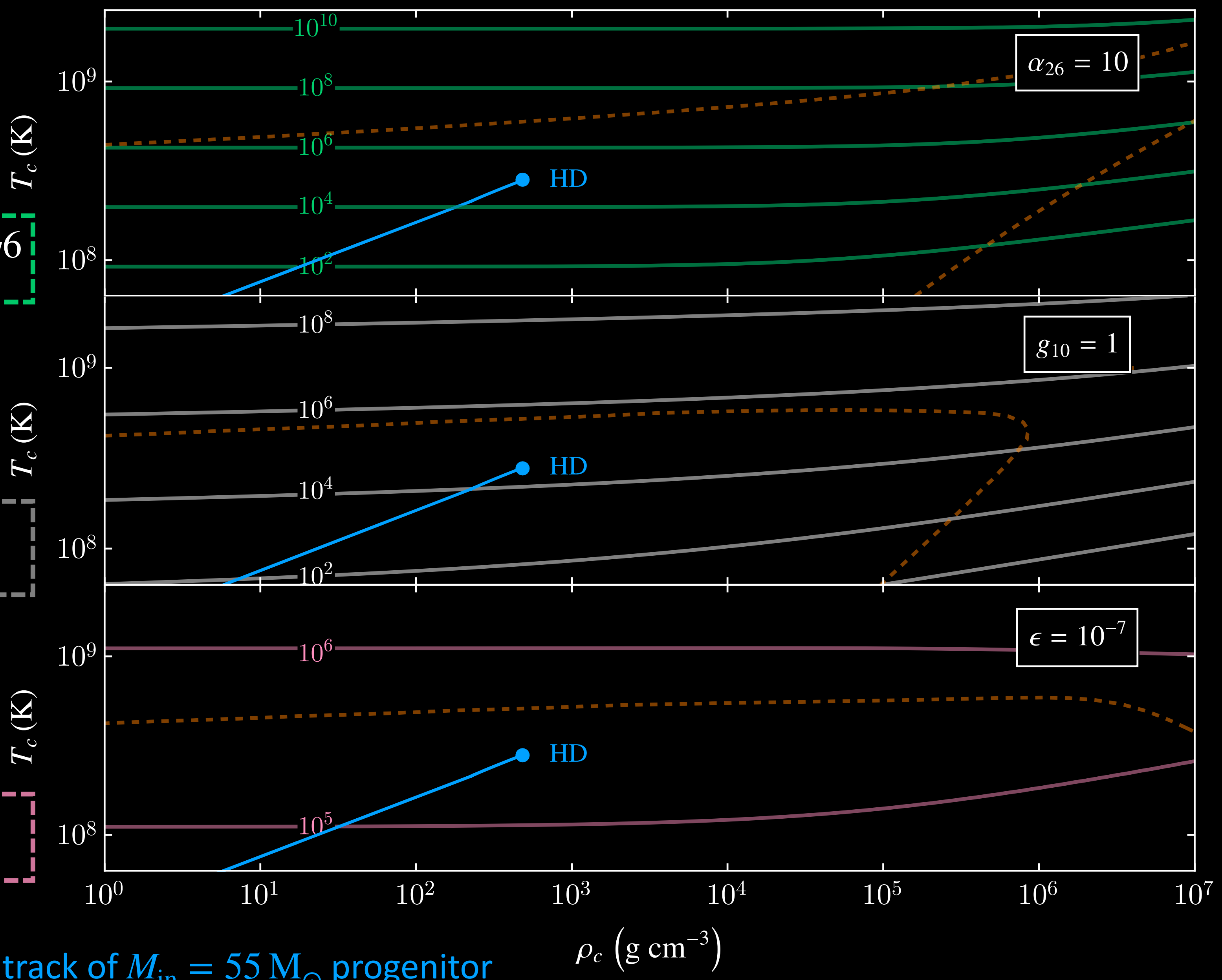
Loss rates

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

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

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

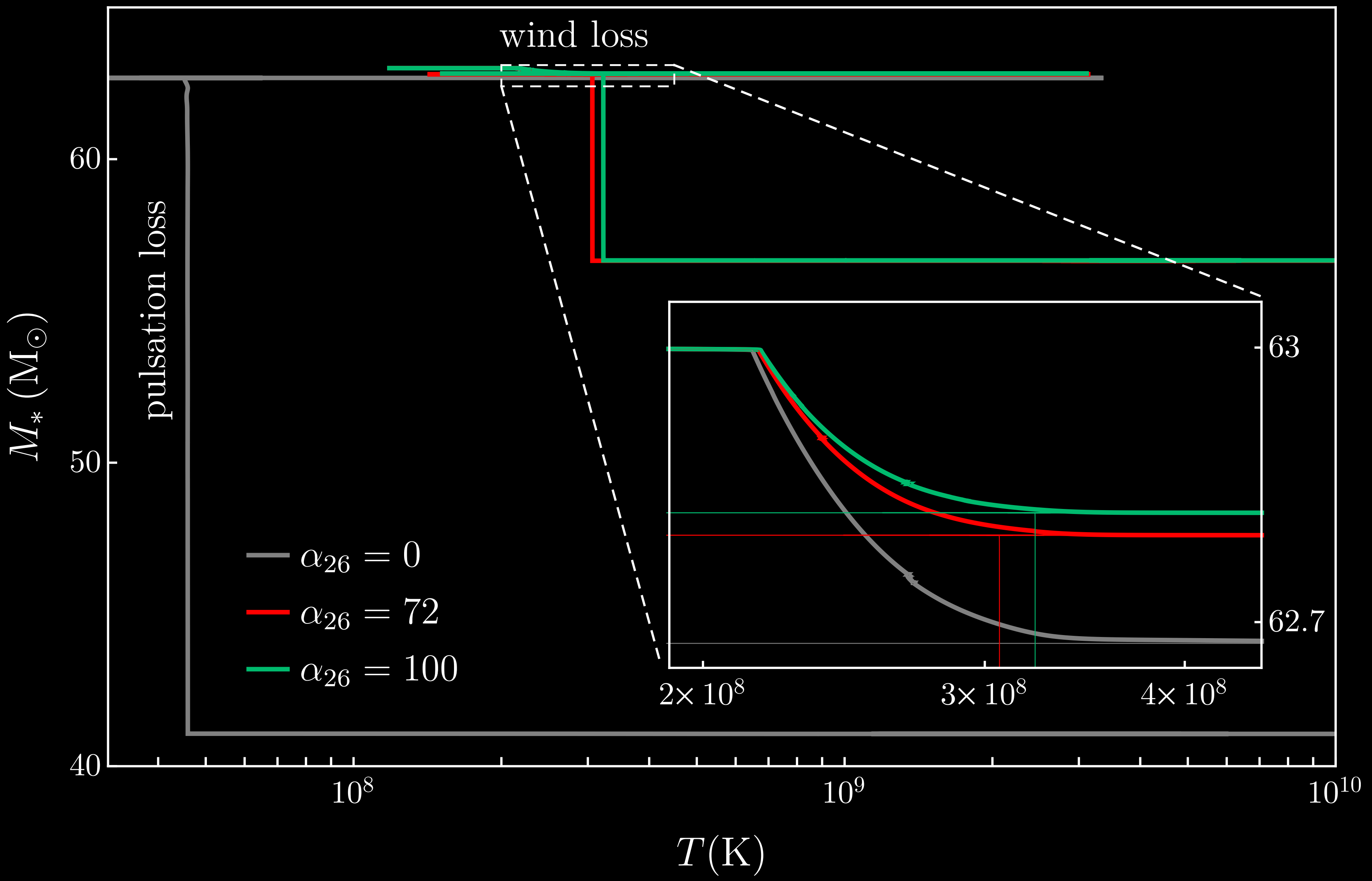
Central losses: Q_{ae}, $Q_{a\gamma}$, $Q_{A'}$ $(\mathrm{erg\,g^{-1}s^{-1}})$



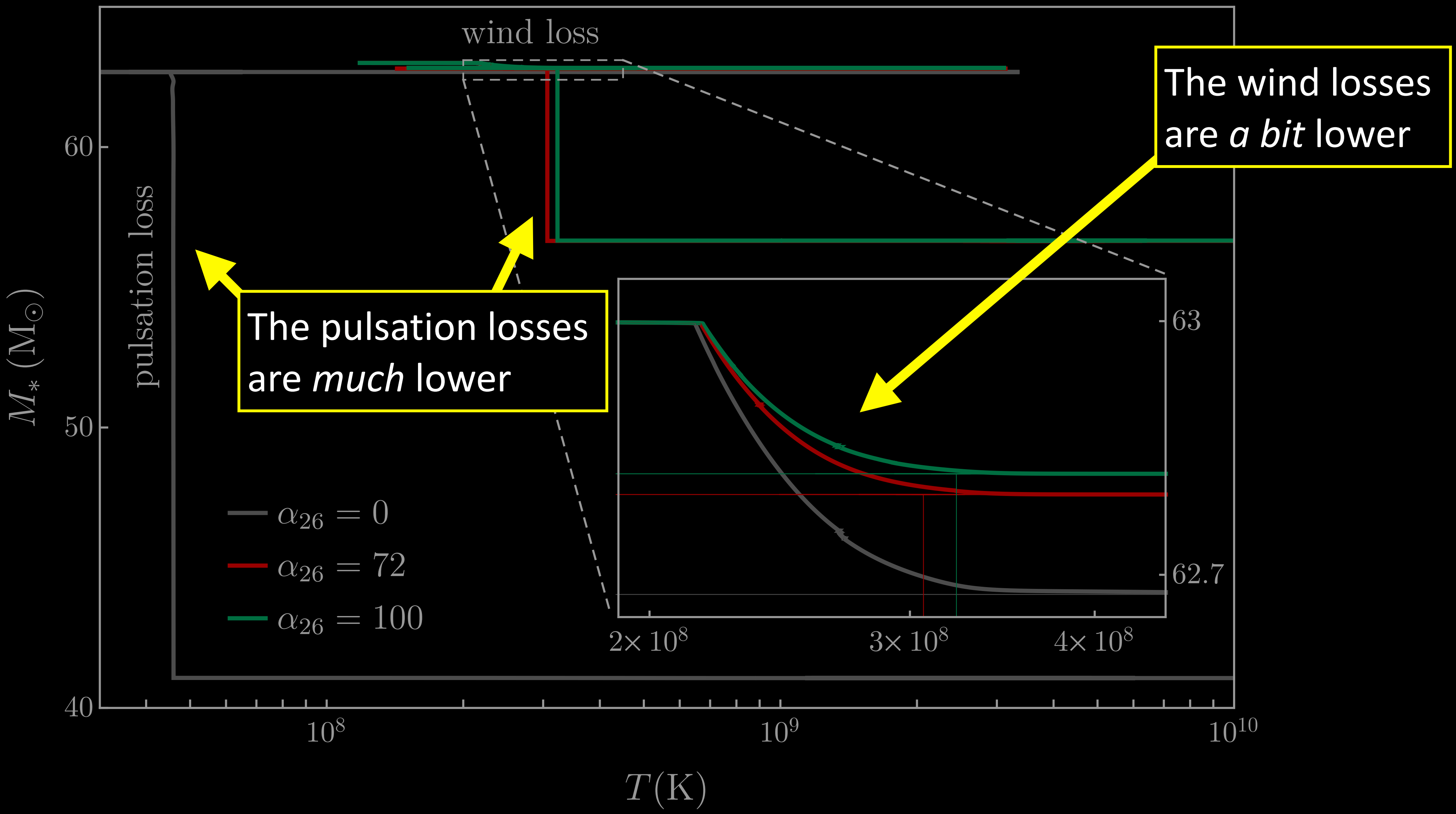
Example track of $M_{\rm in} = 55\ \mathrm{M}_\odot$ progenitor

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

Implications of enhanced losses



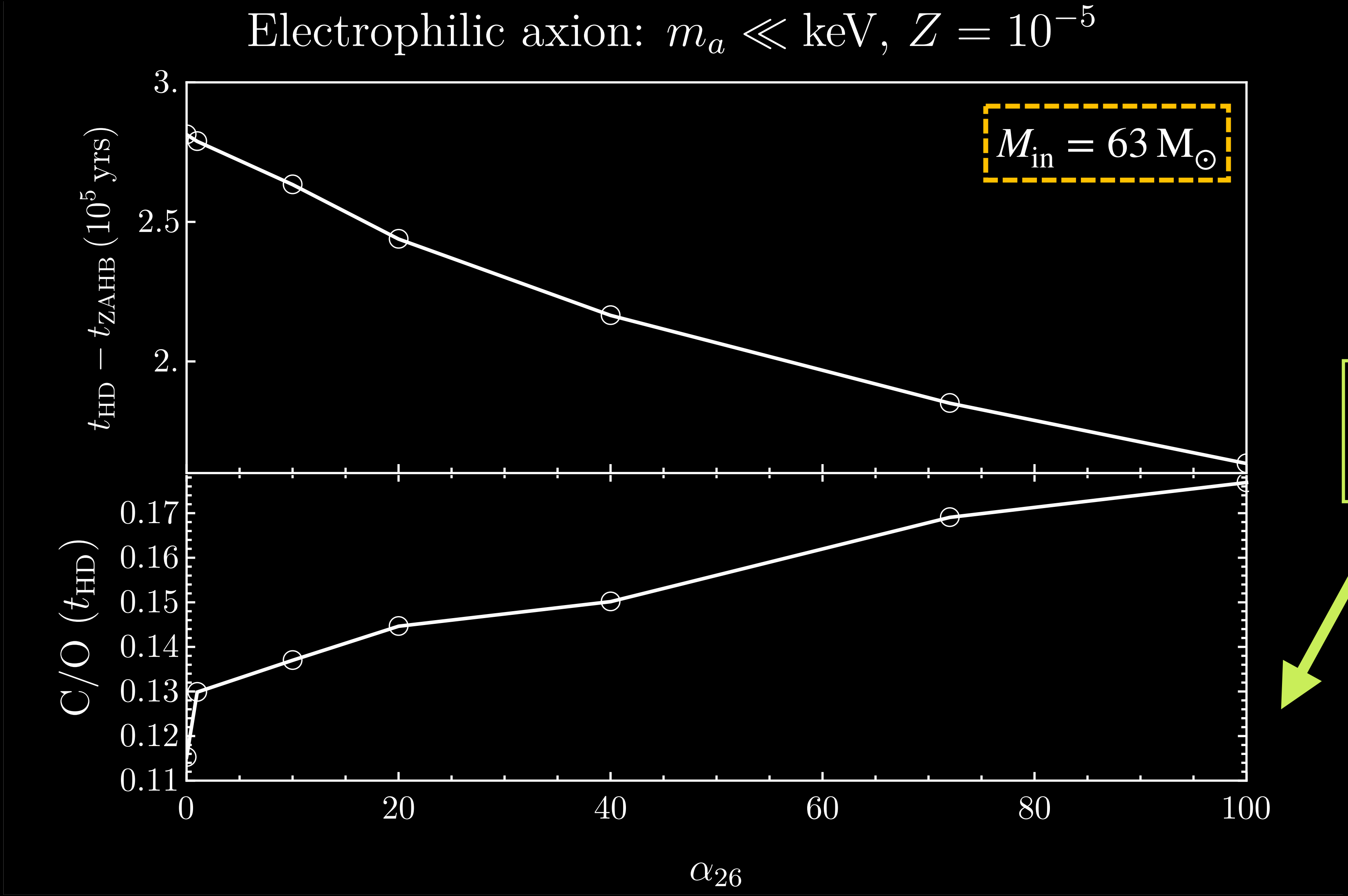
Implications of enhanced losses



The pulsation losses are *much* lower

The wind losses are *a bit* lower

What does the extra energy loss do?



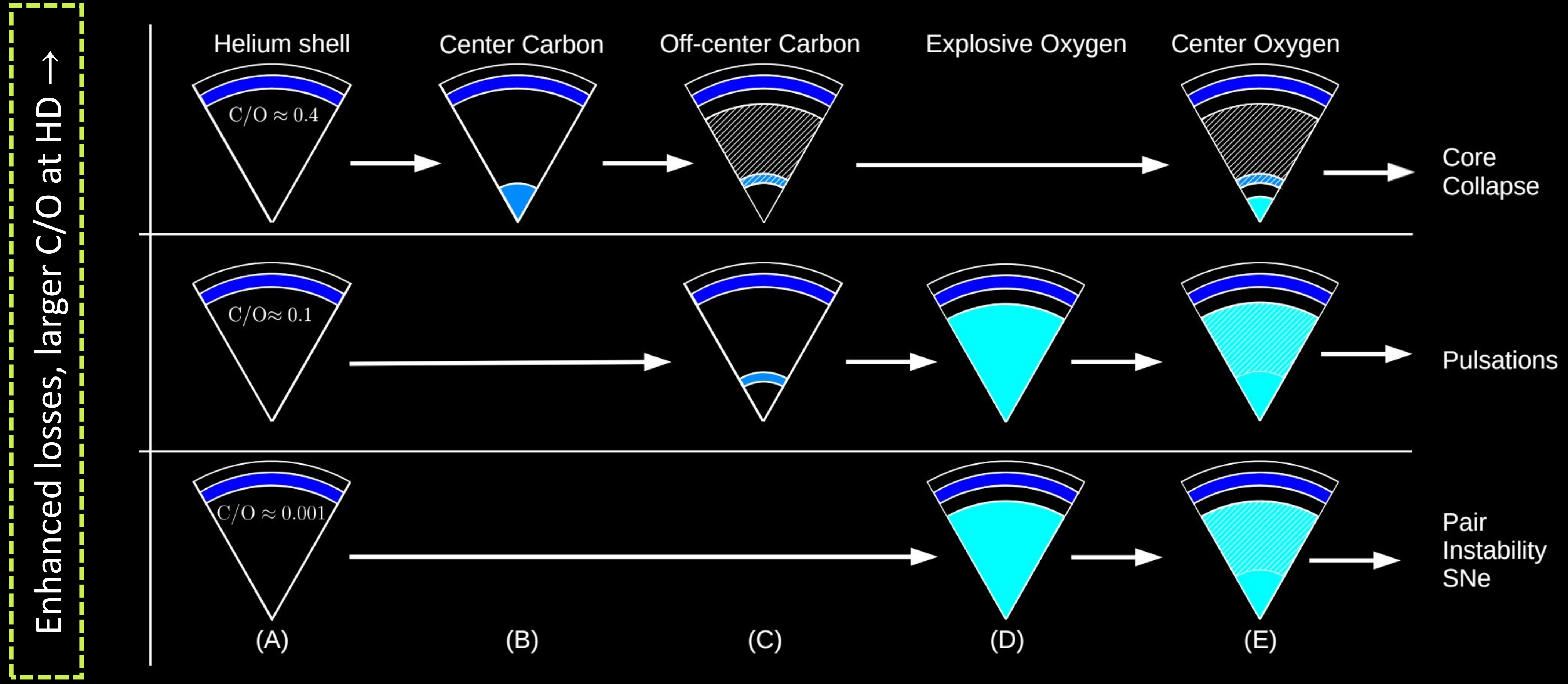
Greater energy losses lead to *shorter He-burning phases*

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

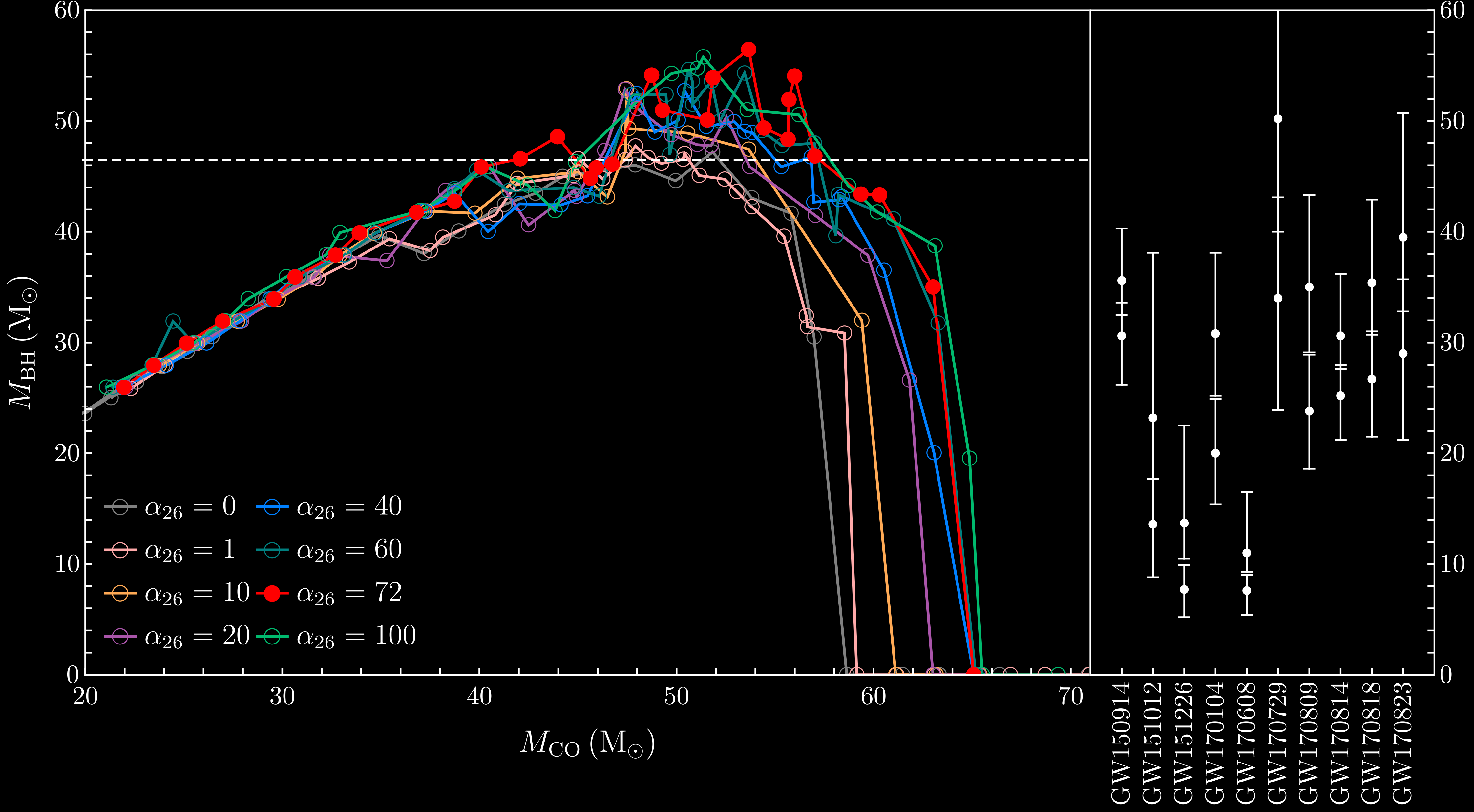
Helium burning
Carbon burning
Oxygen burning



Enhanced losses → greater progenitors collapse → larger black holes

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

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



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

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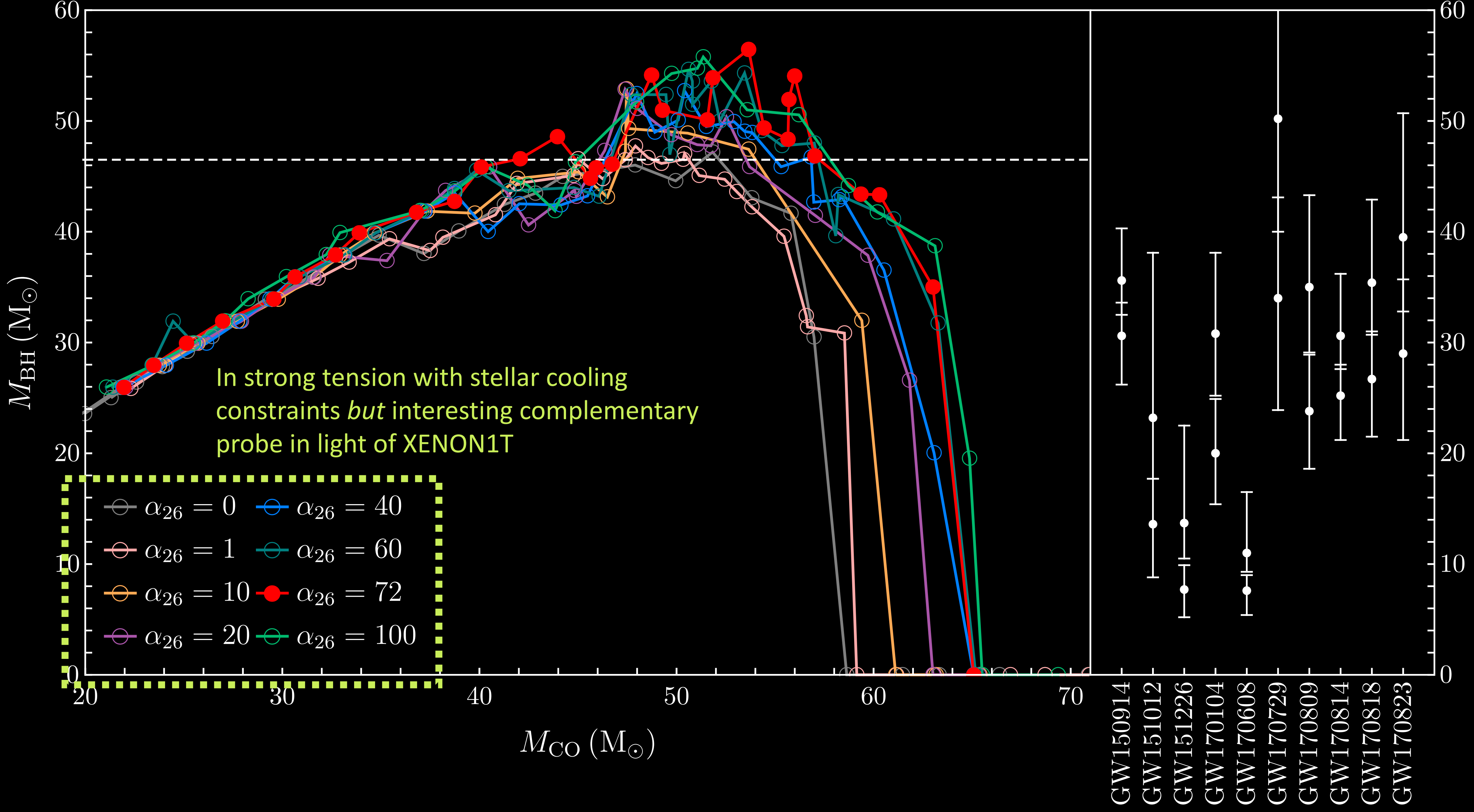
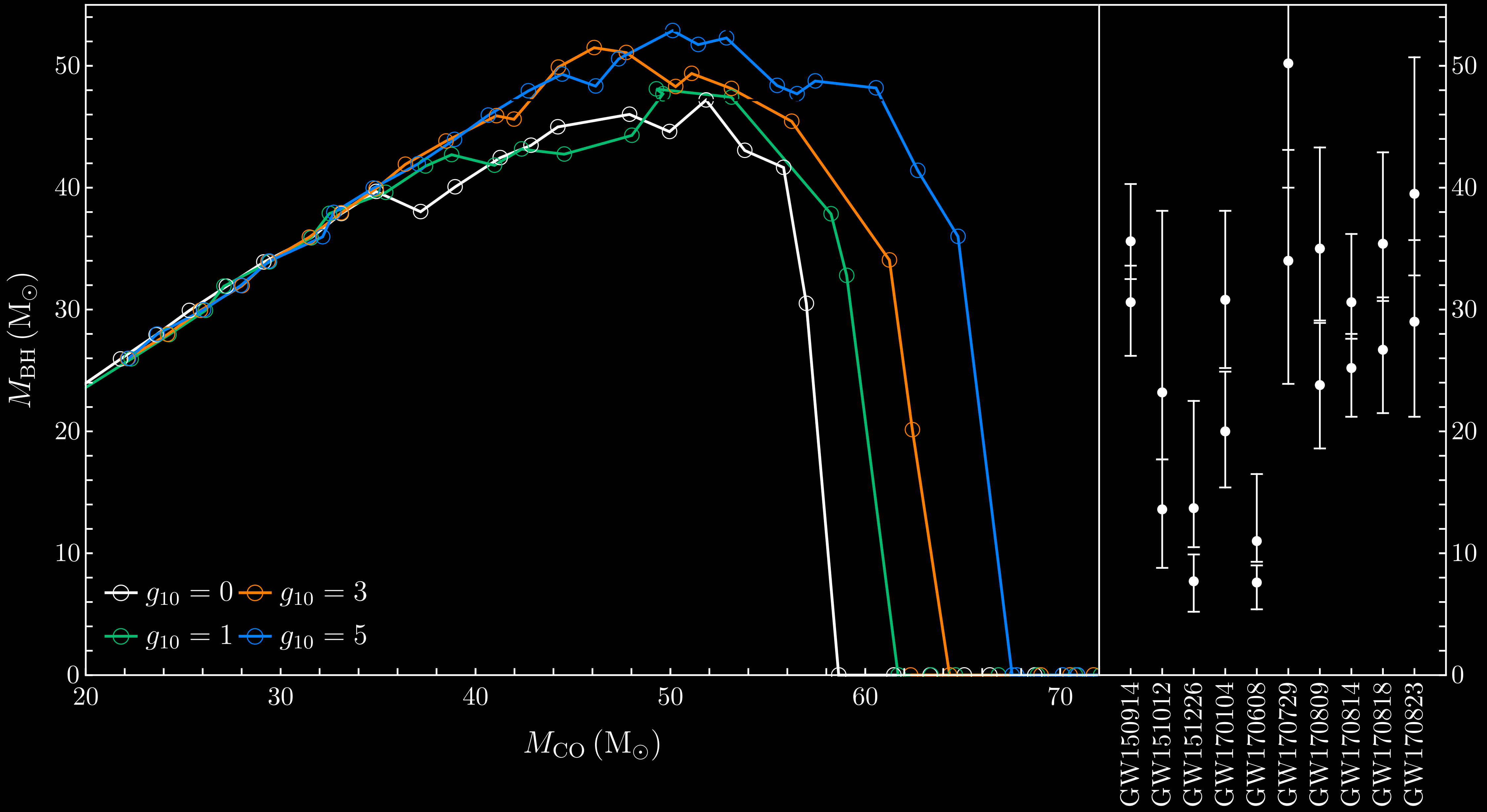


In strong tension with stellar cooling constraints *but* interesting complementary probe in light of XENON1T

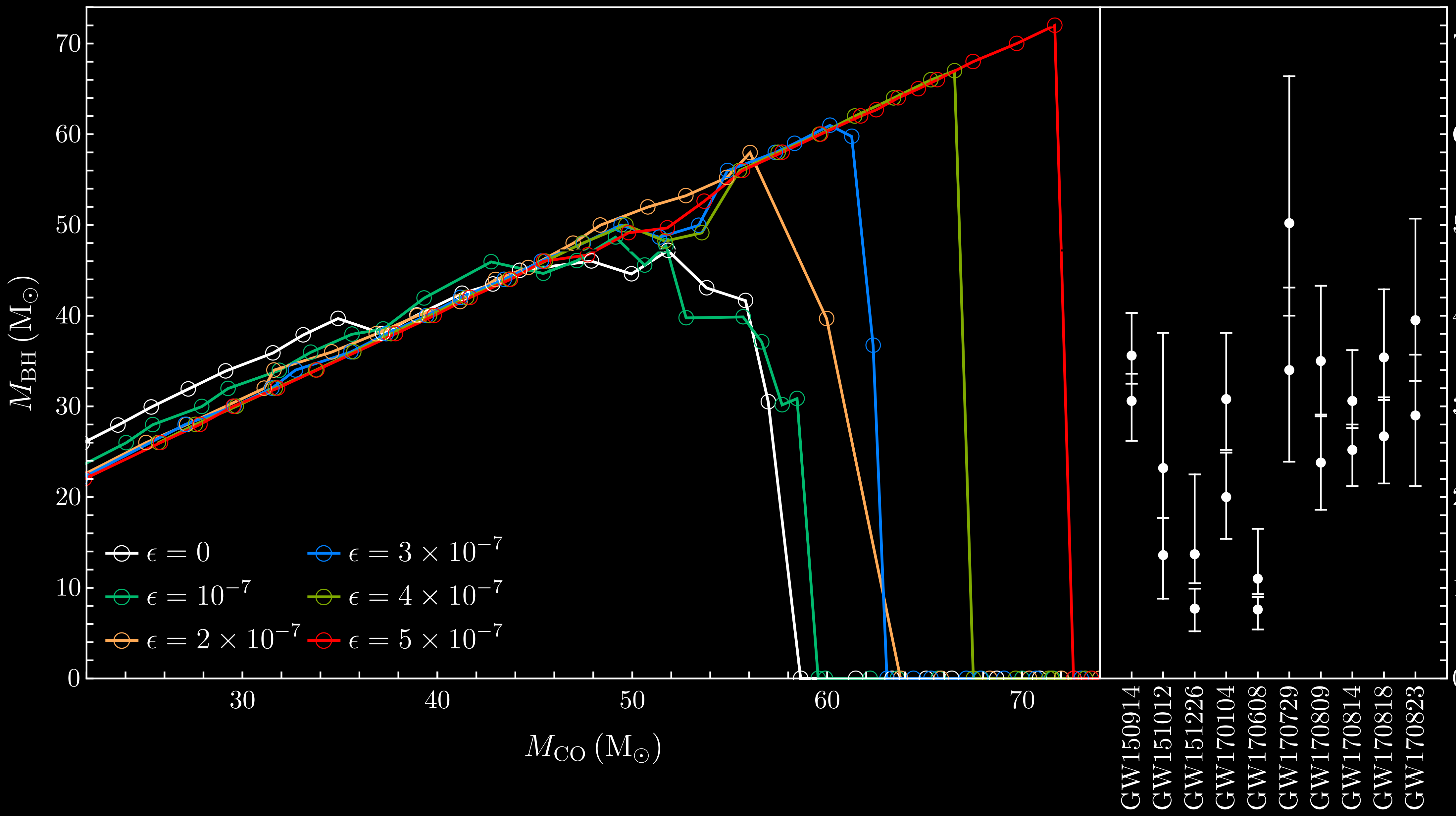
DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

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



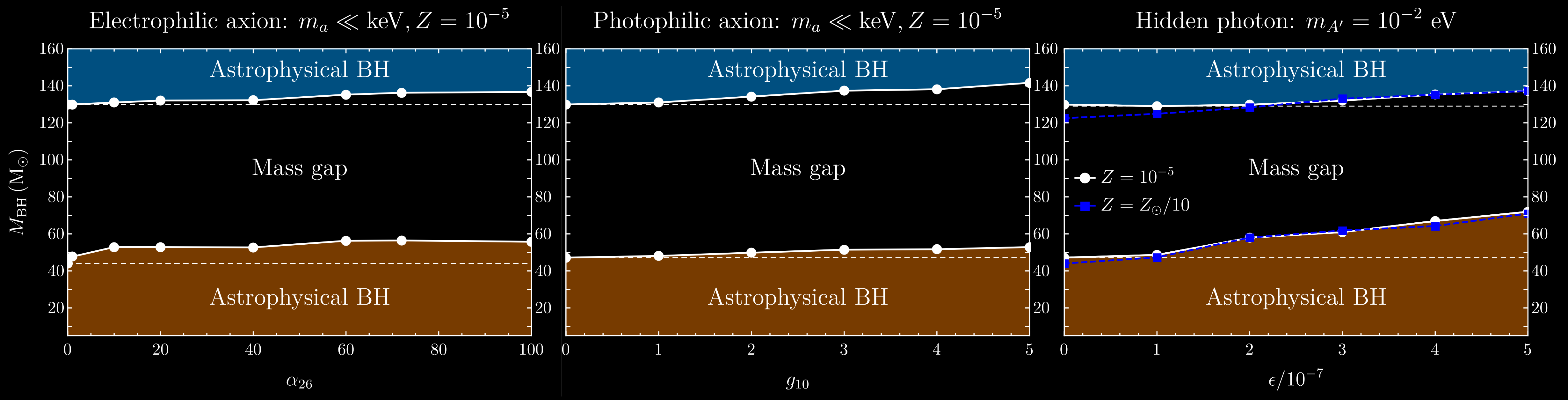
DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

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



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

New physics and the black hole mass gap



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

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

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

Potentially large shifts of the mass gap!

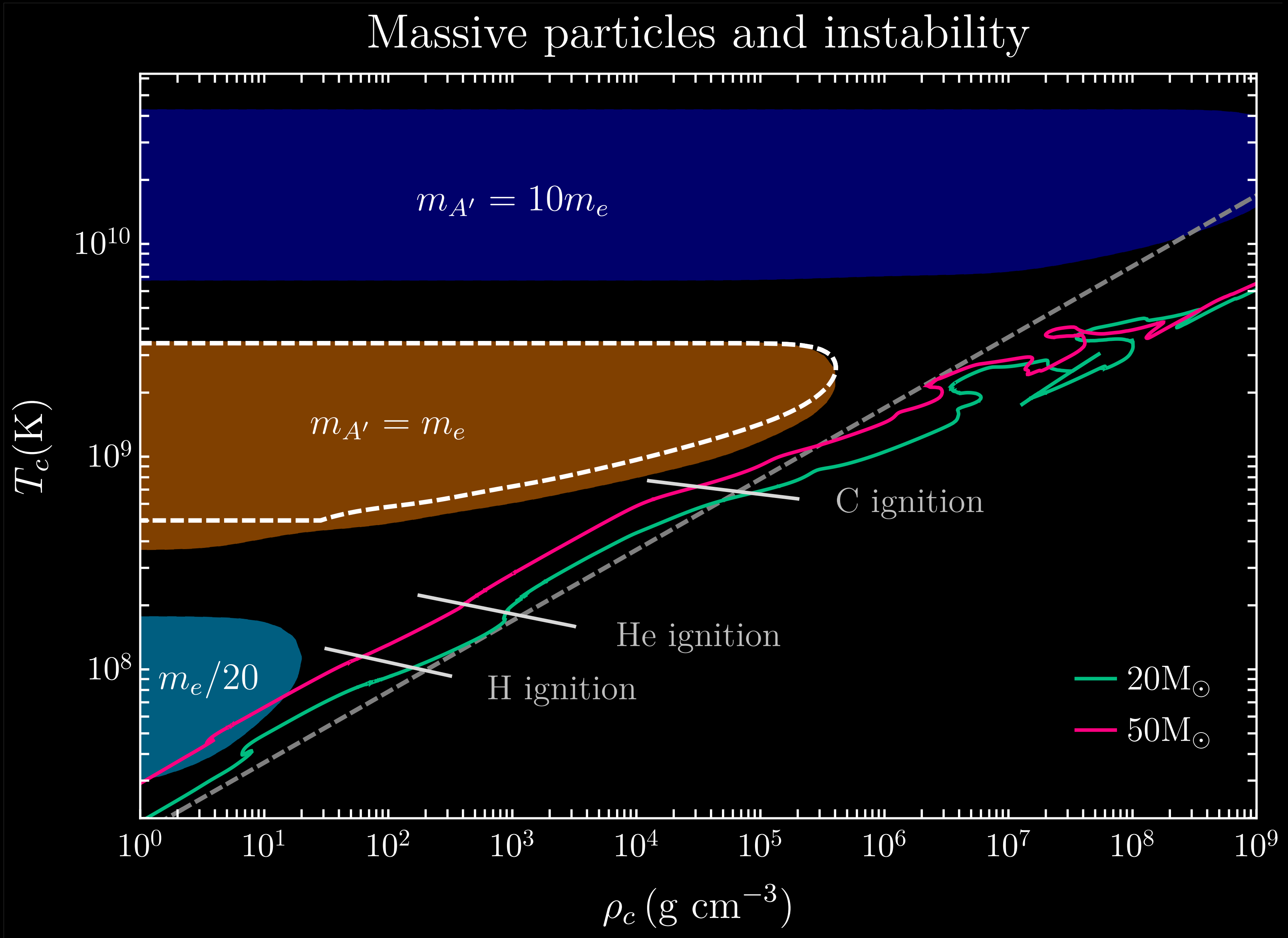
DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

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



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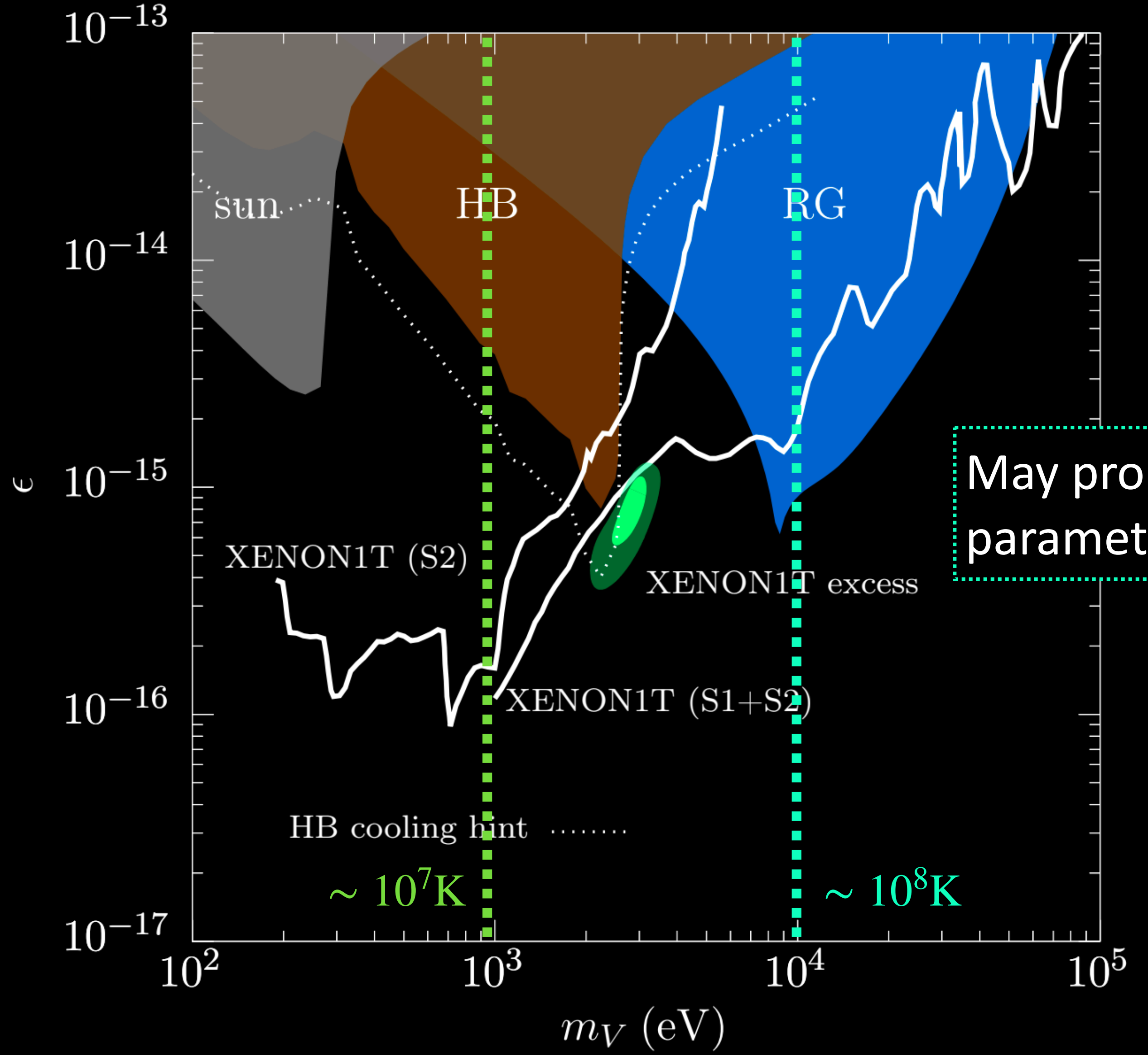
Heavier degrees of freedom?



May probe this parameter space

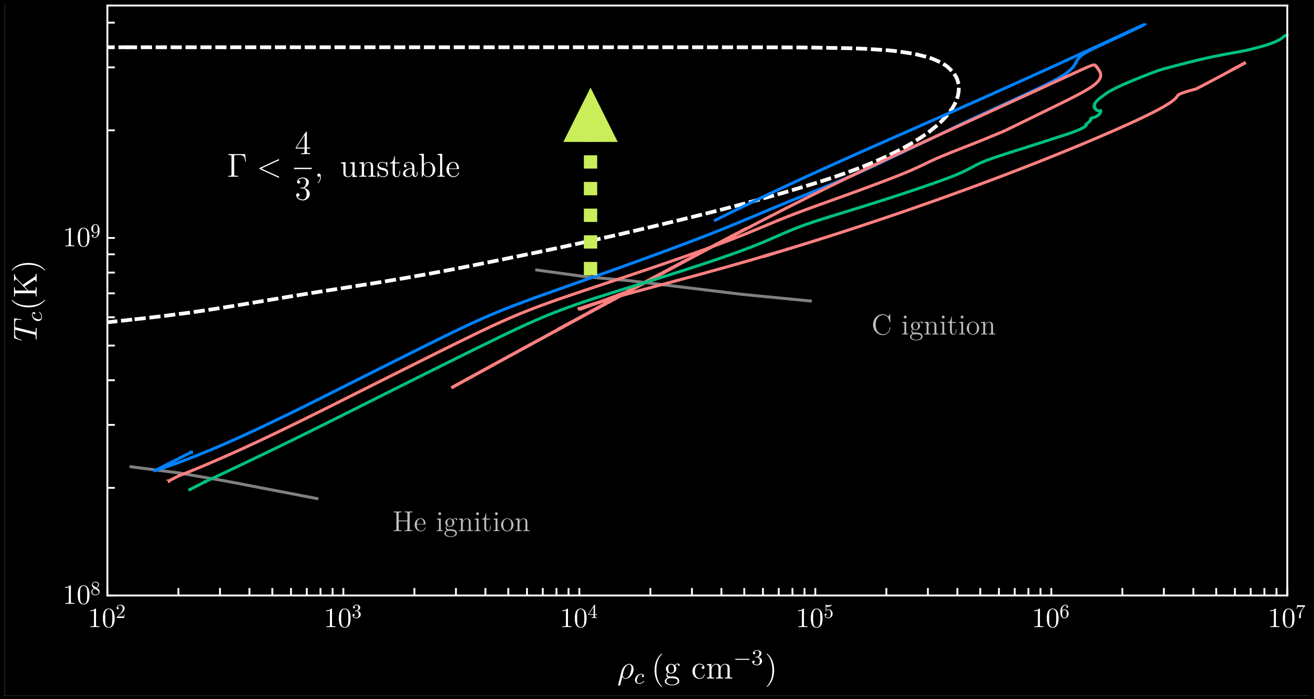
Adapted from Ann, Pospelov, Pradler, Ritz arXiv:2006.13929 [hep-ph]

The BHMG and new physics

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

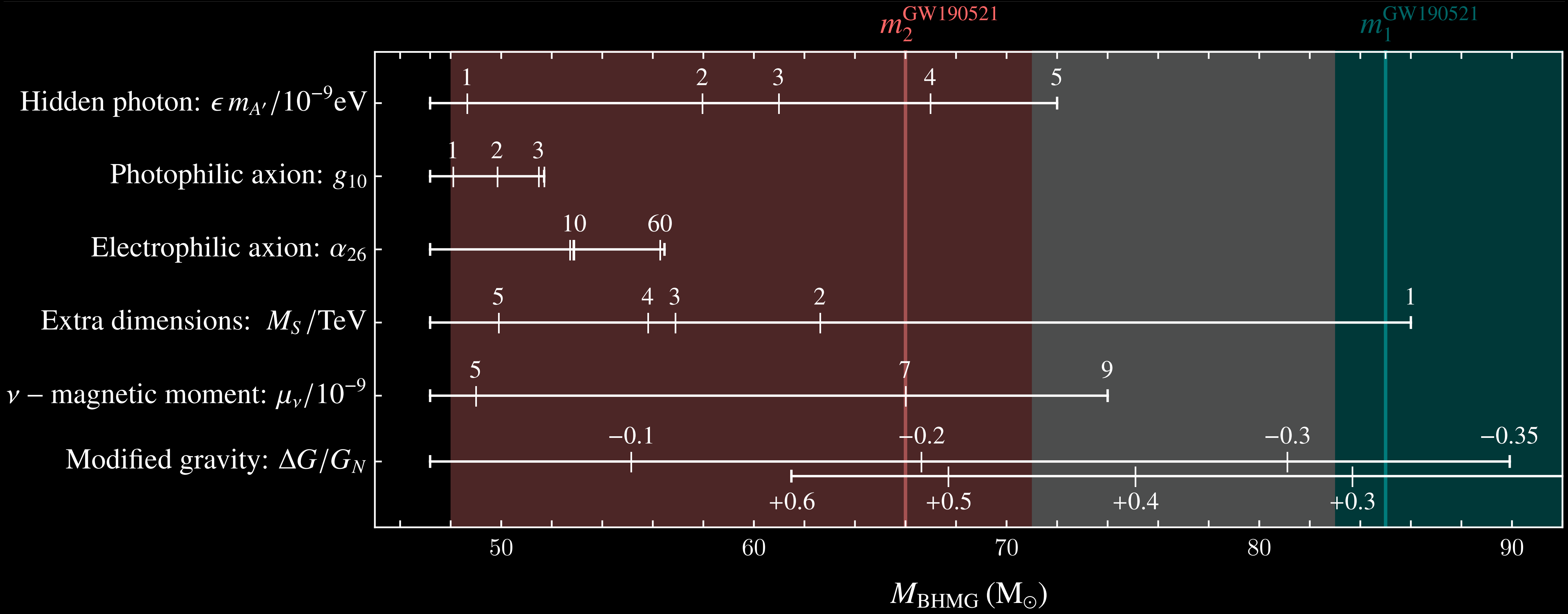
Straight, Sakstein, Baxter, in progress

- 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



GW190521, the impossible black holes

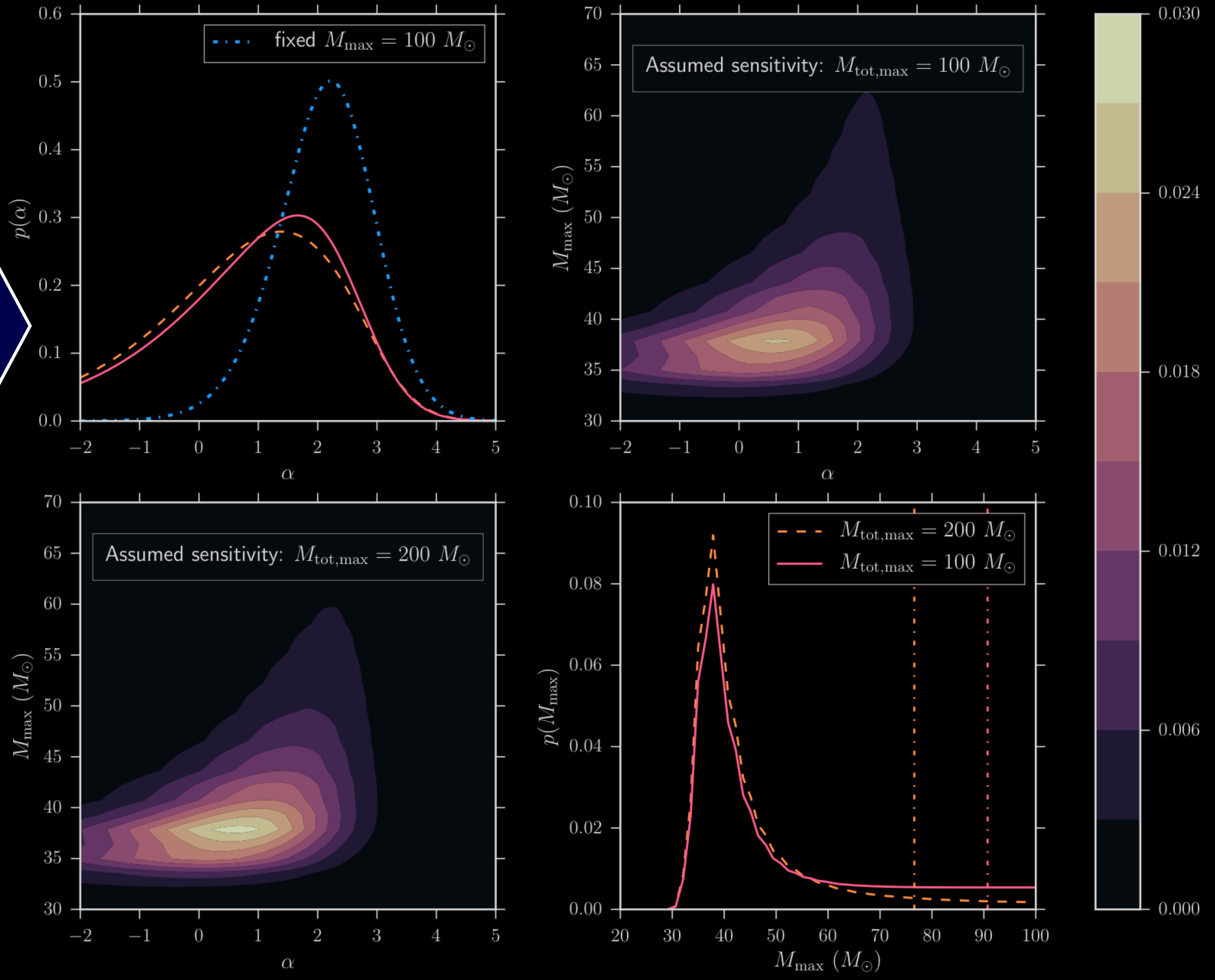
… and Beyond the Standard Model physics



Sakstein, DC, 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

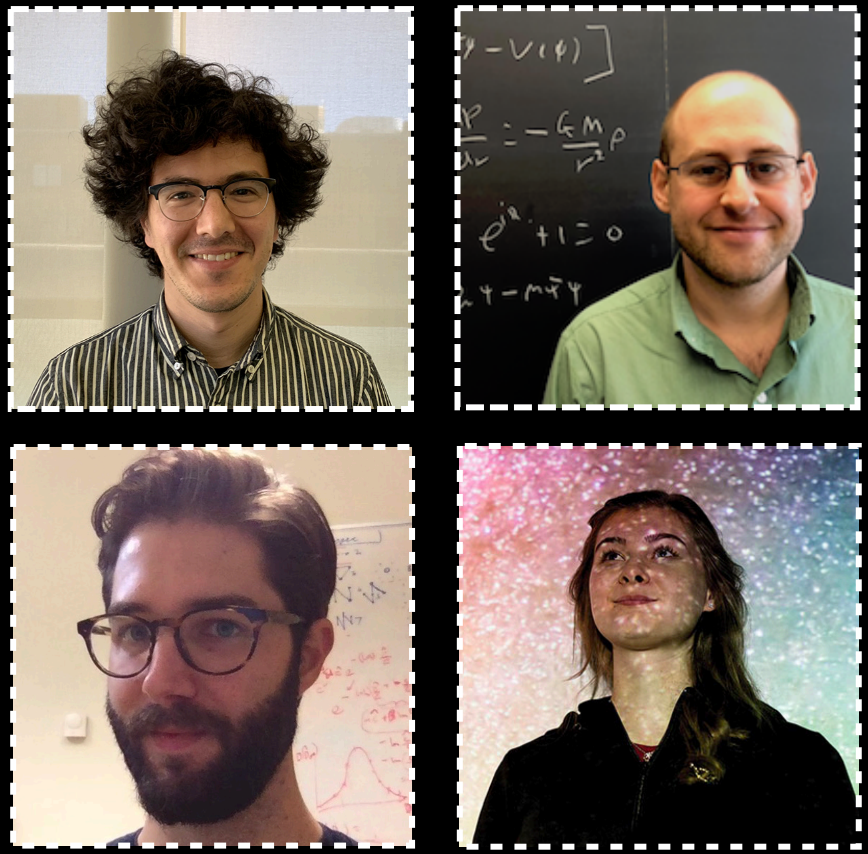
- The black hole mass gap is an exciting probe of new physics, which will come into focus in the next few years

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

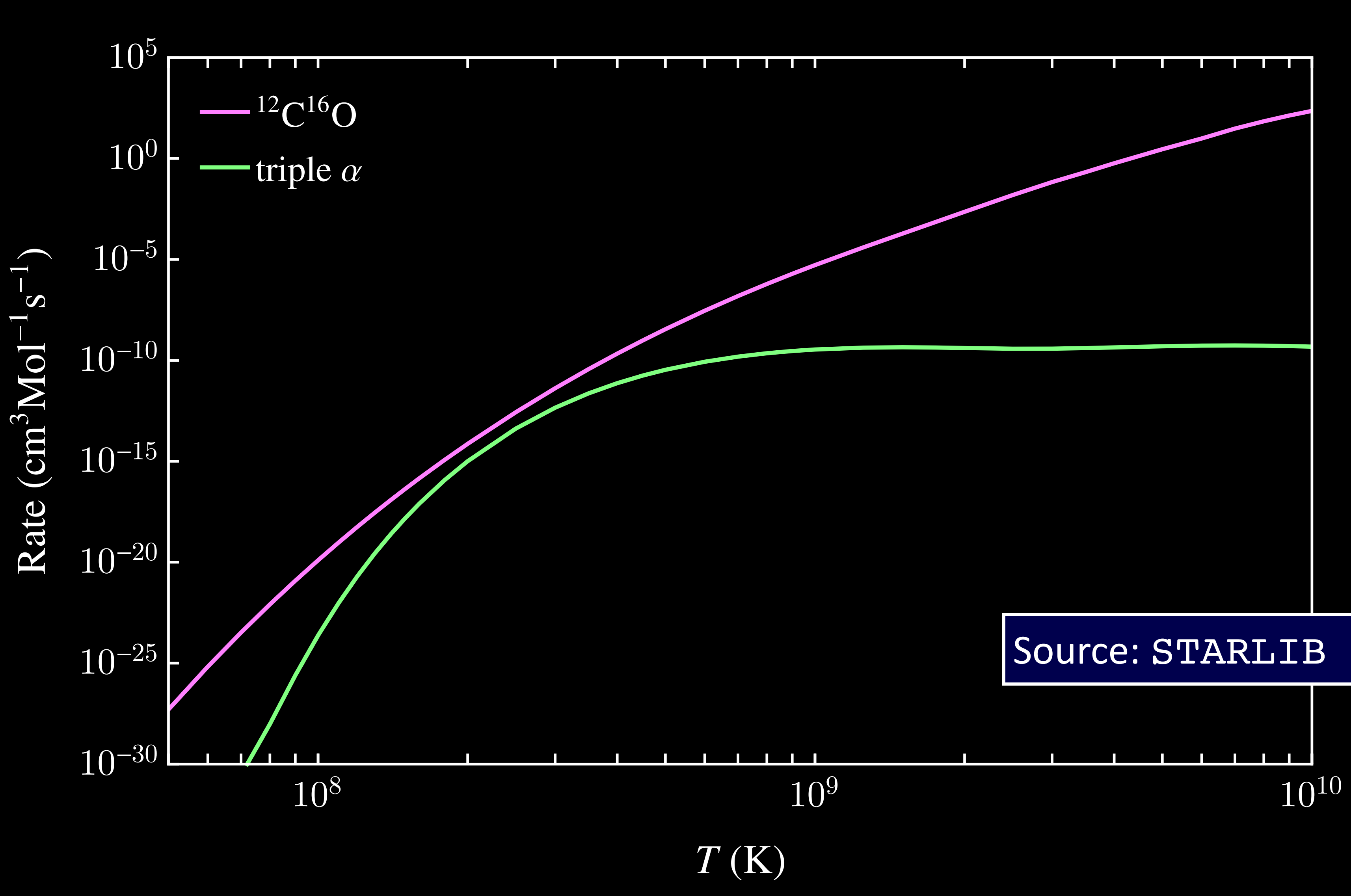
Thank you!

…ask me anything you like!

dcroon@triumf.ca | djunacroon.com

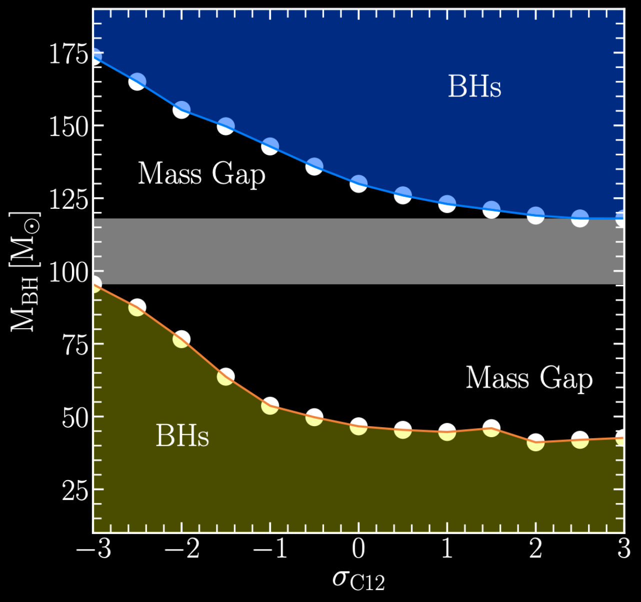


Helium burning rates as a function of T



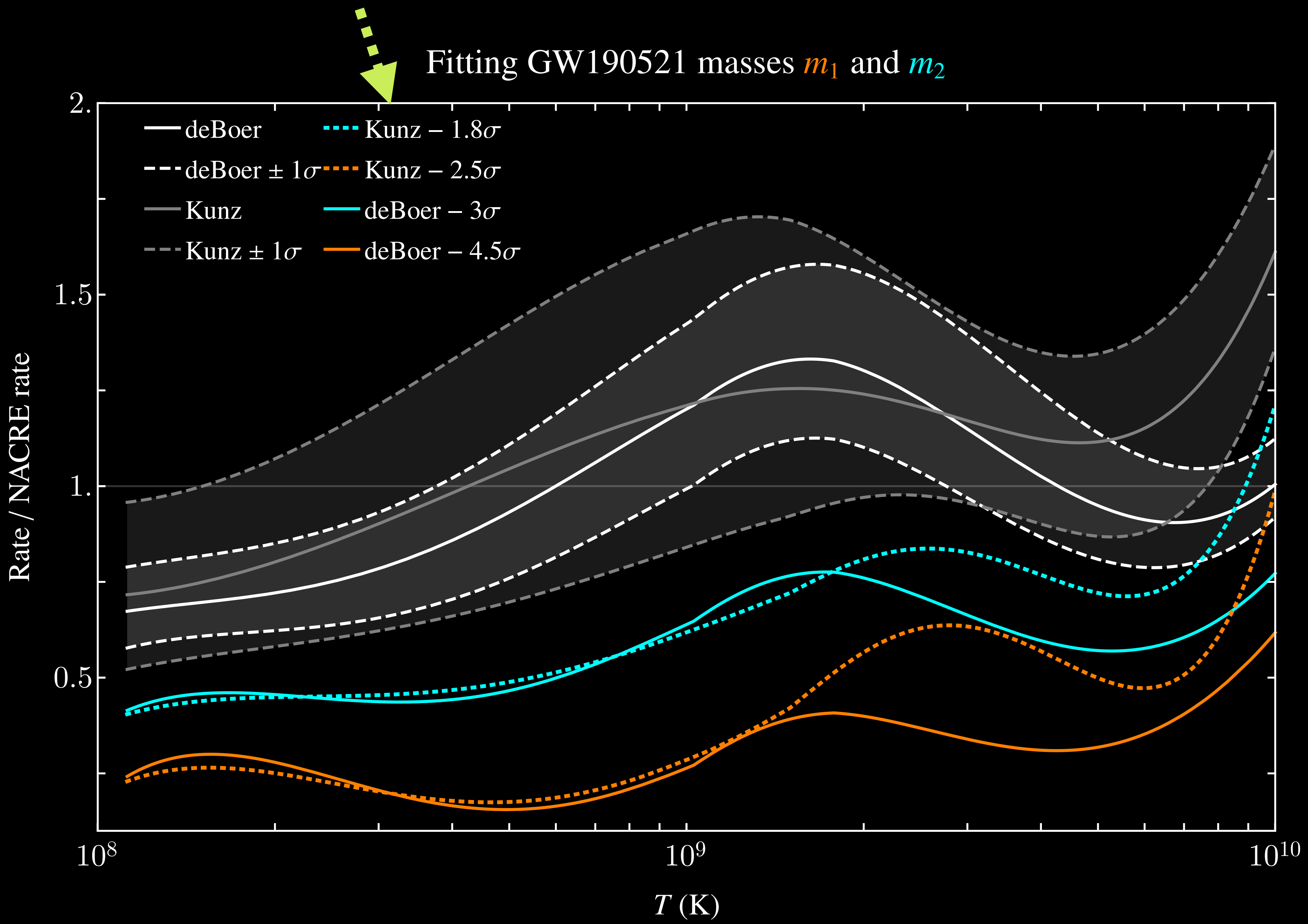
Source: `STARLIB` catalogue

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

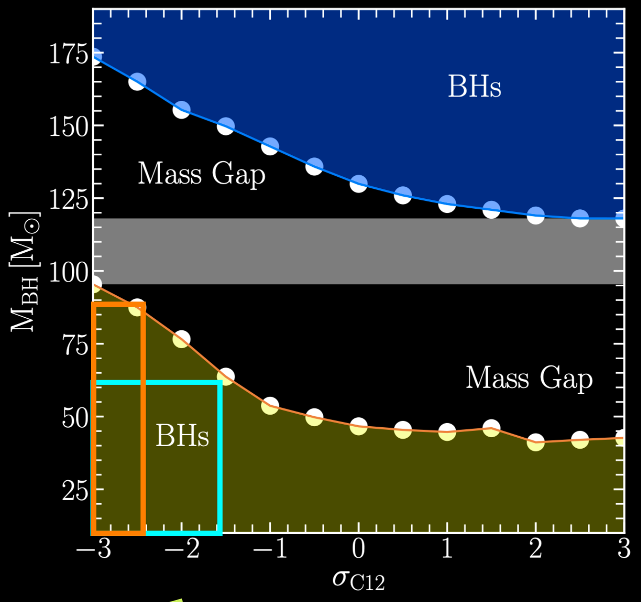


(Kunz is currently used in `STARLIB`)

Fitting GW190521 masses m_1 and m_2



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



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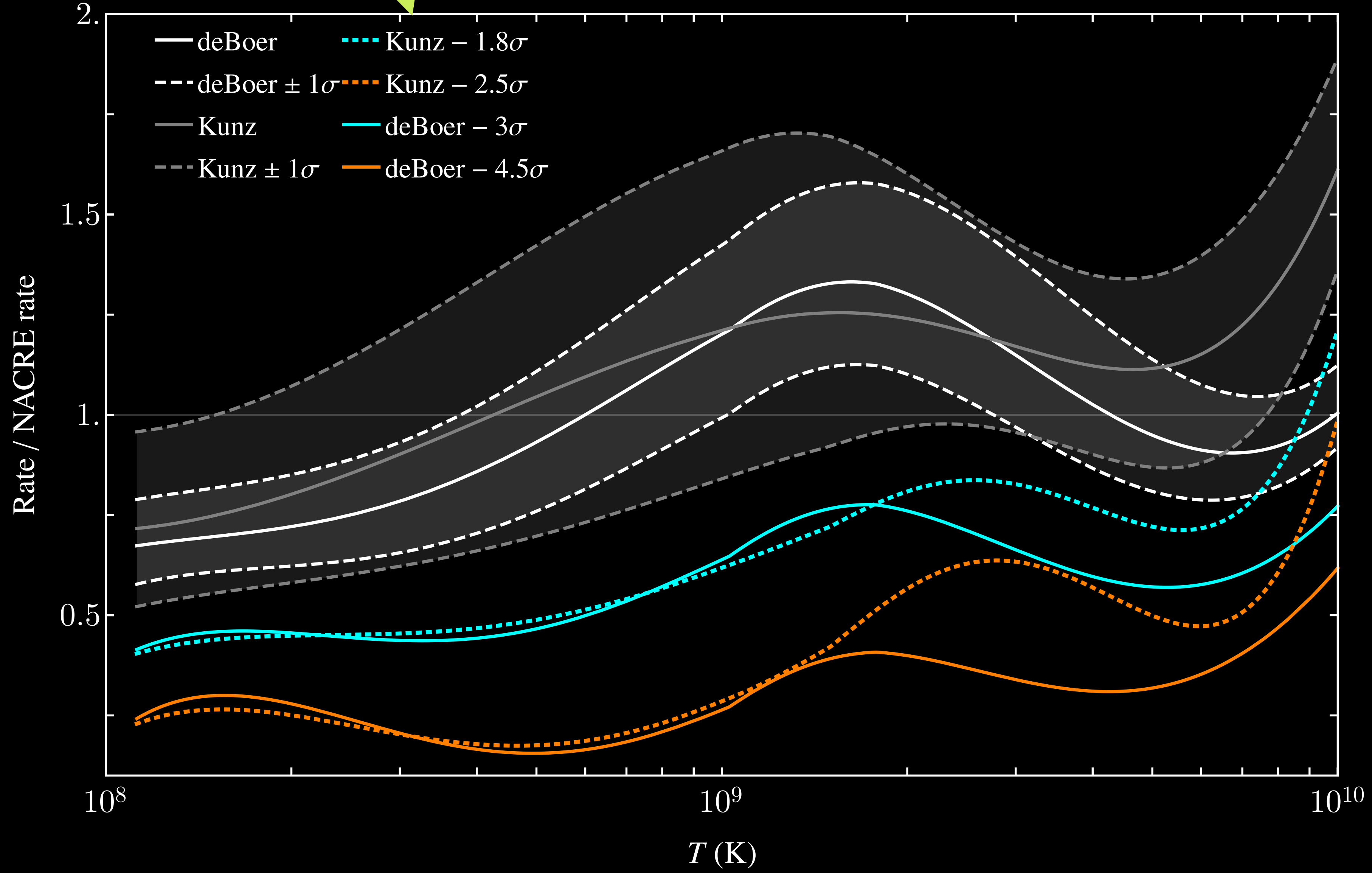
Fitting GW190521 masses m_1 and m_2



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

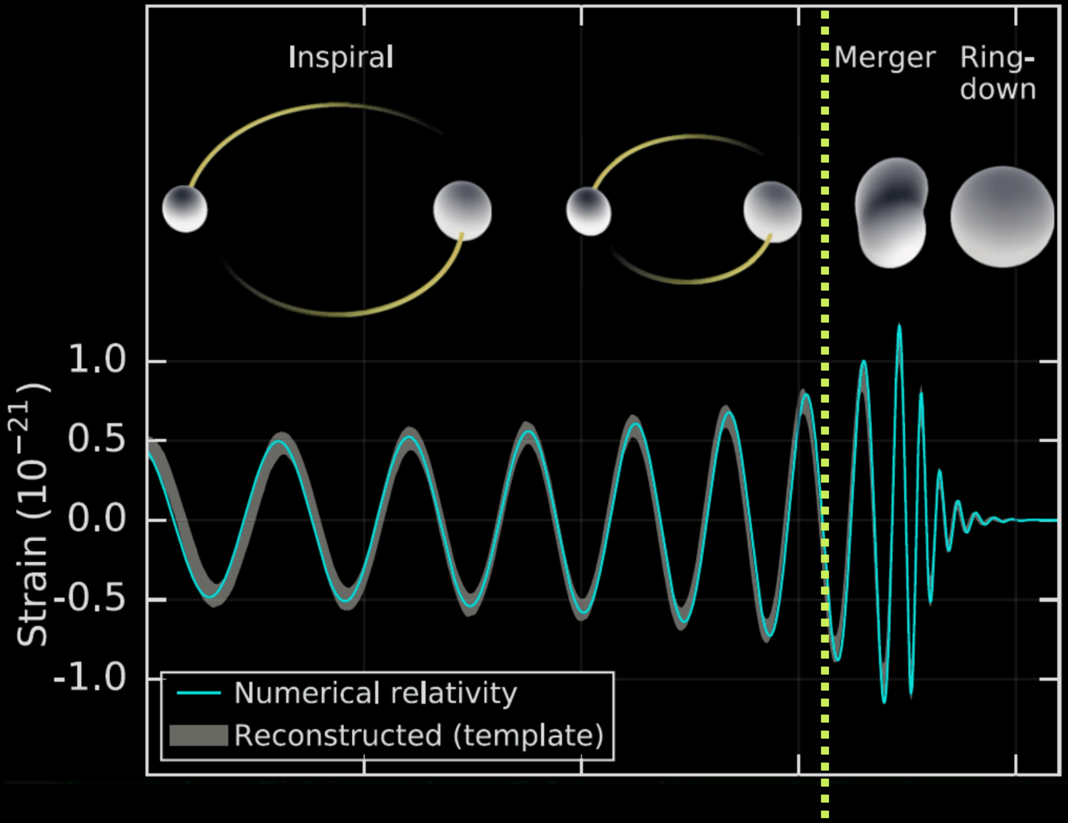


Image credit: LIGO collaboration

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

Compact object merger sensitivity

- Best detection prospects for

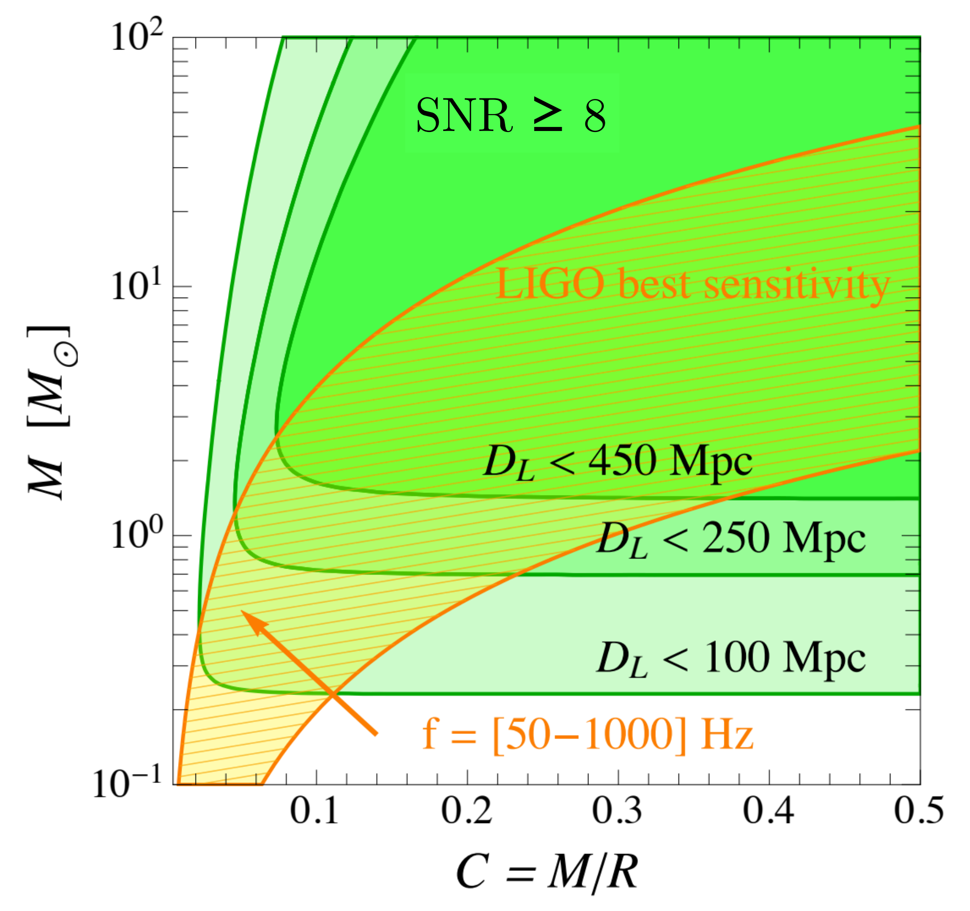
$$f_{\rm min} < f_{\rm peak} \sim f_{\rm ISCO} < f_{\rm max}$$

- Defines an CO sensitivity band

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

$$\boxed{\begin{array}{ll} C_\odot = 2\times 10^{-6} & C_{\rm BH} = 0.5 \\ C_\oplus = 7\times 10^{-10} & C_{\rm NS} \sim 0.1 \end{array}}$$

- 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)

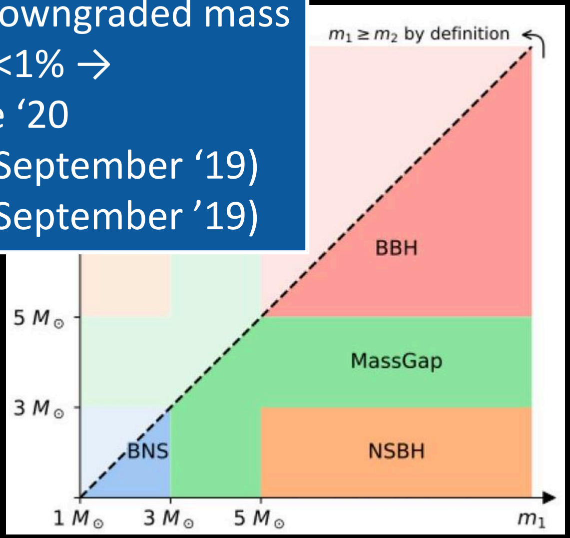


Image credit: LIGO collaboration

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”*