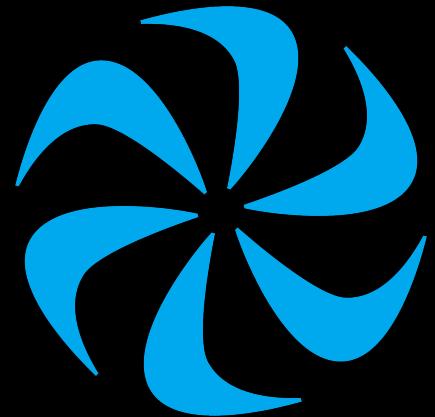


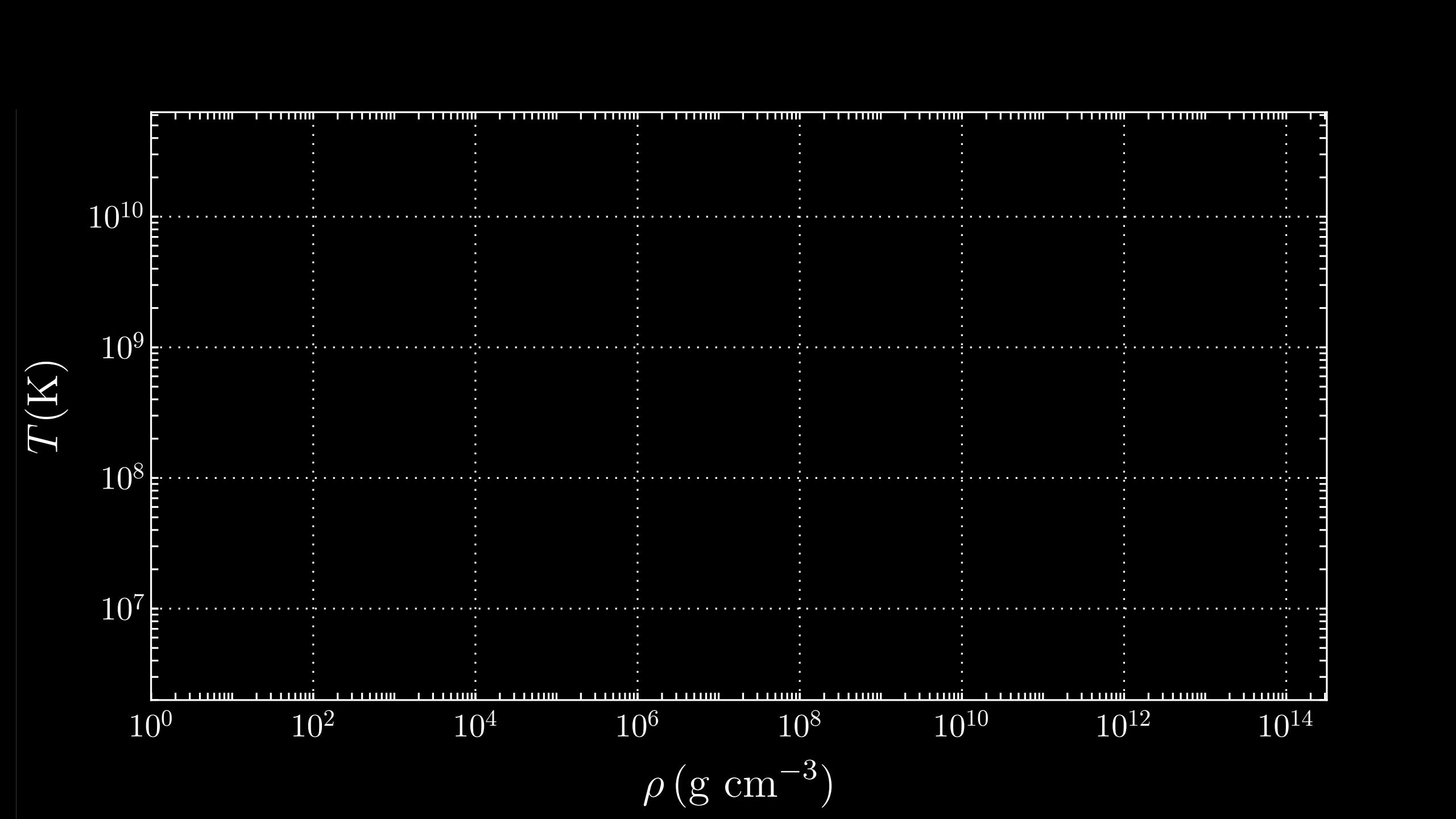
New insights into light particles and supernovae

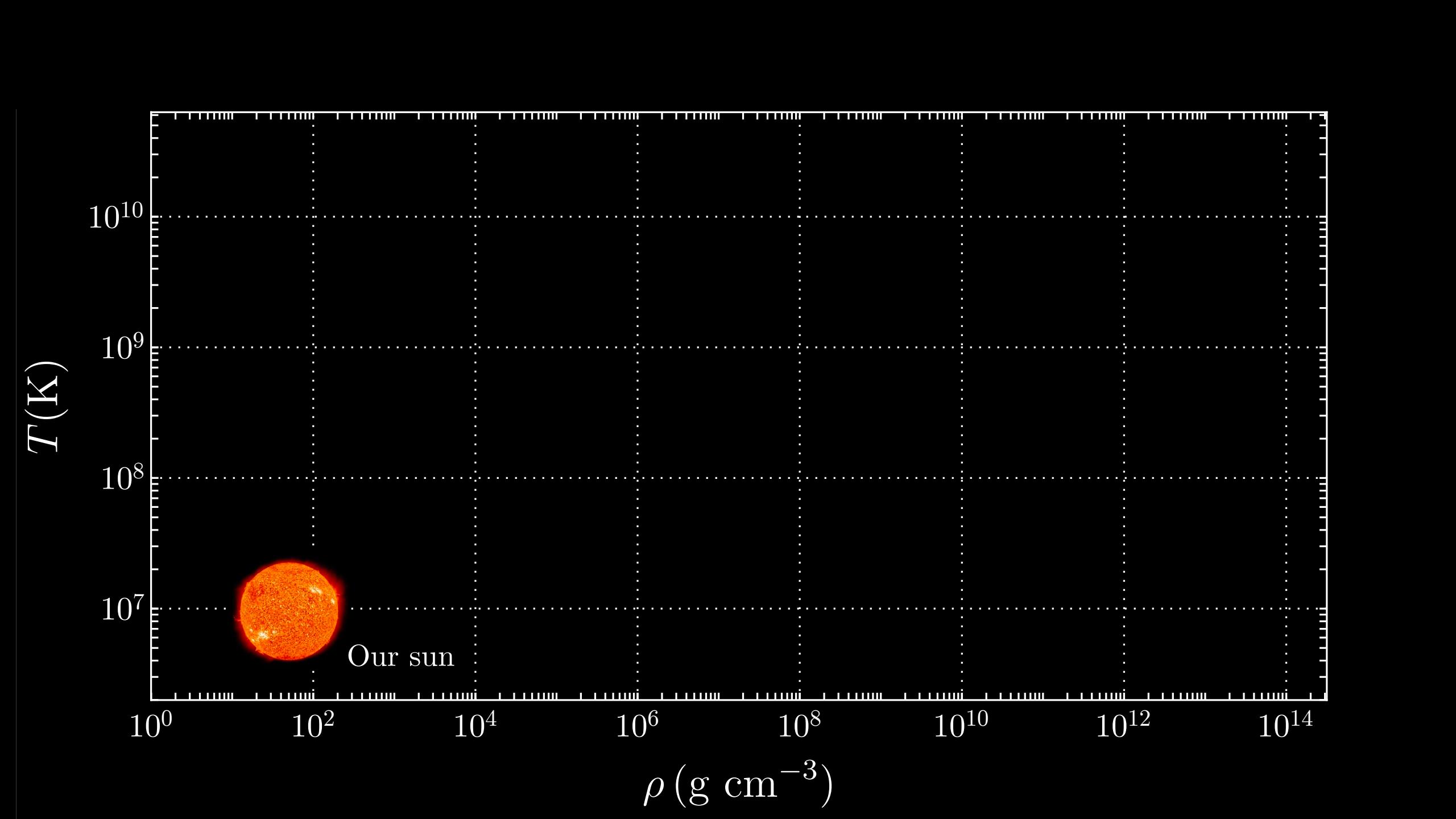
Djuna Lize Croon ([TRIUMF](#))

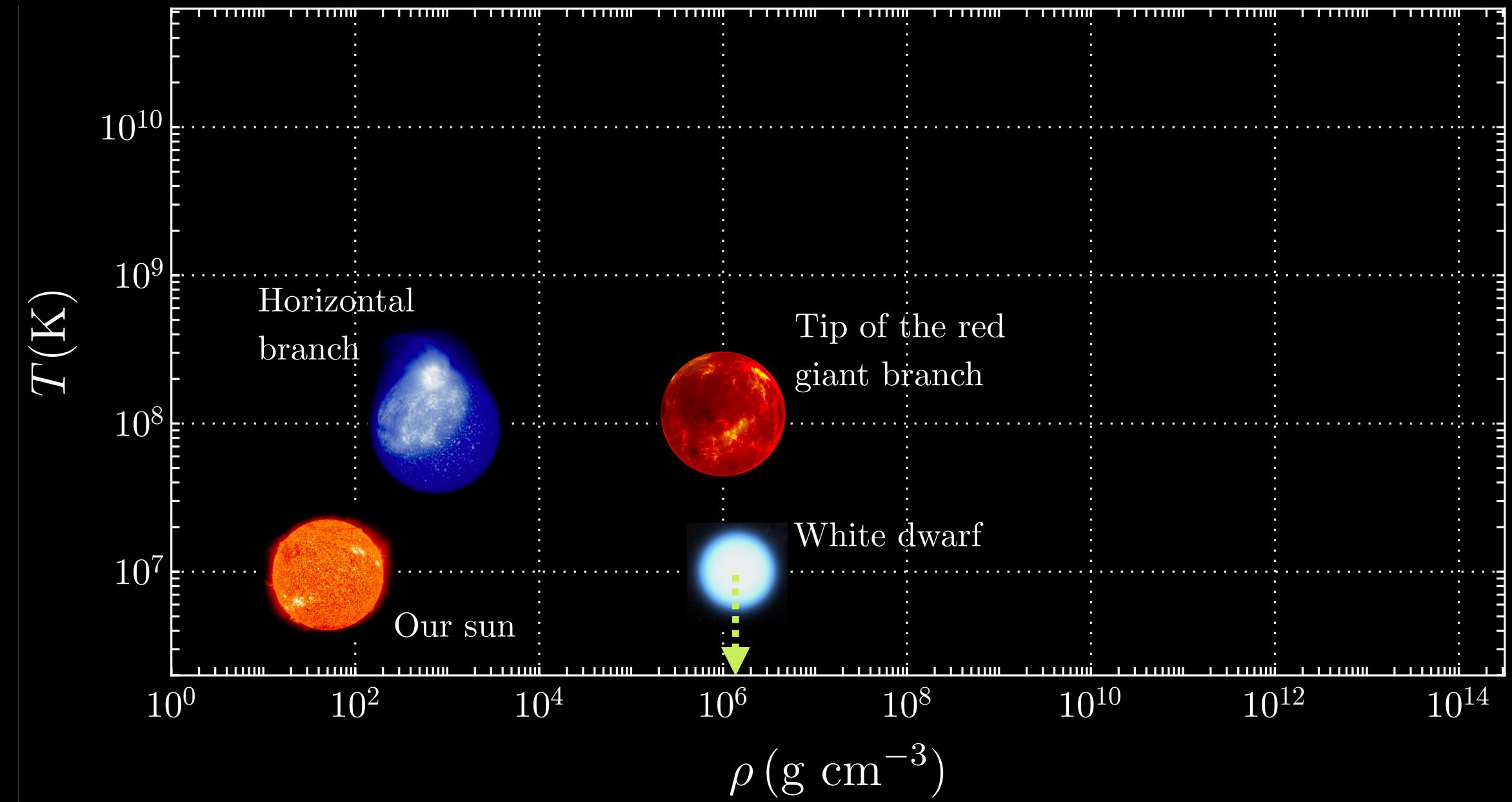
Light Dark World, December 2020

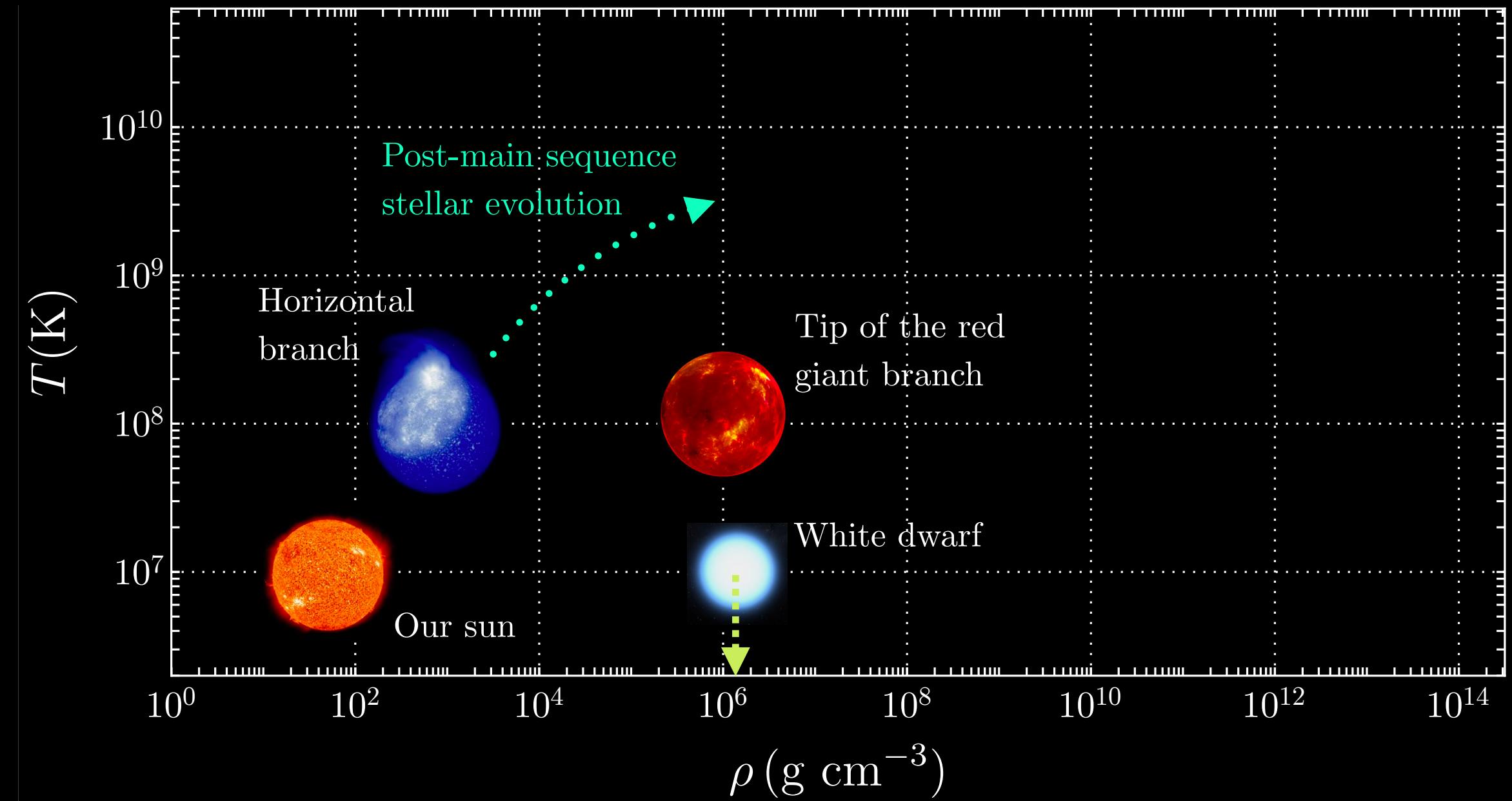
dcroon@triumf.ca | djunacroon.com

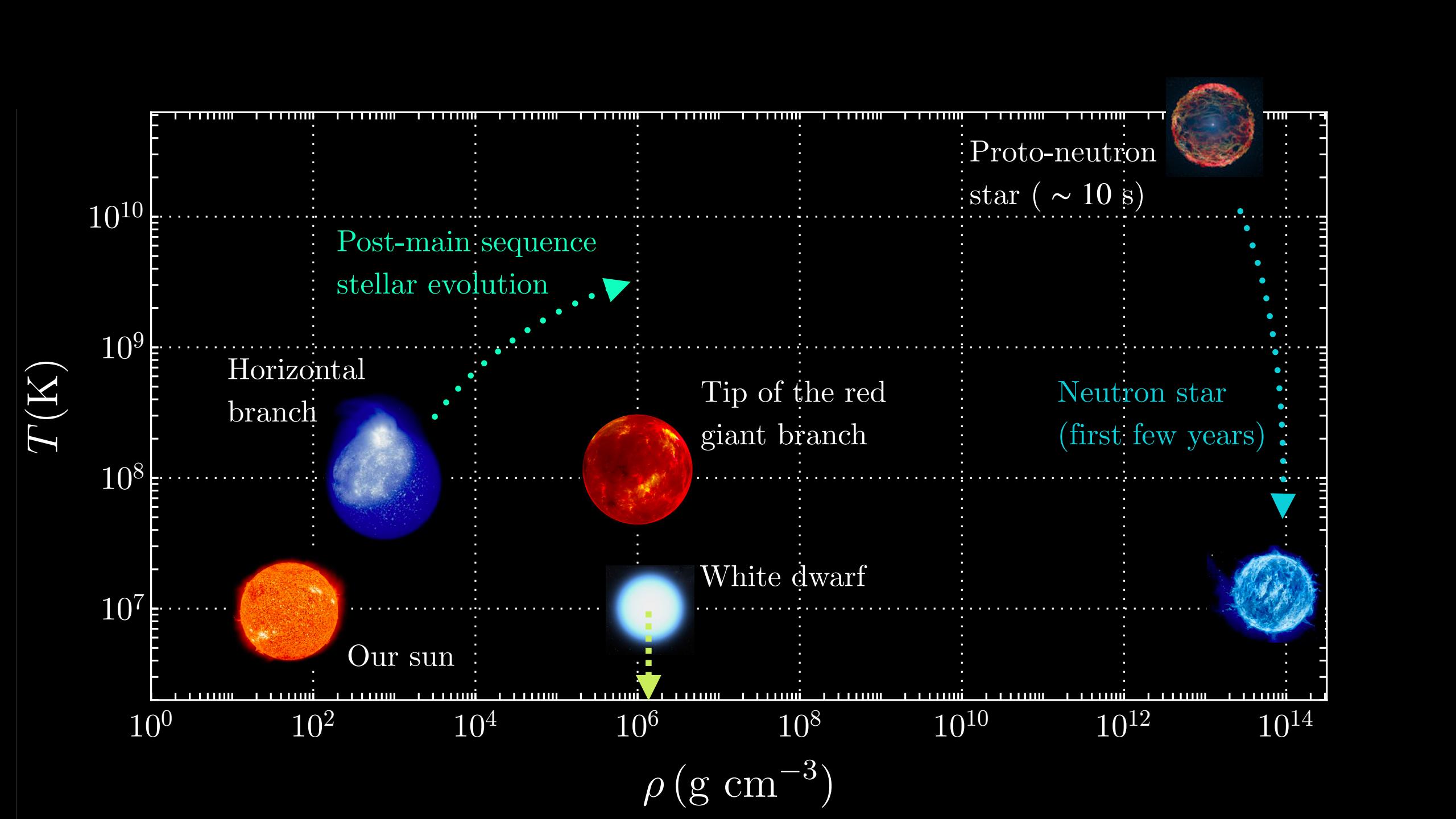


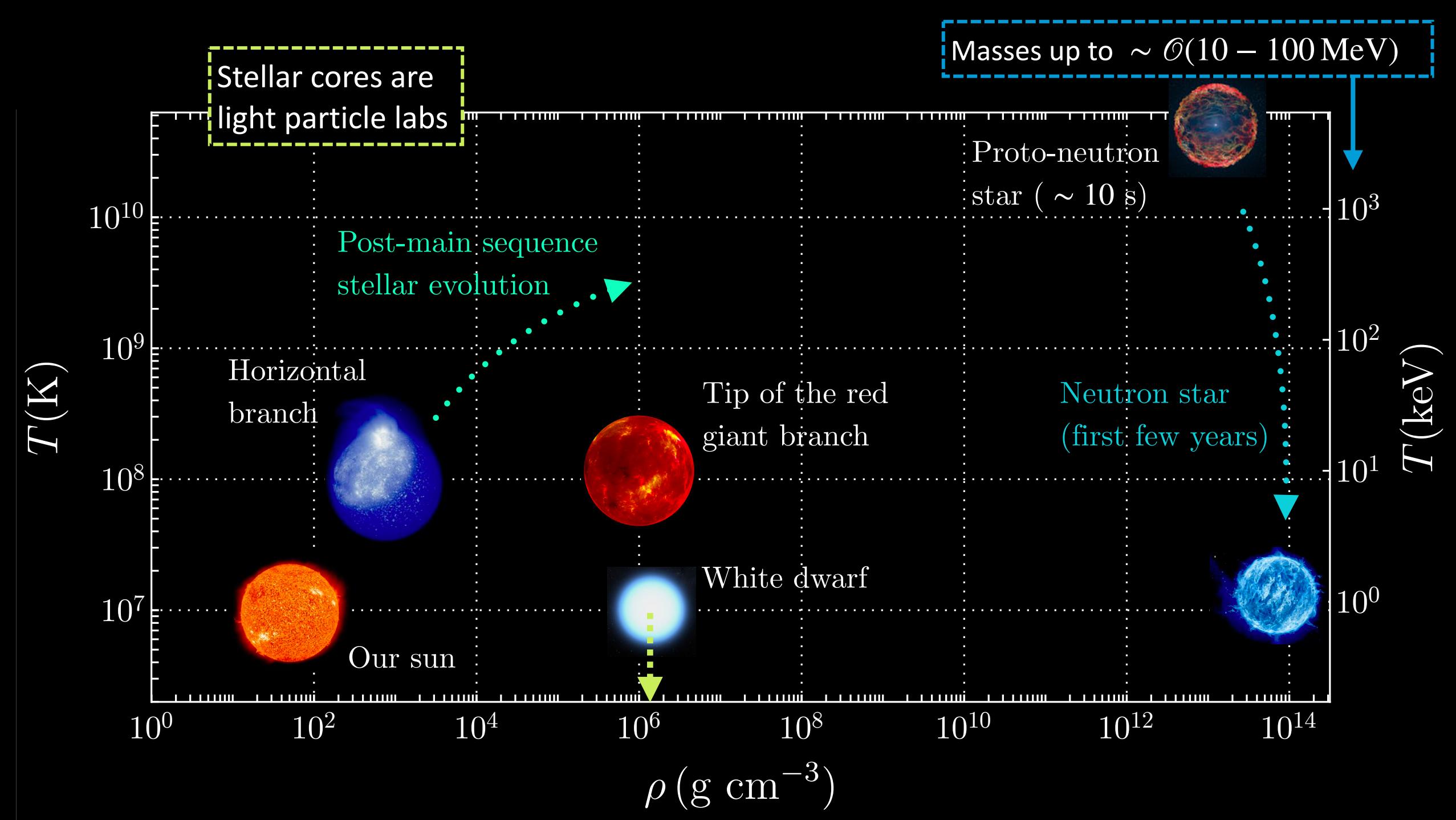


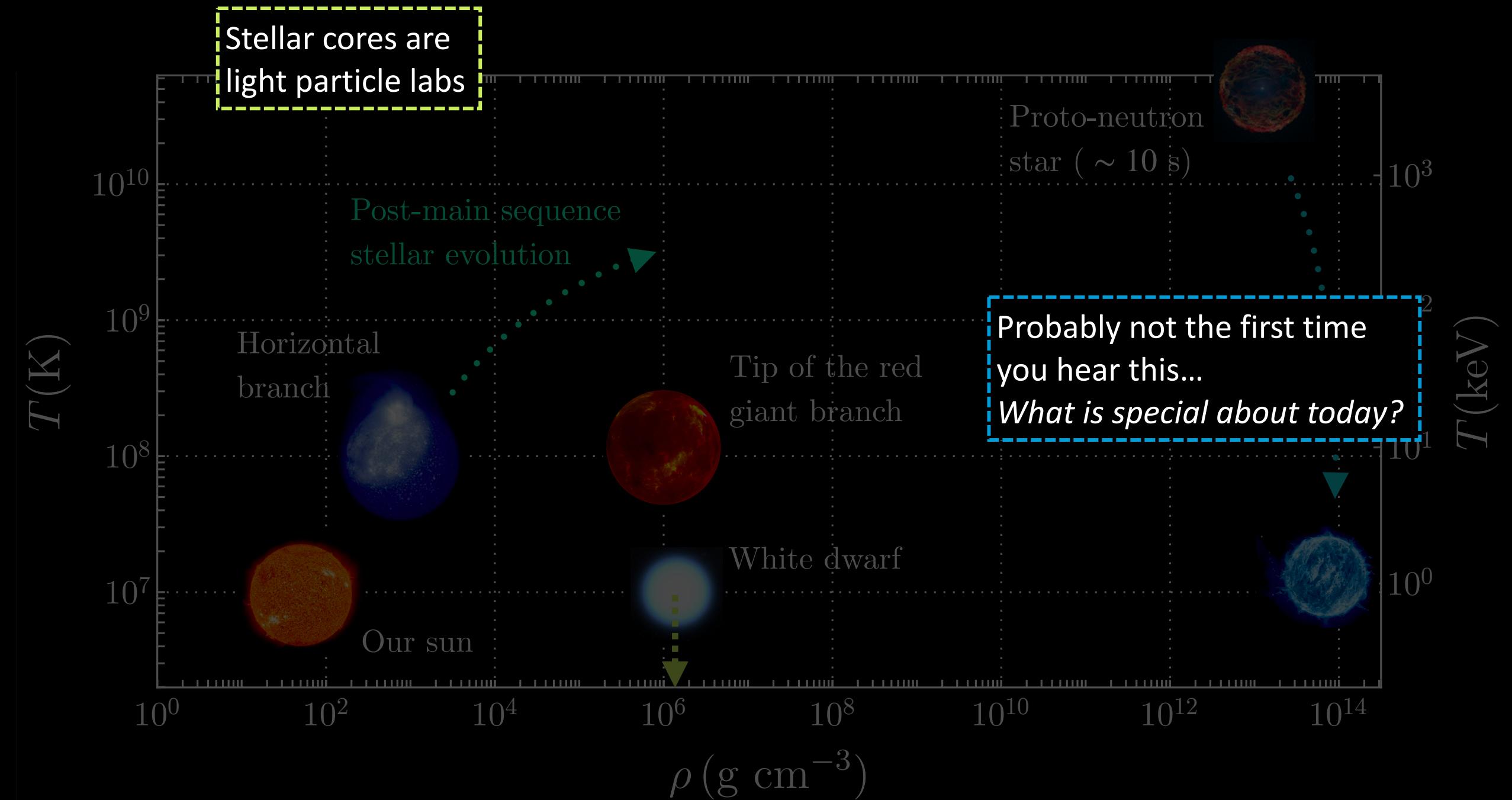












What's special about today?

Gravitational waves! ~ 50 merger events, and counting!

We may learn a lot of (stellar) astrophysics and particle physics from gravitational waves from binary mergers

- Opportunities for stellar astrophysics
- (Black hole) population studies:
distributions in mass, spin, redshift
 - Merger rate → clustering
 - Tidal effects encode EOS
 - Supernova signals
 - ...

- New physics effects in stars
- Cooling
 - Softening/hardening of the EOS
 - Dark matter annihilation in stars
 - Dark binaries
 - BSM effects on the inspiral
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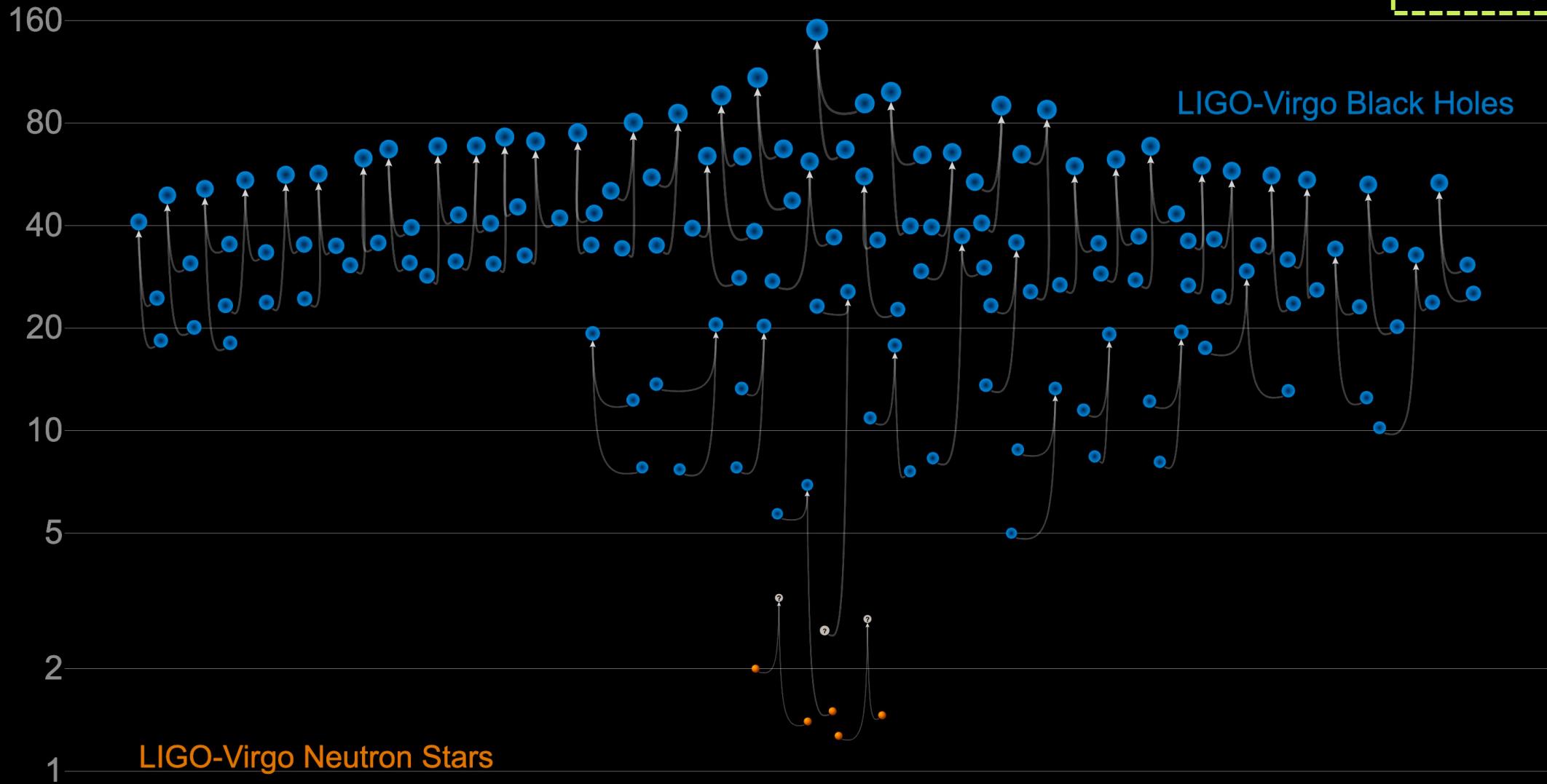
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} in this
talk {

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Binary mergers in LIGO/Virgo 01-3a

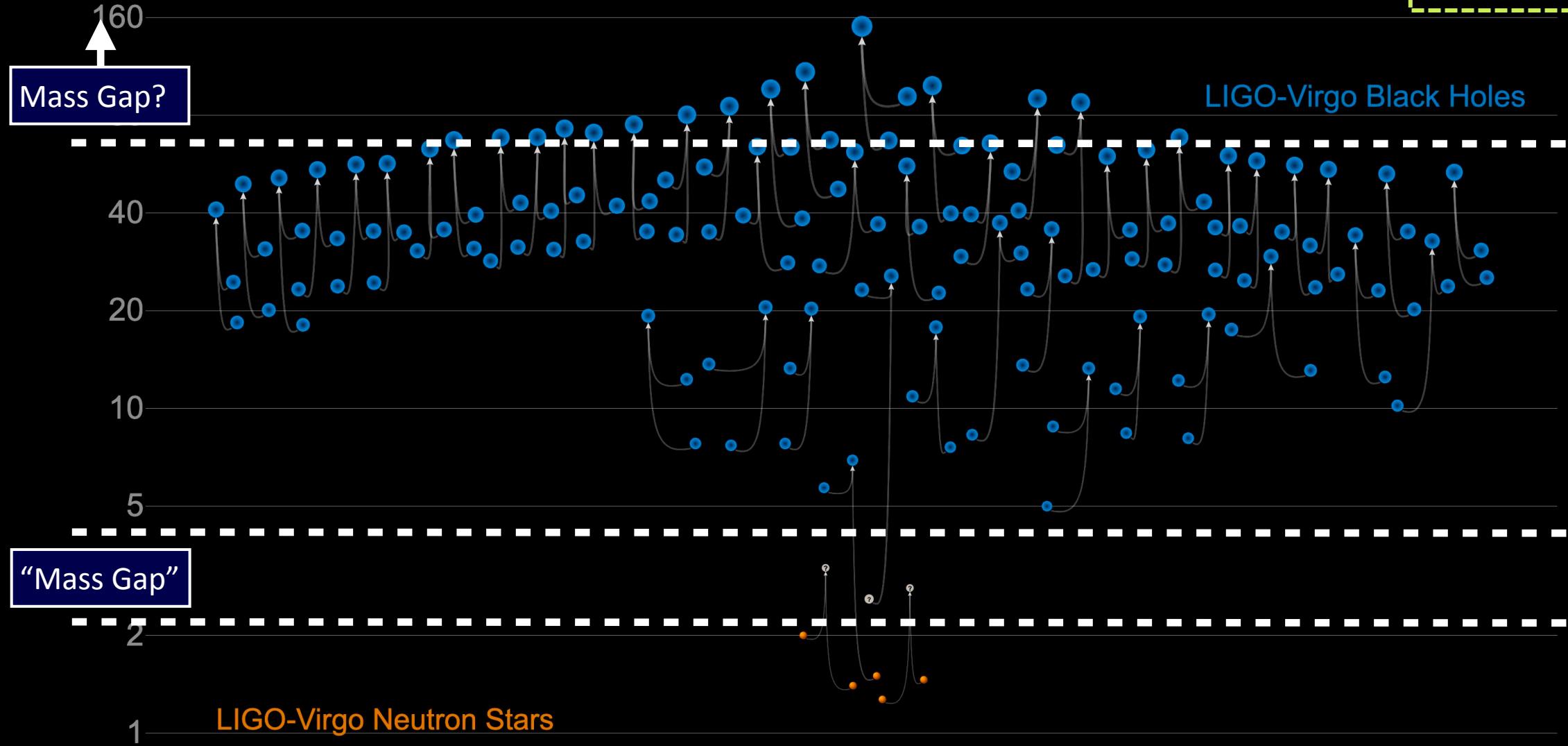
“The Stellar
Graveyard”



Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

Binary mergers in LIGO/Virgo 01-3a

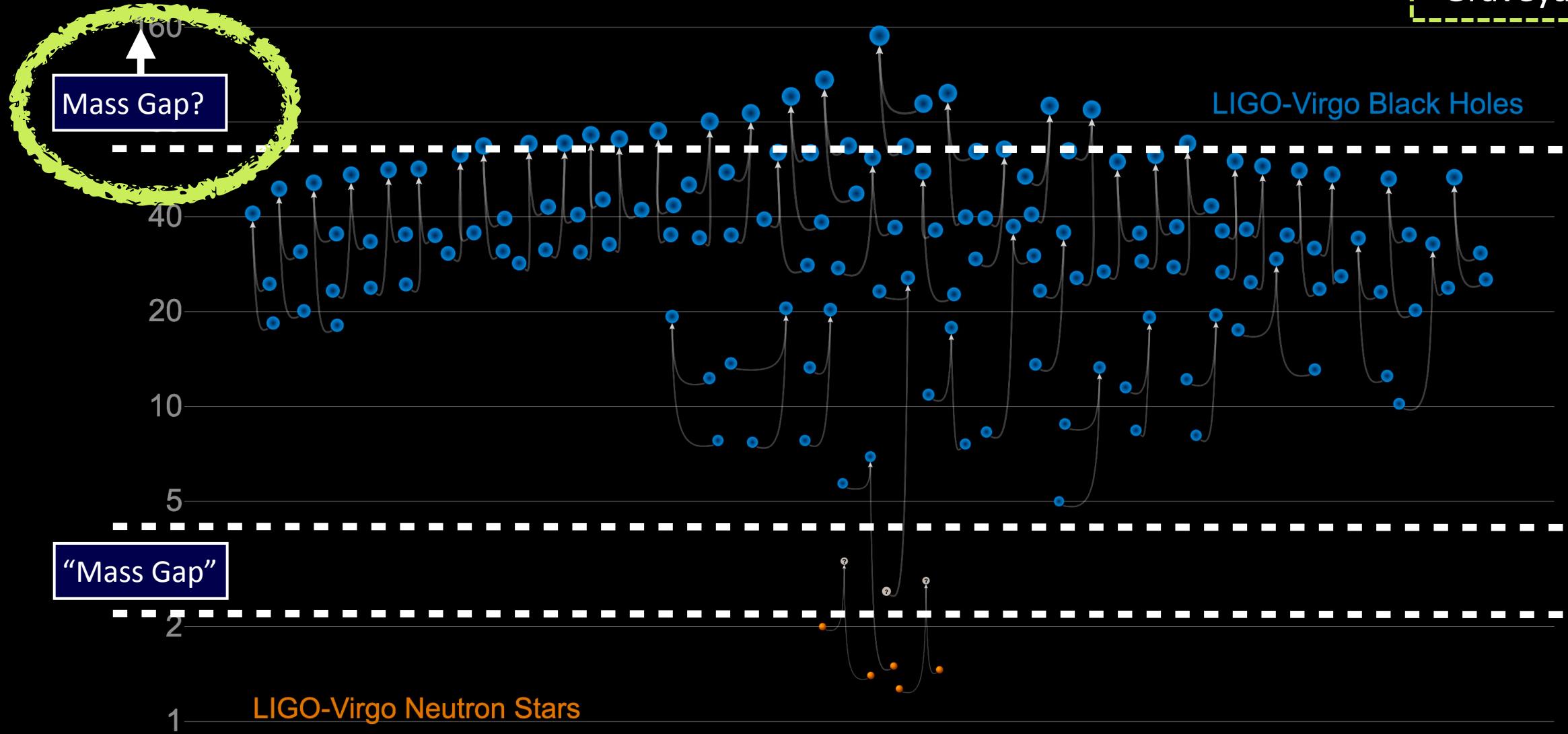
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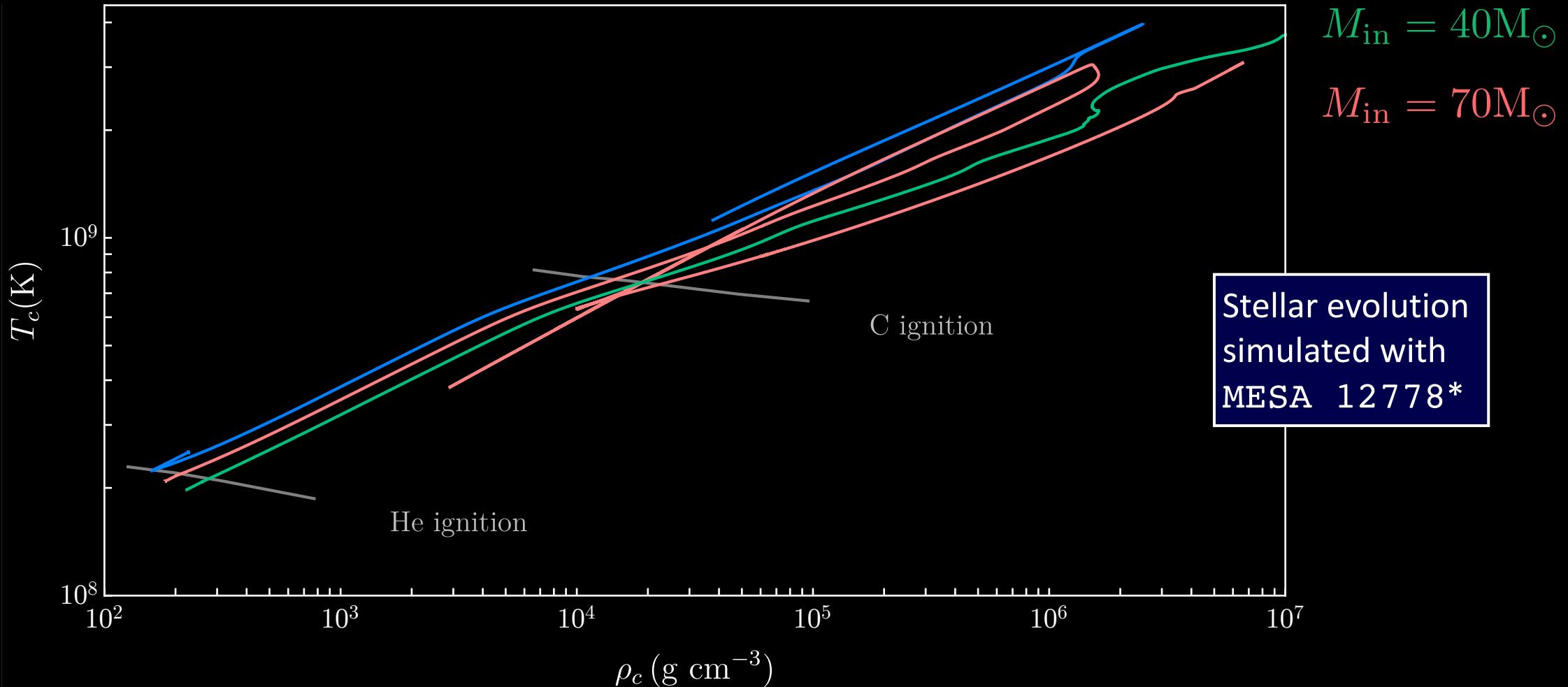
Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

What populates the stellar graveyard?

- In the LIGO/Virgo mass range: predominantly **remnants of heavy, low-metallicity (population-III) stars**
 - Primarily made of hydrogen (H) and helium (He)
 - Would have existed for $z \gtrsim 6$, $M \sim 20 - 130 M_{\odot}$
 - Have not been directly observed yet (JWST target)
- Eventually collapsed into black holes in core-collapse supernova explosions (*or did they?*)
- We study their evolution from the Zero-Age Helium Branch (ZAHB)

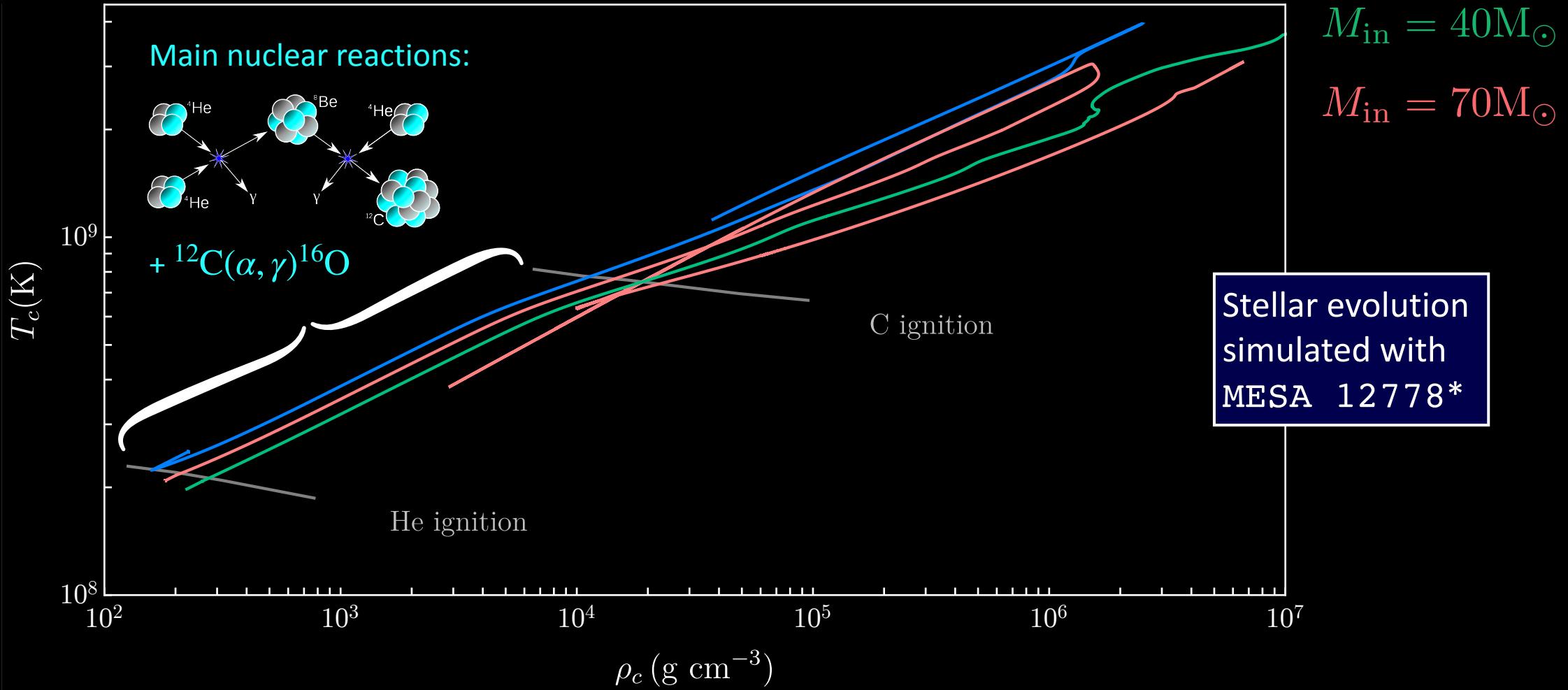
Evolution of old population-III stars

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

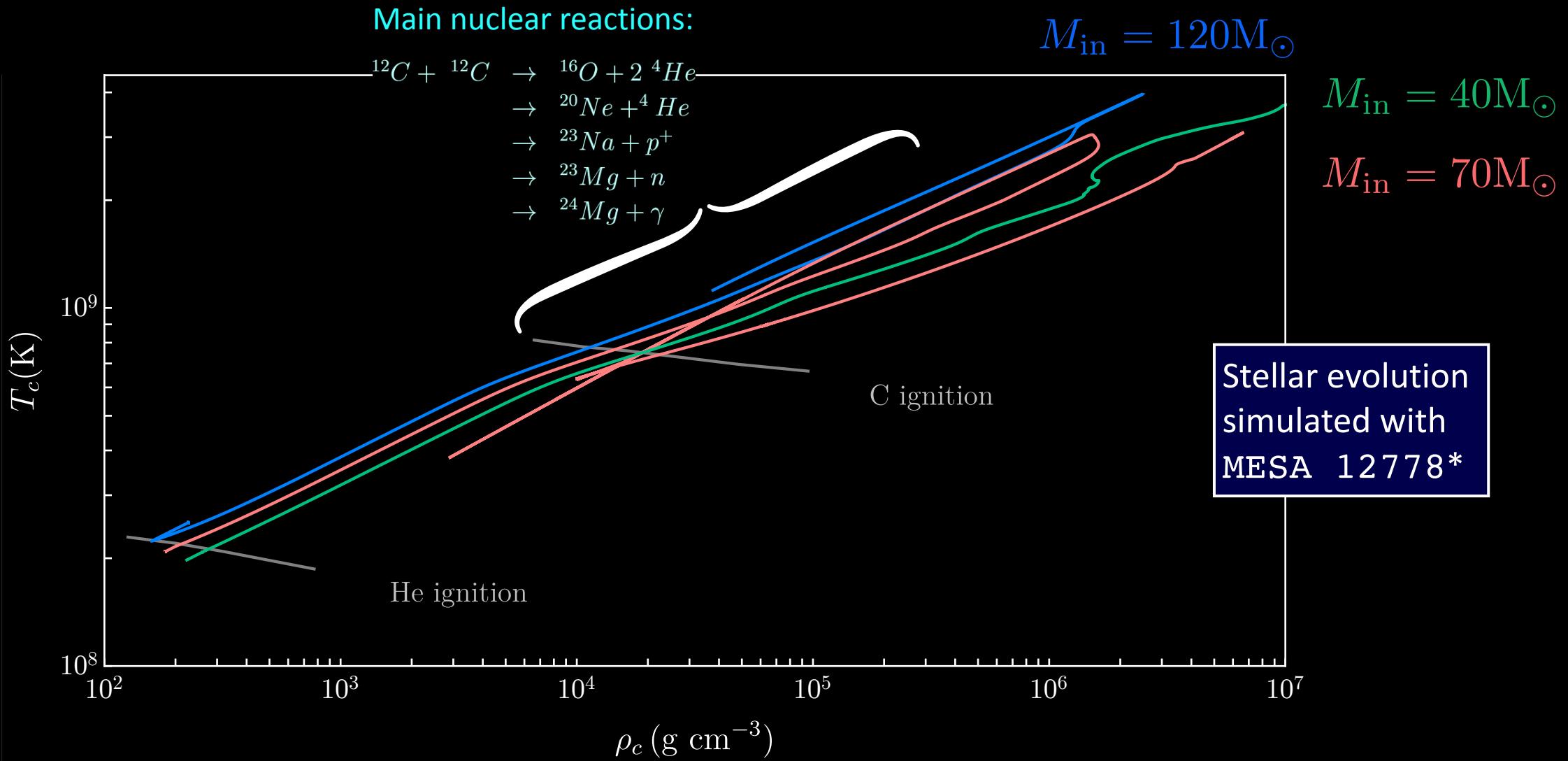


Evolution of old population-III stars

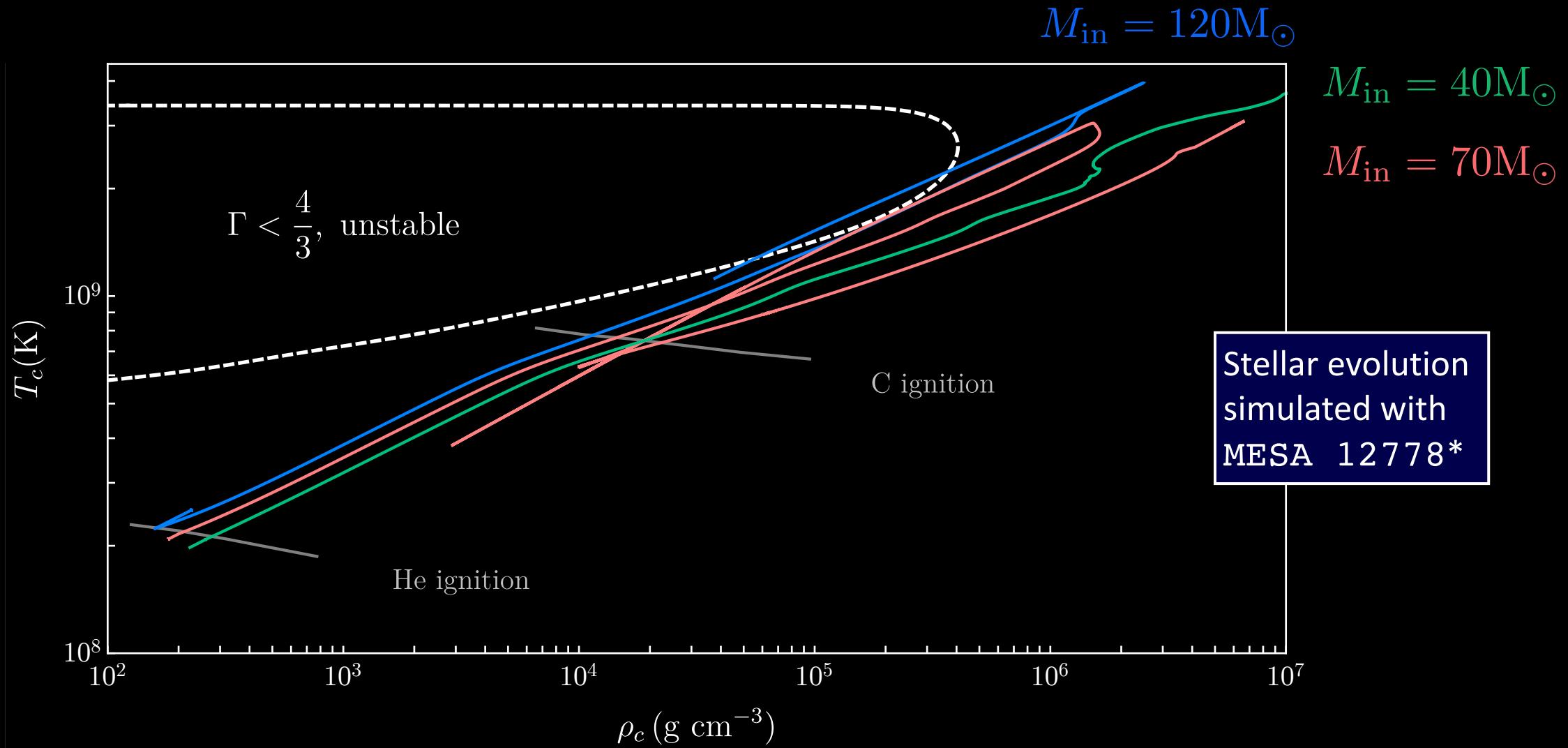
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Evolution of old population-III stars



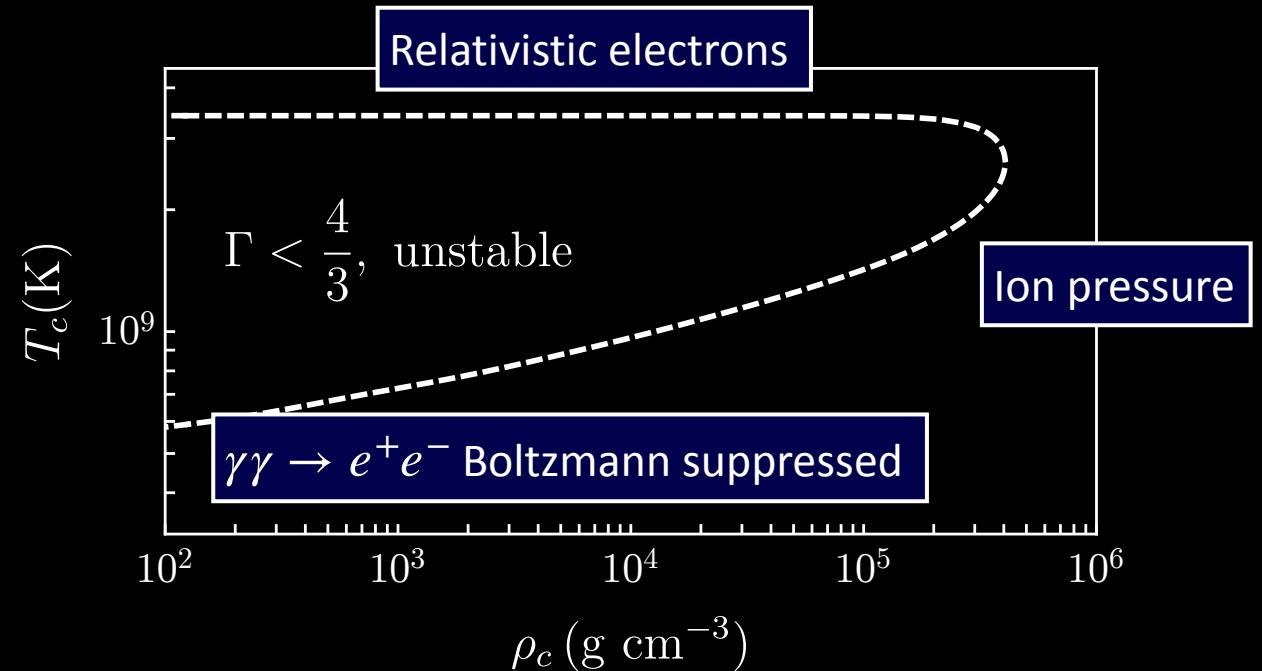
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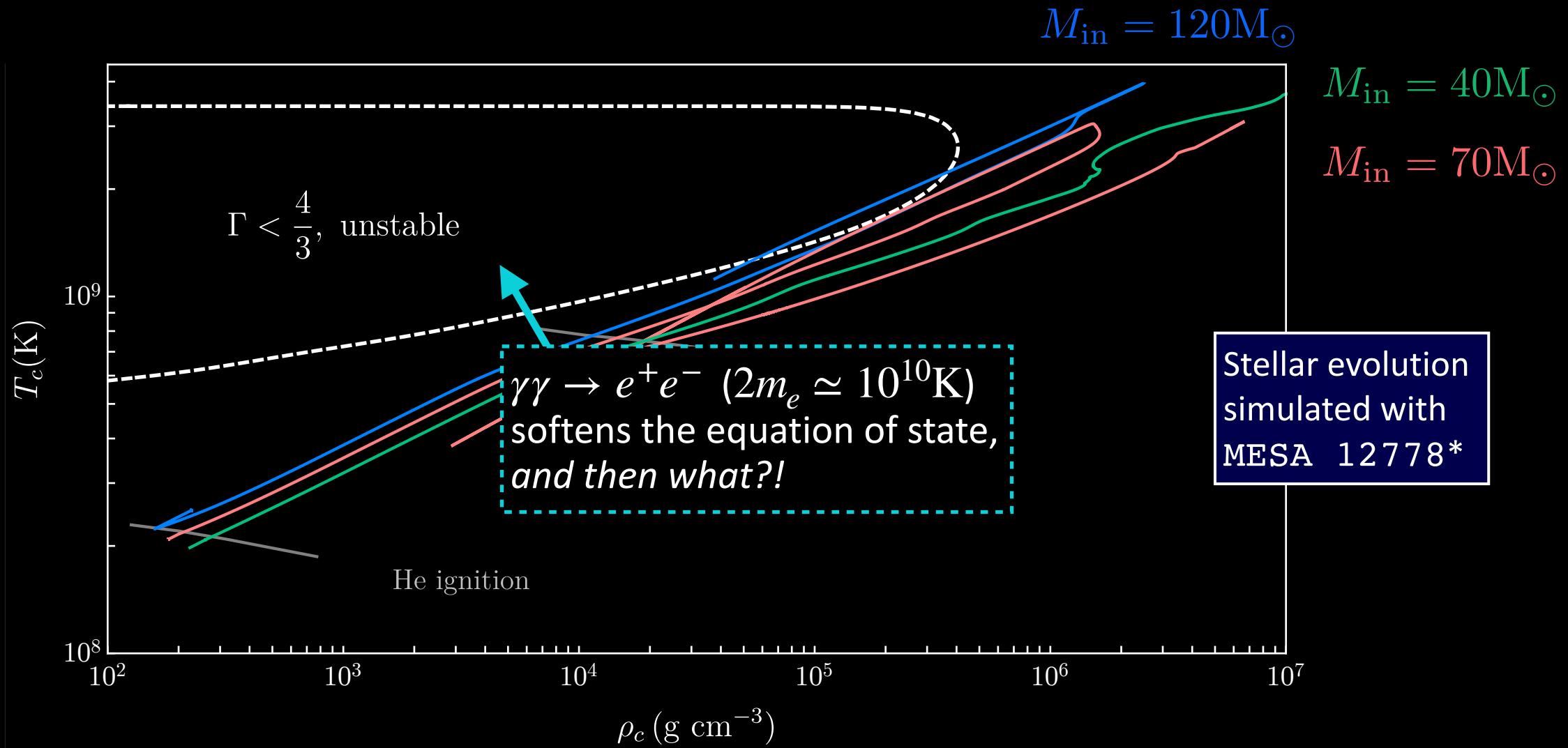
*Paxton et al, arXiv:1710.08424 [astro-ph.SR]

Pair-instability

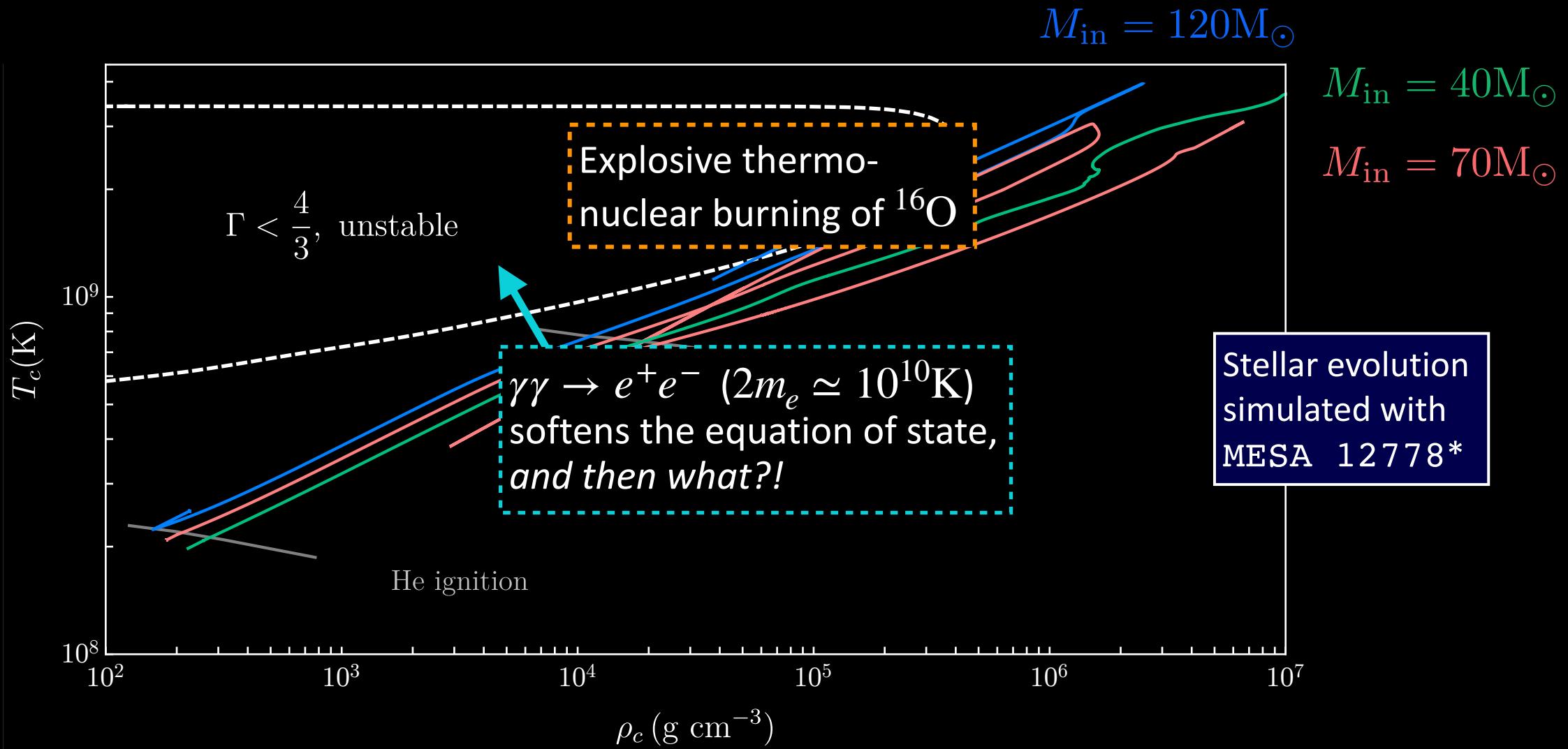
- The high temperatures of the pop-III stars lead to **electron-positron pair creation** in the thermal plasma via $\gamma\gamma \rightarrow e^+e^-$ ($2m_e \simeq 10^{10}$ K)
- Stars supported by radiation pressure $\Gamma = (\partial P / \partial \rho)_s \approx 4/3$
- Instability occurs for $\Gamma < 4/3$
 - Non-relativistic electrons destabilize the star



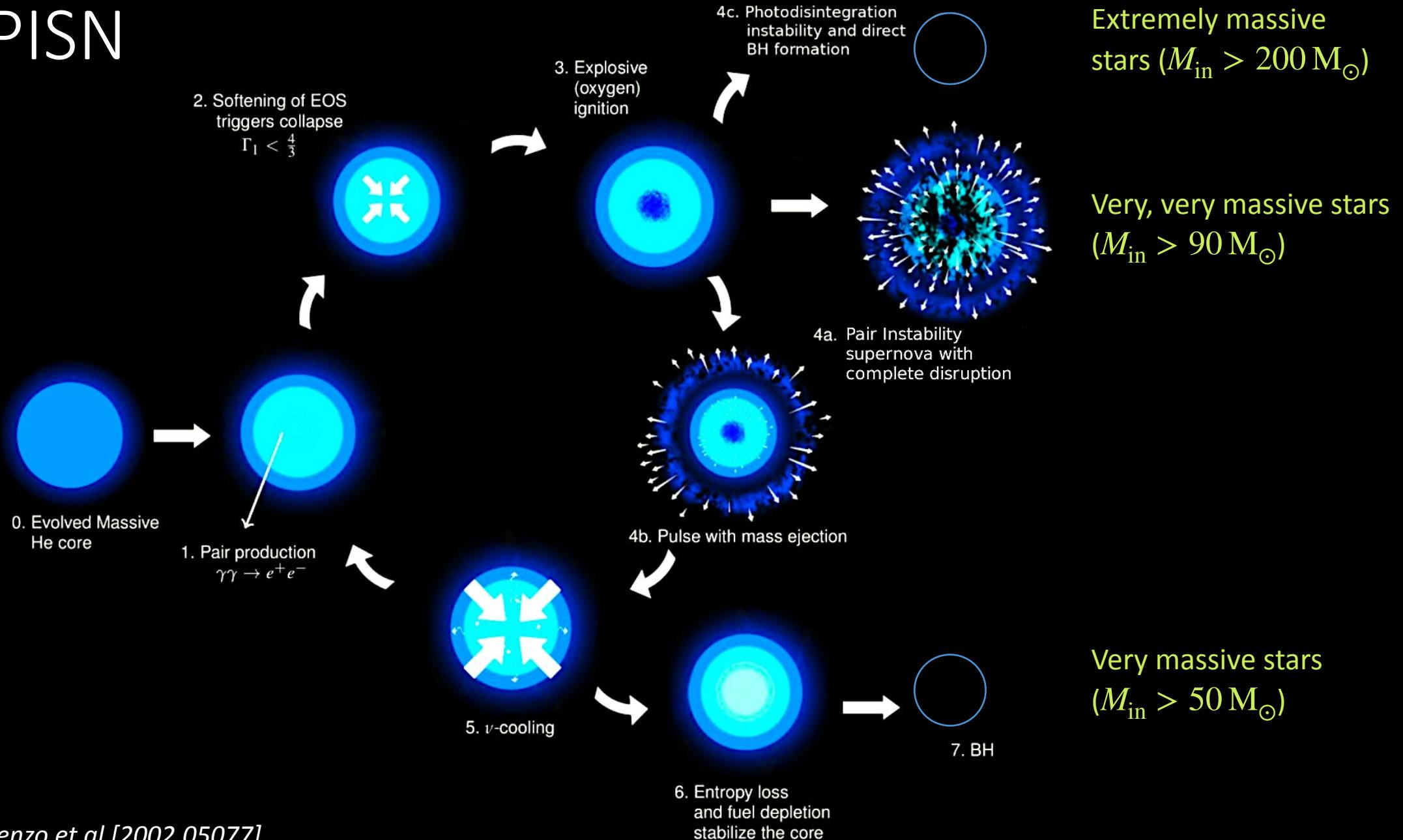
Evolution of old population-III stars



Evolution of old population-III stars

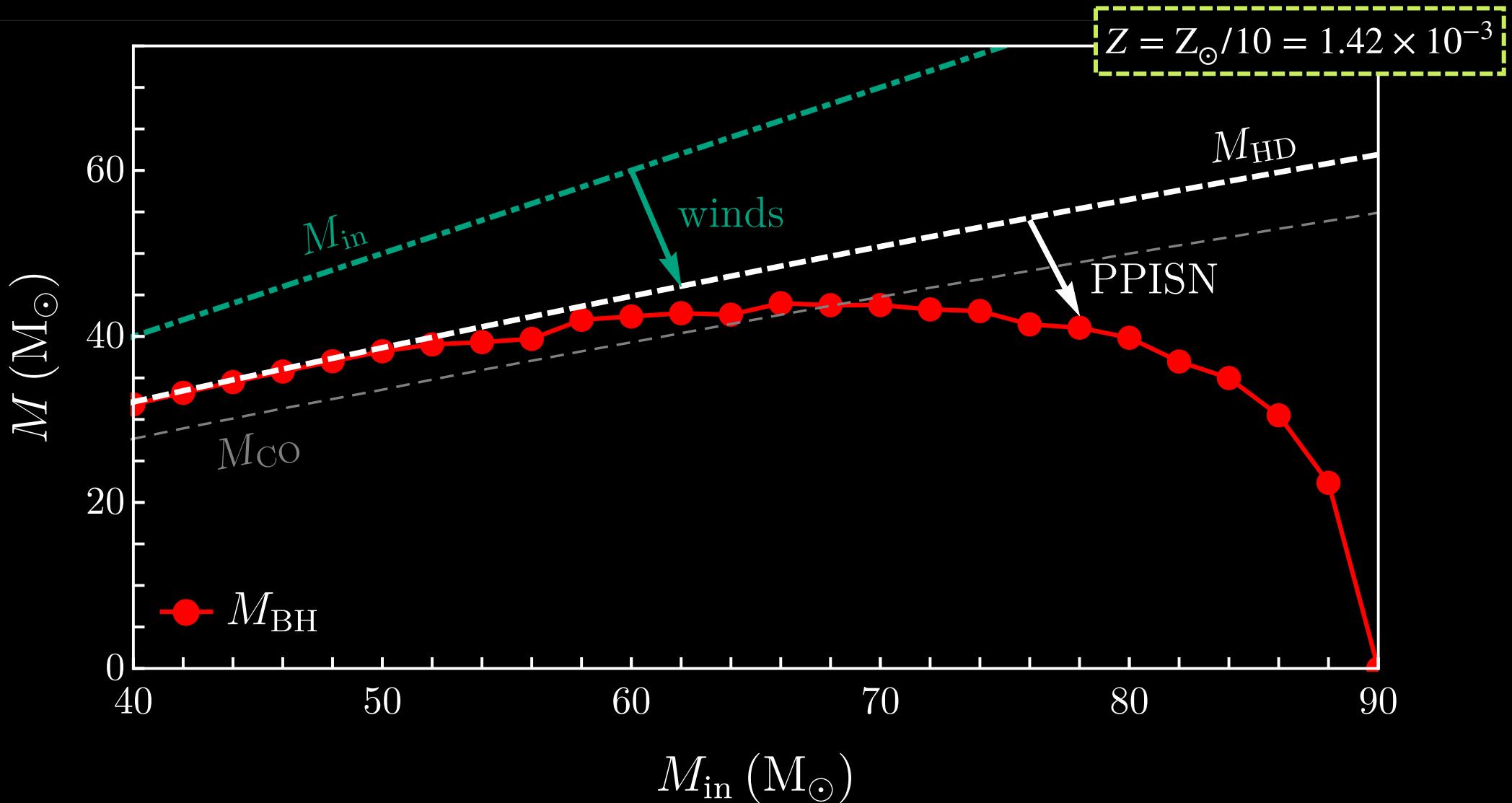


(P)PISN



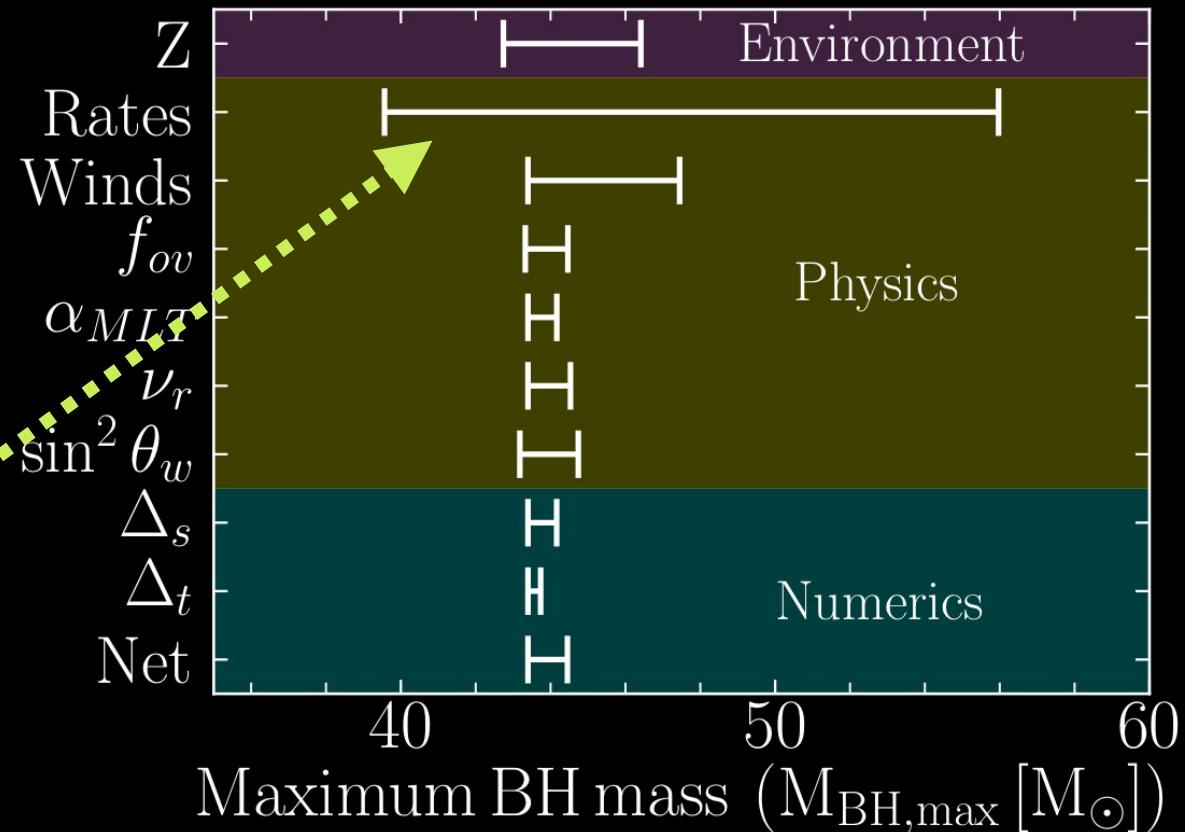
Adapted from Renzo et al [2002.05077]

Pair-instability and the BHMG



Known physics dependence of the BHMG

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

- Quickly recapping, the black hole mass gap is an SM prediction and a direct consequence of
 - The temperature and density of post-MS evolution
 - The mass of the electron
 - The burning products of helium
- BSM physics may affect post-MS evolution and therefore directly imprint on the black hole mass gap

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

DC, McDermott, Sakstein, PRD (editor's suggestion), arXiv:2007.07889 [gr-qc]

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

Ziegler, Freese arXiv:2010.00254 [astro-ph]

Several other works in progress...

The BHMG and BSM cooling

- Scenario: new, light particles coupled to material in the star introduce **new loss channels**
- Case studies: $\mathcal{L}_{\text{SM}} + \dots$
 - the electrophilic axion $\mathcal{L}_{ae} = -ig_{ae}\bar{\psi}_e\gamma_5\psi_e a$ (will also work with $\alpha_{26} \equiv 10^{26}g_{ae}^2/4\pi$ for convenience)*
 - the photophilic axion $\mathcal{L}_{a\gamma} = -\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\widetilde{F}^{\mu\nu}$ (will also define $g_{10} \equiv 10^{10}g_{a\gamma}$ GeV)
 - the hidden photon $\mathcal{L}_{A'\gamma} = -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu$ (and define nothing)

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

The BHMG and BSM cooling

- Scenario: 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: $\mathcal{L}_{\text{SM}} + \dots$
 - the electrophilic axion $\mathcal{L}_{ae} = -ig_{ae}\bar{\psi}_e\gamma_5\psi_e a$ (will also work with $\alpha_{26} \equiv 10^{26}g_{ae}^2/4\pi$ for convenience)*
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The BHMG and BSM cooling

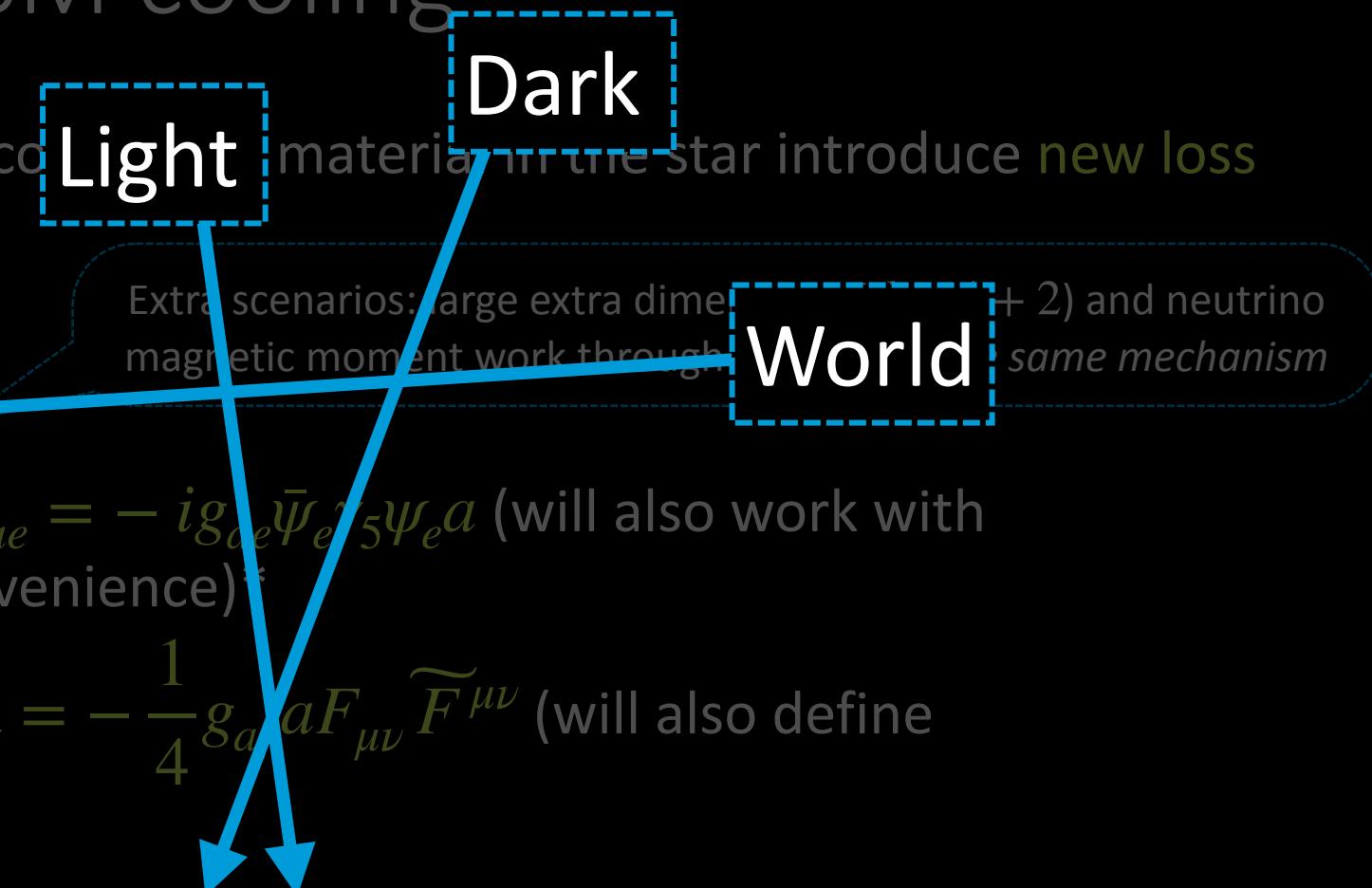
- Scenario: new, light particles cool material star introduce new loss channels

- Case studies: $\mathcal{L}_{\text{SM}} + \dots$

• the electrophilic axion $\mathcal{L}_{ae} = -ig_{ae}\bar{\psi}_e \gamma_5 \psi_e a$ (will also work with $\alpha_{26} \equiv 10^{26}g_{ae}^2/4\pi$ for convenience)*

• the photophilic axion $\mathcal{L}_{ay} = -\frac{1}{4}g_a a F_{\mu\nu} \tilde{F}^{\mu\nu}$ (will also define $g_{10} \equiv 10^{10}g_{a\gamma} \text{ GeV}$)

• the hidden photon $\mathcal{L}_{A'\gamma} = -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu$ (and define nothing)



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

LOSS rates

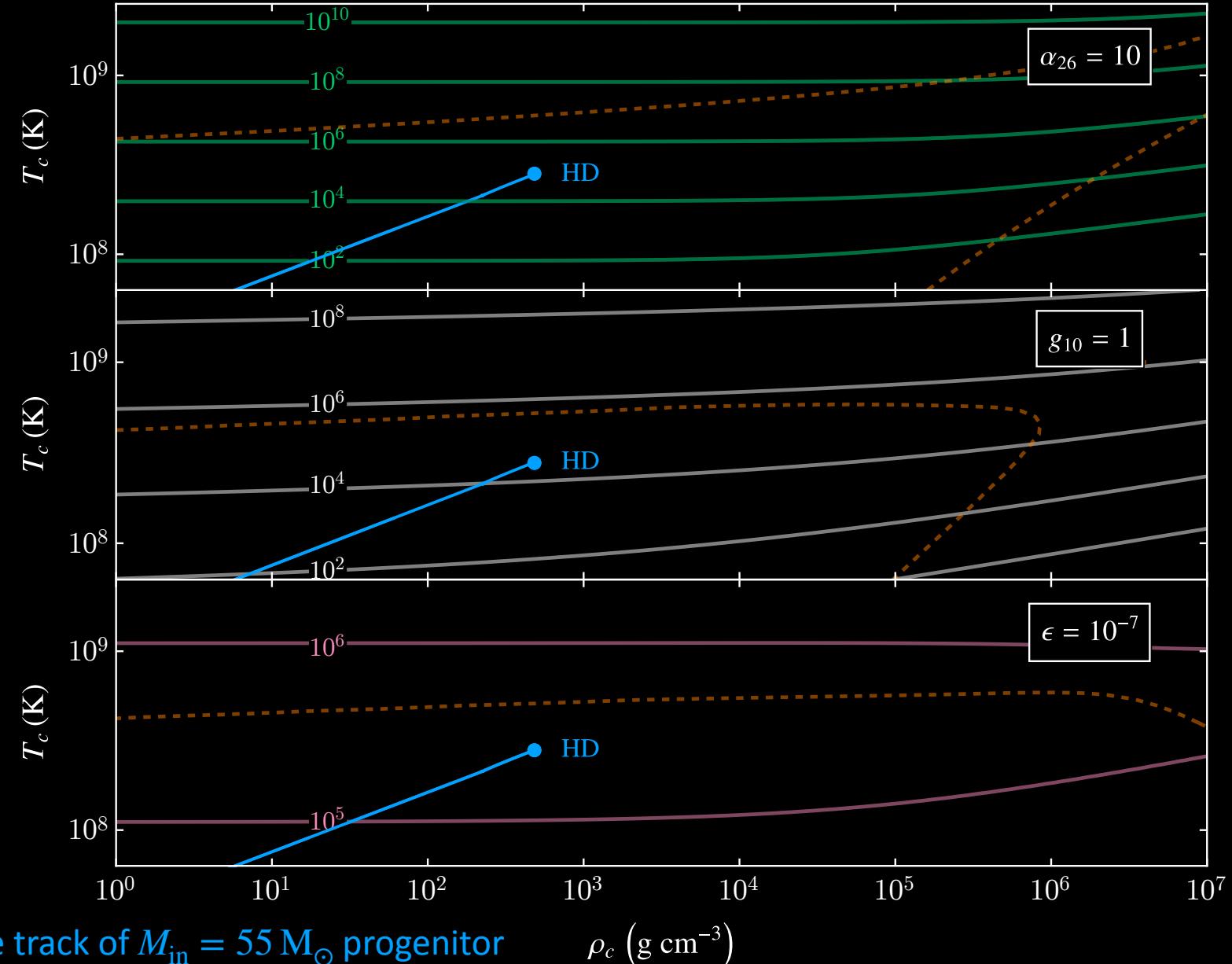
Electrophilic axion: $Q_{ae} \propto T^6$
 $(e + \gamma \rightarrow e + a)$

Photophilic axion: $Q_{ay} \propto T^4$
 $((Z, A) + \gamma \rightarrow (Z, A) + a)$

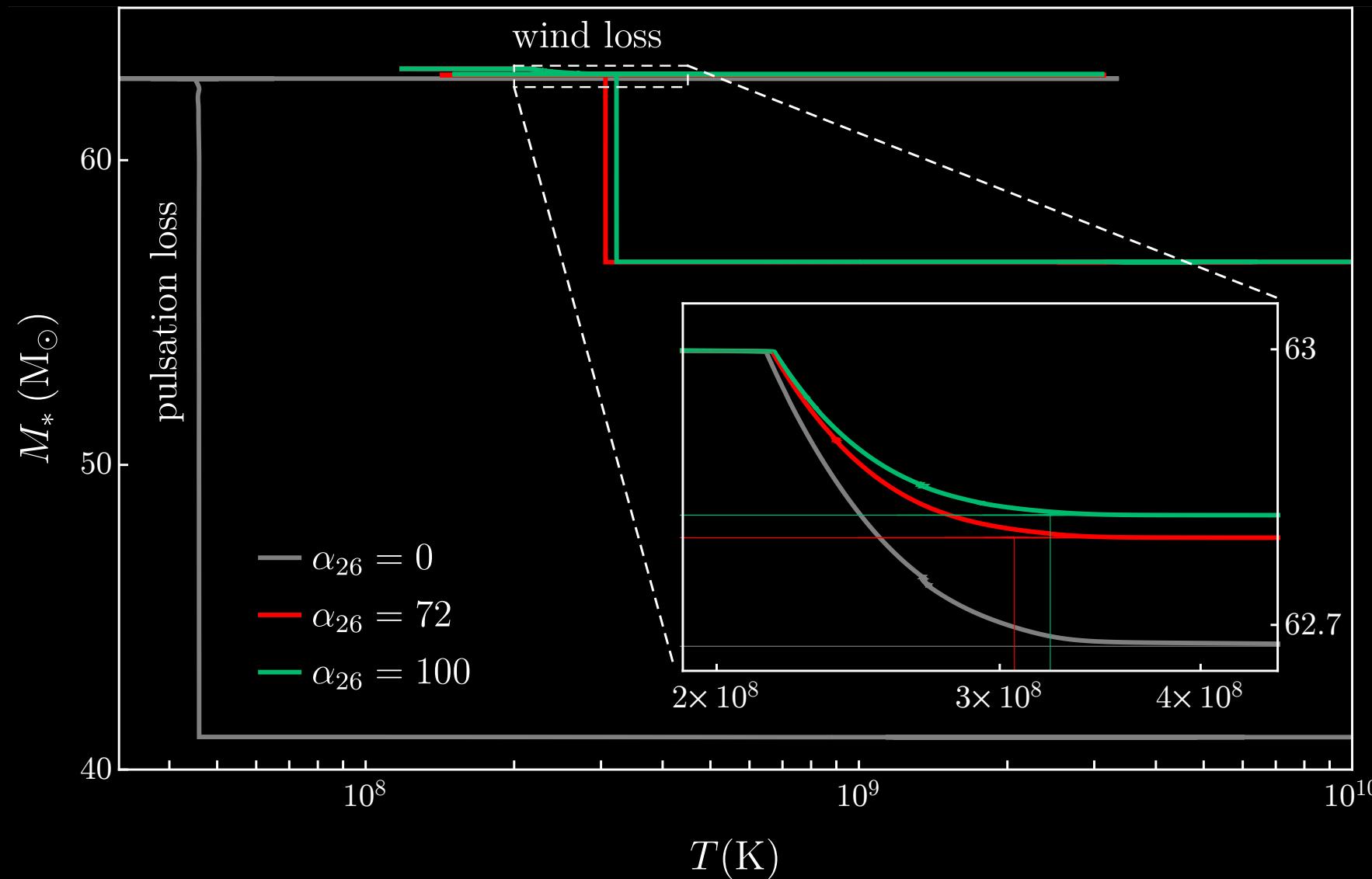
Hidden photon: $Q_{A'} \propto T$
(resonant emission)

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

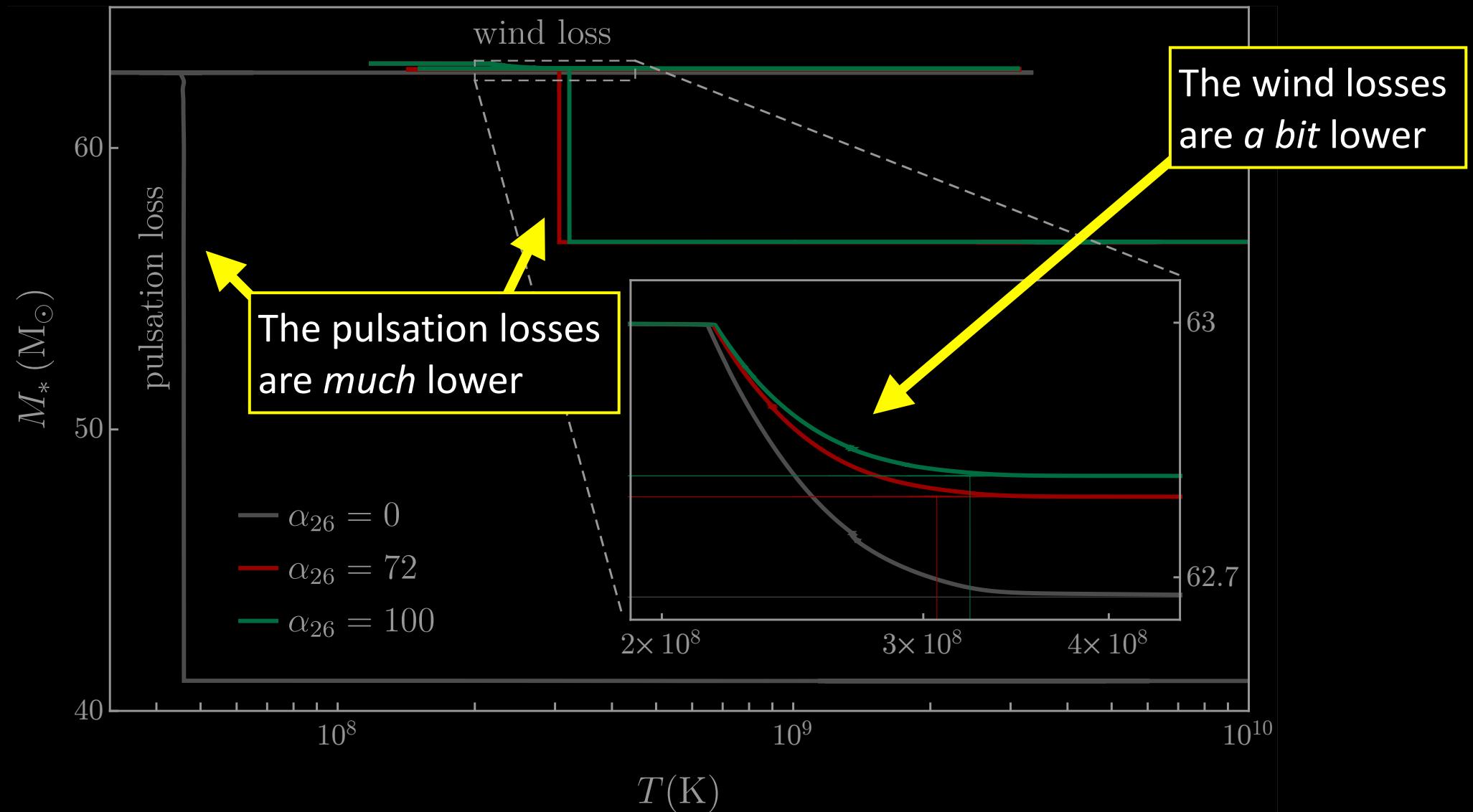
Example track of $M_{\text{in}} = 55 M_\odot$ progenitor



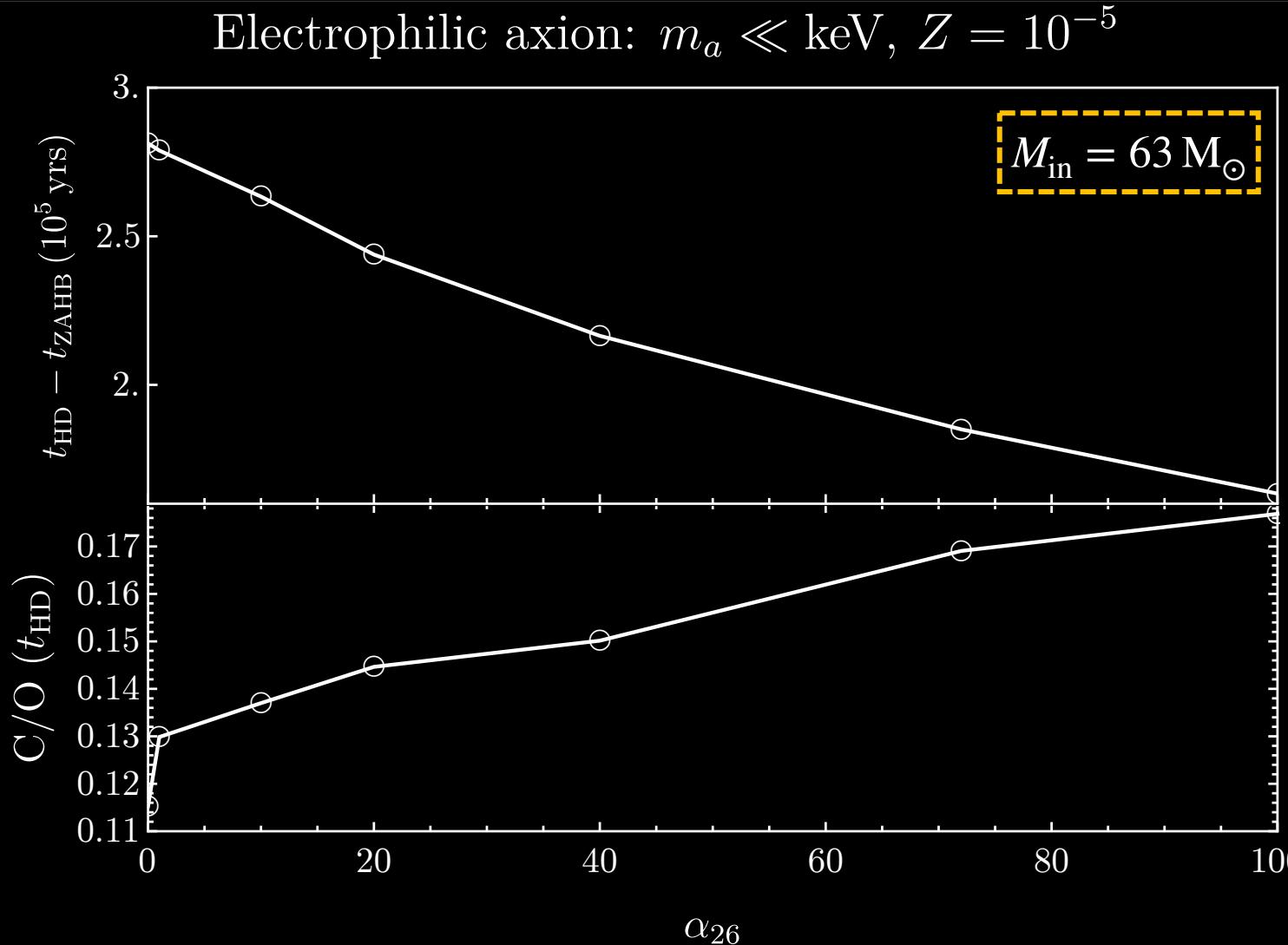
Implications of enhanced losses



Implications of enhanced losses



What does the extra energy loss do?



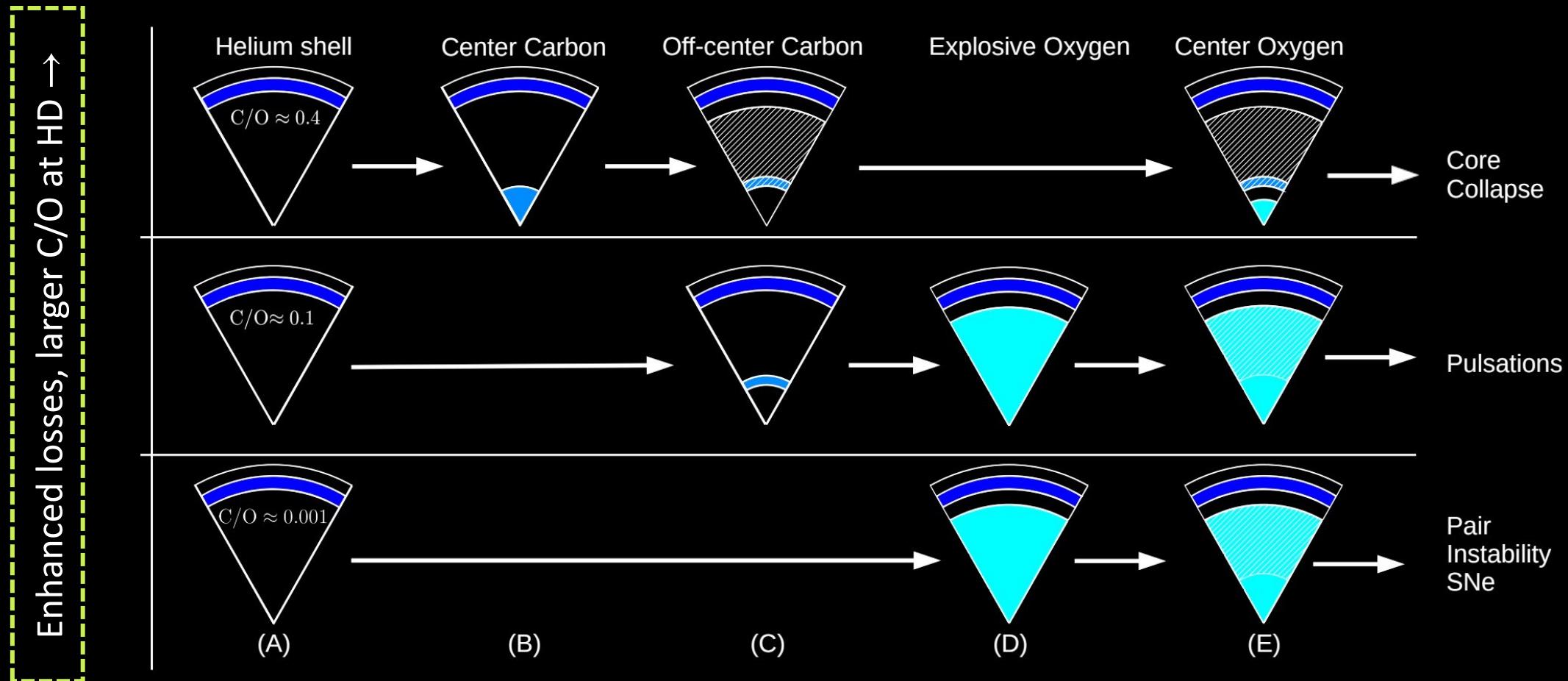
Greater energy losses lead to
shorter He-burning phases

Extra dissipation scales
linearly with α_{26}

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

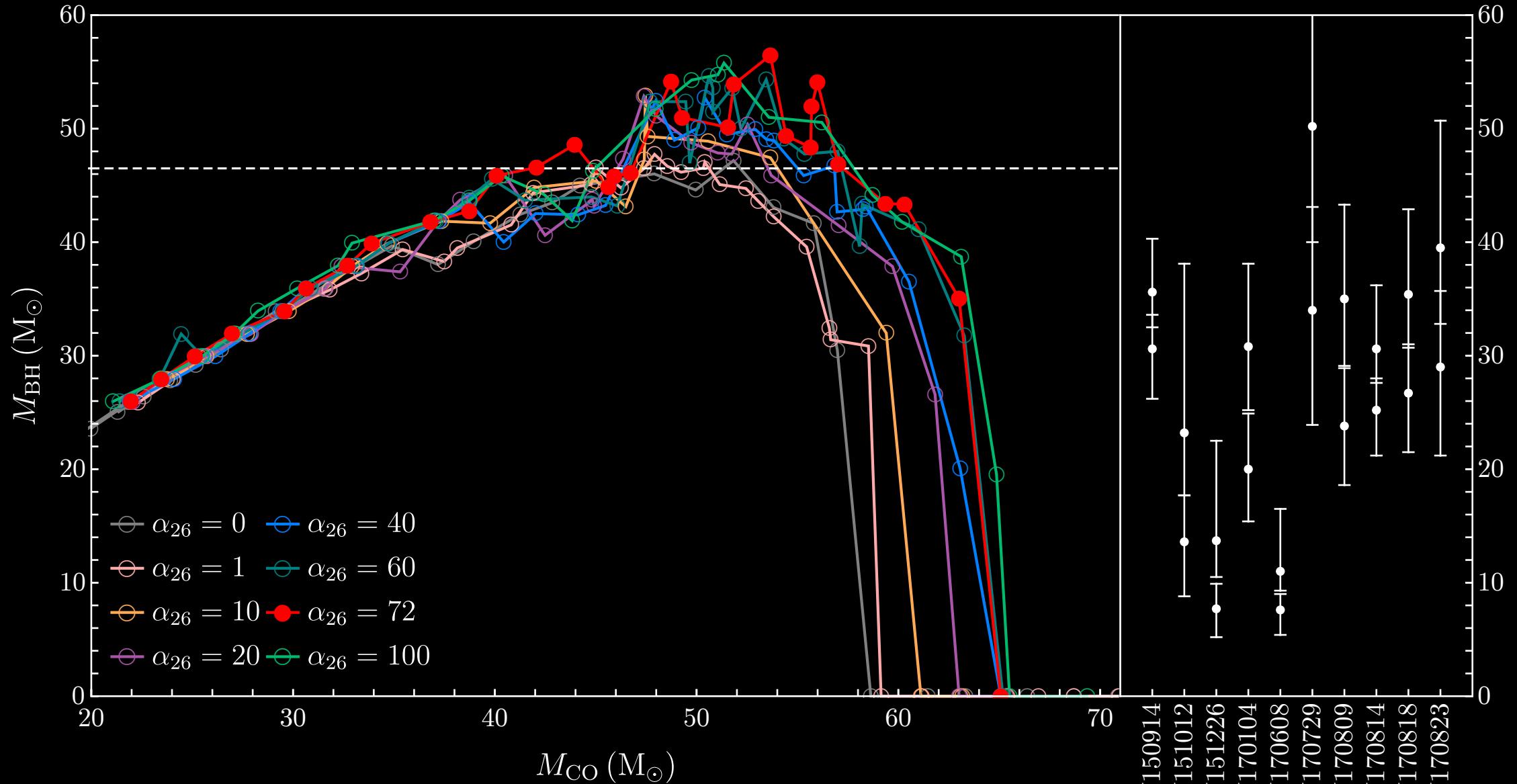
The BHMG and new physics

Helium burning
Carbon burning
Oxygen burning

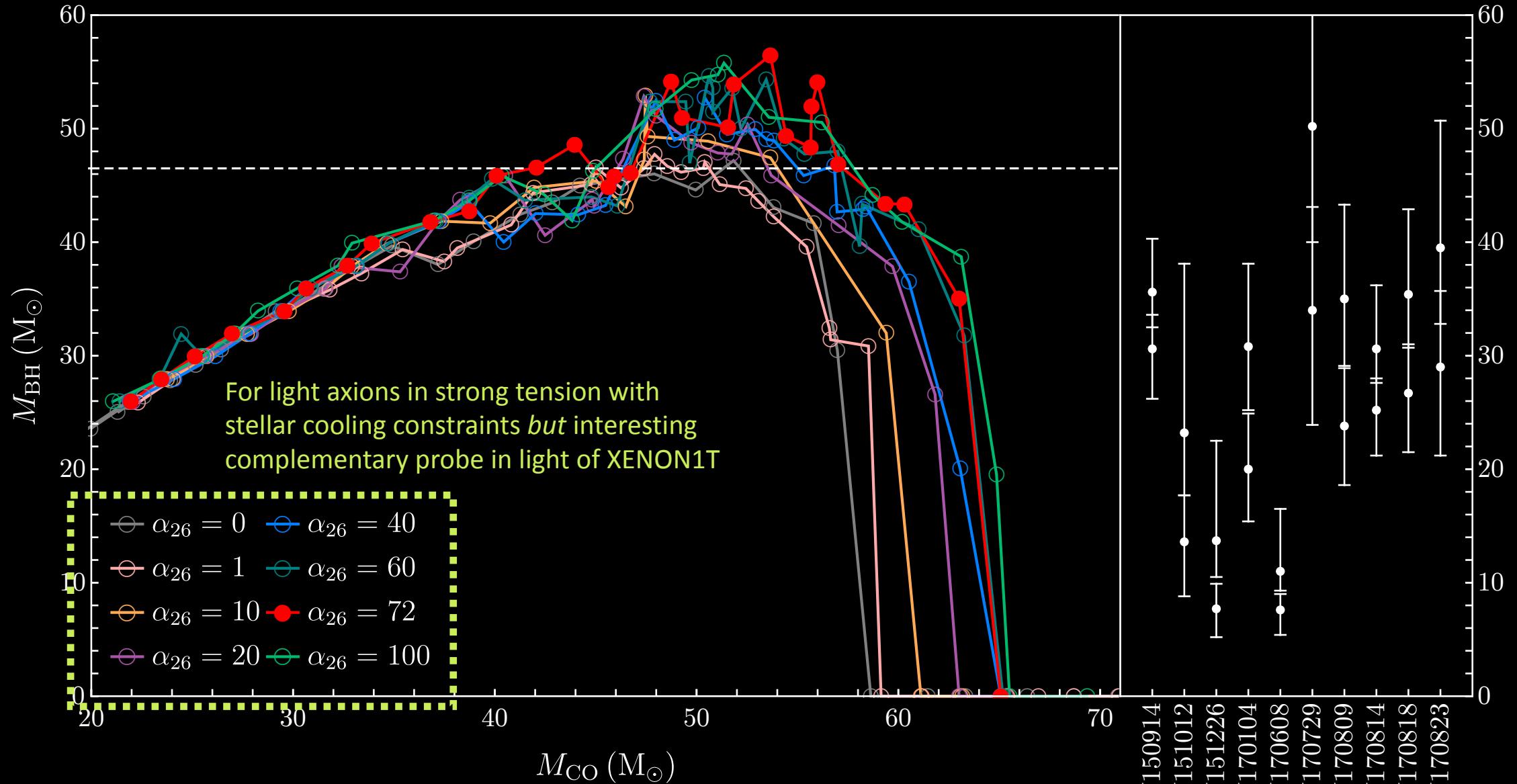


Enhanced losses → greater progenitors collapse → larger black holes

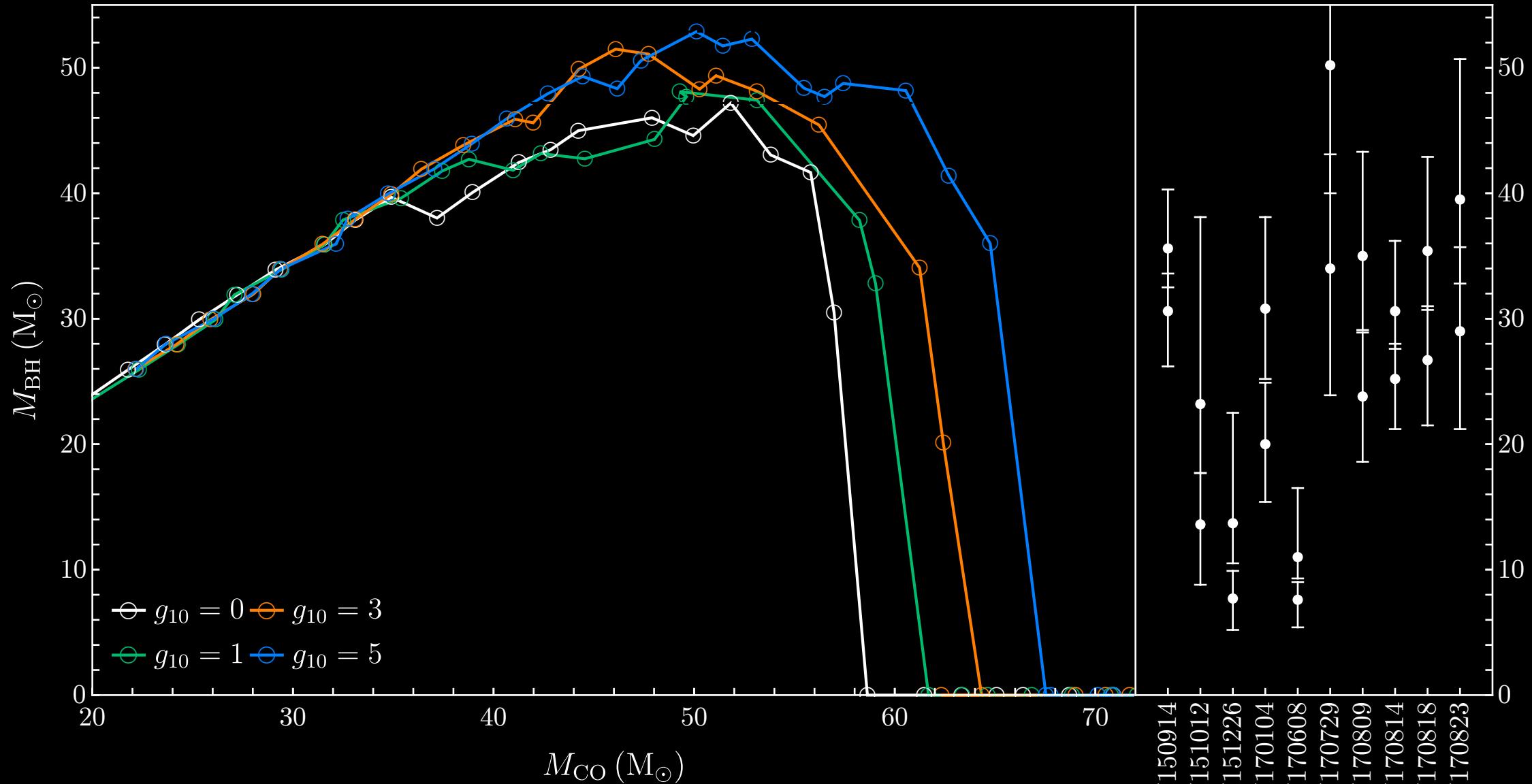
Electrophilic axion: $m_a \ll \text{keV}$, $Z = 10^{-5}$



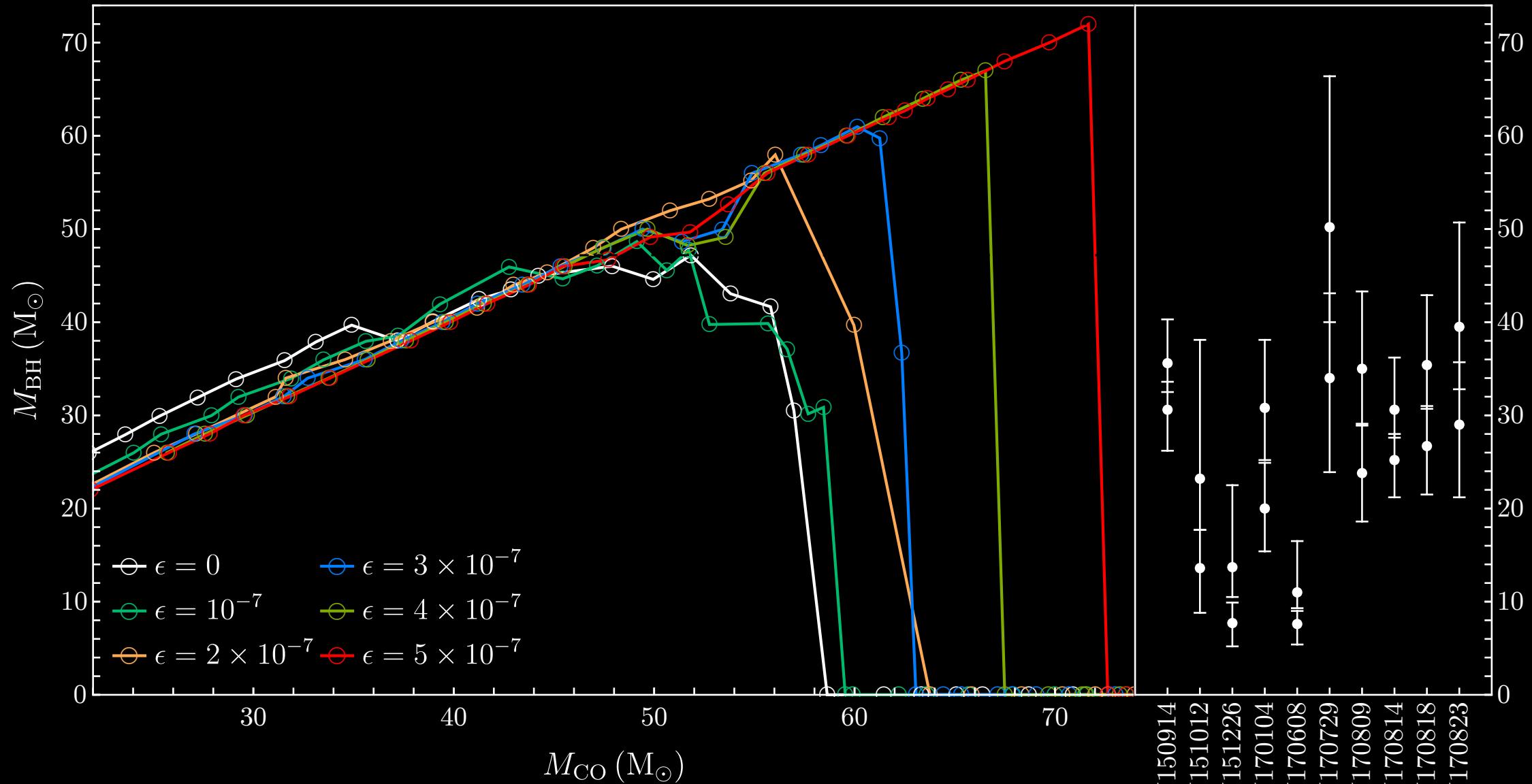
Electrophilic axion: $m_a \ll \text{keV}$, $Z = 10^{-5}$



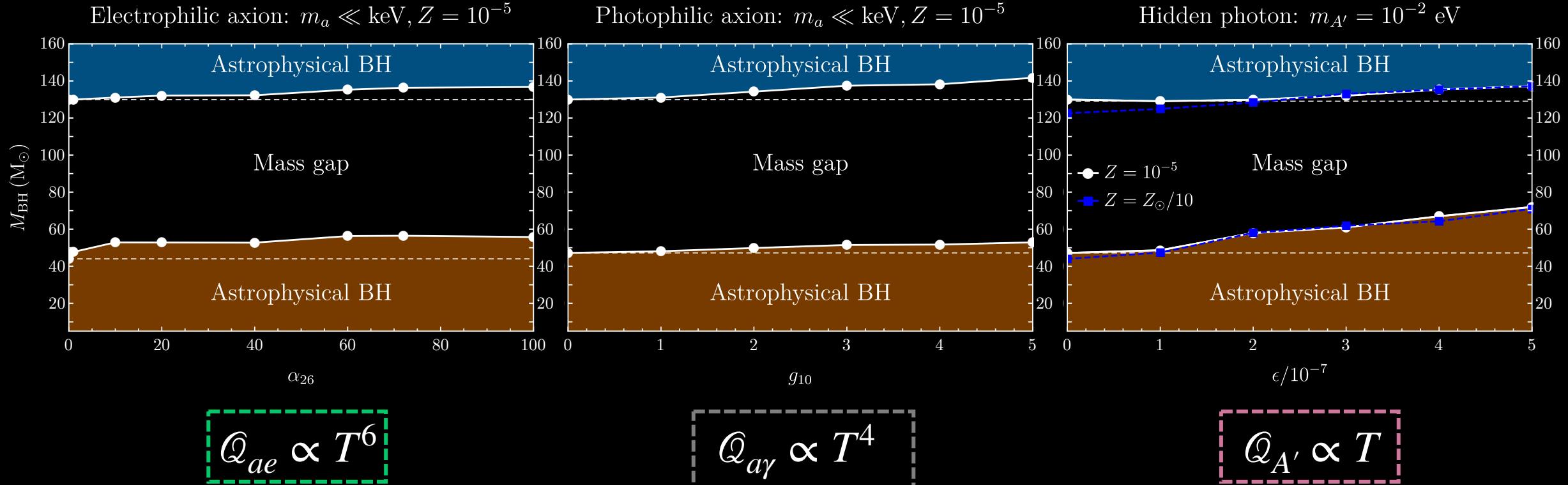
Photophilic axion: $m_a \ll \text{keV}, Z = 10^{-5}$



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



BSM cooling and the black hole mass gap



Potentially large shifts of the mass gap!

Heavier degrees of freedom?

- Heavier (or more strongly coupled) degrees of freedom may instead *remain in the star*
- Then, they affect the stellar structure equations

From Stellar Structure and Evolution (2nd edition), Kippenhahn, Weigert, Weiss

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \varrho} ,$$

Mass function

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} ,$$

Hydrostatic equilibrium

$$\frac{\partial l}{\partial m} = \varepsilon_n - \varepsilon_v - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\varrho} \frac{\partial P}{\partial t} ,$$

Energy flux

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P} \nabla ,$$

Convection

$$\frac{\partial X_i}{\partial t} = \frac{m_i}{\varrho} \left(\sum_j r_{ji} - \sum_k r_{ik} \right) , \quad i = 1, \dots, I .$$

Reactions

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Mass function

Hydrostatic equilibrium

Energy flux

Convection

Reactions

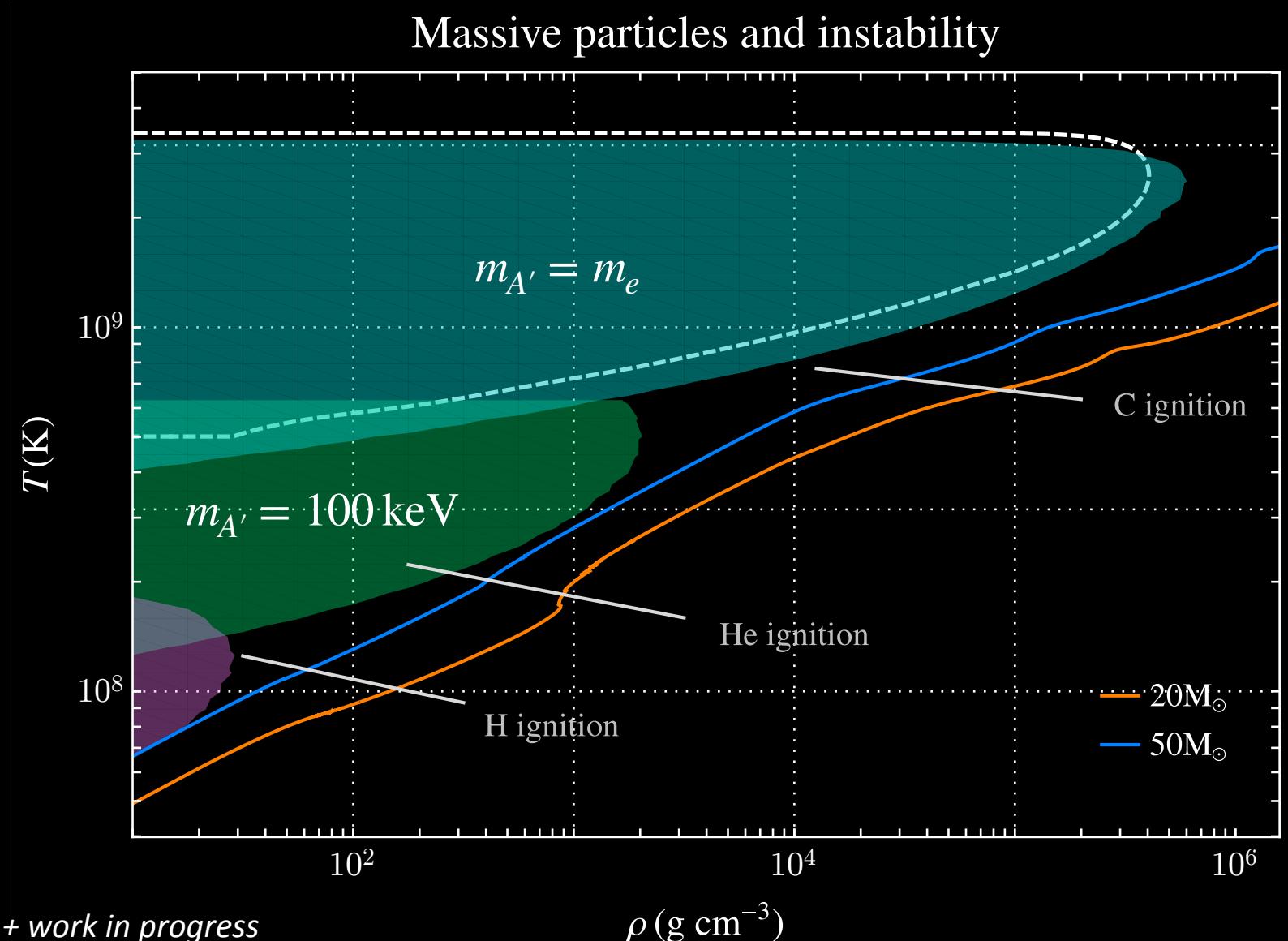
+ BSM physics contributions?

Heavier degrees of freedom?

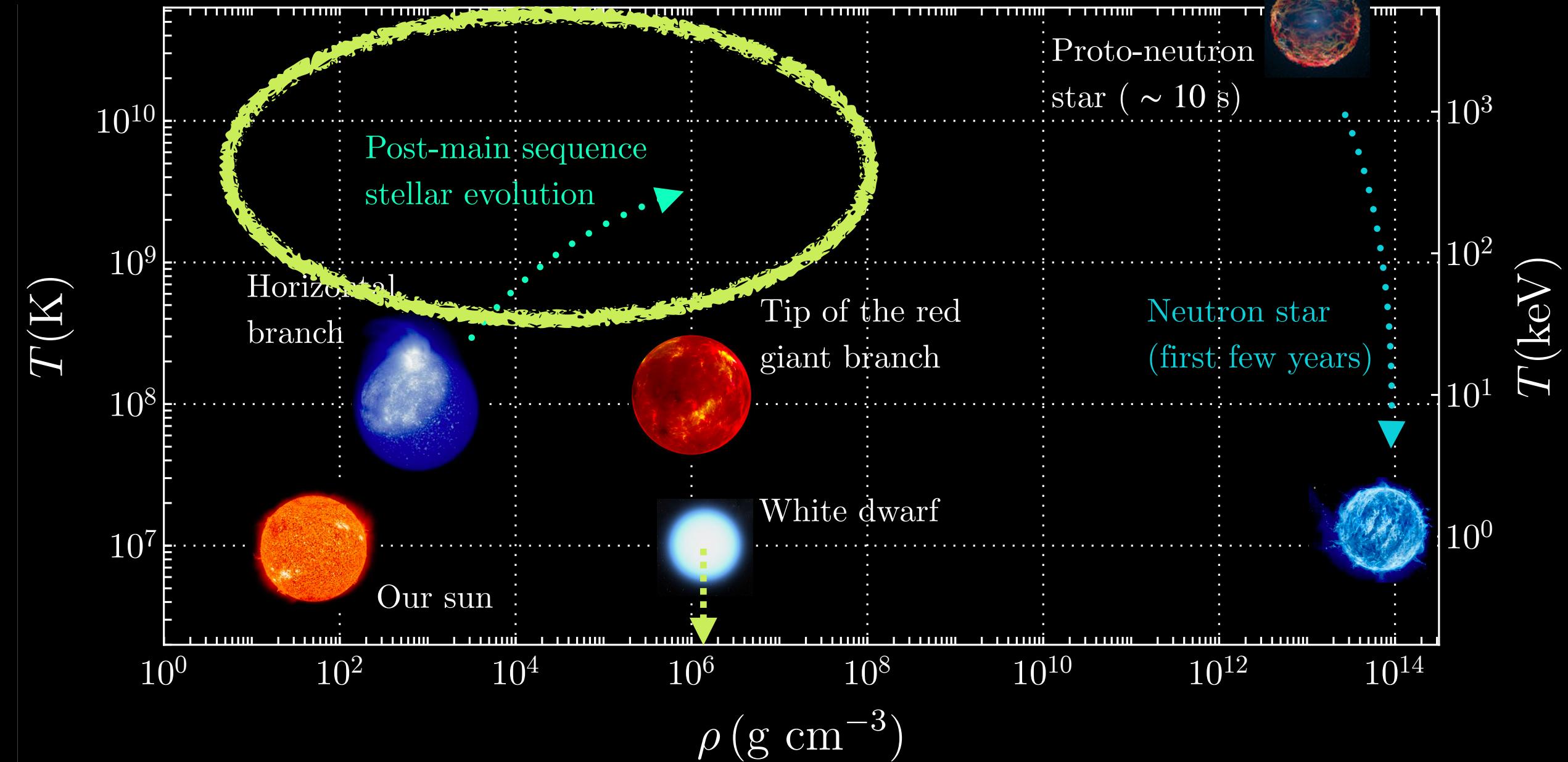
Heavier degrees of freedom may instead *remain in the star*

Then, they may *soften the EOS* (as electron-positron pairs do)

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



Probe this parameter space



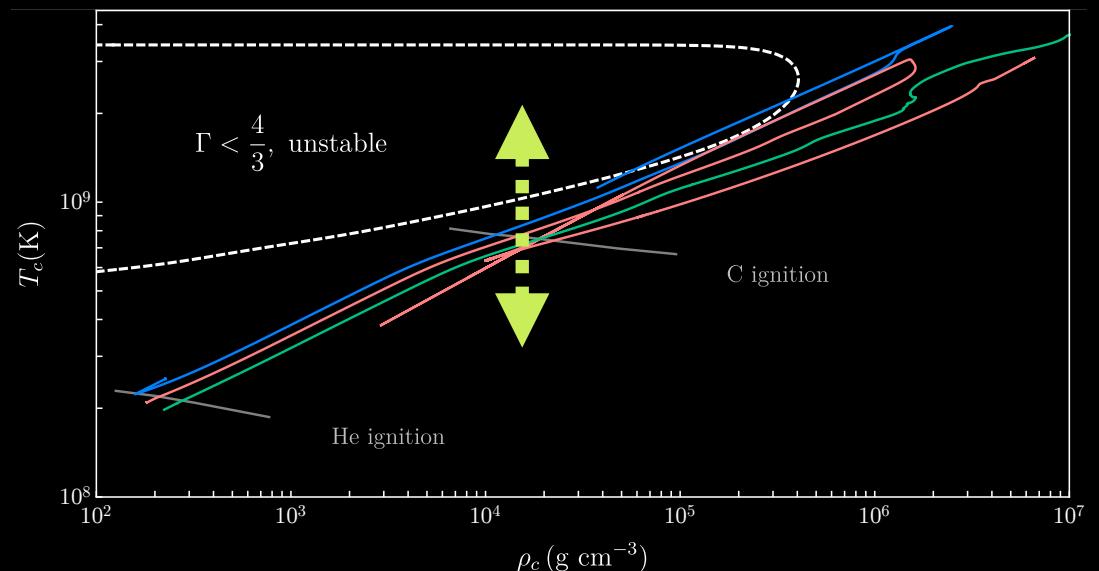
Other scenarios

Sakstein, DC, McDermott, Straight,
Baxter arXiv:2009.01213 [gr-qc]
Straight, Sakstein, Baxter, arXiv:
2009.10716 [gr-qc]

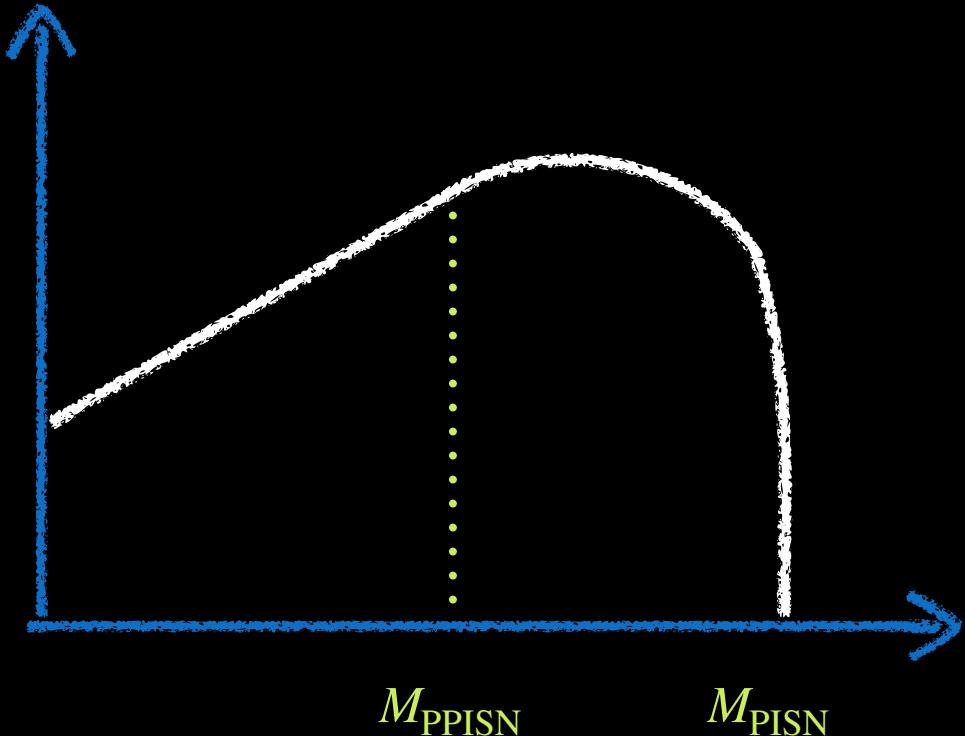
- New forces: screened modified gravity (MG)
 - Increased local strength of gravity → need larger pressure gradient to maintain hydrostatic equilibrium → **larger core temperature at fixed density** → Pair instability is exacerbated → **Lighter black holes**
 - Decreased local strength of gravity works in reverse → **Heavier black holes**
- Dark matter annihilation
 - Extra source of energy
 - + consistent EOS treatment

Ziegler, Freese arXiv:2010.00254 [astro-ph]

DC, McDermott, Sakstein, work in progress



Now, what about population studies?

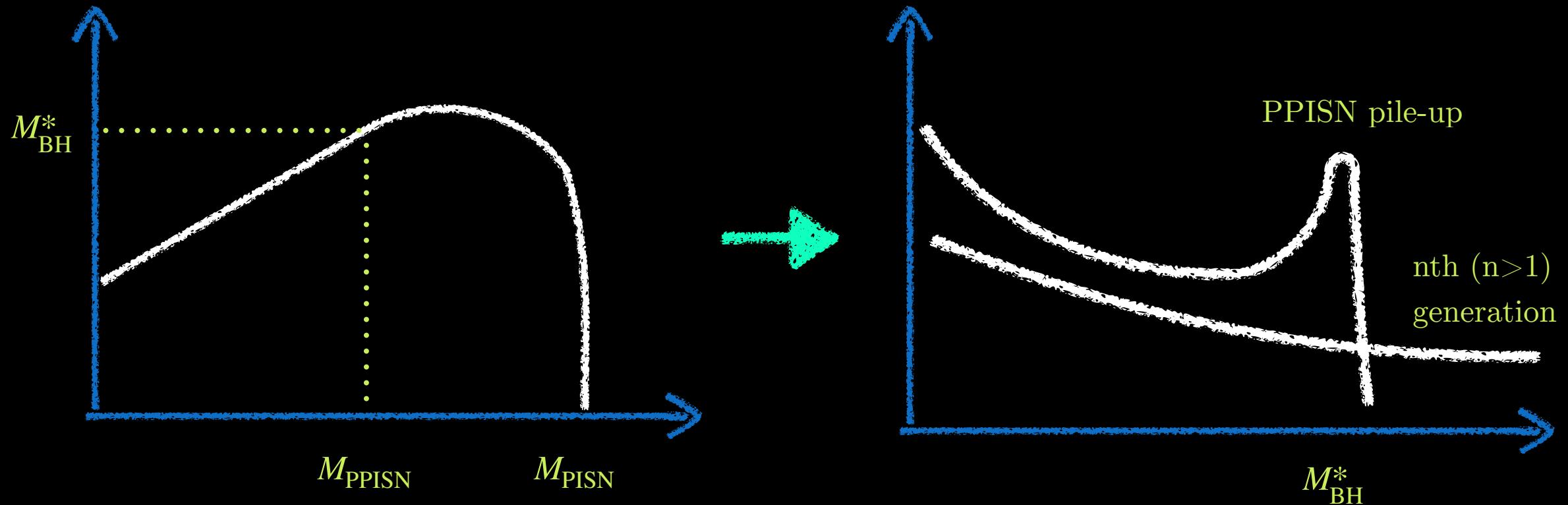


As we have seen, BSM scenarios may affect both M_{PPISN} and M_{PISN}

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

How does that compare to the data?

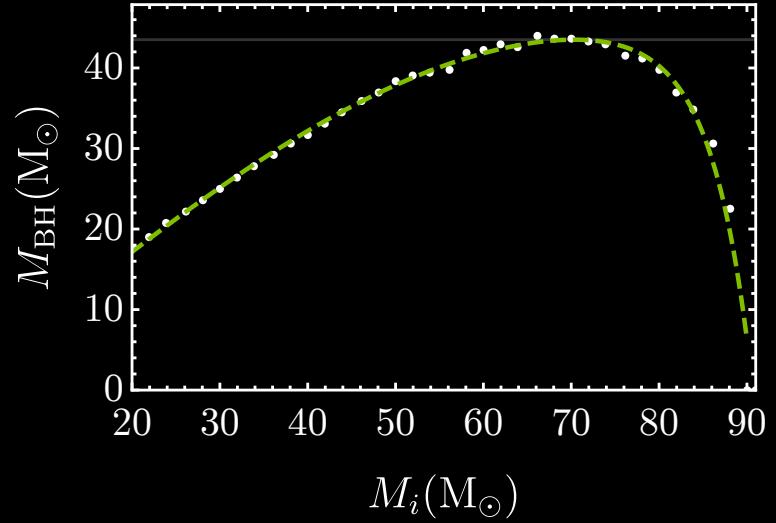
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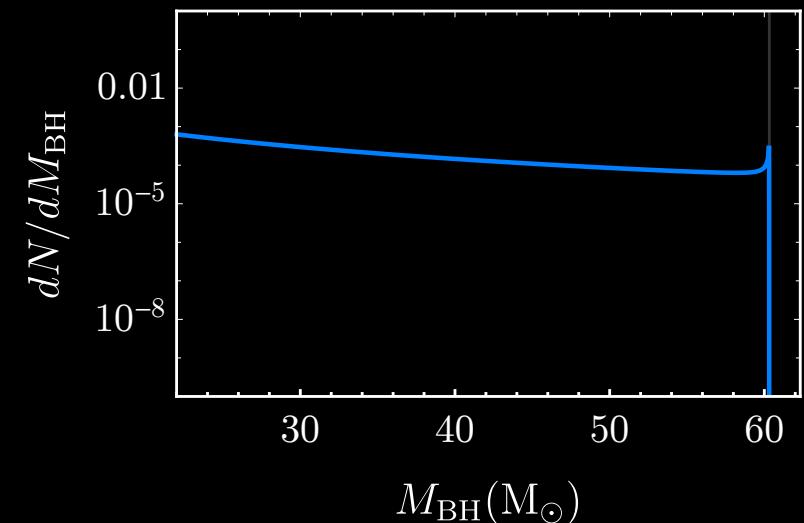
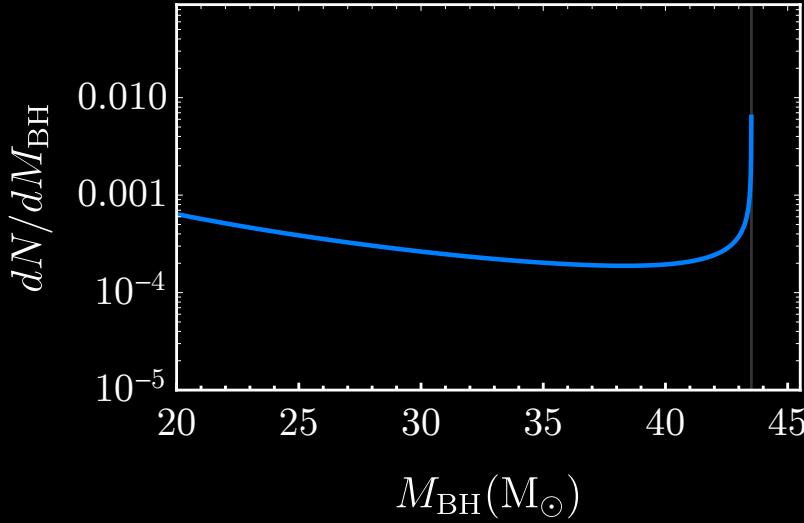
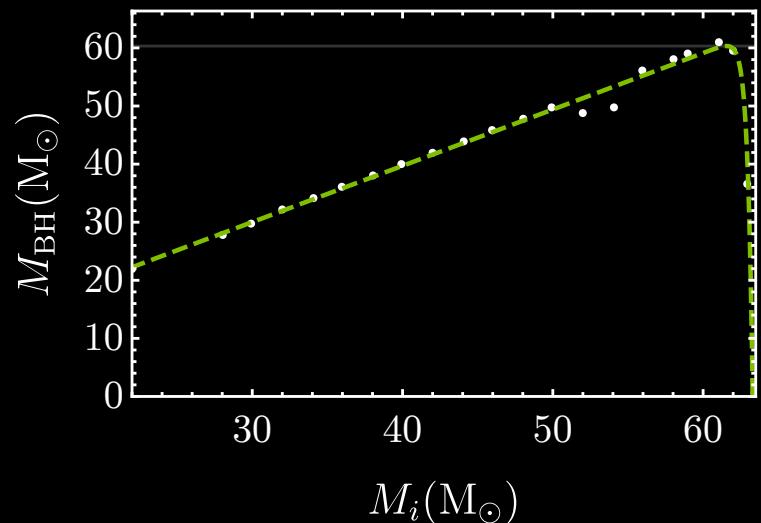
- + Initial mass function
- + Effective detector volume

Now, what about population studies?

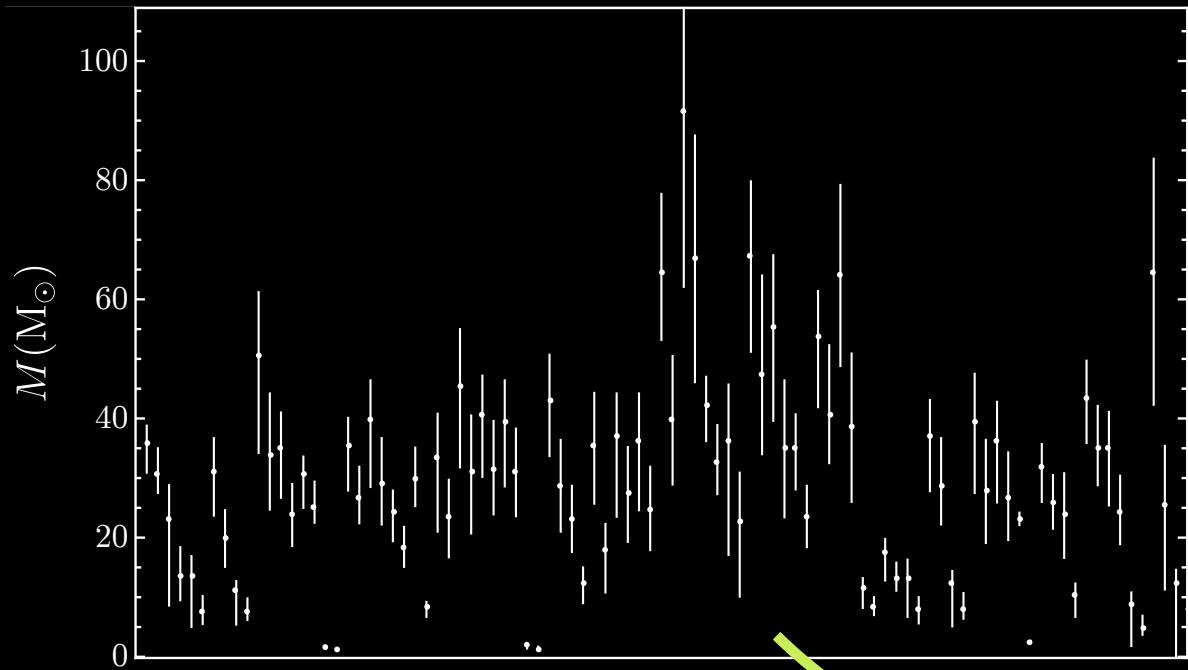
SM scenario



BSM scenario
(example)

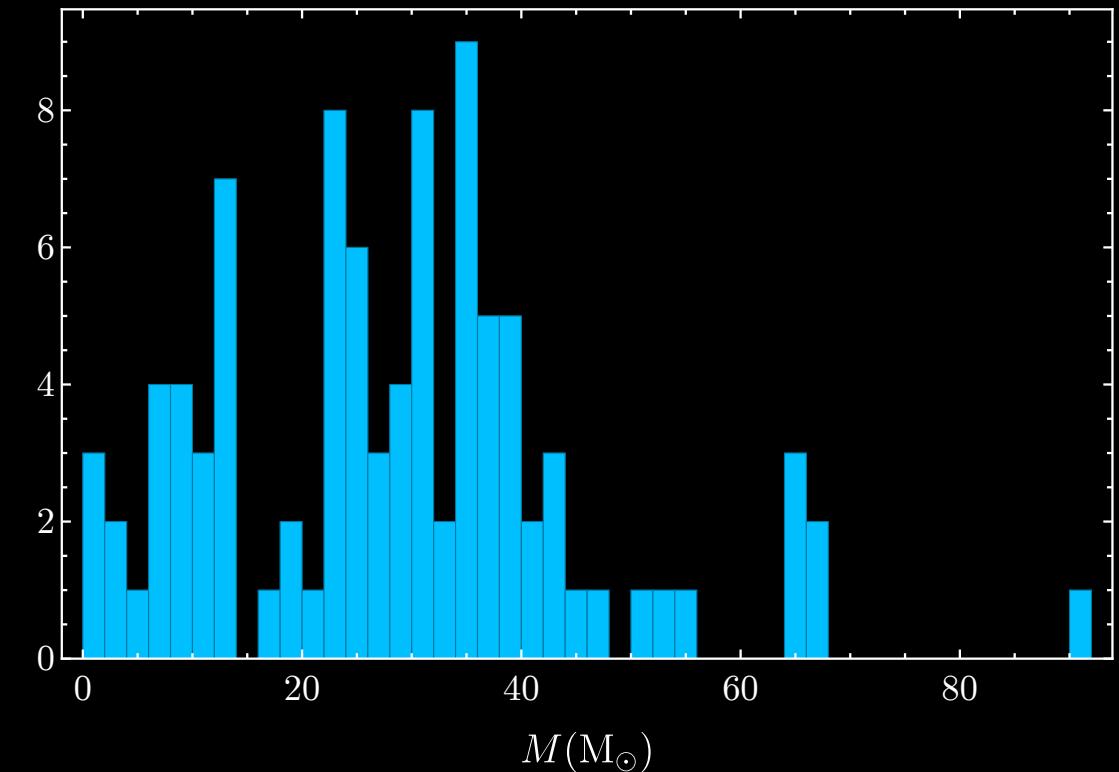


Binary mergers in LIGO/Virgo O3a



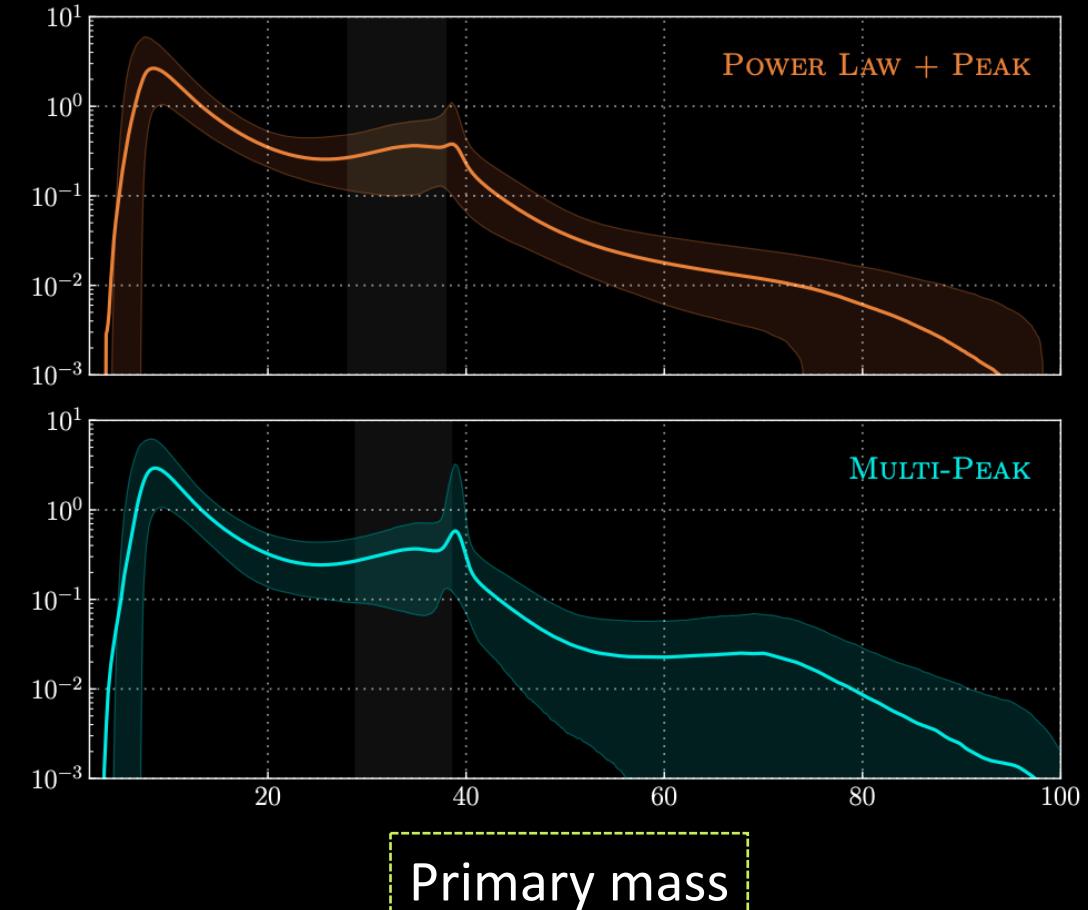
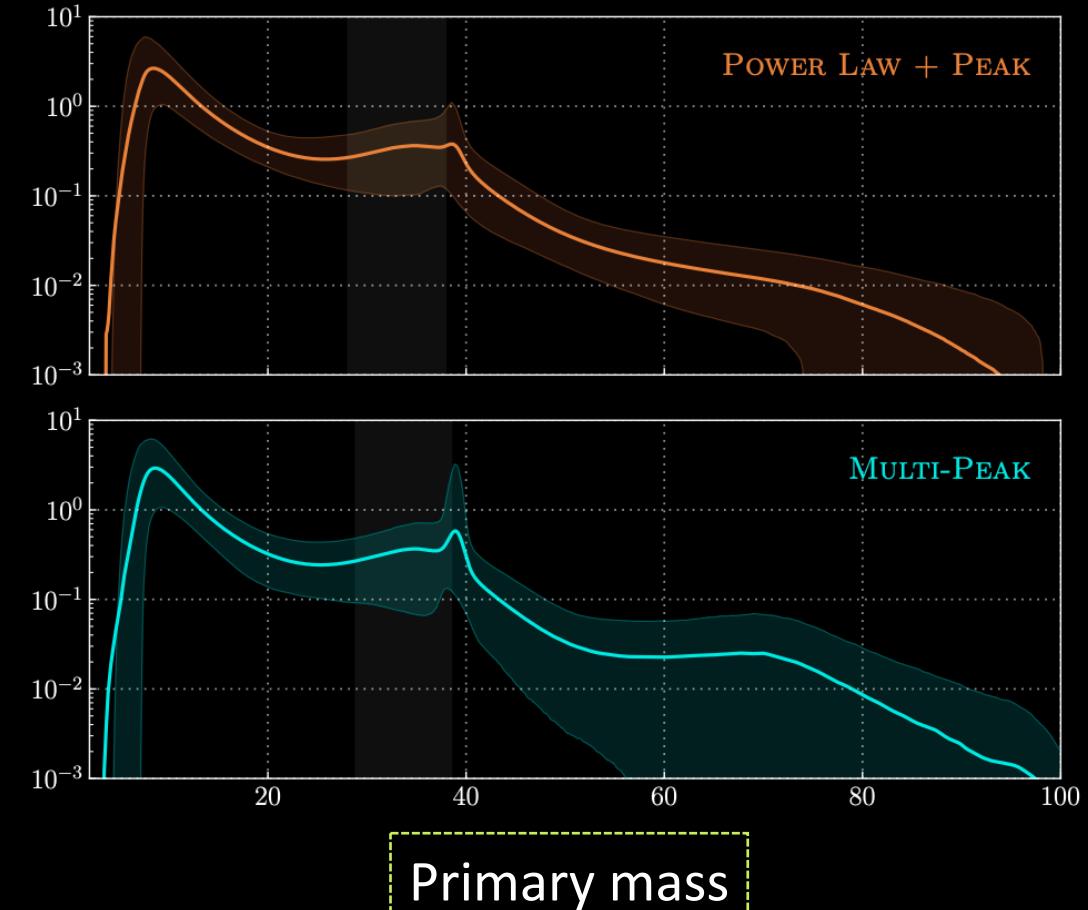
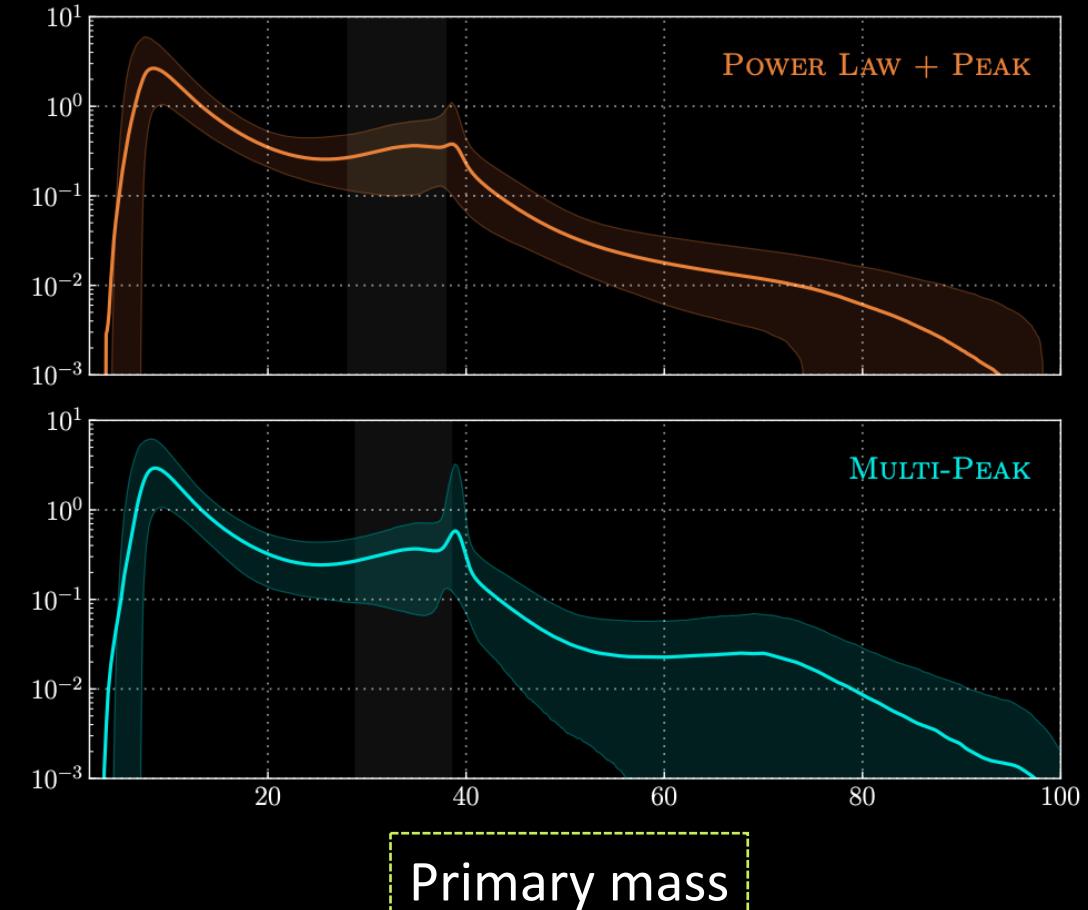
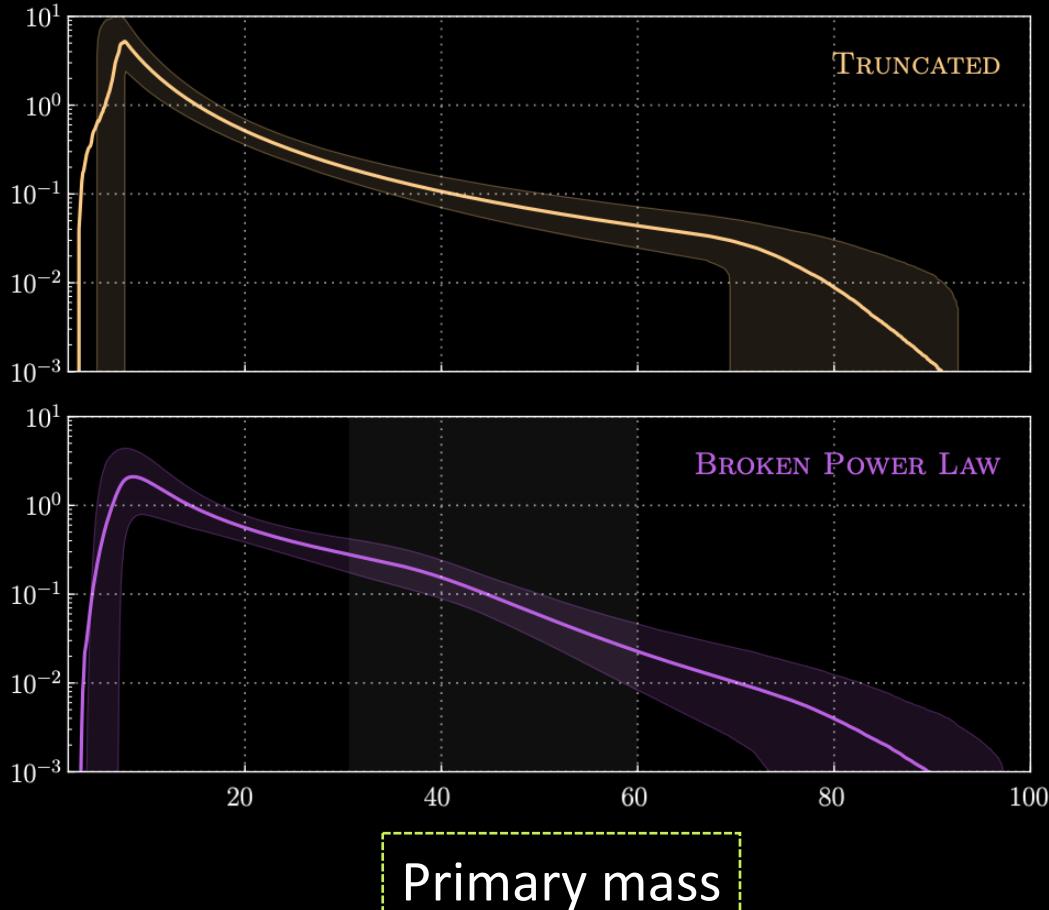
In the case of PPISN: expect a peak
and then a truncation; in the case
of PISN only: just a truncation

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



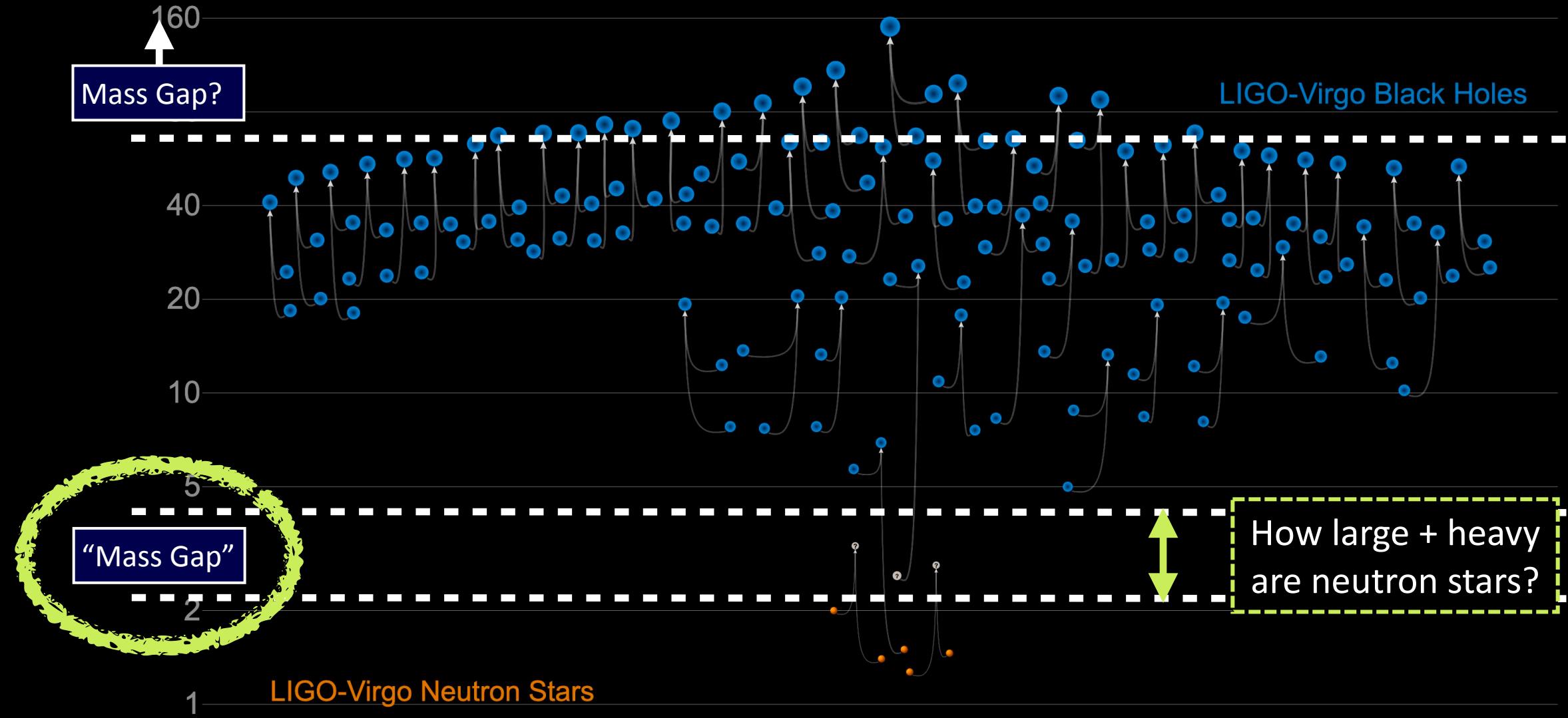
Binary mergers in LIGO/Virgo O3a

Posterior distribution



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

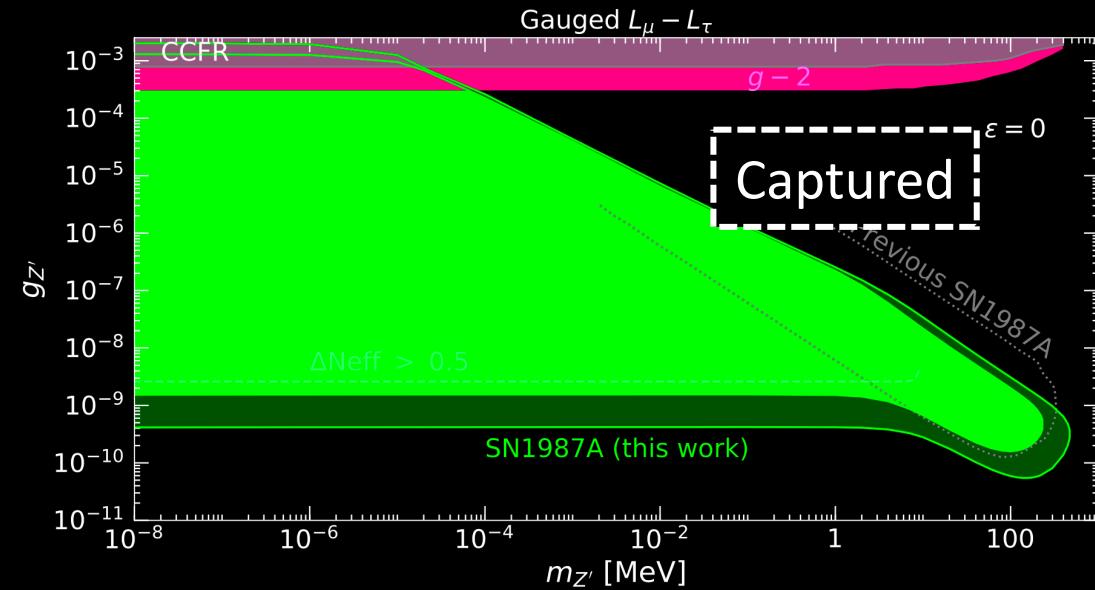
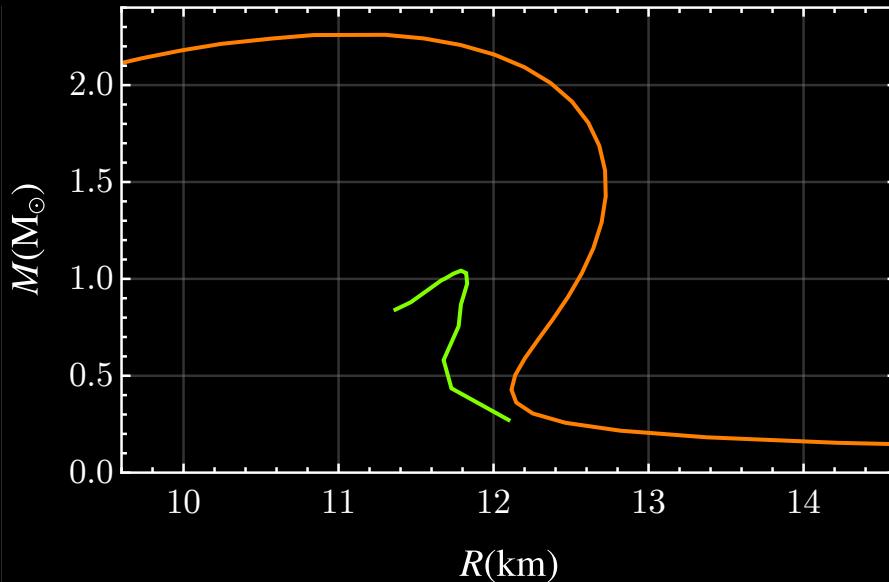
Further adventures in the stellar graveyard



Light new particles in core-collapse SNe

- Dark matter produced in a supernova may be captured
- Asymmetric dark matter may be **asymmetrically captured**

Nelson, Reddy, Zhou, JCAP, arXiv:1803.03266 [hep-ph]



- Depending on DM spin and interactions, capture may lead to modified EOS
 - Harder EOS → tidal forces
 - Softer EOS → instability

To conclude,

- Stars are light particle labs!
- Gravitational waves offer an **exciting new opportunity** to study open questions in stellar astrophysics and particle physics
- **The black hole mass gap** is an entirely new probe of light dark physics, which will come into focus in the next few years
- Other lessons may be learned from neutron star populations and tidal interactions

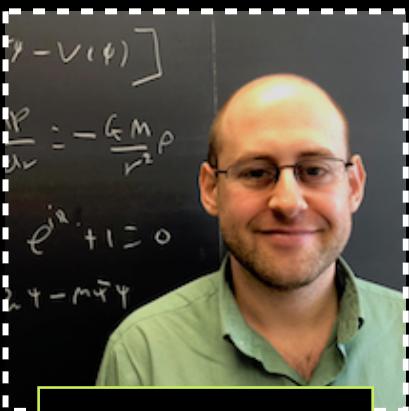
Thank you!

...ask me anything you like!

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Sam McDermott



Jeremy Sakstein



Rebecca Leane



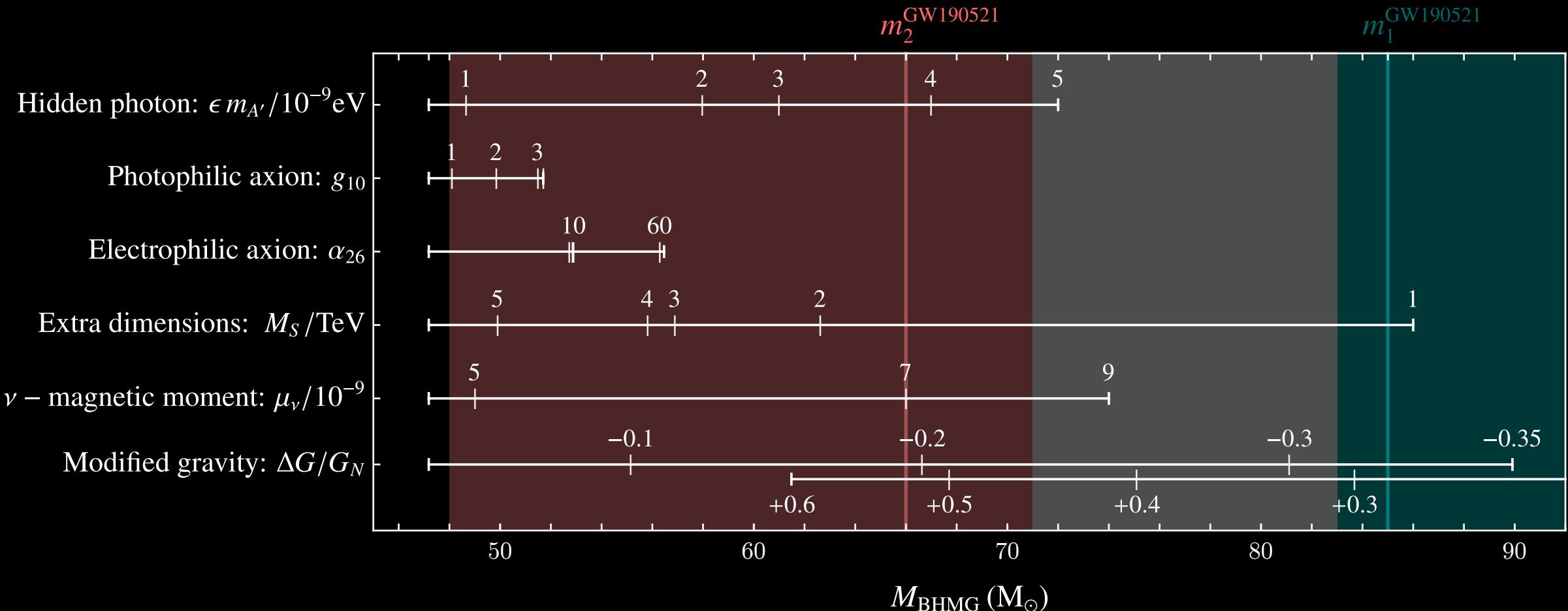
Eric Baxter



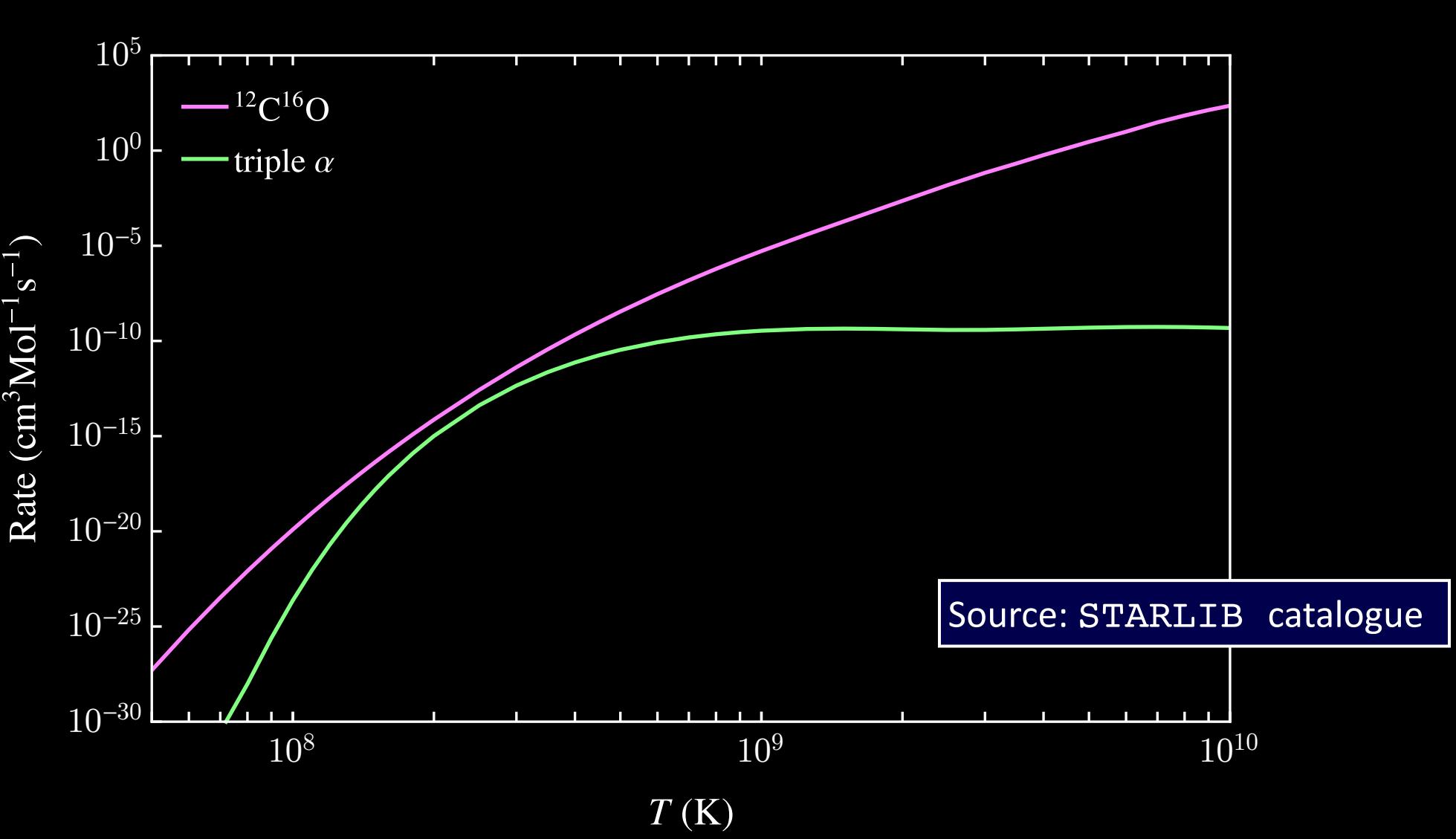
Maria Straight

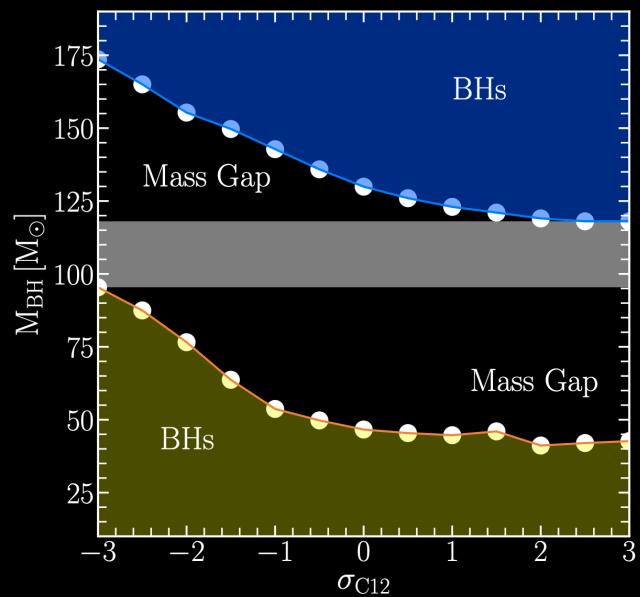
GW190521, the impossible black holes

... and Beyond the Standard Model physics

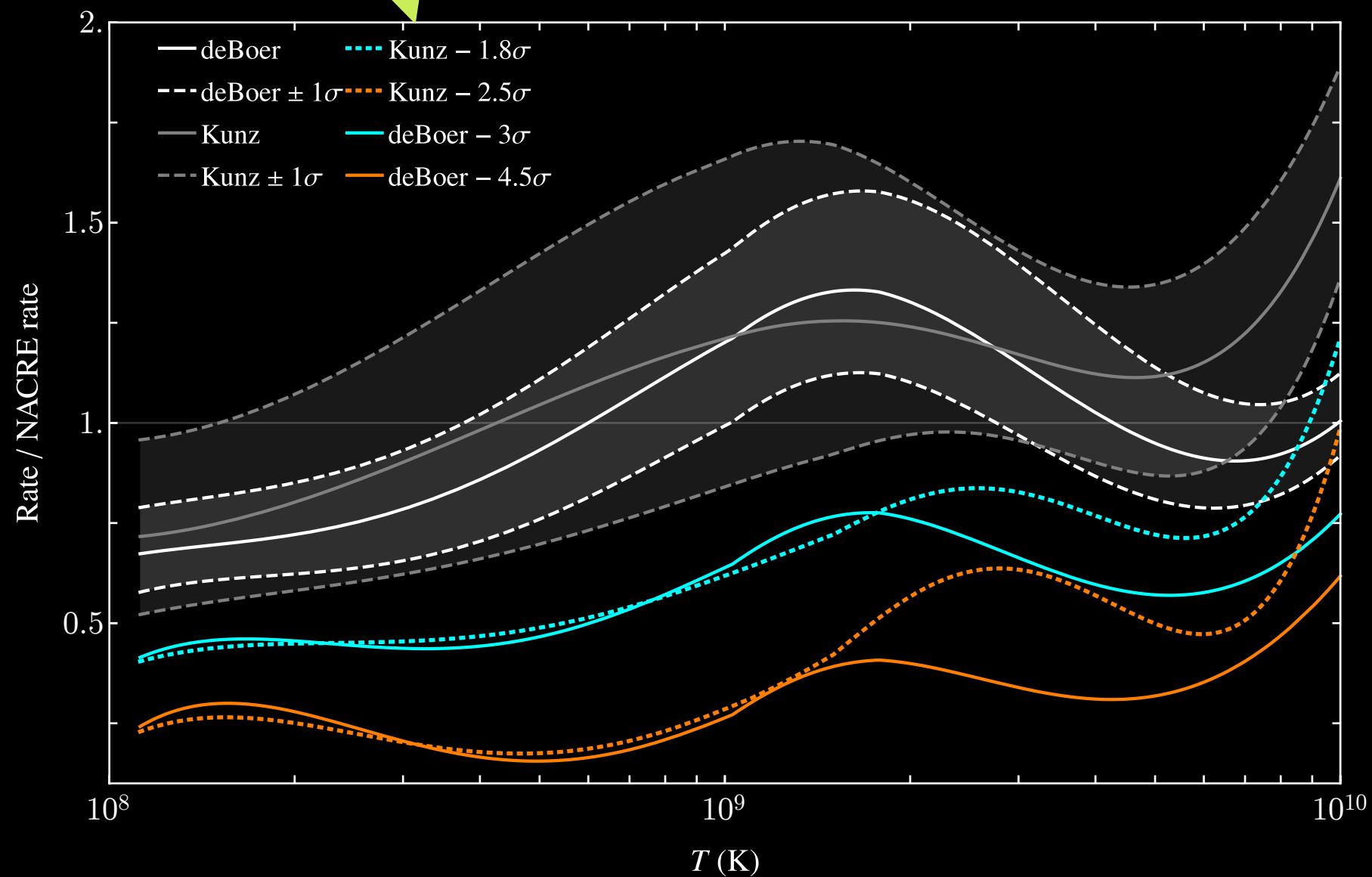


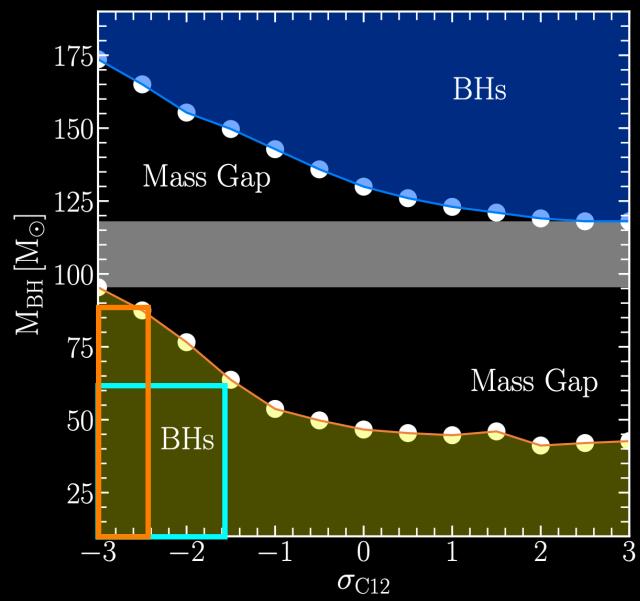
Helium burning rates as a function of T



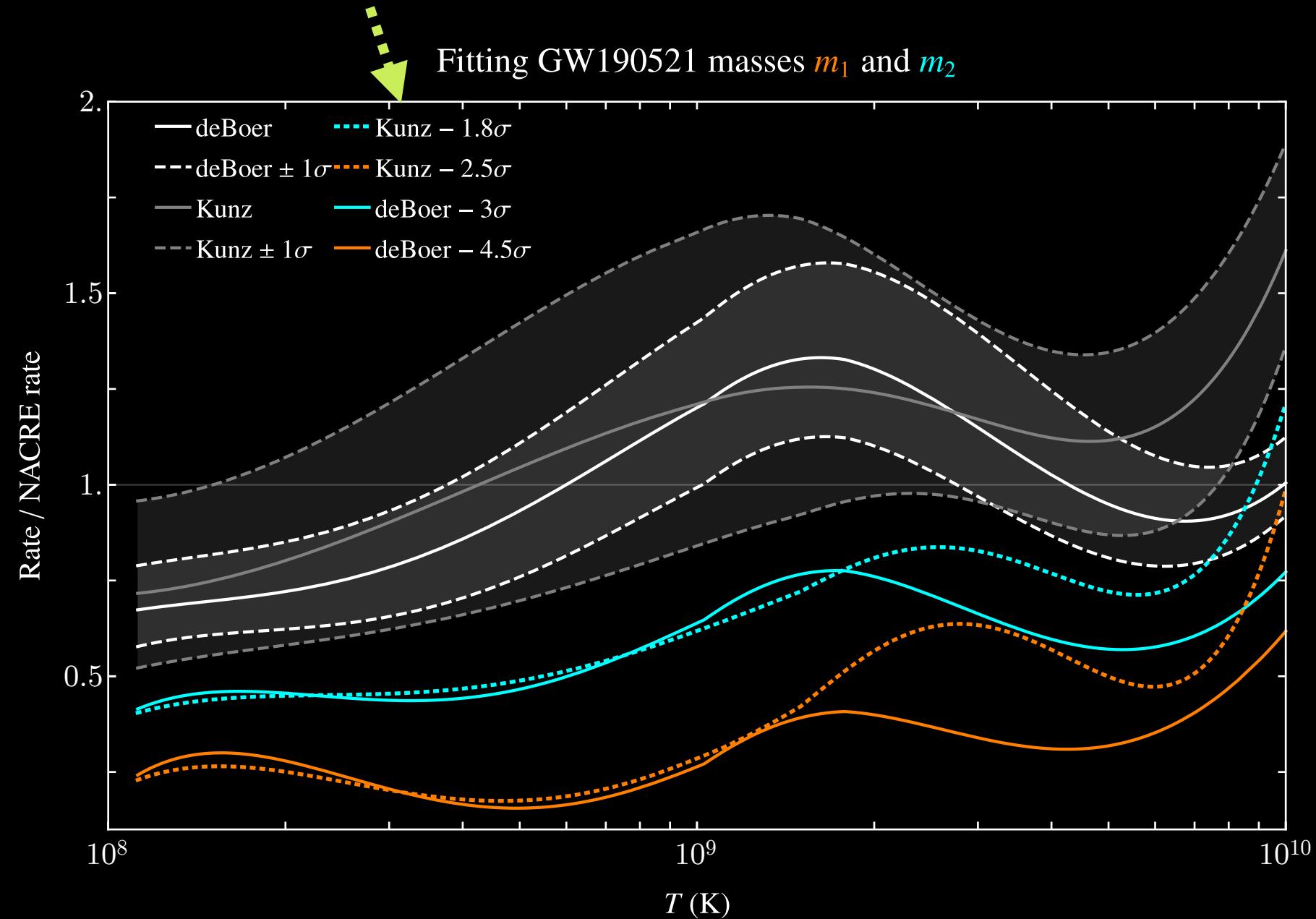


(Kunz is currently used in STARLIB)





(Kunz is currently used in STARLIB)



Large black hole in LB-1?

- Last year, a $70 M_{\odot}$ 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_{ISCO}
- Solvable in a (v/c) expansion
→ Weak gravity, small velocity

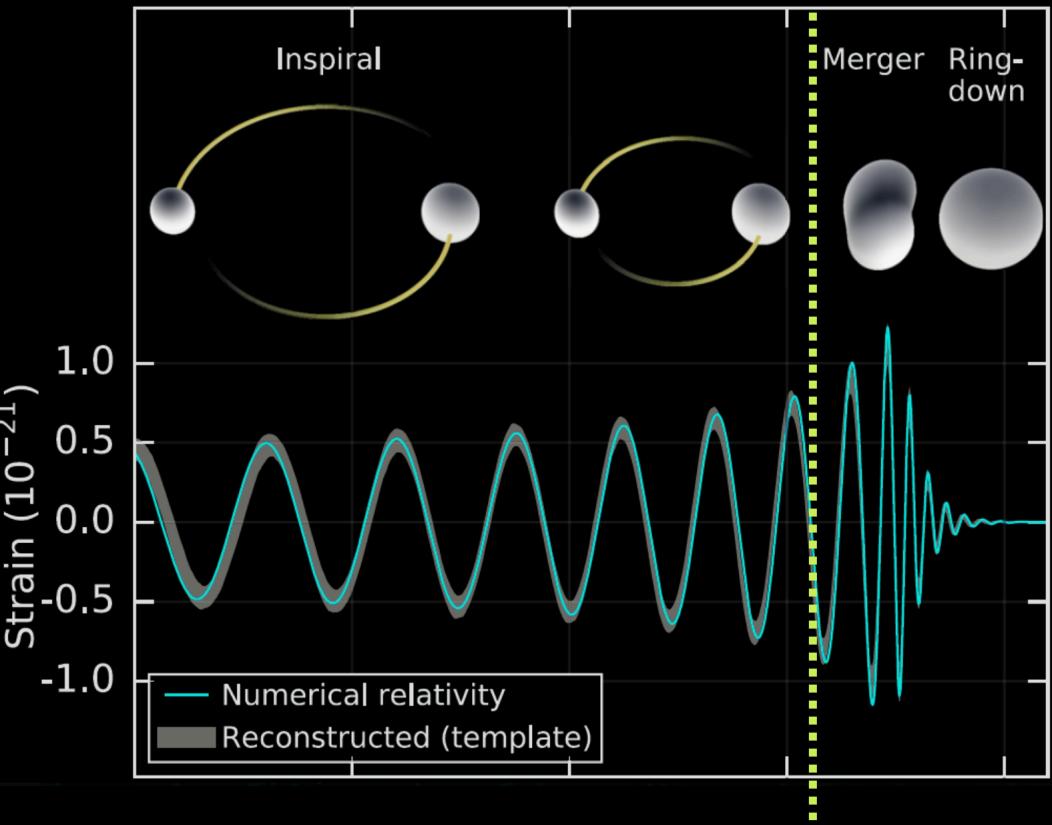


Image credit: LIGO collaboration

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

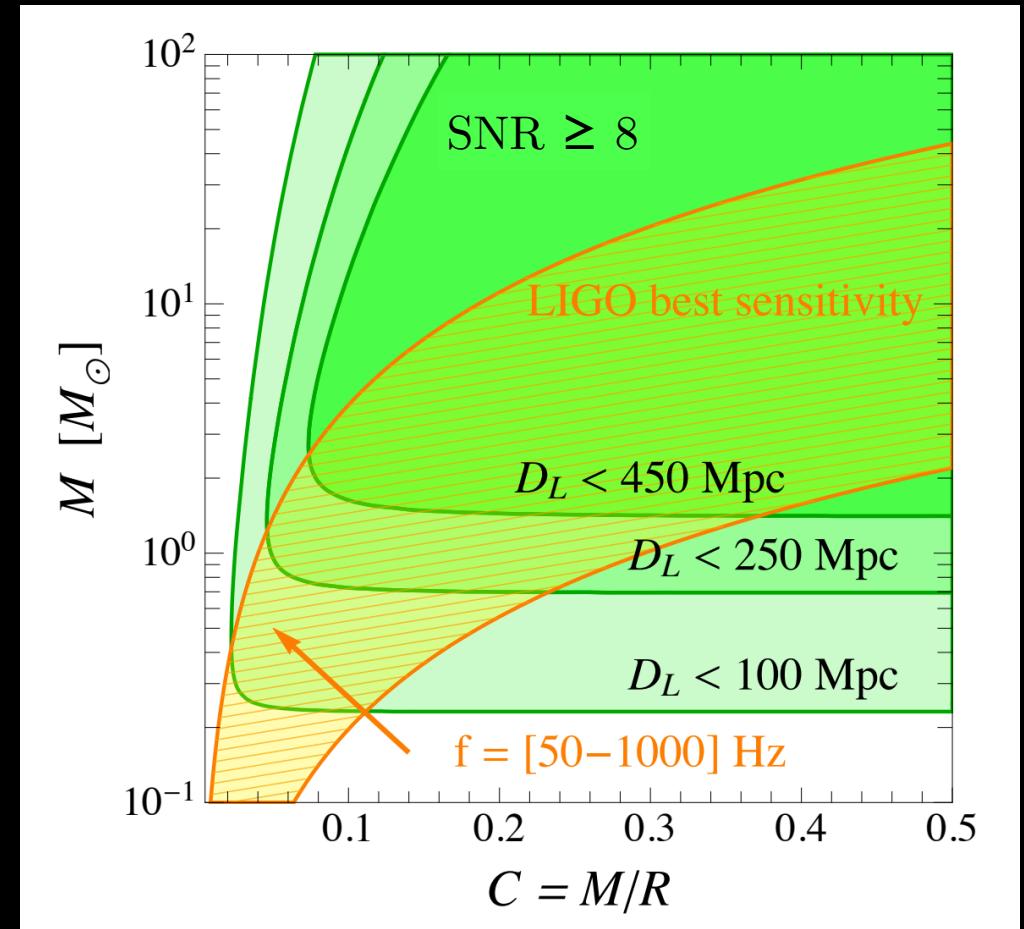
Compact object merger sensitivity

- Best detection prospects for $f_{\min} < f_{\text{peak}} \sim f_{\text{ISCO}} < f_{\max}$
- Defines an CO sensitivity band

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

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

- 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)

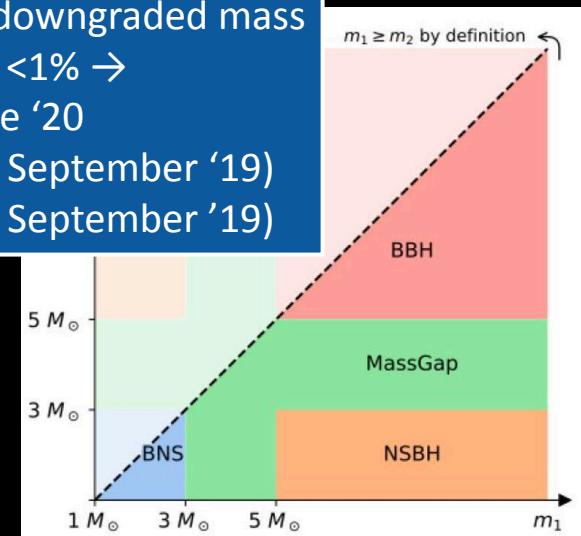


Image credit: LIGO collaboration

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”

Energy loss due to electrophilic axions

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

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

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

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

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

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

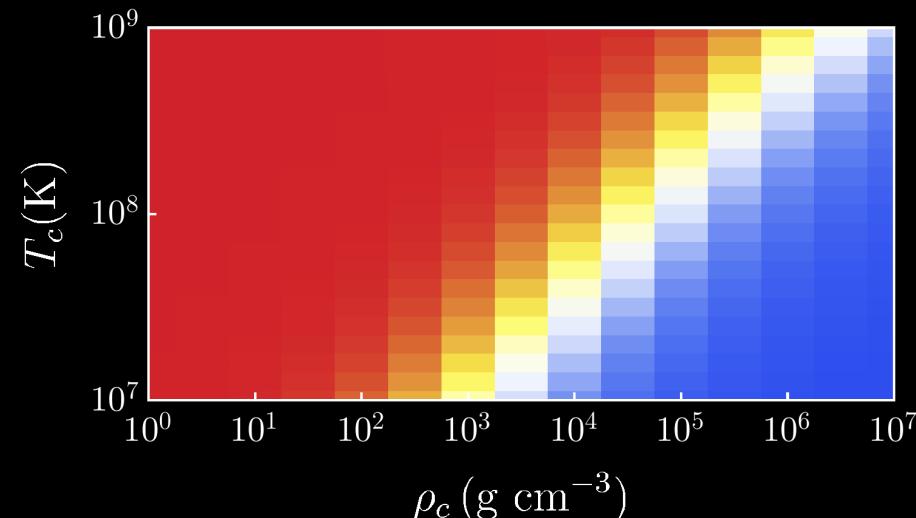
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$$0 < F_{\text{deg}} < 1$$



Semi-Compton emission
dominates throughout the
Helium burning phase

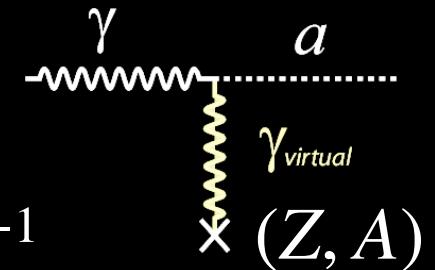
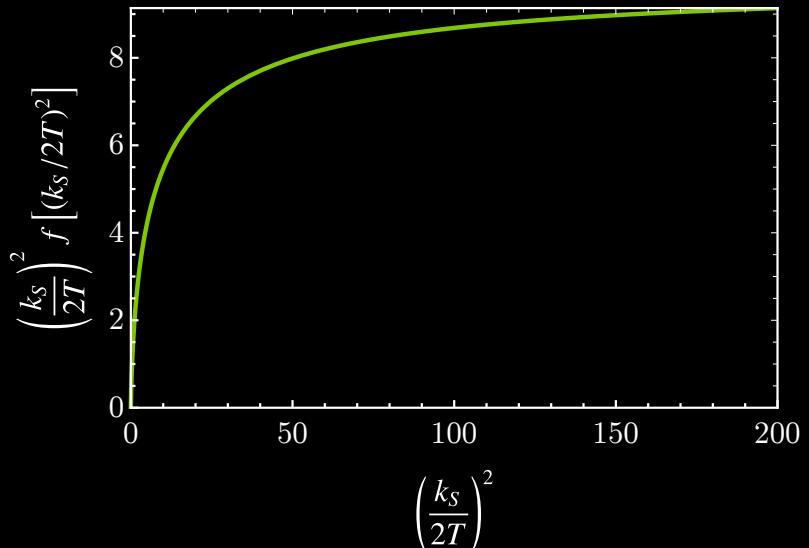
Energy loss due to photophilic axions

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

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

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

Screened at high
 T and low ρ



Energy loss due to hidden photons

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

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

In the limit $\omega_p \ll T$

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

Heavier degrees of freedom?

DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]
+ work in progress

