Black hole archaeology with gravitational waves

Djuna Lize Croon (IPPP Durham)

KCL seminar, May 2022

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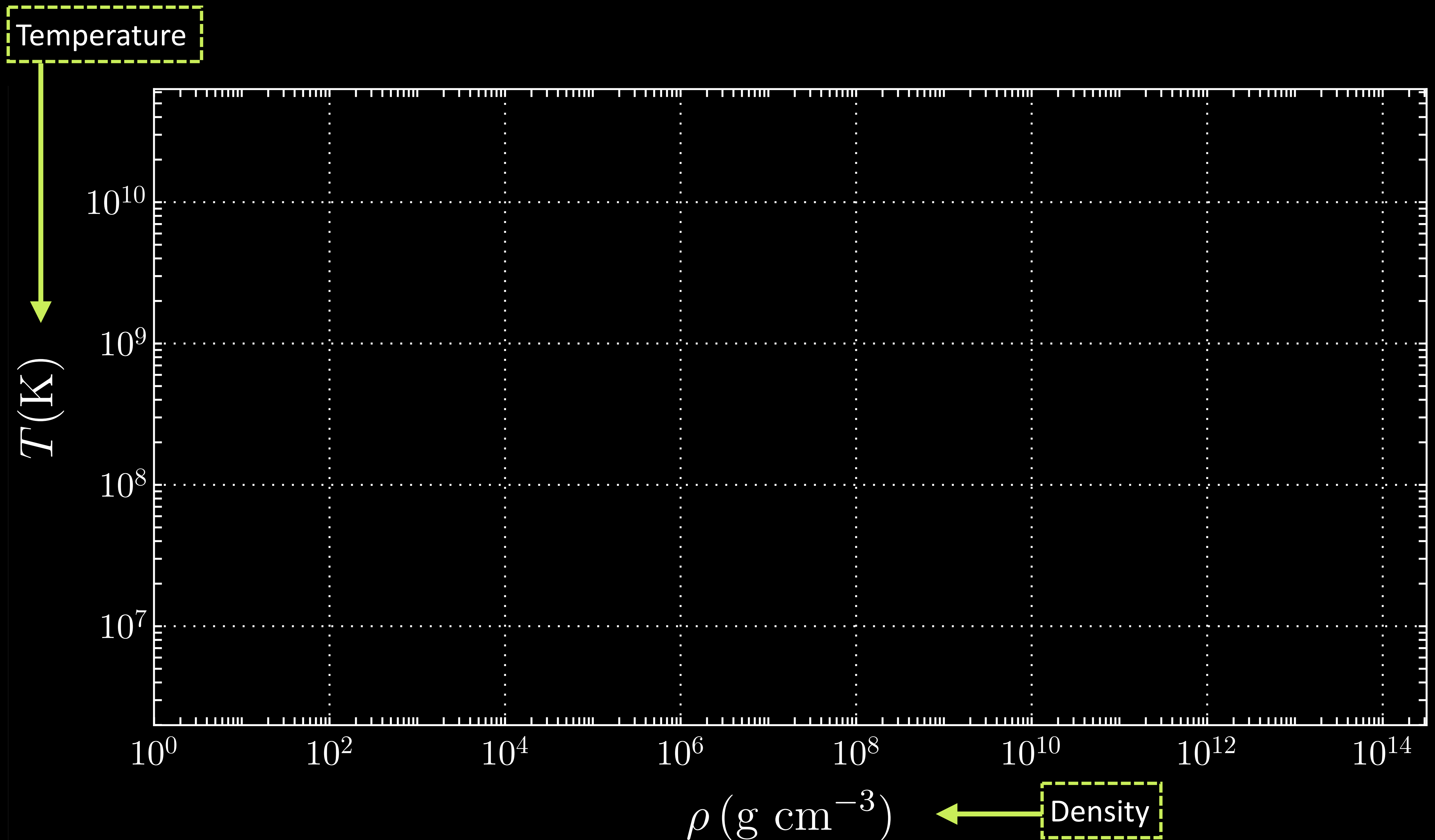
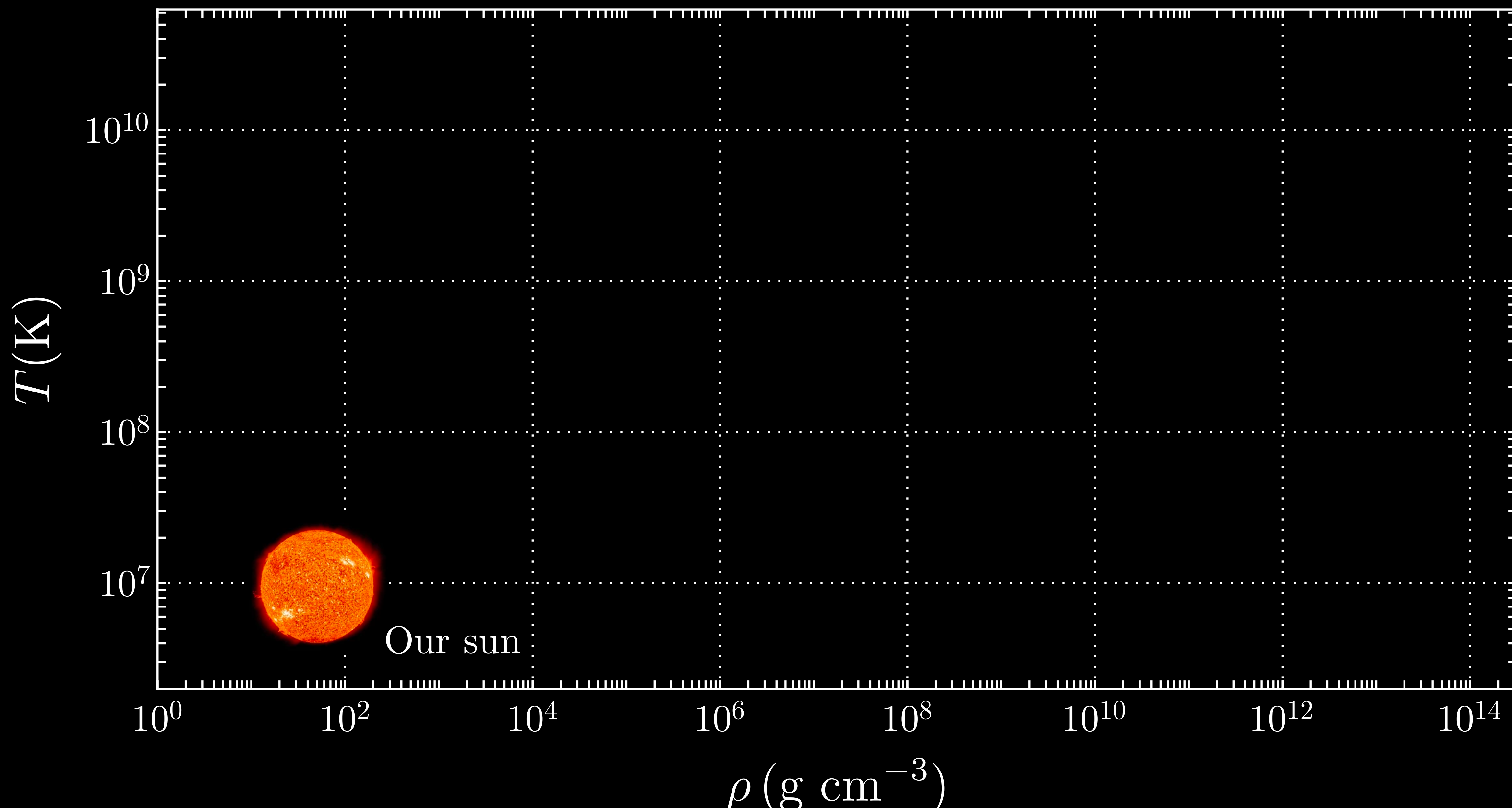
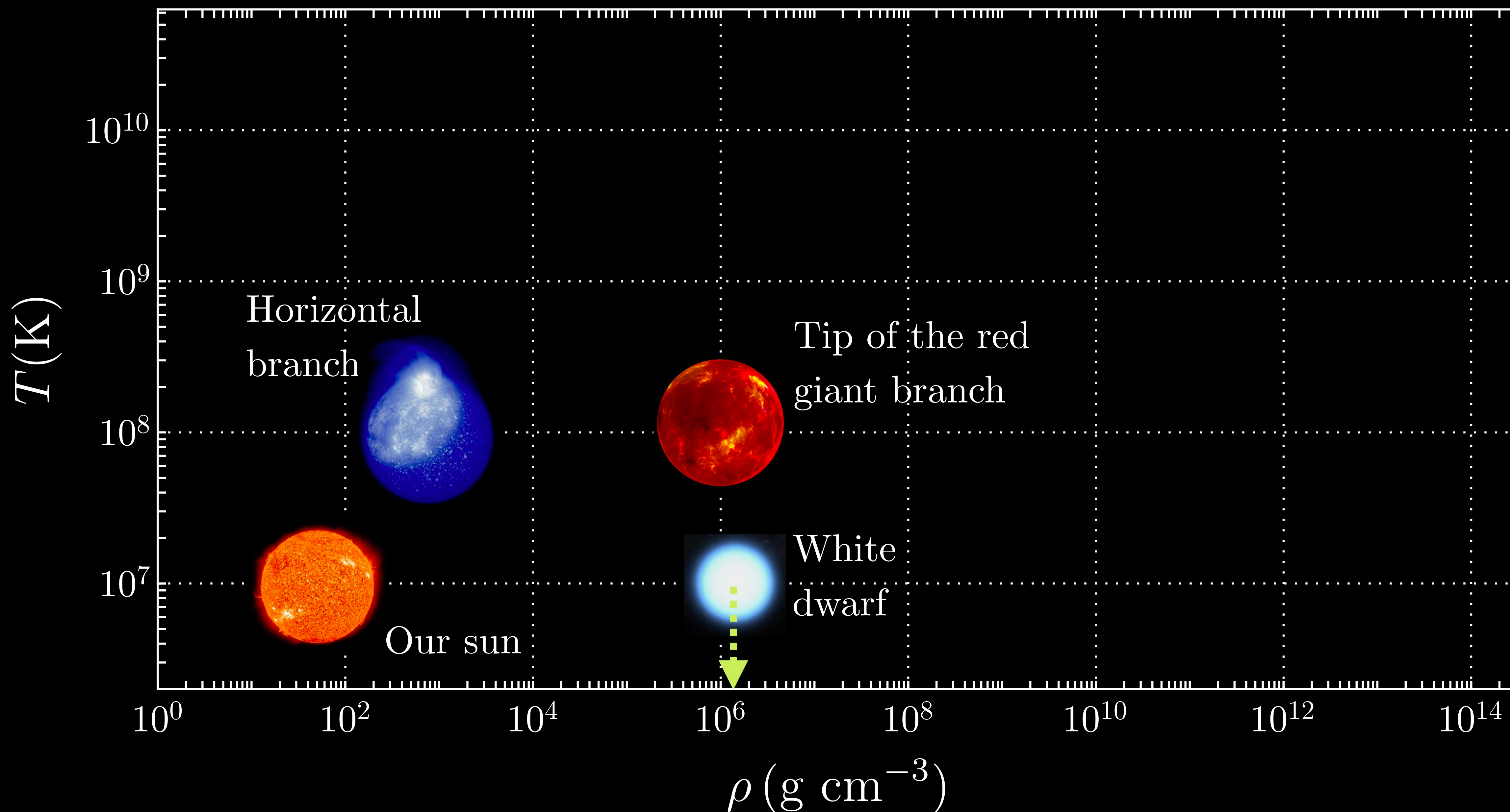
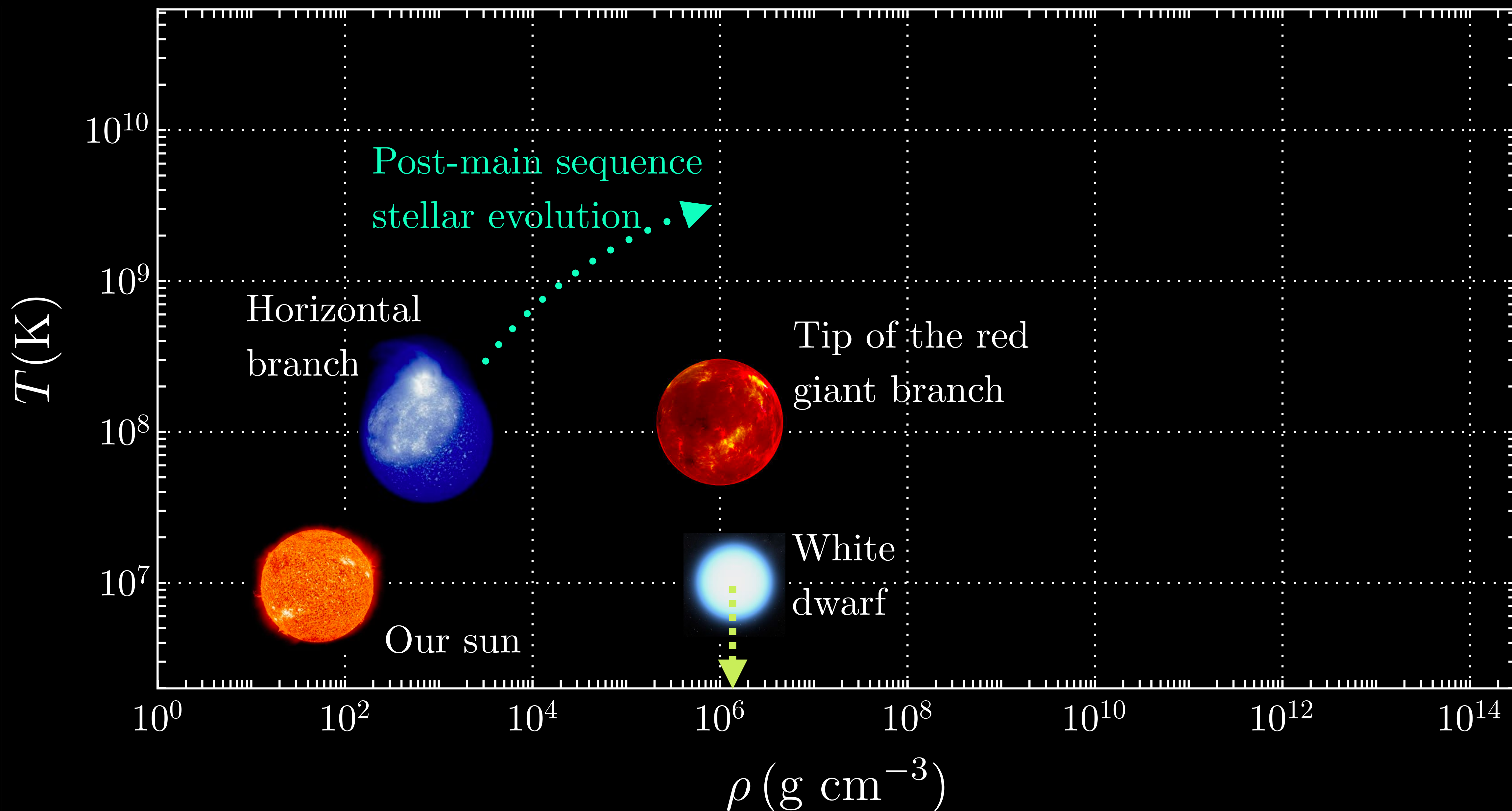

Temperature
$T\,(\mathrm{K})$
10^{10}
10^{9}
10^{8}
10^{7}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
$\rho\,(\mathrm{g\ cm^{-3}})$
Density



$T(\mathrm{K})$
10^{10}
10^{9}
10^{8}
10^{7}
Our sun
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
$\rho\,(\mathrm{g\ cm^{-3}})$



10^{10}
10^{9}
10^{8}
10^{7}
$T(\mathrm{K})$
Horizontal branch
Tip of the red giant branch
White dwarf
Our sun
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
$\rho\,(\mathrm{g\ cm^{-3}})$



Post-main sequence
stellar evolution
Horizontal
branch
Tip of the red
giant branch
White
dwarf
Our sun
10^{10}
10^{9}
10^{8}
10^{7}
$T\,(\mathrm{K})$
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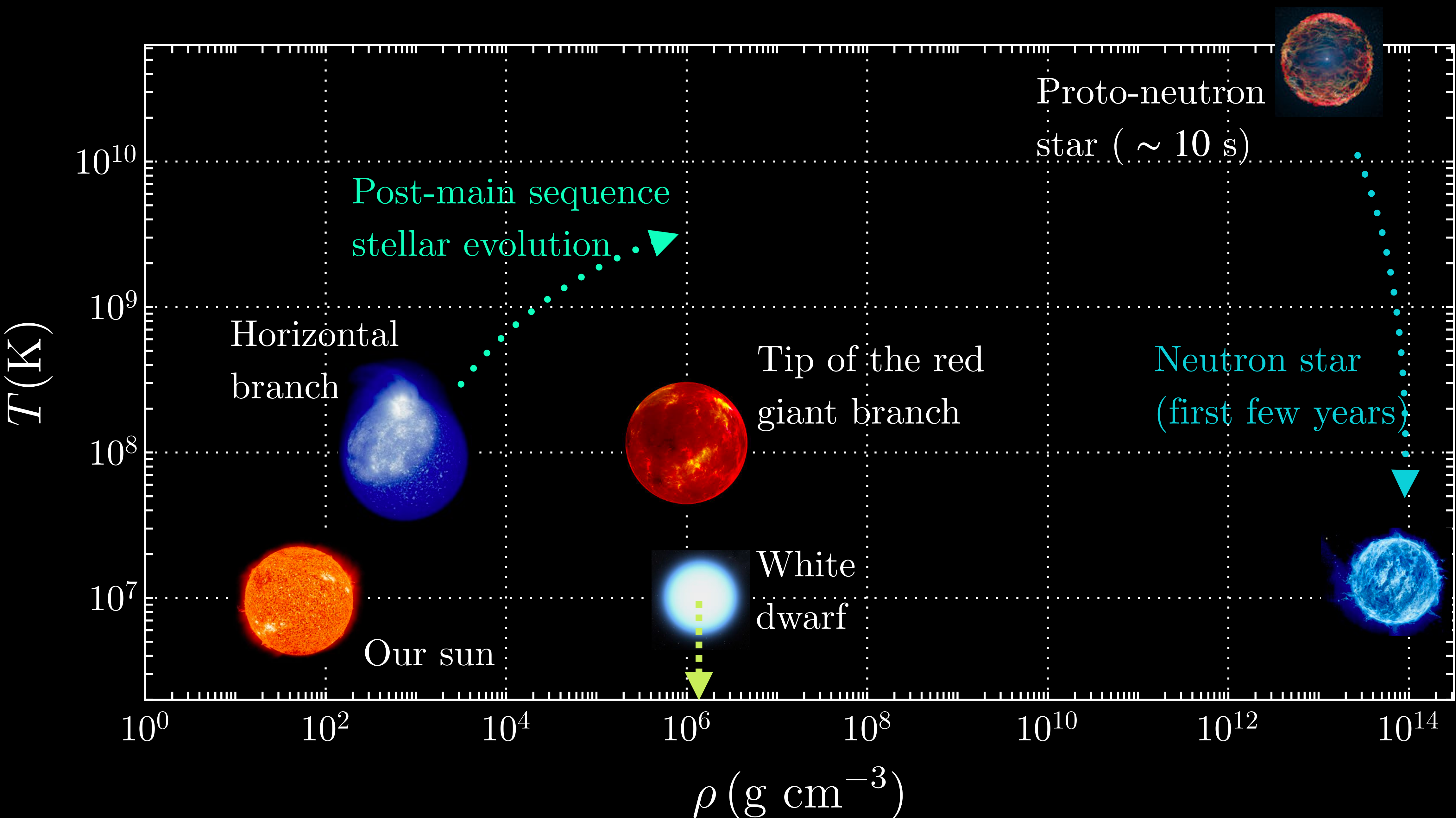
Proto-neutron star (~ 10 s)
Post-main sequence stellar evolution
Horizontal branch
Tip of the red giant branch
Neutron star (first few years)
White dwarf
Our sun
10^{10}
10^{9}
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10^{7}
$T(\mathrm{K})$
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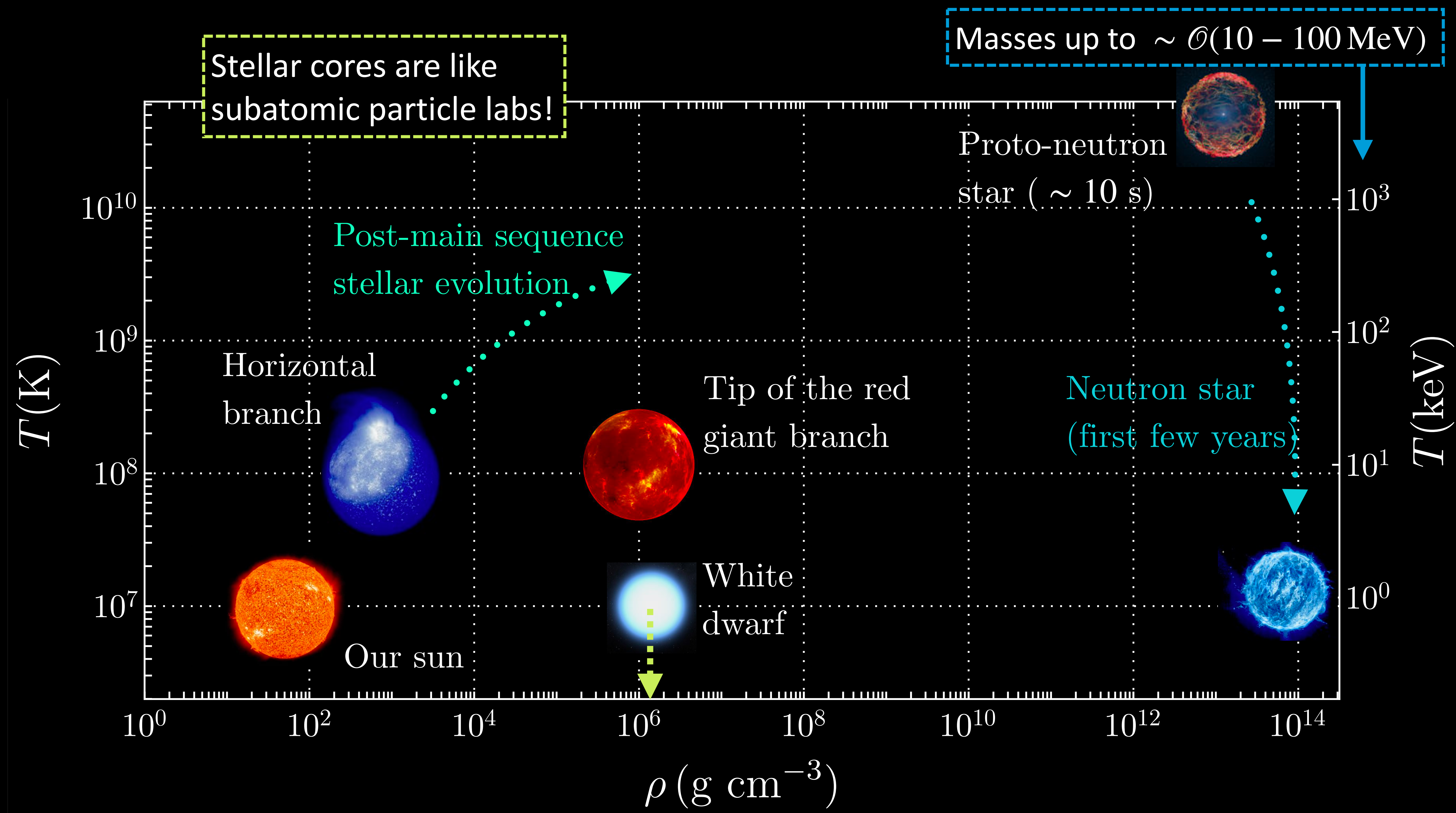
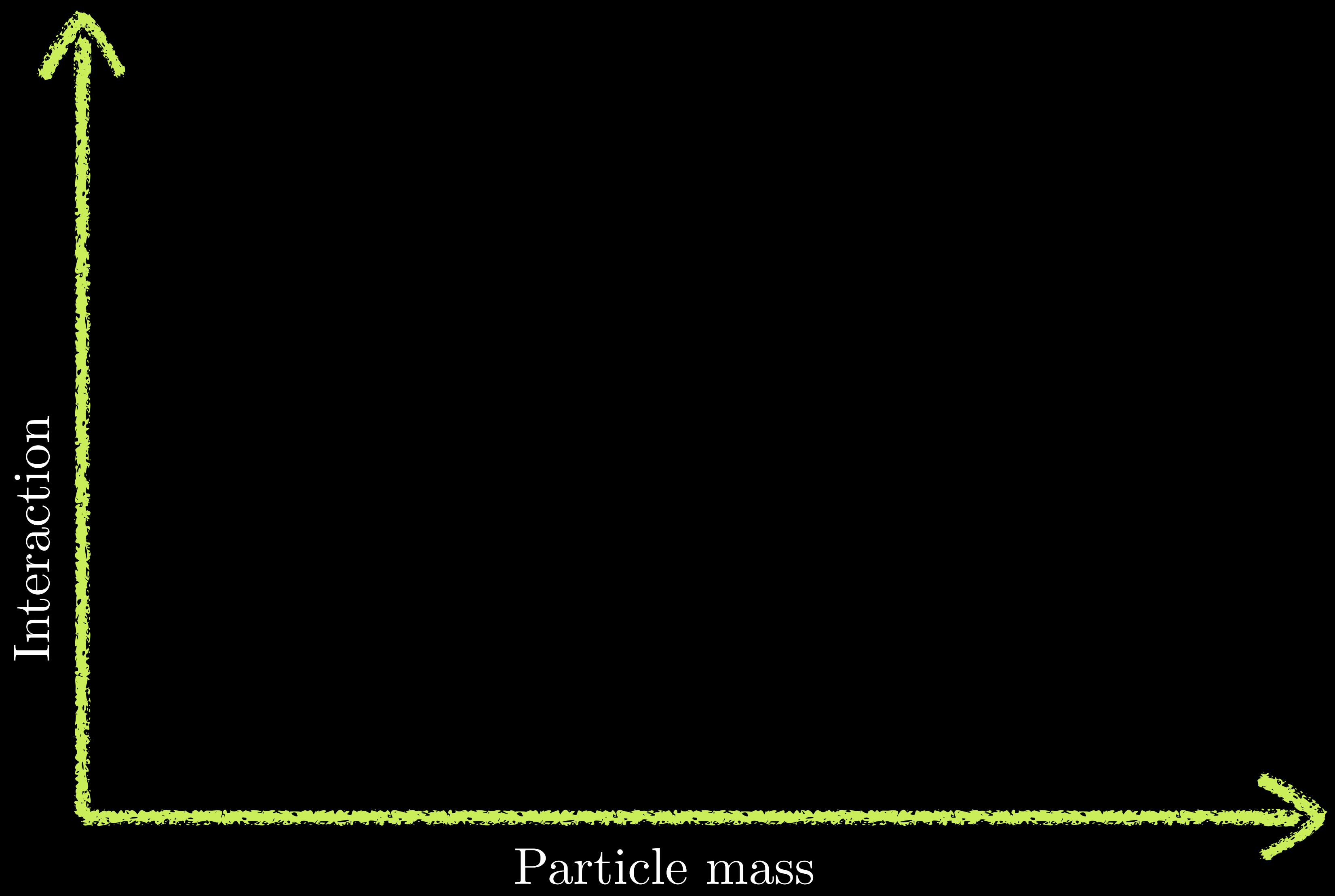
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
$\rho\,(\mathrm{g\ cm^{-3}})$

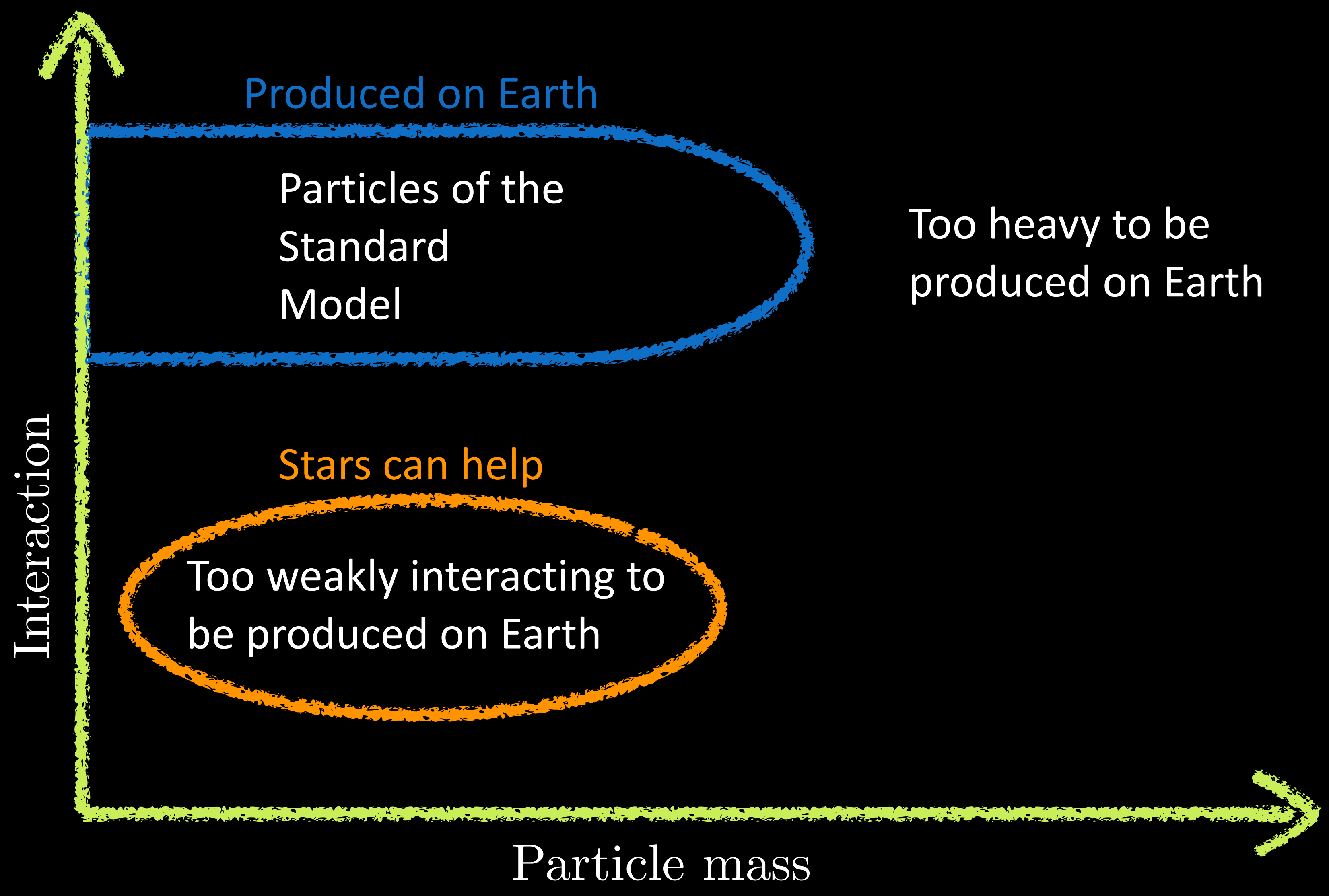


Stellar cores are like subatomic particle labs!
Masses up to $\sim \mathcal{O}(10-100\,\mathrm{MeV})$
Proto-neutron star (~ 10 s)
Post-main sequence stellar evolution
Horizontal branch
Tip of the red giant branch
Neutron star (first few years)
White dwarf
Our sun
T(K)
T(keV)
$\rho\,(\mathrm{g\ cm^{-3}})$
10^{10}
10^{9}
10^{8}
10^{7}
10^{3}
10^{2}
10^{1}
10^{0}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}

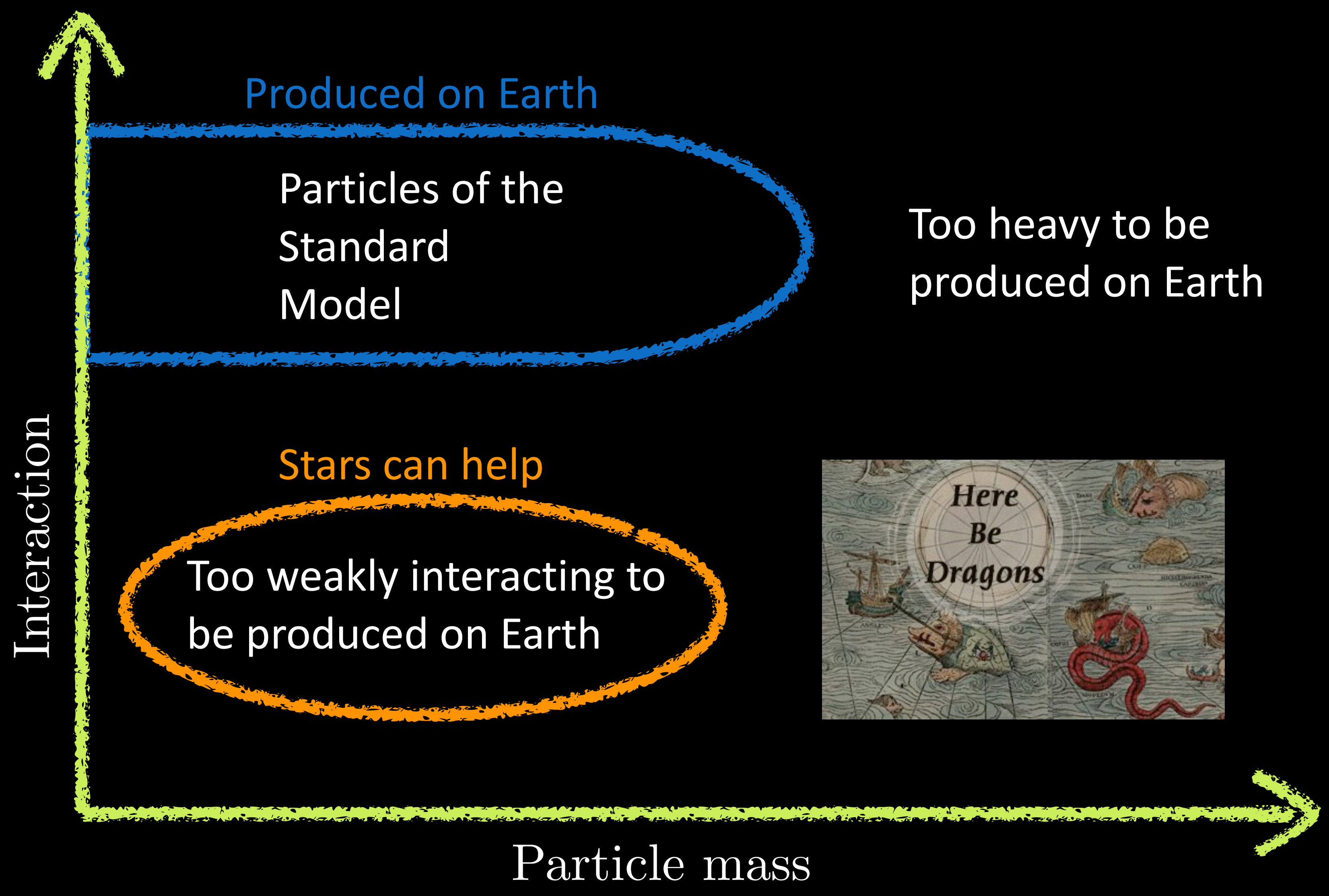
Particle physics in stars



Particle physics in stars



Particle physics in stars



Binary mergers in LIGO/Virgo O1-3

Adapted from LIGO-Virgo-KAGRA, Aaron Geller

Binary mergers in LIGO/Virgo O1-3

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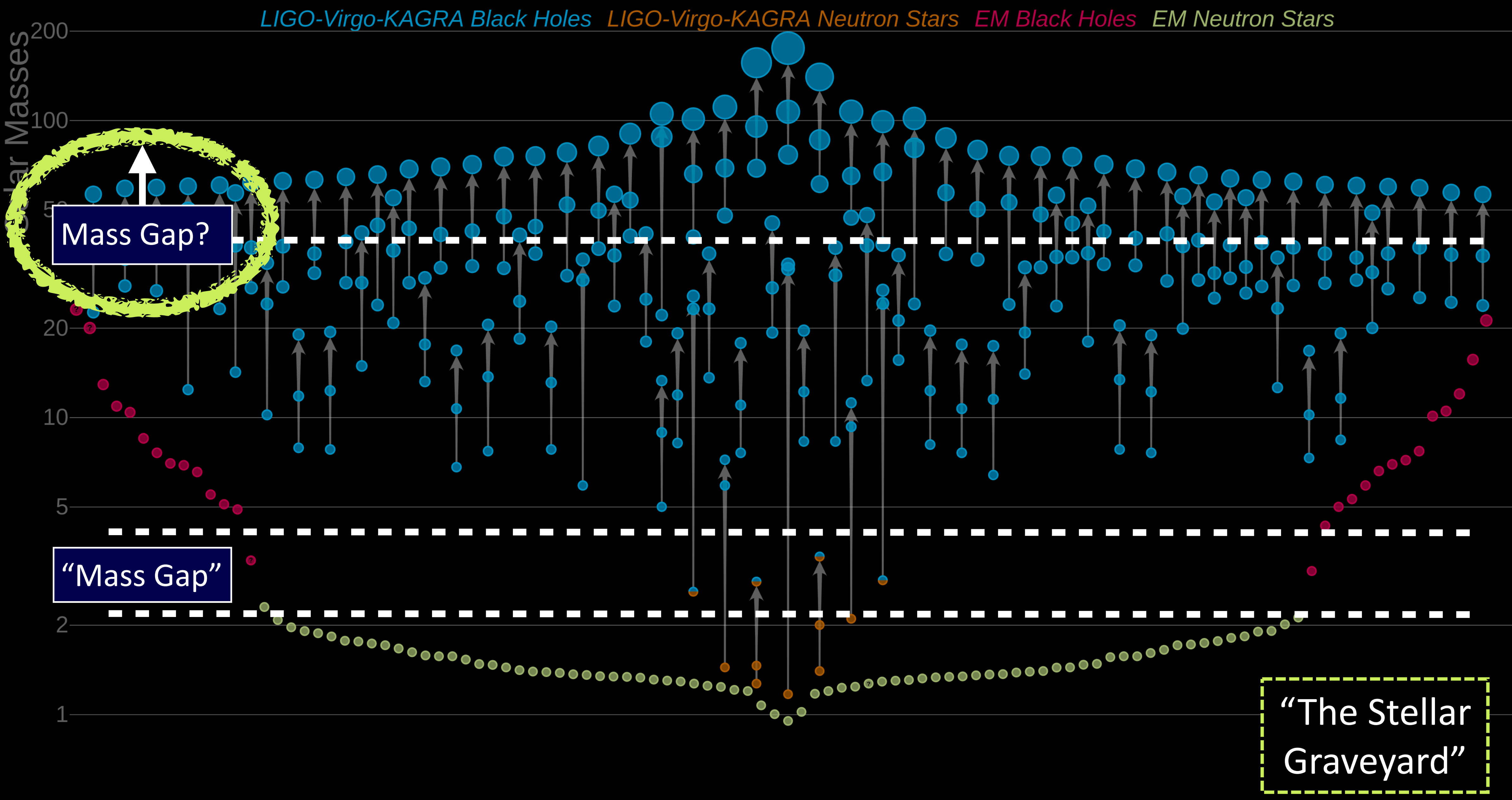
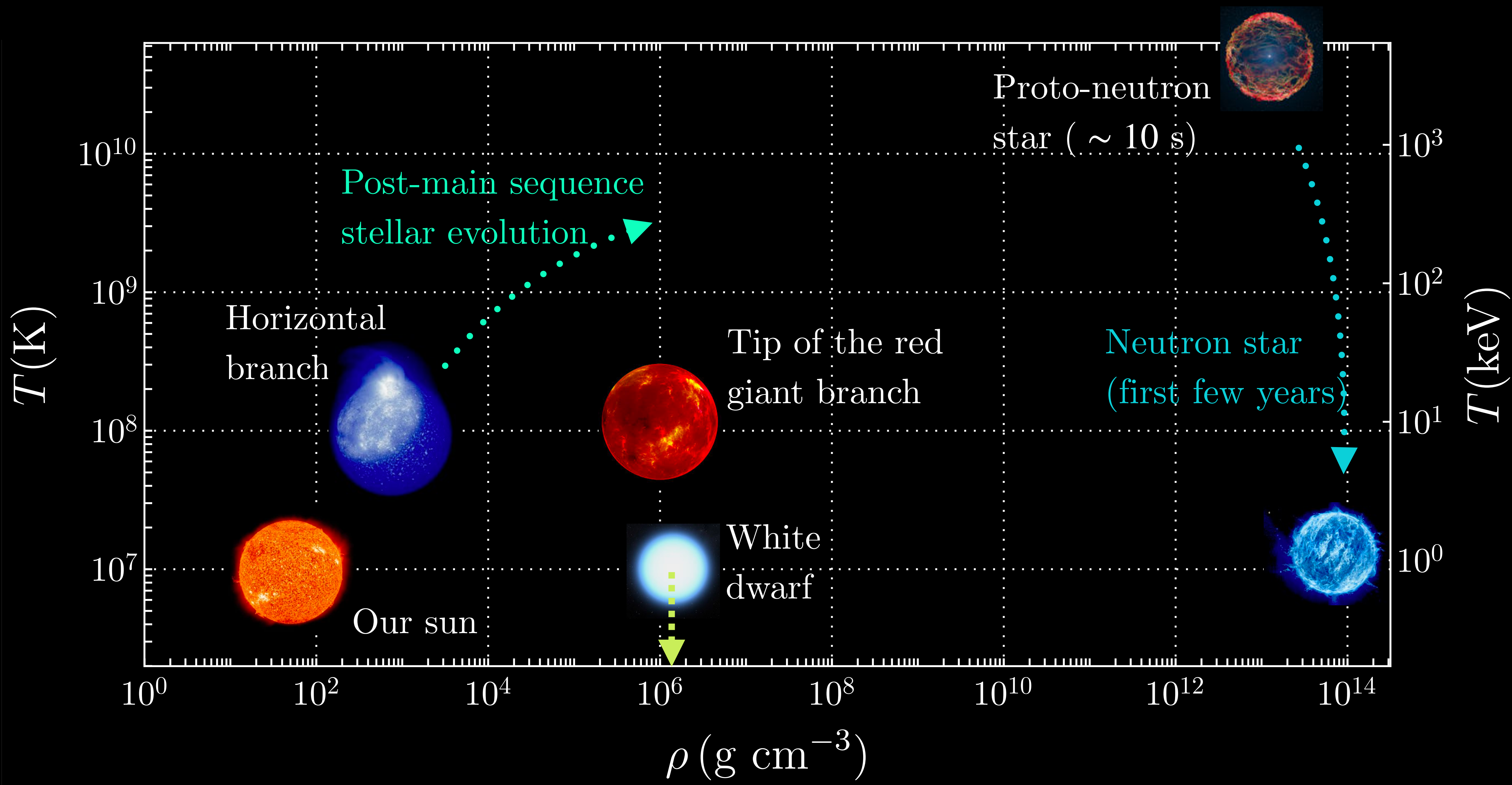


Adapted from LIGO-Virgo-KAGRA, Aaron Geller



Proto-neutron
star (~ 10 s)
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Our sun
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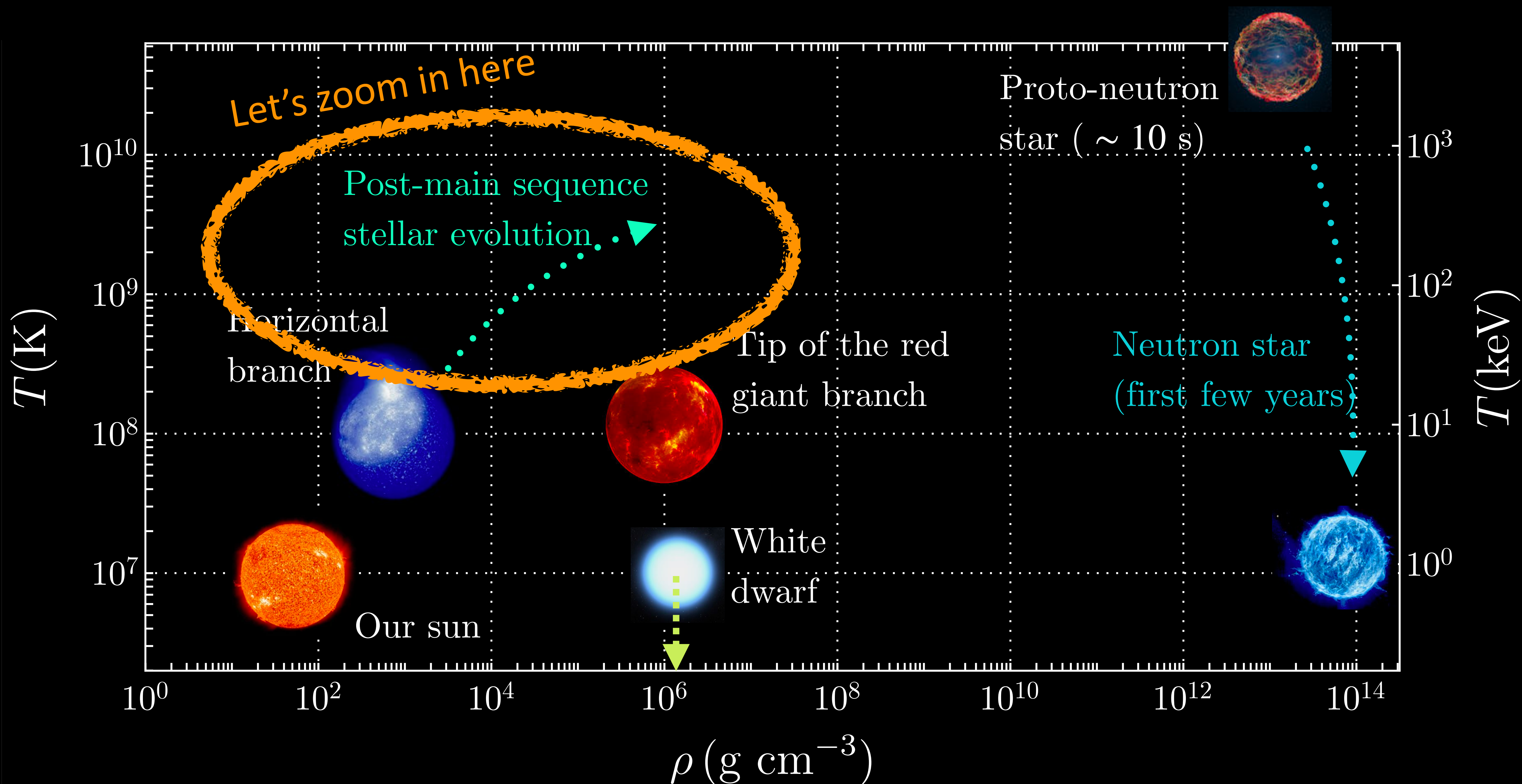
10^1
10^0
10^0
10^2
10^4
10^6
10^8
10^10
10^12
10^14


Let's zoom in here
Proto-neutron star (~ 10 s)
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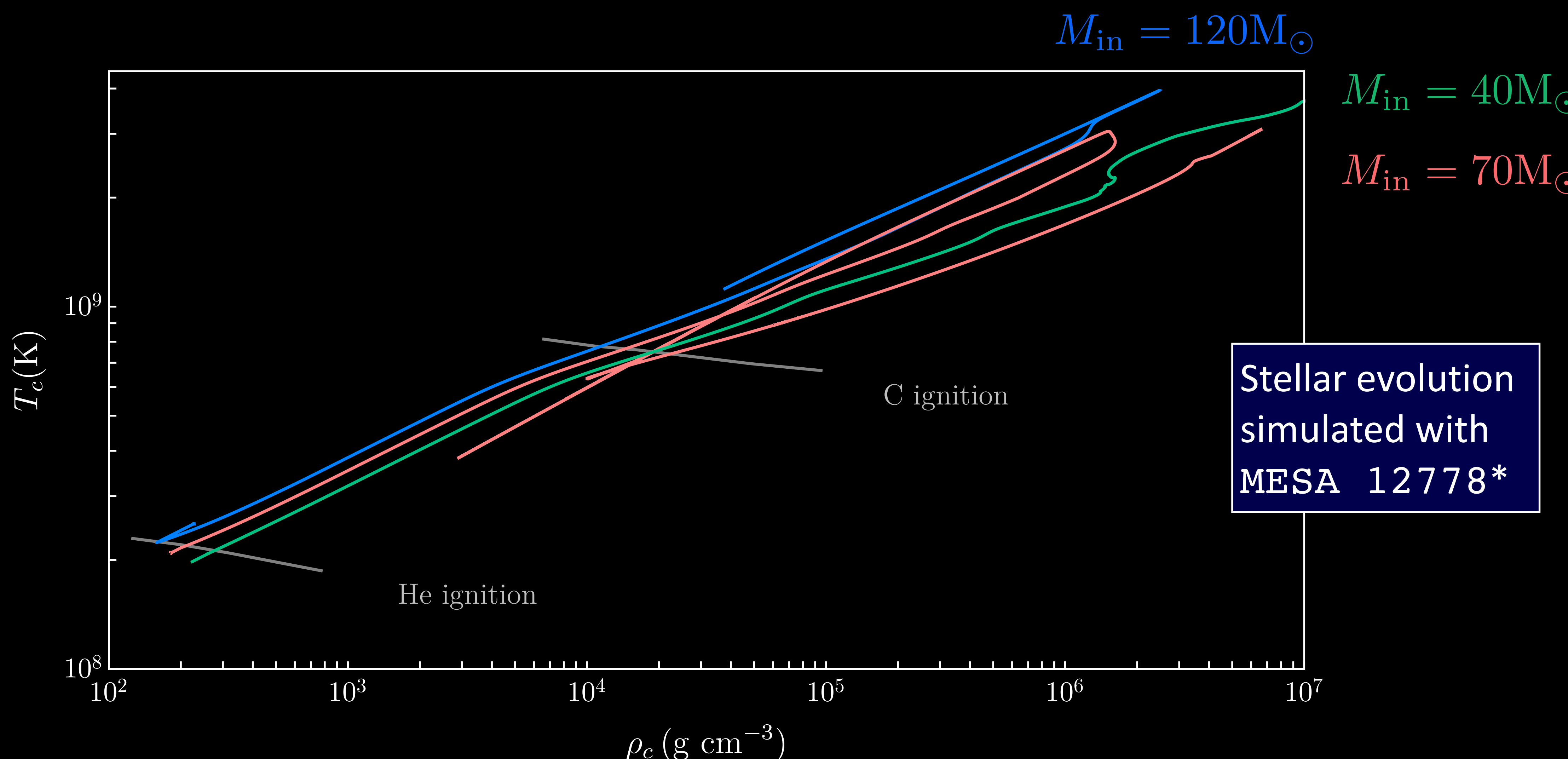
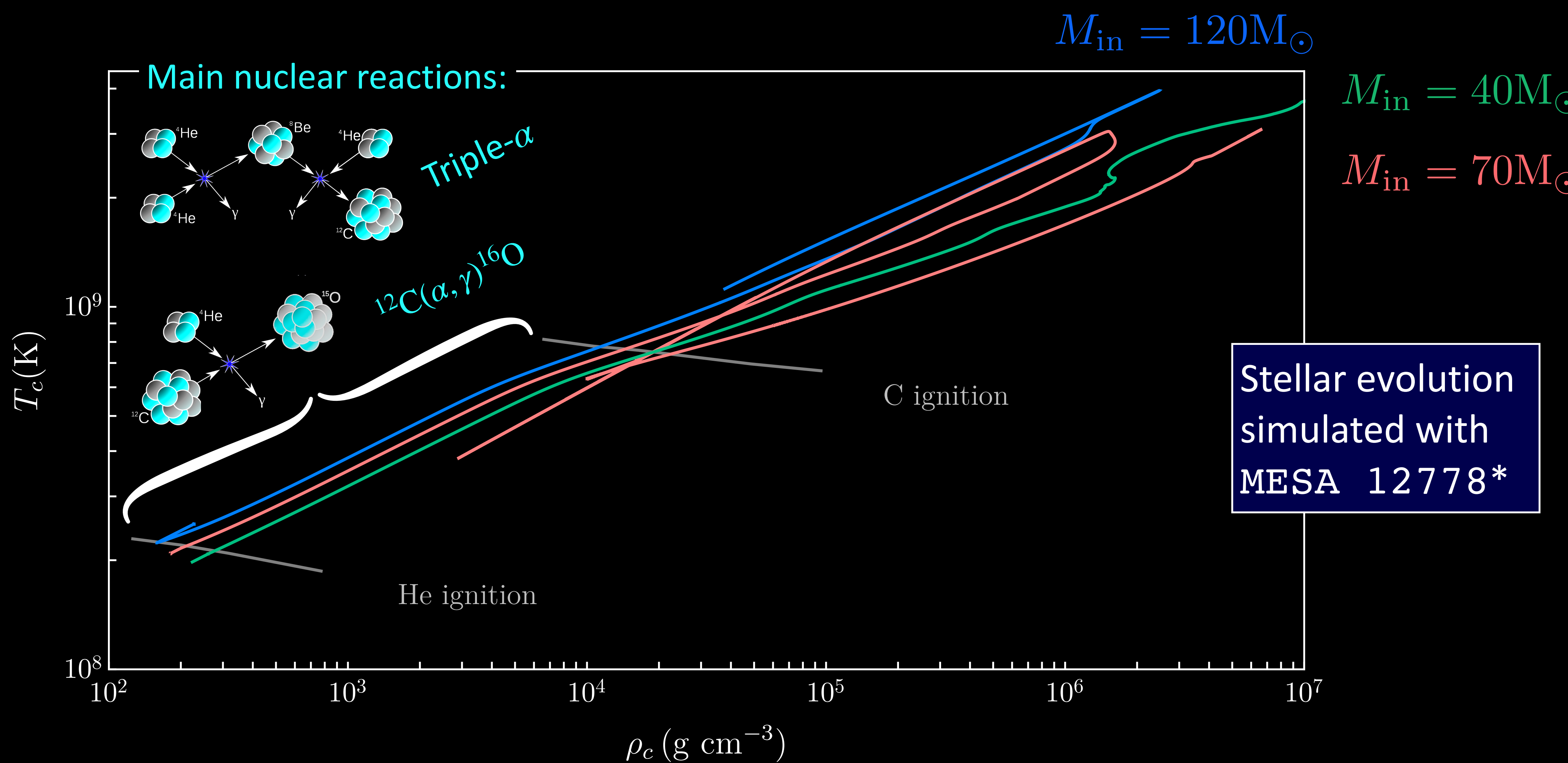
Late evolution of heavy stars



Stellar evolution simulated with `MESA 12778*`

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

Late evolution of heavy stars



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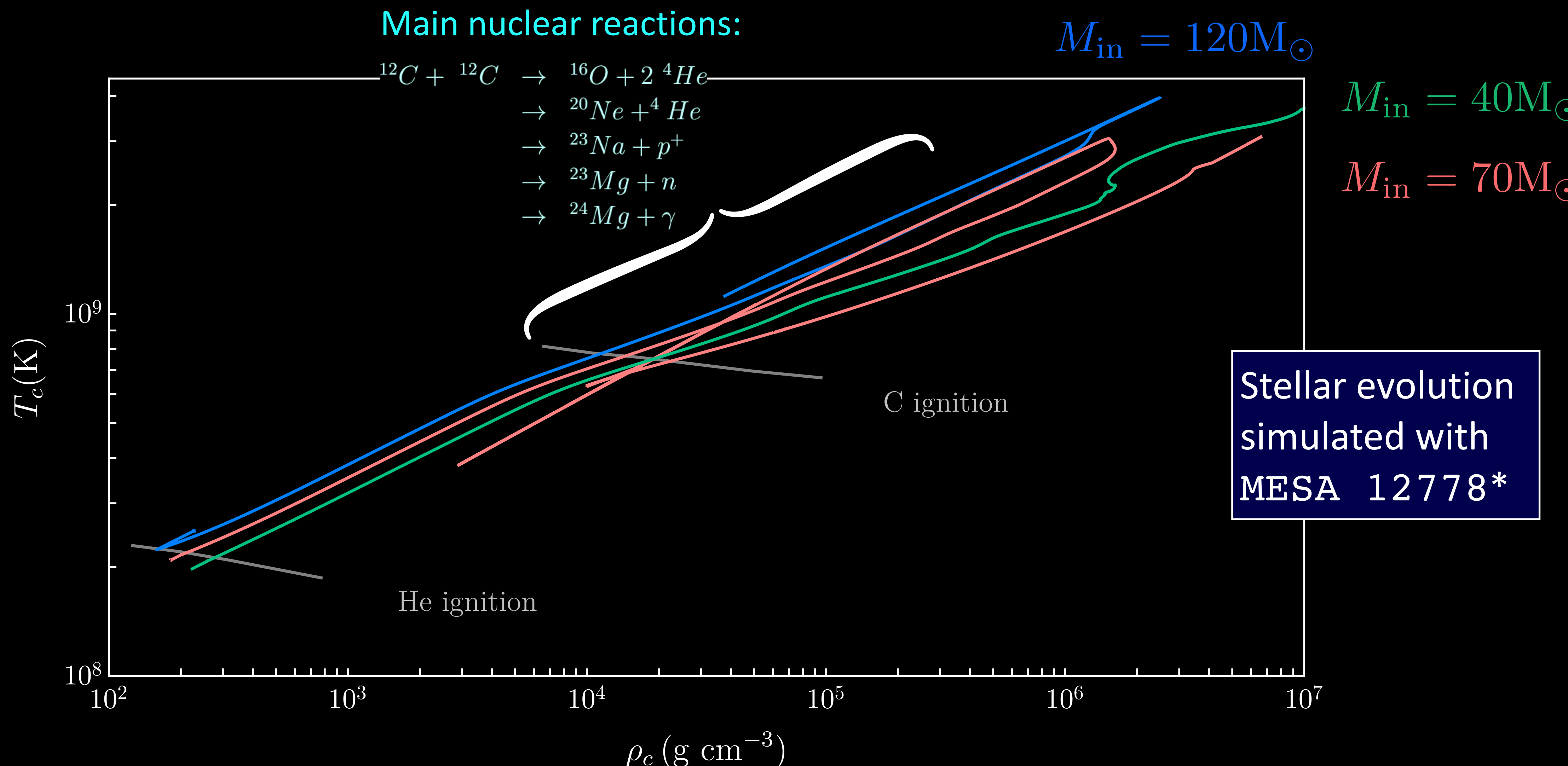

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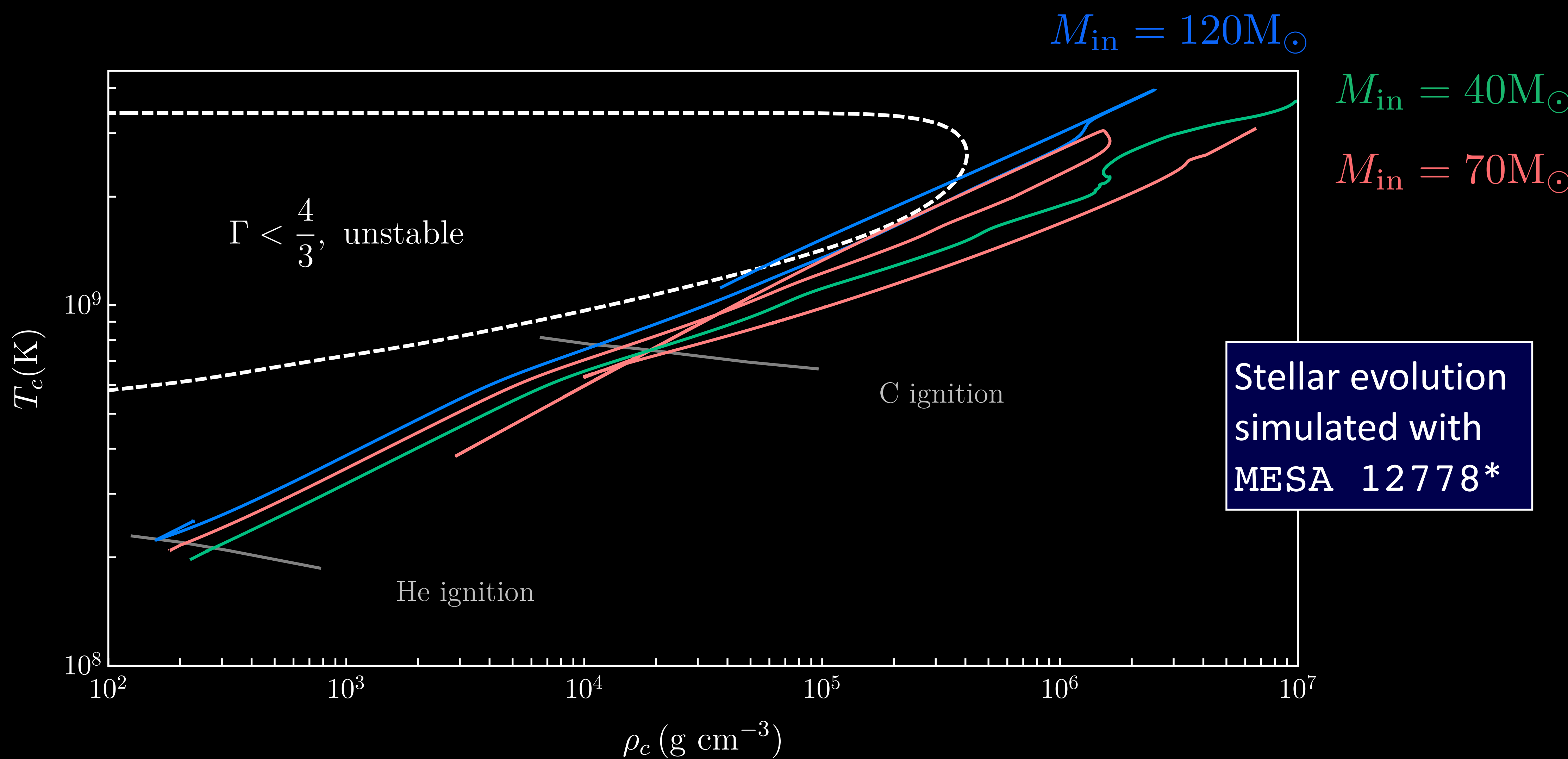

Stellar evolution simulated with MESA 12778*

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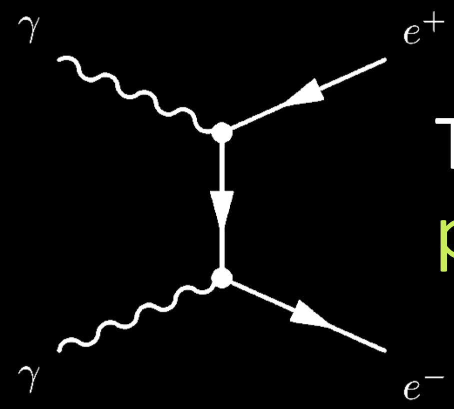
The danger zone: pair-instability

Barkat, Rakavy, Sack PRL (1967)
Rakavy, Shaviv, ApJ (1967)



The high temperatures of stellar cores mean electron-positron pairs can be created from photons: $\gamma\gamma \rightarrow e^+e^-$

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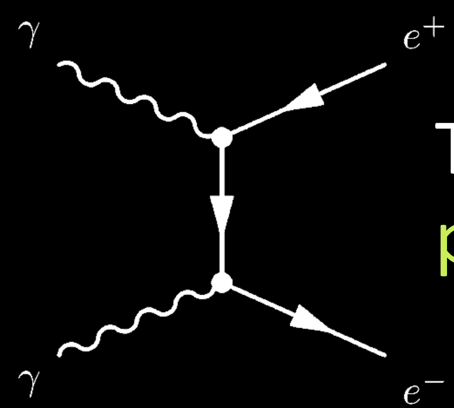


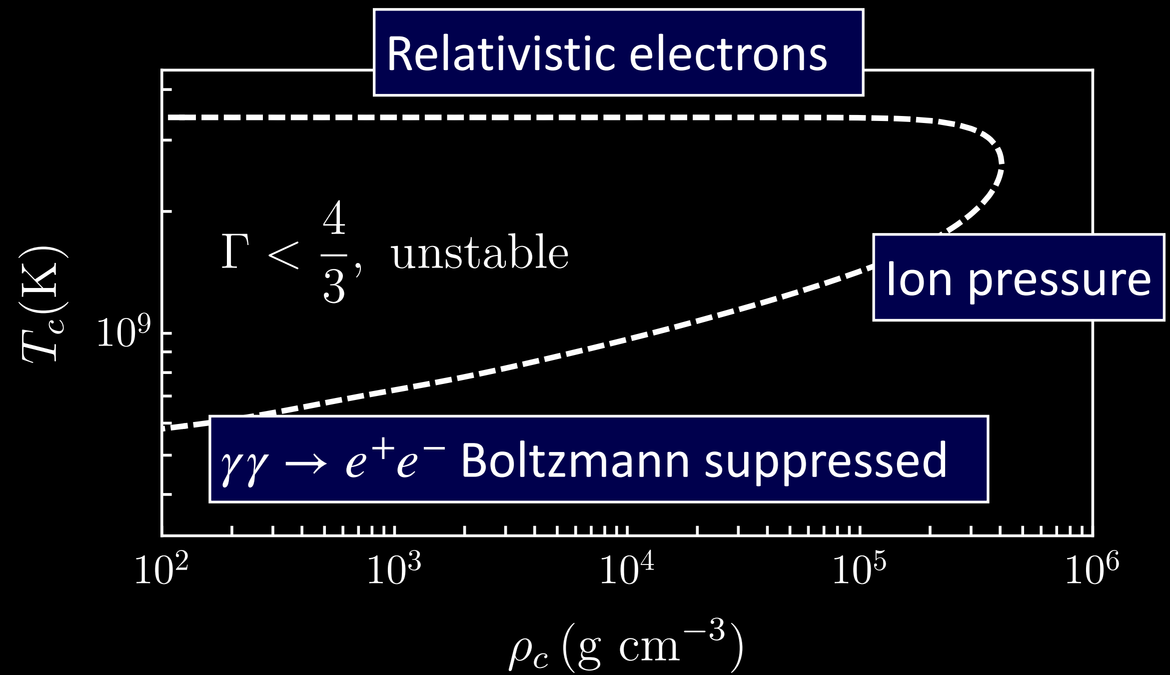
The high temperatures of stellar cores mean electron-positron pairs can be created from photons: $\gamma\gamma \to e^+e^-$

Unstable, because:

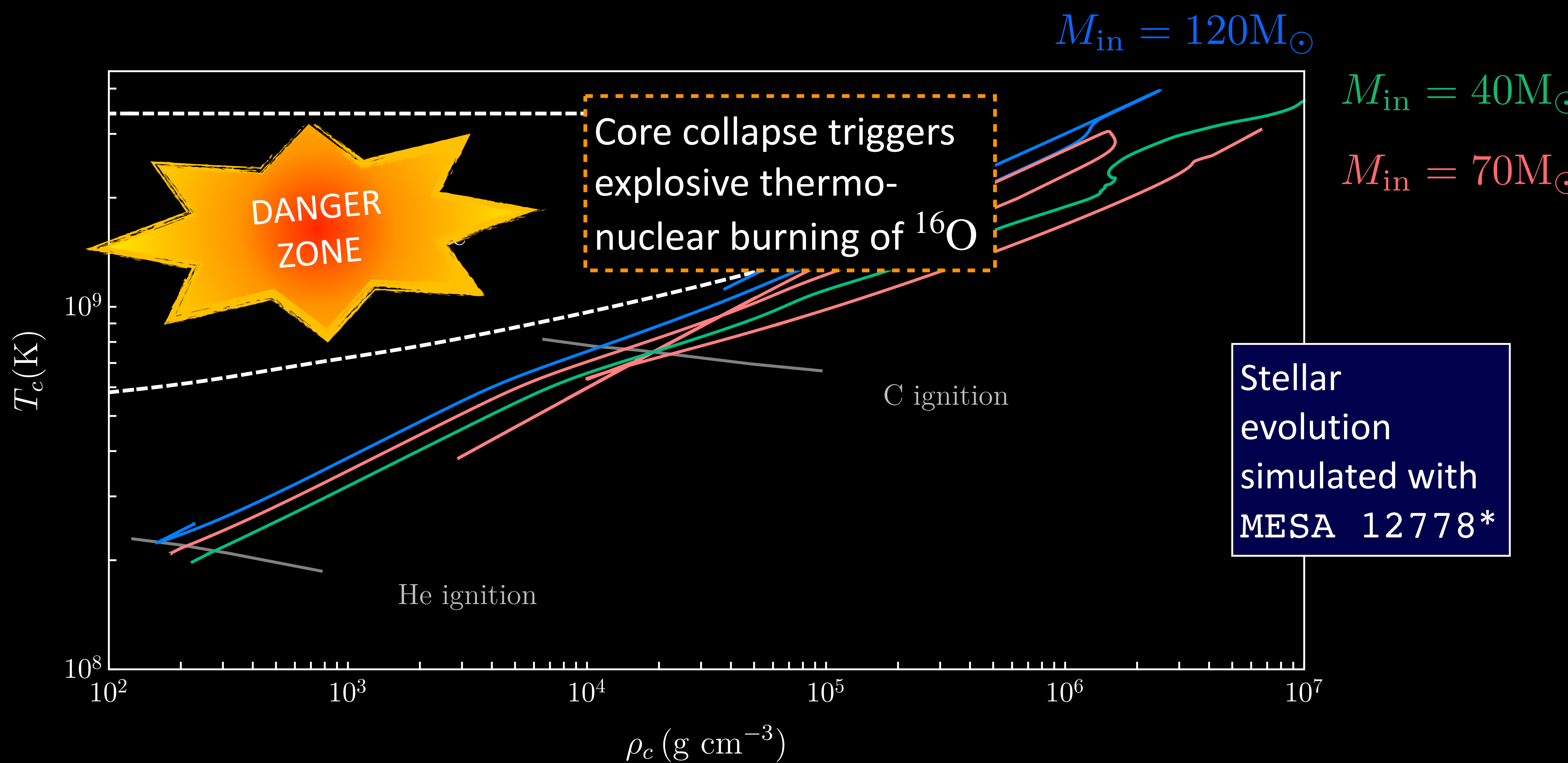
The photons give the star outward pressure

The electron-positron pairs imply extra gravity but no pressure

→ the core starts to collapse



Evolution of old population-III stars



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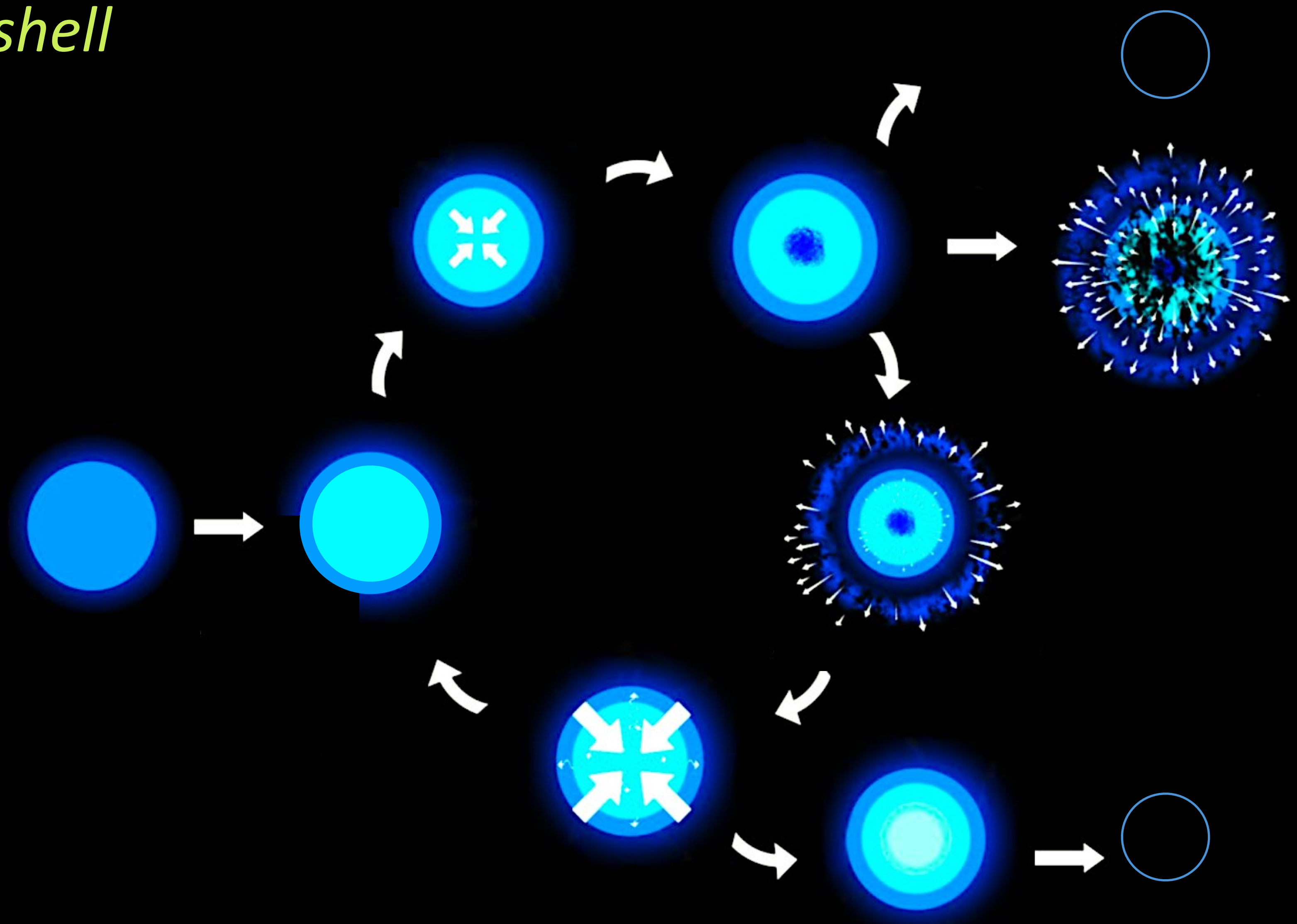
Pair instability

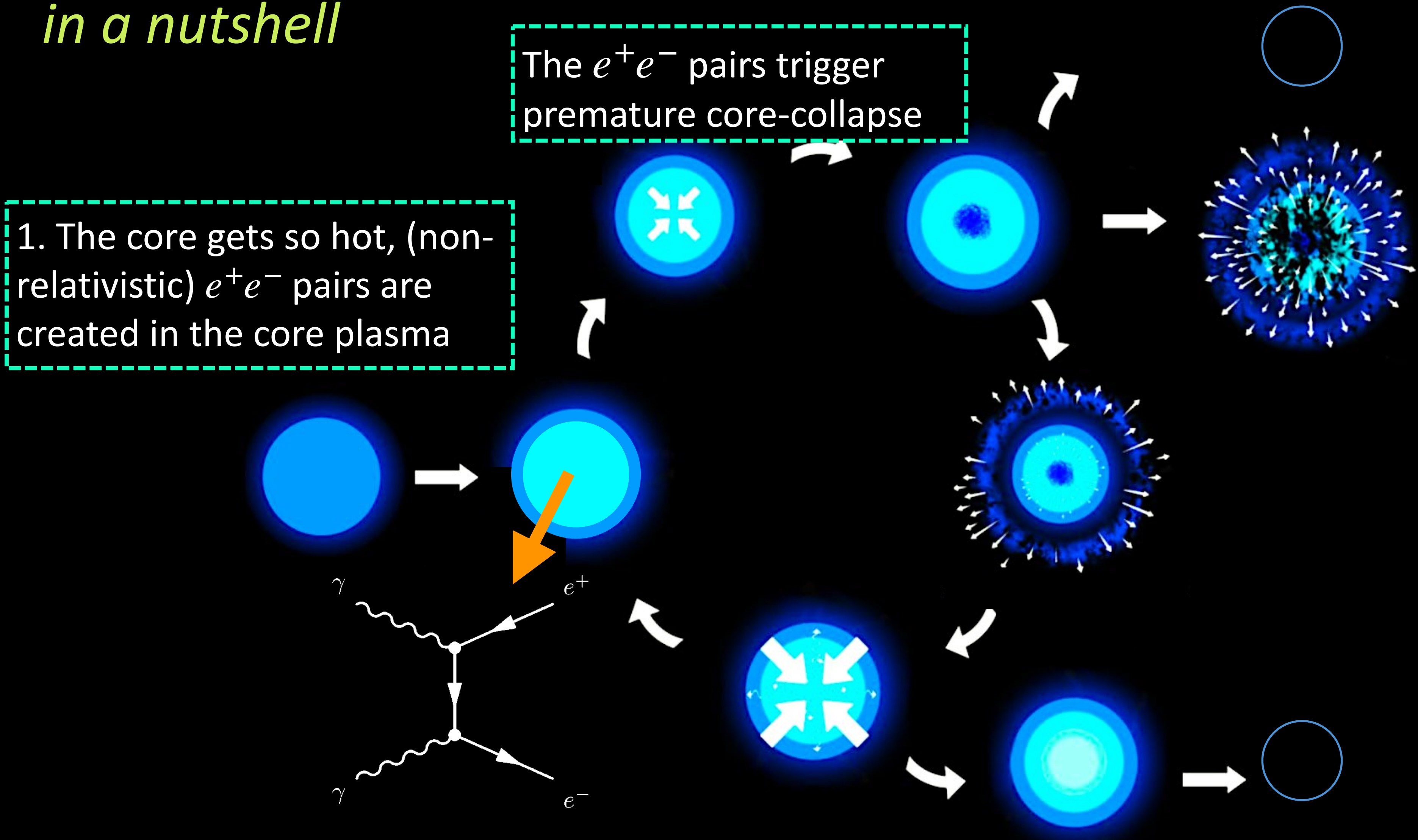
in a nutshell



Adapted from Renzo et al [2002.05077]

Pair instability

in a nutshell



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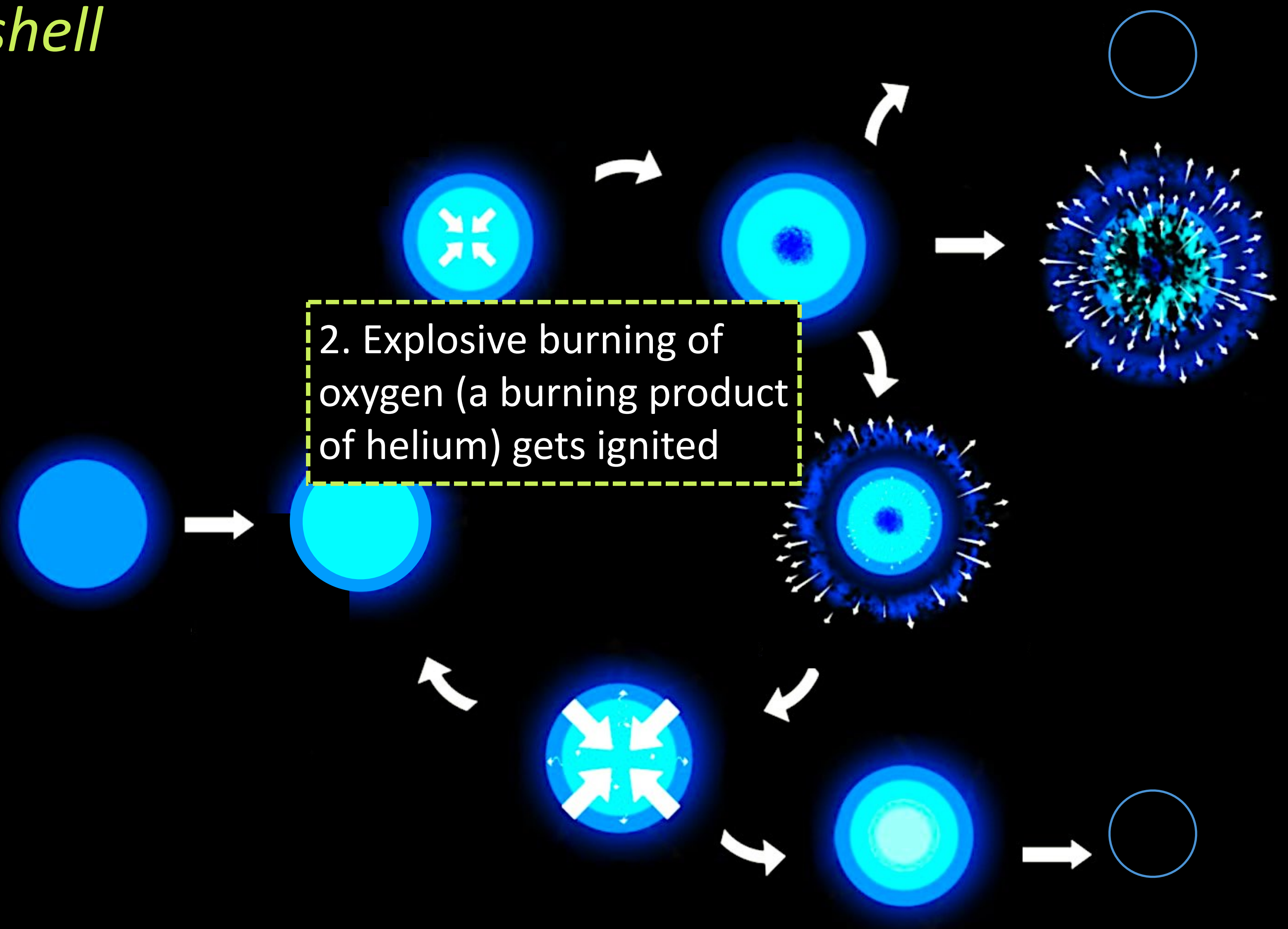

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Pair instability

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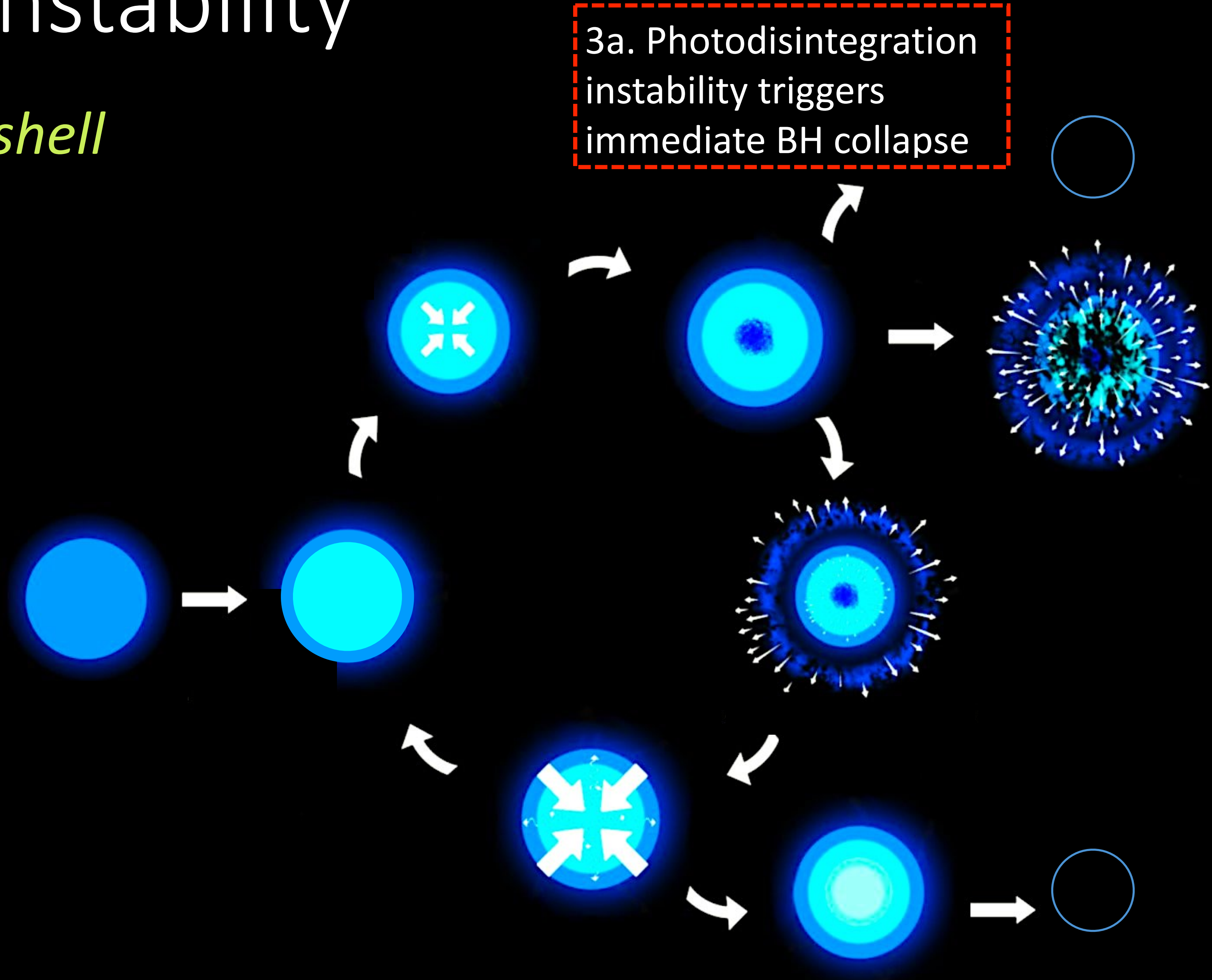


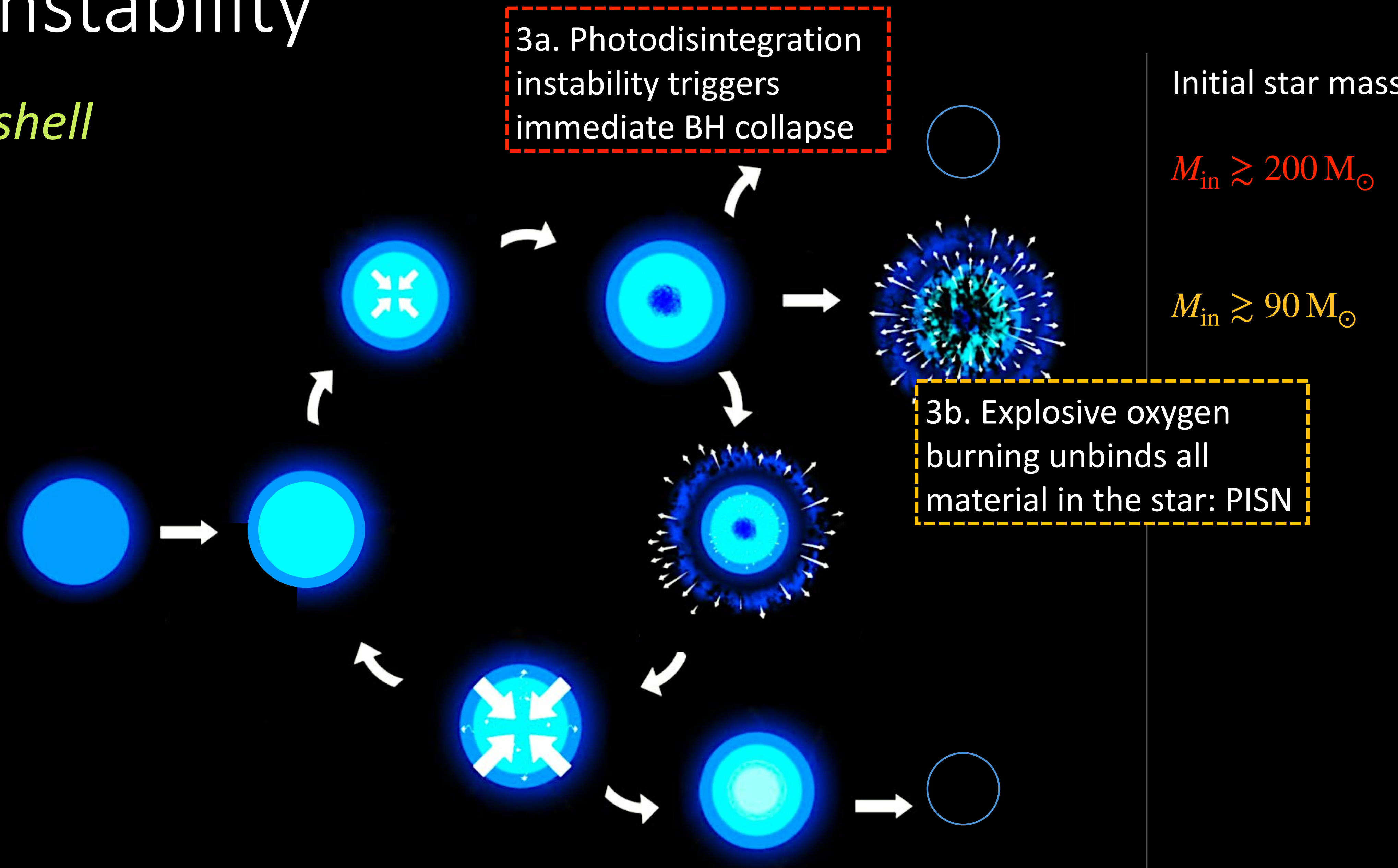
Initial star mass

$M_{\rm in} \gtrsim 200\,{\rm M}_\odot$

Adapted from Renzo et al [2002.05077]

Pair instability

in a nutshell



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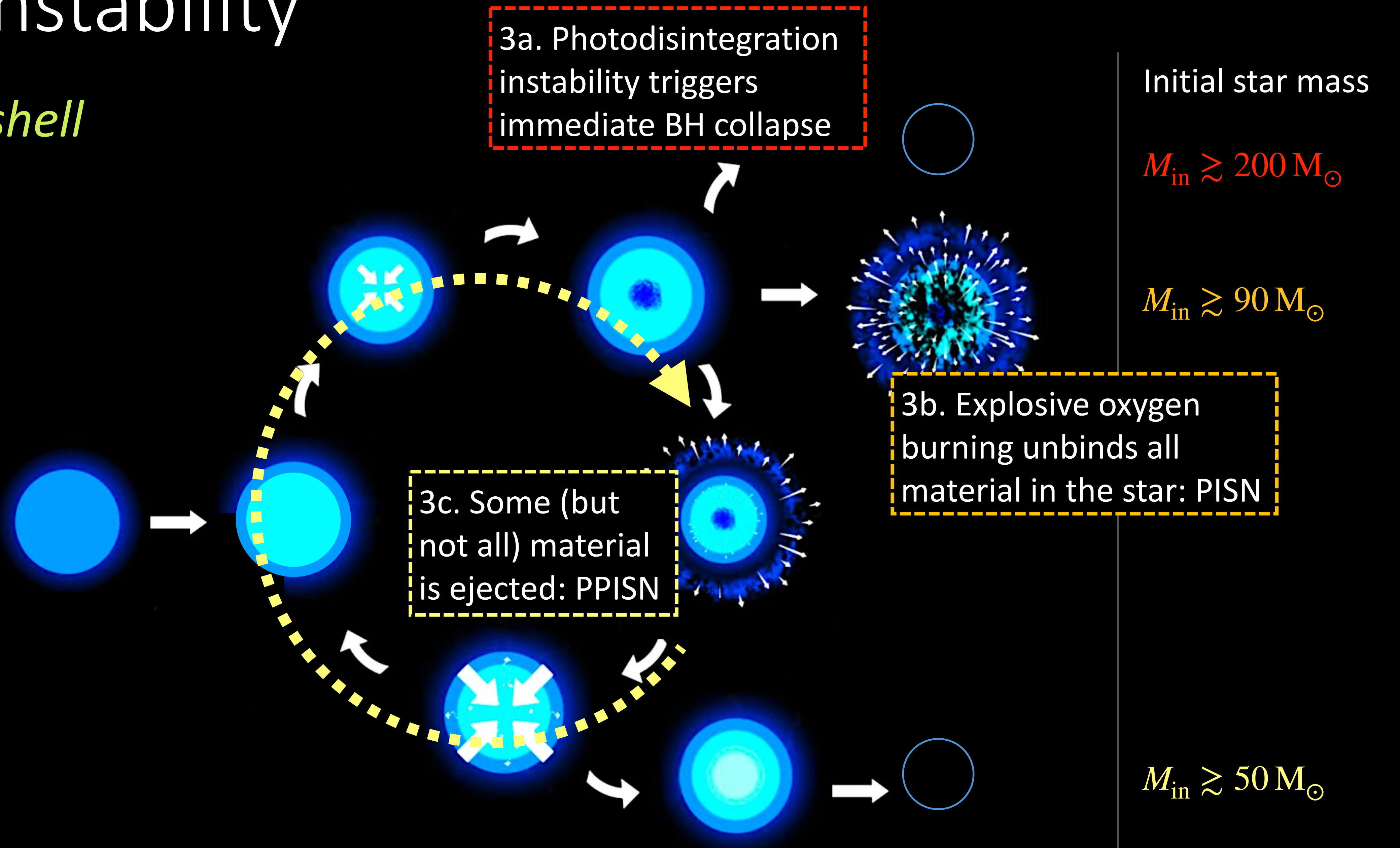

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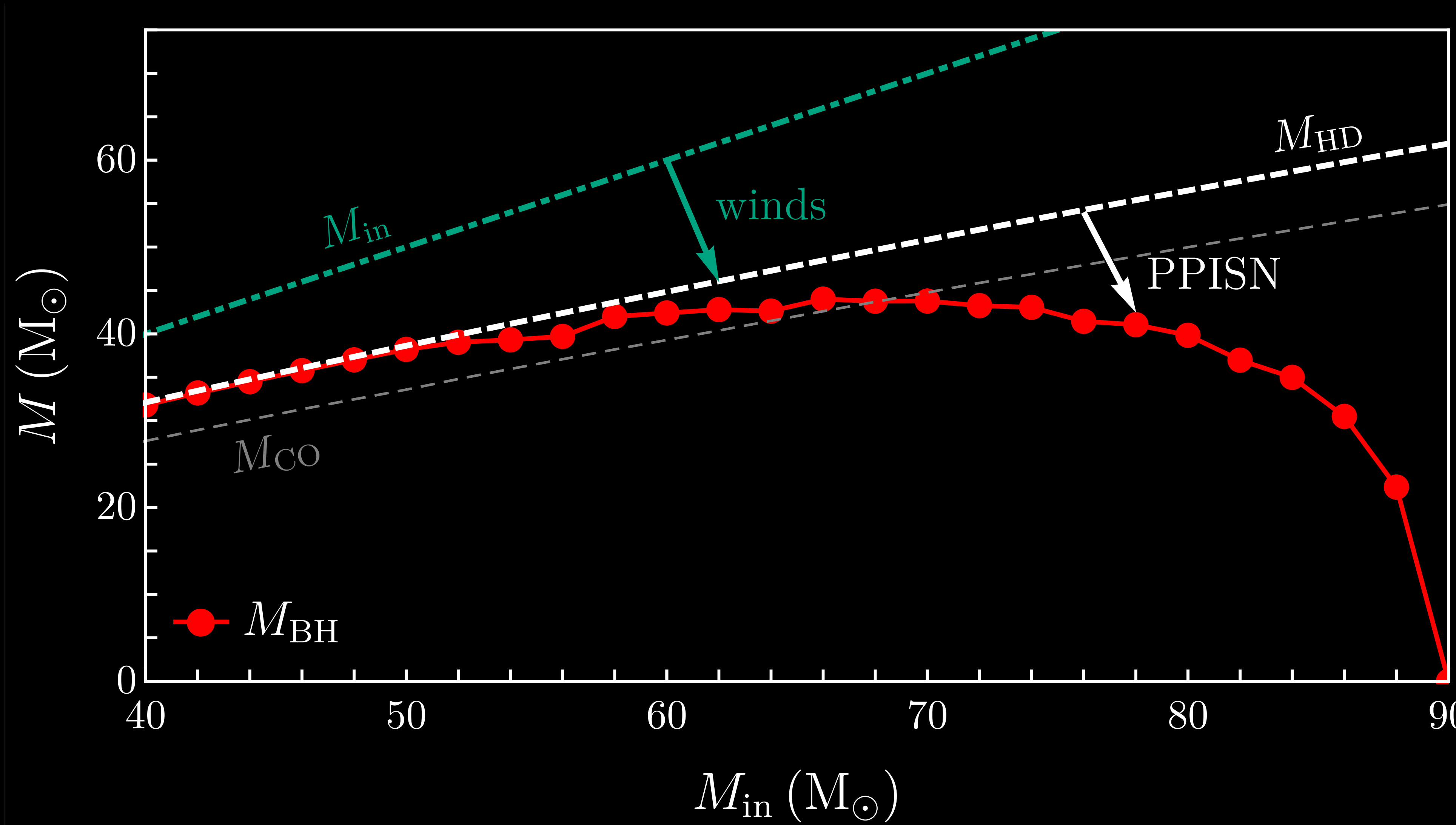
Resulting black hole masses



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

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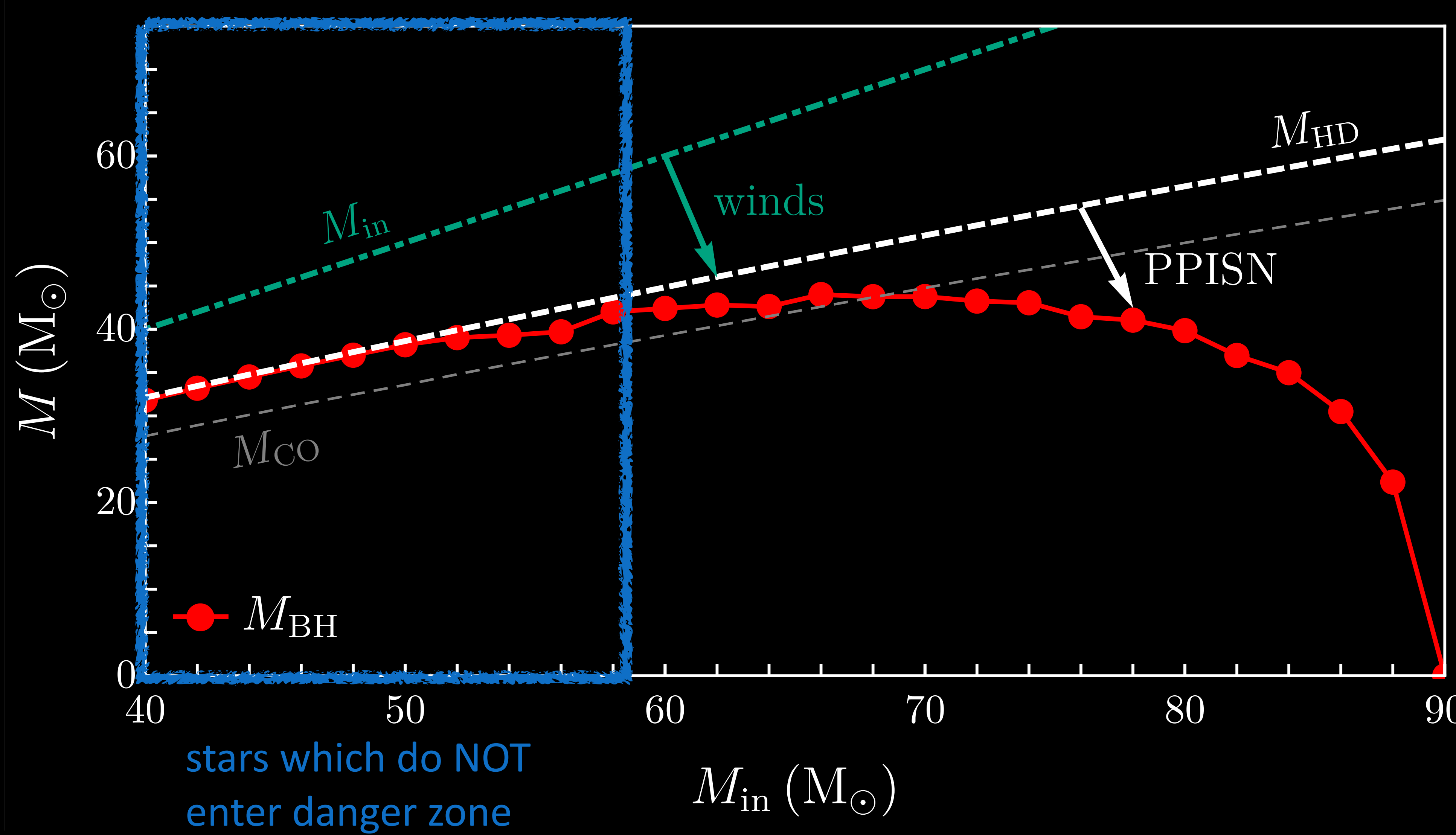

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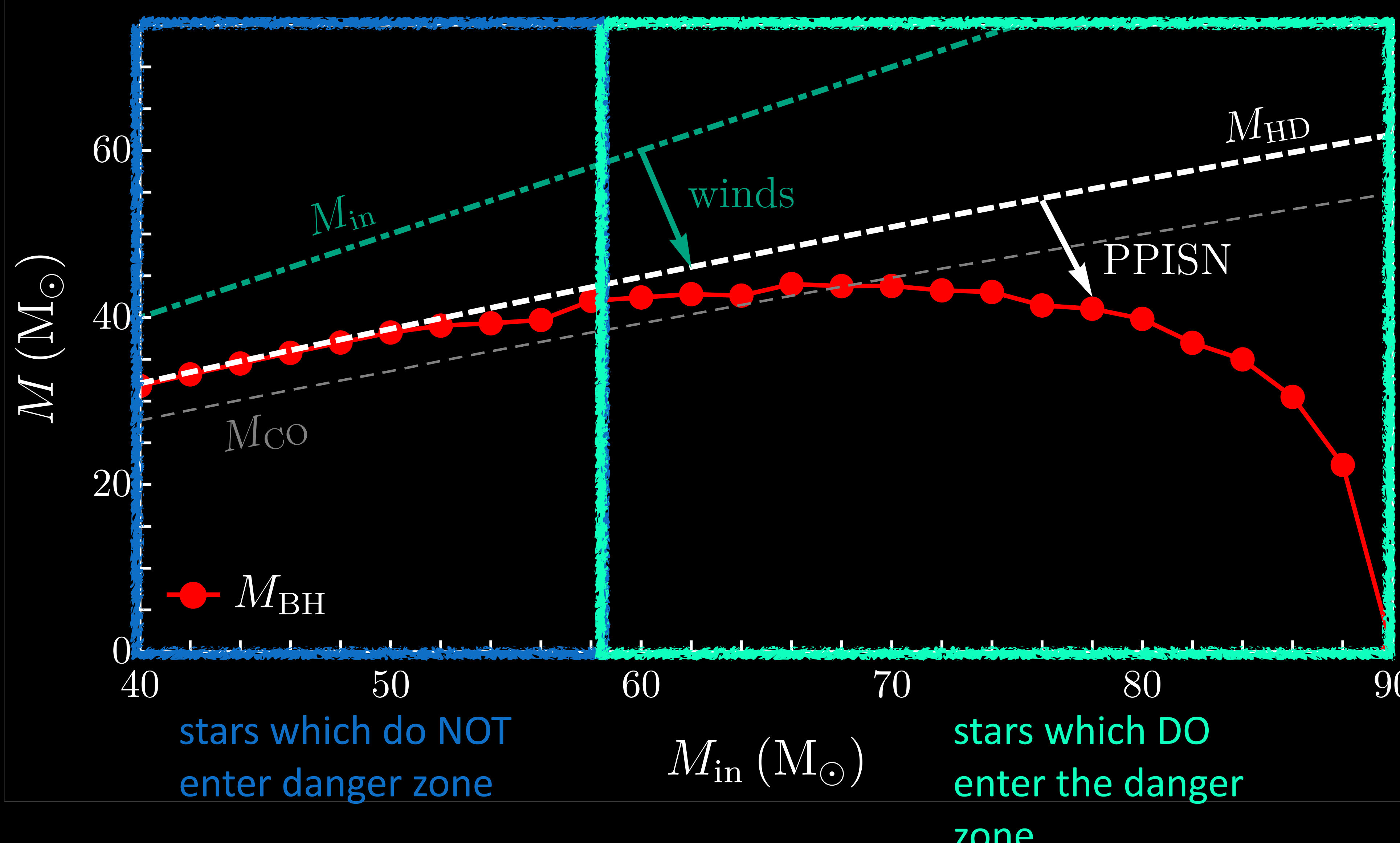

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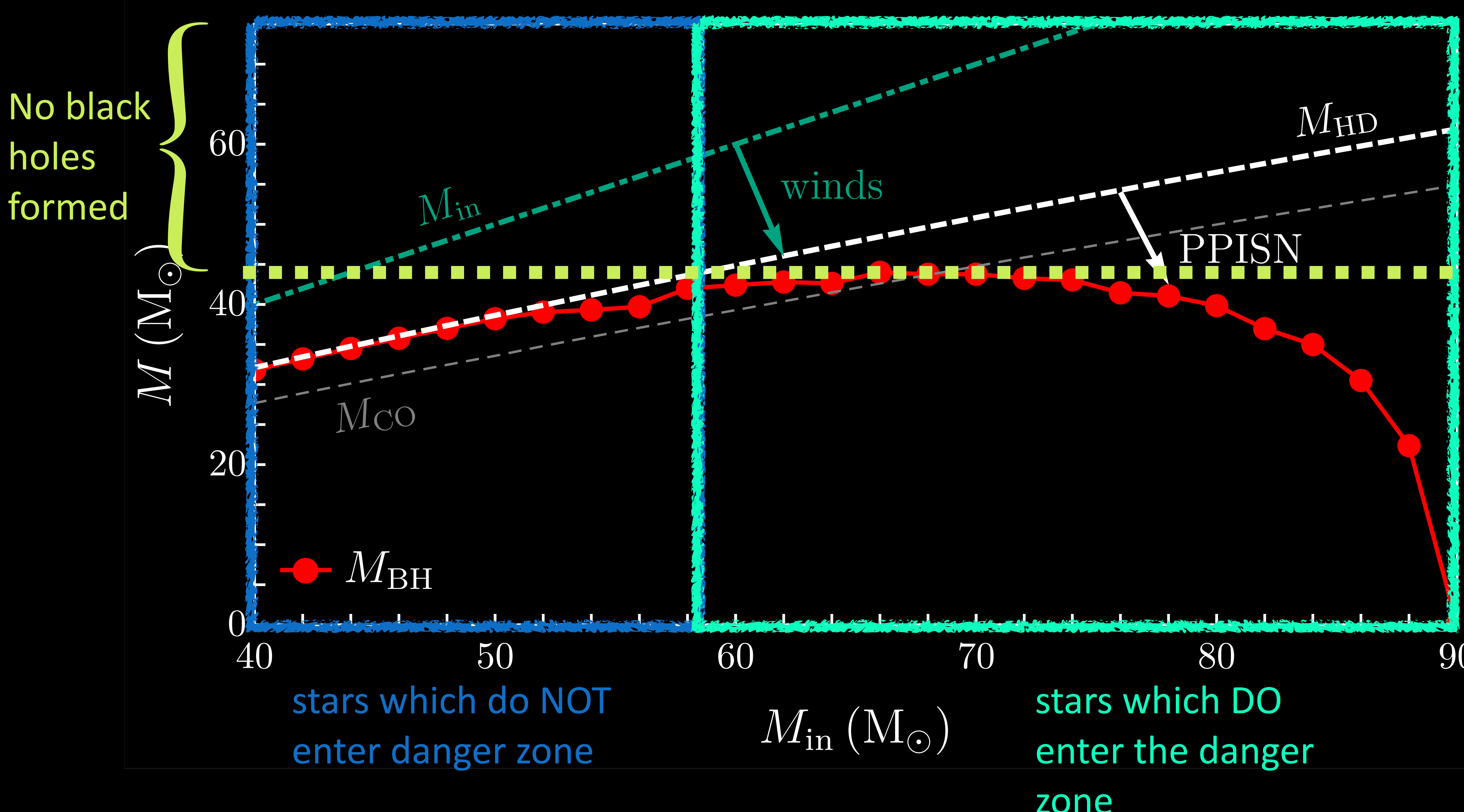

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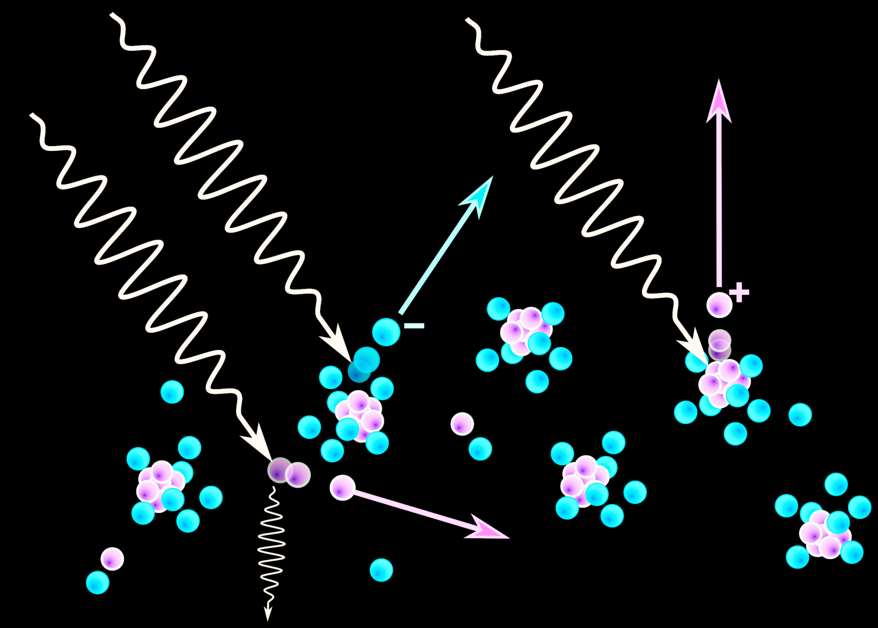
Upper end of the mass gap

Photodisintegration: rapid absorption of high energy photons

Photodisintegration leads to decrease in Γ_1 and therefore a contraction



Upper end of the mass gap

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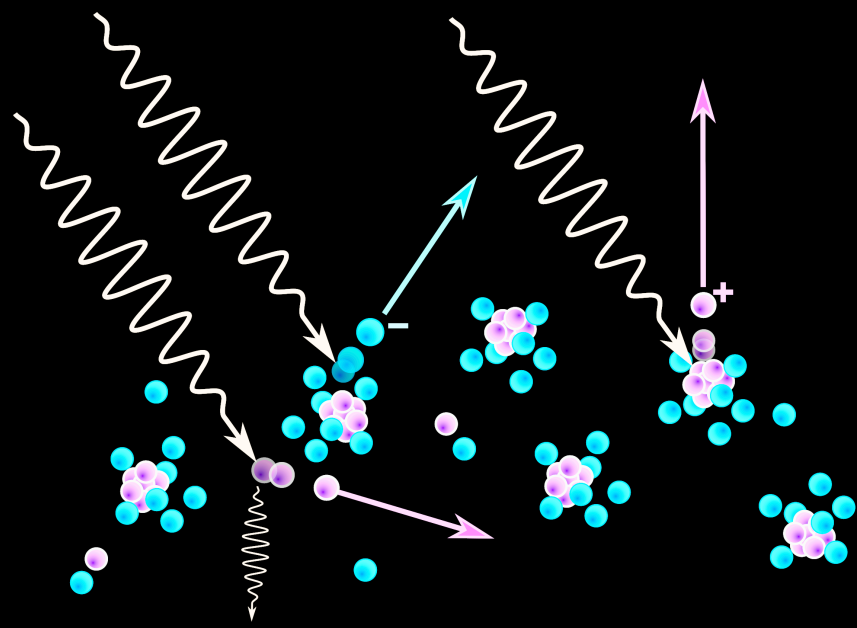
In very high mass stars: oxygen burning can no longer keep up with contraction due to photodisintegration

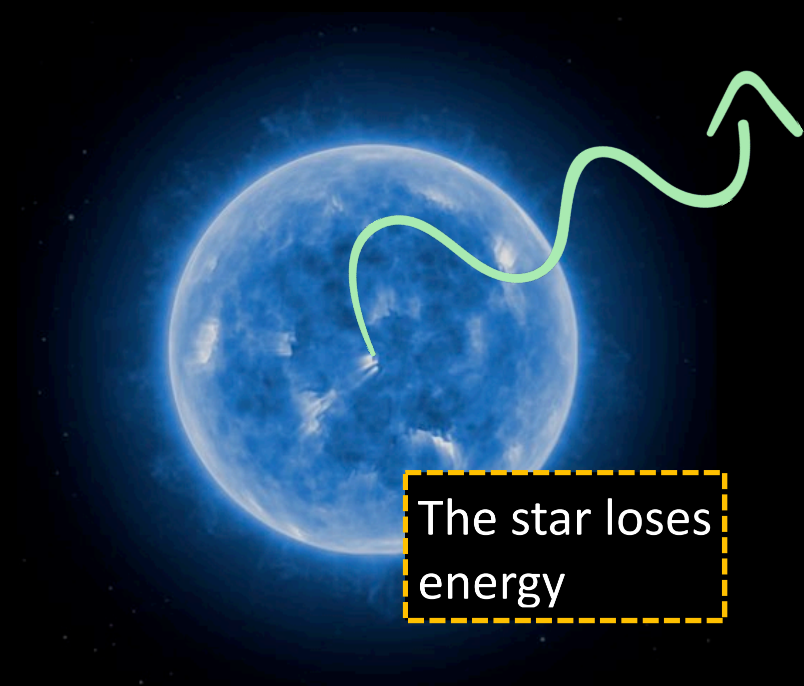
No pulsations, immediate collapse into black holes



What about new particles?

New particles…

- May be produced in the star and *free stream out*

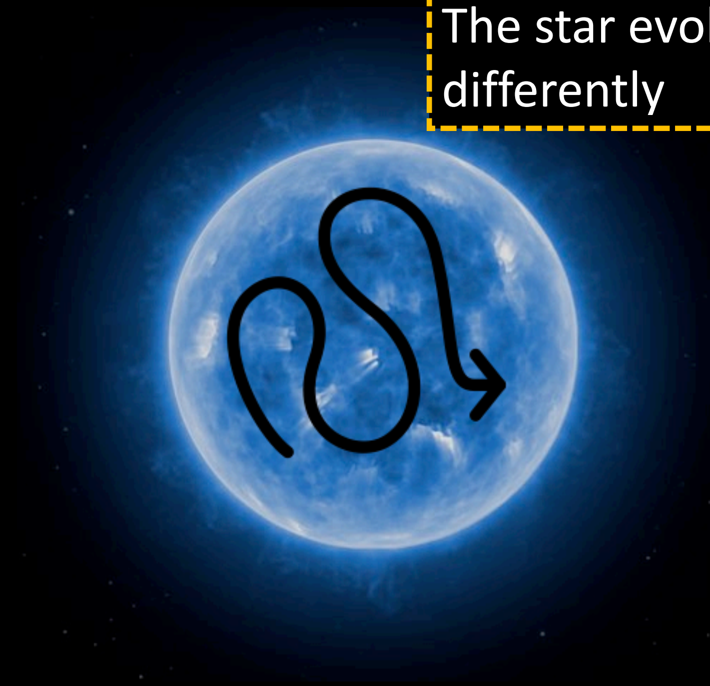


What about new particles?

New particles…

- May be produced in the star and *free stream out*

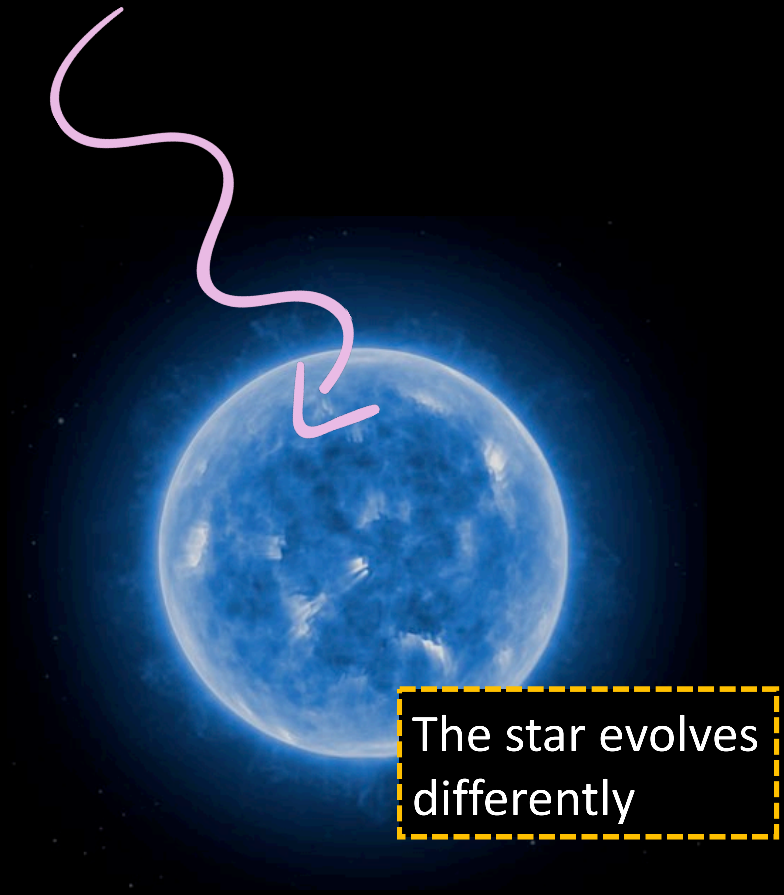
- May be produced in the star and *get trapped*



What about new particles?

New particles…

- May be produced in the star and *free stream out*
- May be produced in the star and *get trapped*
- May collect in the star and annihilate in the core



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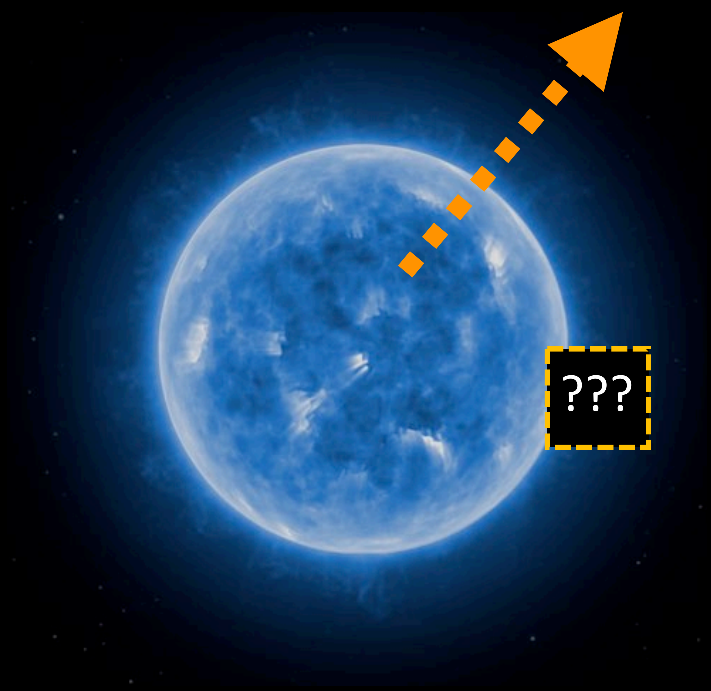
- May collect in the star and annihilate in the core
- May modify other rates in the star



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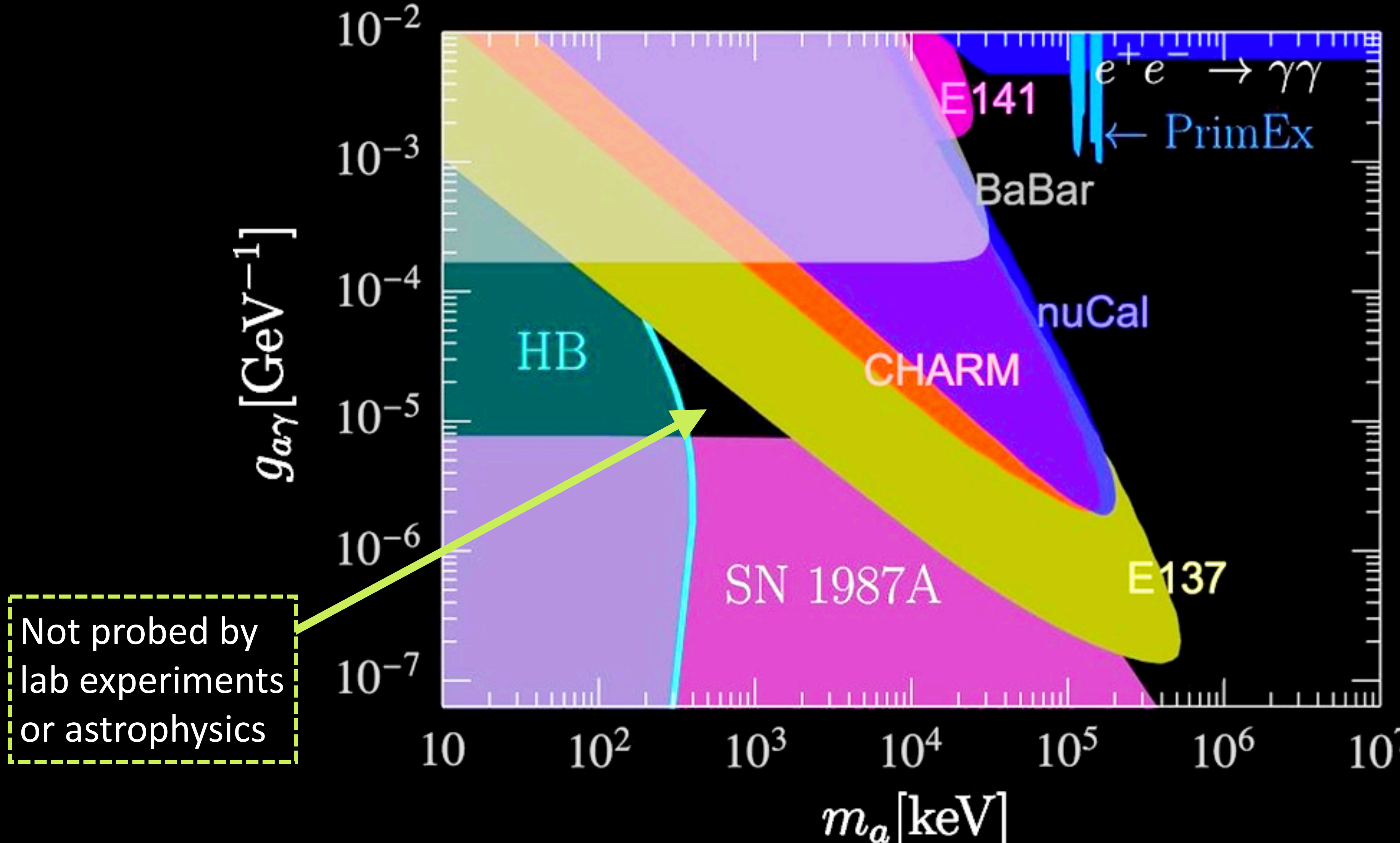
Nuclear astrophysics: pair-instability is a sensitive probe of $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

Farmer, Renzo, de Mink, Fishbach, Justham arXiv:2006.06678

Gravity: the BHMG is a test of G_N in stellar

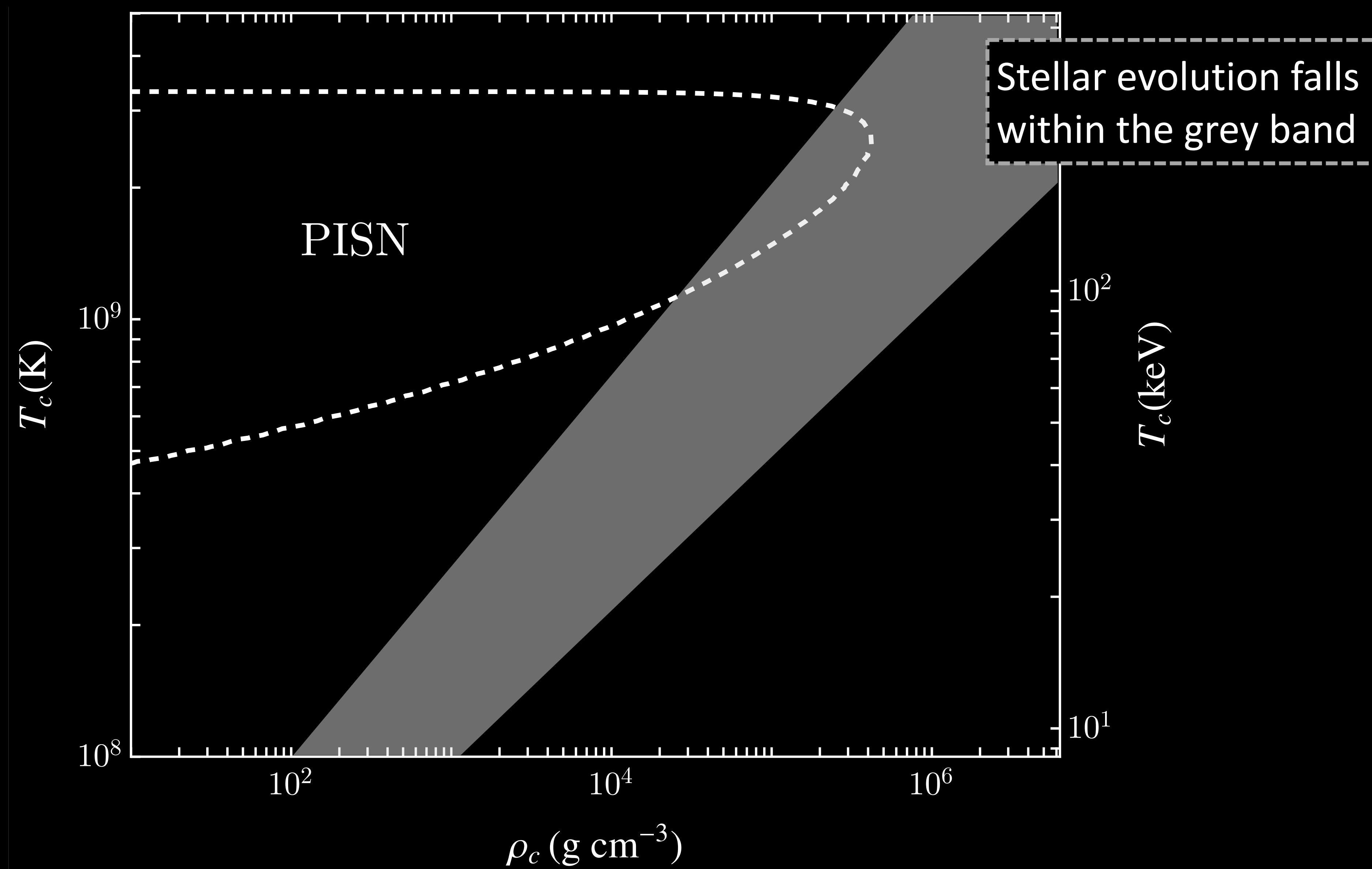
Straight, Sakstein, Baxter, arXiv: 2009.10716

Axions in the cosmological triangle



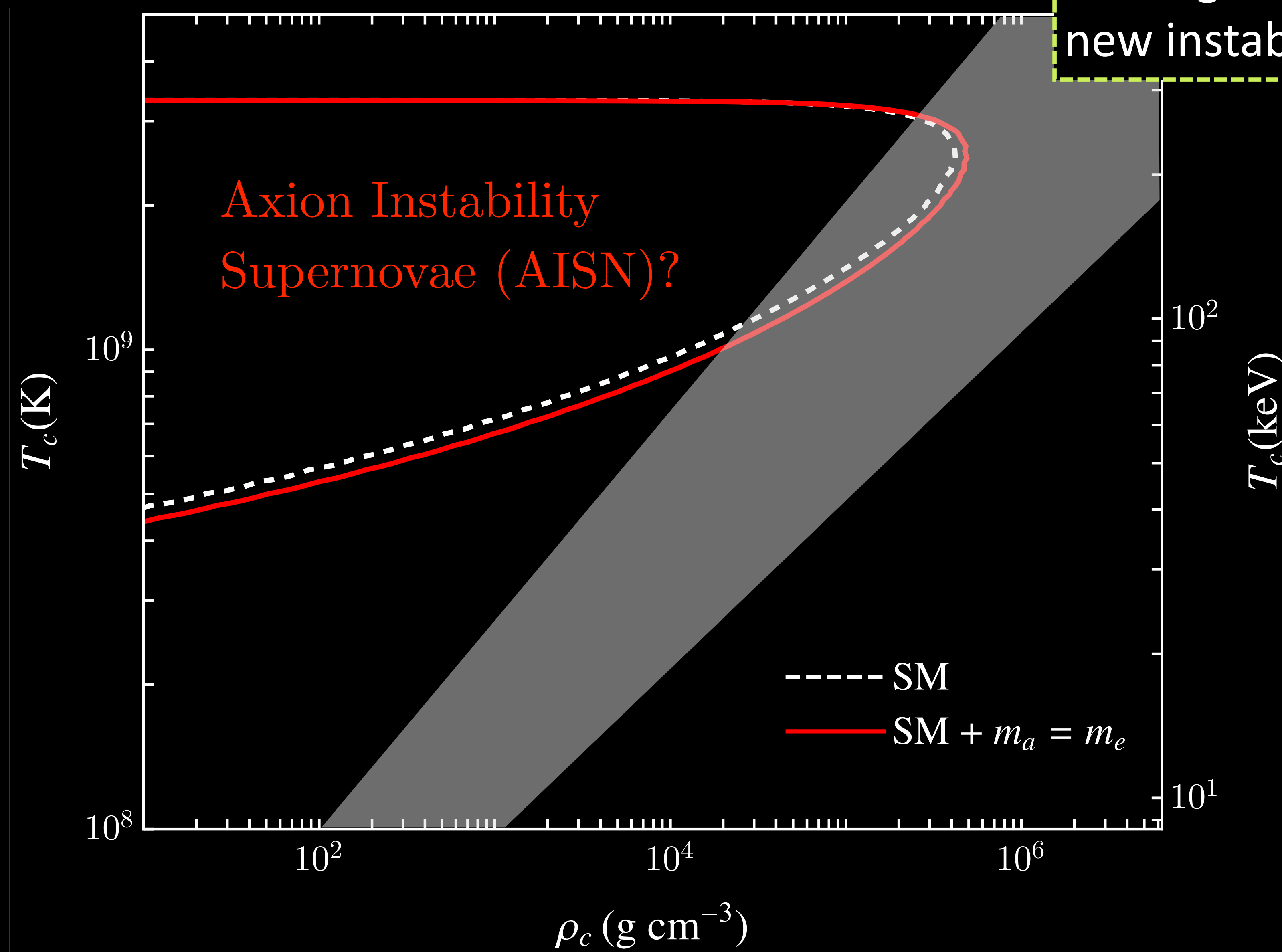
e.g. Carenza, Straniero, Dobrich, Giannotti, Lucente, Mirizzi, PLB, arXiv:2004.08399

Axions in stars



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

Axions in stars



… can give rise to new instabilities!

DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc] + arXiv:2203.06160 [hep-ph]

Axions and the stellar EOS

- Assume an equilibrium distribution of axions, need to update the stellar EOS with axion contributions to:
  - P_g
  - E
  - s
  - $\left(\frac{\partial s}{\partial T}\right)_\rho$
  - $\left(\frac{\partial s}{\partial \rho}\right)_T$
  - c_V
  - c_P
  - χ_p
  - χ_T
  - $\left(\frac{\partial E}{\partial \rho}\right)_T$
  - Γ_1
  - Γ_3
  - ∇_{ad}

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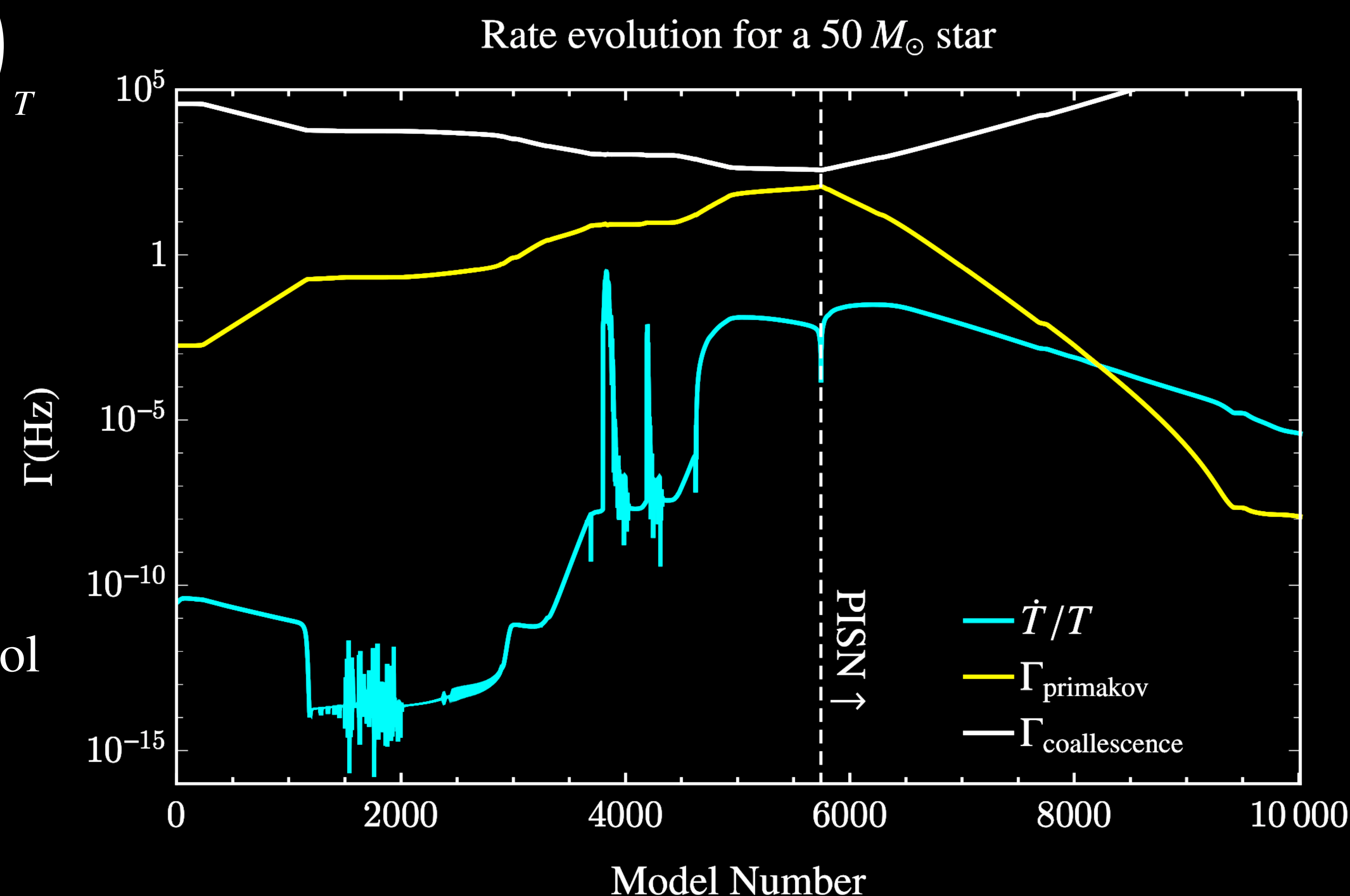
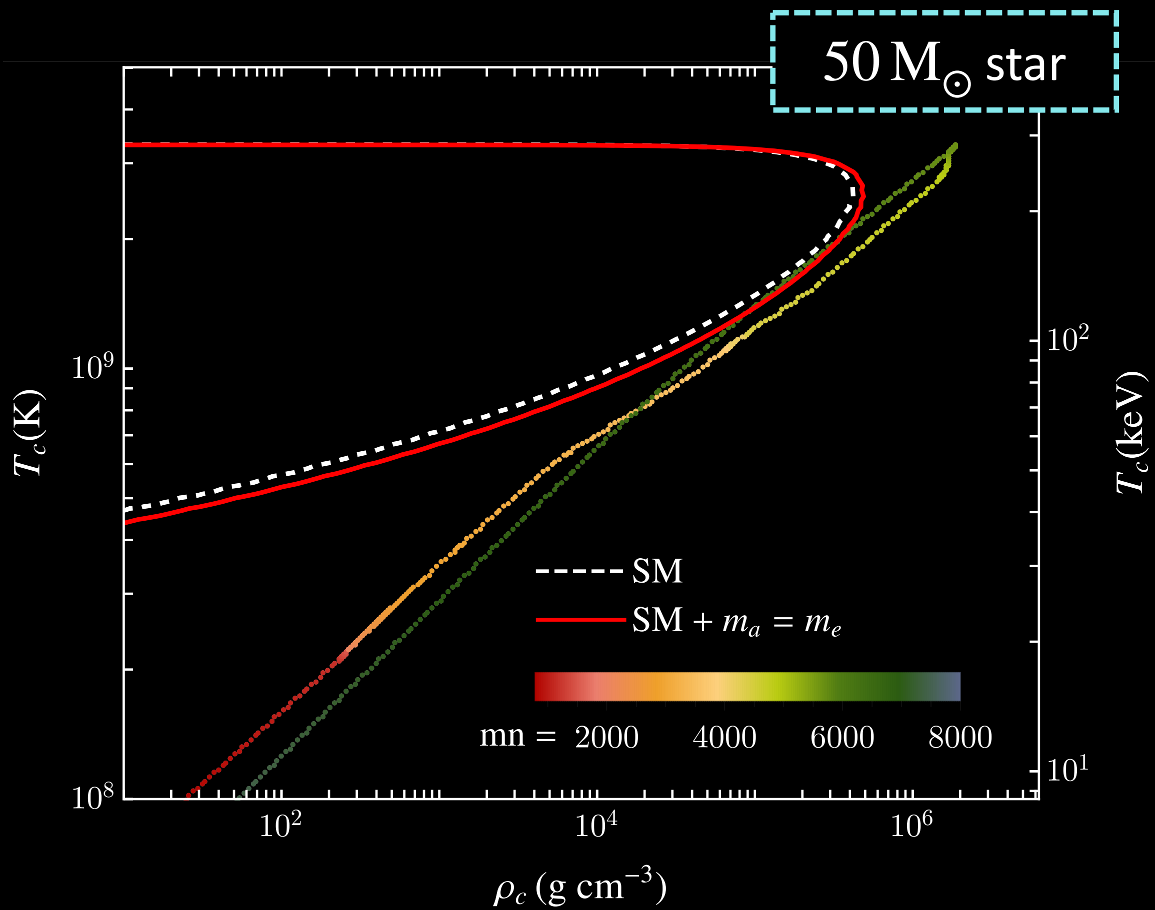
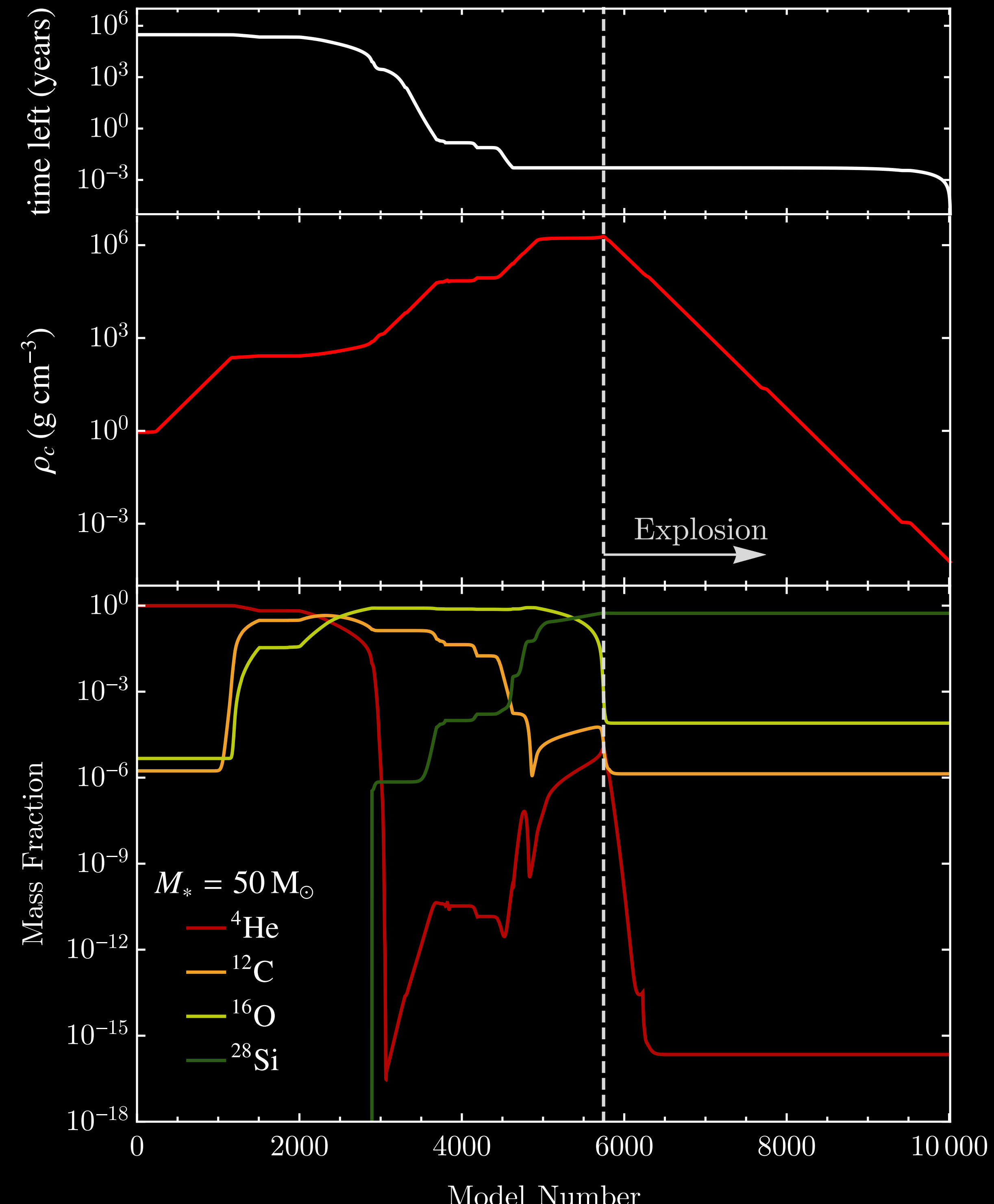
  - c_P
  - χ_p
  - χ_T
  - $\left(\frac{\partial E}{\partial \rho}\right)_T$
  - Γ_1
  - Γ_3
  - ∇_{ad}
- Only valid if $\Gamma_{\gamma \to a} > \Gamma_{\text{evol}}$



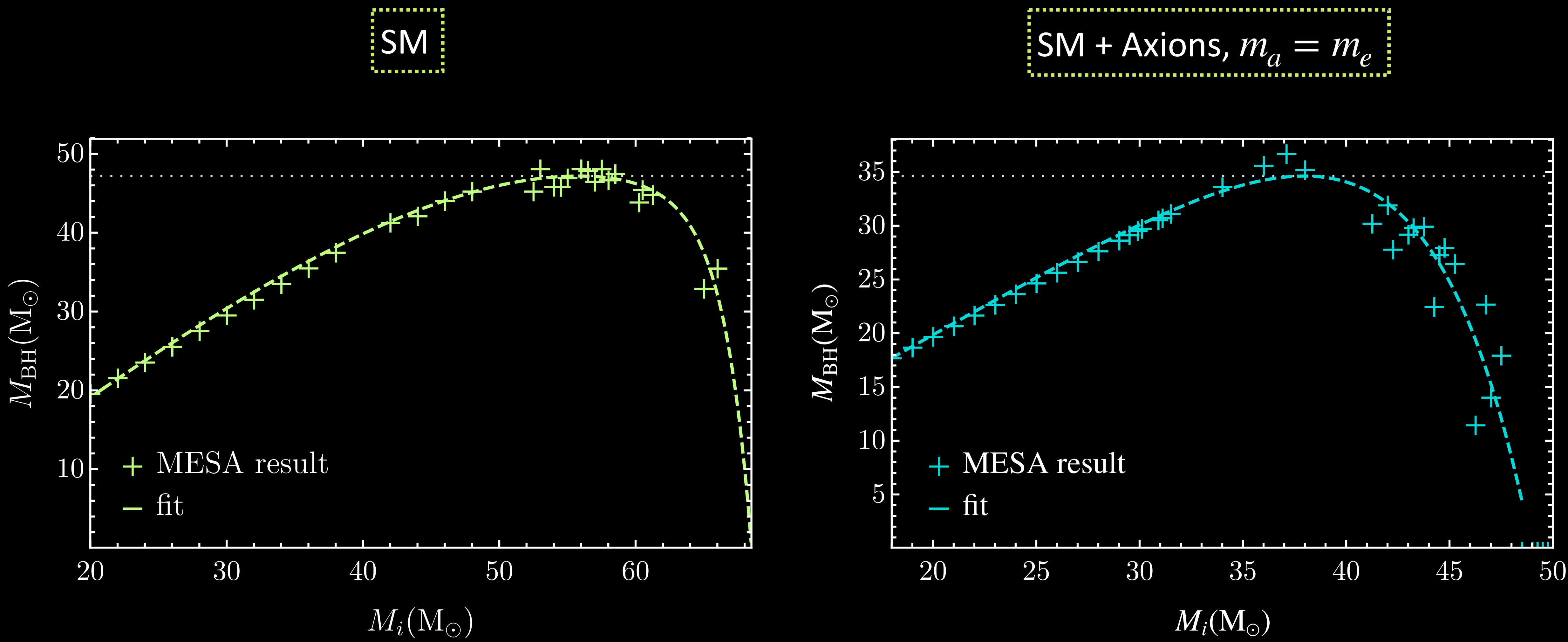
AISN: evolution





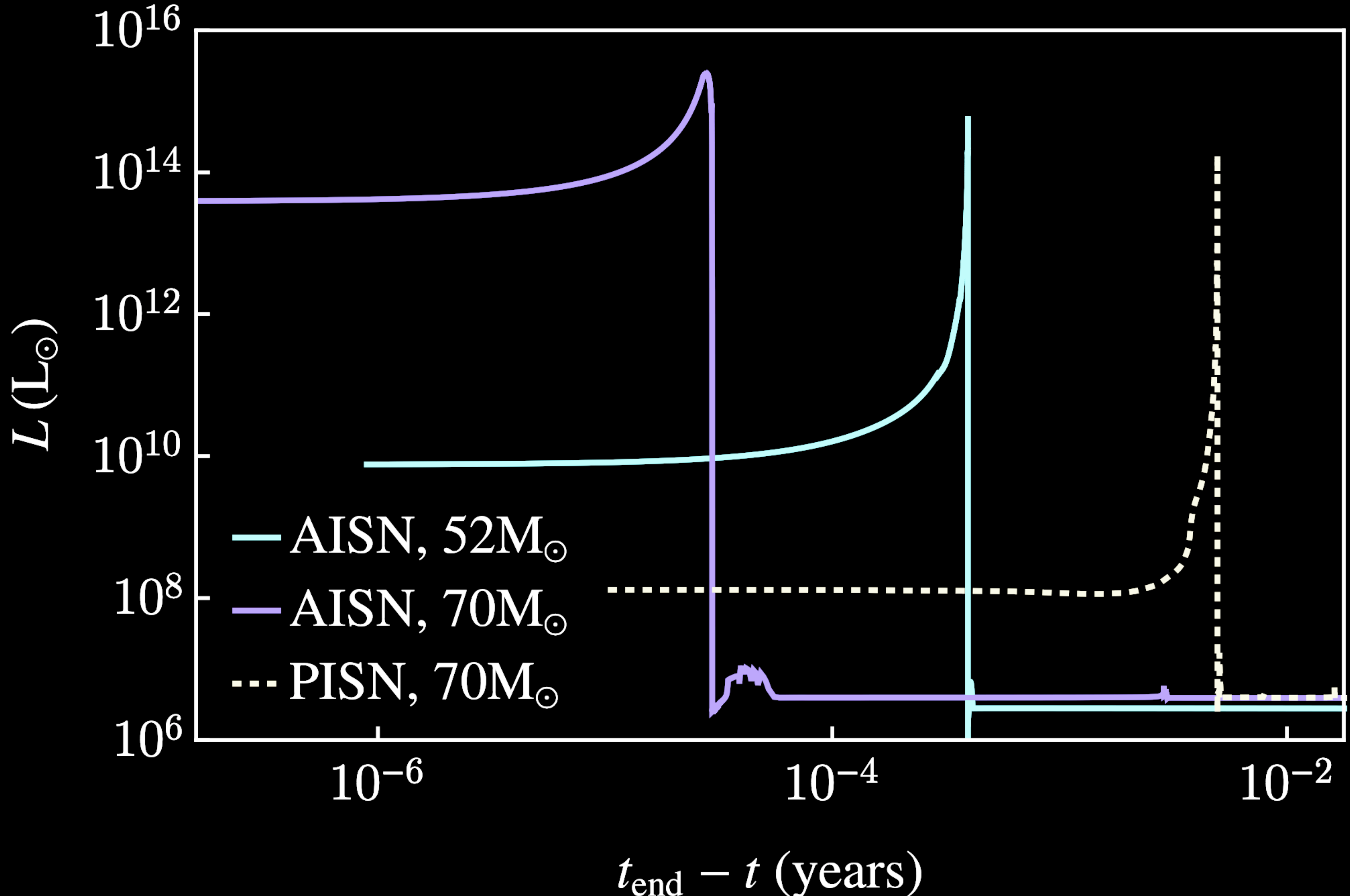
Sakstein, DC, McDermott, arXiv:2203.06160 [hep-ph]

AISN: resulting black holes



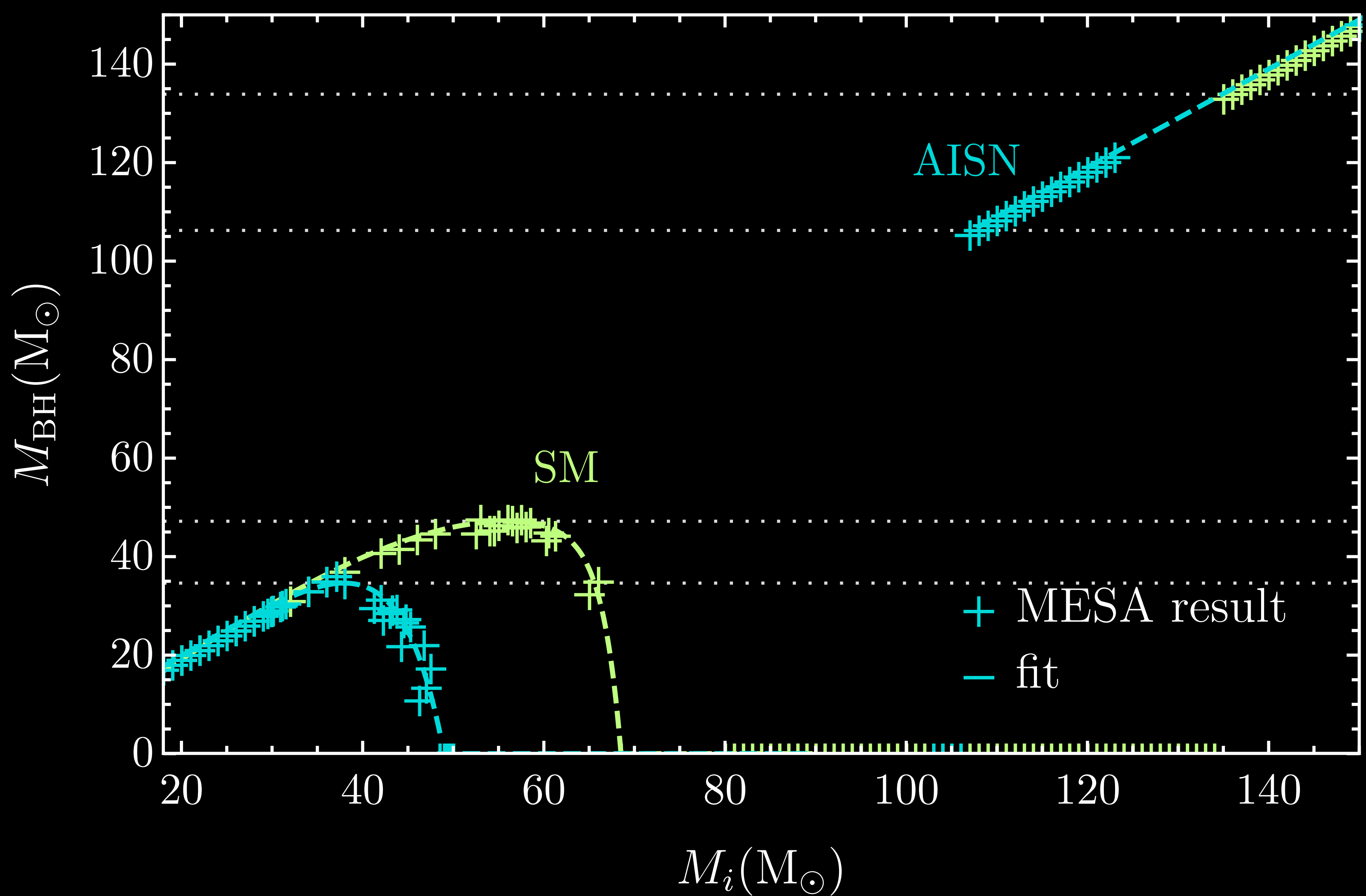
Sakstein, DC, McDermott, arXiv:2203.06160 [hep-ph]

AISN: luminosity



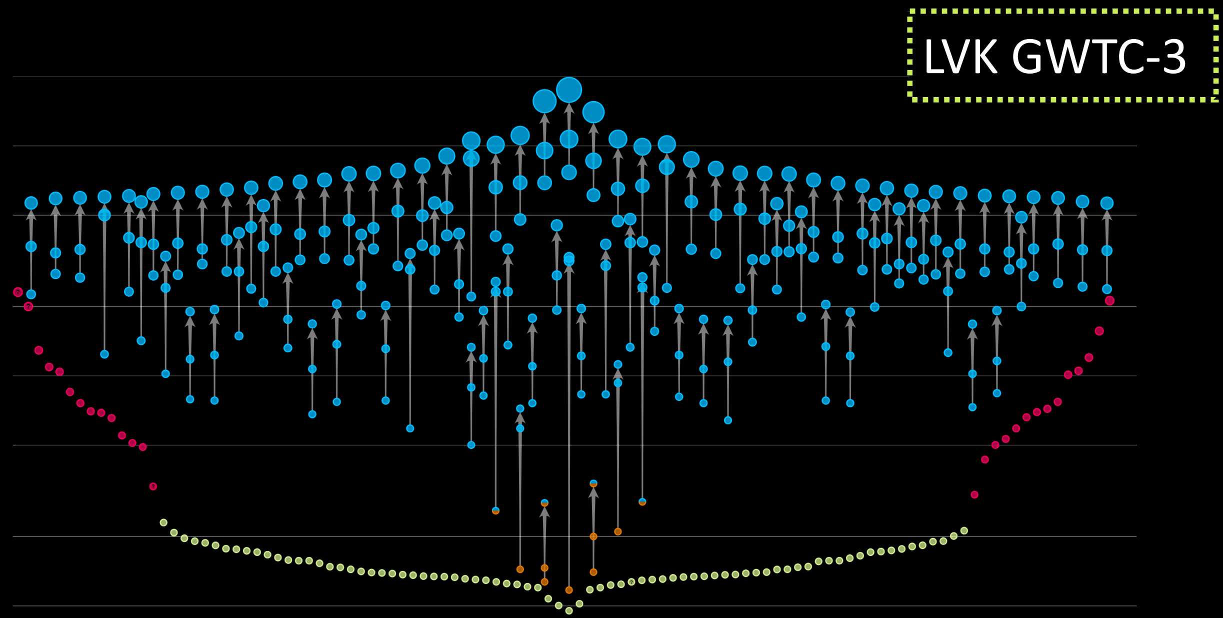
Sakstein, DC, McDermott, arXiv:2203.06160 [hep-ph]

Axions and photo disintegration instability



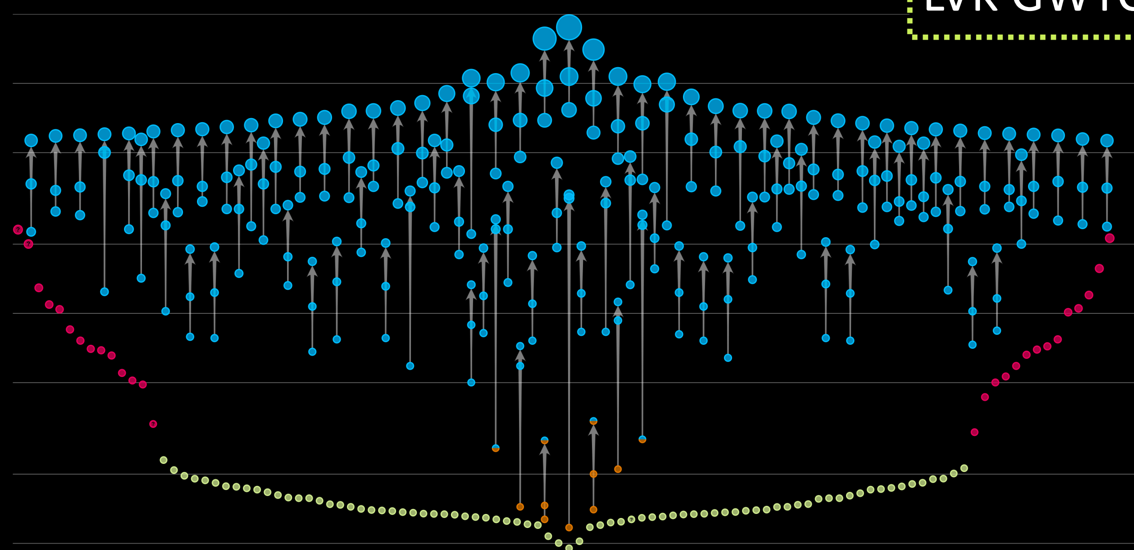
Sakstein, DC, McDermott, arXiv:2203.06160 [hep-ph]

Black hole archeology: what about the data?

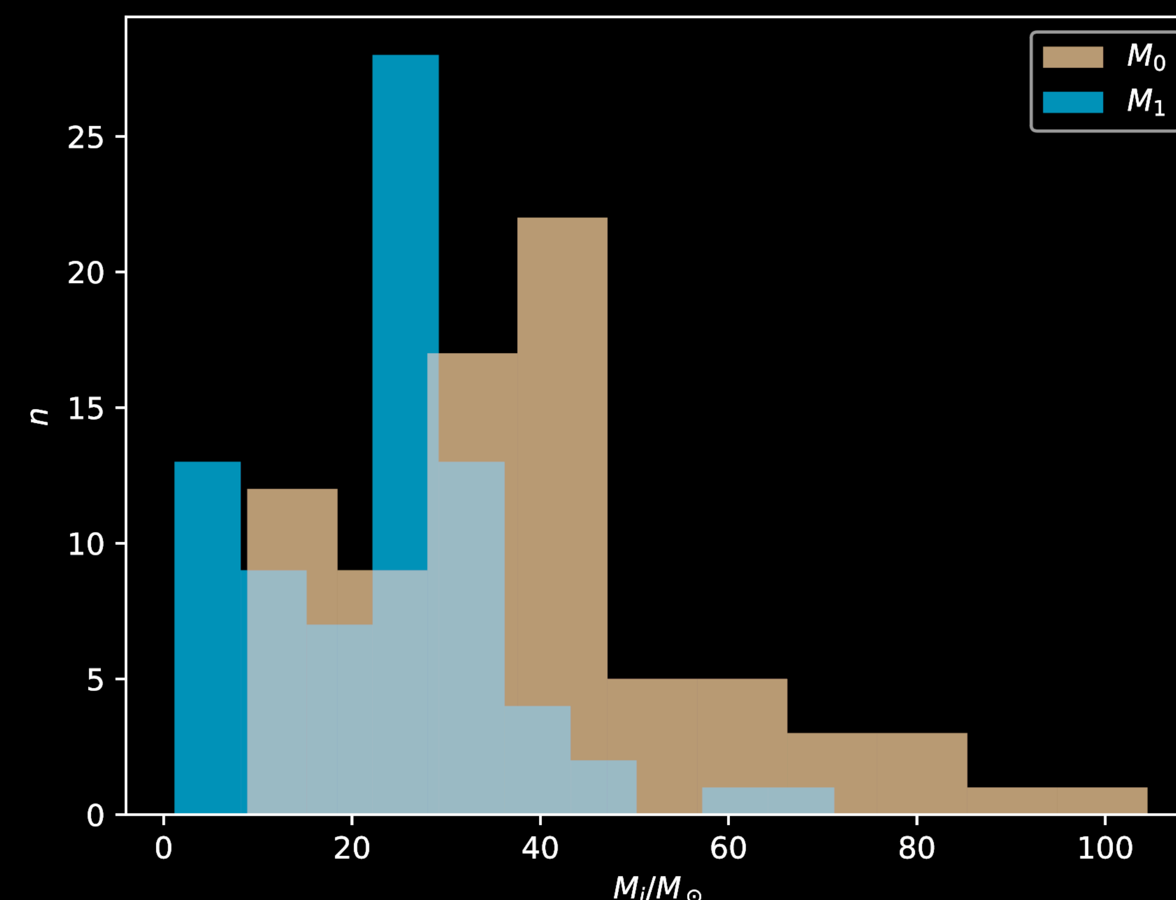


Black hole archeology: what about the data?

LVK GWTC-3

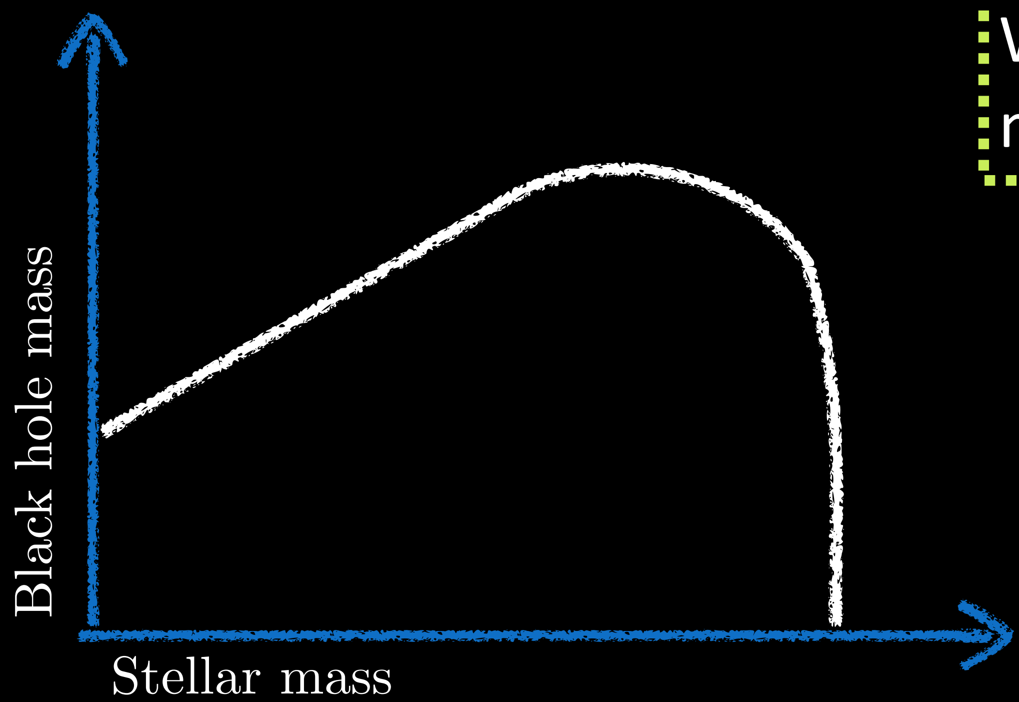


Mass distribution



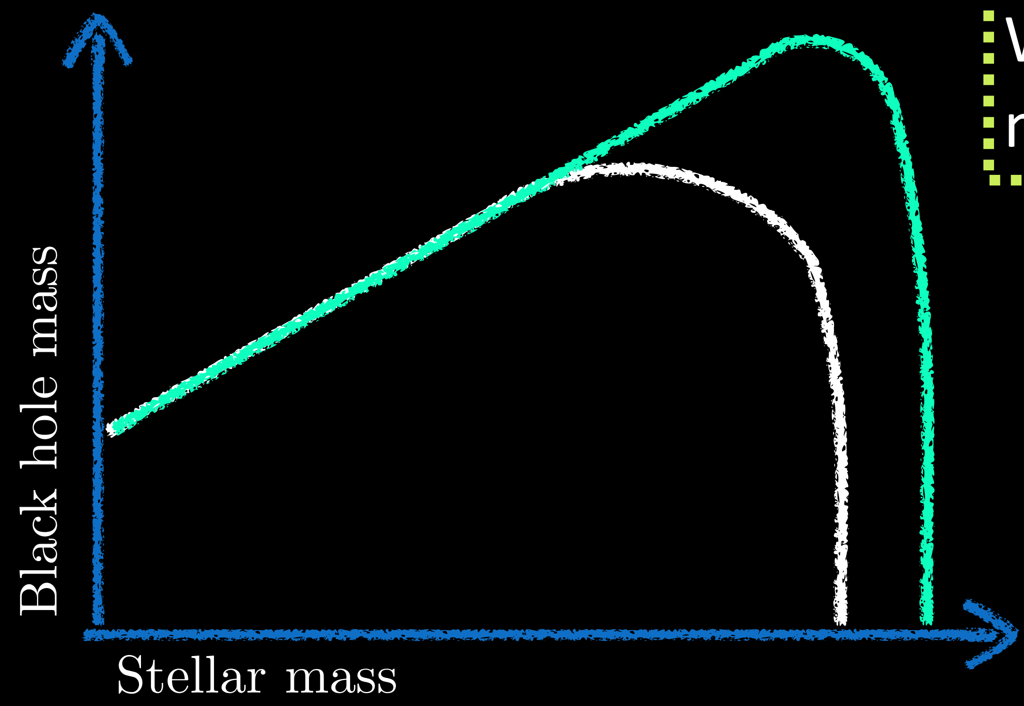
Other parameters, such as spin alignment, eccentricity, redshift, and mass ratio can serve as further evidence for the binary's environment/merger history

Pair-instability and black hole populations



We can predict black hole masses from stellar masses through stellar evolution simulations

Pair-instability and black hole populations



We can predict black hole masses from stellar masses through stellar evolution simulations

New particles or different nuclear physics may change this prediction

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

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

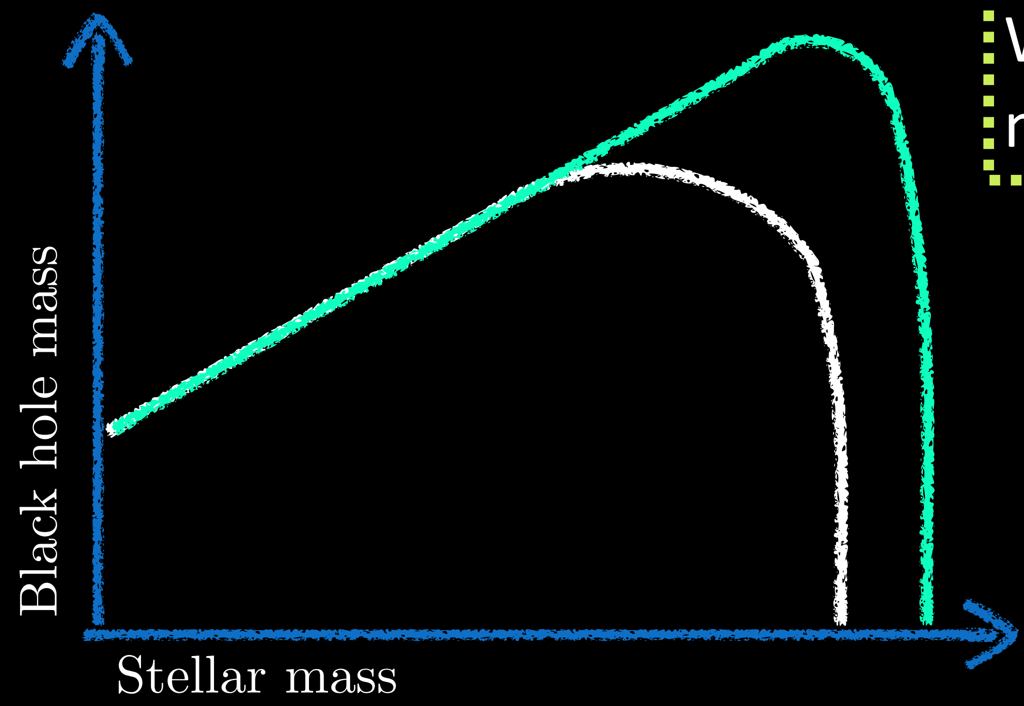
Straight, Sakstein, Baxter, PRD, arXiv:2009.10716 [gr-qc]

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

Ziegler, Freese arXiv:2010.00254 [astro-ph]

…More work in progress

Pair-instability and black hole populations



We can predict black hole masses from stellar masses through stellar evolution simulations

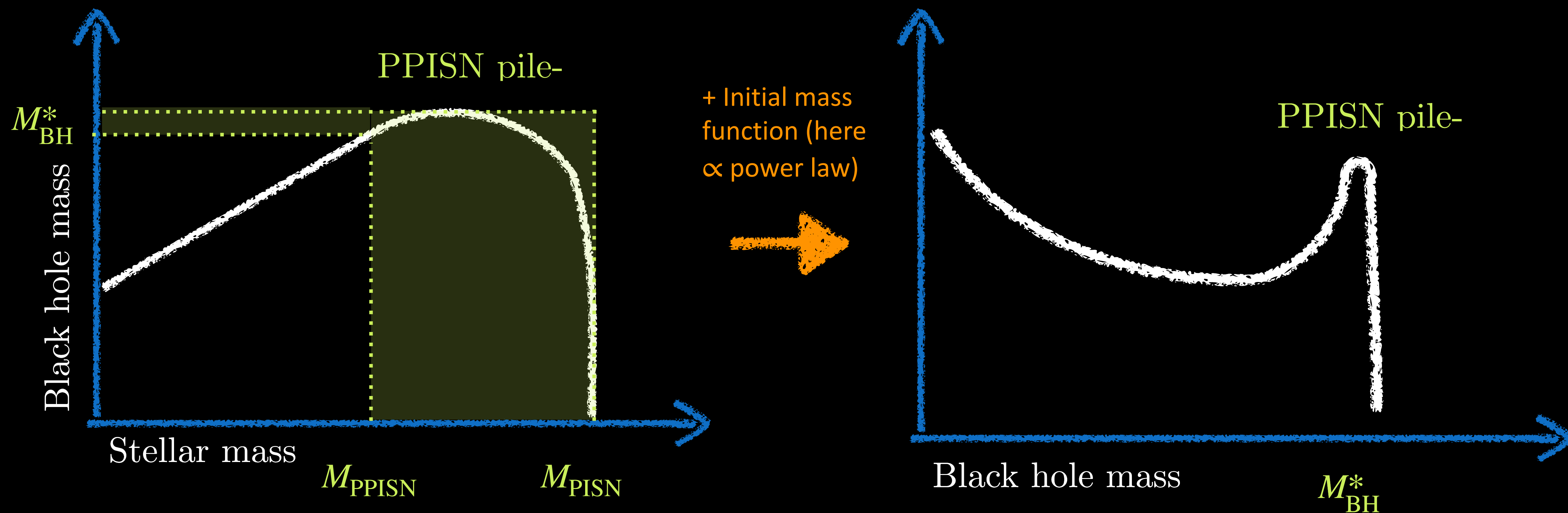
New particles or different nuclear physics may change this prediction

How can we use *data* to test that?

FIND THE GAP

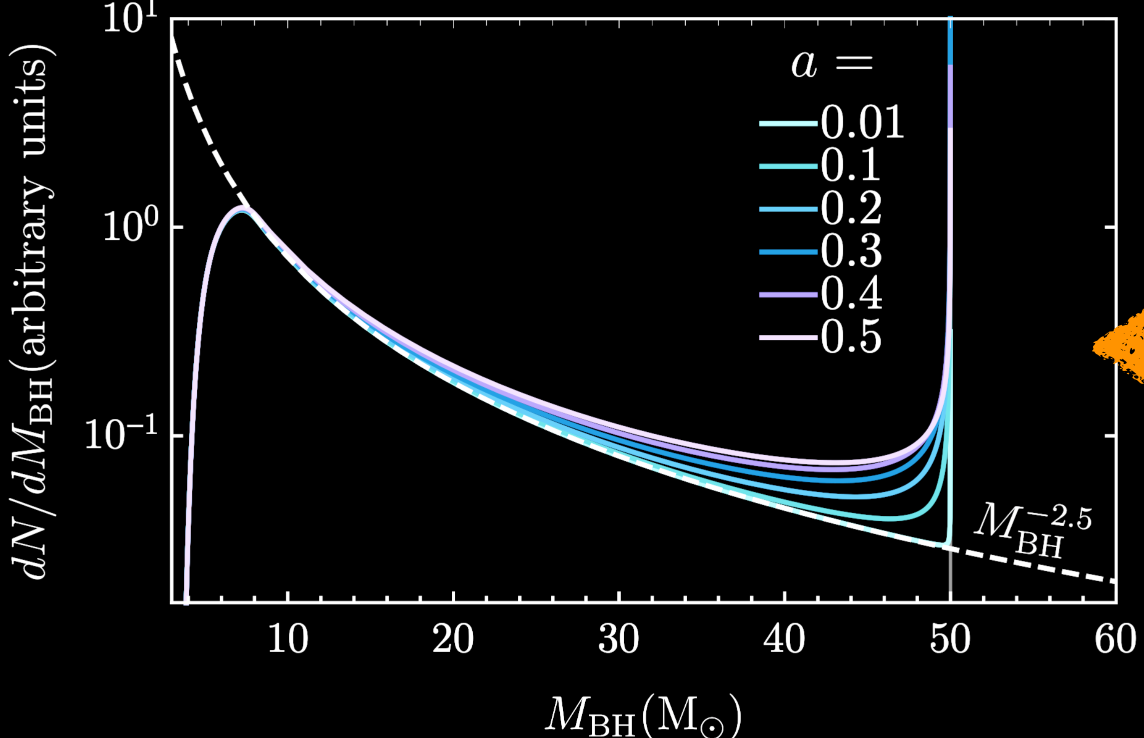
Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

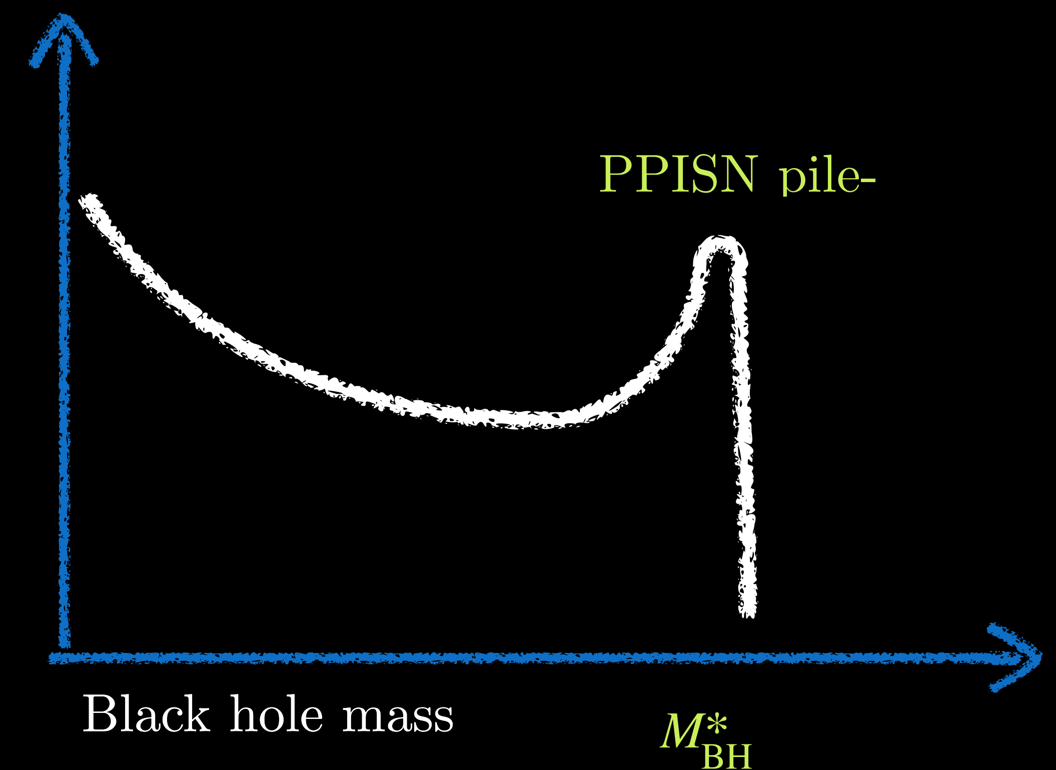
Pair-instability and black hole populations



See also Talbot & Trane, arXiv:1801.02699

Pair-instability and black hole populations





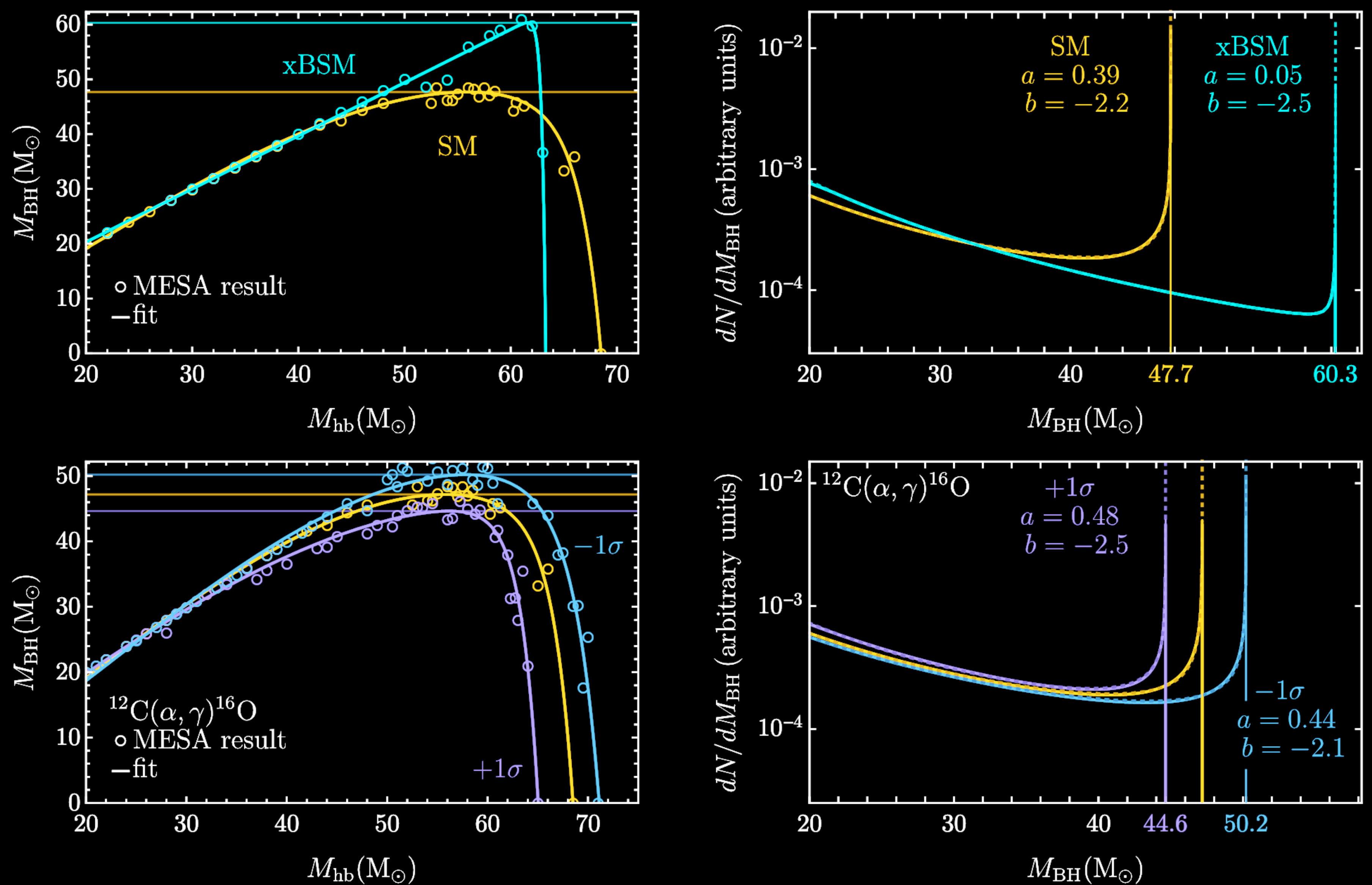
$$\frac{dN_{\rm BH}^{(1g)}}{dM_{\rm BH}} \propto M_{\rm BH}^b \left[1 + \frac{2a^2 M_{\rm BH}^{1/2}(M_{\rm BHMG} - M_{\rm BH})^{a-1}}{M_{\rm BHMG}^{a-1/2}}\right]$$

Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

Pair-instability and black hole populations

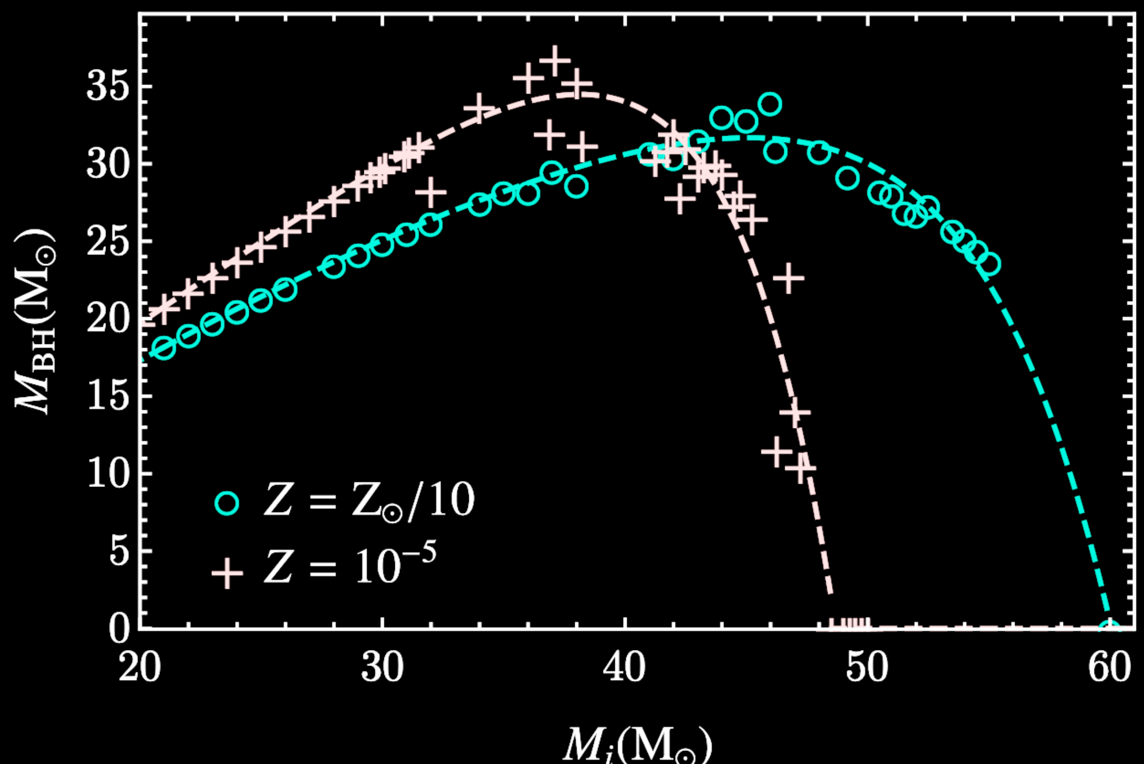
Testing BSM particle physics

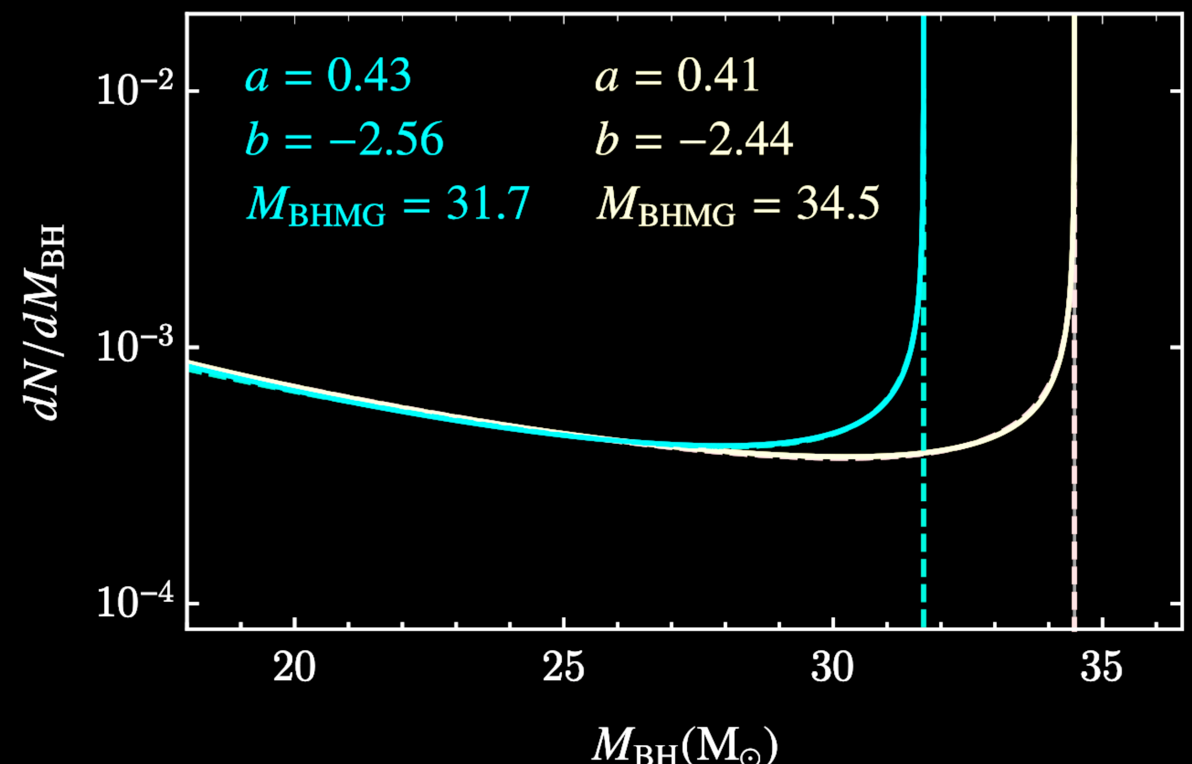
Testing nuclear (astro) physics



Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

AISN and black hole populations



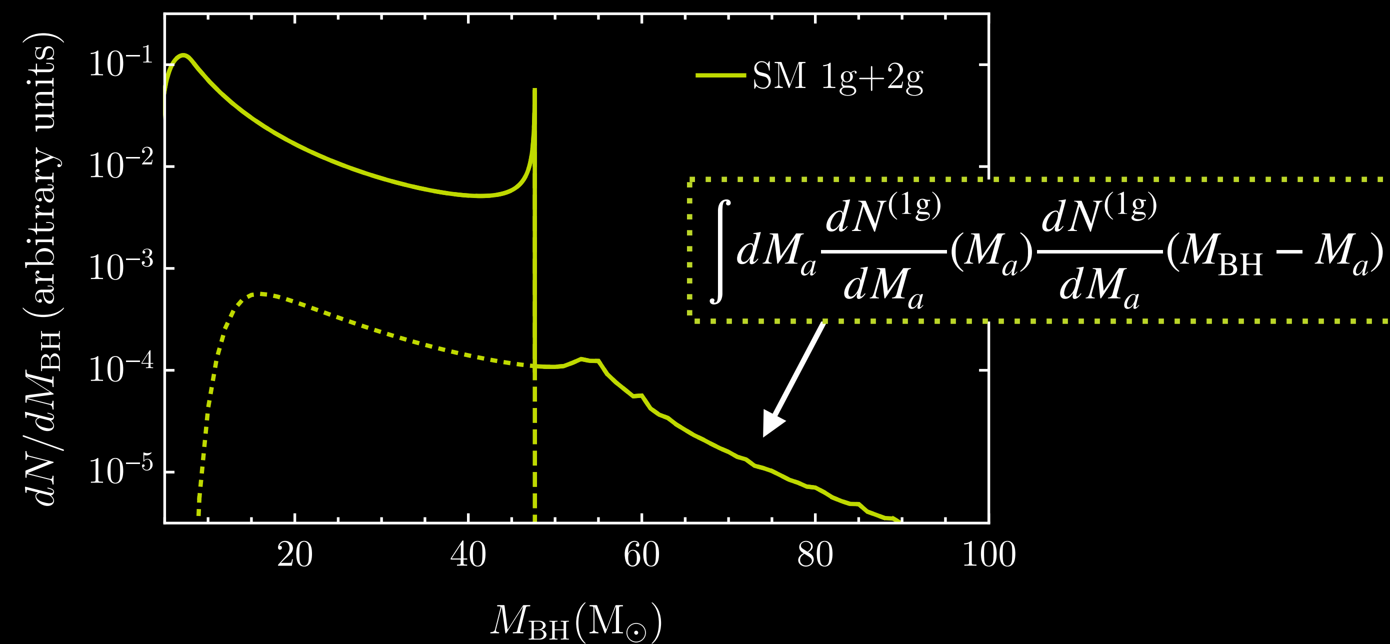


Sakstein, DC, McDermott, arXiv:2203.06160 [hep-ph]

Dynamical mergers and black hole genealogy

Black holes formed in prior mergers may in principle populate the mass gap.

Their mass distribution inherits from the $1g$ mass distribution.



Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

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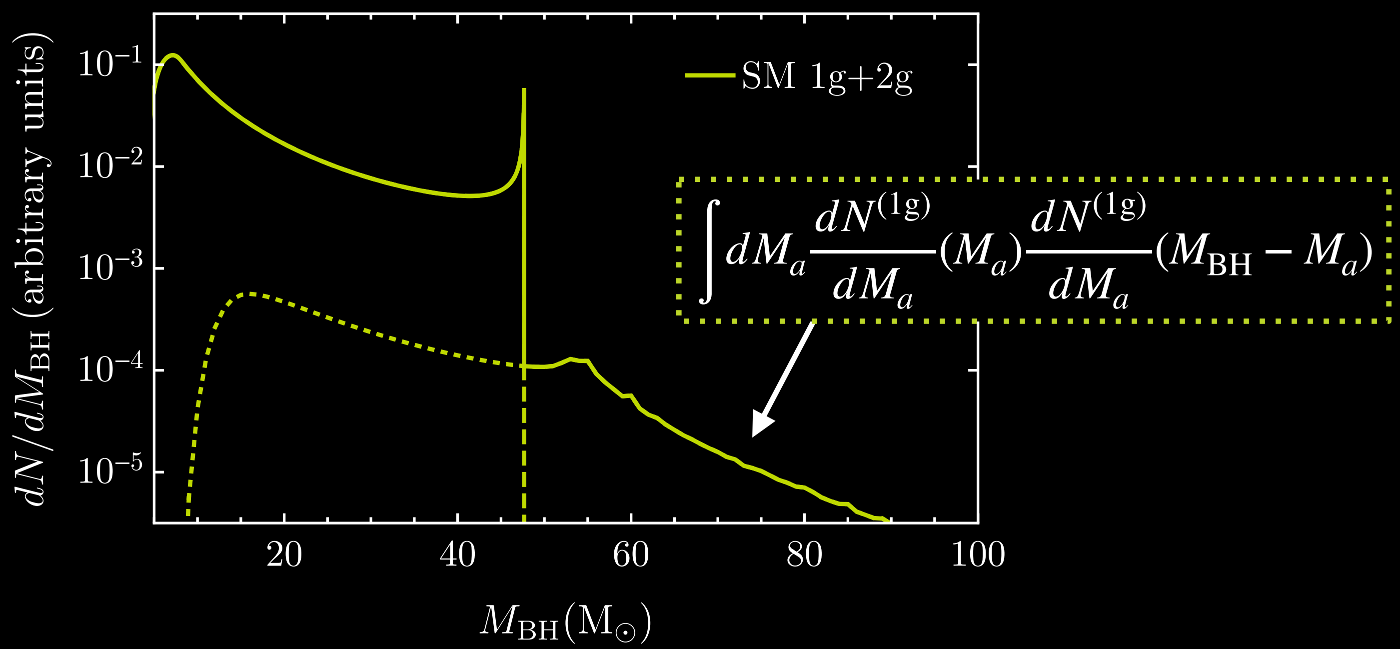
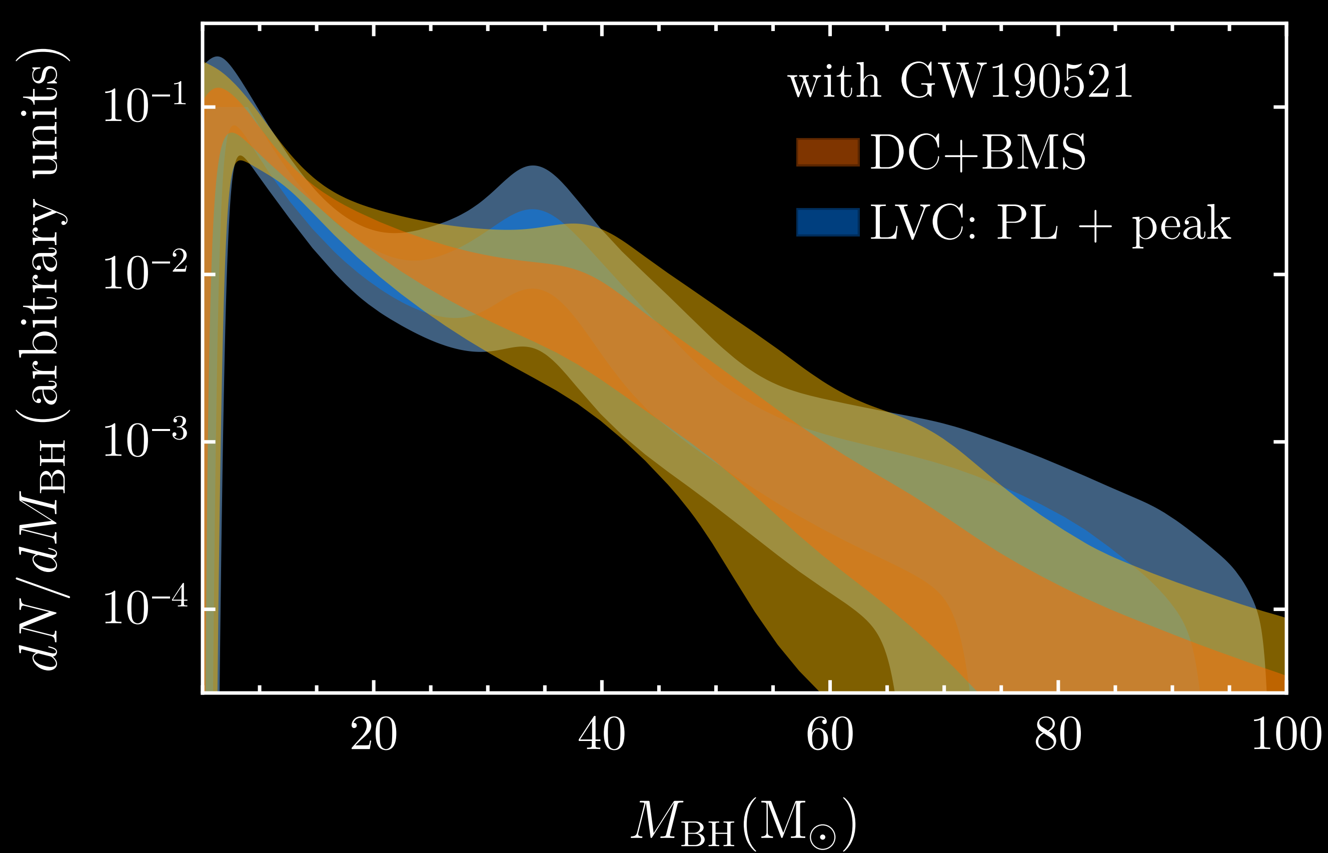


$$\frac{dN}{dM_{BH}} = \frac{dN_{BH}^{(1g)}}{dM_{BH}} + \frac{dN_{BH}^{(2+g)}}{dM_{BH}} \begin{cases} \frac{dN_{BH}^{(1g)}}{dM_{BH}} \propto M_{BH}^b \left[1+\frac{2a^2 M_{BH}^{1/2}(M_{BHMG}-M_{BH})^{a-1}}{M_{BHMG}^{a-1/2}}\right] & \text{: first generation black holes } (a, b, M_{BHMG}) \\ \frac{dN^{(2+g)}}{dM_{BH}} \propto \lambda \min\left[1, \left(\frac{M_{BH}}{M_{BHMG}+M_{min}+\delta_m/2}\right)^d\right] & \text{: “Pollutant” population (2g+) } (d, \lambda) \end{cases}$$

Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

Binary mergers in LIGO/Virgo O3a

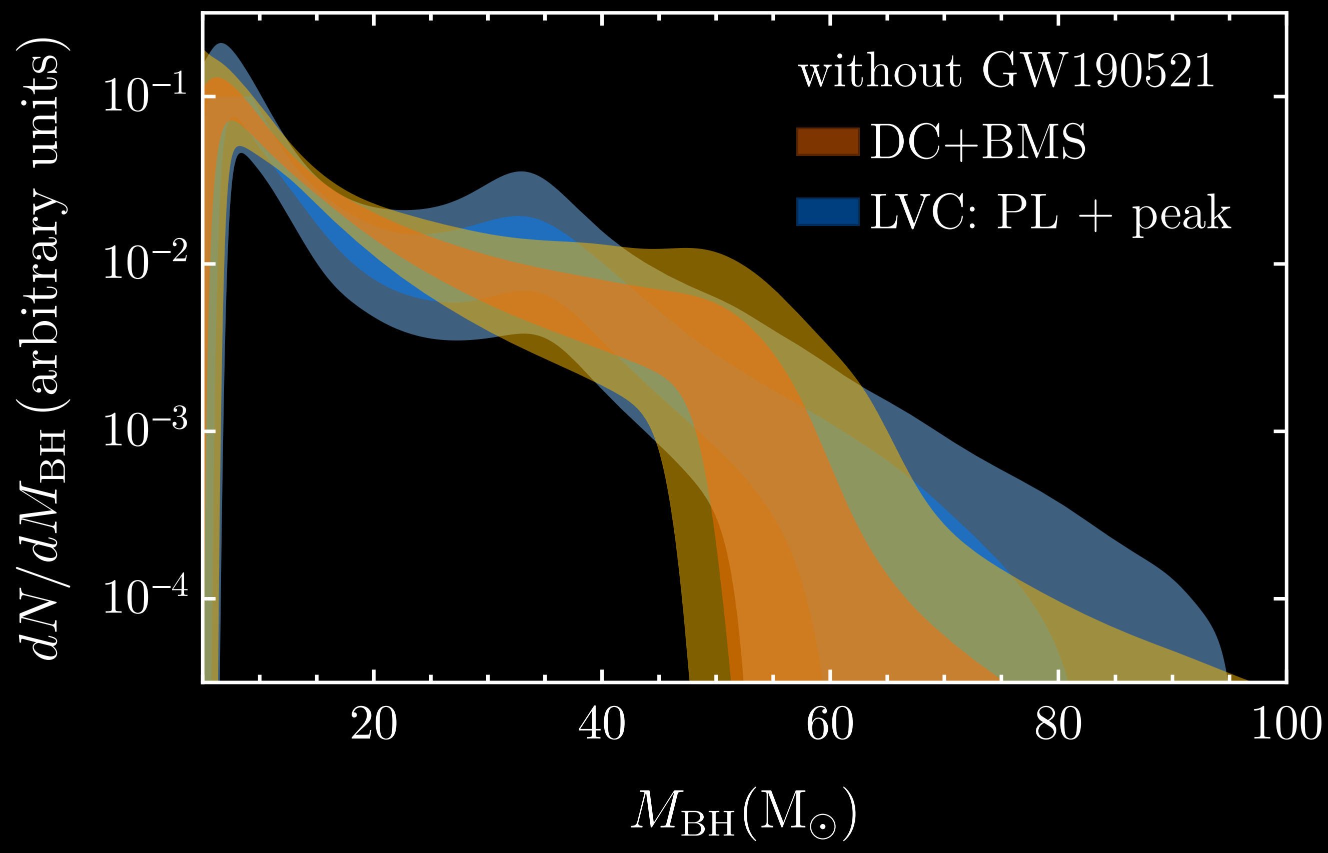


This work, Eq. (7)	with GW190521
$\log_{10}\lambda$	$-0.88^{+0.41}_{-1.46}$
$M_{\rm BHMG}$ [$\mathrm{M}_\odot$]	$46.23^{+16.83}_{-6.15}$
a	$0.23^{+0.17}_{-0.16}$
b	$-1.95^{+0.51}_{-0.54}$
d	$-5.95^{+1.75}_{-2.07}$
$M_{\rm min}$ [$\mathrm{M}_\odot$]	$3.38^{+1.50}_{-1.56}$
δ_m [$\mathrm{M}_\odot$]	$5.12^{+2.97}_{-3.19}$

LVC: PL+peak	with GW190521
α	$2.72^{+0.38}_{-0.48}$
$M_{\rm max}$ [$\mathrm{M}_\odot$]	85^{+10}_{-8}
$\lambda_{\rm peak}$	$0.113^{+0.032}_{-0.094}$
μ_m [$\mathrm{M}_\odot$]	$34.0^{+2.2}_{-1.7}$
σ_m [$\mathrm{M}_\odot$]	$4.7^{+1.8}_{-3.5}$
$M_{\rm min}$ [$\mathrm{M}_\odot$]	$4.40^{+1.3}_{-0.89}$
δ_m [$\mathrm{M}_\odot$]	< 4.75

Baxter, DC, McDermott, Sakstein, arXiv:2104.02685 — +O3b: work in progress with McDermott, Ulrich, Sakstein

Binary mergers in LIGO/Virgo O3a



This work, Eq. (7)	no GW190521
$\log_{10}\lambda$	$-3.92^{+2.40}_{-2.02}$
$M_{\rm BHMG}$ [$\rm M_\odot$]	$54.11^{+5.85}_{-4.96}$
a	$0.23^{+0.18}_{-0.16}$
b	$-1.98^{+0.45}_{-0.42}$
d	$-5.79^{+3.54}_{-2.81}$
$M_{\rm min}$ [$\rm M_\odot$]	$3.33^{+1.47}_{-1.66}$
δ_m [$\rm M_\odot$]	$5.15^{+2.97}_{-3.15}$

LVC: PL+peak	no GW190521
α	$3.08^{+0.51}_{-1.2}$
$M_{\rm max}$ [$\rm M_\odot$]	72^{+9}_{-10}
$\lambda_{\rm peak}$	$0.107^{+0.029}_{-0.092}$
μ_m [$\rm M_\odot$]	$33.4^{+2.5}_{-2.1}$
σ_m [$\rm M_\odot$]	> 4.49
$M_{\rm min}$ [$\rm M_\odot$]	$4.56^{+1.3}_{-0.77}$
δ_m [$\rm M_\odot$]	< 4.04

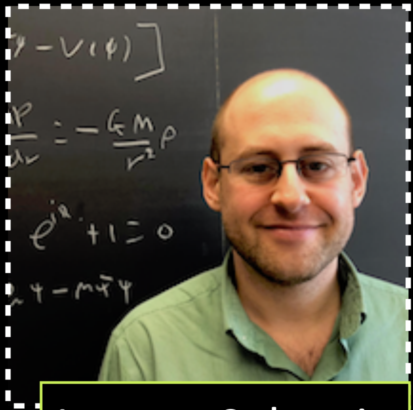
Baxter, DC, McDermott, Sakstein, arXiv:2104.02685 — +O3b: work in progress with McDermott, Ulrich, Sakstein

To conclude,

- Gravitational waves offer an exciting new opportunity to study open questions in stellar astrophysics and particle physics
- Pair-instability supernovae lead to unpopulated space in the stellar graveyard → the black hole mass gap is an entirely new probe of particle & nuclear physics
- Black hole population studies will allow us to study stellar evolution → black hole archeology

Thank you!

Sam McDermott



Jeremy Sakstein

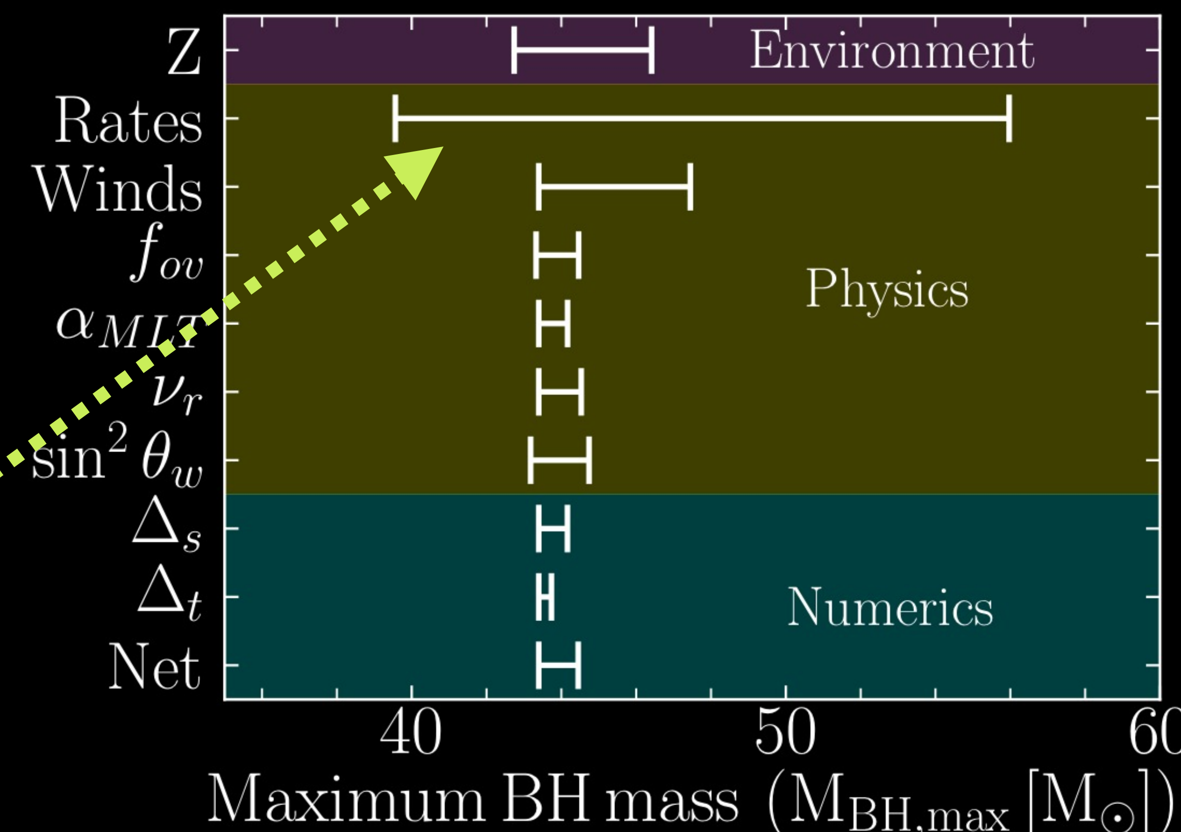
…ask me anything you like!

djuna.l.croon@durham.ac.uk | djunacroon.com

Physics dependence of the BHMG

- Astrophysical + nuclear + numerical dependence
- Most important dependence: $^{12}C(\alpha,\gamma)^{16}O$ rate
- Using updated deBoer et al rate, BHMG found at $48^{+2}_{-3}\,M_\odot$

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



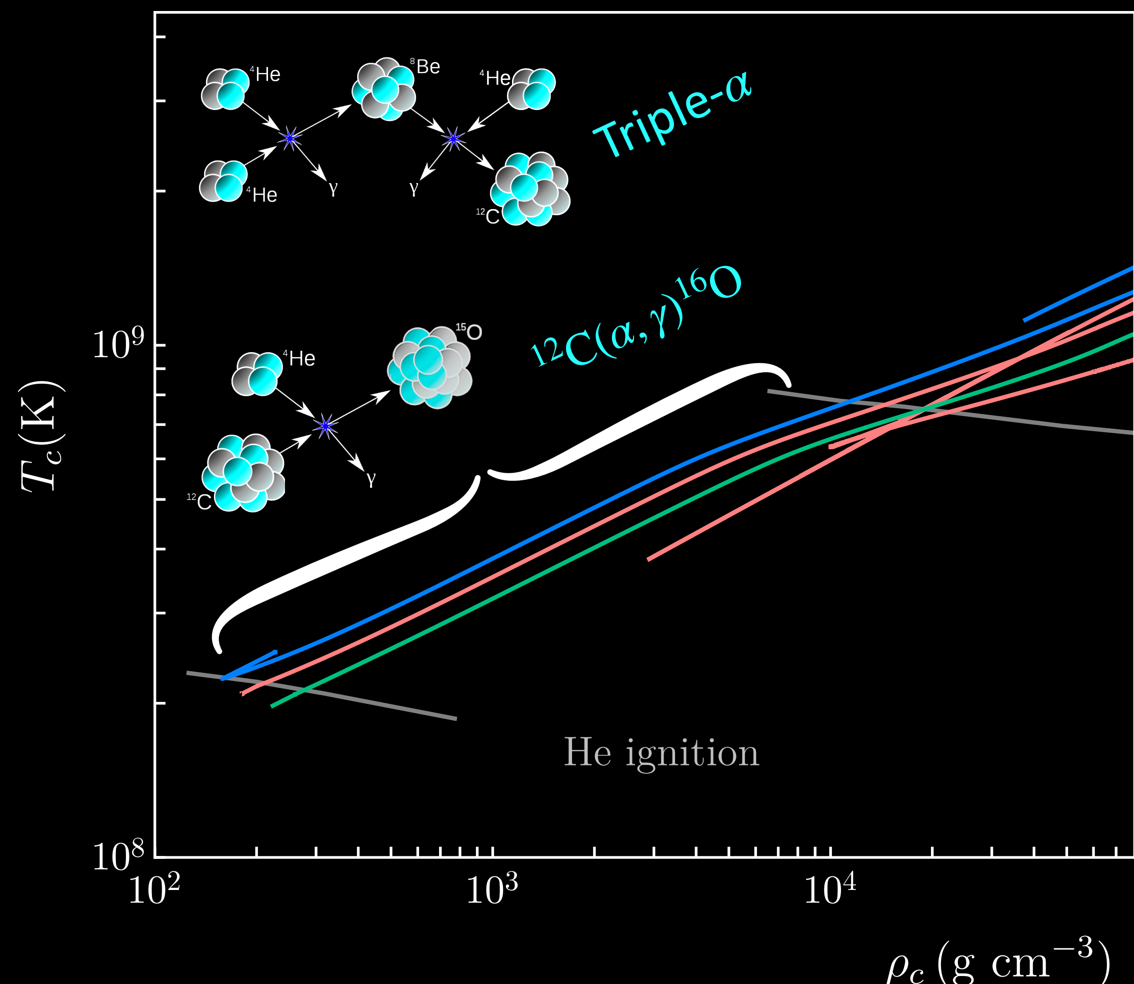
Farmer, Renzo, de Mink, Marchant, Justham arXiv:1910.12874 [astro-ph.SR]

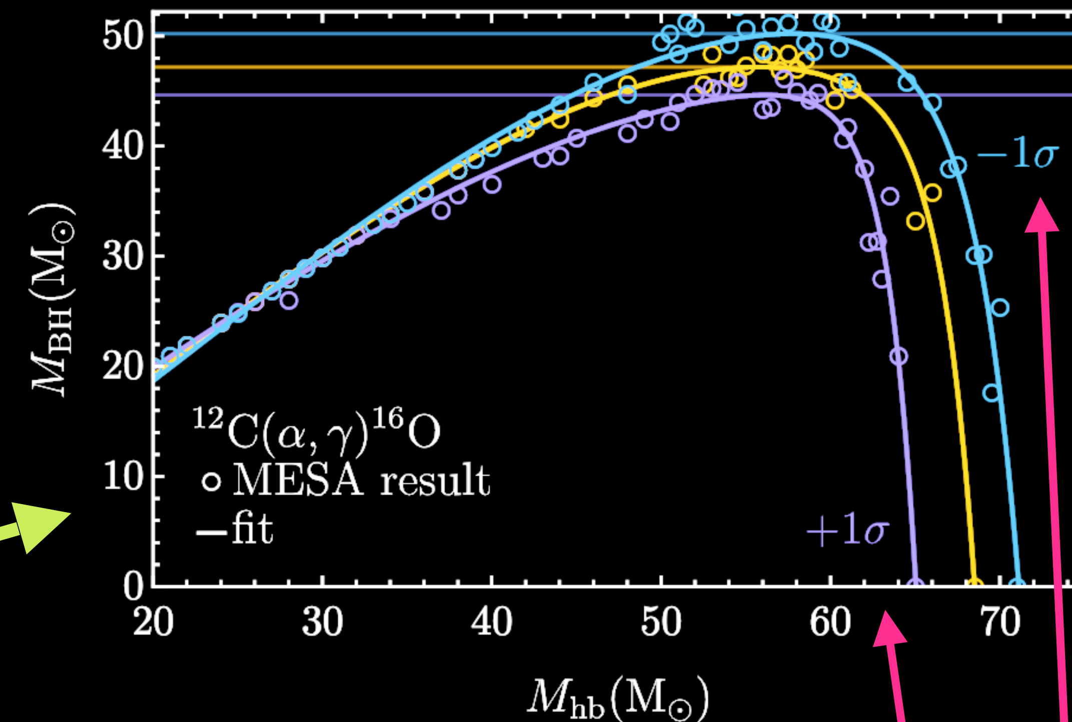
Nuclear physics

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

Baxter, DC, McDermott, Sakstein, arXiv:2104.02685 [astro-ph.CO]

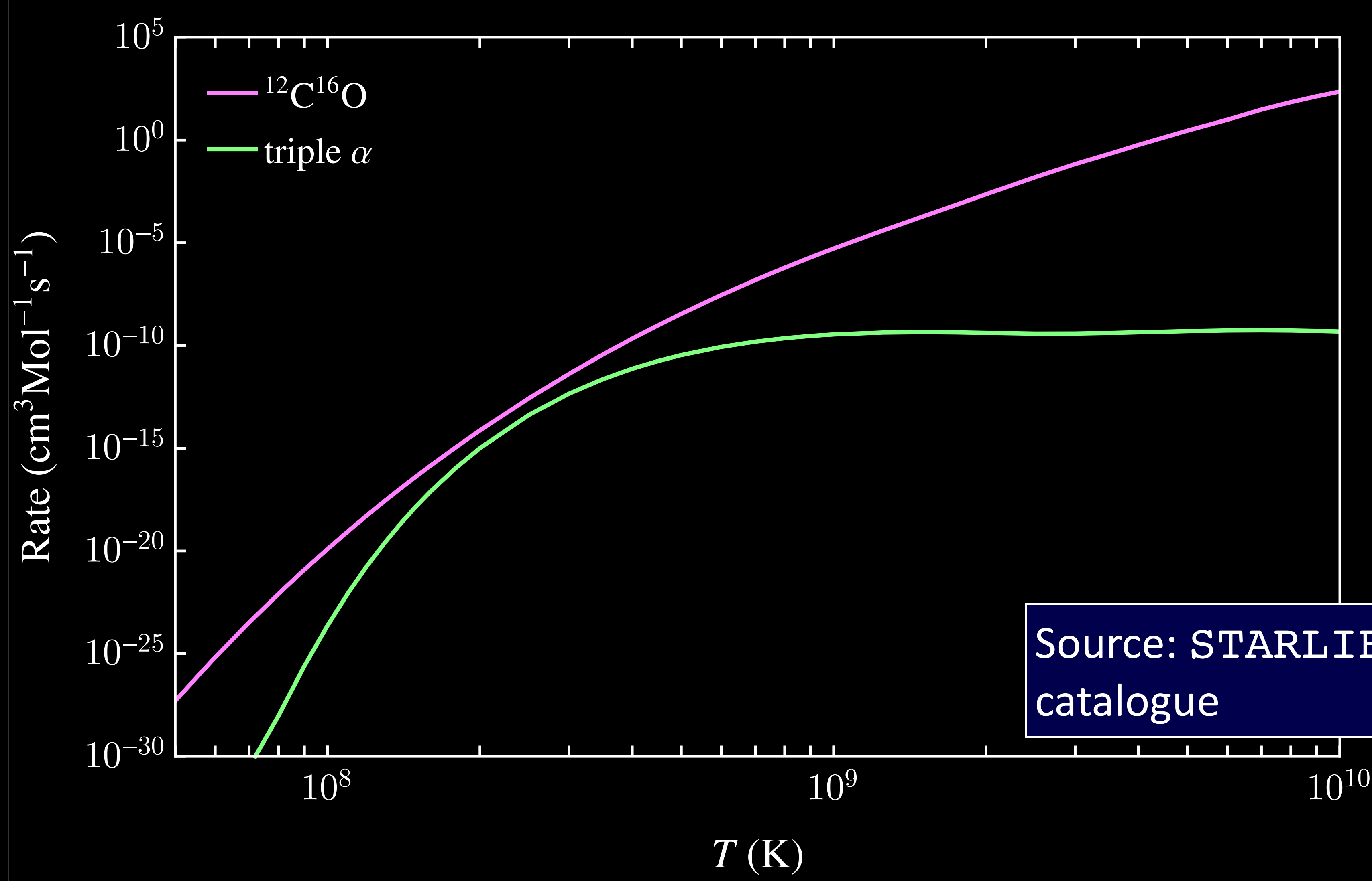
Particularly sensitive to $^{12}C(\alpha,\gamma)^{16}O$





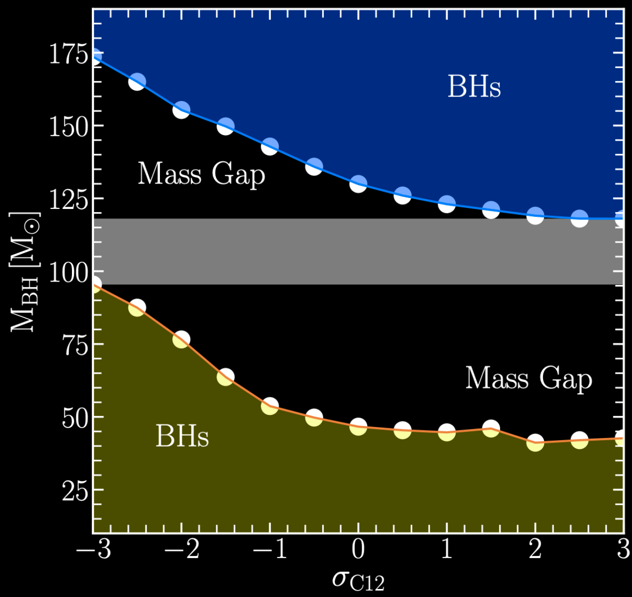
deBoer et al, RMP, arXiv:1709.03144 [hep-ex]

Helium burning rates as a function of T



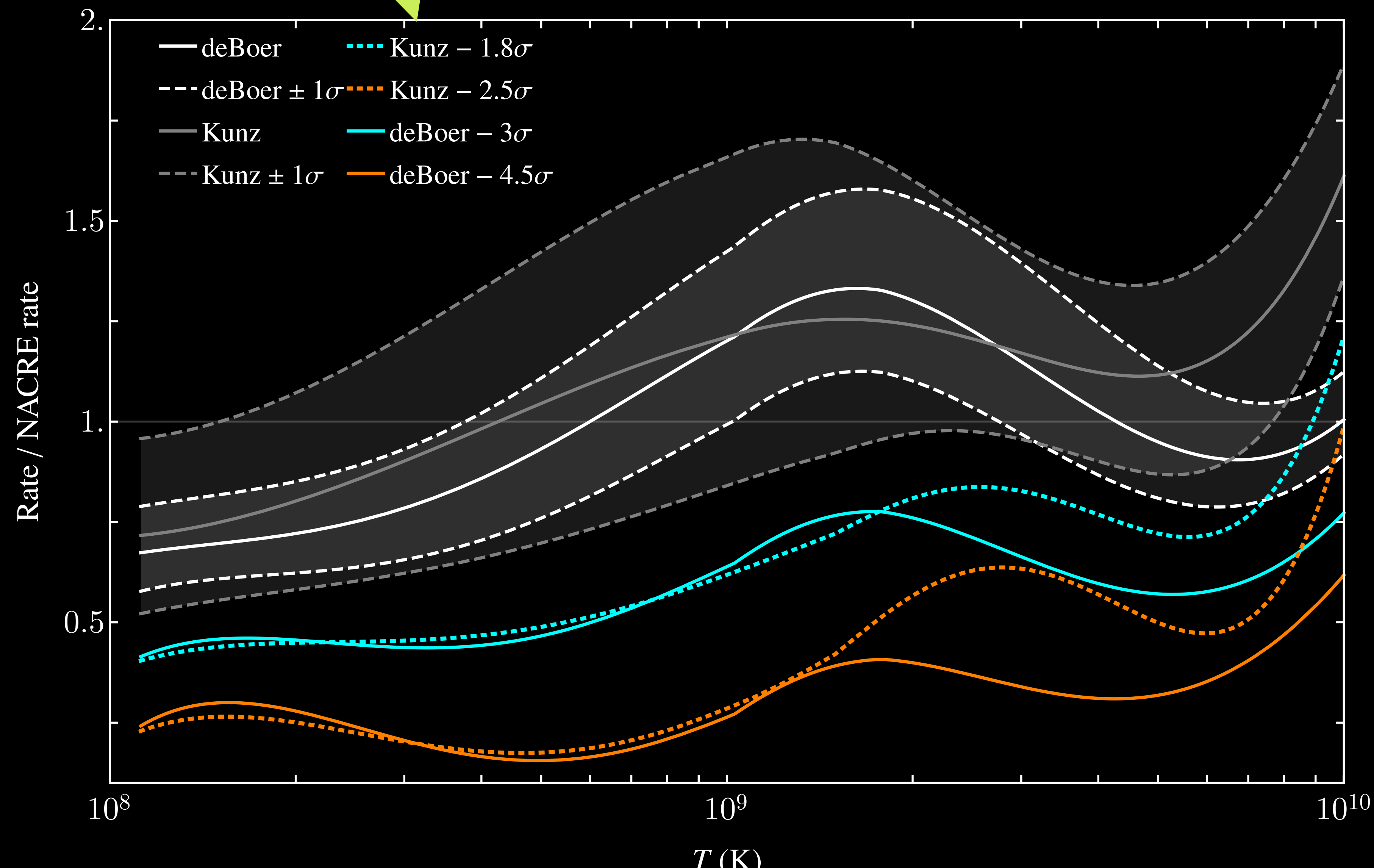
Source: STARLIB catalogue

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

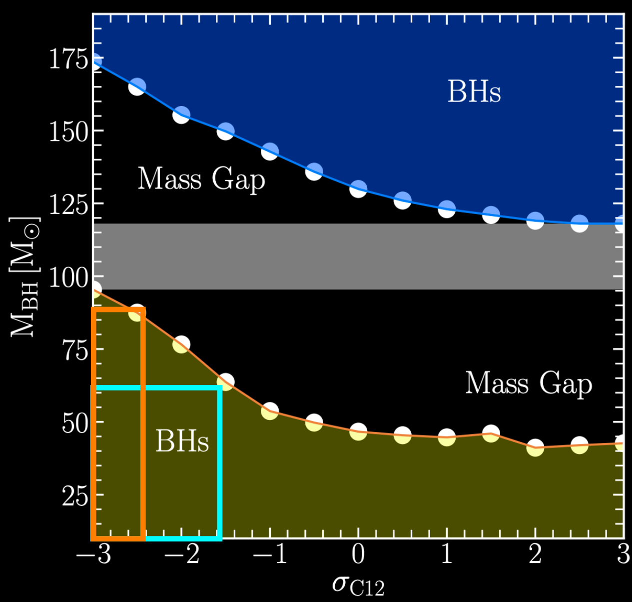


(Kunz is currently used in STARLIB)

Fitting GW190521 masses m_1 and m_2



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



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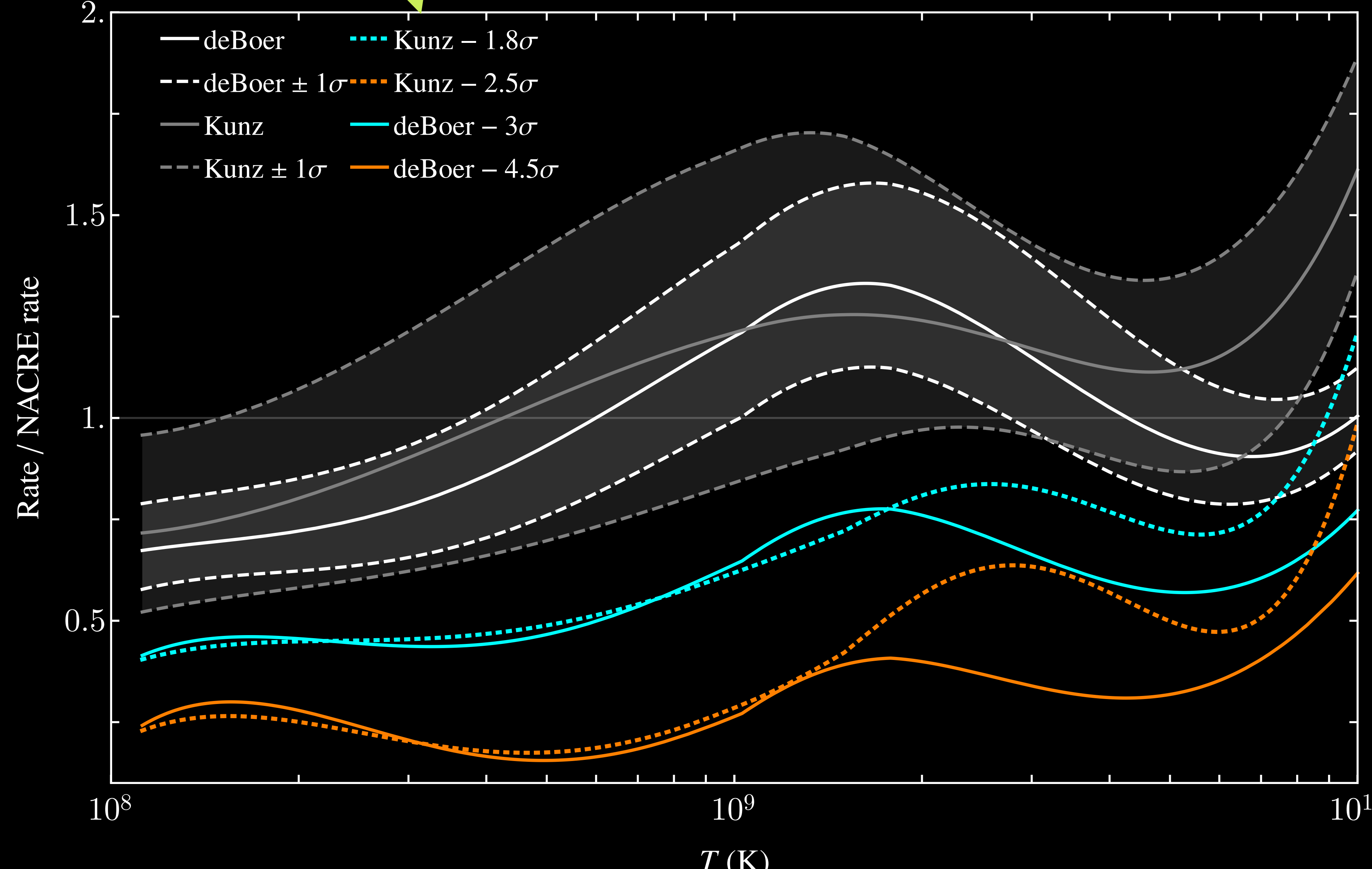
Fitting GW190521 masses m_1 and m_2



The BHMG and BSM cooling

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

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

- 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*

- Case studies: $\mathscr{L}_{\rm SM} + \ldots$
  - 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)

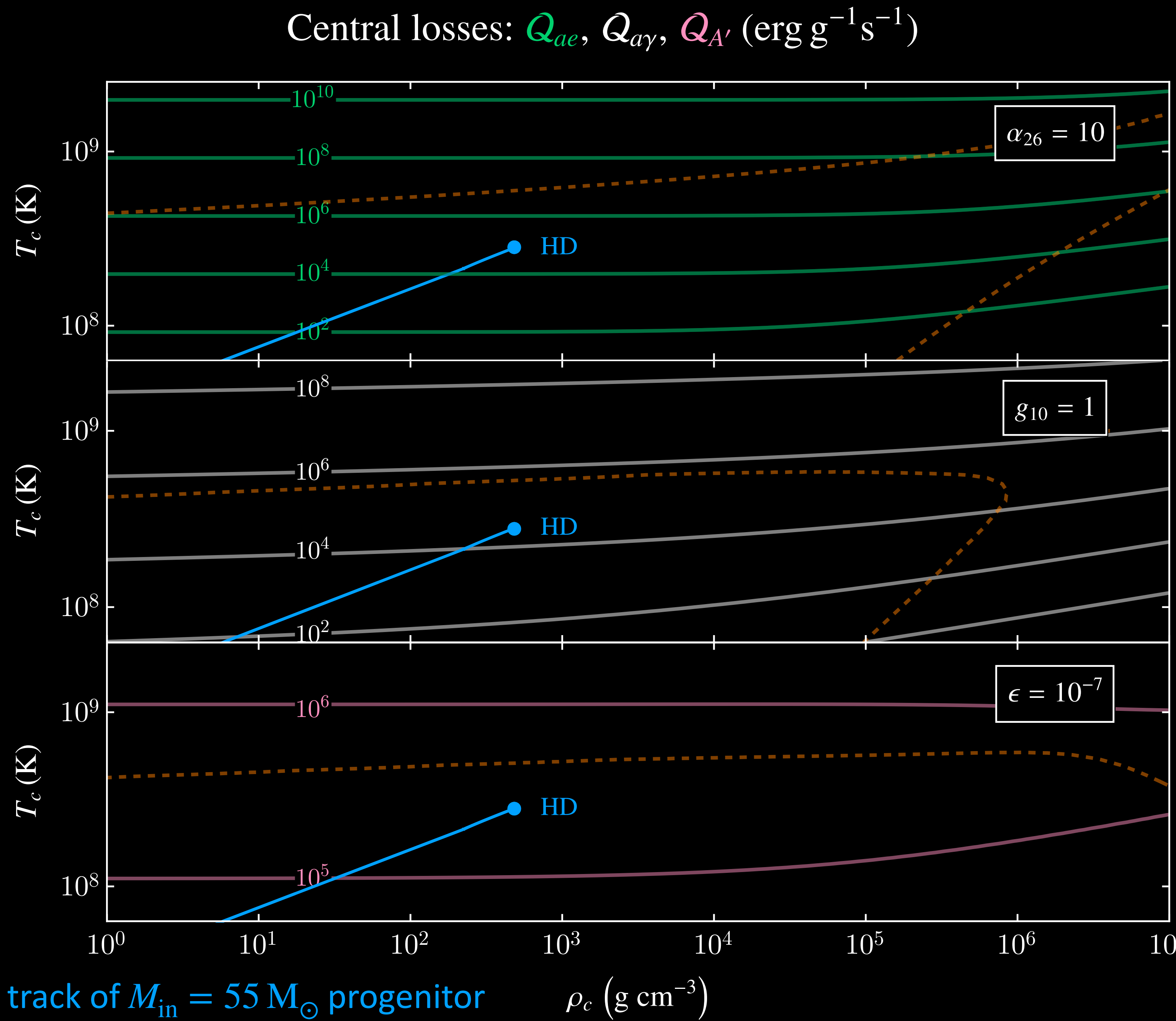
Interesting in light of the XENON1T excess, arXiv:2006.09721 [hep-ex]

Loss rates

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

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

Hidden photon: $\mathcal{Q}_{A'} \propto T$
(resonant emission)



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

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

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, $e + \gamma \rightarrow e + a$:

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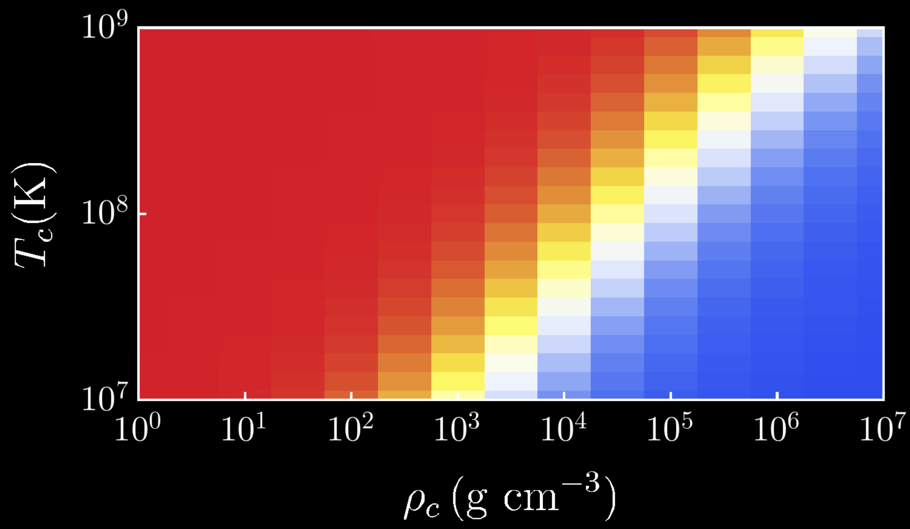
$$\left(T_8 \equiv \frac{T}{10^8 {\rm K}}\right)$$

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

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

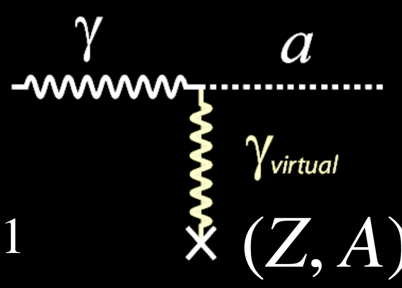


Semi-Compton emission dominates throughout the Helium burning phase

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

Energy loss due to photophilic axions

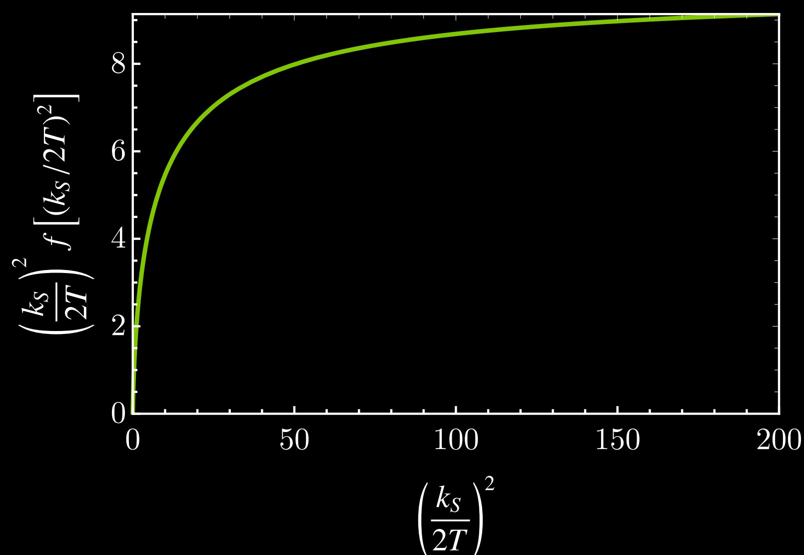
- Primakov effect $(Z,A)+\gamma \rightarrow (Z,A)+a$



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

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

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)

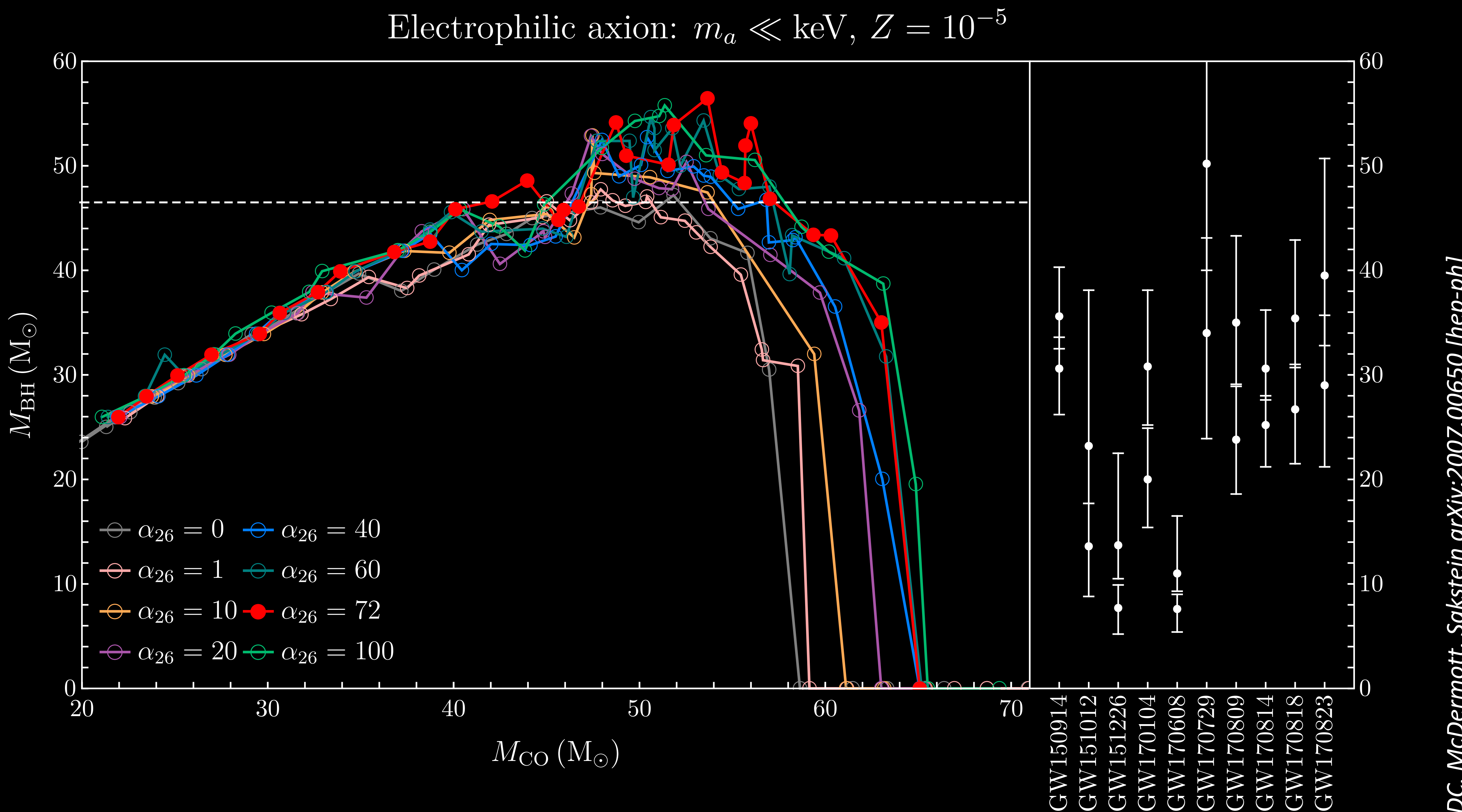
$$\mathcal{Q}_{A'} = \frac{\epsilon^2 m_{A'}^2}{4\pi\rho}\frac{\omega_p^3}{e^{\omega_p/T}-1} \simeq \frac{\epsilon^2 m_{A'}^2}{4\pi}\frac{\omega_p^2 T}{\rho} \simeq 1.8\times 10^3 \frac{\mathrm{erg}}{\mathrm{g\cdot s}}\frac{Z}{A}T_8\left(\frac{\epsilon}{10^{-7}}\frac{m_{A'}}{\mathrm{meV}}\right)^2$$

In the limit $\omega_p \ll T$

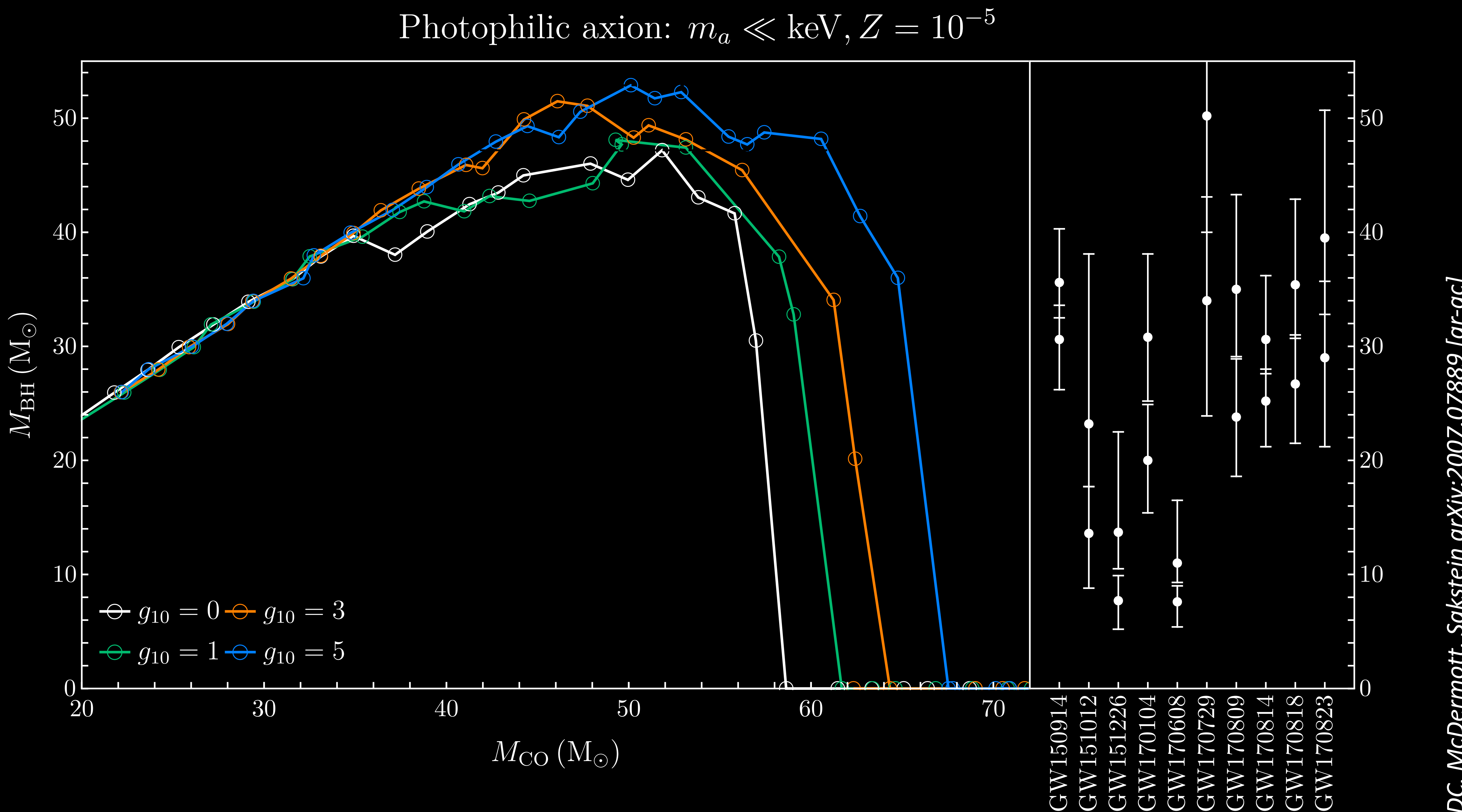
- Where photons have plasma mass

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

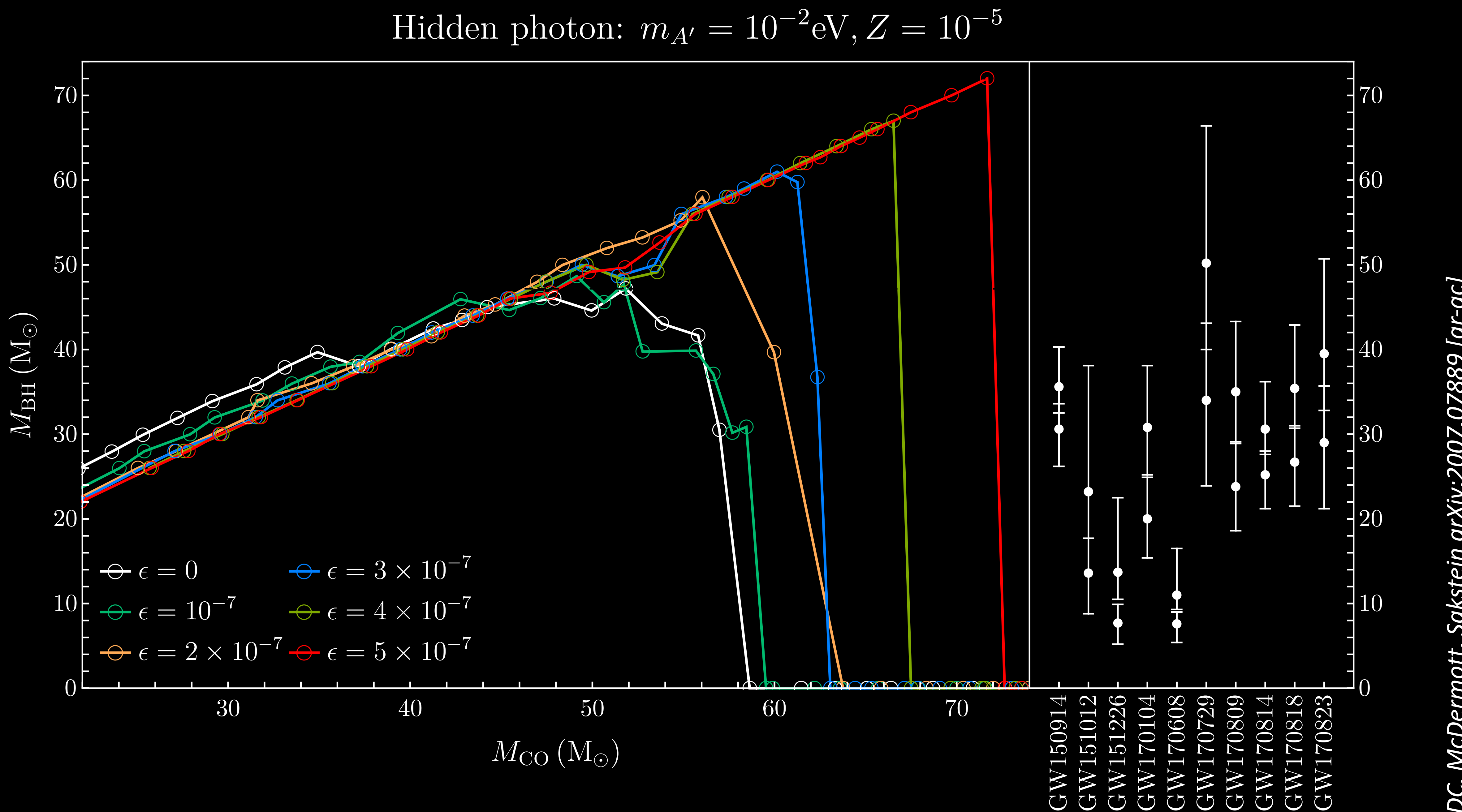
DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]



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



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


Hidden photon: $m_{A'} = 10^{-2}$eV, $Z = 10^{-5}$
$M_{\rm BH}$ ($M_\odot$)
$M_{\rm CO}$ ($M_\odot$)
$\epsilon = 0$
$\epsilon = 10^{-7}$
$\epsilon = 2 \times 10^{-7}$
$\epsilon = 3 \times 10^{-7}$
$\epsilon = 4 \times 10^{-7}$
$\epsilon = 5 \times 10^{-7}$
GW150914
GW151012
GW151226
GW170104
GW170608
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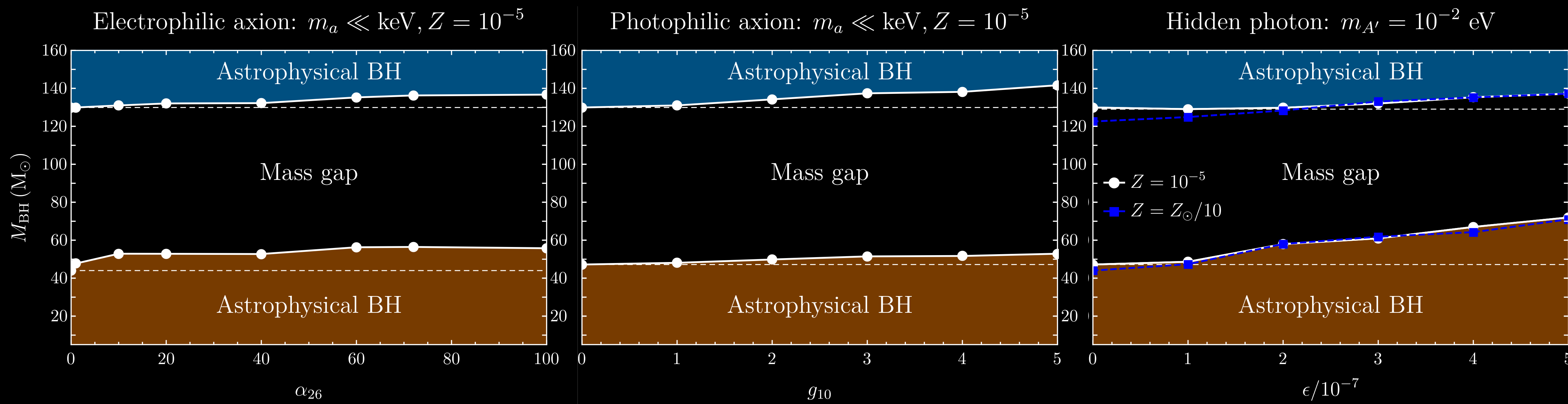
GW170814
GW170818
GW170823
DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

BSM cooling and the black hole mass gap



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

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

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

Important extra cooling = large shifts of the mass gap!

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