On pair-instability supernovae and dark matter

Djuna Lize Croon (IPPP Durham)

PLANCK, May 2023

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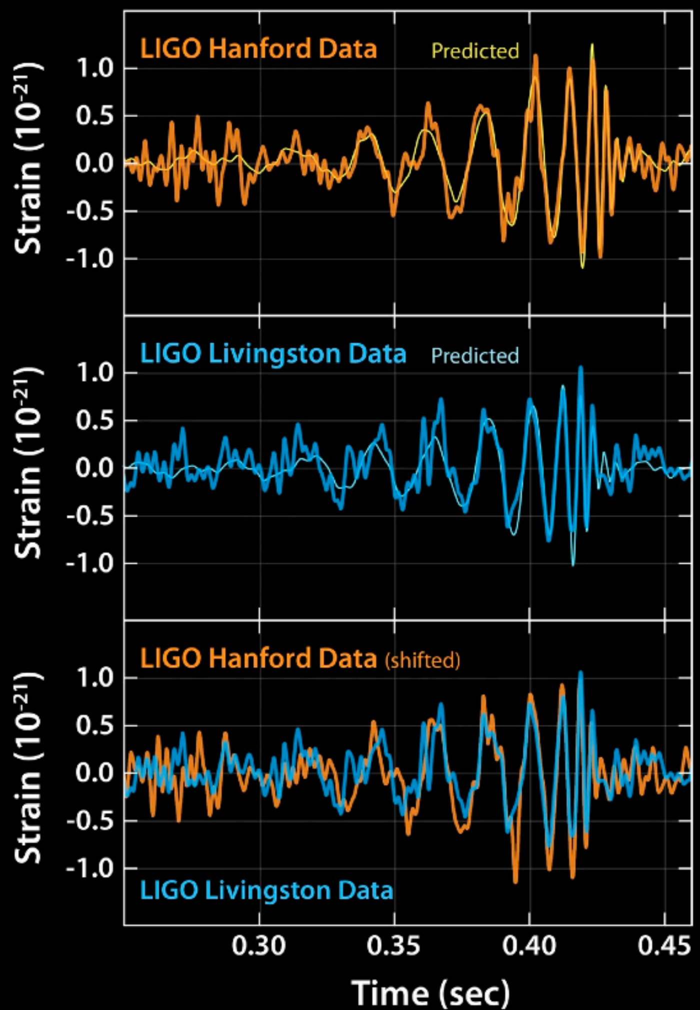
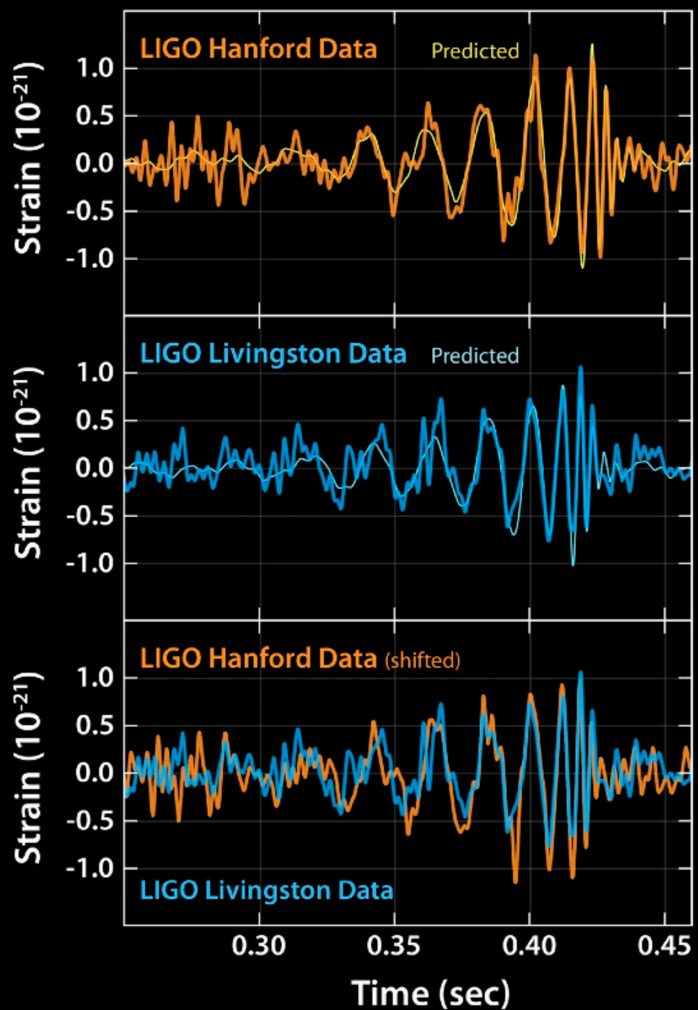
Gravitational wave science



The first event: GW150914

Images: LIGO/Ben Farr/Aaron Geller

Gravitational wave science



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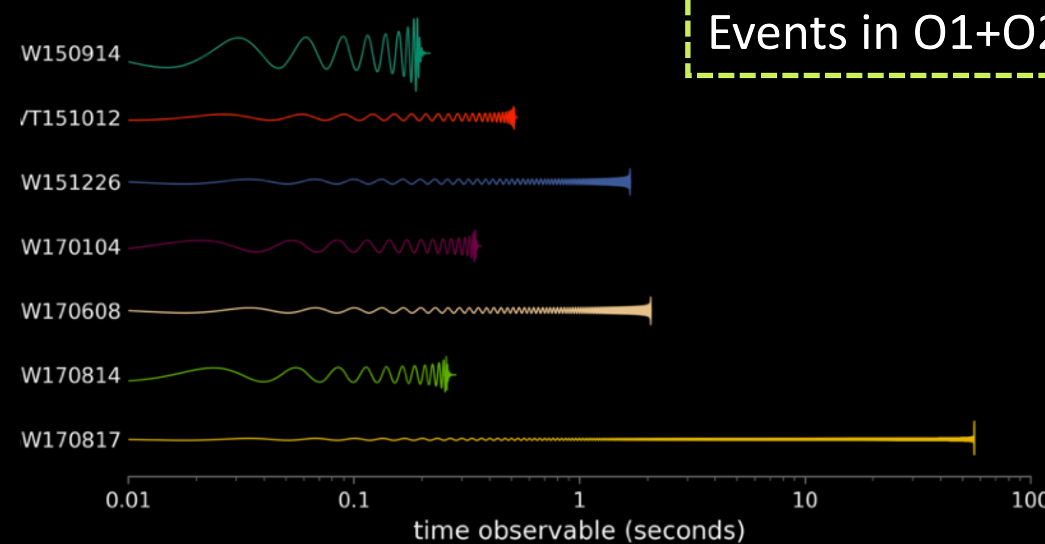

Events in O1+O2

Images: LIGO/Ben Farr/Aaron Geller

Gravitational wave science

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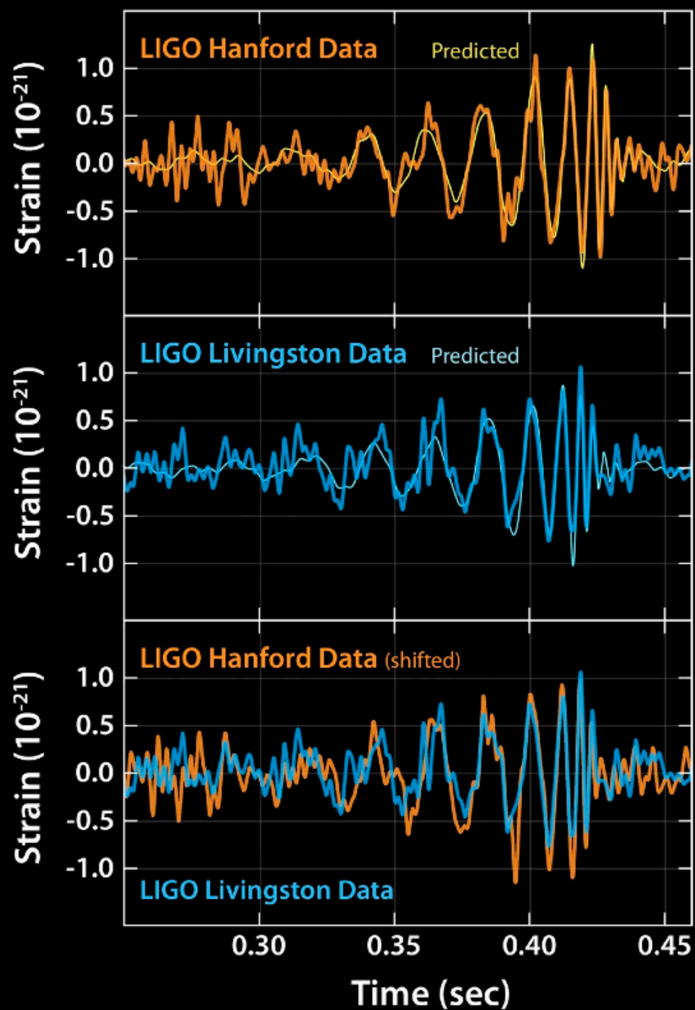

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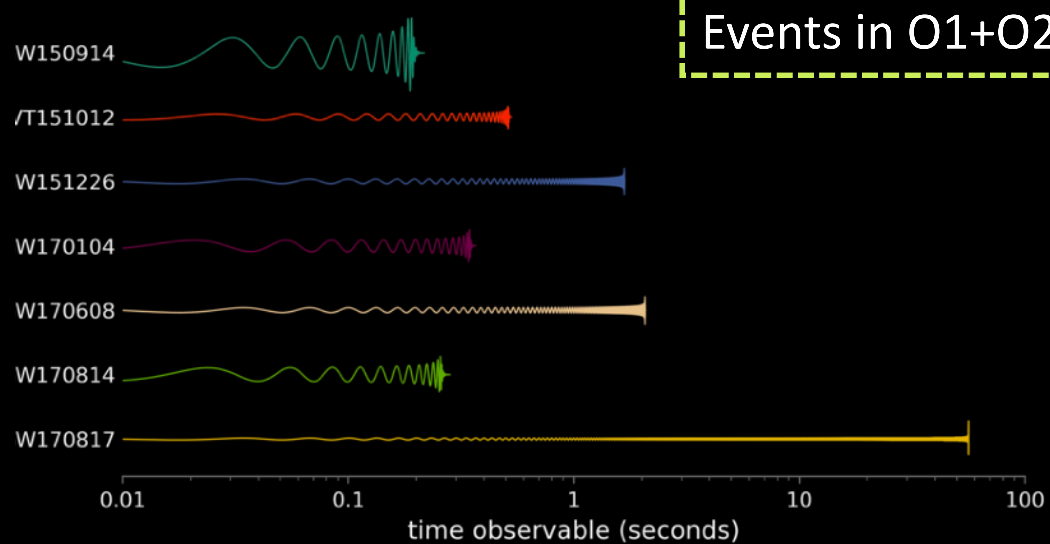

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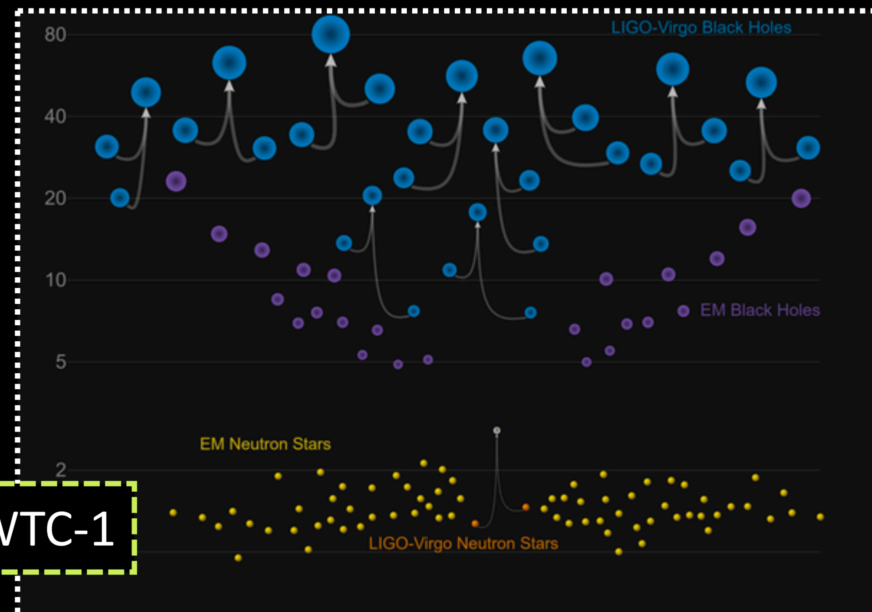
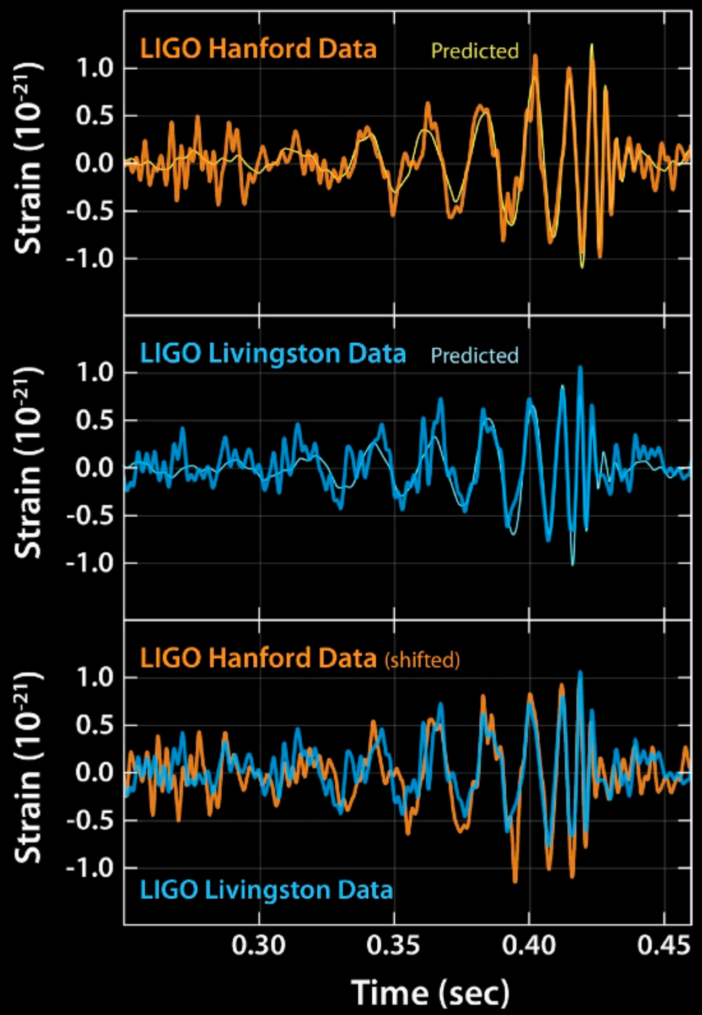


Catalogues: GWTC-1

Gravitational wave science



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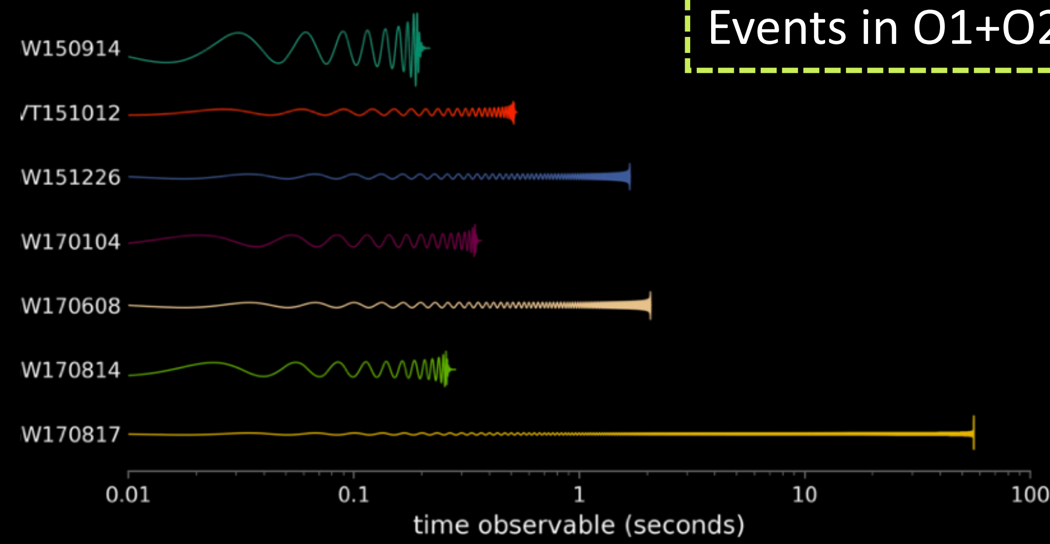
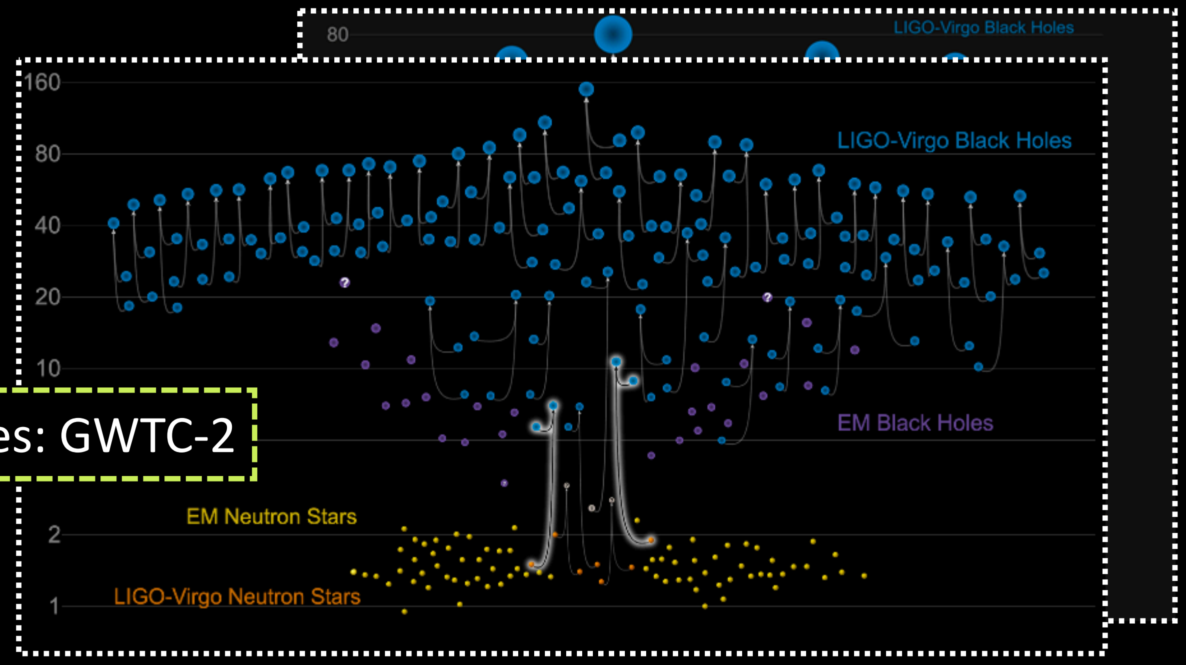
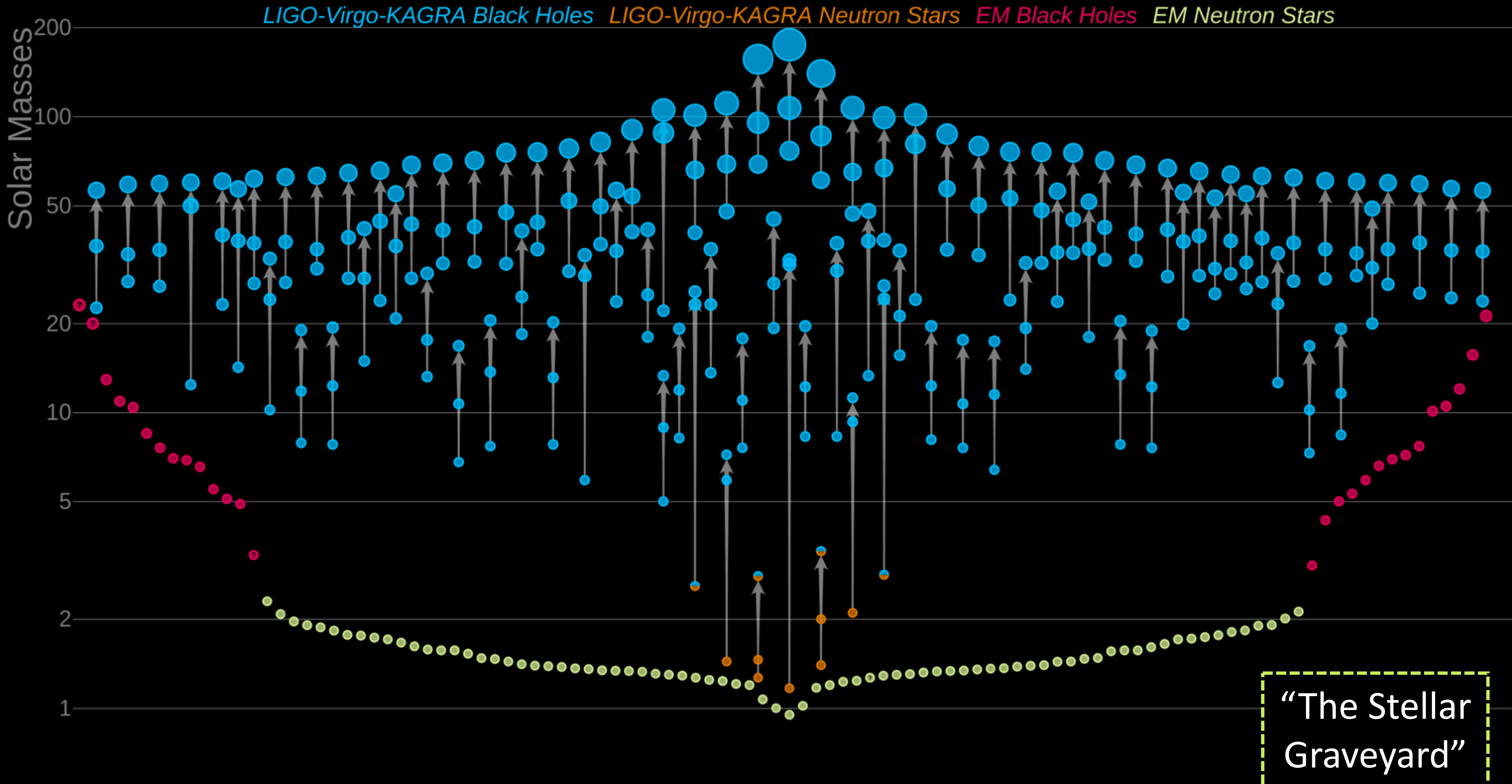


Catalogues: GWTC-2



Images: LIGO/Ben Farr/Aaron Geller

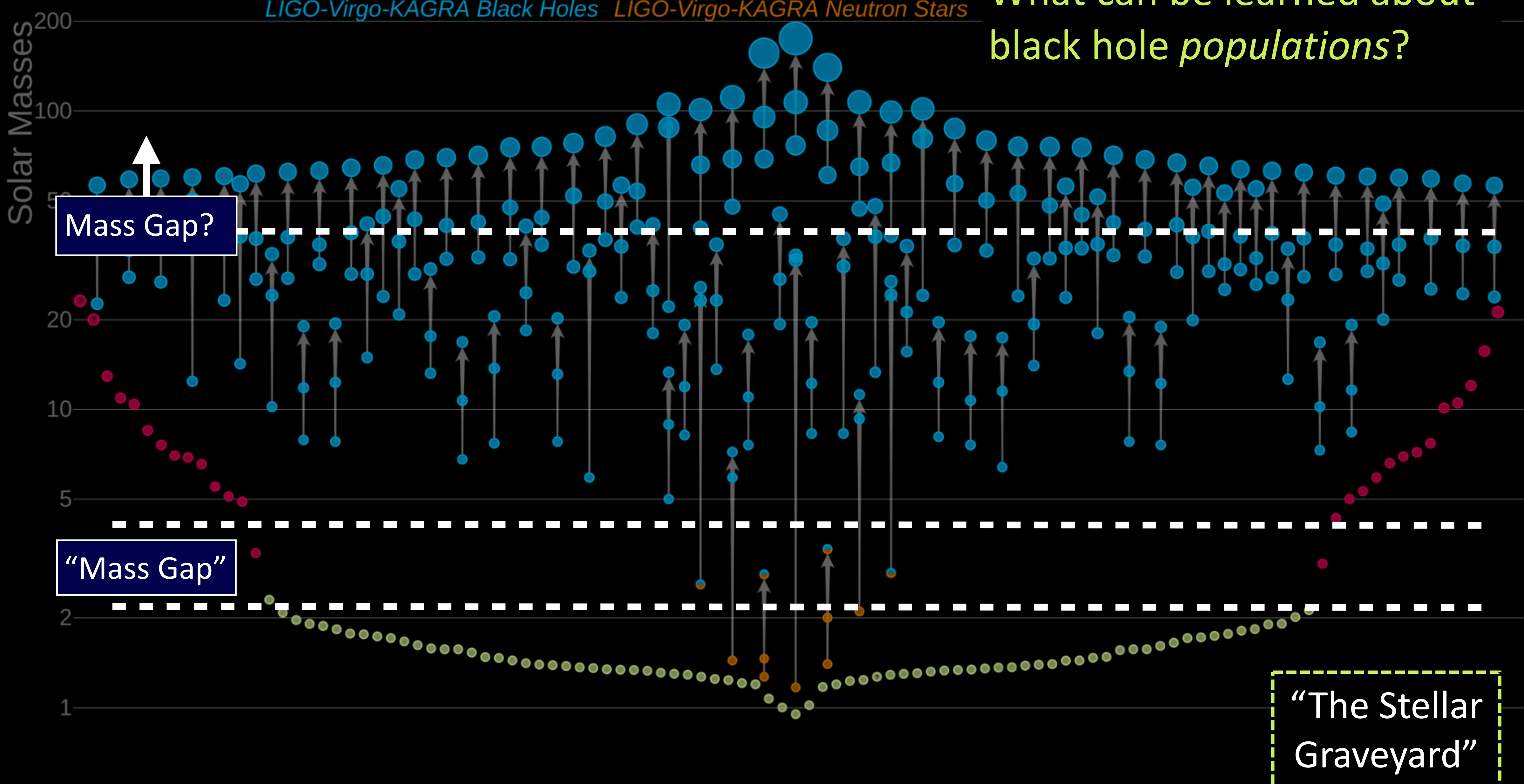
Binary mergers in LIGO/Virgo O1-3



Adapted from LIGO-Virgo-KAGRA, Aaron Geller

Binary mergers in LIGO/Virgo O1-3

What can be learned about black hole *populations*?



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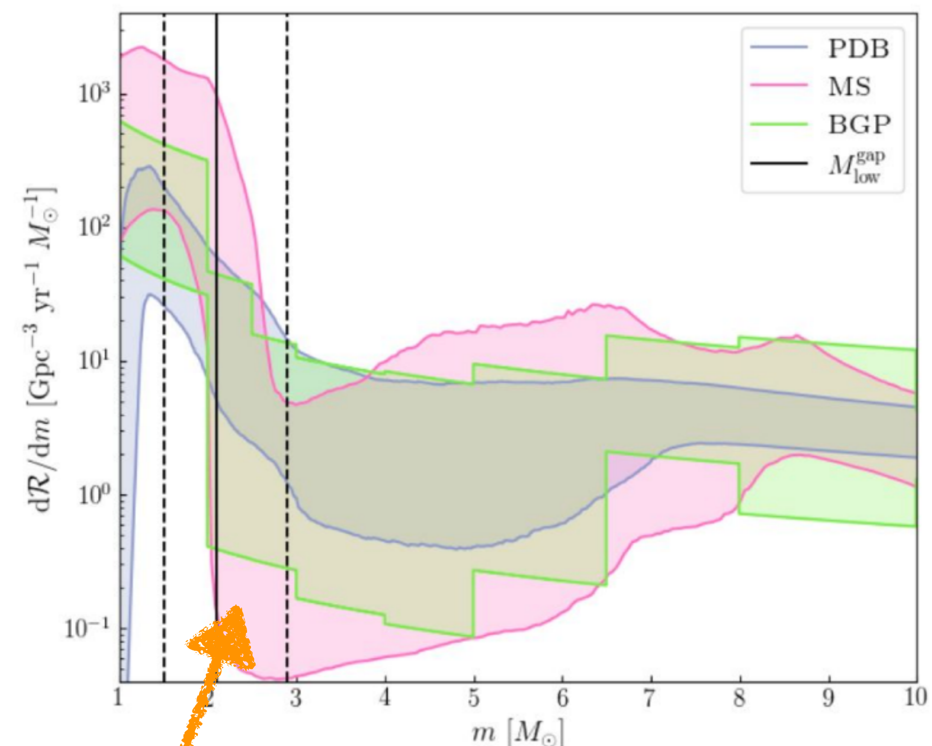
Features in the mass distribution

Lower mass gap



The LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration, Phys. Rev. X **13**, 011048, March 2023

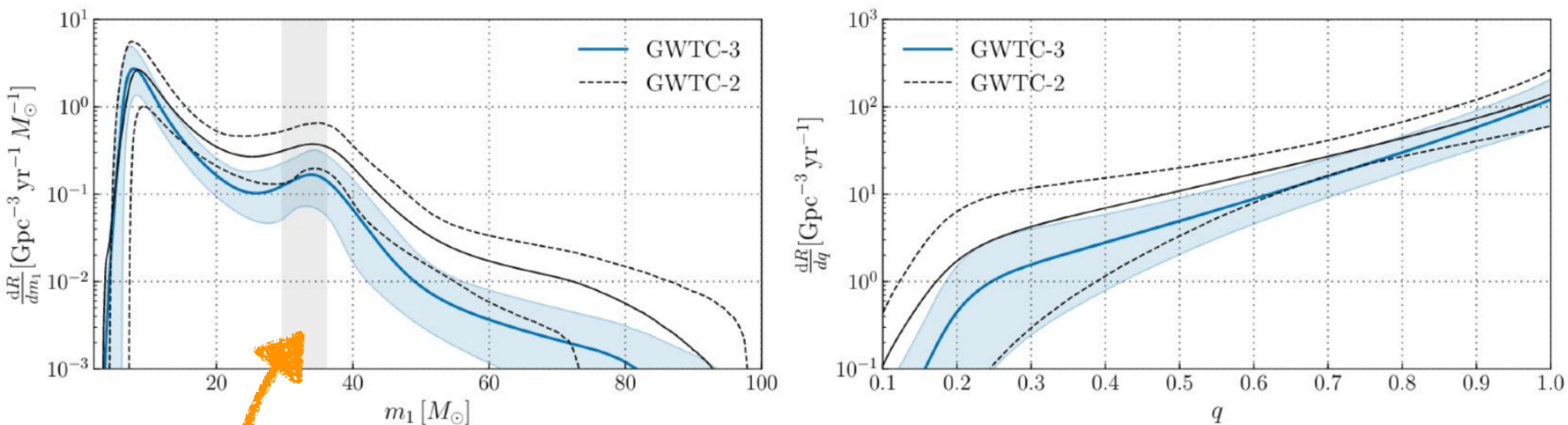
Is the lower mass gap physical?

Rachel Gray's talk, PONT'23

Features in the mass distribution

Lower mass gap

Black hole mass distribution

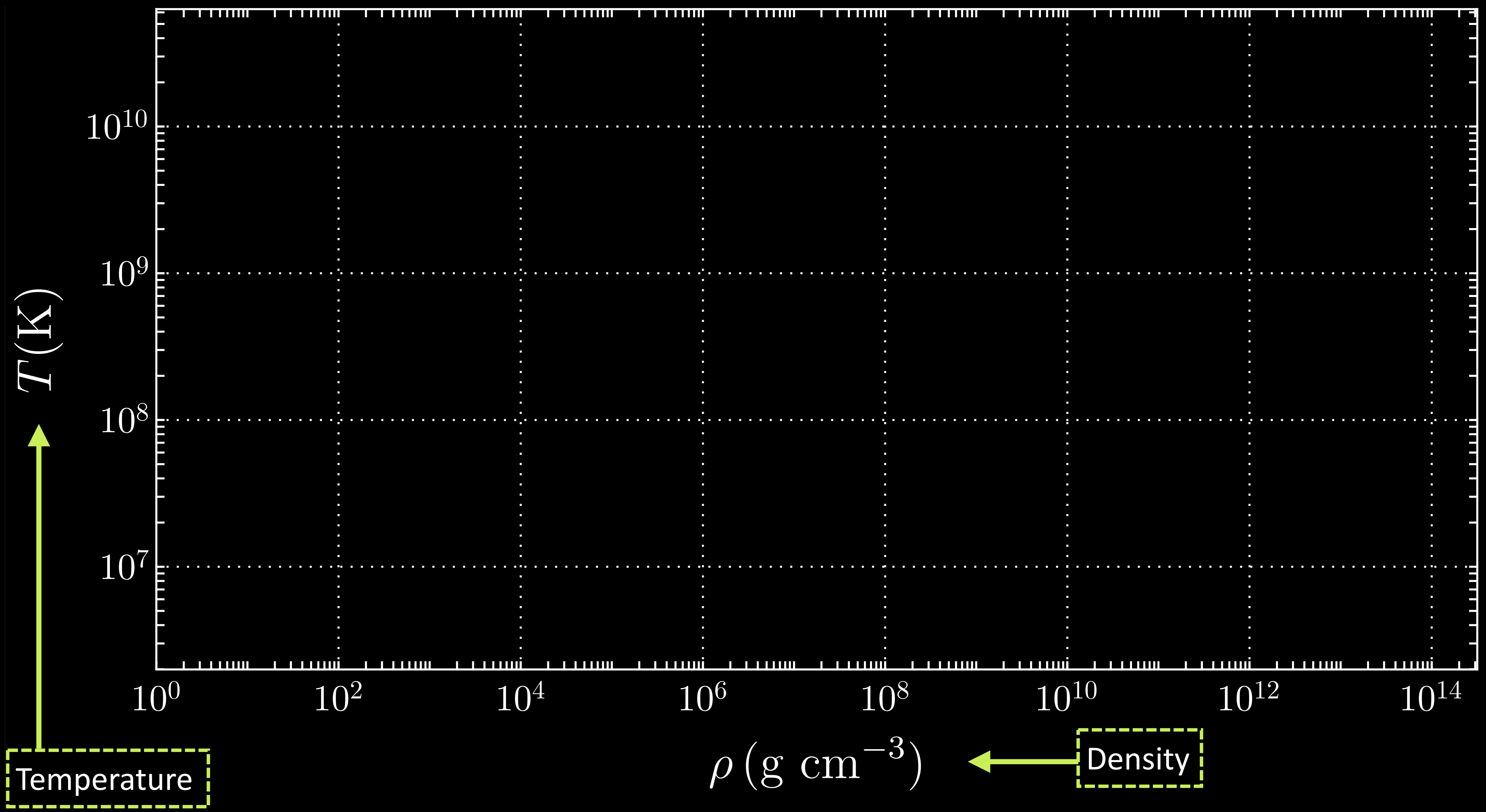


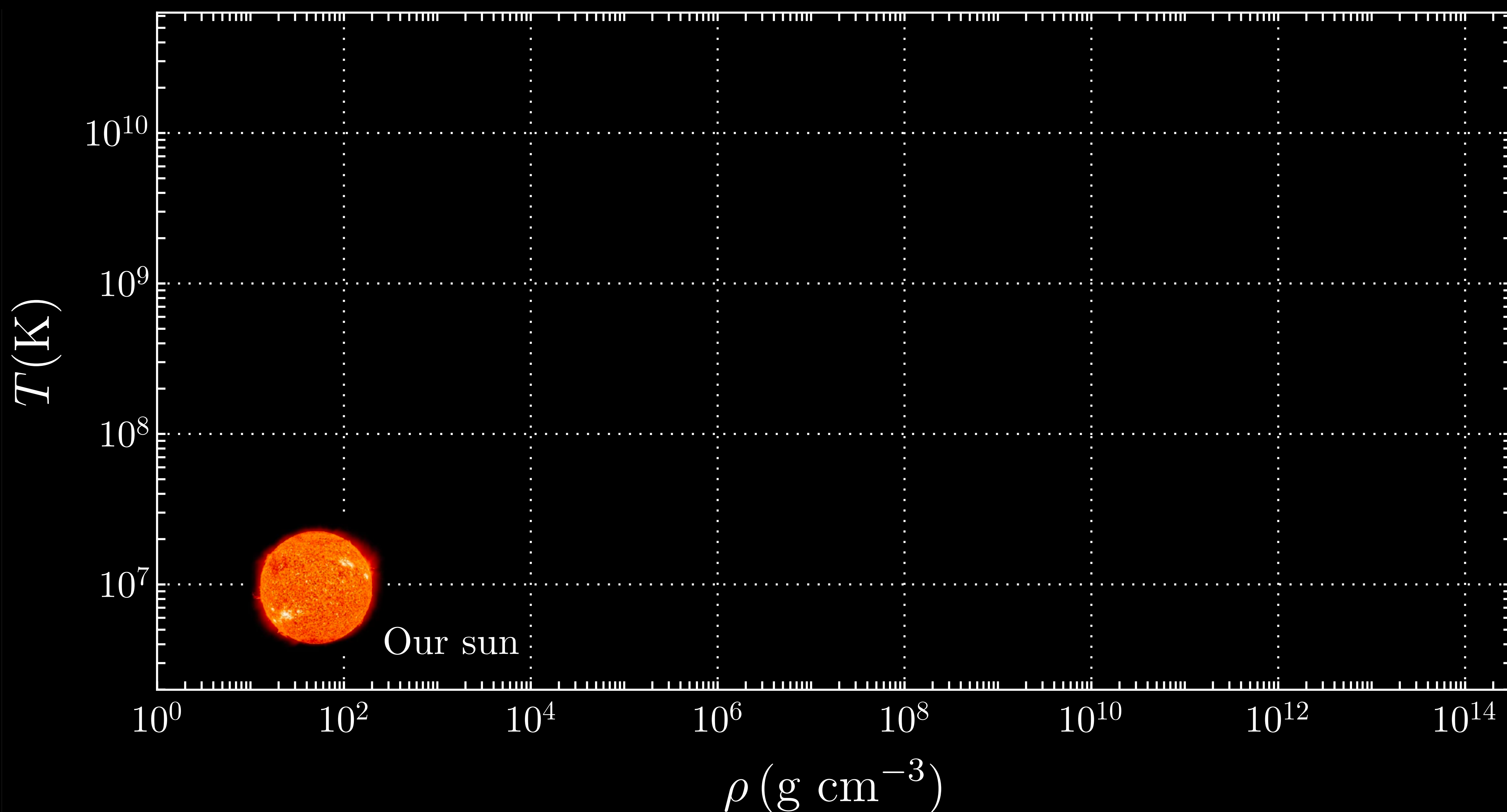
The LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration, Phys. Rev. X **13**, 011048, March 2023

Rachel Gray's talk, PONT'23

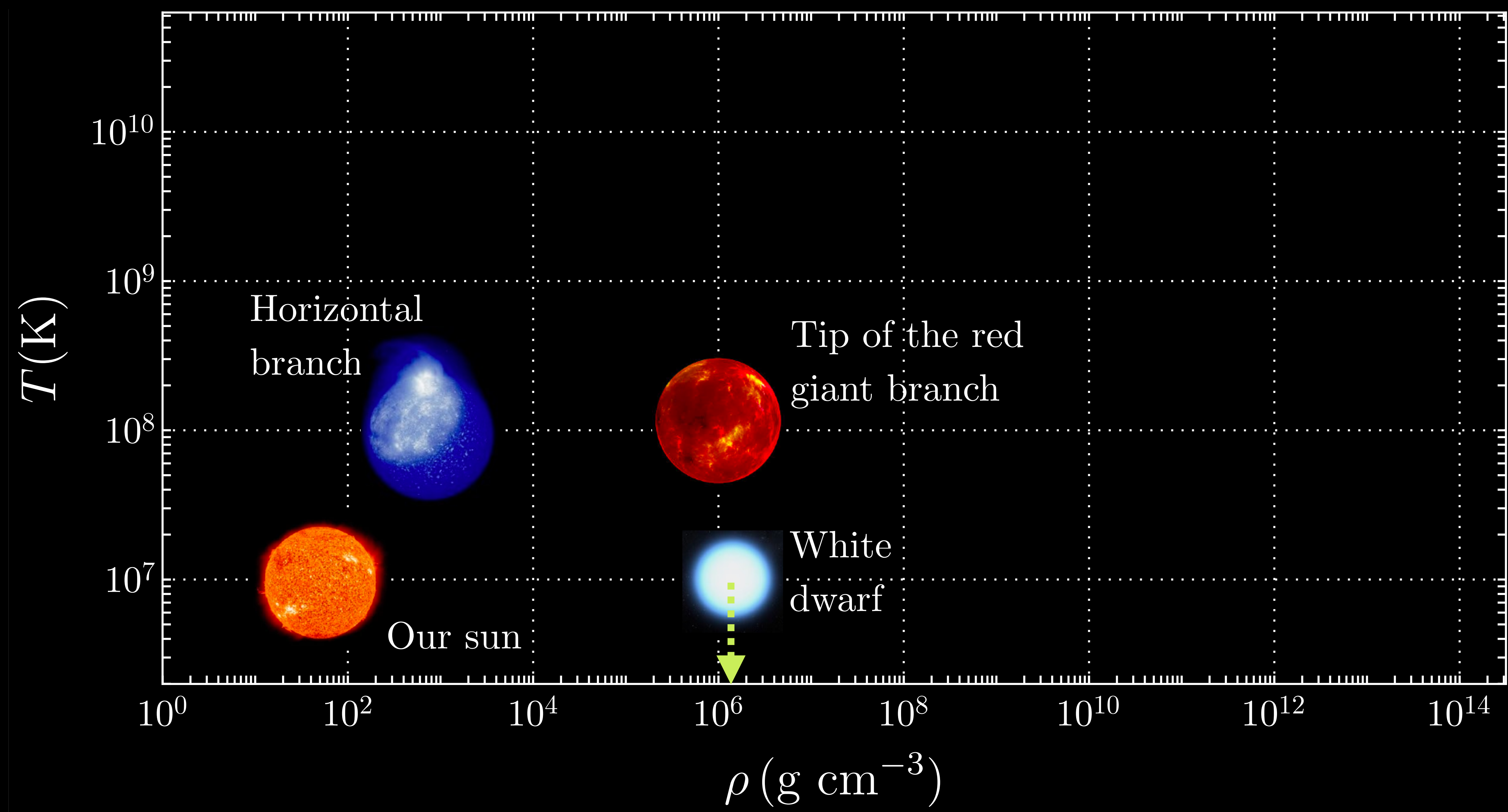
Why is there a peak here? ⟷ H_0

Late evolution of BH progenitor stars





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



$T(\mathrm{K})$
10^{10}
10^{9}
10^{8}
10^{7}
Horizontal branch
Tip of the red giant branch
White dwarf
Our sun
10^{0}
10^{2}
10^{4}
10^{6}
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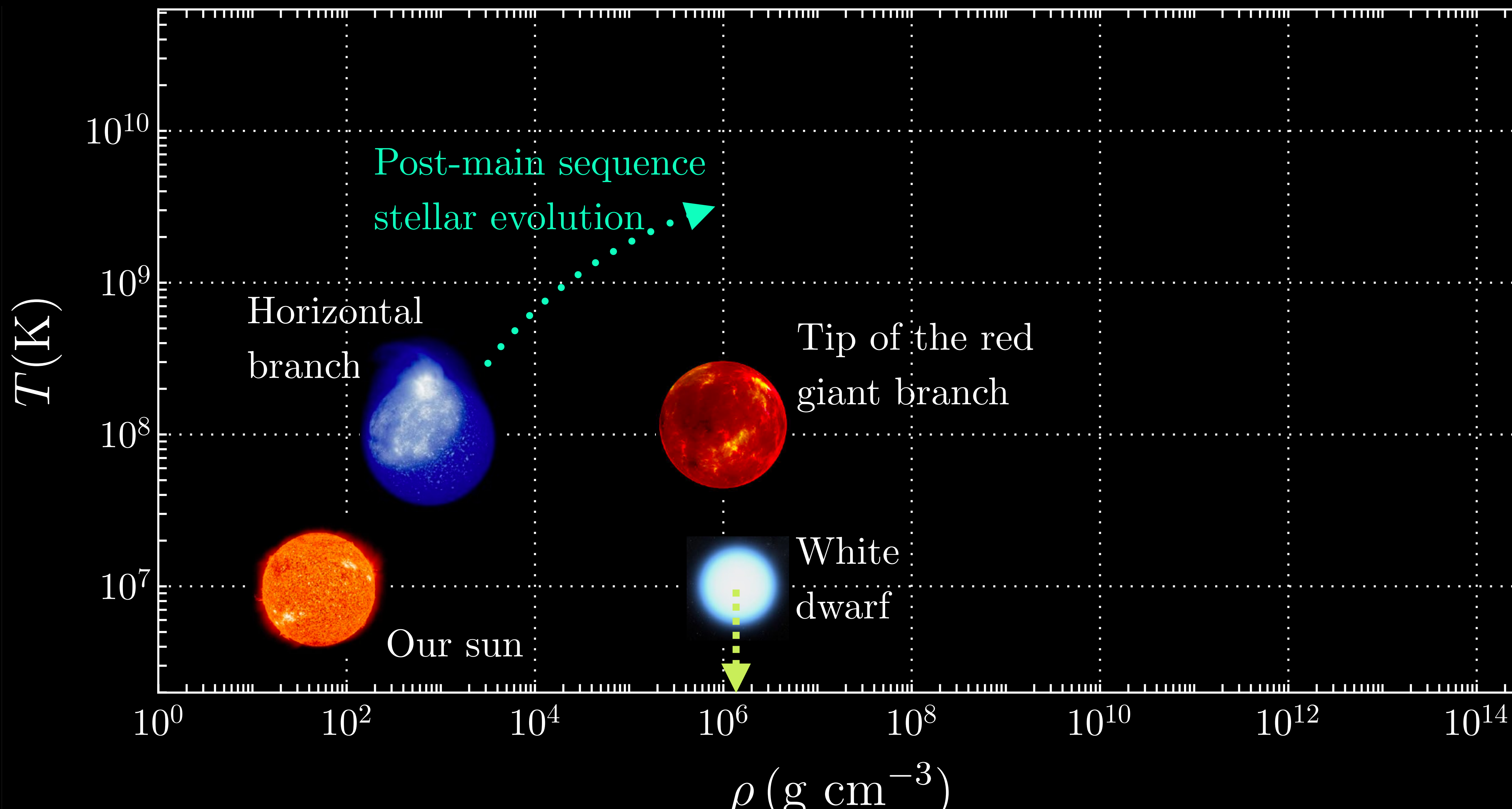

Post-main sequence
stellar evolution
Horizontal
branch
Tip of the red
giant branch
White
dwarf
Our sun
10^{10}
10^{9}
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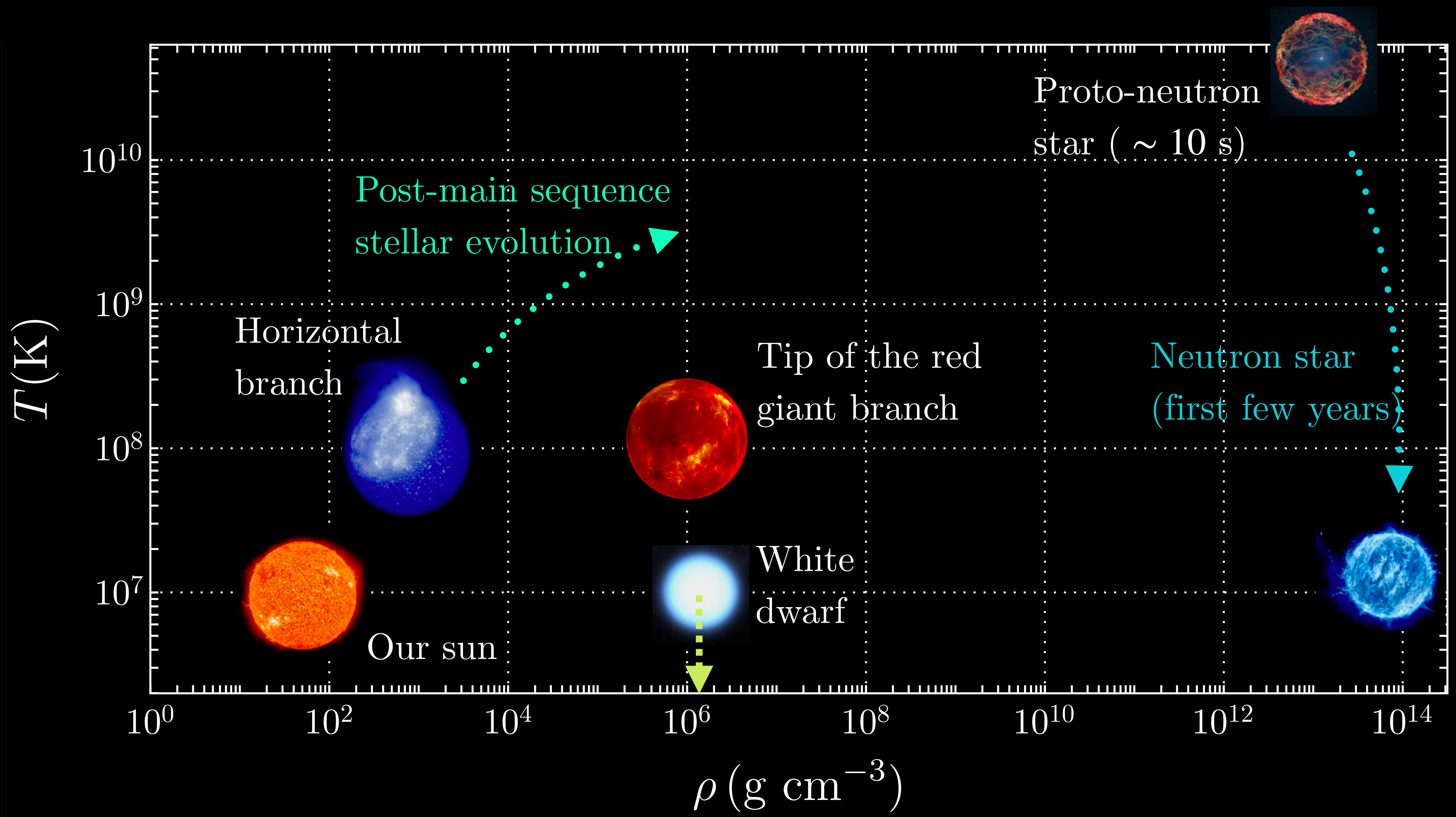

Proto-neutron
star (~ 10 s)
Post-main sequence
stellar evolution
Horizontal
branch
Tip of the red
giant branch
Neutron star
(first few years)
White
dwarf
Our sun
10^{10}
10^{9}
10^{8}
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$T(\mathrm{K})$
10^{0}
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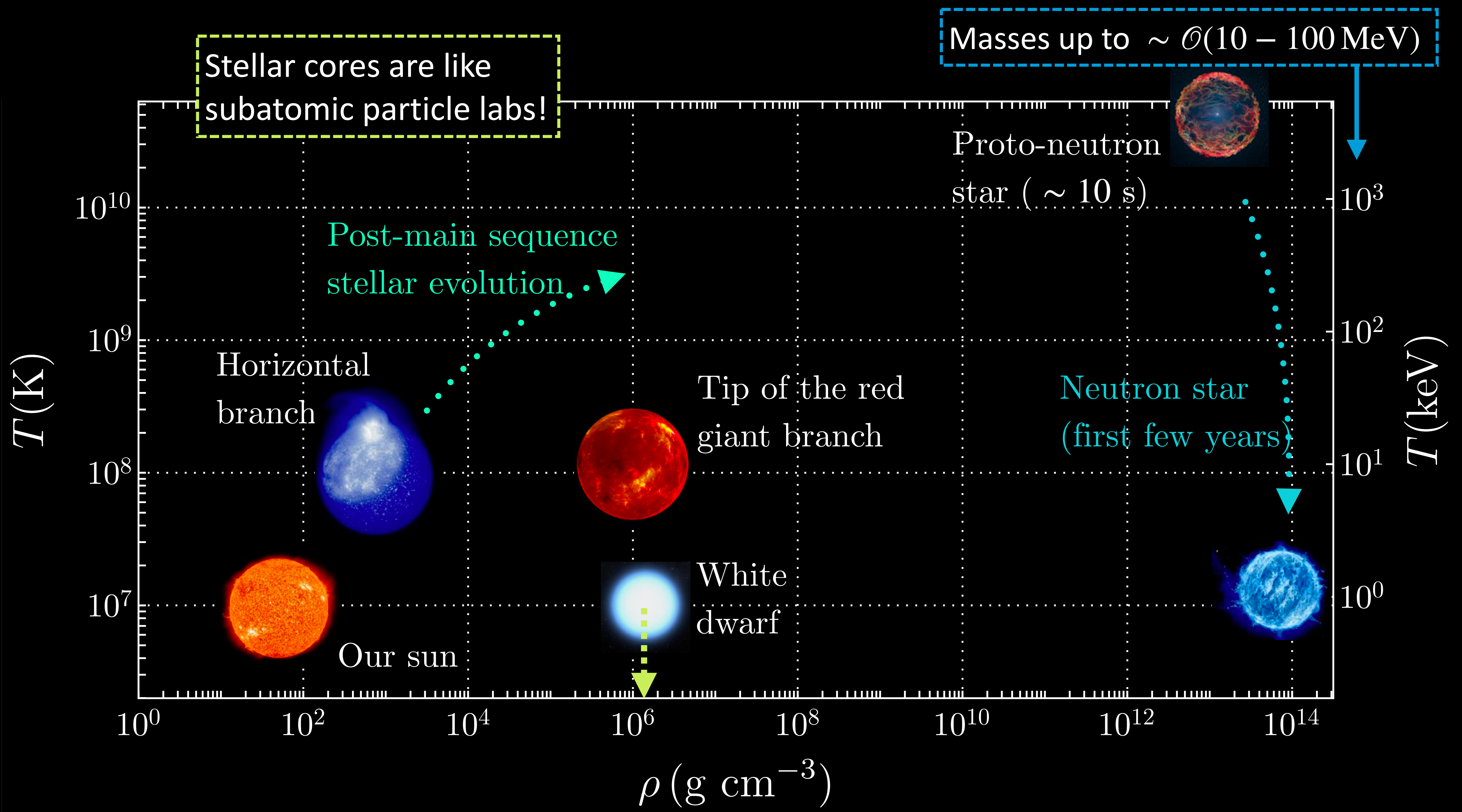
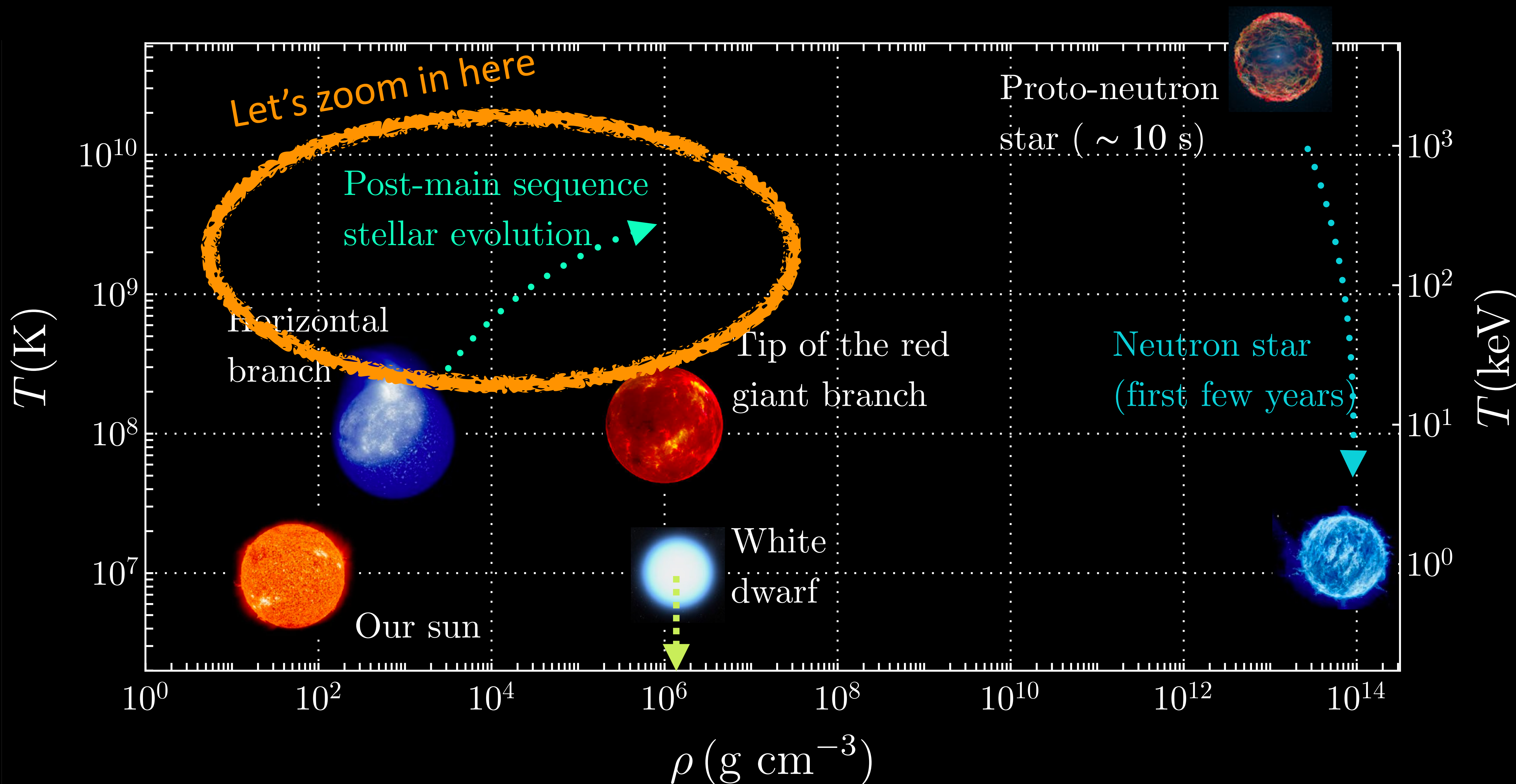


Stellar cores are like subatomic particle labs!
Masses up to $\sim \mathcal{O}(10 - 100\,\mathrm{MeV})$
Proto-neutron star ($\sim$ 10 s)
Post-main sequence stellar evolution
Horizontal branch
Tip of the red giant branch
Neutron star (first few years)
White dwarf
Our sun
$T\,(\mathrm{K})$
$T\,(\mathrm{keV})$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



Let's zoom in here
Post-main sequence
stellar evolution
Horizontal
branch
Tip of the red
giant branch
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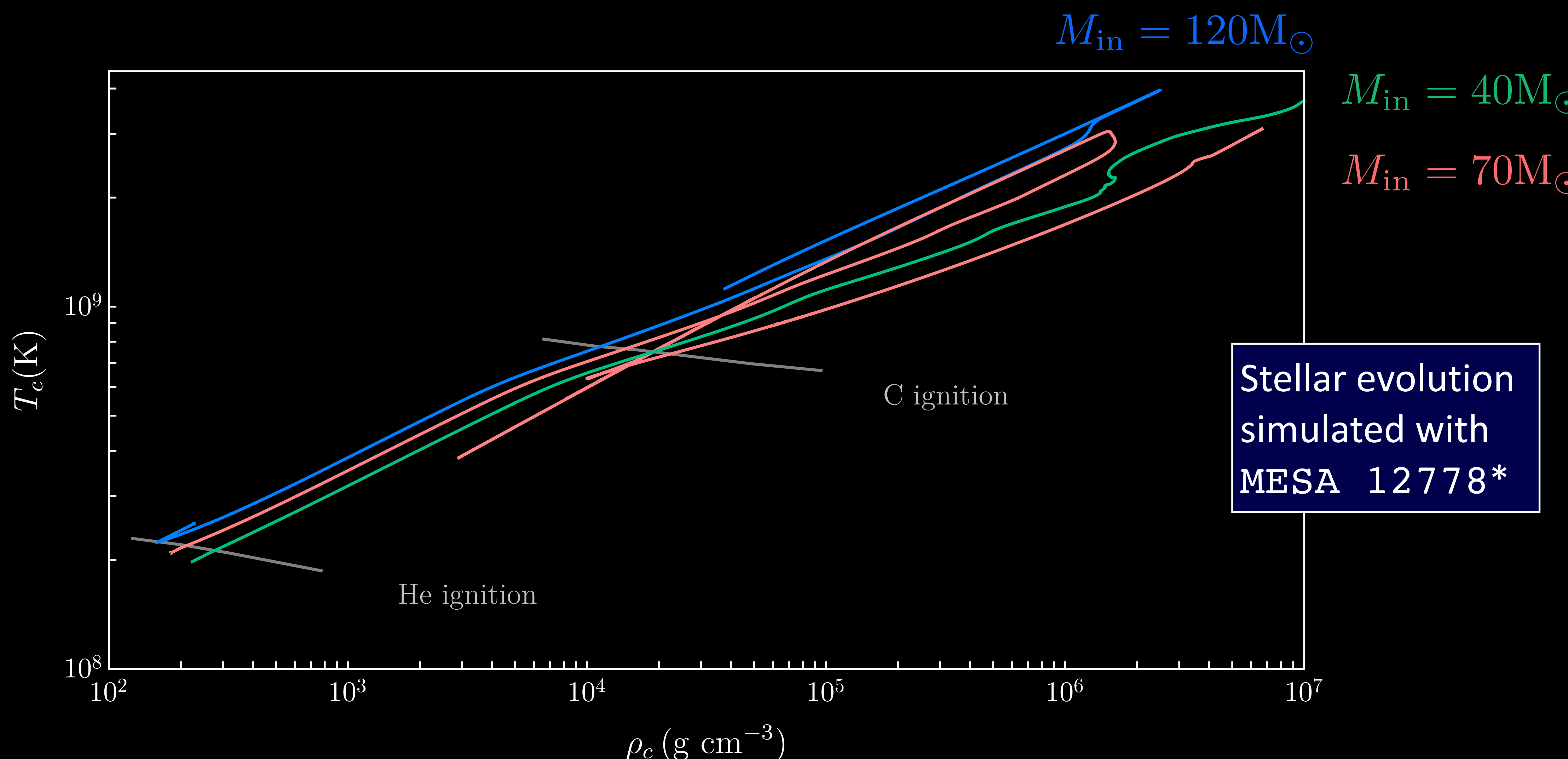
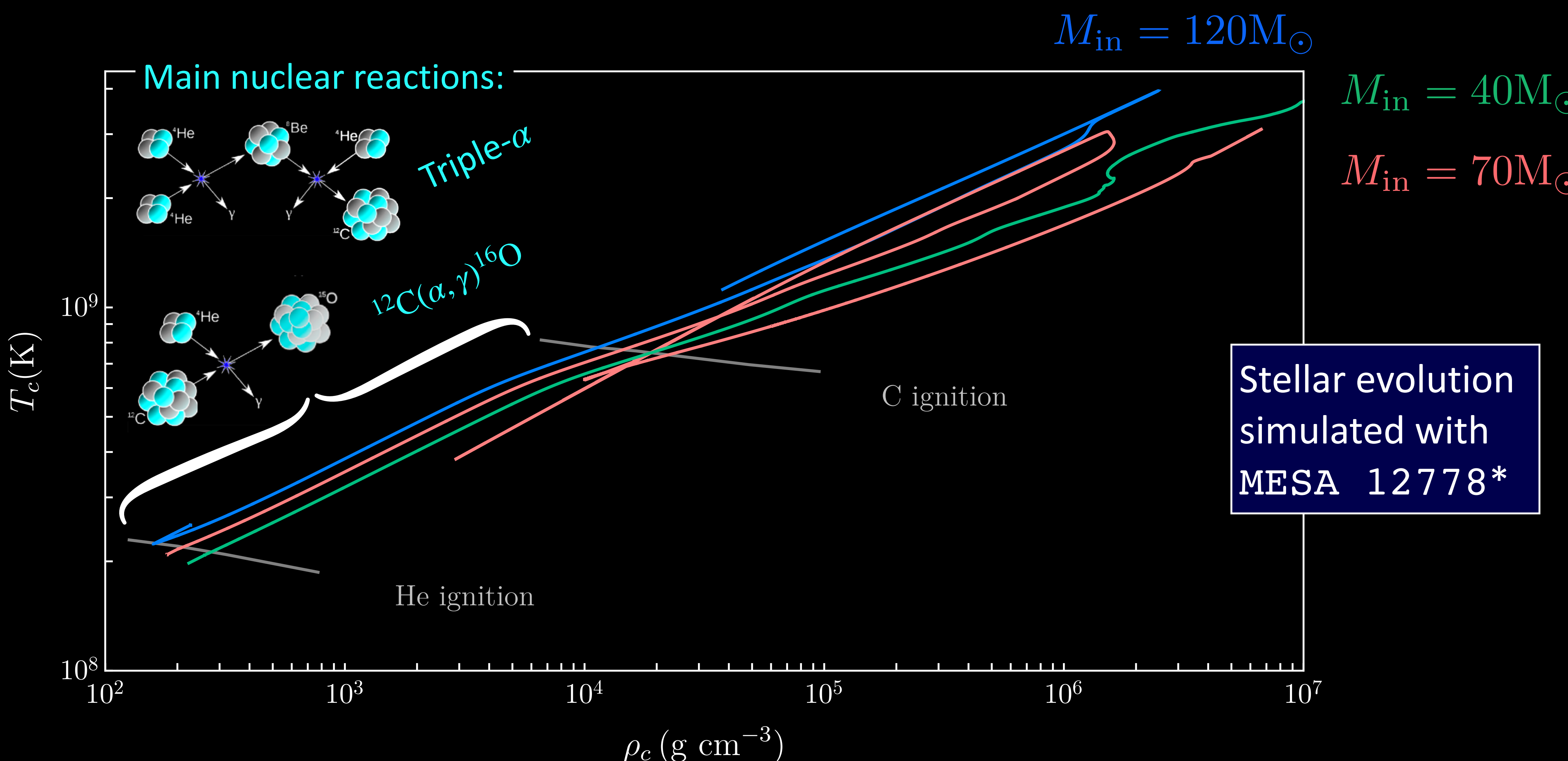
Late evolution of heavy stars



Stellar evolution simulated with `MESA 12778*`

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

Late evolution of heavy stars

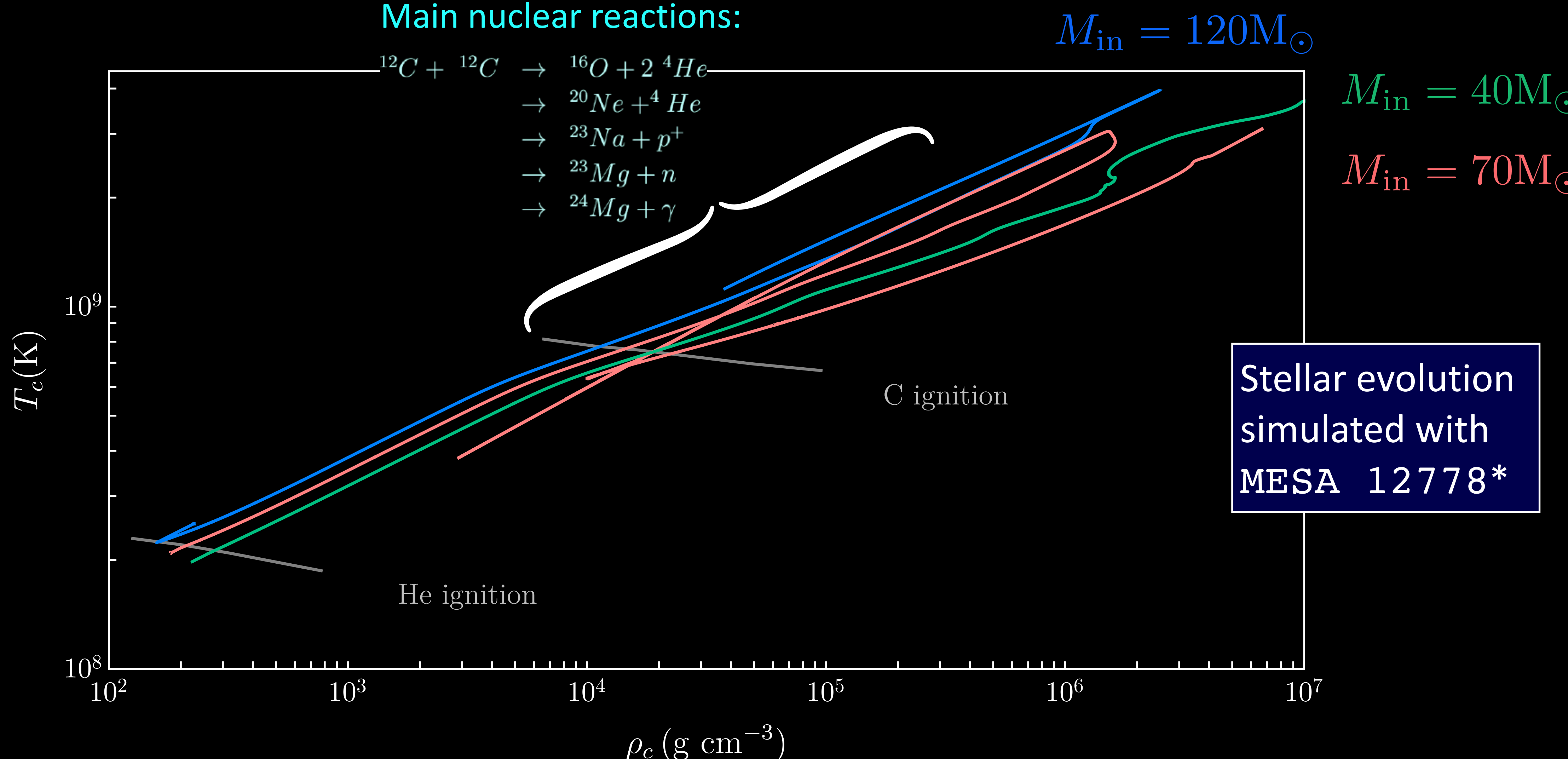


Stellar evolution simulated with `MESA 12778*`

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

Late evolution of heavy stars

Main nuclear reactions:



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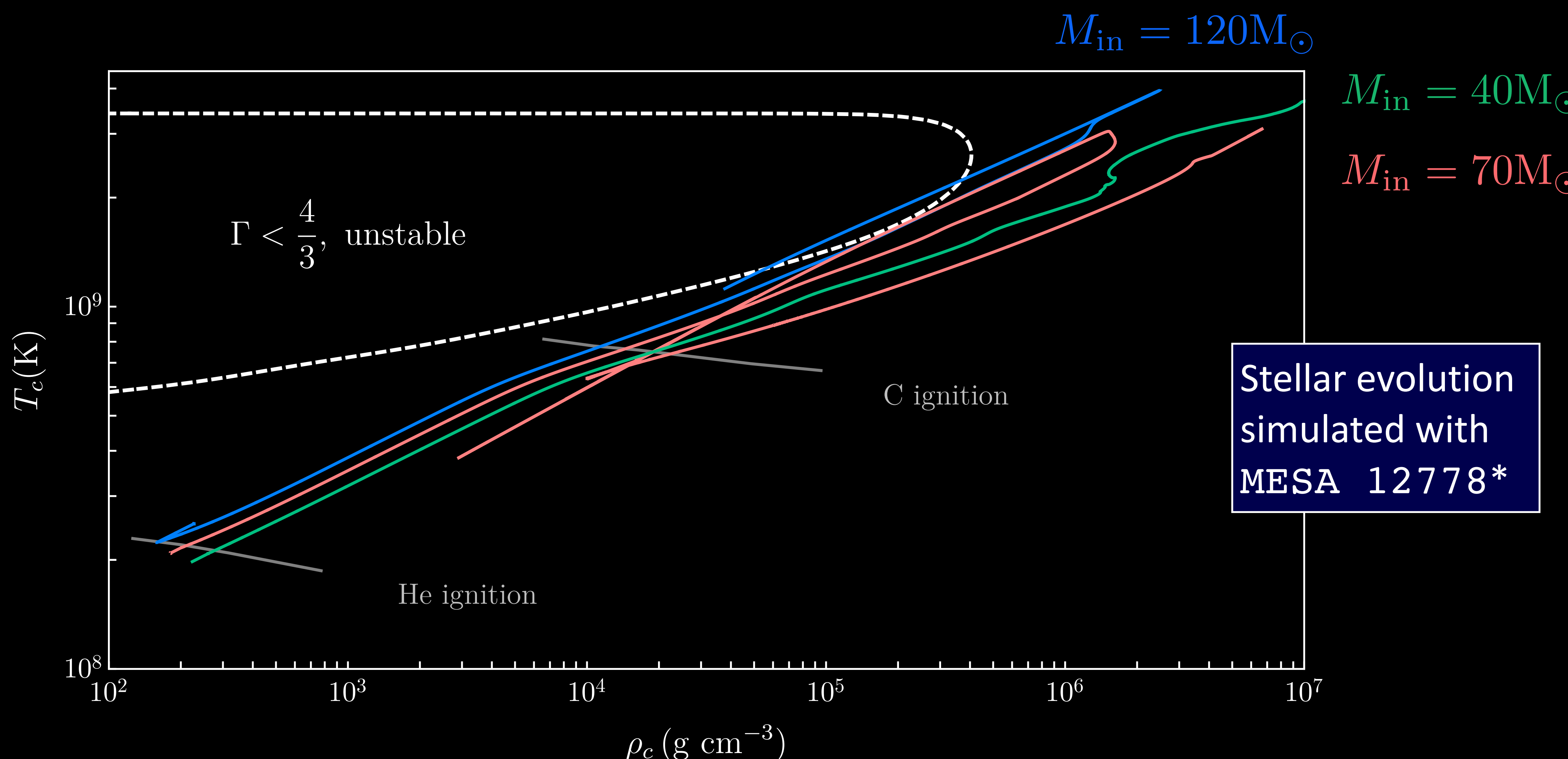
Late evolution of heavy stars



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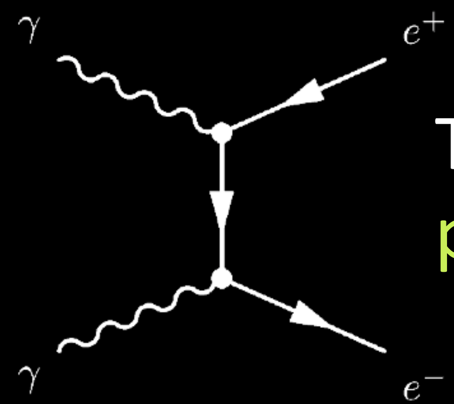
The danger zone: pair-instability

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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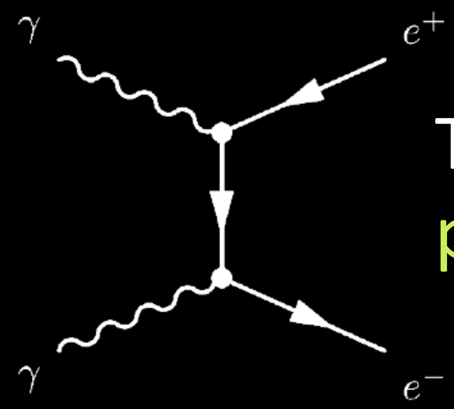


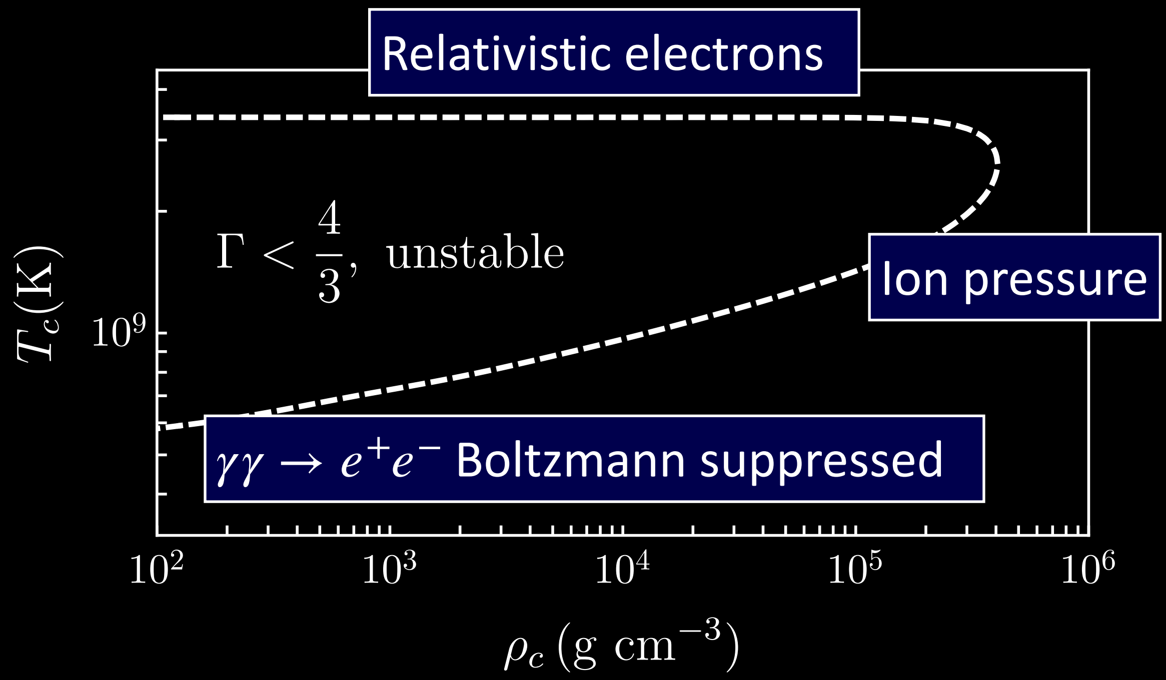
The high temperatures of stellar cores mean electron-positron pairs can be created from photons: $\gamma\gamma \rightarrow e^+e^-$

Unstable, because:

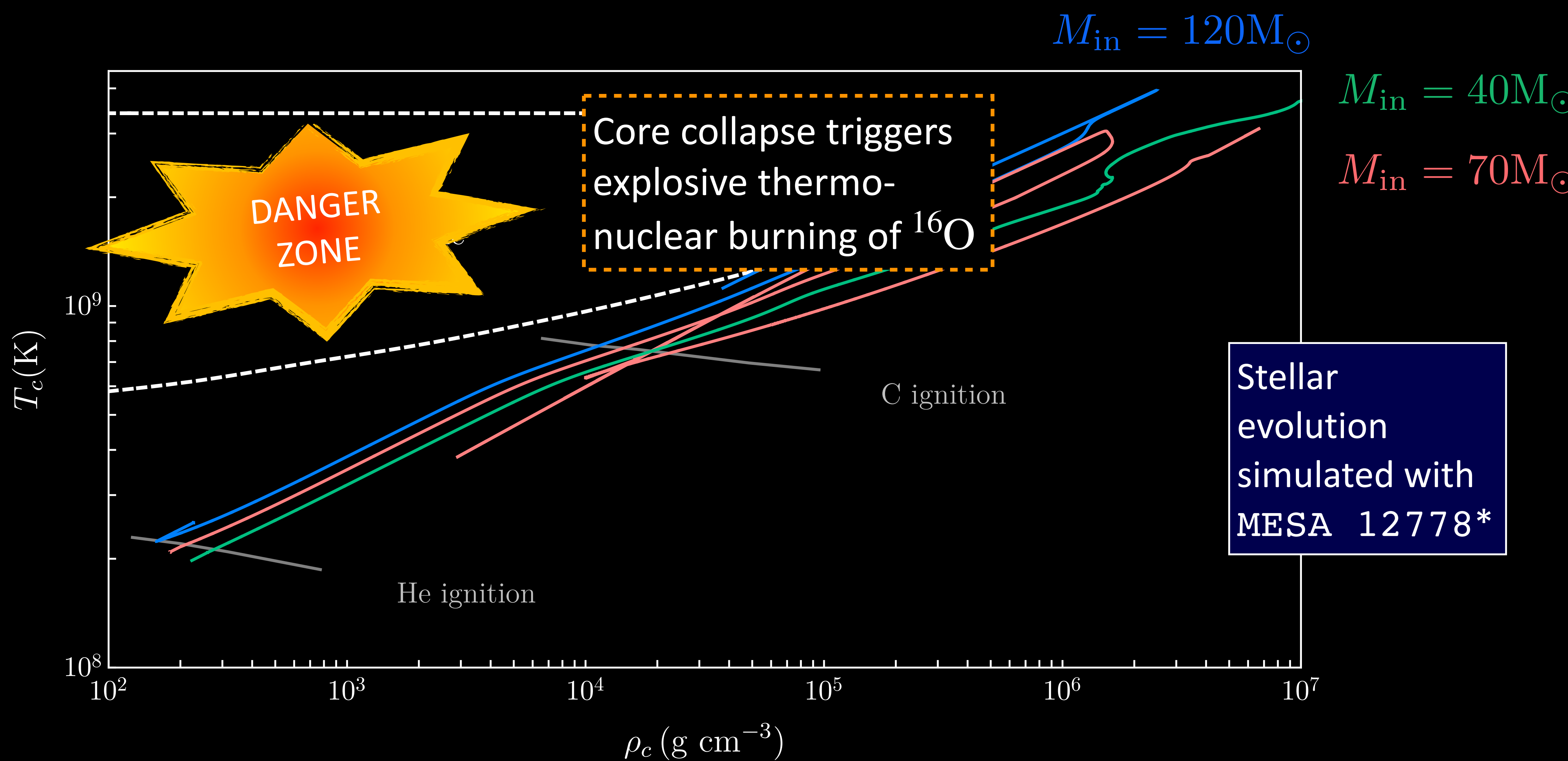
The photons give the star outward pressure

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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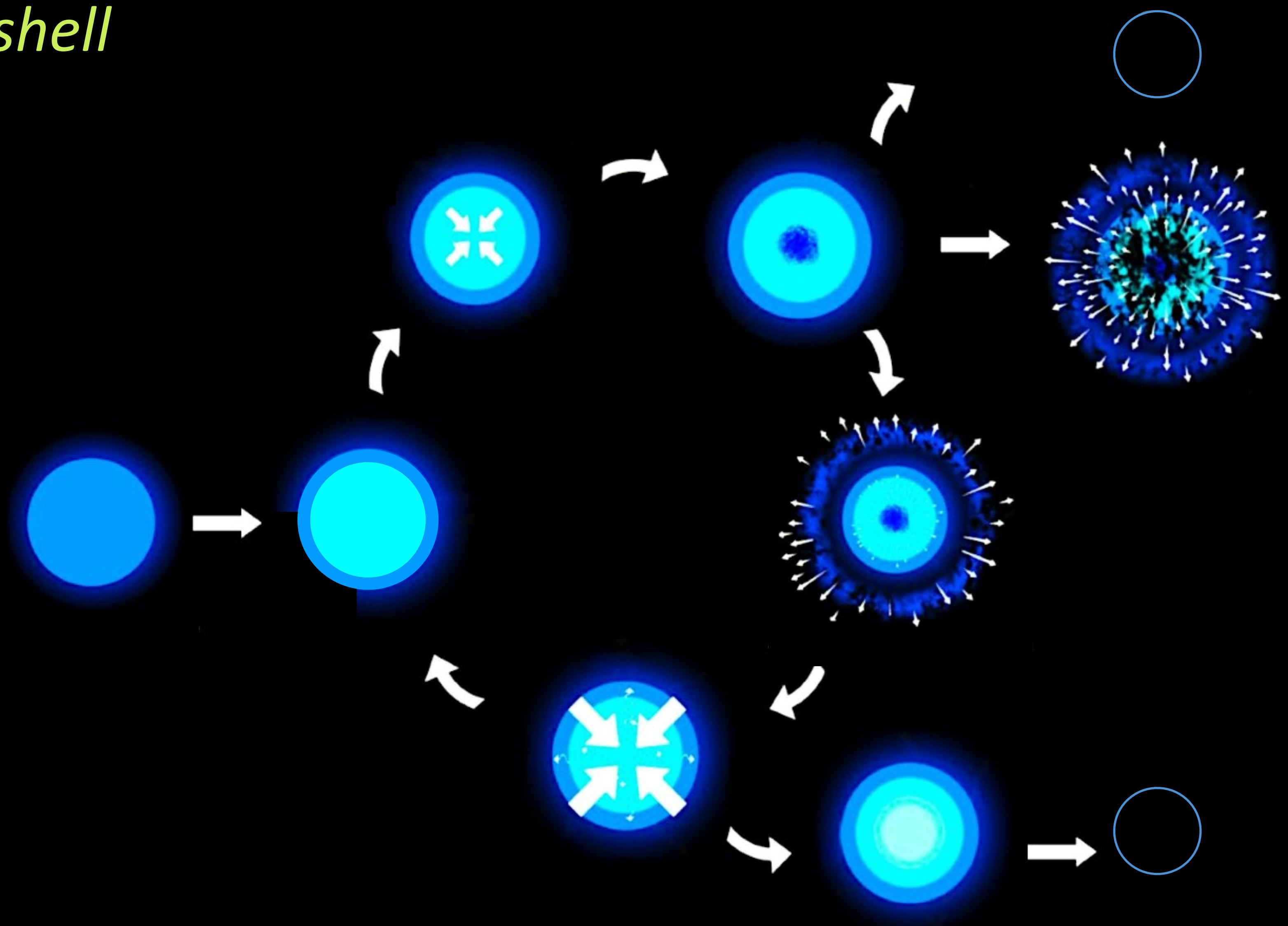
Pair instability

in a nutshell



Adapted from Renzo et al [2002.05077]

Pair instability

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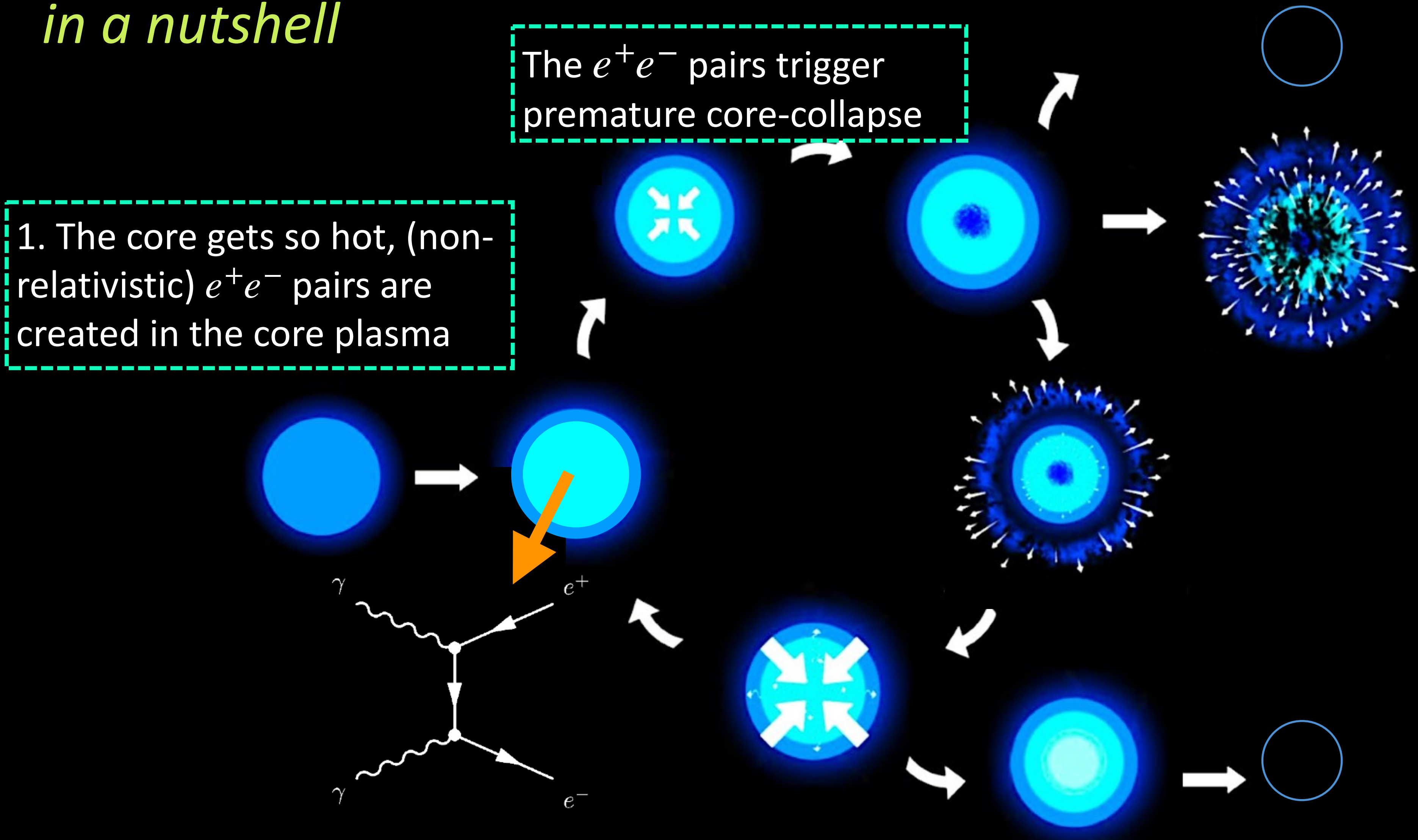

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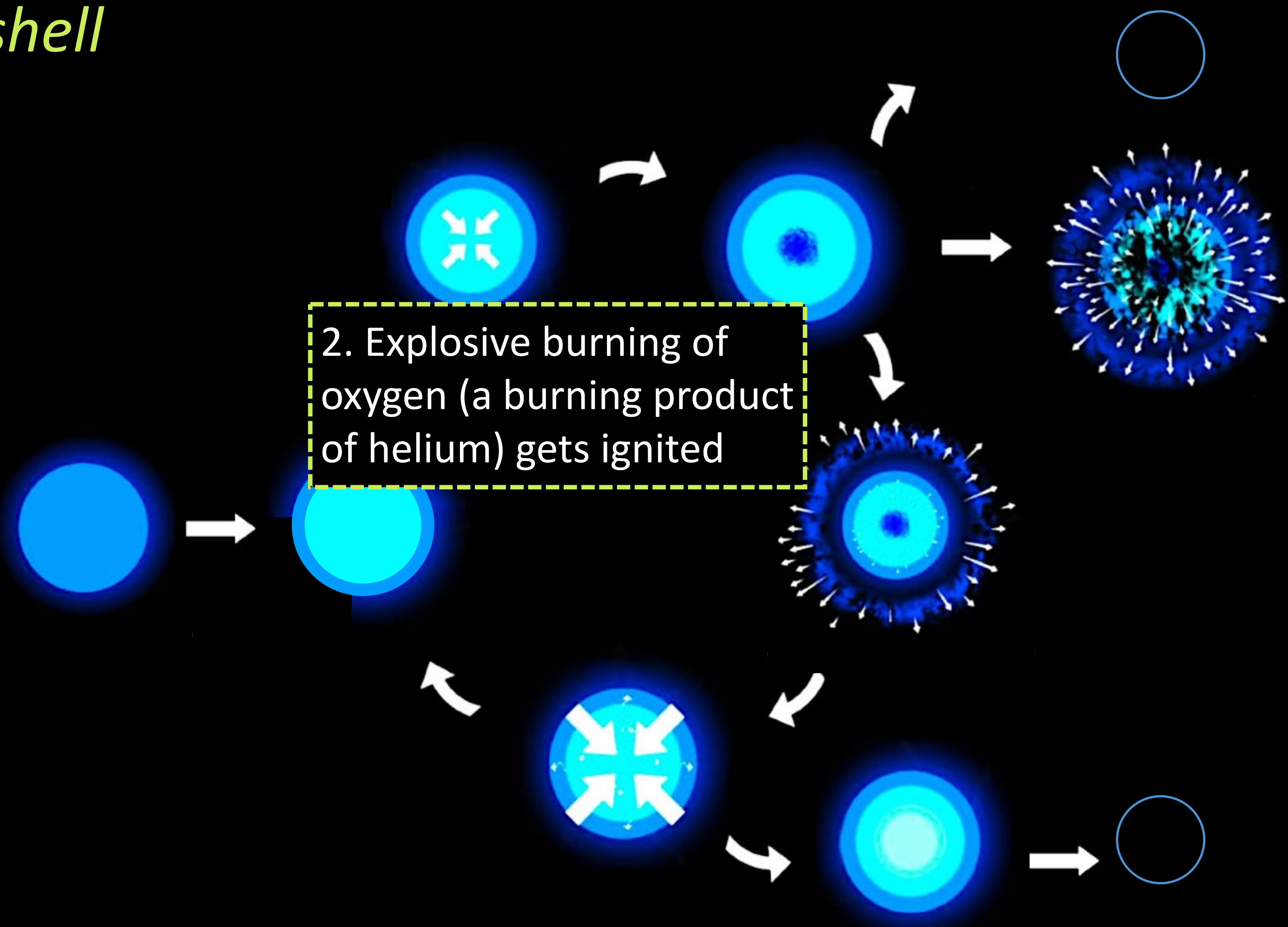

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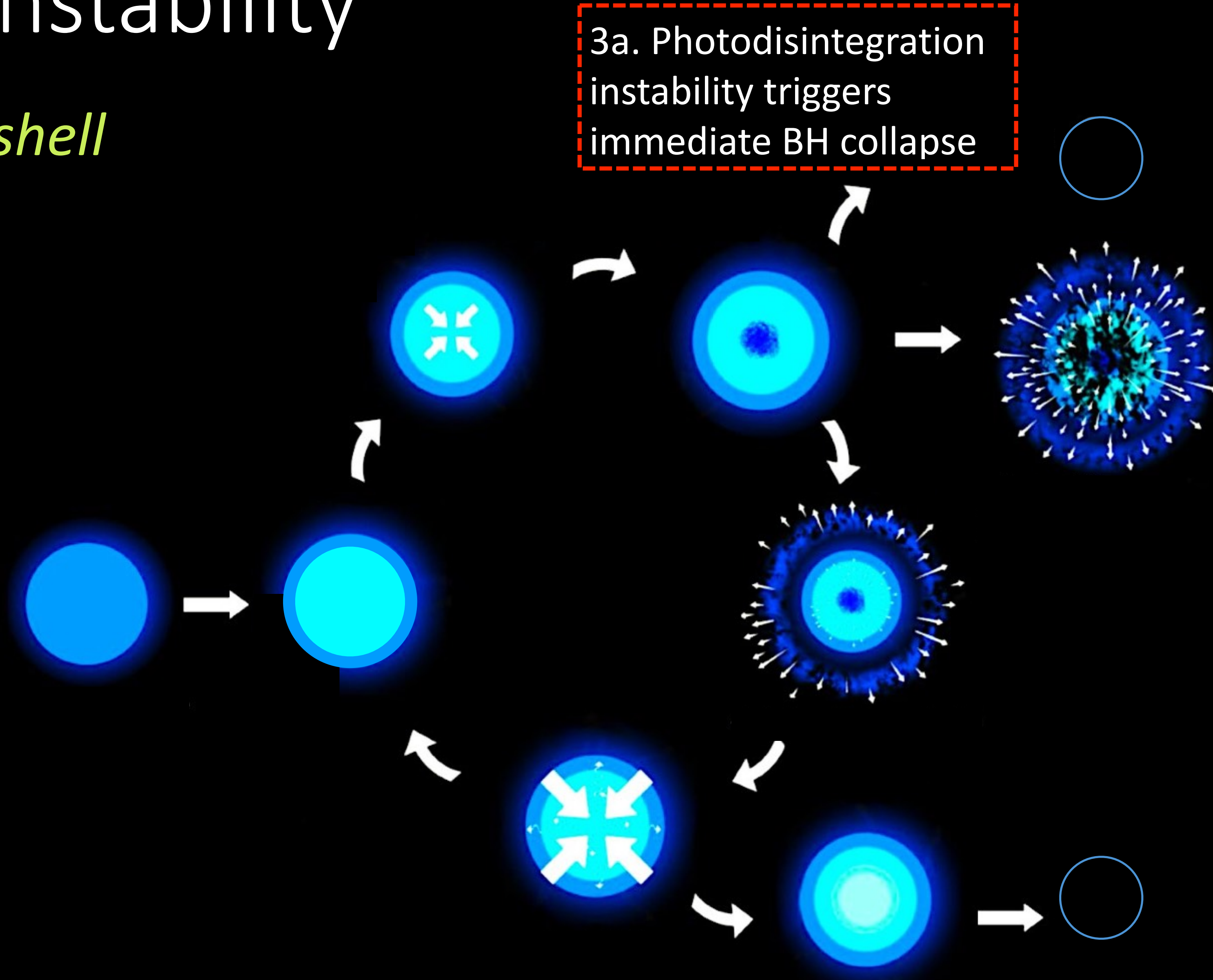
Pair instability

in a nutshell



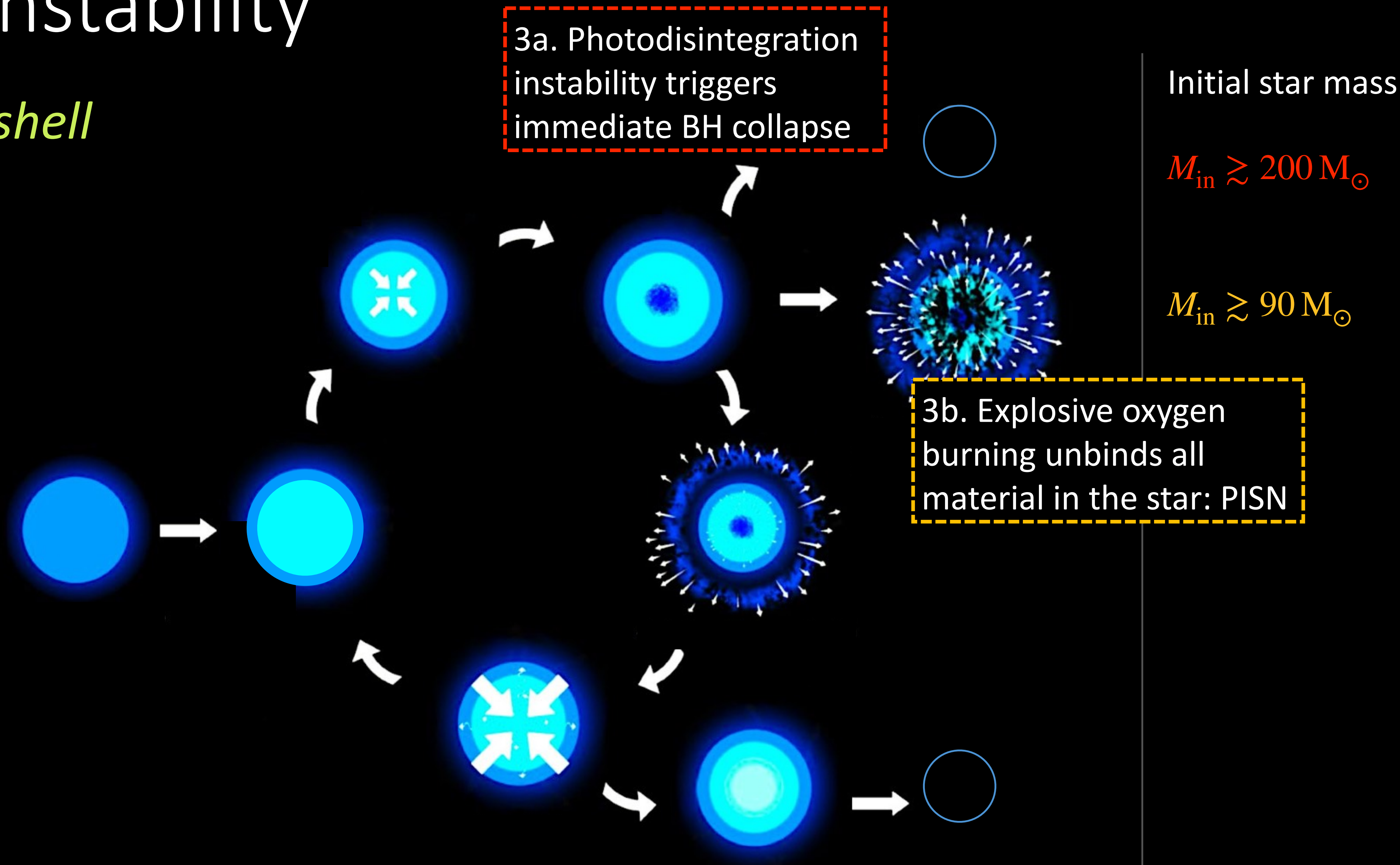
Initial star mass

$M_{in} \gtrsim 200\,M_{\odot}$

Adapted from Renzo et al [2002.05077]

Pair instability

in a nutshell



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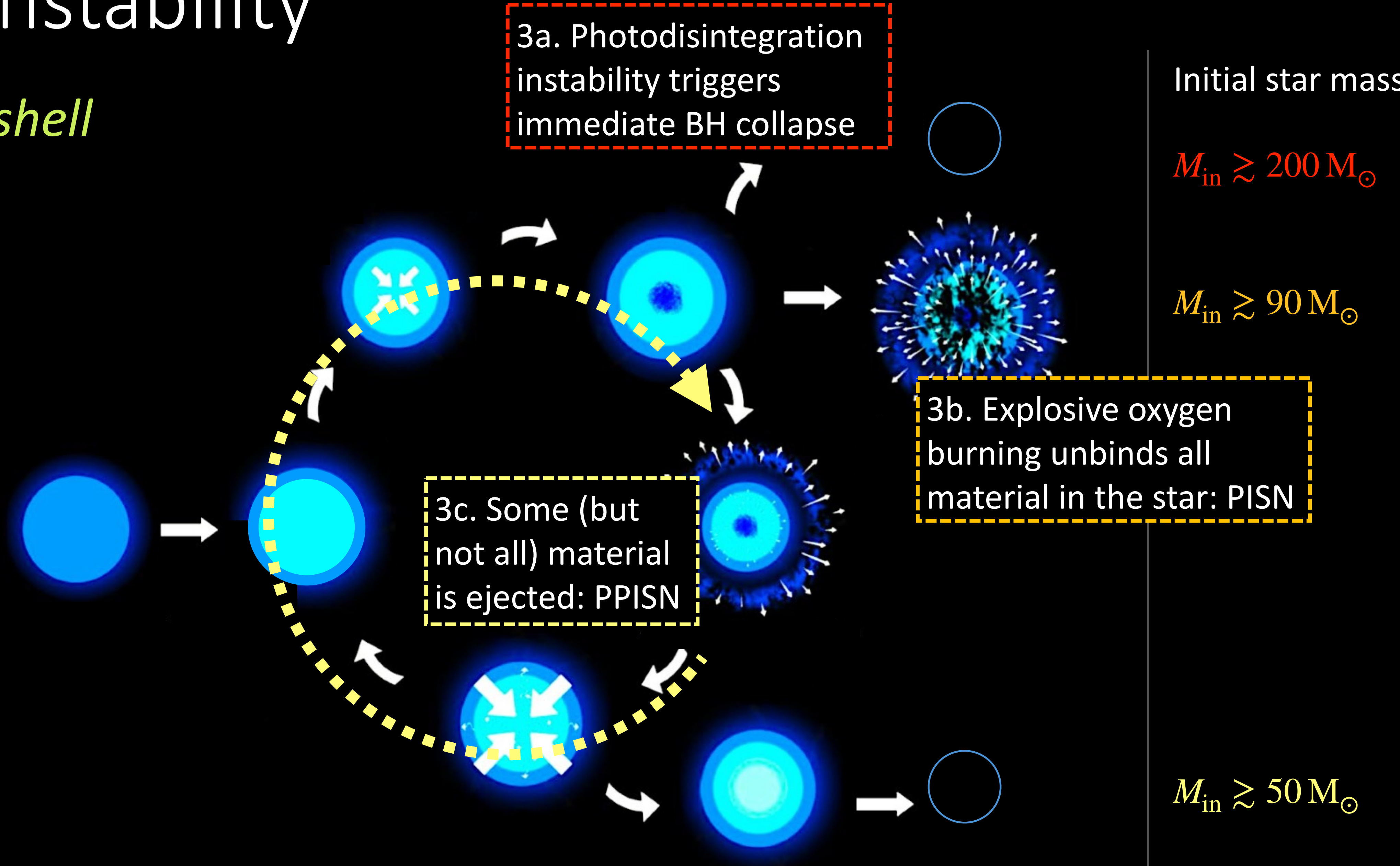
in a nutshell



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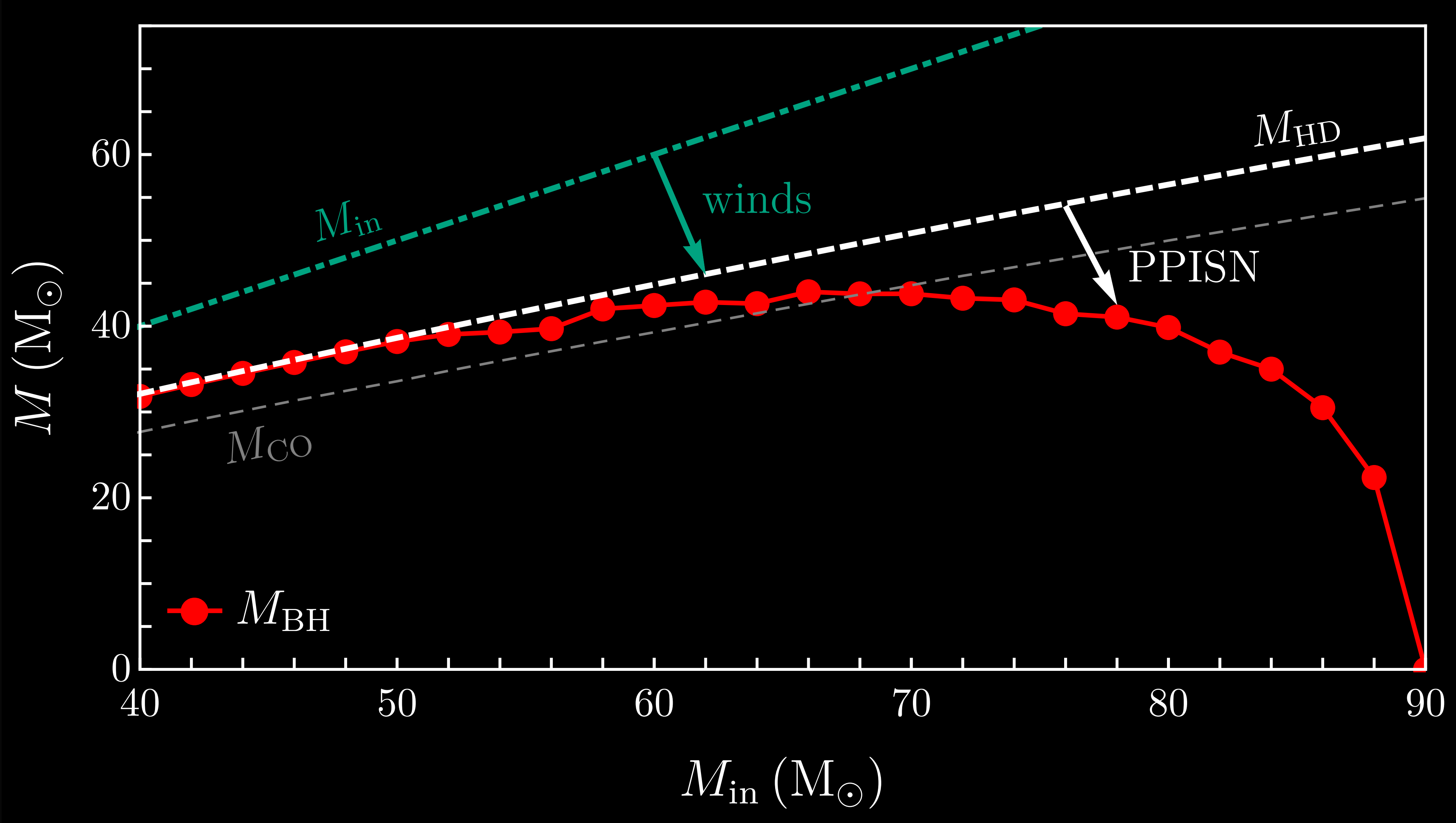
Resulting black hole masses



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

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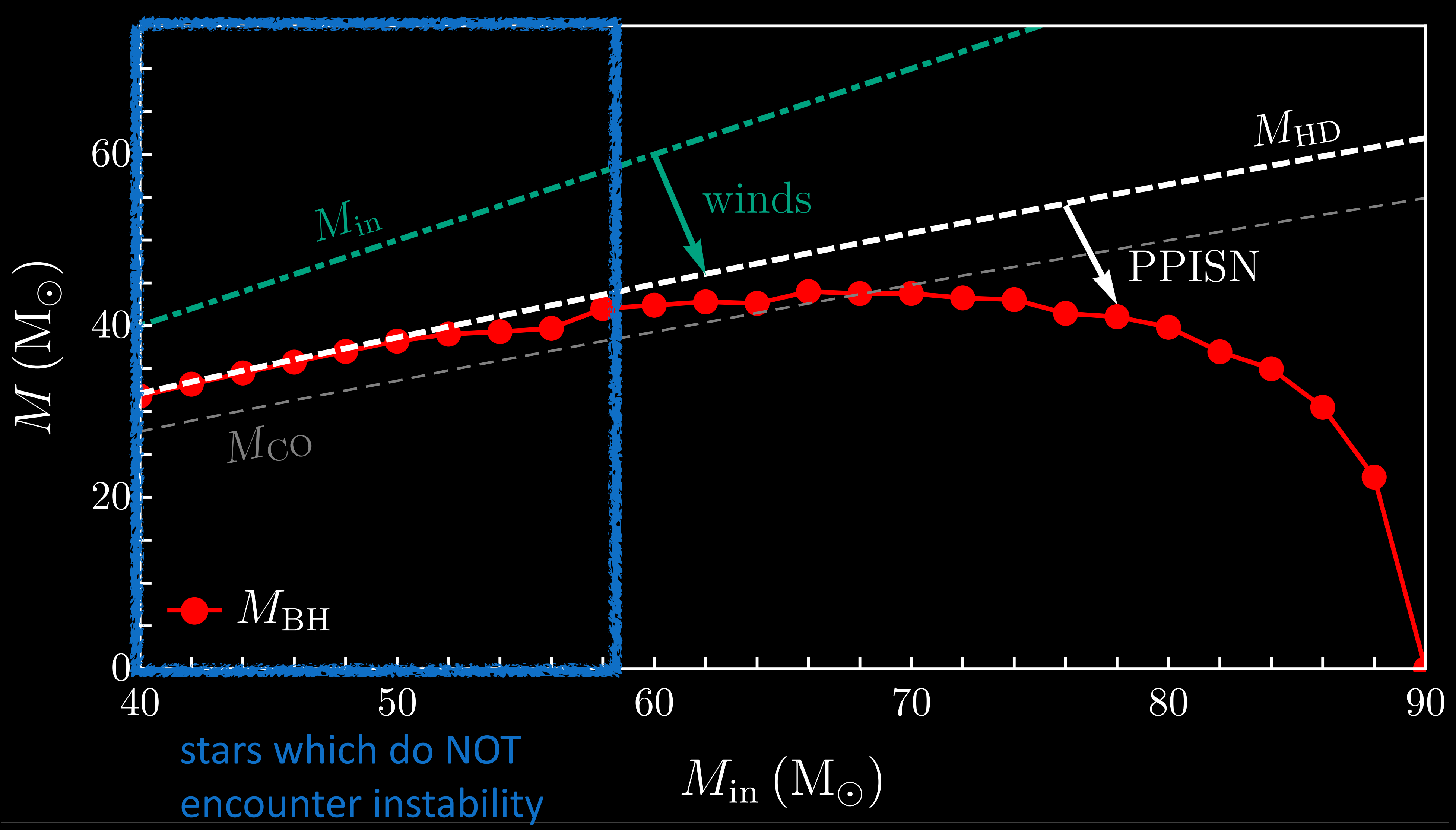

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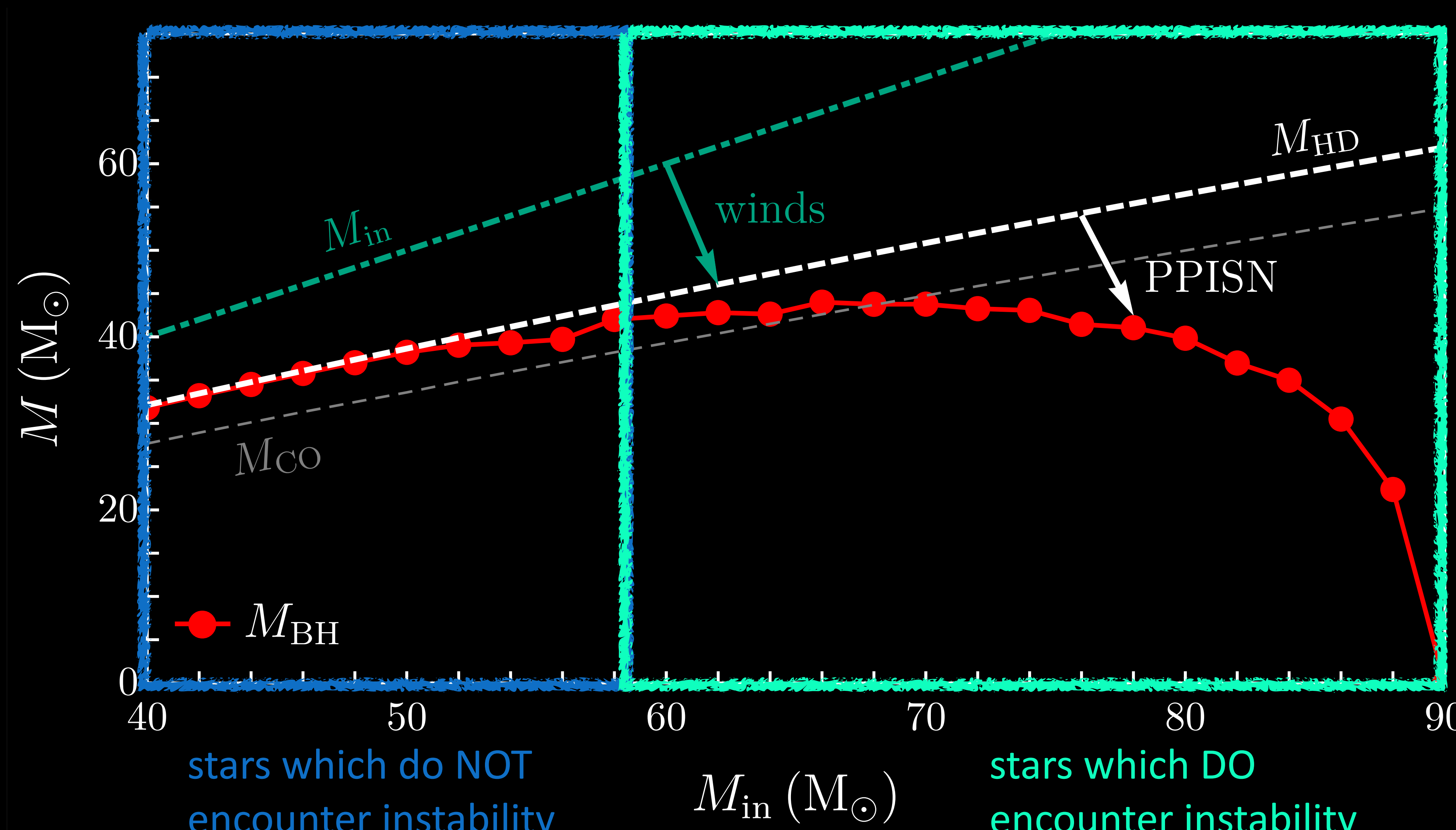

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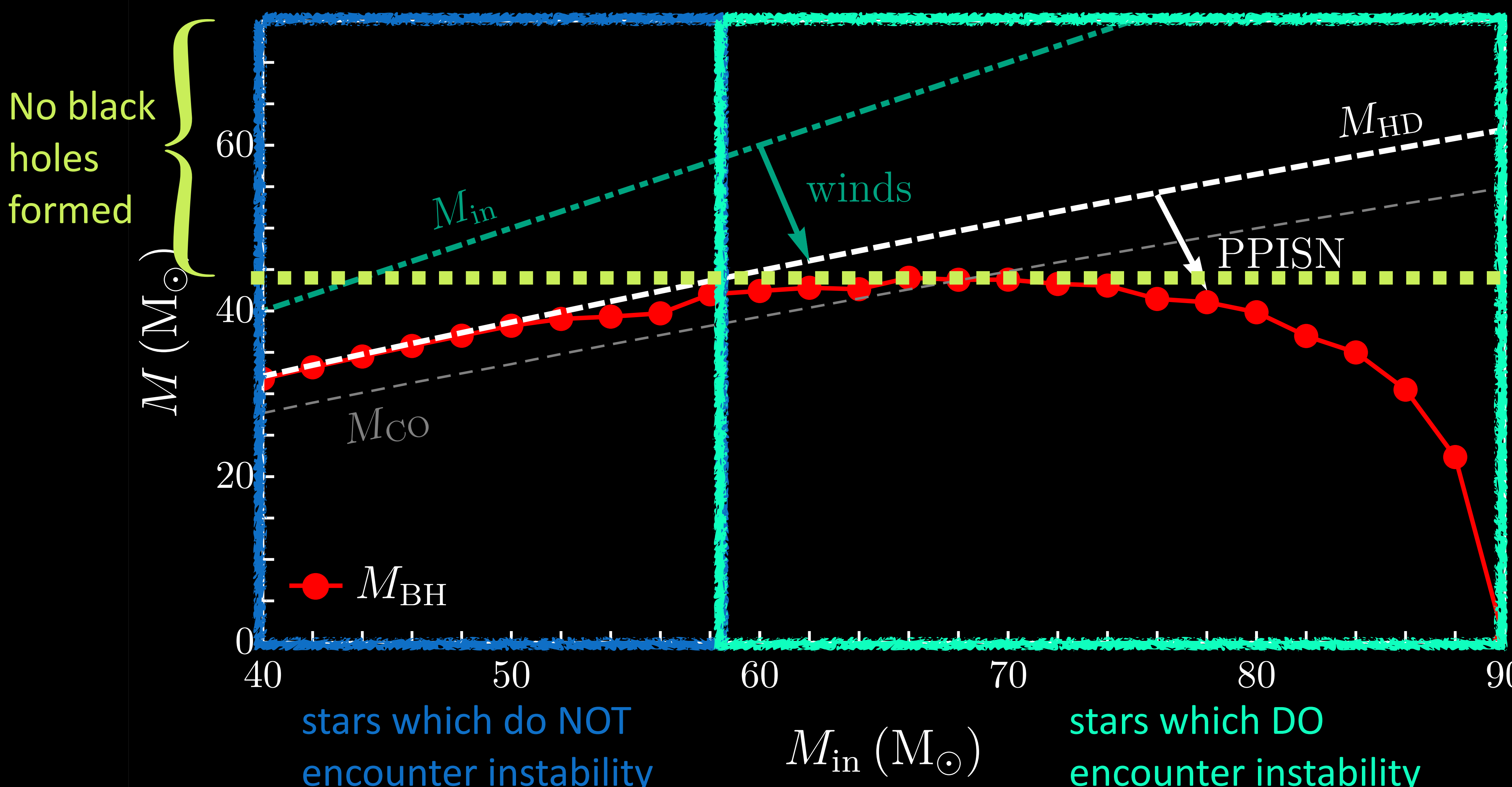

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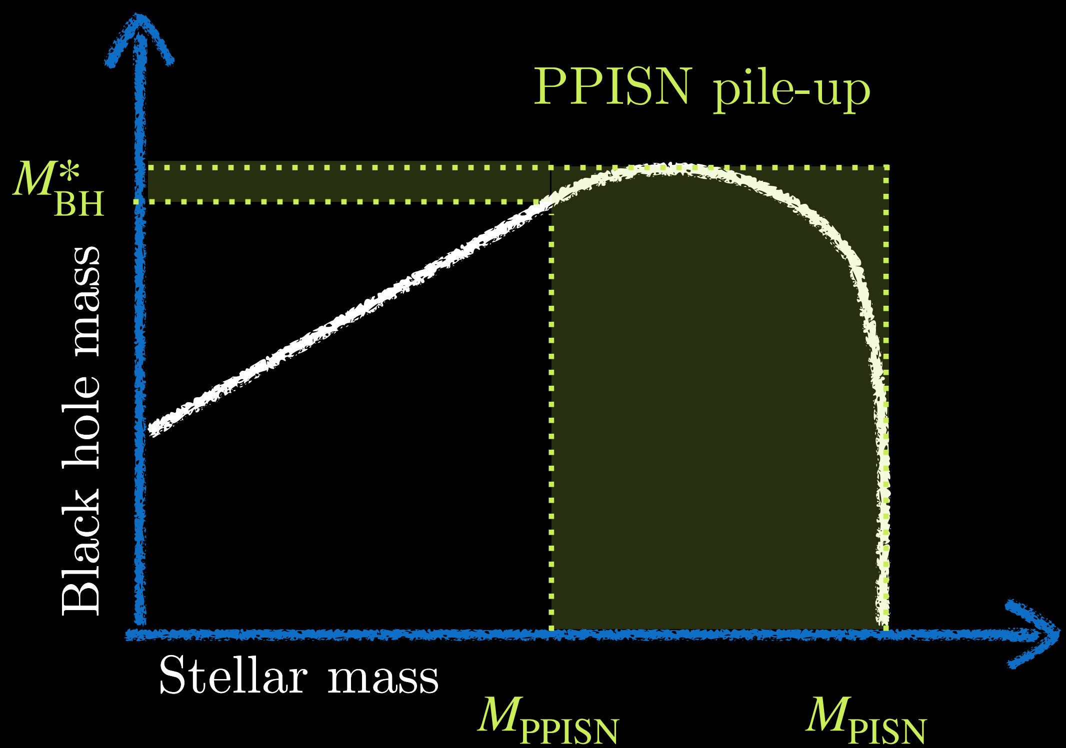
Pair-instability and black hole populations



See also Talbot & Trane, arXiv:1801.02699

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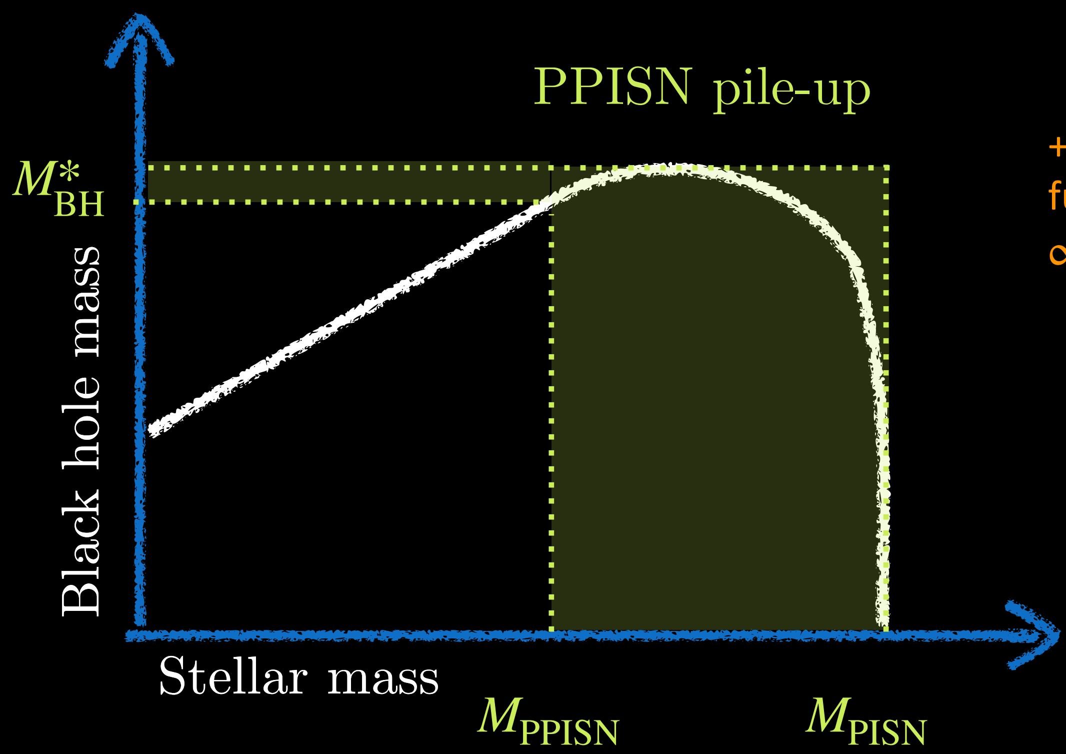
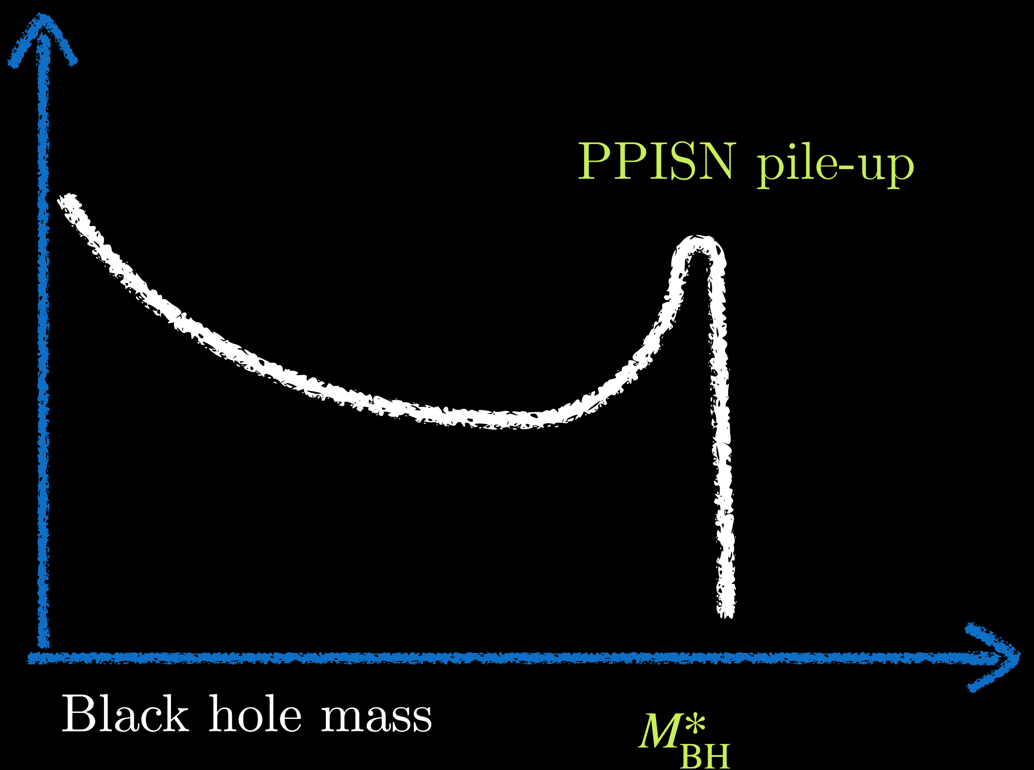


+ Initial mass function (here ∝ power law)



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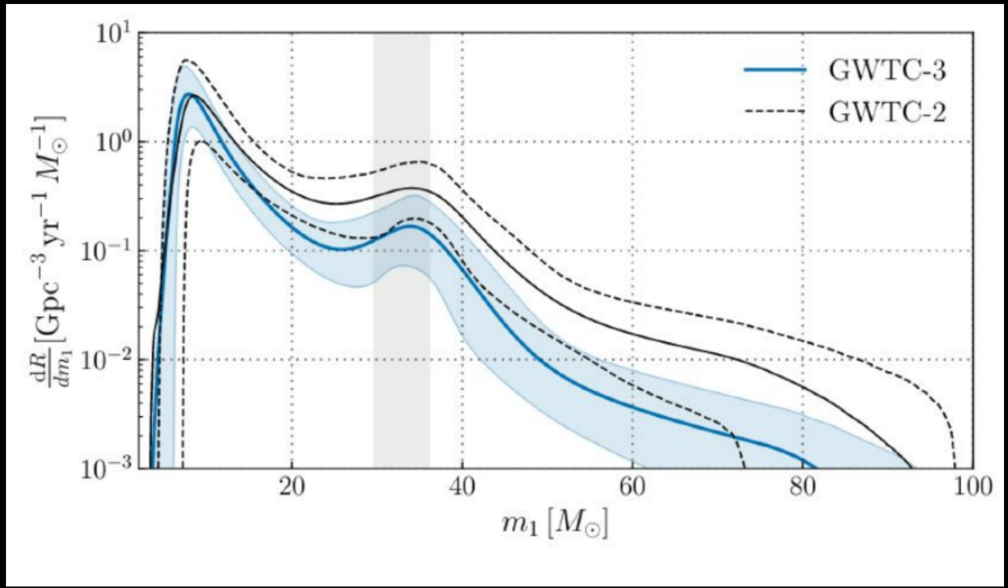
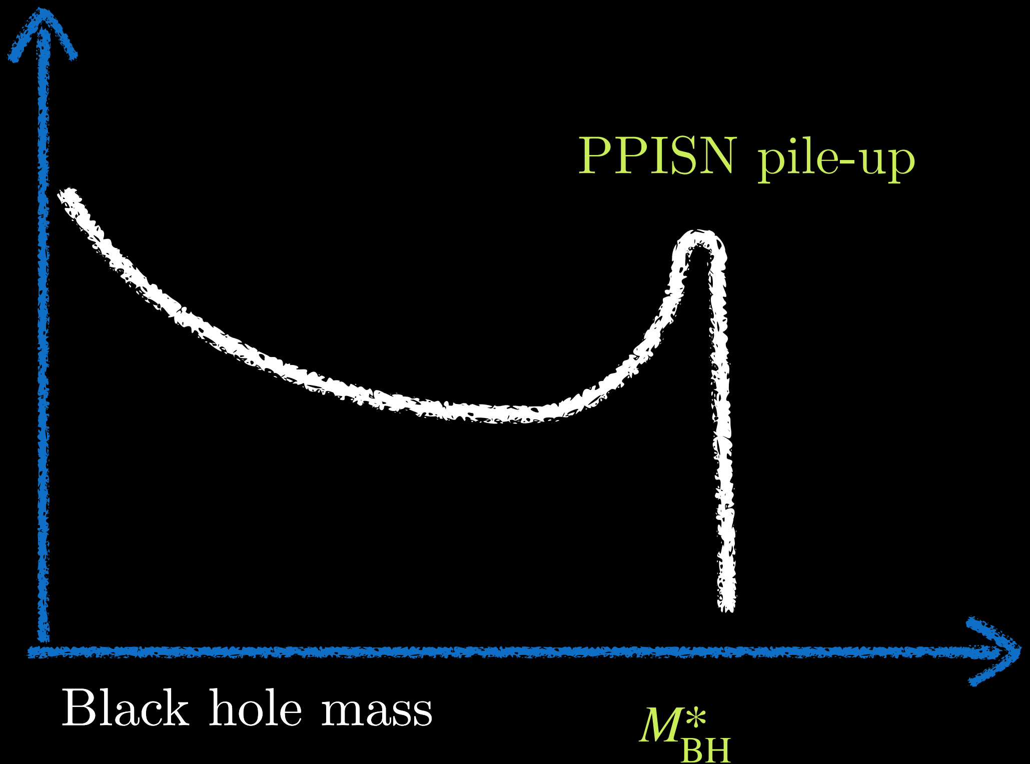
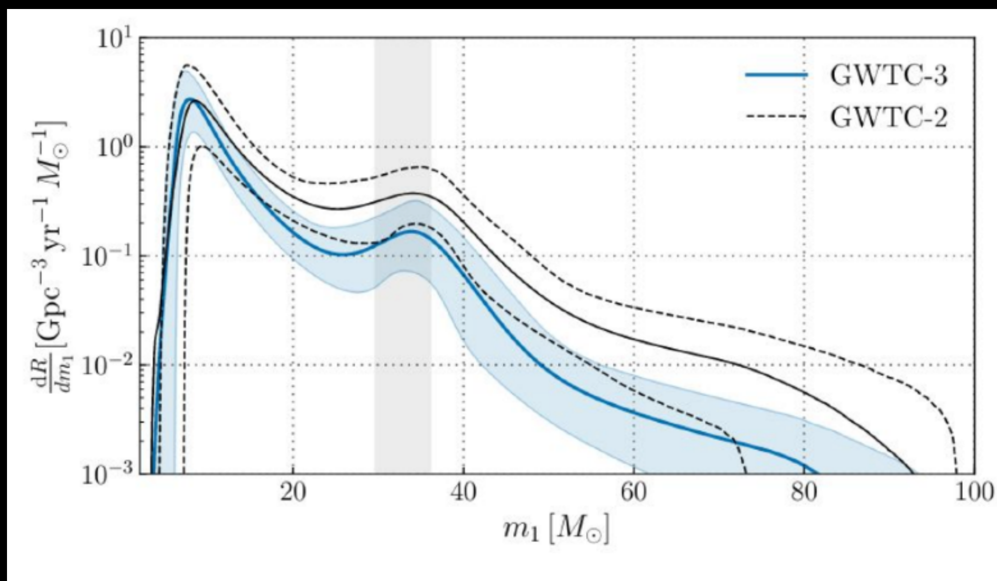
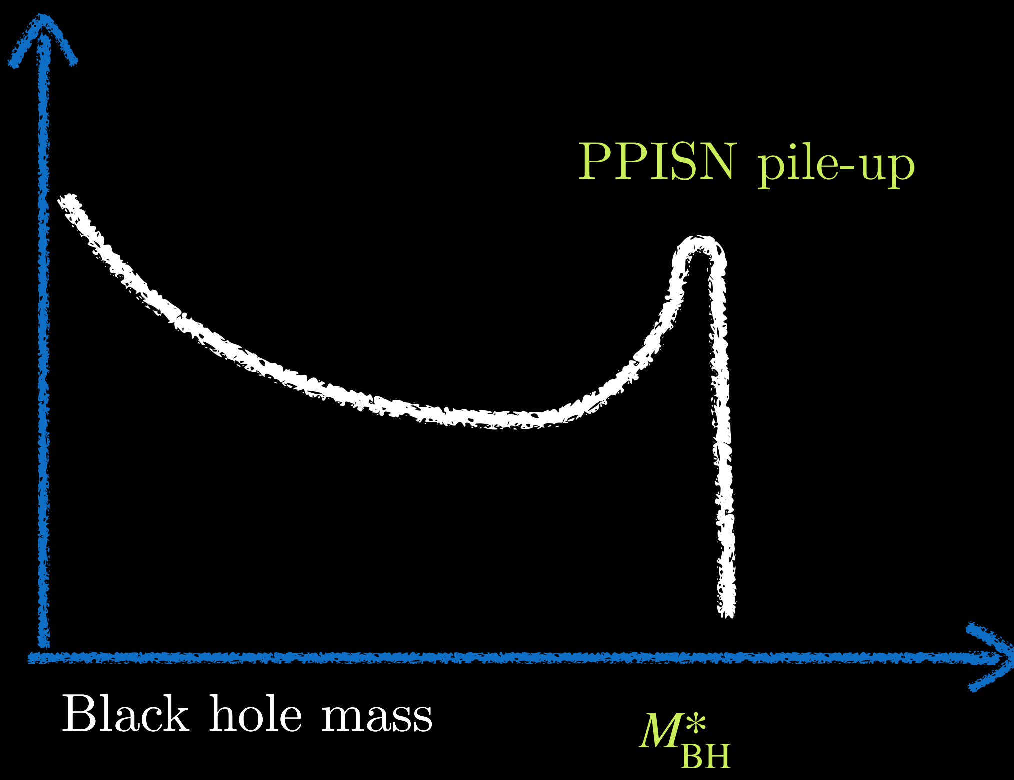




Does this explain the peak in the data?

Pair-instability and black hole populations



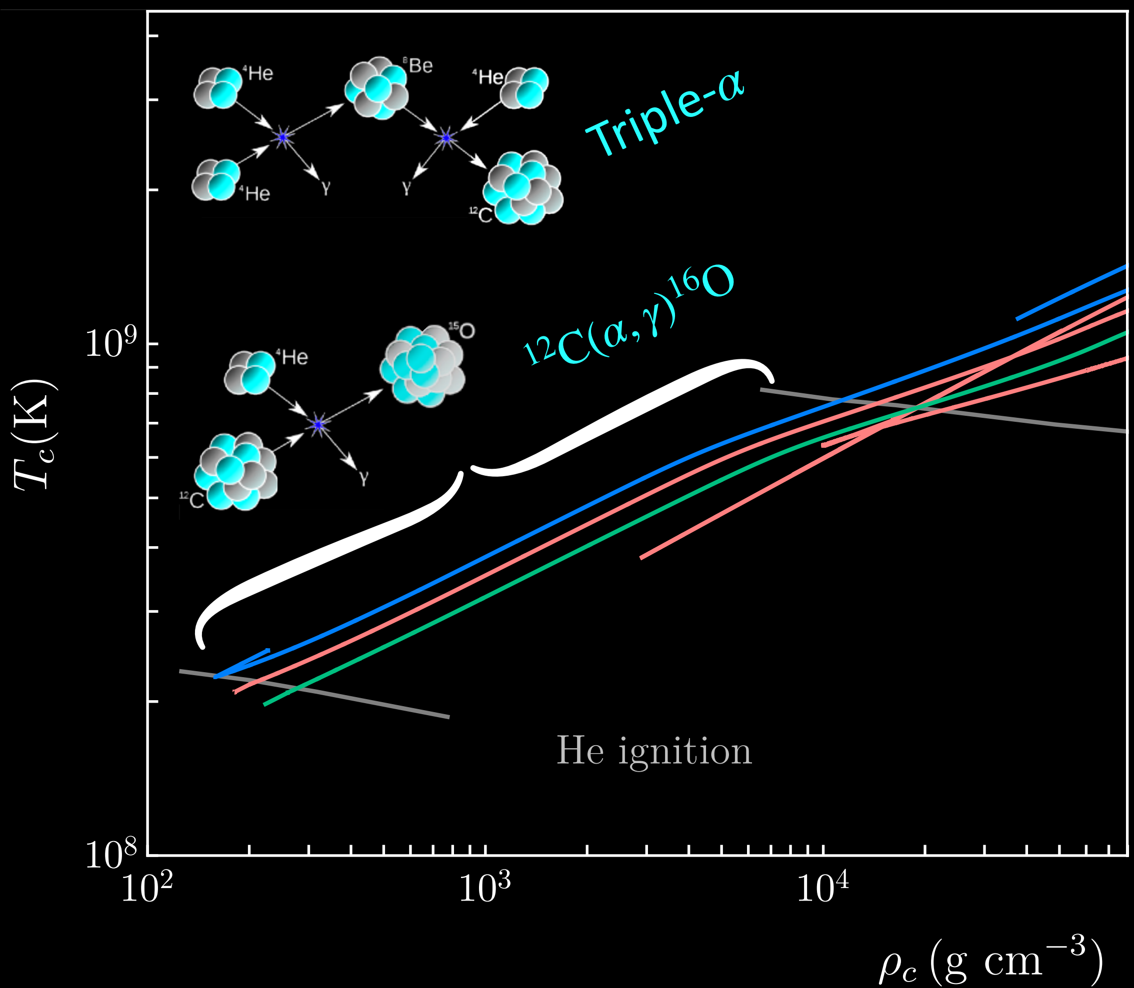


Does this explain the peak in the data?

Stellar evolution simulations put the PPISN mass gap at $\sim 45 - 60\,\mathrm{M}_\odot$

Nuclear physics

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



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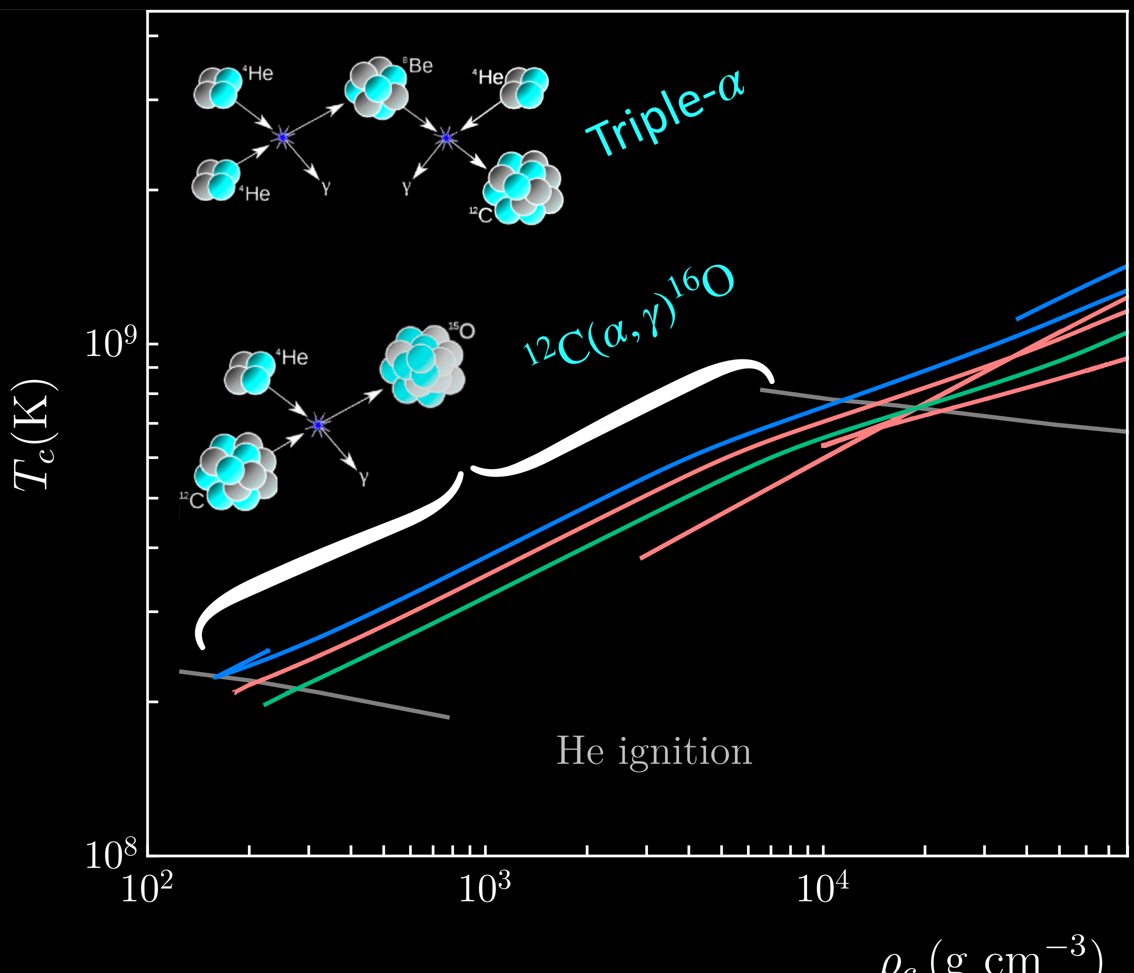
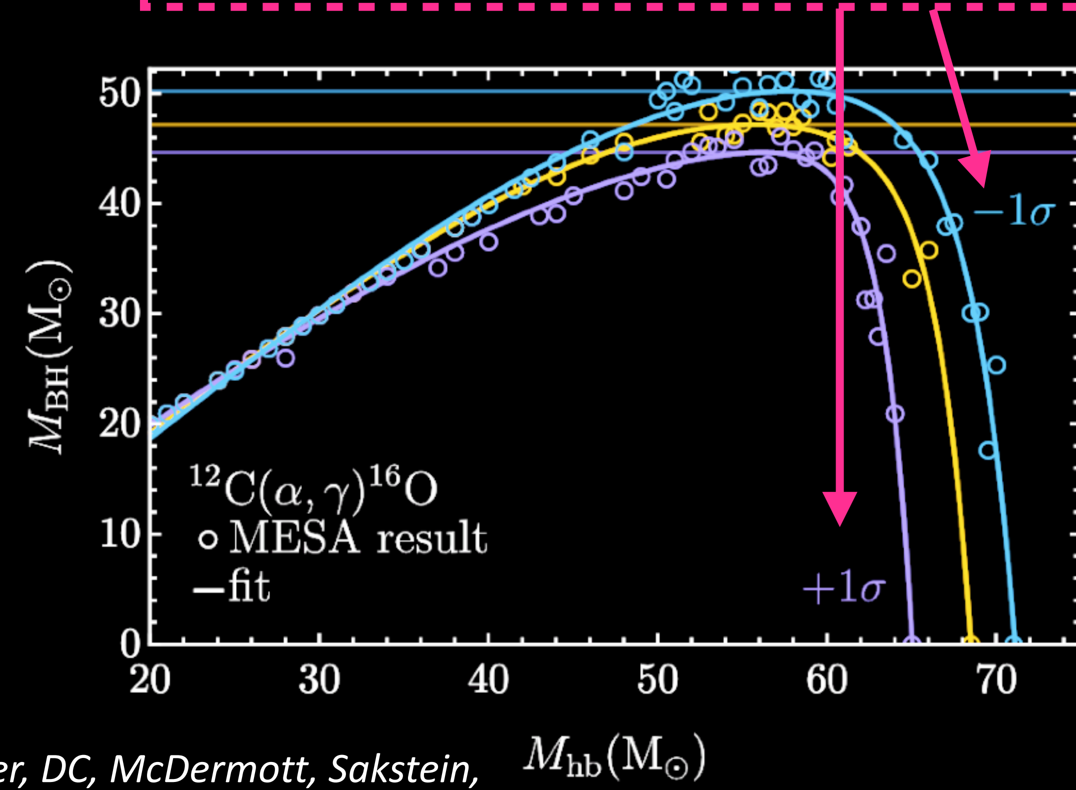


deBoer et al, RMP, arXiv:1709.03144 [hep-ex]



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

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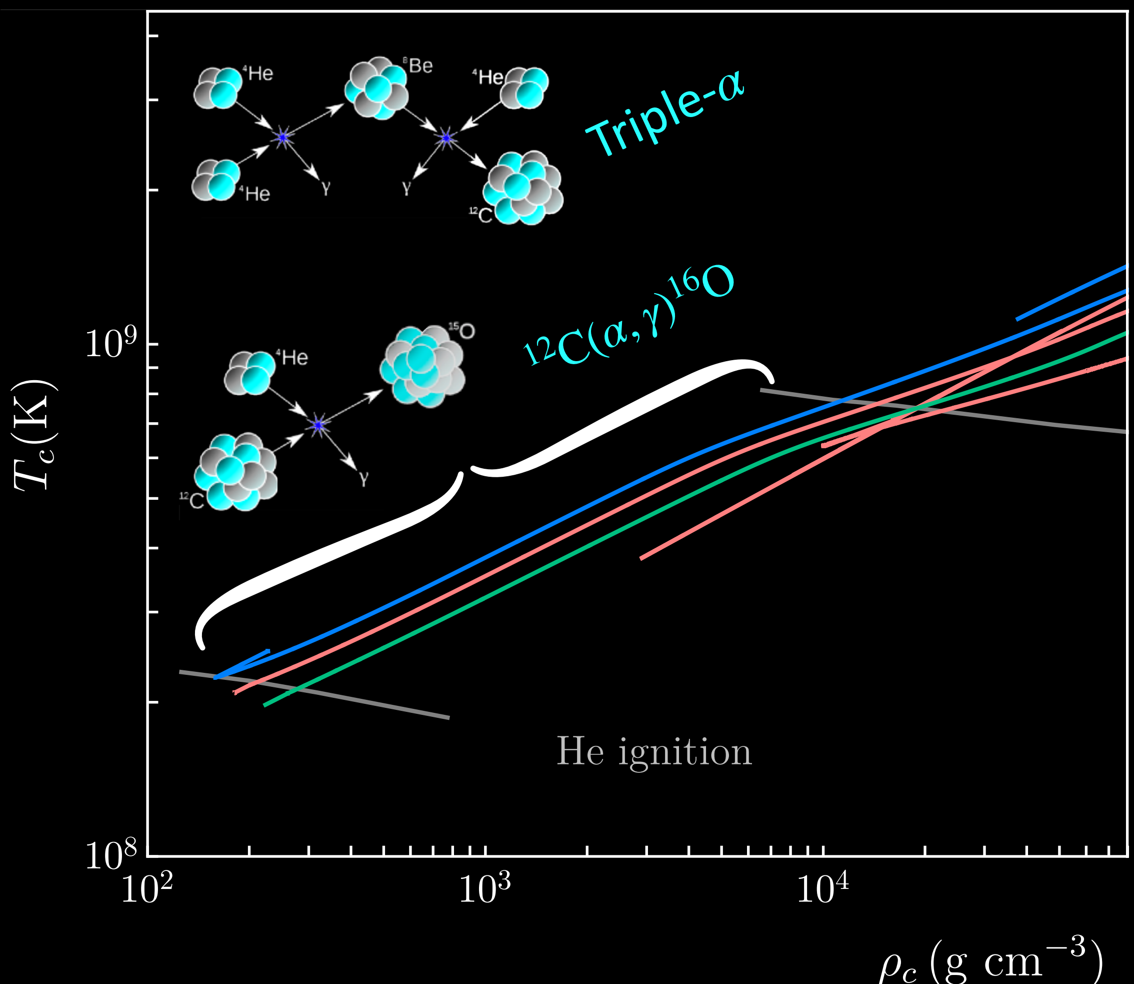

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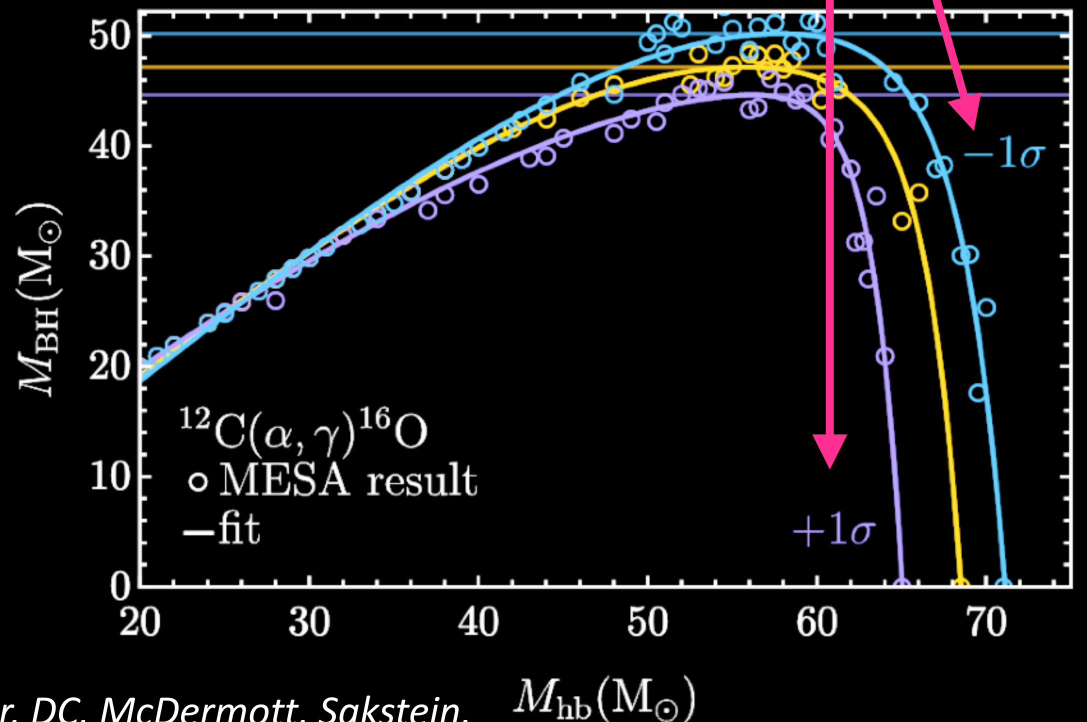
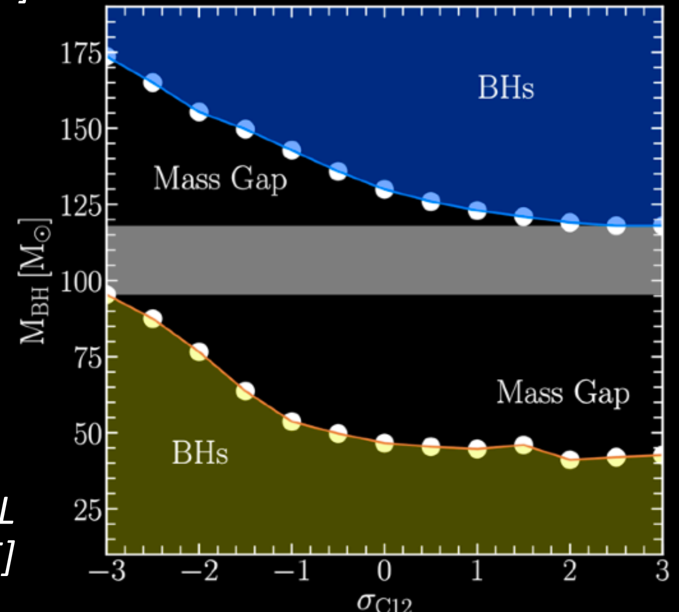


Baxter, DC, McDermott, Sakstein, ApJL, arXiv:2104.02685 [astro-ph.CO]

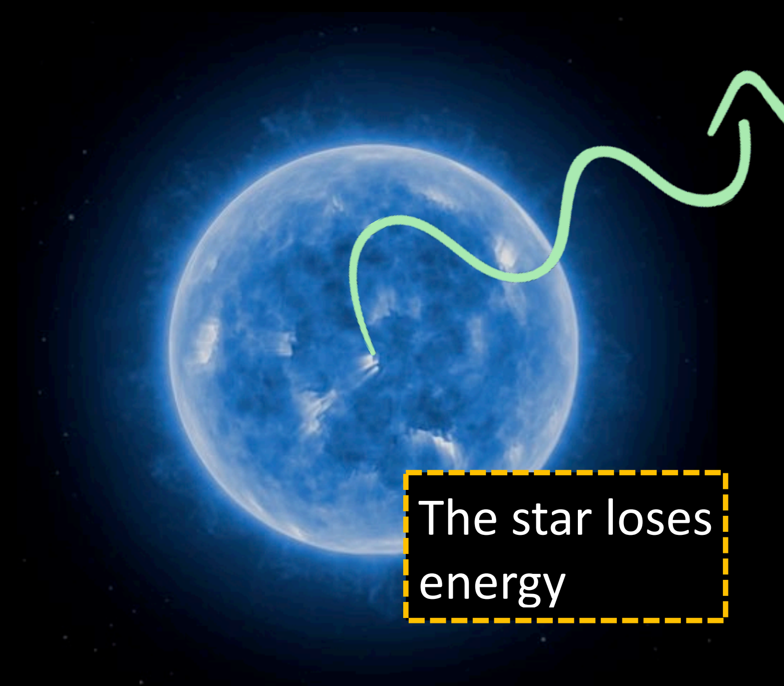


Farmer, Renzo, de Mink, Fishbach, Justham, ApJL arXiv:2006.06678 [astro-ph.HE]

What about new particles?

New particles…

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



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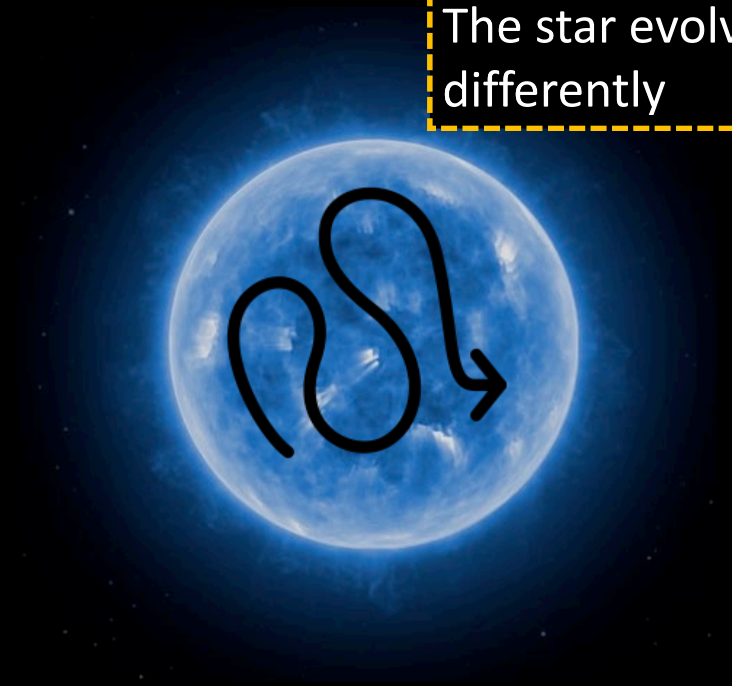
New particles...

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

The star evolves differently



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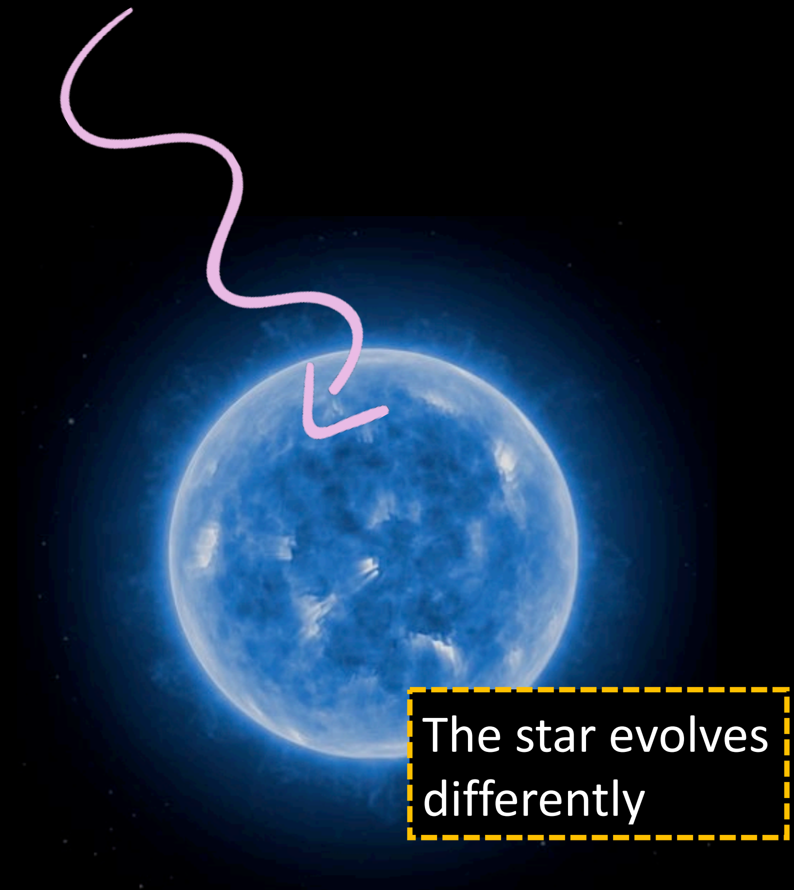
New particles…

- 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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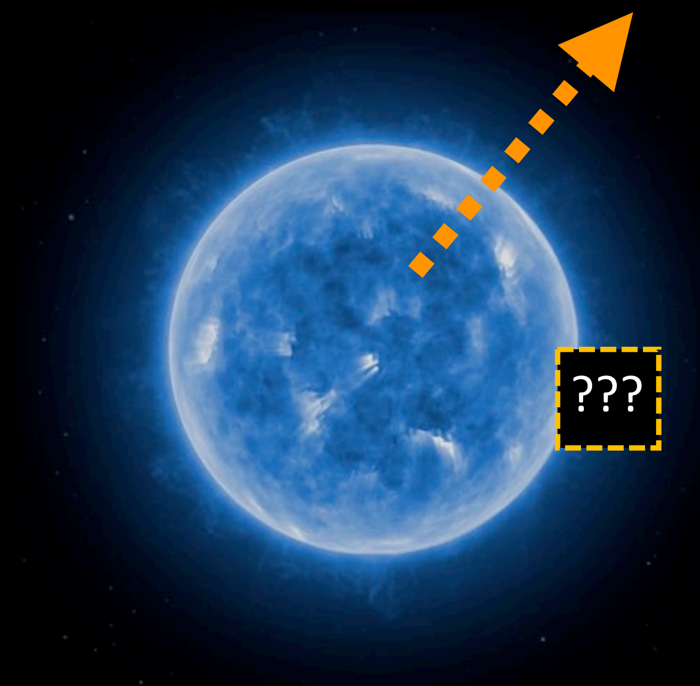

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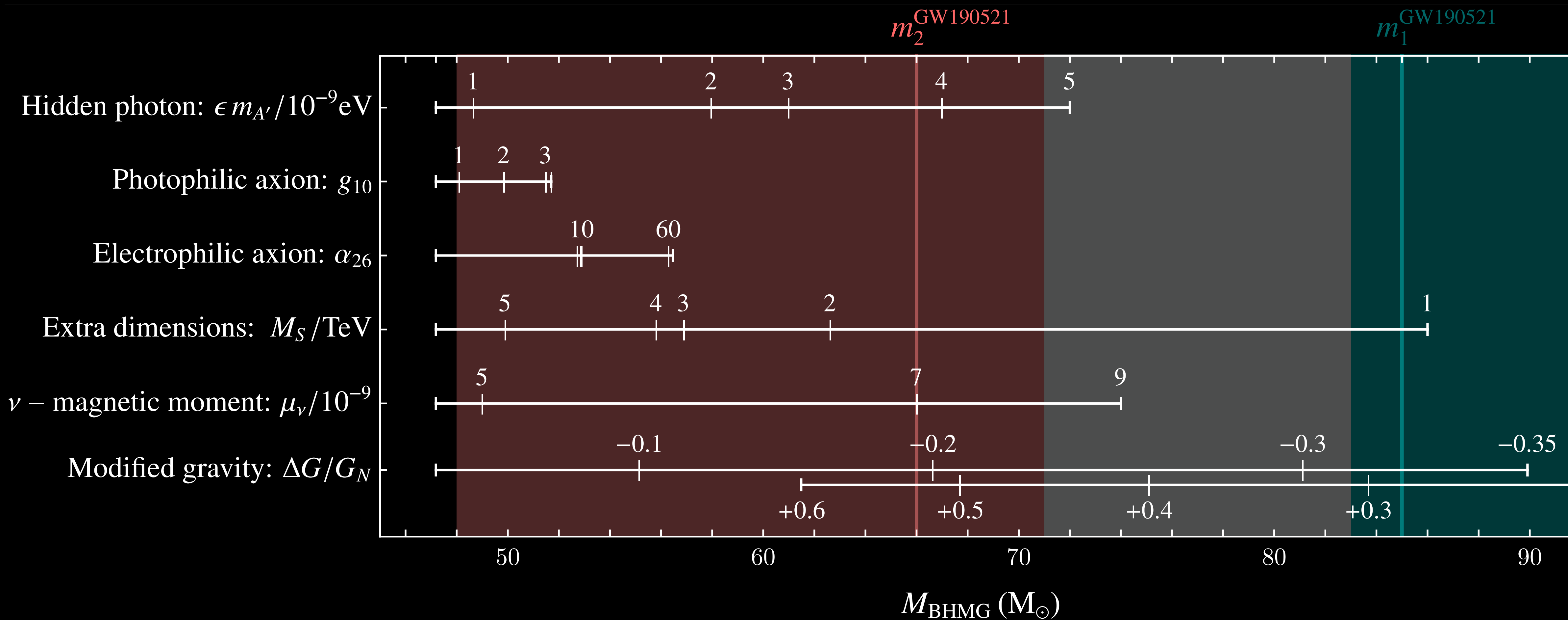
Gravity: the BHMG is a test of G_N in stellar cores

Straight, Sakstein, Baxter, arXiv: 2009.10716

Most new effects shift the mass gap *up*



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

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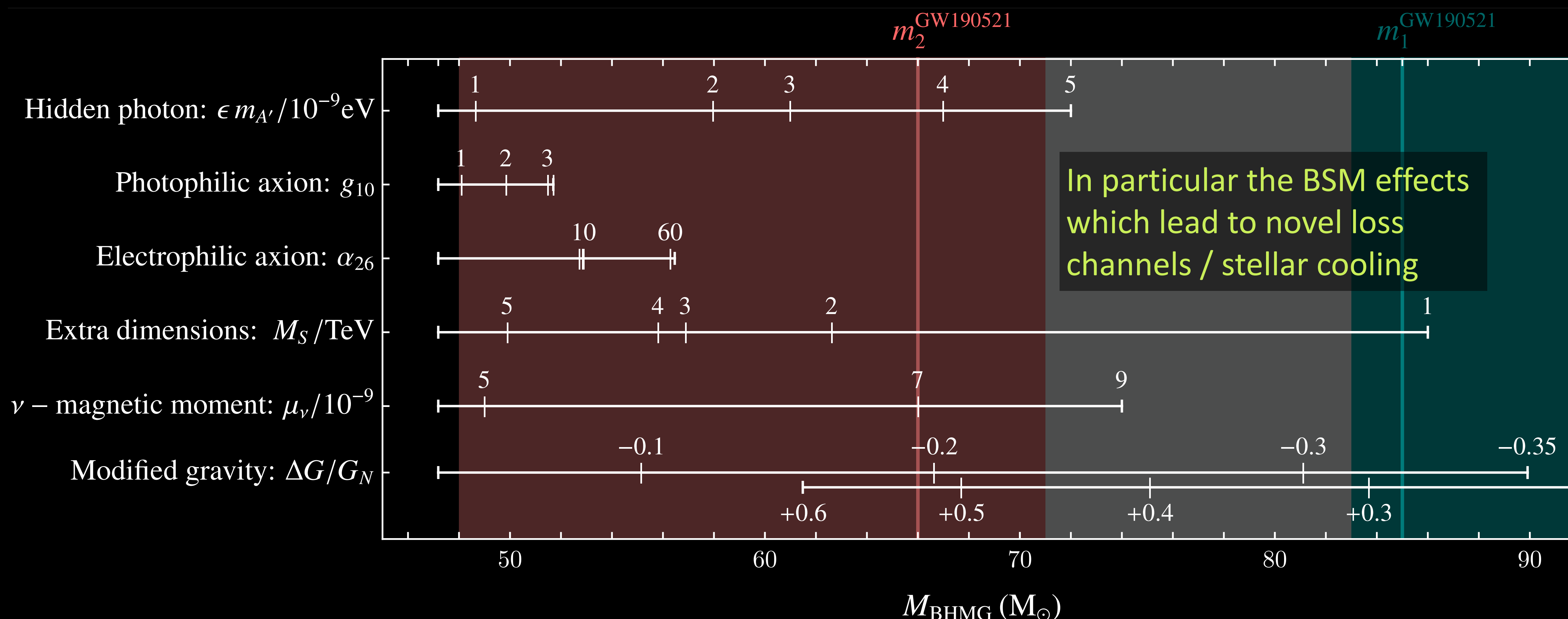

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Stellar response to energy loss/injection

A heuristic approach

Assumption: homologous transformation $r' = yr$

Assumption: chemically homogeneous star

- Energy generation $\epsilon \propto \rho^n T^\nu$
- Opacity $\kappa \propto \rho^s T^p$

DC and Sakstein, arXiv:2208.01110. Generalised from Frieman, Dimopoulos, and Turner, PRD (1987)

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The stellar structure equations are homologous for stars of a given chemical composition

- Conservation of mass: $\frac{dM}{dr} = 4\pi r^2 \rho$
- Hydrostatic equilibrium: $\frac{dp}{dr} = -\frac{GM\rho}{r^2}$
- Thermal equilibrium: $\frac{dL}{dr} = 4\pi r^2 \epsilon \rho$
- Radiative transfer: $\frac{dT}{dr} = -\frac{3\kappa\rho L}{16\pi r^2 T^3}$

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- Extra energy means that energy generation is modified:

$\epsilon = \epsilon_{\rm nuc} - \epsilon_{\rm grav} - \epsilon_{\rm neutrino} + \epsilon_{\rm DM} \equiv \left(1 - \sum \delta\right) \epsilon_{\rm nuc}$ with

$\delta \equiv \delta_{\rm grav} + \delta_{\rm neutrino} - \delta_{\rm DM}$

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$$\delta \equiv \delta_{\rm grav} + \delta_{\rm neutrino} - \delta_{\rm DM}$$

- Equating $L'(r')$ from radiative transfer and energy generation equations,

$$y = \left(1 - \sum \delta\right)^{\frac{1}{3s+p+3n+\nu}}$$

DC and Sakstein, arXiv:2208.01110. Generalised from Frieman, Dimopoulos, and Turner, PRD (1987)

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$$\frac{\delta R}{R}=\frac{-\sum\delta}{3s+p+3n+\nu},\quad \frac{\delta L}{L}=\frac{-(3s+p)\sum\delta}{3s+p+3n+\nu},\quad \frac{\delta T}{T}=\frac{\sum\delta}{3s+p+3n+\nu}$$

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Post-MS evolution of a high mass star: $\kappa \approx$ constant due to electron scattering $\rightarrow s = 0, p = 0$

CNO cycle: $\nu = 17, n = 1$
Tripple-α: $\nu = 40, n = 2$

$$\frac{\delta R}{R} = \mathrm{sign}(\delta), \quad \frac{\delta L}{L} = 0, \quad \frac{\delta T}{T} = -\,\mathrm{sign}(\delta)$$

For injection: radius increases, temperature decreases
For new losses: radius decreases, temperature increases

DC and Sakstein, arXiv:2208.01110. Generalised from Frieman, Dimopoulos, and Turner, PRD (1987)

Stellar cooling and the BHMG

Enhanced losses → faster evolution → larger C/O at HD

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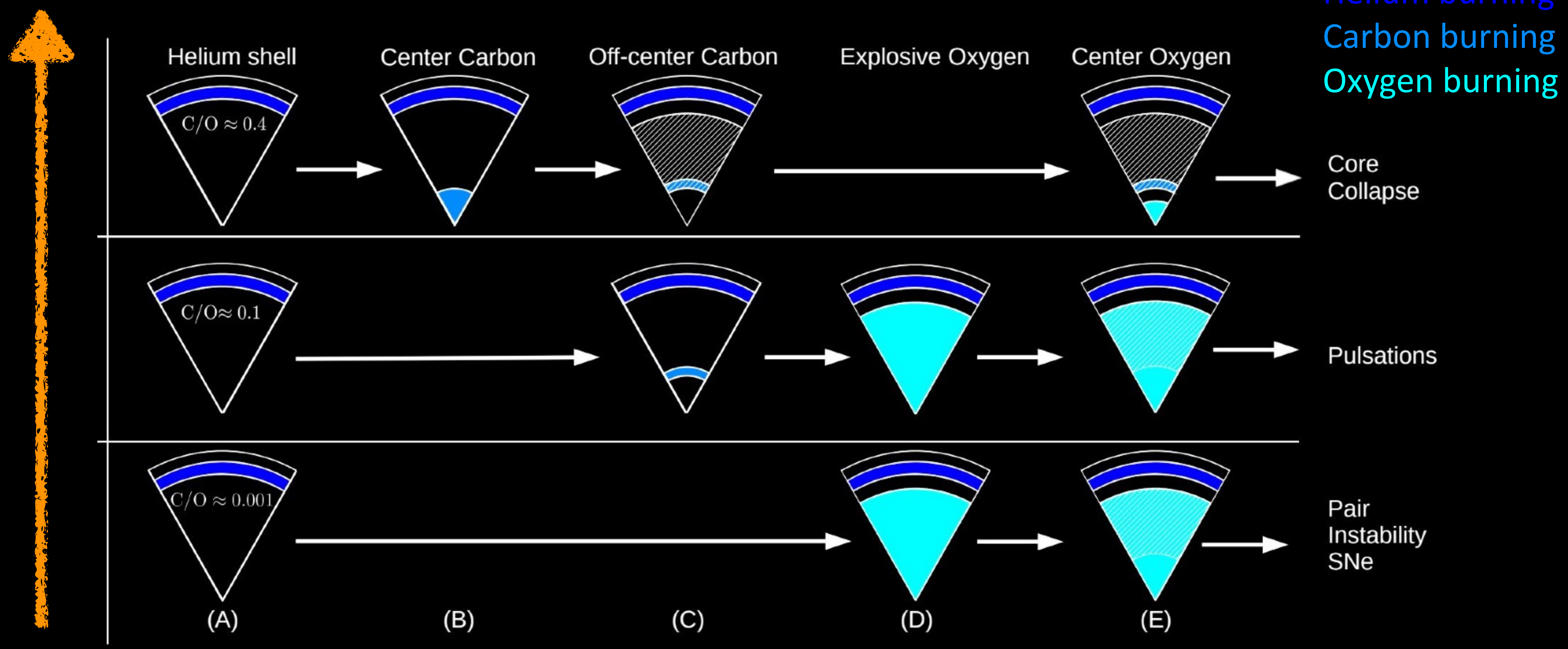

Larger C/O at HD → greater progenitors collapse → larger black holes

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

What about new particles?

Maybe it is natural to look at energy injection...

New particles...

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Recent claim: (P)PISN can be *avoided altogether* by DM annihilation in Pop-III stars

Freese and Ziegler, arXiv:2212.13903

Dark matter in stars

- Distribution:

Gould & Raffelt, ApJ, 1990

  - local thermal equilibrium $\left(\frac{n_{\rm DM}(r)}{n_{\rm DM}(0)}\right)_{\rm LTE} = \left(\frac{T(r)}{T(0)}\right)^{3/2} e^{-\int_0^r d\tilde{r}\,\frac{\alpha(\tilde{r})dT/d\tilde{(r)} + m_{\rm DM}g(\tilde{r})}{T(\tilde{r})}}$
  - isothermal $\left(\frac{n_{\rm DM}(r)}{n_{\rm DM}(0)}\right)_{\rm ISO} = \frac{e^{-(r/r_{\rm DM})^2}}{r_{\rm DM}^3\pi^{3/2}}, \quad r_{\rm DM} = \sqrt{\frac{3kT_c}{2\pi G_N \rho_c m_{\rm DM}}}$

Spergel & Press, ApJ, 1985

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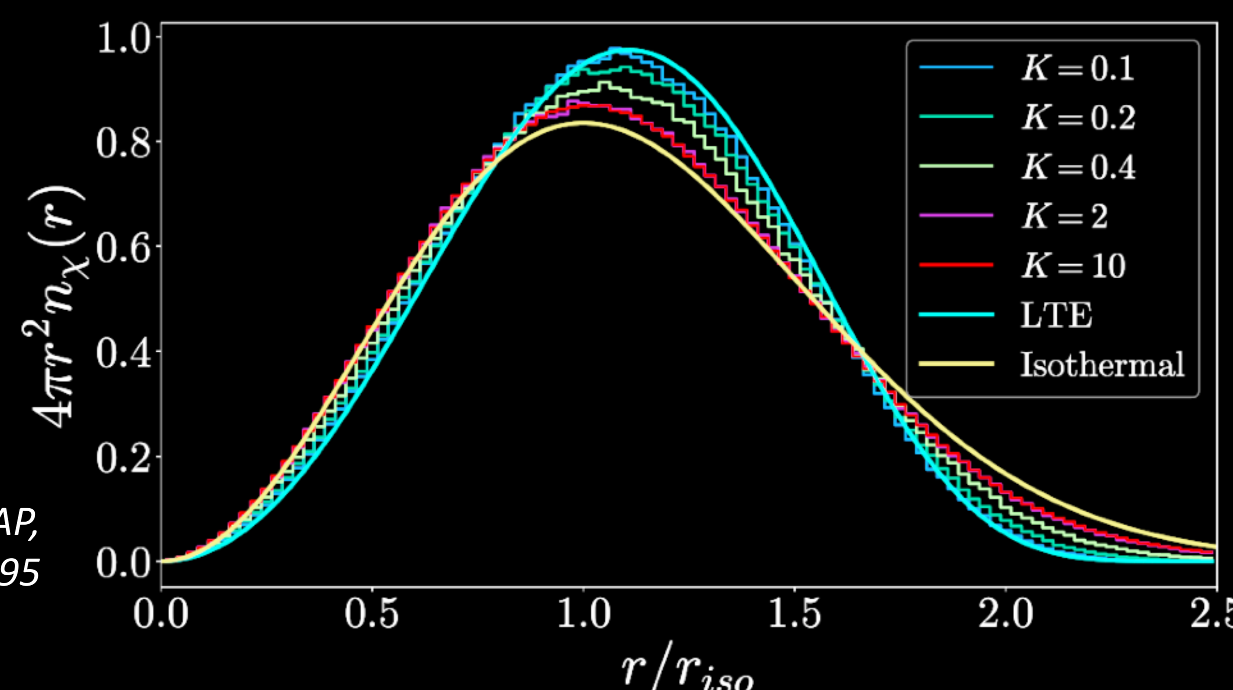
Spergel & Press, ApJ, 1985

- Knudsen numbers
  $K = \lambda(r=0)/r_{\rm DM}$

Banks, Ansari, Vincent, Scott, JCAP, arXiv:2111.06895



Dark matter in stars

- Maximum injection (without depletion): annihilation equilibrium

$$N_{\rm DM} = \sqrt{\Gamma_{\rm cap} N_{\rm DM}^2 / \Gamma_{\rm ann}} \equiv \sqrt{C_{\rm cap}/C_{\rm ann}}$$

- Energy injection then depends on the capture rate:

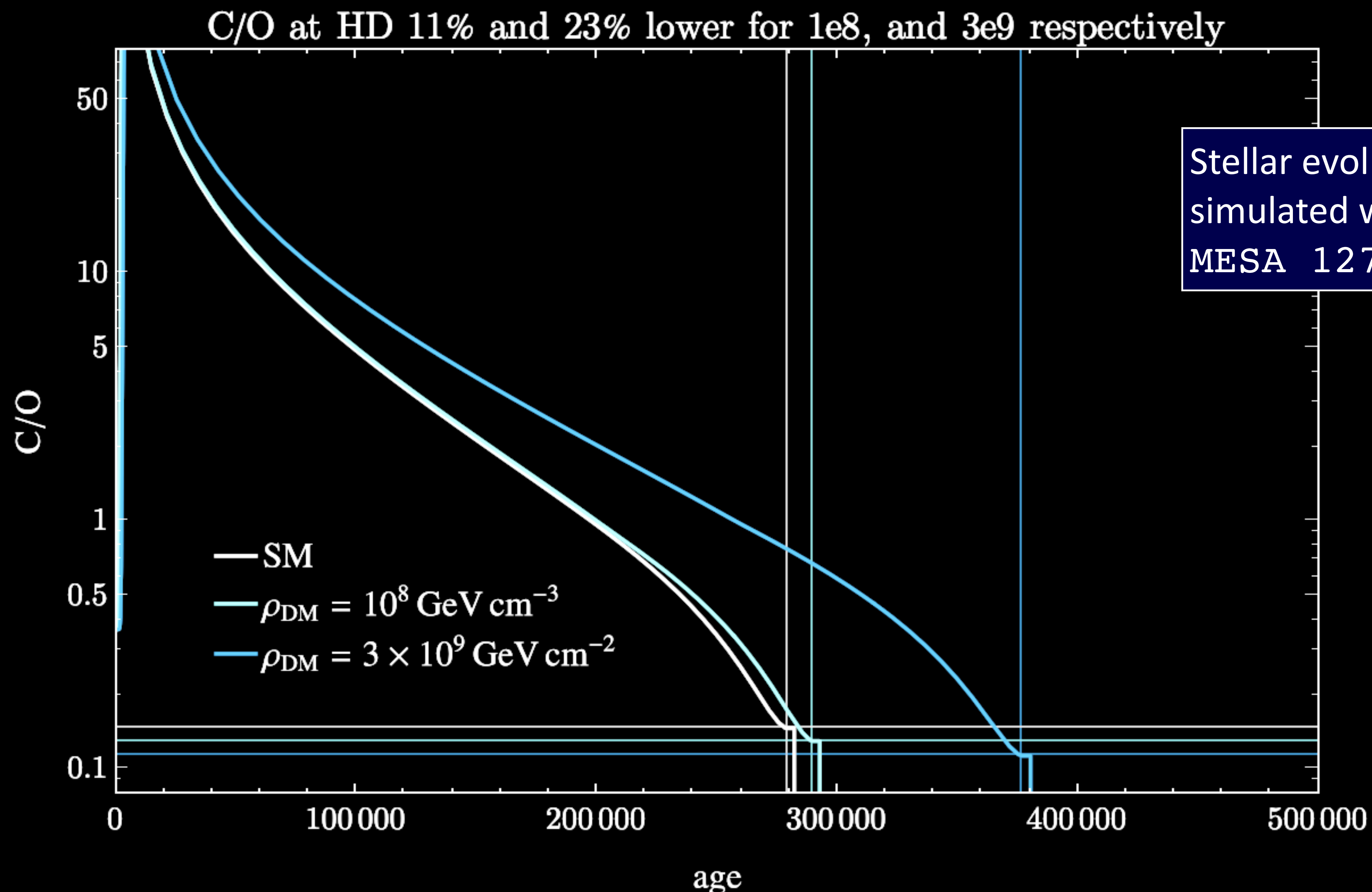
$$\epsilon_{\rm DM} = C_{\rm cap} \frac{\bar{n}_{\rm DM}^2(r)}{\rho(r)} \quad \text{where} \quad \bar{n}_{\rm DM}(r) = \frac{n_{\rm DM}(r)}{N_{\rm DM}}$$

- If all DM is captured,

$$C_{\rm cap} = \Phi \pi R^2 = \pi R^2 v_{\rm DM} \sqrt{\frac{8}{3\pi}} \left[1 + \frac{3}{2} \left(\frac{v_{\rm esc}}{v_{\rm DM}} \right)^2 \right] \frac{\rho_{\rm DM} f_{\rm cap}}{m_{\rm DM}}$$

DC & Sakstein, 2023

Preliminary results: reduced C/O in cores



Stellar evolution simulated with `MESA 12778`*

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

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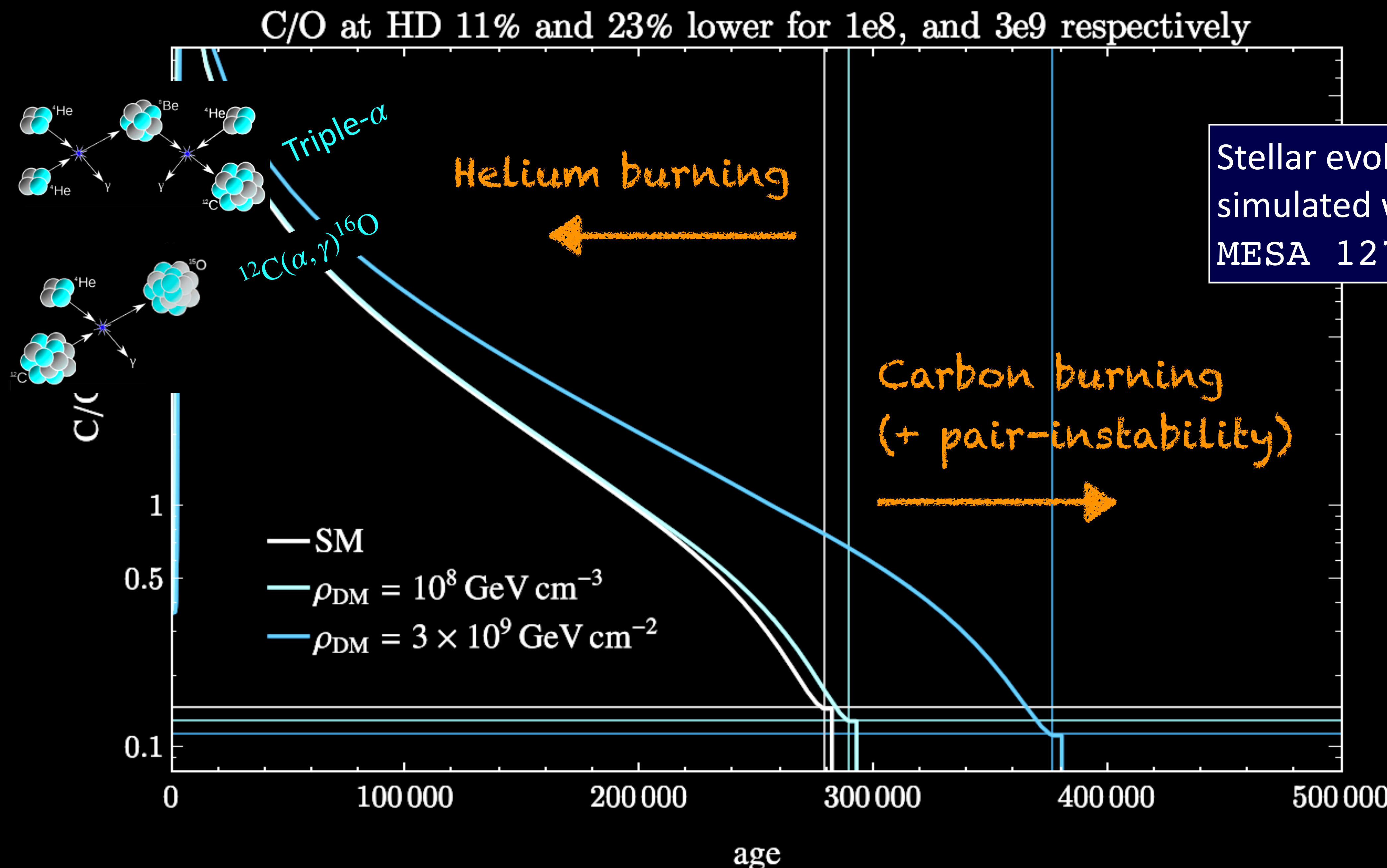

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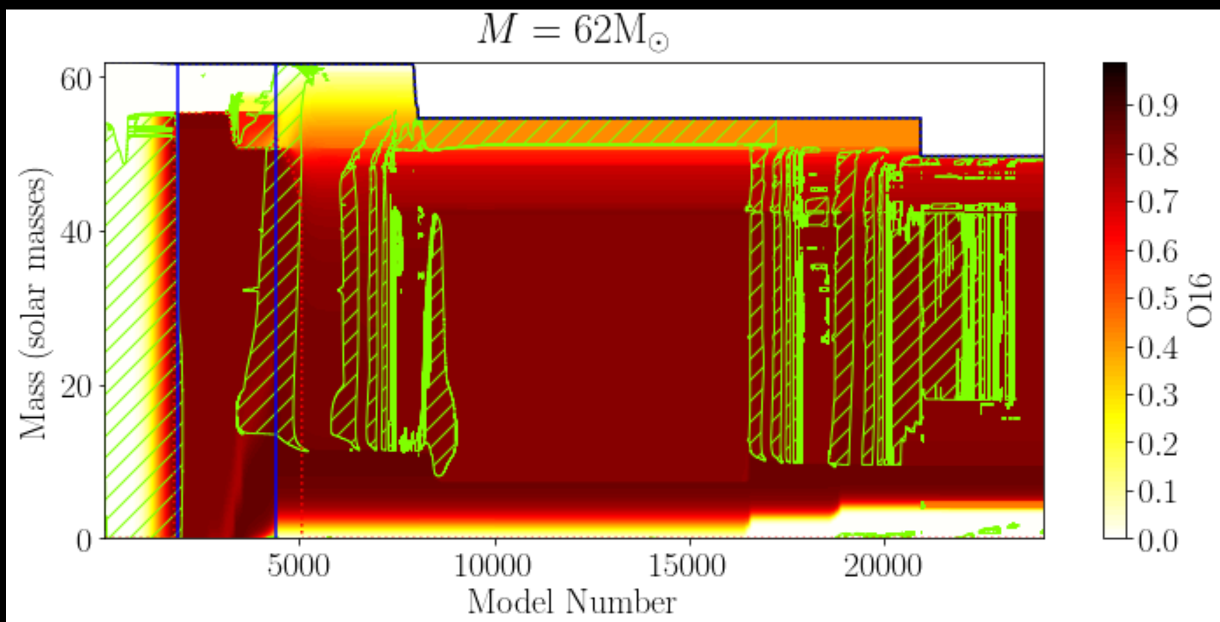
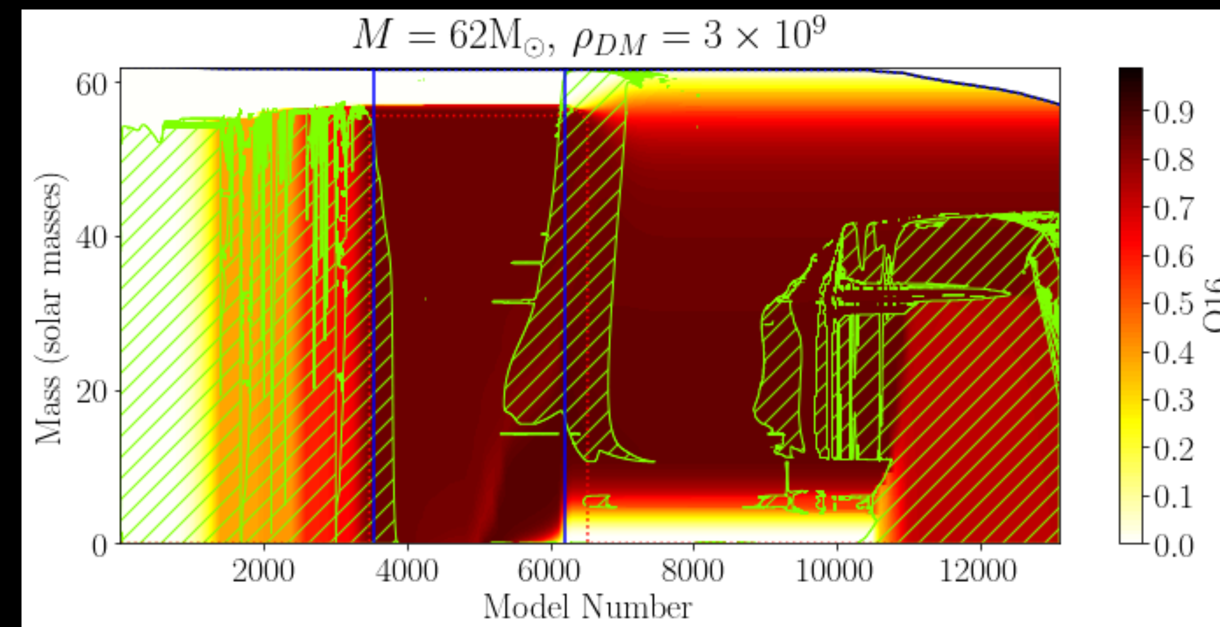
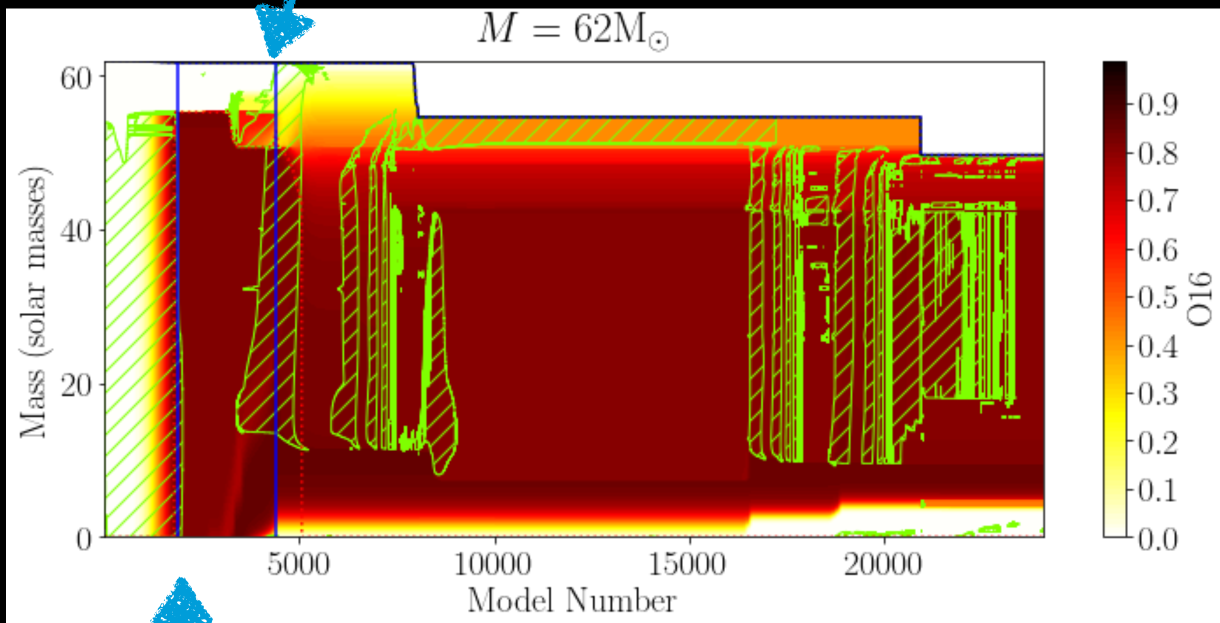


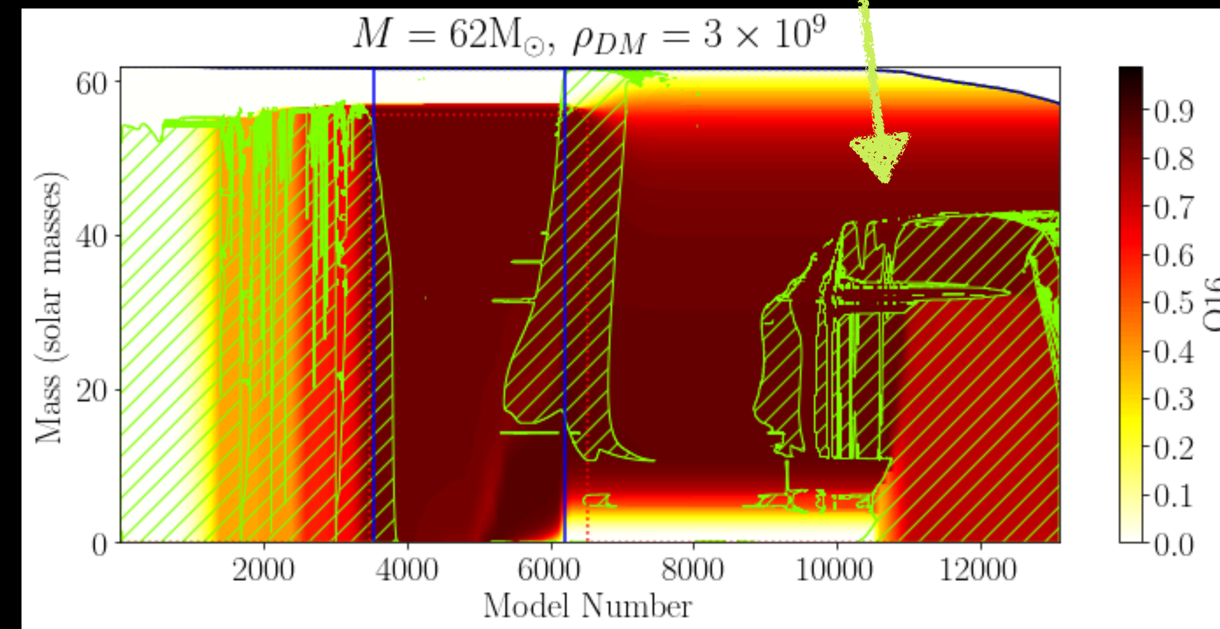


Preliminary results: O^{16} transport

First collapse

Convective transport





Helium depletion

DC & Sakstein, 2023

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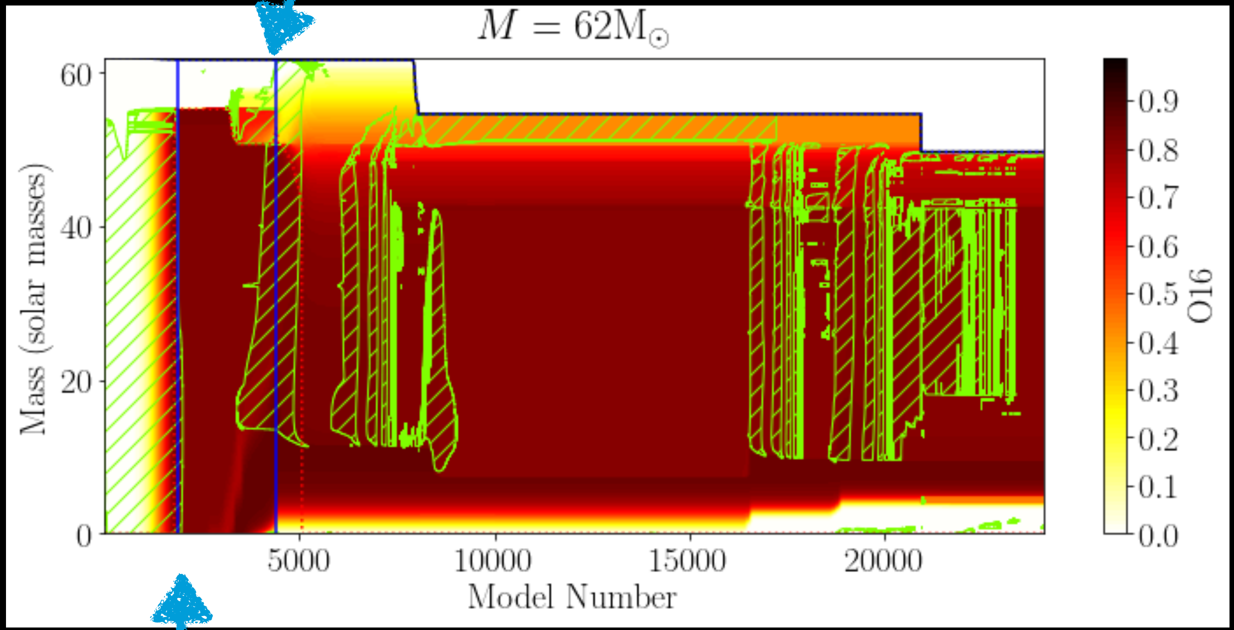

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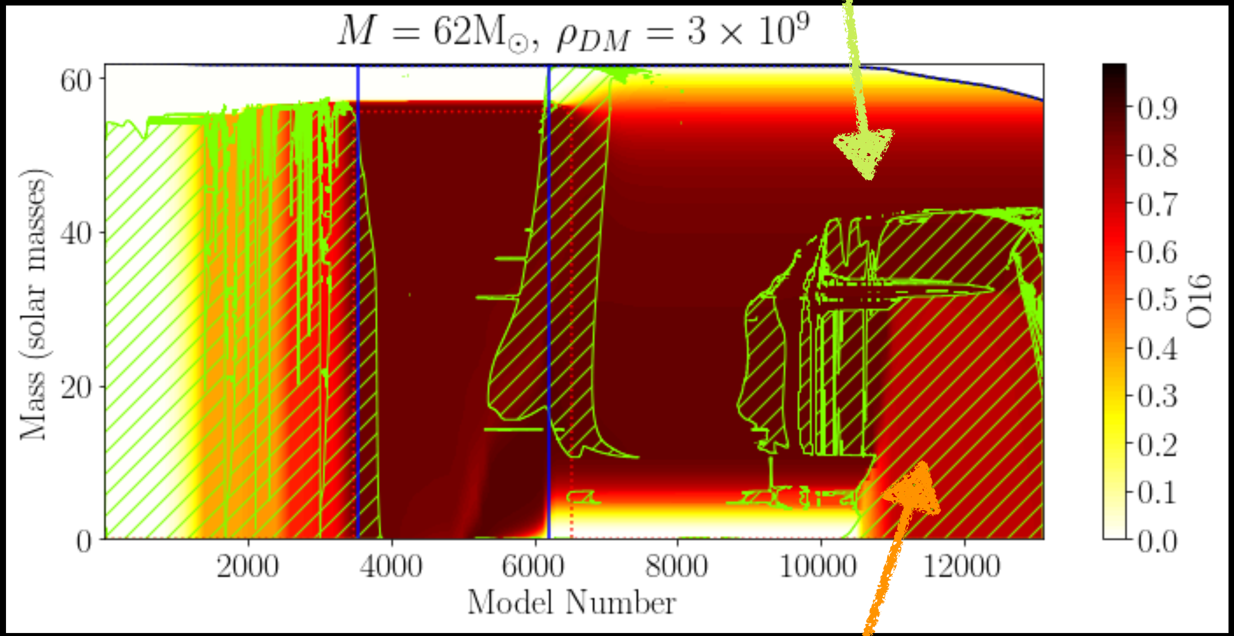
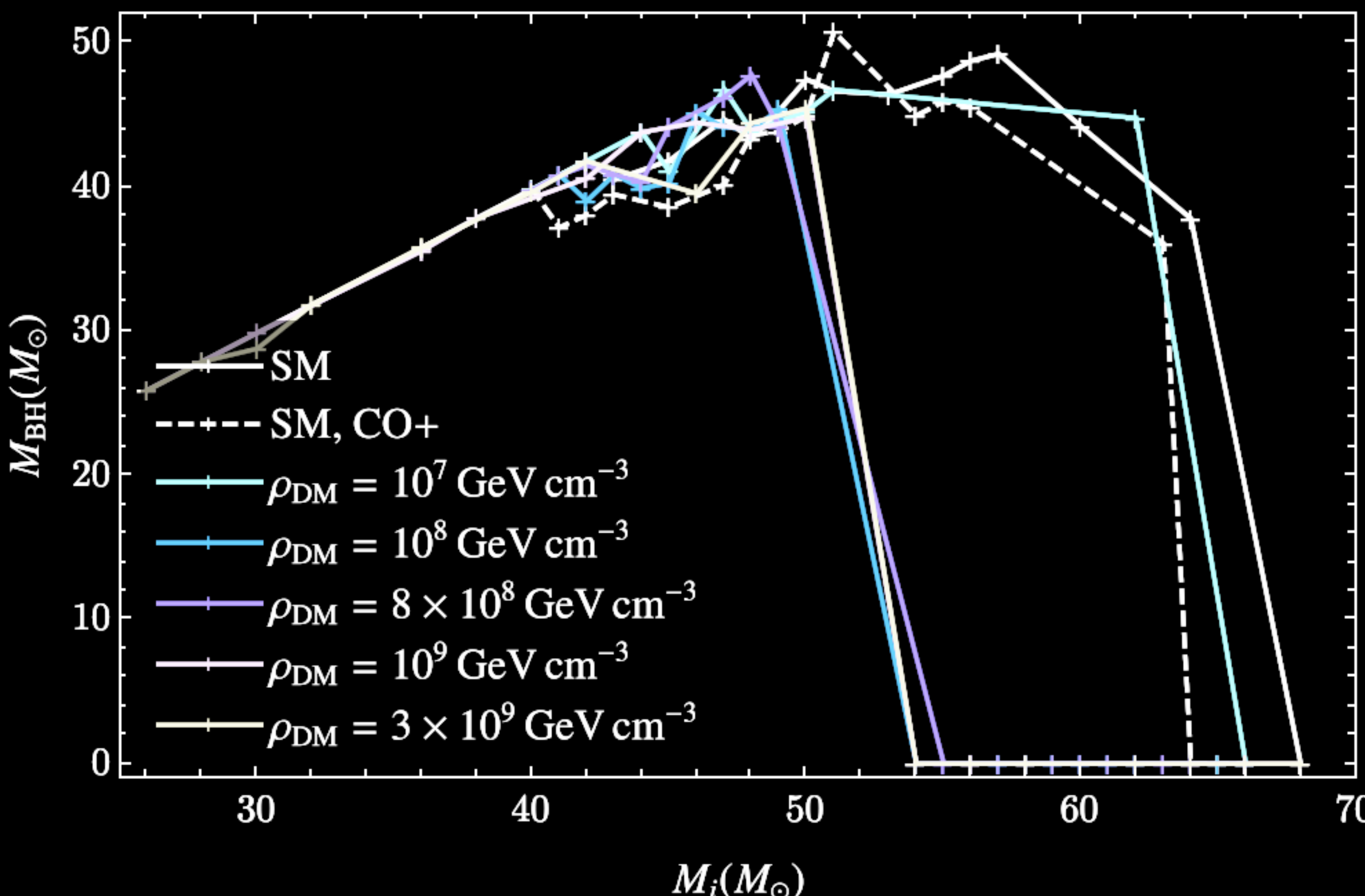


O^{16} is transported back to the core

DC & Sakstein, 2023

Preliminary results: grid of results



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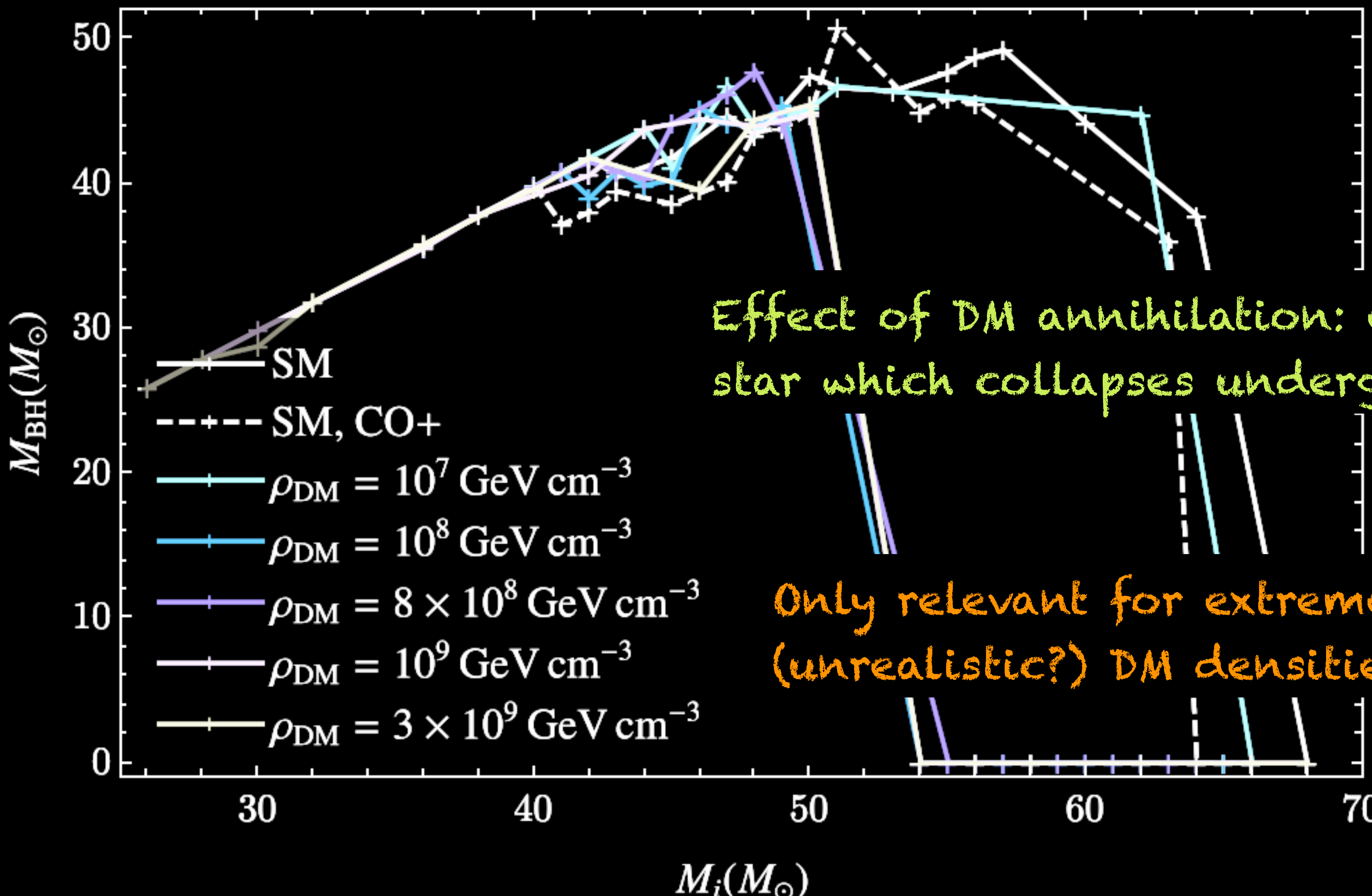


Effect of DM annihilation: every star which collapses undergoes PISN

Only relevant for extremely high (unrealistic?) DM densities

To conclude,

- A peak in the black hole mass function is found at $\sim 35\,\mathrm{M}_\odot$
- Pair-instability supernovae predicts a peak in the mass function at $\sim 45 - 50\,\mathrm{M}_\odot$

- New physics?
  - Novel loss channels shift the peak upwards
  - Preliminary results: dark matter annihilation tends to exacerbate pair-instability, but does not shift the peak

- The mystery remains…

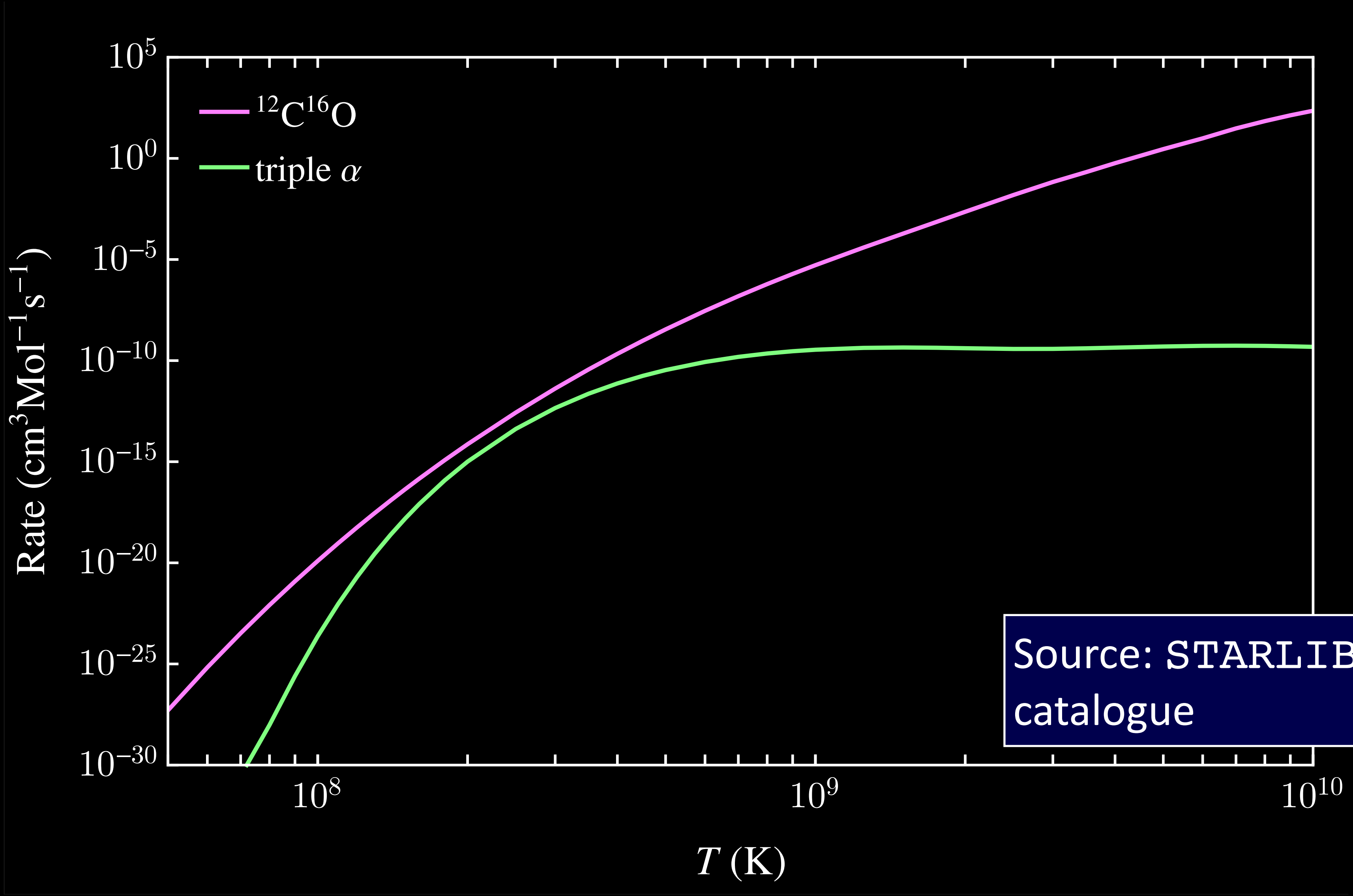
Community survey about the Jan 7 postdoc deadline:

Thank you!

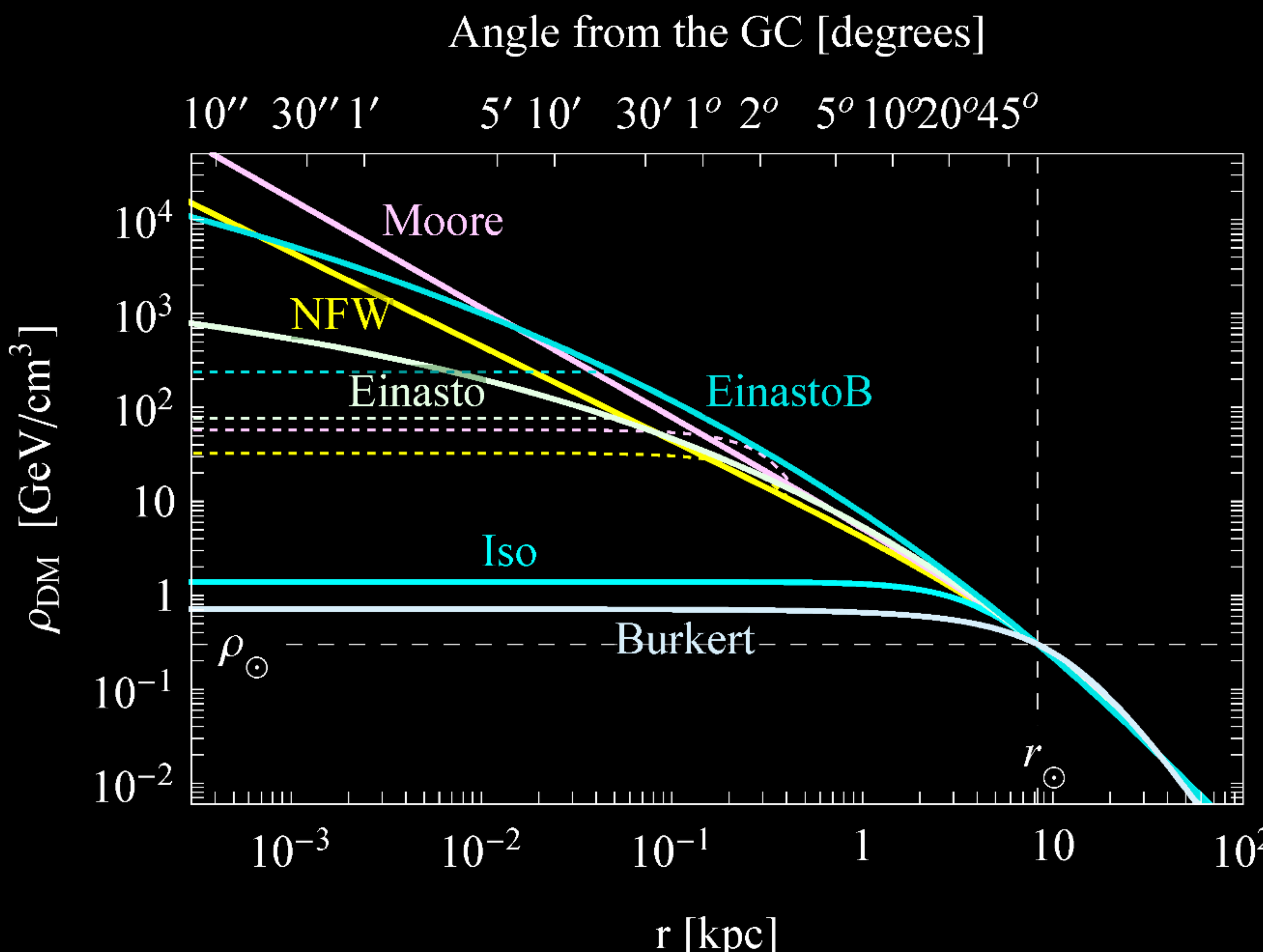
…ask me anything you like!

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

Helium burning rates as a function of T



Source: STARLIB catalogue

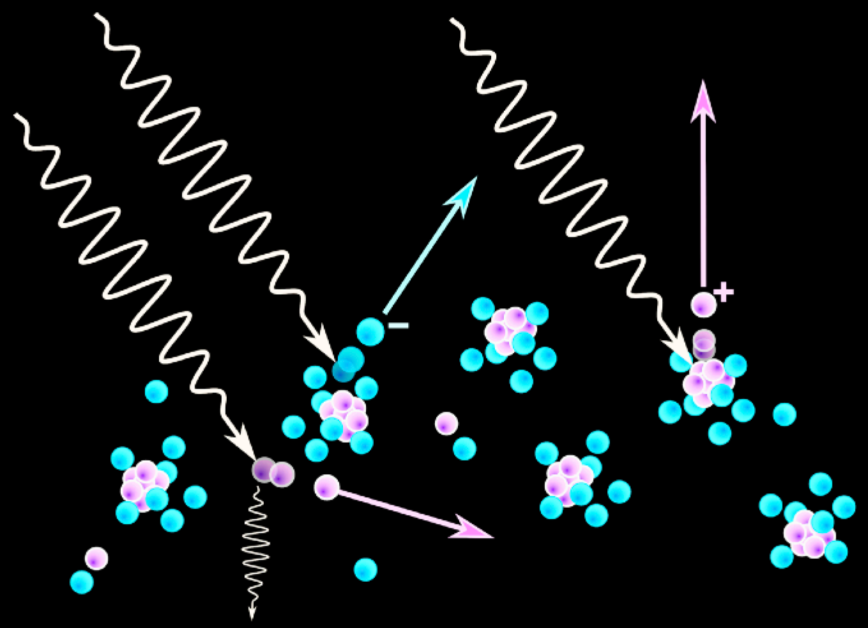


Pérez de los Heros, Symmetry, arXiv:2008.11561

Upper end of the mass gap

Photodisintegration: rapid absorption of high energy photons

Photodisintegration leads to decrease in Γ_1 and therefore a contraction



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Photodisintegration leads to decrease in Γ_1 and therefore a contraction

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

No pulsations, immediate collapse into black holes