Black hole archaeology with gravitational waves

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MPI Heidelberg, June 2021

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The era of gravitational waves

Many opportunities for particle and nuclear astrophysics

+ A unique observational window: a probe of the dark, a memory of the past

+ A growing dataset: ~ 50 merger events (and counting!),

+ Many decades in frequency: experiments planned / under construction

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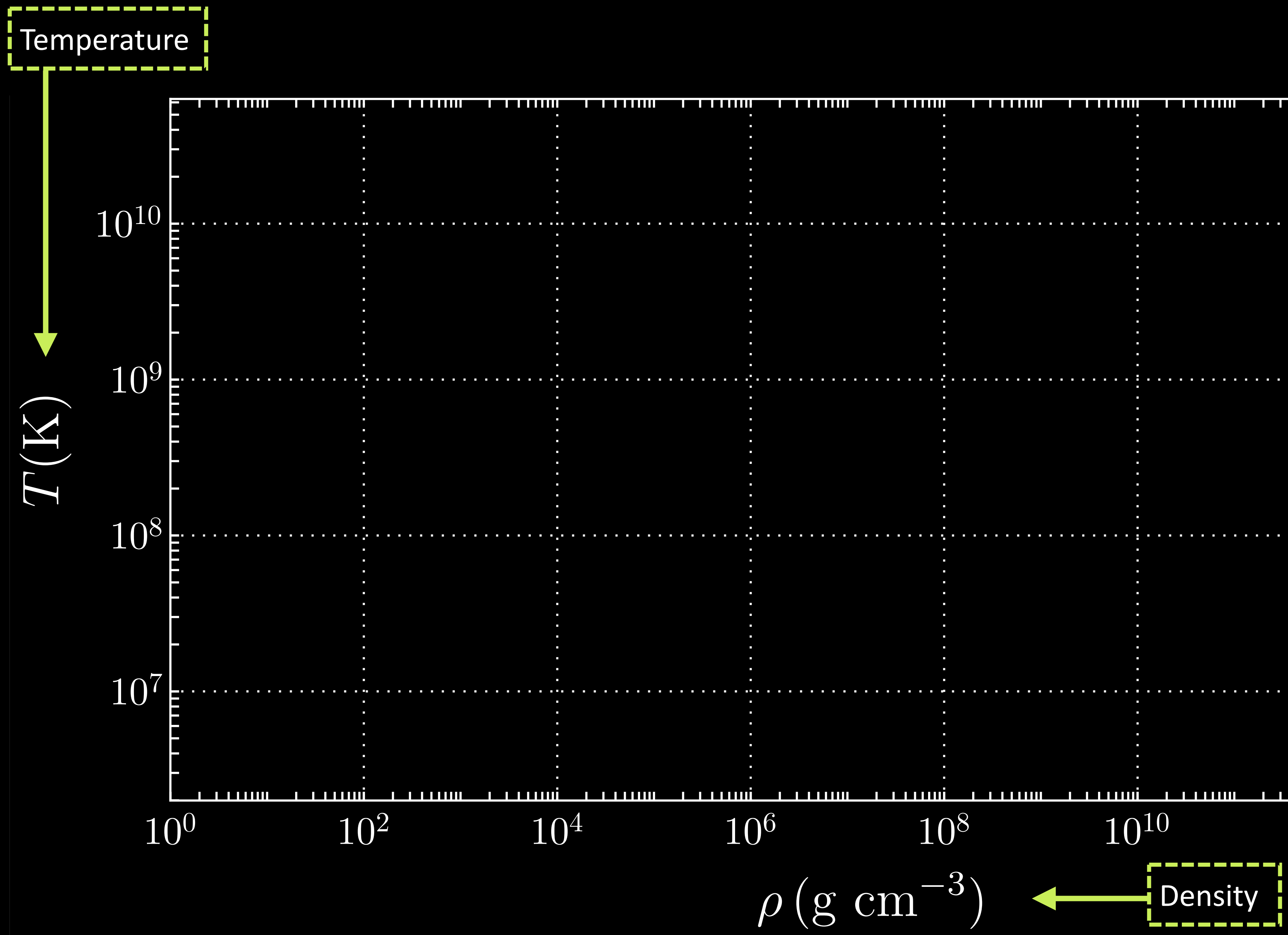
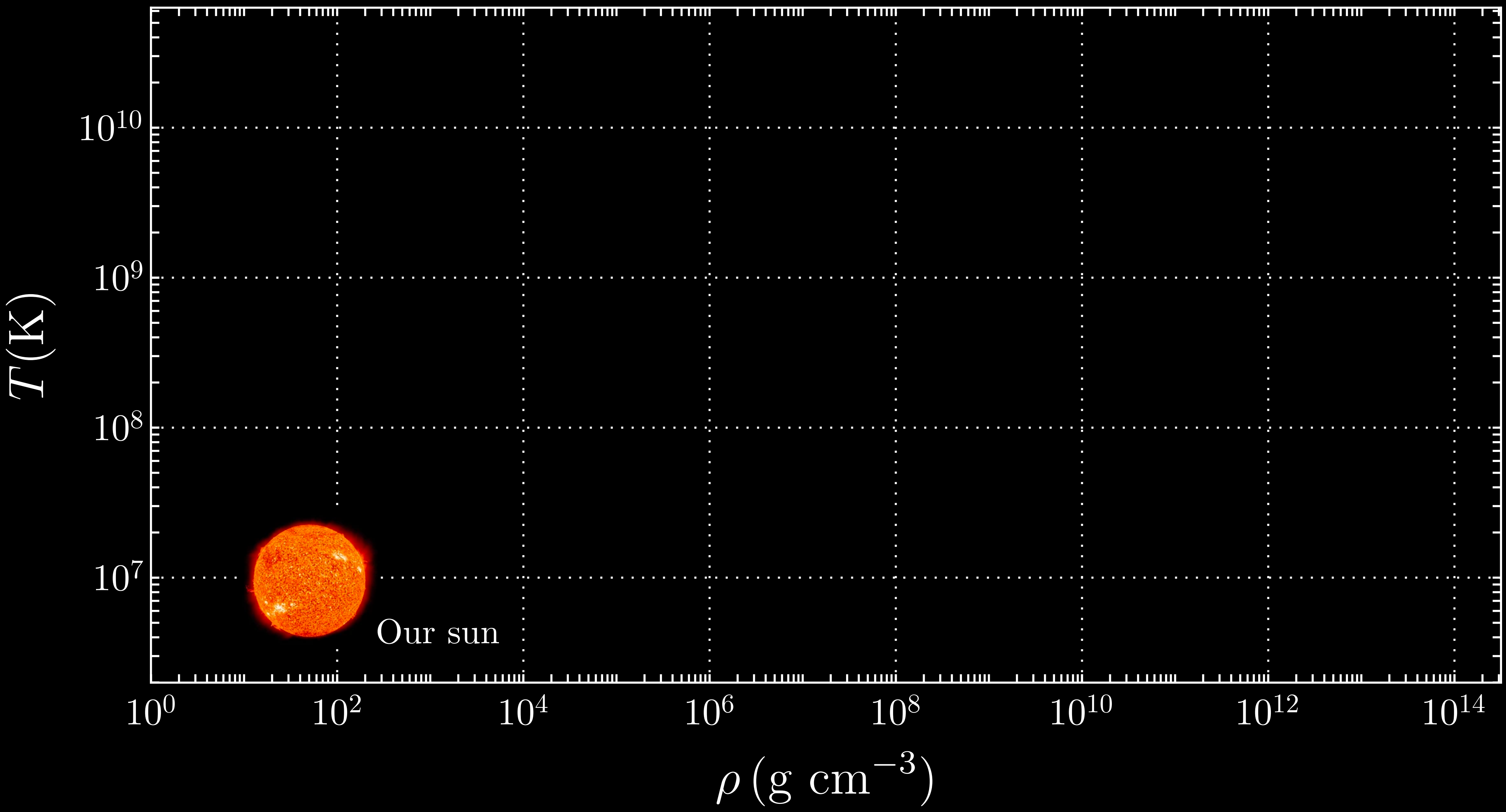
Gravitational waves may help shed light on many open questions



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



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}
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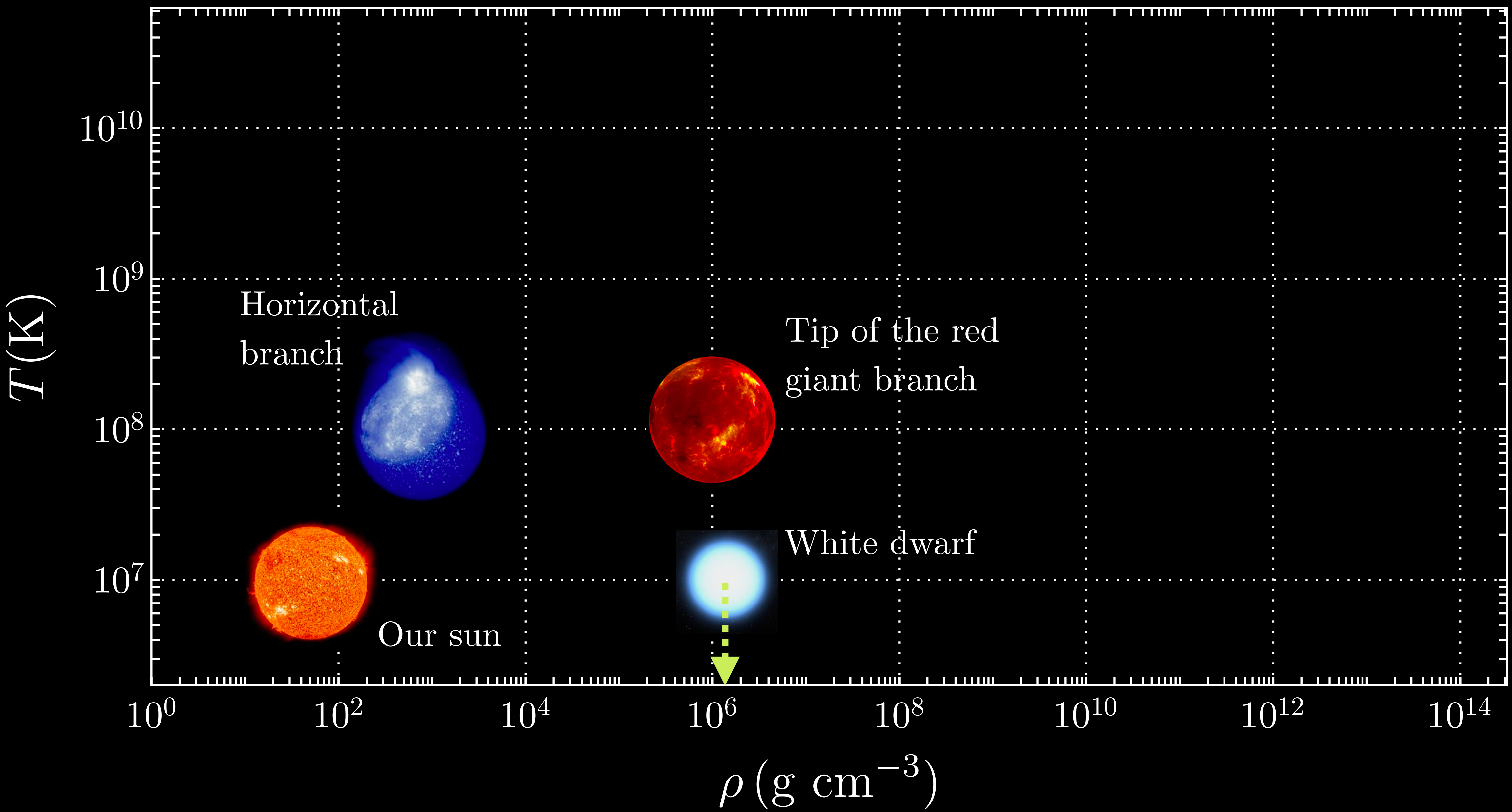
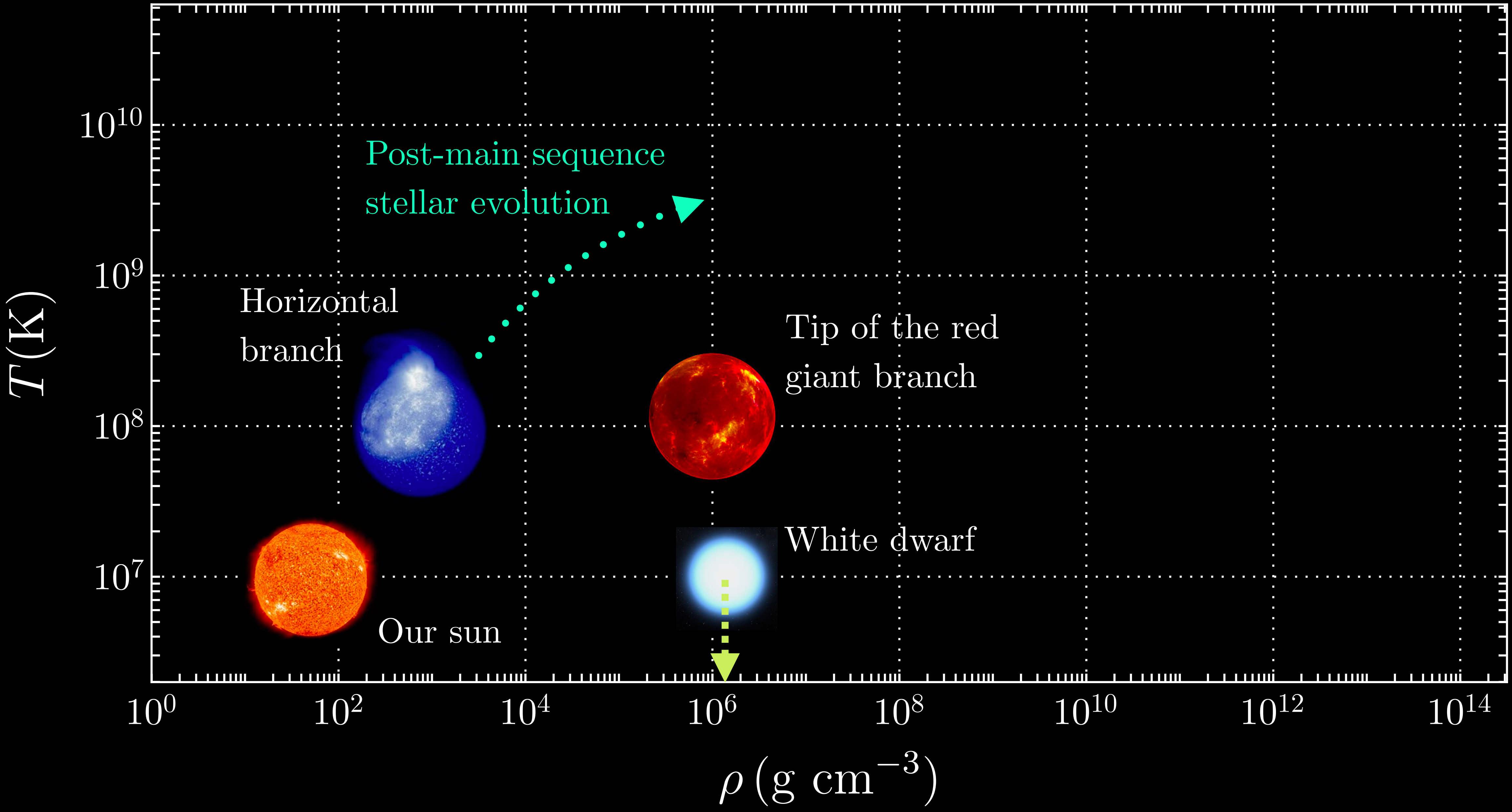
10^{14}
$\rho\,(\mathrm{g\ cm^{-3}})$



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}
$\rho\,(\mathrm{g\ cm^{-3}})$



$T\,(\mathrm{K})$
10^{10}
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Post-main sequence
stellar evolution
Horizontal
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Tip of the red
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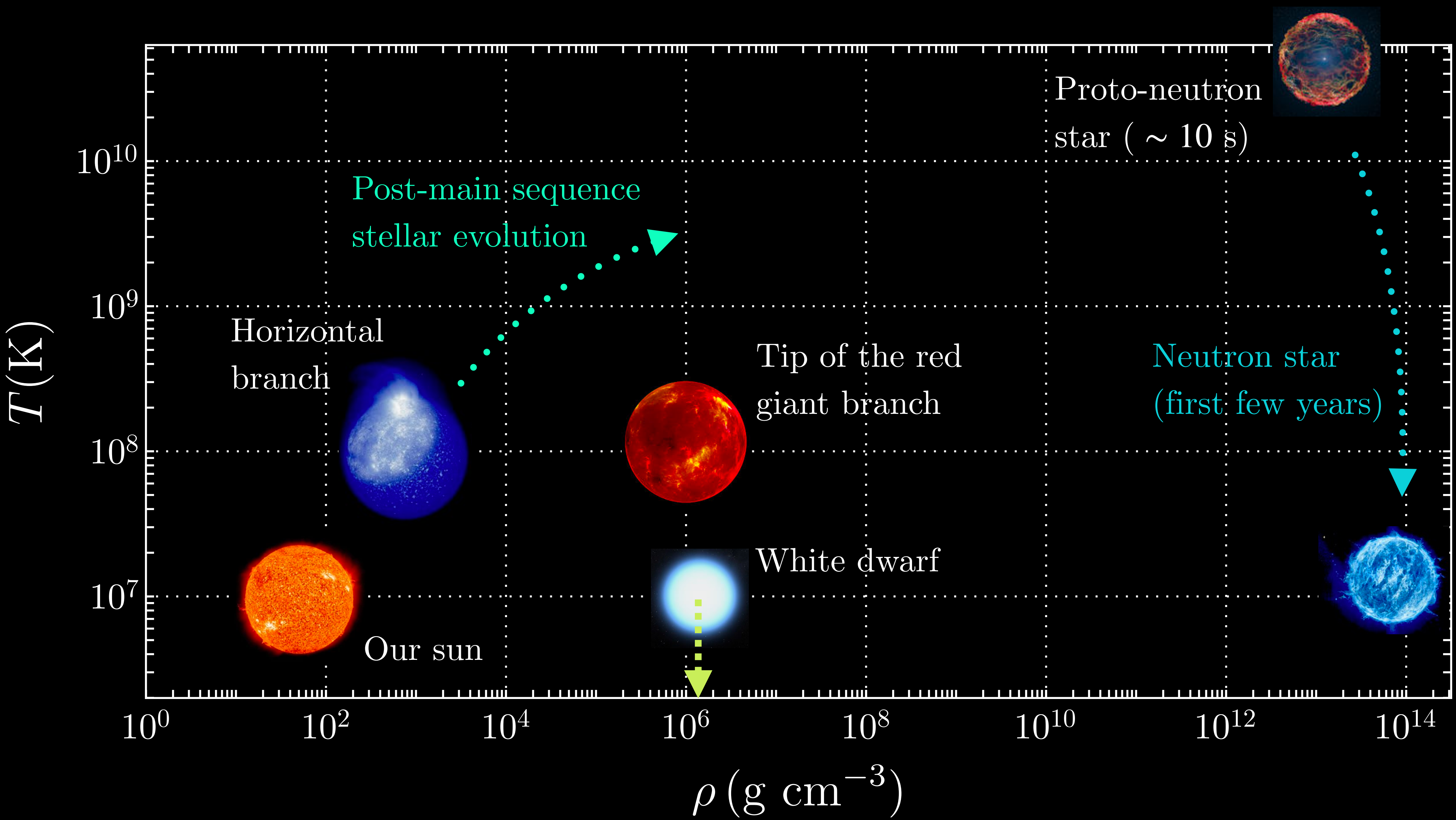

Proto-neutron star (∼ 10 s)
Post-main sequence stellar evolution
Horizontal branch
Tip of the red giant branch
Neutron star (first few years)
White dwarf
Our sun
$T(\mathrm{K})$
10^{10}
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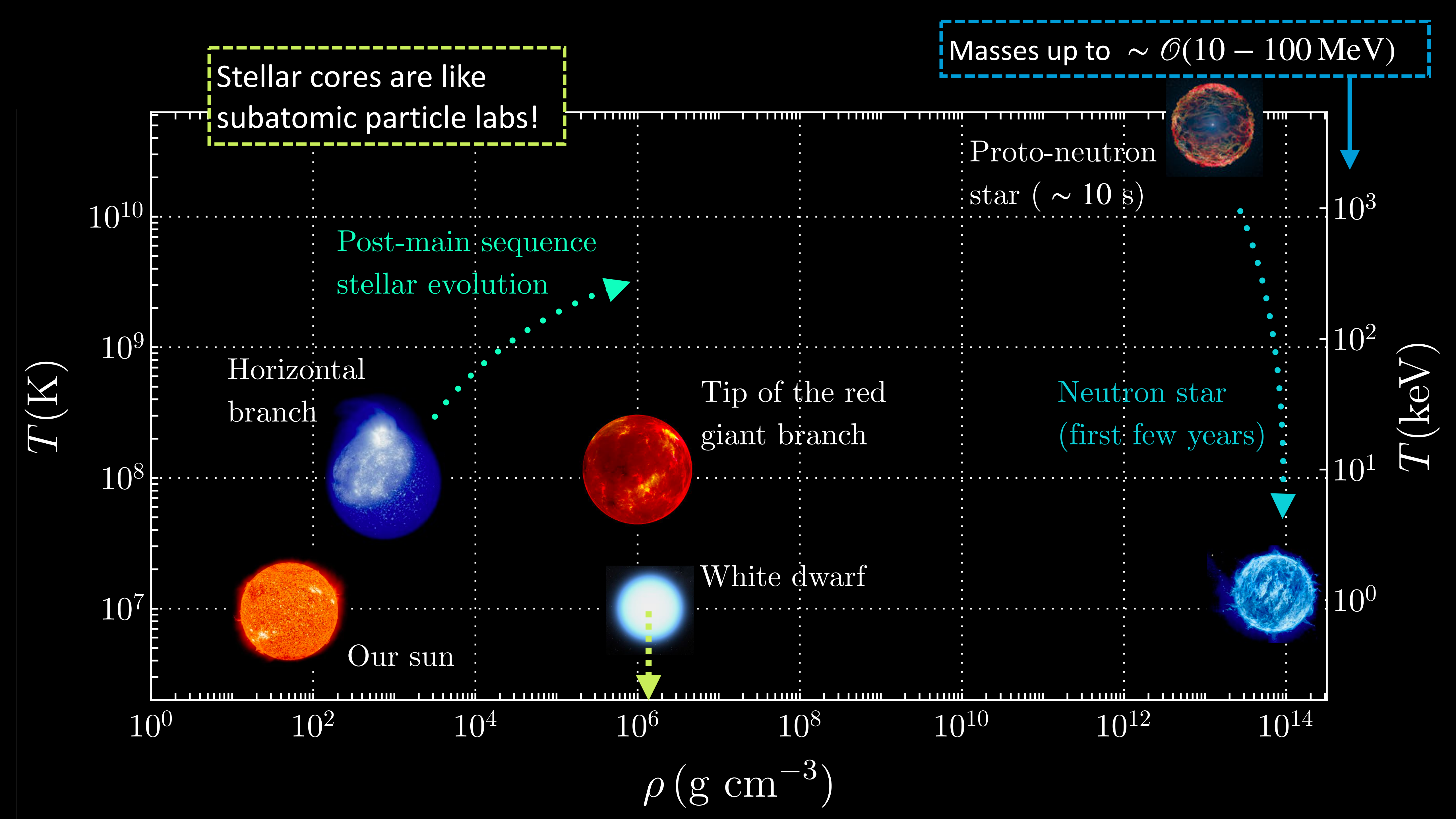
Masses up to $\sim \mathcal{O}(10 - 100\,\mathrm{MeV})$
Stellar cores are like subatomic particle labs!
Proto-neutron star (~ 10 s)
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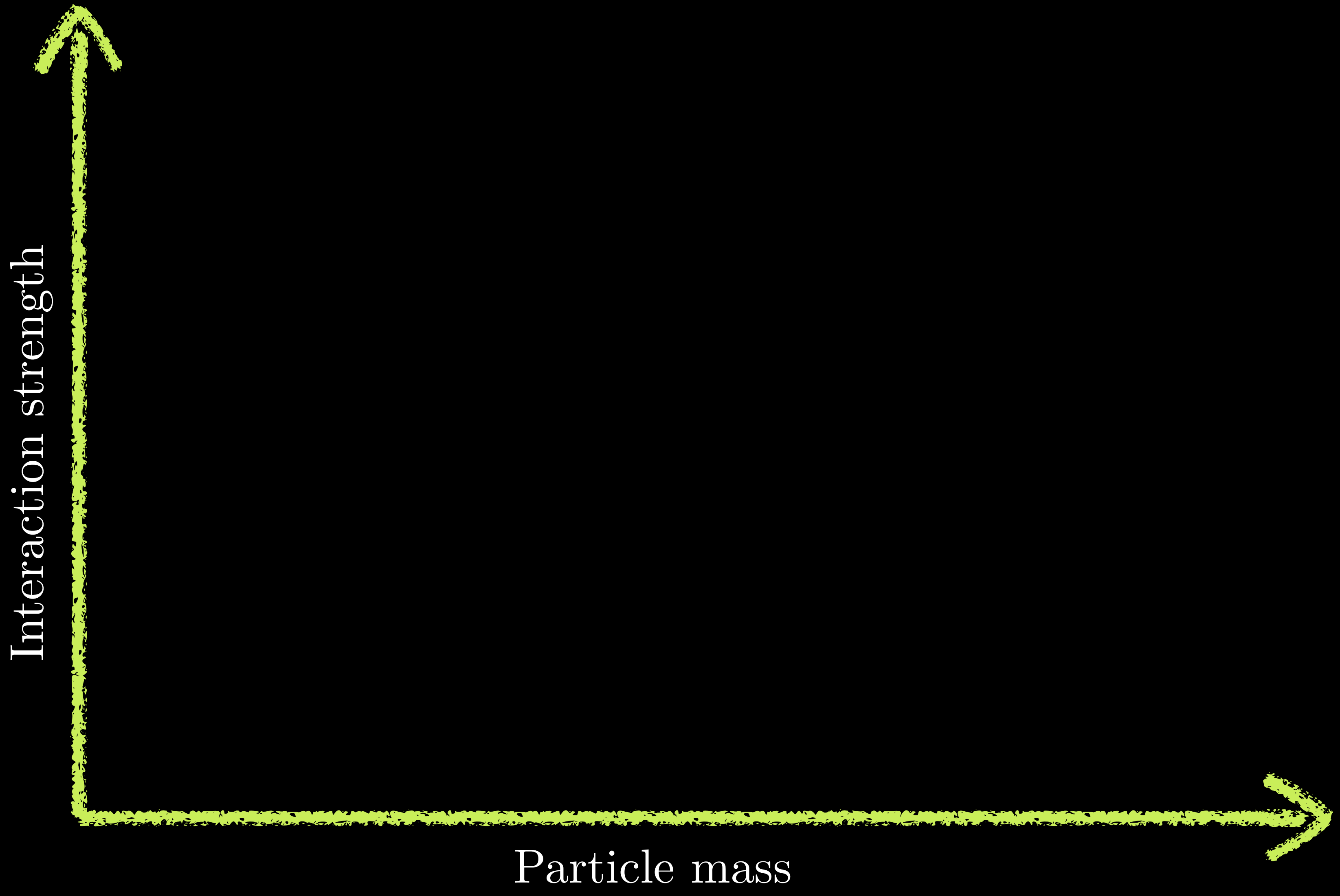
Particle physics in stars



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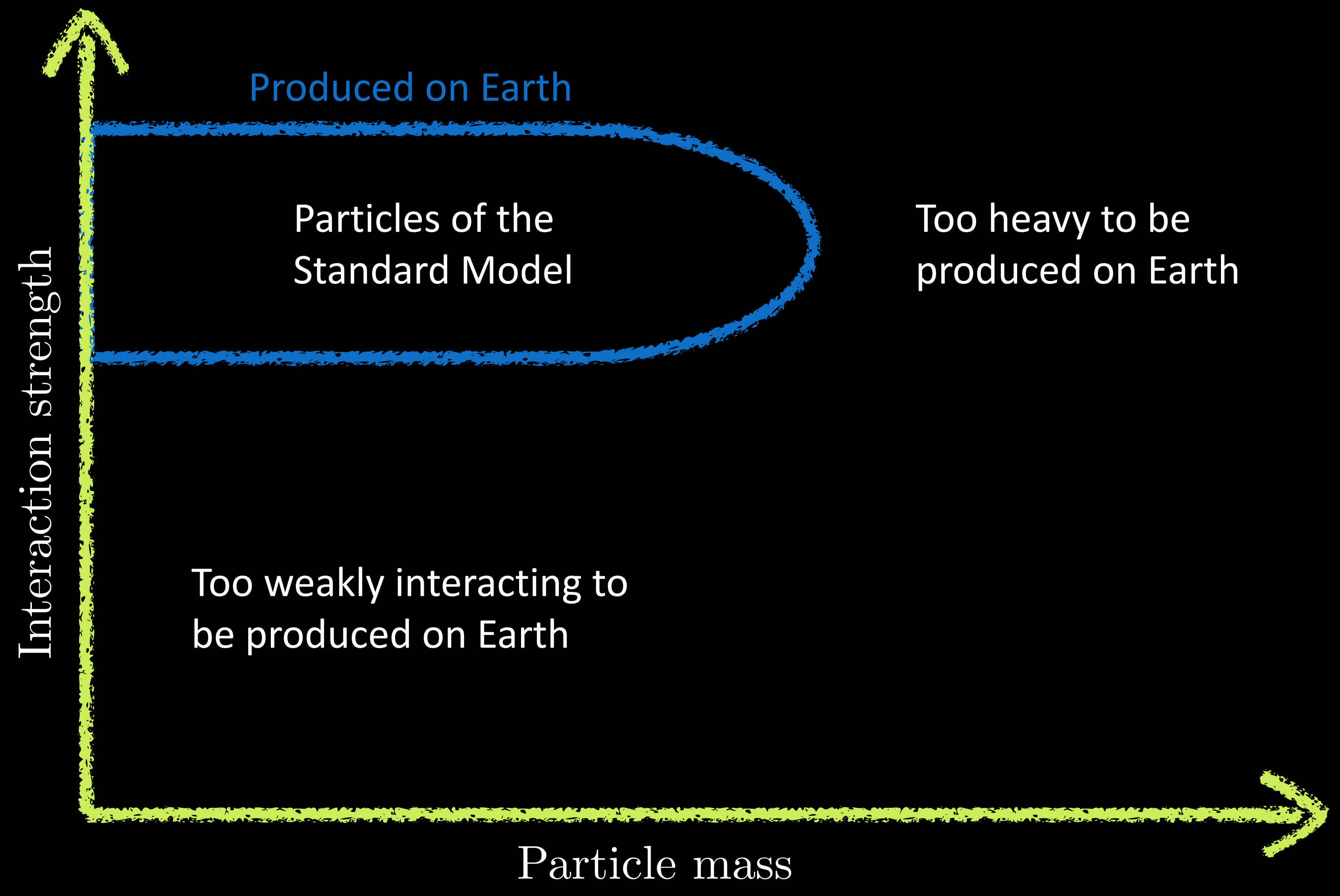

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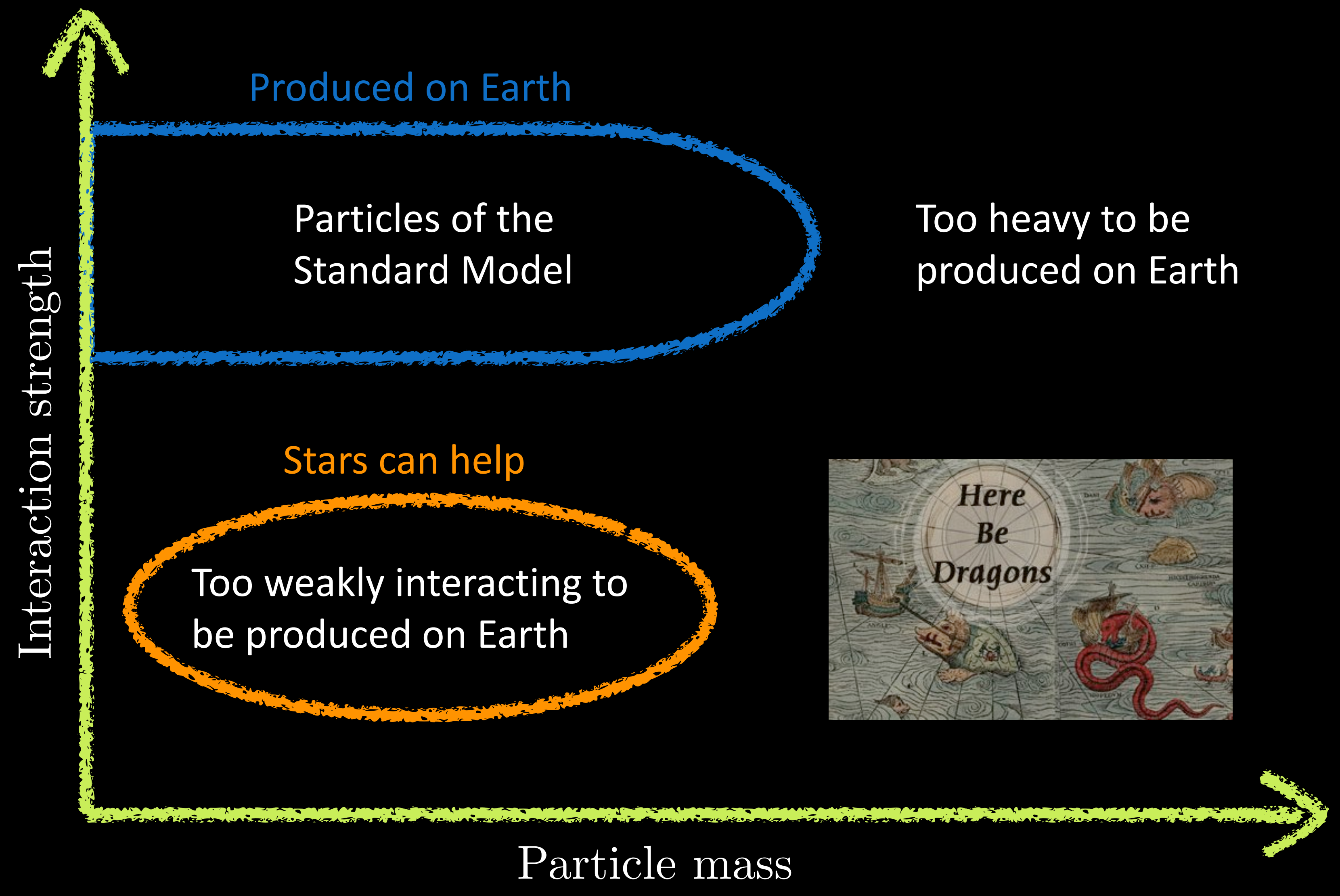
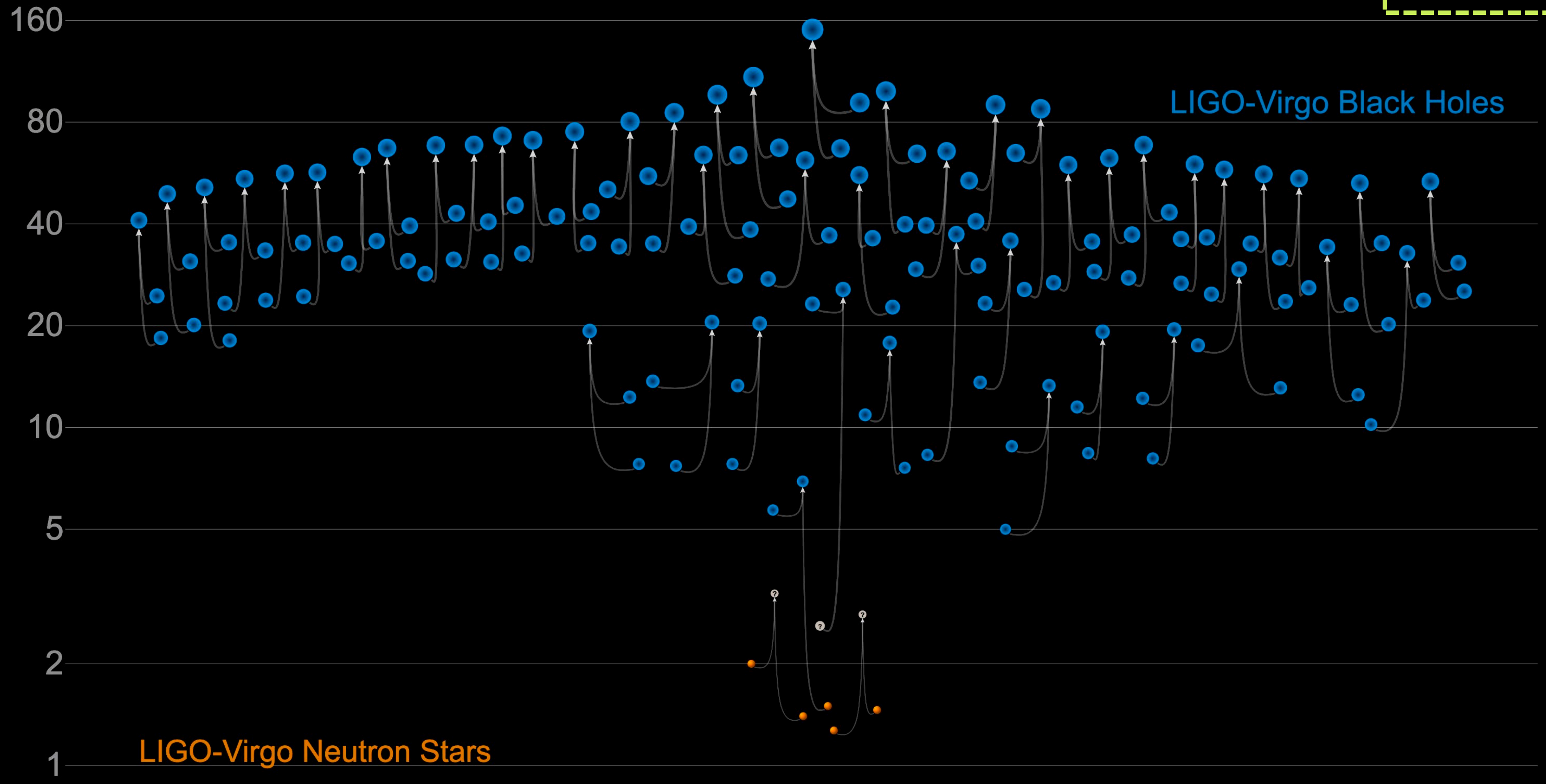


Binary mergers in LIGO/Virgo O1-3a

"The Stellar Graveyard"



Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

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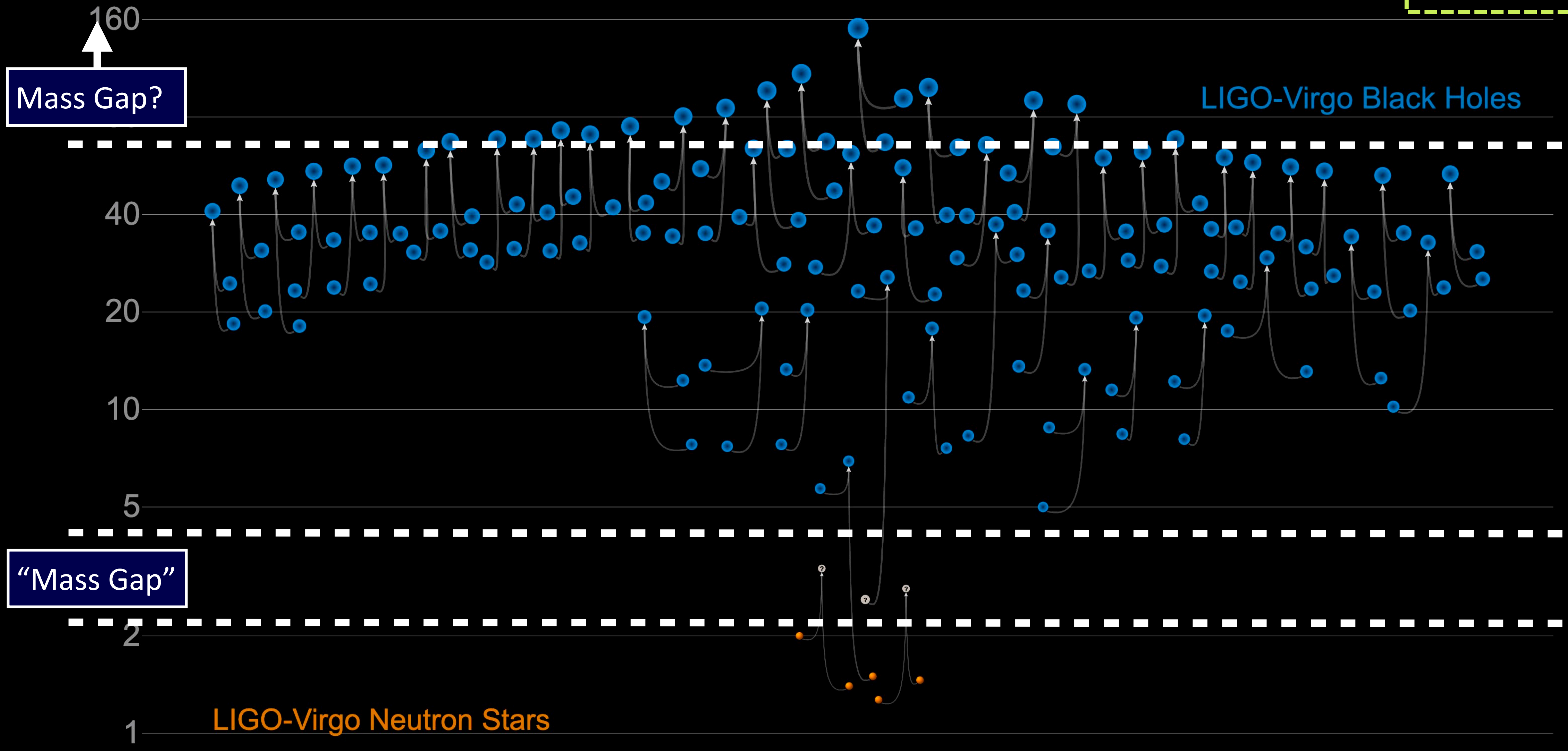

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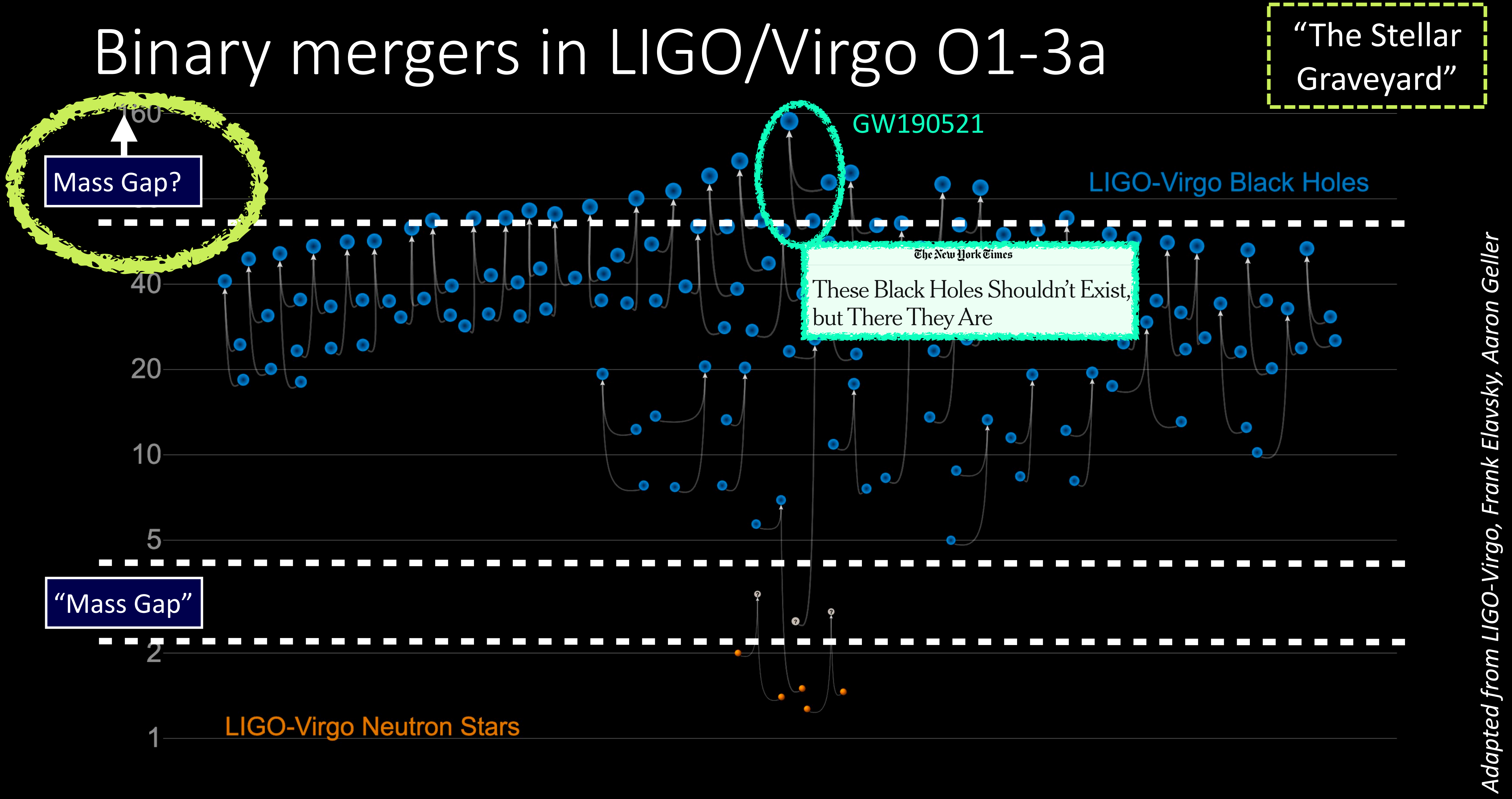

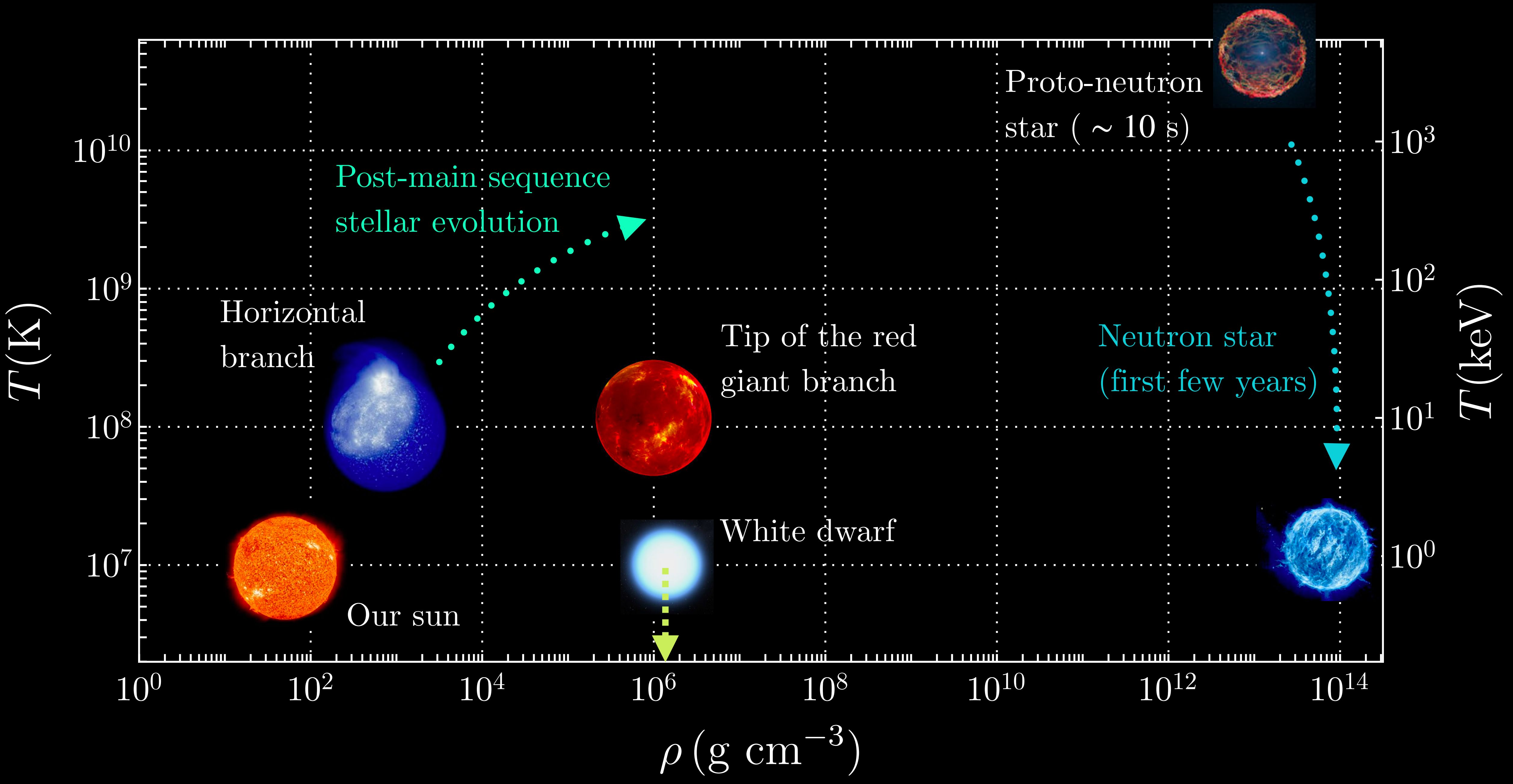

Proto-neutron
star (~ 10 s)
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stellar evolution
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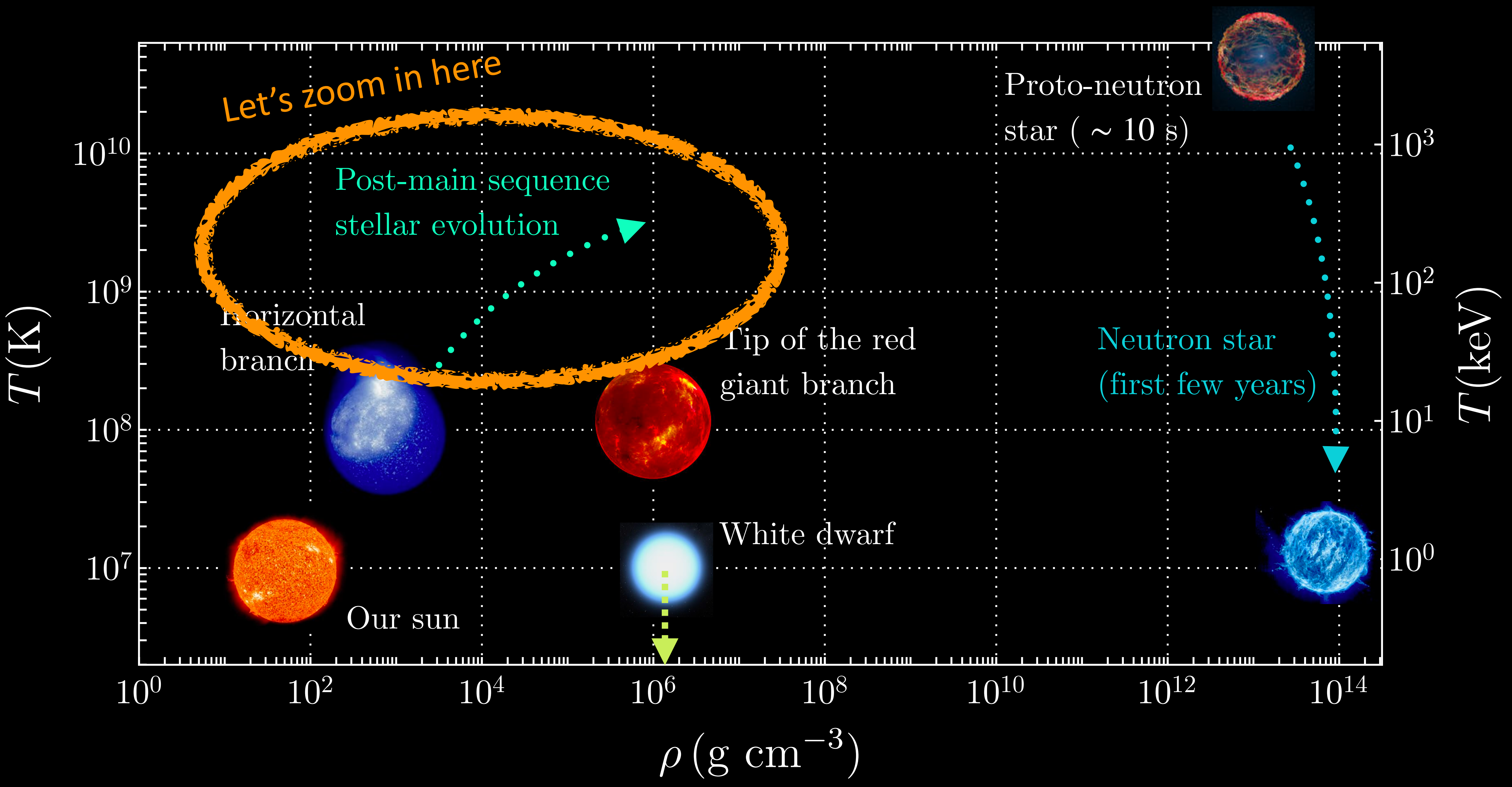

Let's zoom in here
Post-main sequence
stellar evolution
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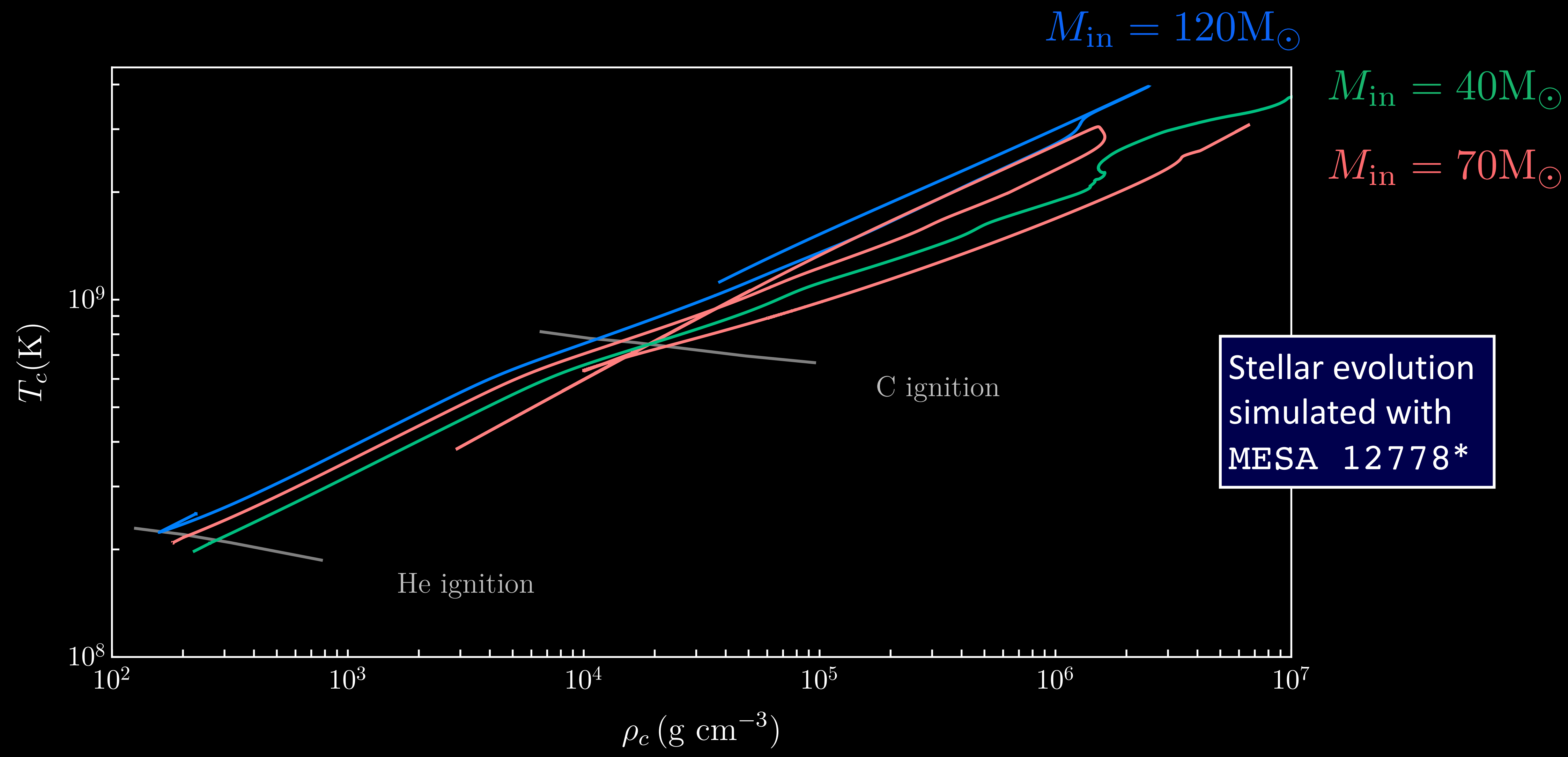
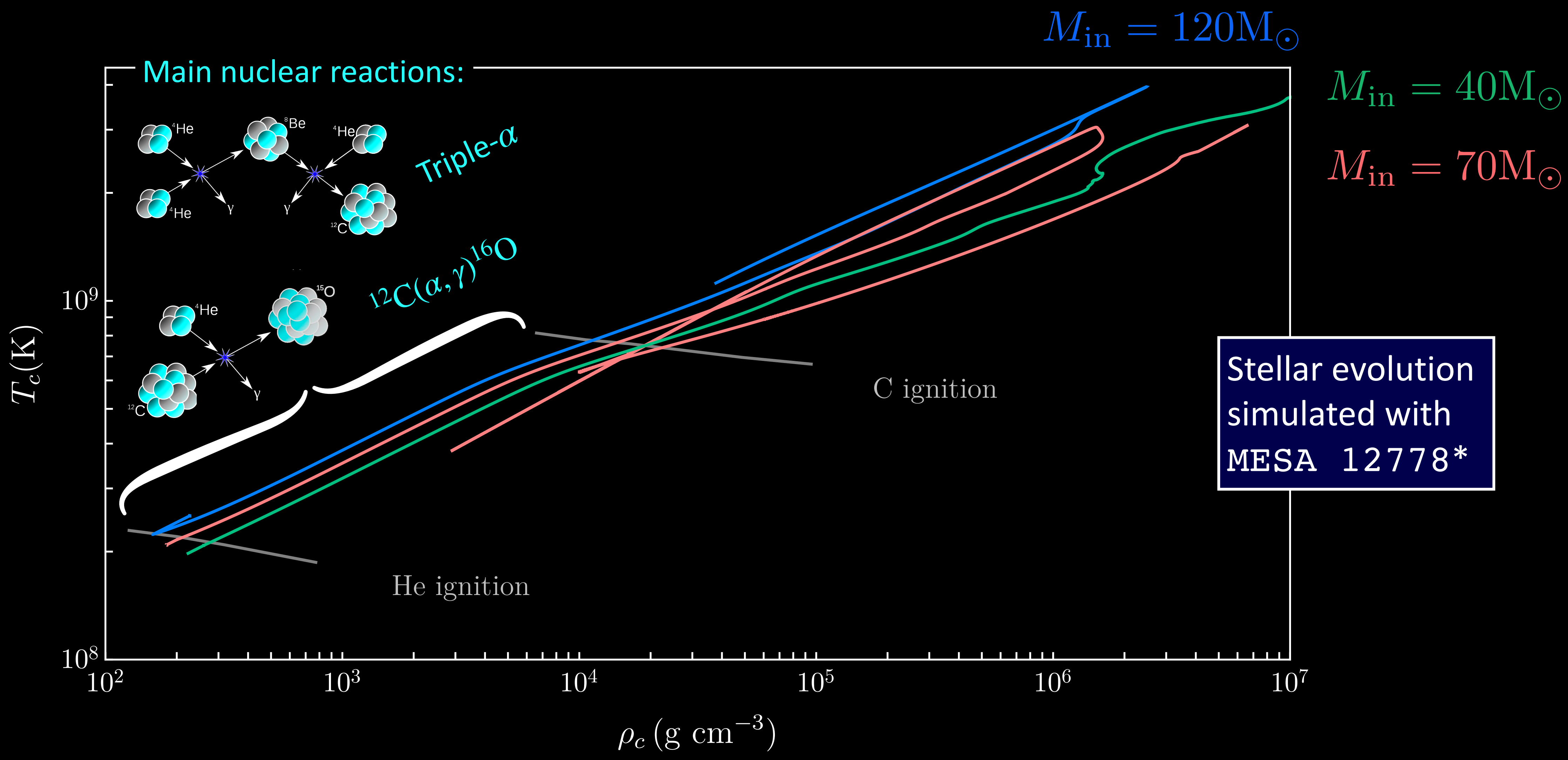
Late evolution of heavy stars



Stellar evolution simulated with `MESA 12778*`

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

Late evolution of heavy stars



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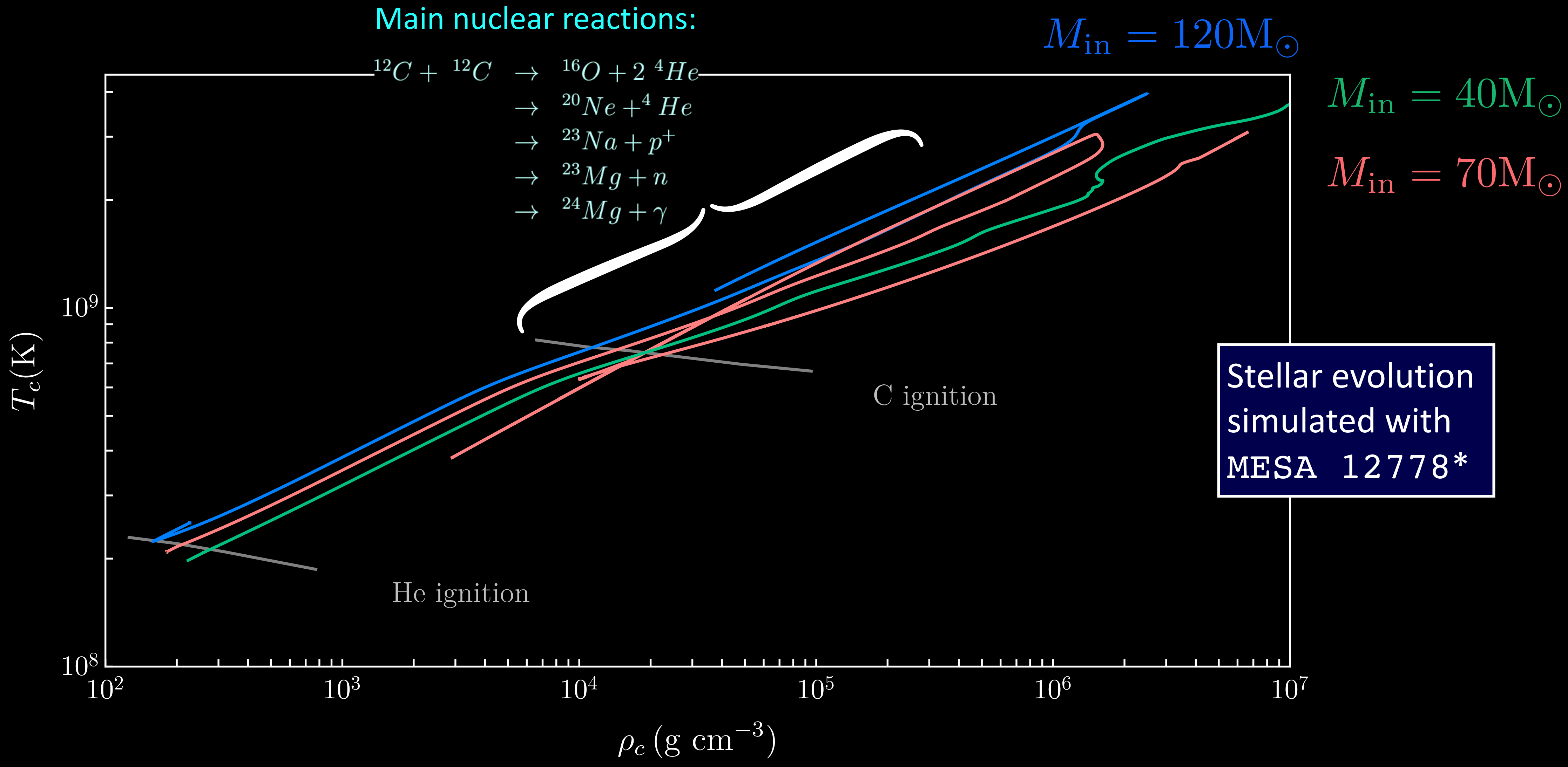

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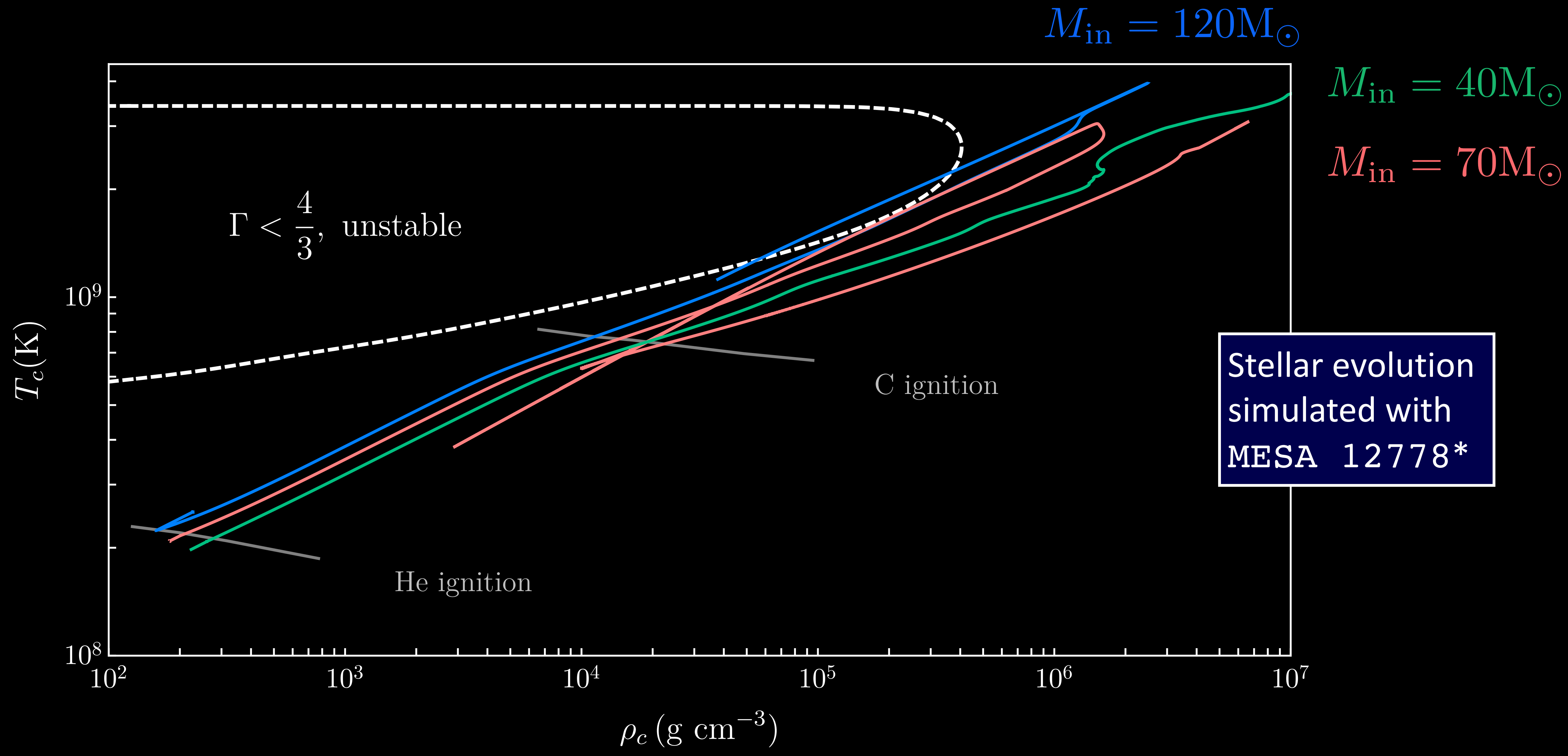

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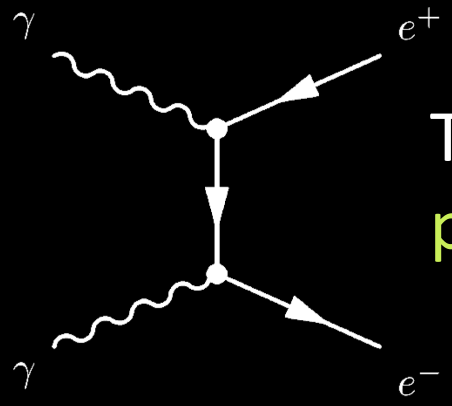
Barkat, Rakavy, Sack PRL (1967)
Rakavy, Shaviv, ApJ (1967)

The danger zone: pair-instability



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

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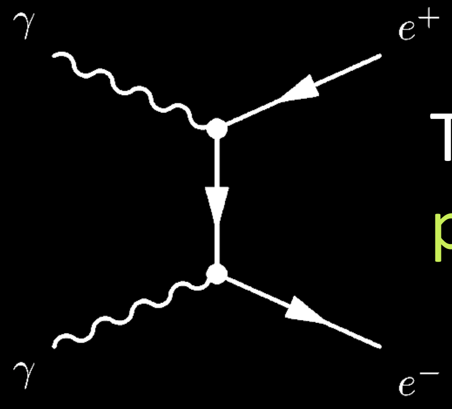


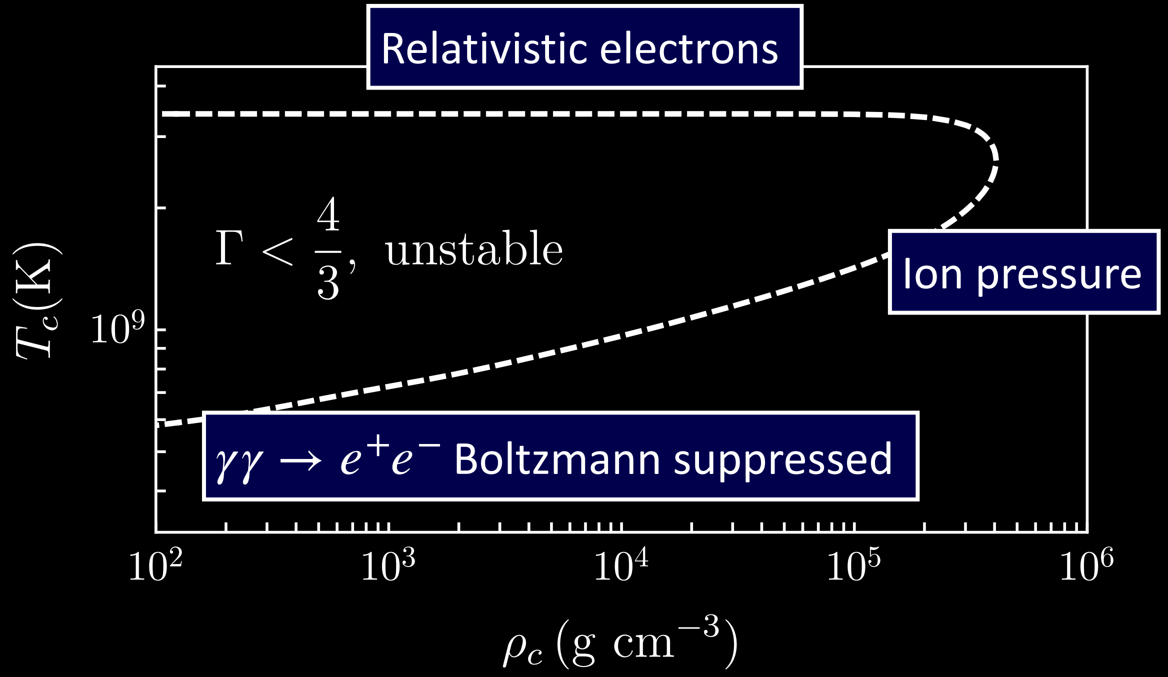
The high temperatures of stellar cores mean electron-positron pairs can be created from photons: $\gamma\gamma \rightarrow e^+e^-$

Unstable, because:

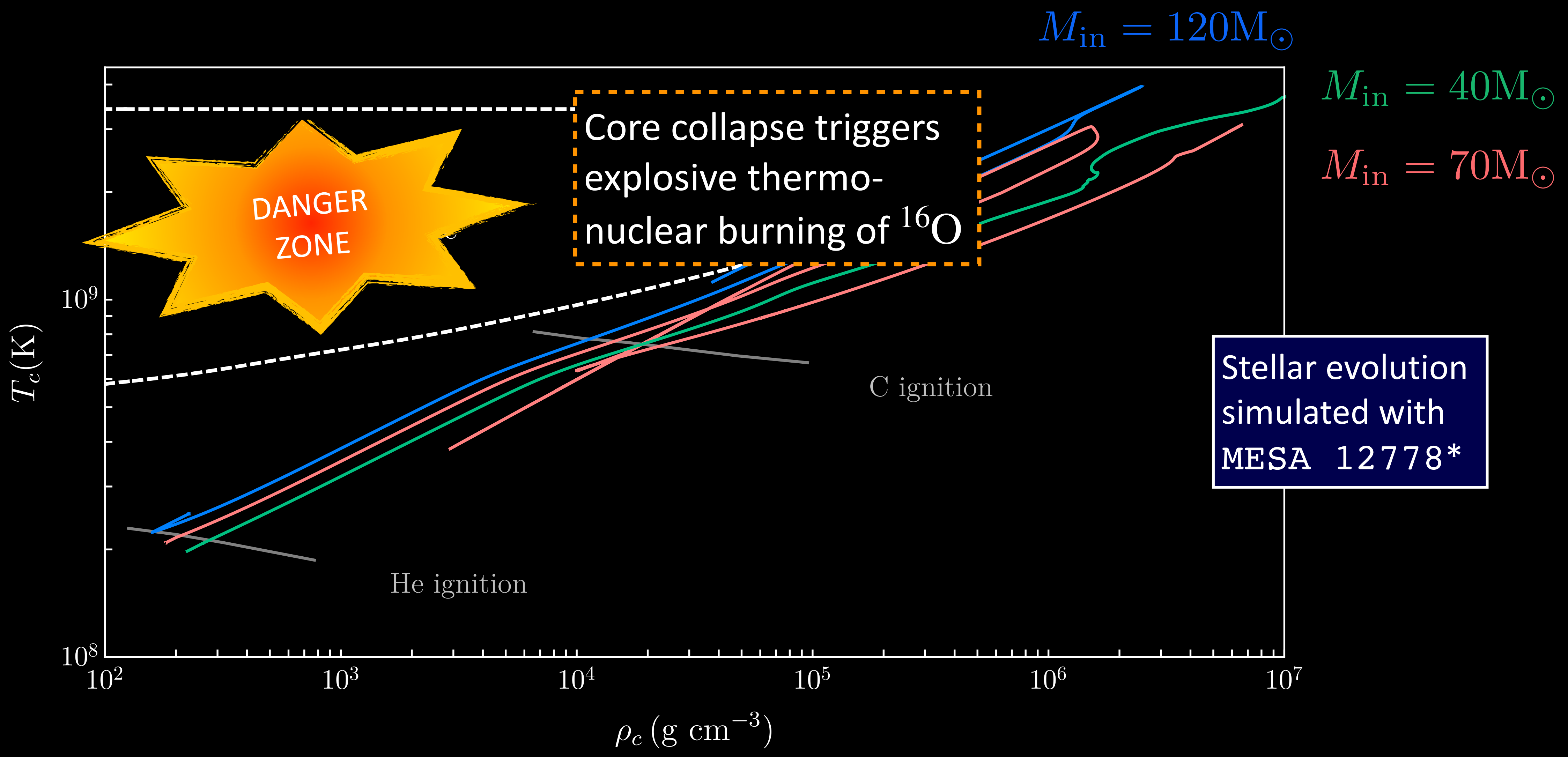
The photons give the star outward pressure

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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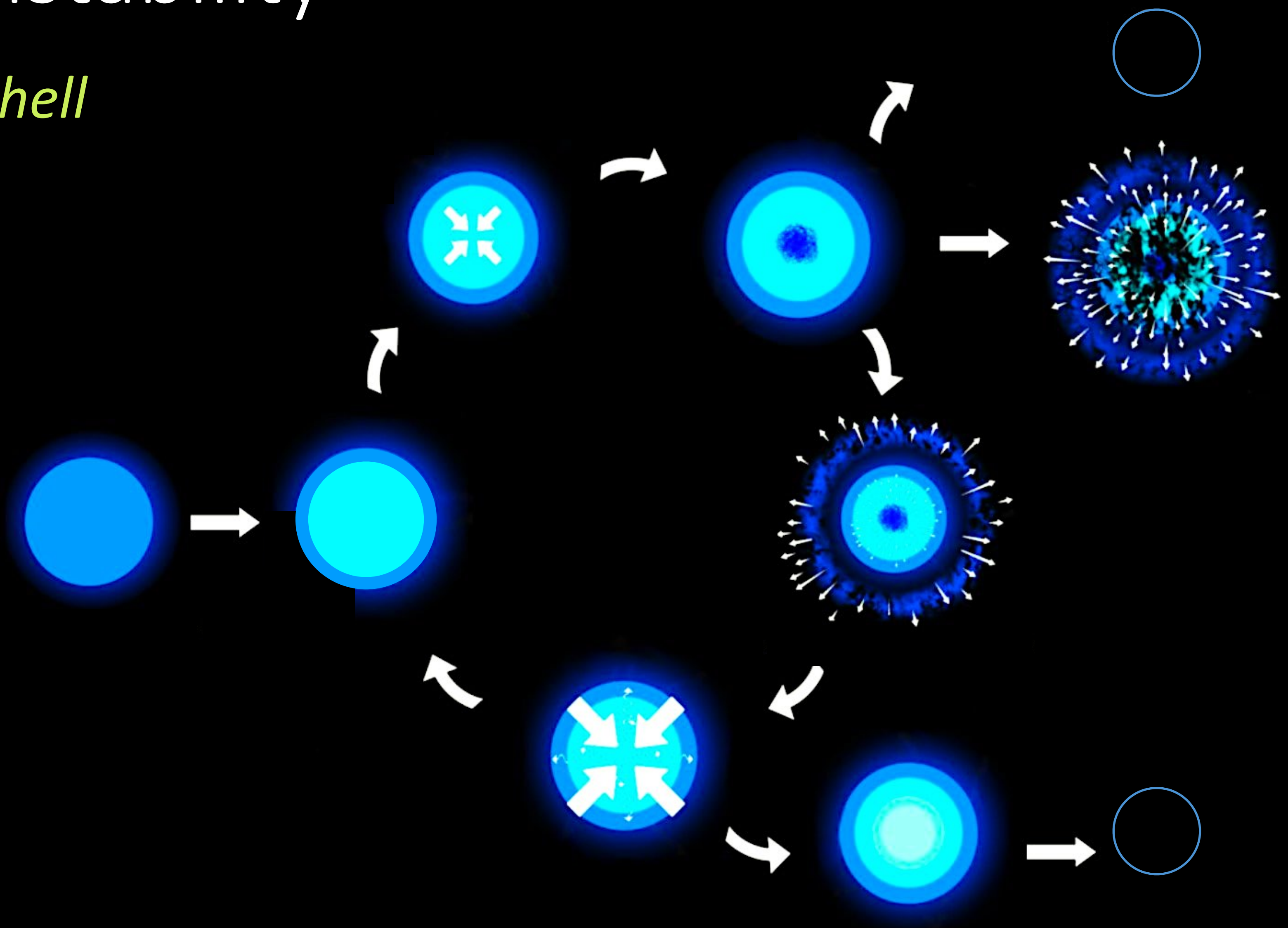
Pair instability

in a nutshell



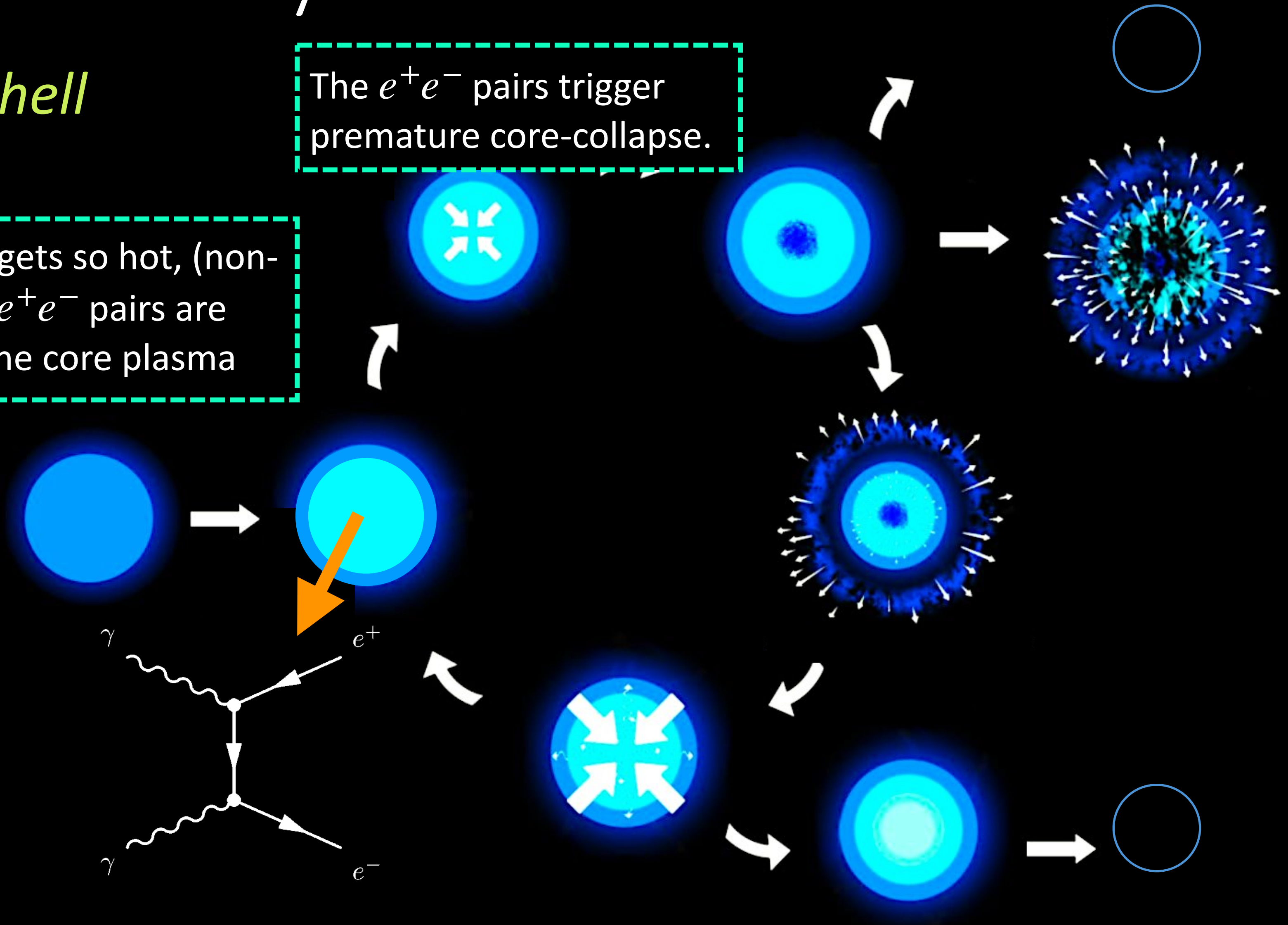
Adapted from Renzo et al [2002.05077]

Pair instability

in a nutshell

The e^+e^- pairs trigger premature core-collapse.

1. The core gets so hot, (non-relativistic) e^+e^- pairs are created in the core plasma



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Pair instability

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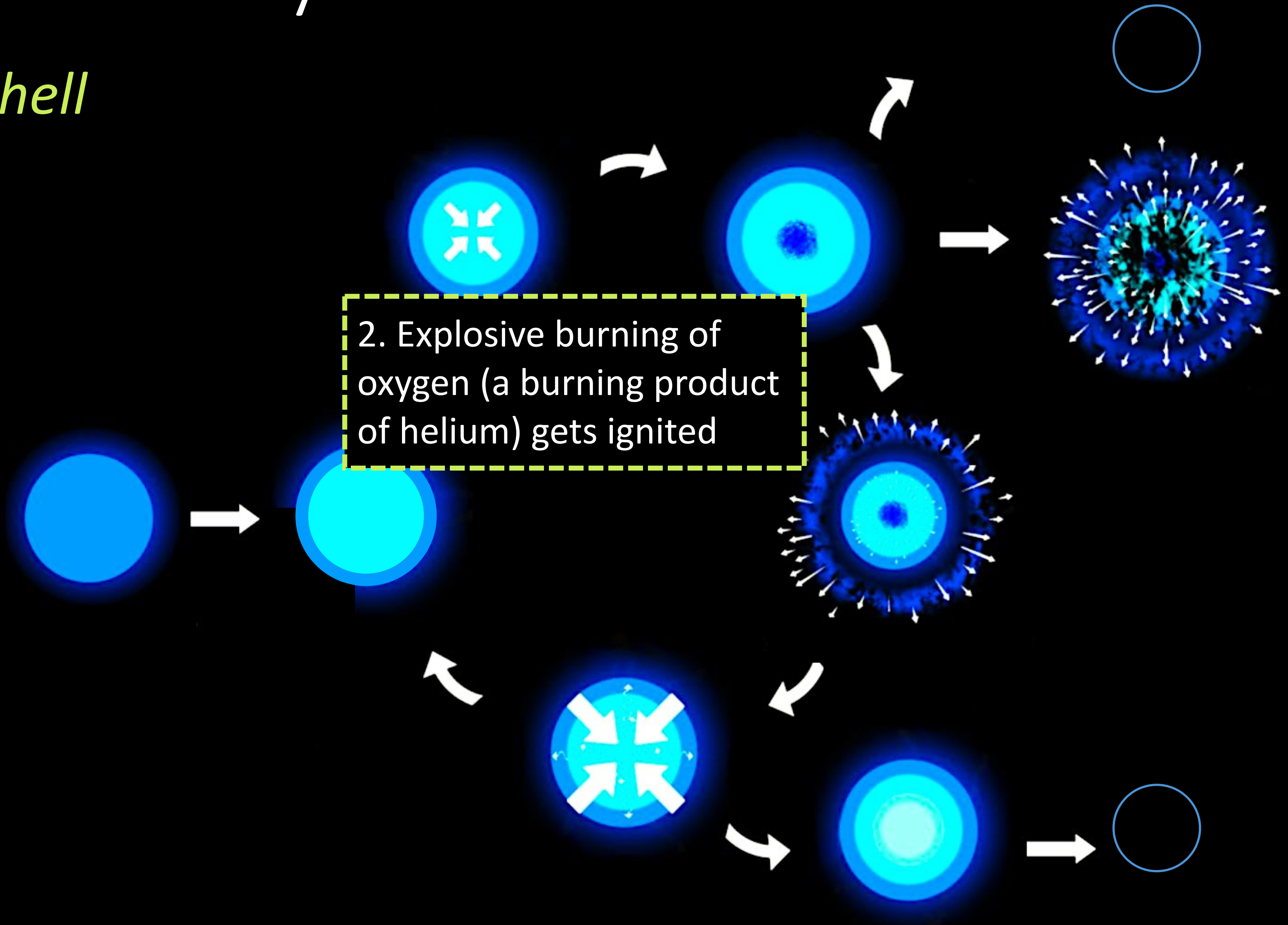

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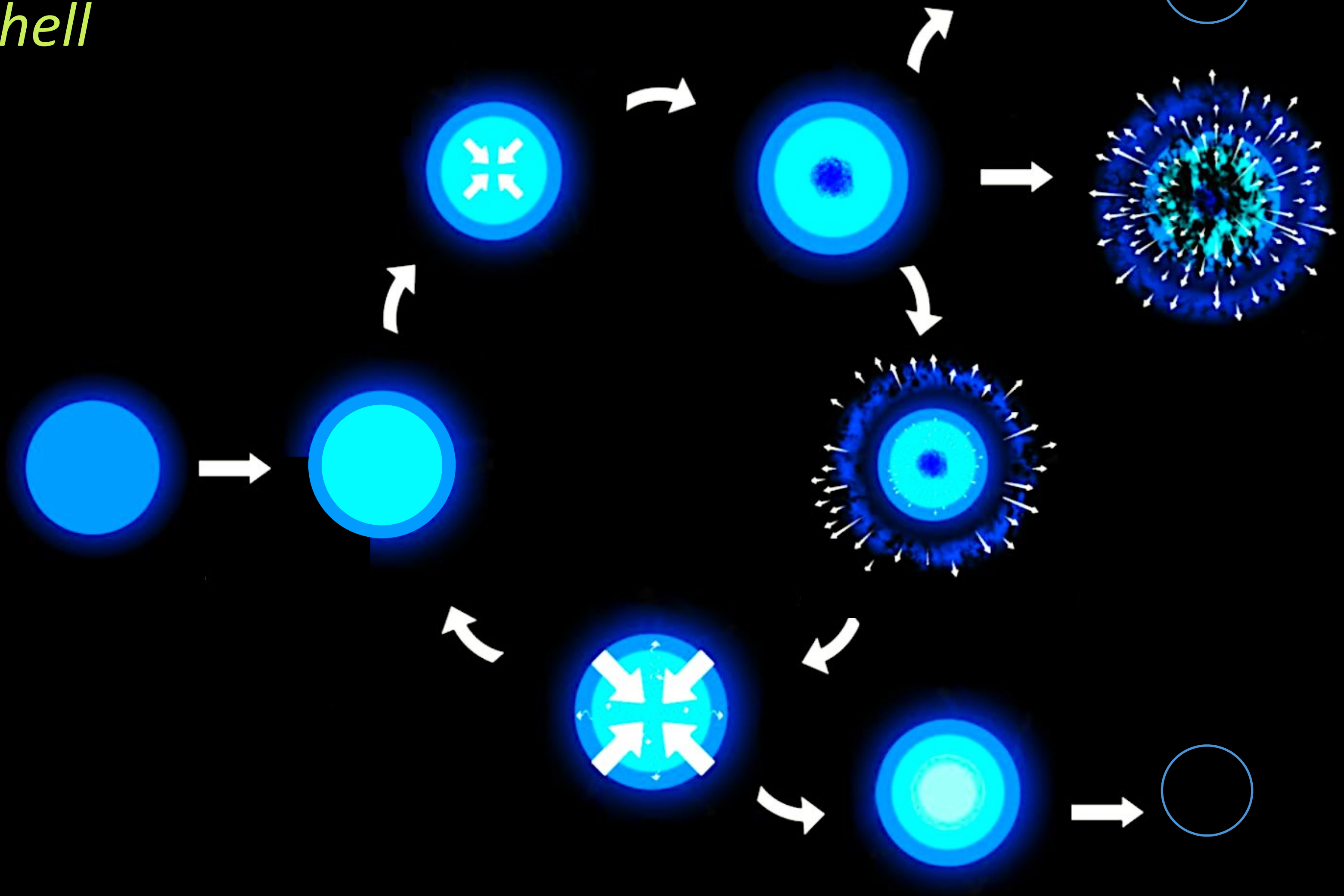
Pair instability

in a nutshell

3a. Photodisintegration instability triggers immediate BH collapse



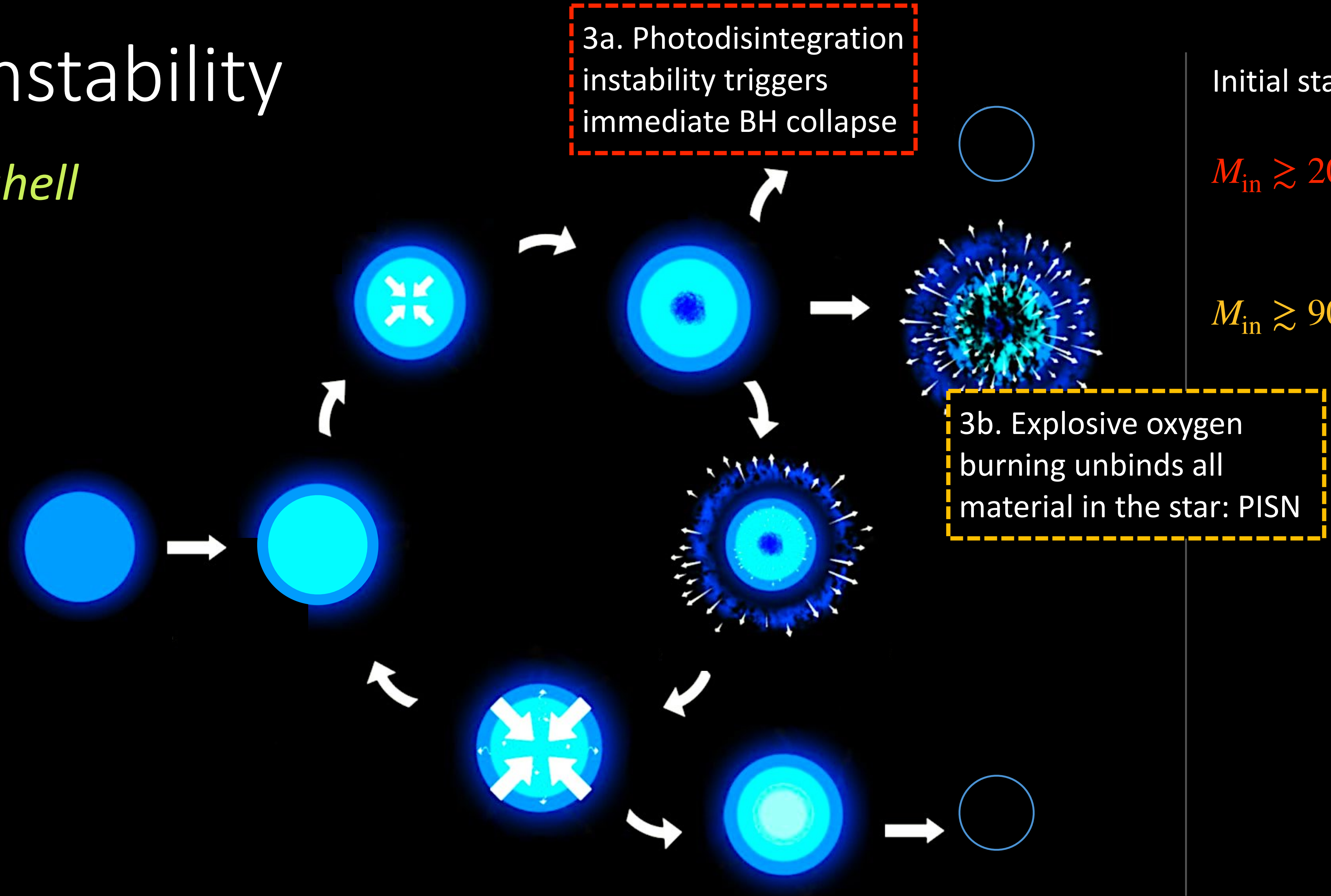
Initial star mass

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

Adapted from Renzo et al [2002.05077]

Pair instability

in a nutshell



Initial star mass

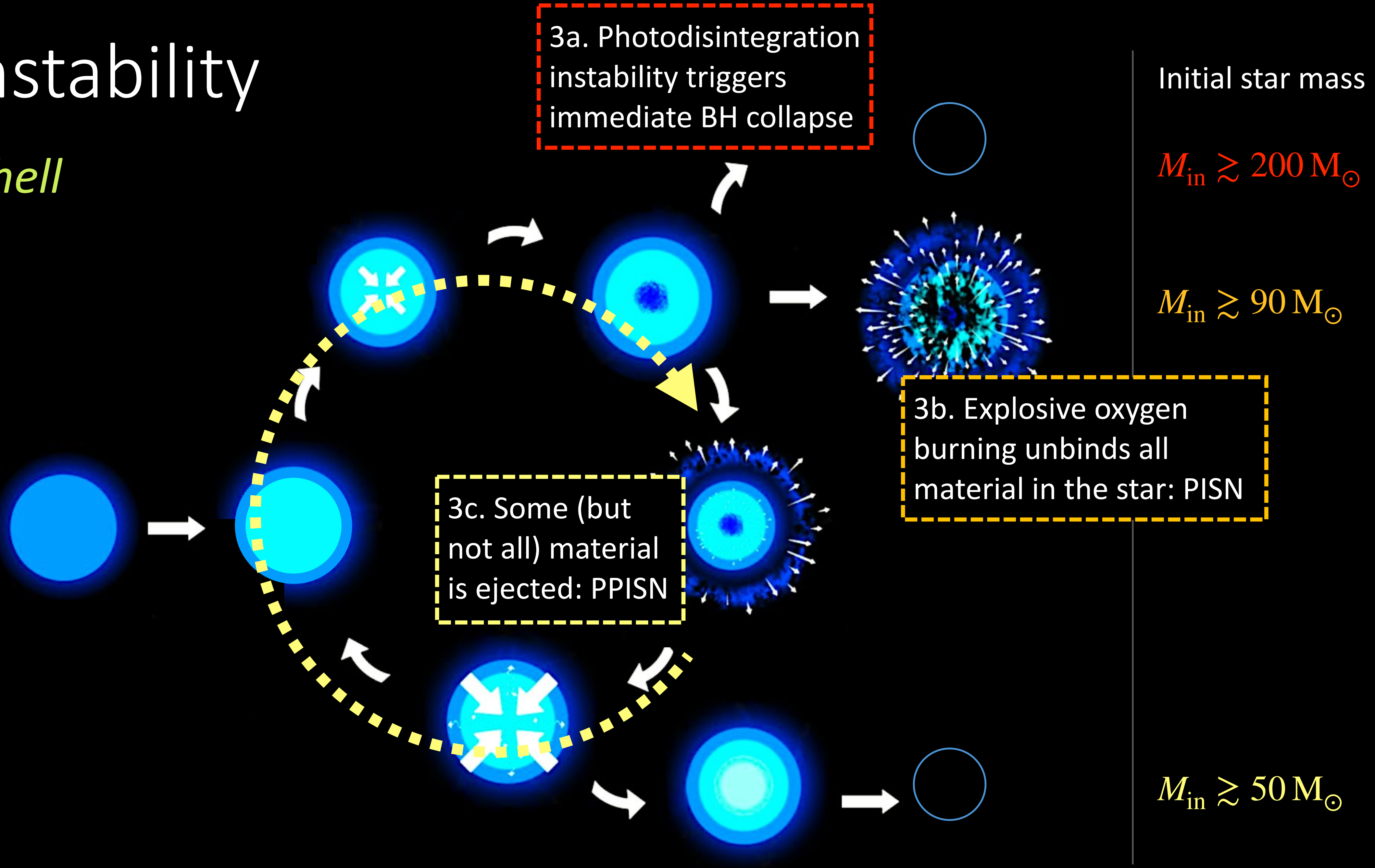
$M_{\rm in} \gtrsim 200\,{\rm M}_{\odot}$

$M_{\rm in} \gtrsim 90\,{\rm M}_{\odot}$

Adapted from Renzo et al [2002.05077]

Pair instability

in a nutshell



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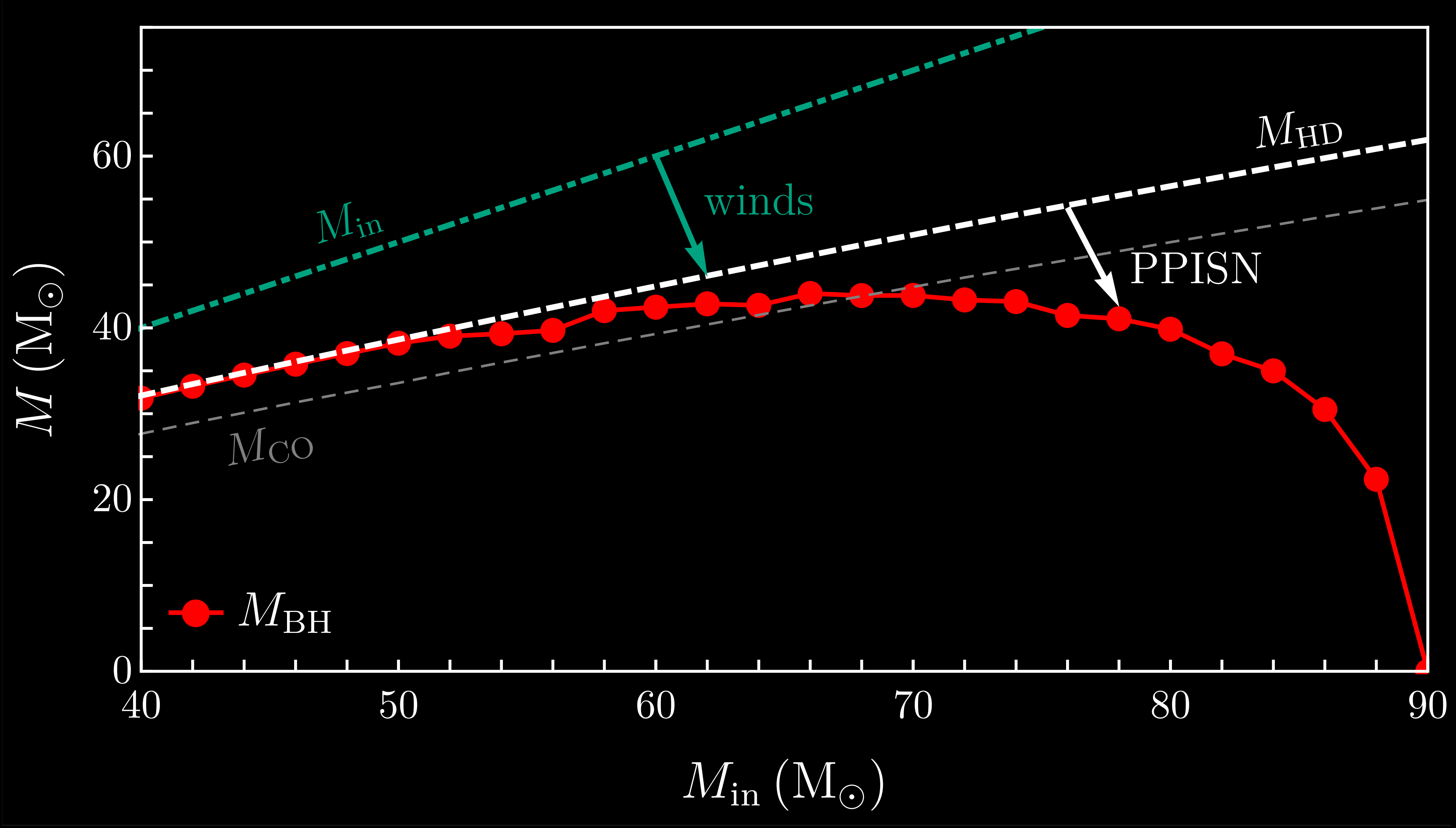
Resulting black hole masses



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

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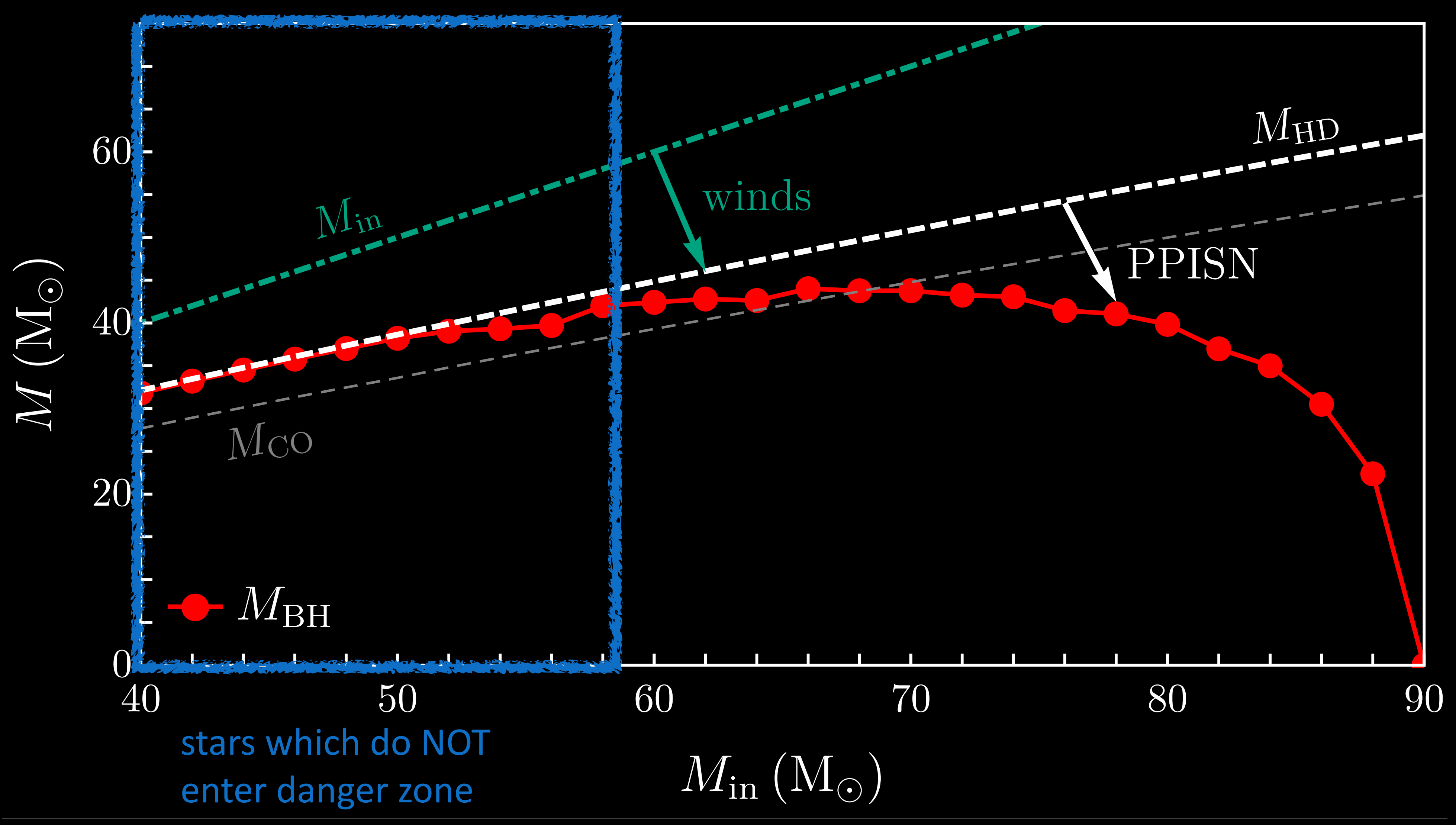

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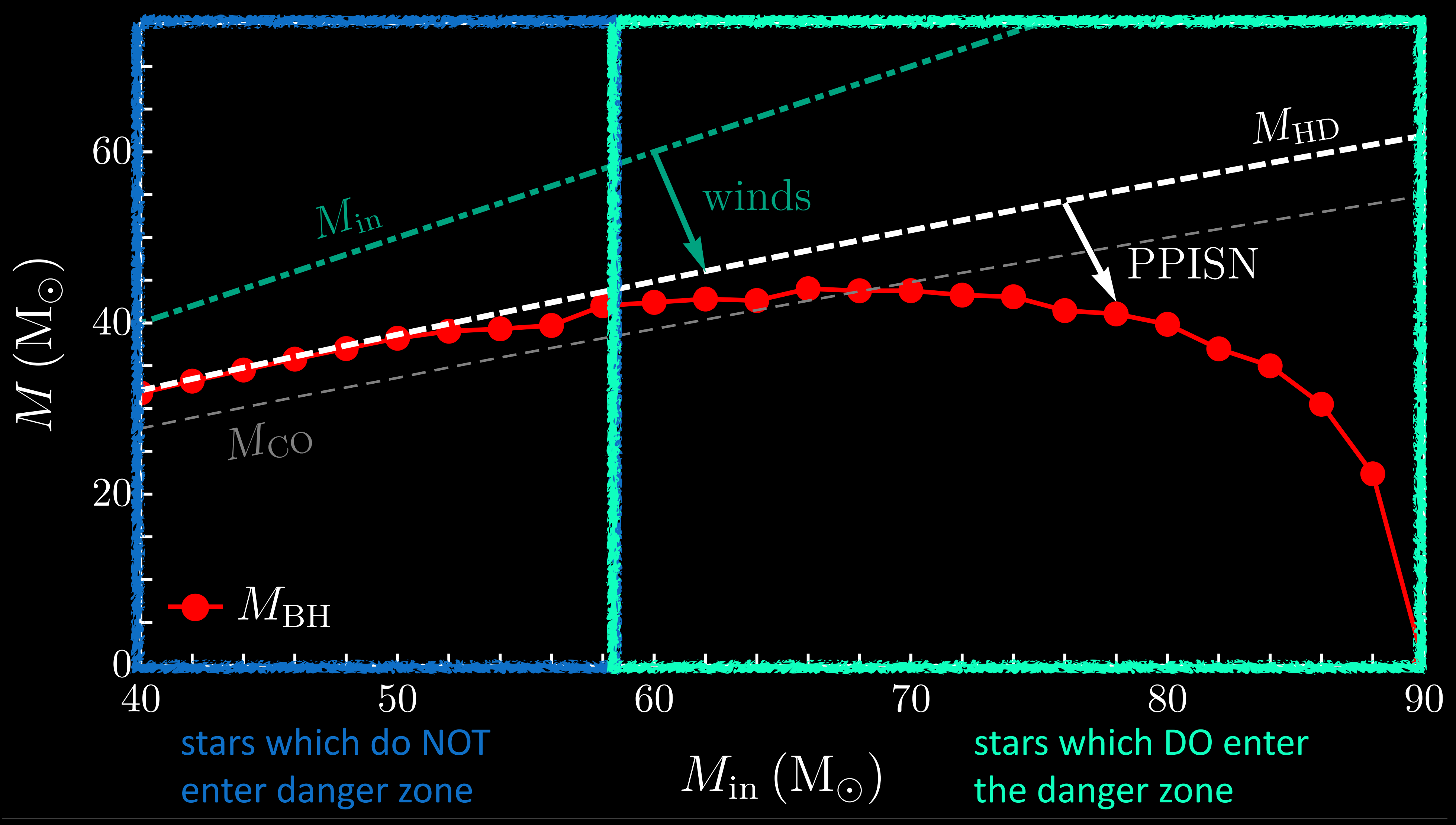

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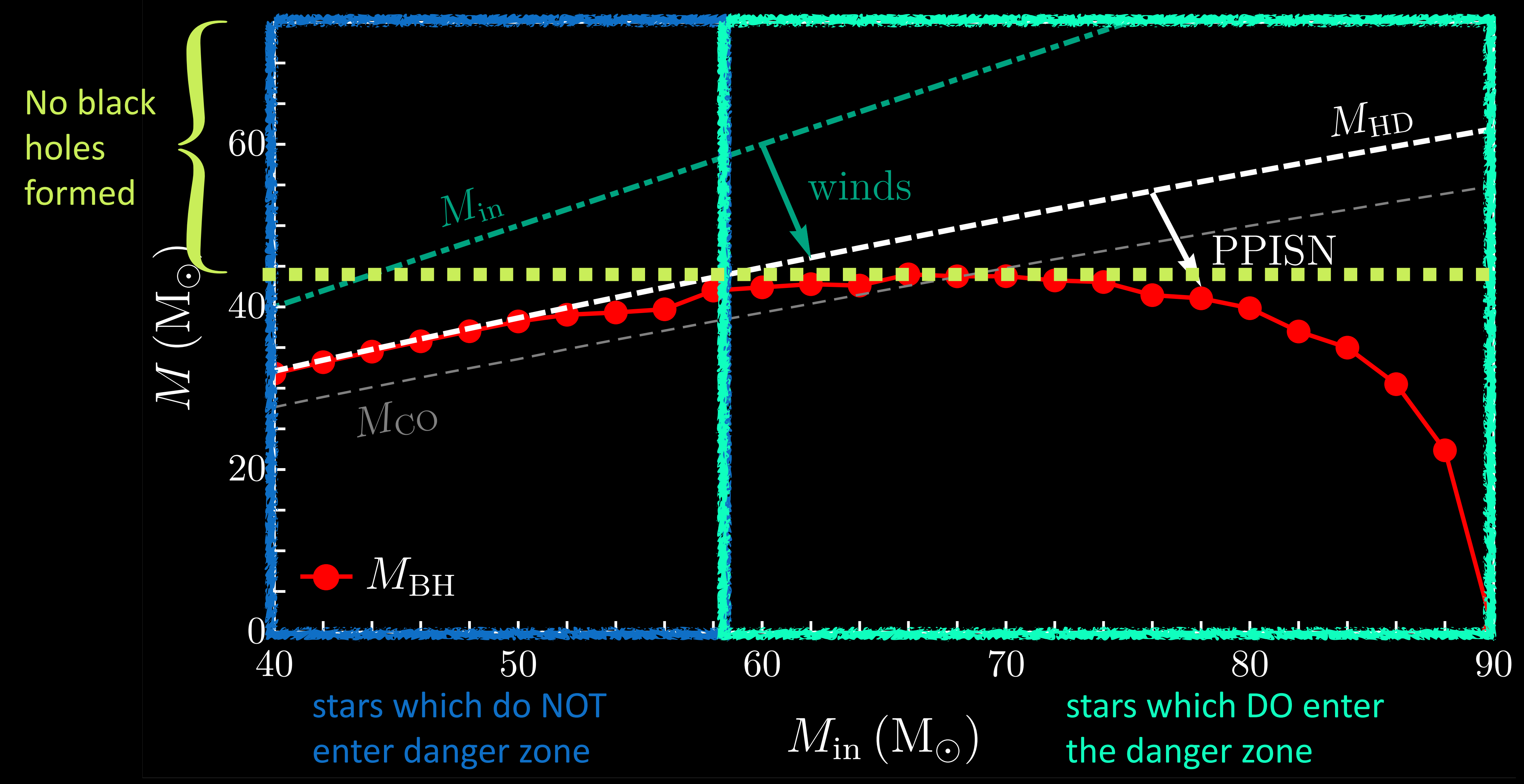

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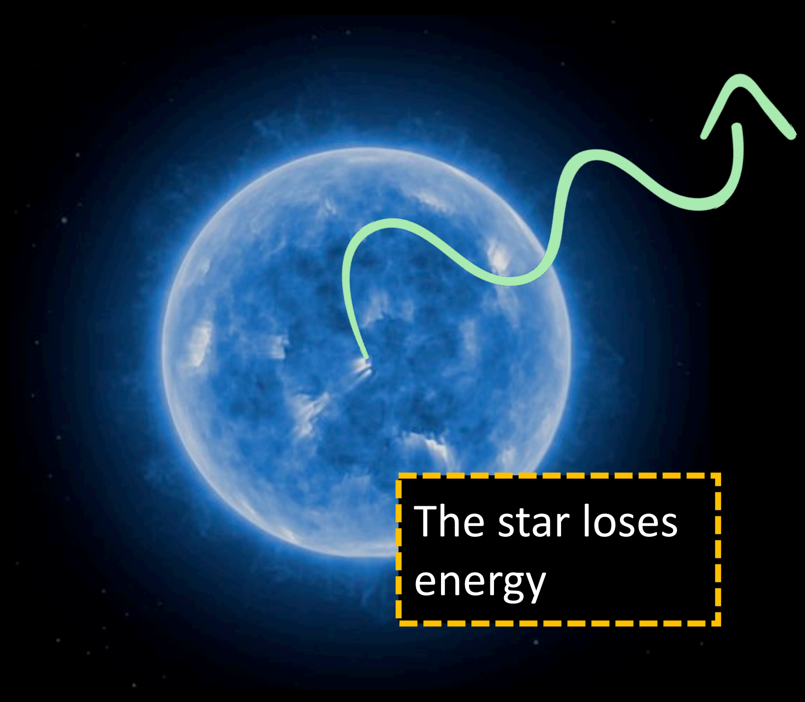
What about new particles?

New particles…

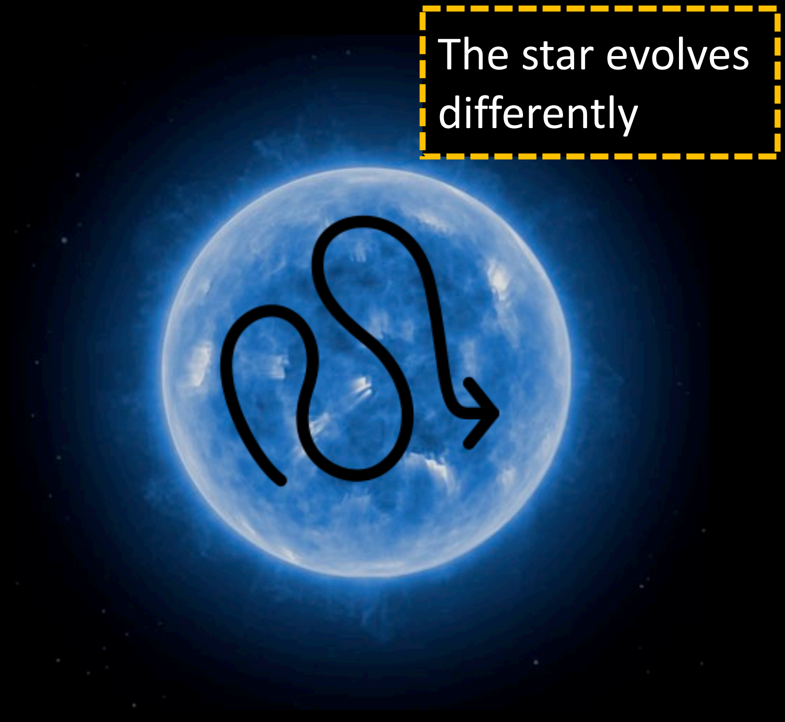
- May be produced in the star and *free stream out*



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*



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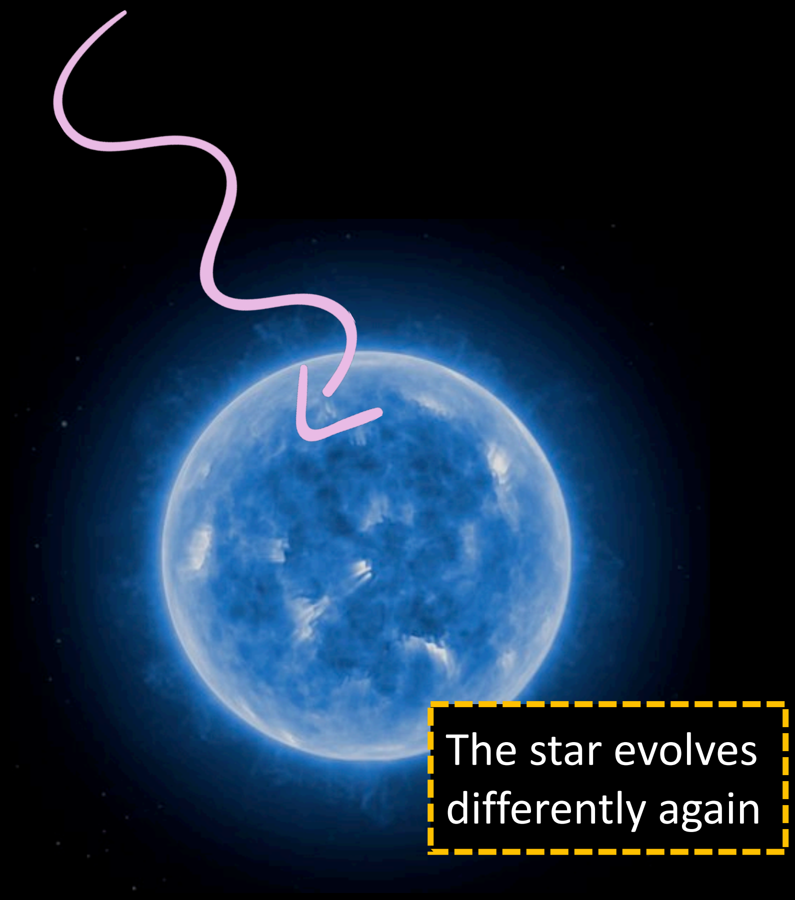

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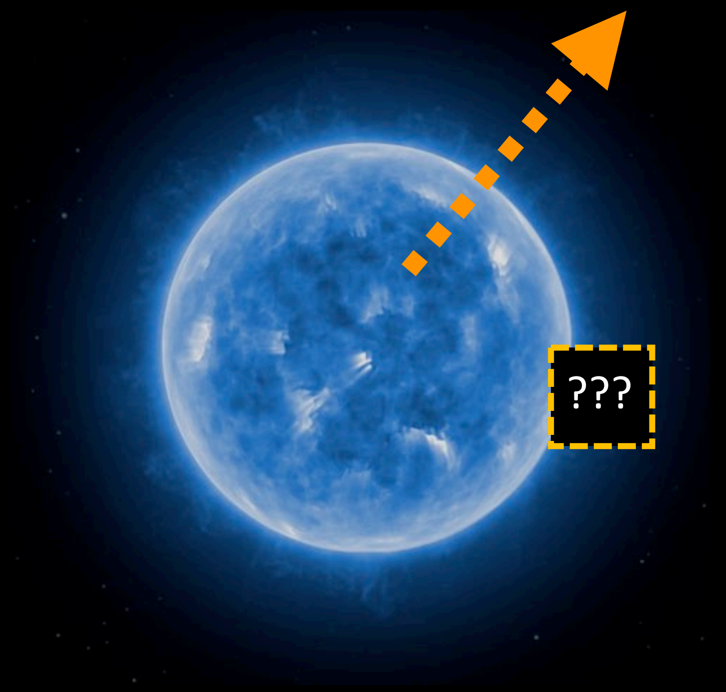

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Nuclear astrophysics: pair-instability is a sensitive probe of $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

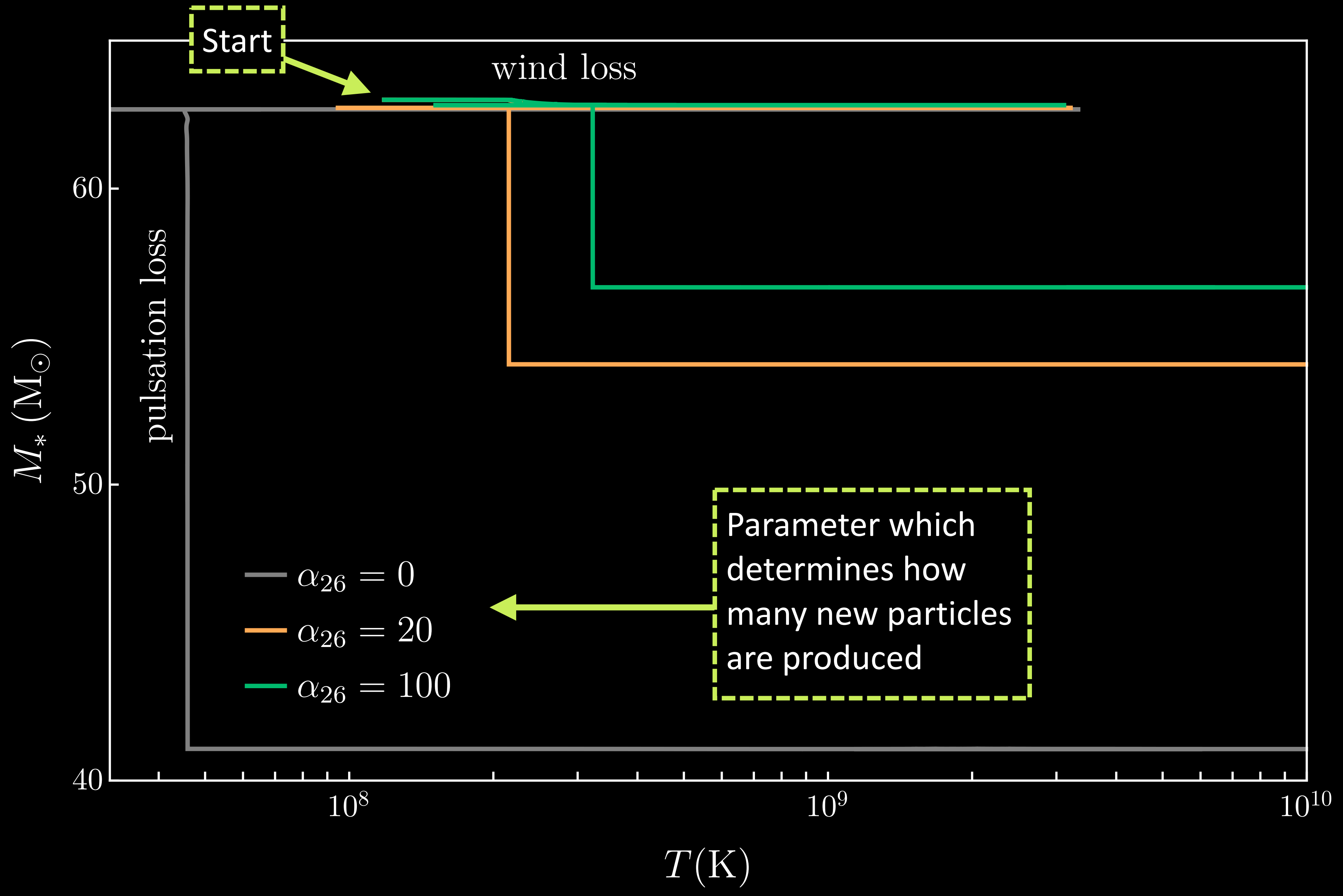
Farmer, Renzo, de Mink, Fishbach, Justham arXiv:2006.06678

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

Straight, Sakstein, Baxter, arXiv: 2009.10716

→ Testing the BHMG hypothesis with GW data

Implications of particles free streaming out



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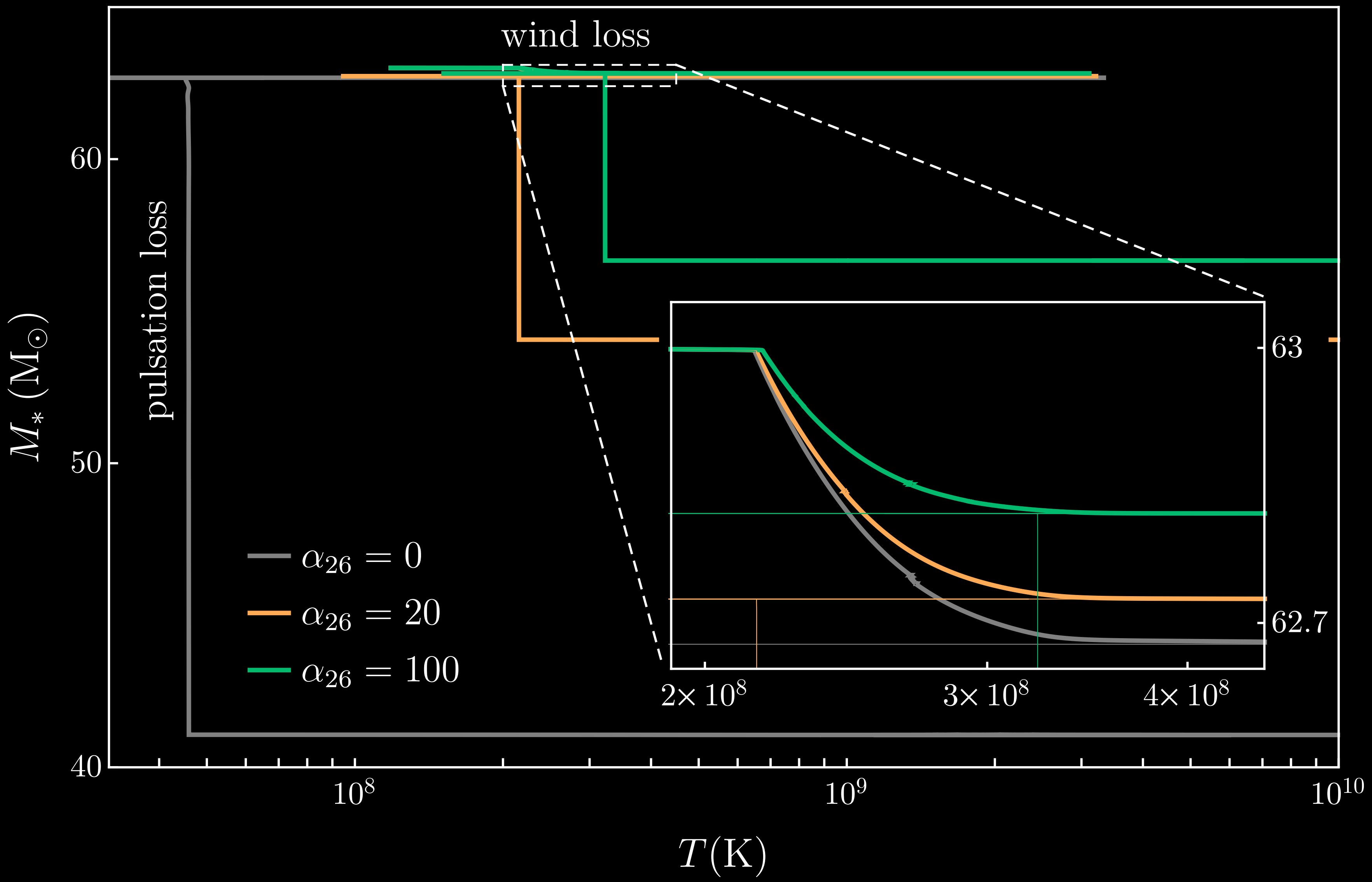
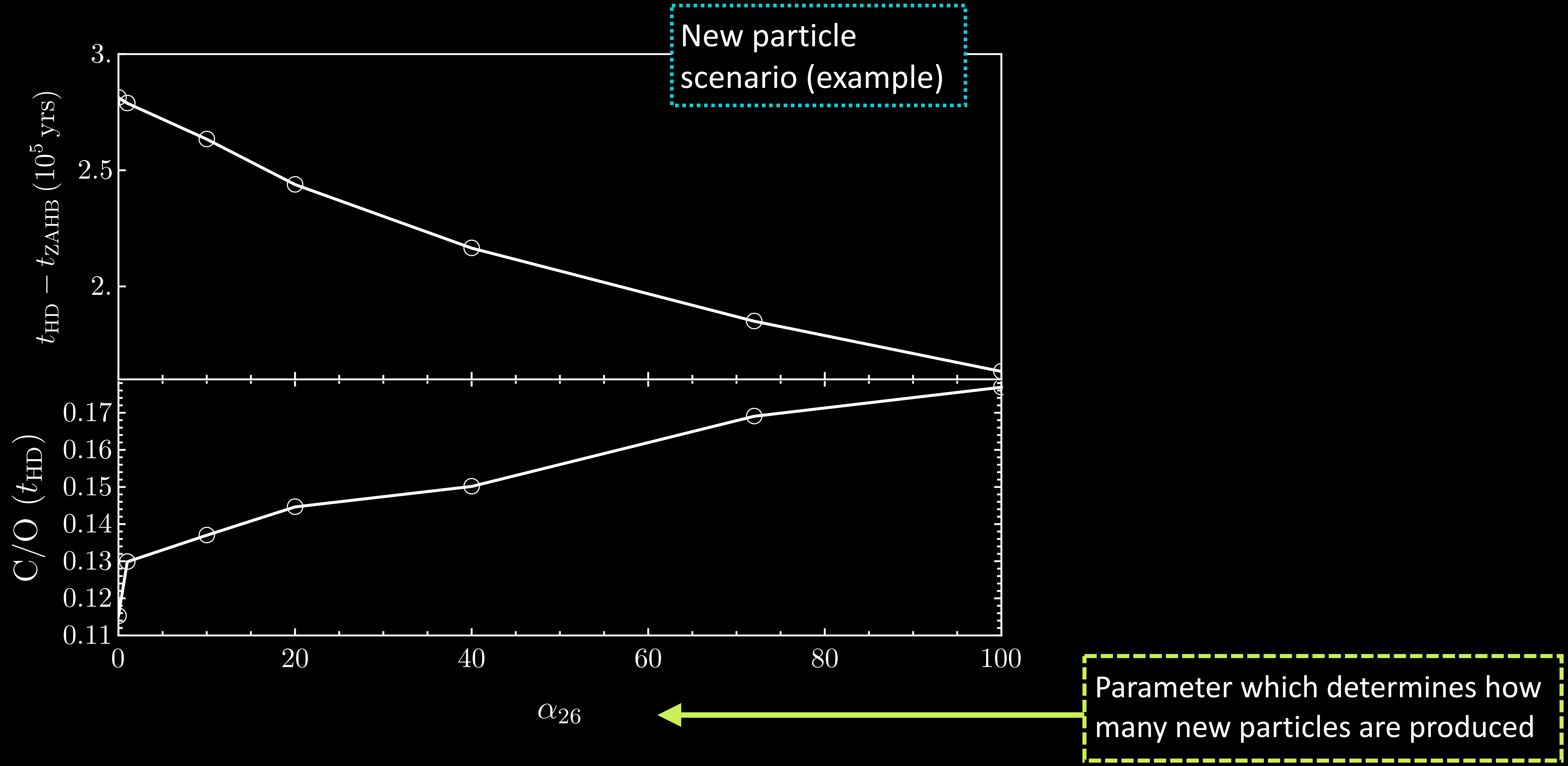


What does the extra energy loss do?



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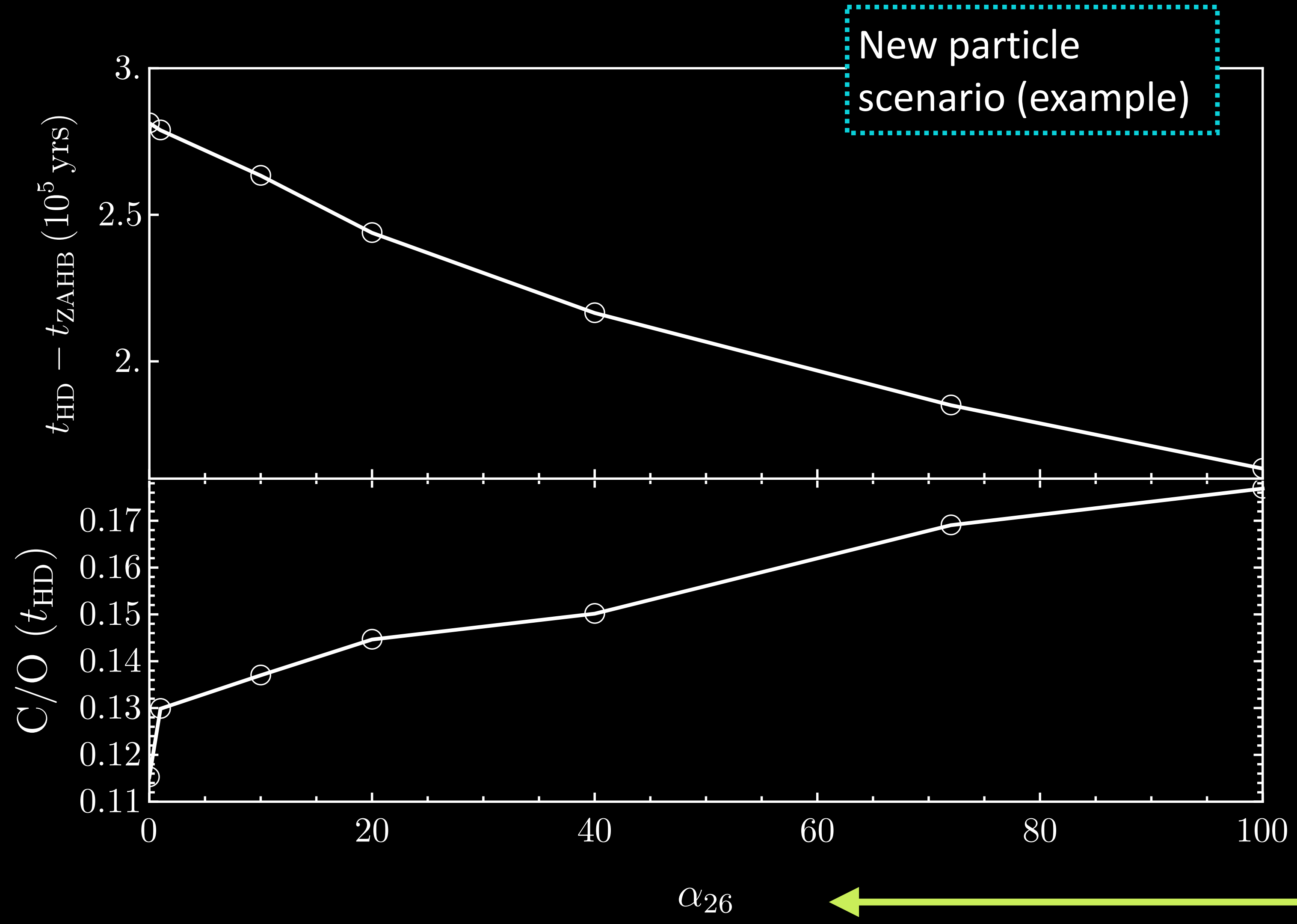
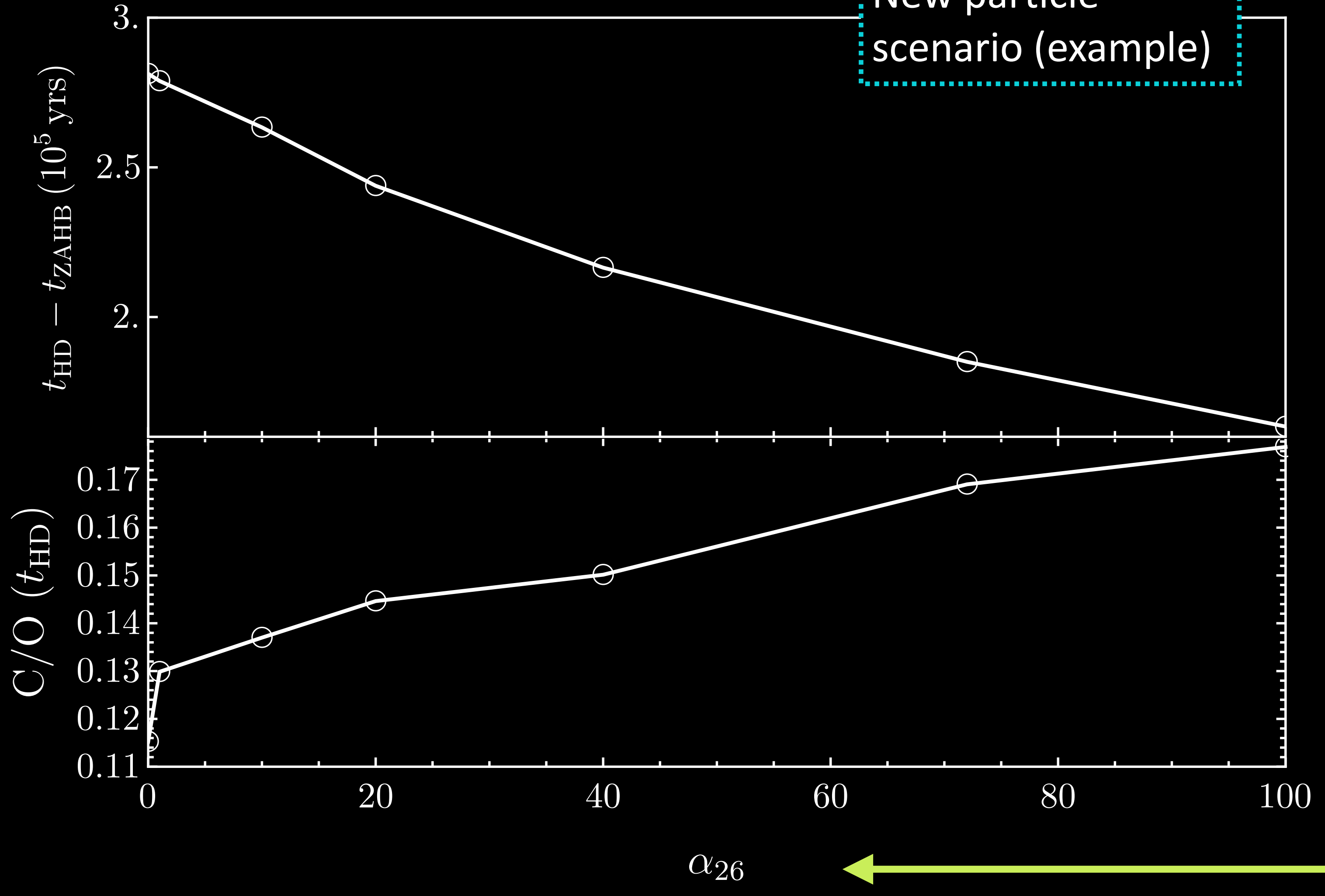


Greater energy losses lead to *shorter He-burning phases*

Parameter which determines how many new particles are produced

What does the extra energy loss do?

New particle scenario (example)

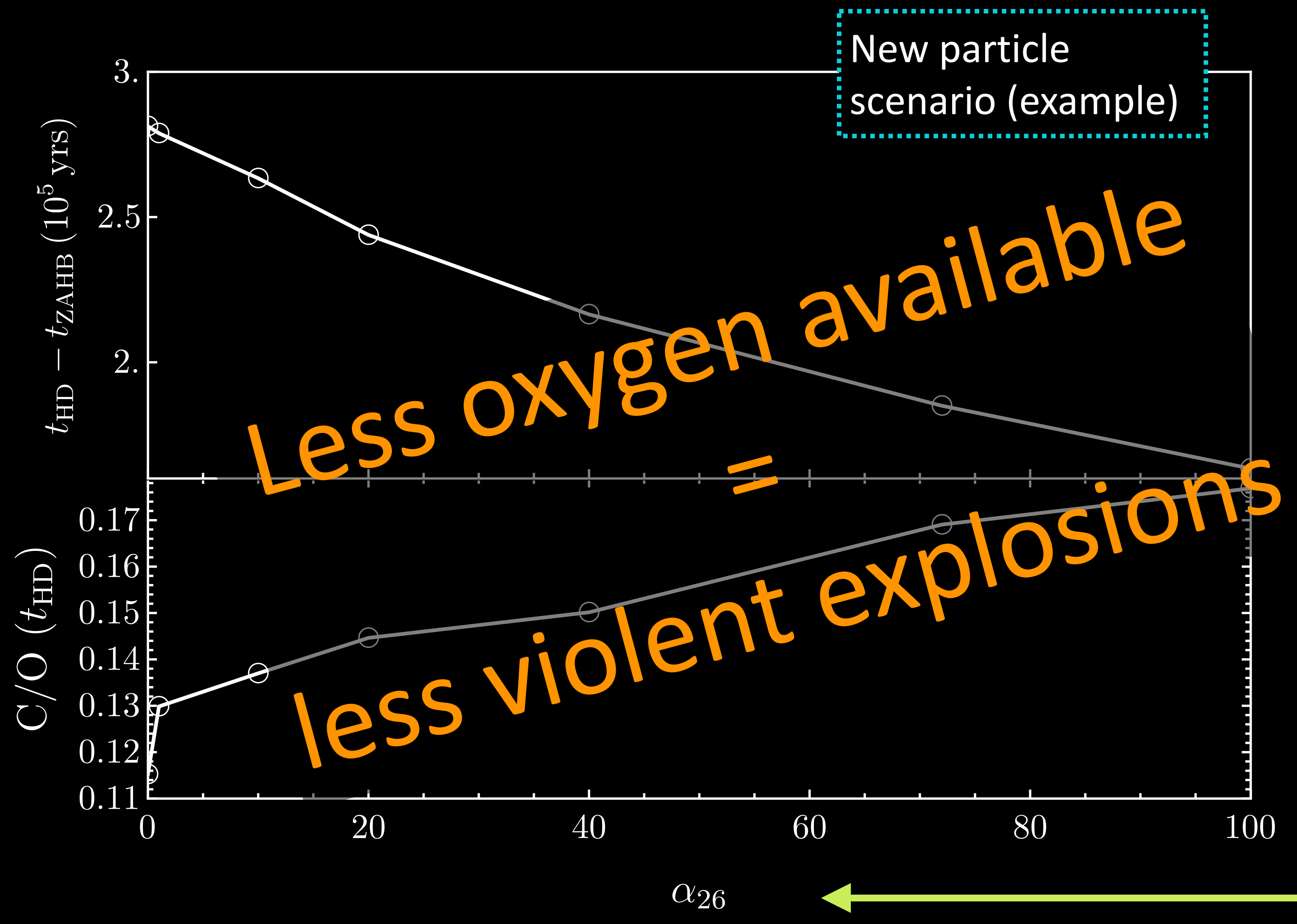


Greater energy losses lead to *shorter He-burning phases*

That means *more* carbon and *less* oxygen at the end!

Parameter which determines how many new particles are produced

What does the extra energy loss do?



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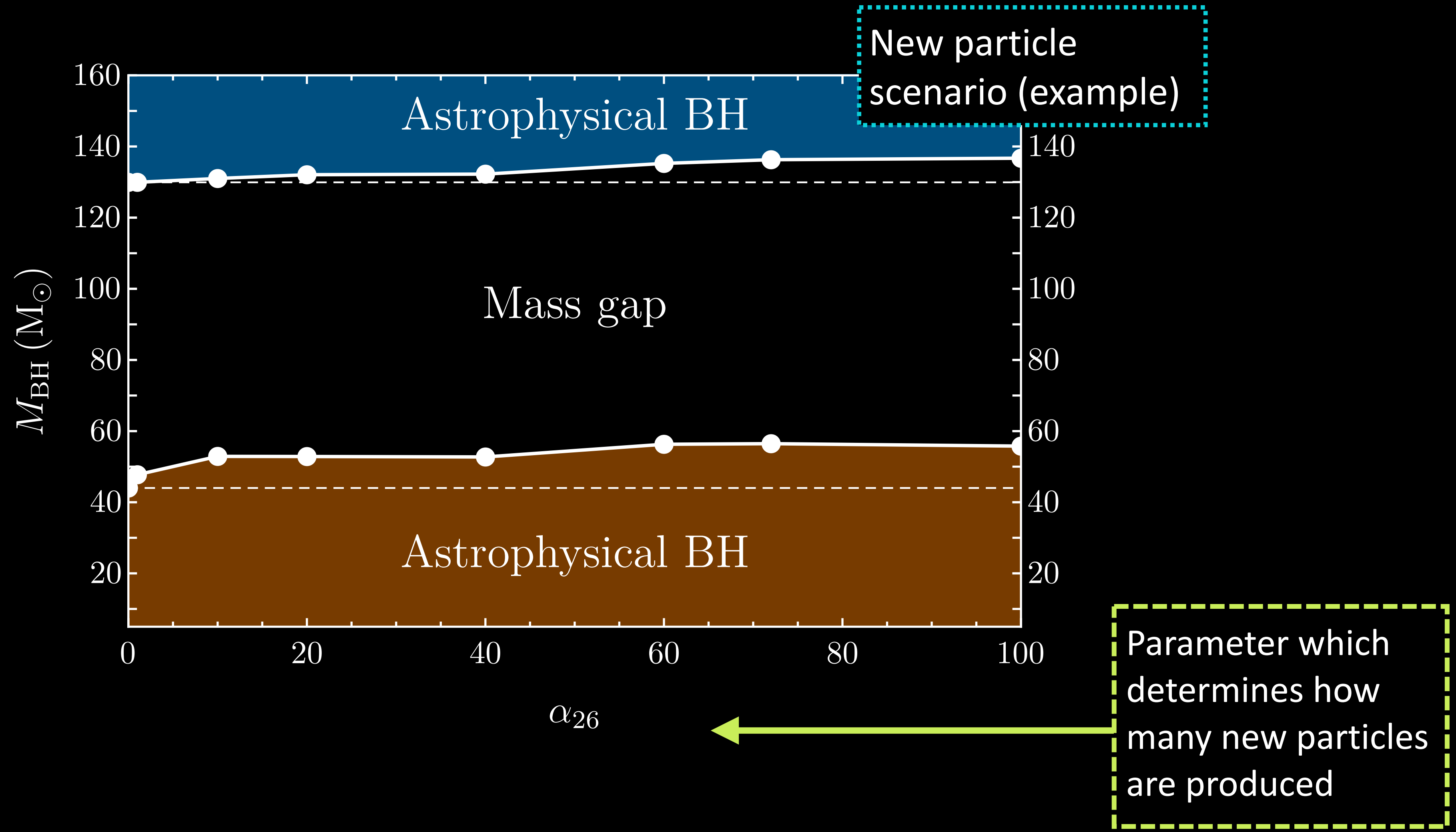
Parameter which determines how many new particles are produced

Less violent explosions = heavier black holes



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

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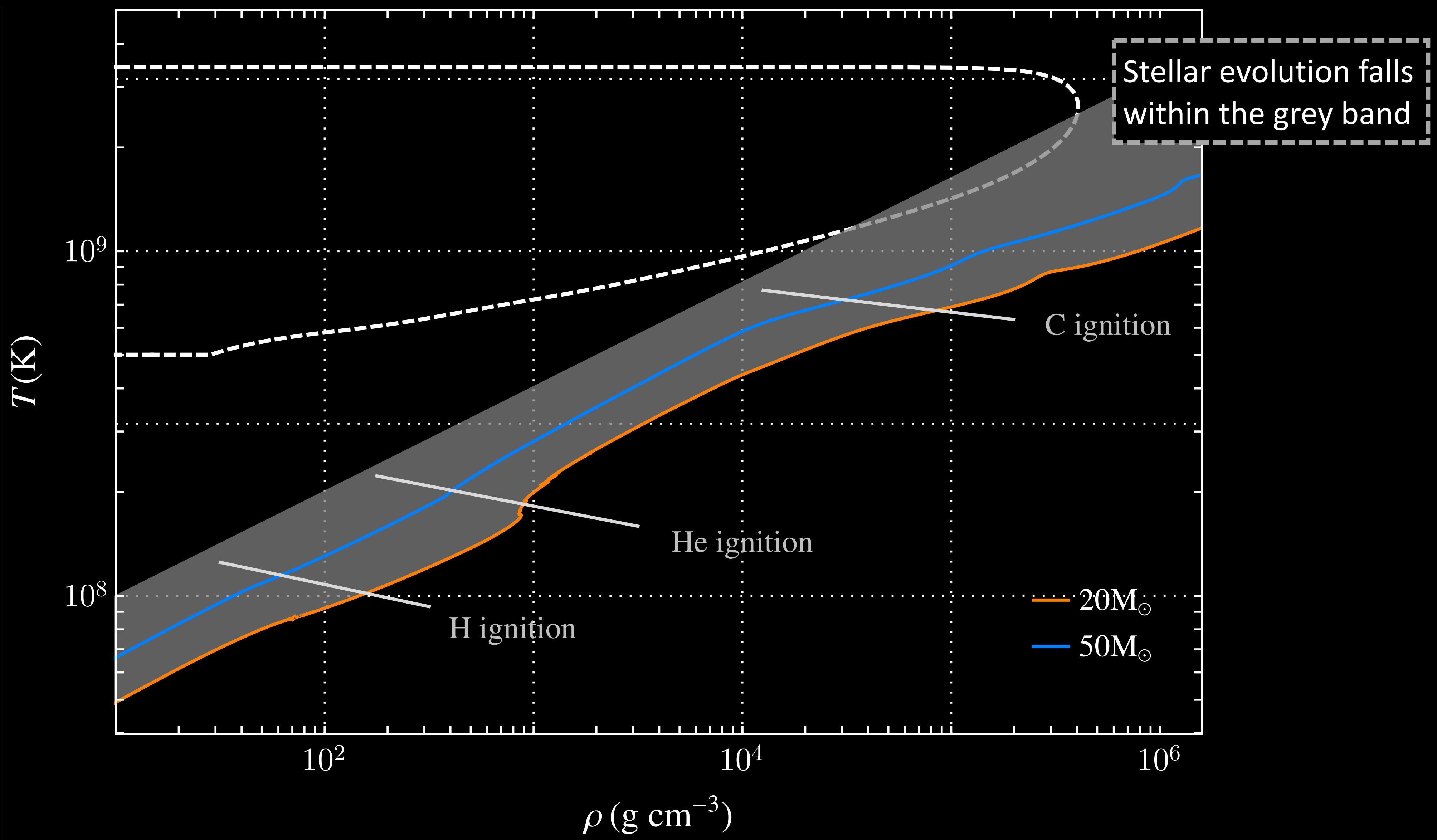

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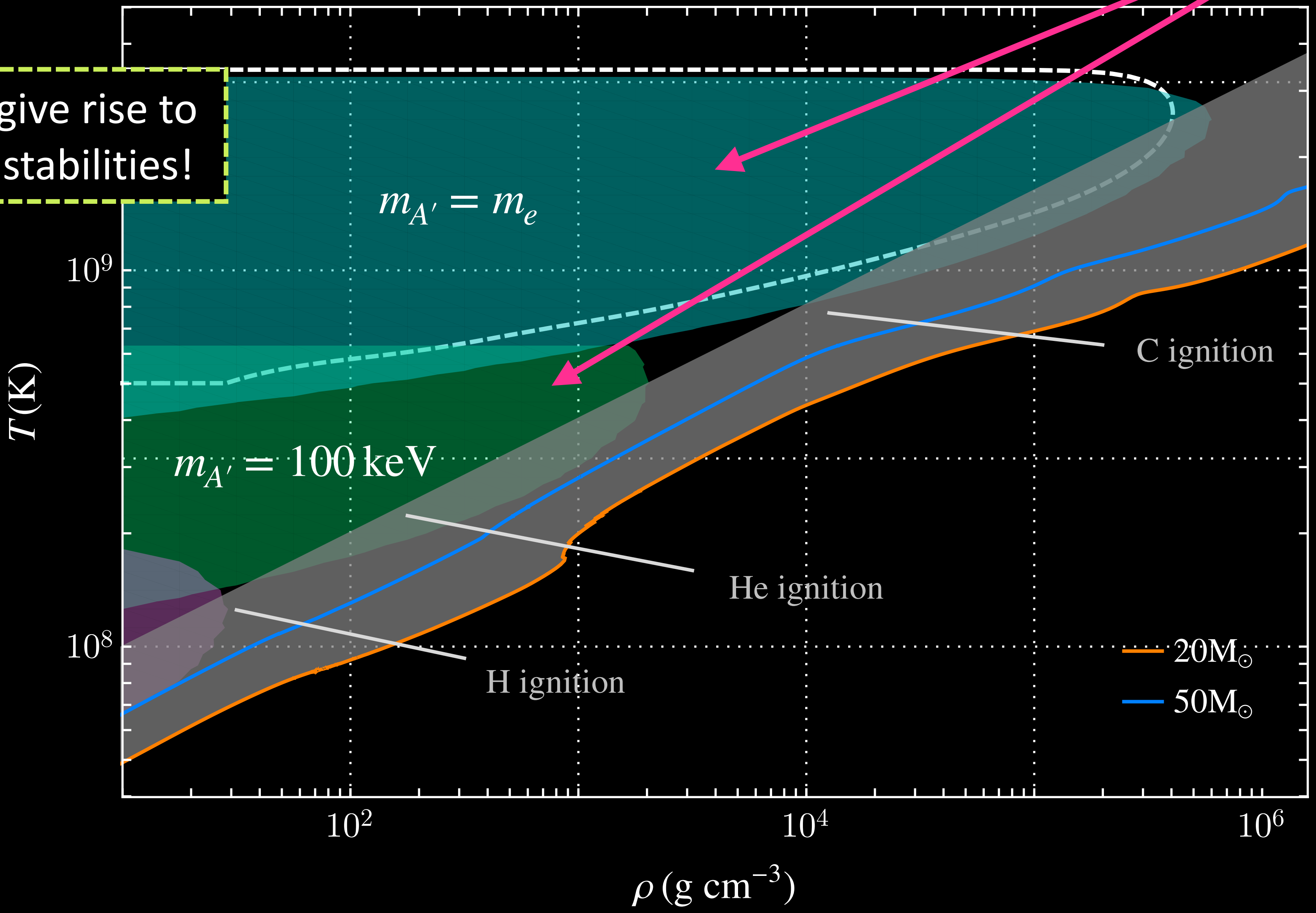
What about new trapped particles?

New particle A'

... can give rise to new instabilities!



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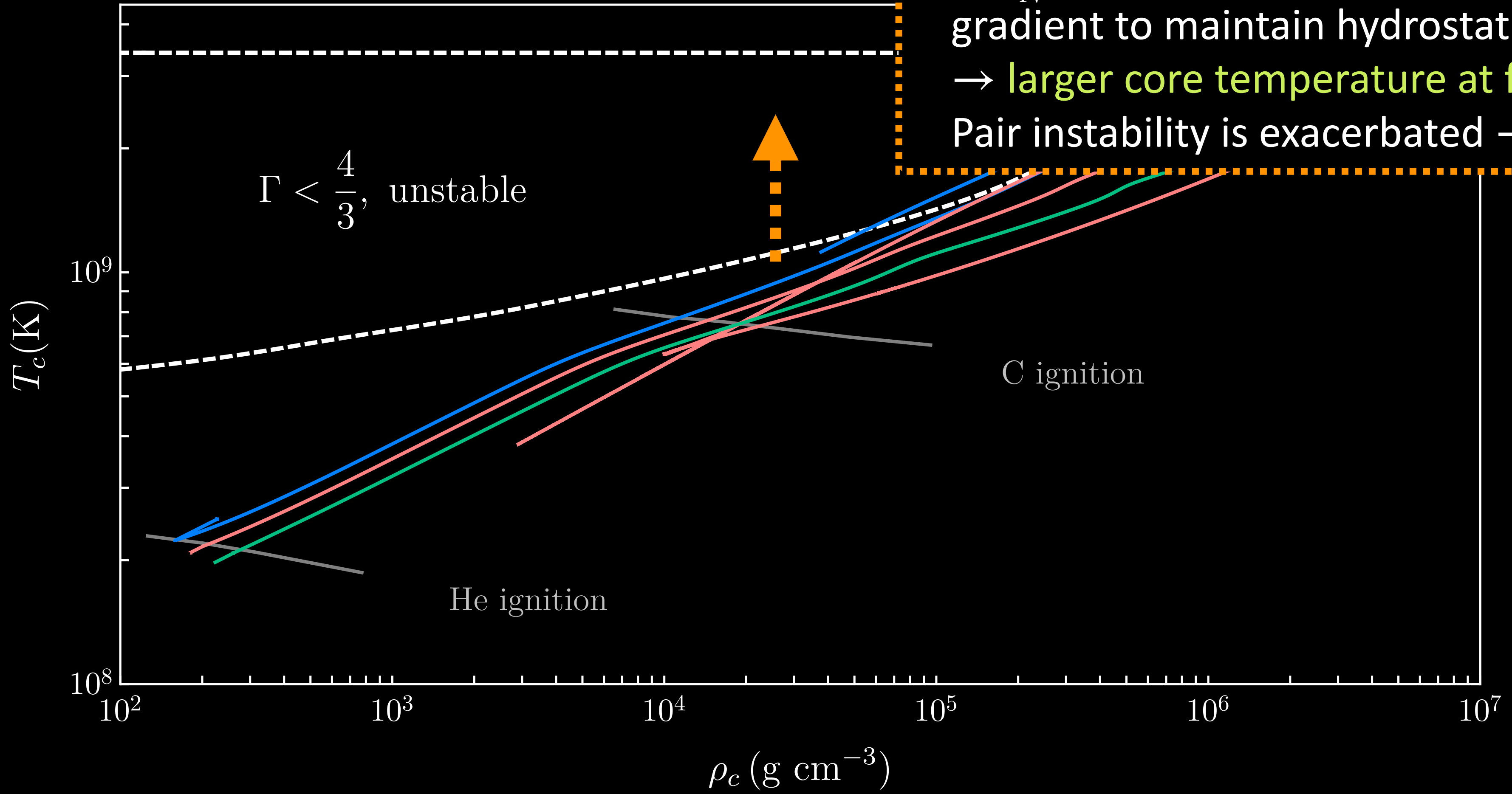
Sakstein, DC, McDermott, Straight, Baxter, PRL, arXiv:2009.01213 [gr-qc]
Straight, Sakstein, Baxter, PRD, arXiv:2009.10716 [gr-qc]

New forces

Screened modified gravity: new force as effective ΔG_N

$\Delta G_N > 0$ (locally) → need larger pressure gradient to maintain hydrostatic equilibrium → larger core temperature at fixed density → Pair instability is exacerbated →Lighter BHs



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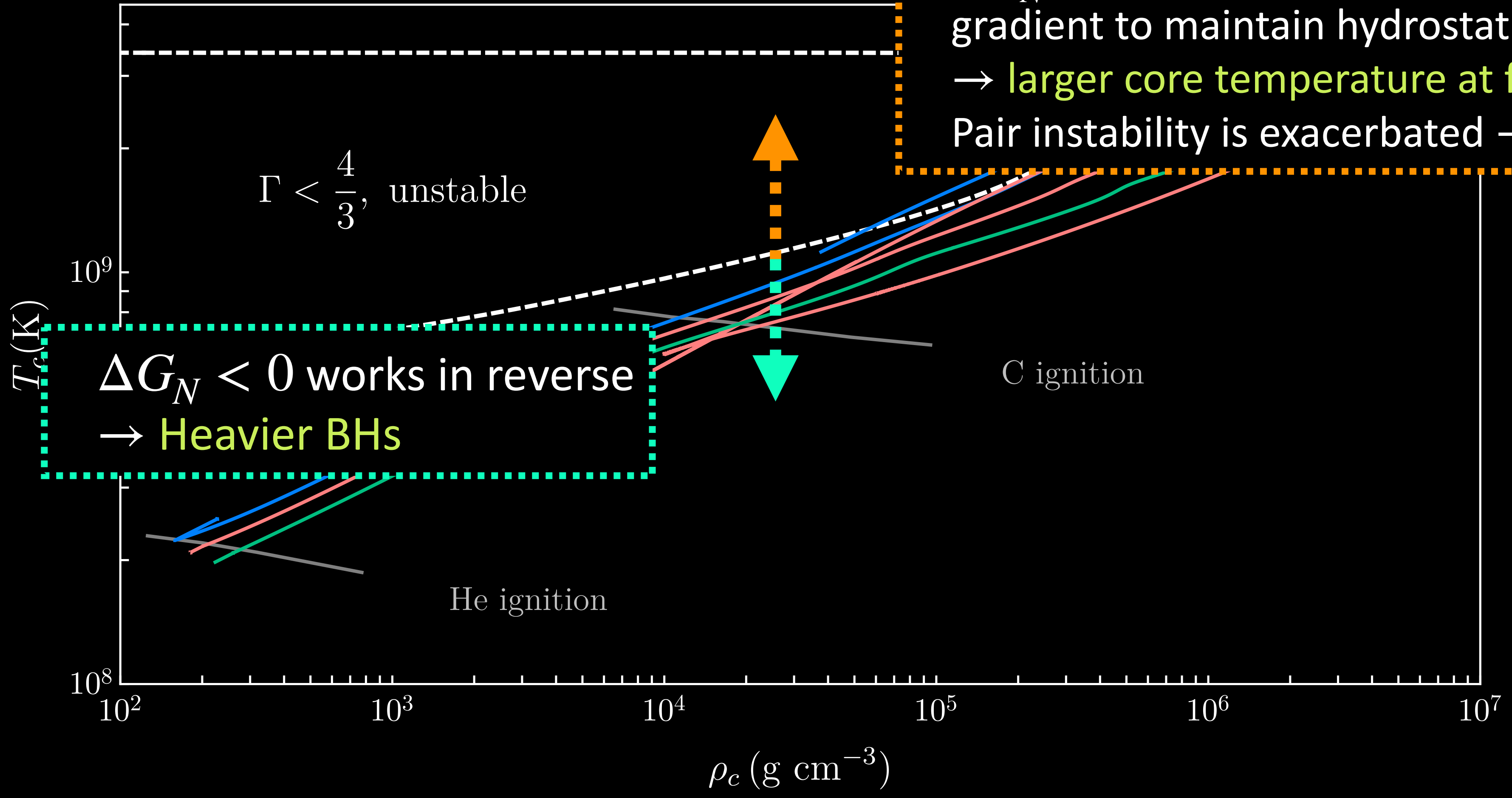


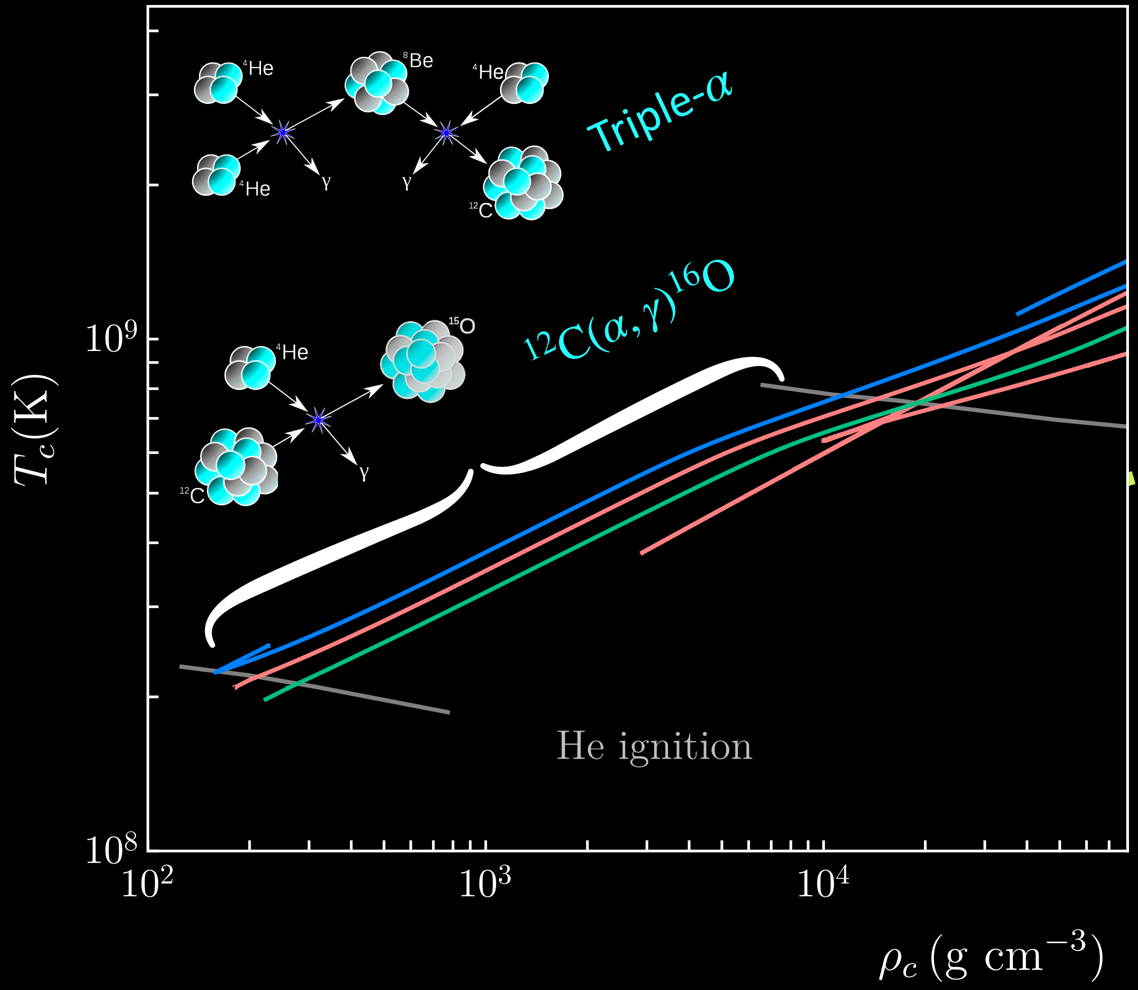
$\Delta G_N < 0$ works in reverse → Heavier BHs

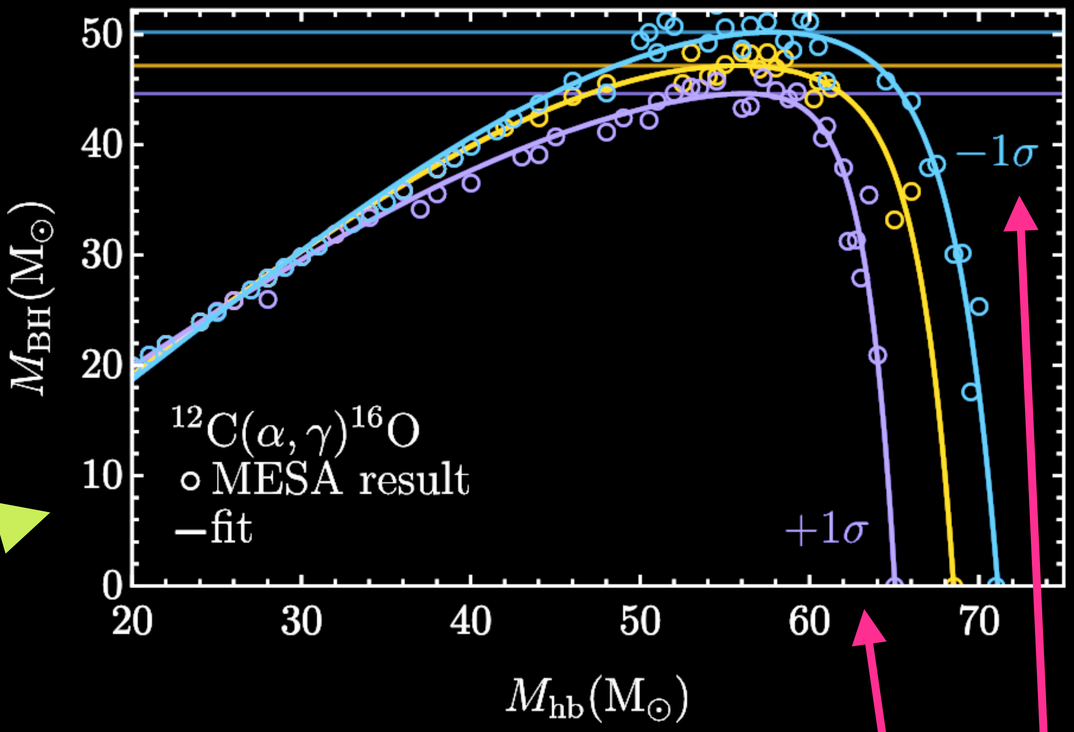
Farmer, Renzo, de Mink, Fishbach, Justham, ApJL arXiv:2006.06678 [astro-ph.HE]

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

Nuclear physics

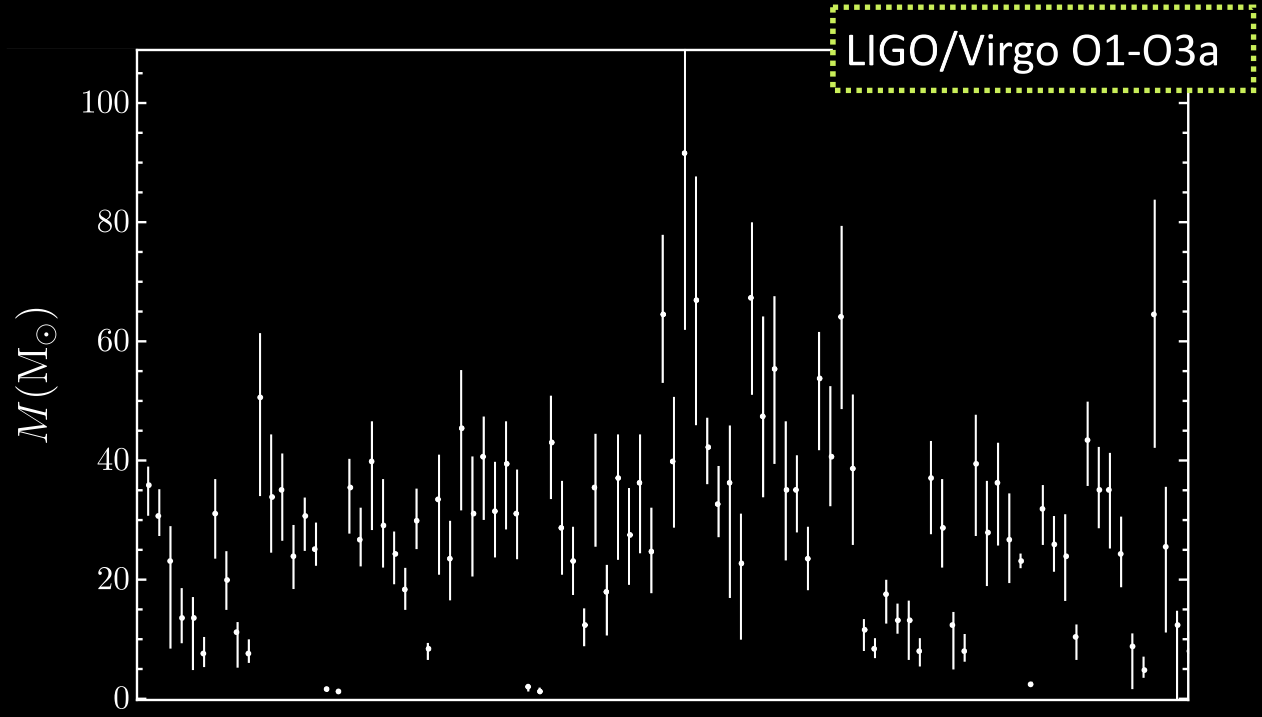
Particularly sensitive to $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$



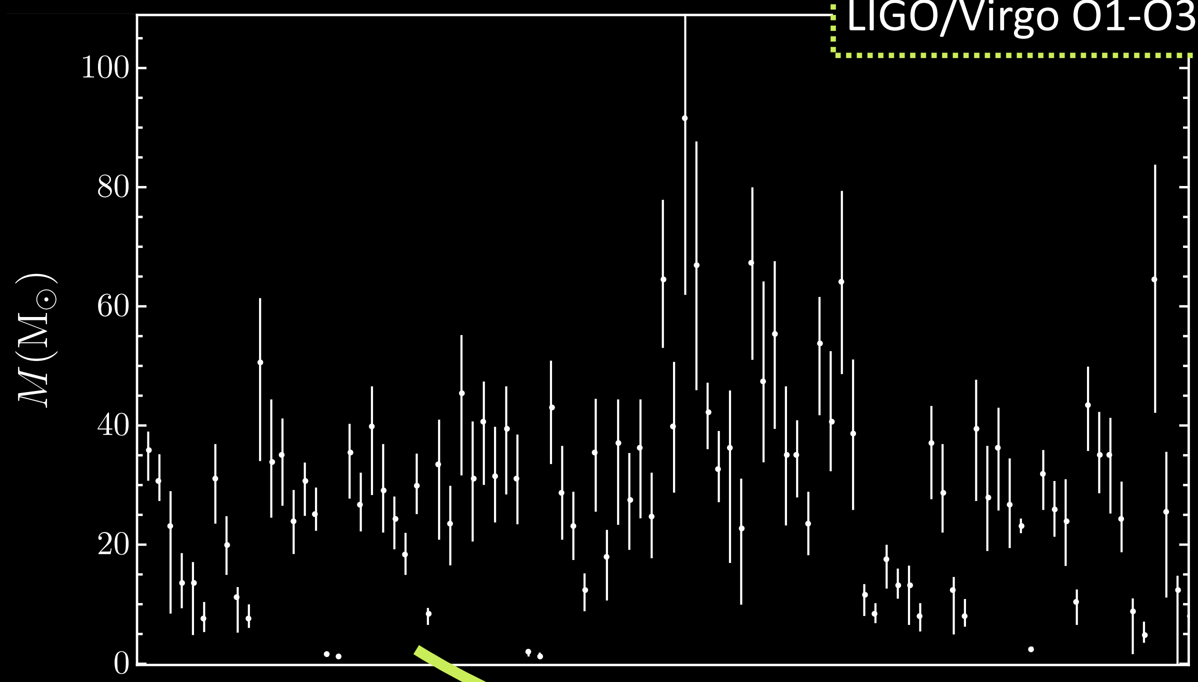


deBoer et al, RMP, arXiv:1709.03144 [hep-ex]

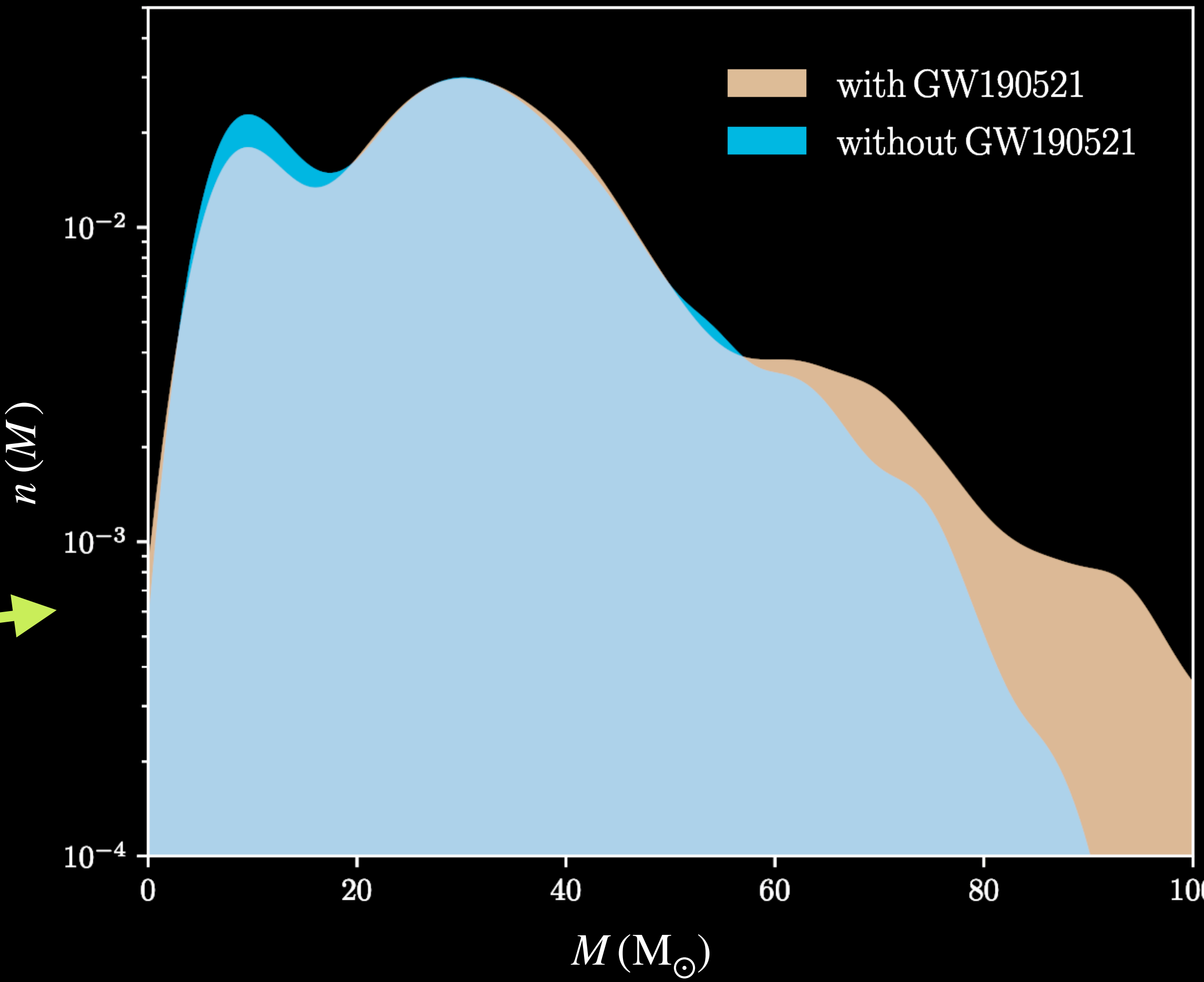
Black hole archeology: what about the data?



Black hole archeology: what about the data?

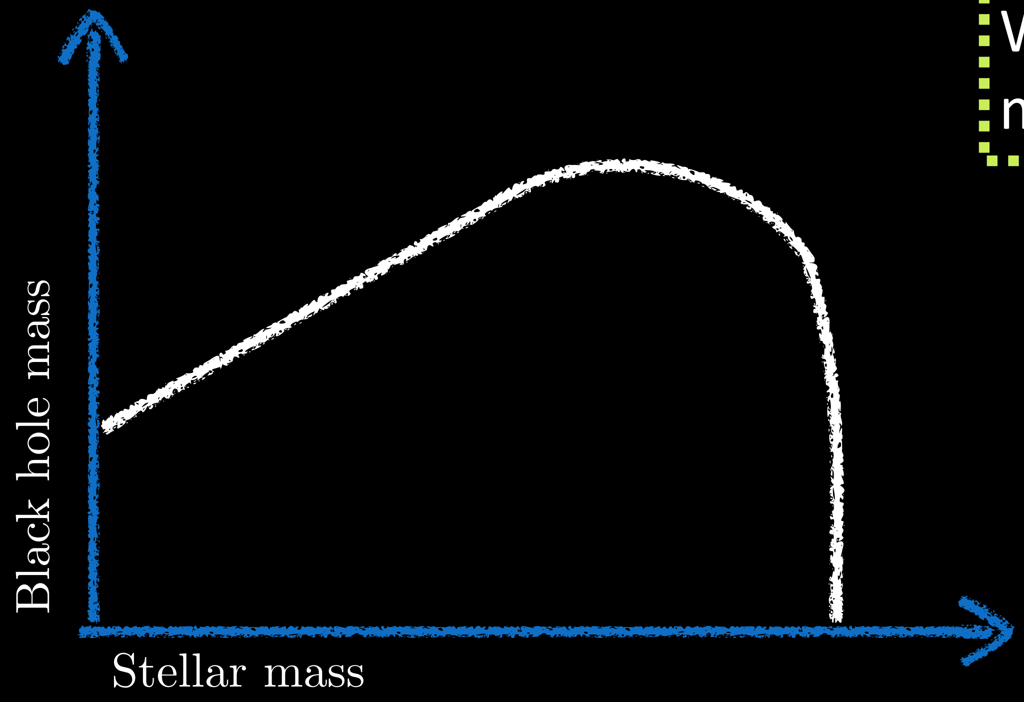


Mass distribution



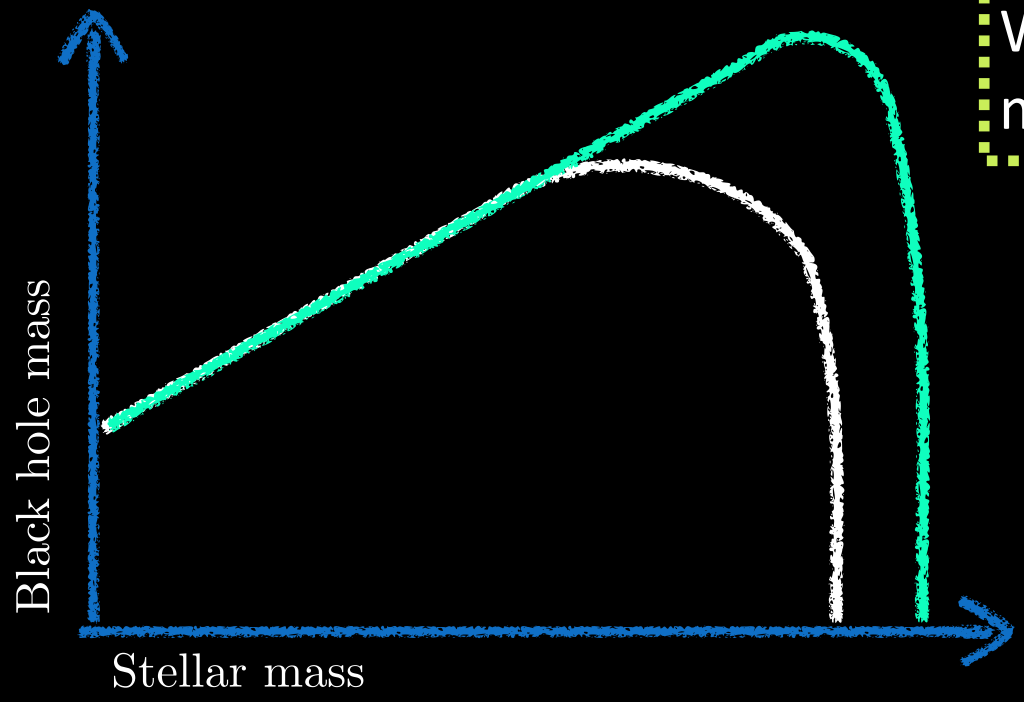
Other parameters, such as spin alignment, eccentricity, redshift, and mass ratio can serve as further evidence for the binary's environment/merger history

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]

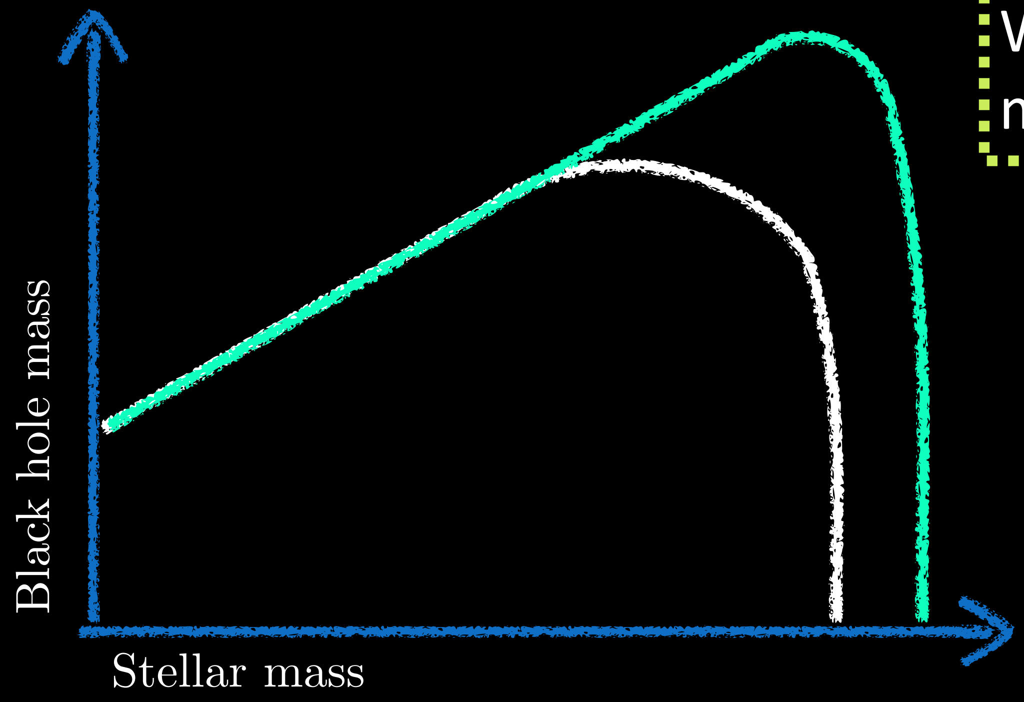
Straight, Sakstein, Baxter, PRD, arXiv:2009.10716 [gr-qc]

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

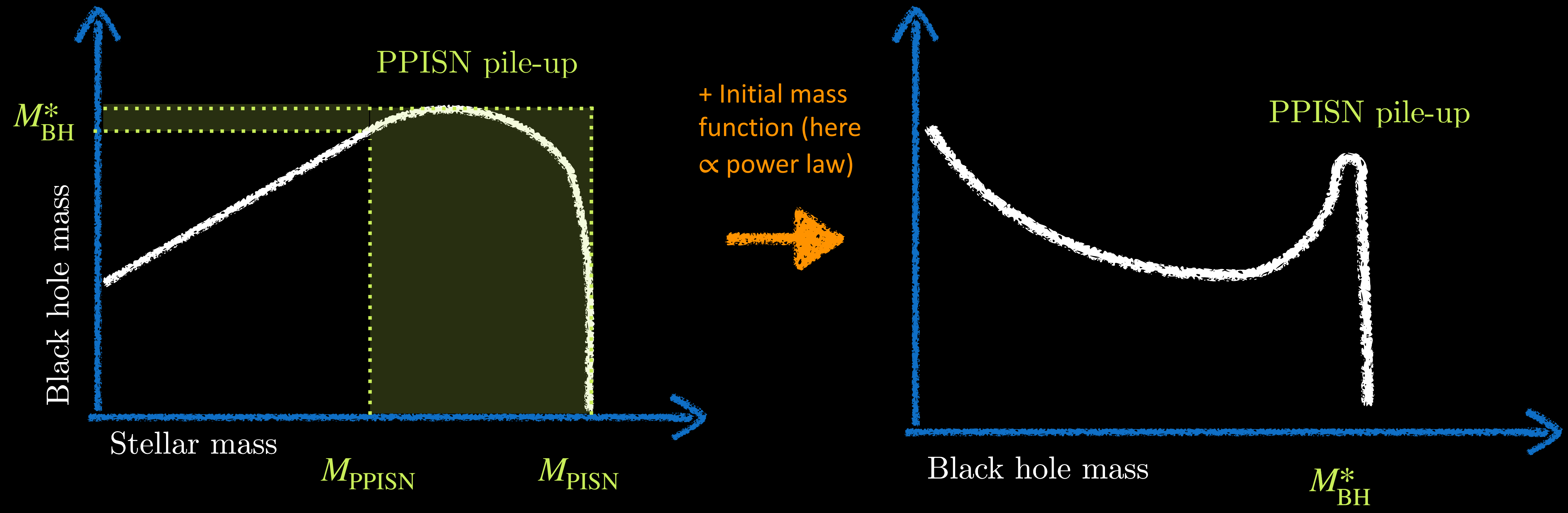
New particles or different nuclear physics may change this prediction

How can we use *data* to test that?

FIND THE GAP

Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

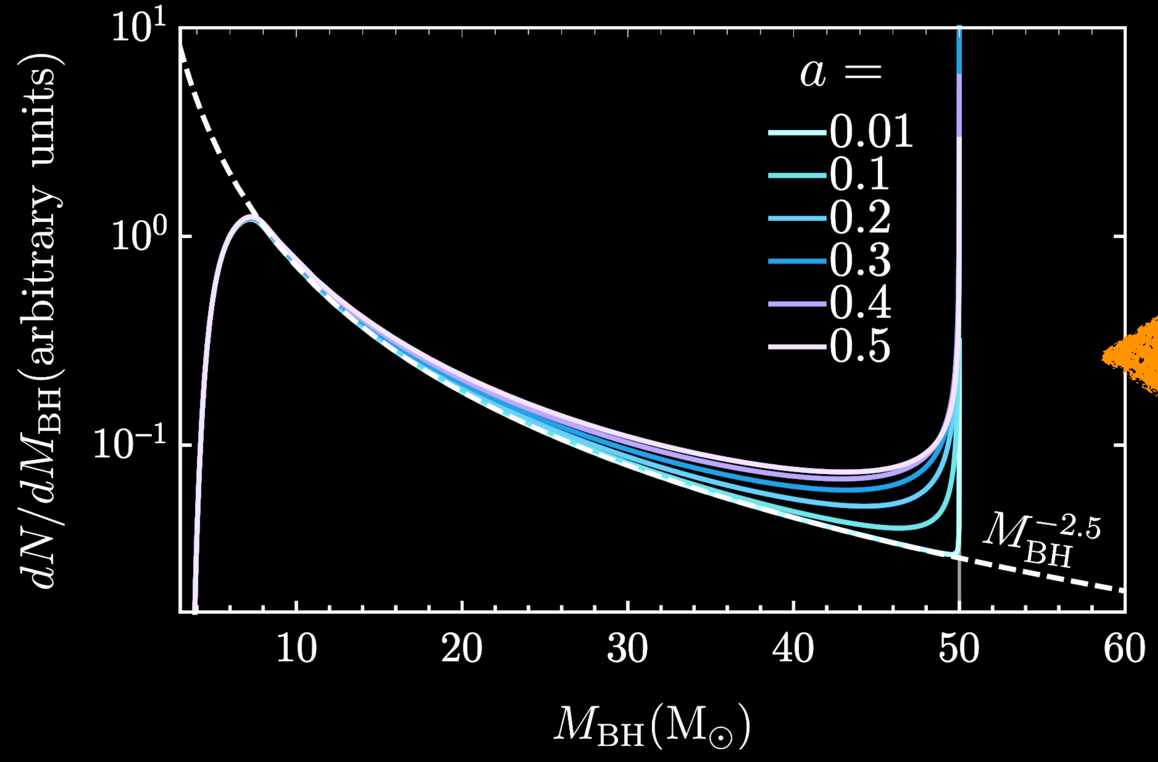
Pair-instability and black hole populations

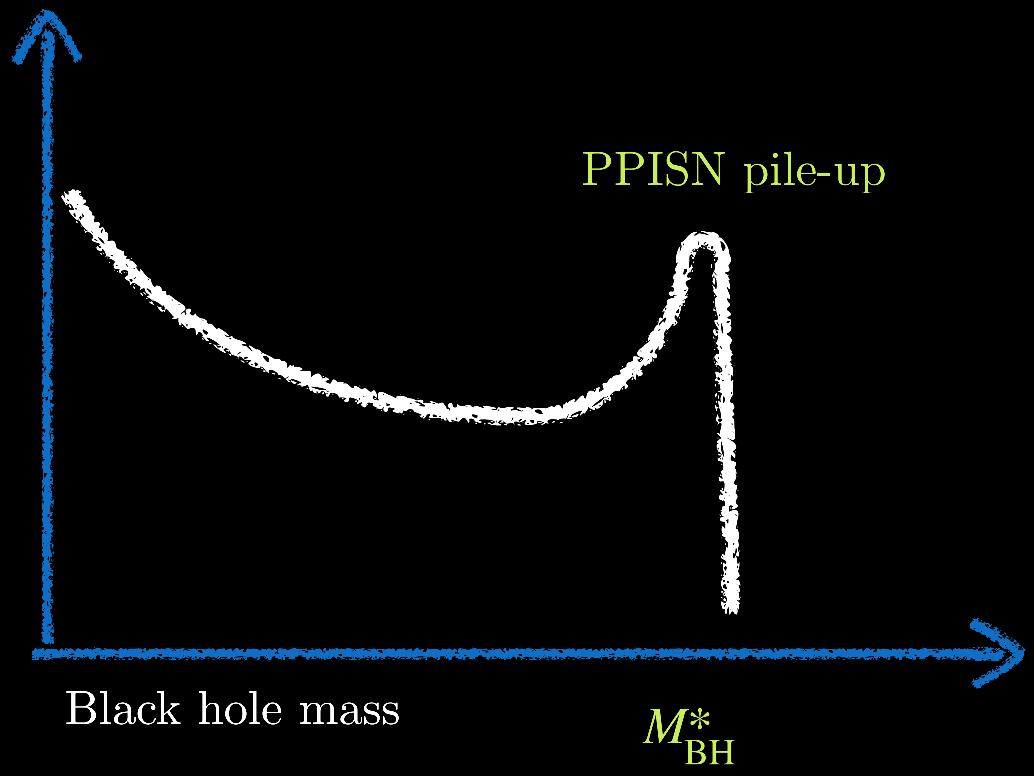


+ Initial mass function (here assumed to be a power law)

See also Talbot & Trane, arXiv:1801.02699

Pair-instability and black hole populations





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

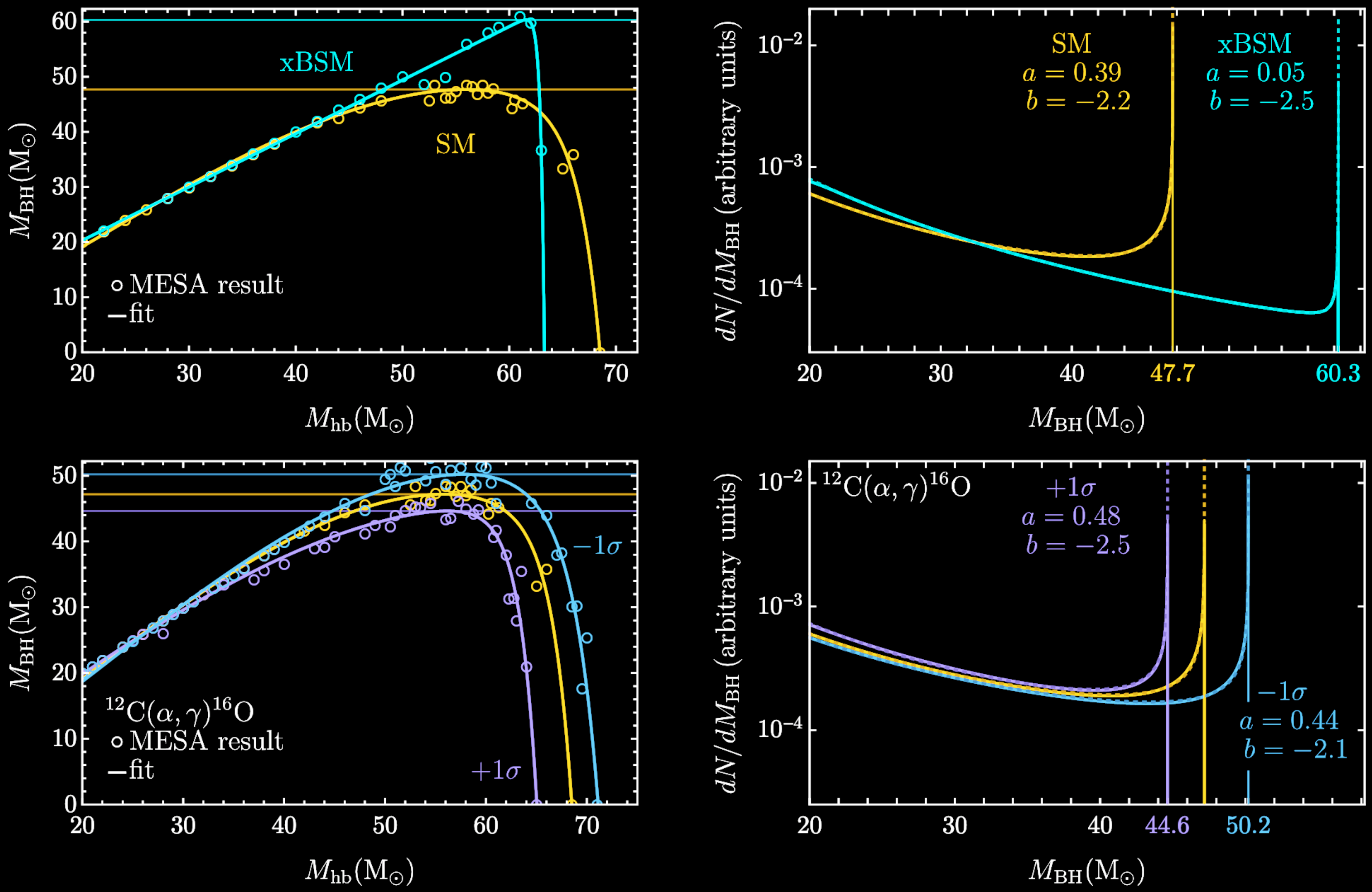
Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

Pair-instability and black hole populations

FIND THE GAP

Testing BSM particle physics

Testing nuclear (astro) physics

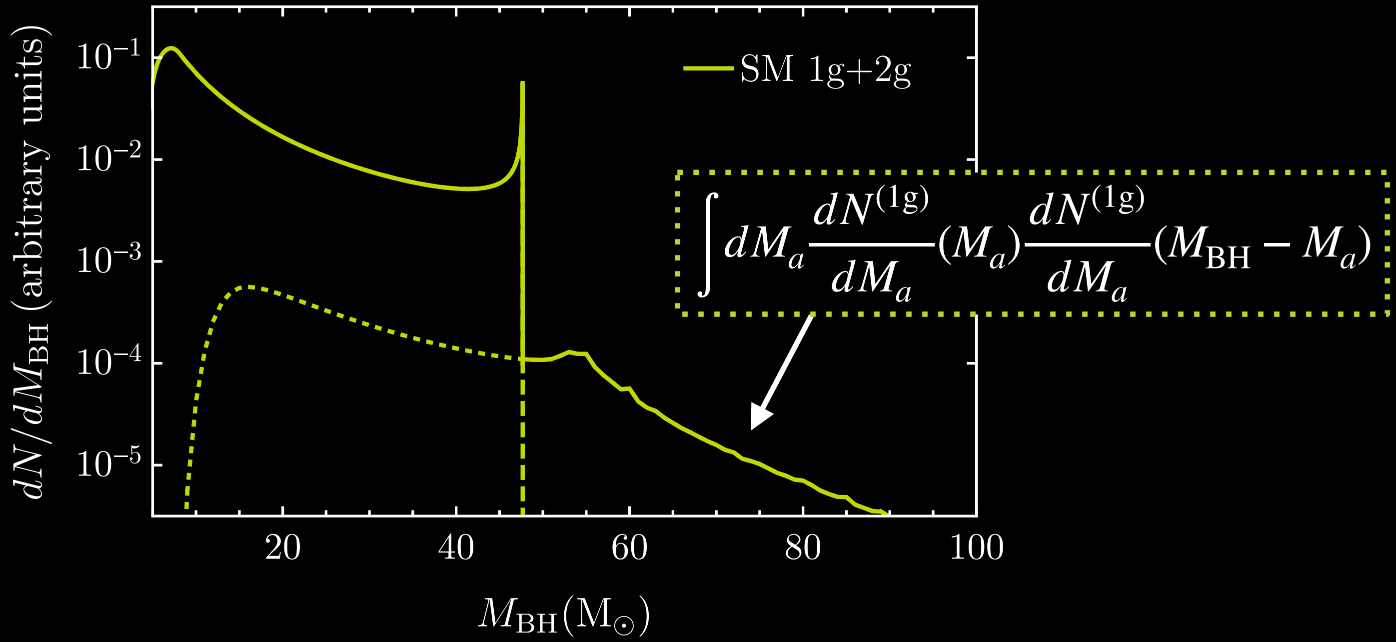


Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

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.



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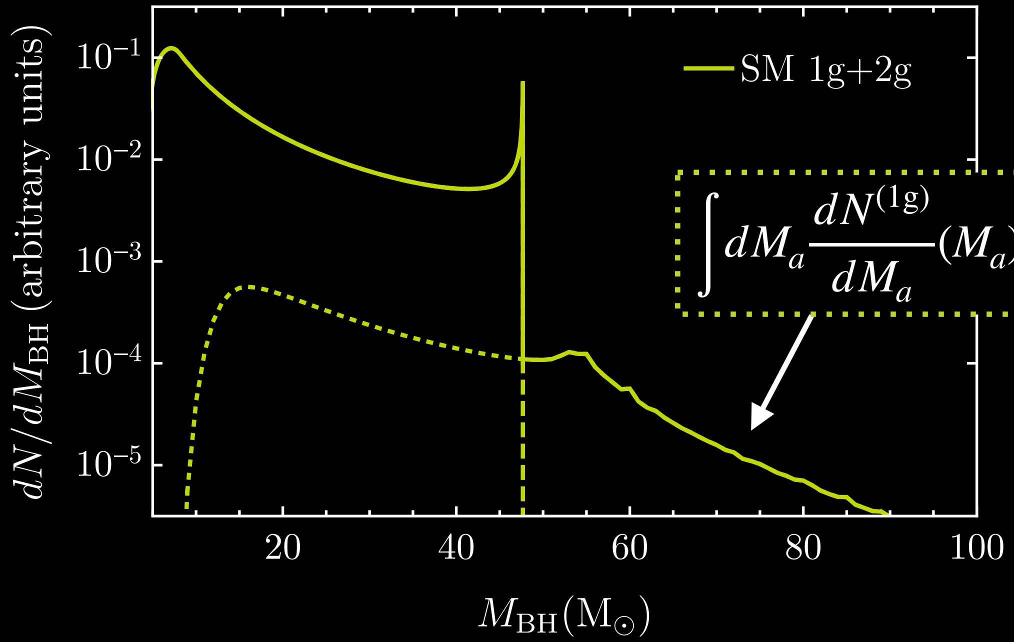


$$\int dM_a \frac{dN^{(1g)}}{dM_a}(M_a)\frac{dN^{(1g)}}{dM_a}(M_{\rm BH}-M_a)$$

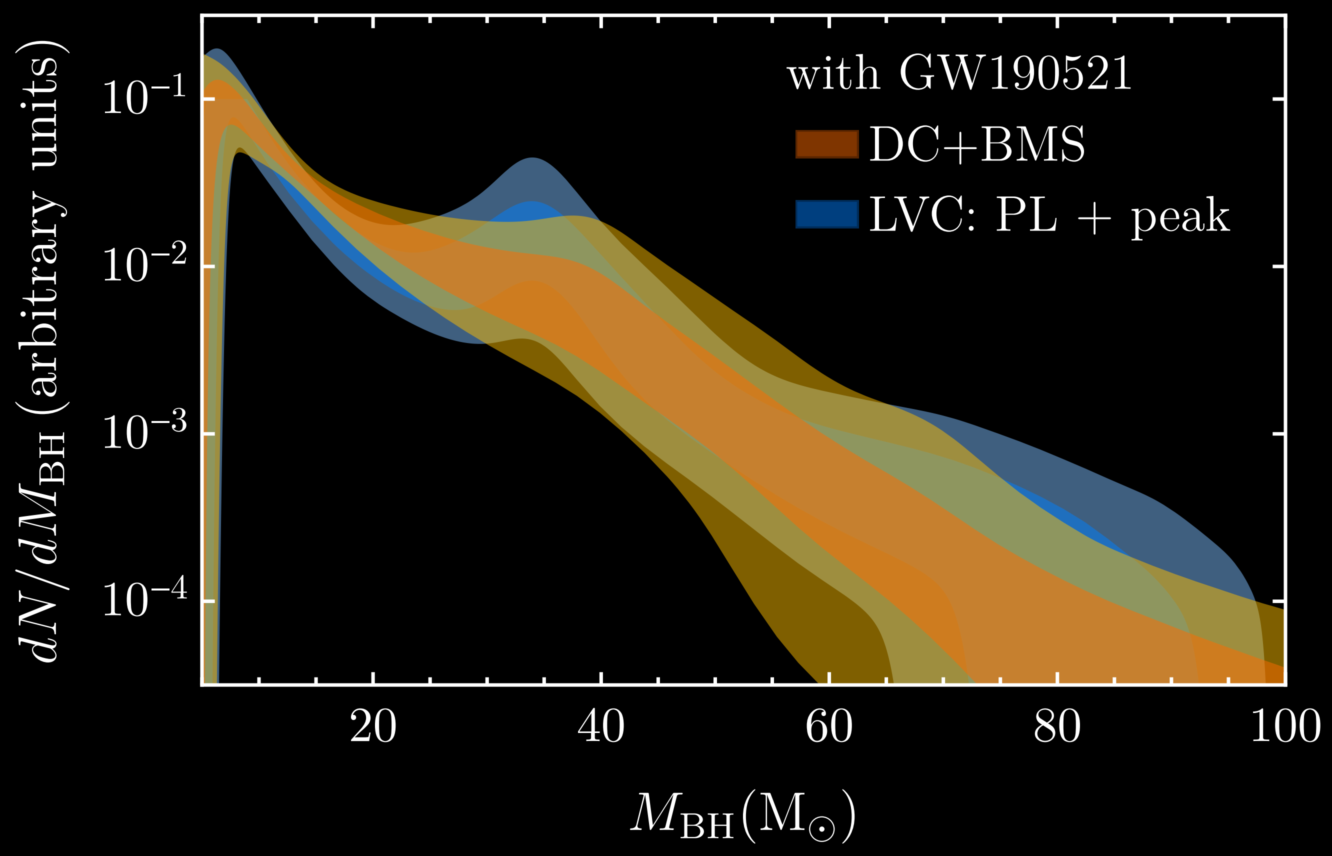
$$\frac{dN}{dM_{\rm BH}} = \frac{dN^{(1g)}_{\rm BH}}{dM_{\rm BH}} + \frac{dN^{(2+g)}_{\rm BH}}{dM_{\rm BH}}$$

$$\frac{dN^{(1g)}_{\rm BH}}{dM_{\rm BH}} \propto M_{\rm BH}^b\left[1+\frac{2a^2 M_{\rm BH}^{1/2}(M_{\rm BHMG}-M_{\rm BH})^{a-1}}{M_{\rm BHMG}^{a-1/2}}\right]$$: first generation black holes ($a, b, M_{\rm BHMG}$)

$$\frac{dN^{(2+g)}}{dM_{\rm BH}} \propto \lambda \min\left[1, \left(\frac{M_{\rm BH}}{M_{\rm BHMG}+M_{\min}+\delta_m/2}\right)^d\right]$$: "Pollutant" population (2g+) (d, λ)

Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

Binary mergers in LIGO/Virgo O3a

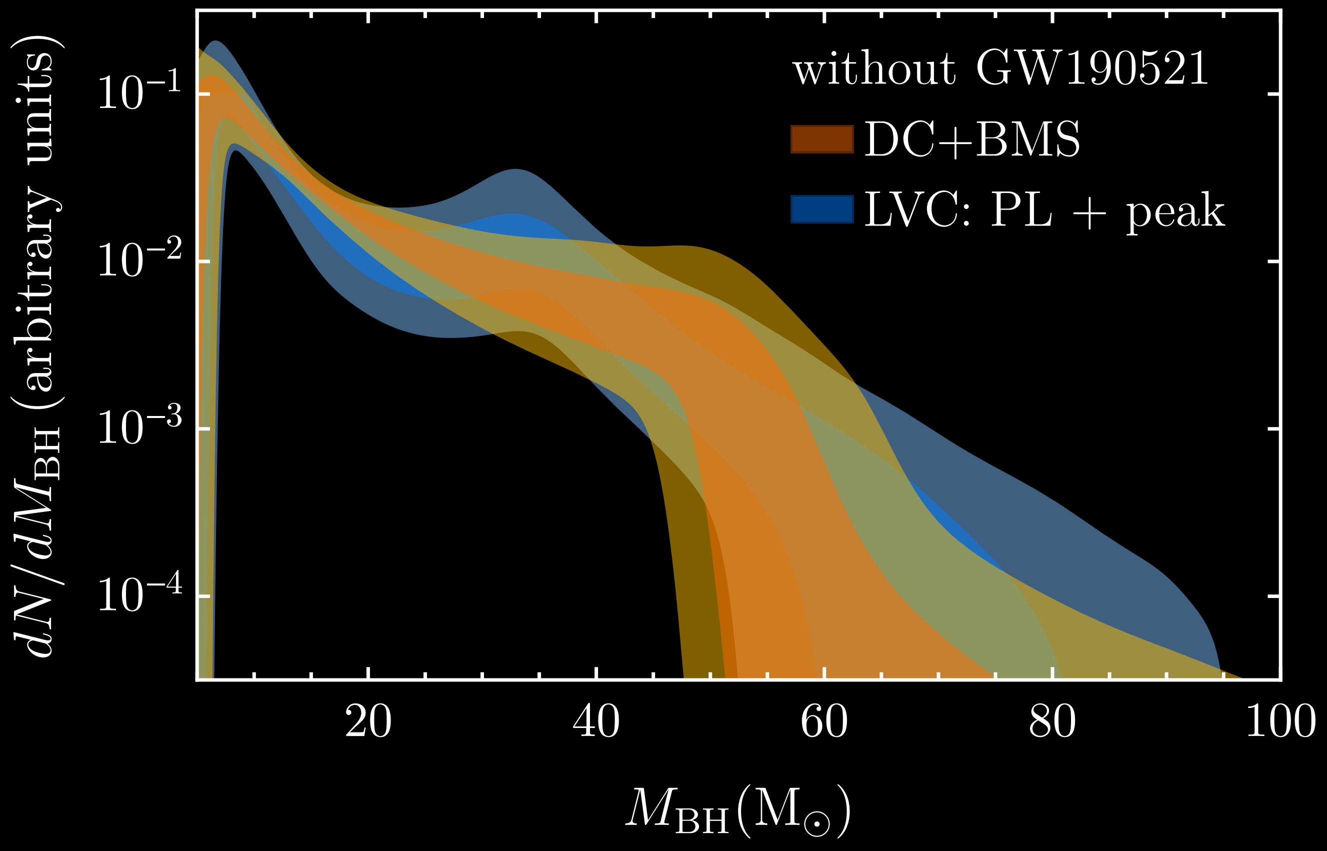


This work, Eq. (7)	with GW190521
$\log_{10}\lambda$	$-0.88^{+0.41}_{-1.46}$
$M_{\rm BHMG}$ $[\rm M_\odot]$	$46.23^{+16.83}_{-6.15}$
a	$0.23^{+0.17}_{-0.16}$
b	$-1.95^{+0.51}_{-0.54}$
d	$-5.95^{+1.75}_{-2.07}$
$M_{\rm min}$ $[\rm M_\odot]$	$3.38^{+1.50}_{-1.56}$
δ_m $[\rm M_\odot]$	$5.12^{+2.97}_{-3.19}$

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

Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

Binary mergers in LIGO/Virgo O3a



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

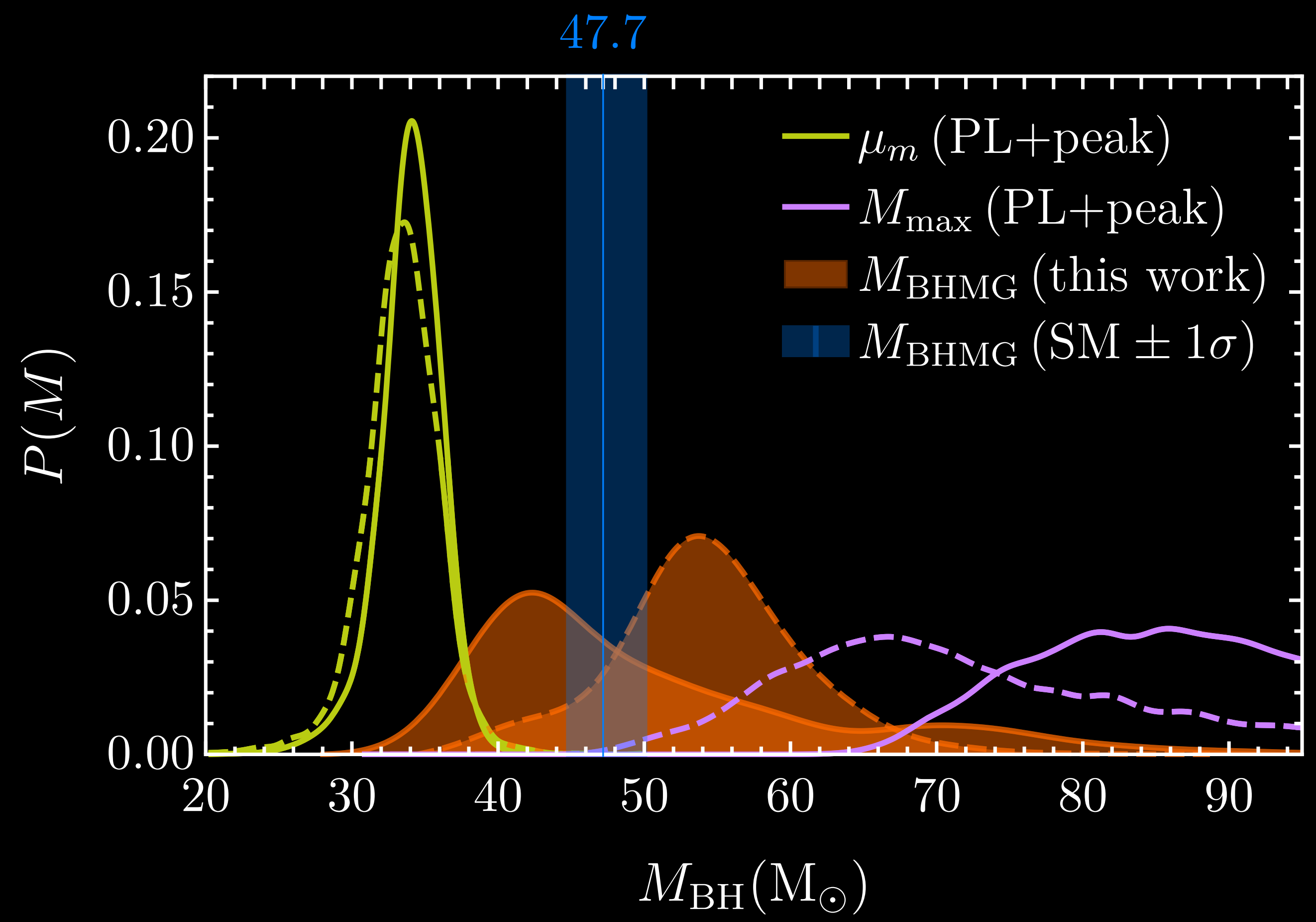
LVC: PL+peak	no GW190521
α	$3.08^{+0.51}_{-1.2}$
$M_{\rm max}$ $[\mathrm{M}_\odot]$	72^{+9}_{-10}
$\lambda_{\rm peak}$	$0.107^{+0.029}_{-0.092}$
μ_m $[\mathrm{M}_\odot]$	$33.4^{+2.5}_{-2.1}$
σ_m $[\mathrm{M}_\odot]$	> 4.49
$M_{\rm min}$ $[\mathrm{M}_\odot]$	$4.56^{+1.3}_{-0.77}$
δ_m $[\mathrm{M}_\odot]$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

Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

GW190521 and the mass gap

The New York Times

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



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GW190521 and the mass gap

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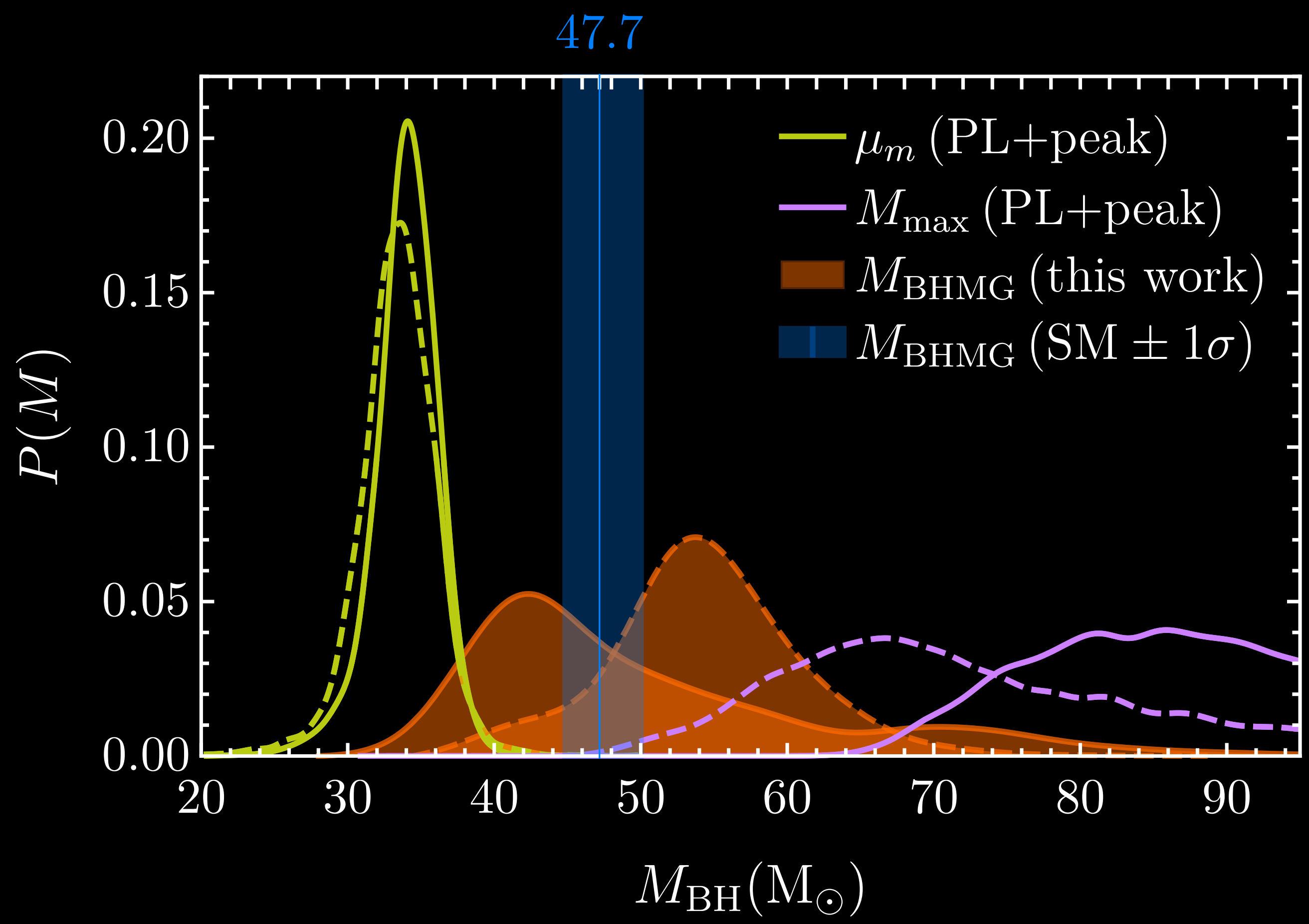

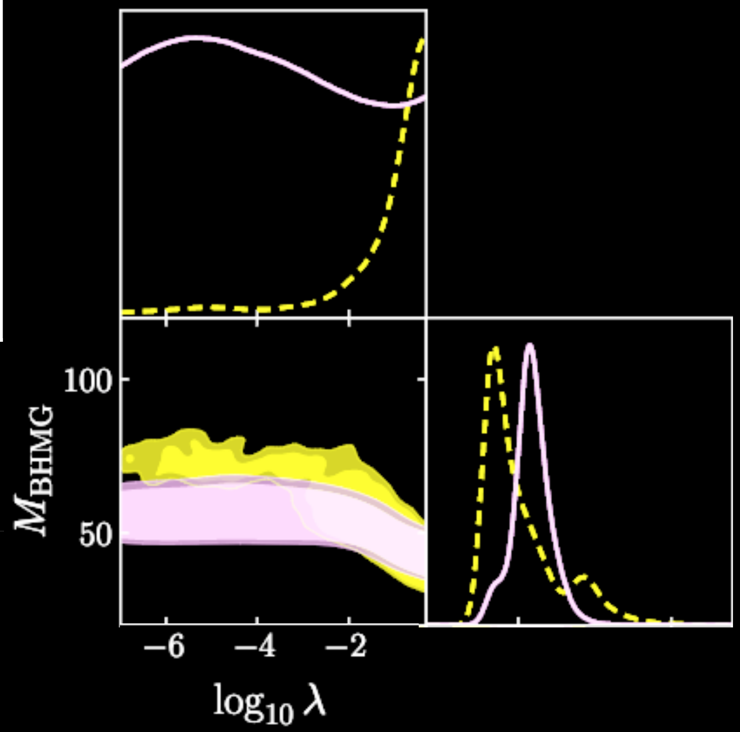

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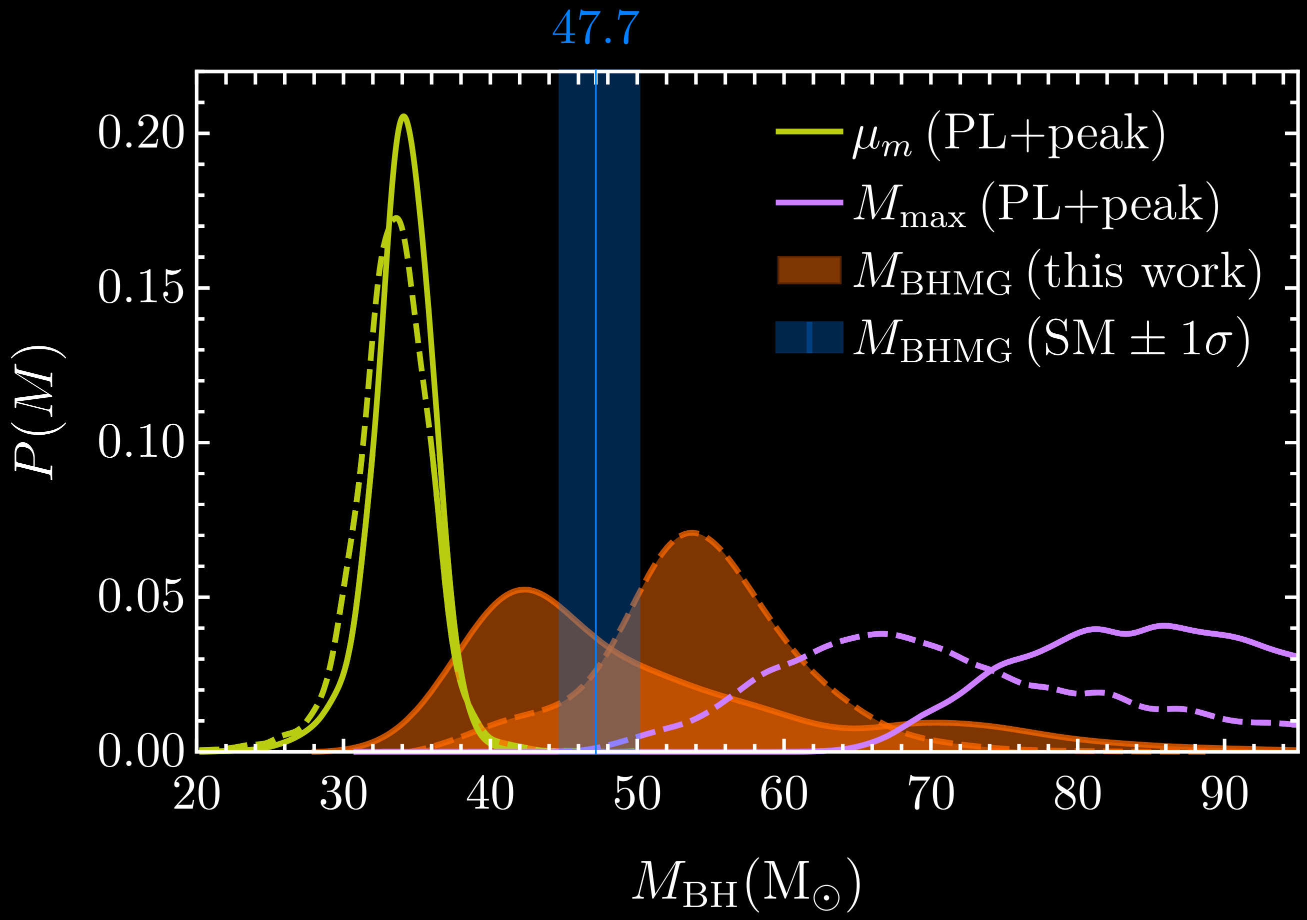
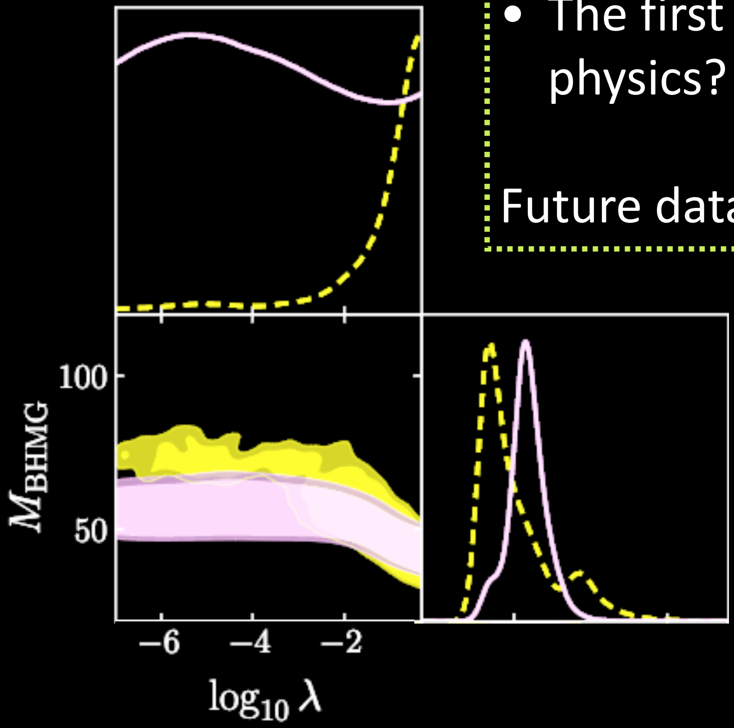




Is GW190521

- A rare $2g$+ event?
- A straddling binary?
- The first hint of new physics?

Future datasets will tell!

Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

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

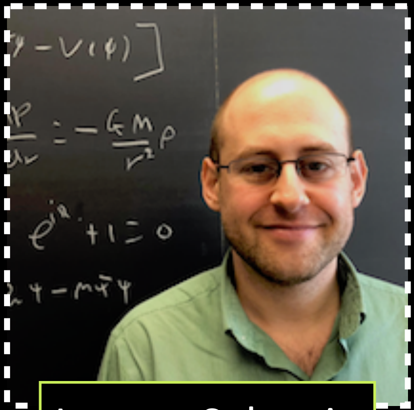
- Black hole population studies will allow us to study stellar evolution → black hole archeology

Thank you!

…ask me anything you like!

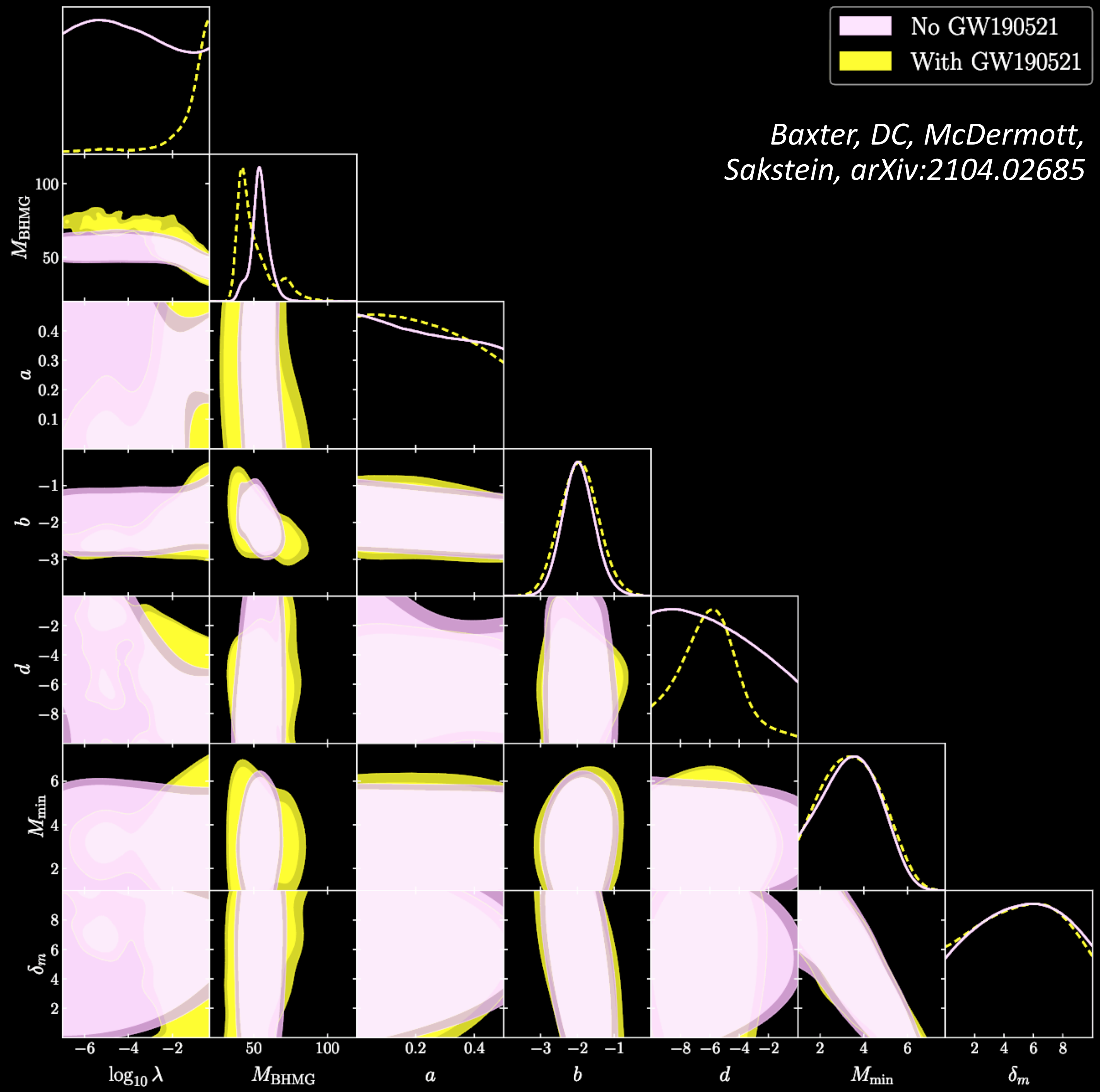
dcroon@triumf.ca | djunacroon.com


Sam McDermott


Jeremy Sakstein


Eric Baxter

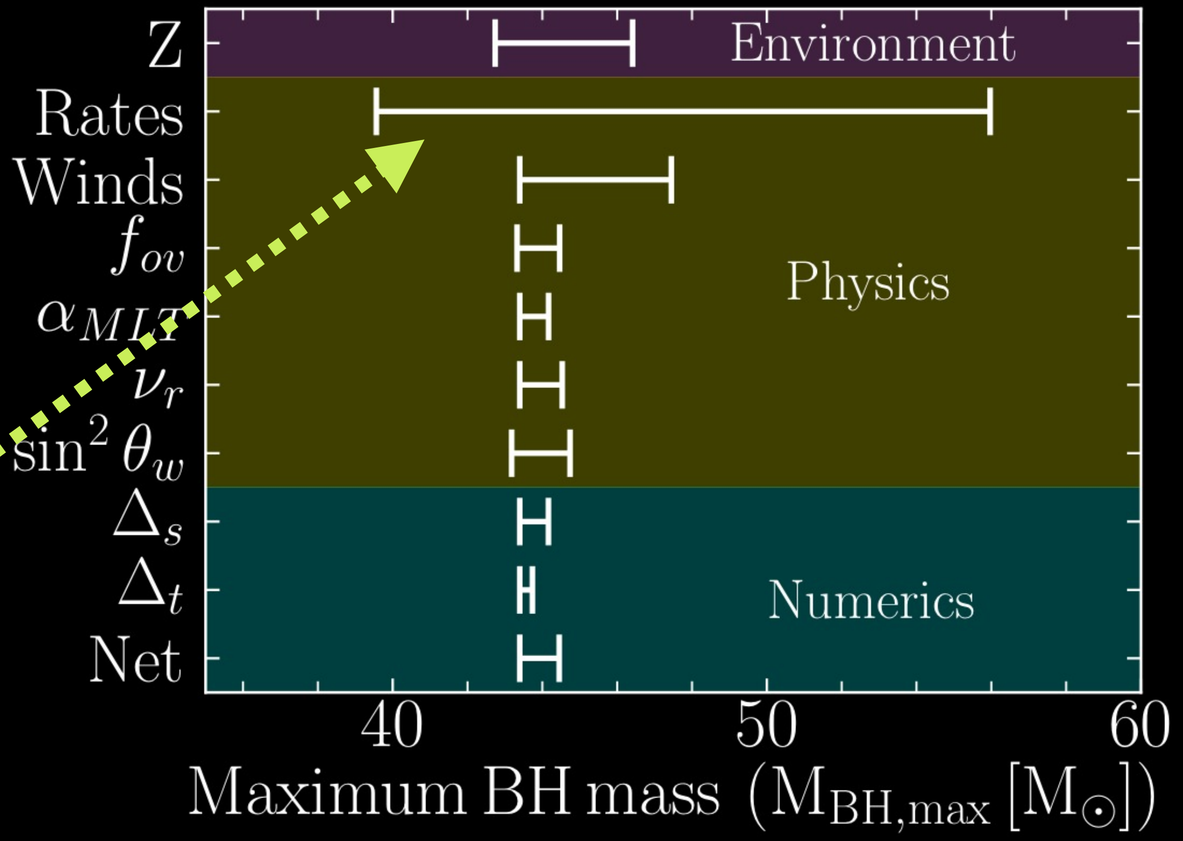

Maria Straight


No GW190521
With GW190521
Baxter, DC, McDermott,
Sakstein, arXiv:2104.02685
$M_{\rm BHMG}$
a
b
d
$M_{\rm min}$
δ_m
$\log_{10}\lambda$

Physics dependence of the BHMG

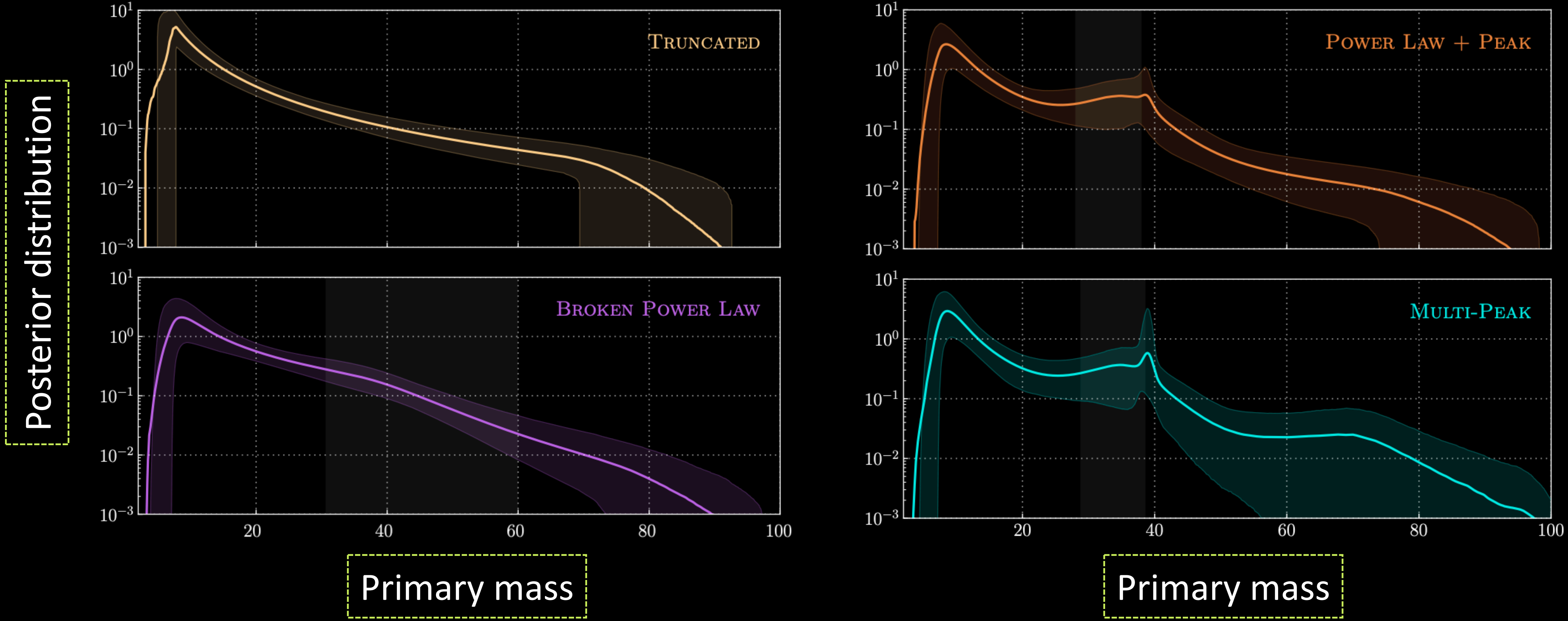
- Astrophysical + nuclear + numerical dependence
- Most important dependence: $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ rate
- Using updated deBoer et al rate, BHMG found at $48^{+2}_{-3}\,\mathrm{M}_\odot$

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



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

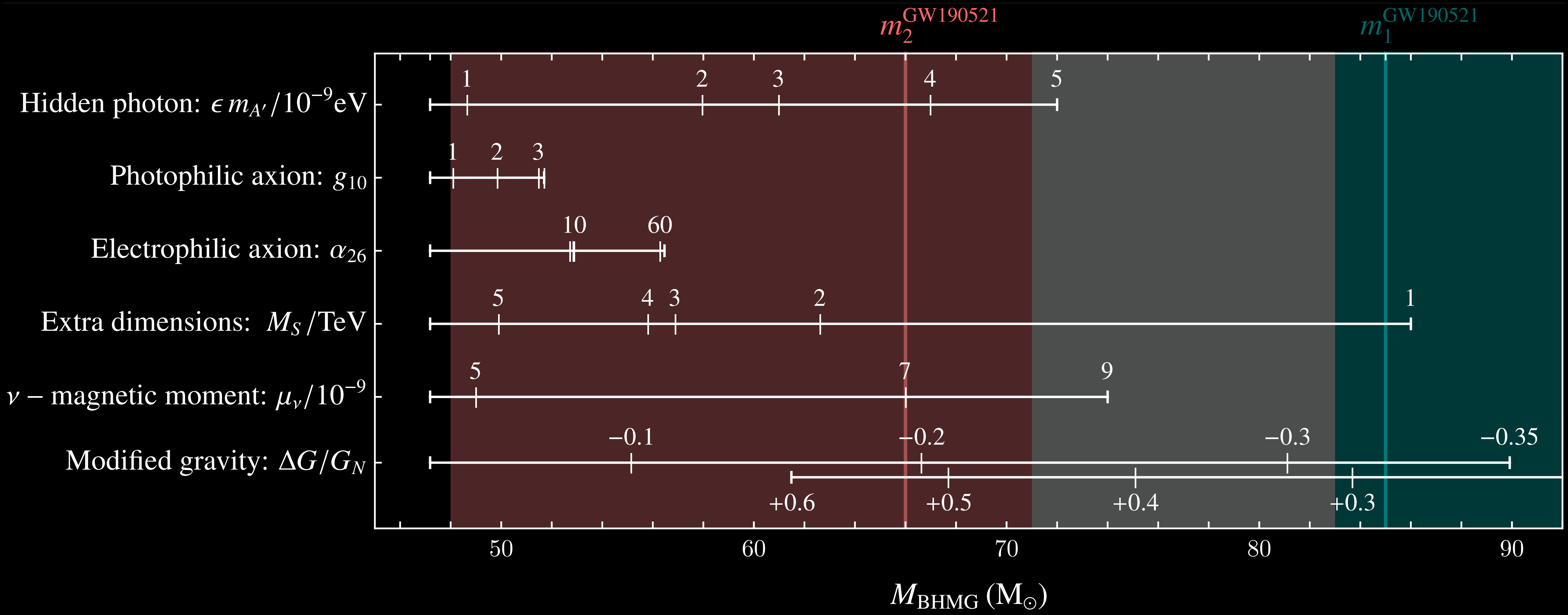
LIGO/Virgo O3a population analysis



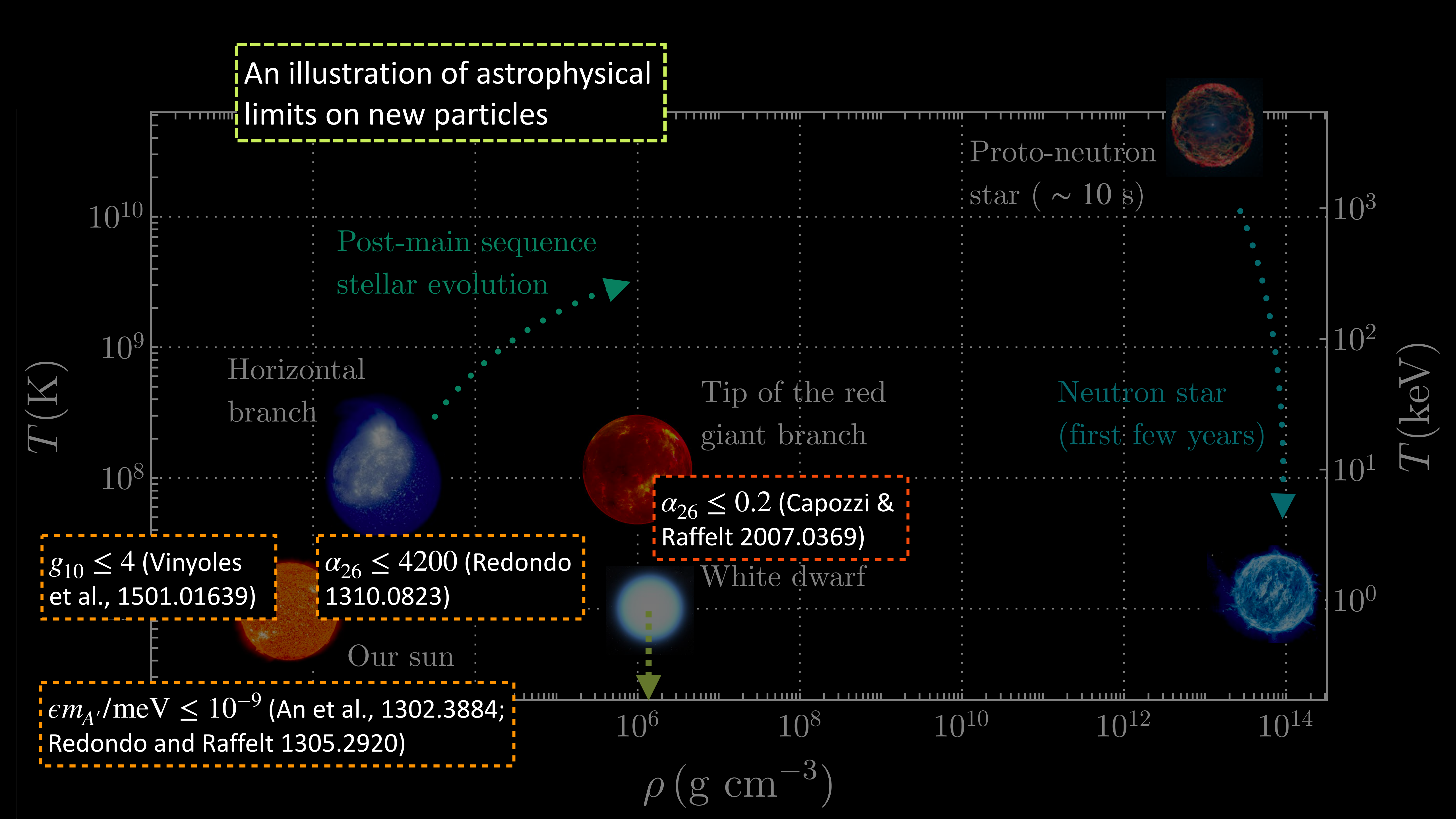
from LIGO-Virgo, arXiv: 2010.14533 [astro-ph.HE]; for Bayesian framework see also Fishbach & Holz, arXiv:1709.08584 [astro.ph]

GW190521, the impossible black holes

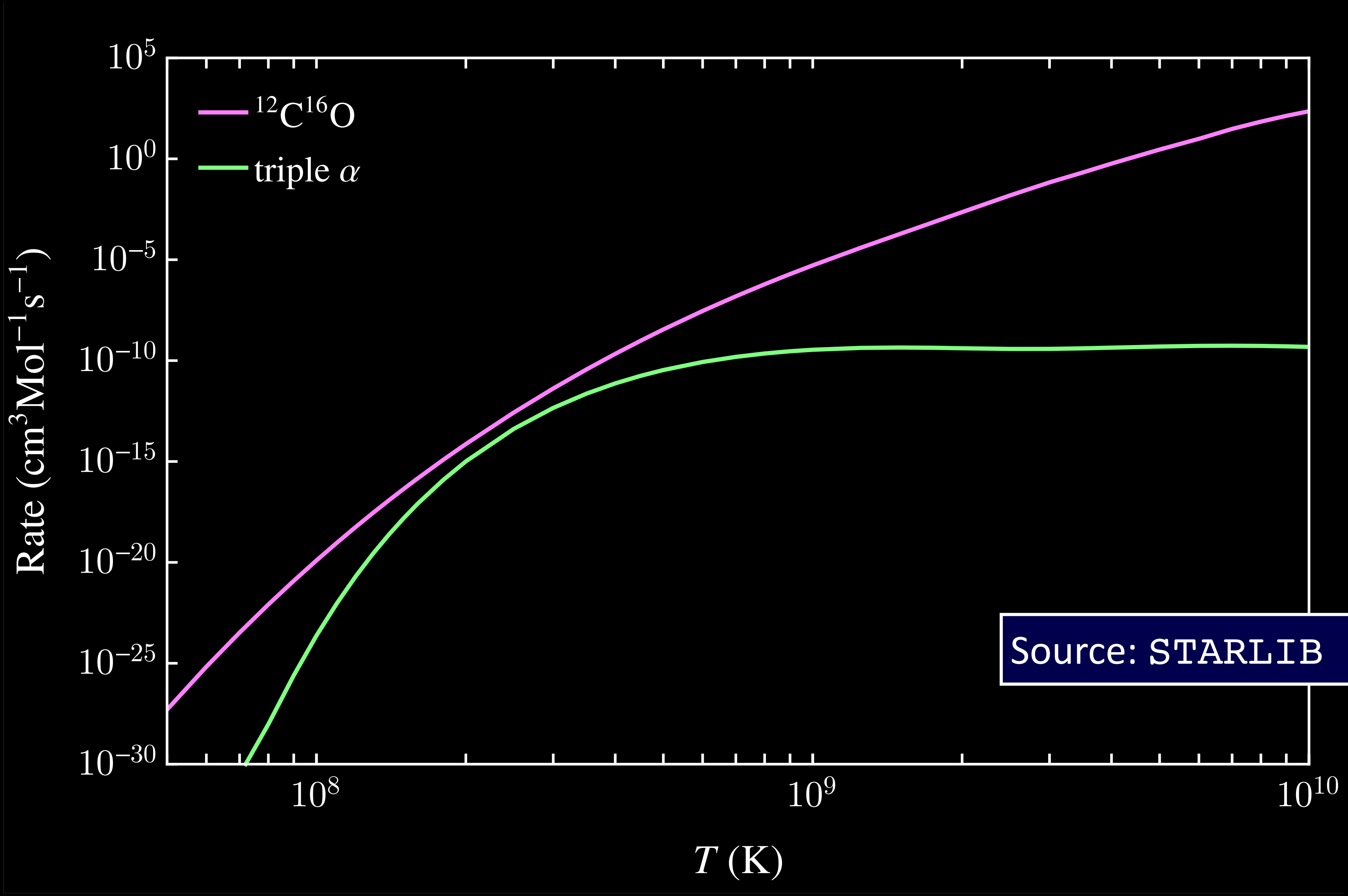
… and Beyond the Standard Model physics



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

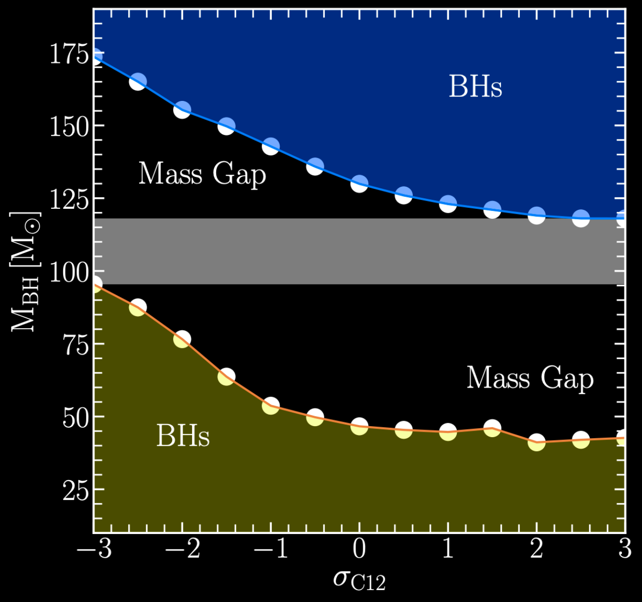

An illustration of astrophysical limits on new particles
Proto-neutron star (~ 10 s)
Post-main sequence stellar evolution
Horizontal branch
Tip of the red giant branch
Neutron star (first few years)
White dwarf
Our sun
$\alpha_{26} \leq 0.2$ (Capozzi & Raffelt 2007.0369)
$g_{10} \leq 4$ (Vinyoles et al., 1501.01639)
$\alpha_{26} \leq 4200$ (Redondo 1310.0823)
$\epsilon m_{A'}/\mathrm{meV} \leq 10^{-9}$ (An et al., 1302.3884; Redondo and Raffelt 1305.2920)
$T(\mathrm{K})$
10^{10}
10^{9}
10^{8}
$T(\mathrm{keV})$
10^{3}
10^{2}
10^{1}
10^{0}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
$\rho\,(\mathrm{g\ cm^{-3}})$

Helium burning rates as a function of T



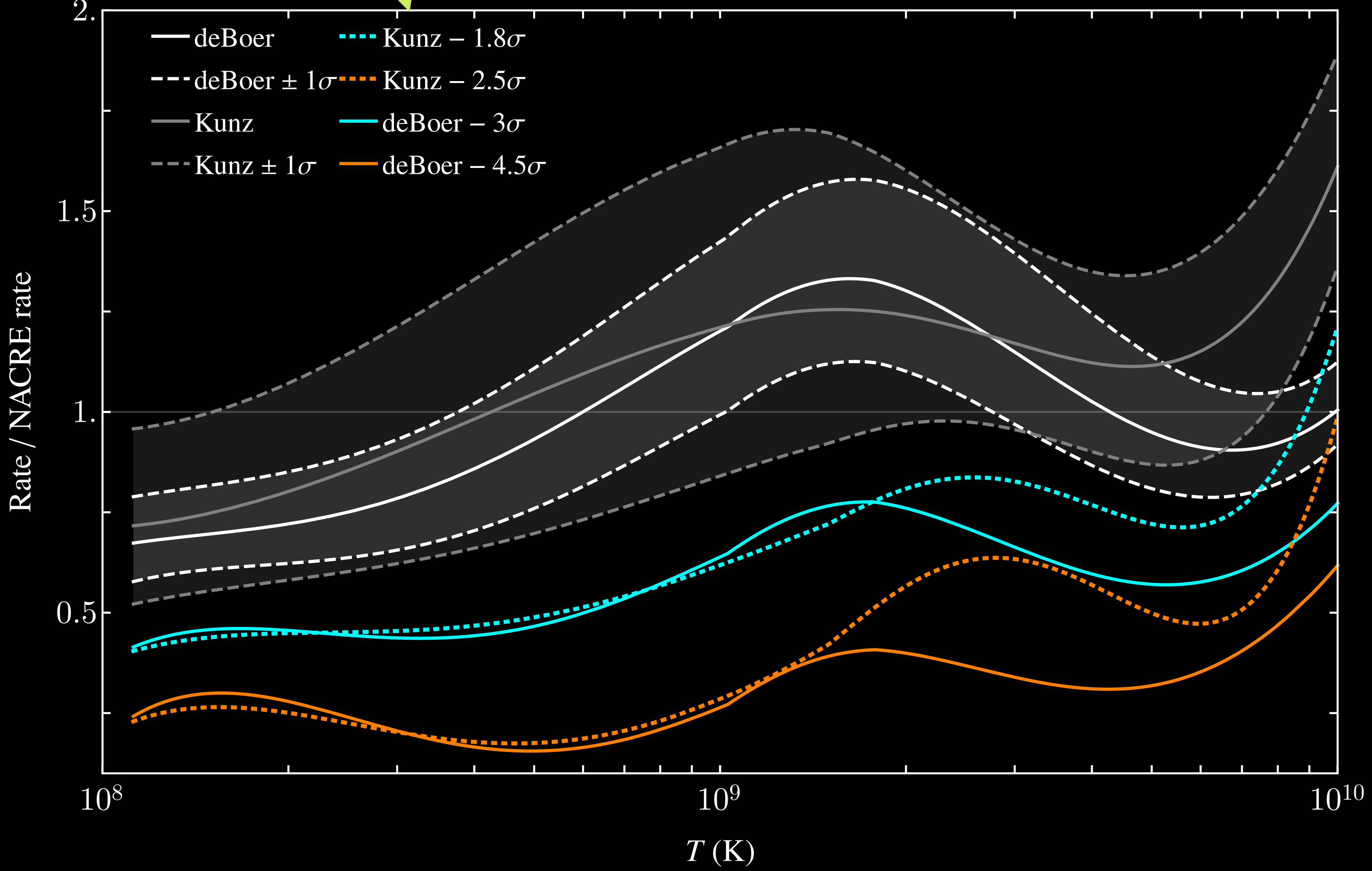
Source: STARLIB catalogue

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

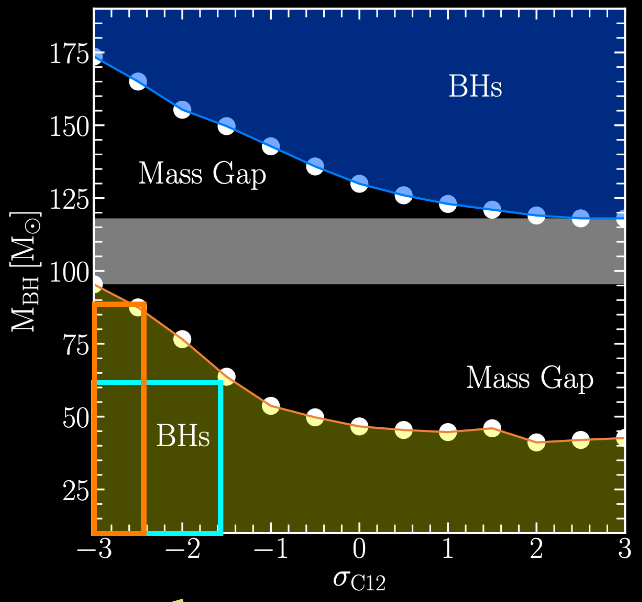


(Kunz is currently used in STARLIB)

Fitting GW190521 masses m_1 and m_2



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



(Kunz is currently used in STARLIB)

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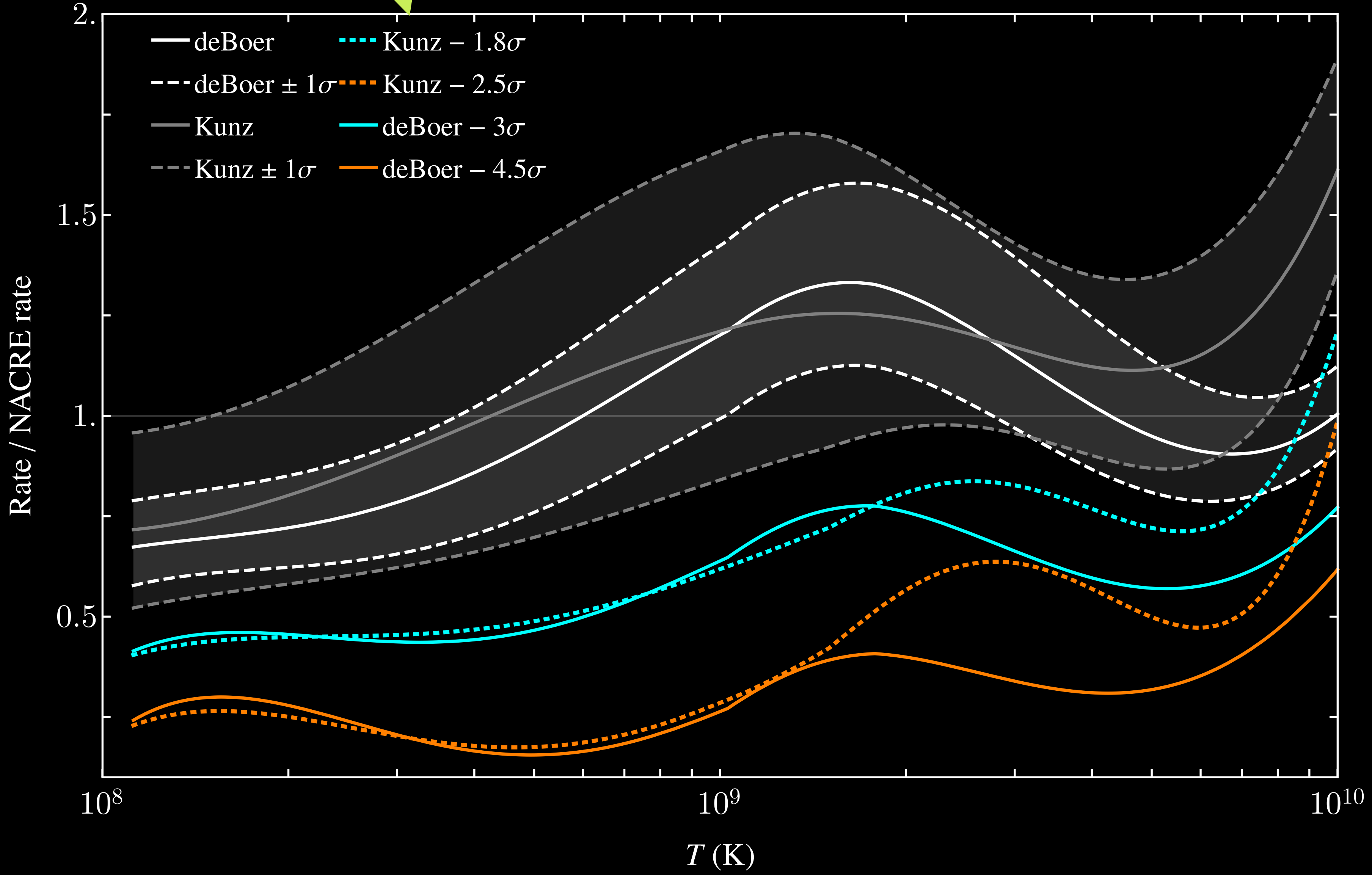


Large black hole in LB-1?

- Last year, a $70\,\mathrm{M}_\odot$ black hole was reported in a binary with a high-metallicity smaller star (from the radial velocity variability of the $H\alpha$ emission line, suggesting an accretion disk)
- It was suggested (1911.12357) that it was formed due to the core-collapse of a high metallicity progenitor with reduced stellar winds
- However, those simulations did not include pulsations (they were stopped at carbon burning)
- The observation has since also been disputed (1912.04185 and 1912.03599) - apparent shifts instead originate from shifts in the luminous star's $H\alpha$ absorption line

Binary merger events ($M_1 \approx M_2$)

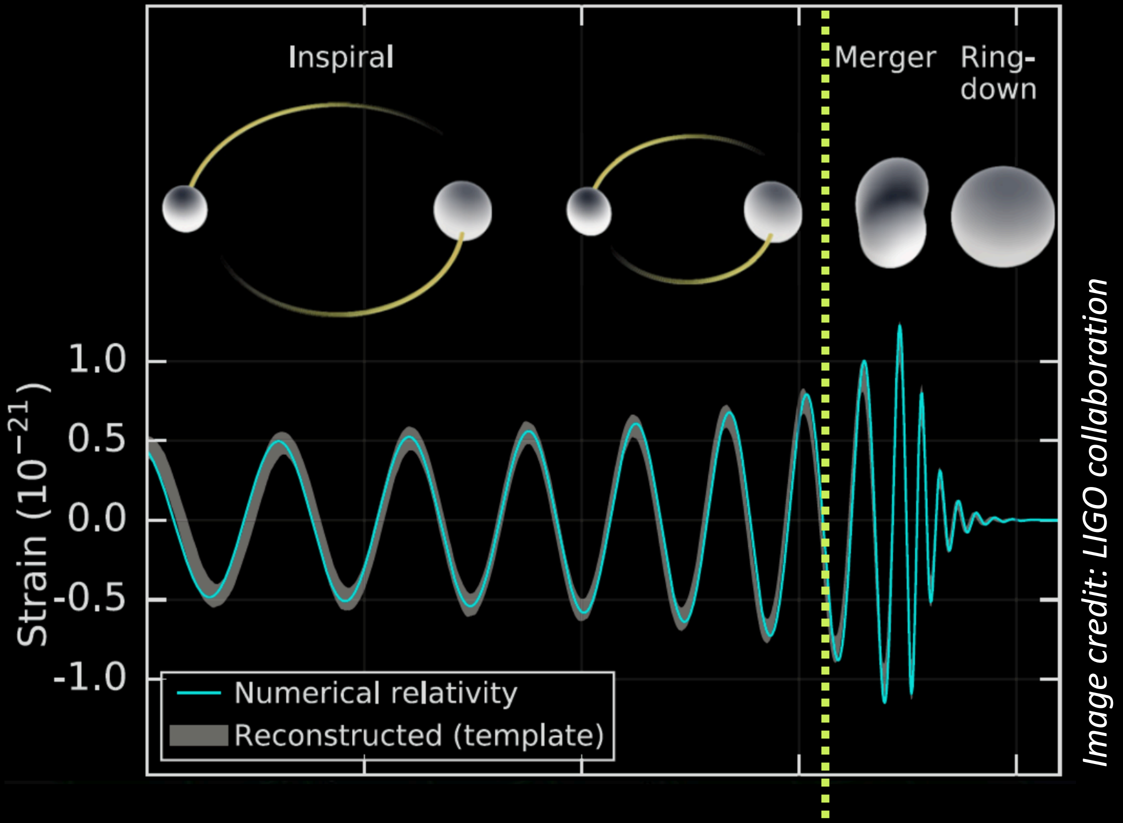
- >50 LIGO/Virgo observations
  - 2017 Nobel Prize in Physics

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

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

- Solvable in a (v/c) expansion

  → Weak gravity, small velocity



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

Compact object merger sensitivity

- Best detection prospects for

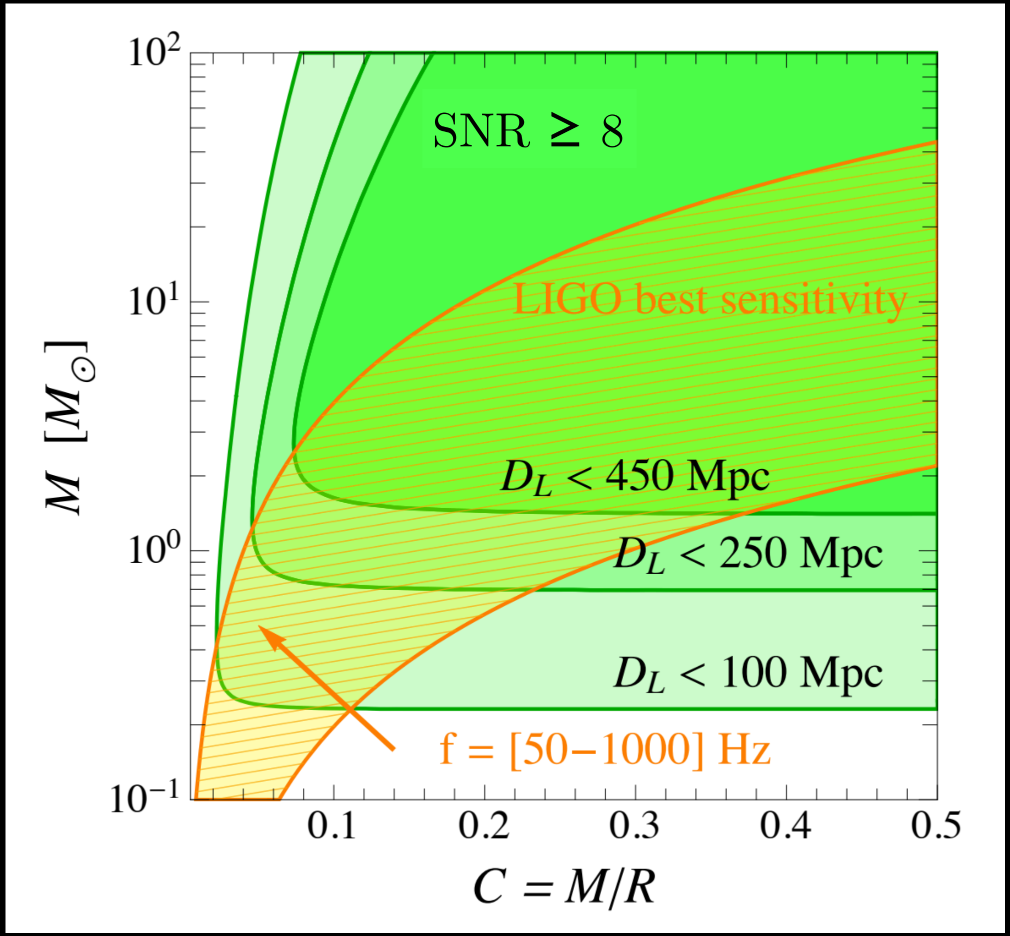
$$f_{\min} < f_{\text{peak}} \sim f_{\text{ISCO}} < f_{\max}$$

- Defines an CO sensitivity band

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

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

- 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)

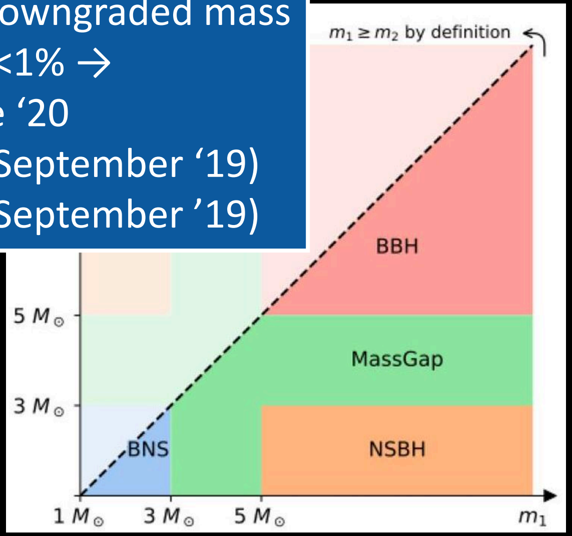


Image credit: LIGO collaboration

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”*

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 same mechanism*

- 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)

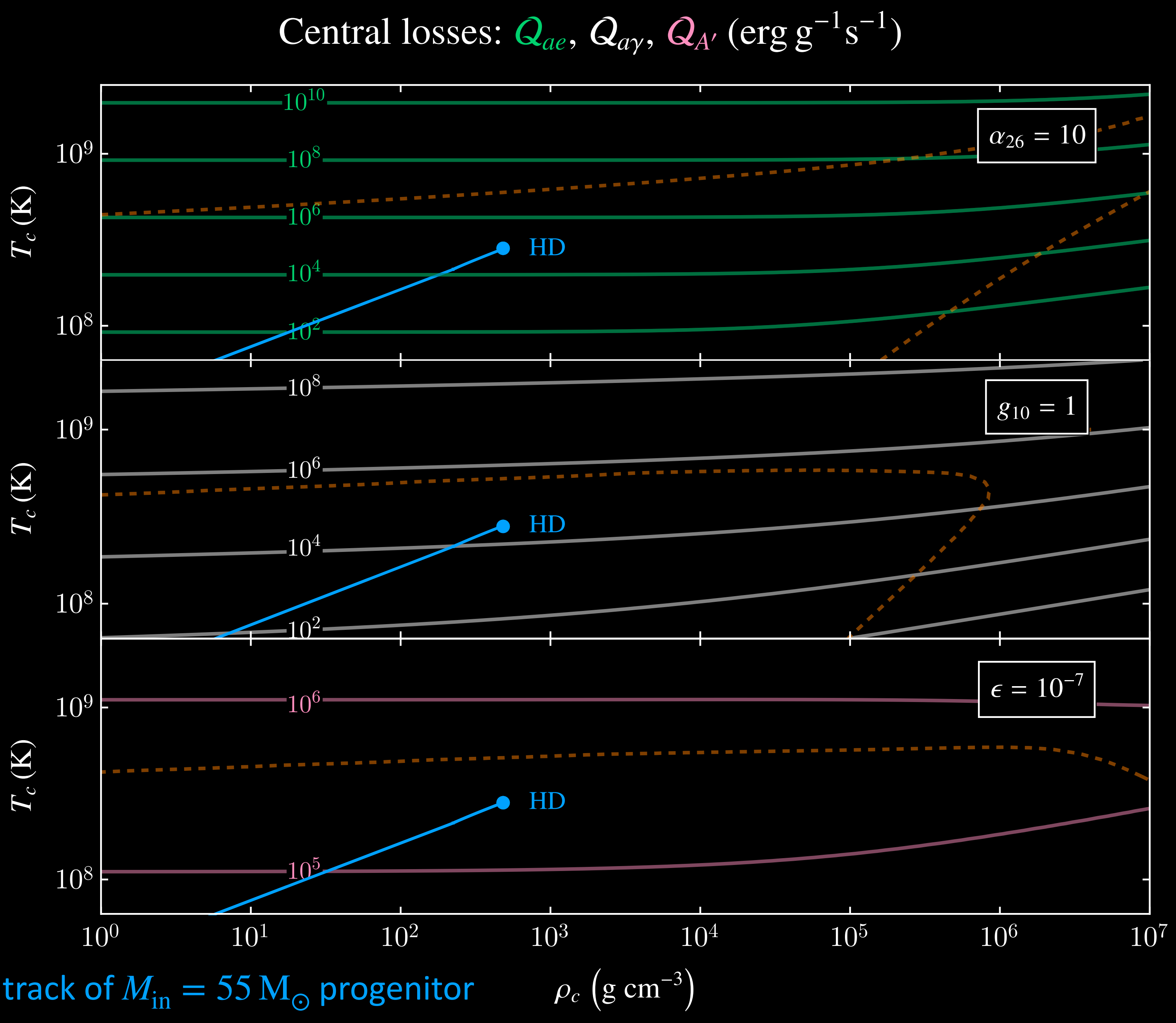
**Interesting in light of the XENON1T excess, arXiv:2006.09721 [hep-ex]*

Loss rates

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

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

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



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

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

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

Energy loss due to electrophilic axions

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

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

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

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

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

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

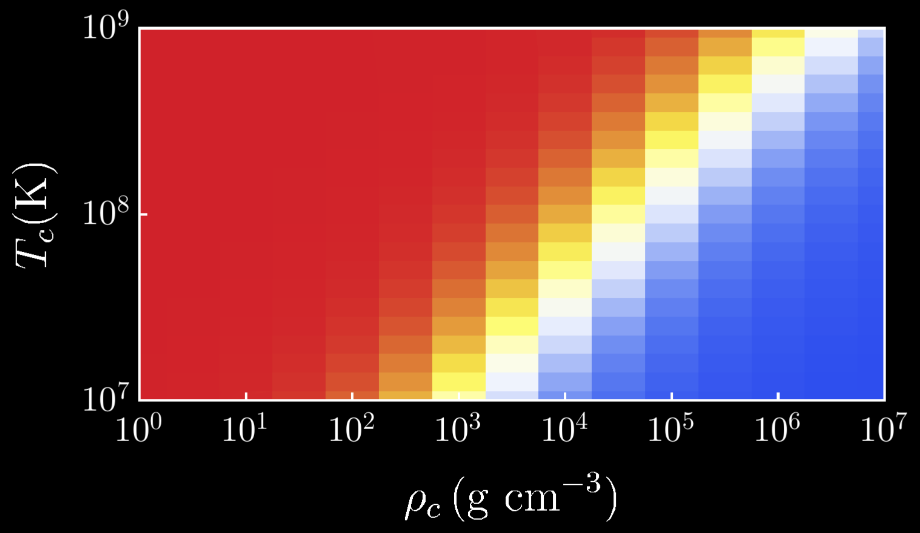
Energy loss due to electrophilic axions

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

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

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

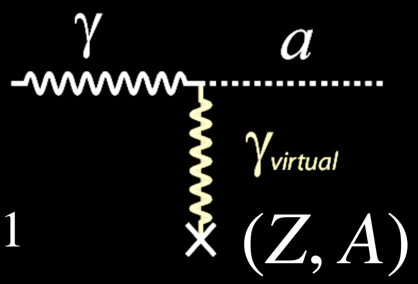
$0 < F_{\rm deg} < 1$



Semi-Compton emission dominates throughout the Helium burning phase

Energy loss due to photophilic axions

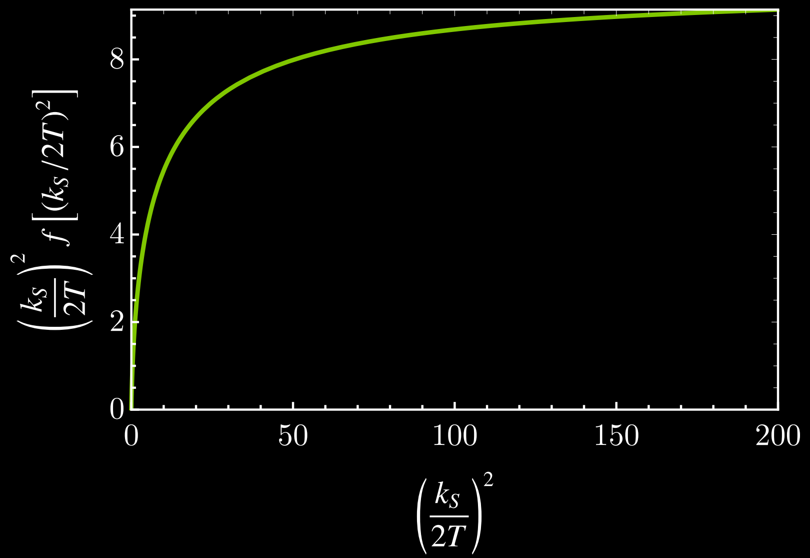
- Primakov effect $(Z, A) + \gamma \rightarrow (Z, A) + a$



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

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

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)

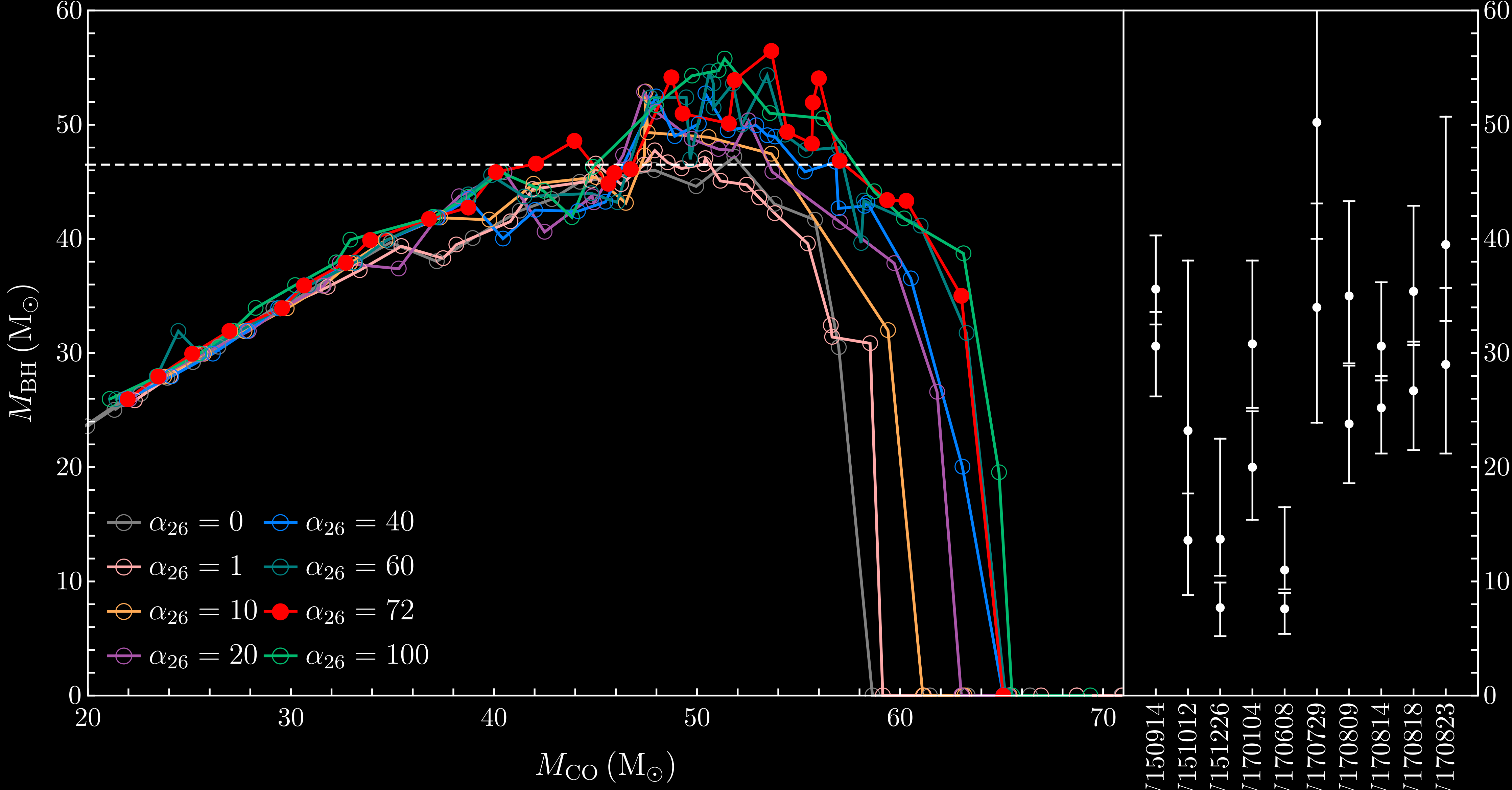
$$\mathcal{Q}_{A'} = \frac{\epsilon^2 m_{A'}^2}{4\pi\rho}\frac{\omega_p^3}{e^{\omega_p/T}-1} \simeq \frac{\epsilon^2 m_{A'}^2}{4\pi}\frac{\omega_p^2 T}{\rho} \simeq 1.8\times 10^3 \frac{\mathrm{erg}}{\mathrm{g\cdot s}}\frac{Z}{A}T_8\left(\frac{\epsilon}{10^{-7}}\frac{m_{A'}}{\mathrm{meV}}\right)^2$$

In the limit $\omega_p \ll T$

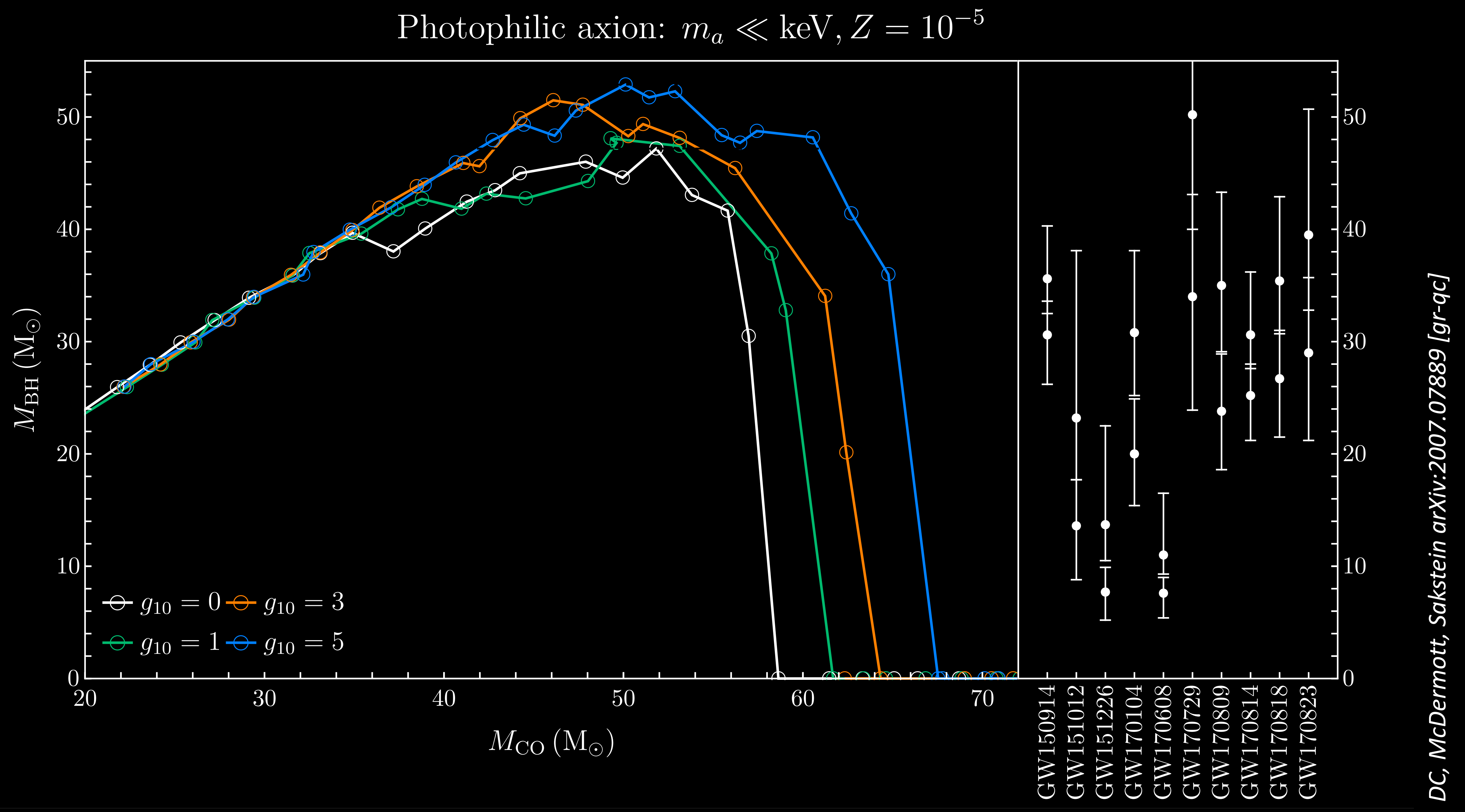
- Where photons have plasma mass $\omega_p \simeq \sqrt{\frac{4\pi\alpha_{\mathrm{EM}} n_e}{m_e}} \simeq 654\mathrm{eV}\sqrt{\frac{Z}{A}\rho_3}$

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

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

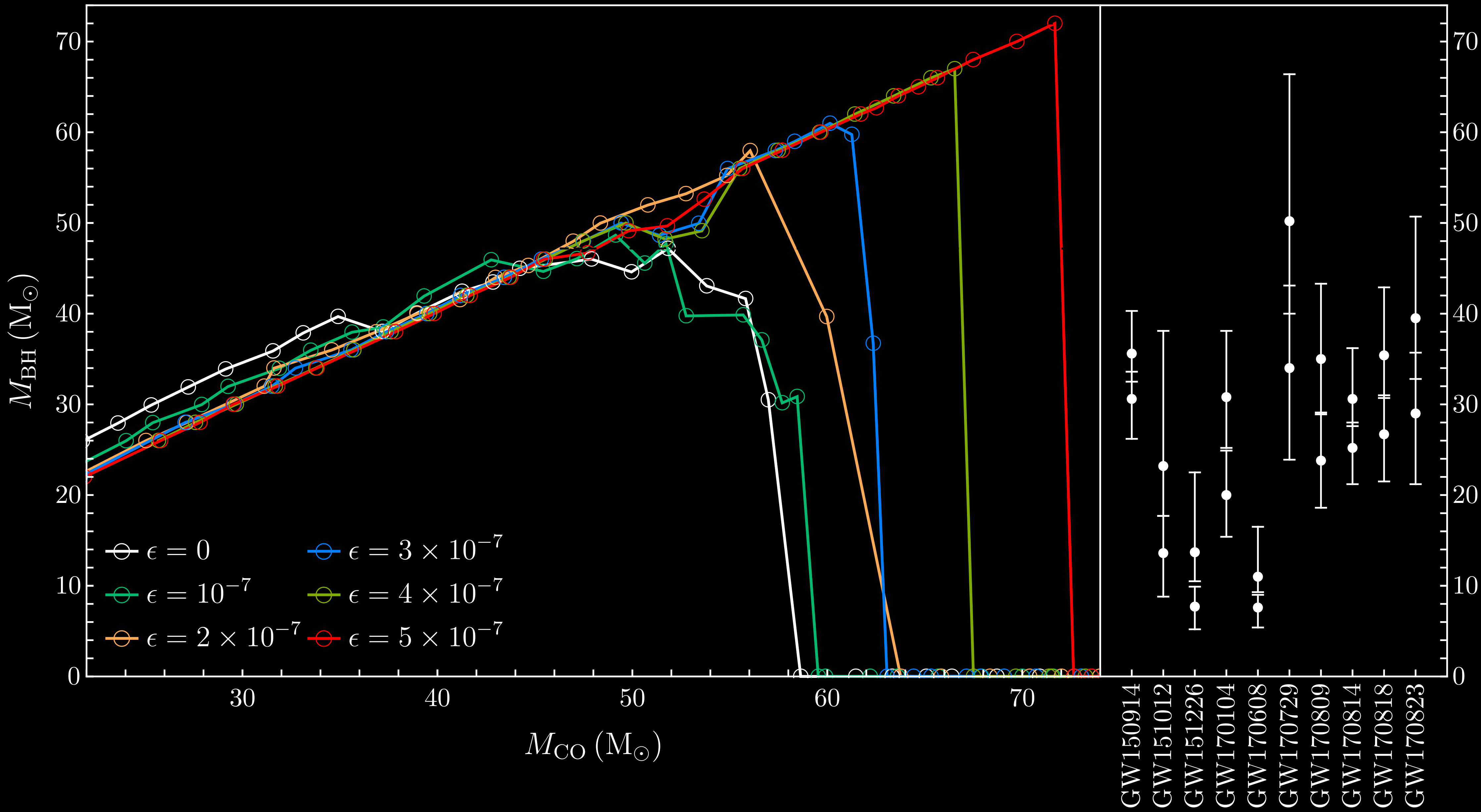


DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]



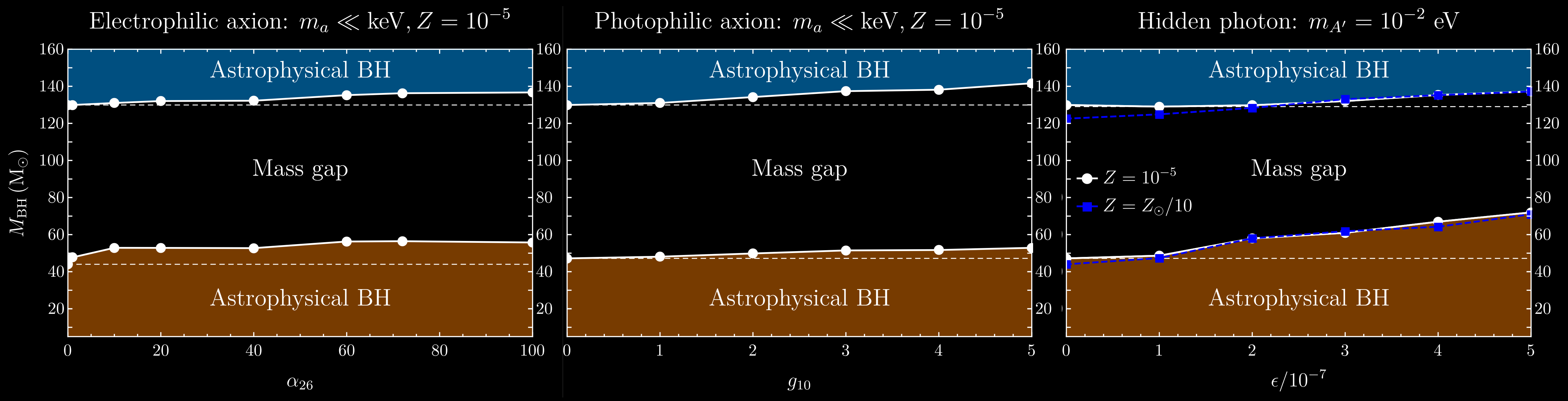
Photophilic axion: $m_a \ll \text{keV}, Z = 10^{-5}$
$M_{\rm BH}$ ($M_\odot$)
$M_{\rm CO}$ ($M_\odot$)
$g_{10} = 0$
$g_{10} = 3$
$g_{10} = 1$
$g_{10} = 5$
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

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



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]

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

What about trapped new physics?

- Heavier and 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

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

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

$$\frac{\partial l}{\partial m} = \varepsilon_{\mathrm{n}} - \varepsilon_{\nu} - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\varrho}\frac{\partial P}{\partial t}\,,$$

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

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

Mass function

Hydrostatic equilibrium

Energy flux

Convection

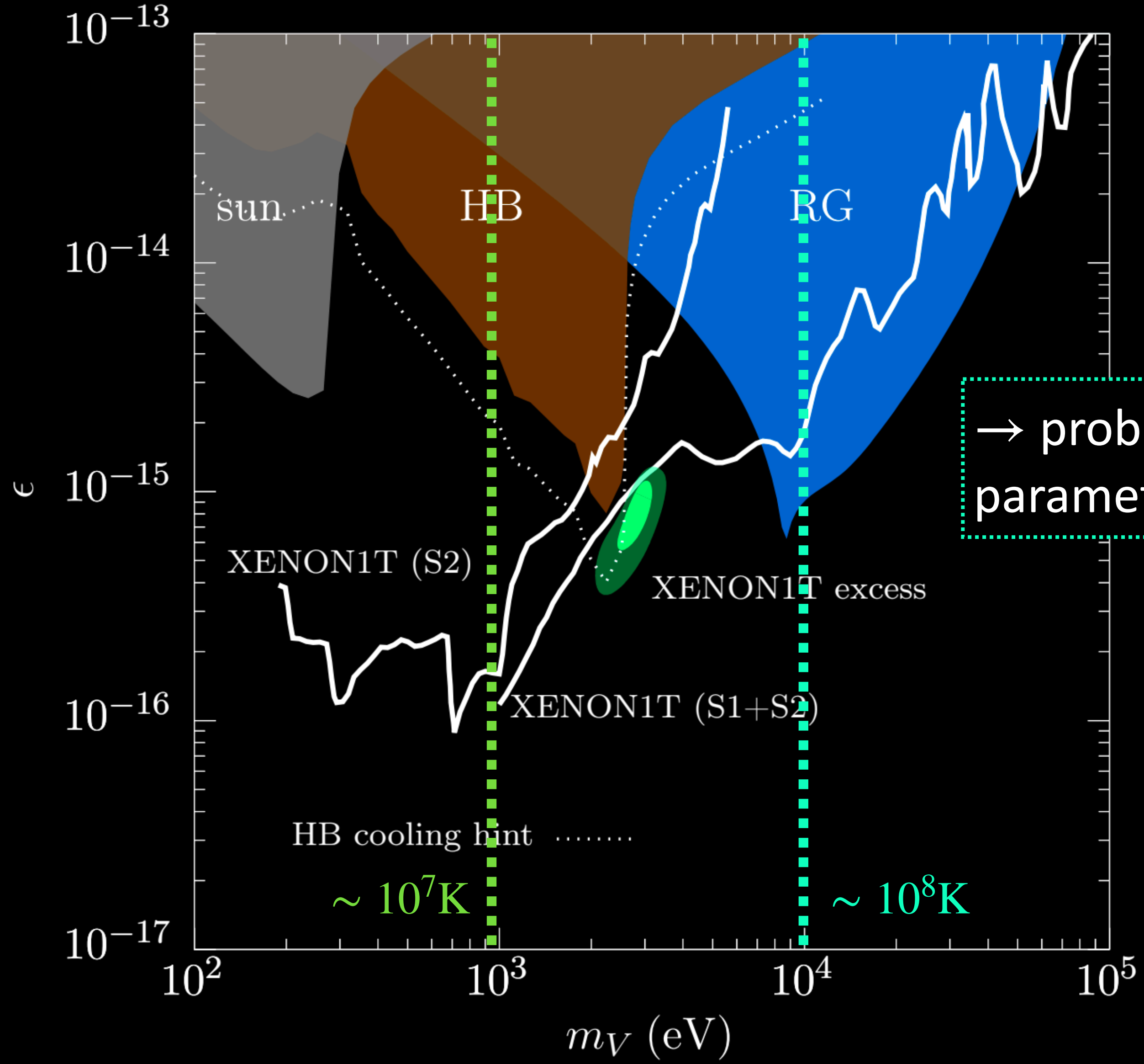
Reactions

+ BSM physics contributions?

Heavier degrees of freedom?

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

+ work in progress



→ probe this parameter space

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