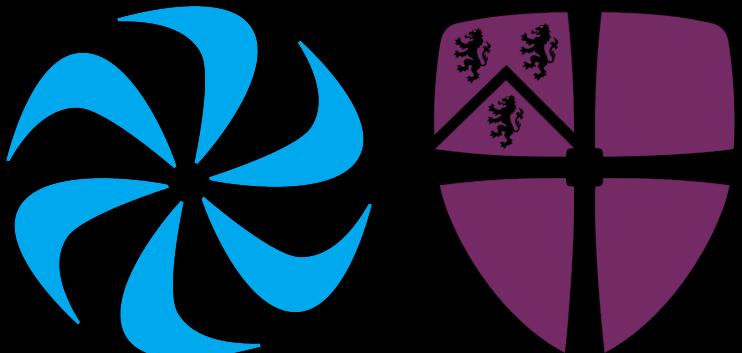


# Black hole archaeology using gravitational waves

Djuna Lize Croon ([TRIUMF](#) → [IPPP Durham](#))

[GWBSM meeting](#), July 2021

[dcroon@triumf.ca](mailto:dcroon@triumf.ca) | [djunacroon.com](http://djunacroon.com)



# Particle physics with gravitational waves

*A new era for beyond the Standard Model physics*

New data, new opportunities...

- + A unique observational window: a probe of the dark, a memory of the past
- + A growing dataset:  $\sim 50$  merger events
- + New experiments under construction

---

*We may learn a lot about particle physics from gravitational waves*

# Particle physics with gravitational waves

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---

*We may learn a lot about particle physics from gravitational waves*



Unprecedented access to **non-luminous masses** and **environments**

- Probes gravitational coupling (mass)
- Sensitivity scales as  $1/r$  (not  $1/r^2$ )

→ Different opportunities:

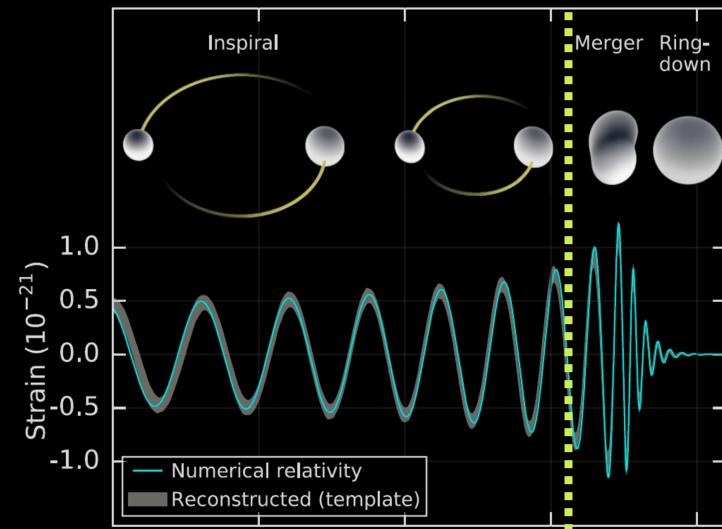
1. Waveform analysis
2. Population analysis

# What can we learn from individual waveforms?\*

*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 of event → age of object
7. “Hair”: multipolar metric deviations (EMRIs) → tests of GR
8. Post-merger quasi-normal modes, “echoes” → GR, ultralight bosons

*So what about Dark Matter?*



*Image credit: LIGO*

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

\*Further information could come from (for example) from multi-messenger signals (or absence thereof)

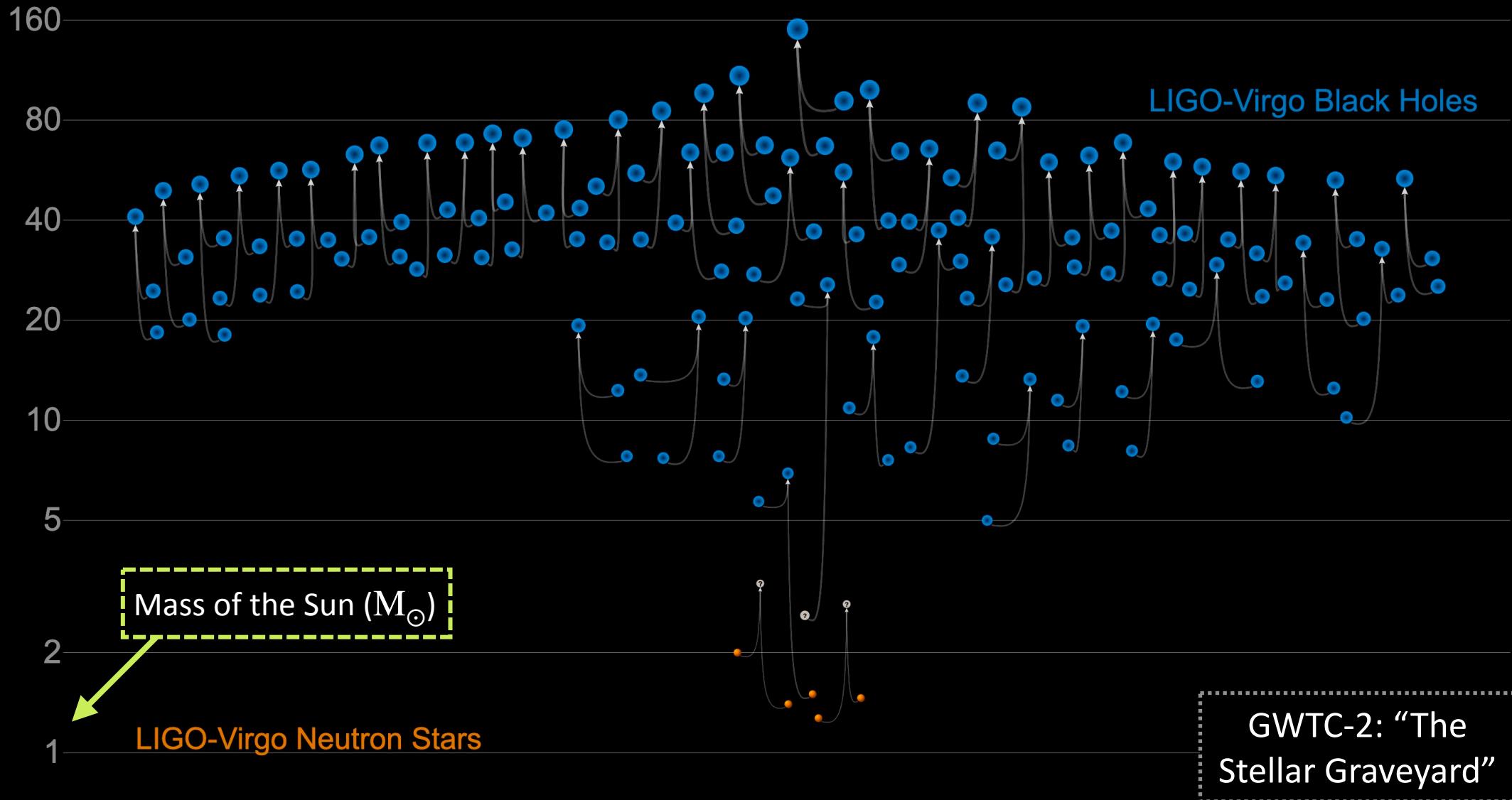
# What can we learn from individual waveforms?\*

*A lot, for example,*

- |   |                        |
|---|------------------------|
| 1. Component masses   | BSM examples:<br>PBHs  |
| 2. Tidal effects → equation of state                                | ECO DM                 |
| 3. Dynamical friction → environmental effects                       | DM spikes              |
| 4. Long-range (dark) forces → BSM effects                           | ULDM, modified gravity |
| 5. Extra dissipation channels → BSM effects                         | ULDM                   |
| 6. Redshift of event → age of object                                | PBHs                   |
| 7. “Hair”: multipolar metric deviations (EMRIs) → tests of GR       | modified gravity       |
| 8. Post-merger quasi-normal modes, “echoes” → GR, ultralight bosons | ULDM                   |

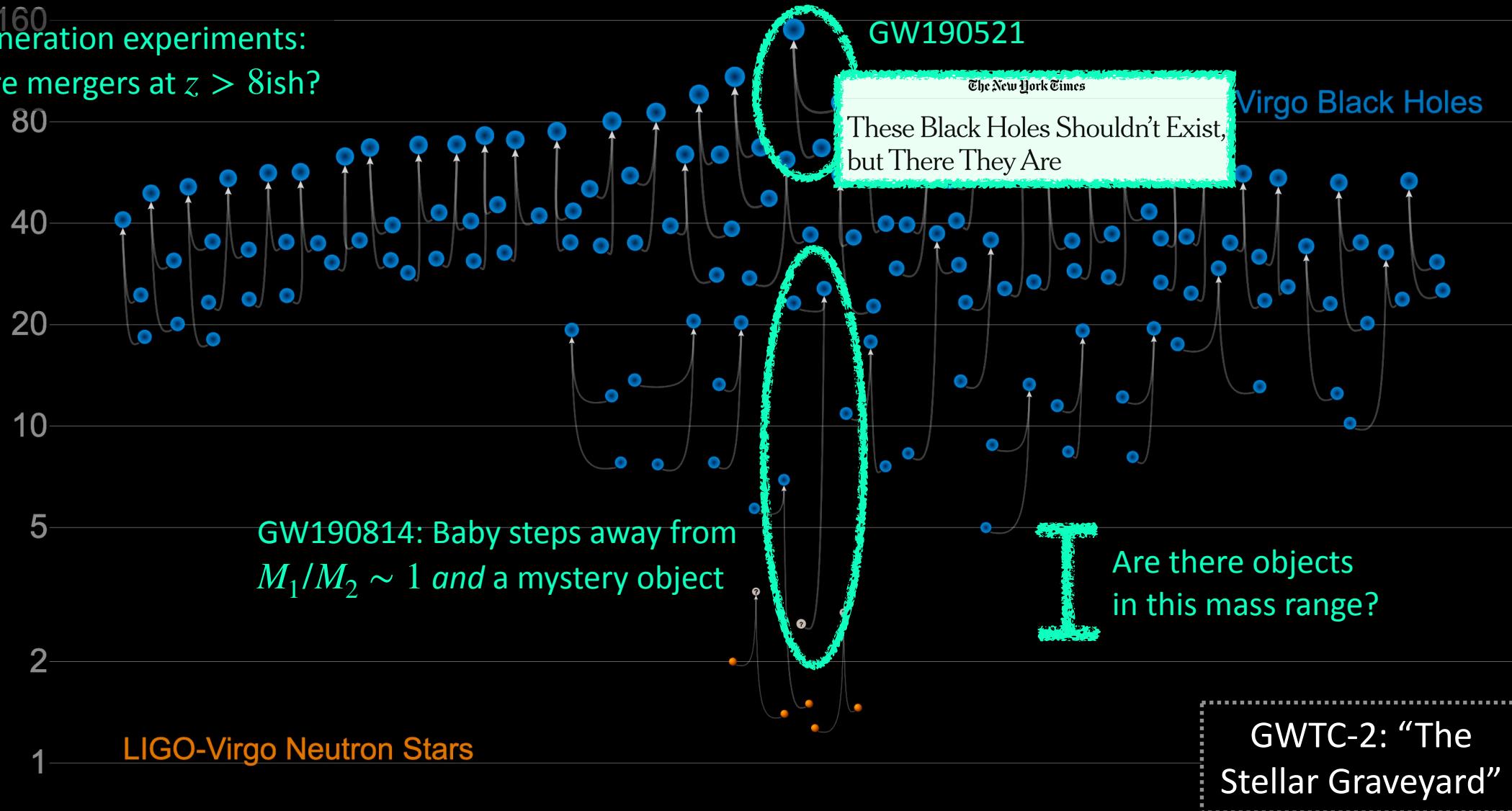
\*Further information could come from (for example)  
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# Binary mergers in LIGO/Virgo 01-3a

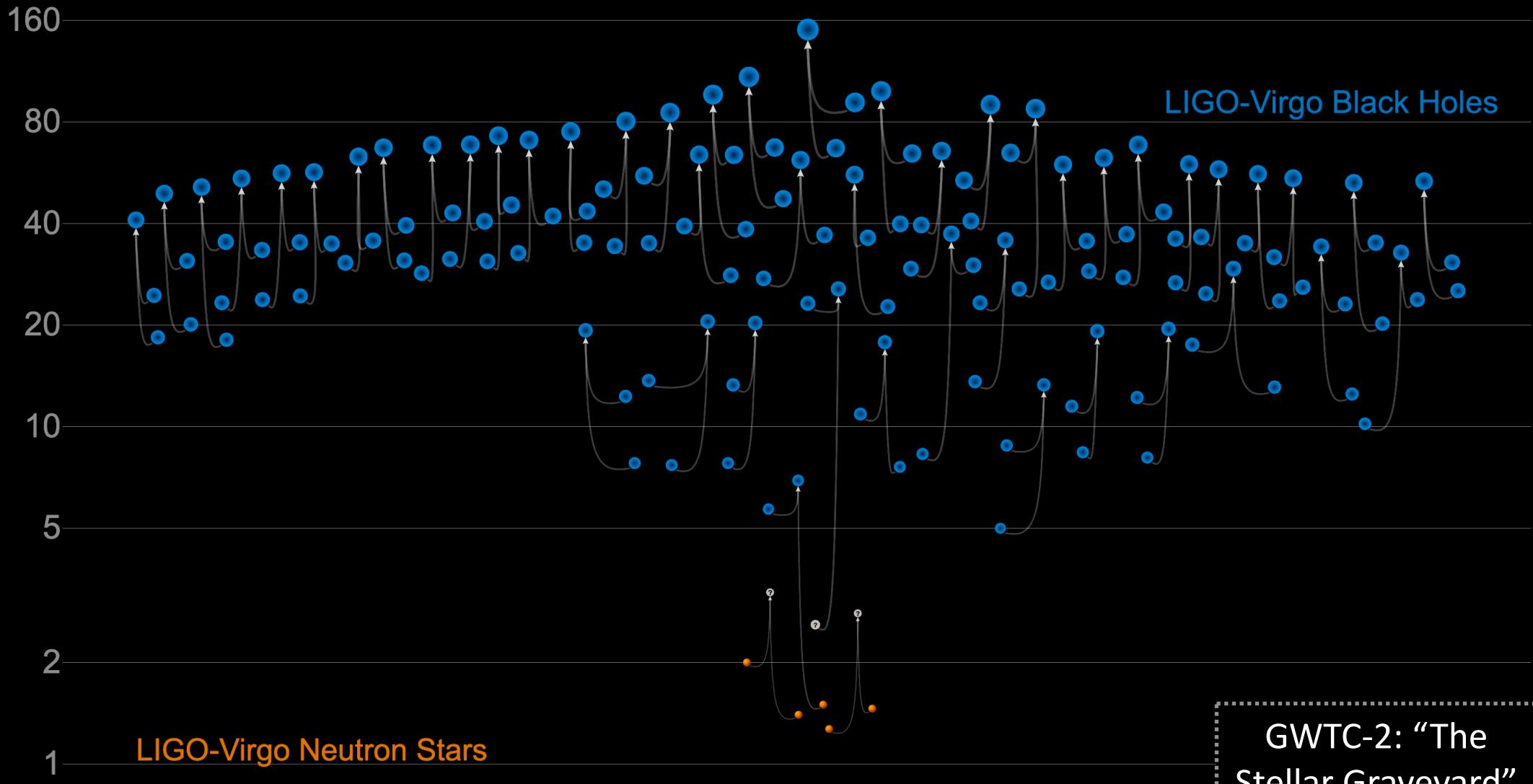


# Binary mergers in LIGO/Virgo 01-3a

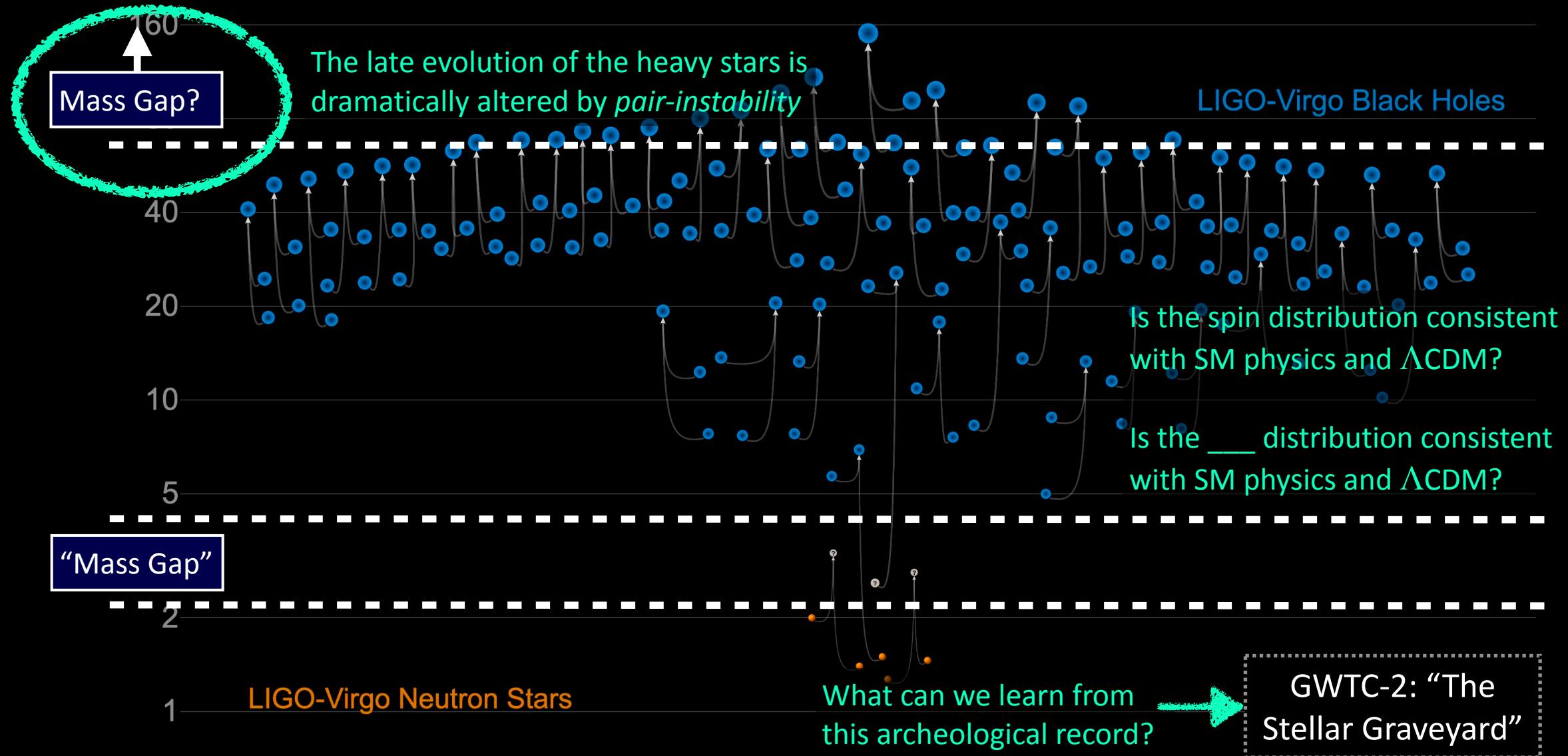
Next generation experiments:  
are there mergers at  $z > 8$ ish?

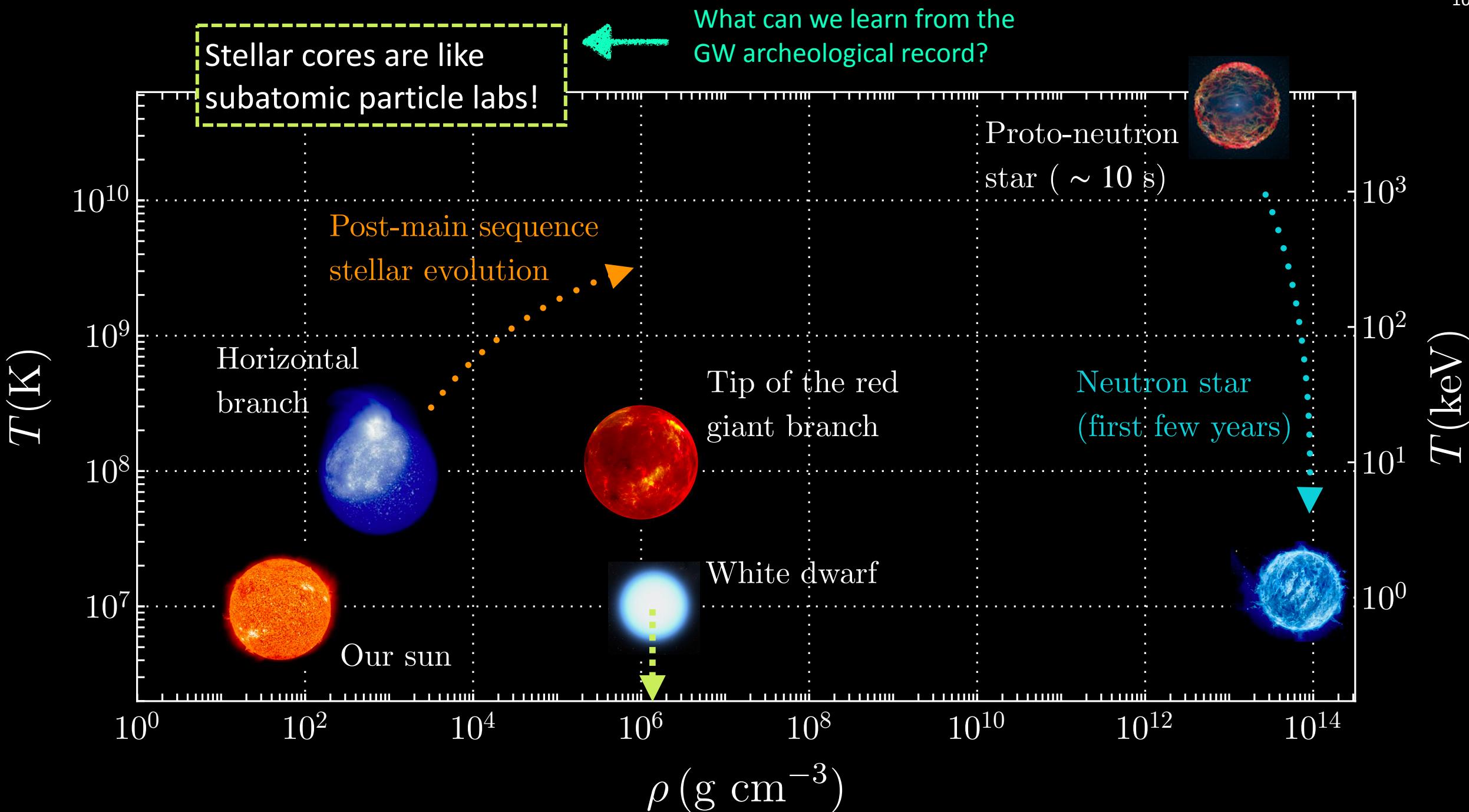


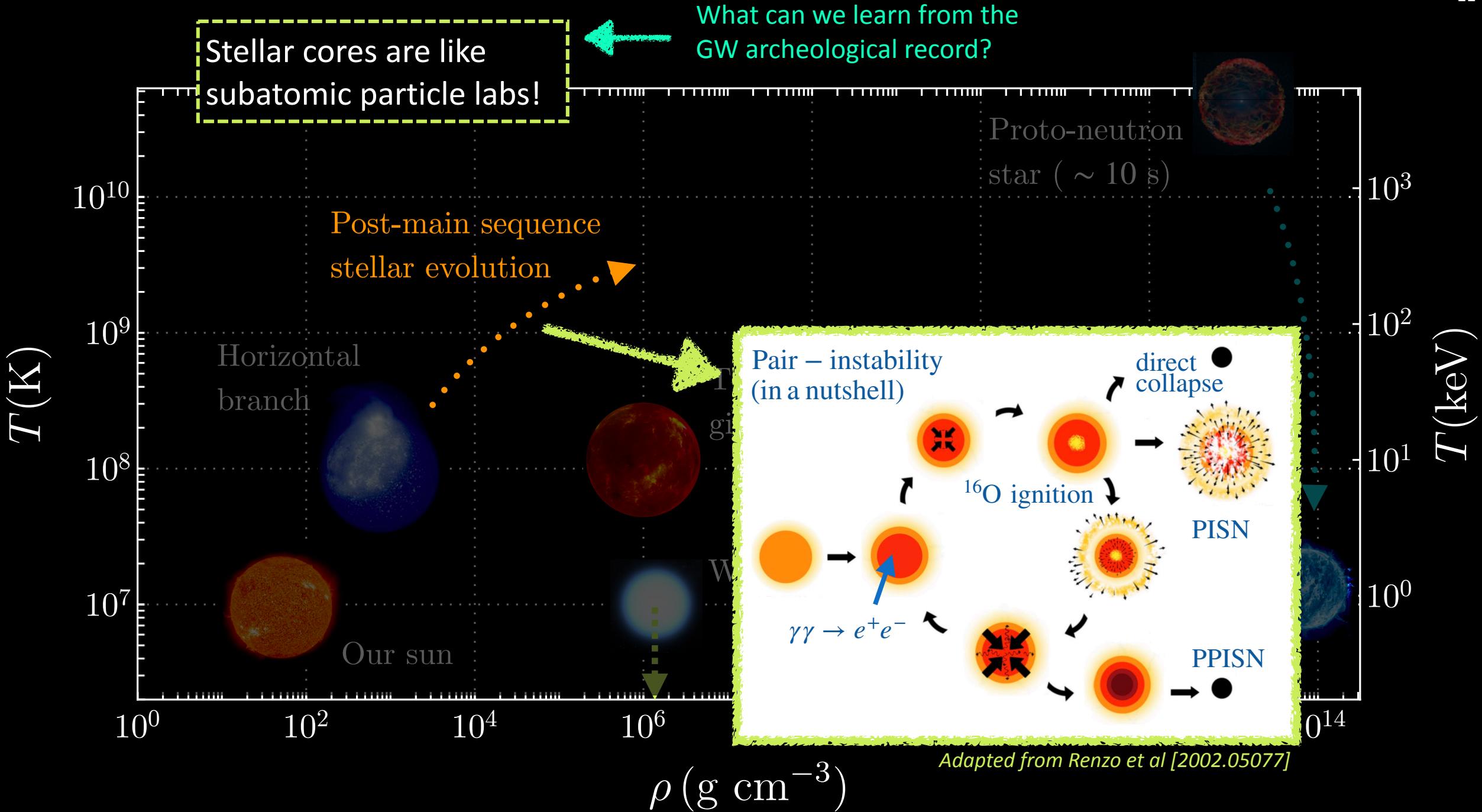
# What can we learn from population analysis?

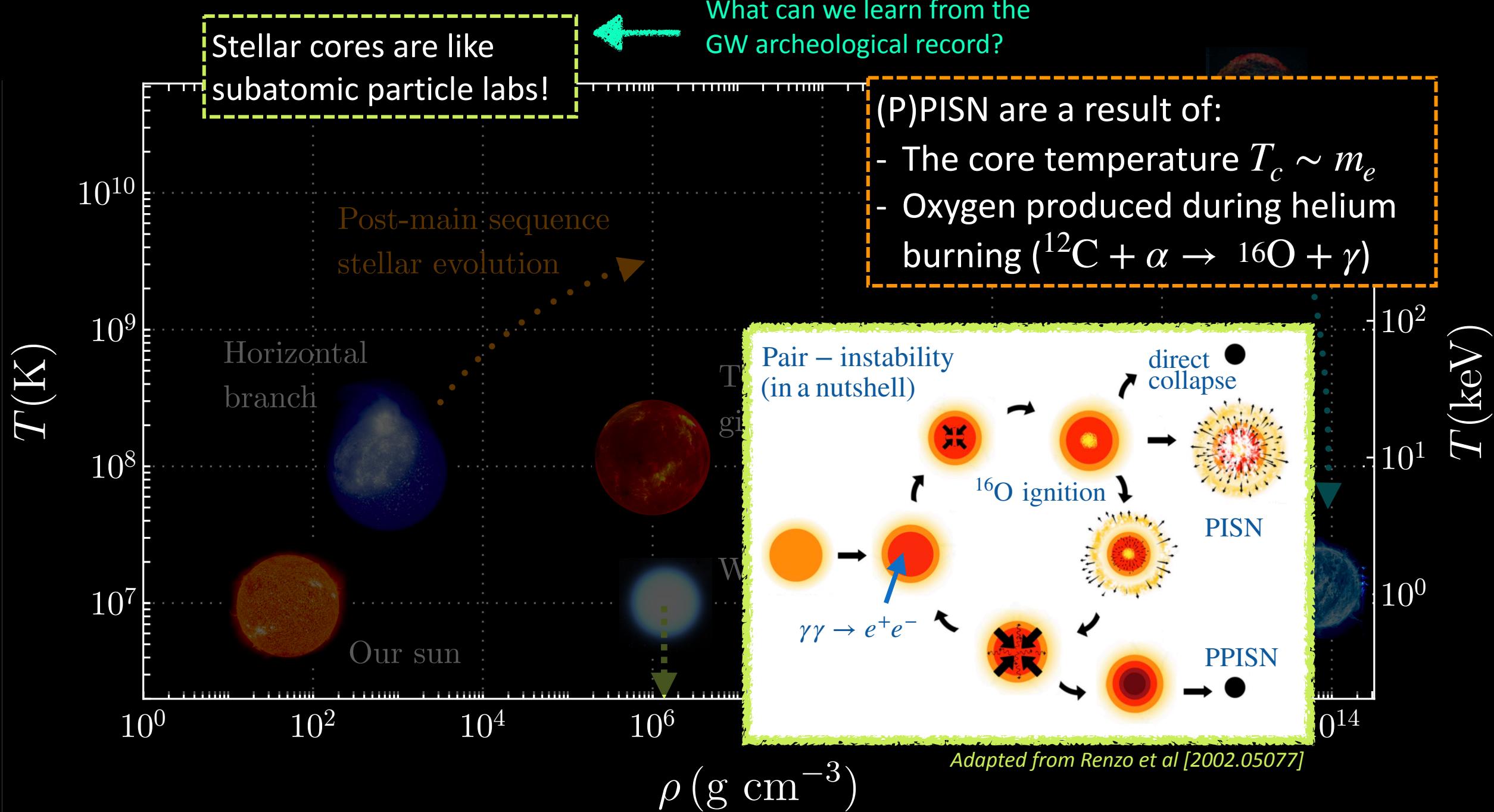


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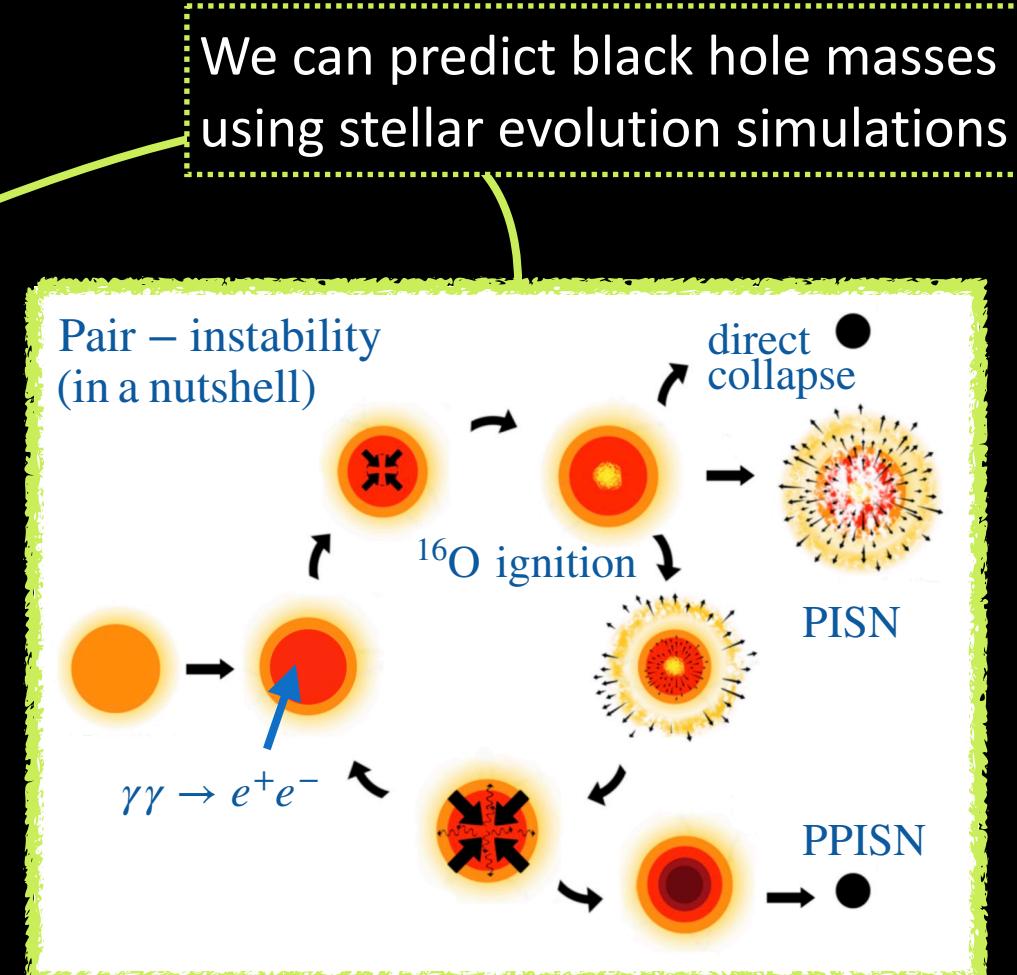
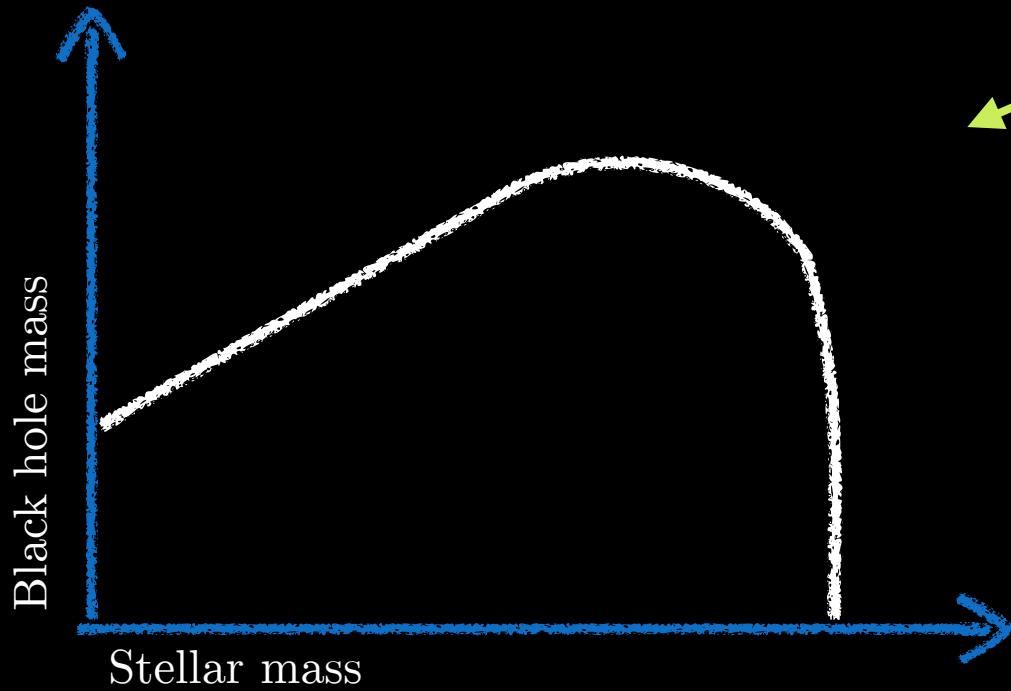




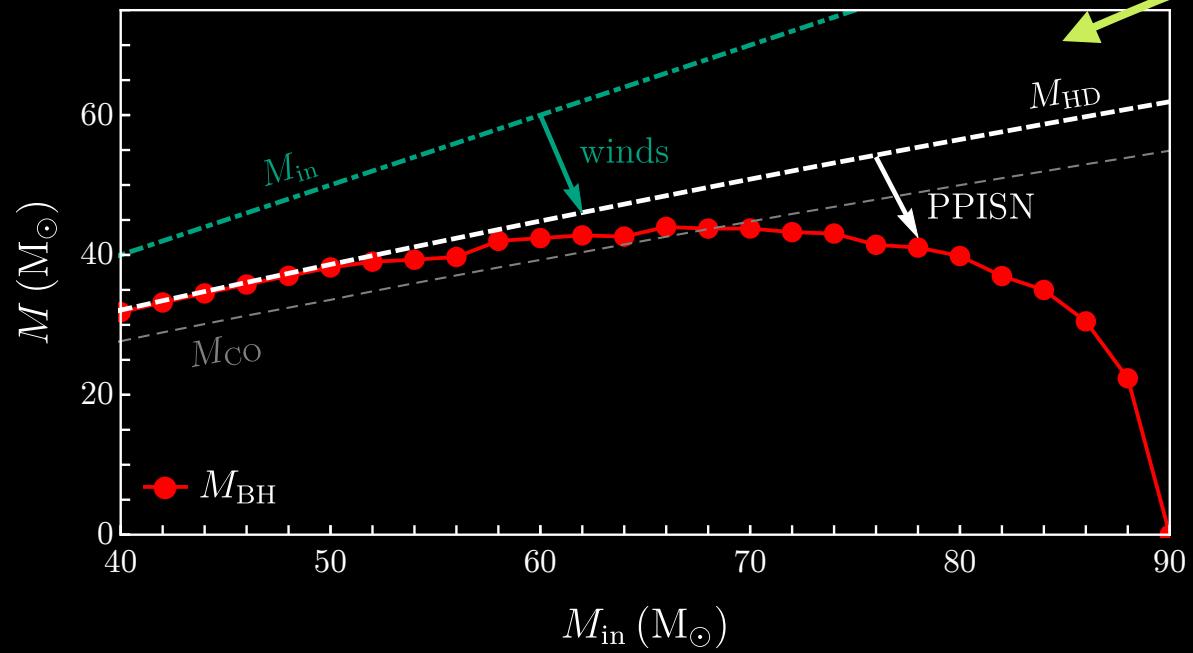




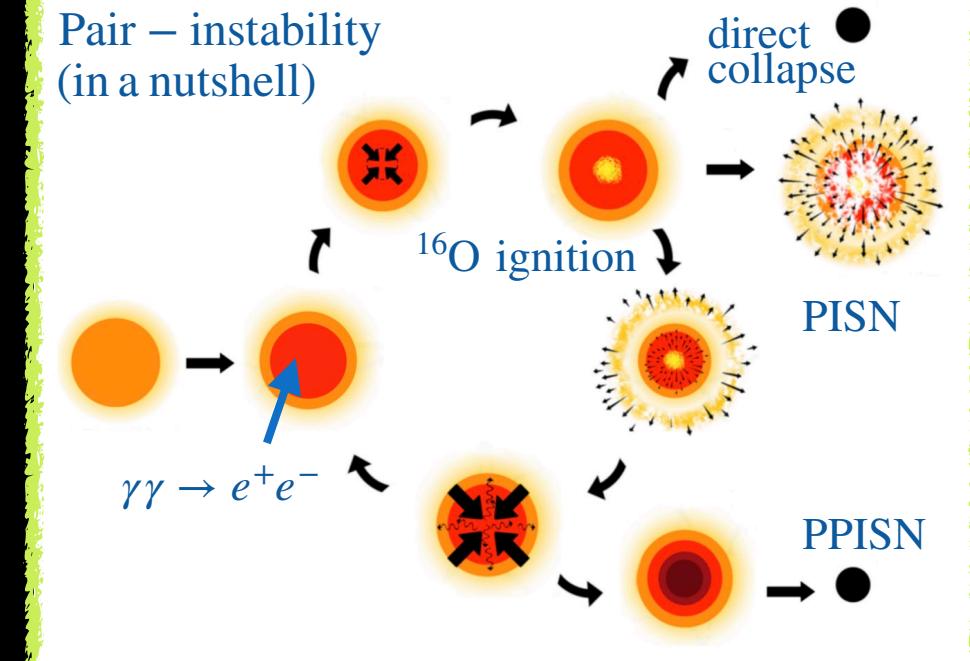
# Pair-instability and black hole populations



# Pair-instability and black hole populations



We can predict black hole masses  
using stellar evolution simulations

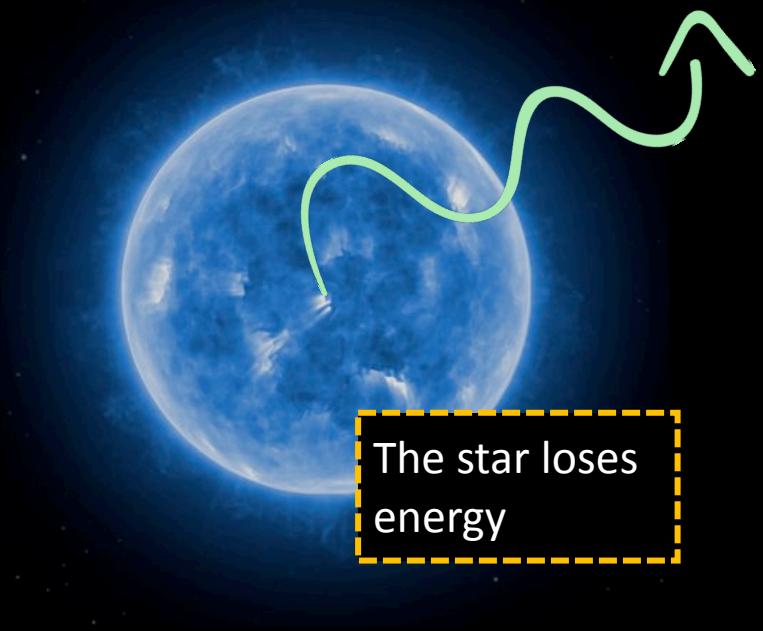


Adapted from Renzo et al [2002.05077]

# What about new particles?

New particles...

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

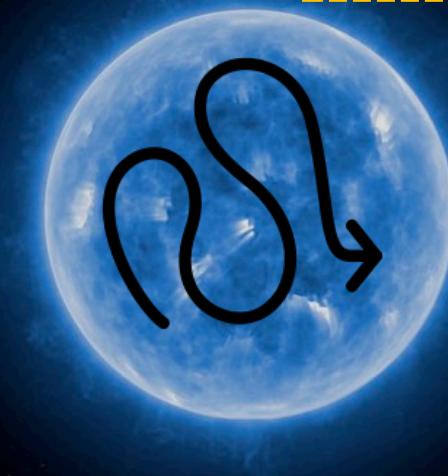


# What about new particles?

New particles...

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

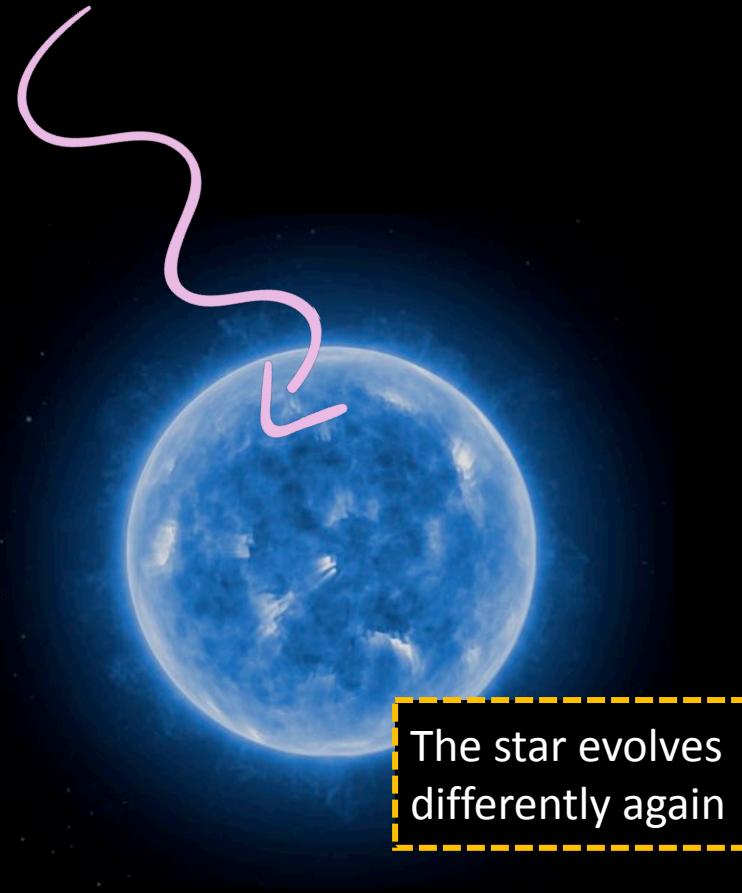
The star evolves  
differently



# 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

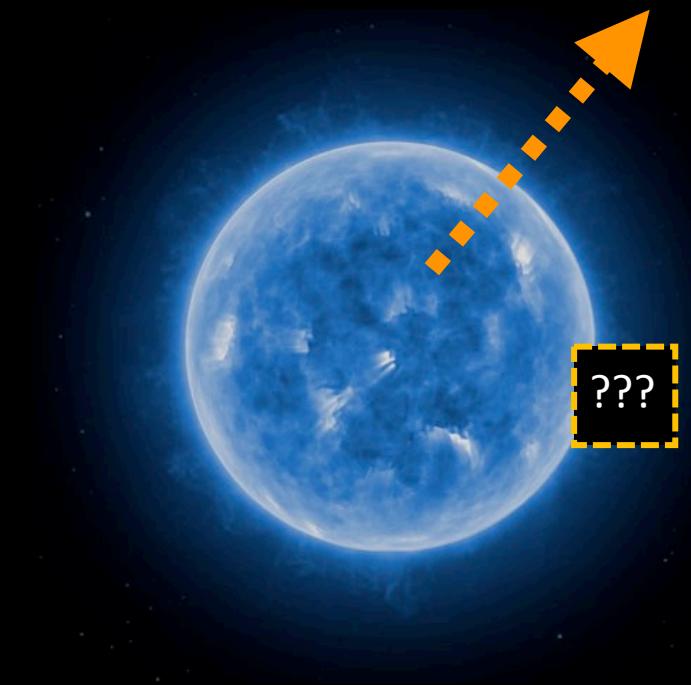


The star evolves  
differently again

# 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
- May modify other rates in the star



# 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
- May modify other rates in the star

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

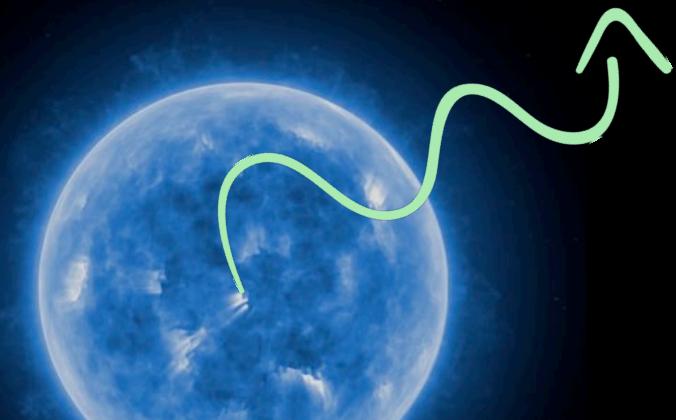
*Farmer, Renzo, de Mink,  
Fishbach, Justham  
arXiv:2006.06678*

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

*Straight, Sakstein, Baxter,  
arXiv: 2009.10716*

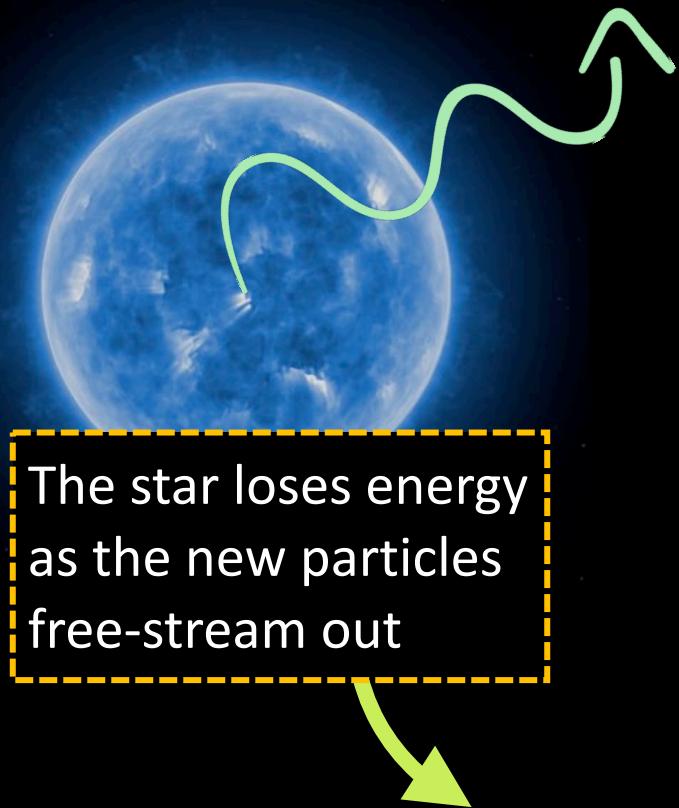
→ Testing the BHMG hypothesis with GW data

# New particles which free-stream out



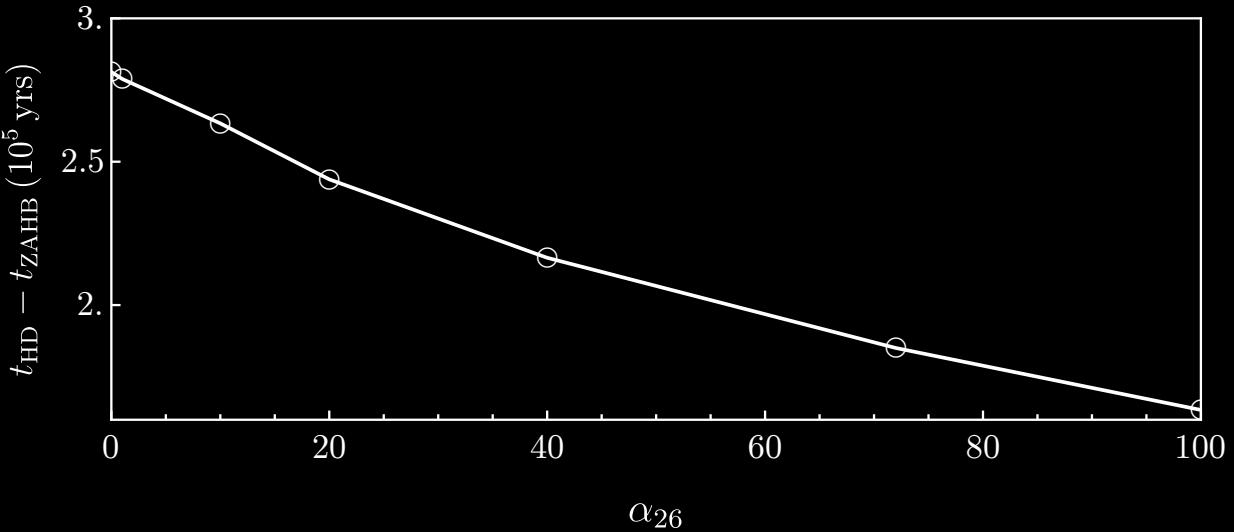
The star loses energy  
as the new particles  
free-stream out

# New particles which free-stream out



The star loses energy  
as the new particles  
free-stream out

To maintain hydrostatic  
equilibrium, the star burns  
through helium more quickly



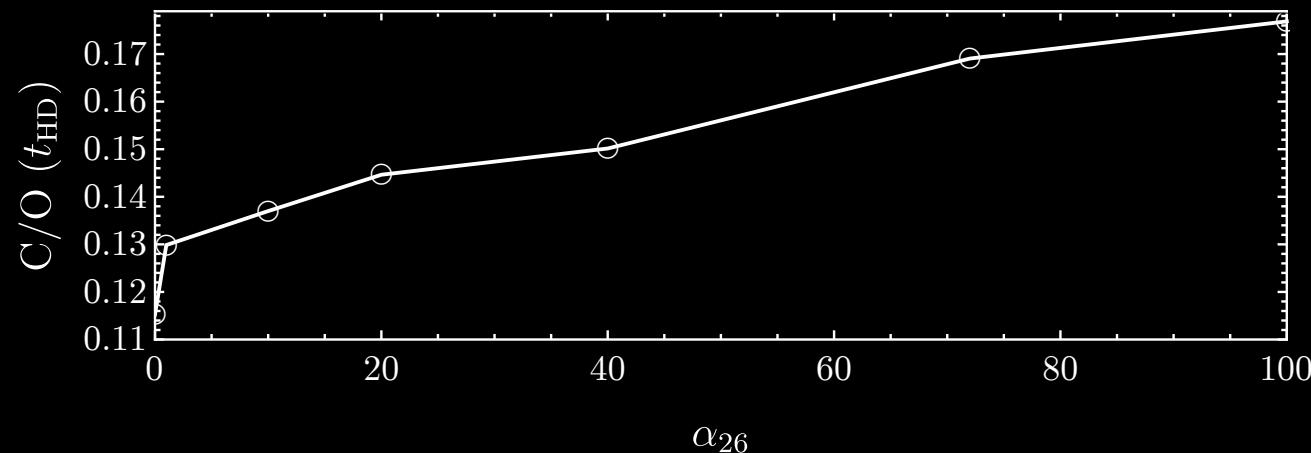
# New particles which free-stream out



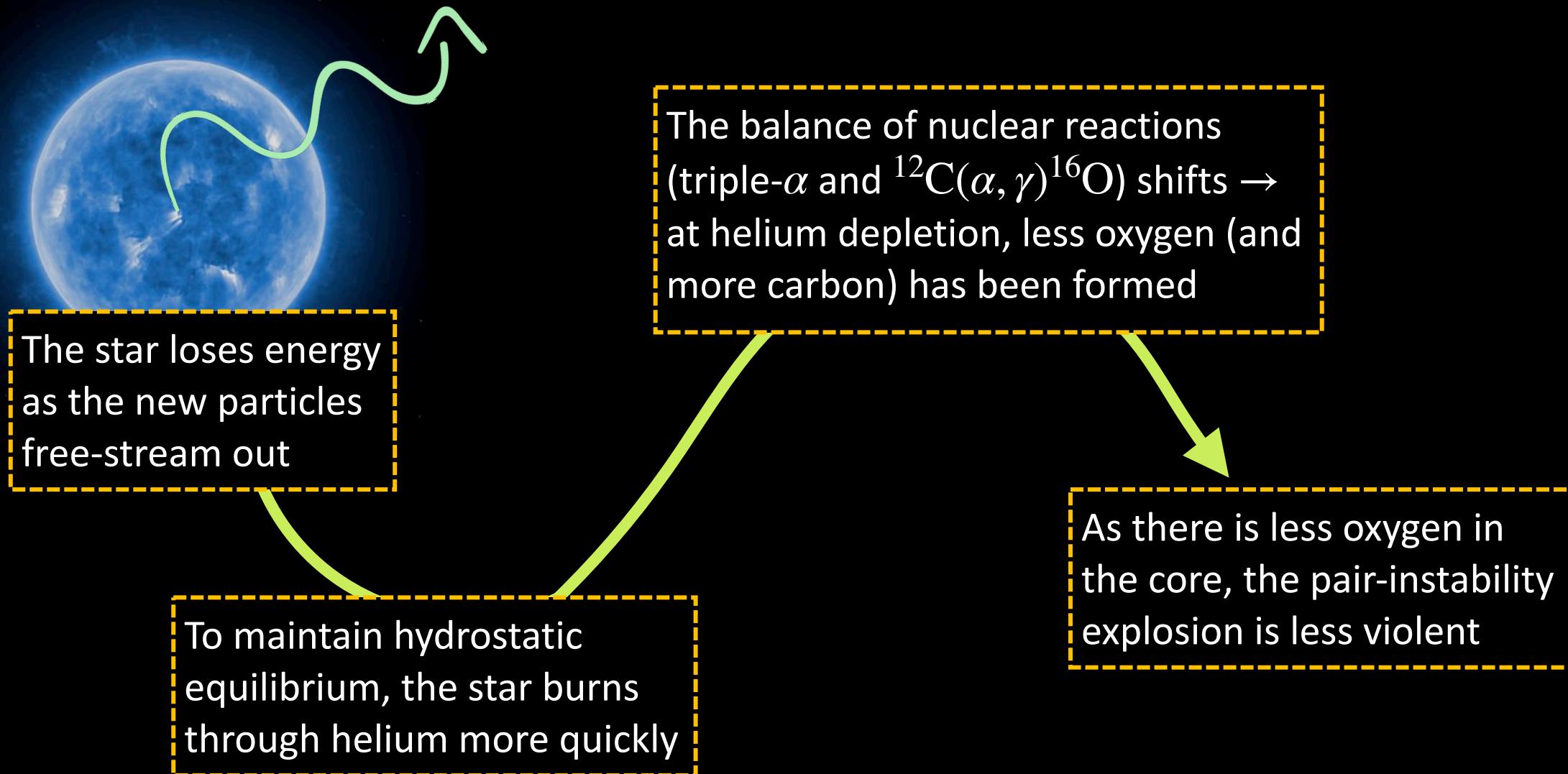
The star loses energy as the new particles free-stream out

To maintain hydrostatic equilibrium, the star burns through helium more quickly

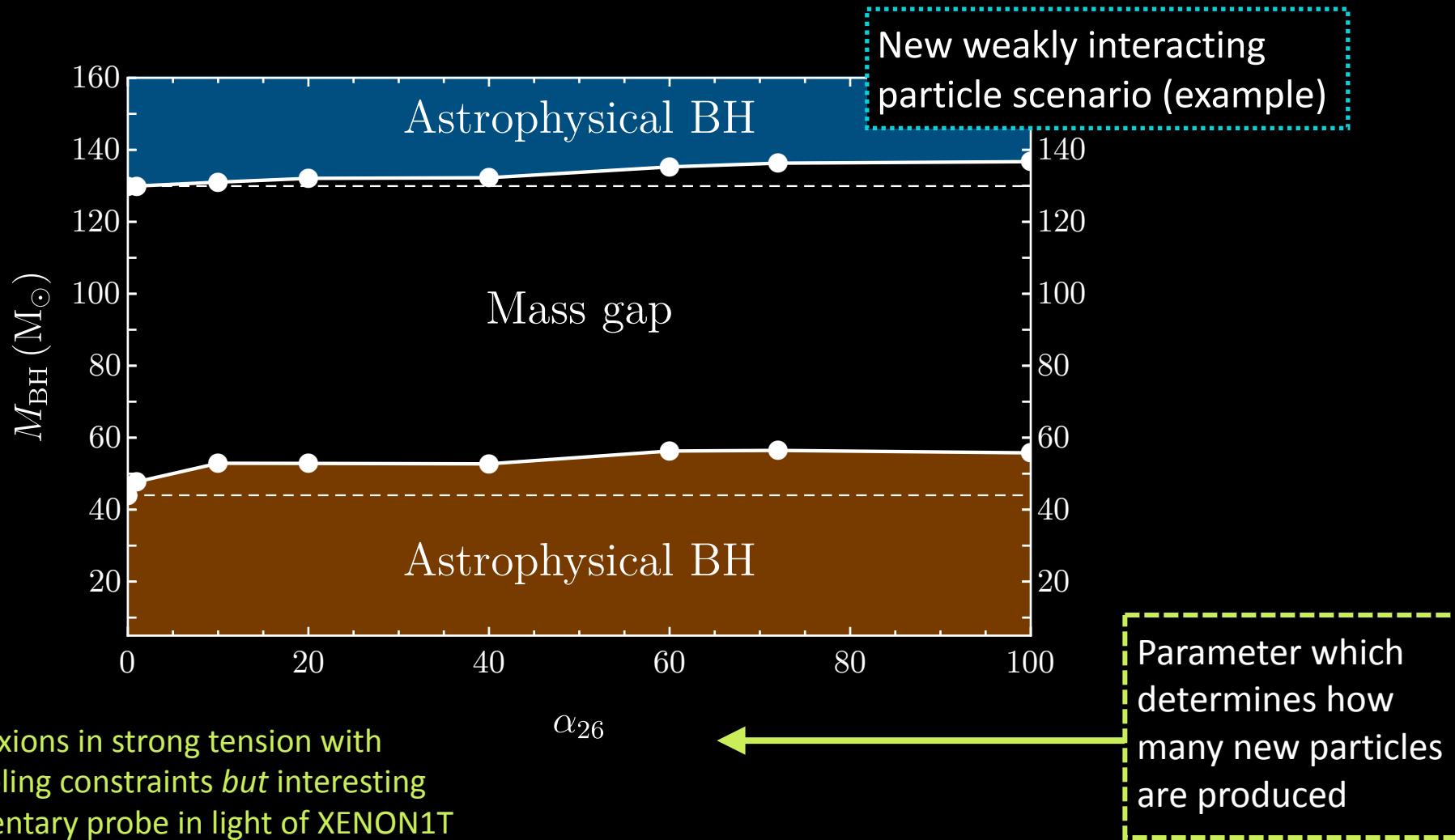
The balance of nuclear reactions (triple- $\alpha$  and  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ ) shifts → at helium depletion, less oxygen (and more carbon) has been formed



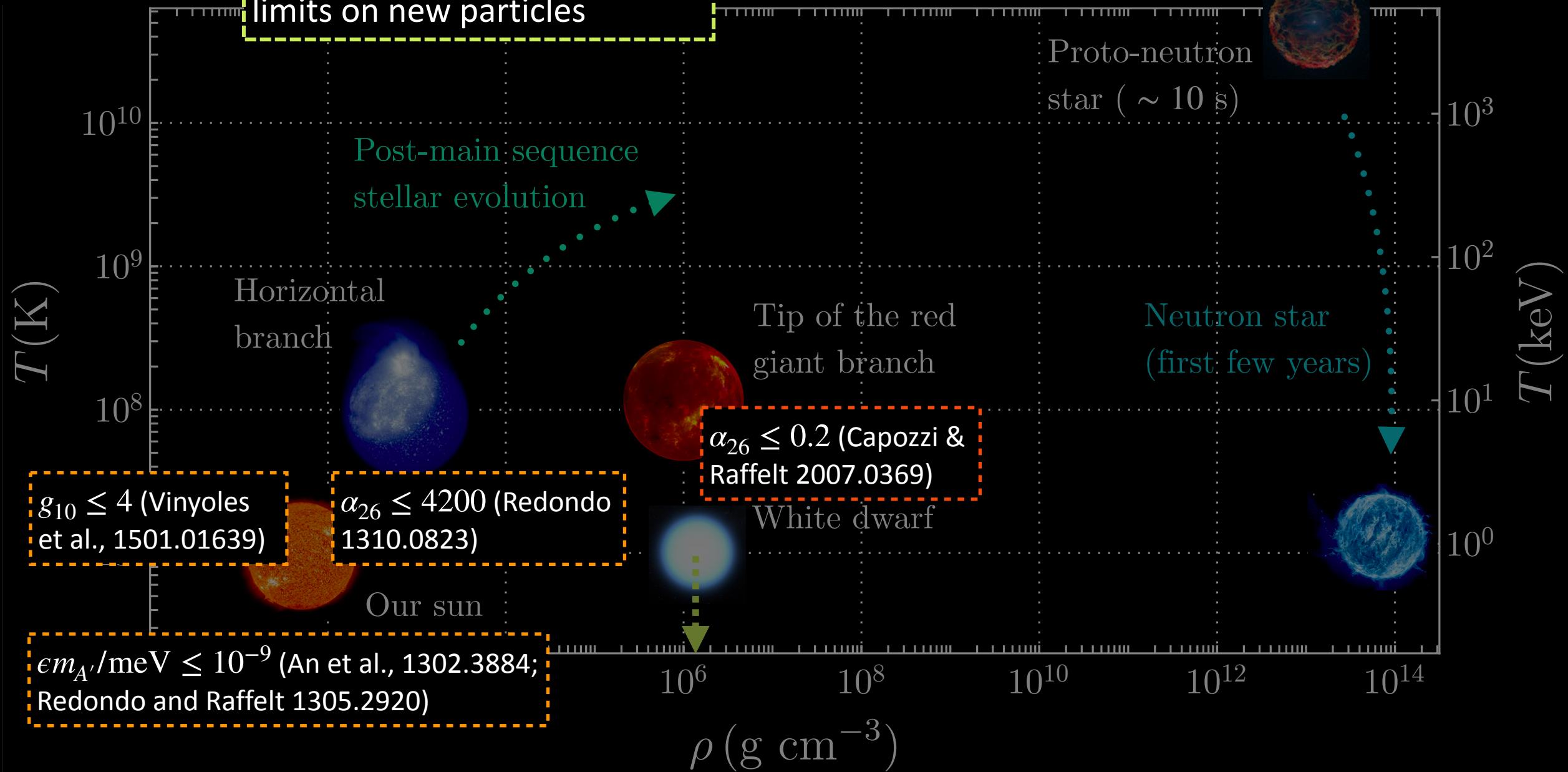
# New particles which free-stream out



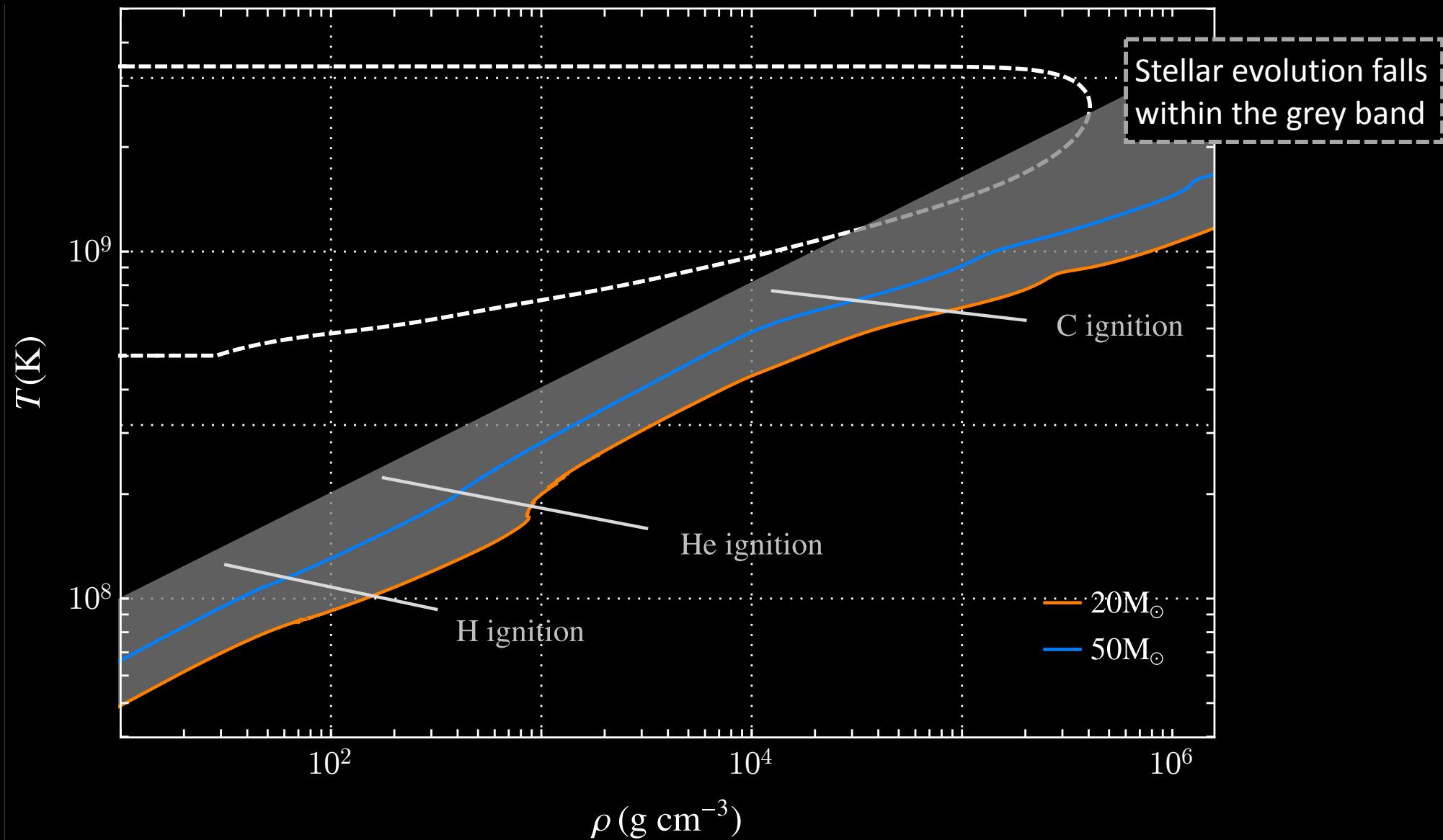
# Less violent explosions = heavier black holes



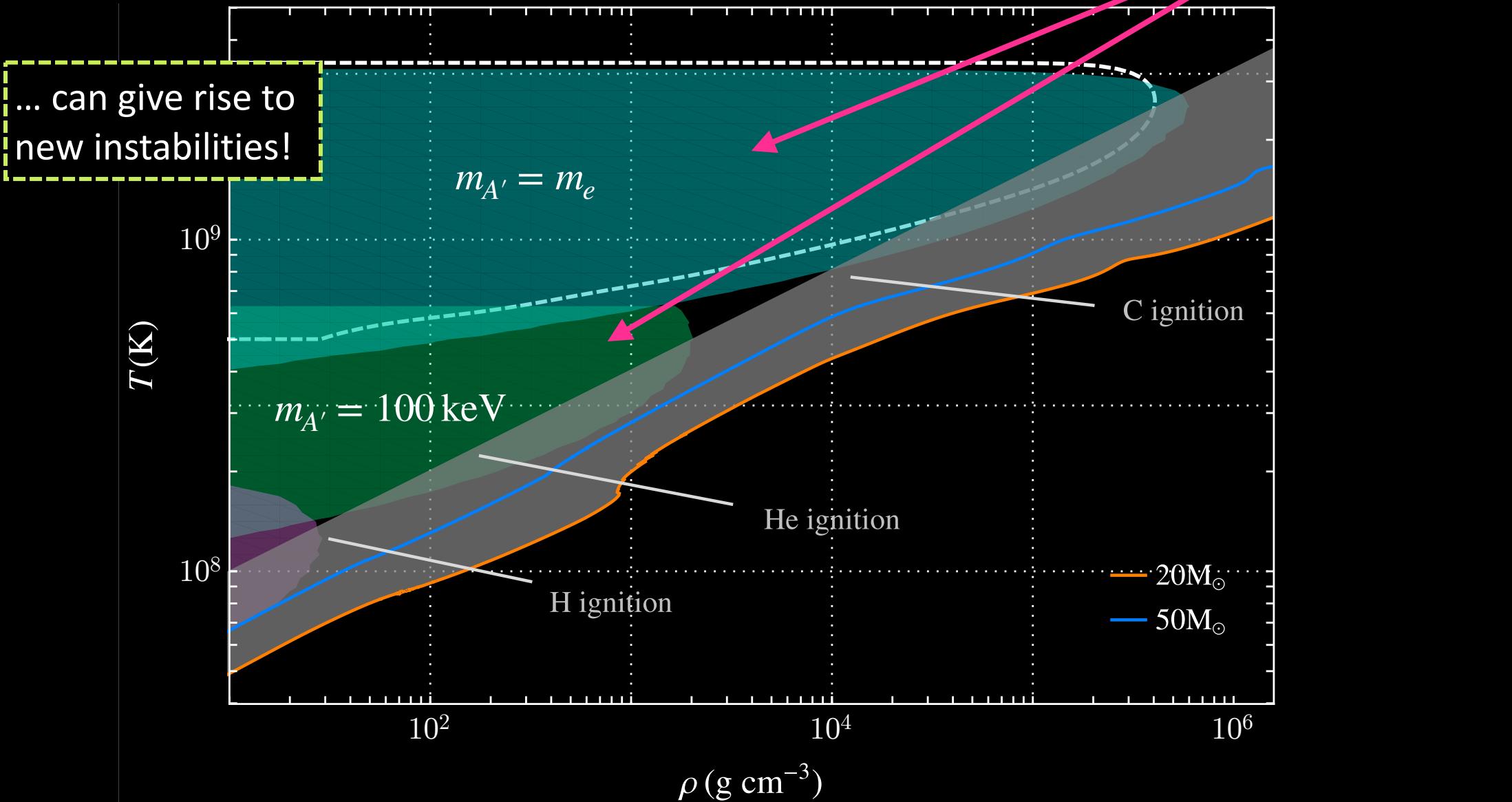
An illustration of astrophysical limits on new particles



# Under study: trapped particles

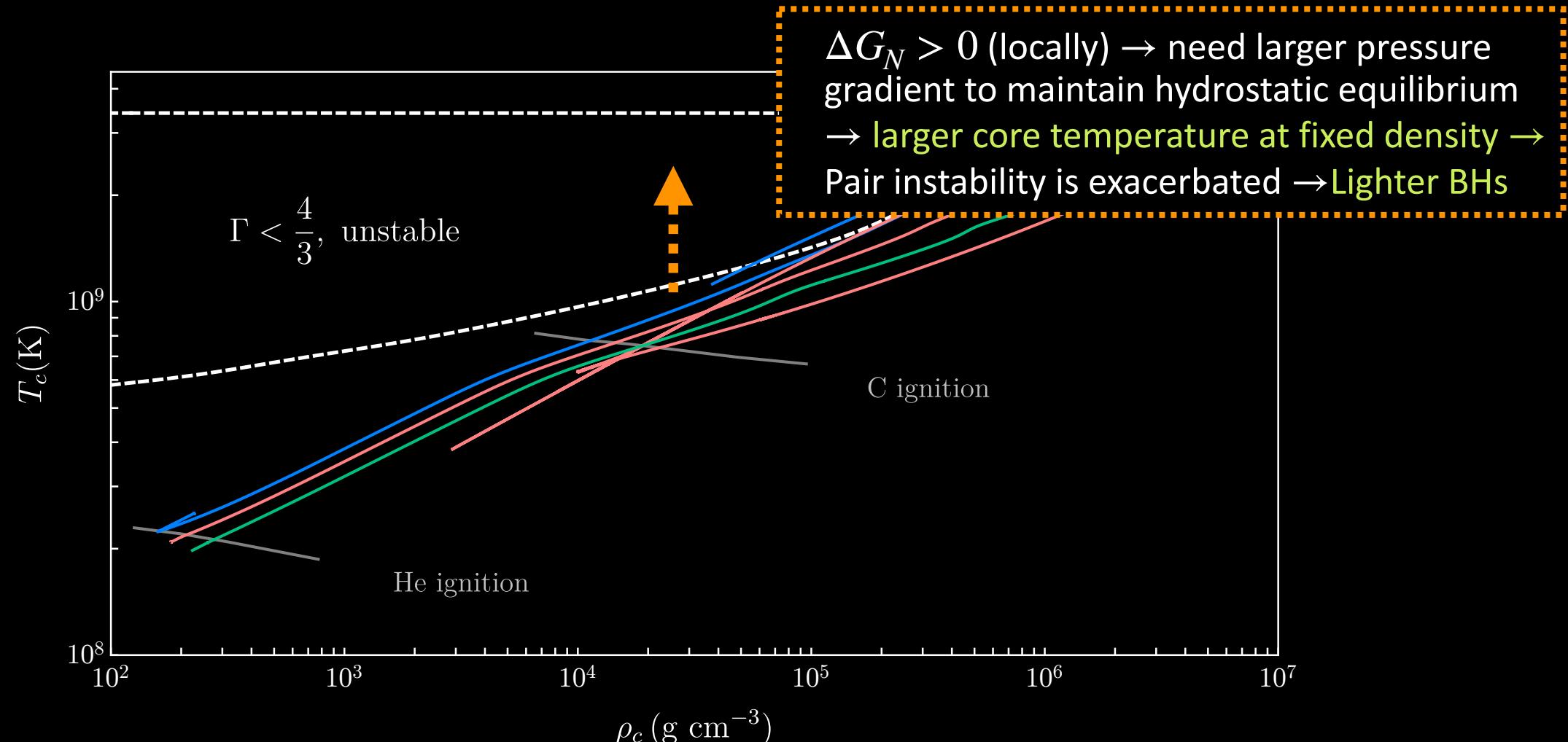


# Under study: trapped particles



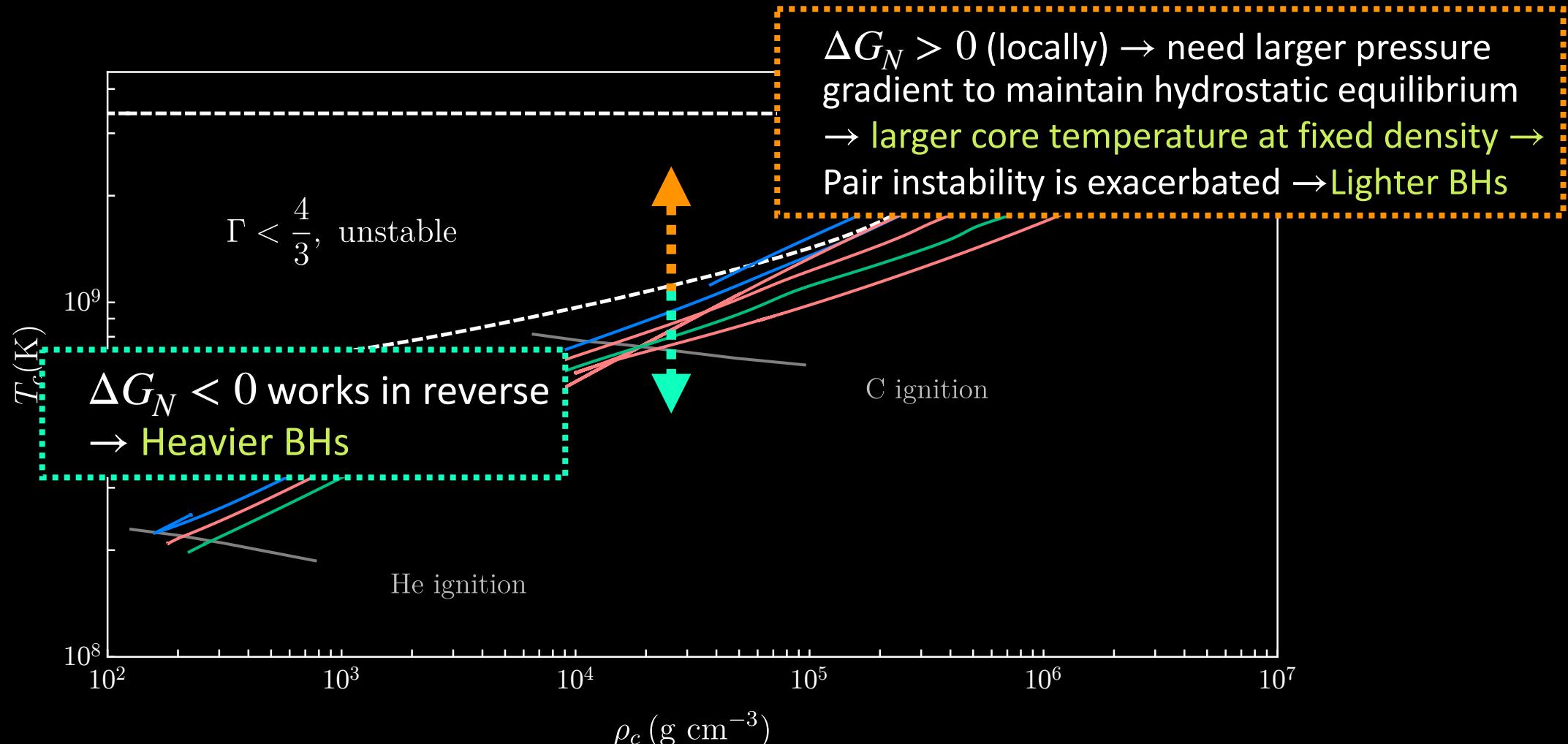
# New forces

Screened modified gravity: new force as effective  $\Delta G_N$



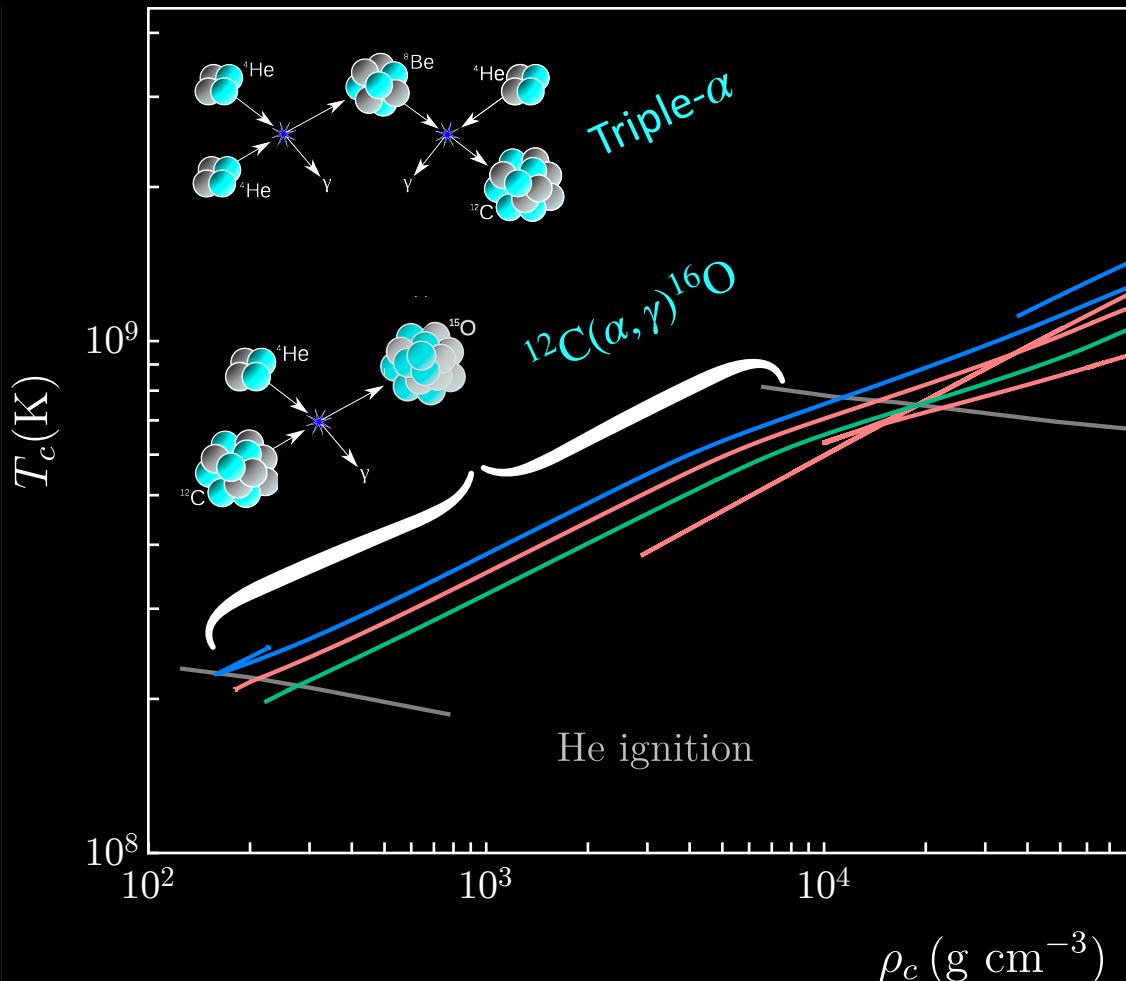
# New forces

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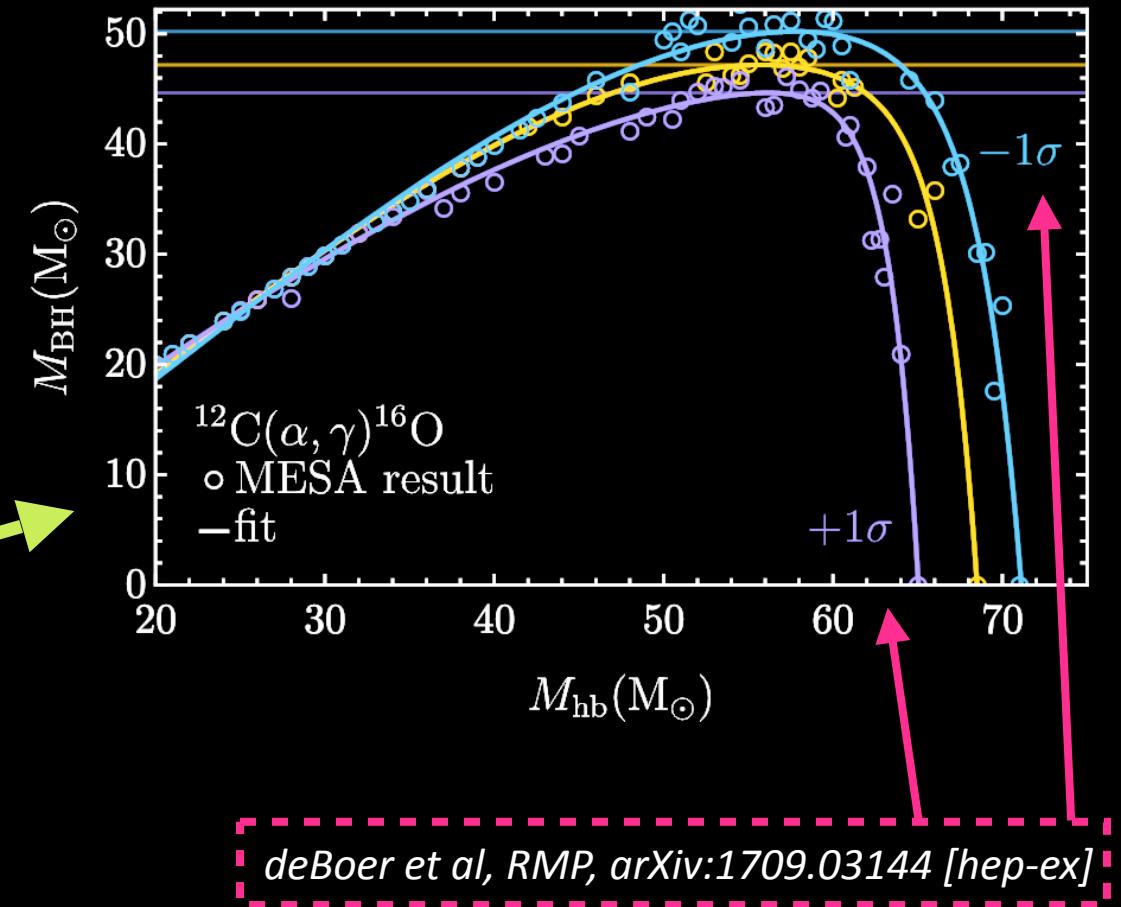
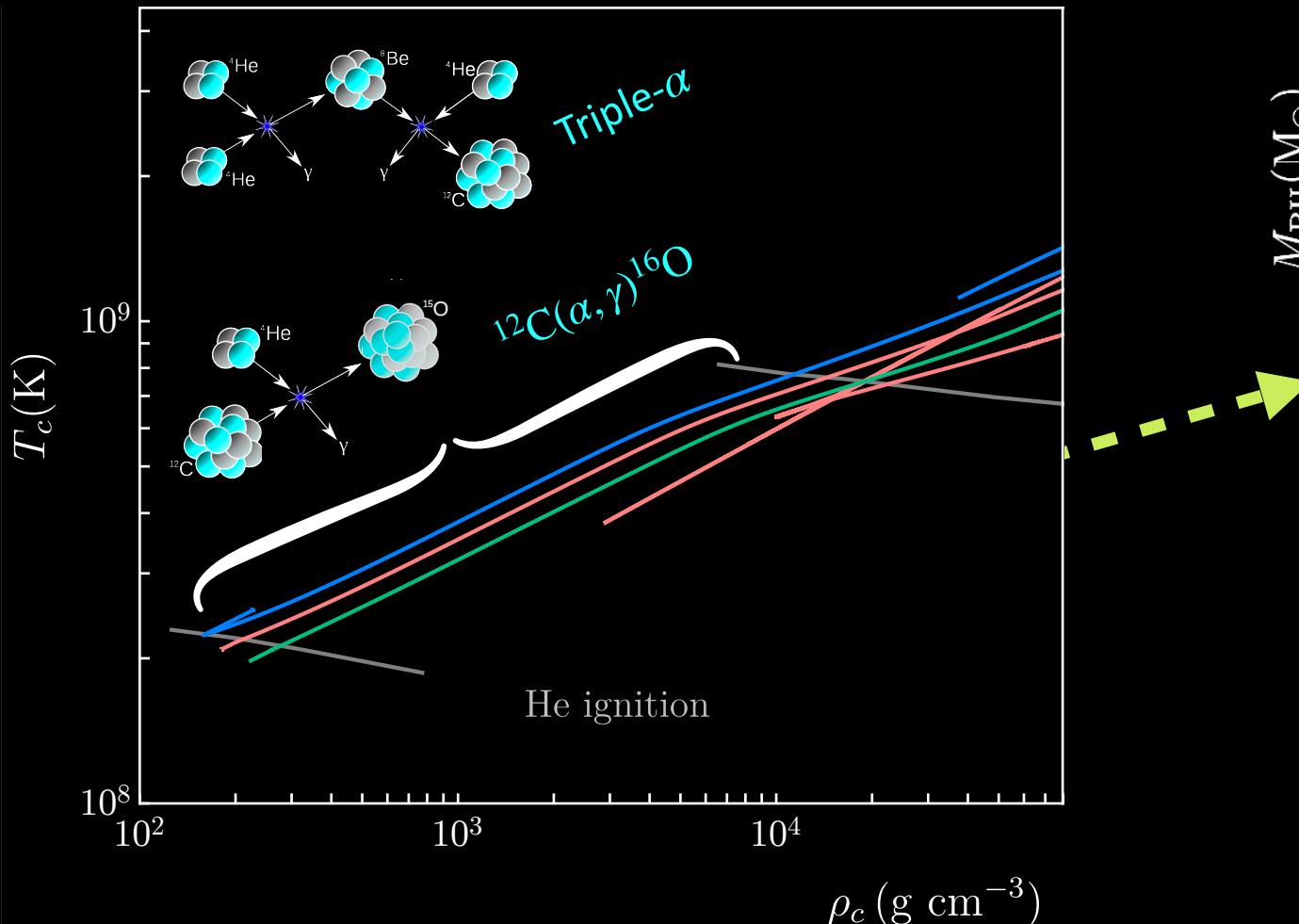
# Nuclear physics

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

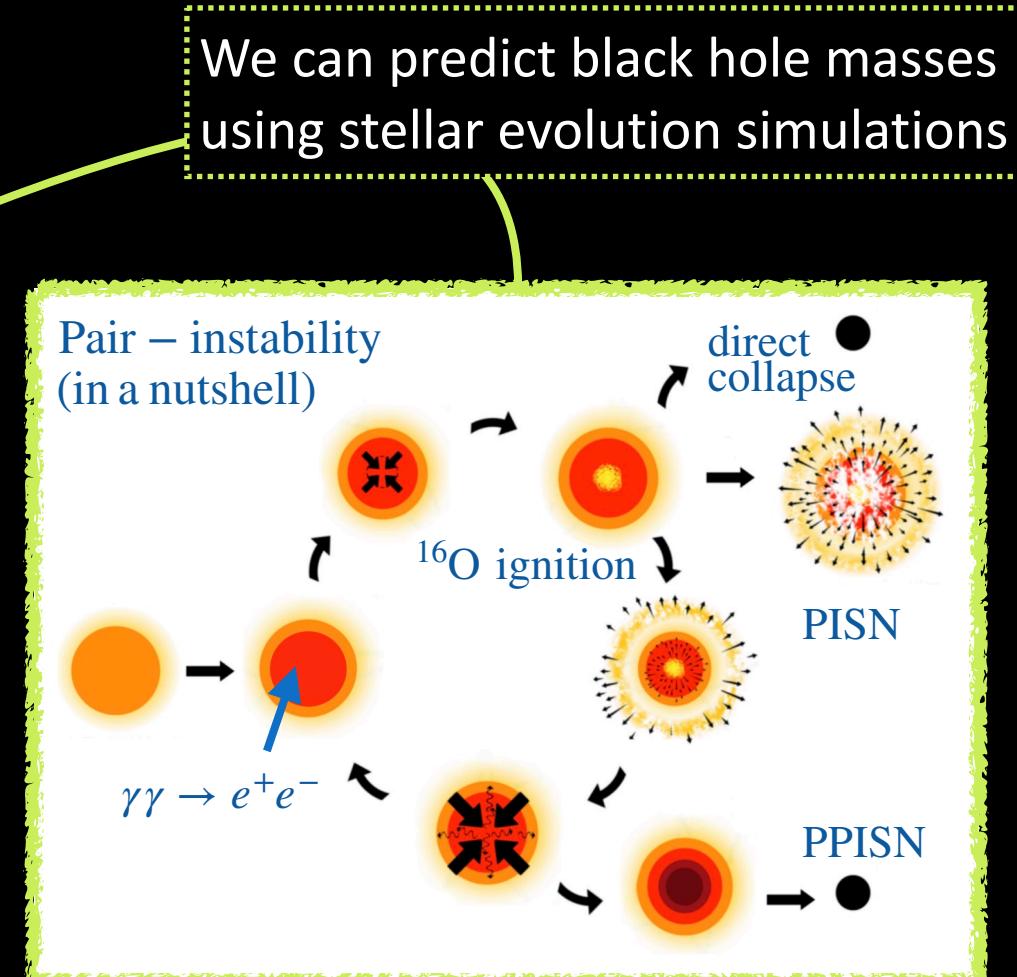
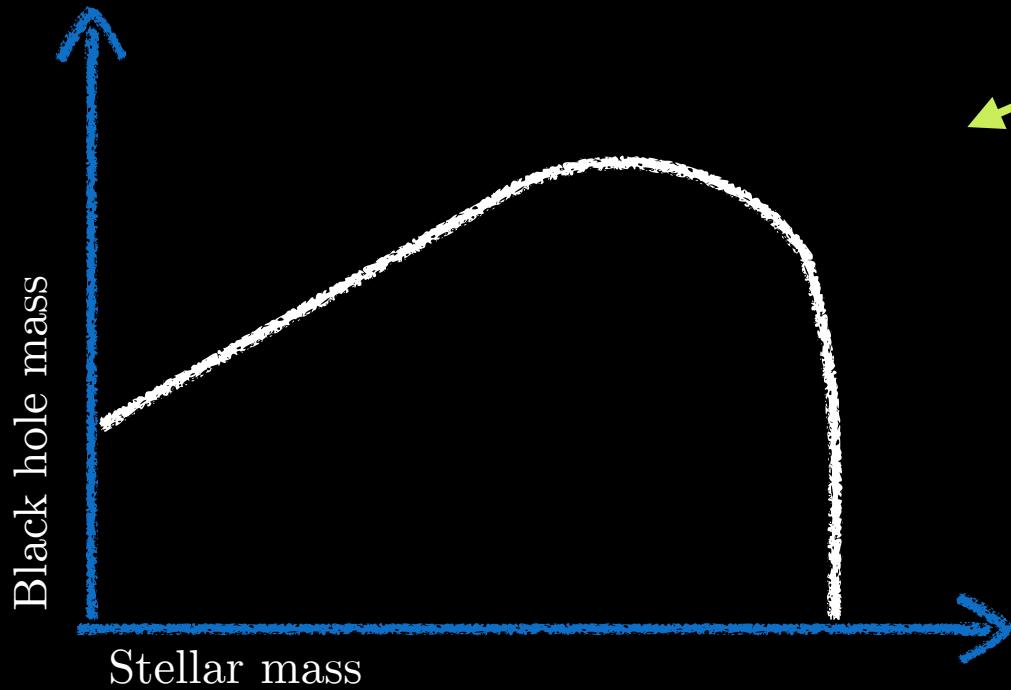


# Nuclear physics

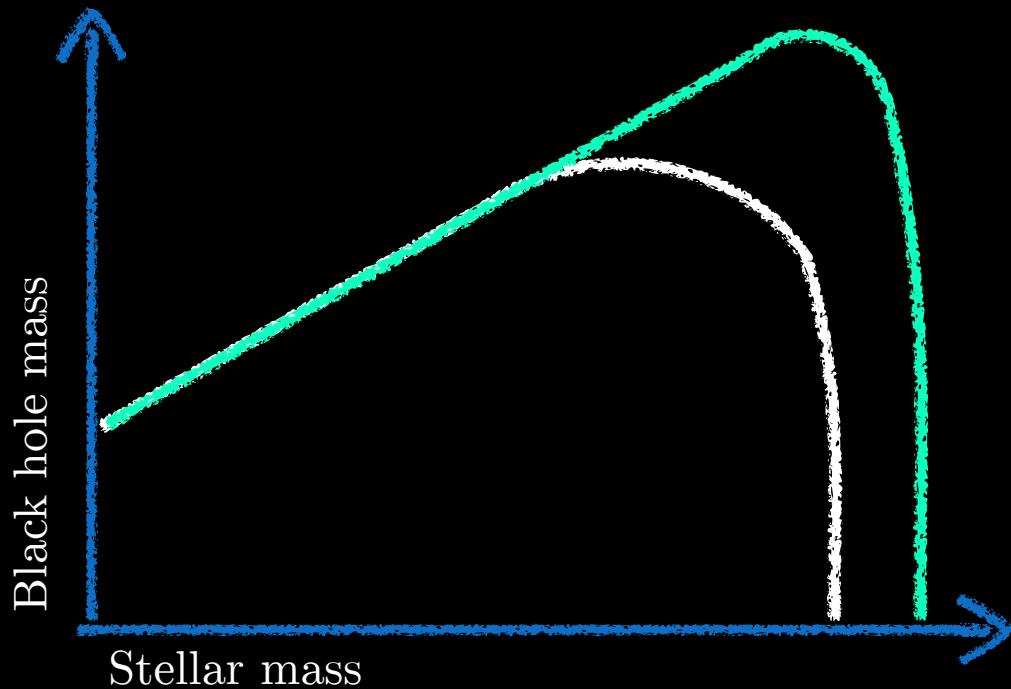
Particularly sensitive to  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$



# Pair-instability and black hole populations



# Pair-instability and black hole populations



We can predict black hole masses using stellar evolution simulations

New particles, dark matter, or different nuclear rates can change this prediction

*See for example...*

*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]*

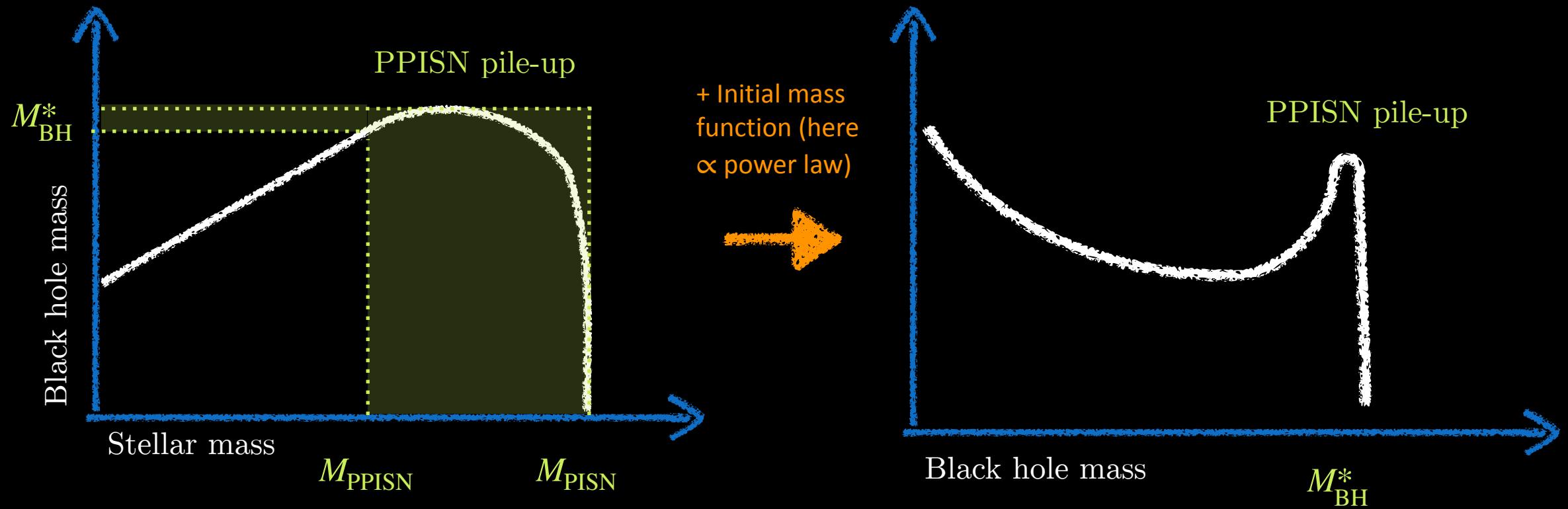
*Sakstein, DC, McDermott, Straight, Baxter, PRL, arXiv:2009.01213 [gr-qc]*

*Ziegler, Freese arXiv:2010.00254 [astro-ph]*

*...More work in progress*

# Pair-instability and black hole populations

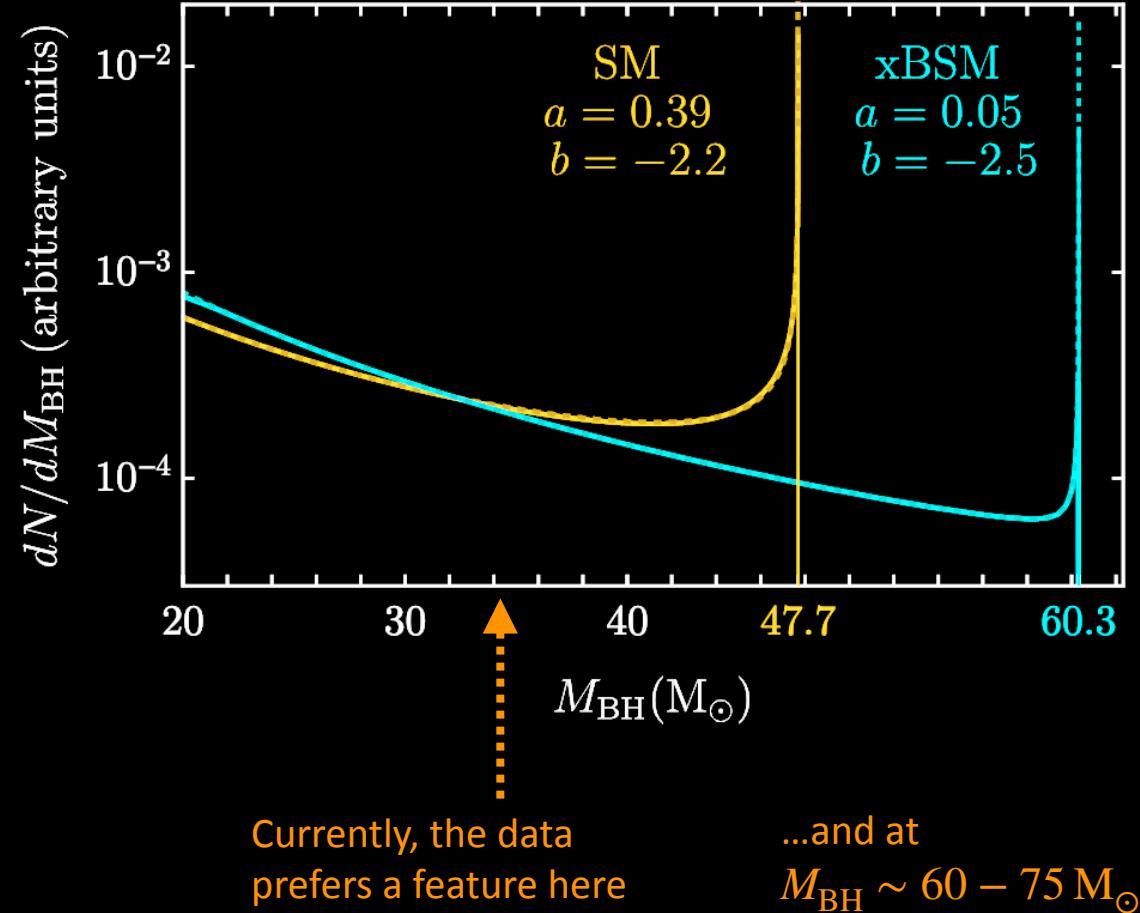
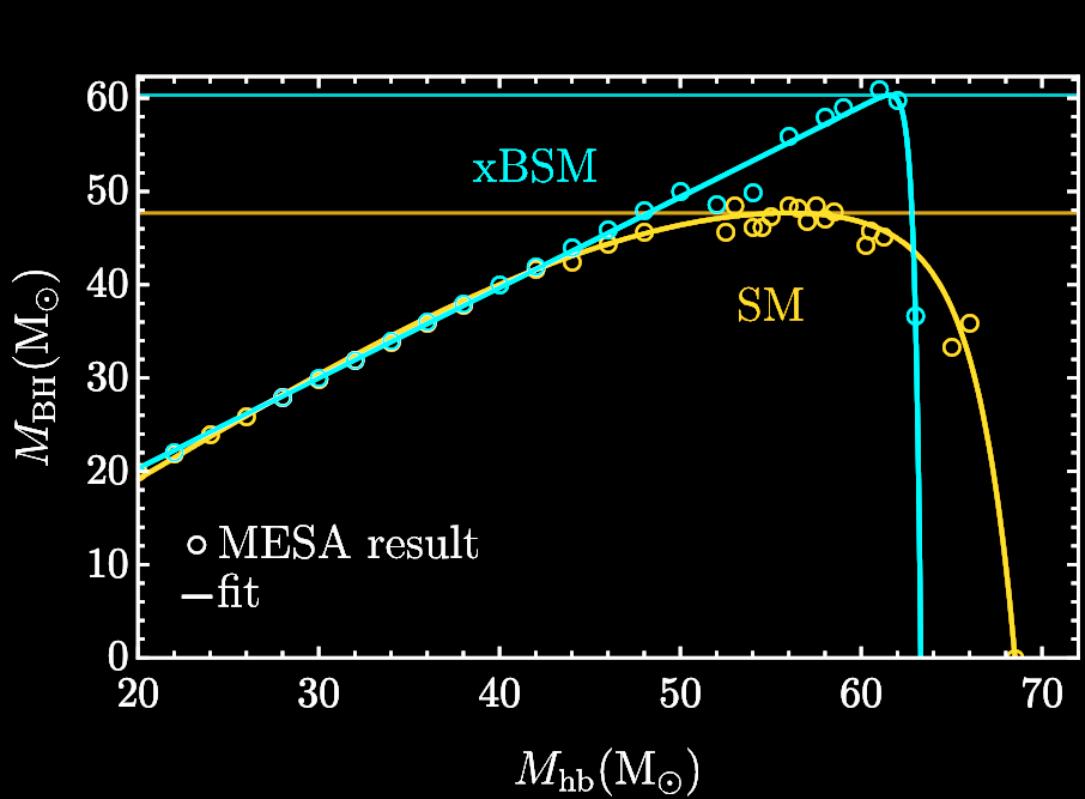
*From stellar evolution simulations to gravitational wave data analysis*



*See also Talbot & Trane, arXiv:1801.02699*

# Pair-instability and black hole populations

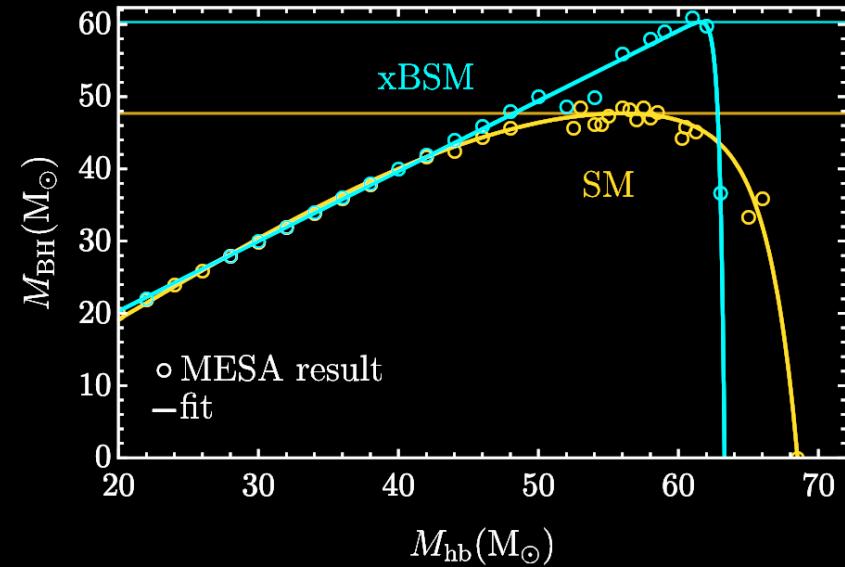
FIND THE GAP



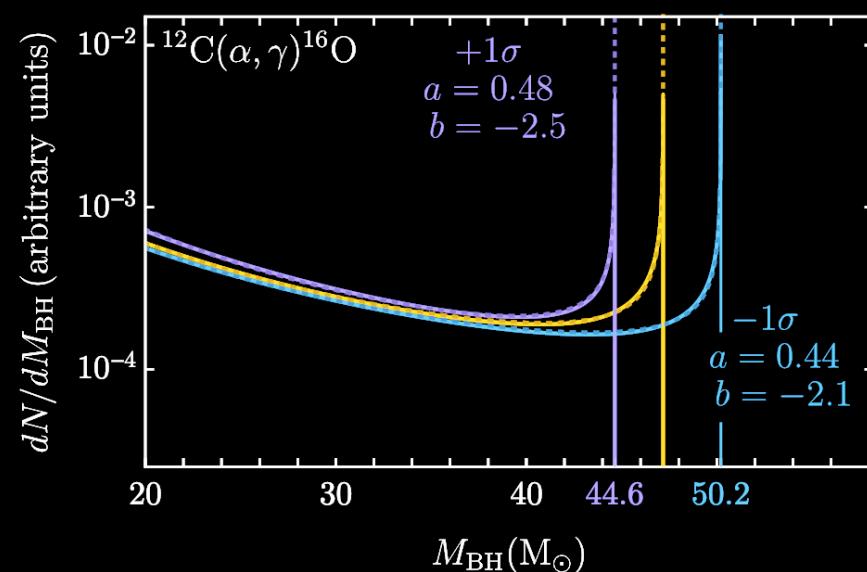
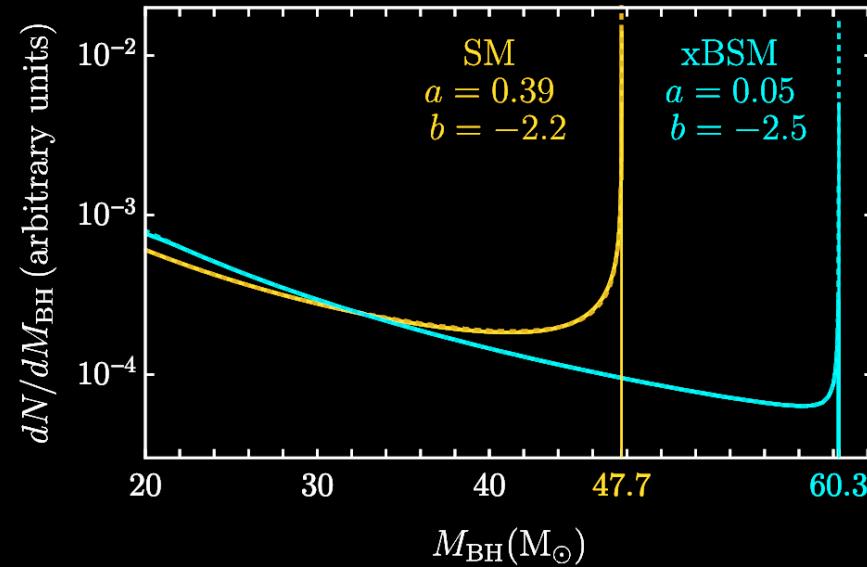
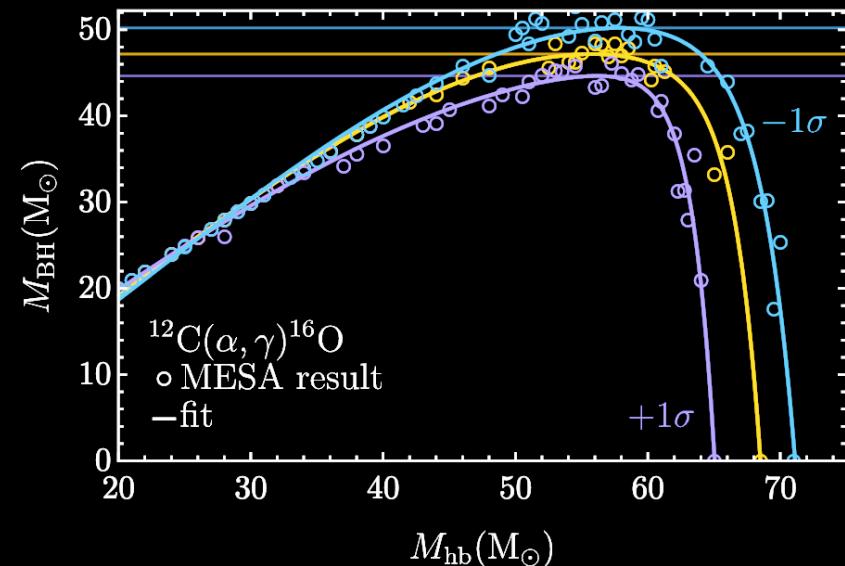
# Pair-instability and black hole populations

FIND THE GAP

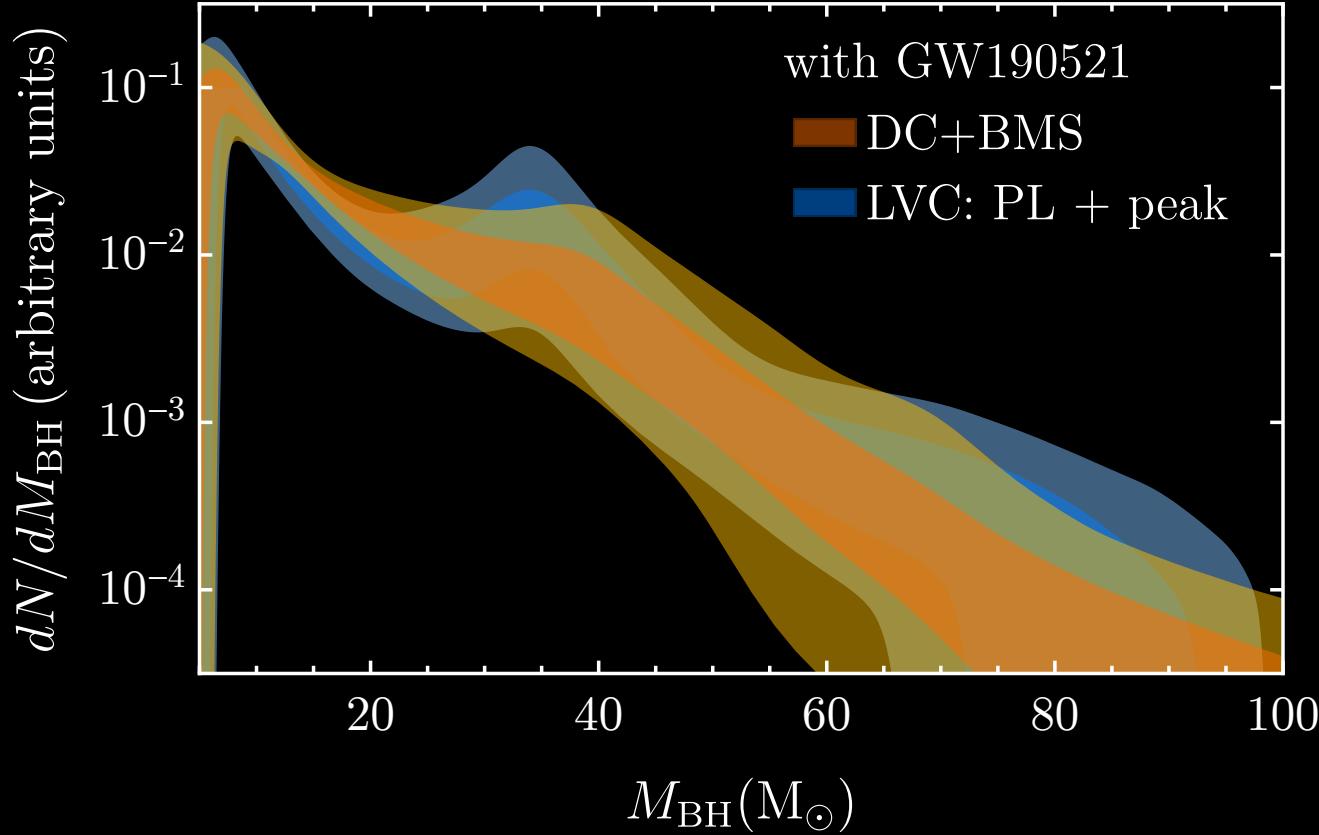
Testing BSM  
particle physics



Testing nuclear  
(astro) physics



# Binary mergers in LIGO/Virgo O3a

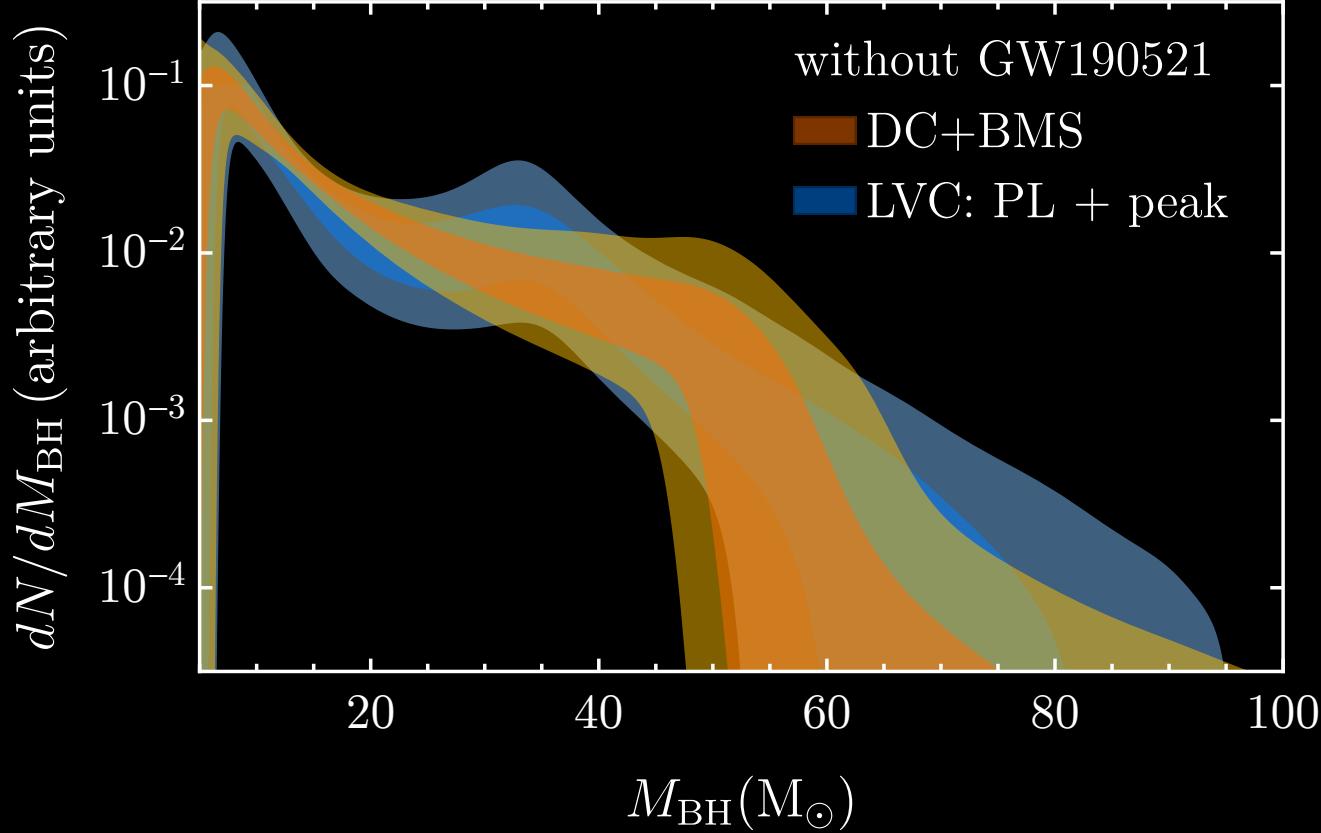


	This work, Eq. (7)	with GW190521
$\log_{10} \lambda$	$-0.88^{+0.41}_{-1.46}$	$46.23^{+16.83}_{-6.15}$
$M_{\text{BHMG}}$ [ $M_{\odot}$ ]	$0.23^{+0.17}_{-0.16}$	$-1.95^{+0.51}_{-0.54}$
$a$	$-5.95^{+1.75}_{-2.07}$	$3.38^{+1.50}_{-1.56}$
$b$	$5.12^{+2.97}_{-3.19}$	$5.12^{+2.97}_{-3.19}$
$d$		
$M_{\min}$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

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

# Binary mergers in LIGO/Virgo O3a



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

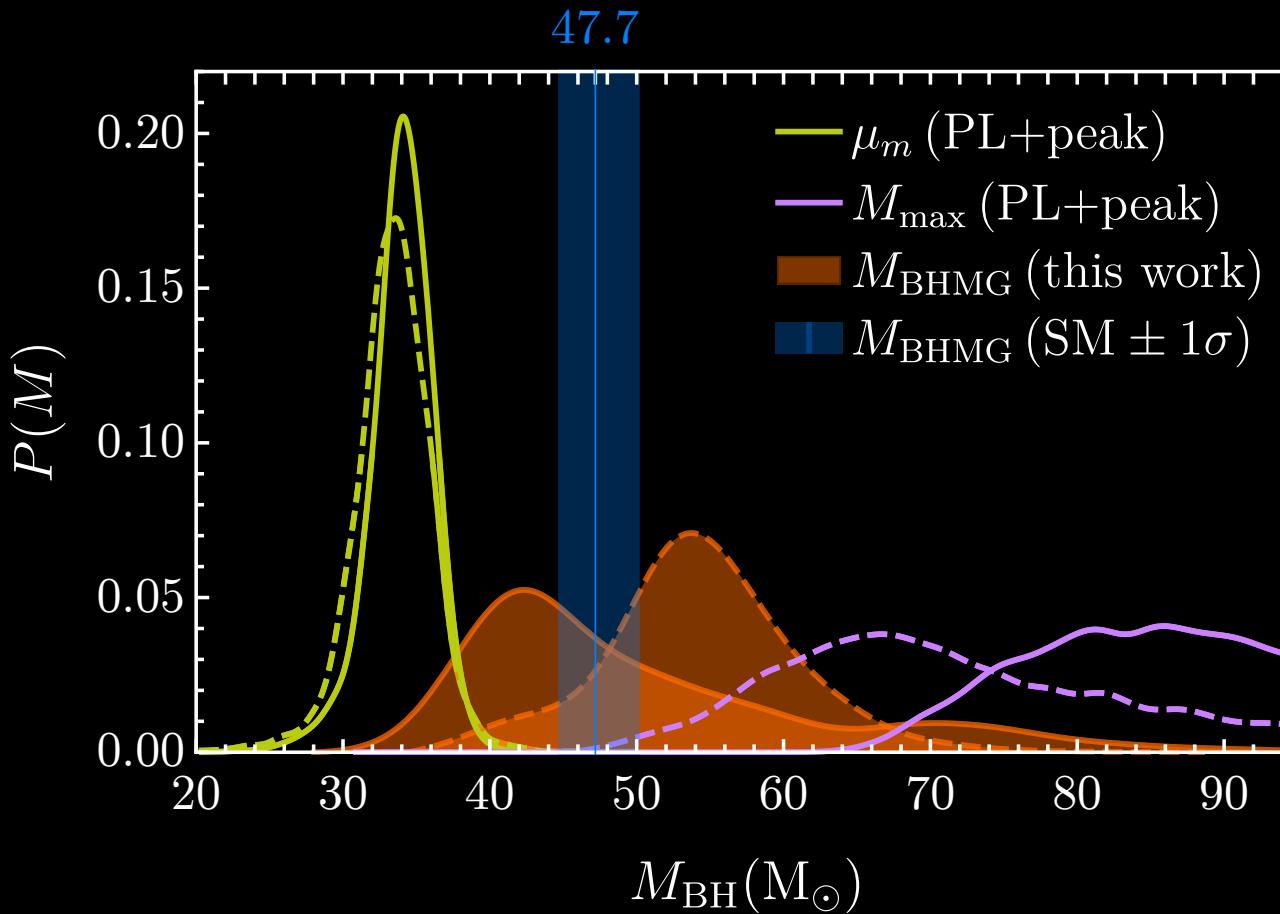
  

LVC: PL+peak		no GW190521
$\alpha$		$3.08^{+0.51}_{-1.2}$
$M_{\max}$ [ $M_{\odot}$ ]		$72^{+9}_{-10}$
$\lambda_{\text{peak}}$		$0.107^{+0.029}_{-0.092}$
$\mu_m$ [ $M_{\odot}$ ]		$33.4^{+2.5}_{-2.1}$
$\sigma_m$ [ $M_{\odot}$ ]		$> 4.49$
$M_{\min}$ [ $M_{\odot}$ ]		$4.56^{+1.3}_{-0.77}$
$\delta_m$ [ $M_{\odot}$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

# GW190521 and the mass gap

The New York Times

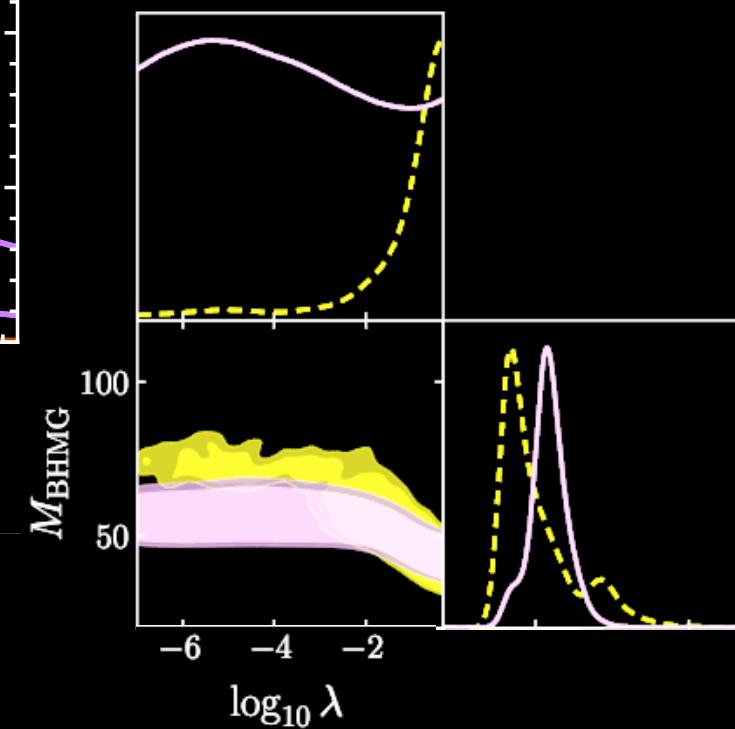
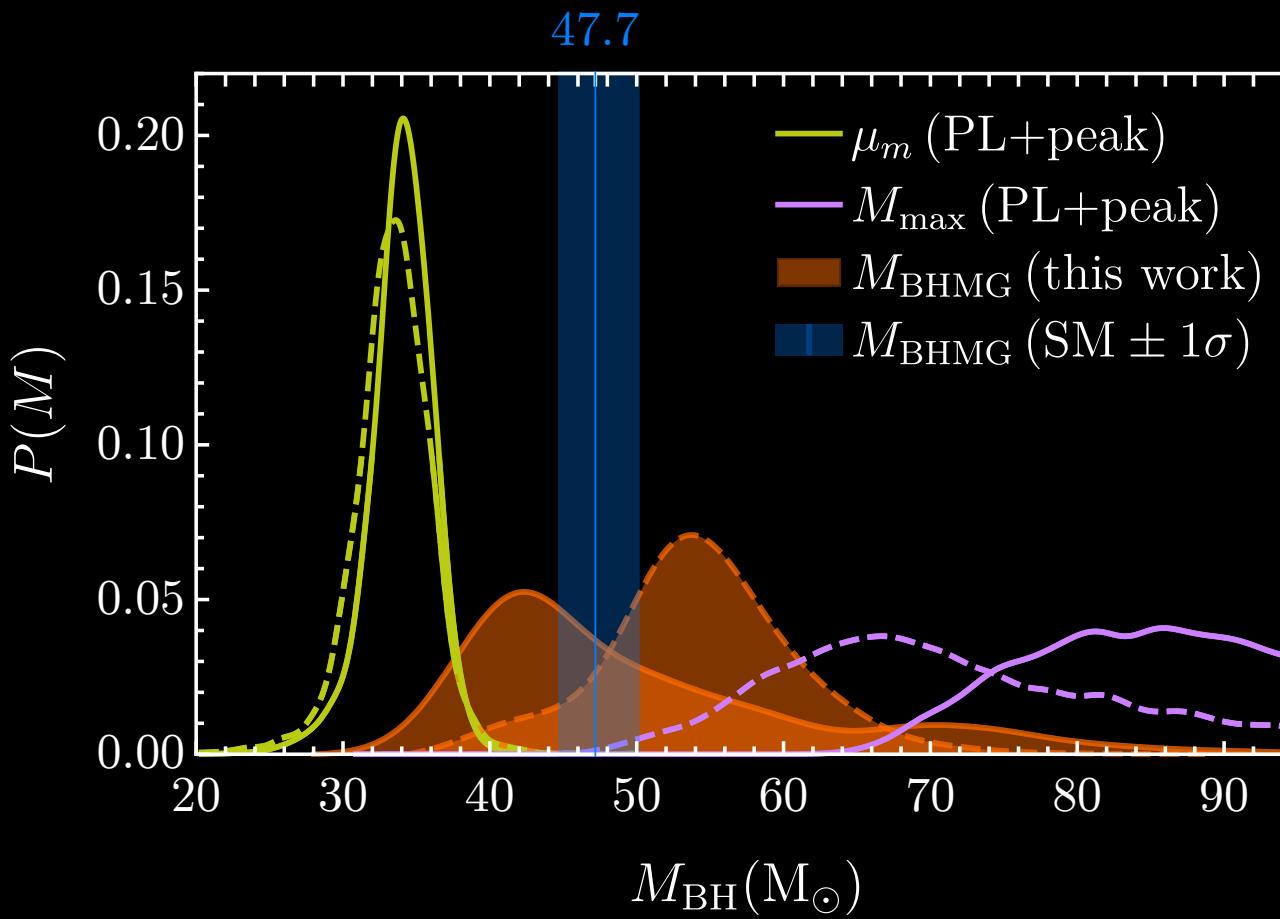
These Black Holes Shouldn't Exist,  
but There They Are



# GW190521 and the mass gap

The New York Times

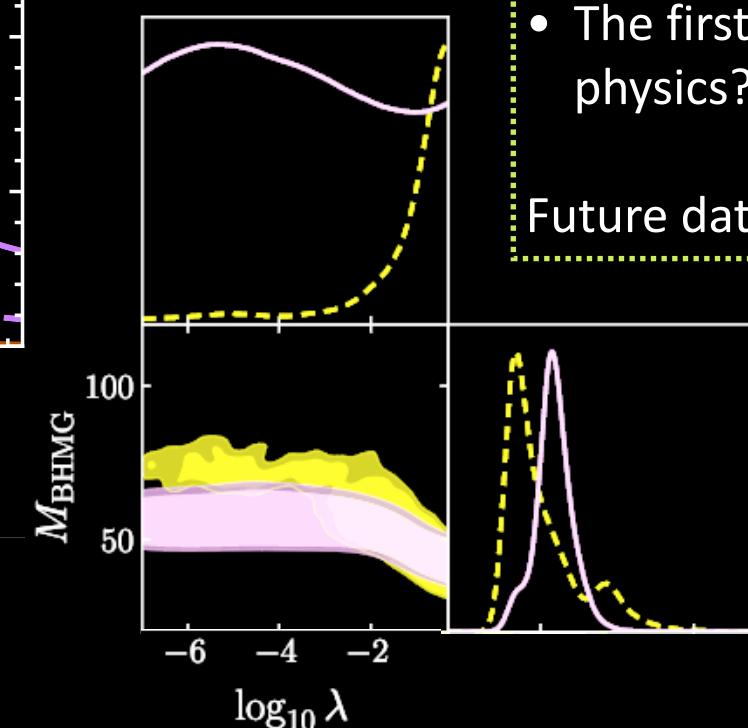
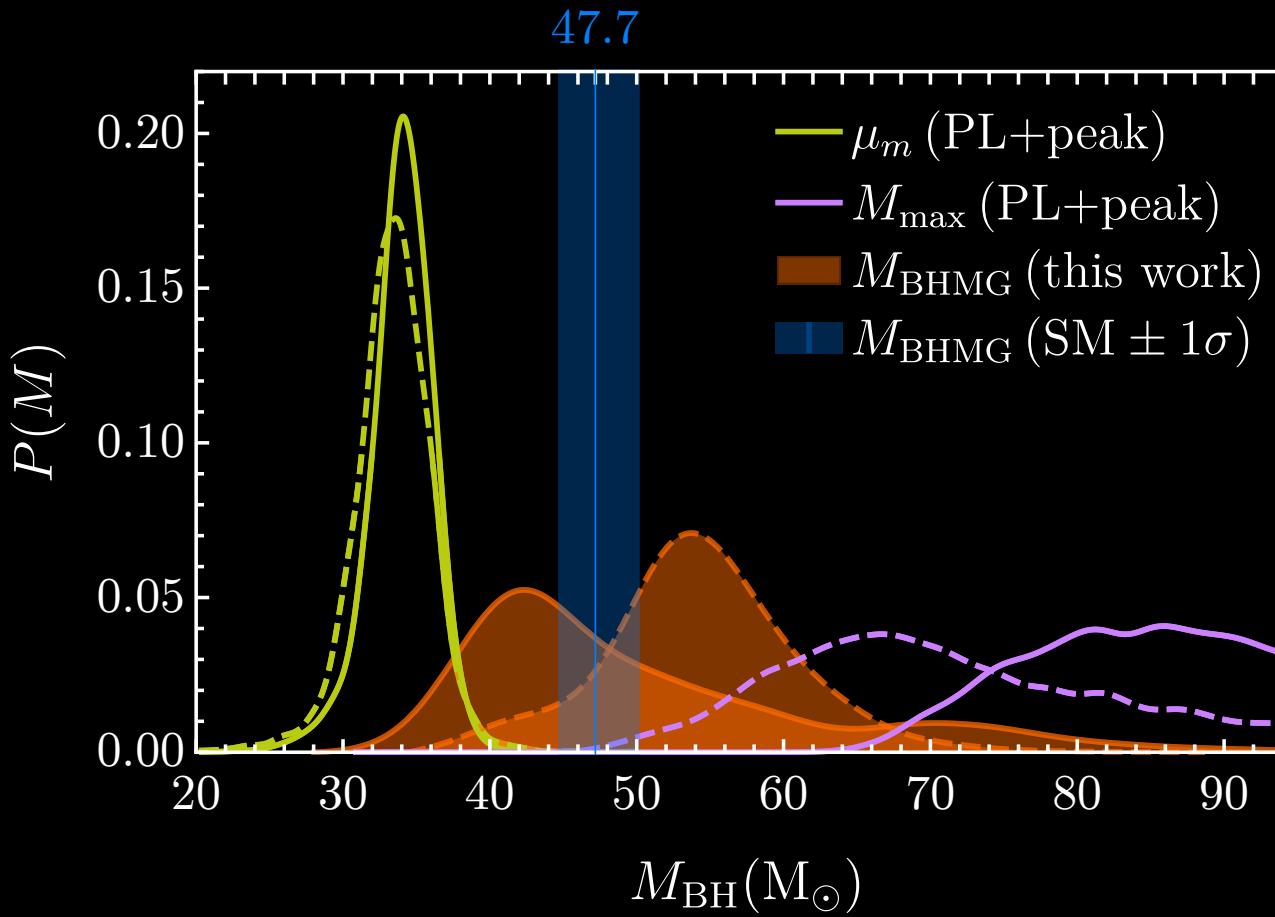
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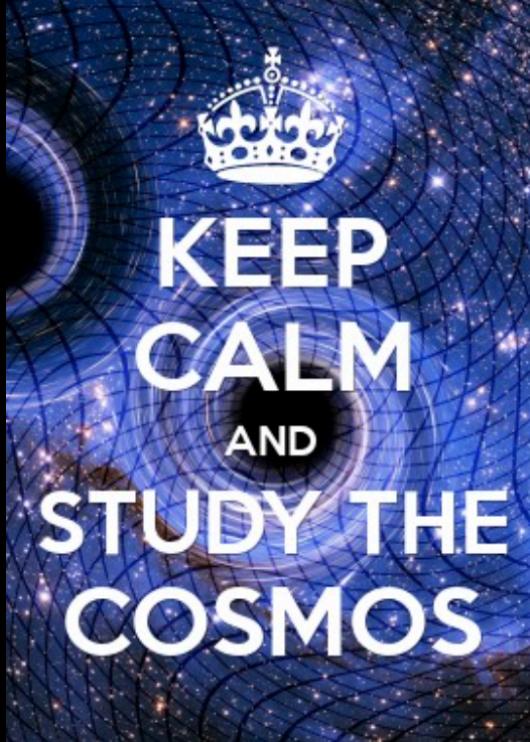
Is GW190521

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

Future datasets will tell!

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**
- In preparation: inclusion of other information (spin, redshift, ...) + code release



# Thank you!

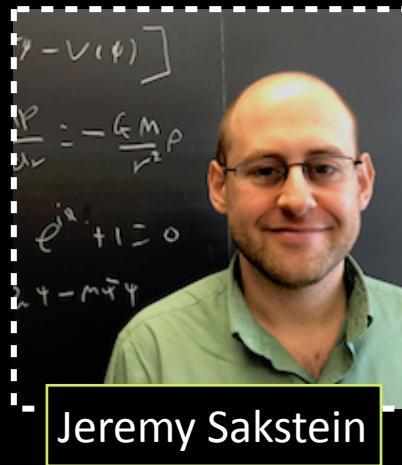
...ask me anything you like!

~~dcroon@triumf.ca~~ | djuna.l.croon@durham.ac.uk  
[djunacroon.com](http://djunacroon.com)

# Back-up slides



Sam McDermott



Jeremy Sakstein



Eric Baxter



Maria Straight

# 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*

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

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

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

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

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

Mass function

Hydrostatic equilibrium

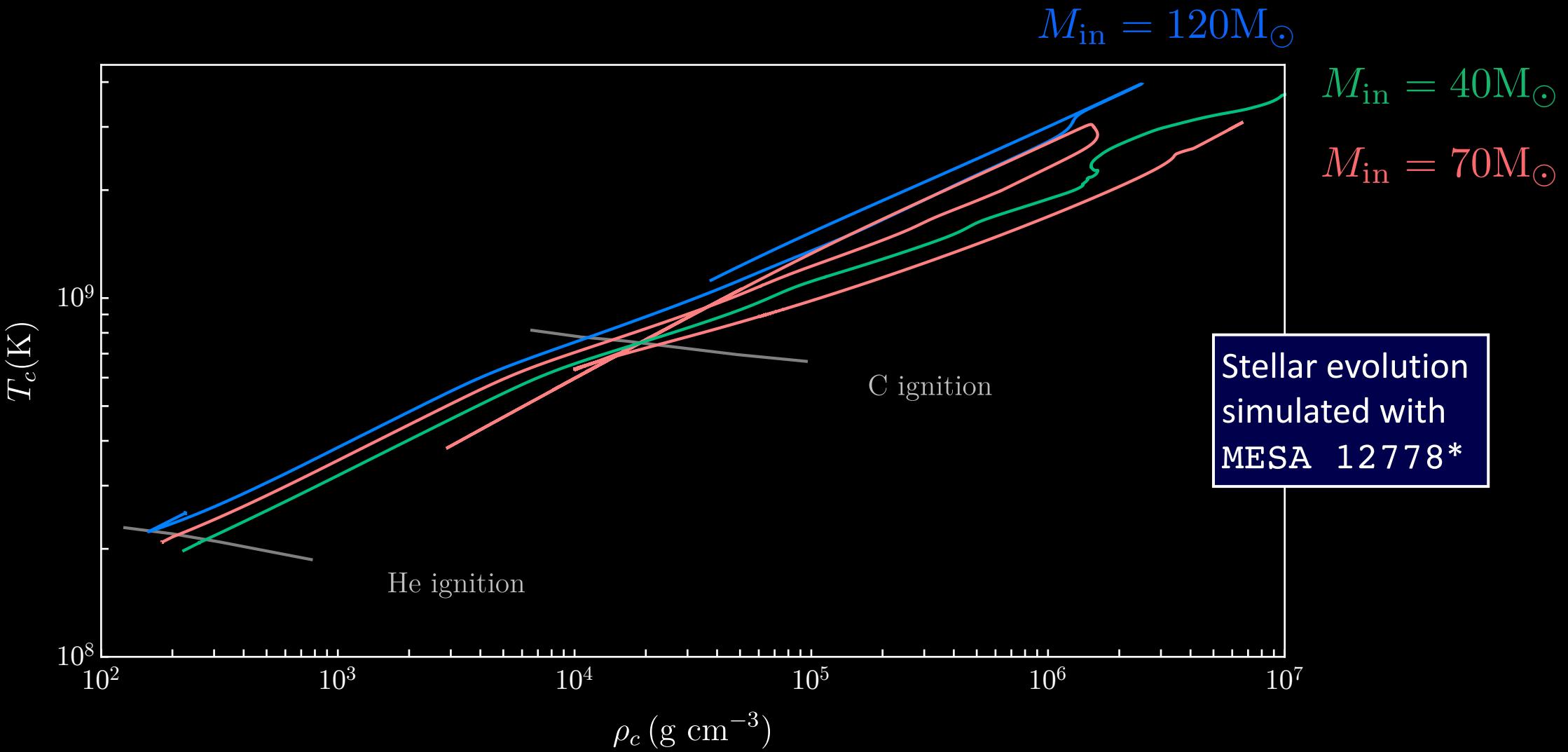
Energy flux

Convection

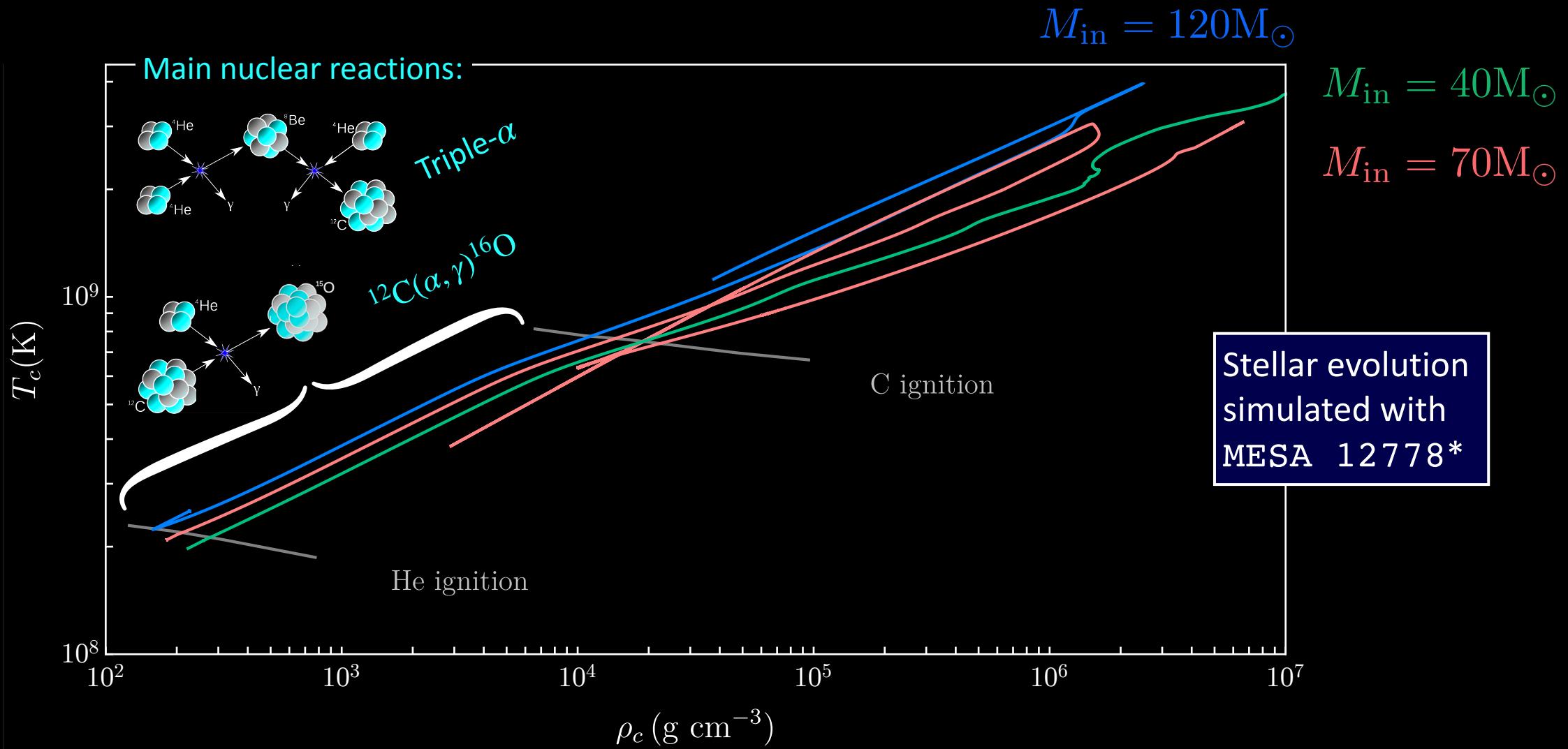
Reactions

+ BSM physics contributions?

# Late evolution of heavy stars

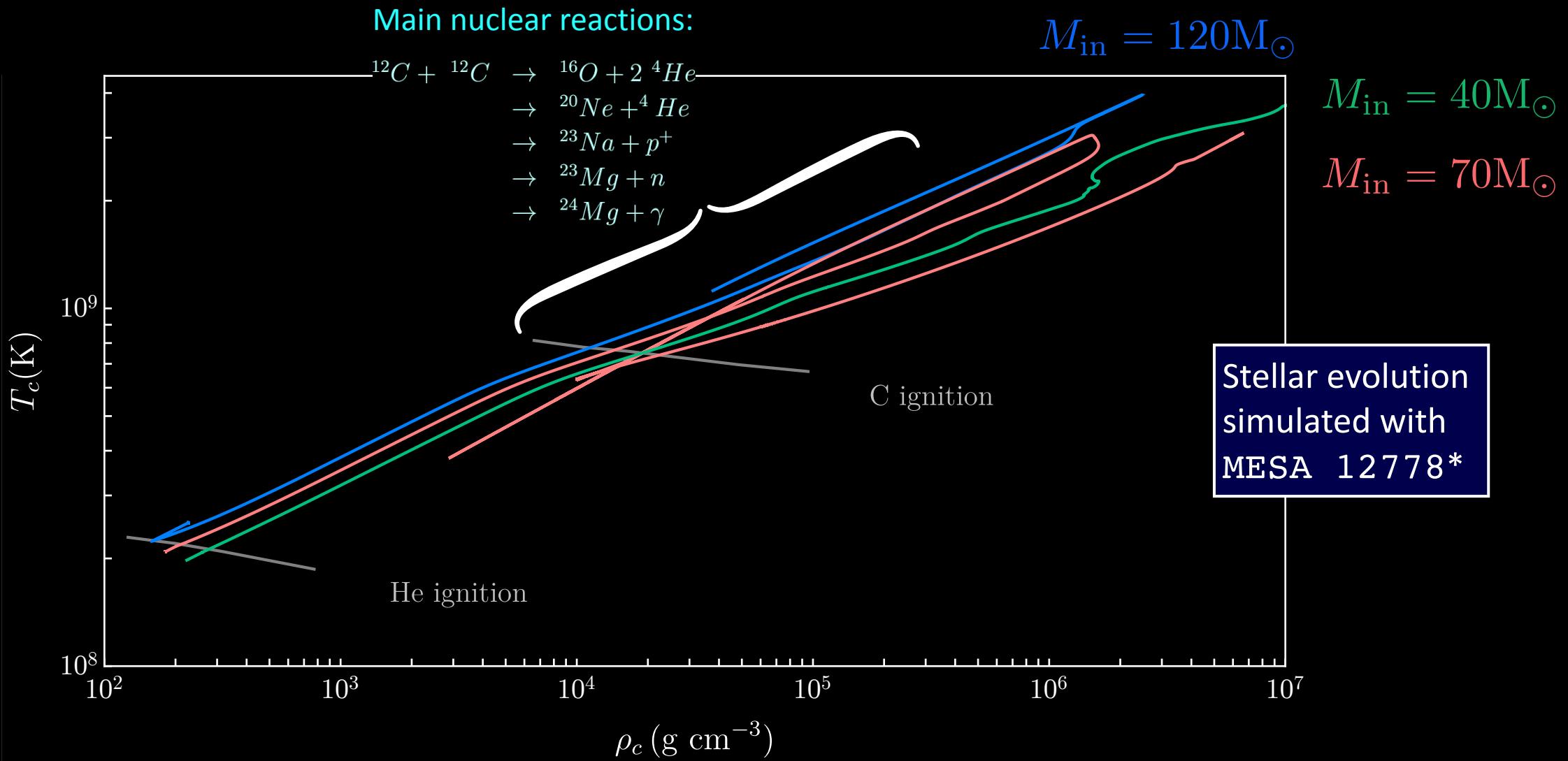


# Late evolution of heavy stars

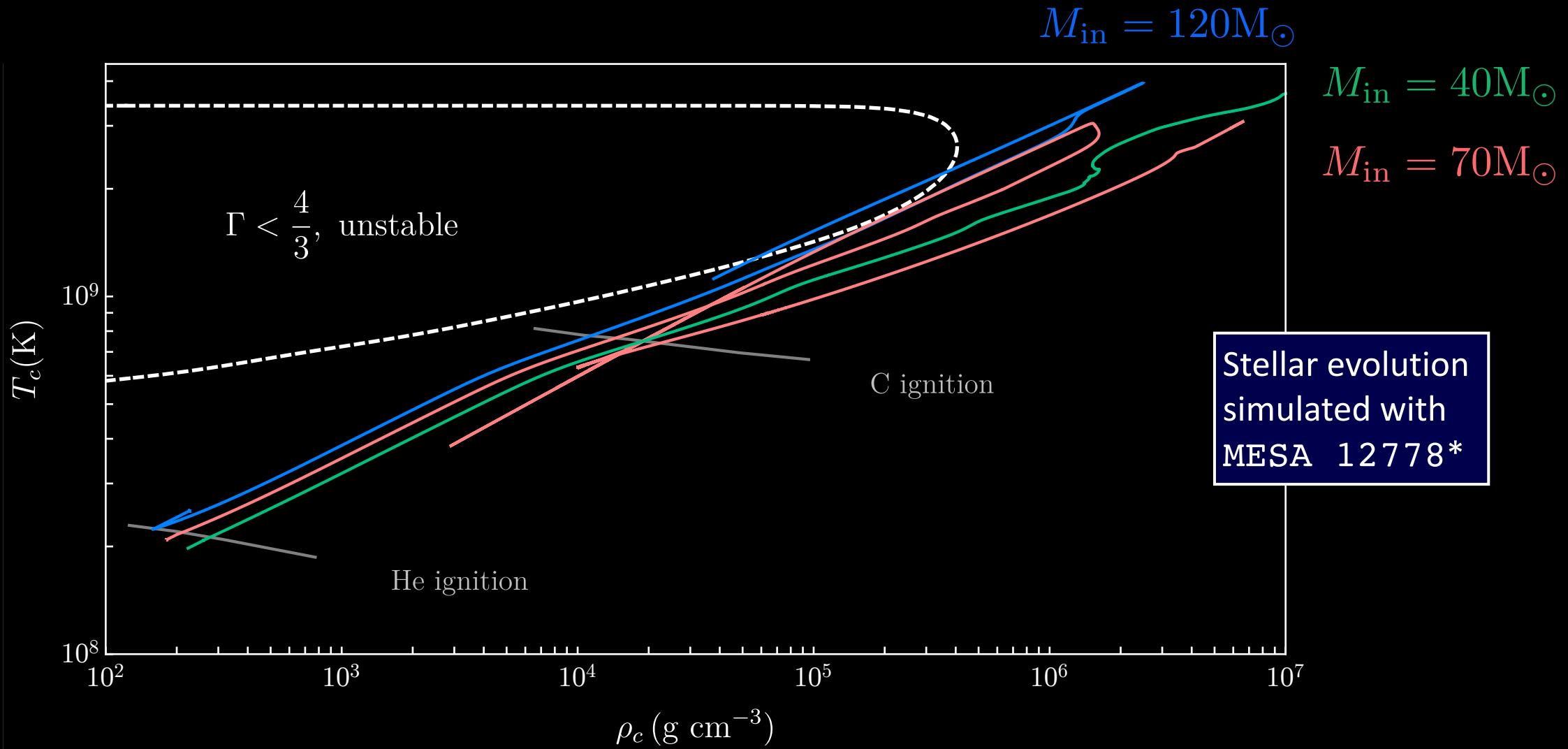


\*Paxton et al, arXiv:1710.08424 [astro-ph.SR]

# Late evolution of heavy stars

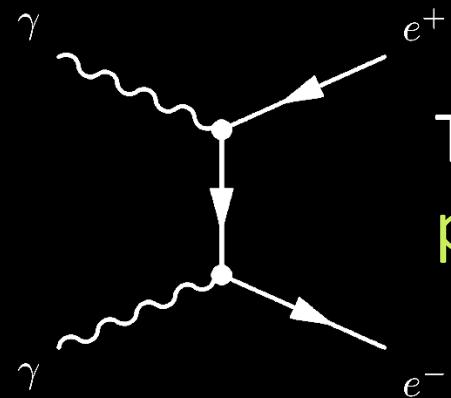


# Late evolution of heavy stars



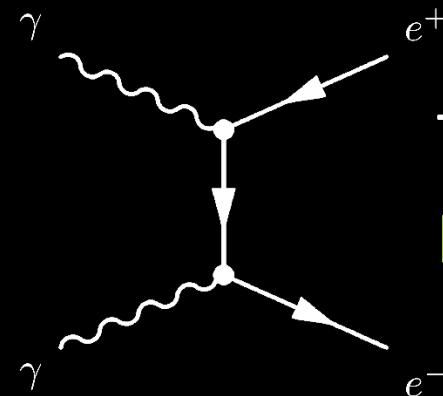
\*Paxton et al, arXiv:1710.08424 [astro-ph.SR]

# The danger zone: pair-instability



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

# The danger zone: pair-instability

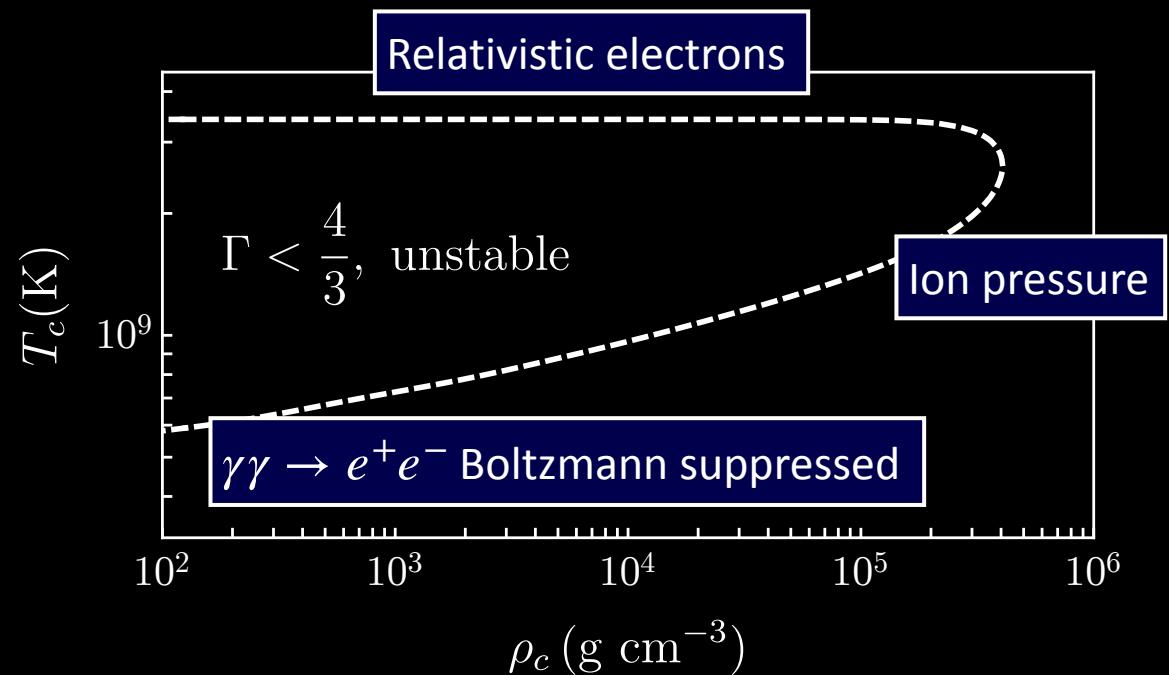


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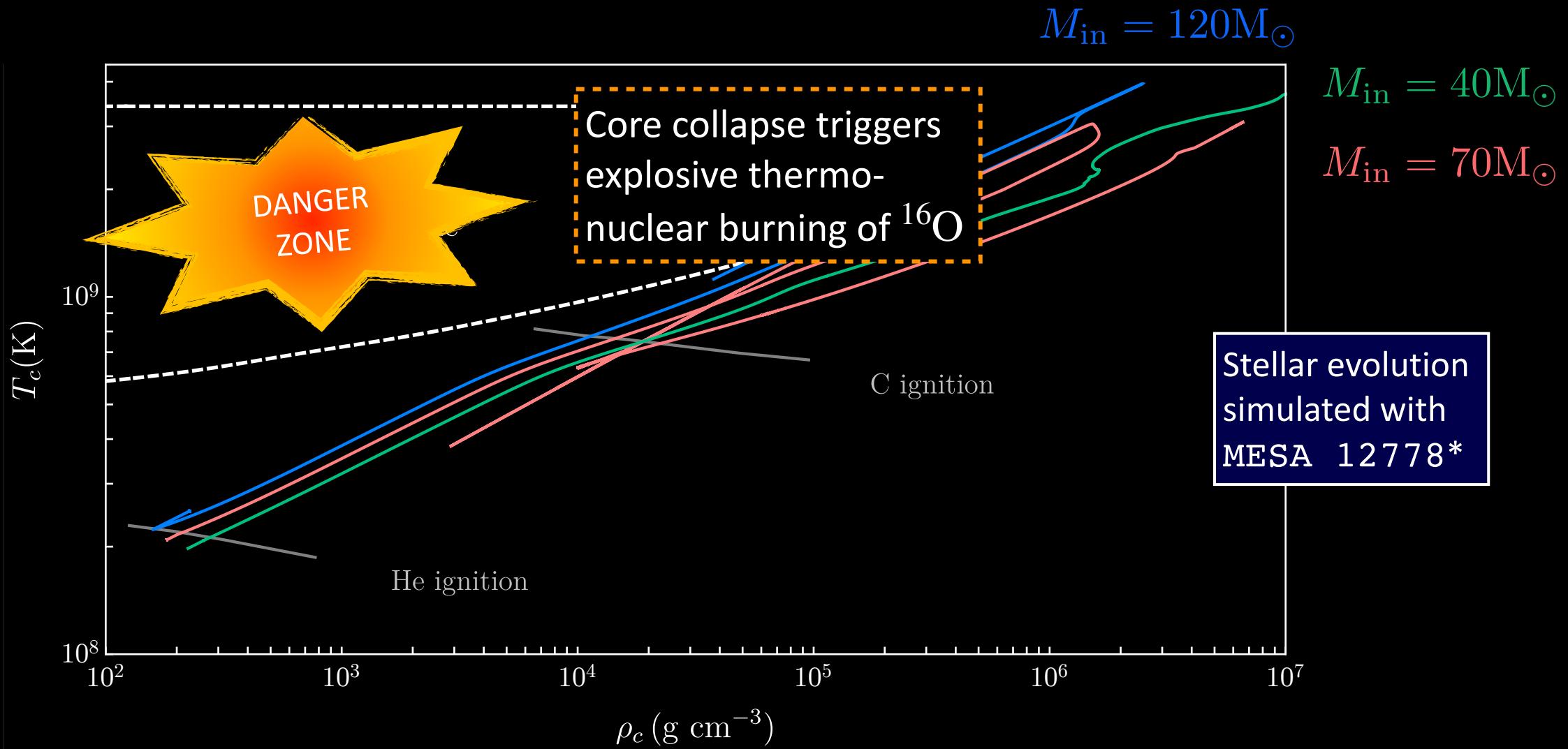
Unstable, because:

The **photons** give the star outward pressure

The **electron-positron** pairs imply extra gravity but no pressure  
 $\rightarrow$  *the core starts to collapse*



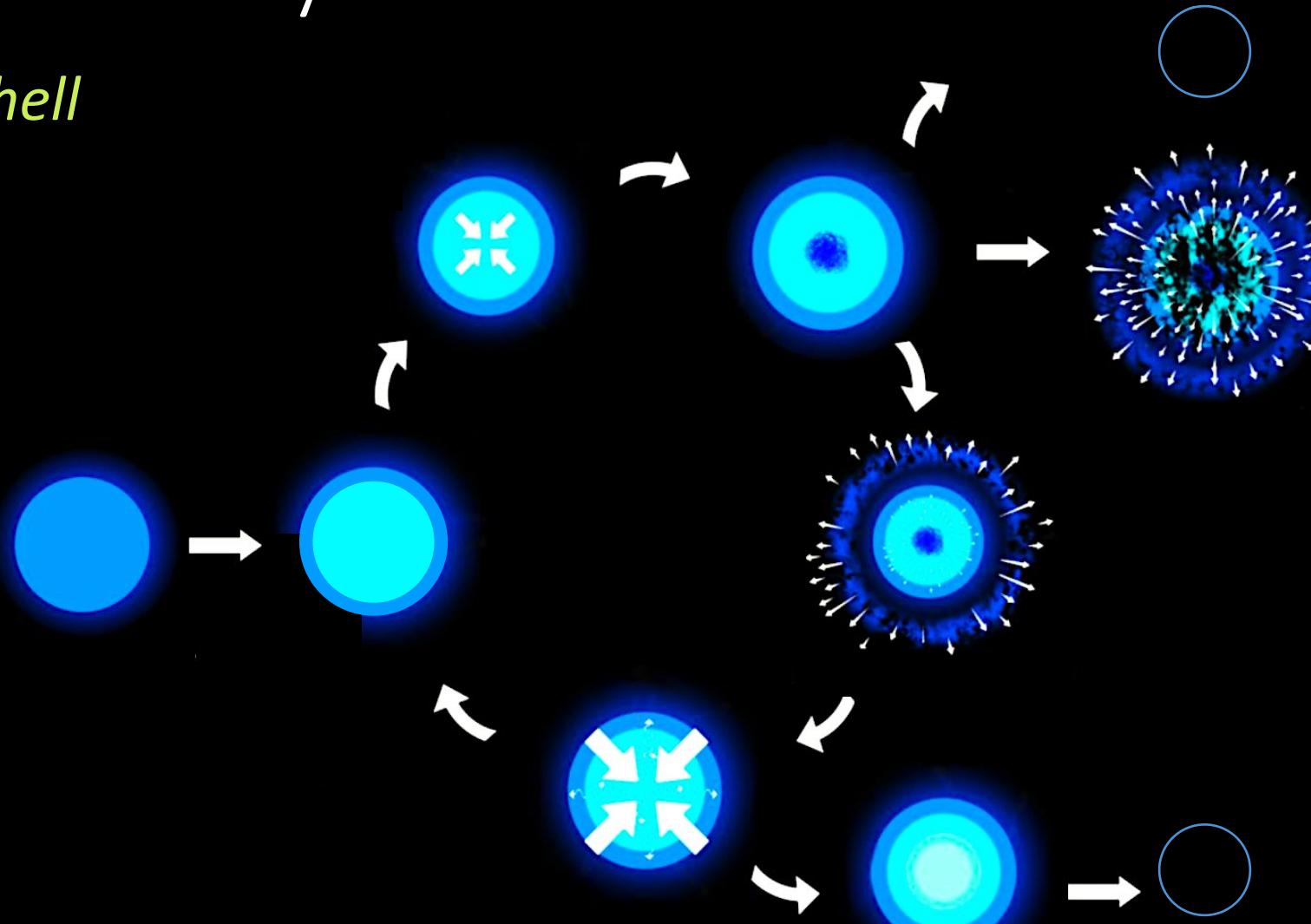
# Evolution of old population-III stars



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

# Pair instability

*in a nutshell*

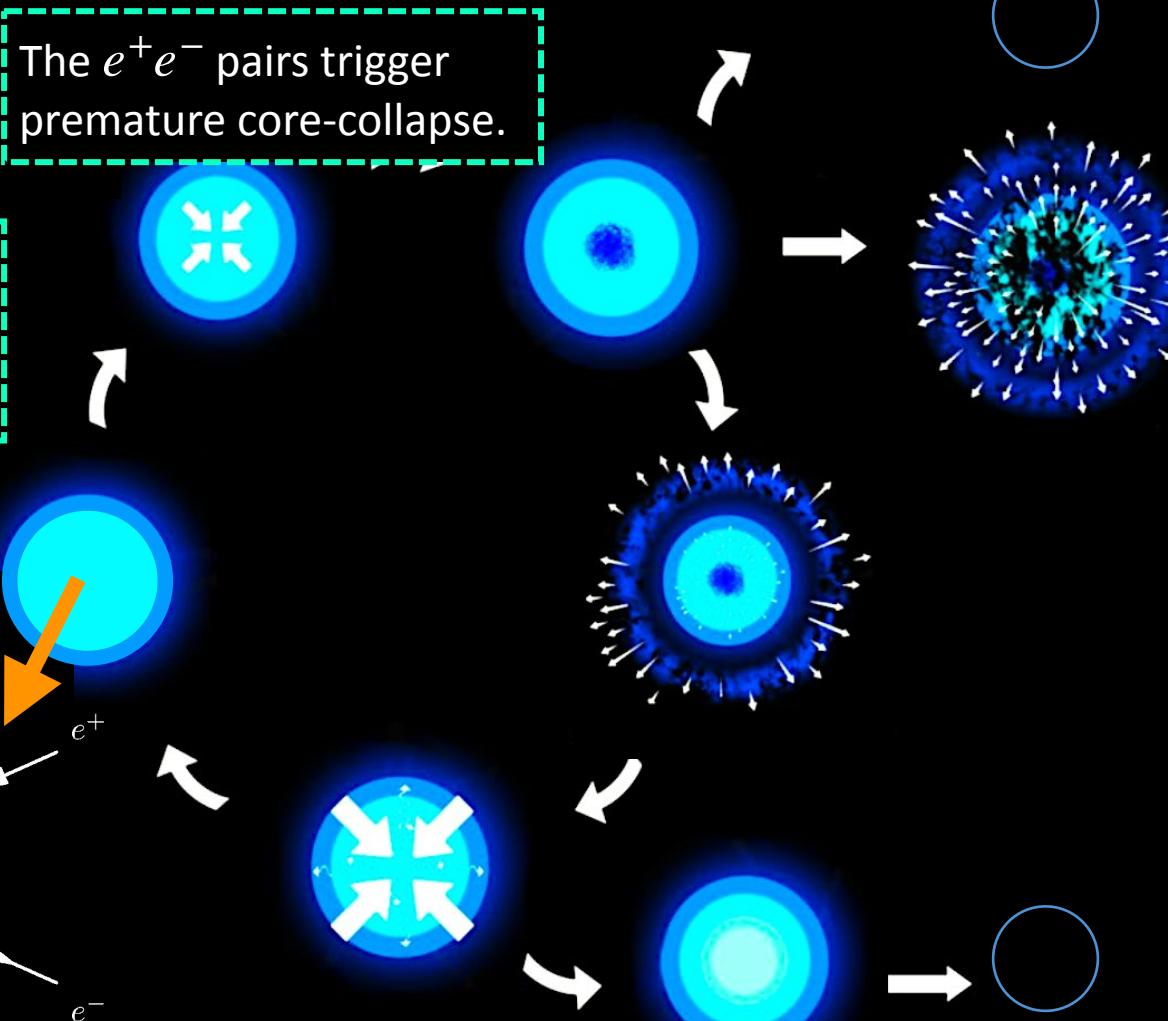


Adapted from Renzo et al [2002.05077]

# Pair instability

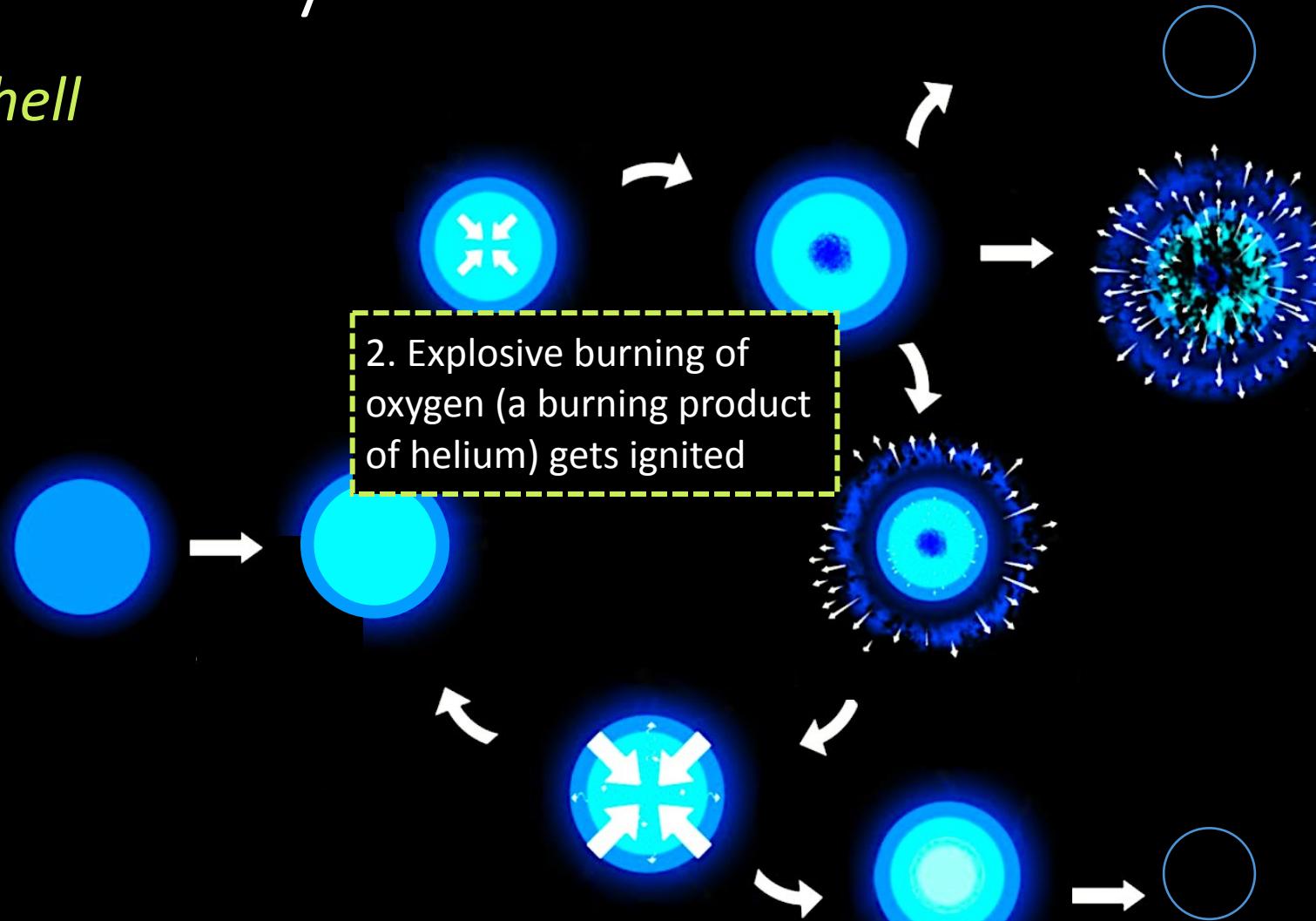
*in a nutshell*

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



# Pair instability

*in a nutshell*

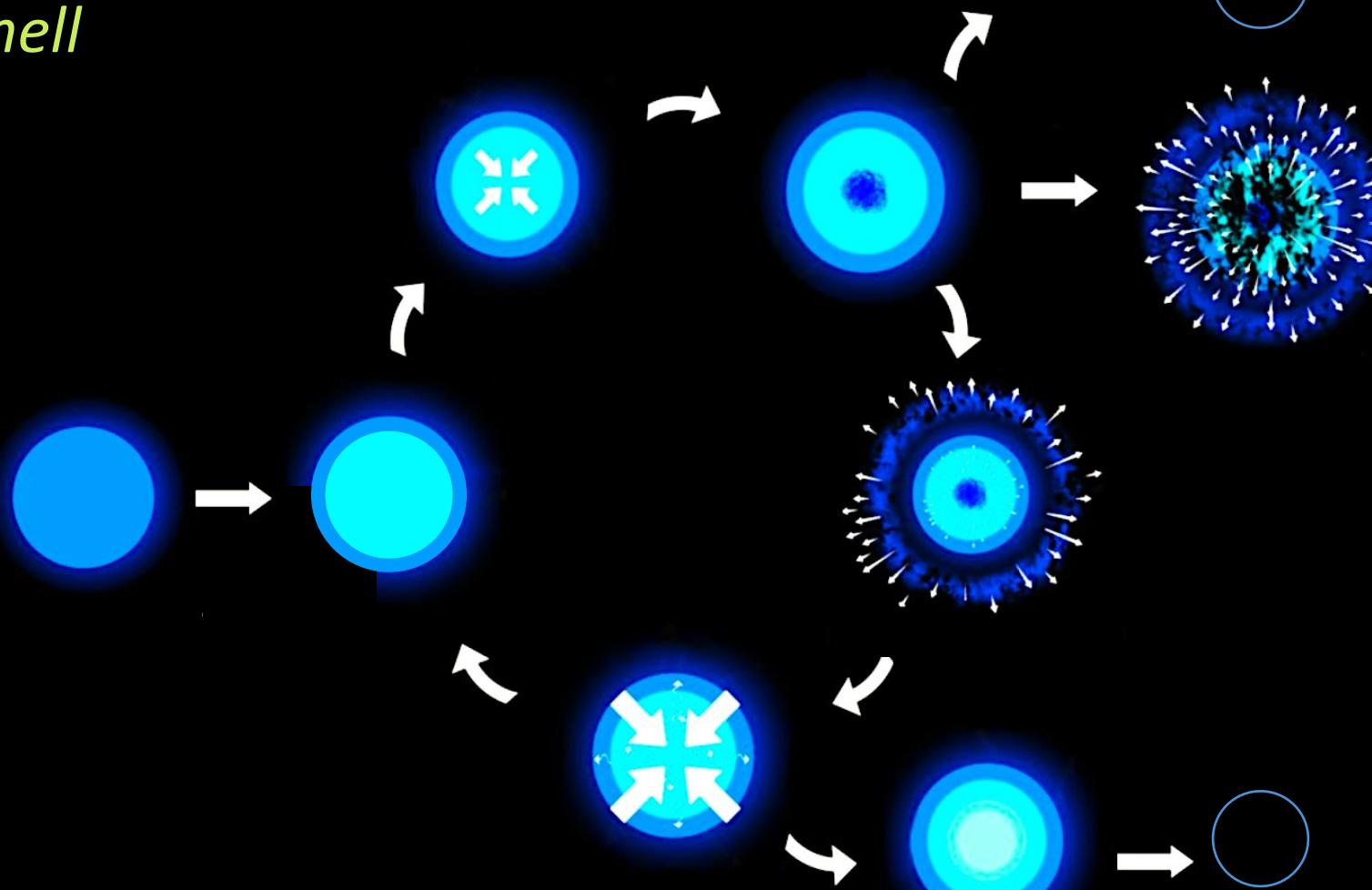


# Pair instability

*in a nutshell*

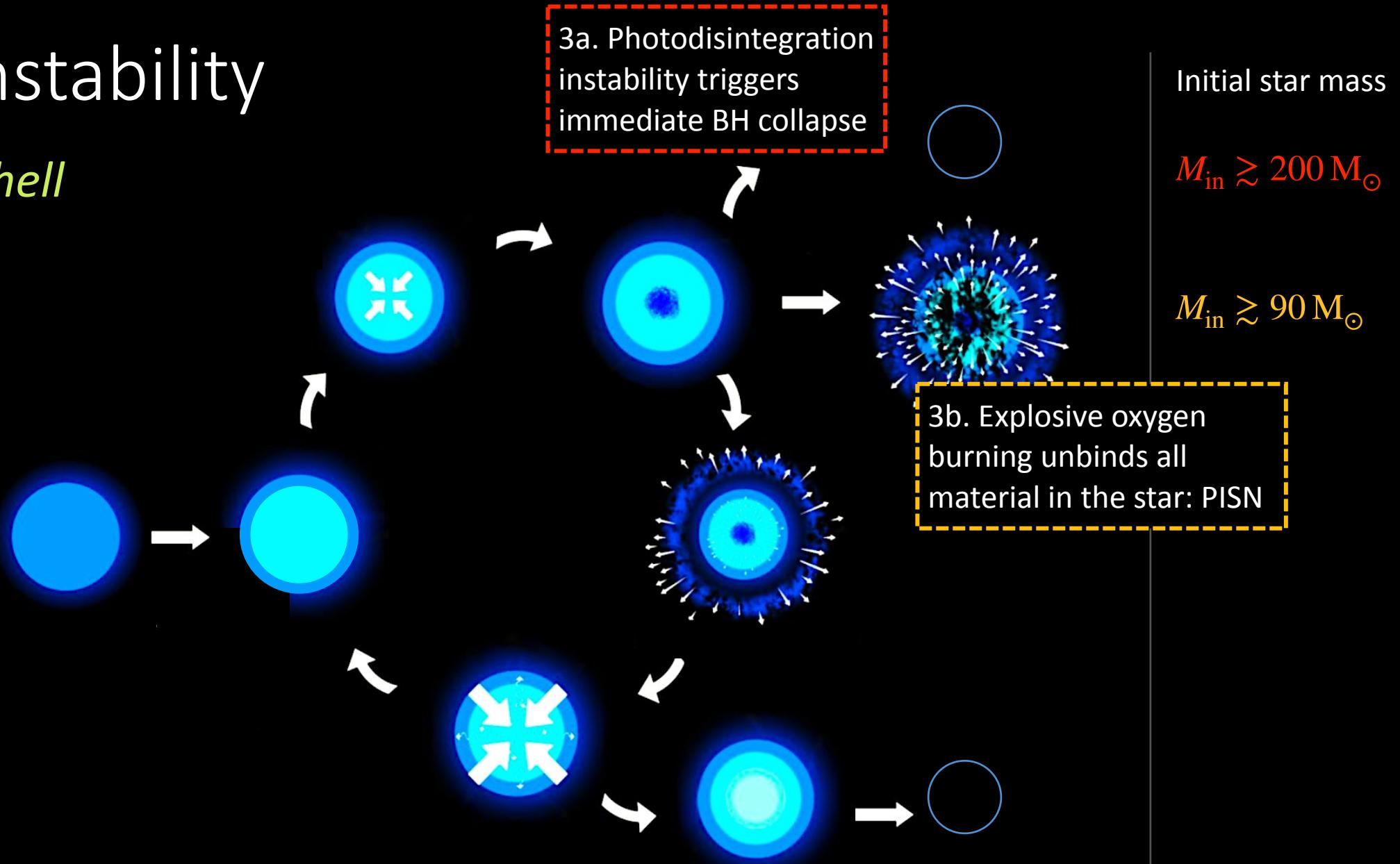
3a. Photodisintegration  
instability triggers  
immediate BH collapse

Initial star mass  
 $M_{\text{in}} \gtrsim 200 M_{\odot}$



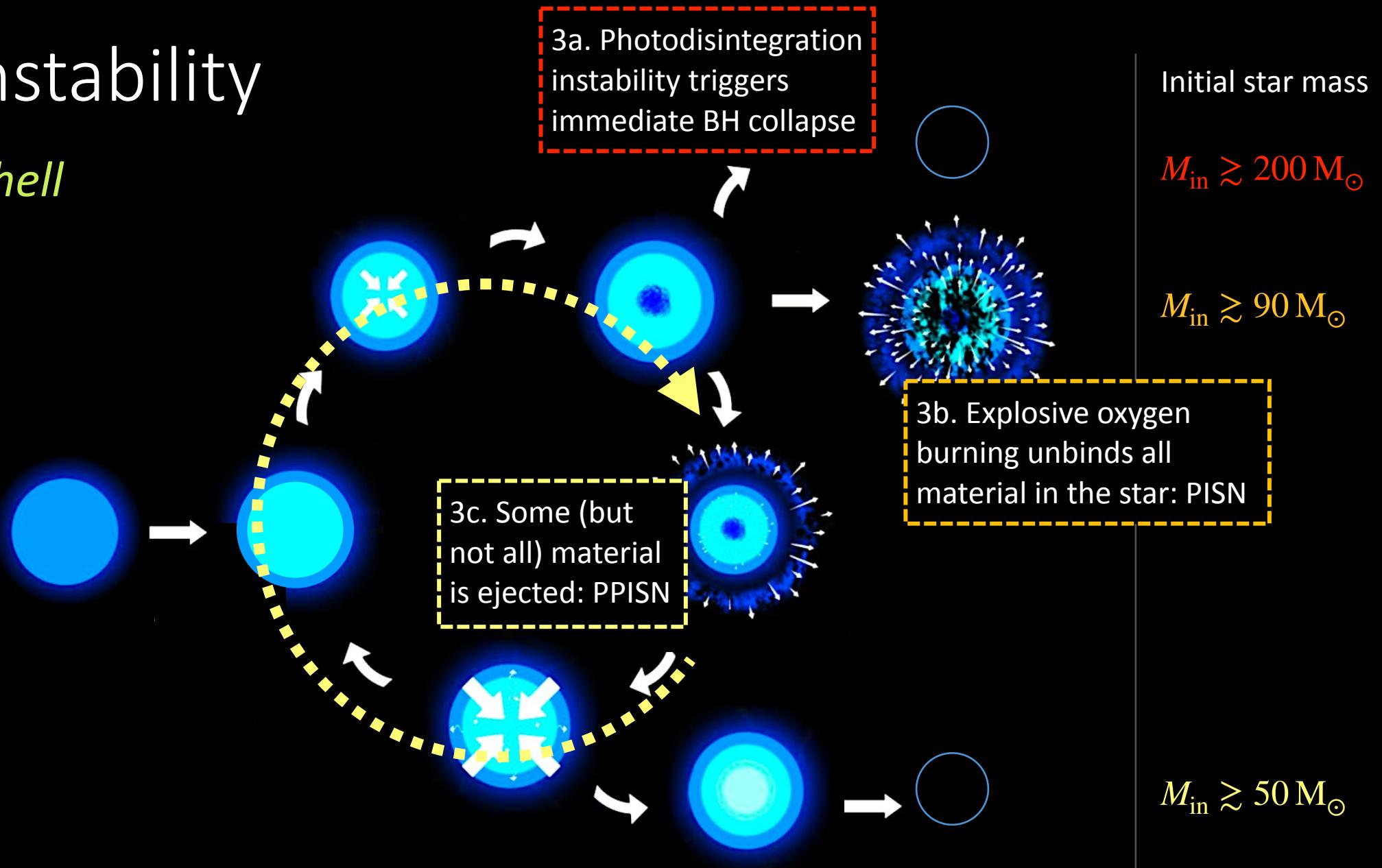
# Pair instability

*in a nutshell*



# Pair instability

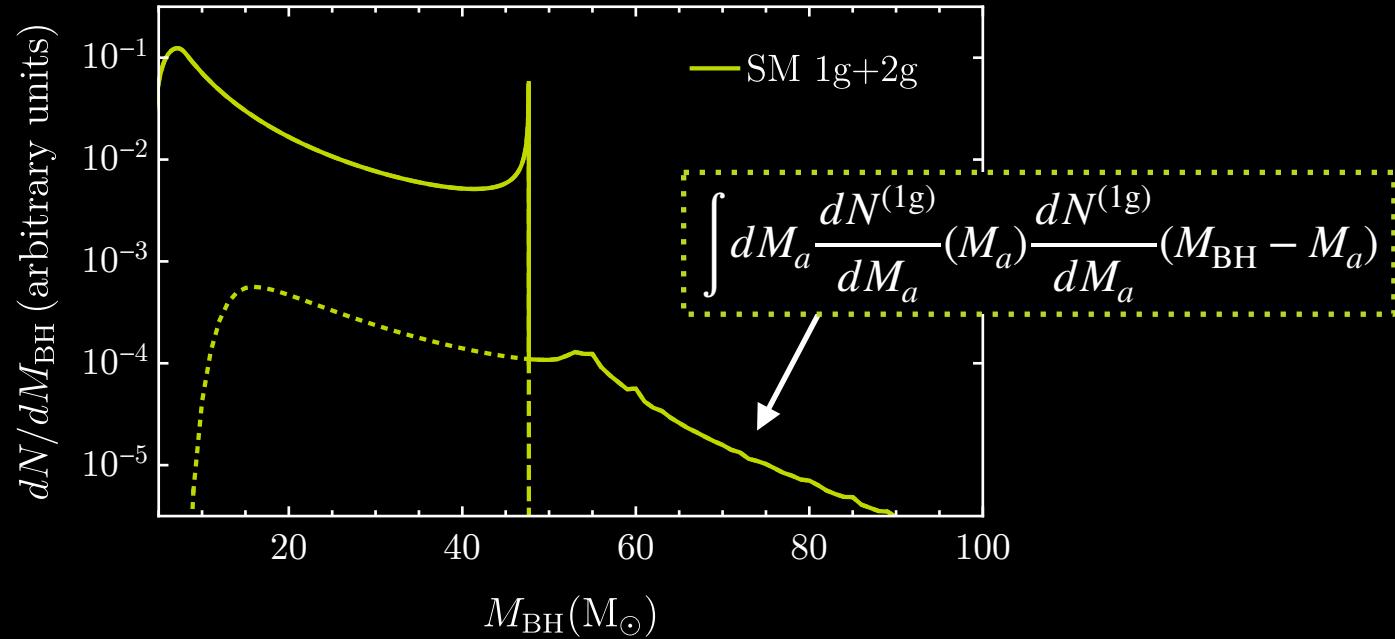
*in a nutshell*



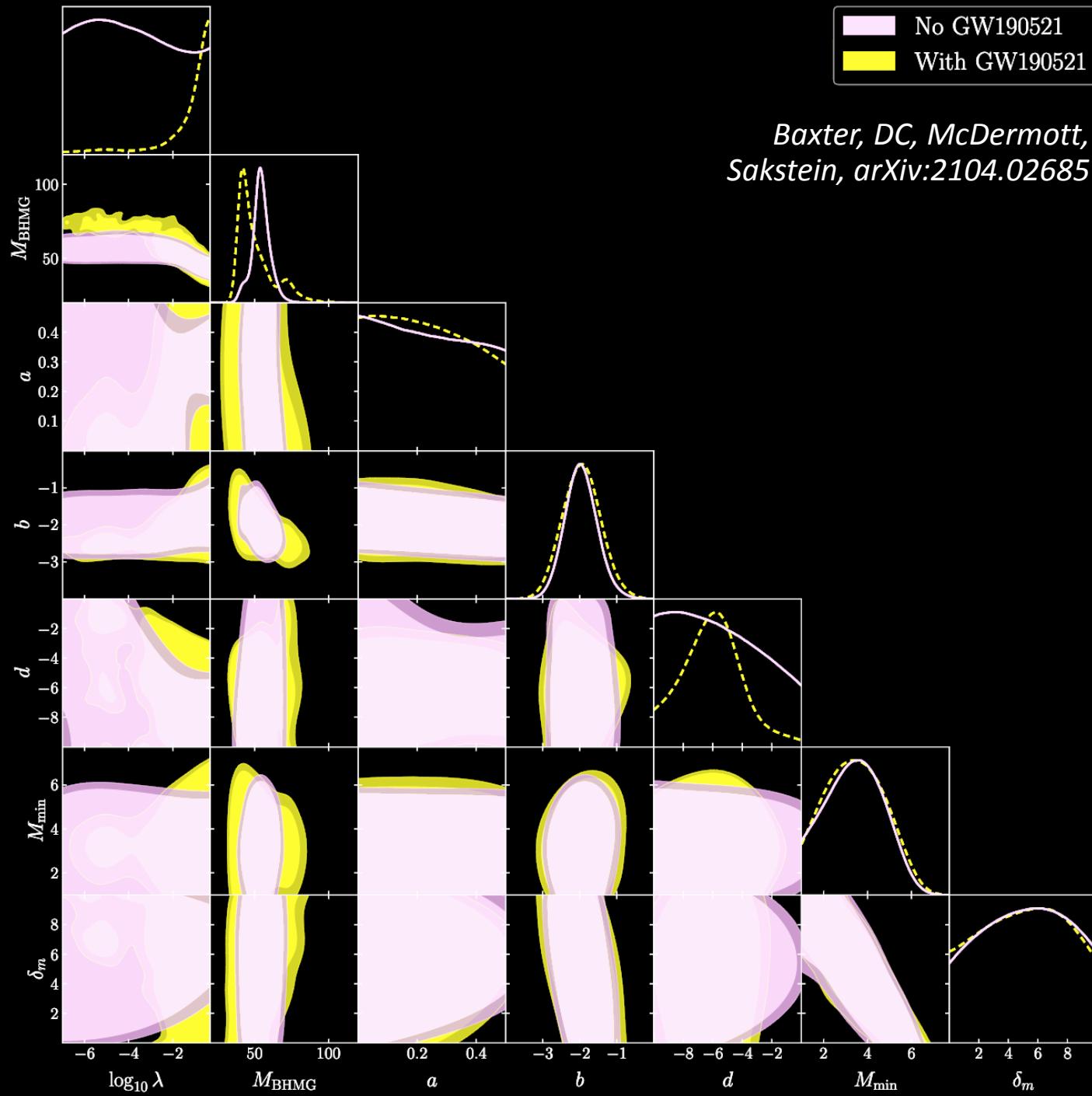
# Dynamical mergers and black hole genealogy

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

Their mass distribution inherits from the 1g mass distribution.

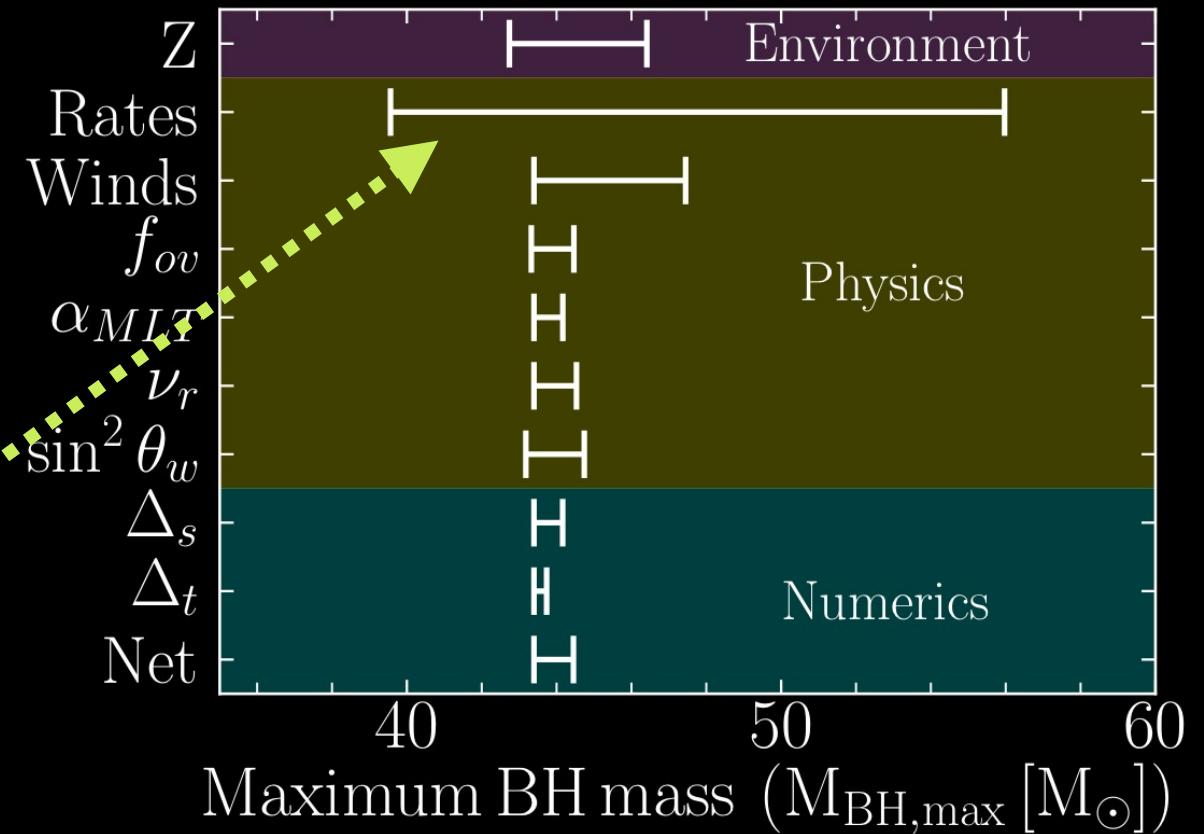


$$\frac{dN}{dM_{\text{BH}}} = \frac{dN_{\text{BH}}^{(1g)}}{dM_{\text{BH}}} + \frac{dN_{\text{BH}}^{(2+g)}}{dM_{\text{BH}}} \left\{ \begin{array}{l} \frac{dN_{\text{BH}}^{(1g)}}{dM_{\text{BH}}} \propto M_{\text{BH}}^b \left[ 1 + \frac{2a^2 M_{\text{BH}}^{1/2} (M_{\text{BHMG}} - M_{\text{BH}})^{a-1}}{M_{\text{BHMG}}^{a-1/2}}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



# Physics dependence of the BHMG

- Astrophysical + nuclear + numerical dependence
- Most important dependence:  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  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]

# Gravitational waves may shed light on dark matter

