Title: Black hole archaeology with gravitational waves

Speakers: Djuna Croon

Series: Cosmology & Gravitation

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Abstract: The growing gravitational wave dataset makes black hole population studies possible. In this talk I will demonstrate how such studies can be used to study particle and nuclear physics. The key insight is that a wide range of initial stellar masses leave no compact remnant, due to the physics of pair-instability; the unpopulated space in the stellar graveyard is known as the black hole mass gap (BHMG). New physics can dramatically alter the late stages of stellar evolution and shift the BHMG, when it acts as an additional source of energy (loss) or modifies the equation of state. I will demonstrate how these predictions can be tested with the gravitational wave observations by the LIGO/Virgo collaboration, and show what we can already infer from GWTC-2.

Black hole archaeology using gravitational waves

Djuna Lize Croon (TRIUMF → IPPP Durham)
Perimeter Institute, April 2021
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Particle physics with gravitational waves

A new era for particle physics phenomenology

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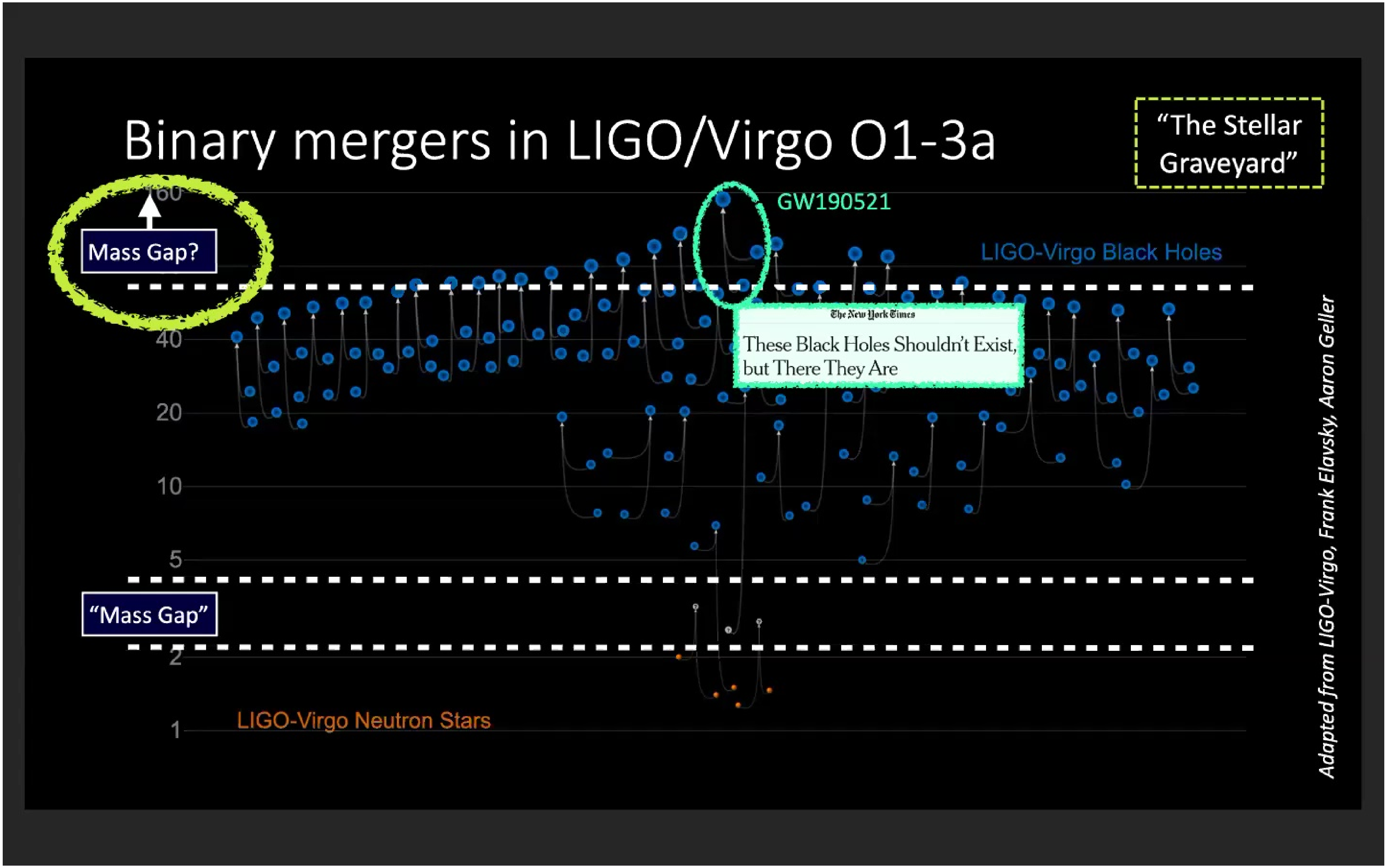
We may learn a lot about particle physics from gravitational waves

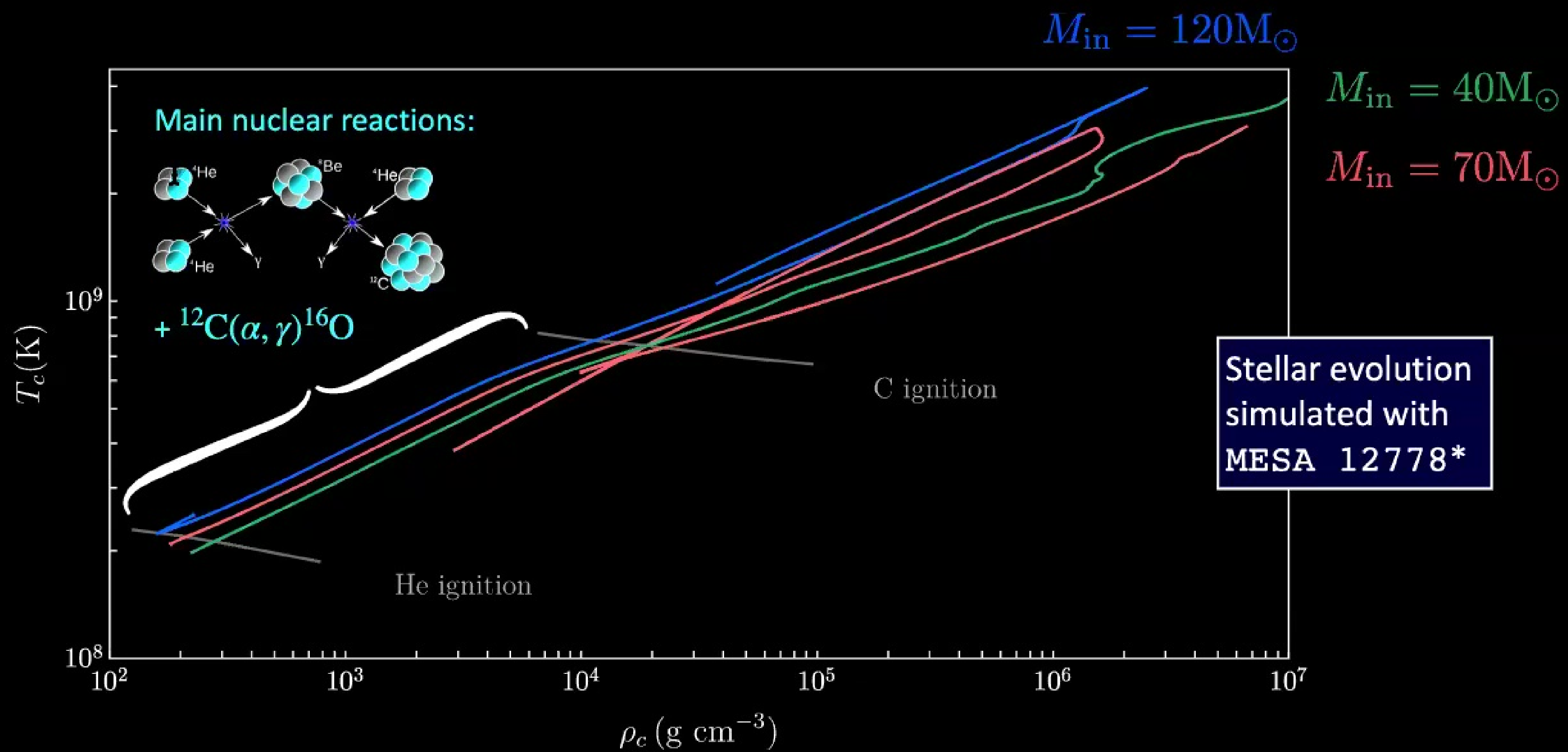

Binary mergers in LIGO/Virgo O1-3a
"The Stellar Graveyard"
GW190521
LIGO-Virgo Black Holes
Mass Gap?
The New York Times
These Black Holes Shouldn't Exist, but There They Are
"Mass Gap"
LIGO-Virgo Neutron Stars
60
40
20
10
5
2
1
Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

What populates the stellar graveyard?

- In the LIGO/Virgo mass range: predominantly remnants of heavy, low-metallicity stars
  - Primarily made of hydrogen (H) and helium (He)
  - Could be pop-III stars ($z \gtrsim 6, M \sim 20 - 130\,\mathrm{M}_\odot$); have not been directly observed yet (JWST target)

- Eventually collapsed into black holes in core-collapse supernova explosions *(or did they?)*
- We study their evolution from the Zero-Age Helium Branch (ZAHB)

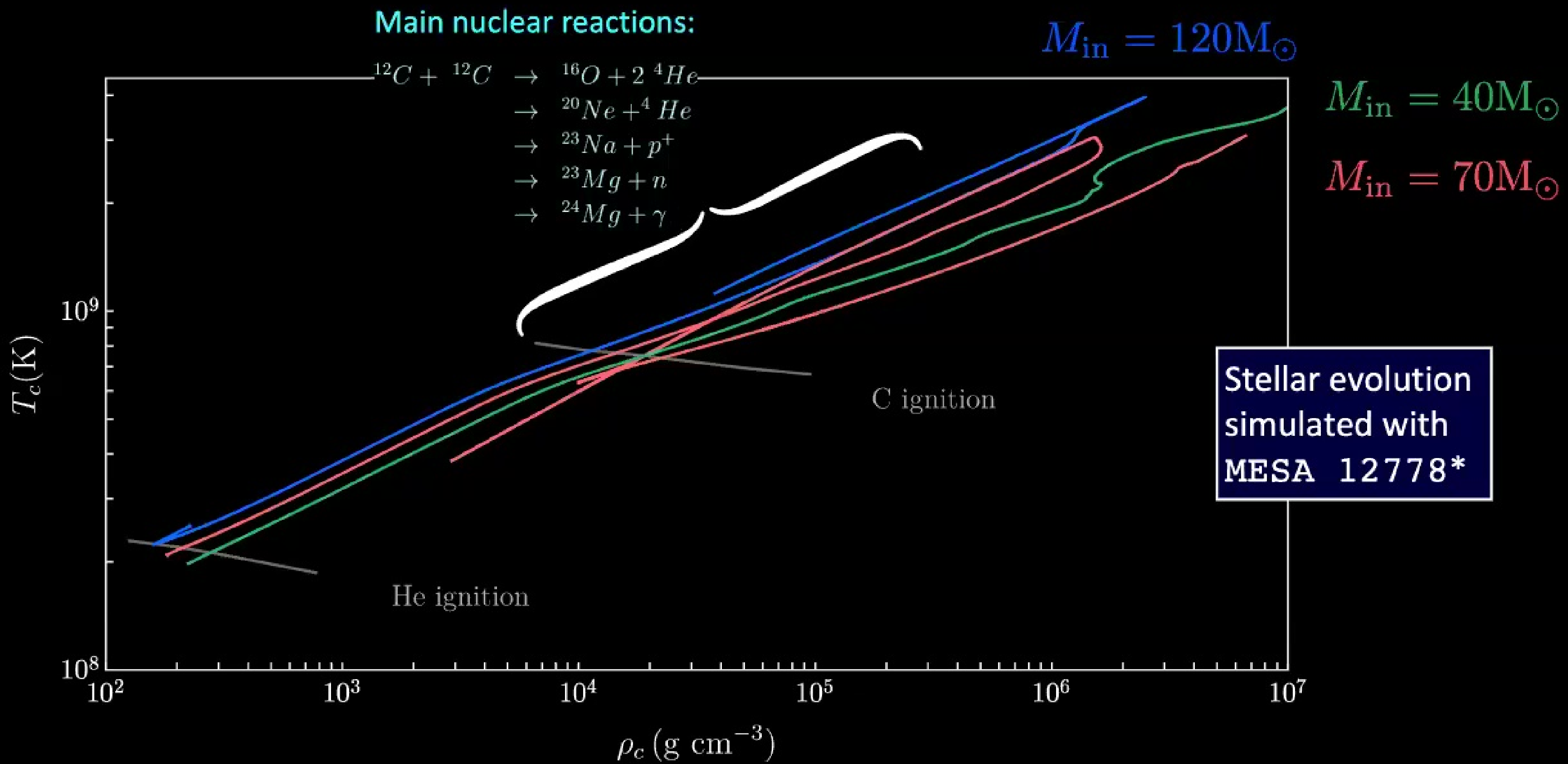
Evolution of old population-III stars



Stellar evolution simulated with `MESA 12778*`

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

Evolution of old population-III stars



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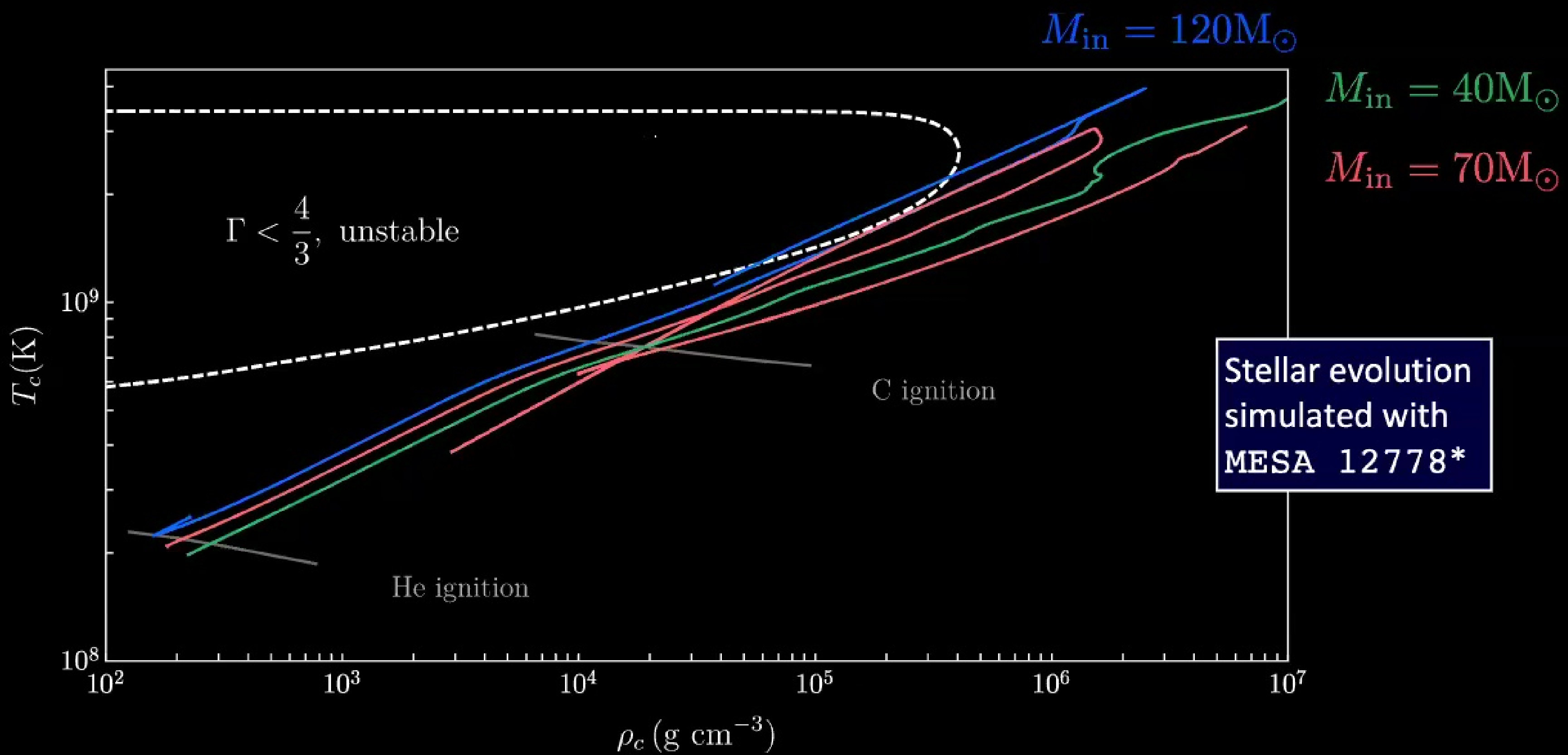
Evolution of old population-III stars



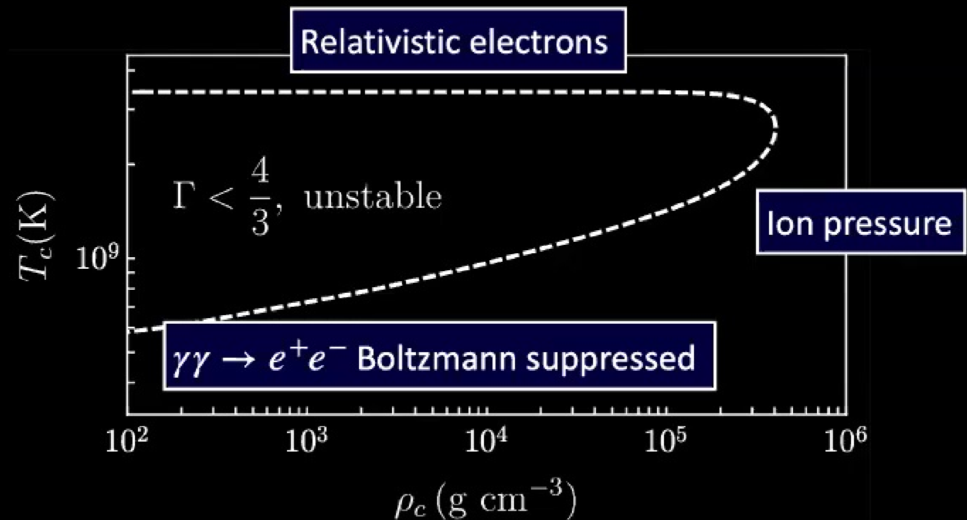
Stellar evolution simulated with `MESA 12778*`

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

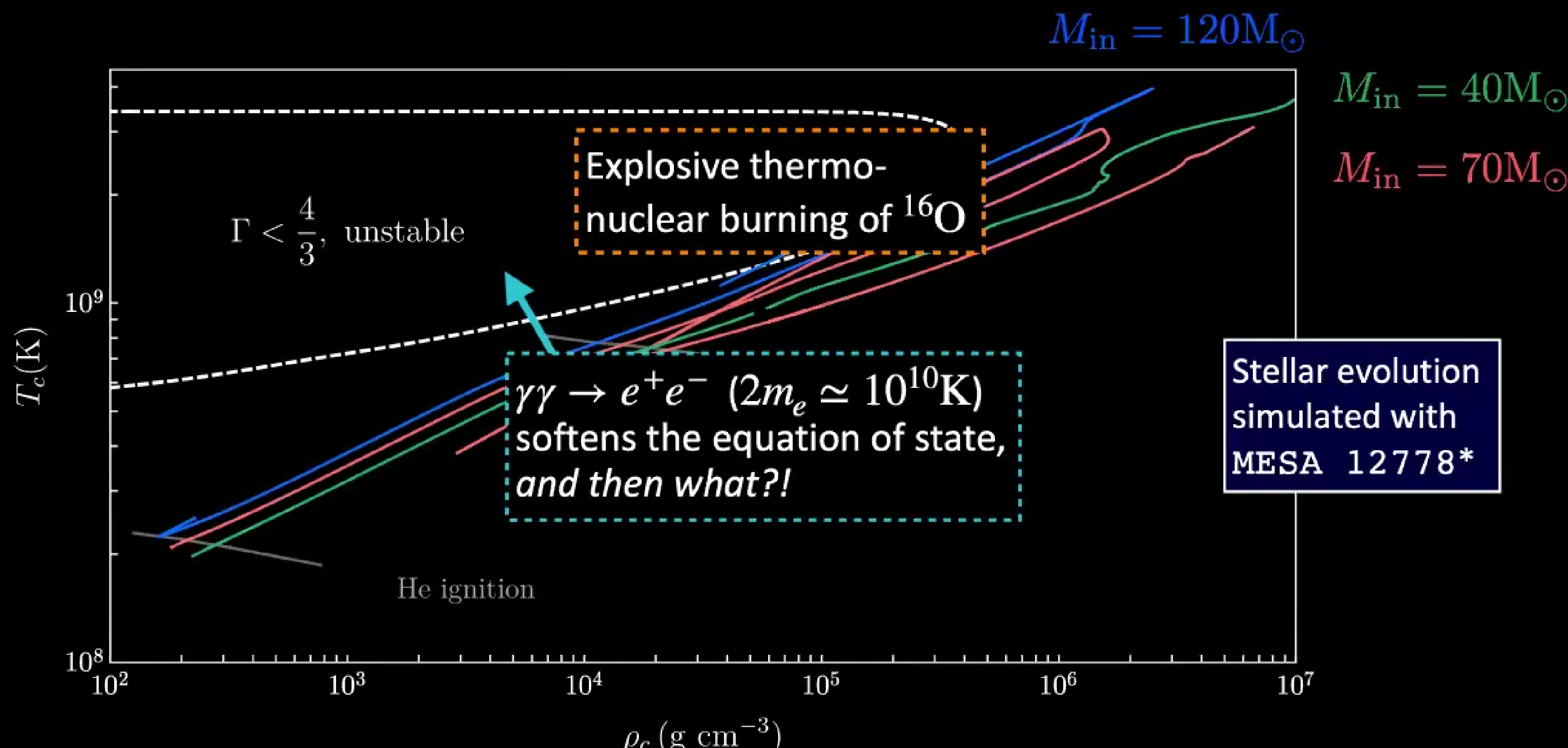
Pair-instability

- The high temperatures of the pop-III stars lead to electron-positron pair creation in the thermal plasma via $\gamma\gamma \rightarrow e^+e^-$ $(2m_e \simeq 10^{10}\mathrm{K})$

- Stars supported by radiation pressure $\Gamma = \left(\partial P/\partial \rho\right)_s \approx 4/3$
- Instability occurs for $\Gamma < 4/3$
  - Non-relativistic electrons destabilize the star



Evolution of old population-III stars

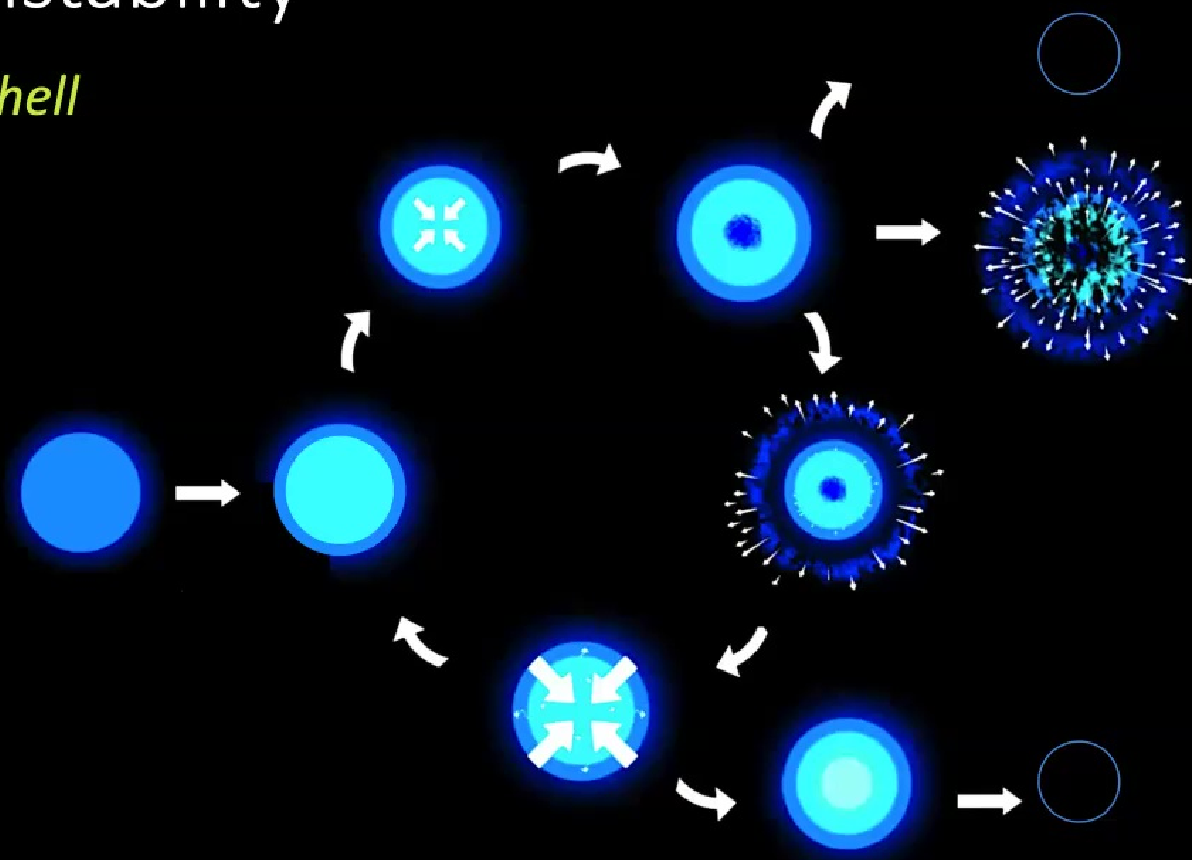


Stellar evolution simulated with MESA 12778*

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

Pair instability

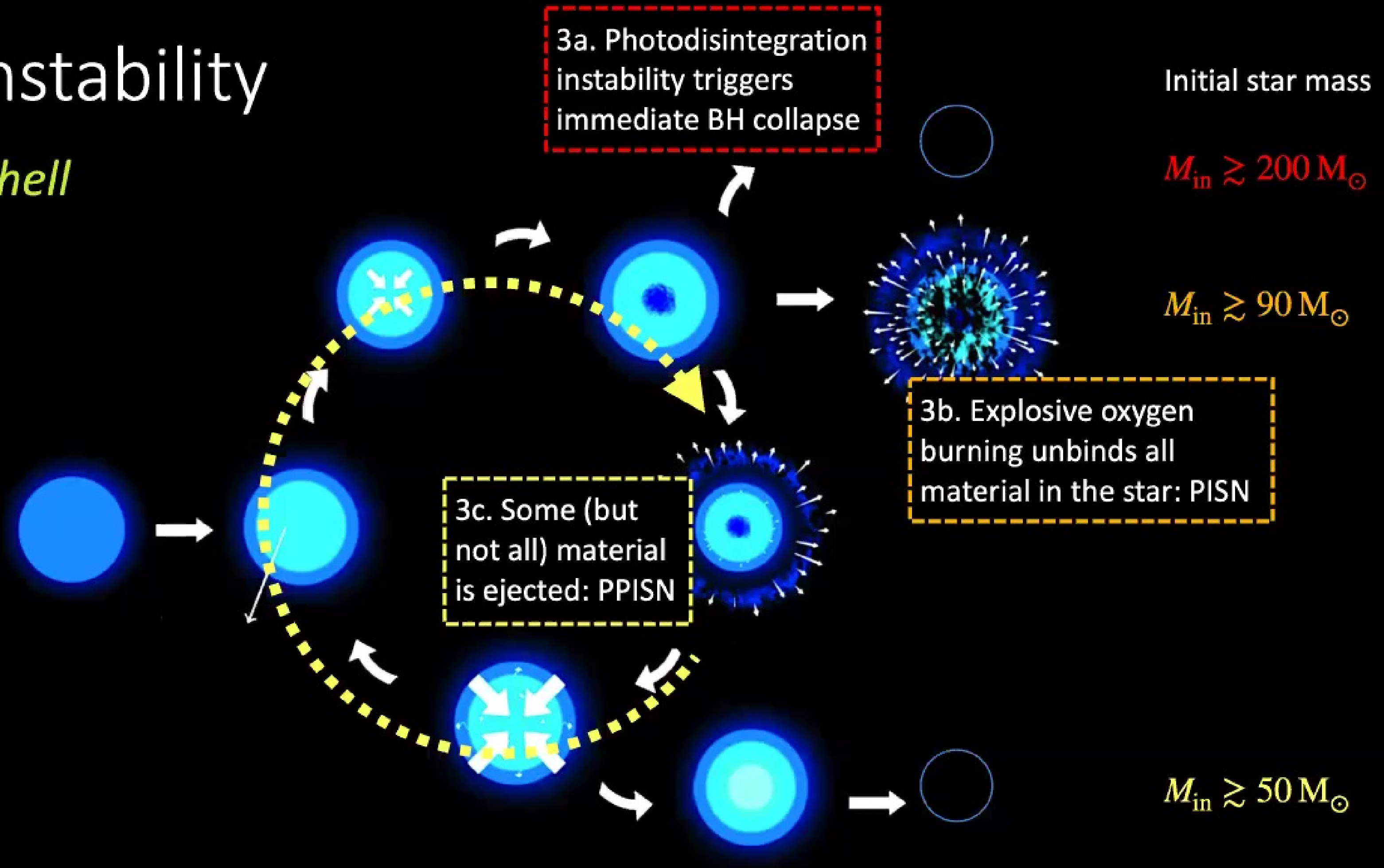
in a nutshell



Adapted from Renzo et al [2002.05077]

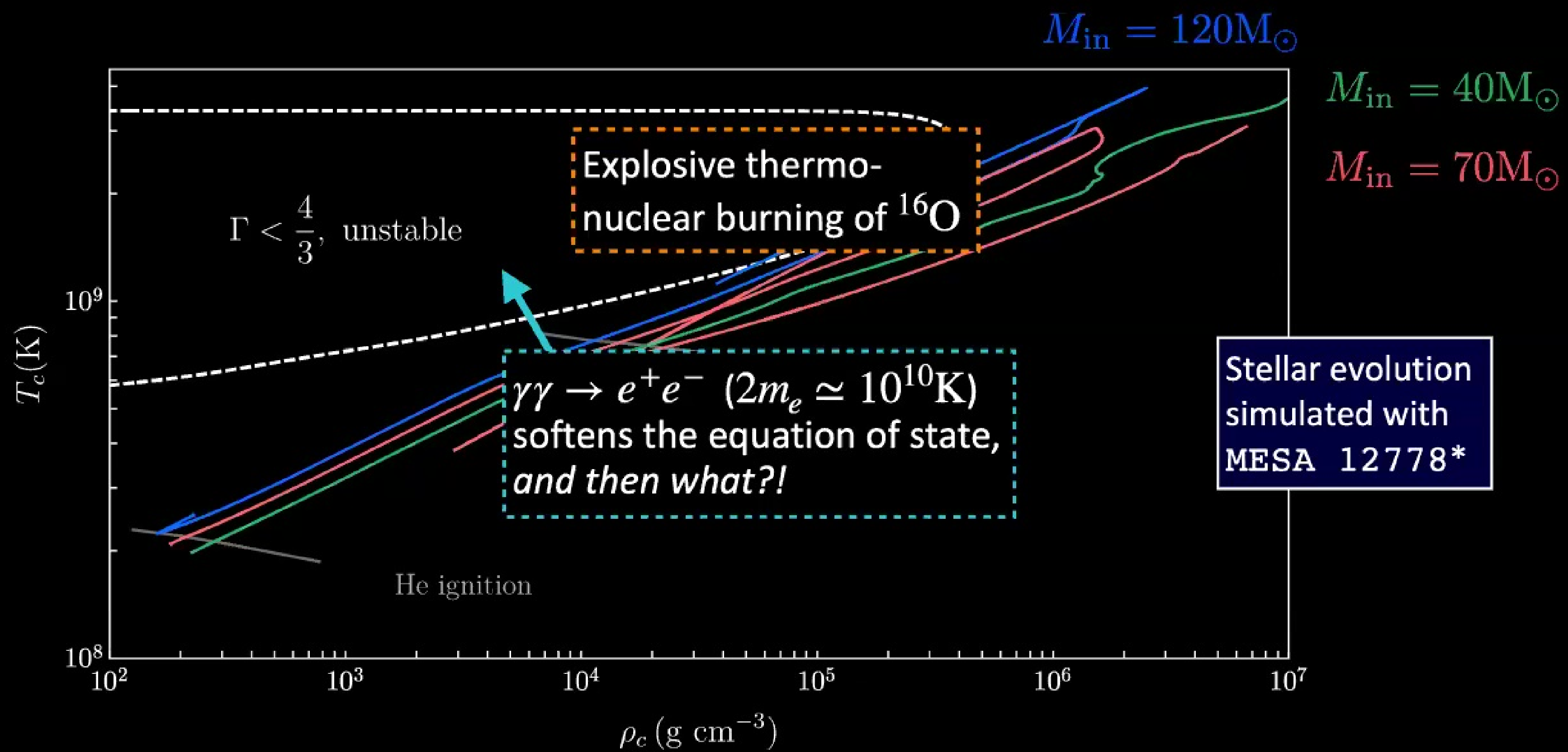
Pair instability

in a nutshell



Adapted from Renzo et al [2002.05077]

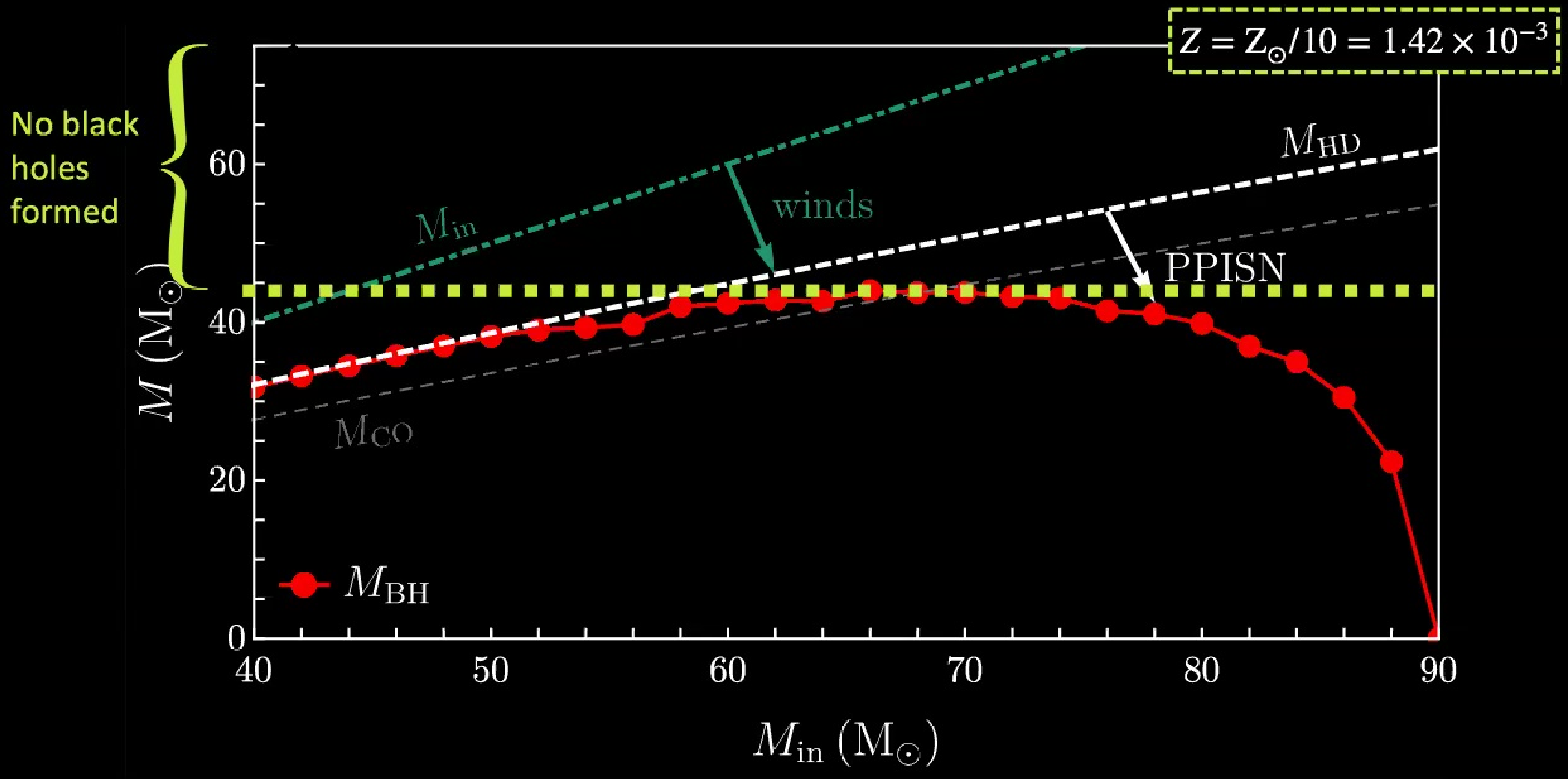
Evolution of old population-III stars



Stellar evolution simulated with `MESA 12778*`

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

Resulting black hole masses

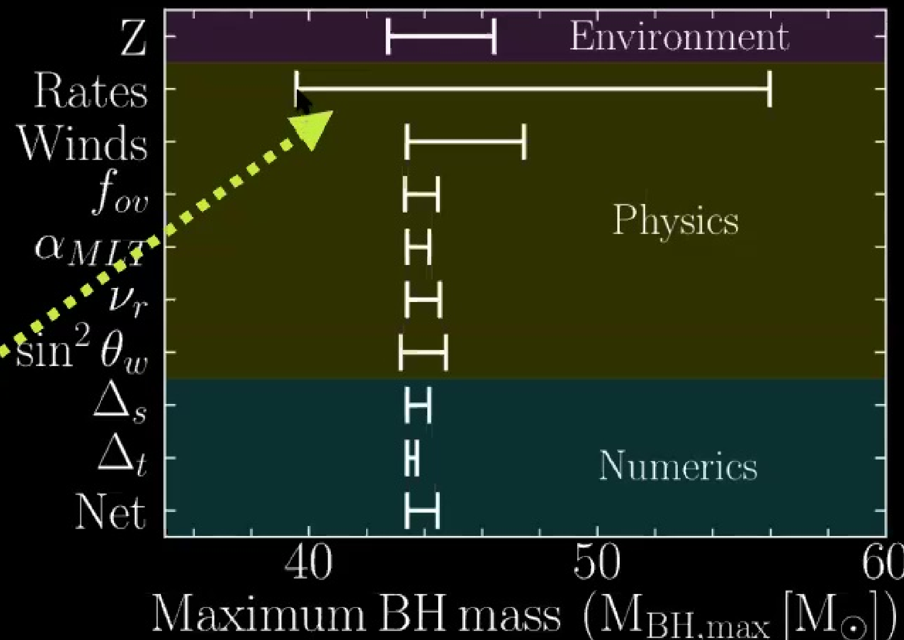


DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

Physics dependence of the BHMG

- Astrophysical + nuclear + numerical dependence
- Most important dependence: $^{12}C(\alpha,\gamma)^{16}O$ rate
- Using updated deBoer et al rate, BHMG found at $51^{+0}_{-4}\,M_\odot$

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



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

What about BSM physics?

- Quickly recap: the existence of a black hole mass gap is a robust SM prediction and a direct a consequence of
    i. The temperature and density of post-MS evolution
    ii. The mass of the electron
    iii. The burning products of helium
- BSM physics may affect post-MS evolution and therefore directly imprint on the black hole mass gap

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

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

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]

Several other works in progress...

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

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

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

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

The BHMG and BSM cooling

- Scenario: new, light particles coupled to material in the star introduce new loss channels

Extra scenarios: large extra dimensions ($d = 4 + 2$) and neutrino magnetic moment work through *essentially the same mechanism*

- Case studies: $\mathscr{L}_{\rm SM} + \ldots$
  - the electrophilic axion $\mathscr{L}_{ae} = -ig_{ae}\bar{\psi}_e\gamma_5\psi_e a$ (will also work with $\alpha_{26} \equiv 10^{26}g_{ae}^2/4\pi$ for convenience)*
  - the photophilic axion $\mathscr{L}_{a\gamma} = -\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\widetilde{F}^{\mu\nu}$ (will also define $g_{10} \equiv 10^{10}g_{a\gamma}\,\mathrm{GeV}$)
  - the hidden photon $\mathscr{L}_{A'\gamma} = -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu$ (and define nothing)

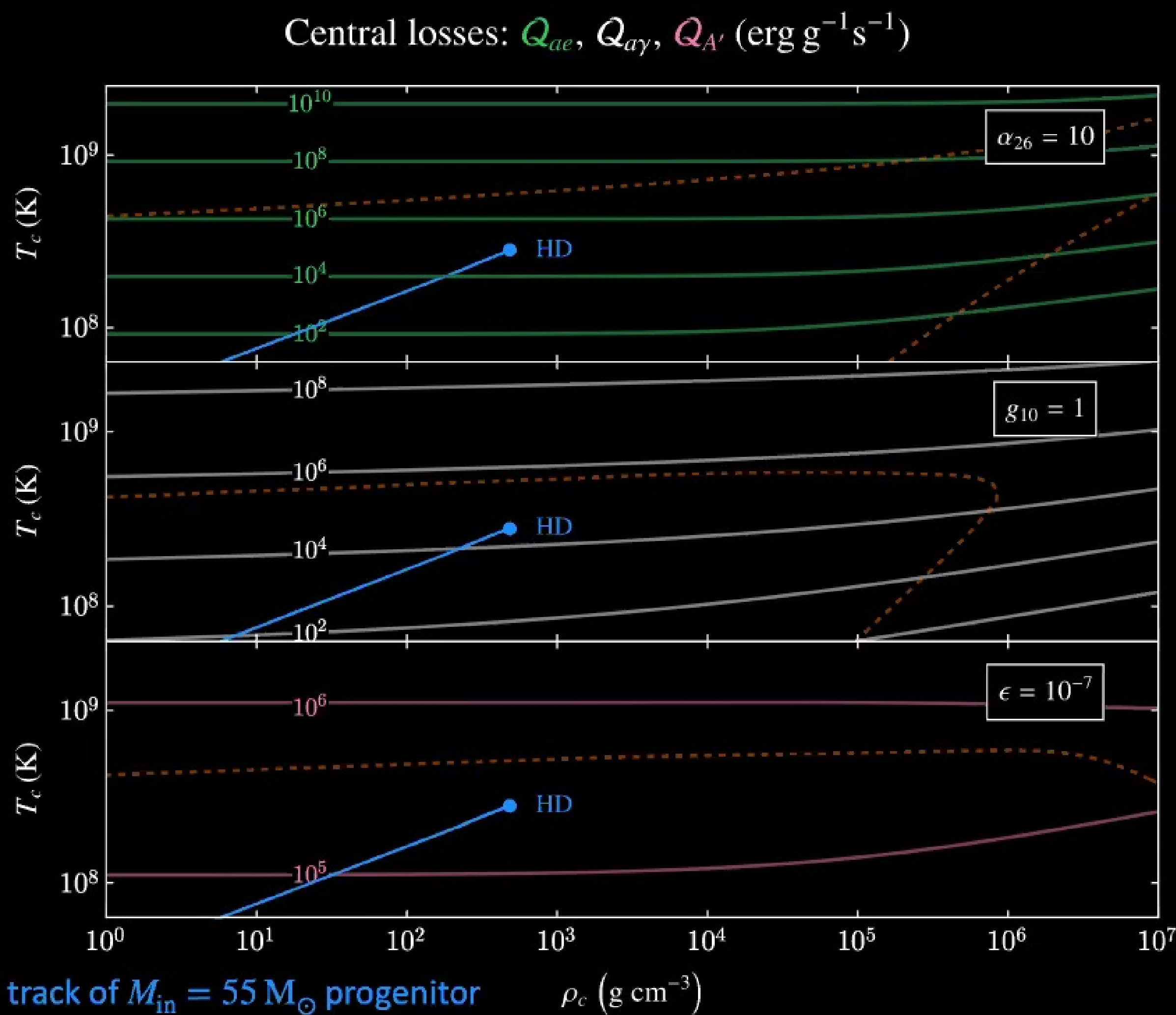
*Interesting in light of the XENON1T excess, arXiv:2006.09721 [hep-ex]

Loss rates

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

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

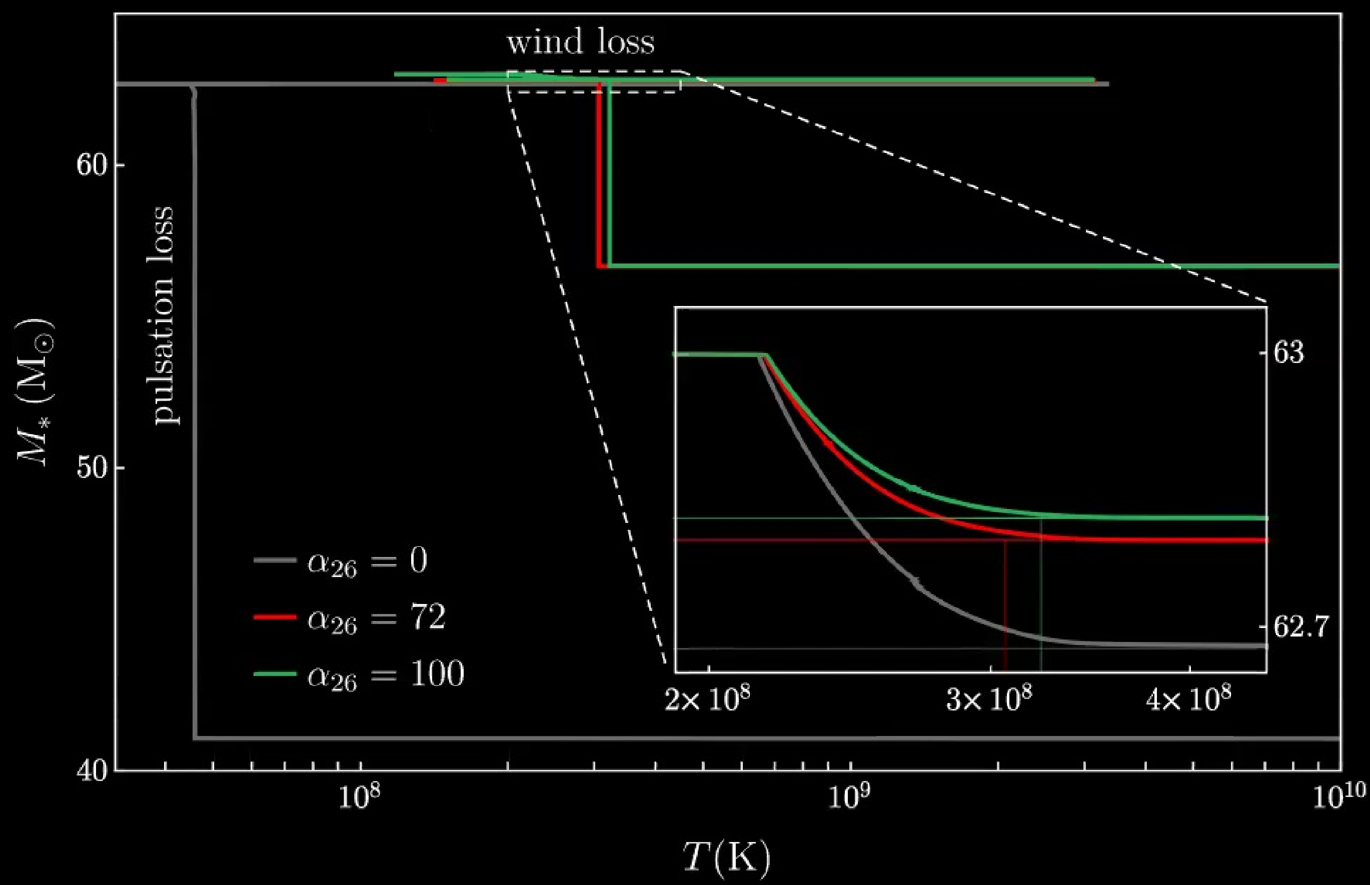
Hidden photon: $\mathcal{Q}_{A'} \propto T$
(resonant emission)



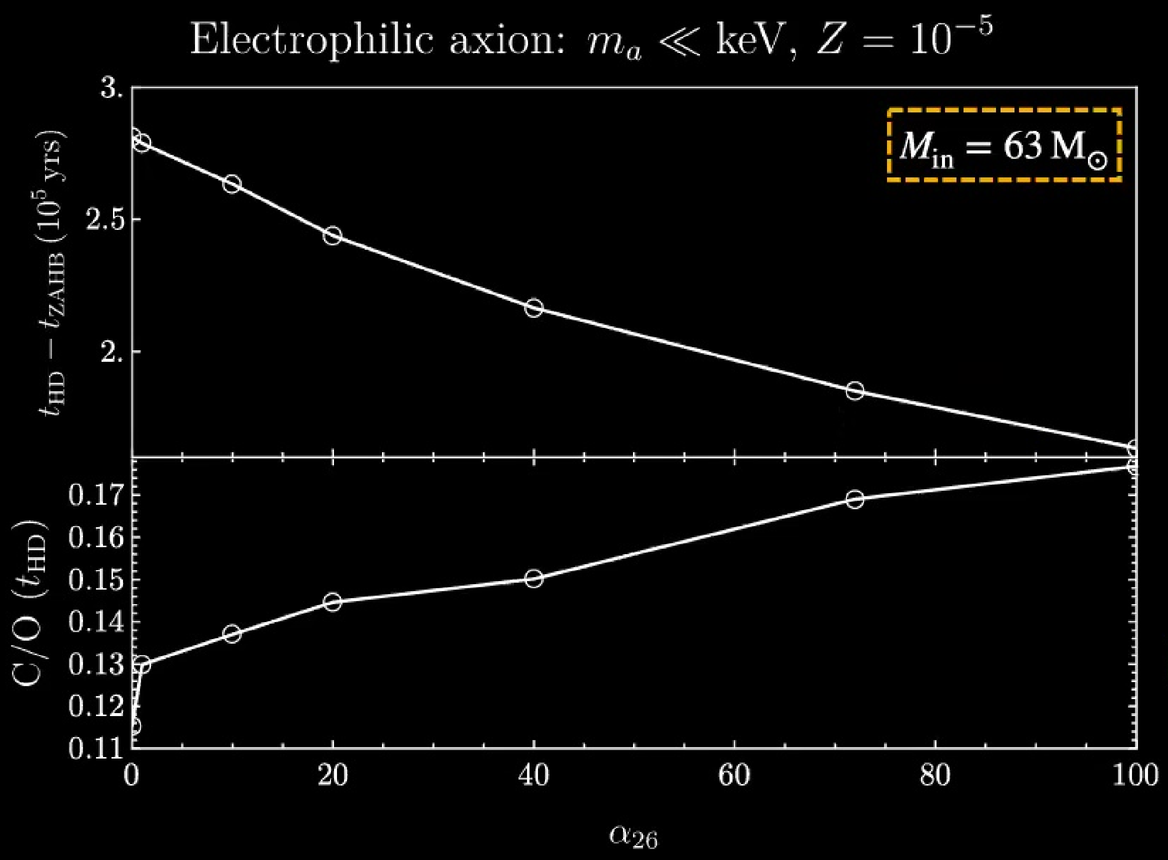
Example track of $M_{\rm in} = 55\,{\rm M}_\odot$ progenitor

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

Implications of enhanced losses



What does the extra energy loss do?



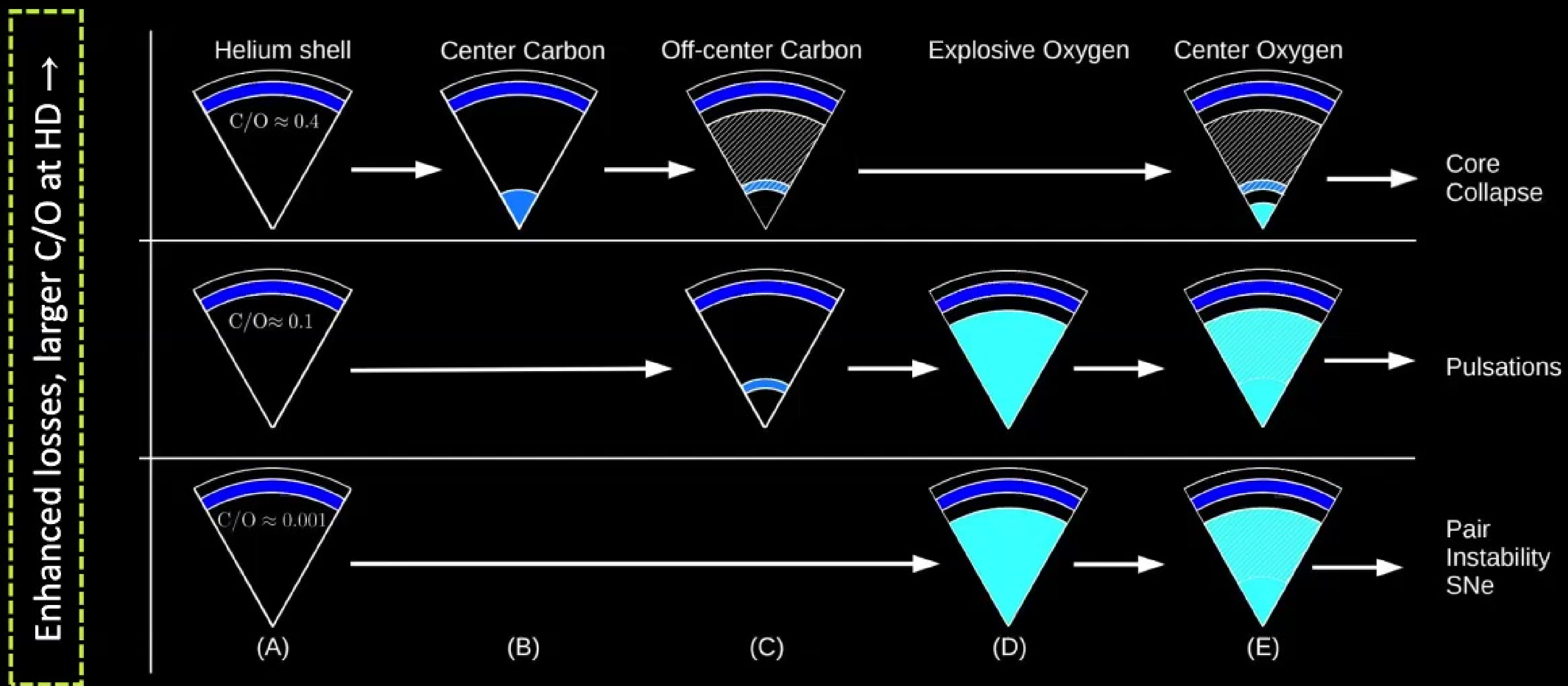
Greater energy losses lead to *shorter He-burning phases*

Extra dissipation scales linearly with α_{26}

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

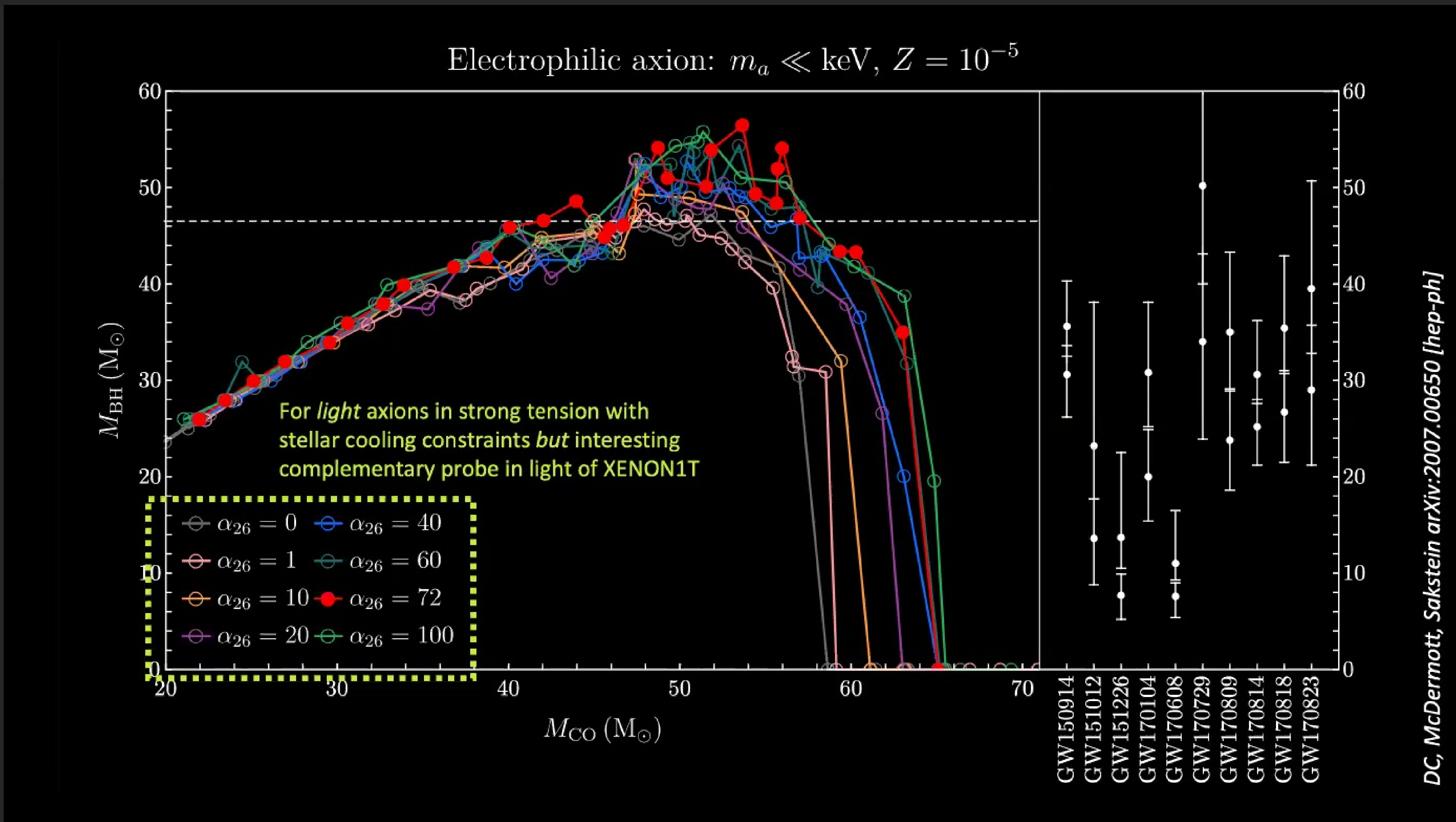
The BHMG and new physics

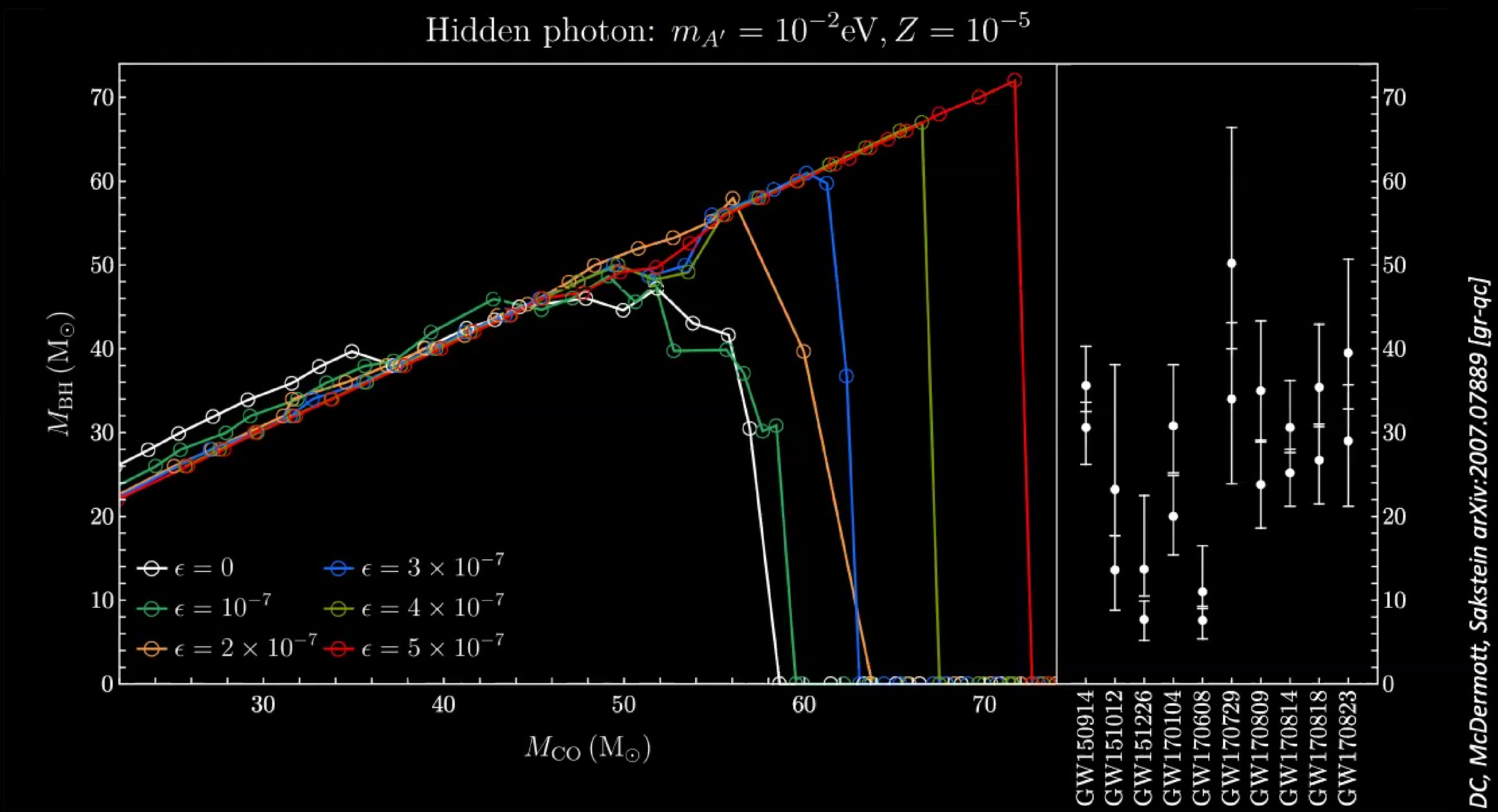
Helium burning
Carbon burning
Oxygen burning



Enhanced losses → greater progenitors collapse → larger black holes

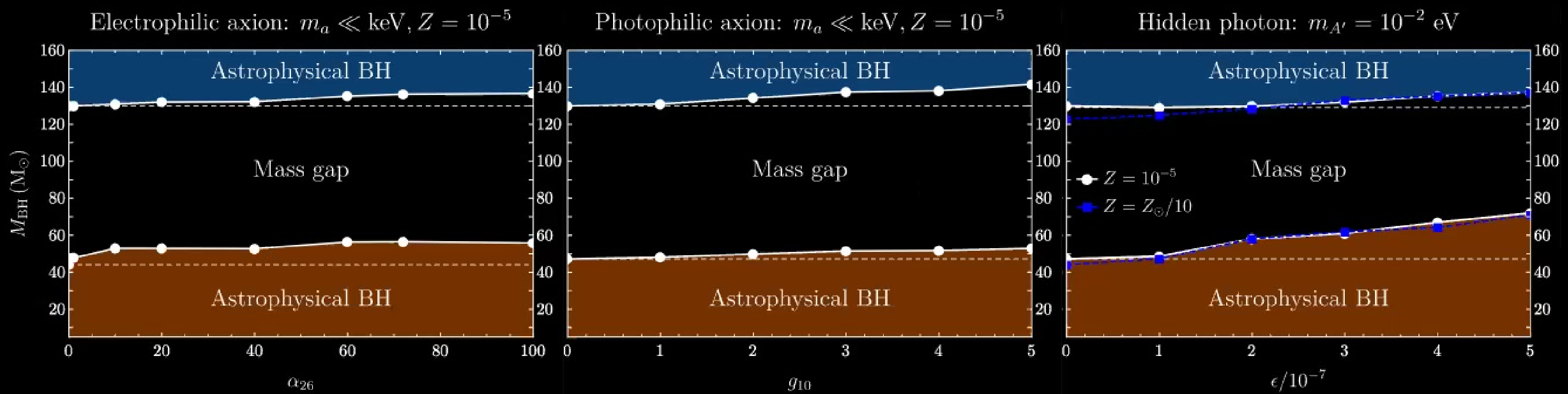
Adapted from Farmer, Renzo, de Mink, Fishbach, Justham [2006.06678]


Electrophilic axion: $m_a \ll \text{keV},\ Z = 10^{-5}$
$M_{\rm BH}\ (M_\odot)$
$M_{\rm CO}\ (M_\odot)$
For *light* axions in strong tension with
stellar cooling constraints *but* interesting
complementary probe in light of XENON1T
$\alpha_{26} = 0$
$\alpha_{26} = 40$
$\alpha_{26} = 1$
$\alpha_{26} = 60$
$\alpha_{26} = 10$
$\alpha_{26} = 72$
$\alpha_{26} = 20$
$\alpha_{26} = 100$
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]



Hidden photon: $m_{A'} = 10^{-2}$eV, $Z = 10^{-5}$
M_{BH} ($M_\odot$)
M_{CO} ($M_\odot$)
$\epsilon = 0$
$\epsilon = 10^{-7}$
$\epsilon = 2 \times 10^{-7}$
$\epsilon = 3 \times 10^{-7}$
$\epsilon = 4 \times 10^{-7}$
$\epsilon = 5 \times 10^{-7}$
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

BSM cooling and the black hole mass gap



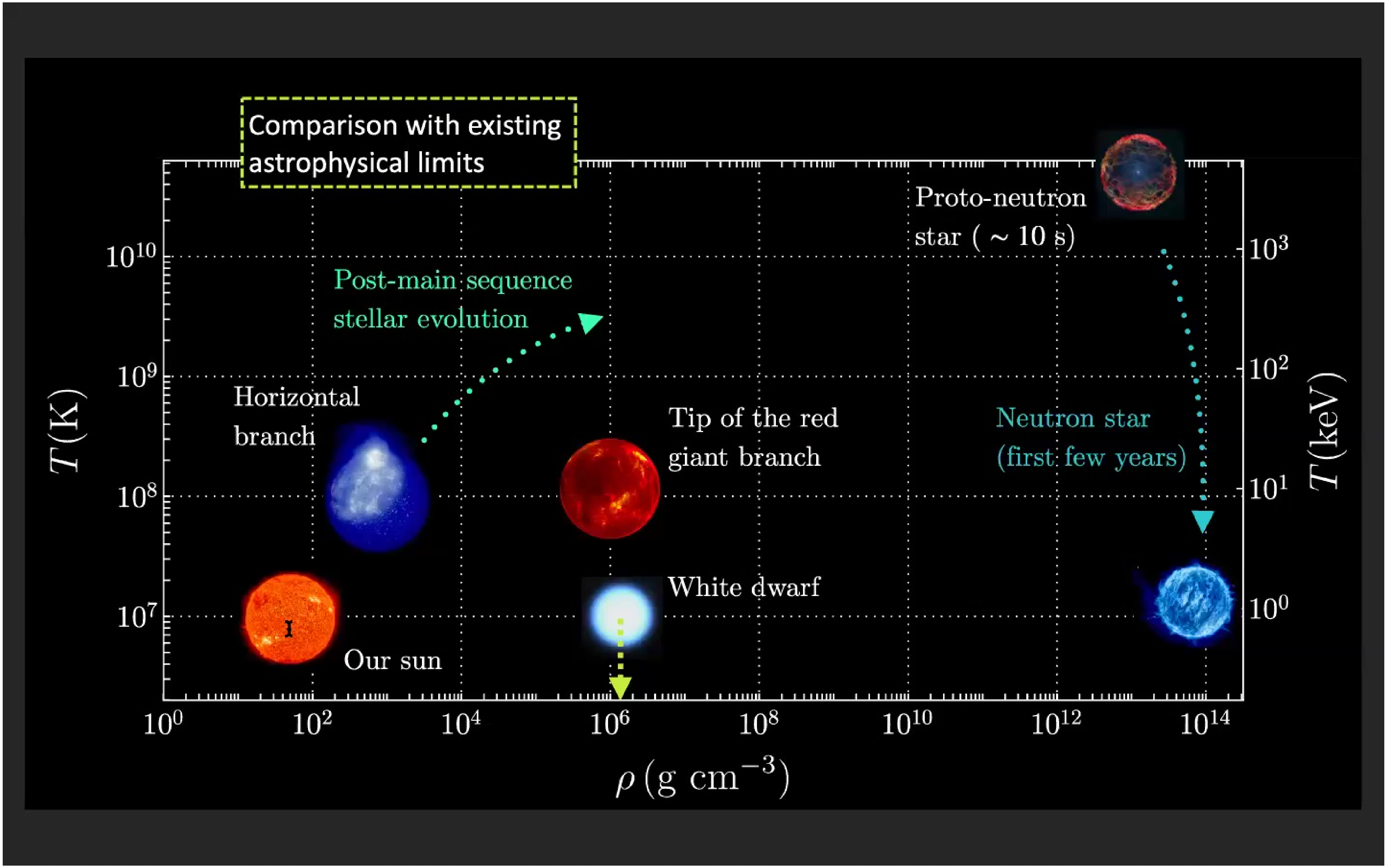
$\mathcal{Q}_{ae} \propto T^6$

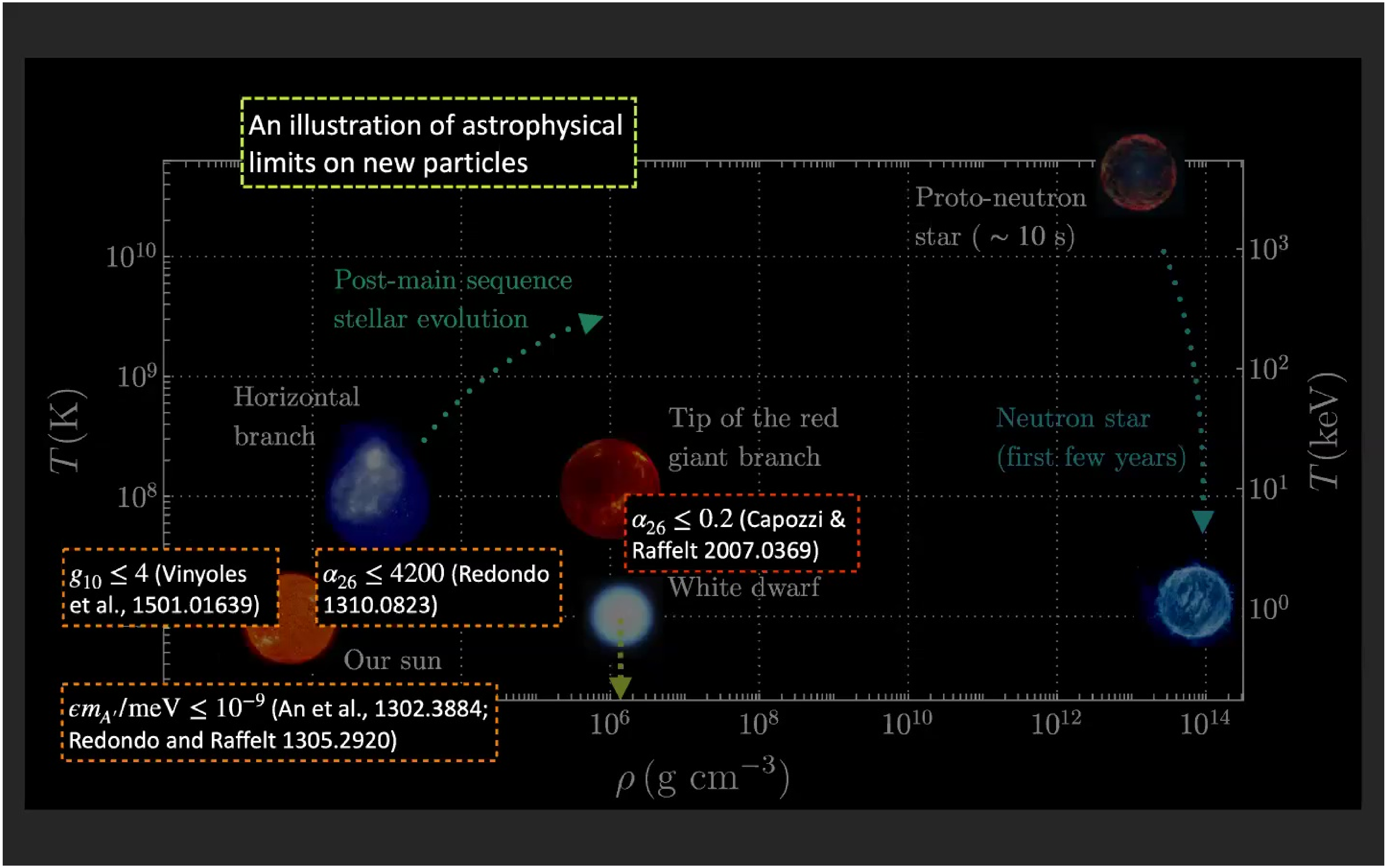
$\mathcal{Q}_{a\gamma} \propto T^4$

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

Important extra cooling = large shifts of the mass gap!

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


Comparison with existing astrophysical limits
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
$T(\mathrm{K})$
$T(\mathrm{keV})$
10^{10}
10^{9}
10^{8}
10^{7}
10^{3}
10^{2}
10^{1}
10^{0}
10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14}
$\rho\,(\mathrm{g\ cm^{-3}})$


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)
$\epsilon m_{A'}/\text{meV} \leq 10^{-9}$ (An et al., 1302.3884; Redondo and Raffelt 1305.2920)
$T\,(\text{K})$
10^{10}
10^{9}
10^{8}
$T\,(\text{keV})$
10^{3}
10^{2}
10^{1}
10^{0}
10^{6} 10^{8} 10^{10} 10^{12} 10^{14}
$\rho\,(\text{g cm}^{-3})$

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

Equation	
$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \varrho},$	Mass function
$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4},$	Hydrostatic equilibrium
$\frac{\partial l}{\partial m} = \varepsilon_{\mathrm{n}} - \varepsilon_{\nu} - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\varrho}\frac{\partial P}{\partial t},$	Energy flux
$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\nabla,$	Convection
$\frac{\partial X_i}{\partial t} = \frac{m_i}{\varrho}\left(\sum_j r_{ji} - \sum_k r_{ik}\right), \quad i = 1, \ldots, I.$	Reactions

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

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

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

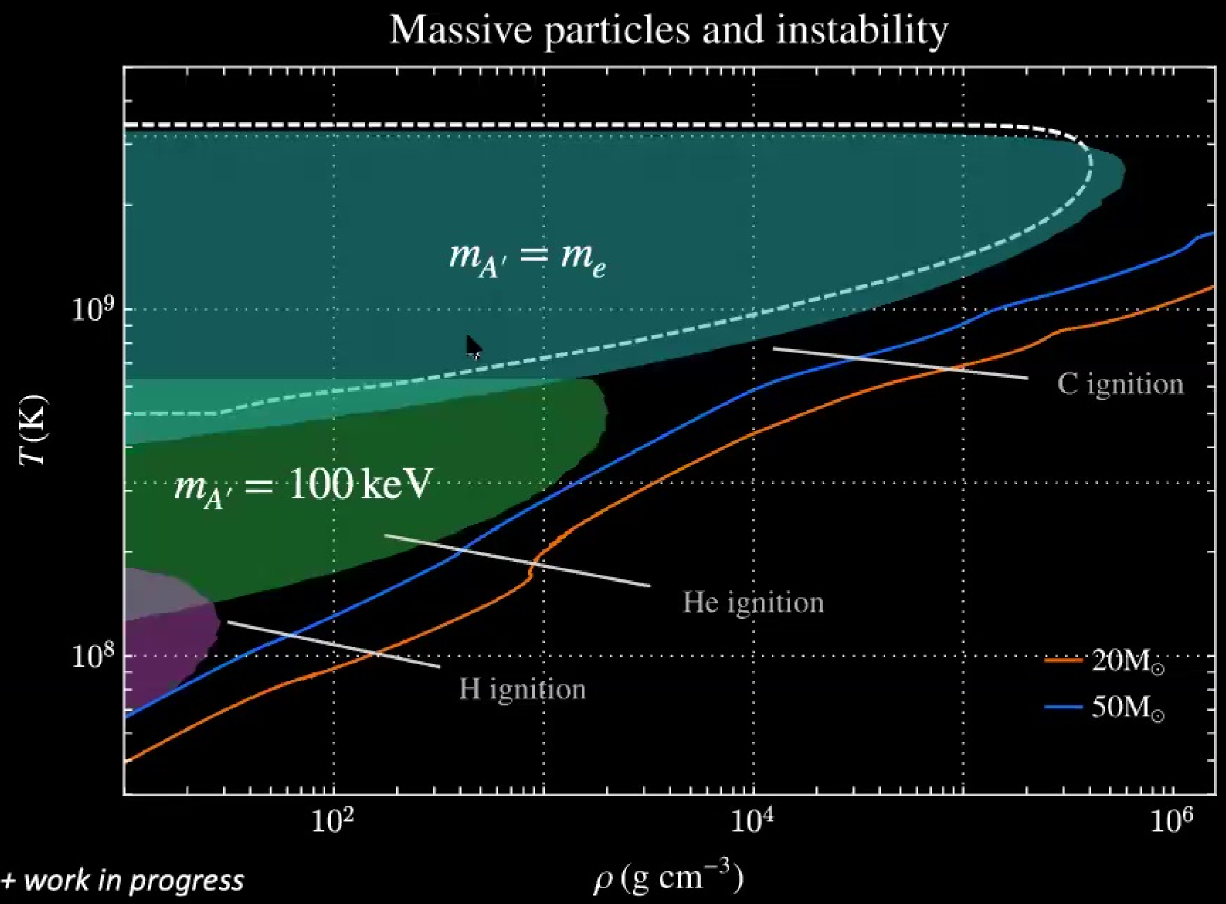
+ BSM physics contributions?

What about trapped new physics?

Non-relativistic DOF *soften the EOS* (as electron-positron pairs do)

Spin-statistics plays a role: bosons soften more than fermions do

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



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

Other new physics

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

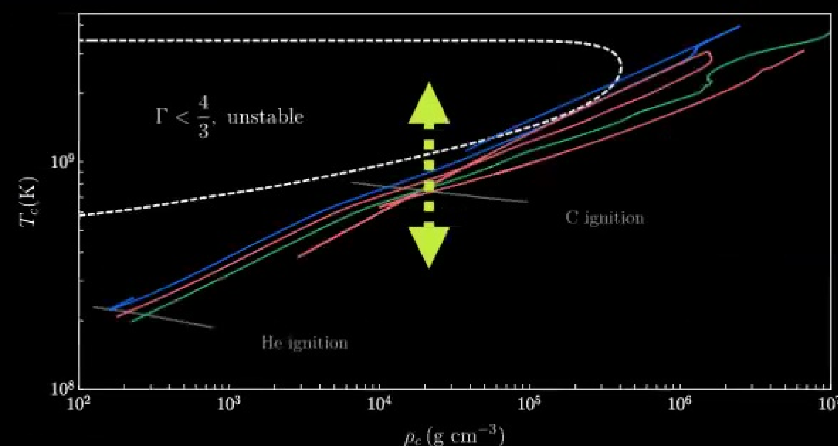
Straight, Sakstein, Baxter, arXiv: 2009.10716 [gr-qc]

- New forces: screened modified gravity (MG)
  - Increased local strength of gravity → need larger pressure gradient to maintain hydrostatic equilibrium → larger core temperature at fixed density → Pair instability is exacerbated →Lighter BHs
  - Decreased local strength of gravity works in reverse → Heavier BHs

- Dark matter annihilation
  - Extra source of energy
  - + consistent EOS treatment

Ziegler, Freese arXiv:2010.00254 [astro-ph]

DC, McDermott, Sakstein, work in progress



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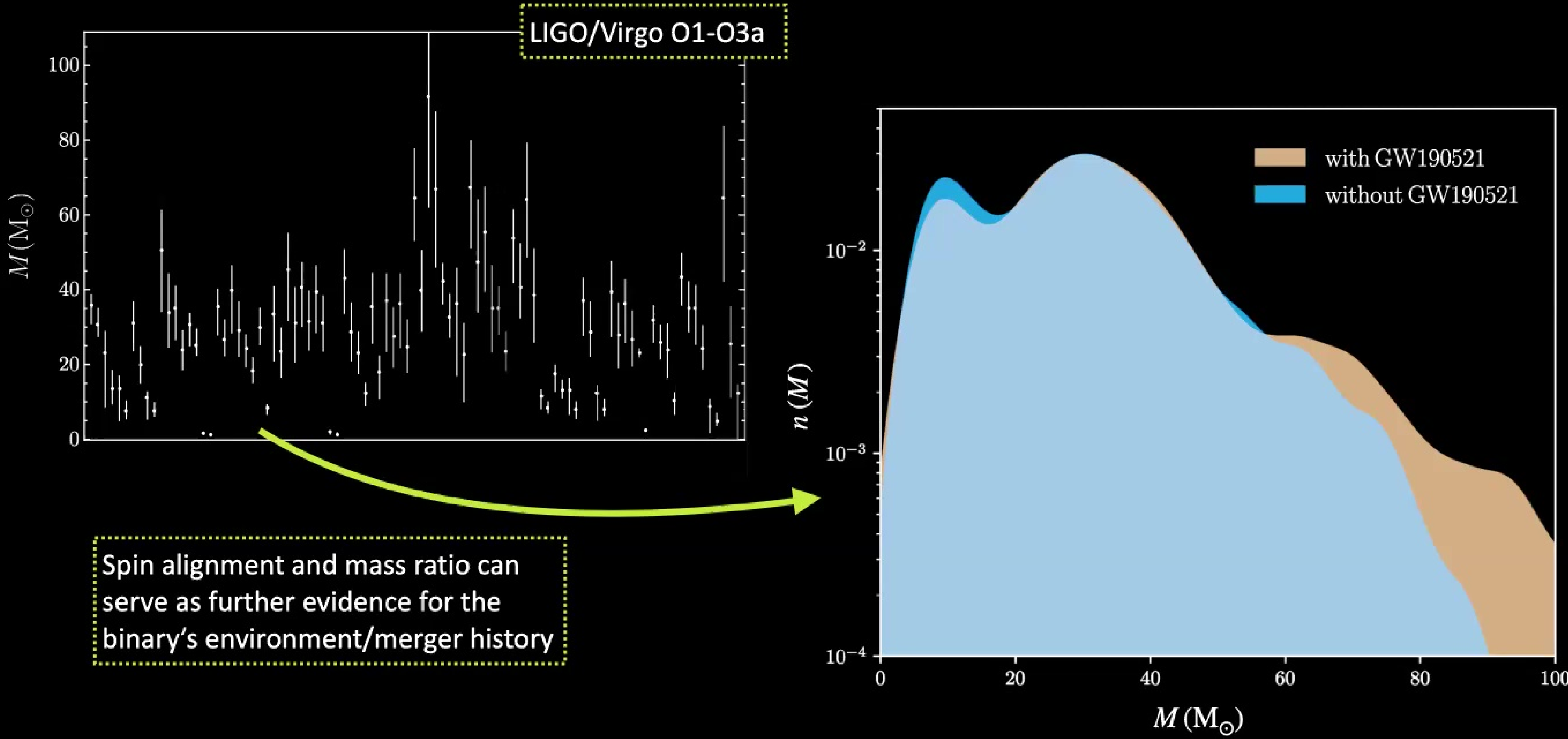
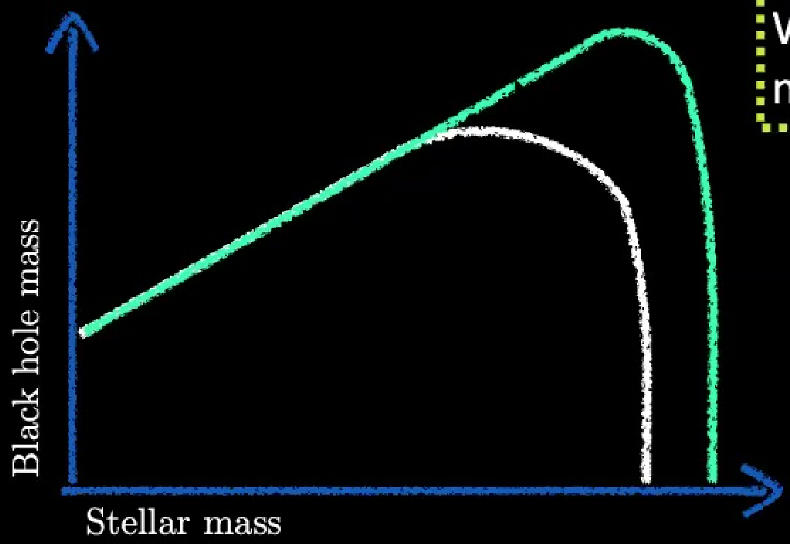
Now, what about gravitational wave data?



Pair-instability and black hole populations



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

BSM 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]

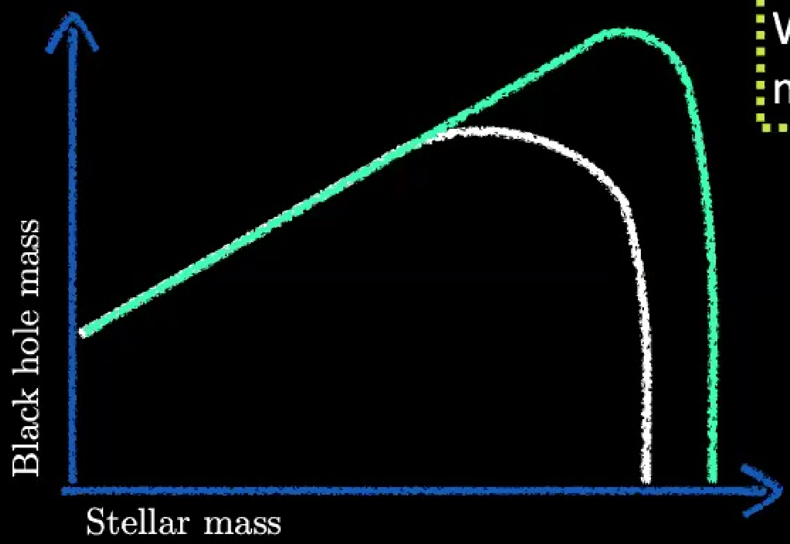
Straight, Sakstein, Baxter, PRD, arXiv:2009.10716 [gr-qc]

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



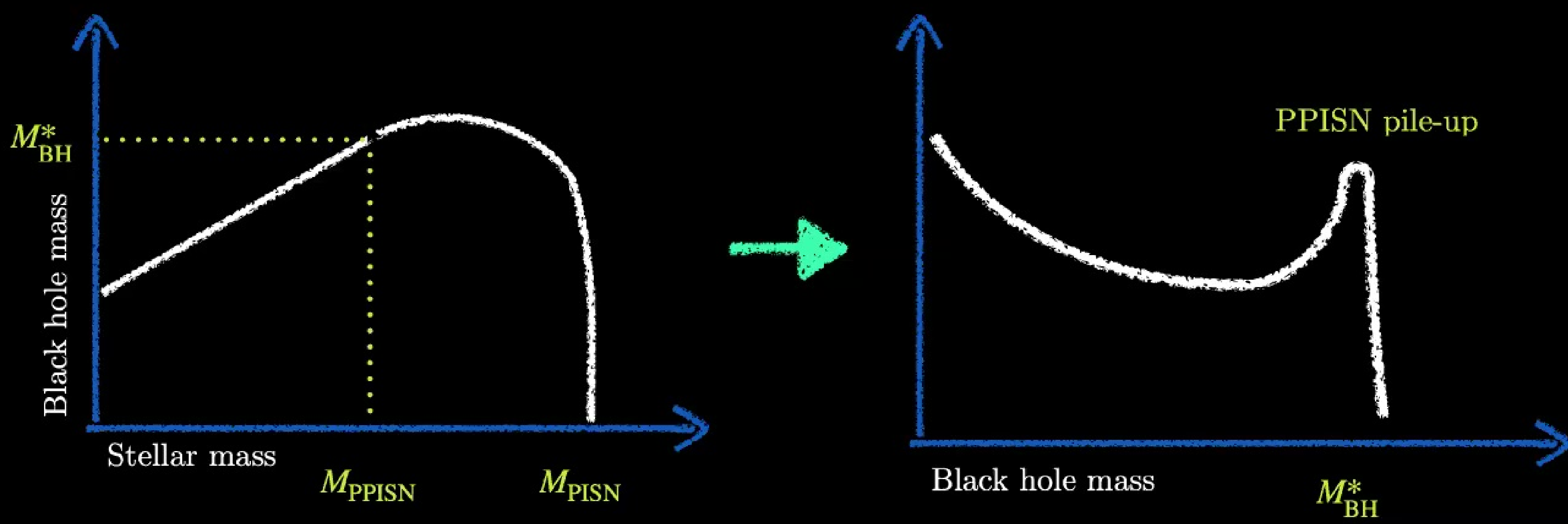
We can predict black hole masses from stellar masses through stellar evolution simulations

BSM physics may change this prediction

How can we use *data* to test that?

Baxter, DC, McDermott, Sakstein, arXiv:2104.XXXX
(on the arXiv tonight)

Pair-instability and black hole populations



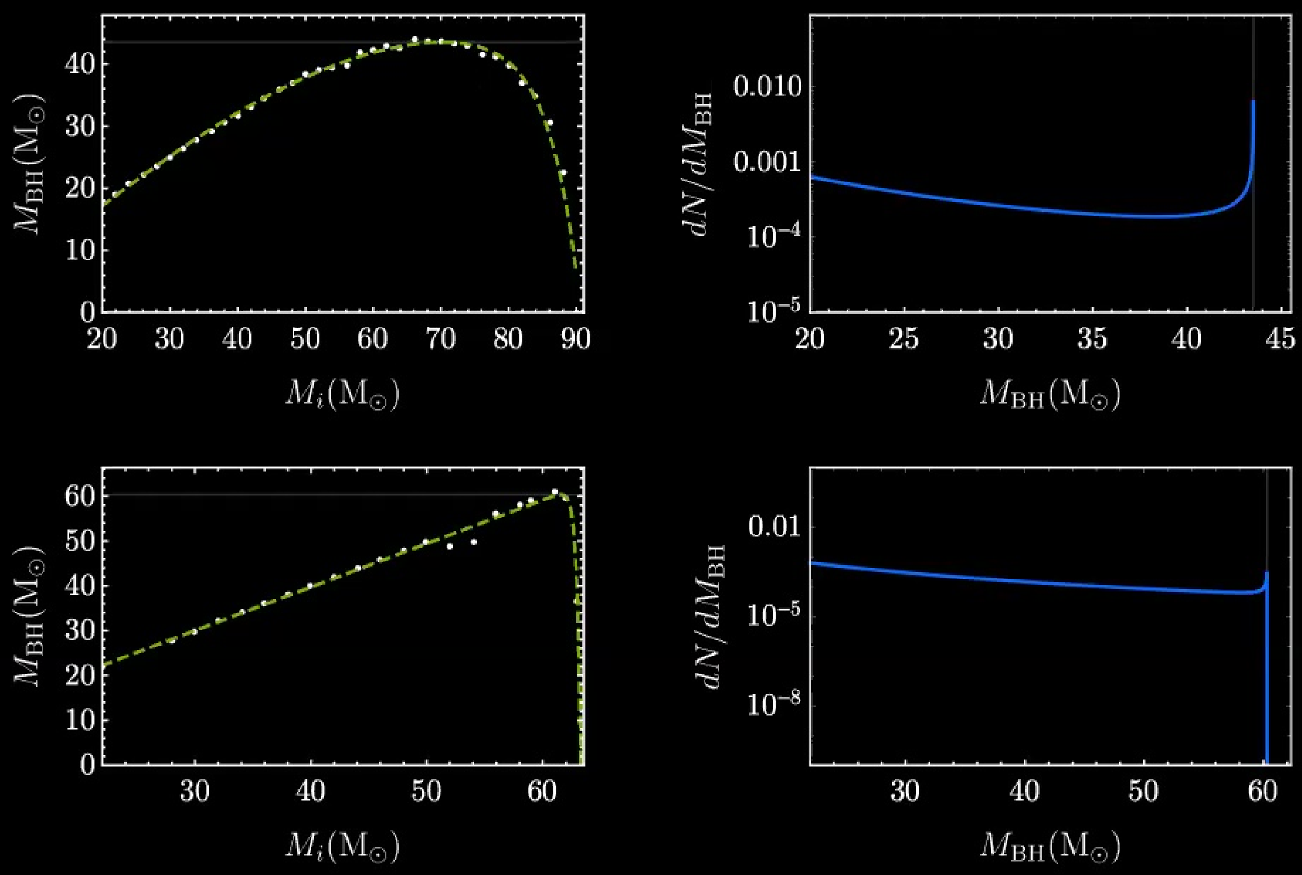
+ Initial mass function (here assumed to be a power law)

See also Talbot & Trane, arXiv:1801.02699

Pair-instability and black hole populations

SM scenario

BSM scenario (example)

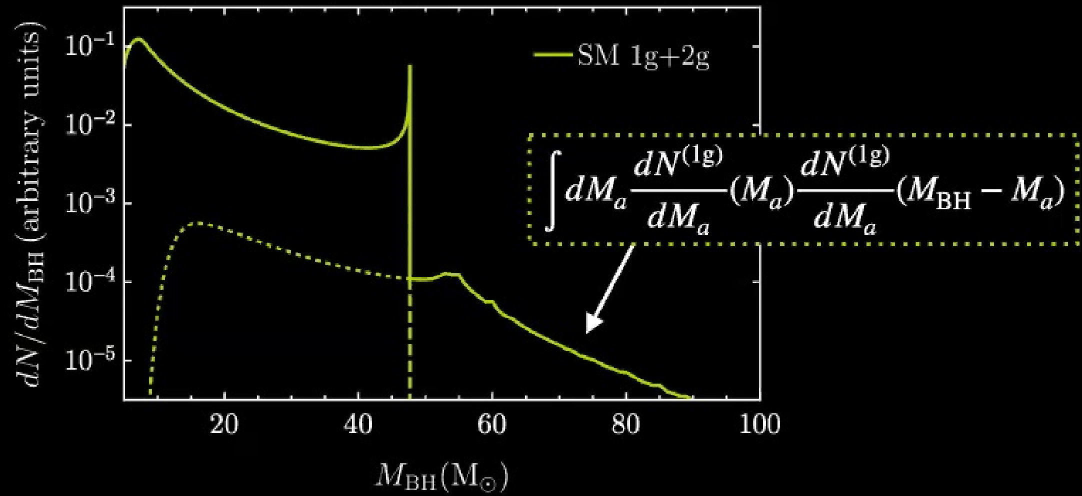


Baxter, DC, McDermott, Sakstein, arXiv:2104.XXXX

Dynamical mergers and BH genealogy

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

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

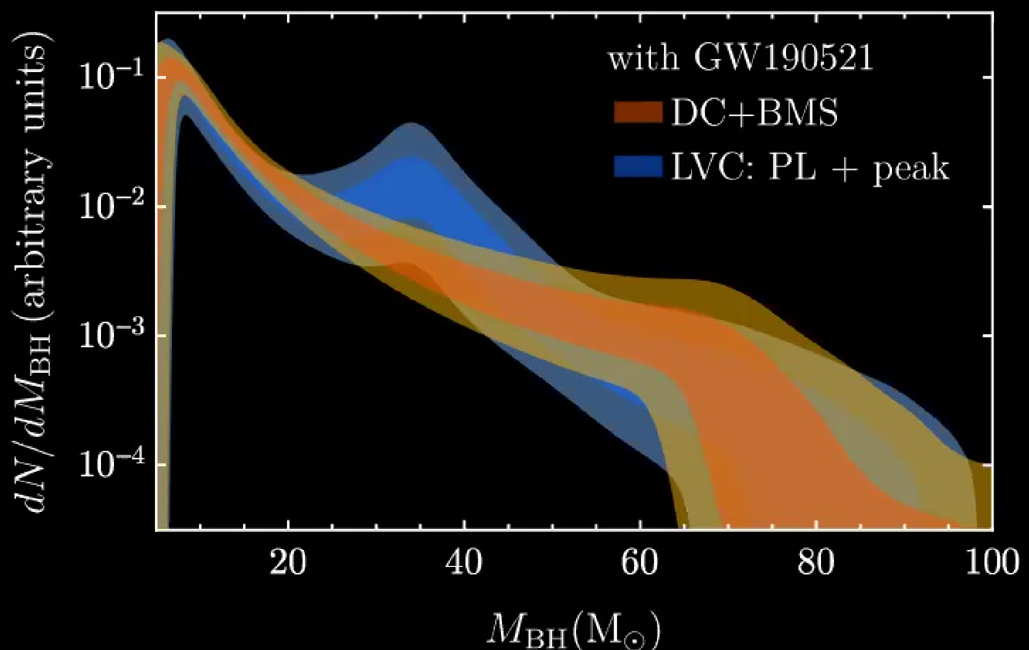


$$\frac{dN}{dM_{\rm BH}} = \frac{dN^{(1g)}_{\rm BH}}{dM_{\rm BH}} + \frac{dN^{(2+g)}_{\rm BH}}{dM_{\rm BH}}$$

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

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

Binary mergers in LIGO/Virgo O3a



This work, Eq. (7)	with GW190521
$\log_{10}\lambda$	$-2.91^{+0.42}_{-0.95}$
$M_{\rm BHMG}$ $[\rm M_\odot]$	$74.8^{+4.3}_{-8.0}$
a	< 0.225
b	-2.47 ± 0.33
d	—
$M_{\rm min}$ $[\rm M_\odot]$	3.2 ± 1.3
δ_m $[\rm M_\odot]$	> 5.00

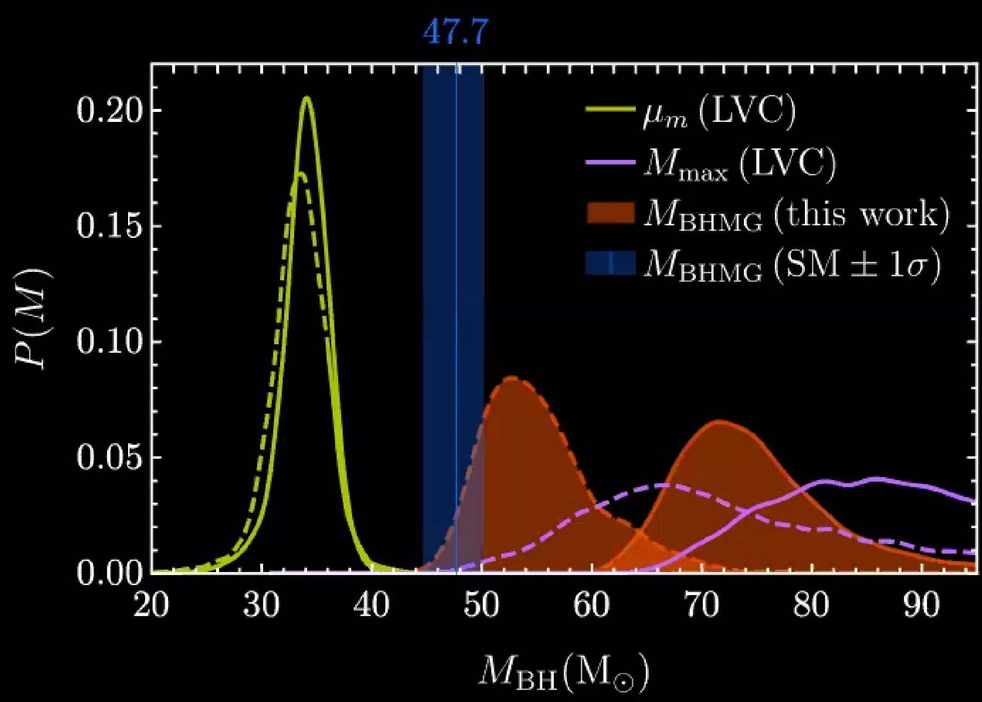
LVC: PL+peak	with GW190521
α	$2.72^{+0.38}_{-0.48}$
$M_{\rm max}$ $[\rm M_\odot]$	85^{+10}_{-8}
$\lambda_{\rm peak}$	$0.113^{+0.032}_{-0.094}$
μ_m $[\rm M_\odot]$	$34.0^{+2.2}_{-1.7}$
σ_m $[\rm M_\odot]$	$4.7^{+1.8}_{-3.5}$
$M_{\rm min}$ $[\rm M_\odot]$	$4.40^{+1.3}_{-0.89}$
δ_m $[\rm M_\odot]$	< 4.75

Baxter, DC, McDermott, Sakstein, arXiv:2104.XXXX

GW190521 remains an enigma

The New York Times

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



Including GW190521, a dimensionful parameters shifts

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.XXXX

GW190521 remains an enigma

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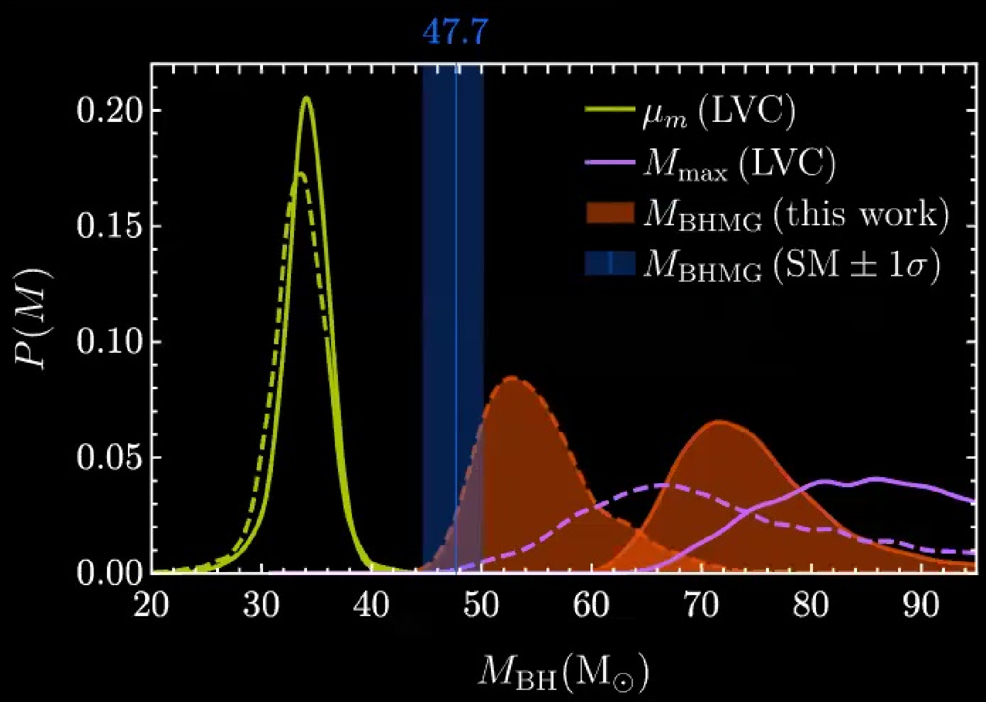

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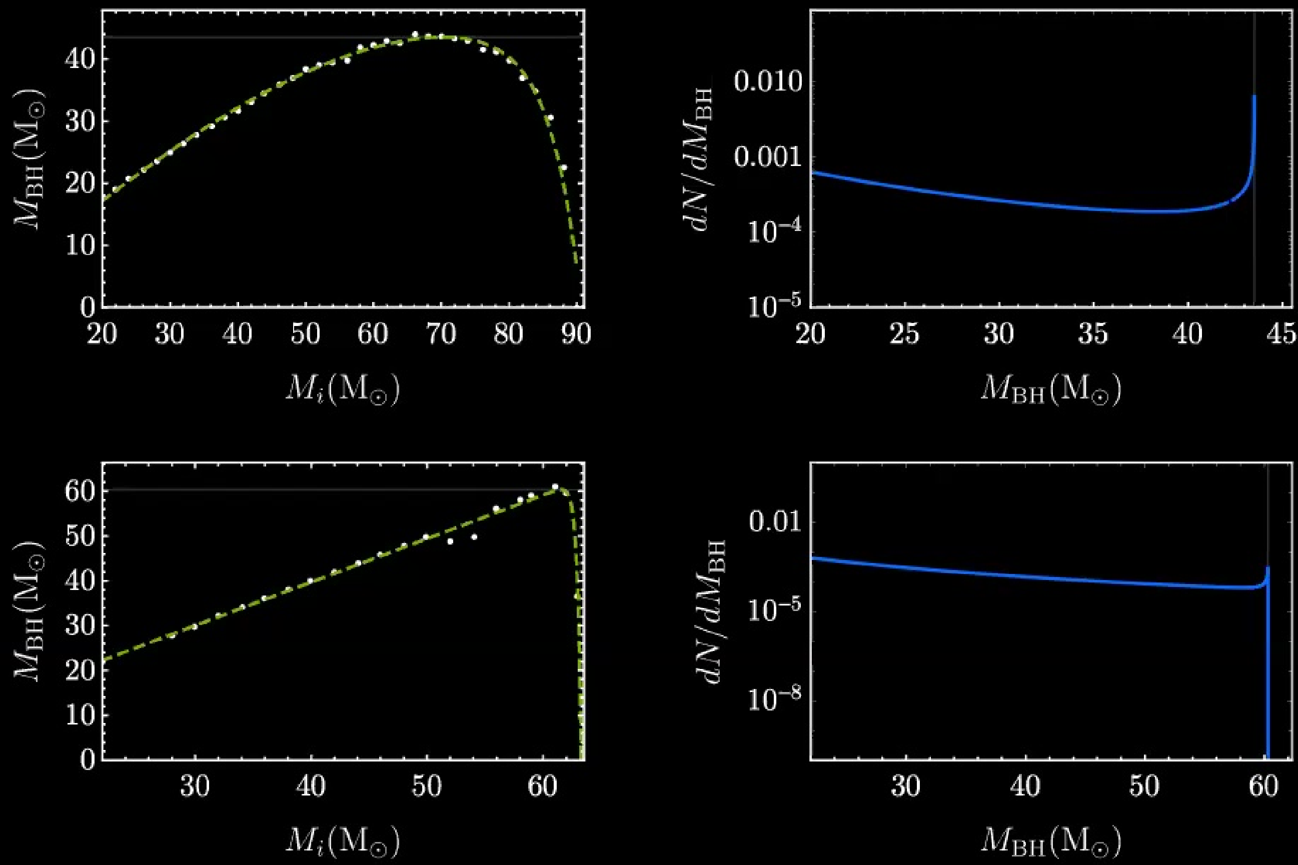
To conclude,

- 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

Pair-instability and black hole populations

SM scenario

BSM scenario (example)



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Thank you!

…ask me anything you like!

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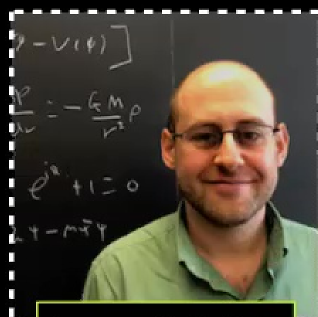
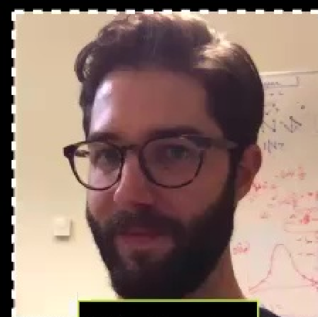
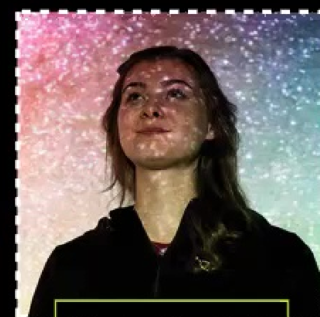
Sam McDermott



Jeremy Sakstein



Eric Baxter



Maria Straight