Black Hole Archaeology

Jeremy Sakstein (University of Hawai'i)

Nuclear Burning in Massive Stars

YITP, Kyoto University & Monash University

July 29th 2021

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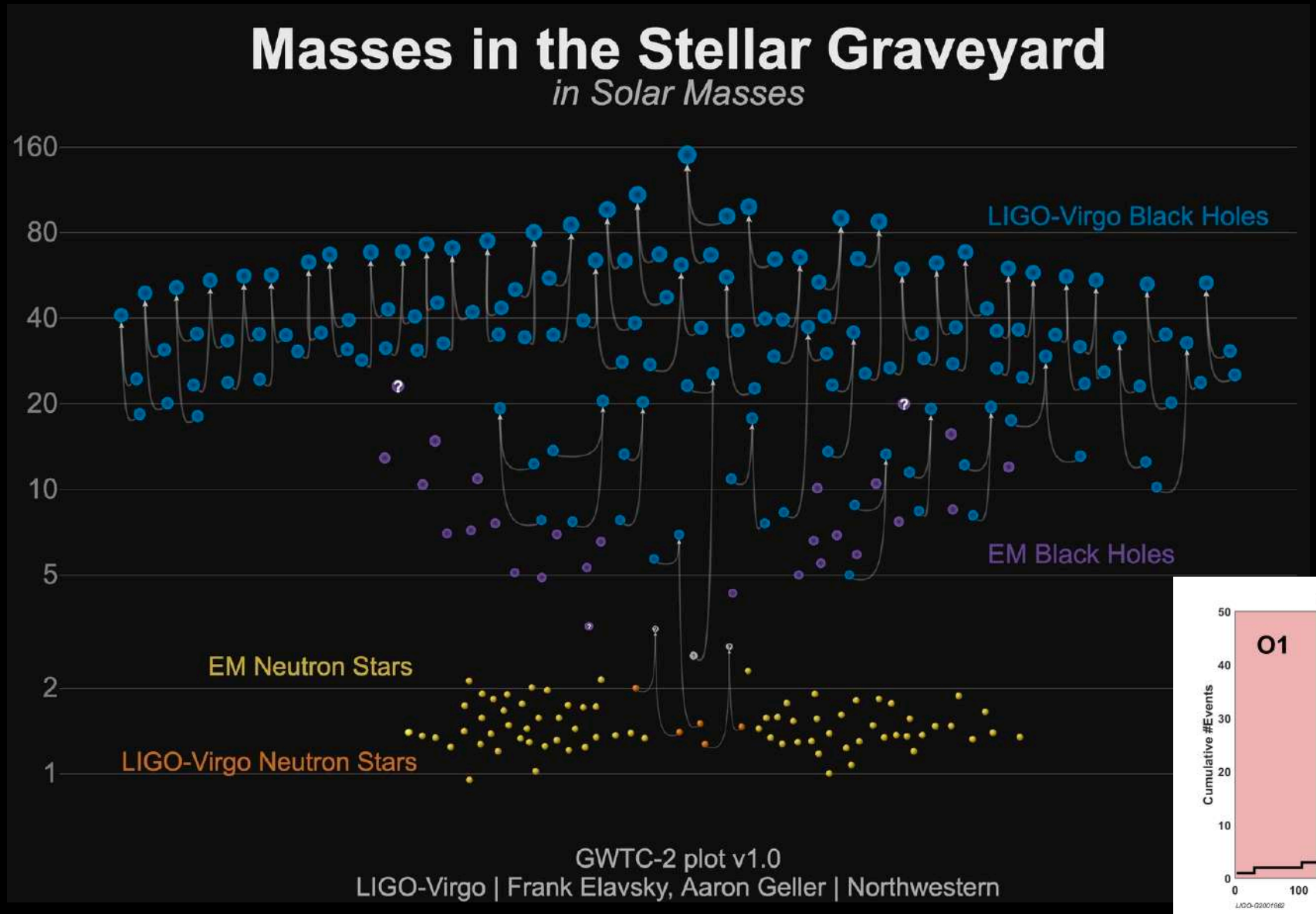
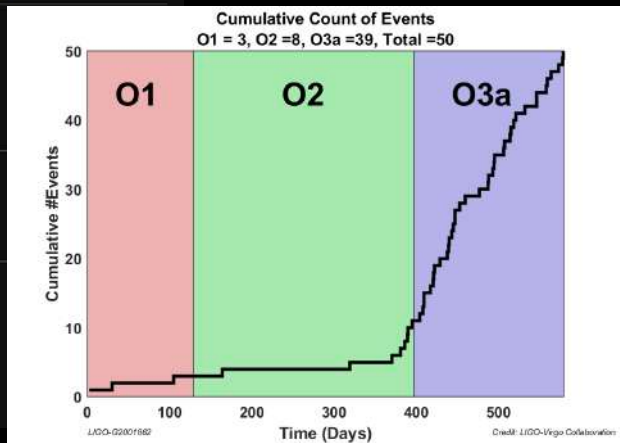
Binary mergers in LIGO/Virgo GWTC-2





Goal: test fundamental physics with GW observations

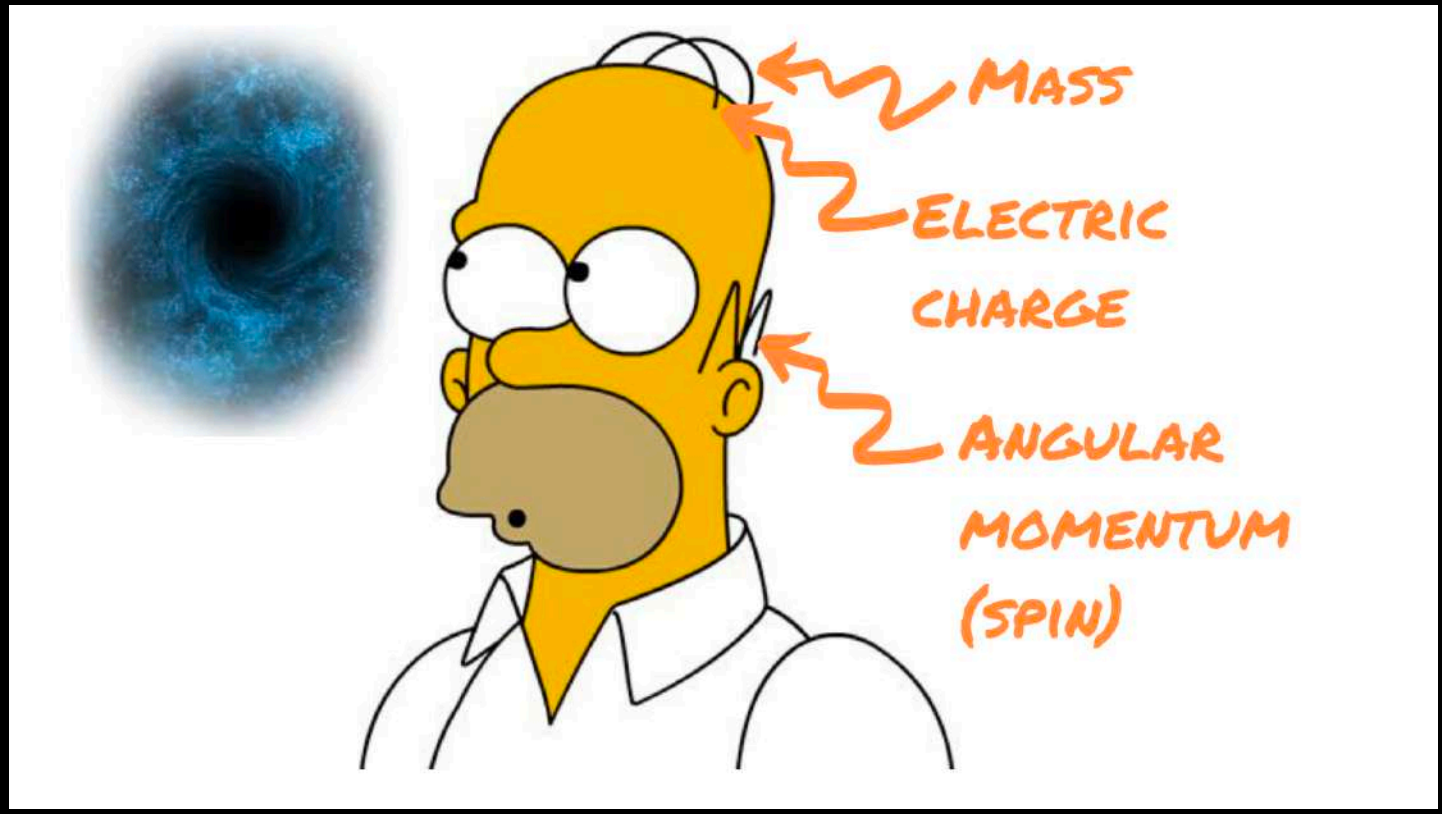
BHs are insensitive to many physical processes

No-hair theorem:

BHs are insensitive to

- Nuclear physics
- Novel particles (dark matter)
- Modified gravity (dark energy)

Their progenitor stars are not!!!



New/different physics changes how stars work

Dark energy/modified gravity

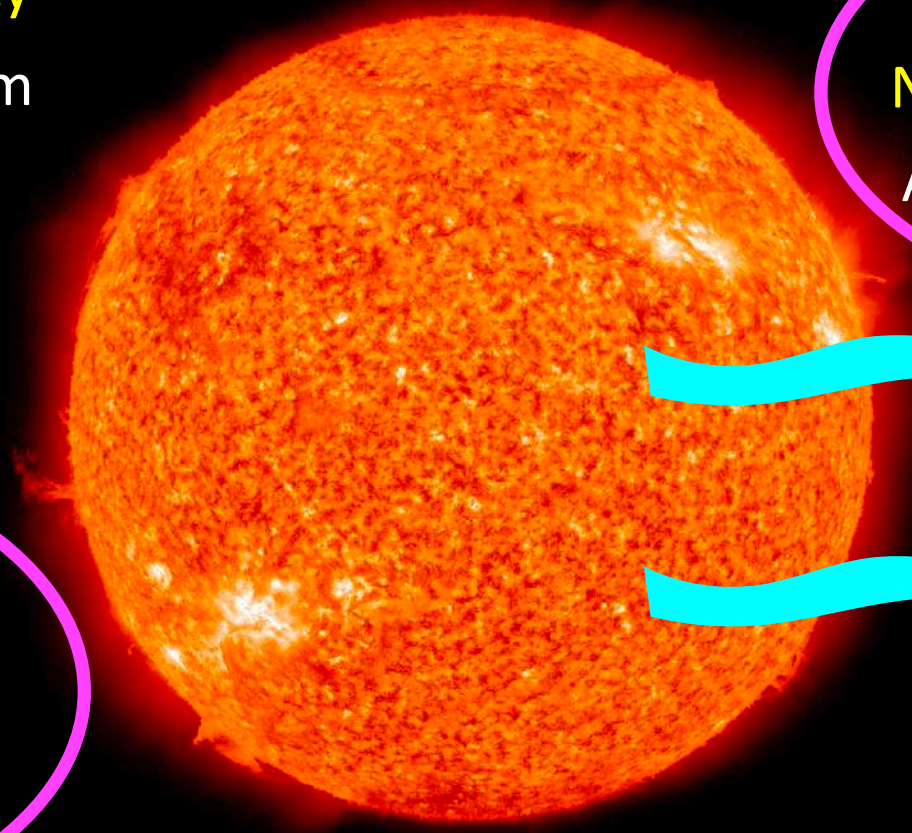
Alters hydrostatic equilibrium

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM(r)\rho(r)}{r^2}$$

Nuclear reaction rates

Triple-α & $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

Determines ratio of C-to-O after core helium burning



Today

New light particles/dark matter

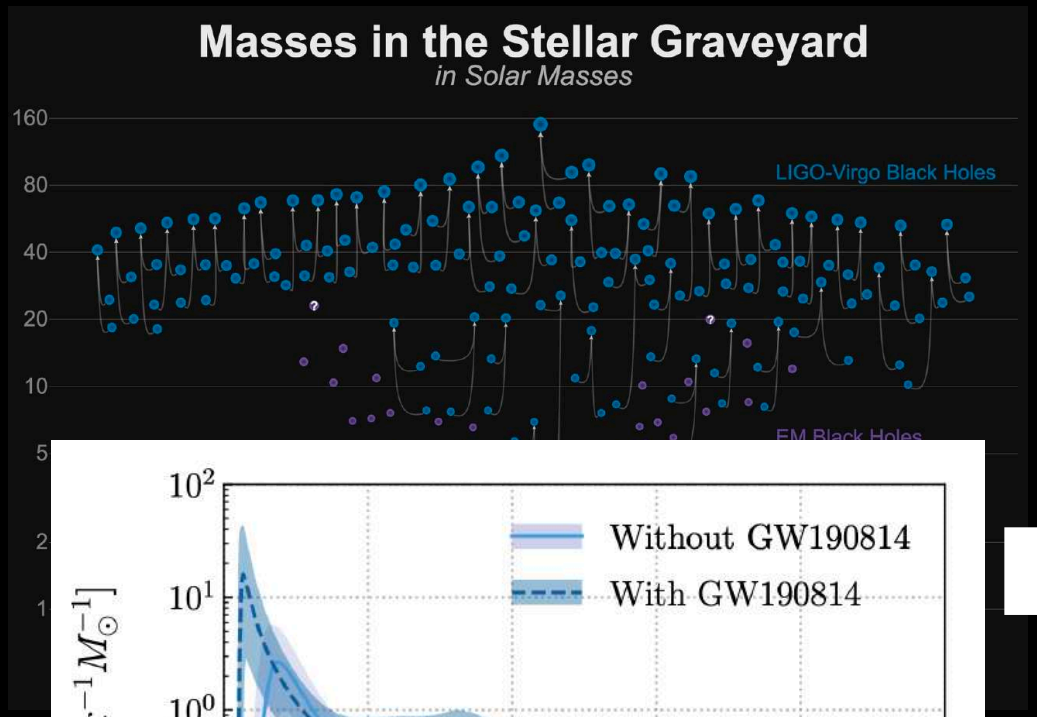
Act as a new source of losses

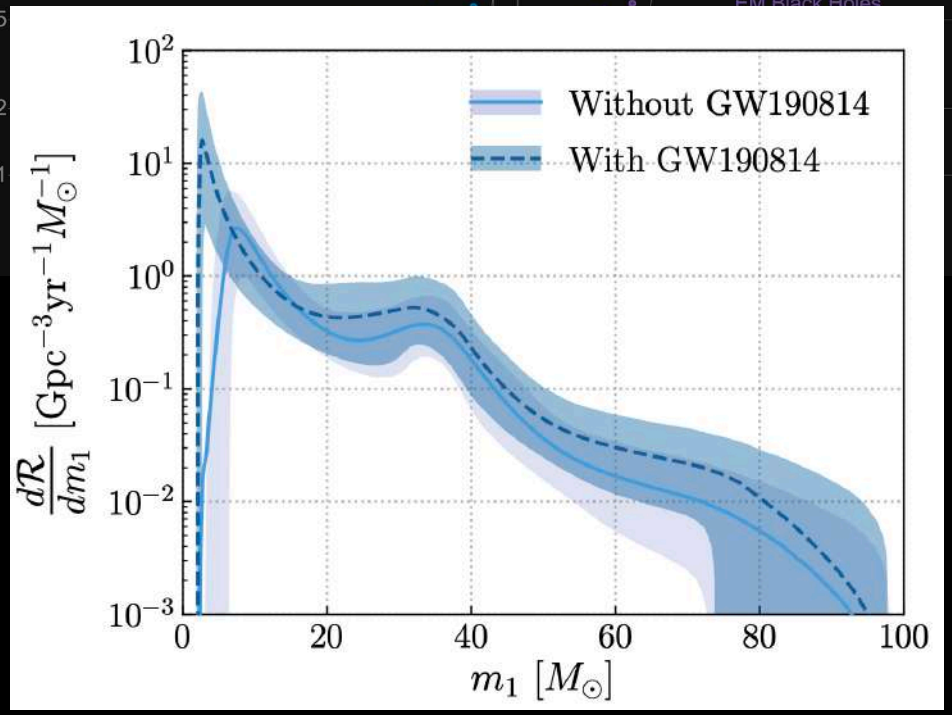
Axions

Hidden photons

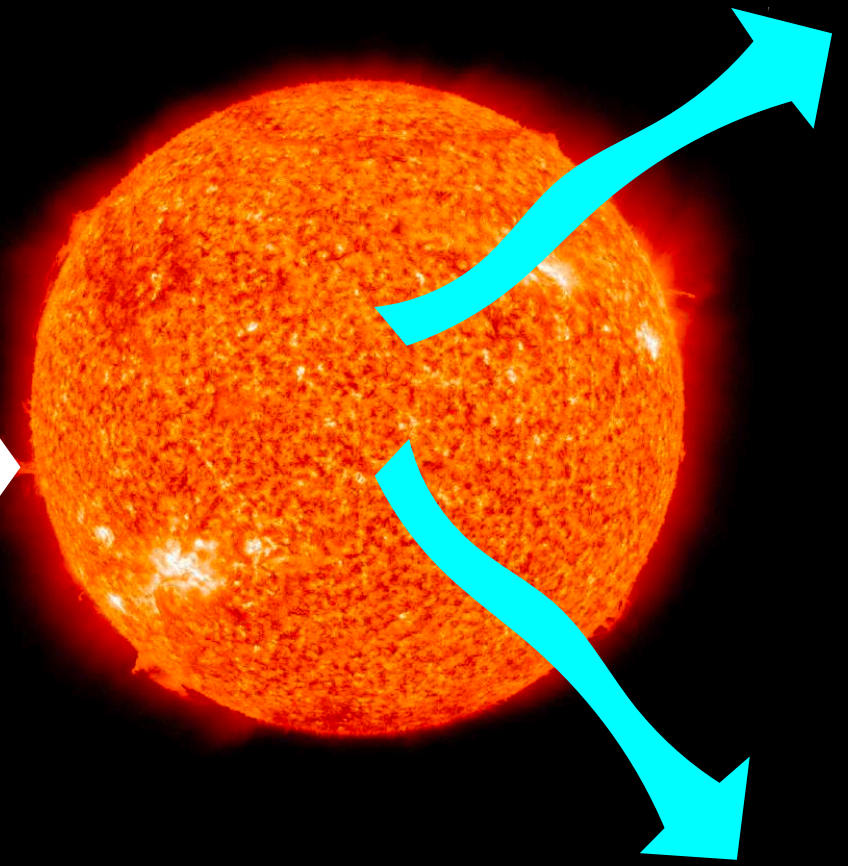
Black hole archaeology

Black hole archaeology



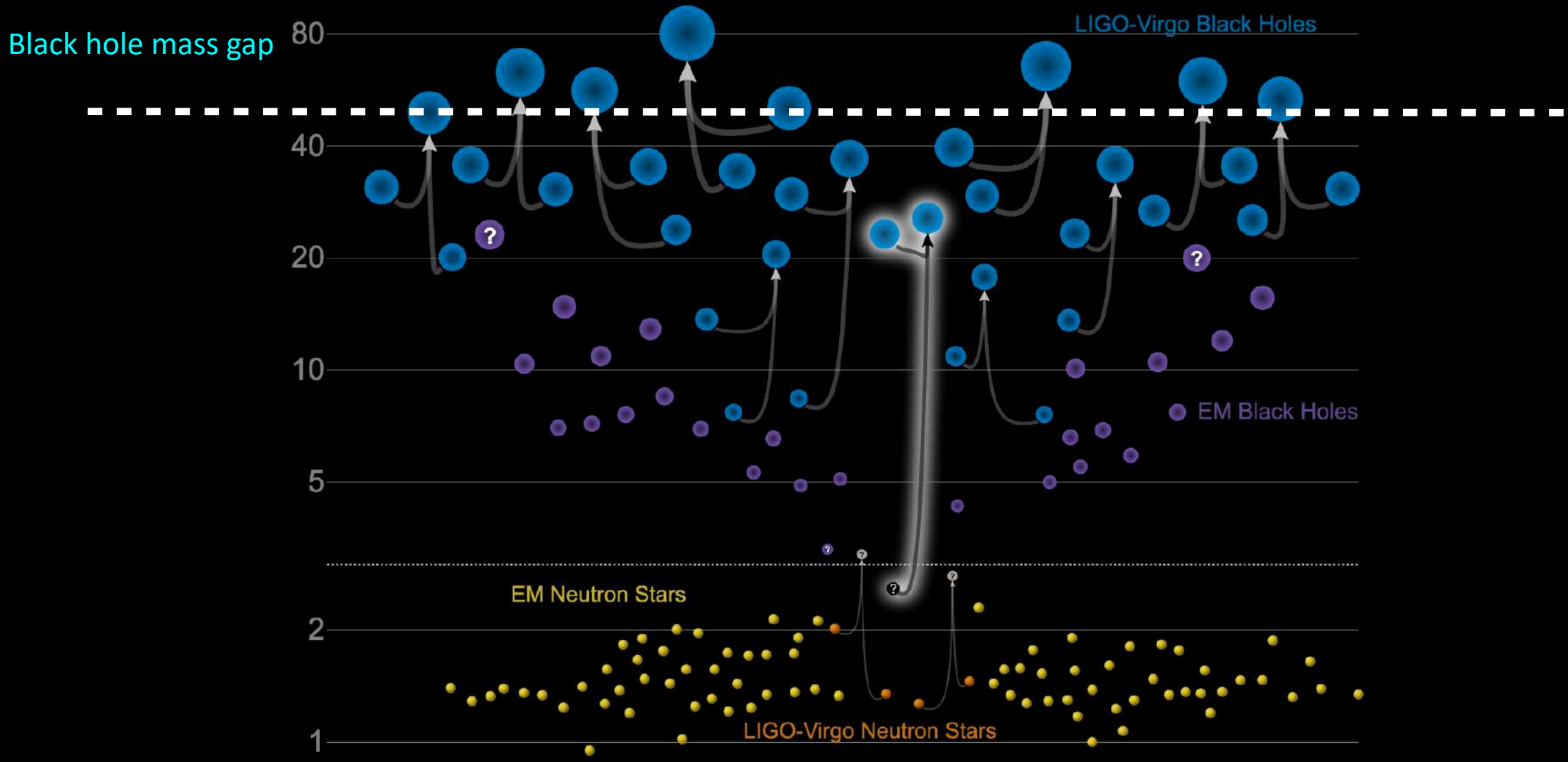


Triple-α & $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

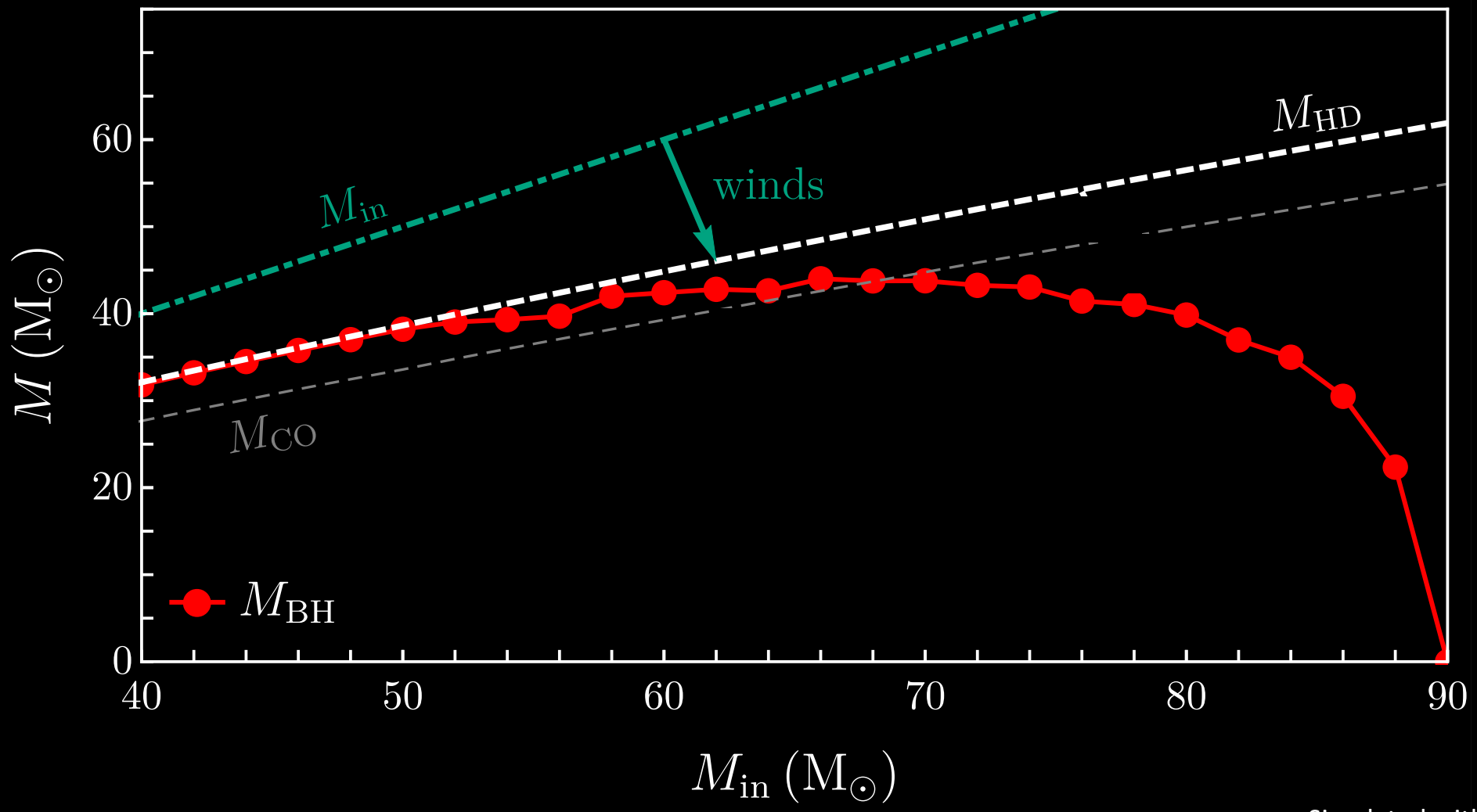


New particles?

Binary mergers in LIGO/Virgo O1+O2

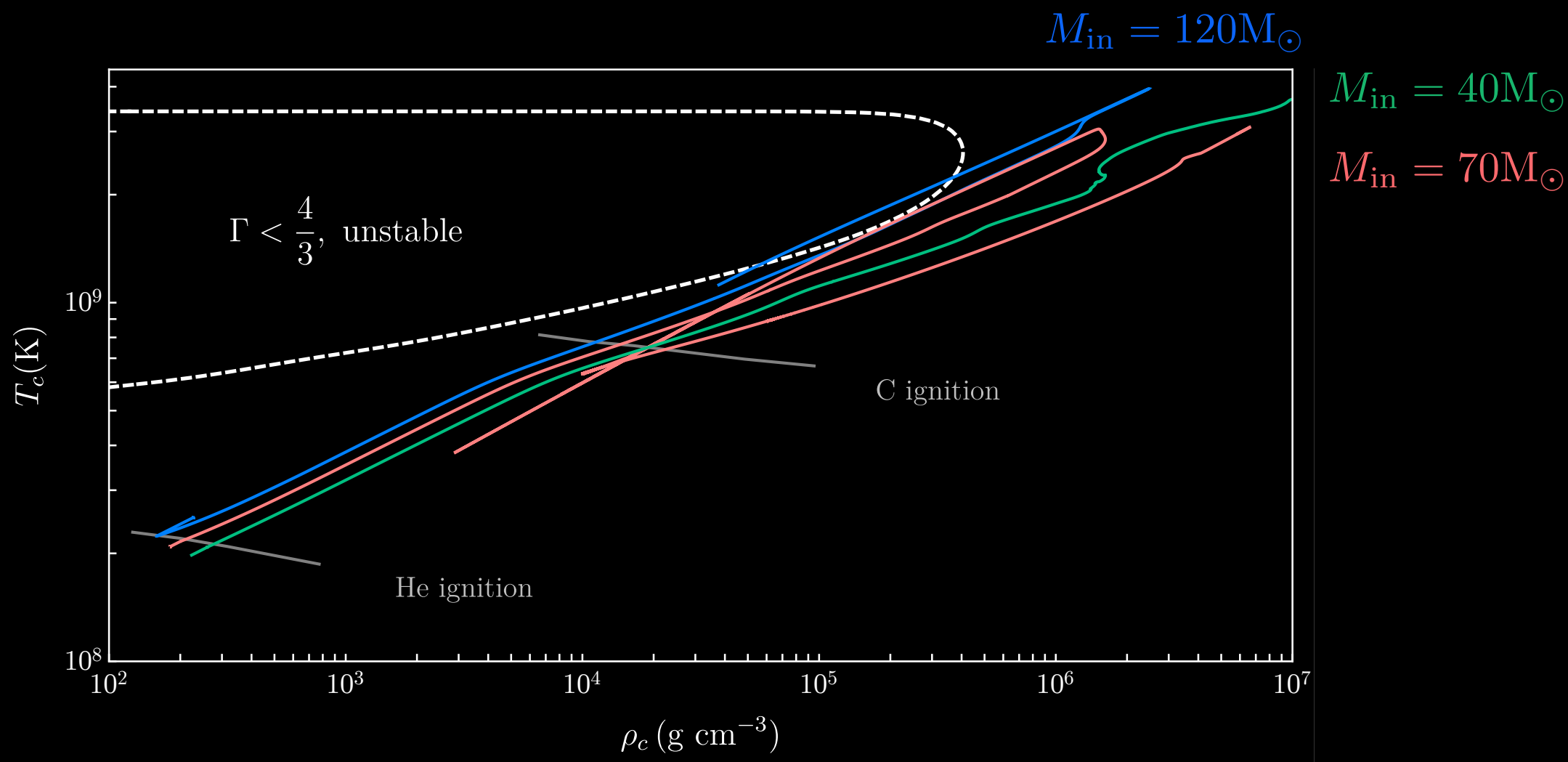


Astrophysical black holes

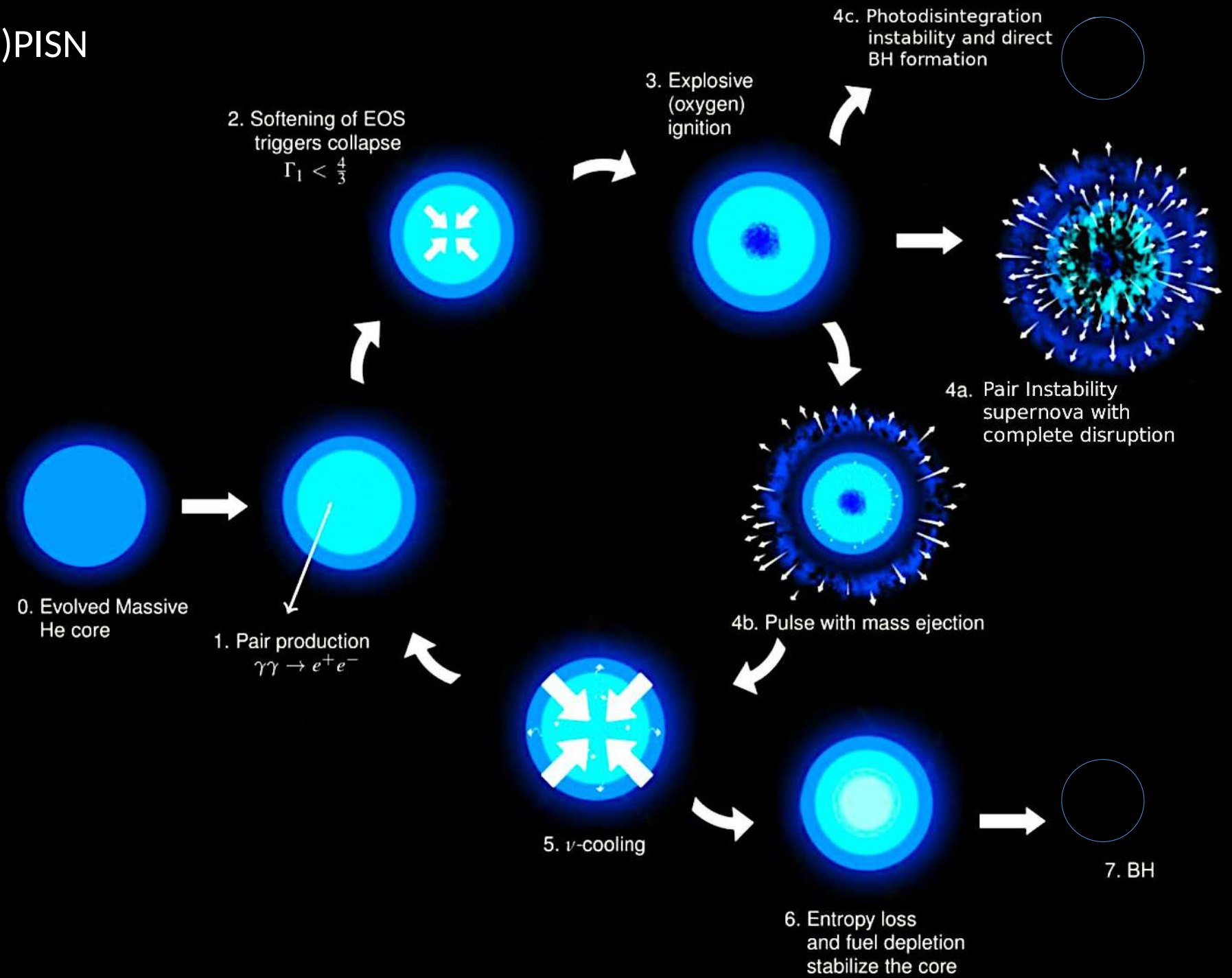


Simulated with MESA version 12778

Evolution of massive stars



(P)PISN



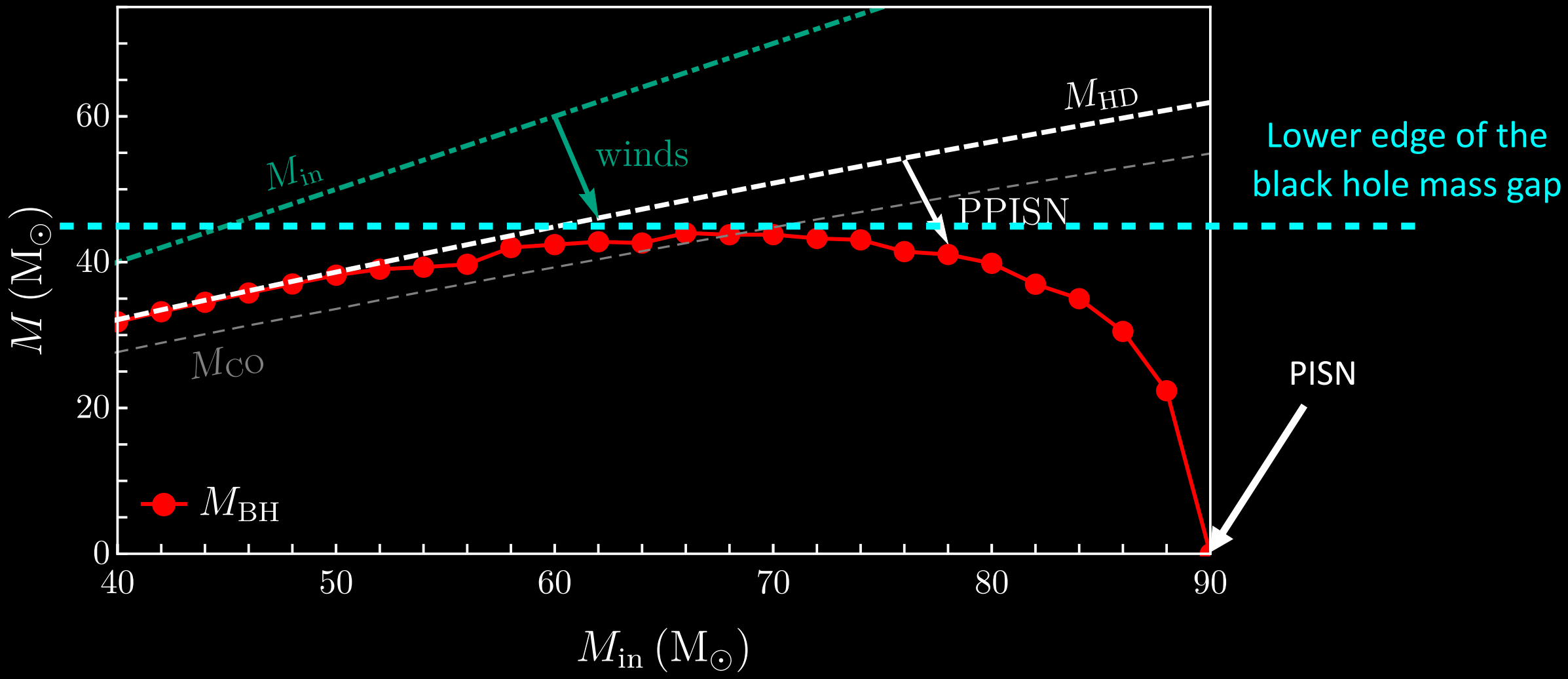
Extremely massive stars
($M_{\rm in} > 200\,{\rm M}_\odot$)

Very, very massive stars
($M_{\rm in} > 90\,{\rm M}_\odot$)

Very massive stars
($M_{\rm in} > 50\,{\rm M}_\odot$)

Croon, McDermott, JS, PRD 2020 (x2)

Astrophysical black holes

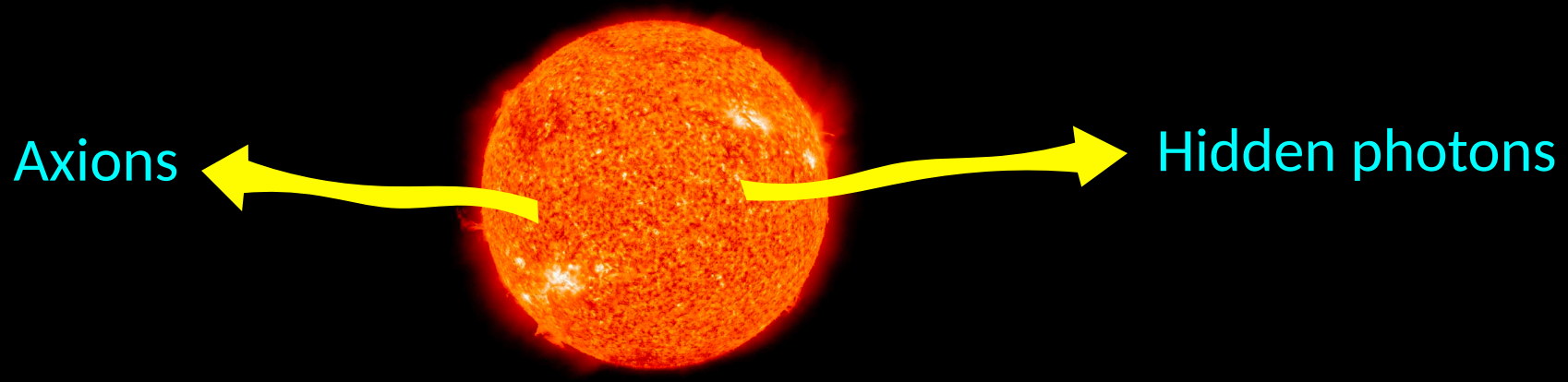


Fundamental physics and the black hole mass gap

What physics could effect the black hole mass gap?

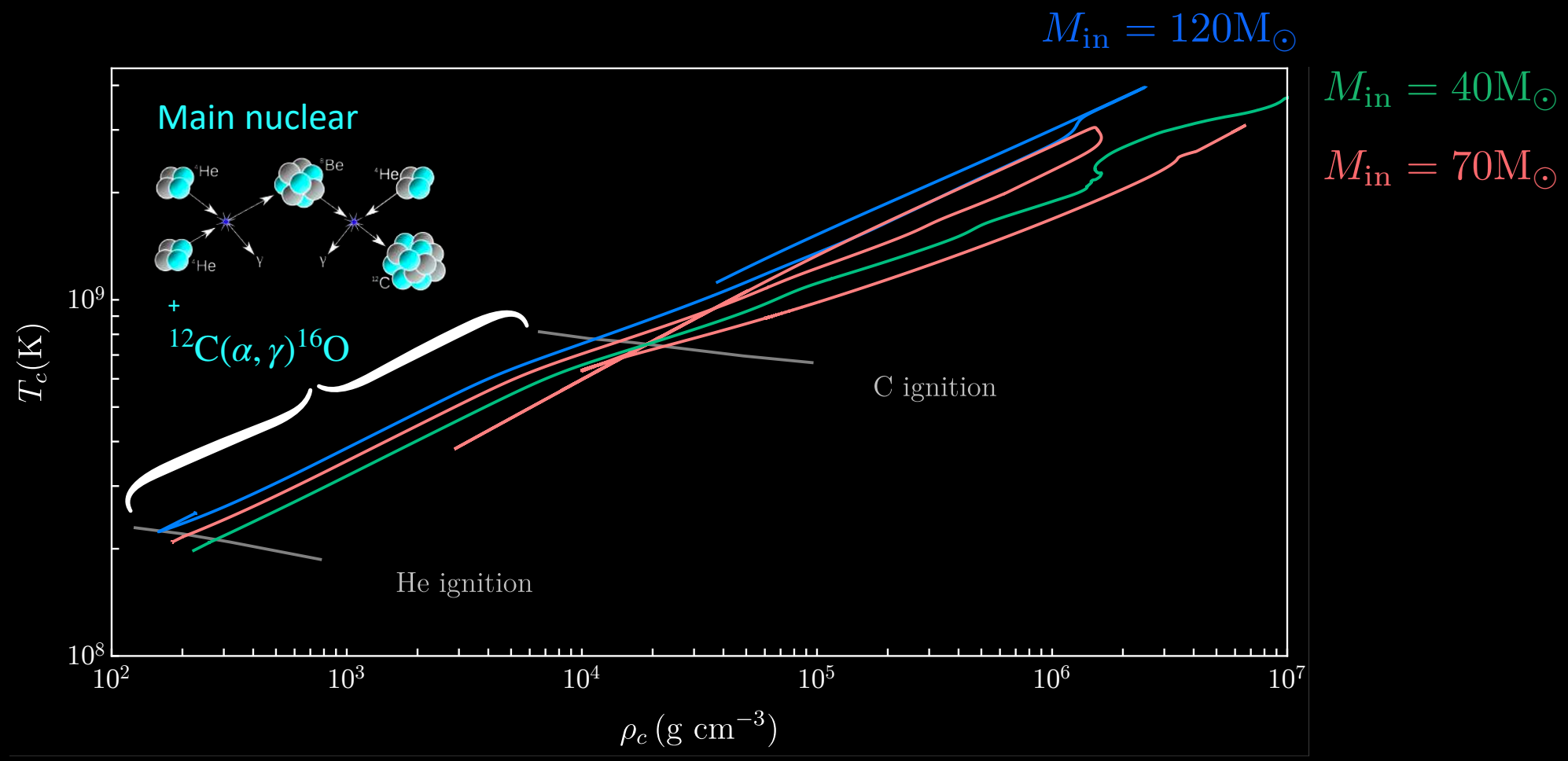
1) Nuclear reaction rates — Triple-α & $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ set ratio of $^{12}\mathrm{C}$ to $^{16}\mathrm{O}$ during pulsations

2) New light particles — act as a new source of losses similar to neutrinos



We can implement both of these into MESA

New physics and the black hole mass gap



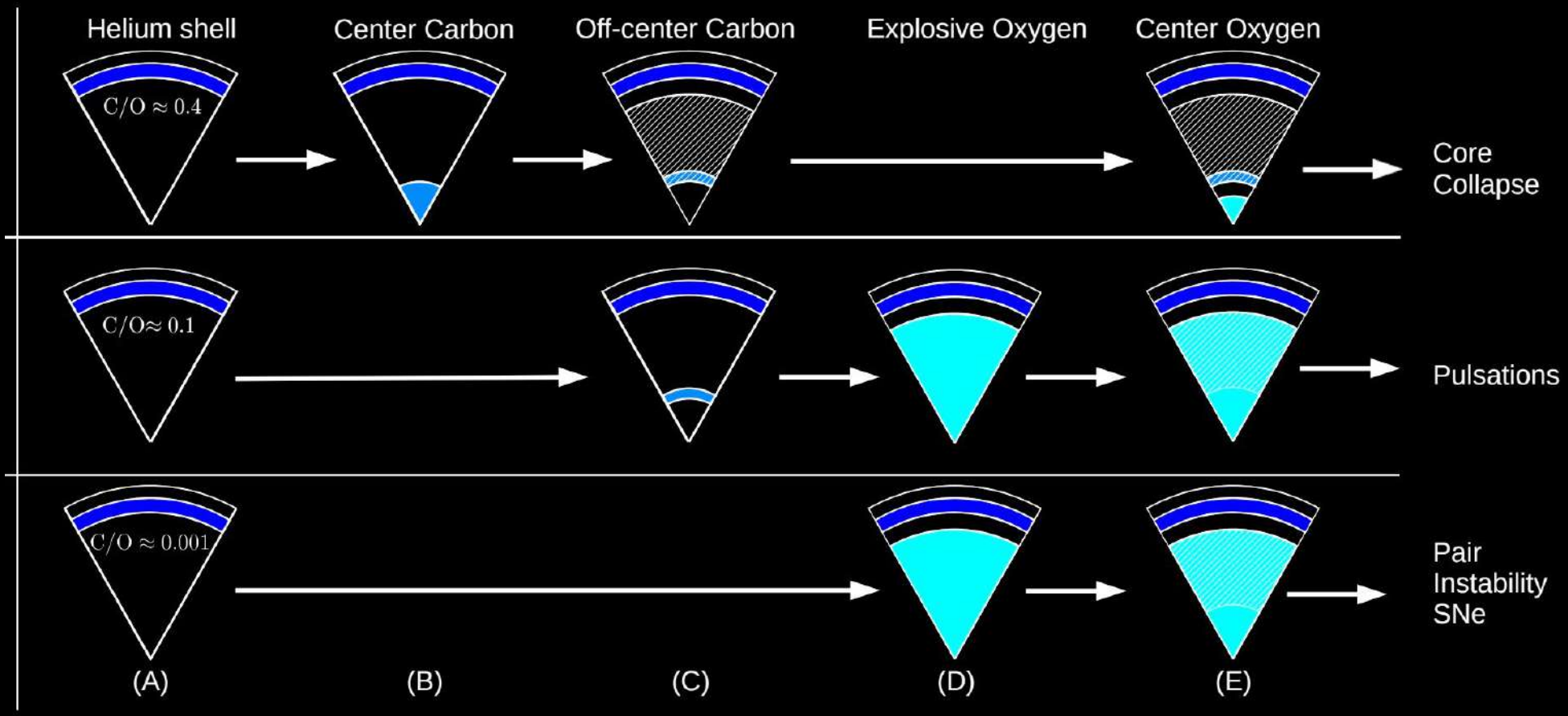
Nuclear reaction rates - $^{12}C(\alpha,\gamma)^{16}O$

Helium burning
Carbon burning
Oxygen burning

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

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

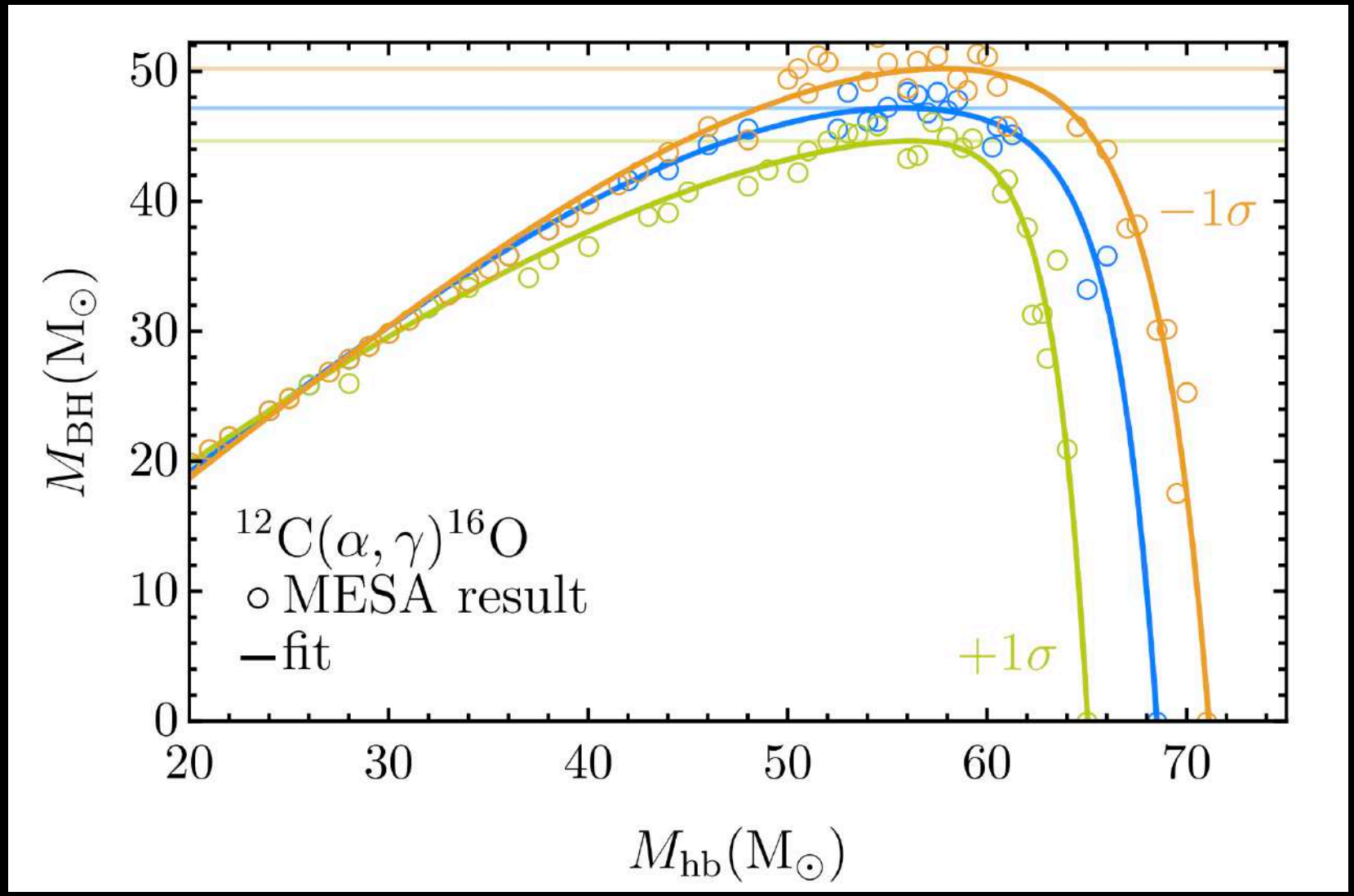
High $^{12}C(\alpha,\gamma)^{16}O$



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

Baxter, Croon, McDermott & JS 2021, ApJL

Nuclear reaction rates

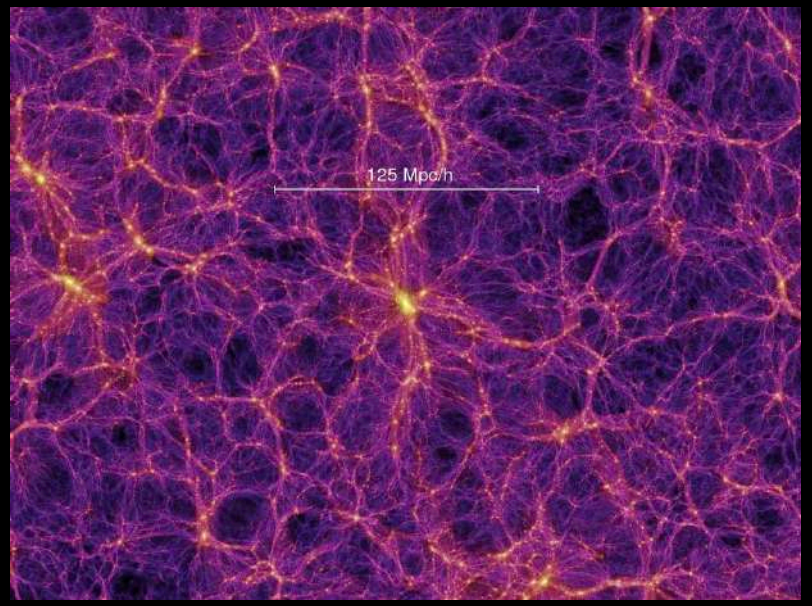


Most recent $^{12}\rm C(\alpha,\gamma)^{16}O$ rate
from de Boer, Gorres & Wiescher 2017

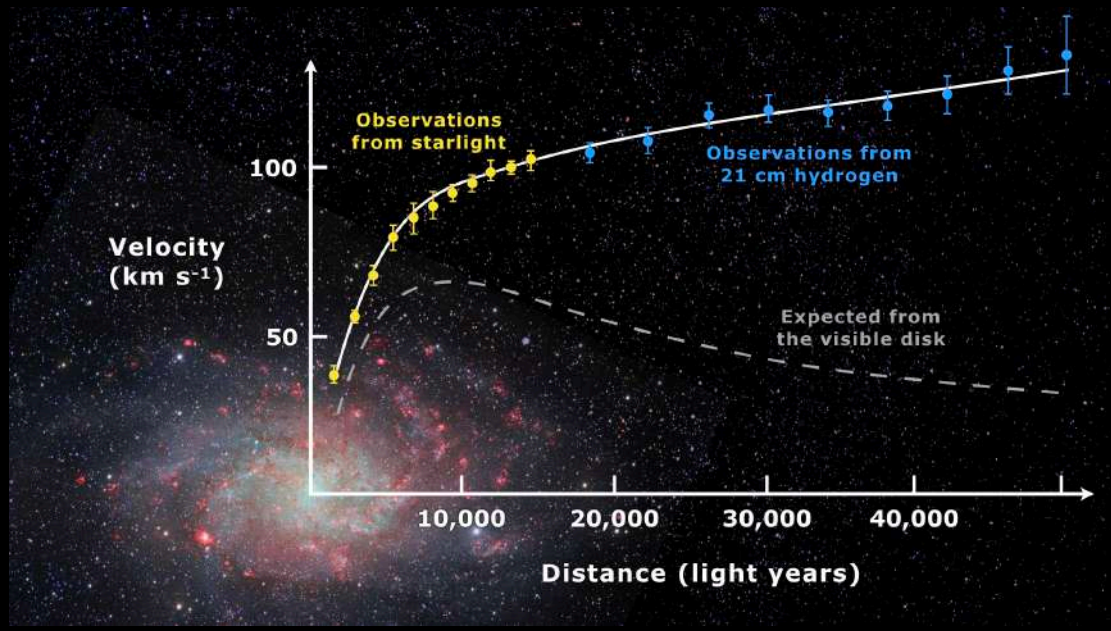
Cold dark matter (CDM)

Weakly-interacting massive particle

- Cold, collisionless, non-interacting
- Responsible for:



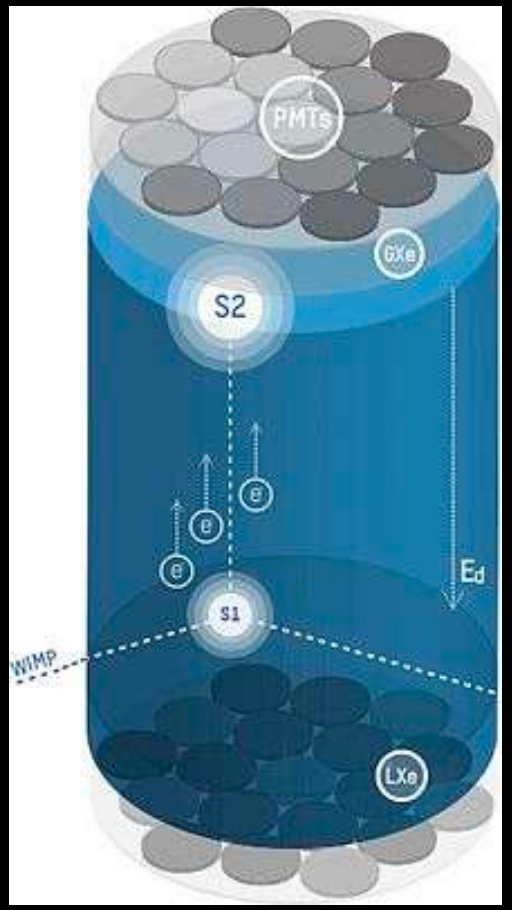
Large scale structure



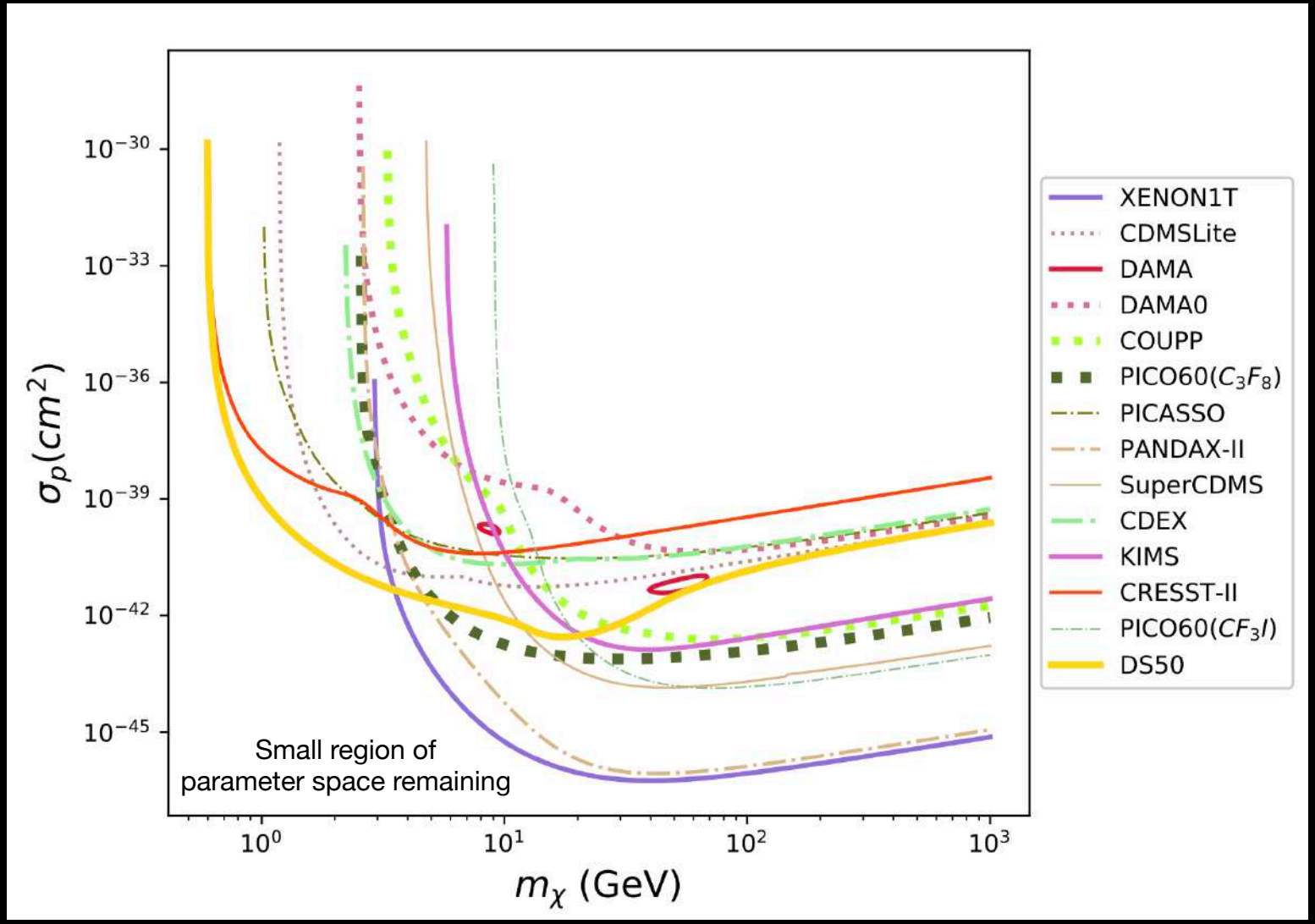
Galactic rotation curves

Problems with CDM

We haven't seen it:



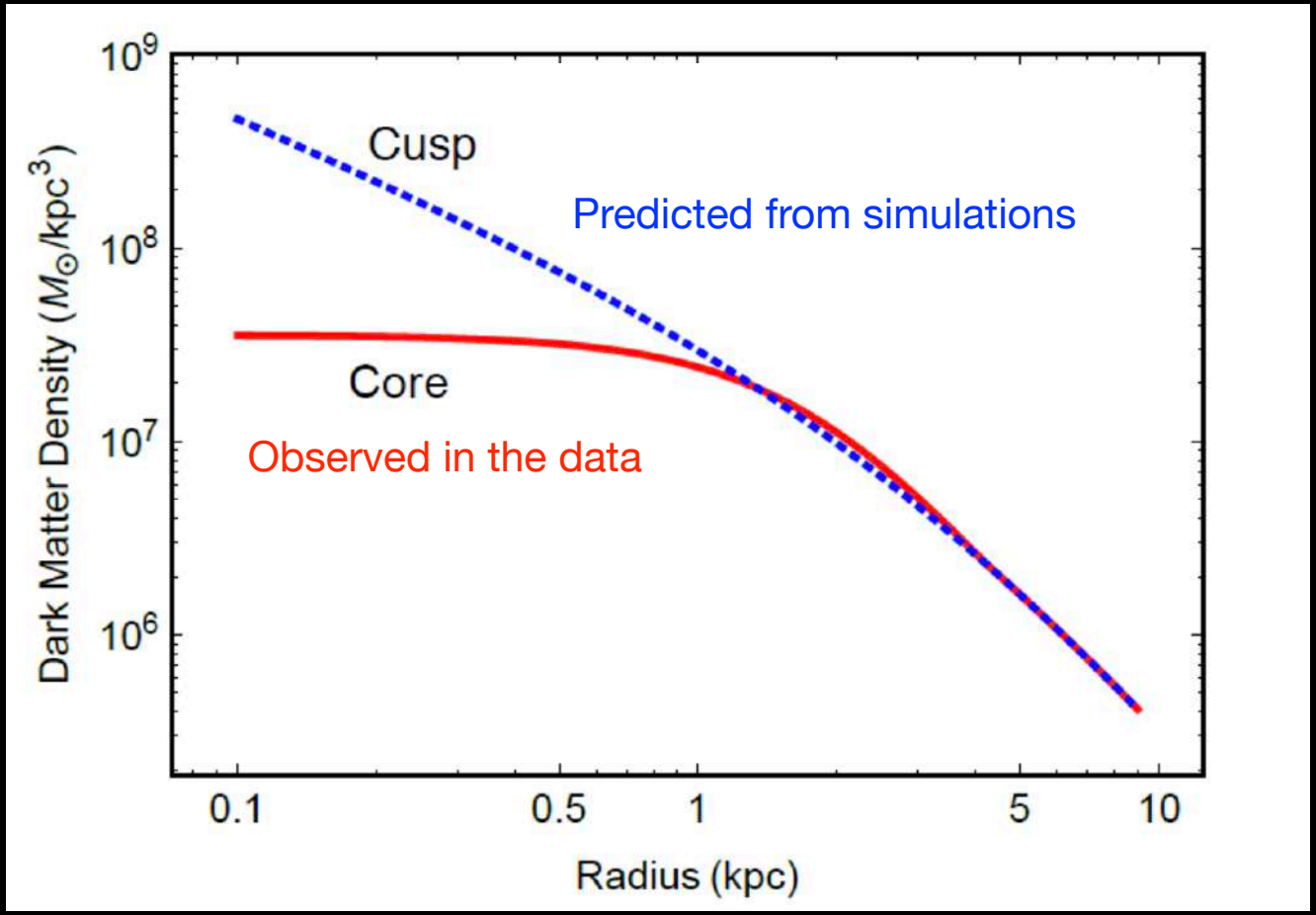
Xenon1T



Problems with CDM

Galaxy-scale astrophysical problems:

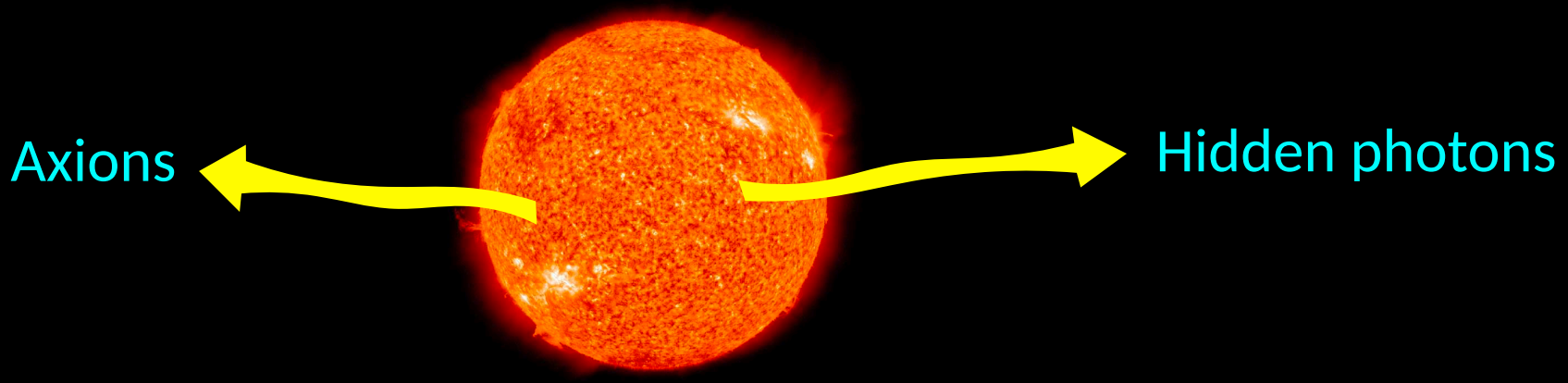
E.g. cusp-core problem



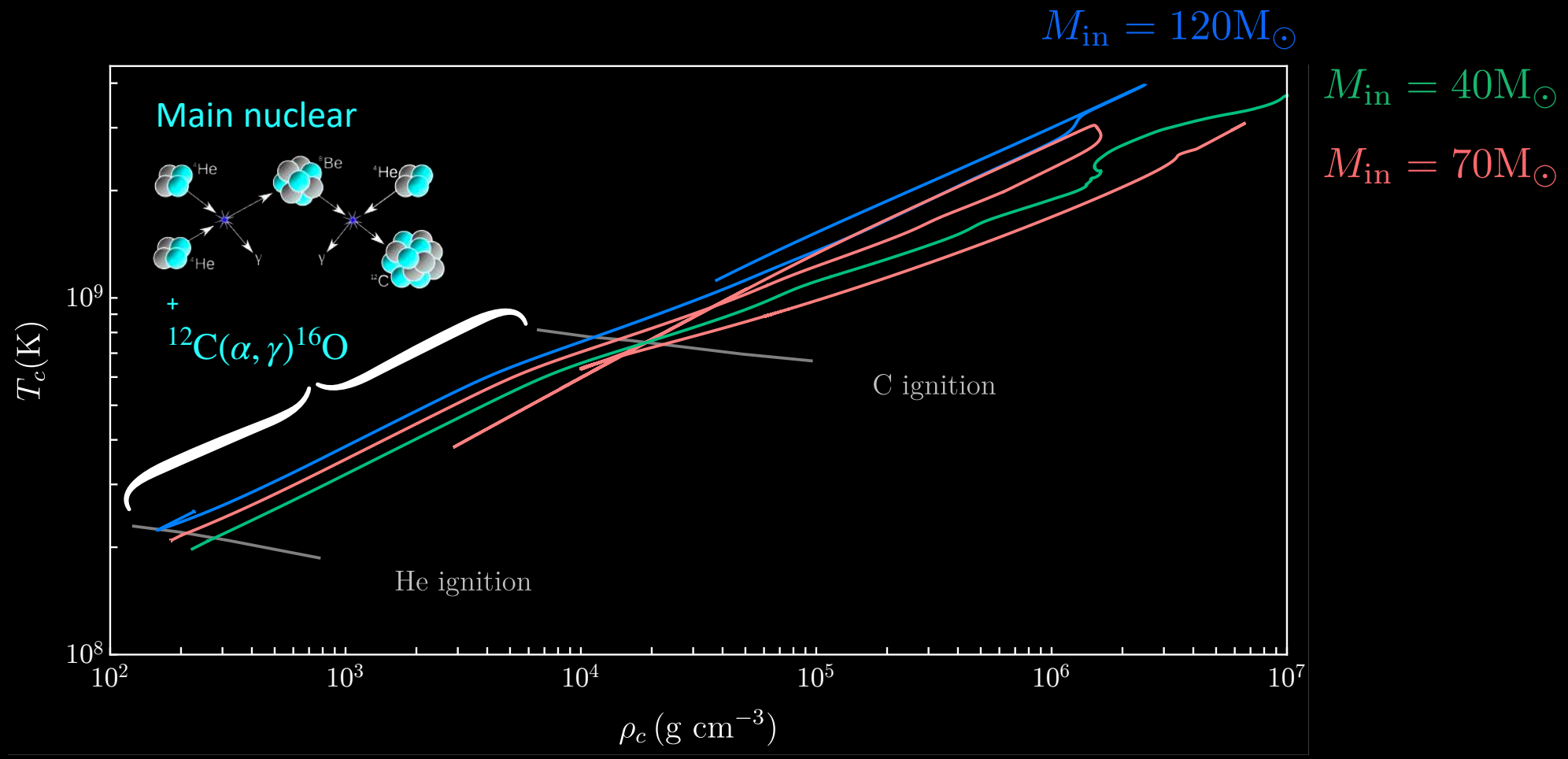
Alternatives to CDM

New light particle coupled to matter?

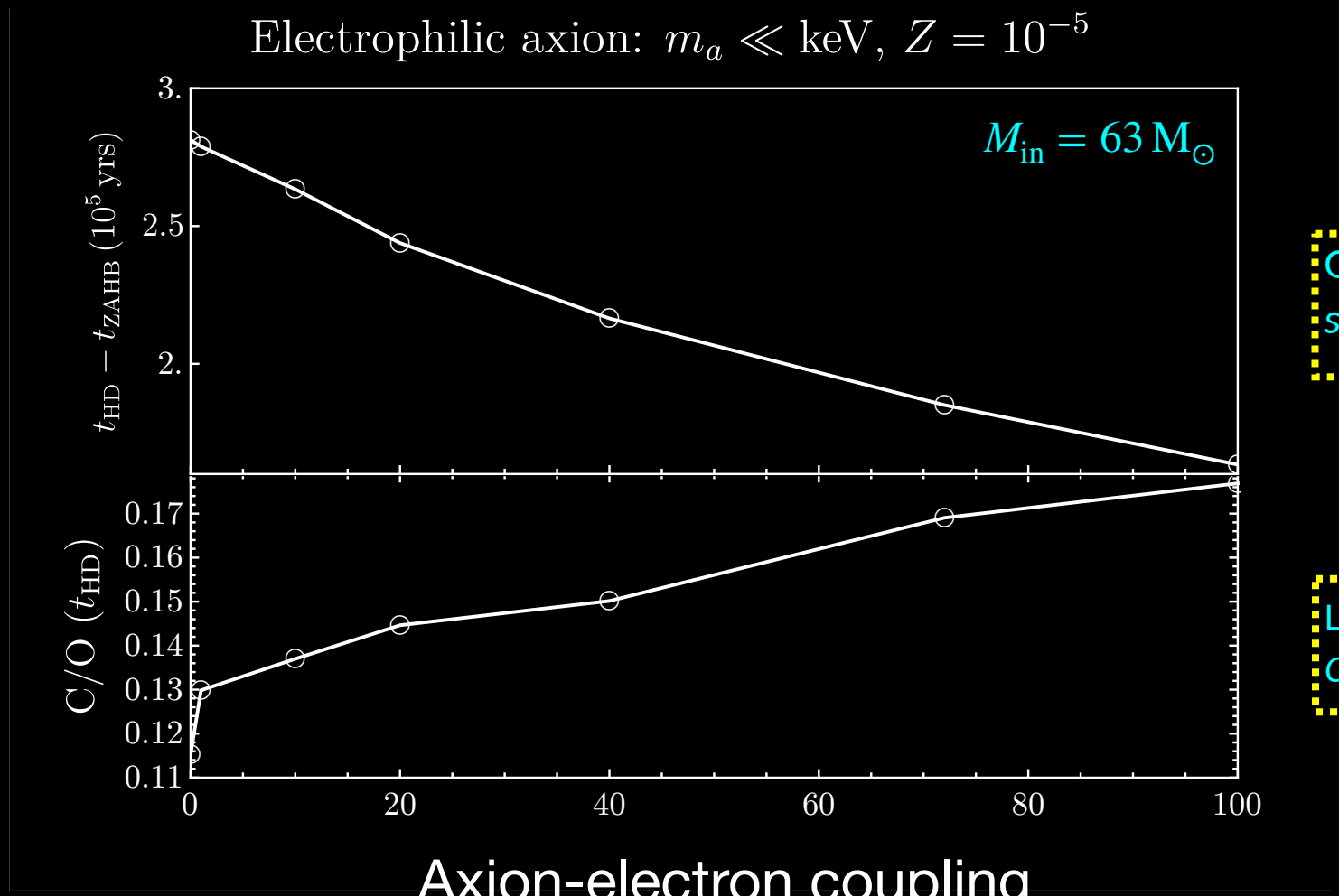
- Axions, hidden photons, milli-charged DM, ……
- Acts like CDM on large scales but solves small-scale problems
- These give rise to new loss channels in stars — can test DM with astronomy



New light particles

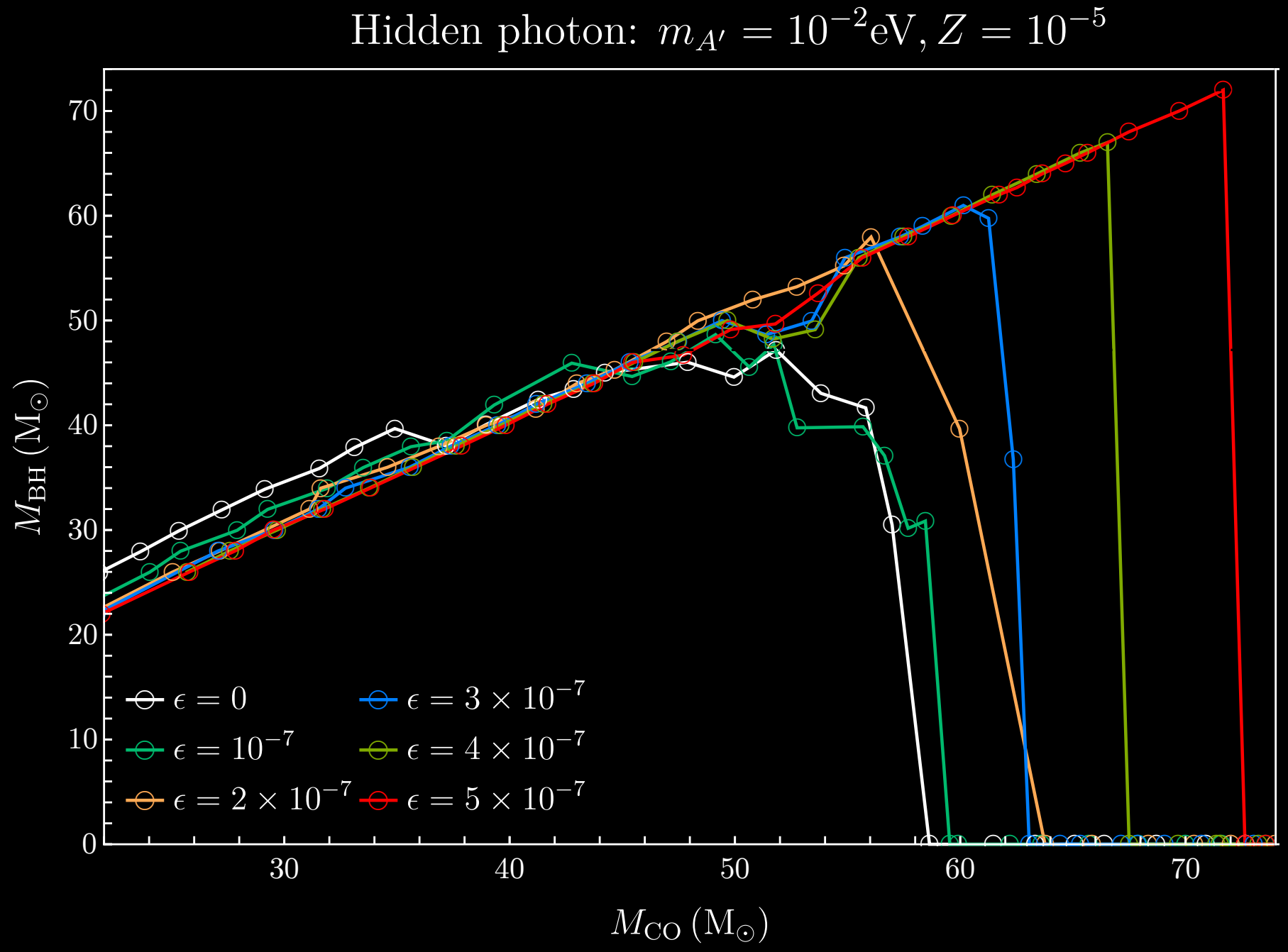


New light particles



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

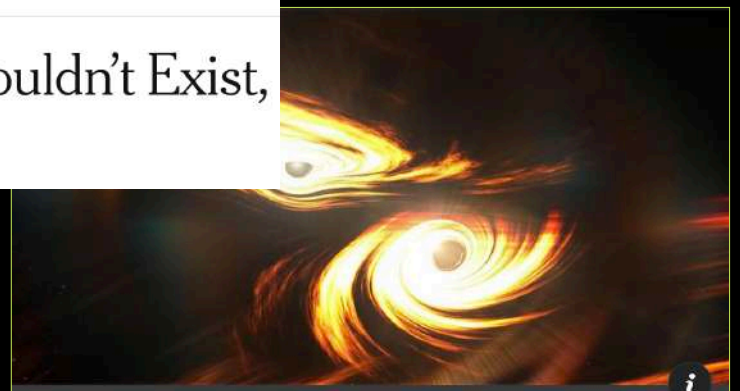
Less time for $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$:
C/O is larger at the time of helium depletion (HD)


Hidden photon: $m_{A'} = 10^{-2}\text{eV}, Z = 10^{-5}$
$M_{\rm BH}\,(\rm M_\odot)$
$M_{\rm CO}\,(\rm M_\odot)$
0
10
20
30
40
50
60
70
30
40
50
60
70
$\epsilon = 0$
$\epsilon = 10^{-7}$
$\epsilon = 2 \times 10^{-7}$
$\epsilon = 3 \times 10^{-7}$
$\epsilon = 4 \times 10^{-7}$
$\epsilon = 5 \times 10^{-7}$

Wait, didn't I hear something about the mass gap?

The New York Times

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



FORBES.COM

LIGO's Biggest Mass Merger Ever Foretells A Black Hole Revolution

Astronomers detect super-rare type of black hole for the first time

BY SOPHIE LEWIS
SEPTEMBER 3, 2020 / 7:03 AM / CBS NEWS

NewScientist
IDEEEN DIE DE WERELD VERANDEREN

BLOGS DOSSIERS RECENSIES MAGAZINE AGENDA

Zwaartekrachtsgolven van 'te zware' zwarte gaten waargenomen

Latest Issues

SCIENTIFIC AMERICAN 175

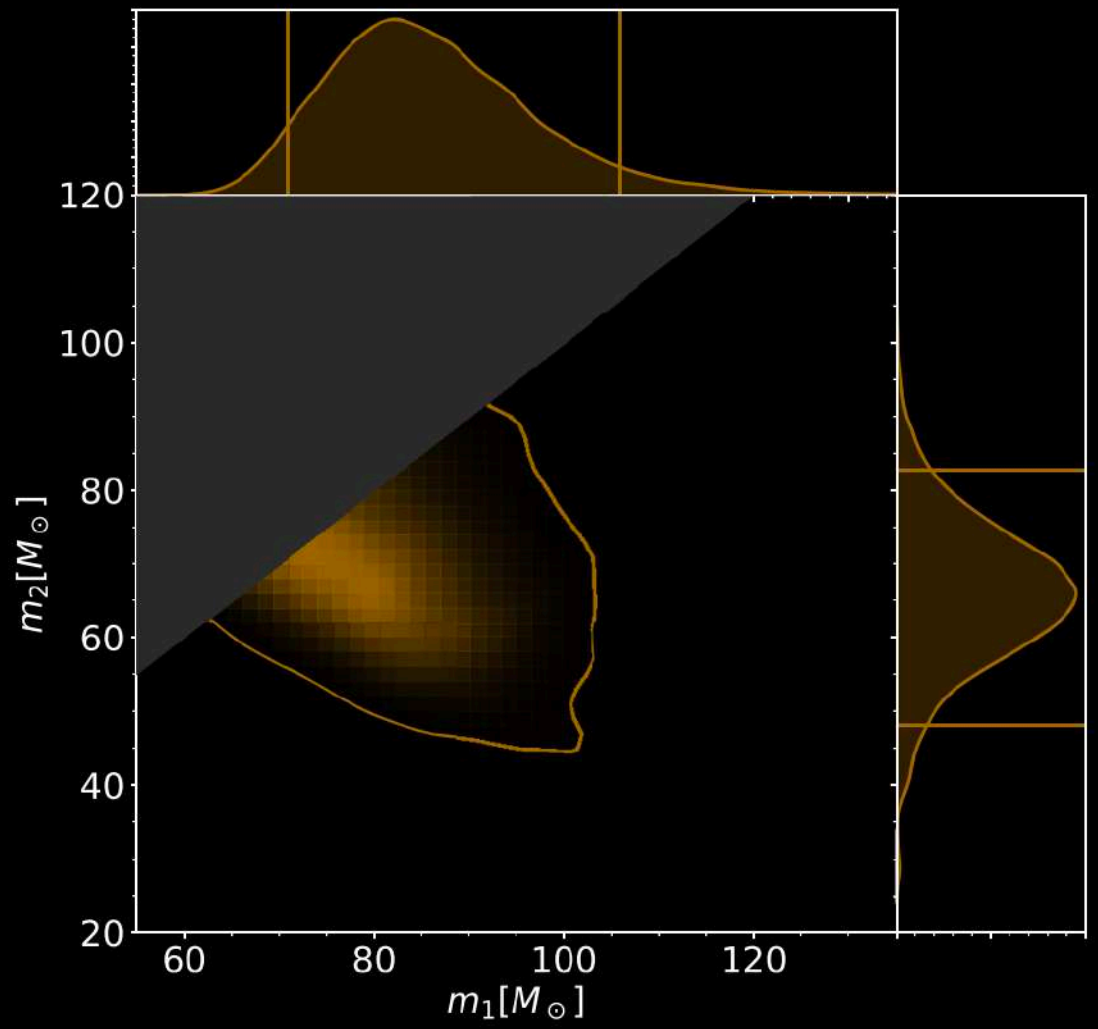
LIGO and Virgo Capture Their Most Massive Black Holes Yet

Black holes: Cosmic signal rattles Earth after 7 billion years

By Jonathan Amos
BBC Science Correspondent

GW190521

A black hole in the mass gap

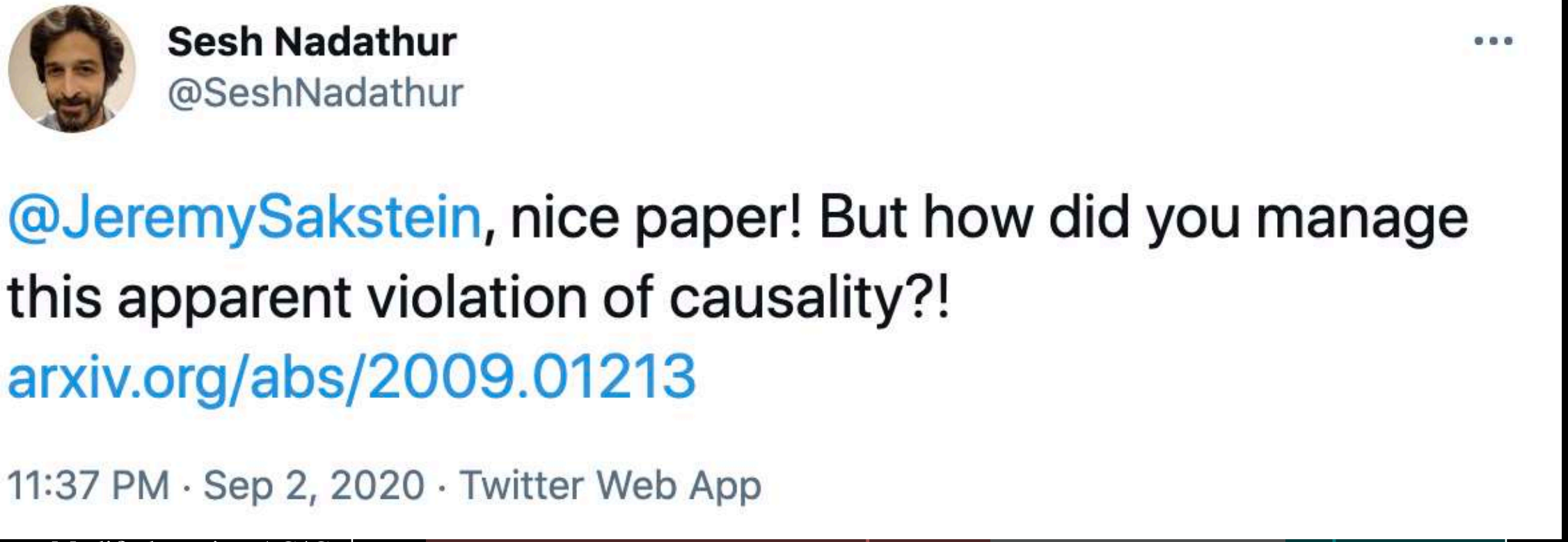


Beyond the Standard Model Explanations of GW190521

Jeremy Sakstein,[1,*] Djuna Croon,[2,†] Samuel D. McDermott,[3,‡] Maria C. Straight,[4,§] and Eric J. Baxter[5,¶]

[1] *Department of Physics & Astronomy, University of Hawai'i, Watanabe Hall, 2505 Correa Road, Honolulu, HI, 96822, USA*

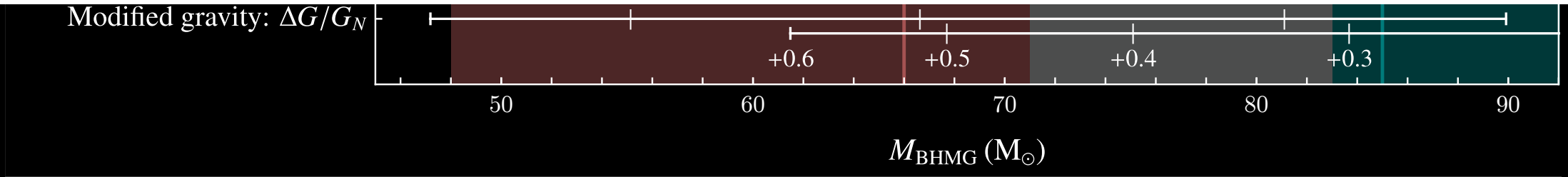
[2] *TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada*



Sesh Nadathur
@SeshNadathur

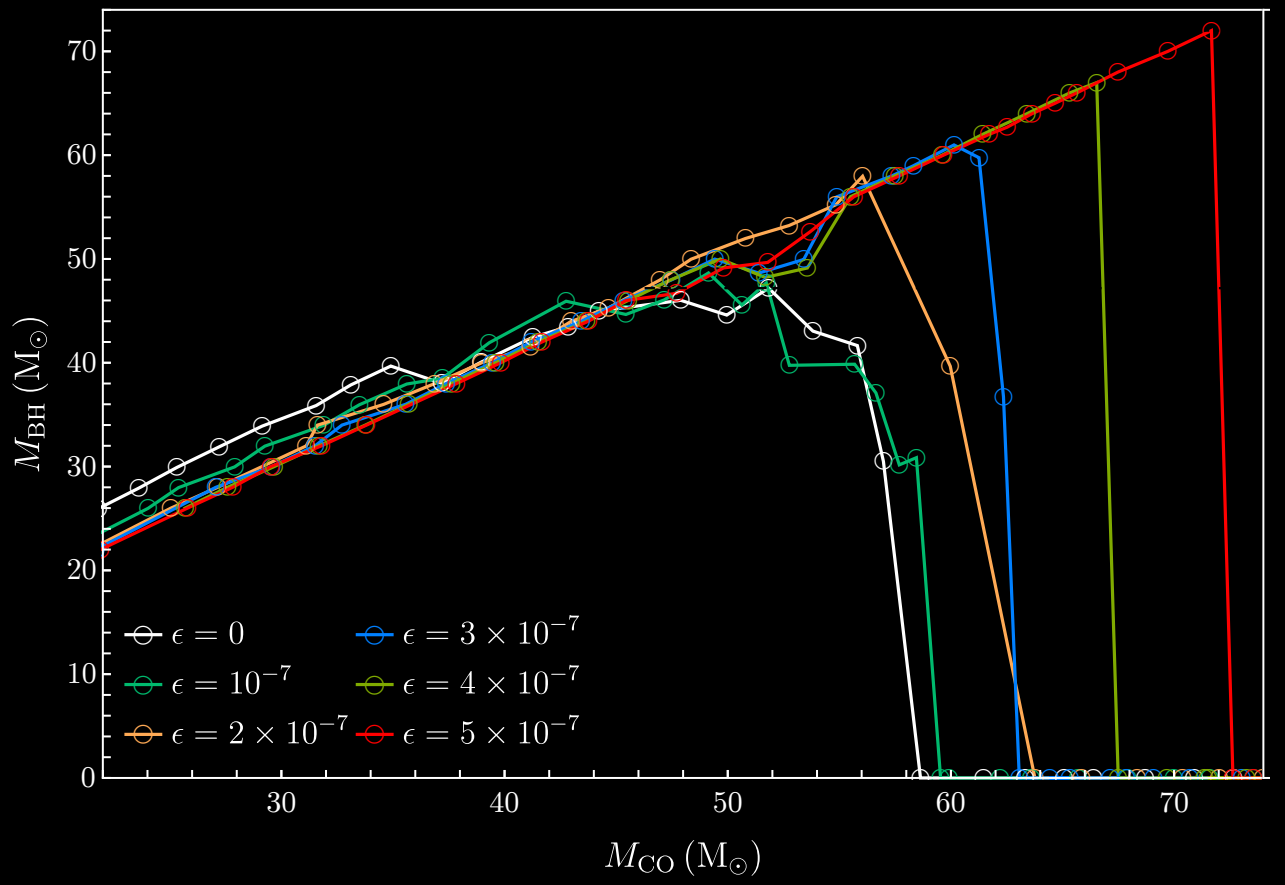
@JeremySakstein, nice paper! But how did you manage this apparent violation of causality?!
arxiv.org/abs/2009.01213

11:37 PM · Sep 2, 2020 · Twitter Web App



JS, Croon, McDermott, Straight & Baxter, PRL (2020)

Black hole archeology



Astrophysically-motivated mass function

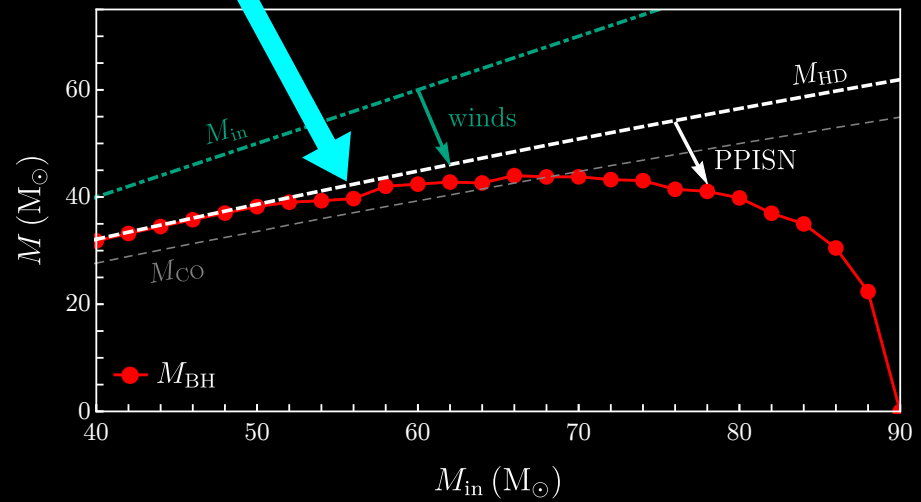
$$\frac{\mathrm{d}N_{\mathrm{BH}}}{\mathrm{d}M_{\mathrm{BH}}} = \frac{\mathrm{d}N_{\mathrm{ZAMS}}}{\mathrm{d}M_{\mathrm{ZAMS}}} \frac{\mathrm{d}M_{\mathrm{ZAMS}}}{\mathrm{d}M_{\mathrm{hb}}} \left(\frac{\mathrm{d}M_{\mathrm{BH}}}{\mathrm{d}M_{\mathrm{hb}}} \right)^{-1}$$

Black hole mass function (what we want)

Initial mass function (IMF)

ZAMS -> helium burning transfer function

Derivative of this



Baxter, Croon, McDermott & JS (2021)

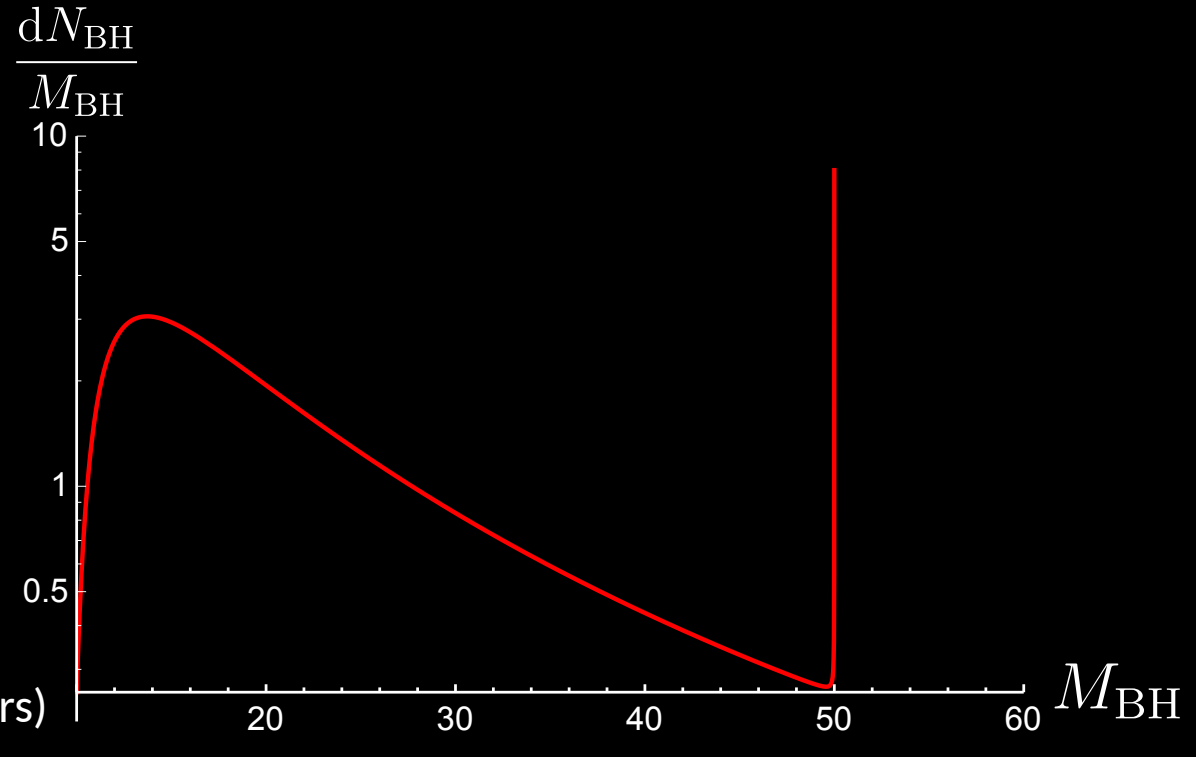
Astrophysically-motivated mass function

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

Three physical parameters:

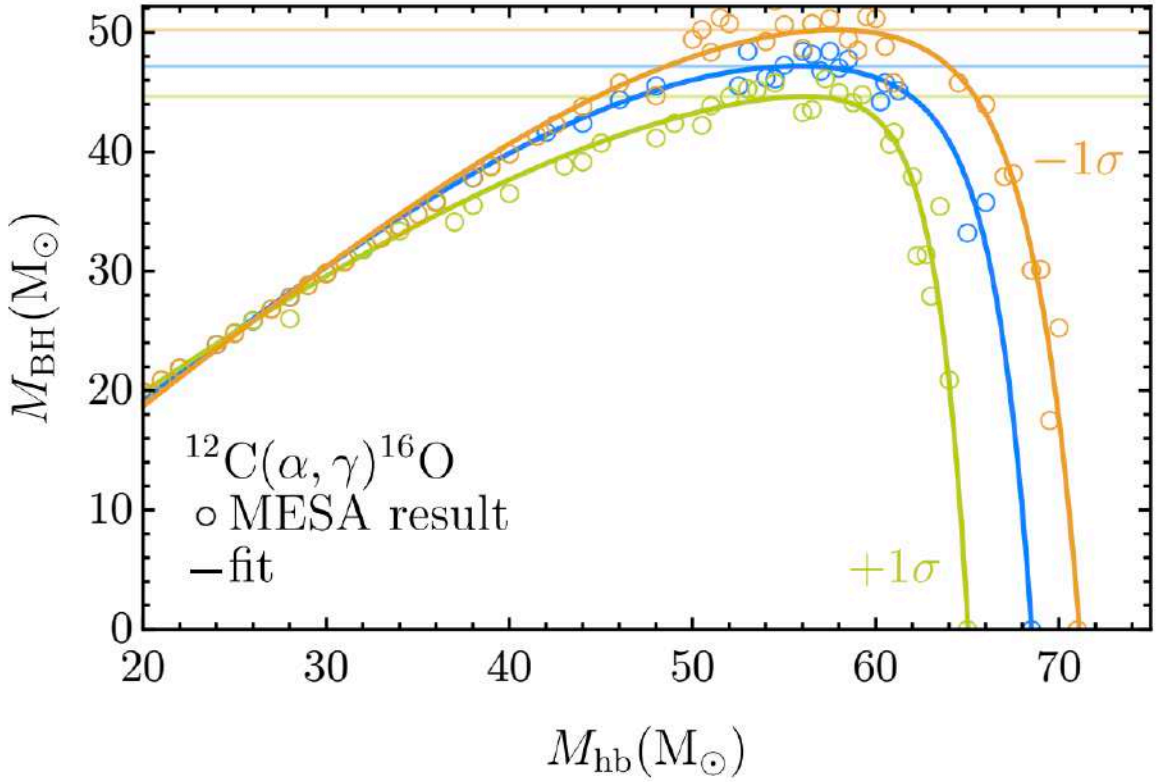
- $M_{\rm BHMG}$ — edge of the black hole mass gap
- a — sharpness of the peak
- b — IMF + transfer function

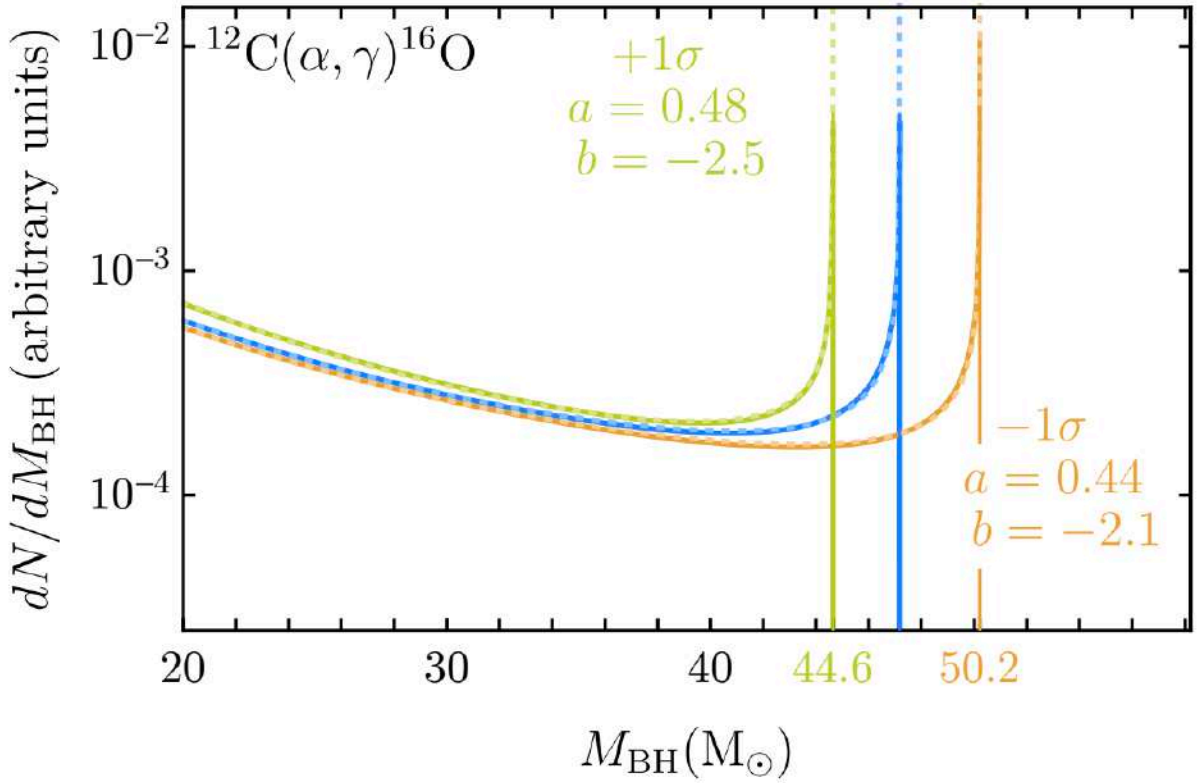
+2 low-mass smoothing parameters + second-gen BHs (2 parameters)



Baxter, Croon, McDermott & JS (2021)

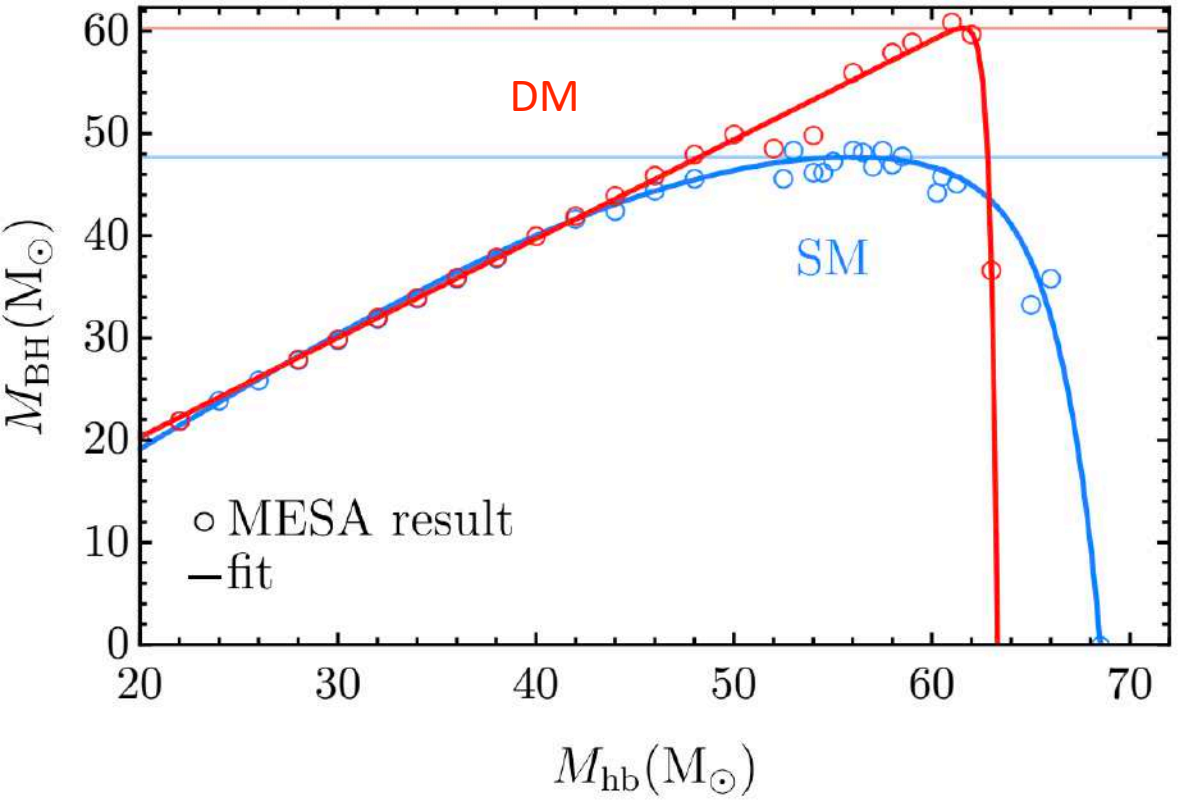
Nuclear reaction rates

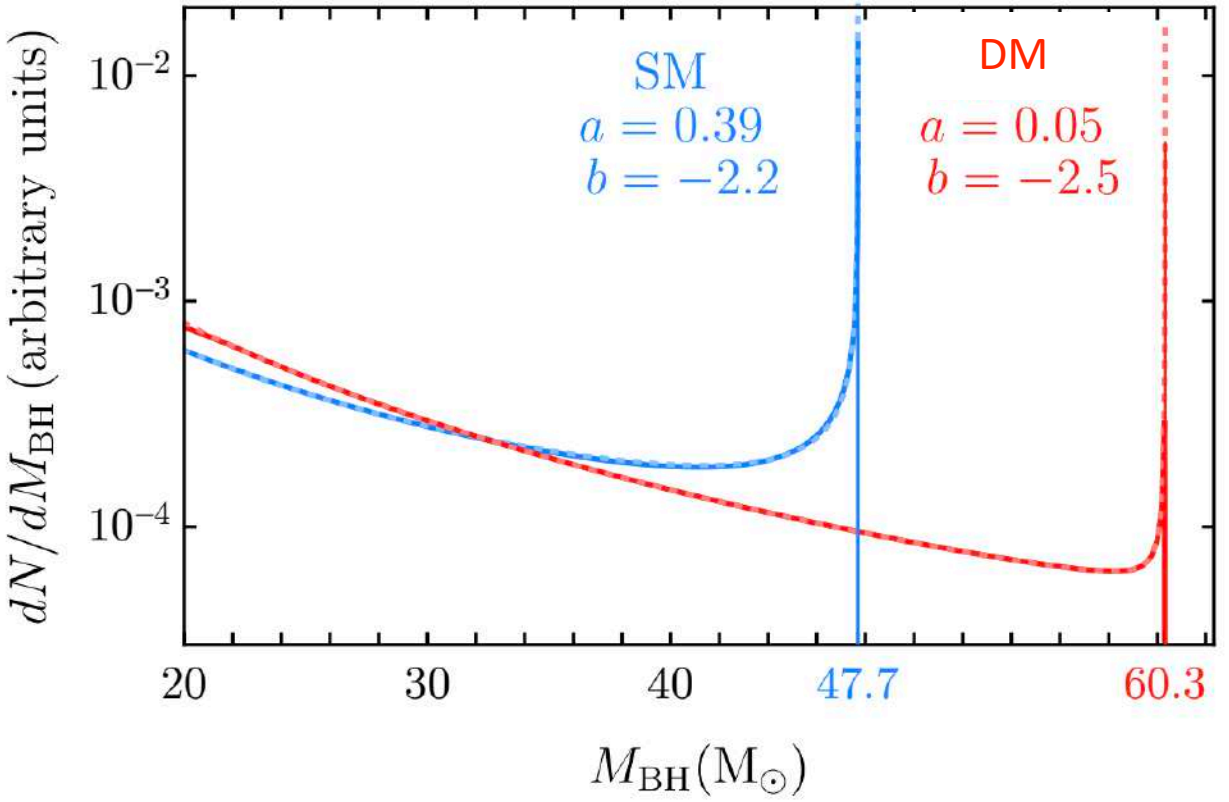




Baxter, Croon, McDermott & JS (2021)

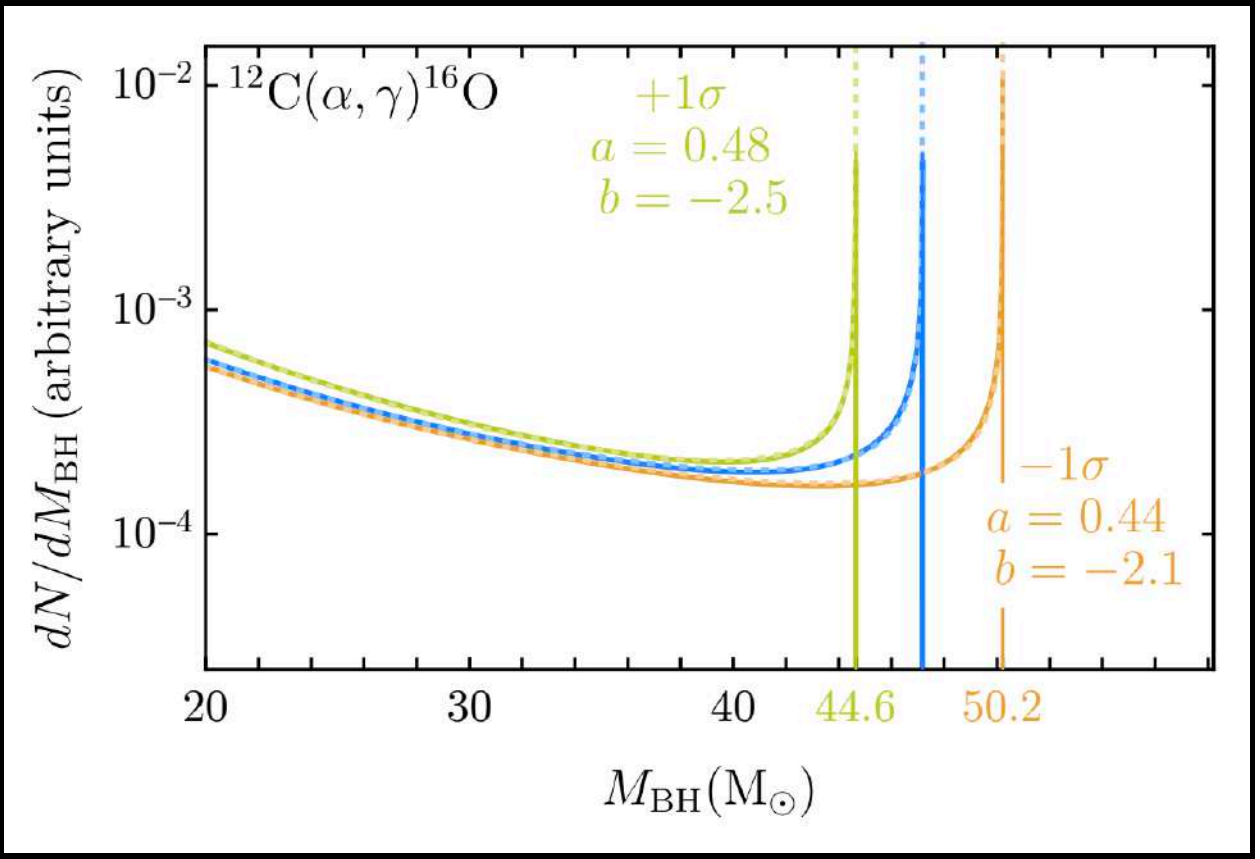
New particles



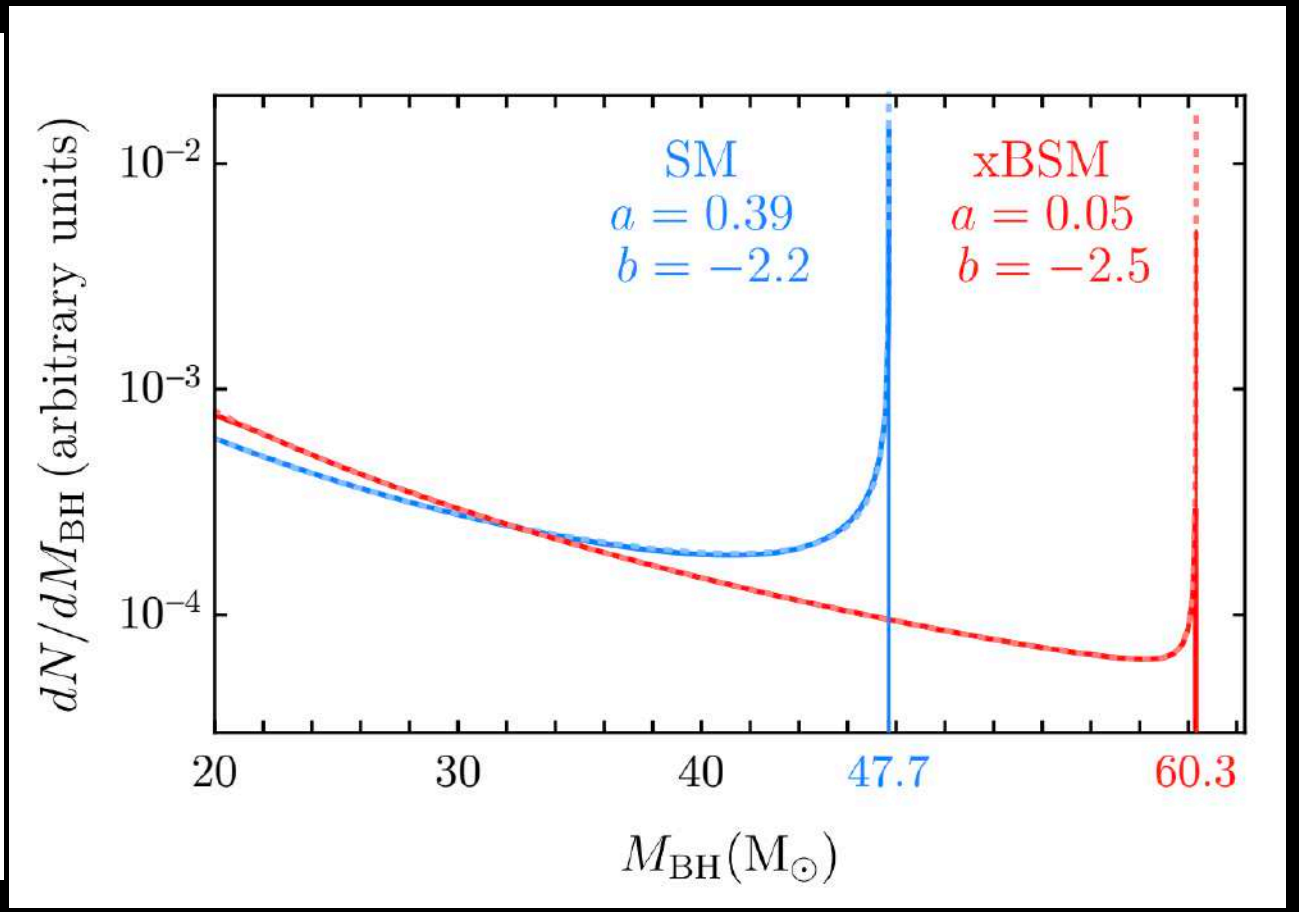


Baxter, Croon, McDermott & JS (2021)

Degeneracies can be mitigated!



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

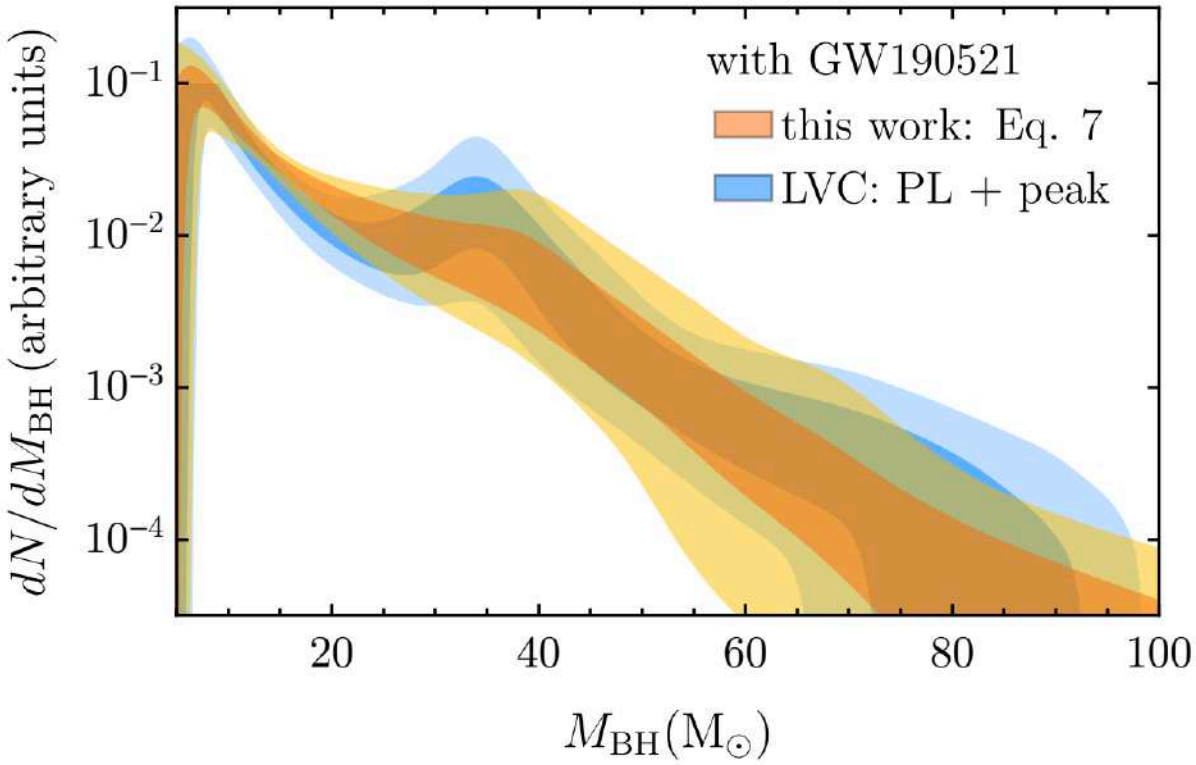


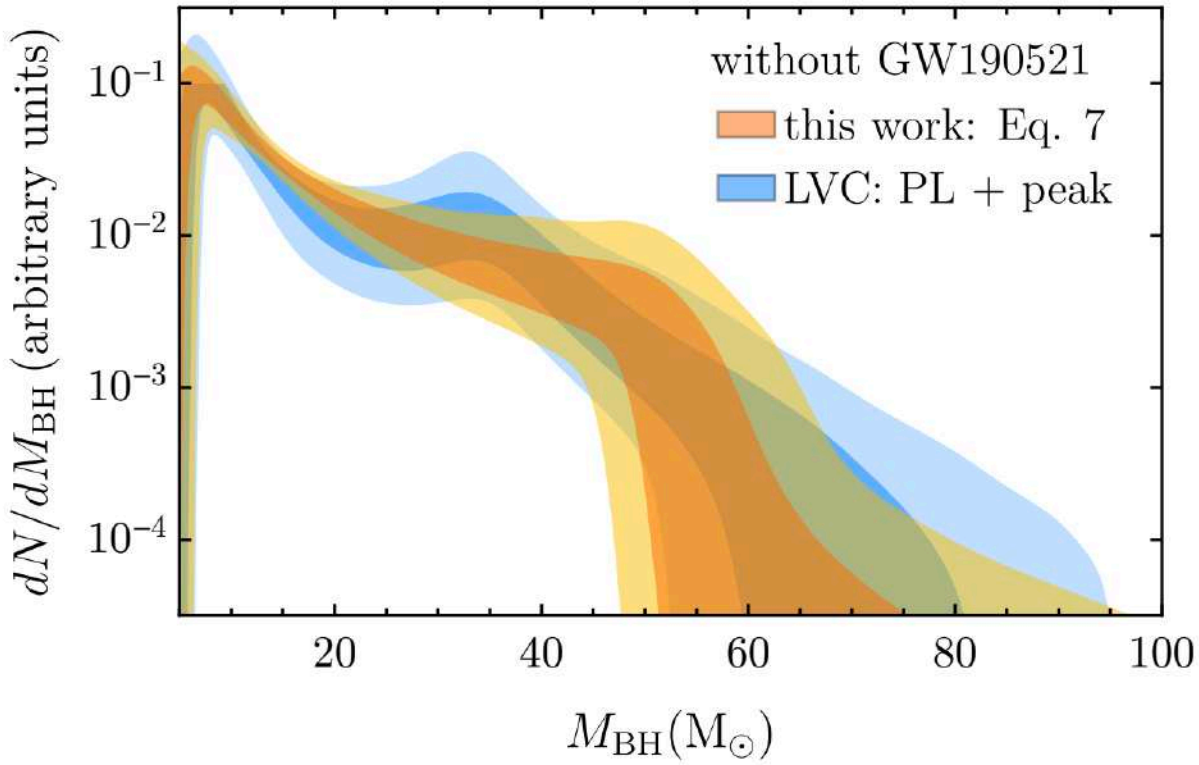
Hidden photon

Baxter, Croon, McDermott & JS (2021)

Application to GWTC-2

Results are sensitive to GW190521

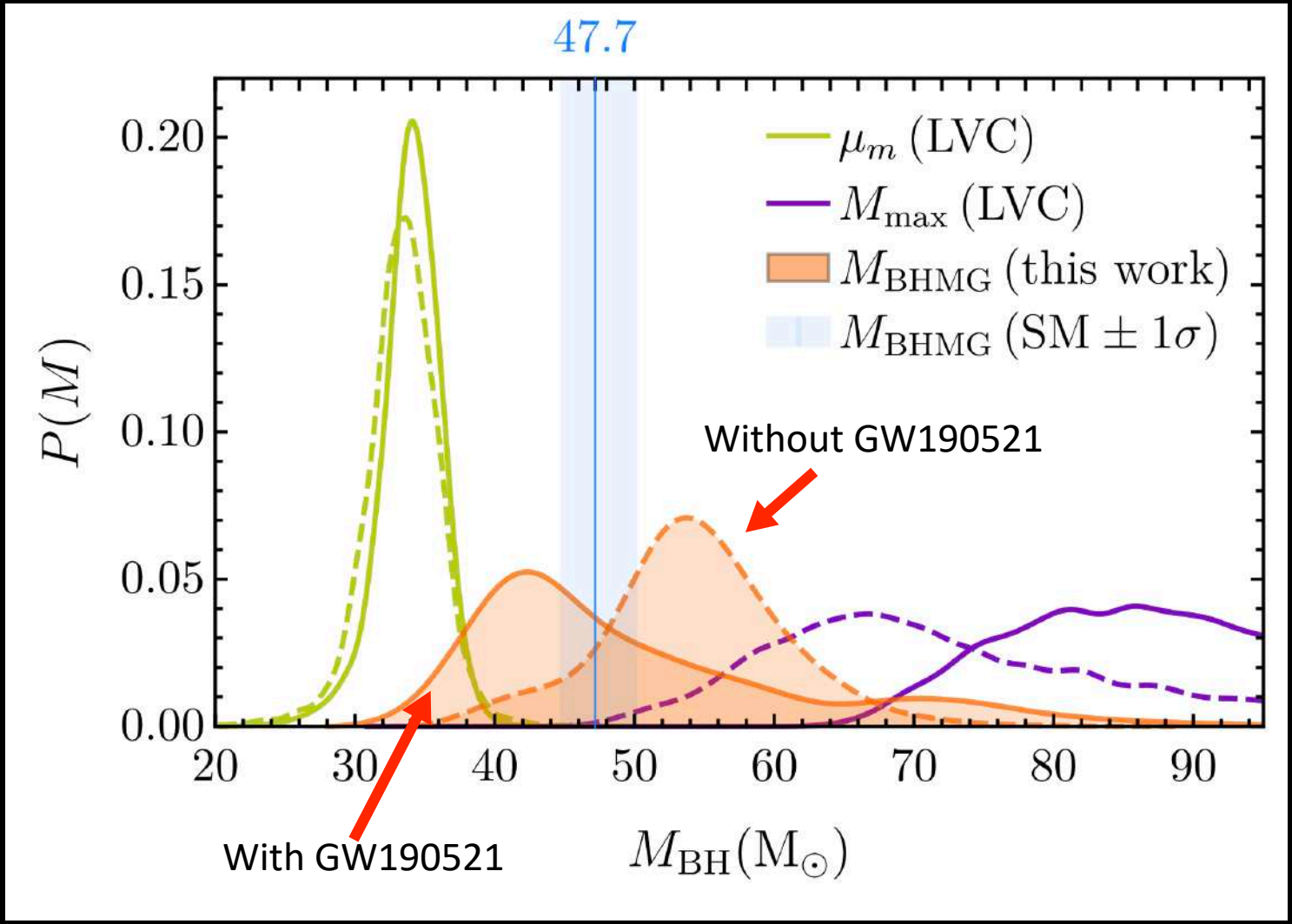




GW190521 could be: second-gen, a straddling binary, highly-eccentric, ...

Application to GWTC-2

Results are sensitive to GWTC-2



With GW190521:

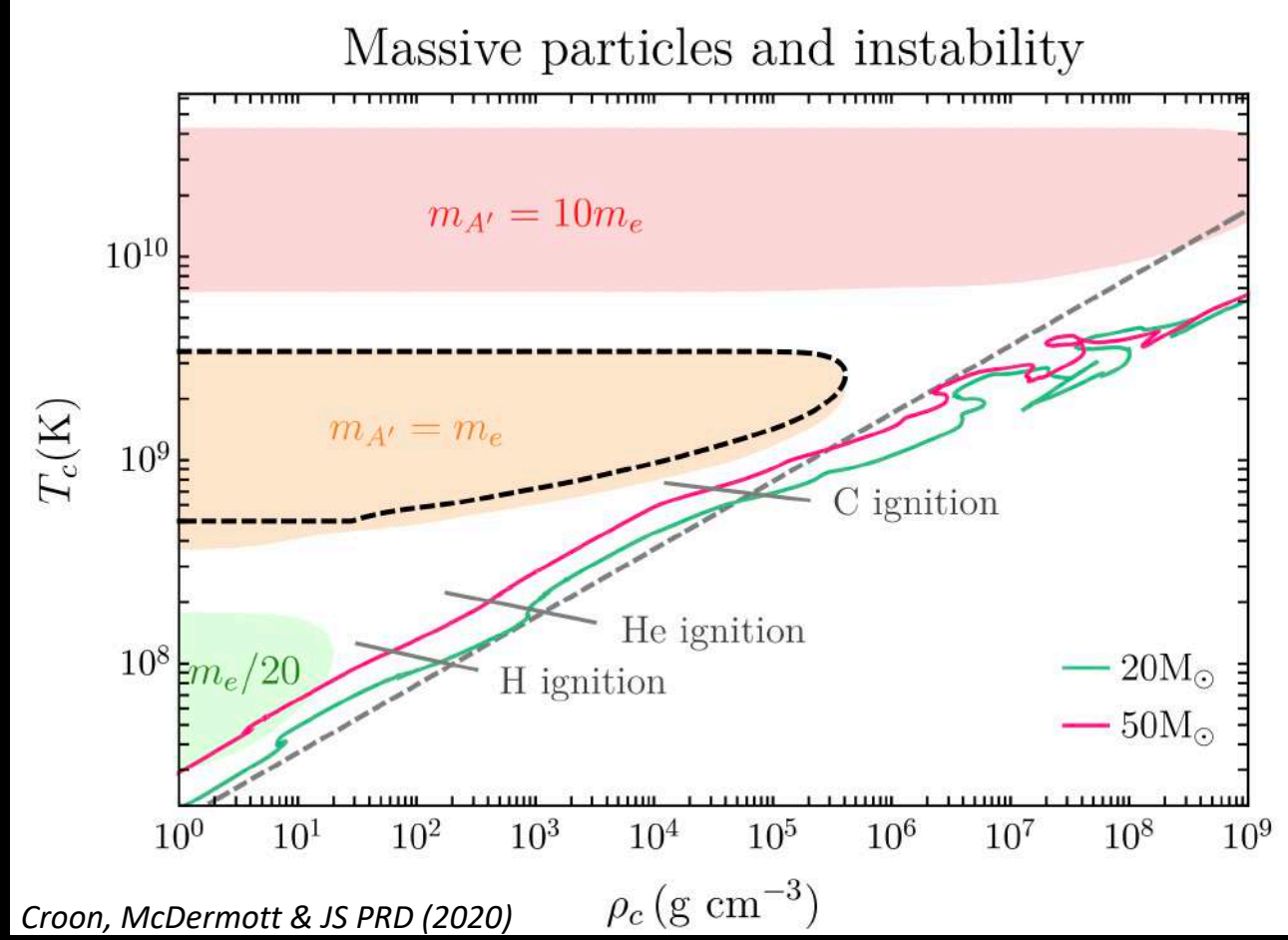
$$M_{\rm BHMG} = 46^{+17}_{-6}\mathrm{M}_\odot$$

Without GW190521:

$$M_{\rm BHMG} = 54^{+6}_{-6}\mathrm{M}_\odot$$

Looking forward

- Data analysis after O3b release
- Constrain new particles + nuclear physics
- Effects of heavy DM on the BHMG
- Modified gravity — more work needed
- Very exciting!!!!!

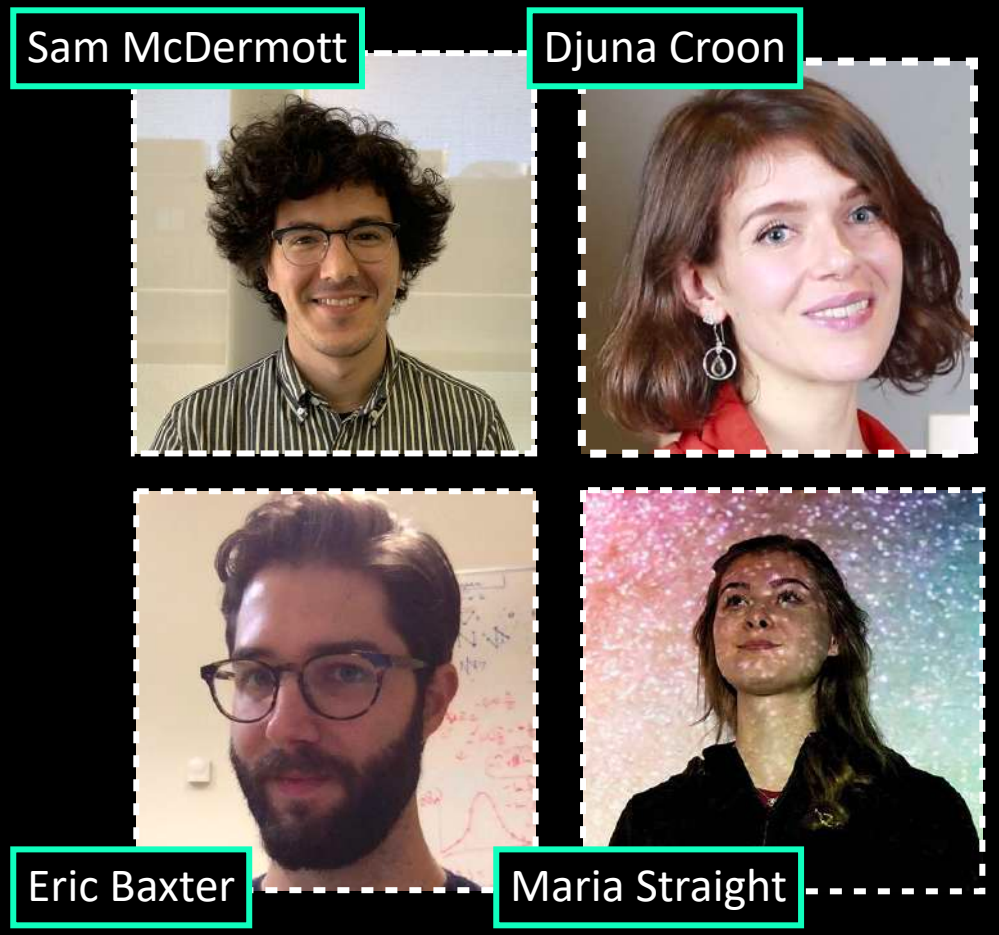


Croon, McDermott & JS PRD (2020)

Thank you to my amazing collaborators

Papers:

- New particles: 2007.00650, 2007.07889
- Modified gravity: 2009.10716
- GW190521: 2009.01213
- BH mass function: 2104.02685



Thank you!

sakstein@hawaii.edu | jeremysakstein.com

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