

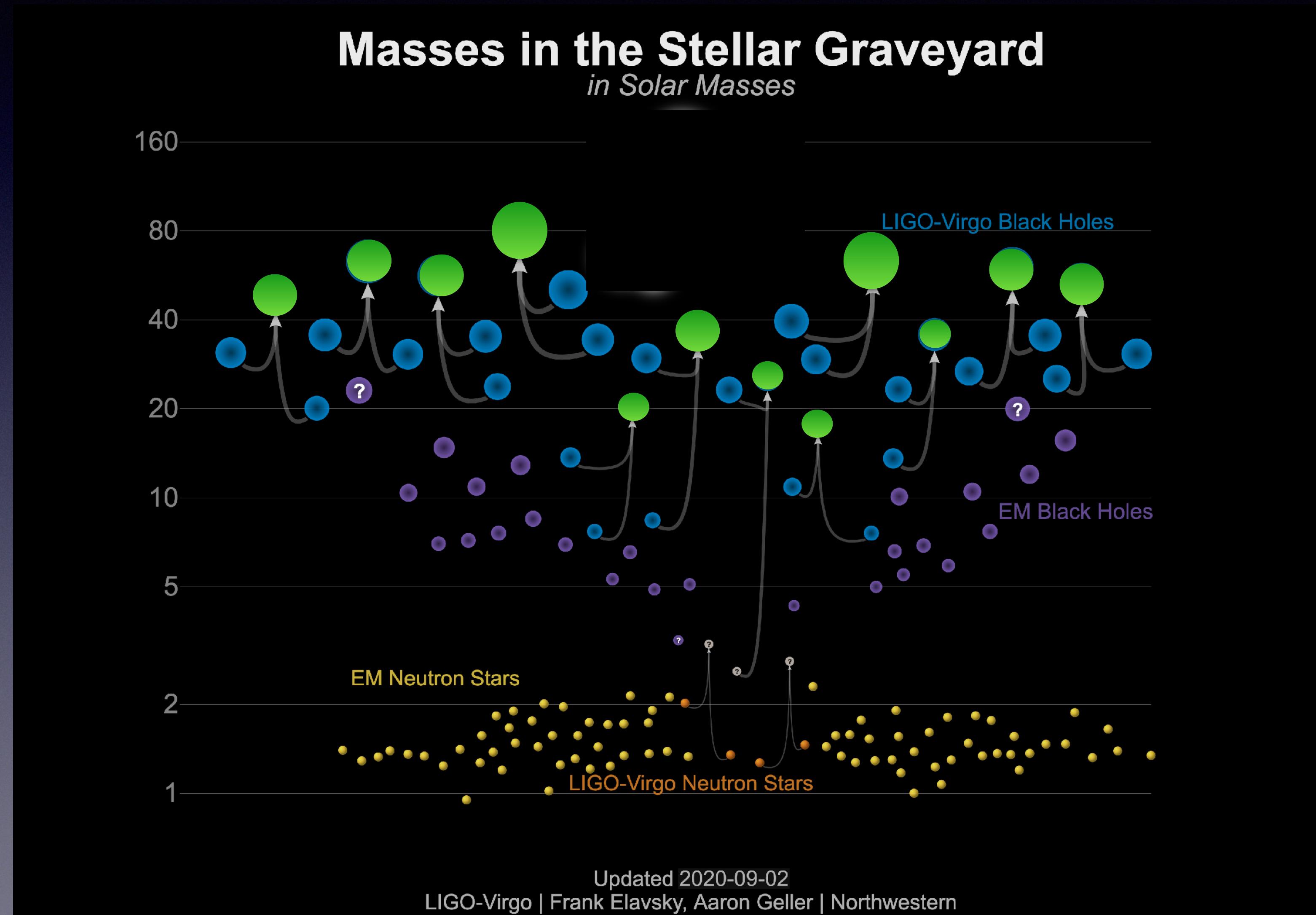
~FIND THE GAP~

New Physics and the Black Hole Mass Gap

Samuel D. McDermott

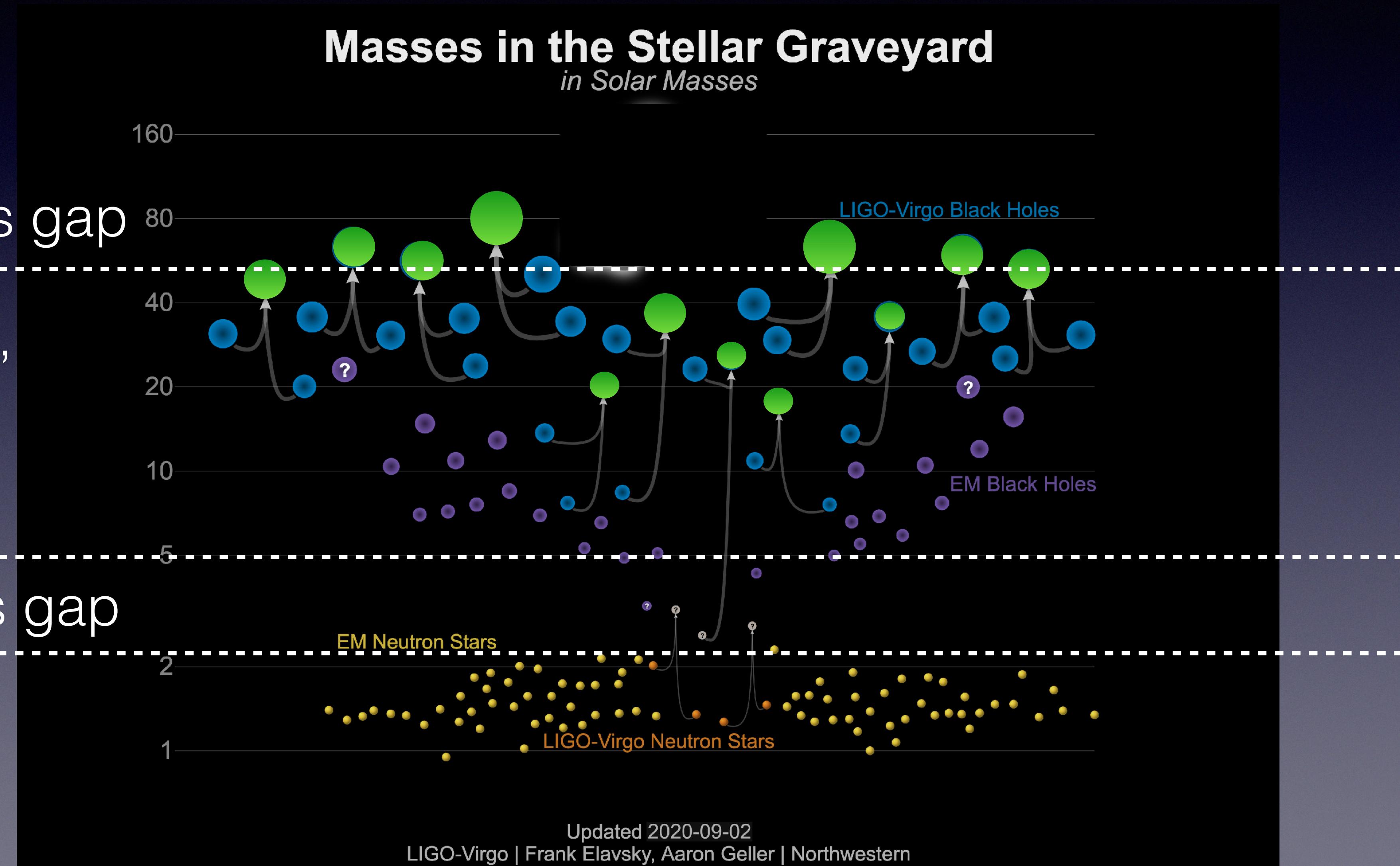
work with Djuna Croon + Jeremy Sakstein: PotDU & 2007.00650 [hep-ph], PRD & 2007.07889 [gr-qc]
&/+ Maria Straight and Eric Baxter: PRL & 2009.01213 [gr-qc]
&/+ Eric Baxter: @ApJL & 2104.02685 [astro-ph.CO]
+ code development in progress (email me for updates/release info)

LIGO Observations: O1+O2

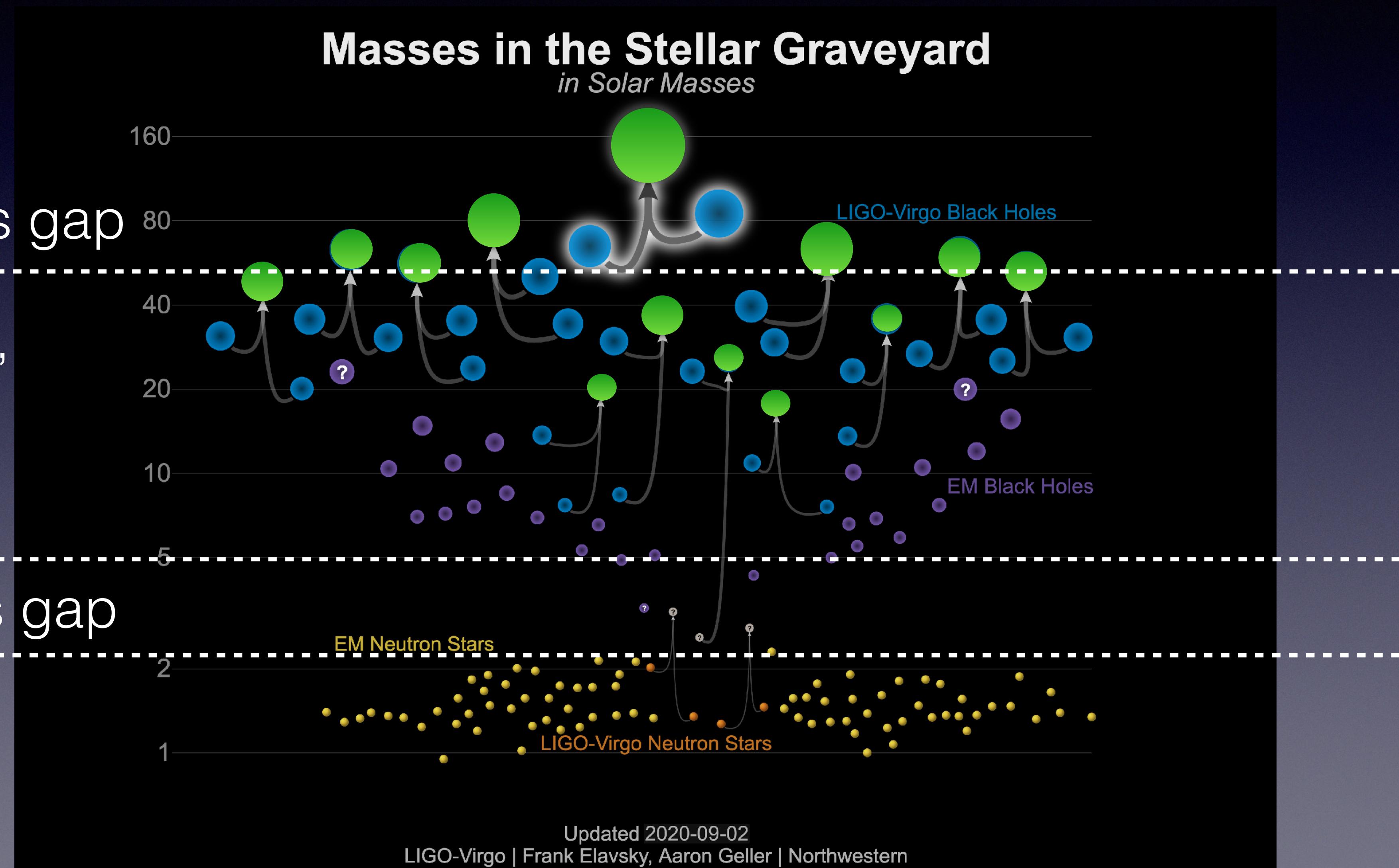
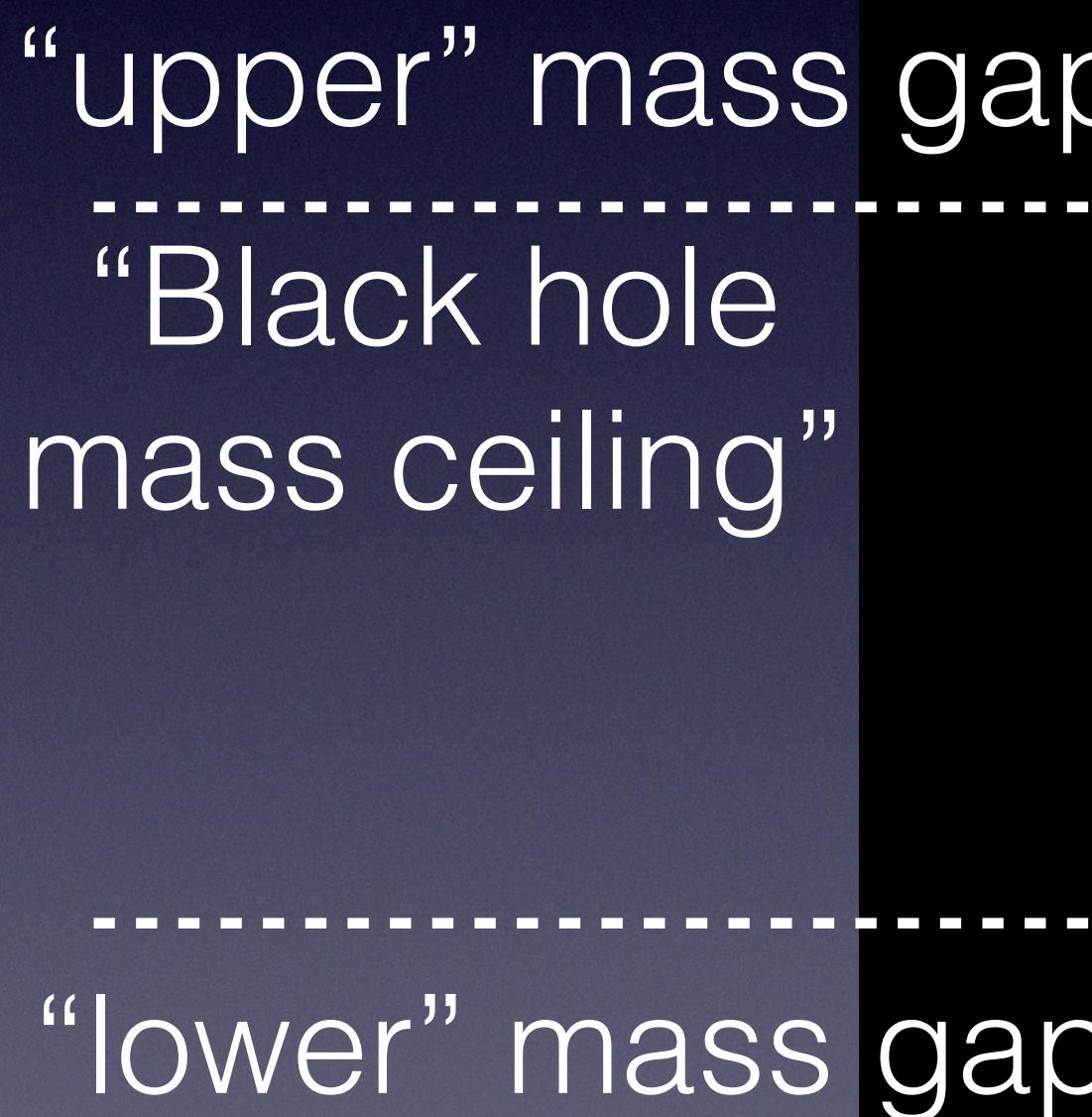


LIGO Observations: O1+O2

“upper” mass gap
“Black hole
mass ceiling”
“lower” mass gap



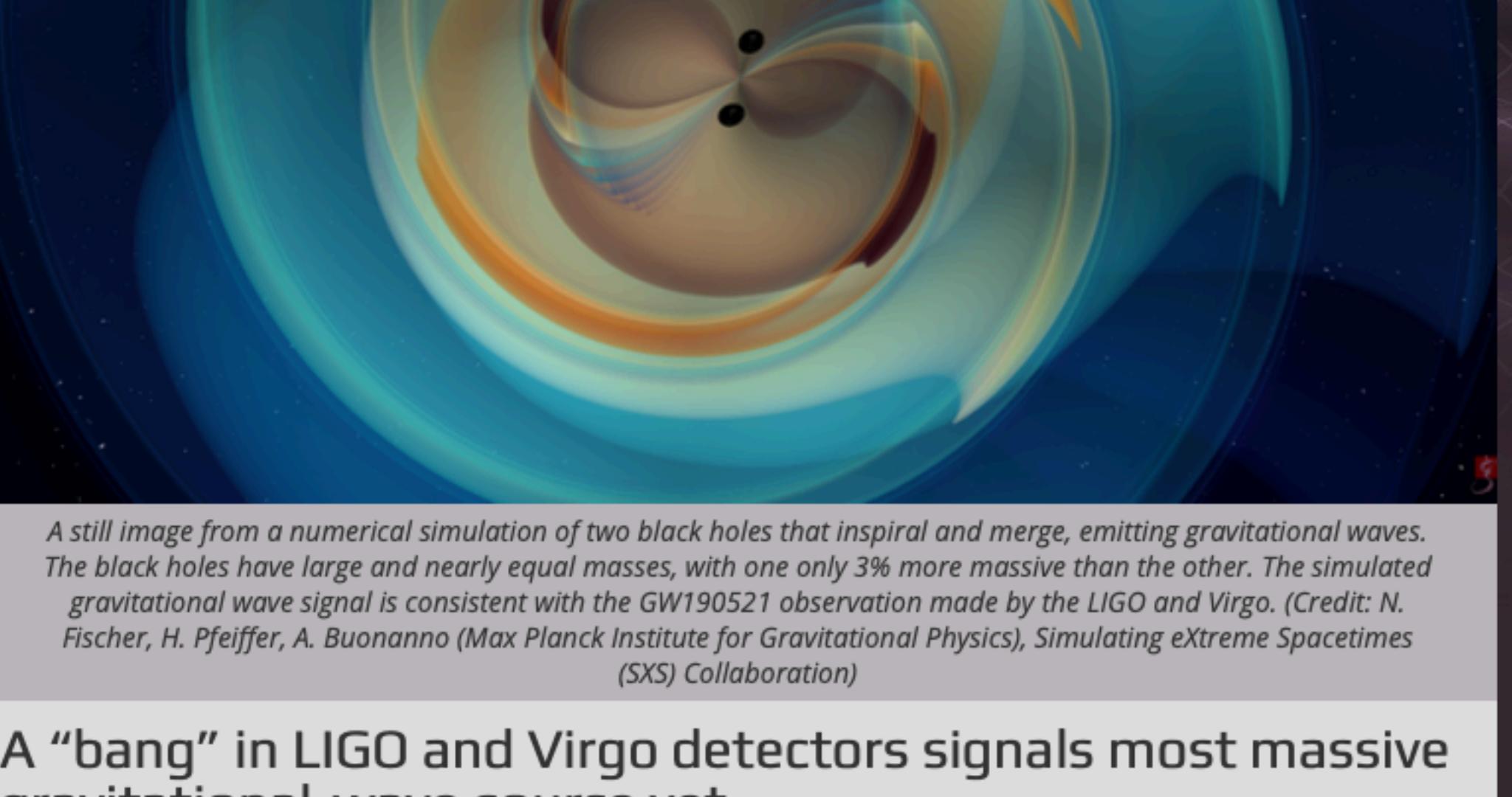
LIGO Observations: O1+O2



From R. Abbott et al. (LIGO Scientific Collaboration),
Phys. Rev. Lett. 125, 101102 (2020)

(collaboration),

<https://www.ligo.caltech.edu/news/ligo20200902>



A still image from a numerical simulation of two black holes that inspiral and merge, emitting gravitational waves. The black holes have large and nearly equal masses, with one only 3% more massive than the other. The simulated gravitational wave signal is consistent with the GW190521 observation made by the LIGO and Virgo. (Credit: N. Fischer, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes (SXS) Collaboration)

A “bang” in LIGO and Virgo detectors signals most massive gravitational-wave source yet

News Release • September 2, 2020

A binary black hole merger likely produced gravitational waves equivalent to the energy of eight suns.

“Black hole mergers are the most energetic events in the universe,” said Dr. Sophie Lewis, lead author of the study and a research scientist at CBS News. “This event is the most massive black hole merger ever detected.”

BY SOPHIE LEWIS

SEPTEMBER 3, 2020 / 7:03 AM / CBS NEWS

10

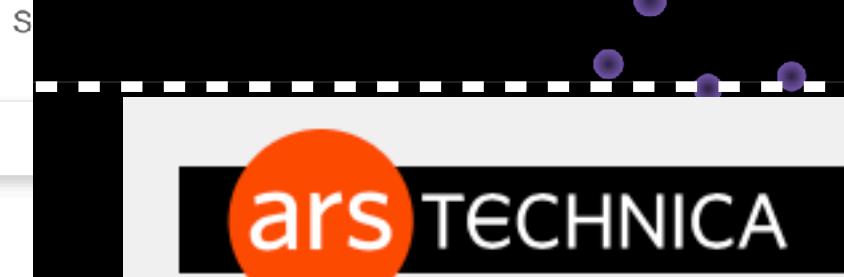
SCIENTIFIC
AMERICAN
CELEBRATING
175 YEARS

Cart 0

S

LIGO and Virgo Capture Their Most Massive Black Holes Yet

1



CHIRP, CHIRP, BANG, BANG —

Meet GW190521—a black-hole merger for the record books

It's the most massive, distant, and energetic black-hole merger yet.

JENNIFER OUELLETTE - 9/2/2020, 11:54 AM

Observations



FORBES.COM

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

Black Holes

Black holes: Cosmic signal rattles after 7 billion years

By Jonathan Amos
BBC Science Correspondent

BLOGS

DOSSIERS

RECENSIES

MAGAZINE

AGENDA

LOGIN

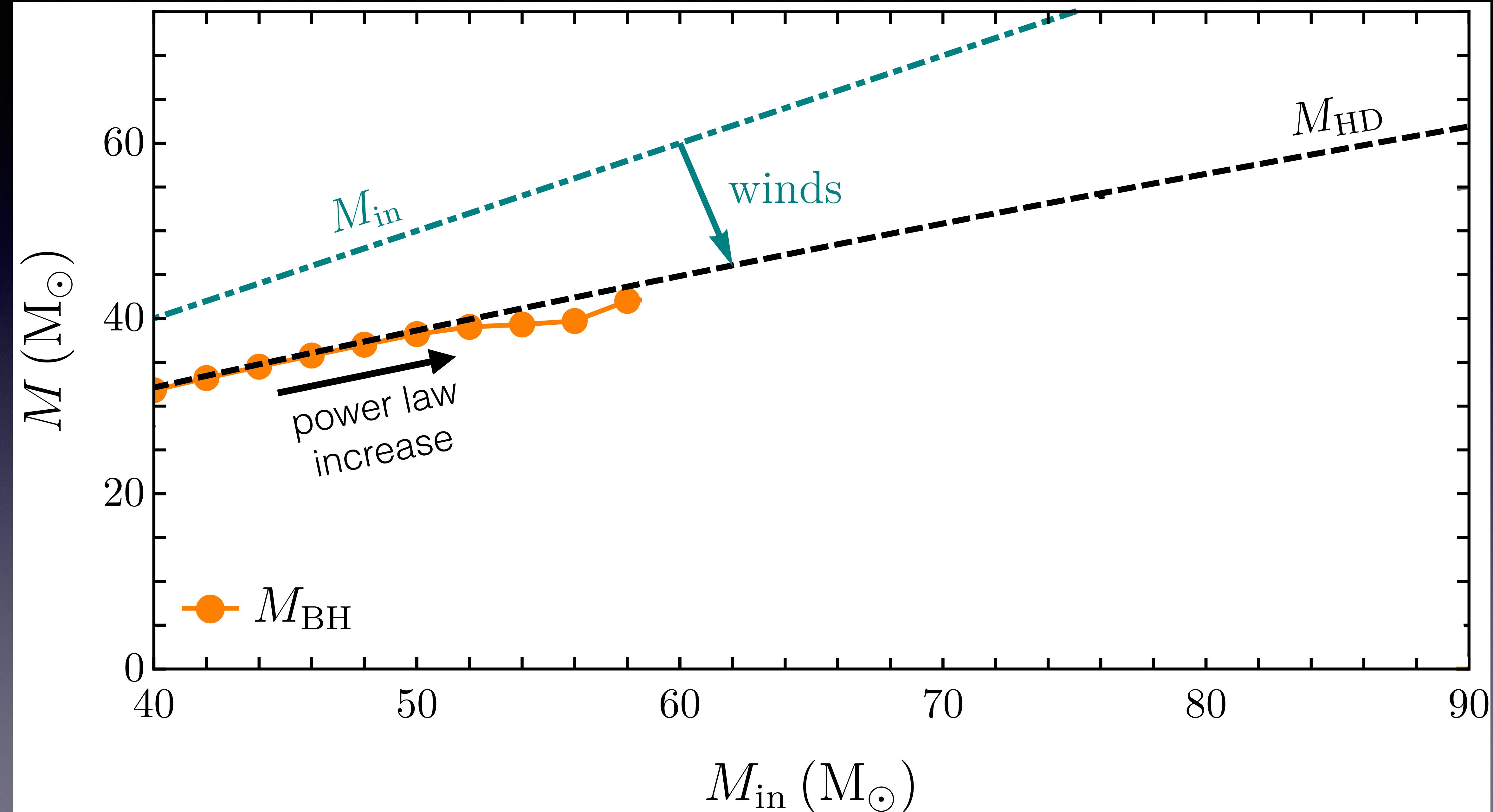
Q

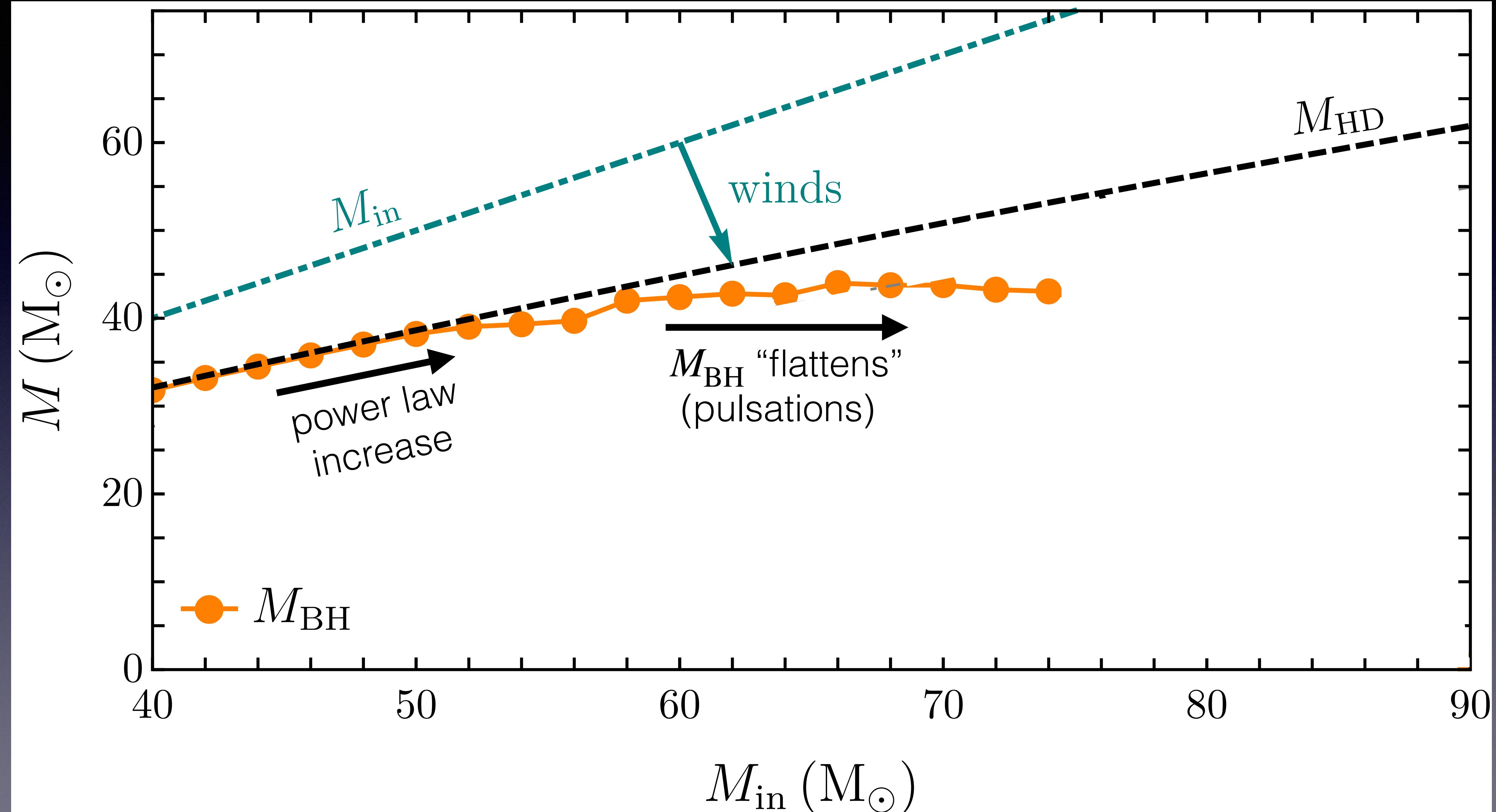
SHOP

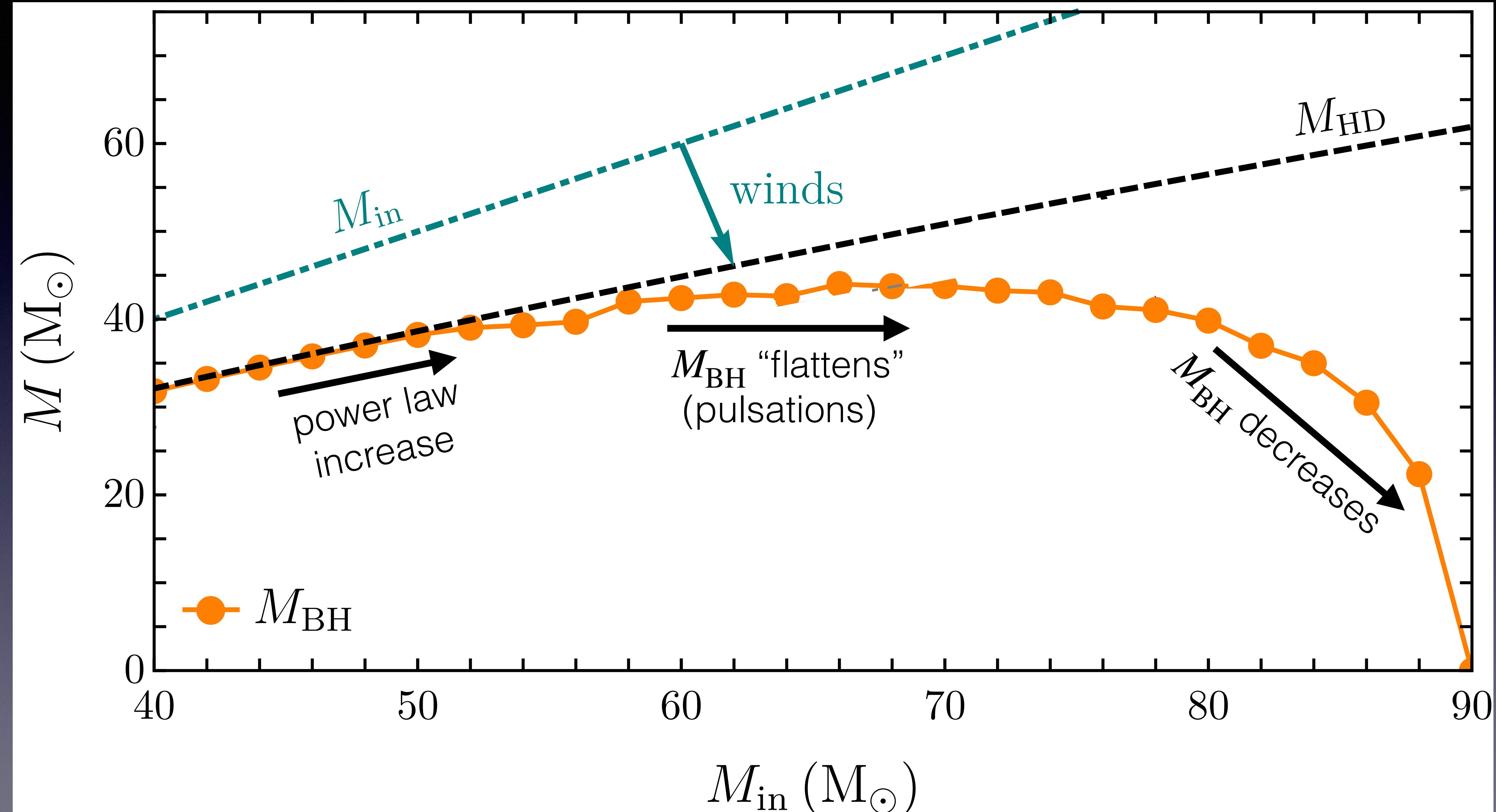
Zwaartekrachtsgolven van ‘te zware’ zwarte gaten waargenomen

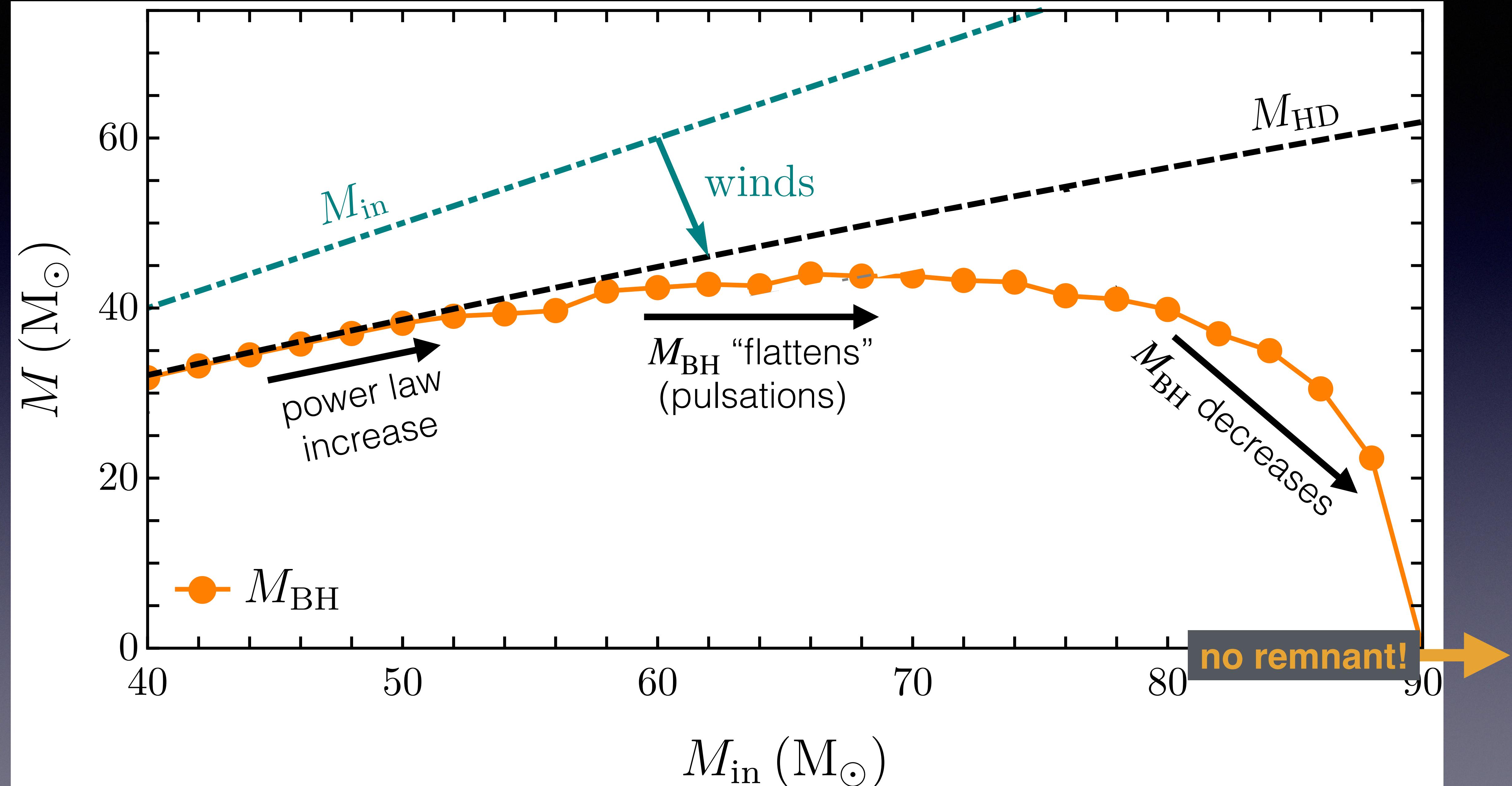
It's the most massive, distant, and energetic black-hole merger yet.

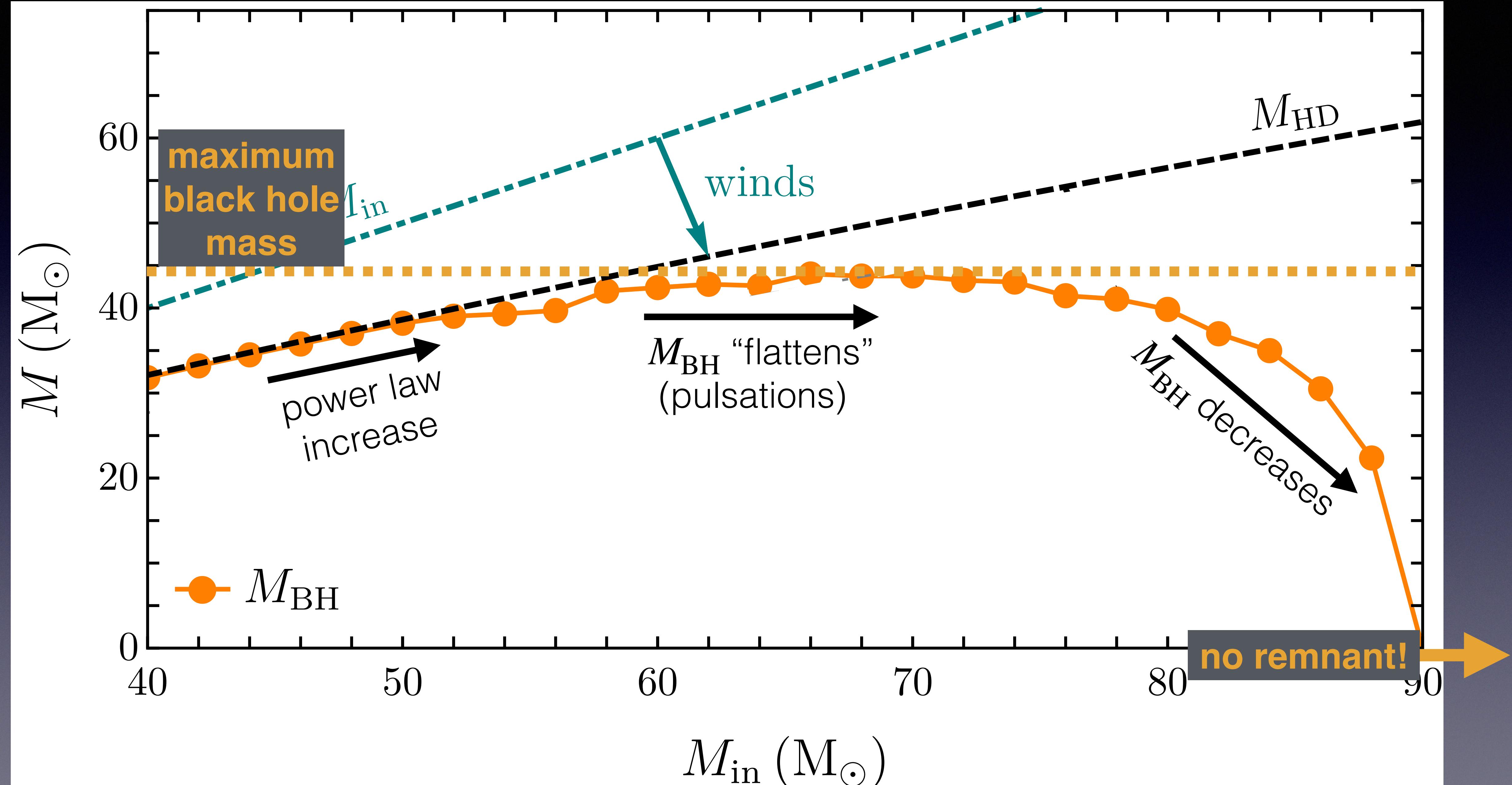
JENNIFER OUELLETTE - 9/2/2020, 11:54 AM



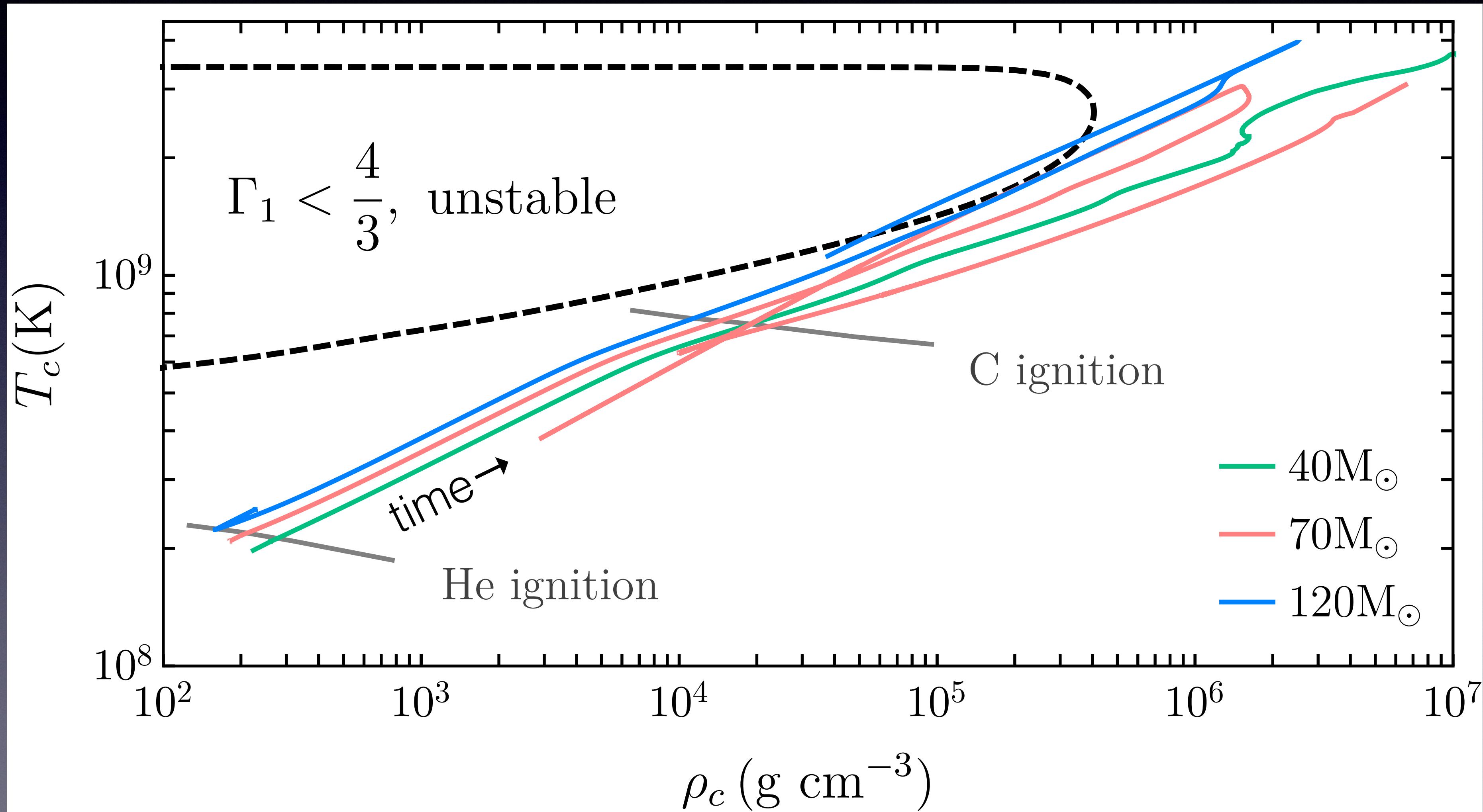




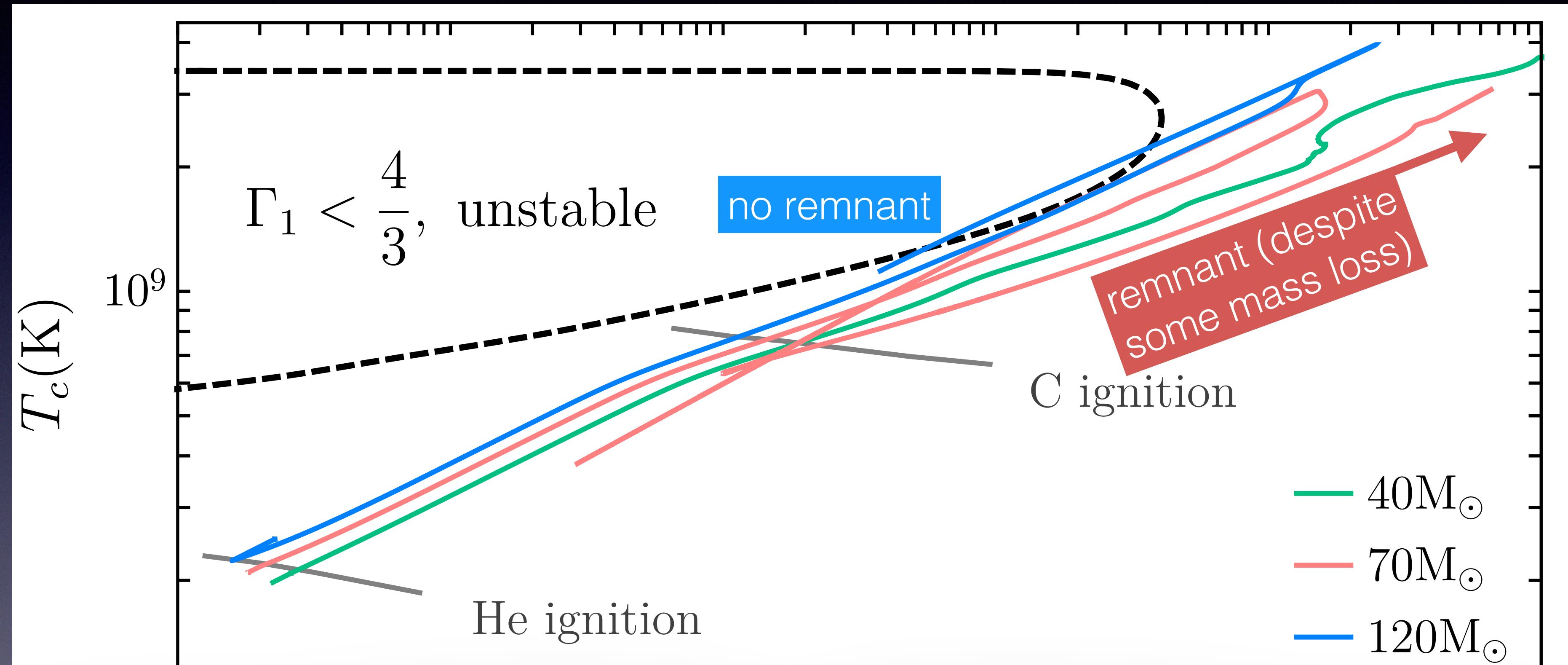




Evolution* of Pop III Stars



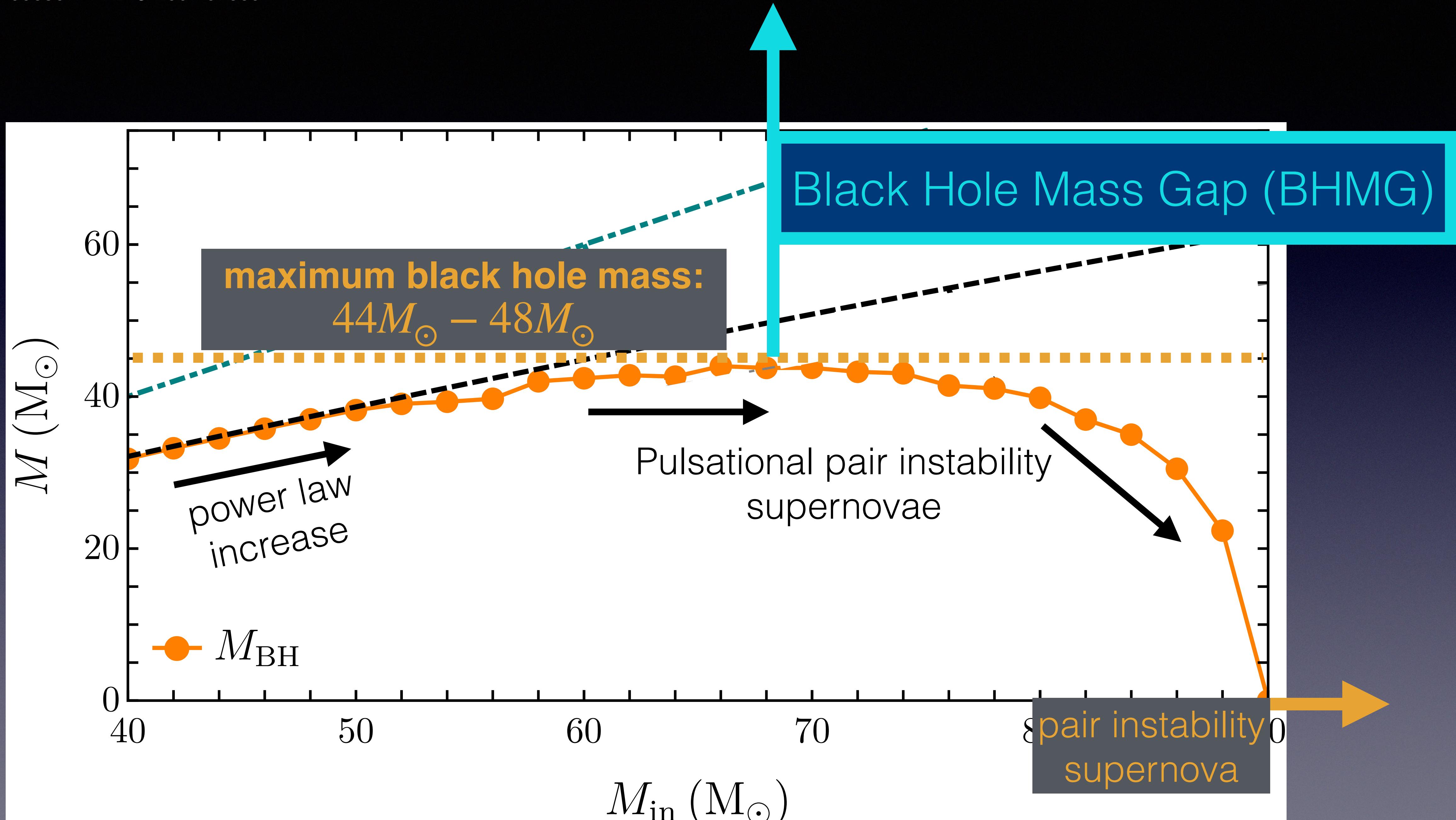
Outcome of Pulsations



$70M_{\odot} \lesssim M_{\text{in}} \lesssim 100M_{\odot}$ — pulsational pair instability supernova (PPISN)

vs

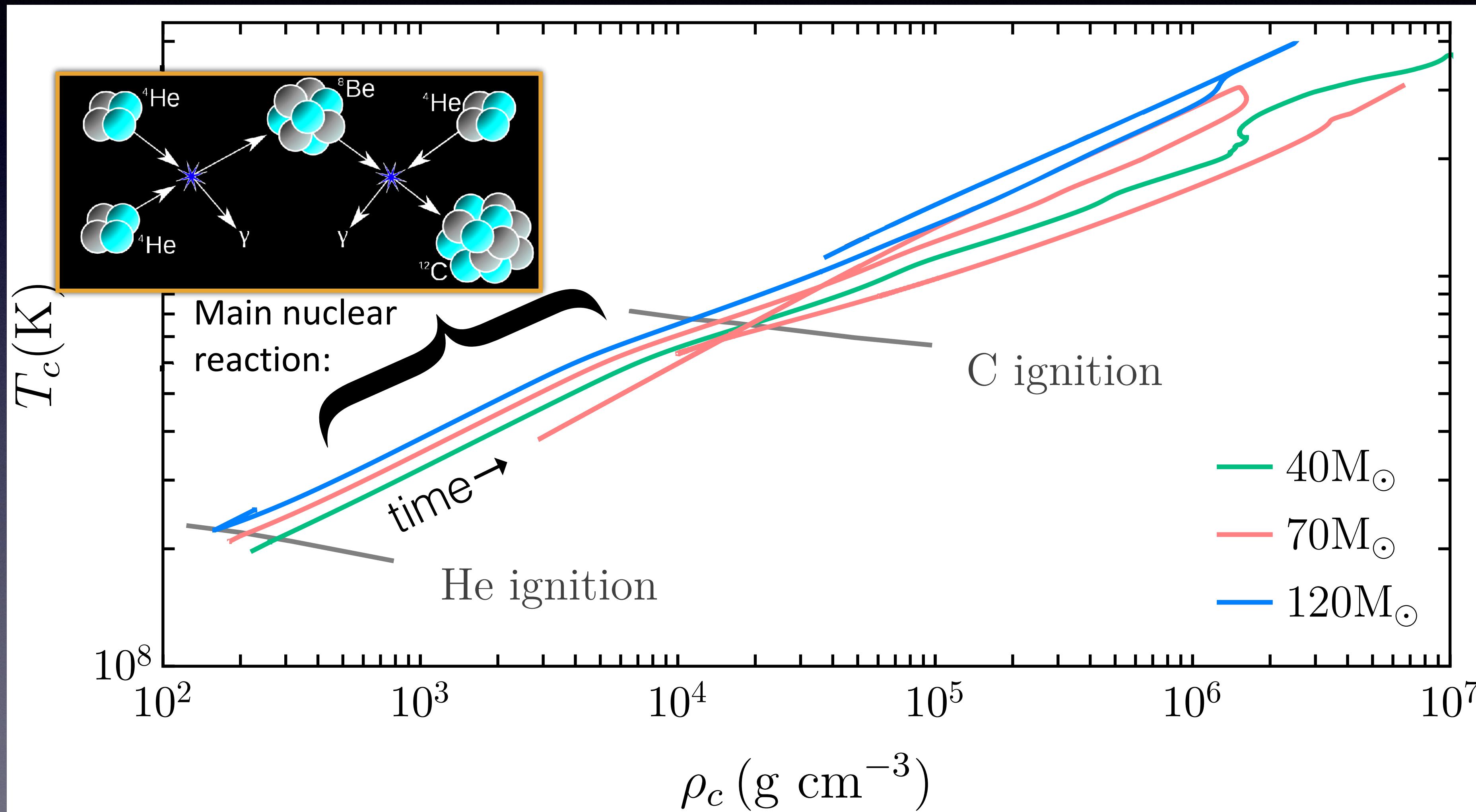
$100M_{\odot} \lesssim M_{\text{in}} \lesssim 250M_{\odot}$ — pair instability supernova (PISN)



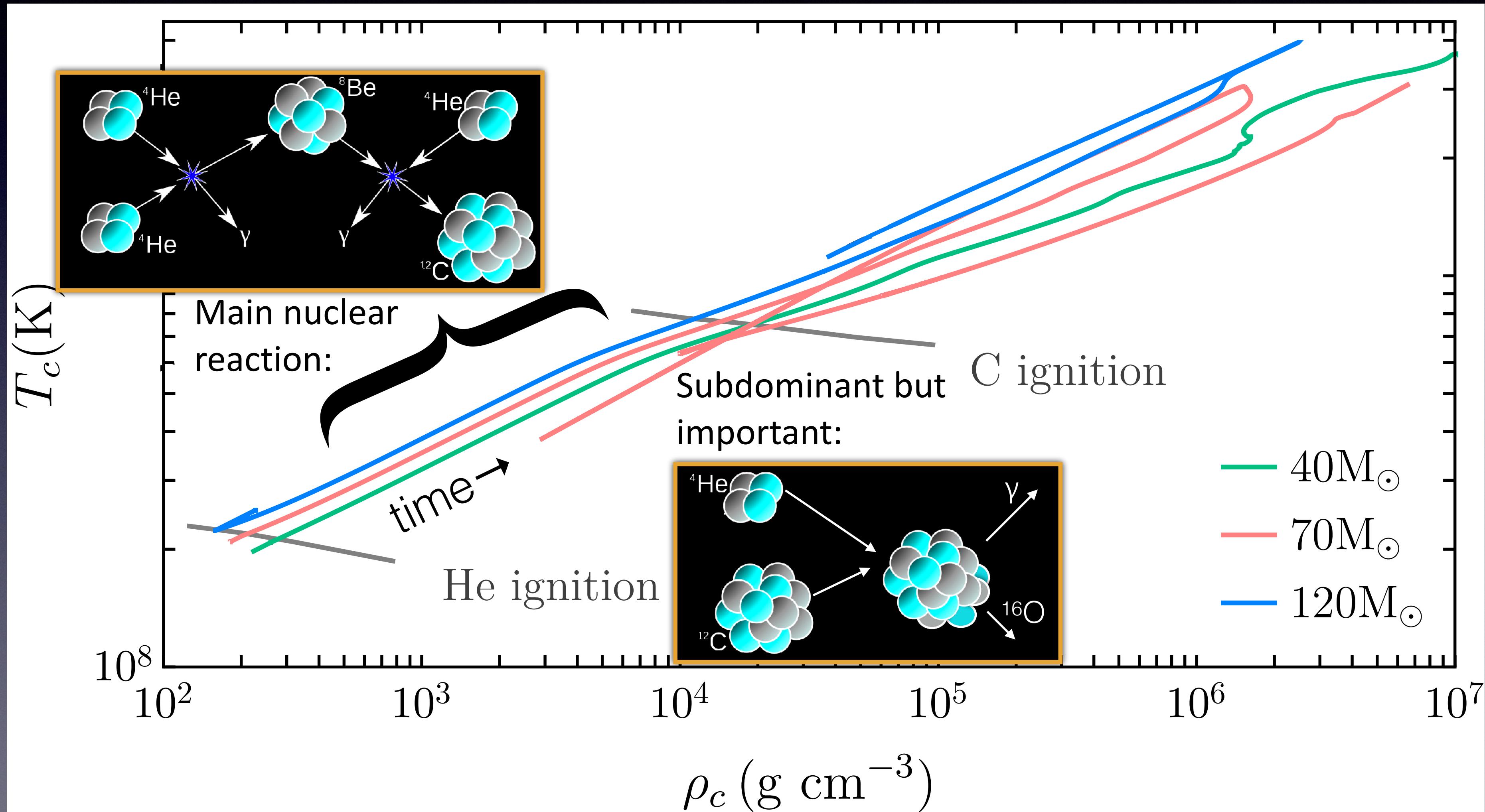
Can we Change the BHMG?

- New light degree(s) of freedom are **produced in the core** of a massive star during helium burning
- This additional loss channel causes the star to **consume fuel more quickly** and **end helium burning earlier**
- This **reduces** the amount of ^{16}O available **during pulsations**
- Explosions are less violent \implies mass loss is less pronounced \implies a **heavier black hole**

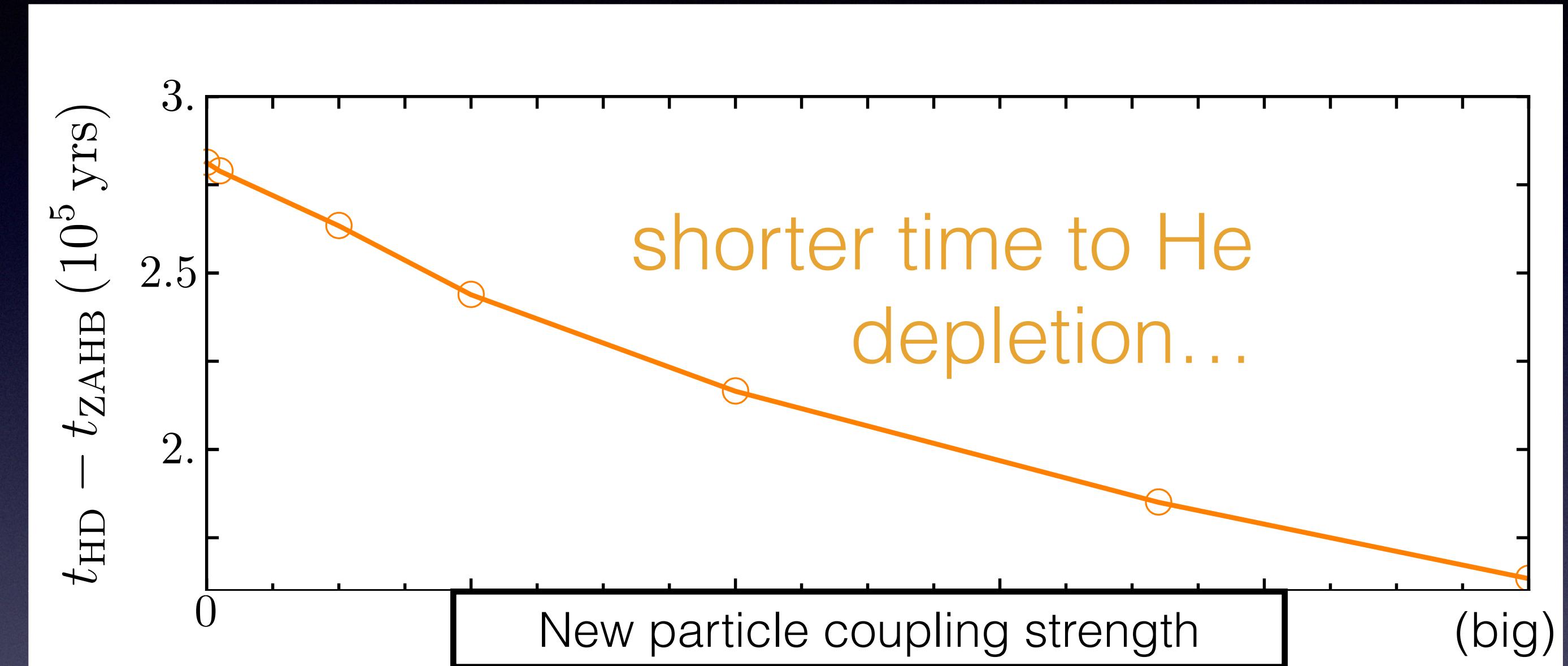
Reactions in Pop III Stars



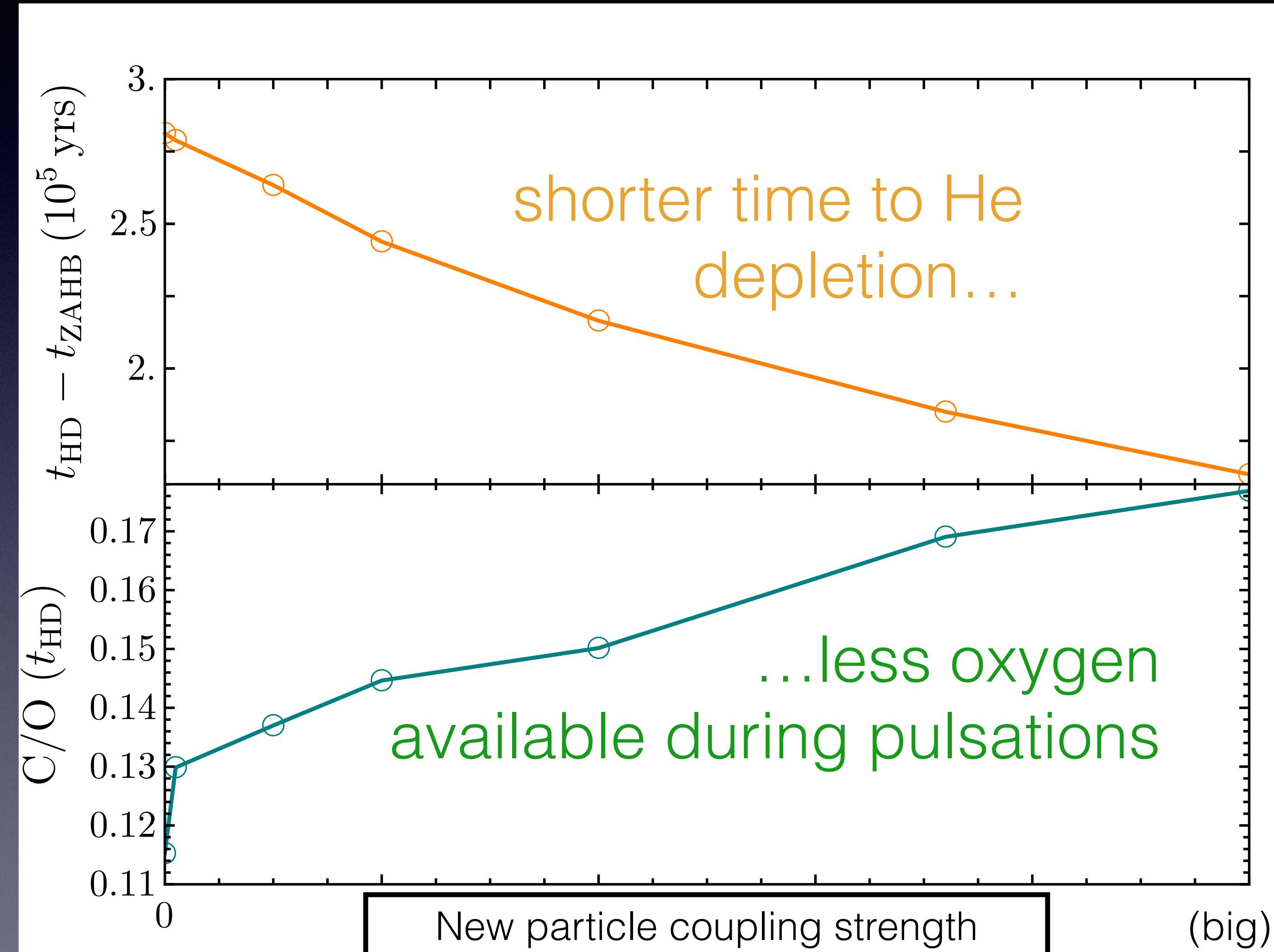
Reactions in Pop III Stars



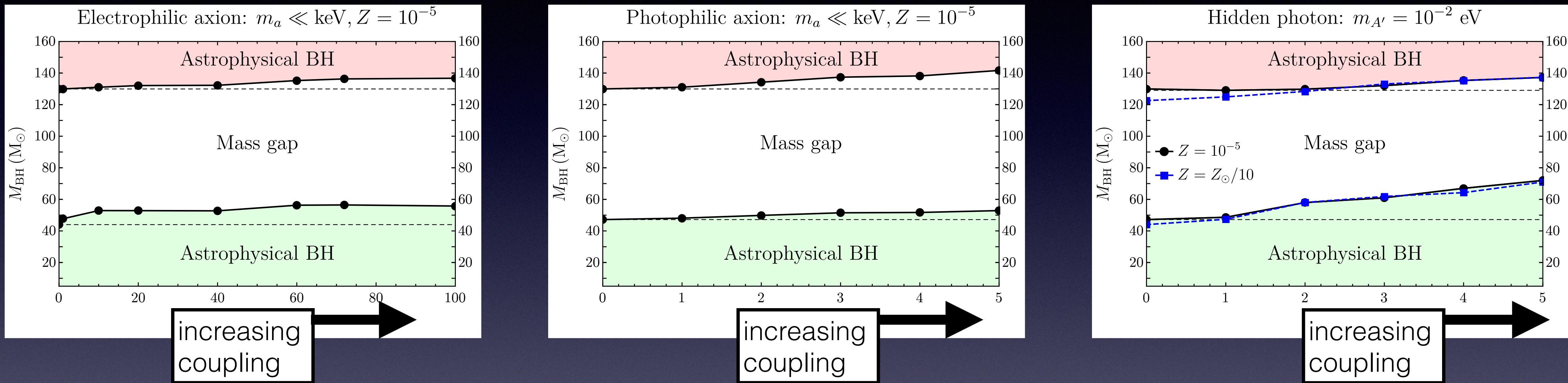
Implications for Oxygen Production



Implications for Oxygen Production

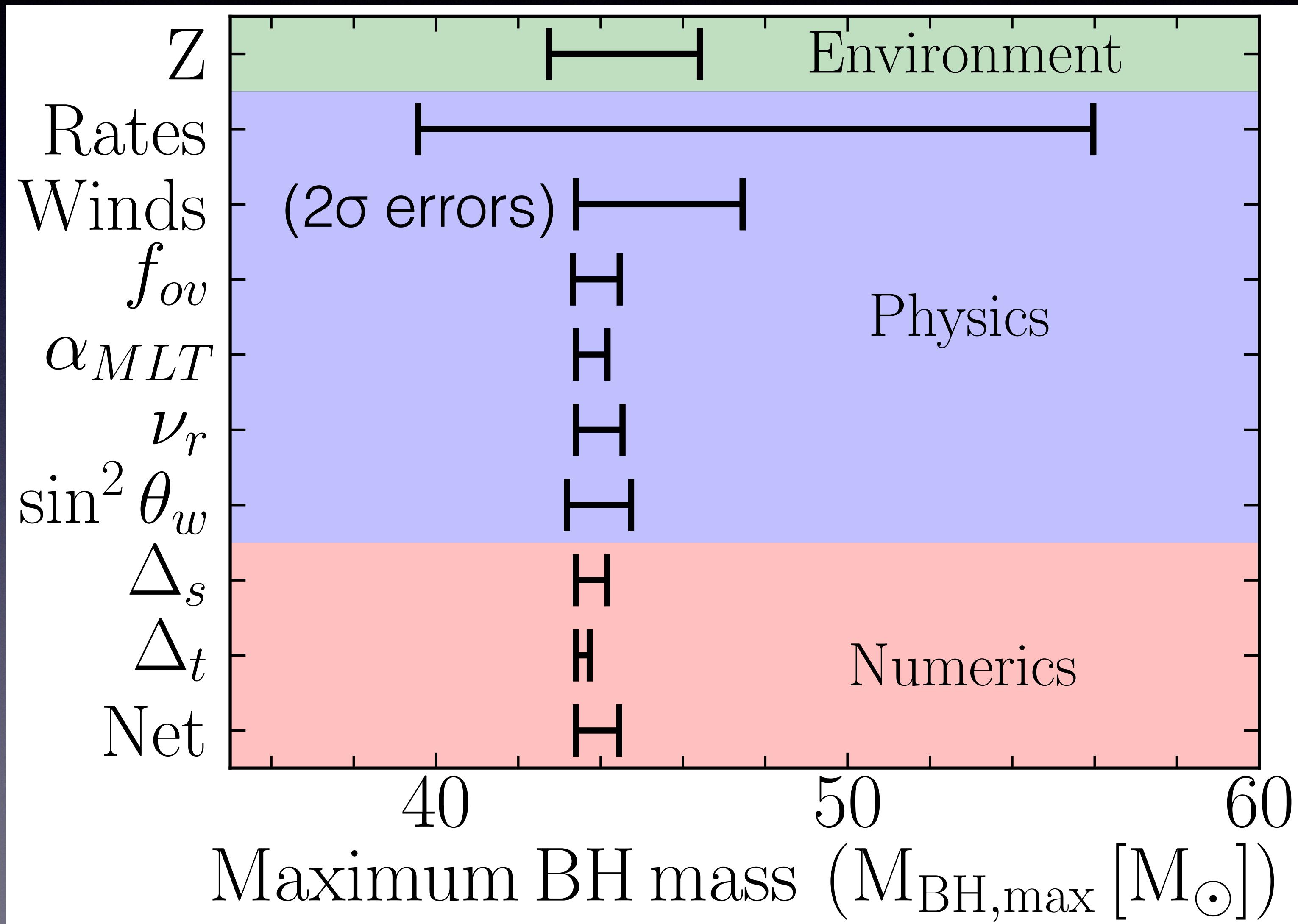


Implications for Black Hole Masses



larger coupling to new physics \implies larger black hole mass

SM Uncertainties



also rare events:

- pre- & post-collapse mergers
- accretion after formation
- binarity
- rotation
- ...

Farmer et al.,
1910.12874

Surprisingly Massive: SM vs BSM

SM physics

- “Location” of the mass gap is the SM-only calculation prediction*

*unless $\sim 5\sigma$ deviations from nuclear rates

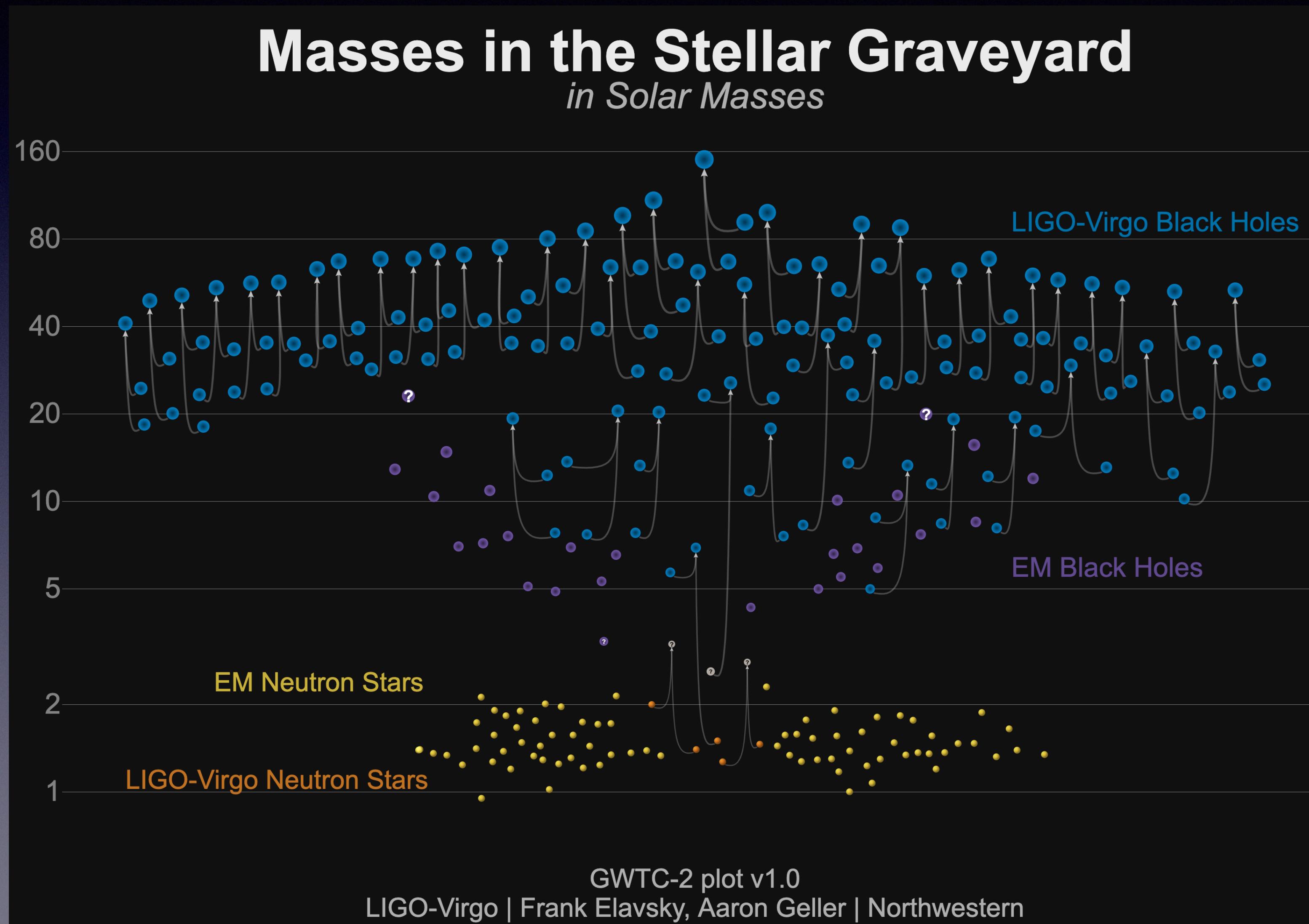
- Systems with no mergers give a continuous distribution of M_{BH} up to **expected** value of the gap plus **rare** excursions to higher masses that “pollute” the gap

BSM physics

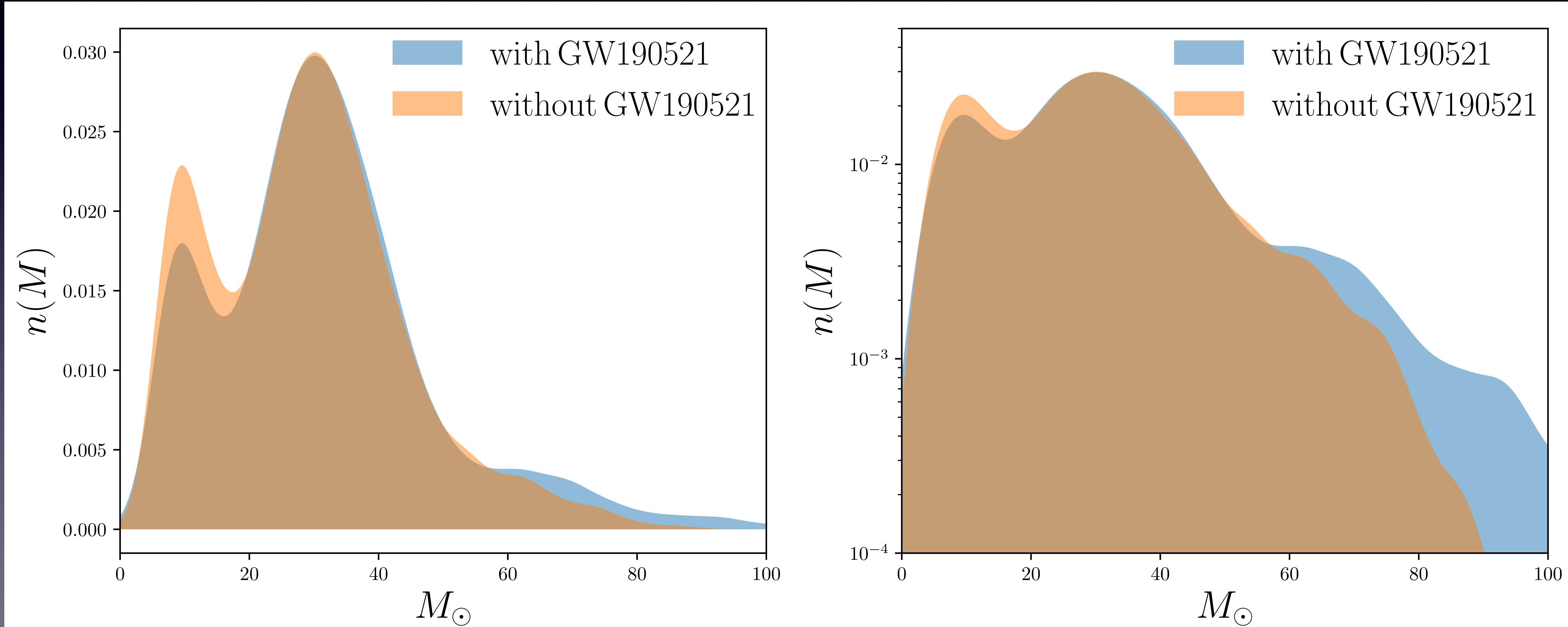
- “Location” of the mass gap is **not** as expected from SM-only calculation: objects “in the (SM) mass gap” form from isolated evolution, no mergers required
- Implies a **continuous^t** distribution of BH masses up to a new, higher value of M_{BH}

^tplus higher-gen BH mergers

LIGO Observations: Oct 2020



Black Hole Population Statistics

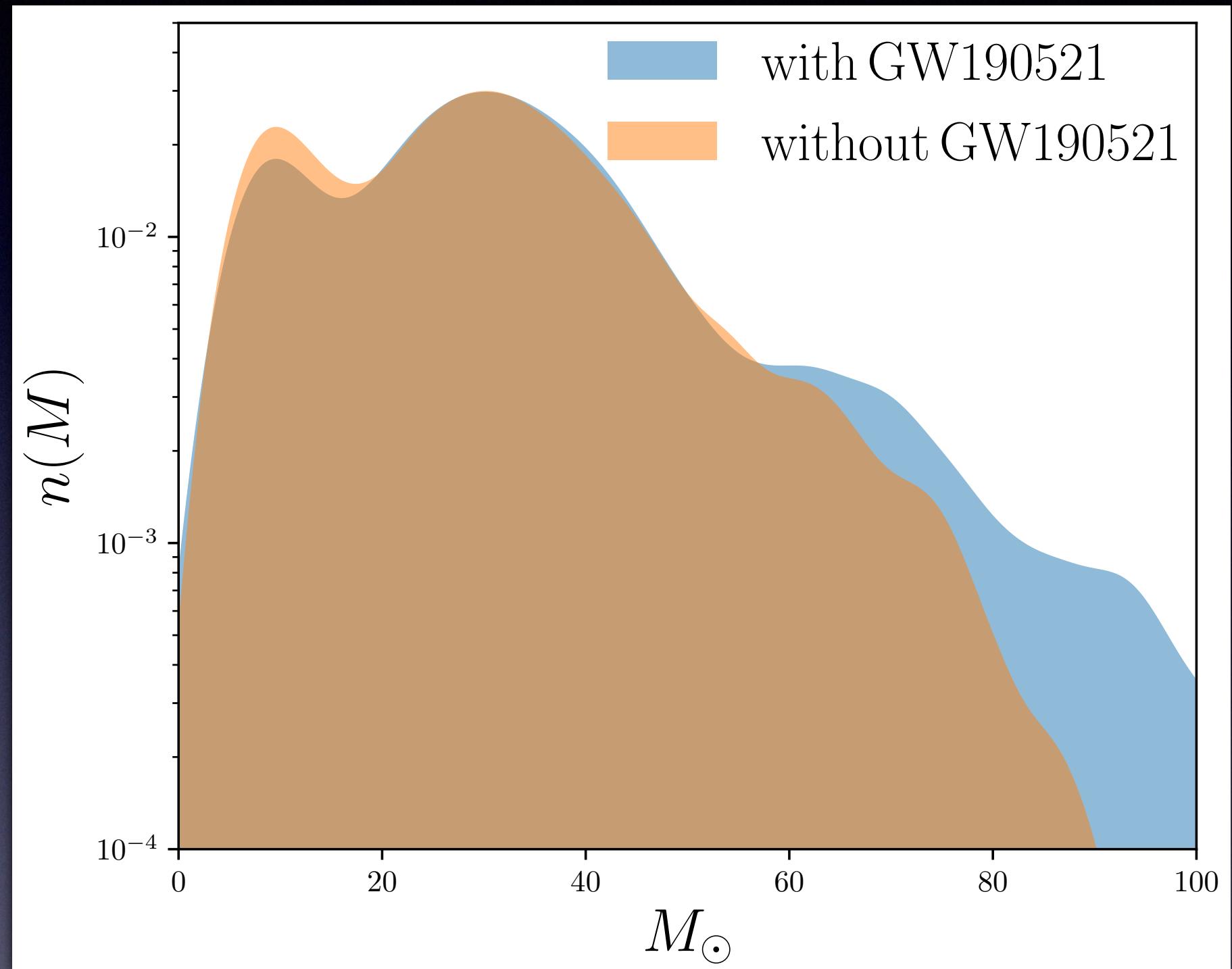


Black Hole Population Statistics

$$p(m_1, m_2 | \vec{\theta}) \propto \frac{dN^{(1g)}}{dM_{\text{BH}}} + \lambda \frac{dN^{(2g)}}{dM_{\text{BH}}}$$

BHs formed from
isolated stellar
evolution

“pollutants” ($\lambda < 1$)



Baxter, Croon, SDM, Sakstein
@ApJL & 2104.02685

MODIFIED BAYES' THEOREM:

$$P(H|x) = P(H) \times \left(1 + P(C) \times \left(\frac{P(x|H)}{P(x)} - 1 \right) \right)$$

H: HYPOTHESIS

x: OBSERVATION

P(H): PRIOR PROBABILITY THAT H IS TRUE

P(x): PRIOR PROBABILITY OF OBSERVING x

P(C): PROBABILITY THAT YOU'RE USING
BAYESIAN STATISTICS CORRECTLY

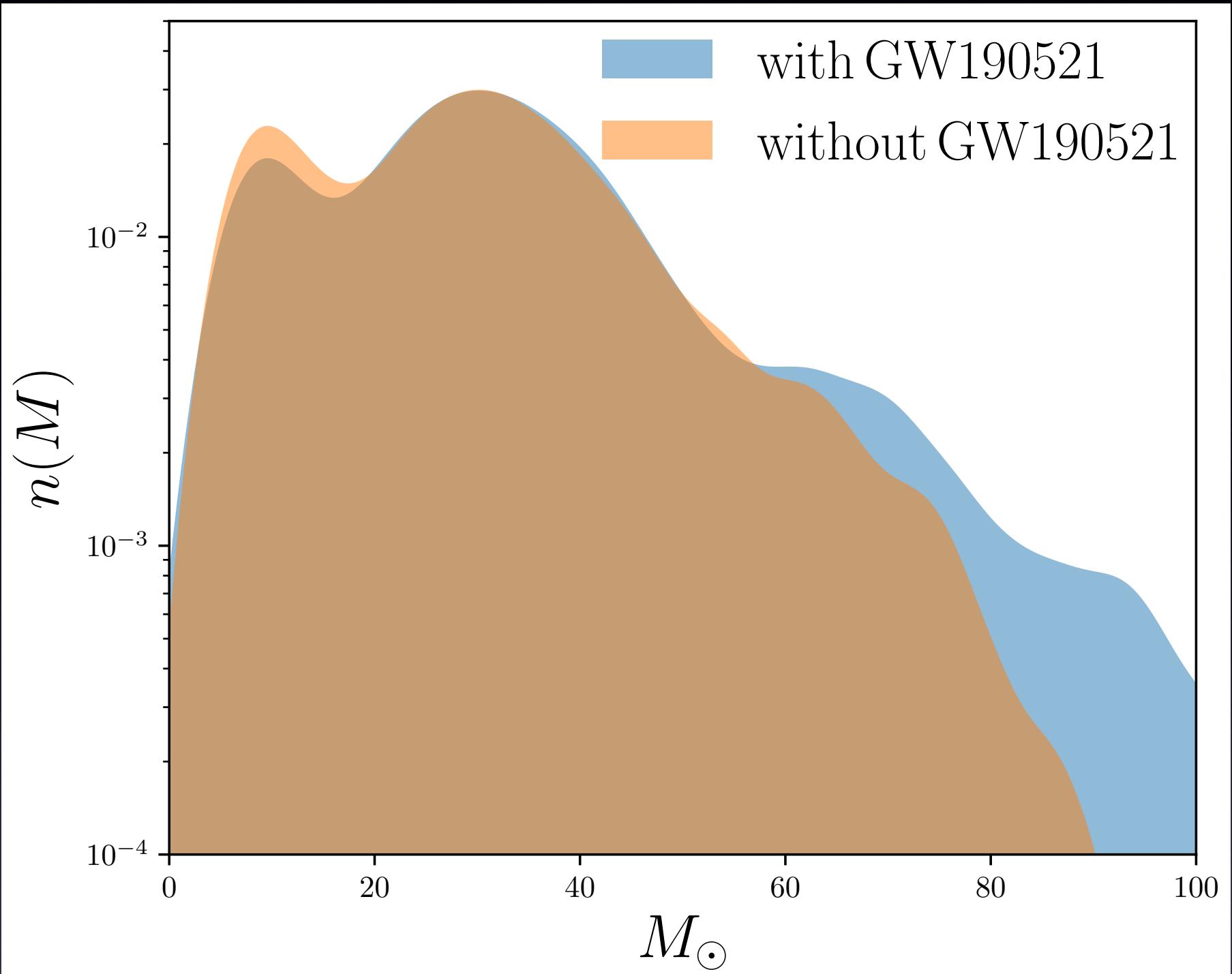
xkcd.com/2059/

Black Hole Population Statistics

$$p(m_1, m_2 | \vec{\theta}) \propto \frac{dN^{(1g)}}{dM_{\text{BH}}} + \lambda \frac{dN^{(2g)}}{dM_{\text{BH}}}$$

BHs formed from isolated stellar evolution

“pollutants” ($\lambda < 1$)



$$\frac{dN^{(1g)}}{dM_{\text{BH}}} \sim \int d\theta \frac{dN_*}{dM_*} \frac{1}{dM_{\text{BH}}(\theta)/dM_*}$$

this is exactly what we get from MESA!

Baxter, Croon, SDM, Sakstein
@ApJL & 2104.02685

MODIFIED BAYES' THEOREM:

$$P(H|x) = P(H) \times \left(1 + P(C) \times \left(\frac{P(x|H)}{P(x)} - 1 \right) \right)$$

H: HYPOTHESIS

x: OBSERVATION

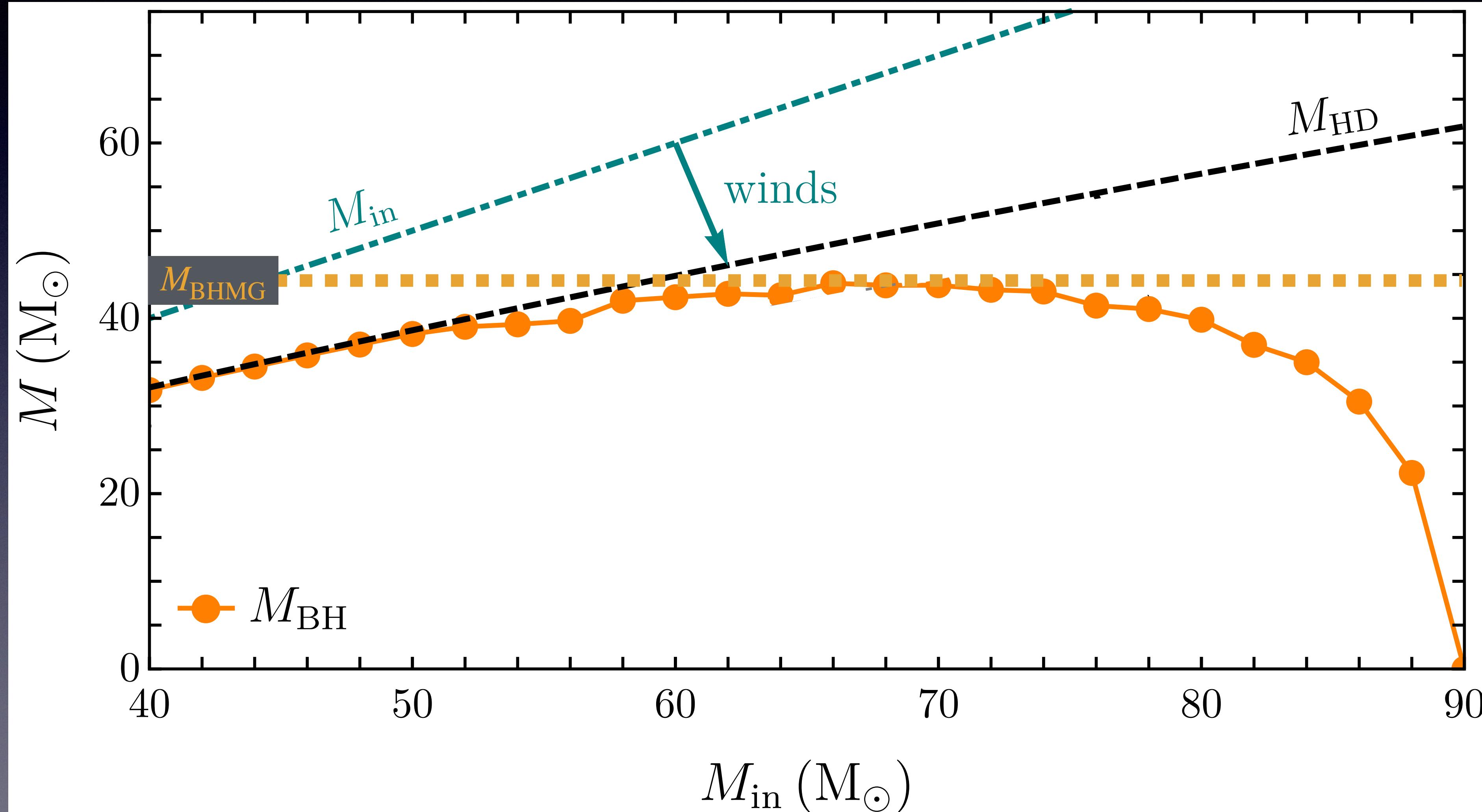
P(H): PRIOR PROBABILITY THAT H IS TRUE

P(x): PRIOR PROBABILITY OF OBSERVING x

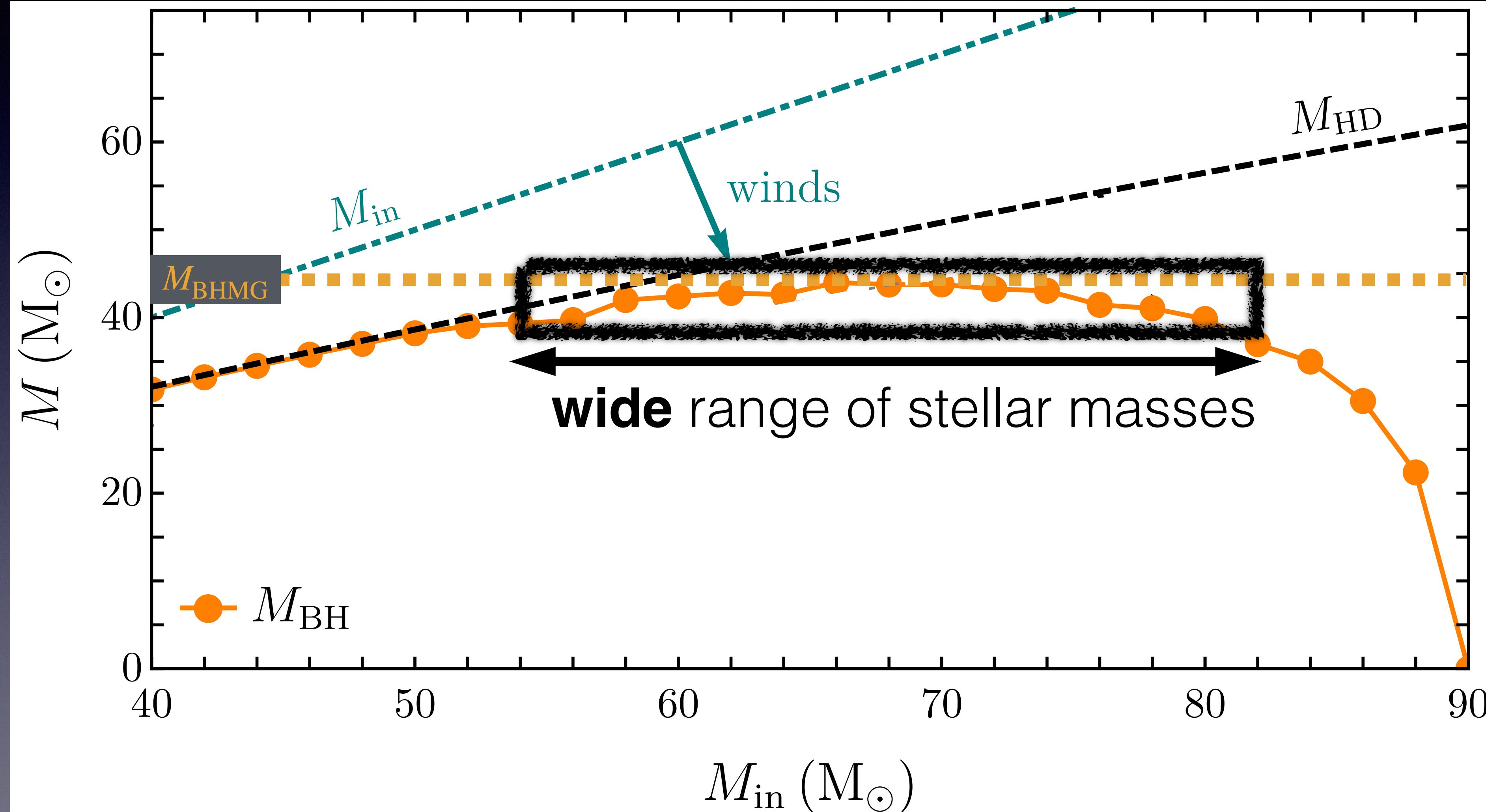
P(C): PROBABILITY THAT YOU'RE USING BAYESIAN STATISTICS CORRECTLY

xkcd.com/2059/

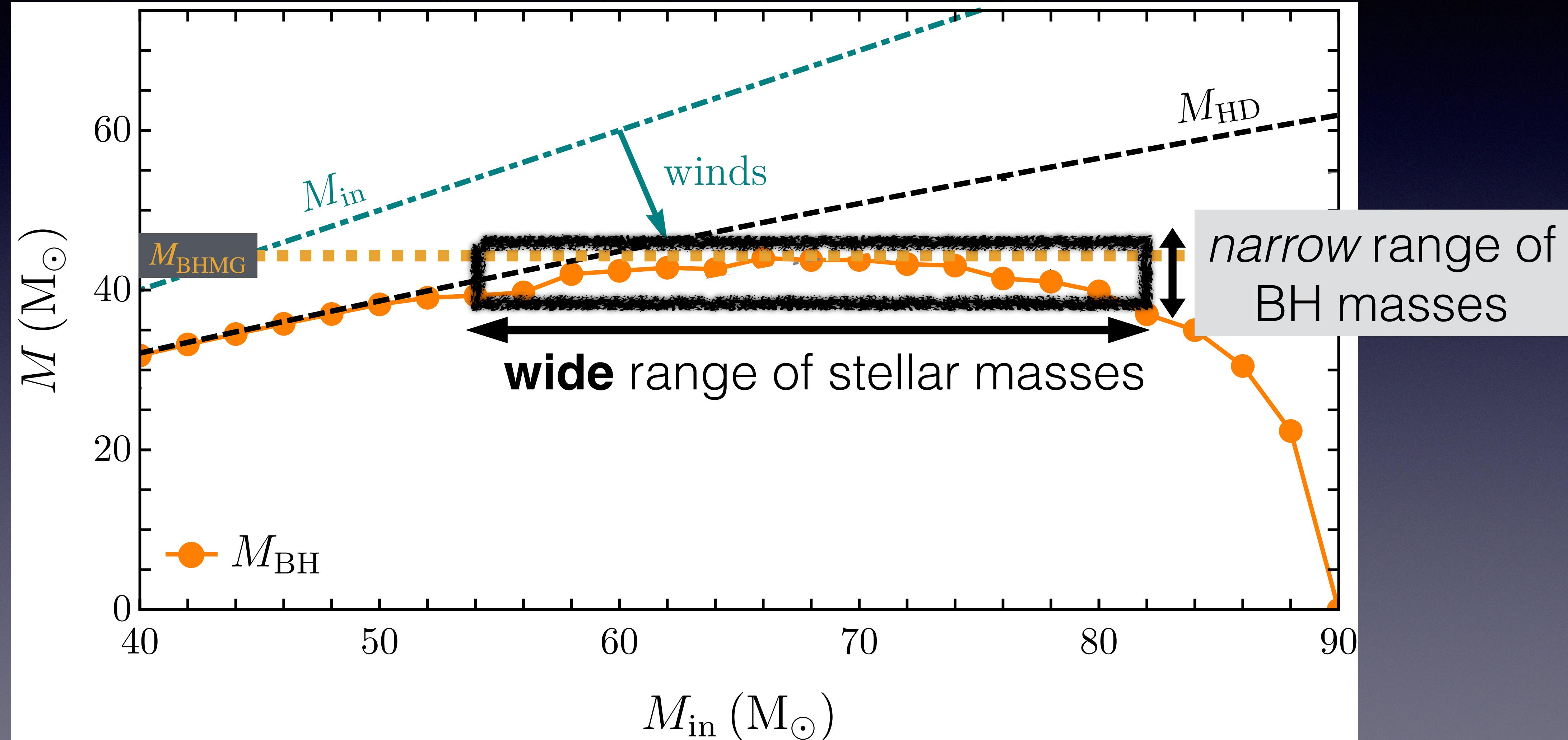
dM_{BH}/dM_*



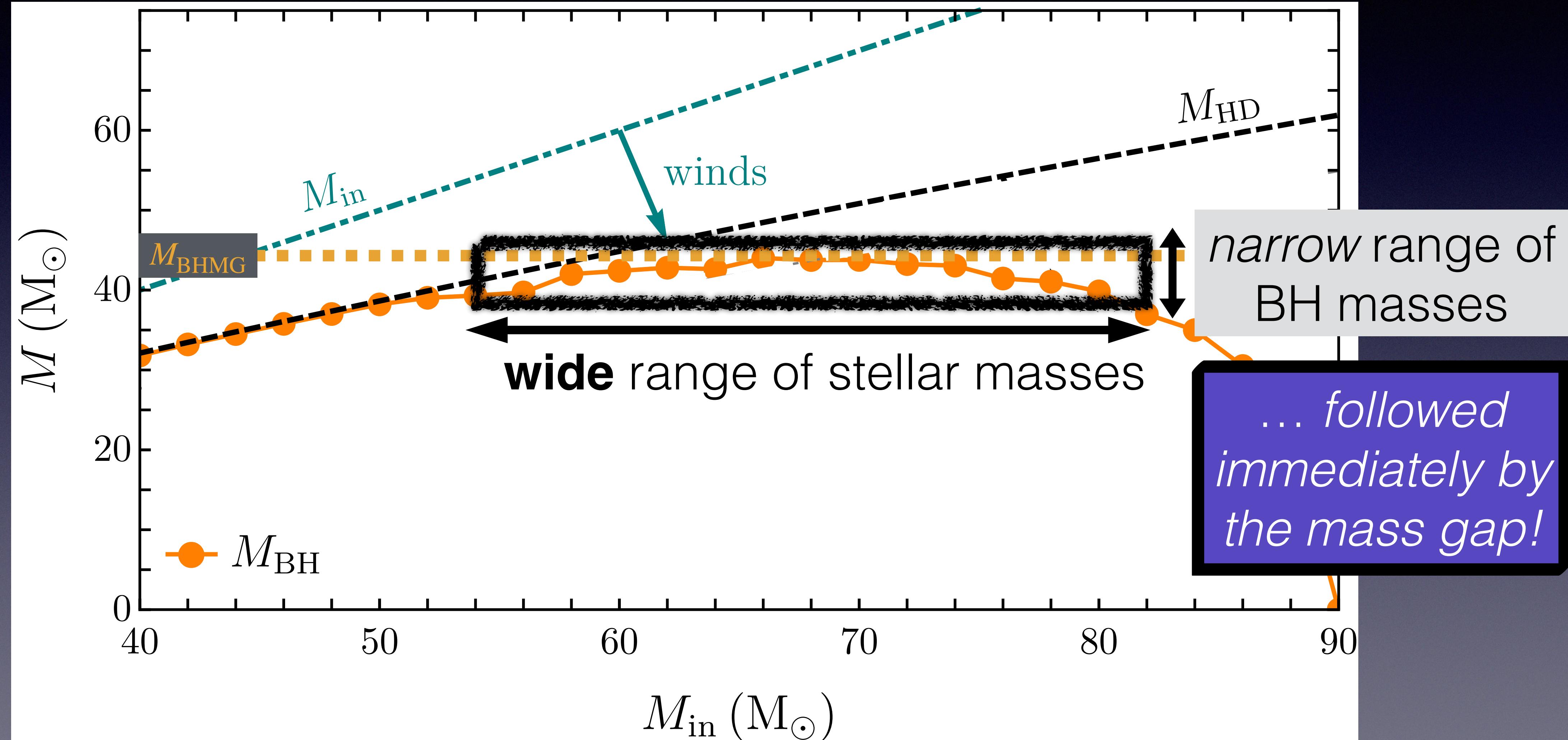
dM_{BH}/dM_*



dM_{BH}/dM_*



dM_{BH}/dM_*



Black Hole Population Statistics

after GWTC-2

$$p(m_1, m_2 | \vec{\theta}) \propto \frac{dN^{(1g)}}{dM_{\text{BH}}} + \lambda \frac{dN^{(2g)}}{dM_{\text{BH}}}$$

Baxter, Croon, SDM, Sakstein
@ApJL + 2104.02685

flexible fitting function with a sharp peak followed by a gap:

$$\frac{dN_{\text{BH}}^{(1g)}}{dM_{\text{BH}}} \propto \left[1 + 2a^2 \sqrt{\frac{M_{\text{BH}}}{M_{\text{BHMG}}}} \left(1 - \frac{M_{\text{BH}}}{M_{\text{BHMG}}} \right)^{a-1} \right] \Theta(M_{\text{BHMG}} - M_{\text{BH}})$$

Black Hole Population Statistics

after GWTC-2

$$p(m_1, m_2 | \vec{\theta}) \propto \frac{dN^{(1g)}}{dM_{\text{BH}}} + \lambda \frac{dN^{(2g)}}{dM_{\text{BH}}}$$

Baxter, Croon, SDM, Sakstein
@ApJL + 2104.02685

flexible fitting function with a sharp peak followed by a gap:

$$\frac{dN_{\text{BH}}^{(1g)}}{dM_{\text{BH}}} \propto \left[1 + 2a^2 \sqrt{\frac{M_{\text{BH}}}{M_{\text{BHMG}}}} \left(1 - \frac{M_{\text{BH}}}{M_{\text{BHMG}}} \right)^{a-1} \right] \Theta(M_{\text{BHMG}} - M_{\text{BH}})$$

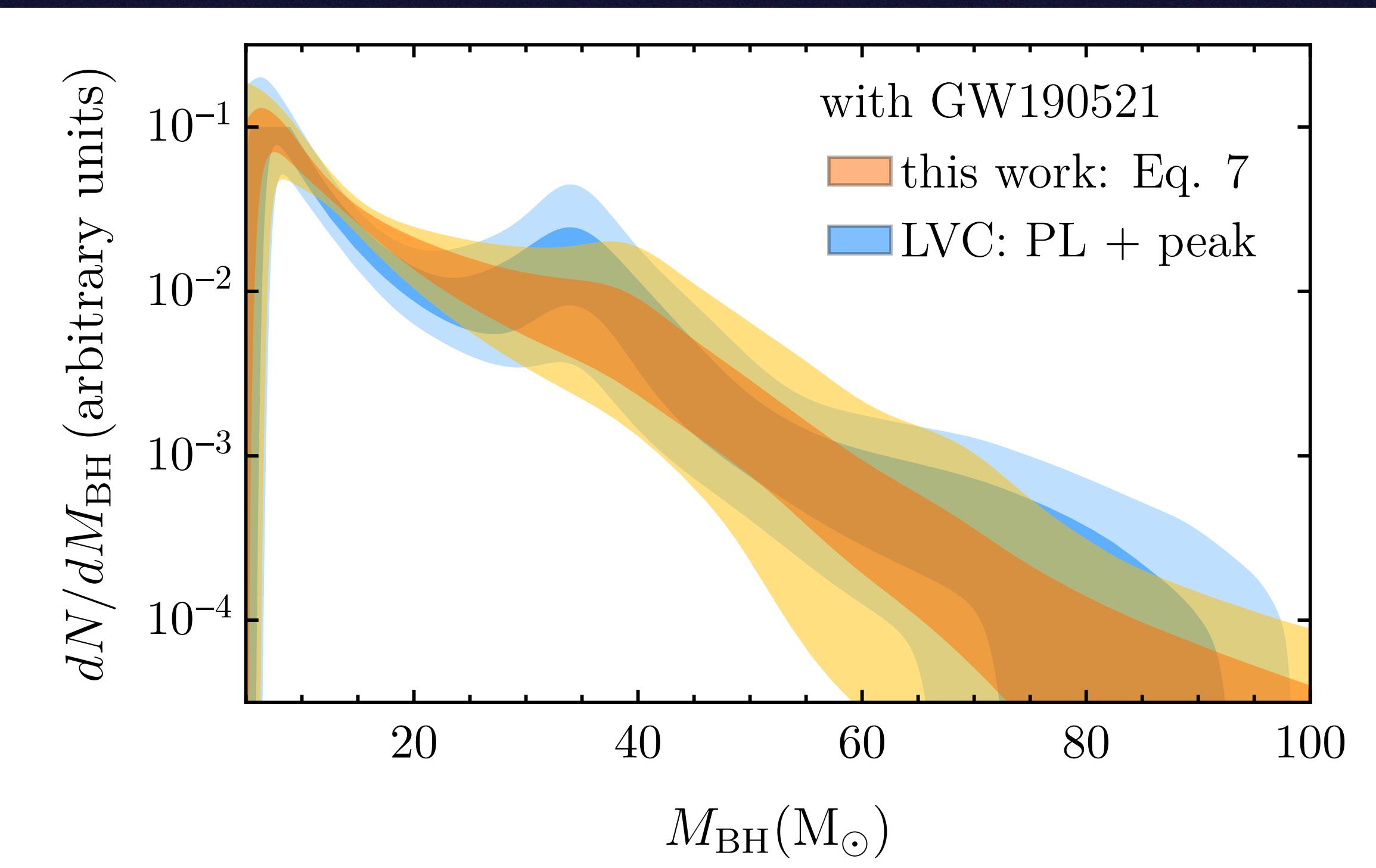
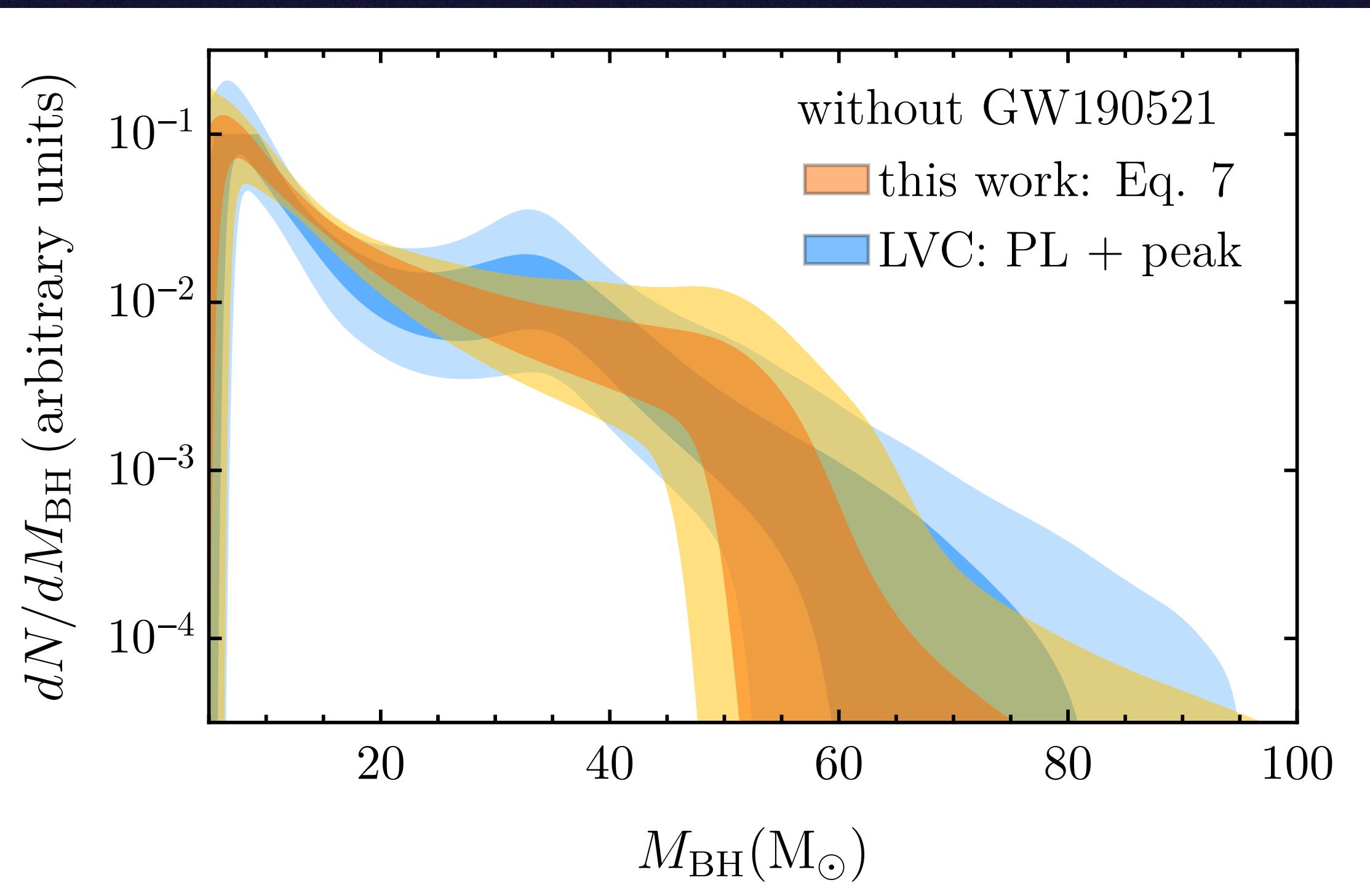
$$\frac{dN^{(2g)}}{dM_{\text{BH}}} \sim \int dM_a \frac{dN^{(1g)}(M_a)}{dM_a} \frac{dN^{(1g)}(M_{\text{BH}} - M_a)}{dM_a}$$

Black Hole Population Statistics

after GWTC-2

$$p(m_1, m_2 | \vec{\theta}) \propto \frac{dN^{(1g)}}{dM_{\text{BH}}} + \lambda \frac{dN^{(2g)}}{dM_{\text{BH}}}$$

Baxter, Croon, SDM, Sakstein
@ApJL + 2104.02685v2



Conclusions



Conclusions



- LIGO is in the middle of its “discovery bump”
 - we are learning so much more about the Universe all the time!
- Physically motivated mass functions will soon reveal intimate details of the black hole creation mechanism
- The future is exciting!

Thanks!

sammcd00@fnal.gov

home.fnal.gov/~sammcd00/