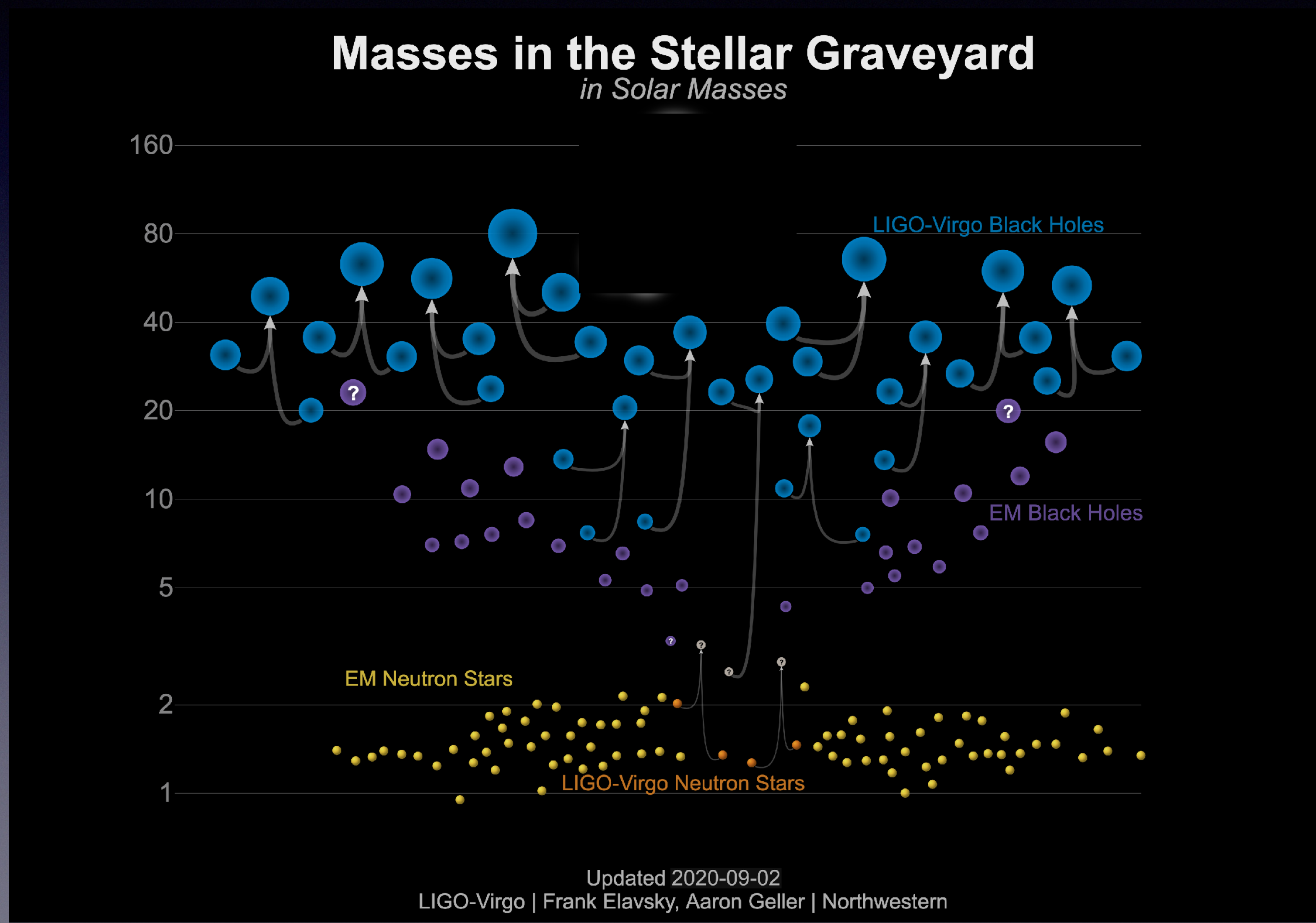


New Physics and the Black Hole Mass Gap

Samuel D. McDermott, Fermilab (6th Floor)

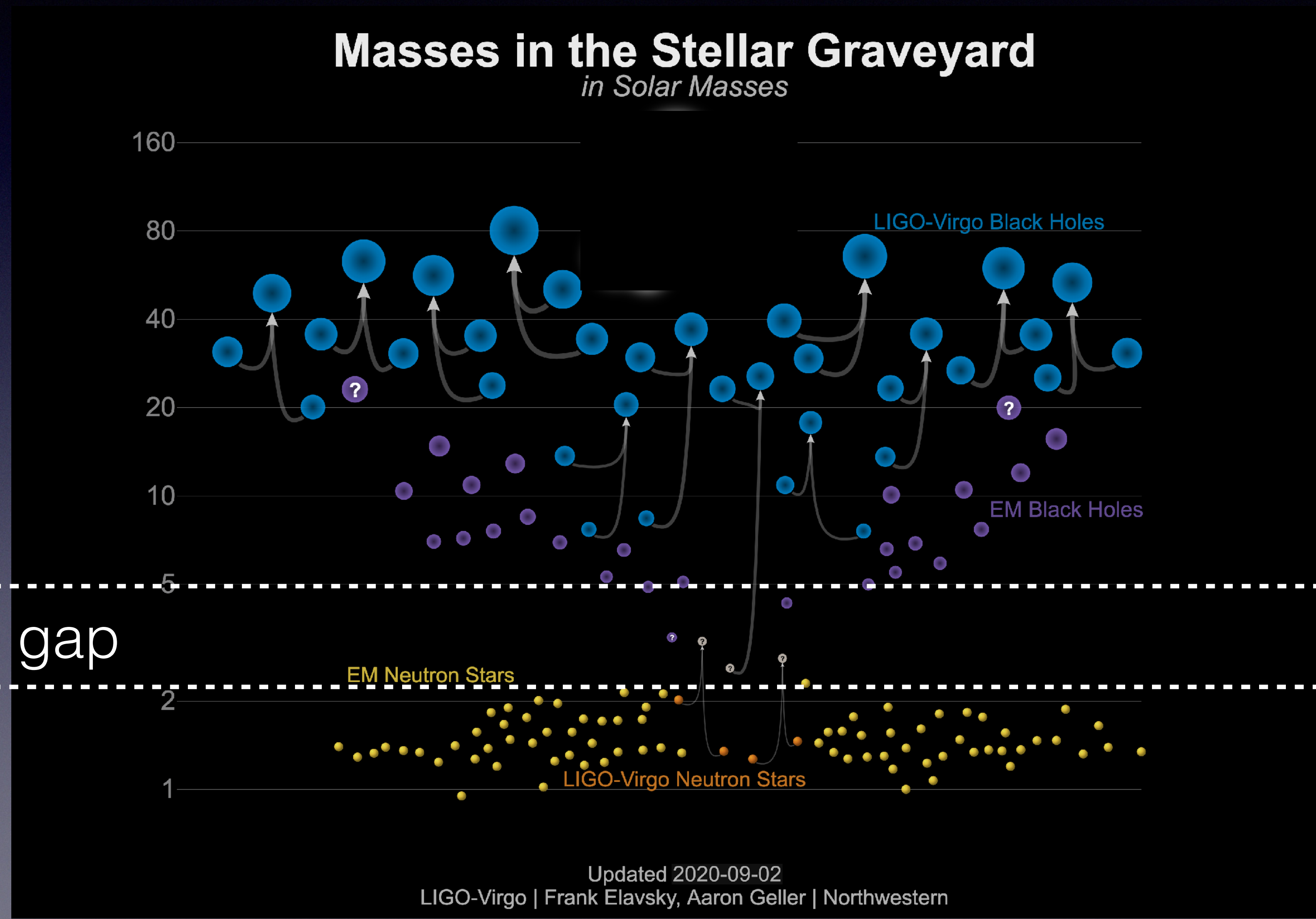
Work with Djuna Croon + Jeremy Sakstein: 2007.00650 [hep-ph], 2007.07889 [gr-qc]
(&/+ Maria Straight and Eric Baxter): 2009.01213 [gr-qc]

LIGO Observations so Far



LIGO Observations so Far

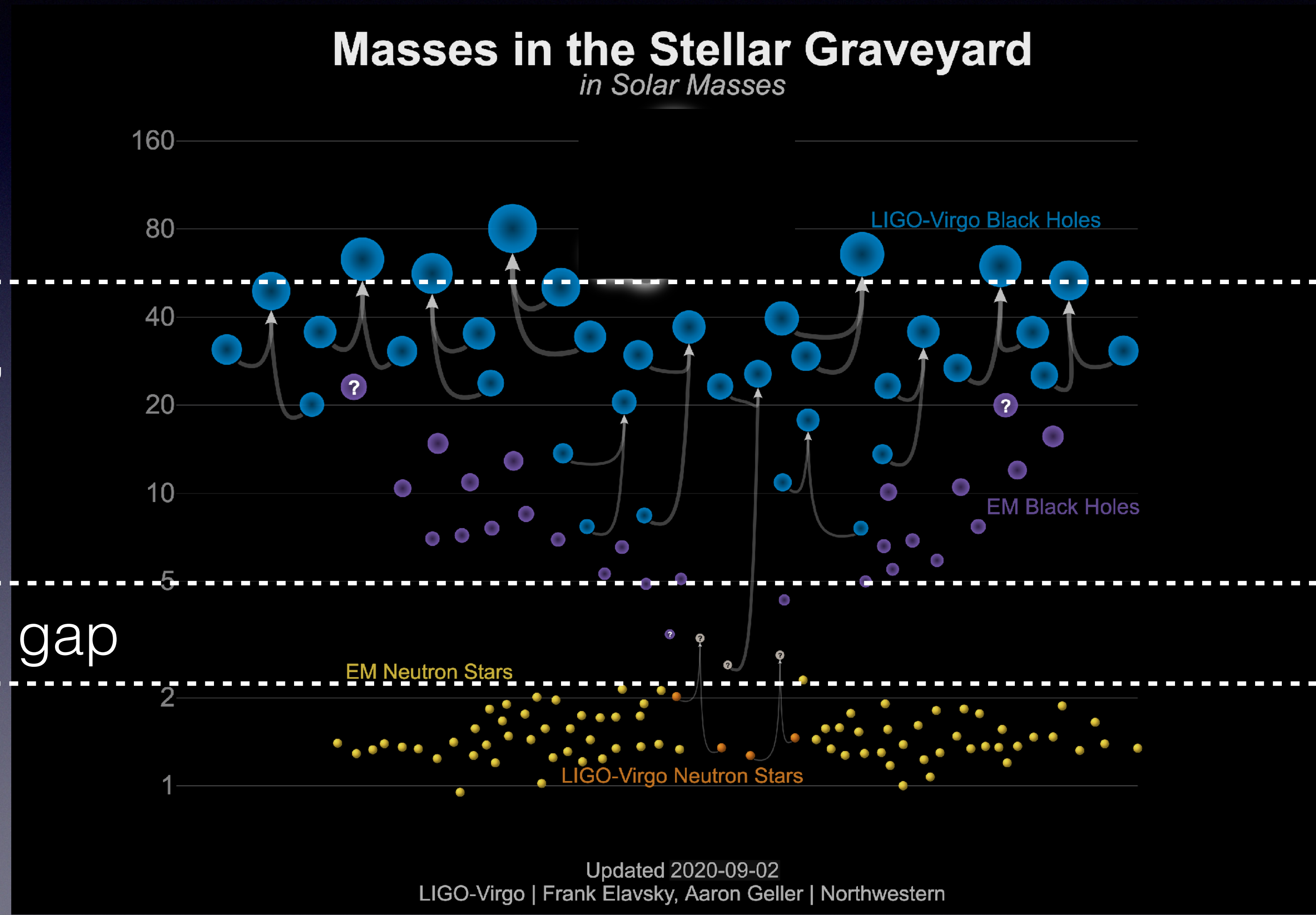
“lower” mass gap



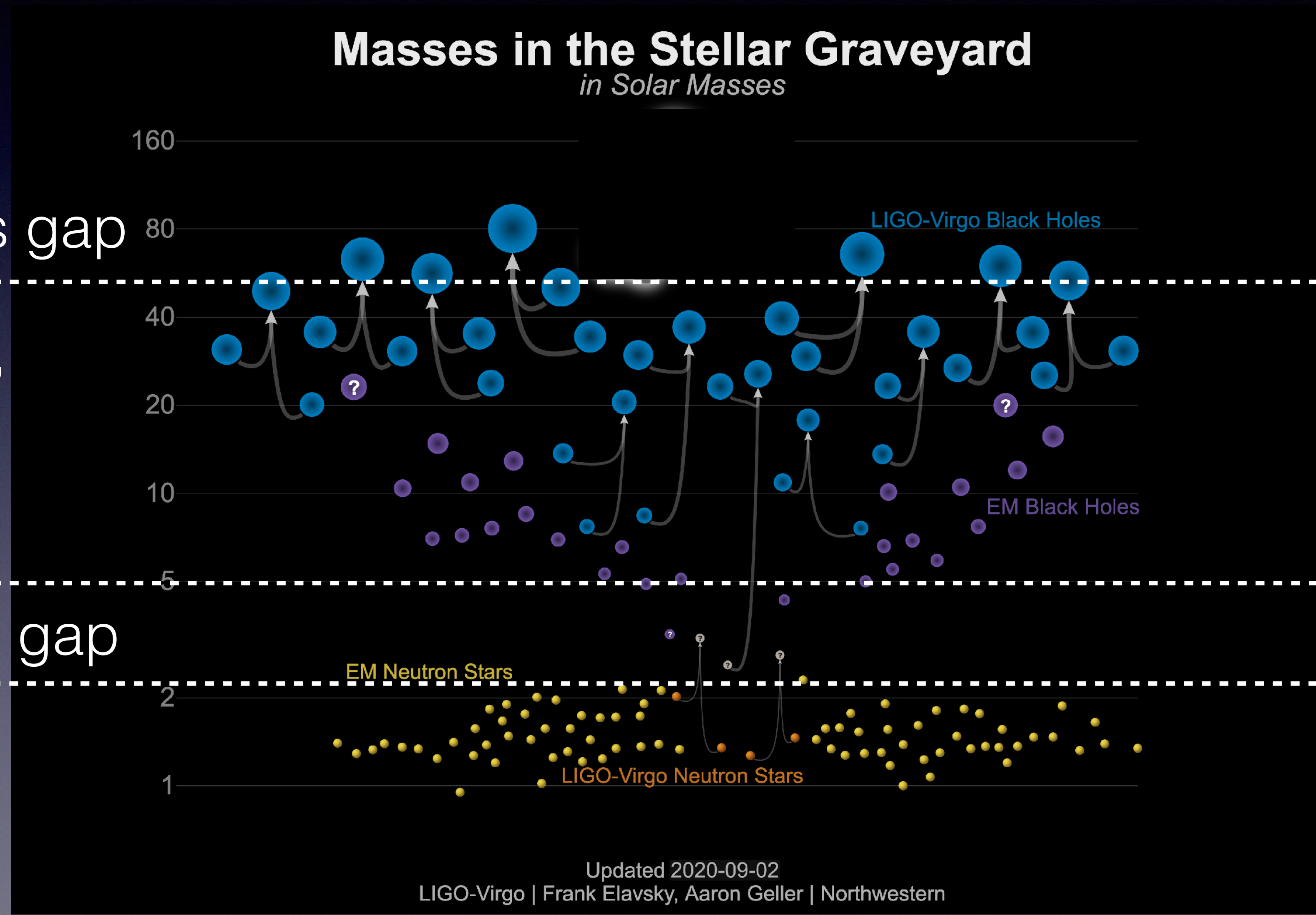
LIGO Observations so Far

“Black hole
mass ceiling”

“lower” mass gap



LIGO Observations so Far

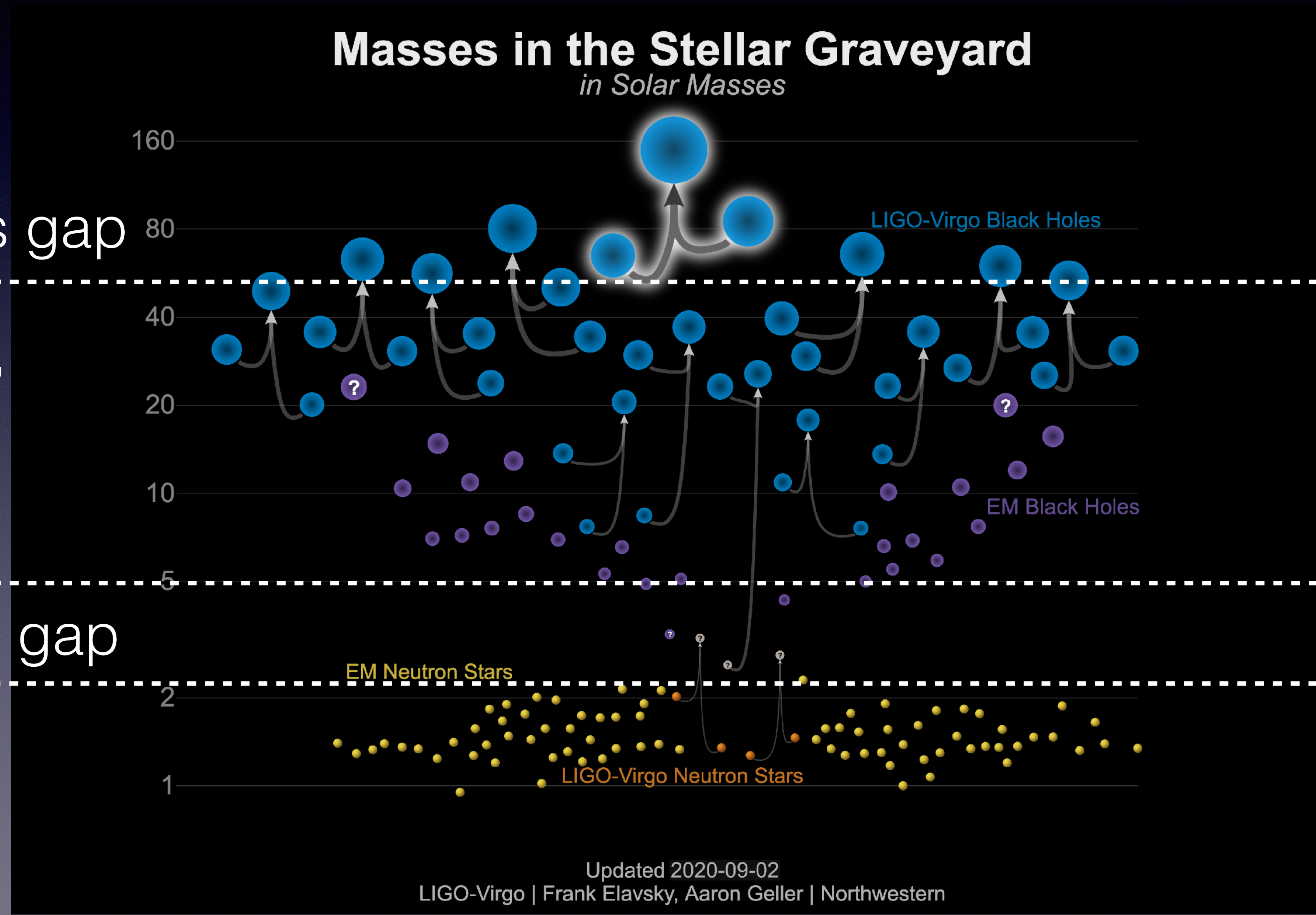


“upper” mass gap

“Black hole
mass ceiling”

“lower” mass gap

LIGO Observations so Far

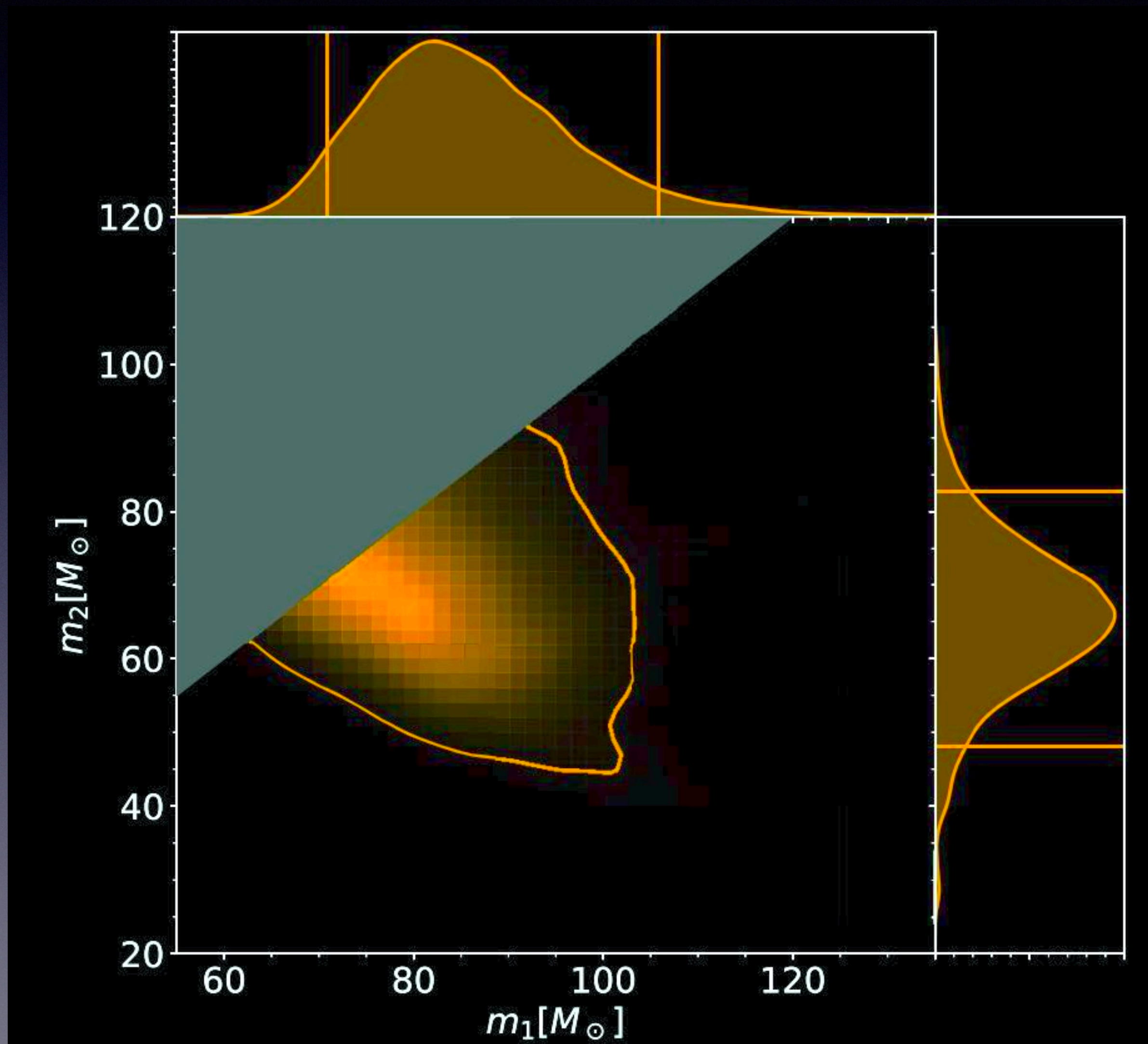


“upper” mass gap

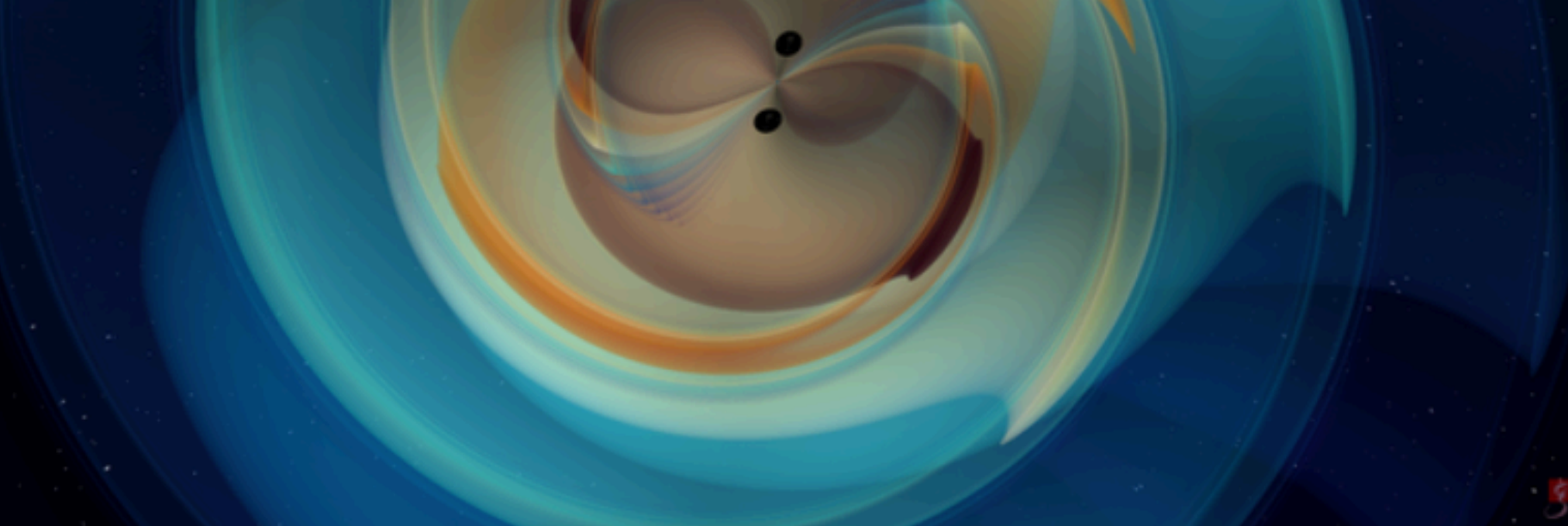
“Black hole
mass ceiling”

“lower” mass gap

GW190521



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



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 to the energy of eight suns.

Astronomers detect most massive black hole for the first time

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

GW190521



FORBES.COM

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

The New York Times

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

Black holes: Cosmic signal rattles after 7 billion years

By Jonathan Amos
BBC Science Correspondent

NewScientist
IDEEËN DIE DE WERELD VERANDEREN

BLOGS

DOSSIERS

RECENSIES

MAGAZINE

AGENDA

LOGIN

Q

SHOP

Zwaartekrachtsgolven van 'te zware' zwartgaten waargenomen

ars TECHNICA

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

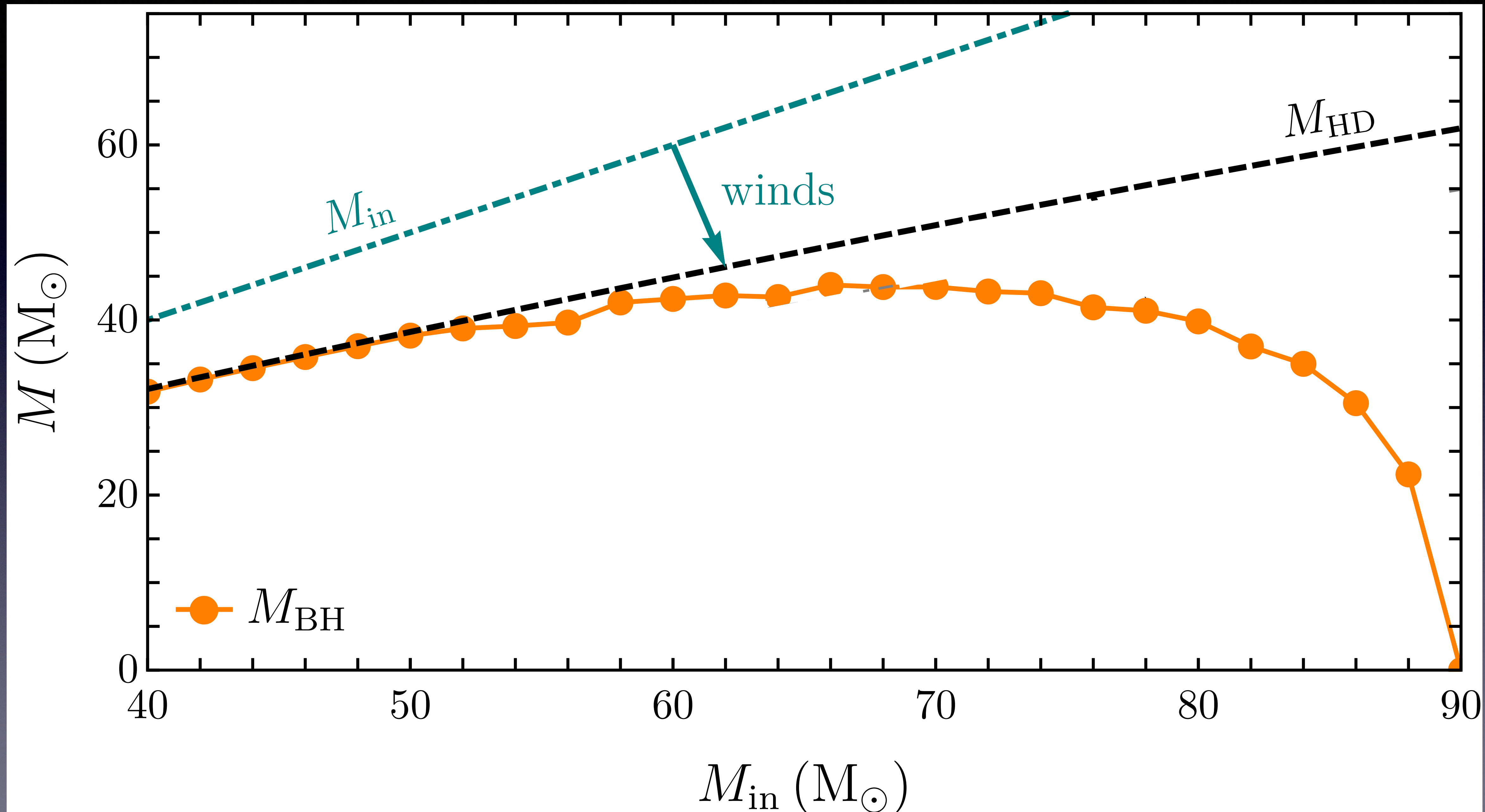
Latest Issues

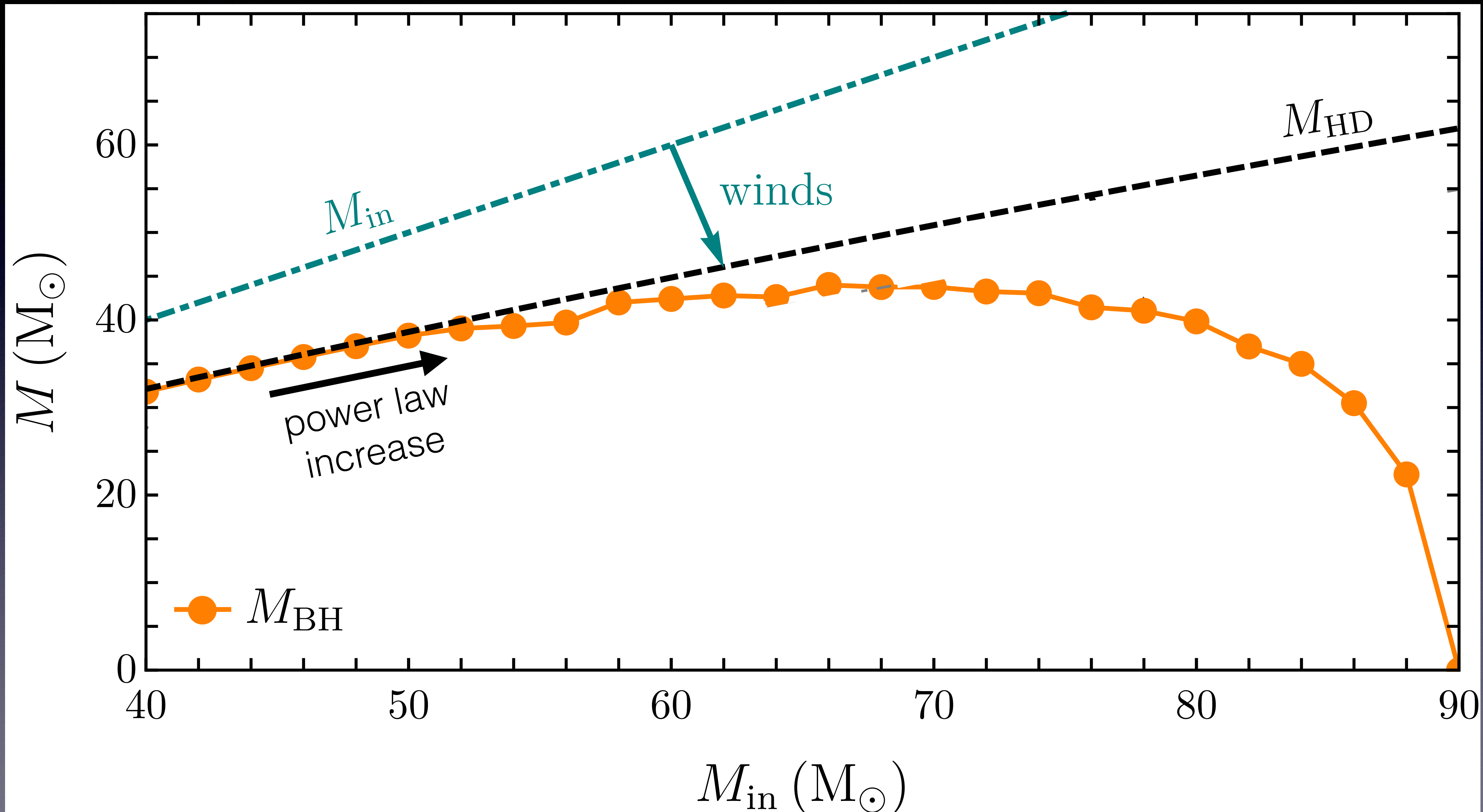
SCIENTIFIC AMERICAN
CELEBRATING 175 YEARS

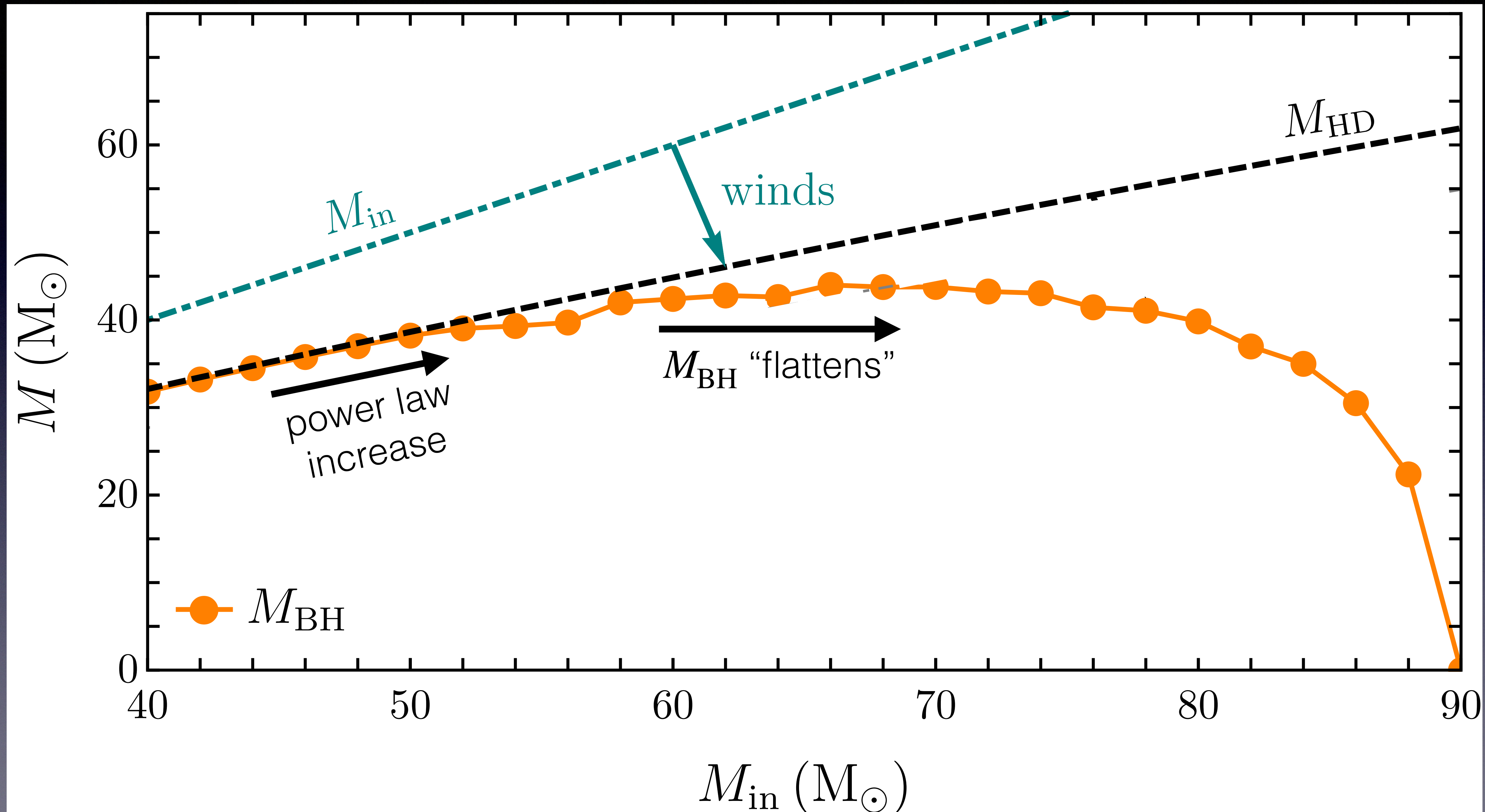
Cart 0

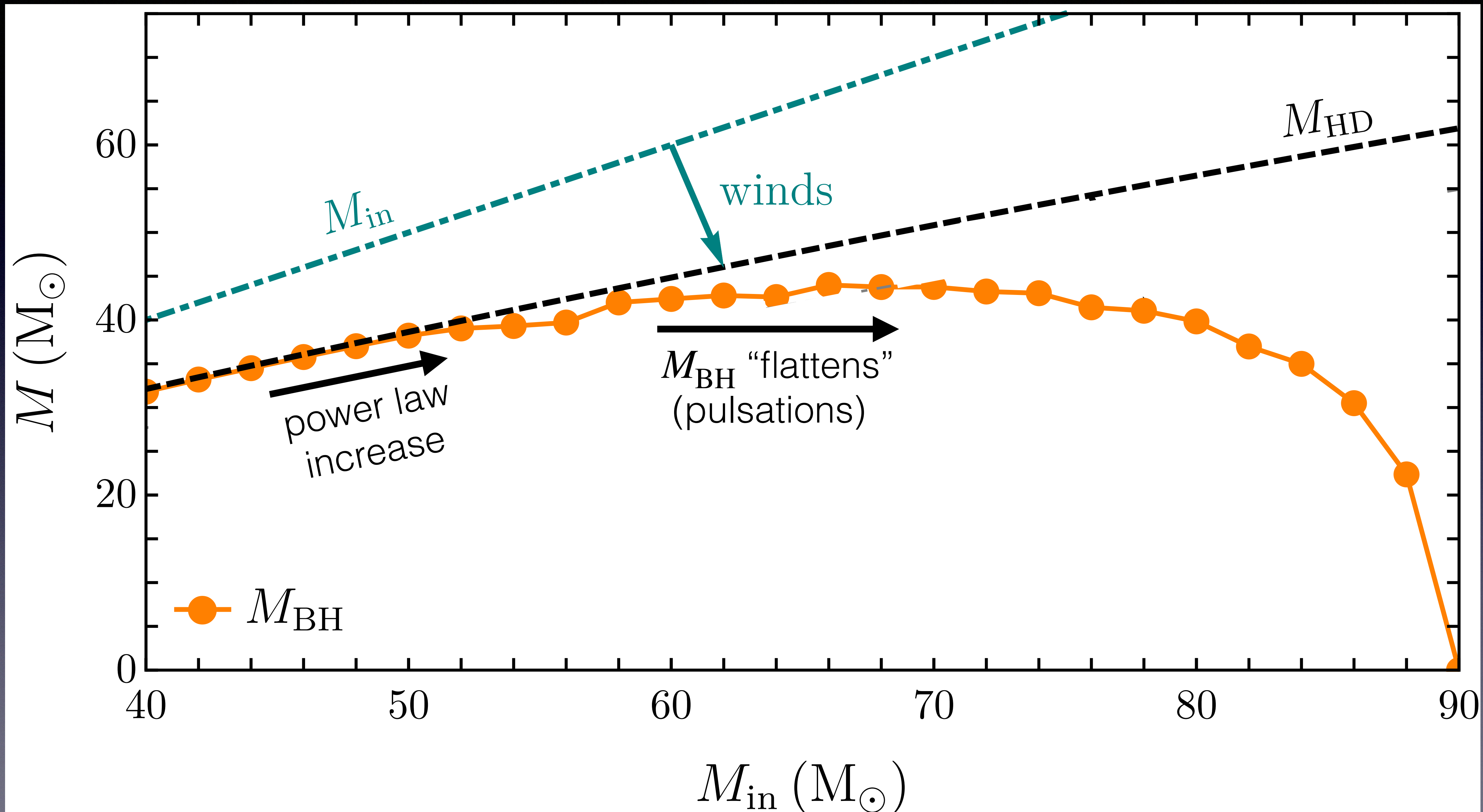
LIGO and Virgo Capture Their Most Massive Black Holes Yet

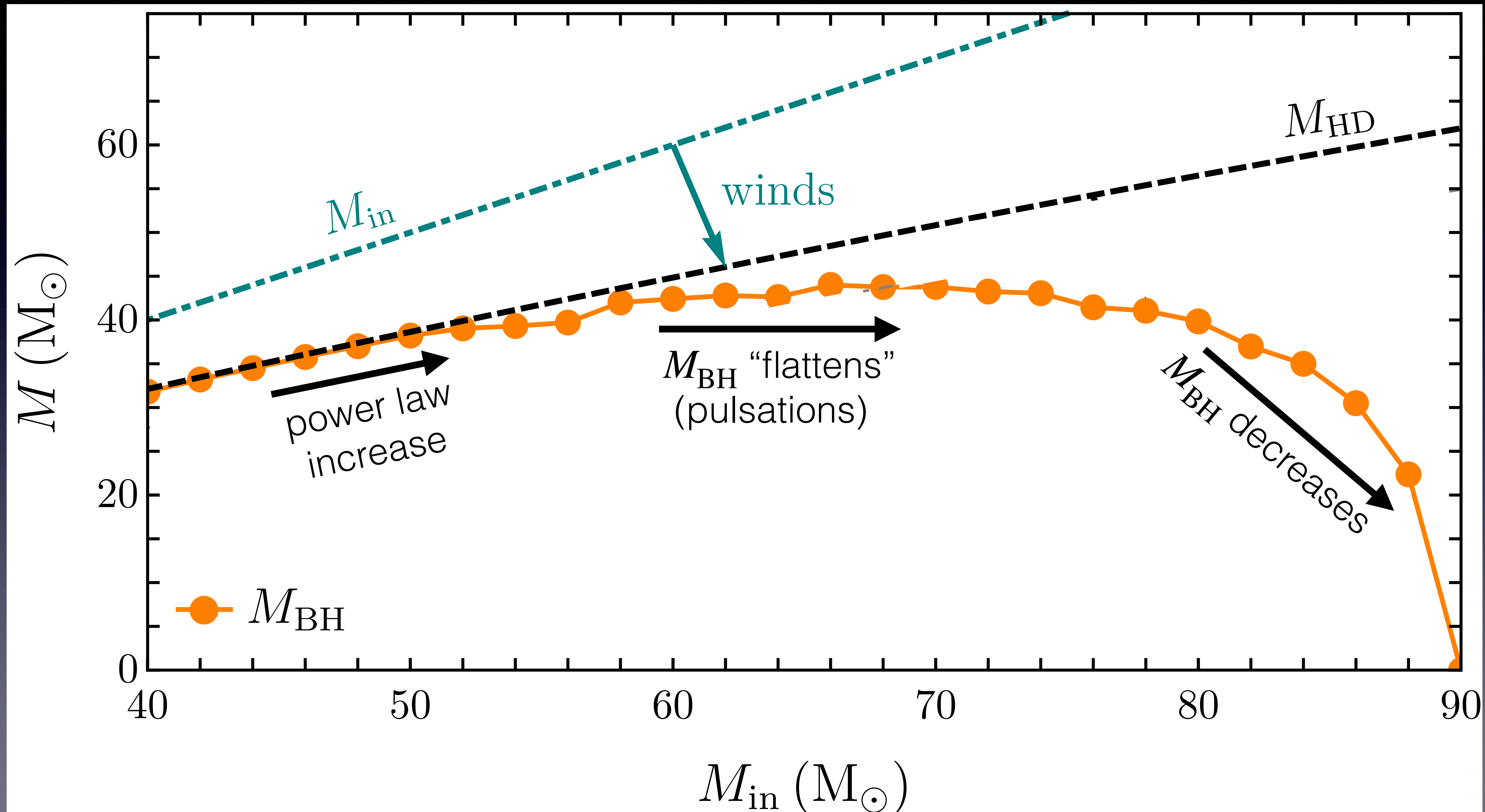
laboration),

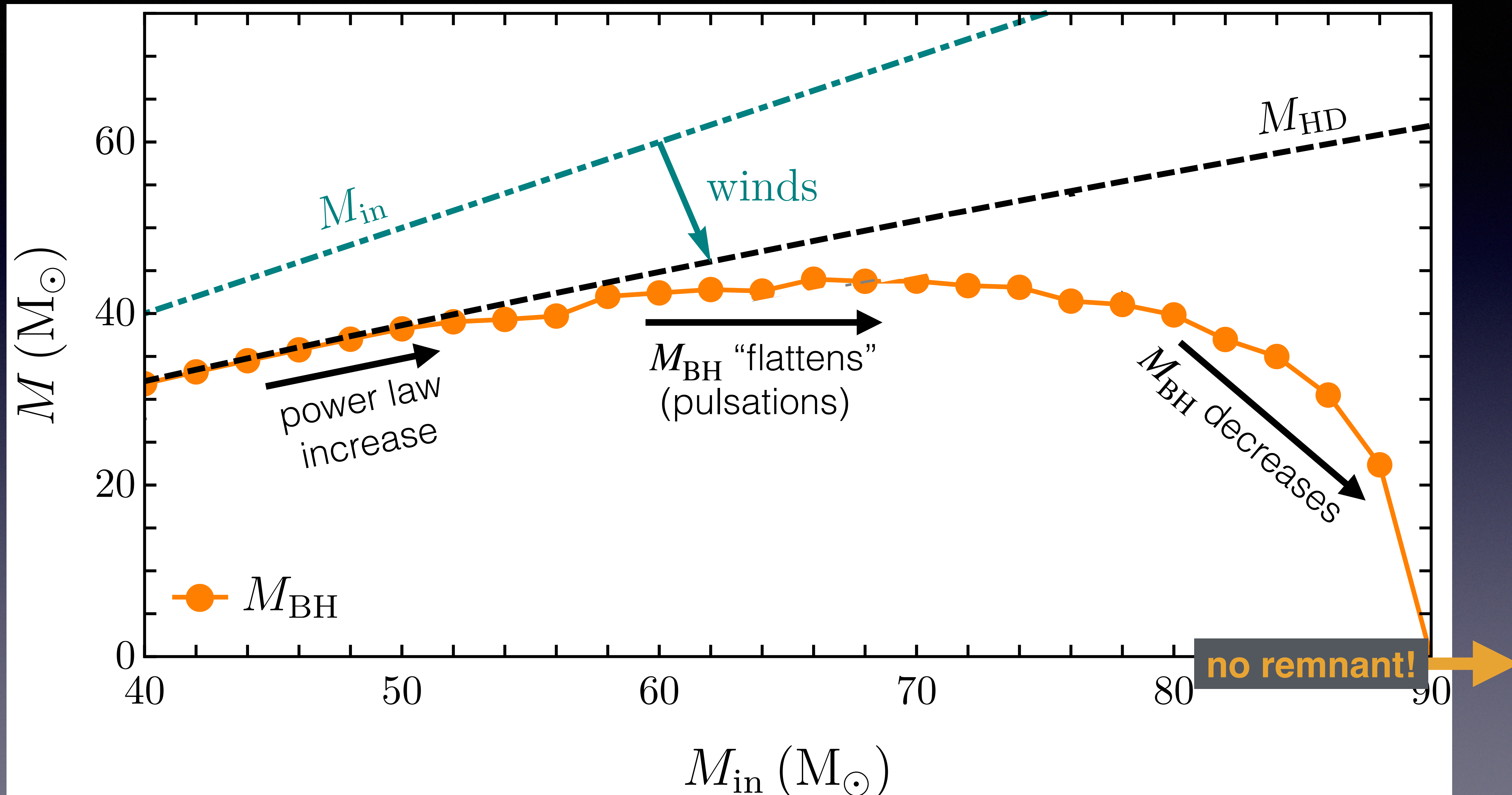


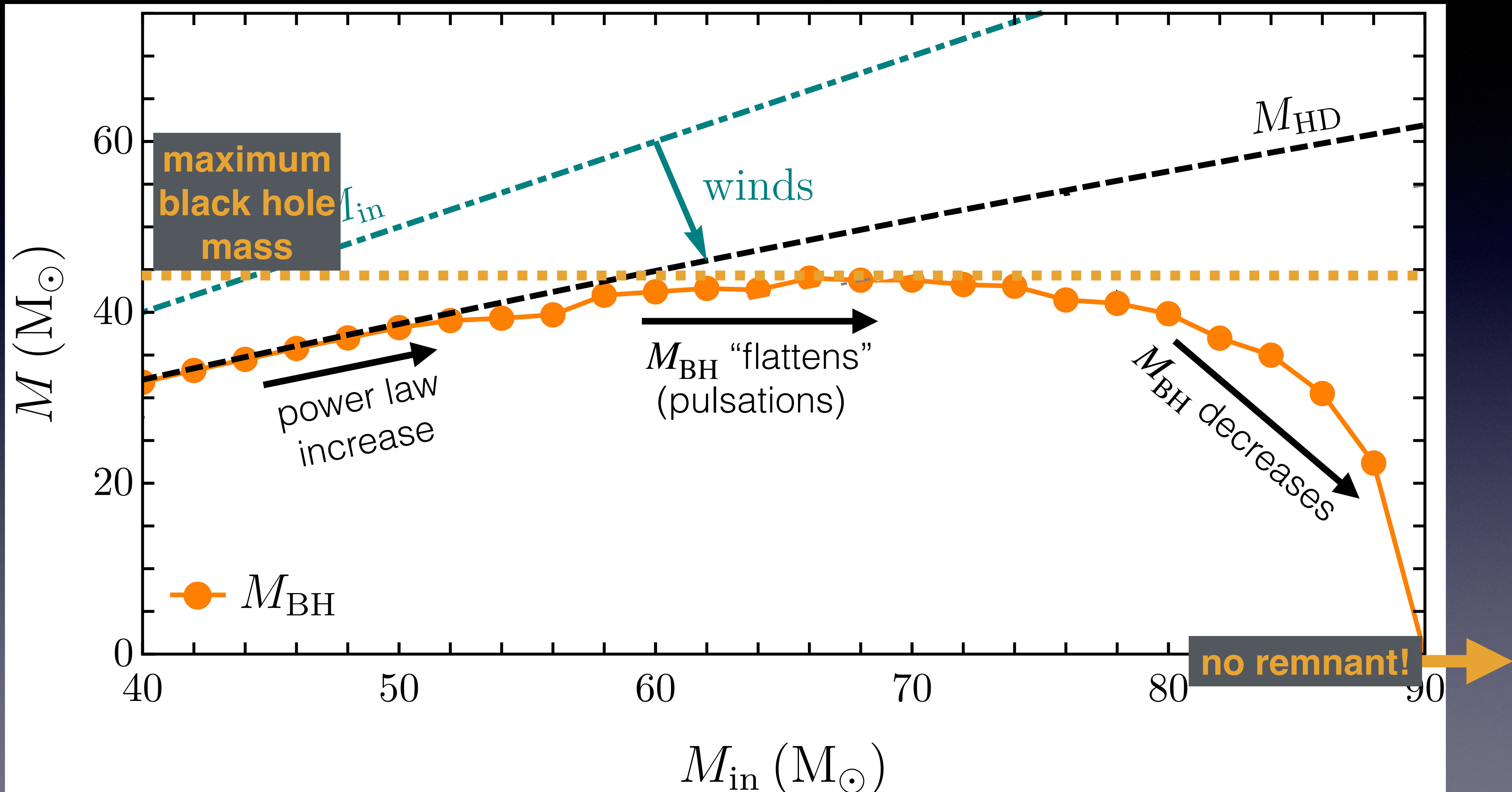












Outline

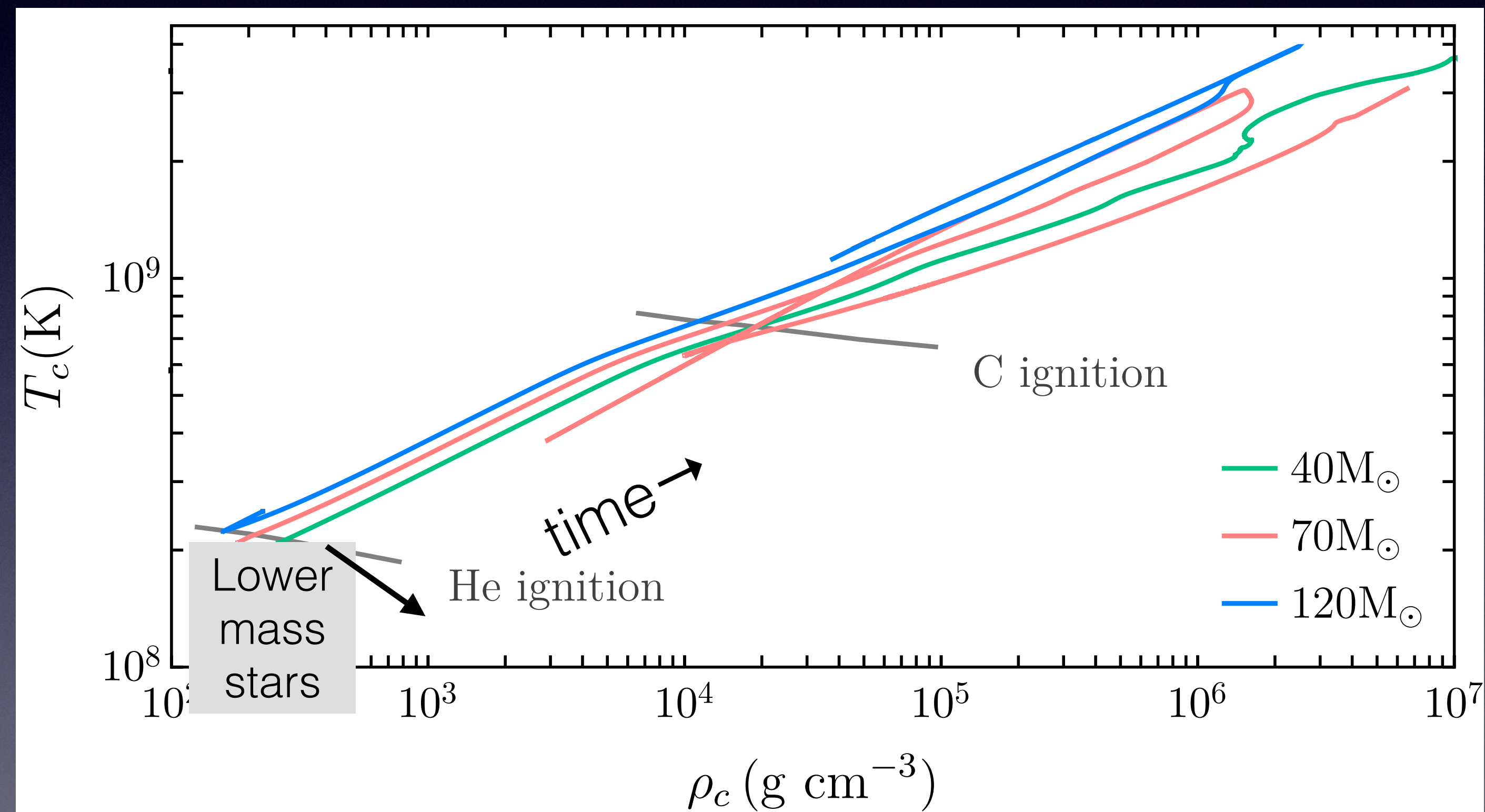
1. Physics of the pair instability mechanism
2. Beyond-the-Standard-Model explanations of GW190521
3. Standard Model explanations of GW190521
4. Future prospects

Outline

1. Physics of the pair instability mechanism
2. Beyond-the-Standard-Model explanations of GW190521
3. Standard Model explanations of GW190521
4. Future prospects

Evolution of Pop III Stars

- Simulate stars with MESA v12778* starting from the zero-age helium branch through pulsations
- Final BH mass is the material gravitationally bound to the core after hydrostatic equilibrium is regained (following pulsations)

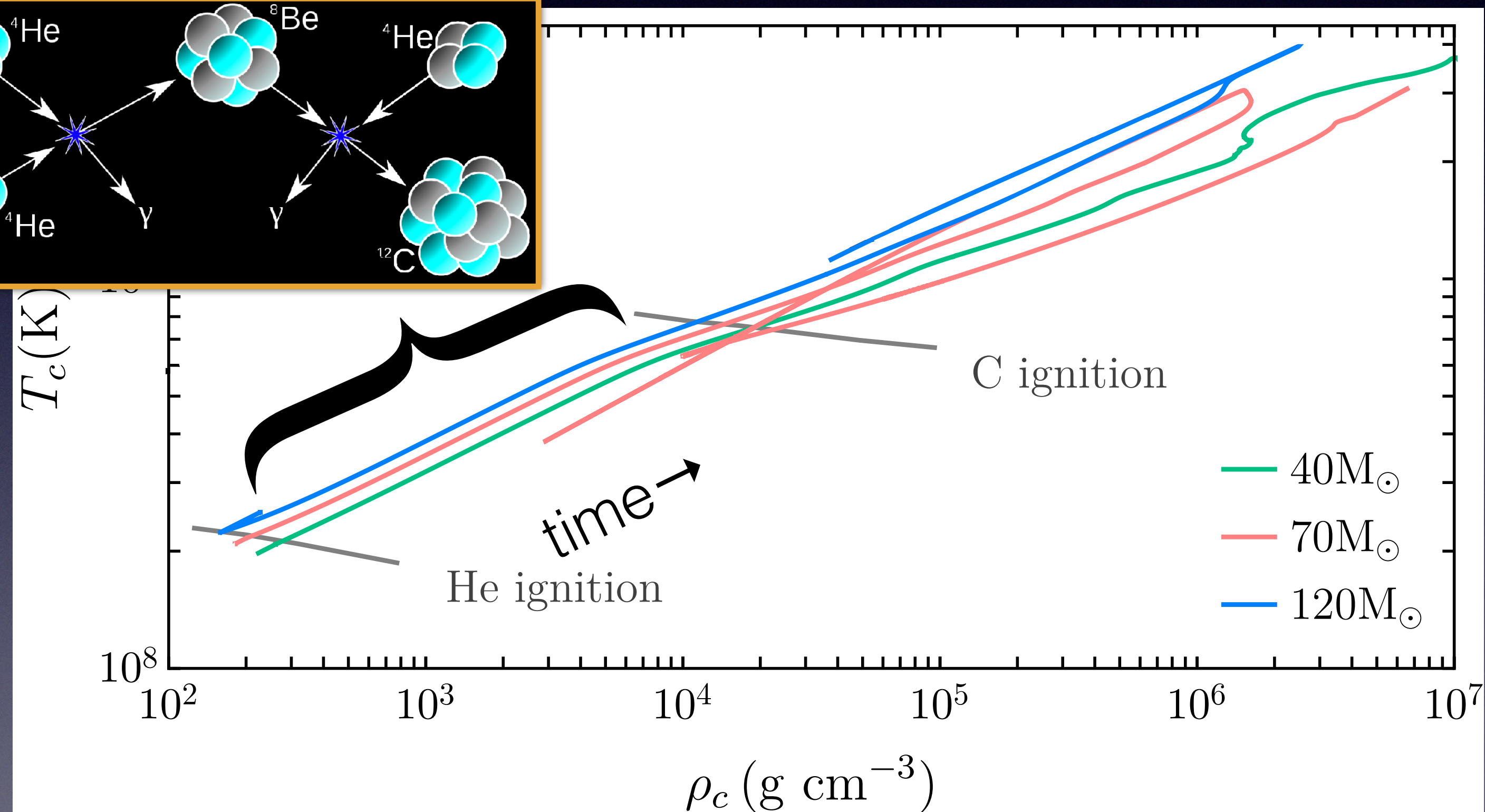
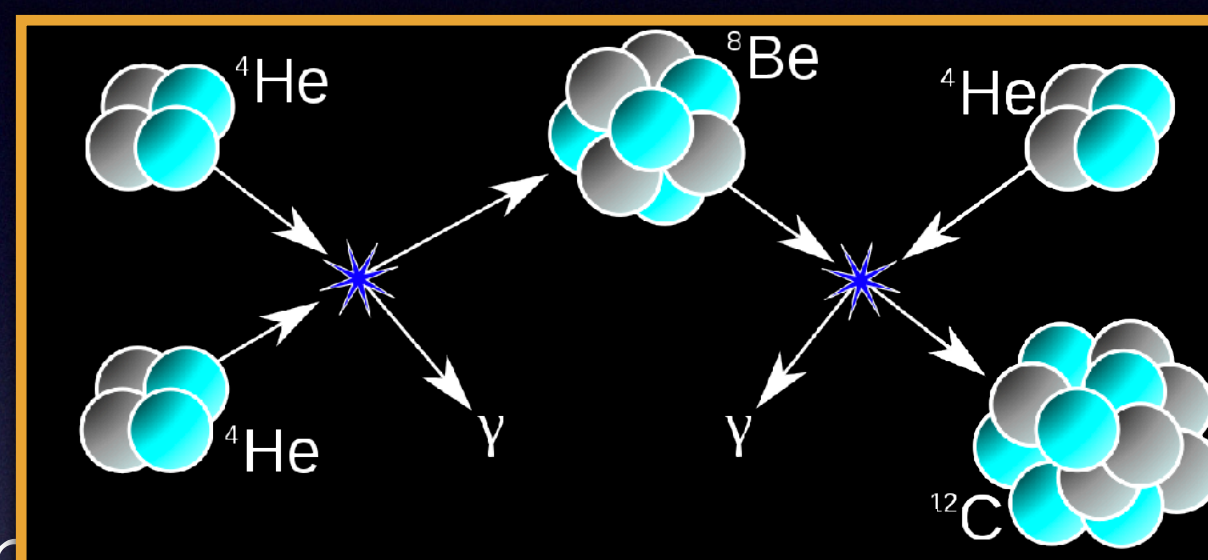


*Paxton et al, arXiv:1710.08424 [astro-ph.SR]

Evolution of Pop III Stars

- Simulate stars with **MESA v12778*** starting from the zero-age helium branch through pulsations
- Final BH mass is the material gravitationally bound to the core after hydrostatic equilibrium is regained (following pulsations)

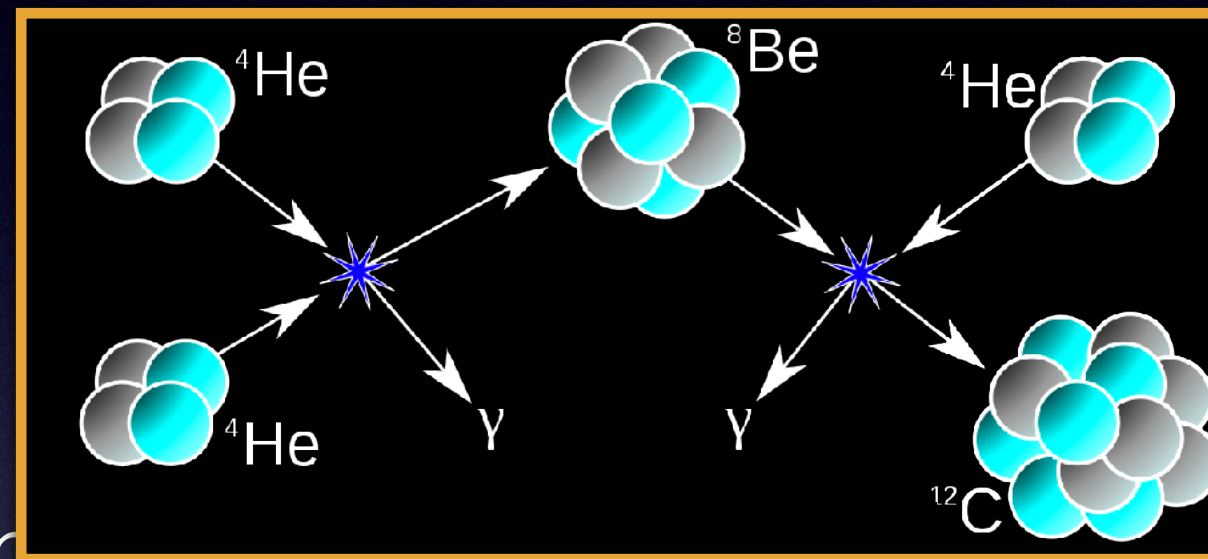
Main nuclear reaction:



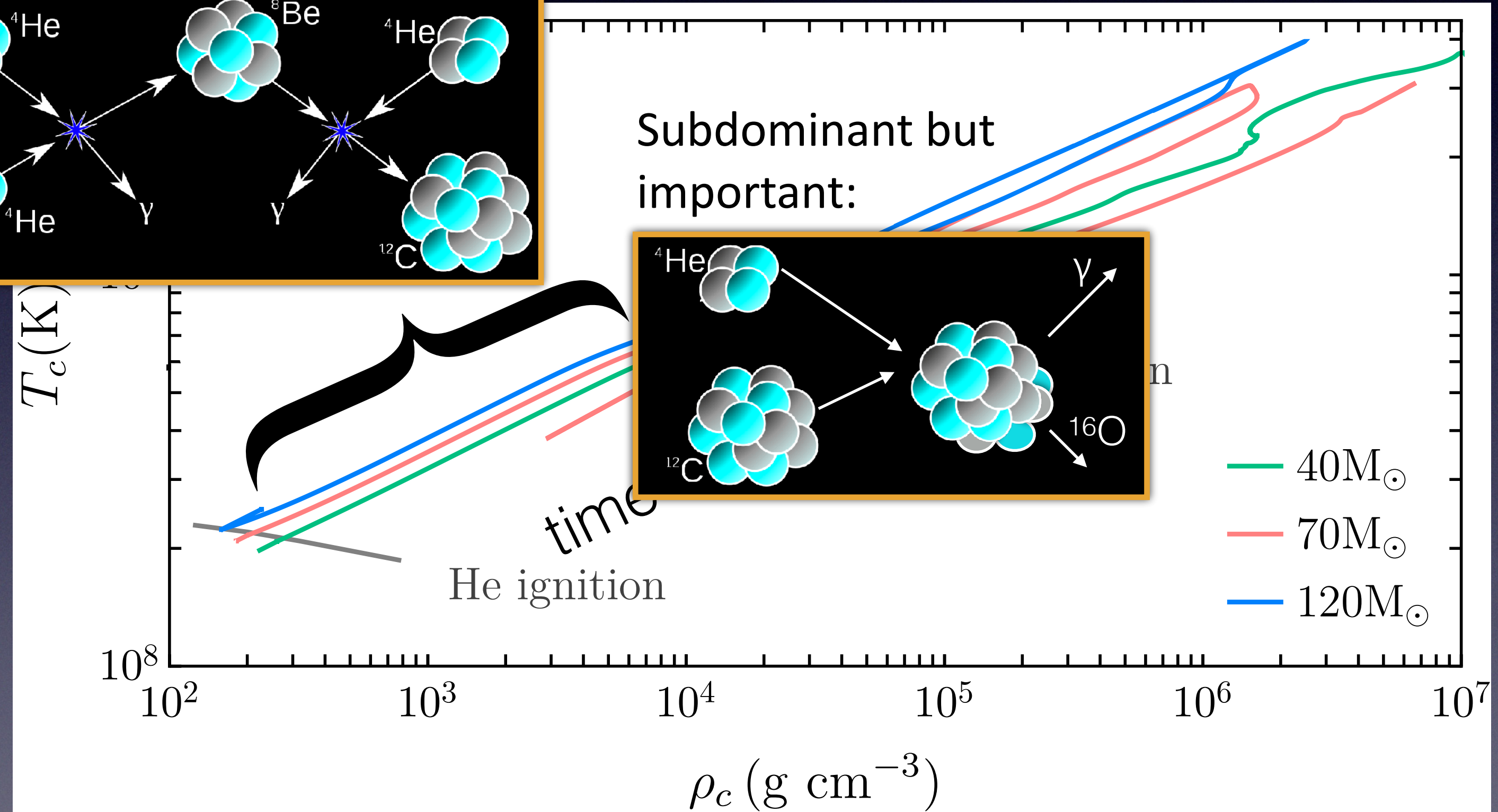
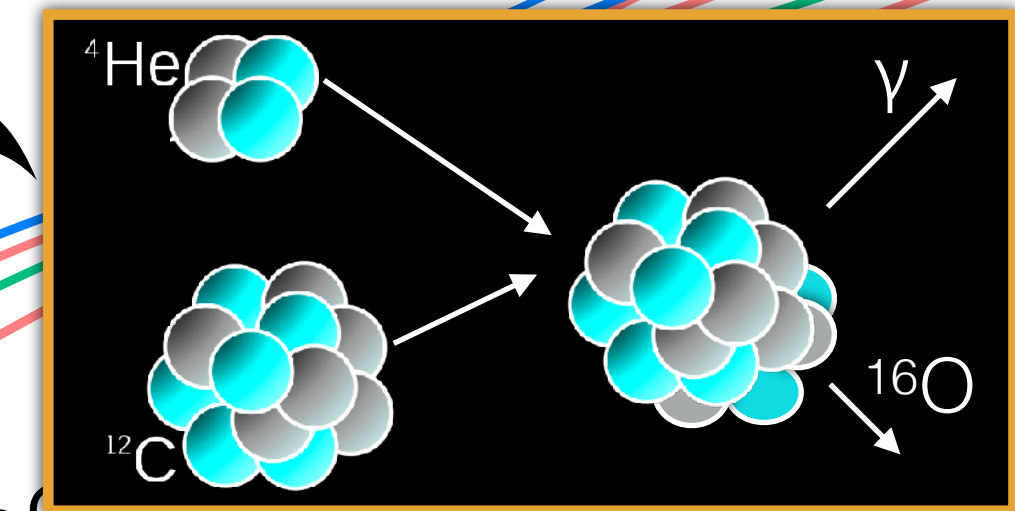
Evolution of Pop III Stars

- Simulate stars with **MESA v12778*** starting from the zero-age helium branch through pulsations
- Final BH mass is the material gravitationally bound to the core after hydrostatic equilibrium is regained (following pulsations)

Main nuclear reaction:



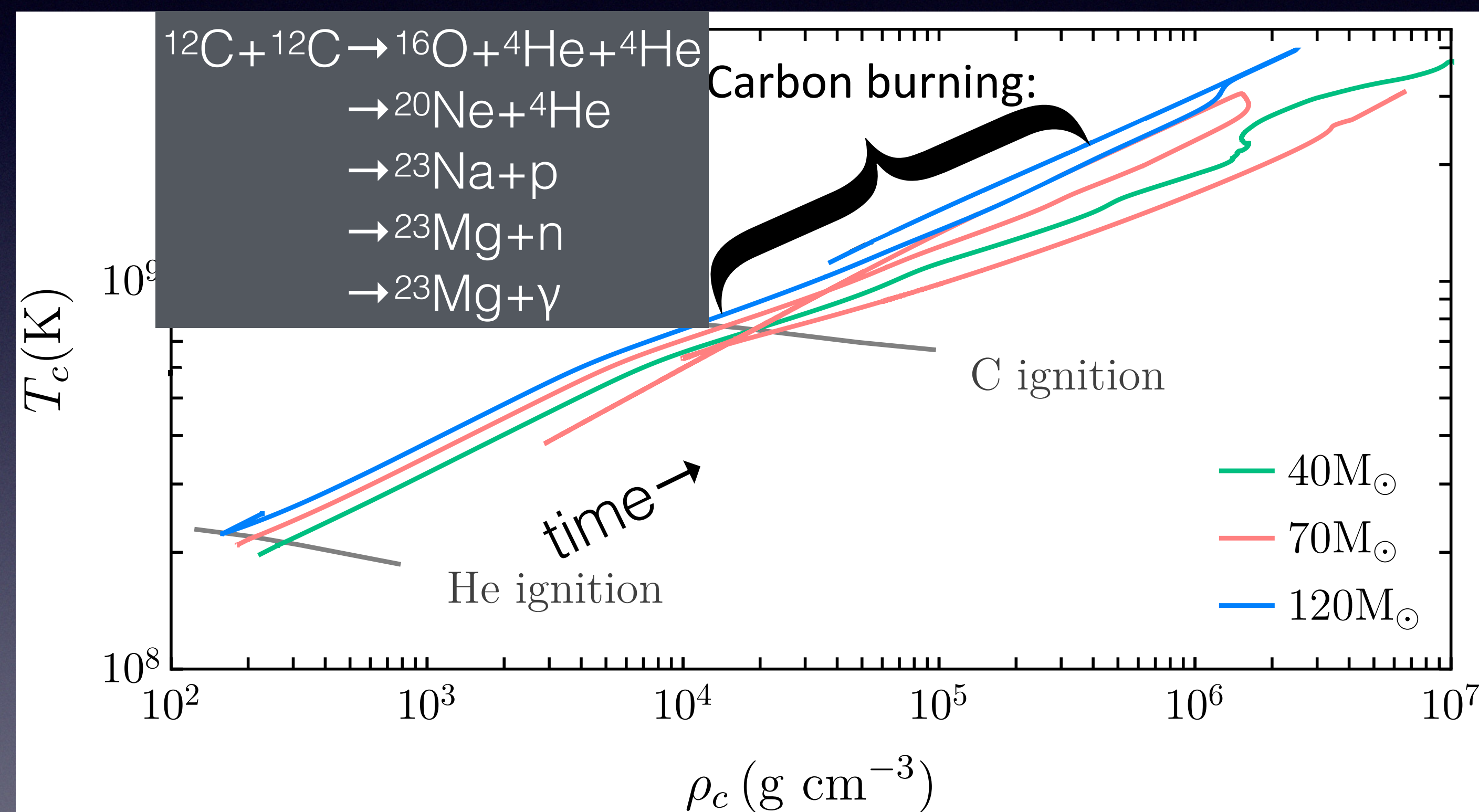
Subdominant but important:



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

Evolution of Pop III Stars

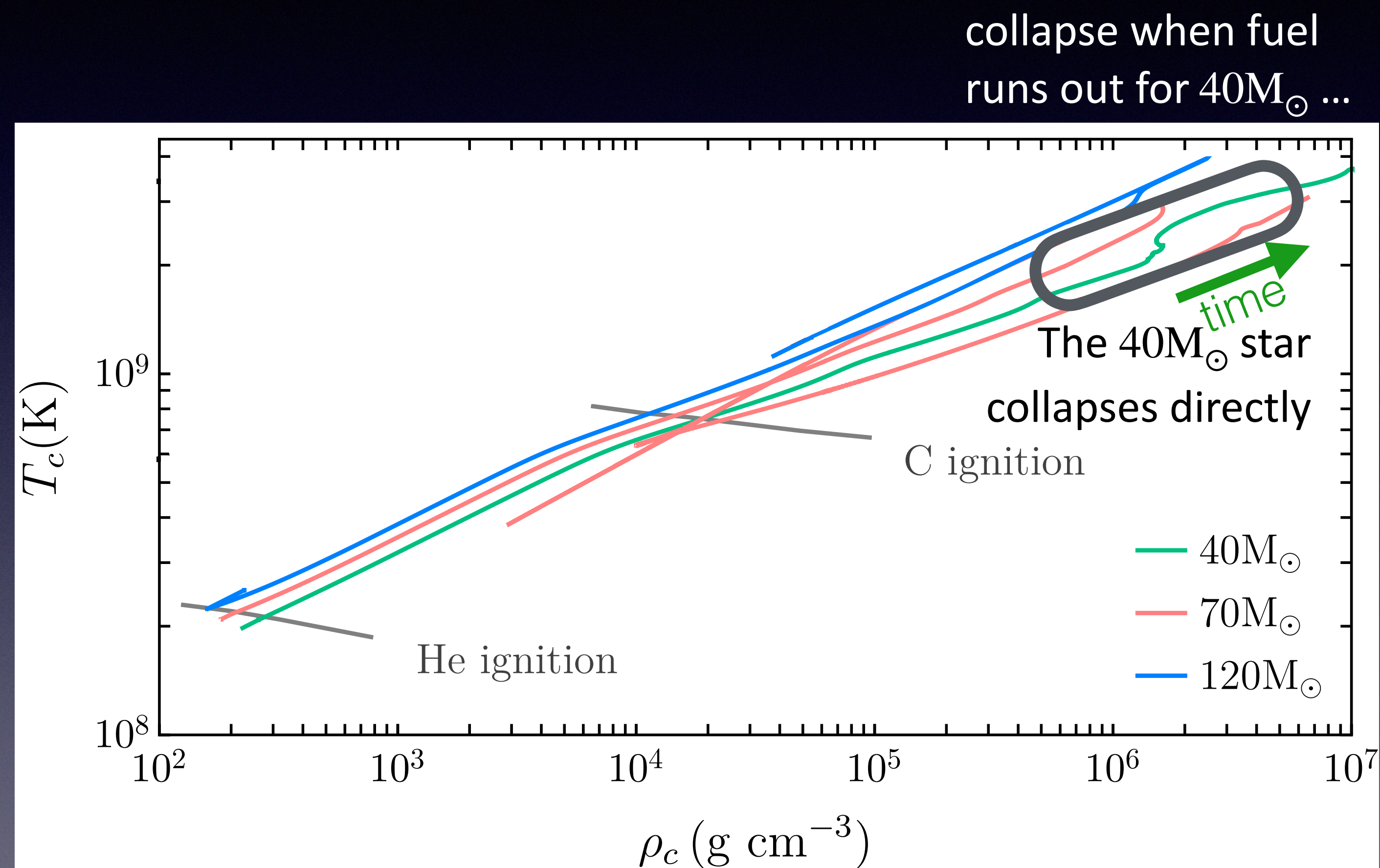
- Simulate stars with **MESA v12778*** starting from the zero-age helium branch through pulsations
- Final BH mass is the material gravitationally bound to the core after hydrostatic equilibrium is regained (following pulsations)



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

Evolution of Pop III Stars

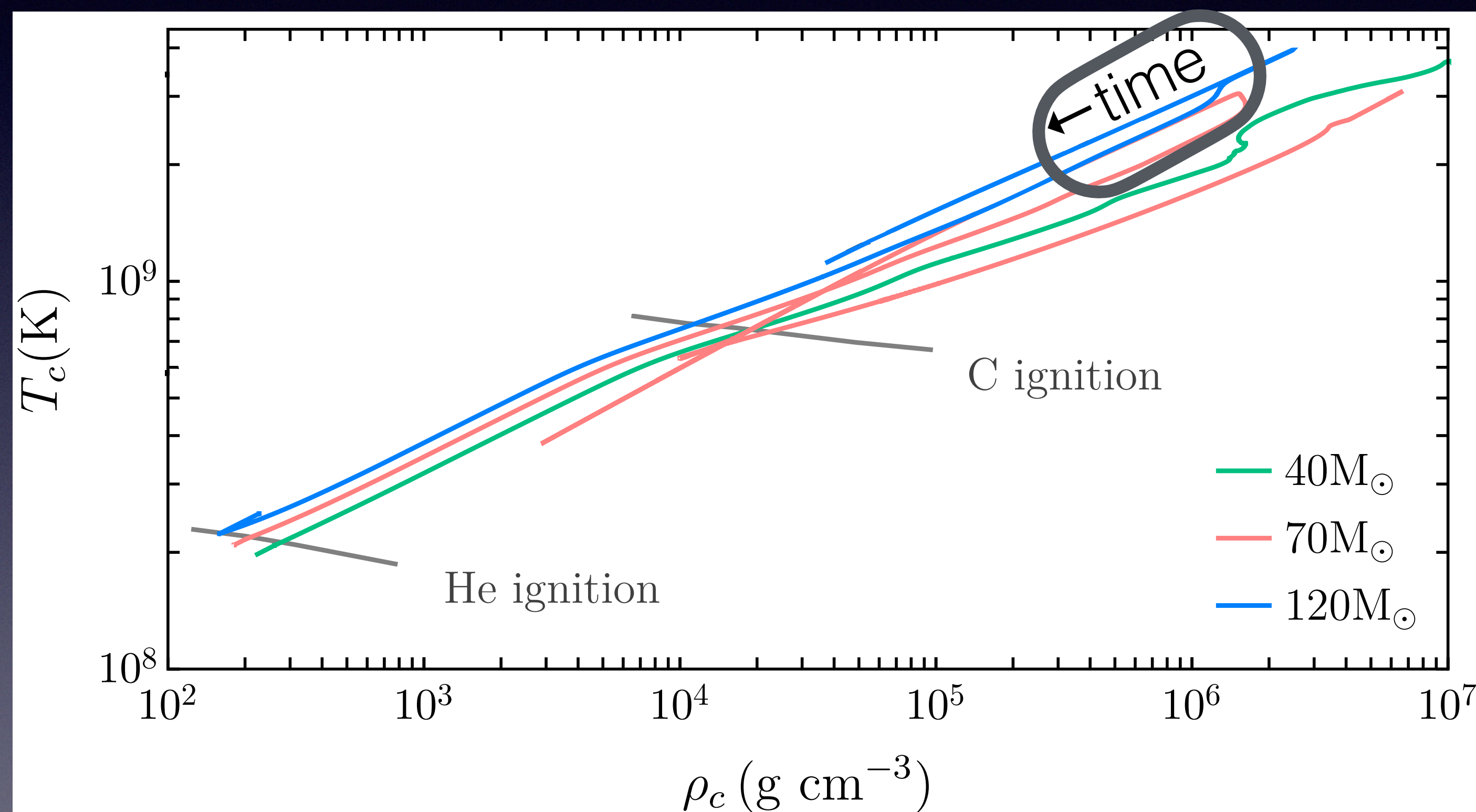
- Simulate stars with MESA v12778* starting from the zero-age helium branch through pulsations
- Final BH mass is the material gravitationally bound to the core after hydrostatic equilibrium is regained (following pulsations)



Evolution of Pop III Stars

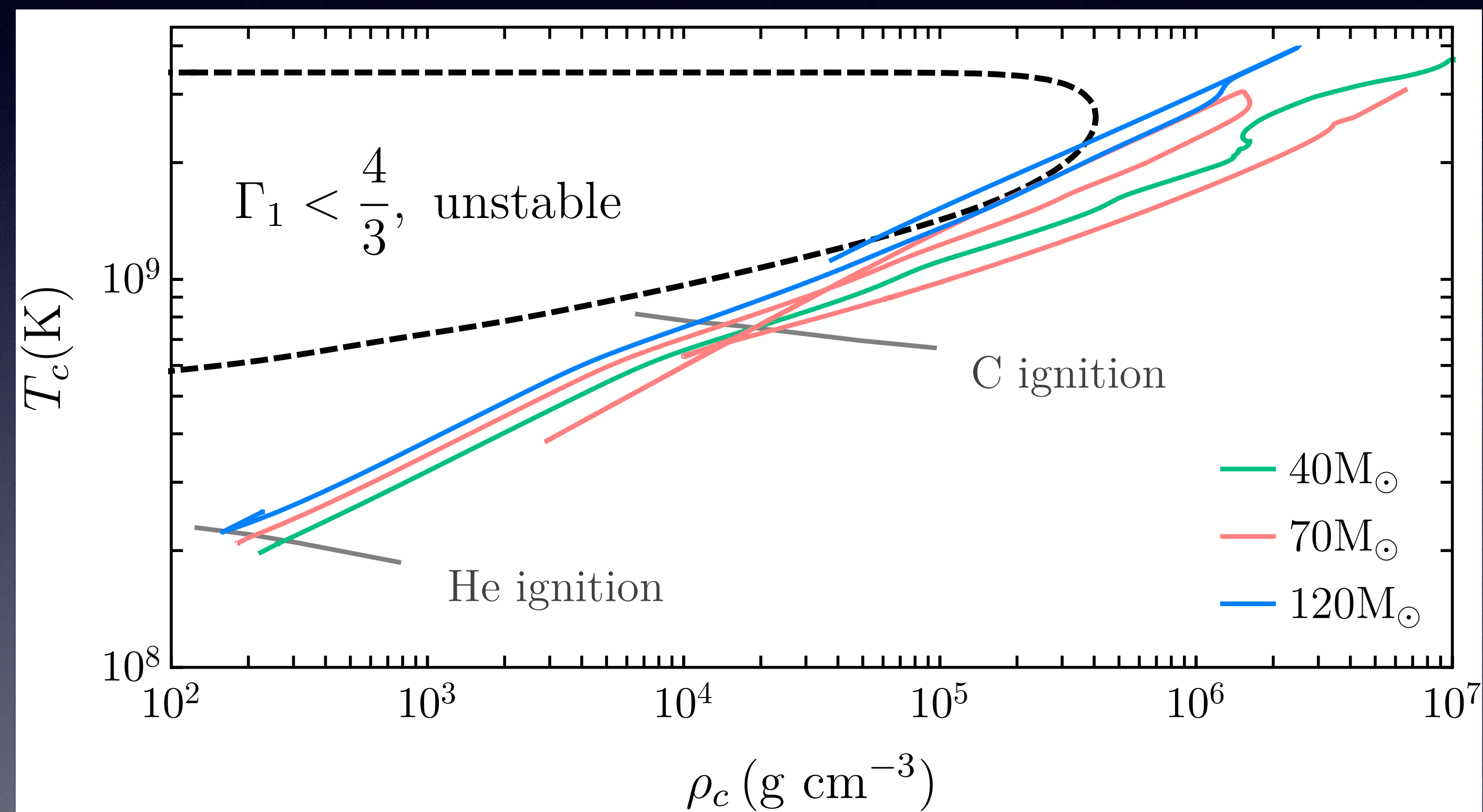
- Simulate stars with MESA v12778* starting from the zero-age helium branch through pulsations
- Final BH mass is the material gravitationally bound to the core after hydrostatic equilibrium is regained (following pulsations)

The more massive of these stars “pulse”:



(Pulsational) Pair Instability

Why do these stars collapse?

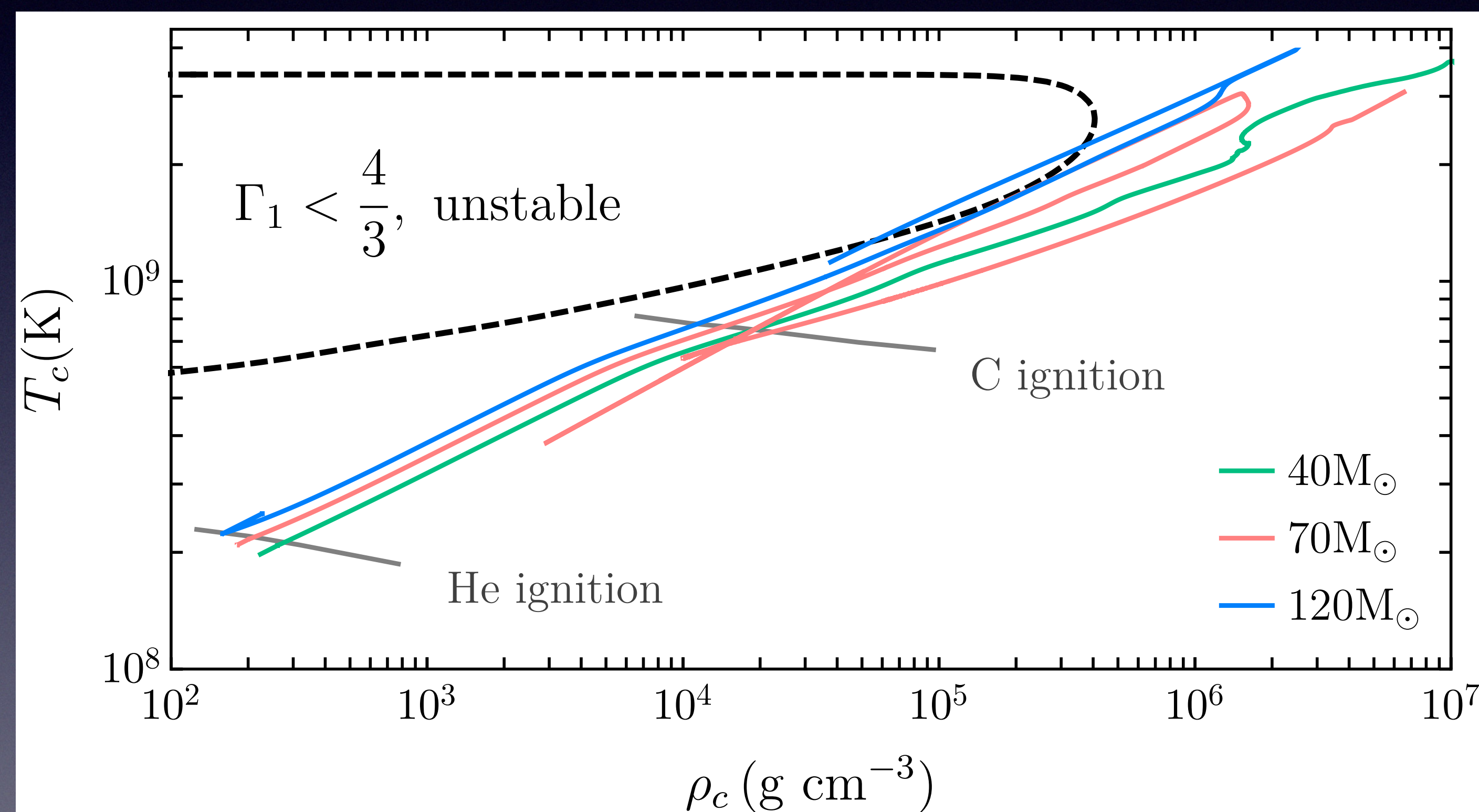


(Pulsational) Pair Instability

Why do these stars collapse?

the e^+e^- pair instability

- $m_e \approx 6 \times 10^9$ K — instability appears in the range $T_c \approx m_e/10$ up to $T_c \approx m_e/2$
- these stars are radiation supported, so the process $\gamma\gamma \rightarrow e^+e^-$ can destabilize the star if the e^+e^- are nonrelativistic

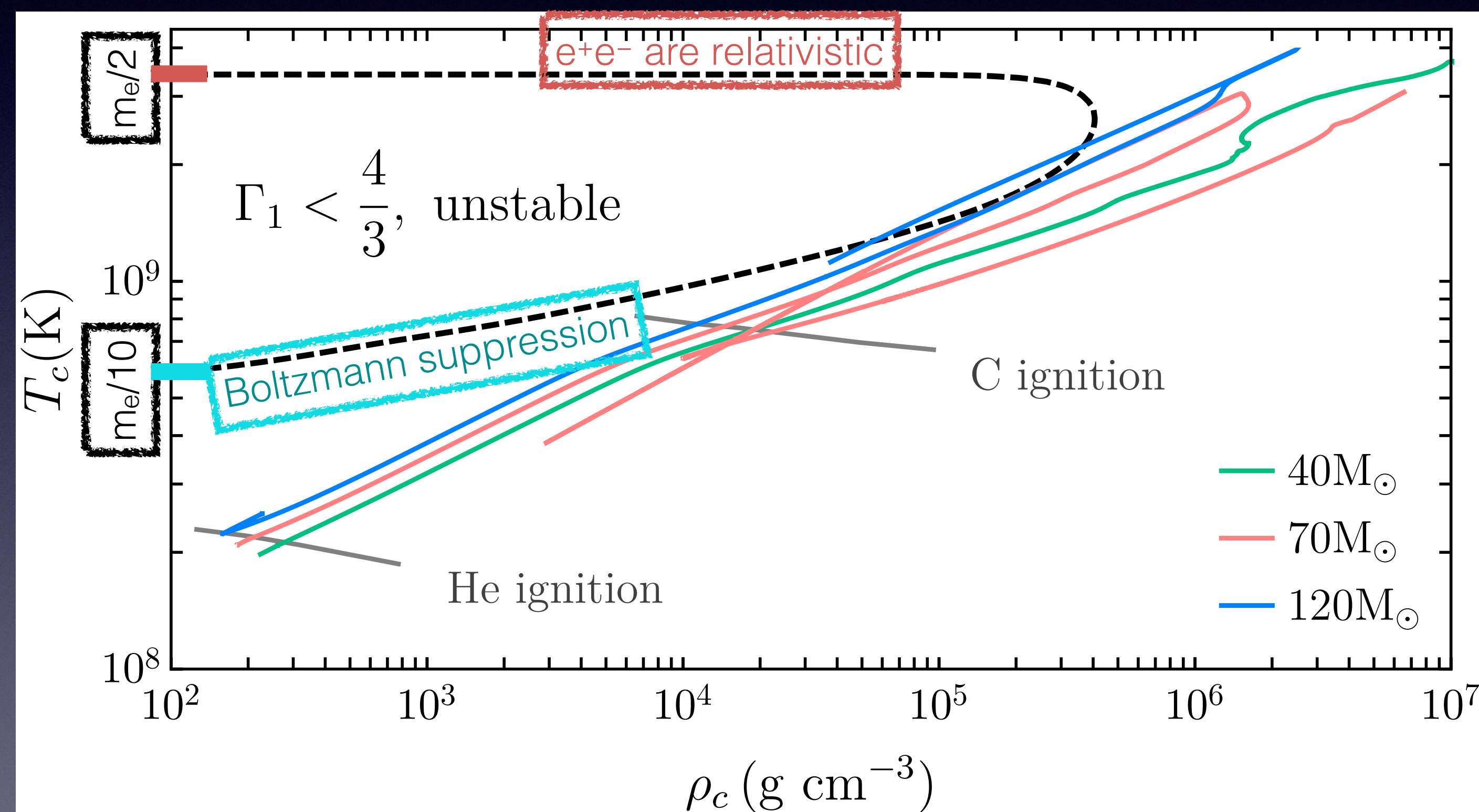


(Pulsational) Pair Instability

Why do these stars collapse?

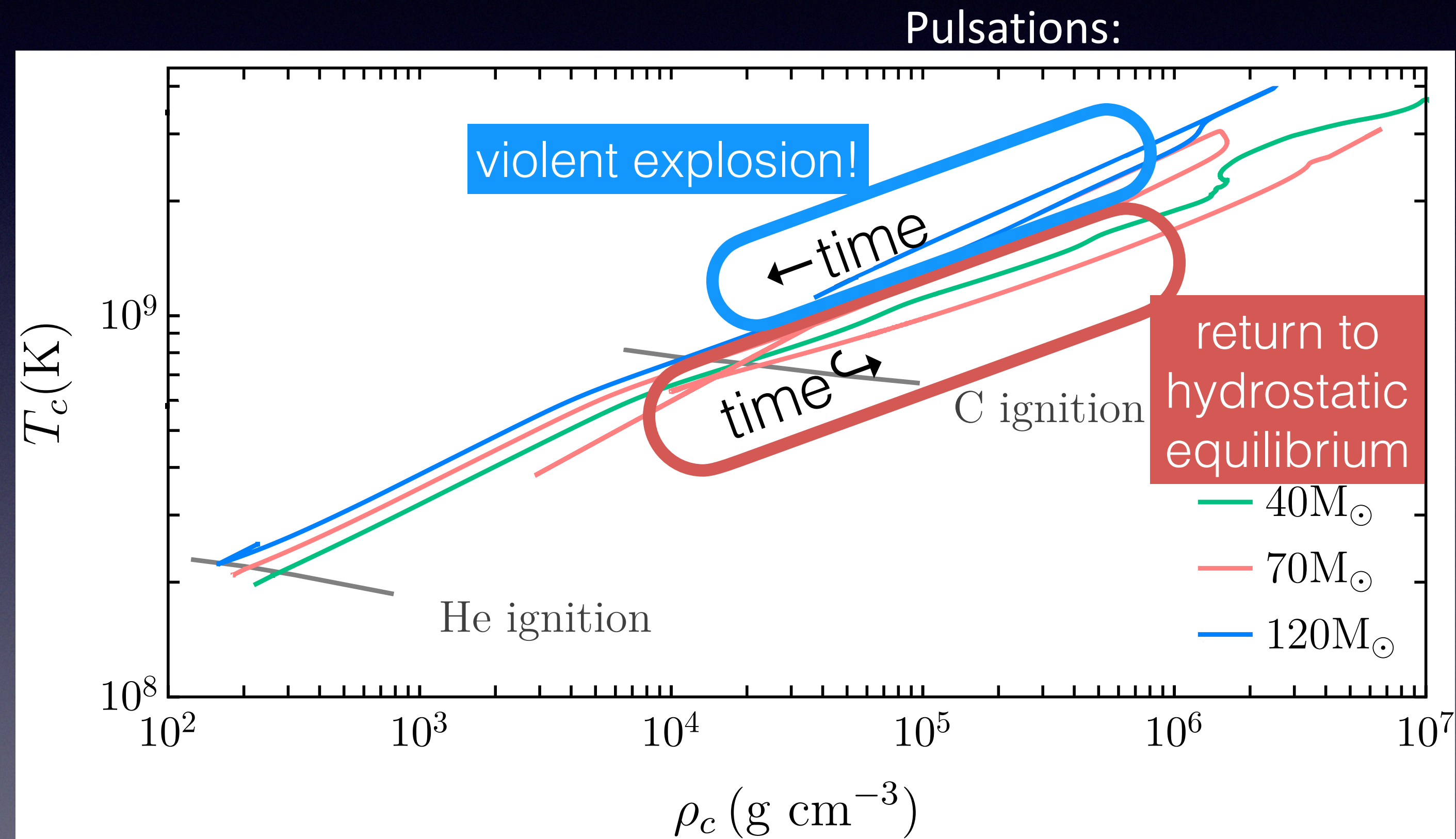
the e^+e^- pair instability

- $m_e \approx 6 \times 10^9$ K — instability appears in the range $T_c \approx m_e/10$ up to $T_c \approx m_e/2$
- these stars are radiation supported, so the process $\gamma\gamma \rightarrow e^+e^-$ can destabilize the star if the e^+e^- are nonrelativistic



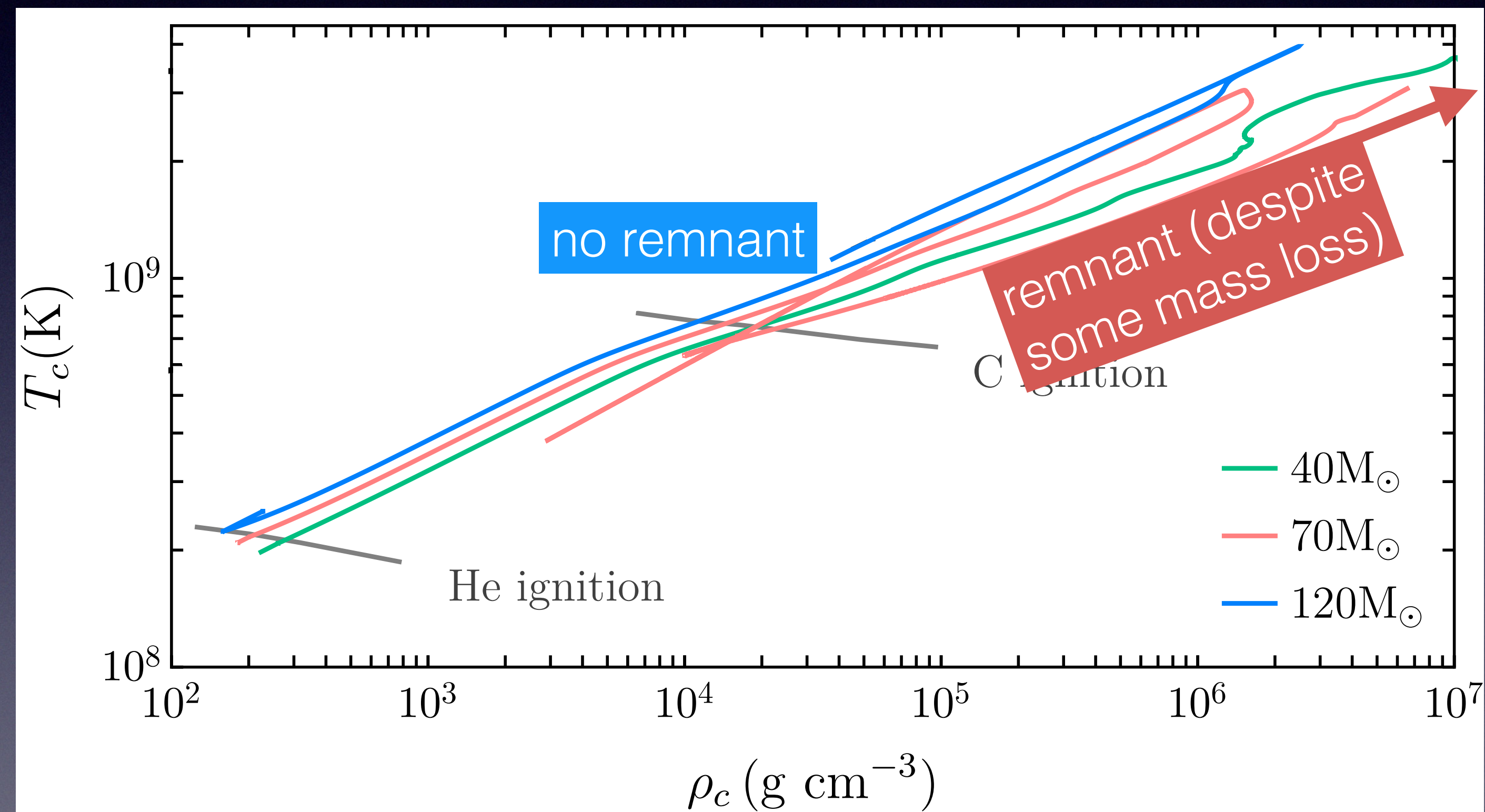
Outcome of Pulsations

- “Very massive” stars unbind entirely (until you get to such large masses that heavy elements photodissociate during infall)
- Somewhat less massive stars lose some mass to pulsations, but eventually leave behind a compact remnant



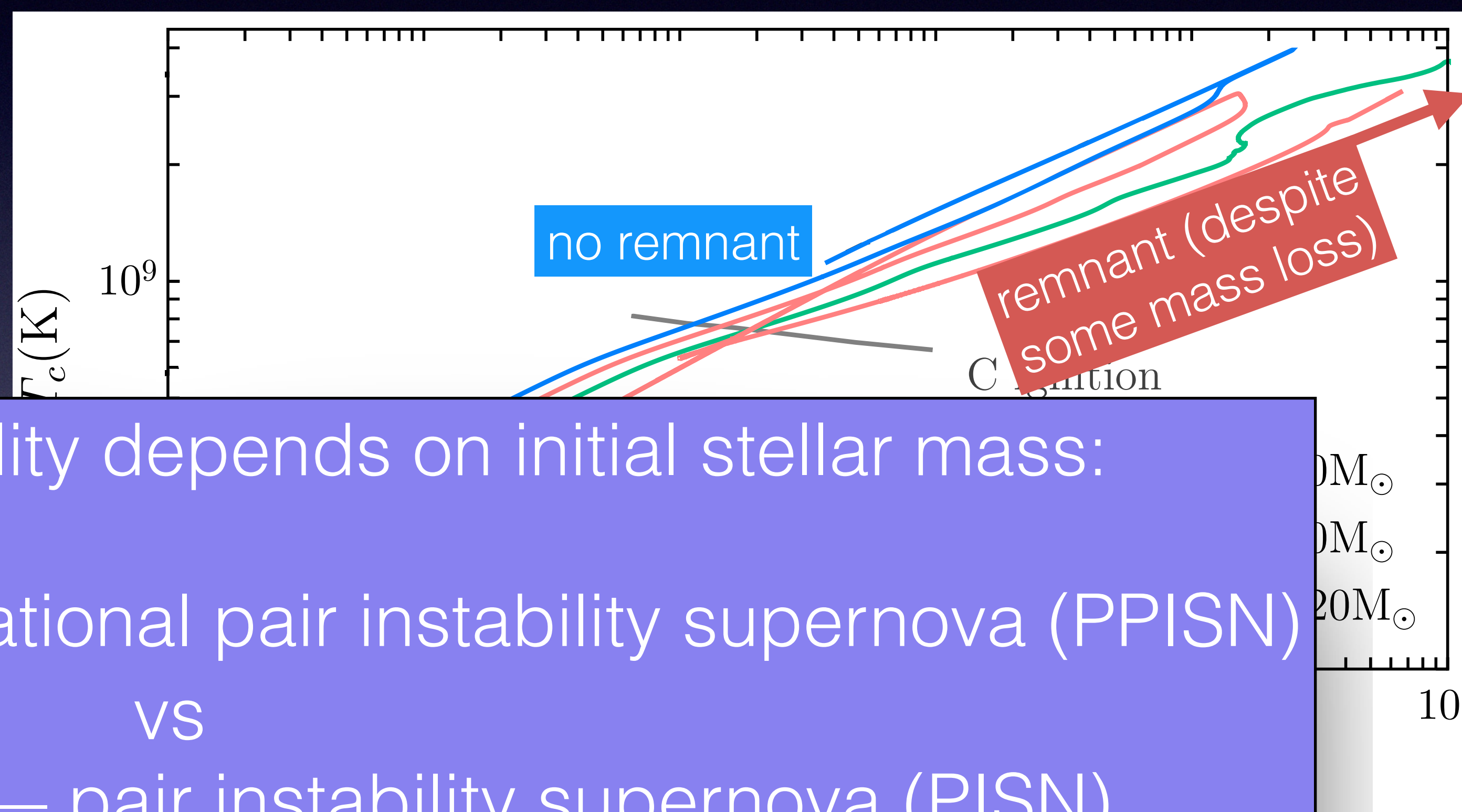
Outcome of Pulsations

- “Very massive” stars unbind entirely (until you get to such large masses that heavy elements photodissociate during infall)
- Somewhat less massive stars lose some mass to pulsations, but eventually leave behind a compact remnant



Outcome of Pulsations

- “Very massive” stars unbind entirely (until you get to such large masses that heavy elements photodissociate during infall)



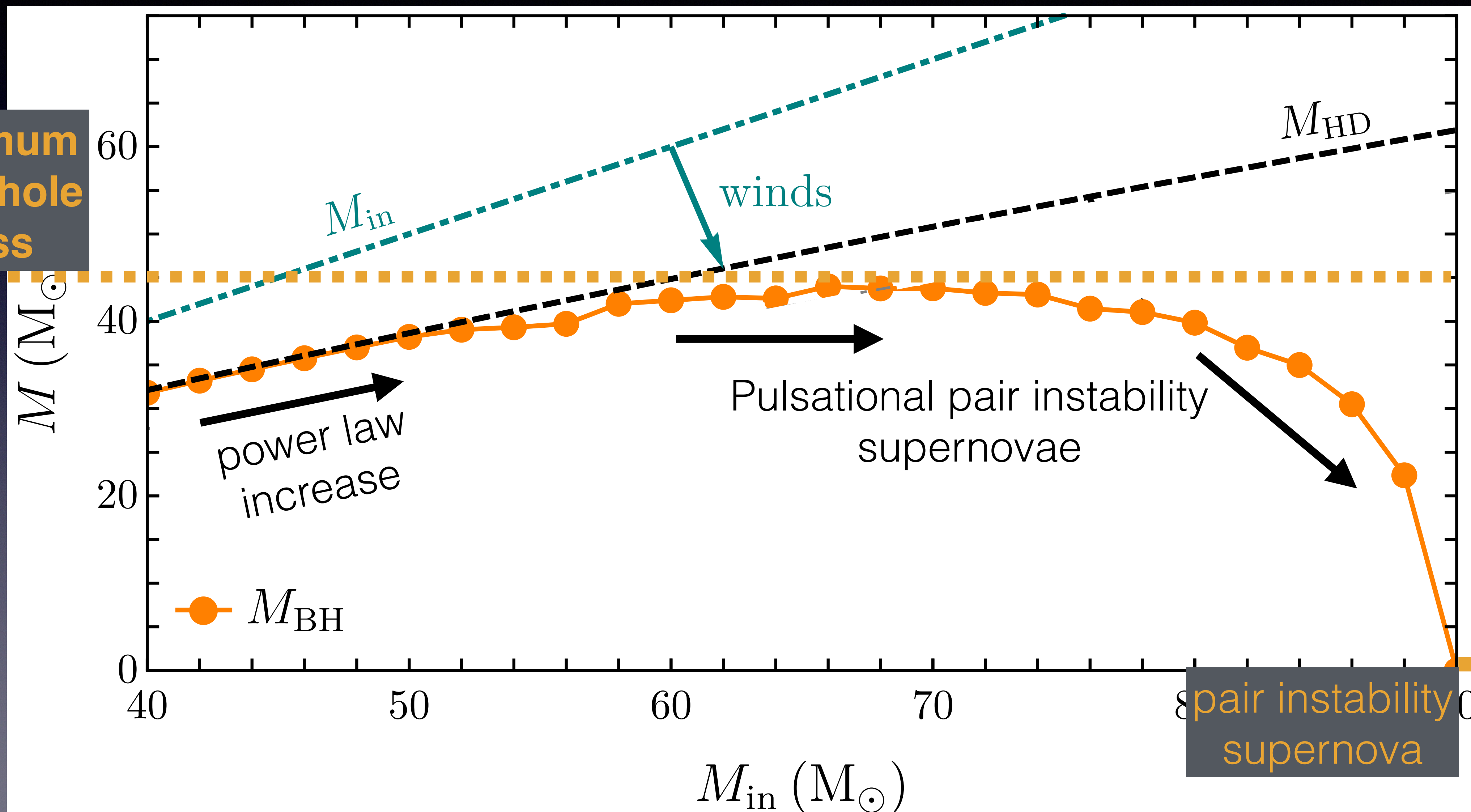
Outcome of pair instability depends on initial stellar mass:

- Some massive stars behave differently depending on their initial mass:
 $70M_{\odot} \lesssim M_{\text{in}} \lesssim 100M_{\odot}$ — pulsational pair instability supernova (PPISN)

vs

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

maximum
black hole
mass



pair instability
supernova

Black Hole Mass Gap (BHMG)

Outline

1. Physics of the pair instability mechanism
2. Beyond-the-Standard-Model explanations of GW190521
3. Standard Model explanations of GW190521
4. Future prospects

Recipe for Changing 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**

Models of Light BSM Physics

- Electrophilic axion: $\mathcal{L}_{ae} \supset -ig_{ae}\bar{\psi}_e\gamma_5\psi_e a$, $\alpha_{26} = 10^{26}g_{ae}^2/4\pi$
- Photophilic axion: $\mathcal{L}_{a\gamma} \supset -\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$, $g_{10} = g_{a\gamma} \times 10^{10}\text{GeV}$
- Dark photon: $\mathcal{L}_{A'} \supset -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu$

Models of Light BSM Physics

- Electrophilic axion: $\mathcal{L}_{ae} \supset -ig_{ae}\bar{\psi}_e\gamma_5\psi_e a$, $\alpha_{26} = 10^{26}g_{ae}^2/4\pi$

additional models: Sakstein, Croon, McDermott, Straight, Baxter
2009.01213

- Ph Neutrino dipole moment: $\mathcal{L}_\nu \supset \frac{\mu_\nu}{2}\bar{\nu}\sigma_{\alpha\beta}\nu F^{\alpha\beta}$
- Large extra dimensions: $\mathcal{L}_{\text{LED}} \supset -2\sqrt{\pi}M_{\text{Pl}}^{-1}\int d^4x h^{\mu\nu,(n)}T_{\mu\nu}$
- Modified gravity*: $G = G_N(1 + \Delta G/G_N)$ "Dramatic violations of the equivalence principle outside of the Milky Way"
- Dark photon: $\mathcal{L}_{A'} \supset -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu$

*see also
Straight, Sakstein, Baxter
2009.10716

Losses to Light Particles

- Electrophilic axion: $Q_{\text{sC}} = \frac{40 \zeta_6 \alpha_{\text{EM}} g_{ae}^2}{\pi^2} \frac{Y_e T^6}{m_N m_e^4} F_{\text{deg}} \simeq 33 \frac{\text{erg}}{\text{g} \cdot \text{s}} \alpha_{26} Y_e T_8^6 F_{\text{deg}}$

$T_8 \equiv \frac{T}{10^8 \text{K}}$
- Photophilic axion: $Q_{a\gamma} = \frac{g_{a\gamma}^2 T^7}{4\pi^2 \rho} \left(\frac{k_S}{2T} \right)^2 f \left[\left(\frac{k_S}{2T} \right)^2 \right] \simeq 283.16 \frac{\text{erg}}{\text{g} \cdot \text{s}} g_{10}^2 T_8^4$

$\left(\frac{k_S}{2T} \right)^2 = 0.166 \frac{\rho_3}{T_8^3} \sum_j Y_j Z_j^2$
- Dark photon: $Q_{A'} = \frac{\epsilon^2 m_{A'}^2}{4\pi \rho} \frac{\omega_p^3}{e^{\omega_p/T} - 1} \simeq 1800 \frac{\text{erg}}{\text{g} \cdot \text{s}} \frac{Z}{A} \left(\frac{\epsilon}{10^{-7}} \frac{m_{A'}}{\text{meV}} \right)^2 T_8$

$\omega_p^2 \simeq \frac{4\pi \alpha_{\text{EM}} n_e}{m_e} \simeq (654 \text{eV})^2 \frac{Z}{A} \rho_3$

Losses to Light Particles

- Electrophilic axion: $Q_{\text{sC}} = \frac{40 \zeta_6 \alpha_{\text{EM}} g_{ae}^2}{\pi^2} \frac{Y_e T^6}{m_N m_e^4} F_{\text{deg}} \simeq 33 \frac{\text{erg}}{\text{g} \cdot \text{s}} \alpha_{26} Y_e T_8^6 F_{\text{deg}}$

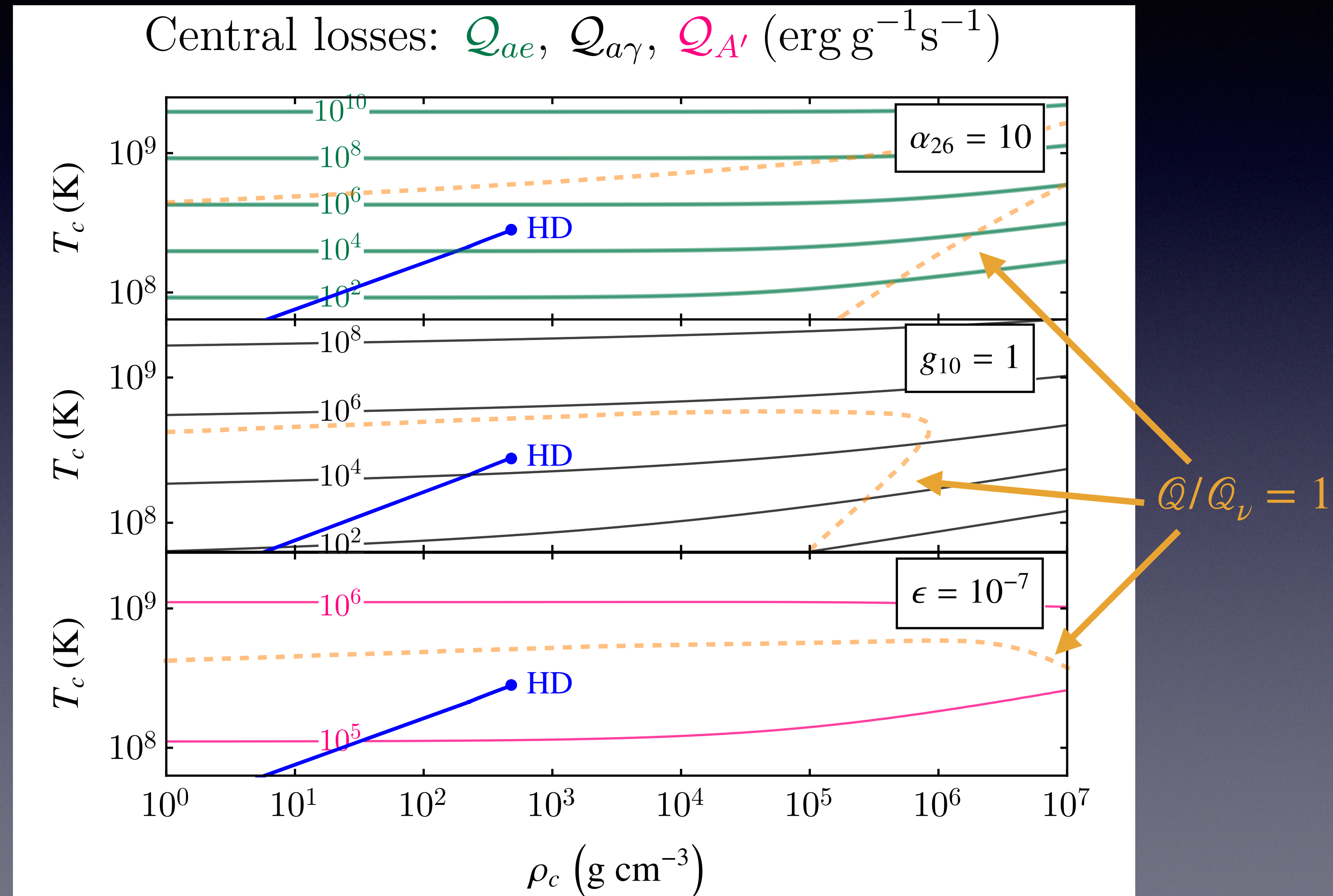
$T_8 \equiv \frac{T}{10^8 \text{K}}$
- Photophilic axion: $Q_{a\gamma} = \frac{g_{a\gamma}^2 T^7}{4\pi^2 \rho} \left(\frac{k_S}{2T} \right)^2 f \left[\left(\frac{k_S}{2T} \right)^2 \right] \simeq 283.16 \frac{\text{erg}}{\text{g} \cdot \text{s}} g_{10}^2 T_8^4$

$\left(\frac{k_S}{2T} \right)^2 = 0.166 \frac{\rho_3}{T_8^3} \sum_j Y_j Z_j^2$
- Dark photon: $Q_{A'} = \frac{\epsilon^2 m_{A'}^2}{4\pi \rho} \frac{\omega_p^3}{e^{\omega_p/T} - 1} \simeq 1800 \frac{\text{erg}}{\text{g} \cdot \text{s}} \frac{Z}{A} \left(\frac{\epsilon}{10^{-7}} \frac{m_{A'}}{\text{meV}} \right)^2 T_8$

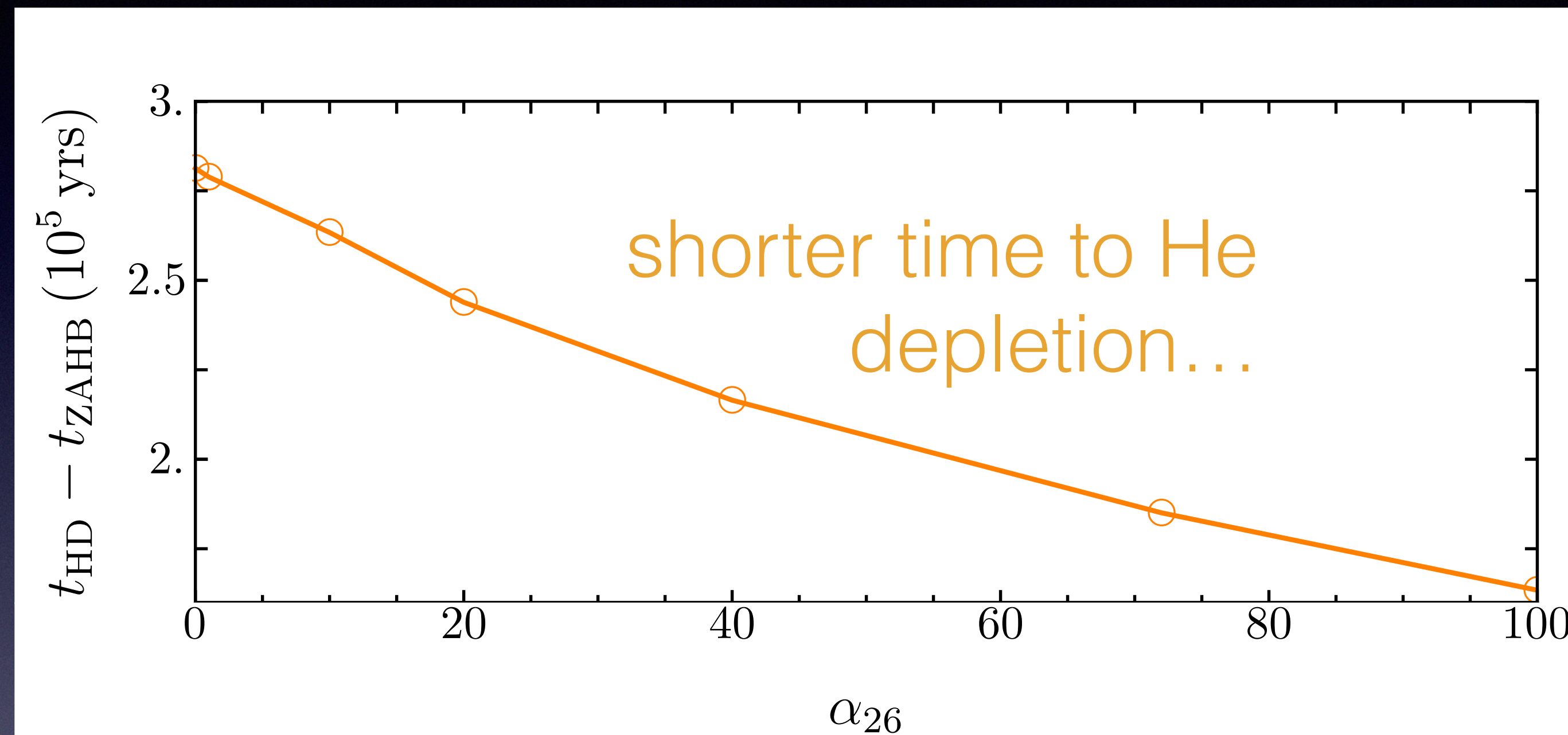
$\omega_p^2 \simeq \frac{4\pi \alpha_{\text{EM}} n_e}{m_e} \simeq (654 \text{eV})^2 \frac{Z}{A} \rho_3$

Losses to Light Particles

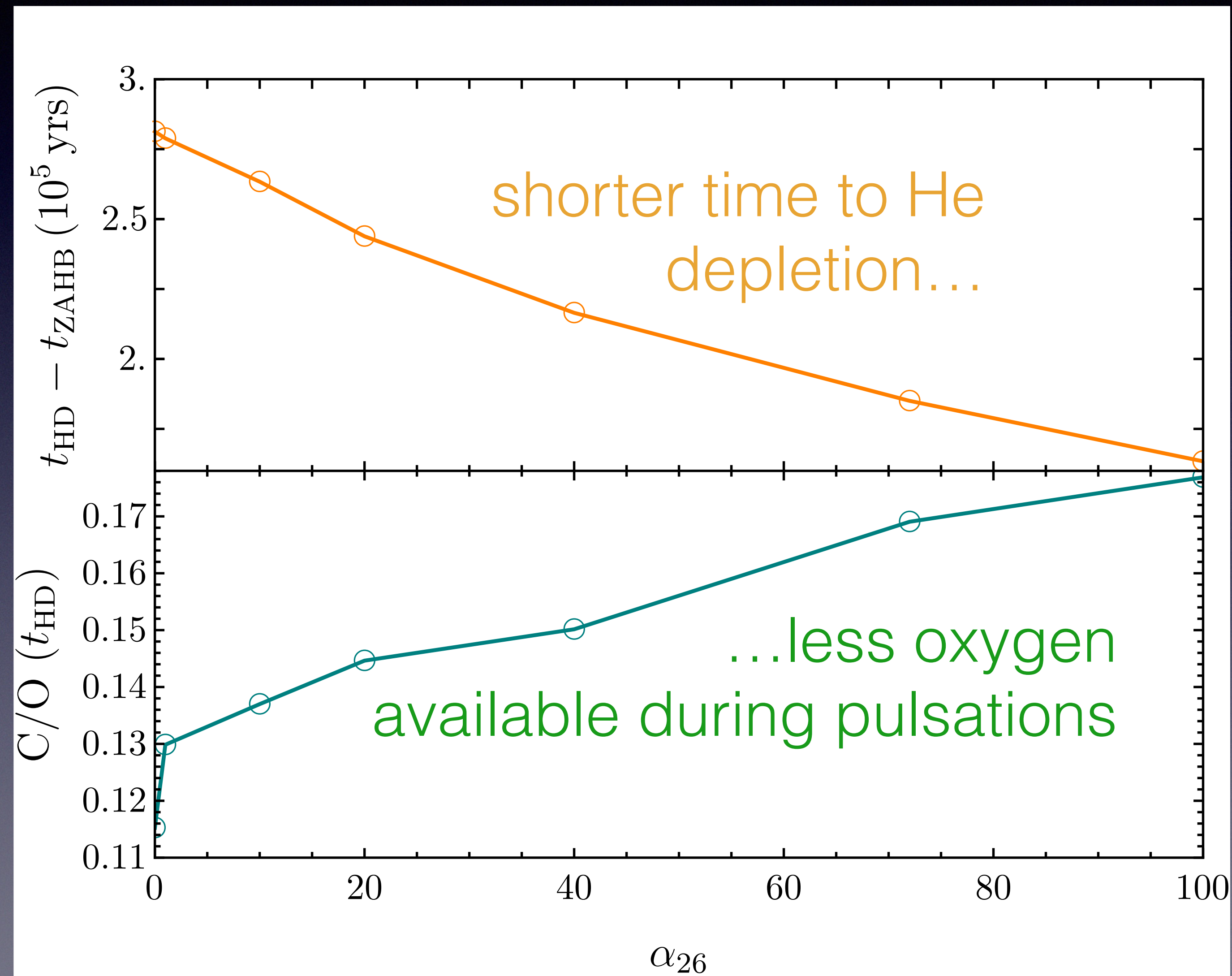
- Electrophilic axion:
- Photophilic axion:
- Dark photon:



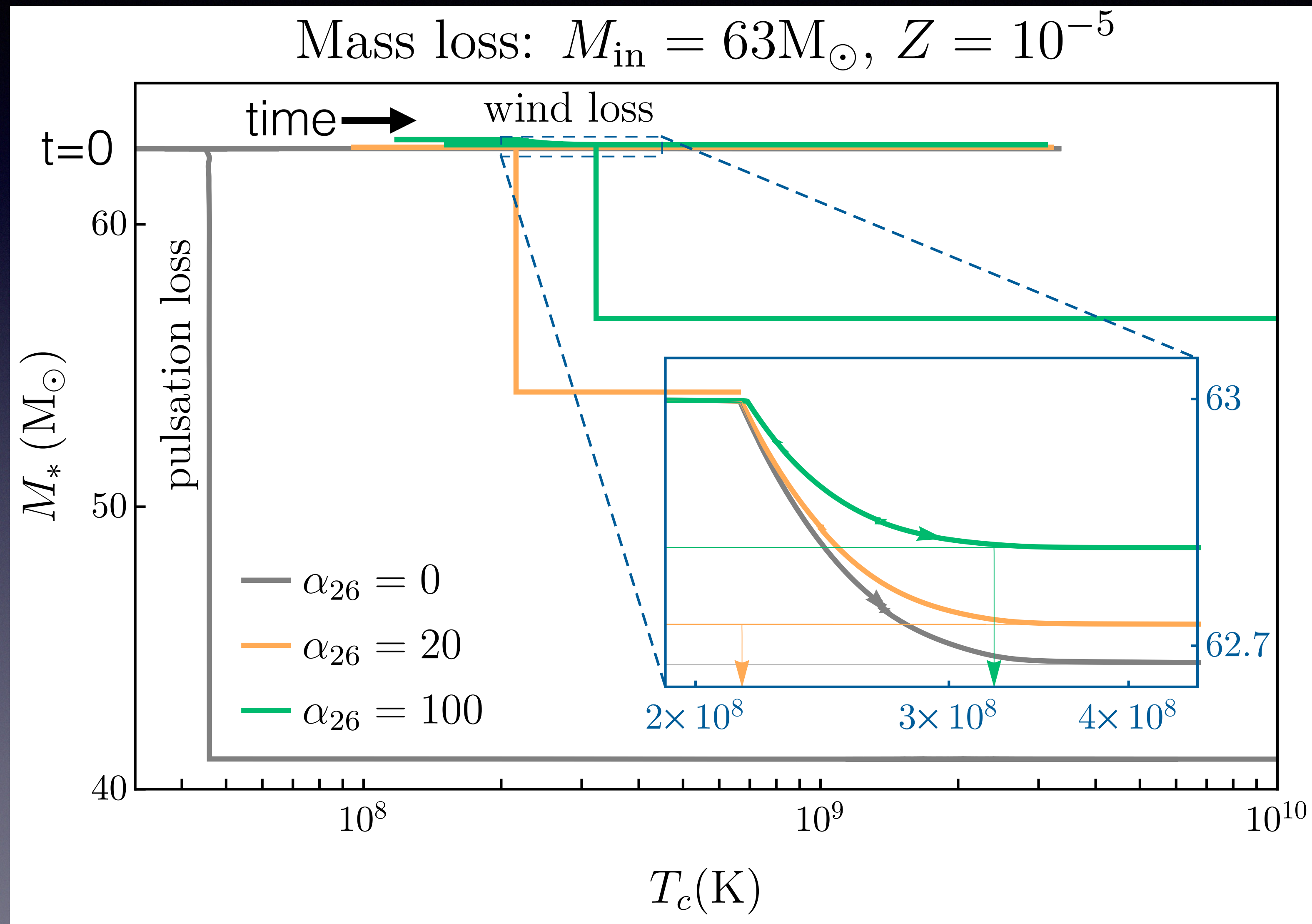
Implications for Oxygen Production



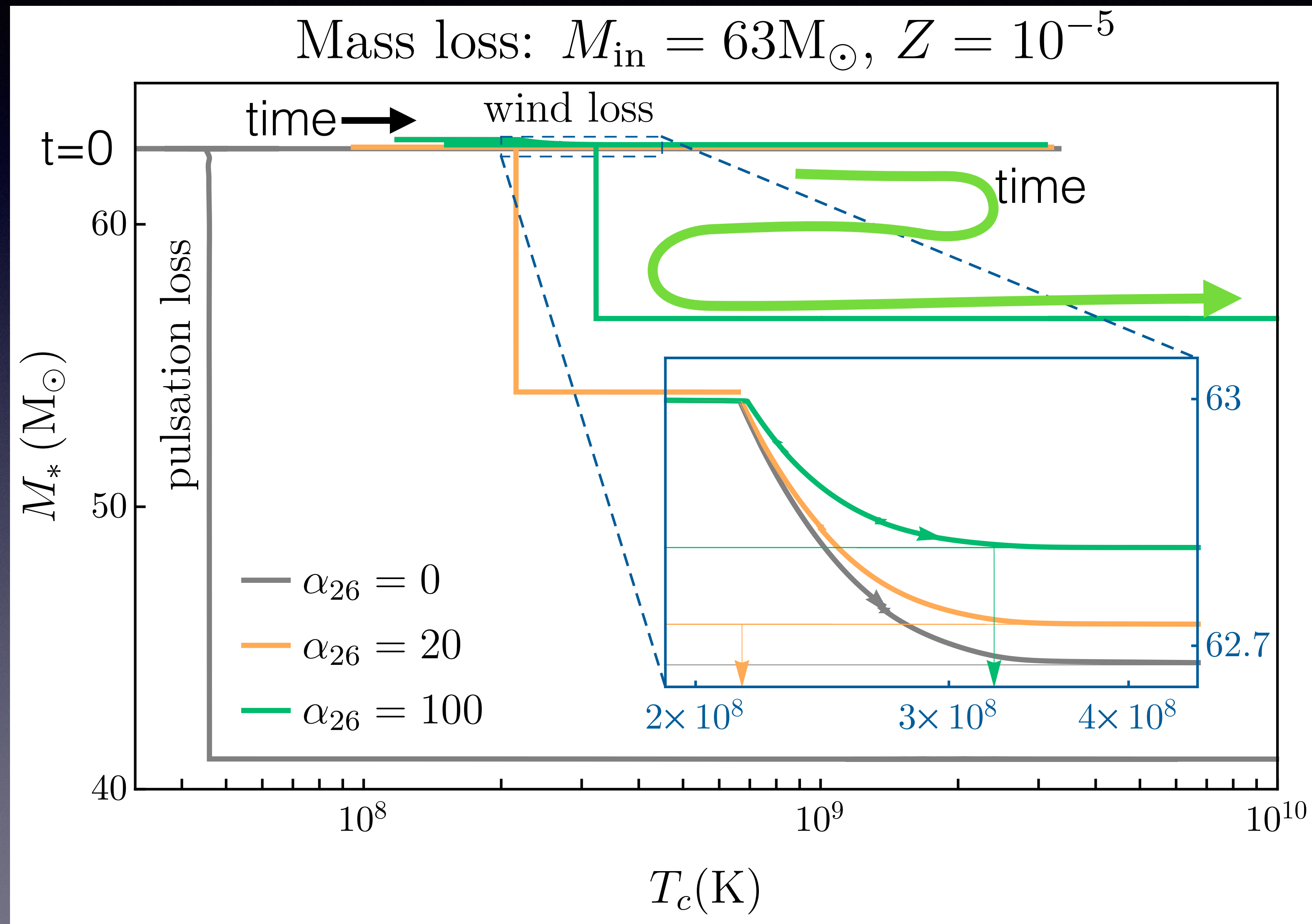
Implications for Oxygen Production



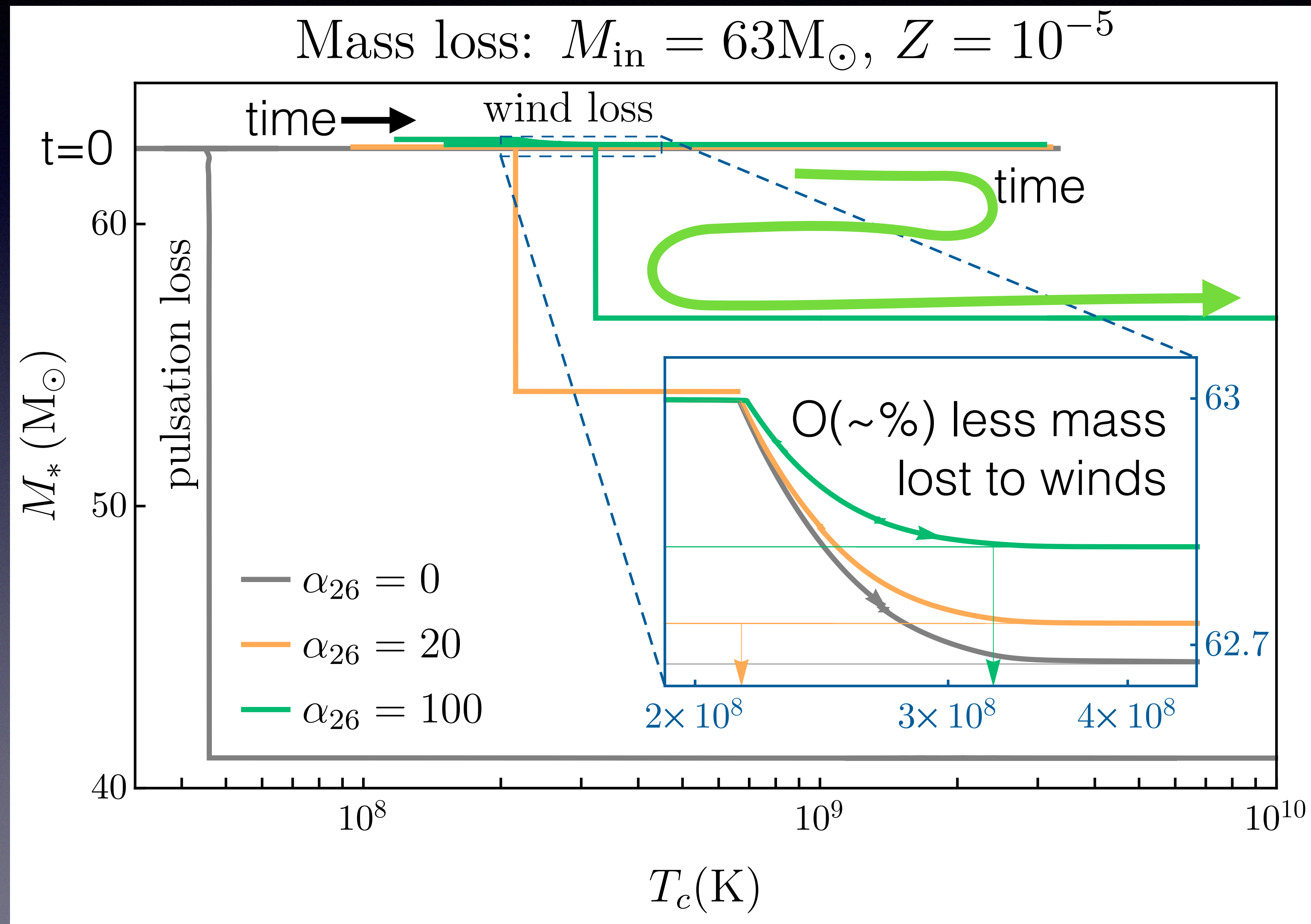
Implications for Pulsations



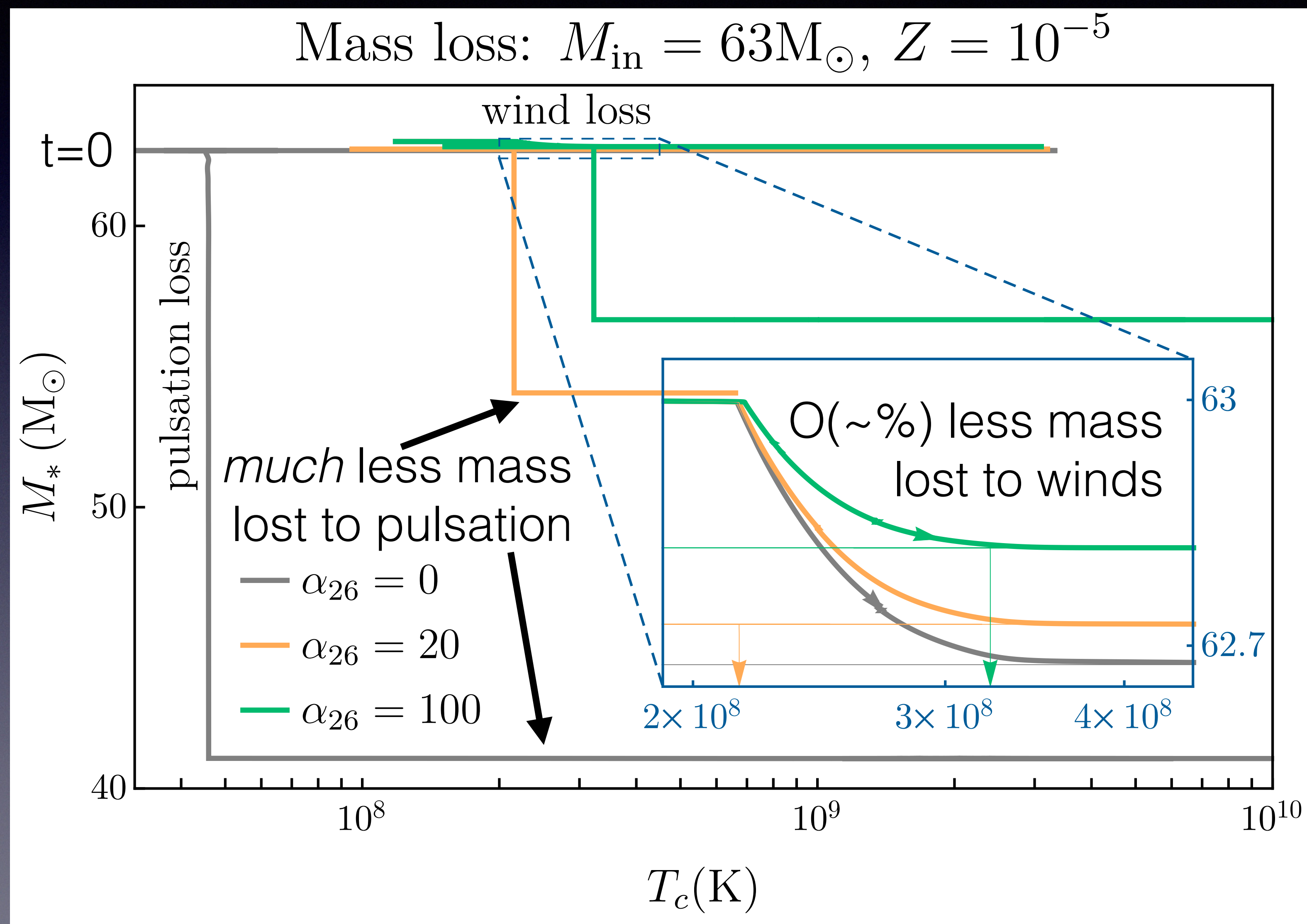
Implications for Pulsations



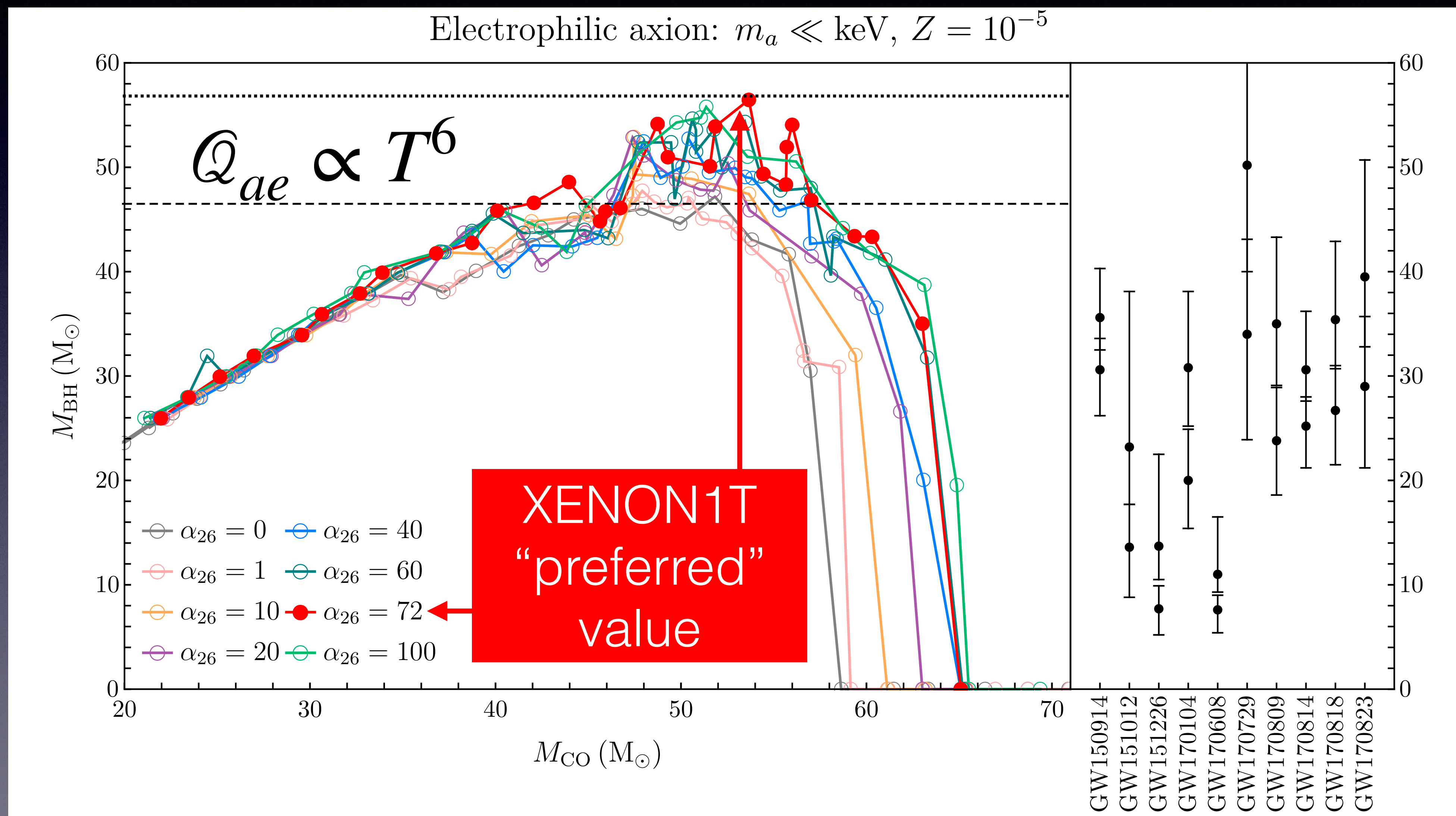
Implications for Pulsations



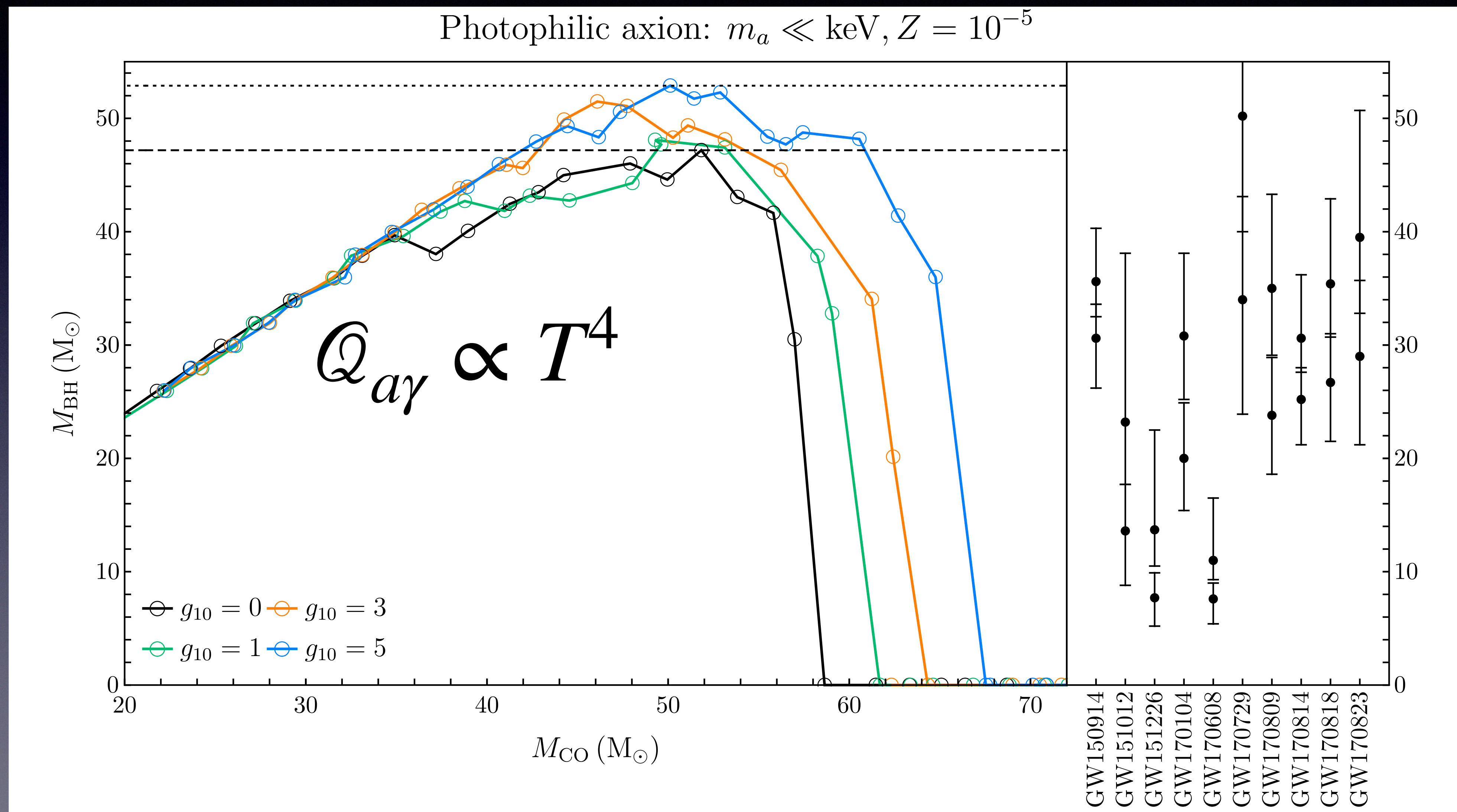
Implications for Pulsations



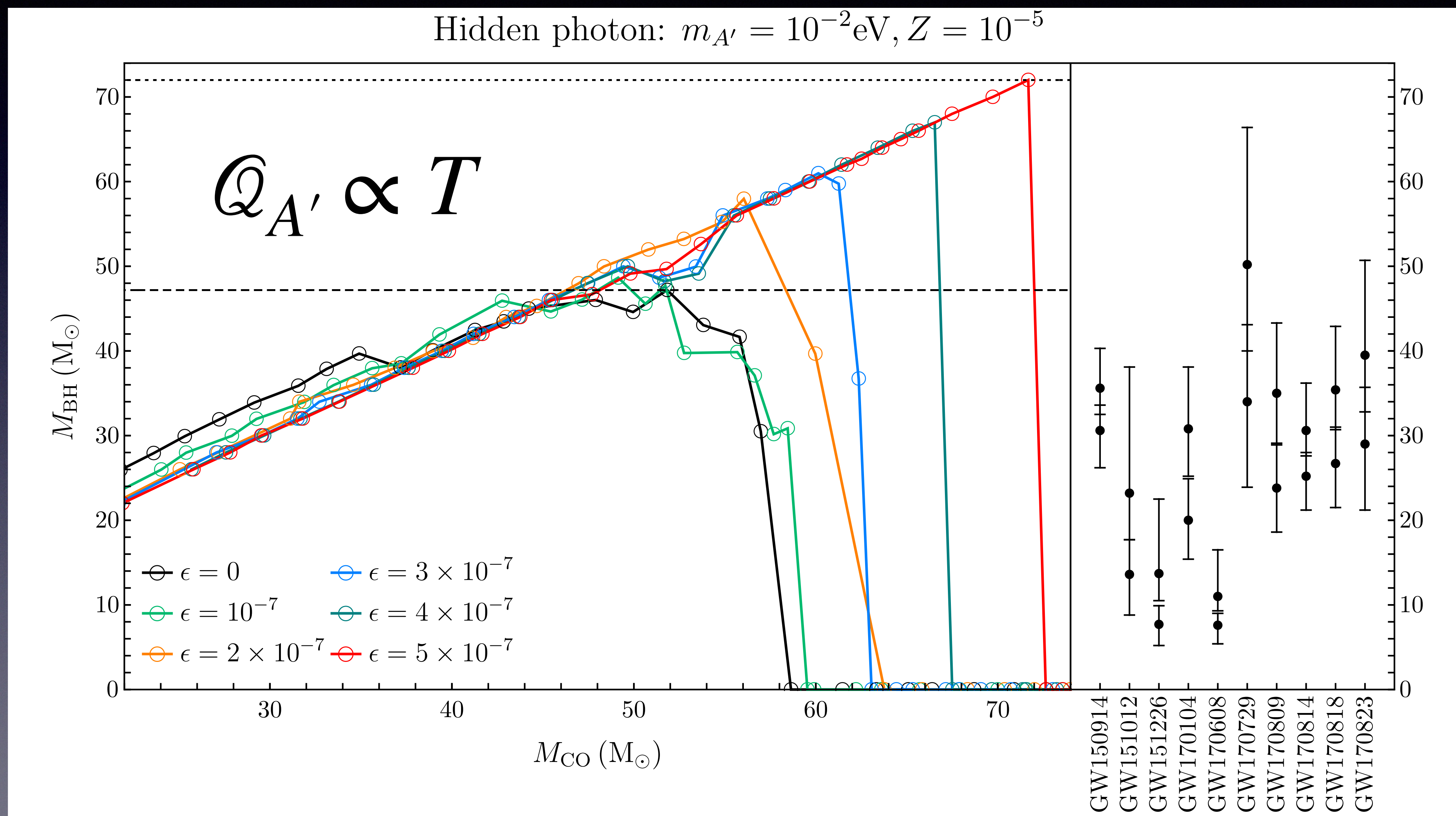
Implications for Black Hole Masses



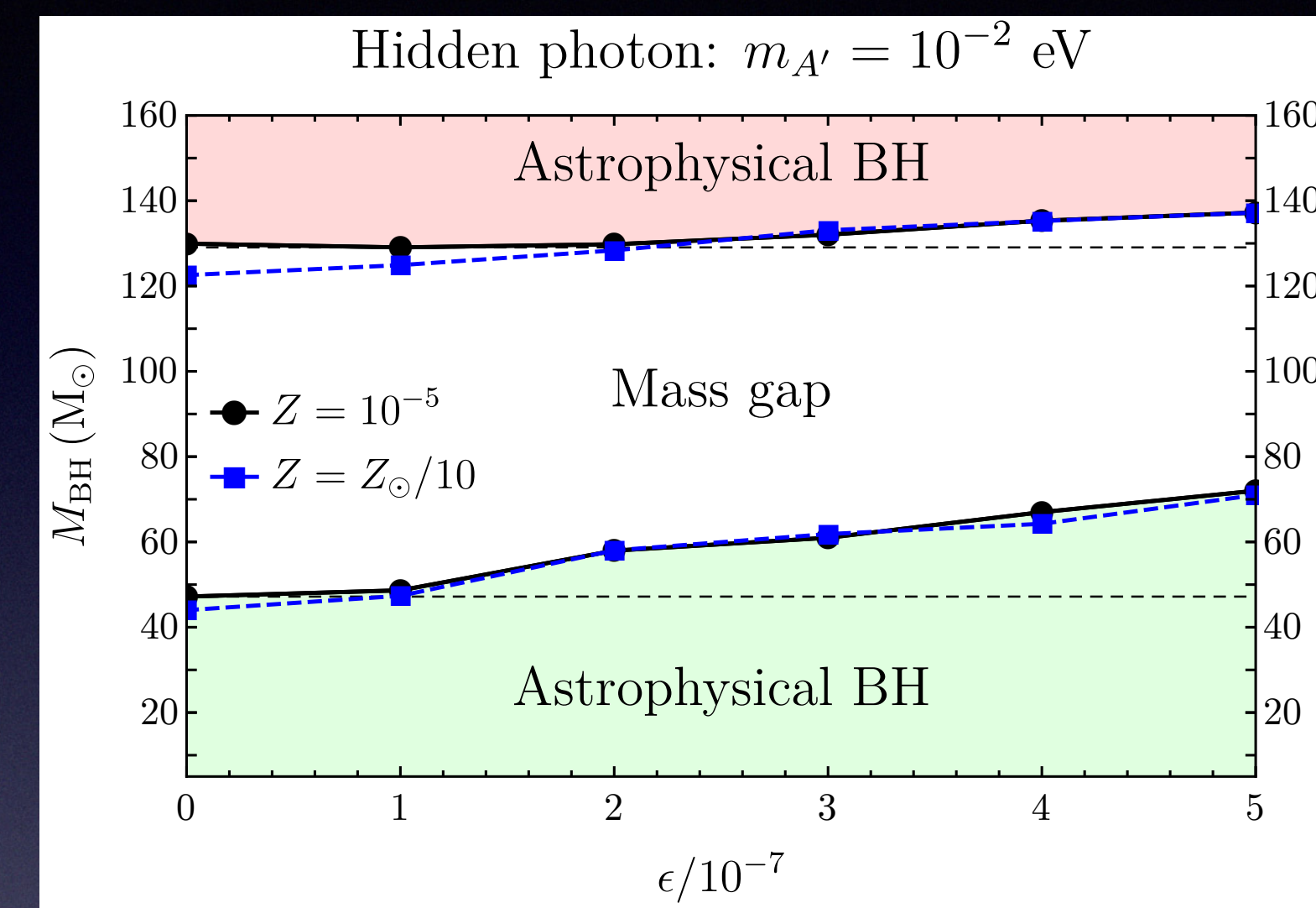
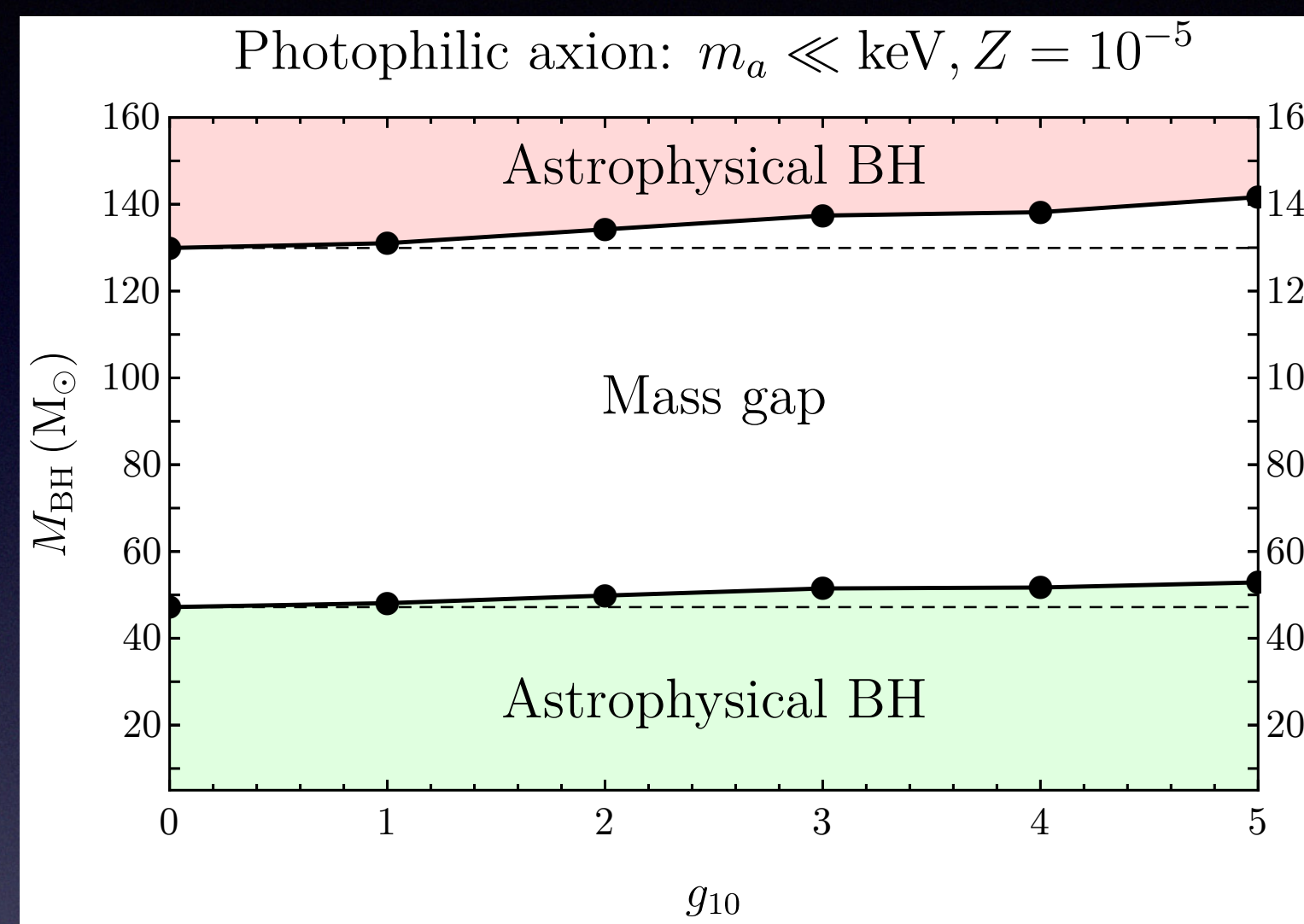
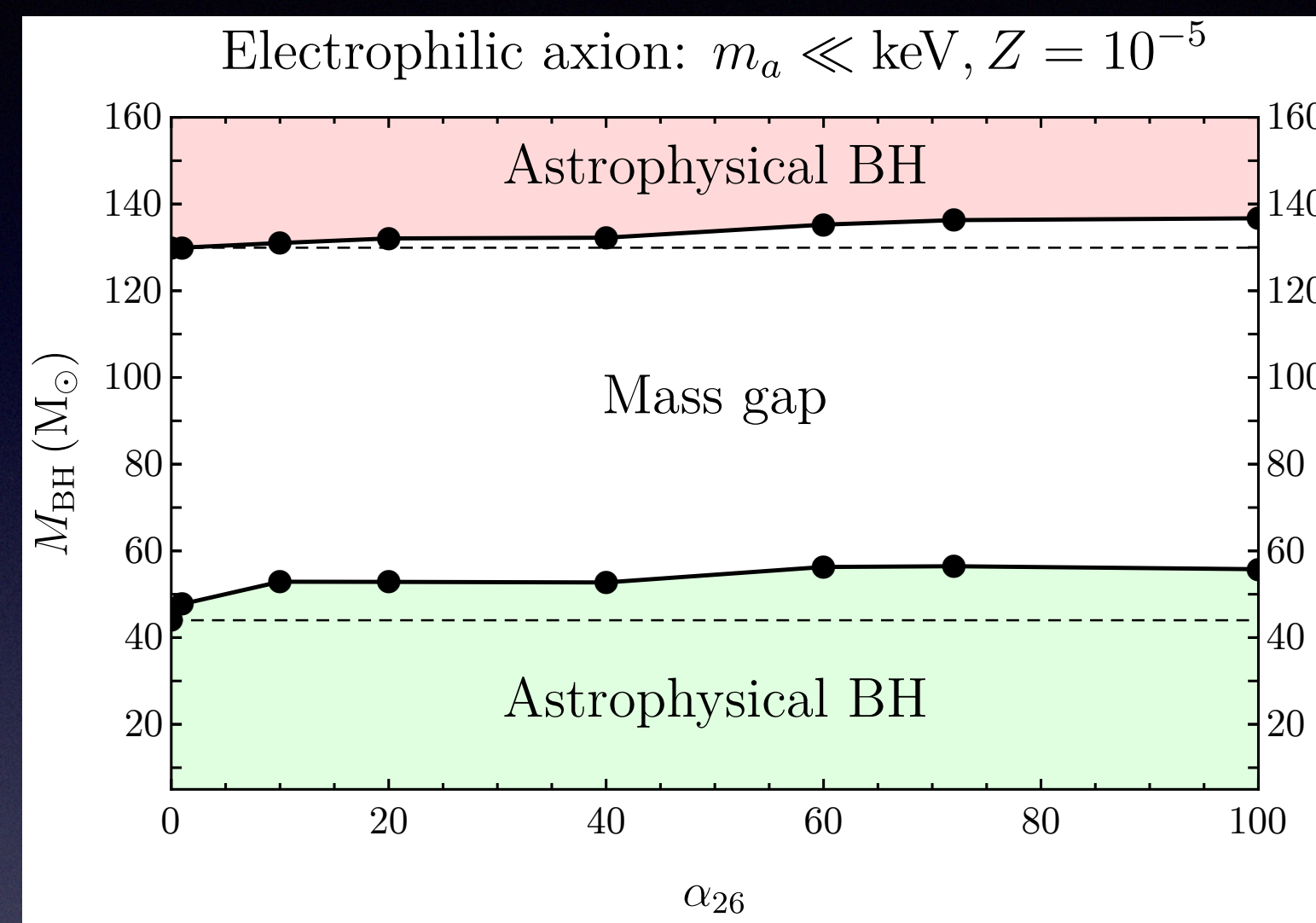
Implications for Black Hole Masses



Implications for Black Hole Masses

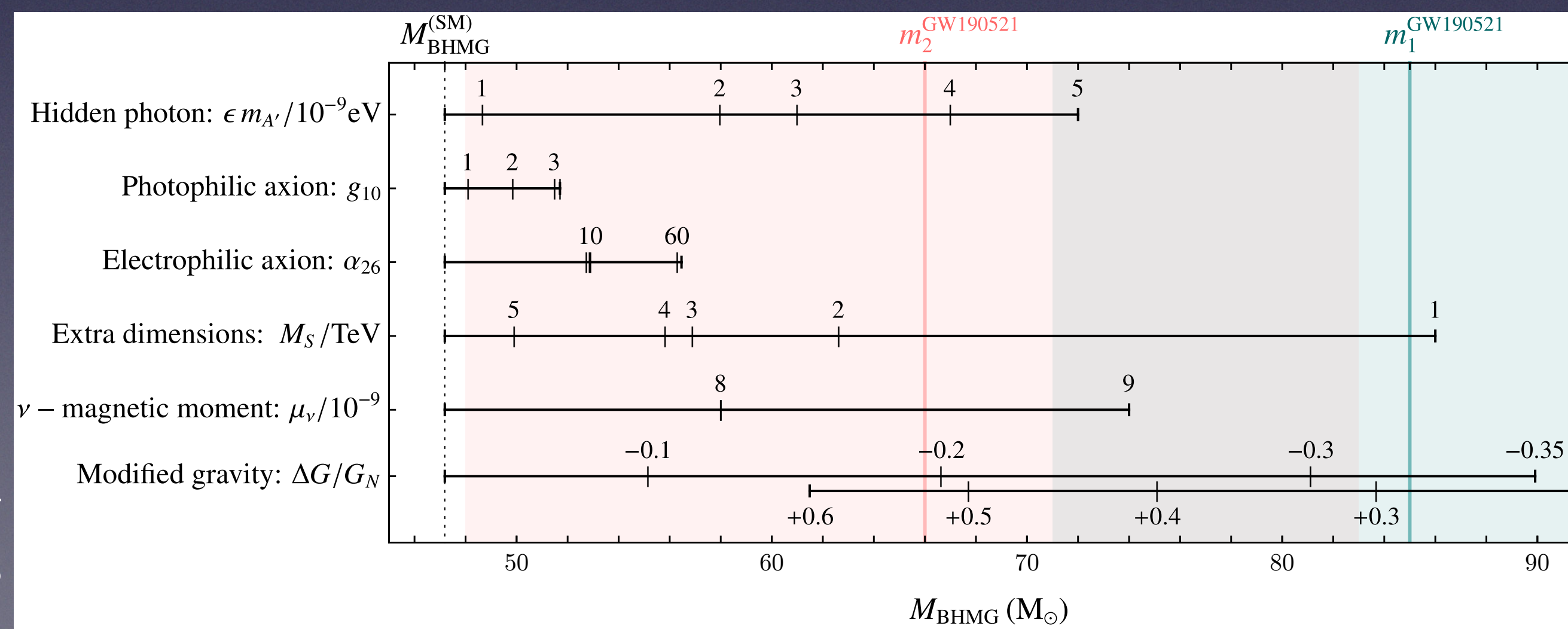
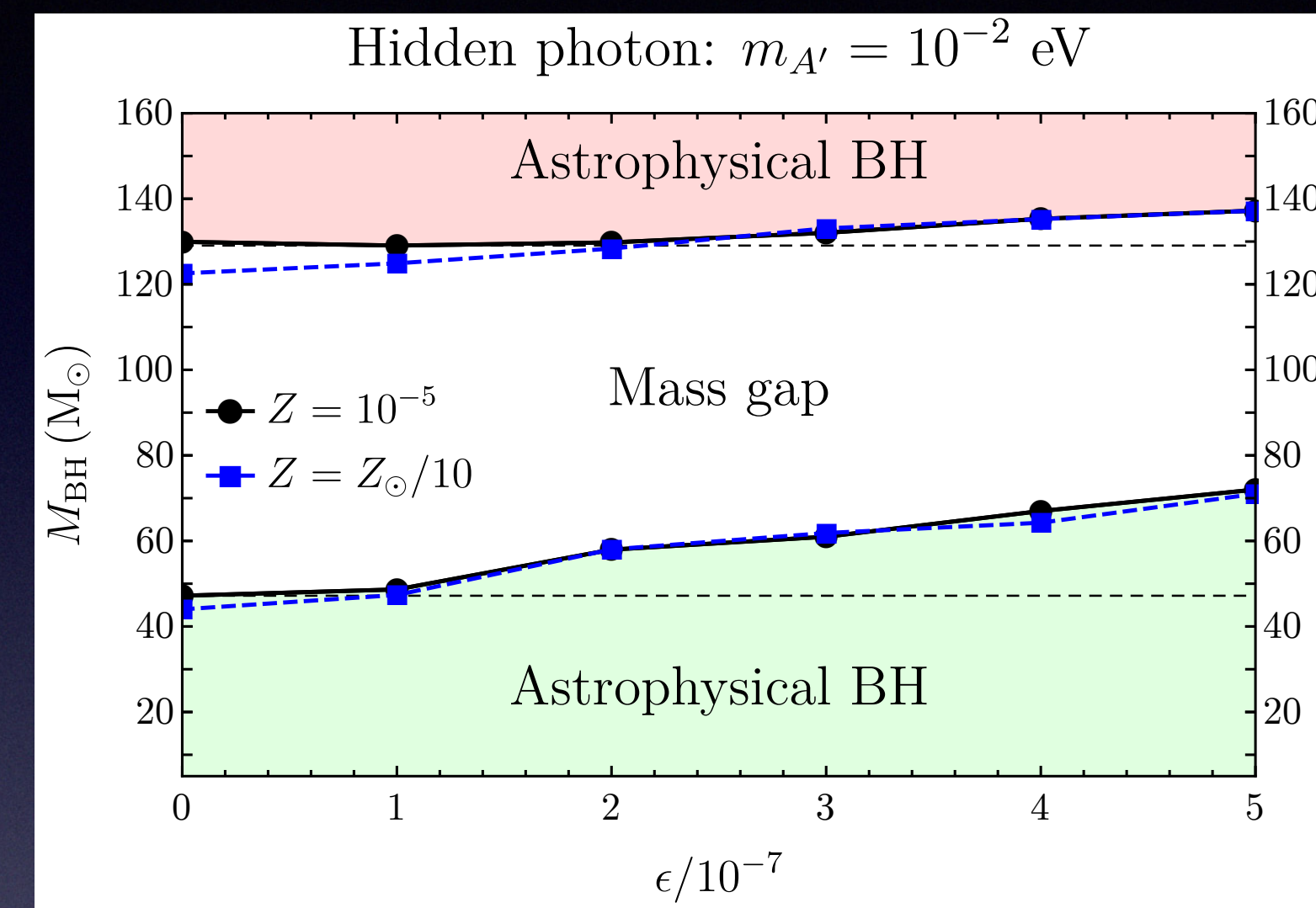
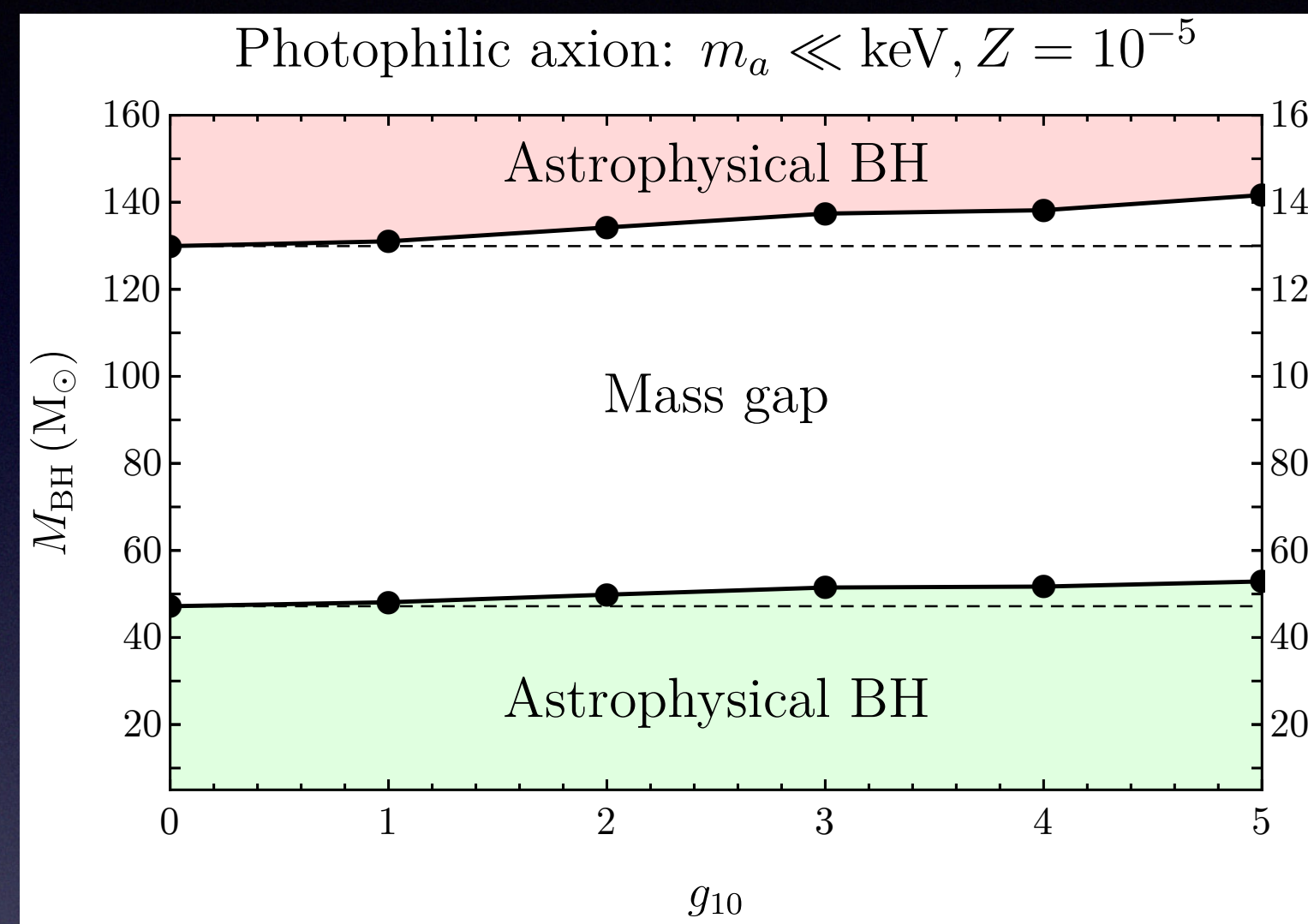
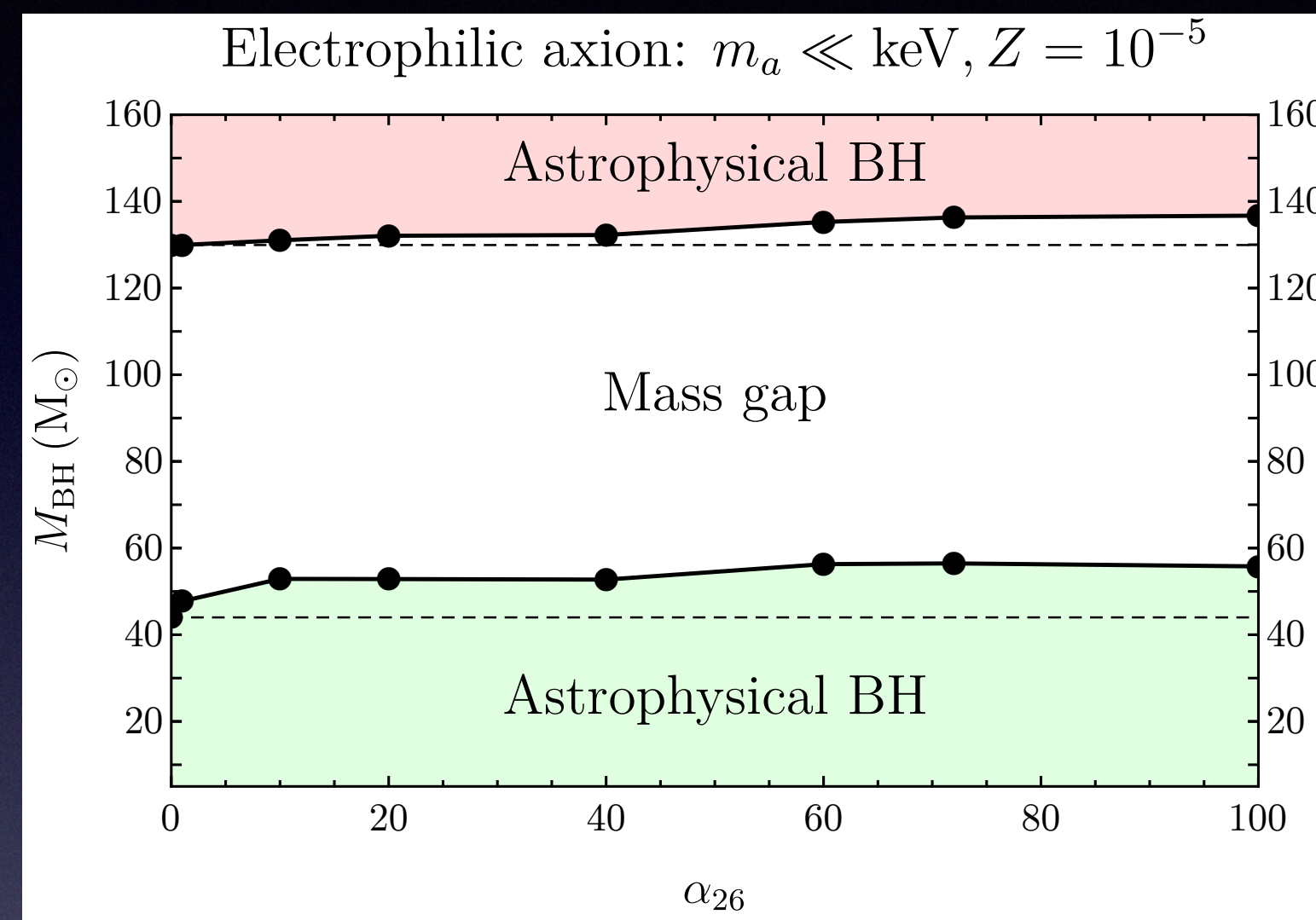


Implications for Black Hole Masses



larger coupling to new physics $\implies$ larger black hole mass

Implications for Black Hole Masses



But... Limits!

Claimed constraints from other stellar systems are in “tension”

- Capozzi & Raffelt 2007.03694: “The evolution of a low-mass star as it ascends the red-giant branch (RGB) is driven by the growing mass and shrinking size of its degenerate core until helium ignites and the core quickly expands” $\implies \alpha_{26} \leq 0.2$
- CAST excludes $g_{10} \leq 0.7$ up to $m_a \sim 0.02$ eV, weakening linearly at larger m_a ; helioseismology requires $g_{10} \leq 4$ (Vinyoles et al., 1501.01639)
- Exceeding the luminosity of photons from the sun unacceptably changes the ^8B neutrino flux, limiting $\epsilon m_{A'}/\text{meV} \lesssim 10^{-9}$ (An et al., 1302.3884; Redondo and Raffelt 1305.2920)

But... Limits!

Claimed constraints from other stellar systems are in “tension”

- Capozzi & Raffelt 2007.03694: “The evolution of a low-mass star as it ascends the red-giant branch (RGB) is driven by the growing mass and shrinking size of its degenerate core until helium ignites and the core quickly expands” $\Rightarrow \alpha_{26} \leq 0.2$
- CAST excludes $g_{10} \leq 0.7$ up to $m_a \sim 0.02$ eV, weakening linearly at larger m_a ; helioseismology requires $g_{10} \leq 4$ (Vinyoles et al., 1501.01639)
- Exceeding the luminosity of photons from the sun unacceptably changes the ^8B neutrino flux, limiting $\epsilon m_A / \text{meV} \lesssim 10^{-9}$ (An et al., 1302.3884; Redondo and Raffelt 1305.2920)

the Sun is pretty well (though as yet imperfectly) understood

But... Limits!

Claimed constraints on these stars have uncertainties (mixing, structure) and unexplored parameter degeneracies (age, metallicity; distance, reddening)

- Capozzi & Raffelt 2007.03694: “The evolution of a low-mass star as it ascends the red-giant branch (RGB) is driven by the growing mass and shrinking size of its degenerate core until helium ignites and the core quickly expands” $\Rightarrow \alpha_{26} \leq 0.2$
- CAST excludes $g_{10} \leq 0.7$ up to $m_a \sim 0.02$ eV, weakening linearly at larger m_a ; helioseismology requires $g_{10} \leq 4$ (Vinyoles et al., 1501.01639)
- Exceeding the luminosity of photons from the sun unacceptably changes the ^8B neutrino flux, limiting $\epsilon m_A / \text{meV} \lesssim 10^{-9}$ (An et al., 1302.3884; Redondo and Raffelt 1305.2920)

the Sun is pretty well (though as yet imperfectly) understood

But... Limits!

Claimed constraints on these stars have uncertainties (mixing, structure) and unexplored parameter degeneracies (age, metallicity; distance, reddening)

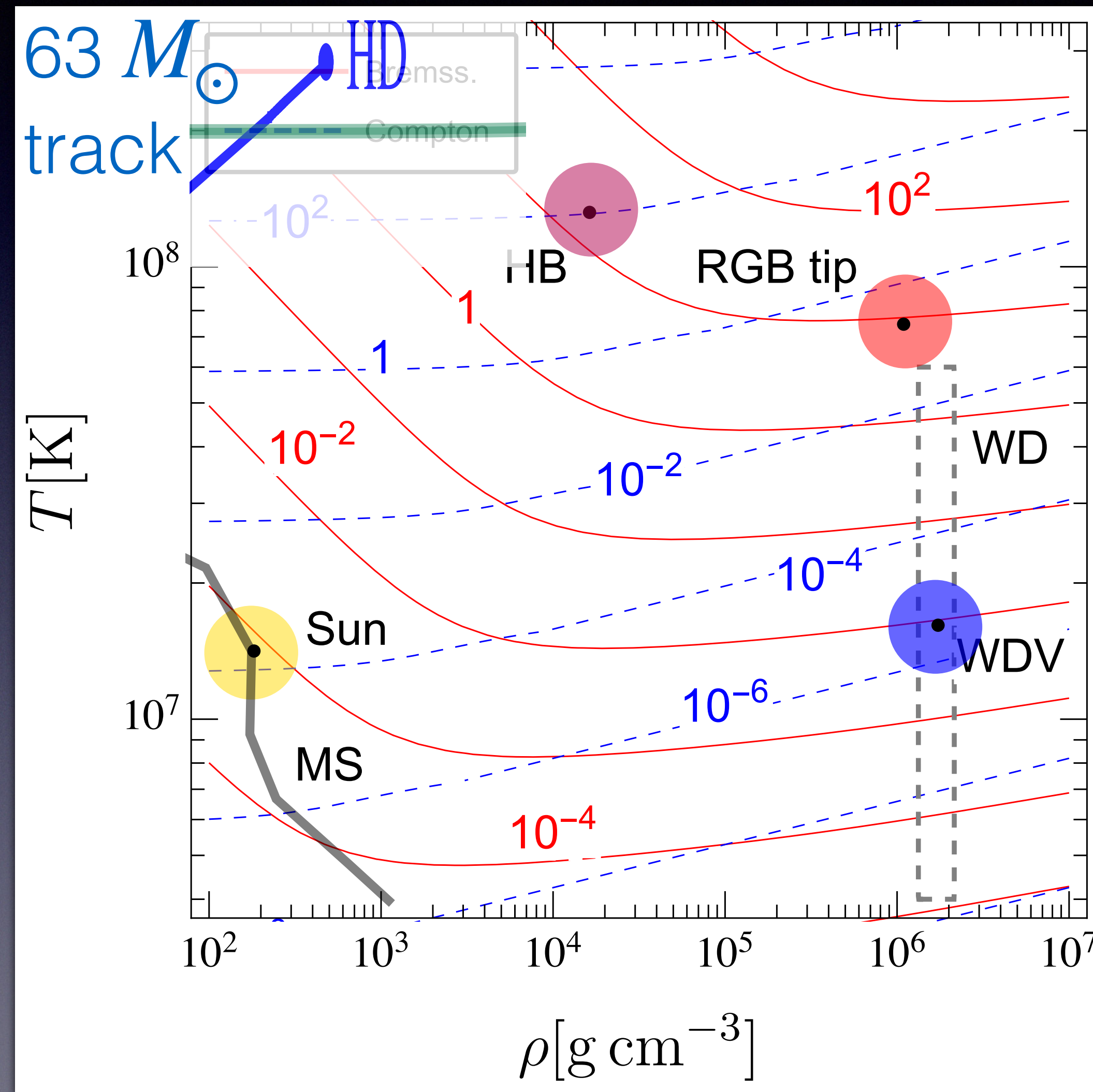
- Capozzi & Raffelt 2007.03694: “The evolution of a low-mass star as it ascends the red-giant branch (RGB) is driven by the growing mass and shrinking size of its degenerate core until helium ignites and the core quickly expands” $\Rightarrow \alpha_{26} \leq 0.2$

Solar bound only $\alpha_{26} \leq 4200$ (Redondo 1310.0823)

- CAST excludes $g_{10} \leq 0.7$ up to $m_a \sim 0.02$ eV, weakening linearly at larger m_a ; helioseismology requires $g_{10} \leq 4$ (Vinyoles et al., 1501.01639)
- Exceeding the luminosity of photons from the sun unacceptably changes the ^8B neutrino flux, limiting $\epsilon m_A / \text{meV} \lesssim 10^{-9}$ (An et al., 1302.3884; Redondo and Raffelt 1305.2920)

the Sun is pretty well (though as yet imperfectly) understood

Also: different characteristic T_c



~ 10 keV

New Physics: Summary

- New light particles can shorten helium burning, reduce the amount of oxygen, and increase the black hole mass
- The picture (including effects on other stars) is not perfectly tidy as degeneracies / observational uncertainties are underexplored
- Constraints on hidden photon, photophilic axion, and neutrino dipole moment seem robust; electrophilic axion potentially less so
- Model building routes to skirt bounds?

New Physics: Summary

- New light particles can shorten helium burning, reduce the amount of oxygen, and inc
- The picture (including degeneracies / obs) is not perfectly tidy as underexplored
- Constraints on hidden photon, photophilic axion, and neutrino dipole moment seem robust; electrophilic axion potentially less so
- Model building routes to skirt bounds?

**Lots of room
remains for better
understanding!**

Outline

1. Physics of the pair instability mechanism
2. Beyond-the-Standard-Model explanations of GW190521
3. Standard Model explanations of GW190521
4. Future prospects

Three Routes for SM Explanations

1. Increase the mass *before* PPISN

Three Routes for SM Explanations

1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN

Three Routes for SM Explanations

1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN
3. Increase the mass *after* PPISN

Three Routes for SM Explanations

1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN
3. Increase the mass *after* PPISN

 **Limited and biased overview follows** 

Three Routes for SM Explanations

1. Increase the mass *before* PPISN →
2. Increase the mass *during* PPISN
3. Increase the mass *after* PPISN

Stellar merger, no mass loss,
retention of H envelope

Three Routes for SM Explanations

1. Increase the mass *before* PPISN →
2. Increase the mass *during* PPISN
3. Increase the mass *after* PPISN

Stellar merger, no mass loss,
retention of H envelope

The Stellar Merger Scenario for Black Holes in the Pair-instability Gap

M. RENZO,^{1,2} M. CANTIELLO,^{1,3} B. D. METZGER,^{2,1} AND Y.-F. JIANG (姜燕飞)¹

¹Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA

²Department of Physics, Columbia University, New York, NY 10027, USA

³Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA

2010.00705

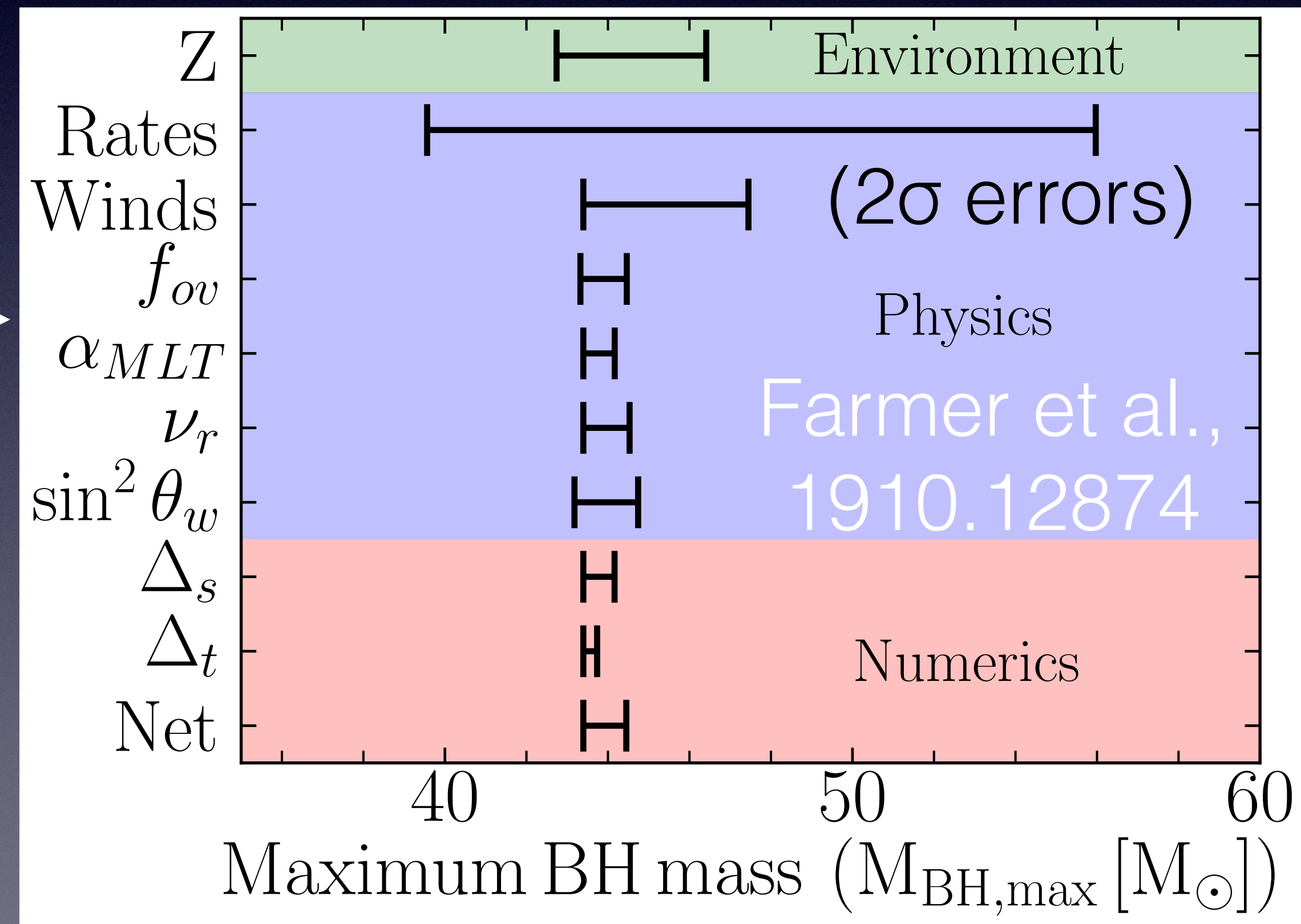
akin to luminous blue variable (LBV) eruptions are expected. An energetic estimate of the amount of mass loss neglecting the back-reaction of the star suggests that the total amount of mass that can be removed at low metallicity is $\lesssim 1 M_{\odot}$. This is small enough that at core-collapse our models are retaining sufficient mass to form black holes in the pair-instability gap similar to the recent ones detected by LIGO/Virgo. However, mass loss at the time of merger and the neutrino-driven mass loss at core collapse still need to be quantified for these models in order to confirm the viability of this scenario.

Three Routes for SM Explanations

1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN → make pulsations less effective
3. Increase the mass *after* PPISN

Three Routes for SM Explanations

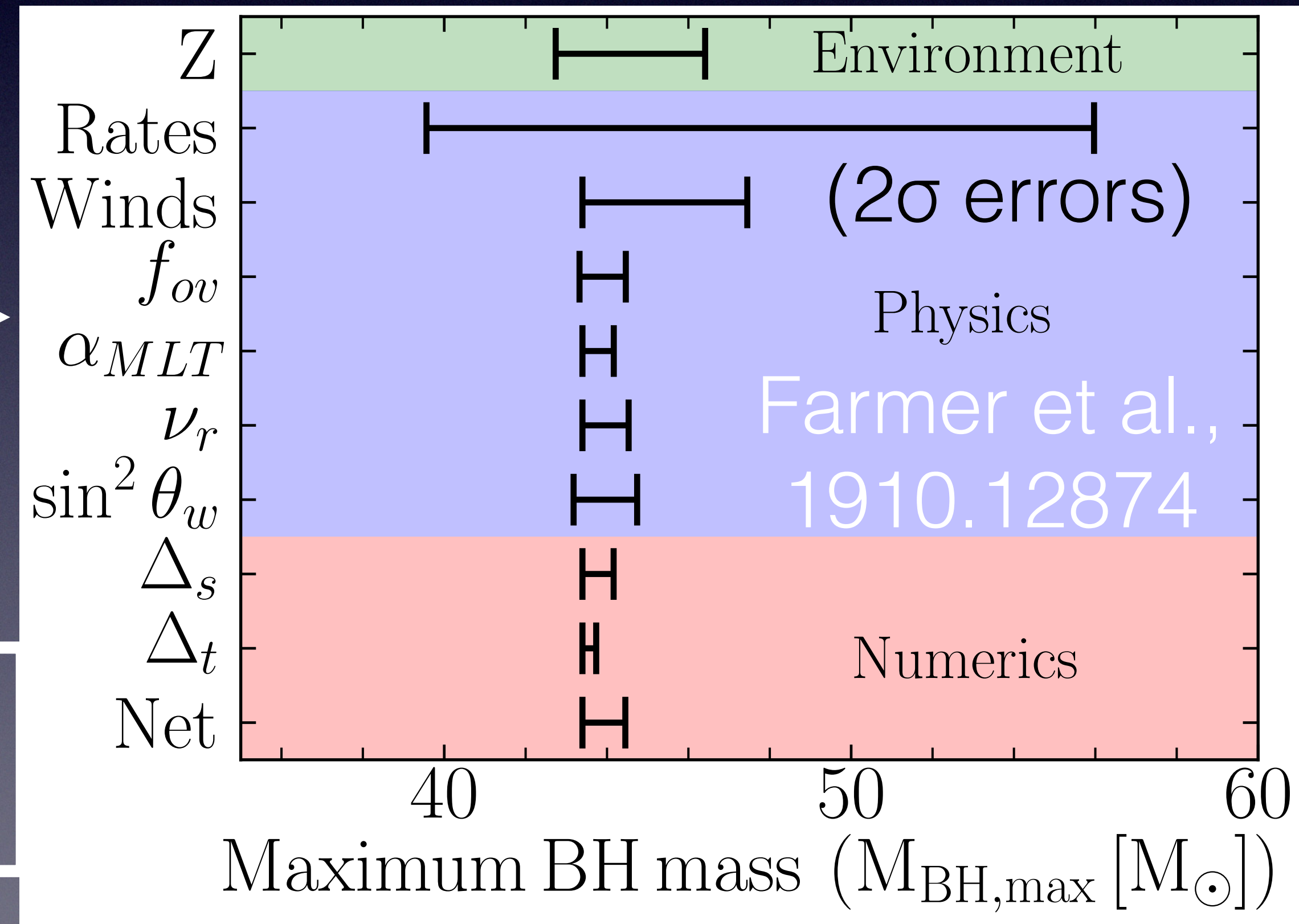
1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN →
3. Increase the mass *after* PPISN



Three Routes for SM Explanations

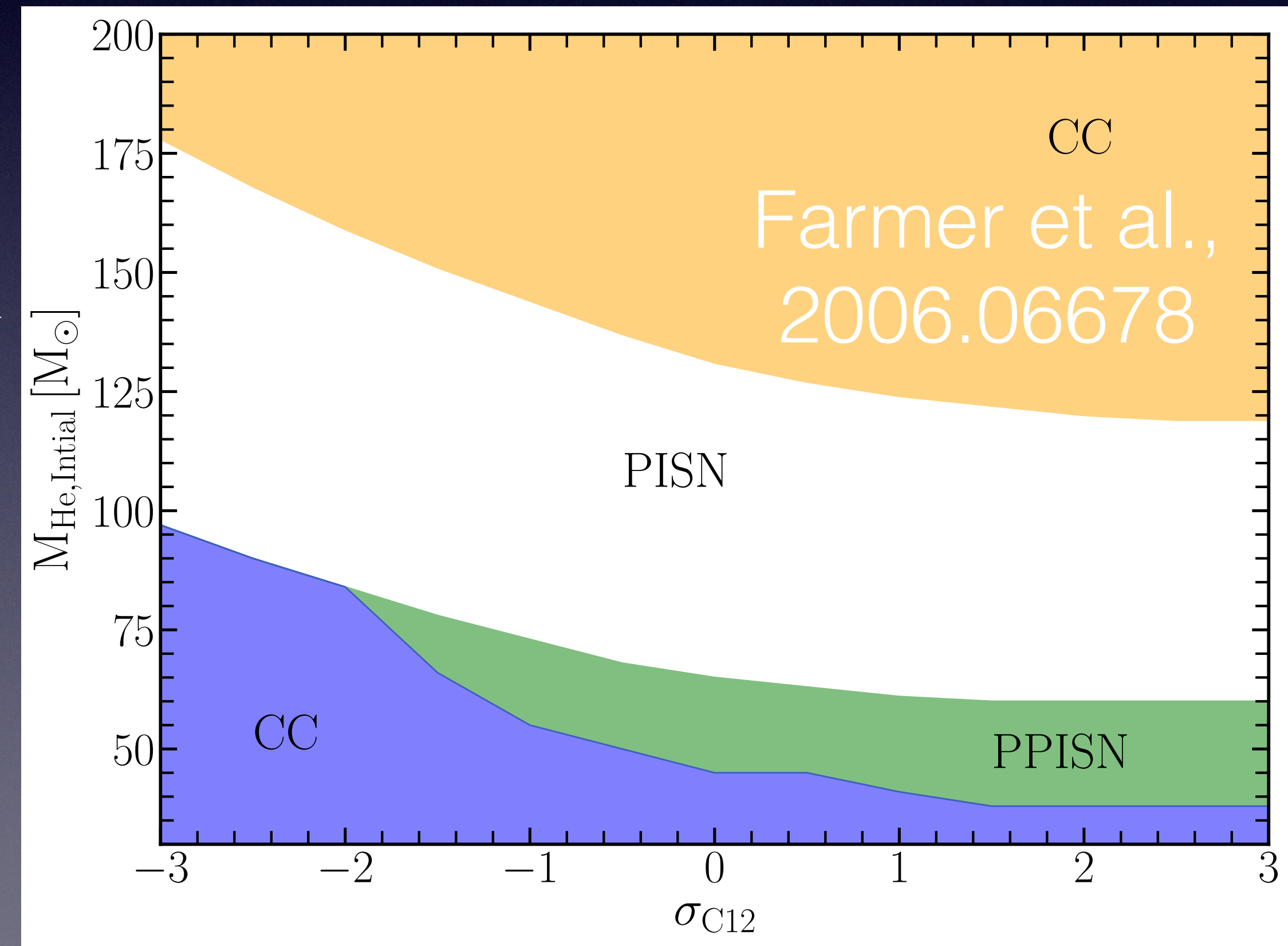
1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN →
3. Increase the mass *after* PPISN

“rates” err bar dominated
by rate of $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$



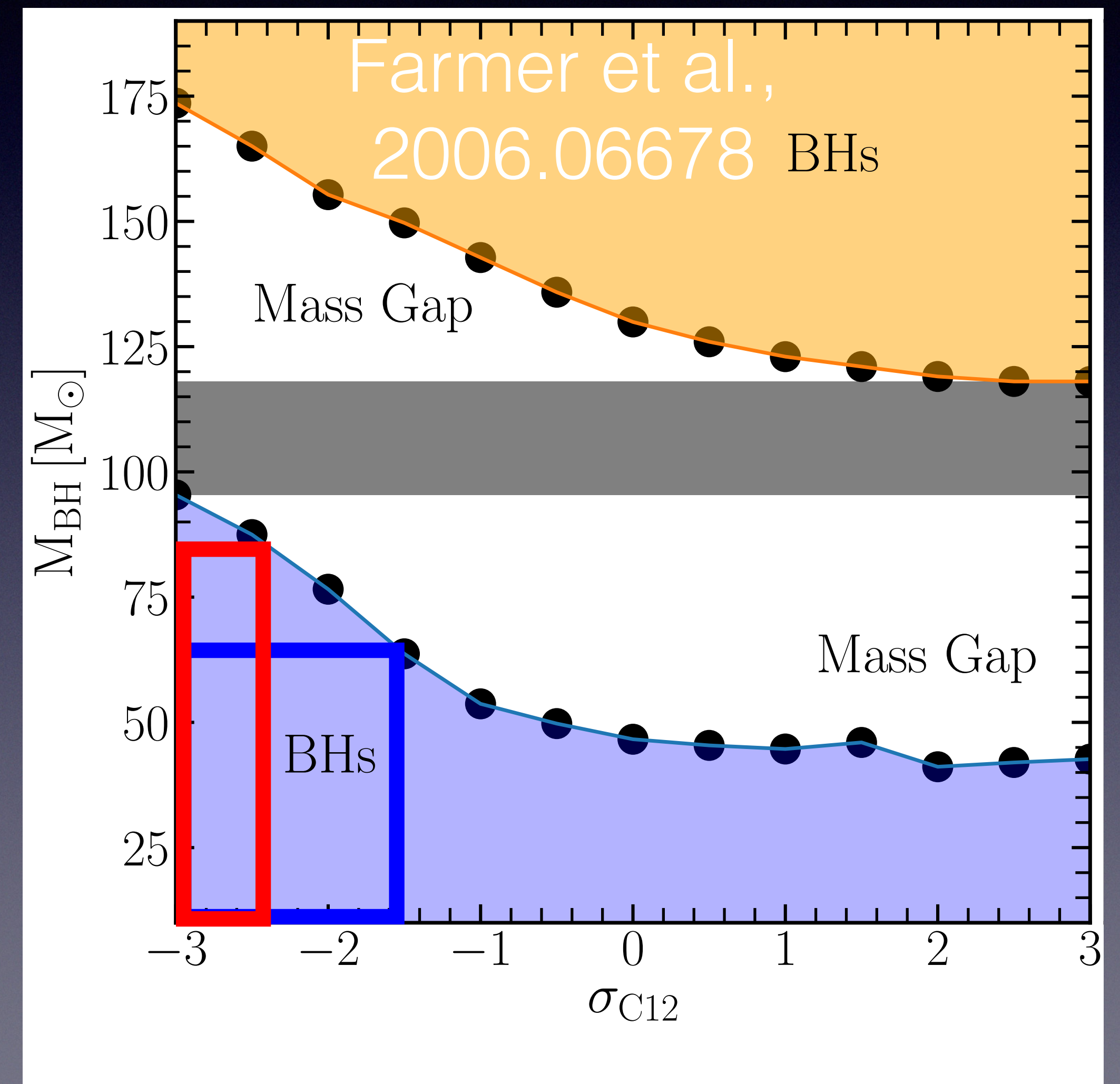
Three Routes for SM Explanations

1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN →
3. Increase the mass *after* PPISN



Three Routes for SM Explanations

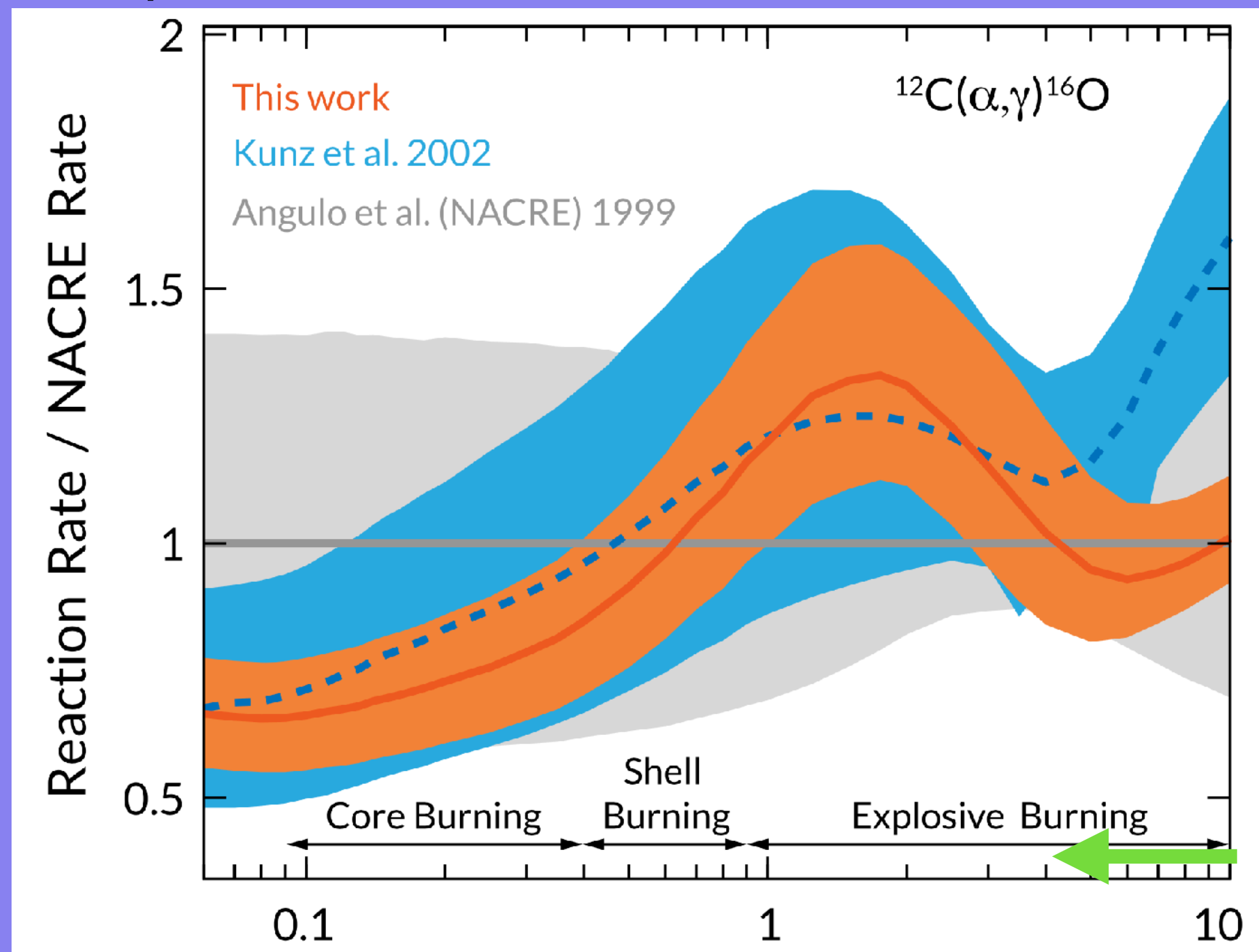
1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN →
3. Increase the mass *after* PPISN



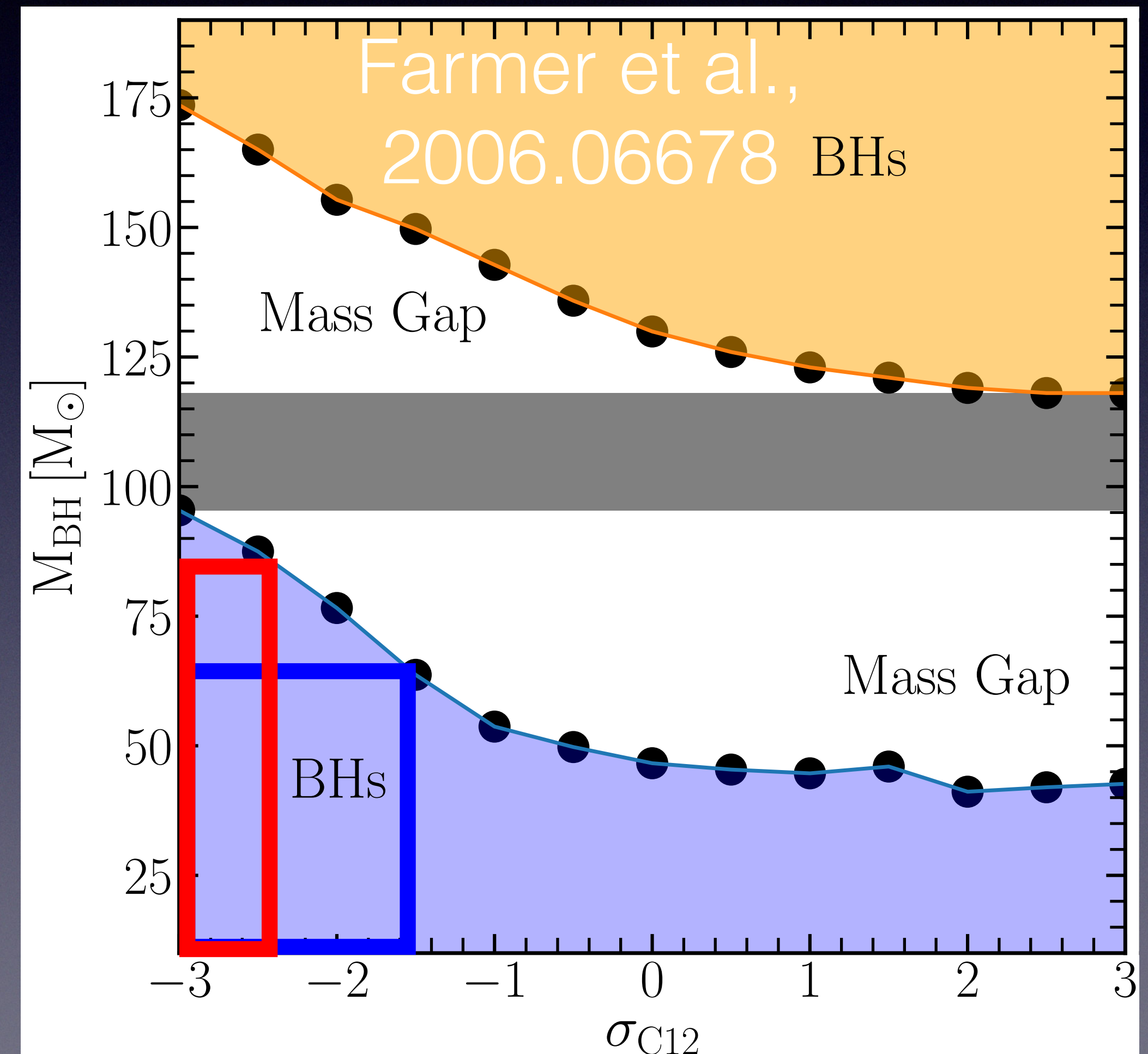
Three Routes for SM Explanations

Update: deBoer et al. 2017

R. J. deBoer, J. Görres, M. Wiescher, R. E. Azuma, A. Best, C. R. Brune, C. E. Fields, S. Jones, M. Pignatari, D. Sayre, K. Smith, F. X. Timmes, and E. Uberseder
Rev. Mod. Phys. **89**, 035007 – Published 7 September 2017

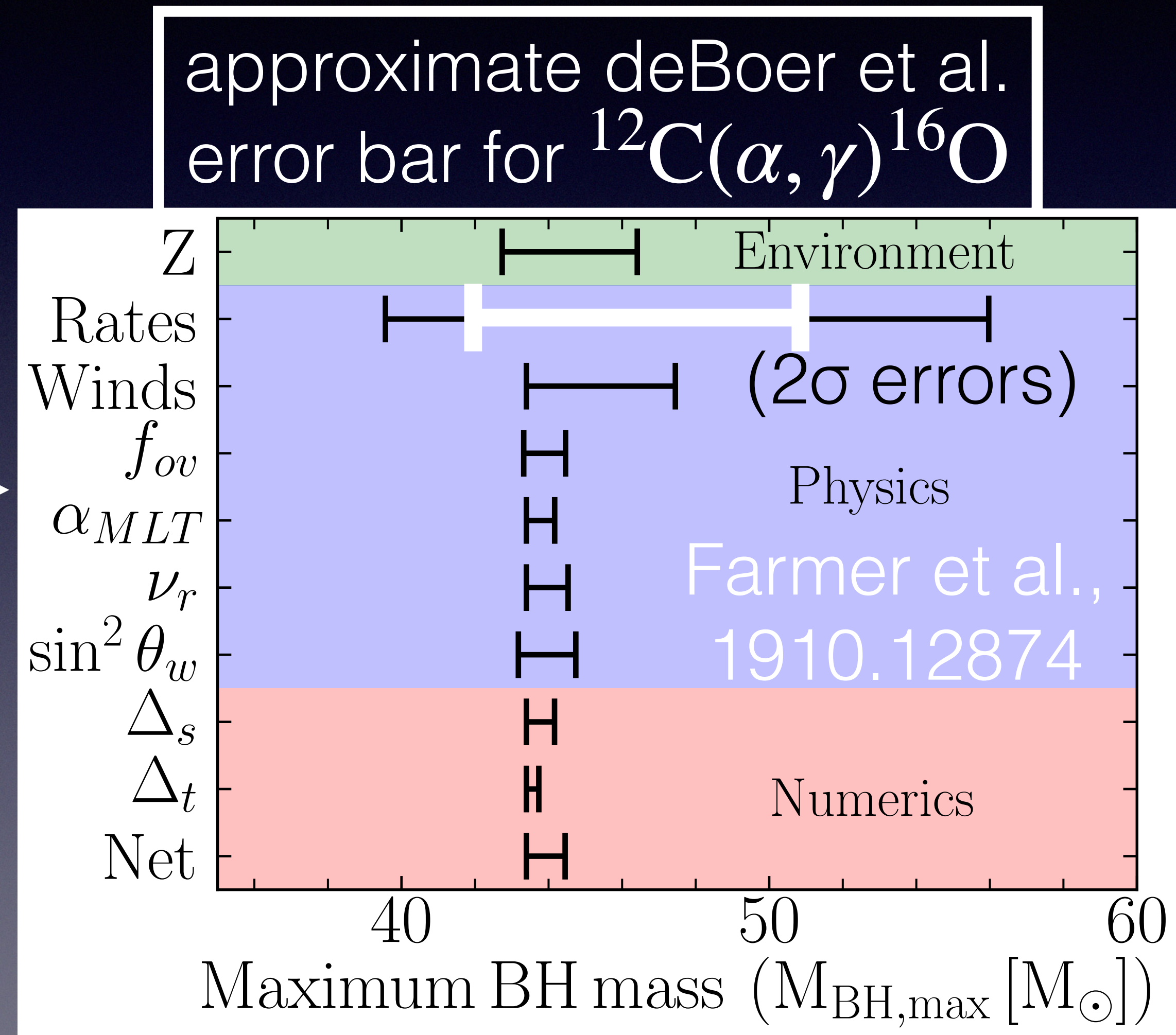


we find $48^{+3.6}_{-1} M_{\odot}$ (vs. $48^{+7}_{-2} M_{\odot}$)



Three Routes for SM Explanations

1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN →
3. Increase the mass *after* PPISN



Three Routes for SM Explanations

1. Increase the mass *before* PPISN

2. Increase the mass *during* PPISN

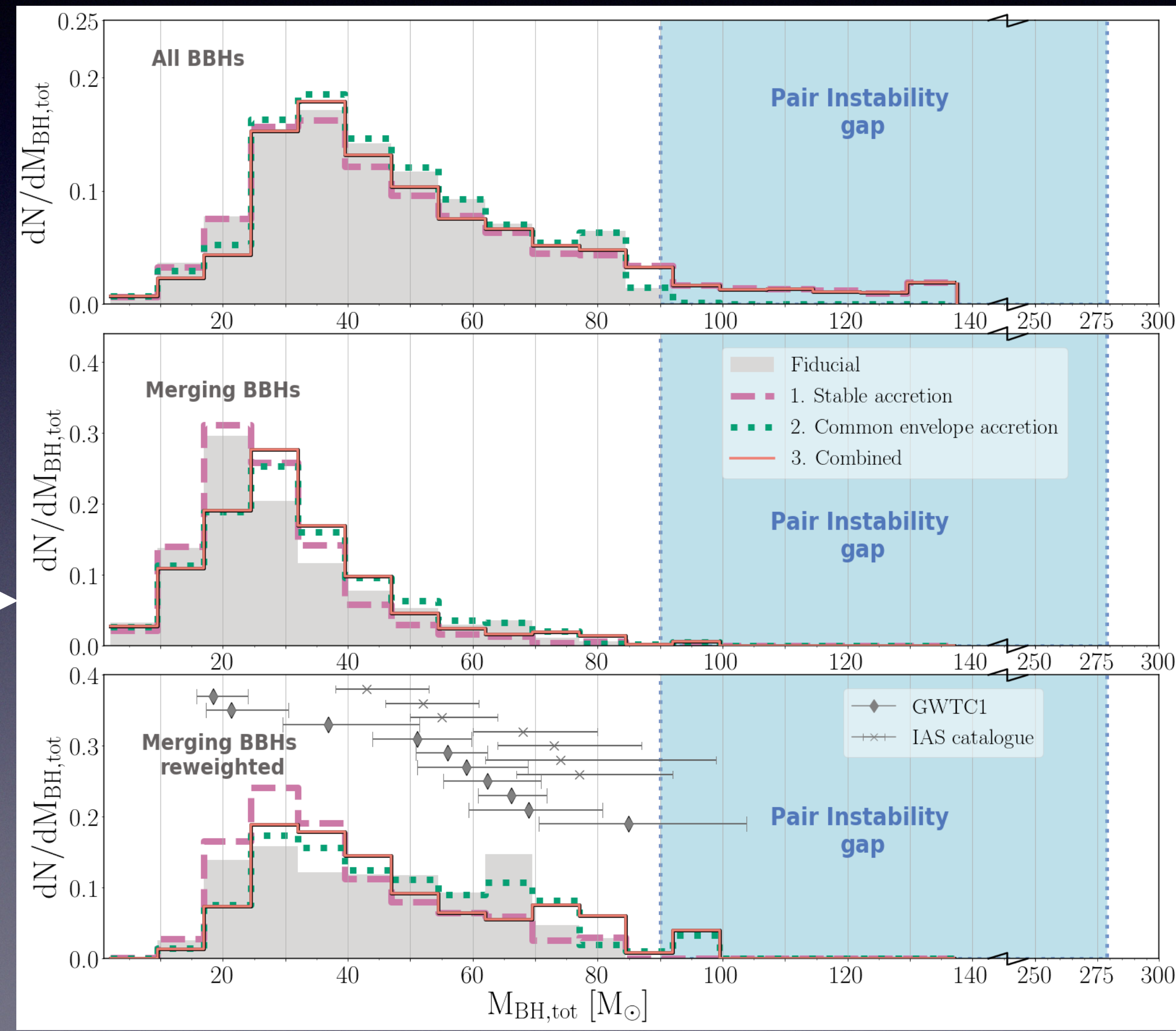
3. Increase the mass *after* PPISN →

N^{th} gen - N^{th} gen mergers,
accretion in nuclear star cluster,
...

Three Routes for SM Explanations

van Son et al., 2004.05187

1. Increase the mass *before* PPISN
2. Increase the mass *during* PPISN
3. Increase the mass *after* PPISN →



SM Explanations: Summary

- There “**definitely may be**” paths to making BHs with masses $M \gtrsim 50M_{\odot}$ through SM mechanisms alone

SM Explanations: Summary

- There “**definitely may be**” paths to making BHs with masses $M \gtrsim 50M_{\odot}$ through SM mechanisms alone
- Reliant on very uncertain SM ((g)astro)physics:
 - nonequilibrium stellar dynamics: how do stars merge / mix? what happens to the new core and envelope?
 - stellar populations: how do binary systems evolve? what are viable pathways for multiple mergers?
 - nuclear physics: how does ^{12}C capture ^4He ?

SM Explanations: Summary

- There “**definitely may be**” paths to making BHs with masses $M \gtrsim 50M_{\odot}$ through SM mechanisms alone
- Reliant on very uncertain SM ((a)astro)physics:
 - nonequilibrium: what happens? If these are responsible for GW190521, we have witnessed a **rare event** (not every star or black hole experiences a merger) / mix?
 - stellar populations: how do binary systems evolve? what are viable pathways for multiple mergers?
 - nuclear physics: how does ^{12}C capture ^4He ?

Outline

1. Physics of the pair instability mechanism
2. Beyond-the-Standard-Model explanations of GW190521
3. Standard Model explanations of GW190521
4. Future prospects

GW190521: BSM vs SM explanations

SM physics

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

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

GW190521: BSM vs SM explanations

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

GW190521: BSM vs SM explanations

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

GW190521: BSM vs SM explanations

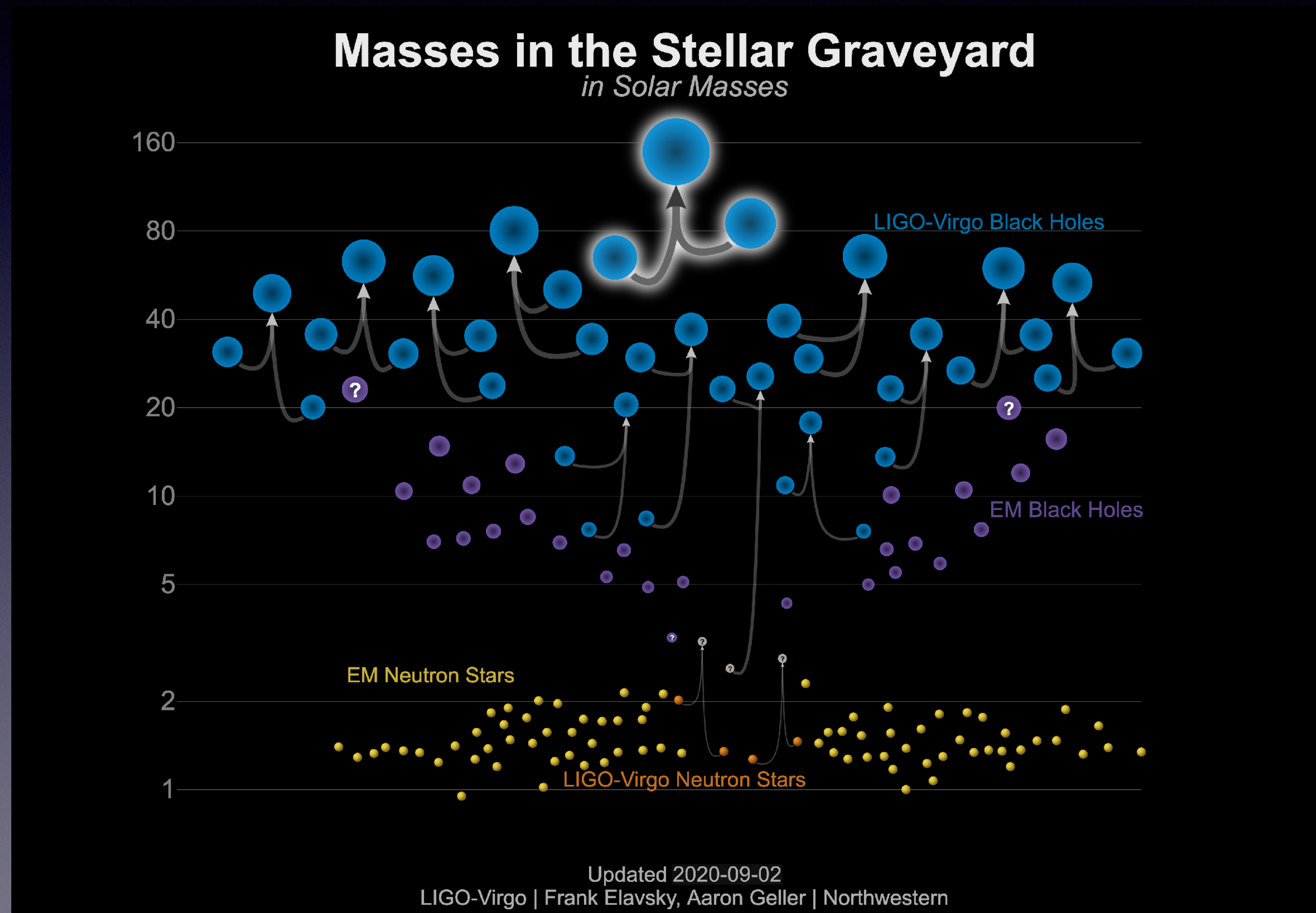
SM physics

- “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

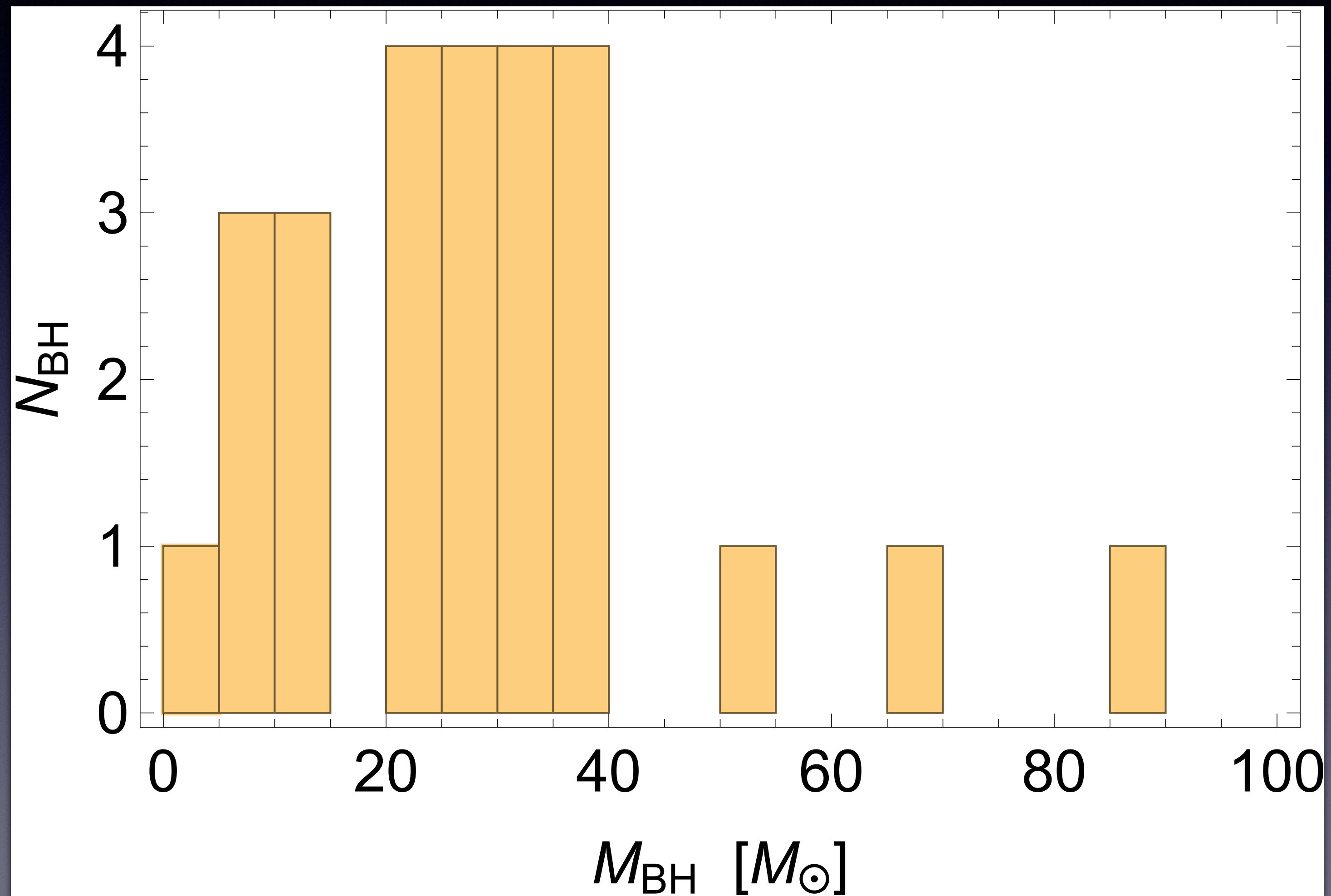
BSM physics

- “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** distribution of BH masses up to a new, higher value of M_{BH}

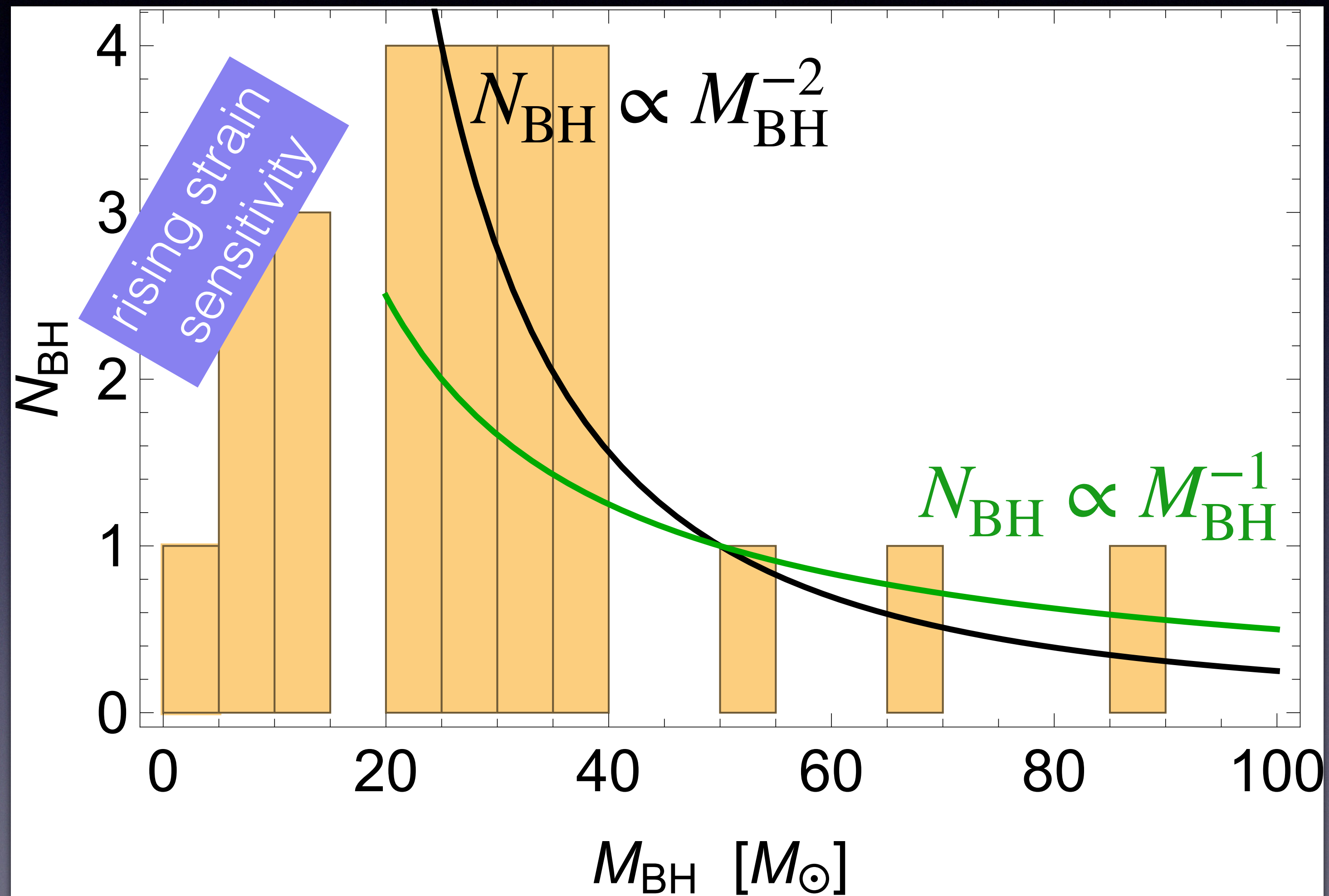
LIGO Observations so Far



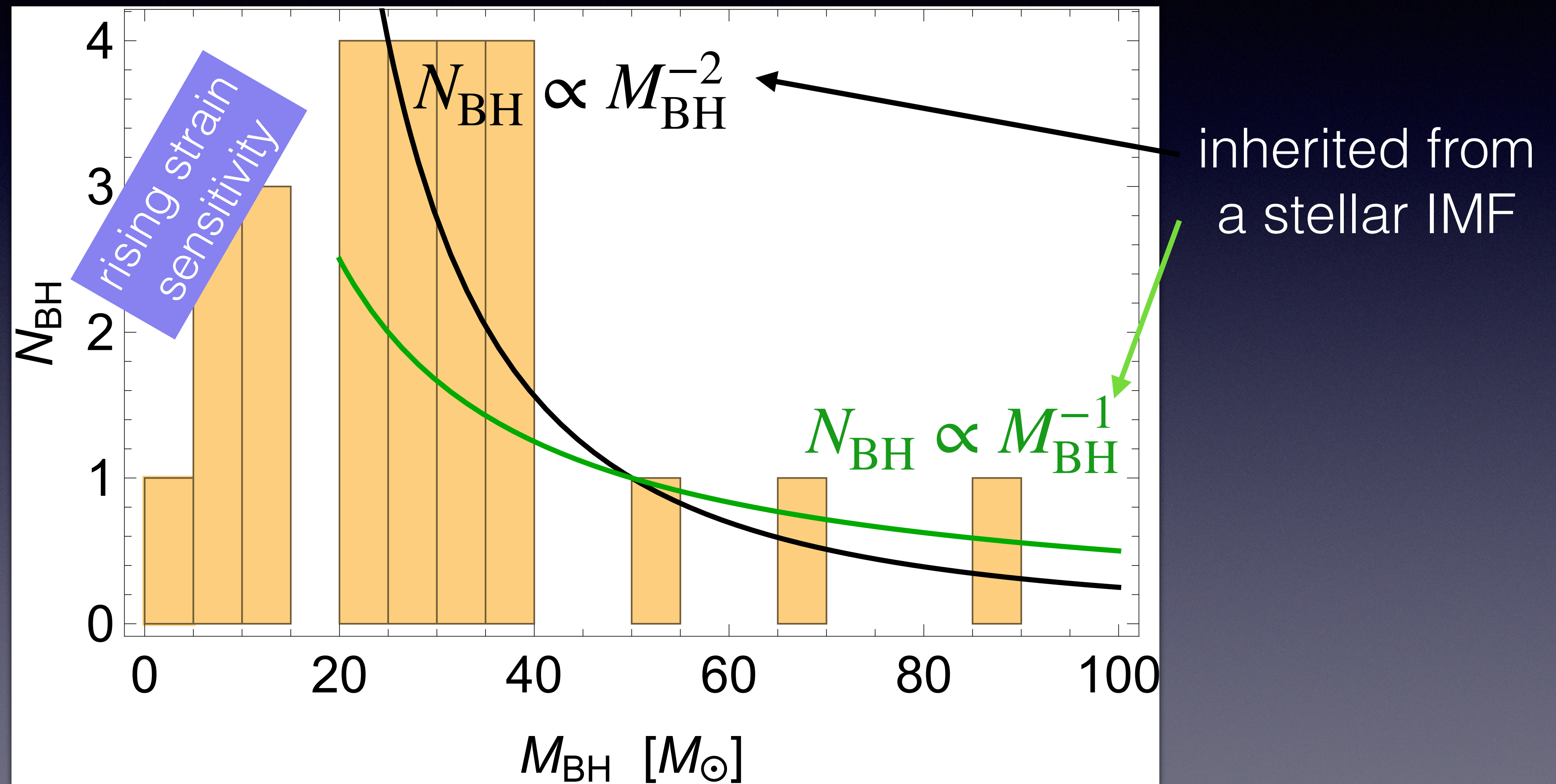
Black Hole Population Statistics



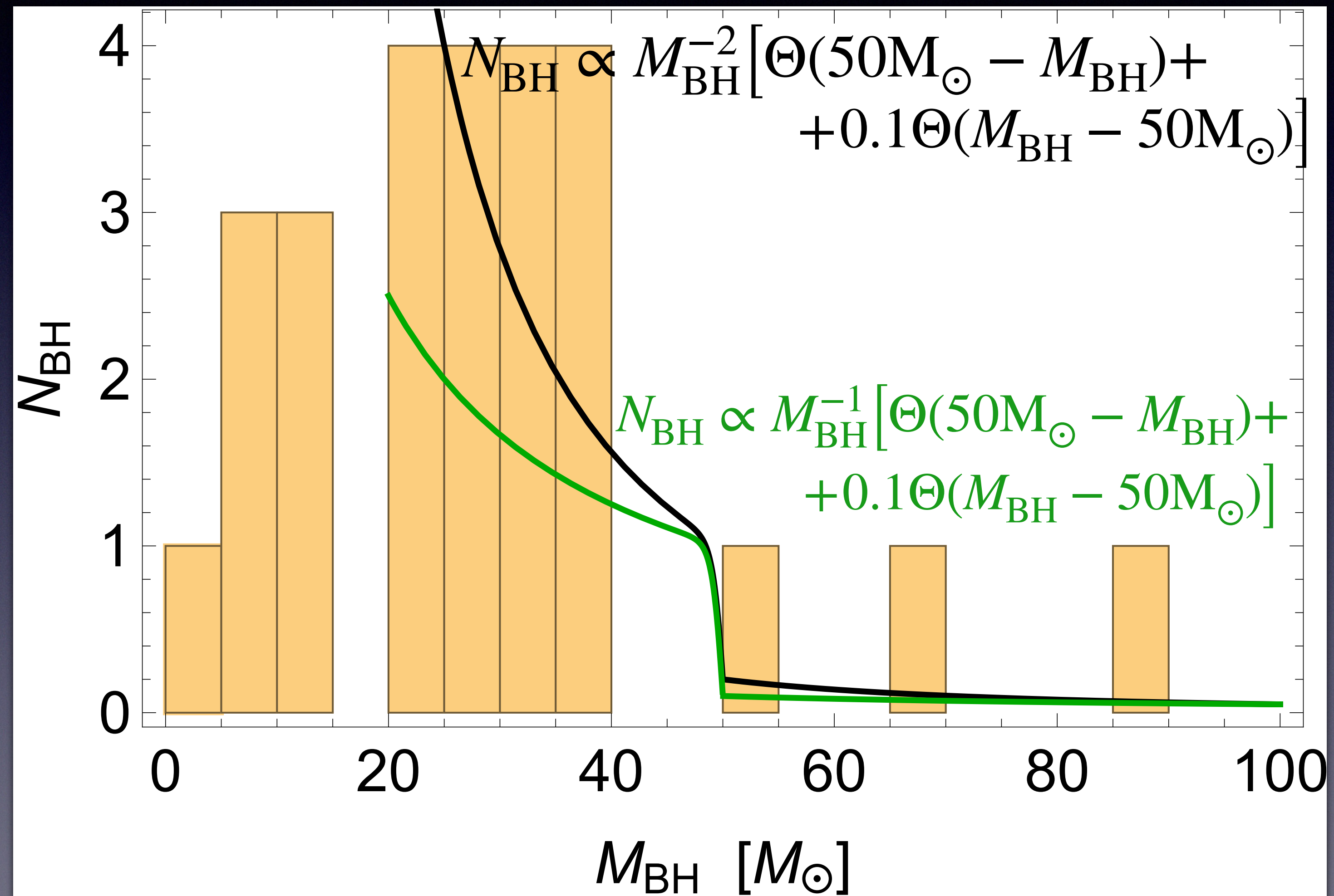
Black Hole Population Statistics



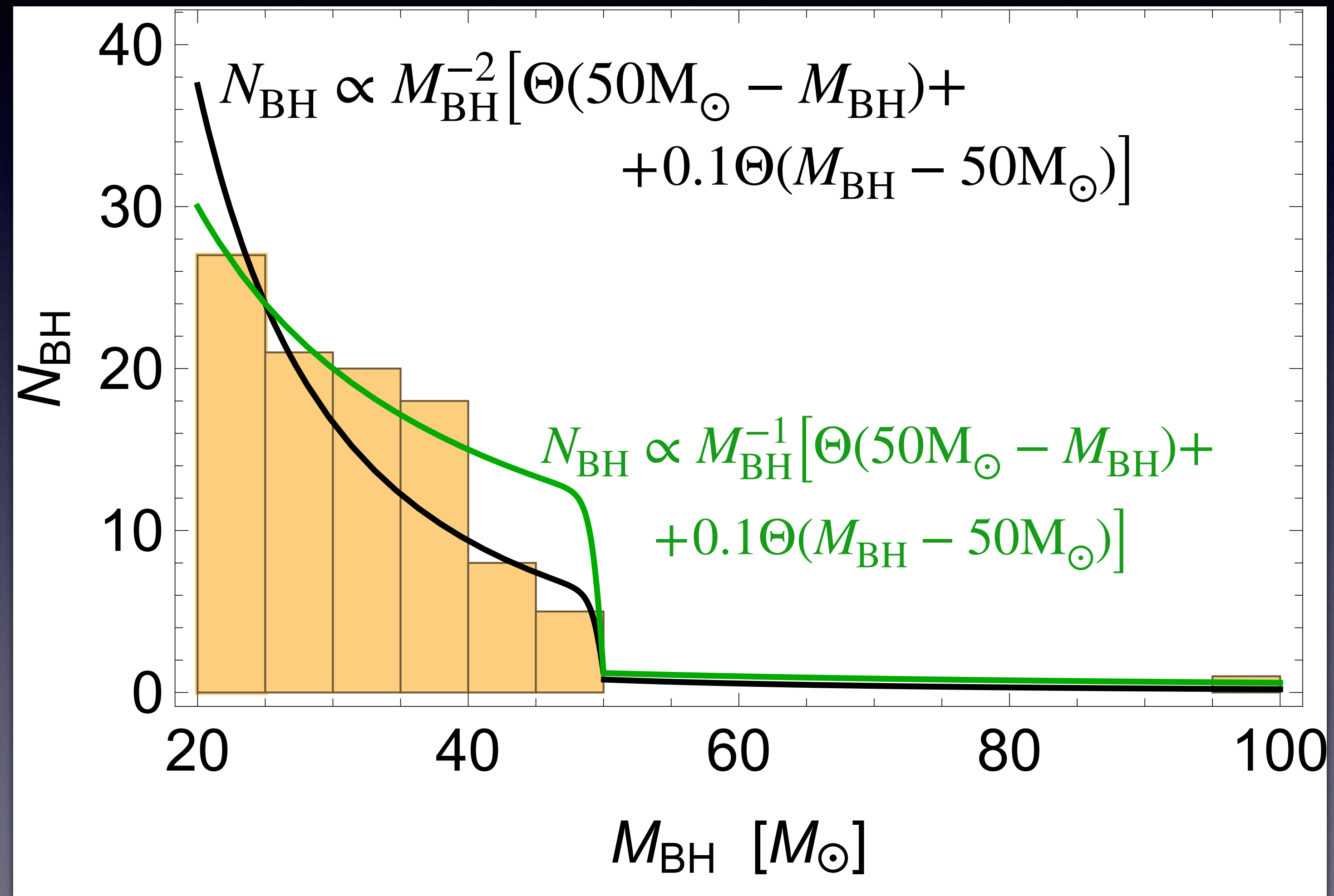
Black Hole Population Statistics



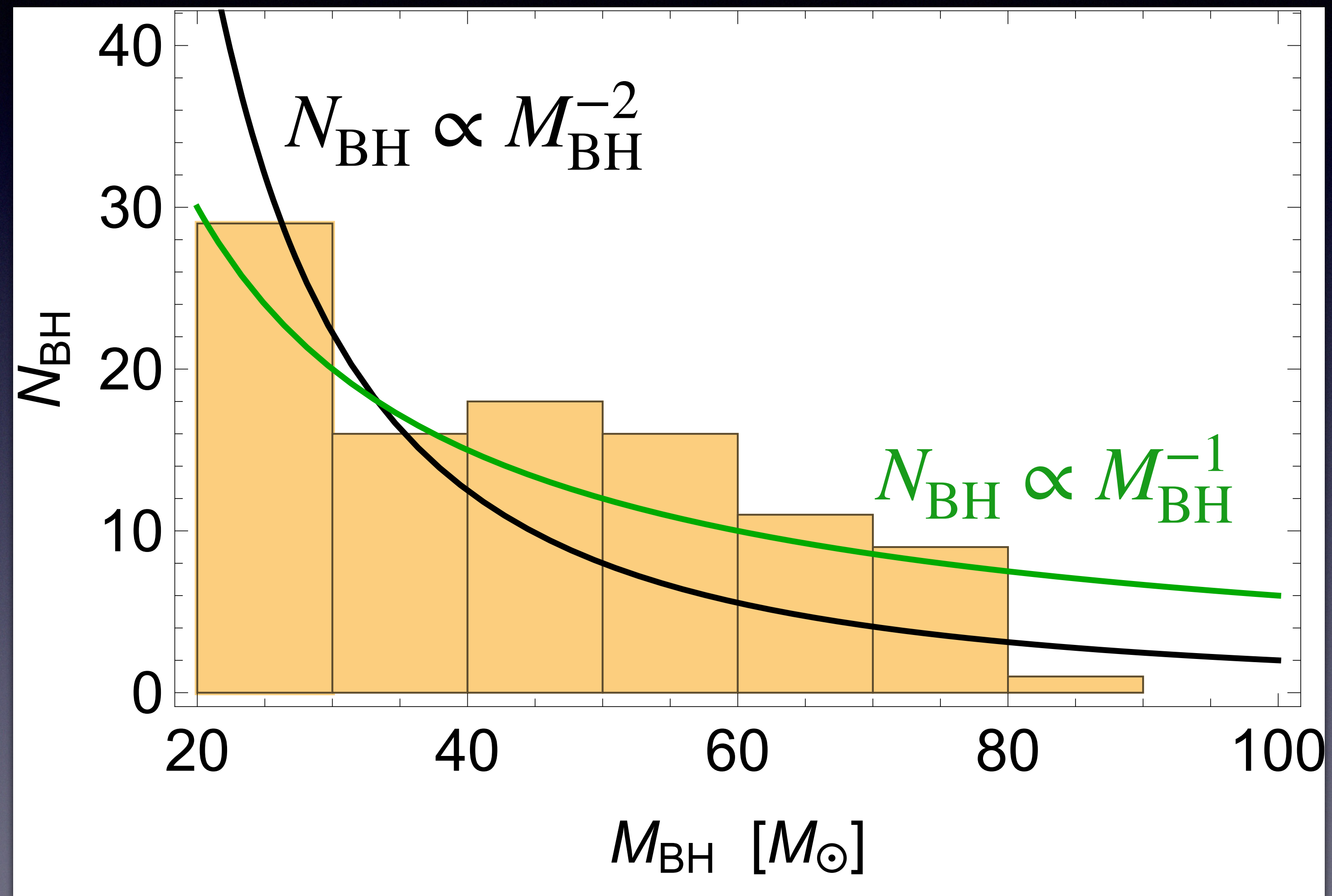
Black Hole Population Statistics



Black Hole Population Statistics



Black Hole Population Statistics

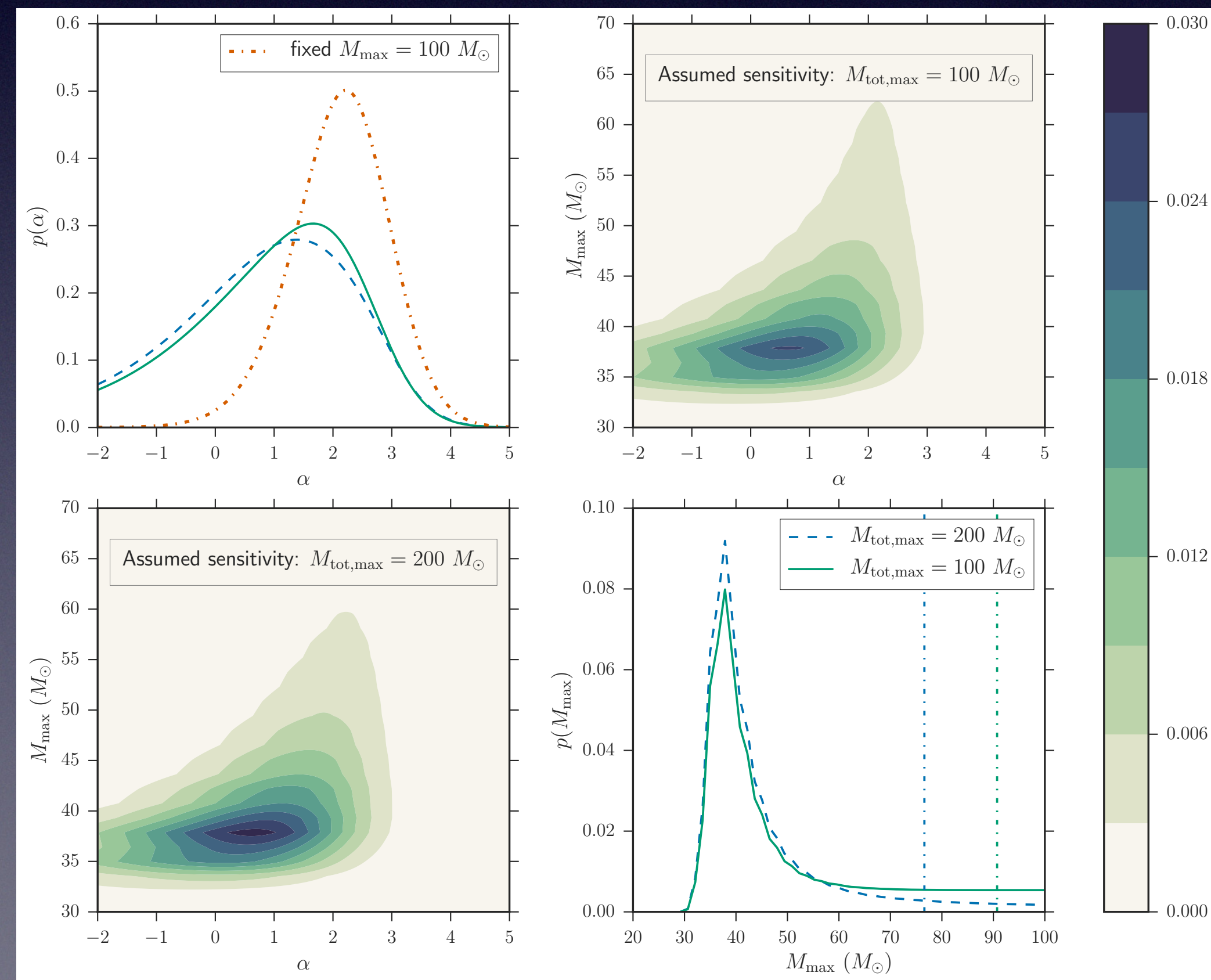


Black Hole Population Statistics

$$p(m_1, m_2 | \alpha, M_{\max}) \propto \frac{m_1^{-\alpha} \mathcal{H}(M_{\max} - m_1)}{\min(m_1, M_{\text{tot,max}} - m_1) - M_{\min}}$$

First four LIGO
detections:

Fishbach & Holz,
1709.08584



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/

Conclusions



PROTIP: IF YOU'RE NOT SURE WHAT TO SAY, TRY "SO IT HAS COME TO THIS"—IT CREATES INSTANT DRAMATIC TENSION AND IS A VALID OBSERVATION IN LITERALLY ANY SITUATION.

Conclusions



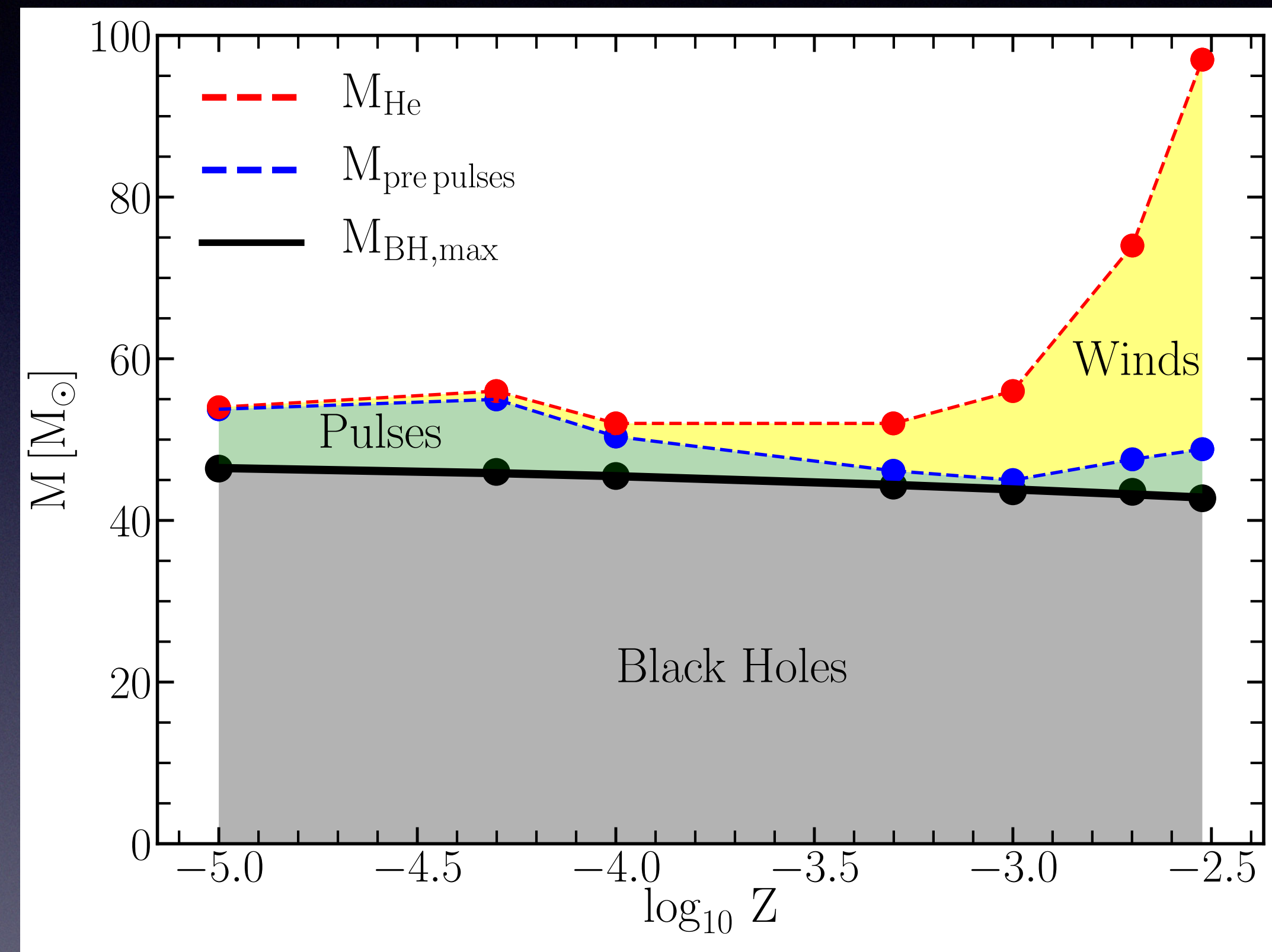
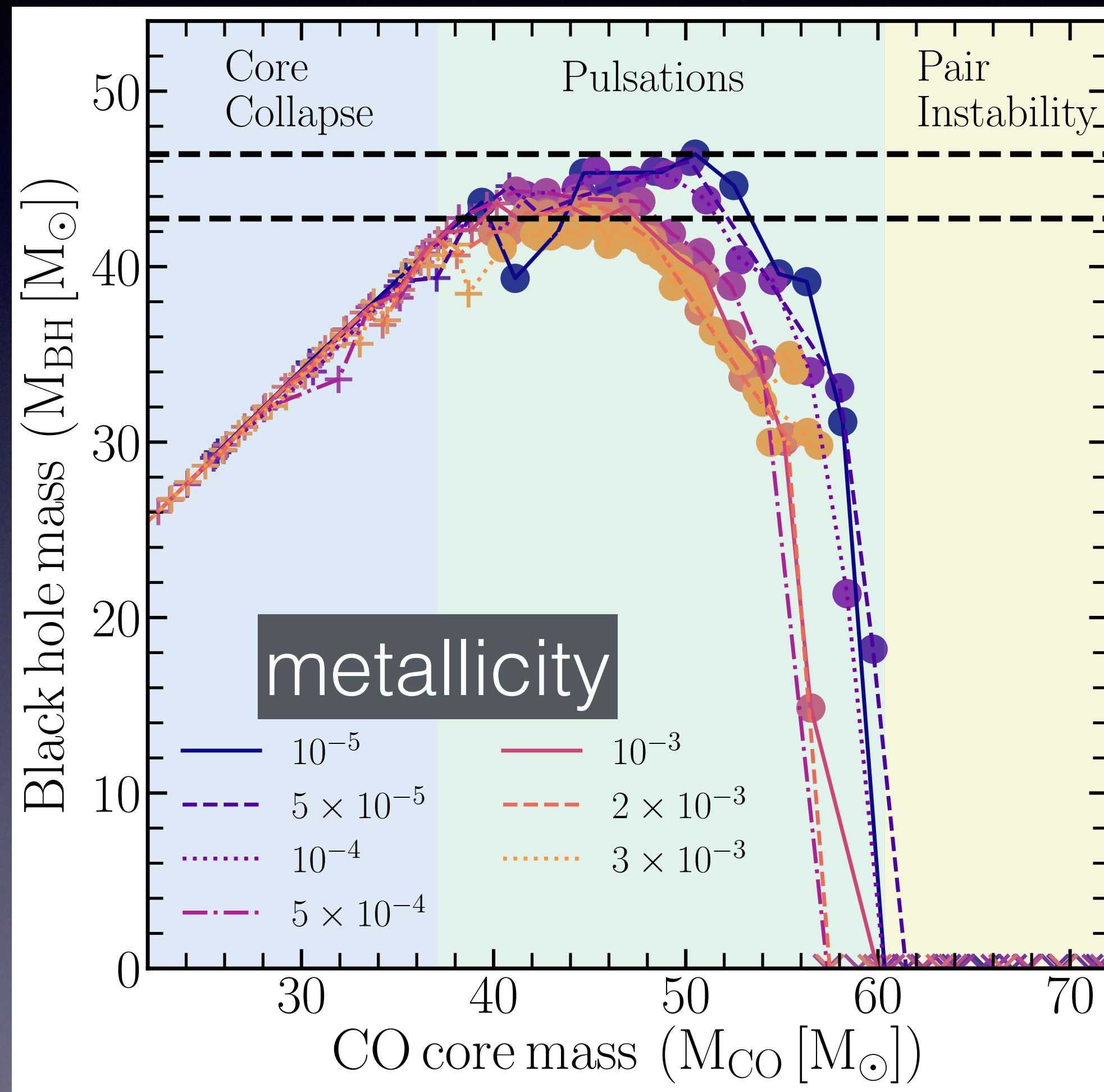
- LIGO is in the middle of its “discovery bump” — we are learning so much more about the Universe all the time!
- GW190521 provides rich fodder for new ideas and tests of both SM and BSM physics
- The future is exciting!

Thanks!

sammcd00@fnal.gov

home.fnal.gov/~sammcd00/

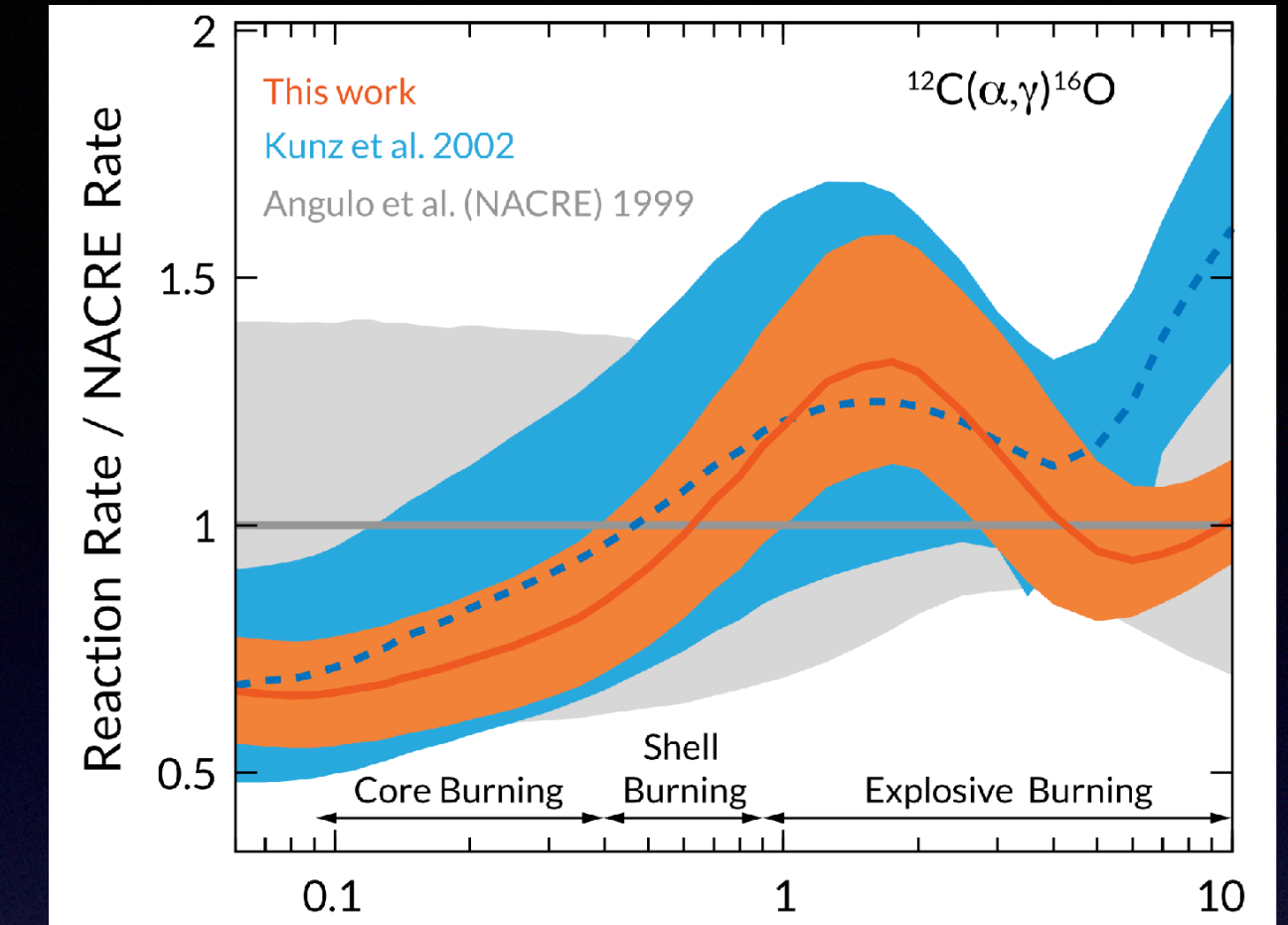
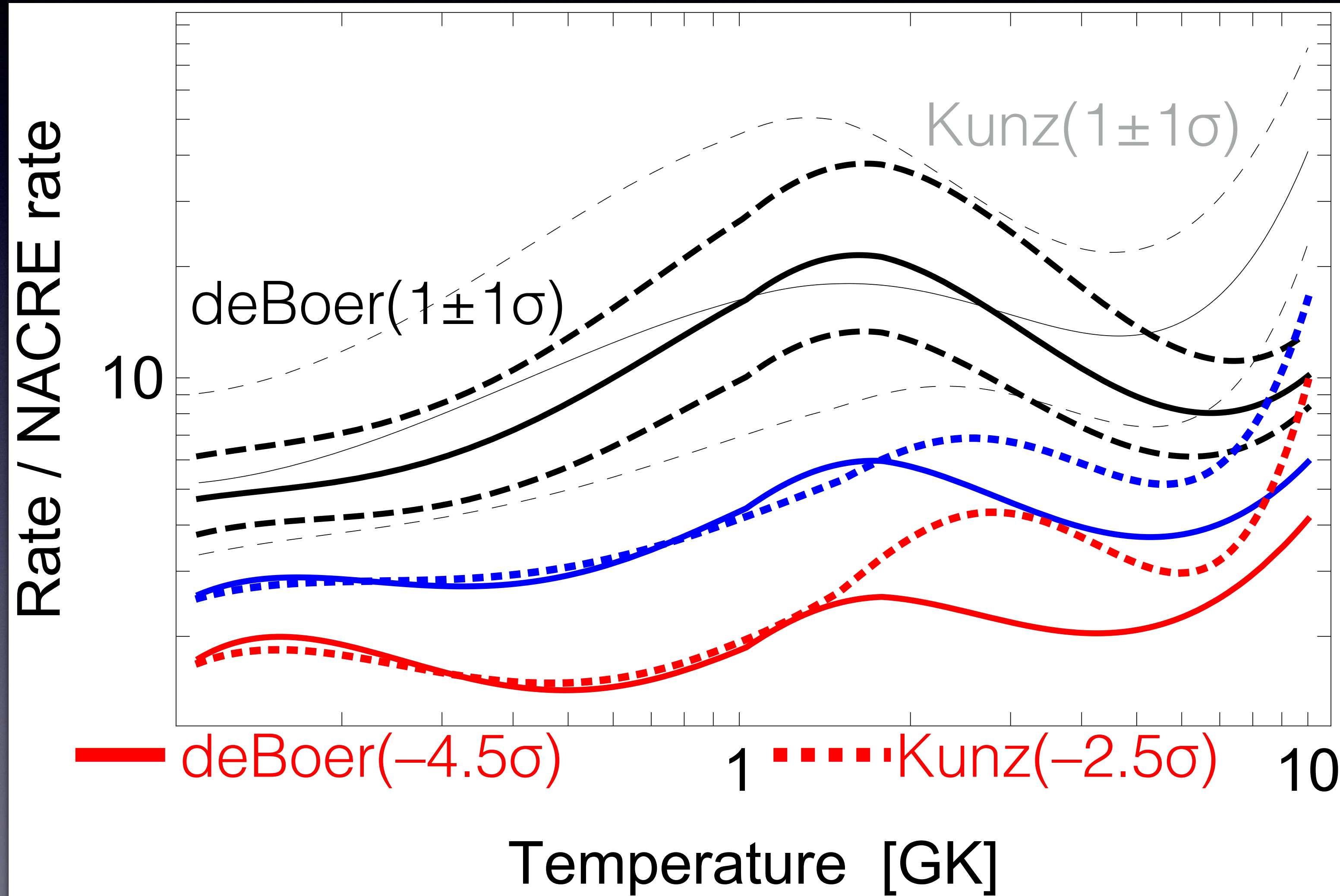
Environmental Variation



Farmer et al.,
1910.12874
ApJ 887 53F

SM prediction: $M_{\text{BH}} < 48 M_{\odot}$

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



— deBoer(-2.7σ)
 - - - Kunz(-1.6σ)

