Dark matter, gravitational waves and primordial black holes

iDMEu meeting, May 2021

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Particle physics with gravitational waves

A new era for particle physics phenomenology

New data, new opportunities…

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

We may learn a lot about particle physics from gravitational waves

Bertone et al. (including DC, BJK) arXiv:1907.10610

Particle physics with gravitational waves

A unique observational window…

Unprecedented access to "dark" masses and environments

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

$\rightarrow$ Different opportunities:

1. Waveform analysis
2. Population analysis

Unprecedented access to the most interesting cosmological era

- Events involving significant energy
- Direct access to times long before the surface of last scattering

$\rightarrow$ Example: 1^{st} order phase transitions

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

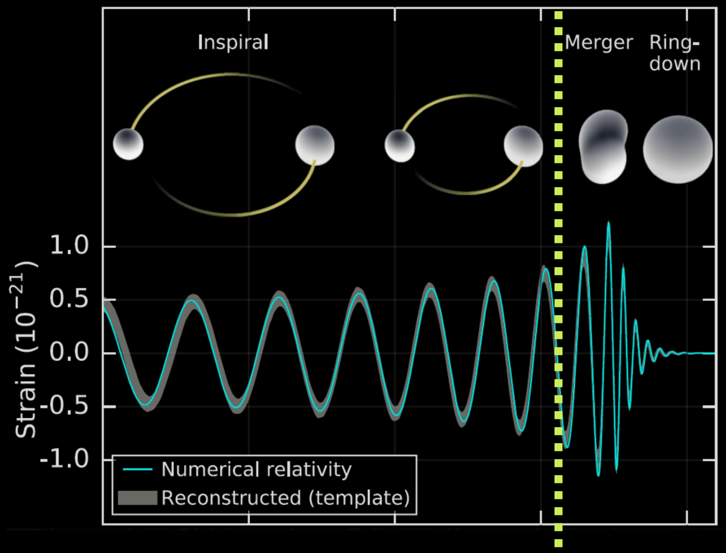


Image credit: LIGO

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

So what about Dark Matter?

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

What can we learn from individual waveforms?*

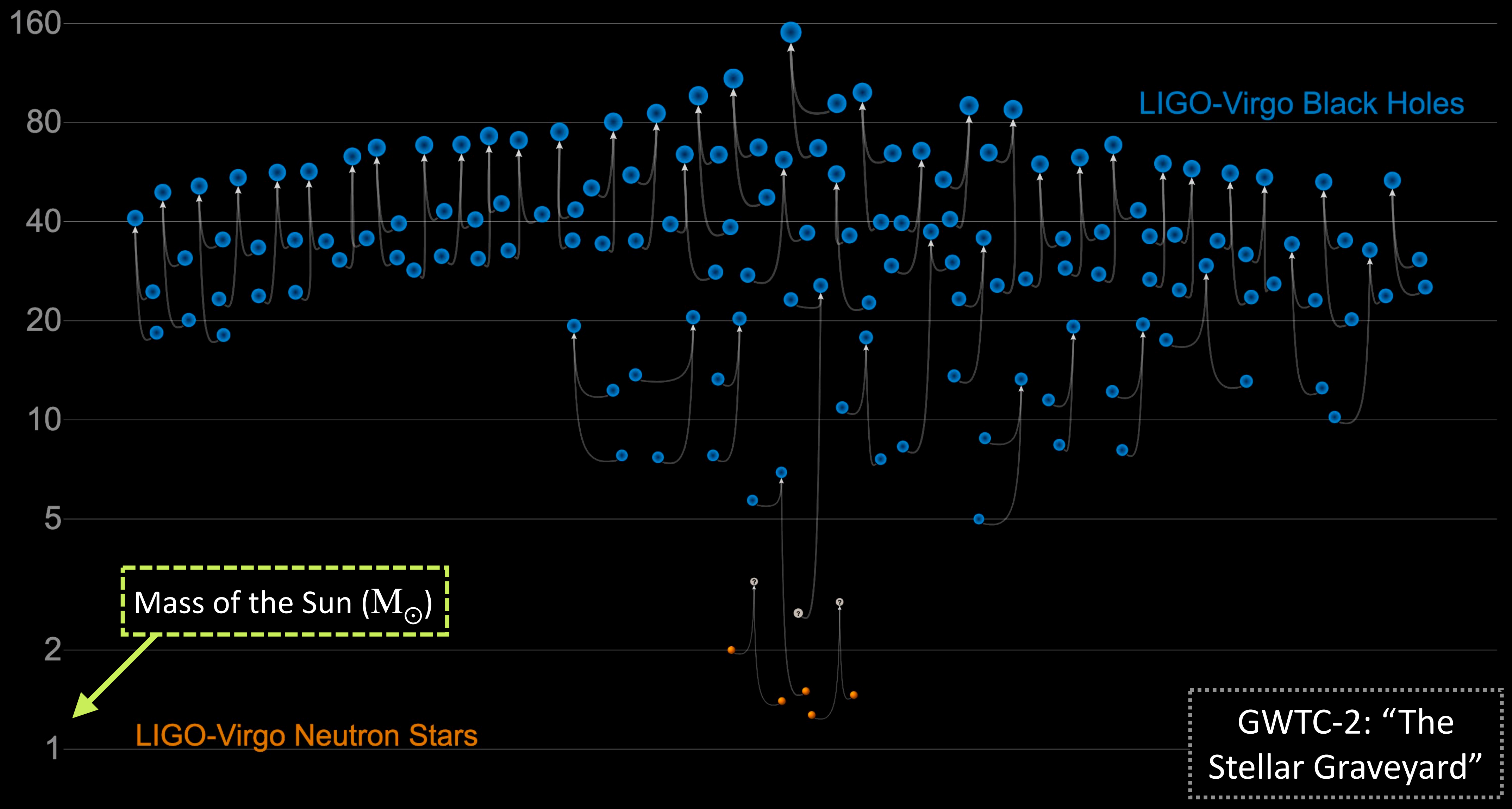
A lot, for example,

DM examples:

1.	Component masses	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) from multi-messenger signals (or absence thereof)*

Binary mergers in LIGO/Virgo O1-3a



Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

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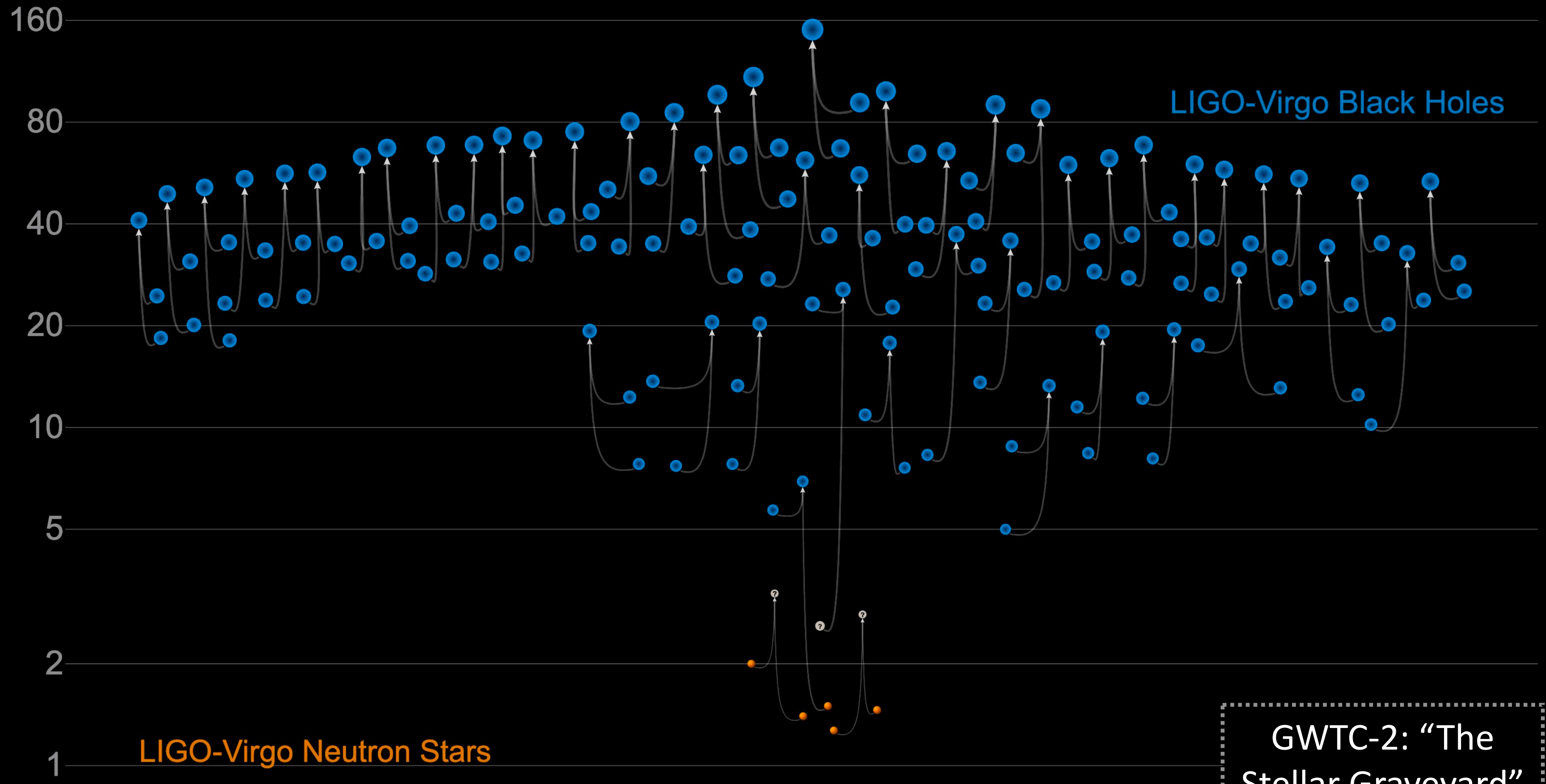
What can we learn from population analysis?



GWTC-2: “The Stellar Graveyard”

Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

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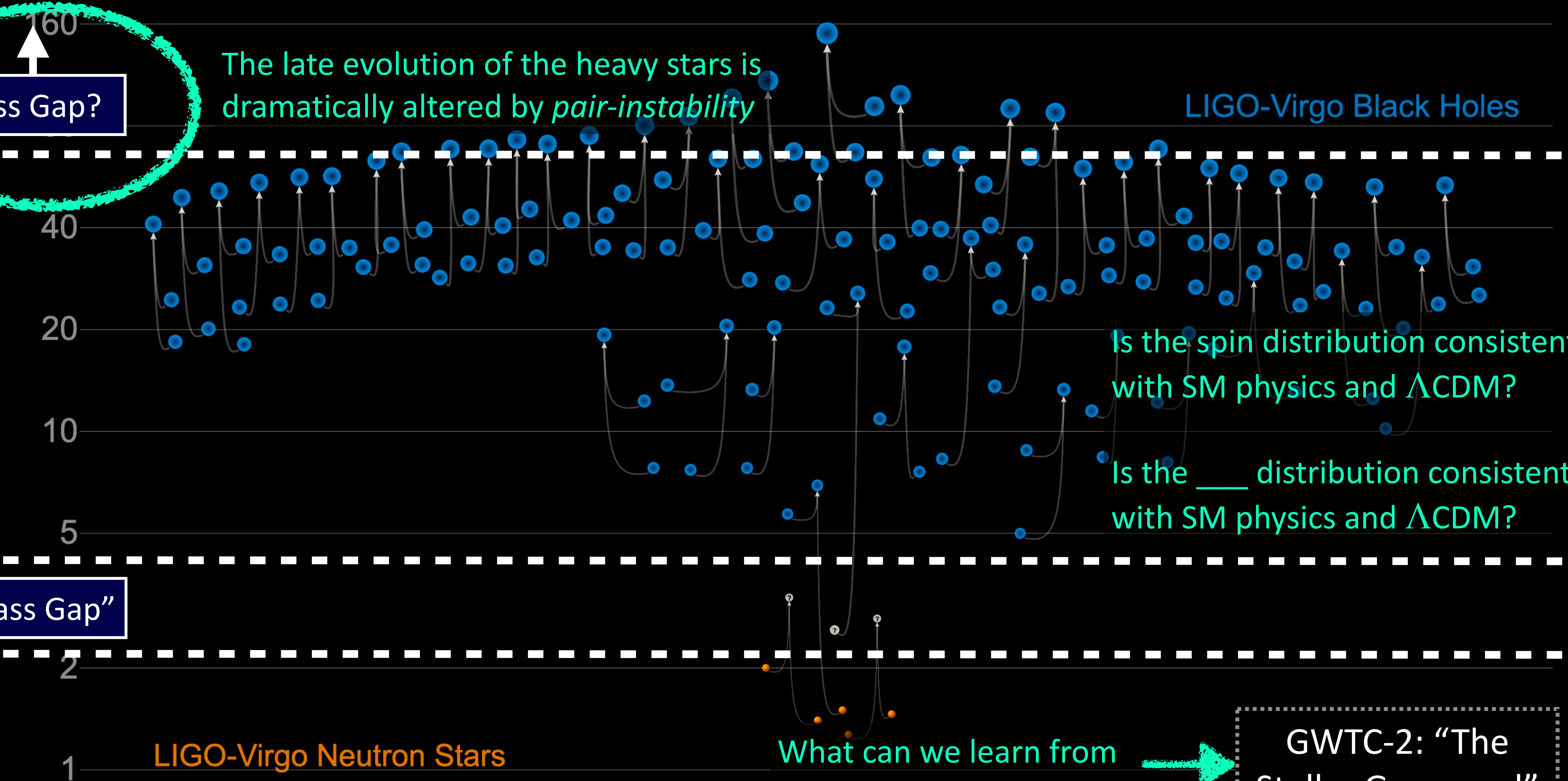


Mass Gap?

The late evolution of the heavy stars is dramatically altered by *pair-instability*

Is the spin distribution consistent with SM physics and ΛCDM?

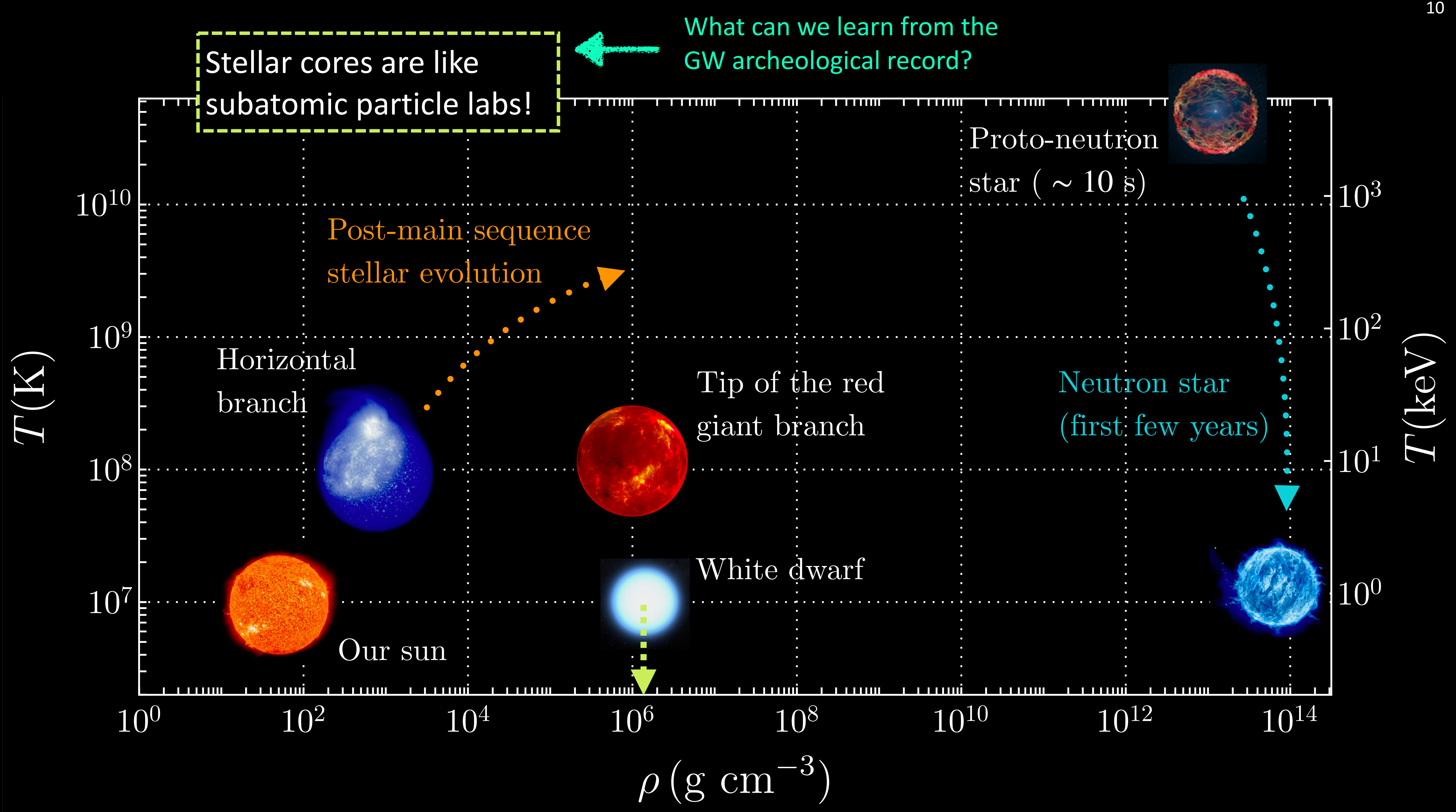
Is the ___ distribution consistent with SM physics and ΛCDM?

"Mass Gap"

What can we learn from this archeological record?

GWTC-2: "The Stellar Graveyard"

Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller


Stellar cores are like subatomic particle labs!
What can we learn from the GW archeological record?
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(K)
T(keV)
ρ (g cm^−3)
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

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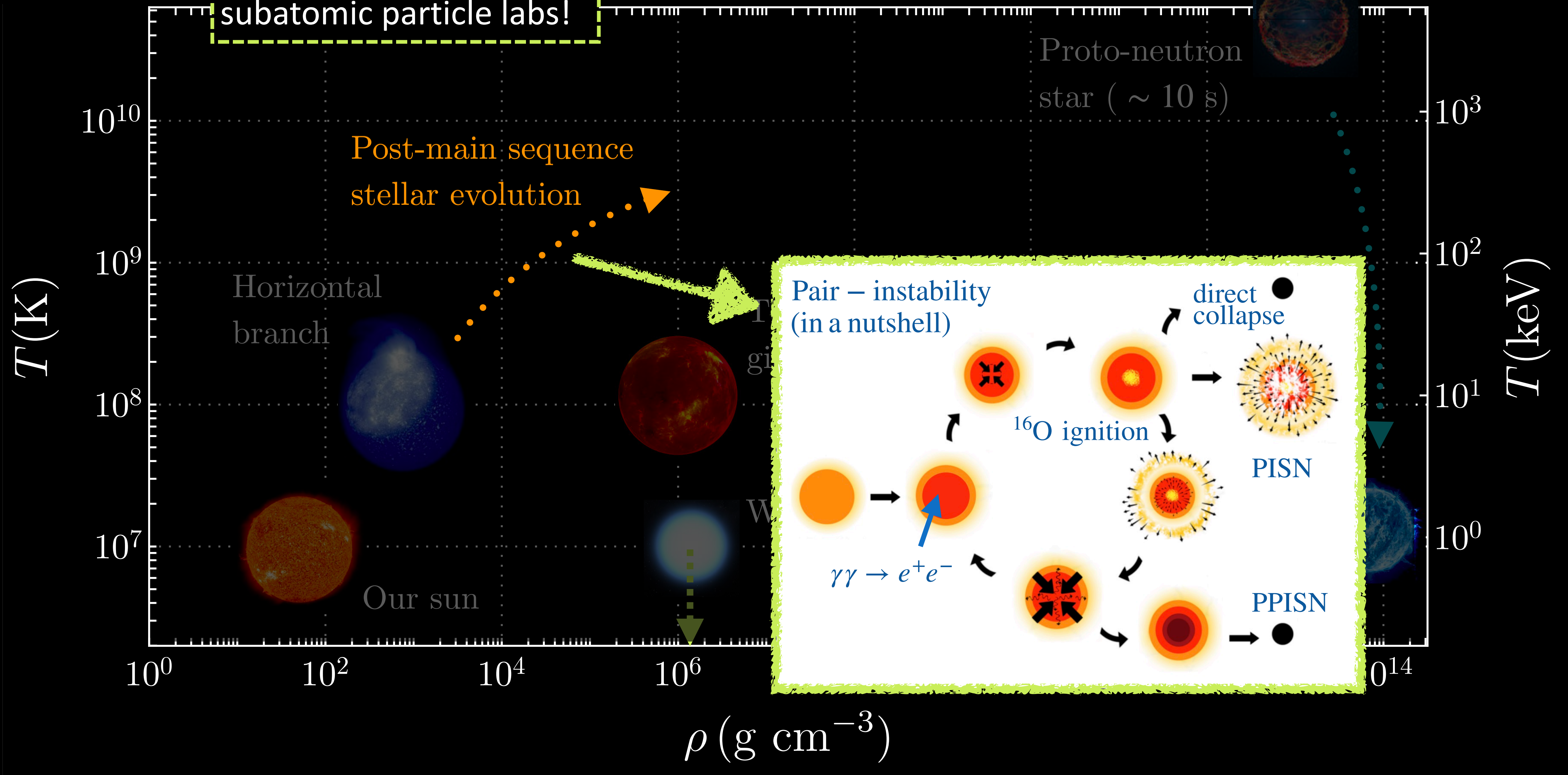
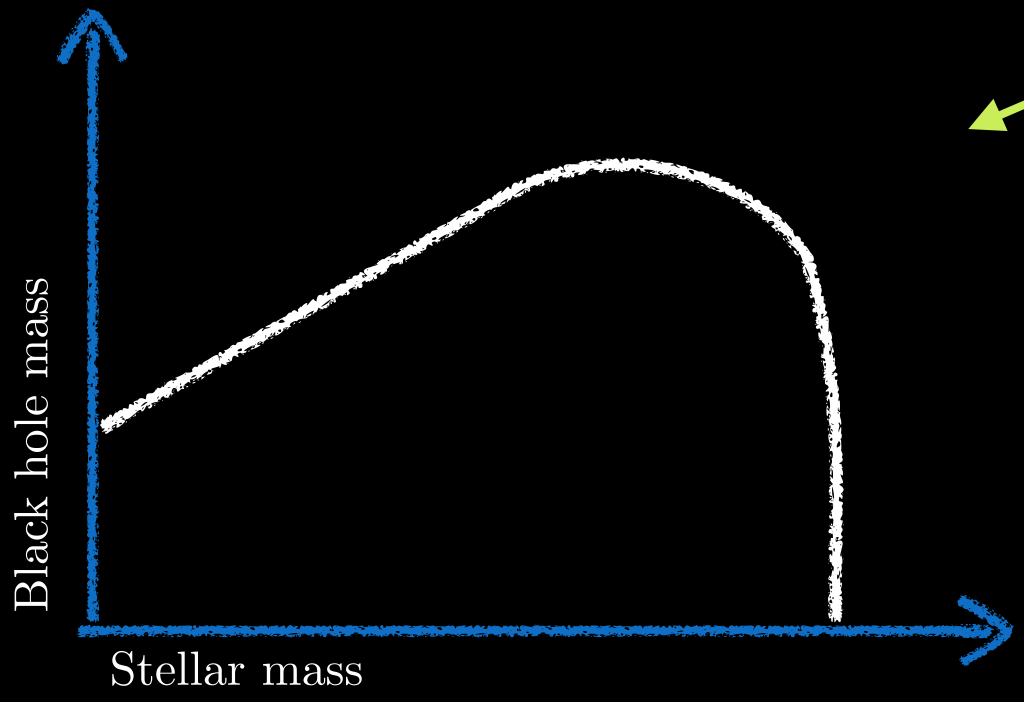
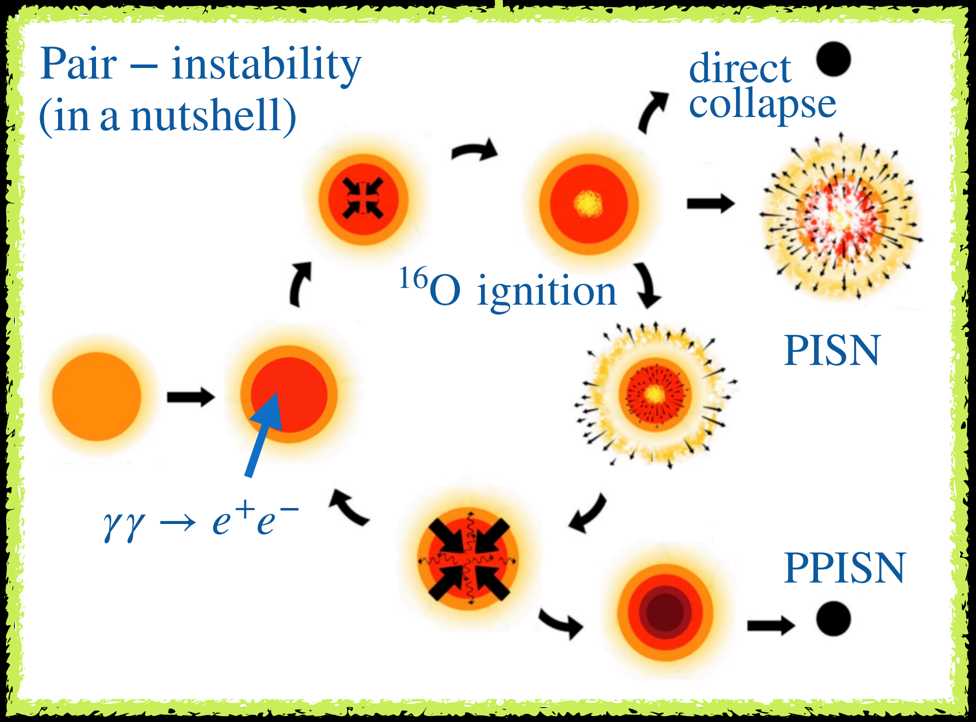
What can we learn from the GW archeological record?



Pair-instability and black hole populations

We can predict black hole masses using stellar evolution simulations





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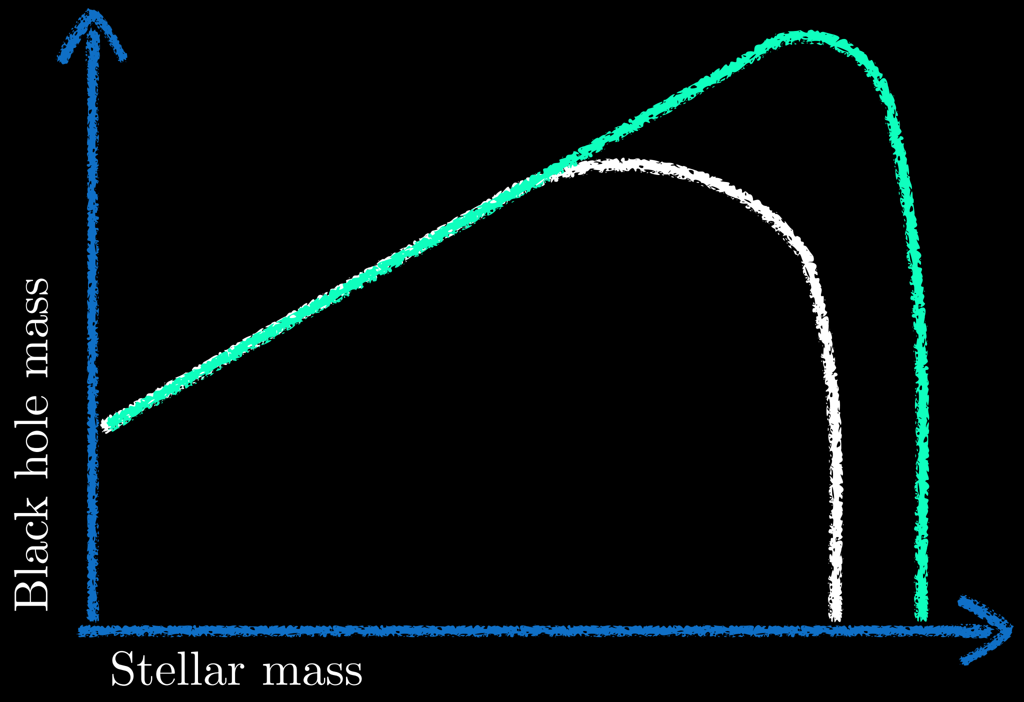


We can predict black hole masses using stellar evolution simulations

New particles, dark matter, or different nuclear physics 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]

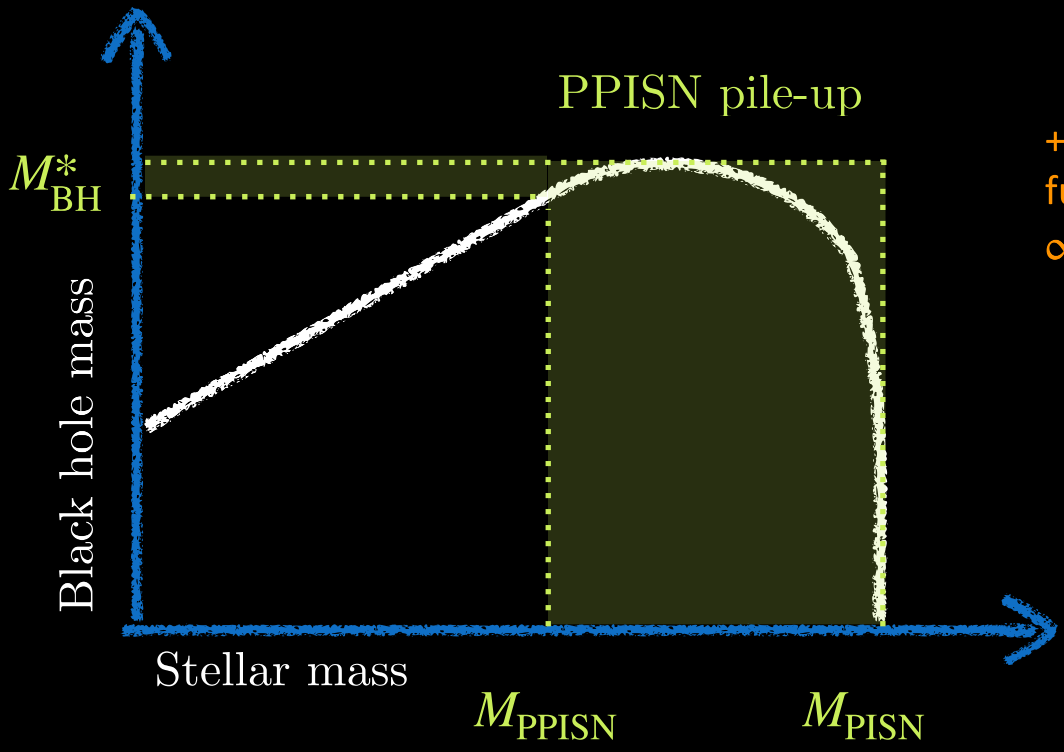
Sakstein, DC, McDermott, Straight, Baxter, PRL, arXiv:2009.01213 [gr-qc]

Ziegler, Freese arXiv:2010.00254 [astro-ph]

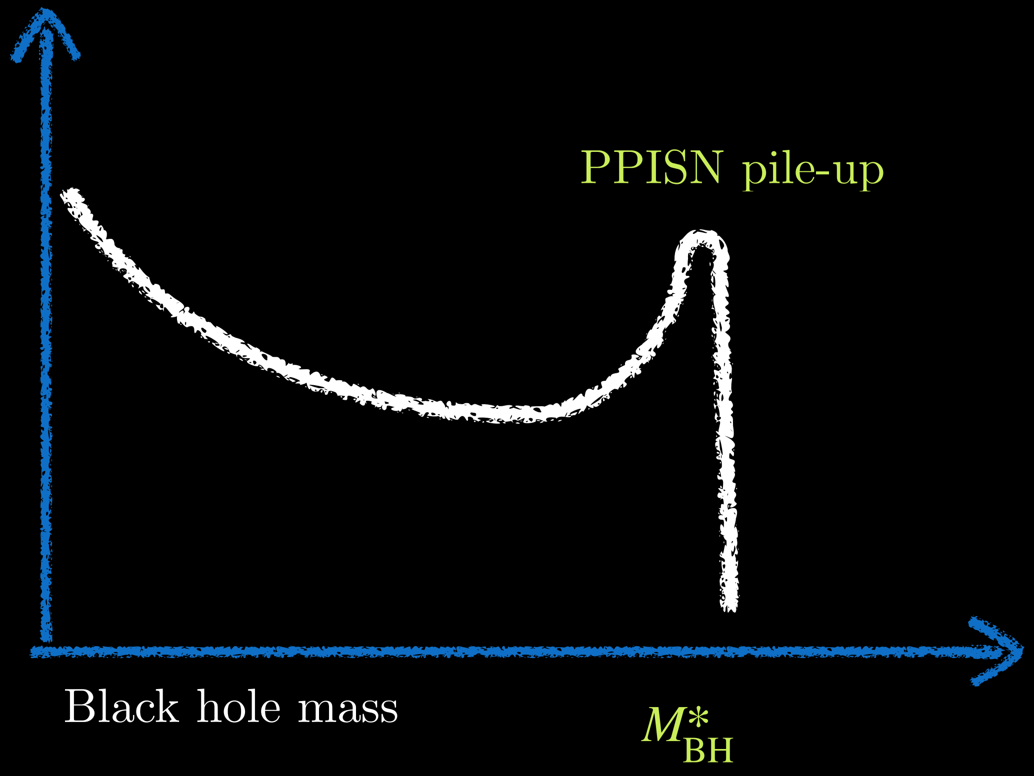
…More work in progress

Pair-instability and black hole populations

From stellar evolution simulations to gravitational wave data analysis



+ Initial mass function (here ∝ power law)



See also Talbot & Trane, arXiv:1801.02699

FIND THE GAP

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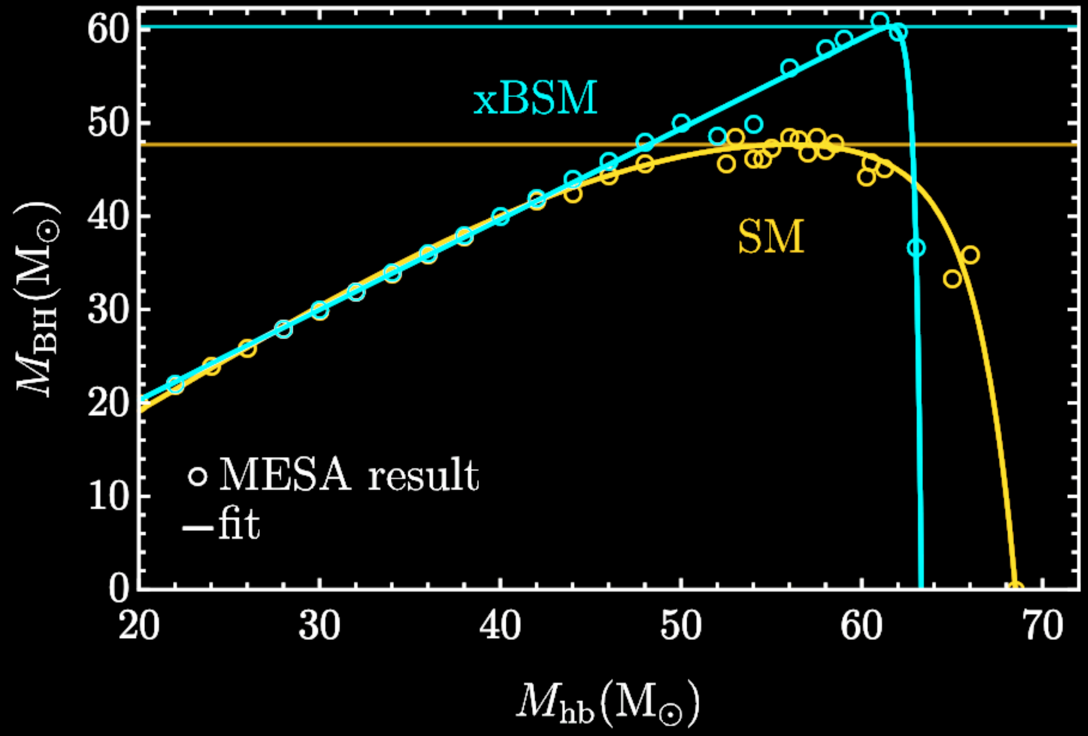

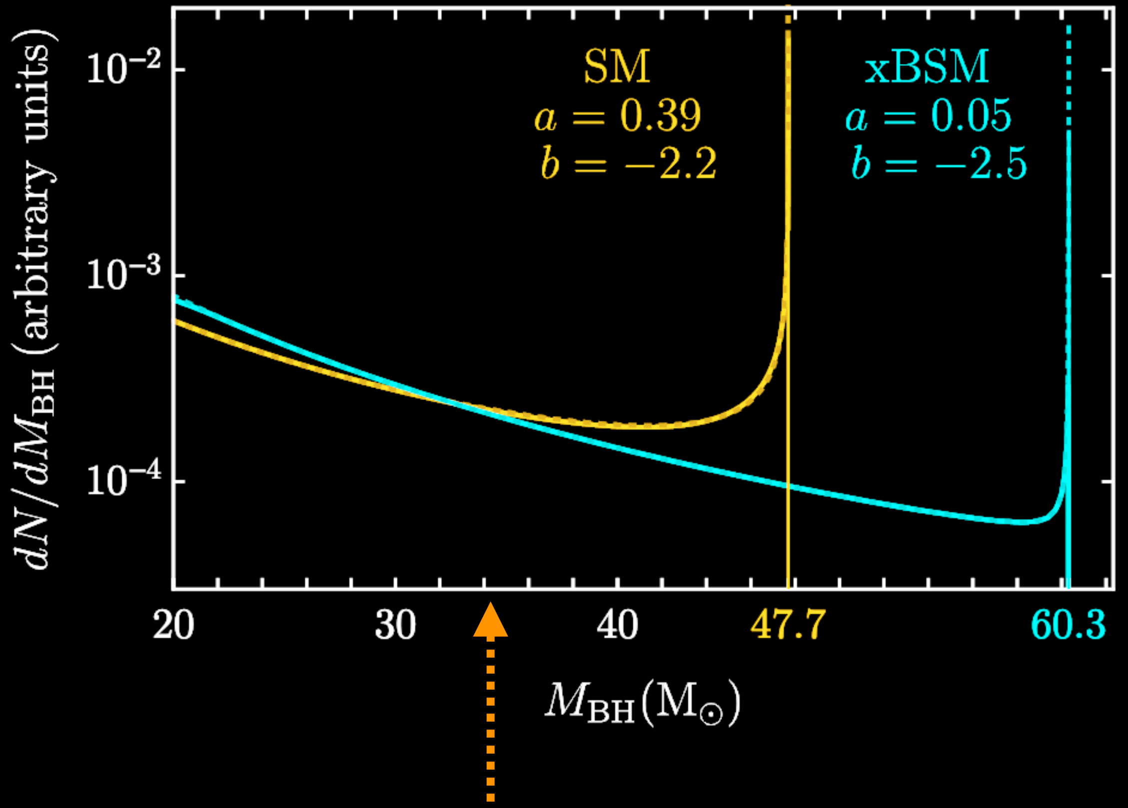

Currently, the data prefers a feature here

...and at $M_{BH} \sim 60 - 75\,M_\odot$

Baxter, DC, McDermott, Sakstein, arXiv:2104.02685

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Unprecedented access to "dark" masses and environments
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Unprecedented access to the most interesting cosmological era
- Events involving significant energy
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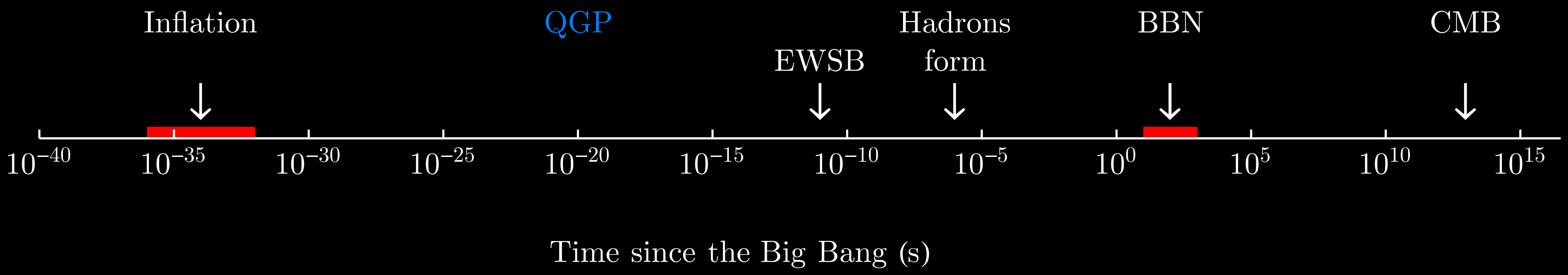
→ Example: $1^{\rm st}$ order phase transitions

Our cosmic timeline

The first second of our Universe yields the answer to big open questions

- Grand Unification of gauge forces?
- Dark Matter production, mass mechanism, and abundance?
- Solution to the strong-CP problem?
- Explanation of the matter-antimatter asymmetry?



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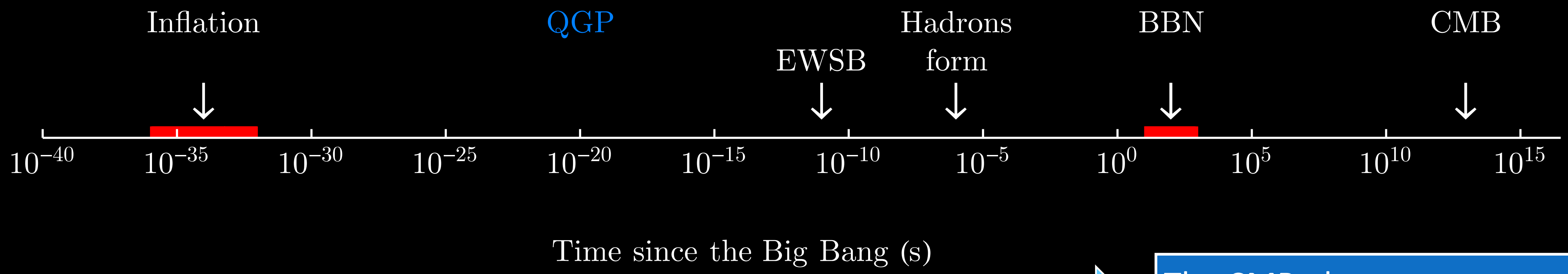


During this second, the Universe was opaque to photons

The CMB photons constitute our earliest *direct* cosmological probe

Gravitational waves released in the Early Universe travel unimpeded until today

Phase transitions in the early Universe

Form a key part of many proposed answers

To generate the baryon asymmetry, you must have...

- Baryon number (B) violation
- Charge (C) and Charge-Parity (CP) violation
- Out of (thermal) equilibrium reactions

  So baryogenesis is irreversible ← 1^{st} order phase transitions!

In a dark sector

Dark gauge symmetry breaking along a relatively flat scalar direction with many coupled DOF gives first order phase transitions

DC, V. Sanz and G. White [JHEP, arXiv:1806.02332]

In particular models of quark confinement / chiral symmetry breaking

$\mathrm{SU(N_f)\times SU(N_f)\rightarrow SU(N_f)}$ where $N_f \geq 3$

e.g.DC, R. Houtz, and V. Sanz [JHEP, arXiv:1904.10967]
DC, J. Howard, S. Ipek, T. Tait [PRD, arXiv:1911.01432]

In a (non-SUSY) GUT

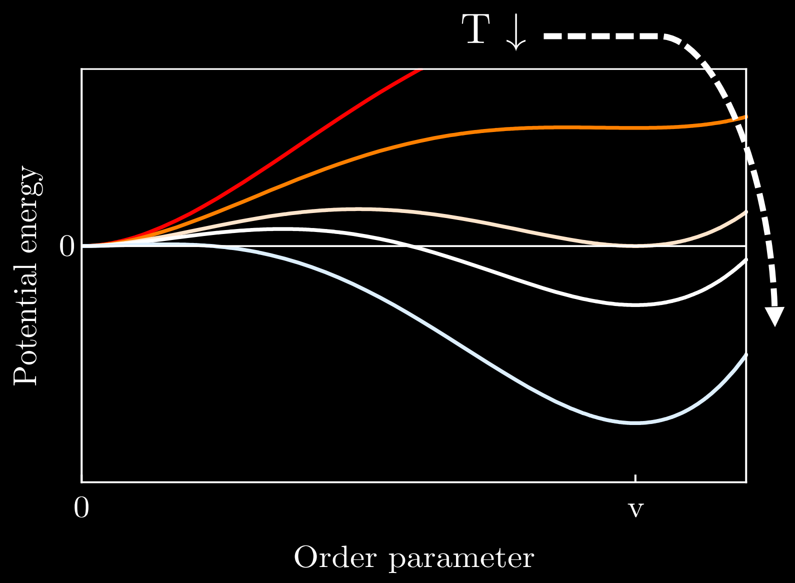
Consecutive intermediate breaking scales, first order phase transition for relatively flat scalar directions and large portal couplings

e.g. DC, T. Gonzalo, G. White [JHEP, arXiv:1812.02747]

Phase transitions in the early Universe

Predict a stochastic gravitational wave background

First order phase transitions are described by tunneling through a potential barrier



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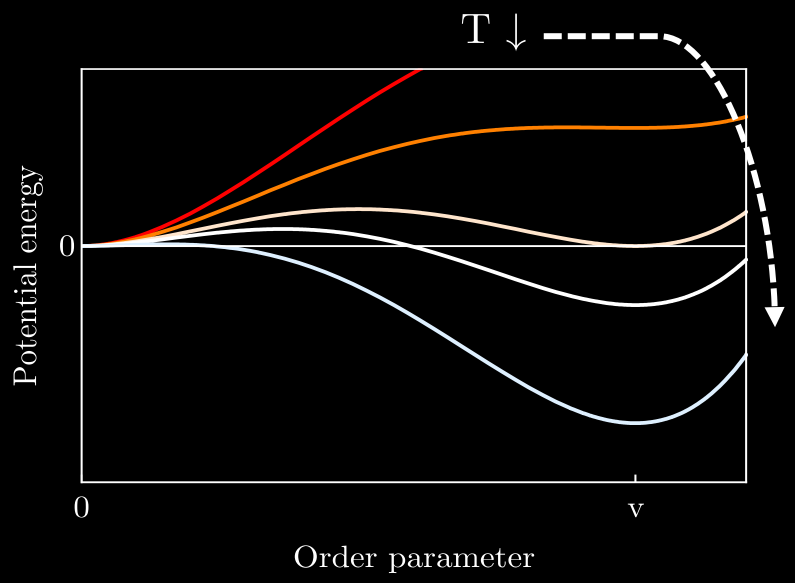
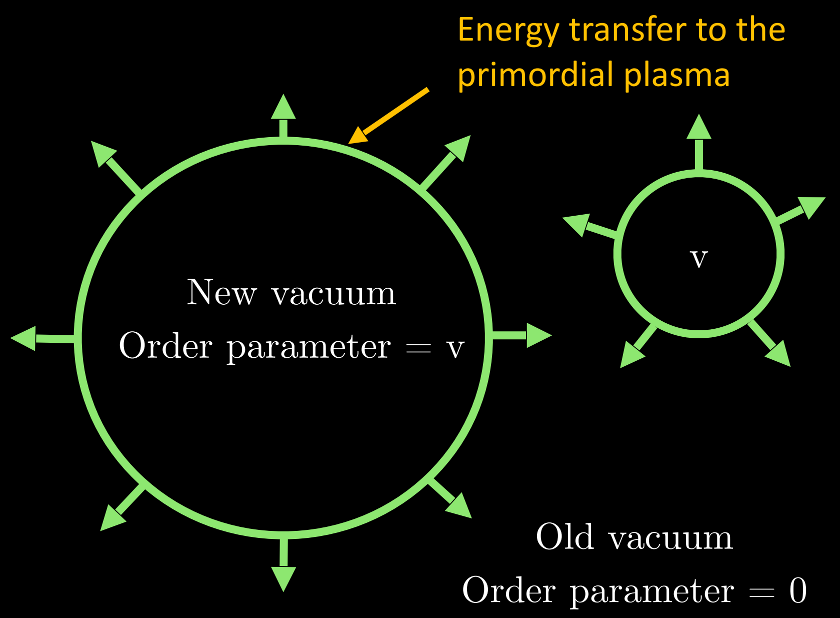


Bubbles nucleate, expand, and interact with the plasma;
Bubble and plasma shell collisions source GWs



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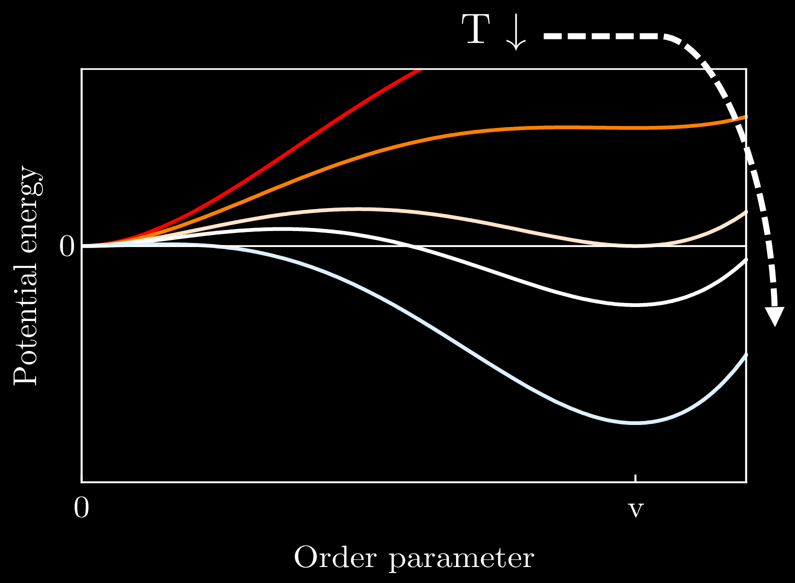

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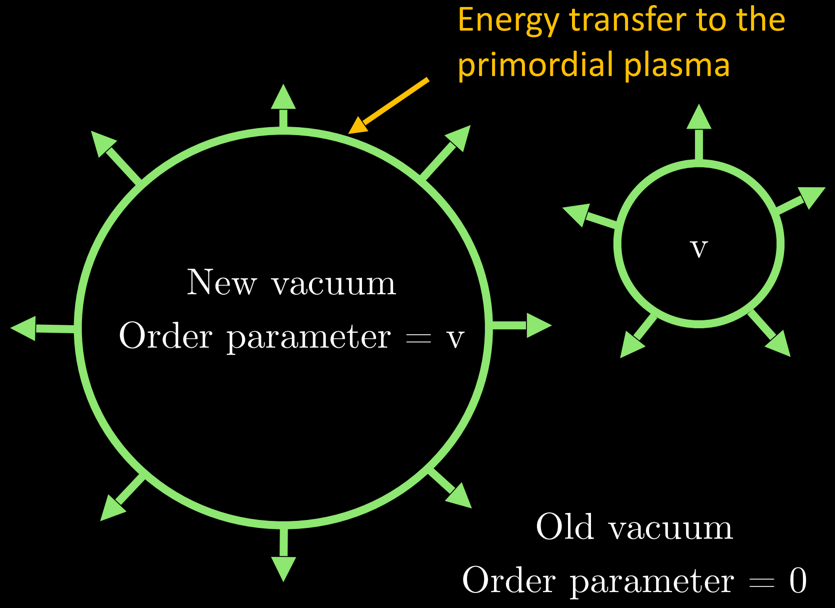
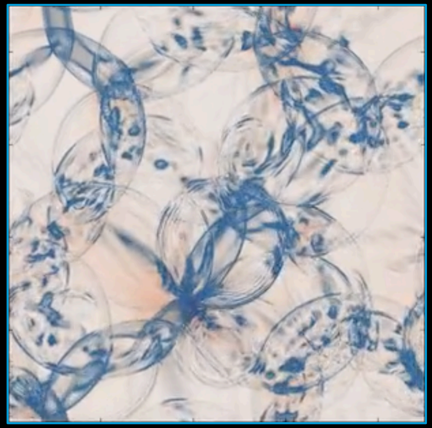


Simulations relate thermal parameters to GW spectra



Snapshot from simulation: Daniel Cutting, private communication

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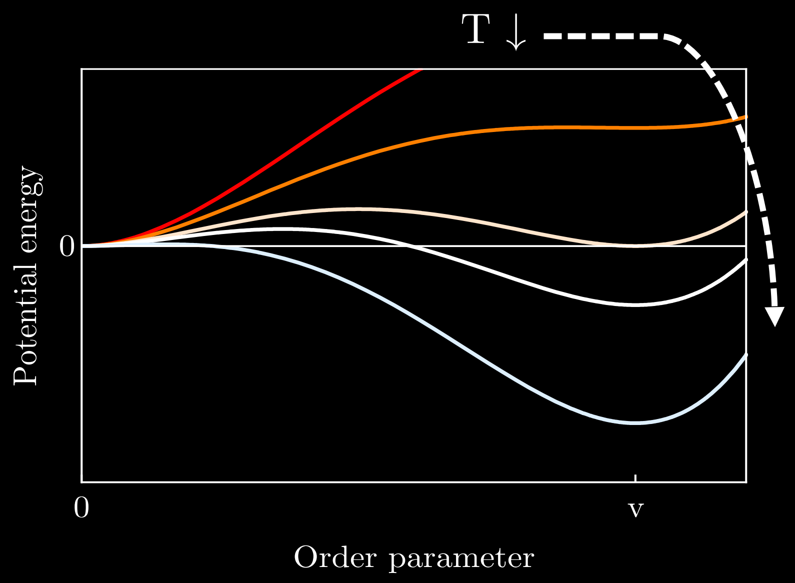
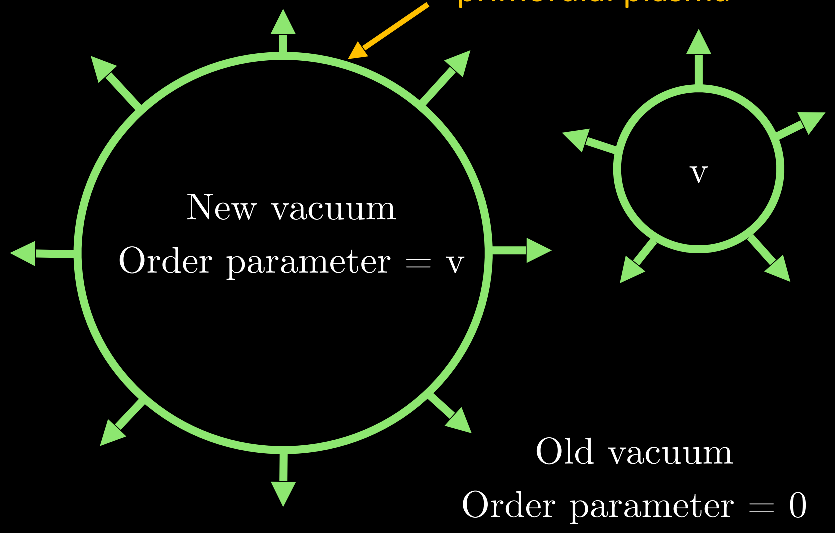


Significant theoretical uncertainties → SGWB amplitude and frequency

(see DC, O. Gould, T. Tenkanen, P. Schicho, G. White JHEP, arXiV: 2009.10080)

Bubbles nucleate, expand, and interact with the plasma; Bubble and plasma shell collisions source GWs



Bubble wall velocity and friction → most important GW source

Timescale onset of non-linear plasma dynamics → SGWB amplitude

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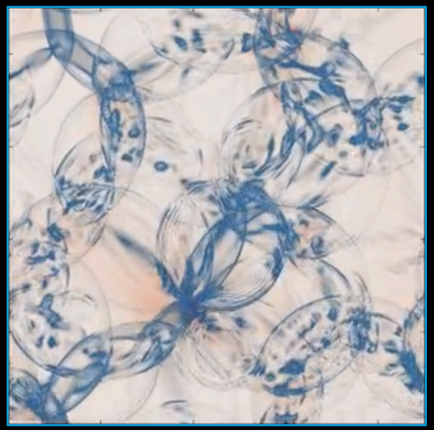

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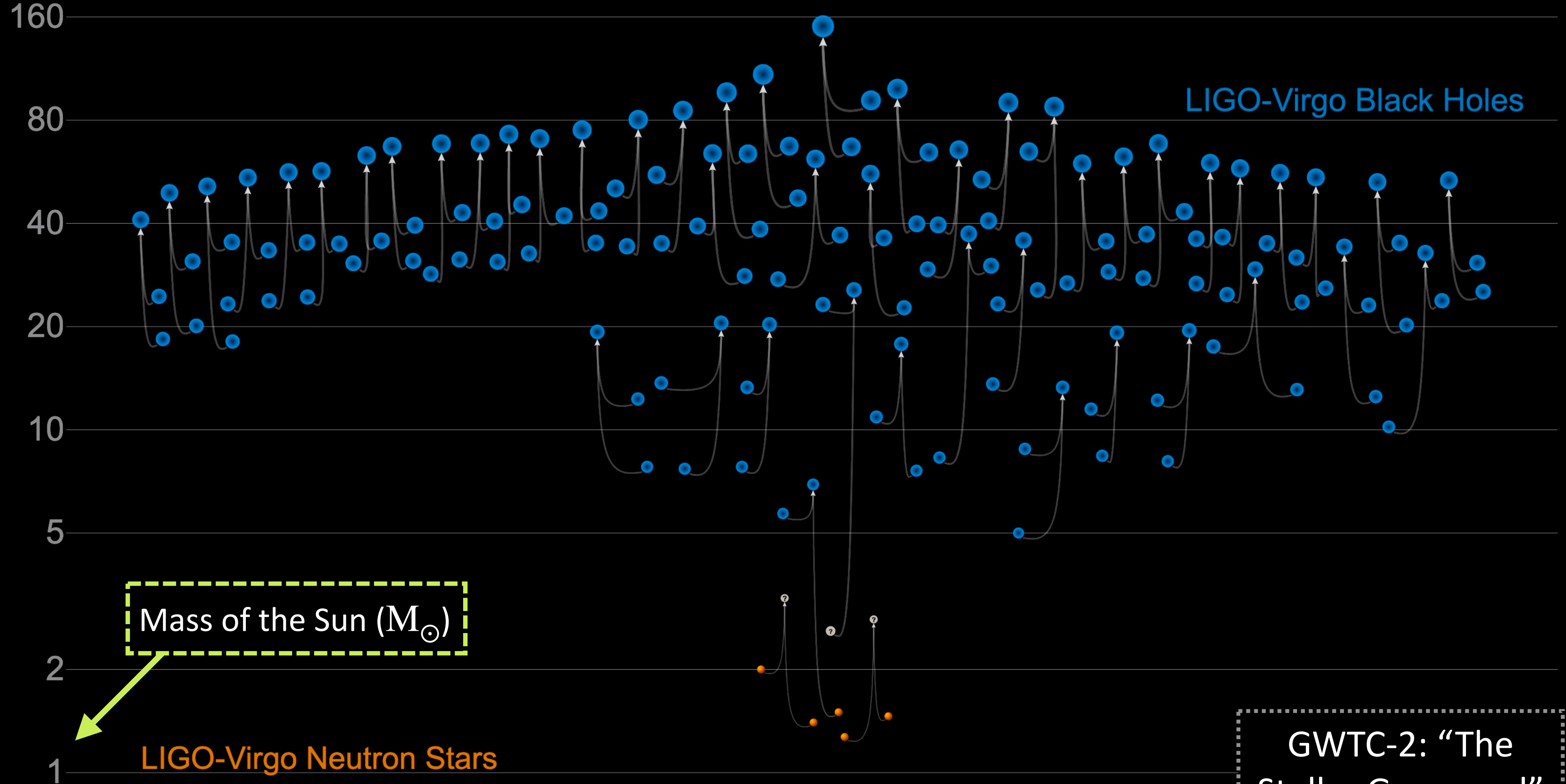

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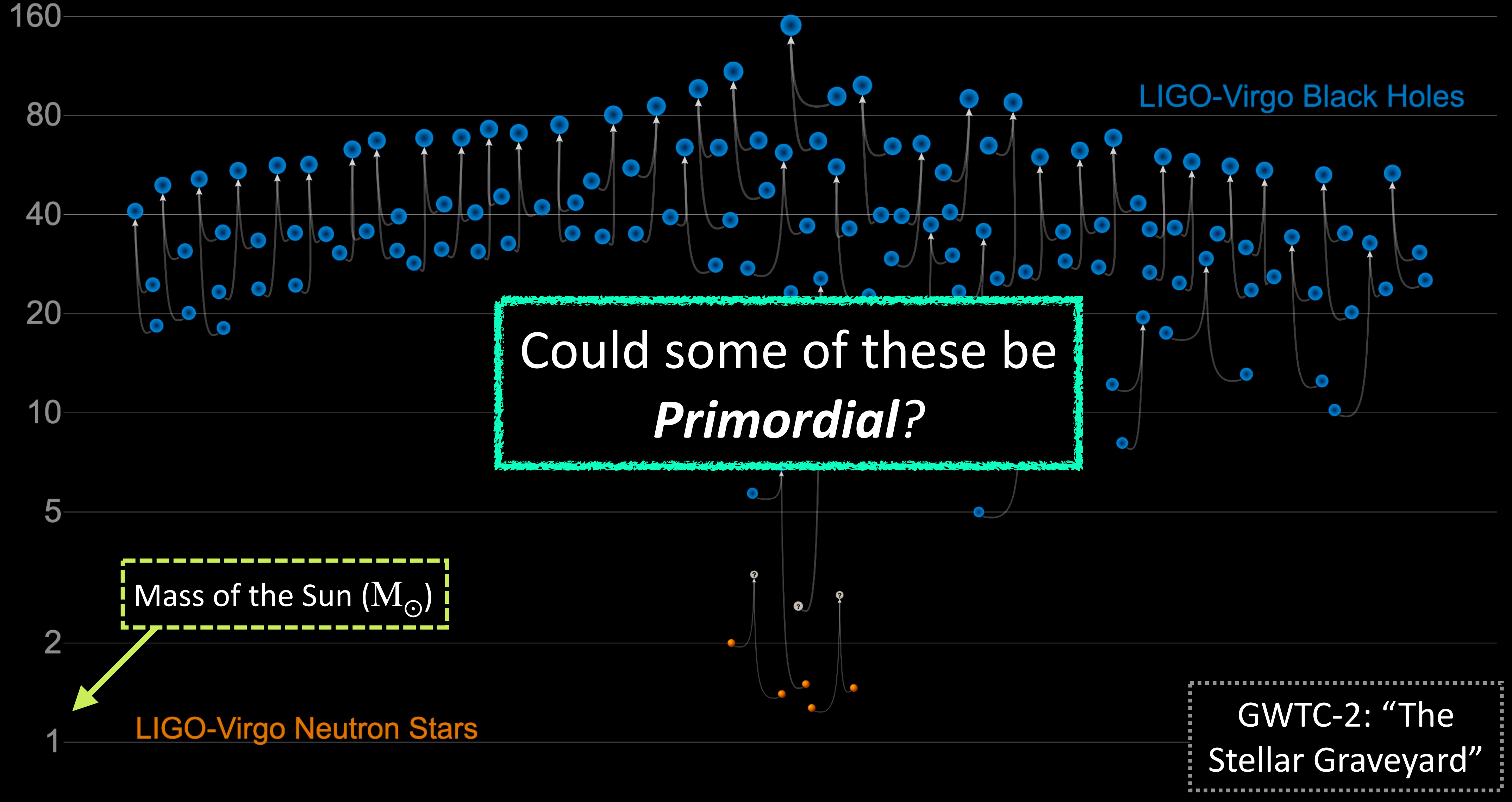

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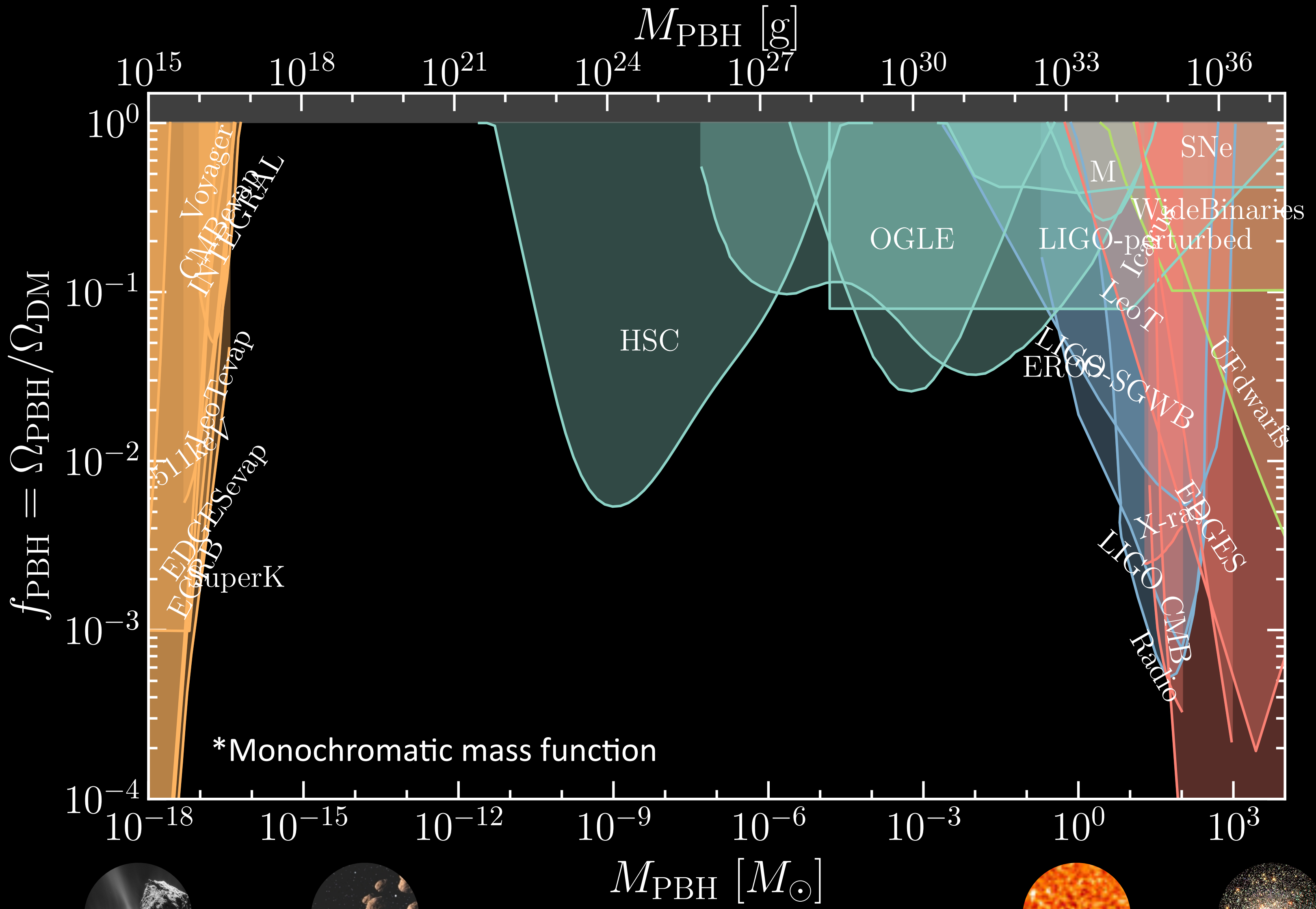
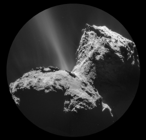
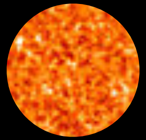
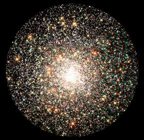
PBH Constraints

[Green & BJK, 1709.06576]
[Code online: github.com/bradkav/PBHbounds]





[Other reviews: 1801.05235, 2002.12778, 2006.02838]

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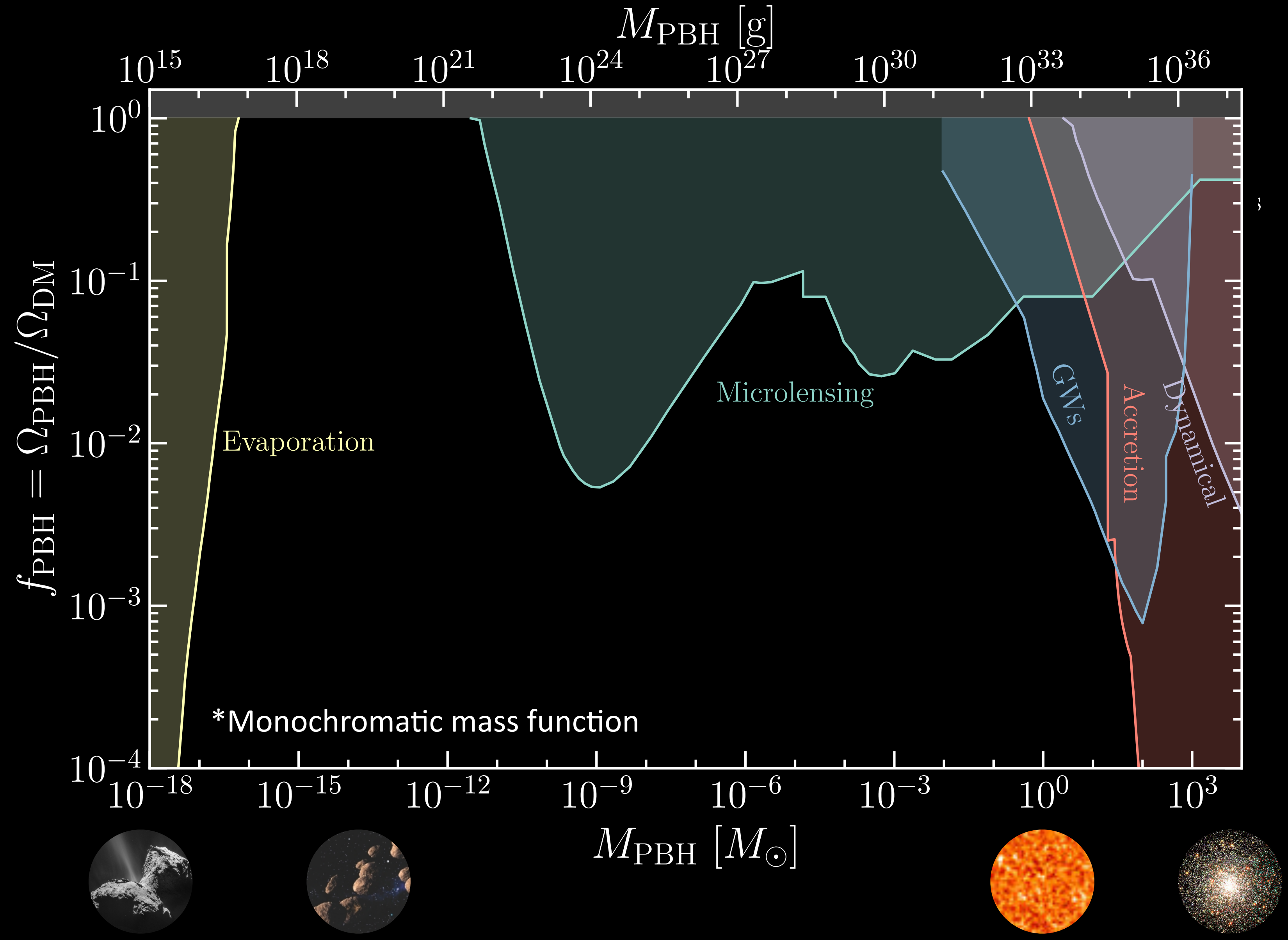

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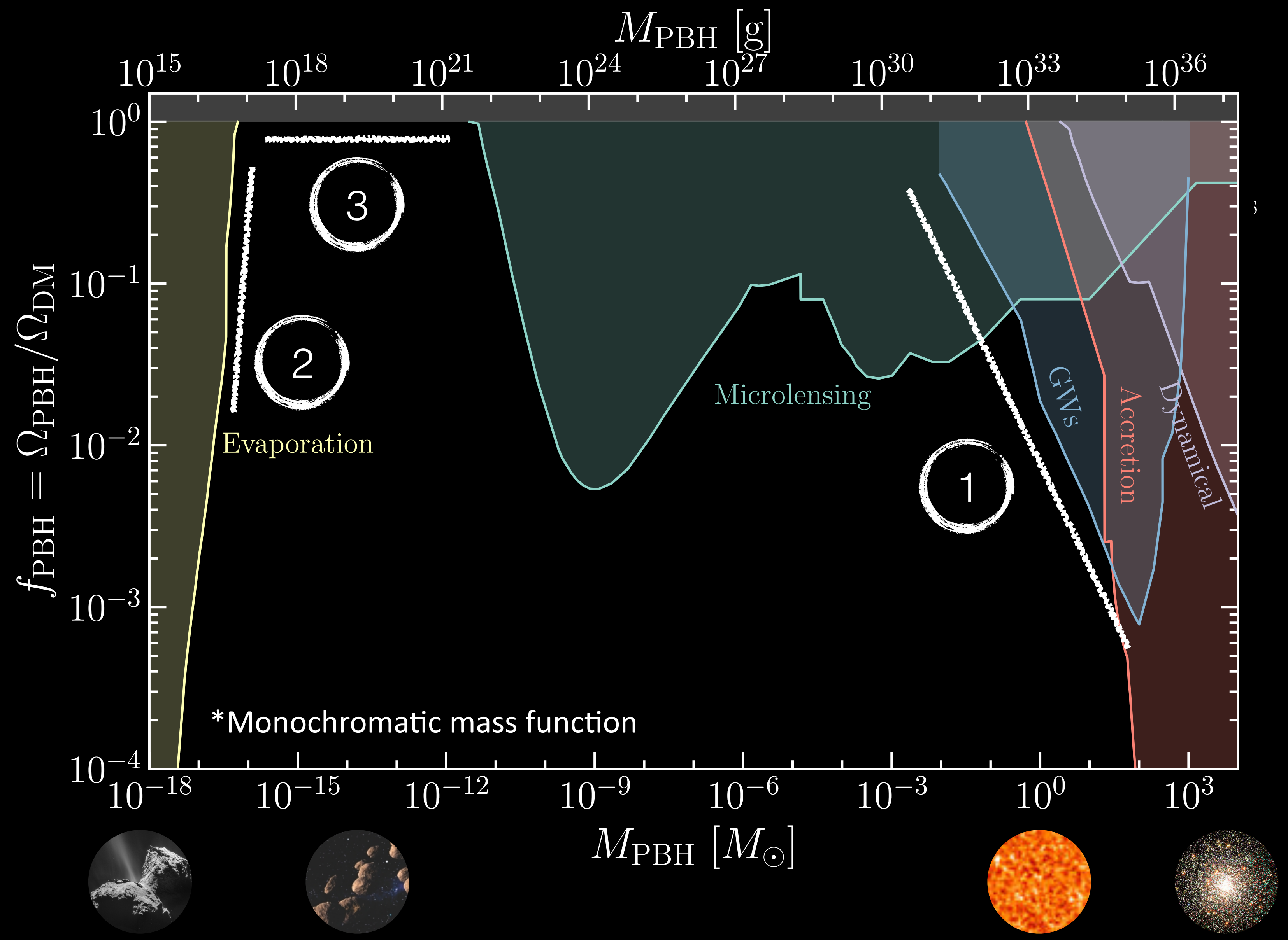

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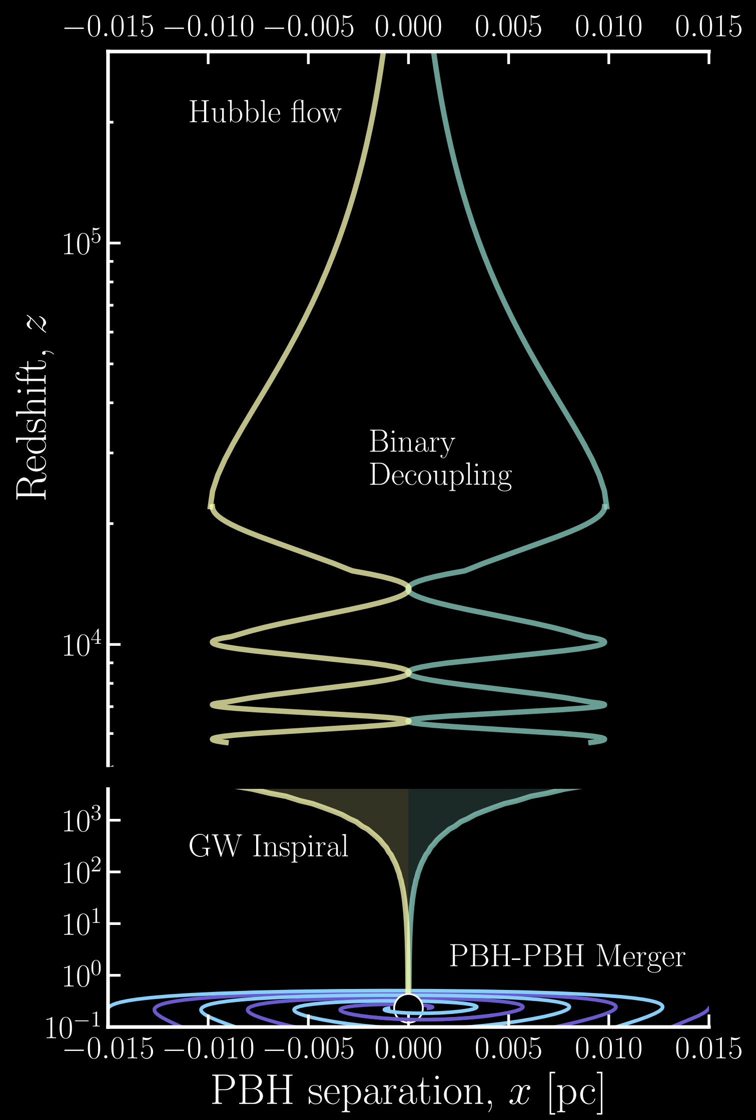
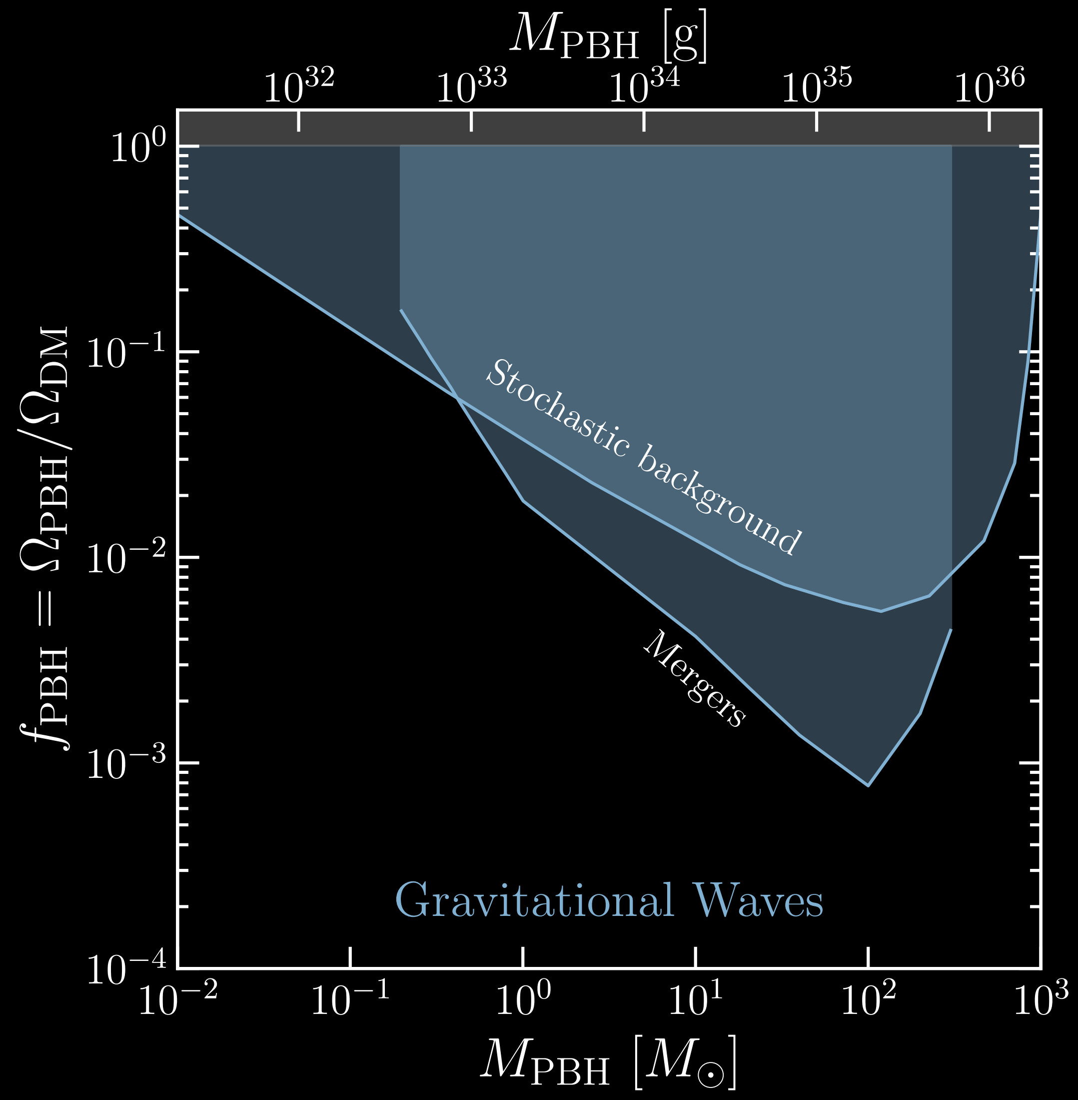
① GW Constraints on PBHs

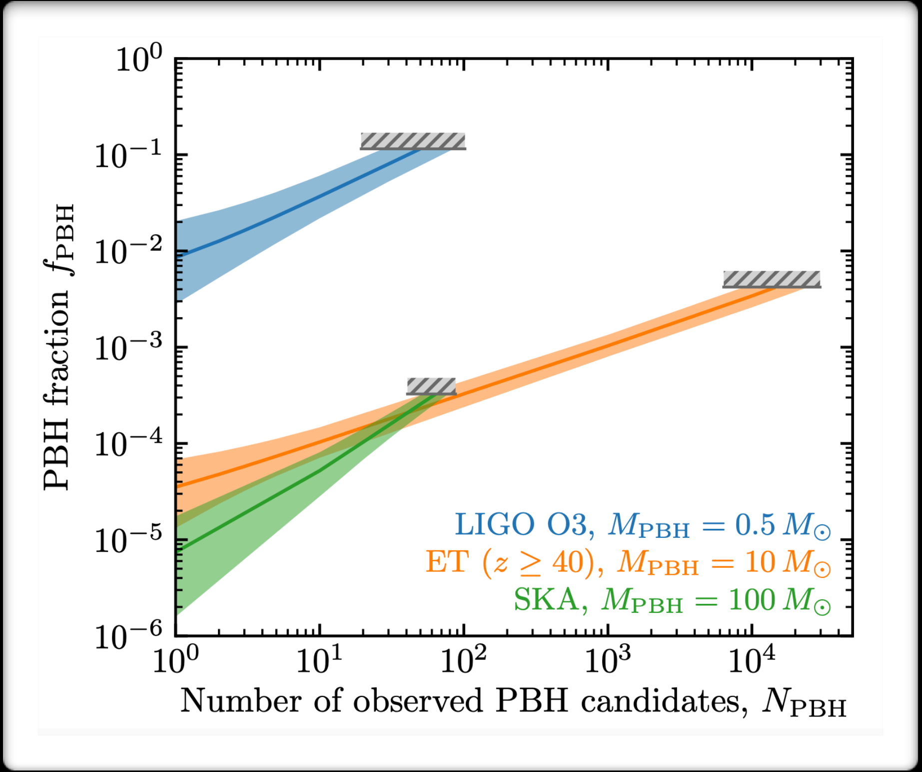
[Ali-Haïmoud+, 1709.06576;
BJK, Gaggero & Bertone, 1805.09034;
Chen & Huang, 1904.02396;
De Luca+, 2005.05641]





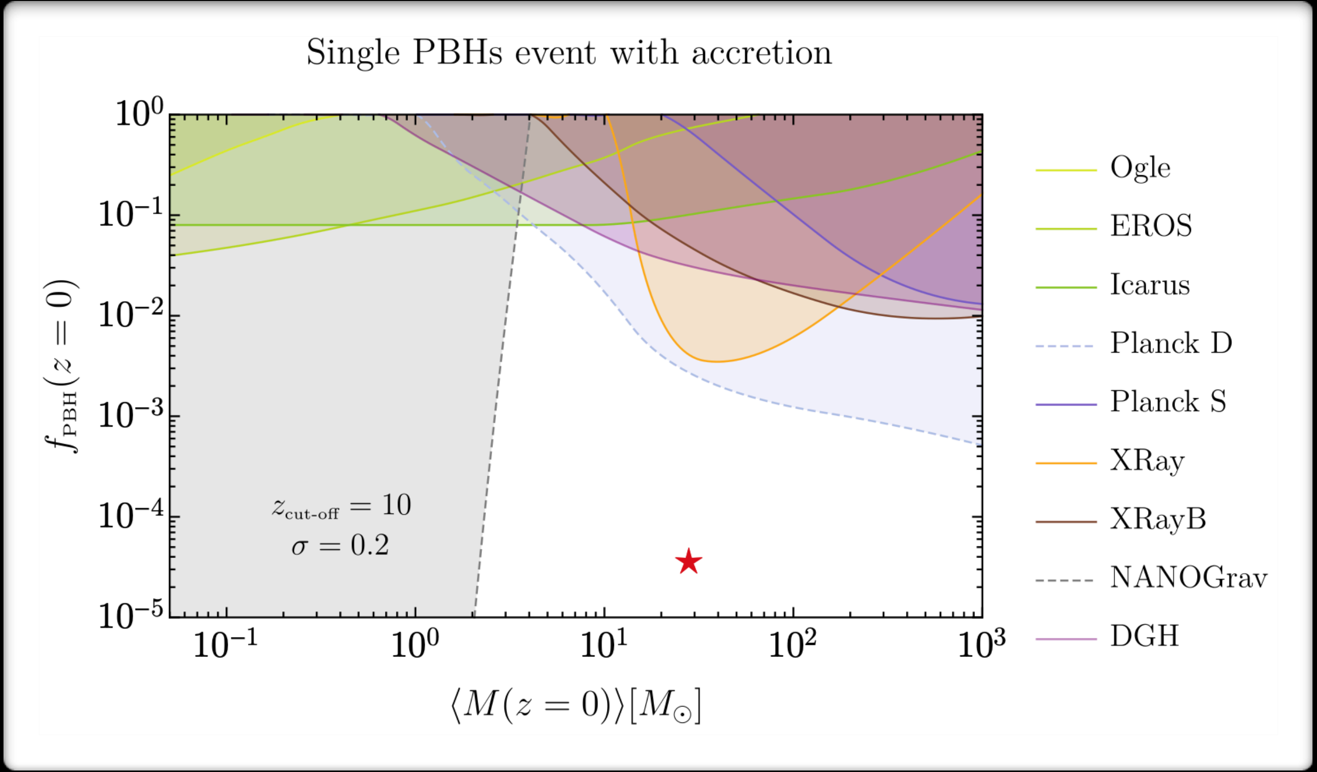
1 GWs, PBHs and unusual masses

Prospects for detecting light and heavy PBHs



[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

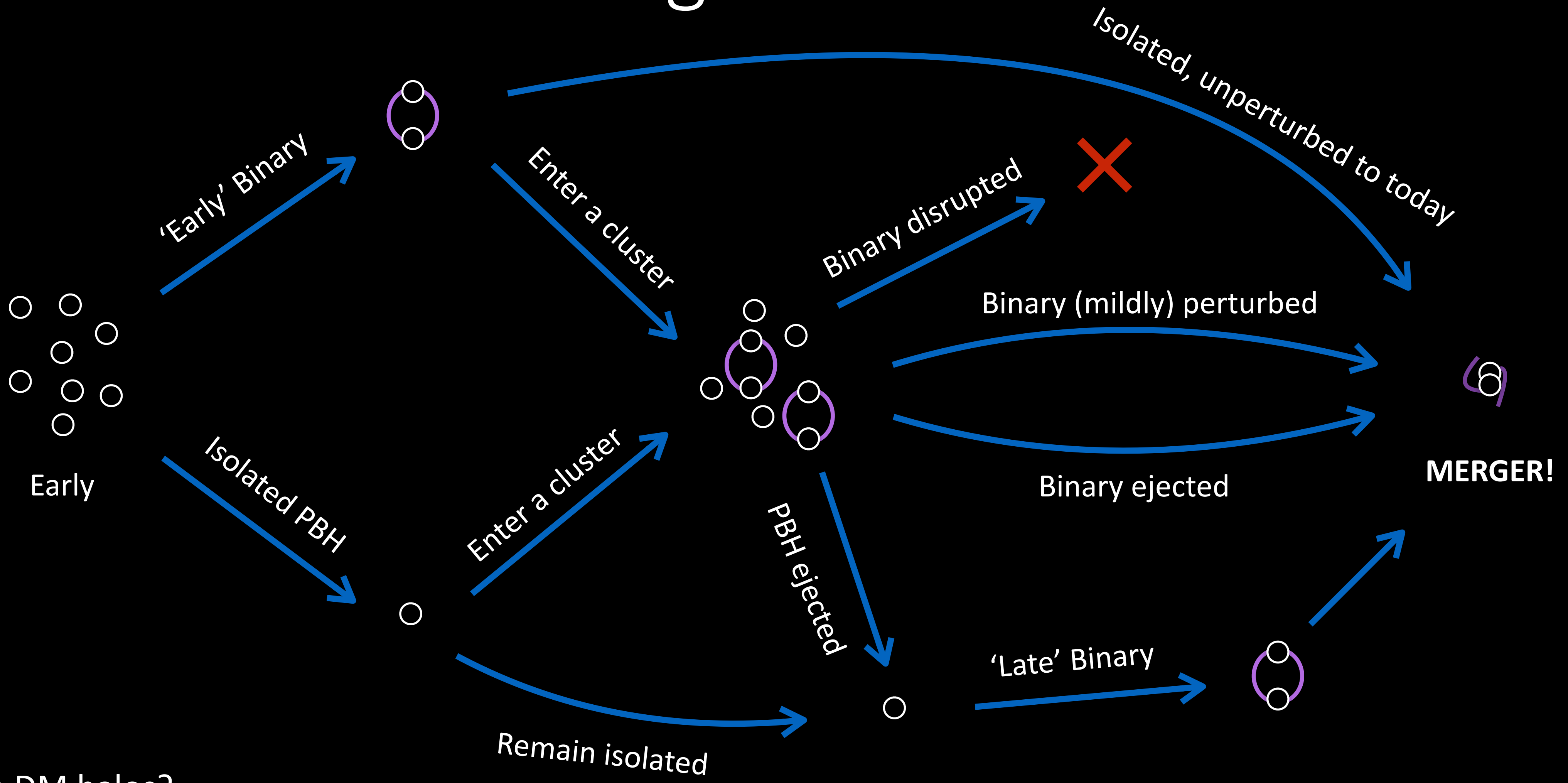
Interpreting the mass-gap event GW190521



[De Luca+, 2009.01728]

See also very recent 'global' analysis: [Franciolini et al., 2105.03349]

① Paths to PBH mergers

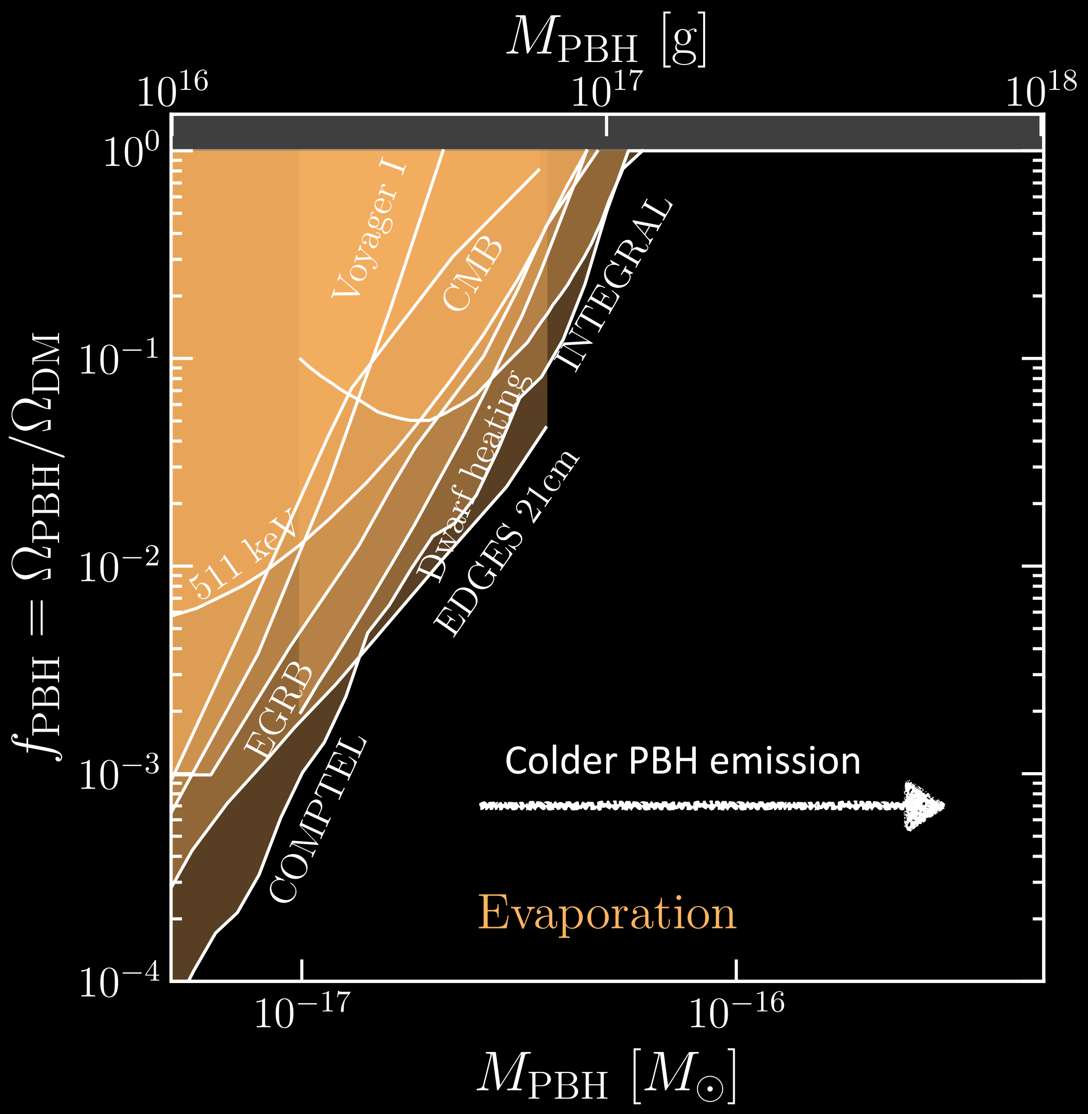


+ particle DM halos?
[**BJK**, Gaggero & Bertone, 1805.09034]

+ baryonic accretion?
[De Luca et al., 2003.12589]

[See e.g. Raidal+, 1812.01930; Vaskonen & Veermäe, 1908.09752; Atal+, 2007.07212; Jedamzik, 2007.03565; De Luca+, 2009.04731; Stasenko & Kirillov, 2103.10503]

② PBH Evaporation



$$T_H = (4\pi G_N M_{\rm PBH})^{-1}$$
$$\simeq 1\,{\rm MeV}\left(\frac{10^{16}\ {\rm g}}{M_{\rm PBH}}\right)$$
$$\tau(M) \simeq 200\,\tau_U \left(\frac{M}{10^{15}\ {\rm g}}\right)^3$$

Many interesting constraints from ‘old’ experiments, e.g.

Voyager I

[Boudaud & Cirelli, 1807.03075]

COMPTEL

[Coogan+, 2010.04797]

Strong synergy with Indirect Detection

3 Asteroid-mass PBHs

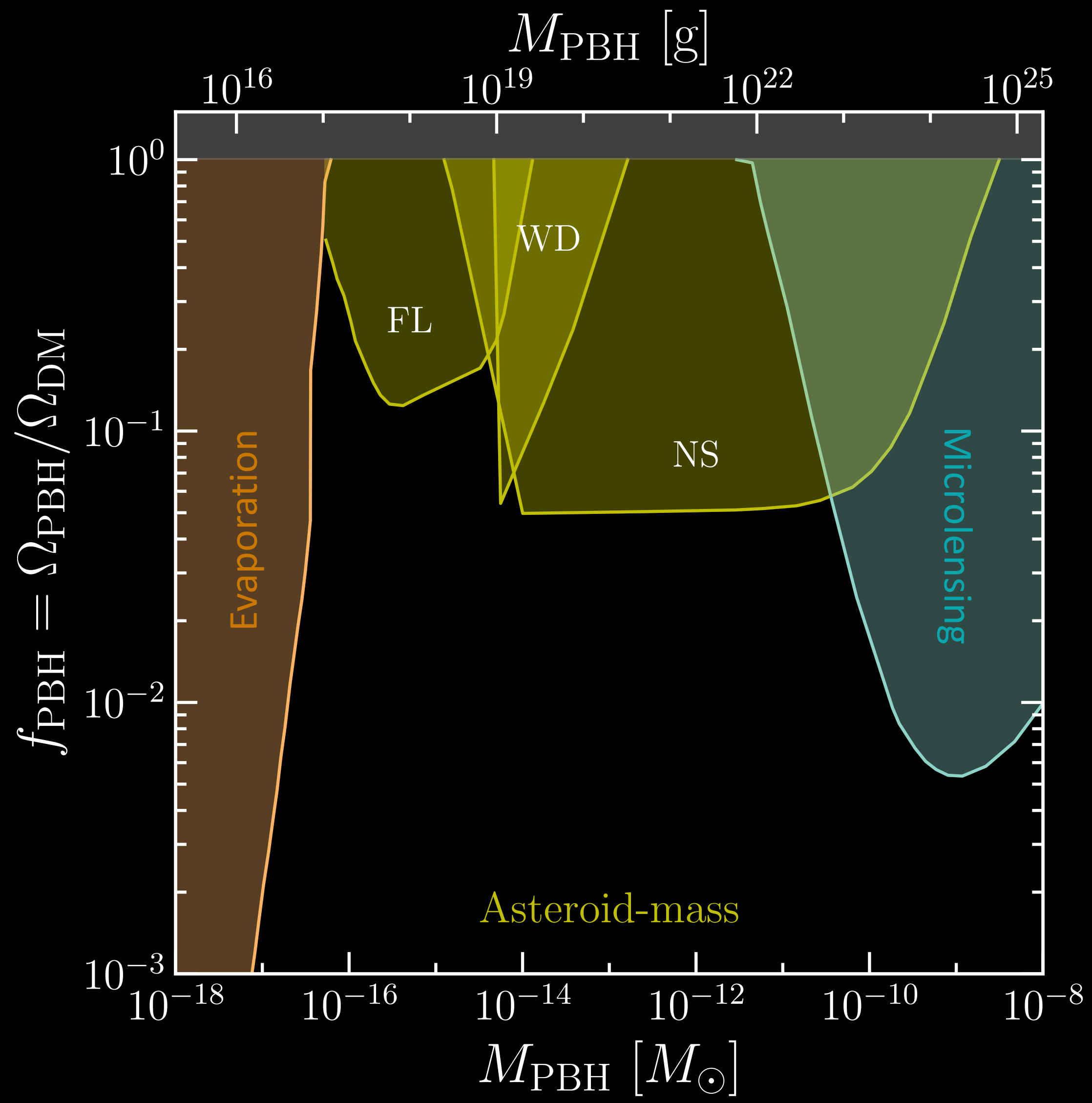
A few years ago this region was well-constrained…

'Femtolensing' of GRBs?

[Barnacka et al., 1204.2056]

PBH capture in compact objects (White Dwarfs/Neutron Stars)

[E.g. Graham et al., 1505.04444, Capela et al., 1301.4984]



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[Katz et al., 1807.11495]

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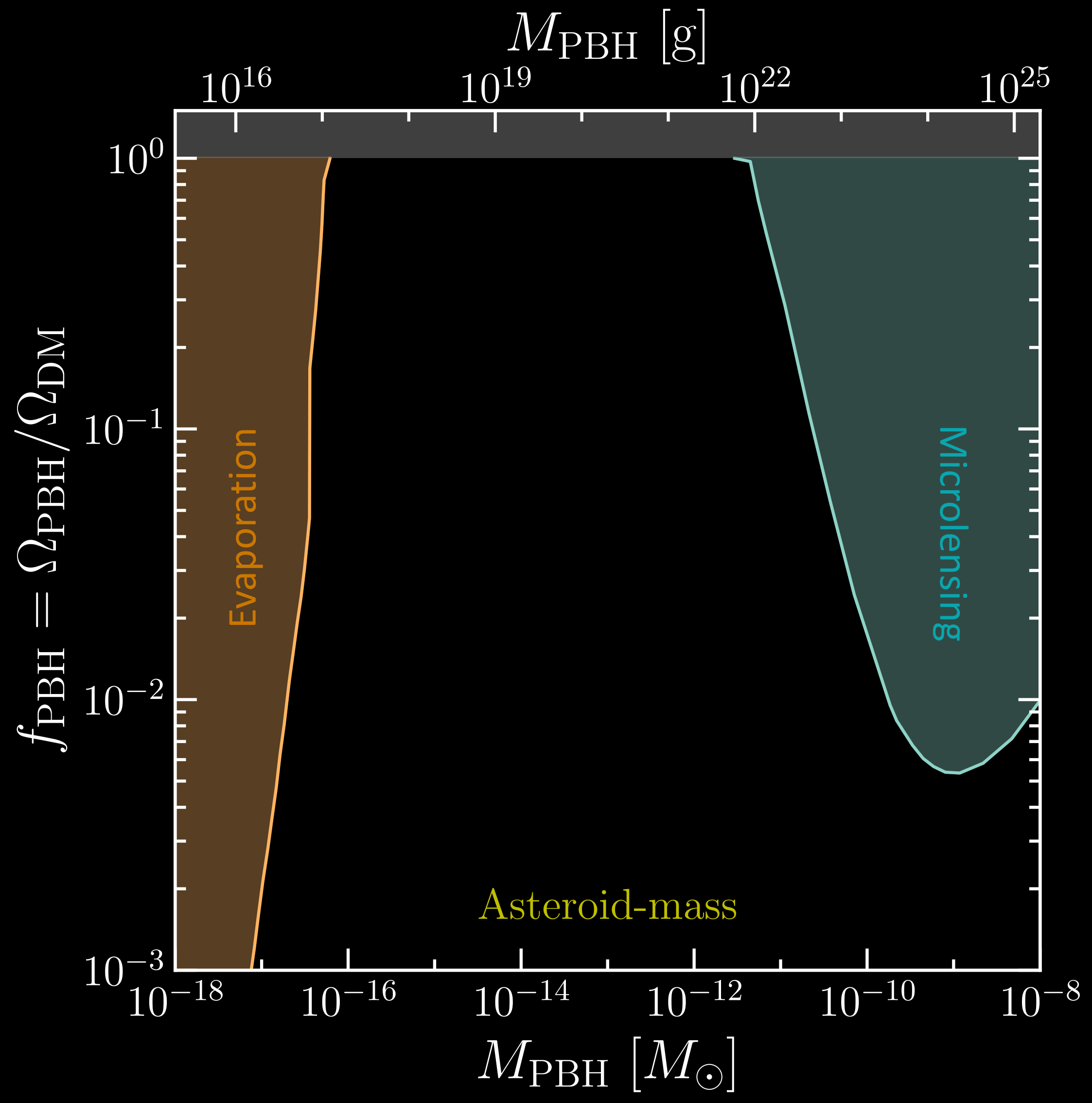
[Montero-Camacho et al., 1906.05950]



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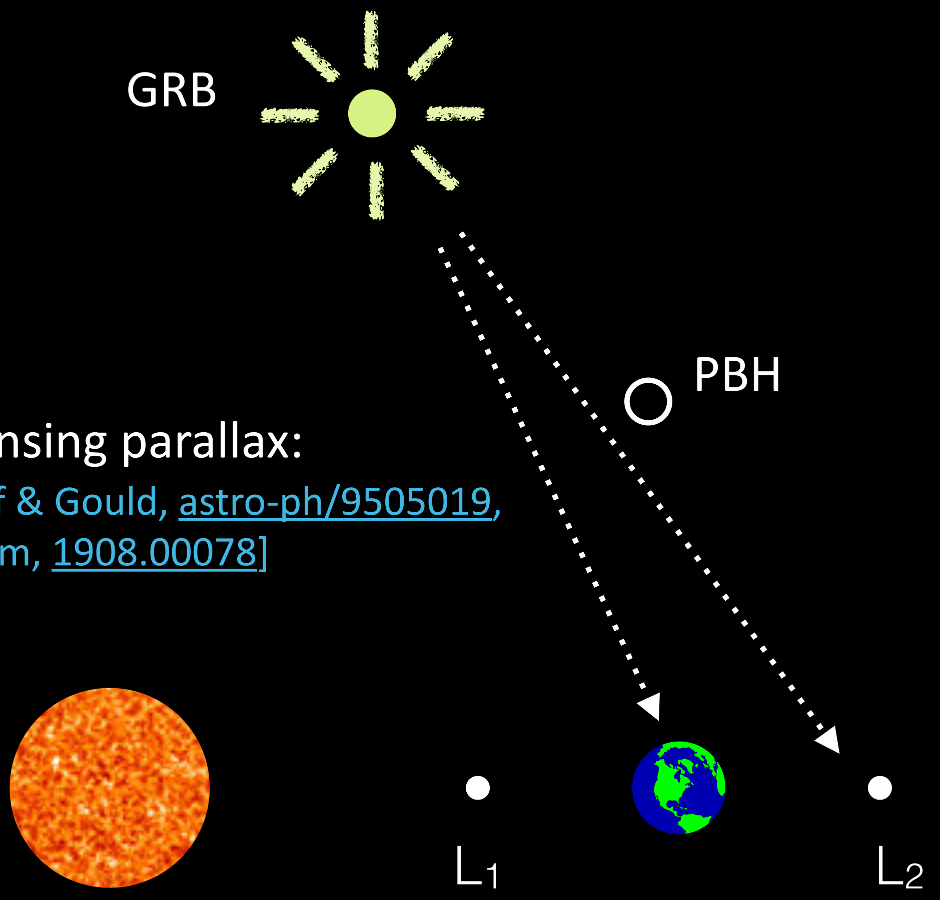
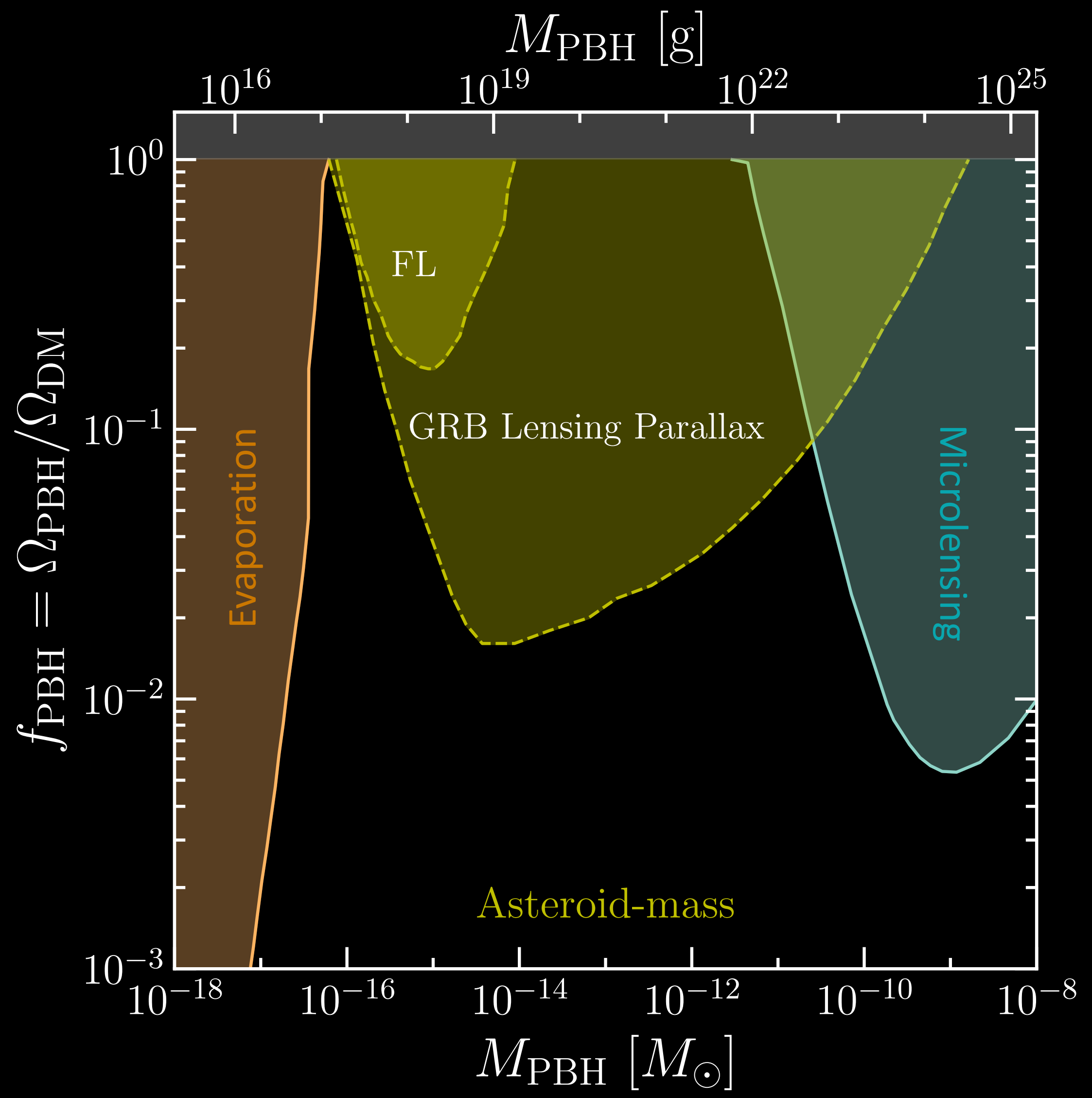


GRB Lensing parallax:
[Nemiroff & Gould, astro-ph/9505019, Jung & Kim, 1908.00078]



Craters on the moon? [Yalinewich & Caplan, 2104.00033]

Disruption of the Kuiper belt? [Siraj & Loeb, 2103.04995]

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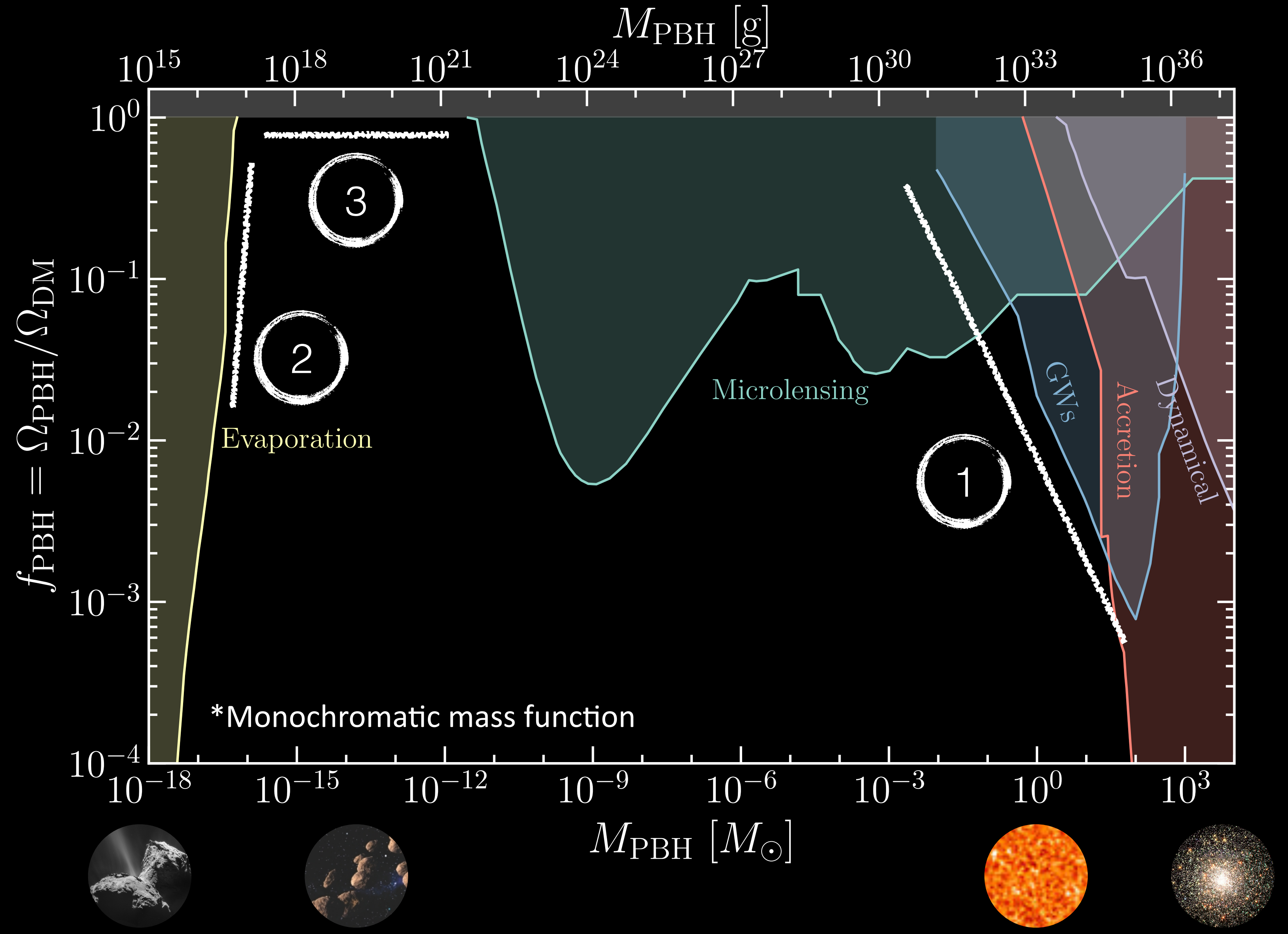

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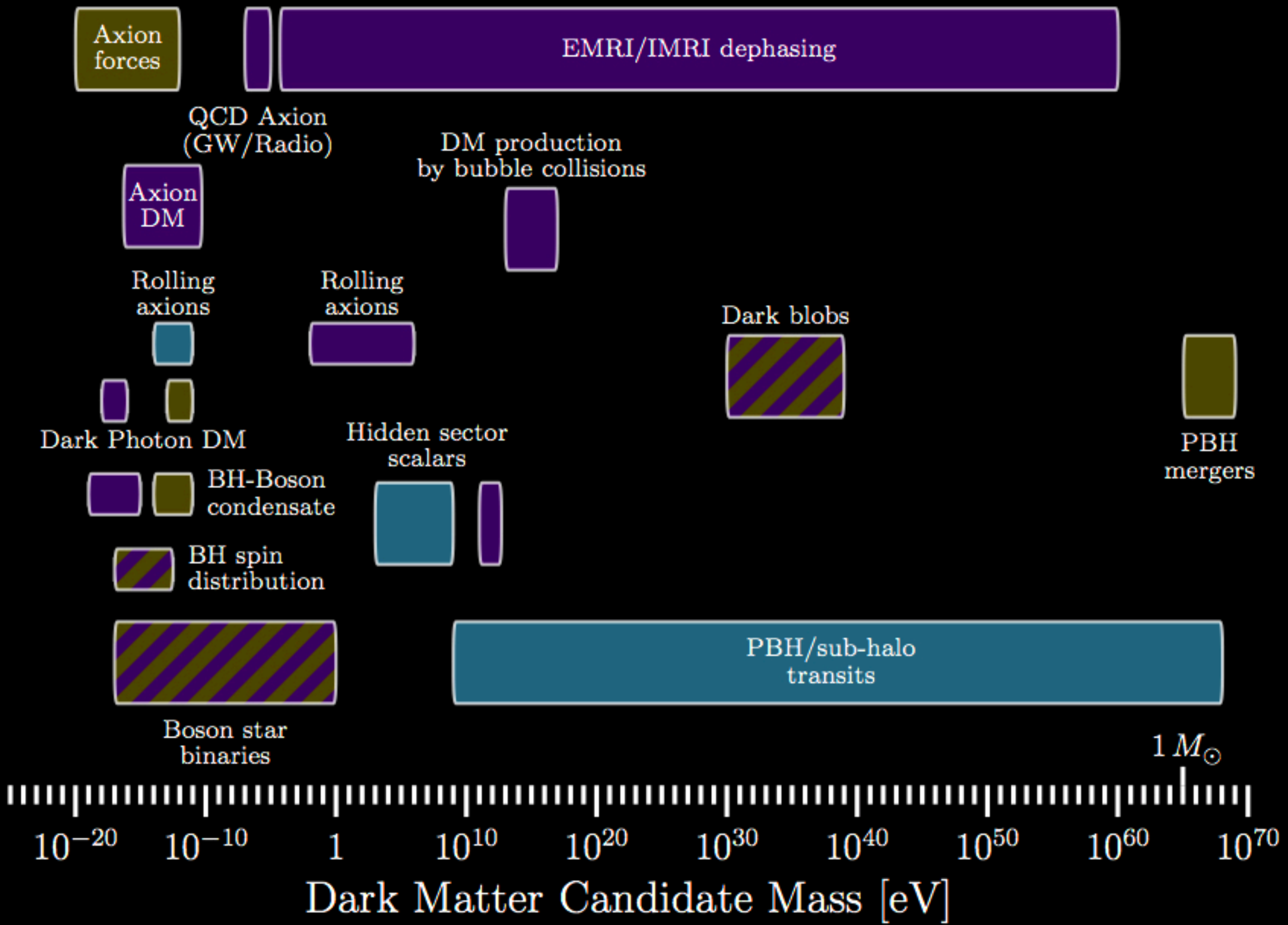
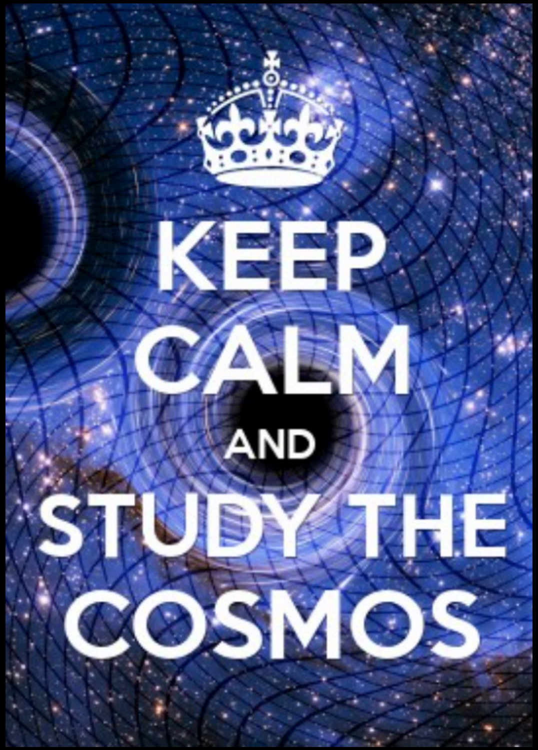
Gravitational waves may shed light on dark matter



Bertone et al. (including DC, BJK) arXiv:1907.10610



Thank you!

...ask us anything you like!

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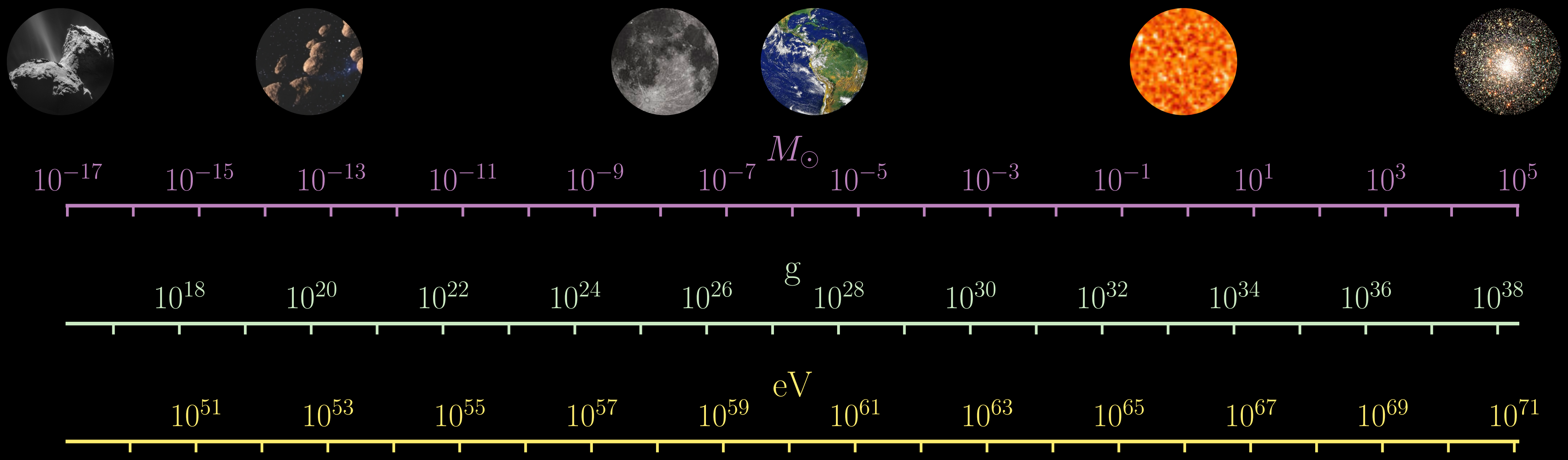
Backup slides

Primordial Black Holes

Primordial Black Holes (PBHs) *could* form in the early Universe ($z \gg 10^8$) from large over-densities

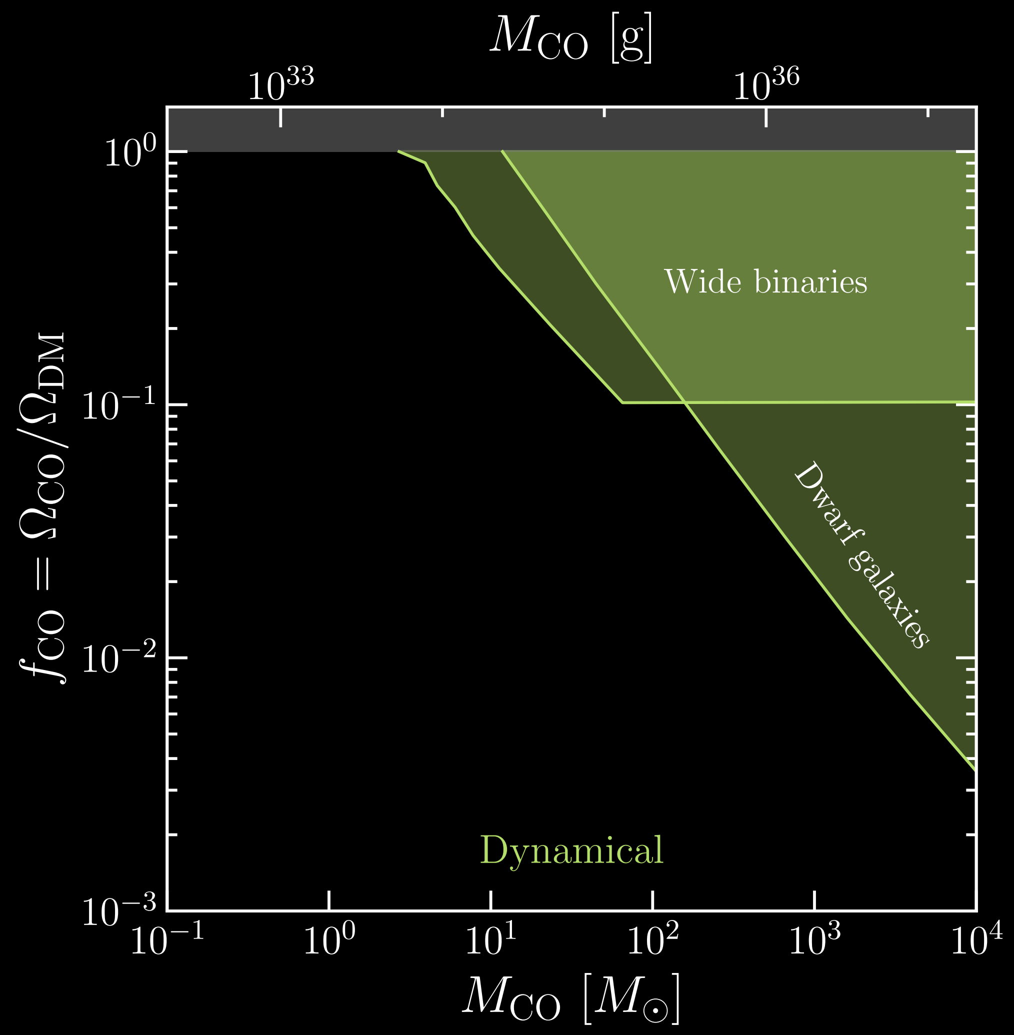
Mass roughly given by mass inside horizon at time of formation:

[Green & Liddle, astro-ph/9901268]

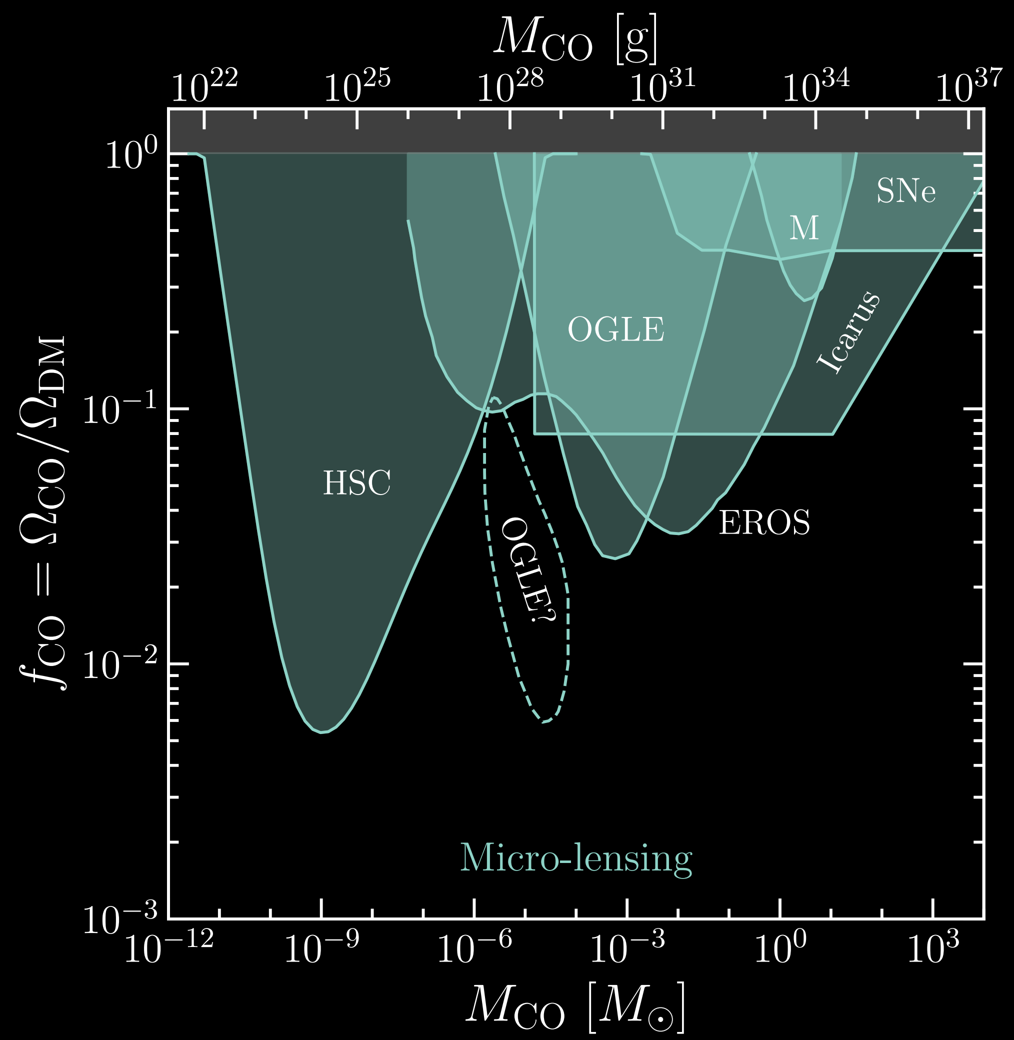


[Zel'dovich & Novikov (1967), Hawking (1971), Carr & Hawking (1974), Carr (1975)]

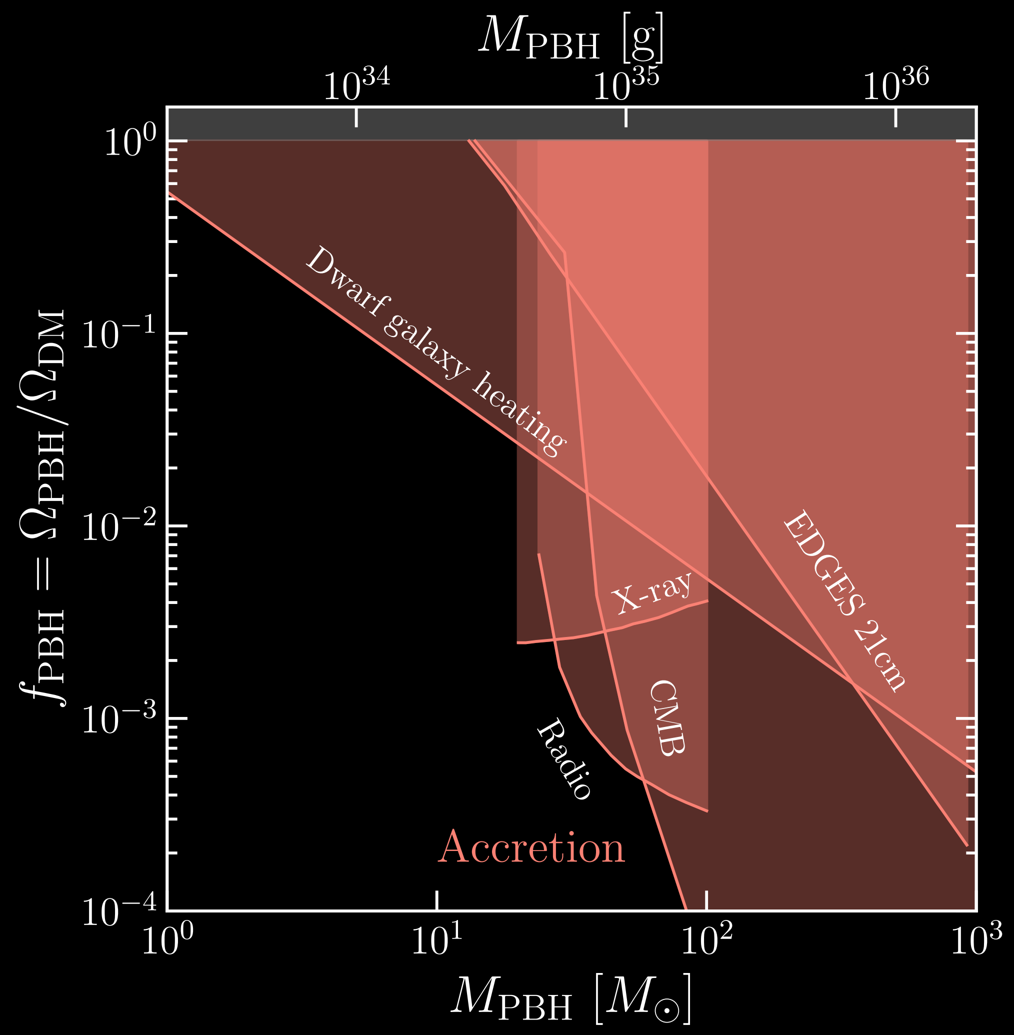
PBH - Dynamical Constraints



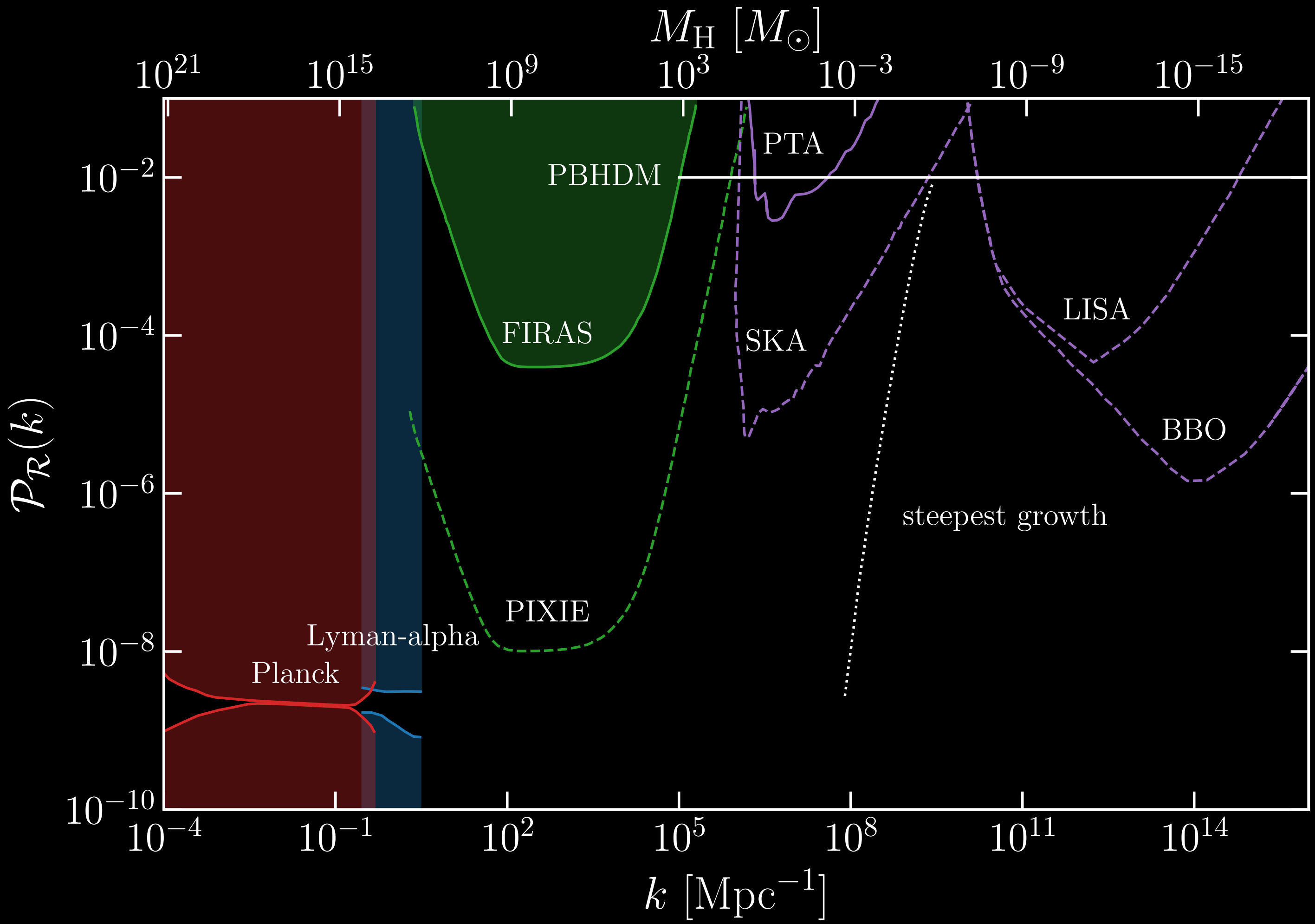
PBH - Microlensing Constraints



PBH - Accretion Constraints



PBH - Power Spectrum Constraints



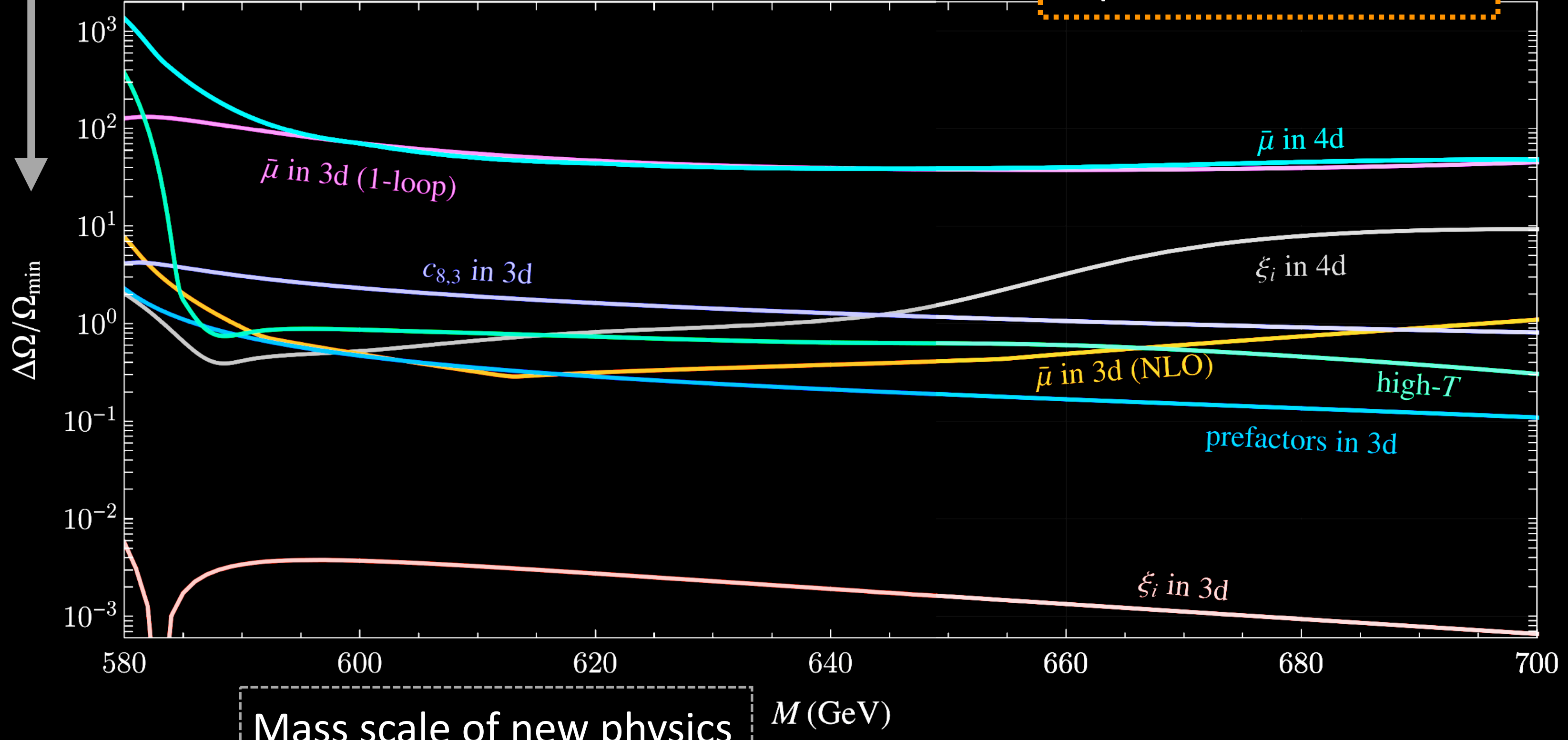
+ newest Nanograv results [e.g. Vaskonen & Veermäe, 2009.07832]

Phase transitions in the early Universe

However, significant theoretical uncertainties exist

Relative uncertainty in the GW spectrum

In perturbative models



Mass scale of new physics

In strongly coupled theories

Popular methods

- The linear Σ-model
- The (P)NJL models
- The MIT Bag model

Range of validity? Predictions often inconsistent

Plot from DC, O. Gould, T. Tenkanen, P. Schicho, G. White [JHEP, arXiV: 2009.10080]