Positive Evidence for Primordial Black Holes

Florian Kühnel

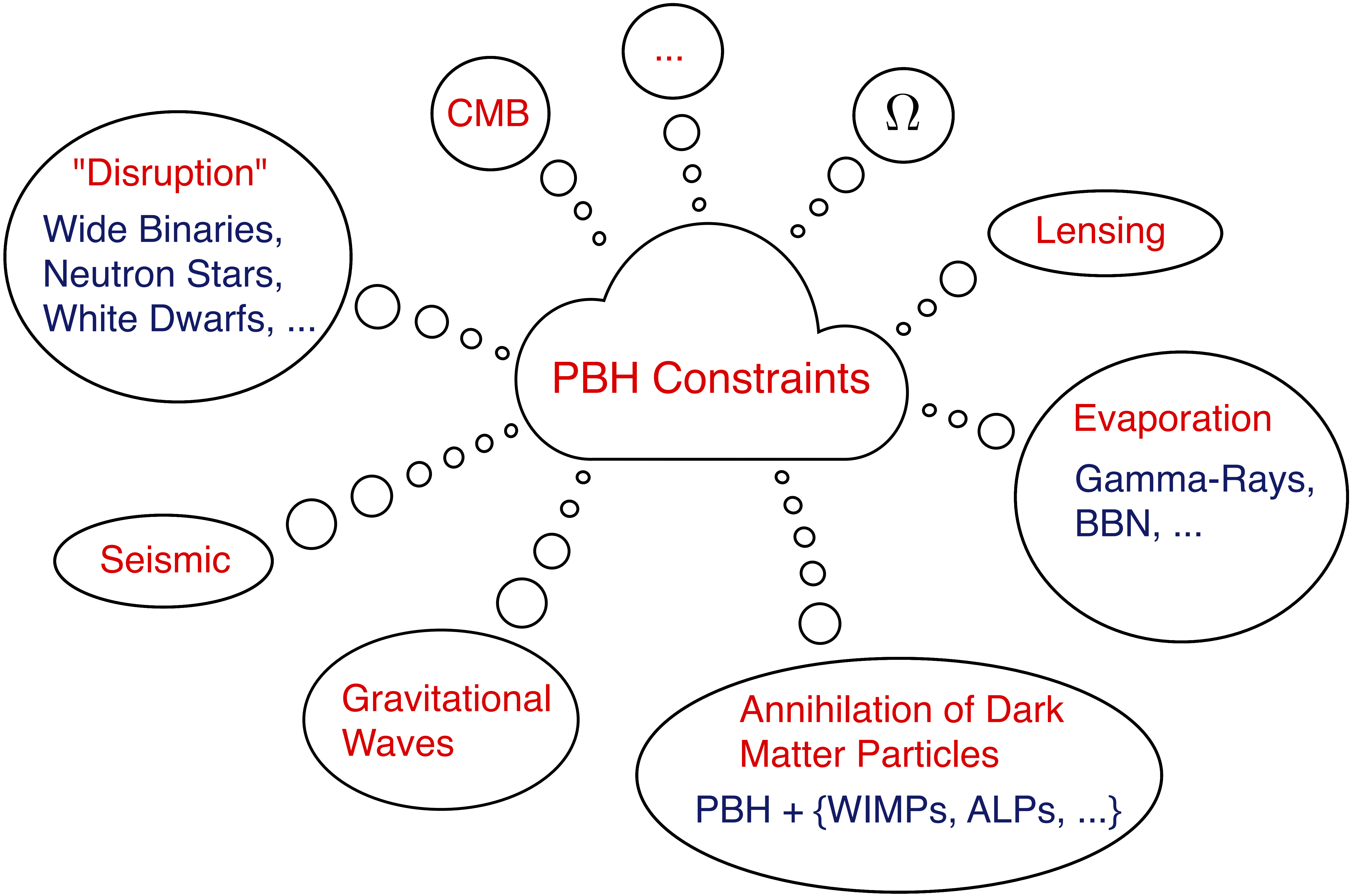
Max Planck Institute for Physics

— Focus Week on Primordial Black Holes —

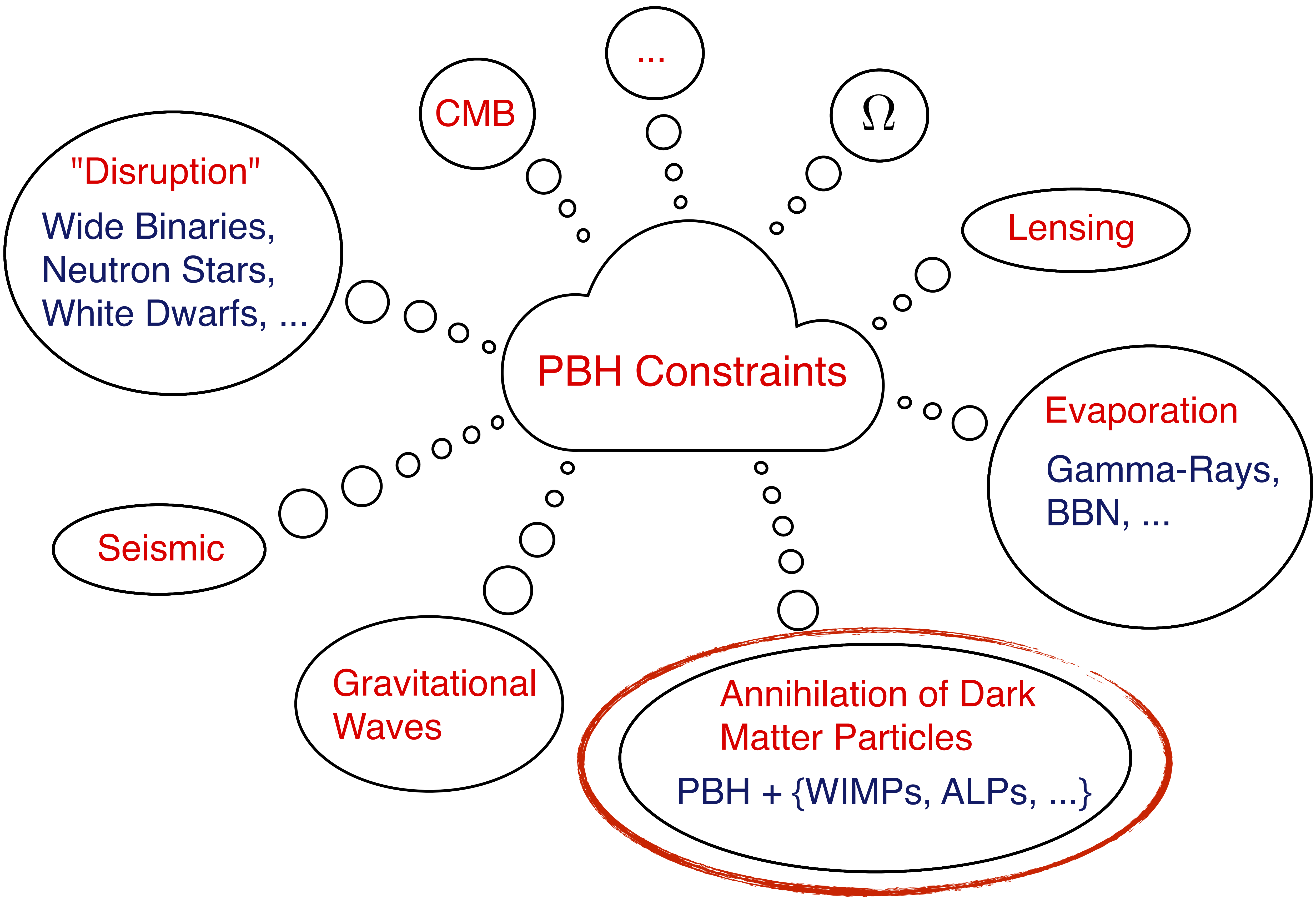
Kavli Institute for the Physics and Mathematics of the Universe

Monday, the 13th of November 2023

Primordial Black Hole Constraints



...
CMB
Ω
"Disruption"
Wide Binaries,
Neutron Stars,
White Dwarfs, ...
Lensing
PBH Constraints
Evaporation
Gamma-Rays,
BBN, ...
Seismic
Gravitational Waves
Annihilation of Dark Matter Particles
PBH + {WIMPs, ALPs, ...}


PBH Constraints
"Disruption"
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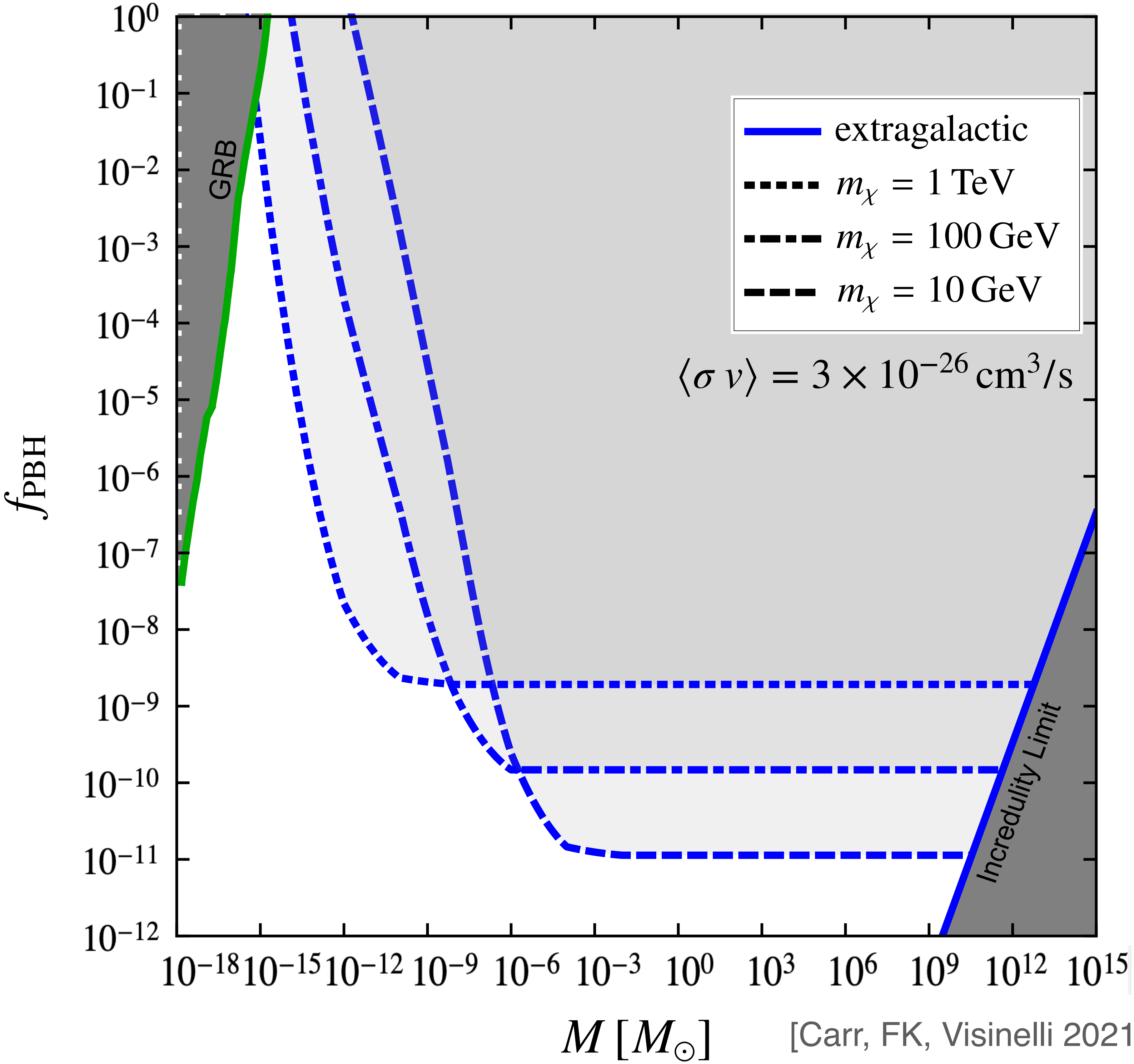
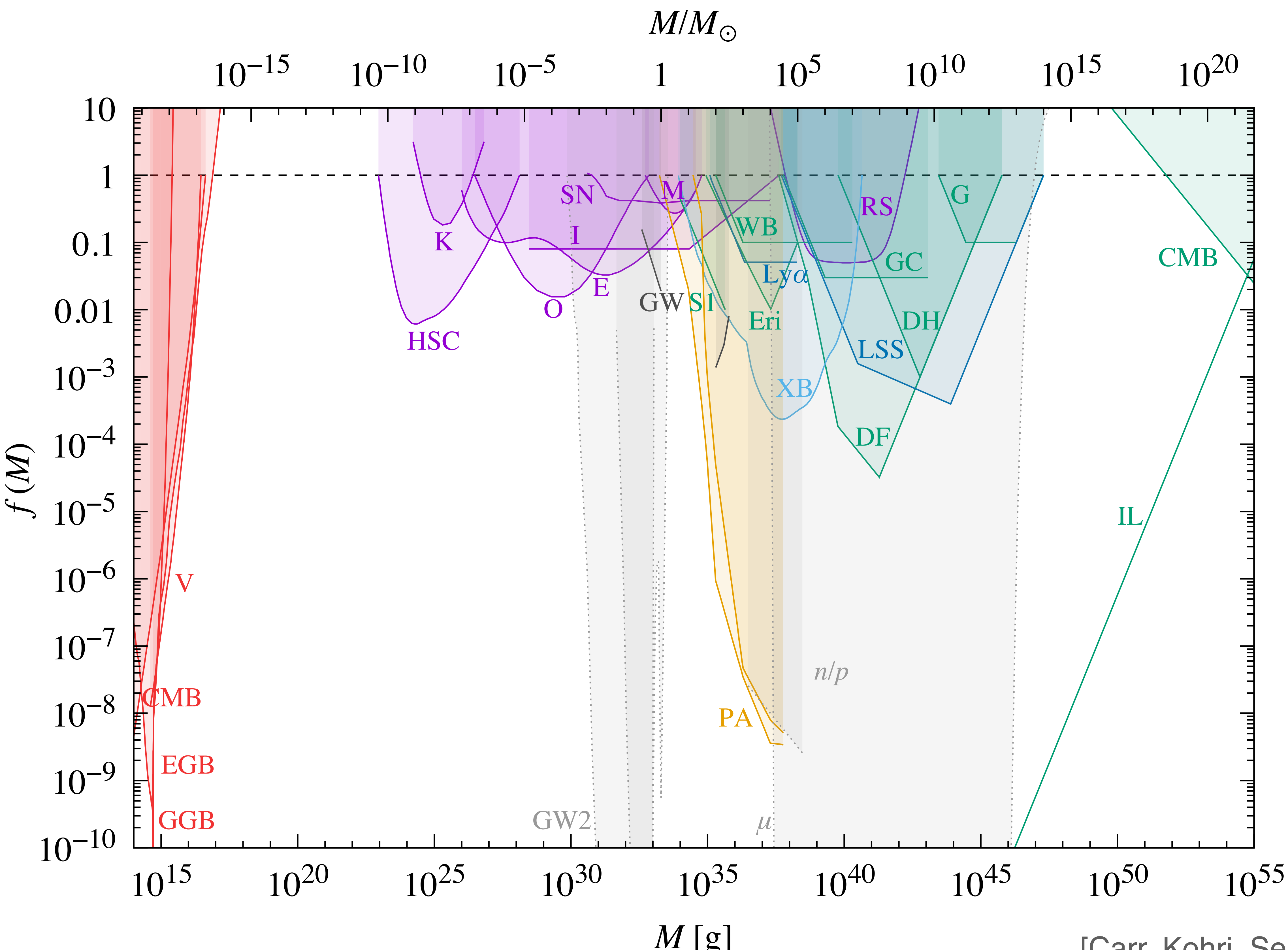
PBHs & WIMPs



[Carr, FK, Visinelli 2021]

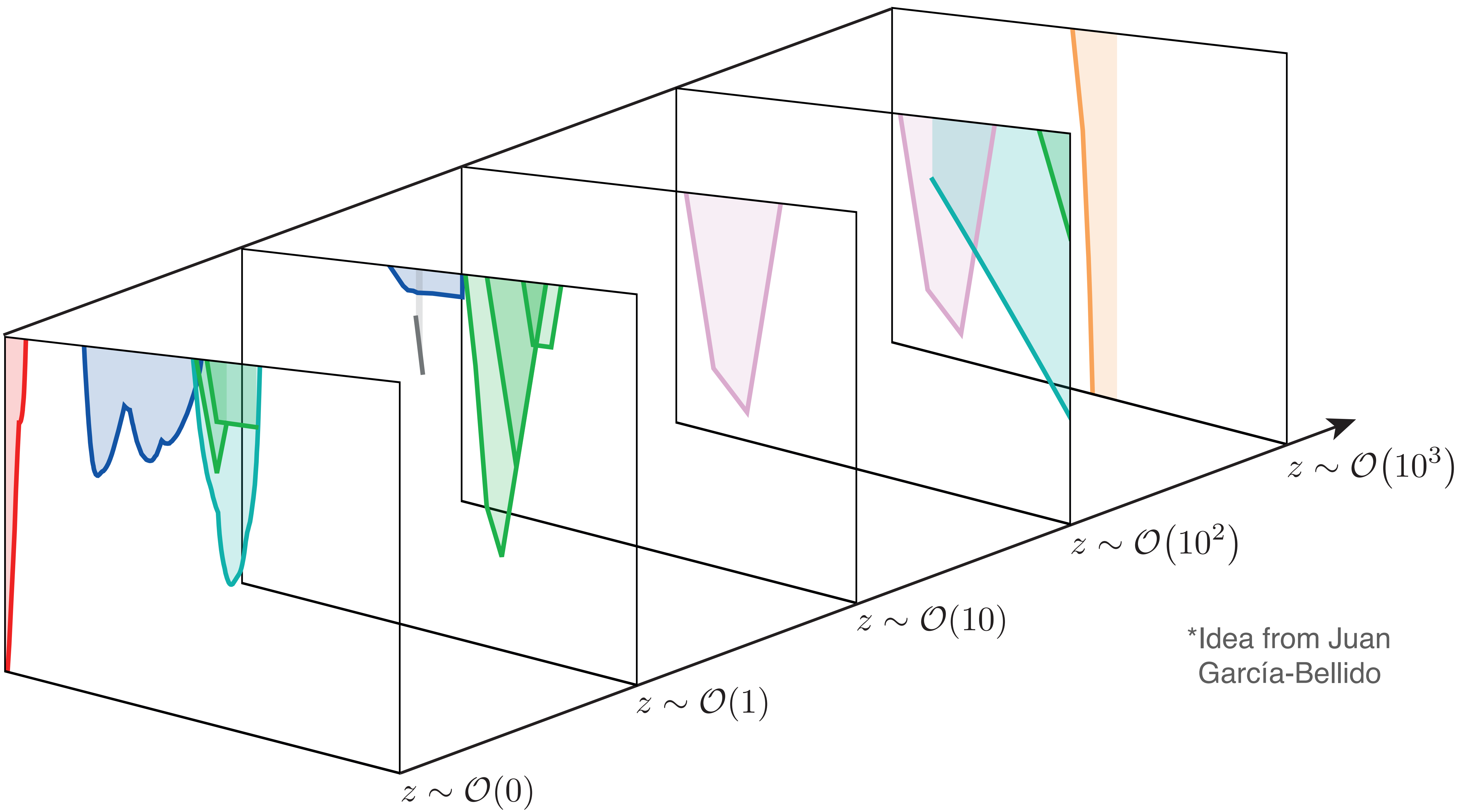
★ If LIGO/Virgo/Kagra detected a single PBH, this would rule out ALL standard WIMP scenarios!

Current PBH Constraints



[Carr, Kohri, Sendouda and Yokoyama 2021]

PBH Constraints — Redshift Dependence



*Idea from Juan García-Bellido

[Carr & FK 2020*]

Constraints — A Worthwhile Remark

★ These constraints are not just nails in a coffin!

(Carr)

★ All constraints have caveats and might change.

★ PBHs are important even if $f_{\rm PBH} \ll 1$.

★ Each constraint is a potential signature.

Constraints — A Worthwhile Remark

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★ Each constraint is a potential signature.

Observational Hints for Primordial Black Holes

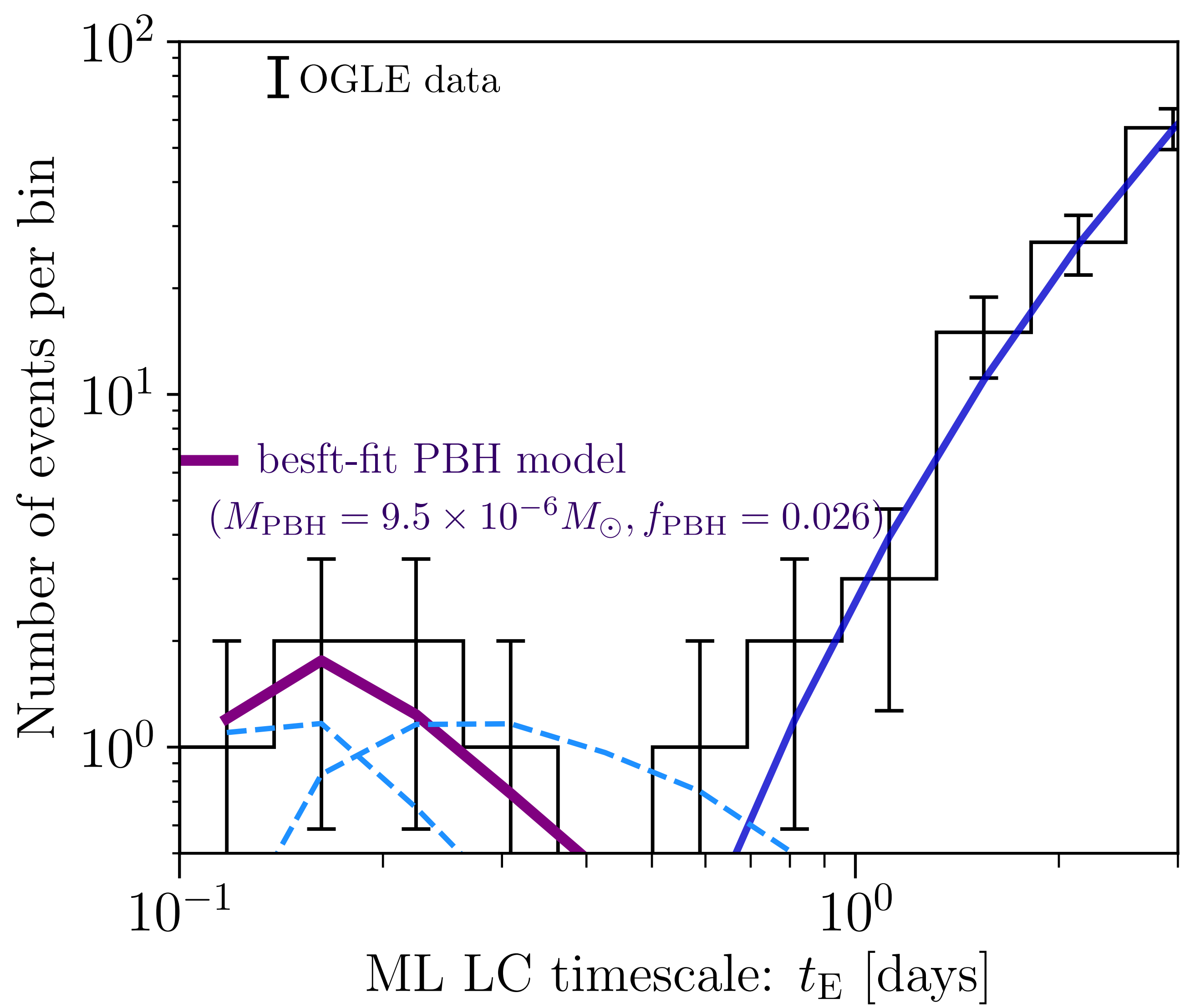
Evidence?

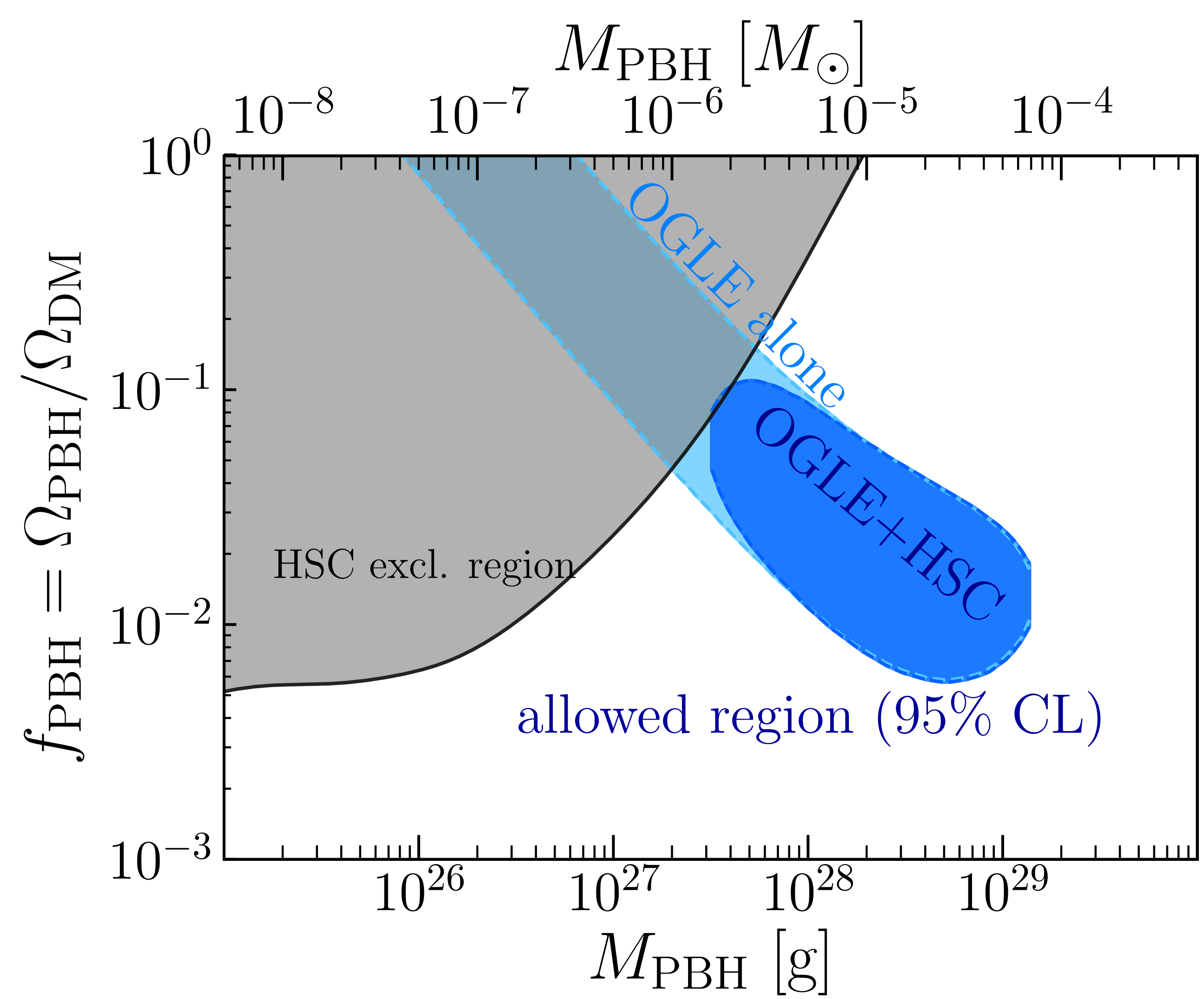
Observational ~~Hints~~ for Primordial Black Holes

*work with Carr, Clesse,
García-Bellido, Hawking

Planetary-Mass Microlensing

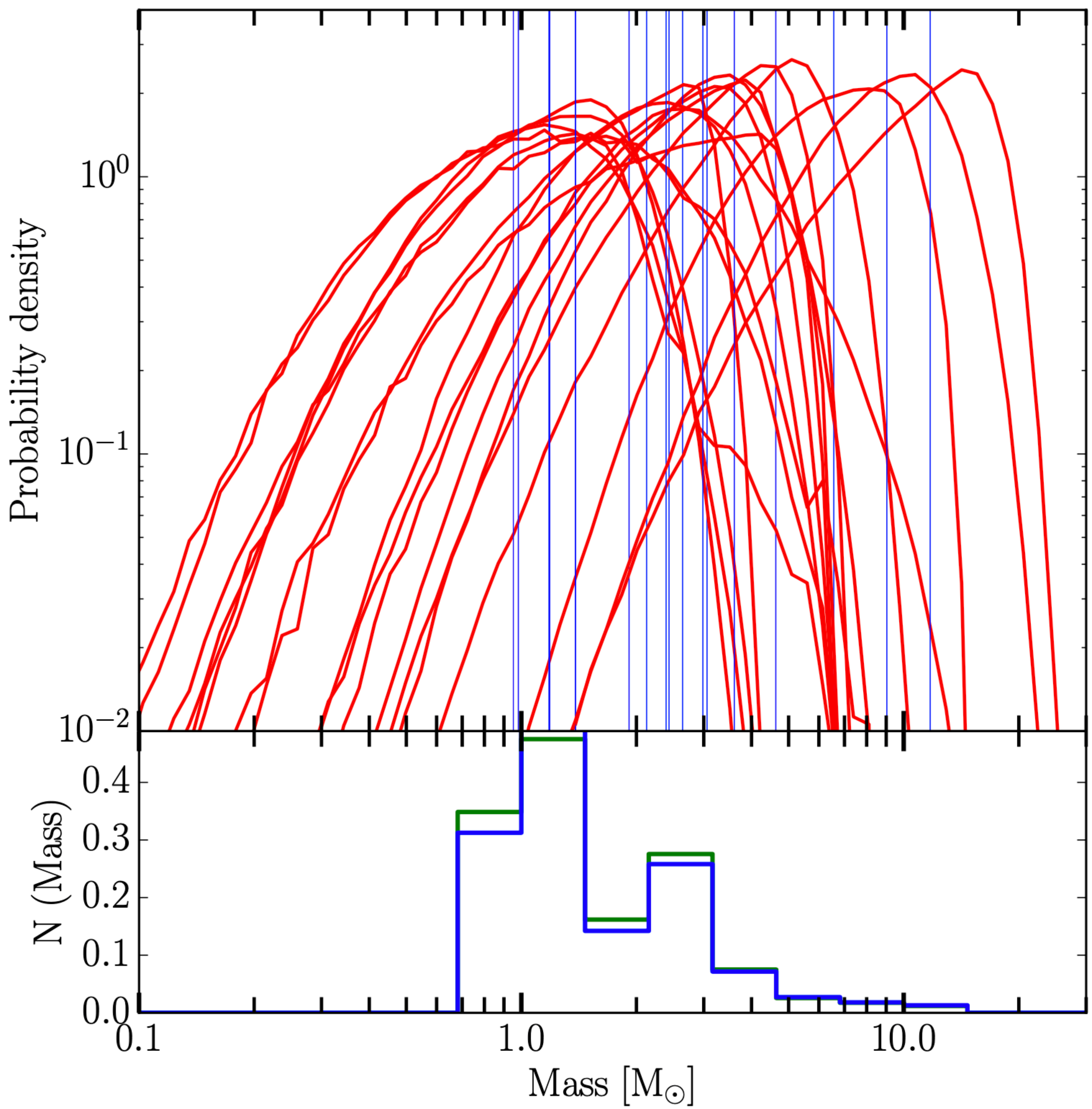
- OGLE detected a particular population of microlensing events:
  - 0.1 - 0.3 days light-curve timescale - origin unknown! Could be free-floating planets... or PBHs!





[Niikura, *Takada, Yokoyama, Sumi, Masaki* 2019]

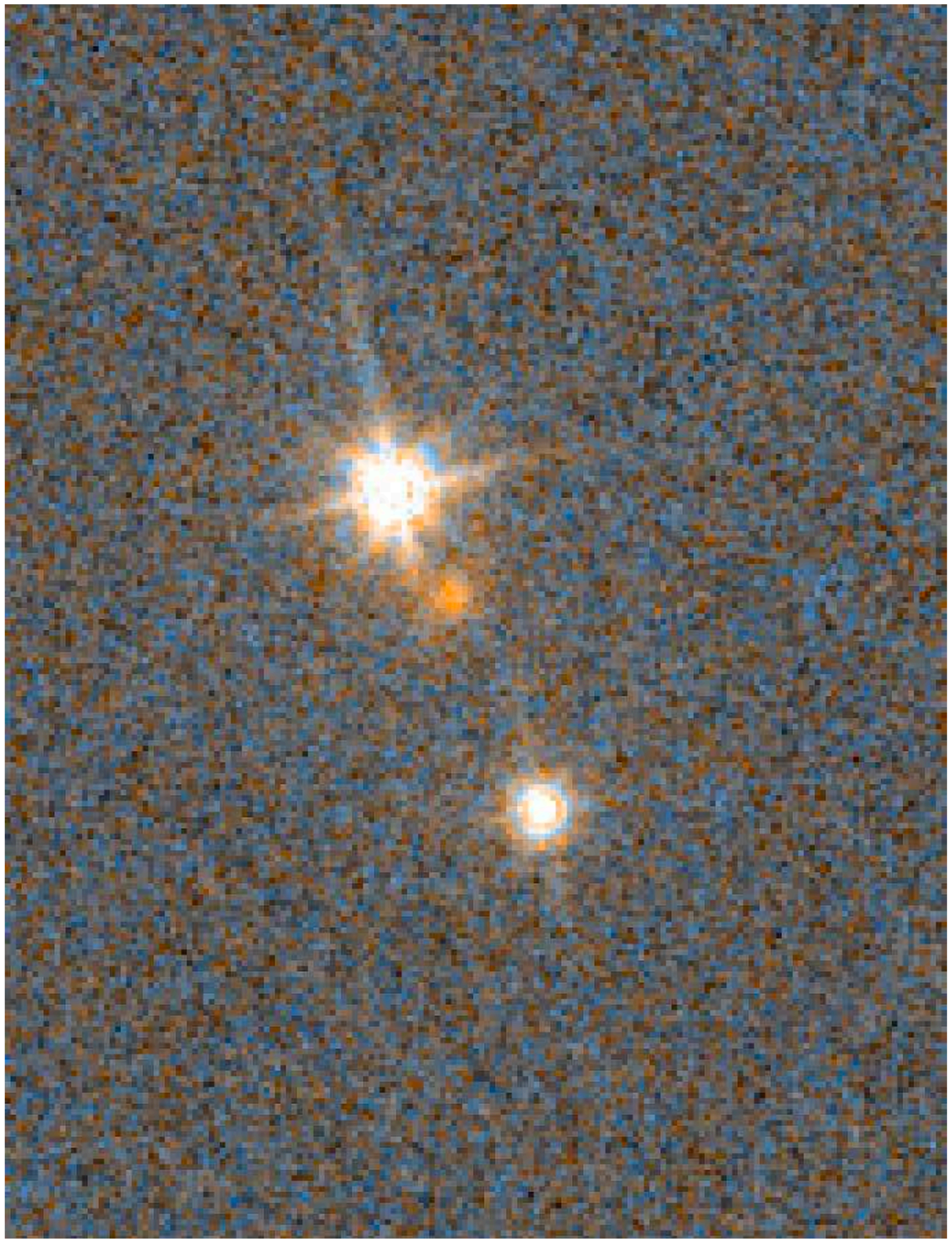
Excess of Lenses in Galactic Bulge



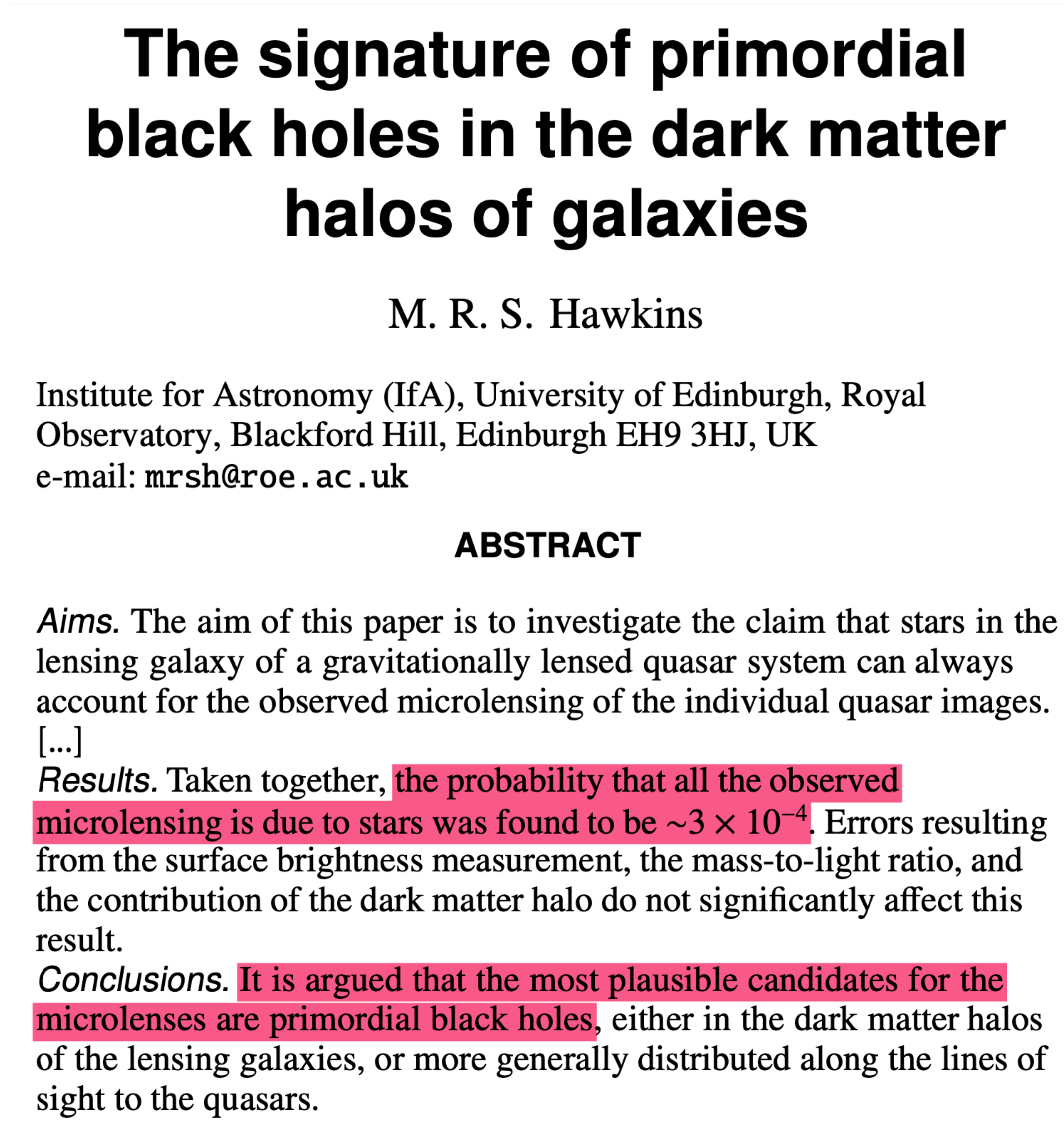
- ★ OGLE has detected 58 long-duration microlensing events in the Galactic bulge.
- ★ 18 of these cannot be main-sequence stars and are very likely black holes.
- ★ Their mass function overlaps the low mass gap from 2 to 5 $M_\odot$.
- ★ These are not expected to form as the endpoint of stellar evolution.

[Wyrzykowski & Mandel 2020]

Quasar Microlensing



HST image of lensed quasar HE1104–1805



The signature of primordial black holes in the dark matter halos of galaxies

M. R. S. Hawkins

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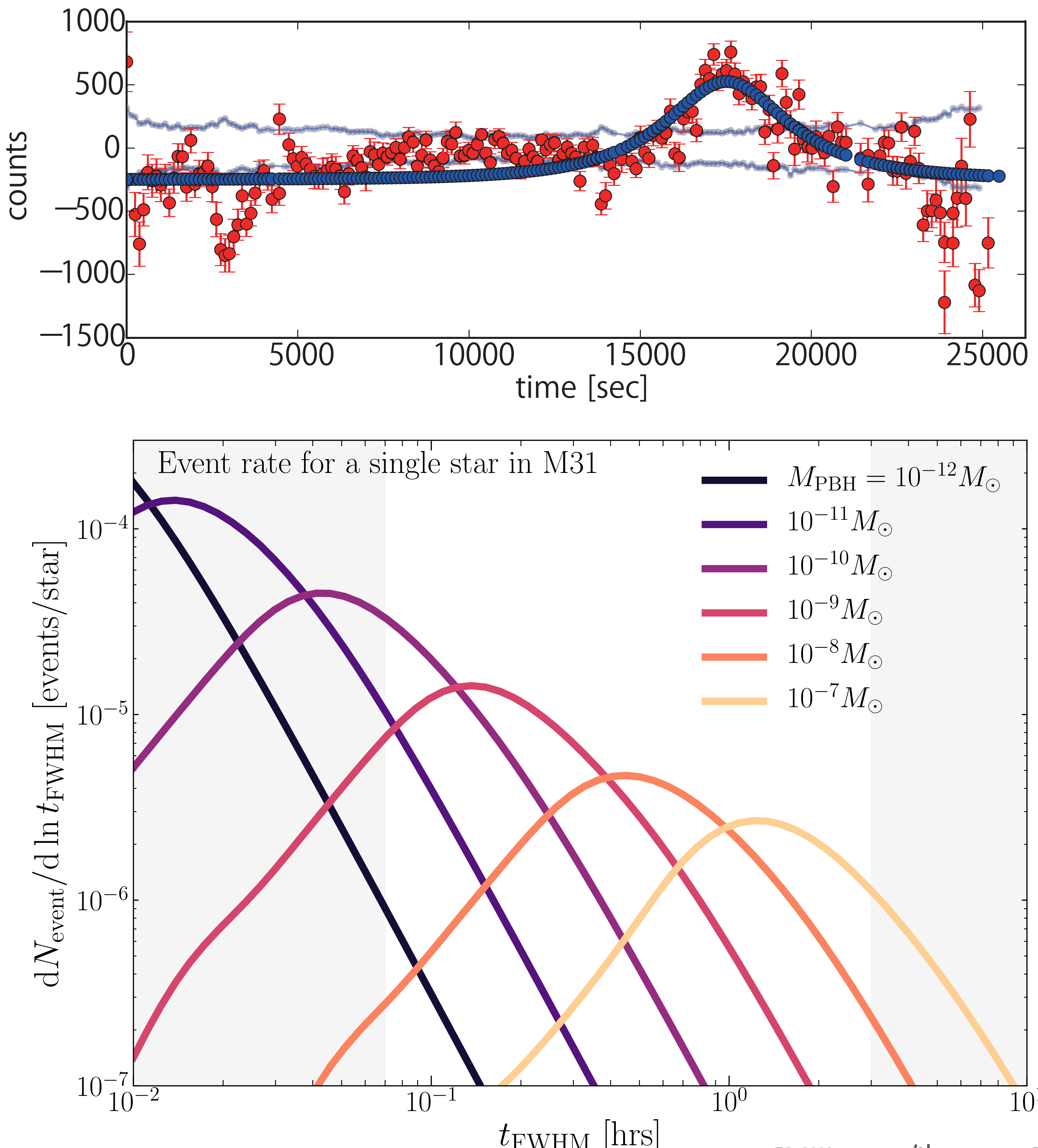
e-mail: mrsh@roe.ac.uk

ABSTRACT

Aims. The aim of this paper is to investigate the claim that stars in the lensing galaxy of a gravitationally lensed quasar system can always account for the observed microlensing of the individual quasar images. [...]
Results. Taken together, the probability that all the observed microlensing is due to stars was found to be $\sim 3 \times 10^{-4}$. Errors resulting from the surface brightness measurement, the mass-to-light ratio, and the contribution of the dark matter halo do not significantly affect this result.
Conclusions. It is argued that the most plausible candidates for the microlenses are primordial black holes, either in the dark matter halos of the lensing galaxies, or more generally distributed along the lines of sight to the quasars.

Pixel Lensing by Subaru Hyper Suprime-Camera (HSC)

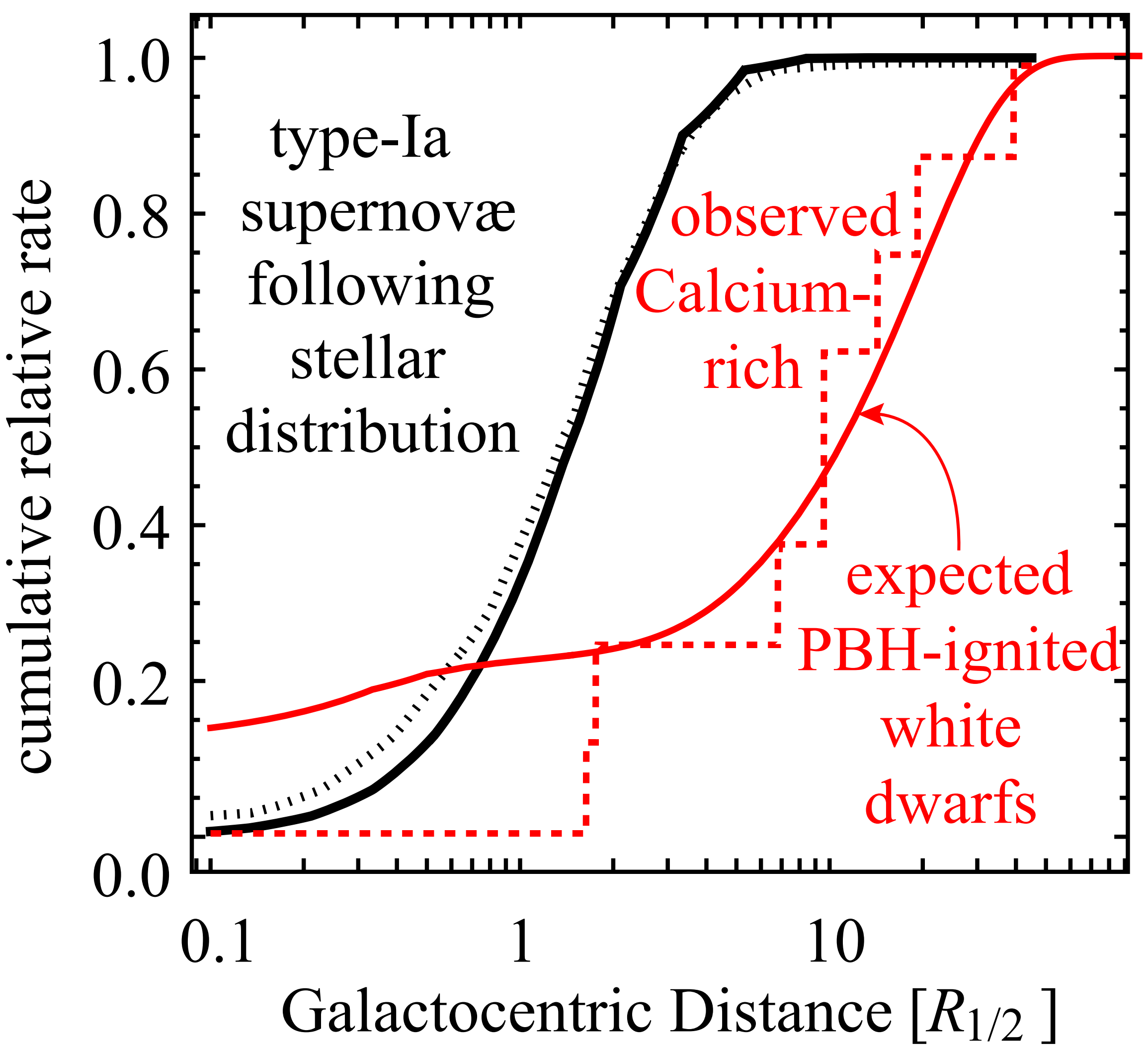


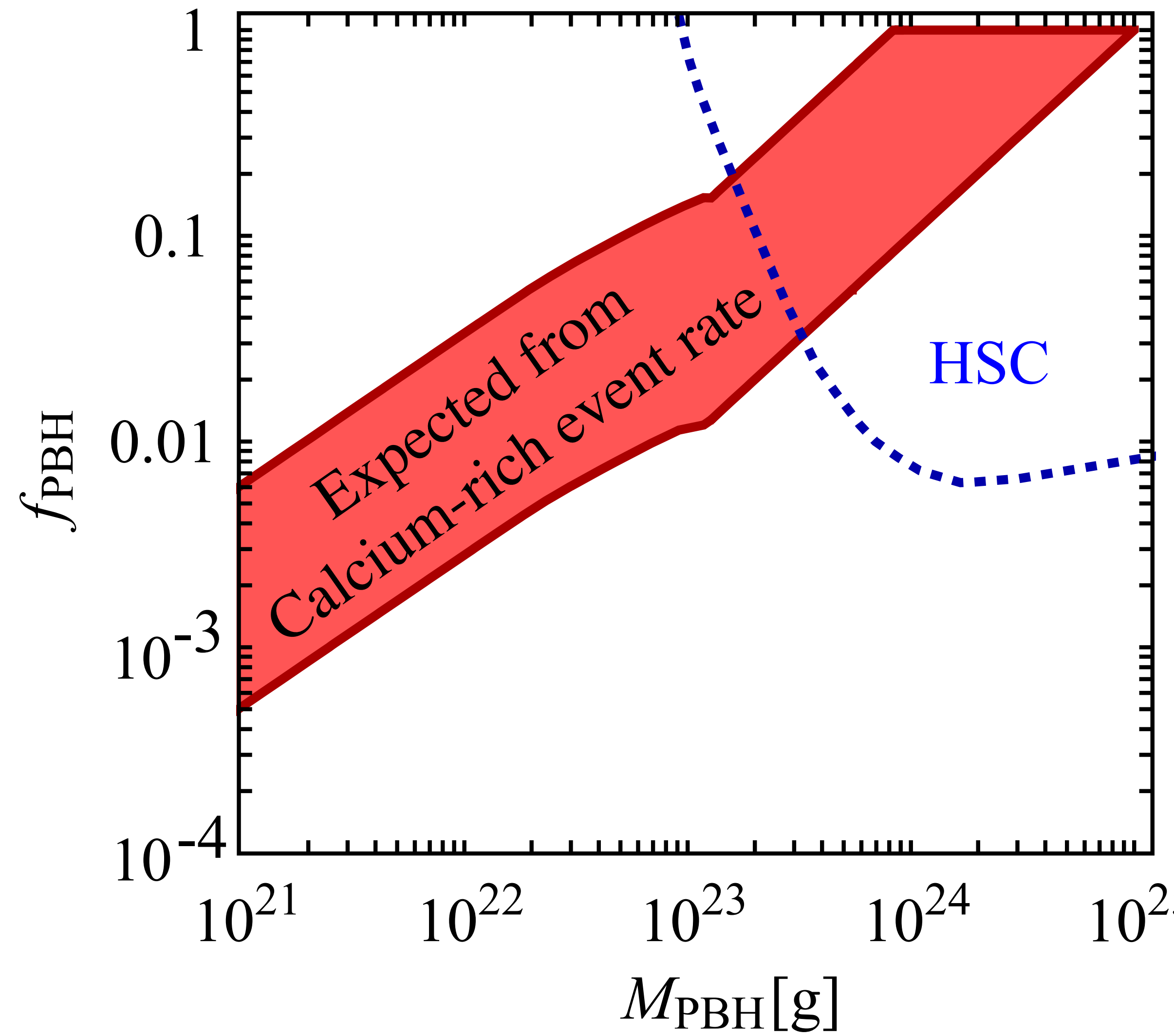
[Niikura 他 2019]

- ★ Seven-hour observation of M31 with the Subaru HSC...
- ★ ... using pixel-lensing technique to search for microlensing of stars by PBHs in the Milky Way or Andromeda.
- ★ 15,571 candidate variable stars were extracted from the difference images...
- ★ ... and one event by a compact body with mass $10^{-11} - 10^{-5}\ M_\odot$ could be identified.

Calcium-Rich Gap Transients

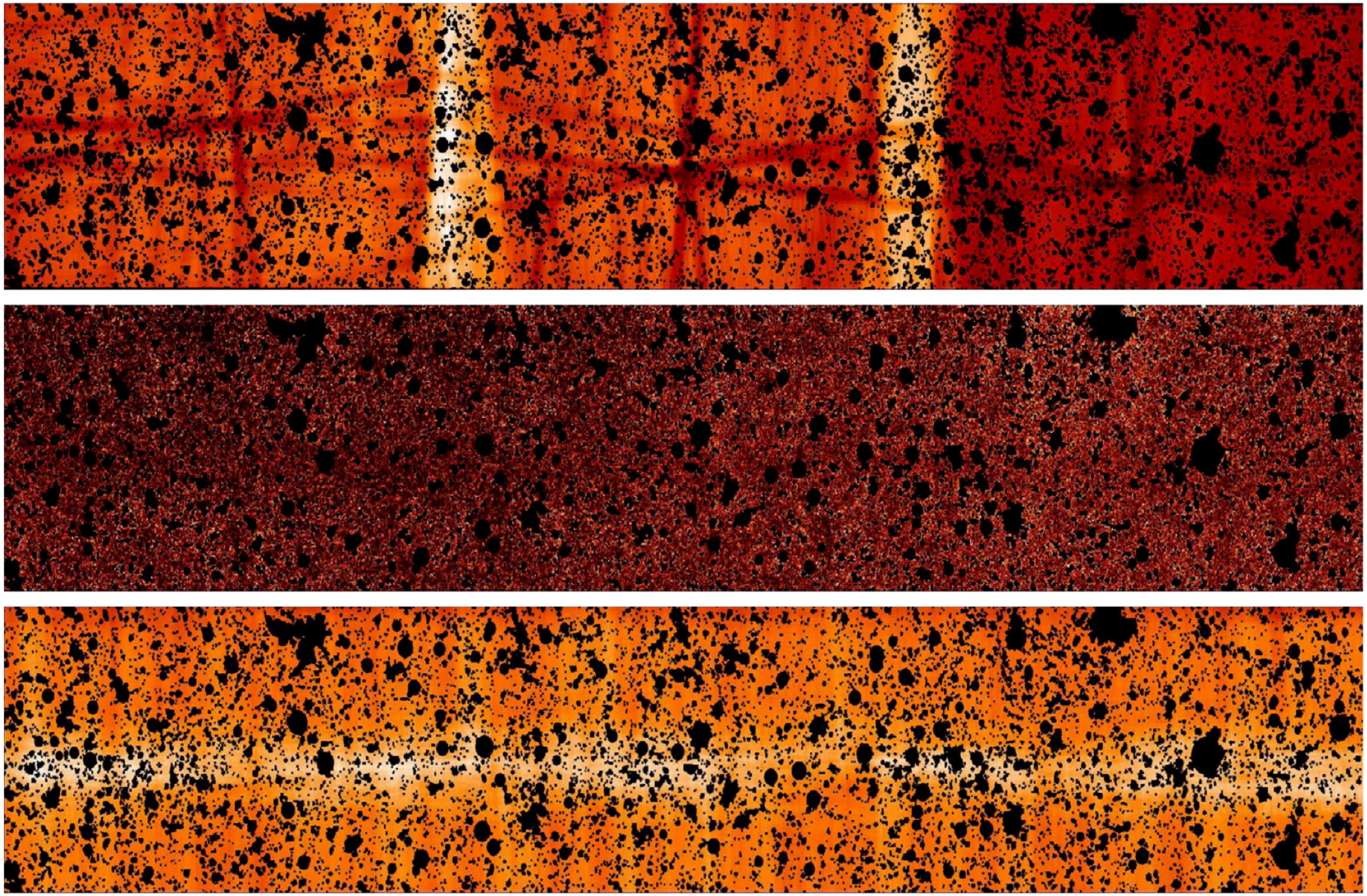
★ A supernova population of so-called calcium-rich gap transients has been shown to clearly not to follow the stellar distribution but rather a would-be compact dark matter one.





[Smirnov *et al.* 2023]

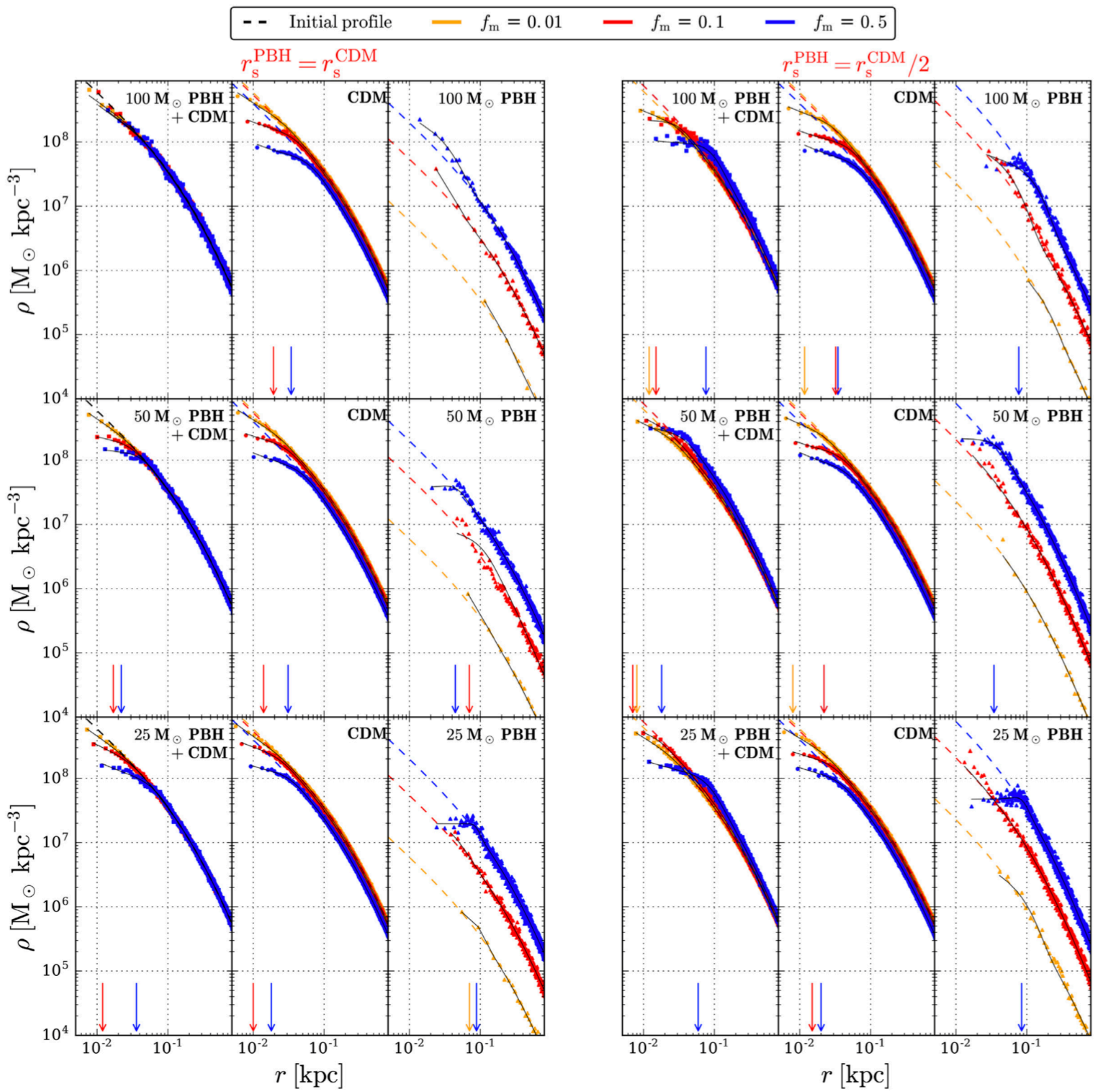
Correlations of Cosmic Infrared/X-Ray Backgrounds



[Cappelluti *et al.* 2013]

★ PBHs generate early structure and respective backgrounds

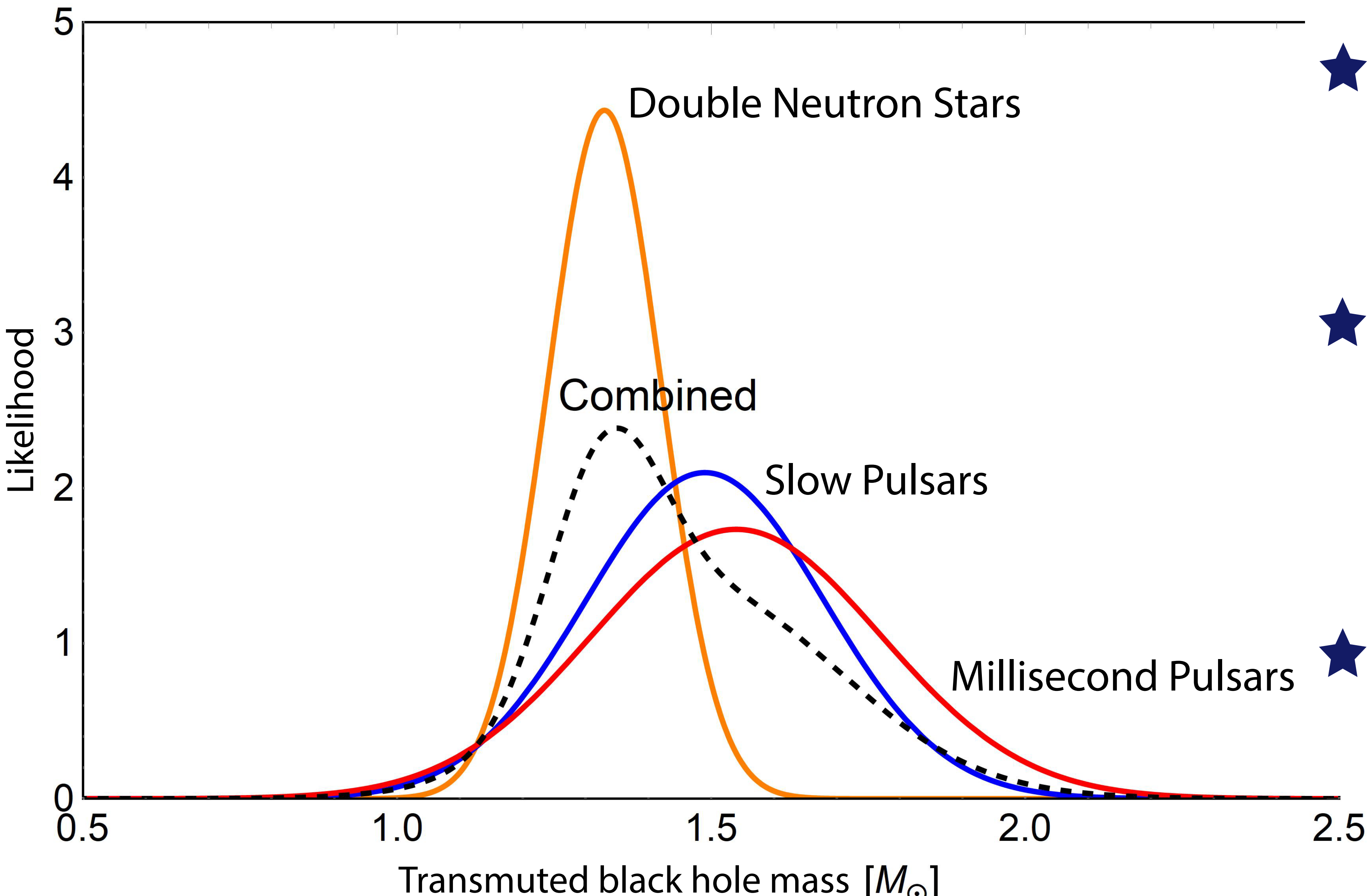
Ultra-faint Dwarf Galaxies



[Boldrini *et al.* 2020]

- ★ Non-detection of dwarf galaxies smaller than ~ 10 – 20 pc
- ★ Ultra-faint dwarf galaxies are dynamically unstable below some critical radius in the presence of PBH dark matter!
- ★ This works with a few percent of PBH dark matter of 25 – 100 $M_\odot$.

Transmuted Solar-Mass Black Holes

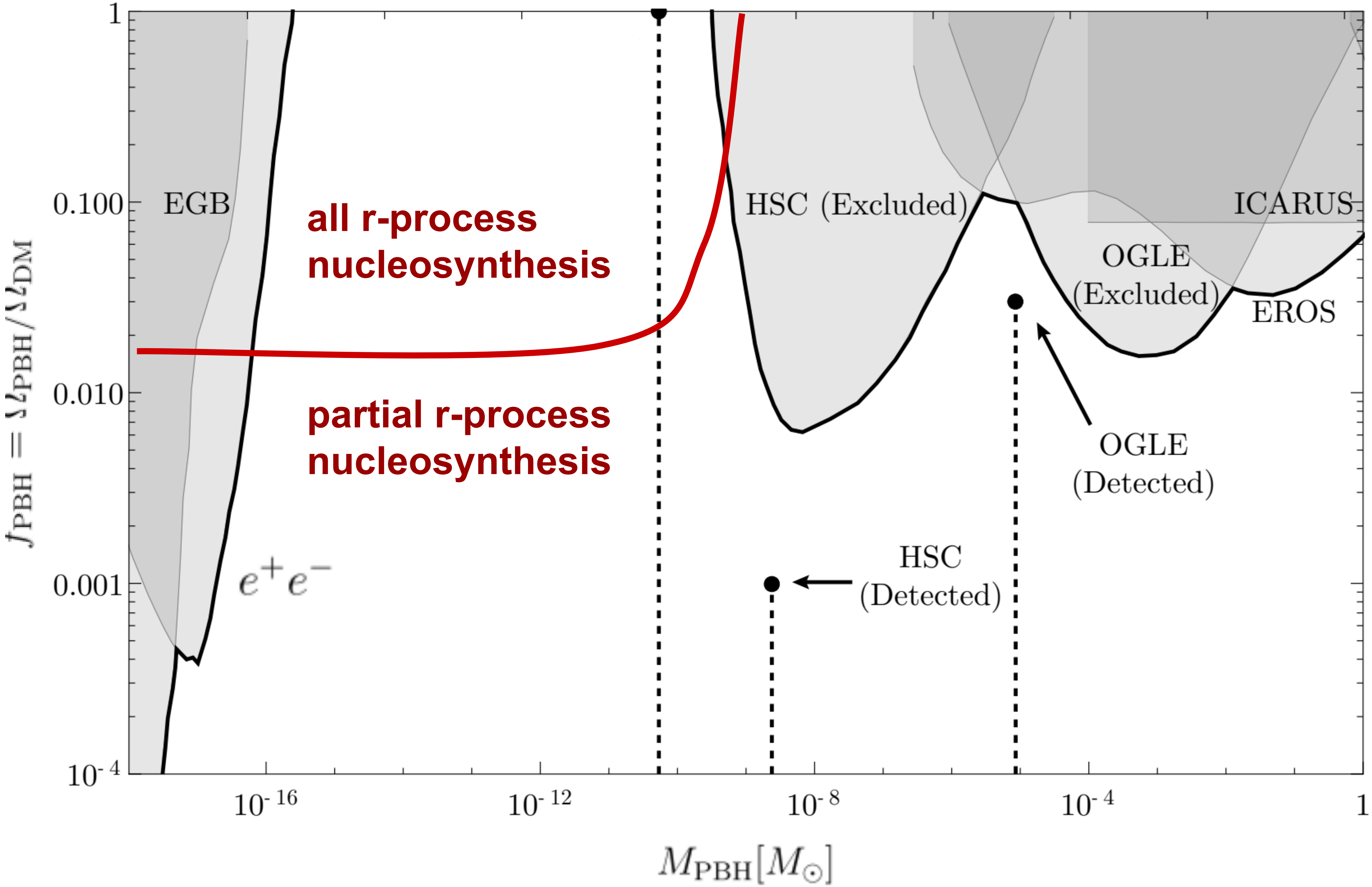


[Takhistov, Fuller, Kusenko 2017]

- ★ Small PBH + Neutron Star = $\mathcal{O}(1)\, M_\odot$ black hole.
- ★ Besides such a characteristic mass distribution of black holes
- ★ this can explain all r-process elements in the Universe, including gold

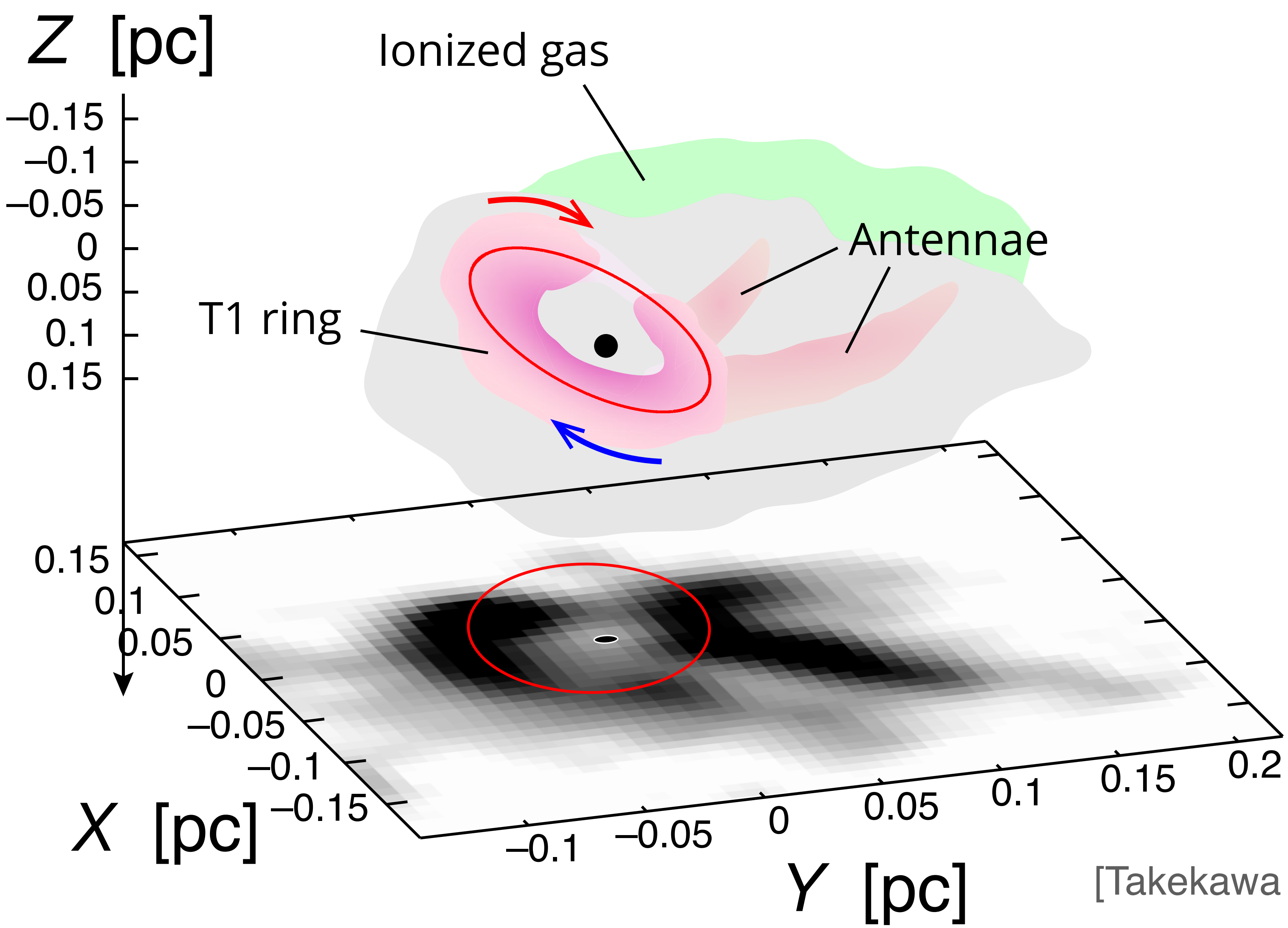
(... of which a single neutron star could generate up to 10 Earth masses $\sim 10^{33}$ ¥*).*

r-Process Elements



(*from talk by Alex Kusenko)

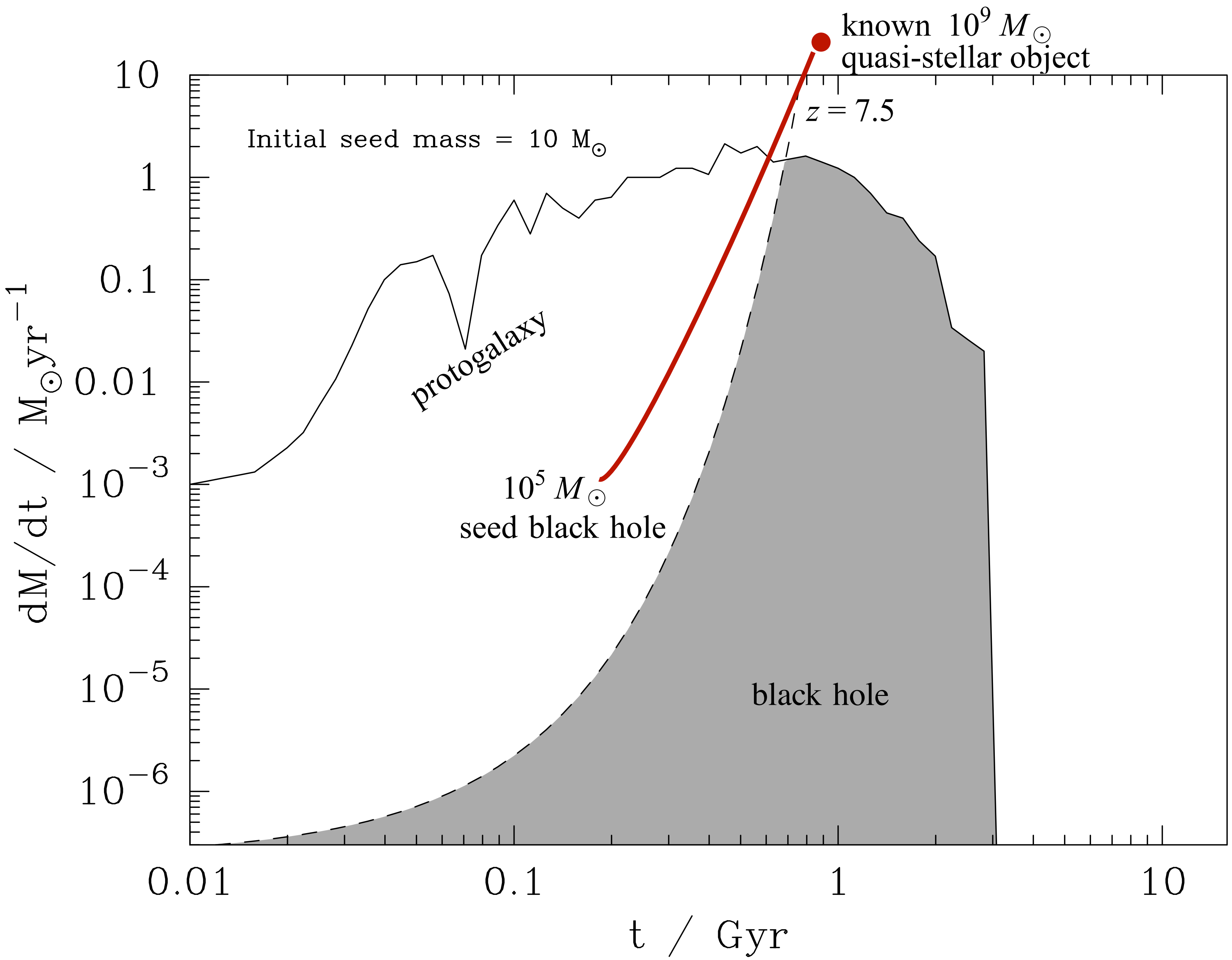
Evidence for Intermediate-Mass Black Holes



[Takekawa *et al.* 2020]

- A number of intermediate-mass black holes ($10^4 - 10^5\, M_\odot$) have been identified in the Galactic Centre, using high-angular resolution ALMA and radio data.

Massive Objects at high Redshifts



[Archibald *et al.* 2002];
(Hasinger priv. comm.)

- ★ Detection of QSOs at high redshifts, such as $\sim 10^9\,M_\odot$ at $z \approx 7.5$

  [Wang *et al.* 2021]

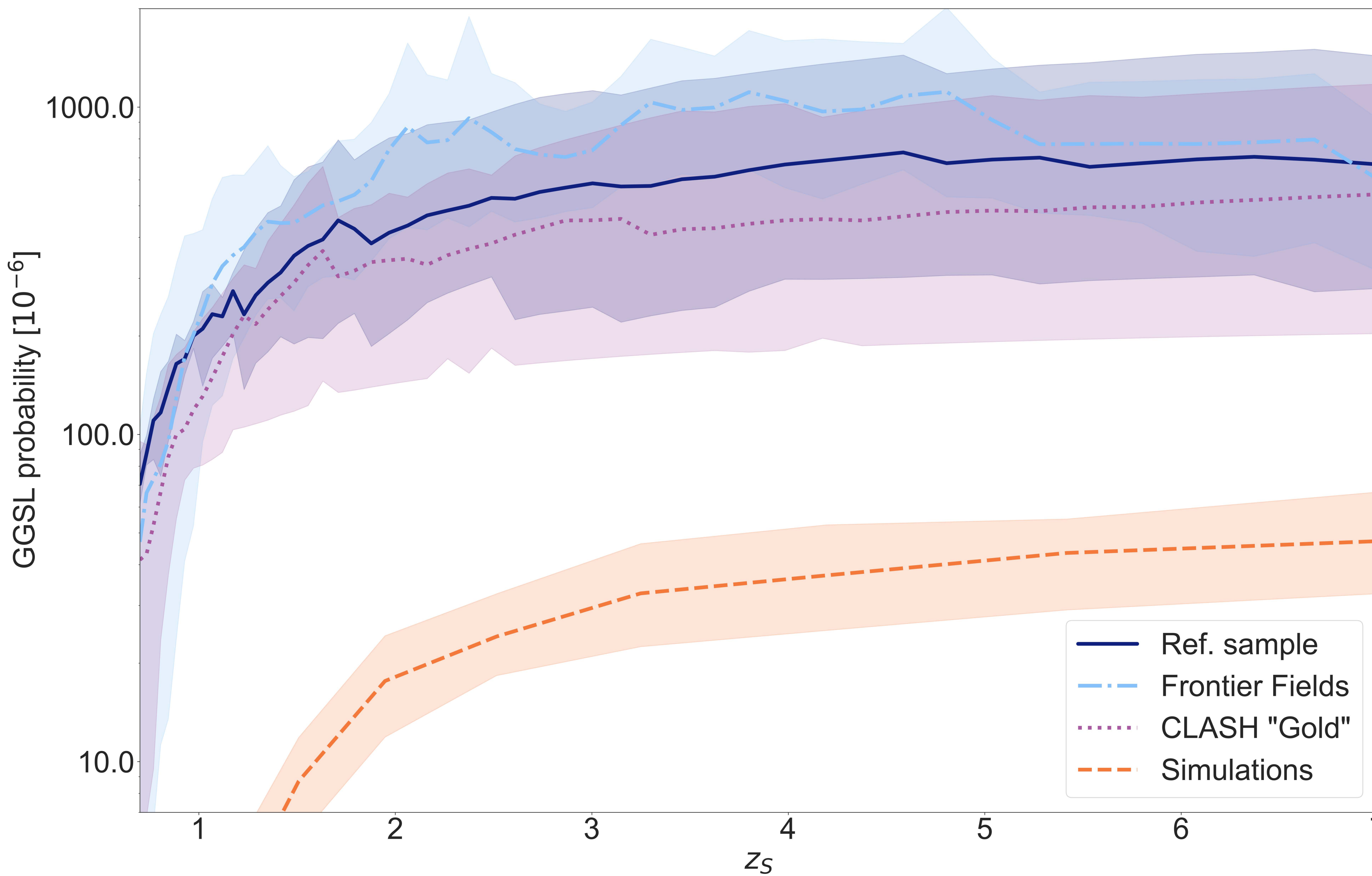
  or $\sim 10^8\,M_\odot$ at $z \approx 13$.

  [Pacucci *et al.* 2022]

  and numerous others.

- ★ Need massive black holes $\sim 10^{4-5}\,M_\odot$ in the early Universe.

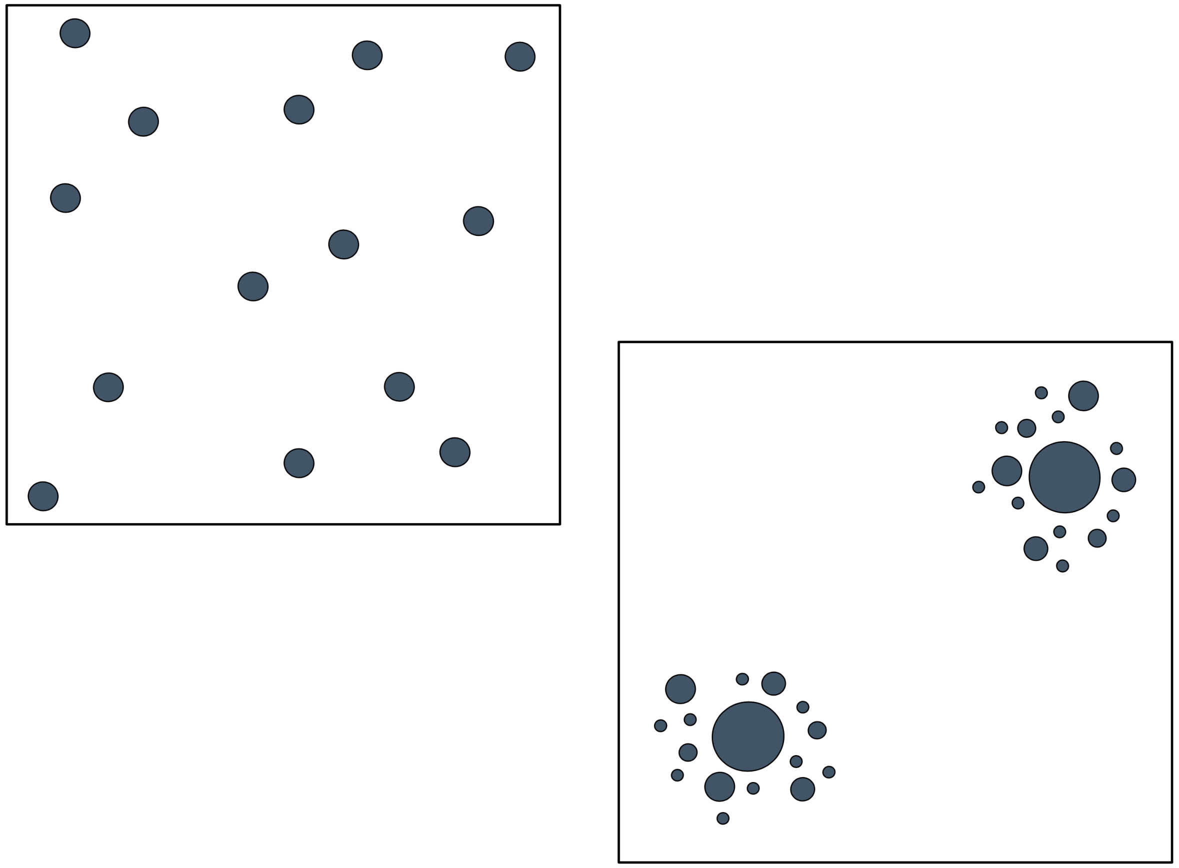
Evidence of Dark Matter Clumping with HST



[Meneghetti, Natarajan, Downer 2020]

Evidence of Dark Matter Clumping with HST

[Meneghetti, Natarajan, Downer 2020]



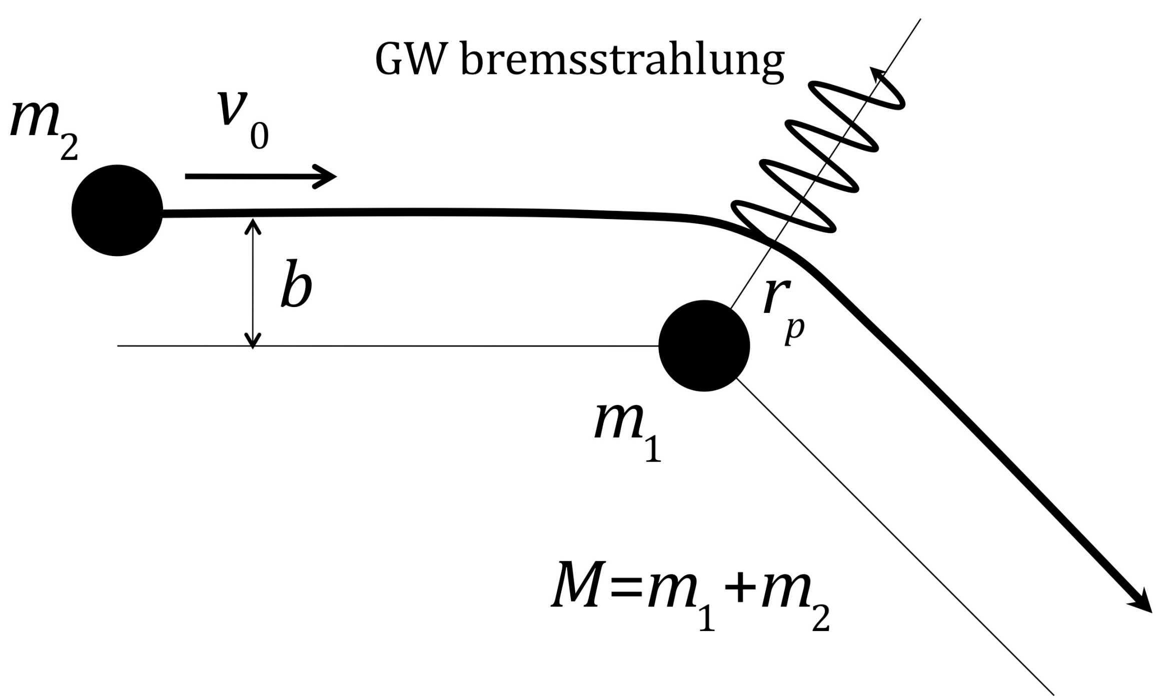
[García-Bellido 2018]

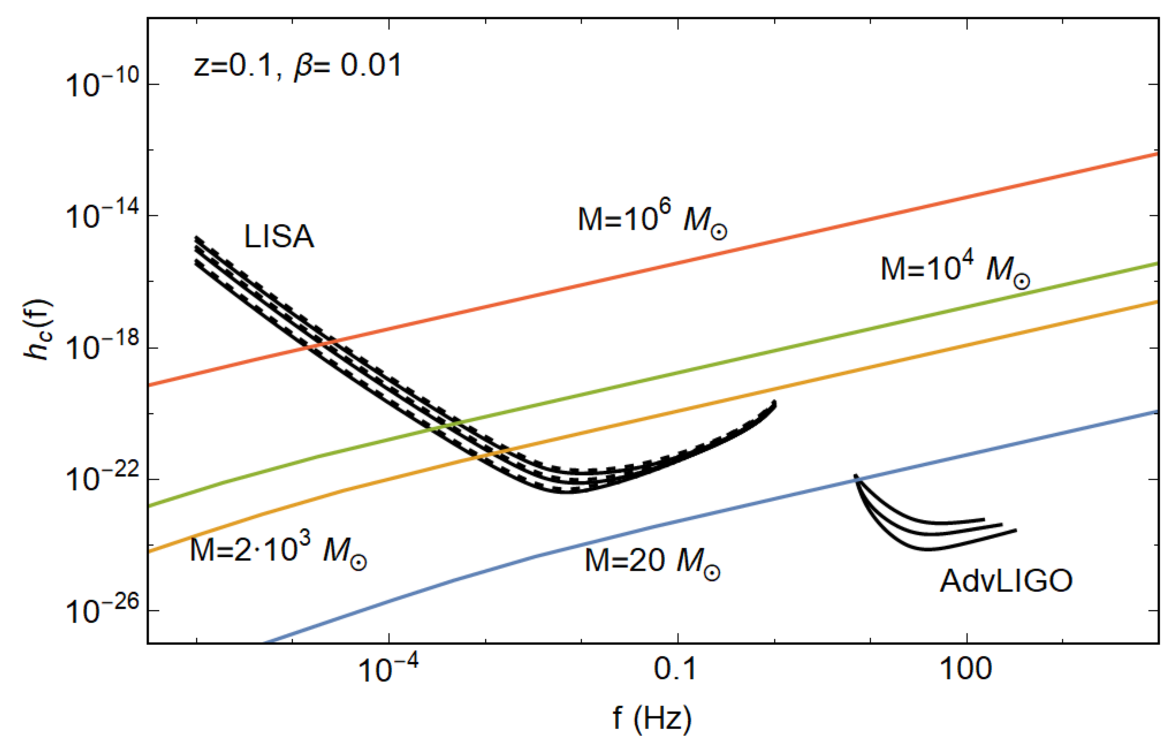
homogeneous versus clumped dark matter distribution

★ This is the norm for PBHs!

Gravitational Waves form PBHs

- PHBs can emit gravitational waves in various instances and times.
  - Gravitational waves from PBH formation.
  - Gravitational-wave emission from PBH binaries:
    1) Stochastic GW background
    2) Individual mergers
  - Gravitational-wave emission from hyperbolic PBH encounters.

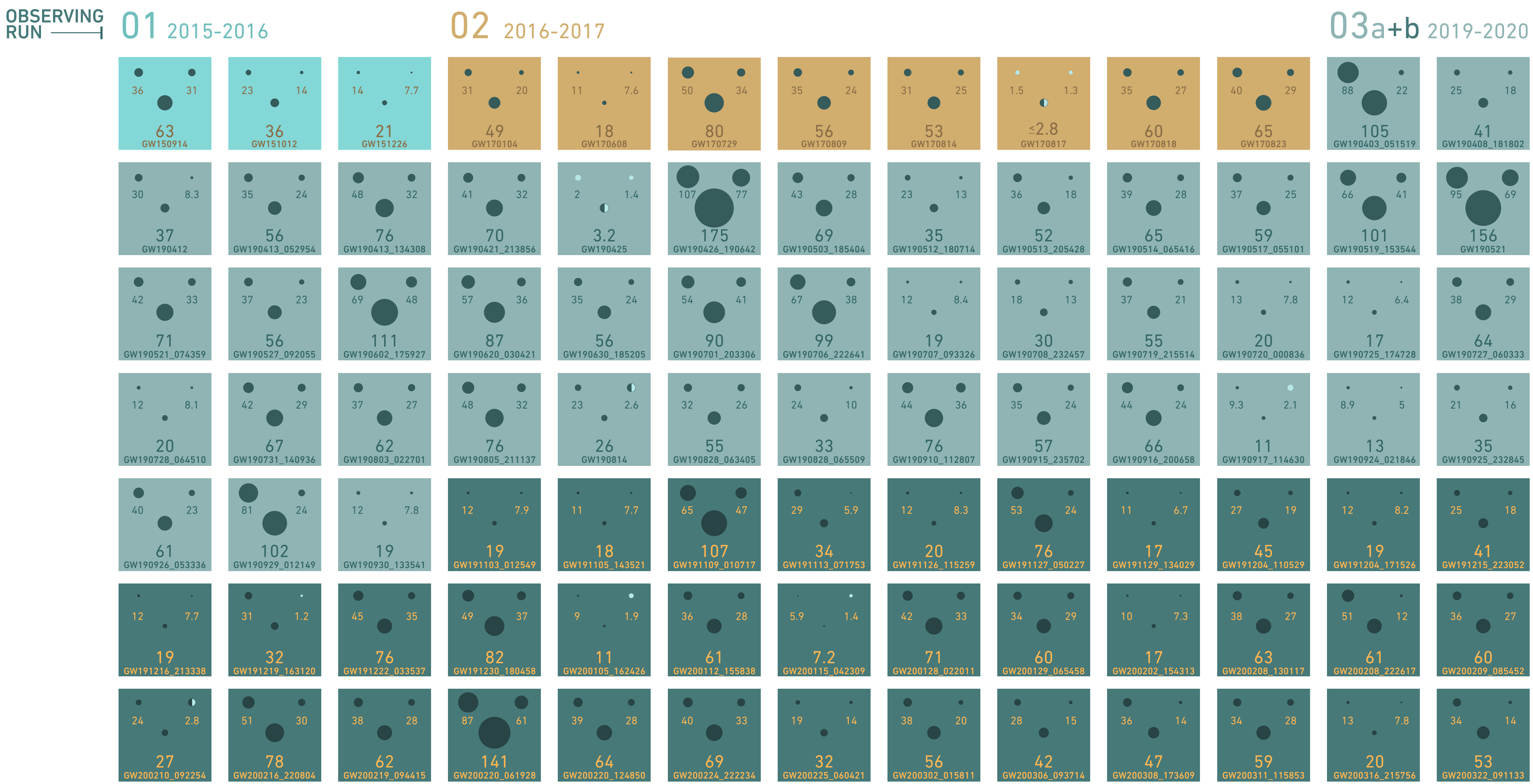




[Garcia-Bellido & Nesseris 2017]

GRAVITATIONAL WAVE **MERGER** DETECTIONS

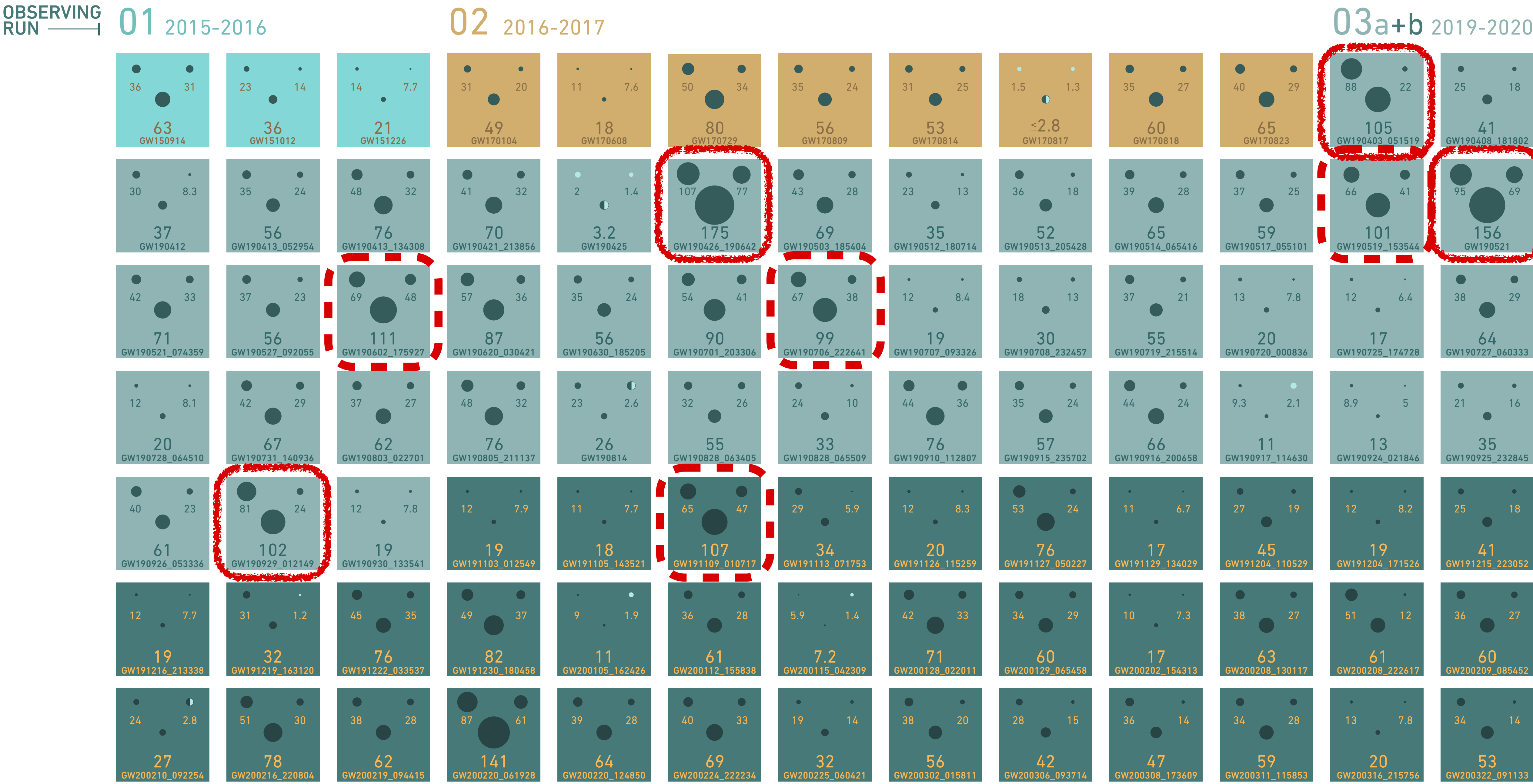
SINCE 2015



LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

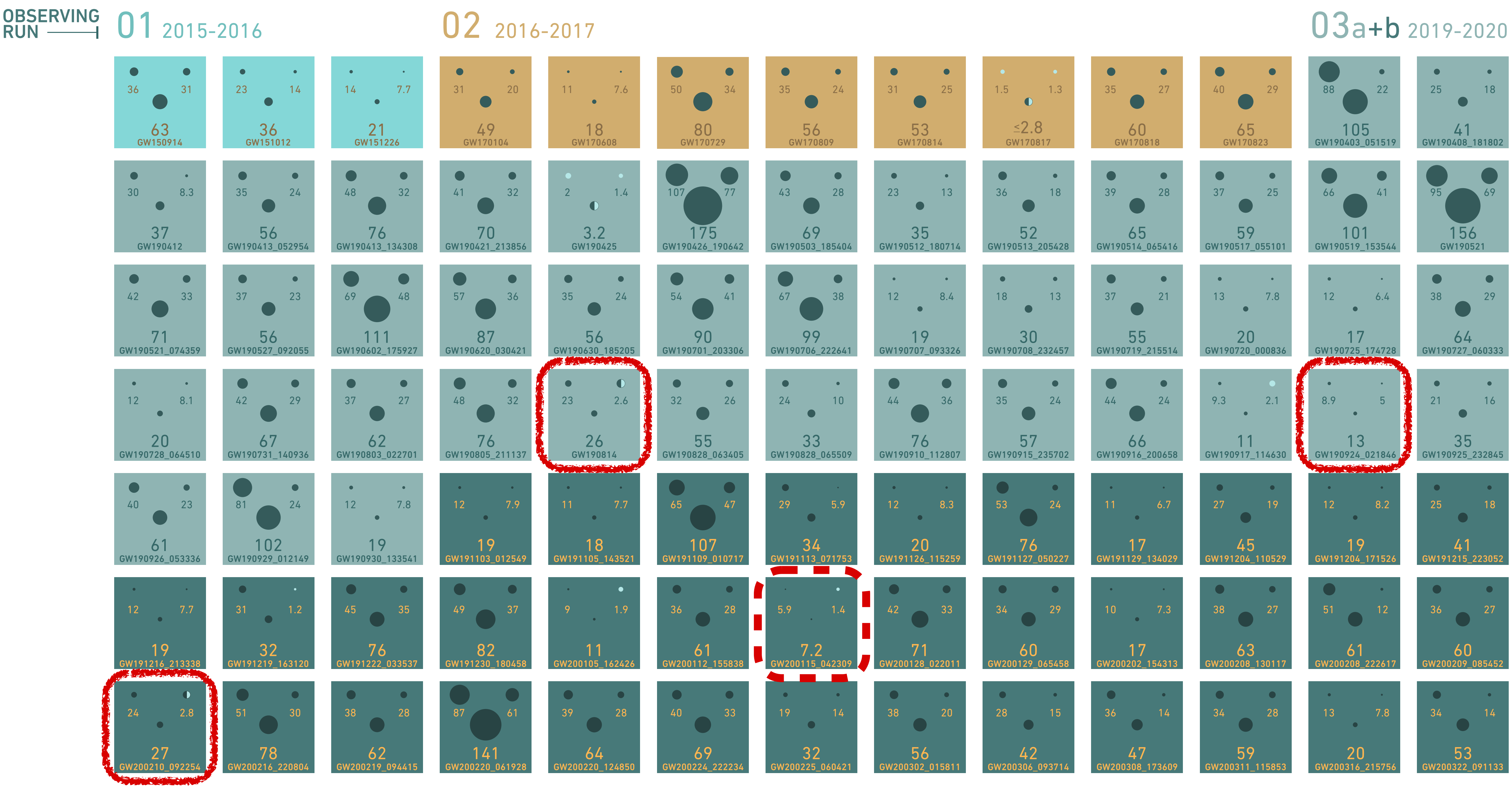


★ Black hole progenitors in the pair-instability mass gap (i.e. above ~ 60 $M_\odot$)

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

SINCE 2015

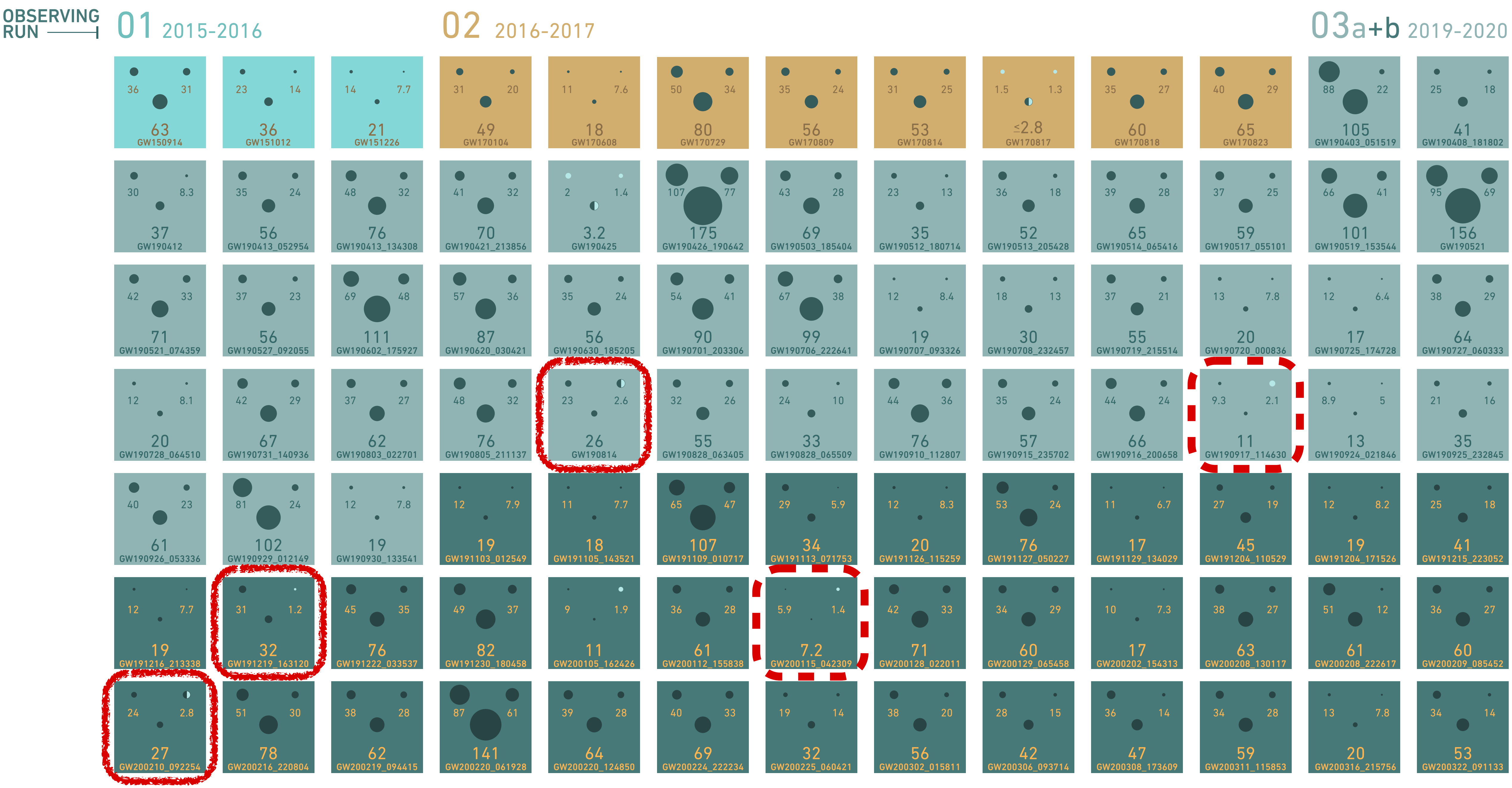


★ Black hole progenitors in the lower mass gap (i.e. between 2 and 5 $M_\odot$)

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

SINCE 2015



★ Asymmetric black hole progenitors (mass ratio $q < 0.25$)

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

THE ASTROPHYSICAL JOURNAL LETTERS, 896:L44 (20pp), 2020 June 20 https://doi.org/10.3847/2041-8213/ab960f

GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object

R. Abbott[1], [...]

Abstract

We report the observation of a compact binary coalescence involving a 22.2–24.3 $M_\odot$ black hole and a compact object with a mass of 2.50–2.67 $M_\odot$ [...] the combination of mass ratio, component masses, and the inferred merger rate for this event challenges all current models of the formation and mass distribution of compact-object binaries.

★ Asymmetric black hole progenitors (mass ratio $q < 0.25$)

LIGO VIRGO KAGRA

Subsolar Black Holes - The Smoking Gun!

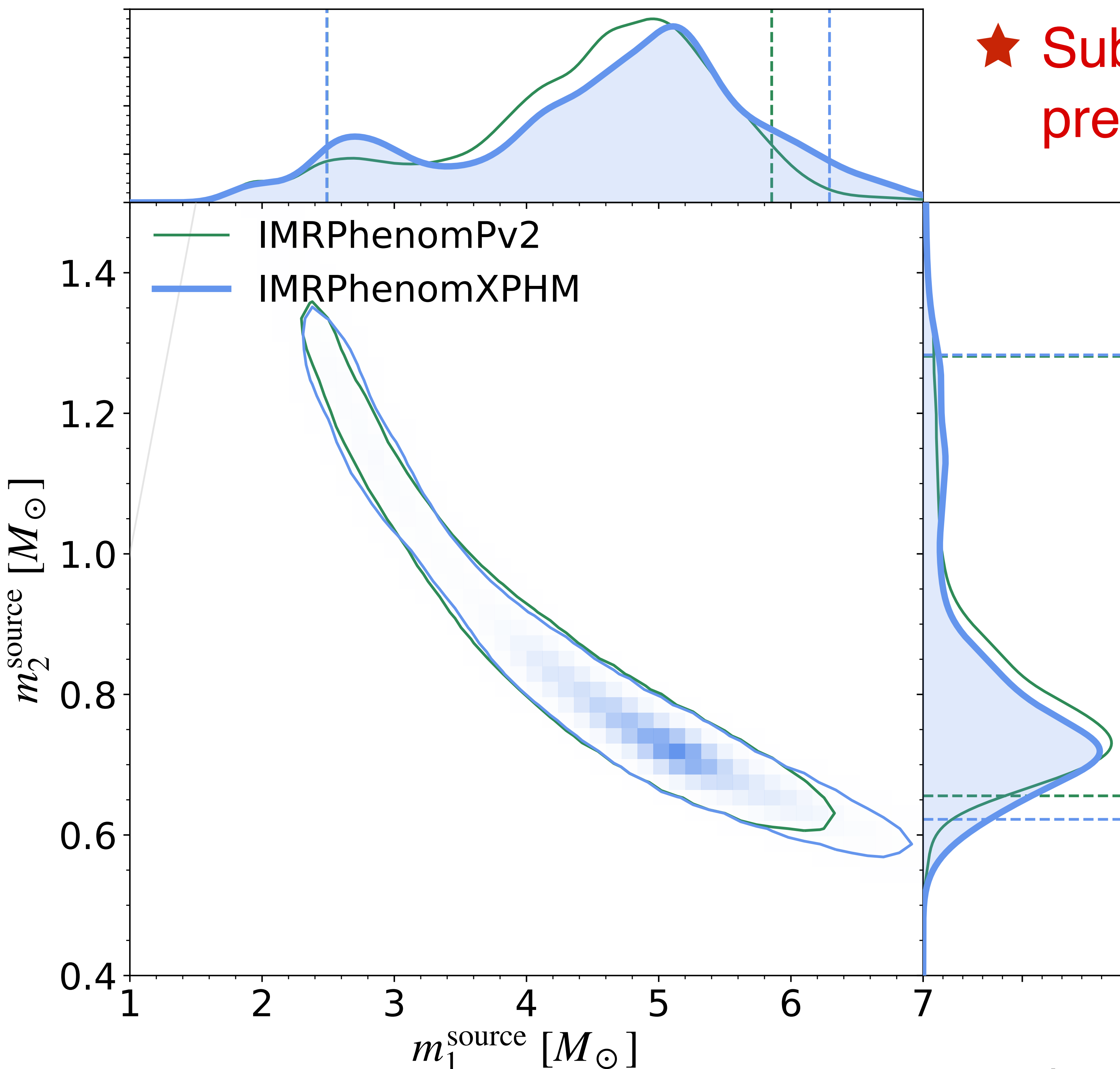
★ Recent reanalysis of LIGO data updated merger rates and low mass ratios:

Date	FAR [yr^{-1}]	$m_1[M_\odot]$	$m_2[M_\odot]$	spin-1-z	spin-2-z	H SNR	L SNR	V SNR	Network SNR
2017-04-01	0.41	4.90	0.78	−0.05	−0.05	6.32	5.94	–	8.67
2017-03-08	1.21	2.26	0.70	−0.04	−0.04	6.32	5.74	–	8.54
2020-03-08	0.20	0.78	0.23	0.57	0.02	6.31	6.28	-	8.90
2019-11-30	1.37	0.40	0.24	0.10	−0.05	6.57	5.31	5.81	10.25
2020-02-03	1.56	1.52	0.37	0.49	0.10	6.74	6.10	-	9.10

★ Five strong subsolar candidates with SNR > 8 and a FAR < 2 yr^{-1}

★ Possibly the first confirmed detection of a subsolar mass PBH with the next 24 months!

Posterior probability for SSM170401



★ Subsolar-mass m_2 preferred at 84% CL.

[Morrás *et al.* 2023]

Subsolar PBHs Discovered in the next 24 Months?

[Chris van den Broeck]

contra

pro

[me]

Subsolar PBHs Discovered in the next 24 Months?

[Chris van den Broeck]

contra

the wager

pro

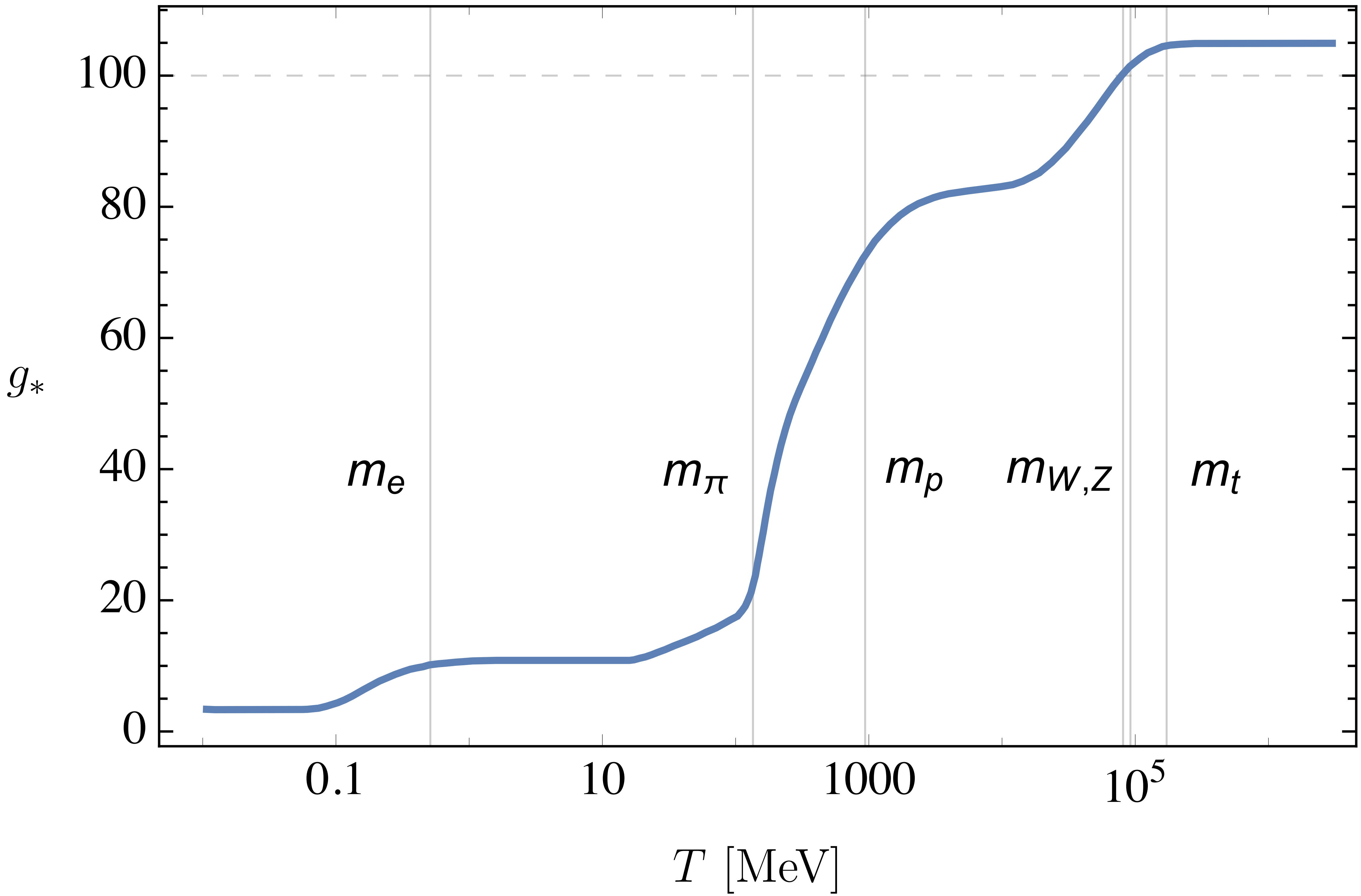
[me]

A Unified Scenario

*work with Carr, Clesse, García-Bellido

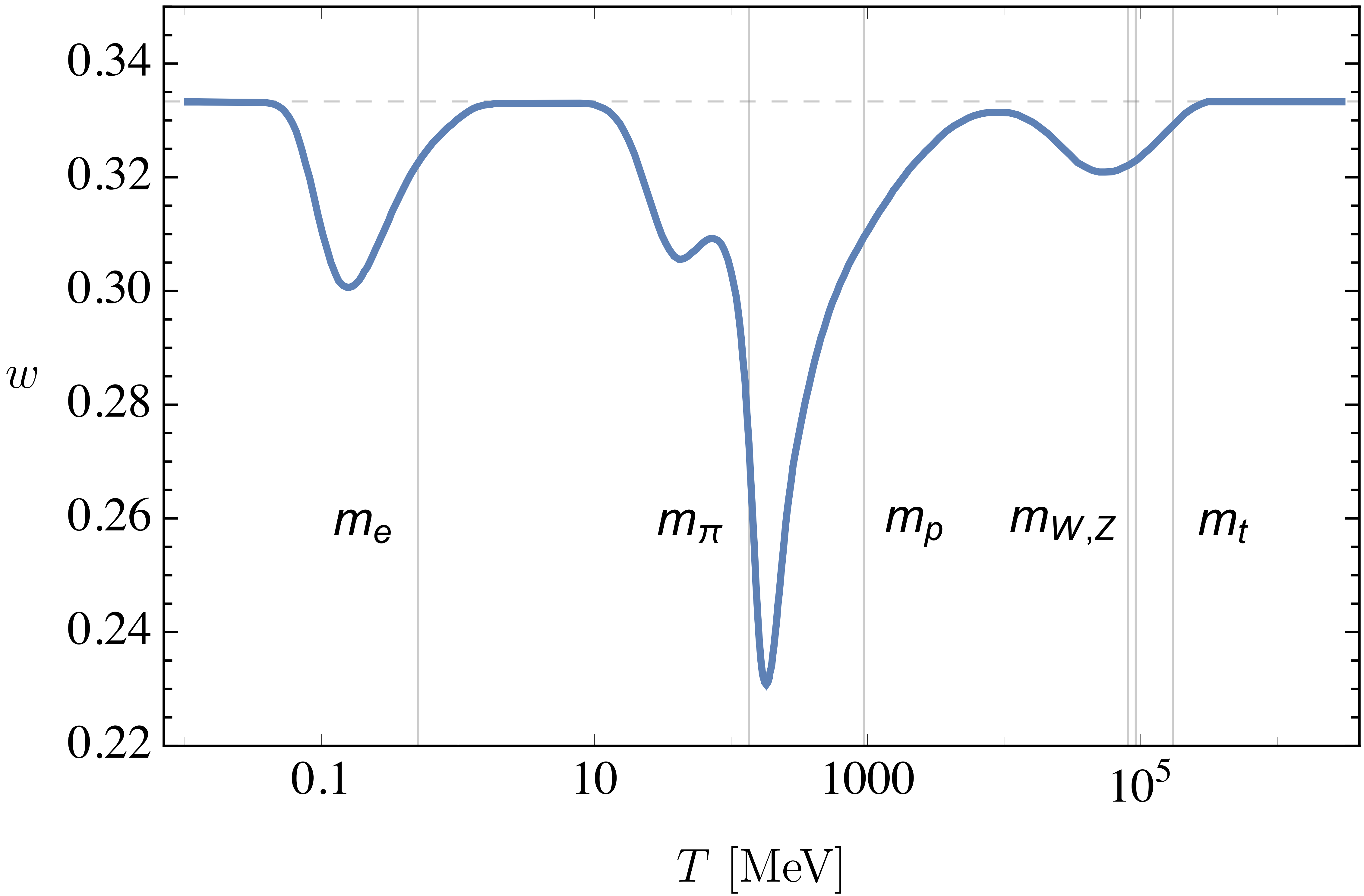
Thermal History of the Universe — Degrees of Freedom

★ Changes in the relativistic degrees of freedom:



Thermal History of the Universe — Equation of State

★ Changes in the equation-of-state parameter $w = p/\rho$:



Primordial Power Spectrum — Planck to PBH

★ Consider an essentially featureless power spectrum:

$$\mathcal{P}(k) \sim k^{n_s - 1 + \frac{1}{2}\alpha_s \ln(k/k_*)}$$

as suggested by Planck, albeit on *large non-PBH scales*...

★ Connection to *small PBH scales* for instance by critical Higgs inflation.

[García-Bellido, Ruiz-Morales 2017]

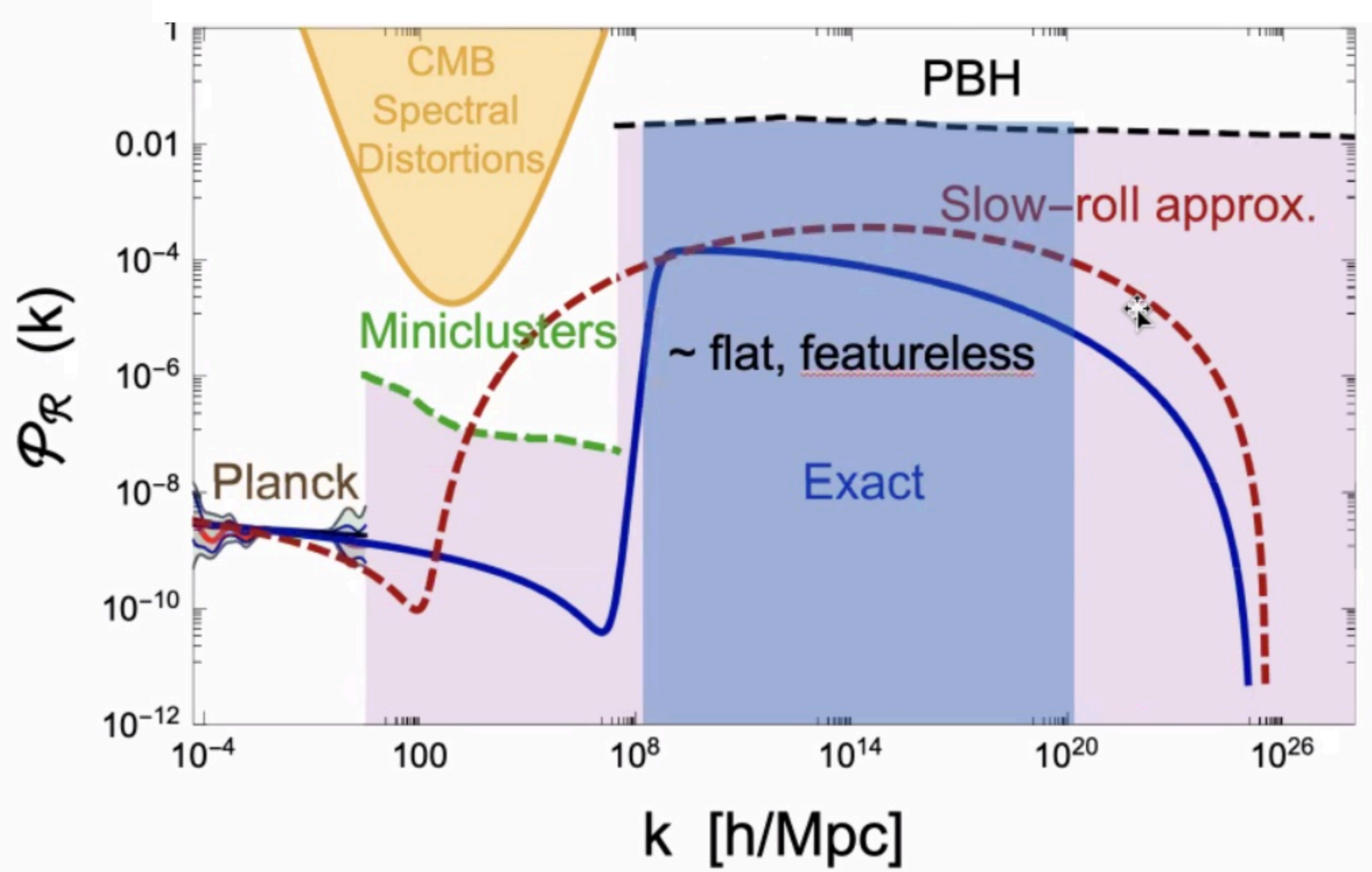
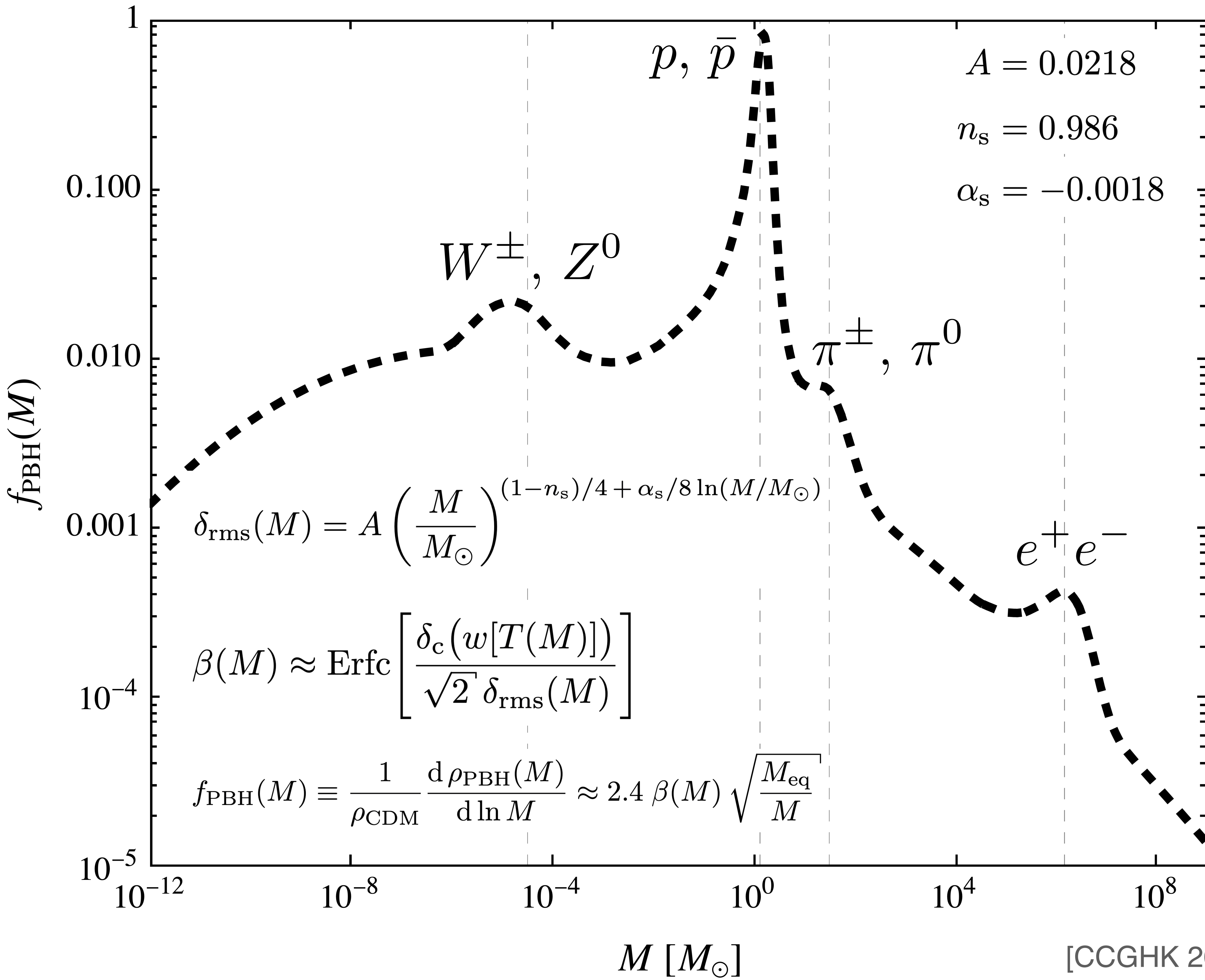


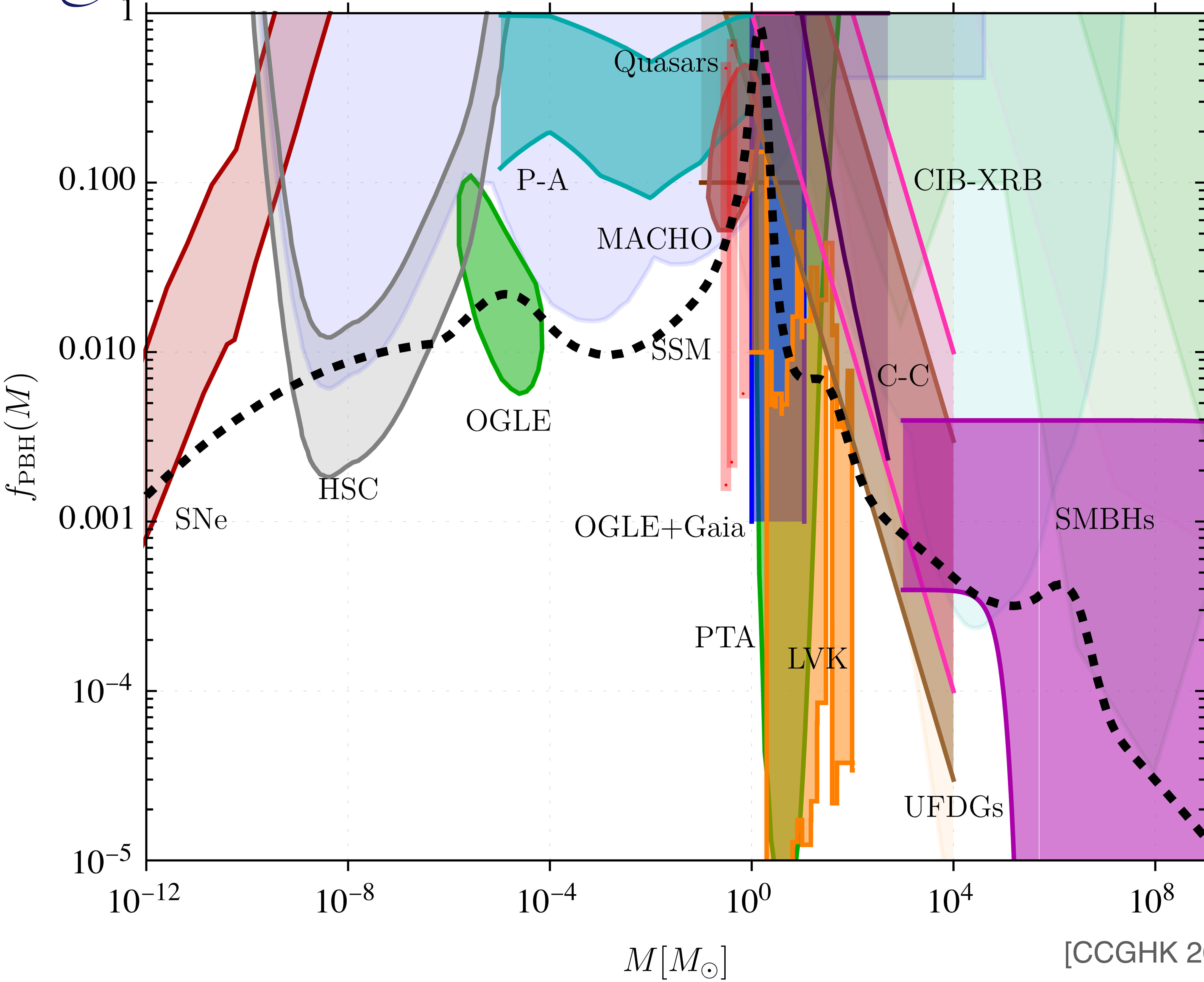
Figure from García-Bellido

PBH Mass Function



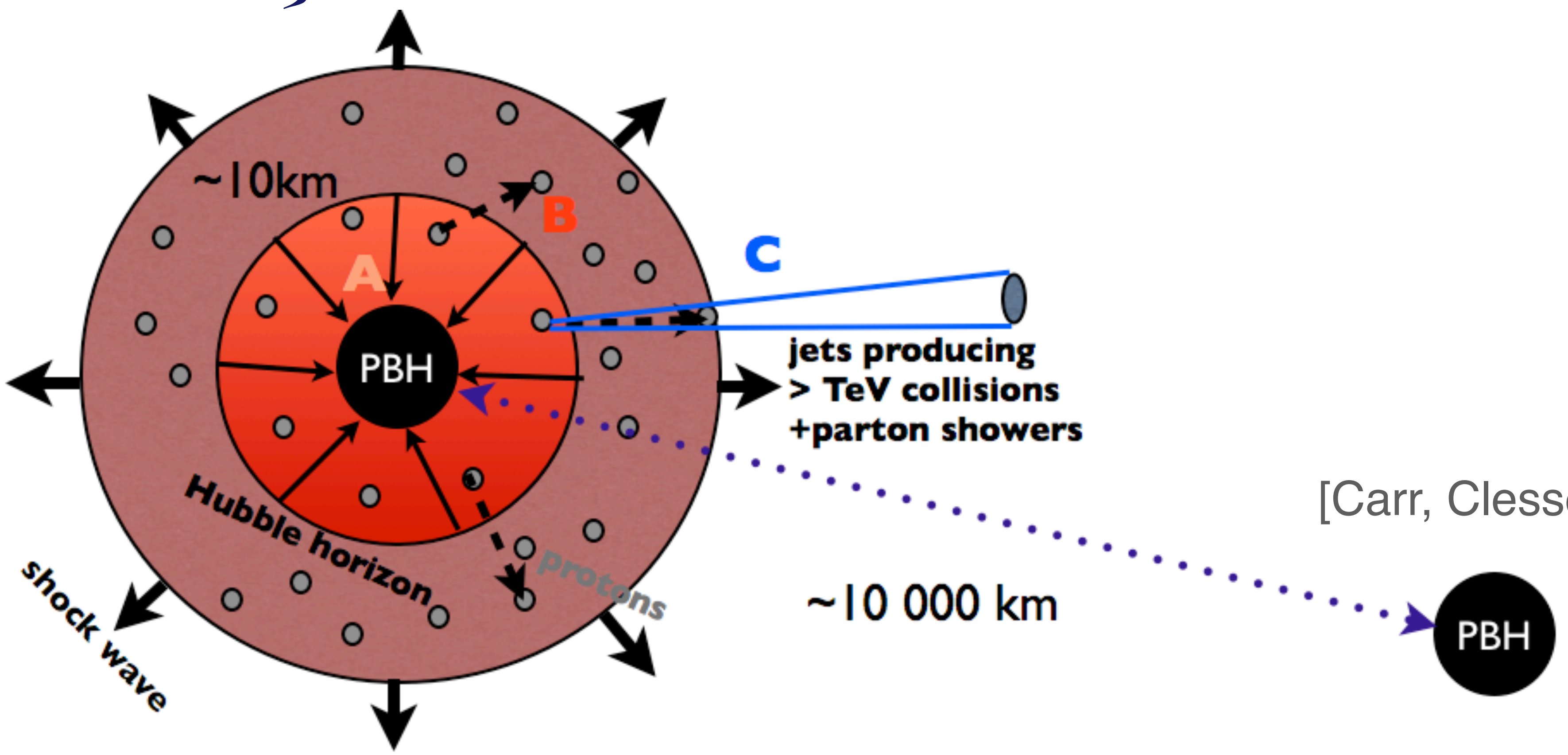
[CCGHK 2023]

Connecting all Positive Evidences!



[CCGHK 2023]

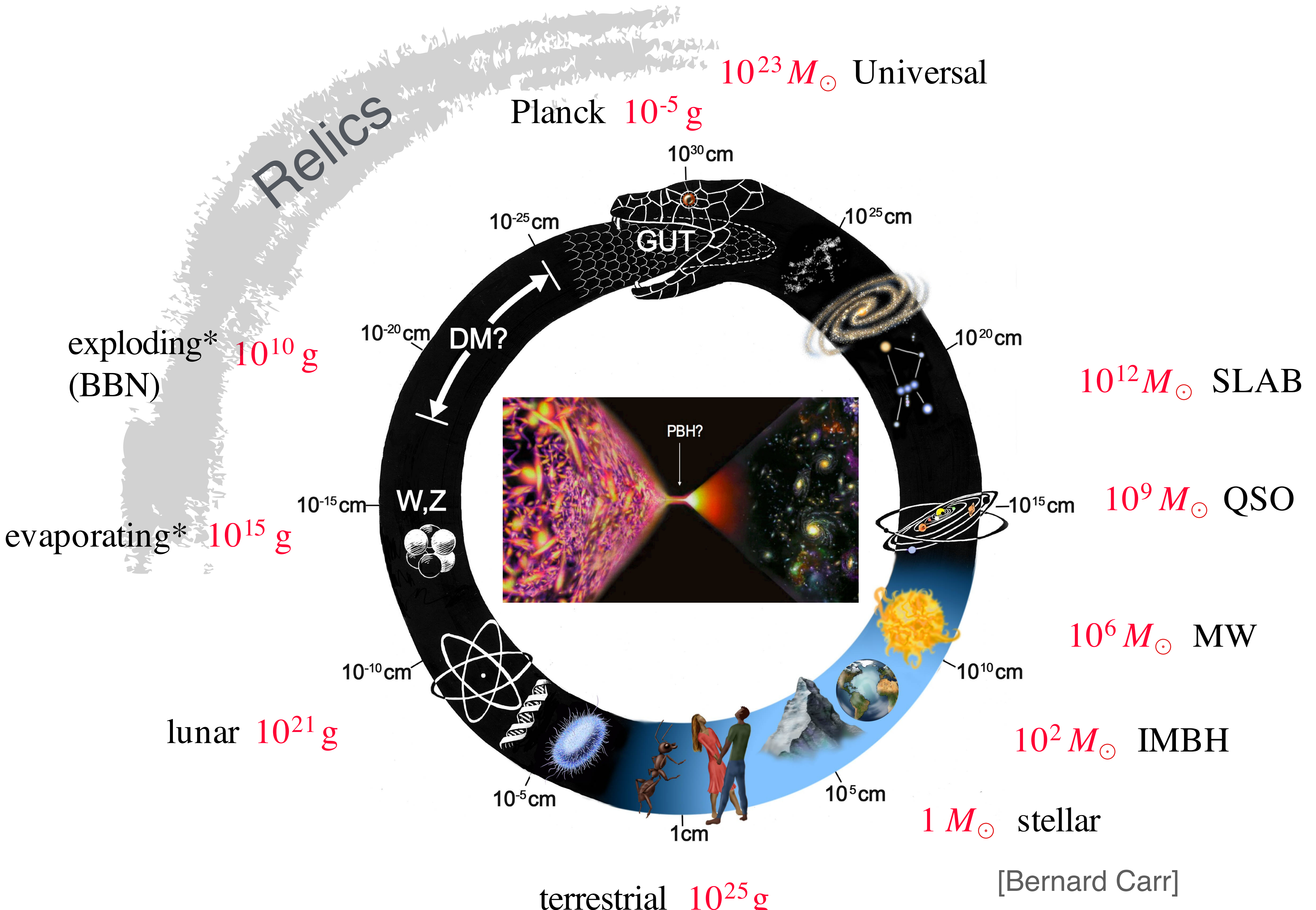
Primordial Supernovae



[Carr, Clesse, García-Bellido 2020]

- ★ PBH collapse during the QCD transition accelerates particles over several orders of magnitude above their rest mass.
- ★ Interactions in the surrounding high-density plasma lead to electro-weak sphaleron processes.
- ★ This *locally* yields an $\mathcal{O}(1)$ baryon asymmetry.
- ★ The fraction of PBHs 10^{-9} in turn explains the observed baryon asymmetry of the Universe!

Black Holes as a Link between Micro and Macro Physics



[Bernard Carr]

*Image of snake from Abrams & Primack 2012

Shall Ye Become Positivists!

Observational Evidence for Primordial Black Holes: A Positivist Perspective

B. J. Carr,[1,*] S. Clesse,[2,†] J. García-Bellido,[3,‡] M. R. S. Hawkins,[4,§] and F. Kühnel[5,¶]

[1]*School of Physics and Astronomy, Queen Mary University of London*

[2]*Service de Physique Théorique, University of Brussels (ULB)*

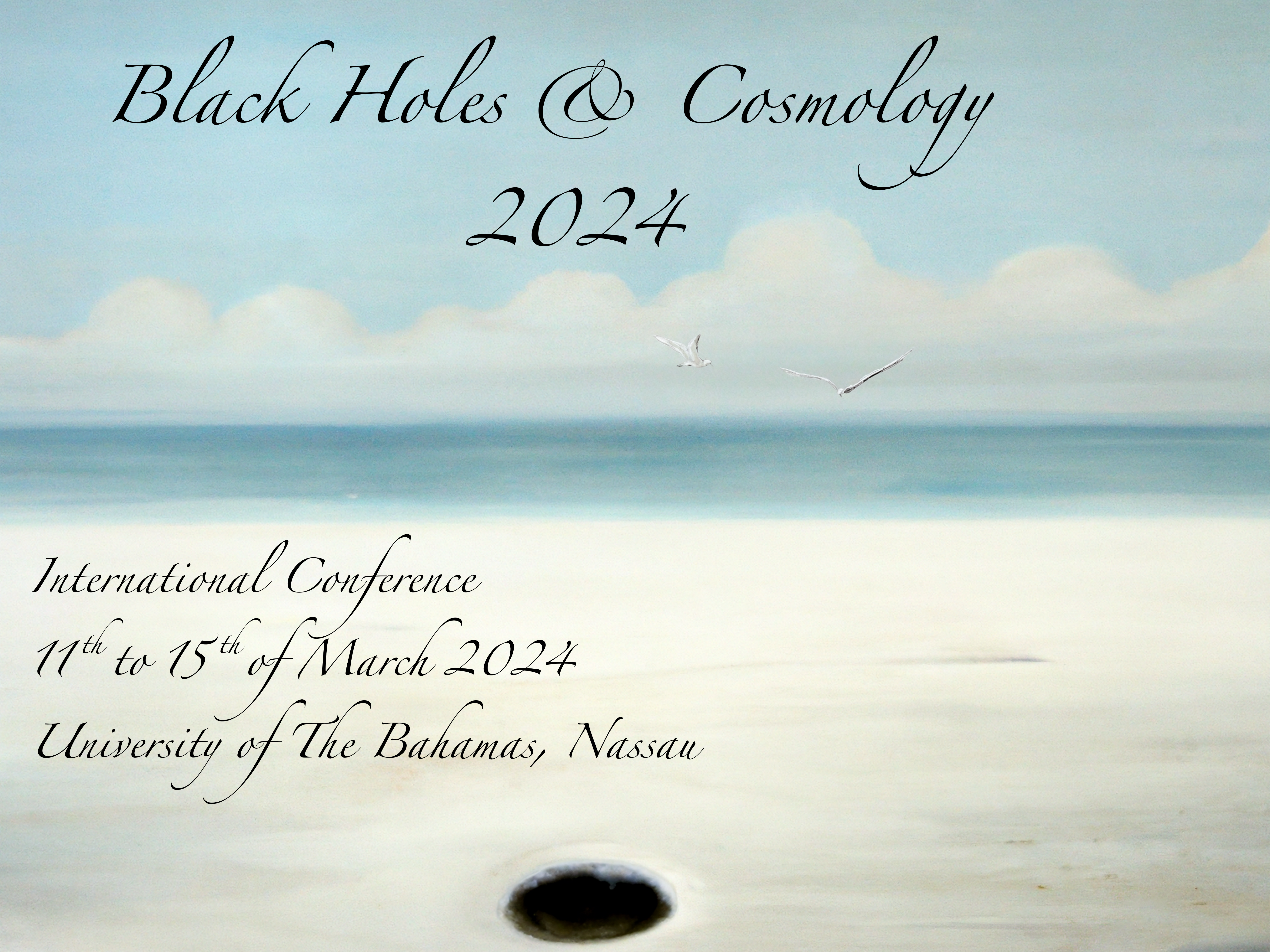
[3]*Instituto de Física Teórica, Universidad Autonóma de Madrid*

[4]*Royal Observatory Edinburgh*

[5]*Max Planck Institute for Physics,*

(Dated: Wednesday 7th June, 2023, 12:34am)

We review numerous arguments for primordial black holes (PBHs) based on observational evidence from a variety of lensing, dynamical, accretion and gravitational-wave effects. This represents a shift from the usual emphasis on PBH constraints and provides what we term a positivist perspective. Microlensing observations of stars and quasars suggest that PBHs of around $1\,M_\odot$ could provide much of the dark matter in galactic halos, this being allowed by the Large Magellanic Cloud observations if the PBHs have an extended mass function. More generally, providing the mass and dark matter fraction of the PBHs is large enough, the associated Poisson fluctuations could generate the first bound objects at a much earlier epoch than in the standard cosmological scenario. This simultaneously explains the recent detection of high-redshift dwarf galaxies, puzzling correlations of the source-subtracted infrared and X-ray cosmic backgrounds, the size and the mass-to-light ratios of ultra-faint-dwarf galaxies, the dynamical heating of the Galactic disk, and the binary coalescences observed by LIGO/Virgo/KAGRA in a mass range not usually associated with stellar remnants. Even if PBHs provide only a small fraction of the dark matter, they could explain various other observational conundra, and sufficiently large ones could seed the supermassive black holes in galactic nuclei or even early galaxies themselves. We argue that PBHs would naturally have formed around the electroweak, quantum chromodynamics and electron-positron annihilation epochs, when the sound-speed inevitably dips. This leads to an extended PBH mass function with a number of distinct bumps, the most prominent one being at around $1\,M_\odot$, and this would allow PBHs to explain much of the evidence in a unified way.


Black Holes & Cosmology
2024
International Conference
11th to 15th of March 2024
University of The Bahamas, Nassau

Invited Speakers include:

Andreas Albrecht
Gianfranco Bertone
Alessandra Buonanno*
Bernard Carr
Gia Dvali*
Glennys Farrar
Carlos Frenk
Enrique Gaztanaga
Reinhard Genzel *
Shirley Ho*
David Kaiser
Will Kinney
Sasha Kashlinsky
Michela Mapelli
Chris Van Den Broeck
Malcolm Perry
Lisa Randall*
Luciano Rezzolla*
Ravi Sheth
Lárus Thorlacius
Joseph Silk

*to be confirmed

Organisational Committee:

Florian Kühnel (Chair), Juan García-Bellido, Katherine Freese
Eduardo Guendelman, Claude McNamarah, Remo Ruffini

https://indico.mpp.mpg.de/e/BHCos24