Primordial Black Holes: Positivist Perspective and Quantum Quiddity

Florian Kühnel

Max Planck Institute for Physics,
Garching (near Munich), Germany

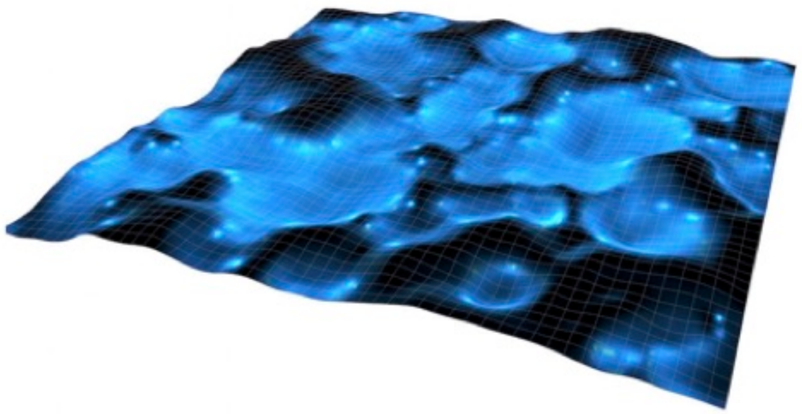
— GEMMA 2, La Sapienza, Rome —

Tuesday, the 17th of September 2024

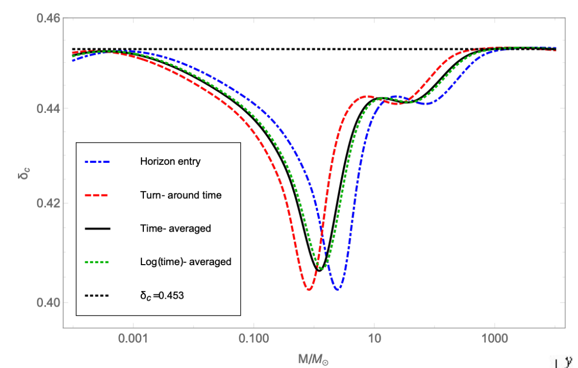
Primordial Black Hole Formation Primer

PBH Formation Mechanisms

- ★ Large density perturbations (inflation)

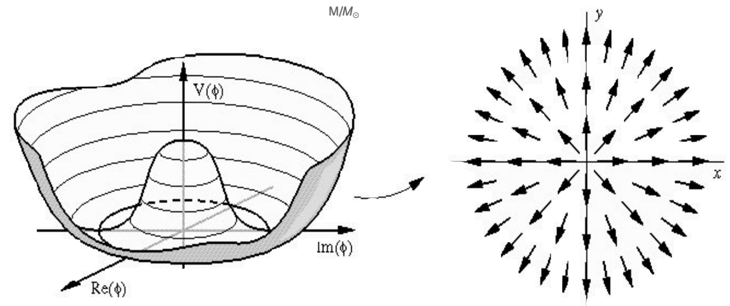


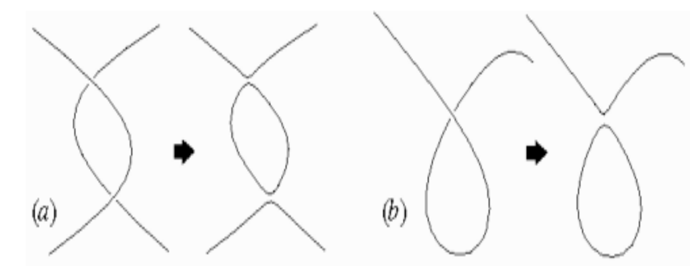
- ★ Pressure reduction



[Byrnes *et al.* 2018]

- ★ Cosmic string loops

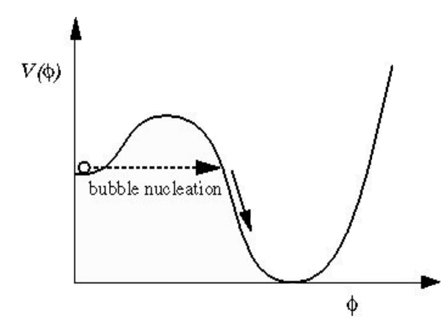


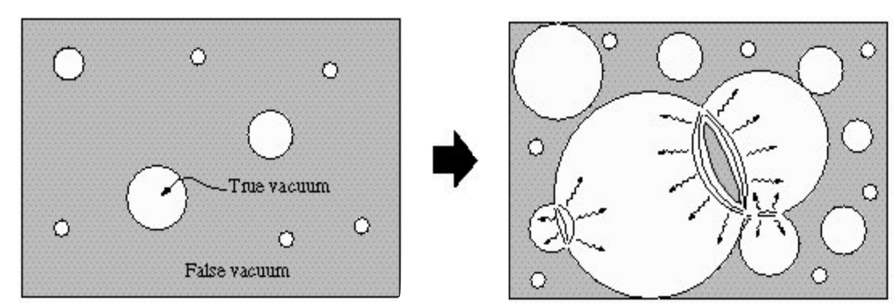


http://www.damtp.cam.ac.uk/research/gr/public/cs_phase.html

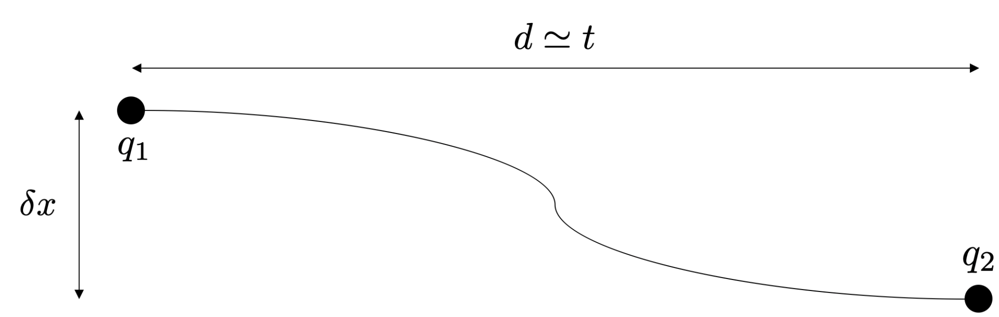
http://www.damtp.cam.ac.uk/research/gr/public/cs_top.html

- ★ Bubble collisions





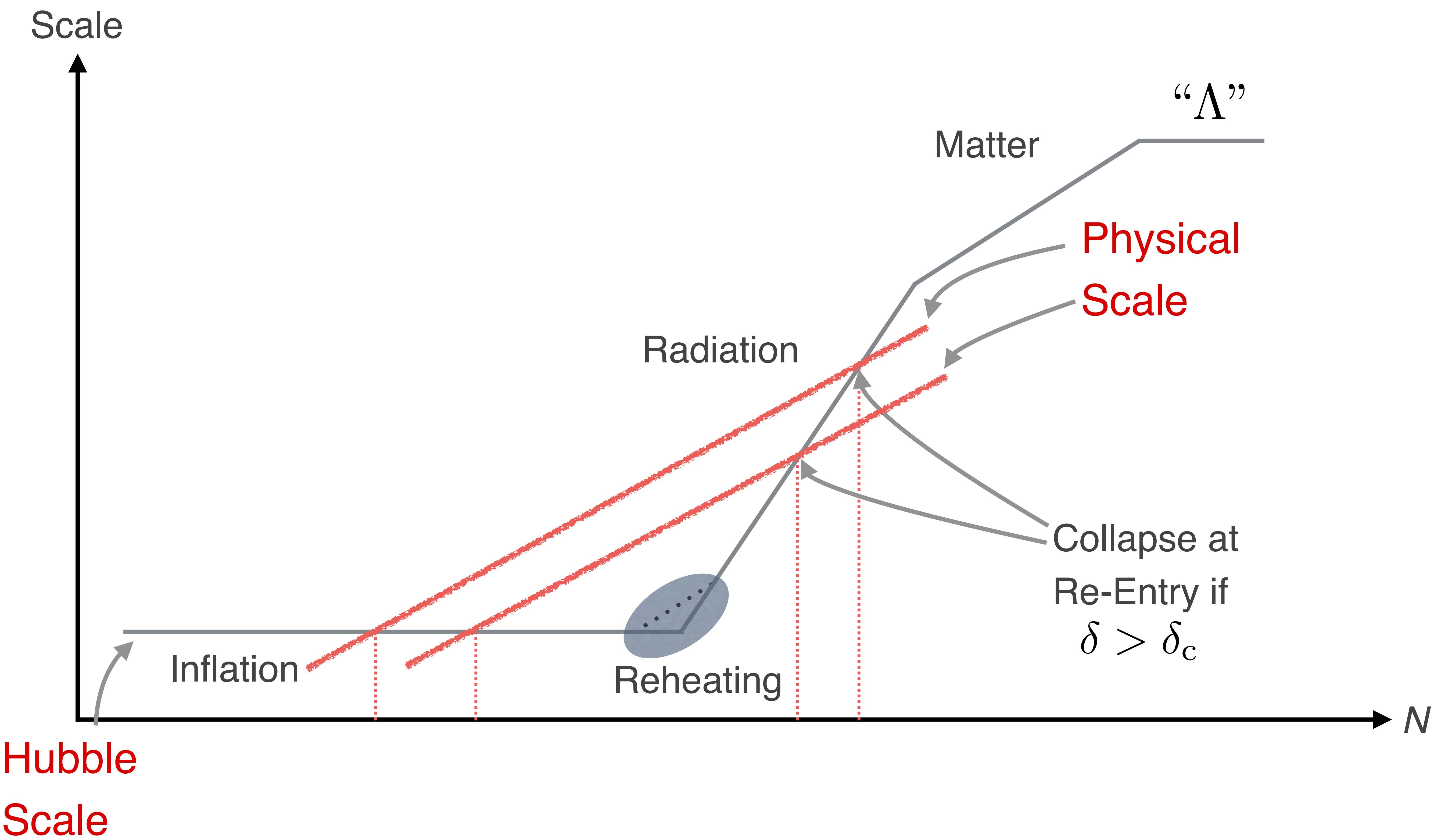
- ★ Quark confinement



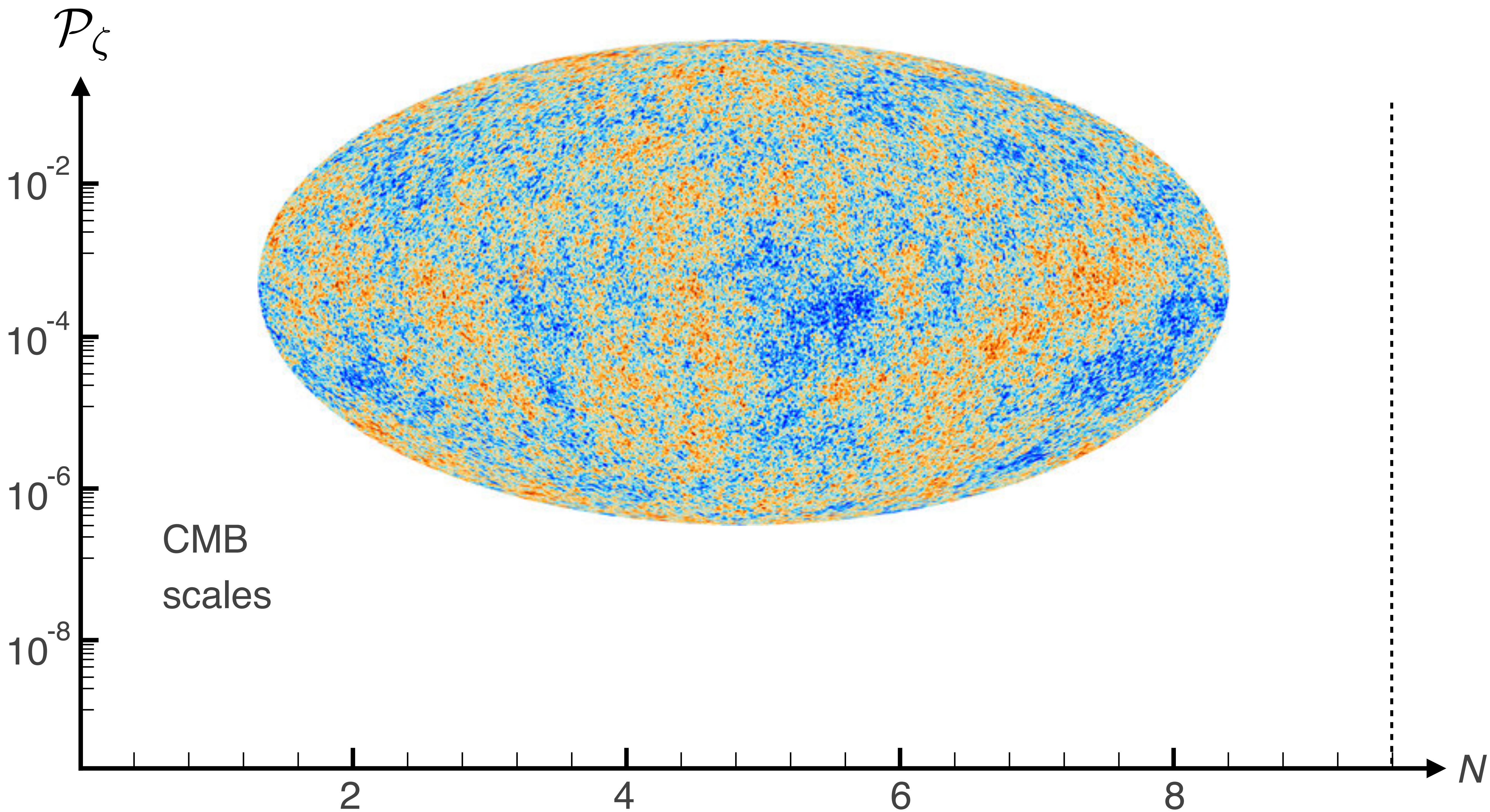
[Dvali, FK, Zantedesschi 2021]

- ★ Scalar-field fragmentation, ...

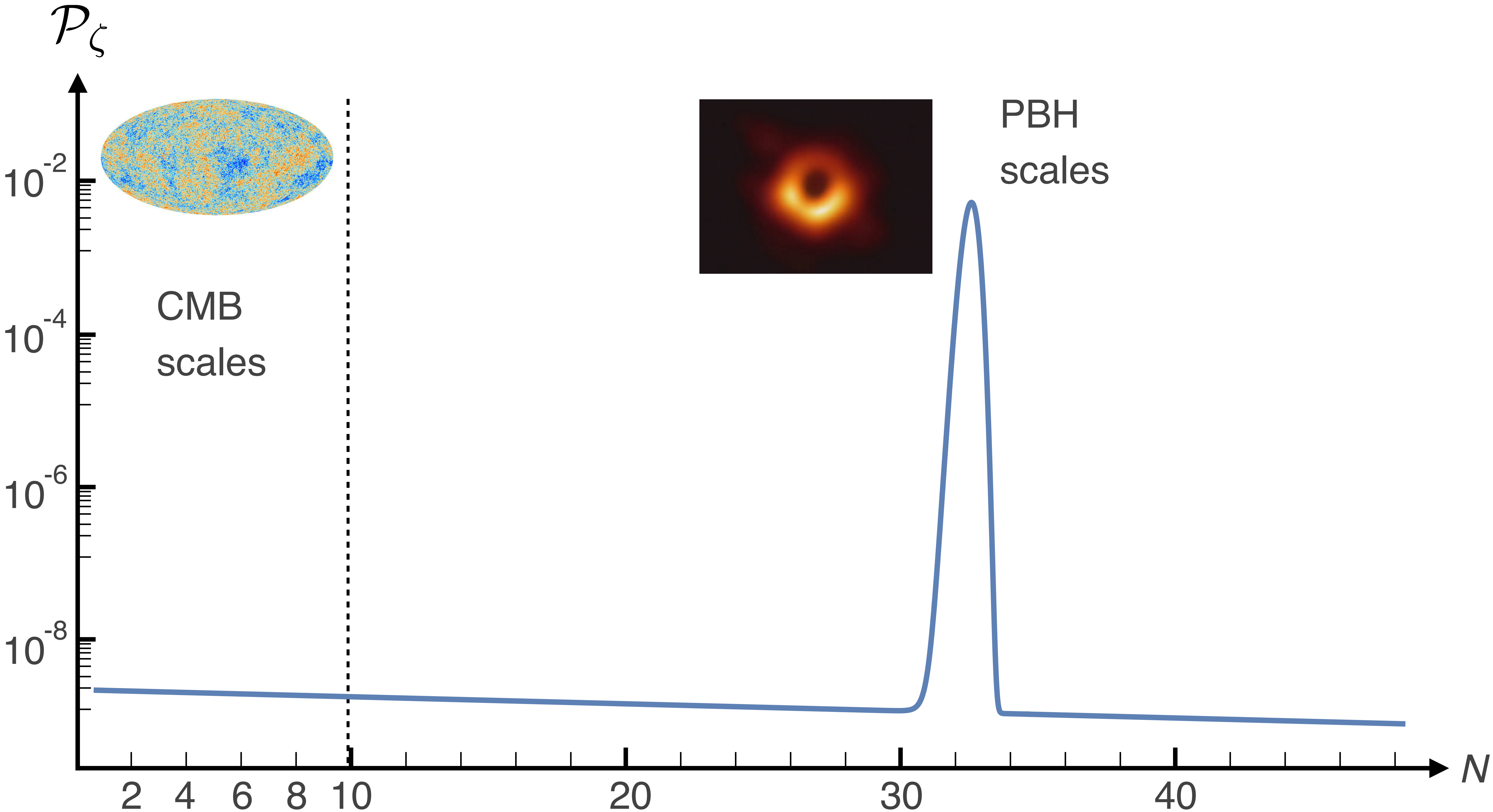
PBH Formation from Inflationary Overdensities



PBH Formation — Scales



PBH Formation — Scales

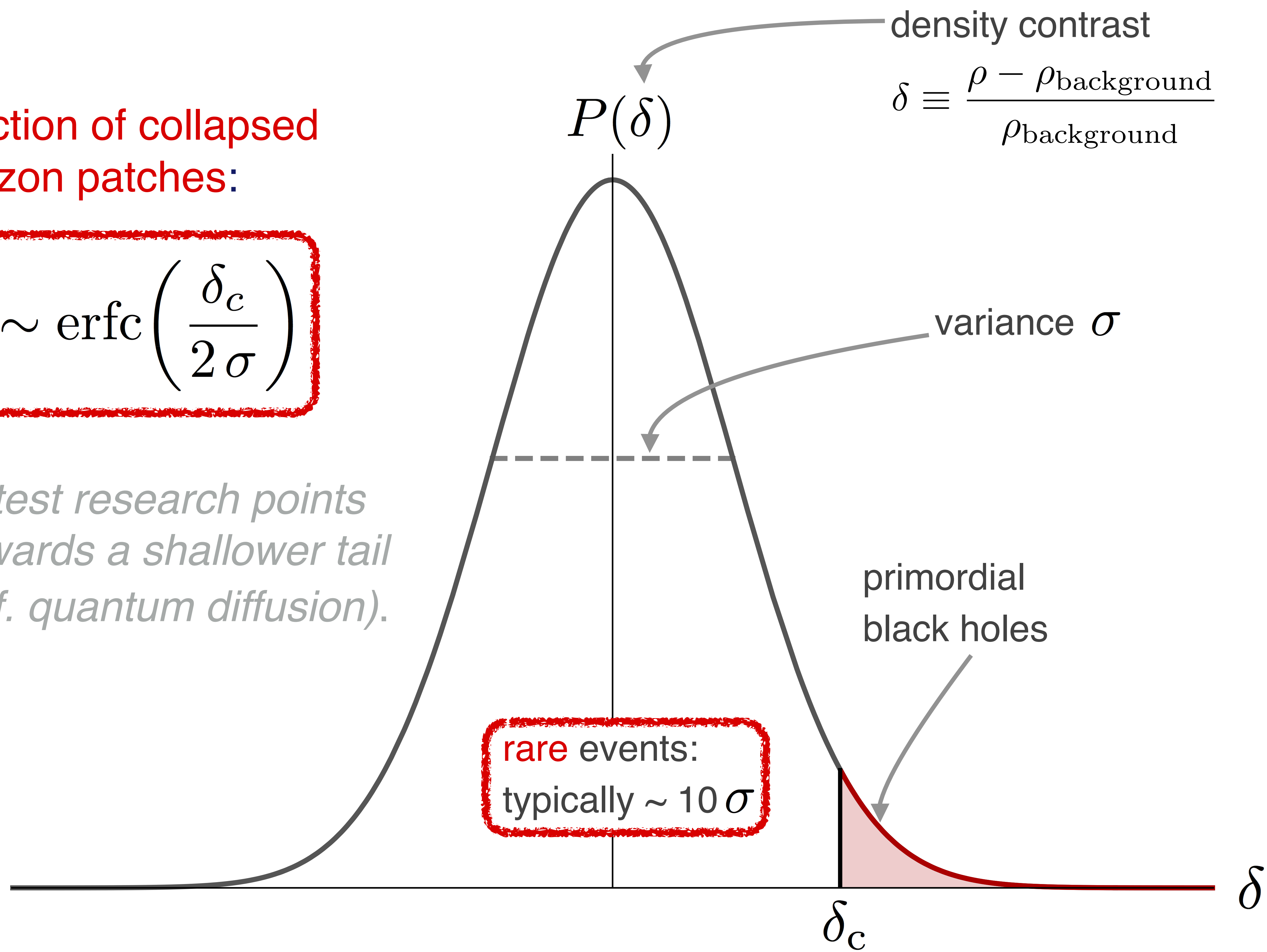


PBH Formation — Rare Events

Fraction of collapsed horizon patches:

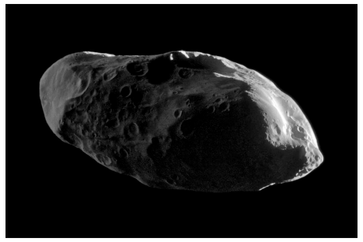
$$\beta \sim \mathrm{erfc}\left(\frac{\delta_c}{2\,\sigma}\right)$$

Latest research points towards a shallower tail (c.f. quantum diffusion).



PBHs — Some Numbers

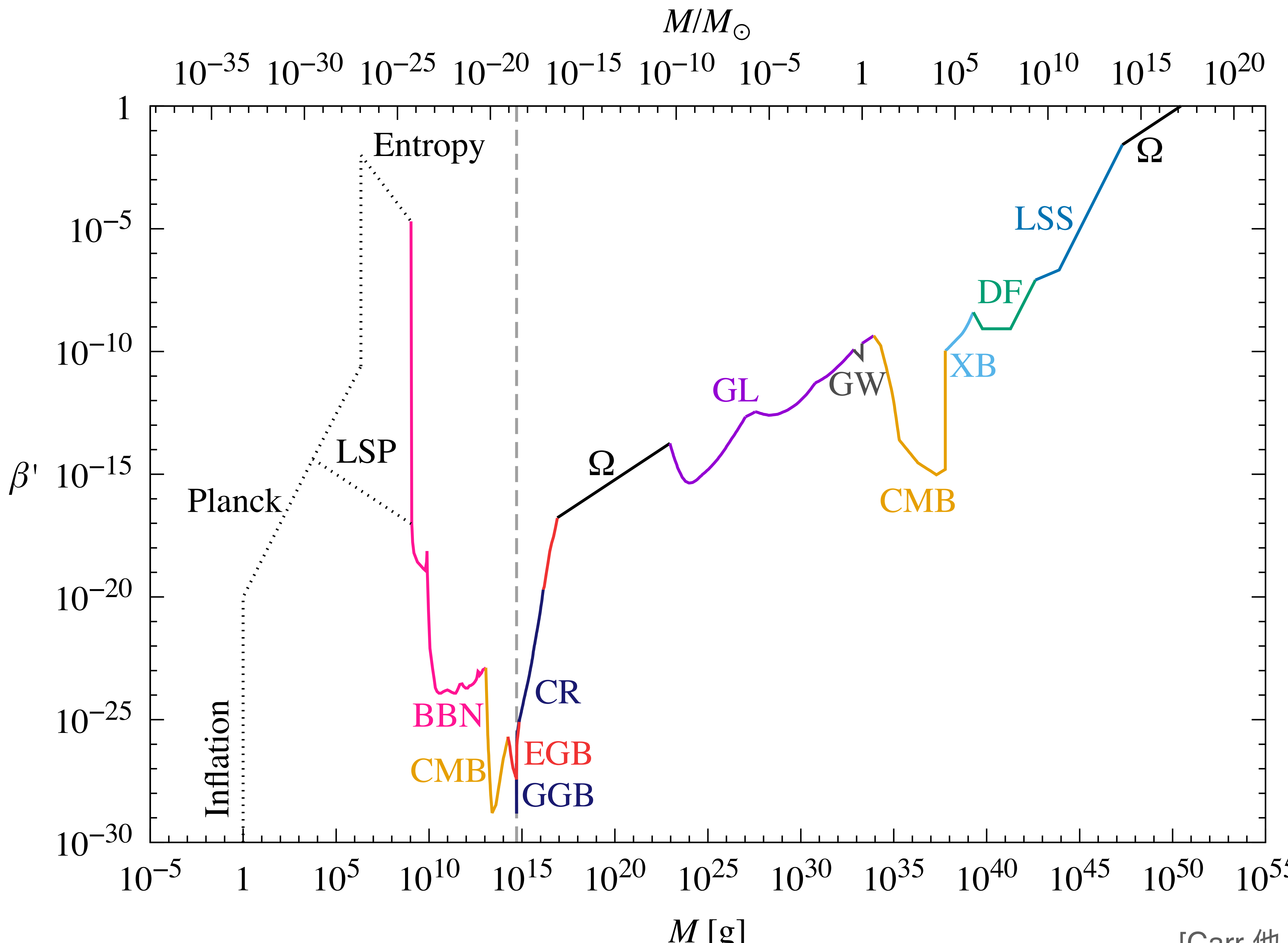
- If primordial black holes constituted all of the dark matter:
    - Assume that all PBH have mass: $10^{20}\ \mathrm{g}$



Saturn satellite *Prometheus*

Primordial Black Hole Constraints

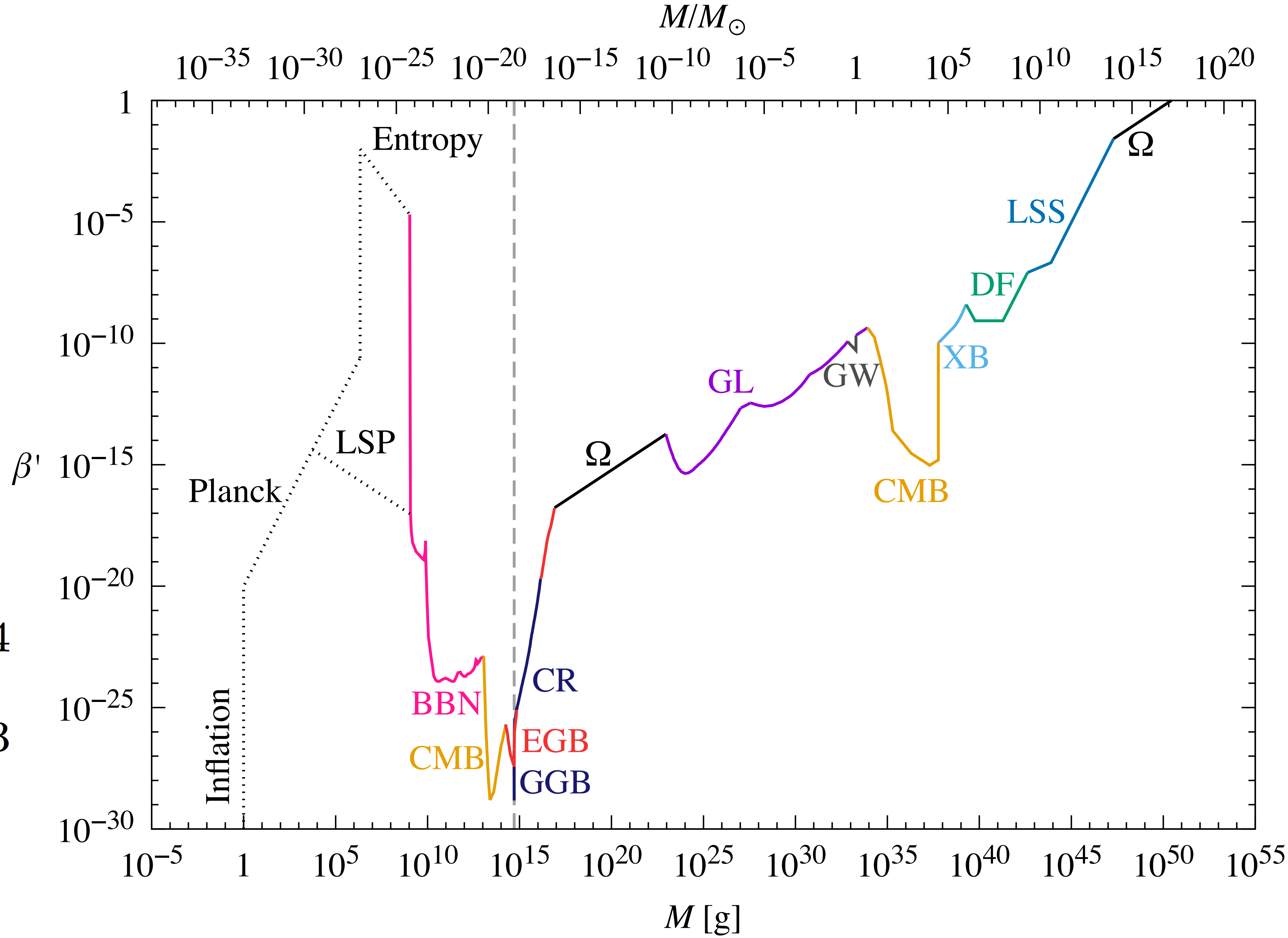
PBH Constraints at Formation



[Carr 他 2021]

PBH Constraints at Formation

$$\propto \Omega_{\rm PBH}\Big|_{\rm form}$$



[Carr 他 2021]

★ Note that

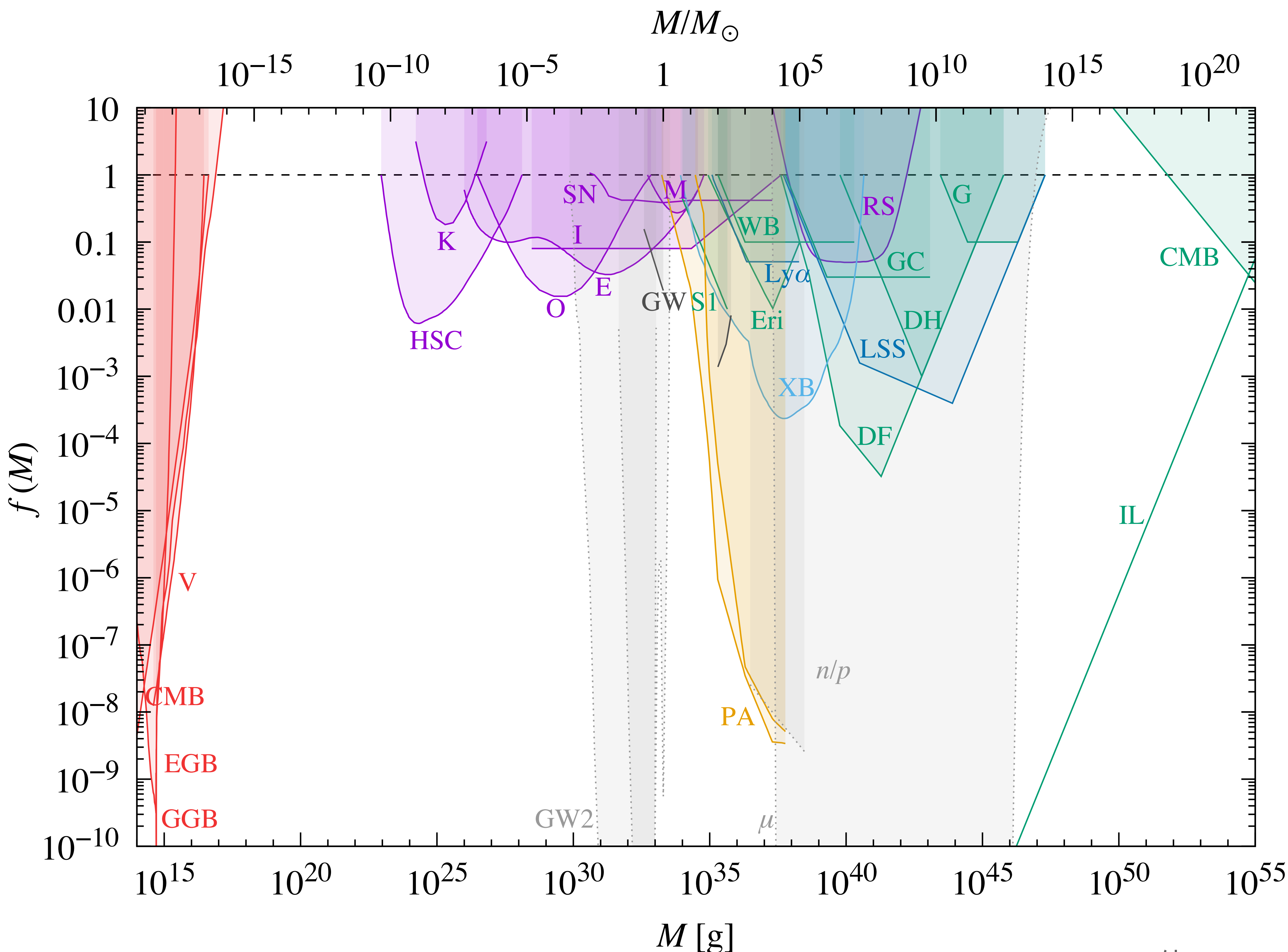
$$\rho_{\rm rad} \propto a^{-4}$$

$$\rho_{\rm PBH} \propto a^{-3}$$

and hence

$$\Omega_{\rm PBH} \propto a$$

Current PBH Constraints



[Carr 他 2021]

Observational Hints for Primordial Black Holes

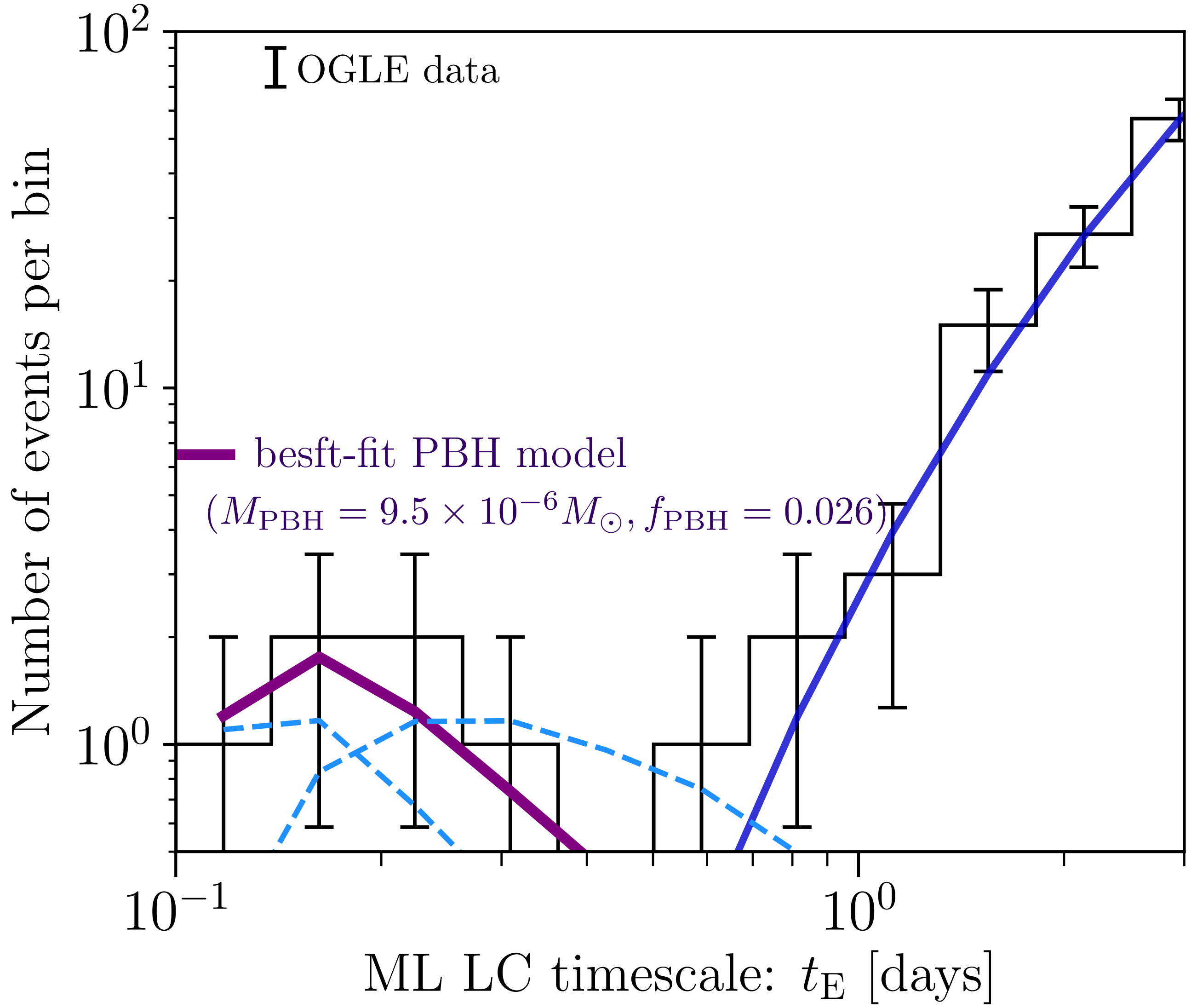
Evidence?

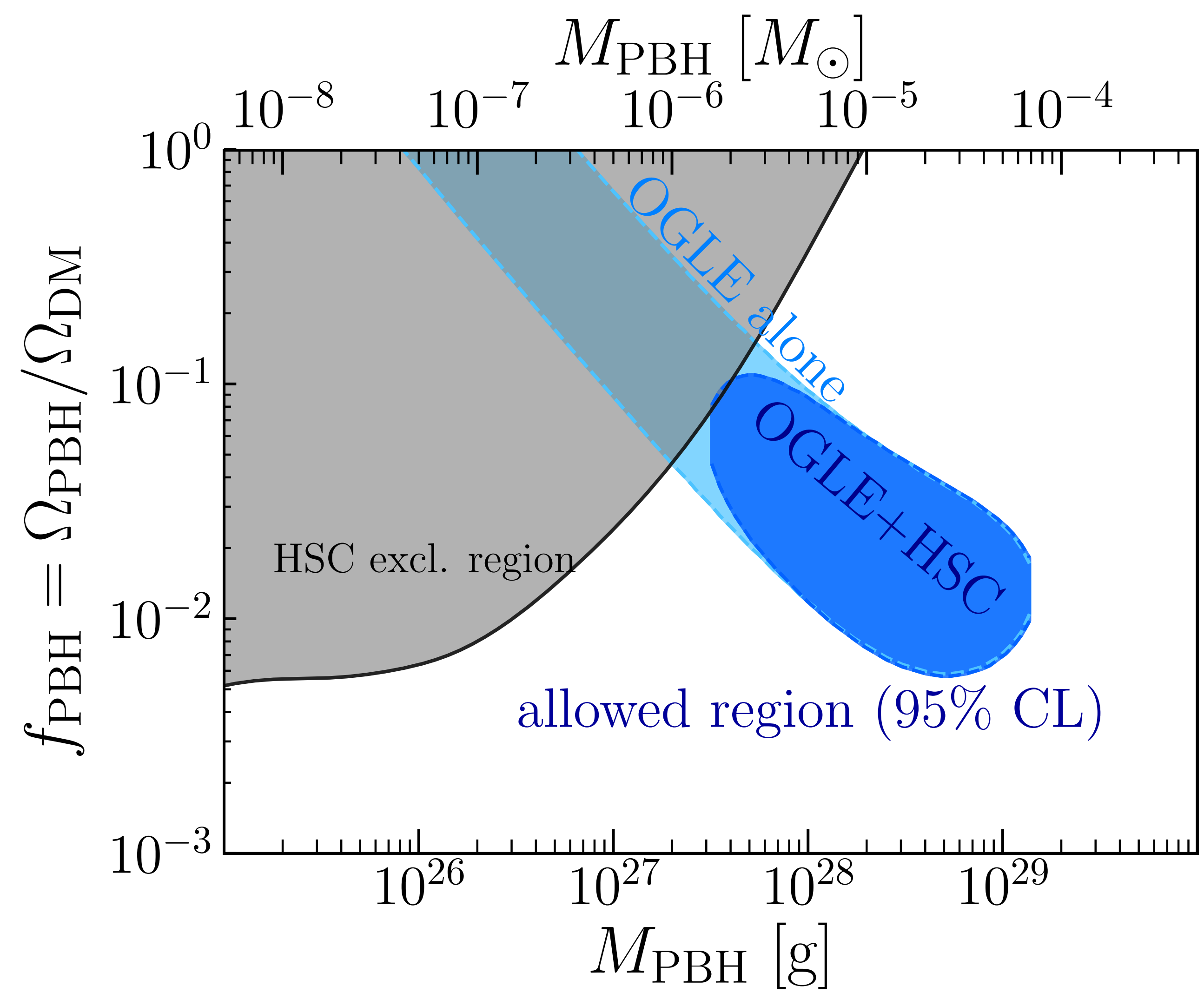
Observational ~~Hints~~ for Primordial Black Holes

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

Planetary-Mass Microlensing

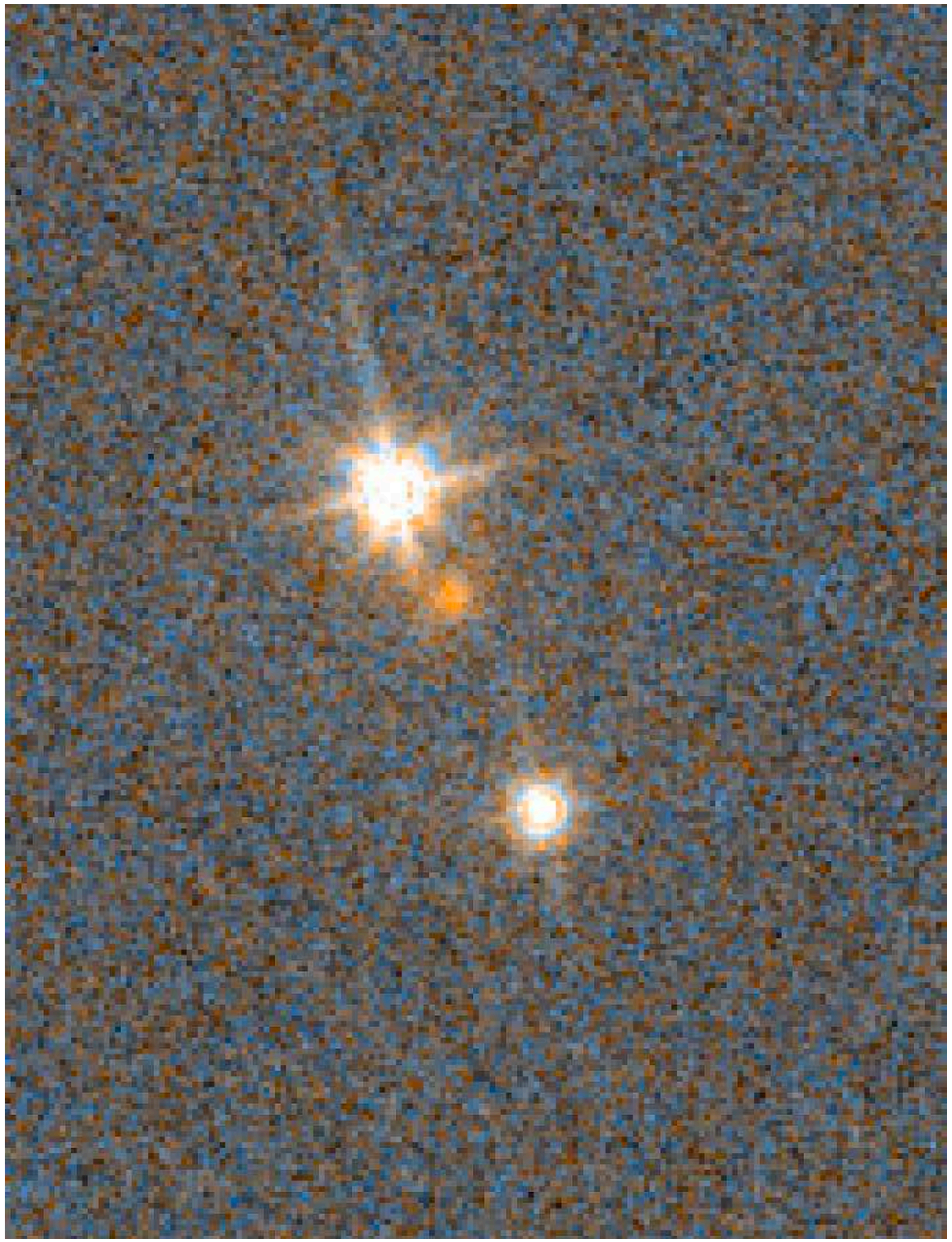
- ★ OGLE detected a particular population of microlensing events:
  - ★ 0.1 - 0.3 days light-curve timescale - origin unknown! Could be free-floating planets... or PBHs!





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

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

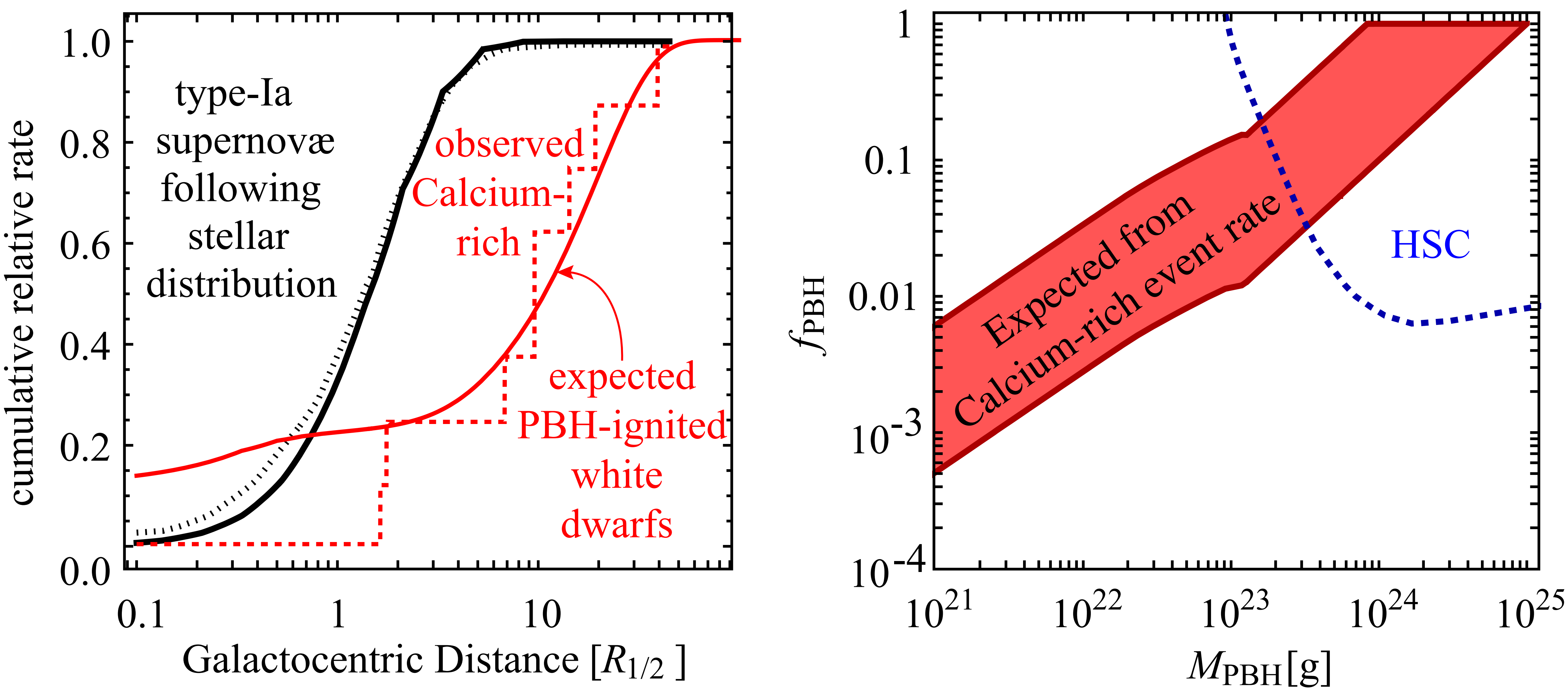
Institute for Astronomy (IfA), University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
e-mail: mrsh@roe.ac.uk

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.

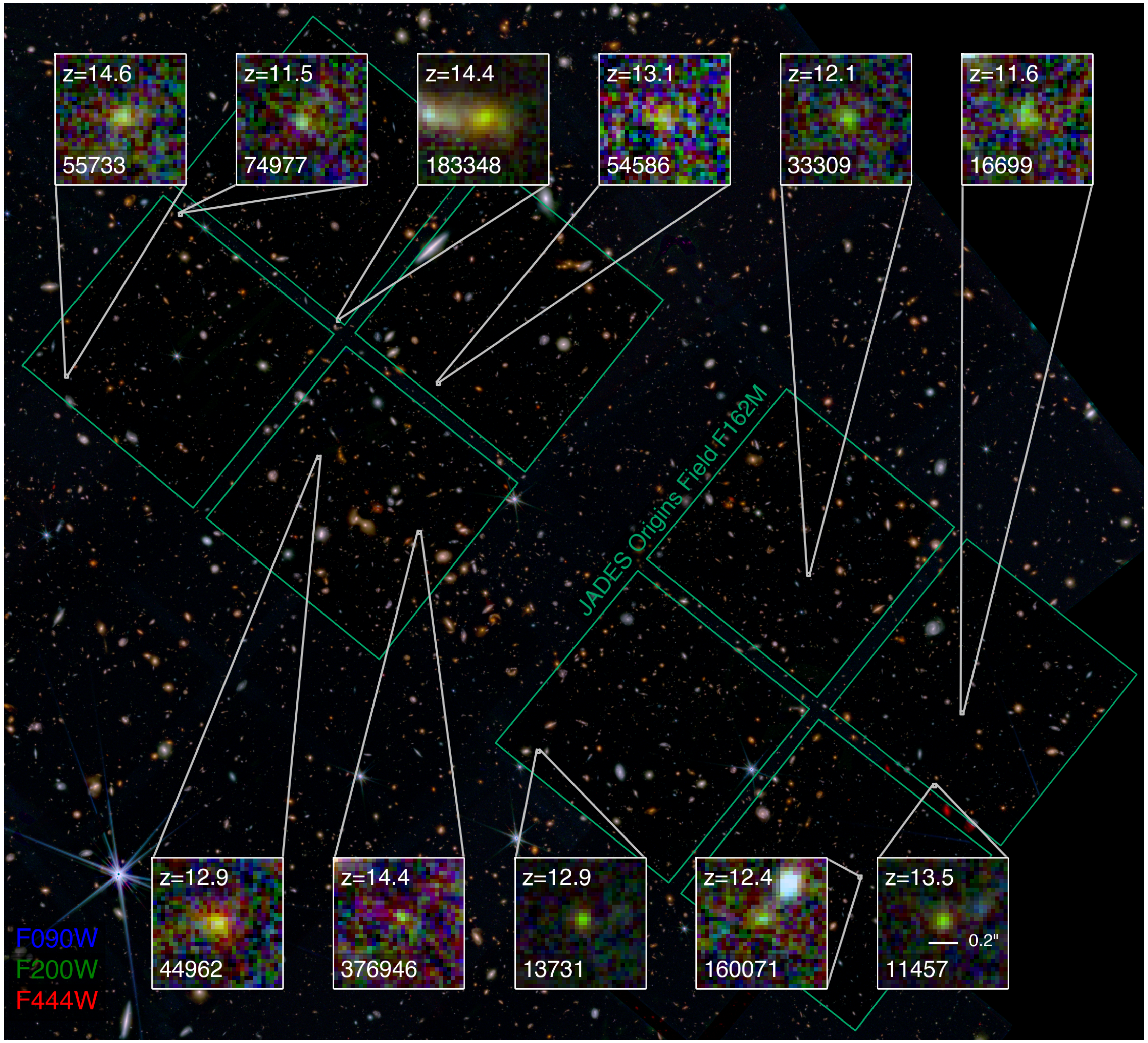
Calcium-Rich Gap Transients

★ 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]

High-Redshift Galaxies

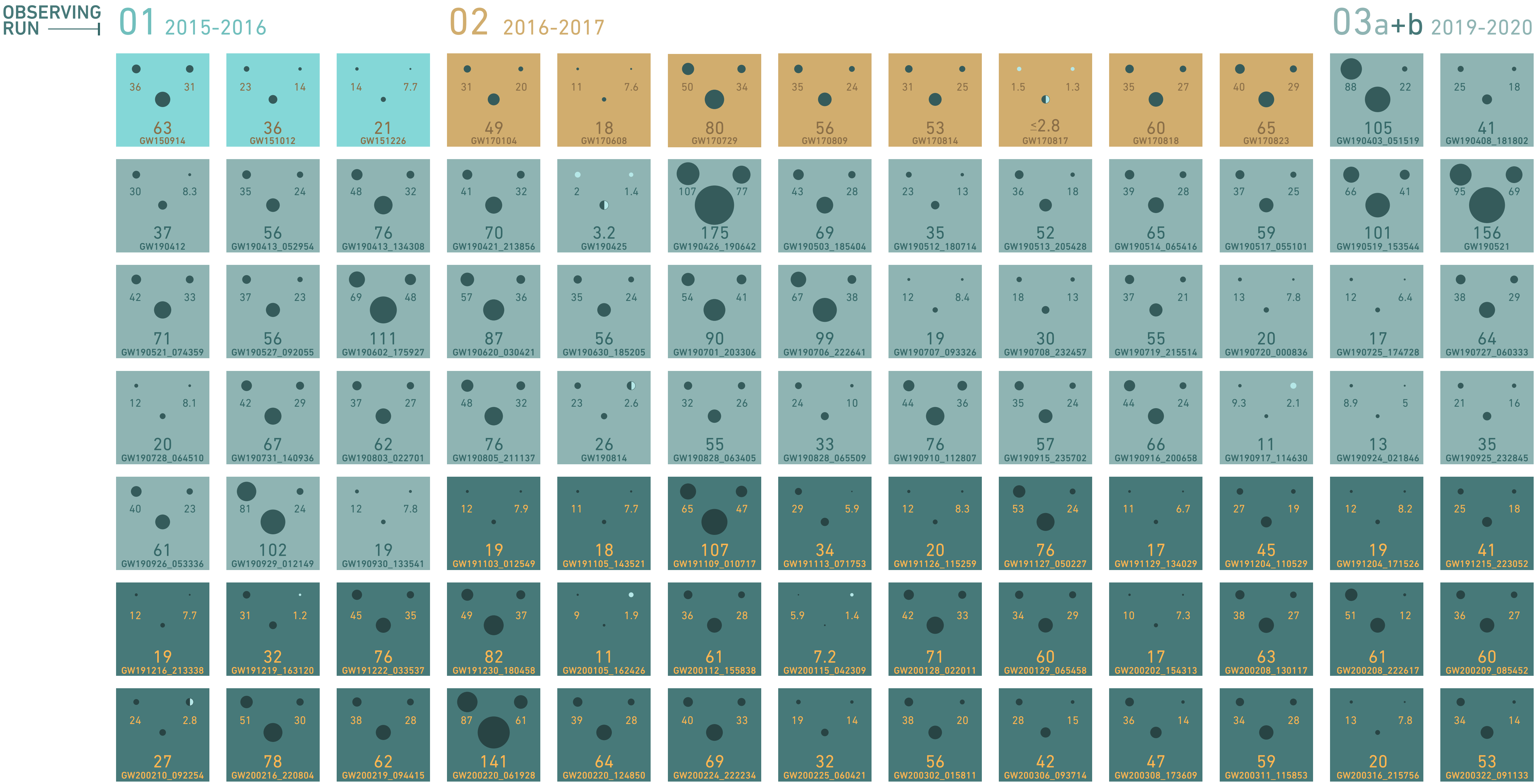


- ★ JWST confirmed a galaxy at $z \simeq 14$.
- ★ It is unclear whether baryonic physics alone could explain its evolution within only 300 Myr!
- ★ PBH dark matter would trigger early formation, easily ensuring compatibility with observations.

[Robertson *et al.* 2024]

GRAVITATIONAL WAVE **MERGER** DETECTIONS

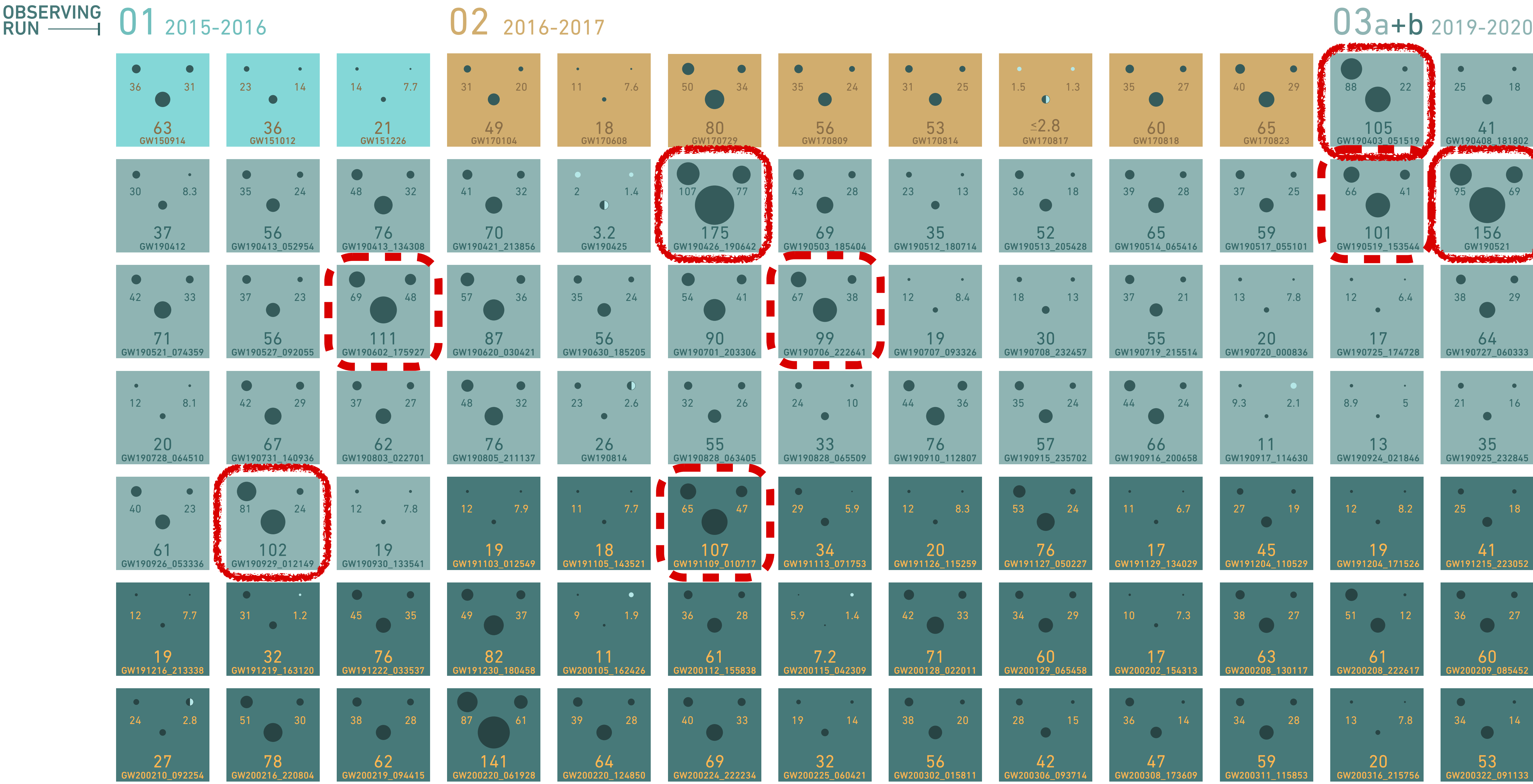
SINCE 2015



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

Subsolar Black Holes - The Smoking Gun!

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

Date	FAR $[\text{yr}^{-1}]$	$m_1[M_\odot]$	$m_2[M_\odot]$	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

[Phukon *et al.* 2021, Abbott *et al.* 2022]

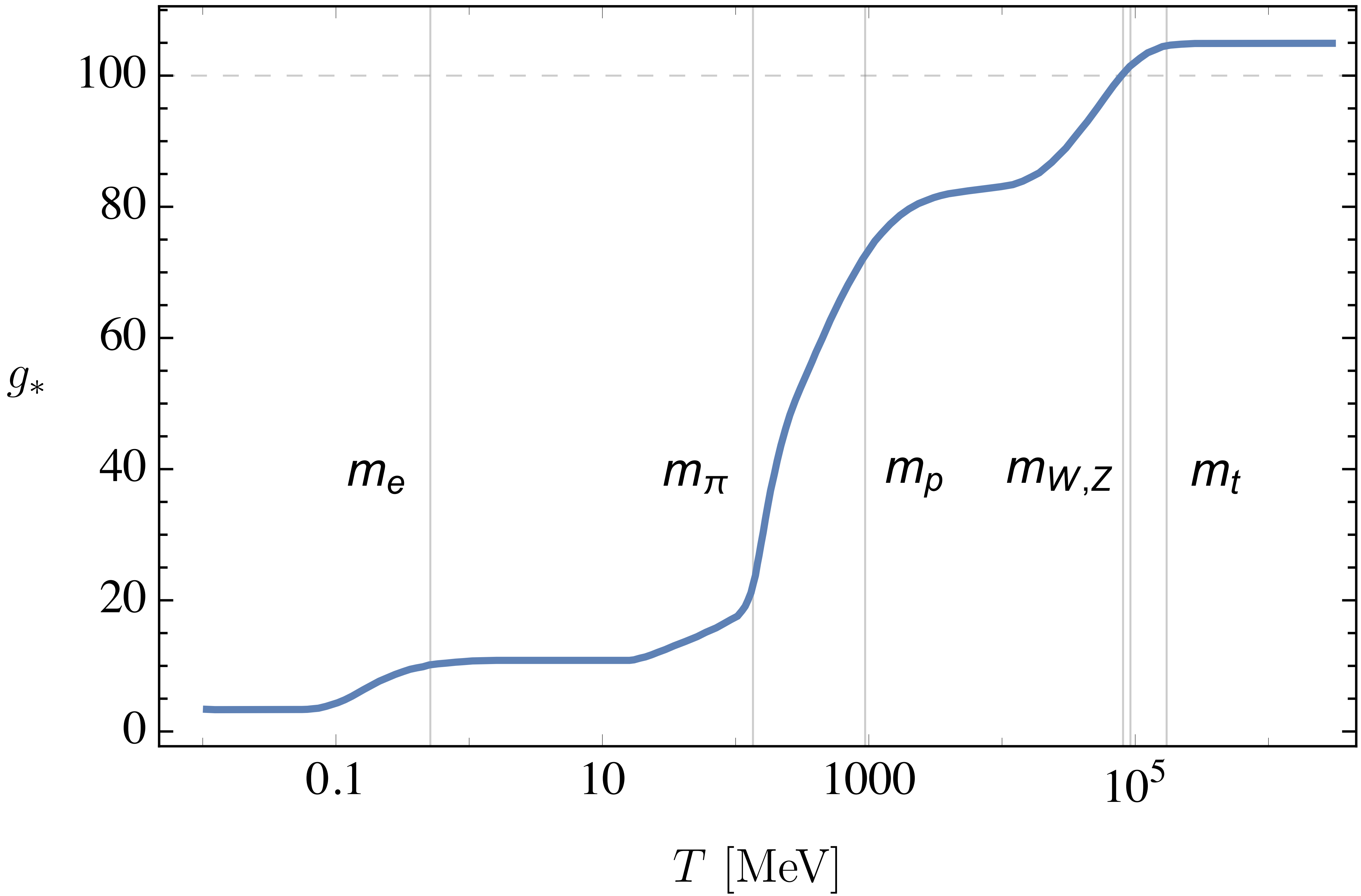
★ Five strong subsolar candidates with SNR > 8 and a FAR < 2 yr^{-1}

A Unified Scenario

*work with Carr, Clesse, García-Bellido

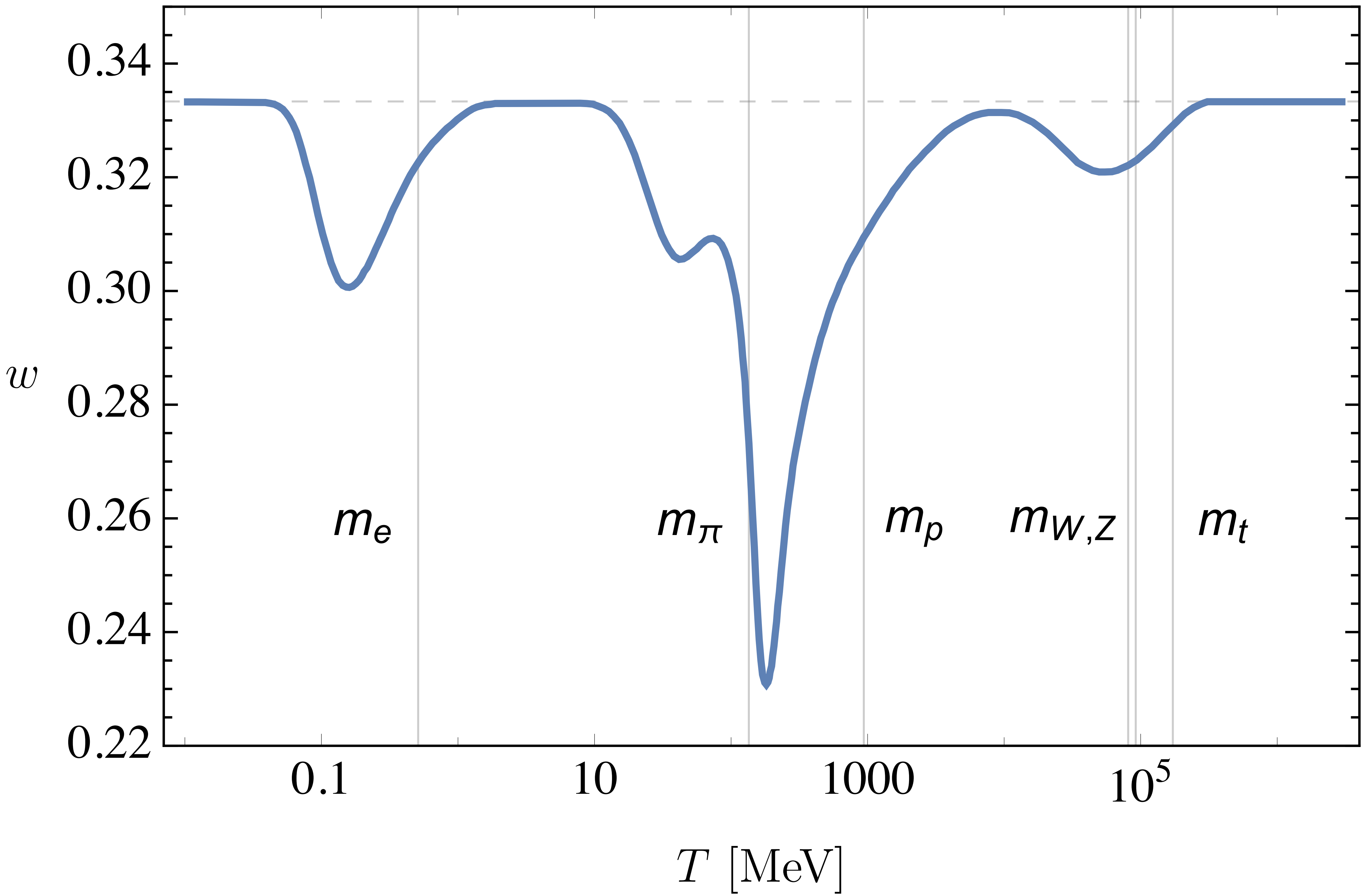
Thermal History of the Universe — Degrees of Freedom

★ 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]

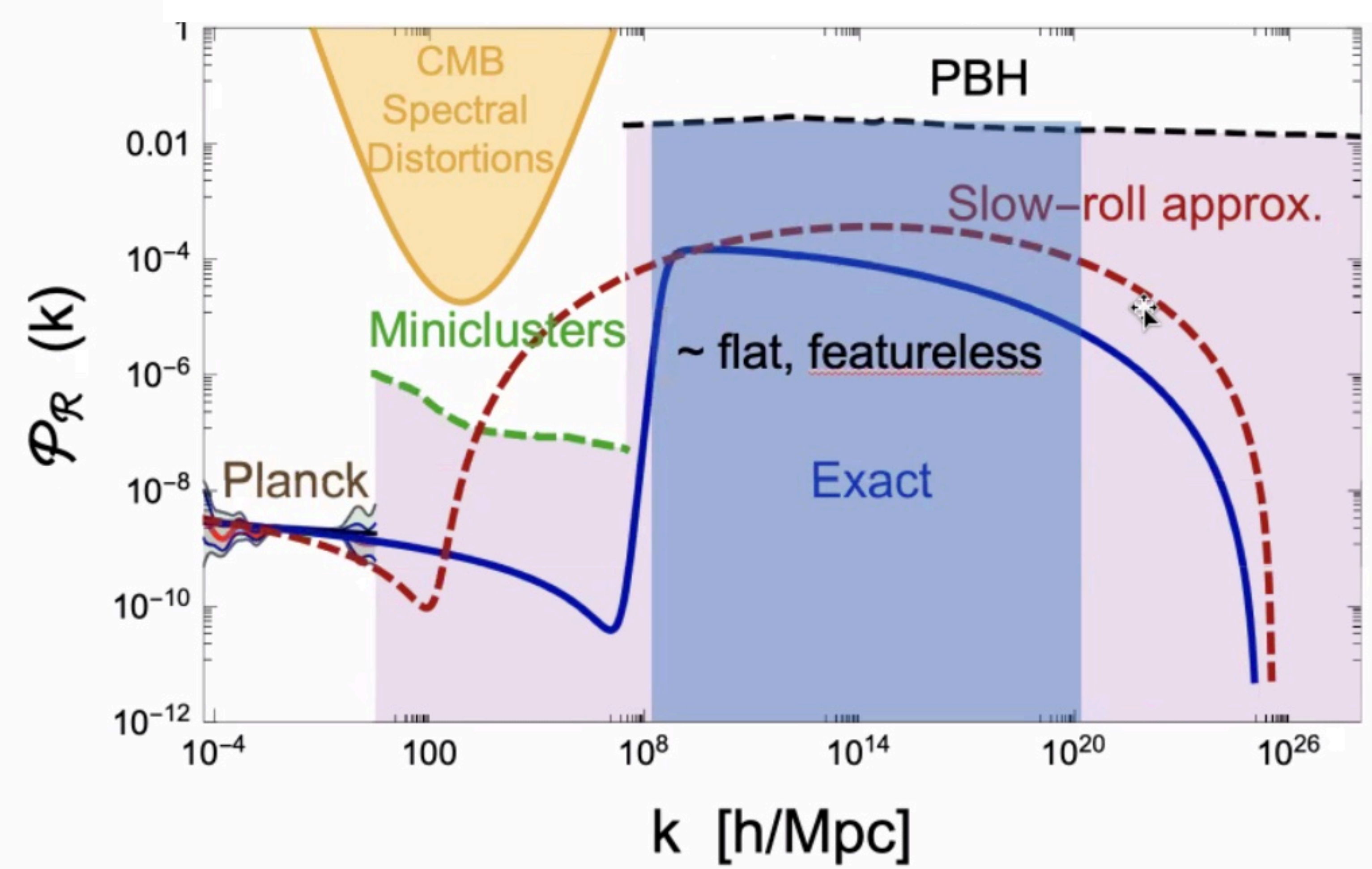
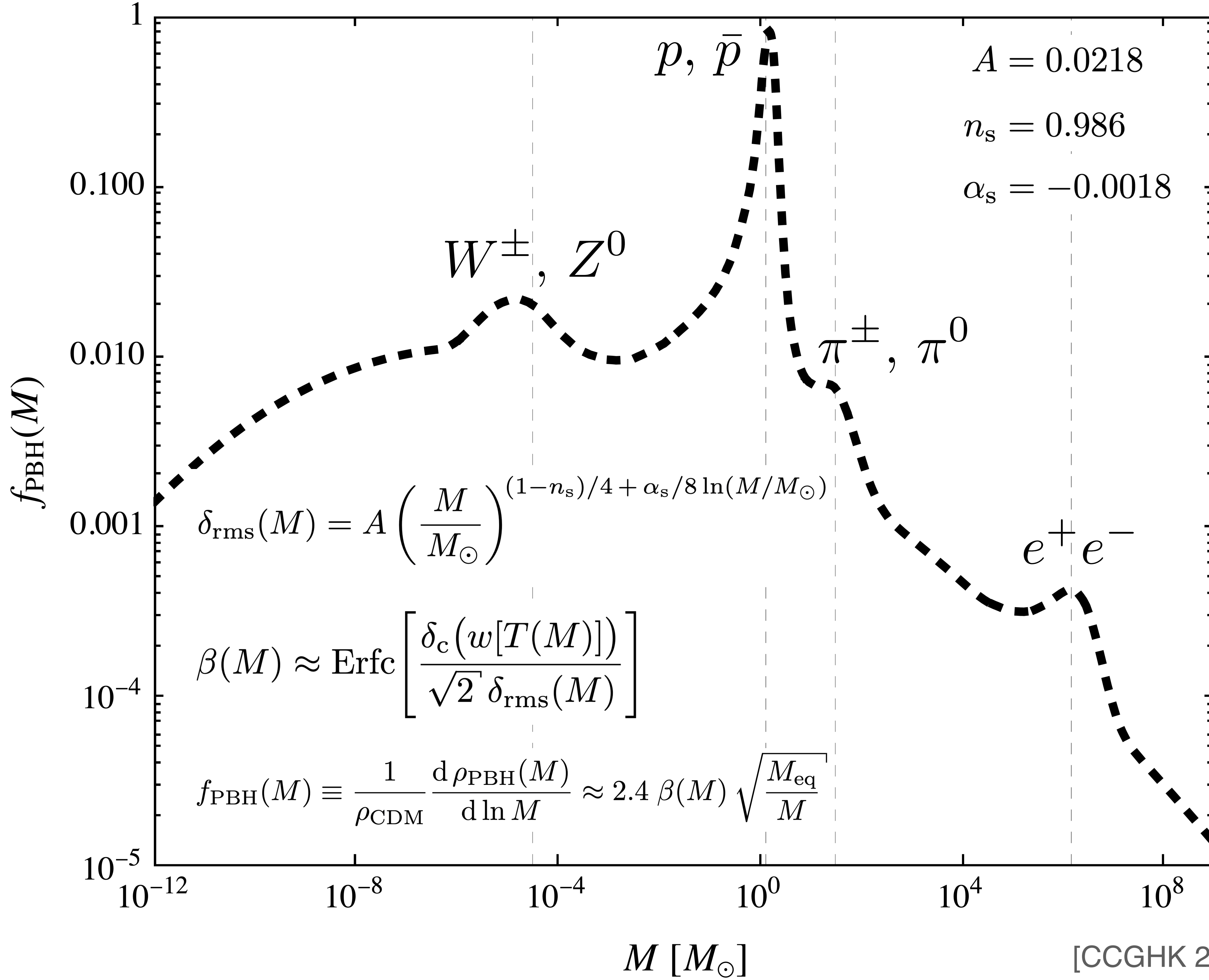


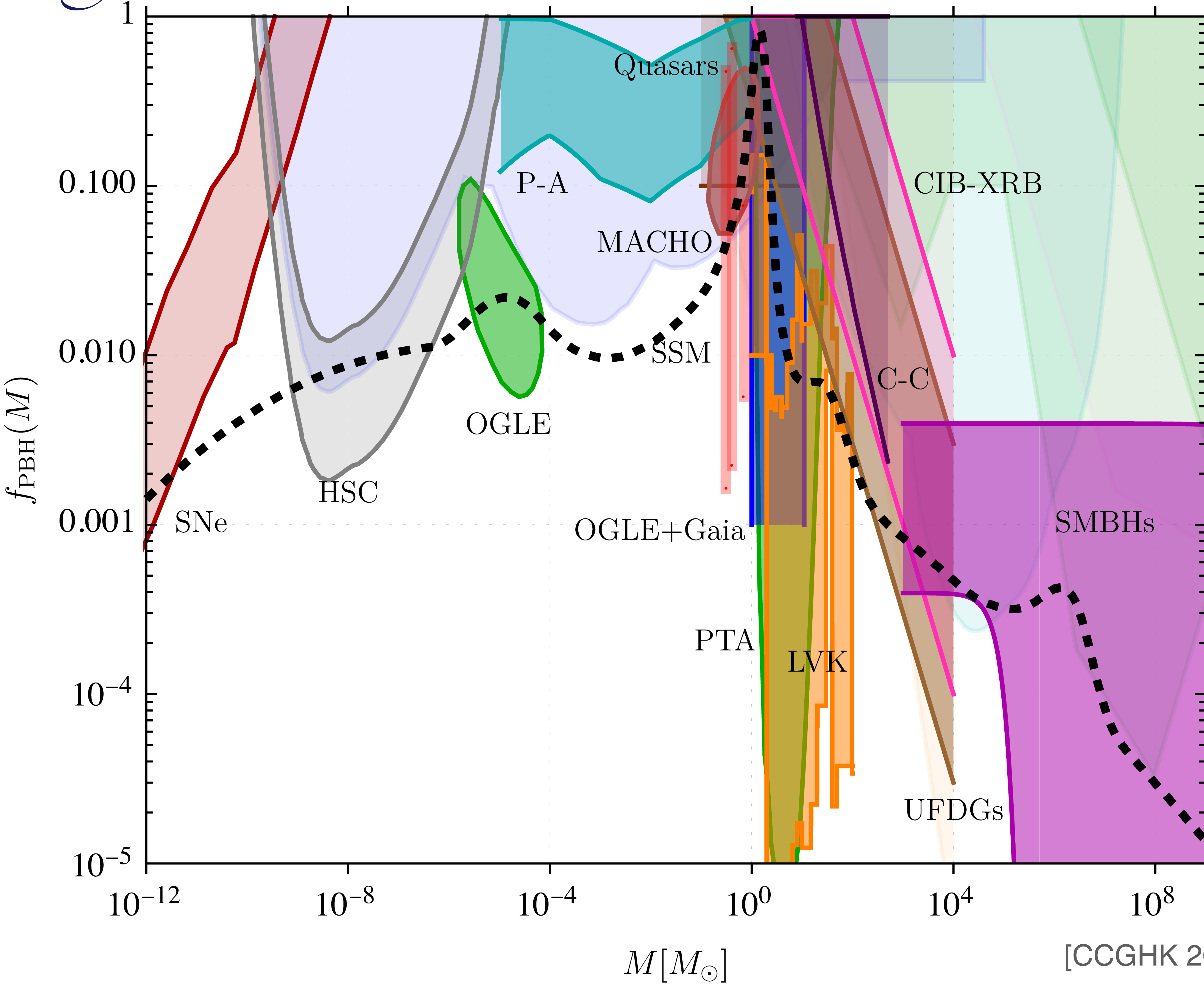
Figure from García-Bellido

PBH Mass Function



[CCGHK 2023]

Connecting all Positive Evidences!



[CCGHK 2023]

Shall Ye Become Positivists!

Physics Reports 1054 (2024) 1–68

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

Observational evidence for primordial black holes: A positivist perspective

B.J. Carr [a], S. Clesse [b], J. García-Bellido [c], M.R.S. Hawkins [d], F. Kühnel [e,*]

[a] *School of Physics and Astronomy, Queen Mary University of London, United Kingdom*
[b] *Service de Physique Théorique, University of Brussels (ULB), Belgium*
[c] *Instituto de Física Teórica UAM/CSIC, Universidad Autonoma de Madrid, Spain*
[d] *Department of Physics and Astronomy, University of Edinburgh, United Kingdom*
[e] *Max Planck Institute for Physics, Germany*

Quantum Quiddity

Quantum Aspects

- ★ Black Holes can be understood as *saturons*, ie. configuration of maximum entropy *compatible with unitarity* (cf. work by *Dvali*).

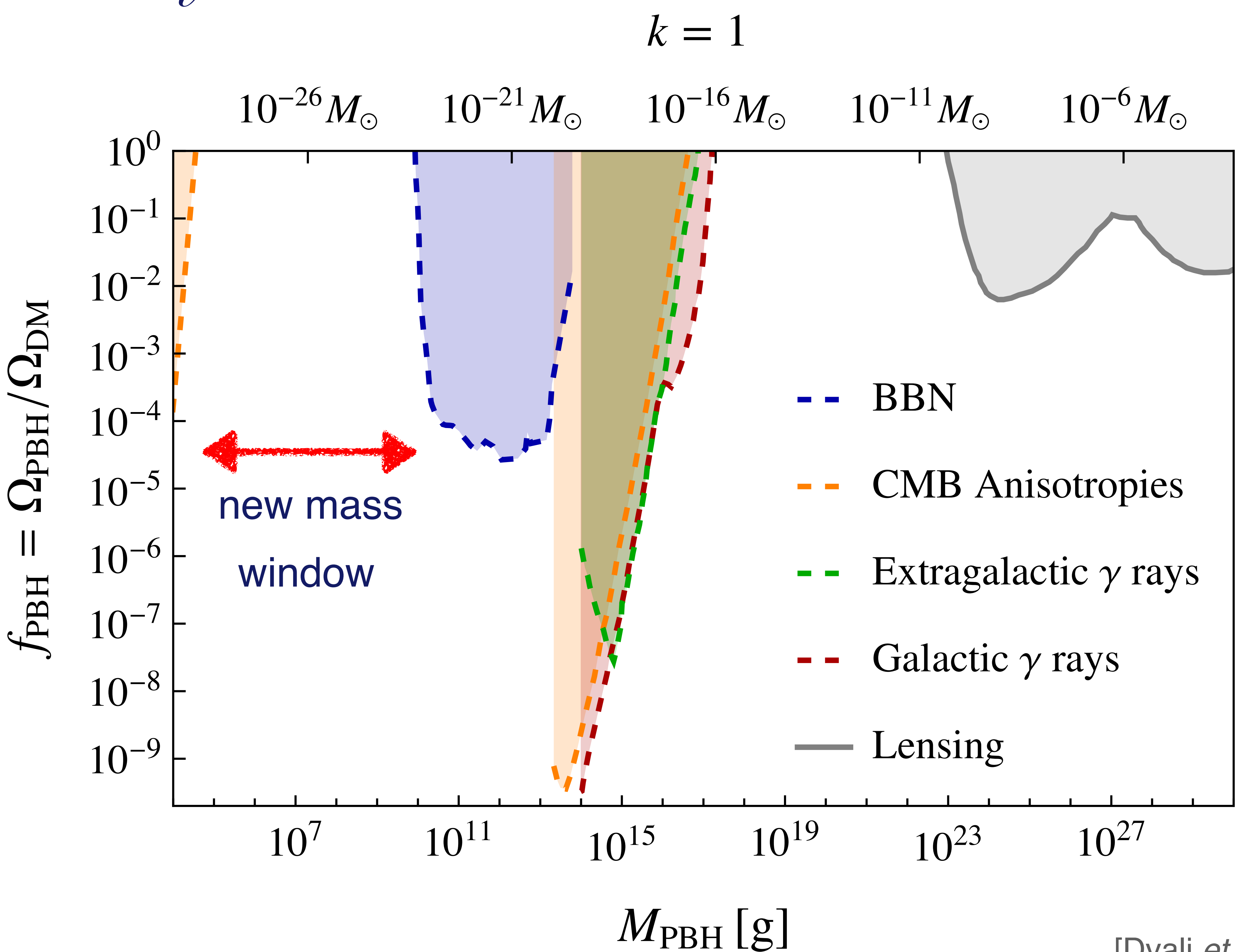
- ★ Black hole evaporation *leaves the semi-classical regime* at latest at half-mass, possibly much earlier.

- ★ Evaporation rate Γ become *entropy suppressed*

$$\Gamma \longrightarrow \frac{1}{S^k}\,\Gamma$$

- ★ This opens up a large mass range for *ultra-light PBHs* as (quasi) remnants!

Quantum Aspects



[Dvali *et al.* 2024]

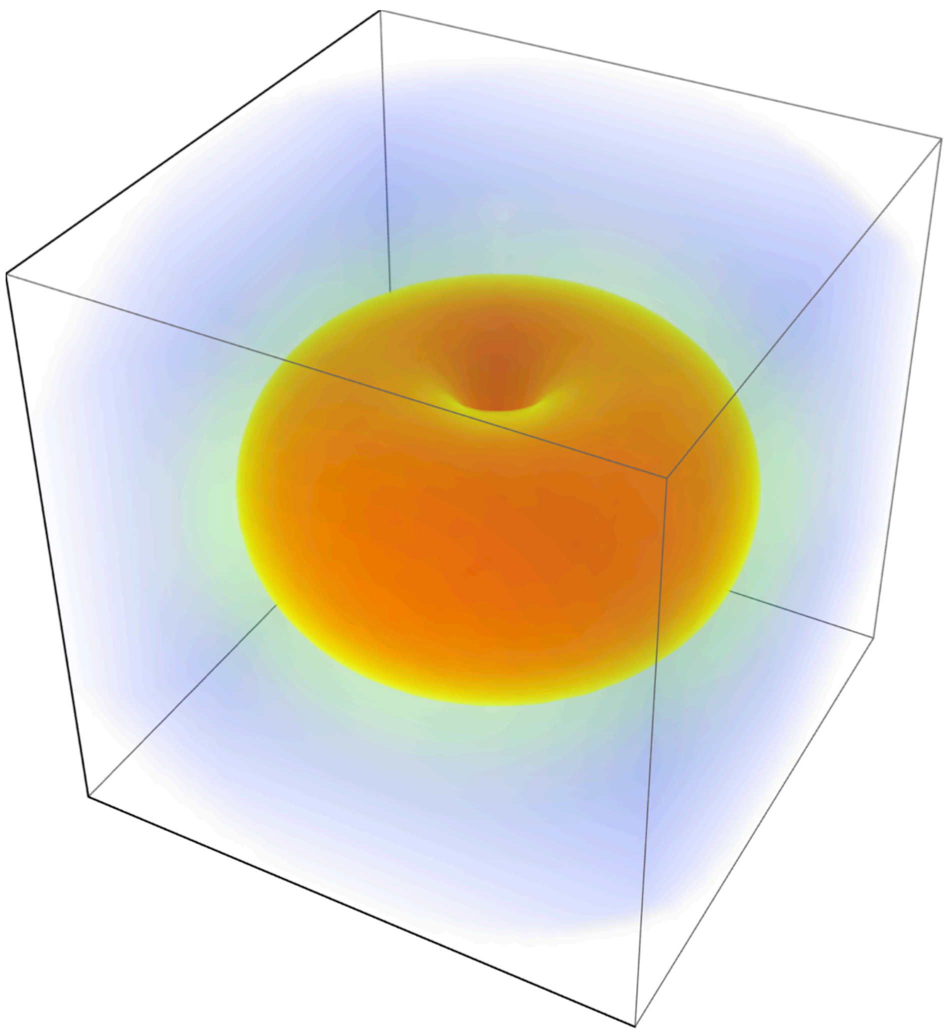
Quantum Aspects

- We showed that (near-)extremally-spinning black holes admit vortex structure (*Dvali, Kühnel, Zantedeschi*)

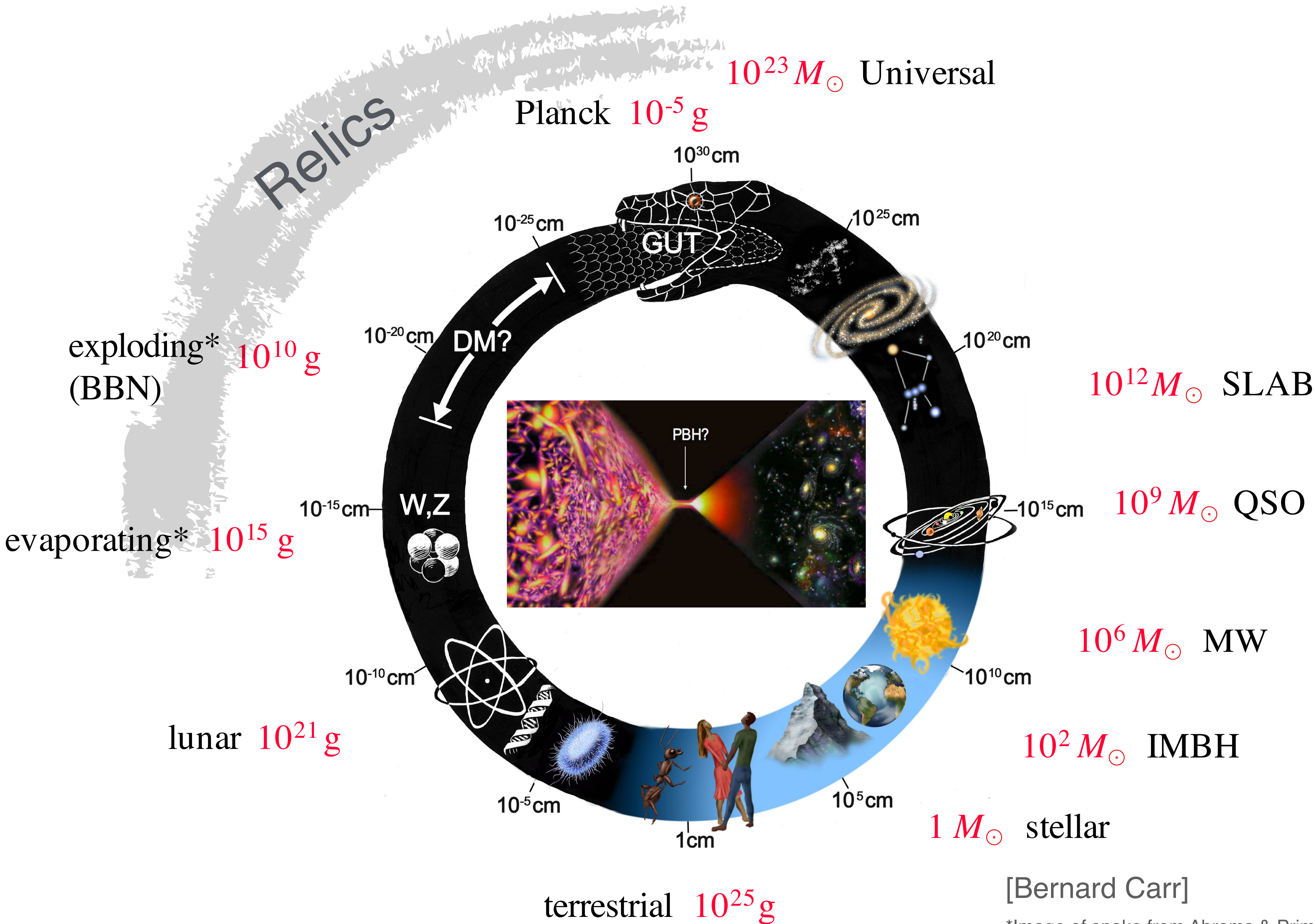
- *PBHs from confinement* (*Dvali, Kühnel, Zantedeschi*) could provide ideal prerequisites for vortex formation due to highly spinning light PBHs.

- If these PBHs provide the dark matter, their vorticity might explain primordial magnetic fields.

- Besides, vorticity provides a topological meaning to the stability of extremal black holes.



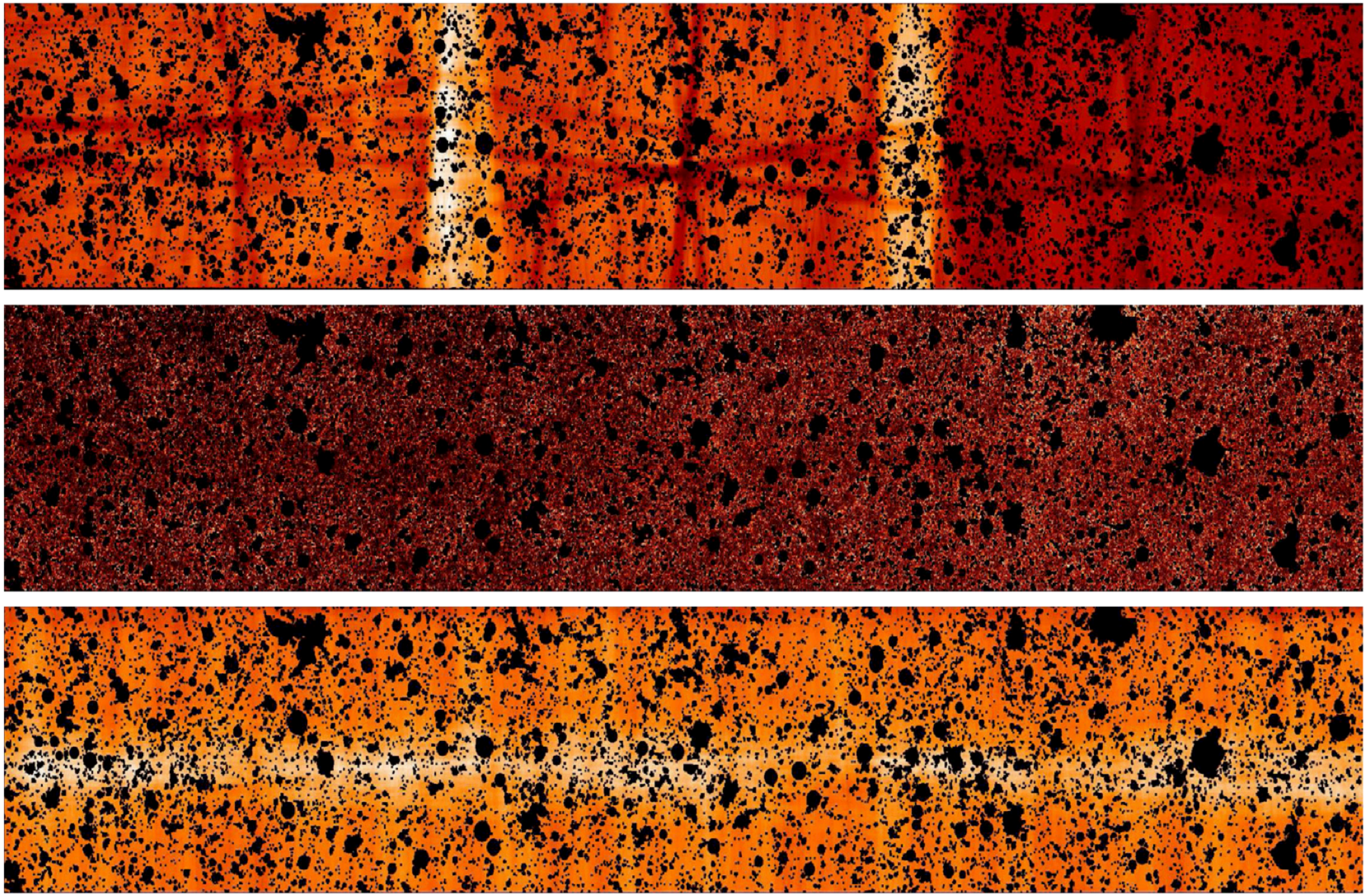
Black Holes as a Link between Micro and Macro Physics



[Bernard Carr]

*Image of snake from Abrams & Primack 2012

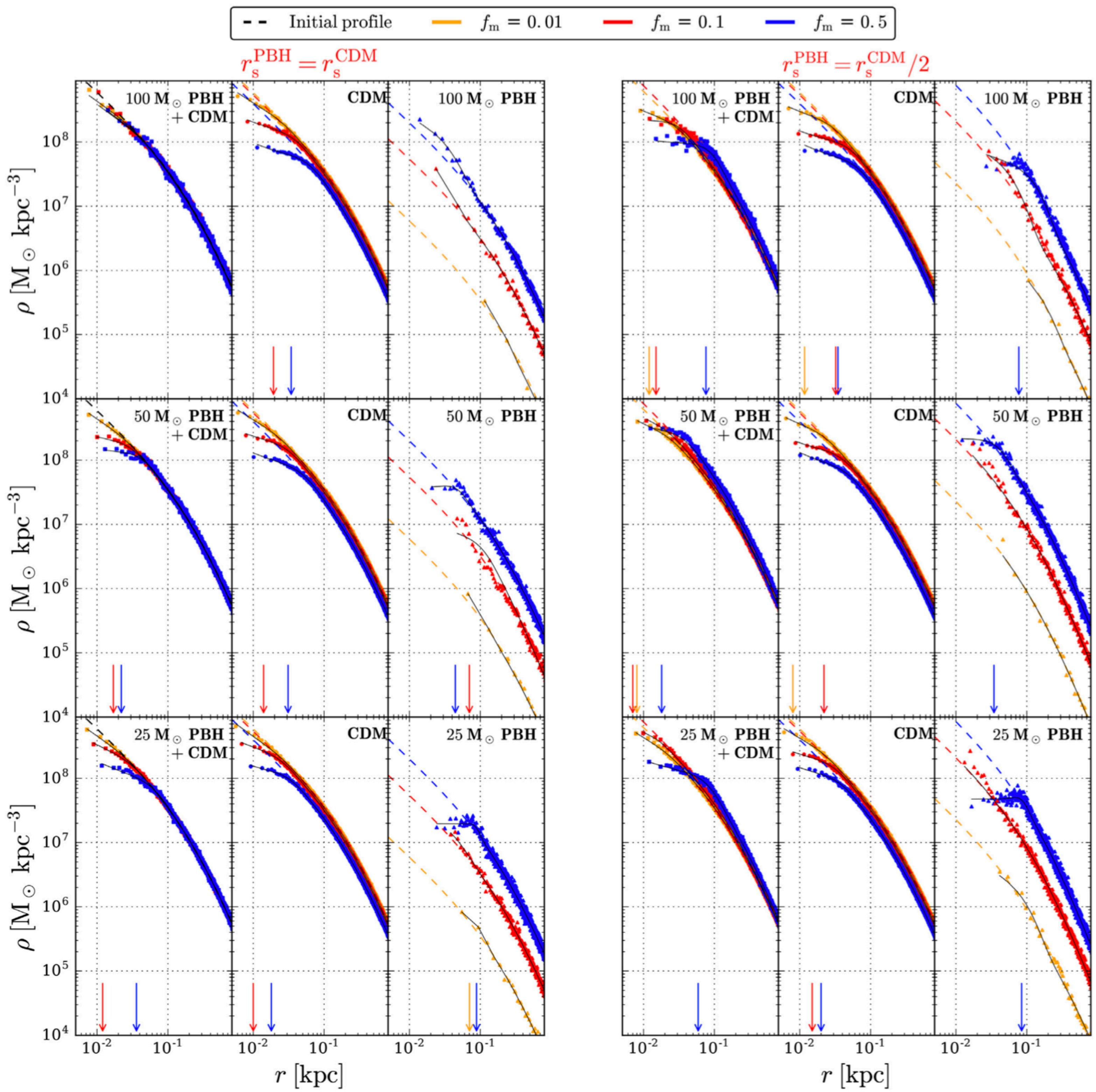
Correlations of Cosmic Infrared/X-Ray Backgrounds



[Cappelluti *et al.* 2013]

★ PBHs generate early structure and respective backgrounds

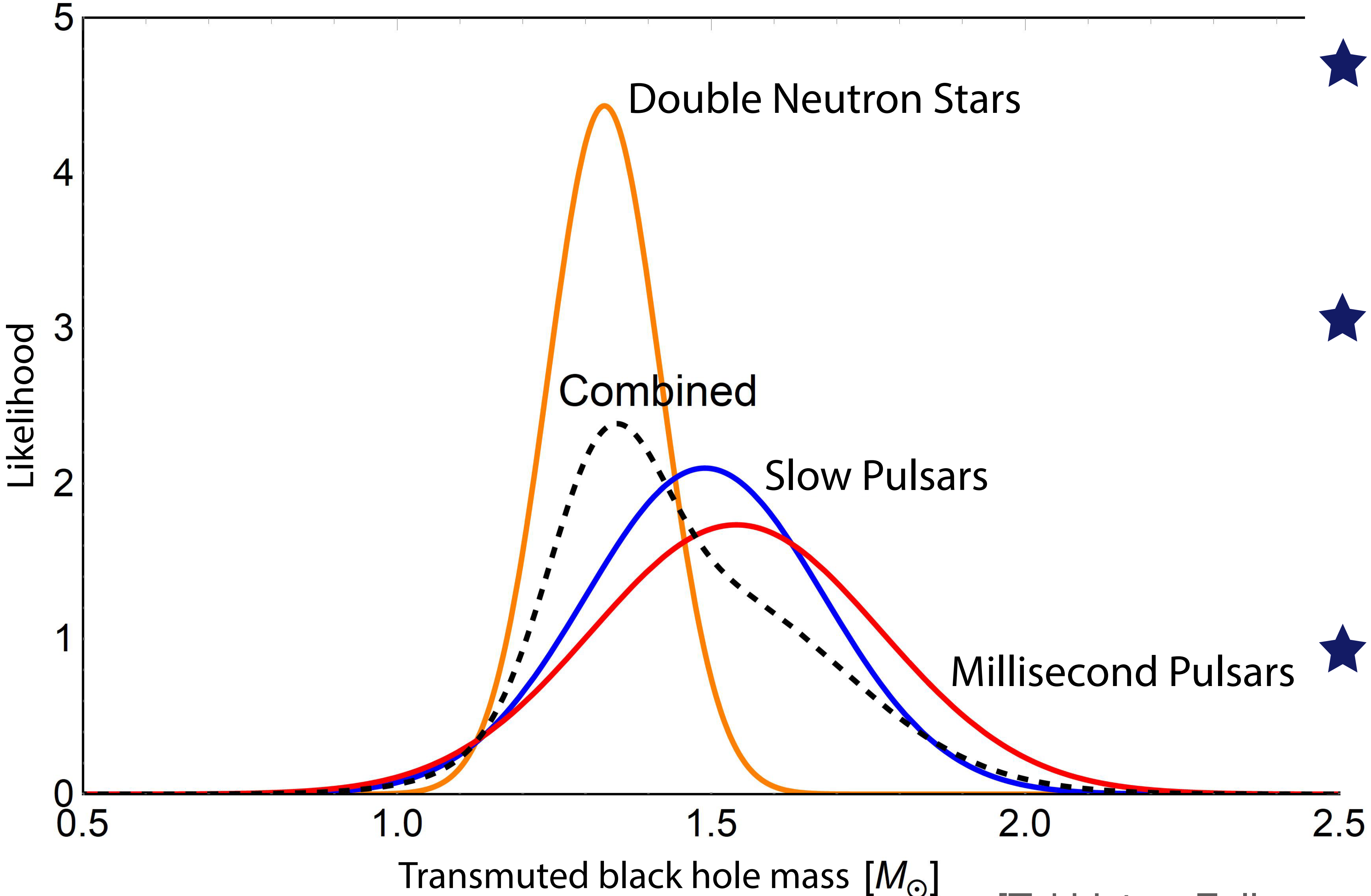
Ultra-faint Dwarf Galaxies



- ★ 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 $M_\odot$.

[Boldrini *et al.* 2020]

Transmuted Solar-Mass Black Holes

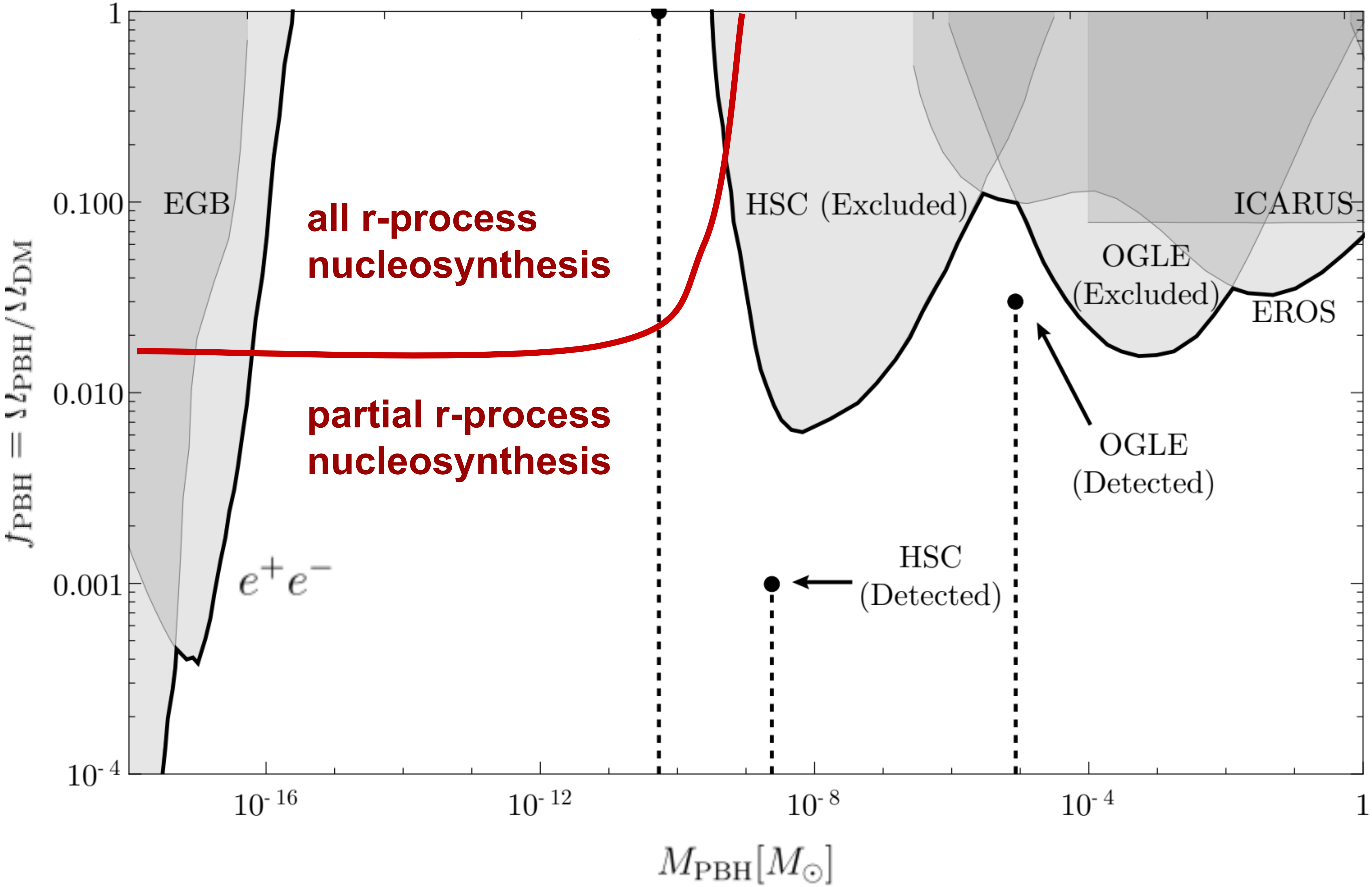


[Takhistov, Fuller, Kusenko 2017]

- ★ 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 $\sim 10^{30}$ GBP*).*

r-Process Elements

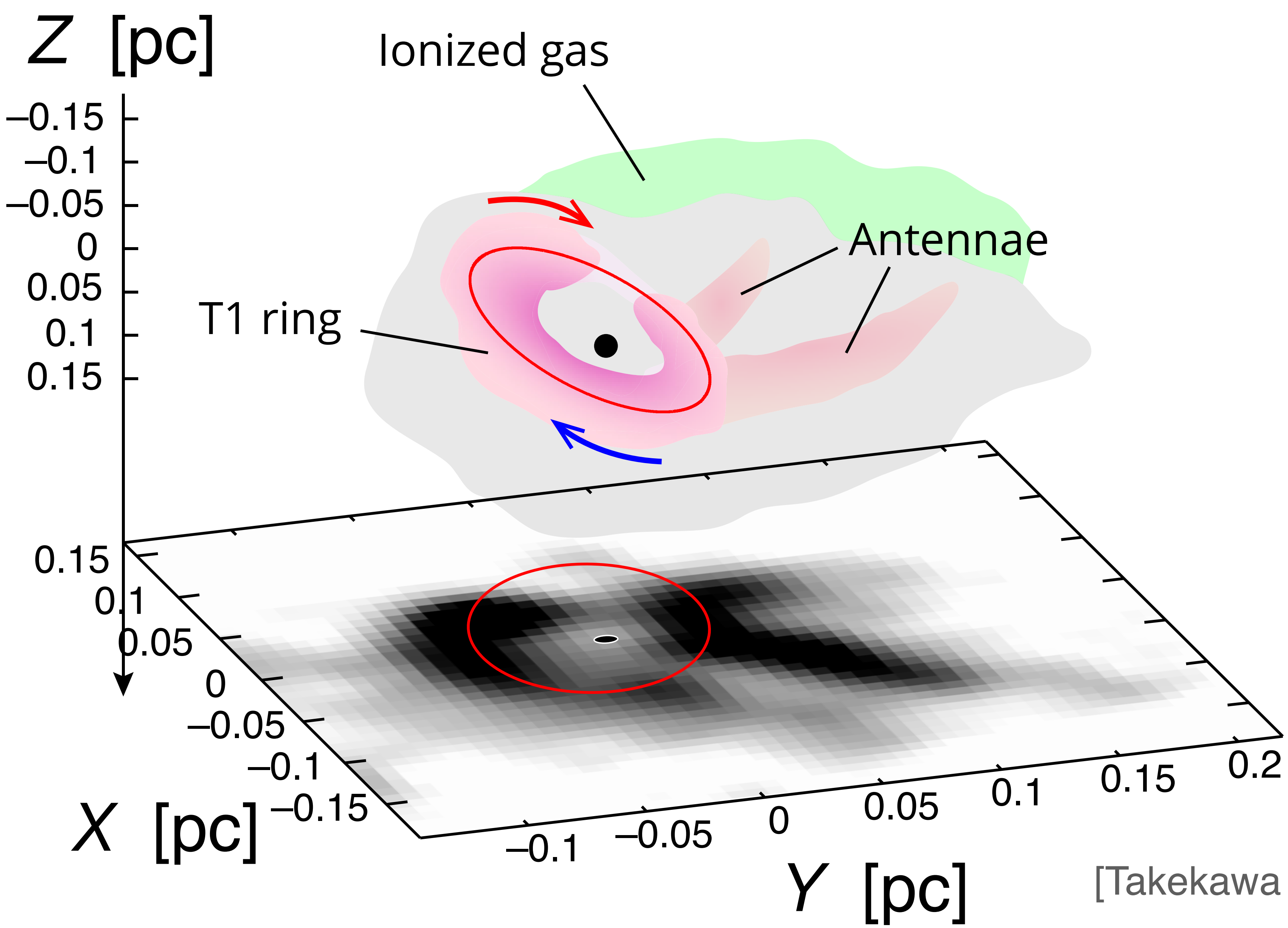


(*from talk by Alex Kusenko)

G Objects

- Population of unresolved objects which show both thermal and dust emission.
- 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.

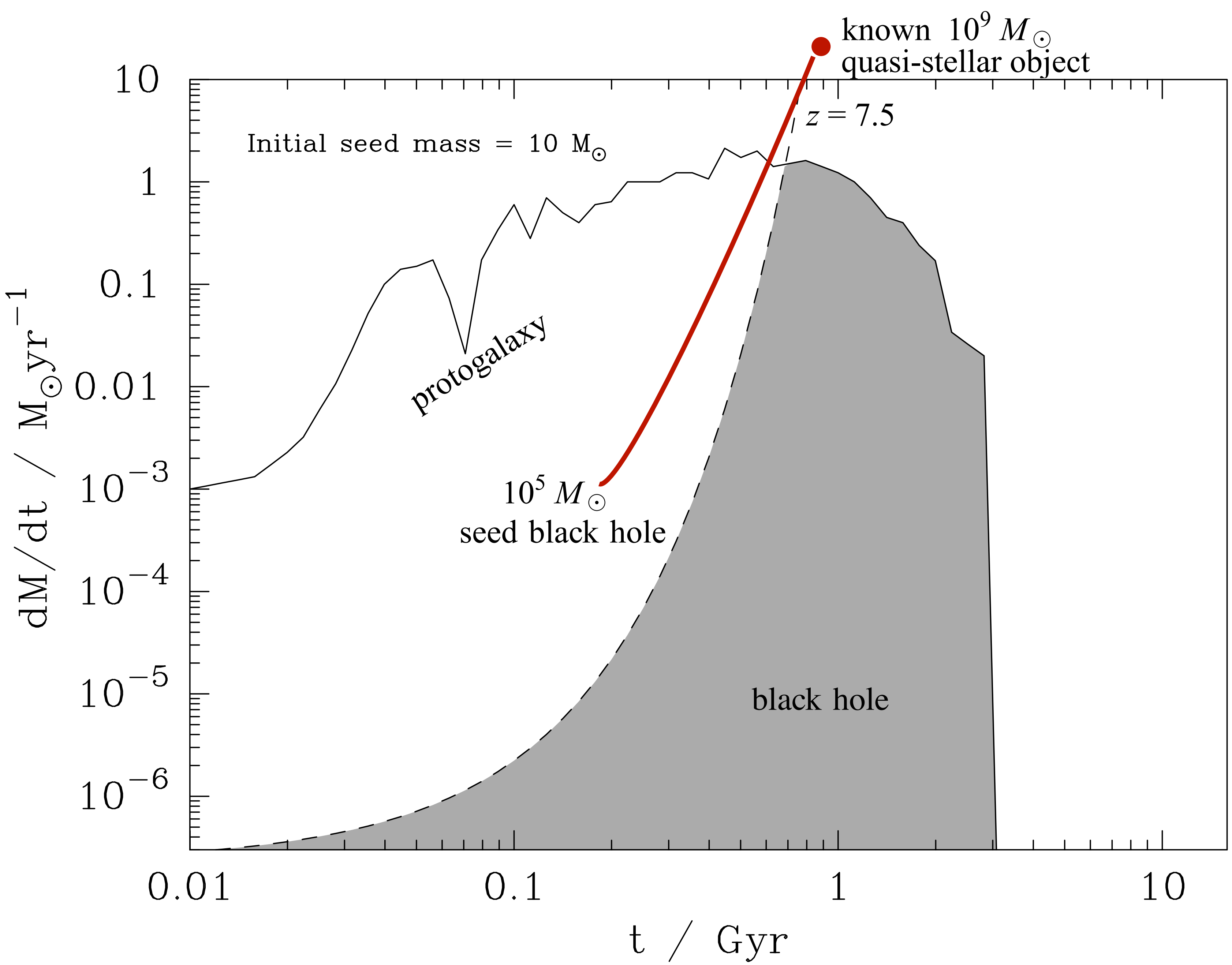
Evidence for Intermediate-Mass Black Holes



[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]

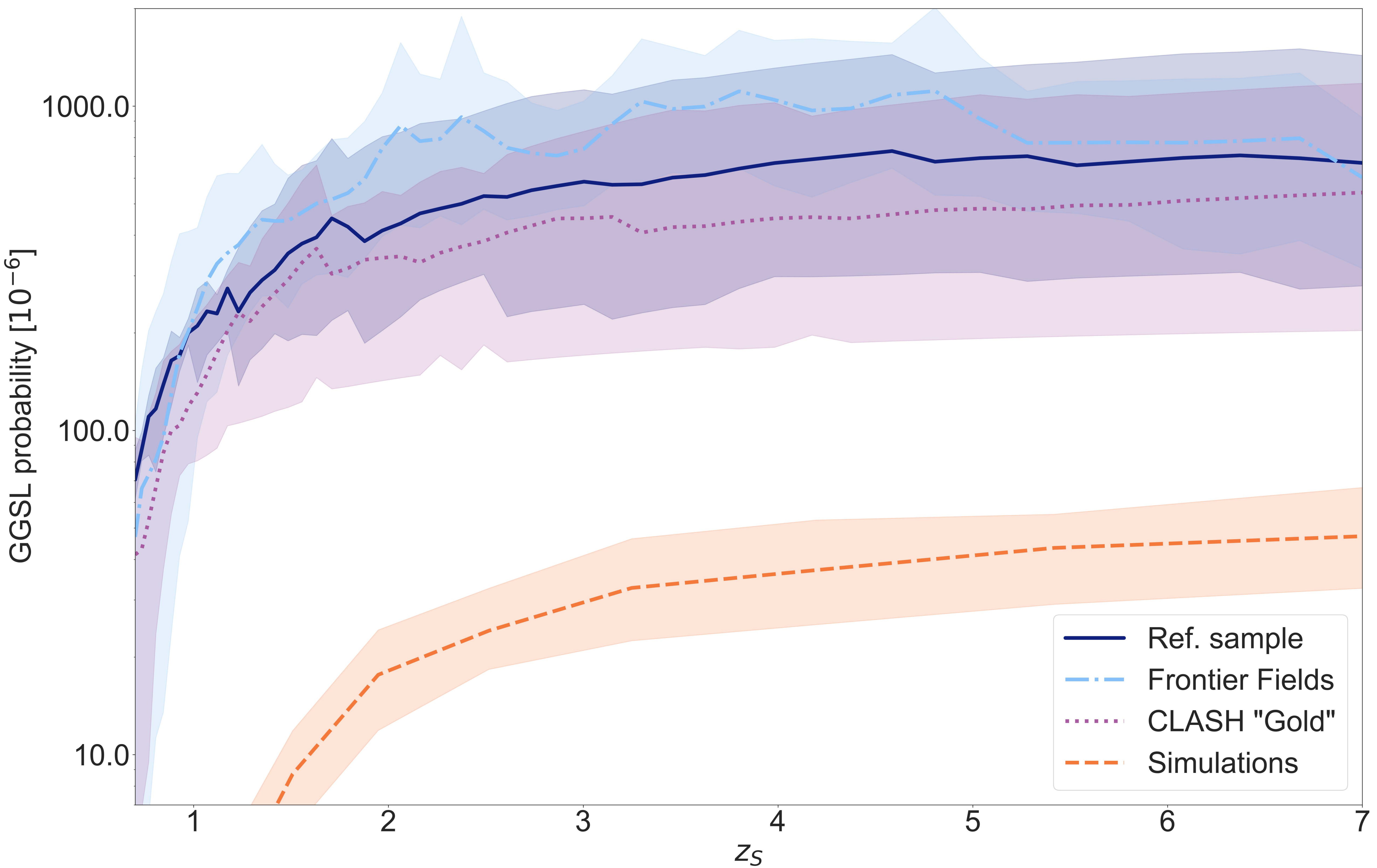
  or $\sim 10^8\,M_\odot$ at $z \approx 13.$

  [Pacucci *et al.* 2022]

  and numerous others.

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

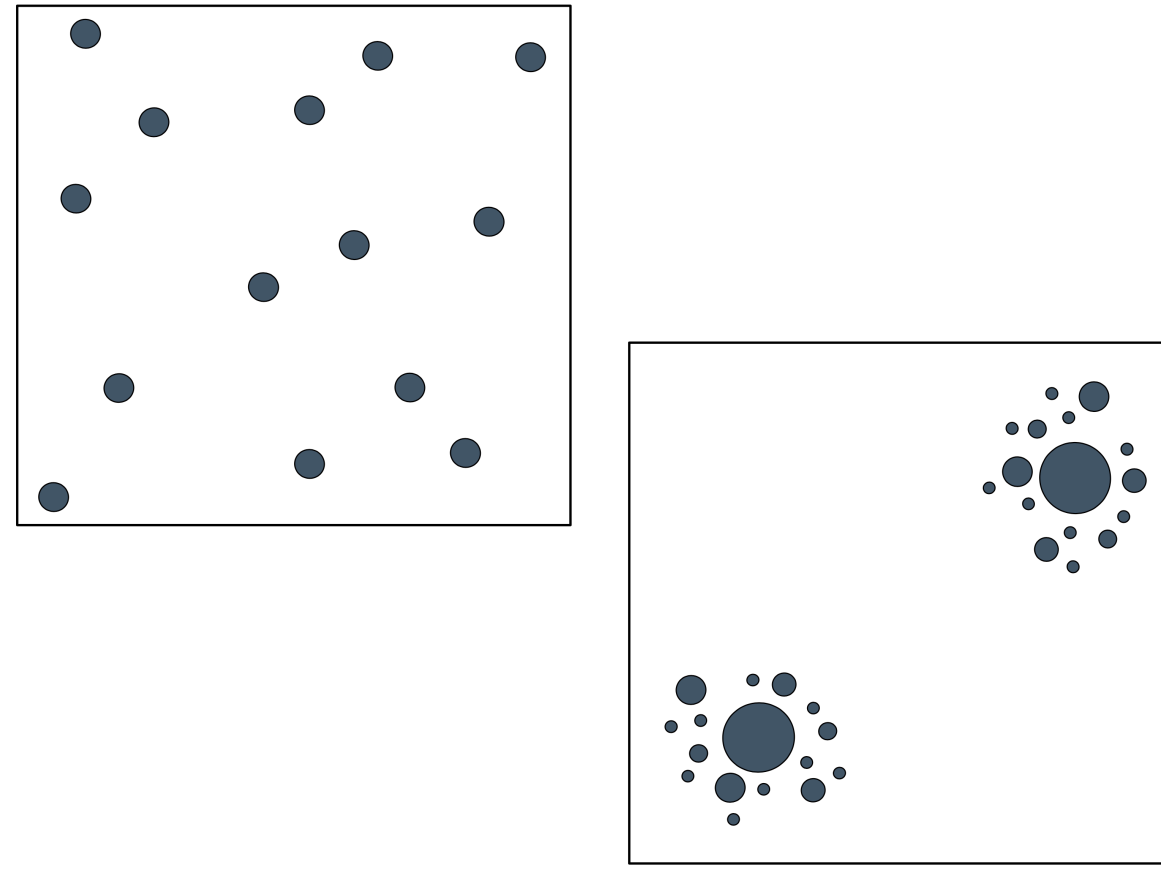
Evidence of Dark Matter Clumping with HST



[Meneghetti, Natarajan, Downer 2020]

Evidence of Dark Matter Clumping with HST

[Meneghetti, Natarajan, Downer 2020]



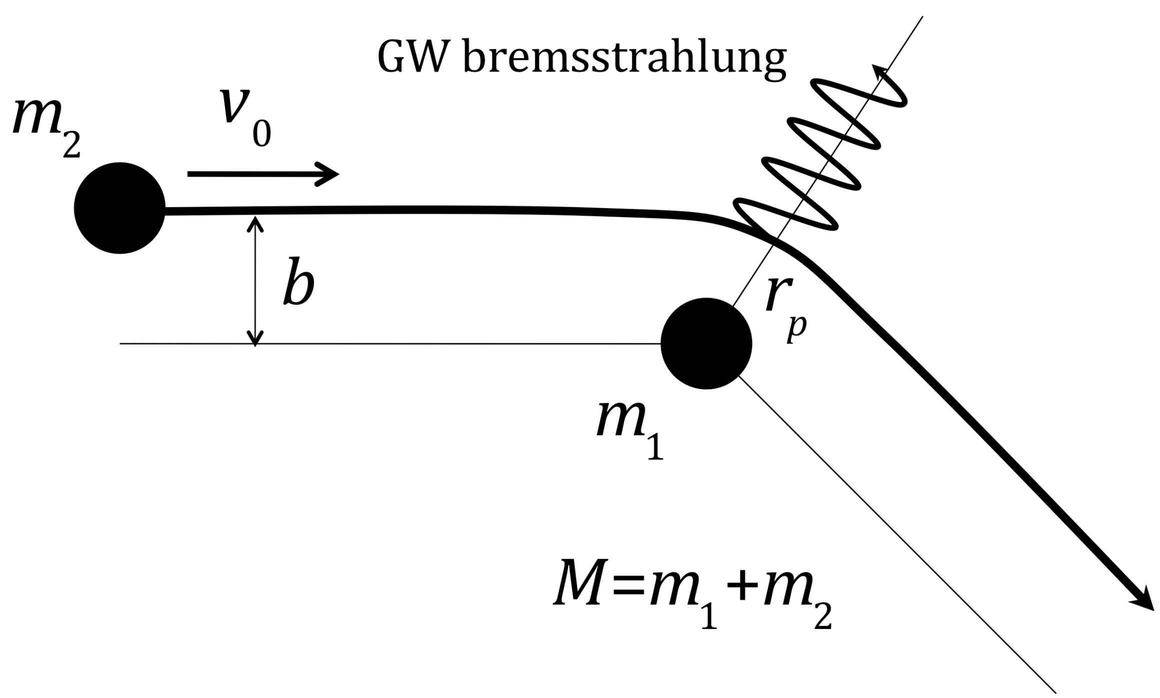
[García-Bellido 2018]

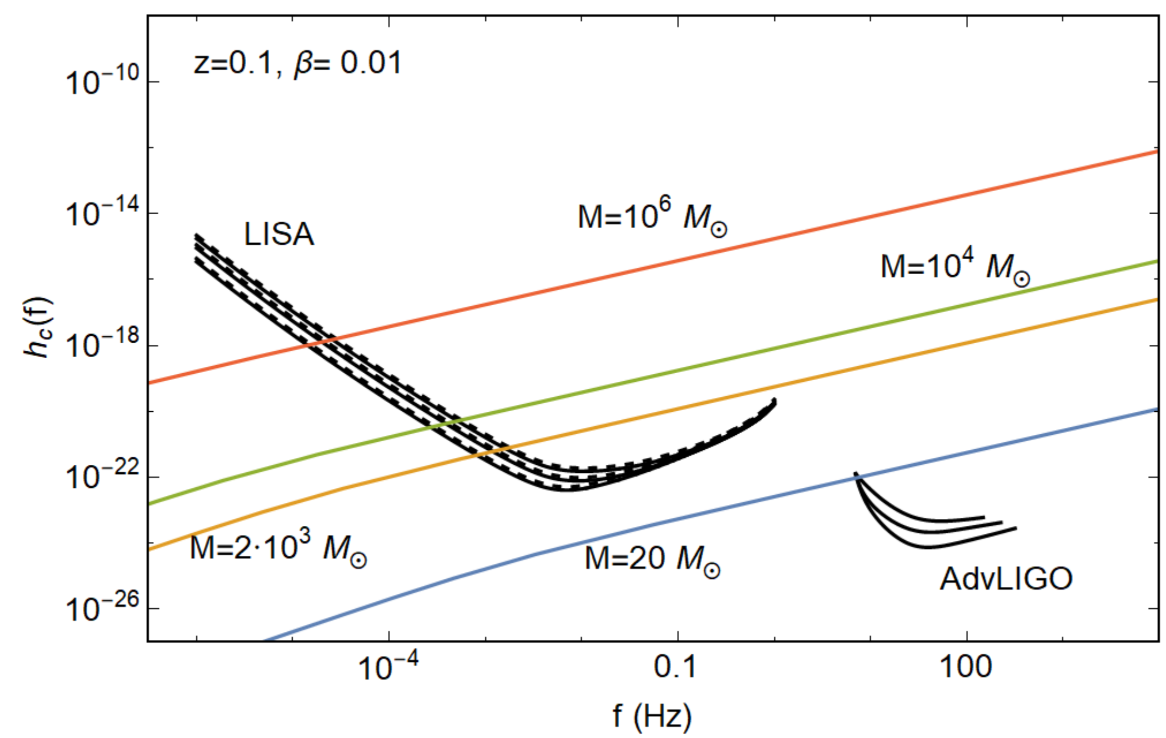
homogeneous versus clumped dark matter distribution

★ 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.

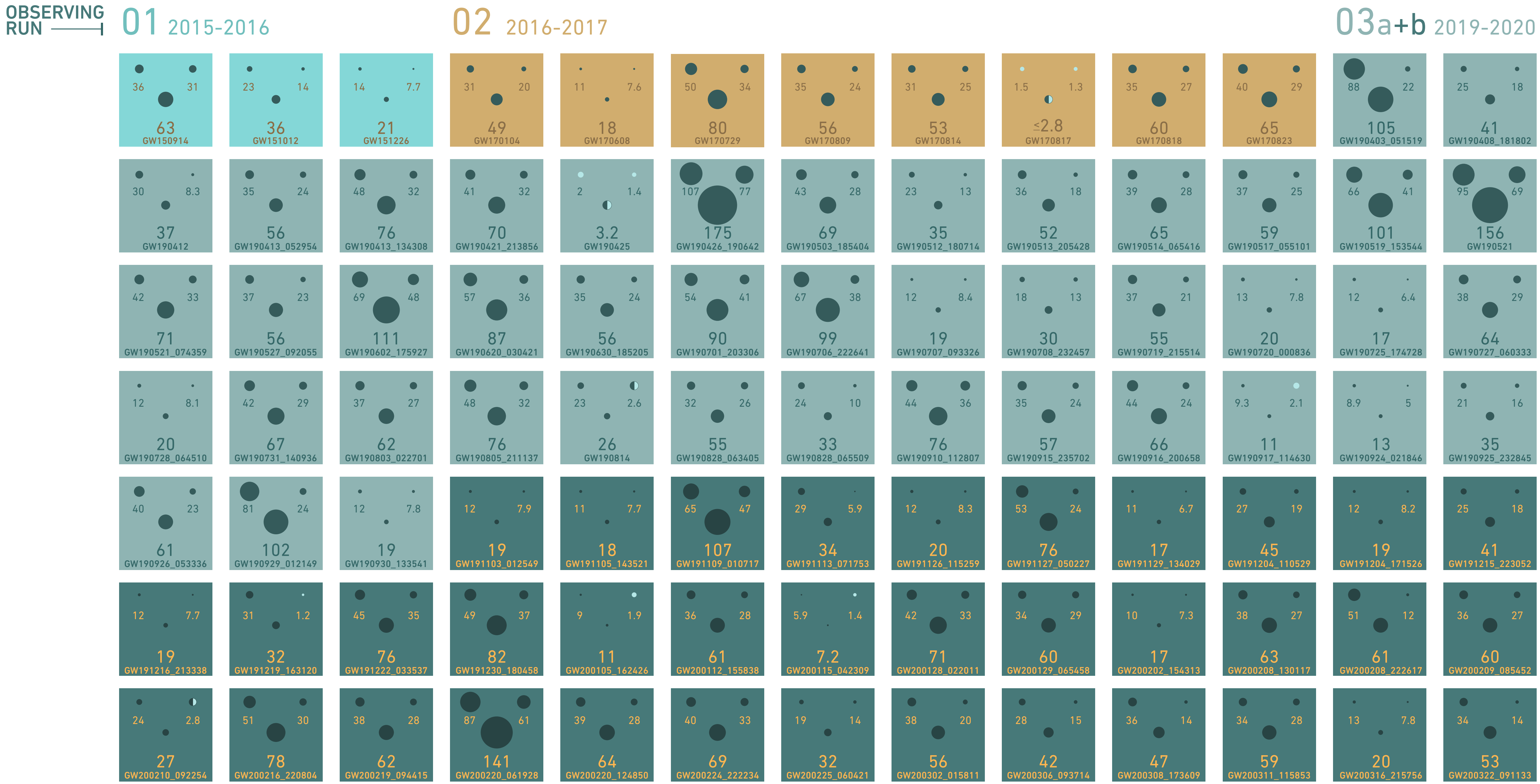




[Garcia-Bellido & Nesseris 2017]

GRAVITATIONAL WAVE **MERGER** DETECTIONS

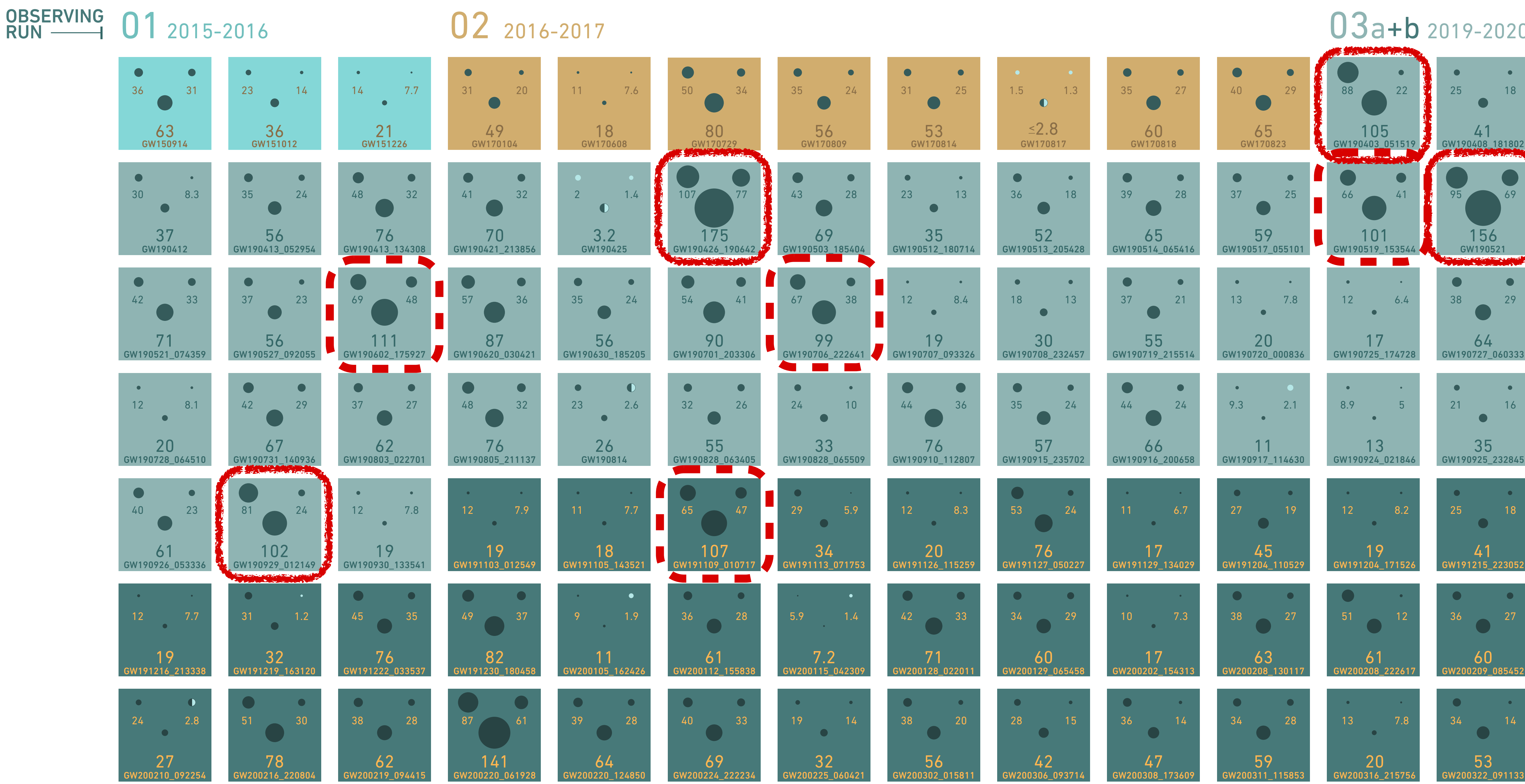
SINCE 2015



LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

SINCE 2015

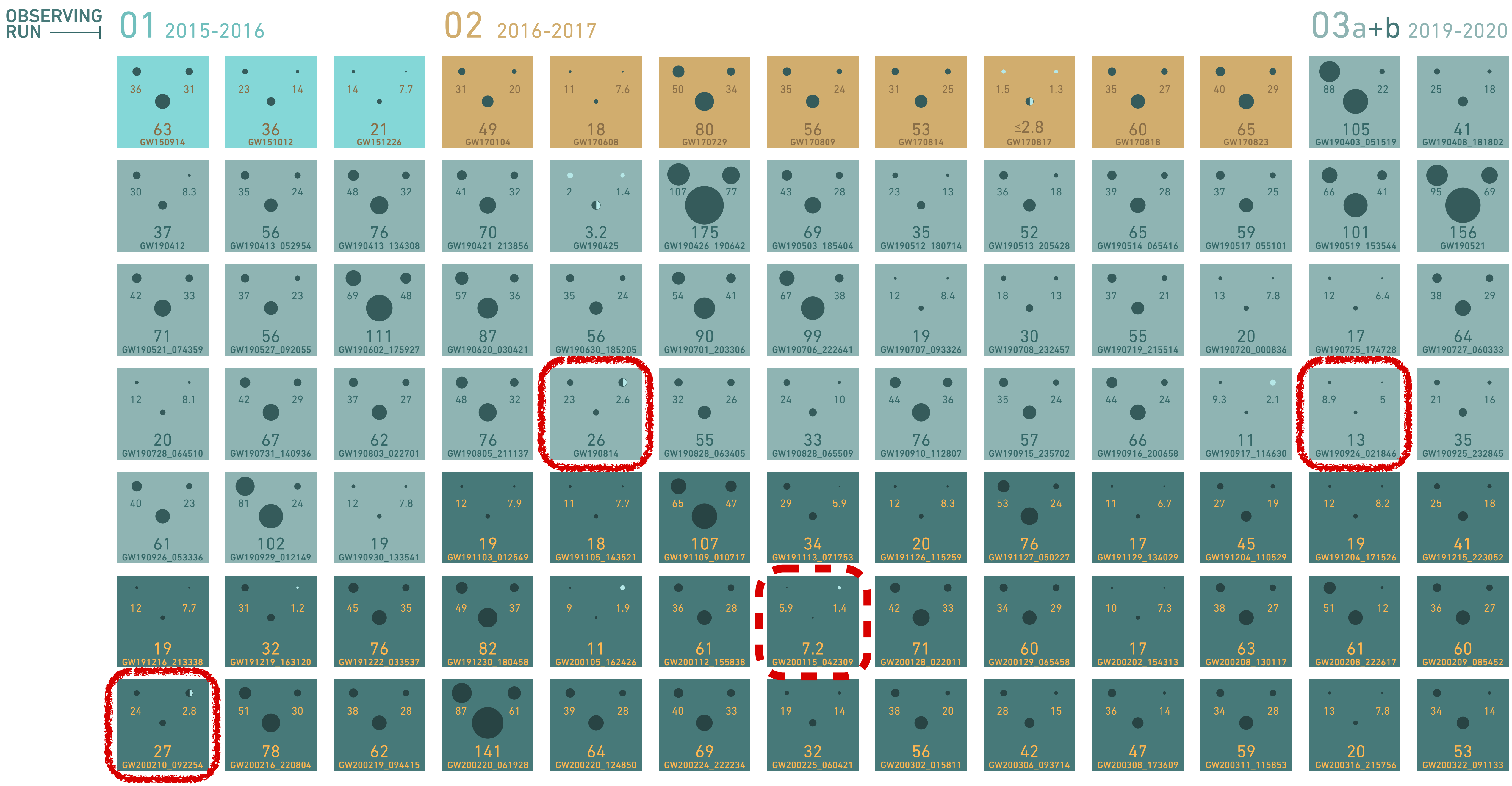


★ Black hole progenitors in the pair-instability mass gap (i.e. above ~ 60 $M_\odot$)

LIGO VIRGO KAGRA

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015



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

GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

The Astrophysical Journal Letters, 896:L44 (20pp), 2020 June 20 https://doi.org/10.3847/2041-8213/ab960f

CrossMark

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:

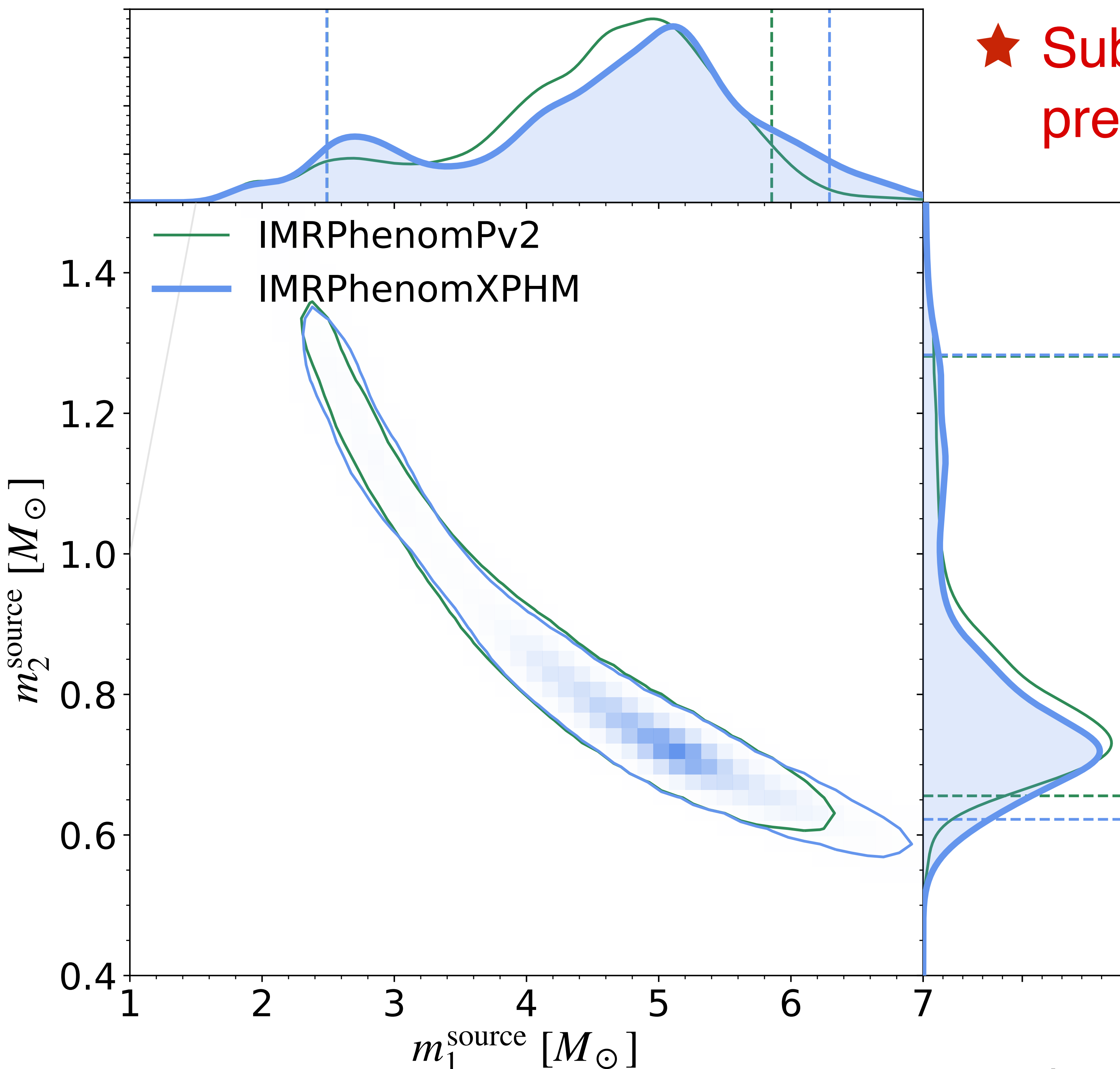
Date	FAR [yr^{-1}]	$m_1[M_\odot]$	$m_2[M_\odot]$	spin-1-z	spin-2-z	H SNR	L SNR	V SNR	Network SNR
2017-04-01	0.41	4.90	0.78	−0.05	−0.05	6.32	5.94	–	8.67
2017-03-08	1.21	2.26	0.70	−0.04	−0.04	6.32	5.74	–	8.54
2020-03-08	0.20	0.78	0.23	0.57	0.02	6.31	6.28	-	8.90
2019-11-30	1.37	0.40	0.24	0.10	−0.05	6.57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

[Phukon *et al.* 2021, Abbott *et al.* 2022]

★ 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]

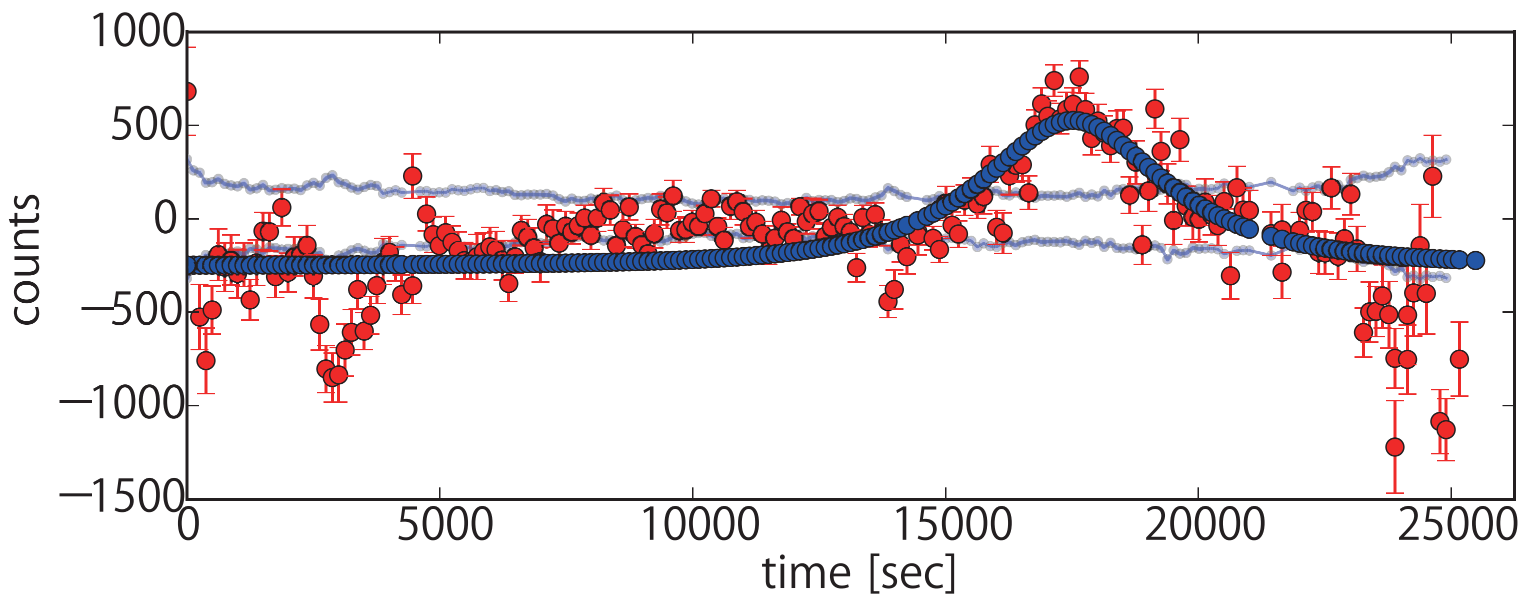
contra

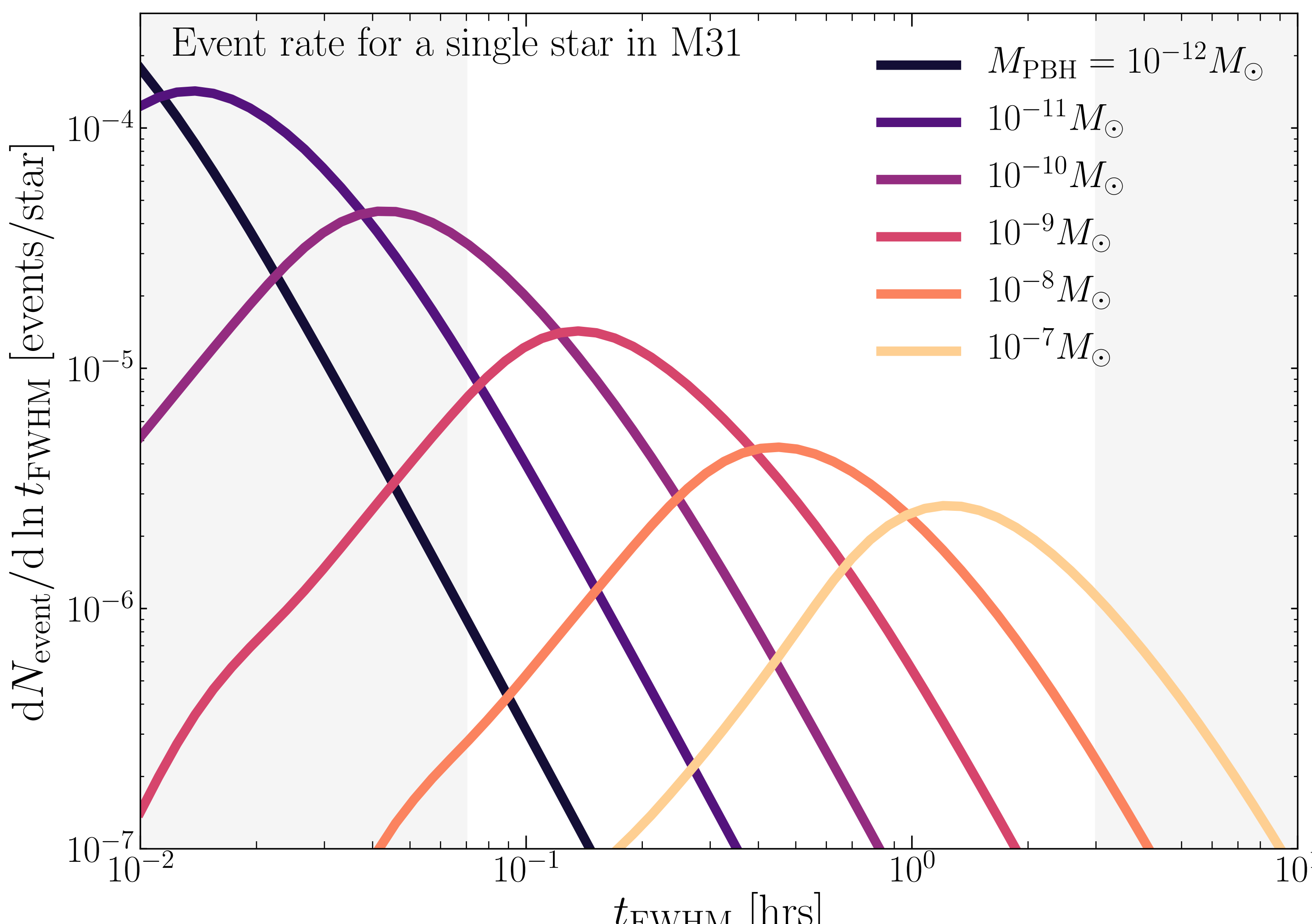
the wager

pro

[me]

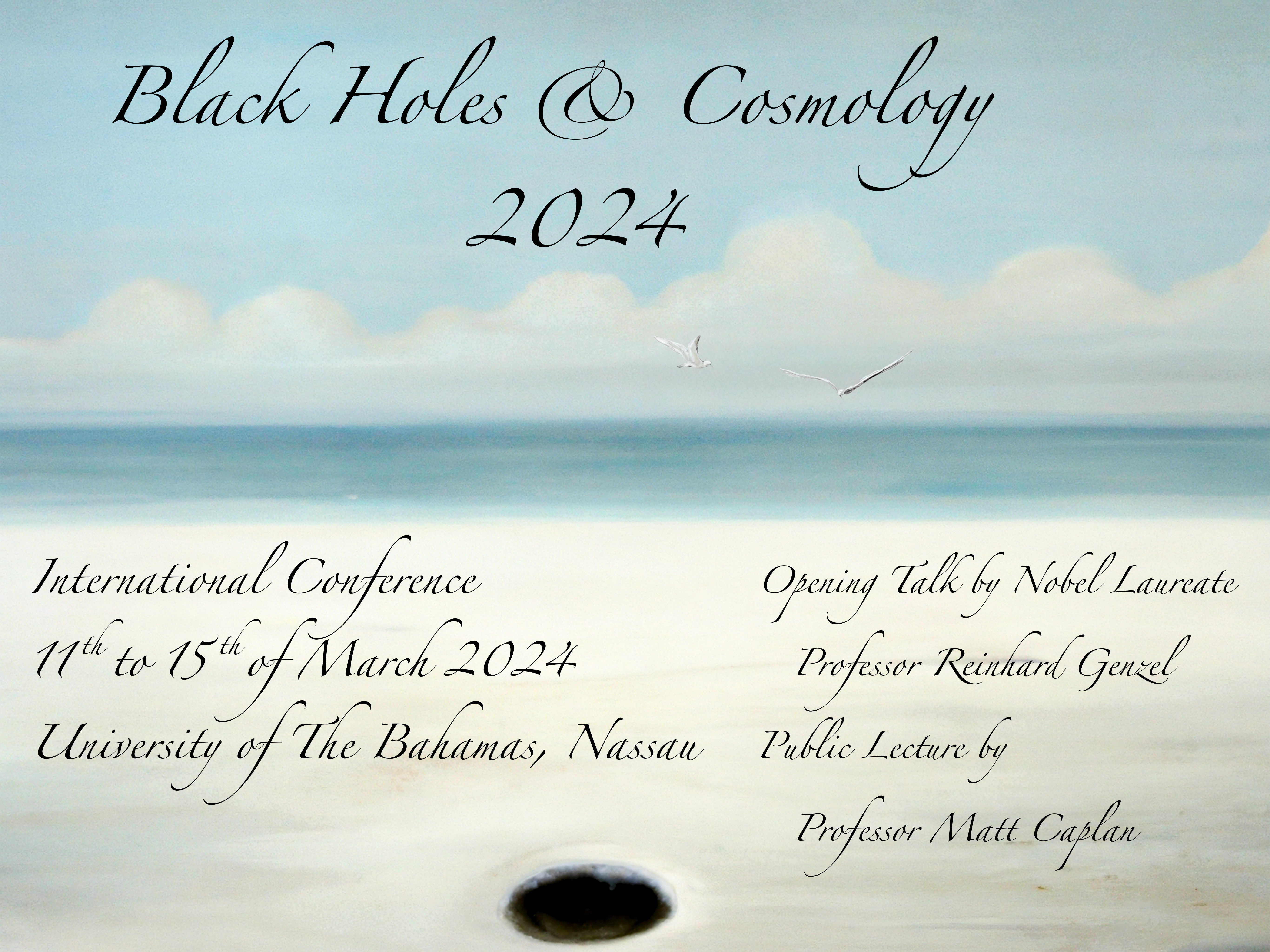
Pixel Lensing by Subaru Hyper Suprime-Camera (HSC)





[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.


Black Holes & Cosmology
2024
International Conference
11th to 15th of March 2024
University of The Bahamas, Nassau
Opening Talk by Nobel Laureate
Professor Reinhard Genzel
Public Lecture by
Professor Matt Caplan

Professor Matt Caplan

Confirmed Invited Speakers include:

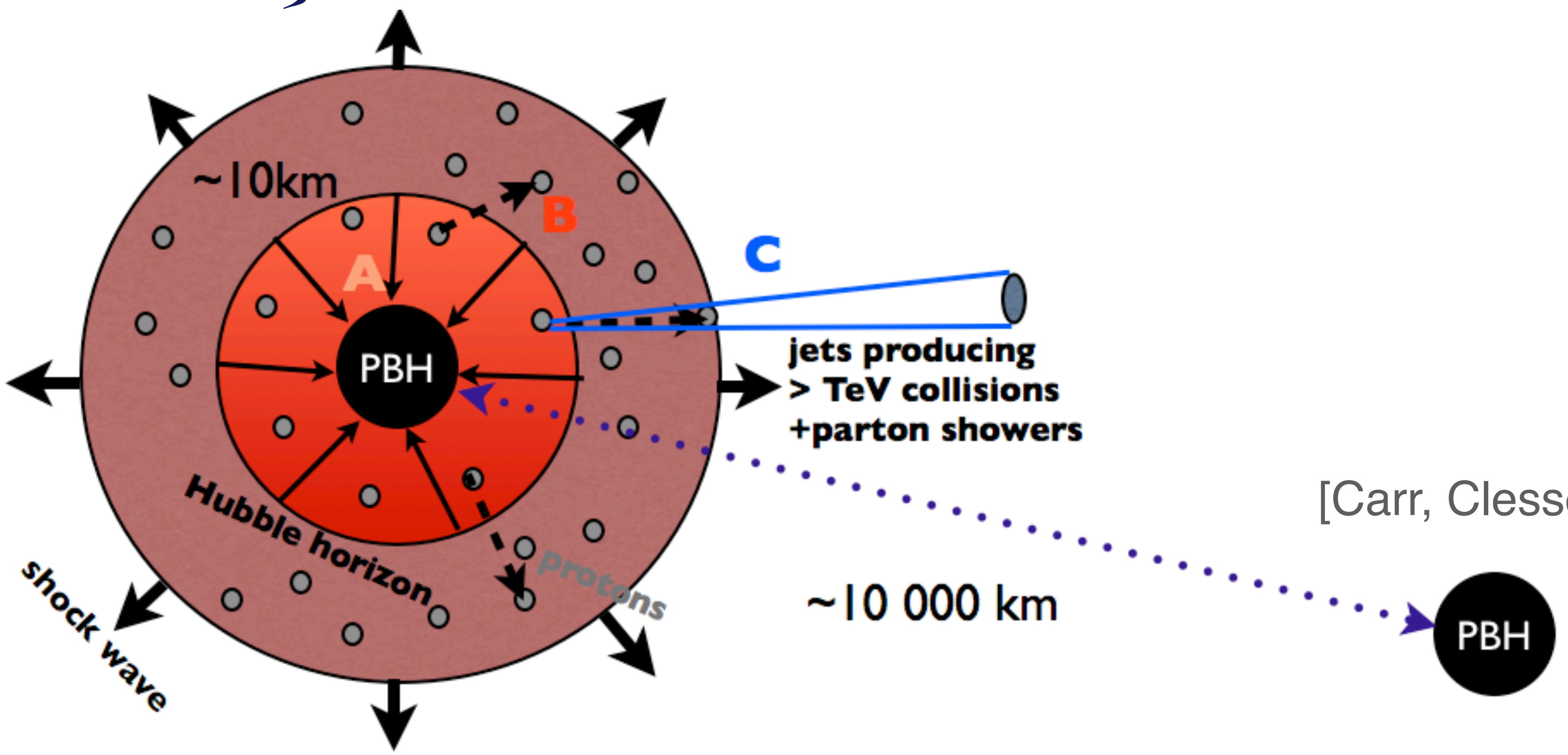
Andreas Albrecht
Earl Bellinger
Gianfranco Bertone
Alessandra Buonanno
Andreas Burkert
Nico Cappelluti
Bernard Carr
Gia Dvali
Glennys Farrar
Juan García-Bellido
Reinhard Genzel
David Kaiser
Will Kinney
Sasha Kashlinsky
Michela Mapelli
Emil Mogola
Samaya Nissanke
Remo Ruffini
Ravi Sheth
Subir Sakar
Lárus Thorlacius

Organisational Committee:

Florian Kühnel (Chair), Jaco de Swart, Katherine Freese, Pandora Johnson, Eduardo Guendelman, Claude McNamarah, Remo Ruffini, Carlton Watson

See you at BHCos '26!

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!

Primordial Black Holes from Confinement

work with Dvali & Zantedeschi

Important Issues

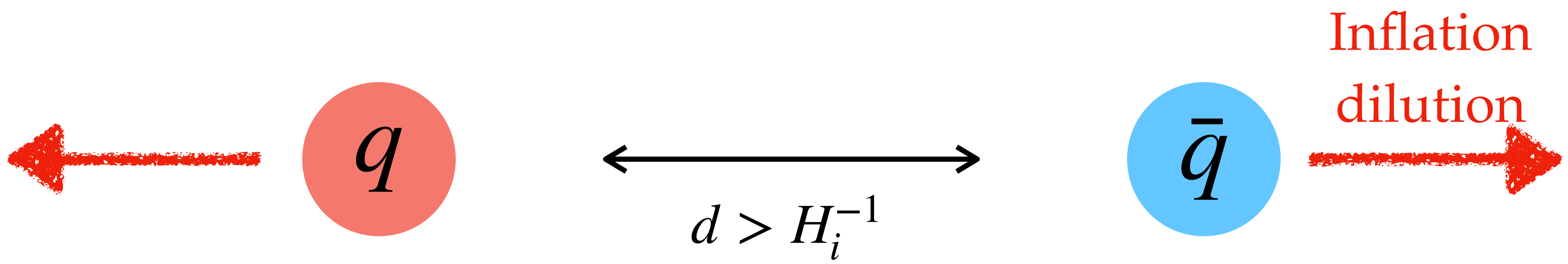
- The standard approach of PBH formation has two main issues:
  - In order to have a given percentage of PBH dark matter requires exponential fine-tuning.
  - PBH formation happens in the strong-coupling regime.

A New Approach

- We propose a novel PBH formation mechanism which is
    - assumption-minimal,
    - free of exponential fine-tuning,
    - avoids strong coupling,
    - works with standard QCD*,
    - compatible with observations.

Confinement Formation Mechanism

★ **1. Ingredient:** de Sitter fluctuations produce quarks during inflation.



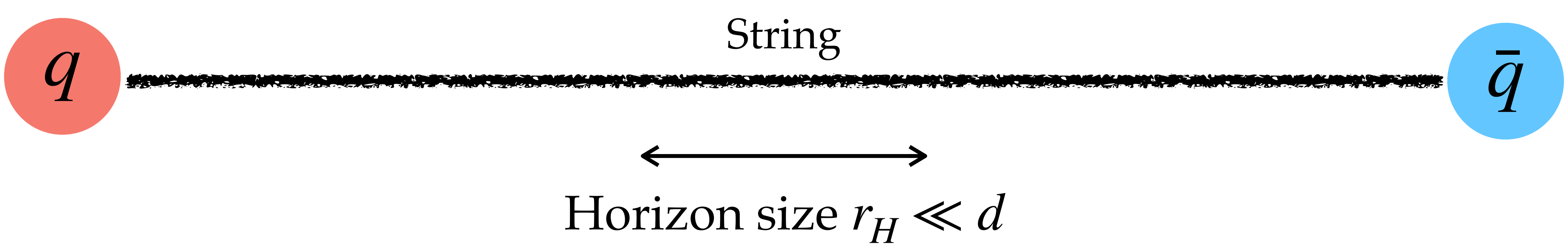
★ Focus on a simple pair case.

★ Distance grows as $d \propto e^{N_e}$.

★ Quarks quickly move out of causal contact.

Confinement Formation Mechanism

★ **2. Ingredient:** Confinement at energy scale Λ_c, $M_q/\Lambda_c \gg 1$



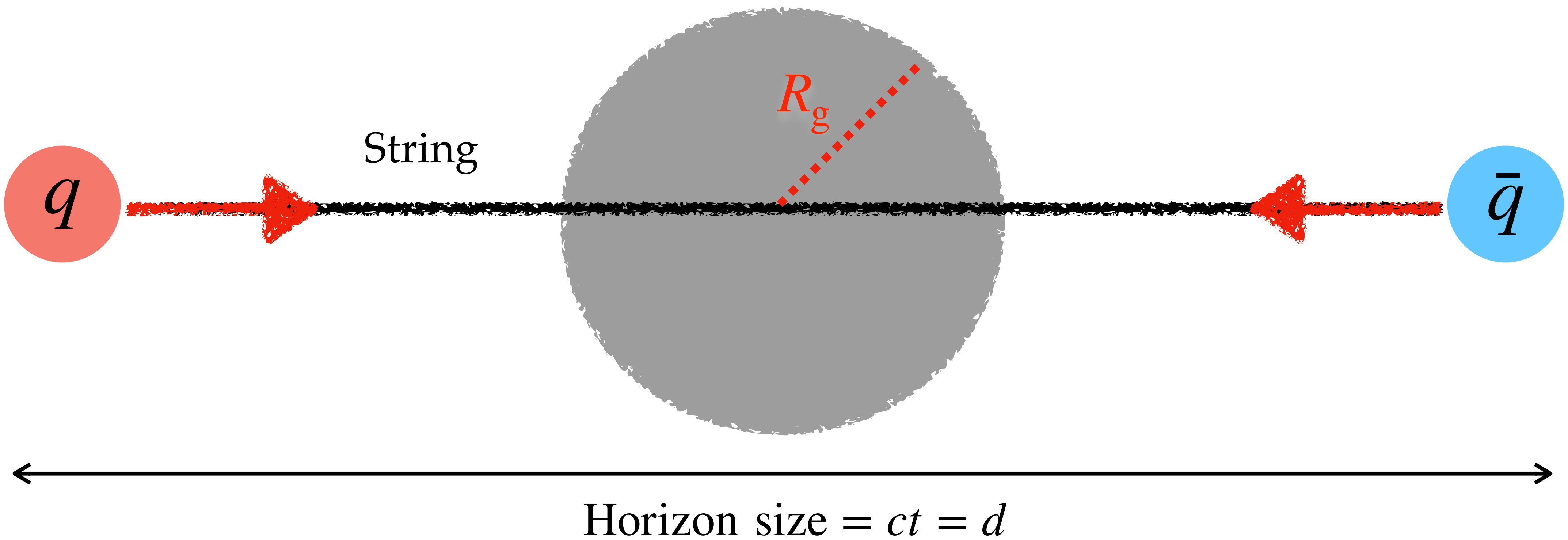
★ Flux tubes form connecting quark/anti-quark pairs.

★ The system cannot collapse as long as $d > r_H$.

★ String breaking into quarks pair, $P_{\text{tunnel}} \propto e^{-\pi\left(M_q/\Lambda_c\right)^2}$, suppressed as long as $M_q/\Lambda_c \gg 1$.

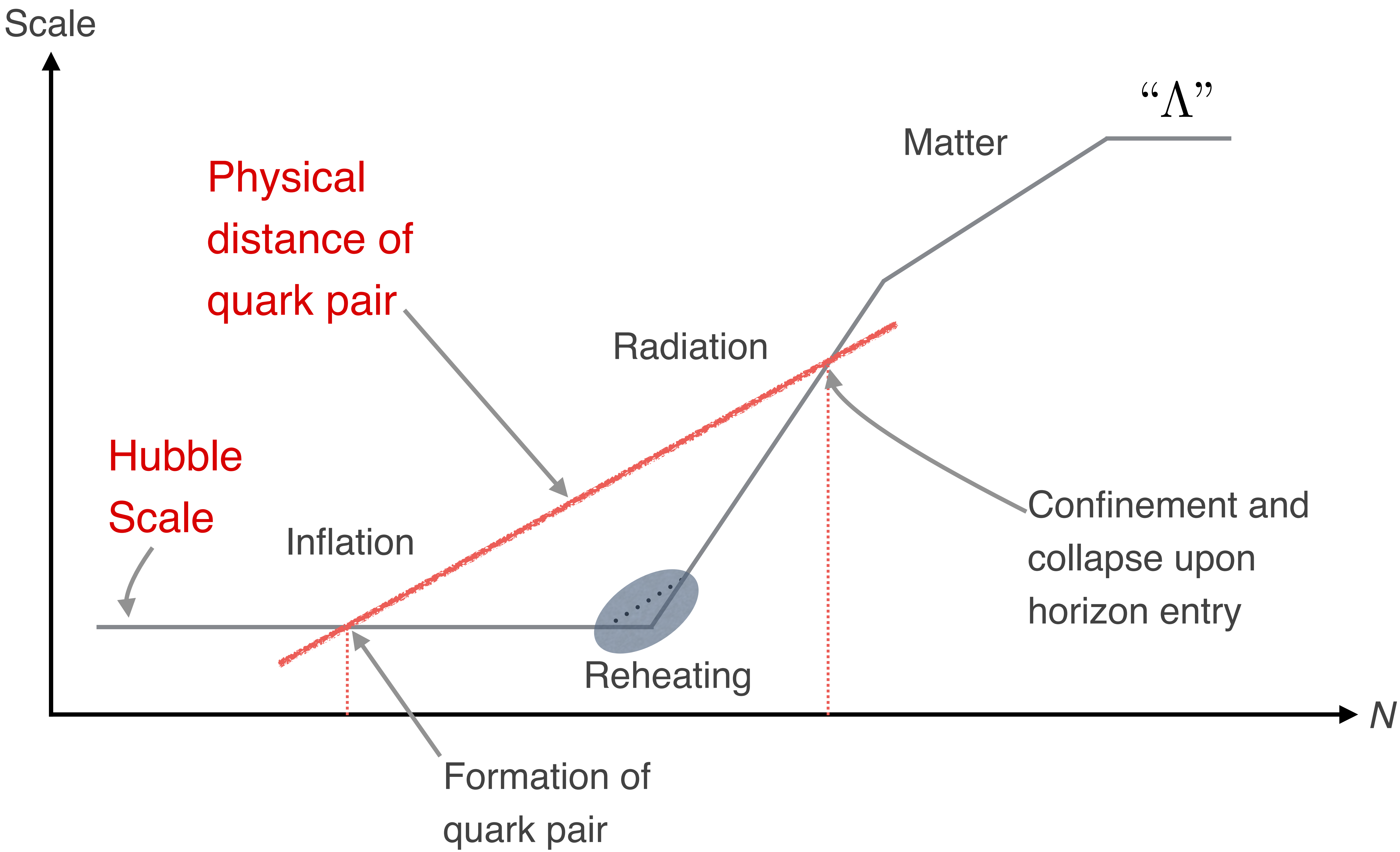
Confinement Formation Mechanism

★ **3. Ingredient:** Black hole formation upon horizon entry



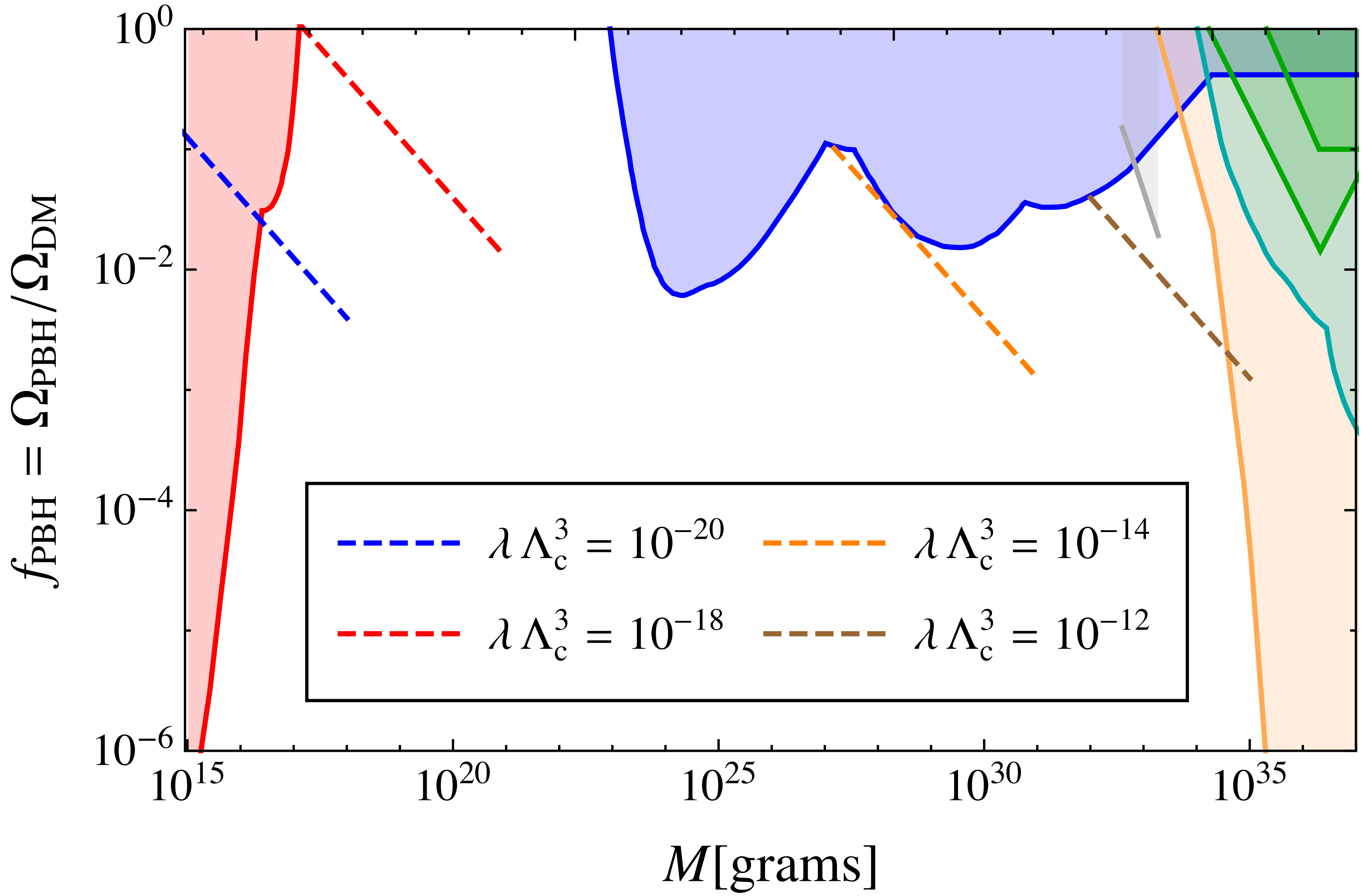
- ★ Acceleration of the quarks $a = \Lambda_c^2/m_q$ quickly leads to their ultra-relativistic motion.
- ★ The energy stored in the string is $E \simeq \Lambda_c^2 t \simeq M_g, \quad R_g \gg \Lambda_c^{-1}$.
- ★ PBHs from inflationary overdensities are heavier by a factor $\sim \Lambda_c^2$.

Formation Scales



Dark Matter from Confinement

★ Present-day dark matter distribution vs *monochromatic* constraints:

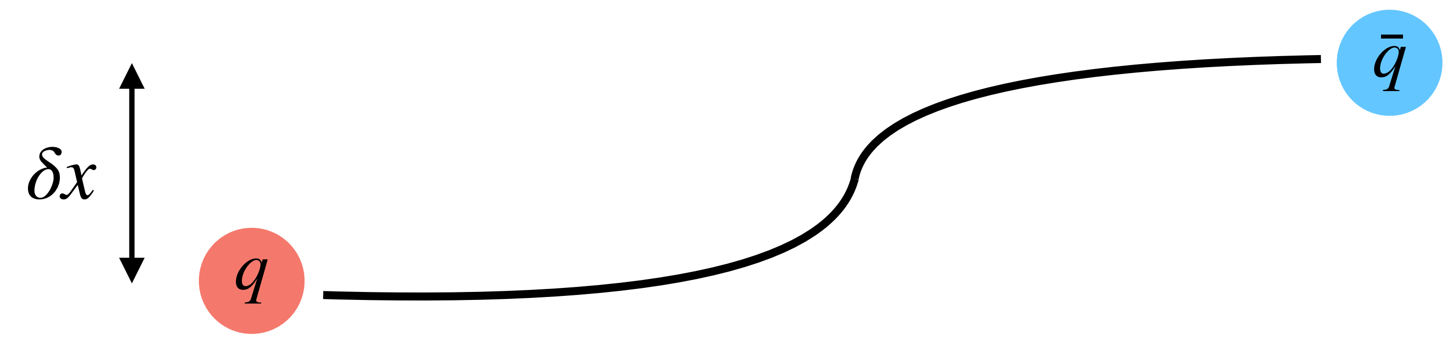


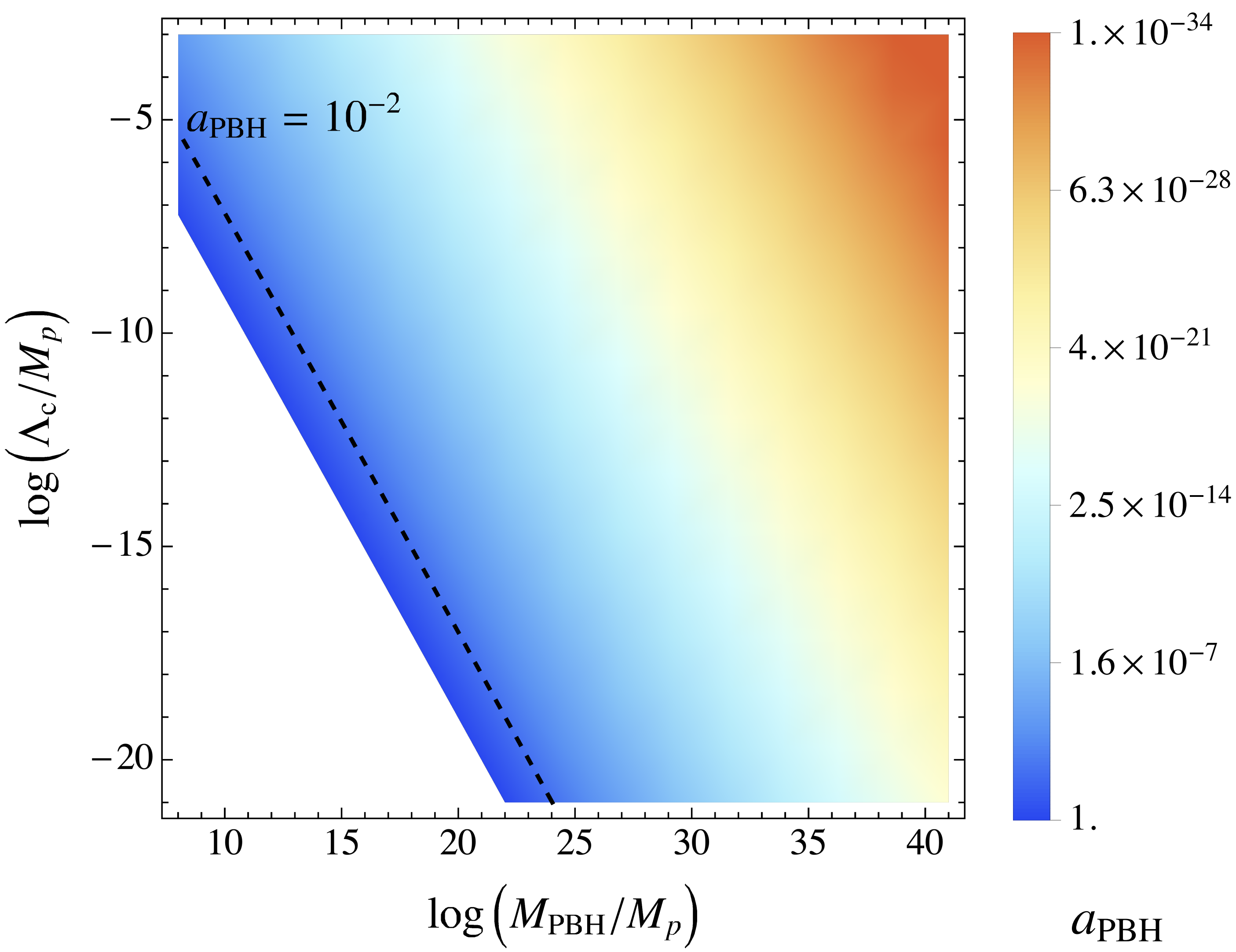
★ Find: $$f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}(t)}{\rho_{\rm CDM}(t)} = \frac{32\pi}{3}\,\lambda\Lambda_c^3\left(\frac{M_{\rm PBH}}{M_{\rm eq}}\right)^{-1/2}$$

High-Spin Subsolar PBHs

★ During inflation, the string undergoes a Brownian motion, induced by de Sitter quantum fluctuations, leading to deviation from straightness:

$$\delta x \simeq \sqrt{N_e}\, H_i^{-1}$$



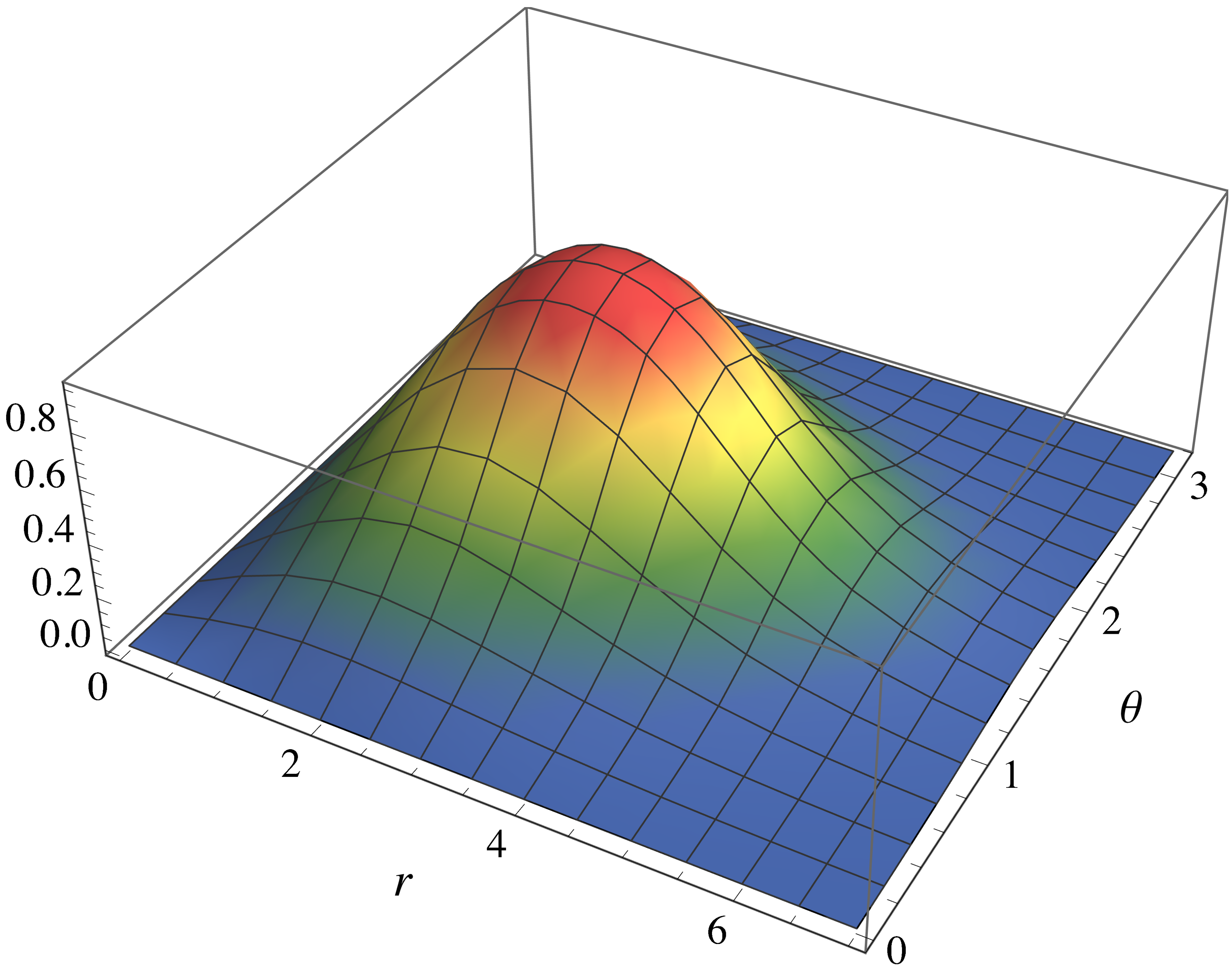


★ This leads to potentially significant spin:

$$a_{\rm PBH} \simeq \frac{\delta x}{R_g}$$

$$\simeq \frac{1}{H\,M_{\rm PBH}} \log\left(\frac{H\,M_{\rm PBH}}{\Lambda_c^2}\right)^{1/2}$$

Formation of Vortices



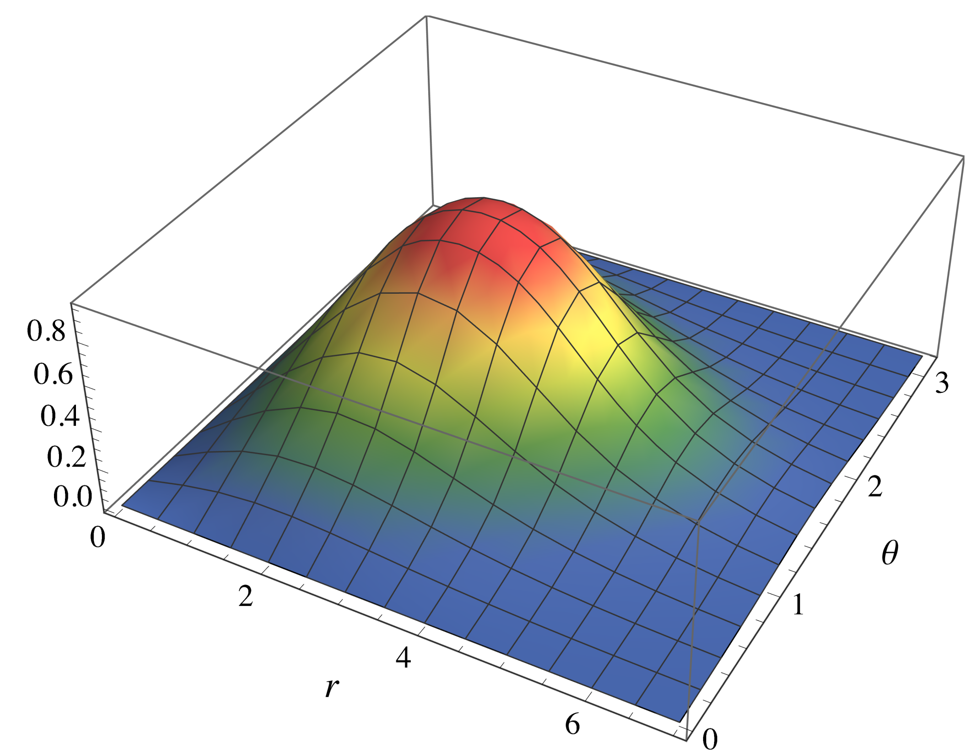
[Dvali, FK, Zantedeschi 2021]

Formation of Vortices

★ Black Holes can be understood as saturons.

★ We showed that these admit vortex structure, in the case of near-extremal spin.

★ PBHs from confinement could provide ideal prerequisites for vortex formation due to highly spinning light PBHs.



[Dvali, FK, Zantedeschi 2021]

★ If these PBHs provide the dark matter, their vorticity might explain primordial magnetic fields.

★ Besides, vorticity provides a topological meaning to the stability of extremal black holes.

Primordial Black Holes

and

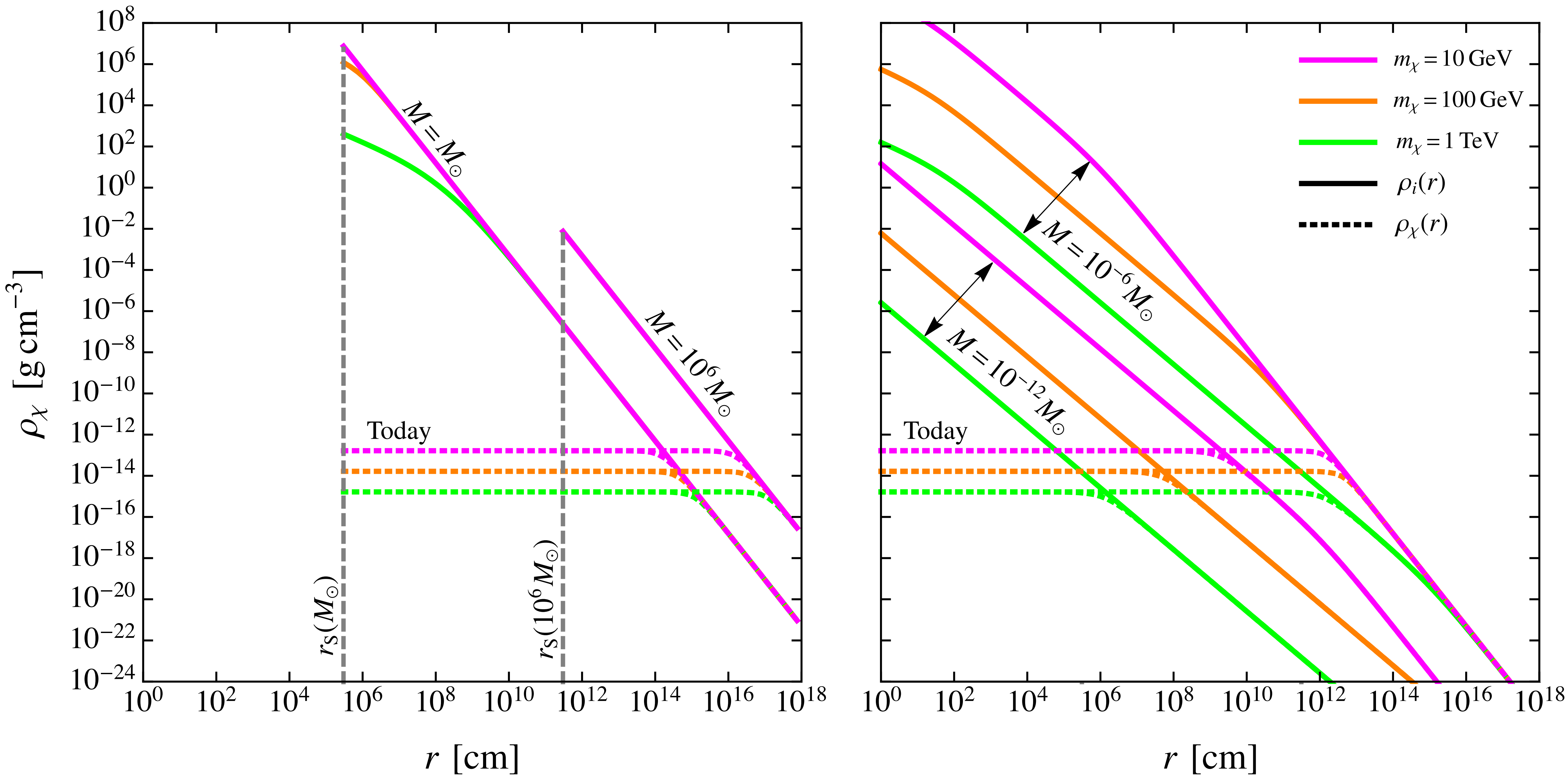
Particle Dark Matter

PBH & Particle Dark Matter

- Always when $f_{\rm PBH} < 1$ there must be another dark matter component!
- Study a combined scenario: Dark Matter = PBHs + Particles
    - The latter will be accreted by the former; formation of halos.
    - Study WIMP annihilations in PBH halos:
        - The annihilation rate $\Gamma \propto n^2$.
        - Halo profile does matter; enhancement of Γ in density spikes.
            1) Derive the density profile of the captured WIMPs;
            2) calculate the annihilation rate;
            3) and compare to data.

[Eroshenko 2016, Boucenna *et al*. 2017, Adamek *et al*. 2019, Carr, FK, Visinelli 2020 & 2021, Witte *et al.* 2022]

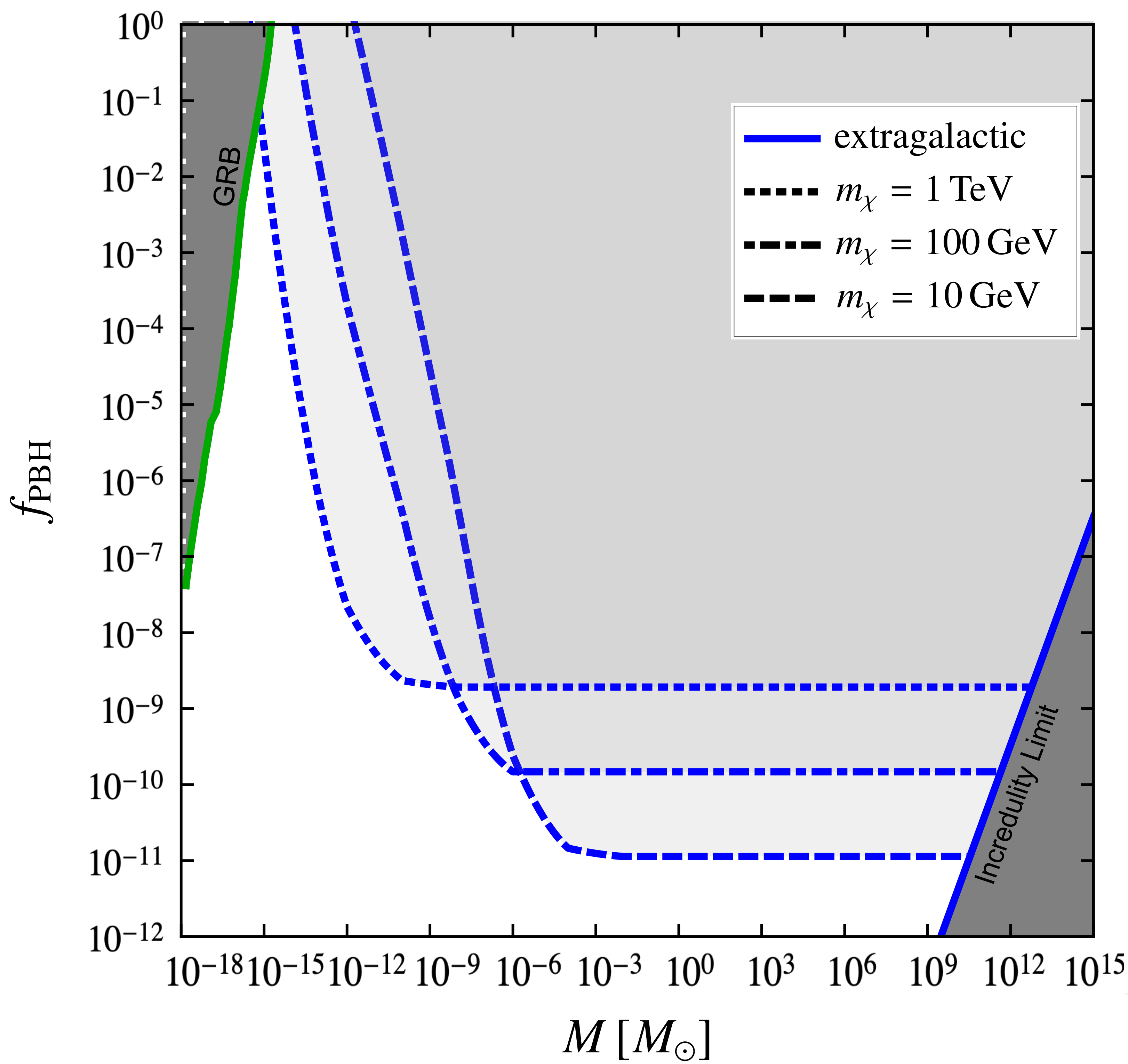
PBHs & WIMPs



[Carr, FK, Visinelli 2021]

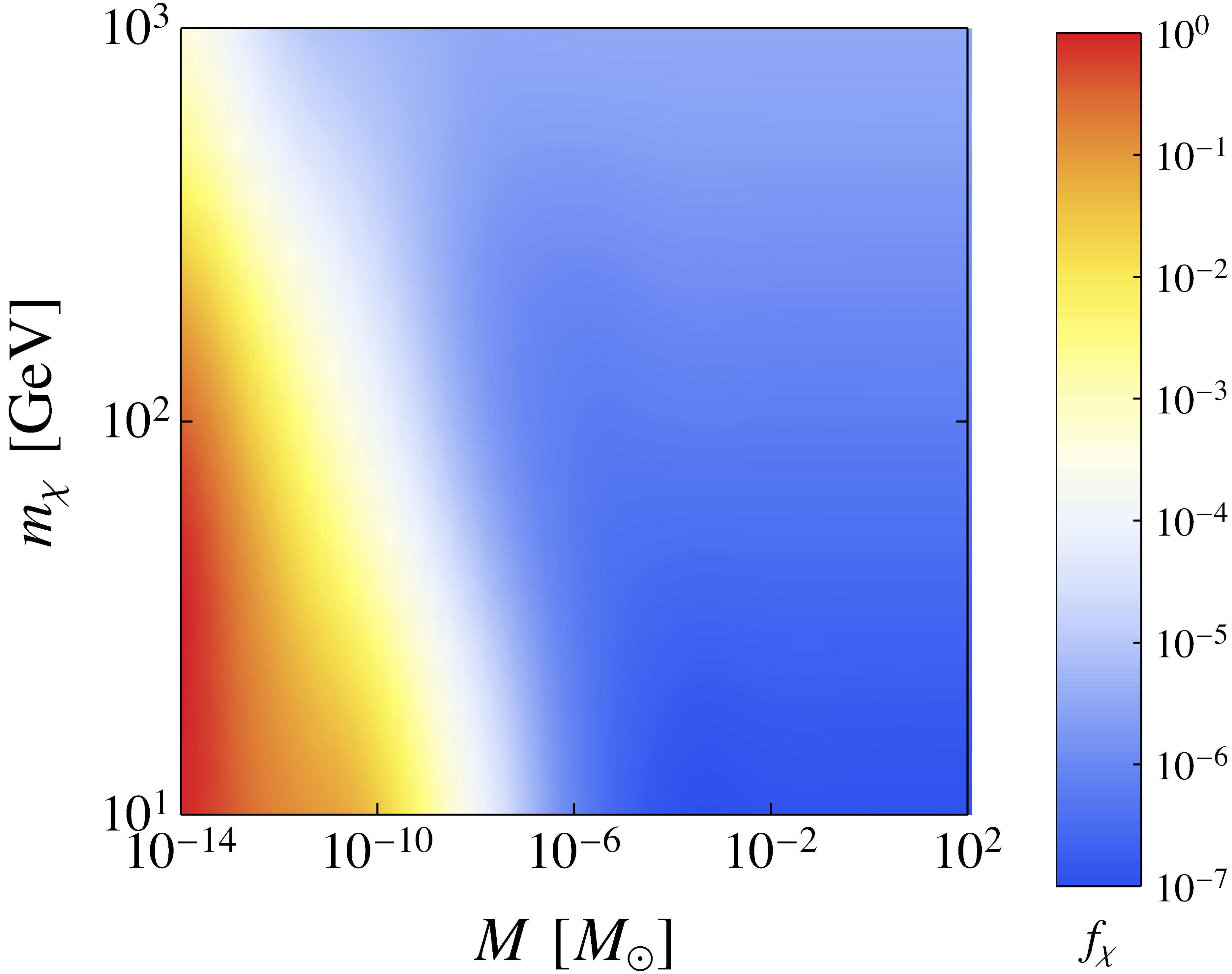
★ Annihilations lead to plateaux in the present-day halos.

PBHs & WIMPs



[Carr, FK, Visinelli 2021]

PBHs & WIMPs



[Carr, FK, Visinelli 2021]

Monochromatic

versus

Extended Mass Spectra

Critical Collapse

★ Usually: Assume

$$M_{BH} \propto M_H$$

horizon mass

★ Critical scaling:

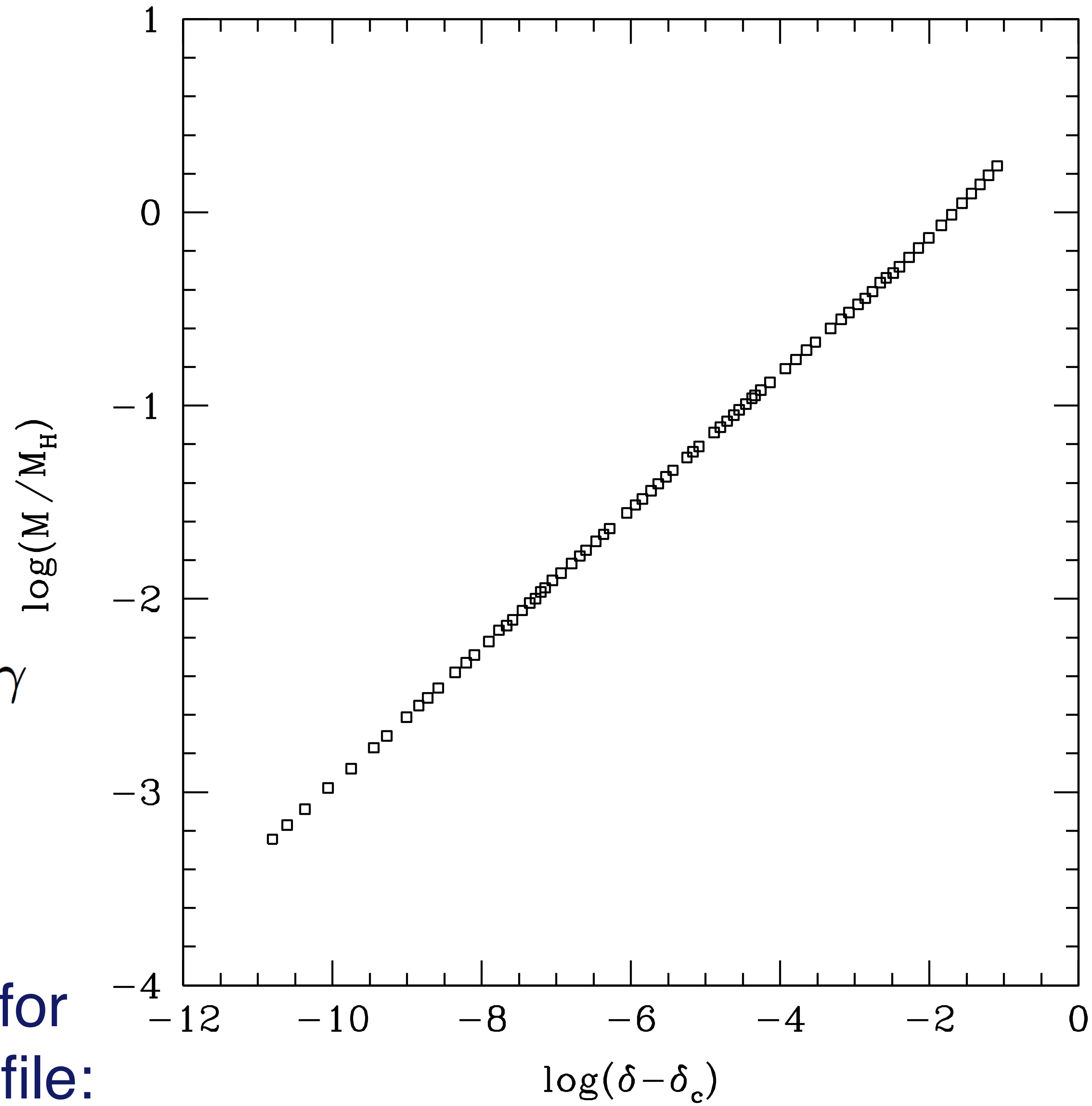
[Choptuik '93]

$$M_{BH} = k\, M_H \left(\delta - \delta_c\right)^{\gamma}$$

density contrast

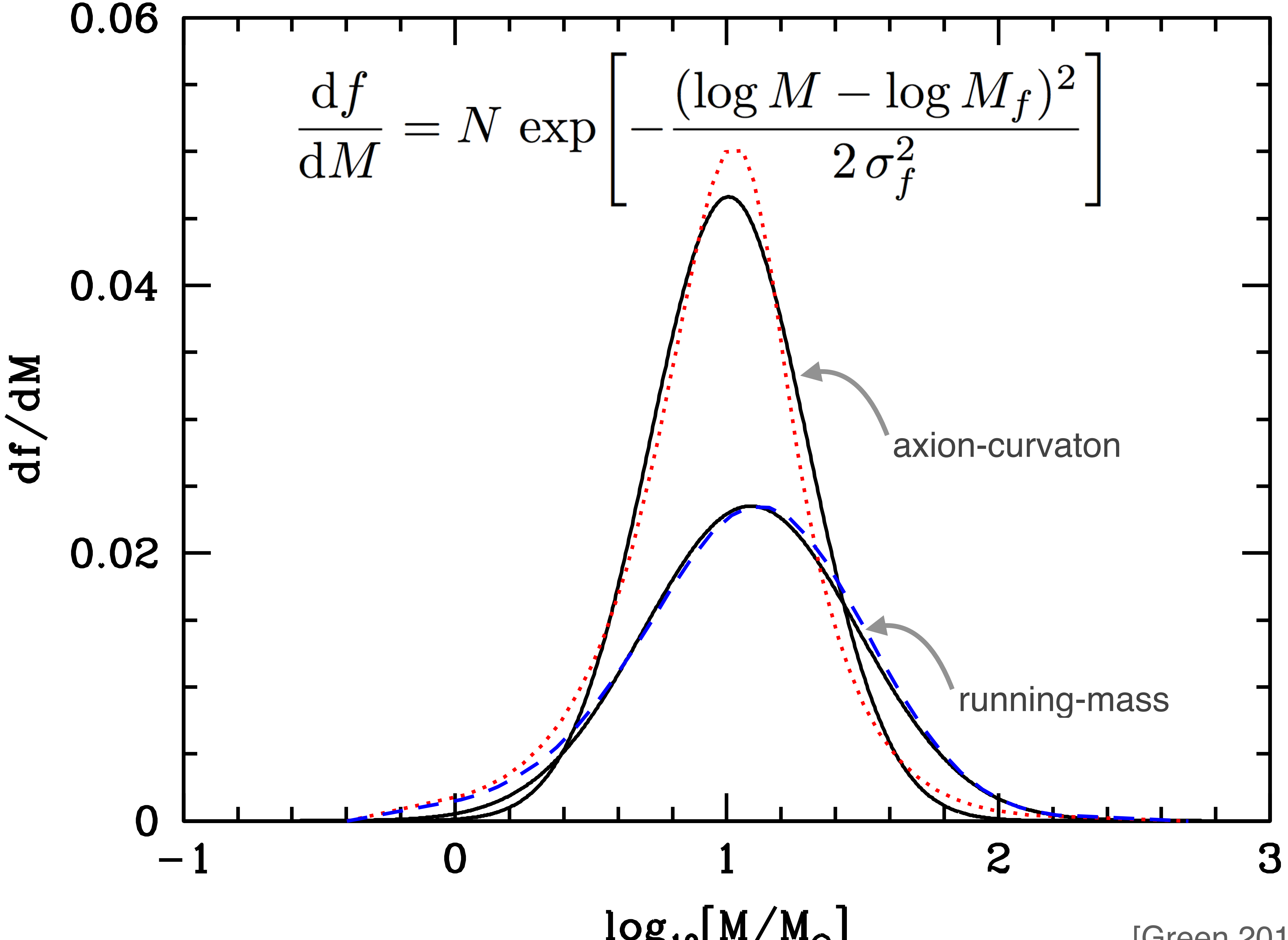
★ Radiation domination and for spherical Mexician-hat profile:

$$k \approx 3.3\ , \quad \delta_c \approx 0.45\ , \quad \gamma \approx 0.36$$



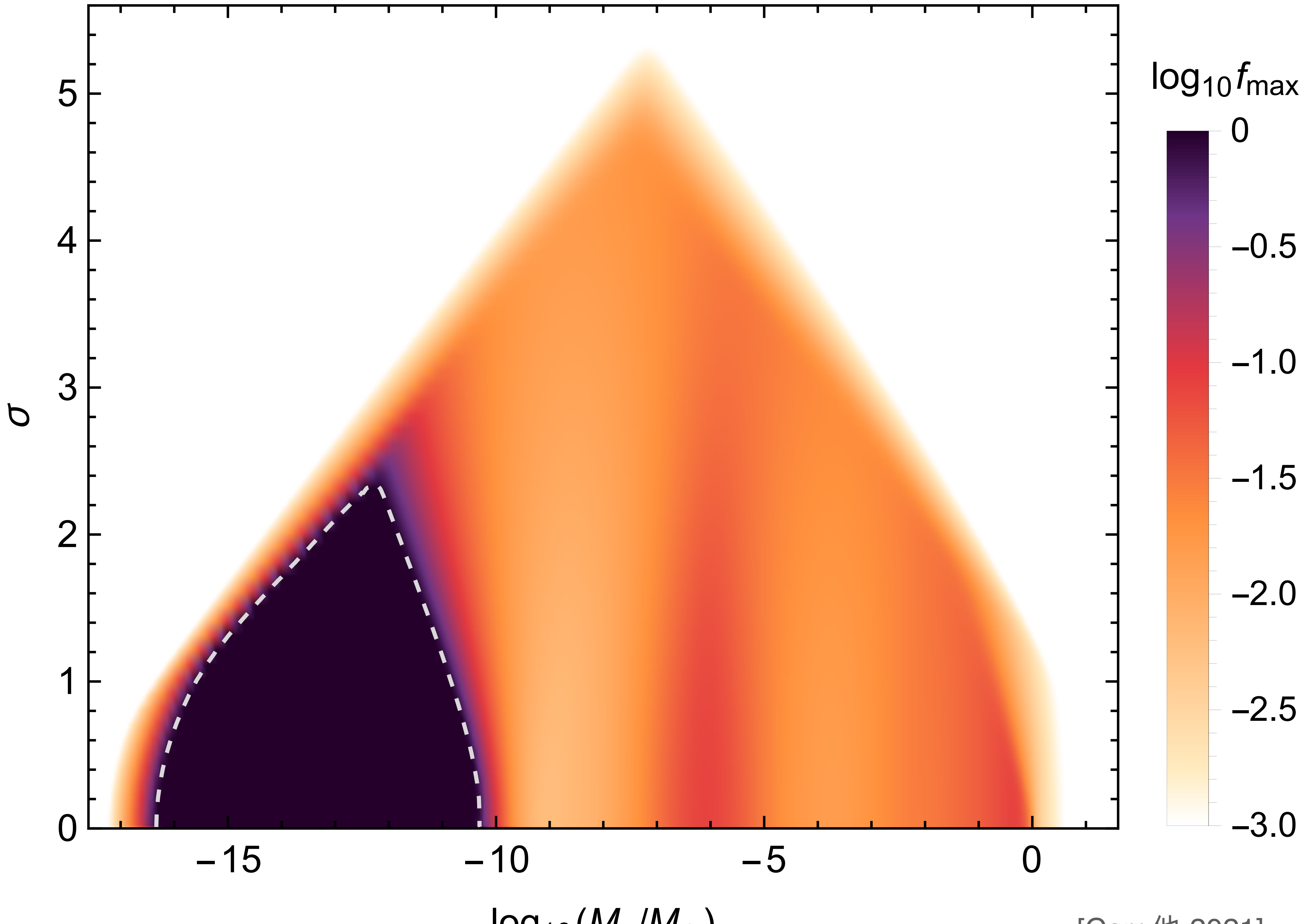
[Musco, Miller, Polnarev 2008]

More Systematic Study

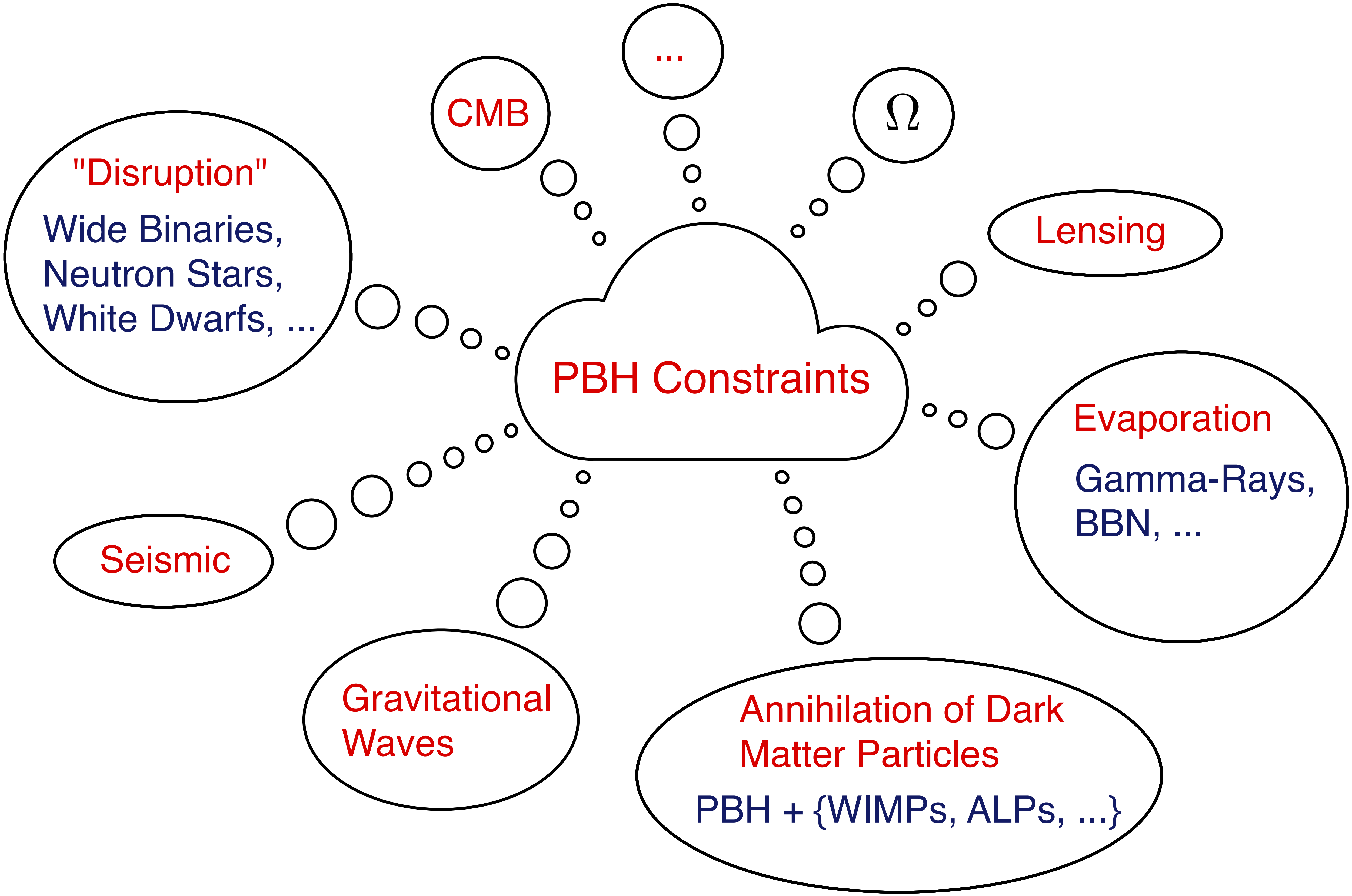


[Green 2016]

More Systematic Study



[Carr 他 2021]


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