Primordial Black Holes: Quantum Quiddity, Correlation Characteristics & Galaxy Genesis

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Florian Kühnel

Max Planck Institute for Physics,

Garching (near Munich), Germany

— News from the Dark 10 —

University of Montpellier, Friday the 12th of September 2025

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What are Primordial Black Holes (PBHs)?

★ Black holes formed in the early* Universe (in particular: *non-stellar*).

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- ★ Huge mass range:

[Bernard Carr]

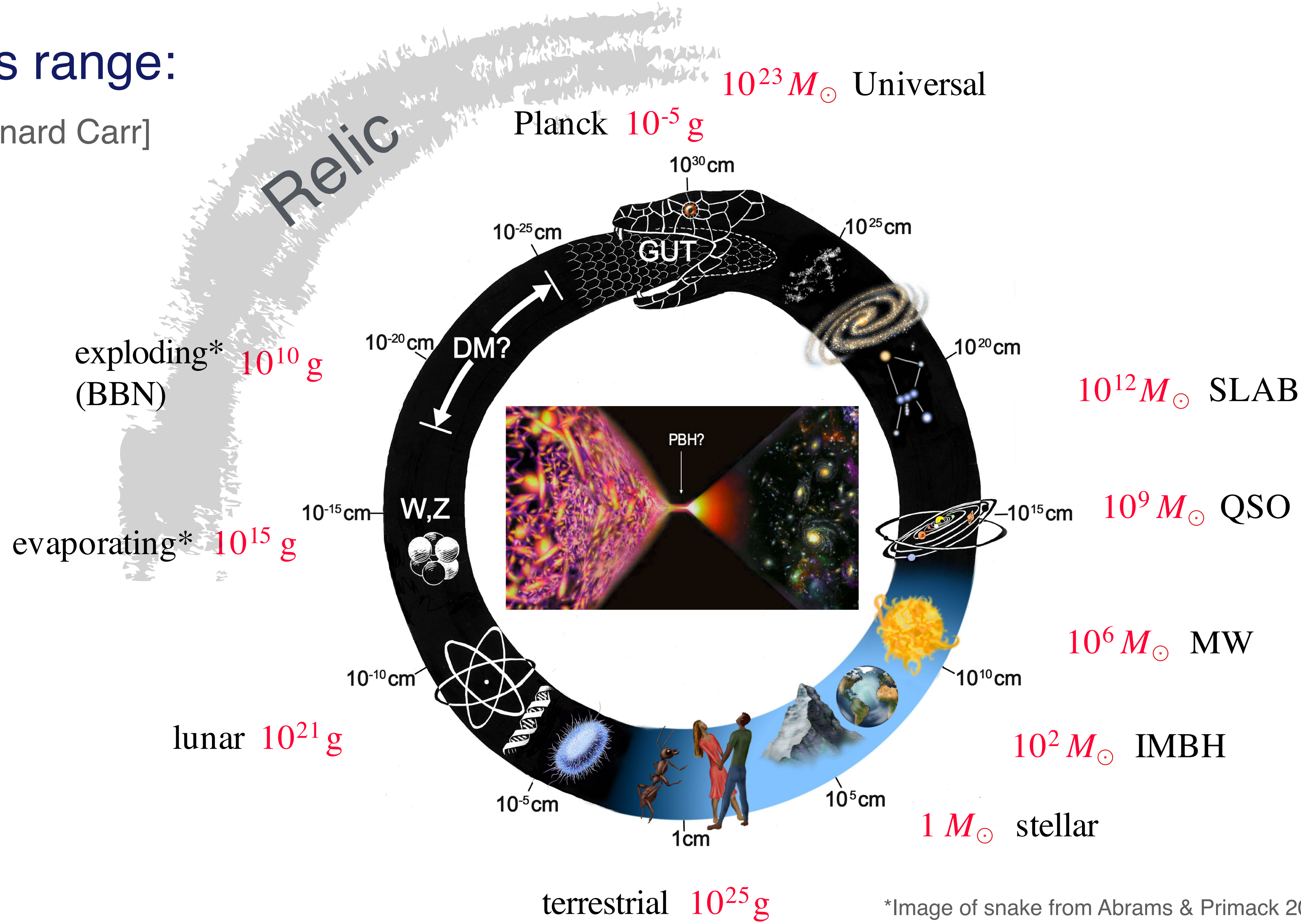

*Image of snake from Abrams & Primack 2012

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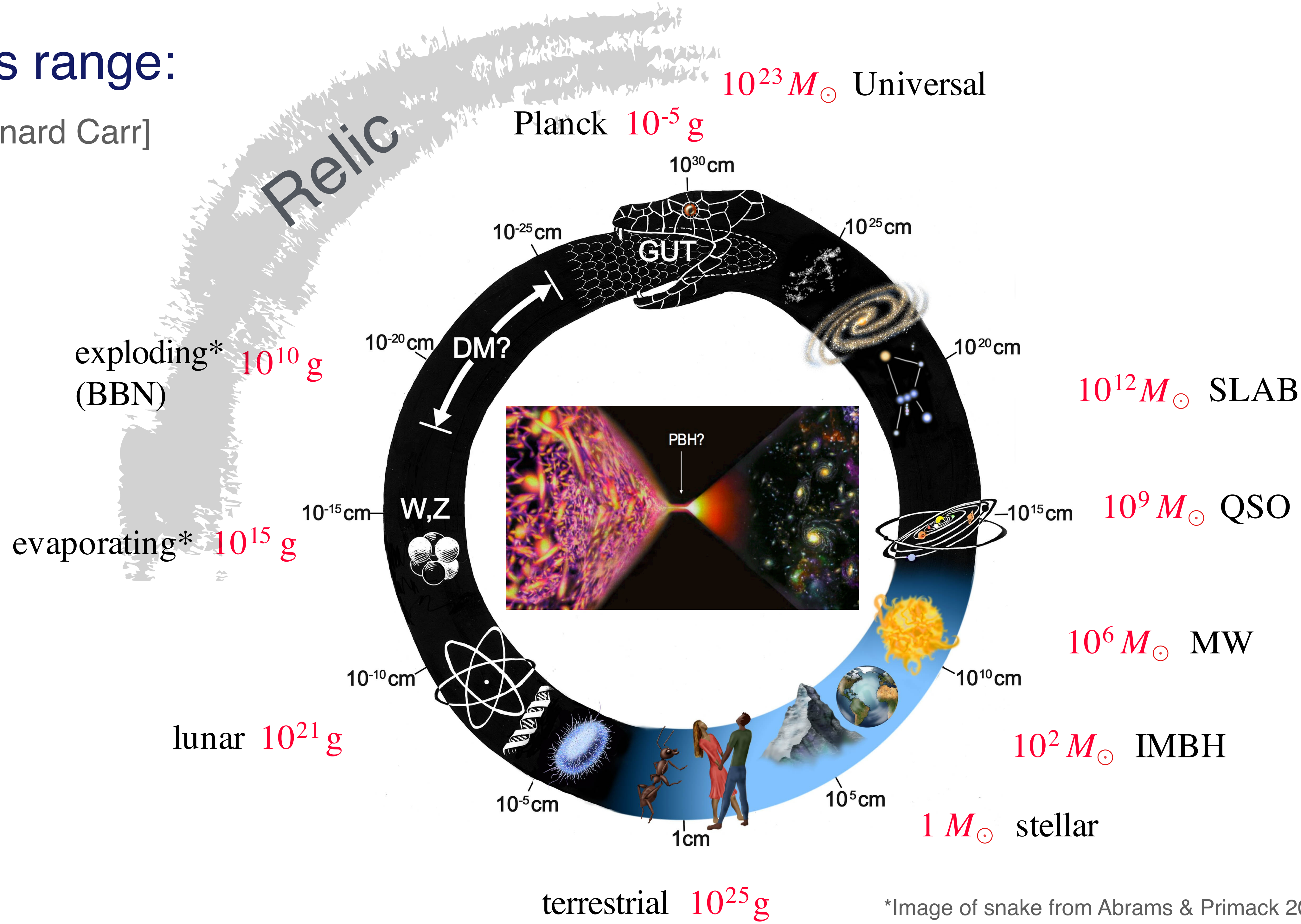
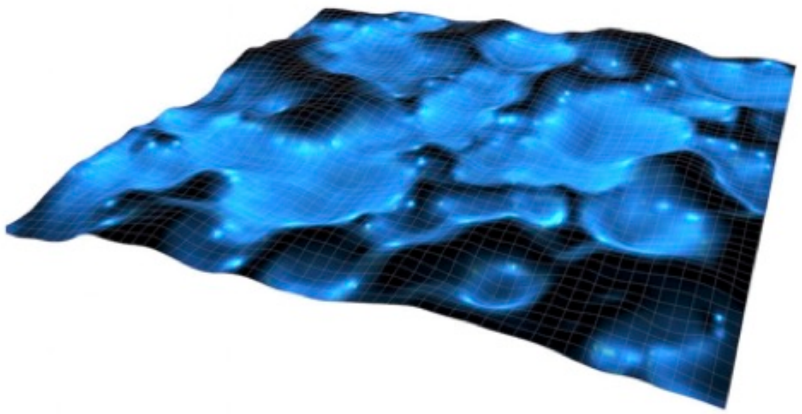


*Image of snake from Abrams & Primack 2012

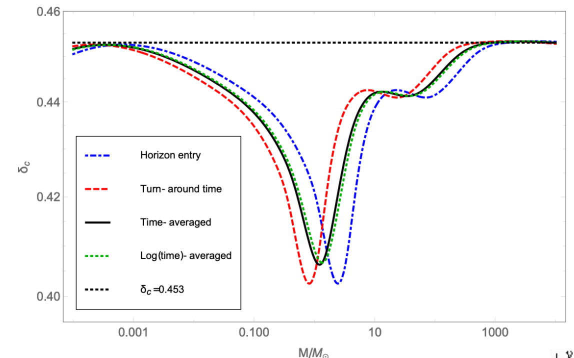
★ PBHs are the only dark matter candidate known to exit in Nature!

Primordial Black Holes Formation Mechanisms

★ Large density perturbations (inflation)

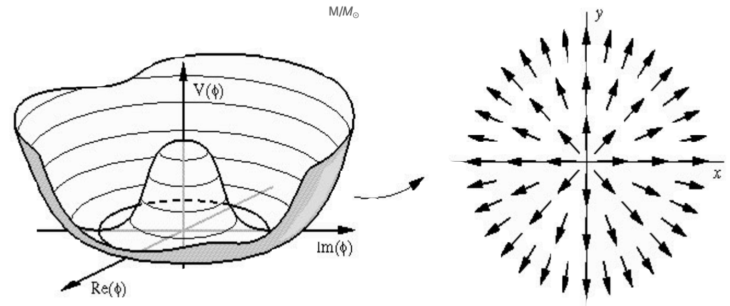


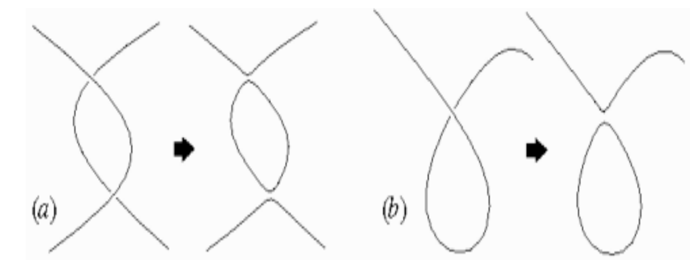
★ Pressure reduction



[Byrnes *et al.* 2018]

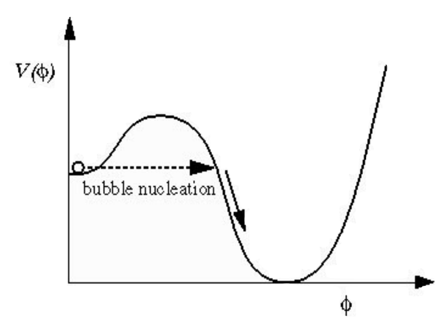
★ Cosmic string loops

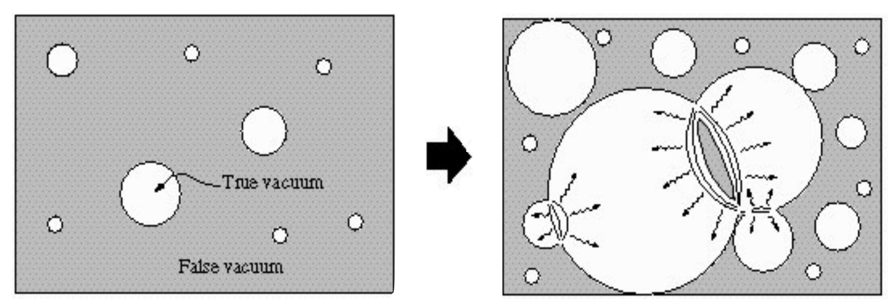




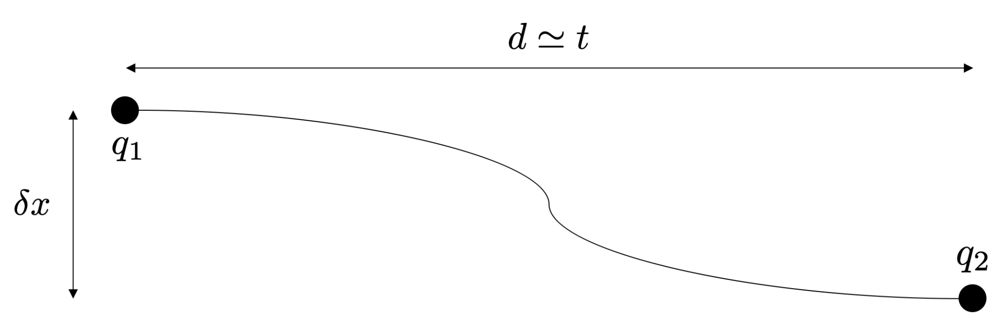
http://www.damtp.cam.ac.uk/research/gr/public/cs_phase.html http://www.damtp.cam.ac.uk/research/gr/public/cs_top.html

★ Bubble collisions





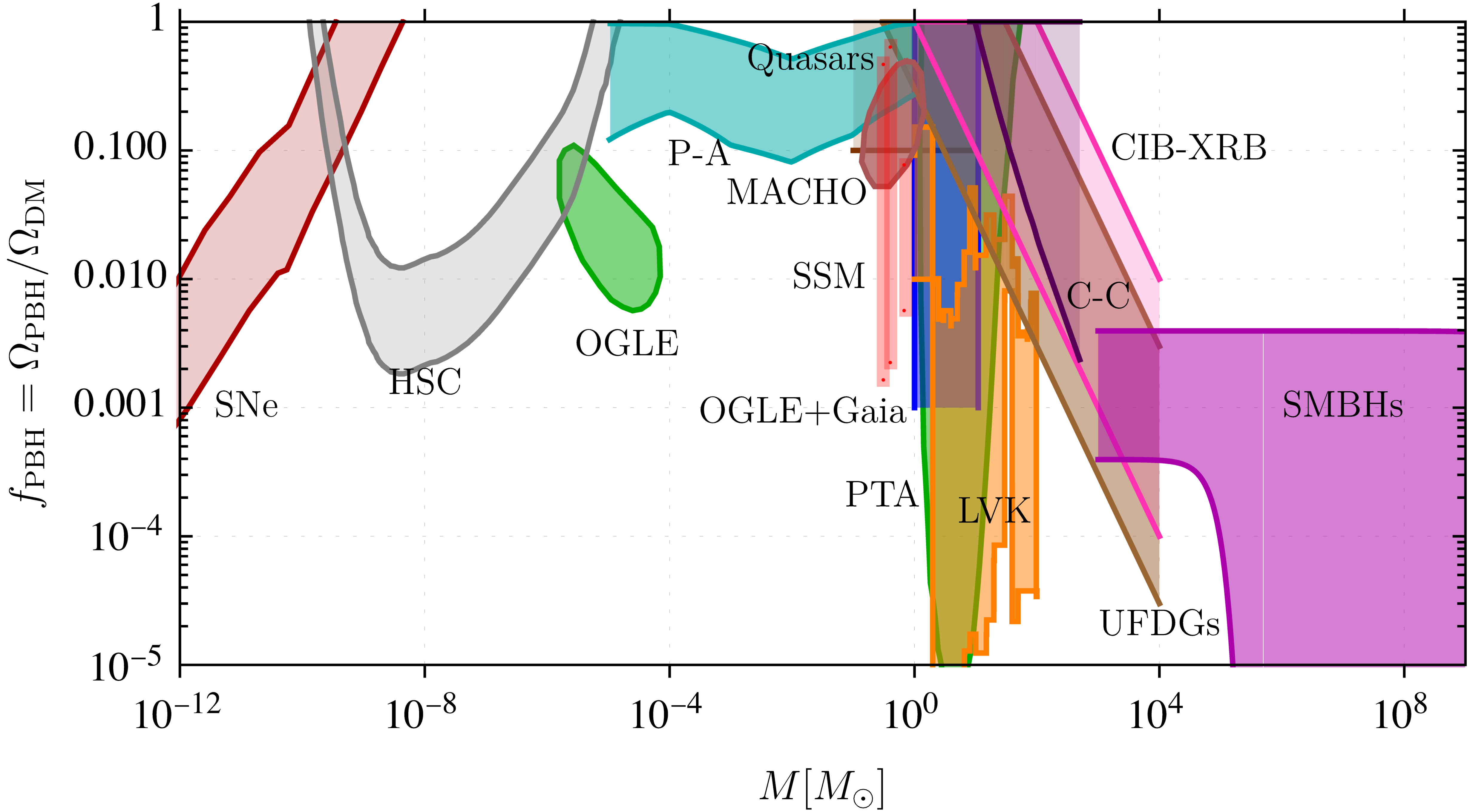
★ Quark confinement



[Dvali, FK, Zantedeschi 2021]

★ Scalar-field fragmentation, ...

Positive Indications for Primordial Black Holes



[Carr, Clesse, García-Bellido, Hawkins, FK 2023]

Road Trip

Road Trip: First Stop

Quantum Quiddity

Memory-Burden Effect

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

[Dvali 2018; Dvali, Eisemann, Michel, Zell 2020]

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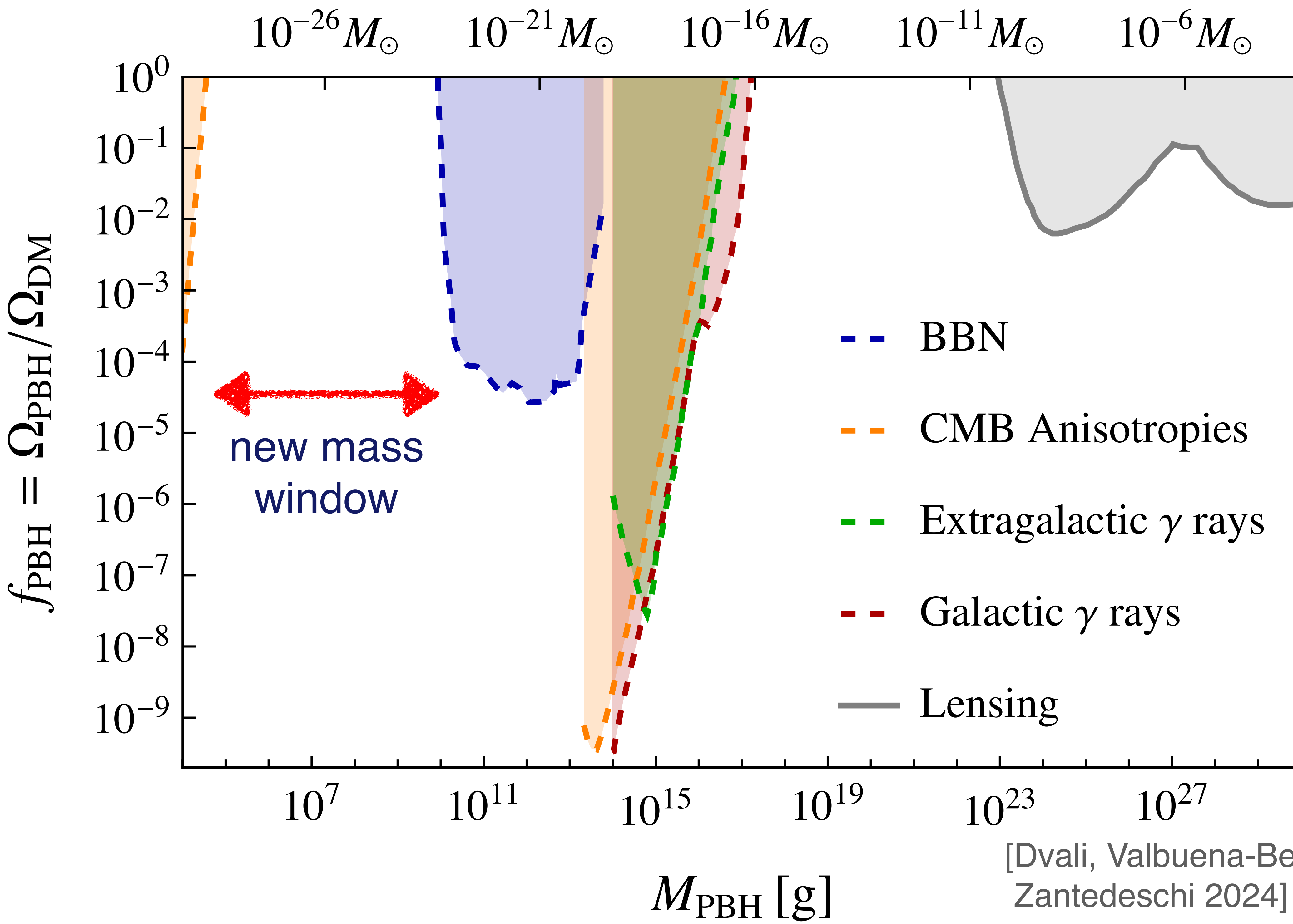
  - Entropy S is huge: $S \sim 10^{30}\left(\frac{M}{10^{10}\,\mathrm{g}}\right)^2$

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

Memory-Burden Effect

$k = 1, \quad t_{\text{burden}} = M/2$



[Dvali, Valbuena-Bermúdez, Zantedeschi 2024]

(see also [Alexandre, Dvali, Koutsangelas 2024; Thoss, Burkert, Kohri 2024] and many more.)

Memory-Burden Effect

- This was for:

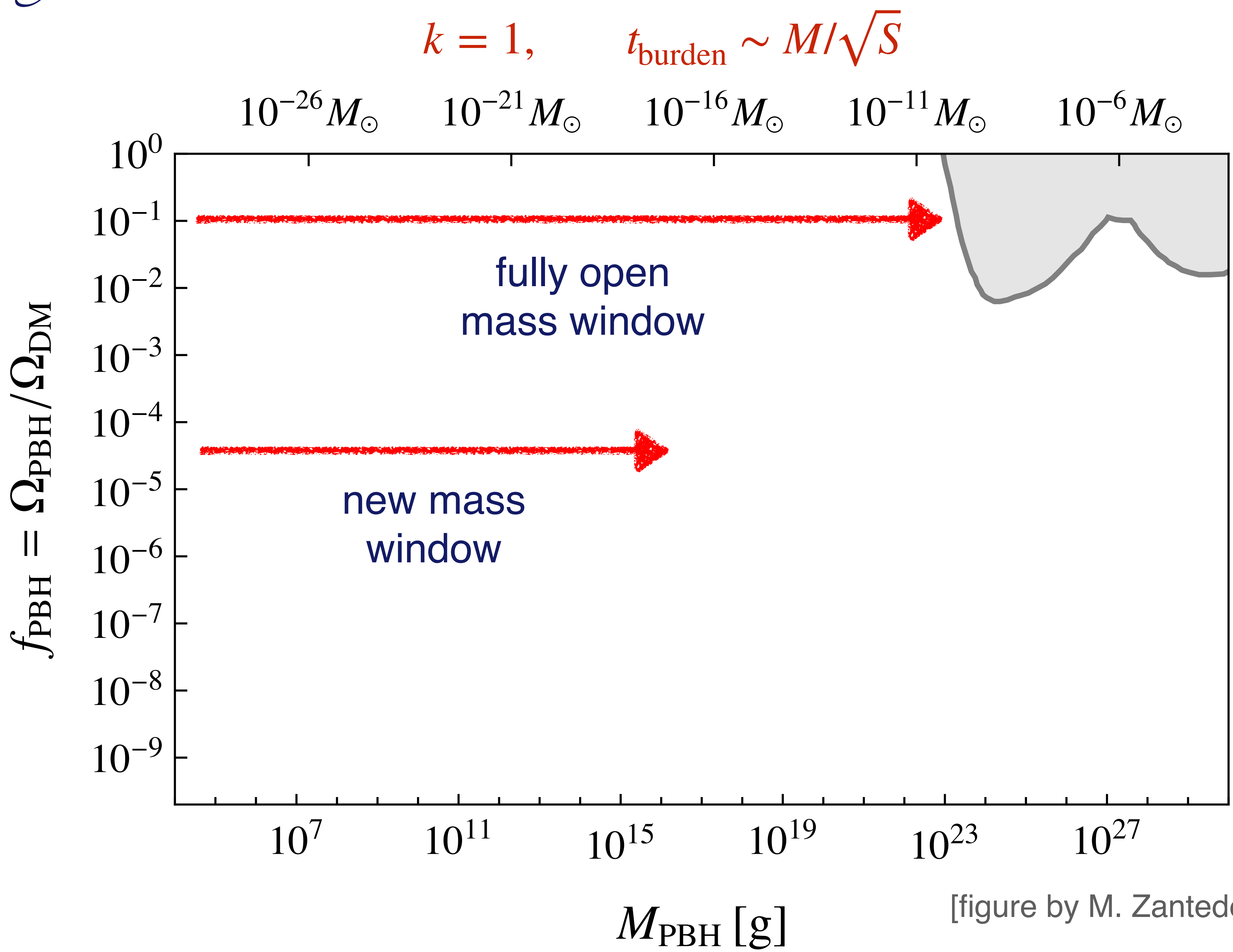
$$k = 1, \qquad t_{\text{burden}} = M/2$$

- There are arguments for the memory-burden effect setting in already at

$$t_{\text{burden}} = M/\sqrt{S} \quad \text{or} \quad t_{\text{burden}} = M/S$$

  - What happens in this case?

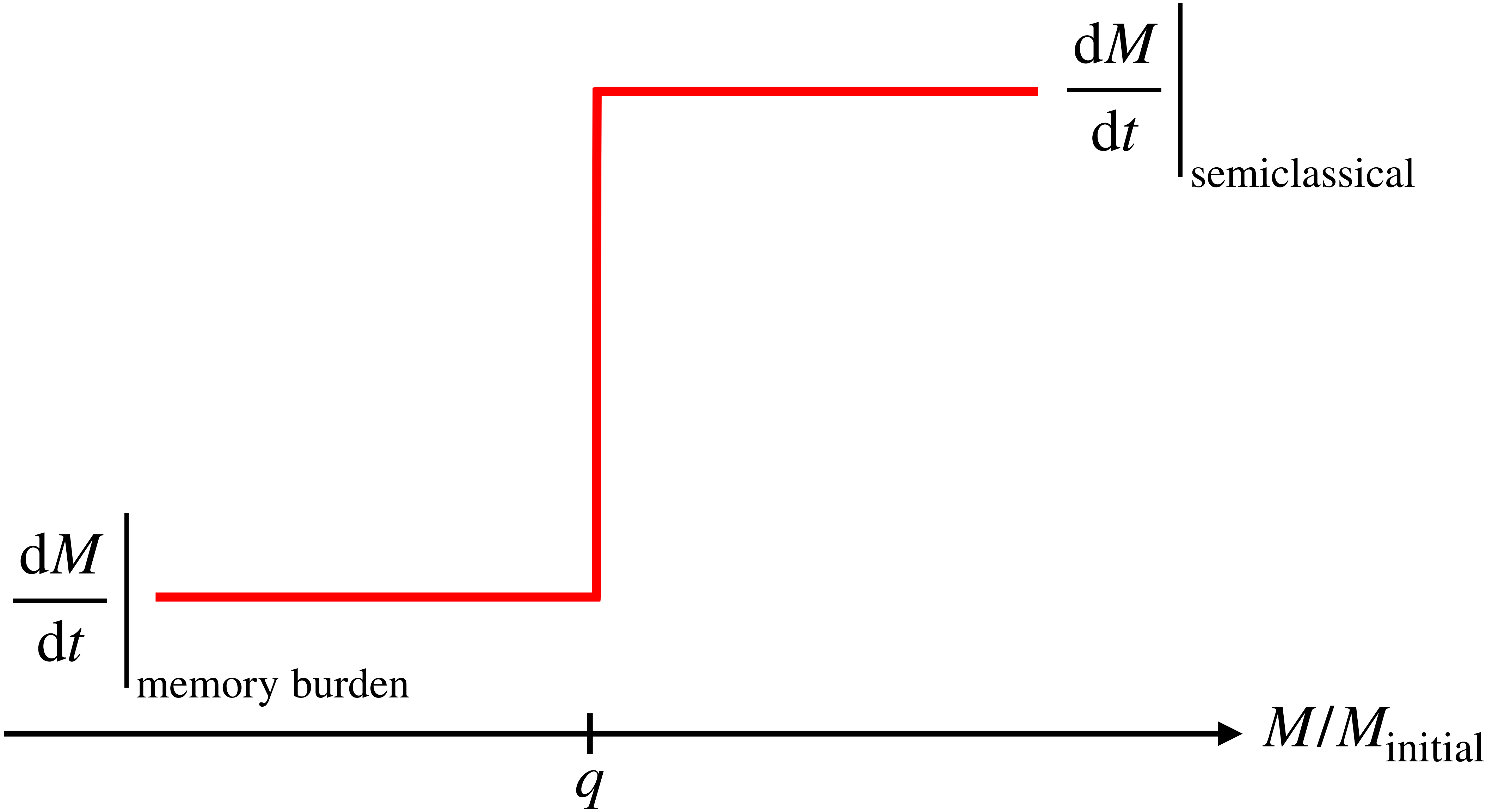
Memory-Burden Effect



[figure by M. Zantedeschi]

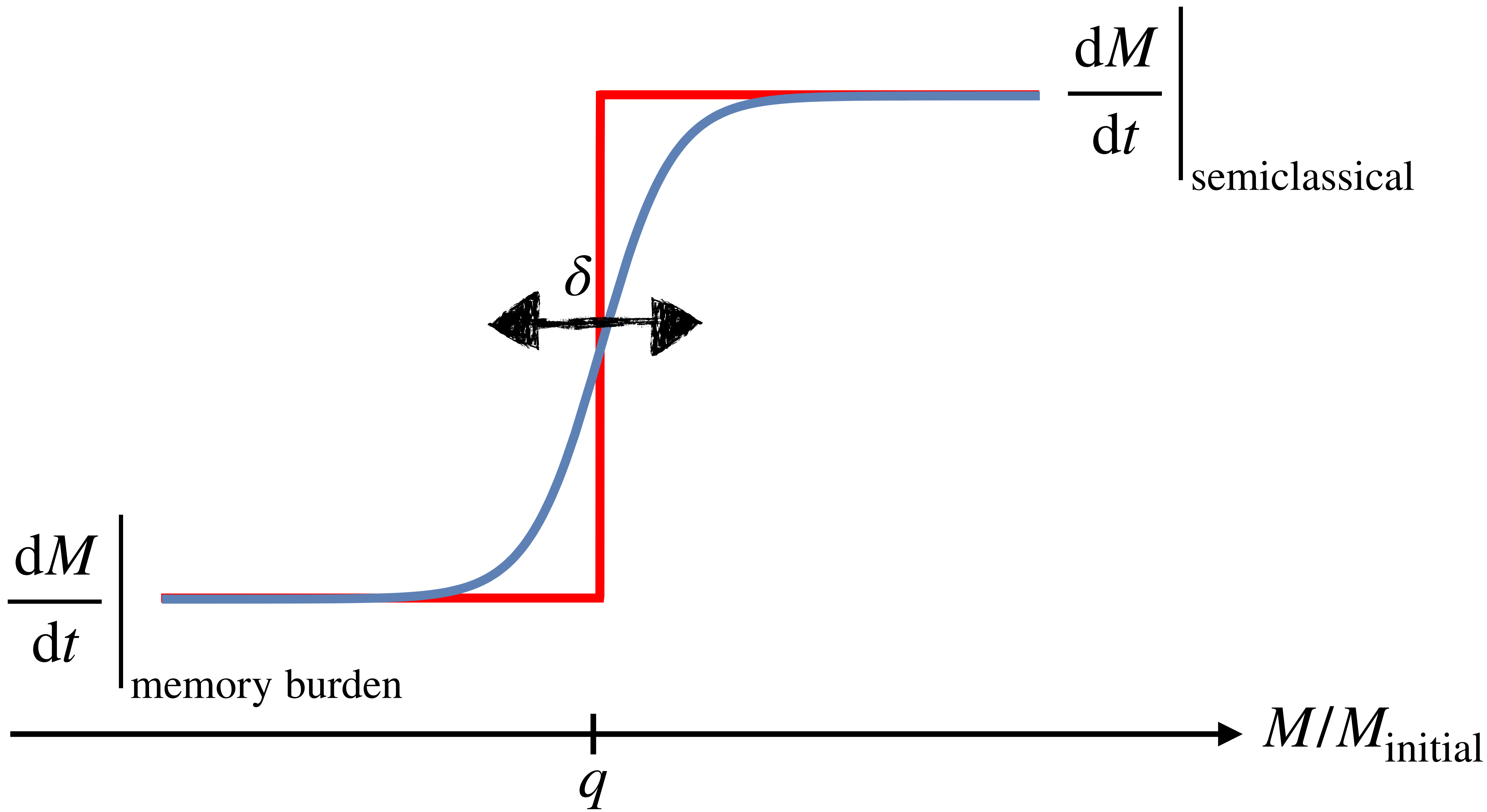
Memory-Burden Effect

★ Most works have utilised a sudden transition from the semiclassical to the memory burden phase.



Memory-Burden Effect — Smooth Transition

- ★ Most works have utilised a sudden transition from the semiclassical to the memory burden phase.
- ★ What happens if the transition is smooth? [Montefalcone, Hooper, Freese, Kelso, FK, Sandick 2025] [Dvali, Zantedeschi, Zell 2025]



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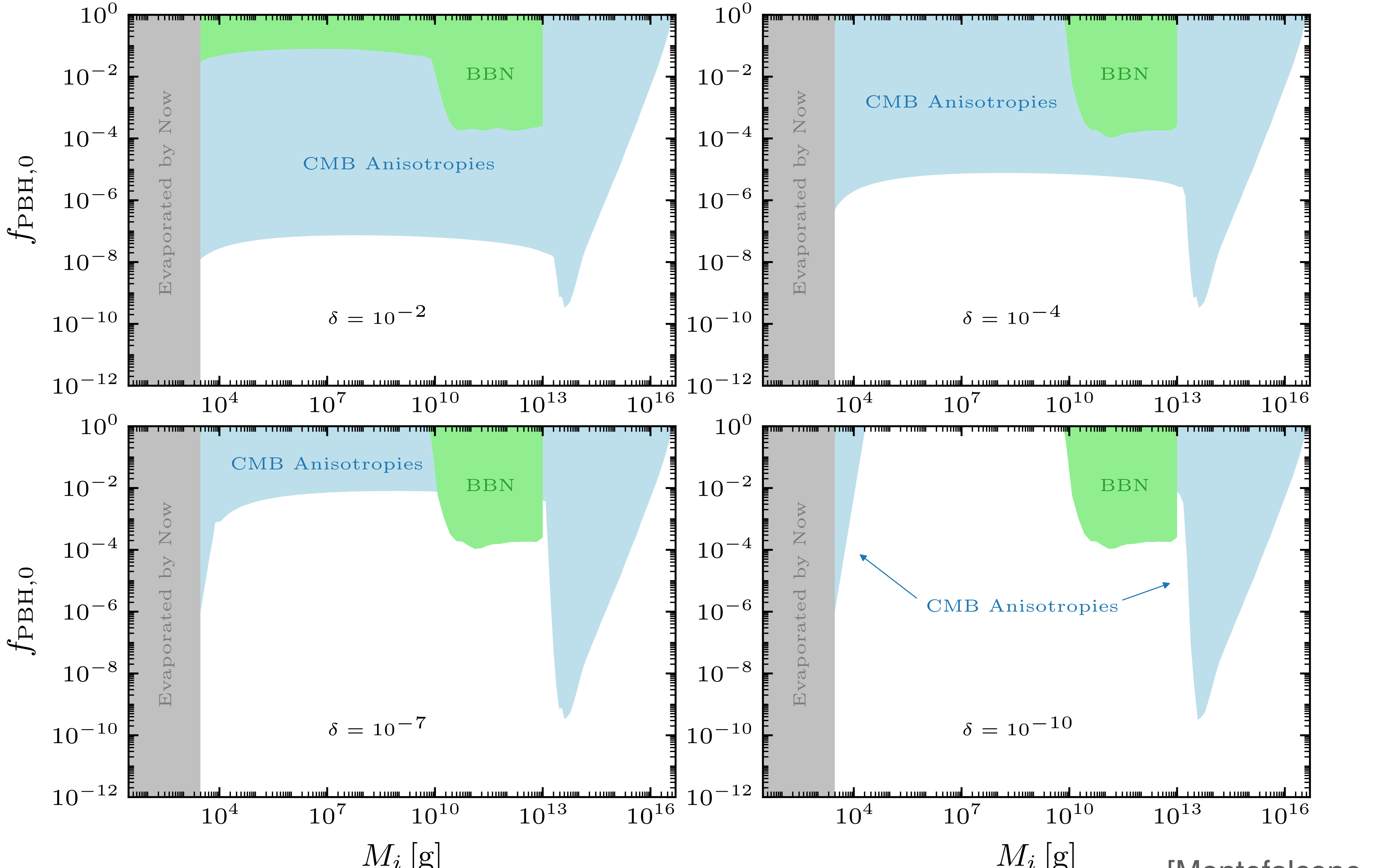
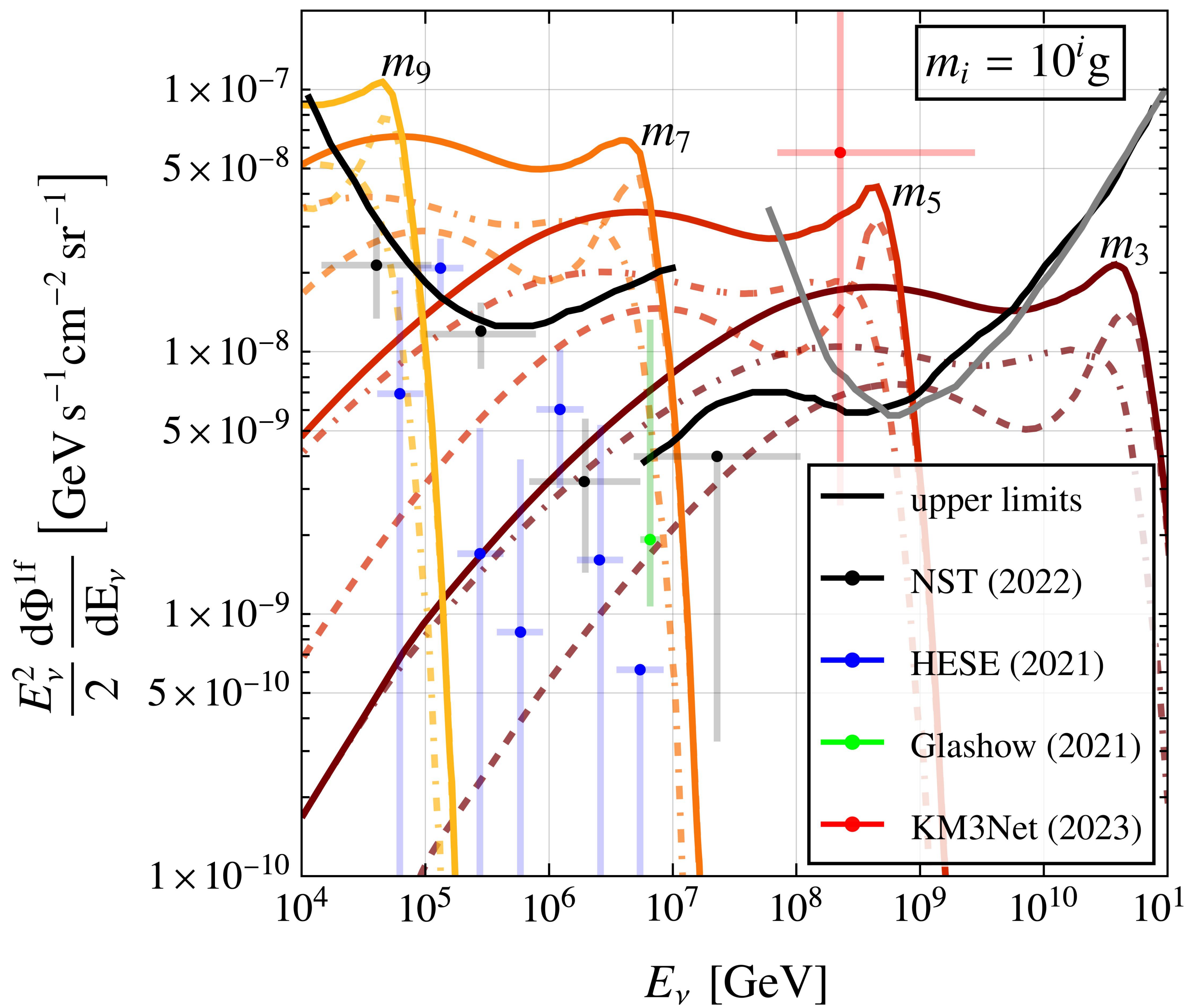


[Montefalcone, Hooper, Freese, Kelso, FK, Sandick 2025]

[see also work by Dvali, Zantedeschi and Zell 2025]

Memory-Burden Effect — As The First Phase

- ★ Light black holes — if sufficiently abundant — merge frequently.
- ★ They would then reenter a second semiclassical phase.
- ★ Intense Hawking radiation could explain observed ultra-high-energy events, such as the KM3Net neutrino event at $P \approx 10^2\,\mathrm{eV}$.



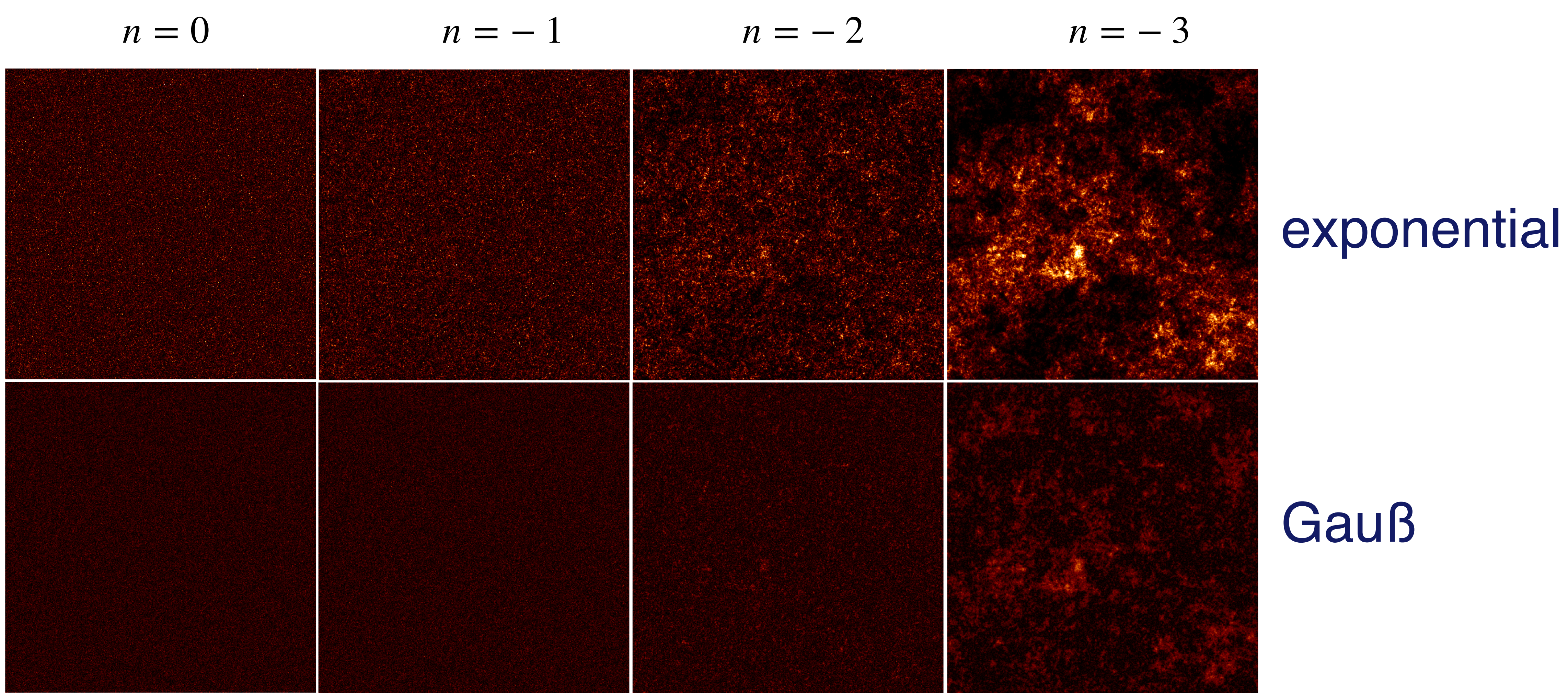
[Visinelli & Zantedeschi 2025]

Road Trip: Second Stop

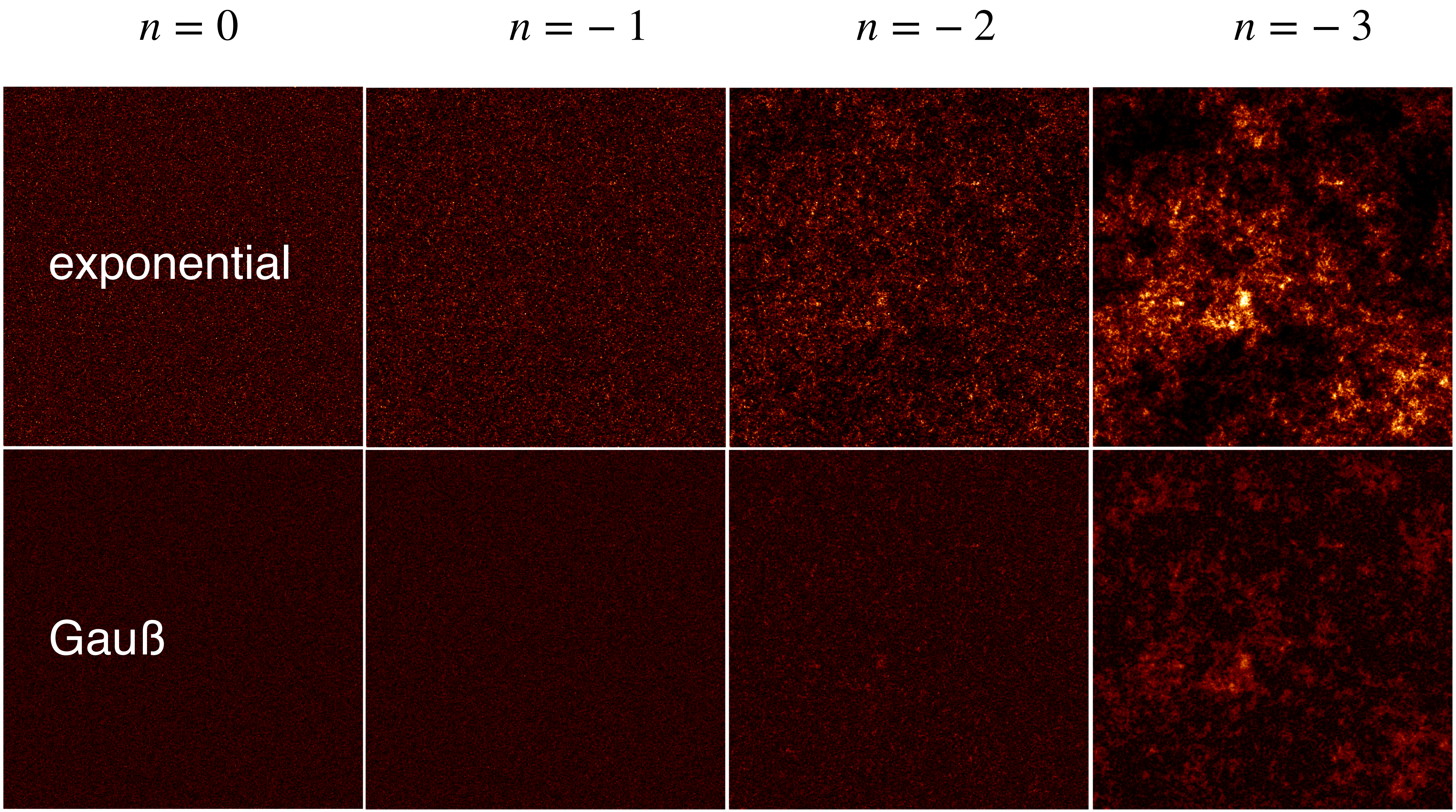
Correlation Characteristics

Correlated Random Fields

- ★ Power spectra at PBH scales essentially unknown.
- ★ Quantum diffusion seems to lead to exponential tails.
- ★ We have performed the currently largest (one in 10^{13}) simulation of spatially-correlated exponential random fields with power spectra of the form $P(k) \propto k^n$



Correlated Random Fields



Correlated Random Fields

★ PBH formation is not instant but takes potentially several e-folds.

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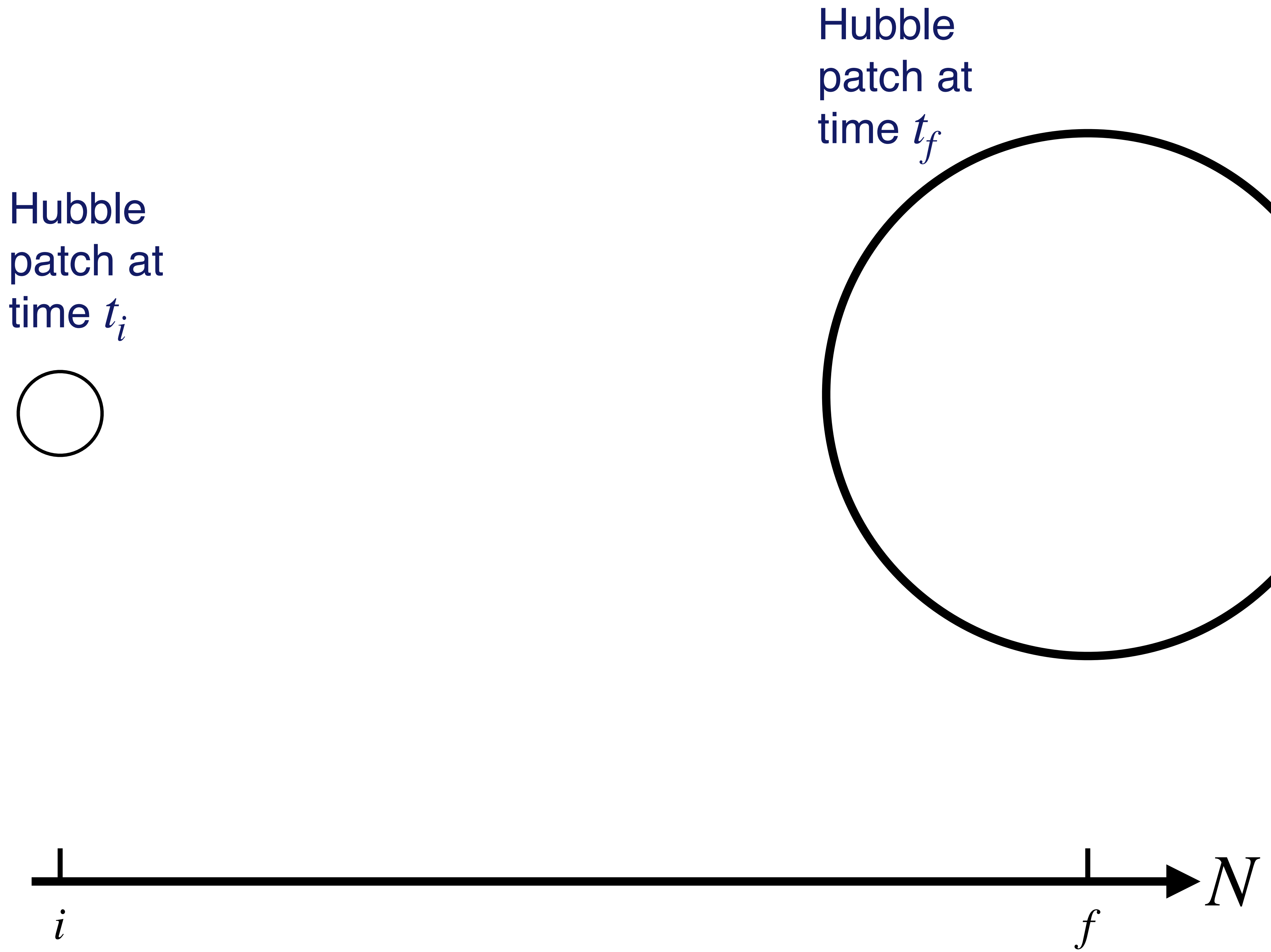

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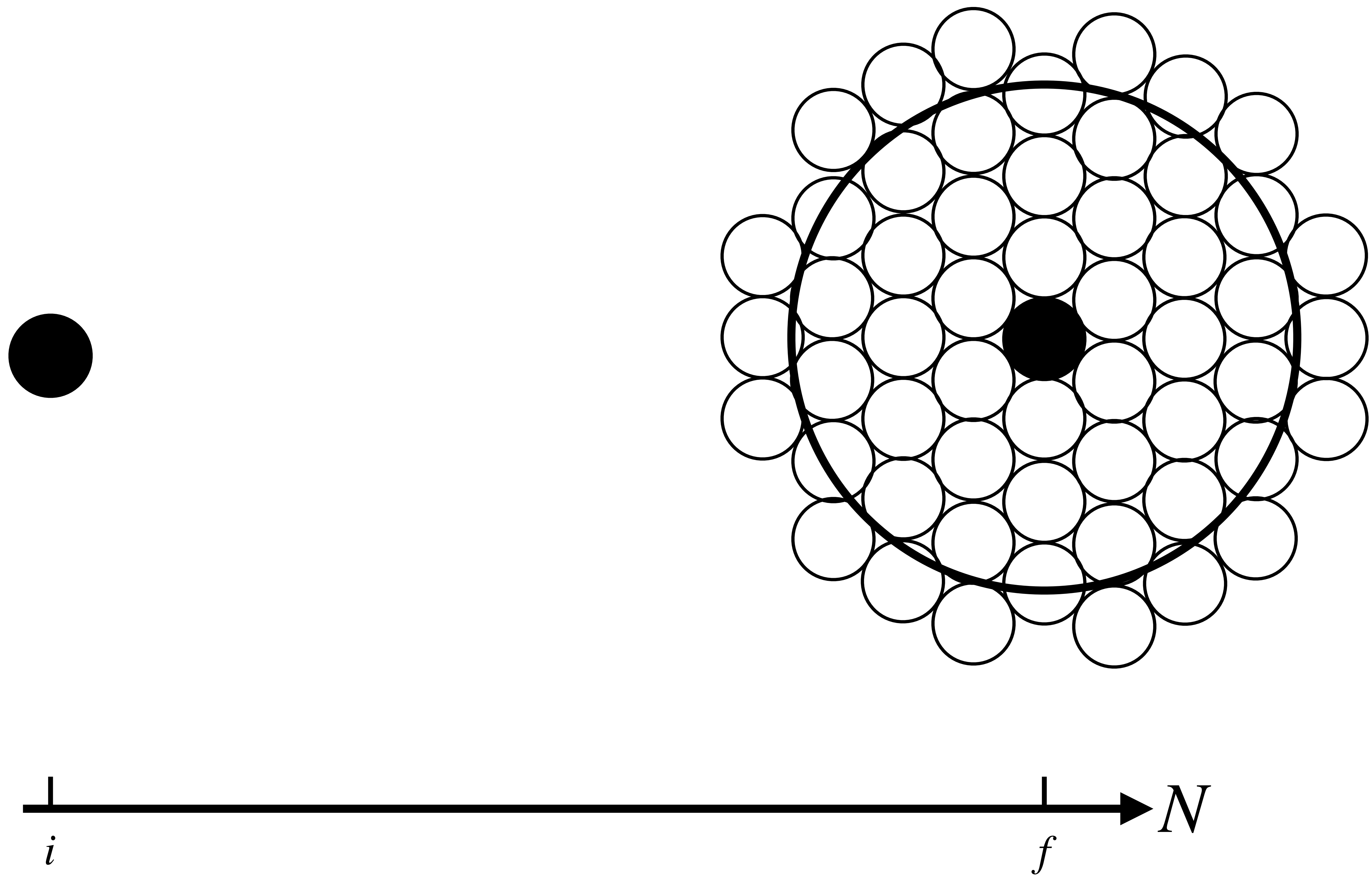
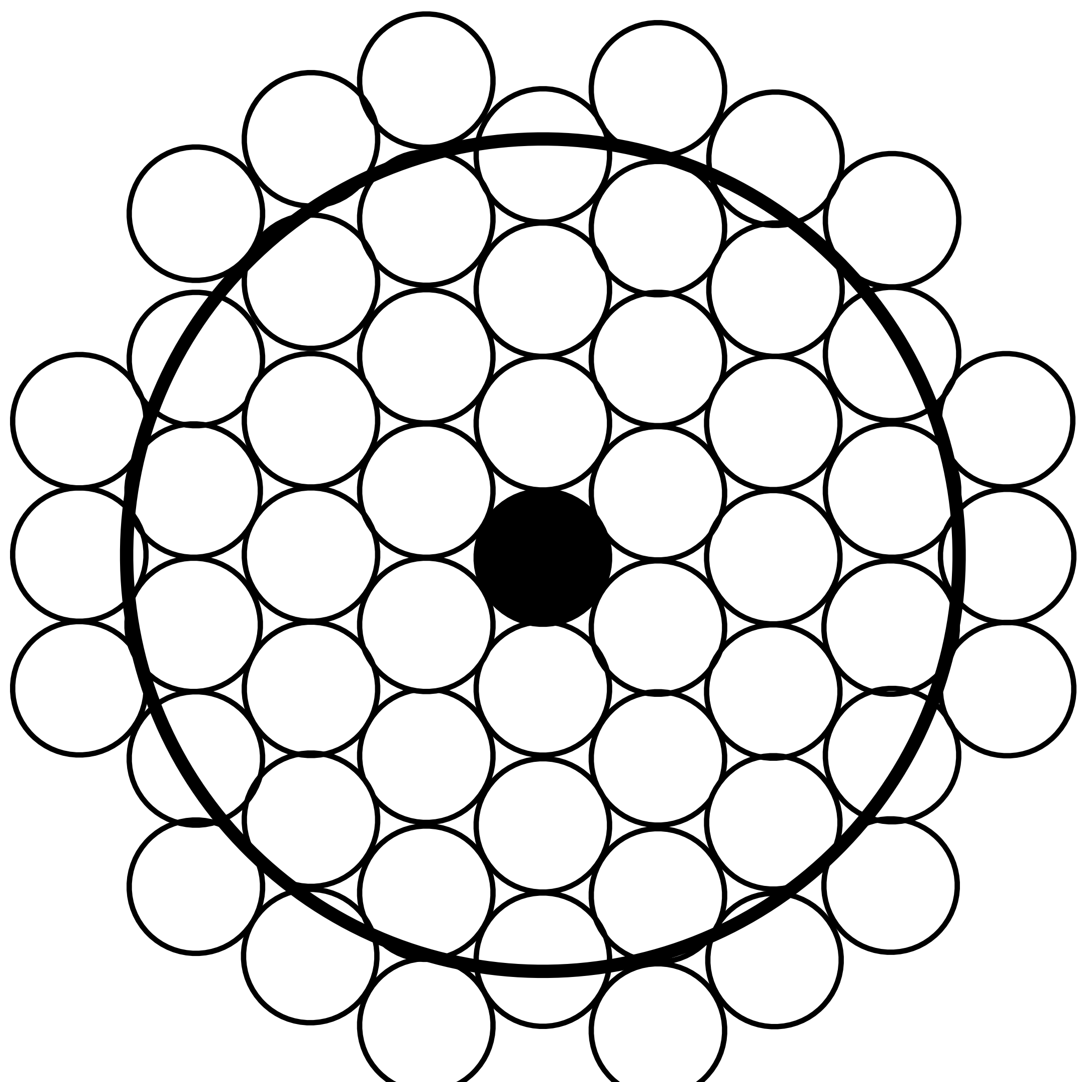


Correlated Random Fields

- PBH formation is not instant but takes potentially several e-folds.

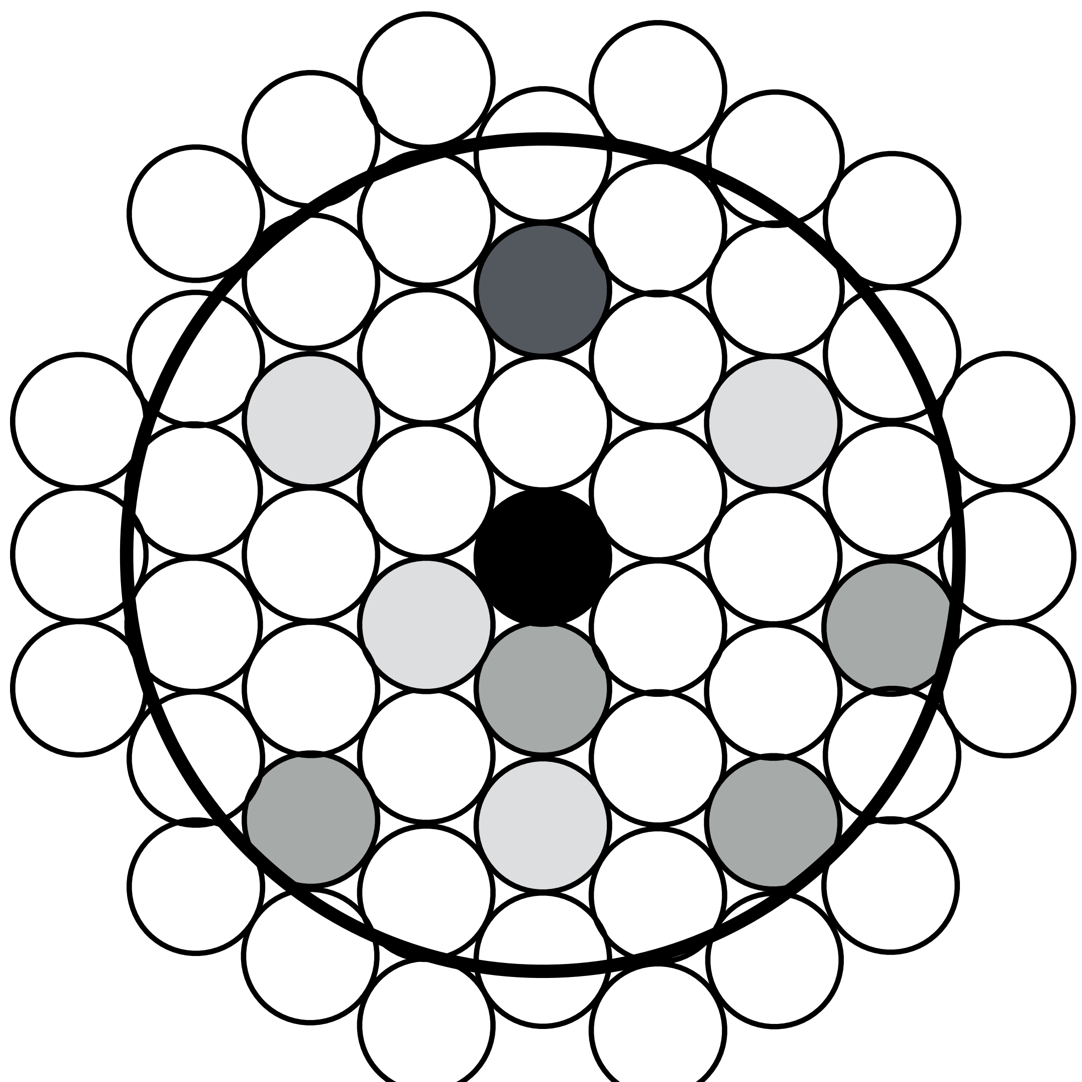
  - no correlation



Correlated Random Fields

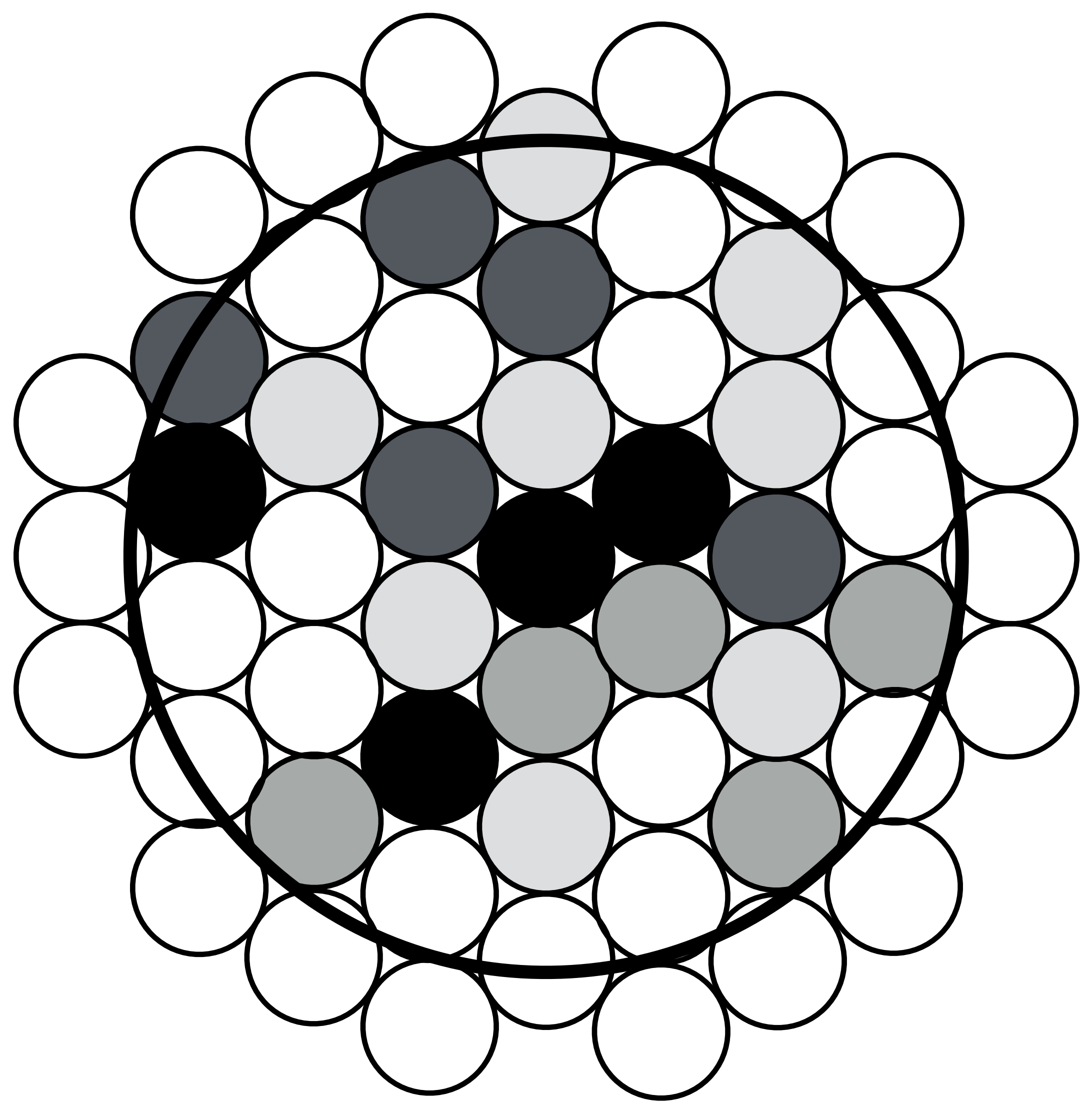
★ PBH formation is not instant but takes potentially several e-folds.

  ★ moderate correlation



Correlated Random Fields

- ★ PBH formation is not instant but takes potentially several e-folds.
  - ★ strong correlation



Central Limit Theorem — A Recapitulation

★ As often as Gauß distributions occur, as little they are questioned.

★ Going back to the *Central Limit Theorem*:

★ Take random variables $\{\Delta_i\}_{i=1}^{N}$ *iid*, with mean μ and variance σ^2

★ Define the sample average $S_N \equiv \frac{1}{N}\sum_{i=1}^{N}\Delta_i$

→ Then $\lim_{N\to\infty} \mathrm{Prob}\left(\frac{S_N - \mu}{\sqrt{\sigma^2/N}} < \delta\right) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\delta} \mathrm{d}t\, \exp(-t^2)$

★ Questions: What happens for extrema, like maxima?

Is this still Gaußian?

Extreme-Value Distributions

- Define the sample maxima $M_N \equiv \max_{i=1,\ldots,N}(\Delta_i)$
  - Then if there exists sequences $\{a_N \in \mathbb{R}\}_{N=1}^{\infty}$ and $\{c_N > 0\}_{N=1}^{\infty}$ with

$$\lim_{N\to\infty} \mathrm{Prob}\left(\frac{M_N - a_N}{c_N} < \delta\right) \equiv H(\delta)$$

where $H(\delta)$ is a non-degenerate CDF, then this function necessarily belongs to one of the following (GEV) classes

[Fischer, Tippett 1928]

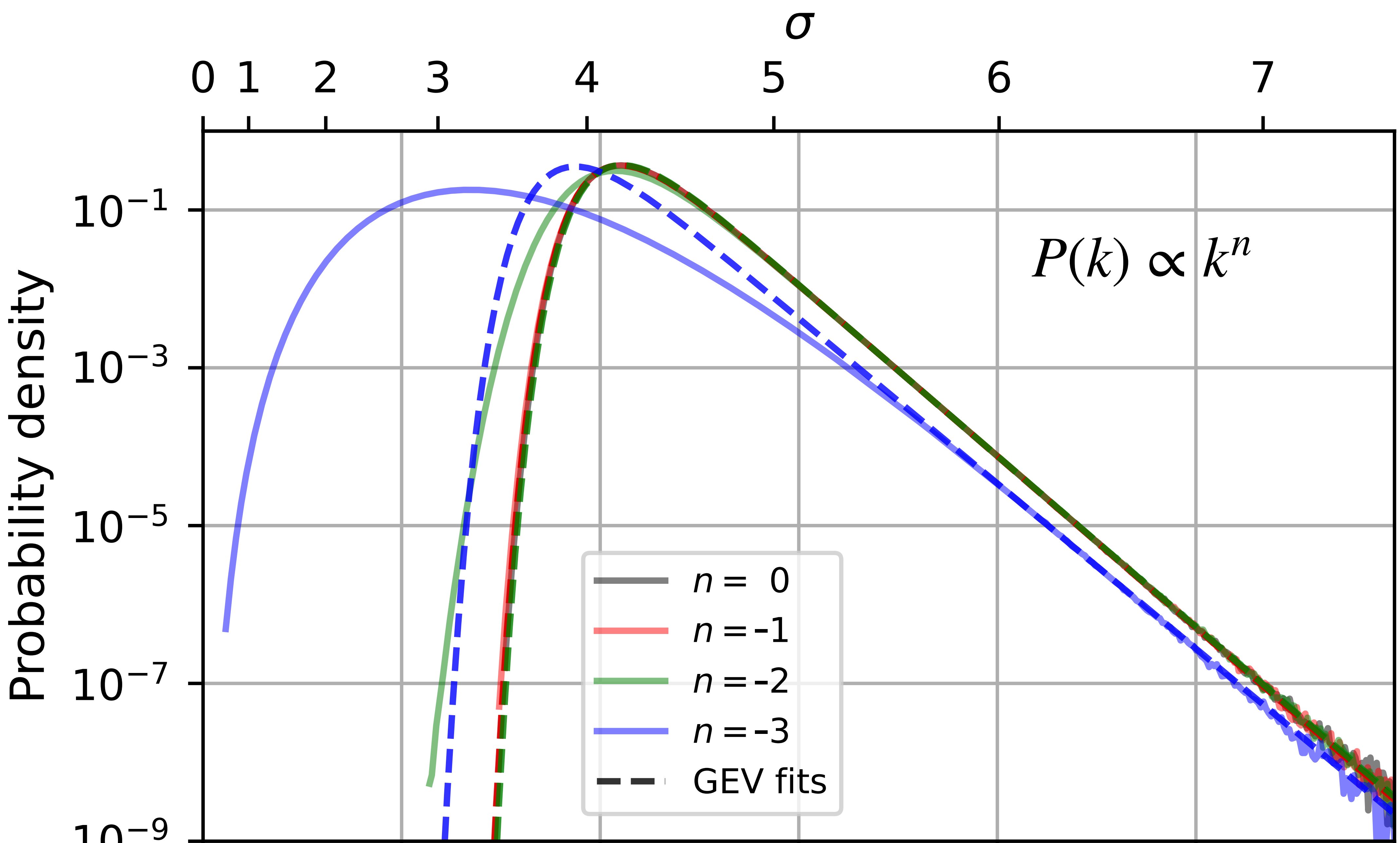
$$H^s_{\alpha,\gamma}(\delta) = \exp\begin{cases} -\left[1 + s\left(\frac{\delta-\alpha}{\gamma}\right)\right]^{-1/s} & (s \neq 0) \\ -\exp\left[-\left(\frac{\delta-\alpha}{\gamma}\right)\right] & (s = 0) \end{cases}$$

s, α and γ are the shape-, location- and scale parameters.

The choices $s = 0$, $s < 0$ and $s > 0$, correspond to the Gumbel, Fréchet, and Weibull distributions, respectively.

Correlated Random Fields

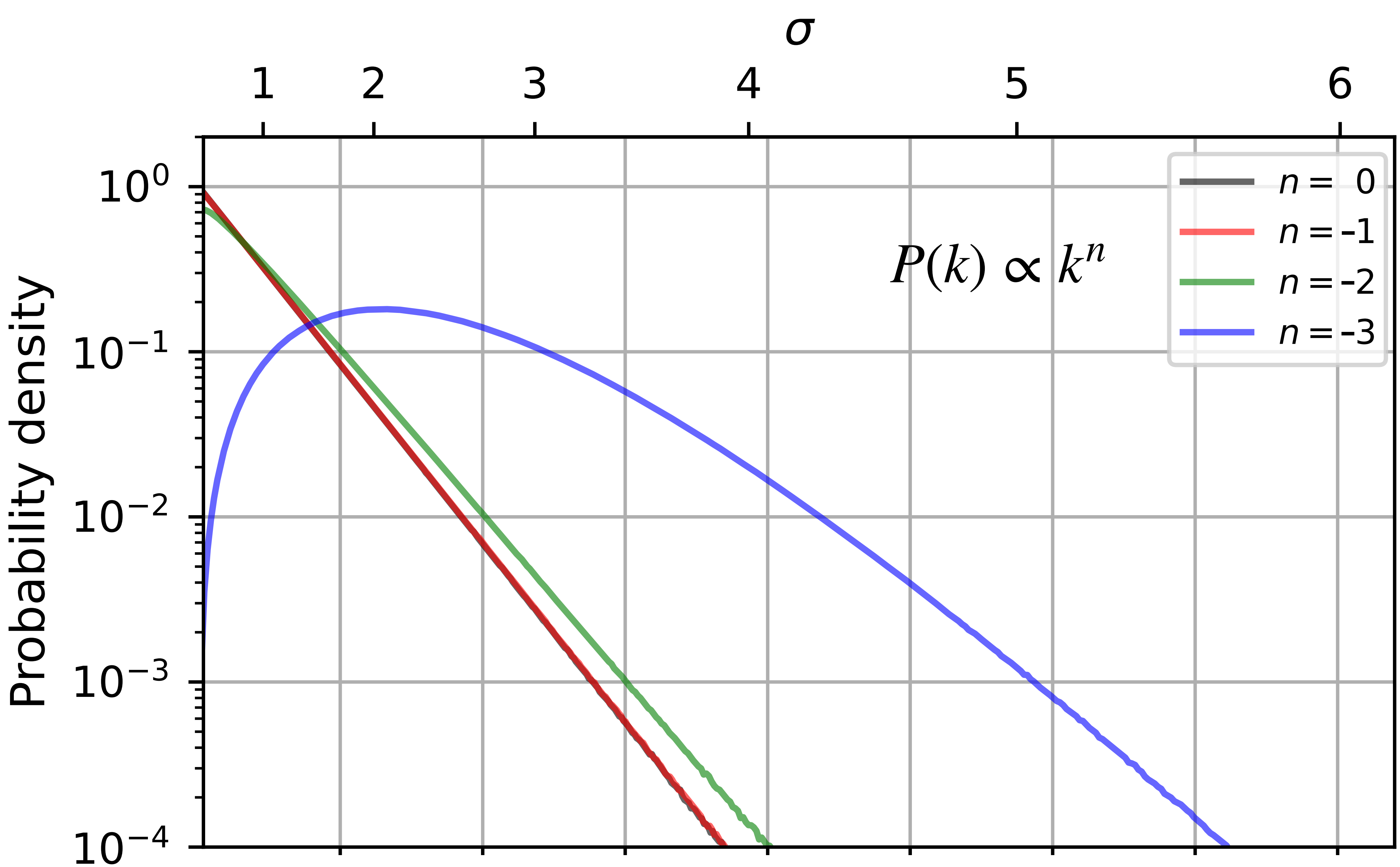
★ Block-maxima PDF obtained by sampling 10^{10} blocks



[Choi, Creswell, FK, Schwarz 2025]

Correlated Random Fields

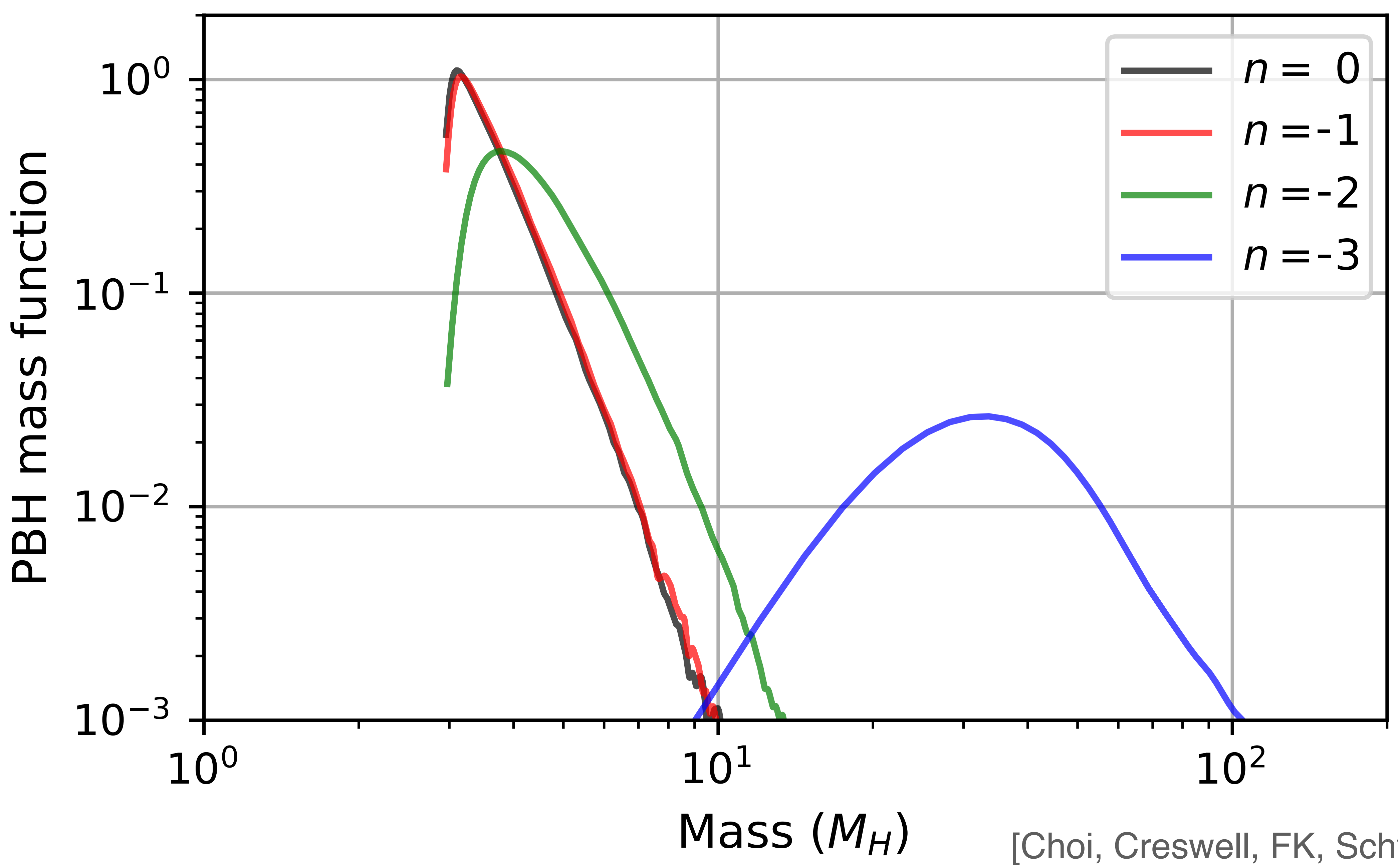
★ PDF *within* each block



[Choi, Creswell, FK, Schwarz 2025]

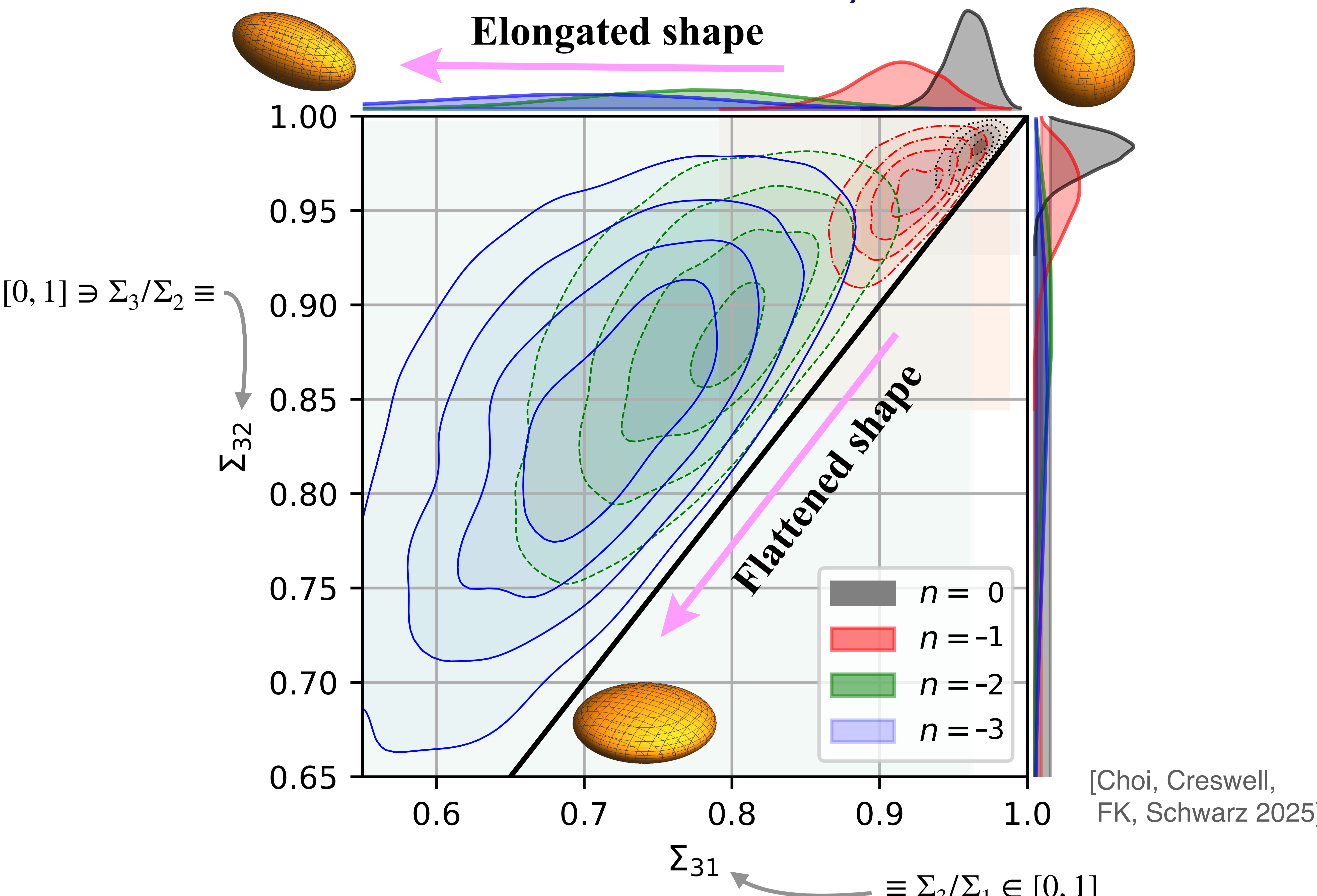
Correlated Random Fields

★ PBH mass distribution (see work by Escrivà & Yoo 2024)



[Choi, Creswell, FK, Schwarz 2025]

Correlated Random Fields — Non-Sphericities



[Choi, Creswell, FK, Schwarz 2025]

Road Trip: Third Stop

Galaxy Genesis

Galaxy Genesis

THE ASTROPHYSICAL JOURNAL, 987:185 (17pp), 2025 July 10 https://doi.org/10.3847/1538-4357/adddb4

How do Massive Primordial Black Holes Impact the Formation of the First Stars and Galaxies?

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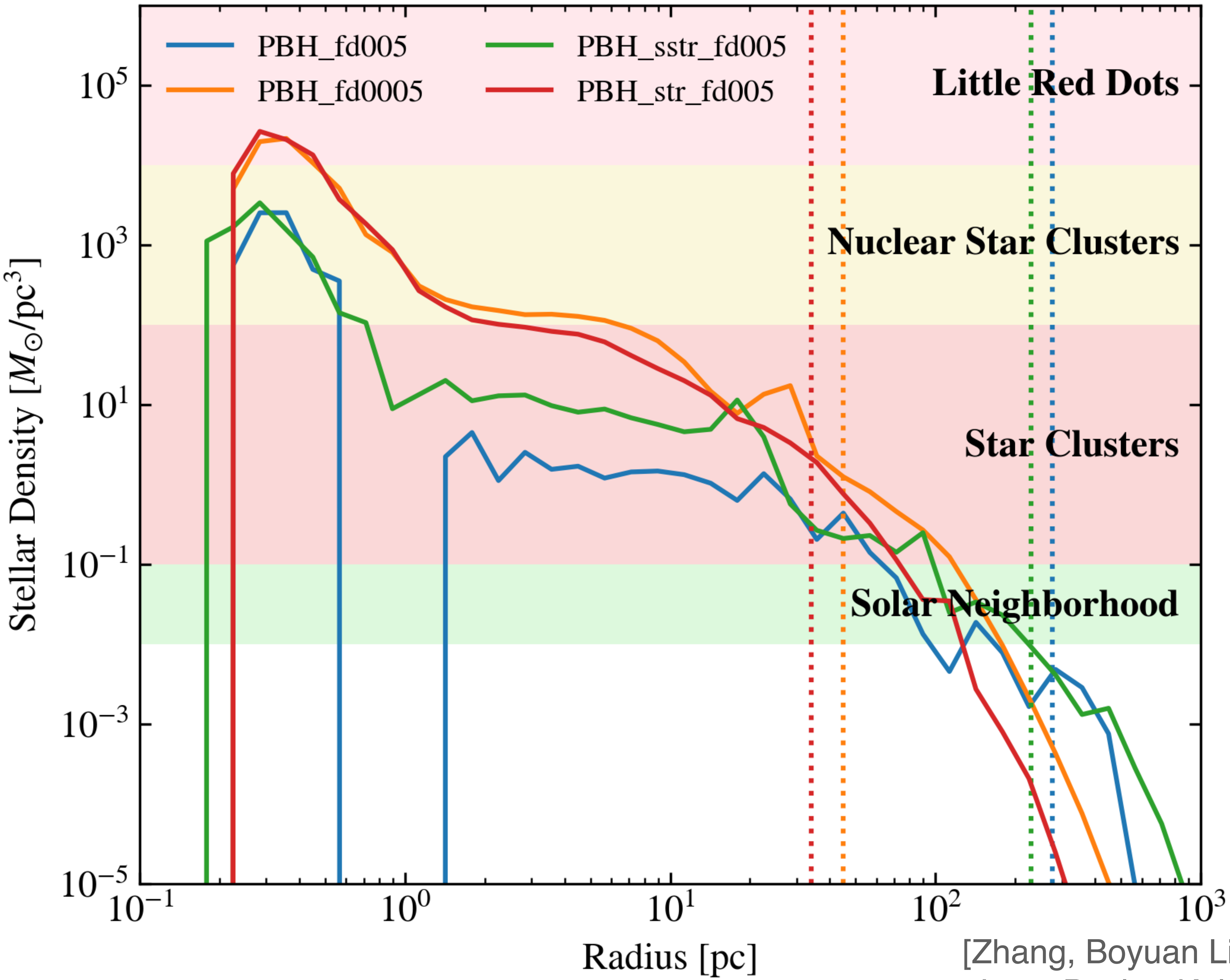
Abstract

We investigate the impact of massive primordial black holes (PBHs; $m_{\rm BH} \sim 10^6\, M_\odot$) on the star formation and first galaxy assembly process using high-resolution hydrodynamical simulations from $z = 1100$ to $z \sim 9$. We find that PBH accretion is self-regulated by feedback, suppressing mass growth unless feedback is weak. PBHs accelerate structure formation by seeding dark matter (DM) halos and gravitationally attracting gas, but strong feedback can delay cooling and suppress star formation. In addition, the presence of baryon-DM streaming creates an offset between the PBH location and the peaks induced in gas density, promoting earlier and more efficient star formation compared to standard ΛCDM. By $z \sim 10$, PBH-seeded galaxies form dense star clusters, with PBH-to-stellar mass ratios comparable to observed high-z active galactic nuclei like UHZ-1. Our results support PBHs as viable supermassive black hole (SMBH) seeds but do not exclude alternative scenarios. We emphasize that PBH-seeding provides a natural explanation for some of the newly discovered overmassive SMBHs at high redshift, in particular those with extreme ratios of BH-to-dynamical (virial) mass that challenge standard formation channels. Future studies with ultra-deep JWST surveys, the Roman Space Telescope, and radio surveys with facilities such as the Square Kilometre Array and Hydrogen Epoch of Reionization Array will be critical in distinguishing PBH-driven SMBH growth from other pathways.

Unified Astronomy Thesaurus concepts: Dark matter (353); Early universe (435); Galaxy formation (595); Population III stars (1285); Supermassive black holes (1663)

Galaxy Genesis

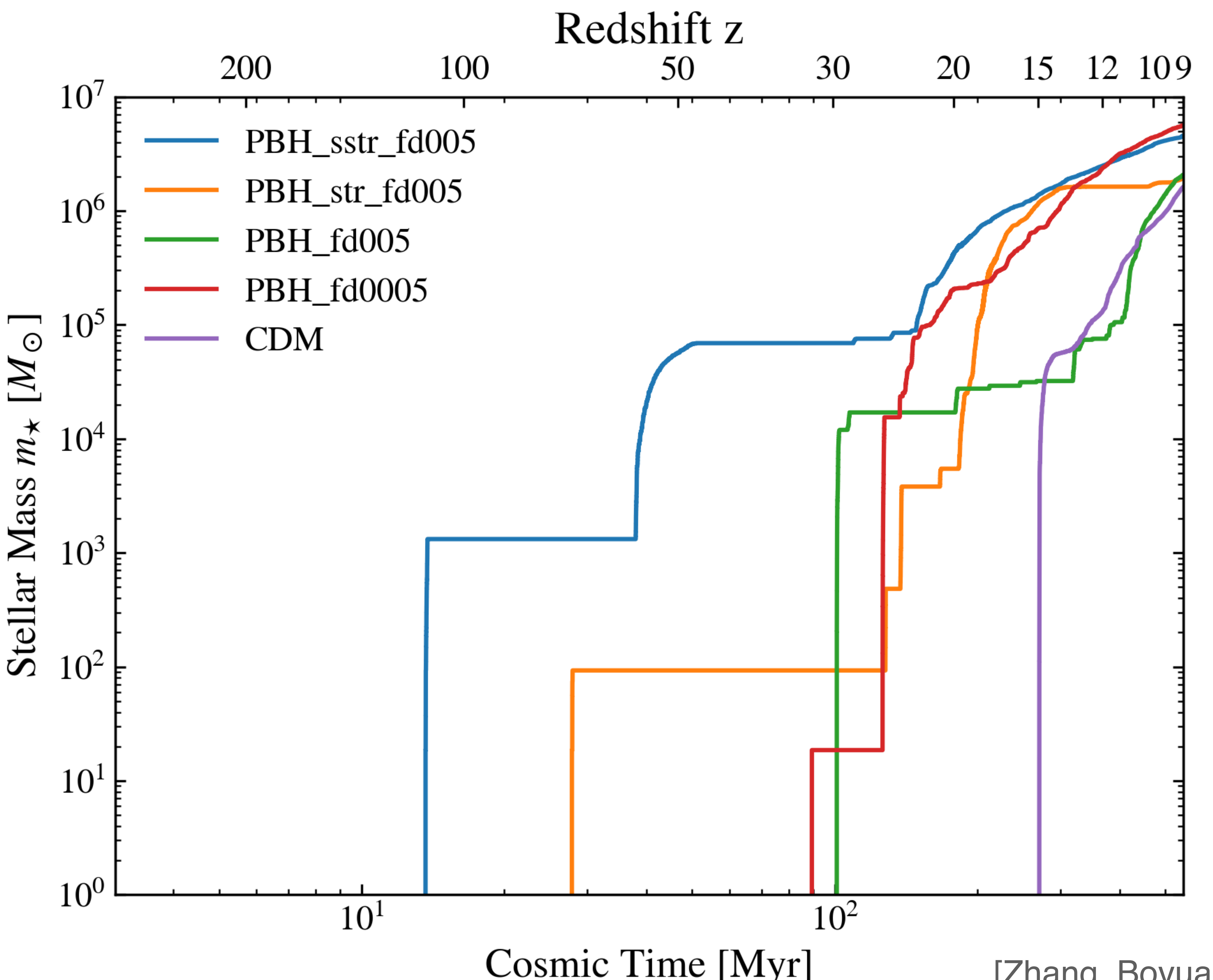
★ Stellar densities in PBH-seeded galaxies at $z \sim 9$



[Zhang, Boyuan Liu, Bromm, Jeon, Boylan-Kolchin, FK 2025]

Galaxy Genesis

★ Stellar mass assembly histories for PBH-seeded galaxies



[Zhang, Boyuan Liu, Bromm, Jeon, Boylan-Kolchin, FK 2025]

Galaxy Genesis

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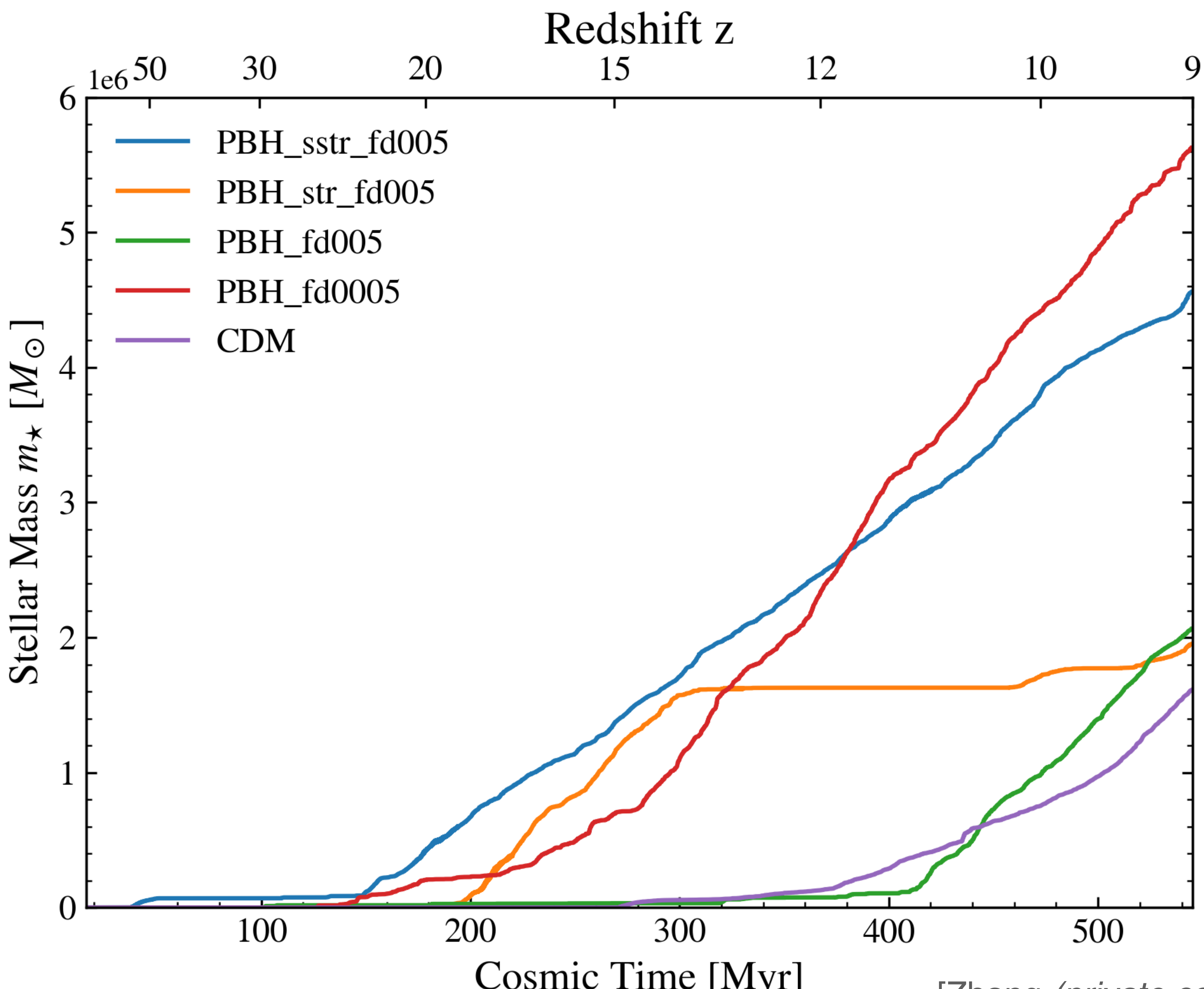
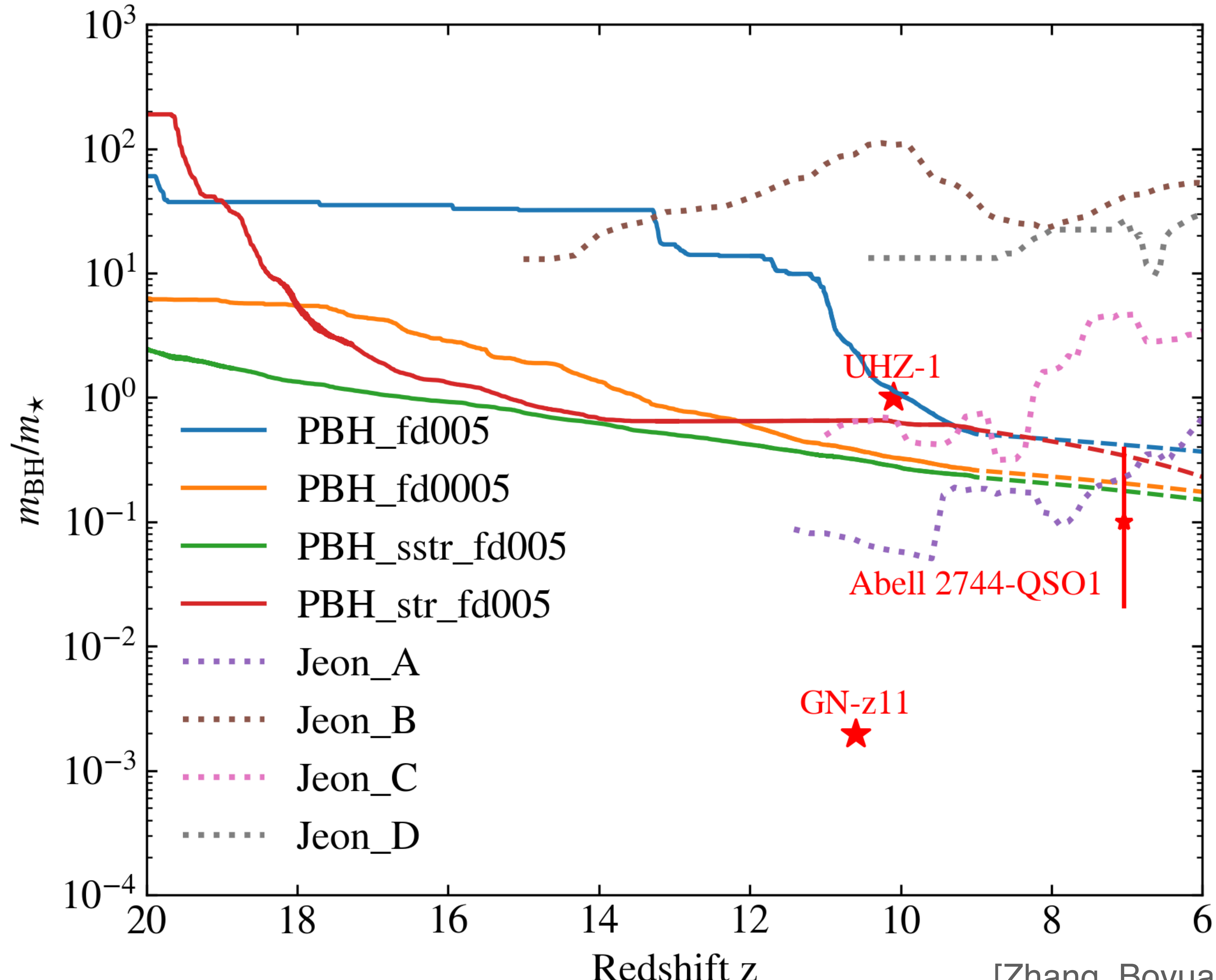


[Zhang *(private communication)* 2025]

Galaxy Genesis

★ Co-evolution of the PBH and its host system



[Zhang, Boyuan Liu, Bromm, Jeon, Boylan-Kolchin, FK 2025]

One Last Thing…


Black Holes
&
Cosmology
2025
University of Iceland
5th to 9th of August 2025

University of Iceland

5th to 9th of August 2025

Reykjavík

Confirmed Invited Speakers include

Earl Bellinger
Alessandra Buonanno
Andreas Burkert
Matt Caplan
Bernard Carr
Sébastien Clesse
Gia Dvali
Alexander Dolgov
Netta Engelhardt
Katherine Freese
Enrique Gaztanaga
Sarah Geller
Marat Gilfanov
Ruth Gregory
Günther Hasinger
Michael Hawkins
Dan Hooper
David Kaiser
Sasha Kashlinsky
William Kinney
Alexander Kusenko
Julien Lavalle
Guido Müller
Priyamvada Natarajan
Don Page
Lisa Randall
Mairi Sakellariadou
Ravi Sheth
Herman Verlinde
Hai-Bo Yu

Organisers: Florian Kühnel, Lárus Thorlacius, David Kaiser, Valentina Giangreco M. Puletti

Black Holes & Cosmology 2025

Credit to Will Kinney


Black Holes
& Cosmology '26
Carmen de la Victoria, Grenada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Cheers!

No OGLE Limits in The Milky Way!

MNRAS 000, 1–8 (2025) Preprint 9 September 2025 Compiled using MNRAS LATEX style file v3.2

A critical analysis of the recent OGLE limits on stellar mass primordial black holes in the halo of the Milky Way

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[2] *Instituto de Física Teórica UAM/CSIC, Universidad Autónoma de Madrid, Nicolás Cabrera 13, Madrid 28049, Spain*

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
This paper is a response to recent claims that a population of primordial black holes in the Galactic halo has been ruled out by the OGLE collaboration. This claim was based on the latest results from the OGLE microlensing survey towards the Large Magellanic Cloud which failed to detect even the number of events expected from known stellar populations. In particular, their results are completely inconsistent with the results of the MACHO survey which detected a population of compact bodies in the Galactic halo which could not be accounted for by any known stellar population. The discrepancy between the results of these two groups has a long history, and includes problems such as different choice of photometric passbands, quality of light curves, microlensing event selection, detection efficiency, self lensing and halo models. In this paper it is demonstrated that these issues not only account for the discrepancy between the OGLE and MACHO results, but imply that the OGLE observations can put no meaningful constraints on a population of primordial black holes in the Galactic halo.

Key words: quasars: general – gravitational lensing: micro – dark matter