Primordial Black Holes: Positivist Perspective, Quantum Quiddity & Correlation Characteristics

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Garching (near Munich), Germany

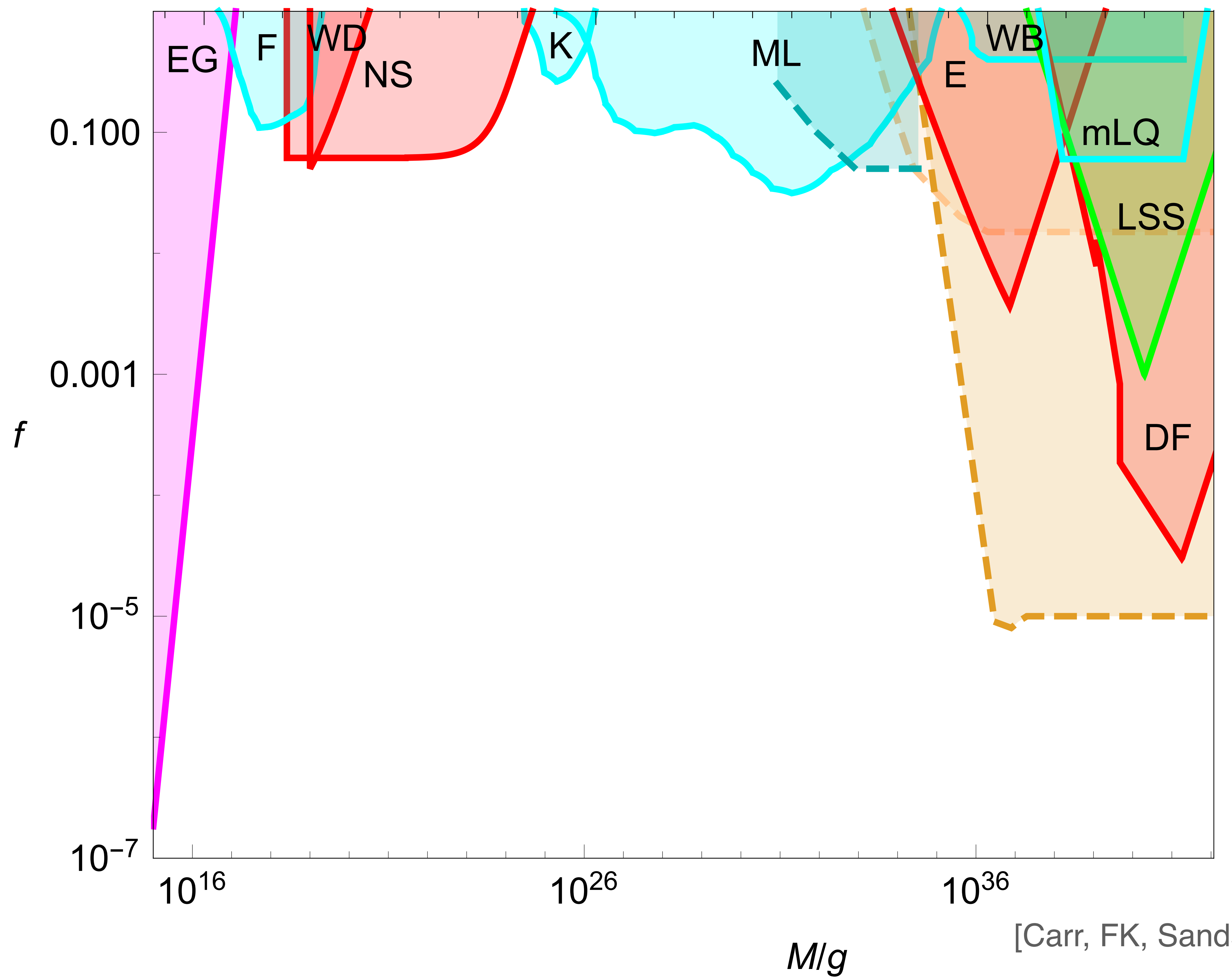
— Focus Week on Primordial Black Holes '24 —
IPMU, Thursday, the 14th of November 2024

Constraints

In 2016…

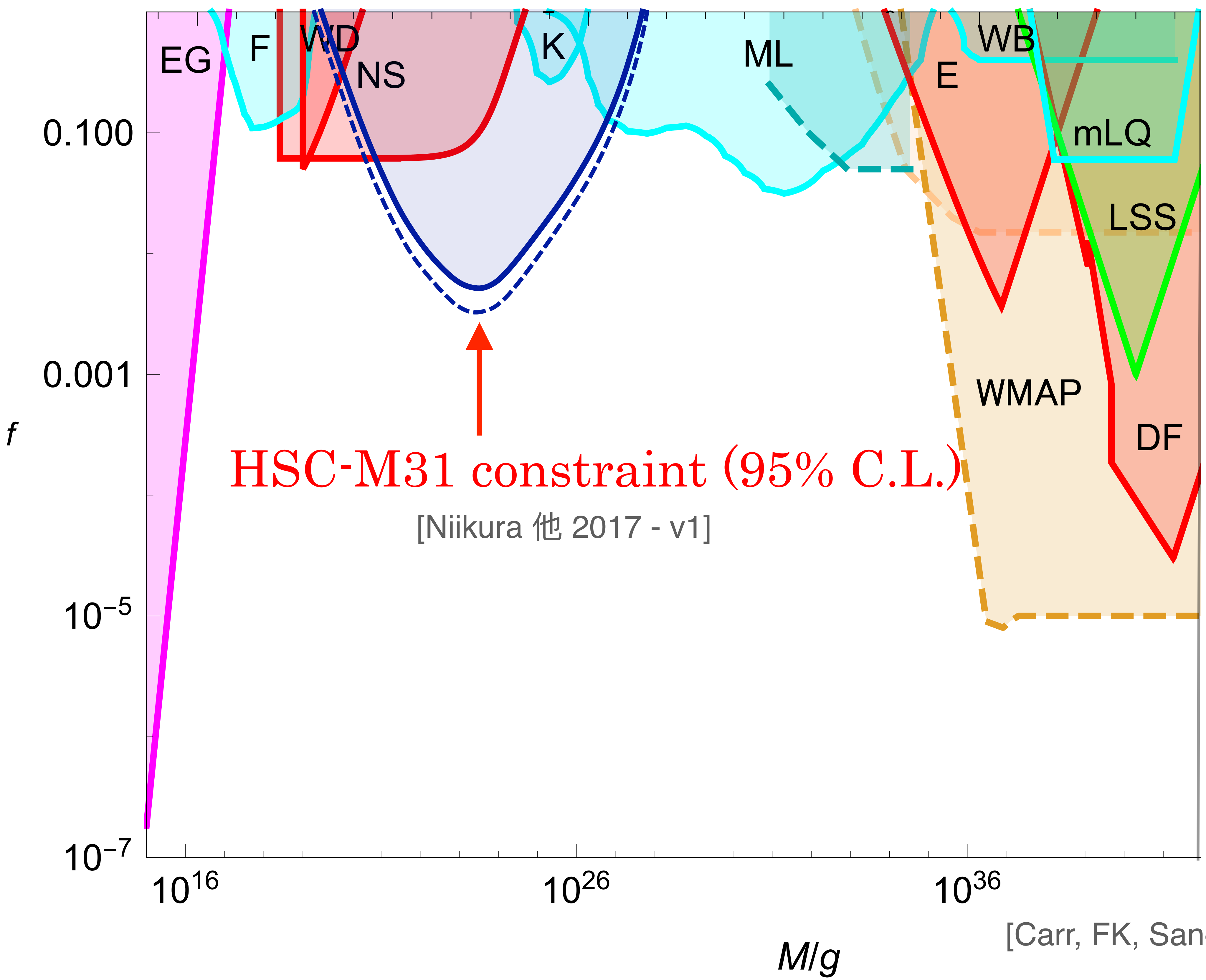
Not only a different President…

… but Strongly Constrained Asteroidal Mass Window



[Carr, FK, Sandstad 2016]

PBH Constraints back in the Days (2017)



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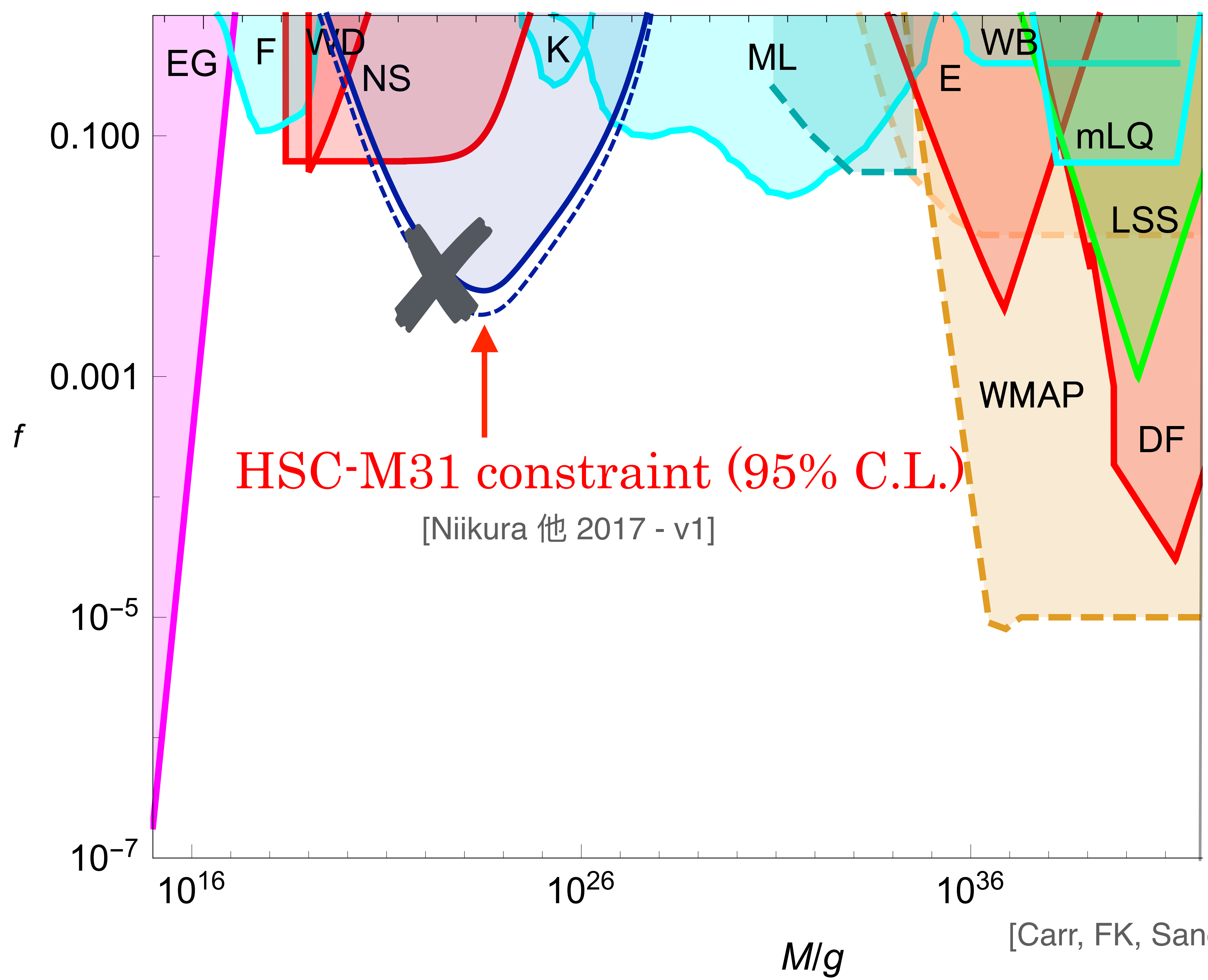

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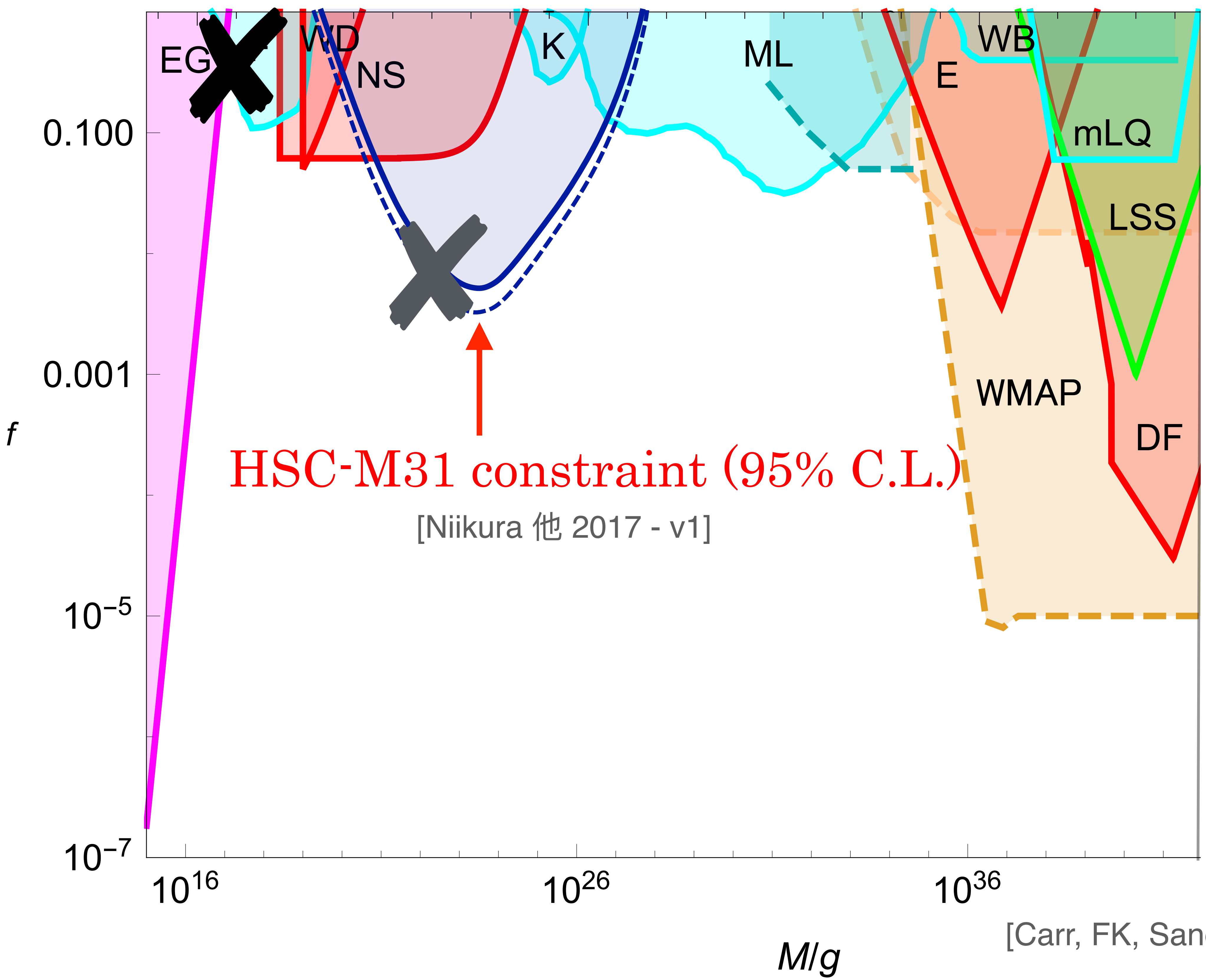

[Carr, FK, Sandstad 2016]

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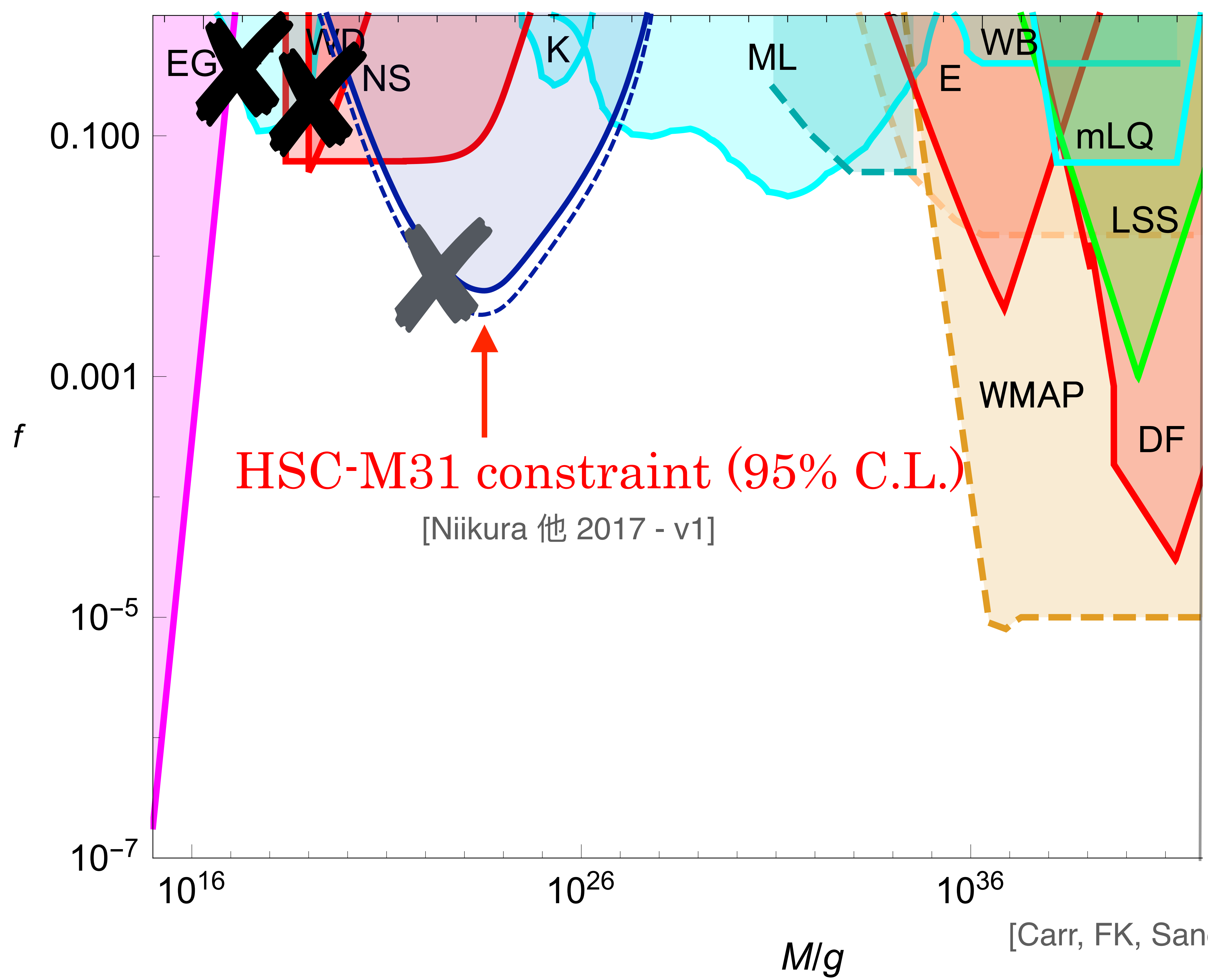

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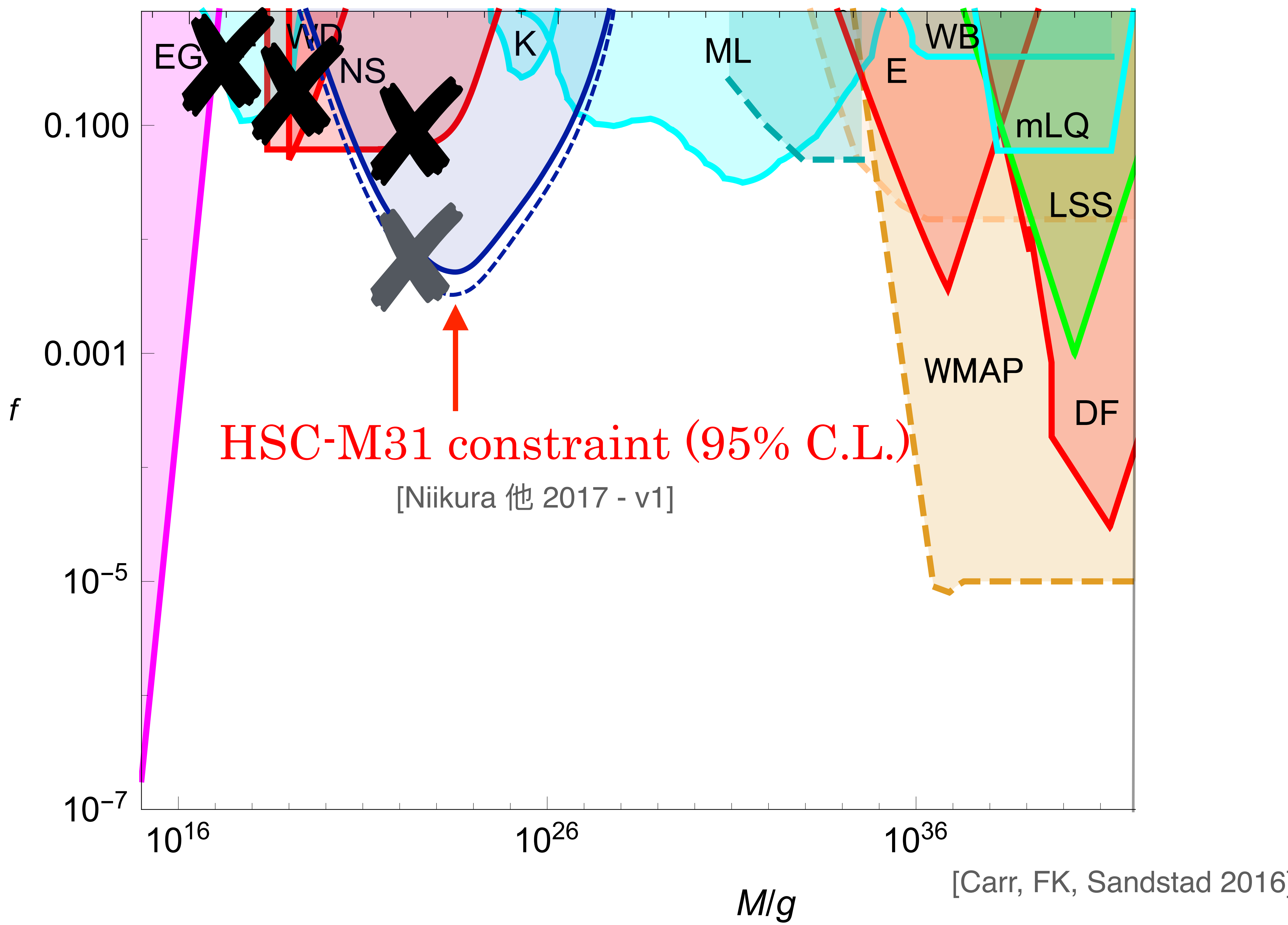
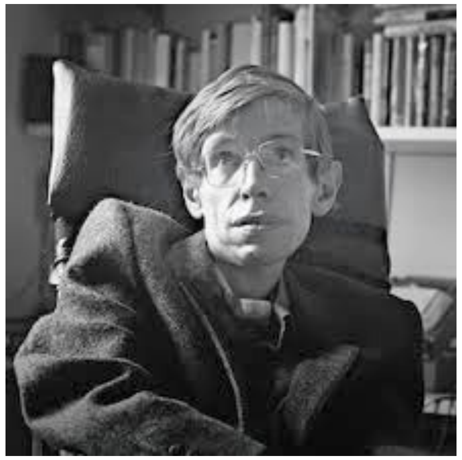


Even the very first paper…

Even the very first paper...

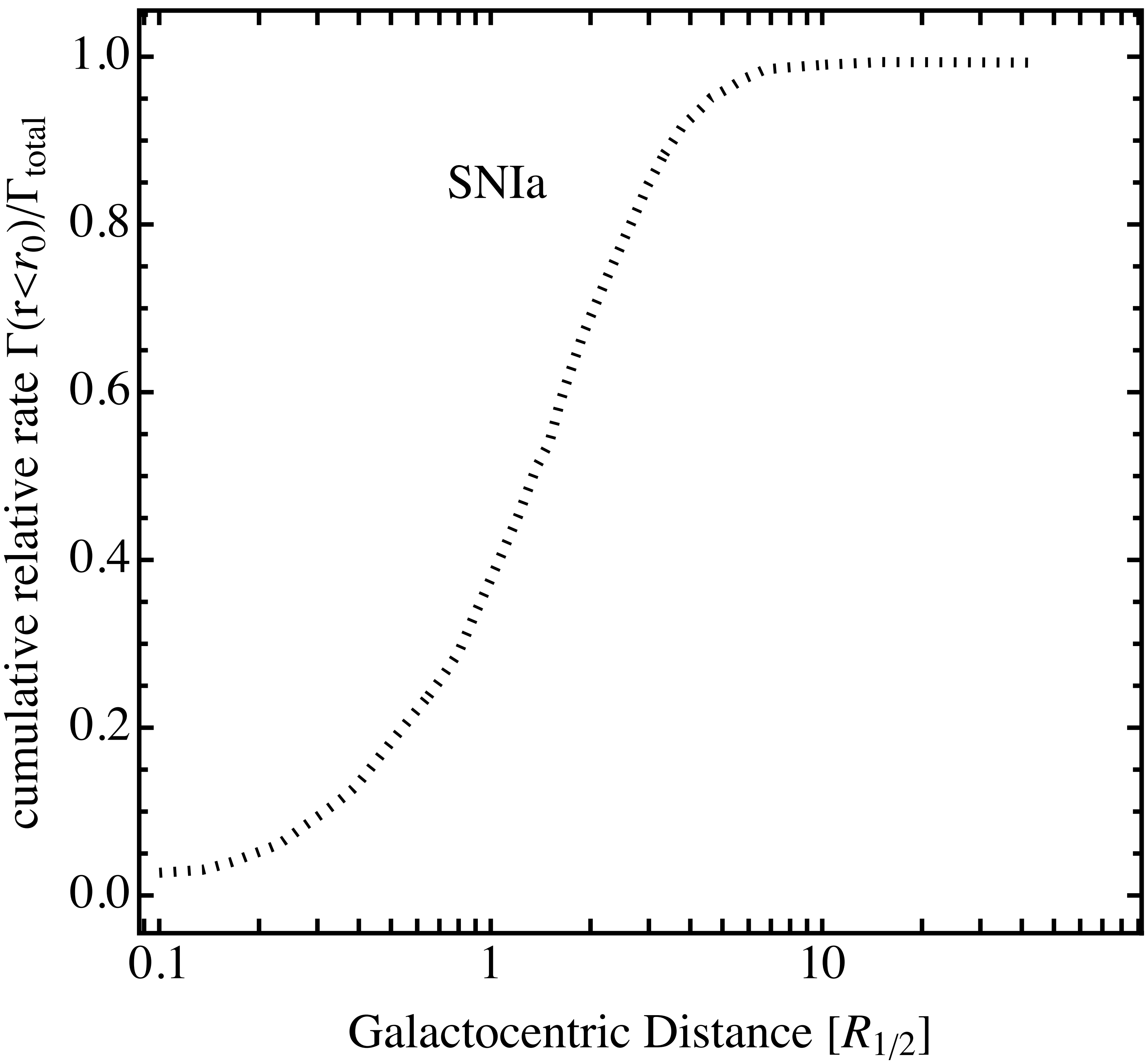
- PBHs first proposed by Novikov and Zel'dovič in 1967, but their conclusion was **negative for the existence of PBHs**!


- Conclusion heroically disproved by Carr & Hawking (1974), **reinvigorated PBH research** (around 2000 papers to date).

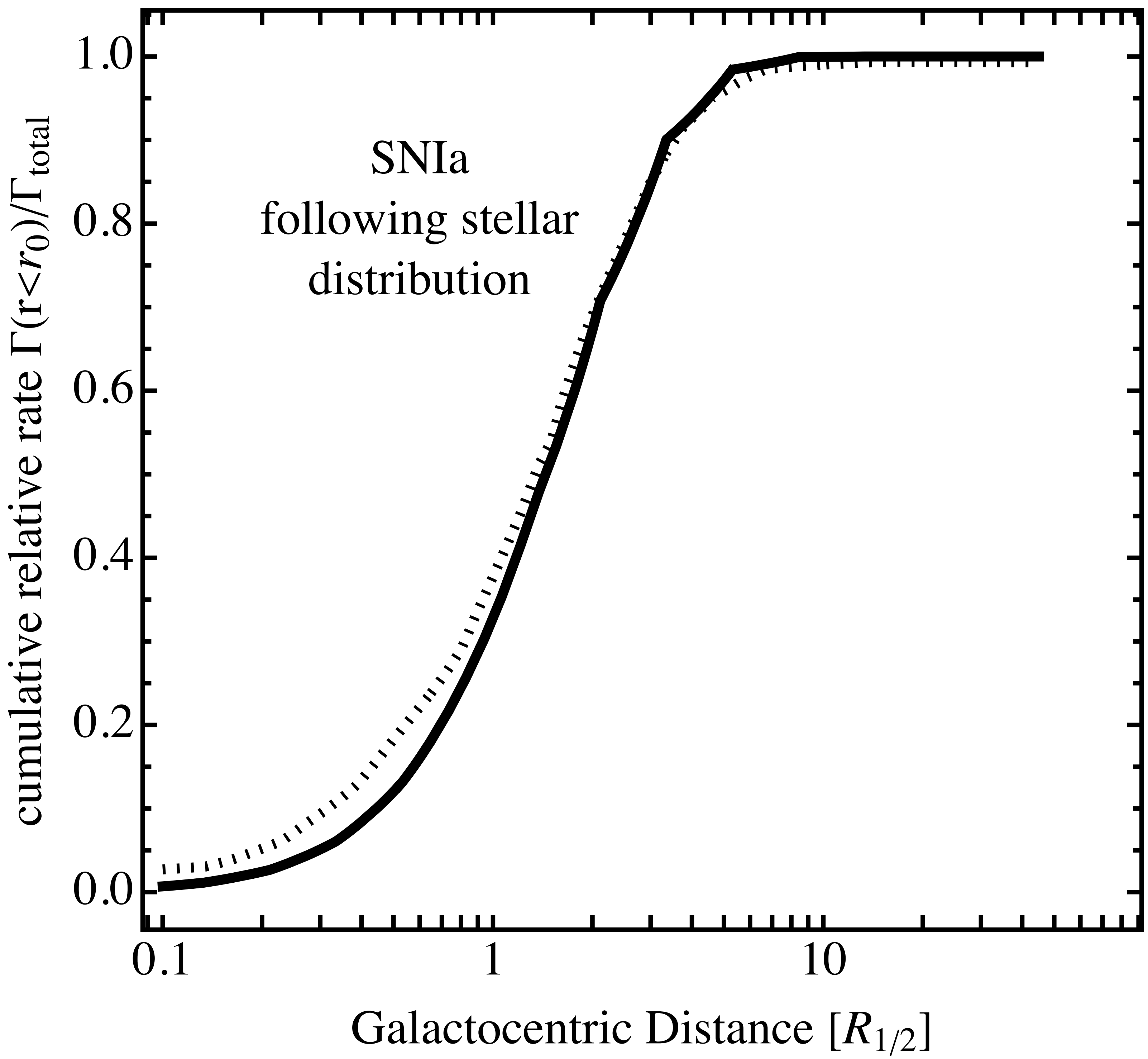
Focus on what is actually observed !

Exemplary: Supernova Evidence



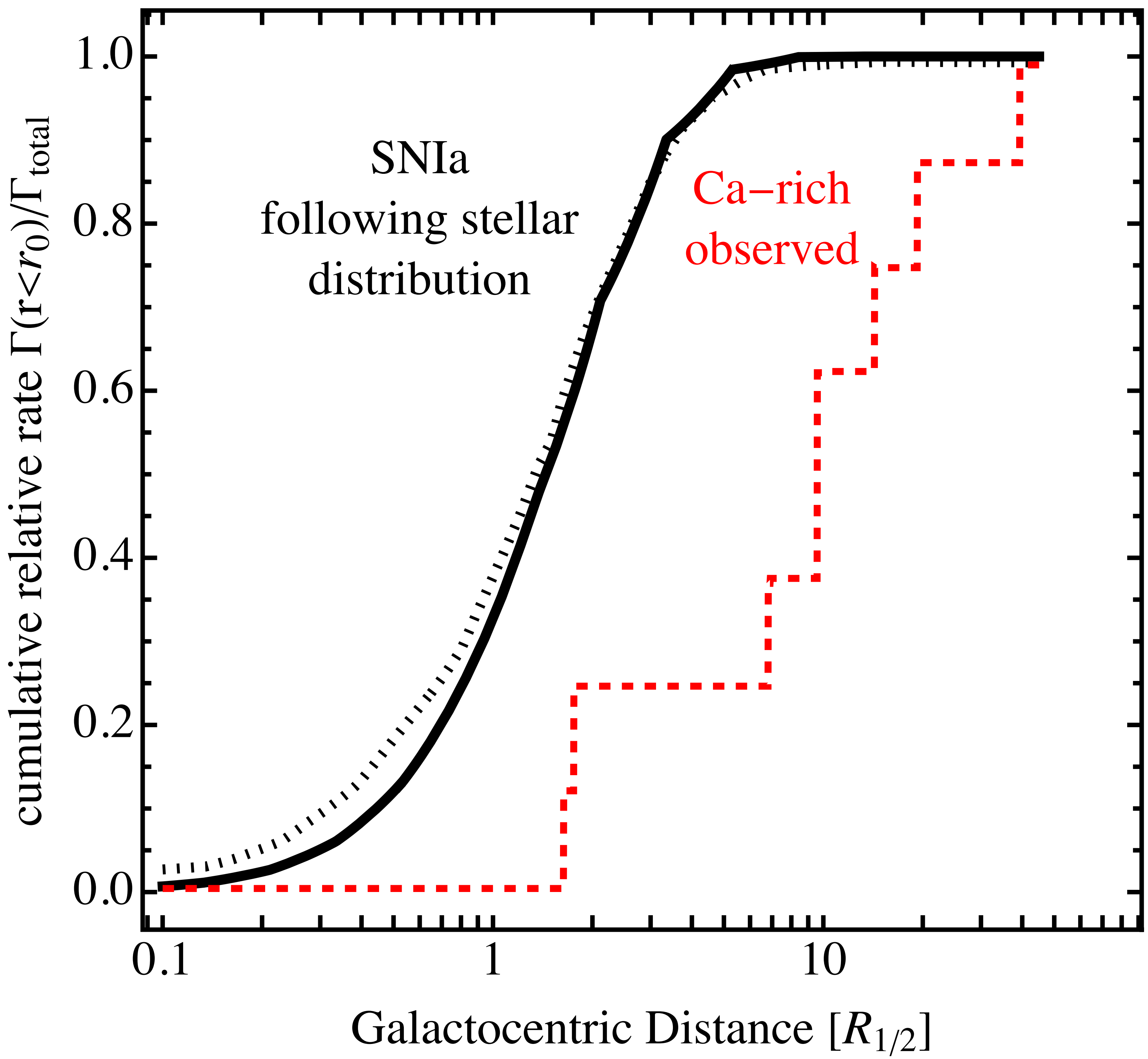
[Smirnov *et al.* 2023]

Exemplary: Supernova Evidence



[Smirnov *et al.* 2023]

Exemplary: Supernova Evidence



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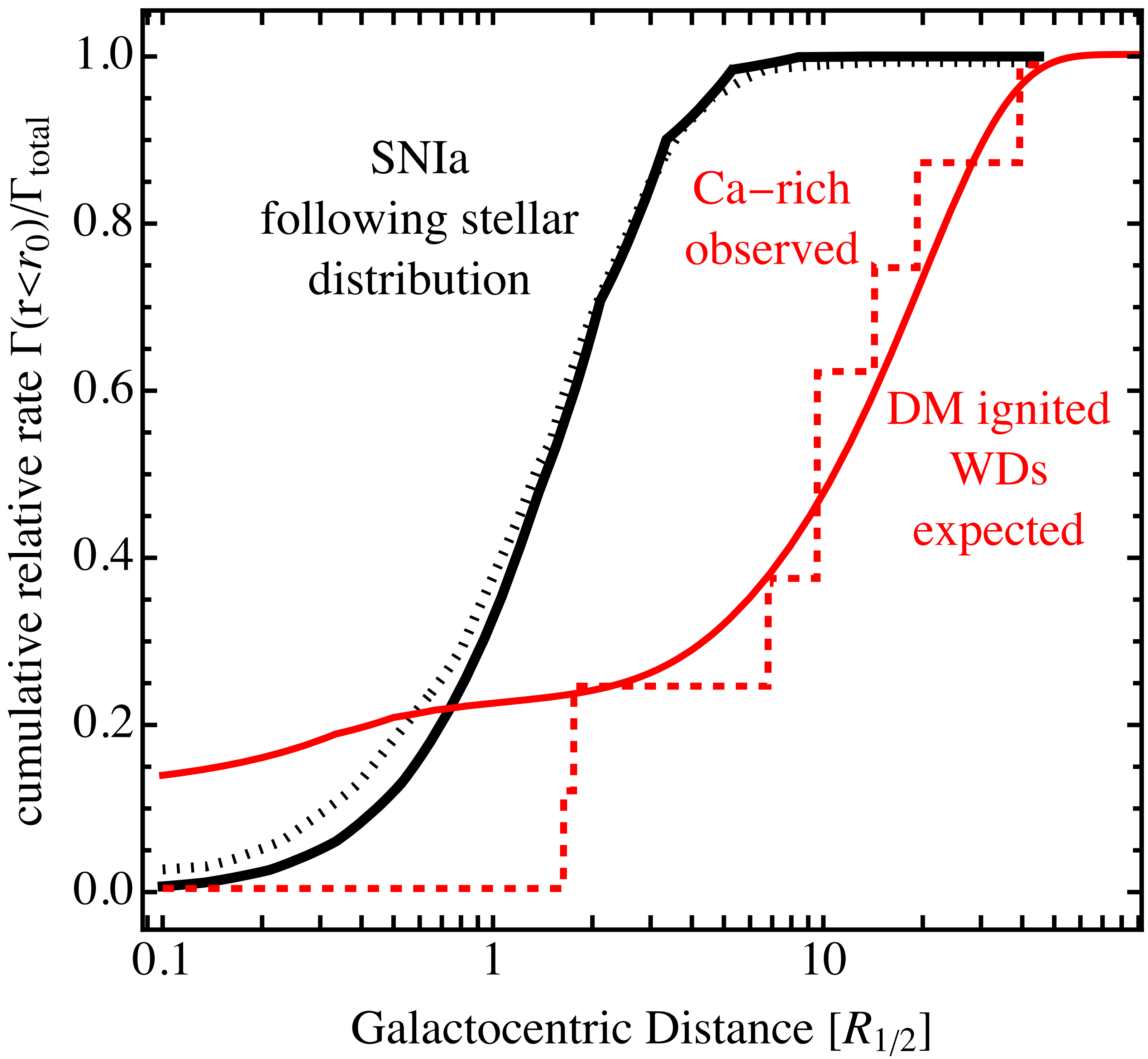
Exemplary: Supernova Evidence



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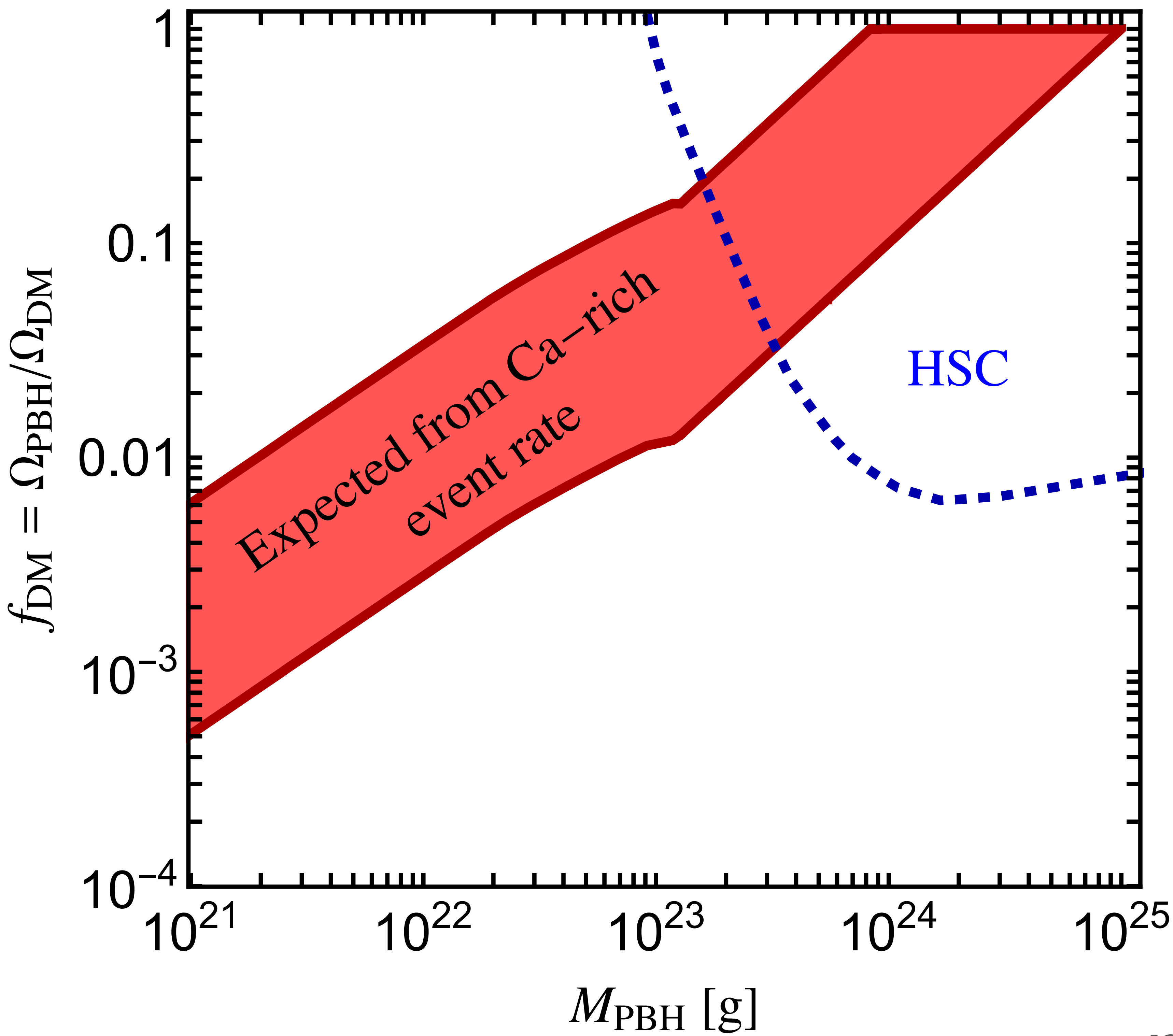
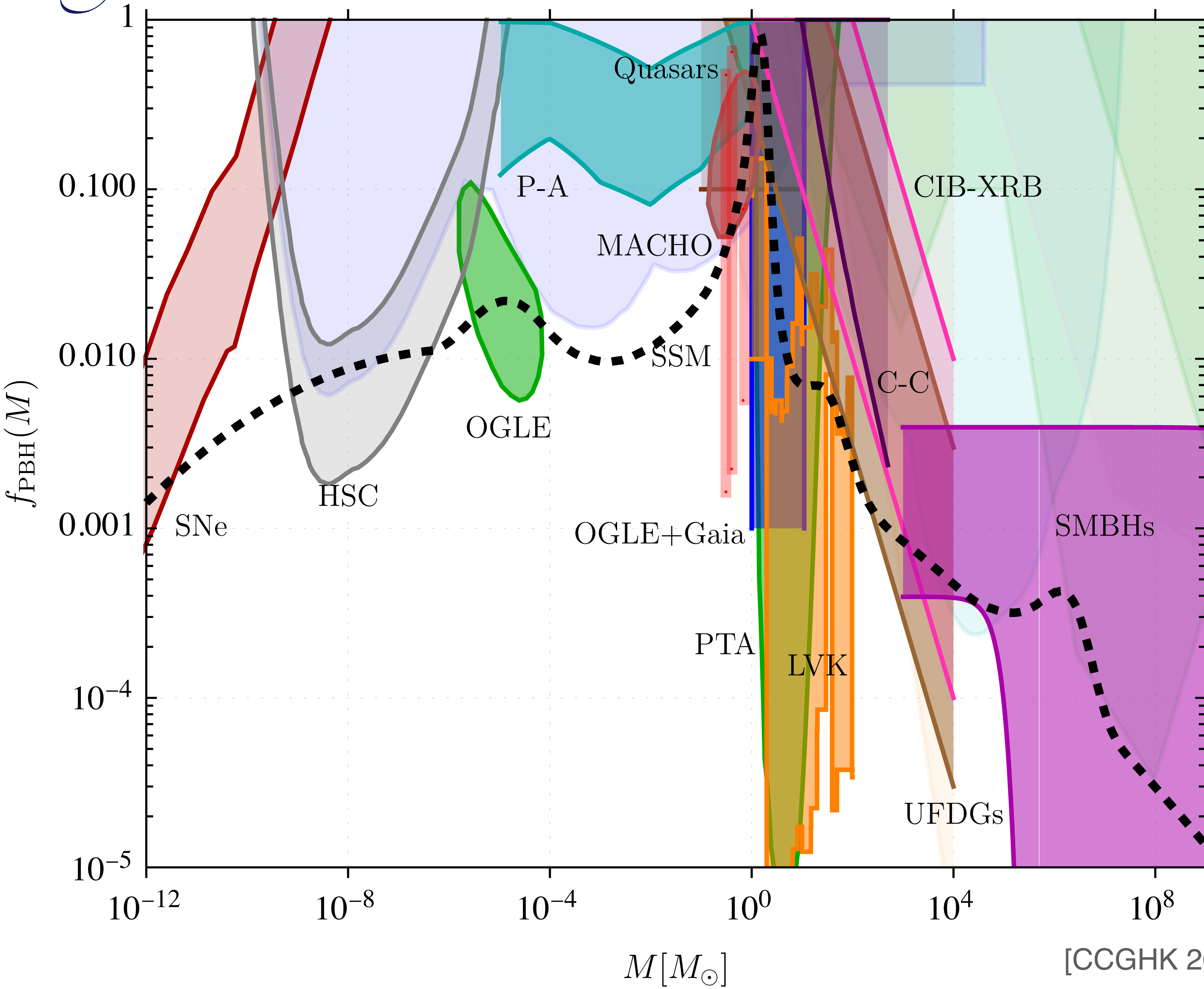
Exemplary: Supernova Evidence



[Smirnov *et al.* 2023]

Connecting all Positive Evidences!



[CCGHK 2023]

Shall Ye Become Positivists!

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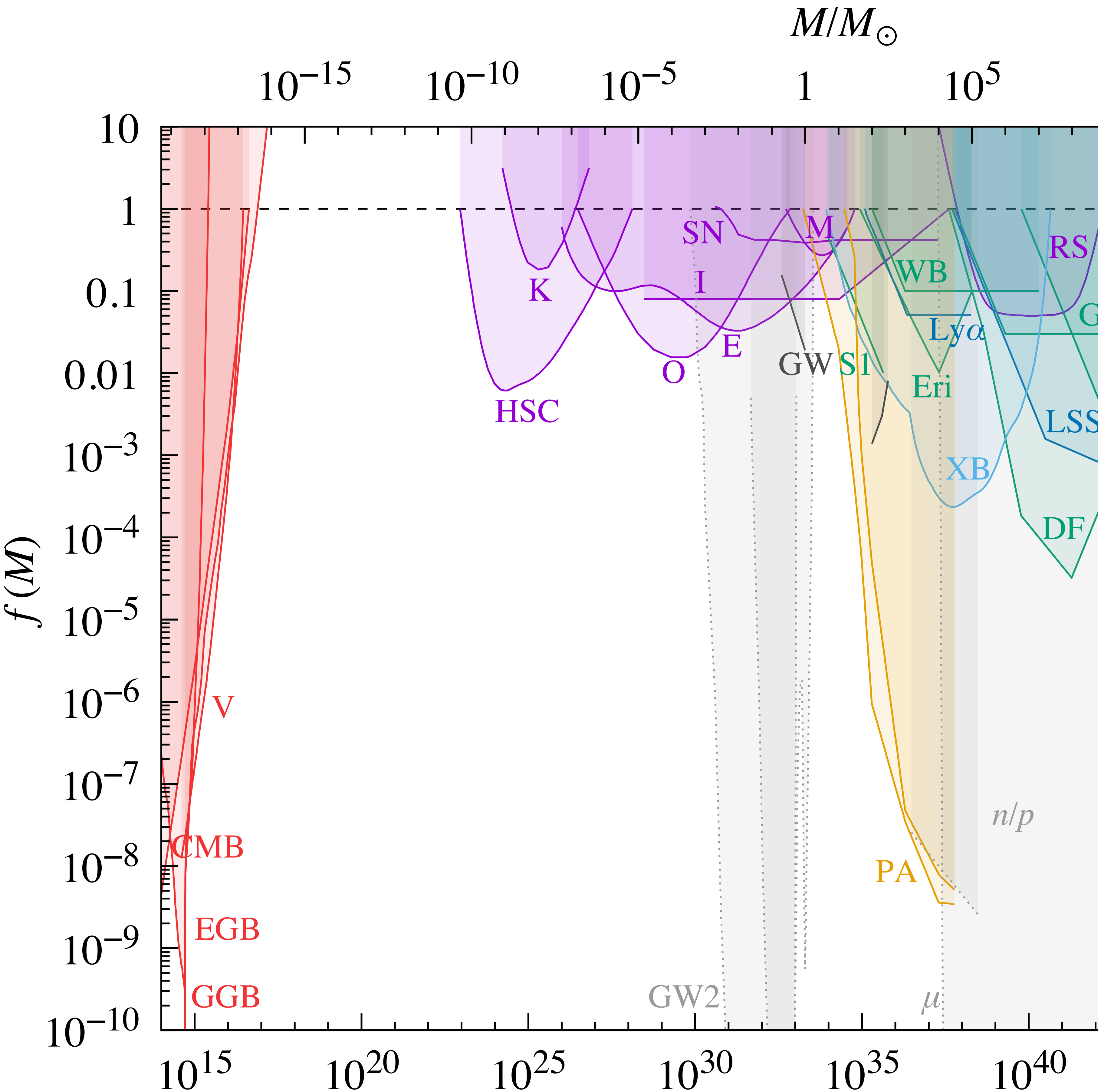
journal homepage: www.elsevier.com/locate/physrep

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,*]

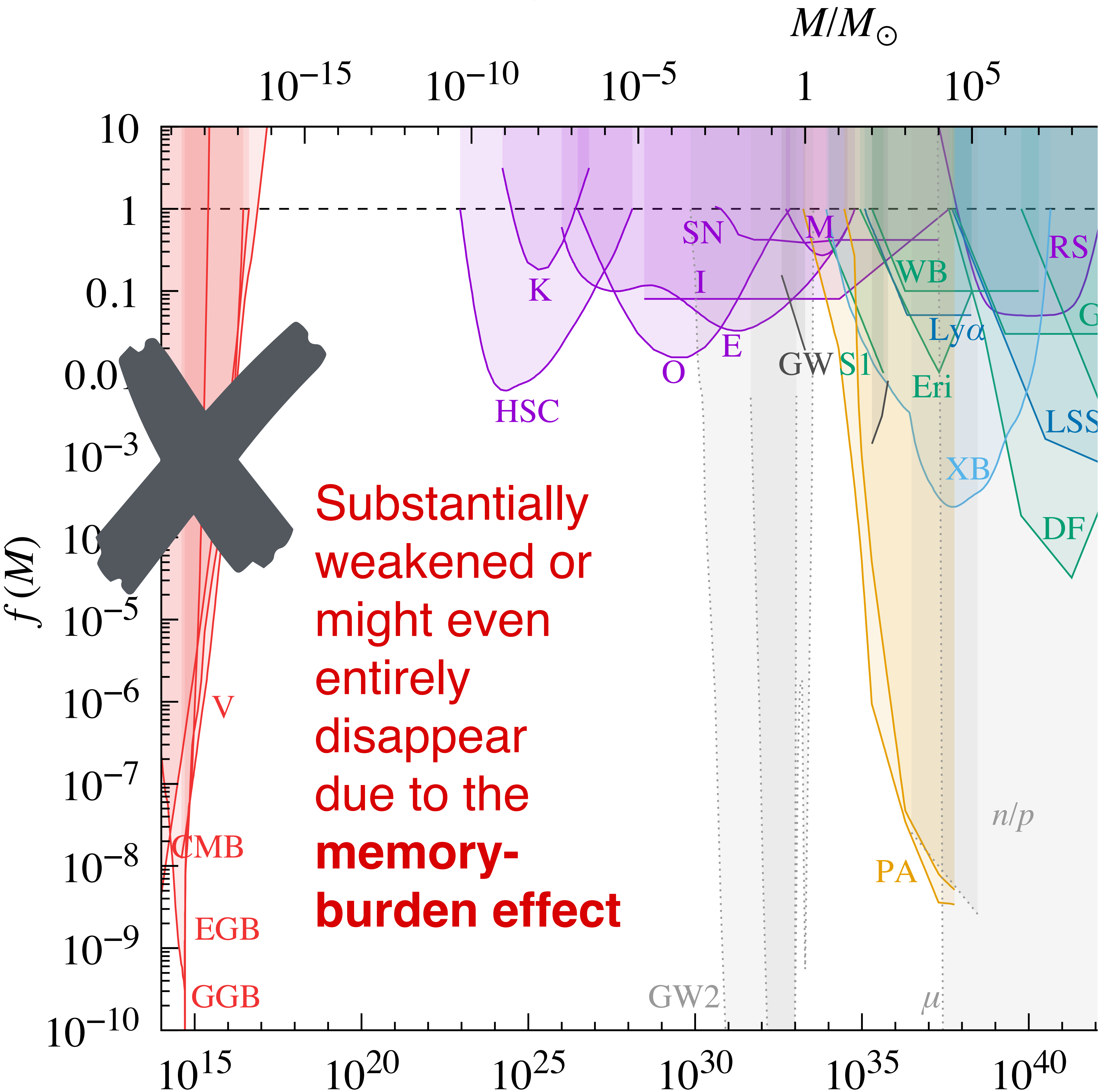
[a] *School of Physics and Astronomy, Queen Mary University of London, United Kingdom*
[b] *Service de Physique Théorique, University of Brussels (ULB), Belgium*
[c] *Instituto de Física Teórica UAM/CSIC, Universidad Autonoma de Madrid, Spain*
[d] *Department of Physics and Astronomy, University of Edinburgh,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

Current PBH Constraints



[Carr, Kohri, Sendouda, Yokoyama 2021]

Current PBH Constraints



Substantially weakened or might even entirely disappear due to the **memory-burden effect**

[Carr, Kohri, Sendouda, Yokoyama 2021]

Quantum Quiddity

Quantum Aspects — Memory-Burden Effect

- Black Holes can be understood as ***saturons***, ie. configurations of maximum entropy ***compatible with unitarity***.

  [Dvali 2021]

- Saturons, universally exhibit:

  [Dvali 2021++]

		black holes
exhibit an entropy area-law	⟷	Bekenstein area-law [Bekenstein 1973]
deplete thermally at a rate proportional to their inverse size	⟷	Hawking radiation [Hawking 1975]
show an information-retrieval timescale	⟷	Page time [Page 1976]

Quantum Aspects — Memory-Burden Effect

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

  [Dvali 2021]

- Evaporation rate Γ becomes *entropy suppressed*

  [Dvali *et al.* 2020]

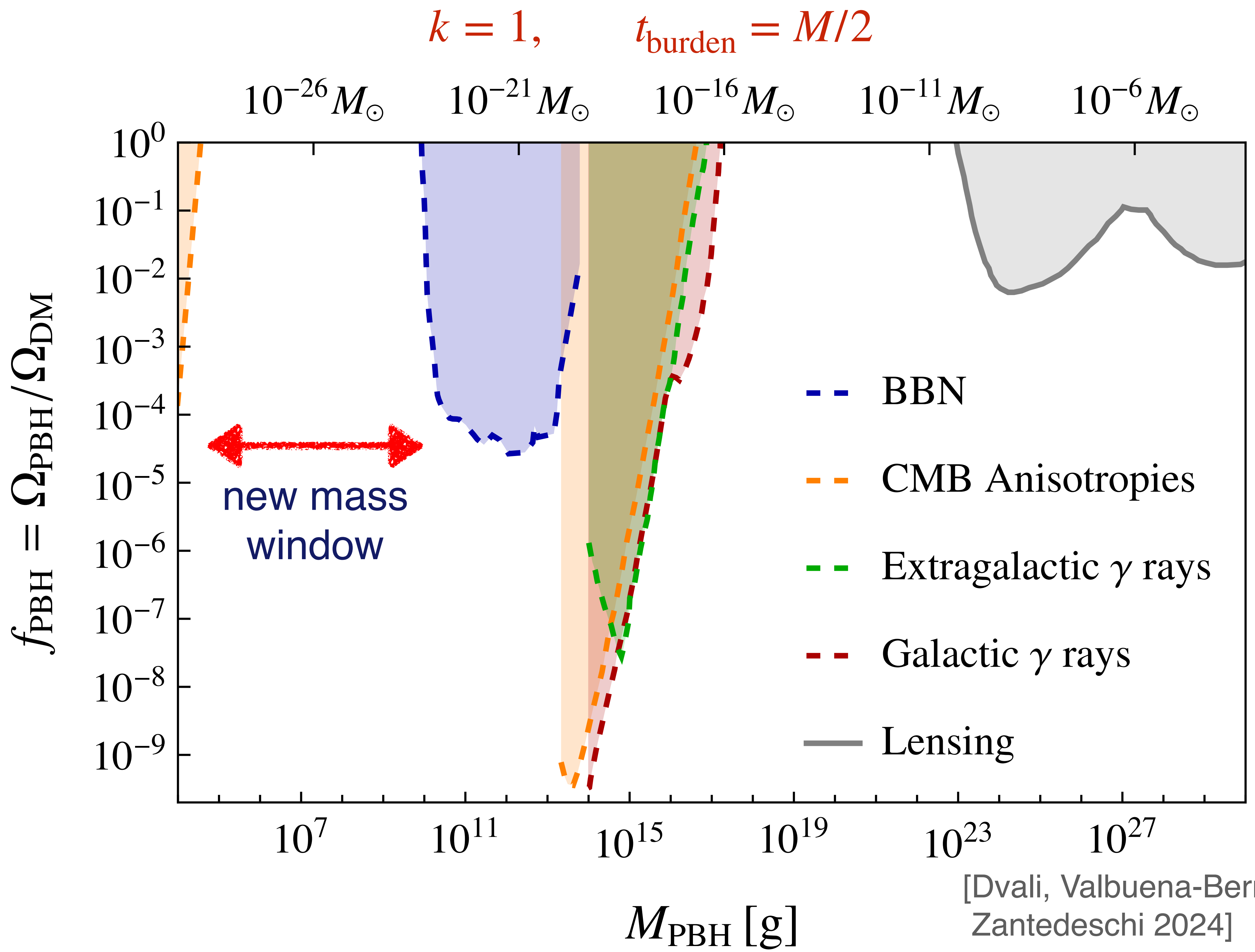
$$\Gamma \longrightarrow \frac{1}{S^k}\Gamma\,, \qquad k \geq 1,\, k \in \mathbb{N}$$

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

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

see talk by K. Kohri

Quantum Aspects — Memory-Burden Effect



[Dvali, Valbuena-Bermúdez, Zantedeschi 2024]

(see also [Alexandre, Dvali, Koutsangelas 2024] and [Thoss, Burkert, Kohri 2024])

Quantum Aspects — Memory-Burden Effect

★ This was for:

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

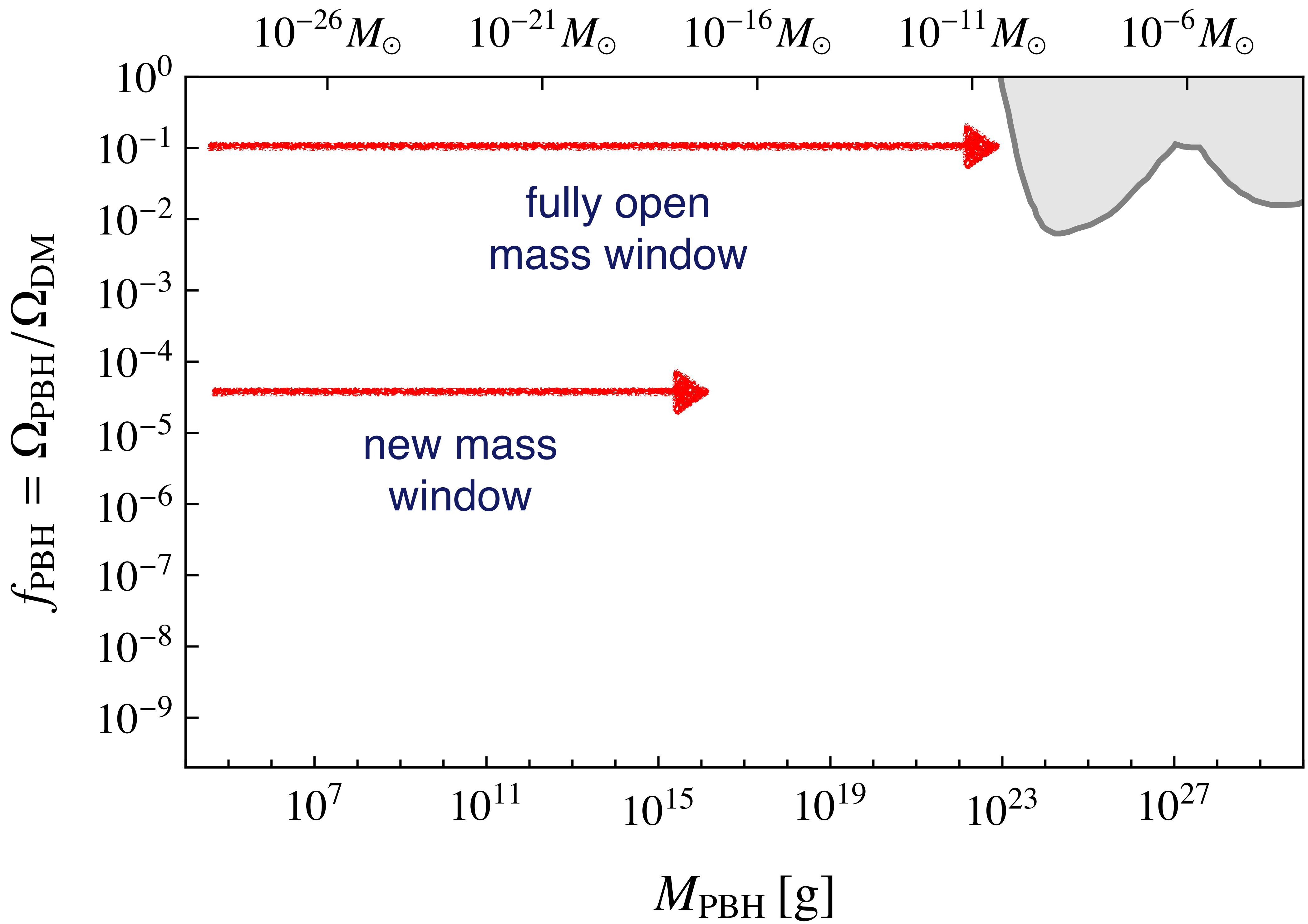
★ There are arguments for the memory-burden effect setting in already at

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

★ What happens in this case?

Quantum Aspects — Memory-Burden Effect

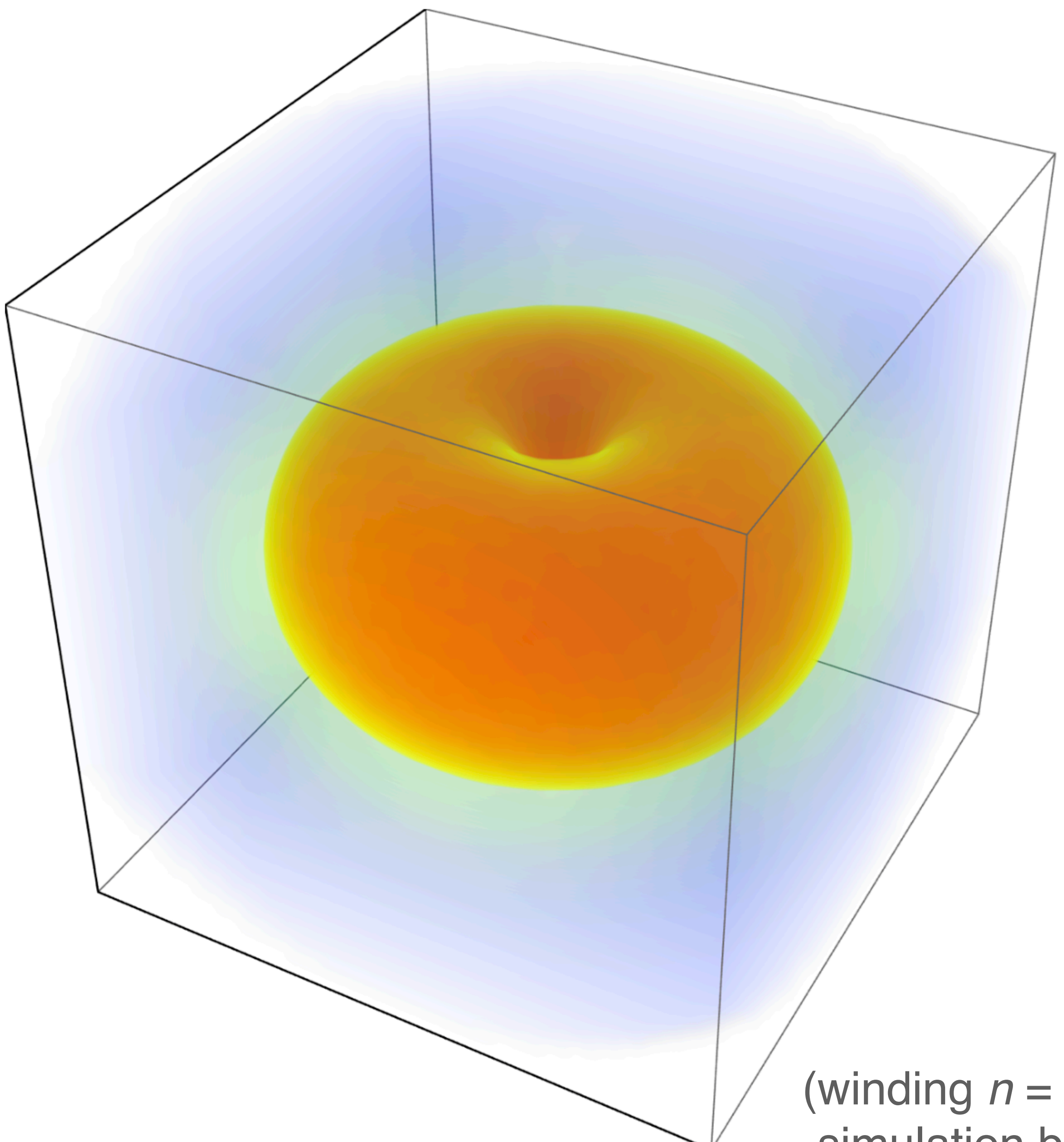
$k = 1, \qquad t_{\rm burden} \sim M/\sqrt{S}$



Quantum Aspects — Vortices

★ We showed that (near-)extremally spinning saturons, and hence likely black holes, admit vortex structure.

[Dvali, FK, Zantedeschi 2022]



(winding $n = 1$; simulation by M. Zantedeschi)

★ Emergence of relation between spin and angular momentum

$$S \sim J$$

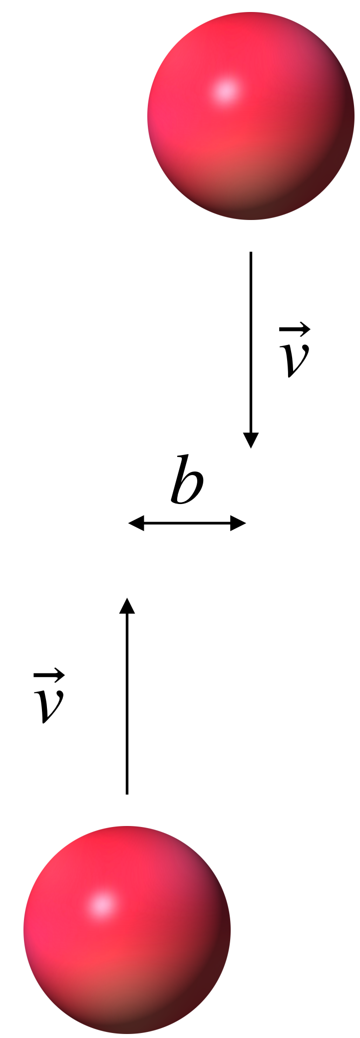
★ Besides, vorticity provides a topological meaning to the stability of extremal black holes.

Quantum Aspects — Vortices

- Merger simulation of black hole analog configurations (non-topological solitons, i.e. Q-balls)

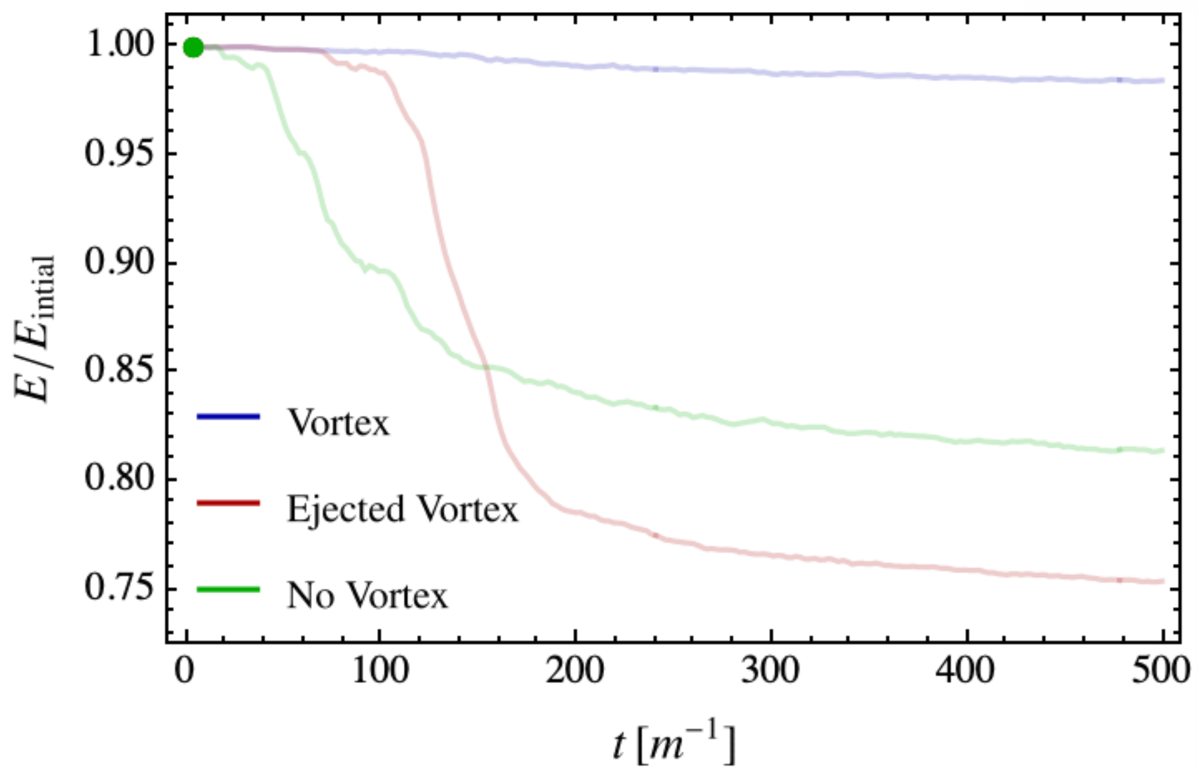
[Dvali, FK, Kaikov, Valbuena-Bermúdez, Zantedeschi 2024]

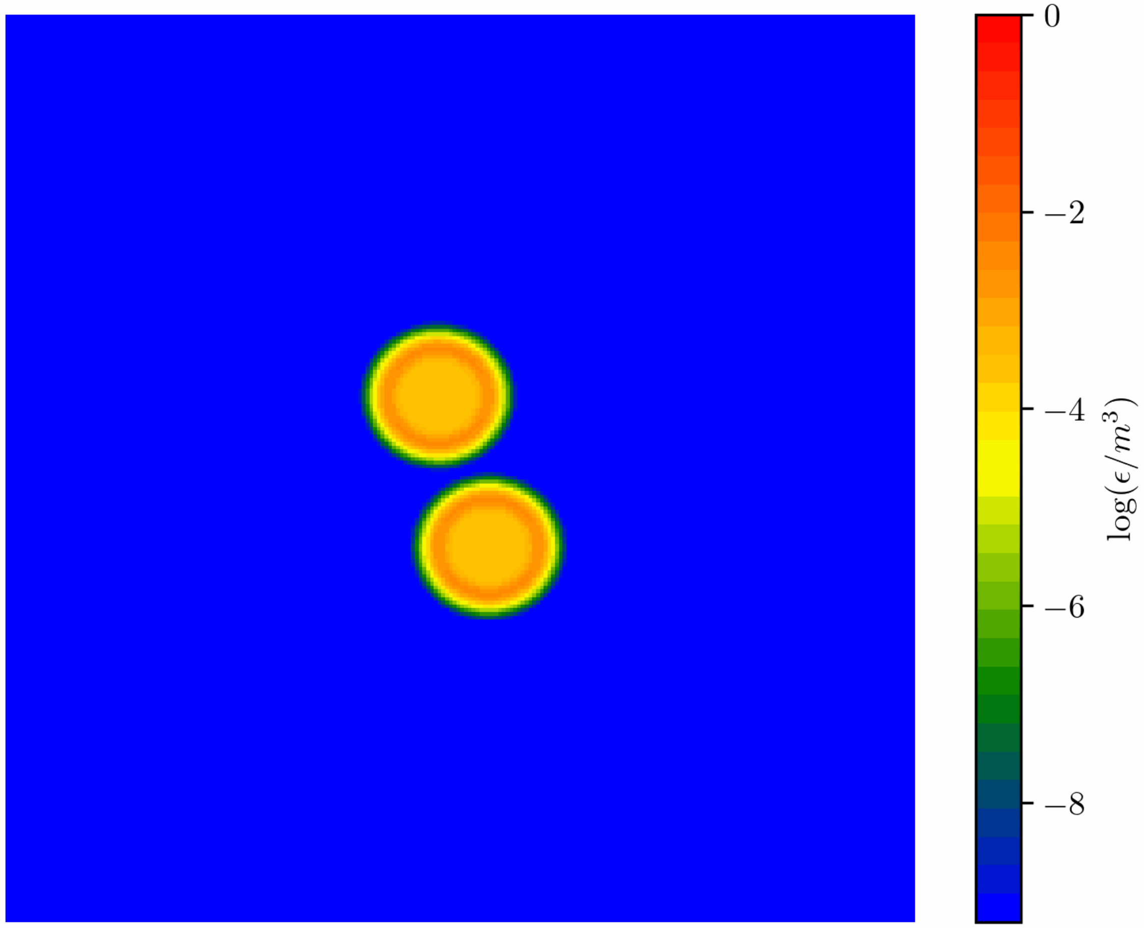
- Three cases:
  - no vortex forms: the solitons simply merge;
  - a vortex forms temporary: the final soliton is near the threshold for vortex formation but is eventually ejected;
  - a vortex forms stably: the final solution attains a vortex.



Quantum Aspects — Vortices

★ No vortex case (two-dimensional perspective):





(simulation by M. Zantedeschi)

[Dvali, FK, Kaikov, Valbuena-Bermúdez, Zantedeschi 2024]

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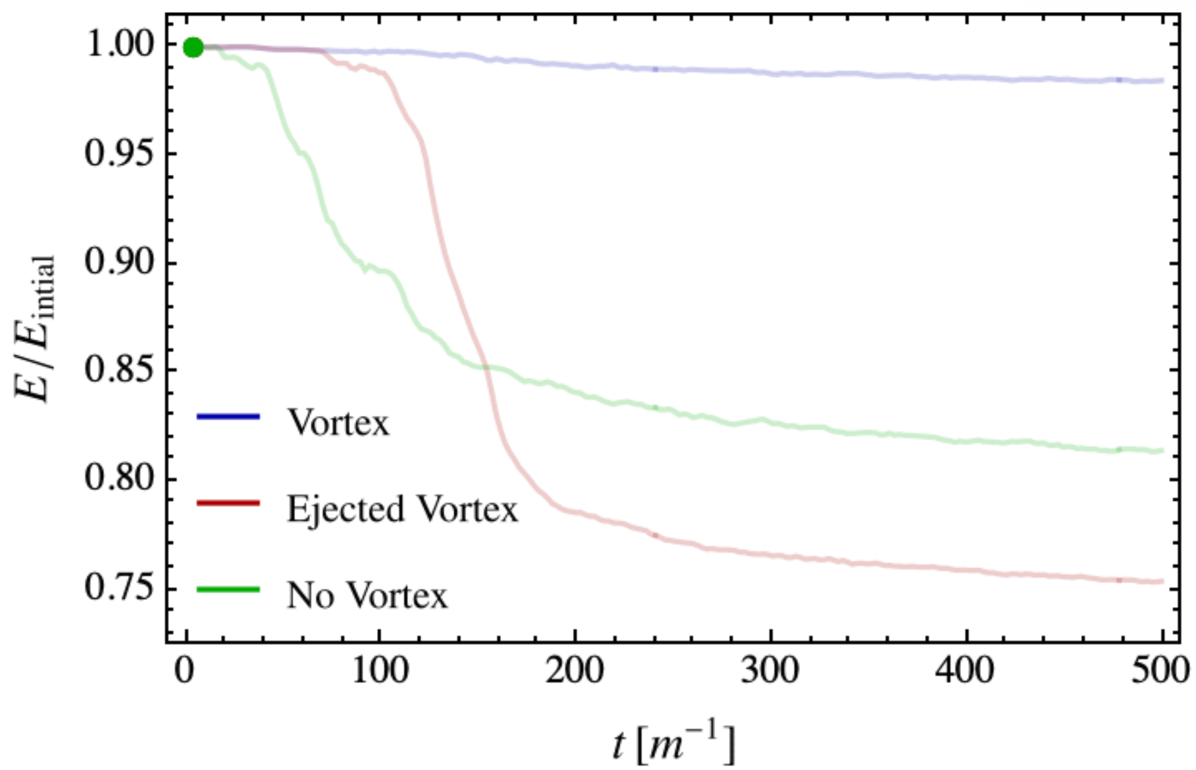

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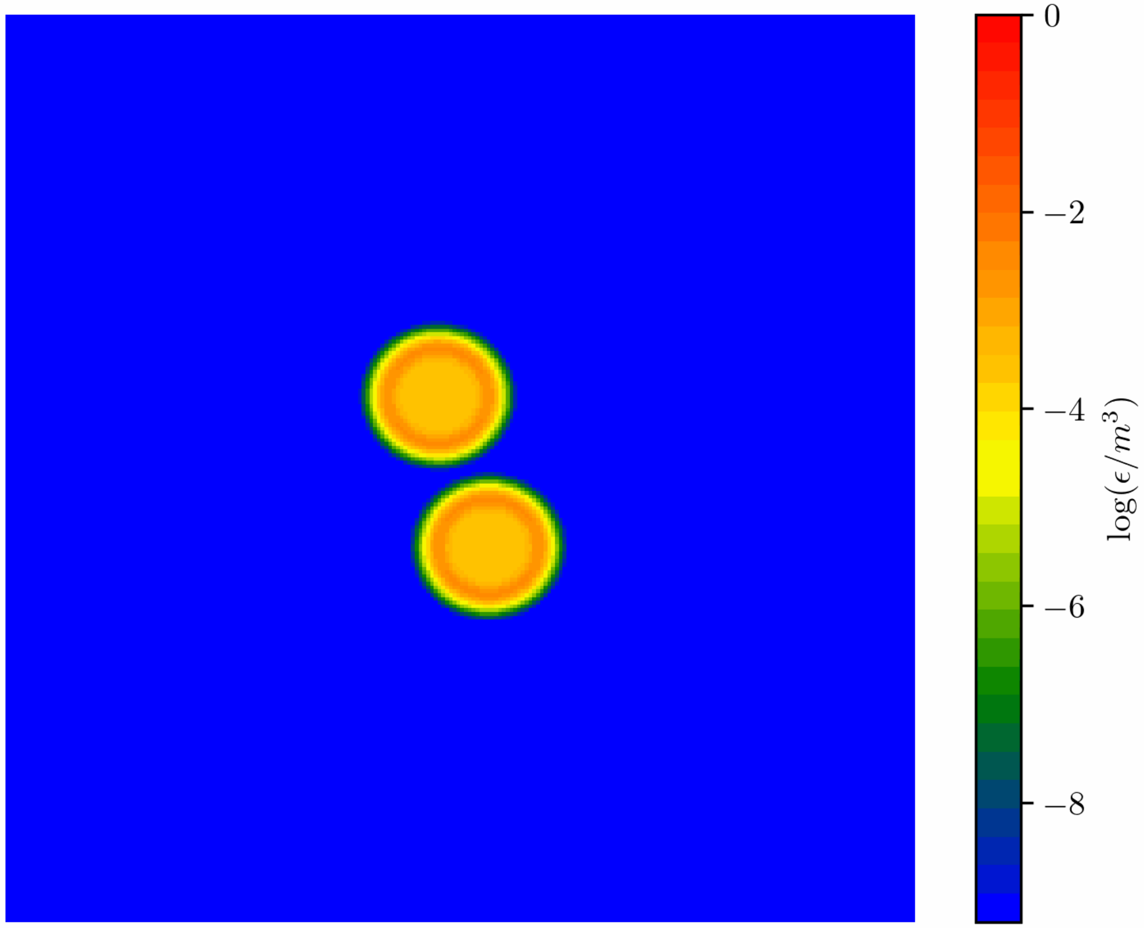

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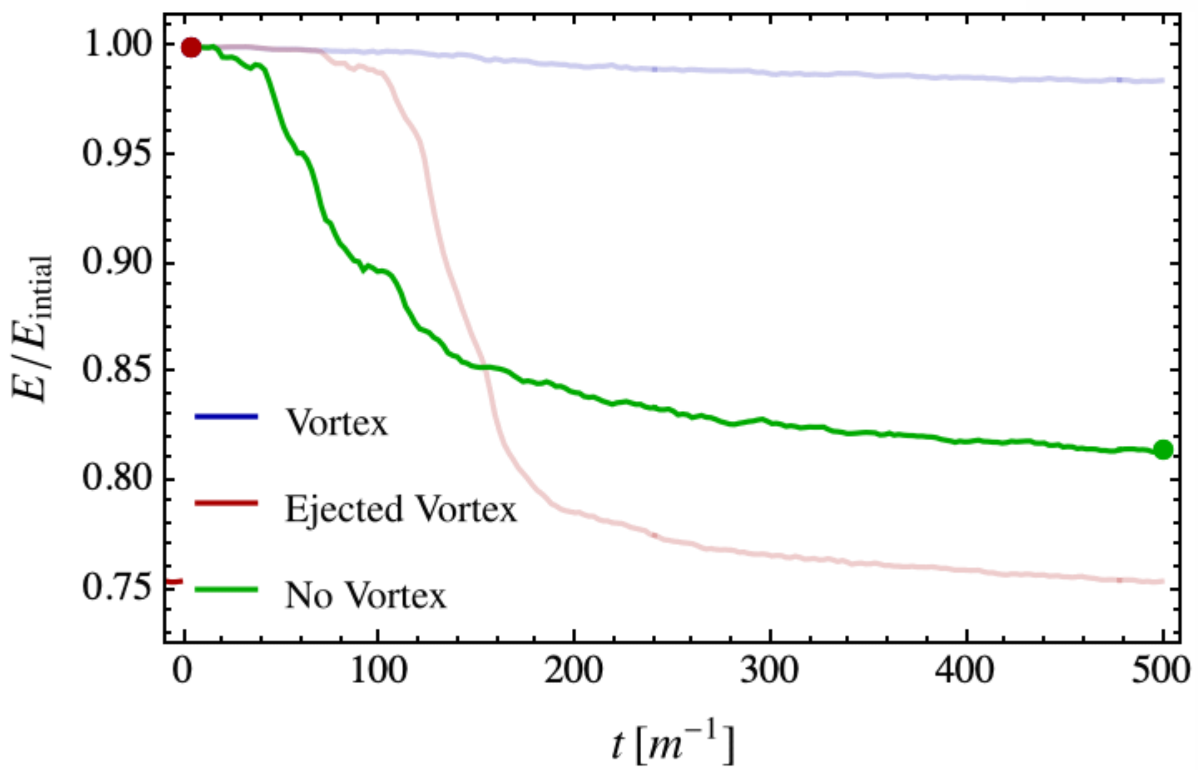
Quantum Aspects — Vortices

★ Temporal vortex formation (two-dimensional perspective):



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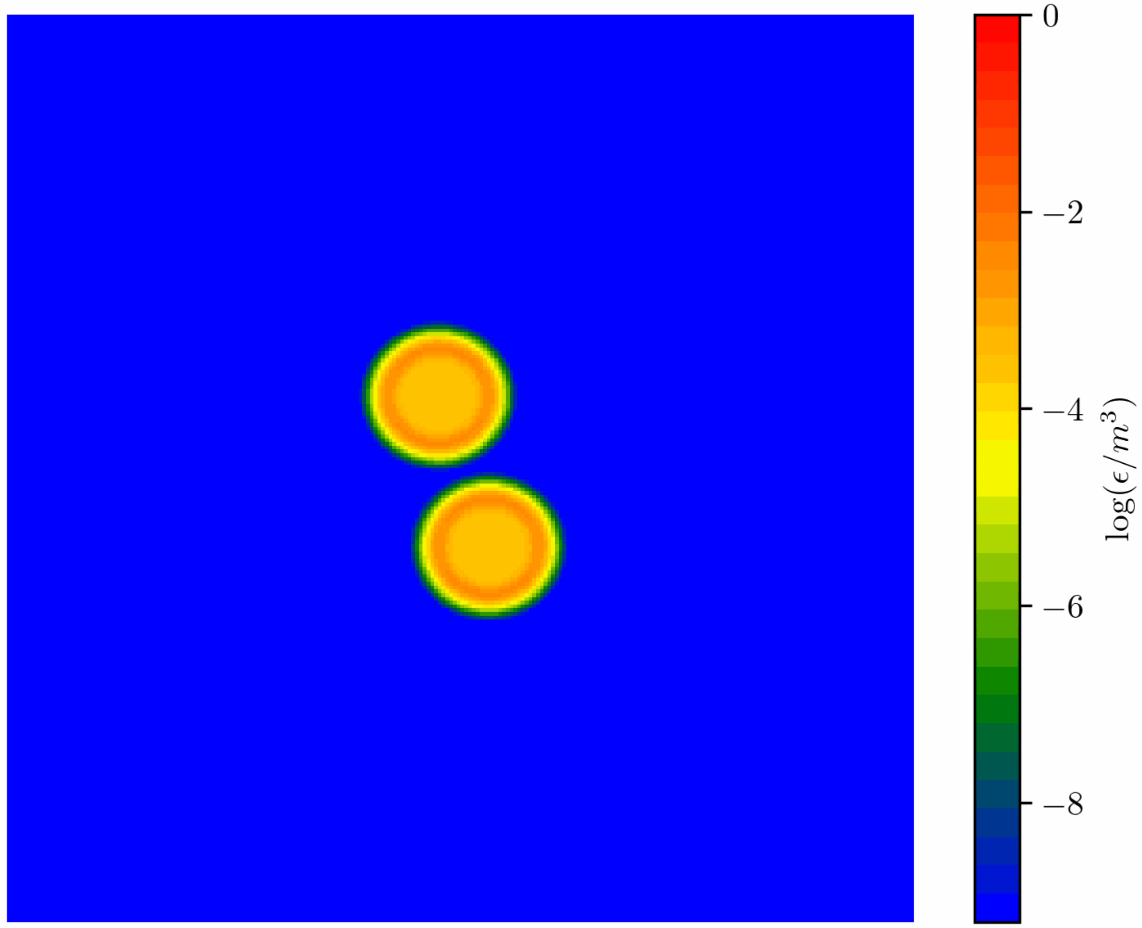

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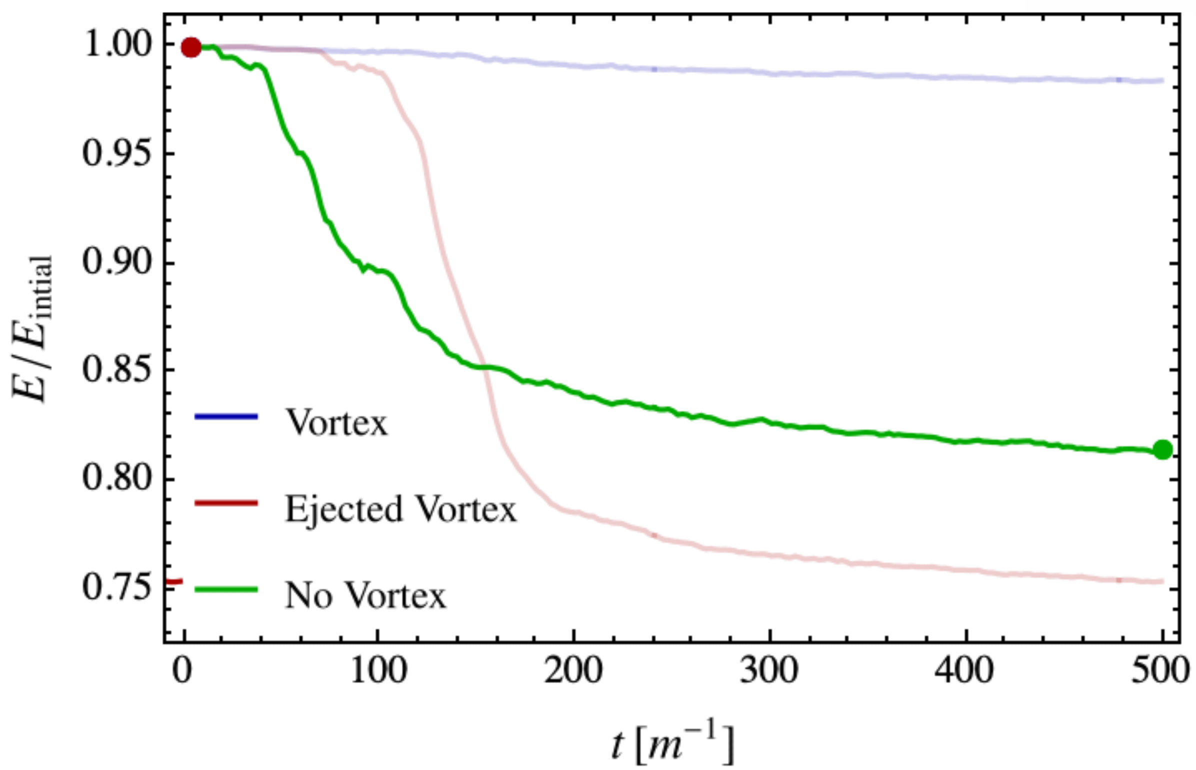

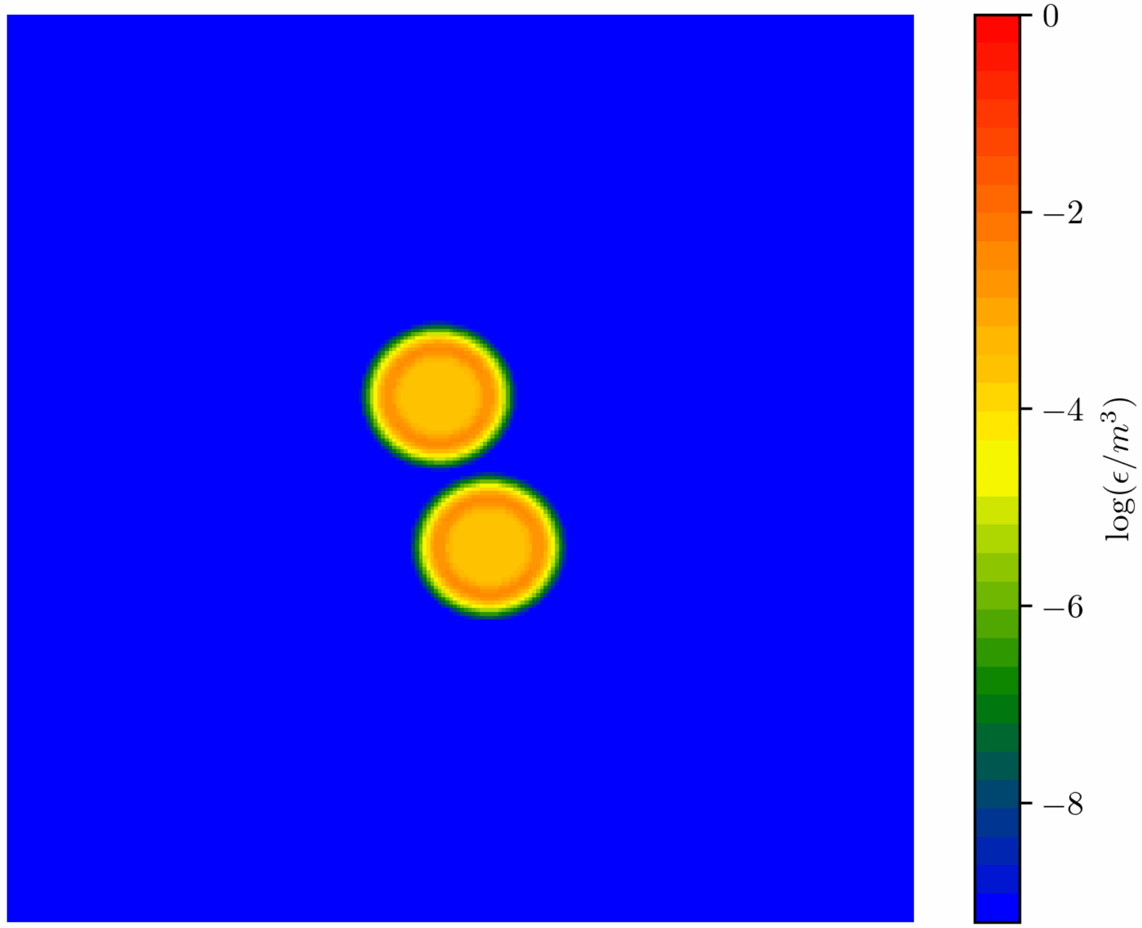

[Dvali, FK, Kaikov, Valbuena-Bermúdez, Zantedeschi 2024]

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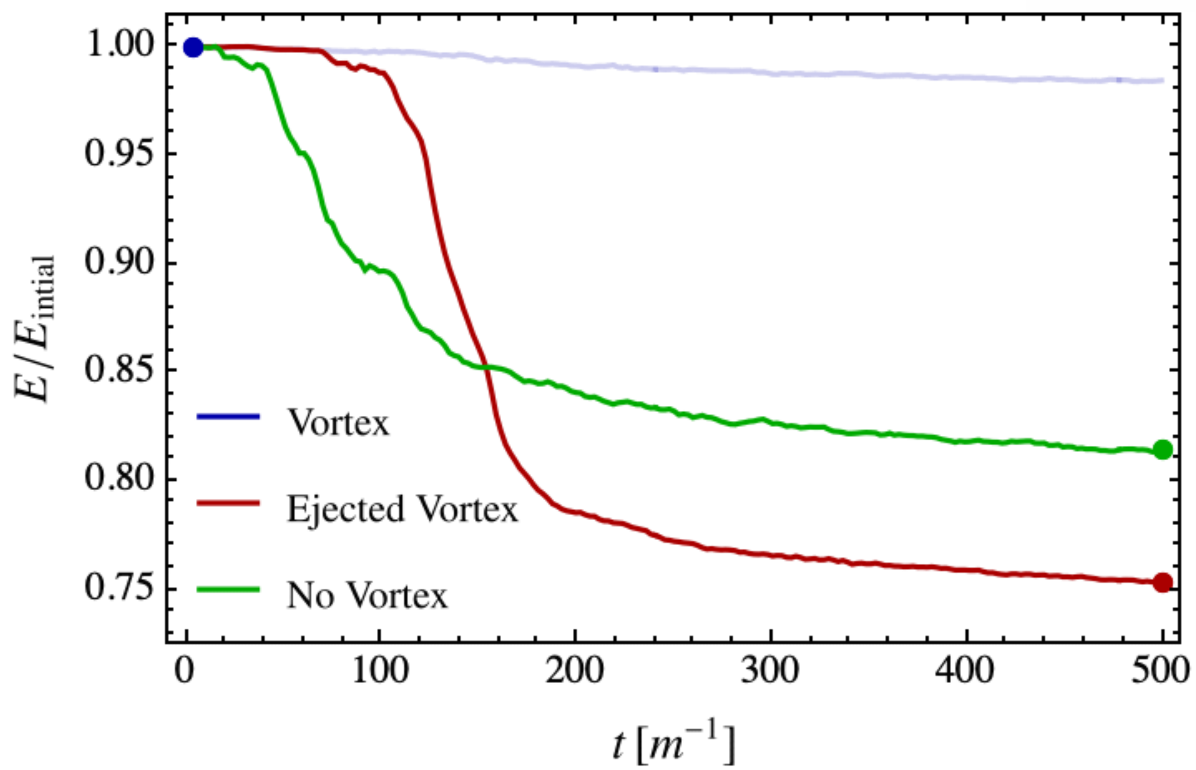
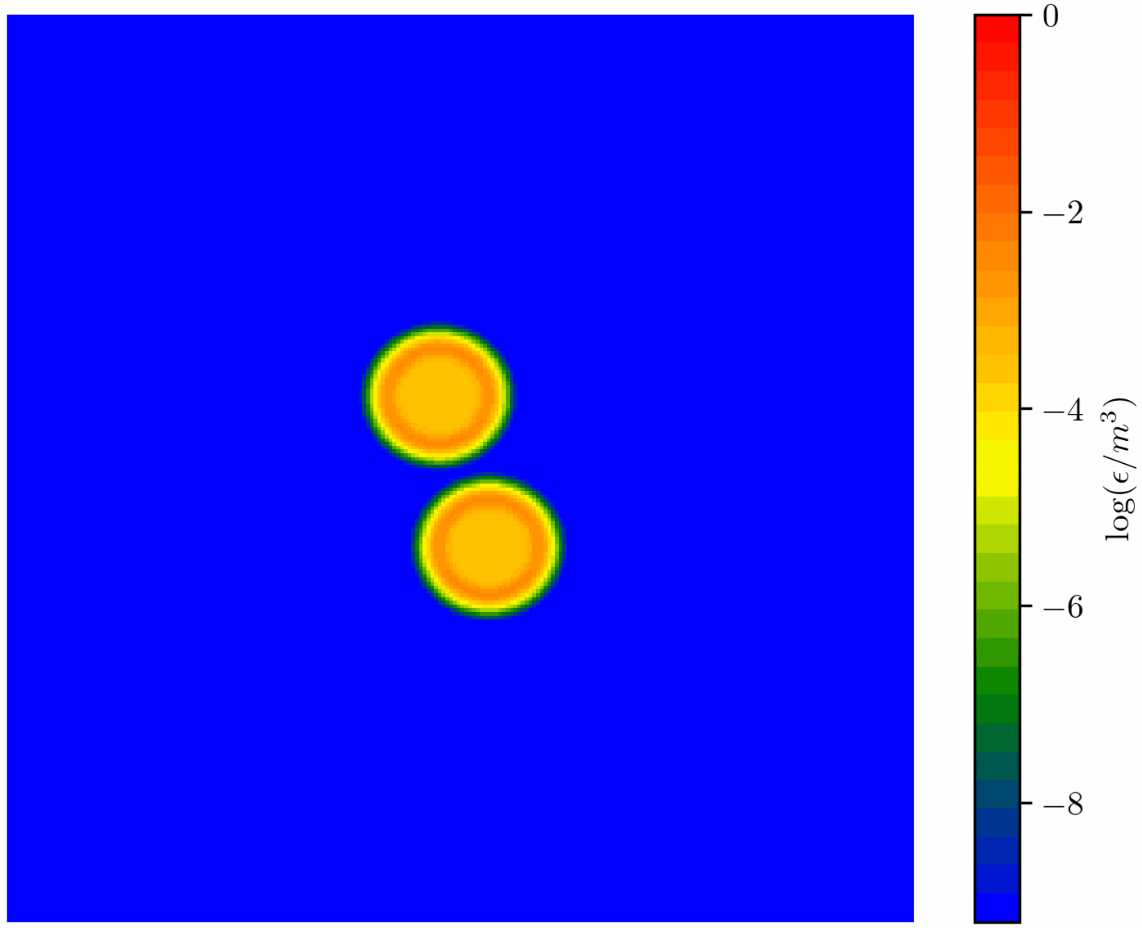
Quantum Aspects — Vortices

★ Proper vortex formation (two-dimensional perspective):





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Quantum Aspects — Vortices

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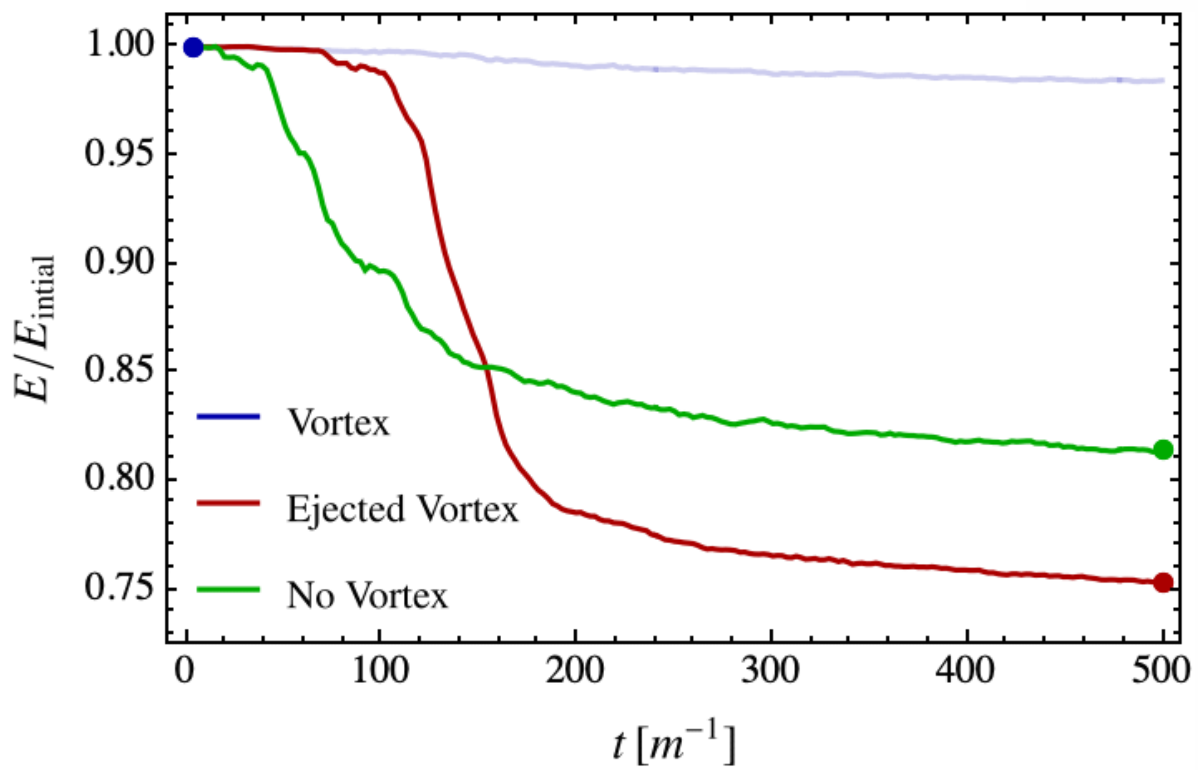
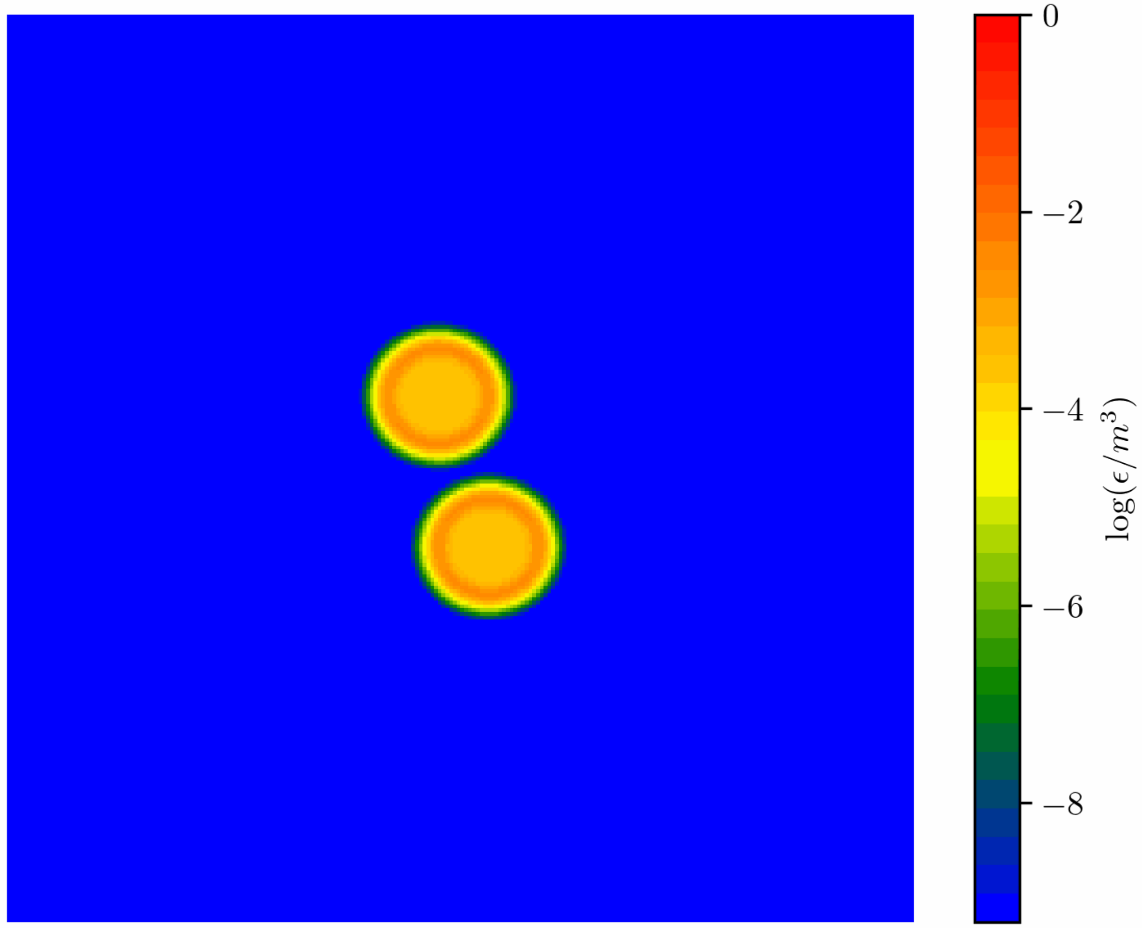


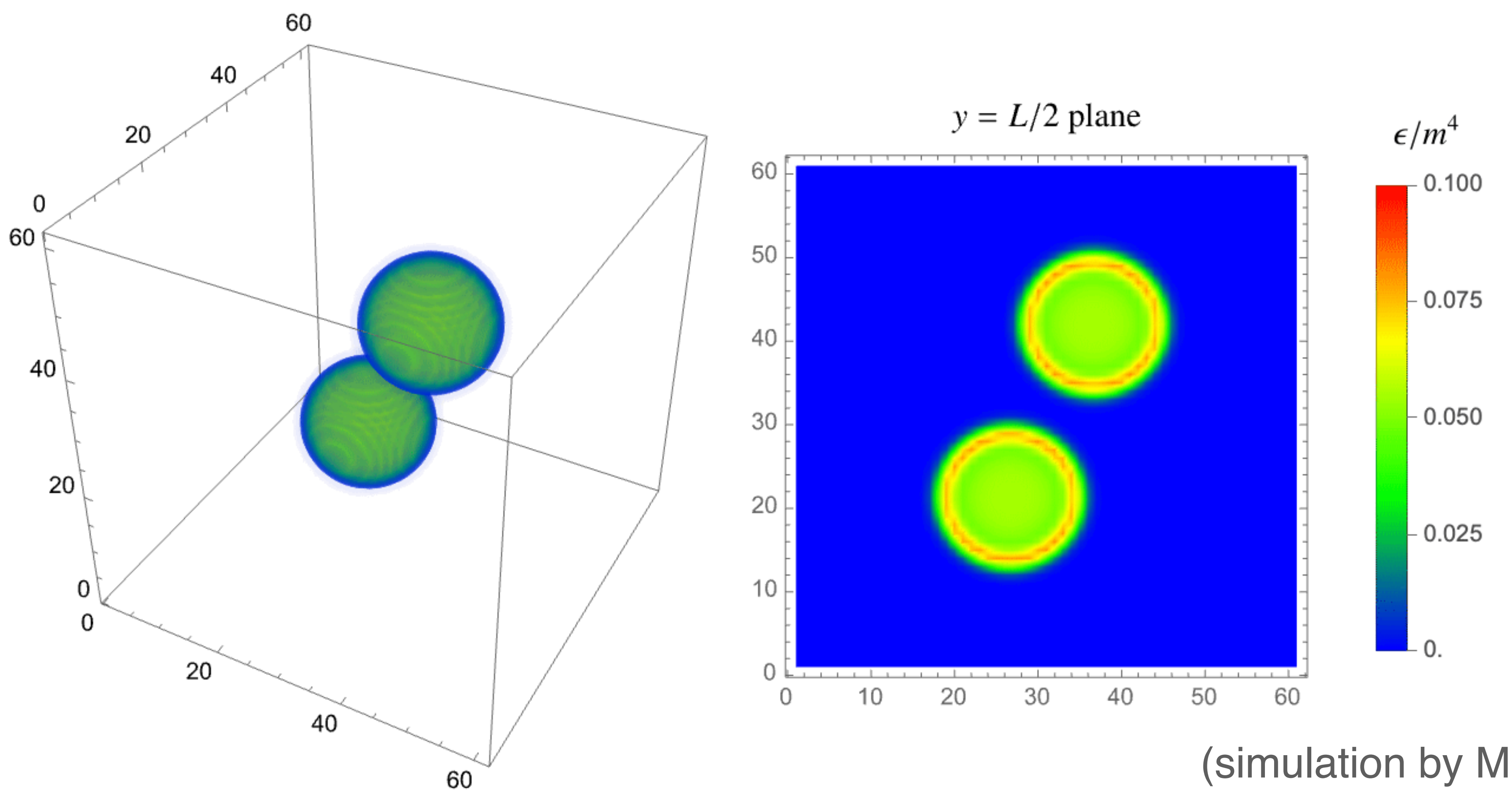


[Dvali, FK, Kaikov, Valbuena-Bermúdez, Zantedeschi 2024]

(simulation by M. Zantedeschi)

Quantum Aspects — Vortices

★ Proper vortex formation (three-dimensional perspective):



(simulation by M. Zantedeschi)

[Dvali, FK, Kaikov, Valbuena-Bermúdez, Zantedeschi 2023]

Quantum Aspects — Vortices

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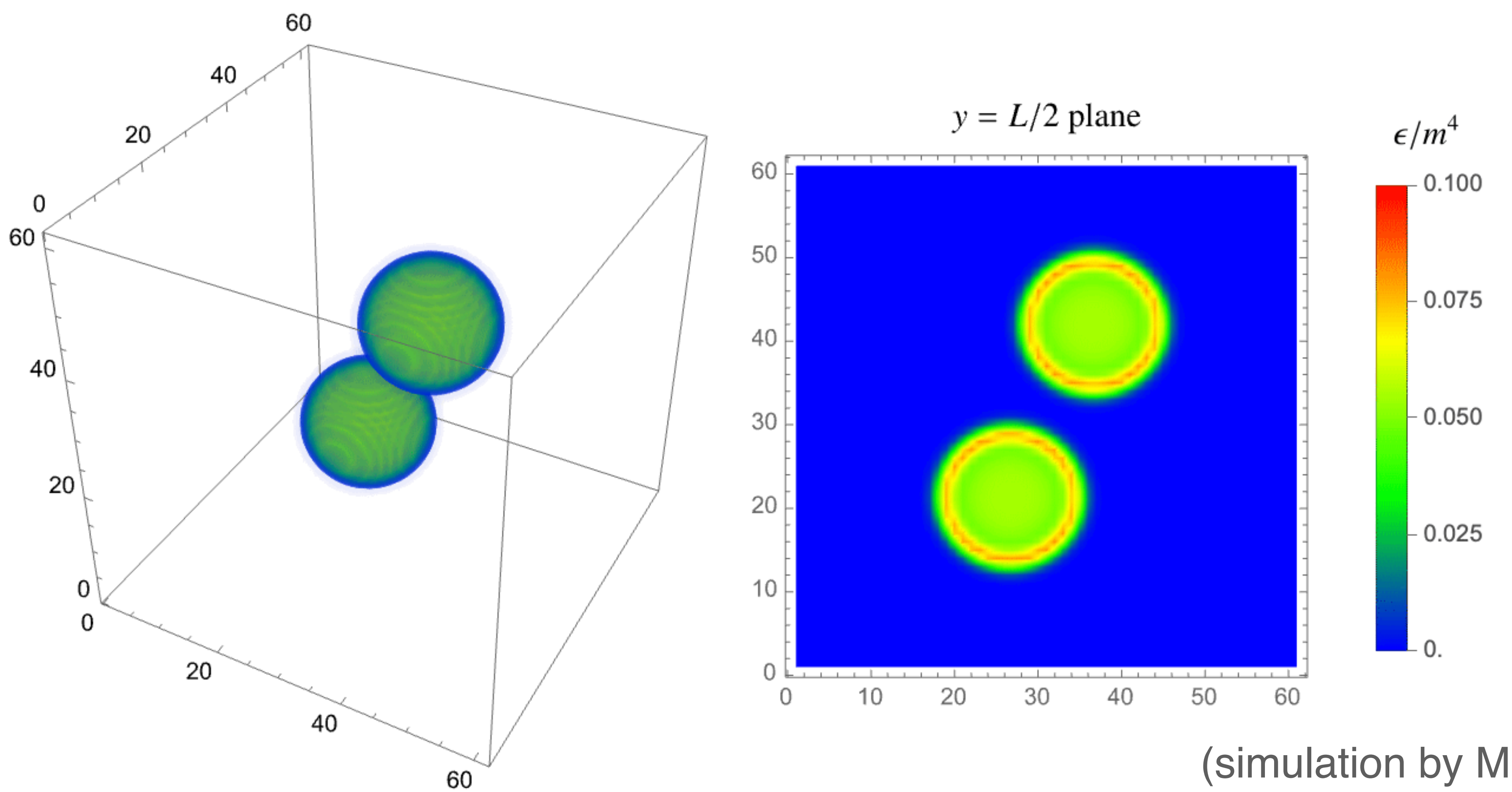


(simulation by M. Zantedeschi)

[Dvali, FK, Kaikov, Valbuena-Bermúdez, Zantedeschi 2023]

Quantum Aspects — Vortices

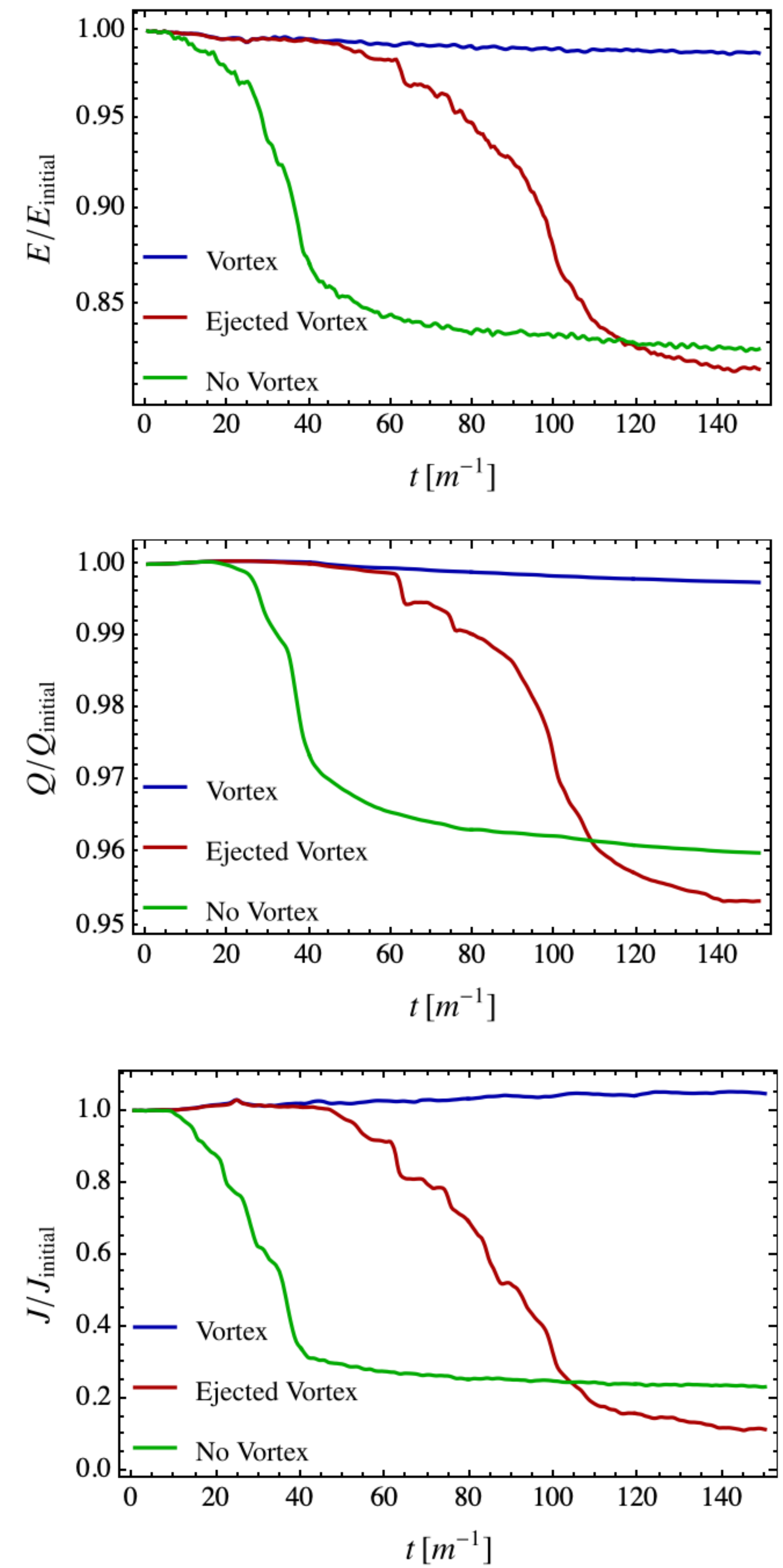
★ Radiation signatures potentially observable in black hole mergers!

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

[Dvali, FK, Zantedeschi 2021]

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

★ If these PBHs provide the dark matter: Could their vorticity might explain primordial magnetic fields?

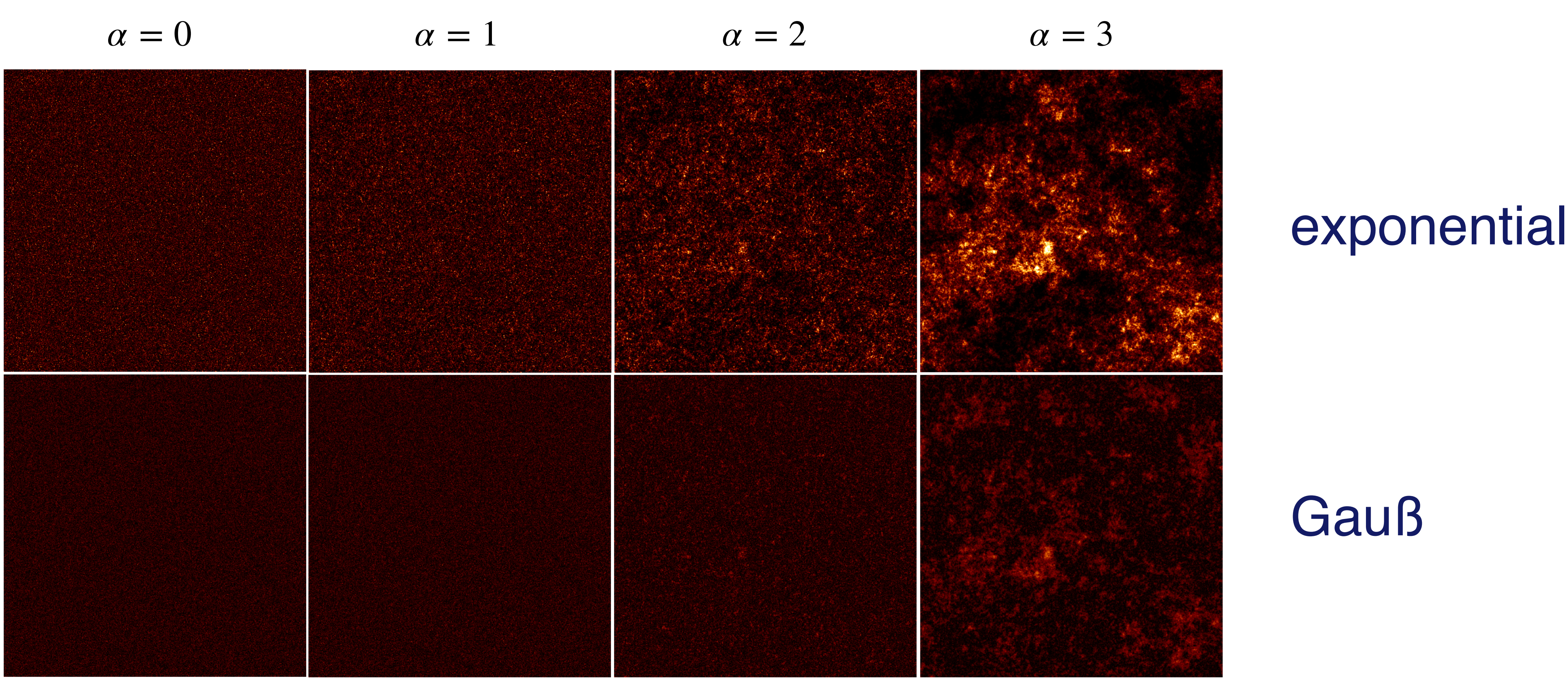


[Dvali, Kaikov, FK, Valbuena-Bermúdez, Zantedeschi 2024]

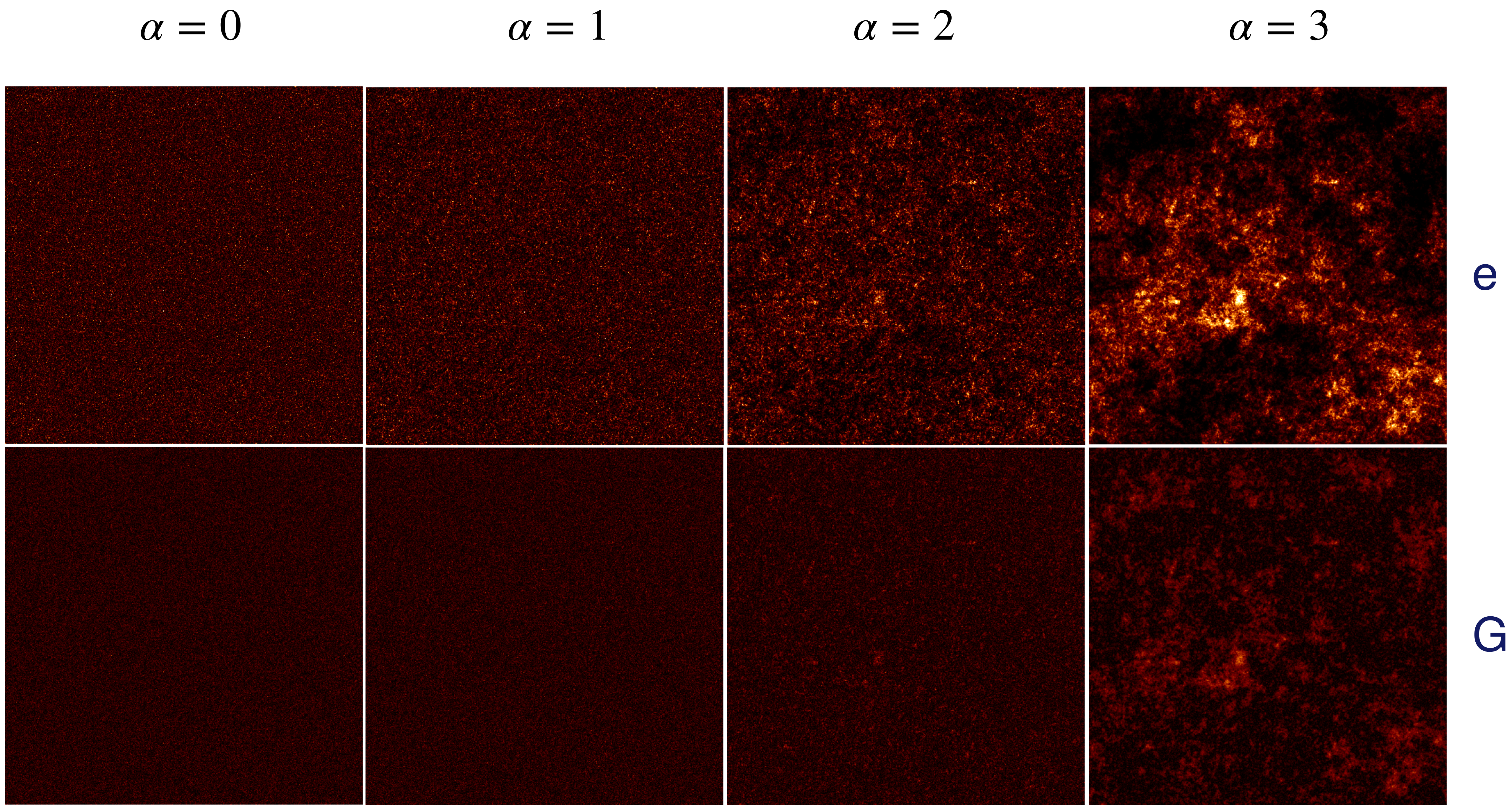
Correlated Random Fields

Correlated Random Fields

- Power spectra at PBH scales essentially unknown.
- Quantum diffusion seems to lead to exponential tails
- Performed large(st) (one in 10^{13}) simulation of spatially-correlated exponential random fields with power spectra of the form $P(k) \sim k^{\alpha}$



Correlated Random Fields



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]

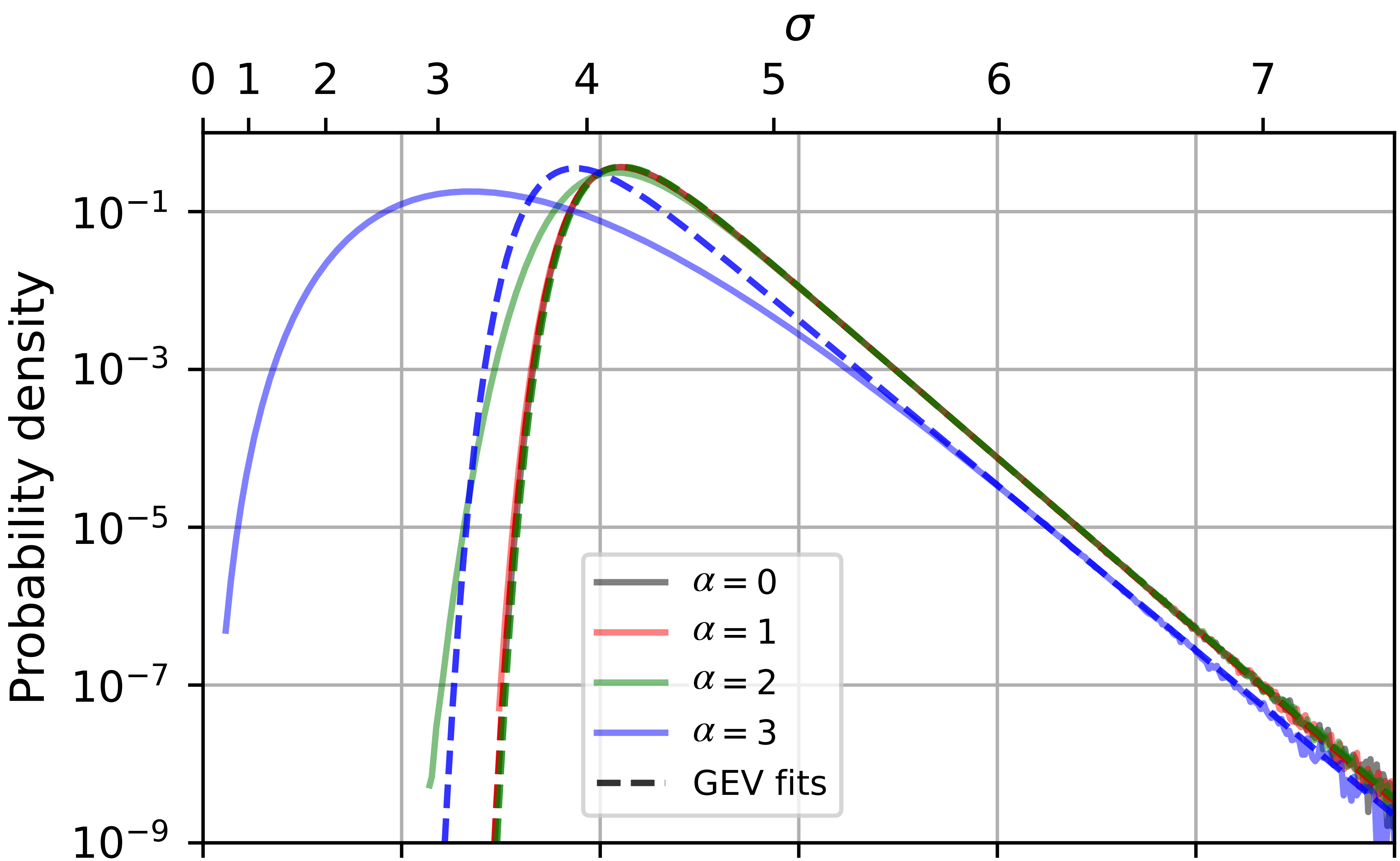
$$H^s_{\alpha,\gamma}(\delta) = \exp\begin{cases} -\left[1 + s\left(\frac{\delta-\alpha}{\gamma}\right)\right]^{-1/s} & (s \neq 0) \\ -\exp\left[-\left(\frac{\delta-\alpha}{\gamma}\right)\right] & (s = 0) \end{cases}$$

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.

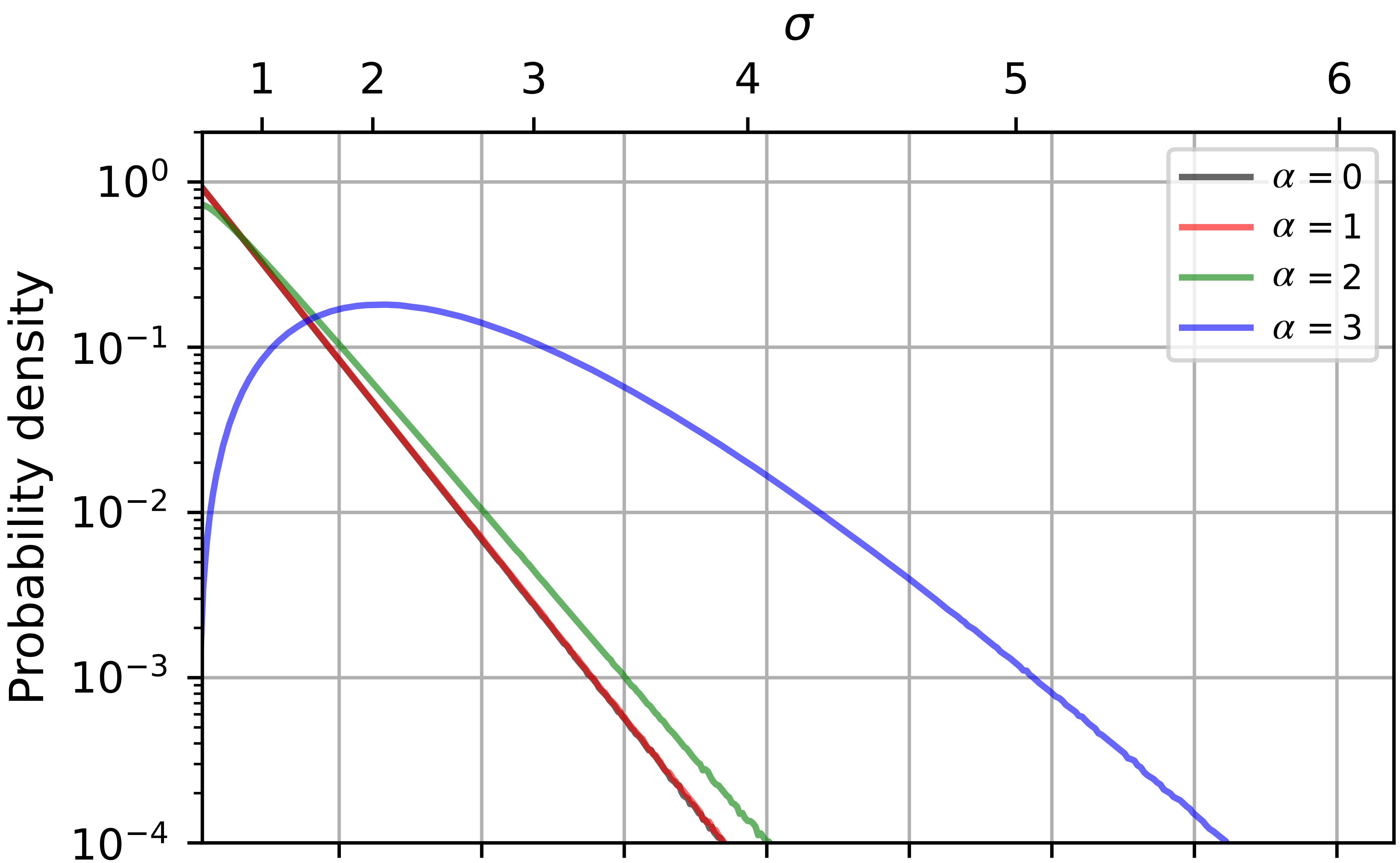
Correlated Random Fields

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

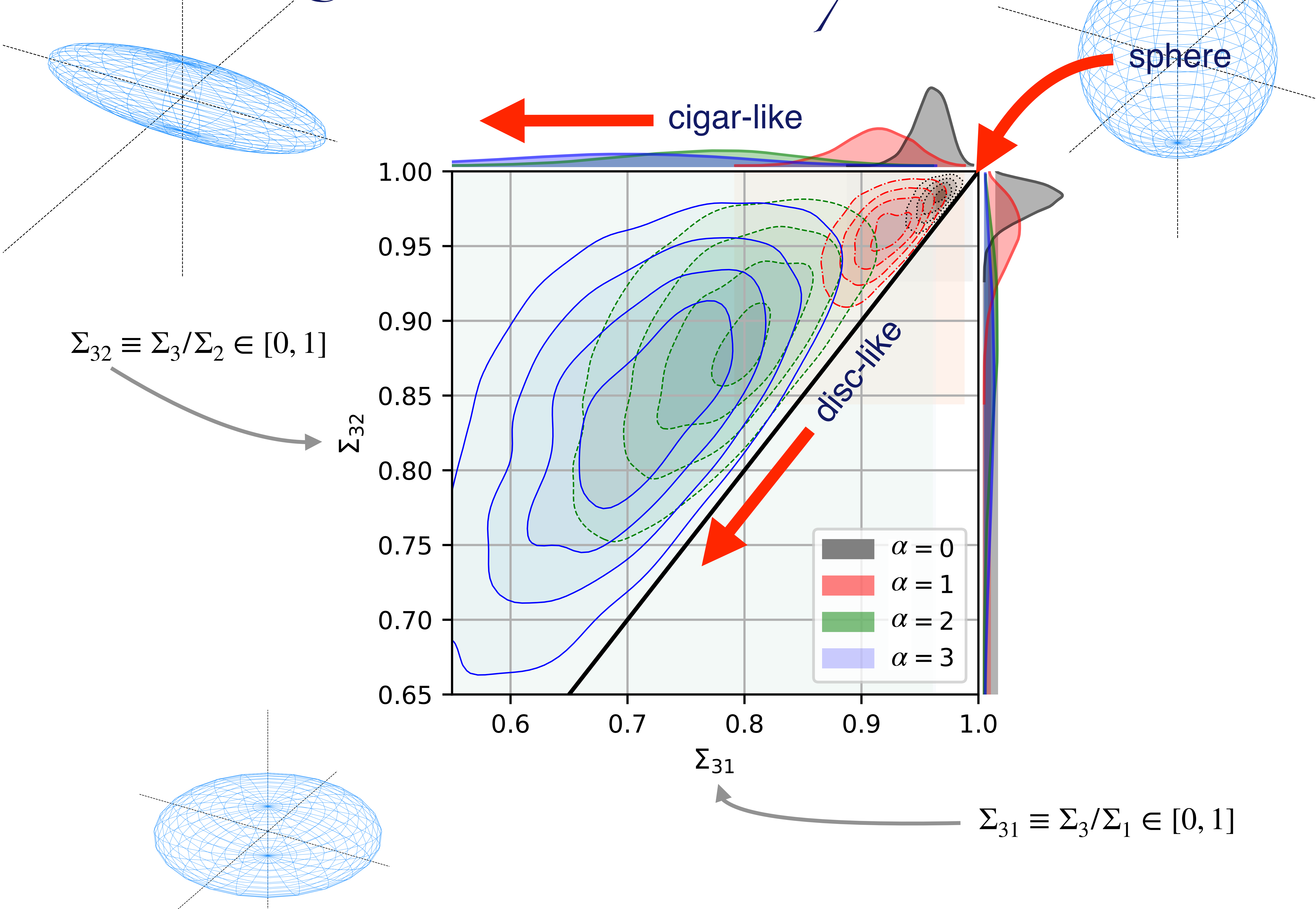


Correlated Random Fields

★ PDF *within* each block

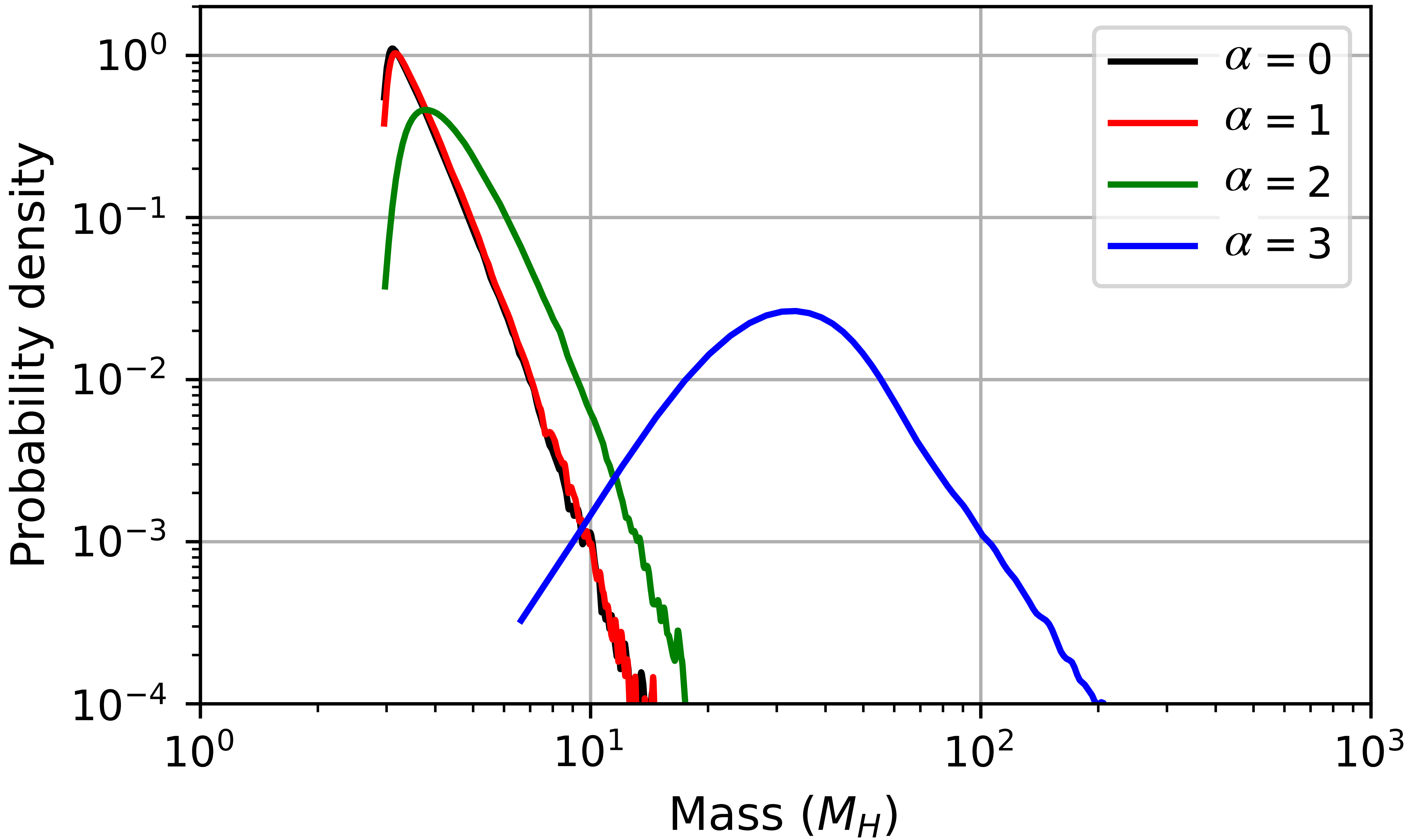


Correlated Random Fields — Non-Sphericities

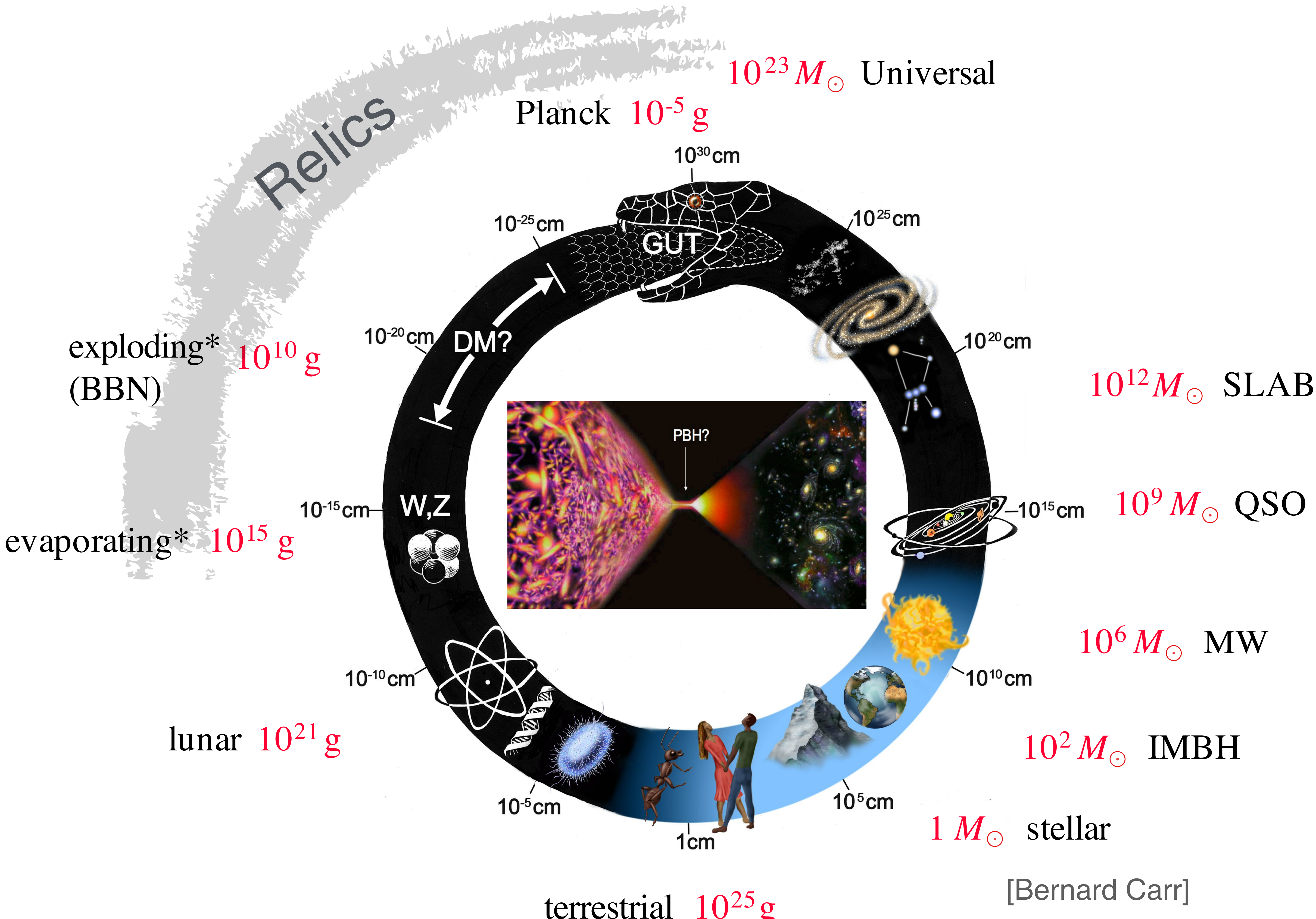


Correlated Random Fields

★ PBH mass distribution (*preliminary*)



Black Holes as a Link between Micro and Macro Physics



[Bernard Carr]

*Image of snake from Abrams & Primack 2012