Axion minicluster streams in the Solar neighbourhood

O'Hare, GP & Redondo, PRL 133 (2024) 8, 081001 [arXiv:2311.17367 [hep-ph]]
Eggemeier, O'Hare, GP, Redondo & Wong, PRD 107 (2023) 8, 083510 [arXiv:2212.00560 [hep-ph]]

Giovanni Pierobon, UNSW Sydney

2nd General Meeting, Istanbul, September 3-6, 2024

Outline

- Why miniclusters, streams and minivoids are interesting for axion DM substructure WG2
- A first numerical study on the **stream density** in the Solar neighbourhood WG2
- Implications for *all* haloscopes WG4

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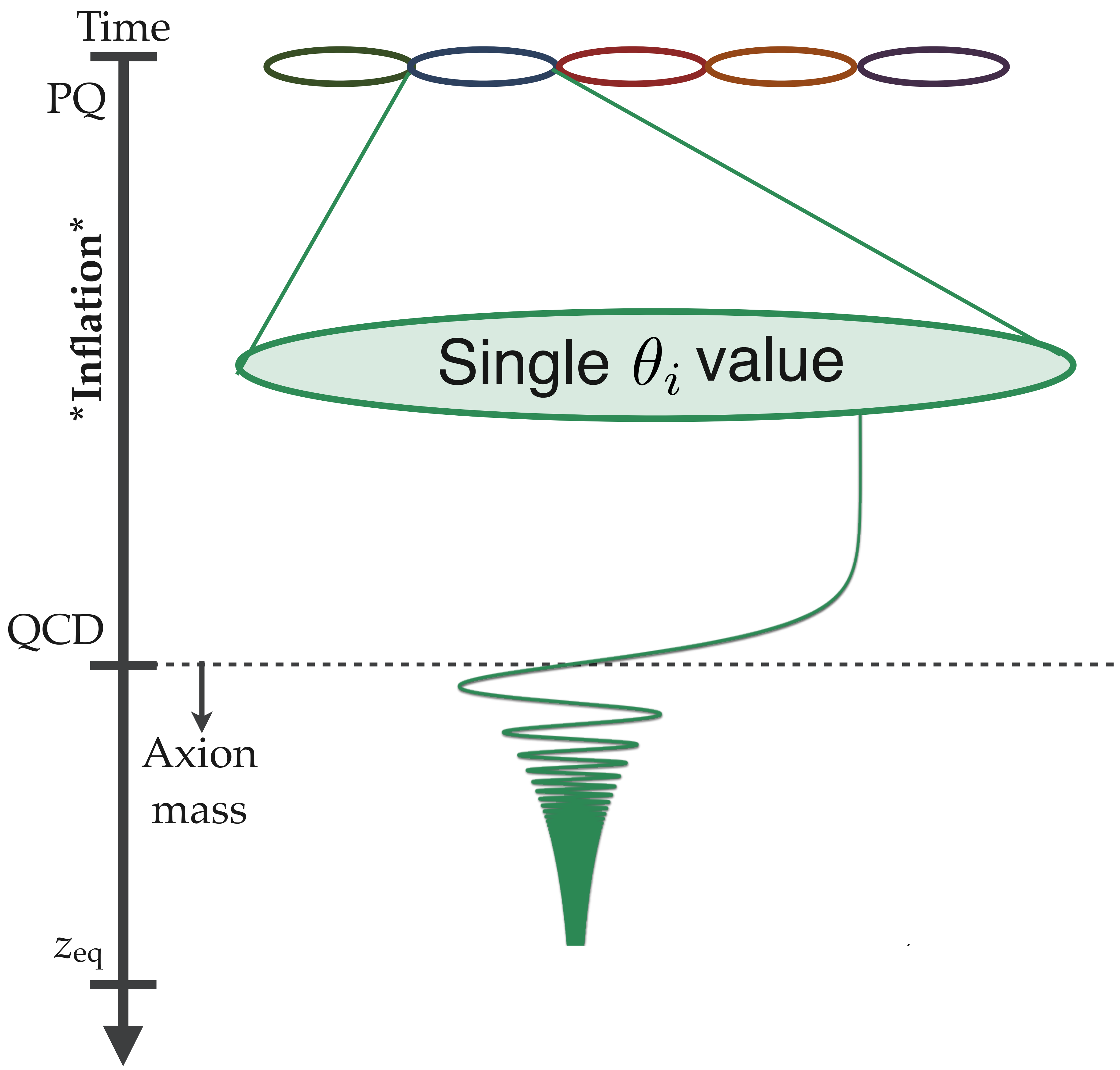
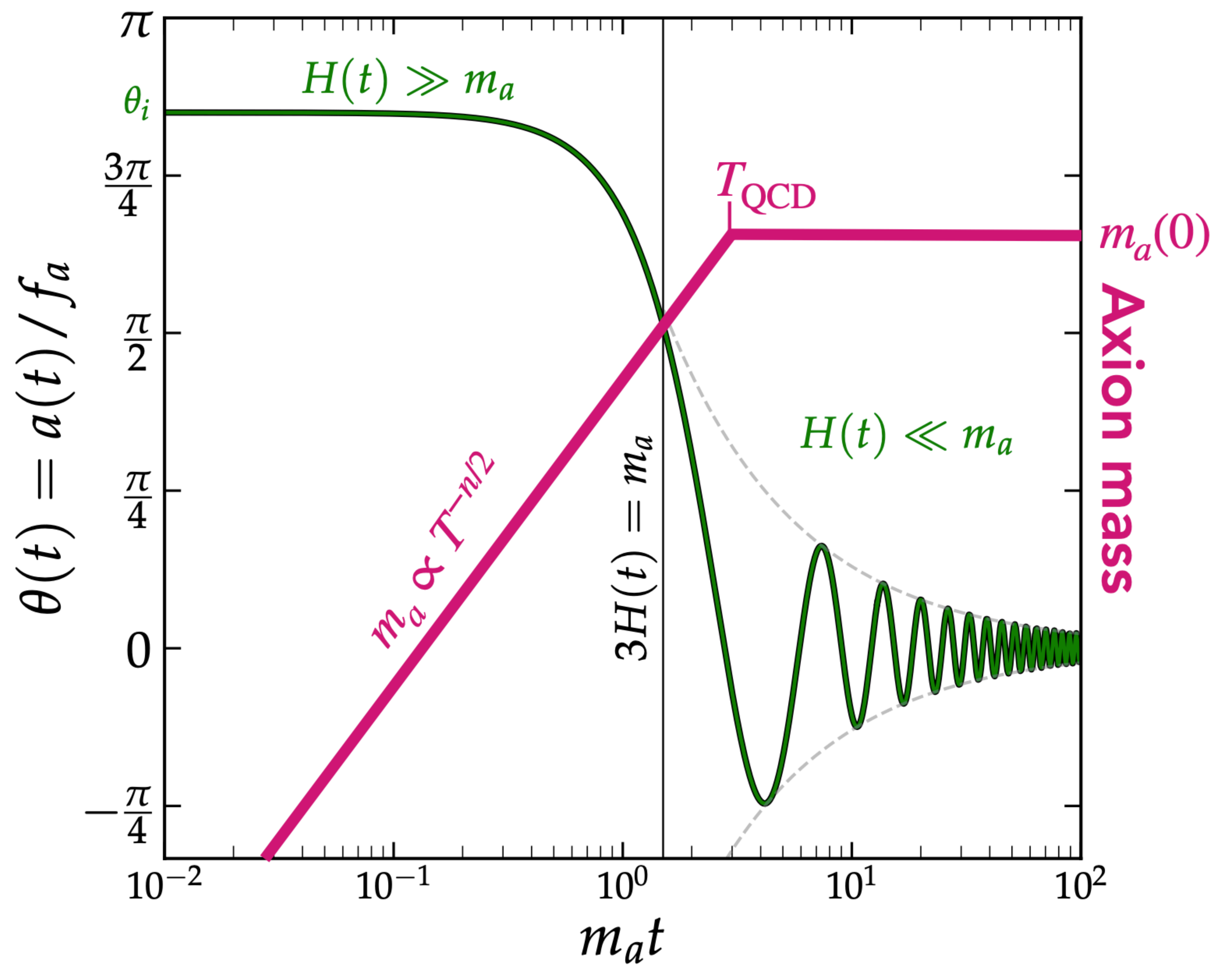
Assumptions

1. Peccei-Quinn model to solve the strong CP problem
2. PQ breaking happens after inflation
3. Axions act as the dark matter

Pre-inflationary scenario



Simple misalignment production

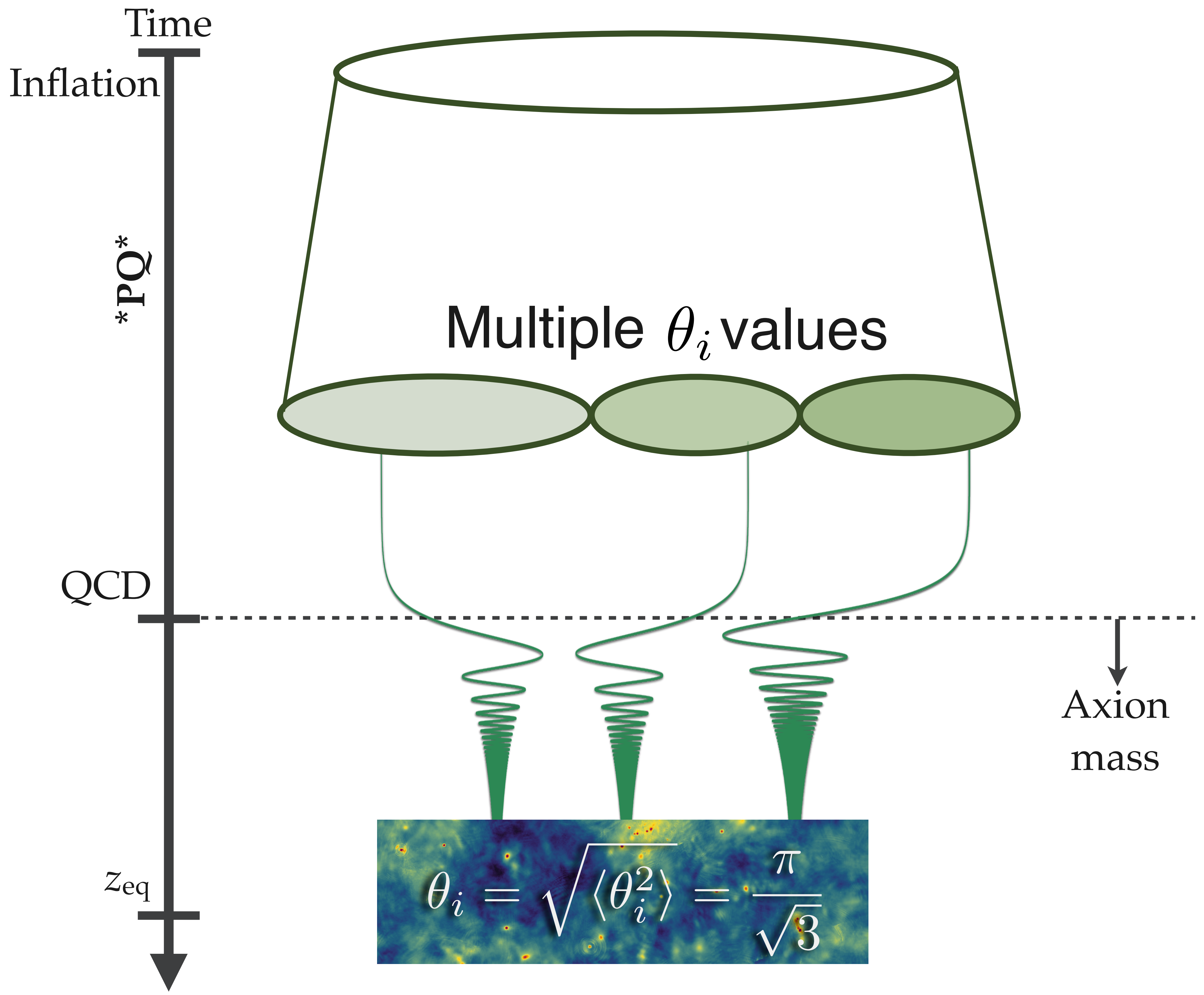


Post-inflationary scenario

Highly inhonomegenous Universe

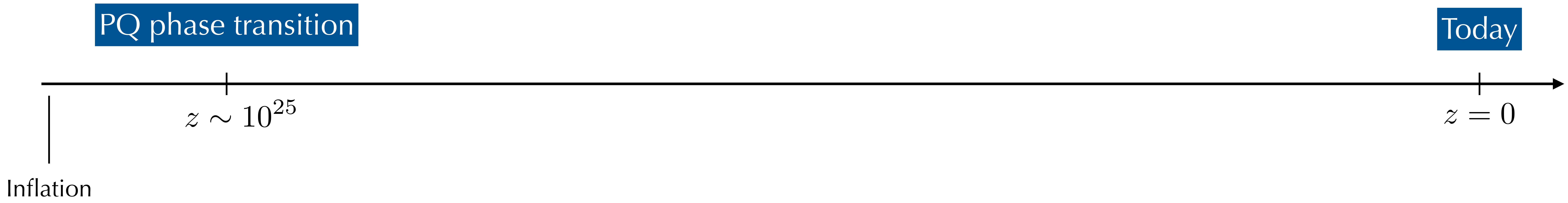
Necessitates numerical treatment

- Axion **strings** form with spontaneous breaking
- Domain **walls** form with explicit breaking
- **Miniclusters** form due $\mathcal{O}(1)$ fluctuations in energy



Distribution of initial misalignment angles
→ distribution highly inhomogeneous

Cosmological timeline



Cosmological timeline

PQ phase transition

Cold axion production

Number density conserved

Today

$z \sim 10^{25}$

$z \sim 10^{12}$

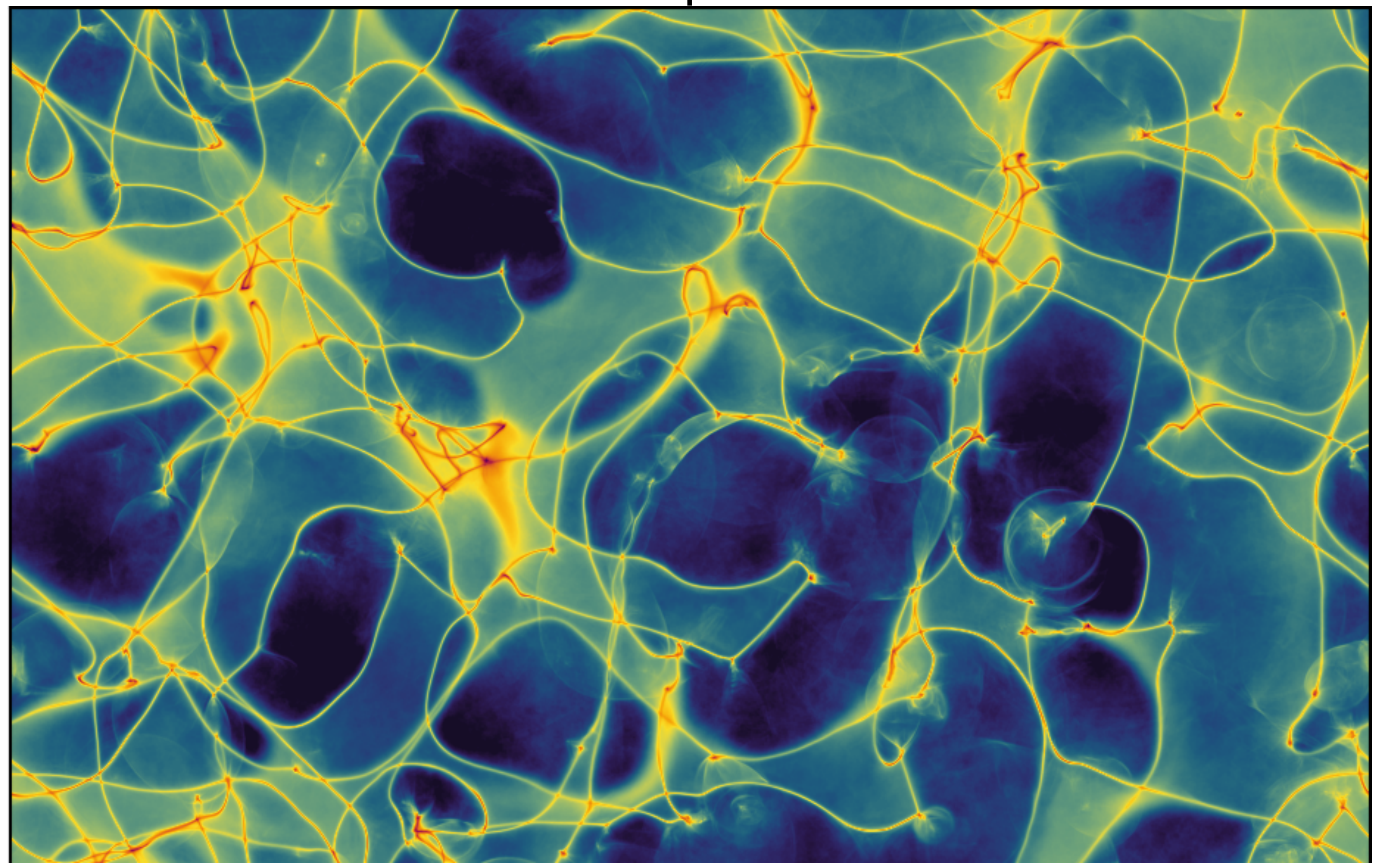
$z = 0$

Inflation

$z \sim 10^{13}$

Energy projection of the axion field from **lattice simulations**

Domain walls and strings



$$m_a = \frac{\rho_{\rm DM}}{n_a} \longrightarrow$$

Goal: find axion number density
axion dark matter mass

Cosmological timeline

PQ phase transition — Cold axion production — Number density conserved — Gravitational collapse — Today

Inflation

$z \sim 10^{25}$ — $z \sim 10^{13}$ — $z \sim 10^{12}$ — $z \sim 10^{2}$ — $z = 0$

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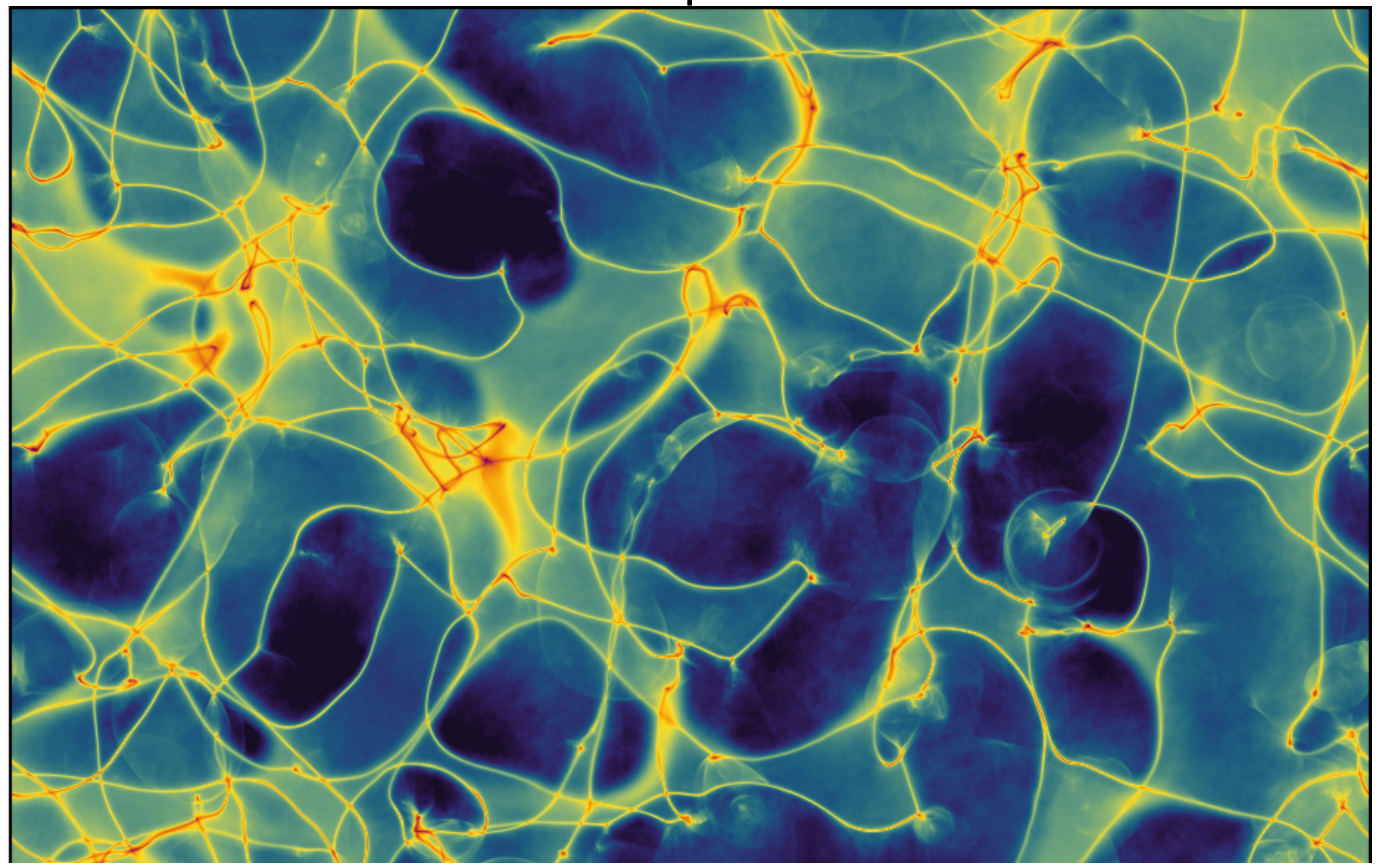
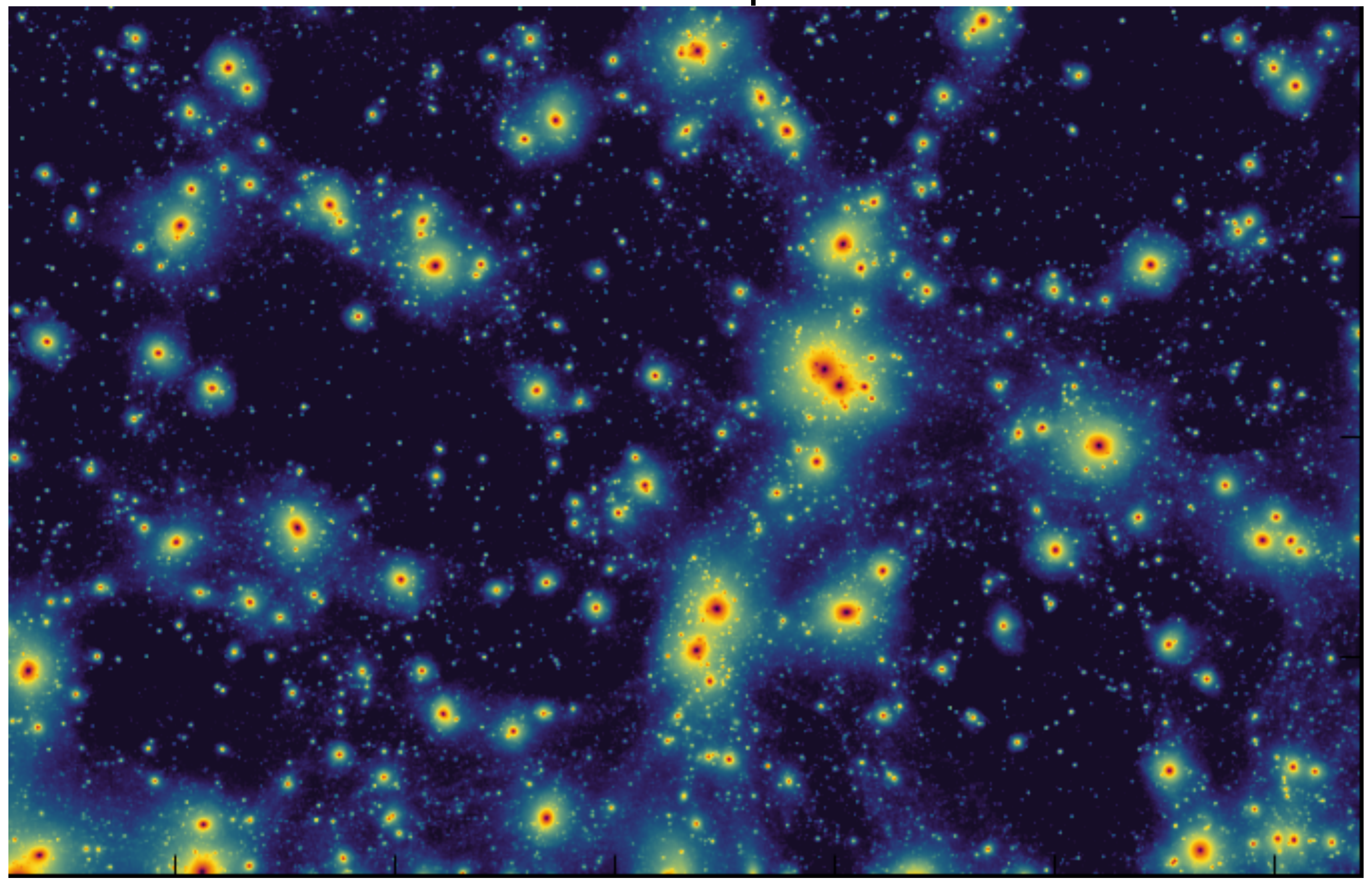




Energy projection of the axion field from **N-body simulations**

Miniclusters and their halos

$$m_a = \frac{\rho_{\rm DM}}{n_a} \longrightarrow$$ **Goal**: find axion number density axion dark matter mass

Goal: find axion field distribution

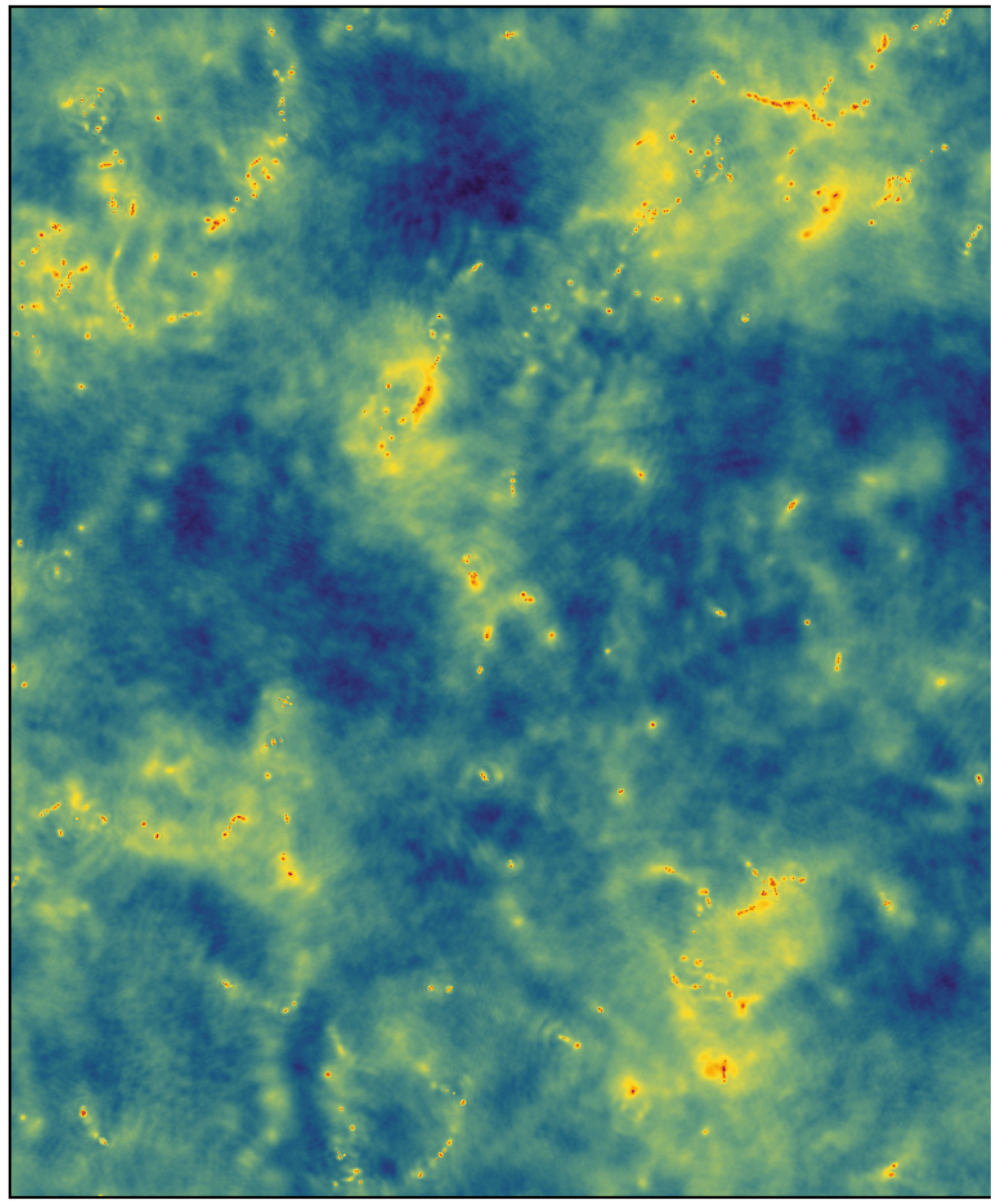
Axion miniclusters

Hogan, Rees (1988)
Kolb, Tkachev (1993)

Smoking gun of post-inflationary scenario on ~pc scales

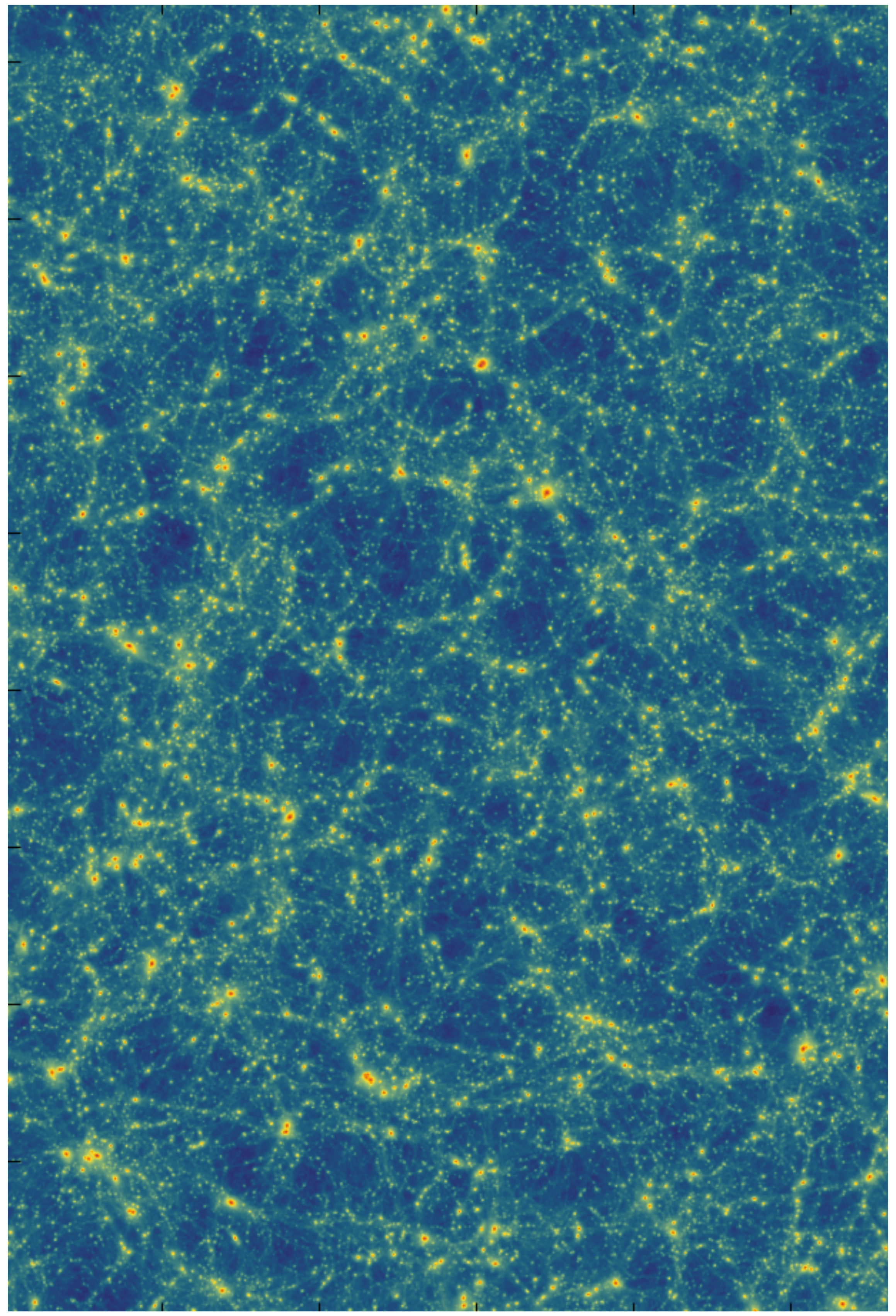
After decay of topological defects there are large small-scale perturbations

$z = 10^6$



Seeding AU-mpc size clumps forming at equality

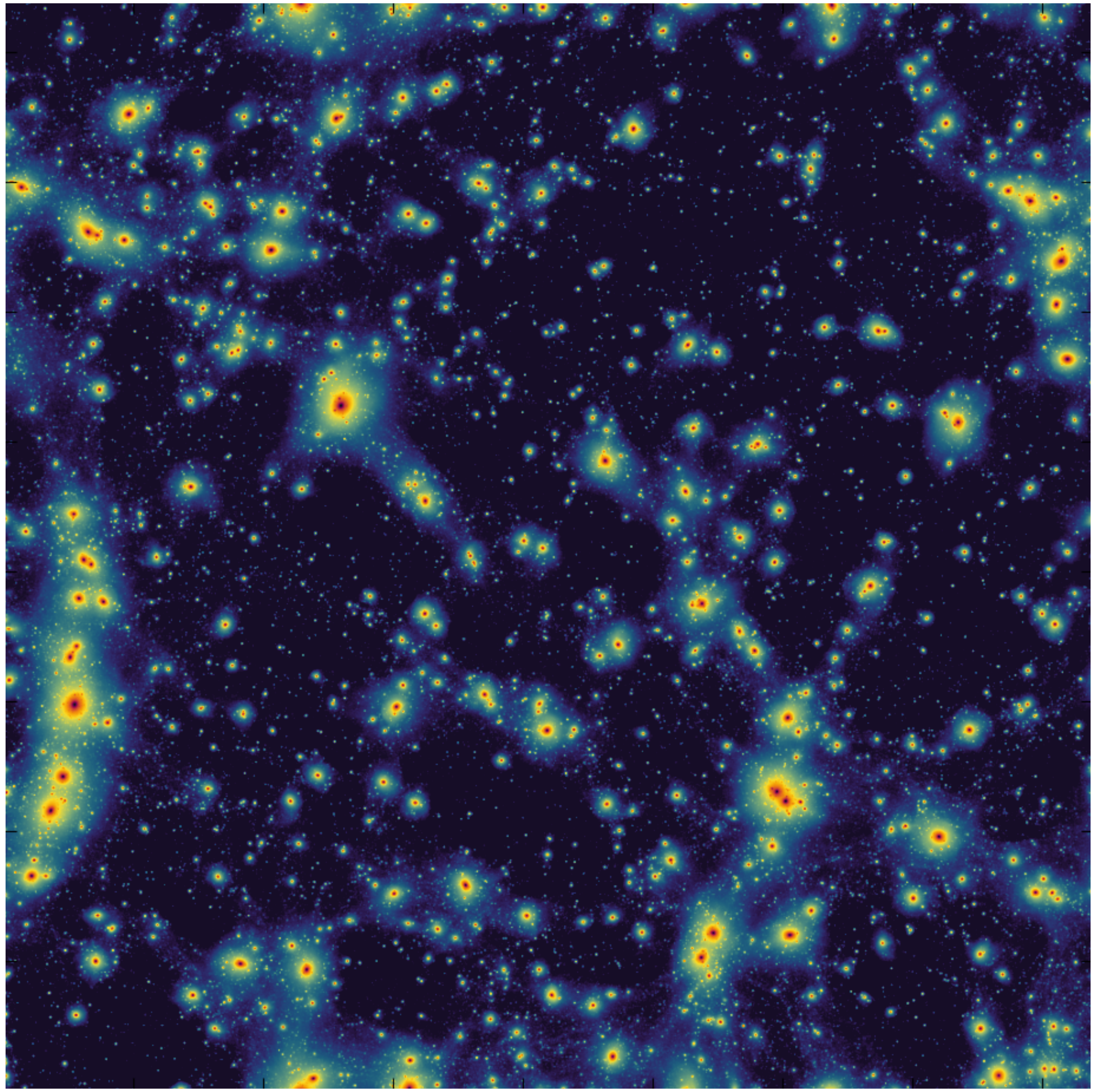
$z = z_{\rm eq} \sim 3.4 \times 10^3$



Box size ~0.5 pc

Gravitational clustering leads to MC halos

$z = 10^2$

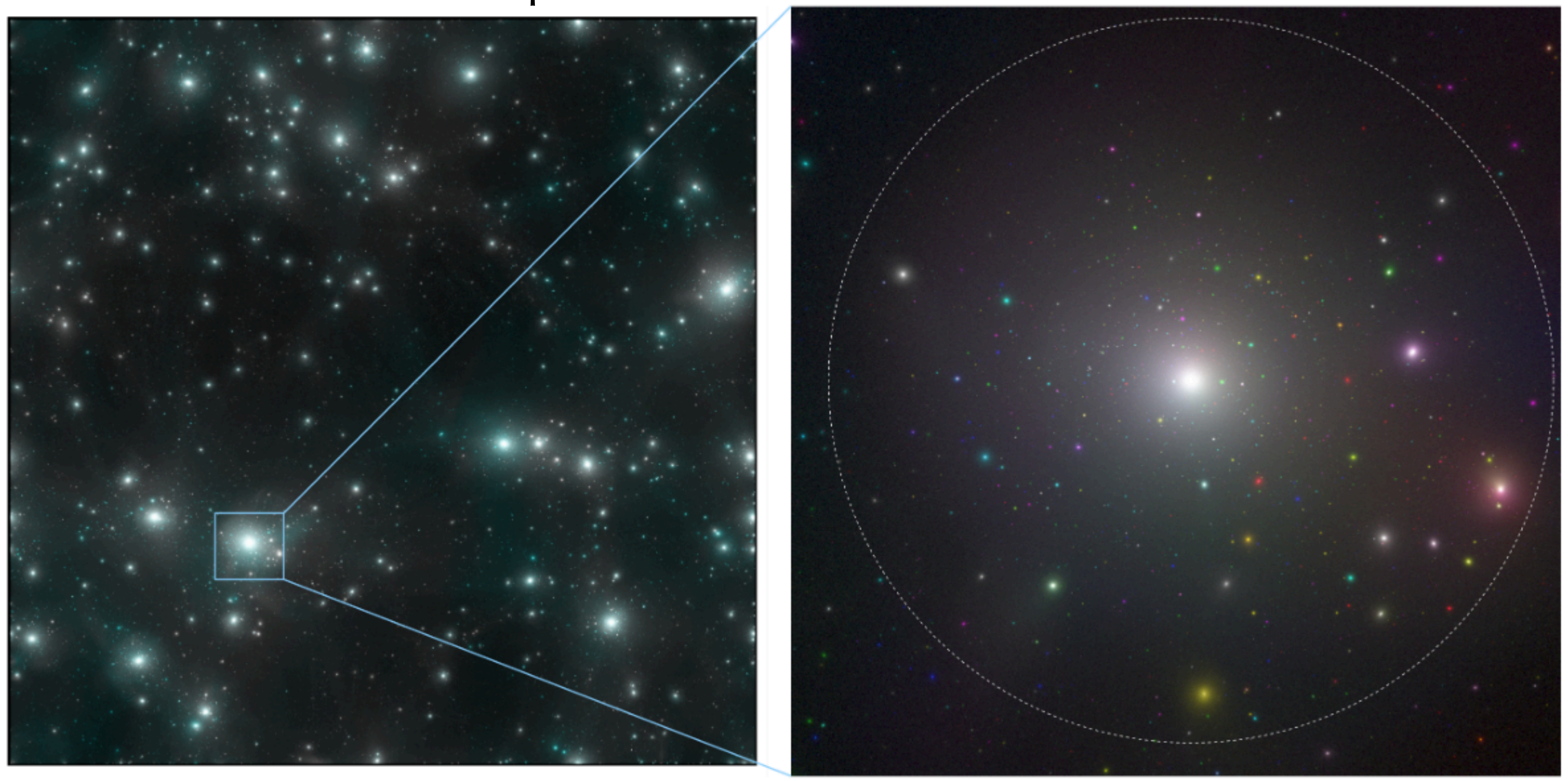


Axion miniclusters

- Can be modelled with N-body simulations (grid to particle conversion)
- Most of DM axions (~**80%**) are **bound** in MC at the end of the simulation

Box size ~0.8 pc

Eggemeier+ [1911.09417]



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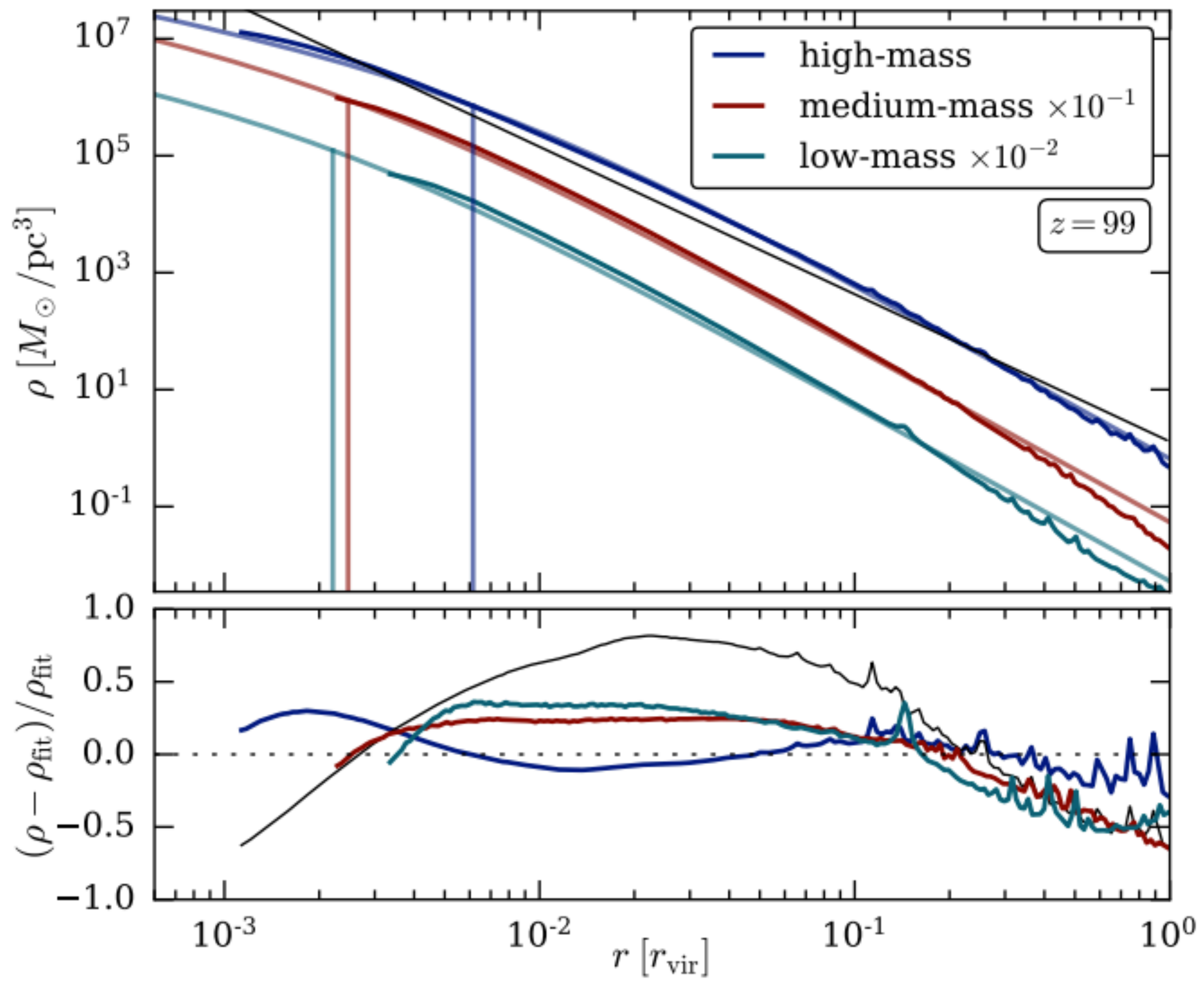

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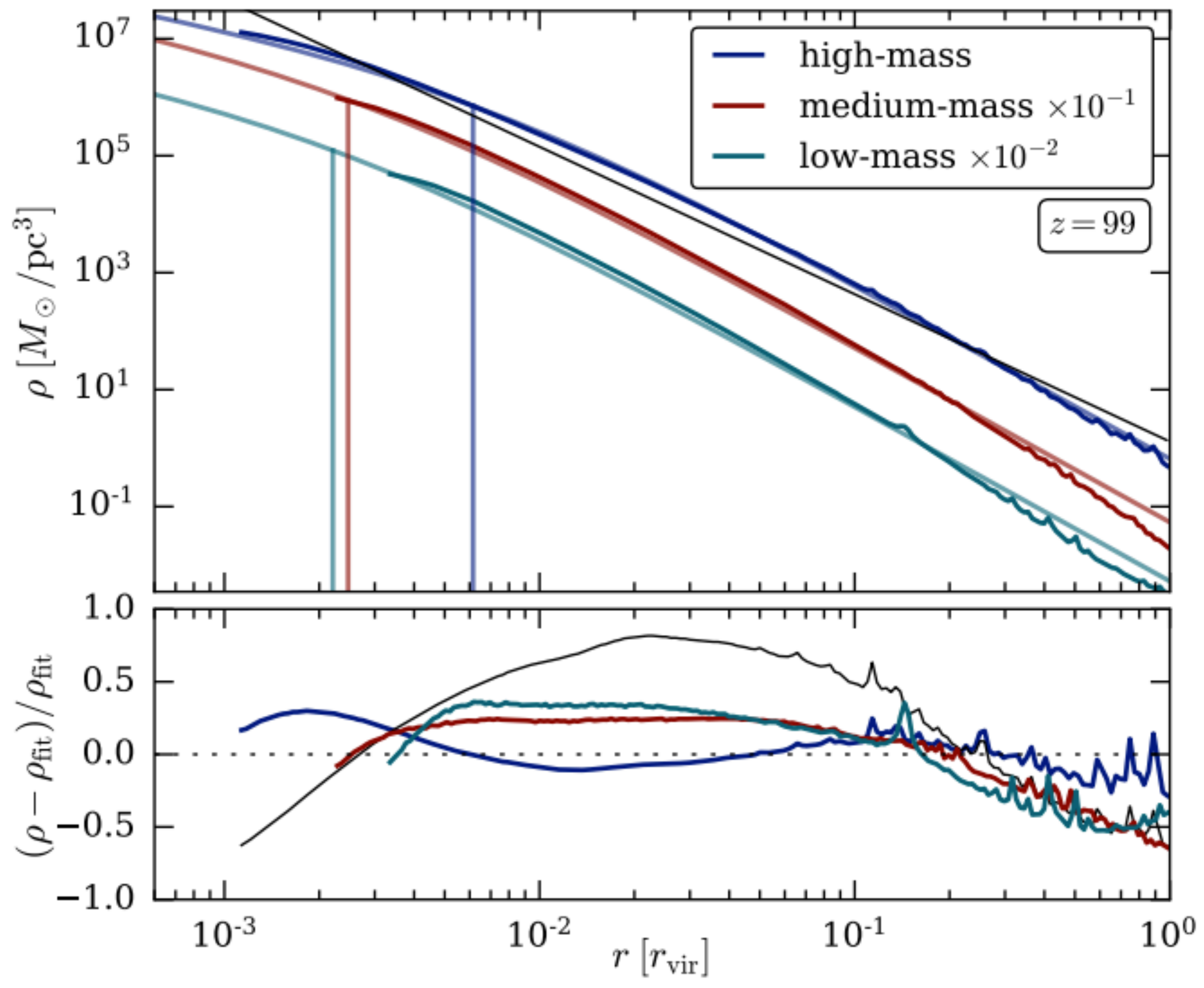

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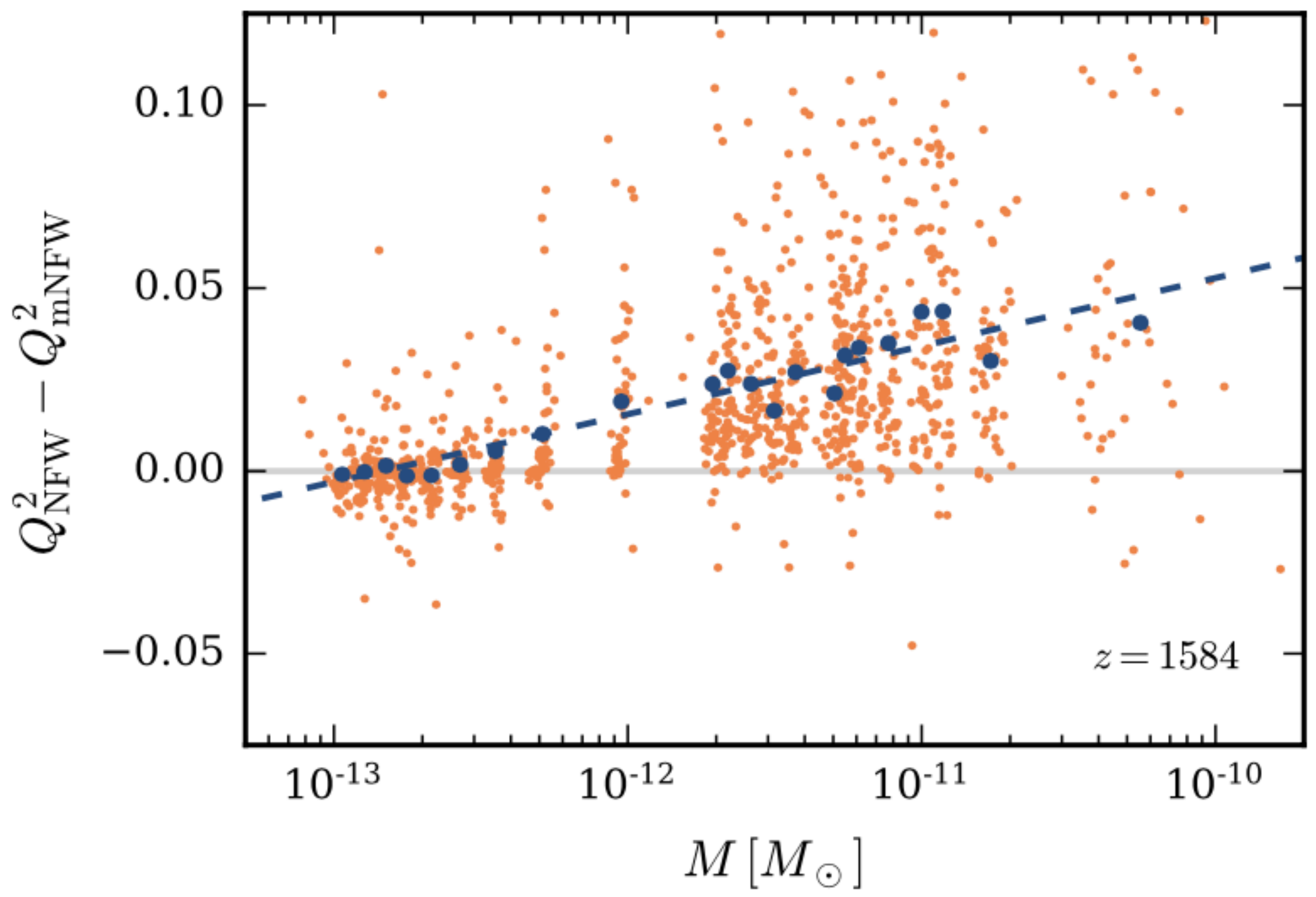
Evidence of a modified profile	$\rho(r) = \frac{\rho_s}{(r/r_s)^2(1+r/r_s)}$

Phenomenological consequences from a steeper profile:

Improves *indirect* detection
Challenges *direct* detection



New 2048^3
N-body run
Eggemeier+ [2402.18221]

Axion miniclusters

Distinction between merged and isolated miniclusters

Fairbairn+ [1707.03310]
Eggemeier+ [1911.09417]
Ellis+ [2204.13187

Isolated MCs

Most abundant, but less massive

$$M \in [10^{-16}, 10^{-12}]\ M_{\odot}$$

Almost all of them **survive** tidal stripping

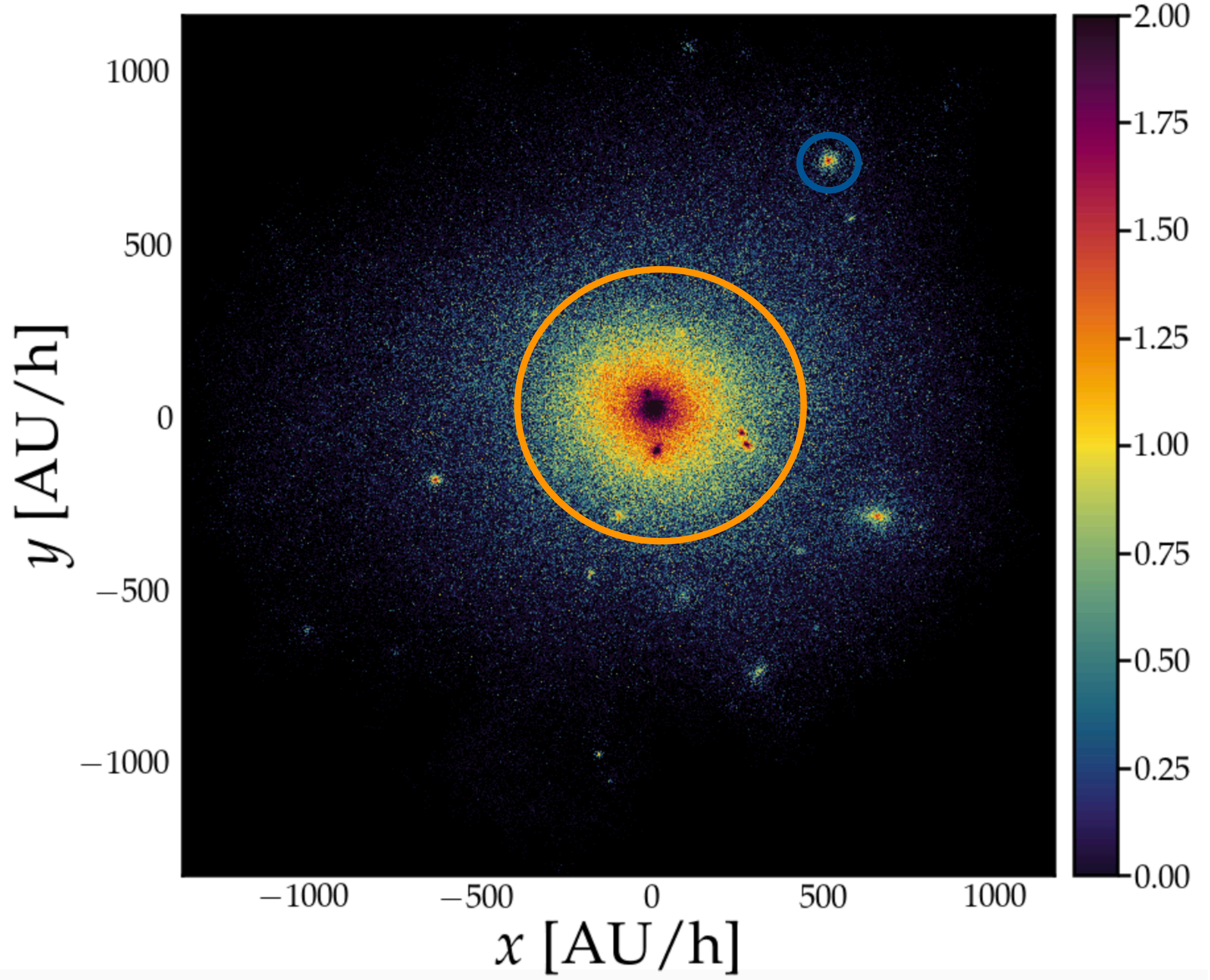
Merged MCs

30% in number, larger and more massive

$$M \in [10^{-12}, 10^{-7}]\ M_{\odot}$$

Modelled with NFW profile

Most are **disrupted** from tidal forces
with stellar encounters



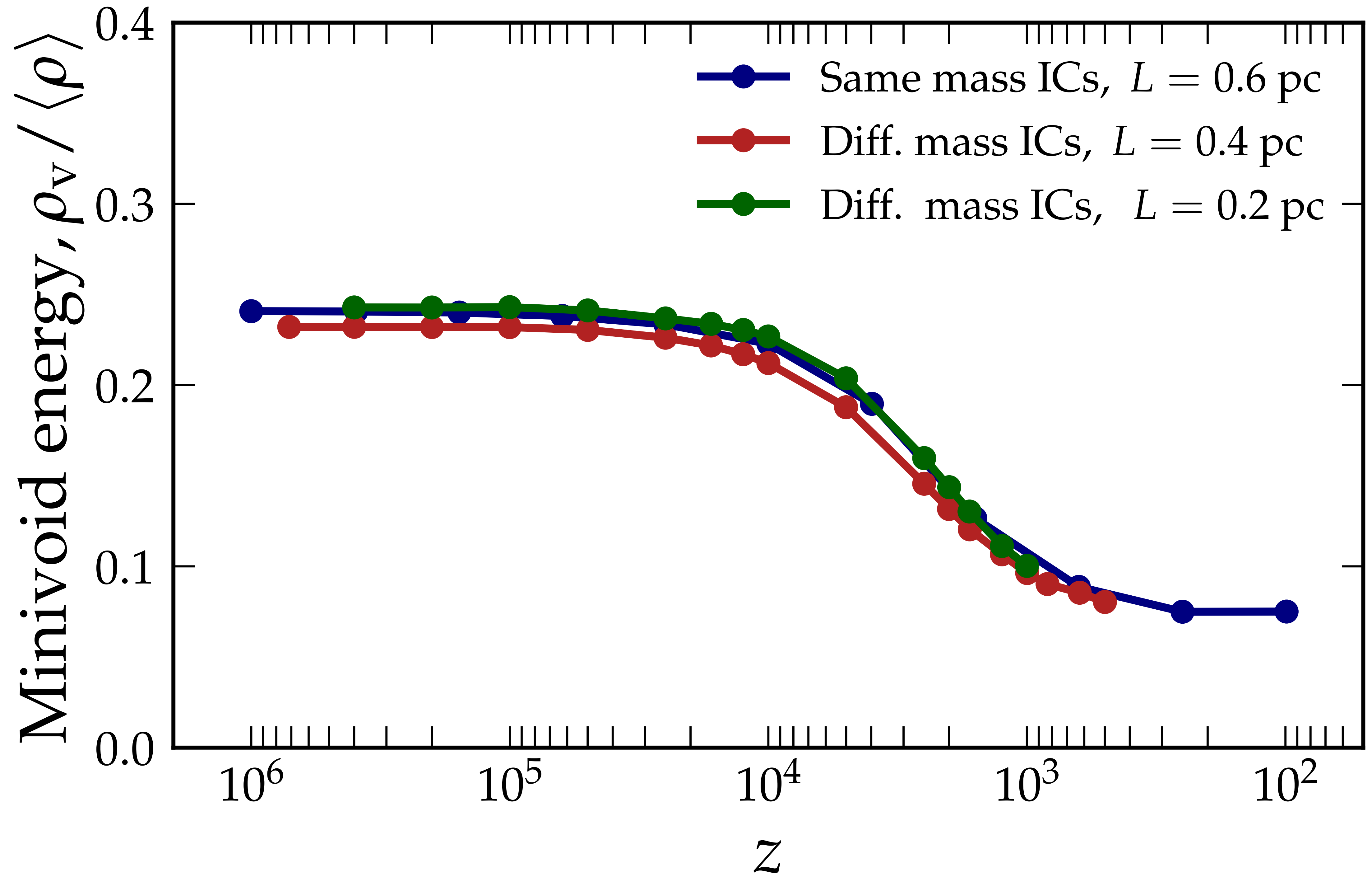
Axion minivoids

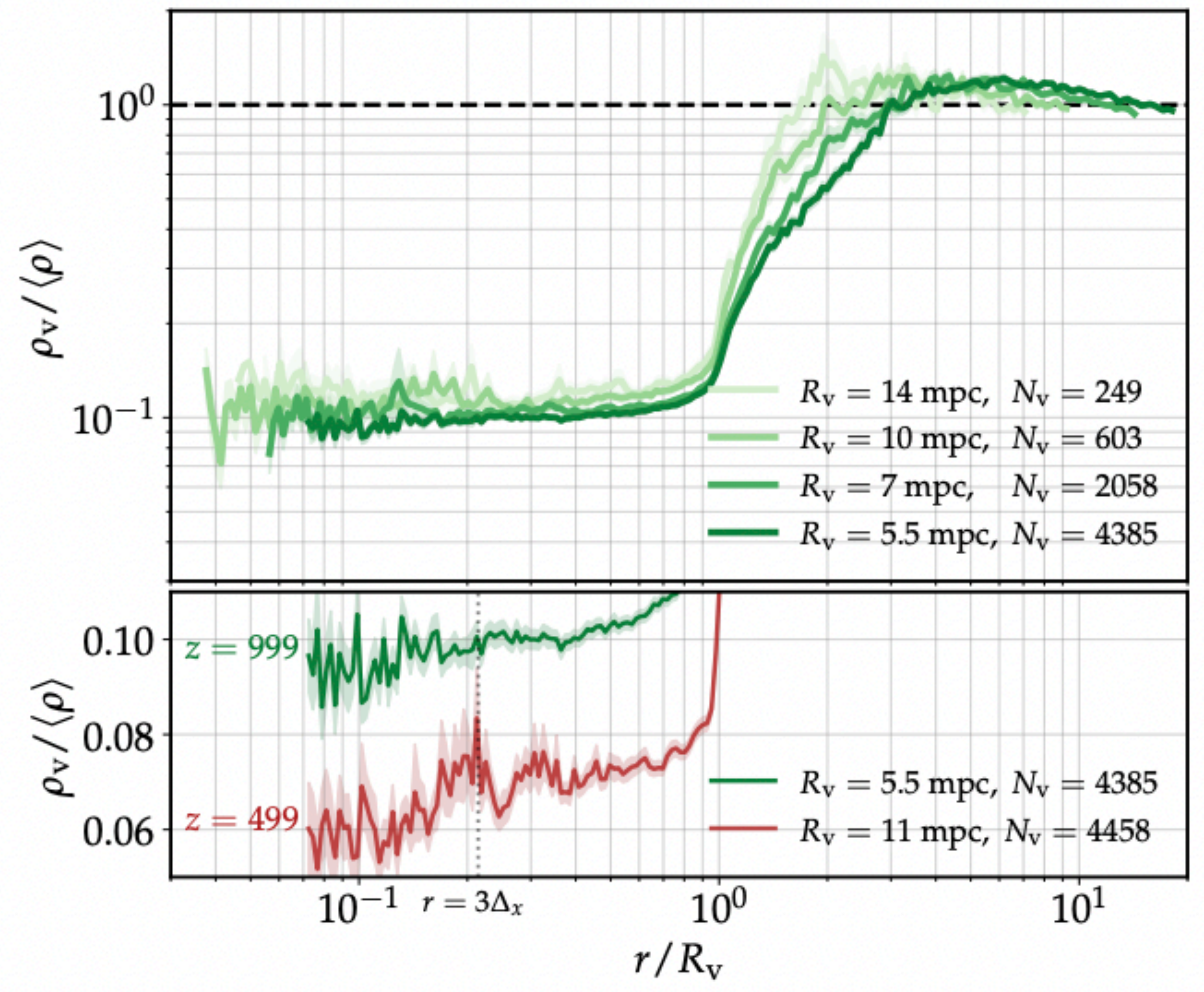
- Most of DM axions (~80%) are bound in MC at the end of the simulation, while occupying **1% of the volume**

Axion minivoids

- Most of DM axions (~80%) are bound in MC at the end of the simulation, while occupying **1% of the volume**
- Minivoids (~pc size) largely take the simulation volume, stable at $z \sim 10^2$
- Density in minivoids is ~10% of the large-scale average value
  worst case scenario

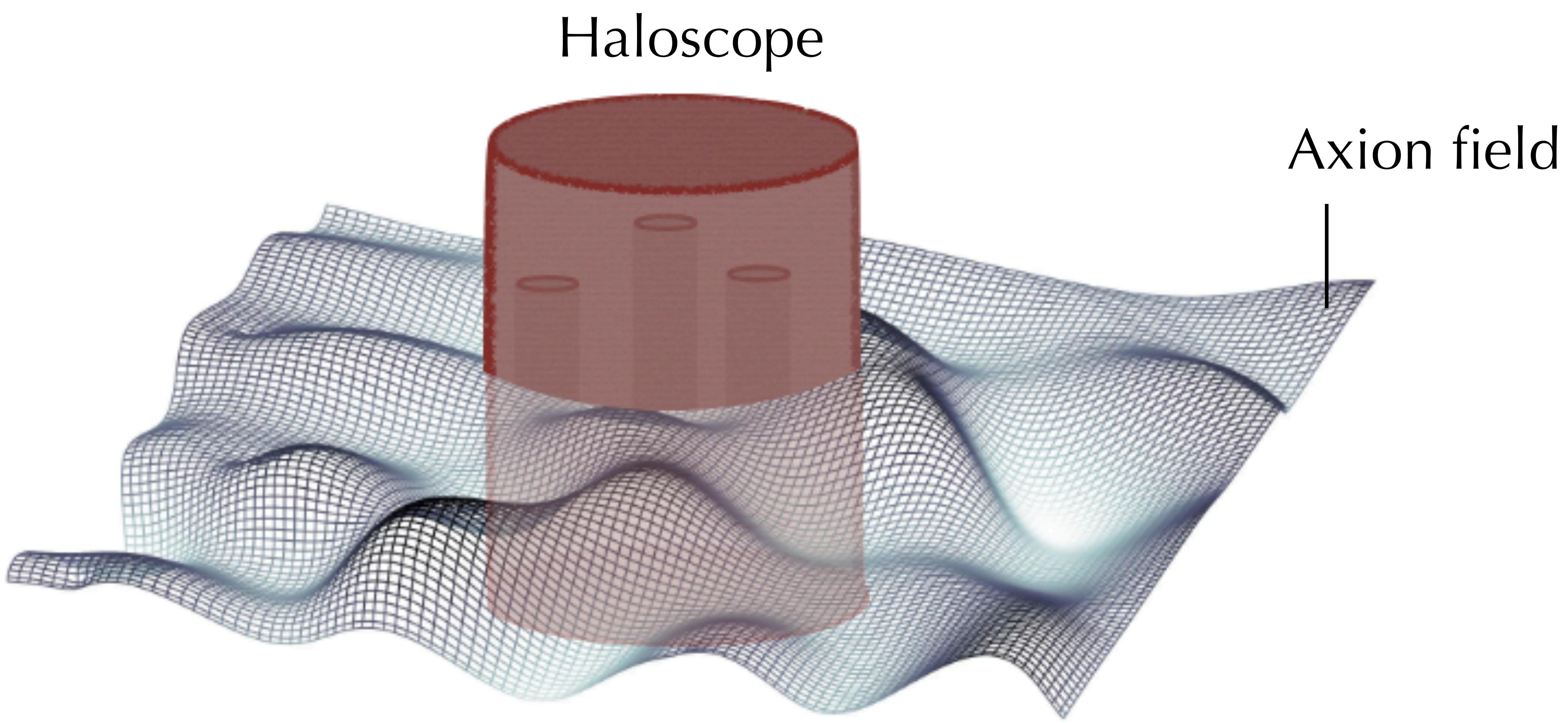
Eggemeier, O'Hare, GP, Redondo & Wong, [2212.00560]





Implications for haloscopes

$$a(x,t) \approx A(t)\cos(\omega_a t + \varphi)$$



Axion field frequency

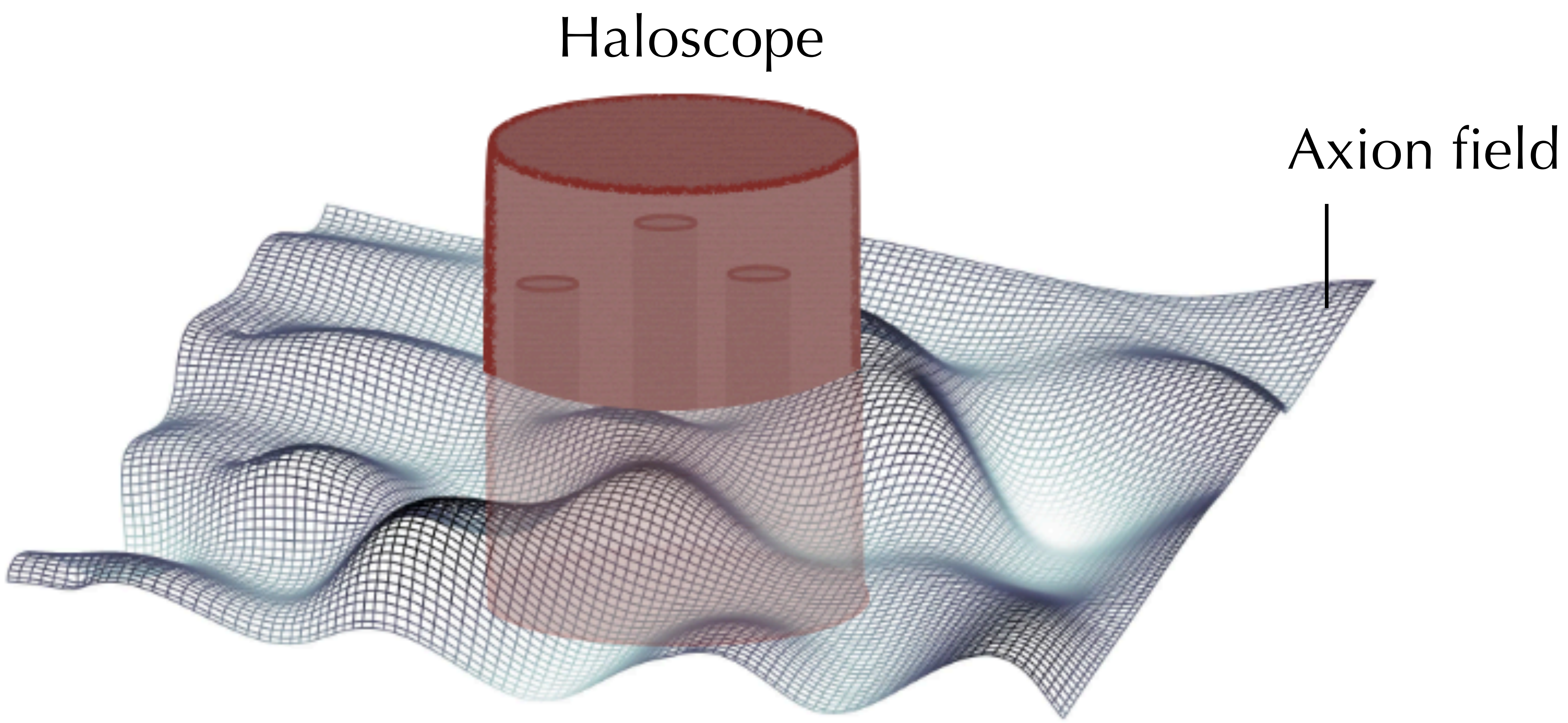
$$m_a = \frac{\rho_{\rm DM}}{n_a} \longrightarrow$$

Goal: find axion number density
axion dark matter mass

Axion field *local* amplitude

Goal: find axion field
distribution

Implications for haloscopes



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Experimental signal (e.g., power deposited by field in the cavity)

$$P(\omega) \propto g^2 \rho_a f(\omega)$$

$\rho_{\rm DM} \sim 0.4\ {\rm GeV/cm^3}$

All experiments types and couplings

AMDX, CAPP, QUAX, ORGAN, MADMAX, ALPHA, DALI, CADEx, BREAD, BRASS, …

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Goal: find axion field distribution

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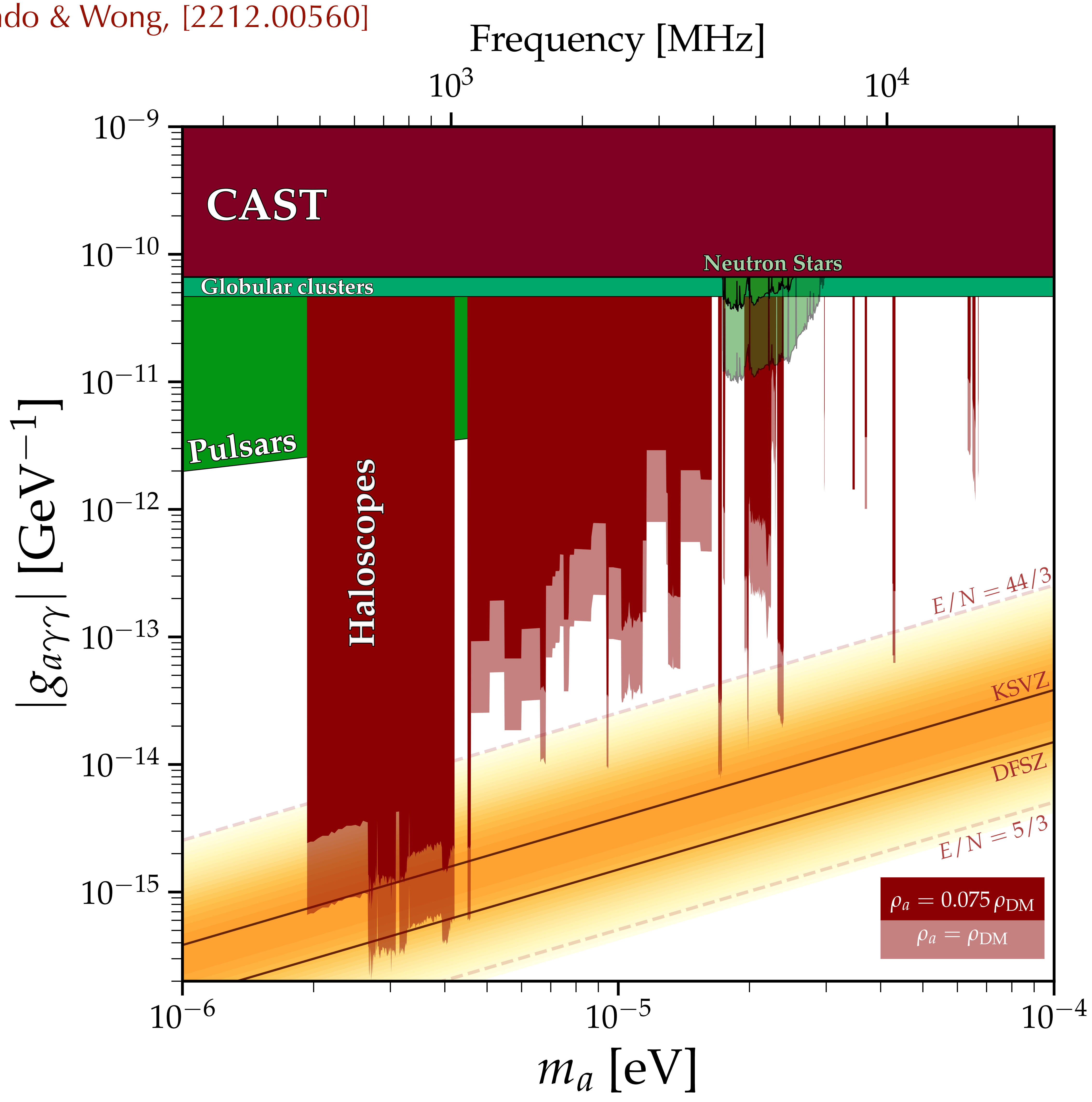


$$P(\omega) \propto g^2 \rho_a f(\omega)$$

Assume $\rho_a = \rho_{\rm DM}$

$$\sqrt{\rho_{\rm DM}}\; g_{a\gamma} \propto T_{\rm int}^{1/4}$$

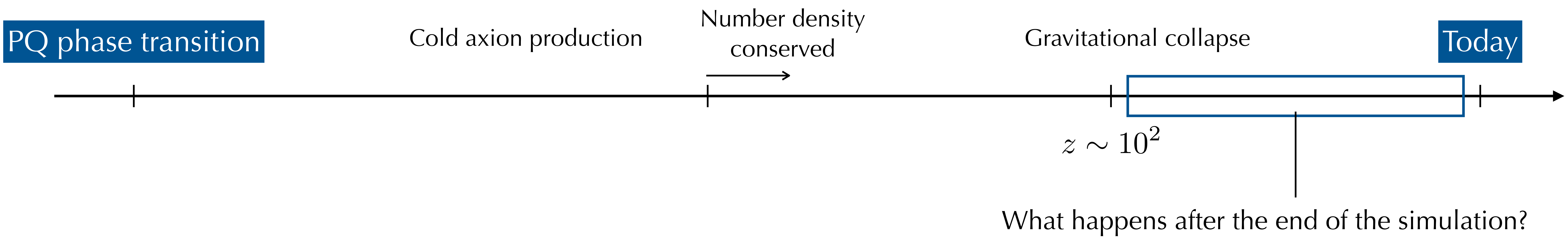
Excluding a certain coupling depends on the local energy density

In the worst case scenario exclusion plots are rescaled by a factor 3!

Axion field *local* amplitude

Goal: find axion field distribution

Cosmological timeline



Cosmological timeline

PQ phase transition

Cold axion production

Number density conserved

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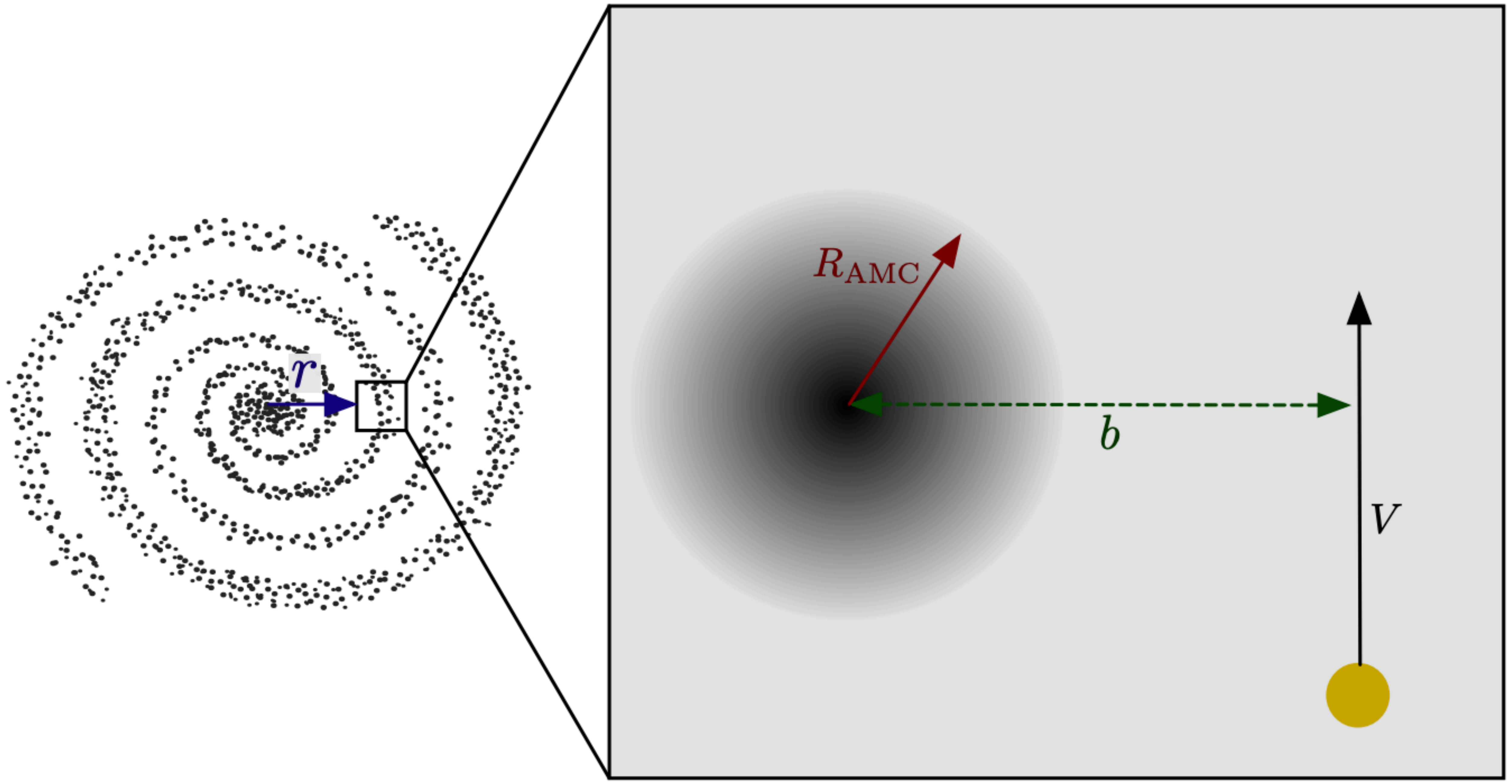
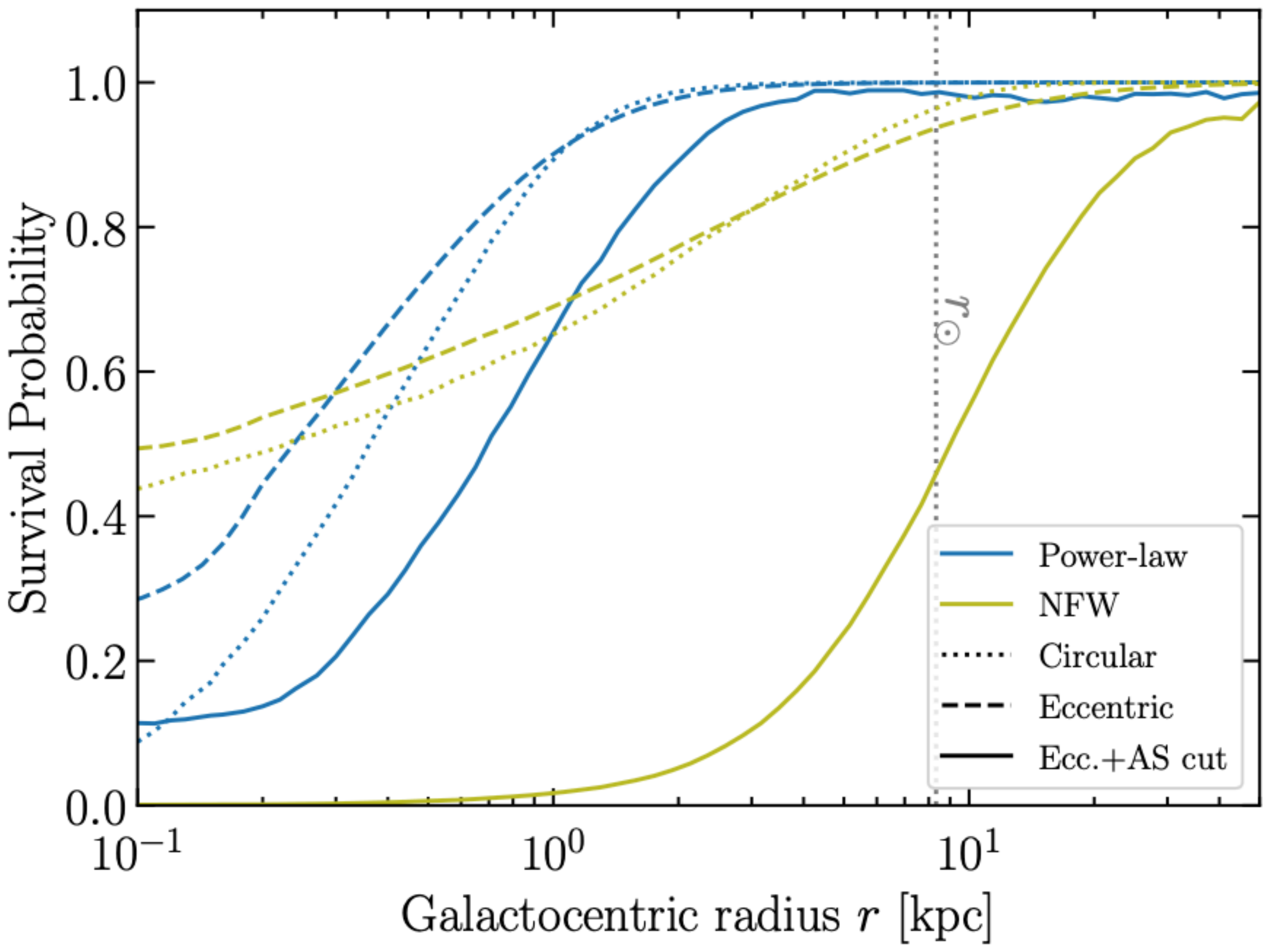
$z \sim 10^2$

Kavanagh+ [2011.05377]



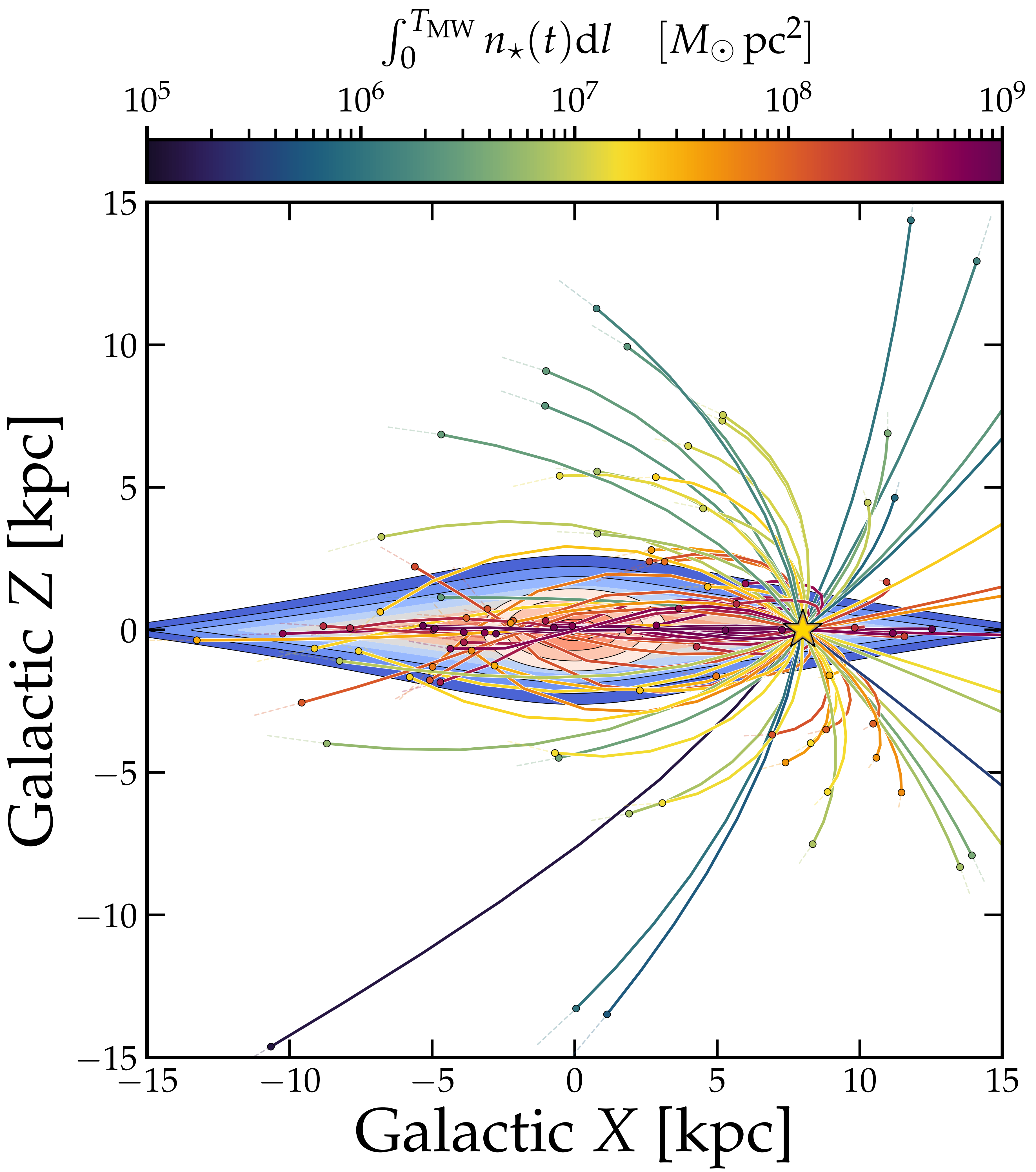
What happens after the end of the simulation?

Miniclusters can be disrupted by tidal forces!



Axion streams

Modelling of axion minicluster streams: Monte Carlo simulations



O'Hare, GP, Redondo [2311.17367]

Energy injected into minicluster at each encounter

$$\Delta E \simeq \left(\frac{2GM_*}{bv_{\rm rel}}\right)^2 \frac{M_{\rm mc}R_{\rm mc}^2}{3}$$

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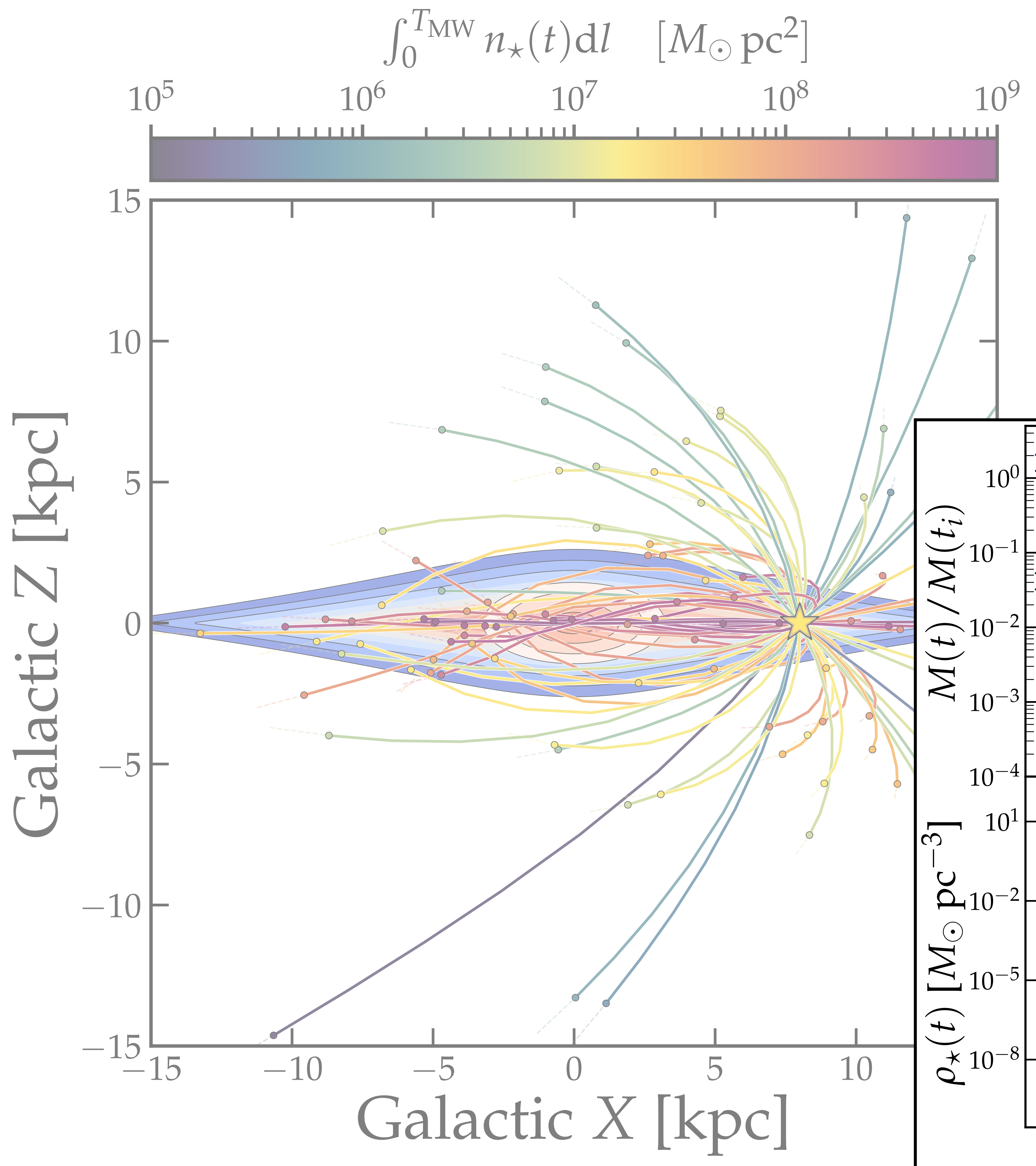

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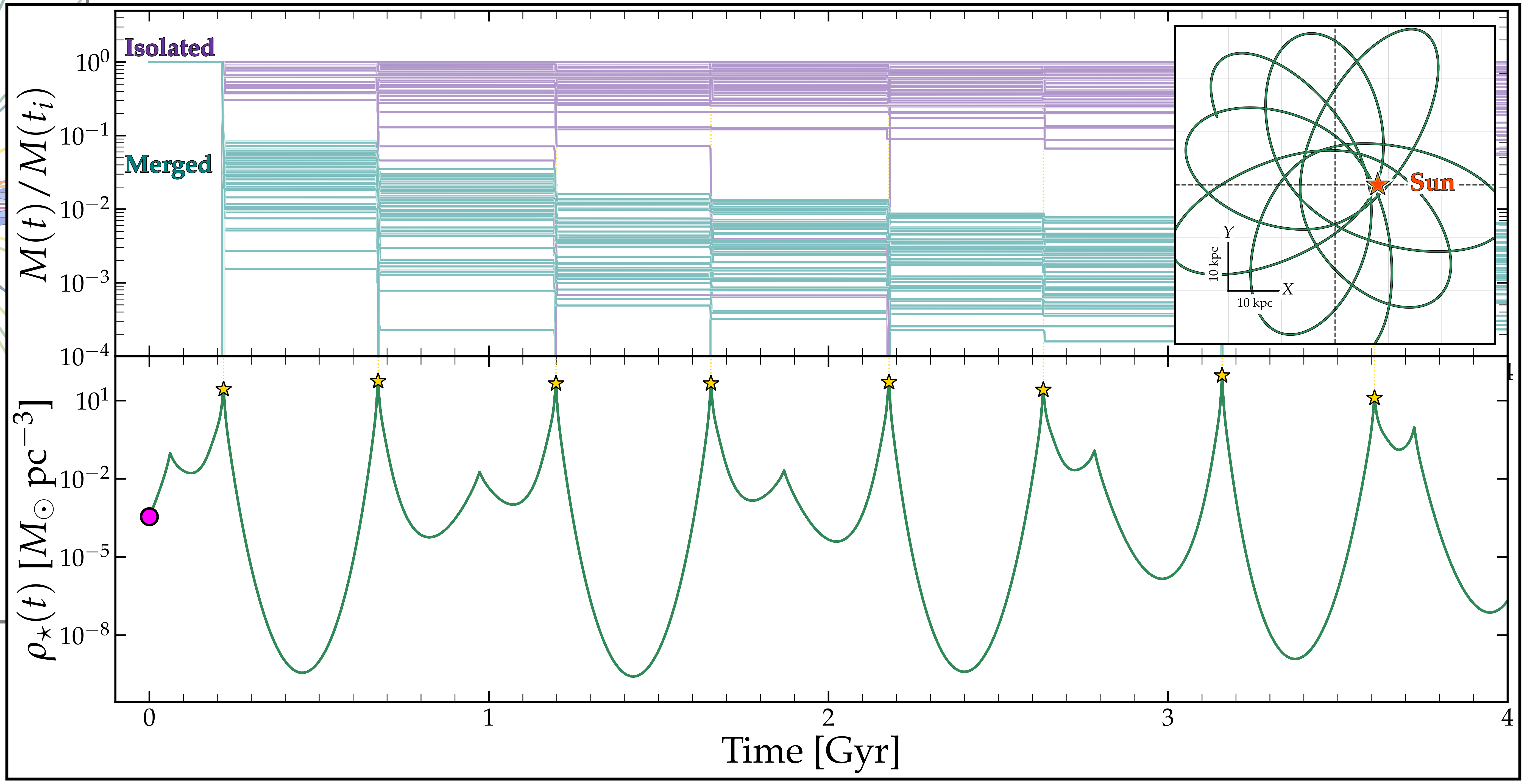

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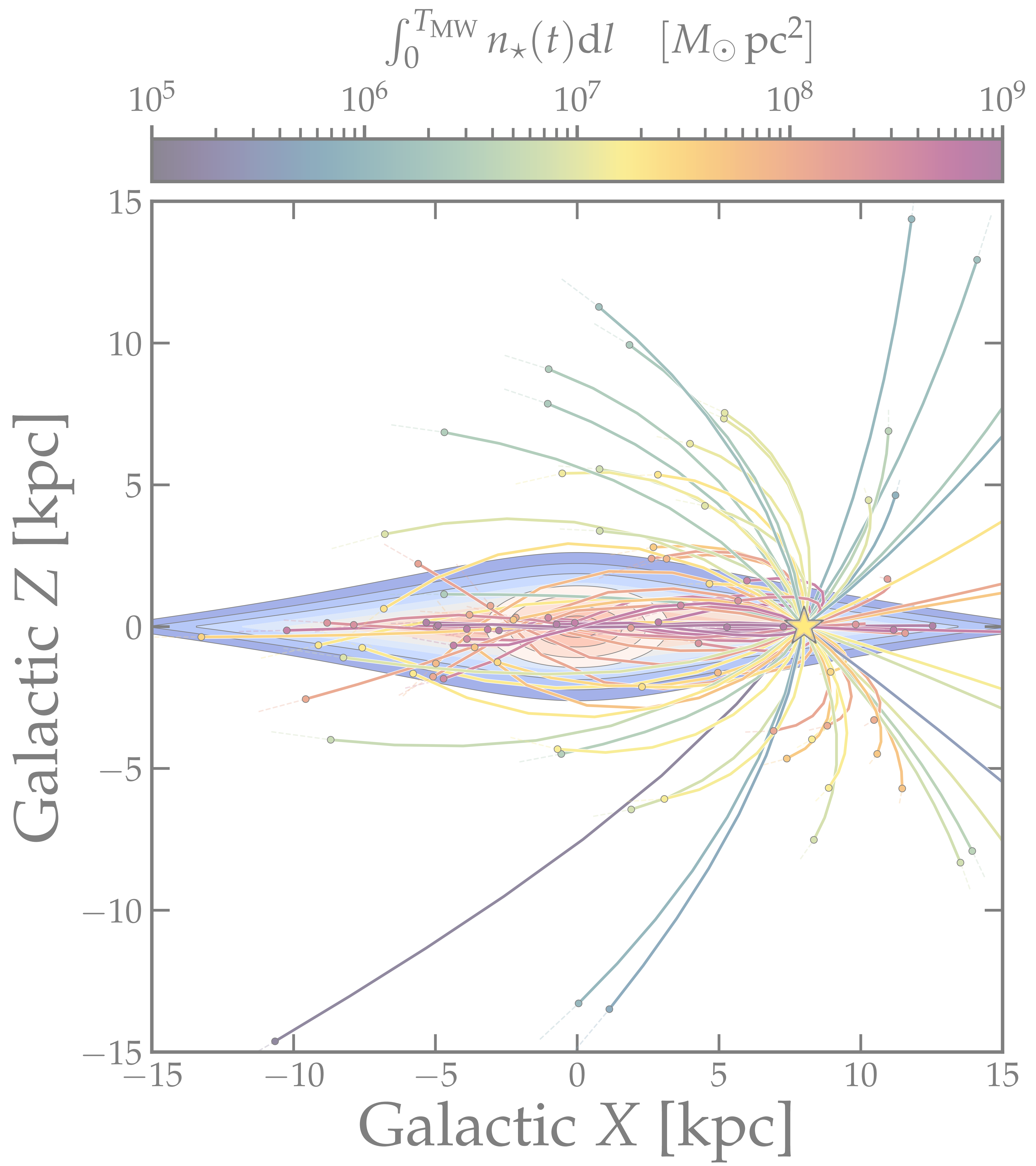

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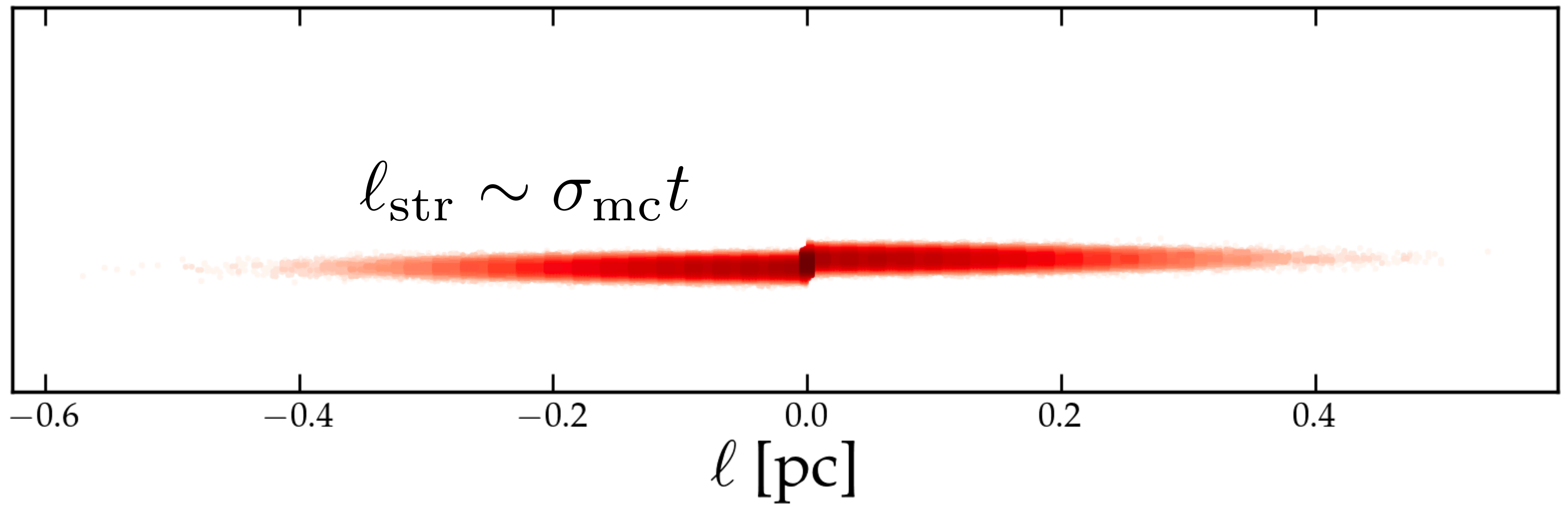
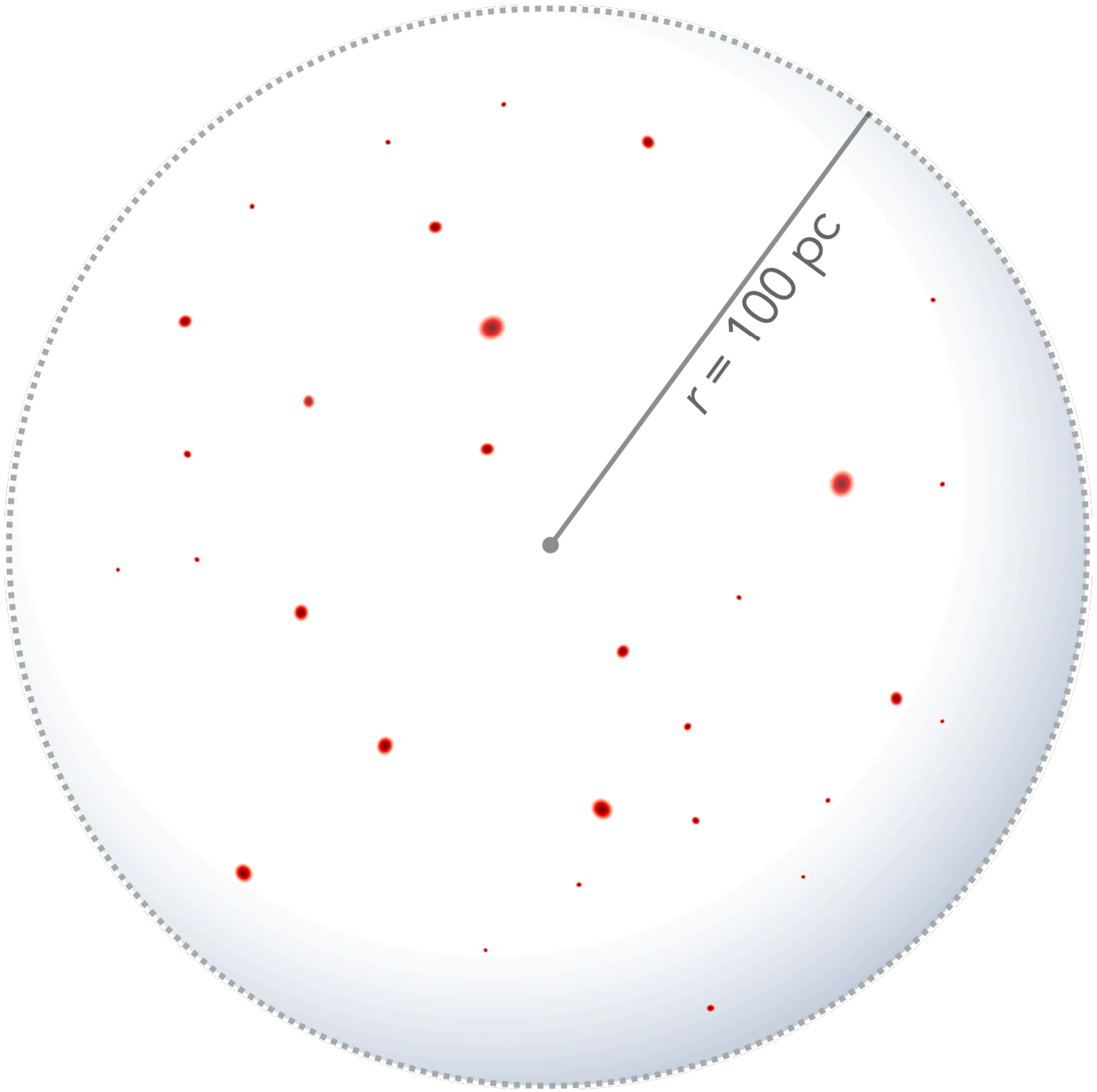
$$\rho_{\rm str}(\ell) = \sum_{i=1}^{N_{\rm enc}} \frac{\Delta M_i}{\pi R_{\rm mc}^2 \sqrt{2\pi(\ell_{\rm str}^i)^2}} \exp\left(-\frac{\ell^2}{2(\ell_{\rm str}^i)^2}\right)$$



Survival probability or **stream density on Earth**?

O'Hare, GP, Redondo [2311.17367]

Streams in the Solar neighbourhood



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We only measure $\rho_{\rm DM}$ on scales ~ 100 pc

The volumes is filled by 10^{14} miniclusters

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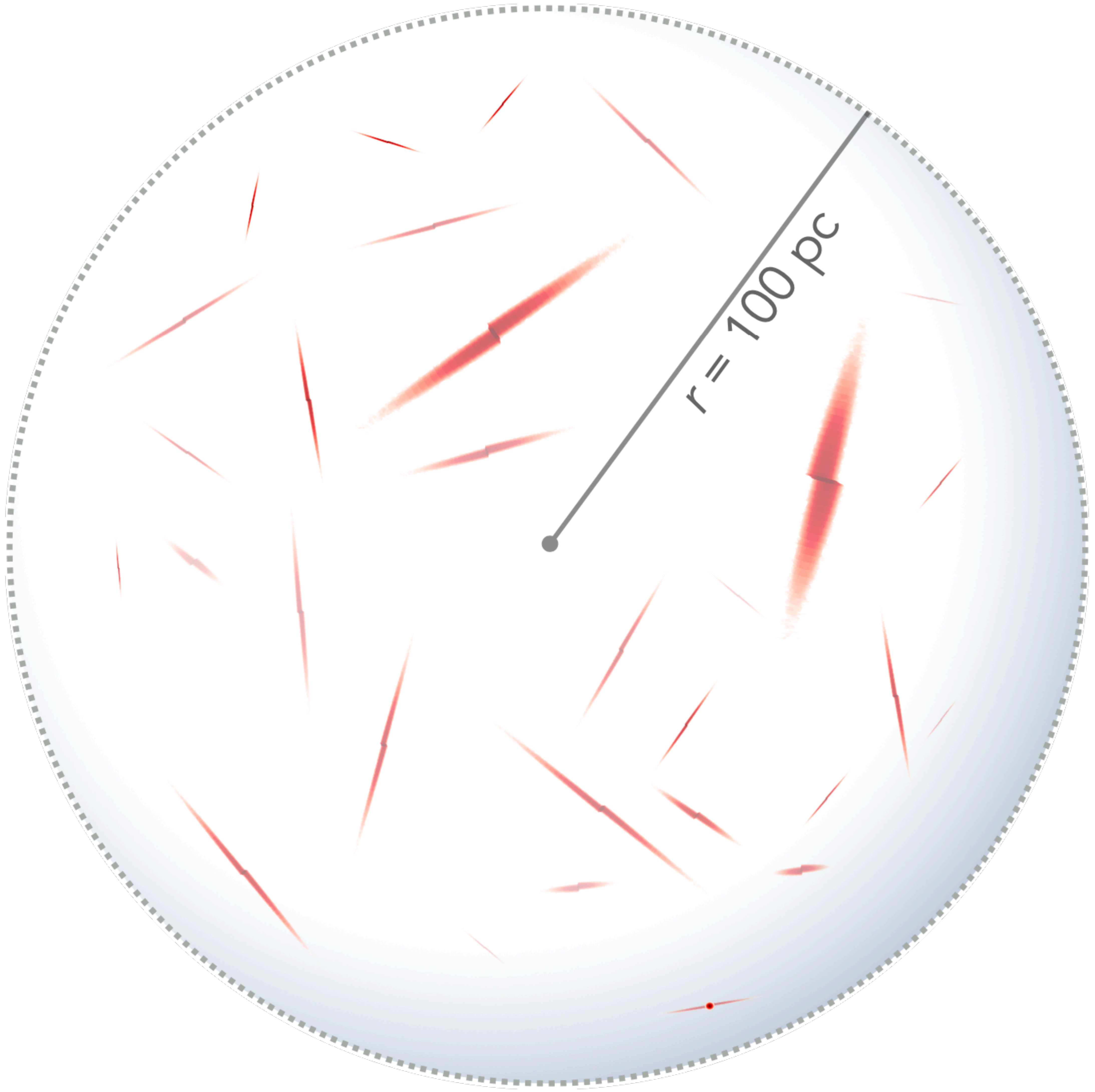

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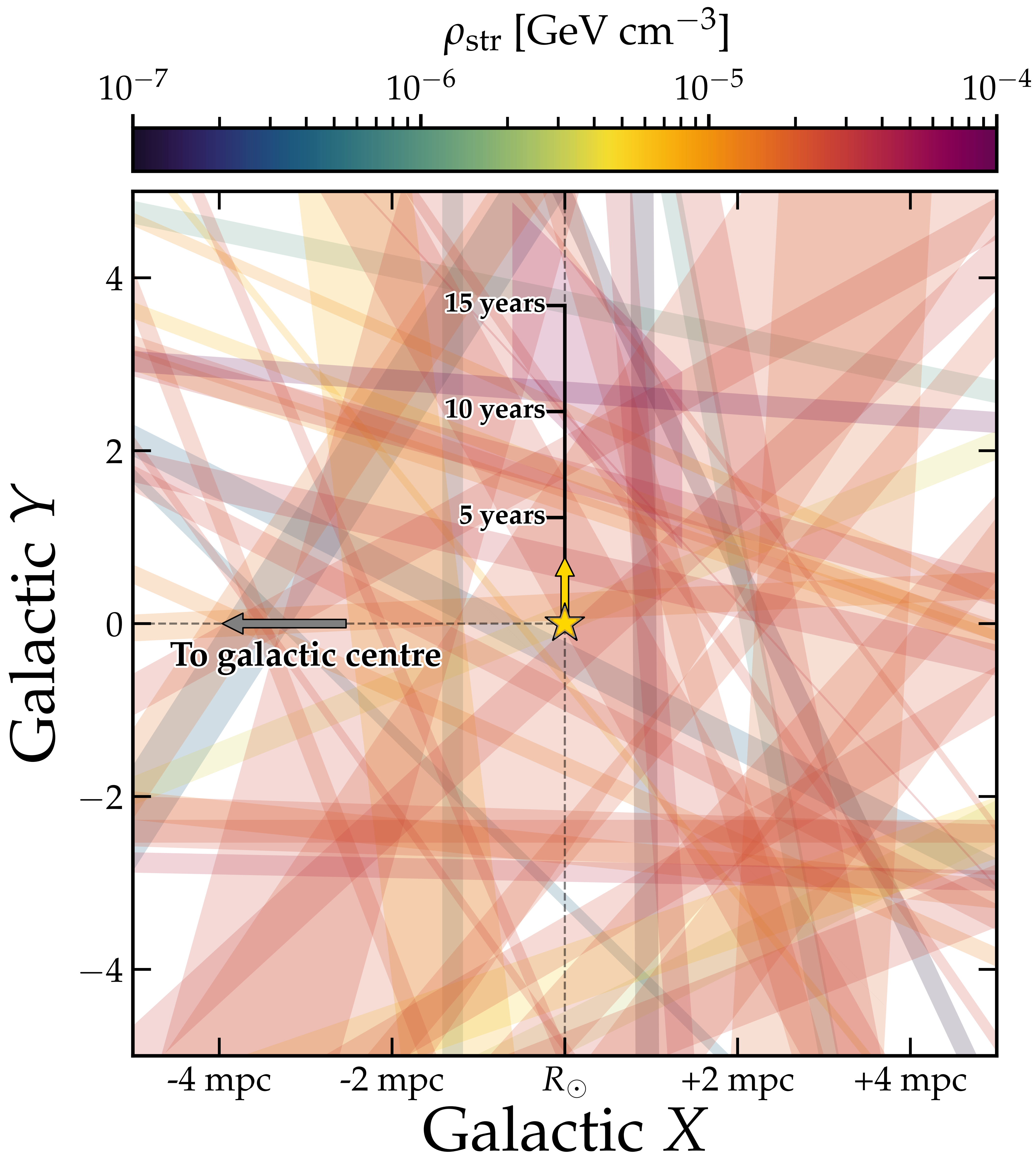

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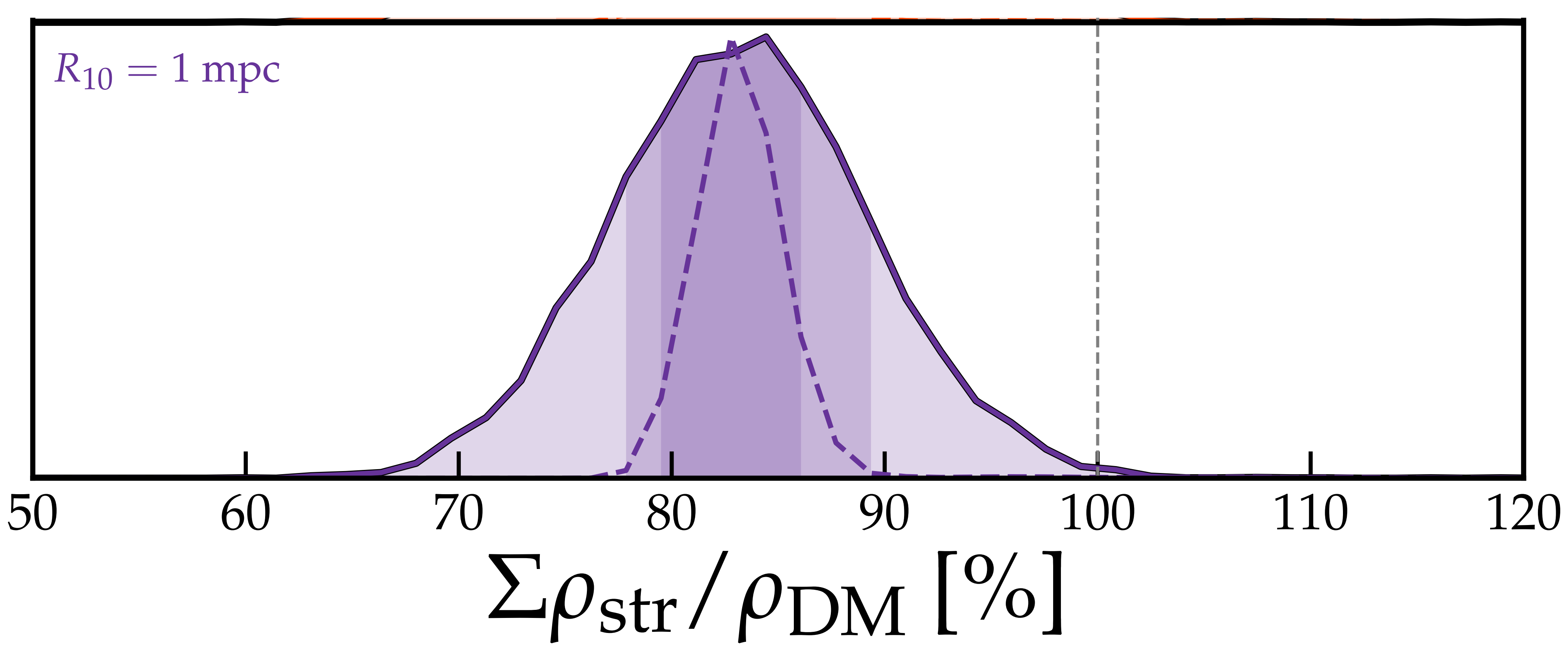
From our Monte Carlo simulations we find

- $\mathcal{O}(1000)$ overlapping streams at a given point
- Their energy adds up to ~80% of the measured value ρ_{DM} (leading to suppression of ~1.2 in the coupling)



Haloscope signal

$v \sim 10^{-3}$

While field is coherent $\omega \approx m_a(1 + v^2/2)$

coherence time

$$\tau_{\rm coh} \sim 10^6\, m_a^{-1}$$

$$\sim 0.01\,{\rm ms}\,(100\mu{\rm eV}/m_a)$$

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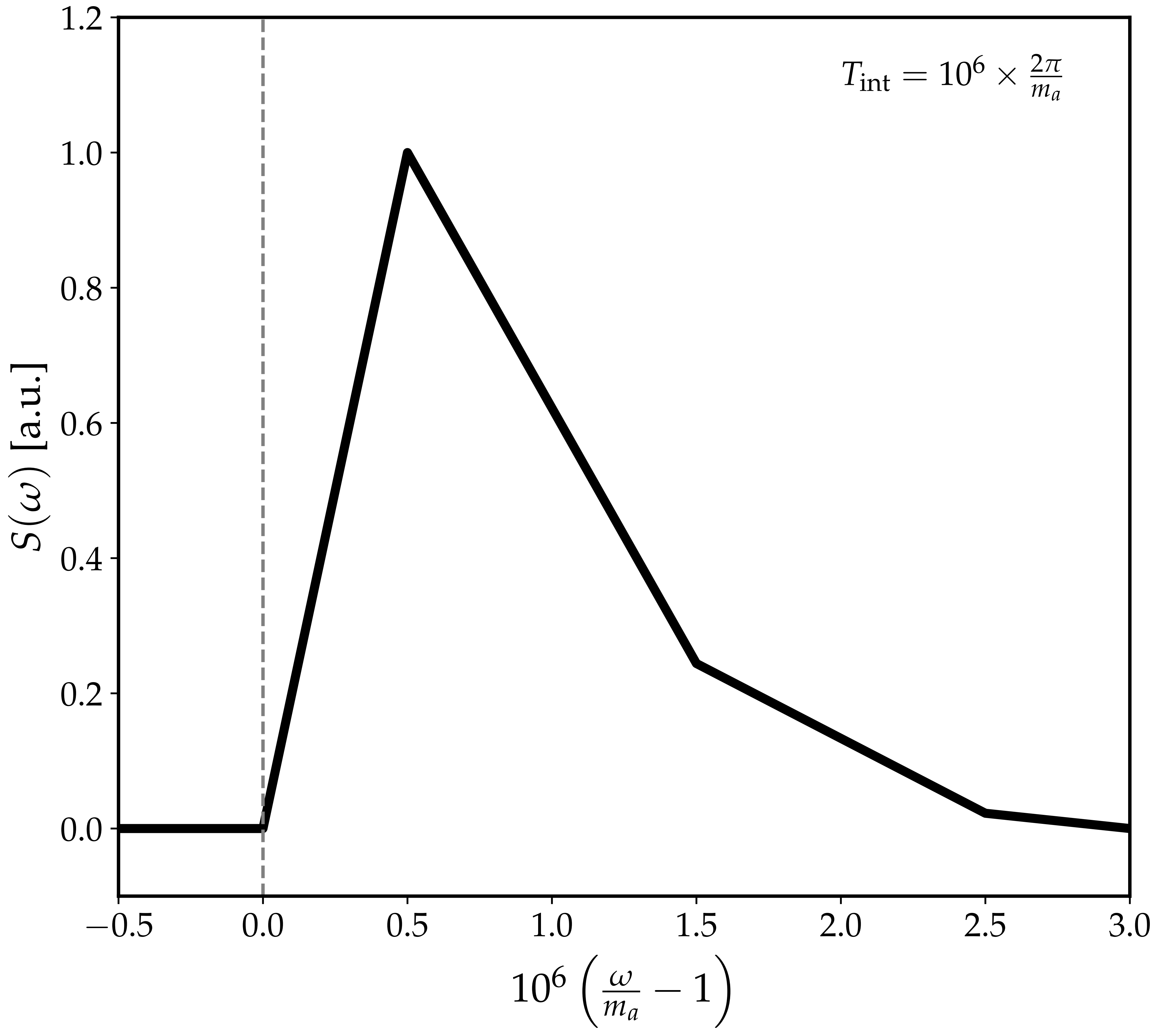

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Measurements when $T_{\rm int} \gg \tau_{\rm coh}$ show a discrete FT the distribution of component frequencies.

$\Delta\omega = \frac{2\pi}{T_{\rm int}}$ Frequency resolution

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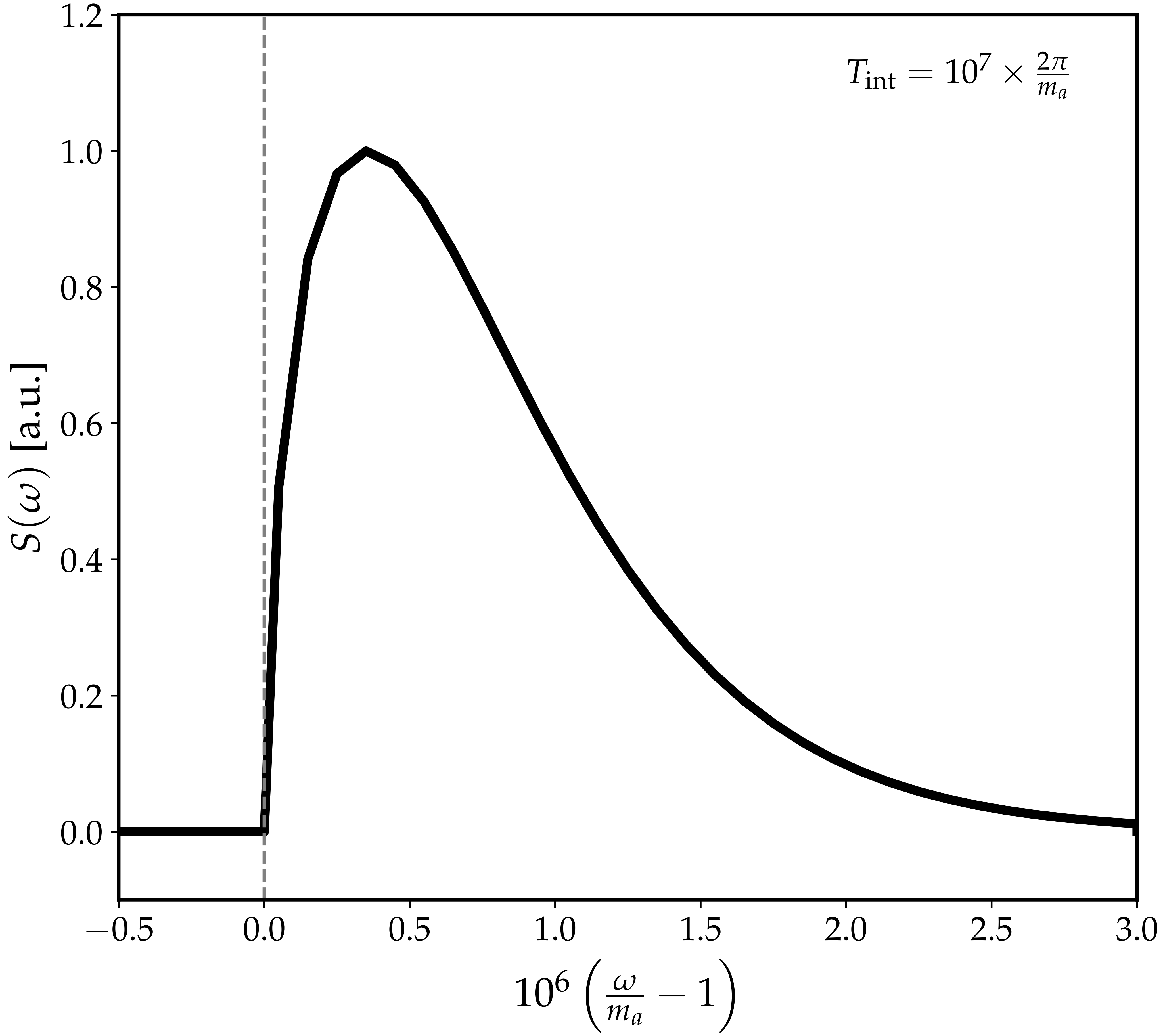

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Axion lineshape

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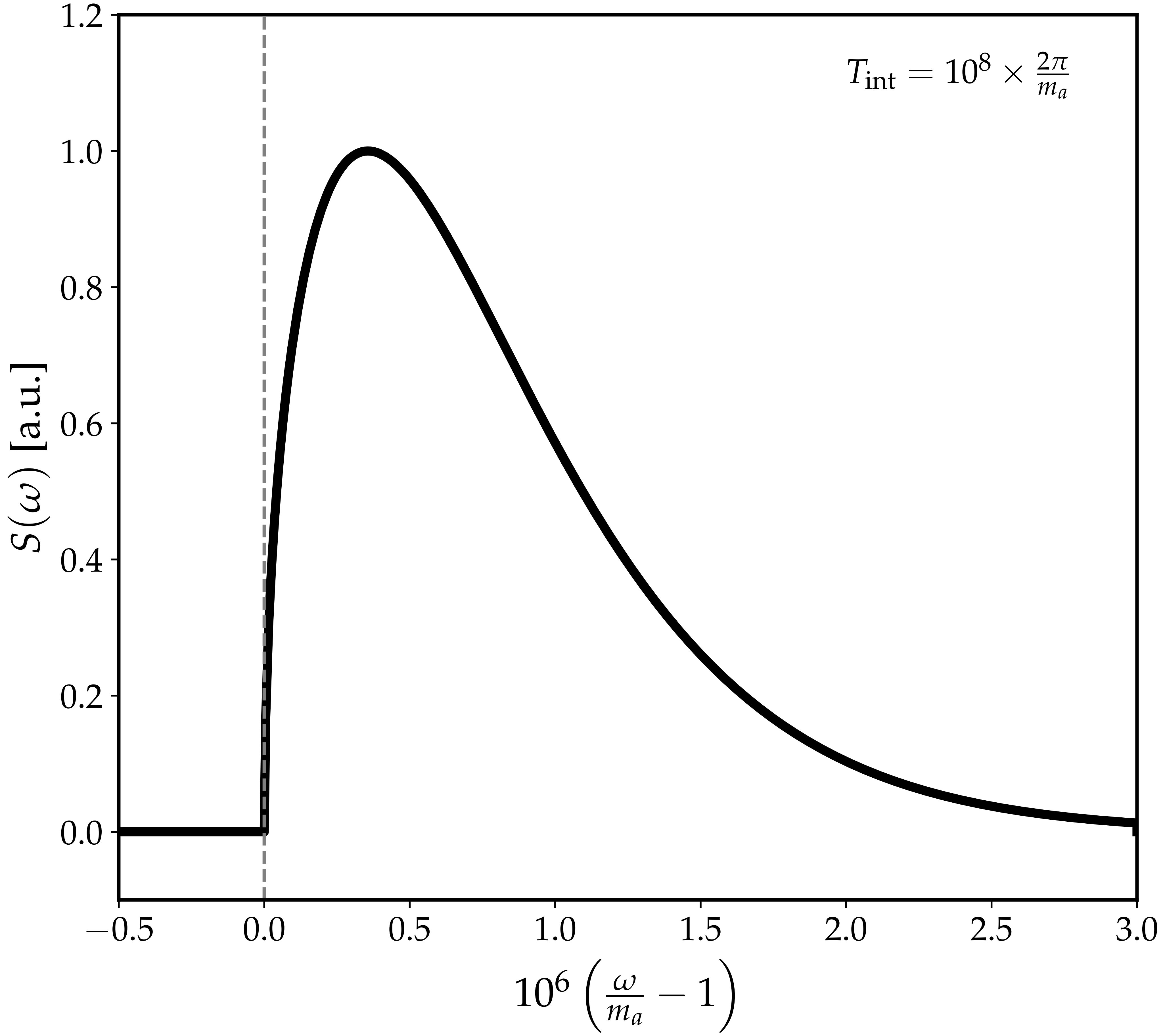

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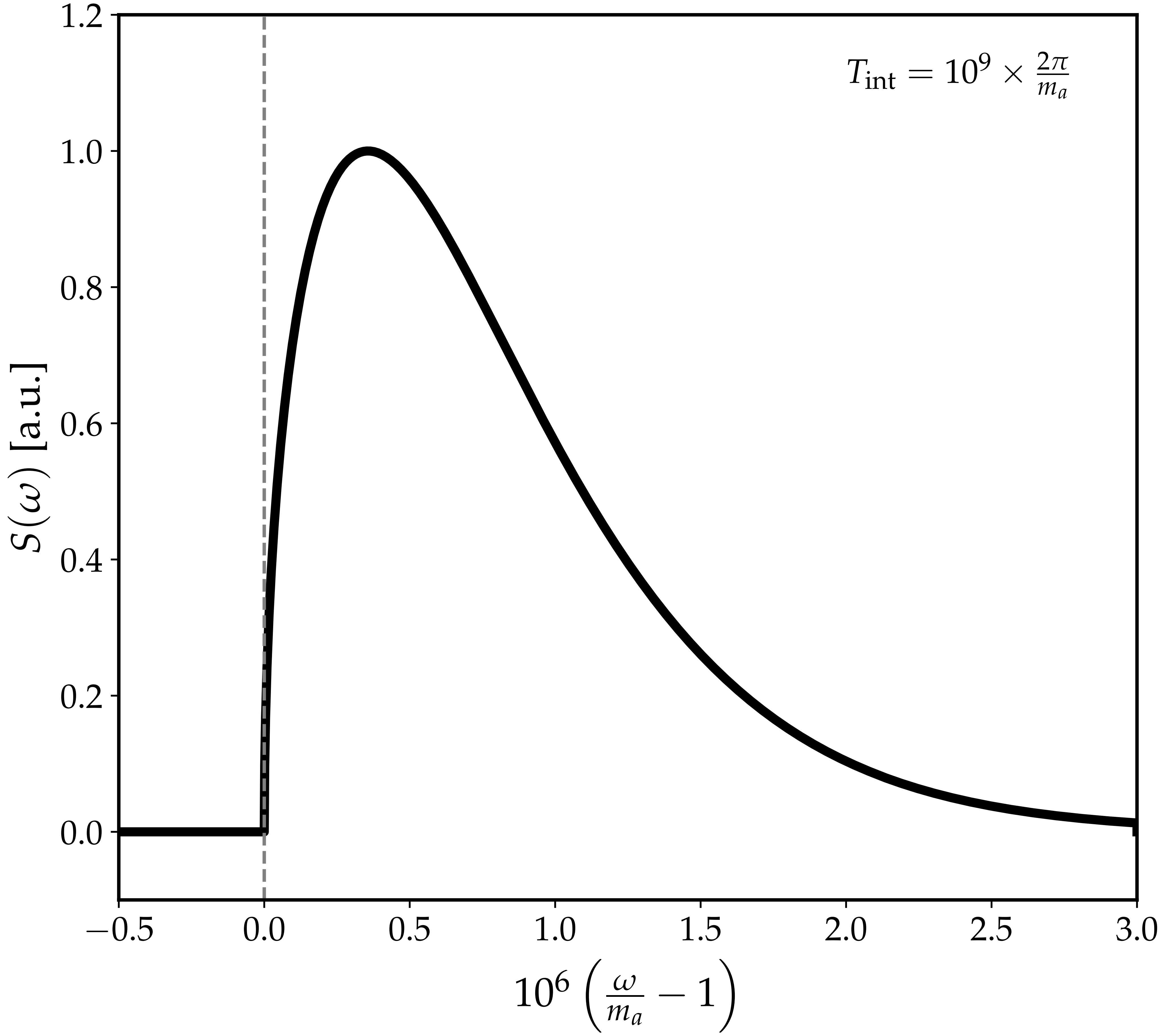

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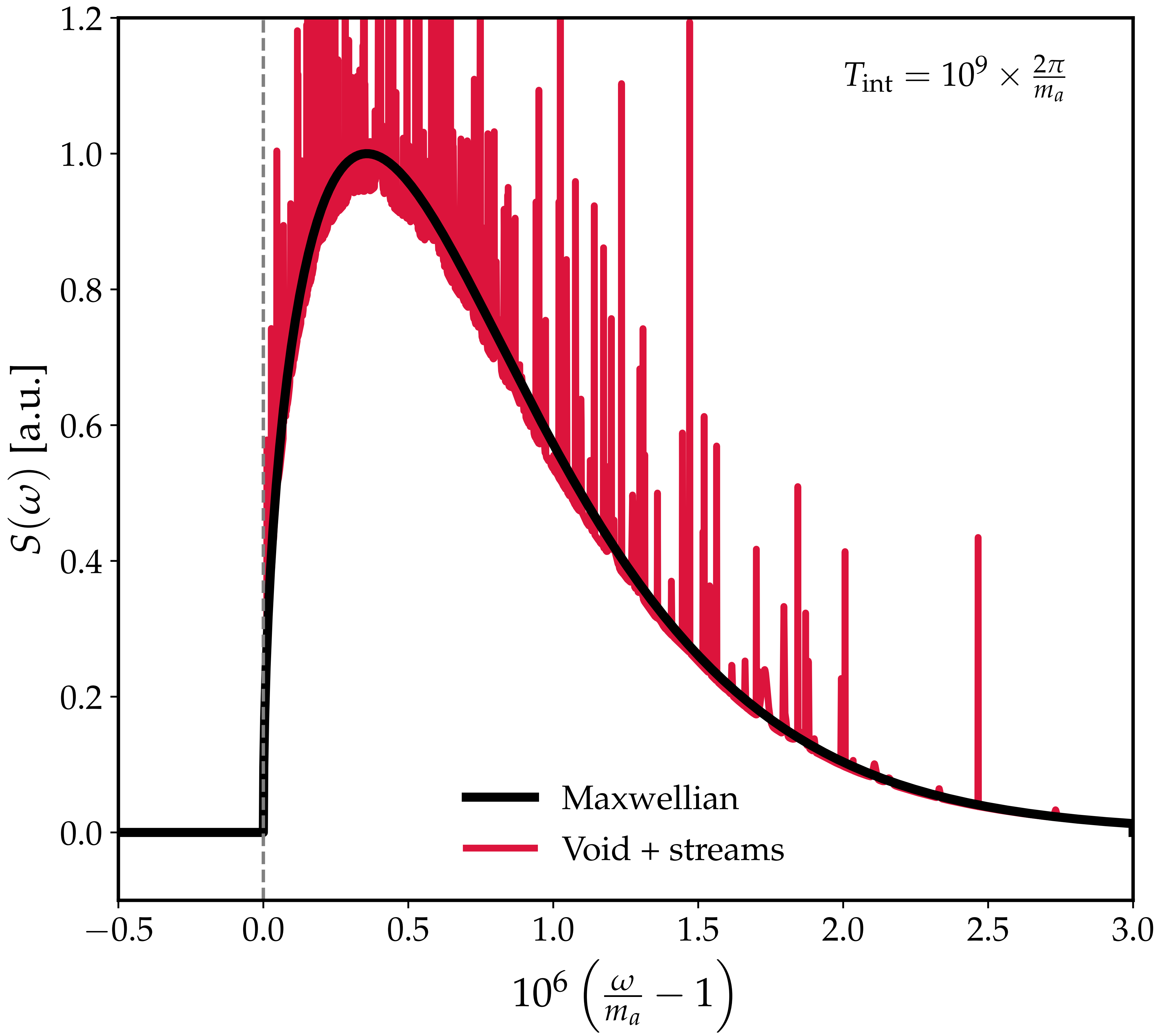

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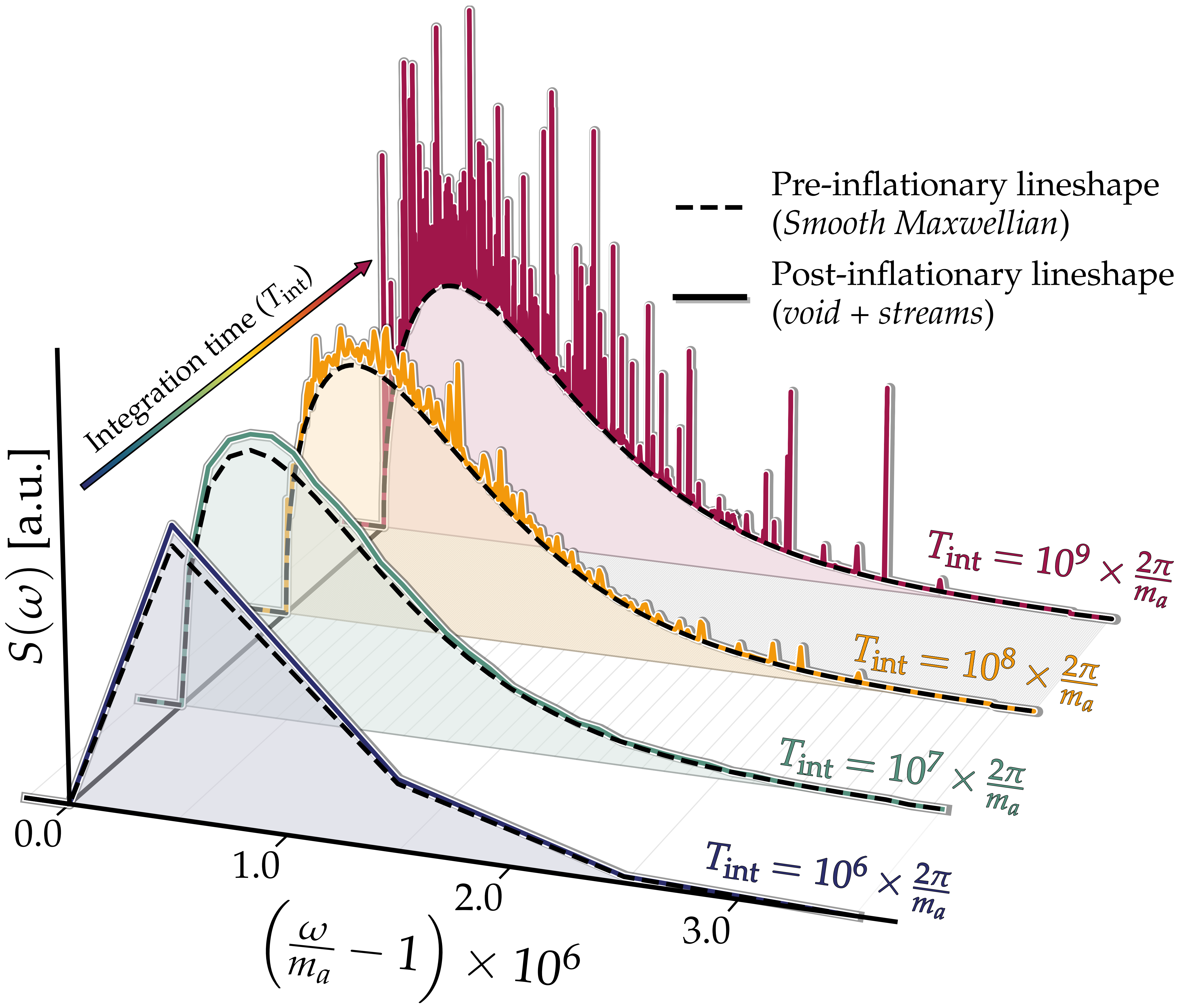
Axion lineshape

$\mathcal{O}(1000)$ streams lead to an overall *enhancement* of ~7 w.r.t. background void

Narrow lines typically last $\mathcal{O}({\rm days} - {\rm years})$

Can be much larger in the resolved lineshape in certain frequency bins

Haloscope signal



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Summary

- **Miniclusters, voids and streams** are a *smoking guns* of the post-inflationary axion dark matter scenario
- In the minivoids, the energy density is only 10% of the large-scale measured value, leading to substantial sensitivity suppression in *all* haloscopes
- With current modelling of tidal disruption, we expect the axion DM signal to reach ~80% of the large-scale measured value, with thousands of overlapping streams at each point
- If haloscopes can measure the axion signal with high-enough frequency resolution, streams reveal a spiky lineshape that can *distinguish* pre- and post-inflation axion DM

Additional slides

Cosmological timeline

PQ phase transition

Cold axion production

Number density conserved

Gravitational collapse

Today

Lattice

N-body

Monte Carlo

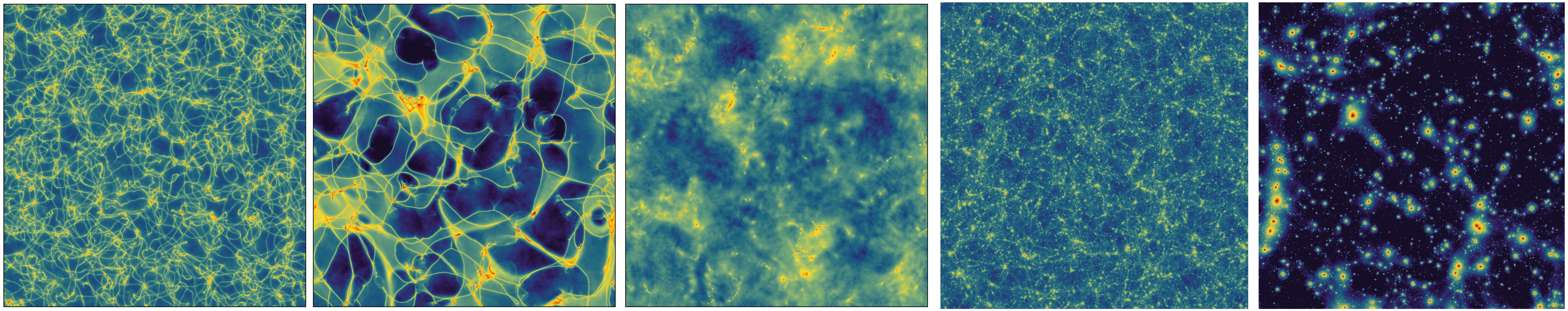
Klein-Gordon (relativistic)
Schrödinger-Poisson (non-relativistic limit)

$z \sim 10^6$

Vlasov-Poisson (collisionless)
Non-relativistic CDM

$z \sim 99$

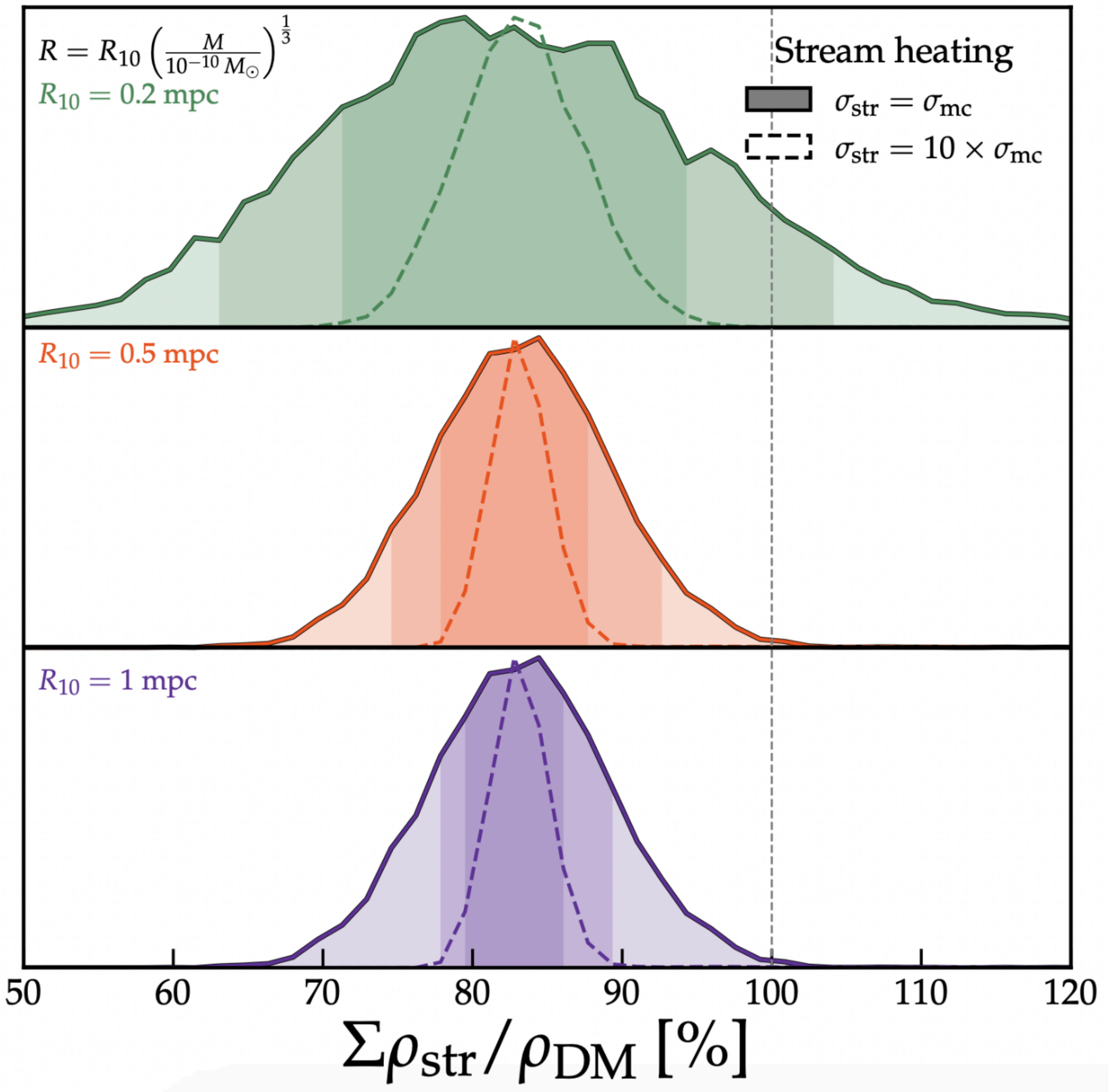
Minicluster orbits
Stellar encounters



jaxions
(J. Redondo, A. Vaquero)
github.com/veintemillas/jaxions

gadget-4
(V. Springel)
wwwmpa.mpa-garching.mpg.de/gadget4/

Axion streams at solar position



We only measure $\rho_{\rm DM}$ on scales ~ 100 pc

The volumes is filled by 10^{14} miniclusters

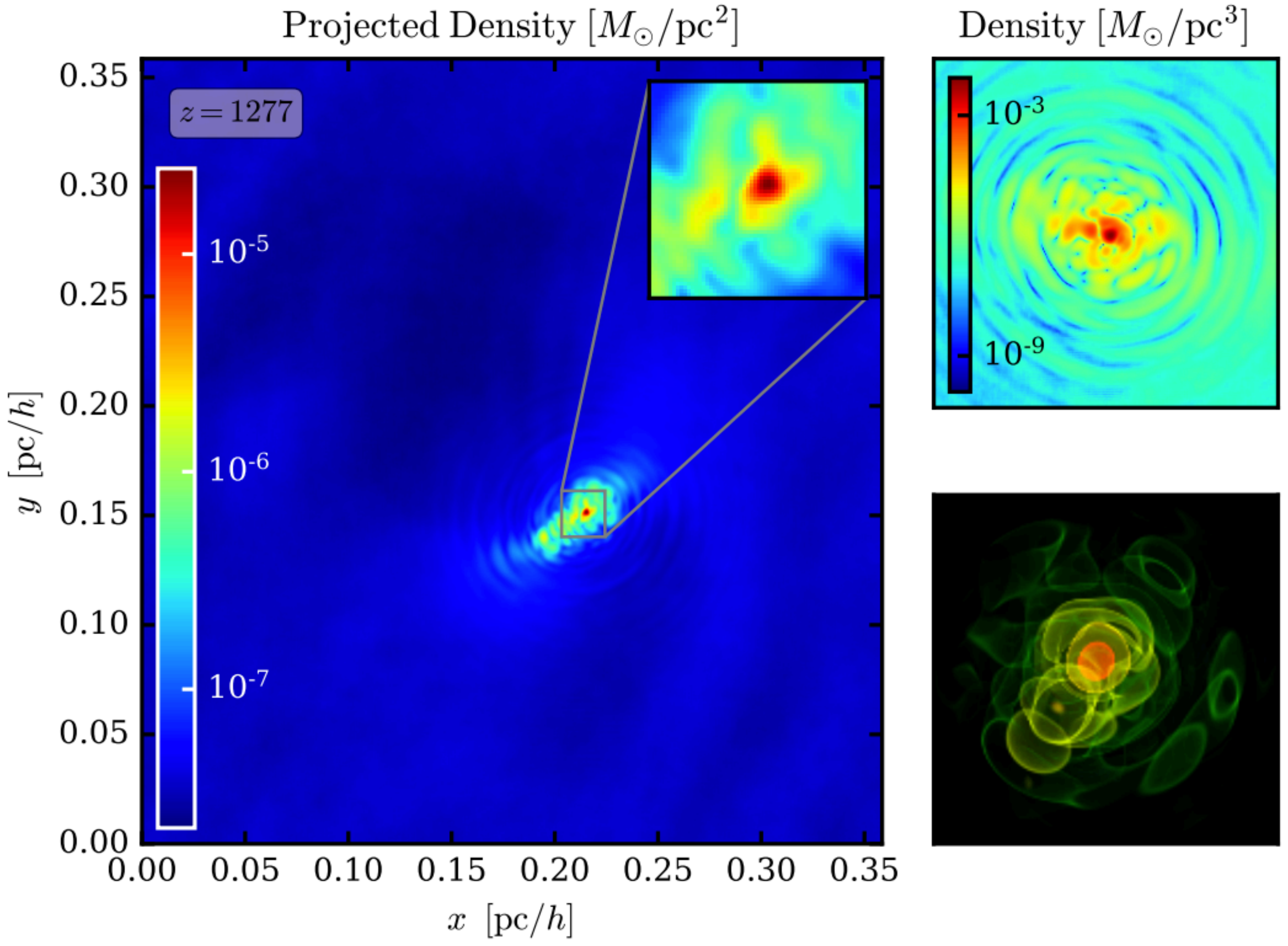
After disruption, they become $\sim$ pc long streams

From our Monte Carlo simulations we find

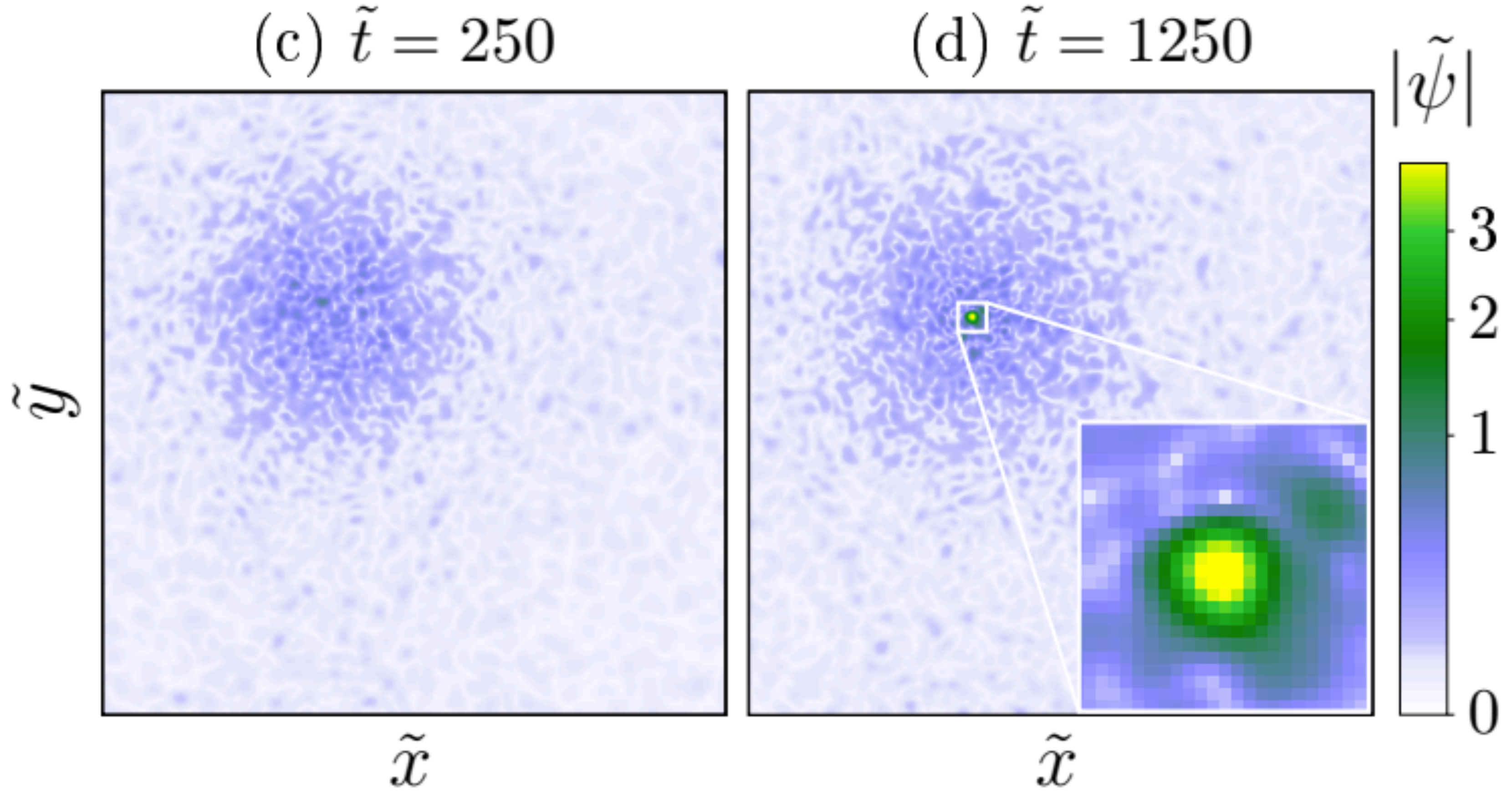
- $\mathcal{O}(1000)$ overlapping streams at a given point
- Their energy adds up to 80% of the measured value $\rho_{\rm DM}$

Axion stars

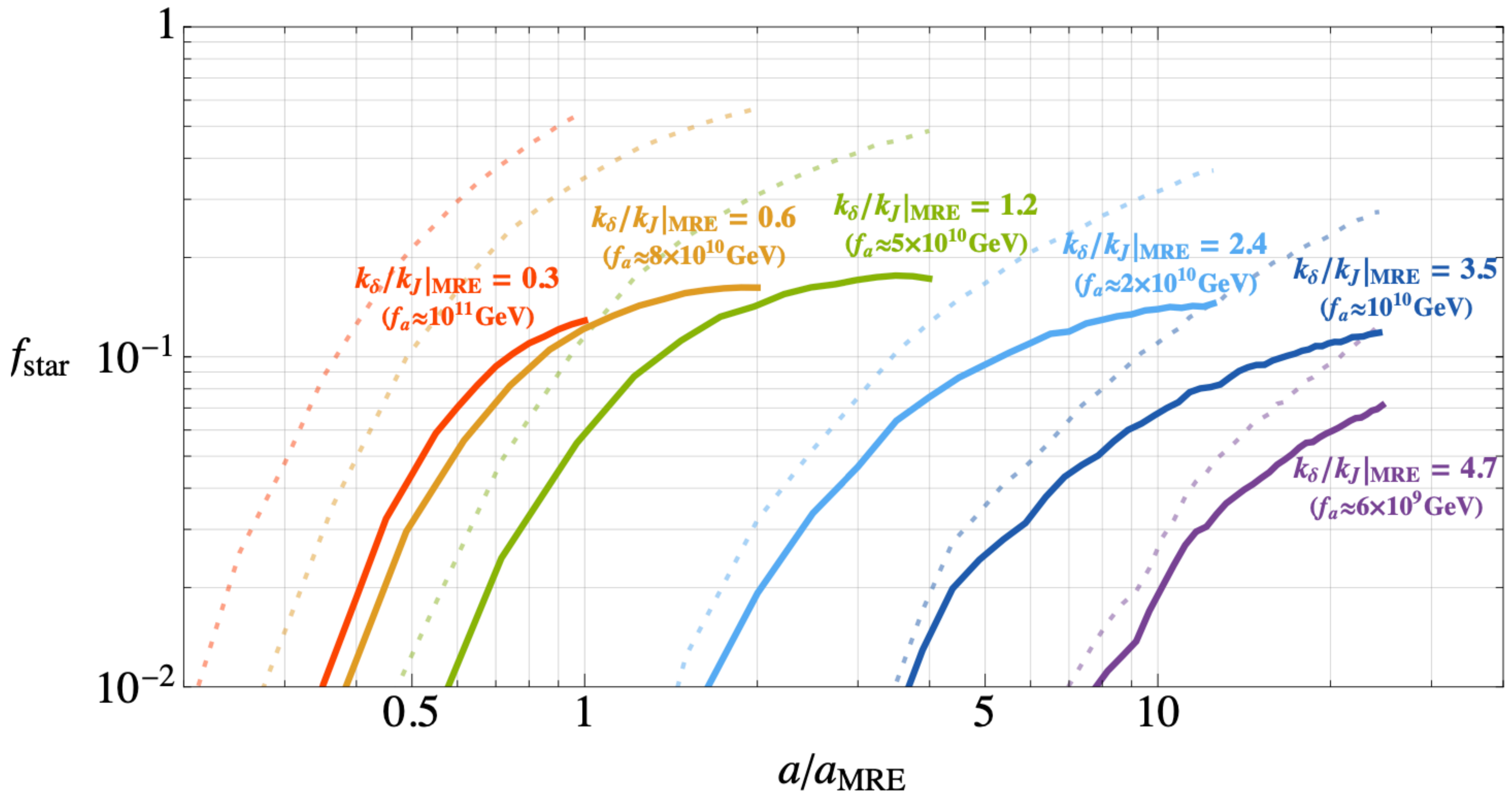
Eggemeier, Niemeyer [1906.01348]



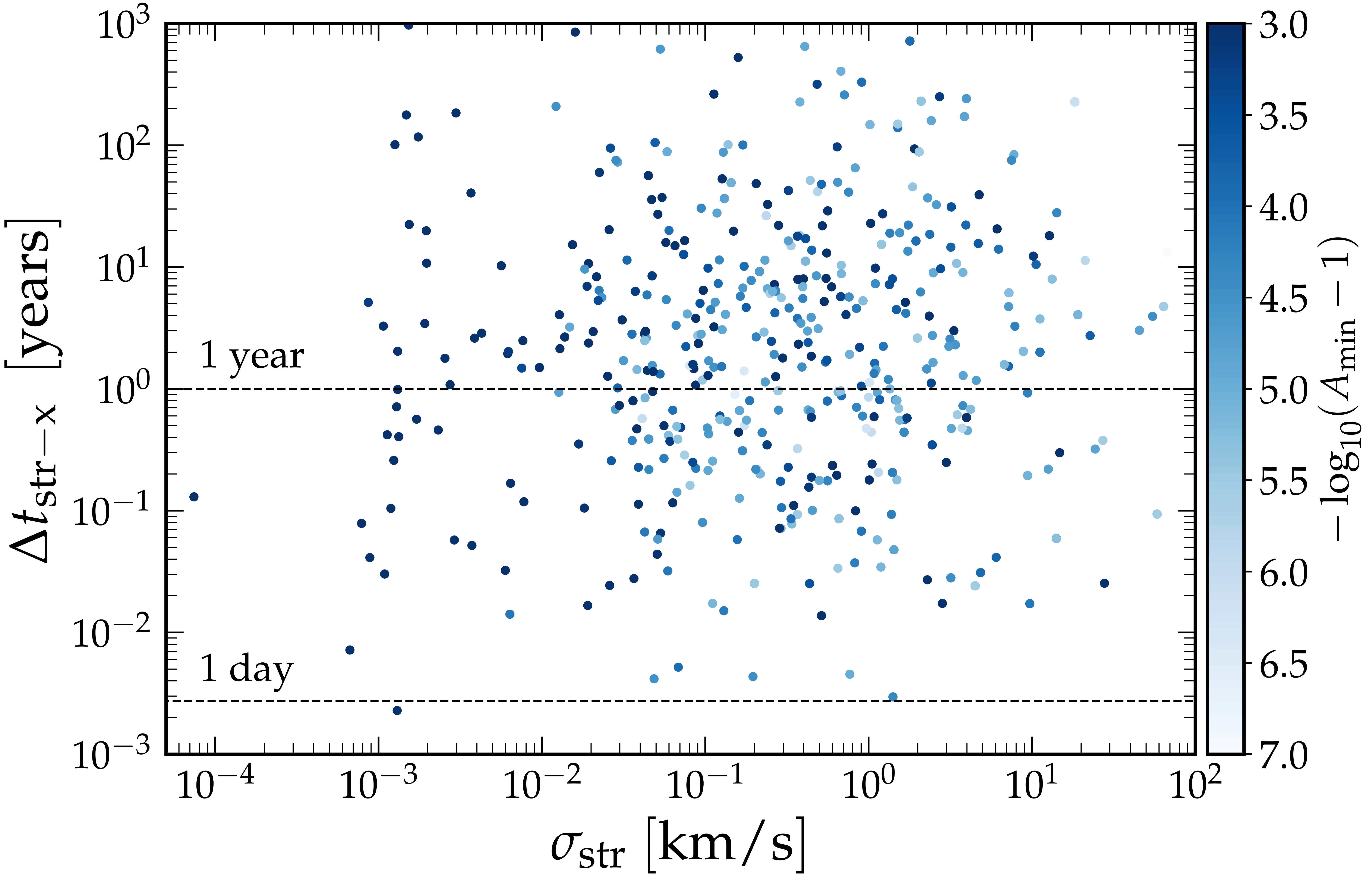
Levkov+ [1804.05857]



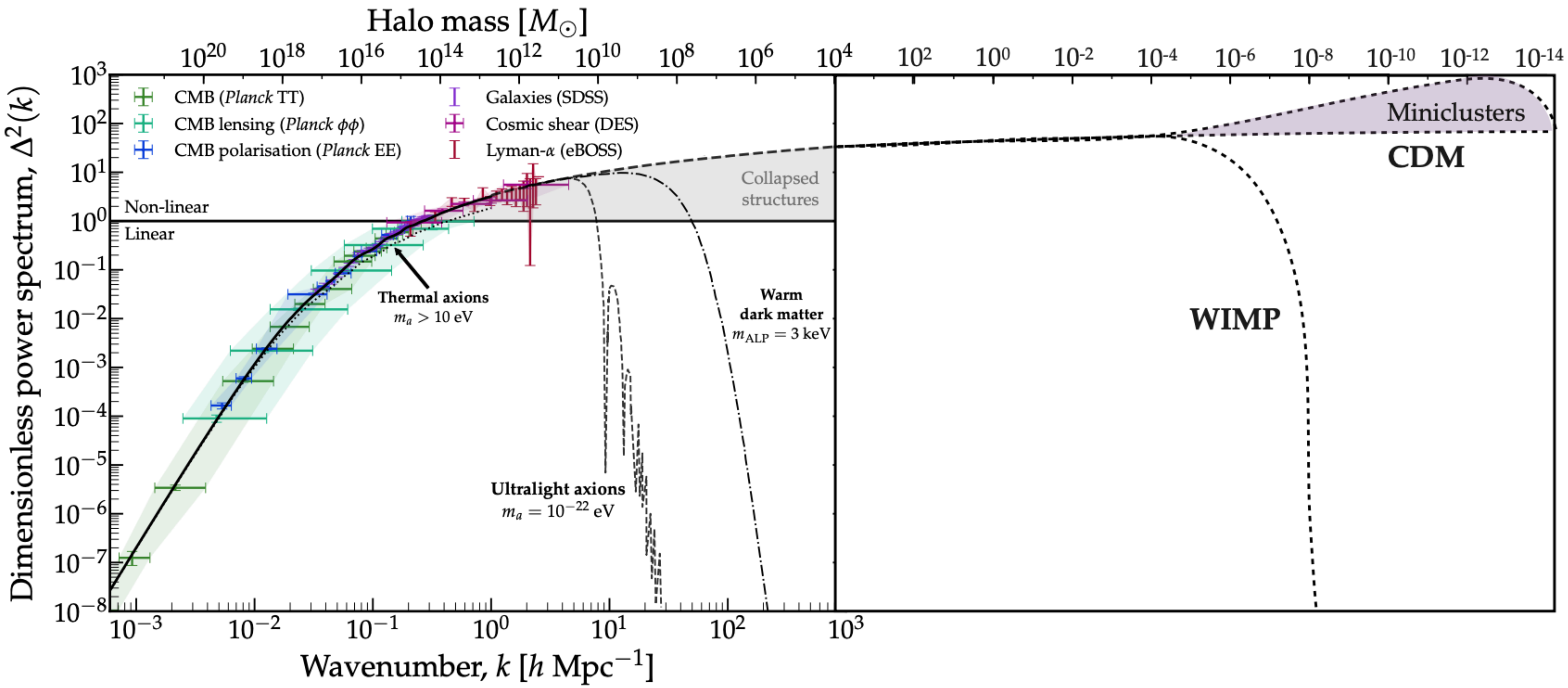
Gorghetto+ [2405.19389]



Stream duration and dispersion velocity

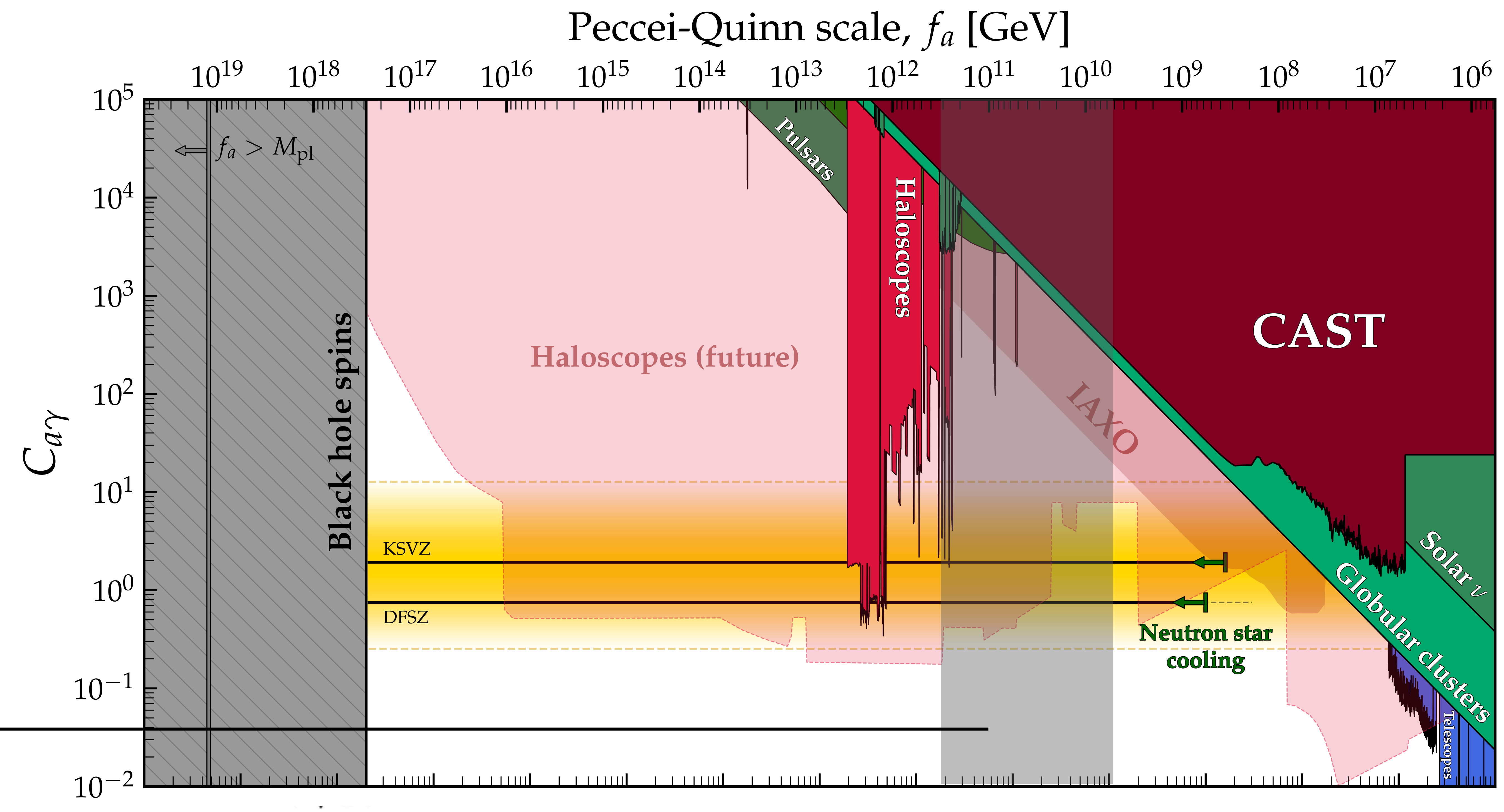


Density fluctuations

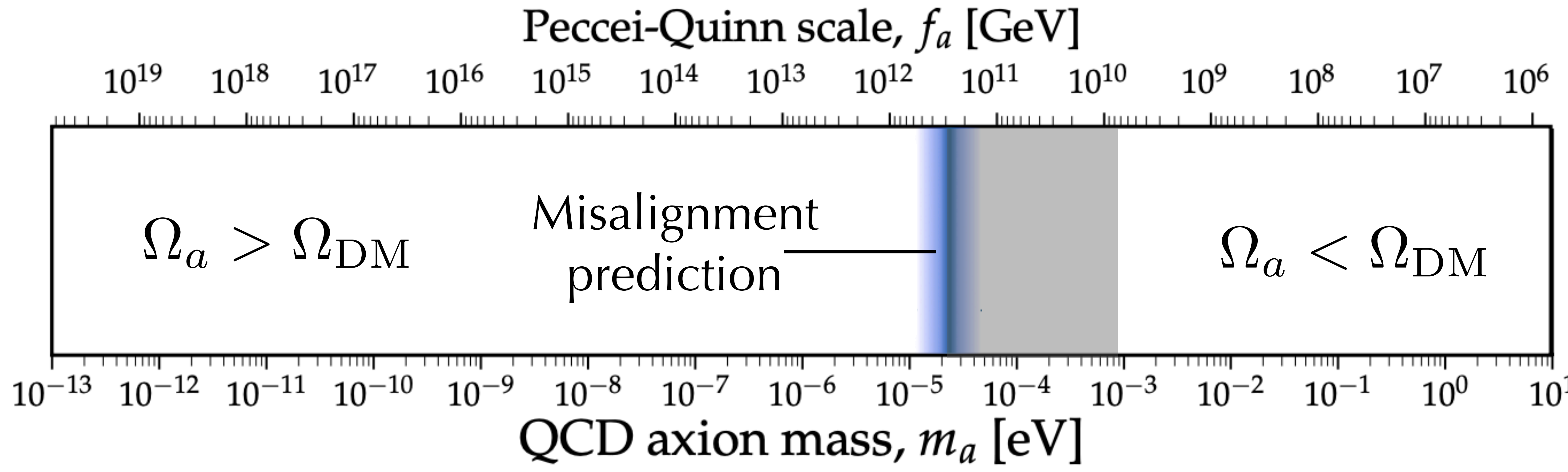


Credits: C. O'Hare

Implications for haloscopes



Contribution from *topological defects*: strings and domain walls

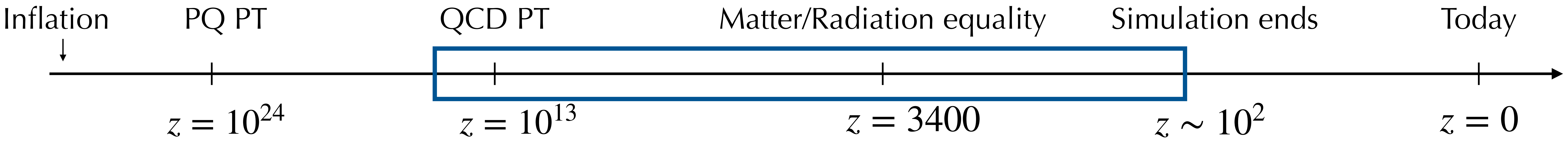


Axion field frequency

$$m_a = \frac{\rho_{\rm DM}}{n_a} \longrightarrow$$

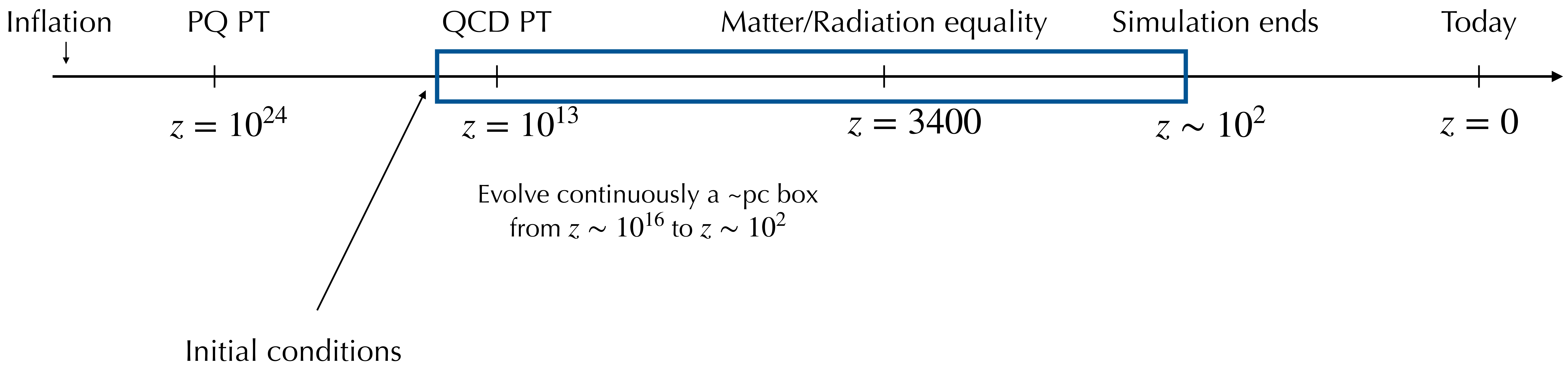
Goal: find axion number dens axion dark matter mass

Why modelling strings is important?



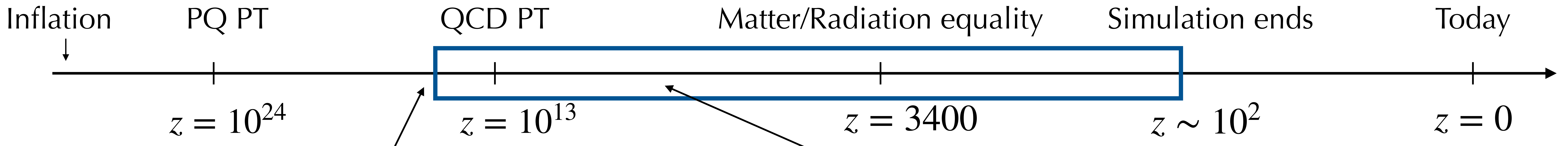
Evolve continuously a ~pc box
from $z \sim 10^{16}$ to $z \sim 10^2$

Why modelling strings is important?



1. Direct, small string tension — Vaquero+ [1809.]
2. Direct, added string tension — Klaer & Moore []
3. Indirect, IR spectrum — Gorghetto+ []

Why modelling strings is important?



Evolve continuously a ~pc box from $z \sim 10^{16}$ to $z \sim 10^{2}$

Initial conditions

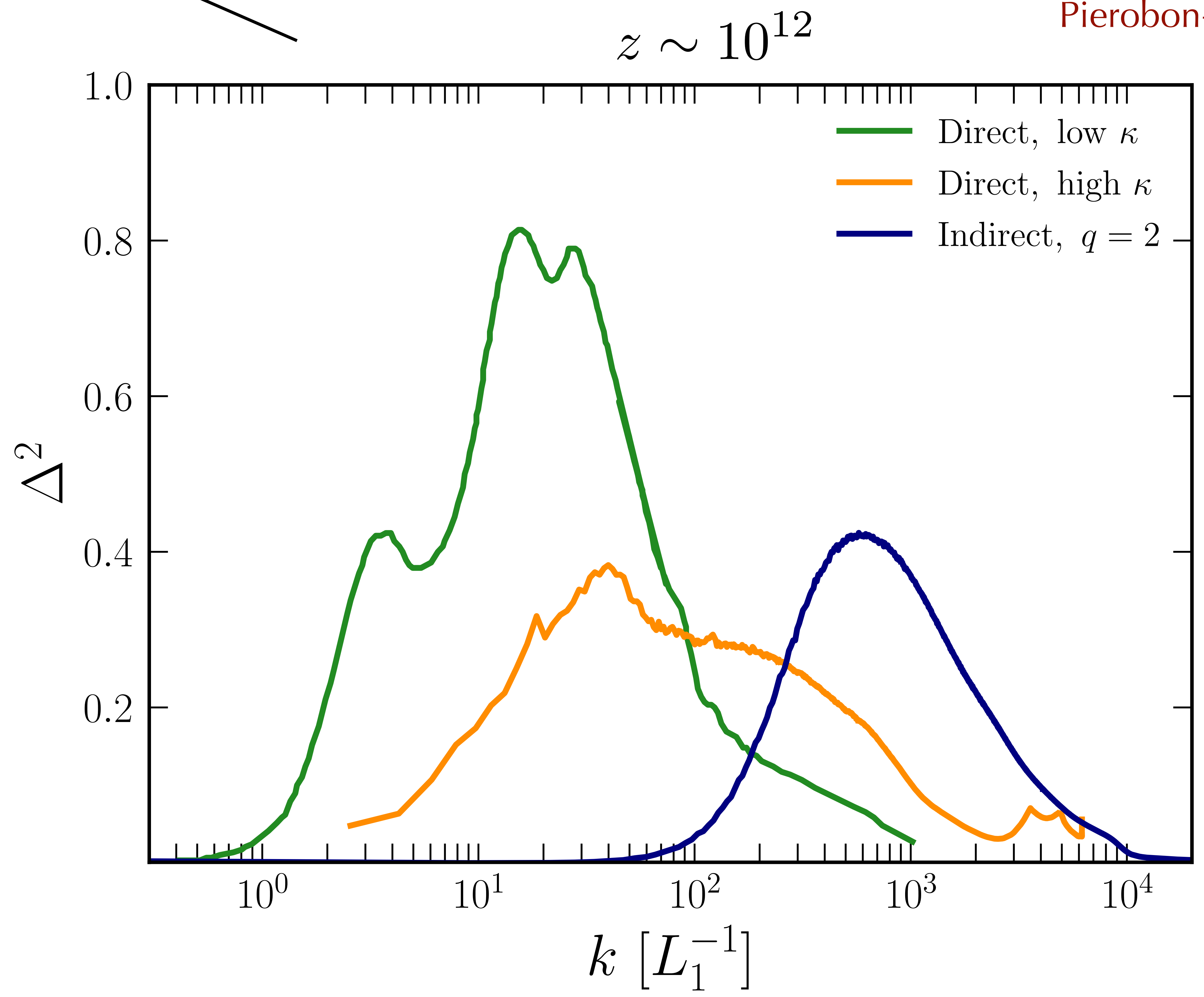
1. Direct, small string tension
2. Direct, added string tension
3. Indirect, IR spectrum

Vaquero+ [1809.]

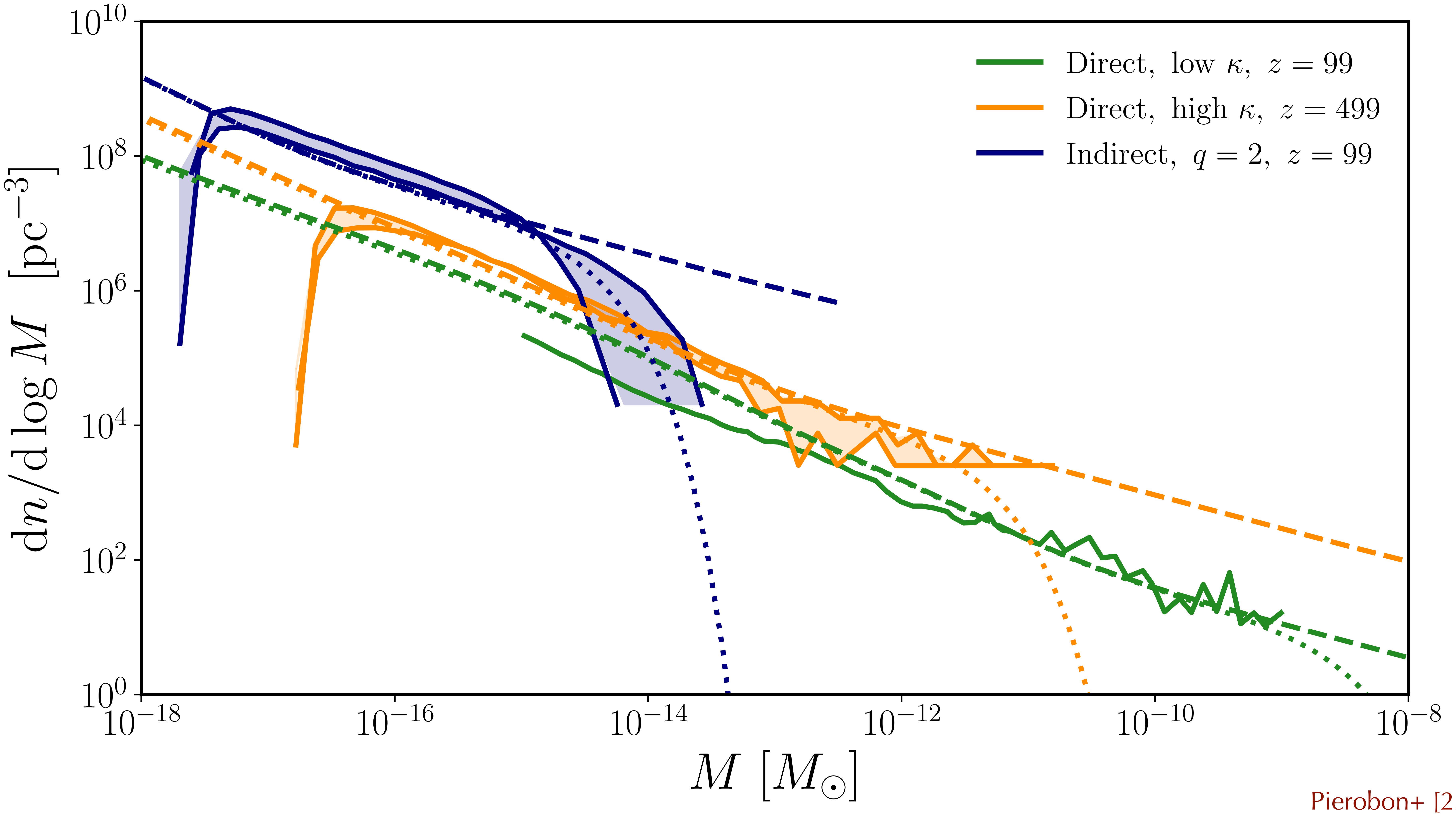
Klaer & Moore []

Gorghetto+ []

Pierobon+ [2307.]



Halo mass function



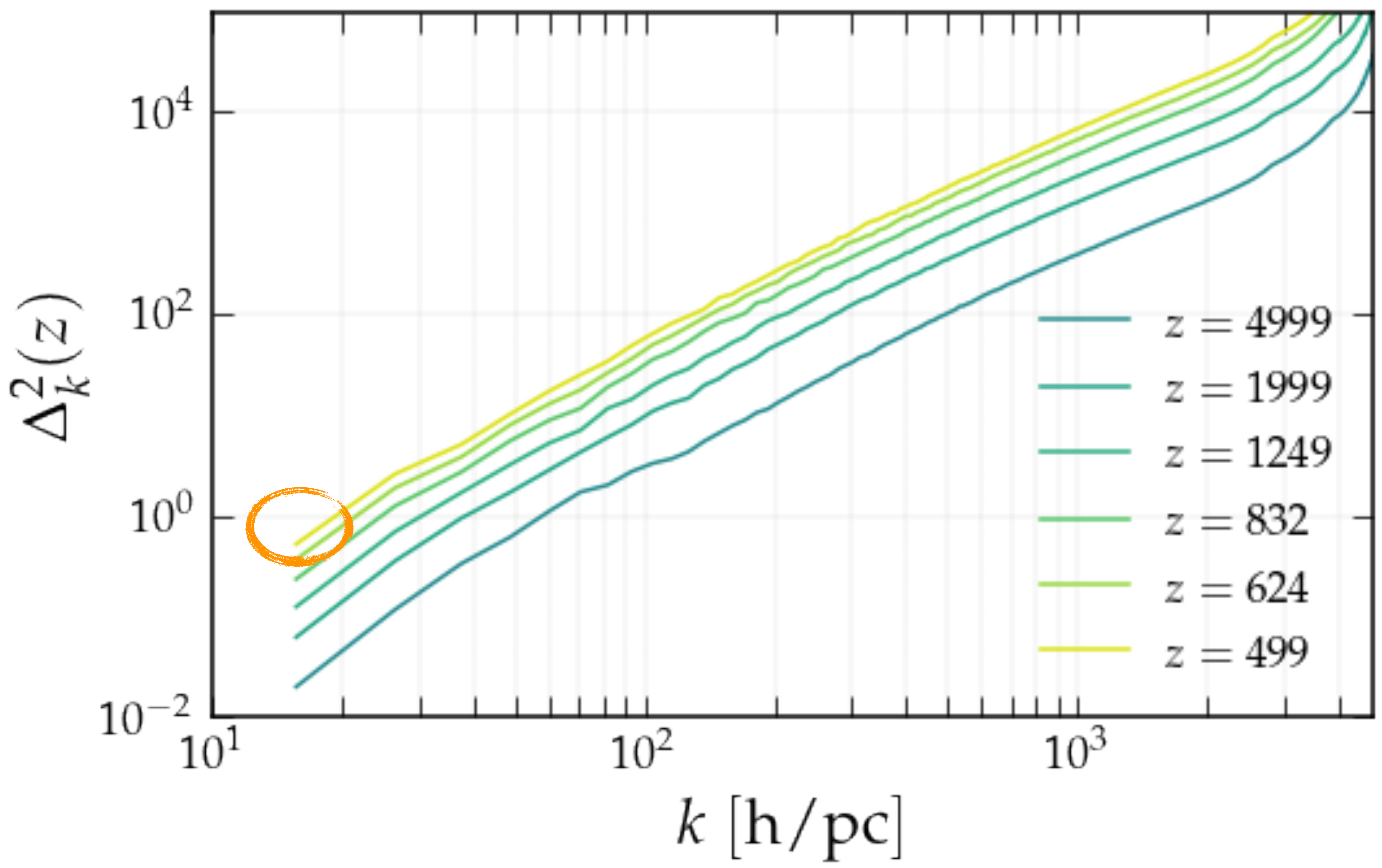
Full: numerical results

Dashed: prediction from Δ^2

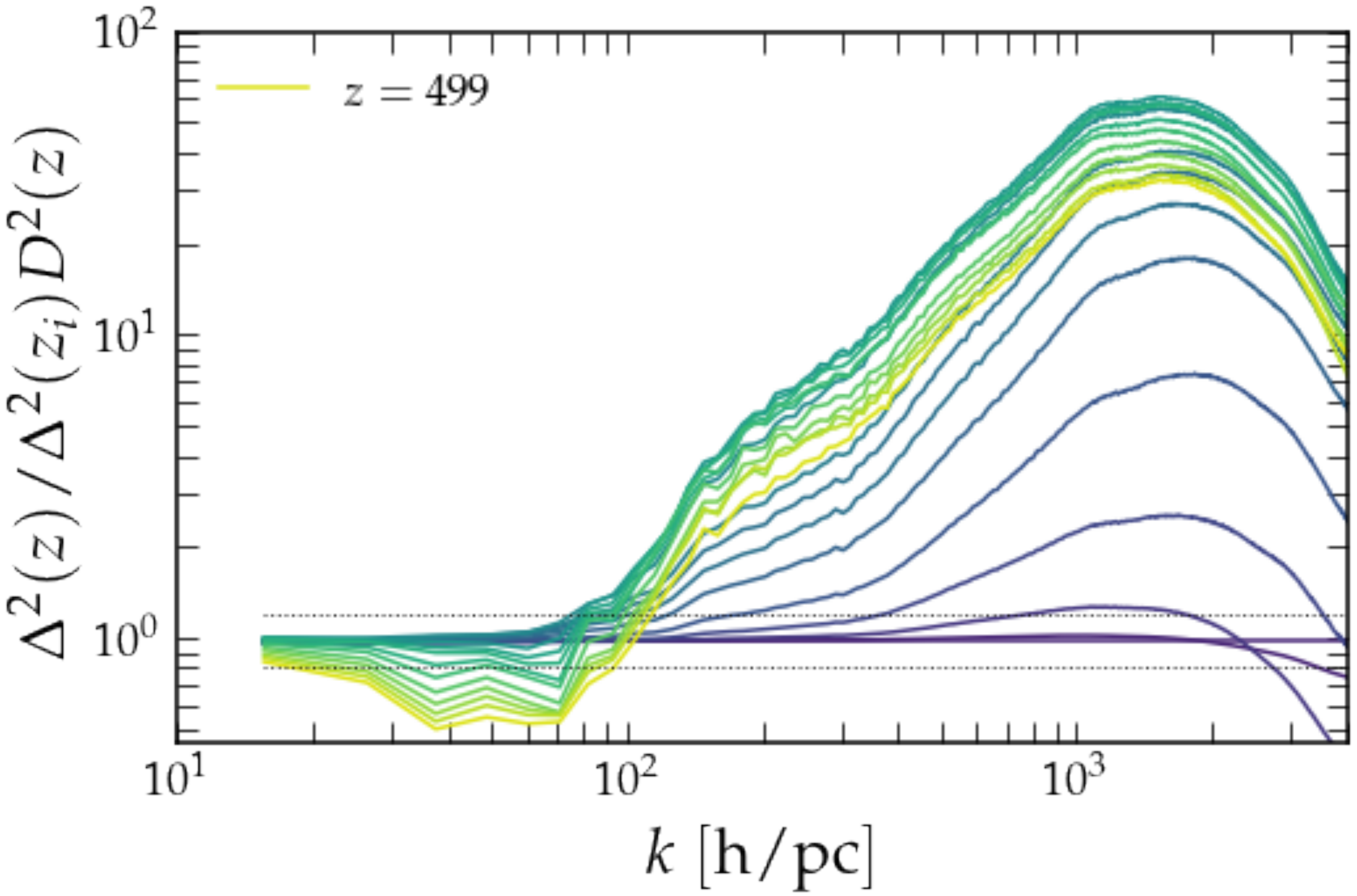
Dotted: prediction from Δ^2 with cutoff

Pierobon+ [2307.]

N-body limitation: box size



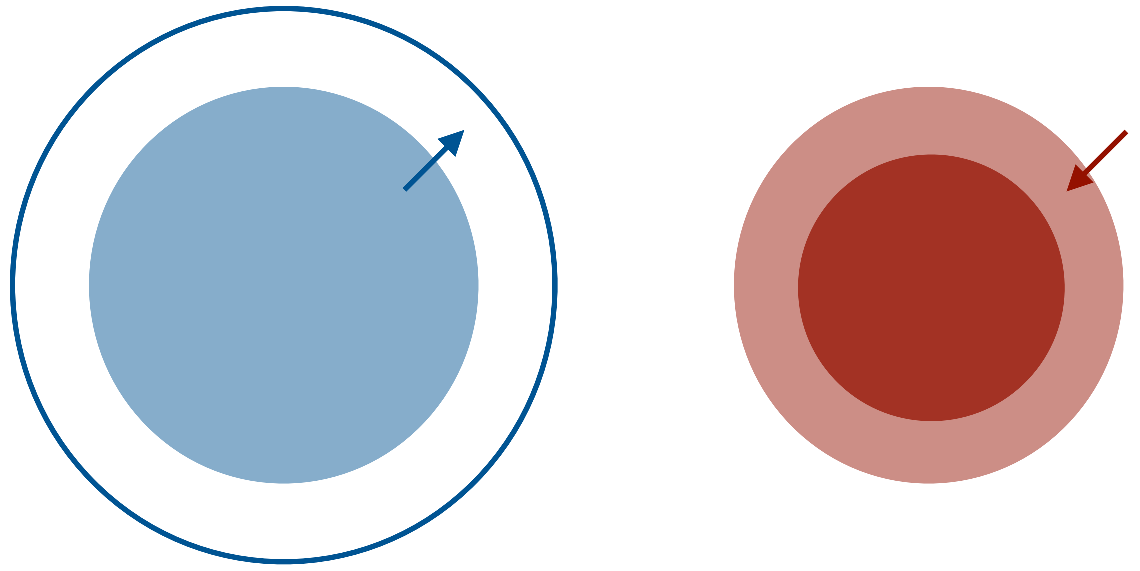
Ratio between simulation and linearly evolved spectrum



Axitons

Oscillons
Pseudo-breathers solutions

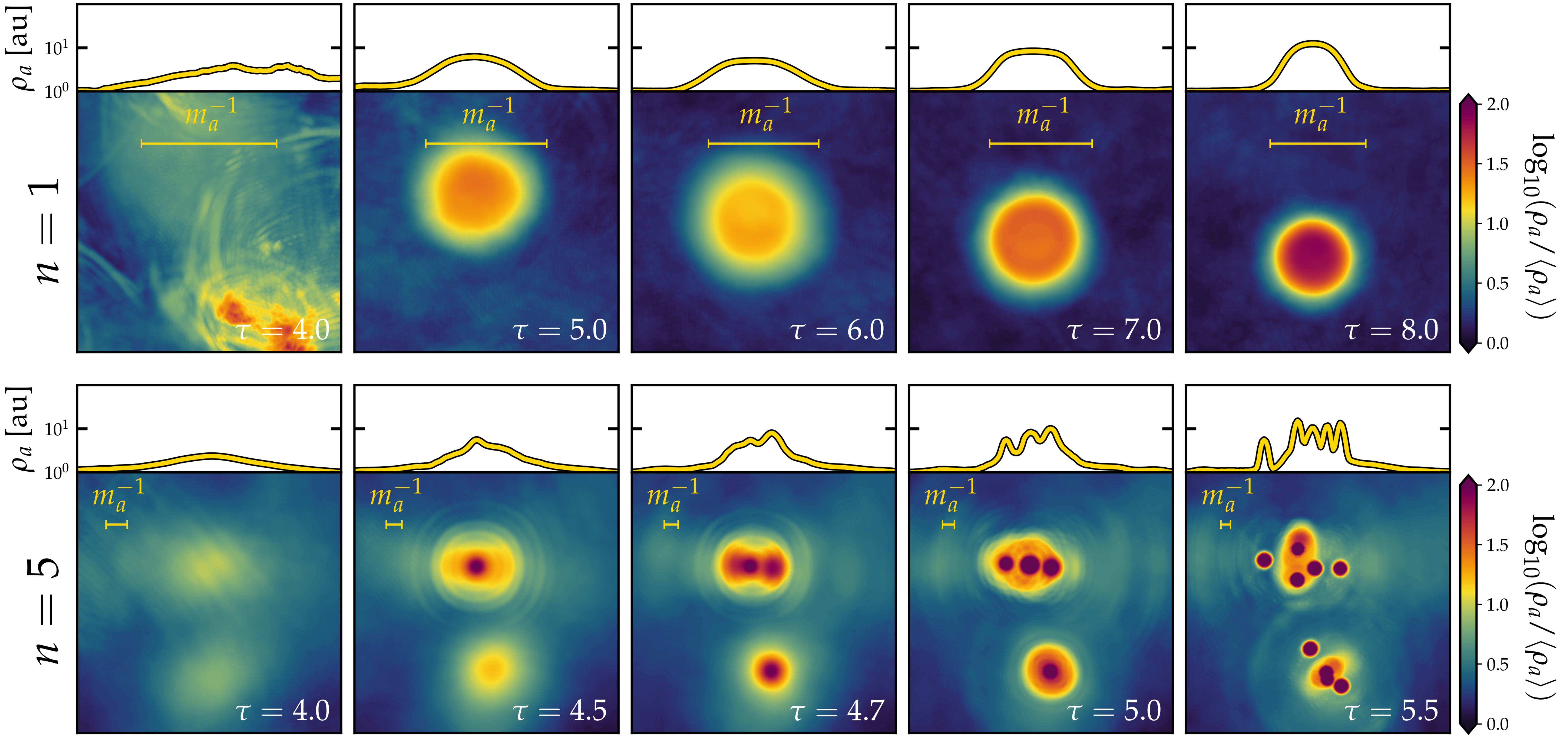
$$V = \chi(1 - \cos\theta)$$



Gradient pressure

self-interaction

O'Hare, GP, Redondo, Wong, 2021



Limitation from axitons

Final simulation time

$$m_a \Delta_x \lesssim \pi \quad m_a \propto \tau^{n/2}$$

$$\tau_f \sim \Delta_x^{-2/(n+2)}$$