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ARC CENTRE OF EXCELLENCE FOR DARK MATTER

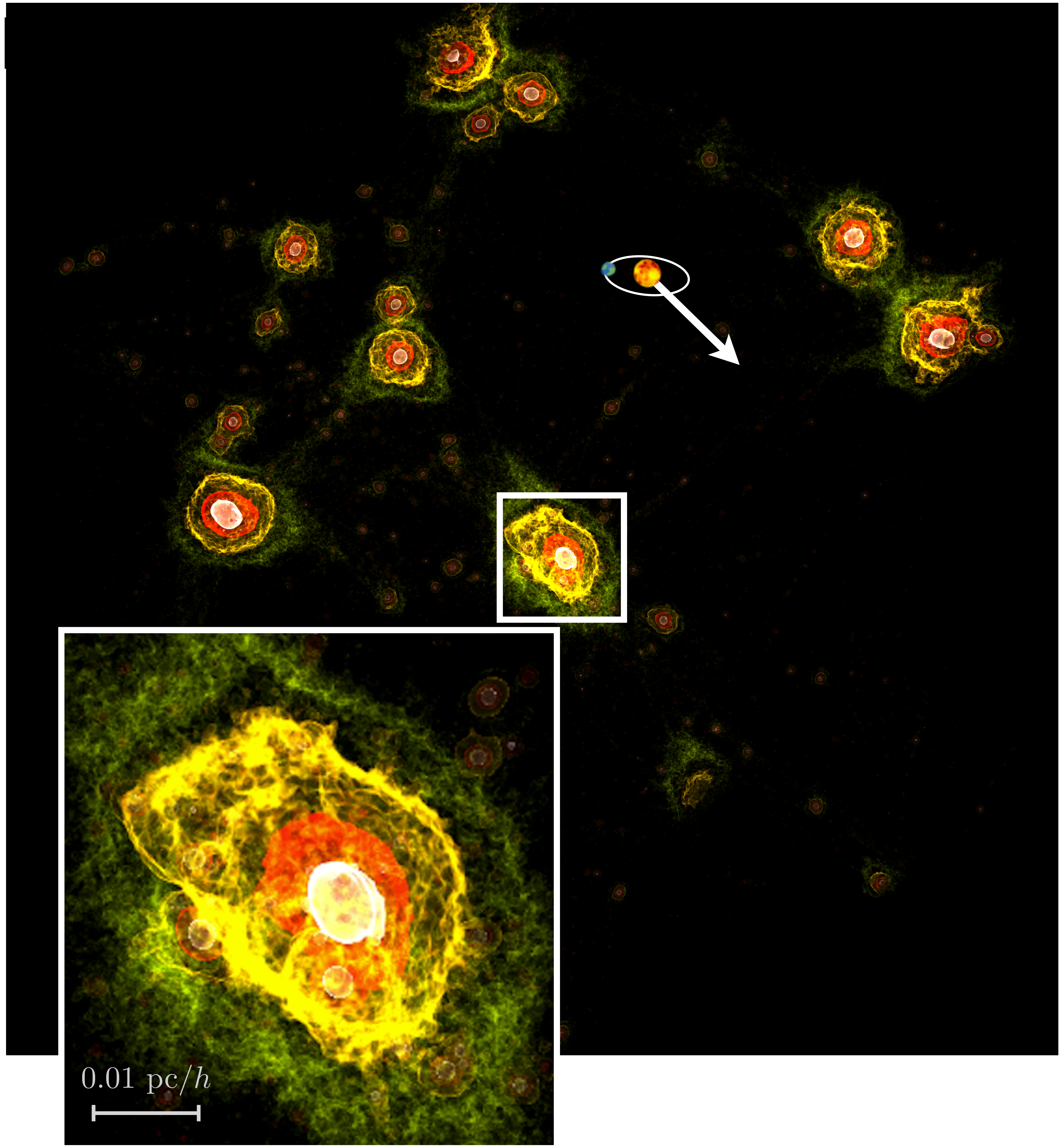
Dark matter substructure in the solar neighbourhood

Ciaran O'Hare
University of Sydney

2212.00560, 2311.xxxxx

All direct detection rests upon the assumption that $\rho_{DM} \approx 0.04\,\mathrm{GeV\,cm^{-3}} \approx 0.01\,M_\odot\,\mathrm{pc^{-3}}$ around the Earth

Eggemeier, CAJO+ [2212.00560]



What if instead DM was bound up in planet/asteroid-mass clumps?

$M_{\rm clump} \gtrsim 10^{-17}\,M_\odot$

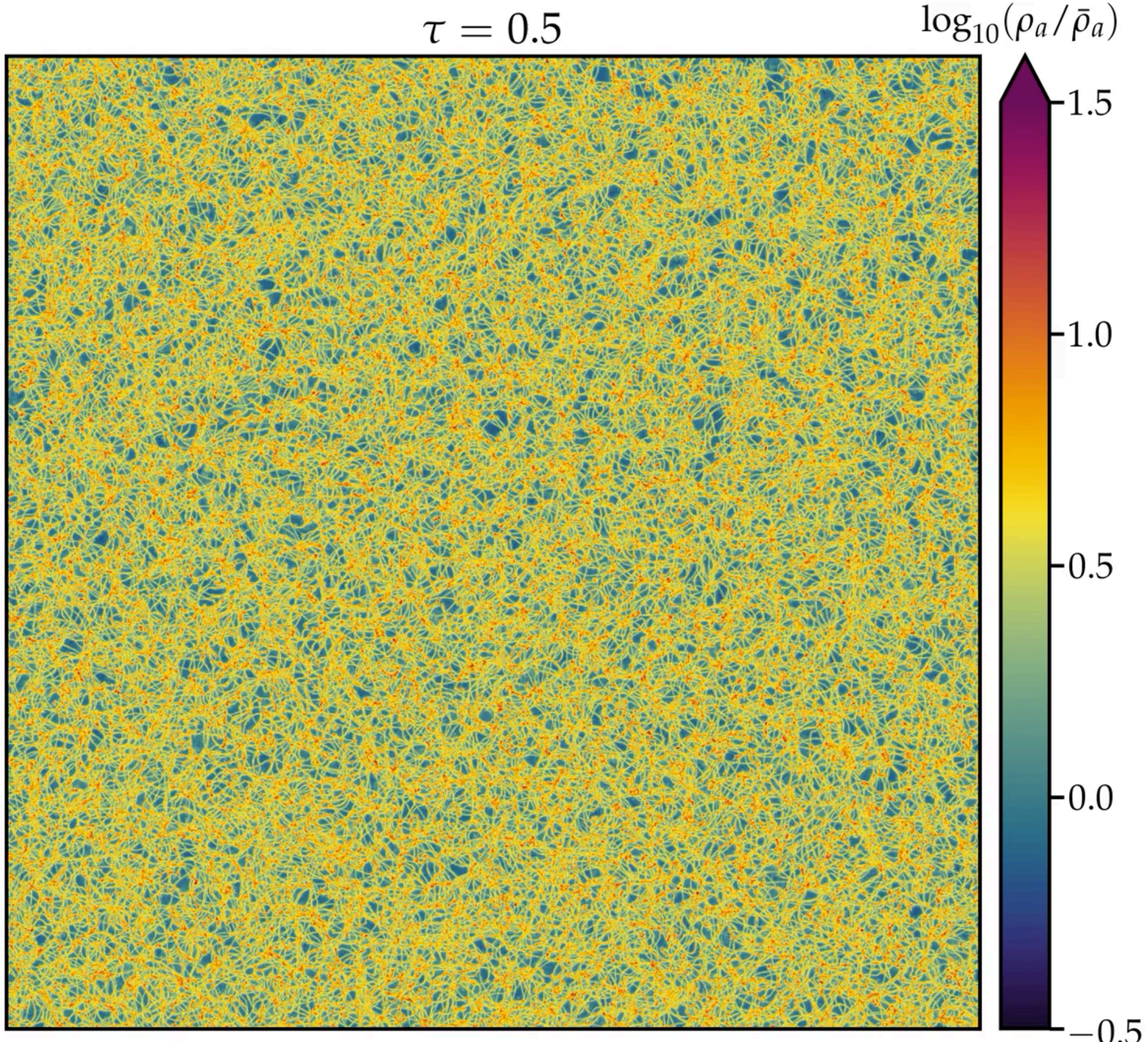
- Astronomical probes measure $\rho_{\rm DM}$ on >100-pc scales, so we would never know any different
- However, we move through the galaxy at a speed of 0.2 milliparsecs/year so the typical value of $\rho_{\rm DM}$ at Earth in this case would be ≈ 0
  → Direct detection is impossible

Are there models where this is the case?

- QCD axions
- Early-matter domination
- Dissipative dark sector

Early-Universe dynamics of QCD axions

In the post-inflationary scenario the axion field undergoes complex multi-scale evolution, leading to topological defects and the eventual collapse of horizon-sized overdensities around the QCD phase transition **in advance of matter-radiation equality**



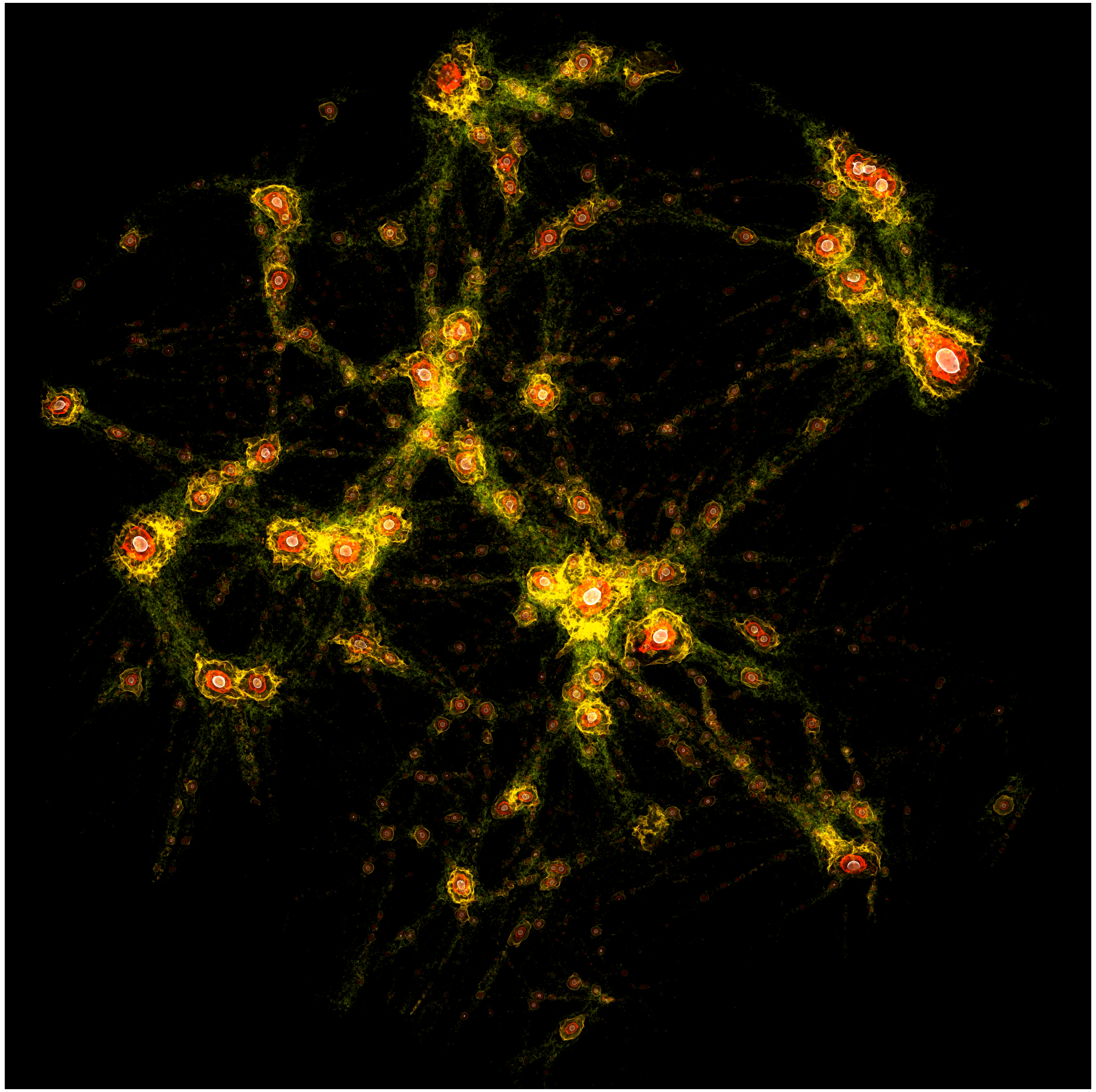
(movie)

Axion miniclusters

Early-Universe inhomogeneities seed AU—mpc clumps of axions with masses $M \in [10^{-16}, 10^{-7}]\ M_\odot$

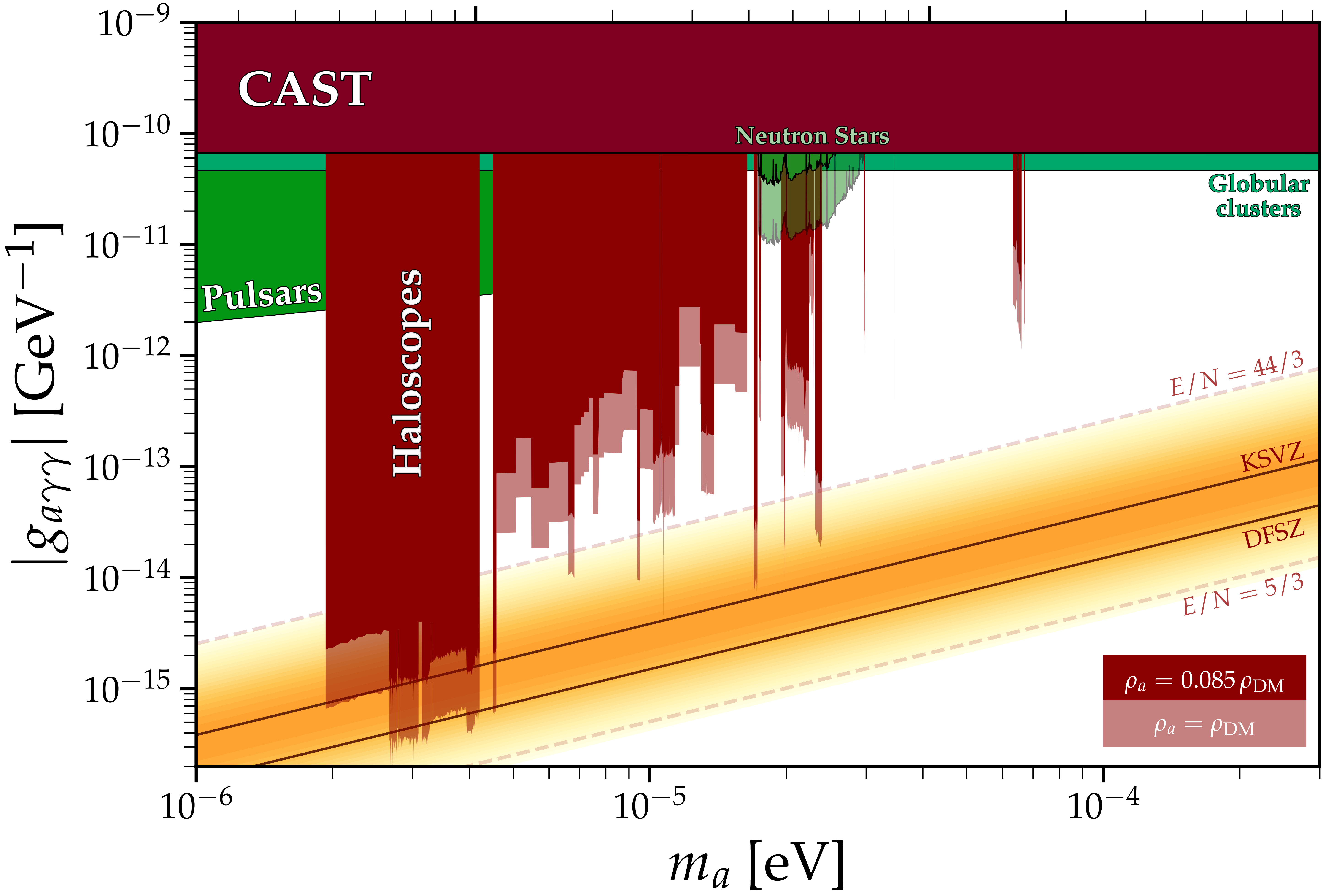
→ axion miniclusters contain over 80% of the DM mass at before galaxy formation, and the density in the “minivoids” is 0–10% of the large-scale $\rho_{\rm DM}$

Eggemeier, CAJO+ [2212.00560]



Why is this a problem for axion direct detection?

→ Axion haloscopes scan the parameter space very slowly.



Sensitivity to a single DM mass point scales with integration time and DM density as:

$$\sqrt{\rho_{\rm DM}}\, g_{a\gamma} \propto \frac{1}{\sqrt[4]{T}}$$

Usually assume $\rho_{\rm DM} = 0.4\,\mathrm{GeV/cm^3}$, but if the actual local value is only ~10% of this, then most experiments do not even reach the QCD band.

The goal of our study:

How substantial is the degree of axion substructure in the solar neighbourhood *today*?

Or…

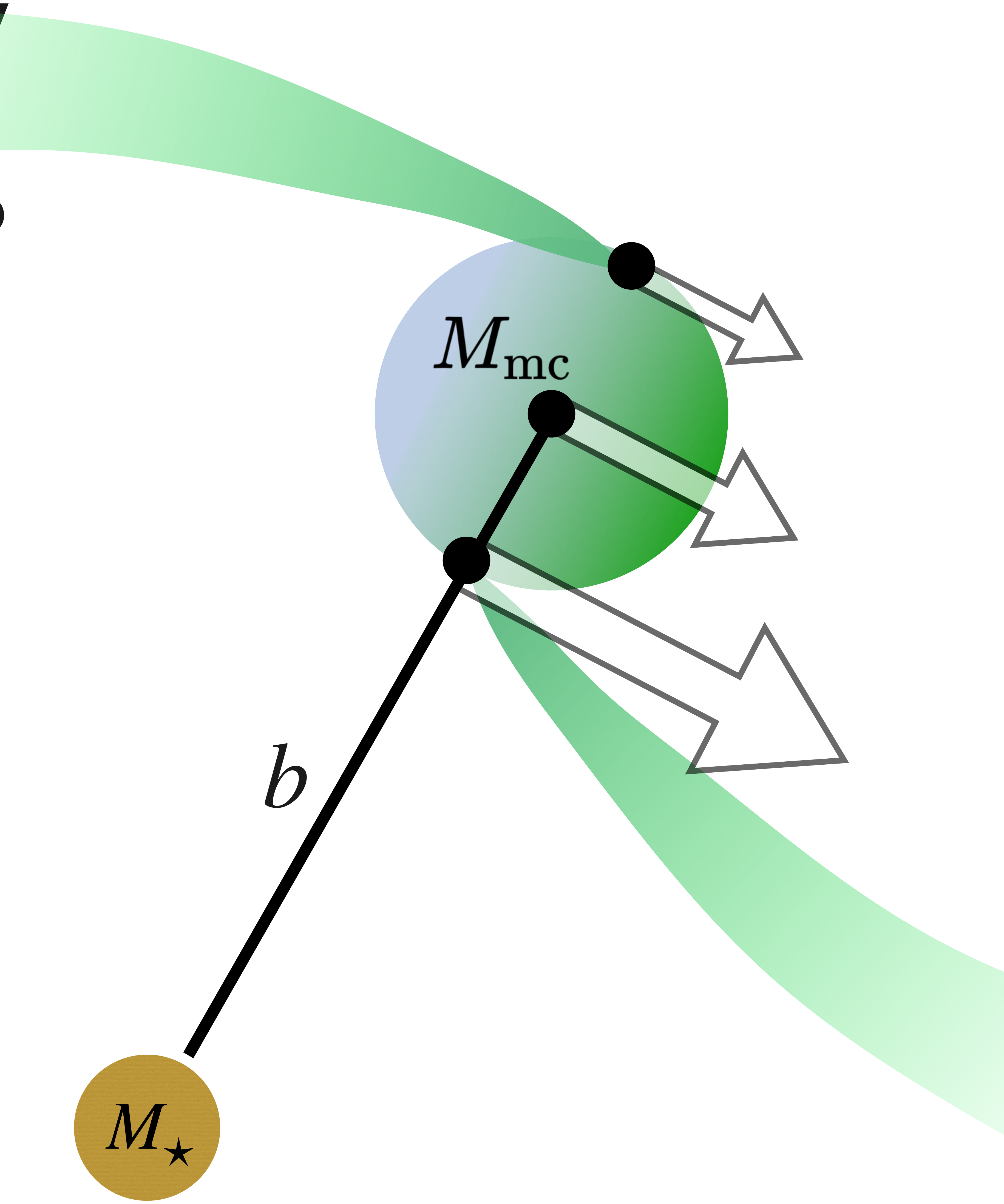
Are axion haloscopes doomed to never discover the axion, even if it exists?

Dark matter doesn't stay clumpy

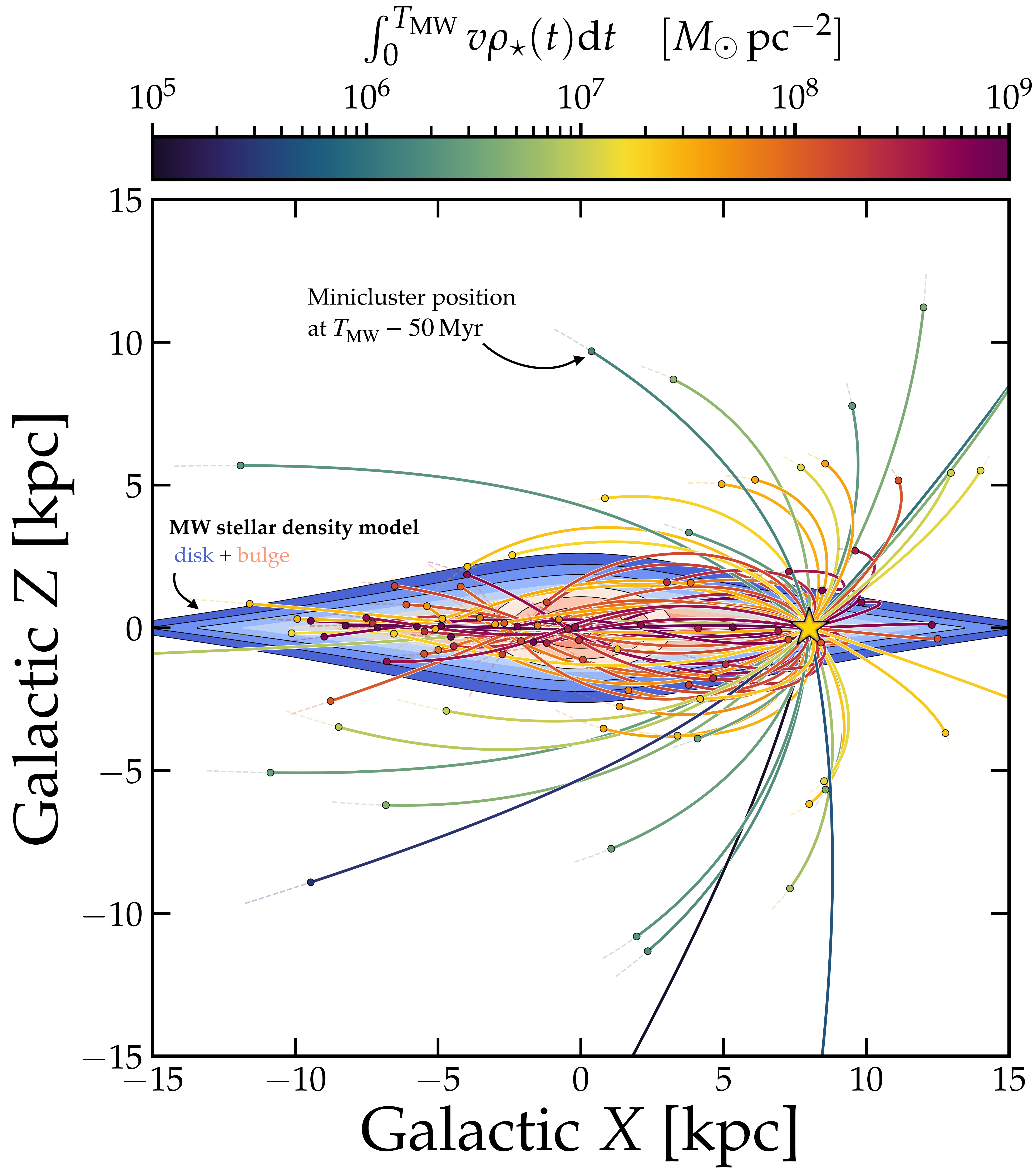
- Loosely bound substructures are susceptible to tidal disruption by stars:

Energy injected into minicluster: $$\Delta E \approx \left(\frac{2GM_\star}{b^2 V}\right)^2 \frac{M_{\rm mc}\langle R^2\rangle}{3}$$

- Axions with E>Binding energy will evaporate away and be elongated by tidal field of MW into a **stream**
- These tidal spread over a large volume and might collectively **re-fill the DM distribution**



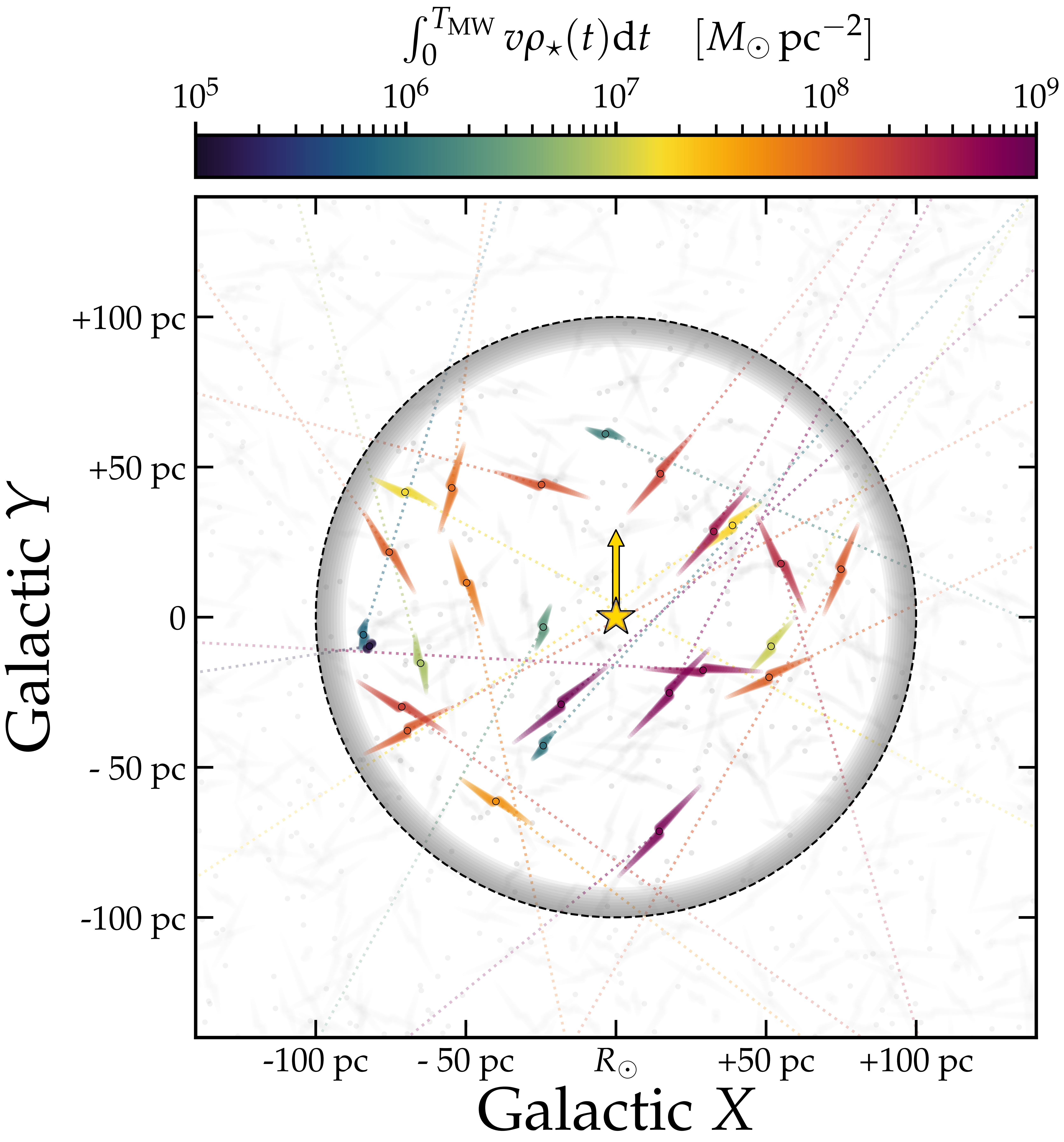
See e.g., Tinyakov+ [1512.02884], Kavanagh+ [2011.05377]



N-body → Monte Carlo tidal disruption simulation

Step 1

Integrate many minicluster orbits that all end in the solar neighbourhood today. In each case we compute how many stellar encounters each miniclister will undergo



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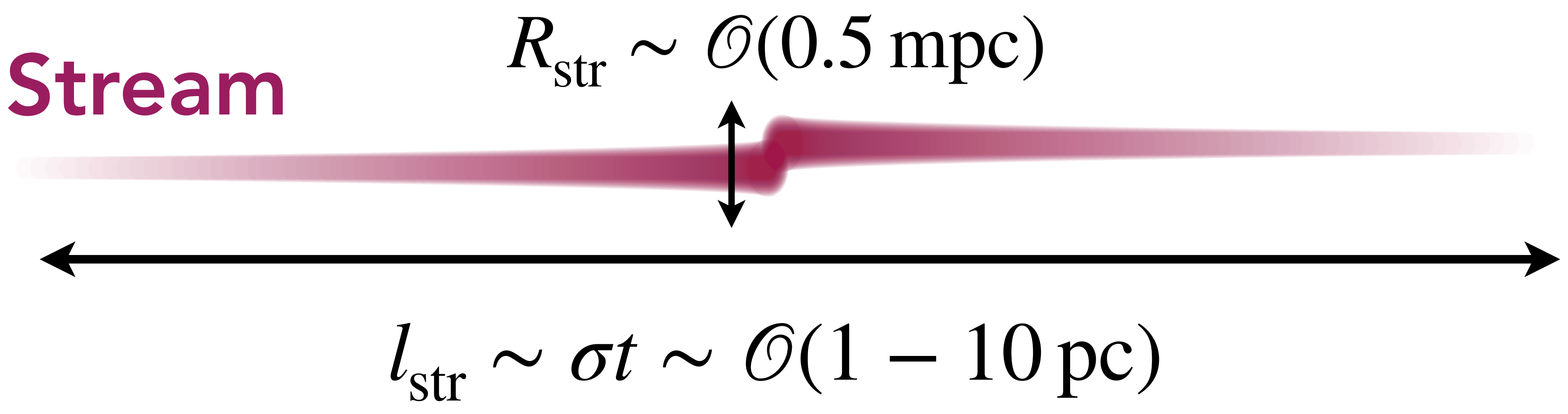
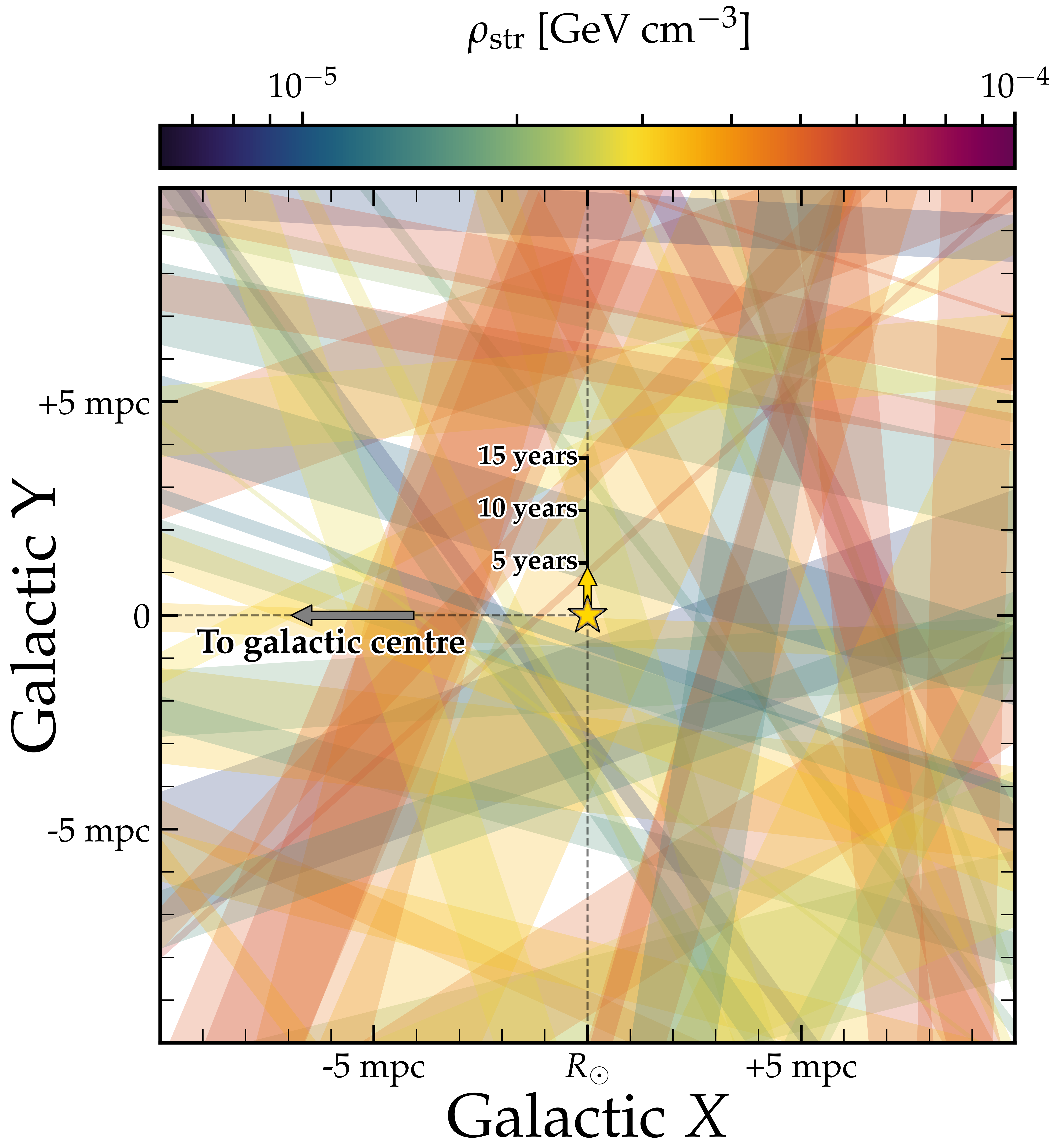
Step 2

Model the formation of pc-long streams of unbound axions due to the energy injection from stars and tidal elongation by the MW





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Step 3

Sum up the network of overlapping streams to quantify how much the DM distribution is re-filled due to their disruption

The result:

Local density sampled at a random point in the solar neighbourhood is given by the sum of several hundreds to thousand minicluster streams.

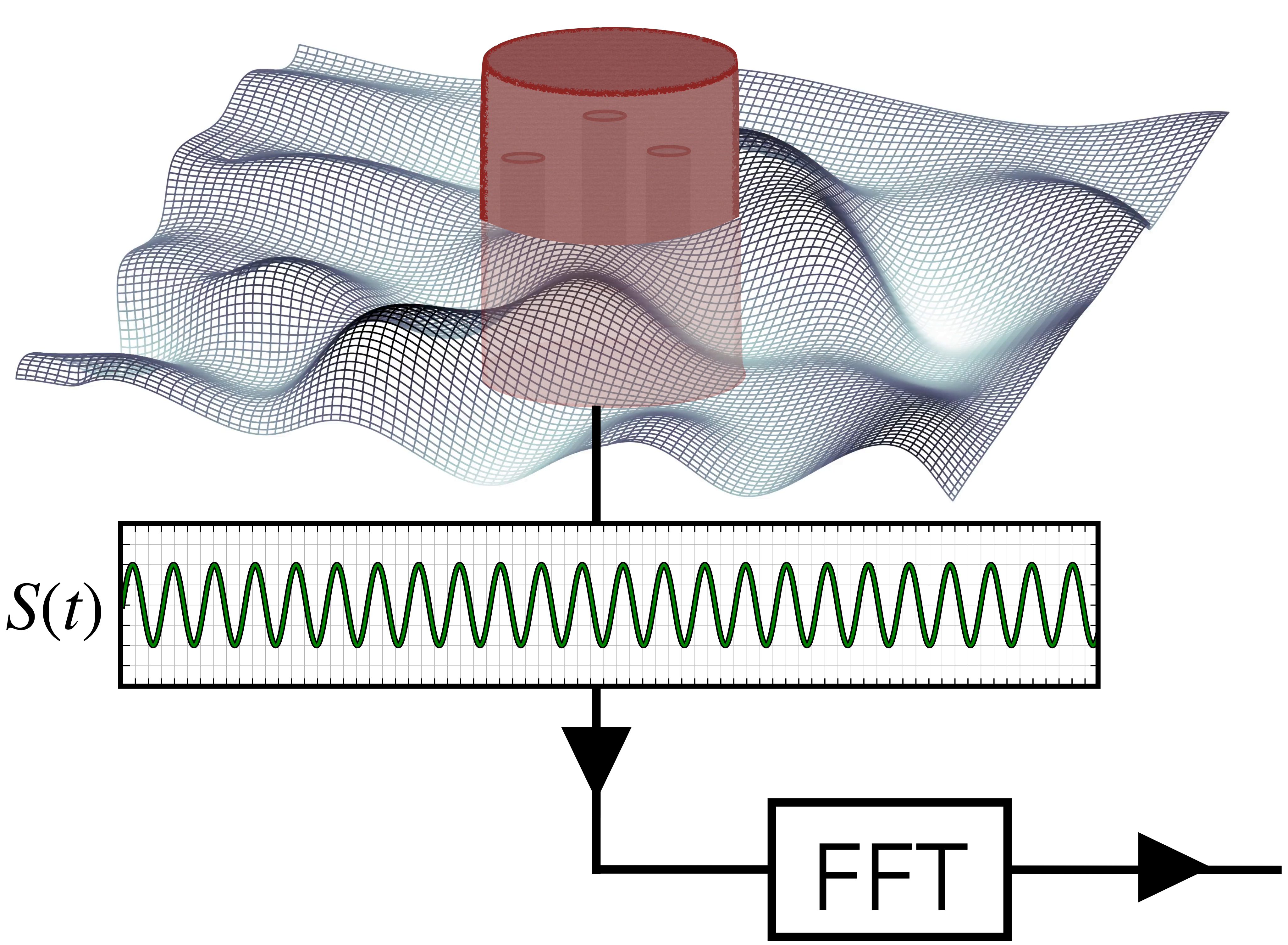
Relative to the known DM density measured on O(100)-pc scales ($\rho_{\rm DM} \approx 0.4$ GeV/cc), collectively these streams add up to:

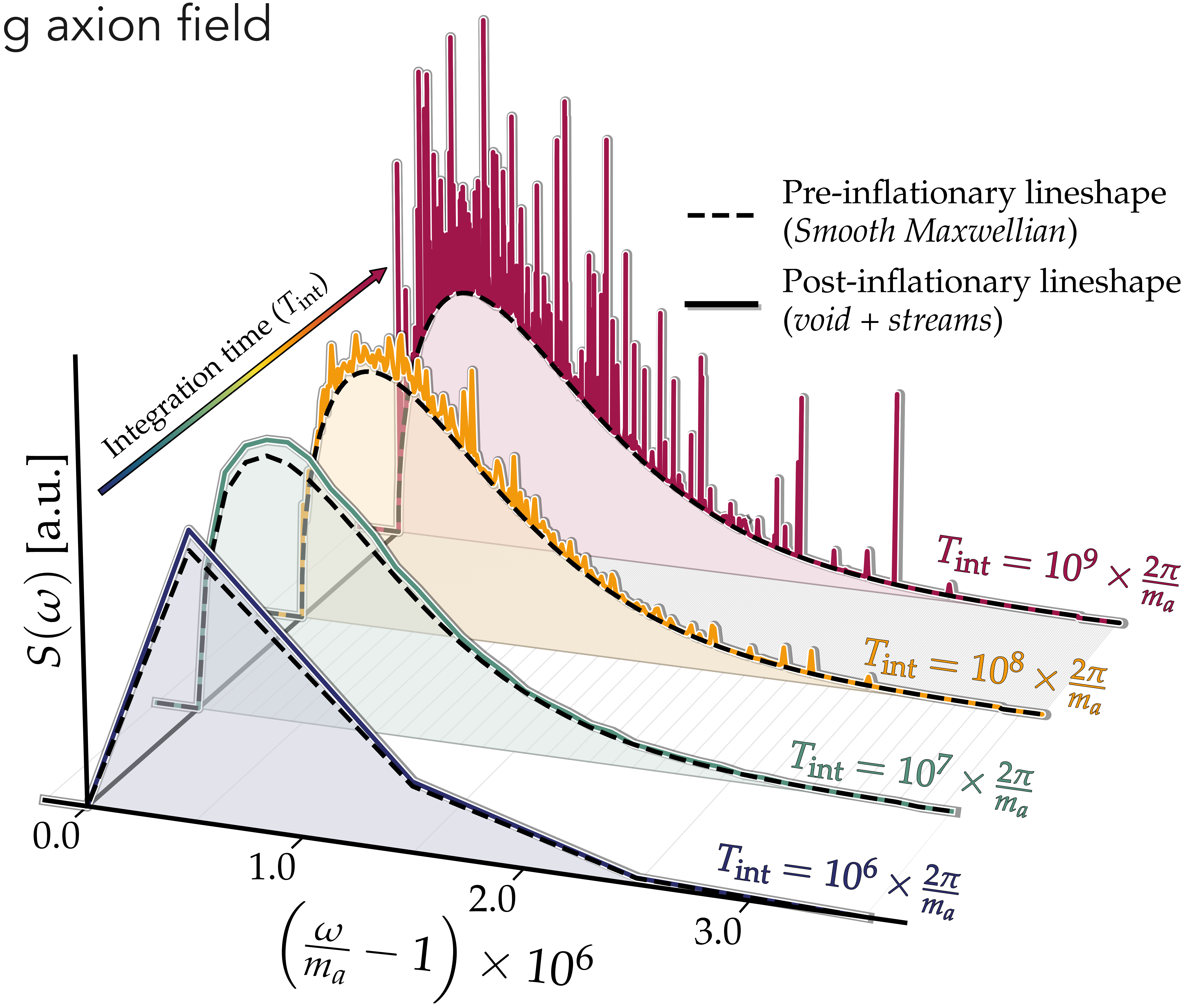
$$\frac{1}{\rho_{\rm DM}} \sum_{i=1}^{N_{\rm str}} \rho^i_{\rm str} = 81 \pm 6\%$$

Therefore: Haloscopes are not doomed, there is only a suppression of 0.8 compared to the standard assumption.

Axion haloscopes can test this scenario directly

→ Experiment couples to the oscillating axion field





Power spectrum $S(\omega)$, of these oscillations is the DM velocity distribution. In our scenario, $S(\omega)$ is intrinsically spiky due to the sum of hundreds of streams

(see also A. Quiskamp talk yesterday)

Summary

- **Miniclusters are a prediction of QCD axions under the post-inflationary scenario**, so their consequences for direct detection cannot be ignored.
- However, once accounting for tidal disruption, the phase space density at the Solar position is almost completely refilled, to about 80% of $\rho_{\rm DM}$
- $\mathcal{O}$(100-1000) ultra-cold tidal streams present in axion lineshape at any one time that persist for $\mathcal{O}$(years) at a time and would be revealed immediately when the axion is discovered

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