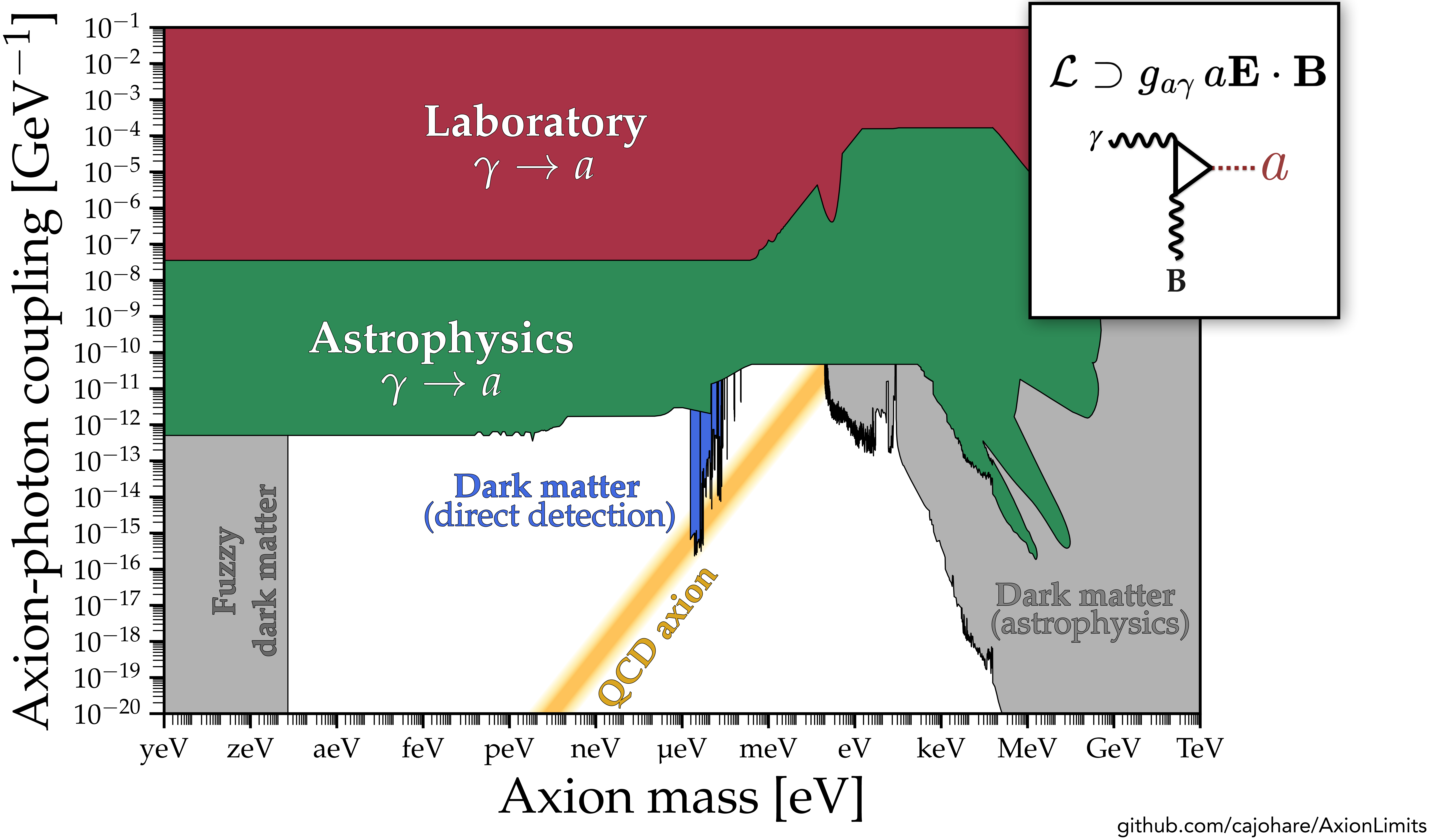
THE UNIVERSITY OF SYDNEY

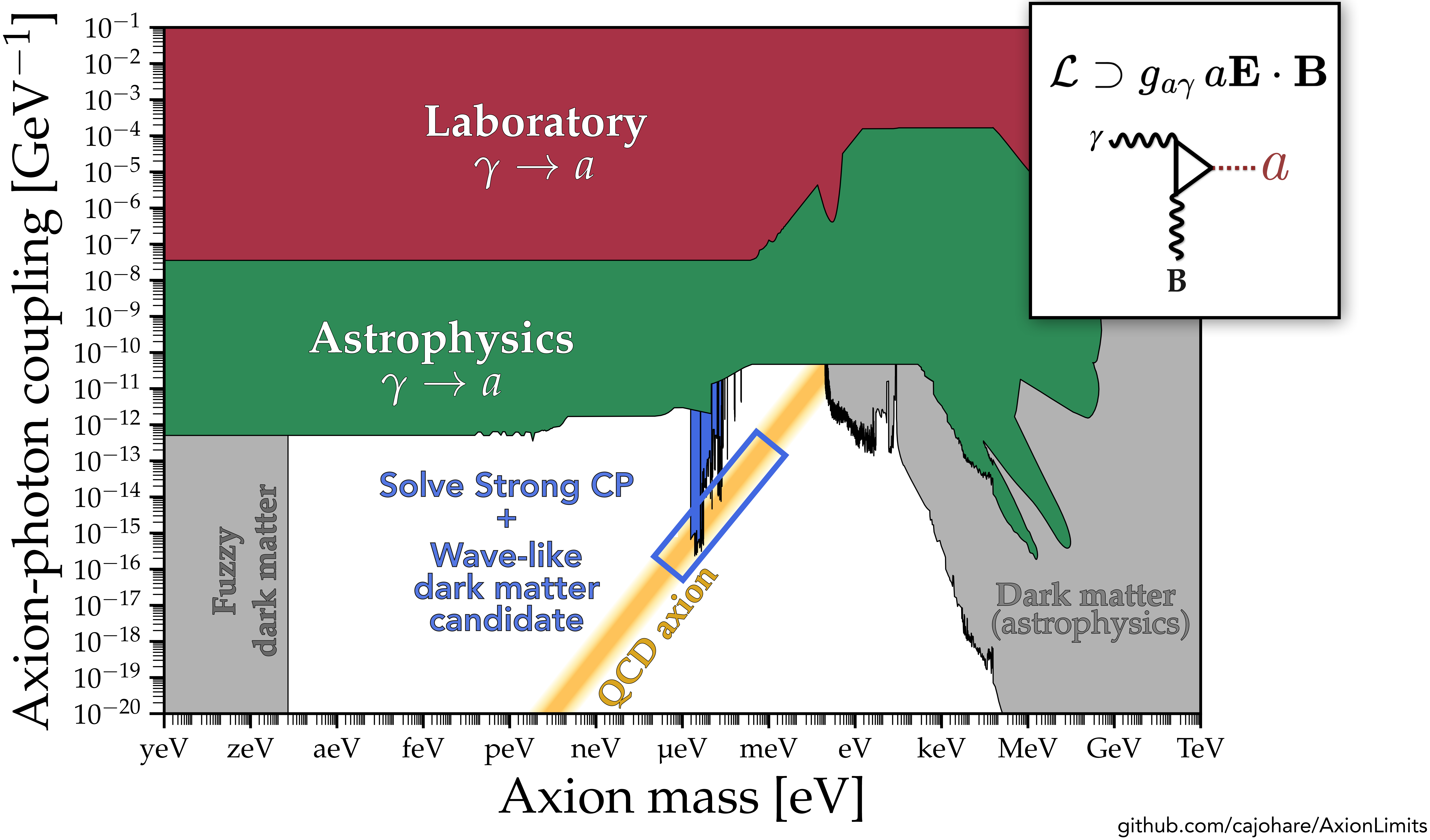
ARC CENTRE OF EXCELLENCE FOR DARK MATTER

# Axion dark matter: late-Universe implications of early-Universe physics

Ciaran O'Hare
University of Sydney



Laboratory
$\gamma \rightarrow a$
Astrophysics
$\gamma \rightarrow a$
Dark matter
(direct detection)
QCD axion
Fuzzy
dark matter
Dark matter
(astrophysics)
$\mathcal{L} \supset g_{a\gamma}\, a\mathbf{E}\cdot\mathbf{B}$
$\gamma$
$a$
B
Axion-photon coupling [GeV$^{-1}$]
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
$10^{-17}$
$10^{-18}$
$10^{-19}$
$10^{-20}$
yeV
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
Axion mass [eV]
github.com/cajohare/AxionLimits



Laboratory
$\gamma \to a$
Astrophysics
$\gamma \to a$
Solve Strong CP
+
Wave-like
dark matter
candidate
QCD axion
Fuzzy
dark matter
Dark matter
(astrophysics)
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$\gamma$
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Axion-photon coupling [GeV$^{-1}$]
Axion mass [eV]
yeV
zeV
aeV
feV
peV
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keV
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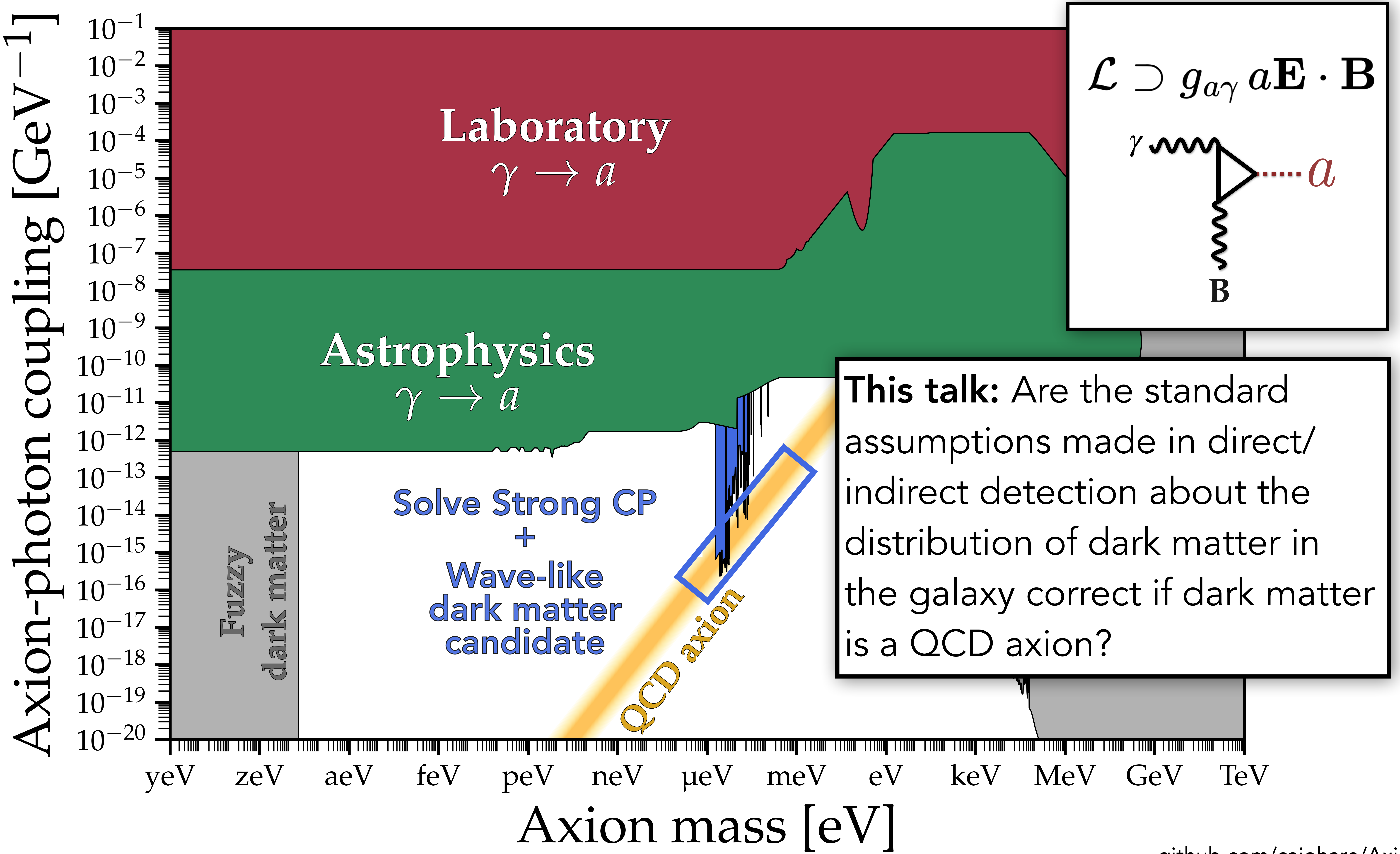
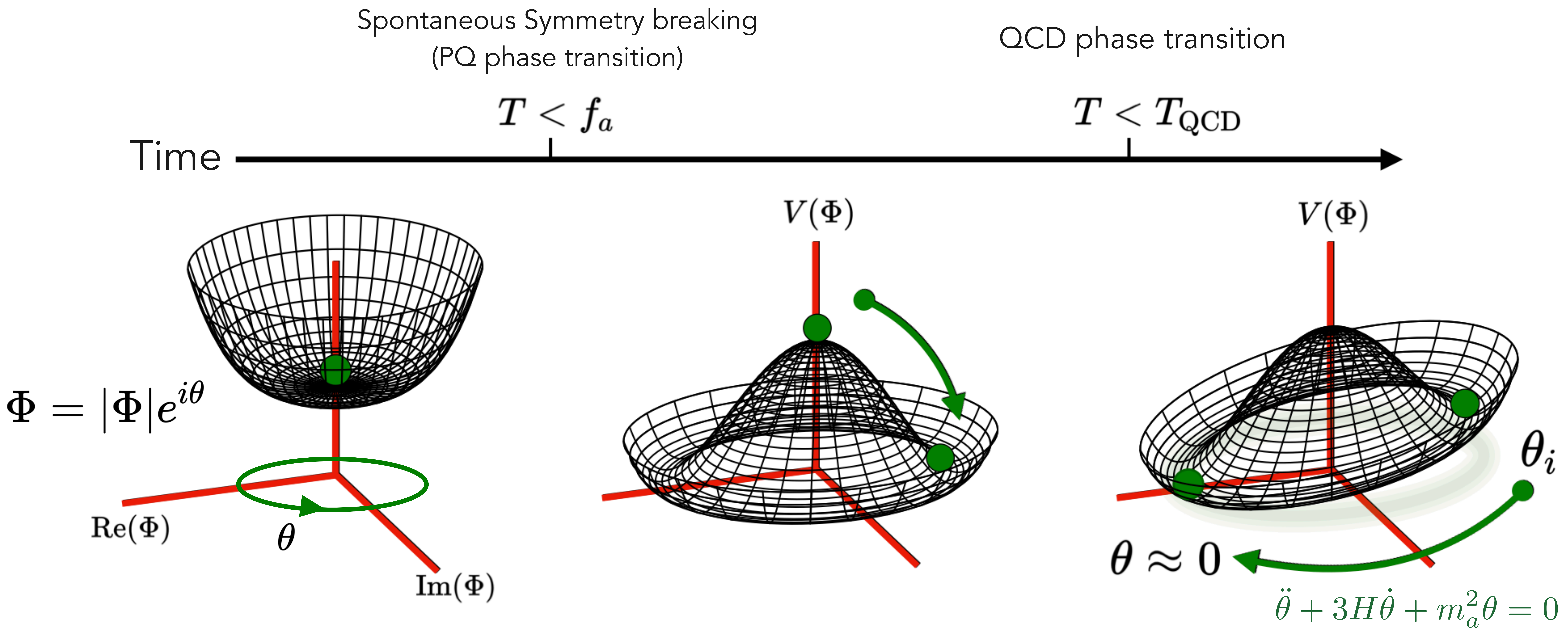



**This talk:** Are the standard assumptions made in direct/ indirect detection about the distribution of dark matter in the galaxy correct if dark matter is a QCD axion?

github.com/cajohare/AxionLimits

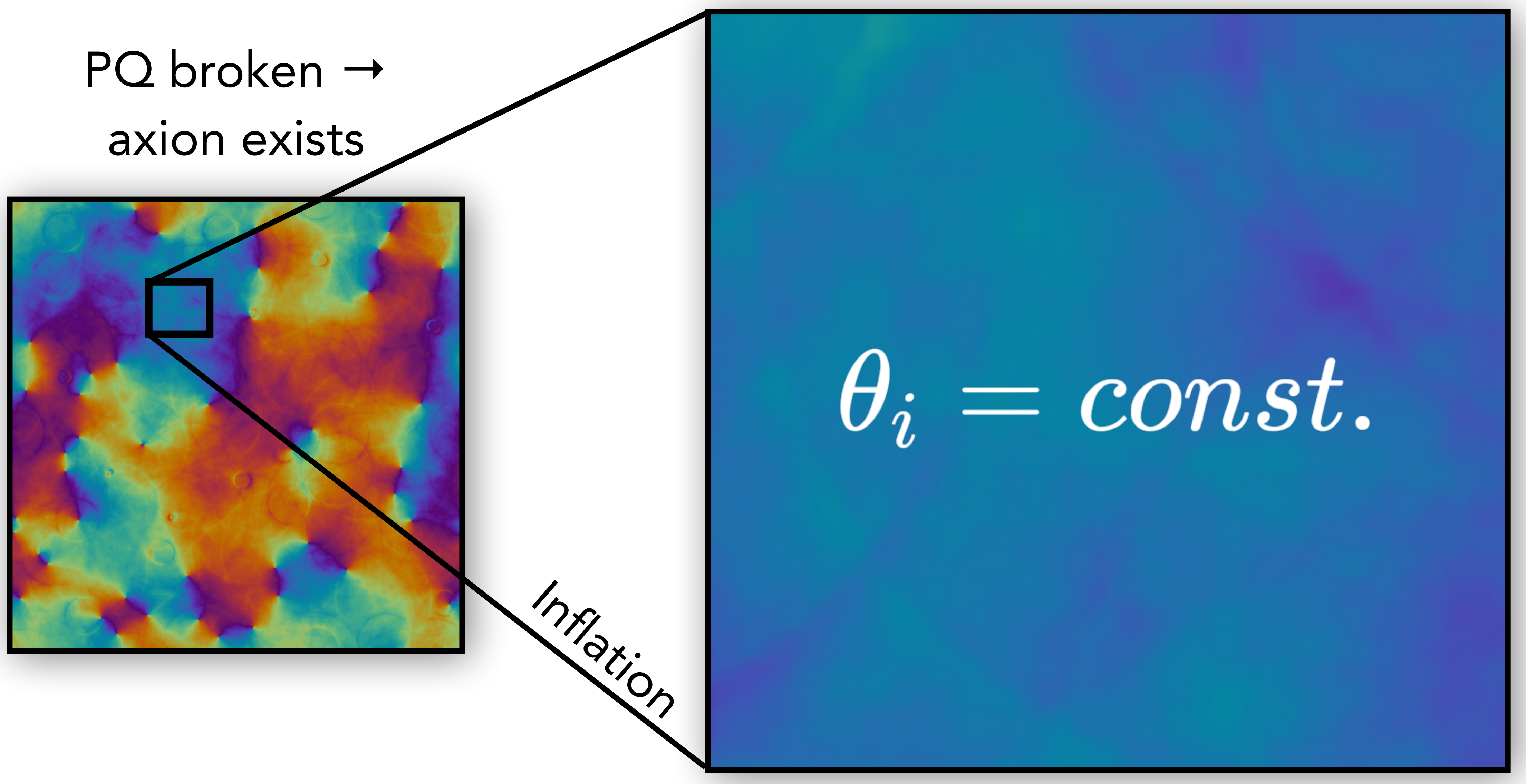
# Production of QCD axion DM: The misalignment mechanism




Present-day abundance of axions controlled by initial angle: $\Omega_a \propto \theta_i^2$

# When did inflation happen?

**Scenario 1:**
SSB *before* inflation




**Pre-inflationary scenario**

# When did inflation happen?

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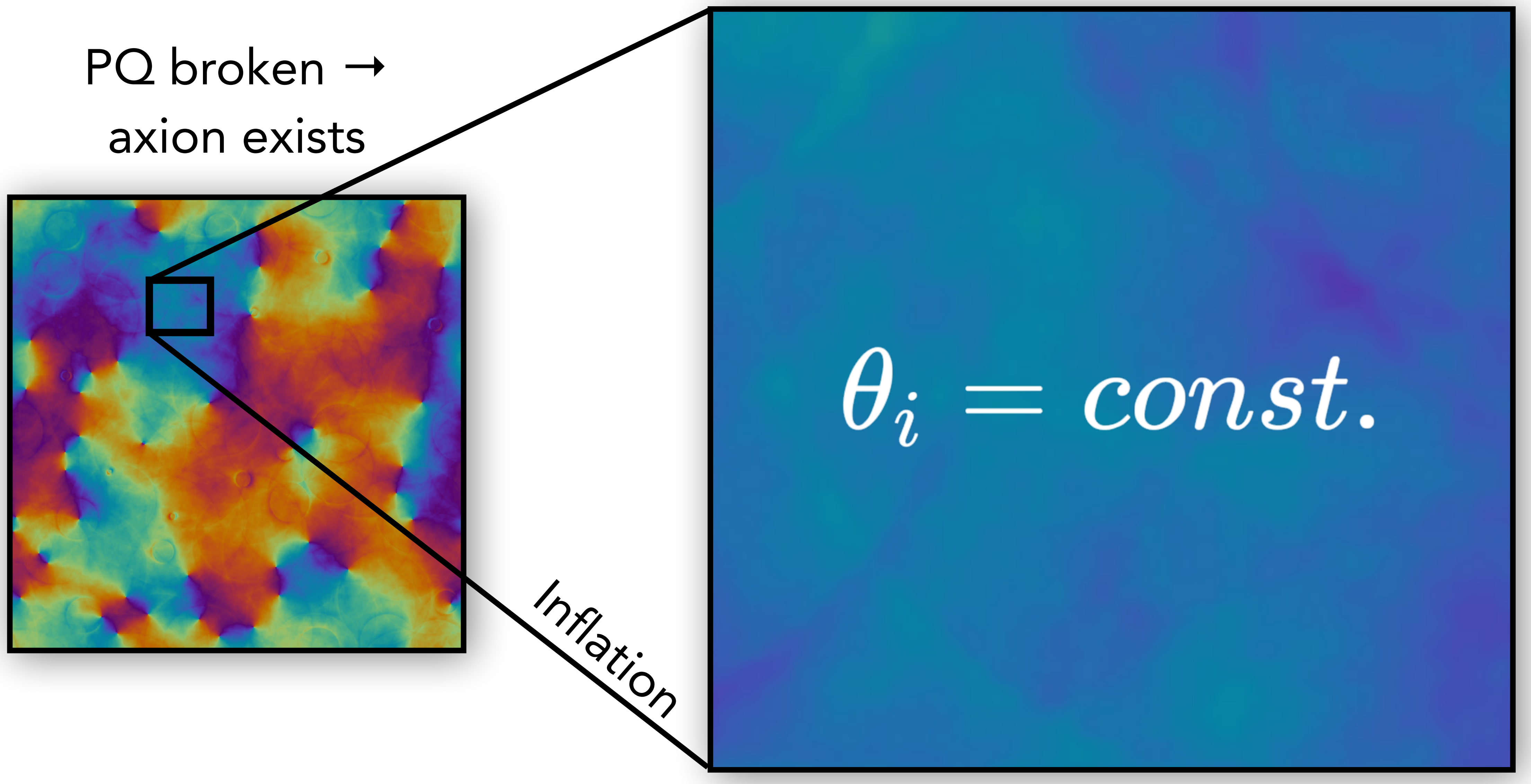
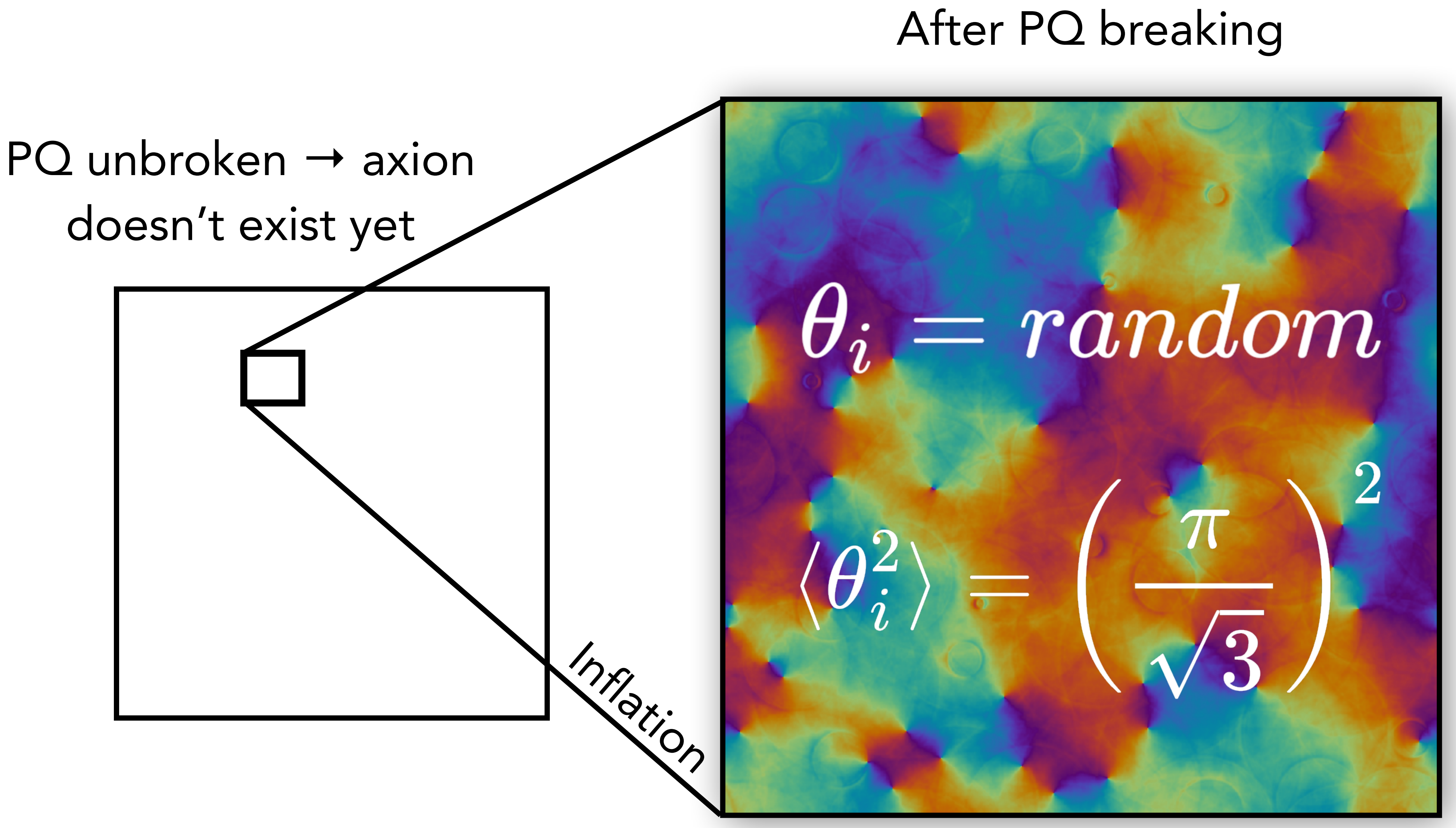



**Pre-inflationary scenario**

## Scenario 2:
SSB *after* inflation

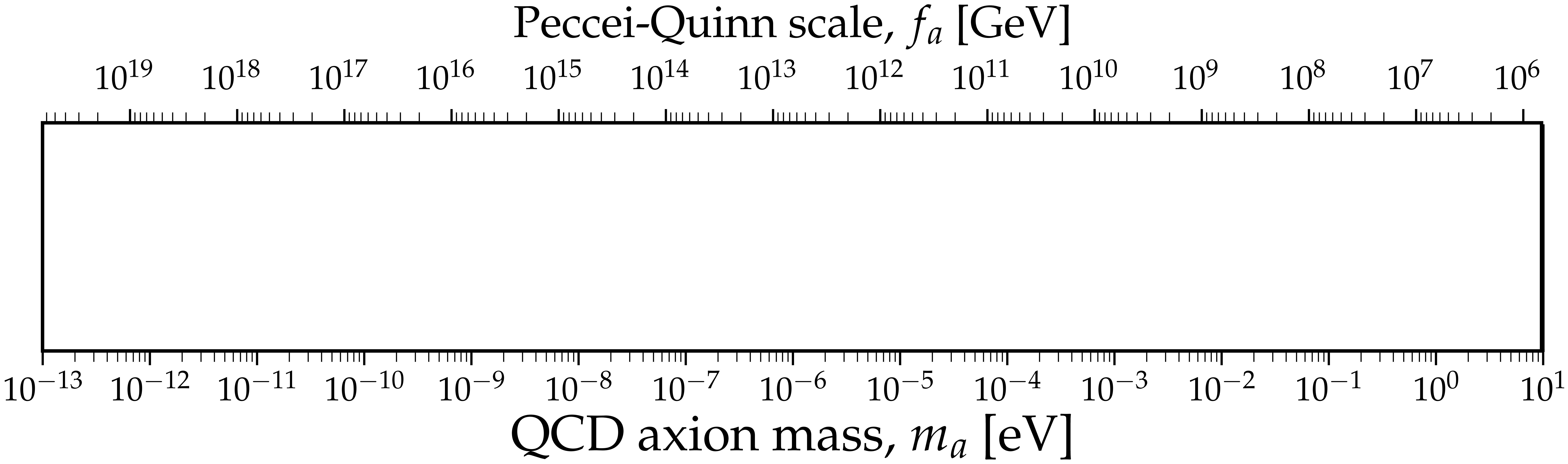



**Post-inflationary scenario**

# Scenario 2: *Post*-inflationary axion

Predictable DM abundance dependent on a single parameter (axion mass)

$$\Omega_a h^2 \approx 0.12 \frac{\langle \theta_i^2 \rangle}{(1.81)^2} \left( \frac{20\mu\text{eV}}{m_a} \right)^{1.17}$$



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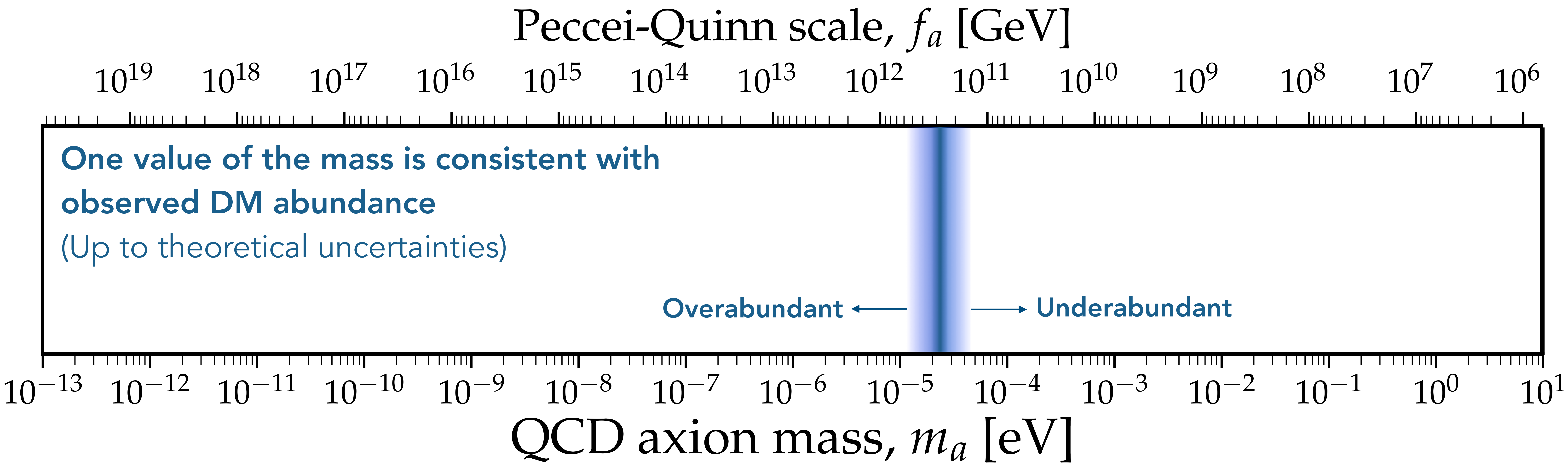
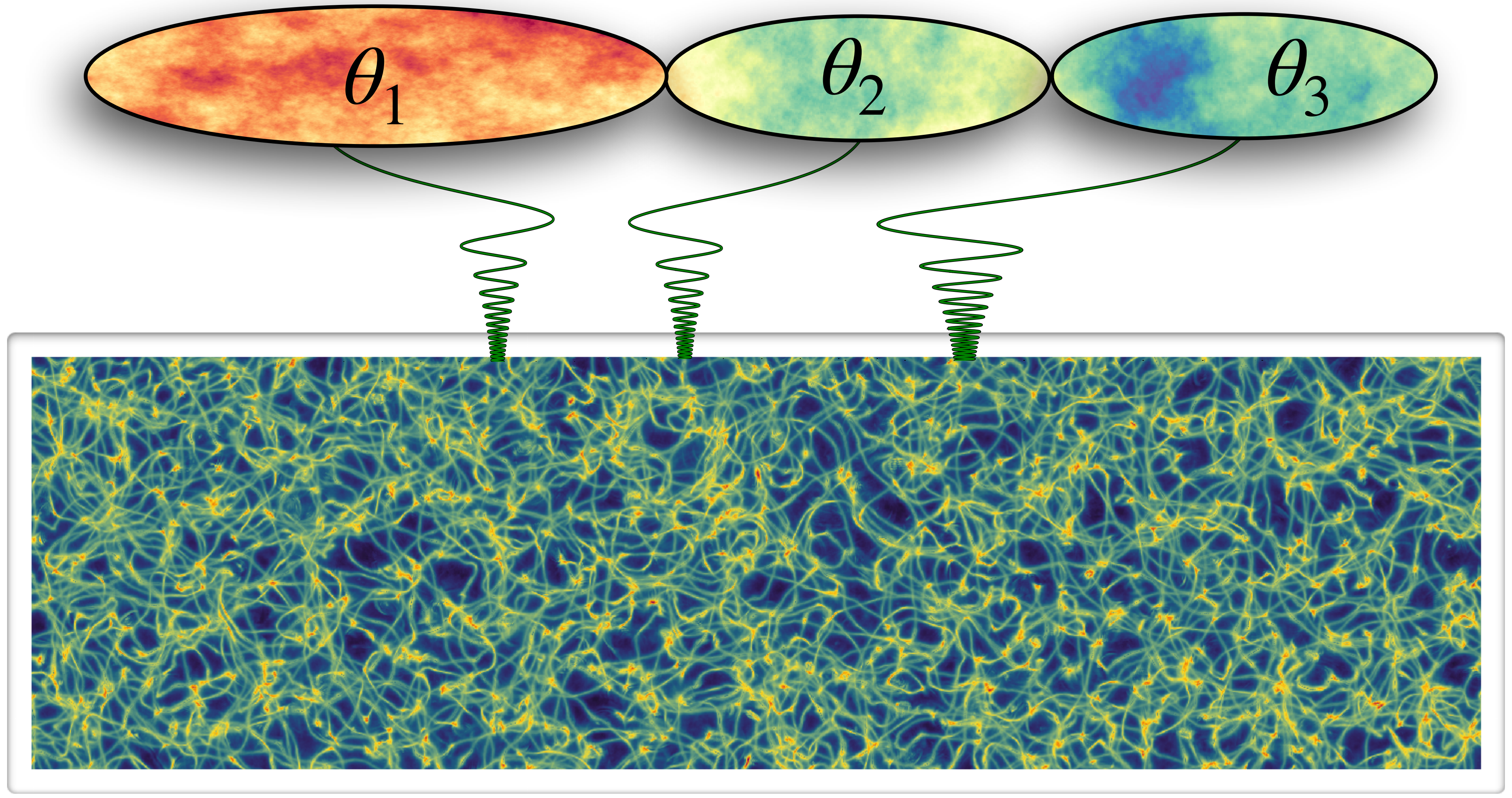


# **Uncertainties:** $\nabla\theta$ and topological defects




→ Field gradients!

$$\longleftarrow \quad \ddot{\theta} + 3H\dot{\theta} \boxed{- \frac{1}{a^2}\nabla^2\theta} + m_a^2\theta = 0$$

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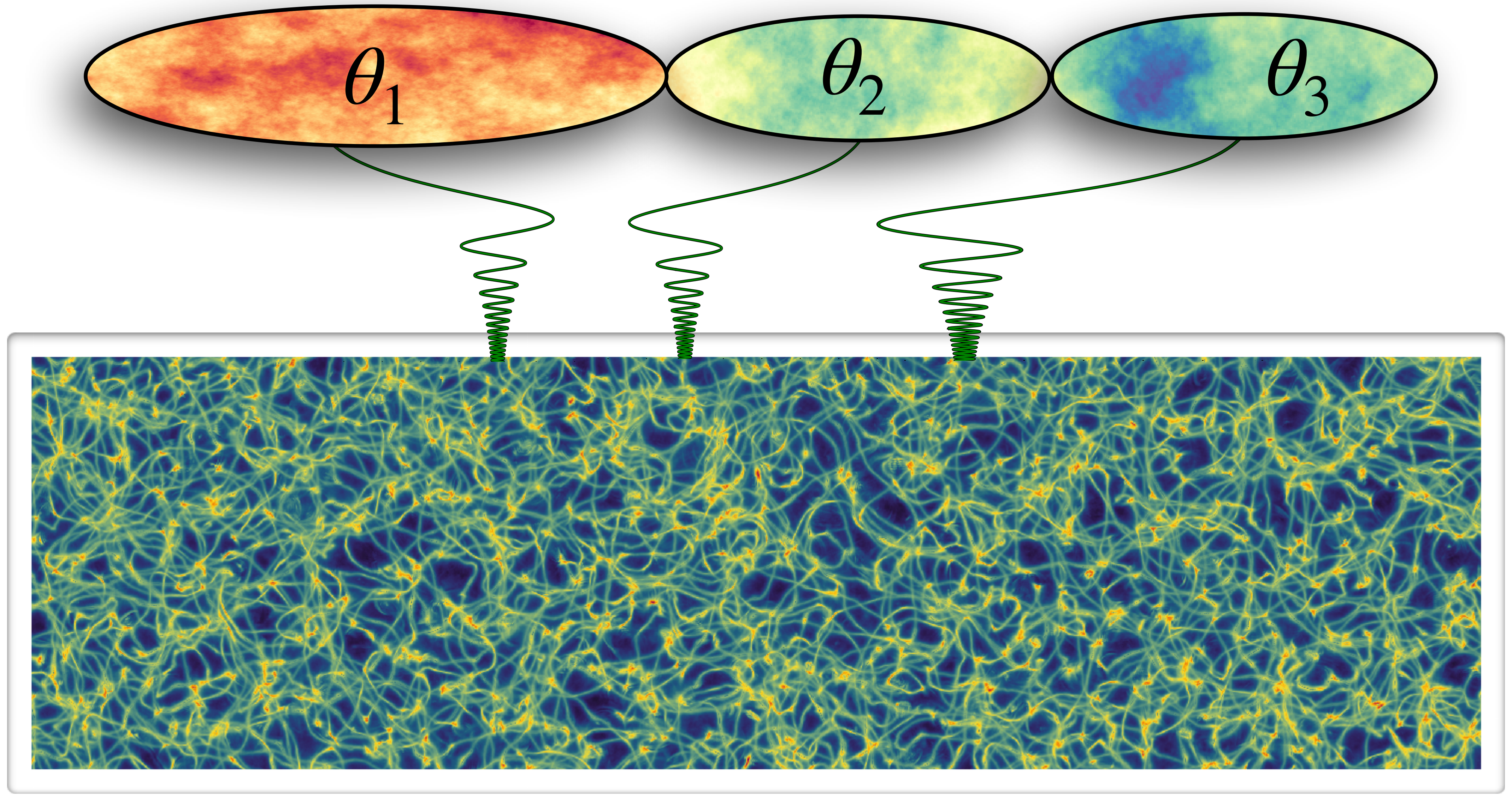


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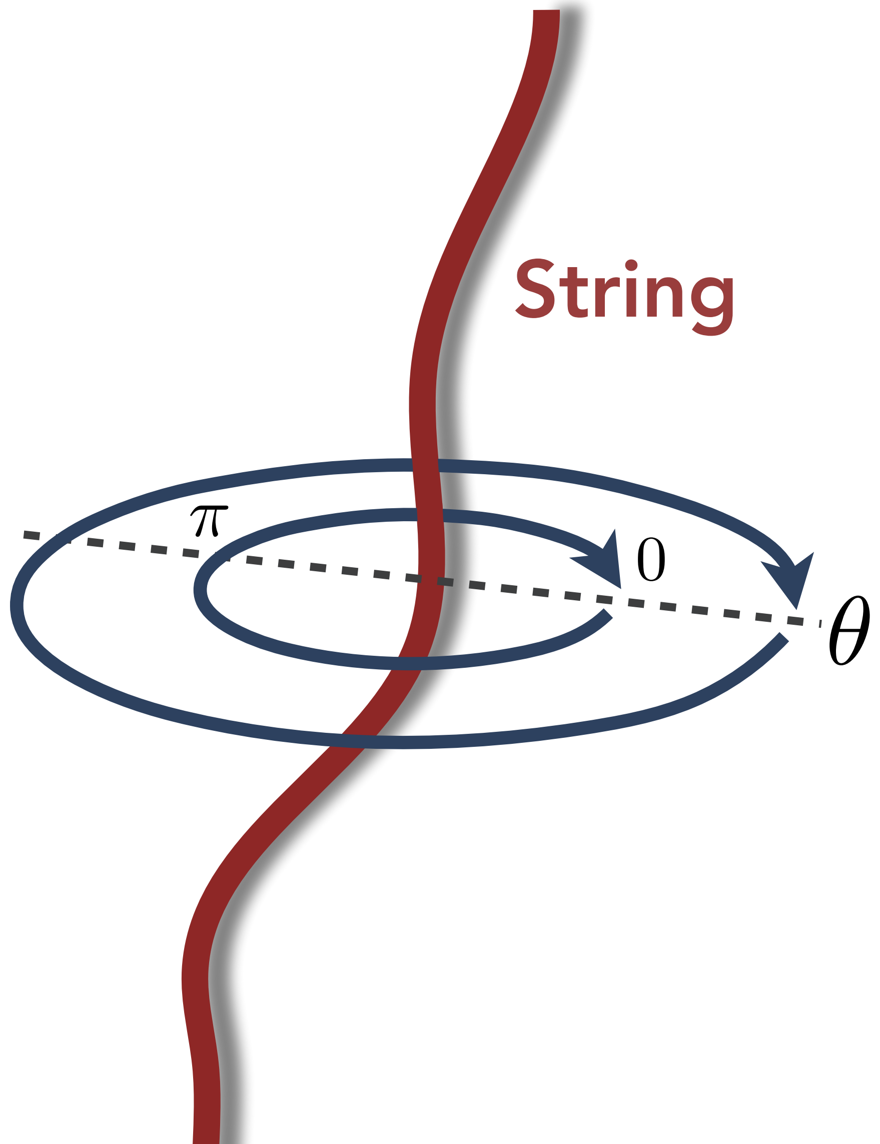
⇒ **Cosmic strings**

from axion field winding around $2\pi$



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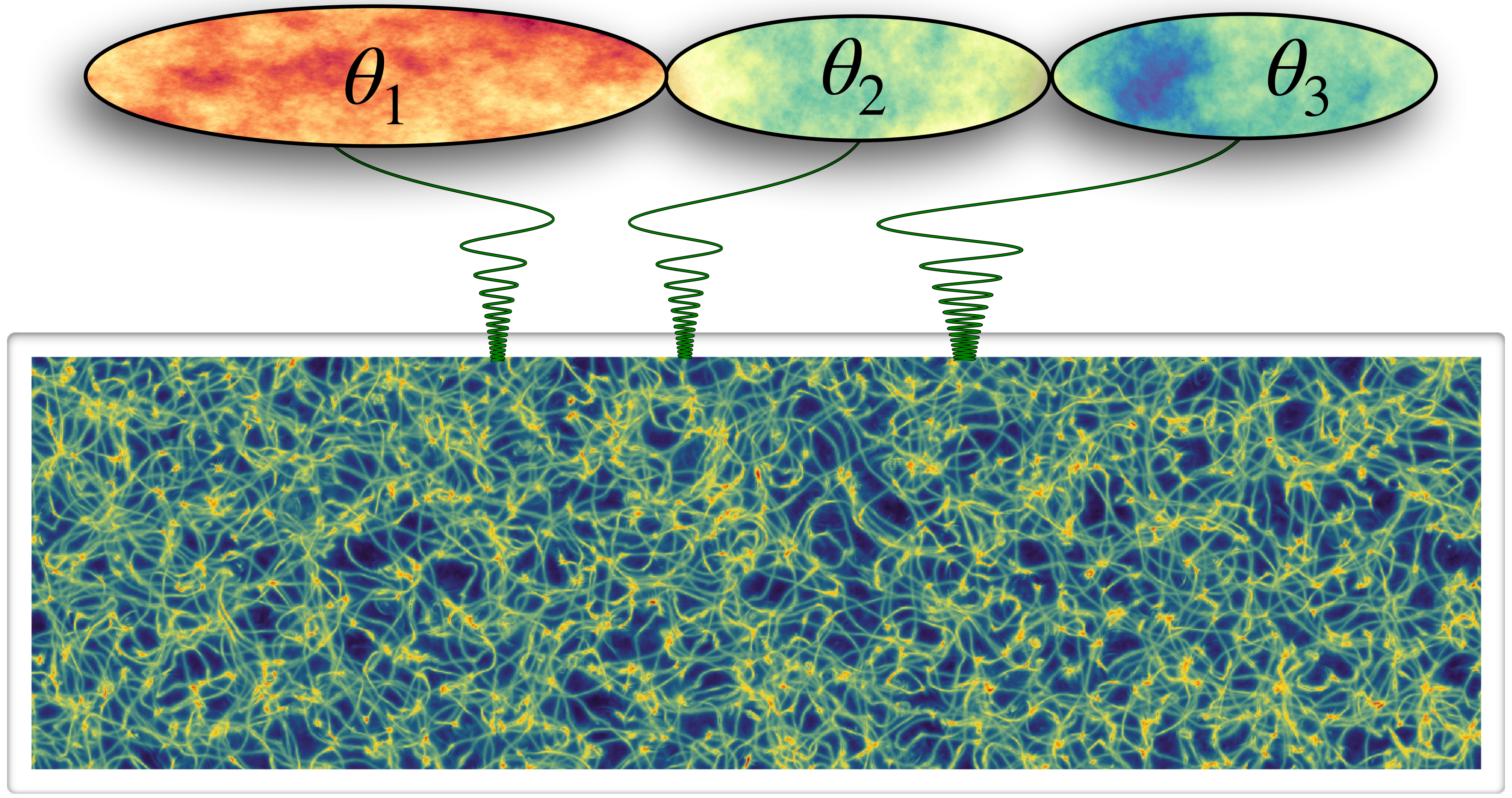


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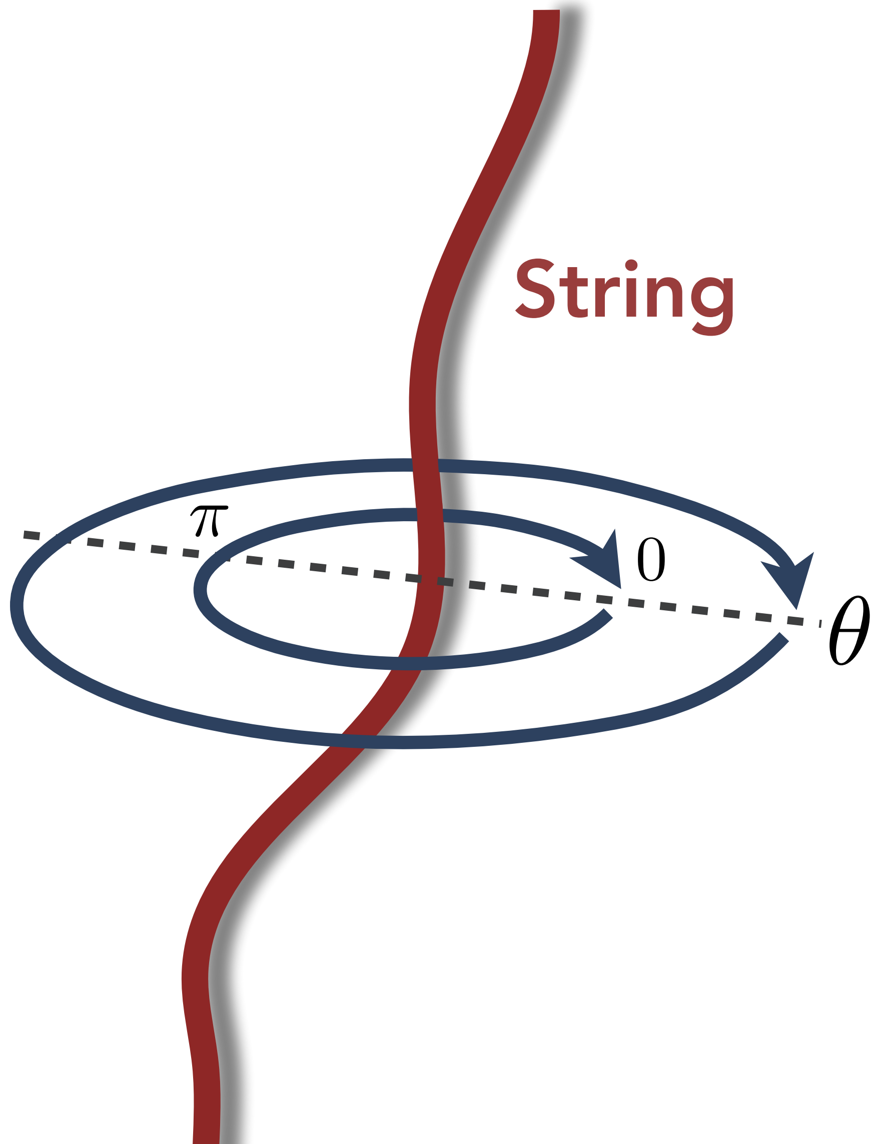
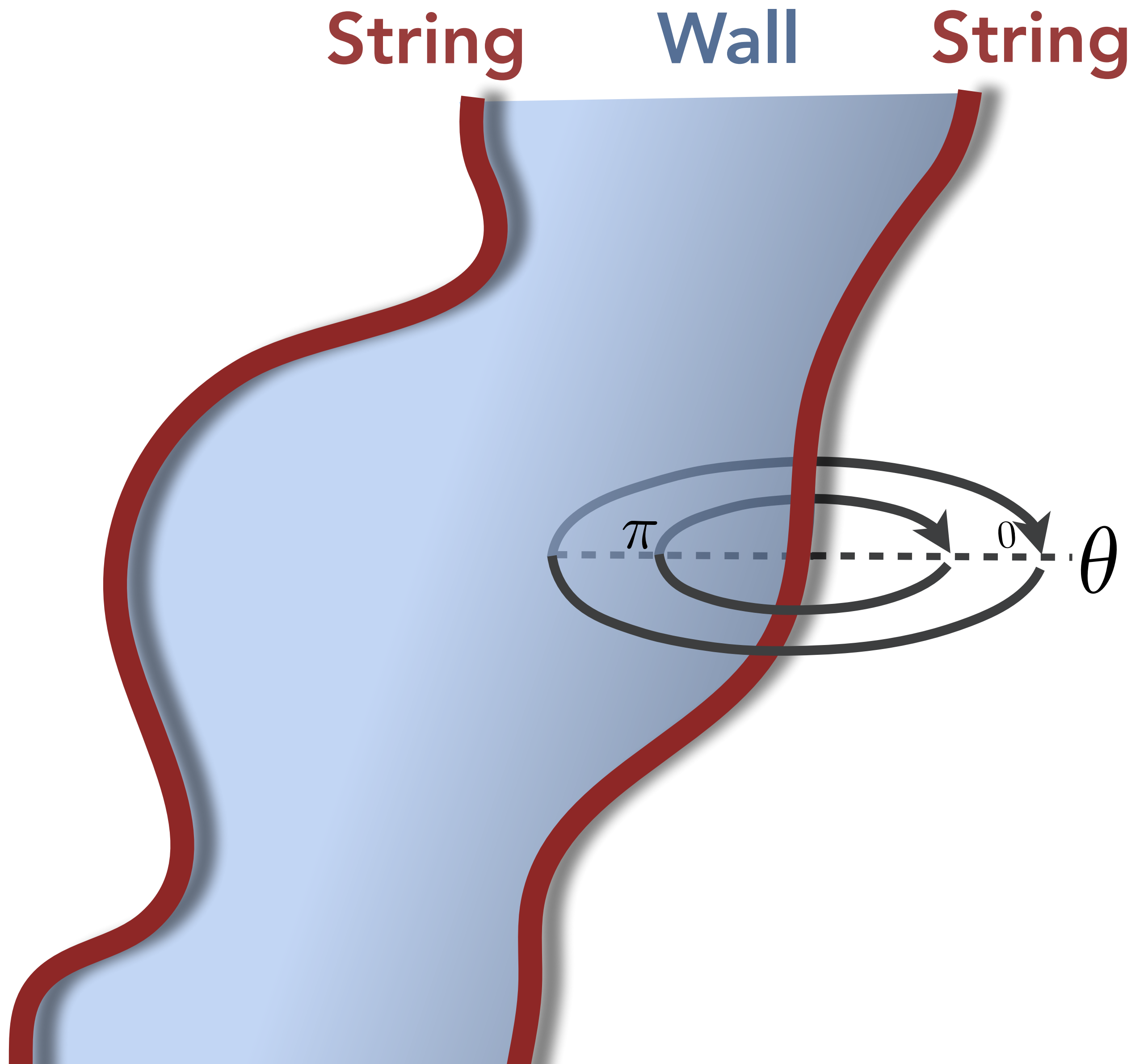


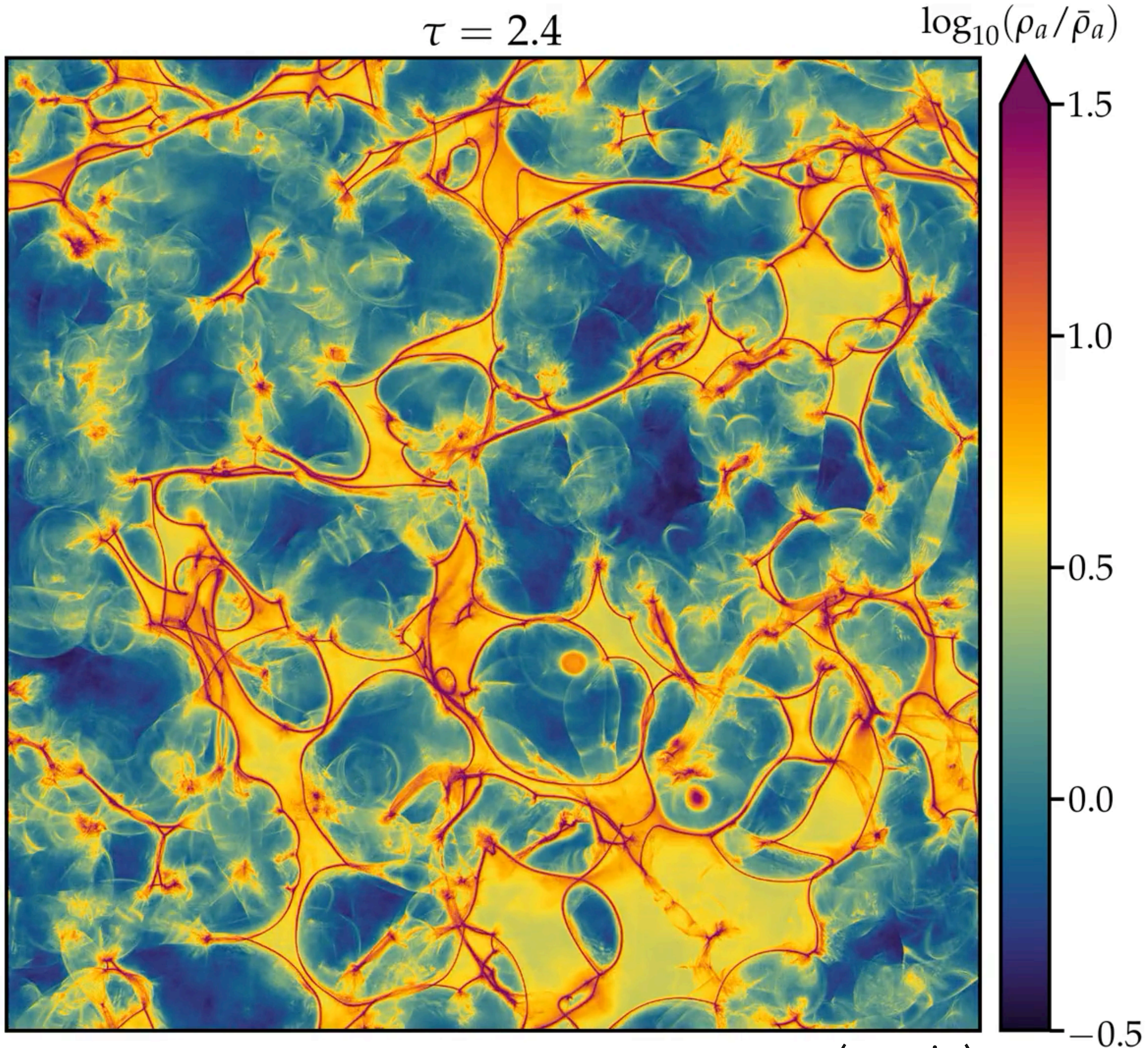

⇒ **Domain walls**

where the field is stuck at $\theta = \pi$ saddle point



# Evolution of the axion field in the post-inflationary scenario

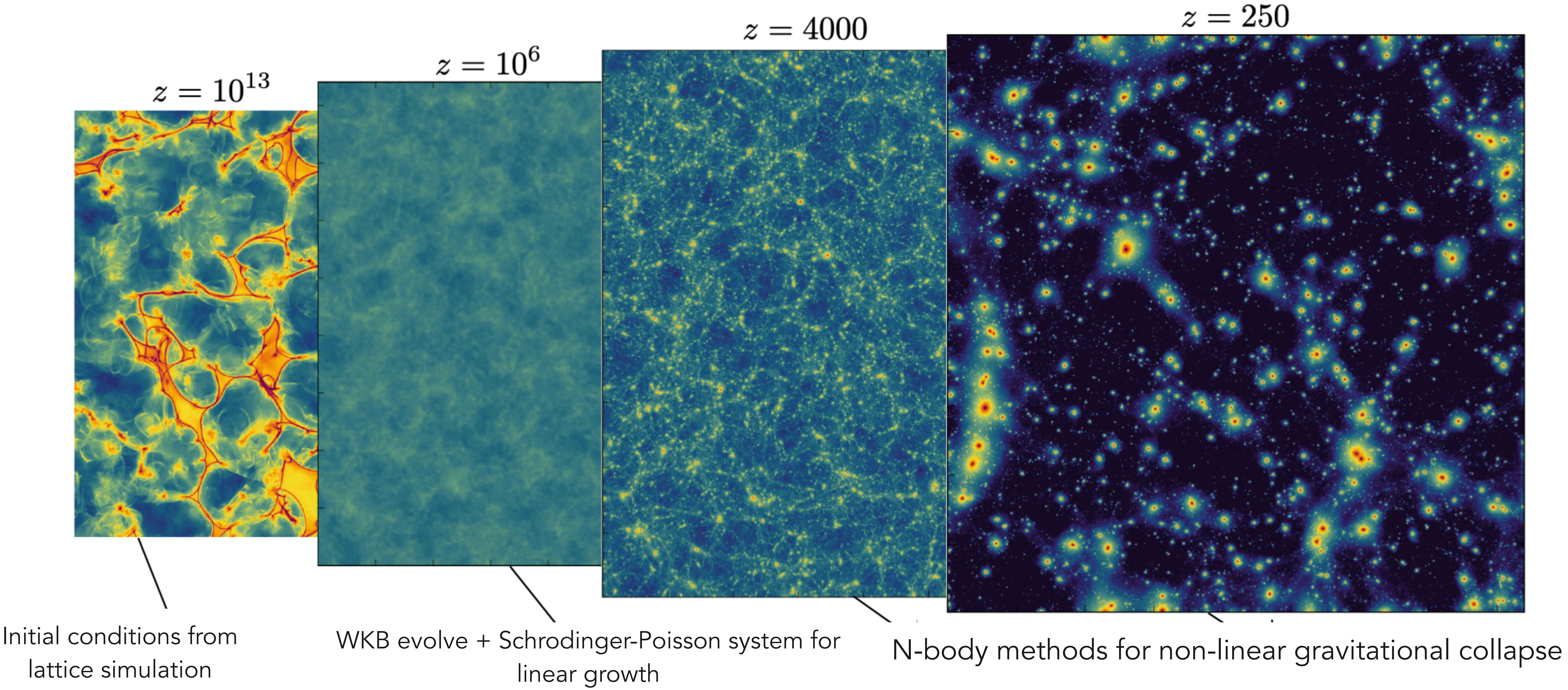
Projection through 3D co-moving box, coloured by integrated axion energy density:




(movie)

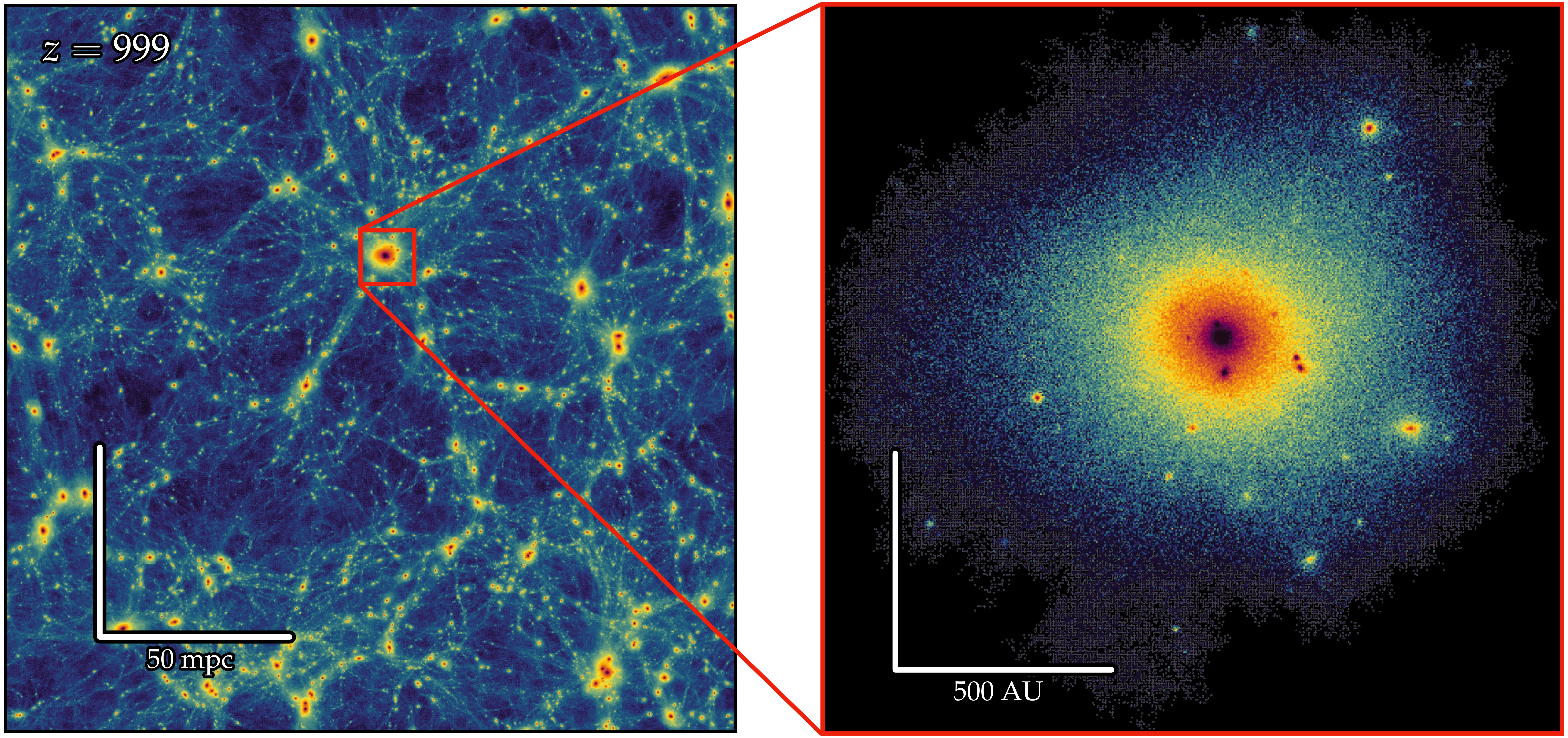
# Gravitational collapse in the post-inflationary scenario

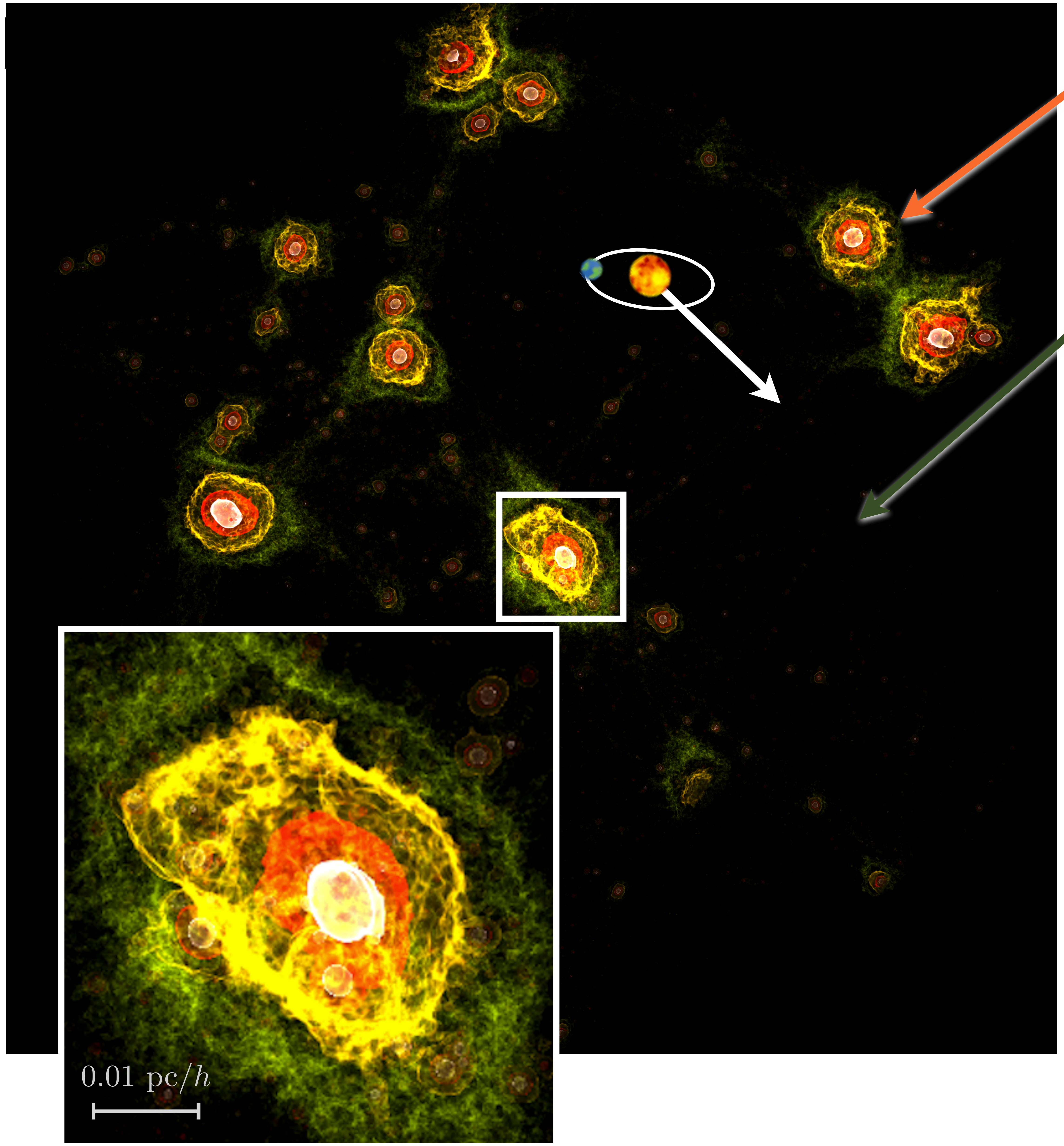
Axion distribution is highly *inhomogeneous:* isocurvature density fluctuations with masses set by the DM contained in the horizon at $T_{\rm QCD}$. Collapse and growth of these fluctuations leads to enhanced small-scale dark matter structure: "**axion miniclusters**"



# Axion miniclusters

AU—mpc sized gravitationally bound clumps of axions with masses $M \in [10^{-15}, 10^{-9}]\ M_\odot$






# Miniclusters

# Minivoids

If we extrapolate this to the present day then miniclusters would contain >80% of the DM by mass but fill only a tiny (<1%) fraction of the volume.

Earth travels through galaxy at about 0.2 mpc per year, so our experiments sample the mini*voids* not the mini*clusters*

This is fairly disastrous for direct detection prospects because accessible DM density is suppressed by up to an order of magnitude

# Not the full story...

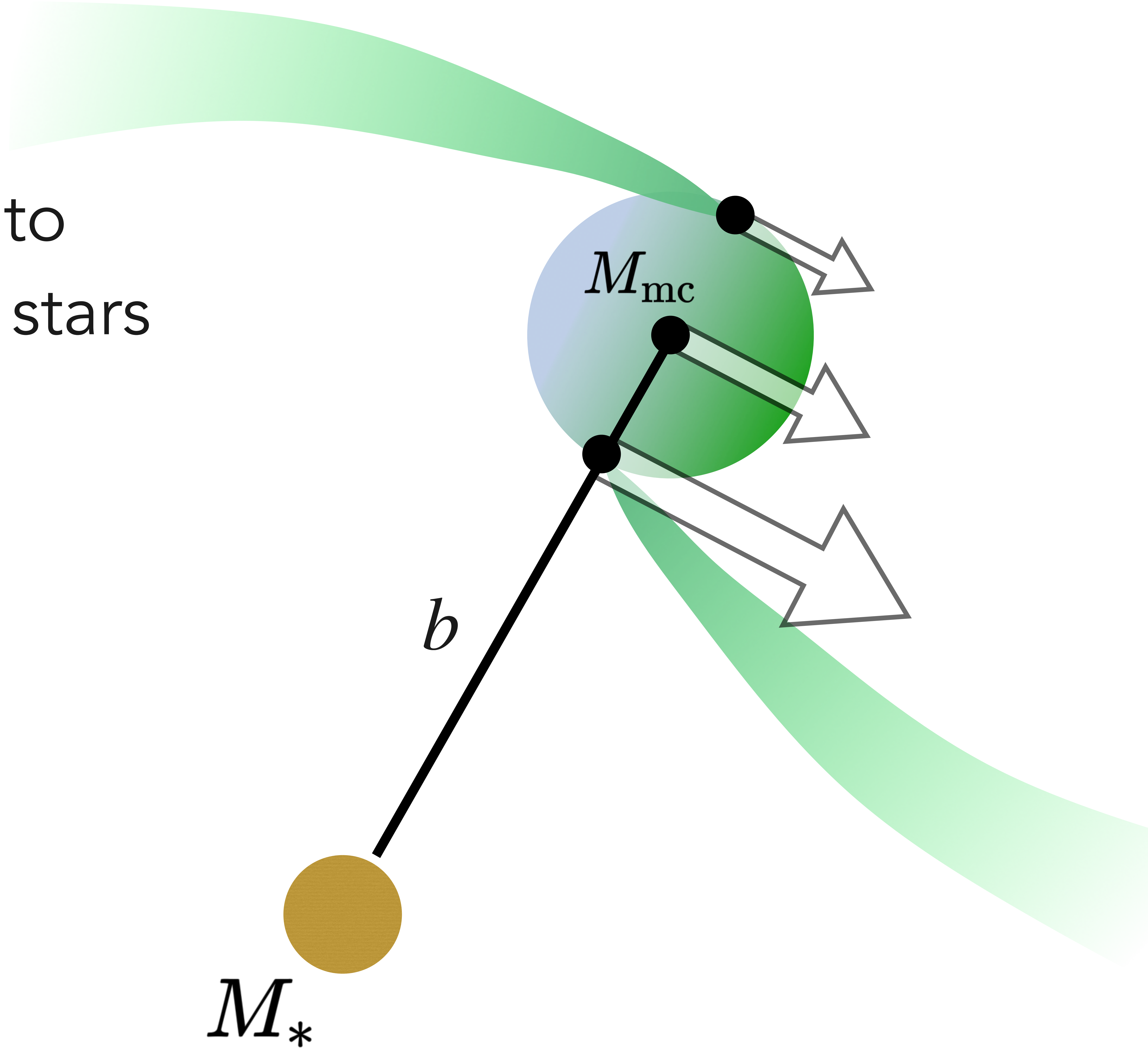
Miniclusters are highly susceptible to tidal disruption, e.g. when passing stars

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

↑

Energy injected into minicluster

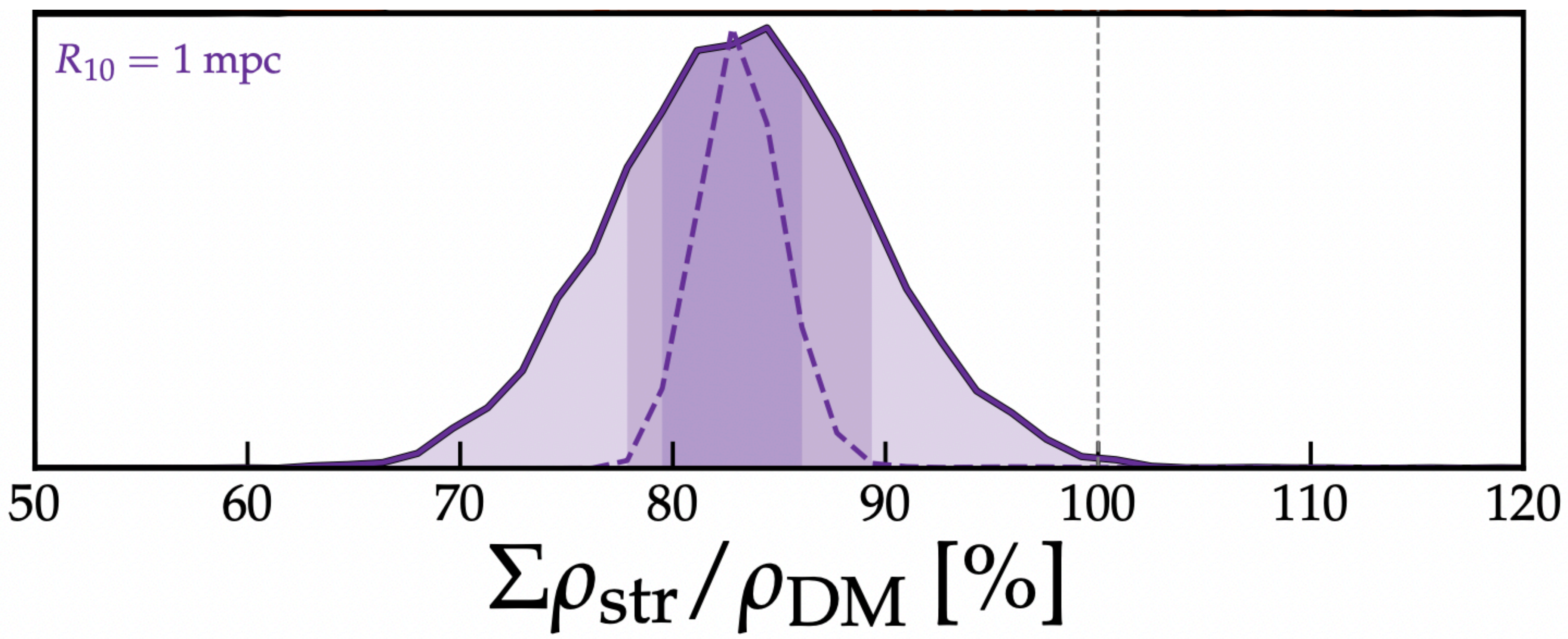
Axions with $E$>Binding energy will evaporate away → form **tidal stream**

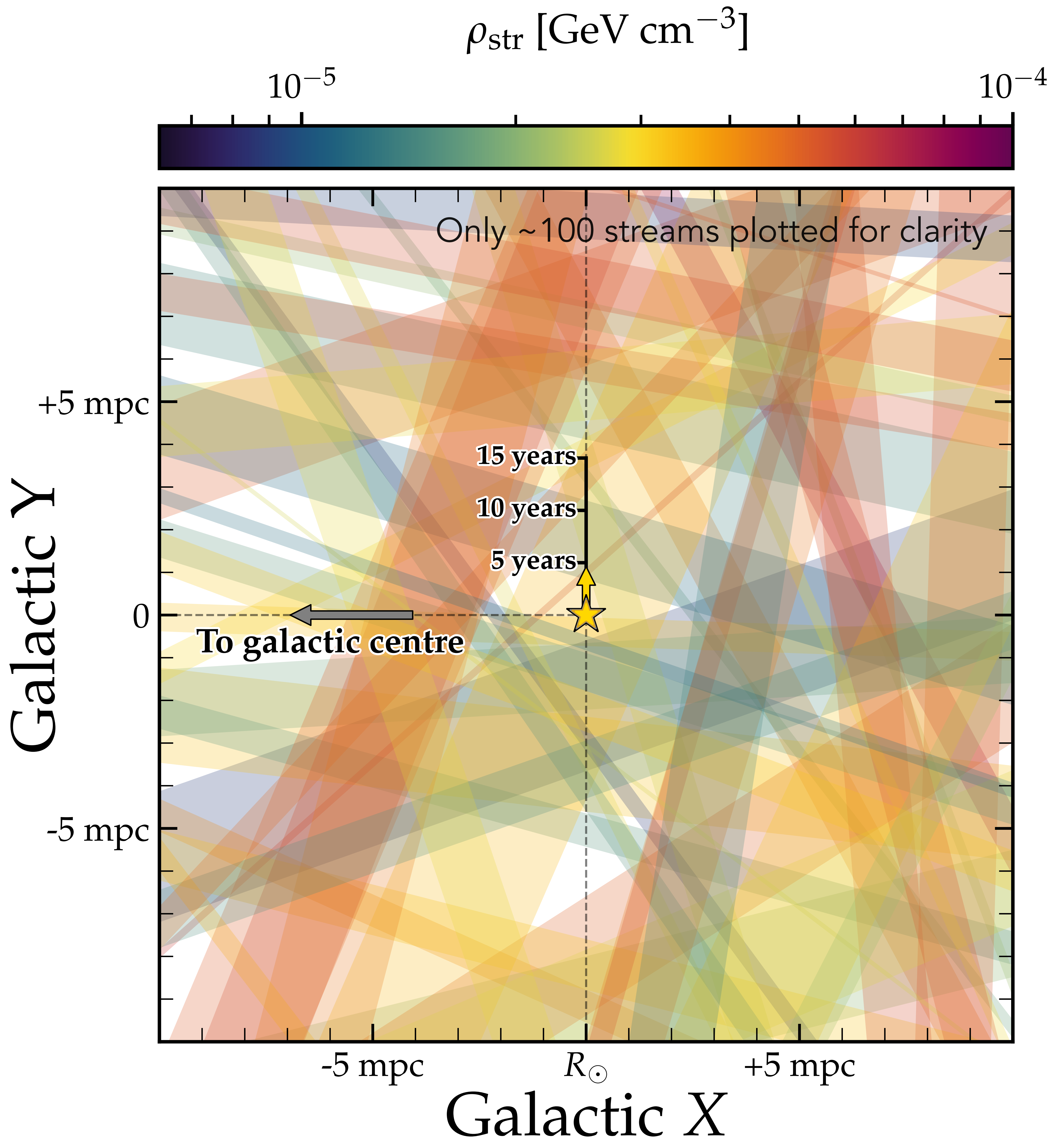


**Axion miniclusters are almost totally tidally disrupted inside galaxies by the present day**

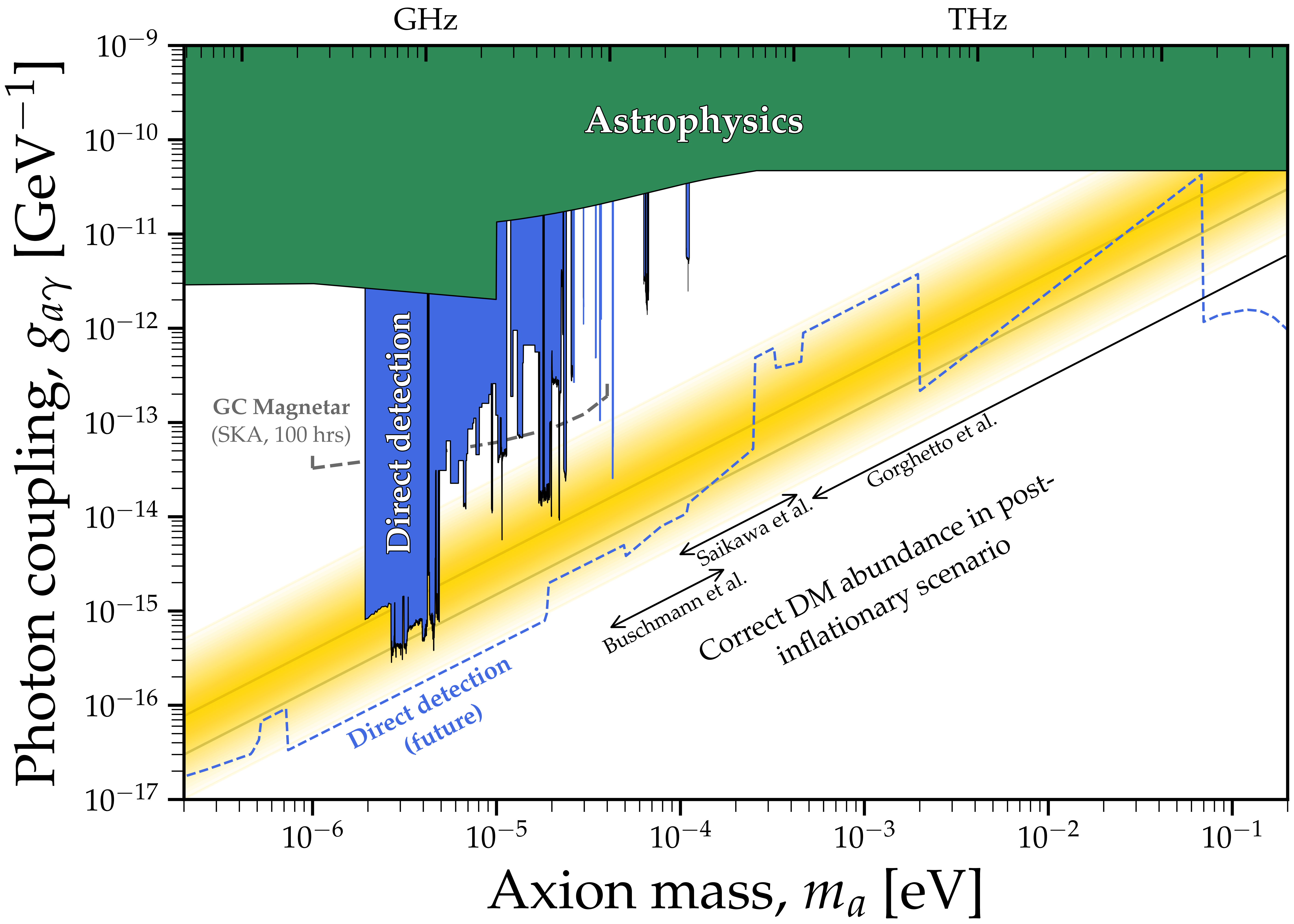
→ We expect the debris of around O(100-1000) tidal streams overlapping at our position in the MW. Vast majority do not contribute substantially to the density but add up to around 70-90% of the large scale average of

$\rho_{\rm DM} = 0.4\,{\rm GeV\,cm^{-3}}$



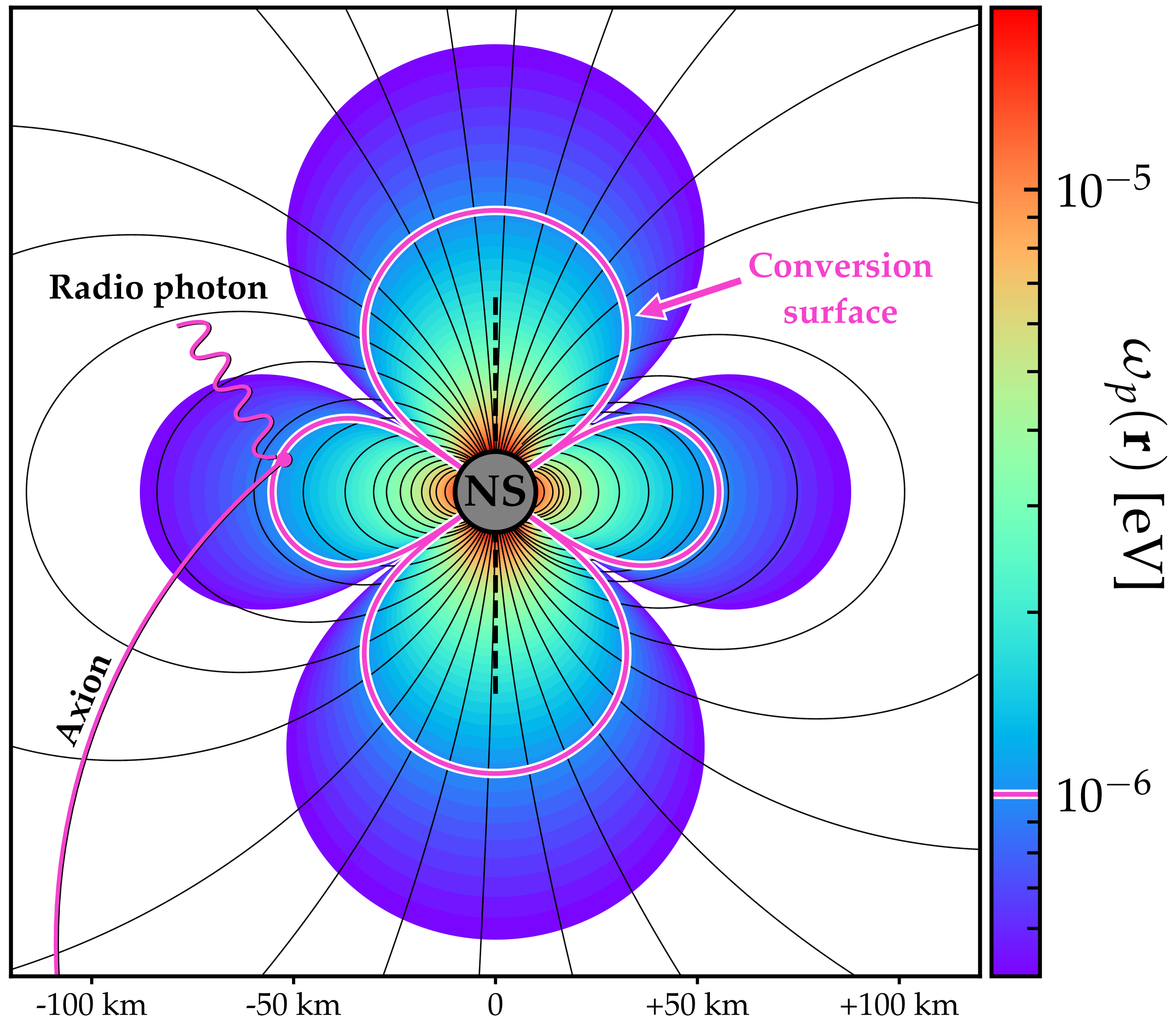
# Observational implications

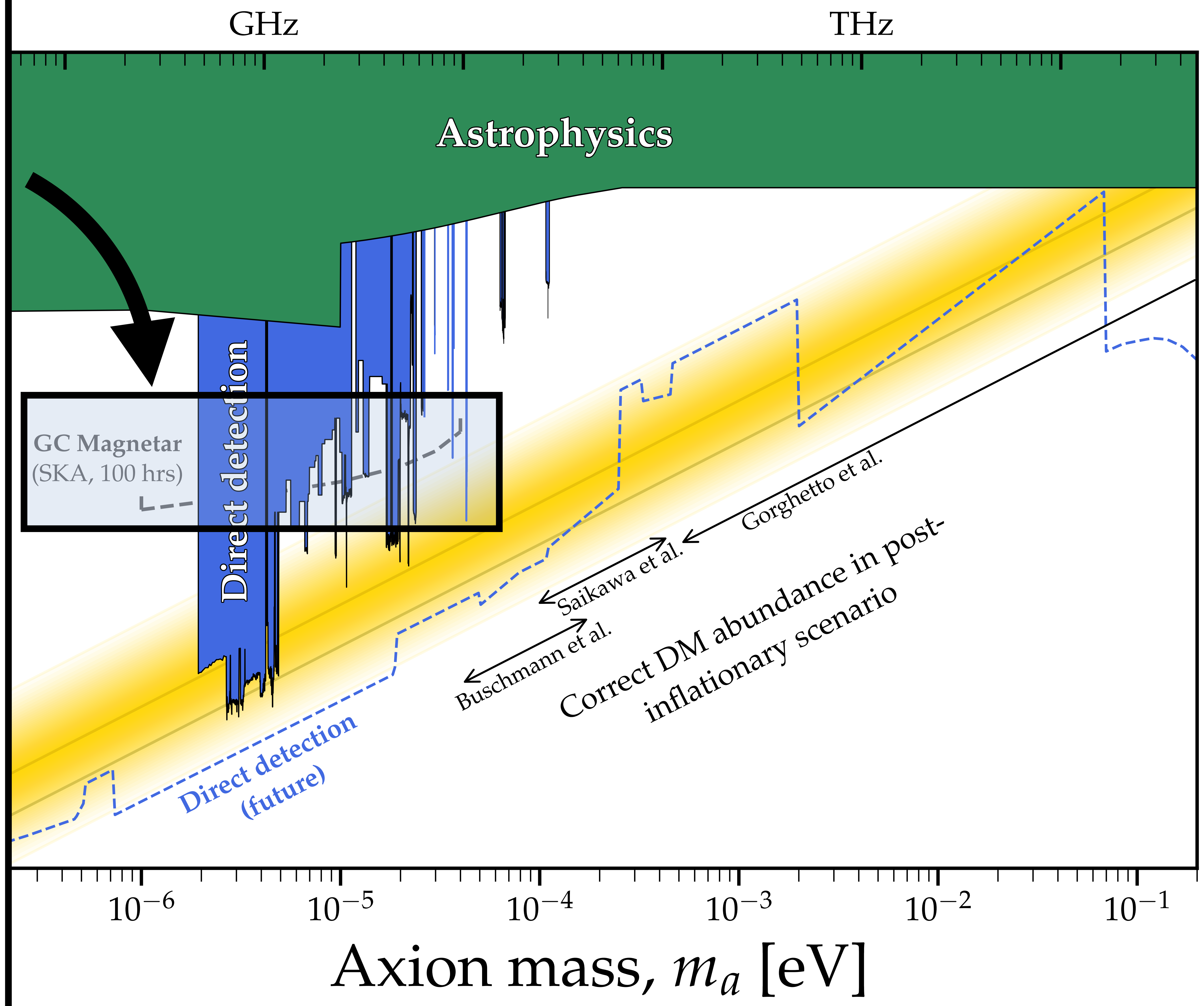


# Observational implications

## Indirect detection

observe narrow *transient* emission lines at $\omega = m_a$ due to axion miniclusters converting to photons around neutron star magnetospheres



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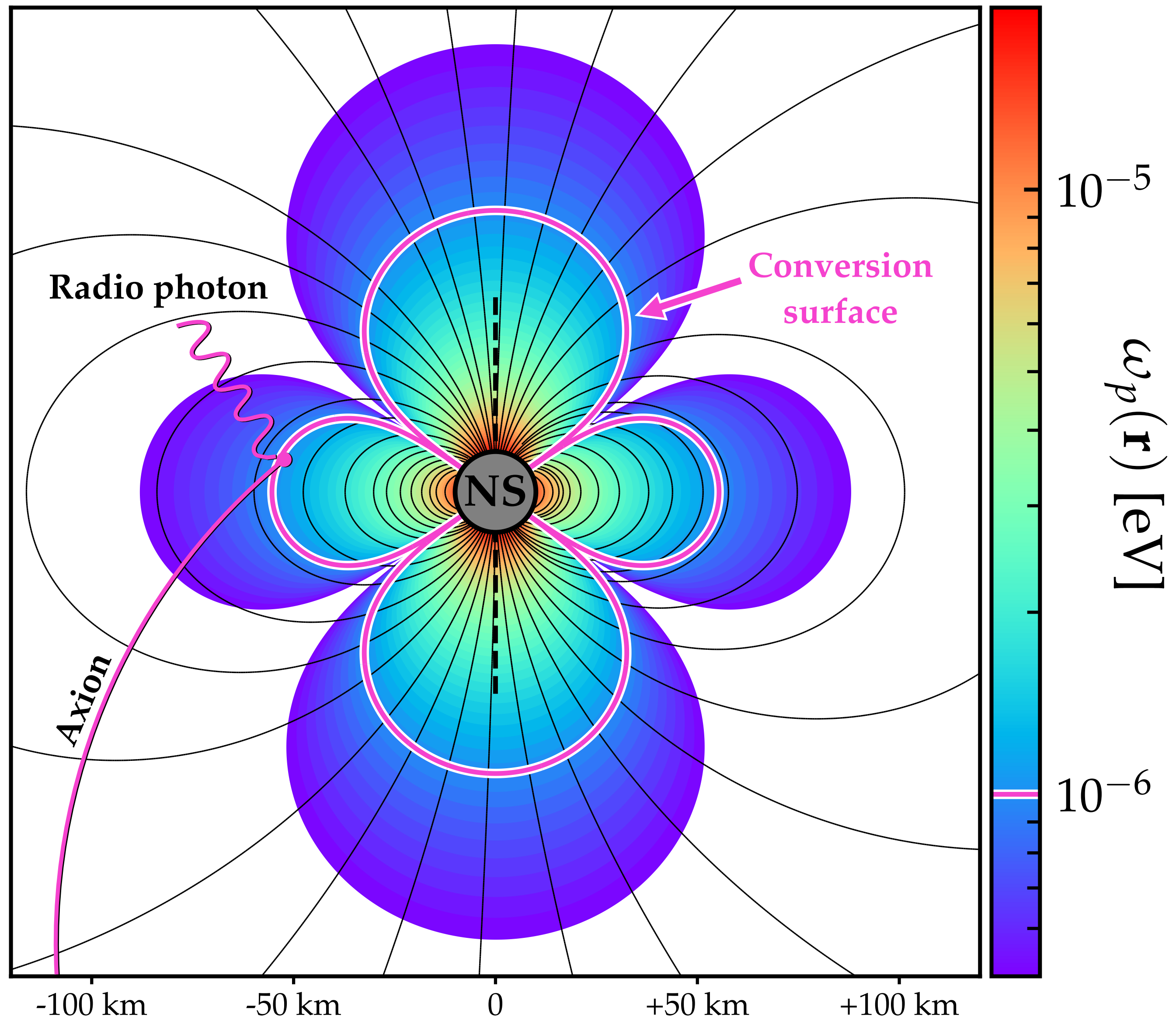
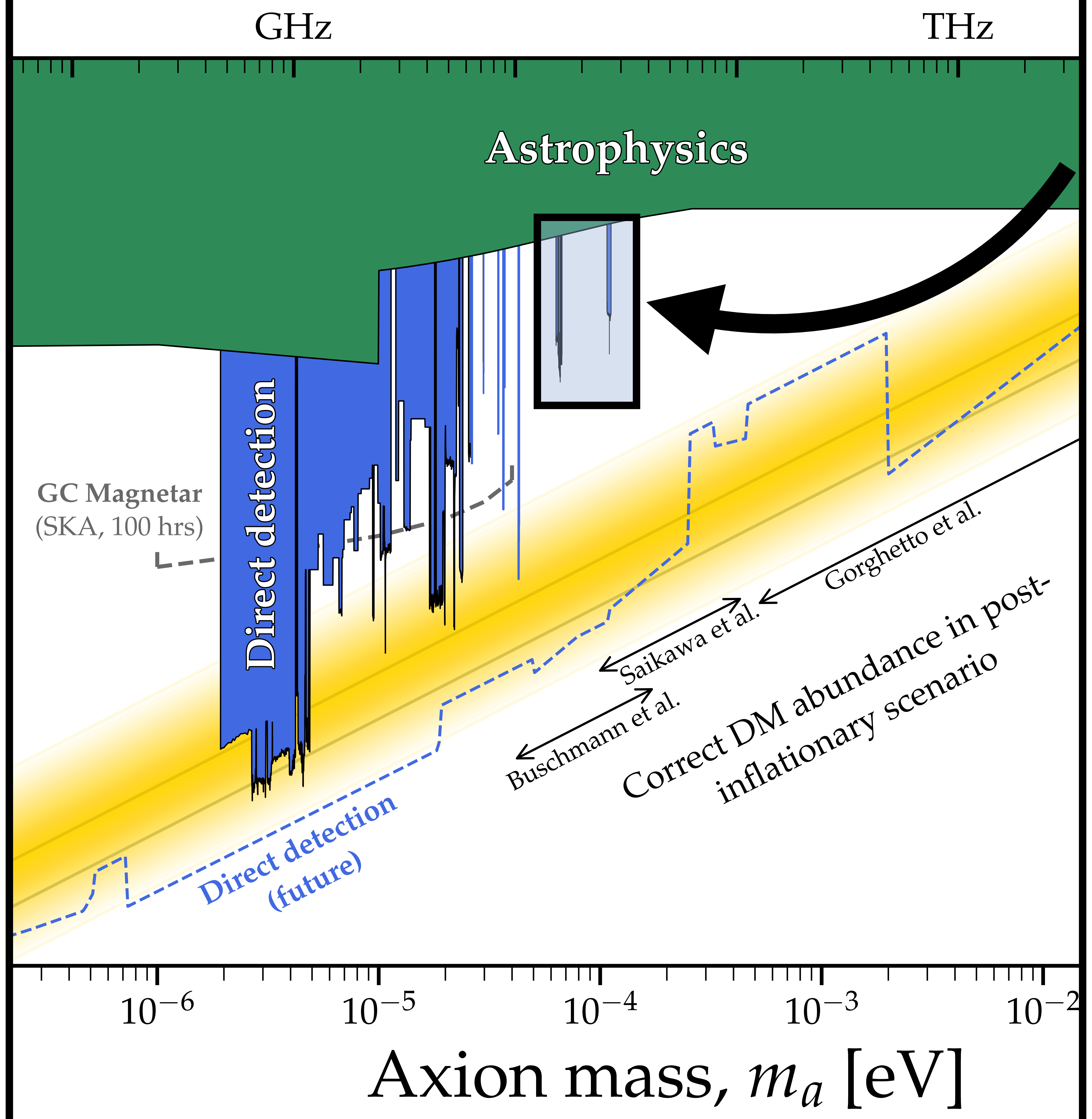
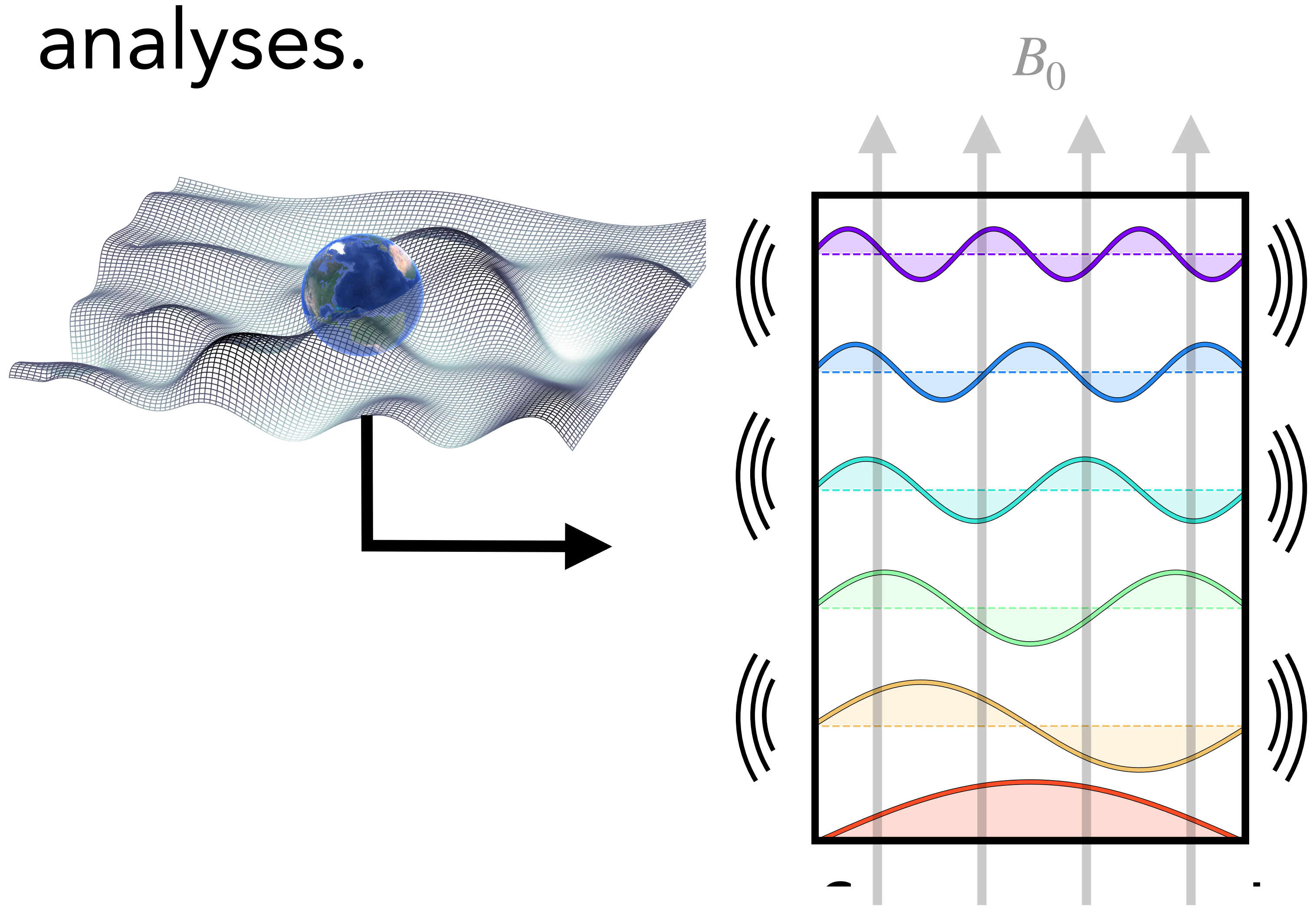


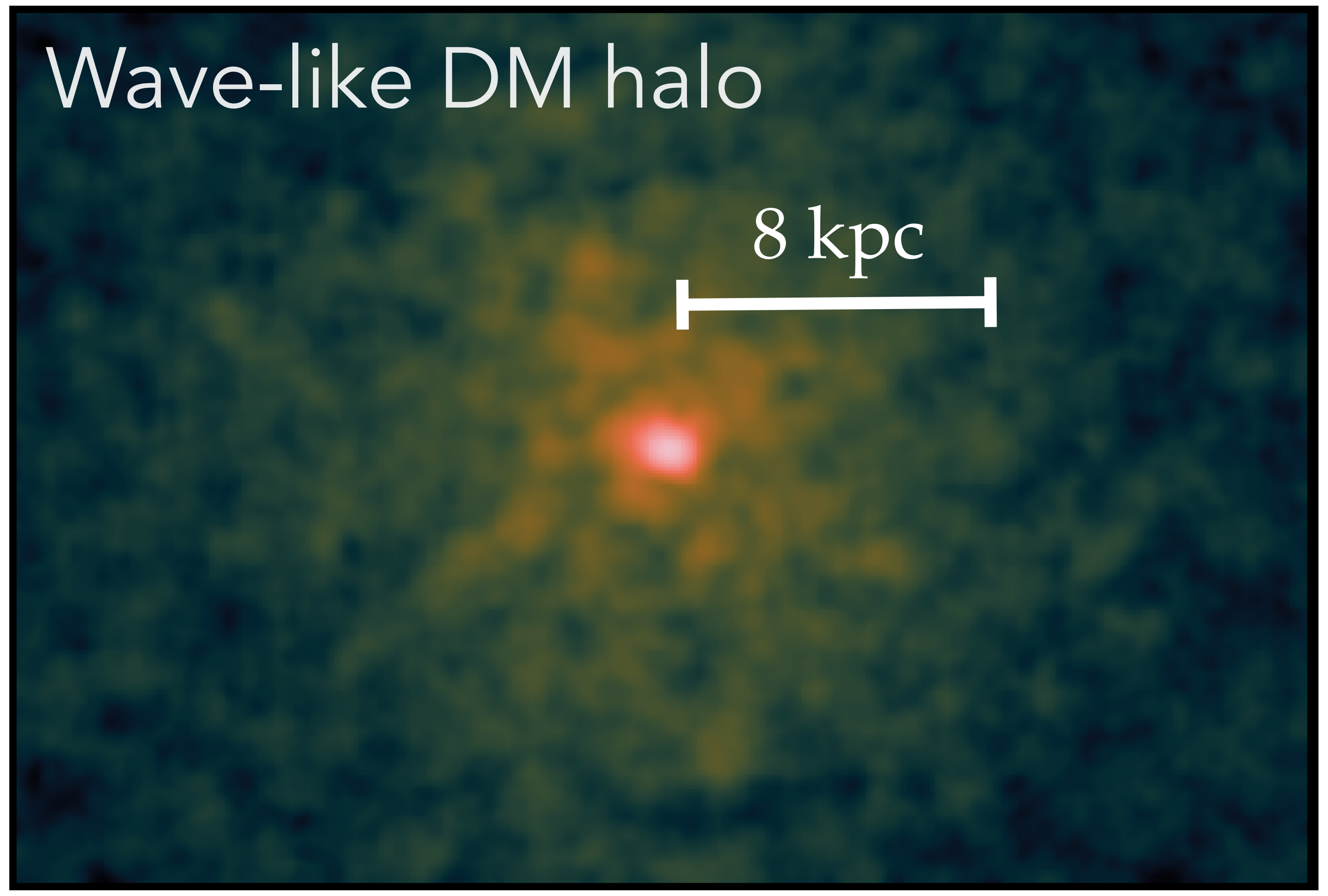

## Direct detection

Presence of axion streams and substructure implies a qualitatively different local distribution of dark matter than the conventional "SHM" assumption.

Important for experimental analyses.



# Direct detection of wave-like dark matter



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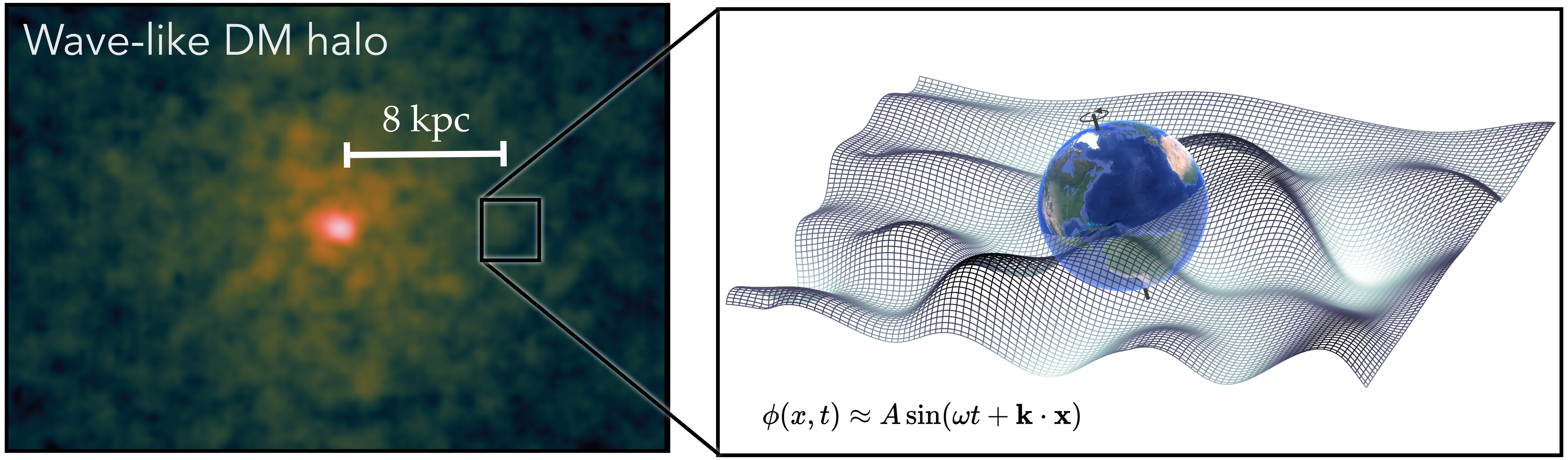

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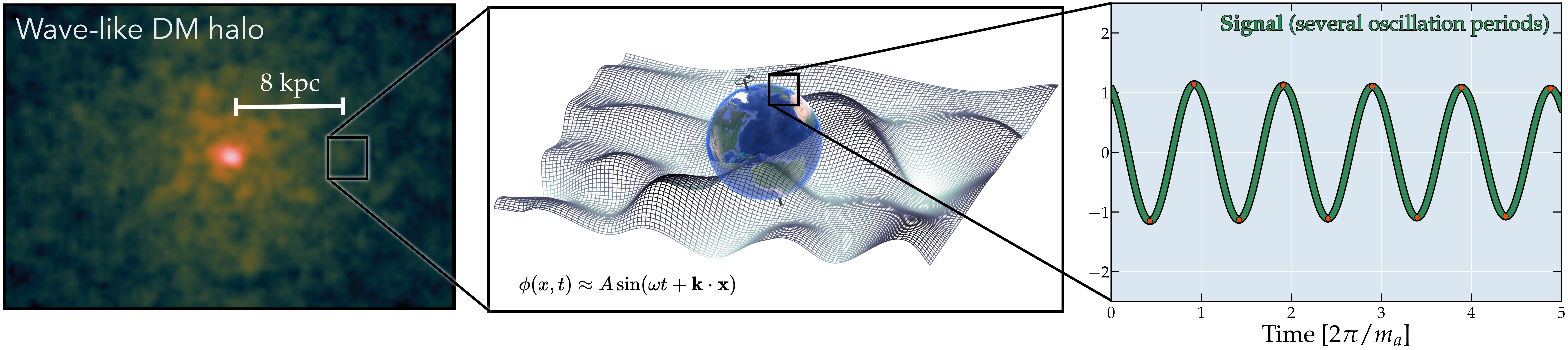

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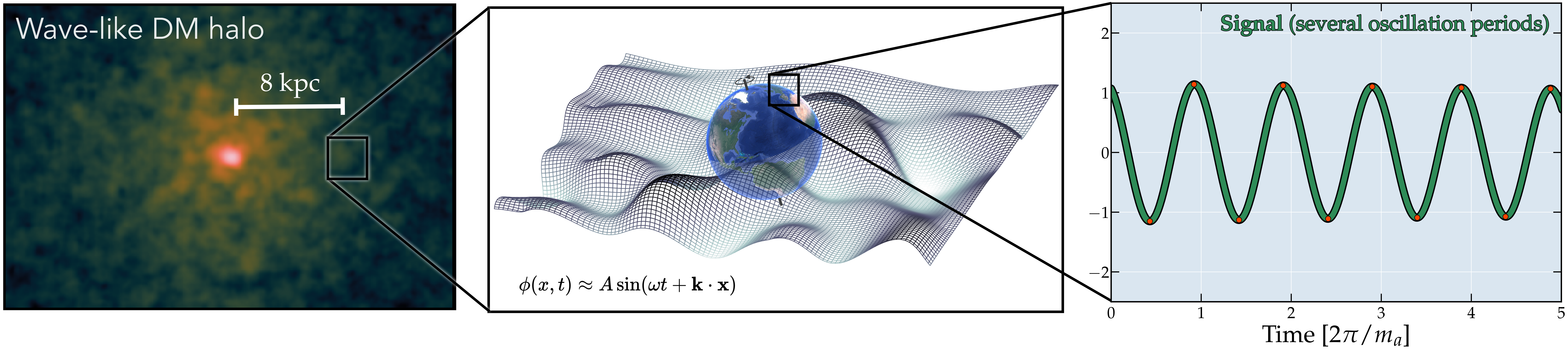


But the oscillations also have a coherence time set by the DM velocity distribution: $\tau_{\rm coh} \sim (mv\sigma_v)^{-1} \sim 10^6 m_a^{-1}$

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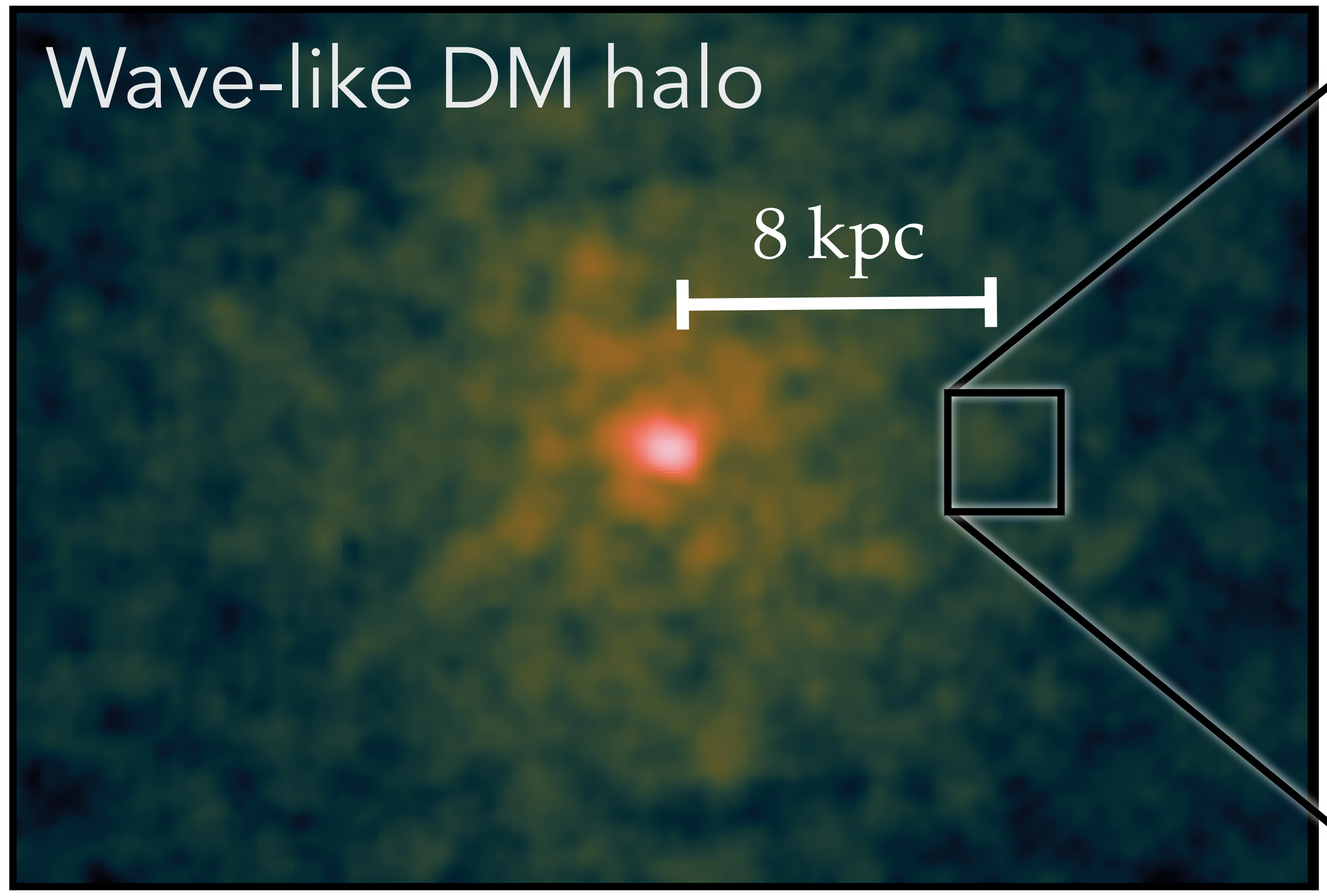


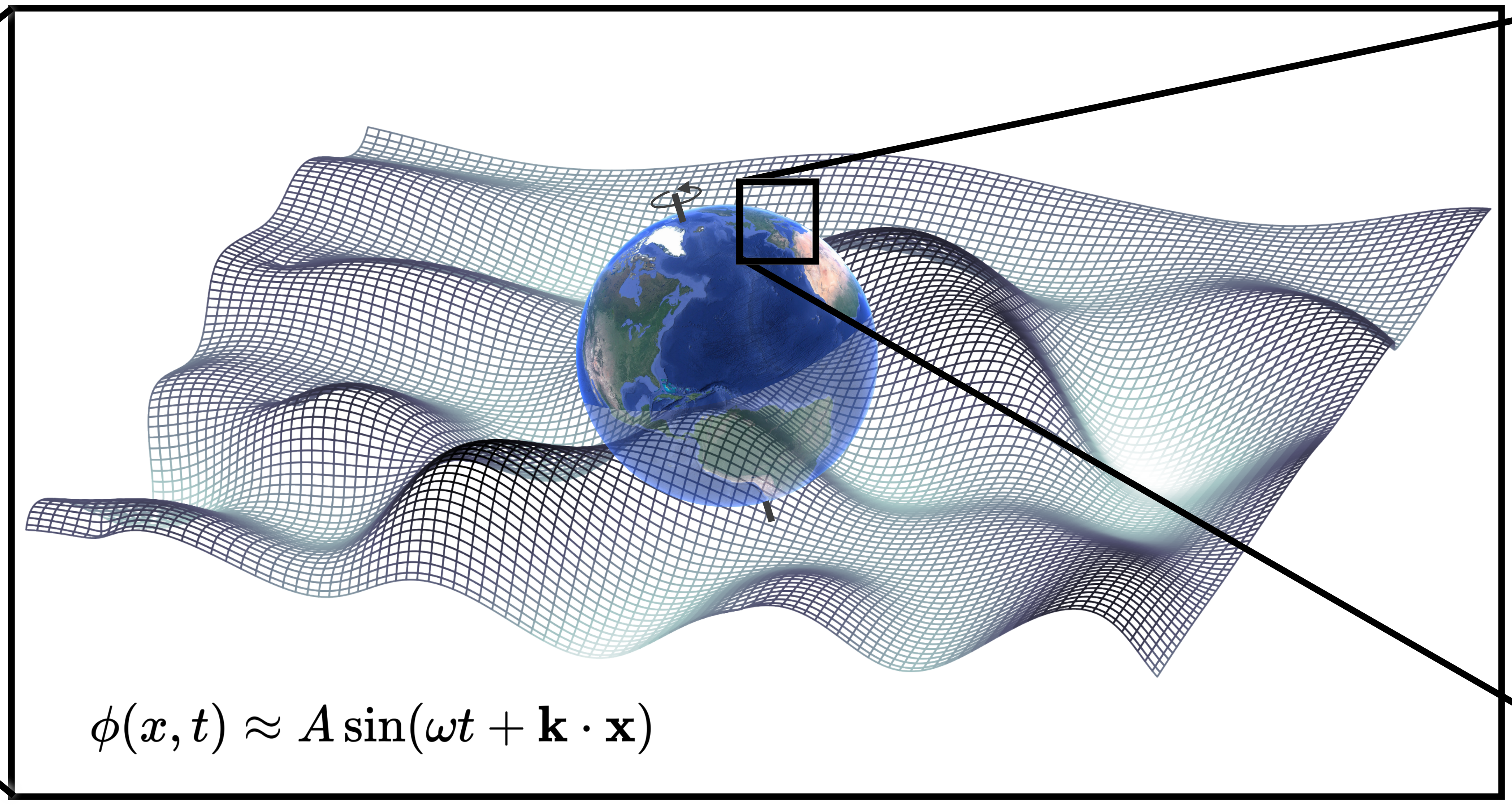


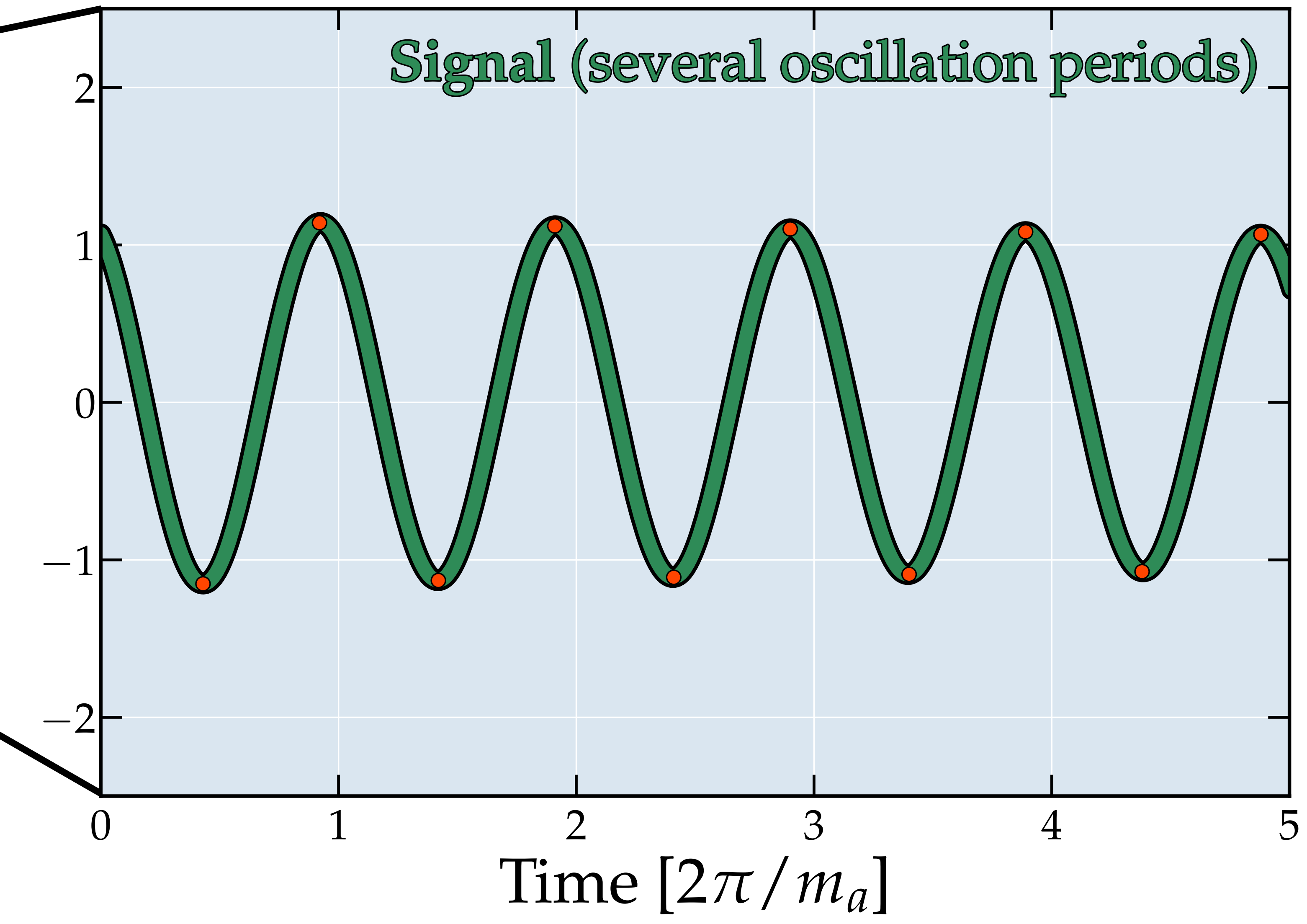


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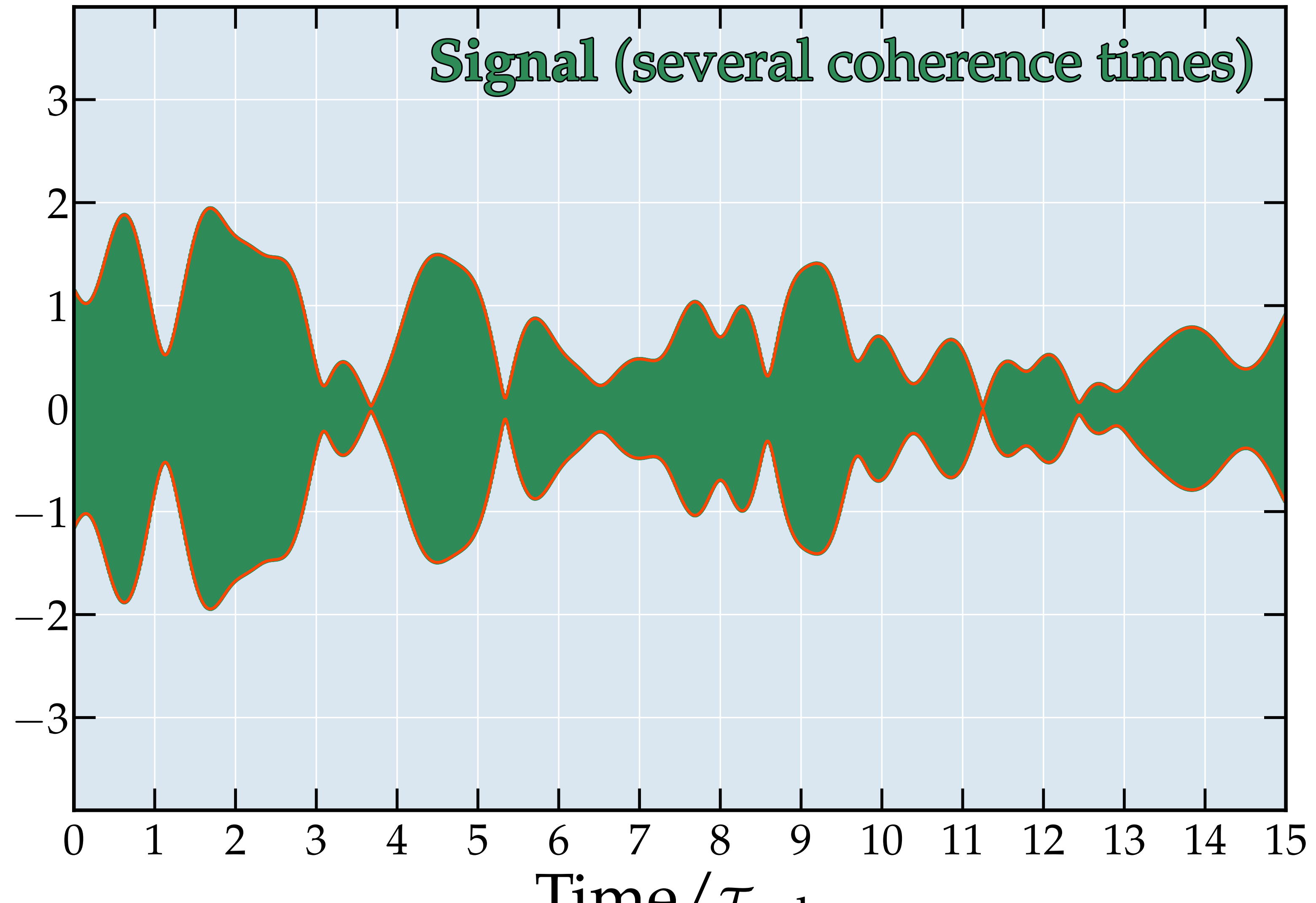

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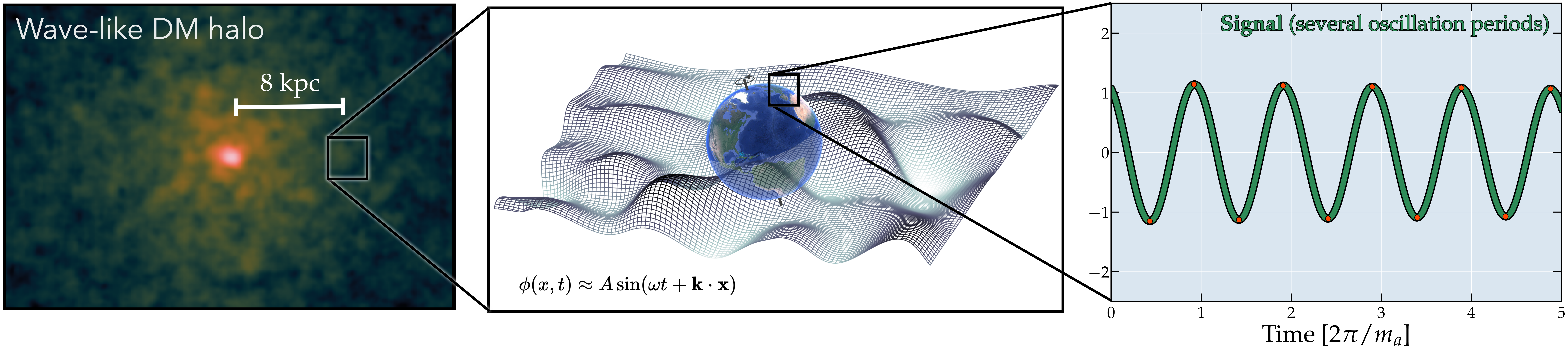


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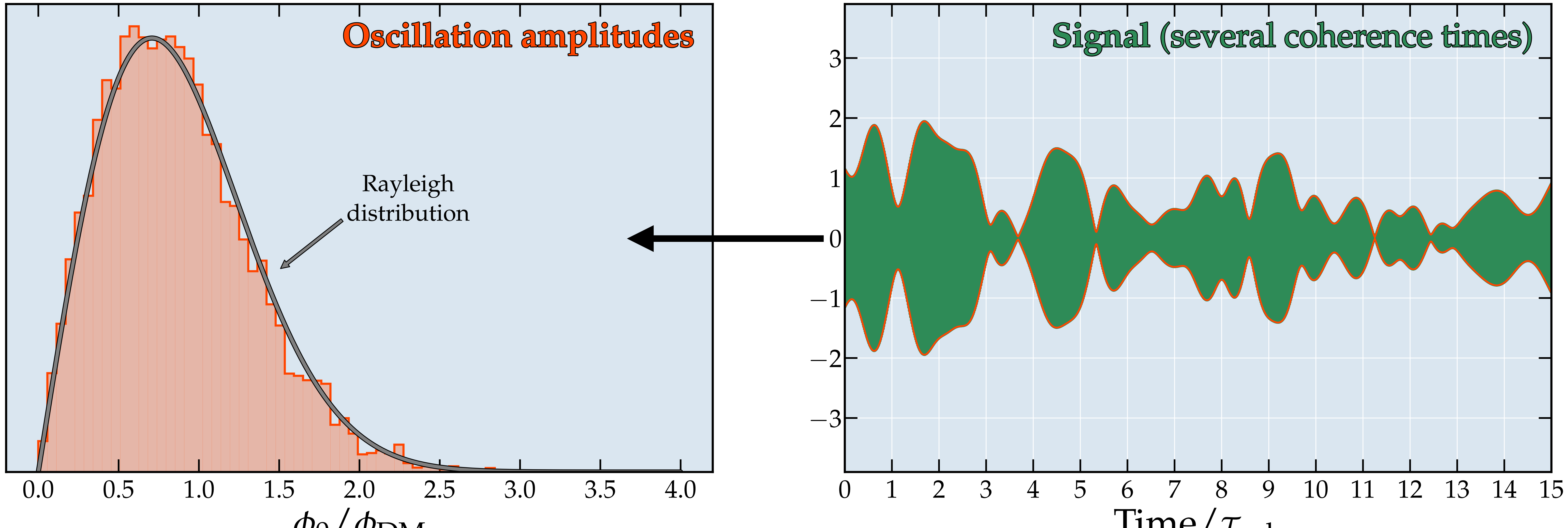

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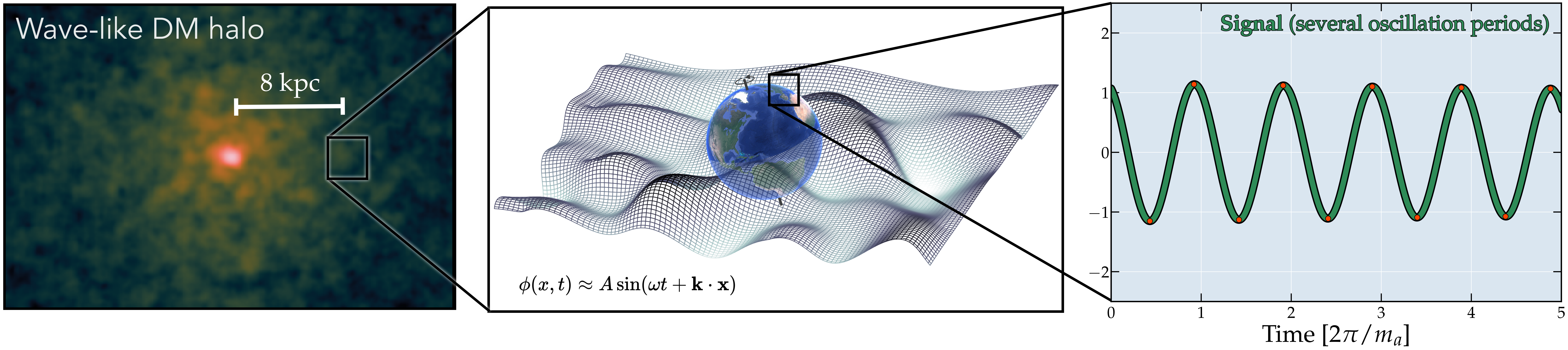


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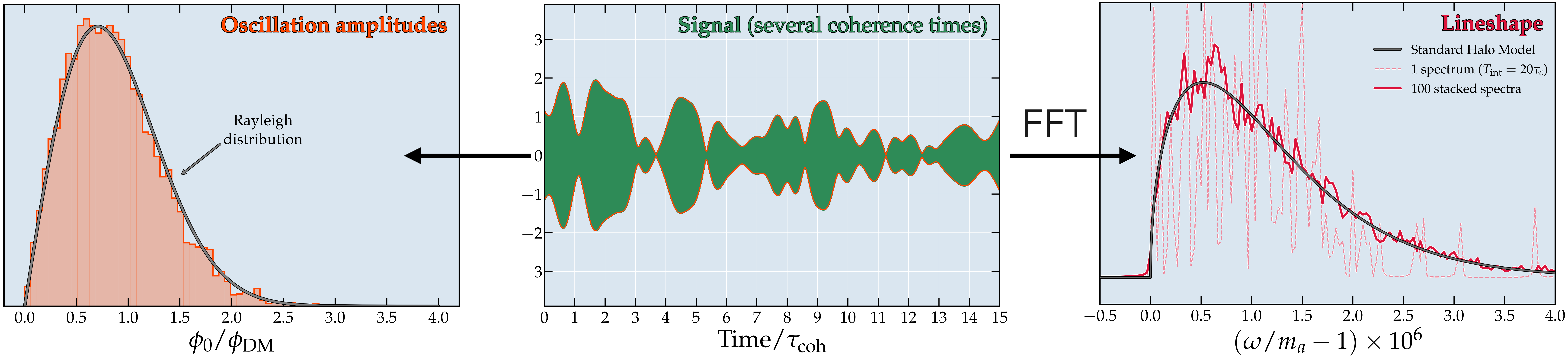
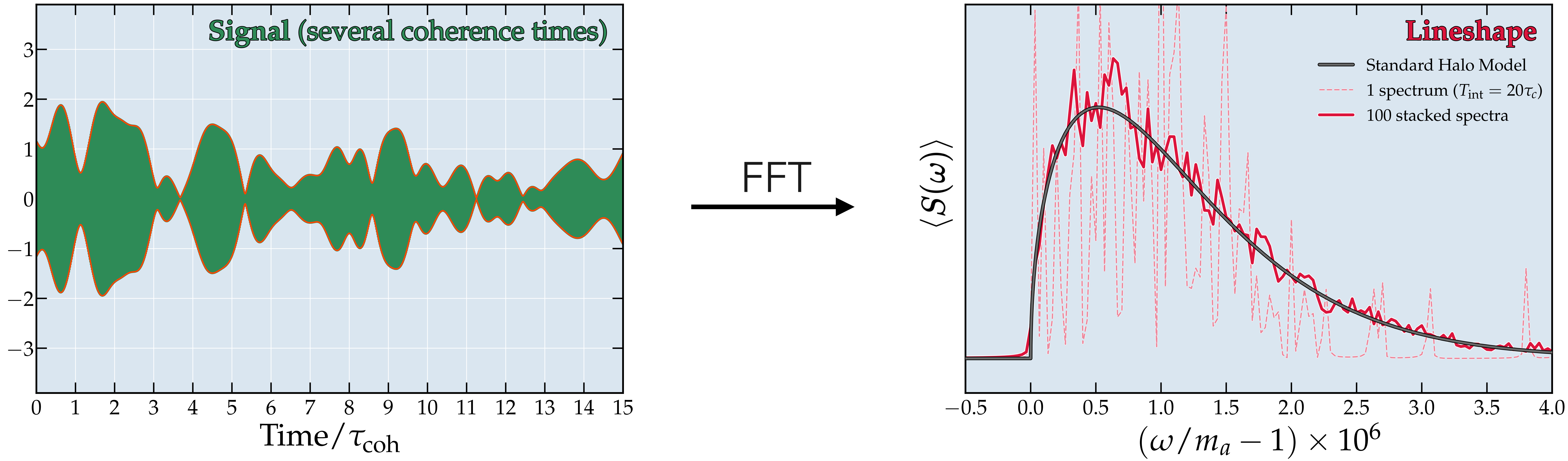


## Time domain ## Frequency domain

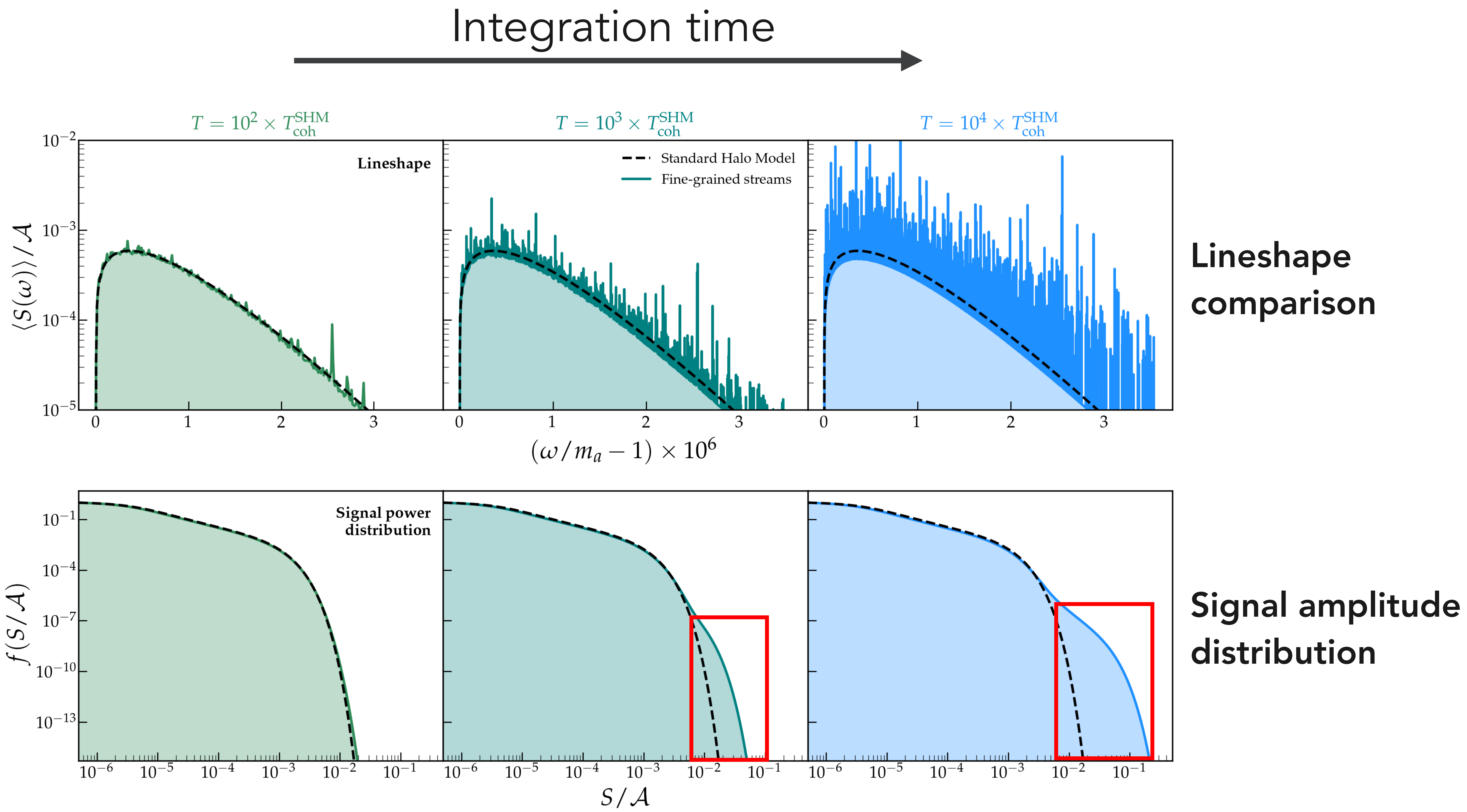



Signal power spectrum depends on local DM speed distribution, $f(v)$, and integration time, $T$

$$\langle S(\omega)\rangle \propto \frac{T}{2}\int_0^\infty \mathrm{d}v\, f(v)\,\mathrm{sinc}^2\left(\frac{1}{2}(\omega_v - \omega)T\right)$$

Frequency resolution is $\Delta\omega = 2\pi/T$ so taking FFTs of longer time-series samples may reveal fine-grained features in the speed distribution that are not resolved otherwise

Integration time
$T = 10^2 \times T_{\rm coh}^{\rm SHM}$
$T = 10^3 \times T_{\rm coh}^{\rm SHM}$
$T = 10^4 \times T_{\rm coh}^{\rm SHM}$
Lineshape
Standard Halo Model
Fine-grained streams
$\langle S(\omega) \rangle / \mathcal{A}$
$(\omega/m_a - 1) \times 10^6$
Lineshape comparison
Signal power distribution
$f(S/\mathcal{A})$
$S/\mathcal{A}$
Signal amplitude distribution



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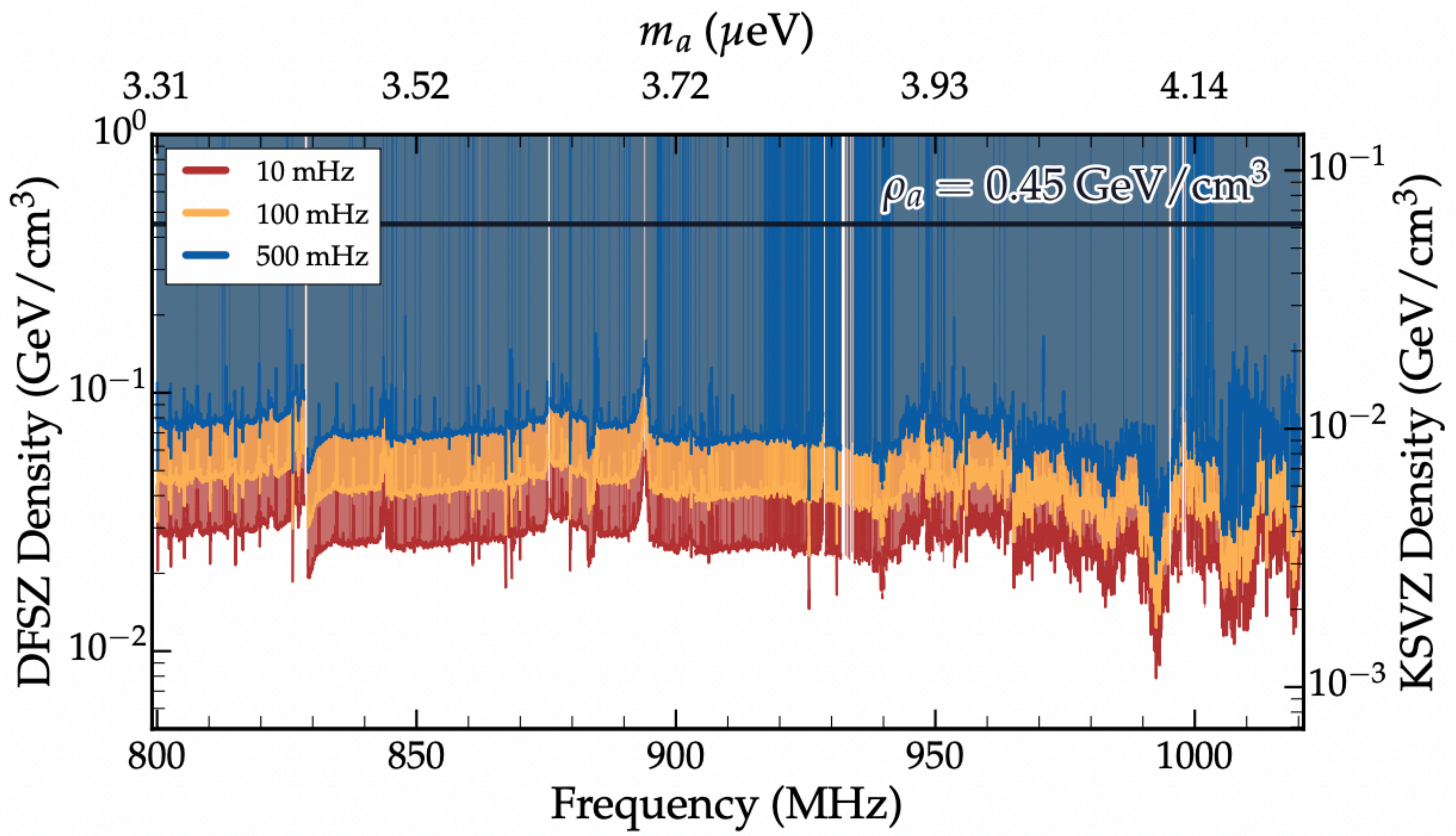
$S/\mathcal{A}$
Signal amplitude distribution

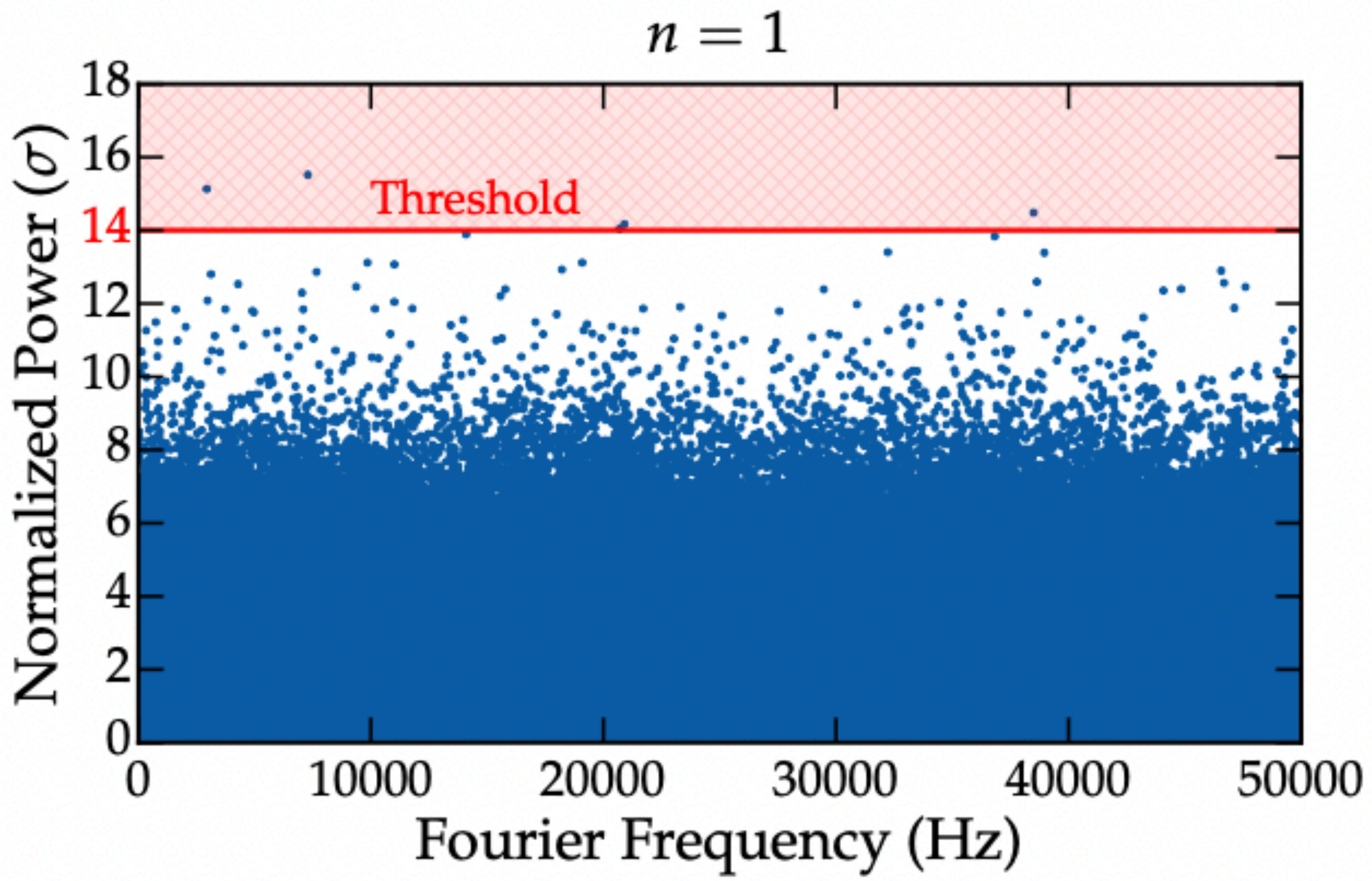
# High-resolution analyses by axion haloscopes

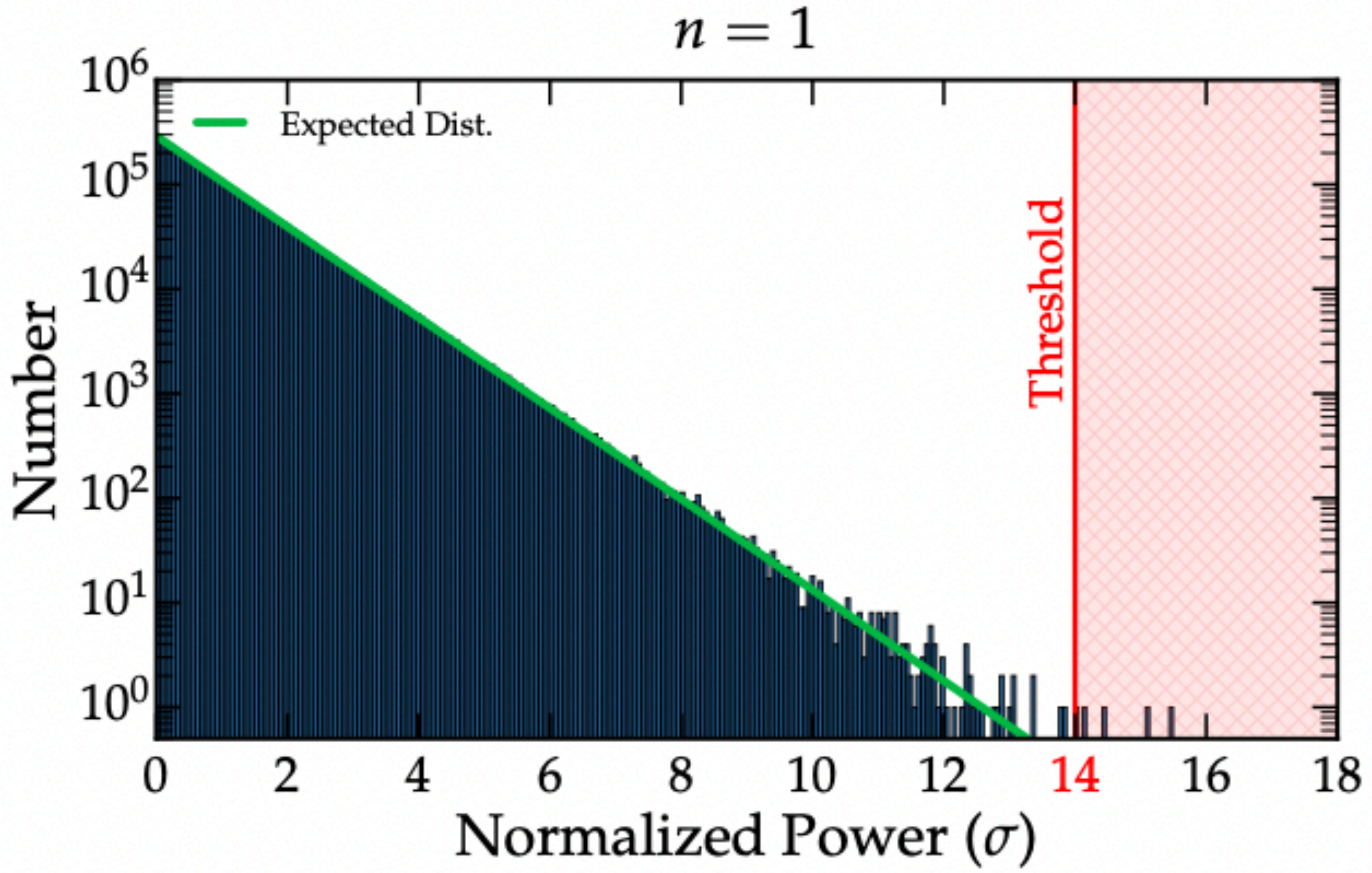
ADMX Collaboration [2410.09203]

**Search for non-virialized axions with 3.3 – 4.2 μeV mass at selected resolving powers**

A. T. Hipp,[1] A. Quiskamp,[2] T. J. Caligiure,[1] J. R. Gleason,[1] Y. Han,[1] S. Jois,[1] P. Sikivie,[1] M. E. Solano,[1] N. S. Sullivan,[1] D. B. Tanner,[1] M. Goryachev,[2] E. Hartman,[2] M. E. Tobar,[2] B. T. McAllister,[3] L. D. Duffy,[4] T. Braine,[5] E. Burns,[5] R. Cervantes,[5] N. Crisosto,[5,6,*] C. Goodman,[5] M. Guzzetti,[5] C. Hanretty,[5] S. Lee,[5] H. Korandla,[5] G. Leum,[5] P. Mohapatra,[5] T. Nitta,[5] L. J Rosenberg,[5] G. Rybka,[5] J. Sinnis,[5] D. Zhang,[5] C. Bartram,[7] T. A. Dyson,[8] C. L. Kuo,[7,8] S. Ruppert,[8] M. O. Withers,[8] M. H. Awida,[9] D. Bowring,[9] A. S. Chou,[9] M. Hollister,[9] S. Knirck,[9] A. Sonnenschein,[9] W. Wester,[9] J. Brodsky,[10] G. Carosi,[10] N. Du,[10] N. Robertson,[10] N. Woollett,[10] C. Boutan,[11] A. M. Jones,[11] B. H. LaRoque,[11] E. Lentz,[11] N. E. Man,[11] N. S. Oblath,[11] M. S. Taubman,[11] J. Yang,[11] R. Khatiwada,[9,12] John Clarke,[13] I. Siddiqi,[13] A. Agrawal,[14] A. V. Dixit,[14] E. J. Daw,[15] M. G. Perry,[15] J. H. Buckley,[16] C. Gaikwad,[16] J. Hoffman,[16] K. W. Murch,[16] and J. Russell[16]
(ADMX Collaboration)



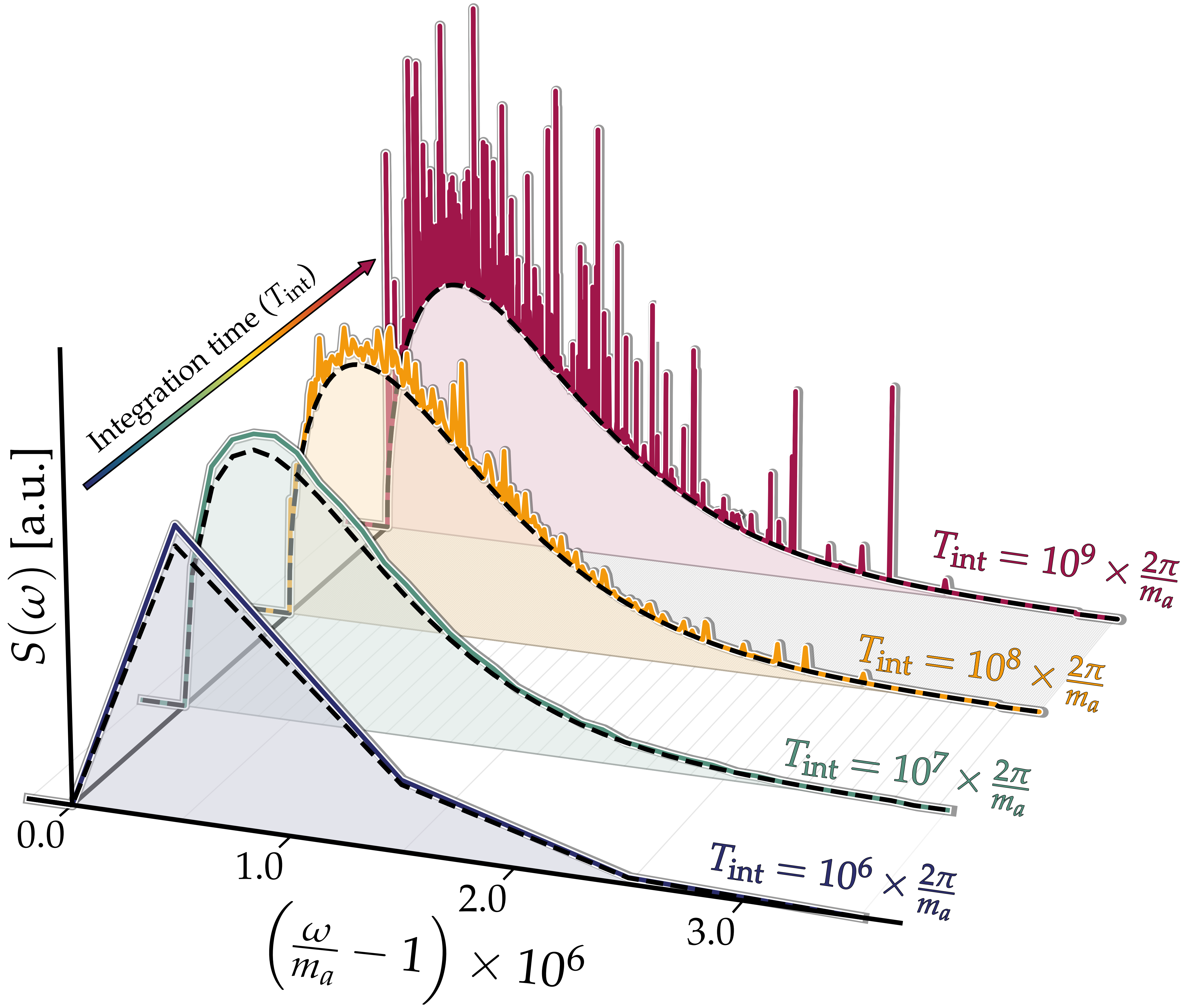



# Summary

- **Miniclusters and their tidal debris** are a *consequence* of the post-inflationary axion dark matter scenario so any observational/experimental test of this scenario must account for them to perform a self-consistent search

- **Direct detection is significantly impacted** by the fact that axion DM distribution was once highly clustered in small scale substructures which are now mostly disrupted.

- **Leads to a lineshape containing many narrow features** which can be resolved in specialised high-resolution analyses of haloscope data. Searches are being done by collaborations like ADMX — enhanced prospects to discover the axion.



# Extras

# What timescales are we talking?

Axion oscillation period

$$T_{\rm ax} \equiv \frac{2\pi}{m_a} = 41\,{\rm ps}\left(\frac{100\mu{\rm eV}}{m_a}\right)$$

Coherence time (SHM)

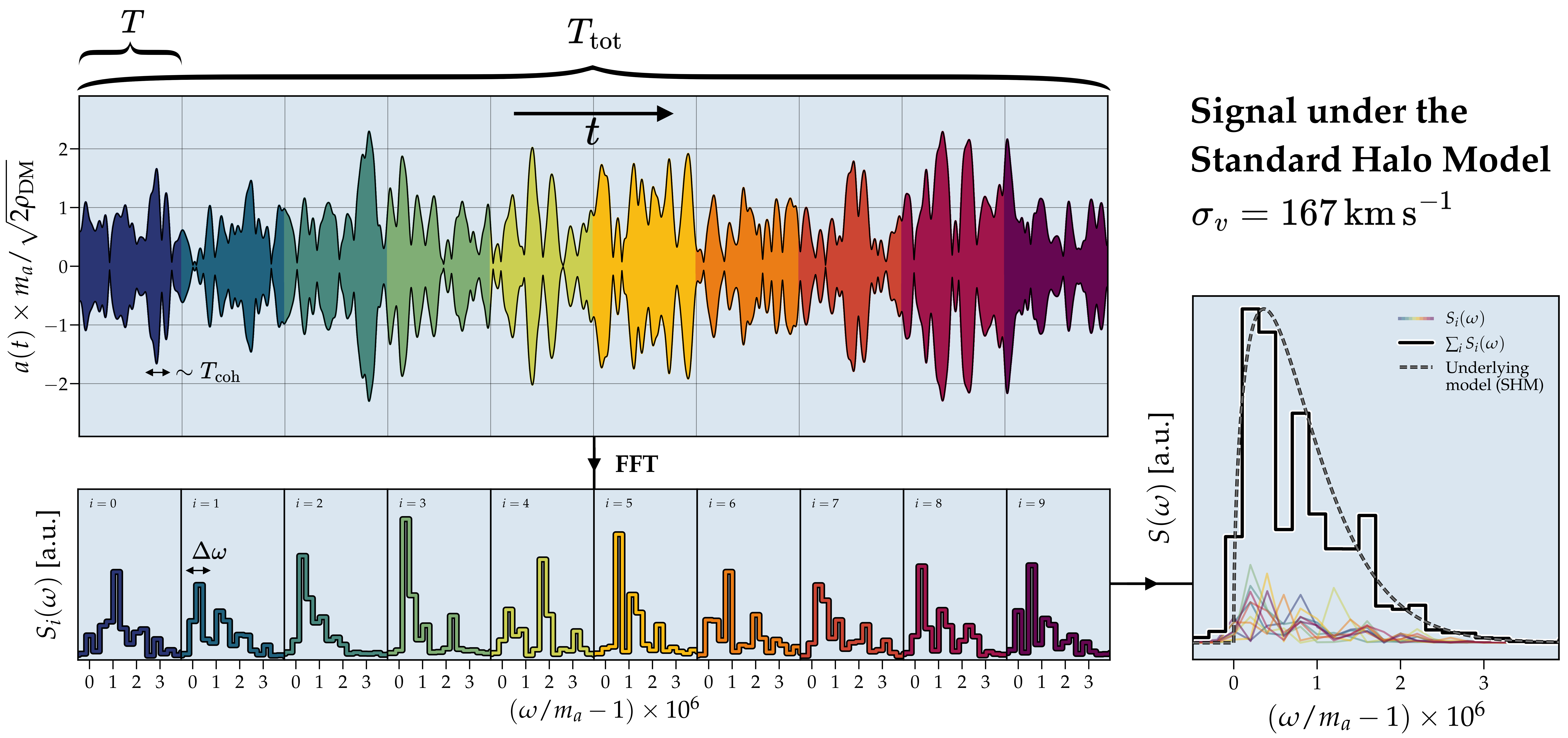
$$\tau_{\rm coh} \approx 10^6 T_{\rm ax} = 41\,\mu{\rm s}\left(\frac{100\mu{\rm eV}}{m_a}\right)$$

Coherence time (Stream)

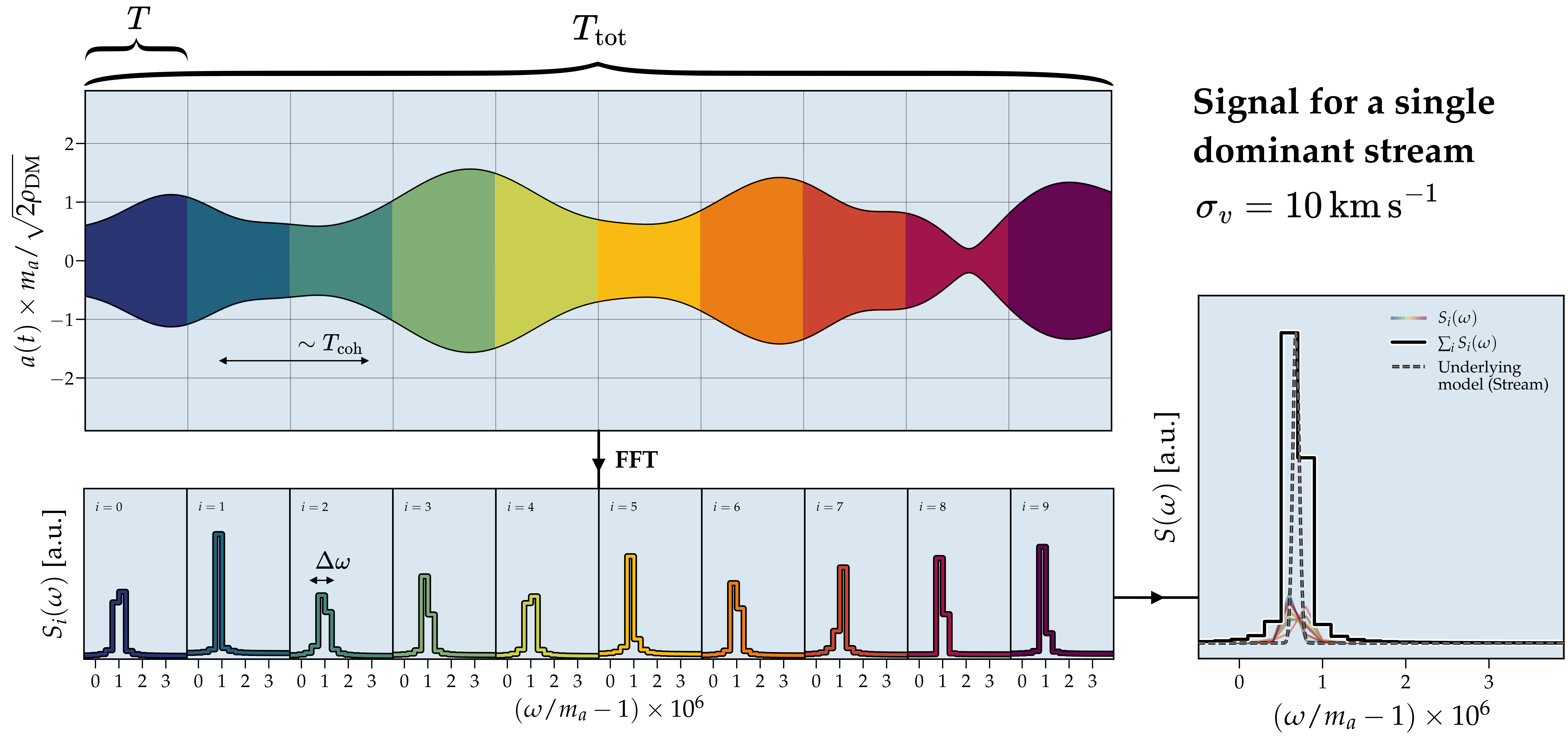
$$\tau_{\rm coh} \approx \frac{T_{\rm ax}}{\sigma_{\rm str} v_{\rm str}} = 0.1\,{\rm s}\left(\frac{100\mu{\rm eV}}{m_a}\right)\left(\frac{0.1\,{\rm km\,s^{-1}}}{\sigma_{\rm str}}\right)\left(\frac{300\,{\rm km\,s^{-1}}}{v_{\rm str}}\right)$$

**Compare to integration time for the ALPHA experiment perform 95%CL exclusion of KSVZ axion at this mass:** $T \sim 7\,s$

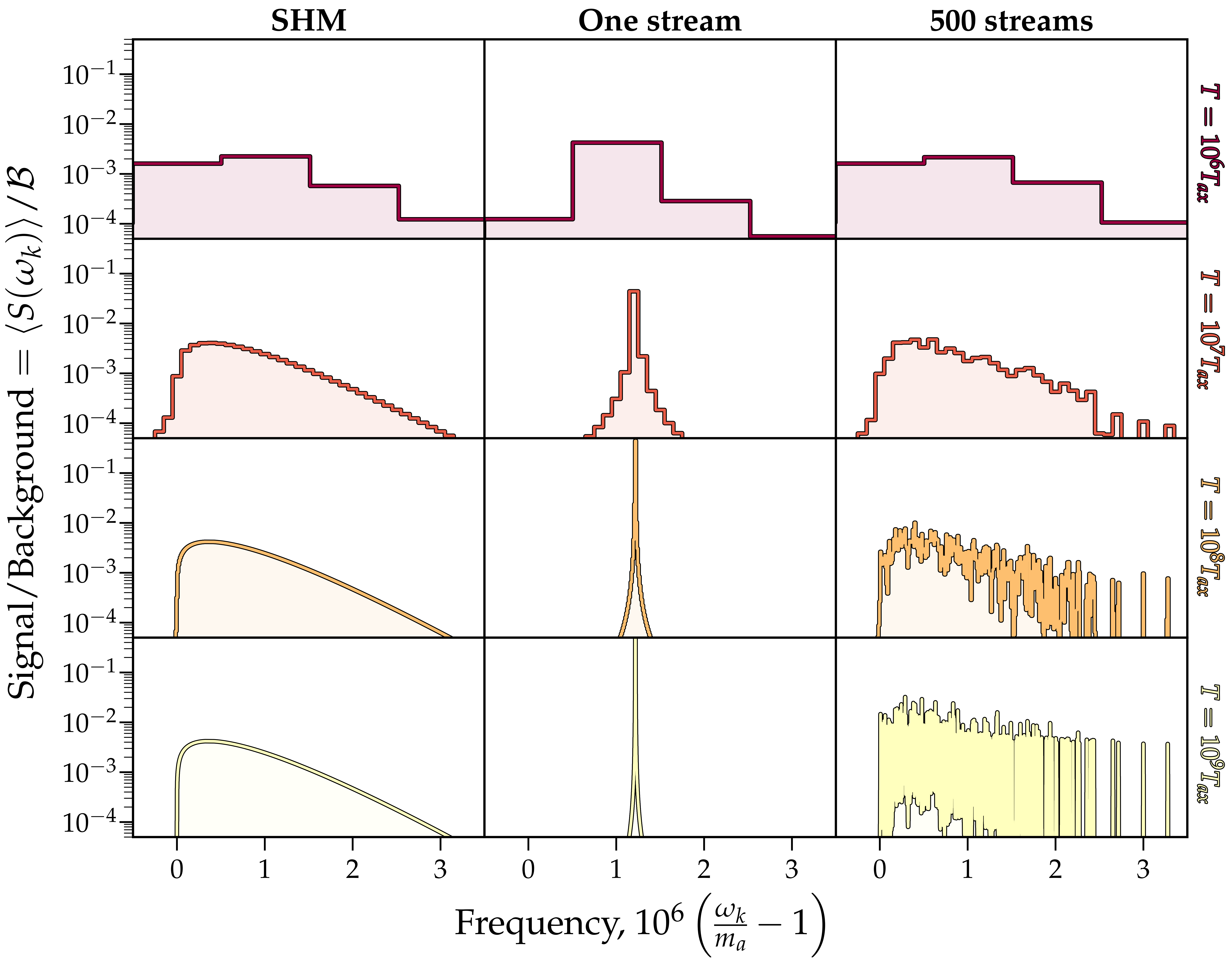
**→ Detecting these features requires a *reanalysis* of data not *more* data.**



$T$
$T_{\rm tot}$
$t$
$a(t) \times m_a/\sqrt{2\rho_{\rm DM}}$
$\sim T_{\rm coh}$
FFT
$S_i(\omega)$ [a.u.]
$i=0$
$i=1$
$i=2$
$i=3$
$i=4$
$i=5$
$i=6$
$i=7$
$i=8$
$i=9$
$\Delta\omega$
$(\omega/m_a - 1) \times 10^6$
Signal under the Standard Halo Model
$\sigma_v = 167\,{\rm km\,s^{-1}}$
$S(\omega)$ [a.u.]
$S_i(\omega)$
$\sum_i S_i(\omega)$
Underlying model (SHM)
$(\omega/m_a - 1) \times 10^6$



$T$
$T_{\rm tot}$
Signal for a single dominant stream
$\sigma_v = 10\,{\rm km\,s^{-1}}$
$a(t) \times m_a / \sqrt{2\rho_{\rm DM}}$
$\sim T_{\rm coh}$
FFT
$S_i(\omega)$ [a.u.]
$i=0$
$i=1$
$i=2$
$i=3$
$i=4$
$i=5$
$i=6$
$i=7$
$i=8$
$i=9$
$\Delta\omega$
$(\omega/m_a - 1) \times 10^6$
$S(\omega)$ [a.u.]
$S_i(\omega)$
$\sum_i S_i(\omega)$
Underlying model (Stream)
$(\omega/m_a - 1) \times 10^6$




**Short integration times**

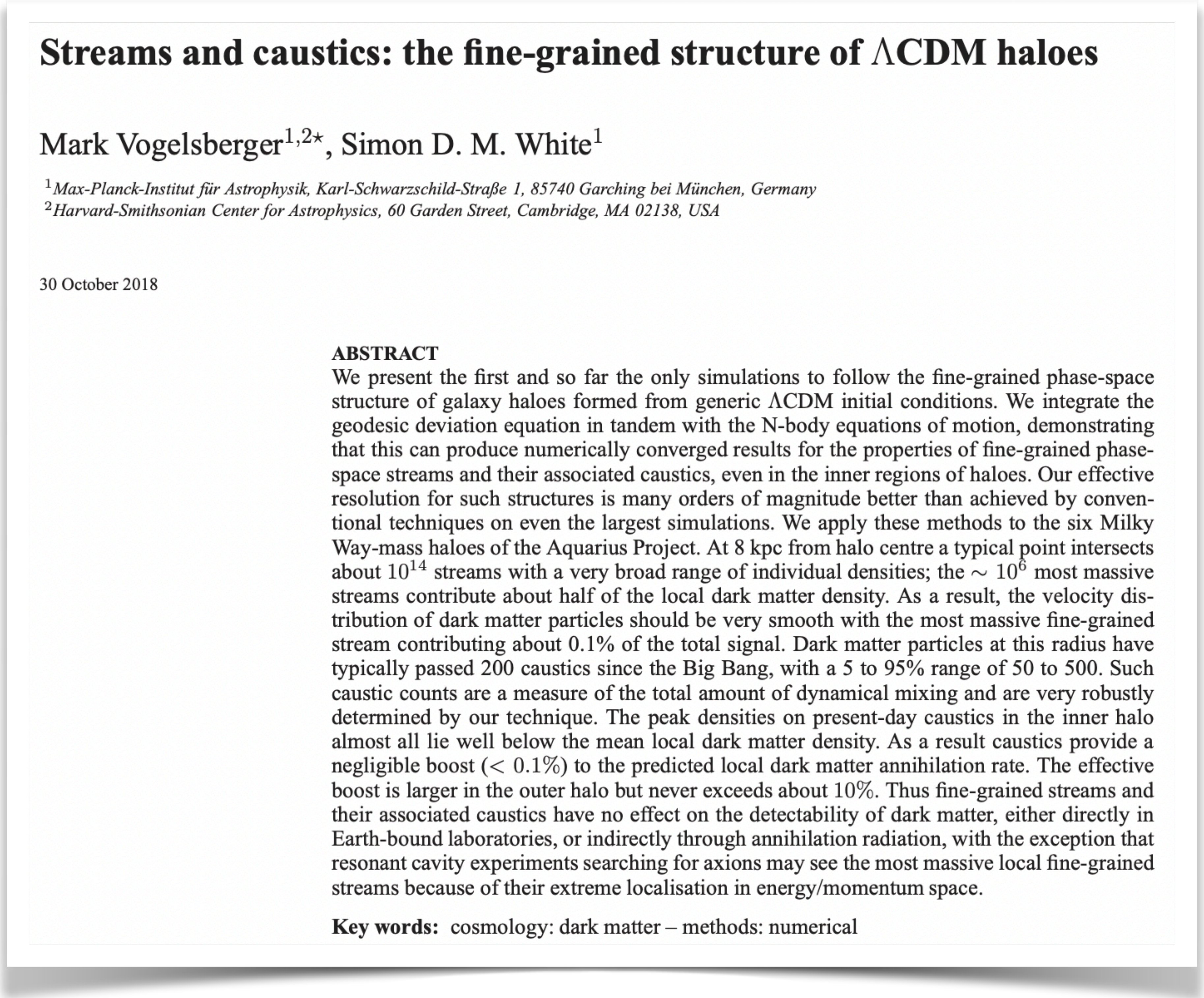
→ signal models look almost identifcal

**Long integration times**

→ signal models look very different.

→ If a frequency bin lands on a narrow feature it can get a huge signal-to-noise boost in that bin.

# Bonus: fine-grained structure of CDM halos



**Streams and caustics: the fine-grained structure of ΛCDM haloes**

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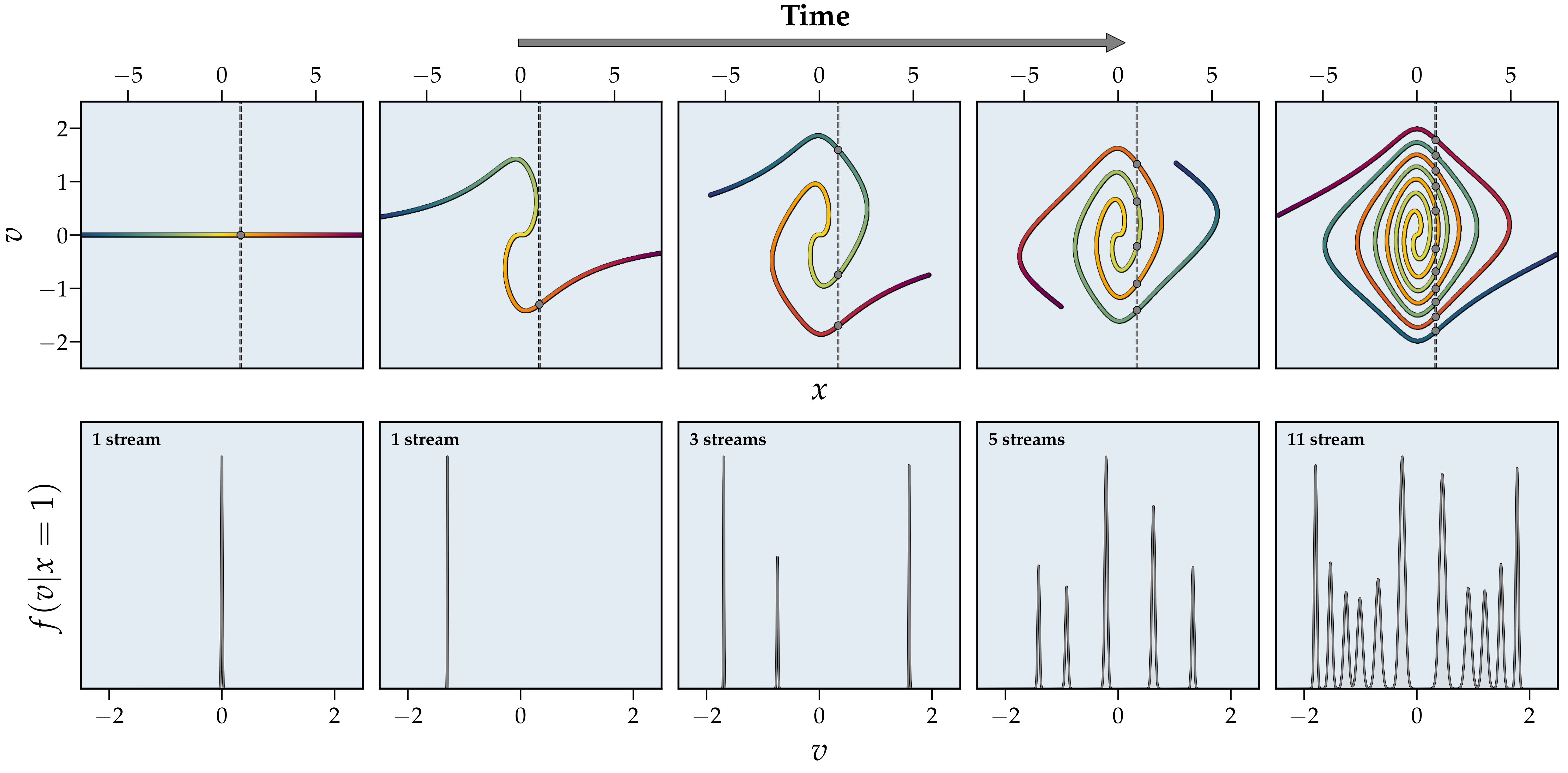
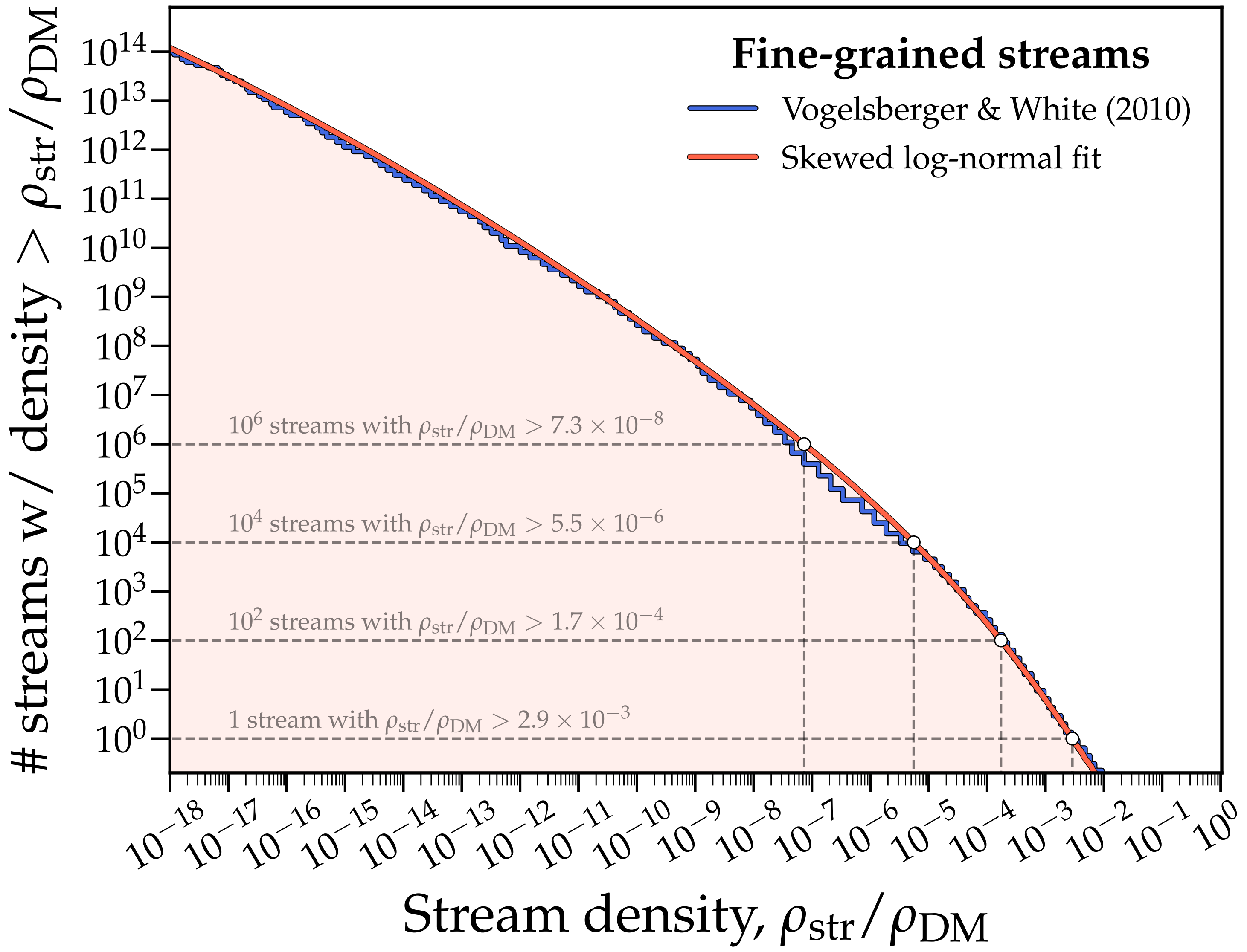
**ABSTRACT**
We present the first and so far the only simulations to follow the fine-grained phase-space structure of galaxy haloes formed from generic ΛCDM initial conditions. We integrate the geodesic deviation equation in tandem with the N-body equations of motion, demonstrating that this can produce numerically converged results for the properties of fine-grained phase-space streams and their associated caustics, even in the inner regions of haloes. Our effective resolution for such structures is many orders of magnitude better than achieved by conventional techniques on even the largest simulations. We apply these methods to the six Milky Way-mass haloes of the Aquarius Project. At 8 kpc from halo centre a typical point intersects about $10^{14}$ streams with a very broad range of individual densities; the $\sim 10^6$ most massive streams contribute about half of the local dark matter density. As a result, the velocity distribution of dark matter particles should be very smooth with the most massive fine-grained stream contributing about 0.1% of the total signal. Dark matter particles at this radius have typically passed 200 caustics since the Big Bang, with a 5 to 95% range of 50 to 500. Such caustic counts are a measure of the total amount of dynamical mixing and are very robustly determined by our technique. The peak densities on present-day caustics in the inner halo almost all lie well below the mean local dark matter density. As a result caustics provide a negligible boost ($< 0.1\%$) to the predicted local dark matter annihilation rate. The effective boost is larger in the outer halo but never exceeds about 10%. Thus fine-grained streams and their associated caustics have no effect on the detectability of dark matter, either directly in Earth-bound laboratories, or indirectly through annihilation radiation, with the exception that resonant cavity experiments searching for axions may see the most massive local fine-grained streams because of their extreme localisation in energy/momentum space.

**Key words:** cosmology: dark matter – methods: numerical

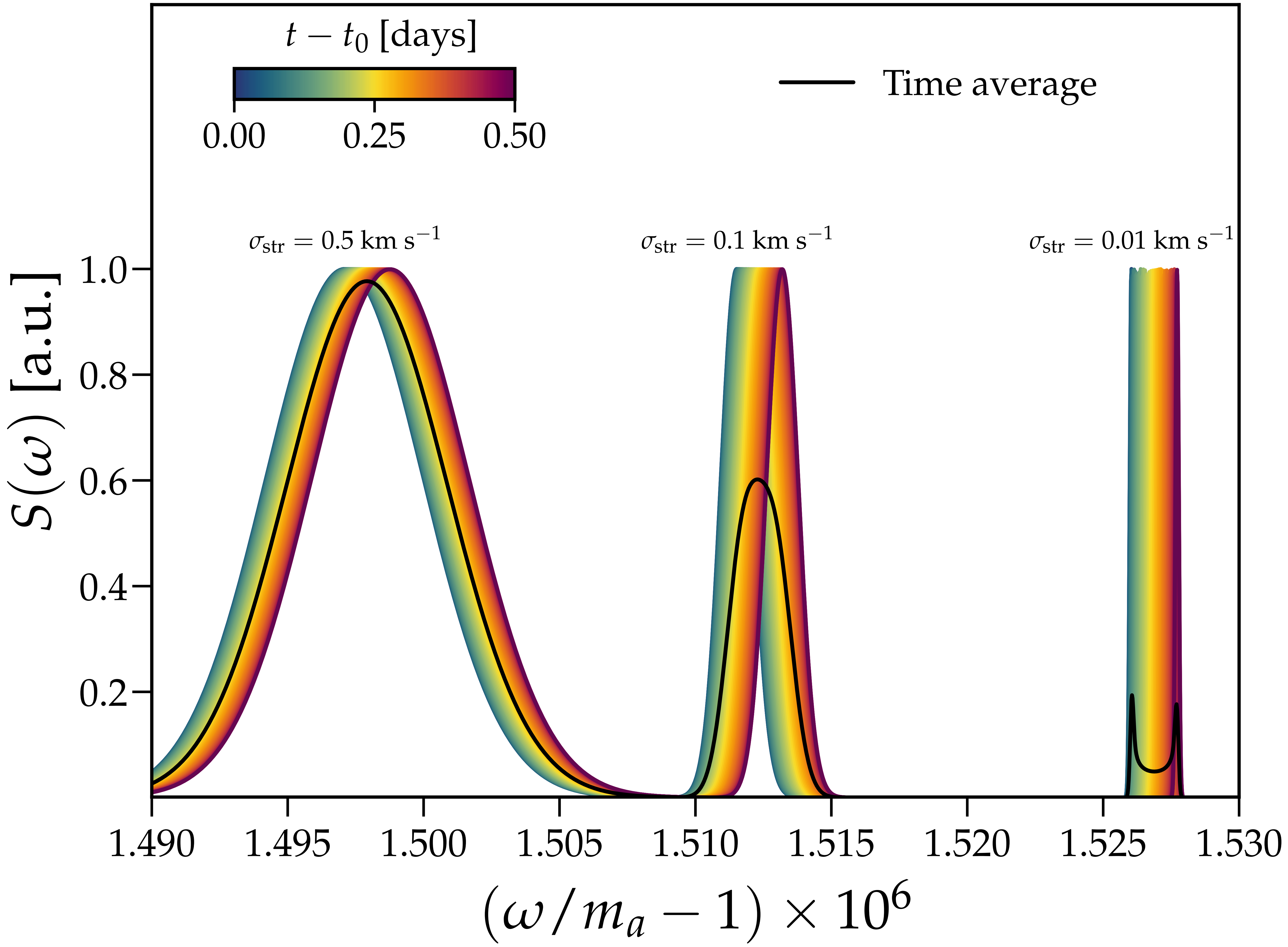


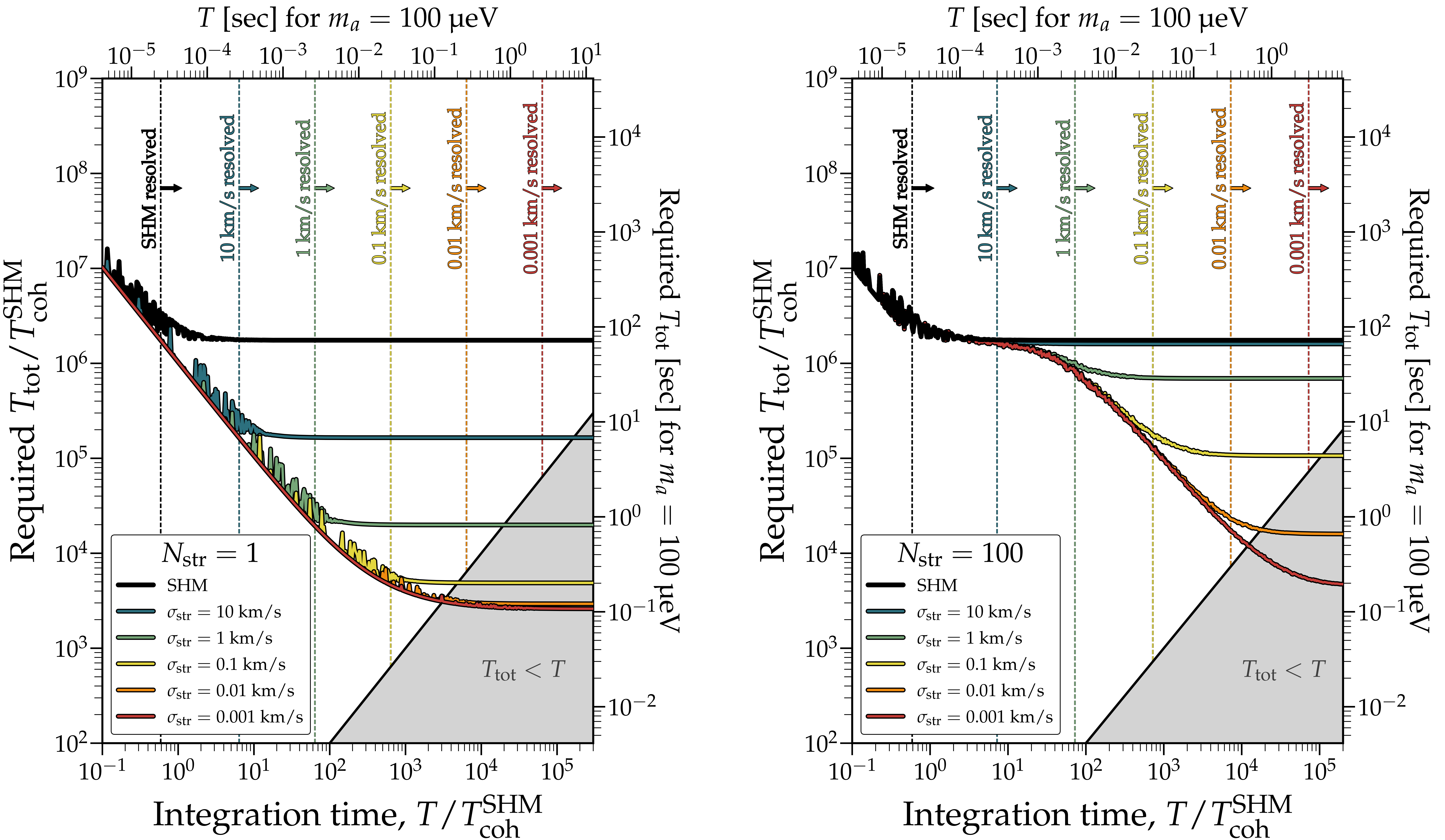




Fine-grained structure is actually a generic expectation for all CDM halos. We should have similar features present even in the pre-inflationary scenario

→ **wave-DM experiments should exploit this!**

# Daily modulation





T [sec] for m_a = 100 μeV
Required T_tot / T_coh^SHM
Required T_tot [sec] for m_a = 100 μeV
Integration time, T / T_coh^SHM
SHM resolved
10 km/s resolved
1 km/s resolved
0.1 km/s resolved
0.01 km/s resolved
0.001 km/s resolved
N_str = 1
N_str = 100
SHM
σ_str = 10 km/s
σ_str = 1 km/s
σ_str = 0.1 km/s
σ_str = 0.01 km/s
σ_str = 0.001 km/s
T_tot < T