Fine-grained dark matter substructure and axion haloscopes

Giovanni Pierobon, UNSW Sydney

20th Patras meeting, Tenerife, September 2025

Outline

Can a high resolution analysis
enhance the search for axion DM?

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1. Impact of *high-Q* streams on the data analysis

2. Relevant for *post-inflationary* case (miniclusters/streams), with numerical predictions from simulations

[2509.14874]

Fine-grained dark matter substructure and axion haloscopes

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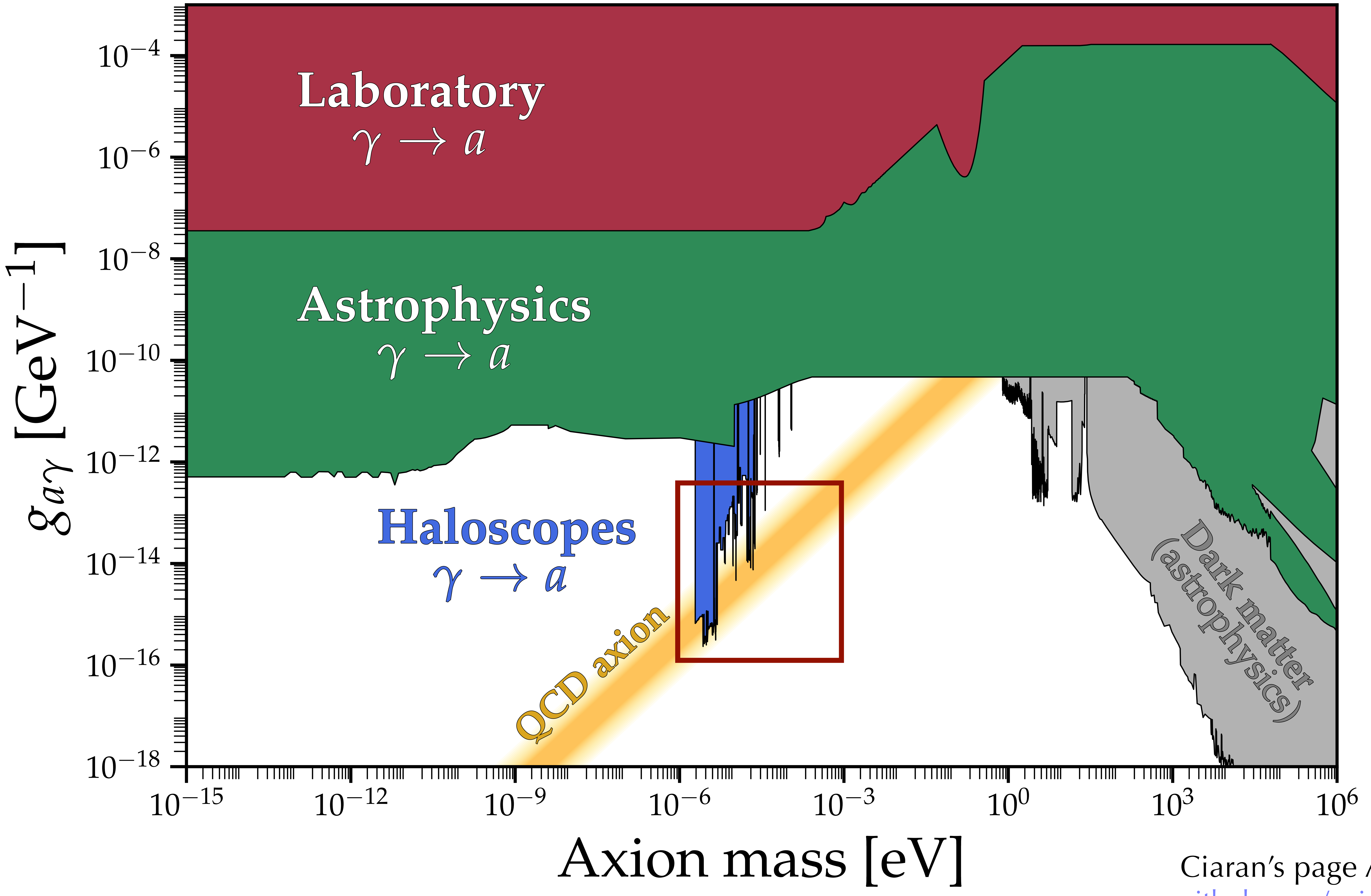
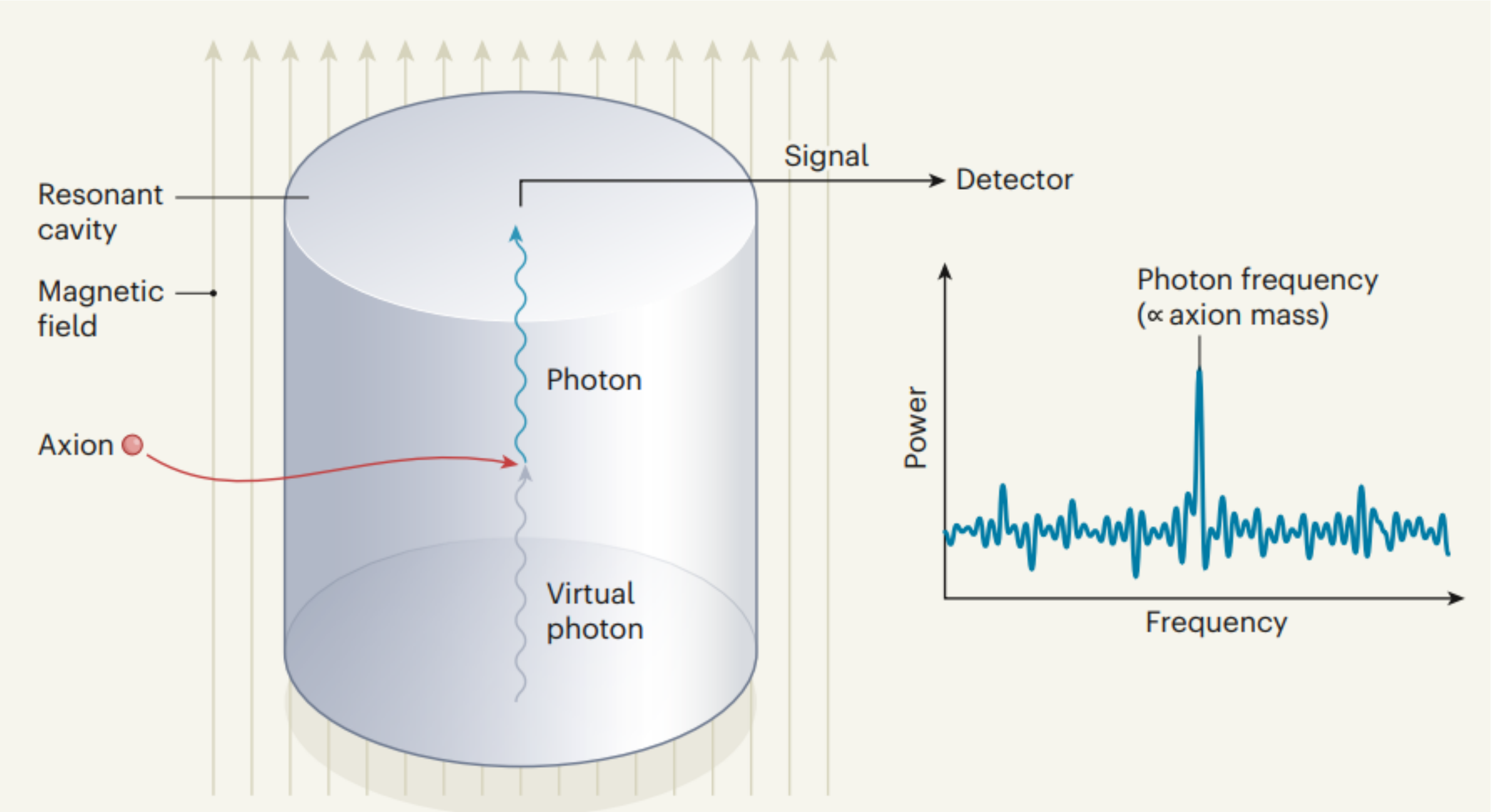
Parameter space



Ciaran's page AxionLimits
github.com/cajohare/AxionLimits

Haloscopes overview



Irastorza, Nature **590,** 226-227, (2021)

Discrete measurements in time interval T

$$y(t_n) = \sqrt{\mathcal{A}} \sum_j \alpha_j \sqrt{f\left(v_j\right) \Delta v} \cos\left[m_a \left(1 + \frac{1}{2} v_j^2\right) t_n + \phi_j\right]$$

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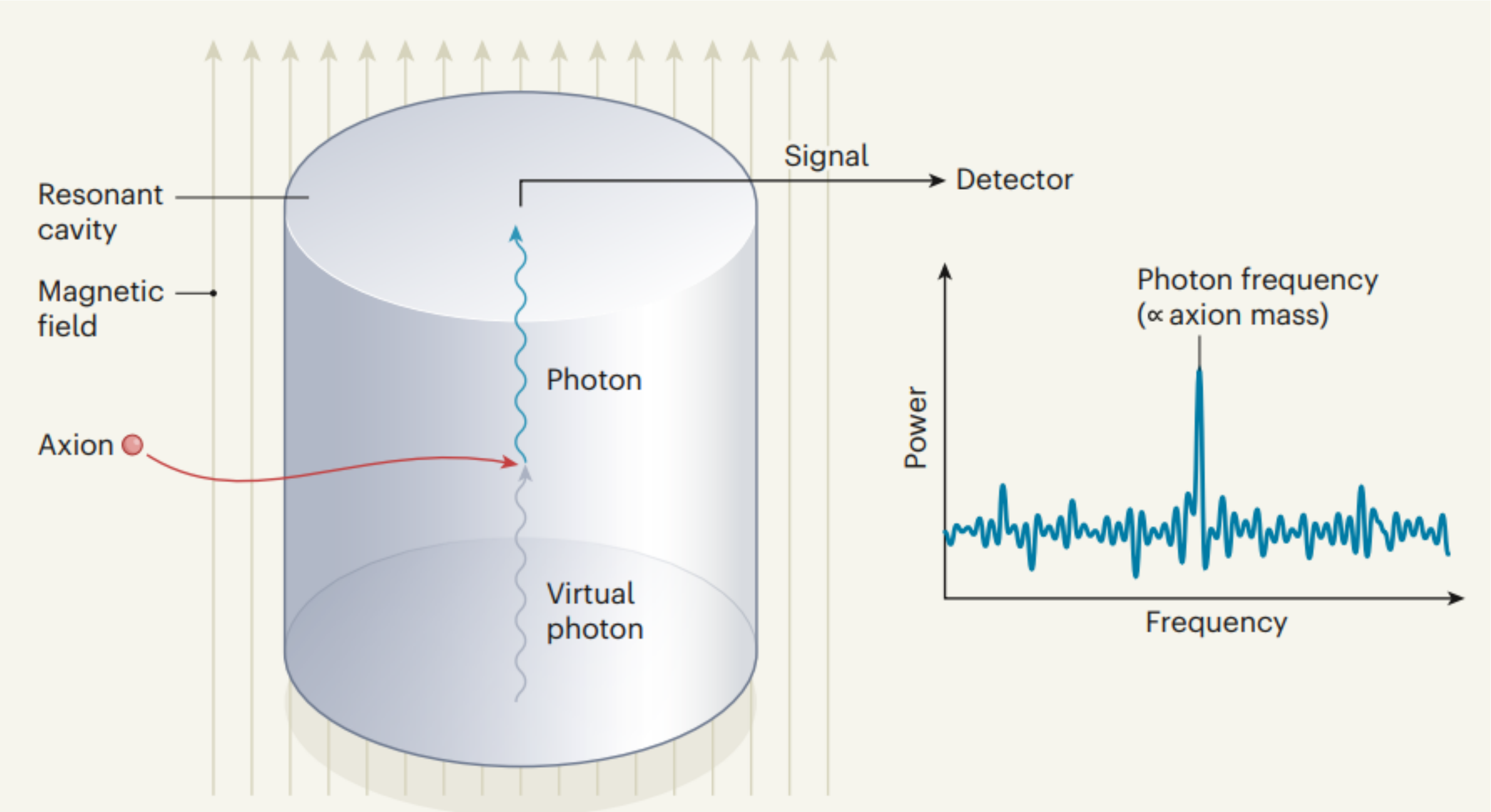

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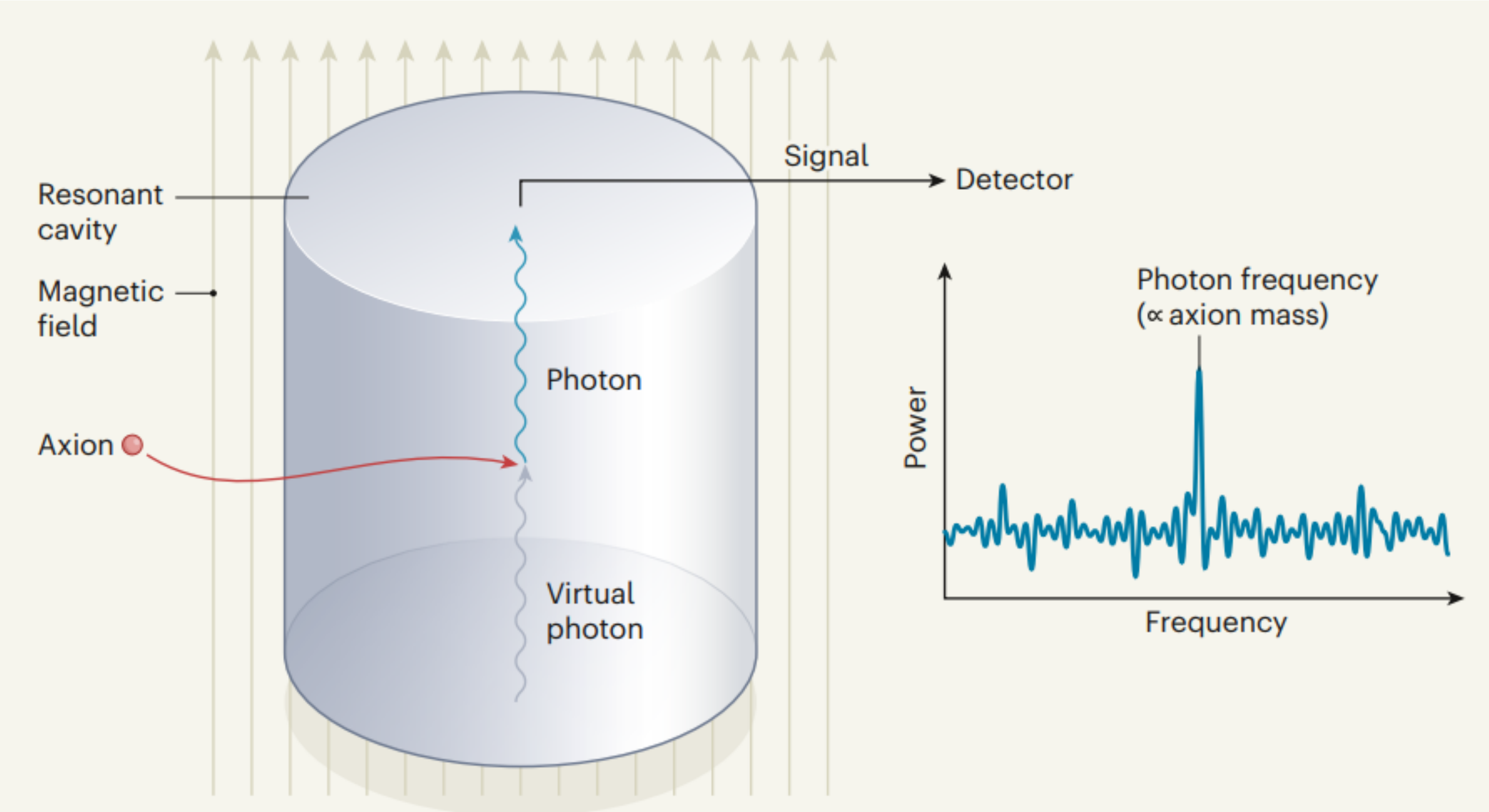
Signal normalisation: experiment dependent, e.g. standard cavity

$$\mathcal{A} = g_{a\gamma\gamma}^2 \frac{\rho_{\mathrm{DM}}}{m_a} \kappa Q B^2 V C$$

Haloscopes overview

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

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



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Coherent oscillation goes out of phase due to speed distribution

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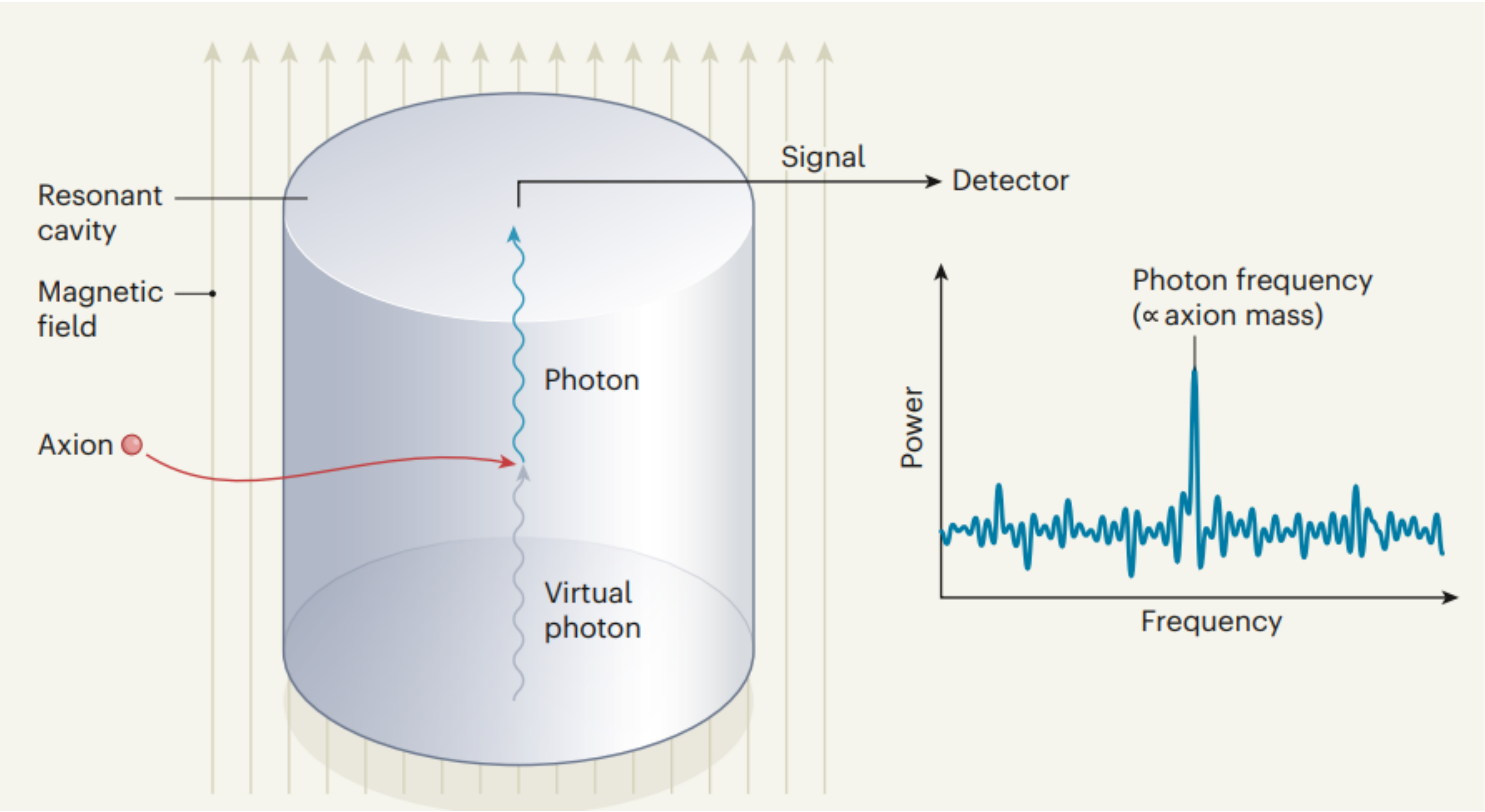

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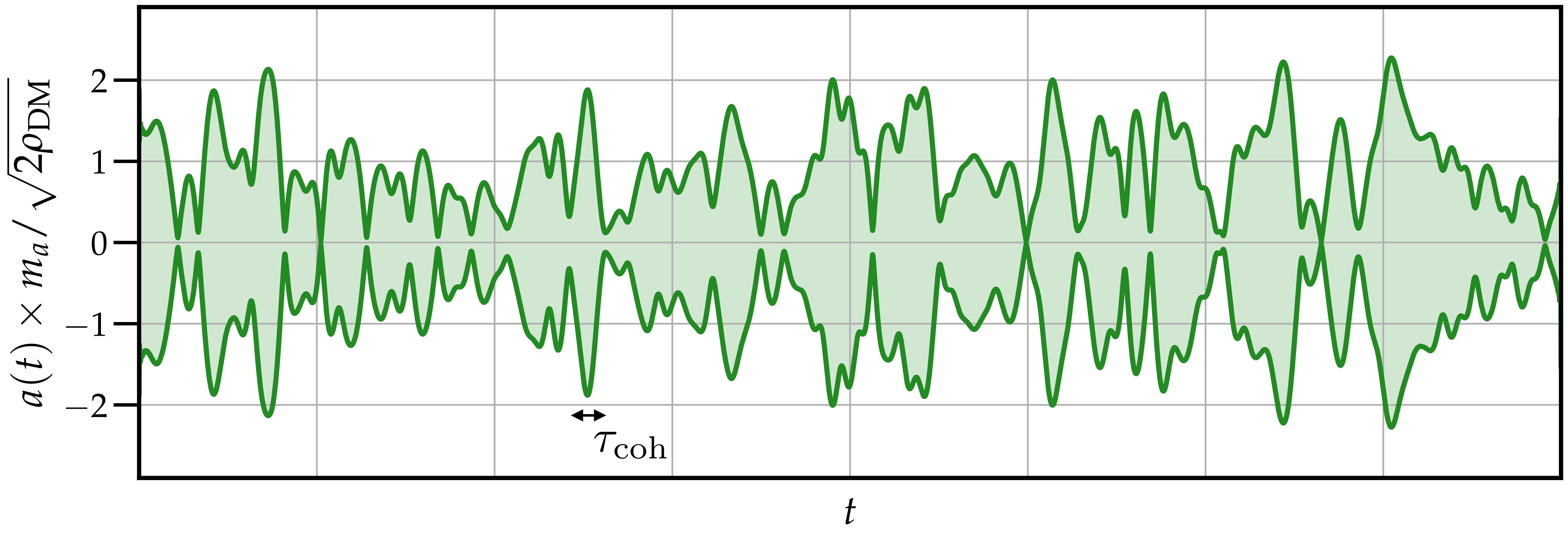
Standard halo model



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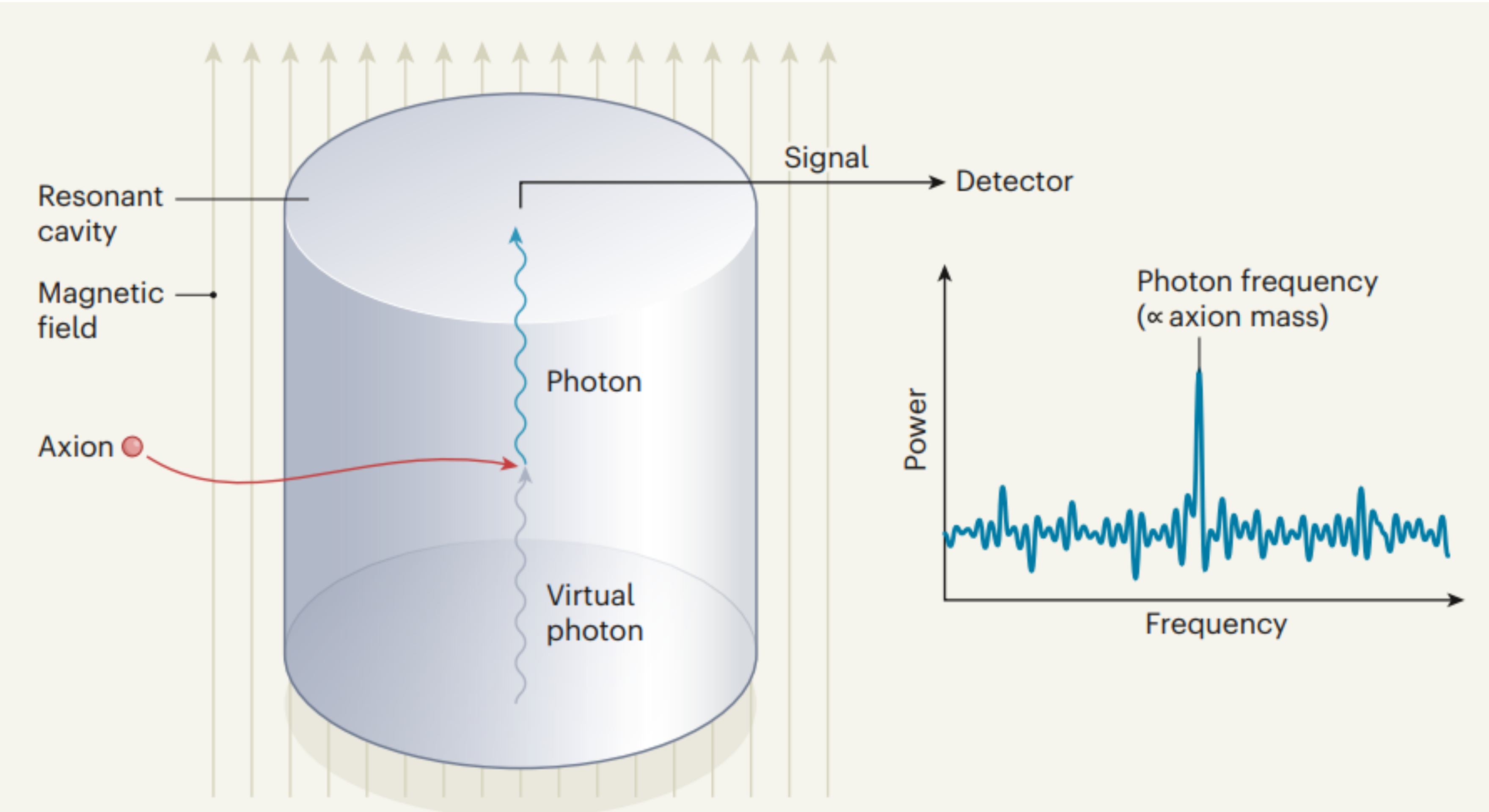

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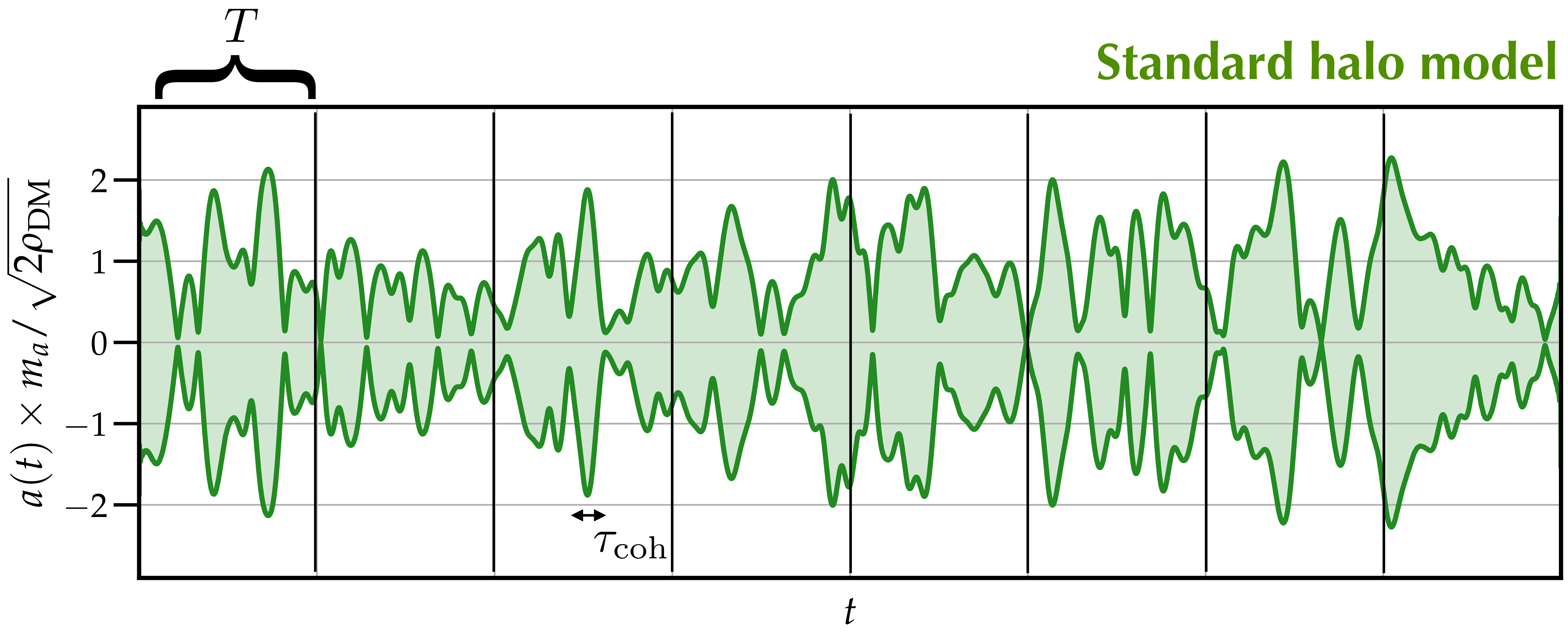
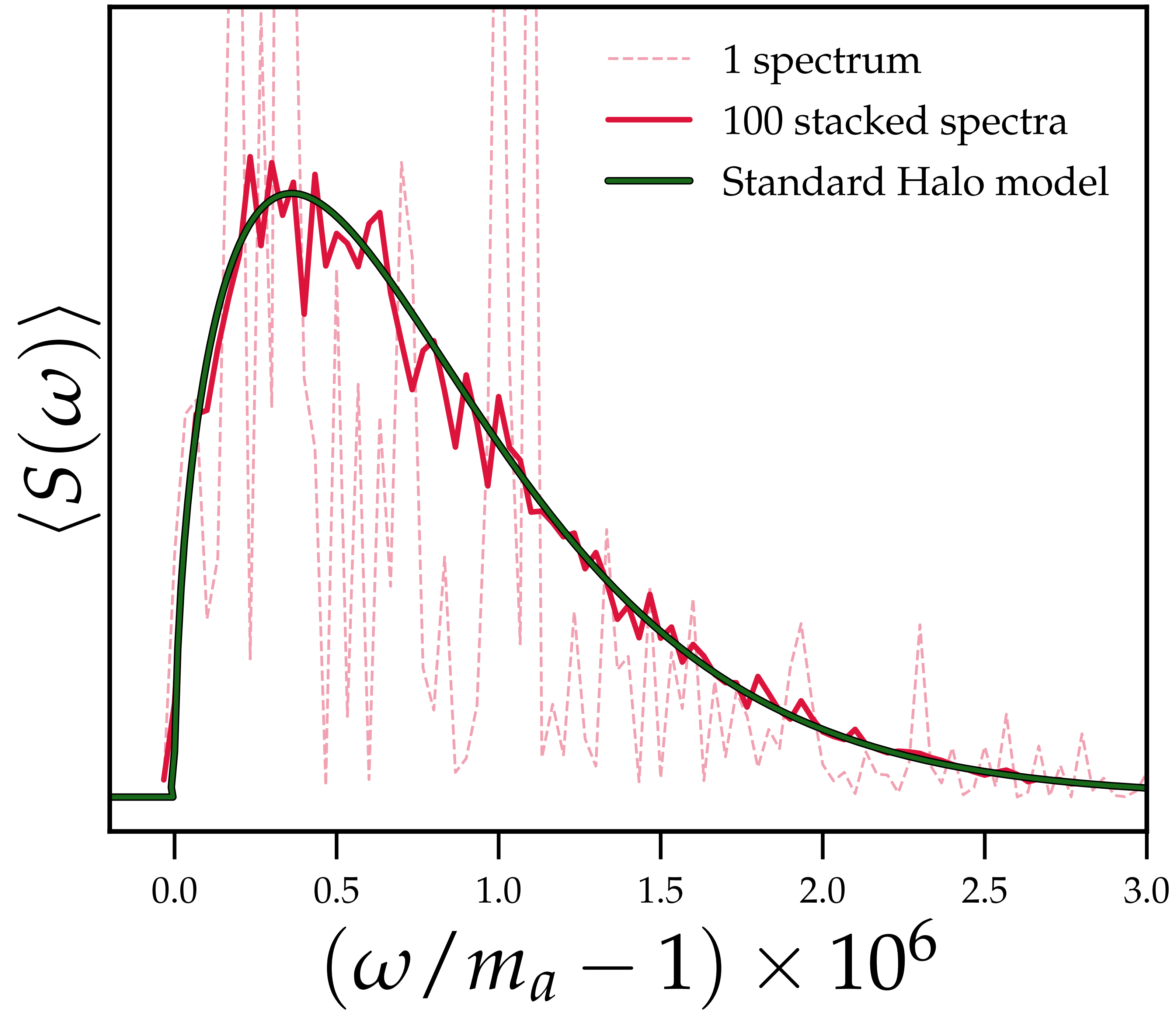
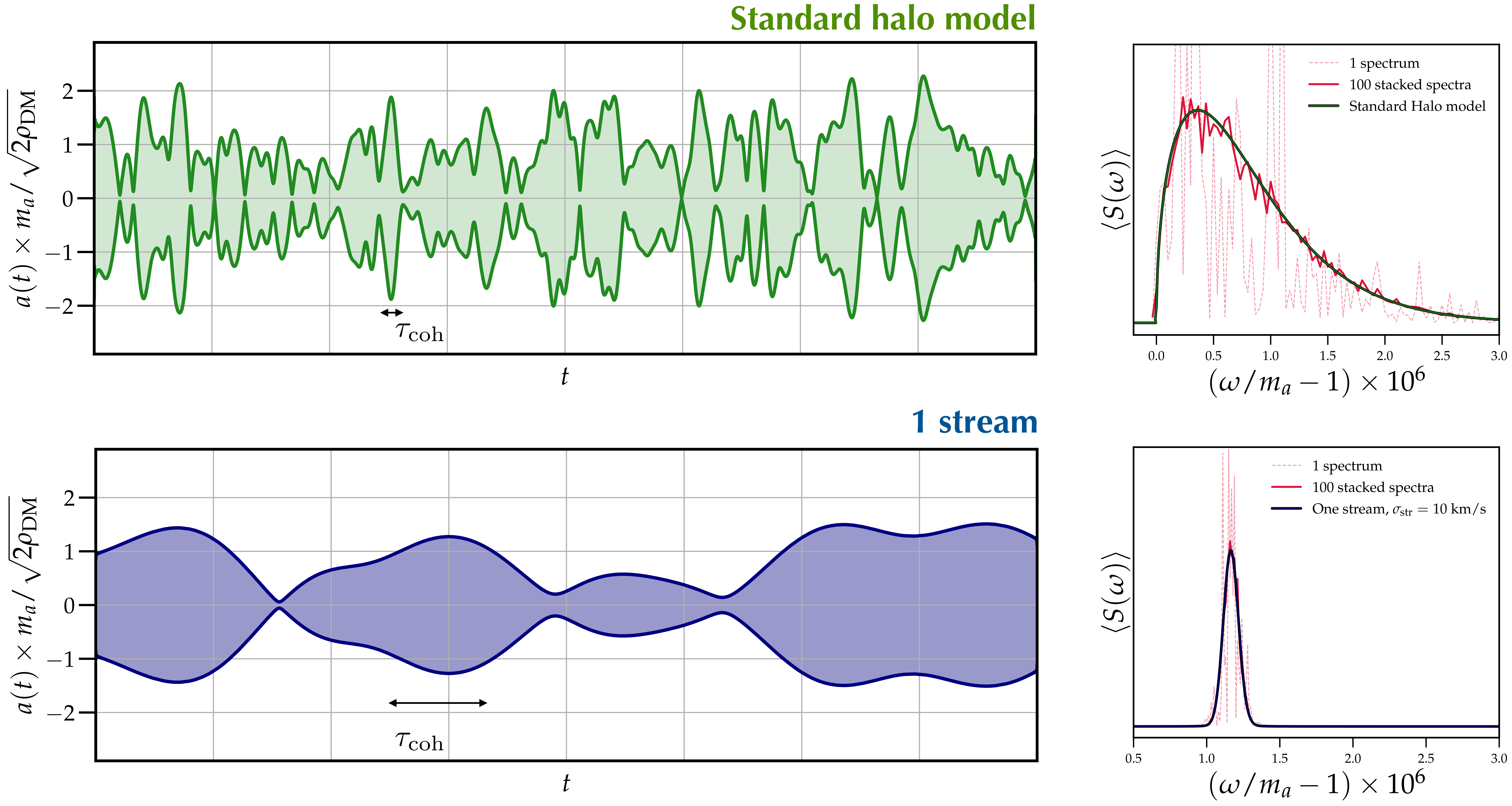


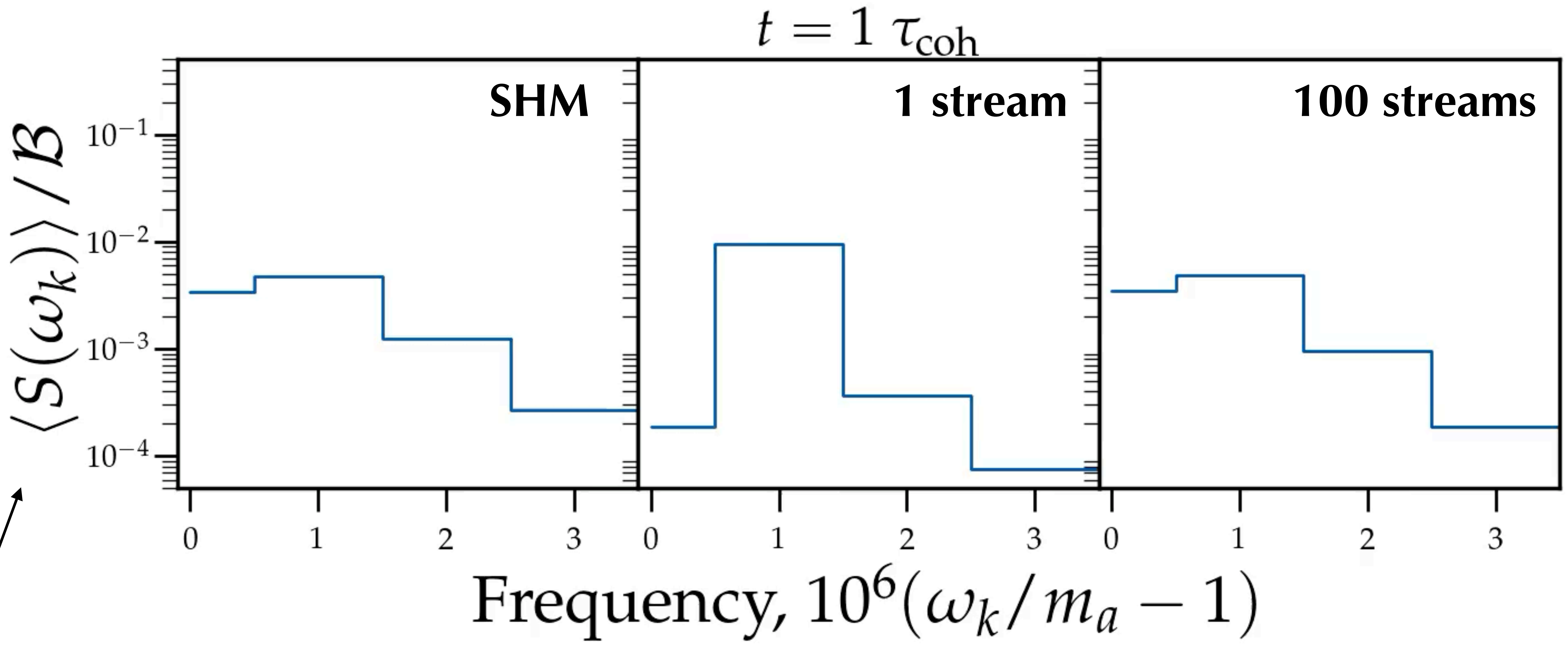


Signal shape: 1 stream



Signal shape: many streams

Simple models, with 2-3 parameters



SHM and 100 streams **appear the same** if integration time is comparable to axion coherence time

Mean lineshape power spectral densities

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

Signal in each bin is the convolution of speed distribution with a window function

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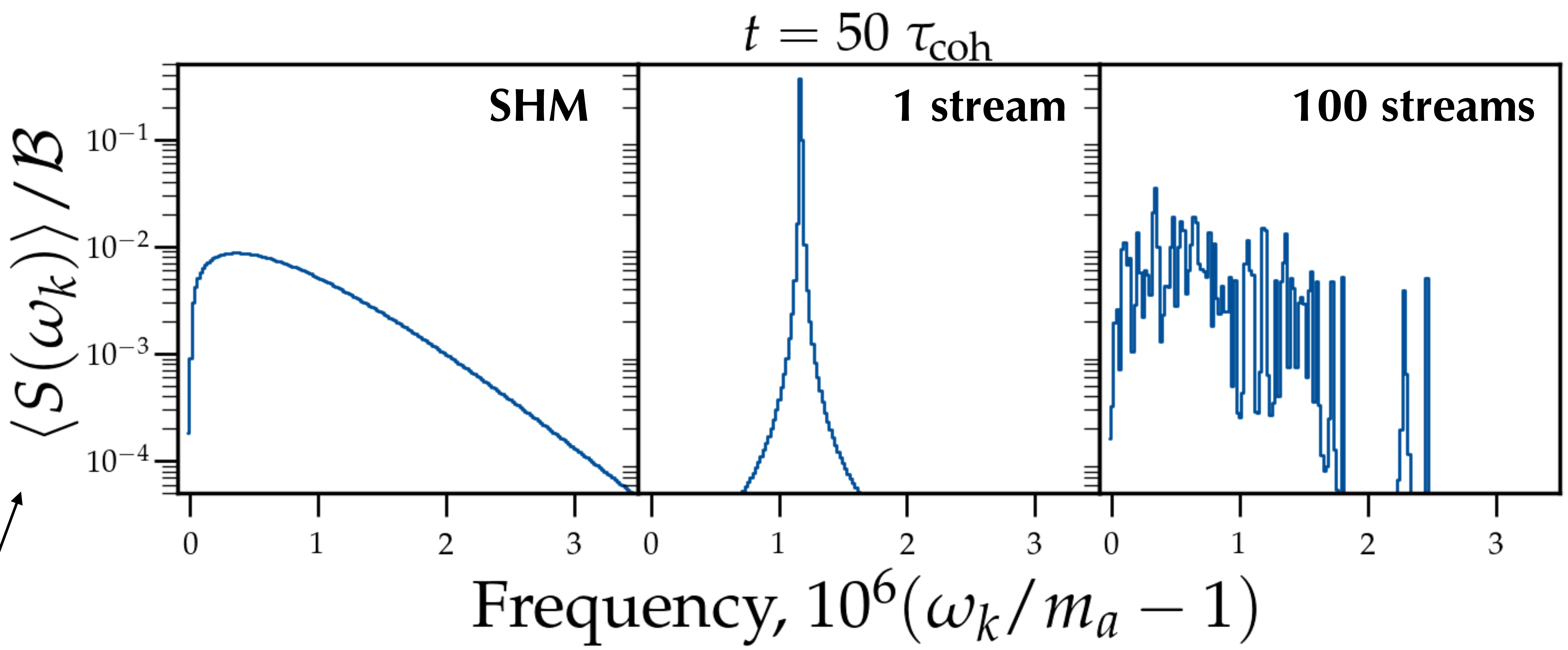

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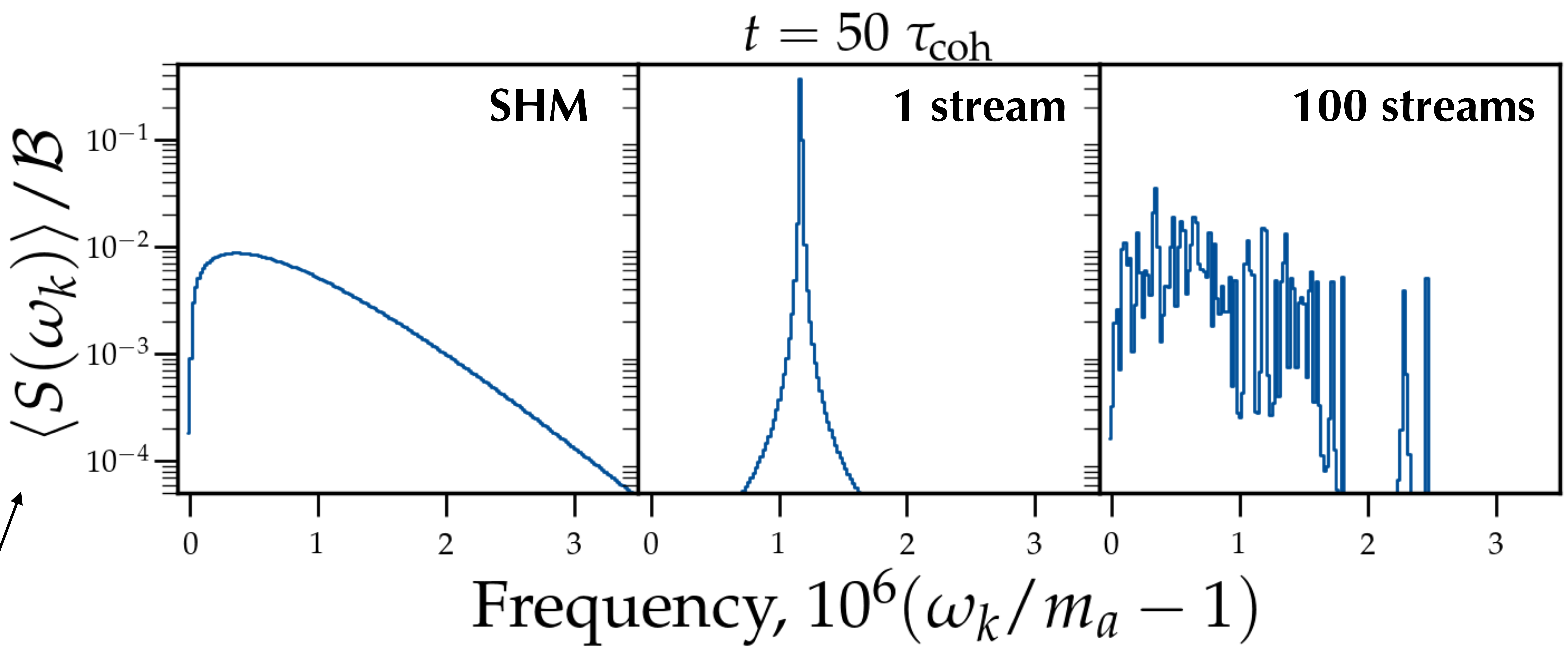

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Signal in each bin is the convolution of speed distribution with a window function

Foster, Rodd, Safdi, Phys.Rev.D **97,** (2018)

$$\langle S(\omega)\rangle_{T\to\infty} = \mathcal{A}\frac{\pi f(v)}{m_a v}\bigg|_{v=\sqrt{2\omega/m_a - 2}}$$

This only works if the signal may be larger than the resolution bandwidth

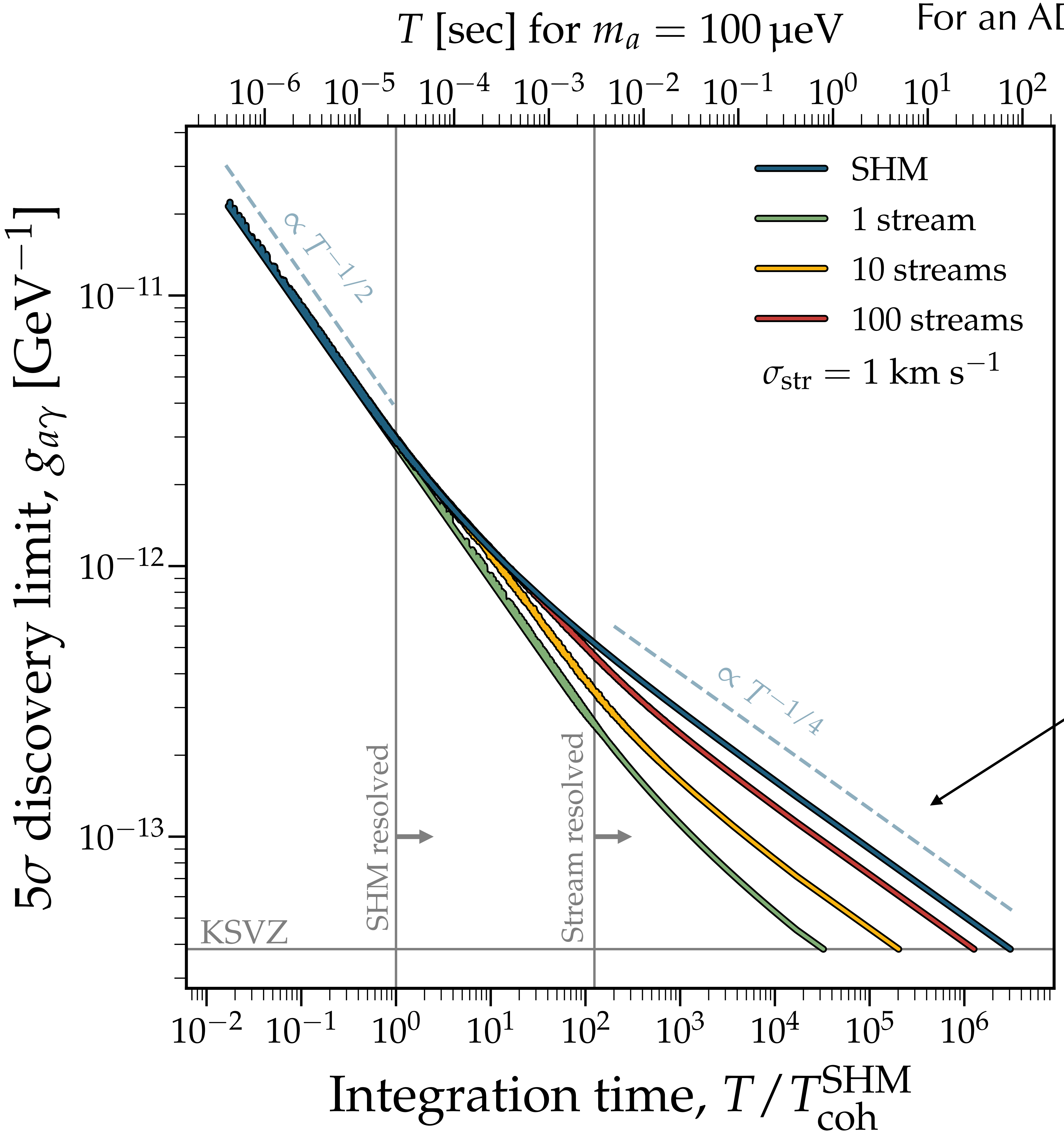
$$\omega_v = m_a(1 + v^2/2)$$

Discovery potential

We can construct a likelihood function for a set of data given a model **expected to describe** the data

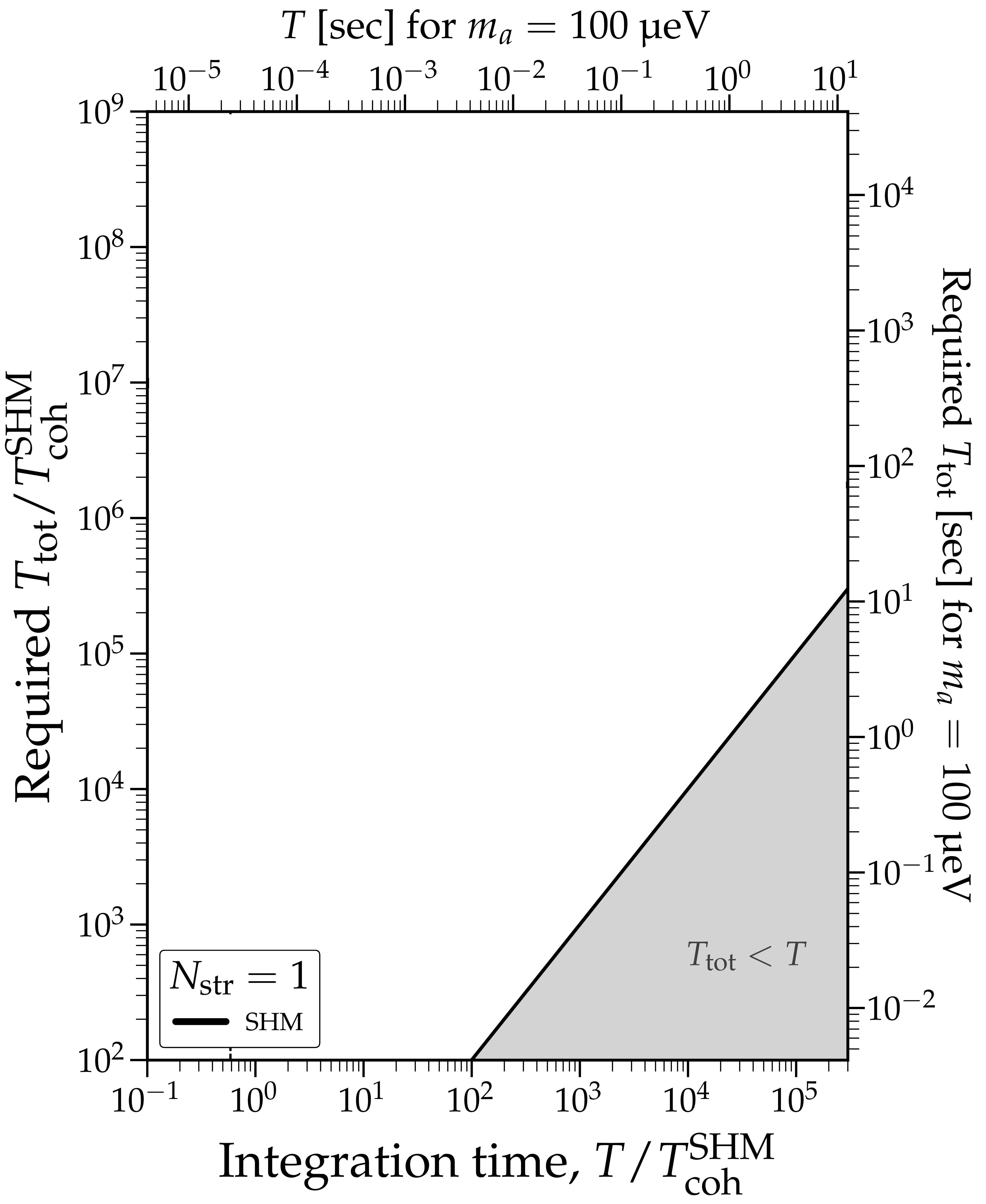
Parametric modelling:
profile likelihood ratio test

For an ADMX-like experiment



well-known scaling

Required scan time



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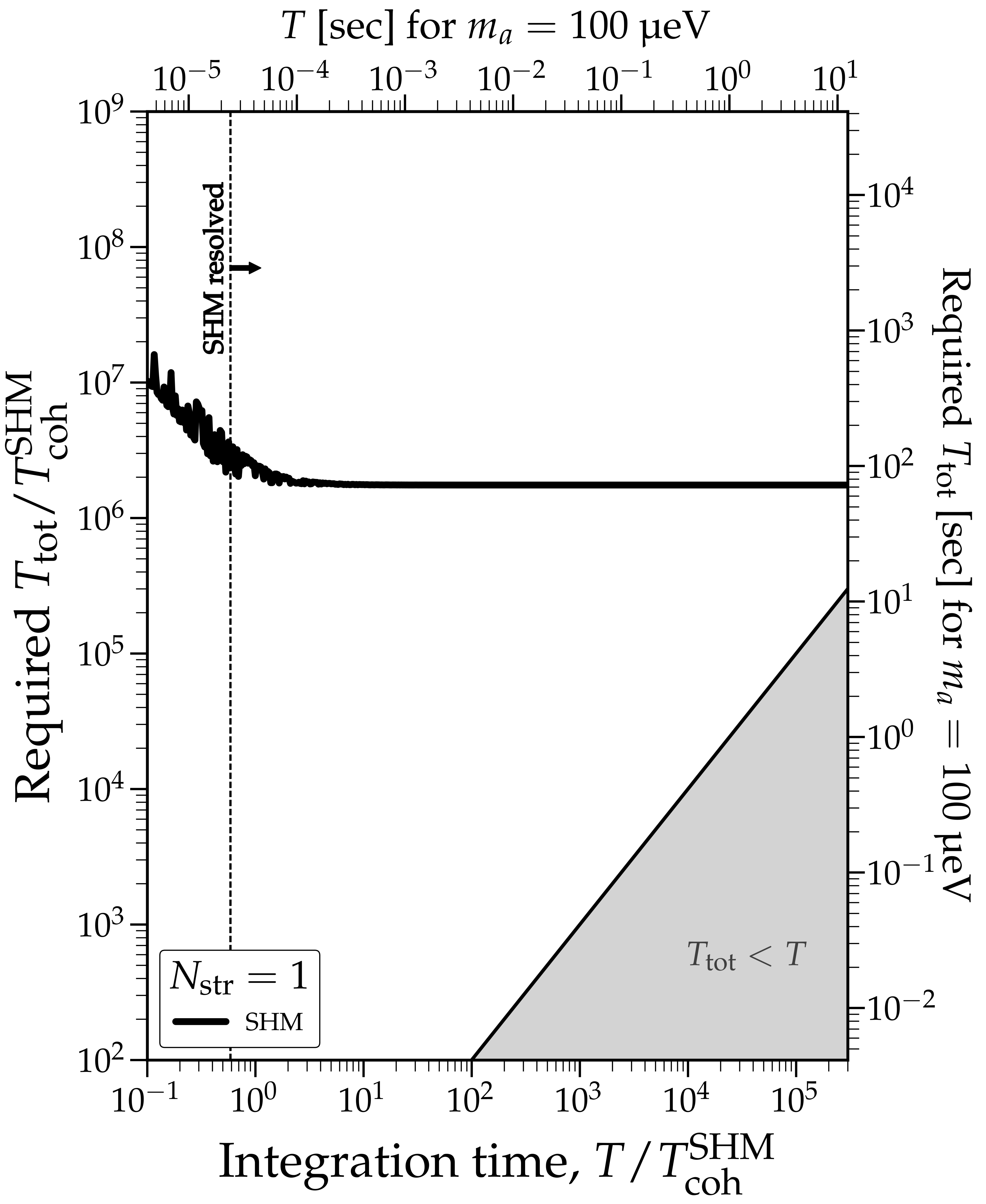

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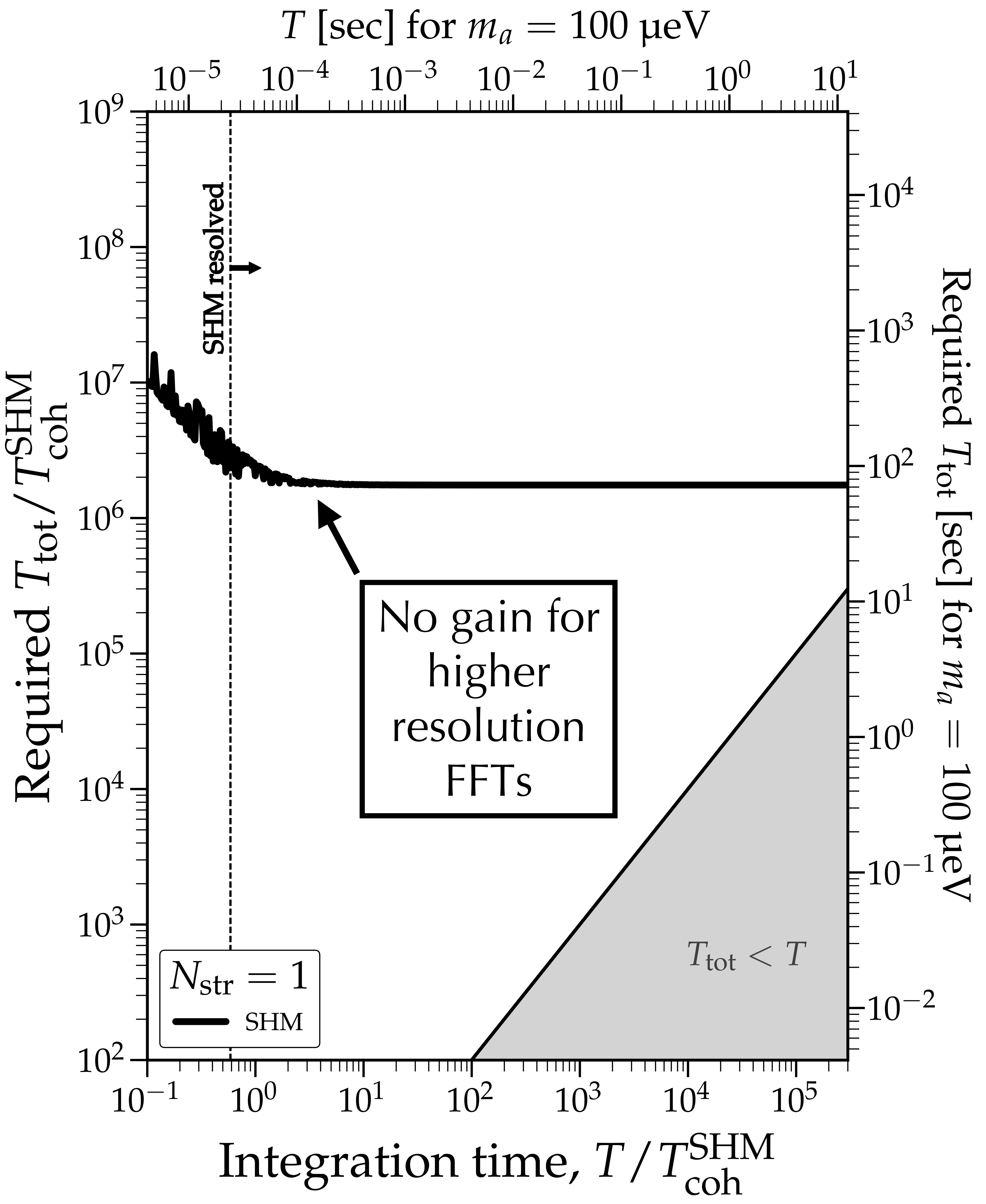

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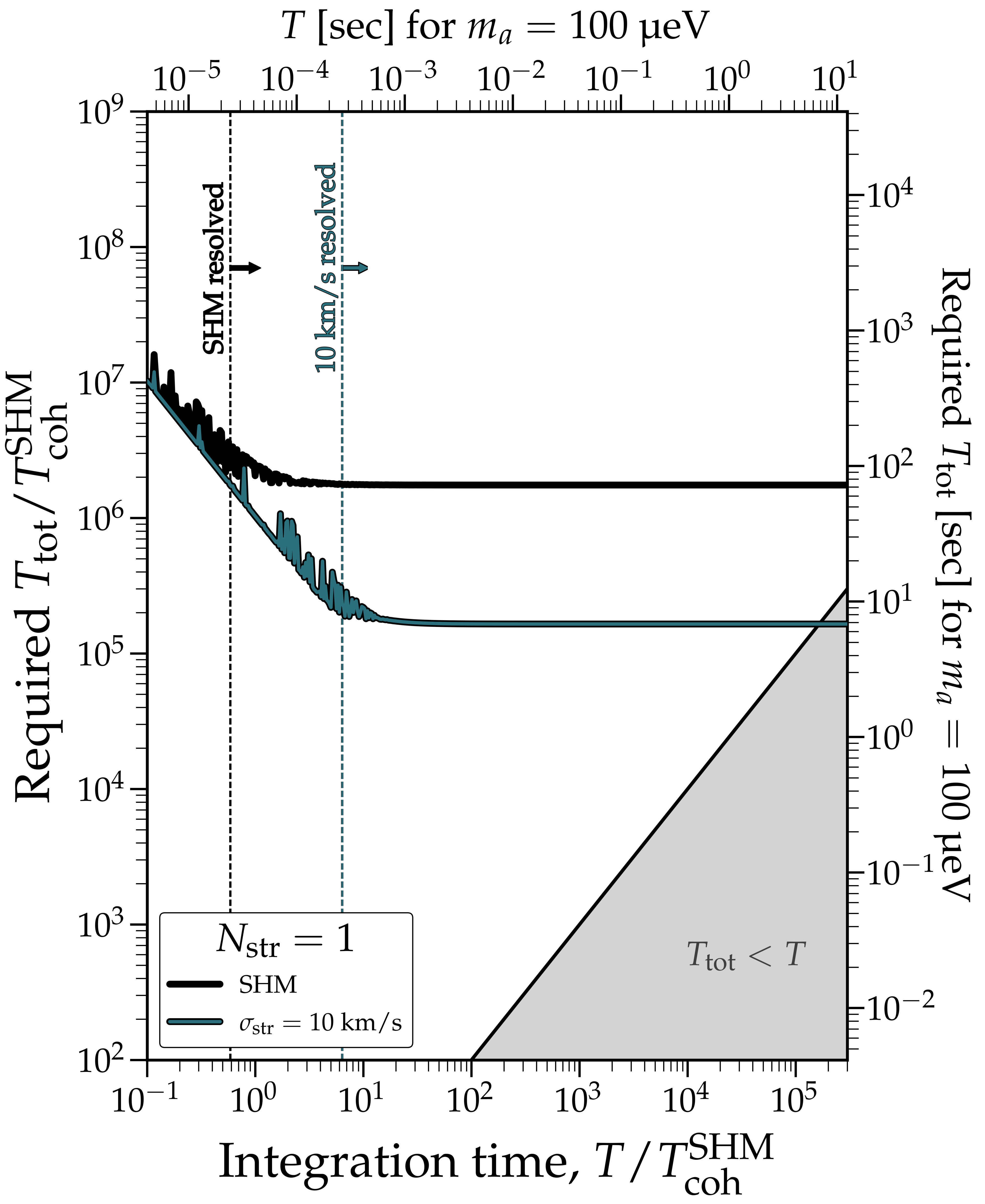

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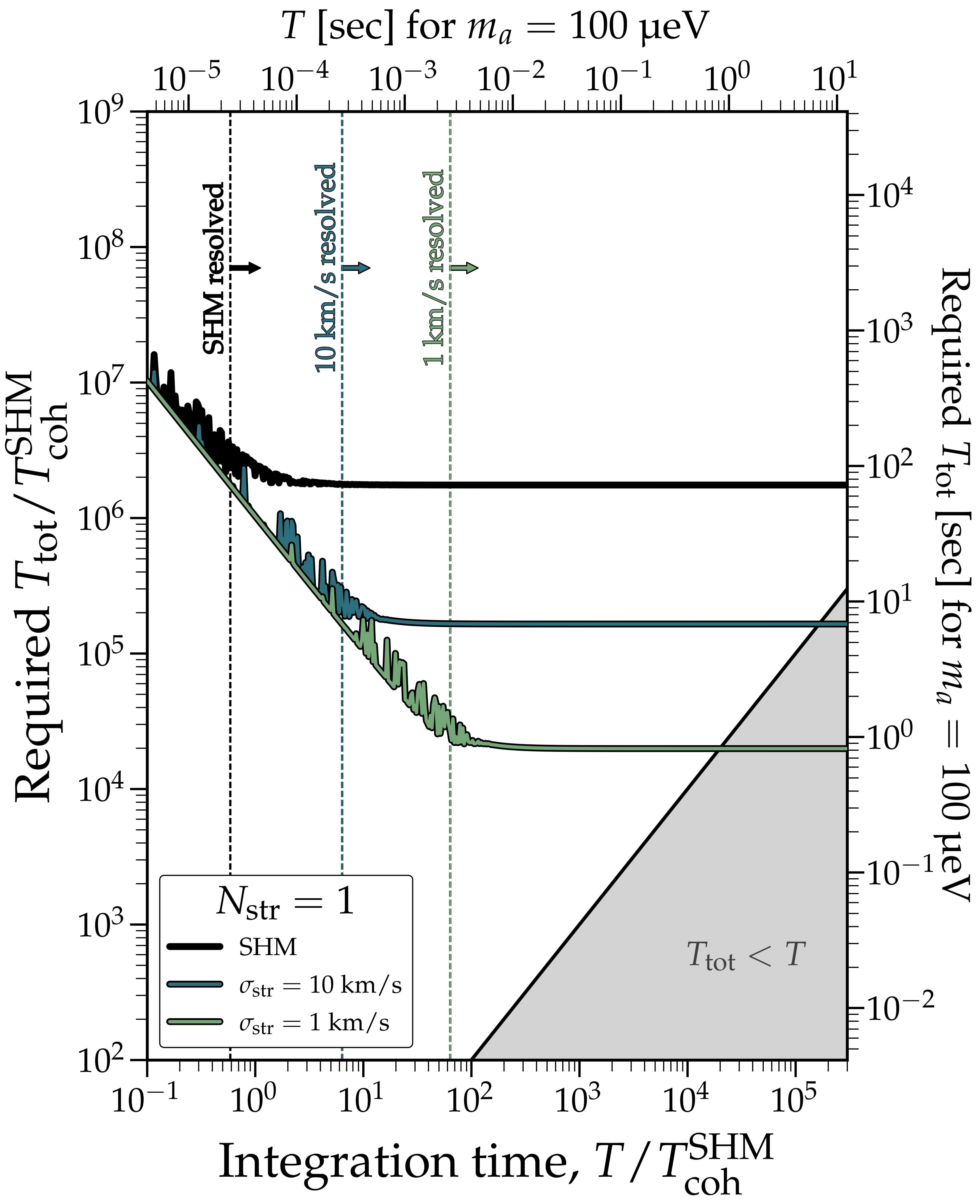

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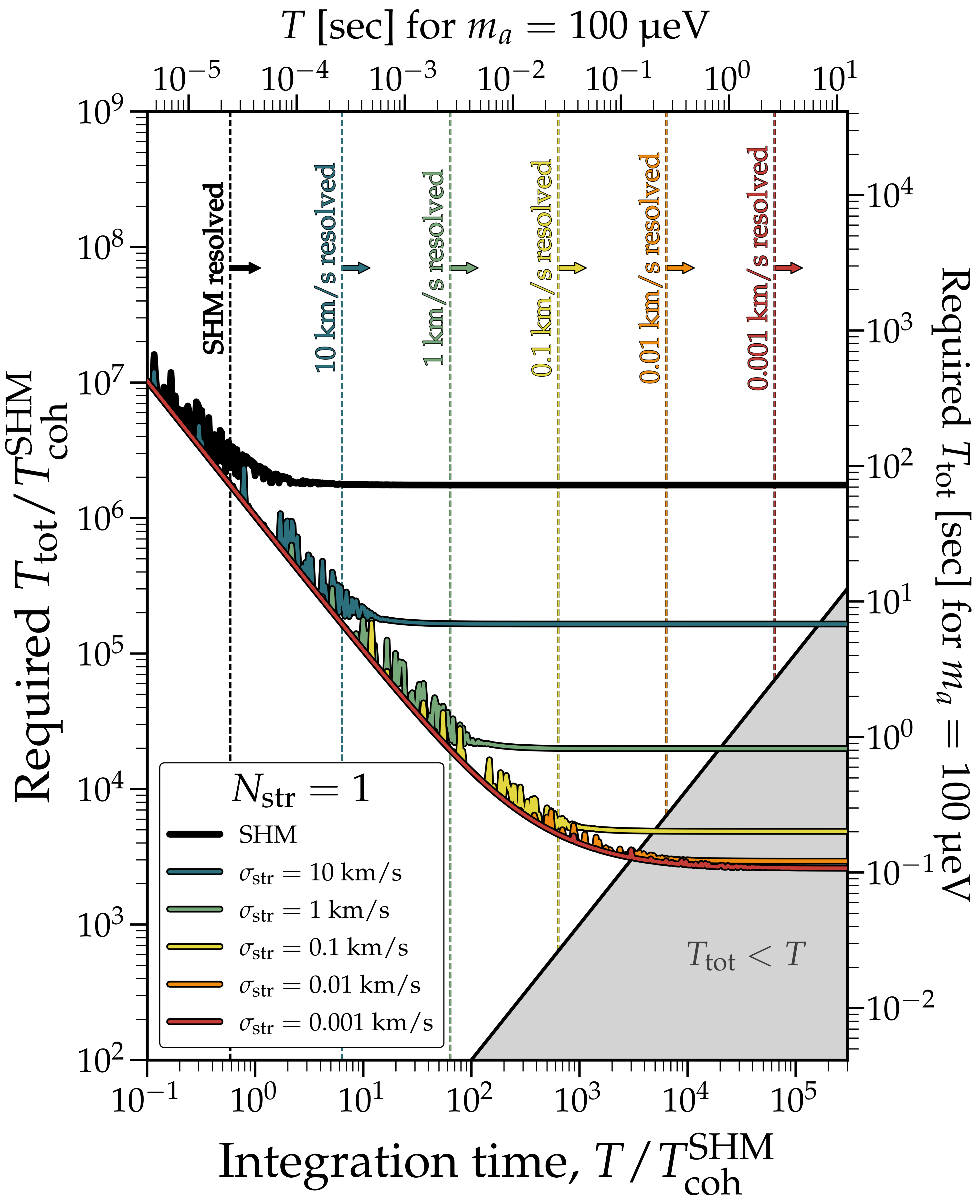

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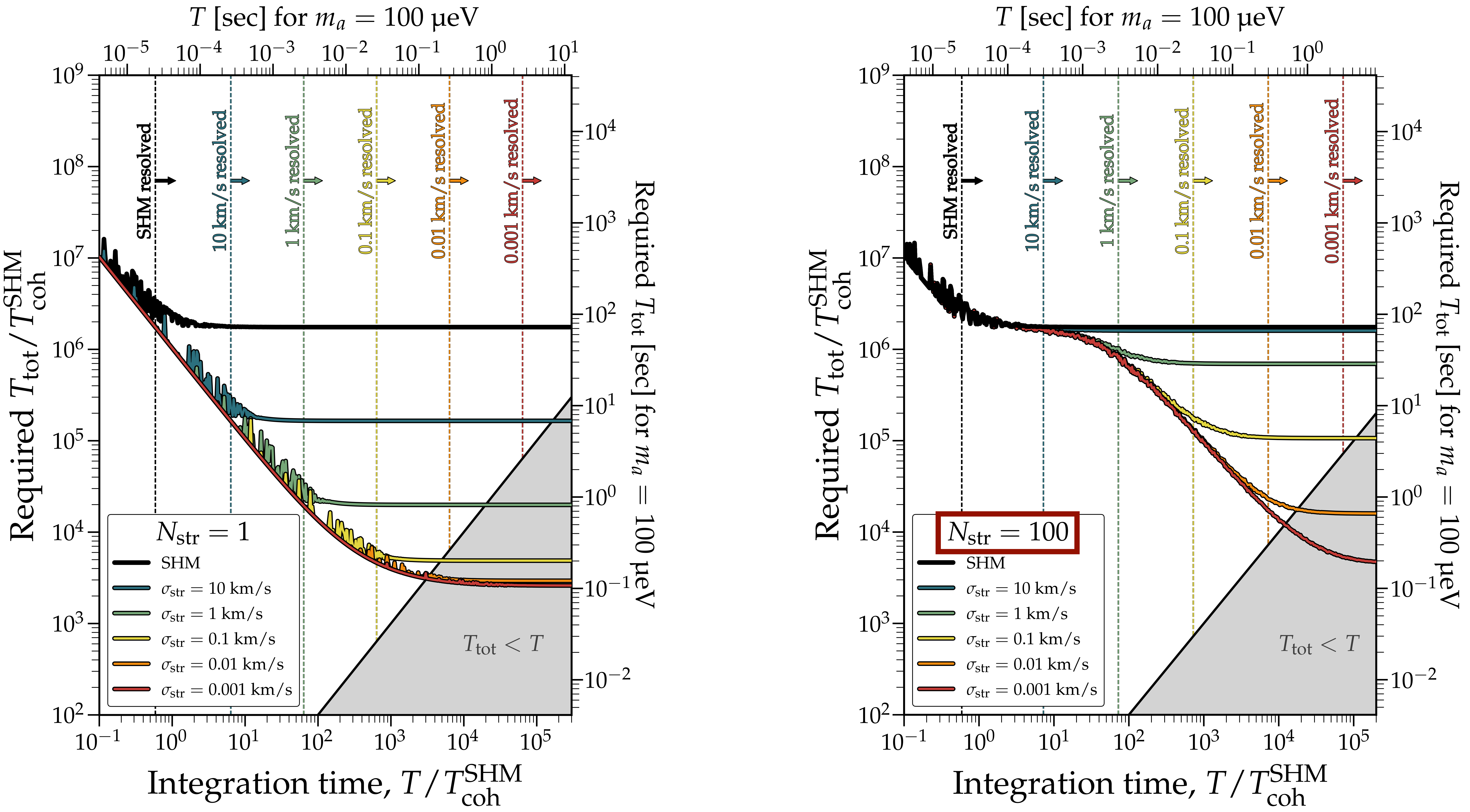

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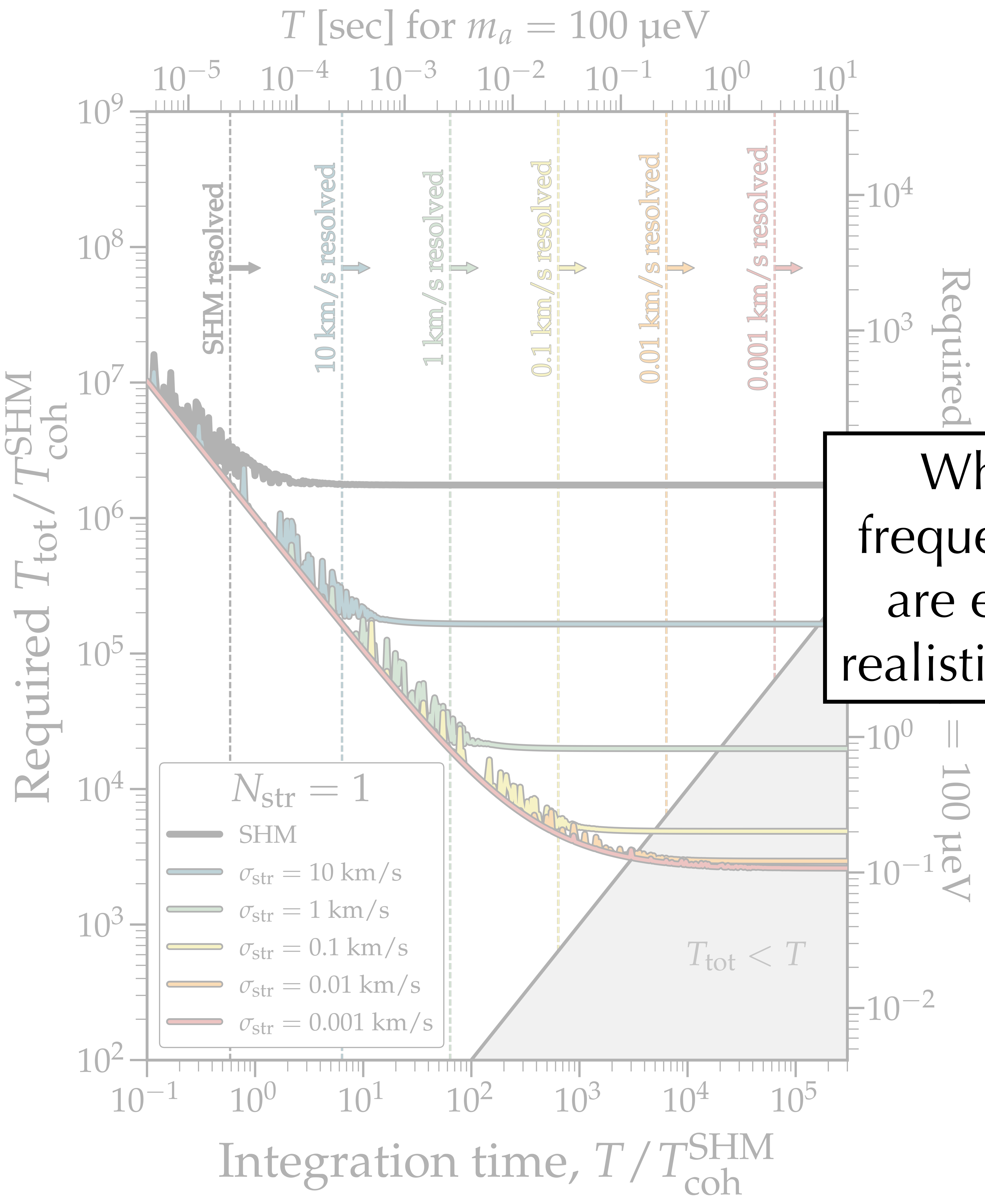
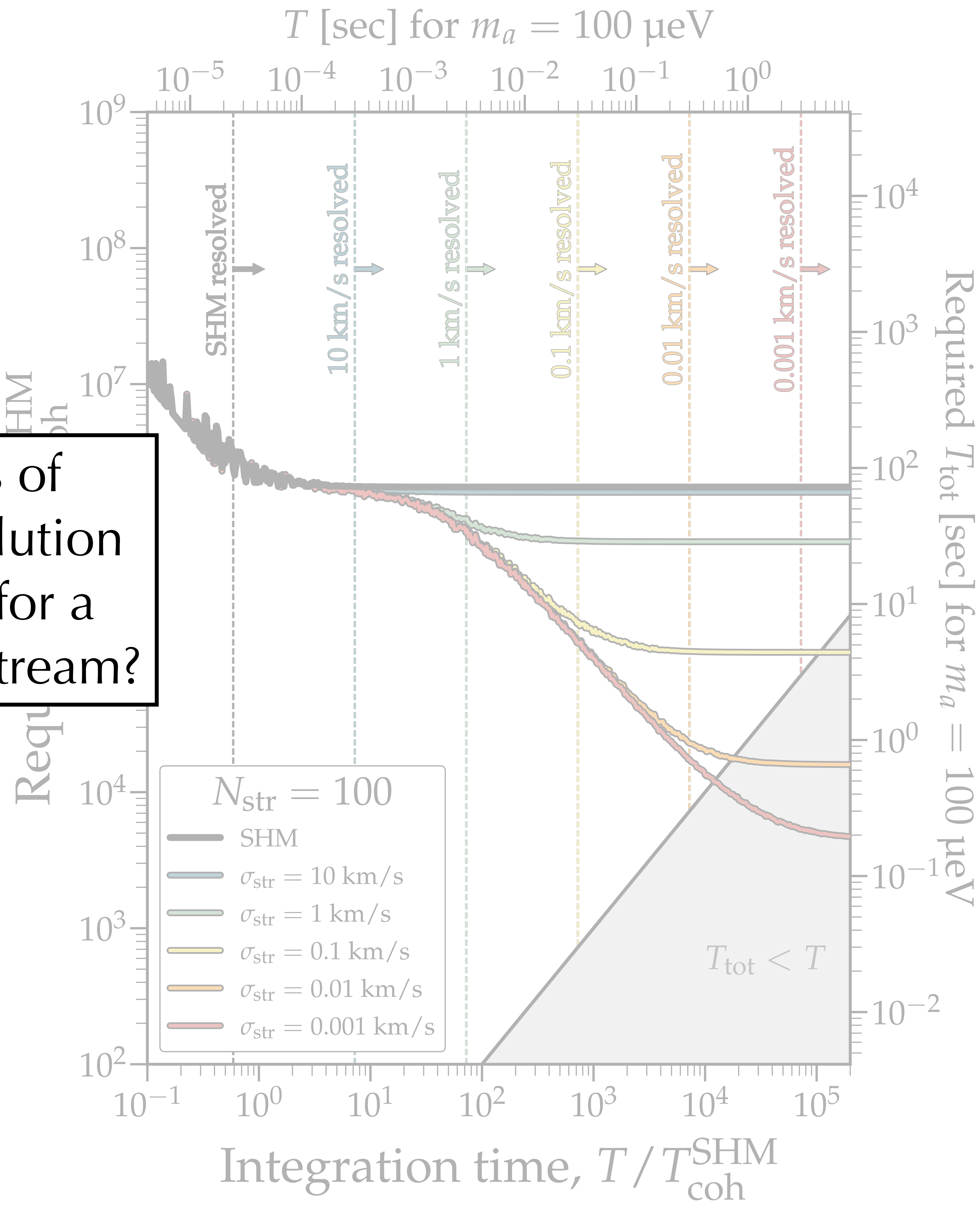
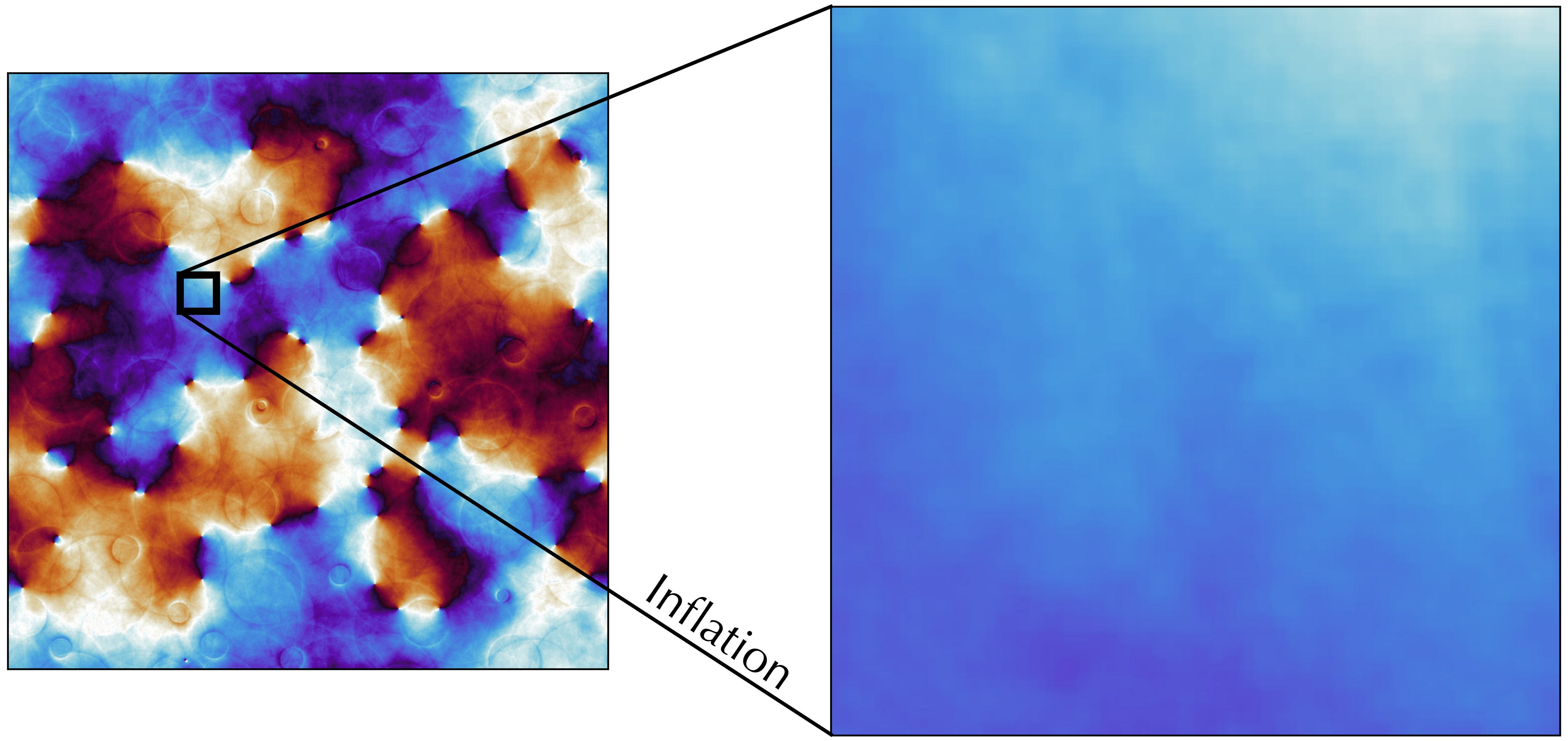


What values of frequency resolution are expected for a realistic axion stream?



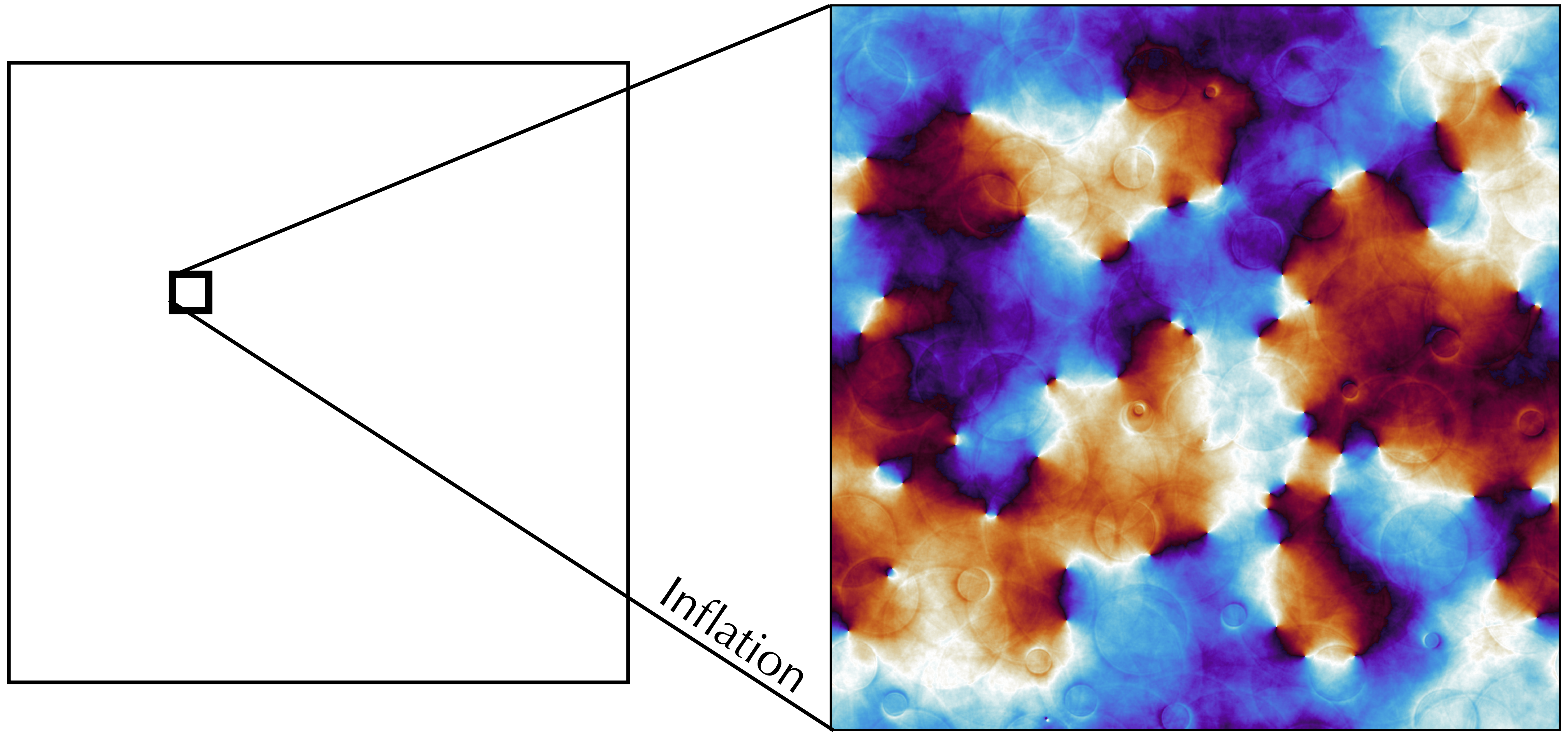
Axion DM in cosmology

Pre-inflationary scenario



Initial conditions dependence

Post-inflationary scenario

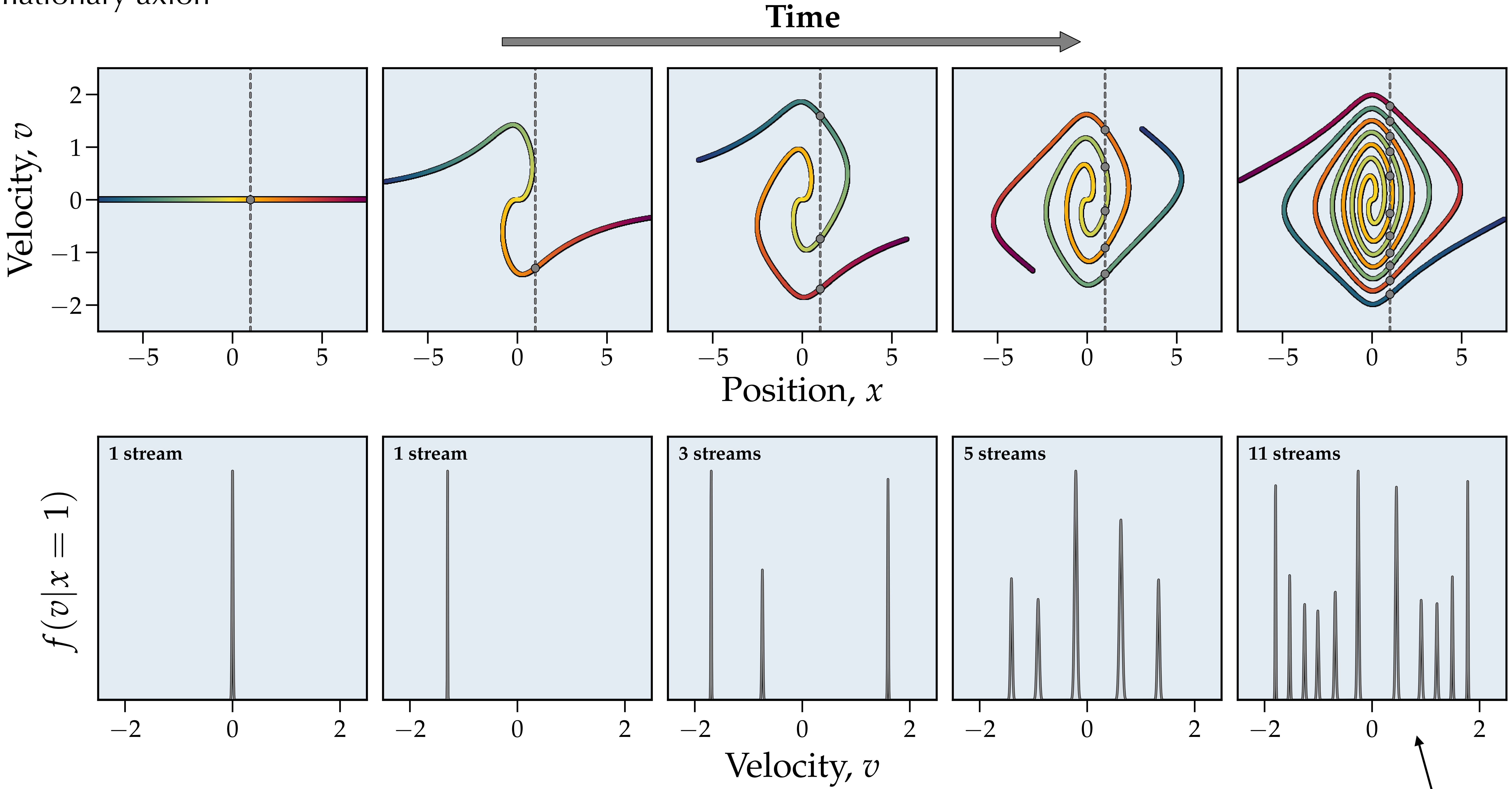


Numerical simulations needed

$m_a \gtrsim 40\ \mu\mathrm{eV}$

Fine-grained streams

e.g., pre-inflationary axion



Typical velocity dispersion very small!

In collaboration with

J. Redondo, C. O'Hare
Y. Wong, B. Eggemeier, K. Saikawa
A. Vaquero, G. Moore

The post-inflationary scenario

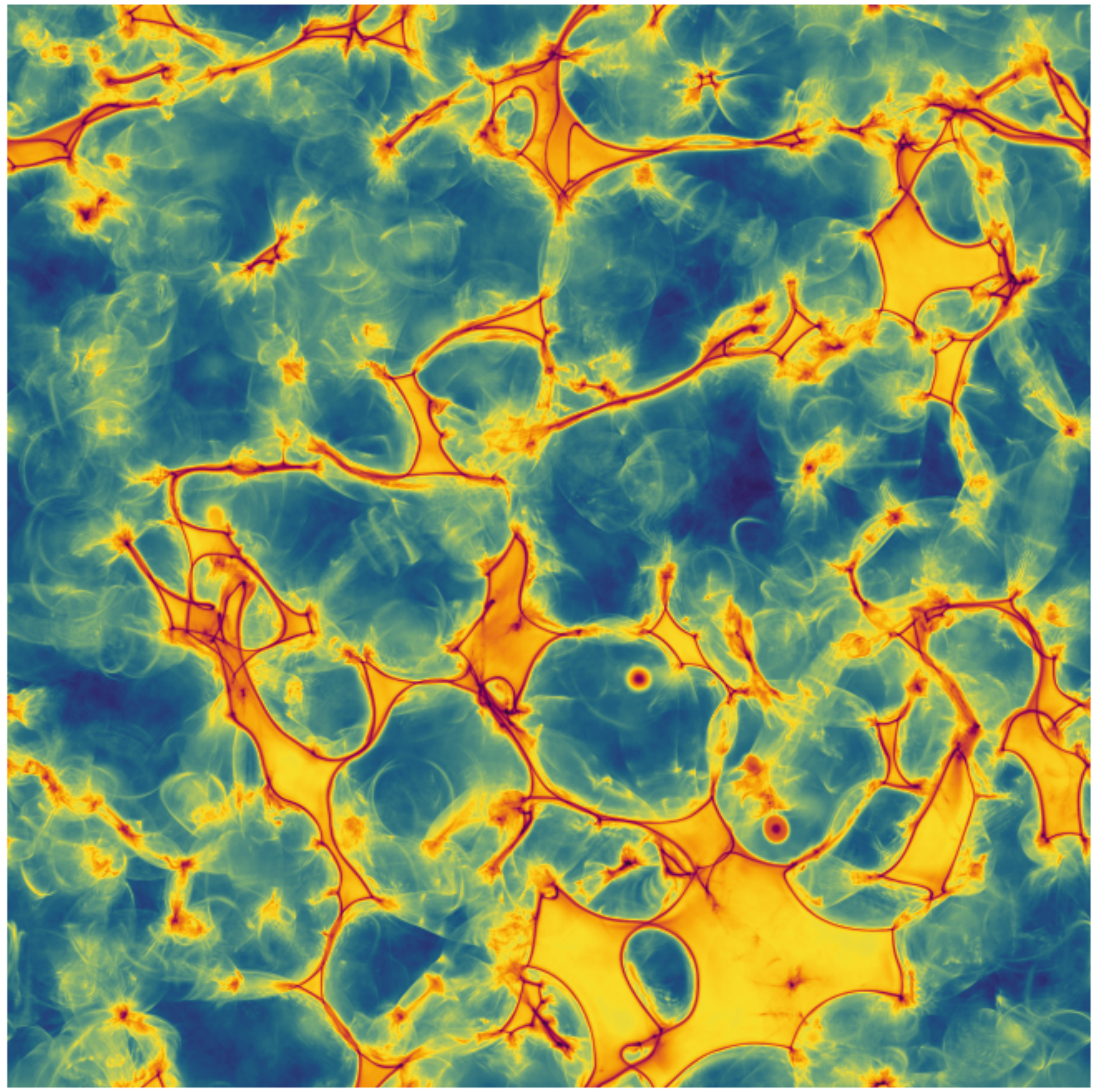
$z \sim 10^{12}$

$z \sim 10^{2}$

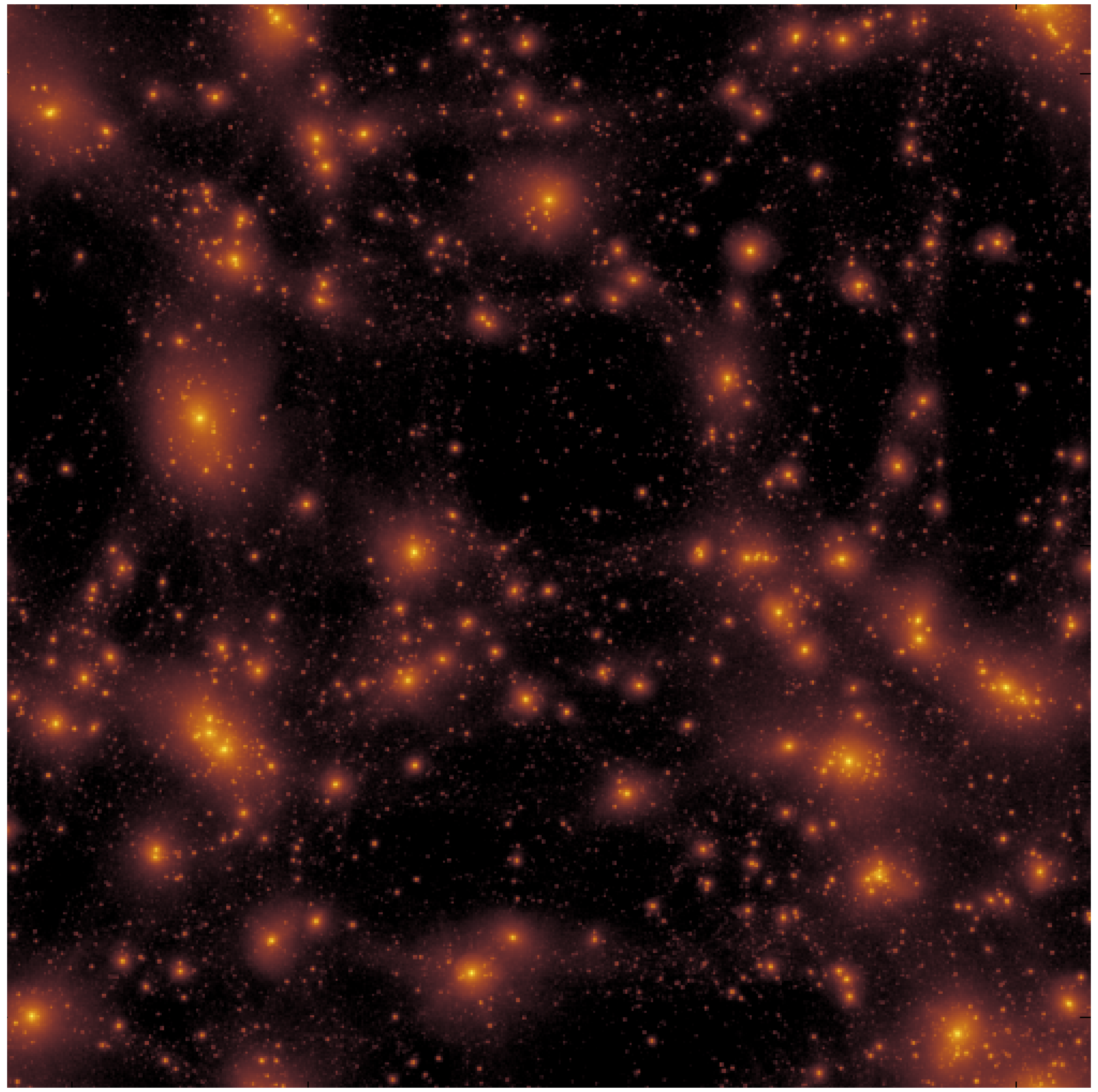
Inflation

Present day

Lattice simulation



N-body simulation



Axion strings
Axion domain walls
Axitons

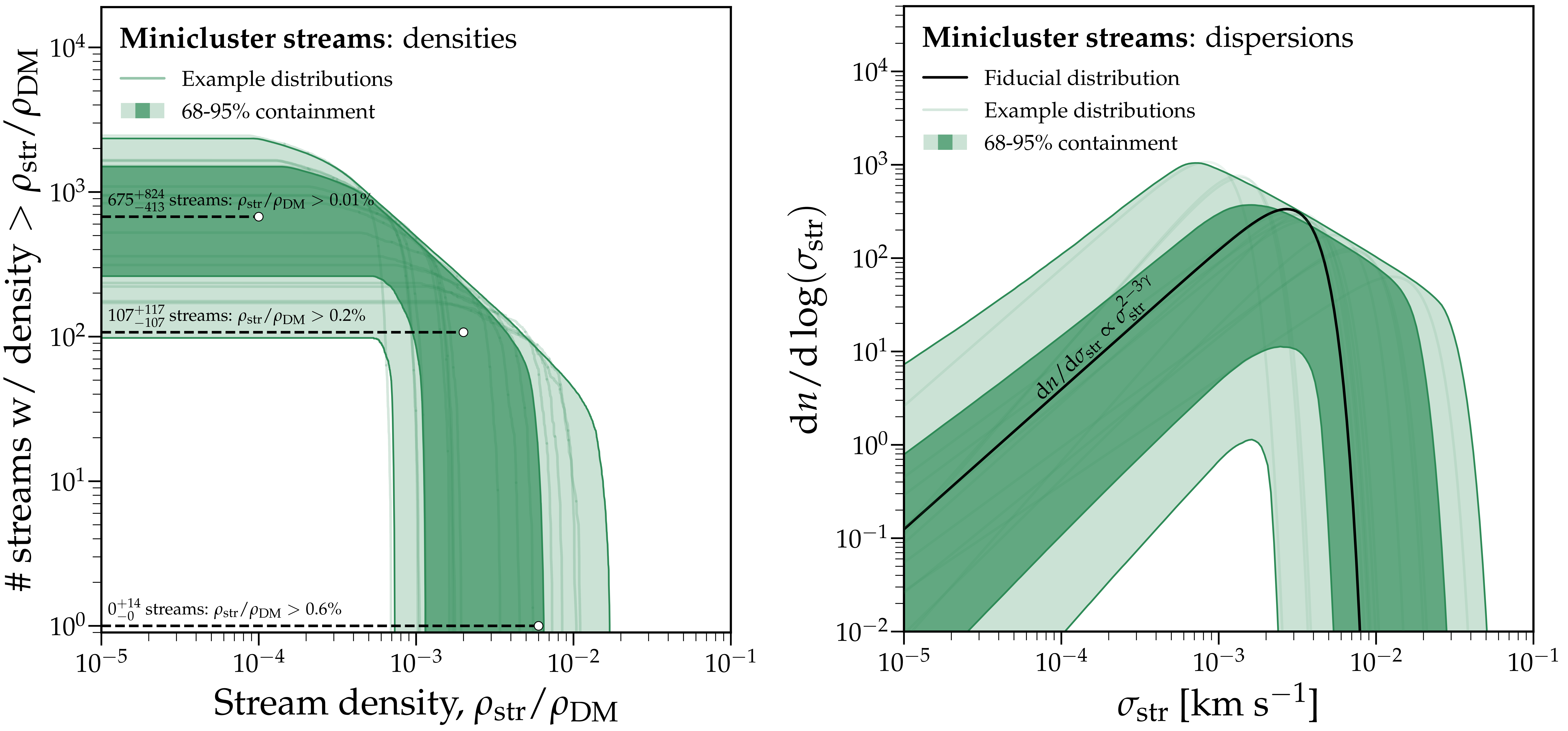
Axion minicluster and minihalos

Minicluster streams

O'Hare, **GP**, Redondo [**2311.17367**]

$\mathcal{O}(1000)$
overlapping streams

Minicluster streams



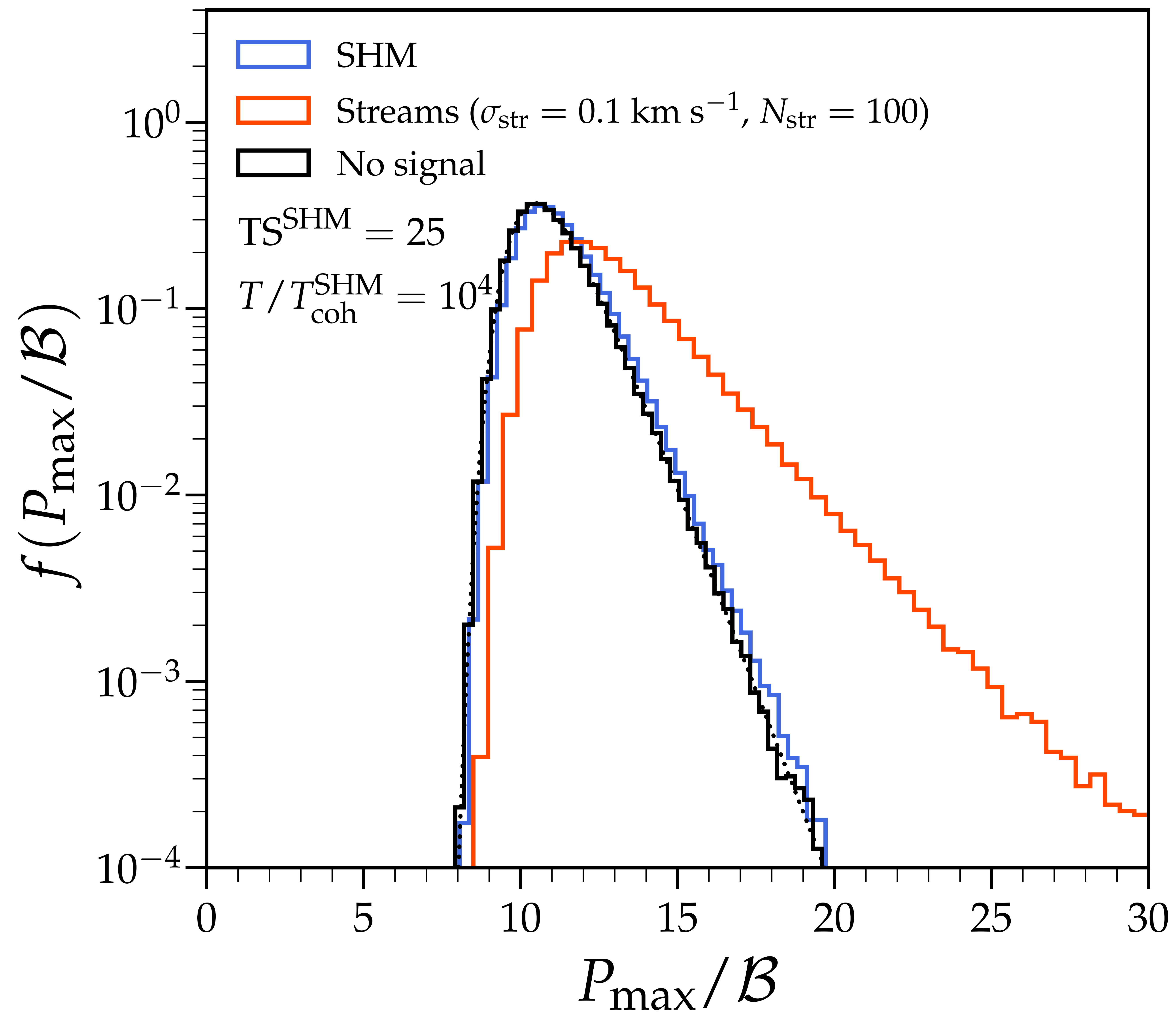
Extreme value statistic

Adopt non-parametric approach: extreme value statistic (**EVS**)

$$P_{\max} \equiv \max(P_{\rm obs}(\omega_k))$$

Analogous to the “re-scan” strategy

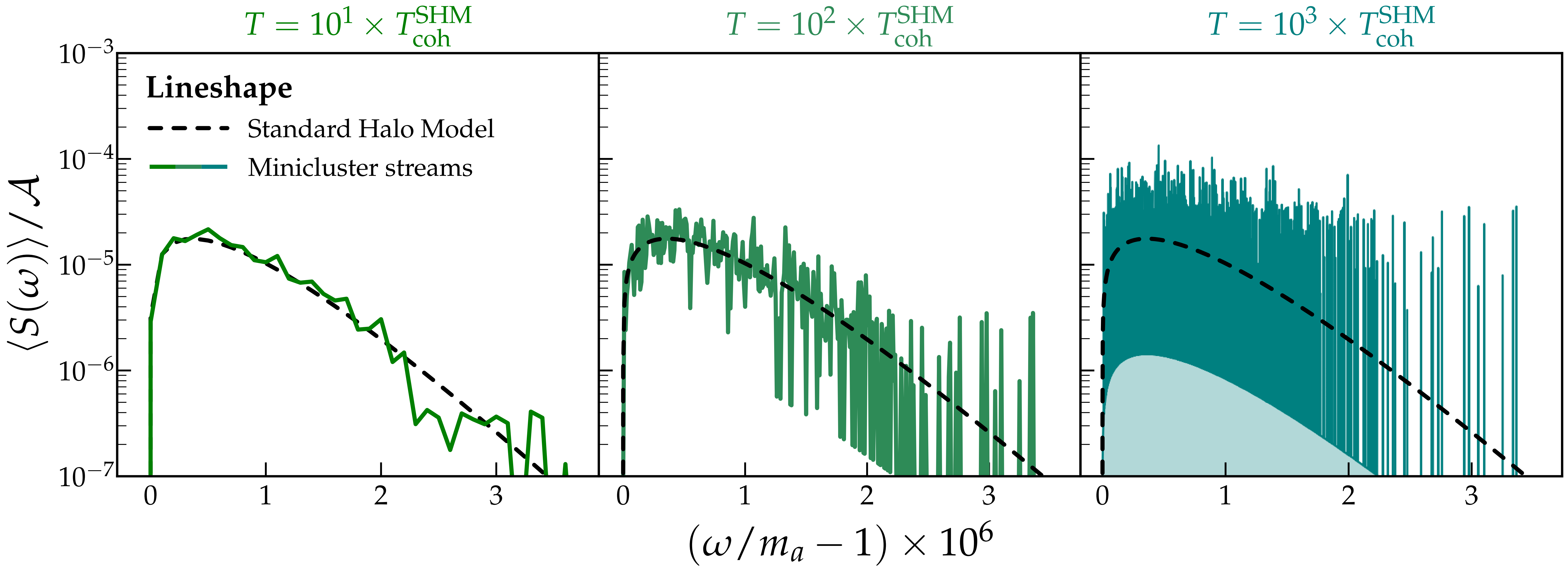
particularly sensitive to signals that can have **large fluctuations** over the noise level, even if those fluctuations are rare



Minicluster lineshape

O'Hare, **GP** [**2509.14874**]

Expectation
mean
value



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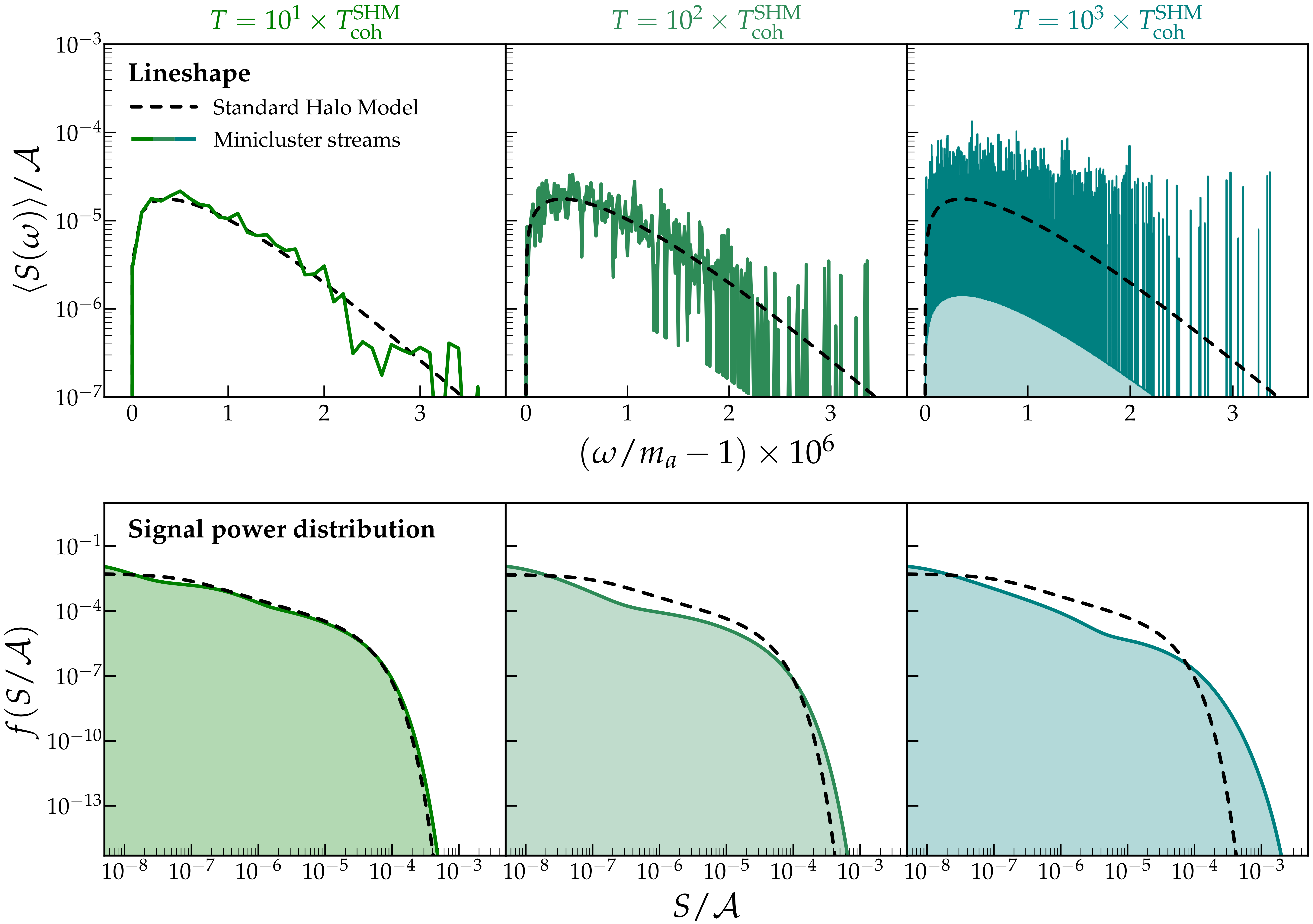
O'Hare, **GP** [**2509.14874**]

Expectation **mean** value

Distributed **signal**

(including randomness)



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O'Hare, **GP** [**2509.14874**]

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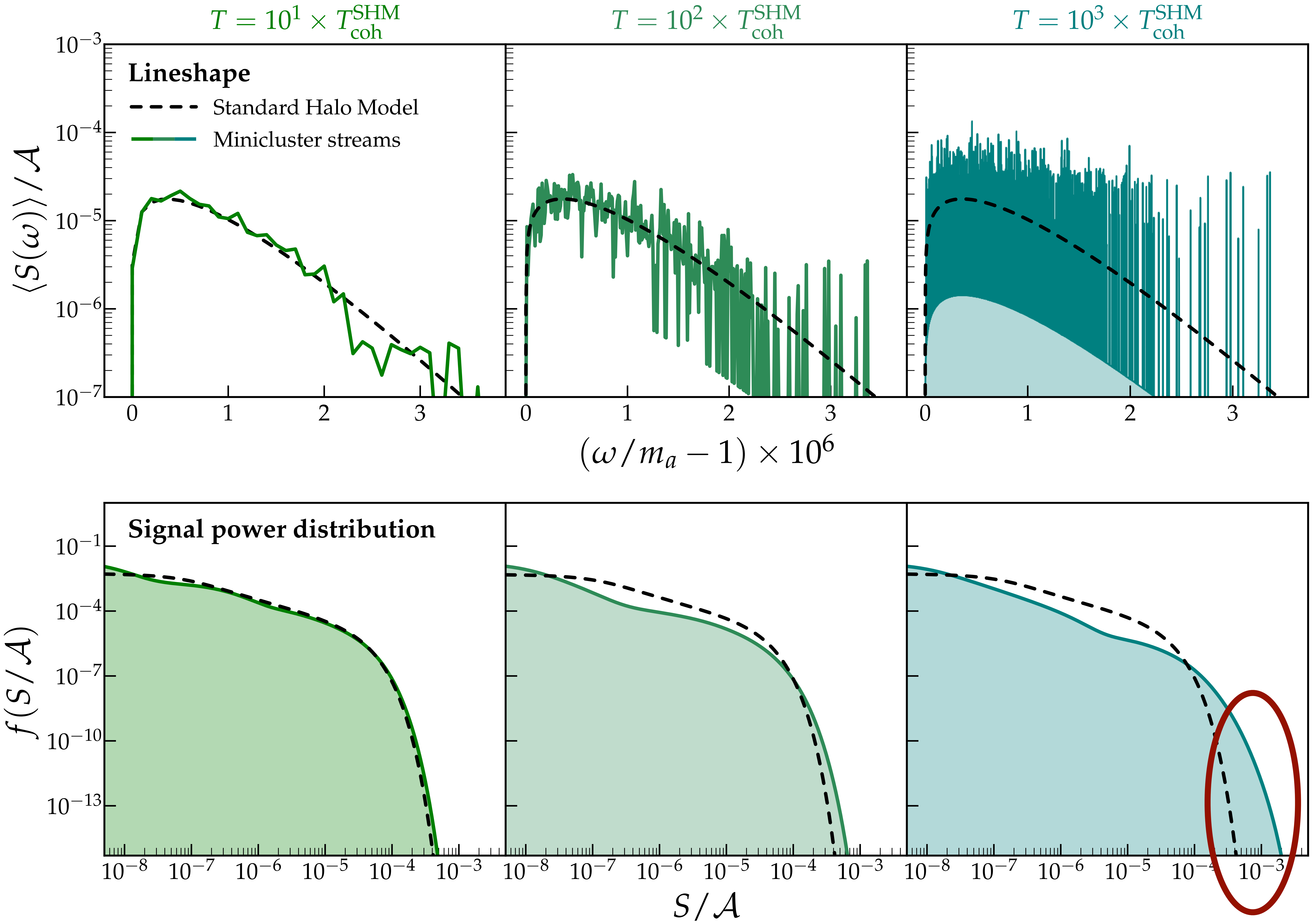
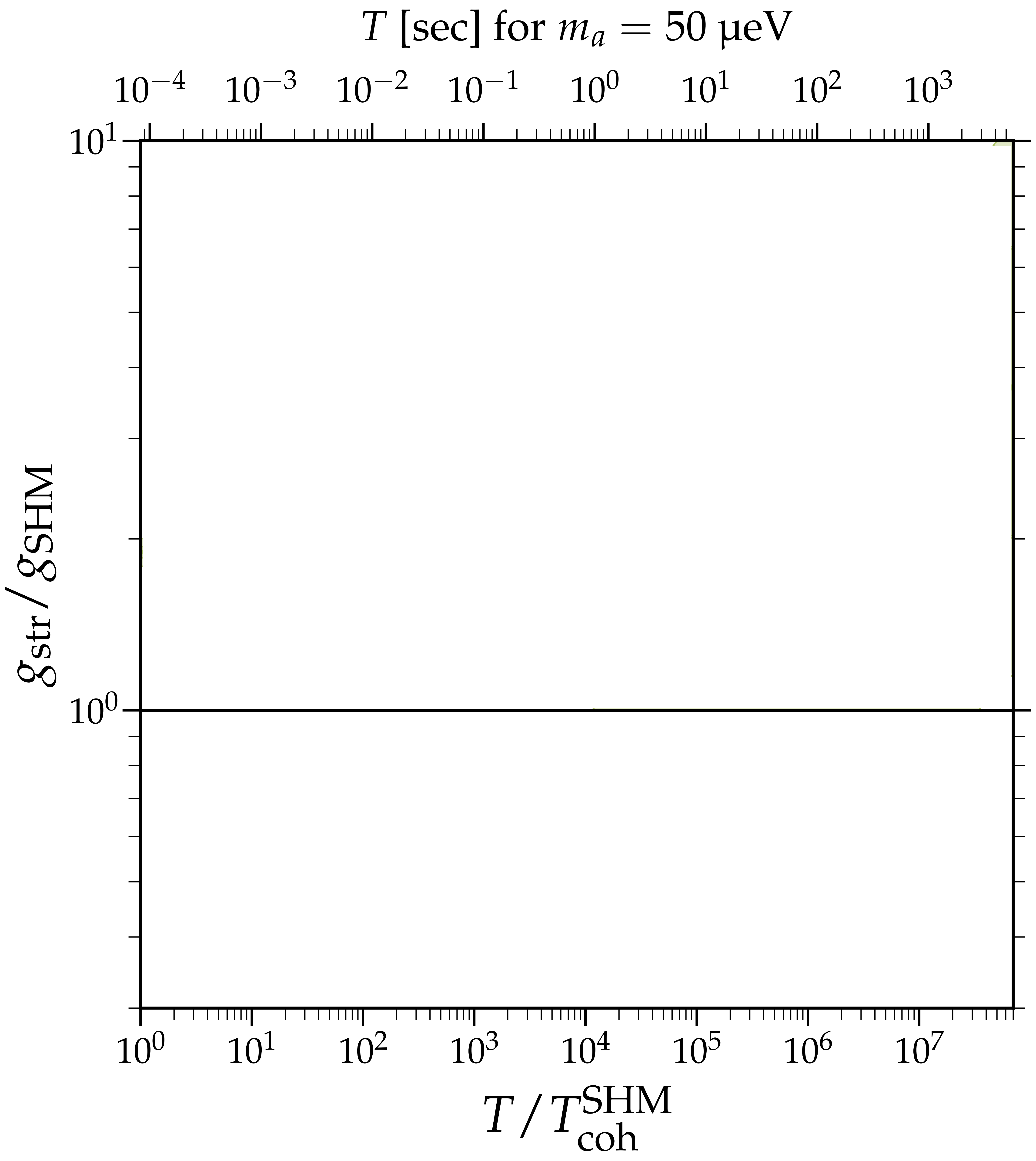


Extended reach

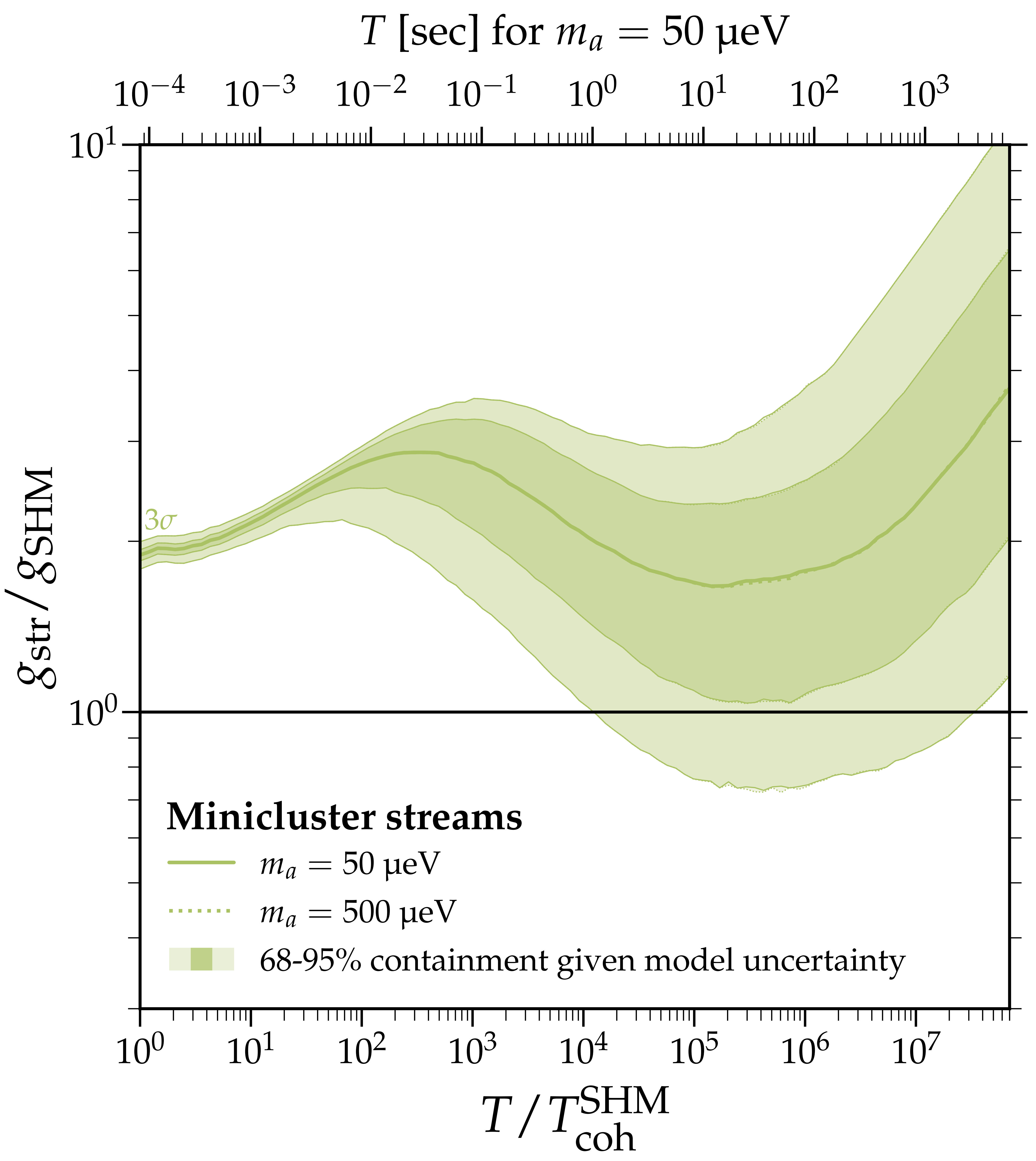
O'Hare, **GP** [**2509.14874**]



Coupling required for the detection of candidate streams relative to the coupling required to exclude the axion under the SHM

Extended reach

O'Hare, **GP** [**2509.14874**]



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Including streams theoretical uncertainties: (distribution, concentration, etc.)

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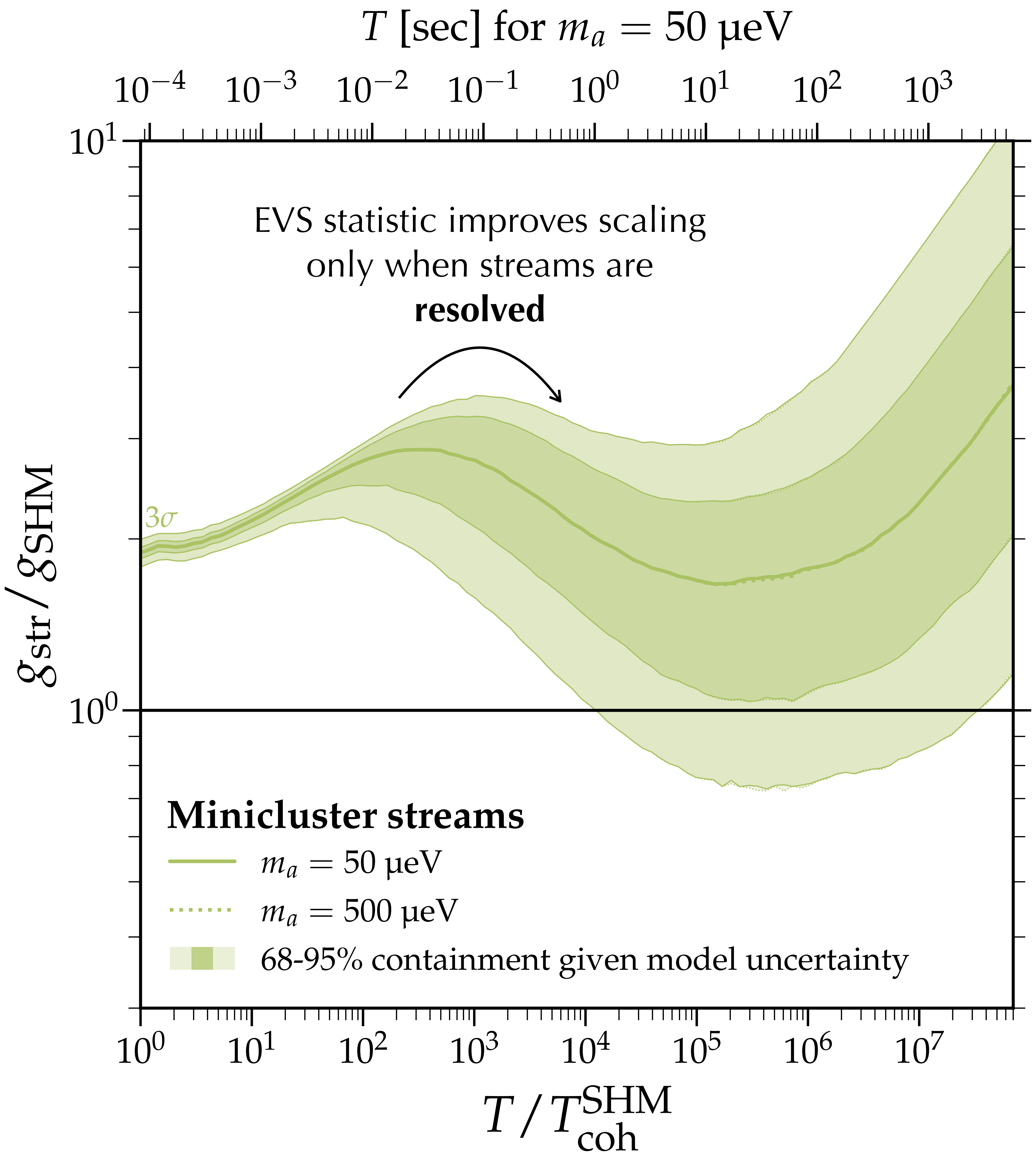

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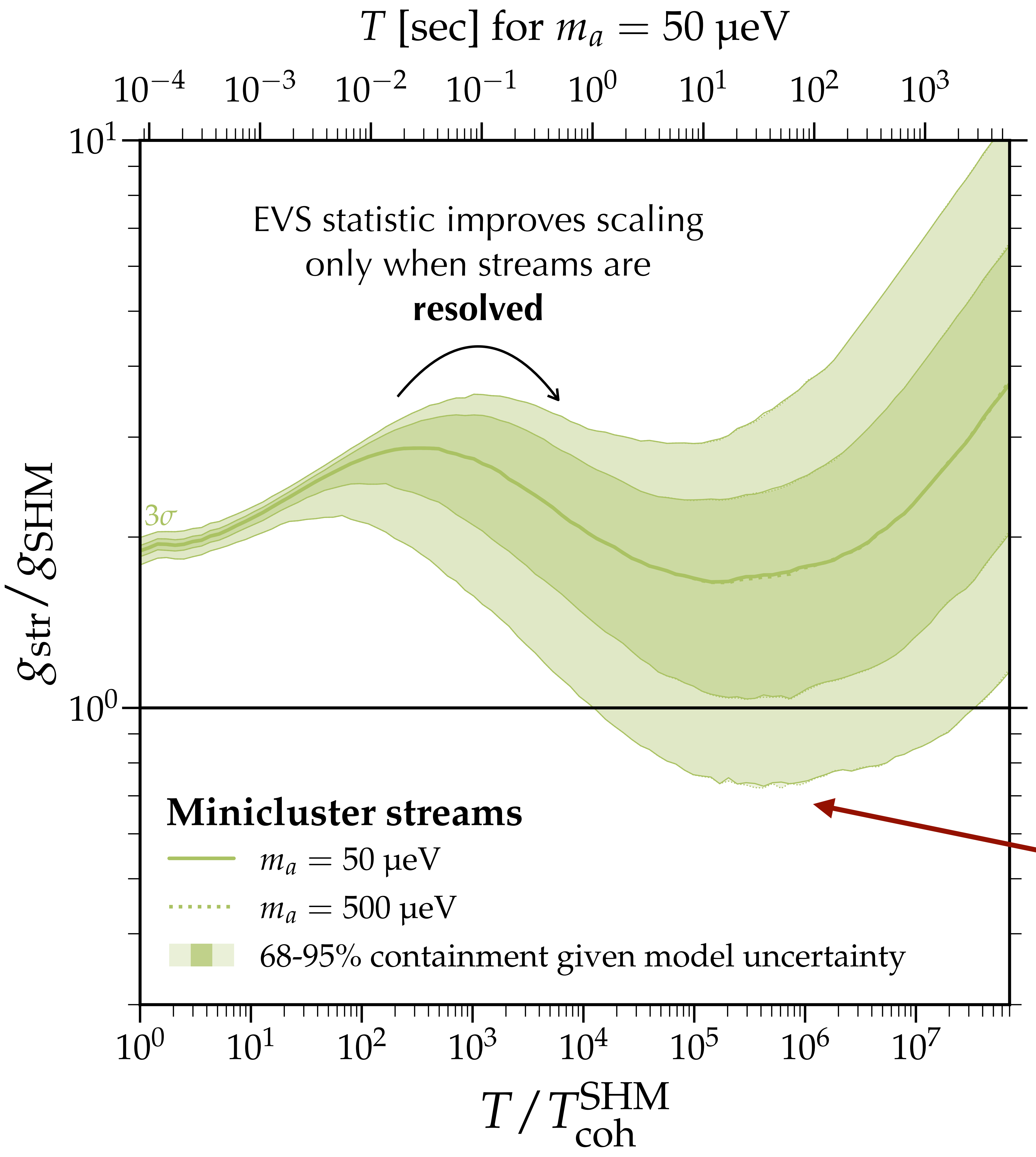

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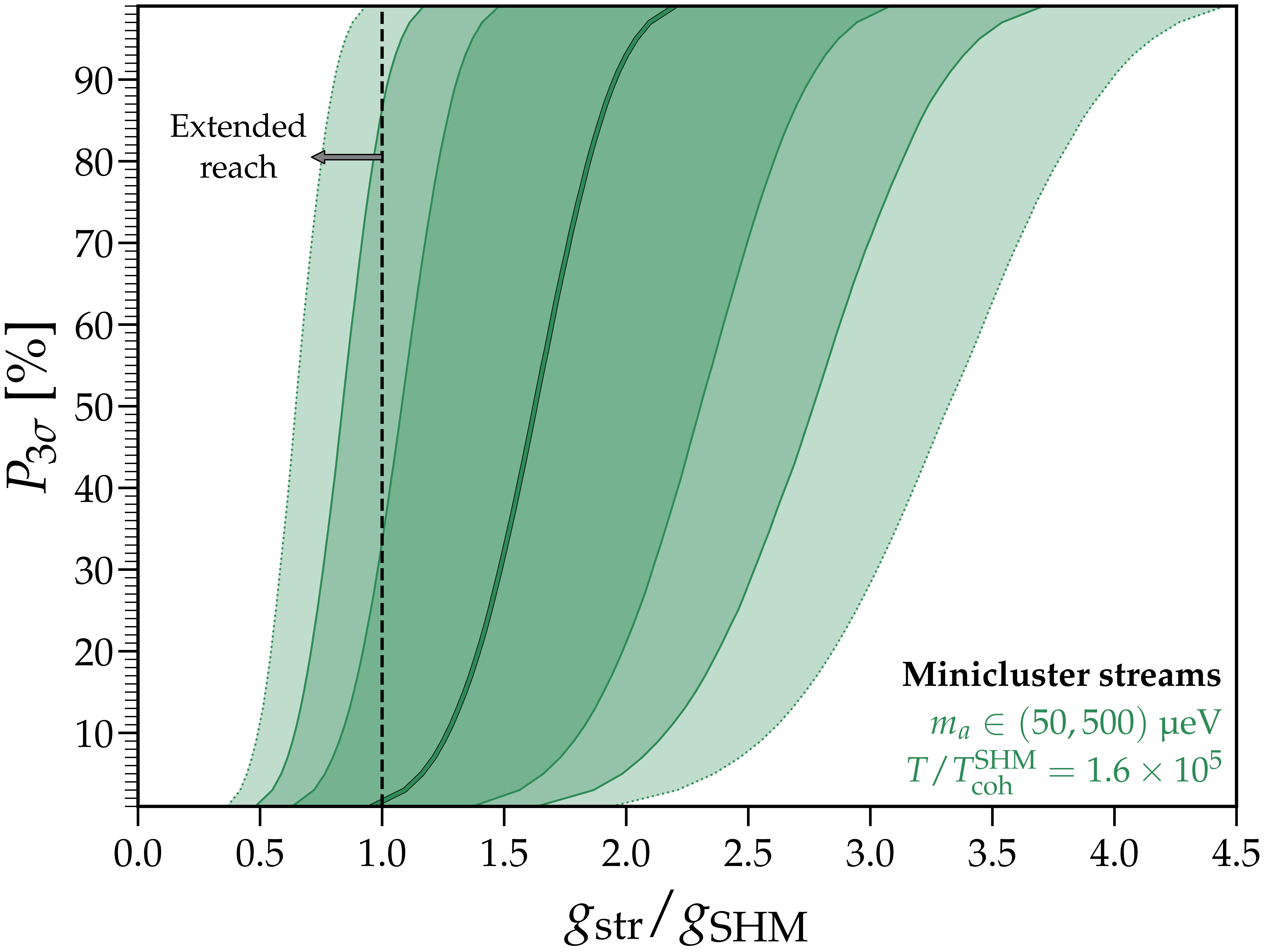
$$T_{\rm opt} \sim 6.56\ {\rm s} \left(\frac{100\ \mu{\rm eV}}{m_a}\right)$$

O'Hare, **GP** [**2509.14874**]

Extended reach

Extended reach

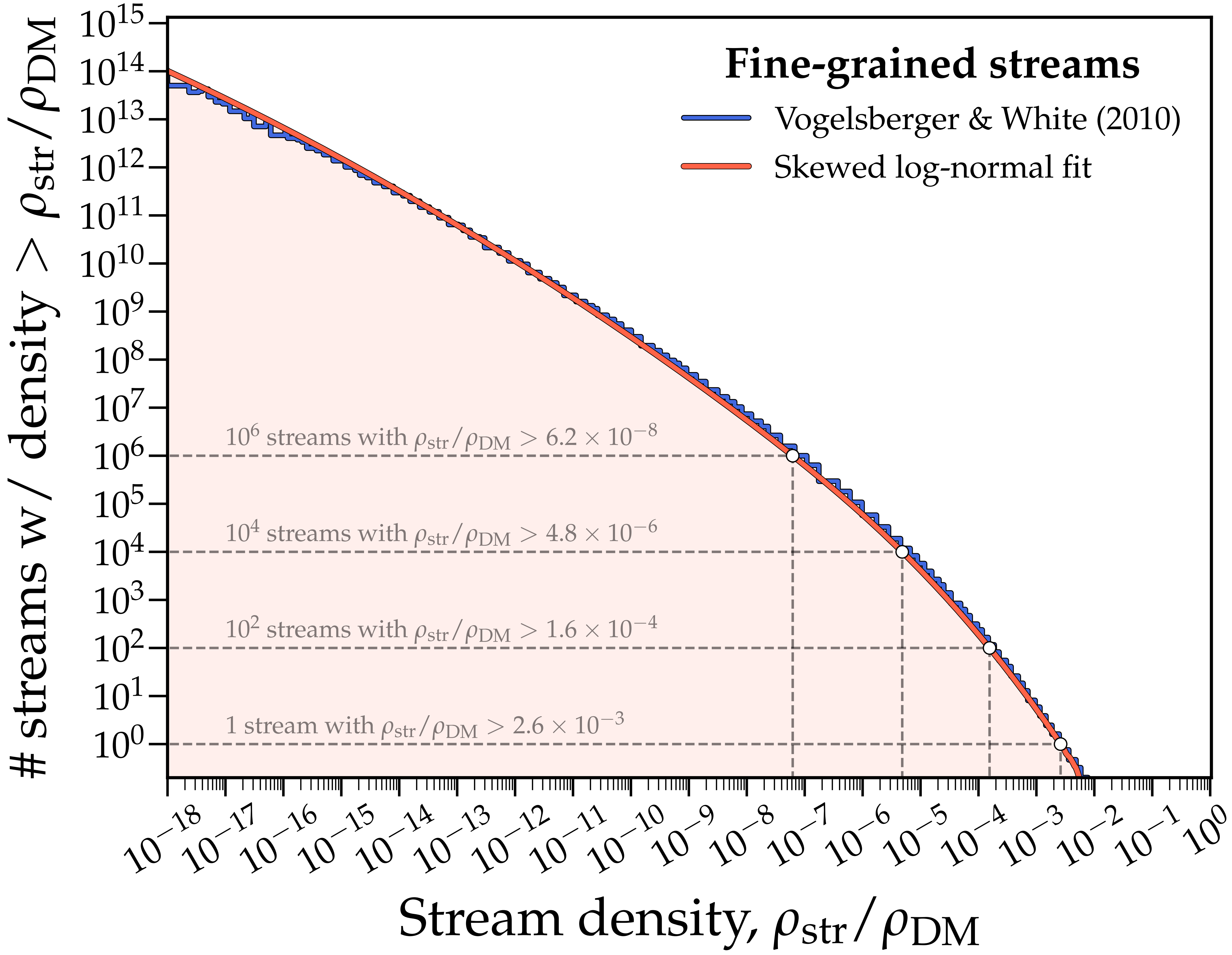
An axion that couples weaker than naive sensitivity has chance to be revealed as an extreme single-bin fluctuation $(n\sigma)$



Relevant for QUAX, ORGAN, BREAD,ALPHA, BRASS, DALI, MADMAX, CADEx, …

Fine-grained streams

Cumulative distribution from N-body simulation of collisionless DM



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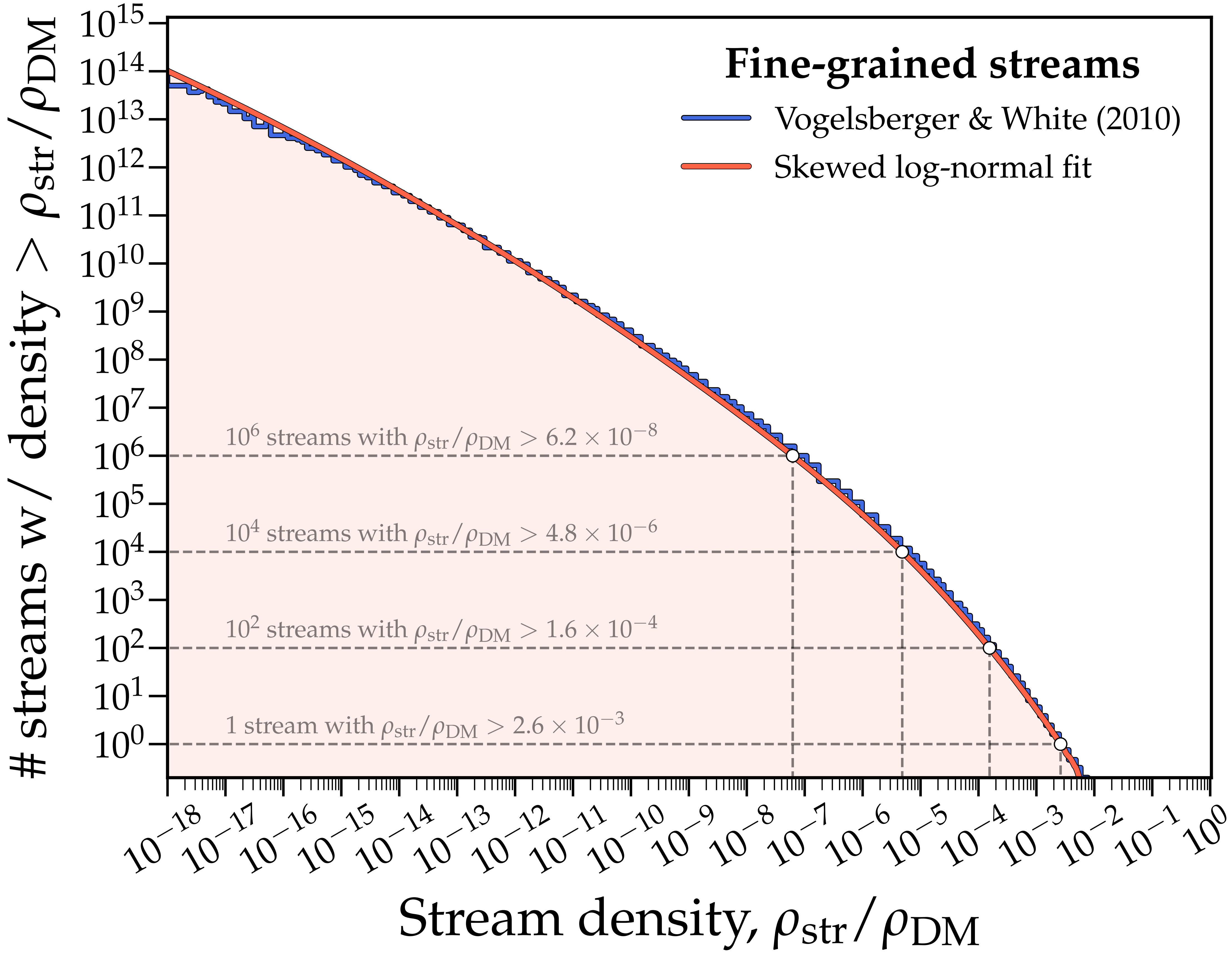
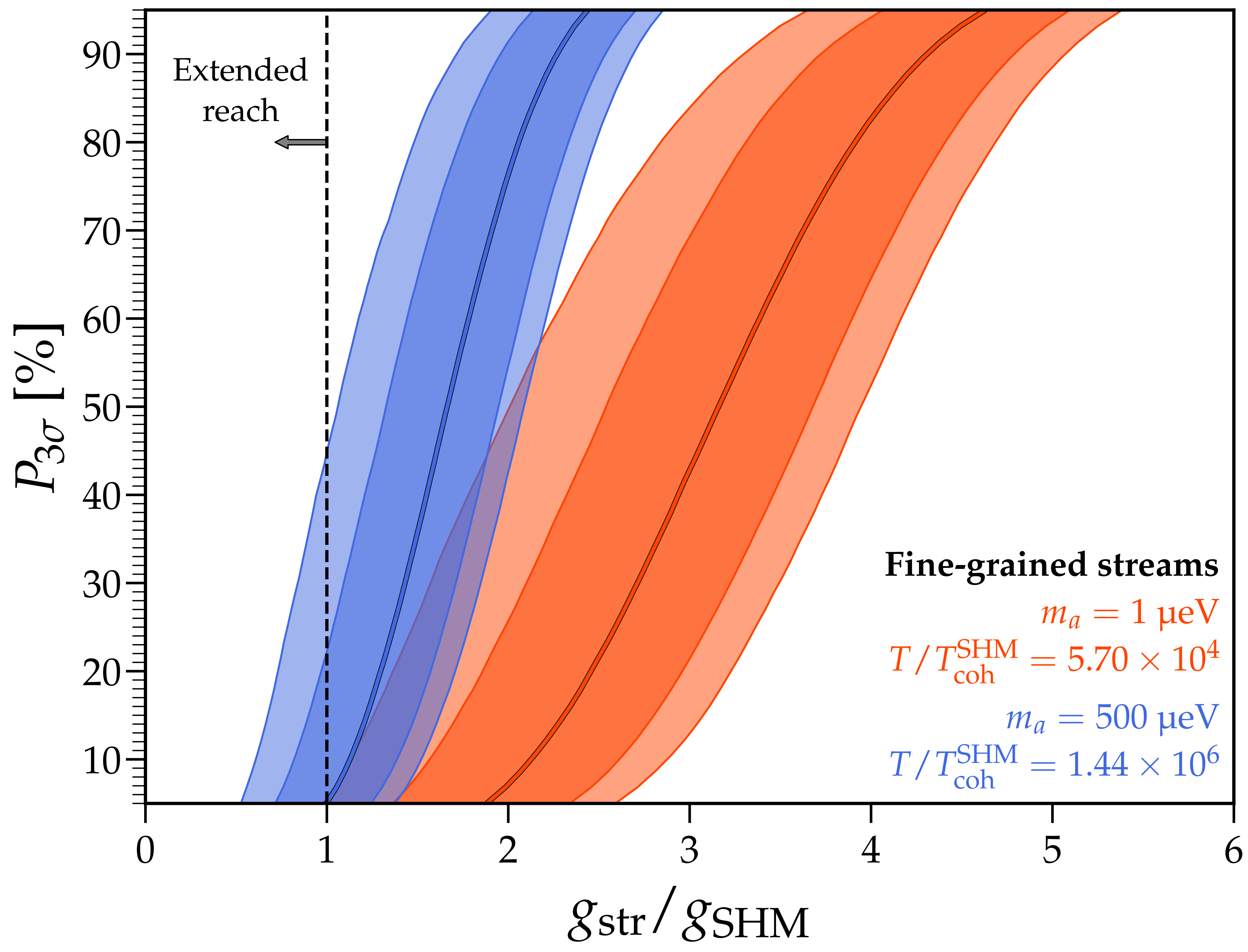


Sensitivity enhancement washed out by daily modulation effects



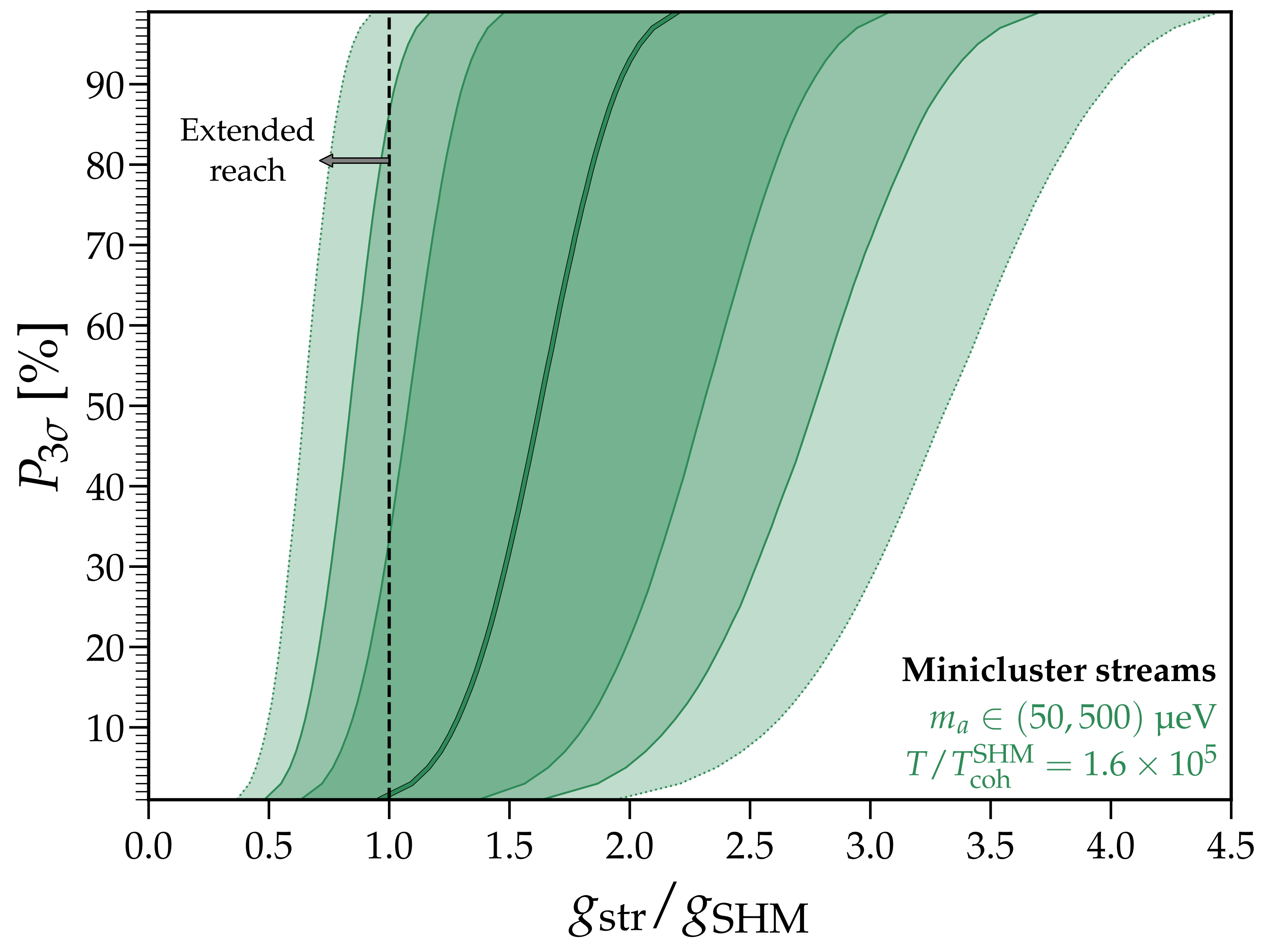
Summary

1. Post-inflationary axion searches can benefit from **extended reach**

2. We can only make probabilistic statements, as we don't know the specific local distribution

3. We find **optimal scan time**, to implement as a dual-channel analysis

$$T_{\rm opt} \sim 6.56\ {\rm s} \left(\frac{100\ \mu{\rm eV}}{m_a}\right)$$



$$T_{\rm opt} \sim 10^5 \tau_{\rm coh}$$

Standard resolution: conservative SHM shape

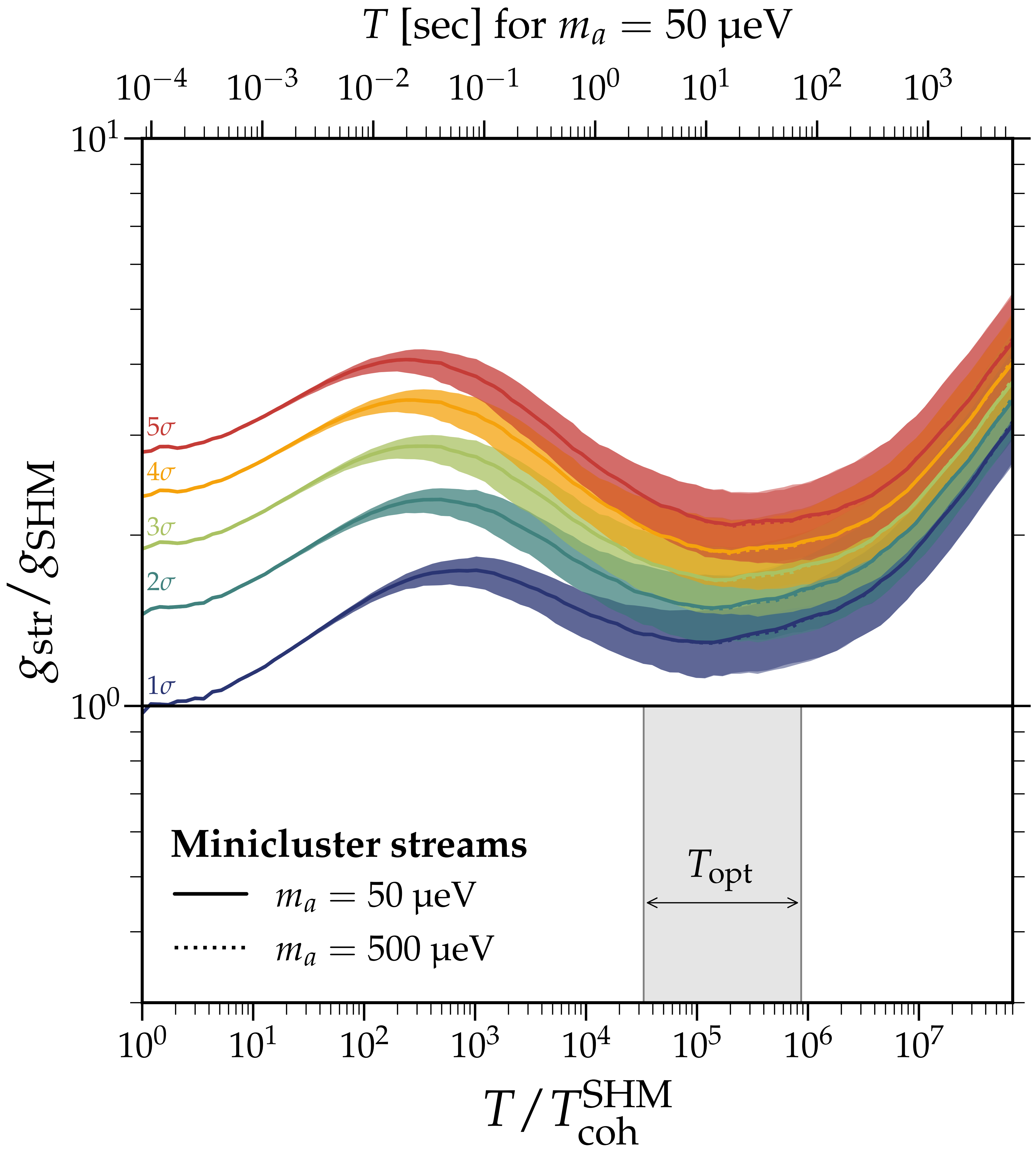
FFT chunks of $\sim \tau_{\rm coh}$

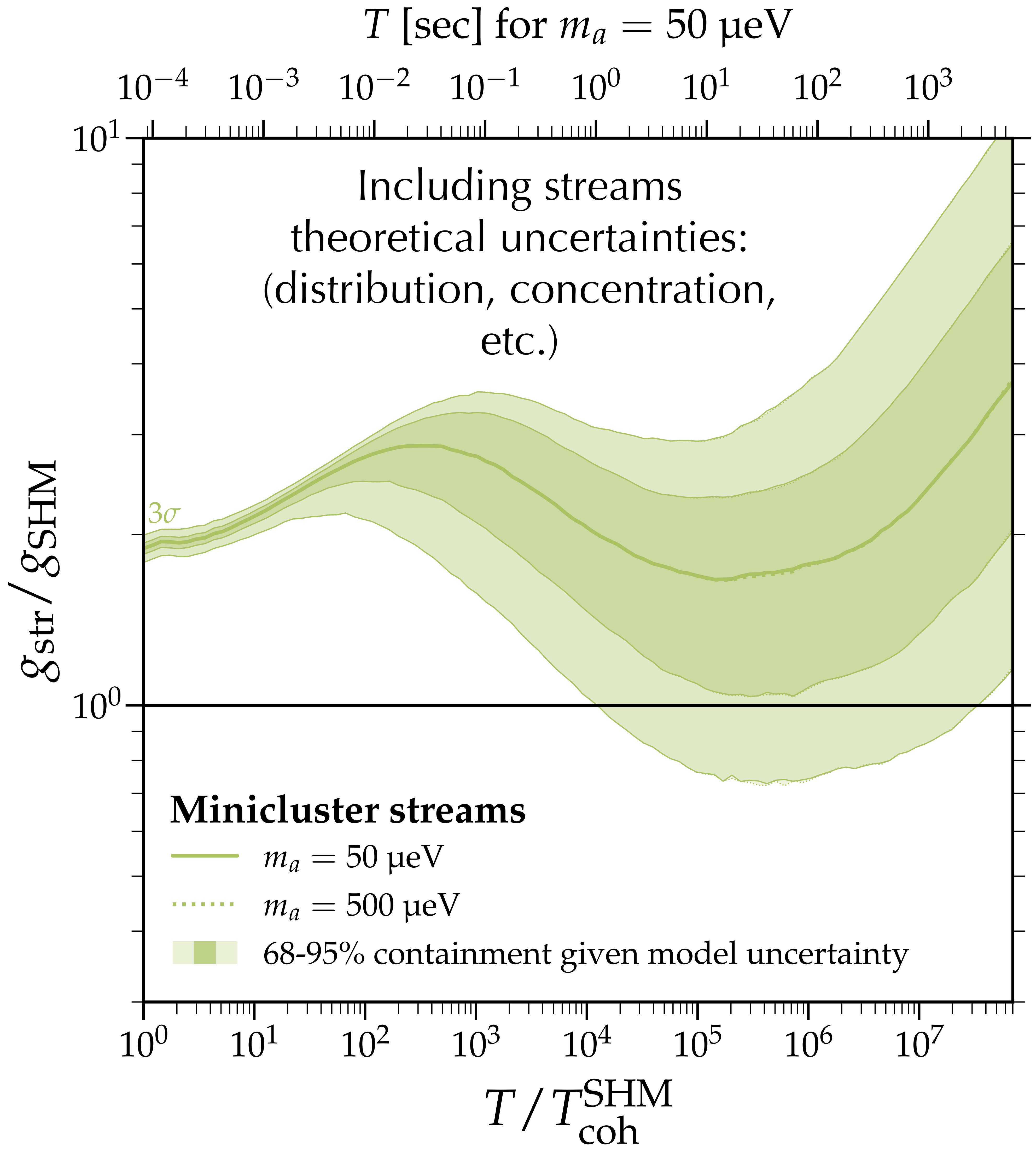
High resolution: optimal for streams

1 single FFT

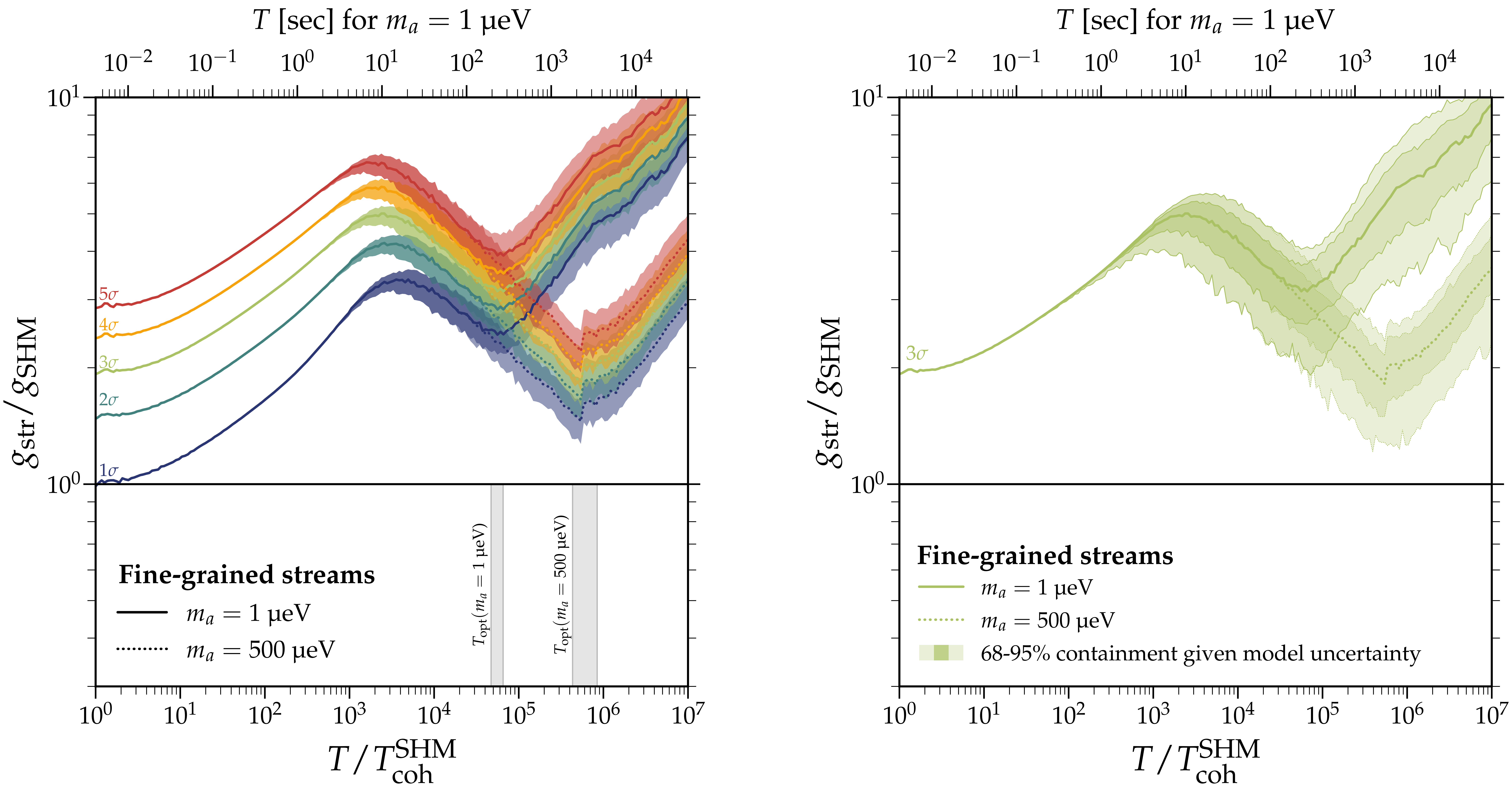
Additional slides

Minicluster streams

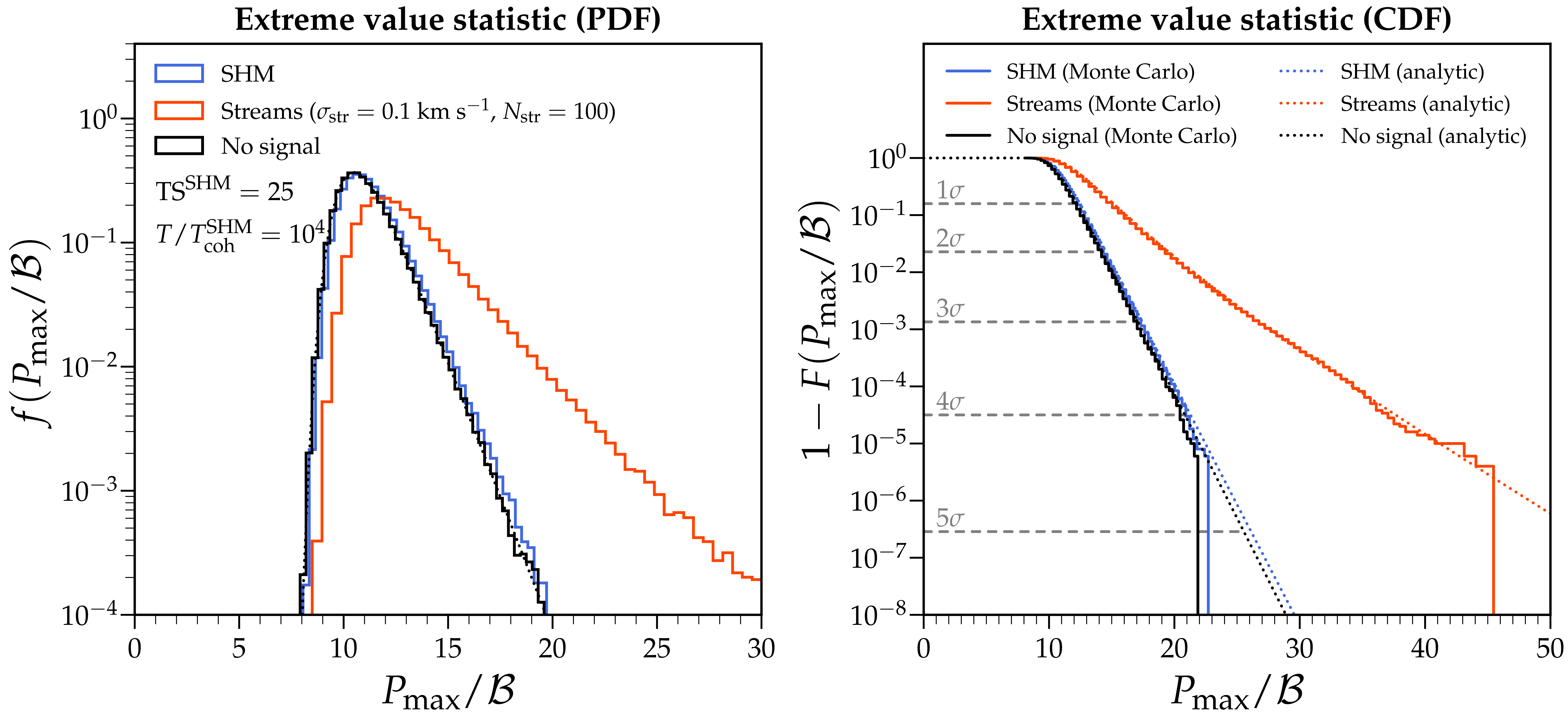




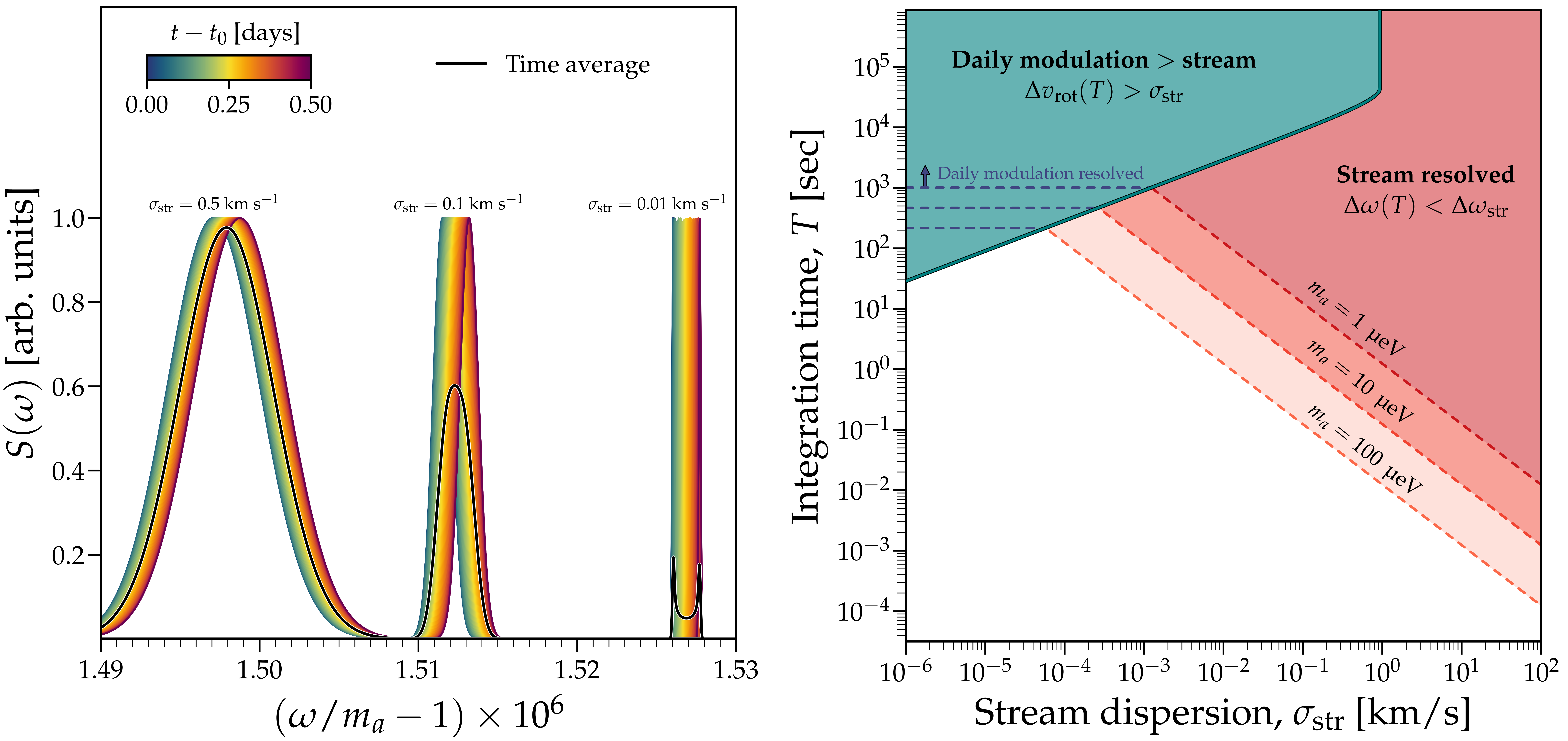
Fine-grained (pre-inf) streams



Extreme value statistic test



Daily modulation



Modelling uncertainties

$$\gamma \in \mathcal{U}(0.3, 0.7)$$

$$\log_{10}\left(\frac{M_{\max}}{M_\odot}\right) \in \mathcal{U}(-7, -4.5)$$

$$\frac{t^i_{\rm disr}}{\rm Gyr} \in \mathcal{U}(10, 8)$$

$$\frac{R_{10}}{\rm mpc} \in \mathcal{U}(0.1, 1)$$

$$h^i \in \mathcal{U}(1, 5)\,,$$