Axions in the Solar neighbourhood: clumps, voids, and streams

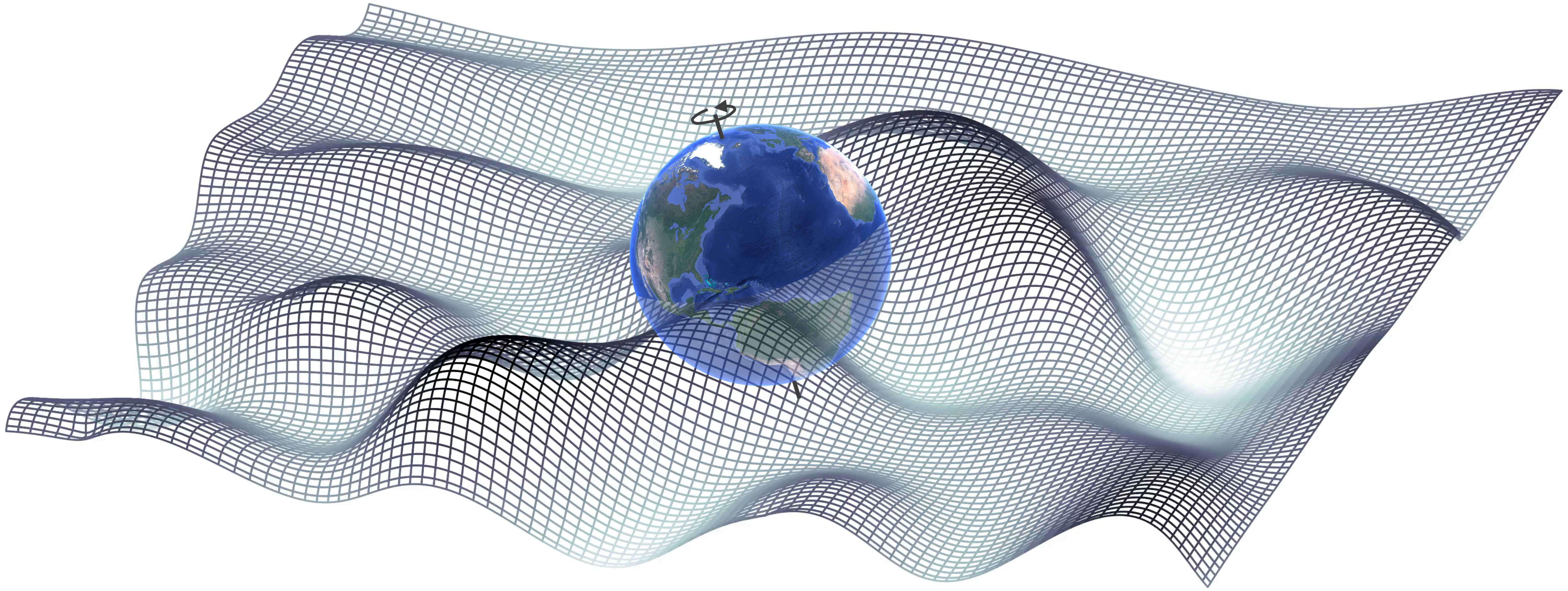
Ciaran O'Hare
U. Sydney

1. The local dark matter density
2. Post-inflationary axions
3. Axion miniclusters, voids, and streams
4. Implications for haloscopes

Based on work with G. Pierobon, J. Redondo, Y. Wong, B. Eggemeier

To calculate *any* experimental signal of dark matter we need to know

1. How much dark matter there is around the Earth, ρ
2. How fast it's moving, v

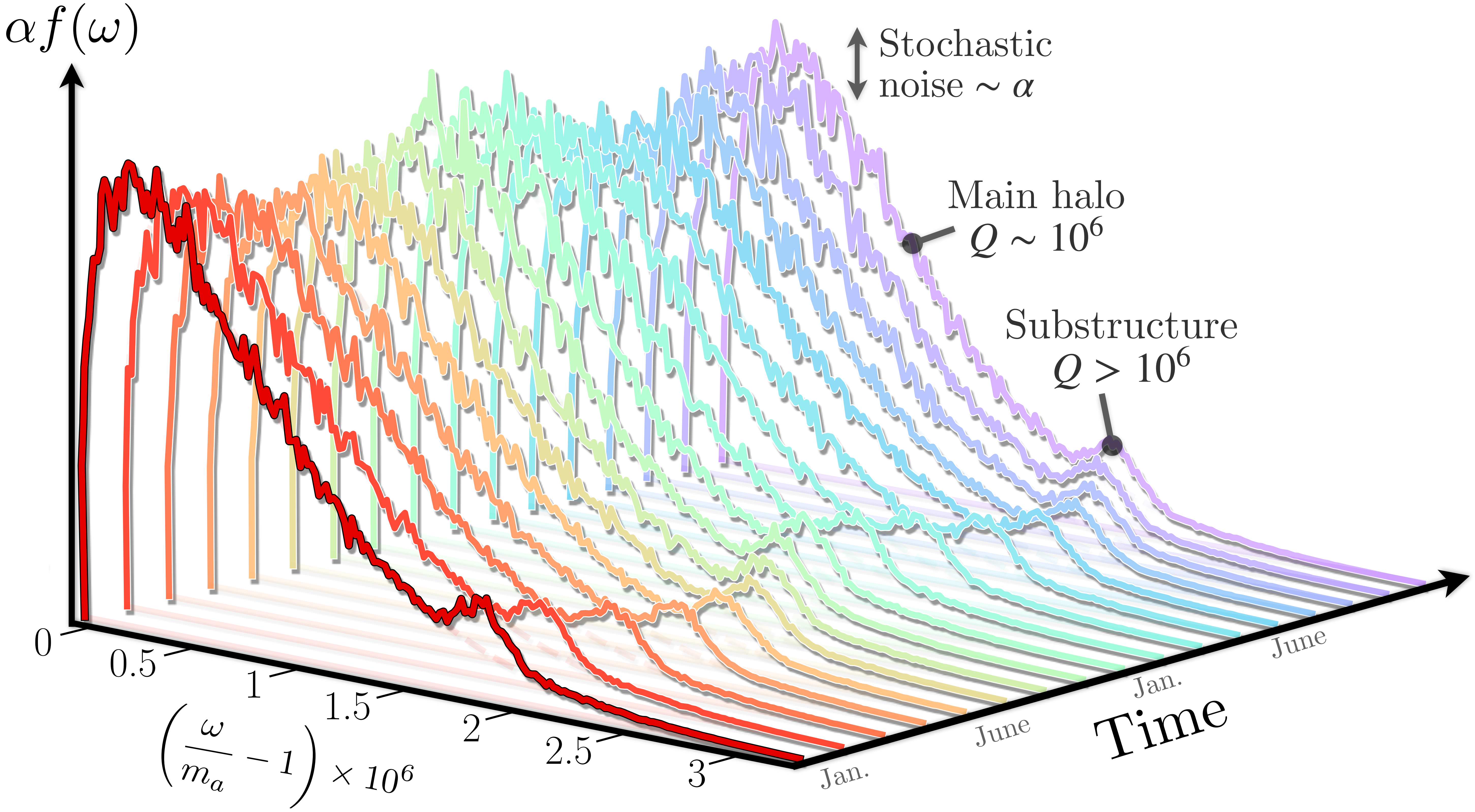


Wave-like dark matter:

Amplitude $A = \frac{\sqrt{2\rho_a}}{m_a}$

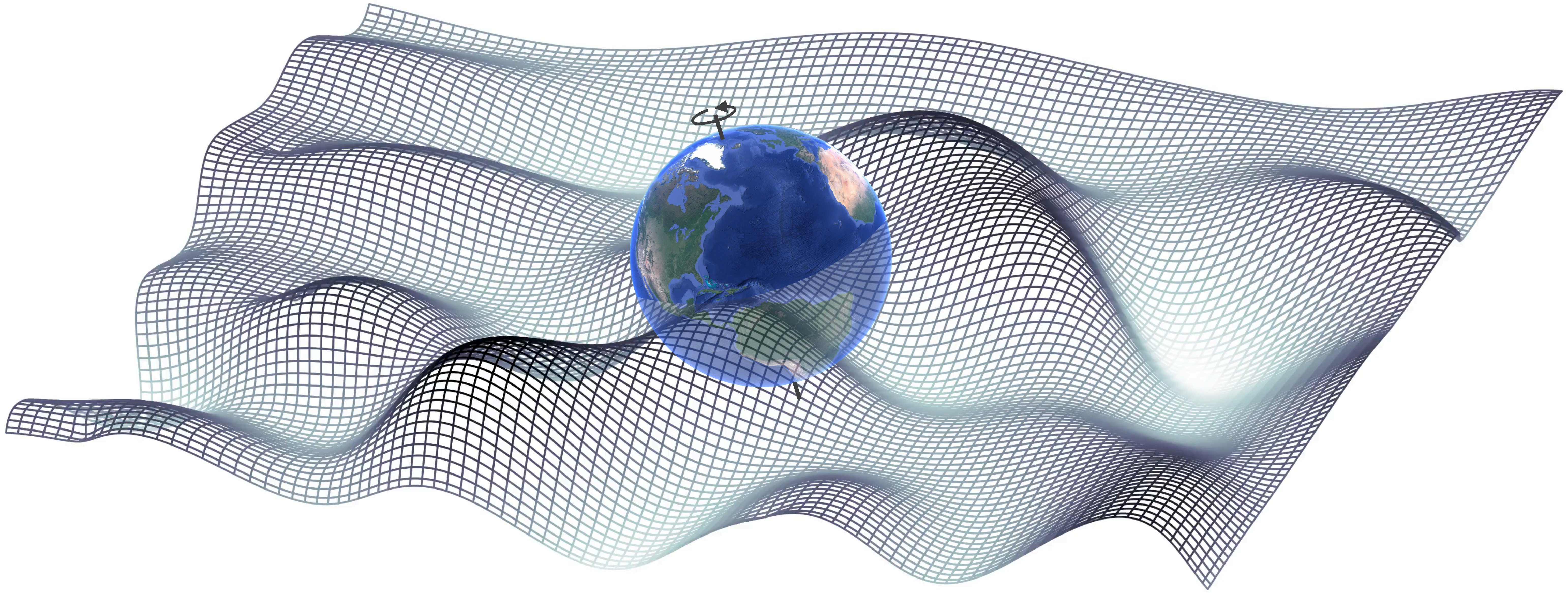
Frequency $\omega = m_a + \frac{1}{2} m_a v^2$

For wave-like DM detected via oscillatory signatures, the signal/noise is enhanced by *higher* densities and *narrower* speed distributions



$$\frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_{\mathrm{DM}}\, g^2}{m_{\mathrm{DM}}^2} f(v)$$

+ Annual modulation
+ Direction dependence
+ Fundamental noise from incoherent distribution of phases



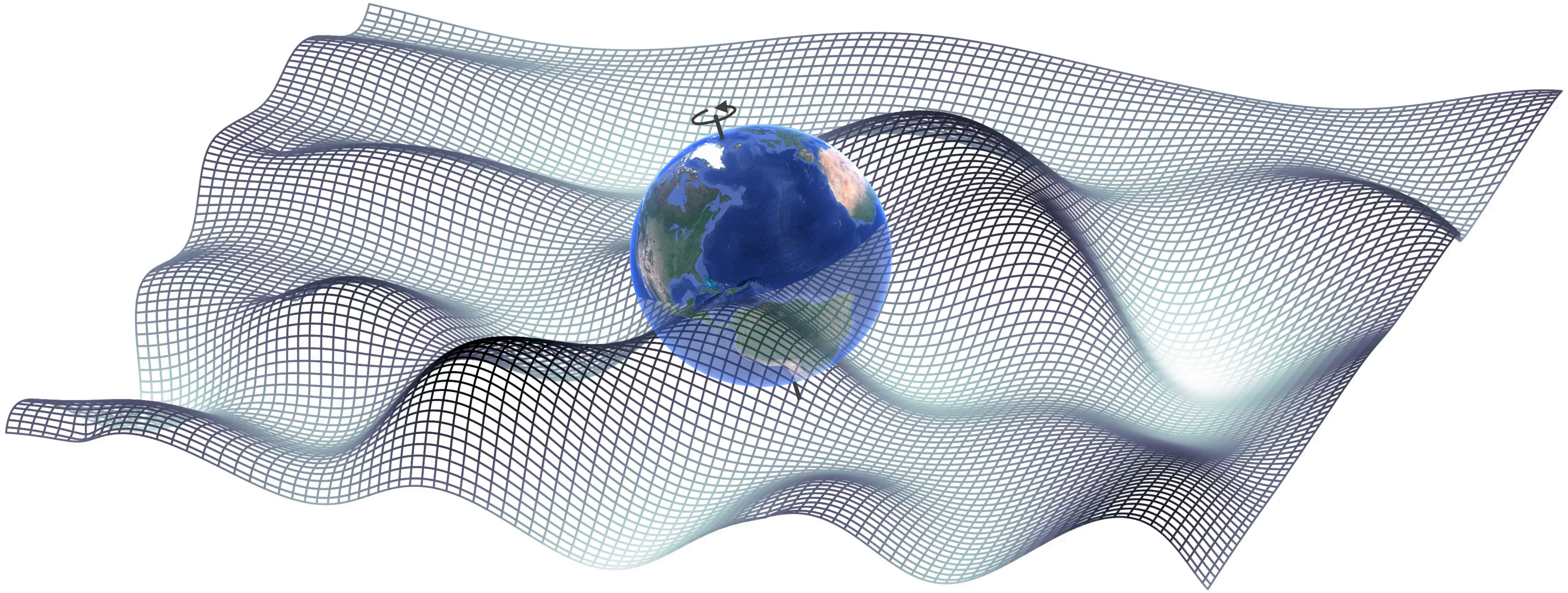
$$\frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_{\rm DM}\, g^2}{m_{\rm DM}^2} f(v)$$

Local density

$\rho_{\rm DM}$

Velocity distribution

$f(\mathbf{v})$



$$\frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_{\mathrm{DM}}\, g^2}{m_{\mathrm{DM}}^2} f(v)$$

Local density

ρ_{DM}

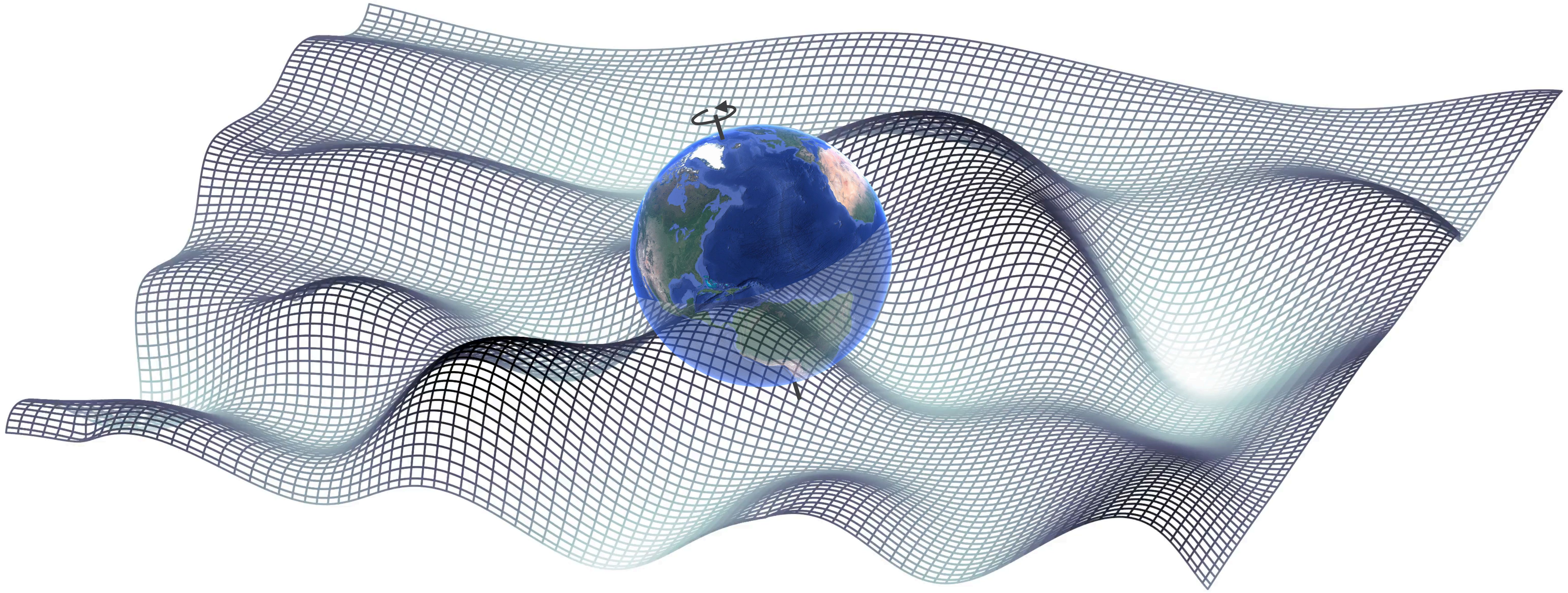
Velocity distribution

$f(\mathbf{v})$

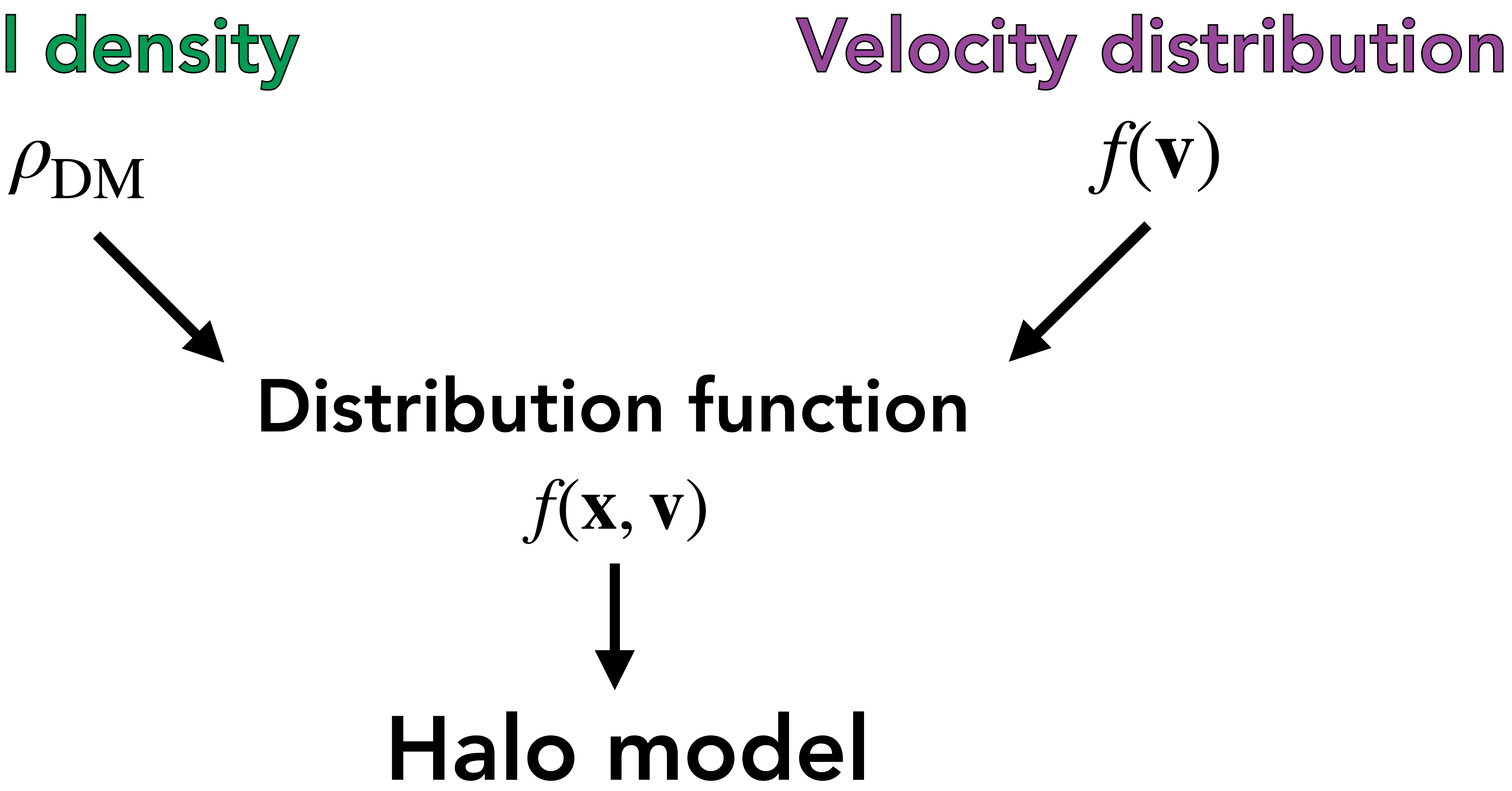
$\searrow \quad \swarrow$

Distribution function

$f(\mathbf{x}, \mathbf{v})$



$$\frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_{\mathrm{DM}}\, g^2}{m_{\mathrm{DM}}^2} f(v)$$



Local density

ρ_{DM}

Velocity distribution

$f(\mathbf{v})$

Distribution function

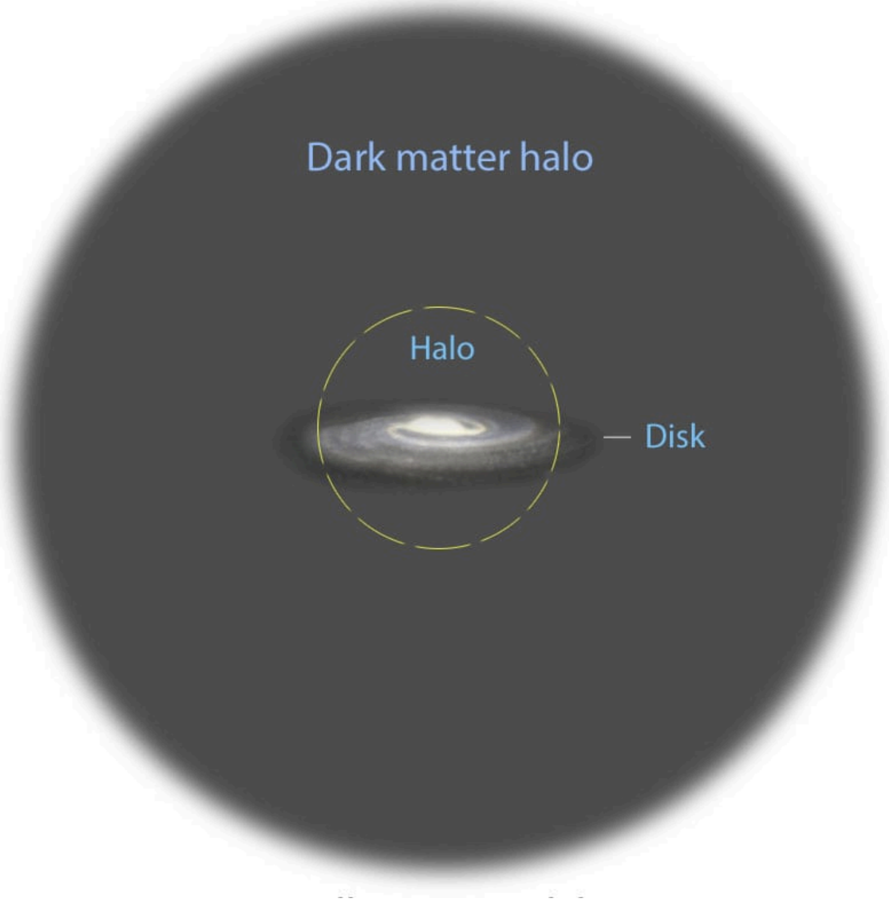
$f(\mathbf{x}, \mathbf{v})$

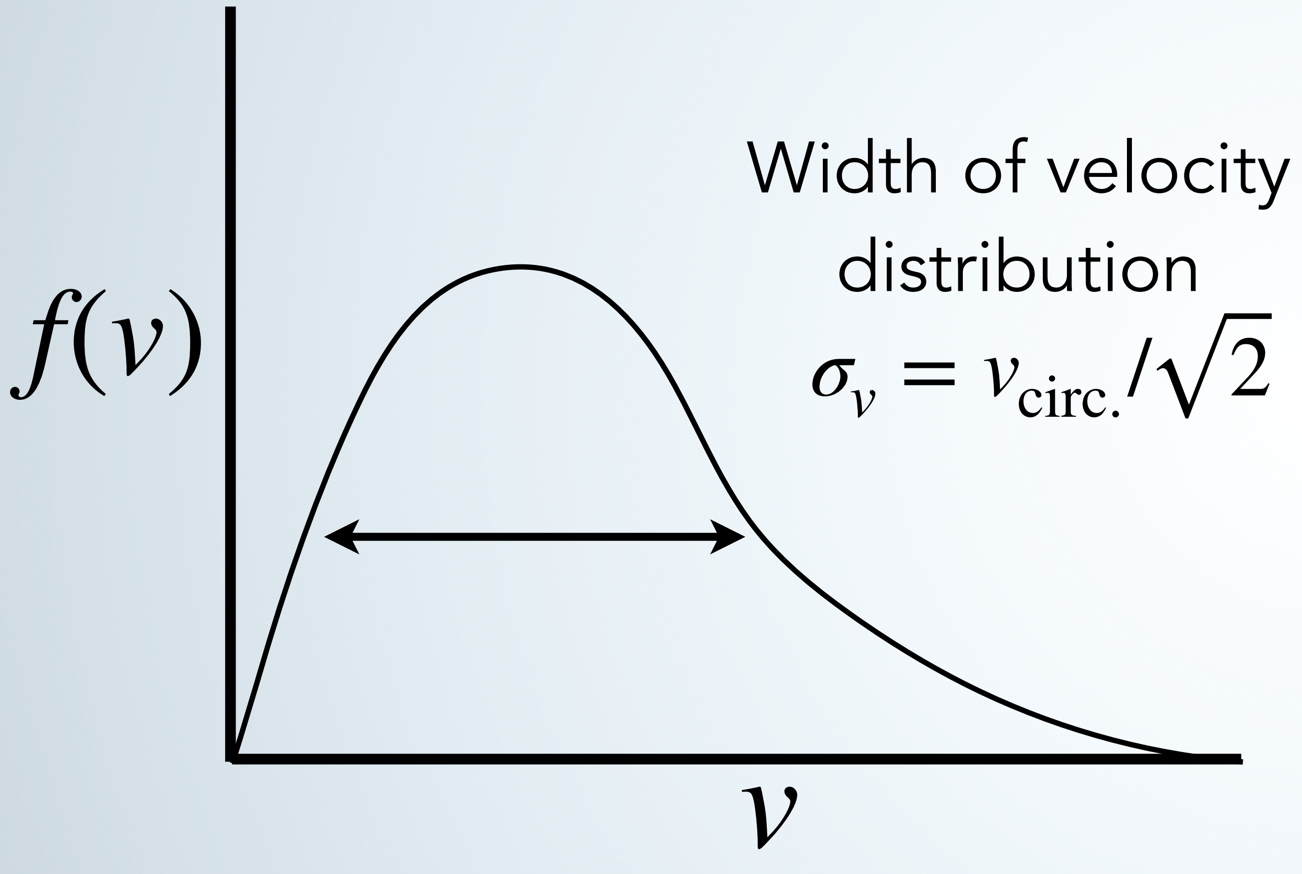
Halo model

The usual assumption: the Standard Halo Model (SHM)

- Infinite isothermal sphere → Simplest halo model that gives a flat asymptotic rotation curve: $v_{\rm circ}(R) \rightarrow {\rm const}$
- We observe it after a boost into our frame of reference by $v_{\rm lab} \approx v_{\rm circ}$

$$\rho \sim 1/r^2$$





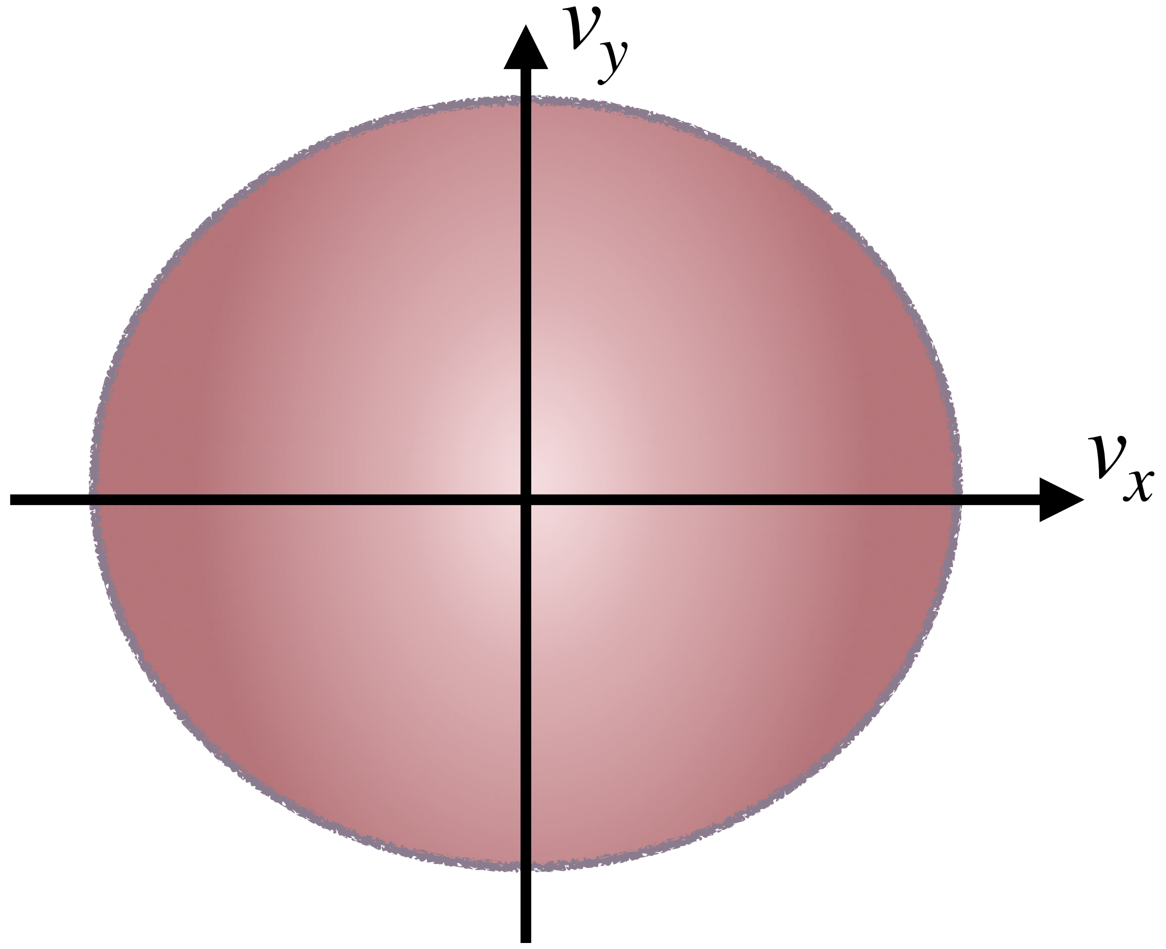
$$@R = 8~{\rm kpc:}$$

$$\rho_{\rm DM} = 0.3\,{\rm GeV\,cm^{-3}}$$

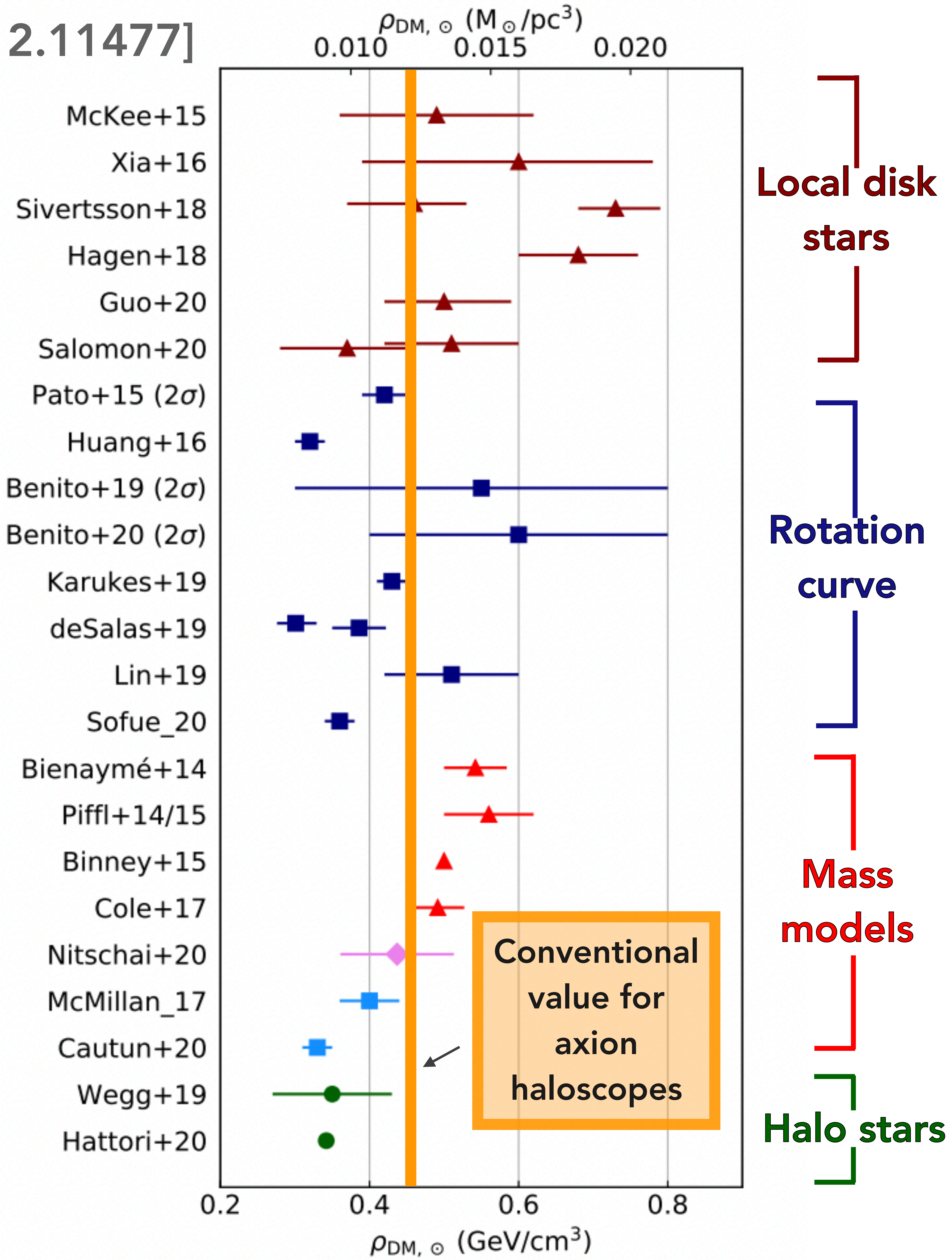
$$v_{\rm circ} = 220~{\rm km~s^{-1}}$$

$$v_{\rm esc} = 544~{\rm km~s^{-1}}$$

$$f(\mathbf{v}) \sim \exp(-|\mathbf{v}^2|/v_{\rm circ}^2)$$



[2012.11477]



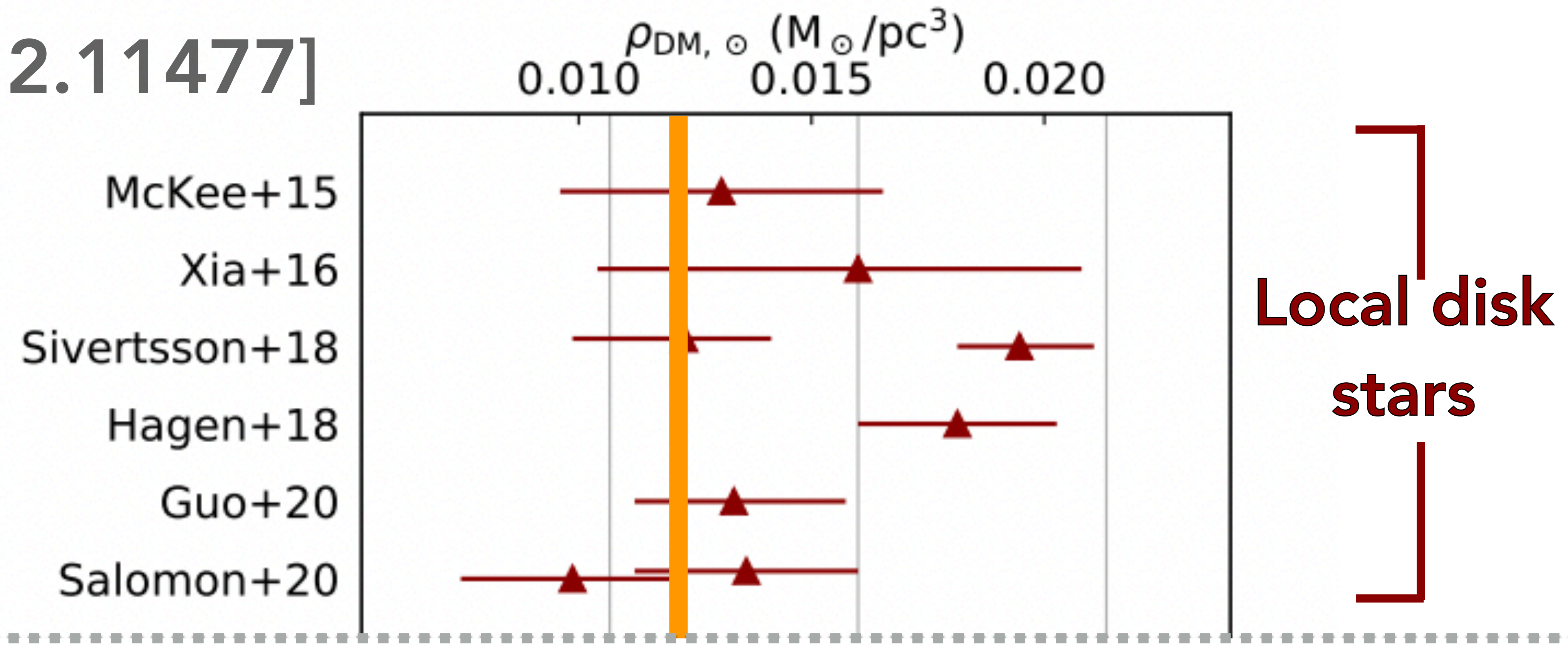
Some recent estimates

Hagen+[1802.09291]
Buch+ [1808.05603]
Widmark [1811.07911]
de Salas+ [1906.06133]
Eilers+ [1810.09466]
Benito+ [1901.02460]

Values span the range 0.3—0.7 GeV cm^{-3} depending on the method and dataset used

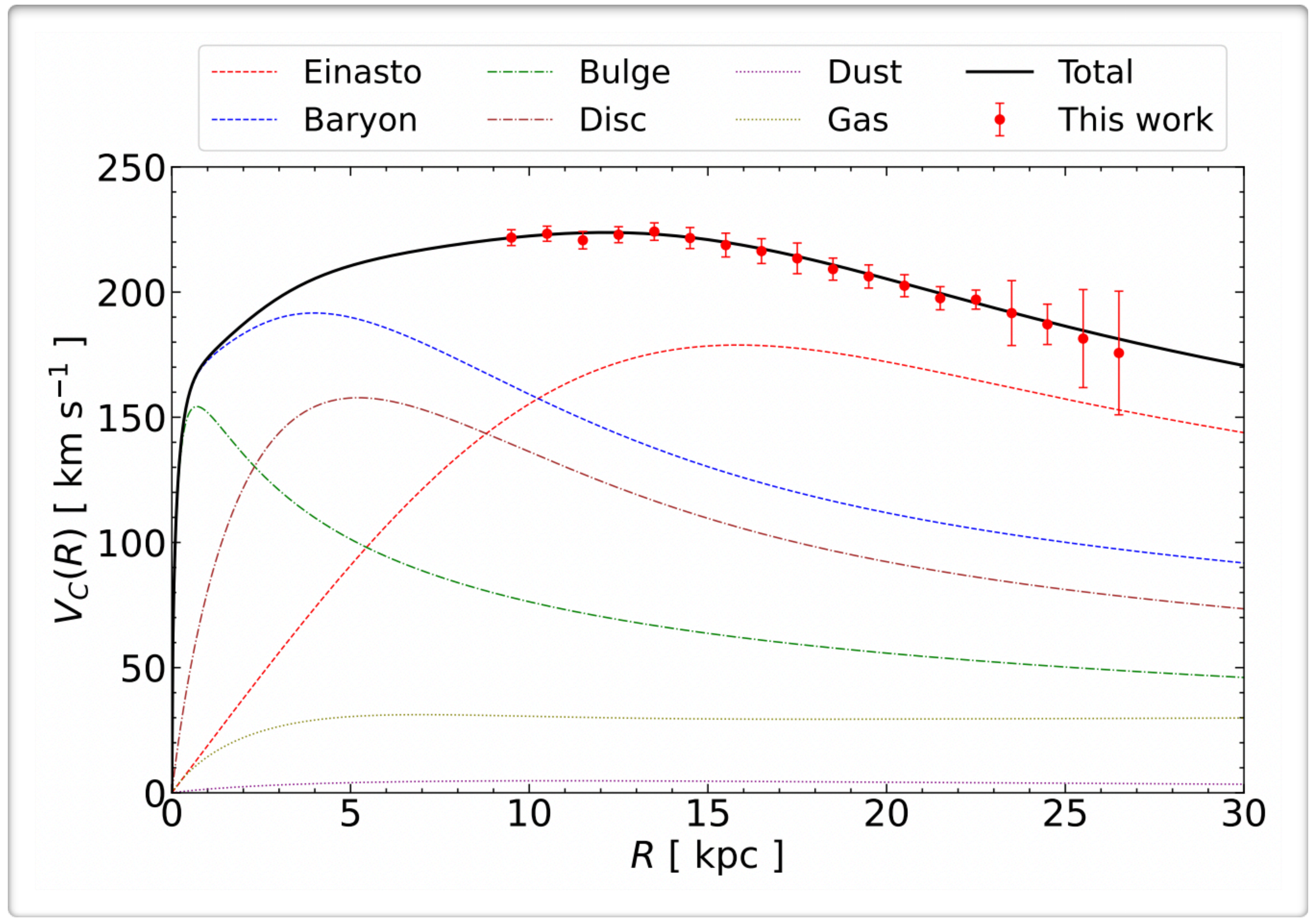
→ Lack of data is no longer the issue. Fundamental problem is modelling, disequilibrium, and systematics in baryonic density model

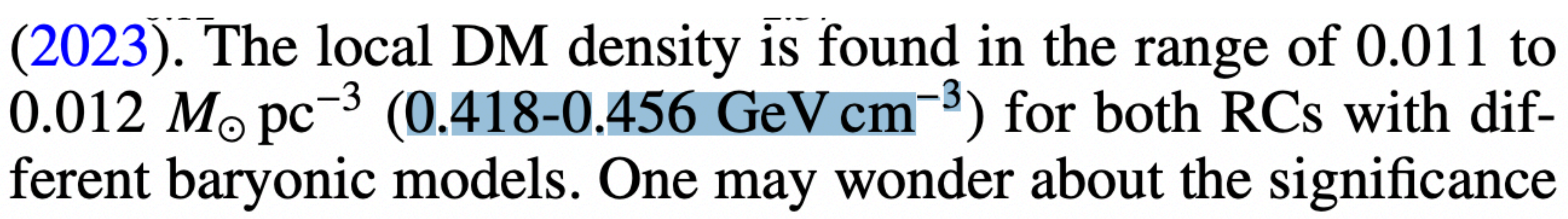
[2012.11477]



Latest *Gaia* DR3 analysis (this Monday)

[2309.00048]





(2023). The local DM density is found in the range of 0.011 to 0.012 $M_\odot\,\mathrm{pc}^{-3}$ (0.418-0.456 GeV cm^{-3}) for both RCs with different baryonic models. One may wonder about the significance

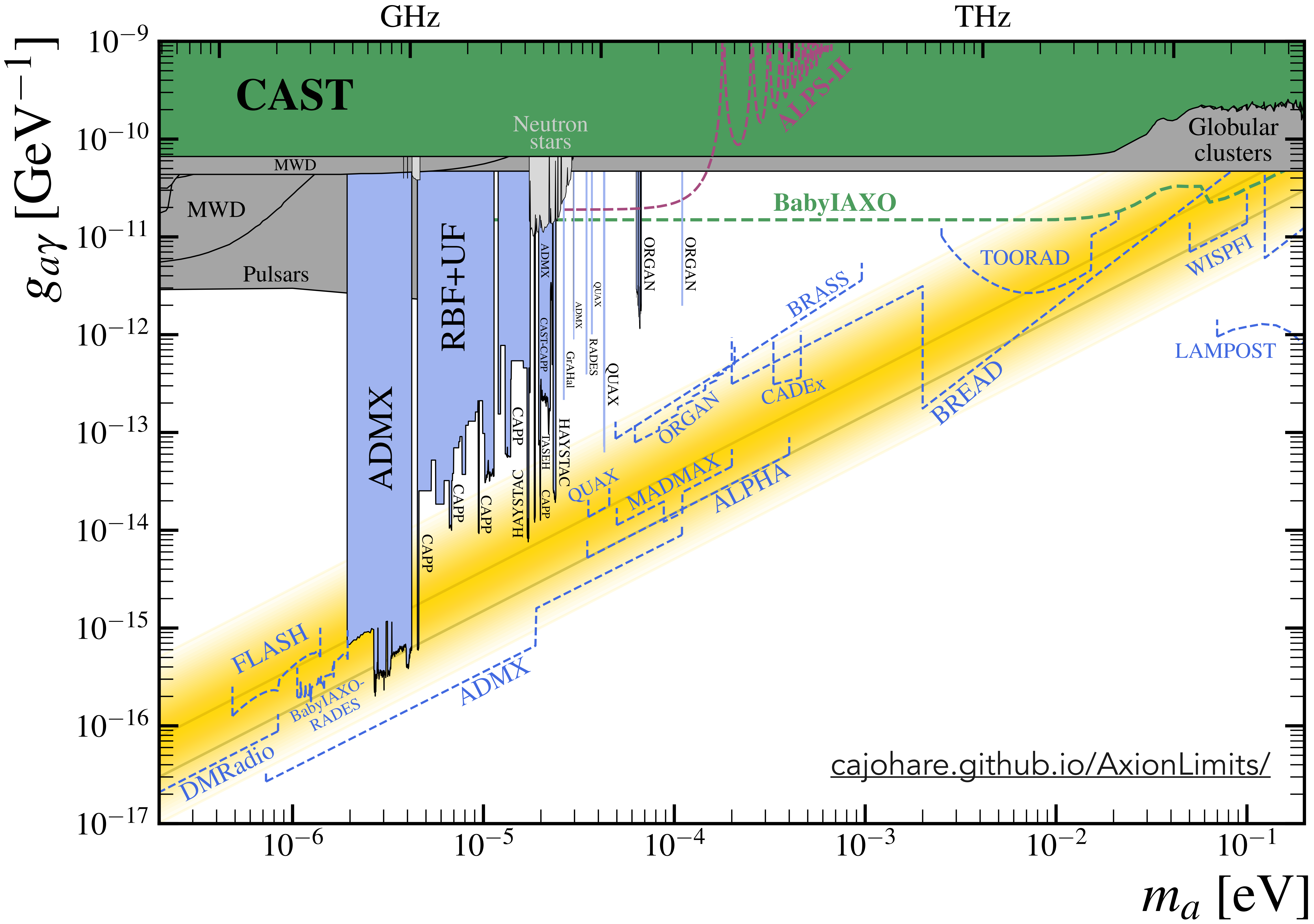
Some recent estimates

Hagen+[1802.09291]
Buch+ [1808.05603]
Widmark [1811.07911]
de Salas+ [1906.06133]
Eilers+ [1810.09466]
Benito+ [1901.02460]

Values span the range 0.3—0.7 GeV cm^{-3} depending on the method and dataset used

→ Lack of data is no longer the issue. Fundamental problem is modelling, disequilibrium, and systematics in baryonic density model

Why care about the value of the dark matter density?



cajohare.github.io/AxionLimits/

Haloscope sensitivity scales *slowly*…

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

If assumed value of $\rho_{\rm DM}$ was too large by, say, 0.15 GeV/cm^3 then DFSZ would take more than twice as long to exclude

So how sure are we about the dark matter density?

What is the distribution of axions in galaxies?

Will it be like vanilla ΛCDM halos?

What is the distribution of axions in galaxies?

Will it be like vanilla ΛCDM halos?

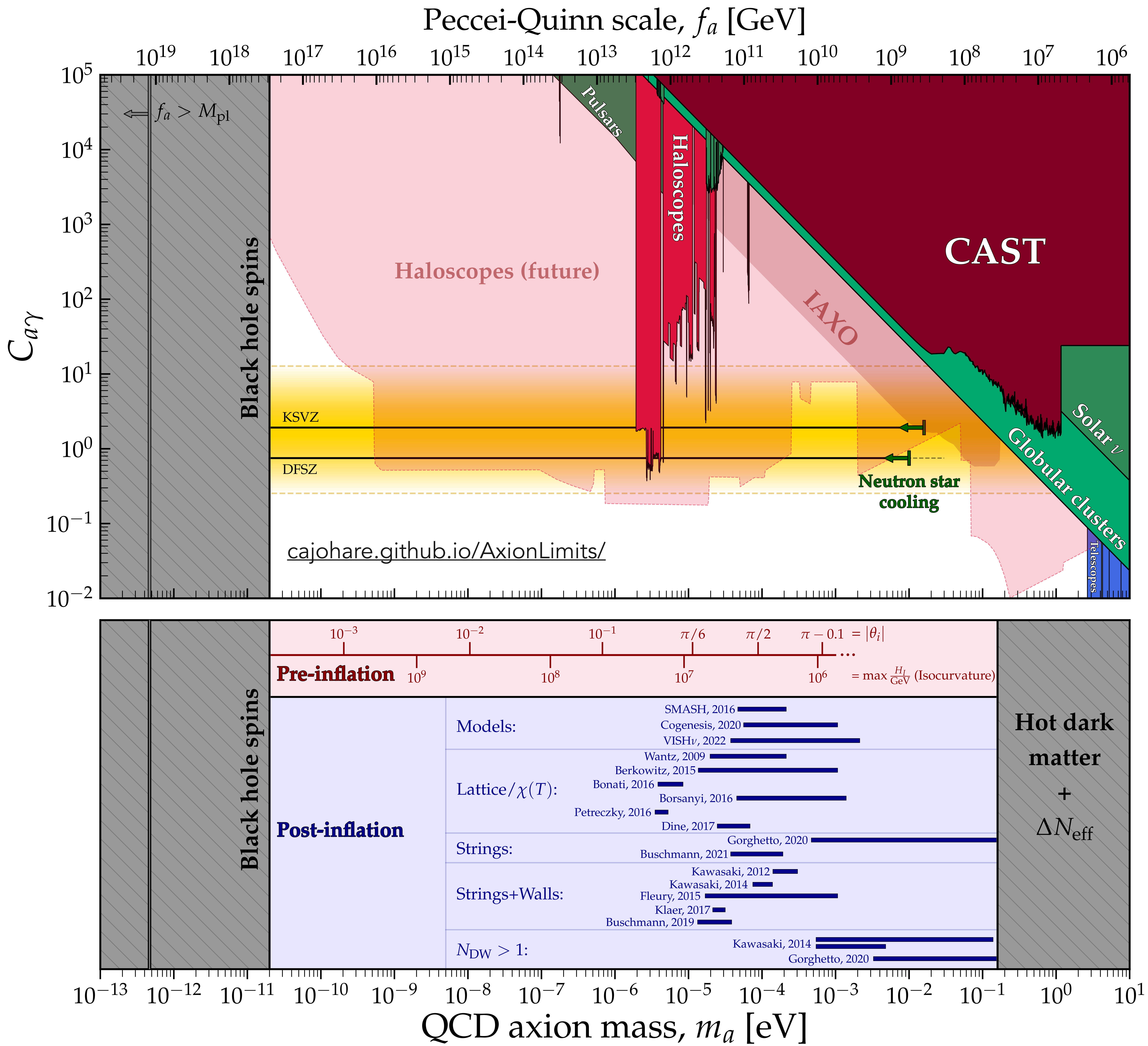
Pre-inflationary axion: probably, yes.

What is the distribution of axions in galaxies?

Will it be like vanilla ΛCDM halos?

Pre-inflationary axion: probably, yes.

Post-inflationary axion: NO



Post-inflationary axion mass range

$\mathcal{O}(10 - 100\,\mu\text{eV})$*

Relevant for experiments like:

→QUAX

→ MADMAX

→ ORGAN

→ ALPHA

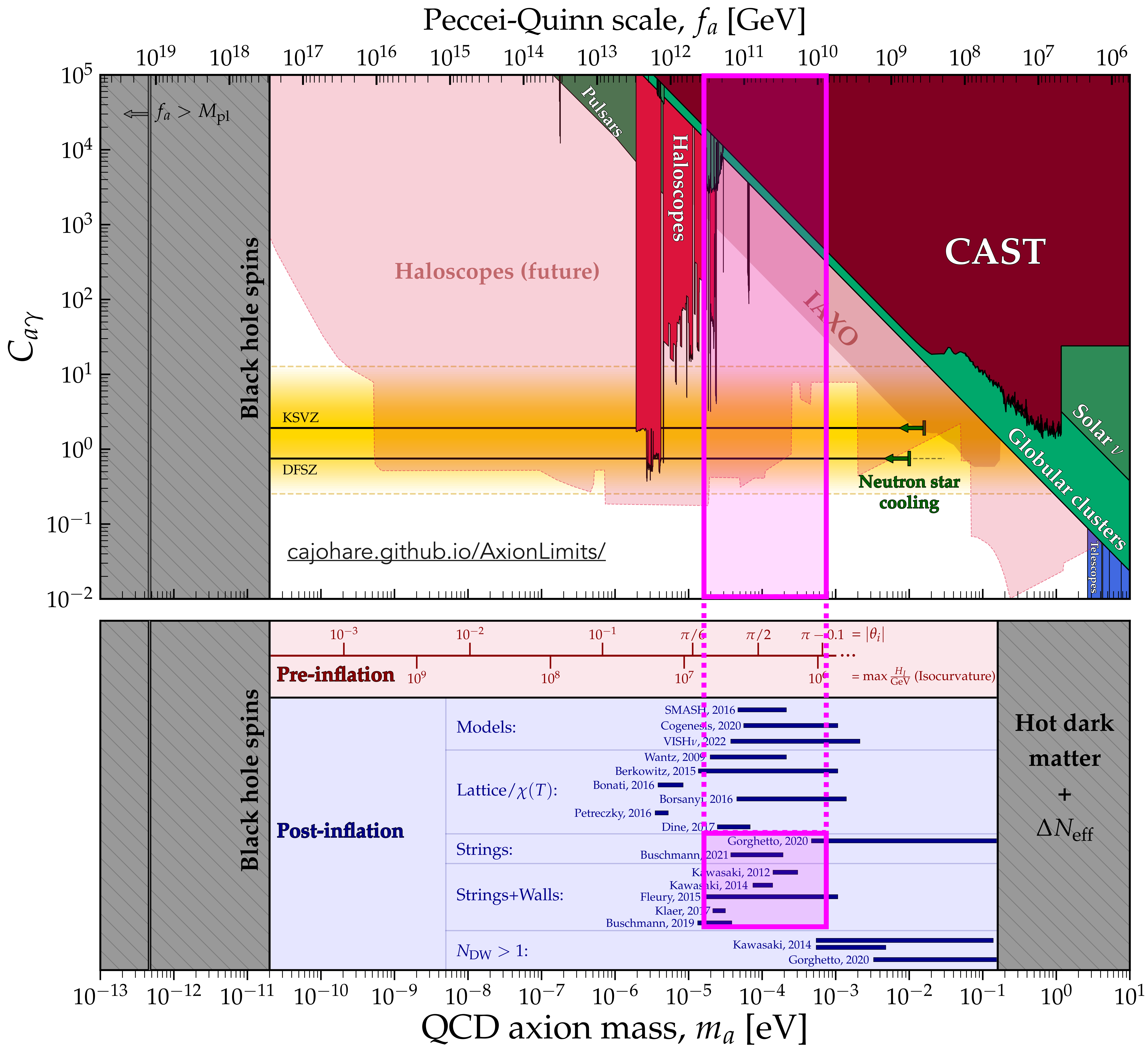
→ DALI

→ CADEx

→ BRASS

→ BREAD

(*modulo uncertainties and limitations in extrapolating simulation results)



Post-inflationary axion mass range

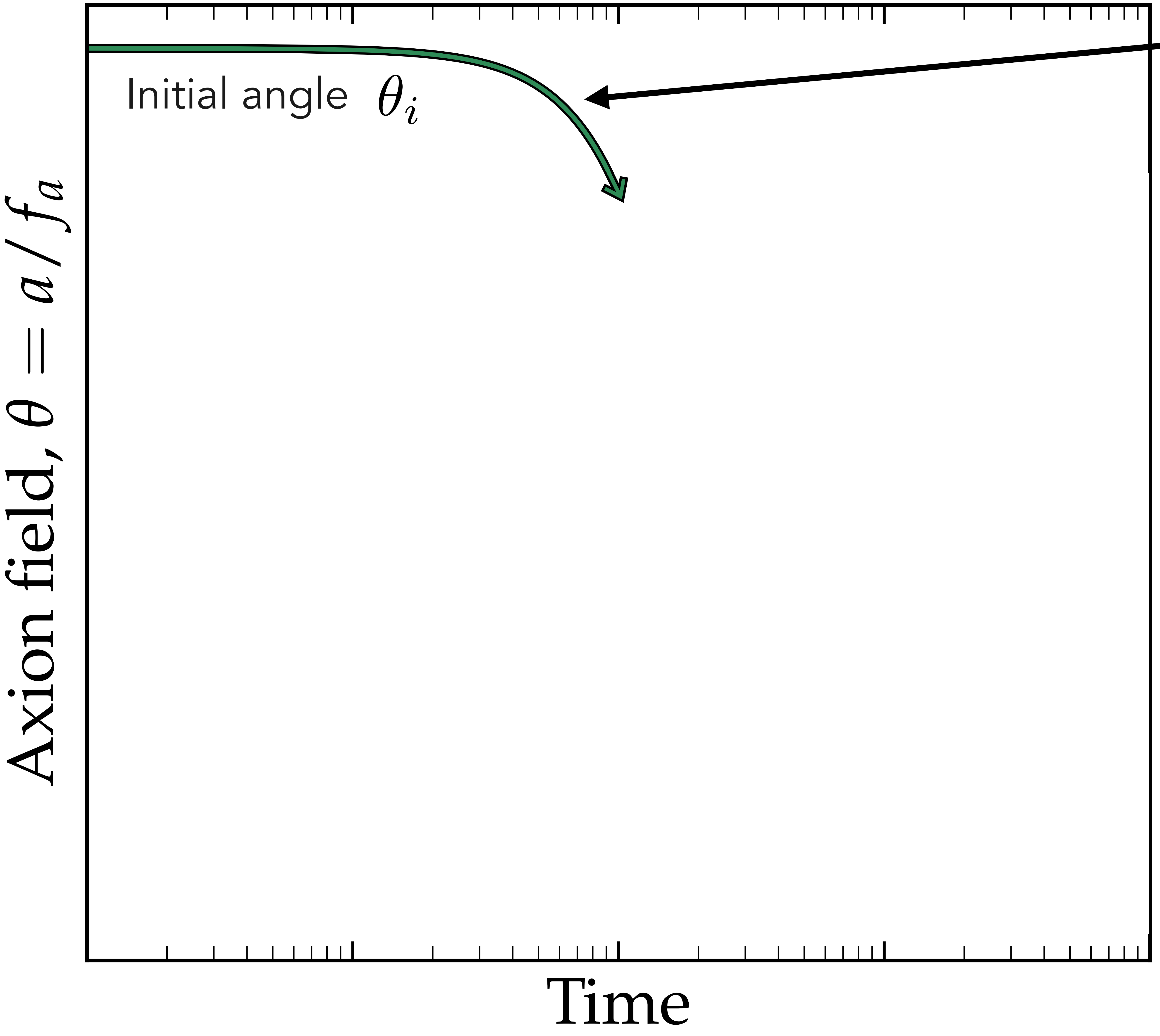
$\mathcal{O}(10 - 100\,\mu\text{eV})$*

Relevant for experiments like:

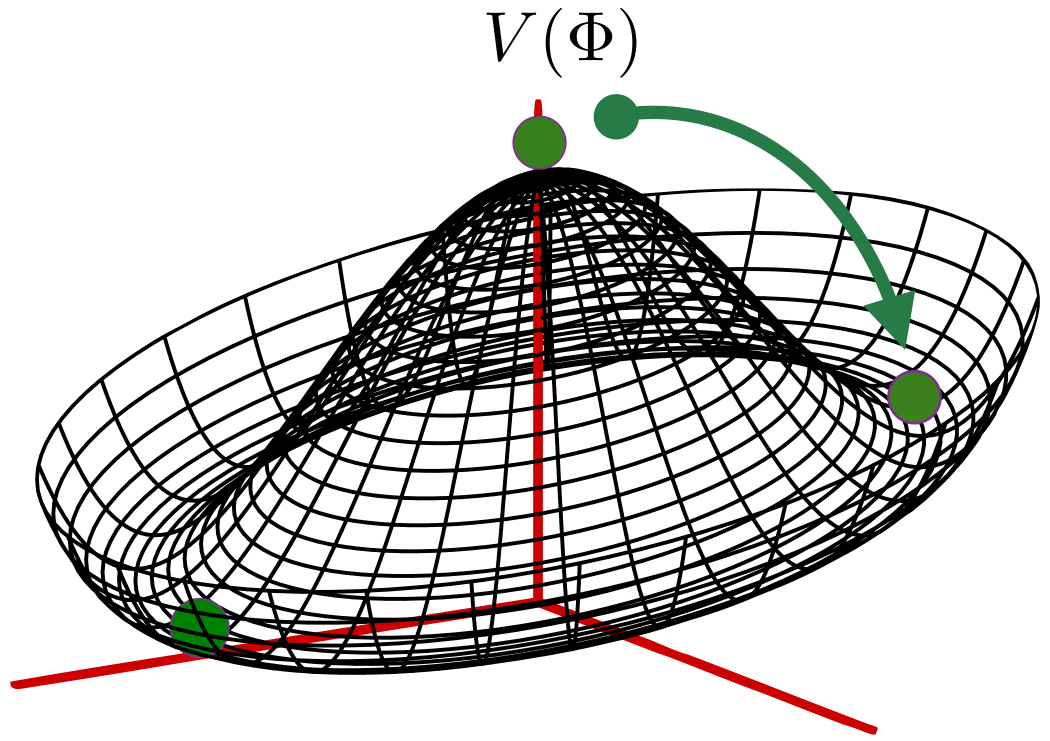
→QUAX
→ MADMAX
→ ORGAN
→ ALPHA
→ DALI
→ CADEx
→ BRASS
→ BREAD

(*modulo uncertainties and limitations in extrapolating simulation results)

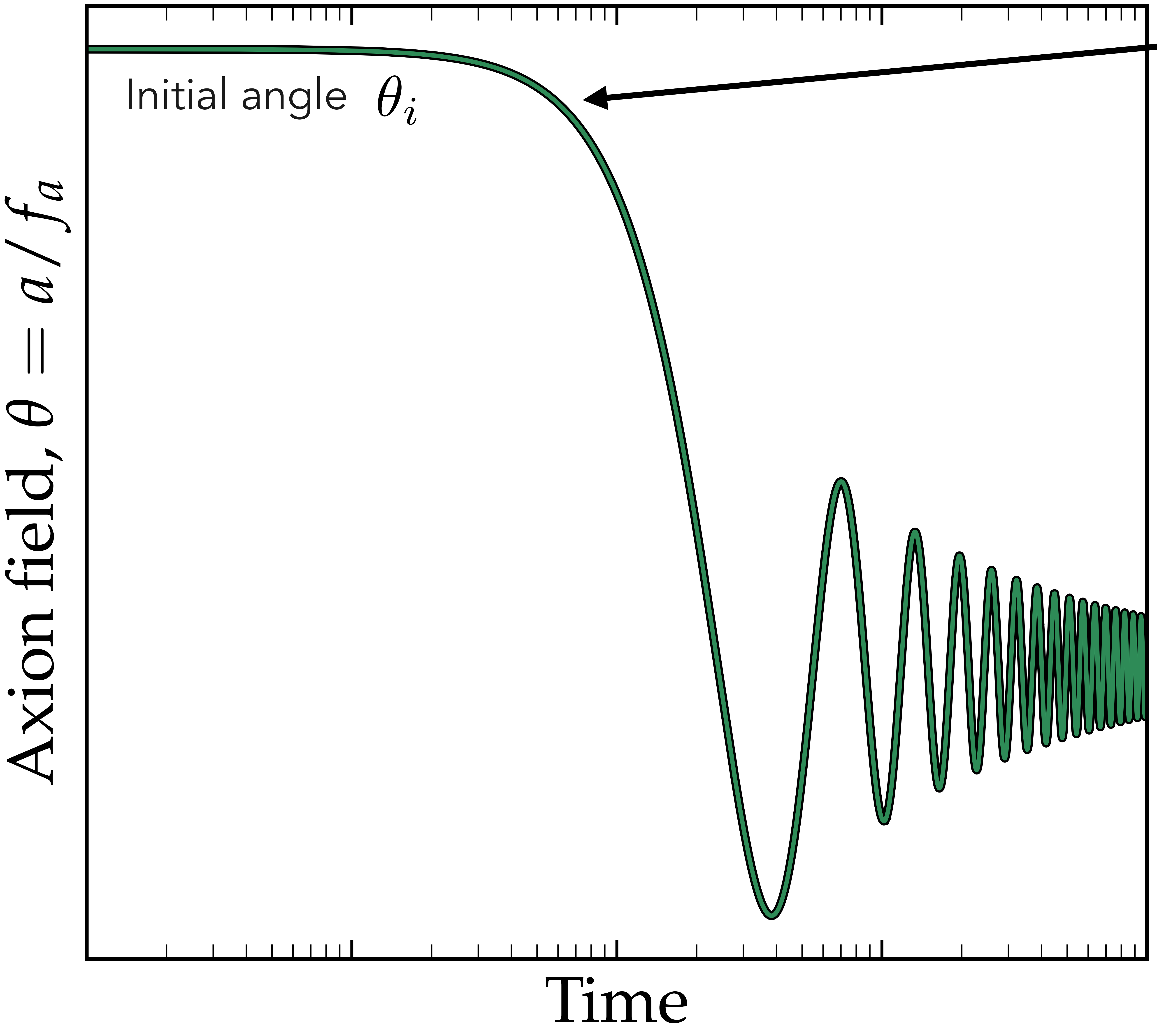
Post-inflationary axions: the misalignment mechanism



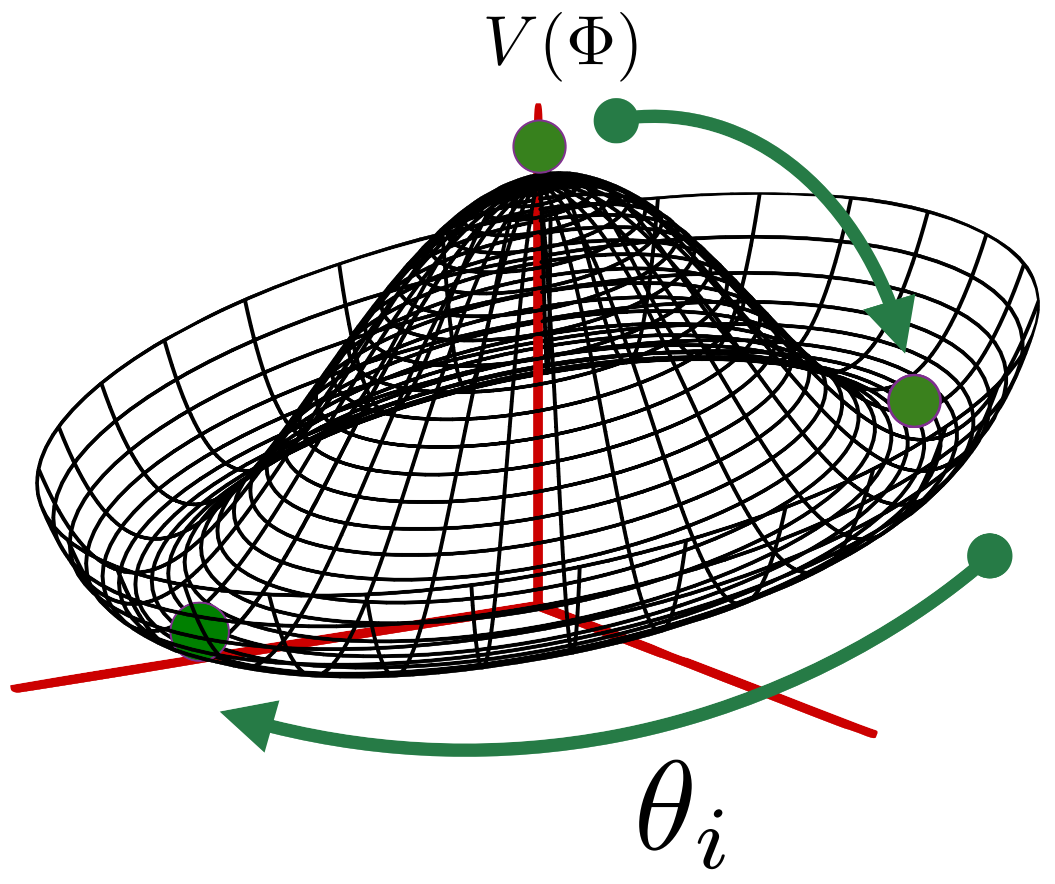
Axion is the phase of a complex scalar field governed by a tilted potential.



Post-inflationary axions: the misalignment mechanism

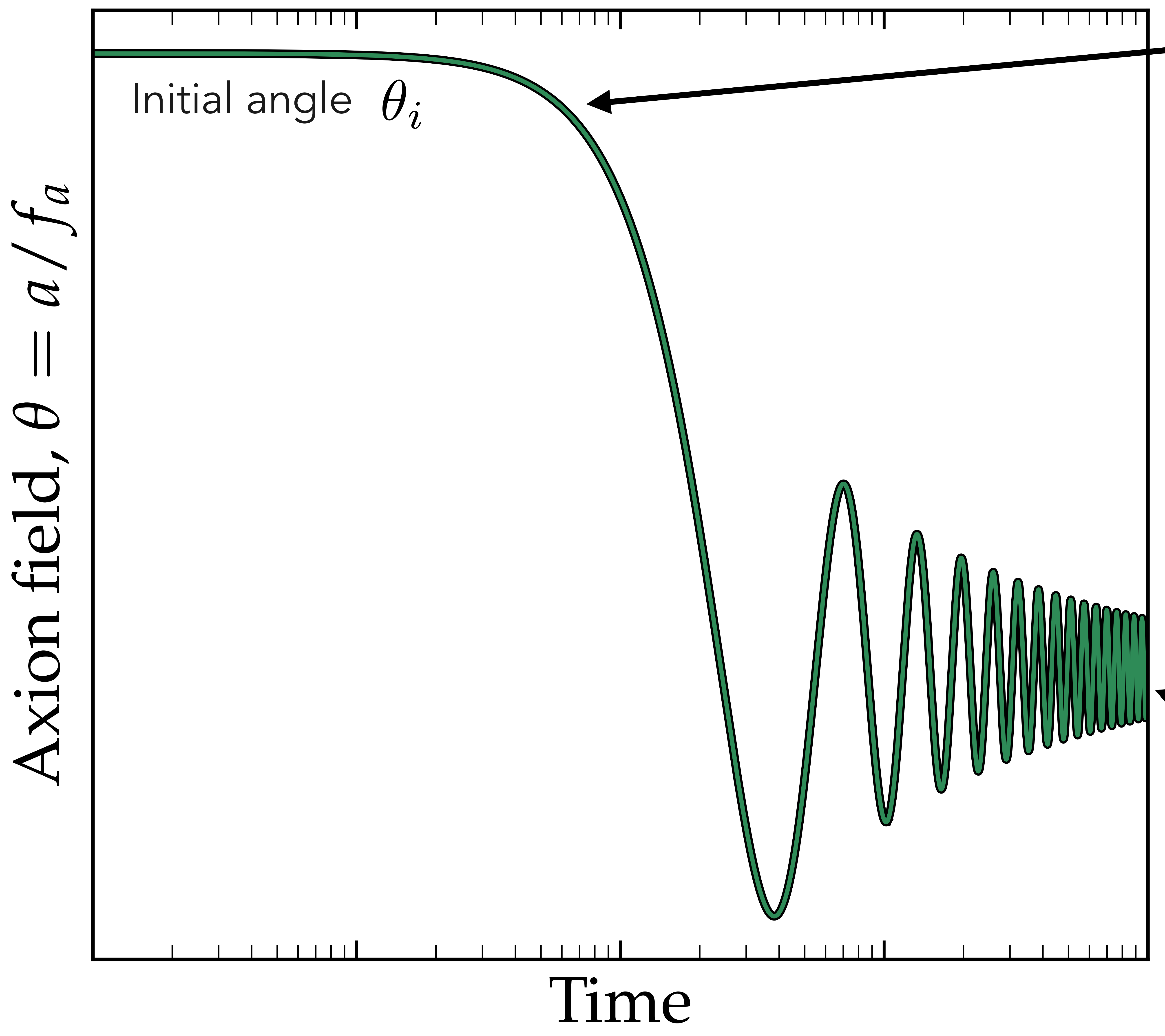


Axion is the phase of a complex scalar field governed by a tilted potential.

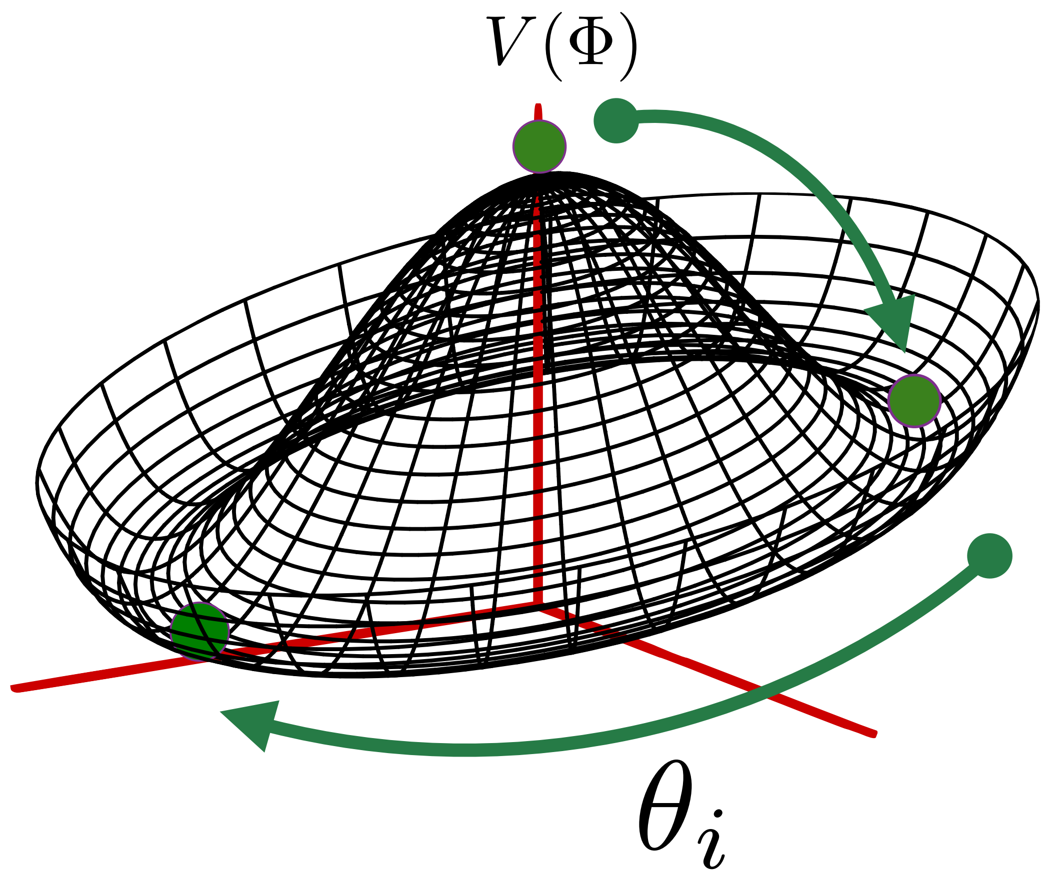


$$\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0$$

Post-inflationary axions: the misalignment mechanism



Axion is the phase of a complex scalar field governed by a tilted potential.



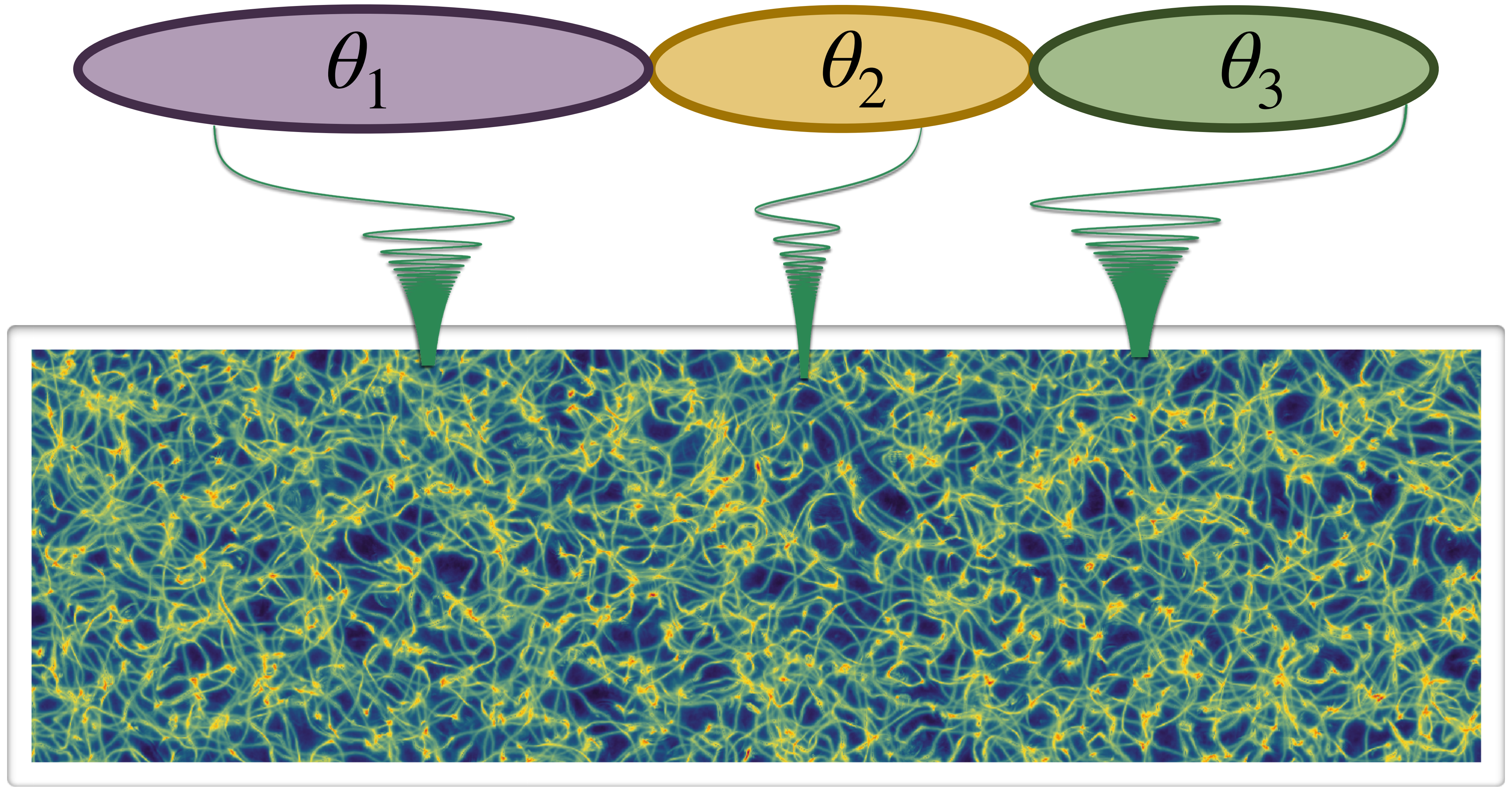
$$\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0$$

Axion field rolls down to minimum and starts damped oscillations

→ **cold dark matter with predictable abundance:**

$$\Omega_a h^2 \propto \theta_i^2$$

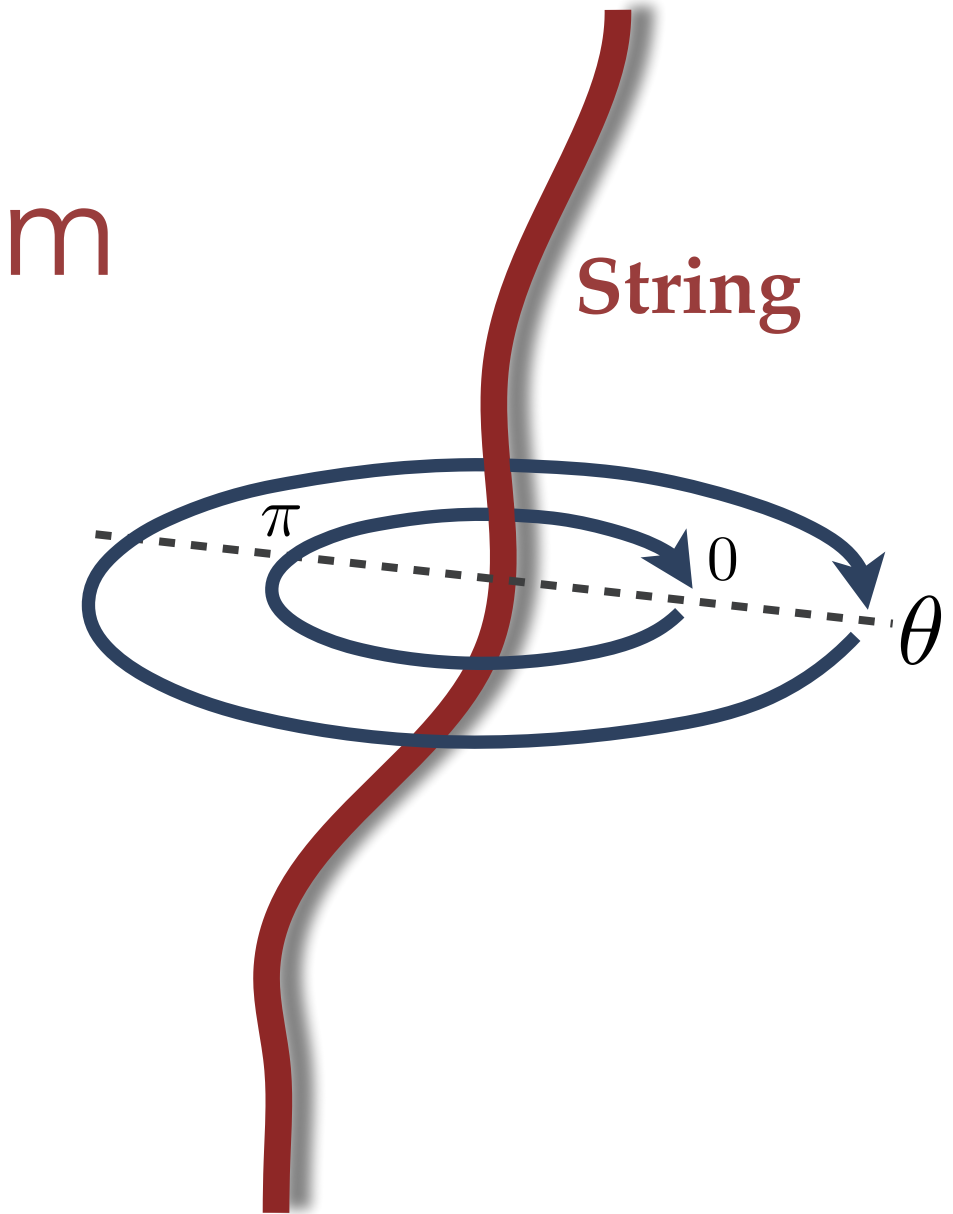
But there's a complication: $\nabla\theta$



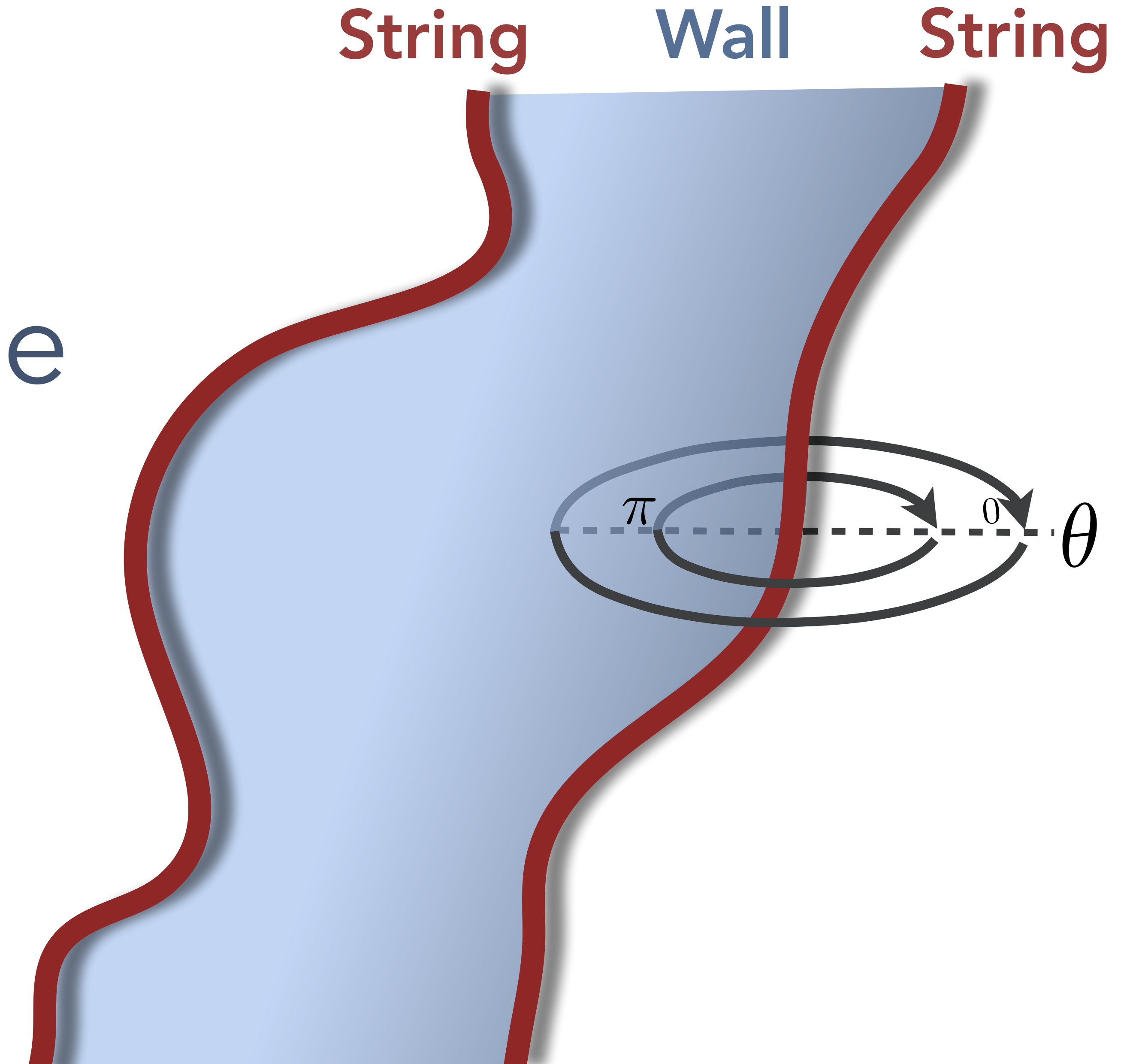
Different causal patches take on different initial angles
→ Field gradients!

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

⇒ **Cosmic strings** from axion field winding around 2π

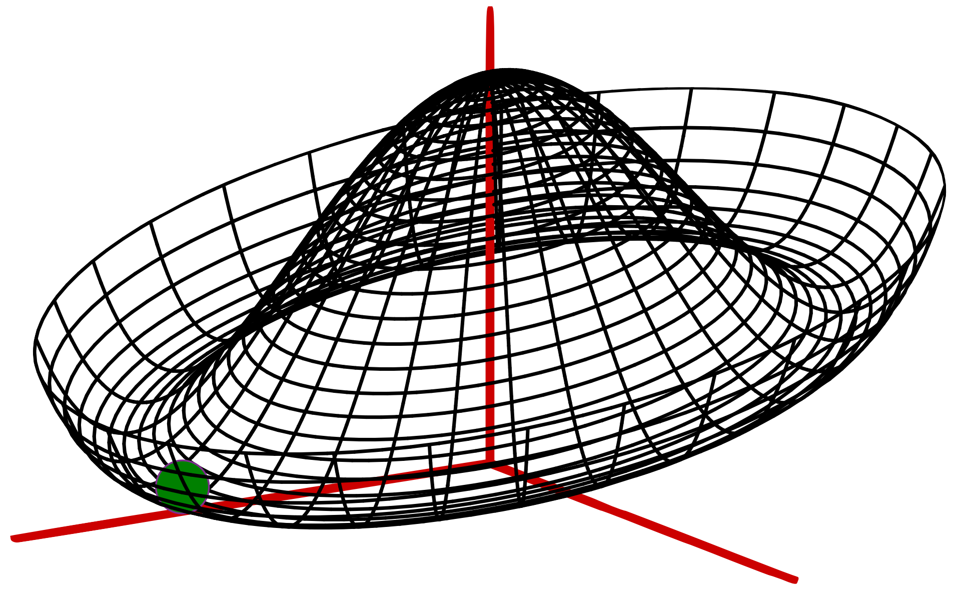


⇒ **Domain walls** between true/false vacuum (0 and π)

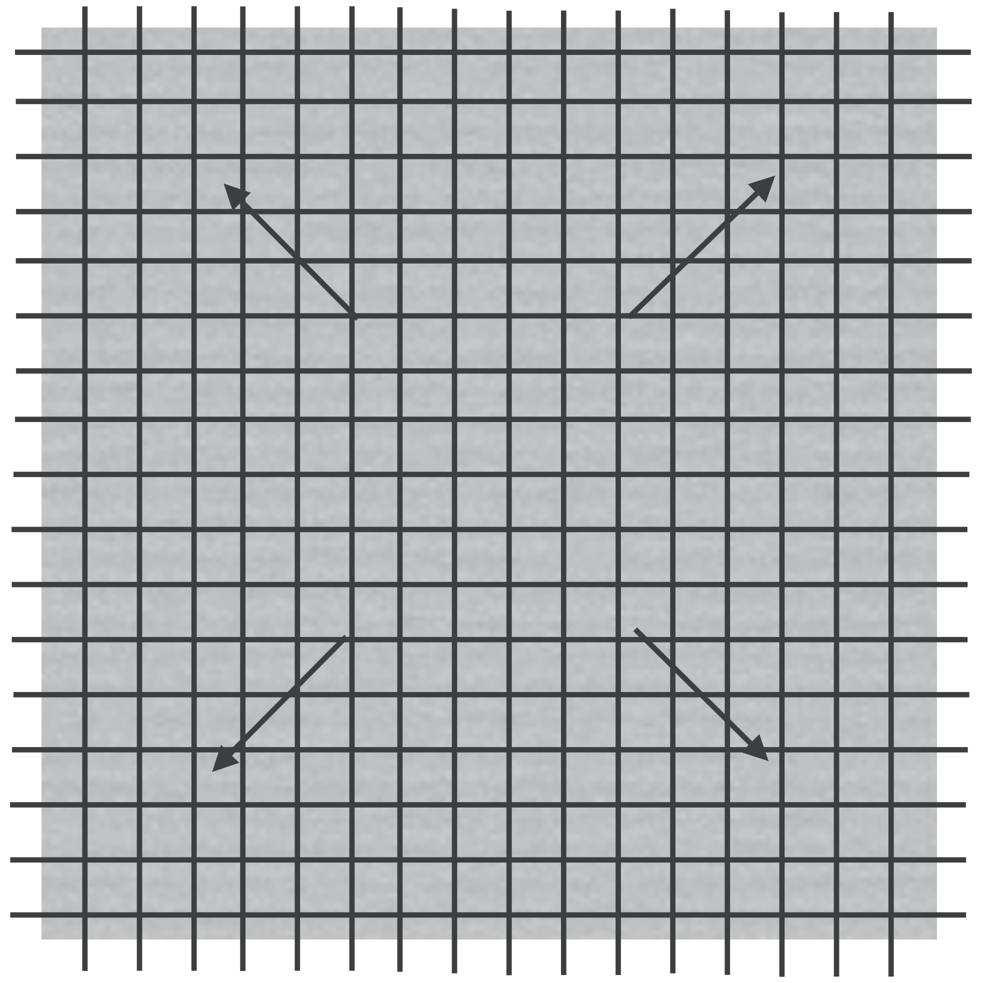


What do we need to do? → simulate

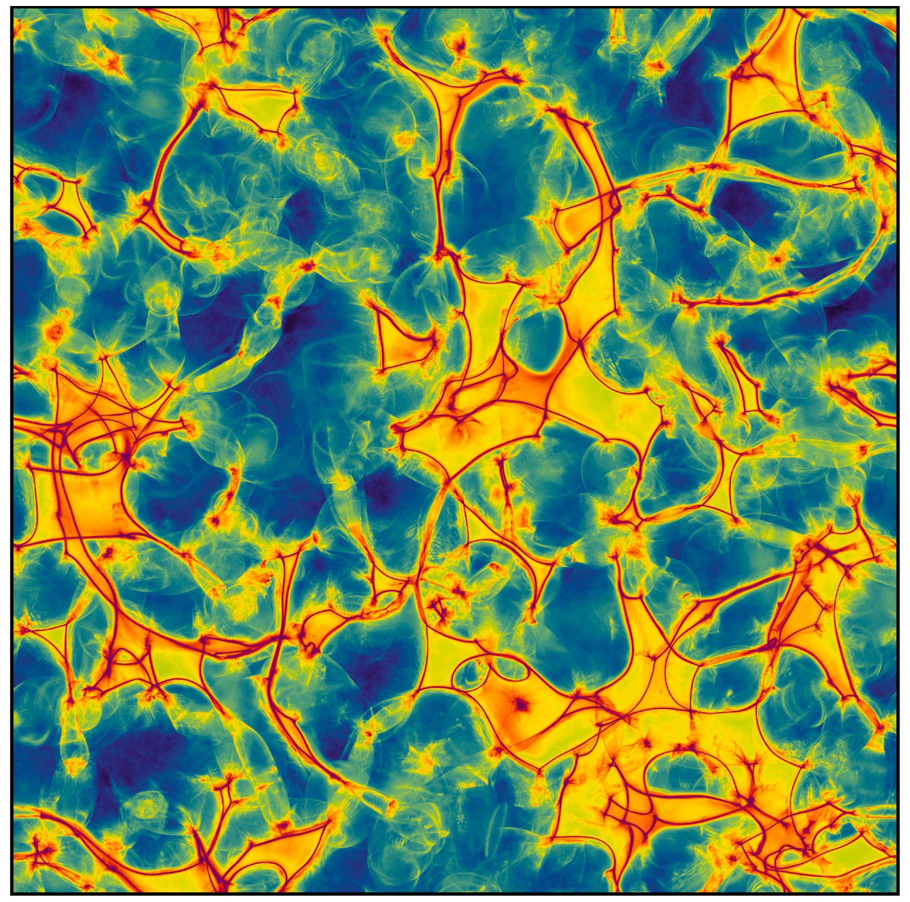
(in a nutshell)



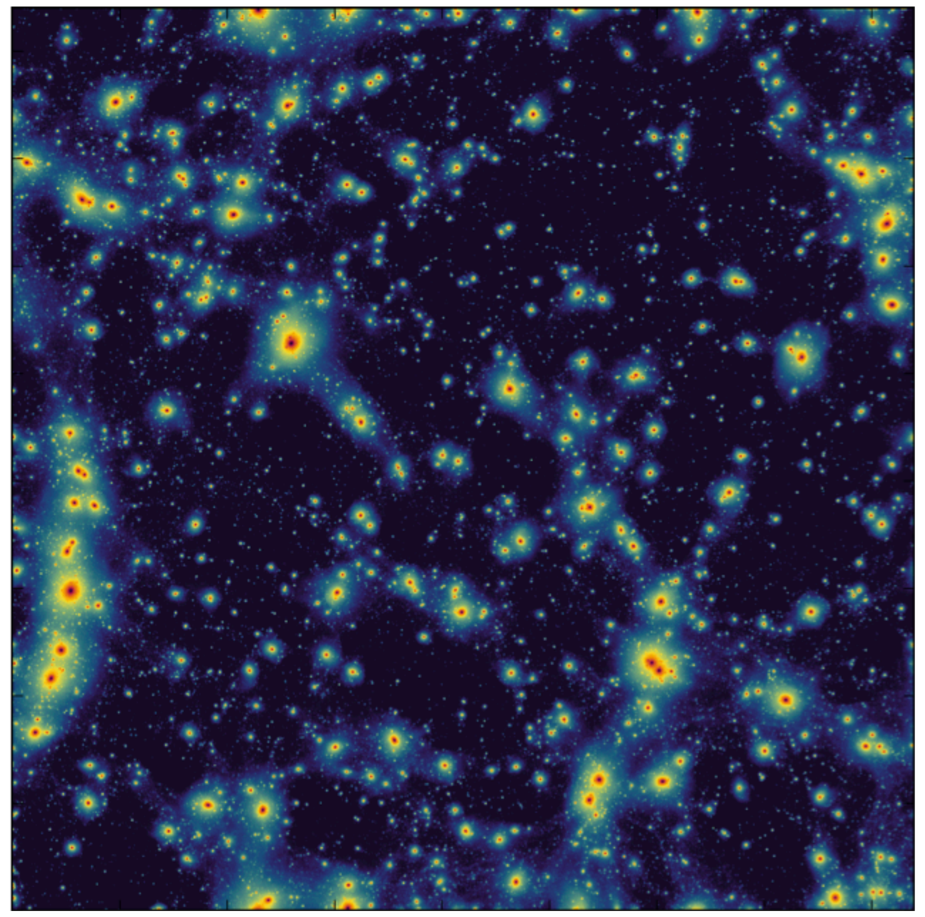
Evolve the axion field…



…on an expanding lattice…



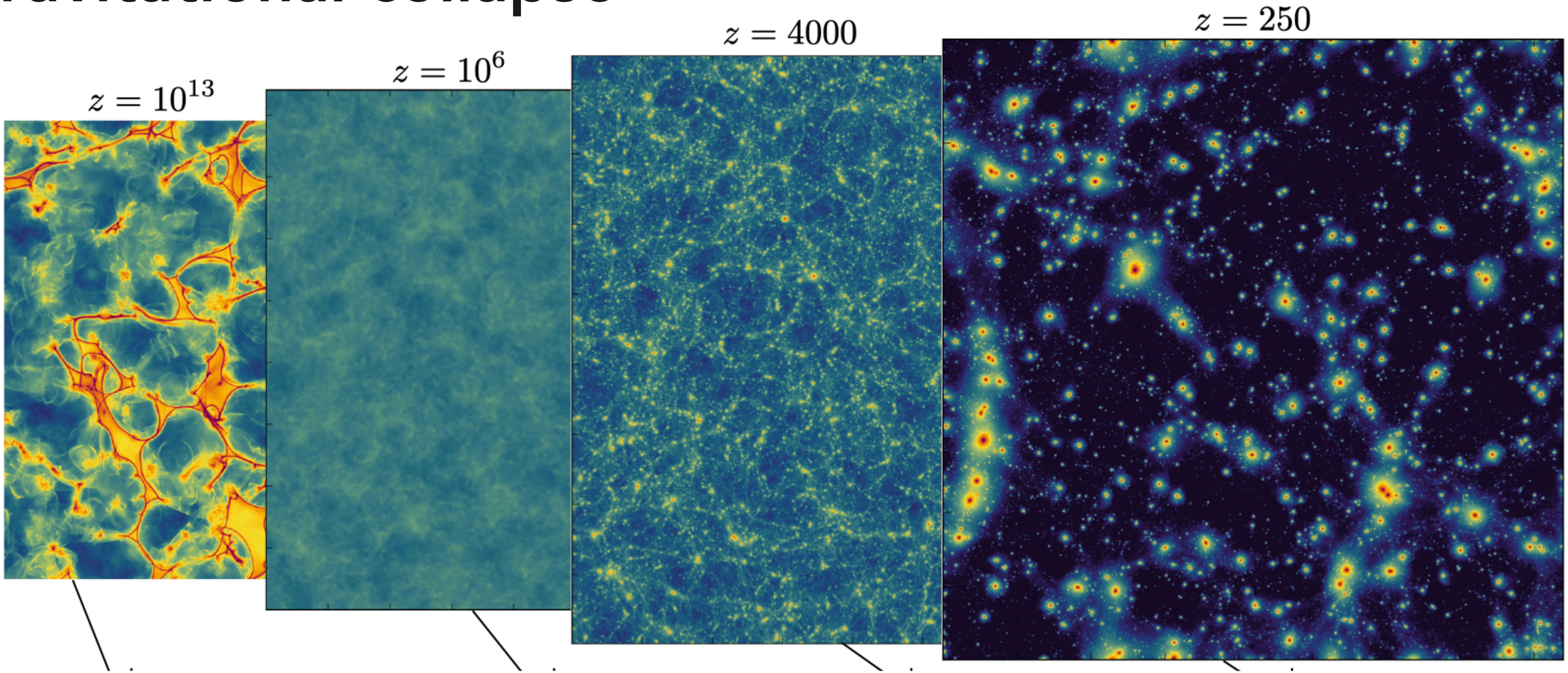
…to measure the relic abundance of axions…



…and predict its present day distribution

For more comprehensive accounts see, e.g.: Gorghetto+[2007.04990], Buschmann+ [2108.05368], Vaquero+ [1809.09241], O'Hare+ [2112.05117]

Gravitational collapse



Initial conditions from lattice simulation

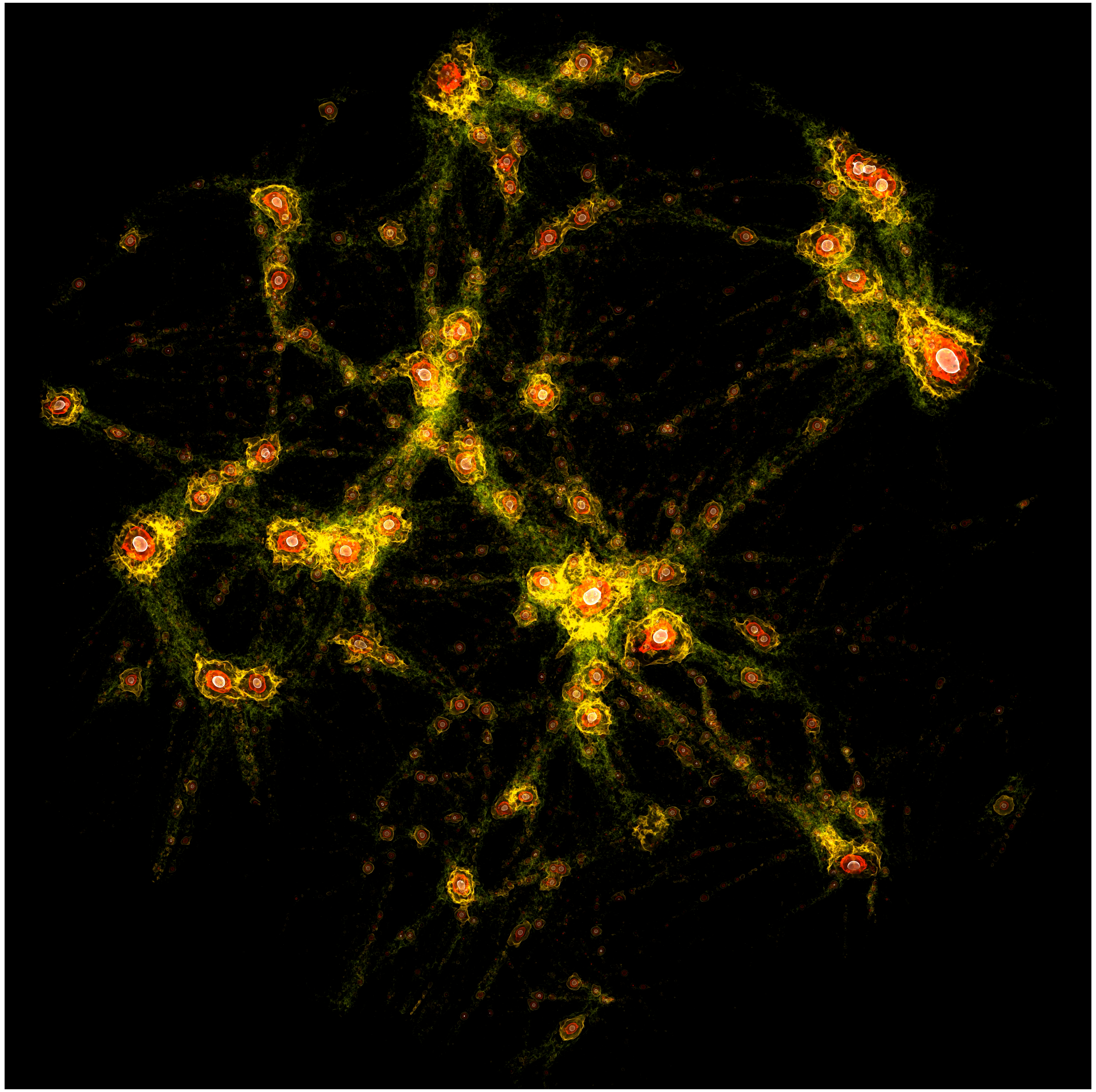
WKB evolve + Schrodinger-Poisson system for linear growth

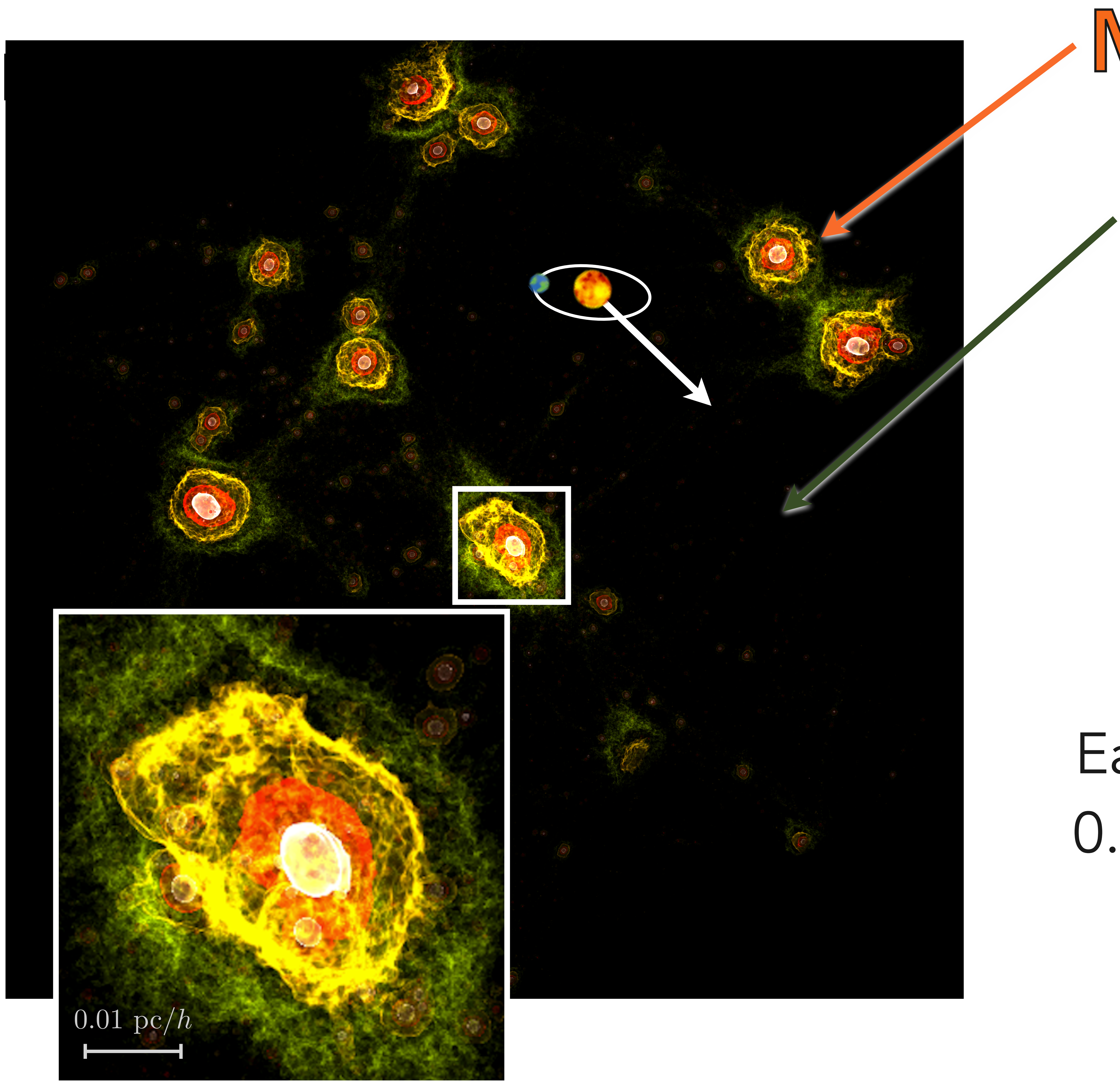
N-body methods for non-linear gravitational collapse

After t_{QCD} axion field forms quasi-stable solitons that lay down small-scale perturbations

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

→ **axion miniclusters**





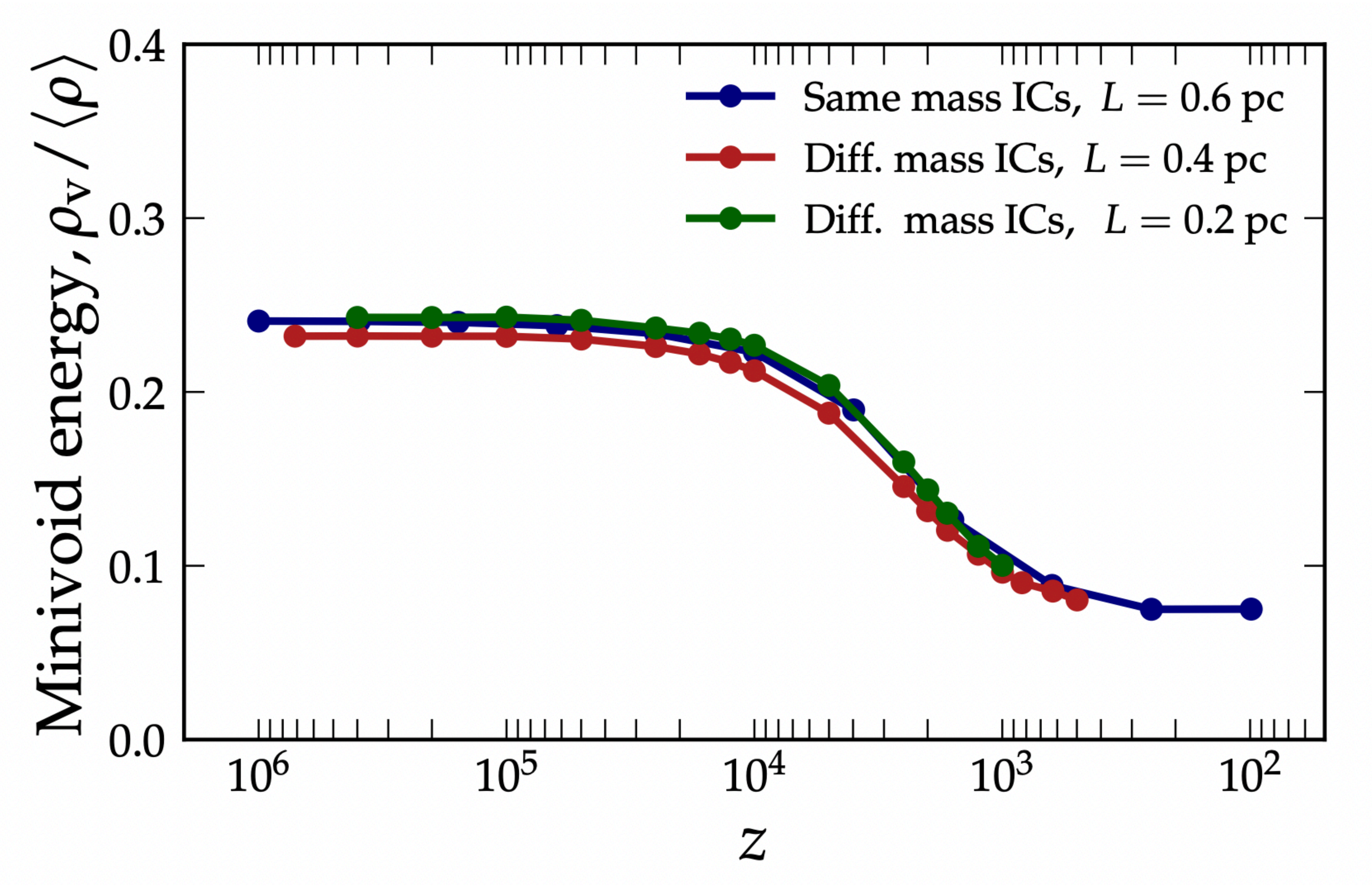
Miniclusters

Minivoids

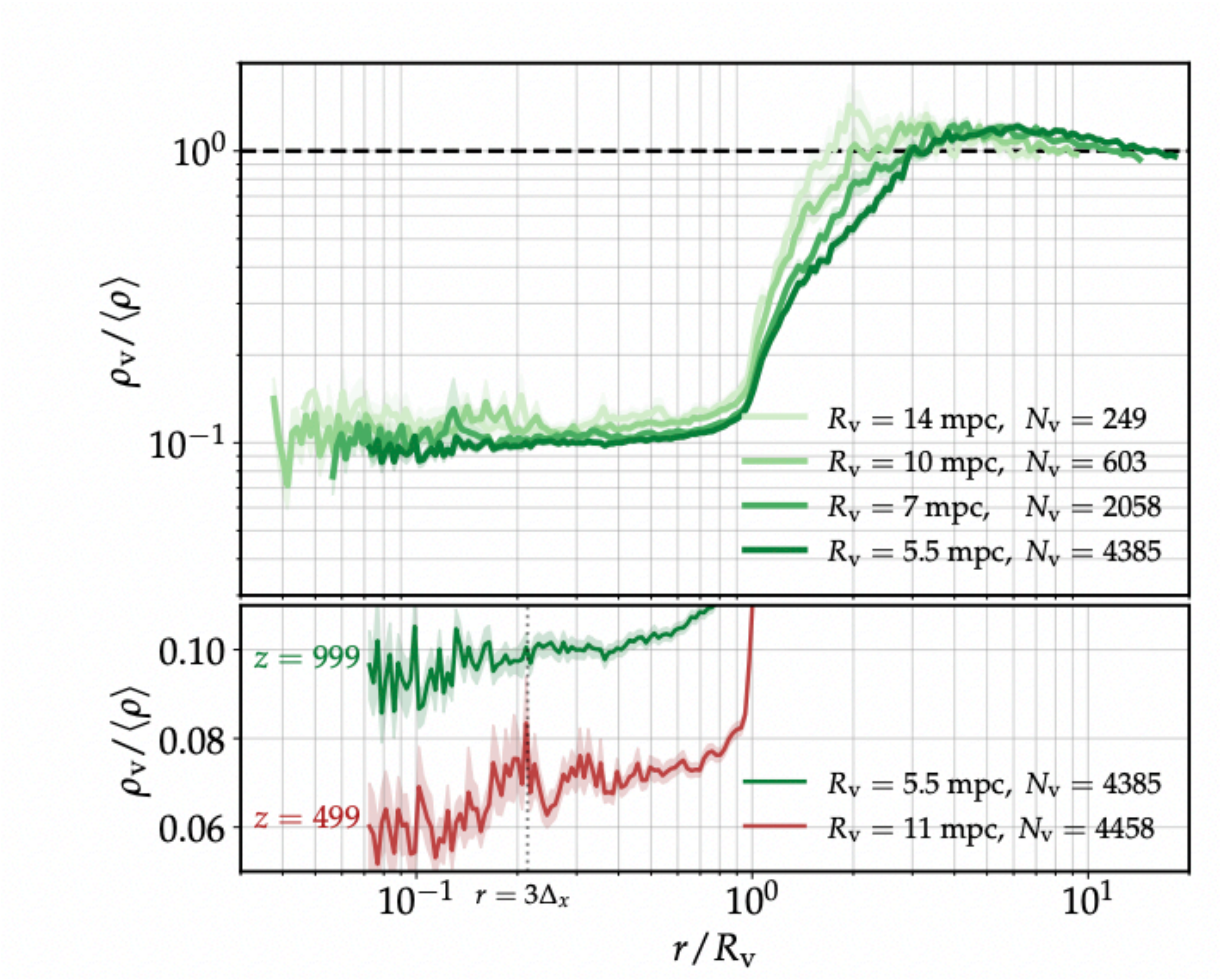
Miniclusters contain >80% of the axions but make up <1% of the volume

Earth travels through galaxy at about 0.2 mpc per year, so experiments are much more likely to sample the mini*voids* than the mini*clusters*

Minivoids are mostly stable by final simulation time (z~100)

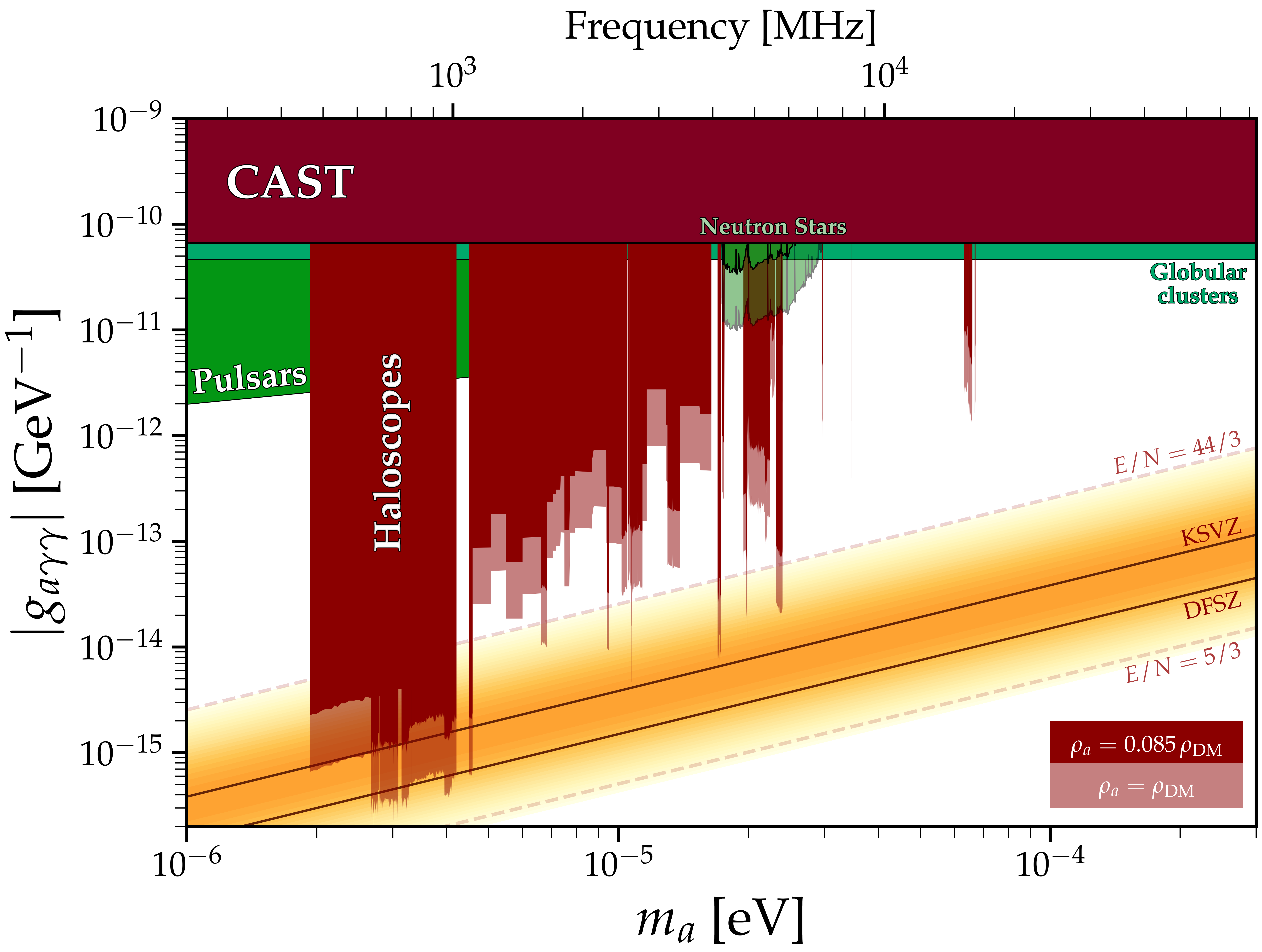


Typical "worst case scenario" density would be inside the minivoids ~10% of large-scale average density



Eggemeier, CAJO+ [2212.00560]

Implications for haloscopes



Eggemeier, CAJO+ [2212.00560]

Typical density in the minivoids is ~0.085 of the mean density of dark matter

→ the miniclusters are no longer growing at the final redshift of the simulation, therefore this places a **lower bound** on the density of axions

→ Not a nice conclusion, but it could have been much worse!

Not the end of the story…

(Results from here quite preliminary)

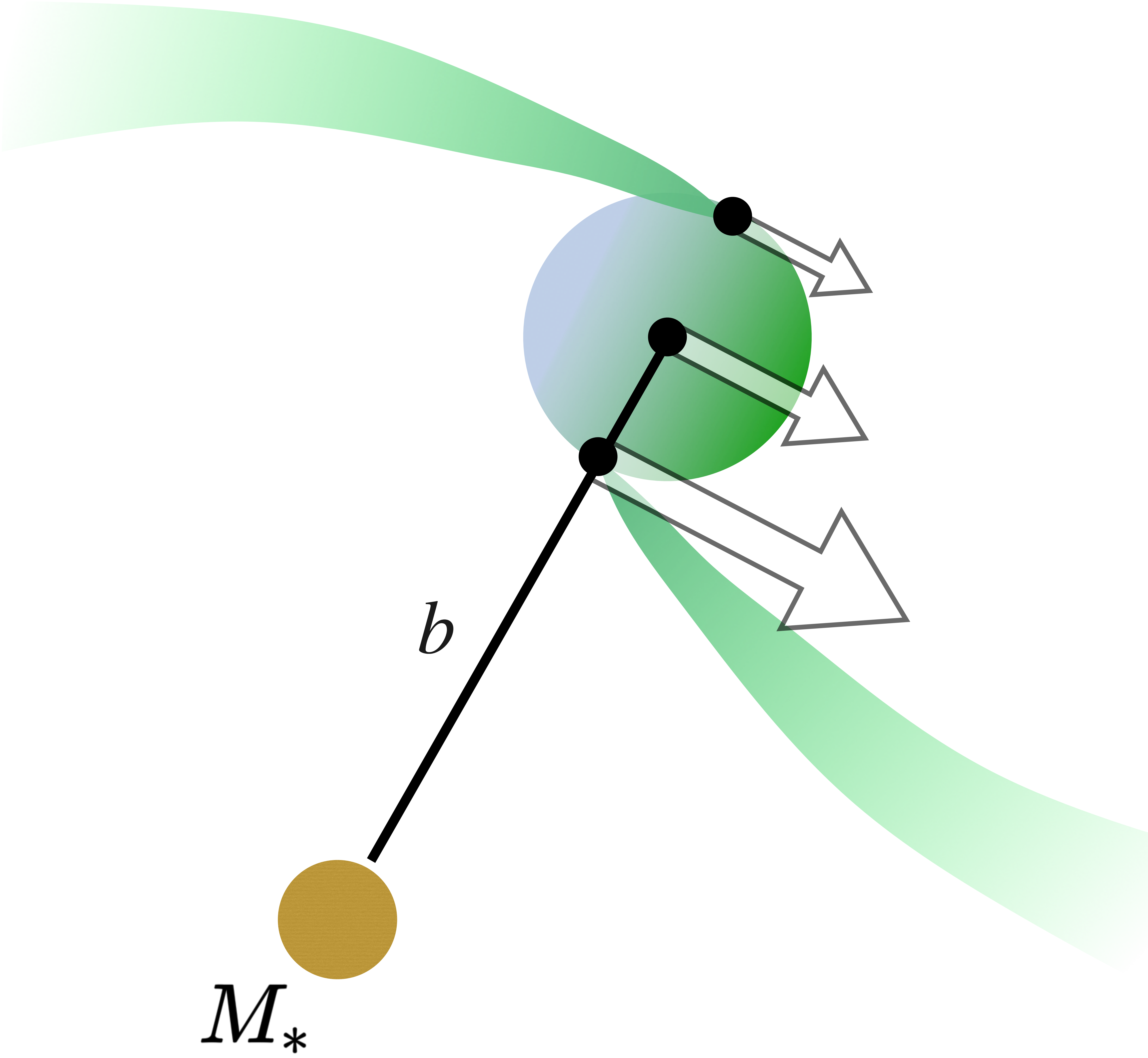
Not the end of the story…

Miniclusters are susceptible to tidal disruption by stars

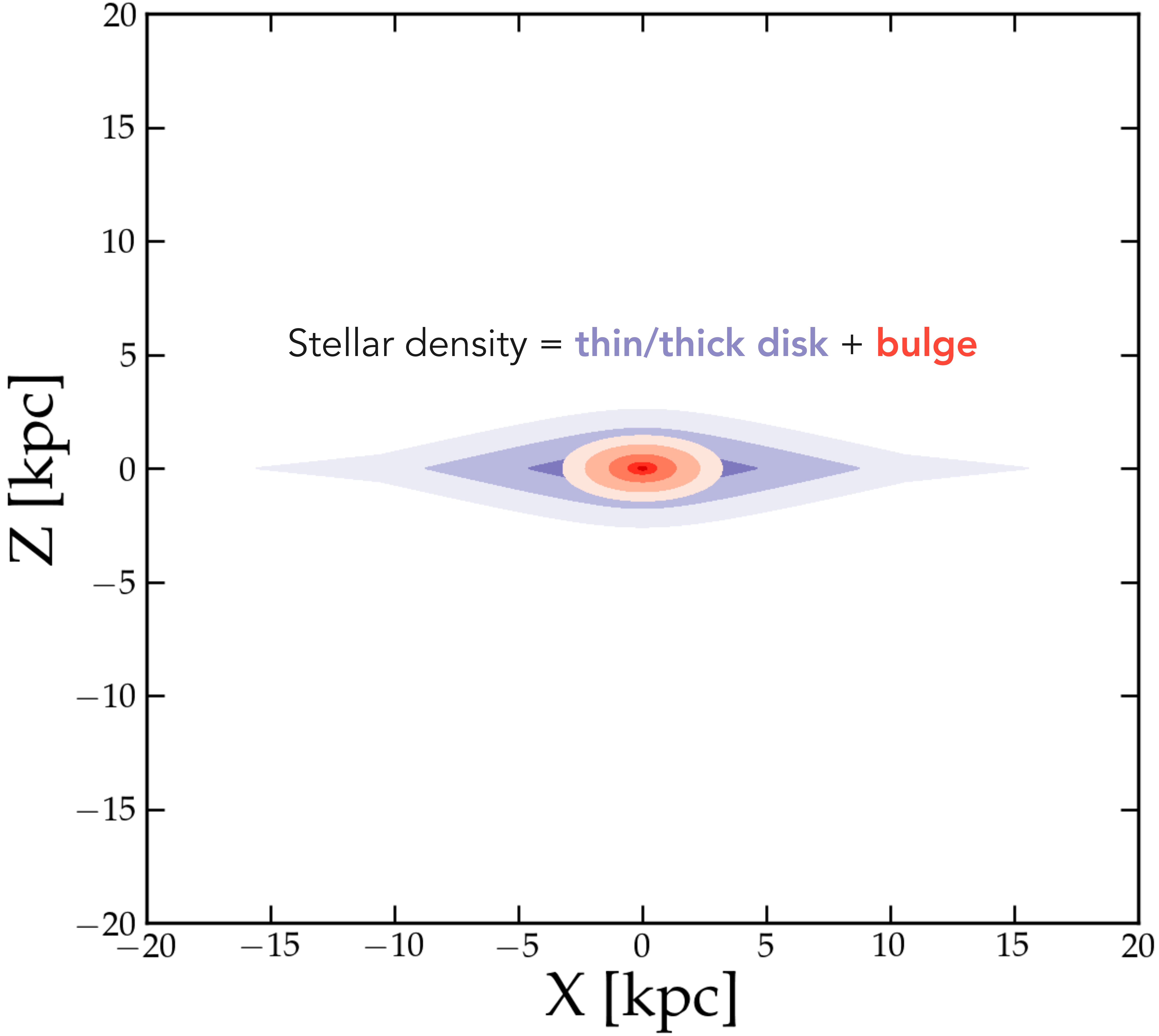
$$\Delta E \simeq \left(\frac{2GM_*}{bv_{\rm rel}}\right)^2 \frac{M_{\rm mc}R_{\rm mc}^2}{3}$$

Energy injected into minicluster

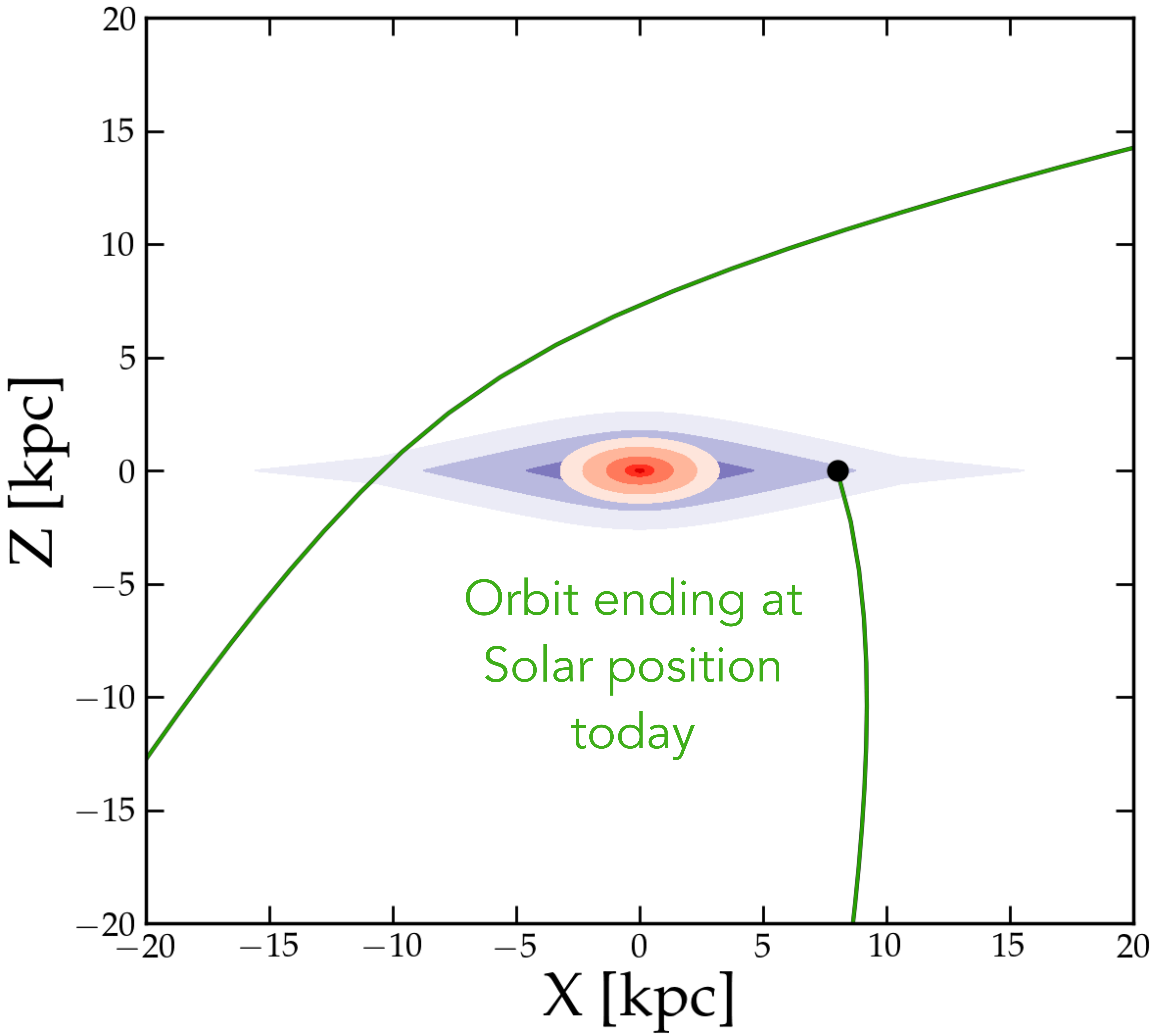
Axions with E>Binding energy will evaporate away → form **tidal stream**



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

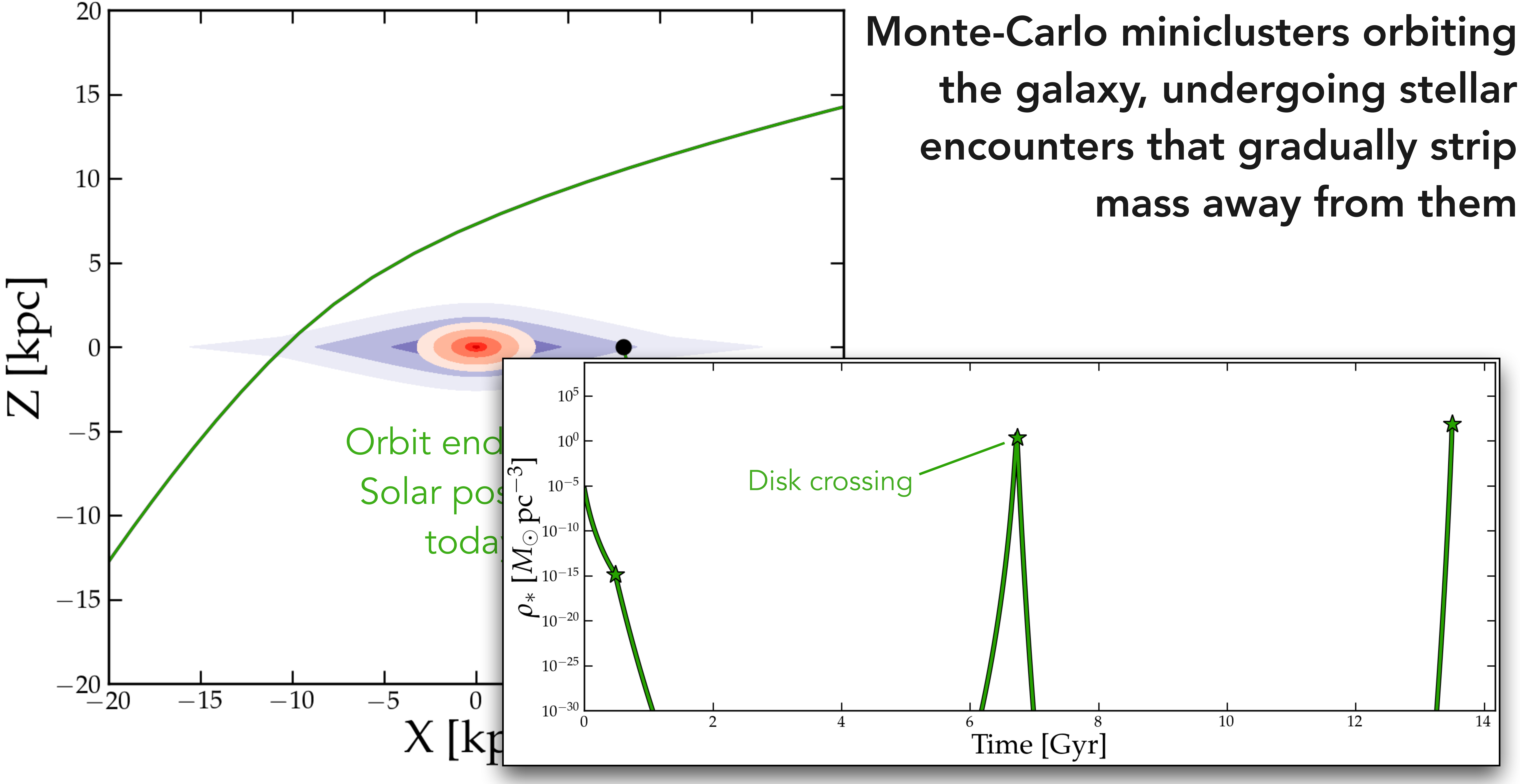


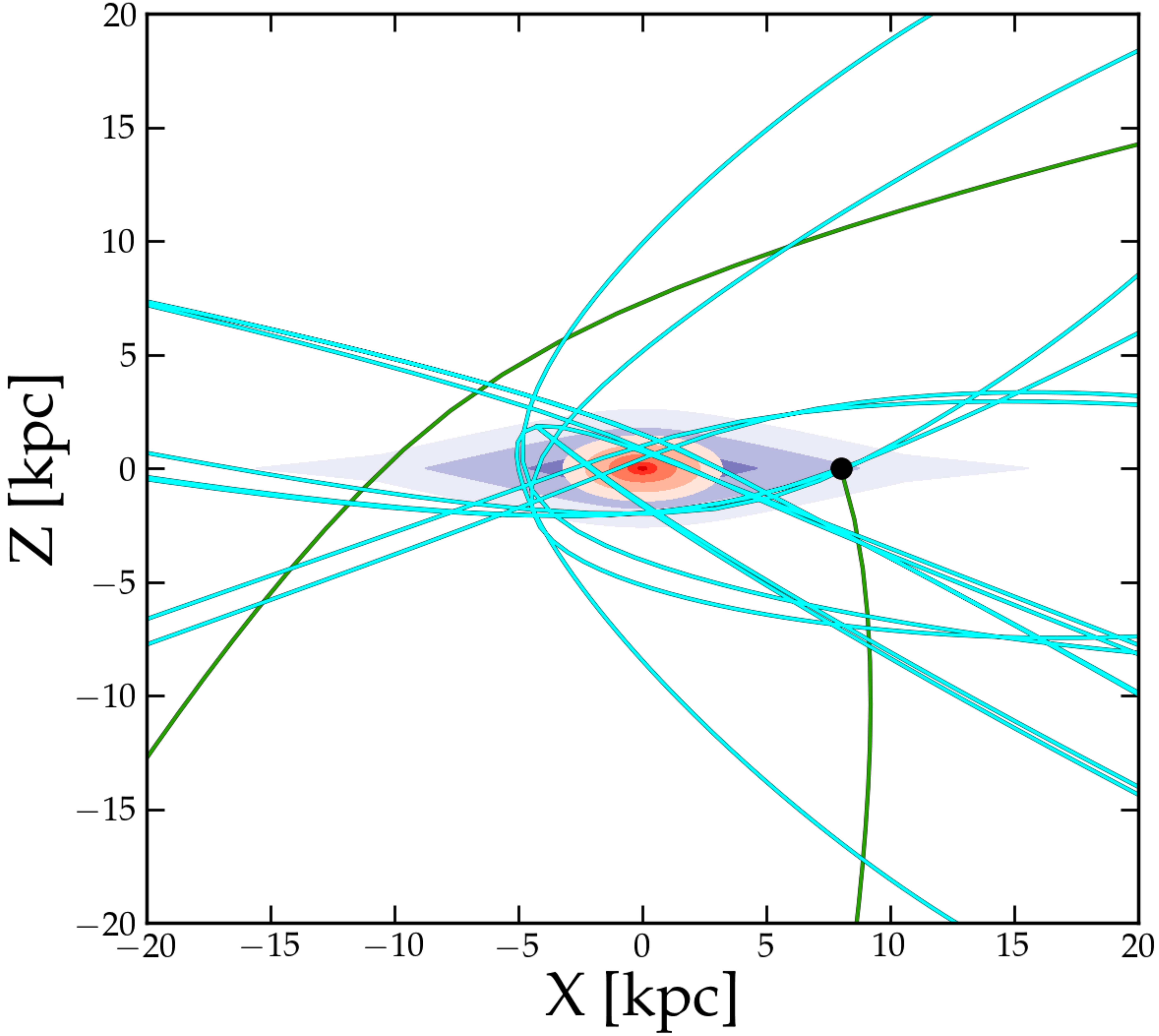
Monte-Carlo miniclusters orbiting the galaxy, undergoing stellar encounters that gradually strip mass away from them



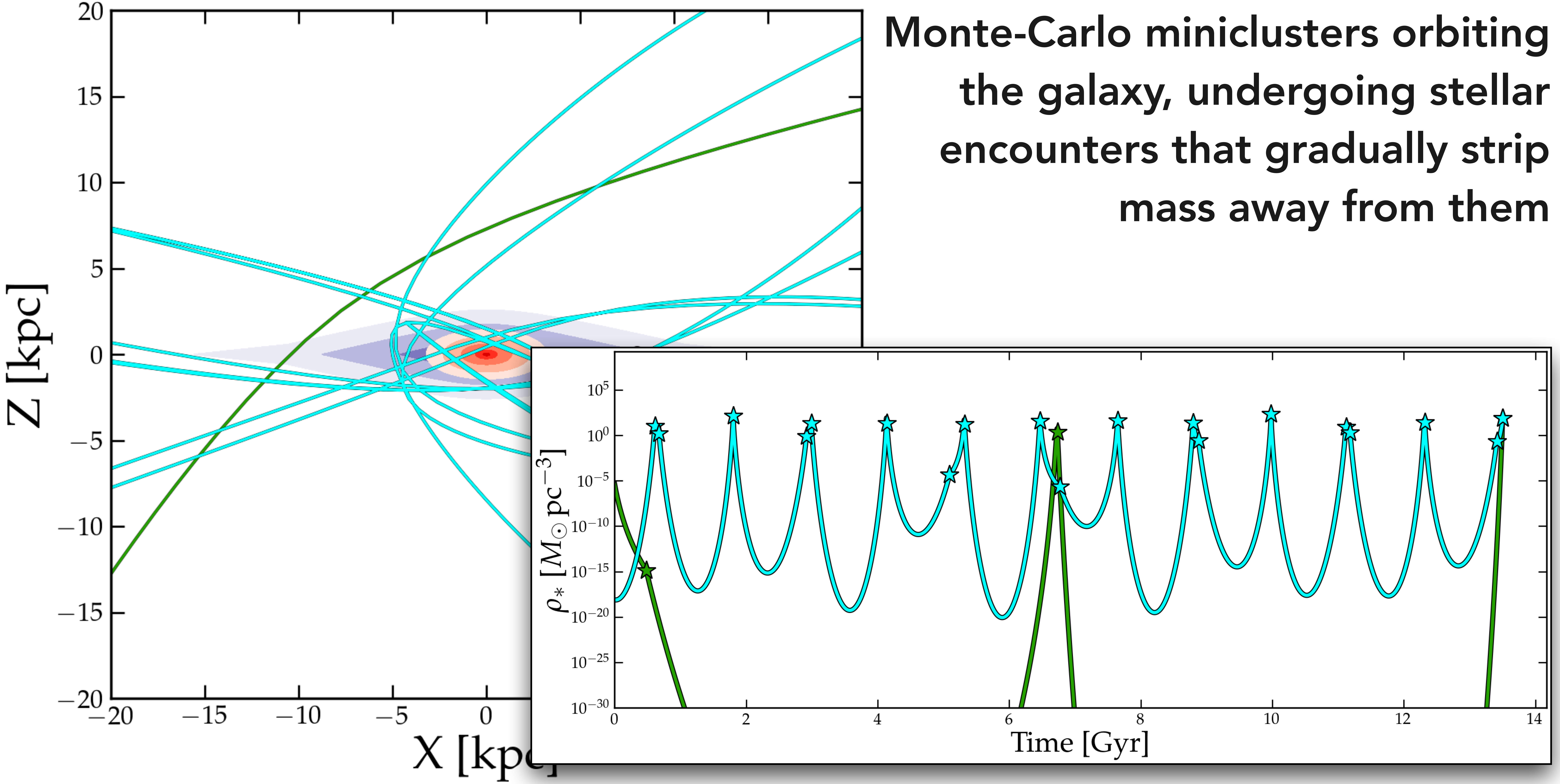
Monte-Carlo miniclusters orbiting the galaxy, undergoing stellar encounters that gradually strip mass away from them

Monte-Carlo miniclusters orbiting the galaxy, undergoing stellar encounters that gradually strip mass away from them



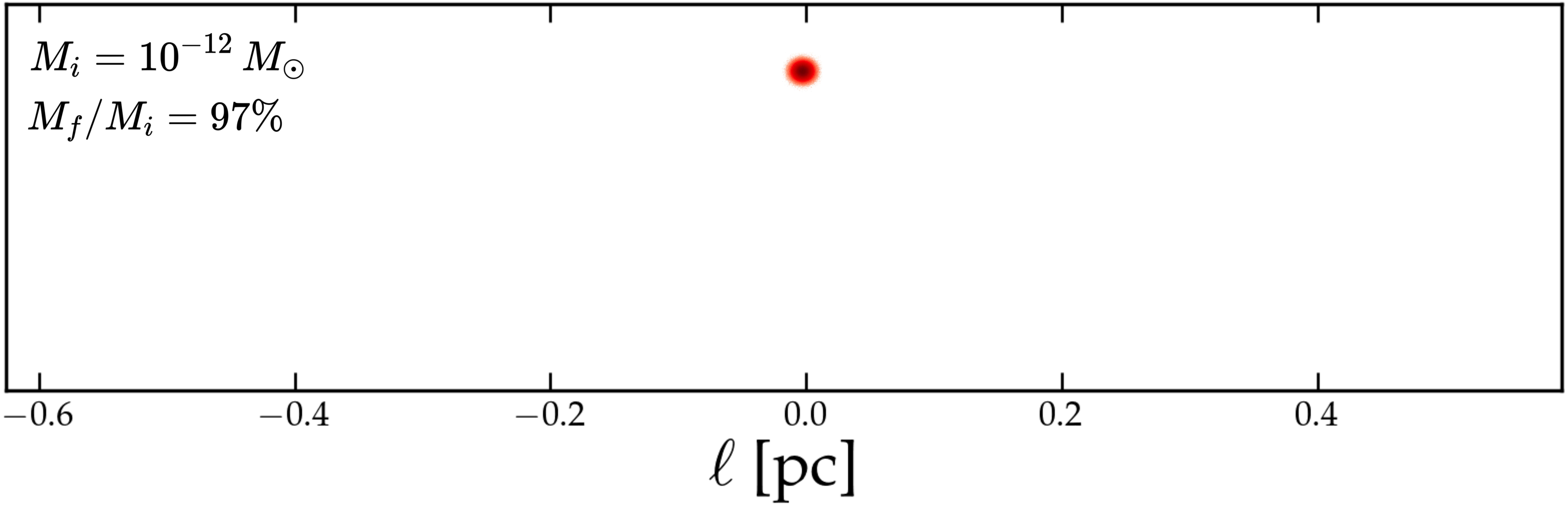


Monte-Carlo miniclusters orbiting the galaxy, undergoing stellar encounters that gradually strip mass away from them



Monte-Carlo miniclusters orbiting the galaxy, undergoing stellar encounters that gradually strip mass away from them

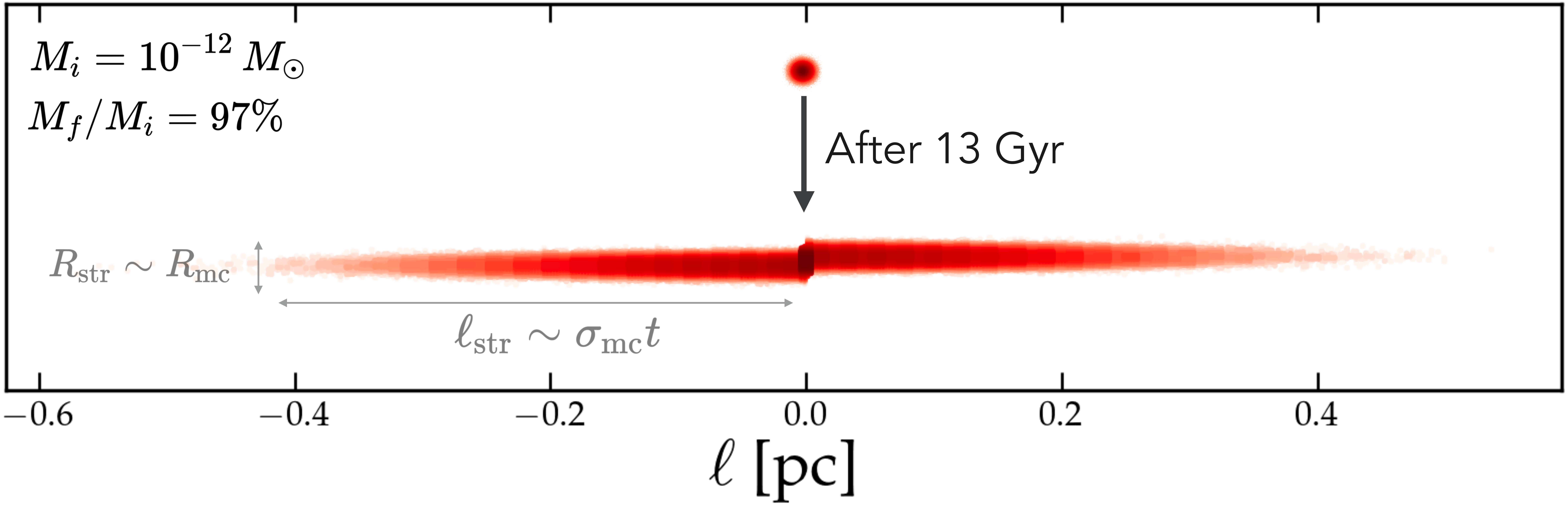
Tidal stream formation



At solar position, most miniclusters are not 100% disrupted.

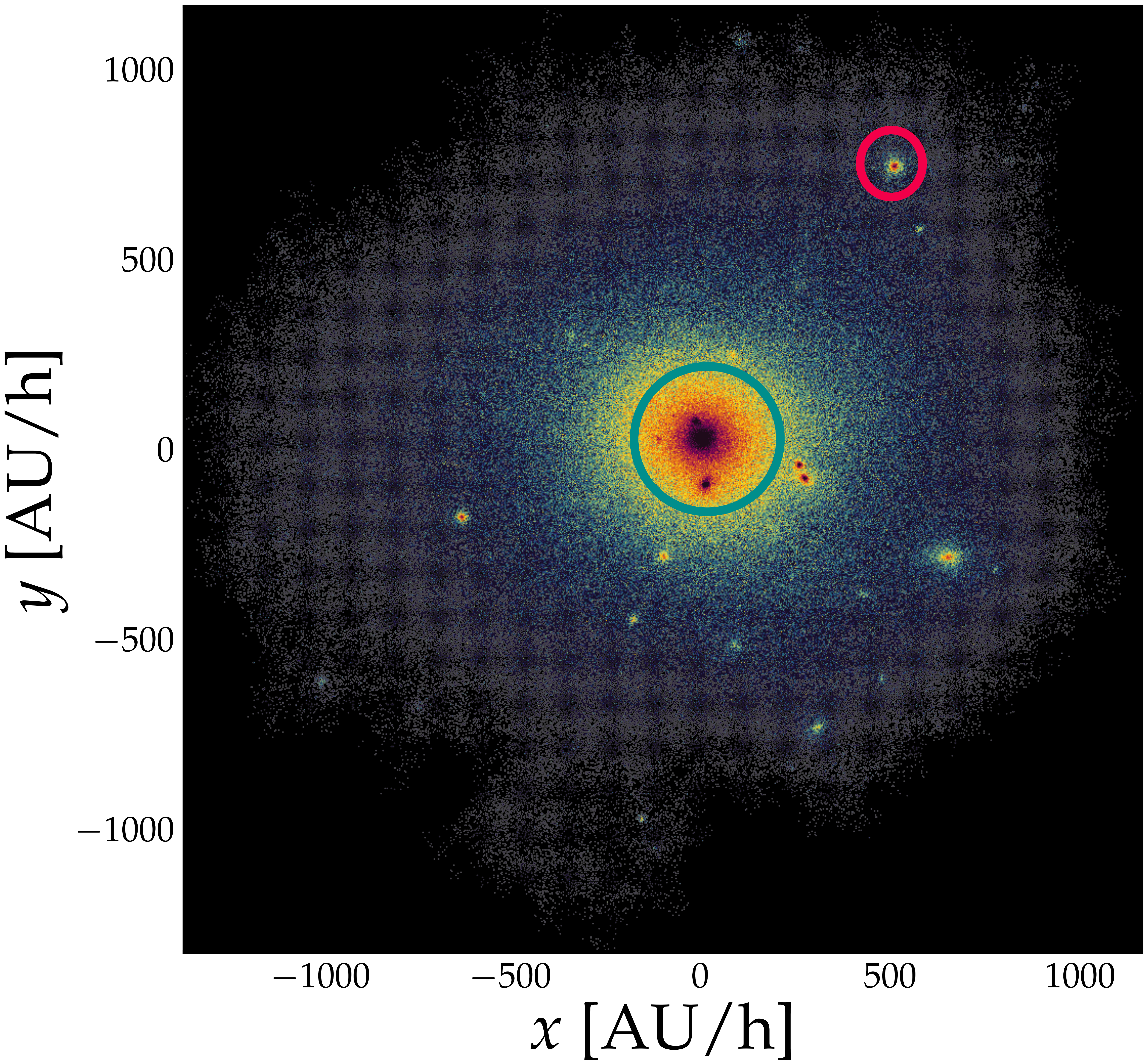
However, a sizeable amount will turn into ~pc-long tidal streams

Tidal stream formation



At solar position, most miniclusters are not 100% disrupted.
However, a sizeable amount will turn into ~pc-long tidal streams

Different populations of miniclusters



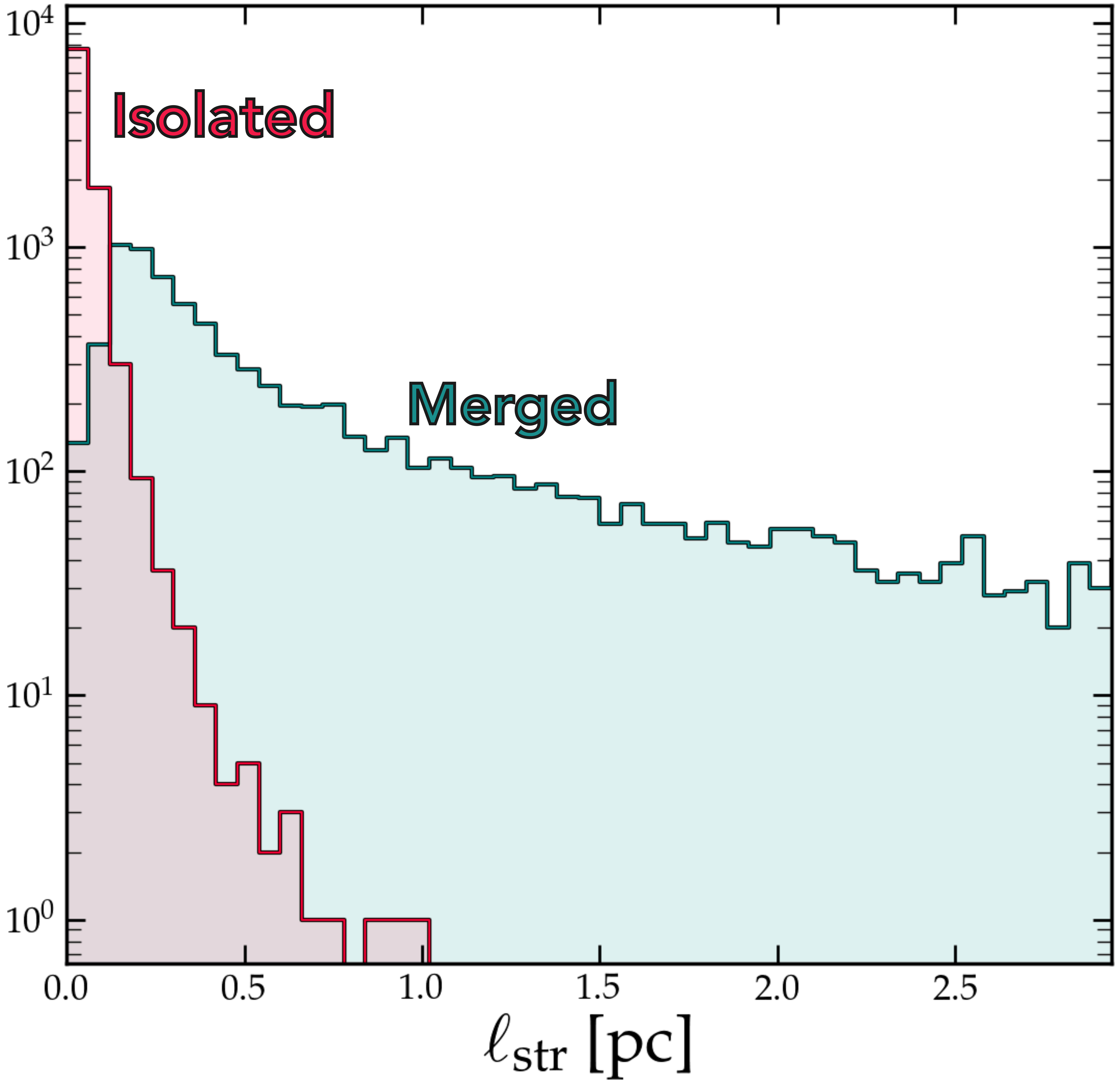
Isolated

→ About 70% of MCs by number
→ Masses $M \in [10^{-16}, 10^{-12}]\, M_\odot$
→ Form from prompt collapse
→ Power law density profiles $\rho \sim r^{-2.71}$
→ ~0% are *fully* disrupted

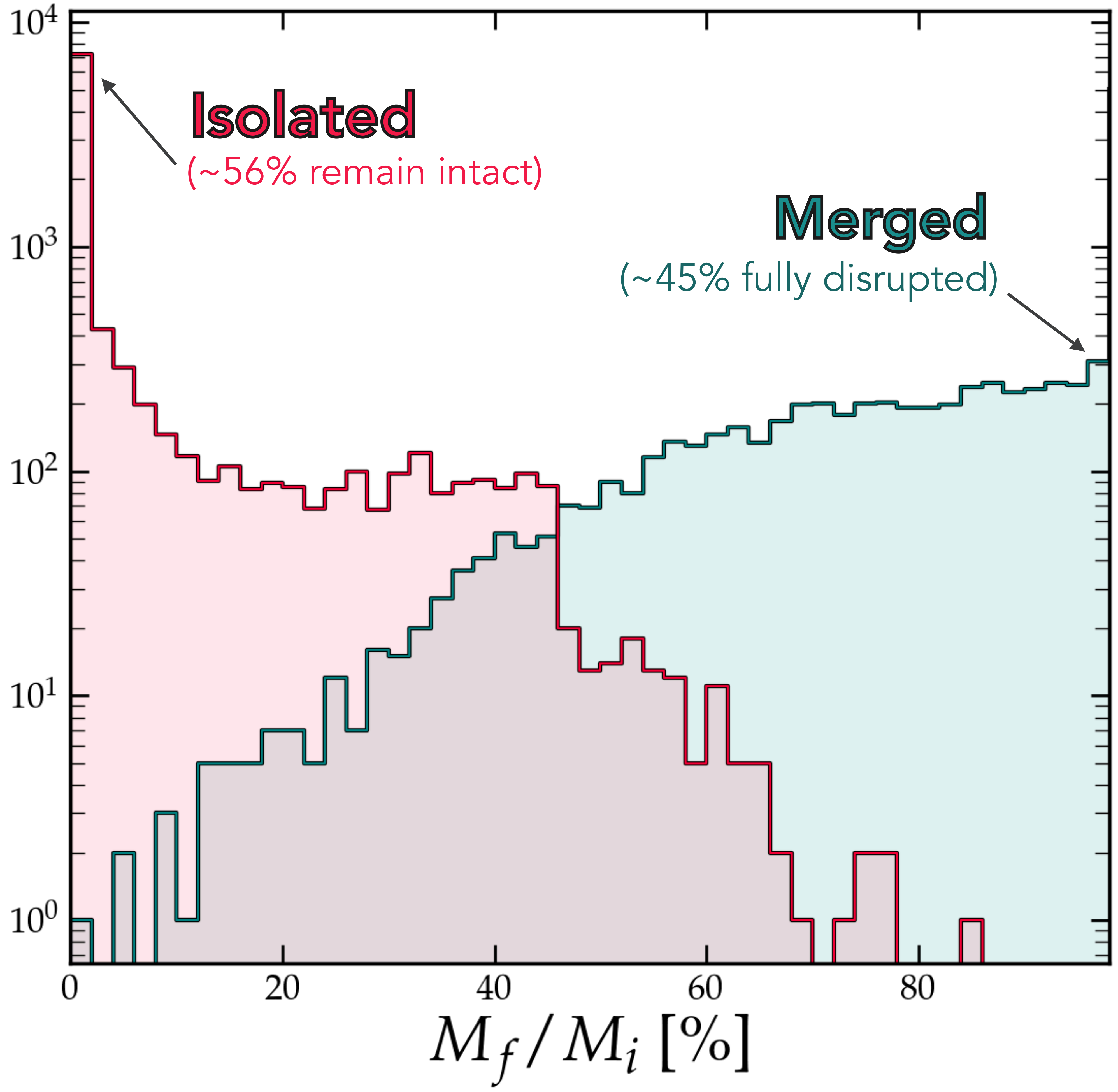
Merged

→ About 30% of MCs by number
→ Masses $M \in [10^{-12}, 10^{-7}]\, M_\odot$
→ Form from mergers of MCs
→ NFW density profile
→ 45% are *fully* disrupted

Average stream length



Fraction of mass lost



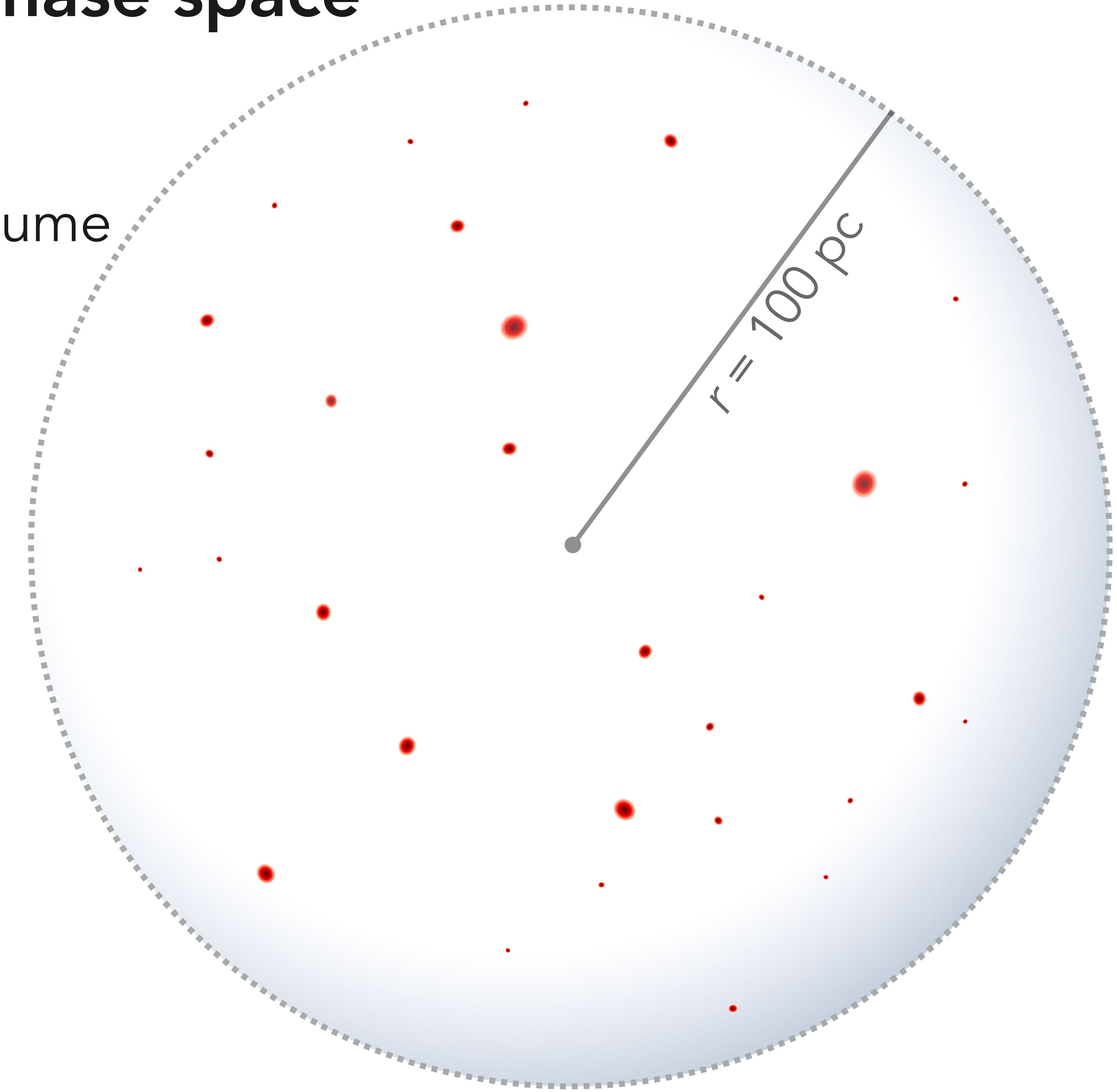
(~56% remain intact)

(~45% fully disrupted)

Tidally stripped MCs refill the phase space

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

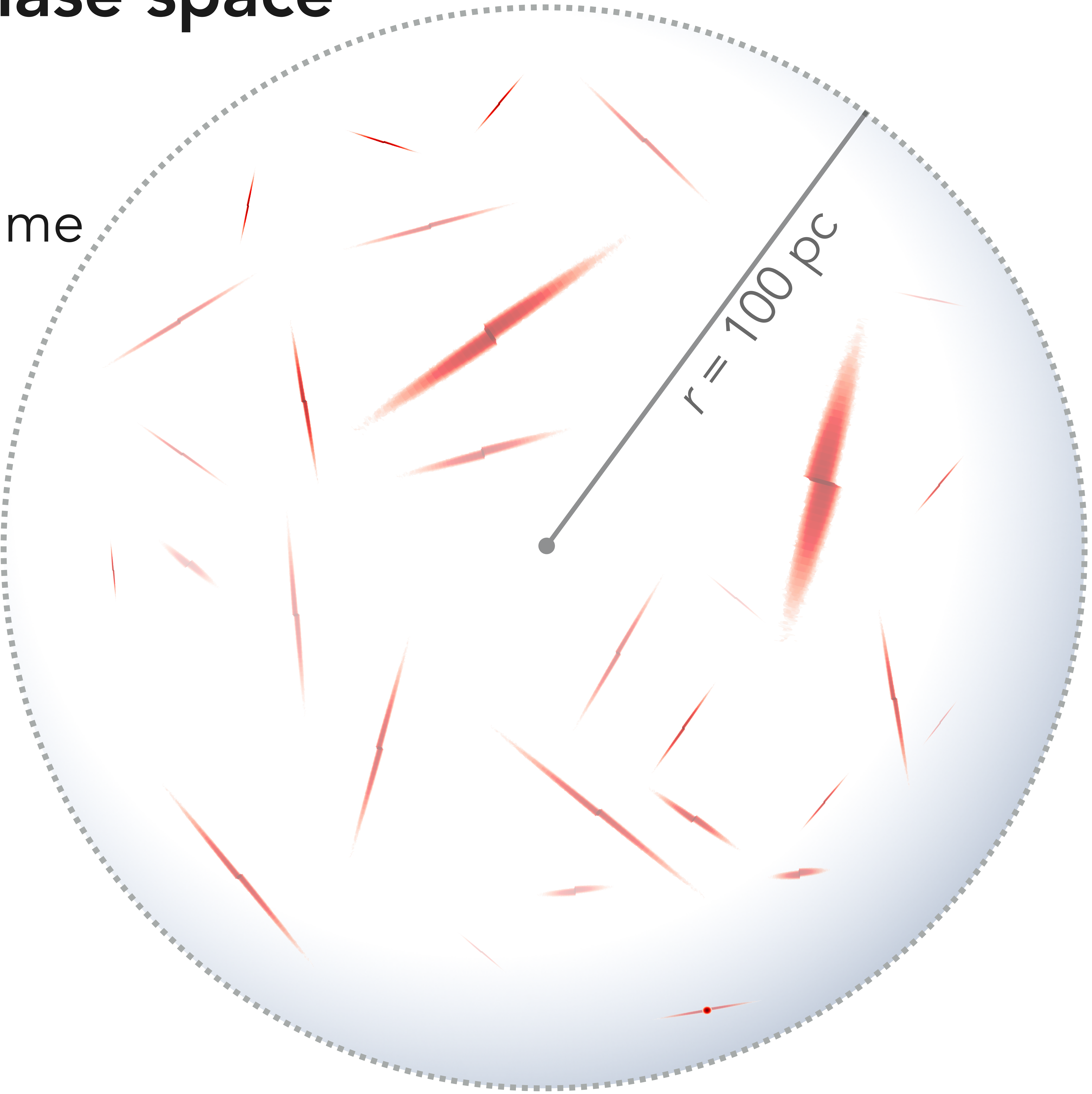
→ Must be $\sim 10^{14}$ miniclusters in that volume



Tidally stripped MCs refill the phase space

We measure ρ_{DM} on scales ~100 pc
→ Must be $\sim 10^{14}$ miniclusters in that volume

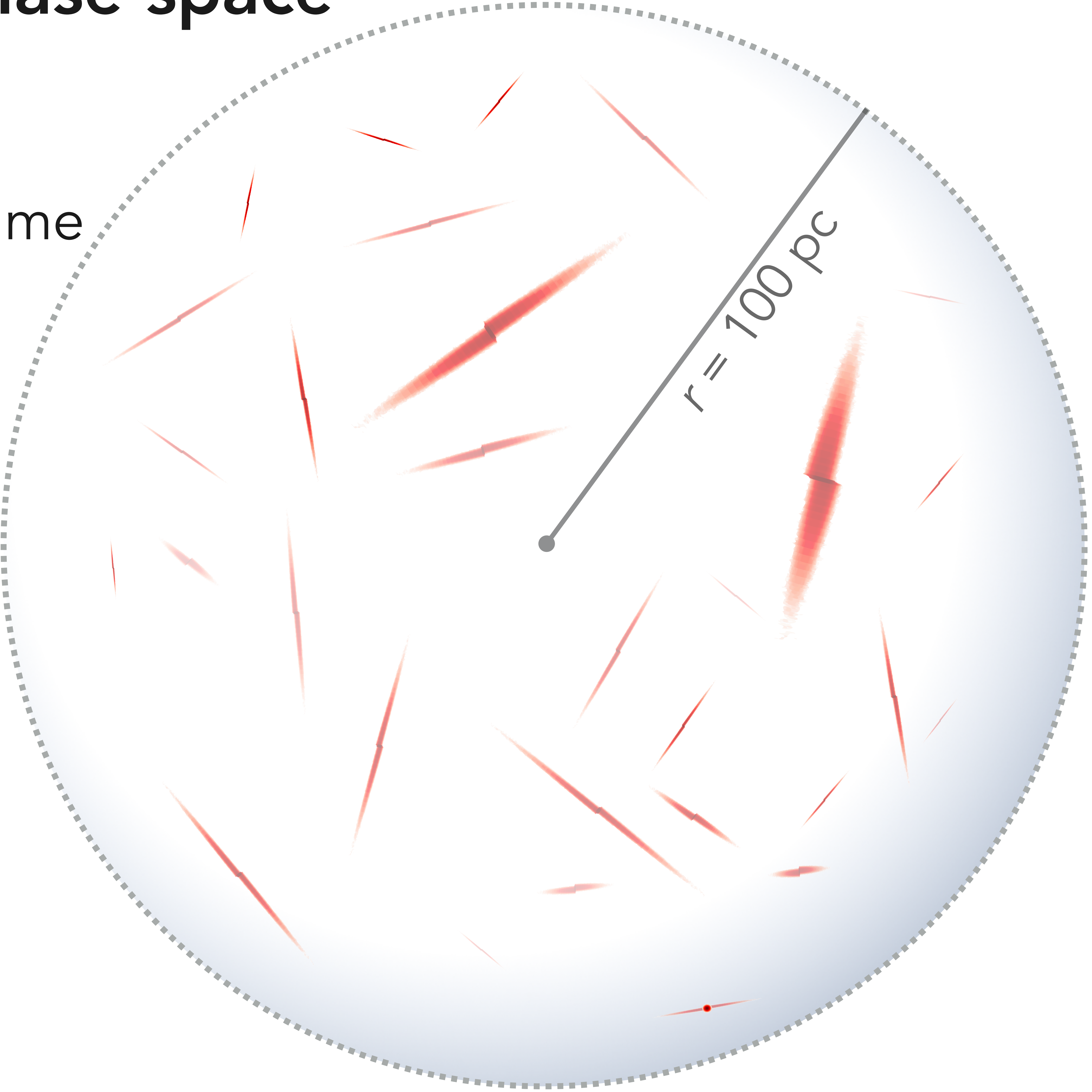
After disruption, MCs turn into extended ~pc-long streams. Volume filled with axions is enhanced by a factor of $\sim 10^{6}$



Tidally stripped MCs refill the phase space

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

→ Must be $\sim 10^{14}$ miniclusters in that volume



After disruption, MCs turn into extended ~pc-long streams. Volume filled with axions is enhanced by a factor of $\sim 10^6$

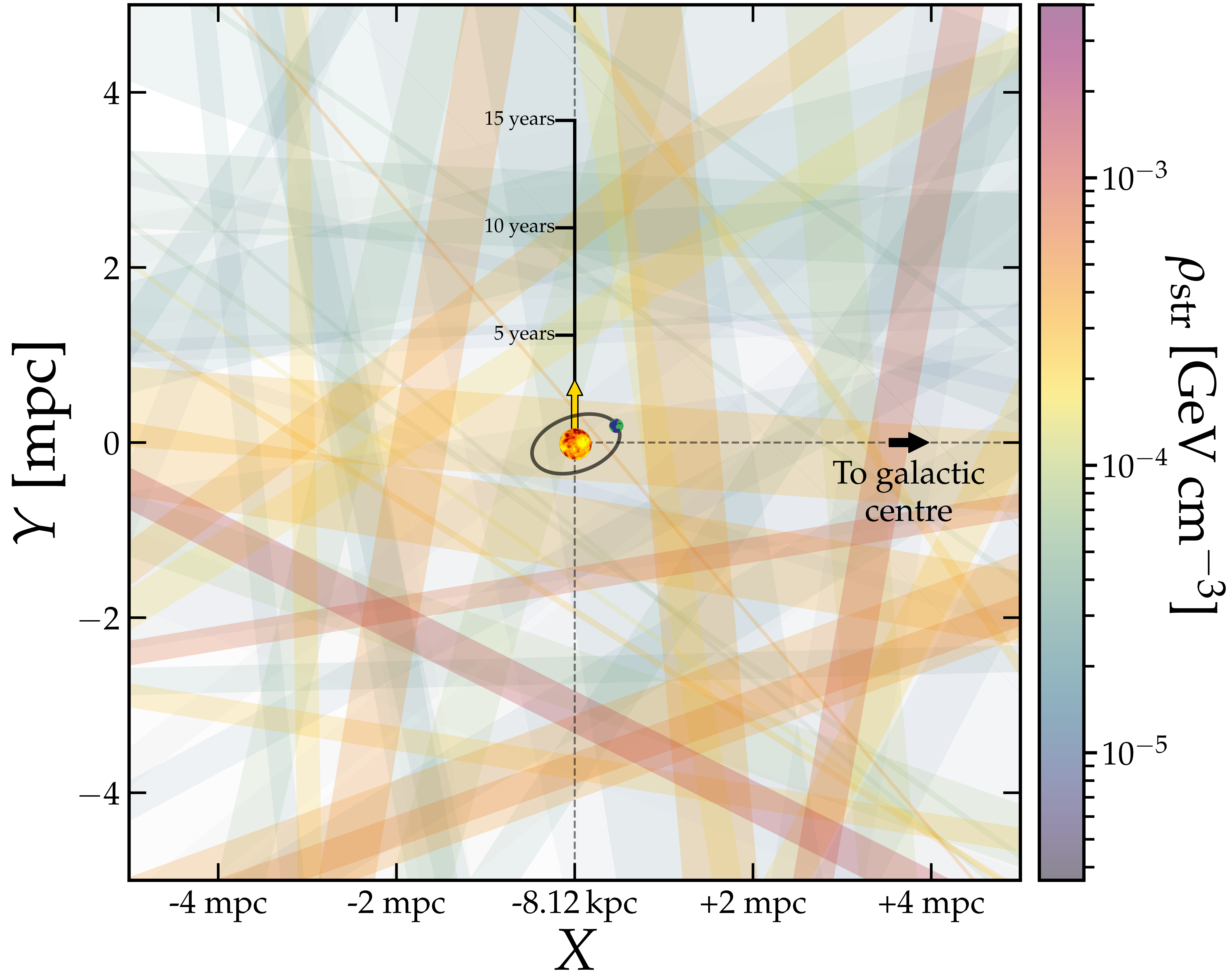
Q: How many streams overlap at a given position in the box?

Q: How much is the density enhanced due to the re-filling of phase space

Axion streams at the Solar position

Answer: typically there are O(1000) tidal streams overlapping a given position. Vast majority do not contribute substantially to the density

Only ~100 streams plotted for clarity



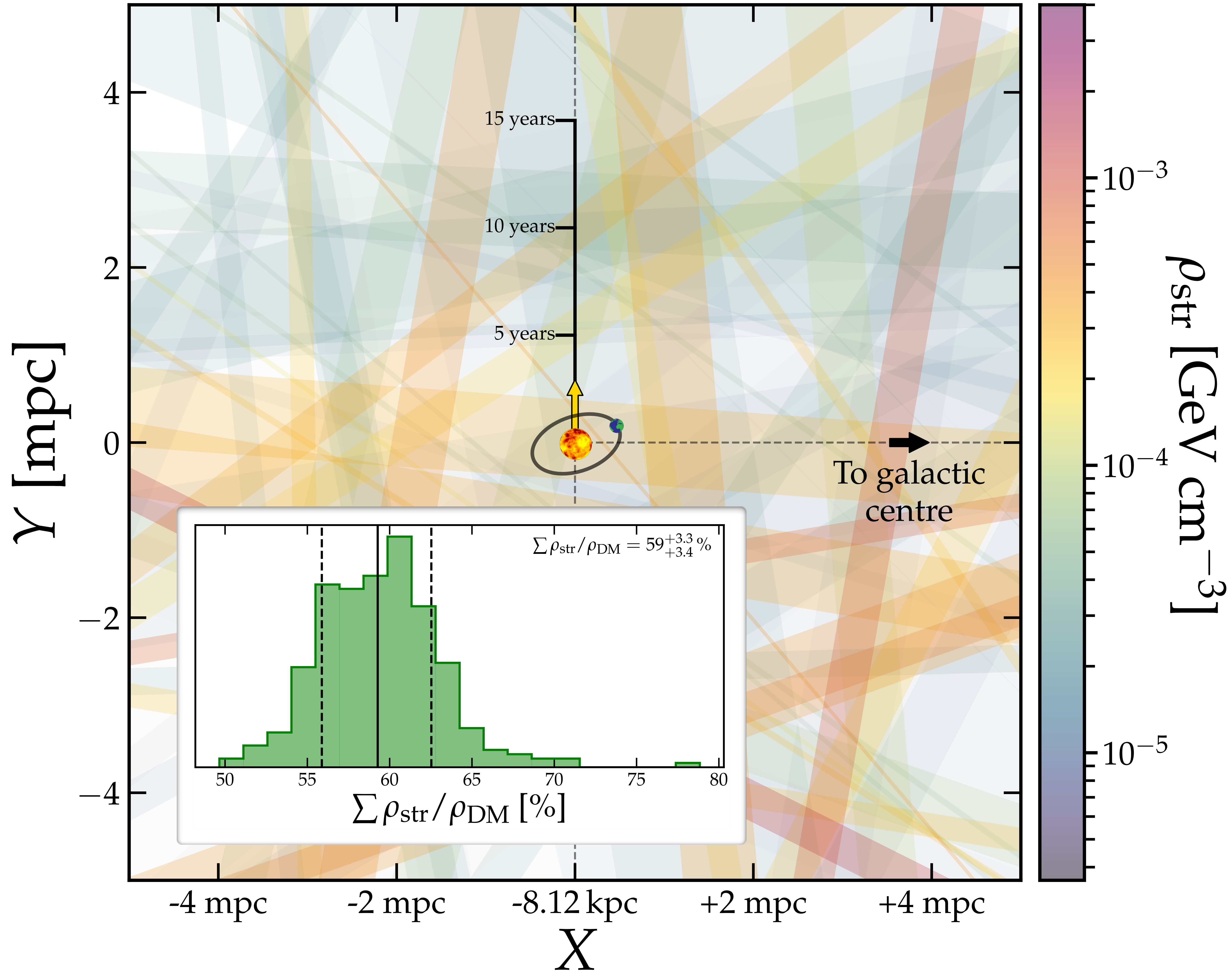
Axion streams at the Solar position

Answer: typically there are O(1000) tidal streams overlapping a given position. Vast majority do not contribute substantially to the density

Together they add up to ~60% of large-scale measured value of $\rho_{\rm DM}$

Small probability ~1% of being in an overdense region with $\rho > \rho_{\rm DM}$

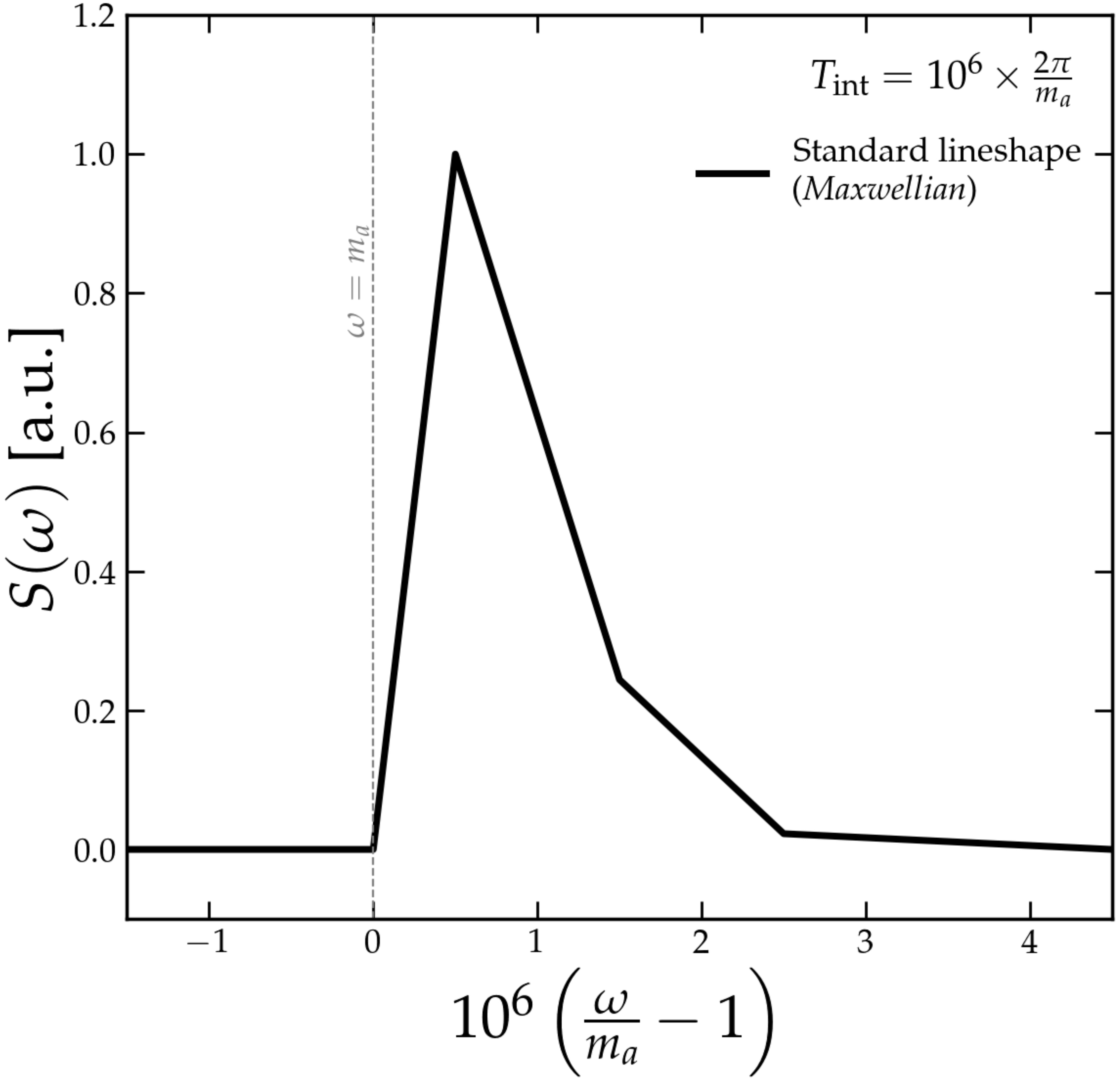
Only ~100 streams plotted for clarity



Haloscope signal

The axion power spectrum signal will have a distinct Maxwellian **lineshape**. Frequency resolution depends on the duration of the timestream samples that are put through a discrete Fourier transform in order to calculate that power spectrum

Signal $S(\omega) \propto$ discrete FT of timestream
Frequency resolution = $\Delta\omega \sim T_{\rm int}^{-1}$

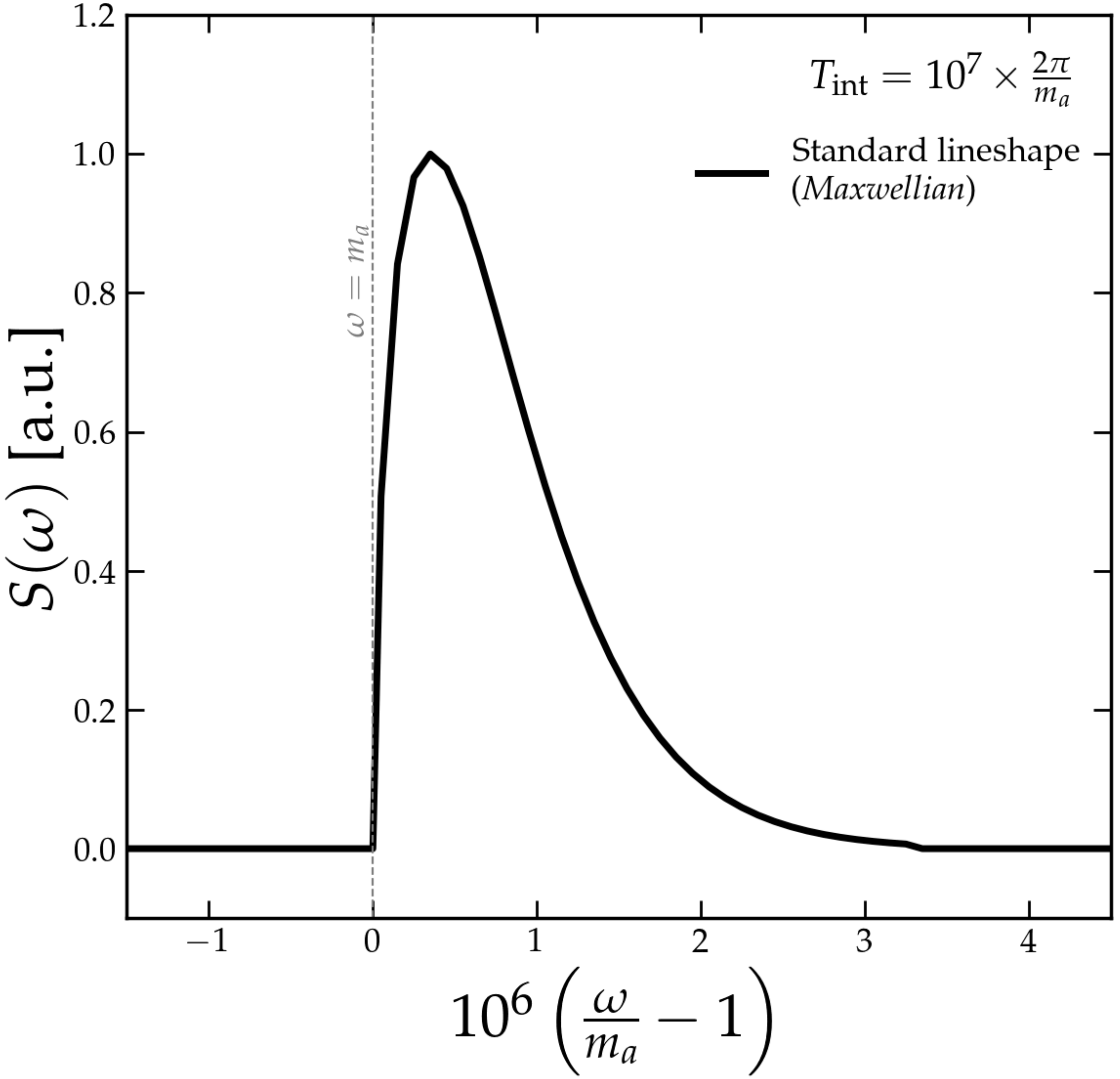


Haloscope signal

The axion power spectrum signal will have a distinct Maxwellian **lineshape**. Frequency resolution depends on the duration of the timestream samples that are put through a discrete Fourier transform in order to calculate that power spectrum

Signal $S(\omega) \propto$ discrete FT of timestream

Frequency resolution = $\Delta\omega \sim T_{\text{int}}^{-1}$

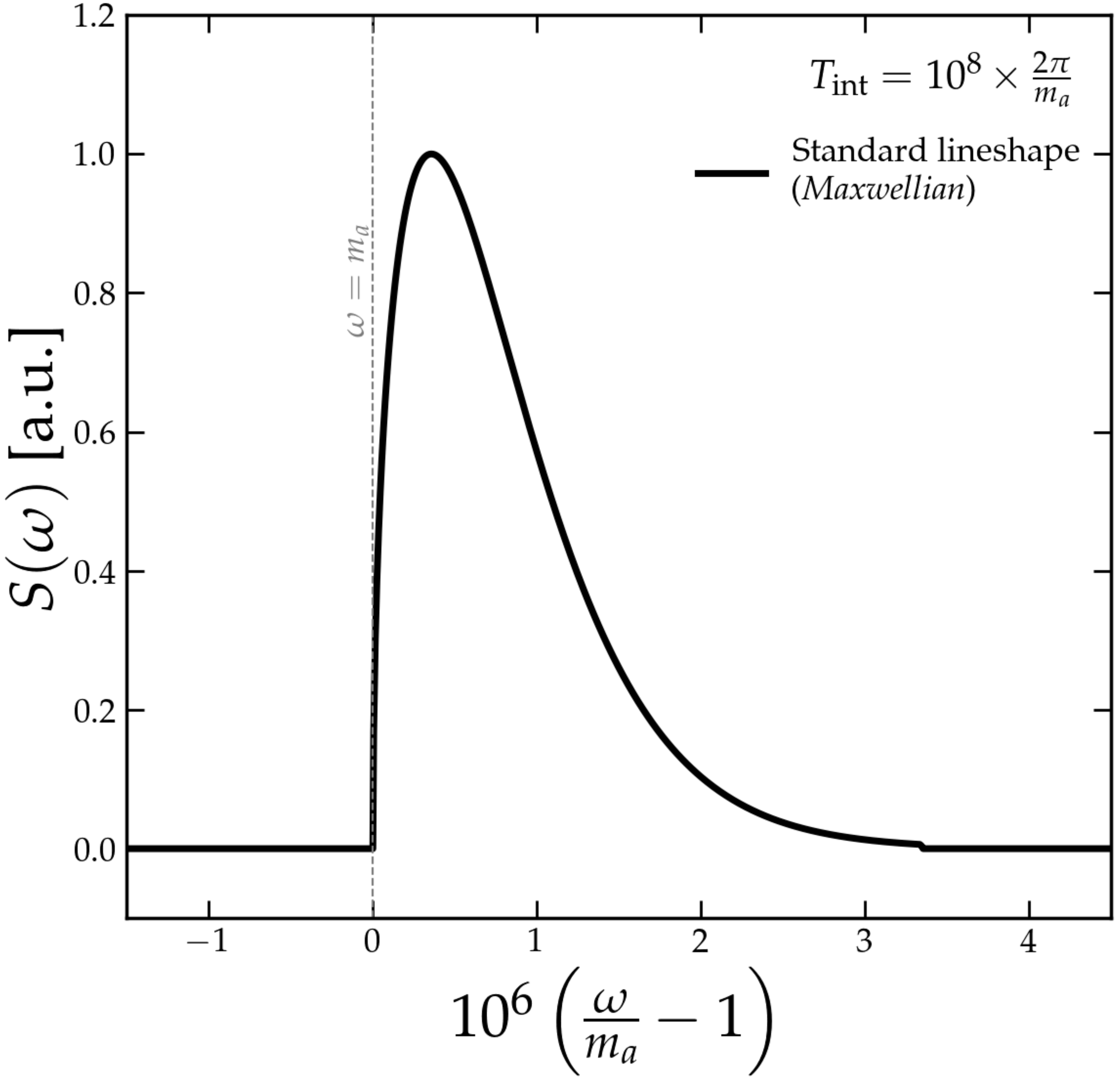


Haloscope signal

The axion power spectrum signal will have a distinct Maxwellian **lineshape**. Frequency resolution depends on the duration of the timestream samples that are put through a discrete Fourier transform in order to calculate that power spectrum

Signal $S(\omega) \propto$ discrete FT of timestream

Frequency resolution = $\Delta\omega \sim T_{\rm int}^{-1}$

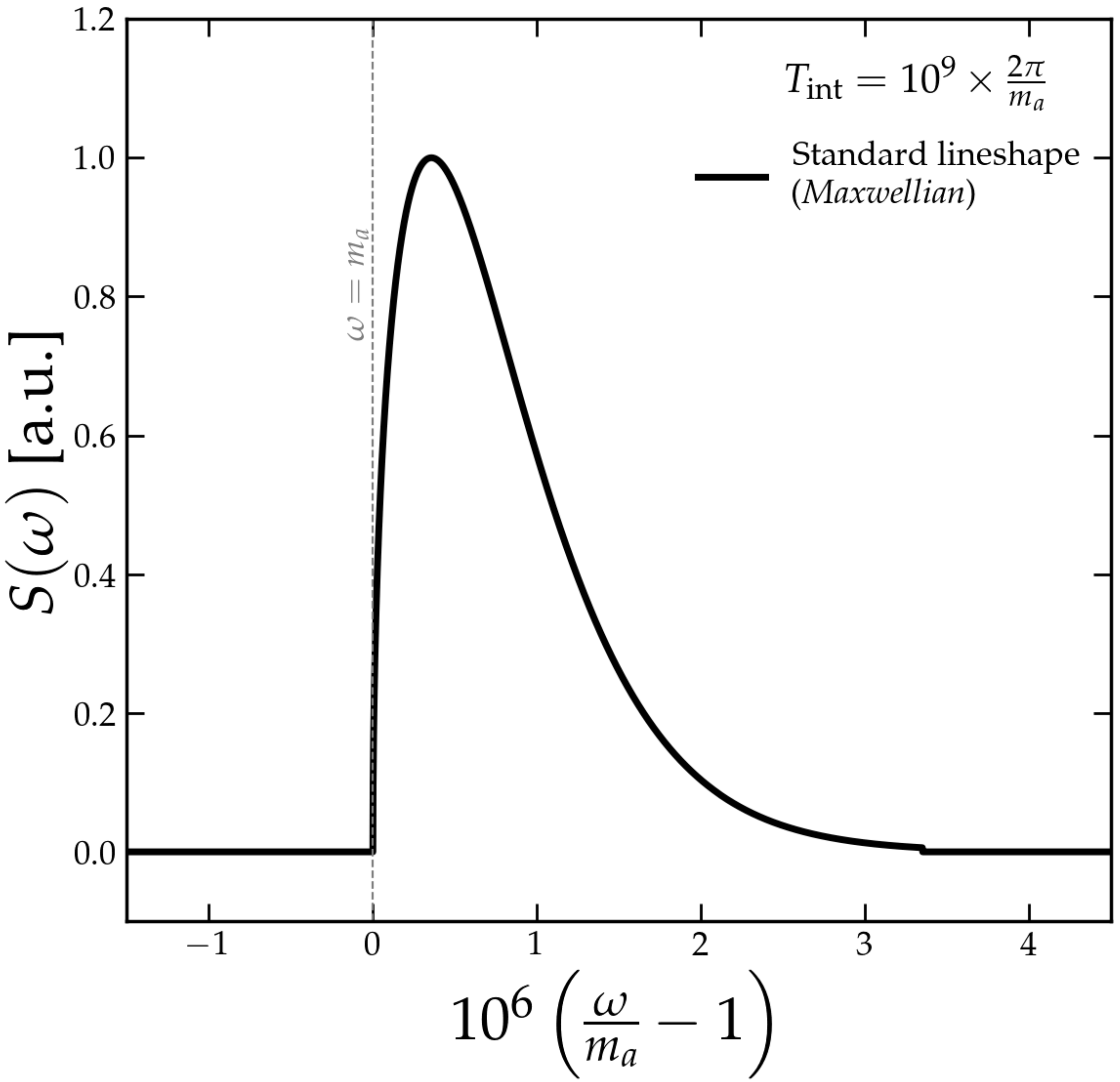


Haloscope signal

The axion power spectrum signal will have a distinct Maxwellian **lineshape**. Frequency resolution depends on the duration of the timestream samples that are put through a discrete Fourier transform in order to calculate that power spectrum

Signal $S(\omega) \propto$ discrete FT of timestream

Frequency resolution = $\Delta\omega \sim T_{\rm int}^{-1}$

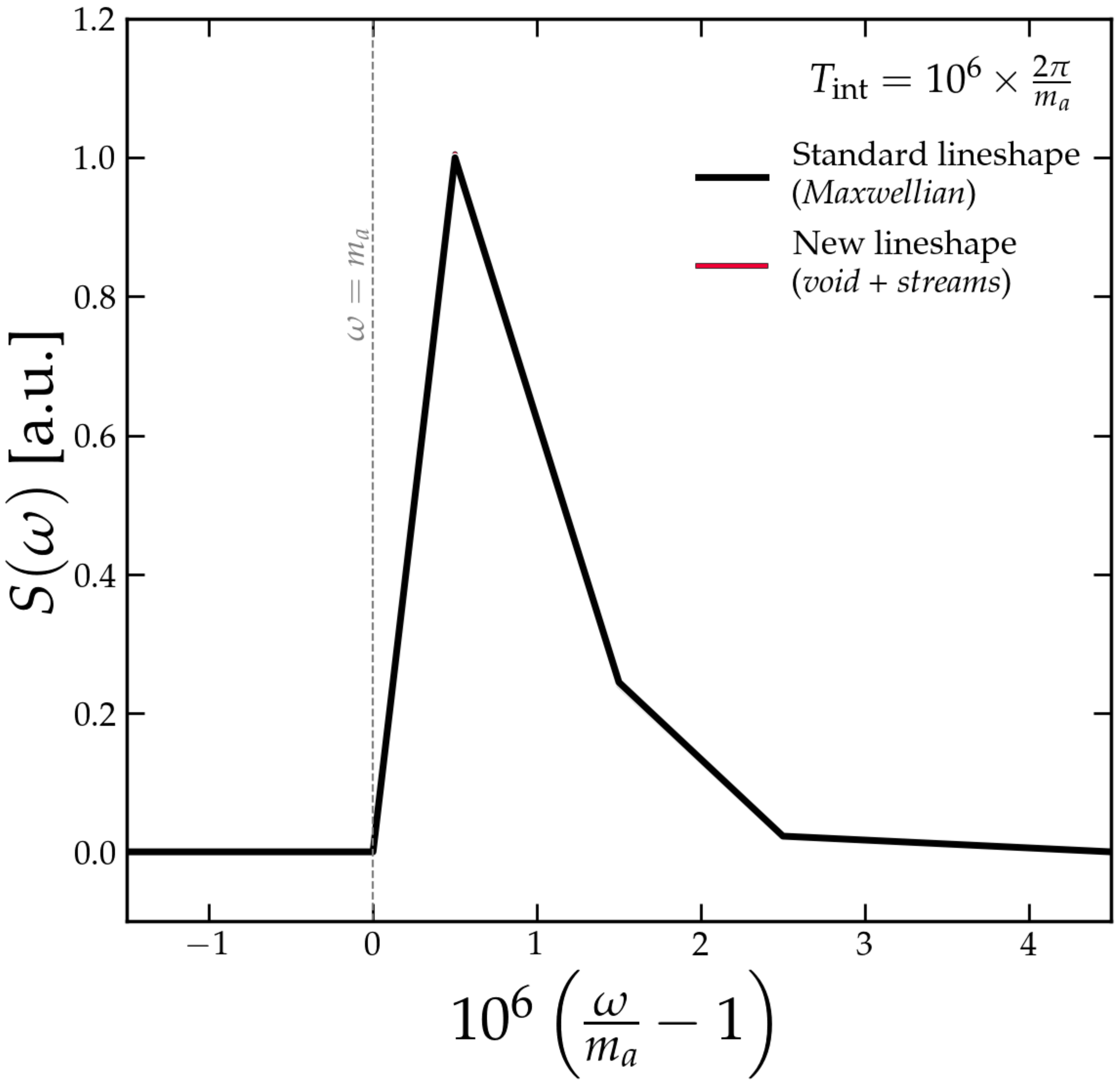


Haloscope signal

Disrupted minicluster **streams** are extremely cold ($\sigma < 1$ km/s) and do not contribute a significant density enhancement. However they become extremely prominent if lineshape is sufficiently well-resolved (long integration times)

Signal $S(\omega) \propto$ discrete FT of timestream

Frequency resolution = $\Delta\omega \sim T_{\rm int}^{-1}$

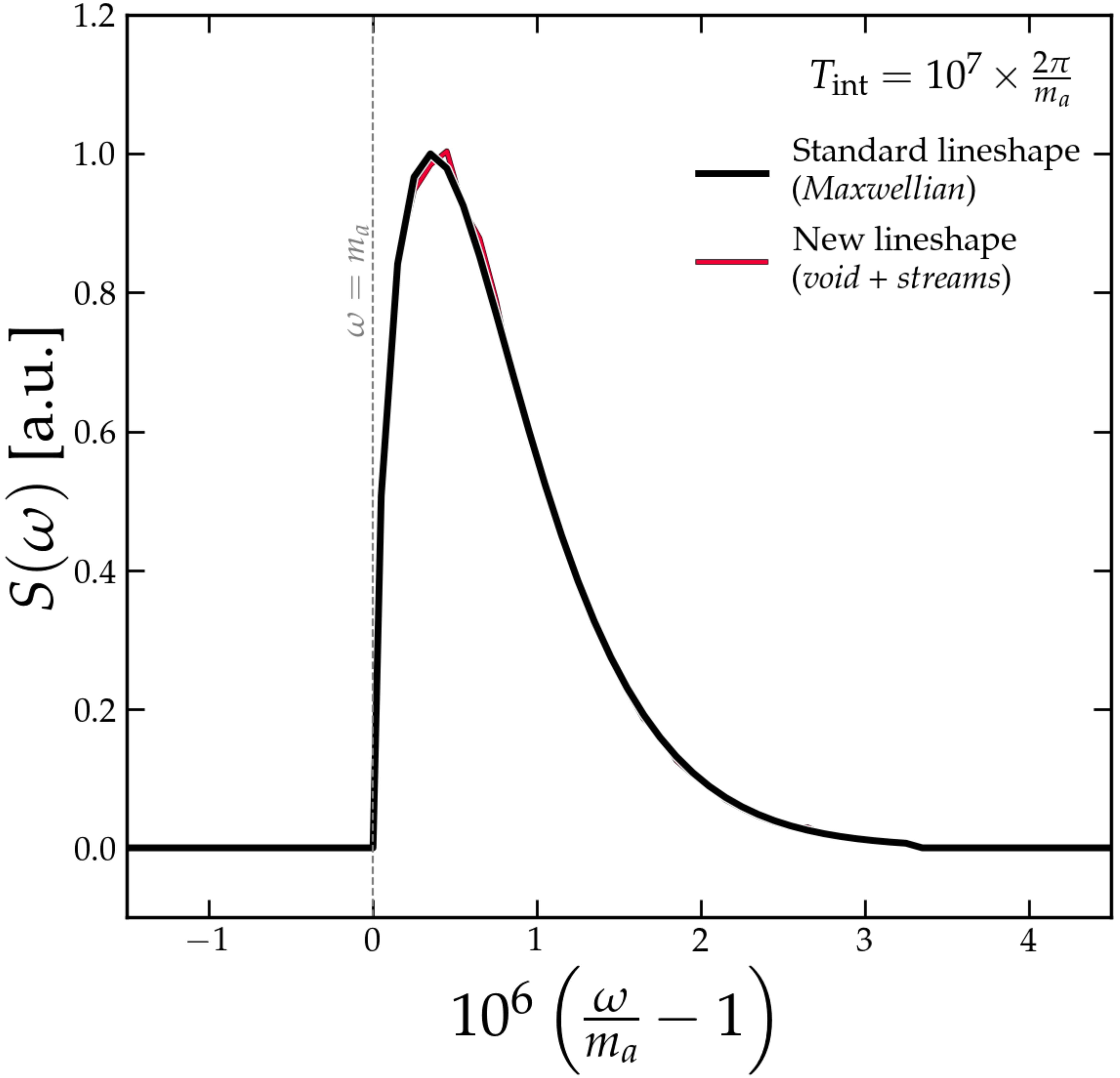


Haloscope signal

Disrupted minicluster **streams** are extremely cold ($\sigma < 1$ km/s) and do not contribute a significant density enhancement. However they become extremely prominent if lineshape is sufficiently well-resolved (long integration times)

Signal $S(\omega) \propto$ discrete FT of timestream

Frequency resolution = $\Delta\omega \sim T_{\rm int}^{-1}$

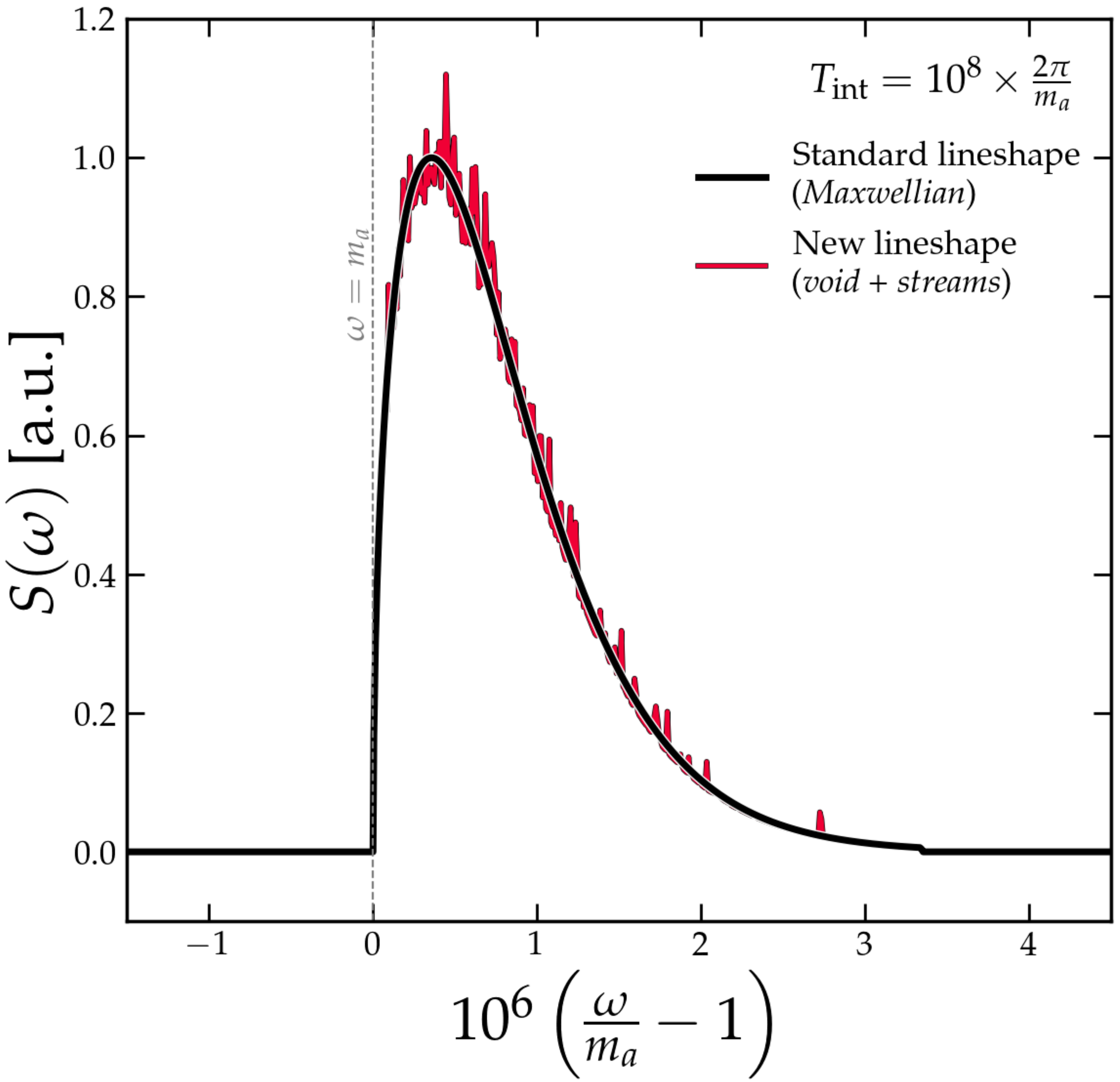


Haloscope signal

Disrupted minicluster **streams** are extremely cold ($\sigma < 1$ km/s) and do not contribute a significant density enhancement. However they become extremely prominent if lineshape is sufficiently well-resolved (long integration times)

Signal $S(\omega) \propto$ discrete FT of timestream

Frequency resolution = $\Delta\omega \sim T_{\rm int}^{-1}$



Haloscope signal

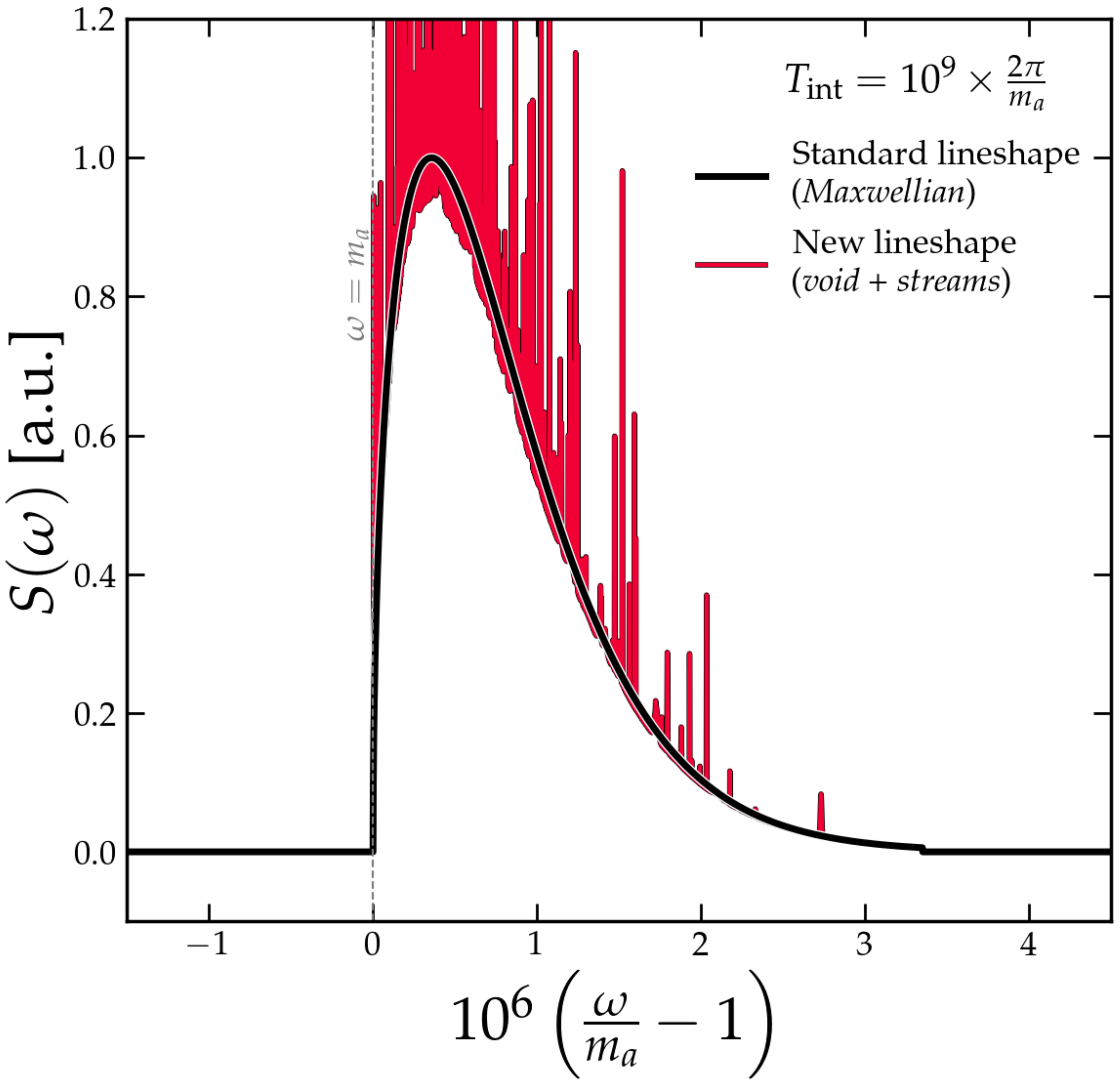
Disrupted minicluster **streams** are extremely cold ($\sigma < 1$ km/s) and do not contribute a significant density enhancement. However they become extremely prominent if lineshape is sufficiently well-resolved (long integration times)

Some important observations:

- Streams only enhance the signal by $\rho_{\rm str}/\rho_{\rm void} \sim 7$, but can enhance it by many orders of magnitude more in the *resolved* lineshape in certain bins
- Many streams are narrower than daily modulation in lab motion $v \sim 0.47$ km/s
- Streams persist in lineshape $\mathcal{O}$(days-years) at a time

Signal $S(\omega) \propto$ discrete FT of timestream

Frequency resolution = $\Delta\omega \sim T_{\rm int}^{-1}$



Summary

- **Miniclusters, voids and streams** are a *consequence* of the post-inflationary axion dark matter scenario so cannot be ignored
- Ignoring tidal disruption, the worst-case scenario is that we are in a minivoid which have only about ~10% of $\rho_{\rm DM}$ (suppression in $g_{a\gamma}$ by a factor of 3)
- Accounting for tidal disruption, phase space at Solar position re-filled by a factor of 6, to about 70% of $\rho_{\rm DM}$ (suppression in $g_{a\gamma}$ by a factor of 1.2)
- $\mathcal{O}$(1000-2000) ultra-cold tidal streams present in axion lineshape at any one time that persist for $\mathcal{O}$(days—years) at a time

THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER