Axion DM mutter

(the post inflationary universe)

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12th September 2023

News from the Dark '23

ULB, Brussels, Belgium

based on ...

MAX-PLANCK-GESELLSCHAFT

Dep. Theoretical Physics
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The University of New South Wales

- 1st News from the Dark I discussed **WISPy Cold Dark matter,**

introduced new generic DM candidates, huge new parameter spaces, brodened the scope ...

- To get some things done, the last few years I 've been trying to narrow down a bit

  I will discuss here my recent results on **QCD axion DM in the post-inflationary scenario**

  it could not get much narrower than that

outline

- Intro

- Axions from strings

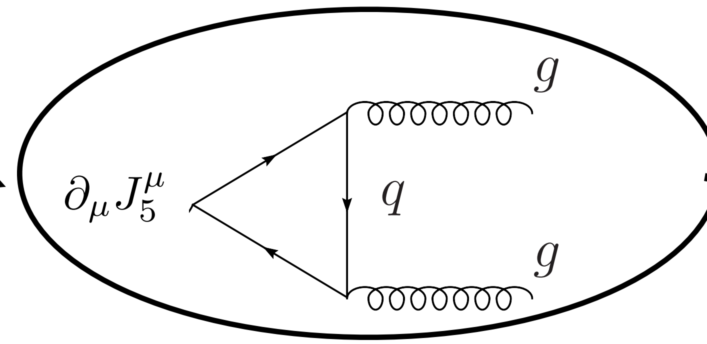
- Miniclusters

- High mass haloscopes ...

QCD Axion motivation: The strong CP “issue”

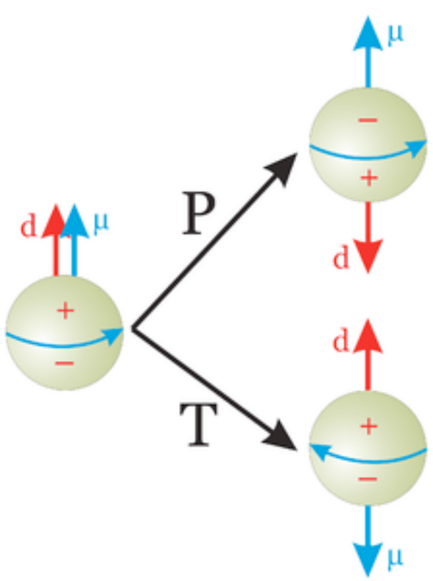
- **CP violation in QCD sector: CKM angle** $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ **AND flavour-neutral phase** $\theta = \theta_{\mathrm{QCD}} + N_f \delta$

$$\mathcal{L}_{\mathrm{SM}} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta/2} & 0 & \dots \\ 0 & m_d e^{i\delta/2} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\,\theta_{\mathrm{QCD}}$$



quark phase redefinition shifts between quark mass phase and QCD vacuum because of the axial anomaly

- **The θ-angle produces flavour-neutral CP violation like Electric Dipole Moments ... never observed!**



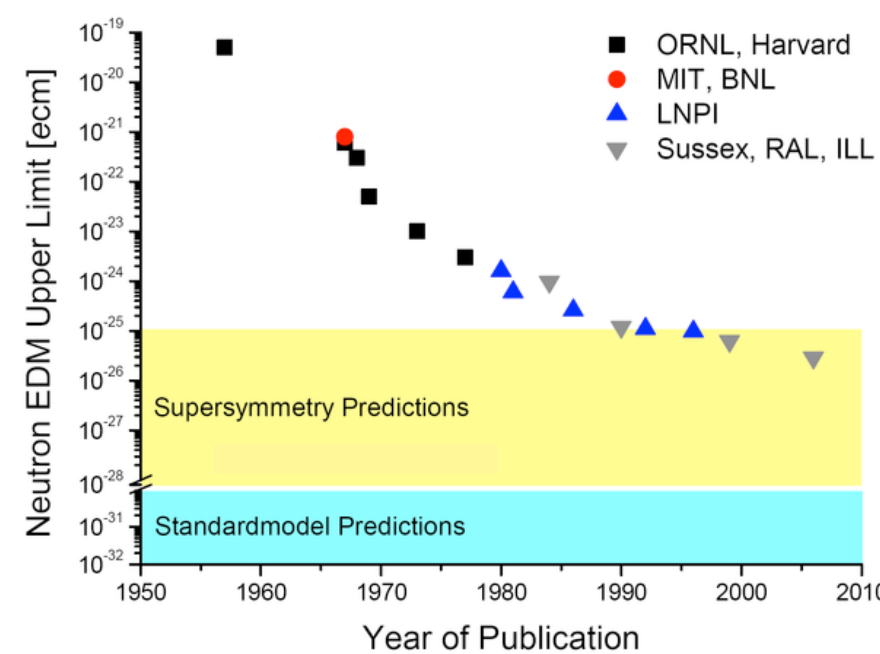
- **Neutron EDM (Pospelov 9908508)**

$$d_n = (2.4 \pm 1.0)\theta \times 10^{-3}\mathrm{e\,fm}$$

- **Experimental upper limit (Grenoble hep-ex/0602020)**

$$|d_n| < 3 \times 10^{-13}\,[\mathrm{e\,fm}]$$

- **Why is $\theta < 10^{-10}$?**



Driving θ dynamically to zero with BSM physics

CP Conservation in the Presence of Pseudoparticles*

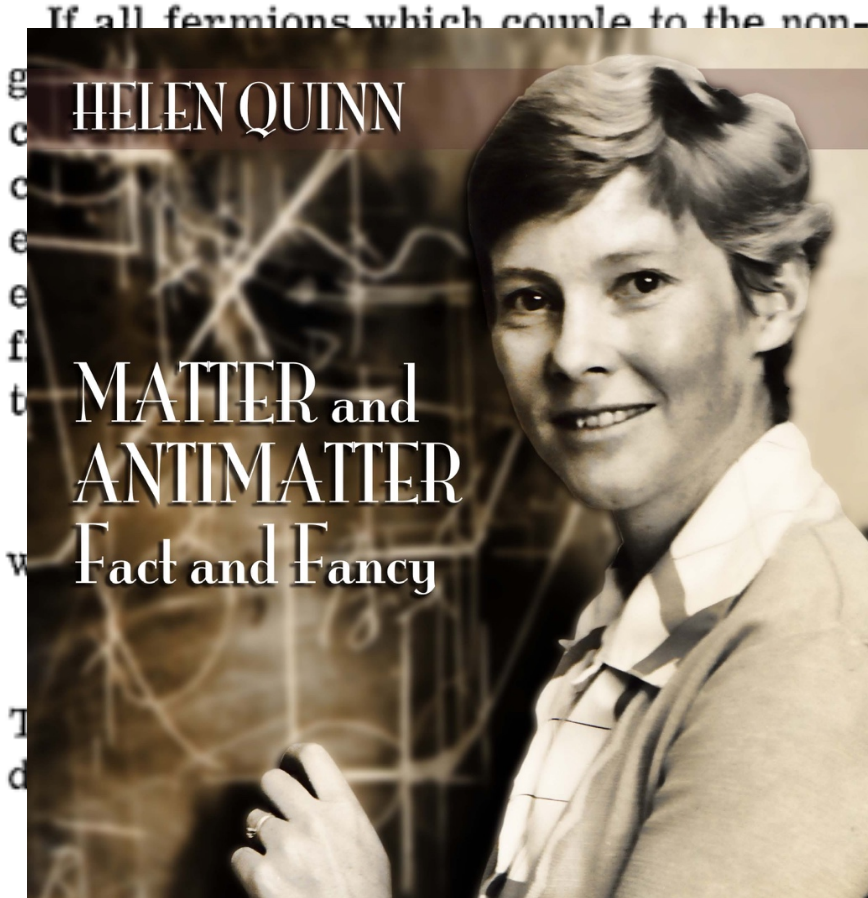
R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

It is experimentally obvious that we live in a

grangian.

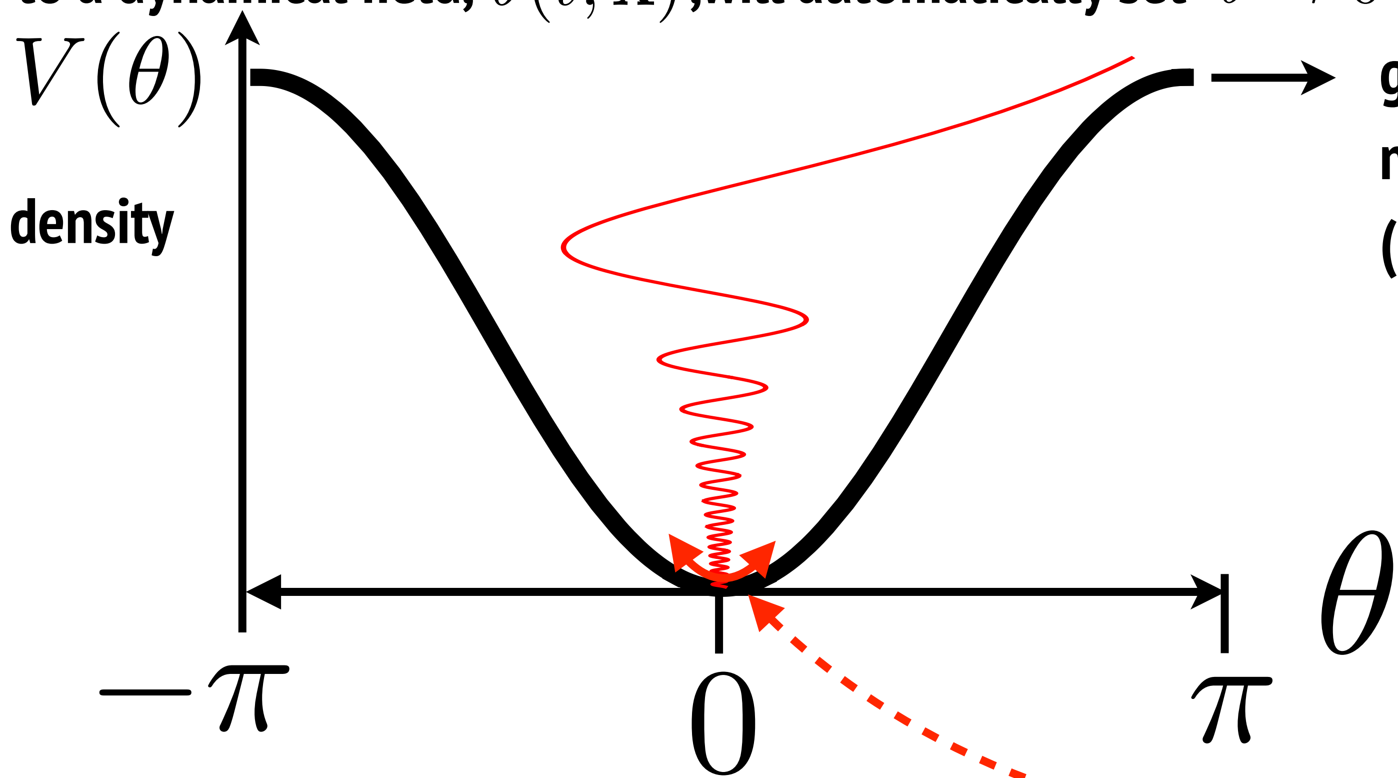
If all fermions which couple to the non-Abelian



QCD vacuum energy is minimised at $\theta = 0$!

- Any theory promoting θ to a dynamical field, $\theta(t, \mathrm{x})$, will automatically set $\theta \to 0$ after some time...

Potential energy density



→ generated by QCD non-perturbative dynamics (instantons)

- PQ Mechanism: Global U(1) symmetry spontaneously broken + color anomaly-> Goldstone boson + QCD term

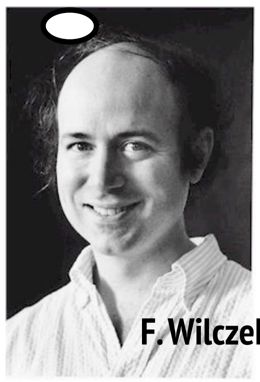
$$\mathcal{L}_\theta = \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f_a^2 - \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}_a^{\mu\nu} \theta$$

Canonically normalised θ-field is the QCD AXION! $a(x) = \theta(x) f_a$

New Spontaneous symmetry breaking [energy] scale f_a

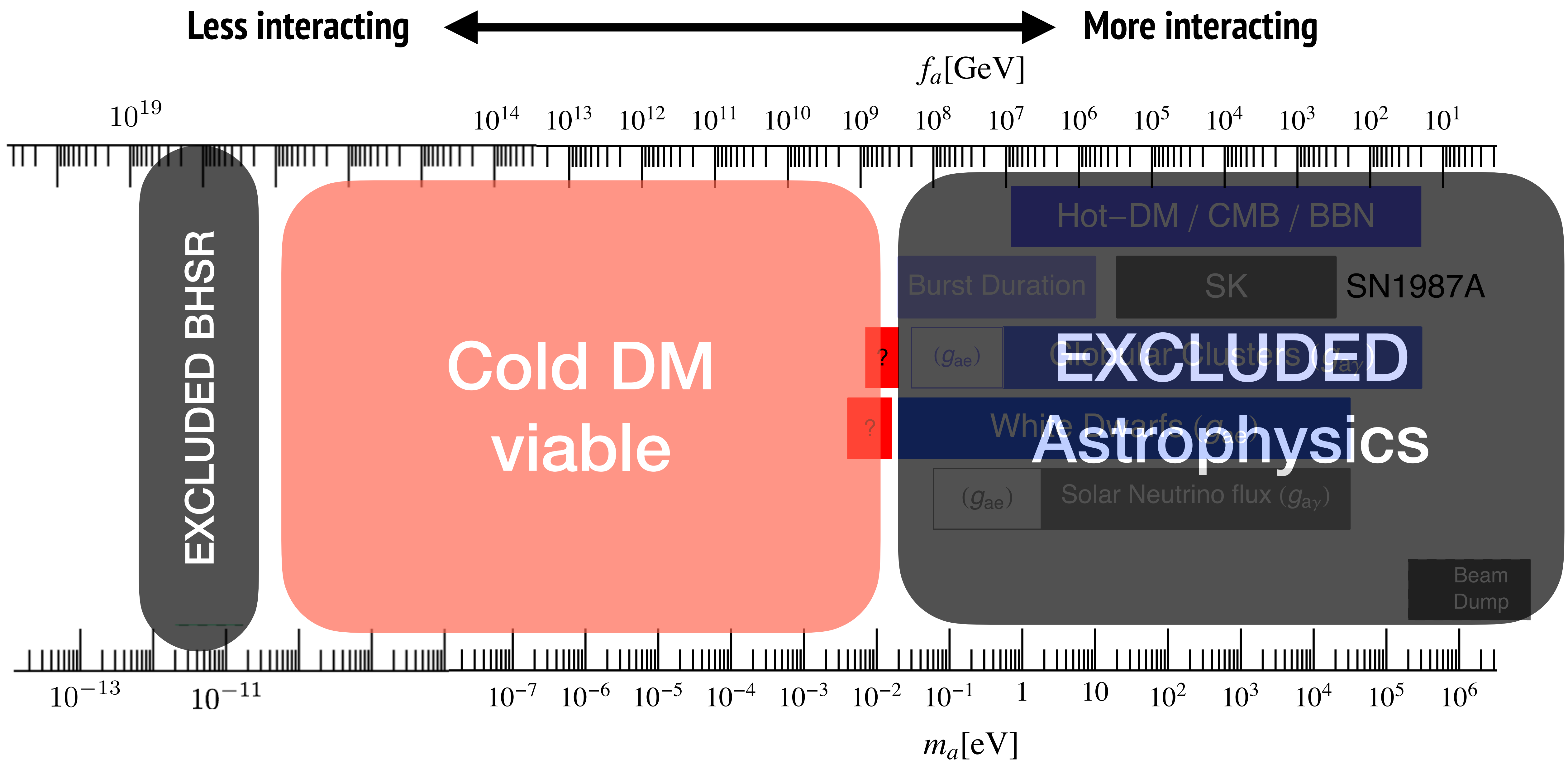
New scale f_a can relate to fundamental scales (string, flavor)

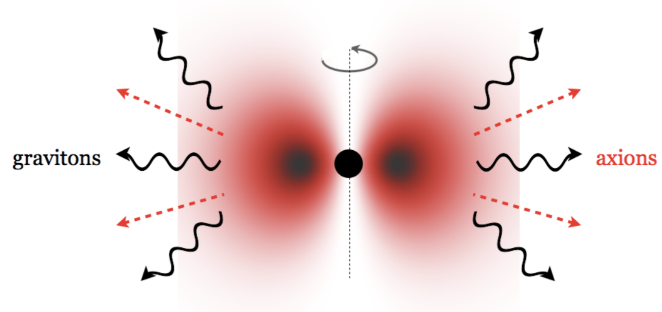
S. Weinberg



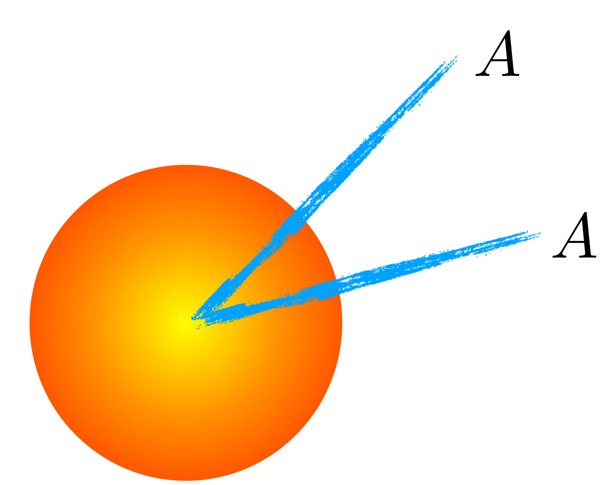
F. Wilczek

what do we know about fA





Black hole spin radiated



Stellar evolution accelerated*

Axion dark matter in a nutshell

$$\Omega_c h^2 \sim 0.12\theta_I^2 \left(\frac{10\mu\text{eV}}{m_A}\right)^{1.17}$$

3: Axions field rolls down potential at

$$t_1 \sim 1/m_A$$

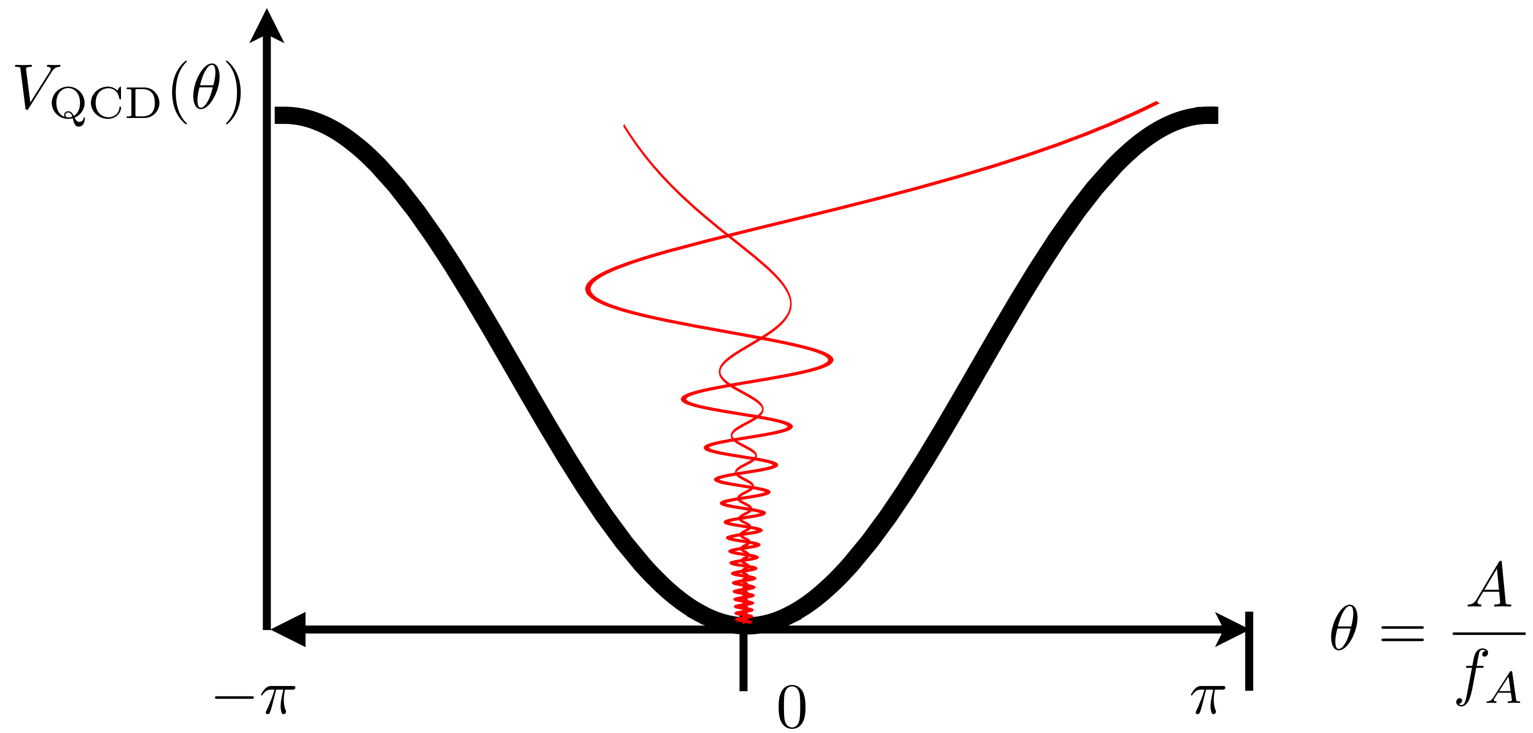
and oscilates around minimum (dust-like)

2: The QCD vacuum energy depends on θ

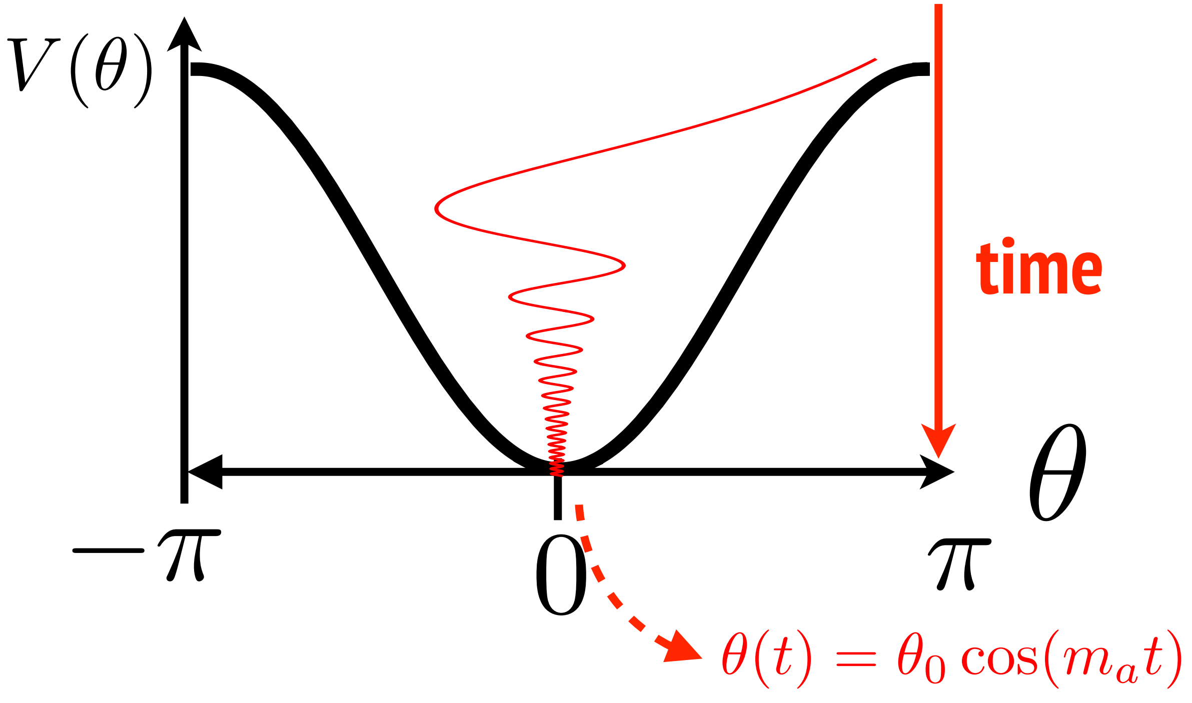
it has a minimum at $\theta = 0$!!!!

1: The axion field (A) is the dynamical version of the theta angle of QCD

We observe $\theta \simeq 0$



Axion DM in the lab



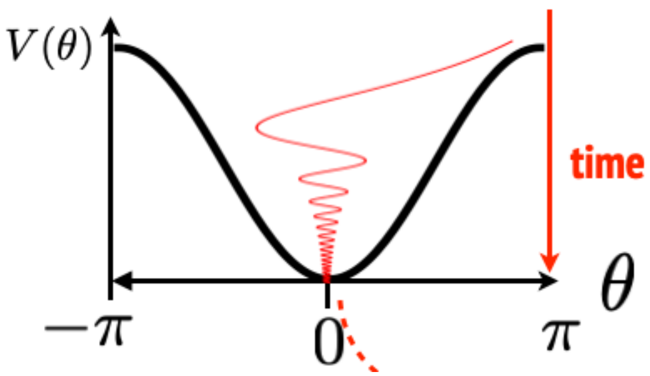
Local Dark Matter density*

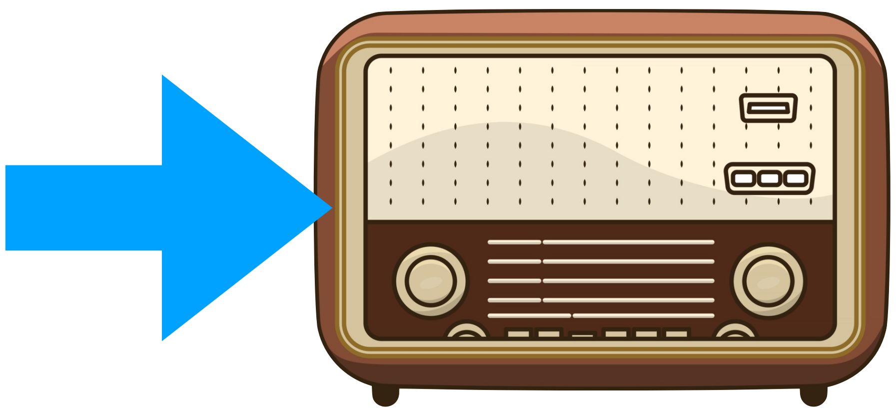
$$\rho_{c,0} \simeq \frac{1}{2}\dot{a}^2 + \frac{1}{2}m_a^2 a^2 = \frac{1}{2}m_A^2 f_A^2 \theta_0^2 = 0.4\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

$$\theta_0 = 3.6 \times 10^{-19}$$

Detecting Axion Dark Matter

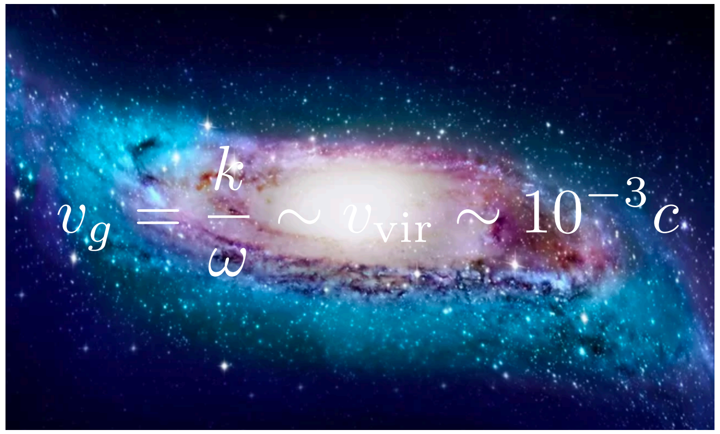
- $\theta_0 = 3.6 \times 10^{-19}$ is a very small number but, oscillations allow for coherent detection!
- Couple a resonator to the axion and SCAN (with the resonant frequency) but is time-consuming!

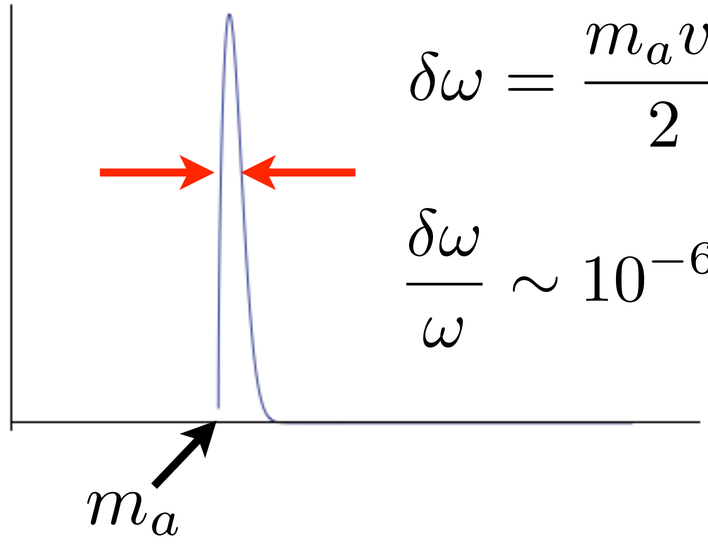




- Axion spectrum is not exactly monochromatic, non-zero velocity of DM in the galaxy -> finite width

frequency $\omega \simeq m_a(1 + v^2/2 + \ldots)$





$$\delta\omega = \frac{m_a v^2}{2}$$

$$\frac{\delta\omega}{\omega} \sim 10^{-6}$$

- Maximum amplification is quality factor of axion resonance* $Q \sim 10^6$

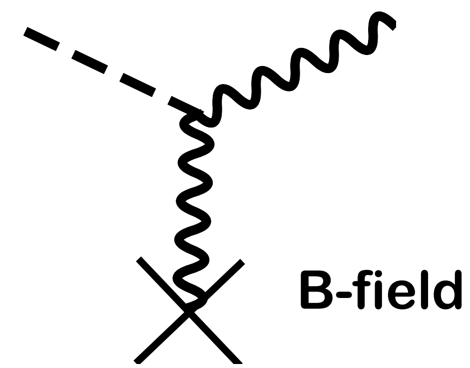
*substructure can have much larger Q's

Axion DM in a B-field

- Axion photon coupling in a strong B-field becomes a source of E-field

$$\mathcal{L}_I = -C_{a\gamma}\frac{\alpha}{2\pi}\theta(t)\,\mathbf{B}_{\rm ext}\cdot\mathbf{E}$$

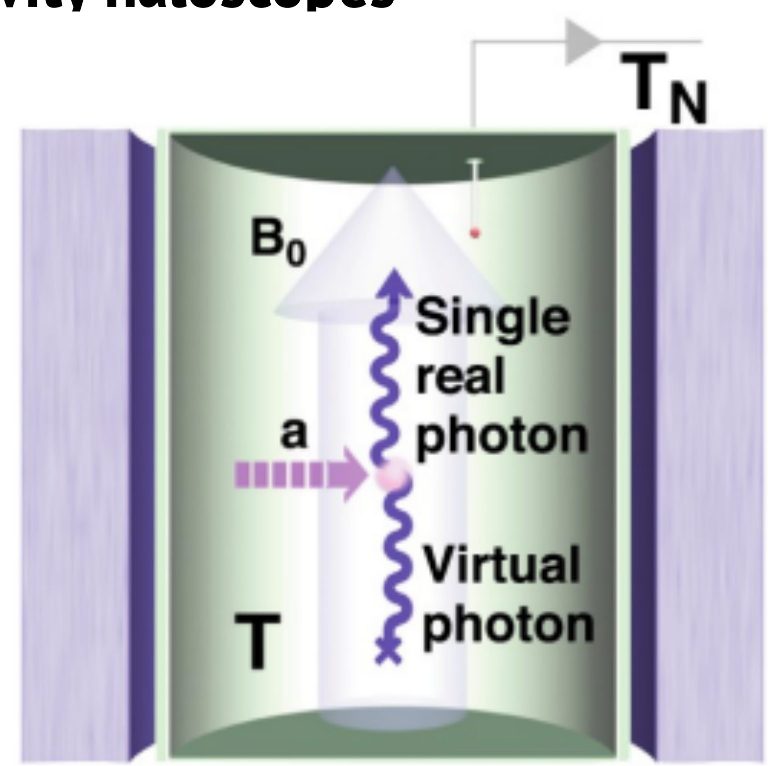
source



E-field $E \sim \mathcal{O}(10^{-12}\mathrm{V/m})\frac{|\mathrm{B}_{\rm ext}|}{10\,\mathrm{T}}C_{a\gamma}\times\cos(m_a t)$

Power $P/Area \sim |\mathbf{E}_a|^2 \sim 2\times 10^{-27}\left(\frac{\mathrm{B}}{5\mathrm{T}}\frac{C_{a\gamma}}{2}\right)^2\frac{\mathrm{Watt}}{1\,\mathrm{m}^2}$

- Axion cavity haloscopes



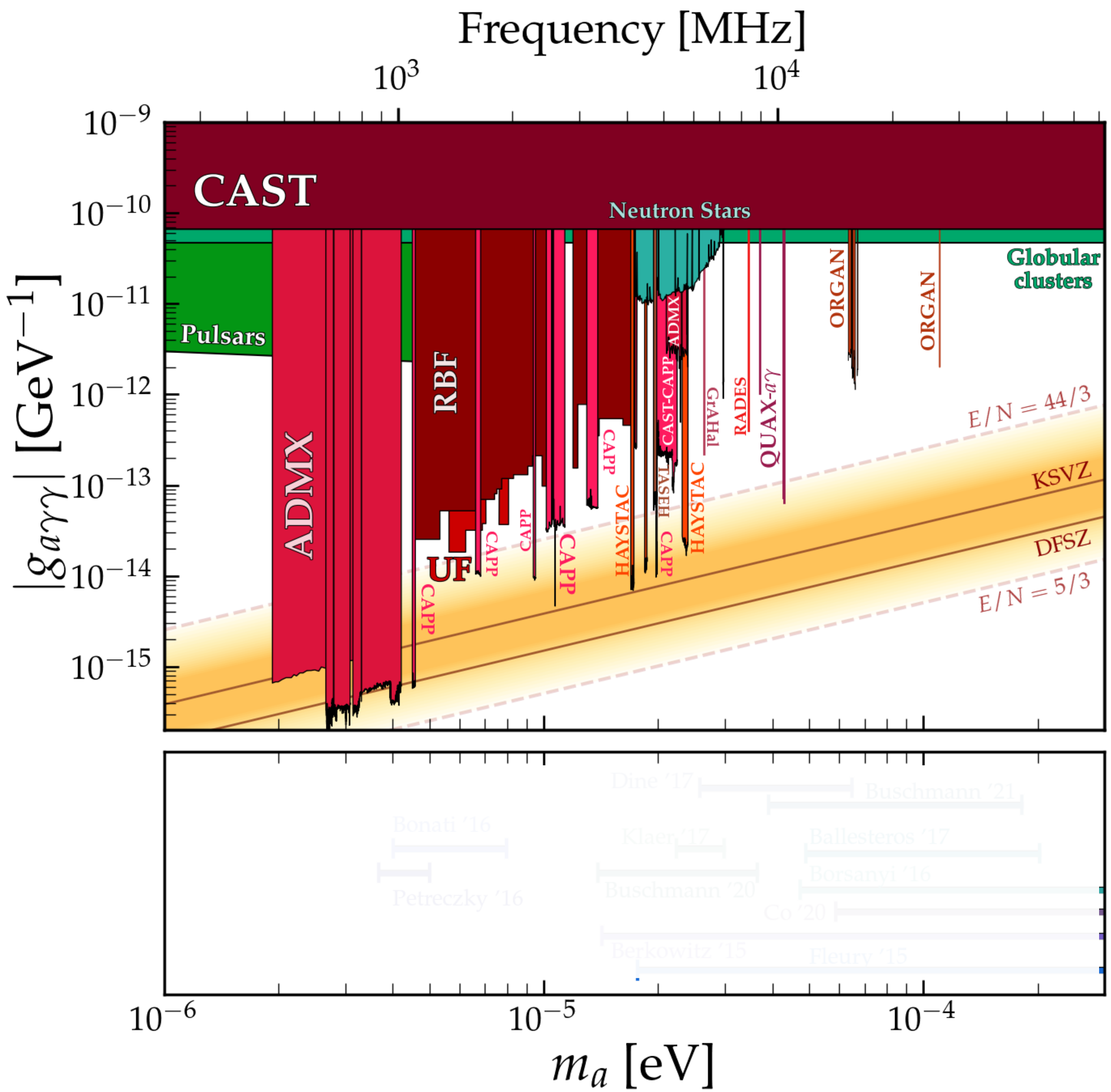
ADMX cavity tunable with metal rods

Experimental results

- micro eV cavities have excluded an octave of parameter space in 30 years

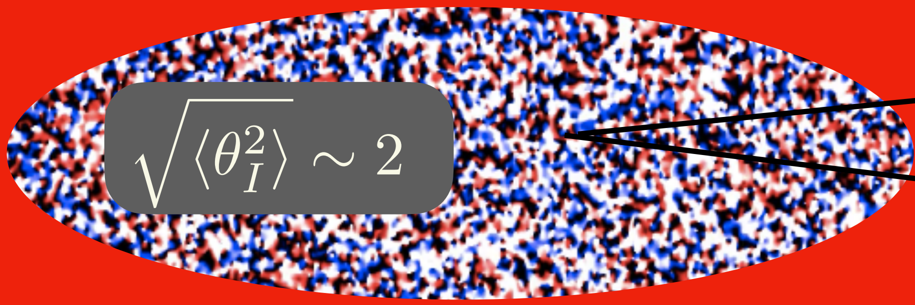
- more competition and faster scanning now

- some theoretical bias could accelerate the search



Dark matter in a nutshell 2

5: post-inflationary scenario : Initial conditions after inflation (only mass dependence!)



6: pre-inflationary scenario : Axion initial conditions before inflation, inflation smoothest them out

$\theta_I = ?$

4: Axion dark matter abundance depends:

- Axion mass
- Initial angle

$$\Omega_c h^2 \sim 0.12\theta_I^2 \left(\frac{10\mu\mathrm{eV}}{m_A}\right)^{1.17}$$

3: Axions field rolls down potential at

$$t_1 \sim 1/m_A$$

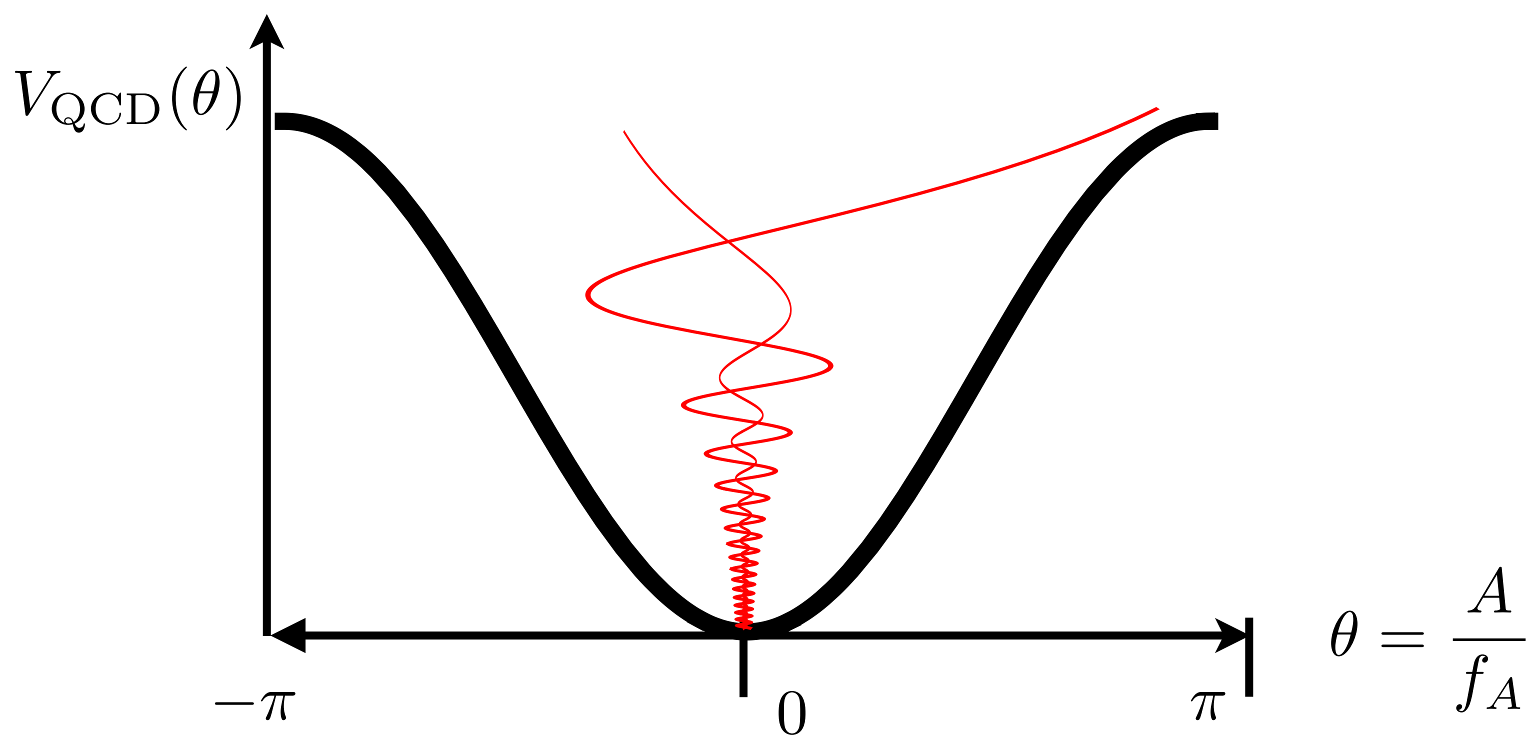
and becomes dark matter (like inflaton)

2: The QCD vacuum energy depends on θ

it has a minimum at $\theta = 0$!!!!

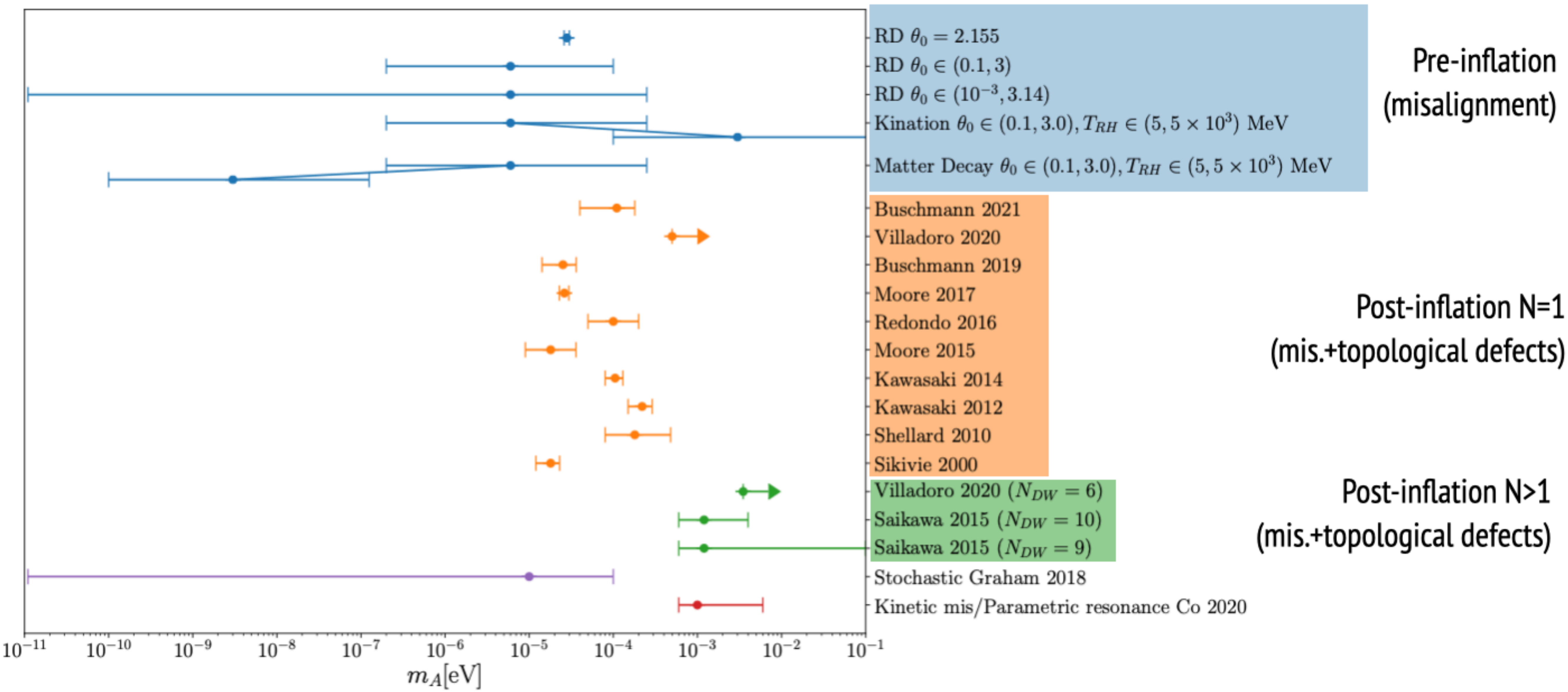
1: The axion field (A) is the dynamical version of the theta angle of QCD

We observe $\theta \simeq 0$



Axion DM mass $\Omega_{A,\mathrm{cdm}} h^2 = 0.12$

- Calculate the axion mass to get all the observed cold dark matter



Post inflationary scenario

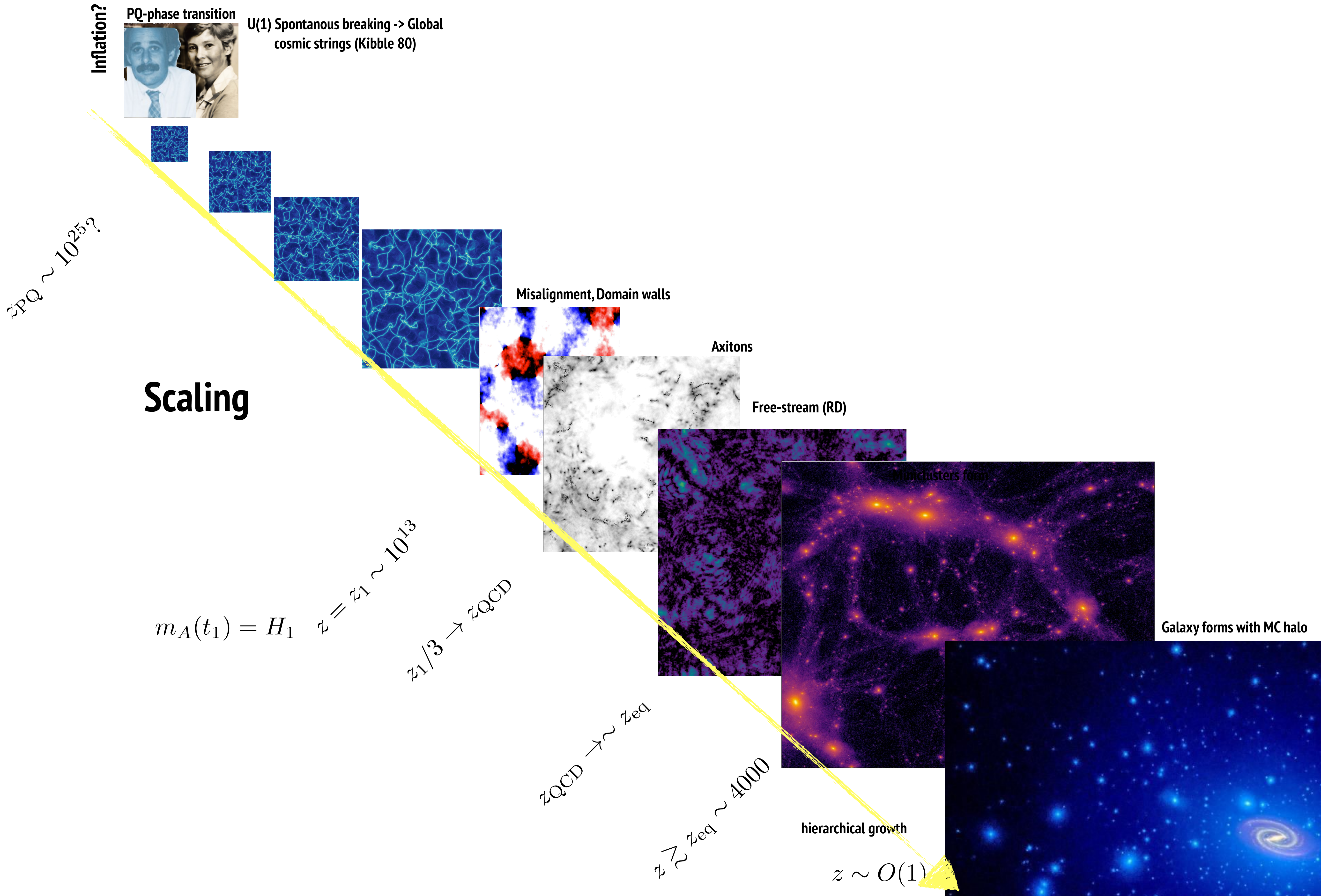
- In principle, we can calculate the initial-condition average and give a clear experimental target

- But 1: current uncertainty comes from axions radiated from global string networks

- But 2: Dark matter is inhomogeneous (miniclusters)
  how much DM is outside MCs available to direct discovery experiments?
  can we detect miniclusters directly?

- But 3: current trends point to mA ~ 10^{-4} eV ... where cavity haloscopes are not sensitive enough
  can we envision haloscopes at 10^{-4} eV?

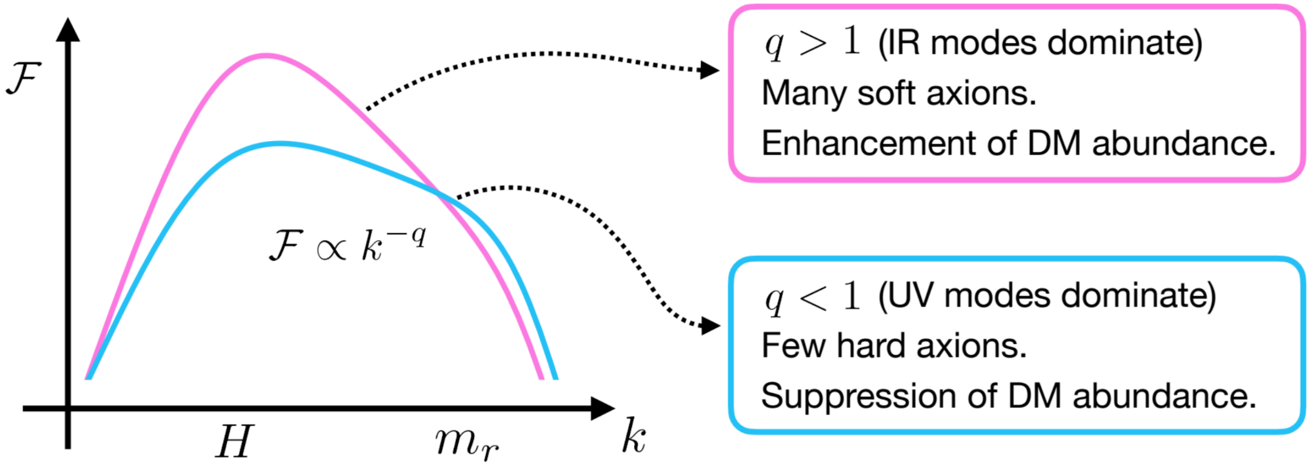
Post inflationary scenario



Axions from strings

- At PQ phase transition, QCD irrelevant, U(1) symmetry good, network of global strings by Kibble mech.
- String network relaxes (loop collapse, straightening...) at distances ~causal horizon
- String energy density is transferred into axion waves
- Differential spectrum

$$\mathcal{F}\left(\frac{k}{RH},\frac{m_r}{H}\right) \equiv \frac{1}{(f_a H)^2}\frac{1}{R^3}\frac{\partial}{\partial t}\left(R^4 \frac{\partial \rho_a}{\partial k}\right)$$



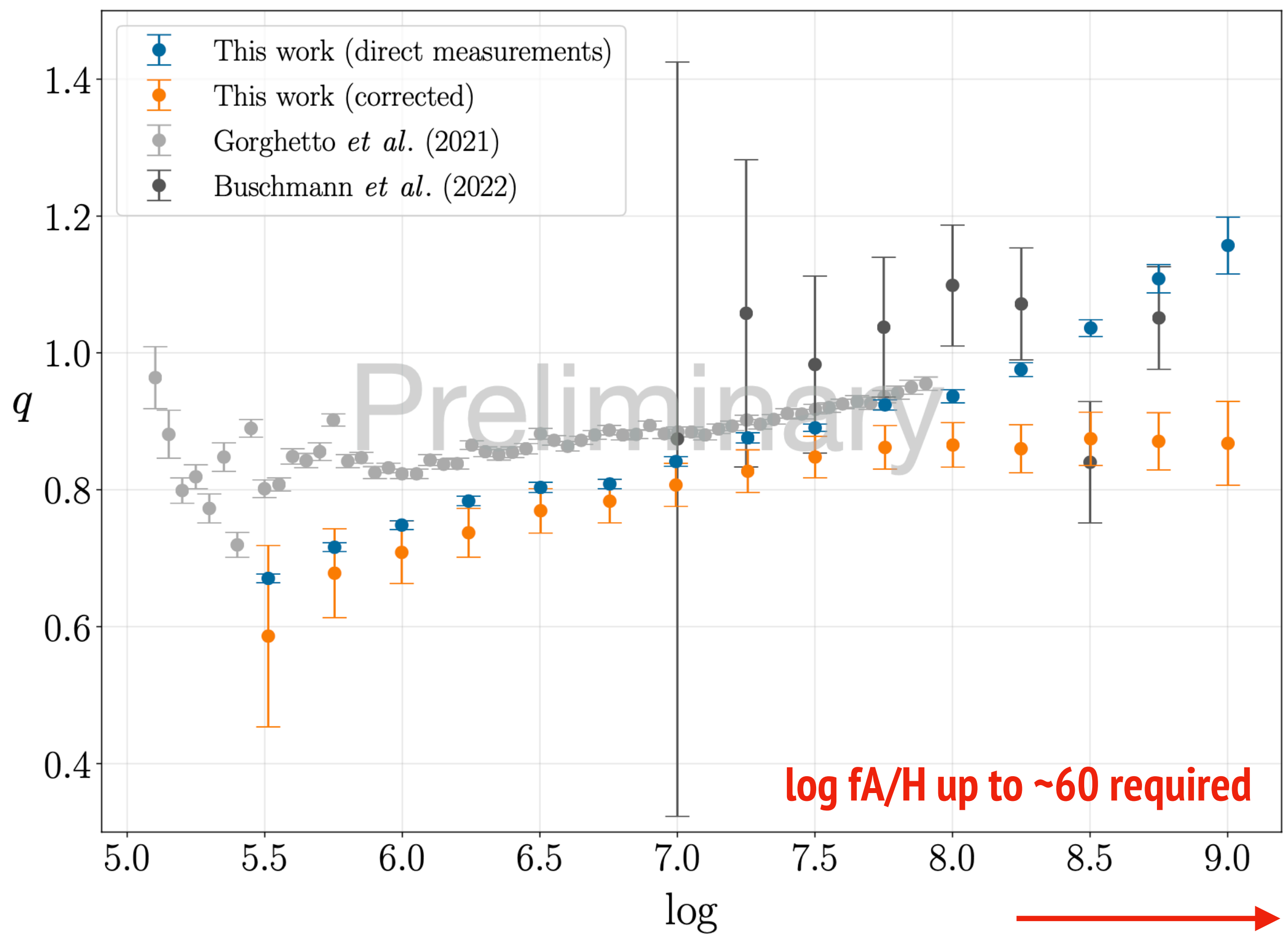
im. from Saikawa 23

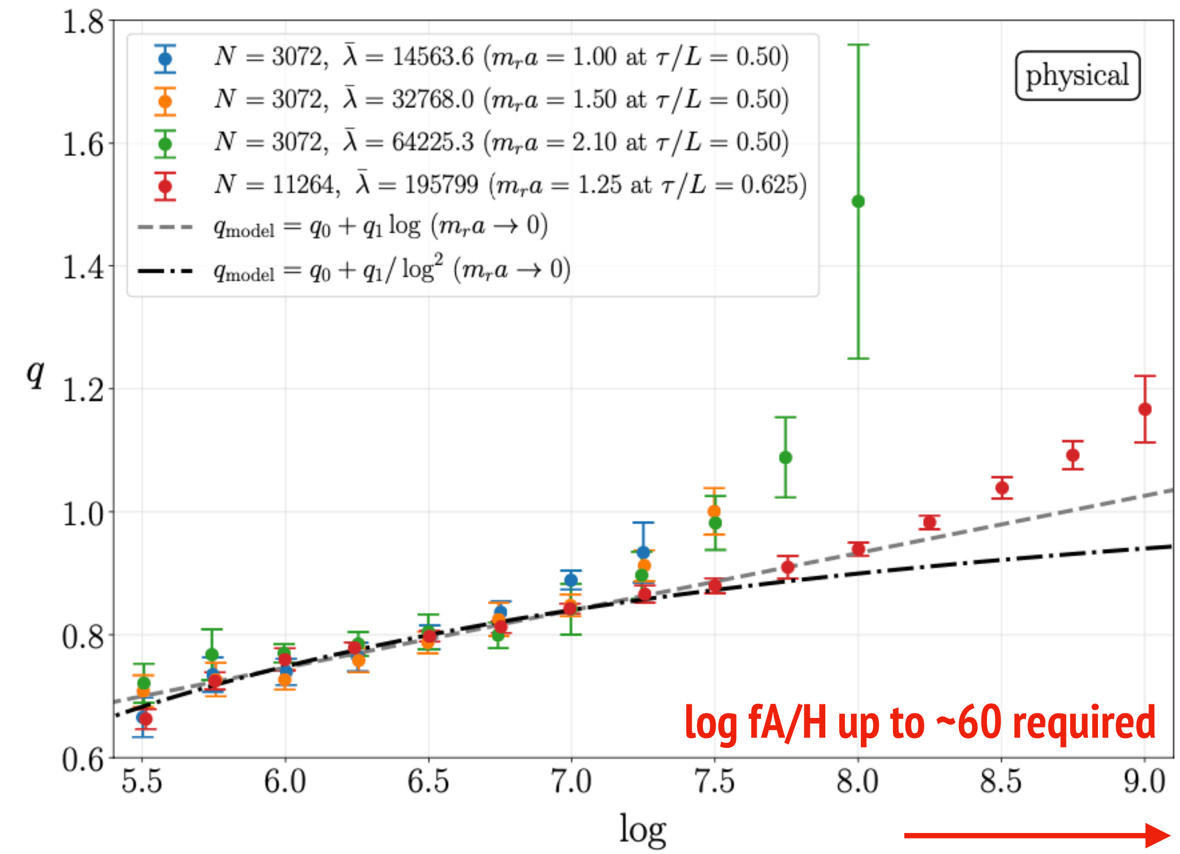
- Theoretical estimates do not converge, we resort to numerical simulations

Spectral index of axion radiation from a global string network

- Gorghetto and Buschmann found very different q's (growing with log (fA/H) vs q~1)
- We can understant part of this difference from their setups (ICs, discretisation errors) *Saikawa, to appear*
- We find the growing trend, but accounting for discretisation errors in the extrapolation leave room for both q>1 and q~1 solutions.
- The next generation of simulations (AMR) could settle the issue ... but we will need theory too

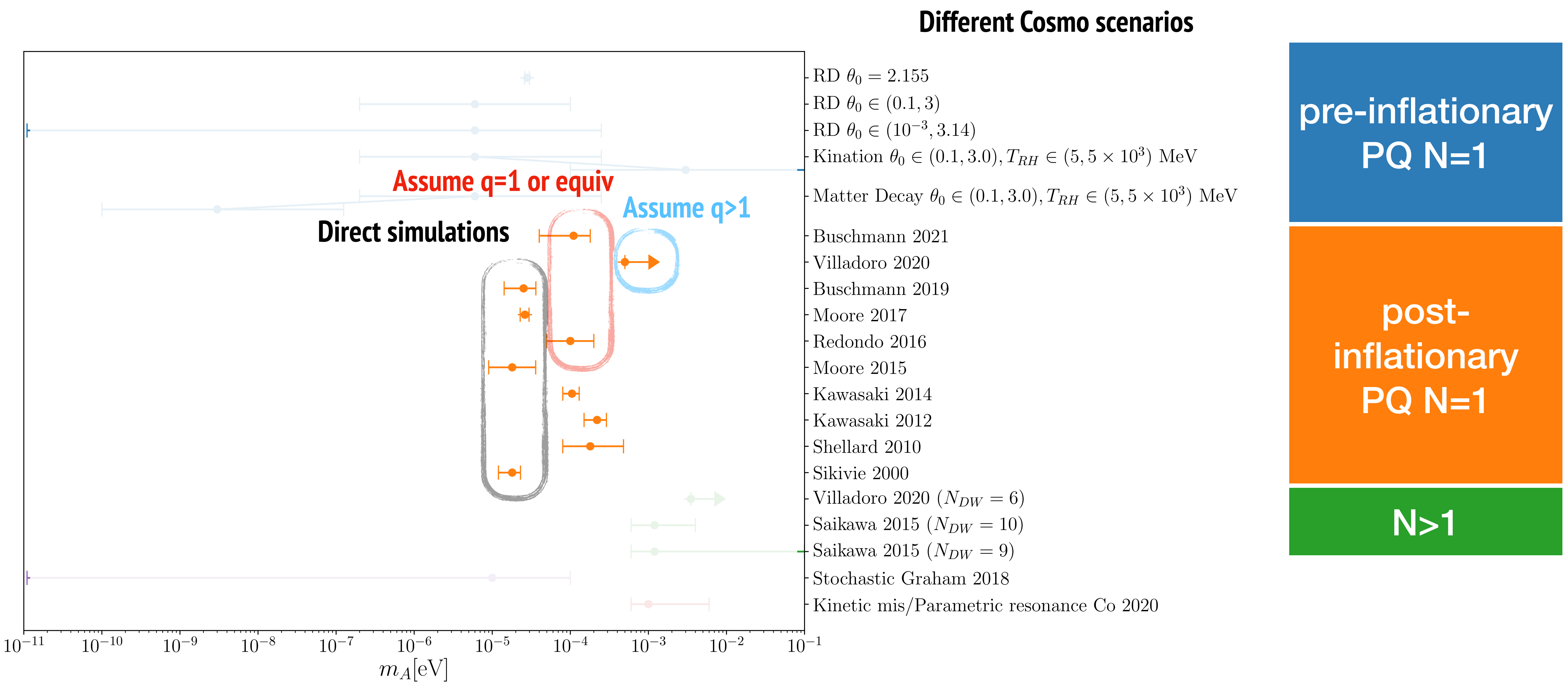
From Saikawa, JR, 2023 (to appear)





Axion DM Mass

- Axion DM mass from theory



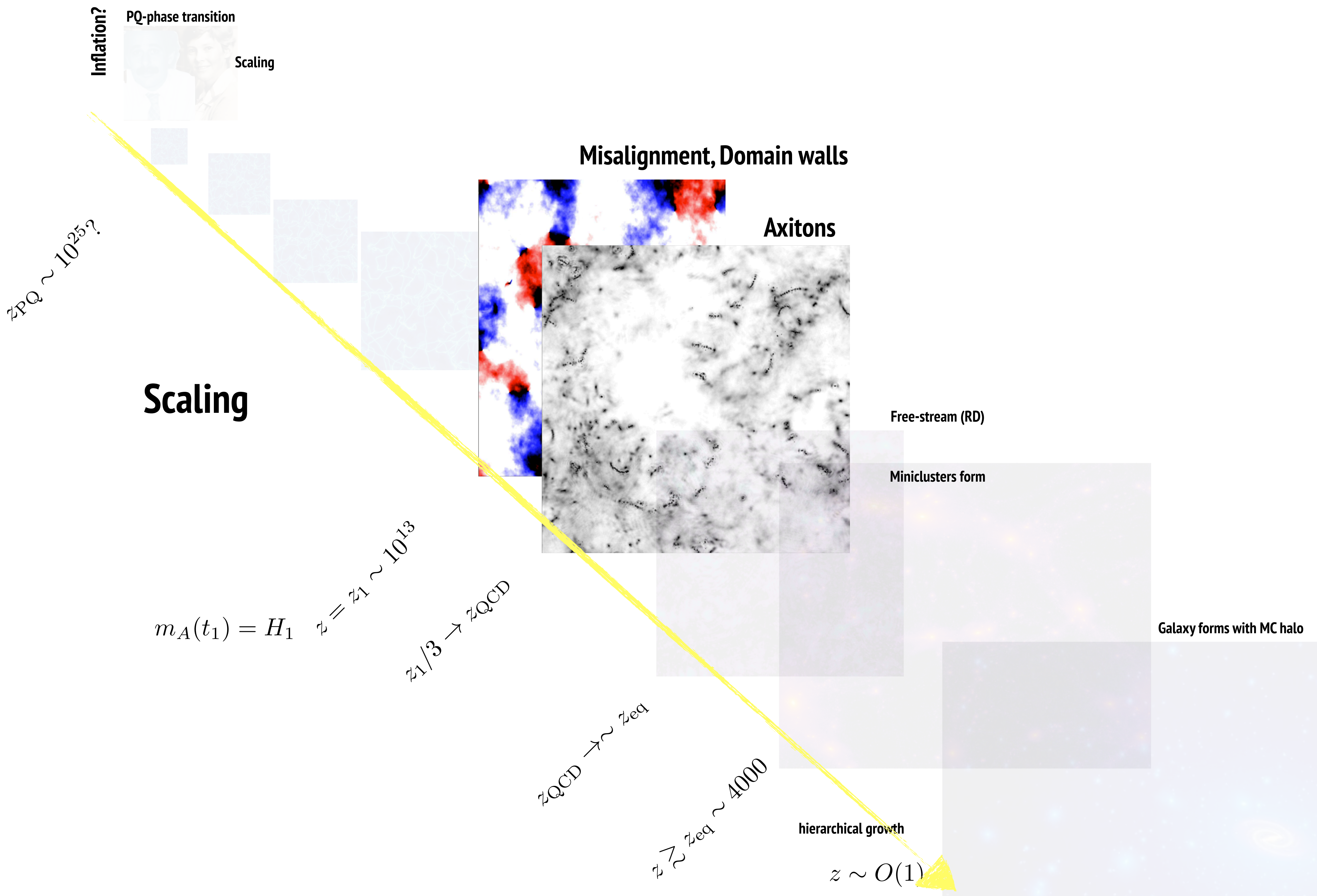
Miniclusters

- A general prediction of post-inflationary scenario is O(1) inhomogeneities at H_1 horizon scales

- We cannot simulate with total certainty because we cannot simulate global strings with adecuate tension at H_1 times (T~GeV) (we can only log ~ 9, we need 60)

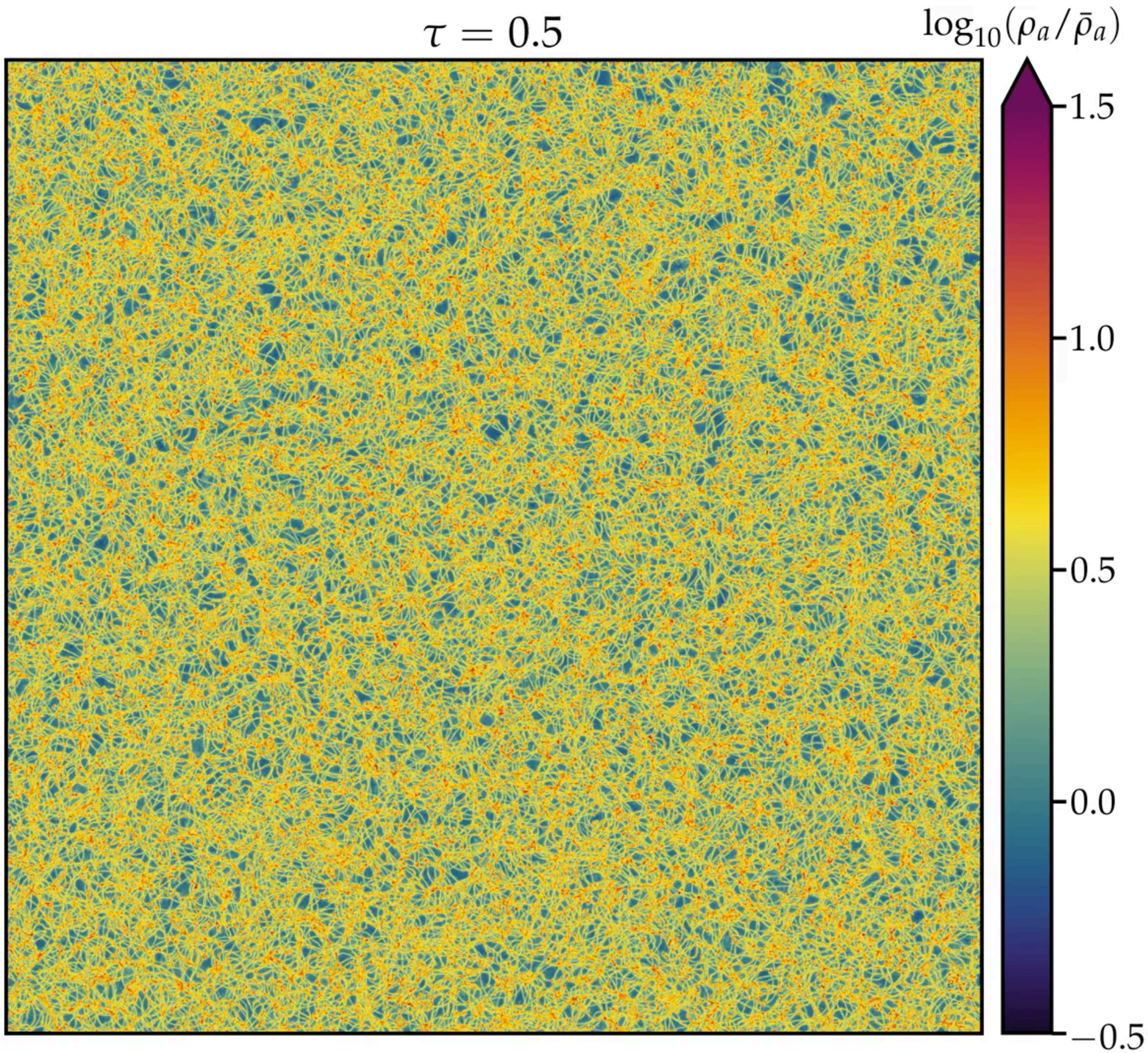
- We have performed simulations in three extreme cases to compare predictions,
  - $q<1$ with small log (low tension strings)
  - $q=2$ removing strings
  - artificial high tension simulations (Moore 17)

post-inflationary scenario



Early Universe, large scales

Simulations of the axion field when it starts oscillating



Current simulations only show q<1

Extrapolation is needed!

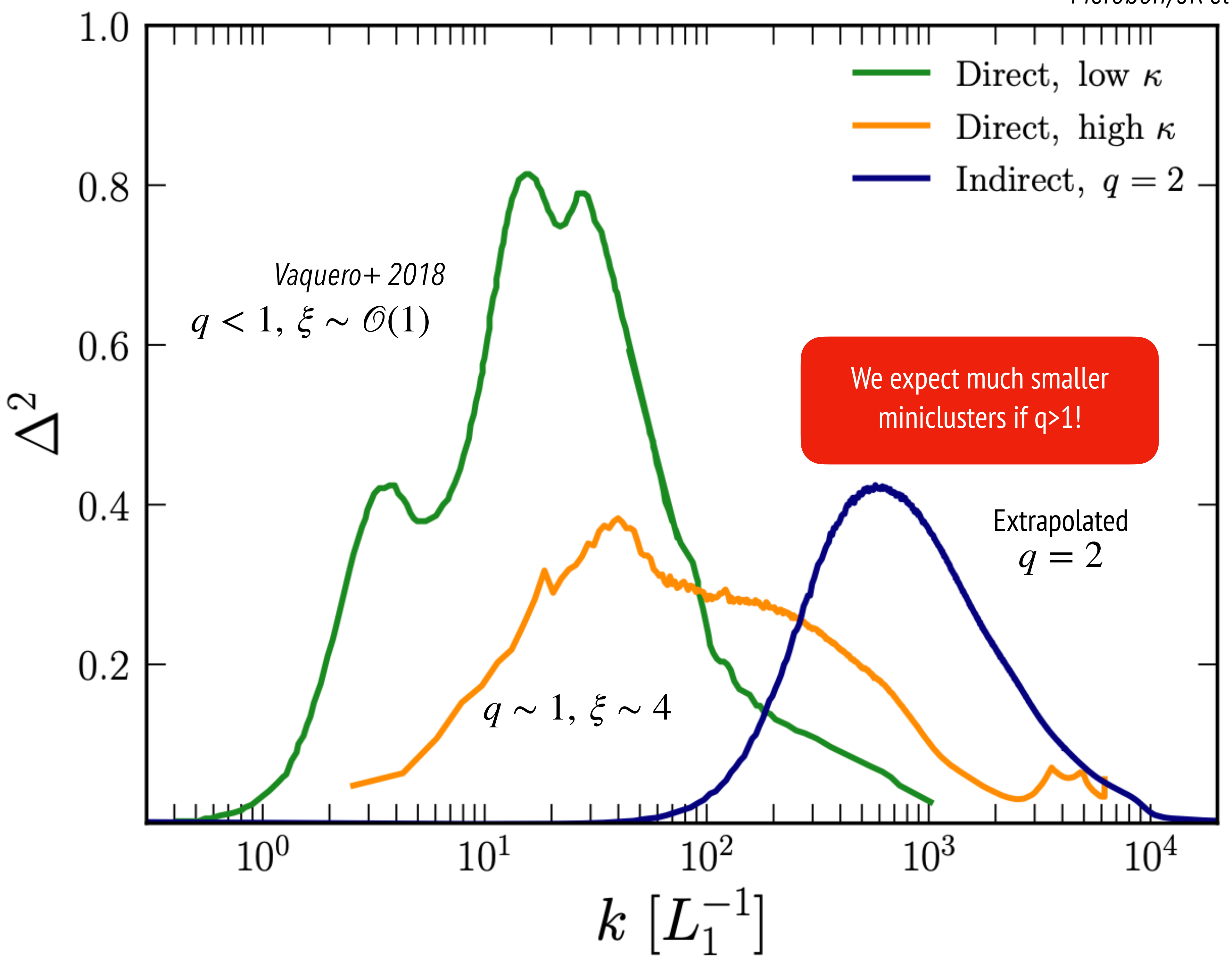
If q>1

Formation and decay and domain walls is delayed by large field values

Early Universe, large scales

Energy density fluctuations as seeds for miniclusters

Pierobon, JR et al 23

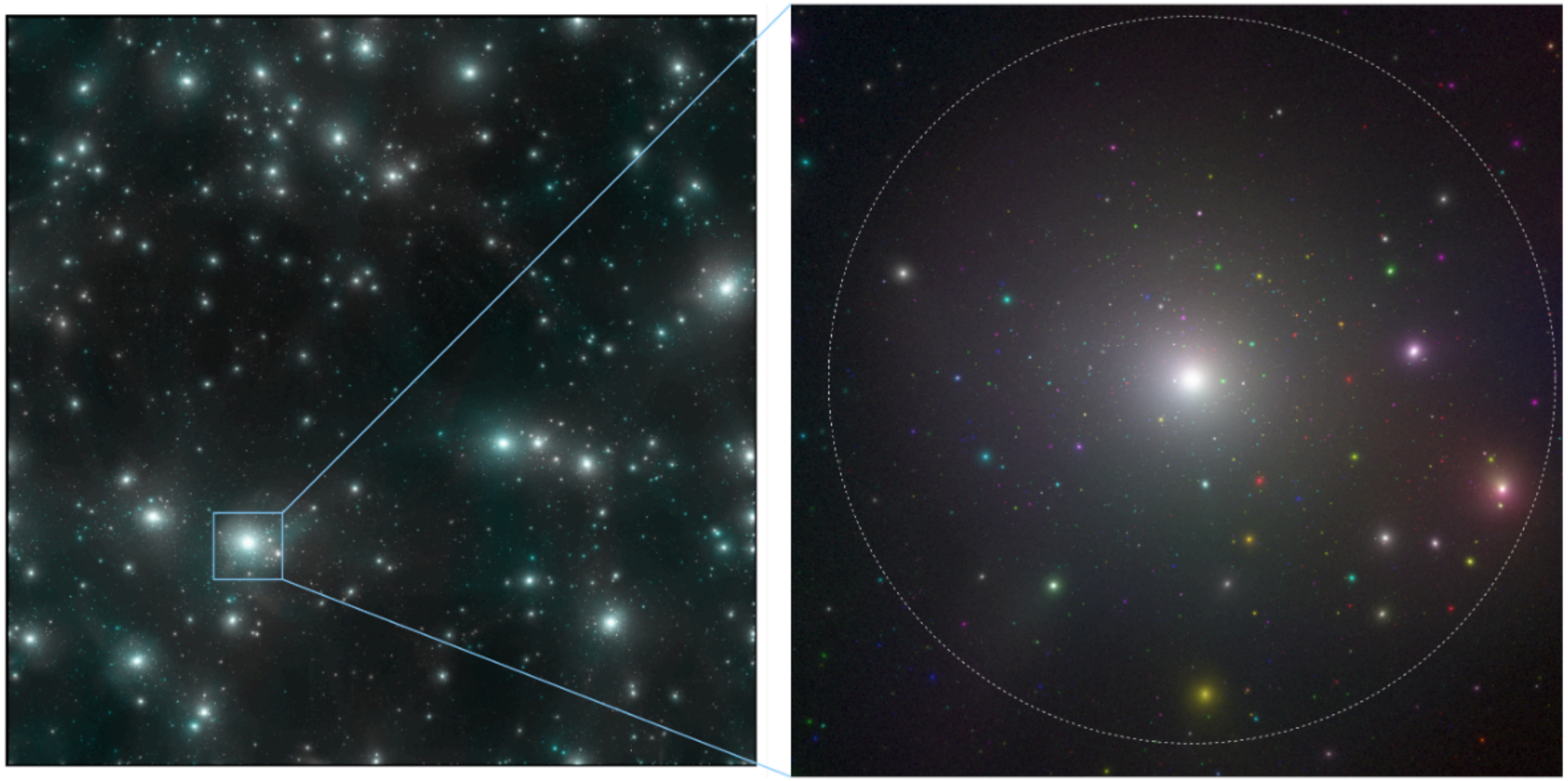


L_1 is the size of the causal horizon when m~H

post-inflationary scenario

Axion miniclusters

- free stream analitically up to $z \sim 100\, z_{eq}$
- Sample the density distribution with N-body particles (de Broglie wavelength too small to resolve)
- Gadget codes for the gravitational evolution ...
    - early collapse of O(1) overdensities into miniclusters
    - Hierarchical formation of clusters of miniclusters



Eggemeier 19

Axion miniclusters

Pierobon 23

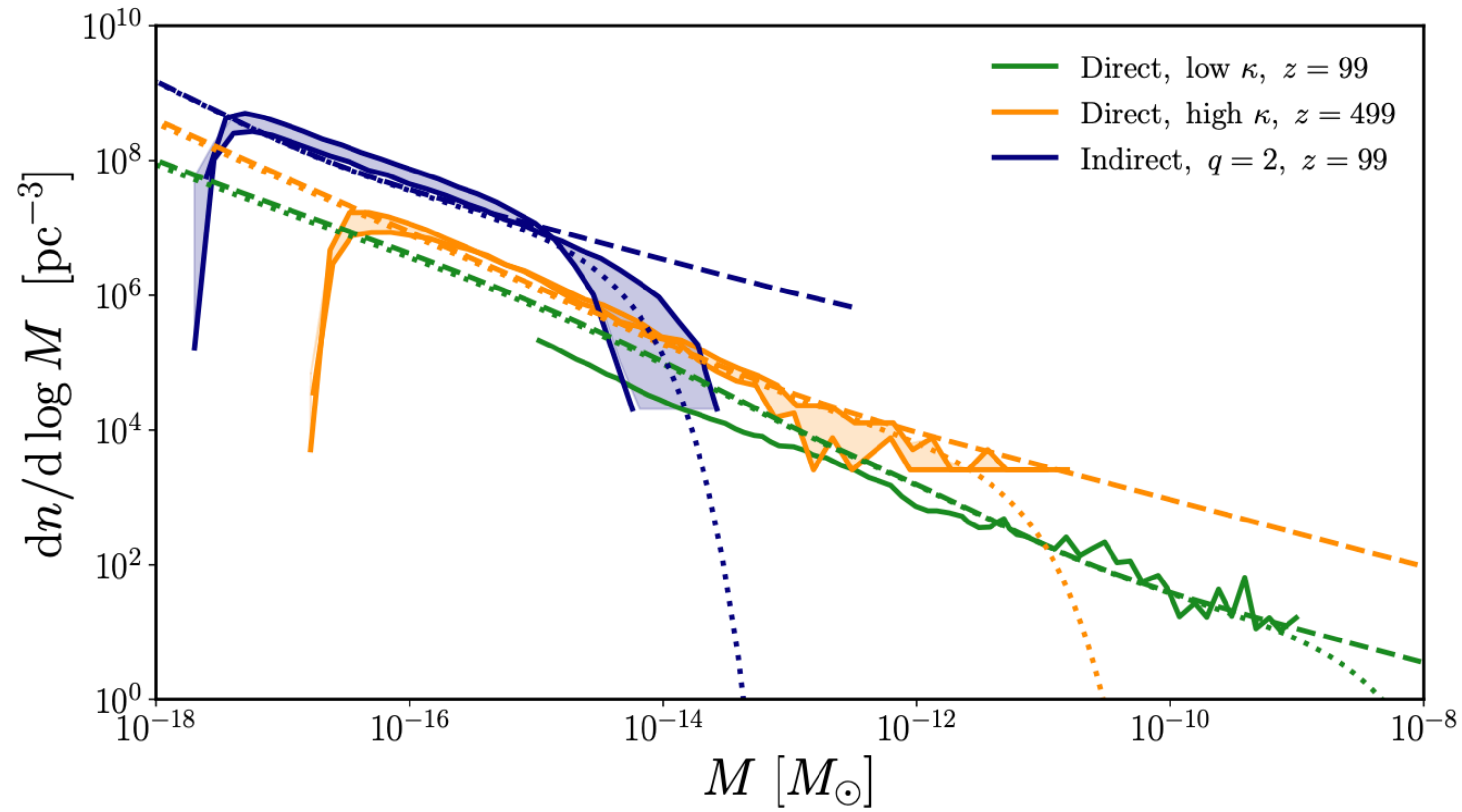
- Halo mass function

  increasing q reduces k1,

  smaller minicluster mass,

  more low-mass objects

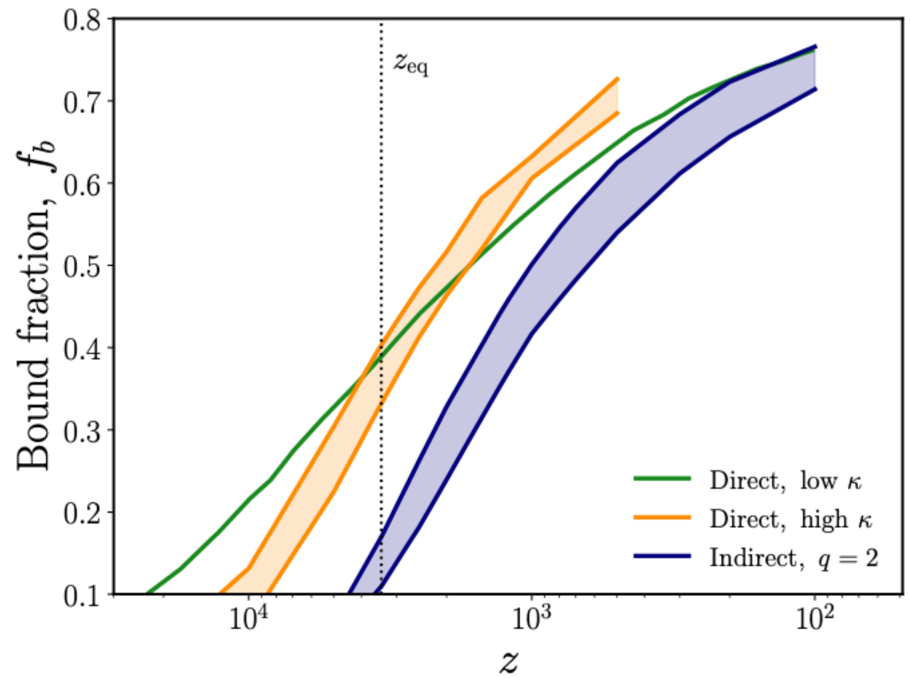
  big uncertainty!

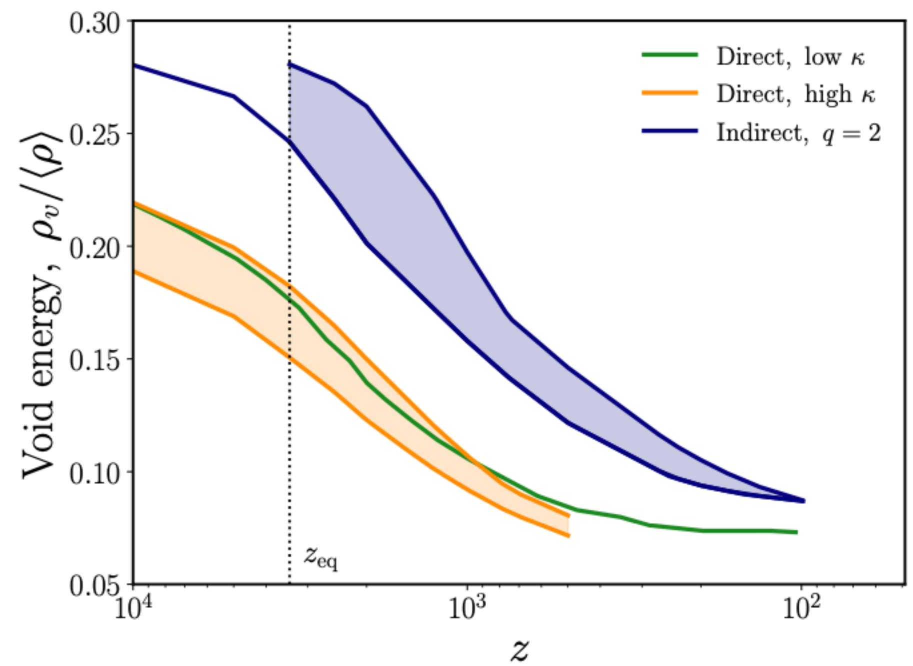


- Fraction of axions bound in MCs, average **VOID** density

  timings are different

  but **convergence**





- Simulations (very small scales) grow non-linear and do not allow to reach redshift 0

Encounters with the Earth

Direct encounters of miniclusters with the Earth occur once in ~10^5 years

Problematic scenario for direct detection (e.g. cavities)

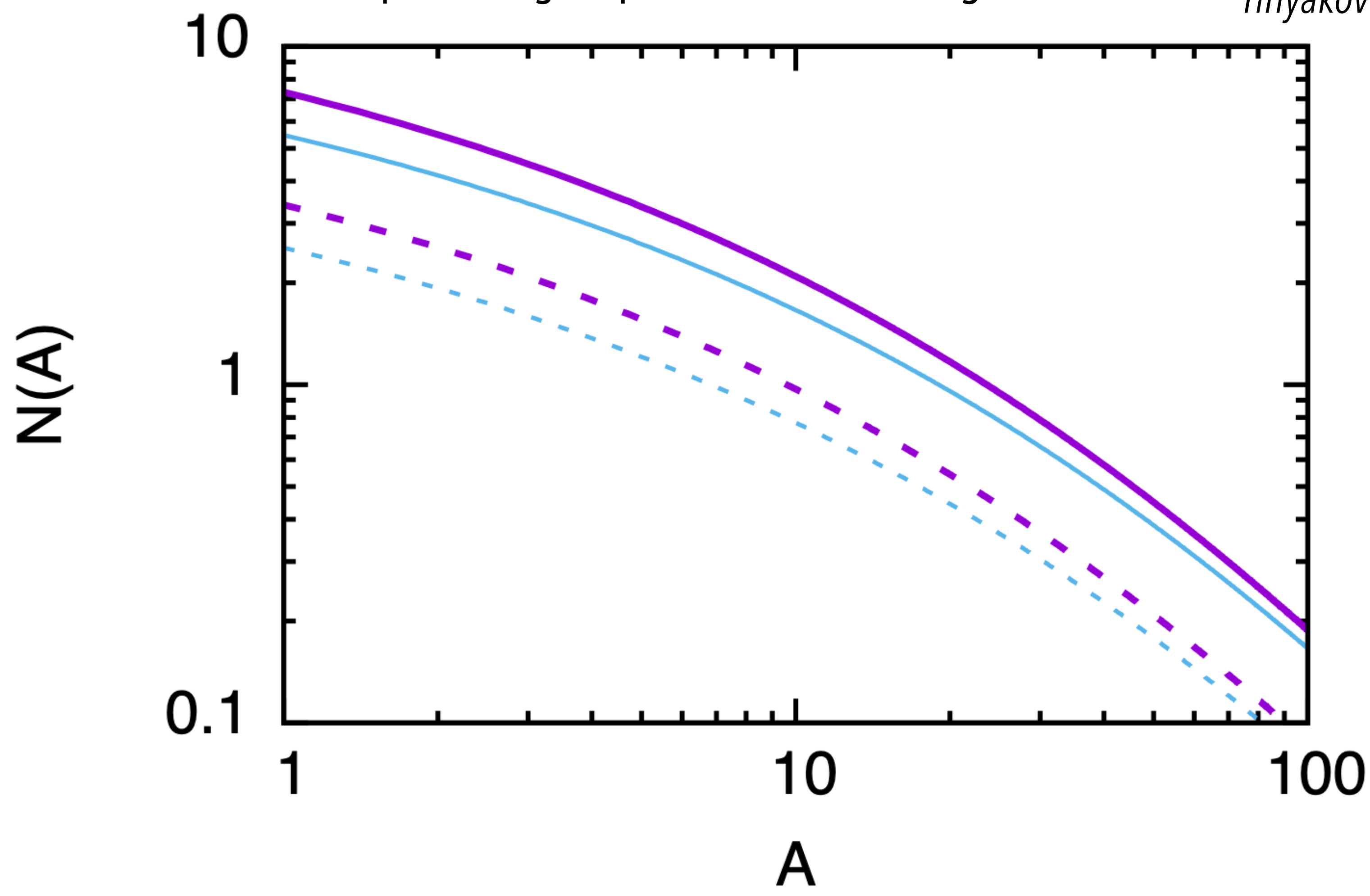
However disrupted miniclusters can form tidal streams

Analytical estimates find factor ~10 amplification for 2-3 days every 20 years

A numerical study needs to be performed!

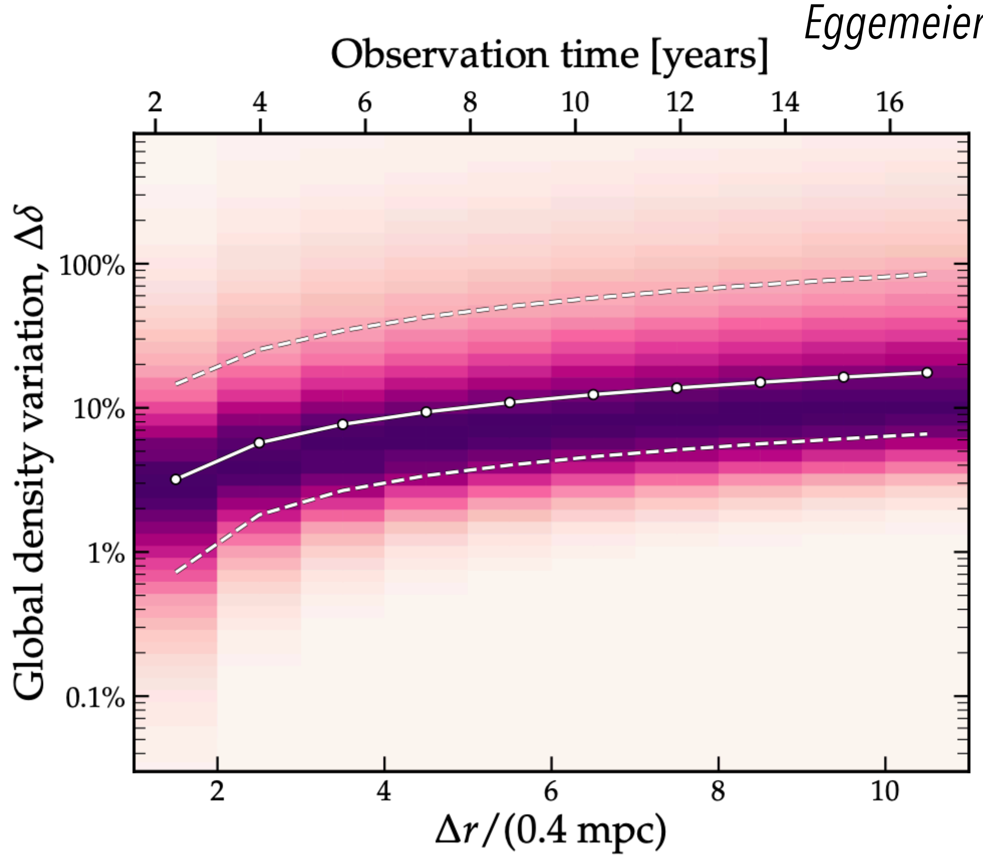
Number of encounters with axion streams producing amplification factor larger than A

Tinyakov+ 2016



Distribution of DM around the Earth: minivoids

Eggemeier 22

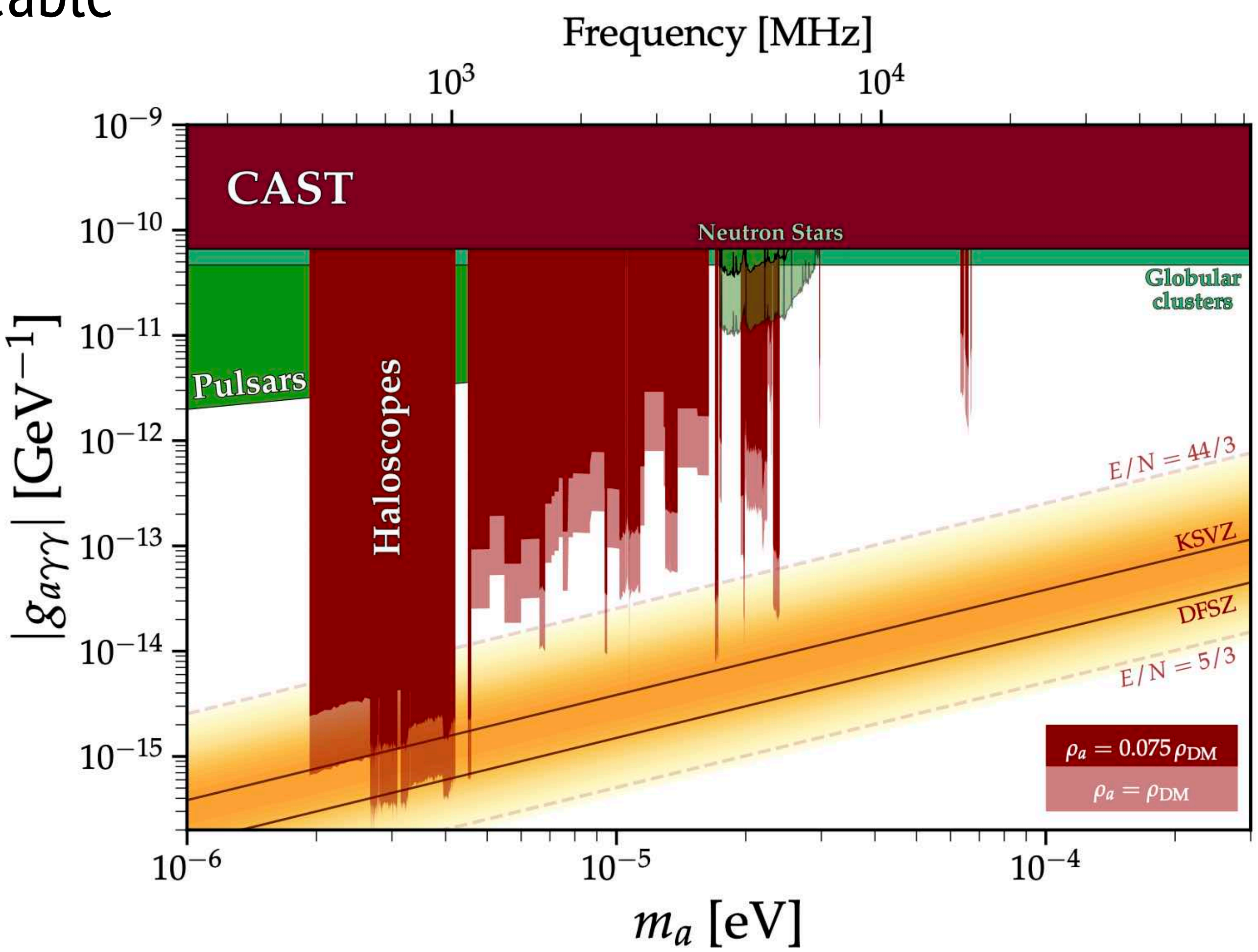


- Ignore tidal disruption, which ejects more axions into the voids, use the converging void density as a conservative lower limit ...

- Using 8% of average DM for detection has sizeable implications for direct detection (but could be much worse!)

$$a(x,t) \approx \frac{\sqrt{2\rho_a}}{m_a}\cos(\omega_a t + \varphi)$$

$$P(\omega_i) \propto g_{a\gamma}^2\ \alpha(\omega_i)\ \rho_a\ f(\omega_i)$$



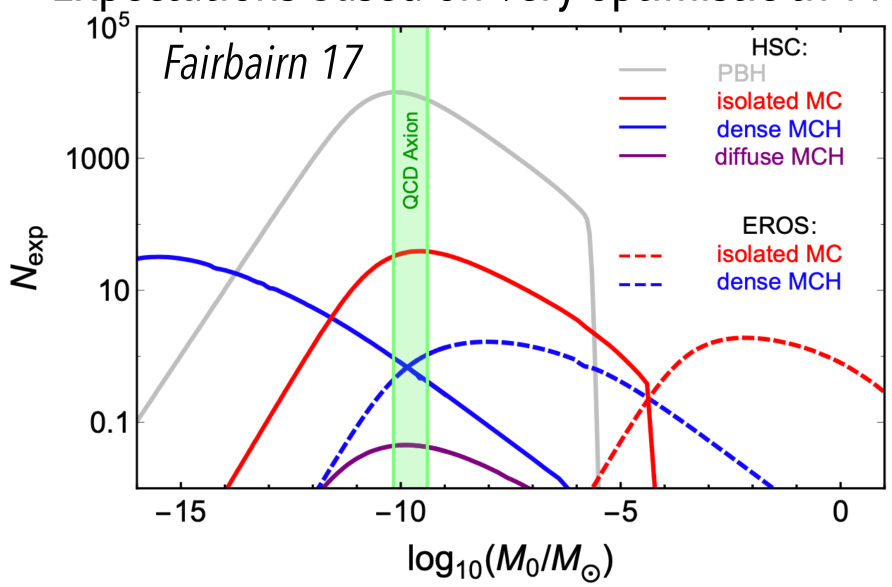
Lensing

- femtolensing of GRBs $M \sim 10^{-16} \sim 10^{-13} M_{\odot}$ *Kolb 95*

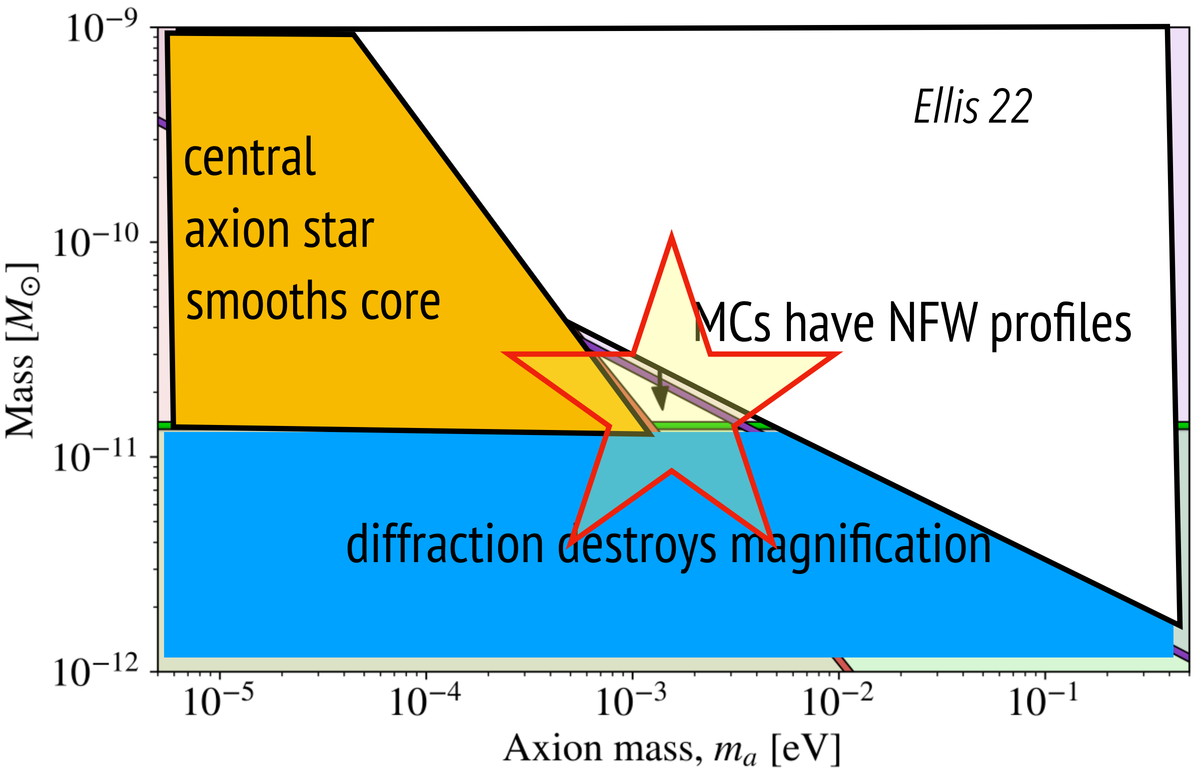
Most GRBs are innappropriate due to large sizes *Katz 18*

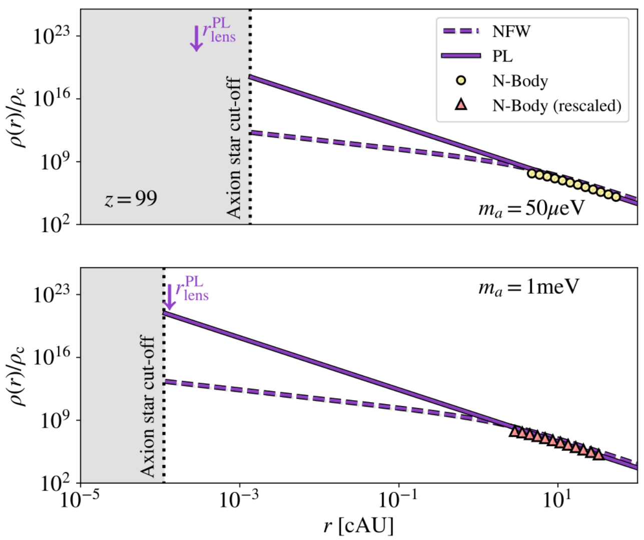
- microlensing of M31 stars *Fairbairn 17*

Expectations based on very optimistic th-MCs



Revisited after numerical simulations (optimistic)





Ellis 22

Need to study better NFWness of central profiles

Conclusions

- **QCD axion is a compeling DM candidate**

- **Post-inflationary scenario is free from IC uncertainty**
    - clear experimental target -> quick discovery?
    - other uncertainties are ~ small

- **Axion string radiation** not completely understood, q~1 and growing?
    - next generation simulations could answer

- Axion miniclusters
    - Typical **mass is uncertain** (decreases with increasing q)
    - bound fraction (~80%) and void density (~8%) not very sensitive!
    - **Conservative lower bound on intracluster density for experiments**

- We need experiments that can target the **10^{-4} eV mass** area
    - MADMAX (dielectric haloscope)
    - ALPHA (plasma haloscopes)
    - Dish antennas ....

tchüüüss

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