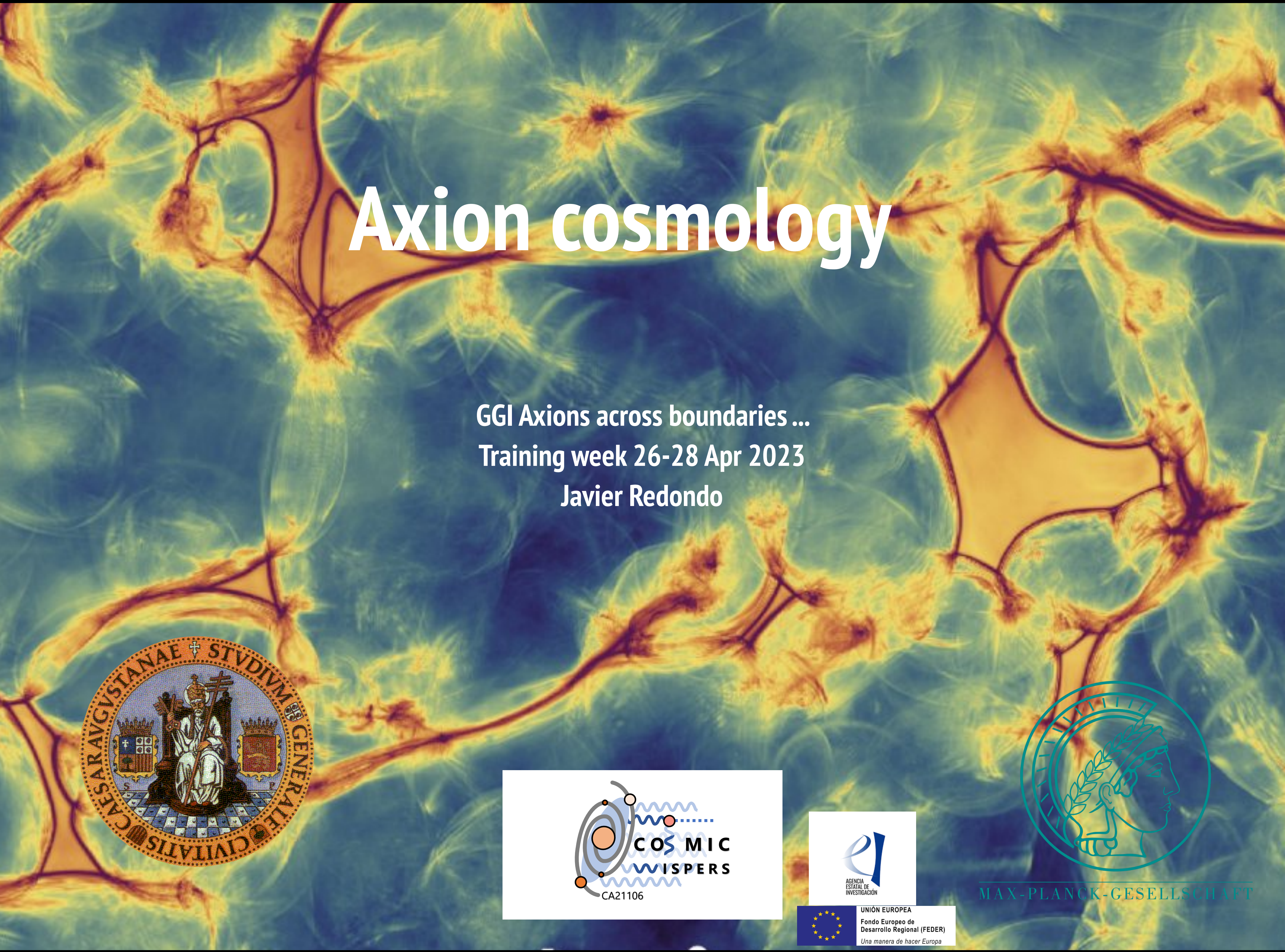


Axion cosmology

GGI Axions across boundaries …
Training week 26-28 Apr 2023
Javier Redondo

COSMIC WISPERS
CA21106

AGENCIA ESTATAL DE INVESTIGACIÓN

UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional (FEDER)
Una manera de hacer Europa

MAX-PLANCK-GESELLSCHAFT

outline

- thermal axion production

- misalignment, pre/post inflationary

- isocurvature fluctuations

- post-inflationary scenario

- cosmic strings and walls

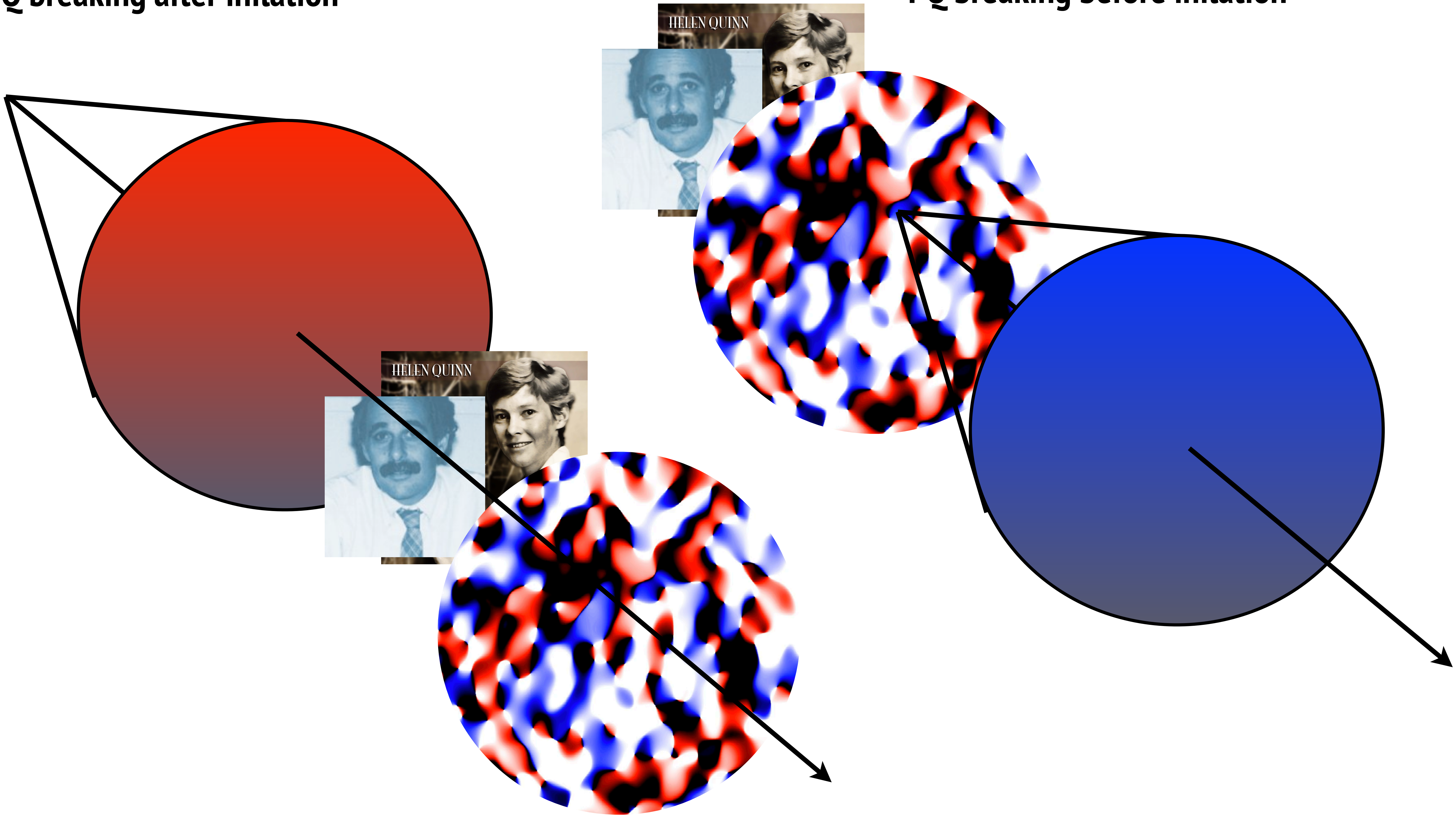
- axion miniclusters

- axion stars

Two (main) scenarios

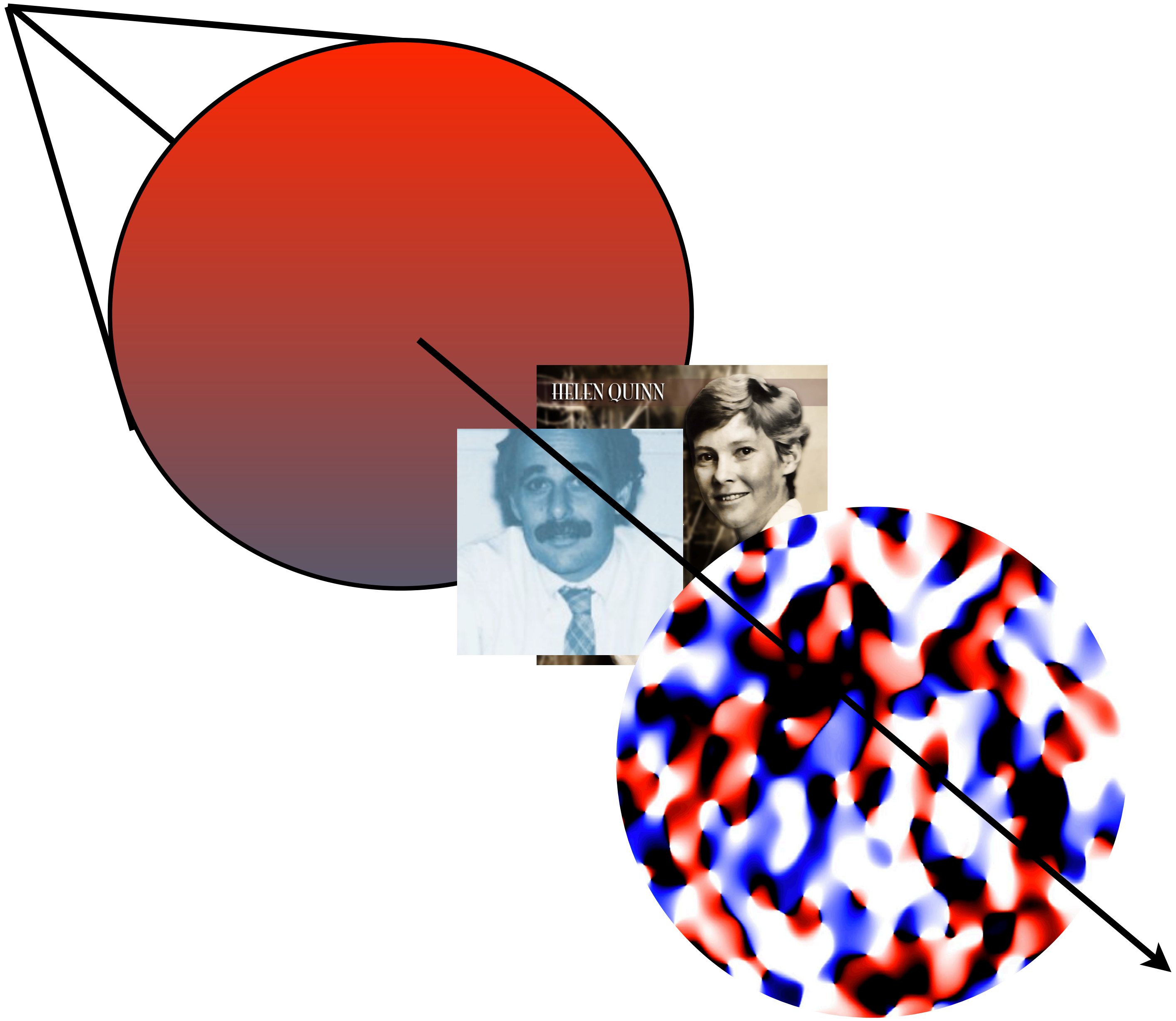
- PQ breaking after inflation

- PQ breaking before inflation



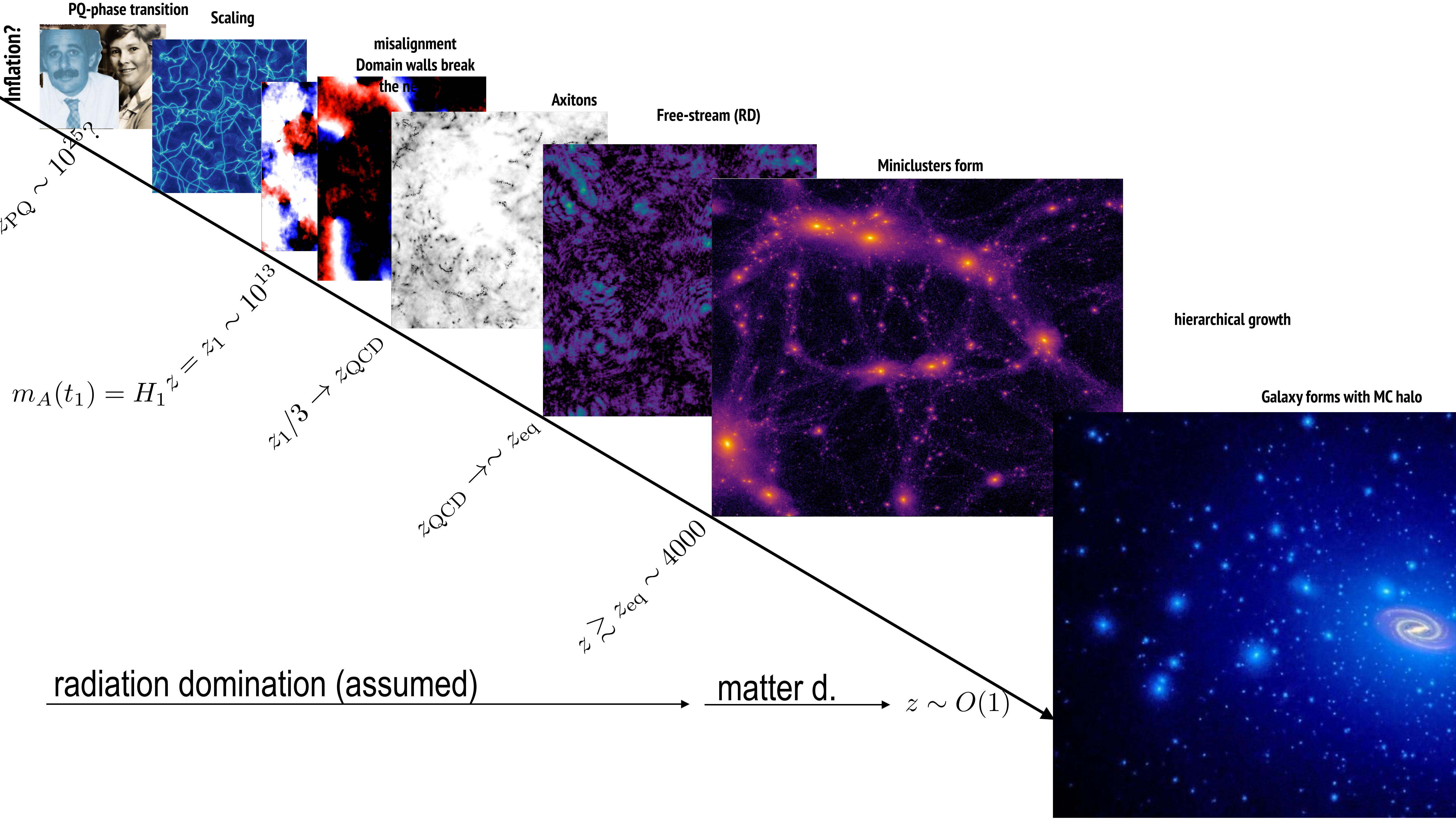
Post inflationary PQ breaking scenario

- PQ breaking after inflation



- No uncertainty over initial conditions
- All values of $\theta 0$ realised in different early causally disconnected patches all inside our Universe today
- DM is inhomogeneous at small scales
- Small scale DM halos (Miniclusters)
- Problems with topological defects

Post inflationary PQ breaking scenario



Inflation?

PQ-phase transition

Scaling

misalignment

Domain walls break

the ne

Axitons

Free-stream (RD)

Miniclusters form

hierarchical growth

Galaxy forms with MC halo

$z_{PQ} \sim 10^{25}$?

$m_A(t_1) = H_1$ $z = z_1 \sim 10^{13}$

$z_1/3 \to z_{QCD}$

$z_{QCD} \to \sim z_{eq}$

$z \gtrsim z_{eq} \sim 4000$

radiation domination (assumed)

matter d.

$z \sim O(1)$

axion dark matter abundance

- Misalignment contribution ... average over initial angles?

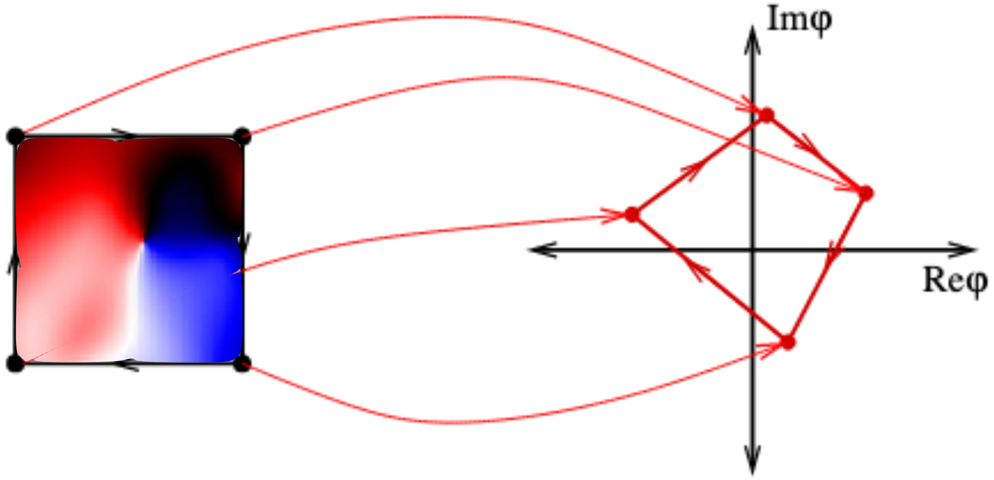
$$\rho_a(t) \simeq \theta_0^2 \chi(t_1) \frac{m_A}{m_A(t_1)} \left(\frac{R_1}{R(t)} \right)^3 \to \langle \theta_0^2 \rangle \chi(t_1) \frac{m_A}{m_A(t_1)} \left(\frac{R_1}{R(t)} \right)^3$$

this assumes exact zero mode, but correlation length is not infinite

- Most of the energy in the axion field is now NOT in the zero modes ...

At PQ phase transition a network of GLOBAL COSMIC STRINGS FORM! *Kibble 76*

Global string is a 1D region that is topologically (i.e. forced by boundry conditions) to take all values of θ



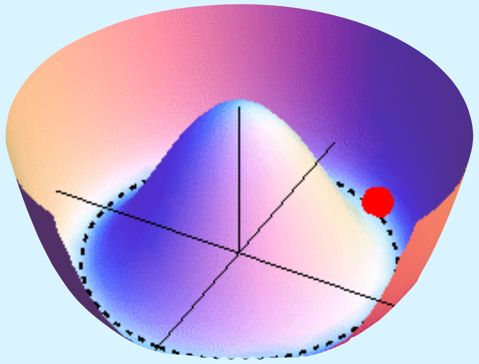
Formally, energy would be infinity, practice is regulated by the UV completion of axion theory

Simple model KSVZ

- Peccei-Quinn symmetry, color anomalous, spontaneously broken at f_a

$$\mathcal{L} \ni +i\bar{Q}DQ + \frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi^*) - (y\bar{Q}_L Q_R\phi + \mathrm{h.c}) - \frac{1}{4}\lambda(|\phi|^2 - v^2)^2$$

$$\phi(x) = r(x)e^{ia(x)/f_A} \quad , \quad f_A = v \quad , \quad m_r = \sqrt{2\lambda}f_A$$

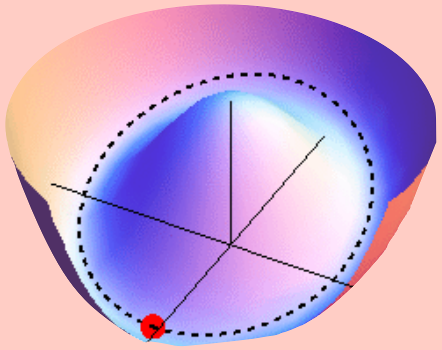


- At energies below f_a**(SSB)**

$$\mathcal{L} \in \frac{1}{2}(\partial a)^2 + \frac{\alpha_s}{8\pi}G\widetilde{G}\frac{a}{f_a}$$

- At energies below $\Lambda_{\rm QCD}$, $a - \eta' - \pi^0 - \eta - \ldots$ **mixing**

axion mass $m_a \simeq \frac{m_\pi f_\pi}{f_a} \sim 6\mathrm{meV}\frac{10^9\mathrm{GeV}}{f_a}$



couplings $\mathcal{L}_{a,I} = \sum_N c_{N,a}\bar{N}\gamma^\mu\gamma_5 N\frac{a}{f_a} + c_{a\gamma}\frac{\alpha}{2\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}\frac{a}{f_a} + \ldots$

nucleons ... photons ... mesons ...

ENERGY

~GeV

~f_a

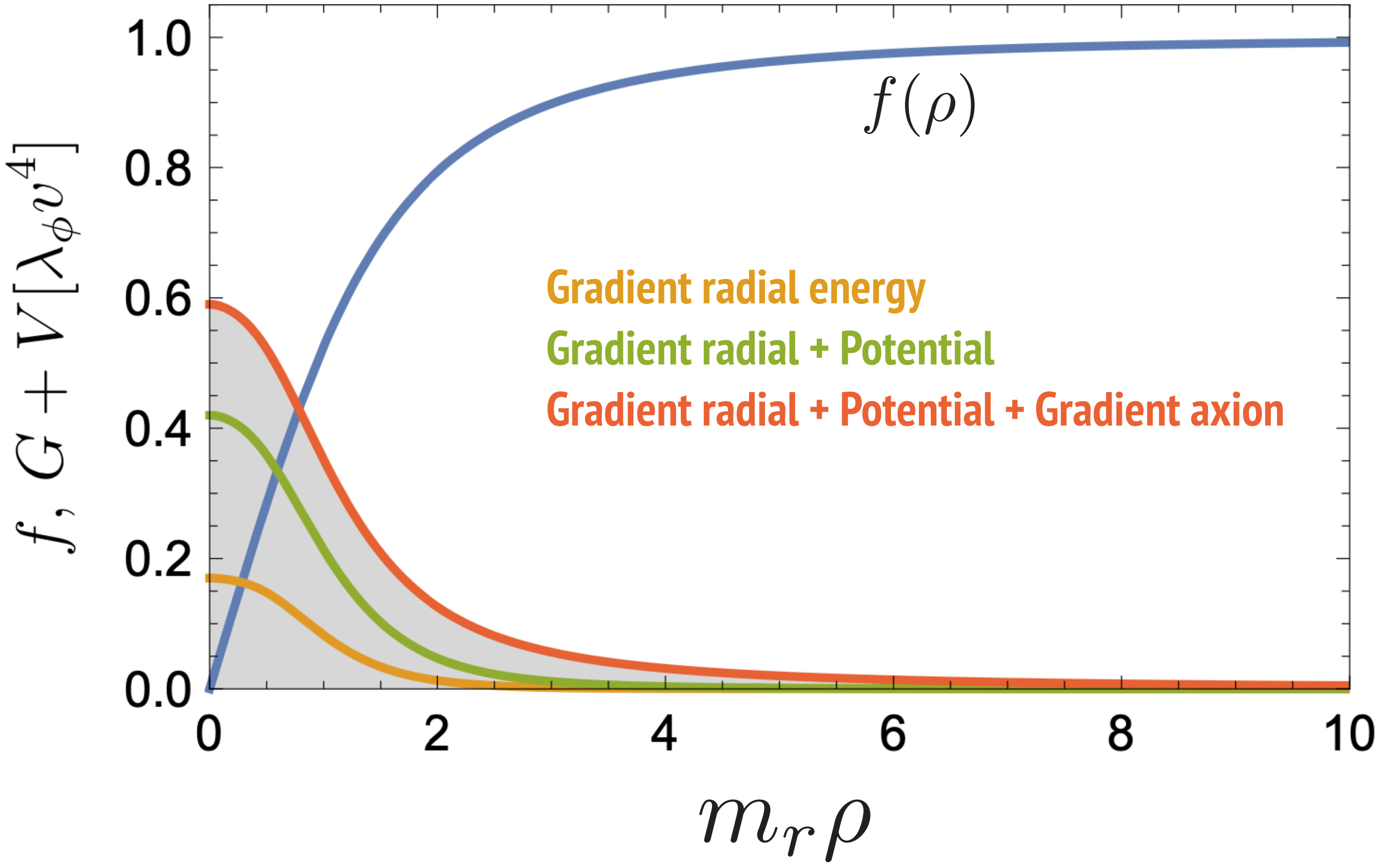
Global strings solution

- **Force** $\phi = v f(\rho) e^{i\varphi}$ $(\rho, \varphi, z, \text{cylindrical coordinates})$

i.e. θ wraps 2pi around the origin ...

- **Static EOM for the radial field**

$$\left[\frac{f_\rho + \rho f_{\rho\rho}}{\rho} - \frac{f}{\rho^2}\right] = \lambda_\phi v^2 f(f^2 - 1)$$



- **Energy/length (string tension)**

$$\mu \sim 2\pi v^2 \int \rho d\rho \left(f_\rho^2 + m_r^2 (f^2 - 1)^2 + \frac{f^2}{\rho^2} \right) \sim v^2 \left(2.6 + \pi \log \frac{m_r \rho}{1.55} \right)$$

logaritmic divergence from $\frac{1}{\rho}\frac{\partial \phi}{\partial \varphi}$

Global string network

- Strings have no end, form loops

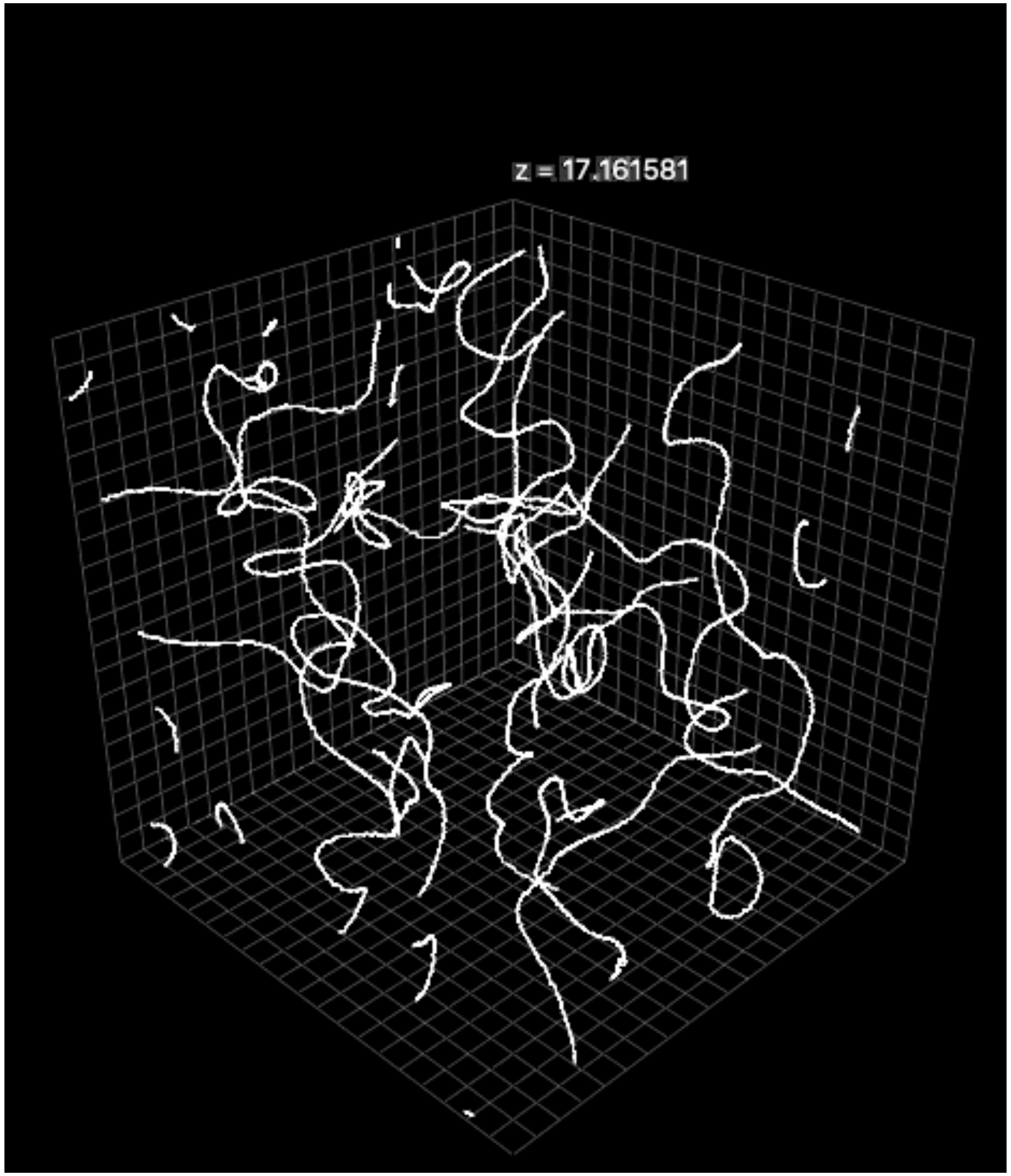
- Dynamics:
  - Strings straighten, intersect, loops collapse
  - Energy released in GWs, axions (mostly)
  - relativistic speeds
  - limited by causality
  - scaling solution

$$\frac{\text{string length}}{\text{causal volume}} \sim \frac{d_H}{d_H^3}$$

  - energy density of network

$$\frac{\mu d_H}{d_H^3} \sim \mu H^2 \sim f_A^2 H^2 \log \frac{m_r}{H}$$

typical distance between strings $\rho \sim d_H = 1/H$



axion dark matter abundance at t_1

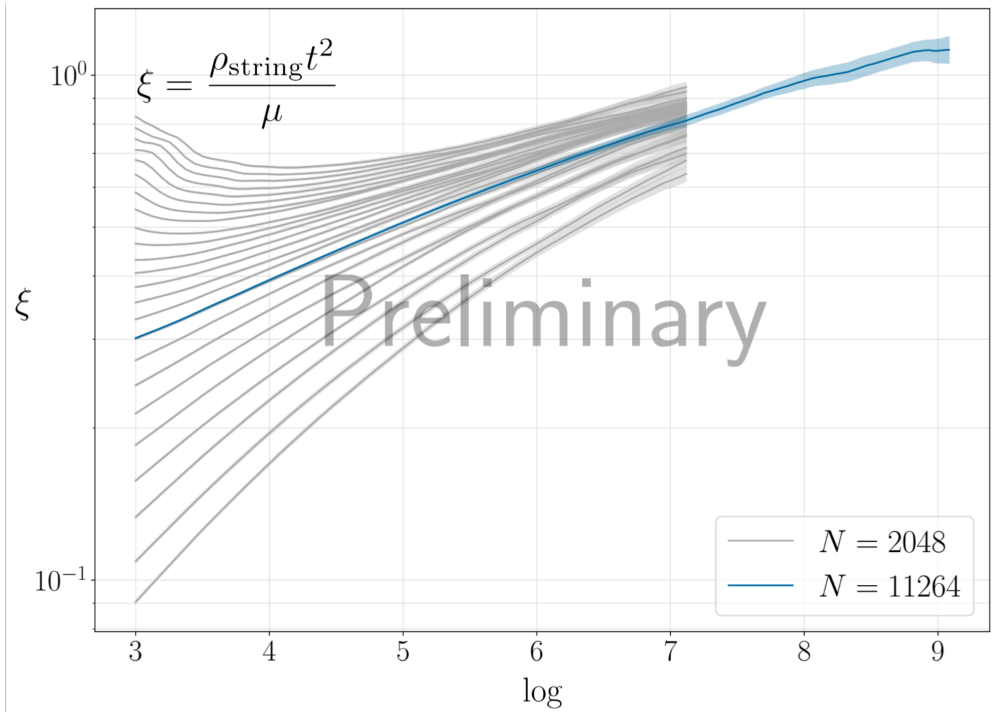
- **Misalignment contribution …** $H_1 = m_A(t_1)$

$$\rho(t_1) \sim f_A^2 H_1^2 \quad , \quad n_1 \sim f_A^2 H_1$$

- **Most of the energy in the axion field is in axion GRADIENTS around the strings**

$$\rho_s \sim f_A^2 H^2 \log \frac{m_r}{H} \times \xi$$

$$\xi = \frac{\frac{\text{string length}}{\text{causal volume}}}{\frac{d_H}{d_H^3}}$$



Saikawa 23

density doubly log enhanced… xi grows logarithmically

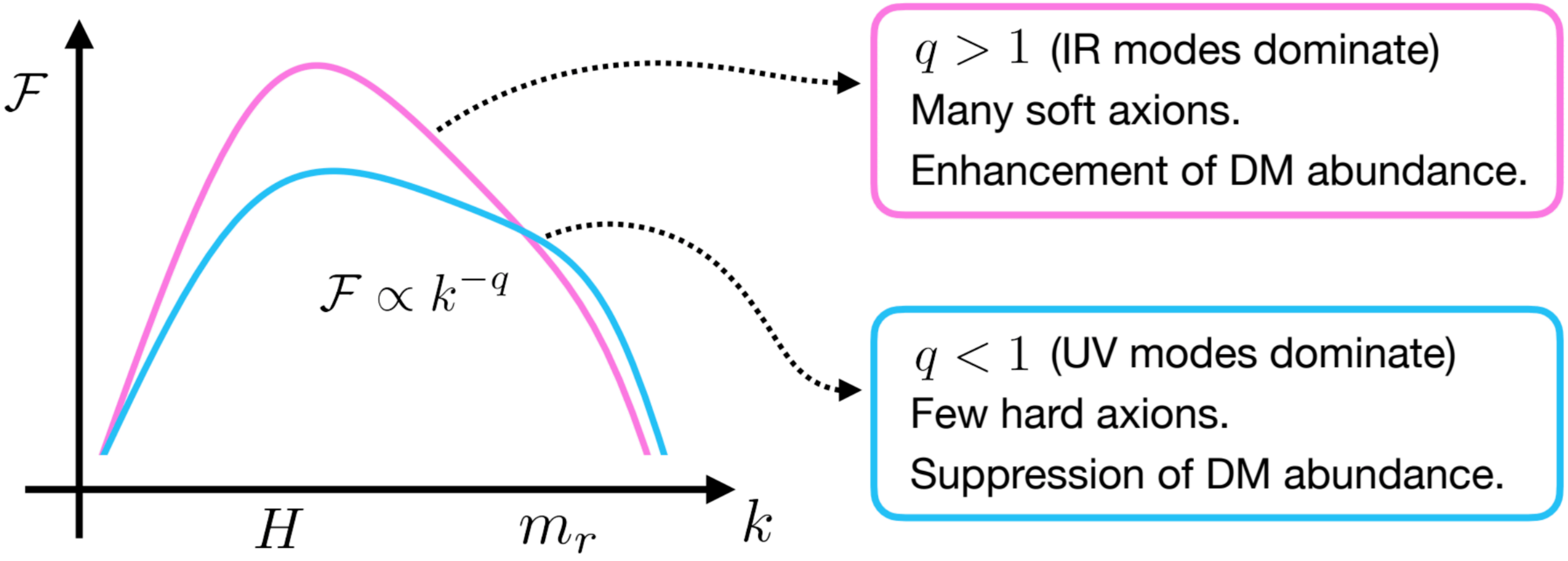
Axions emitted from cosmic strings can easily superseed misalignment average!!!

axions from strings

- **The AXION NUMBER radiated by strings depends on the AVERAGE RADIATED ENERGY**

Differential energy transfer rate

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



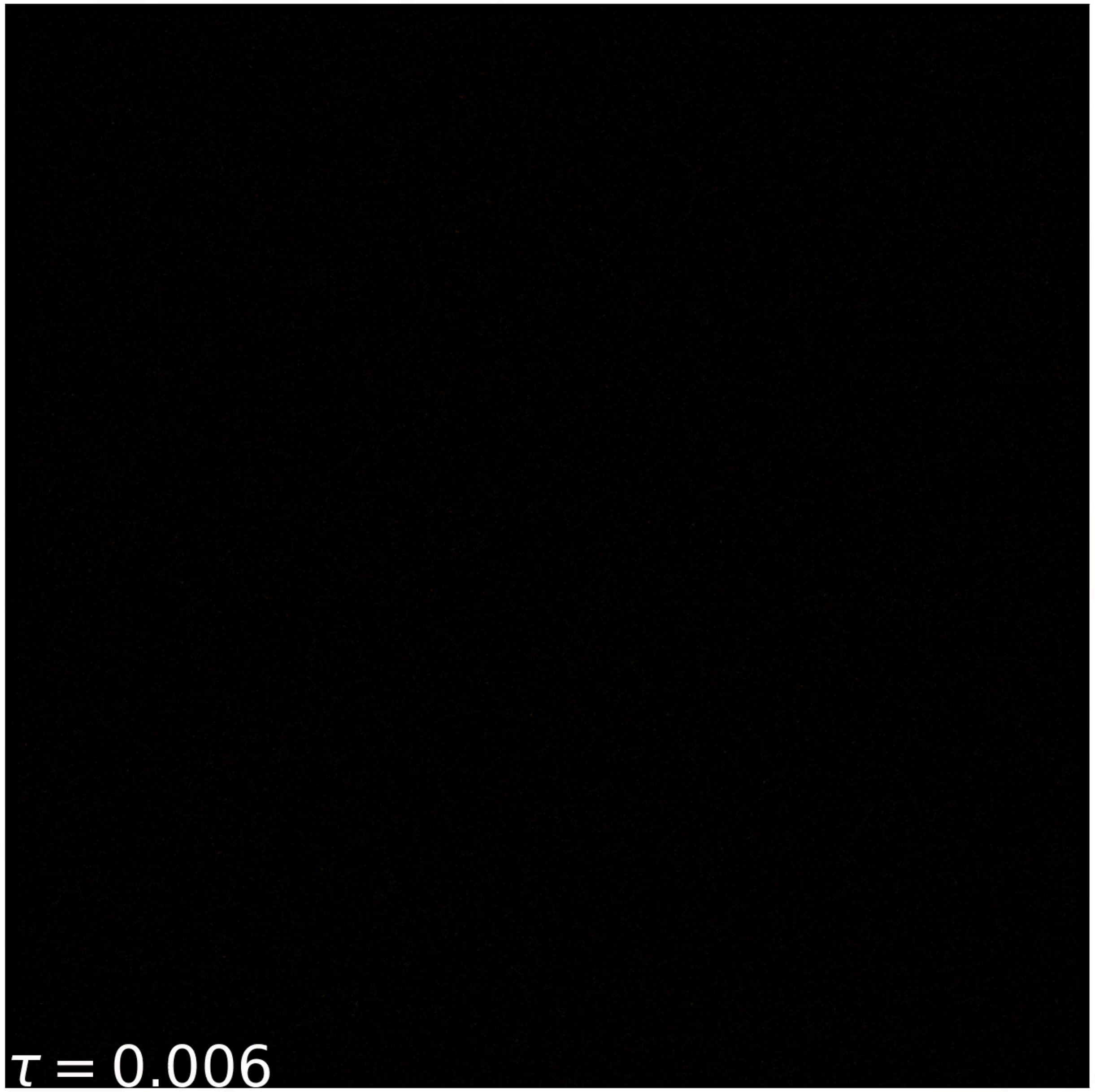
$q > 1$ (IR modes dominate)
Many soft axions.
Enhancement of DM abundance.

$q < 1$ (UV modes dominate)
Few hard axions.
Suppression of DM abundance.

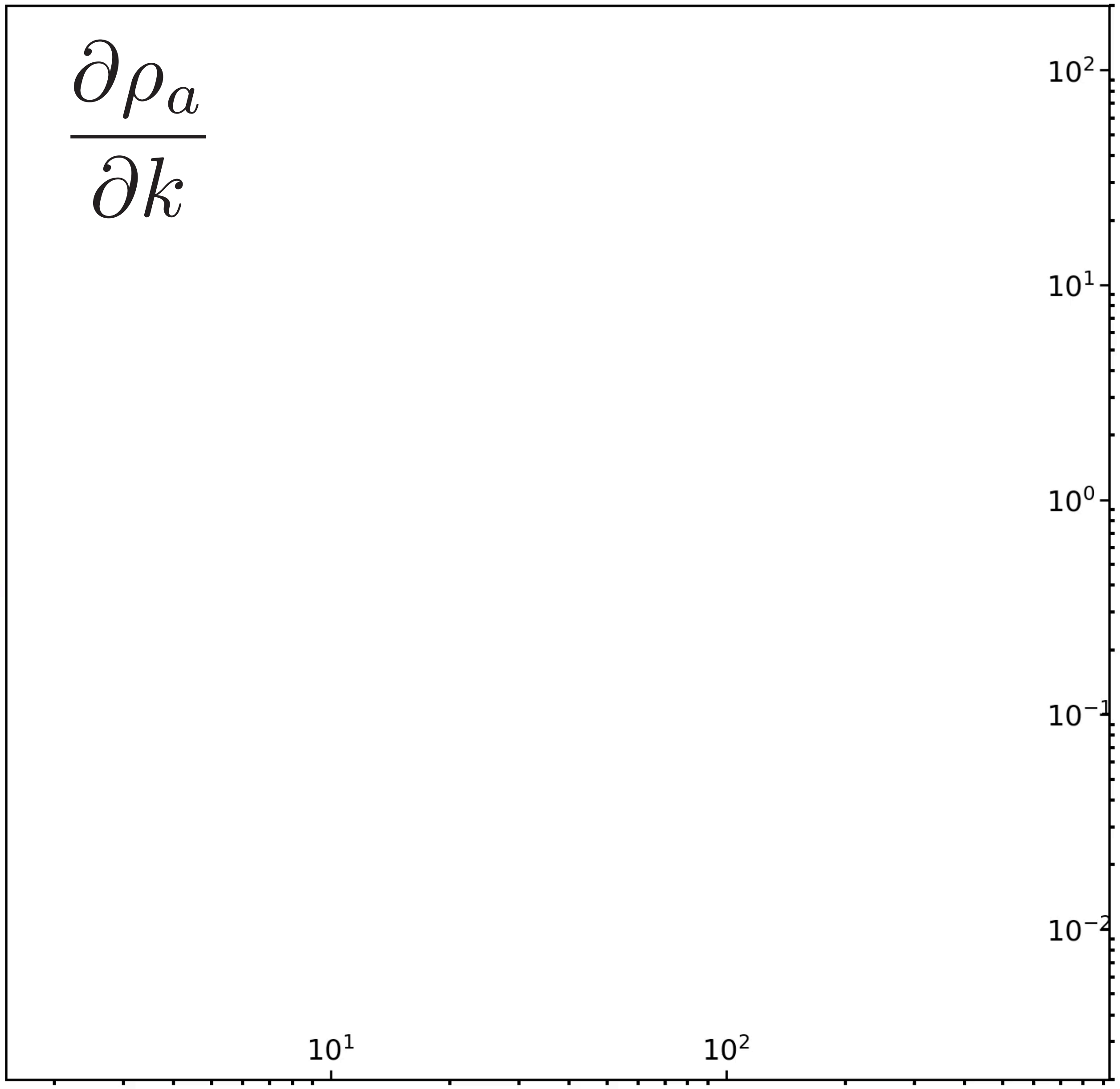
numerical simulations

- Simulate complex scalar field in N^3 cartesian grids (N~11000)
- Calculate axion spectrum at several times
- Calculate time derivative and measure q

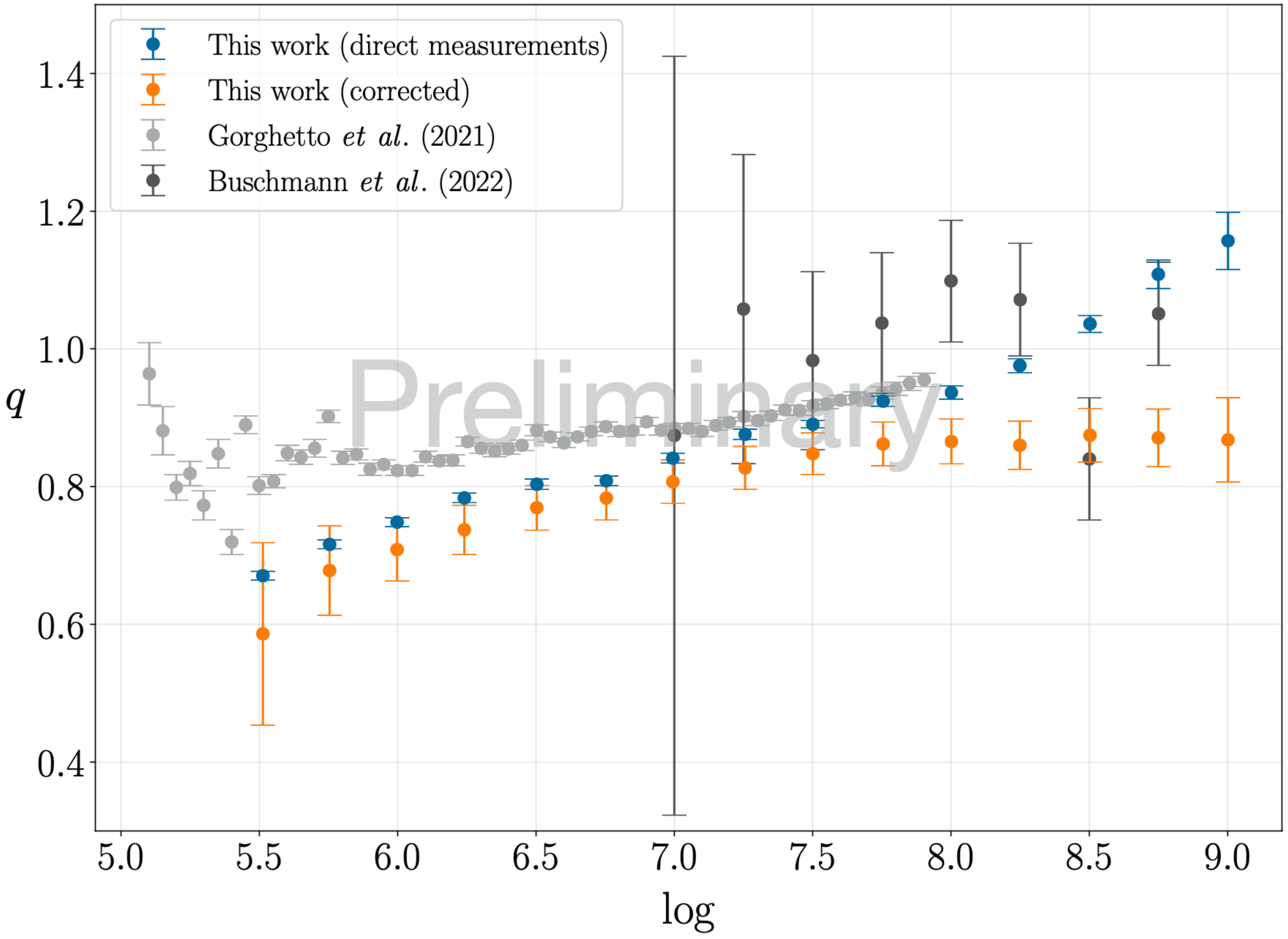
Energy density proyection plot



Spectrum (PRS strings)

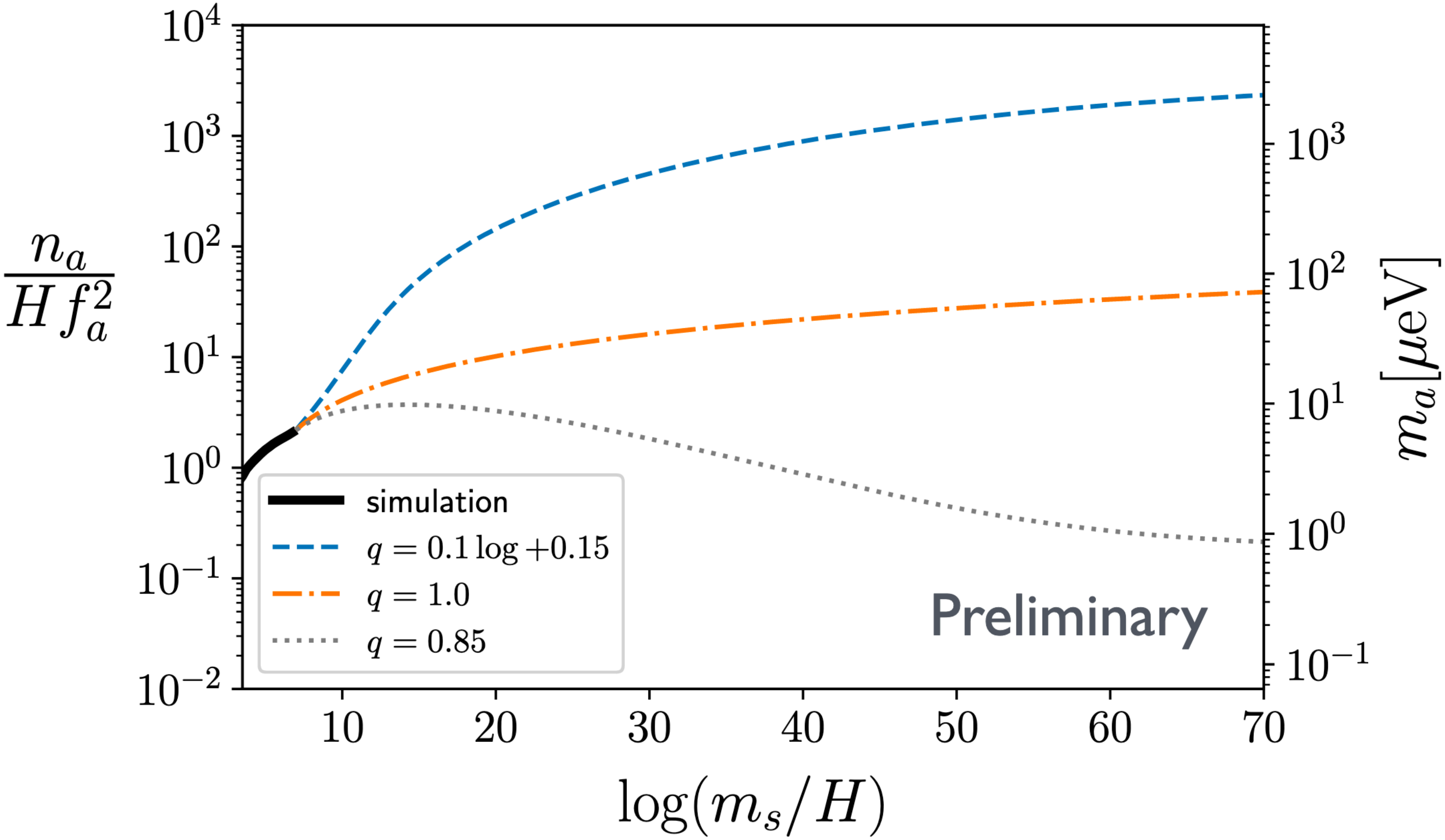


state of the art numerical simulations



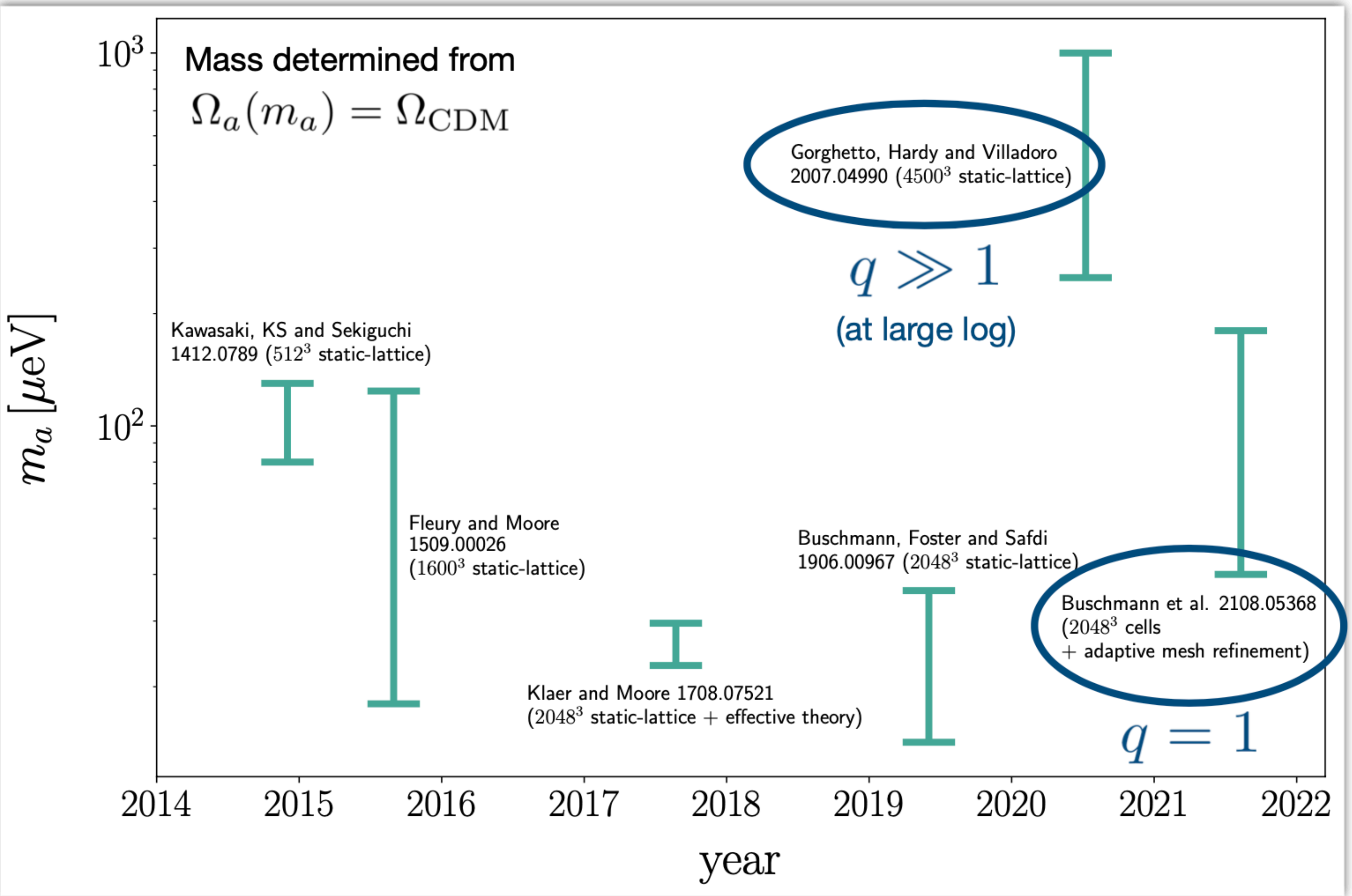
Saikawa 23

extrapolation



axion DM mass

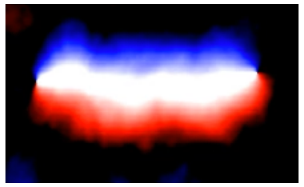
- For which value of mA (fA) do we obtain the observed DM abundance in the post-inflationary scenario?



Saikawa 23

Domain walls and the end of the network

- The scaling solution continues as long as the U(1) is a good symmetry
- Axion potential becomes relevant around t1 to favour θ=0
- Domain walls form attached to the strings



- Regions of θ~π, trapped by boundary conditions
  (θ wraps 2π around the string)
- Form membranes attached to strings
- Energy / Area ~ $\dfrac{\chi \times A \times m_A^{-1}}{A} \sim m_A f_A^2$
- All DW energy density (1 DW per Horizon)

$$\rho_{\rm DW} \simeq \frac{m_A f_A^2 d_H^2}{d_H^3} \sim m_A H f_A^2$$

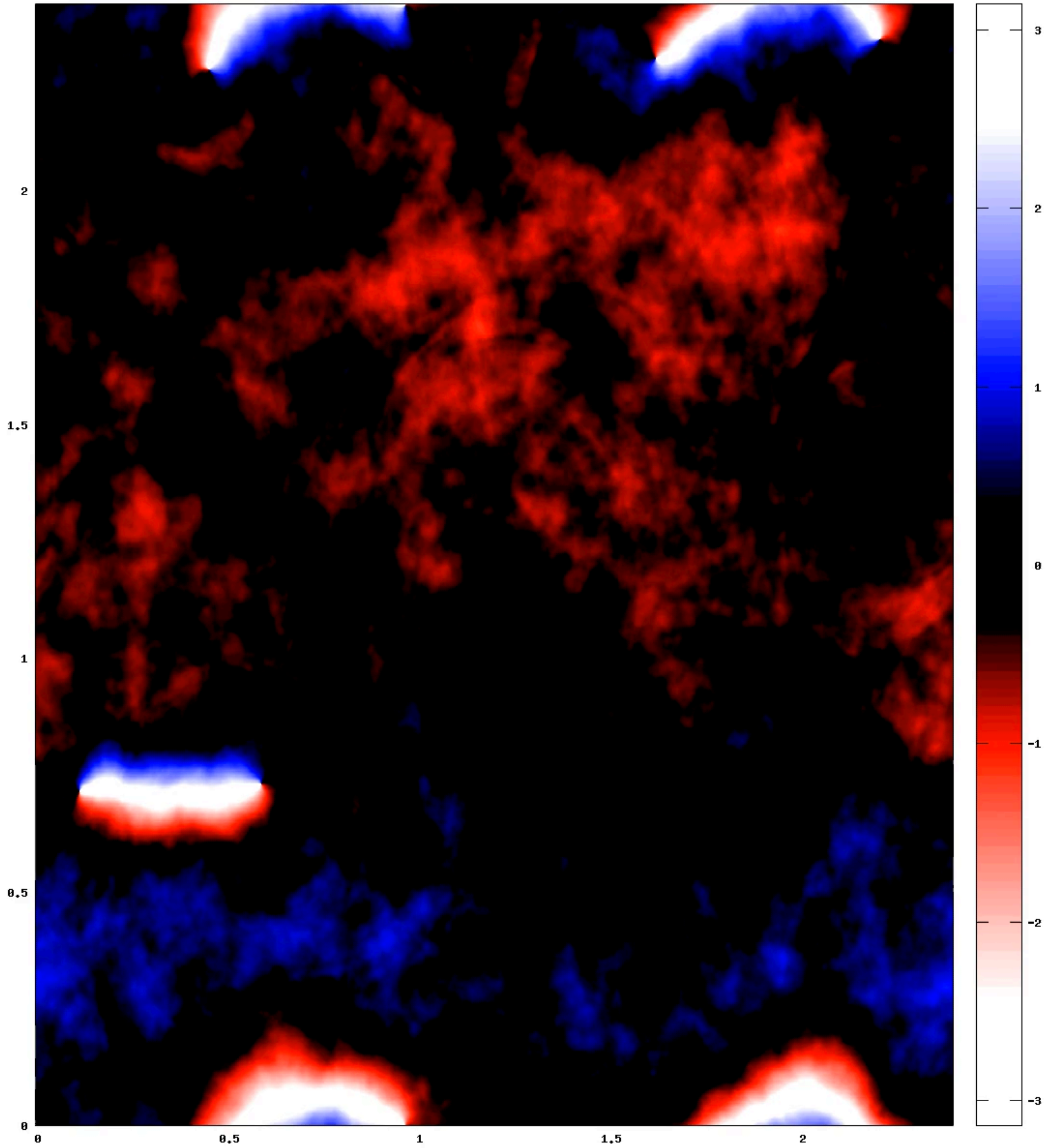
- DWs VS strings ...

$$\rho_{\rm s} \sim H^2 f_A^2 \log^2$$

$$\rho_{\rm DW} > \rho_{\rm s} \rightarrow \frac{m_A}{H} \sim (t/t_1)^{n/4+1} \gg \log^2$$

$$\rho_{\rm DW} \sim \rho_{\rm s} \rightarrow \frac{m_A}{H} \sim (t/t_1)^{n/4+1} \sim \log^2$$

shortly after t1, they dominate and pull the strings to destruction

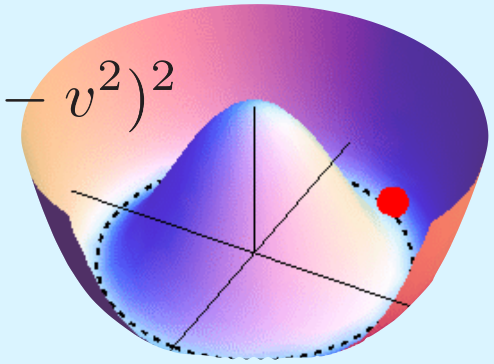


Domain Wall problem

- All said is fair for the simplest KSVZ model with exactly 1 extra quark
- When N>1 the situation is VERY different

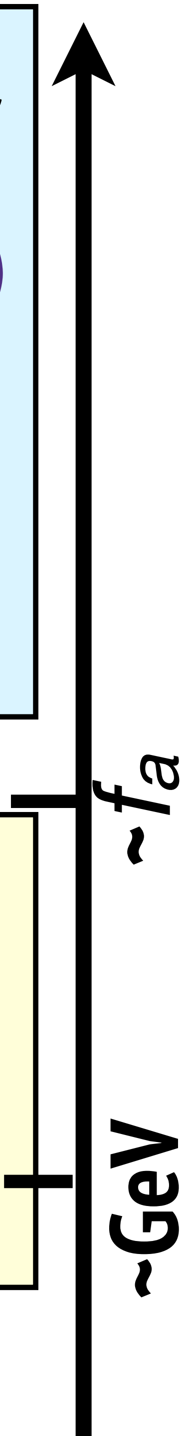
- Peccei-Quinn symmetry, color anomalous, spontaneously broken at f_a

$$\mathcal{L} \ni +i\sum_Q \bar{Q}DQ + \frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi^*) - \sum_Q (y_Q\bar{Q}_L Q_R\phi + \mathrm{h.c}) - \frac{1}{4}\lambda(|\phi|^2 - v^2)^2$$



$$\phi(x) = r(x)e^{ia(x)/f_A} \quad , \quad f_A = v \quad , \quad m_r = \sqrt{2\lambda}f_A$$

physically $\frac{a}{f_A} \equiv \theta \in [0, 2\pi), [0] \equiv [2\pi n]$ **is the angle of a complex scalar !**

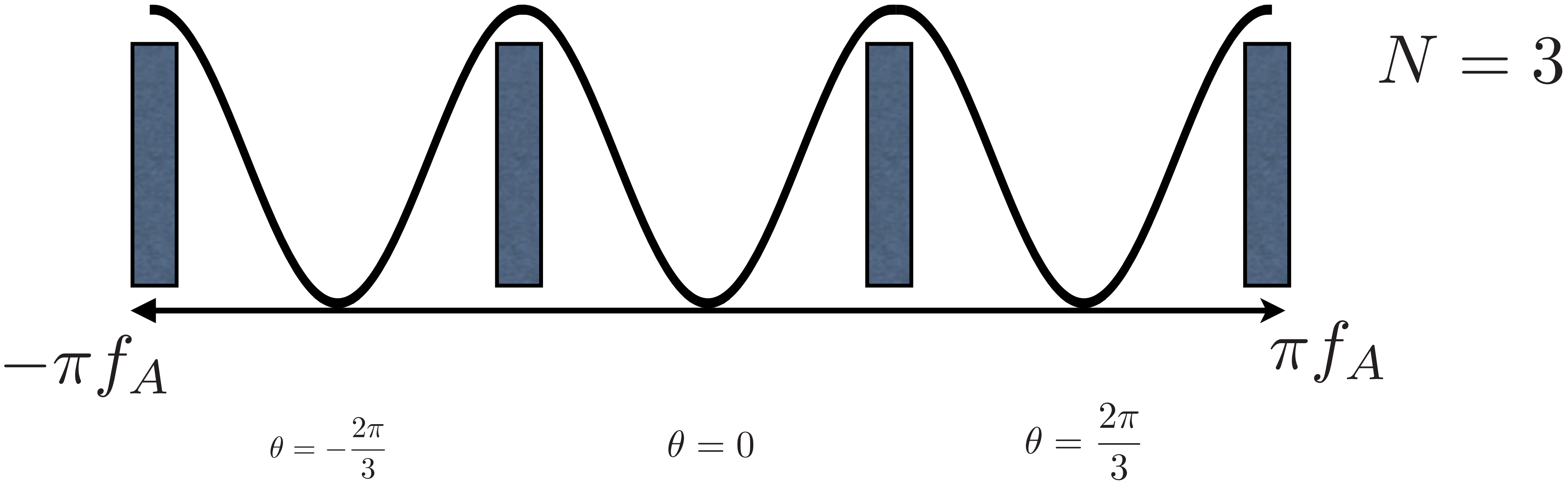


- At energies below f_a**(SSB)** $\mathcal{L} \in \frac{1}{2}(\partial a)^2 + \frac{\alpha_s}{8\pi}G\widetilde{G}\frac{a}{f_a} \times N$

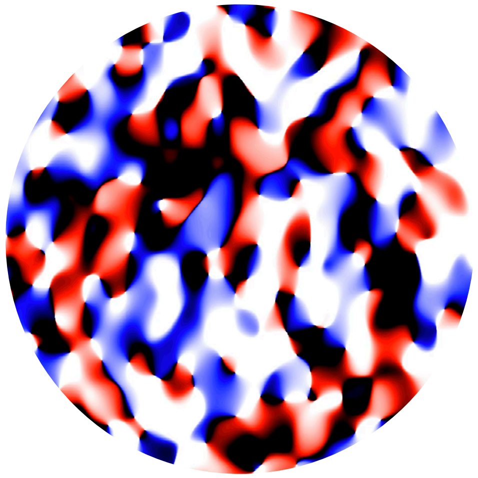
$$V(\theta) = \chi_T(1 - \cos(N\theta))$$

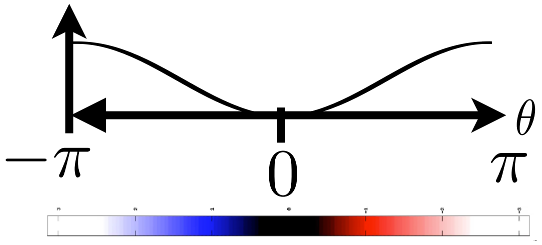
Domain wall problem

- The physical field theta can experience N times the QCD potential
- There are N degenerate CP conserving vacua
- There are N domain walls separating these pysically different vacua!



- All these values are populated after the PQ phase transition

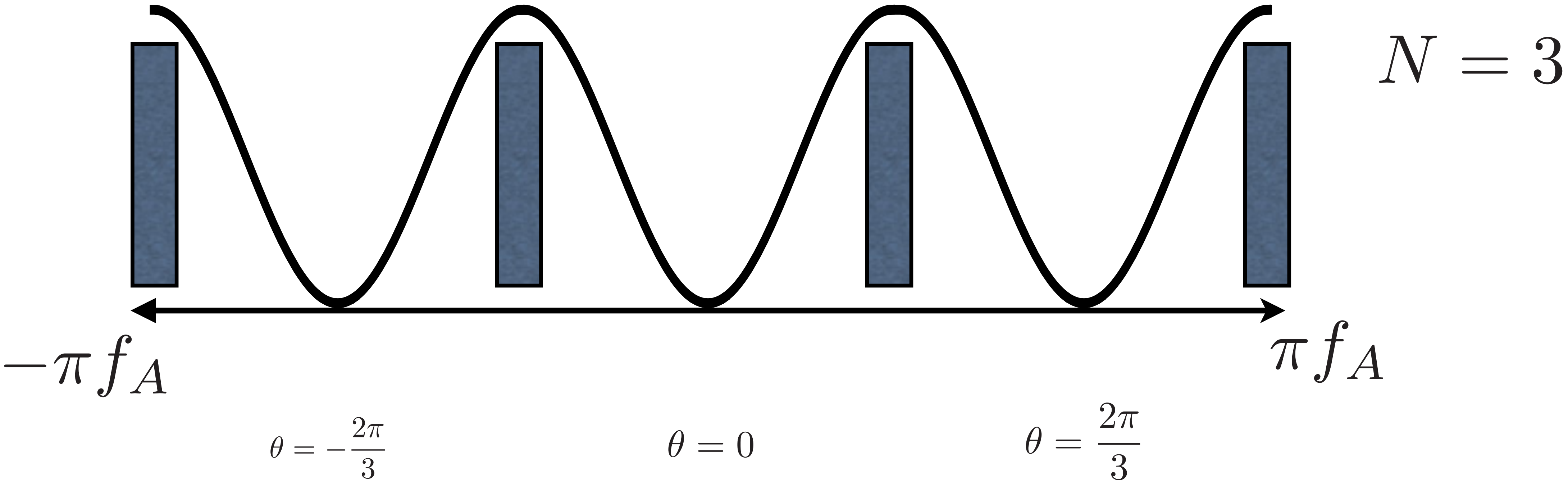




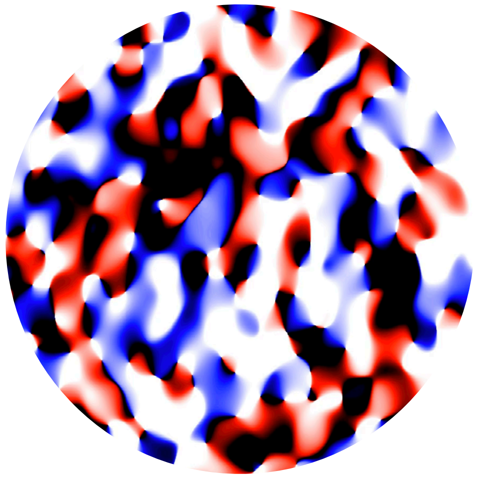
- But now cosmic strings have no preferred direction to collapse at t_2, no preferred vacuum!

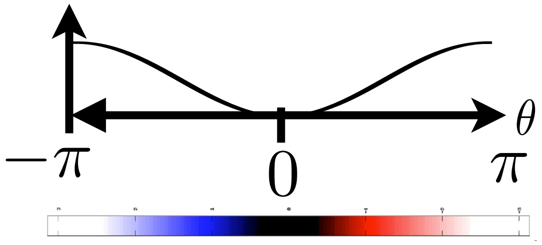
Domain wall problem

- The physical field theta can experience N times the QCD potential
- There are N degenerate CP conserving vacua
- There are N domain walls separating these pysically different vacua!



- All these values are populated after the PQ phase transition





- But now cosmic strings have no preferred direction to collapse at t_2, no preferred vacuum!

Simulations N=2

movie!

Domain wall problem

- String network cannot collapse
- Energy is dominated by domain walls

$$\rho_{\rm DW} \simeq \frac{m_A f_A^2 d_H^2}{d_H^3} \sim m_A H f_A^2$$

$$\rho_{\rm DW} \sim \frac{1}{t} \sim \frac{1}{R^2}$$ **Radiation domination**

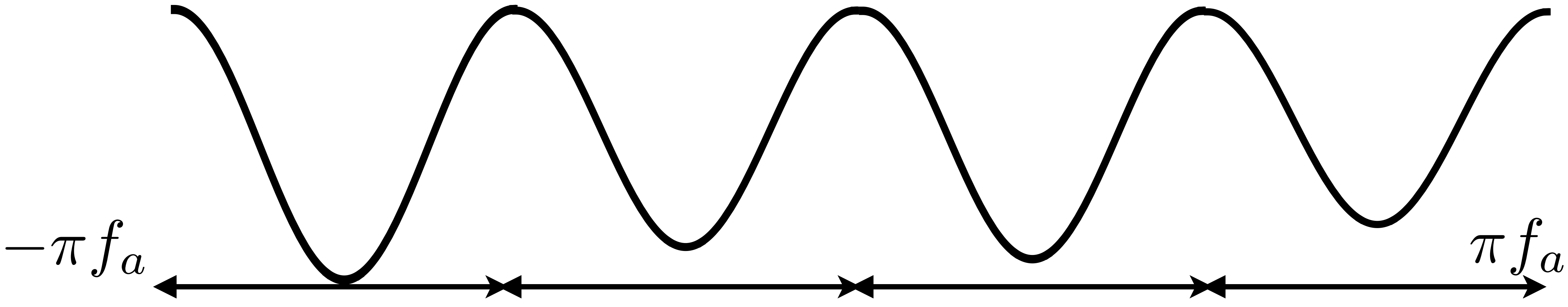
$$\rho_{\rm DW} \sim \frac{1}{t} \sim \frac{1}{R^{3/2}}$$ **Matter domination**

- Energy density in the DW network redshifts much slower than Rad or Matter and quickly dominates the Universe... (the problem is that we do not observe it!

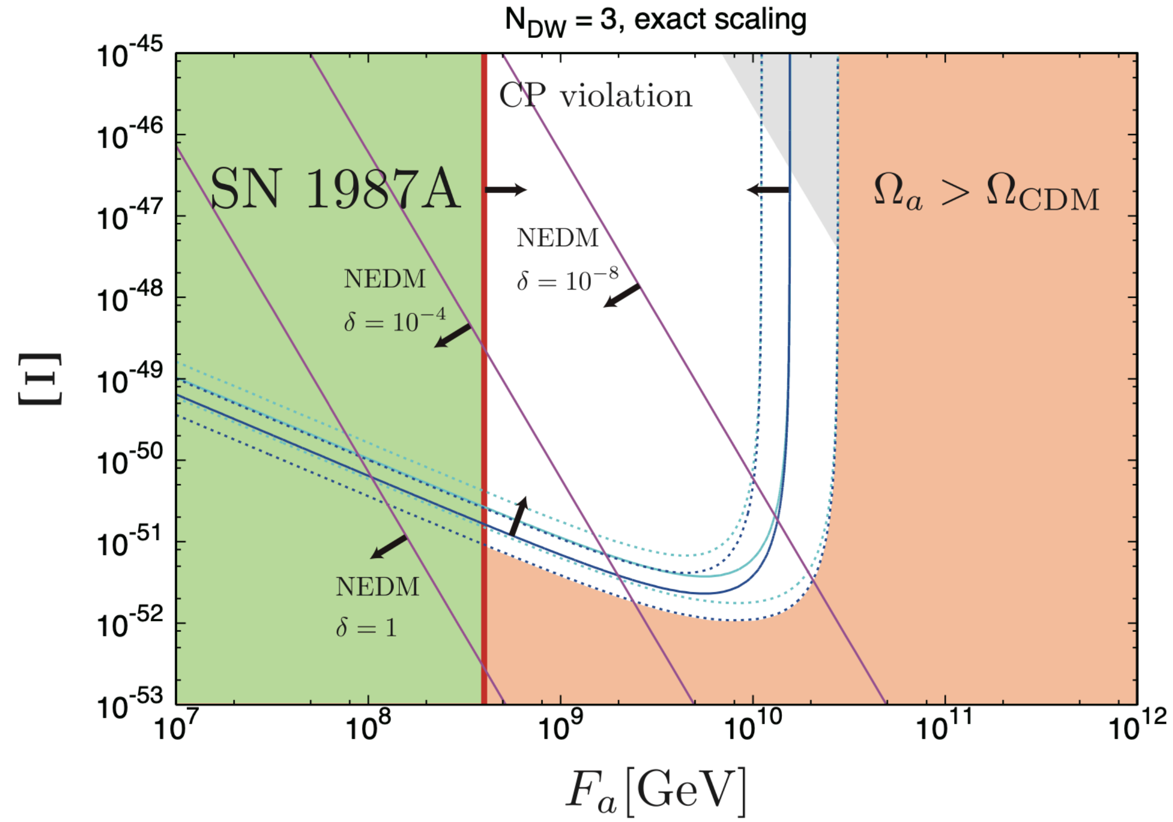
Domain wall problem … solutions

- Break degeneracy between vacua (break explicitly PQ… expected to some extent

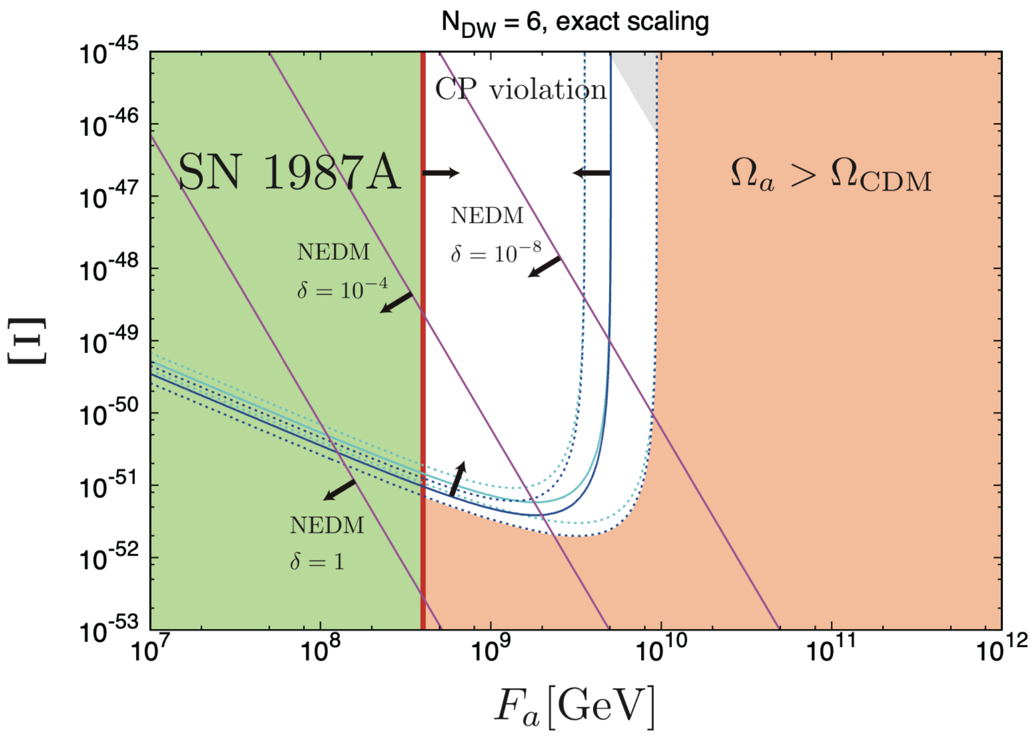
$$V_{\rm bias}(\Phi) = -\Xi\eta^3\left(\Phi e^{-i\delta} + {\rm h.c.}\right)$$



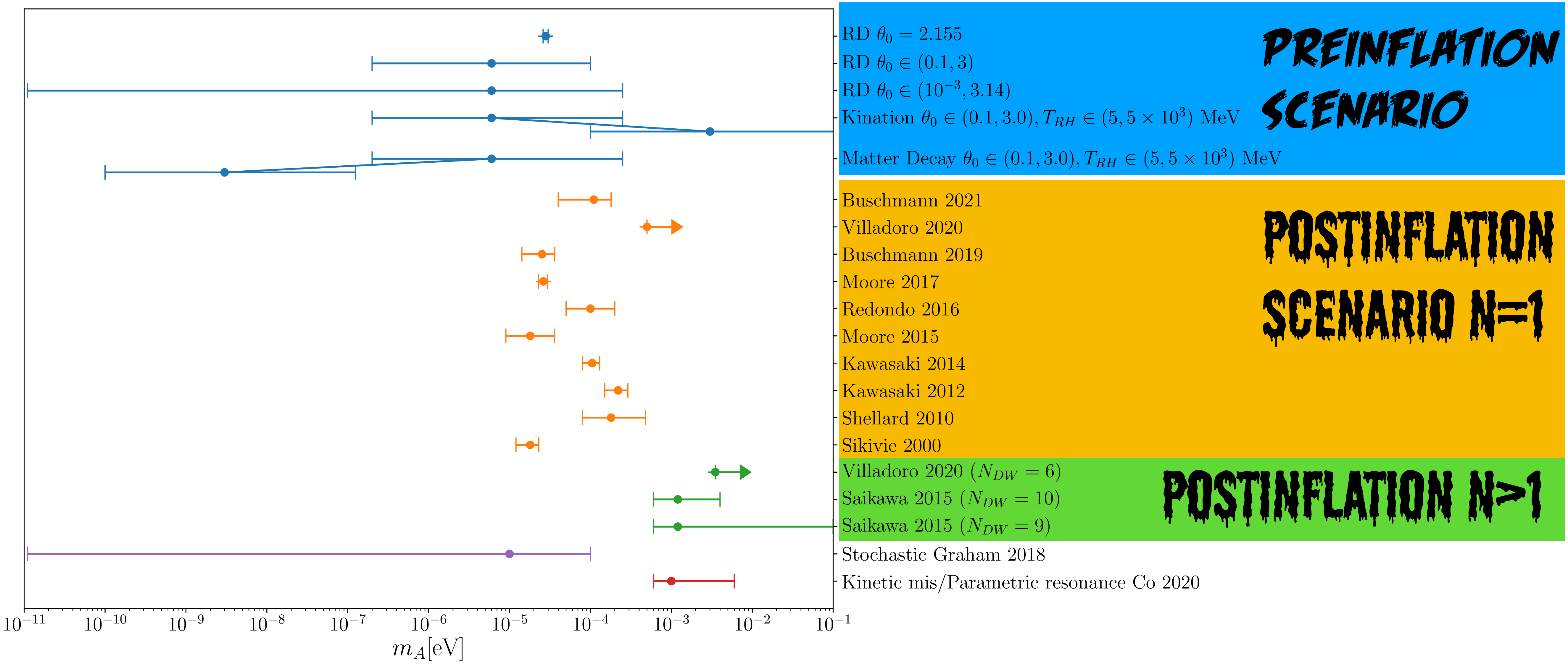
- But watch out not to spoil axion solution to strong CP problem (or overproduce DM)



Saikawa 2014

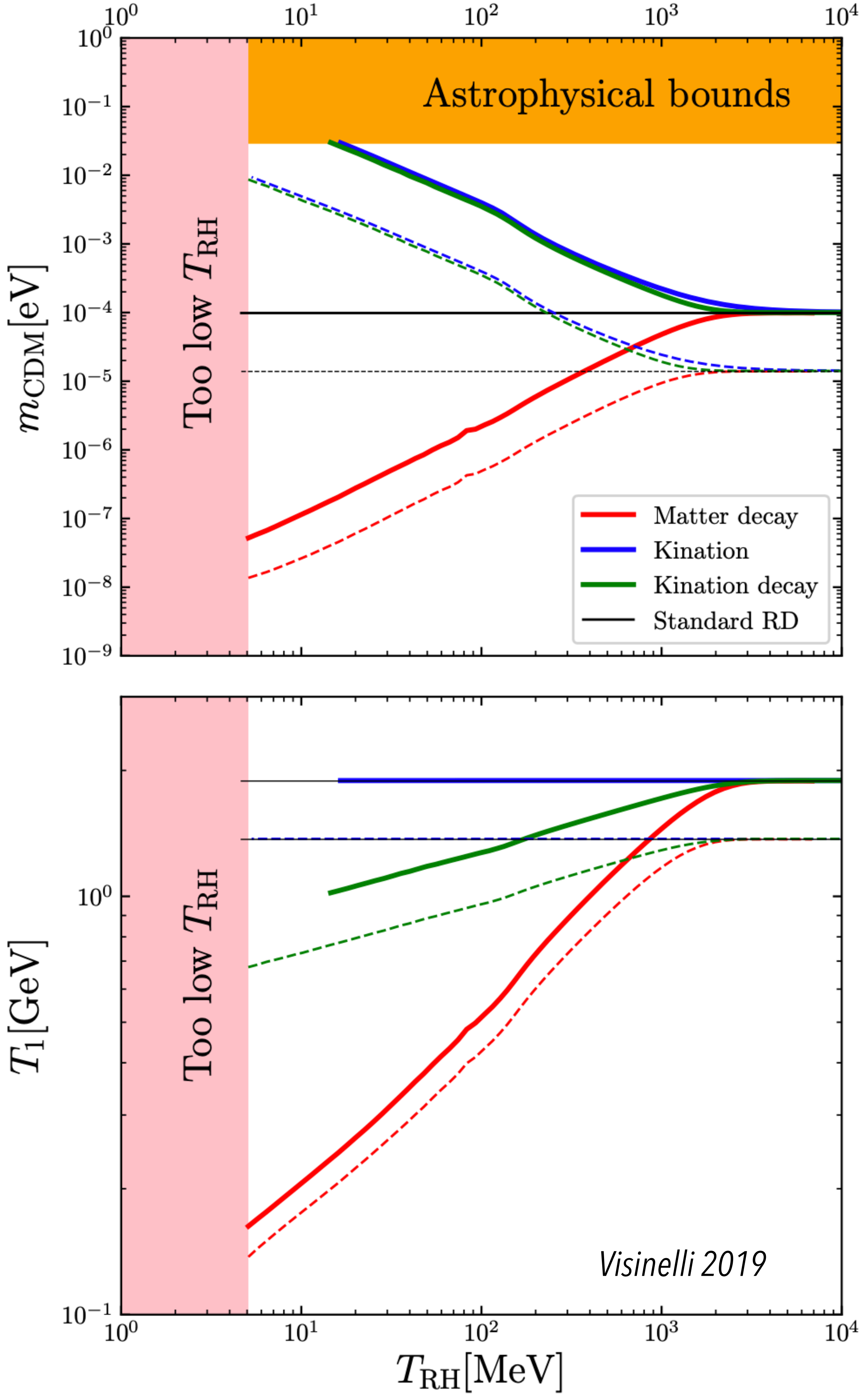


Axion DM mass



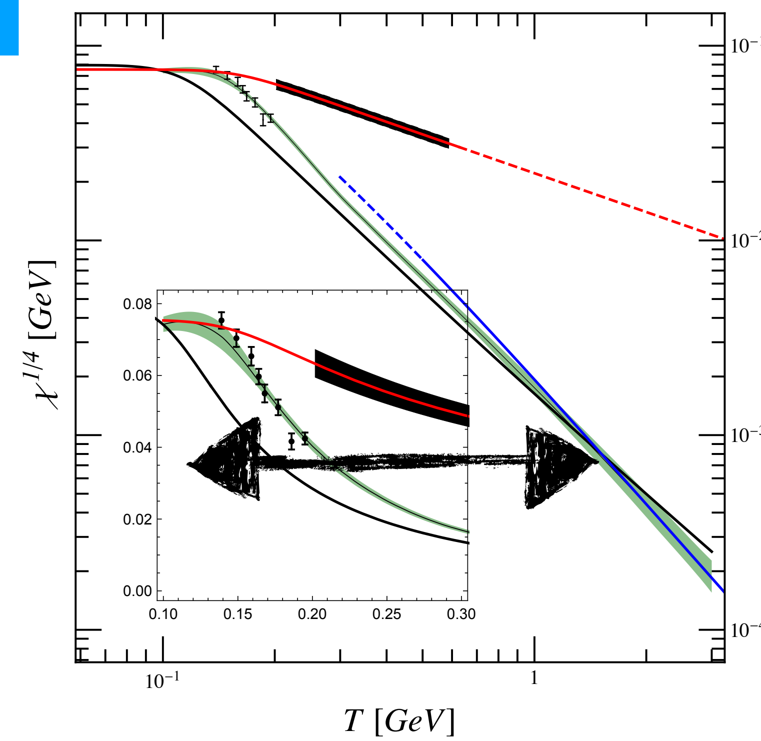
Alternative cosmologies

- Domination of other fluids at t_1, changes dilution factors



Visinelli 2019

Axion miniclusters

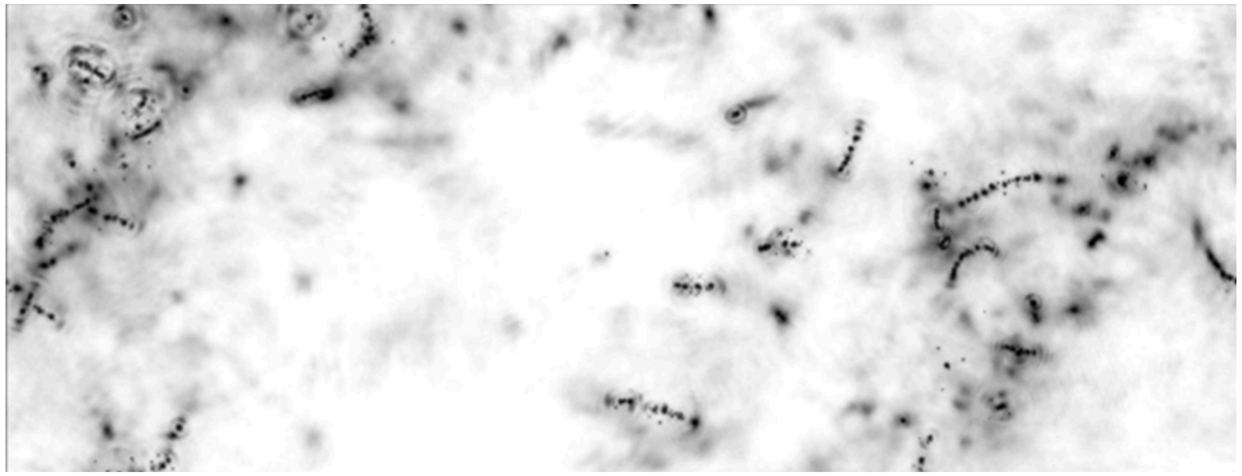


- Shortly after t_2 "ZERO" mode axions (H_1) are extremely non-relativistic

(mA continues to grow after H_1 by a factor of 10^4 or so ...)

- The density field essentially freezes

*Some non-linearities appear at very dense regions (axitons)
axions have attractive self-interactions
recurrently collapse and explode as bose-novas
until the density is low enough

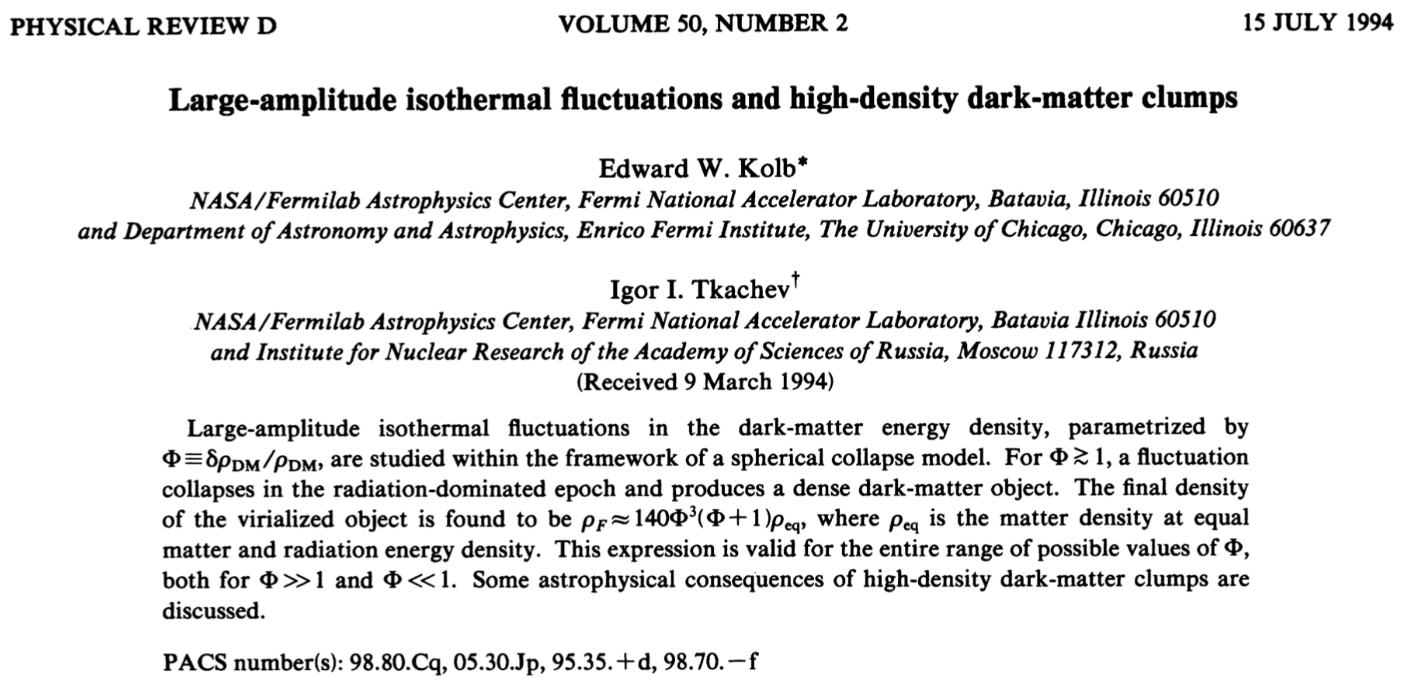


- The density field essentially freezes but it has O(1) inhomogeities at ~L_1 distances

$$L_1 \equiv \frac{1}{H_1 R_1} \simeq 1.116 \times 10^{17}\text{cm} \left(\frac{50\,\mu\text{eV}}{m_a}\right)^{0.167} = 0.0362\,\text{pc} \left(\frac{50\,\mu\text{eV}}{m_a}\right)^{0.167}$$

Gravitational collapse

- O(1) overdensities collapse gravitationally very early



PHYSICAL REVIEW D VOLUME 50, NUMBER 2 15 JULY 1994

Large-amplitude isothermal fluctuations and high-density dark-matter clumps

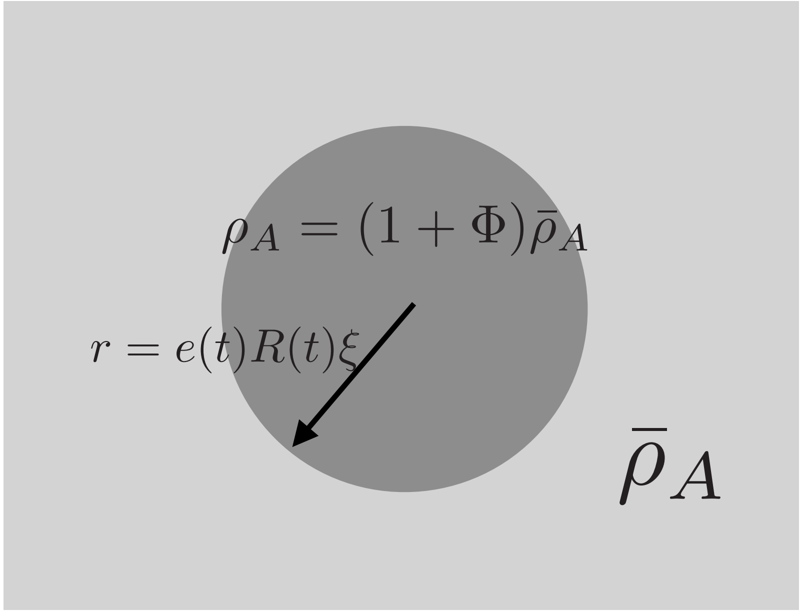
Edward W. Kolb*
NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510
and Department of Astronomy and Astrophysics, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

Igor I. Tkachev†
NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia Illinois 60510
and Institute for Nuclear Research of the Academy of Sciences of Russia, Moscow 117312, Russia

(Received 9 March 1994)

Large-amplitude isothermal fluctuations in the dark-matter energy density, parametrized by $\Phi \equiv \delta\rho_{DM}/\rho_{DM}$, are studied within the framework of a spherical collapse model. For $\Phi \gtrsim 1$, a fluctuation collapses in the radiation-dominated epoch and produces a dense dark-matter object. The final density of the virialized object is found to be $\rho_F \approx 140\Phi^3(\Phi+1)\rho_{eq}$, where ρ_{eq} is the matter density at equal matter and radiation energy density. This expression is valid for the entire range of possible values of Φ, both for $\Phi \gg 1$ and $\Phi \ll 1$. Some astrophysical consequences of high-density dark-matter clumps are discussed.

PACS number(s): 98.80.Cq, 05.30.Jp, 95.35.+d, 98.70.−f



$$M_{tot} \equiv \frac{4\pi}{3}\rho_{eq}a_{eq}^3[1+\Phi(\xi)]\xi^3$$

- Collapse "redshift" is $z_c \sim z_{eq}\Phi$

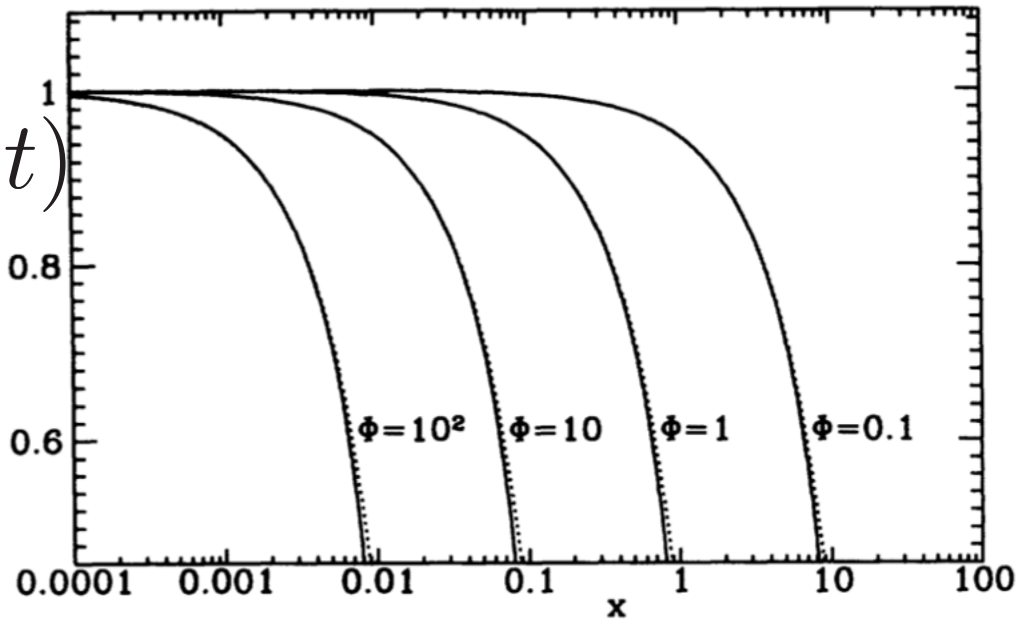
- Virialised radius $L_1/z_c \sim L_1/(\Phi z_{eq})$

- Virialised density ~ $\bar{\rho}_A(z_{eq})\Phi^3(1+\Phi)$

$$\rho_c \sim 6.7\times 10^6(1+\Phi)\Phi^3\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

depart from Hubble flow

$e = e(t)$

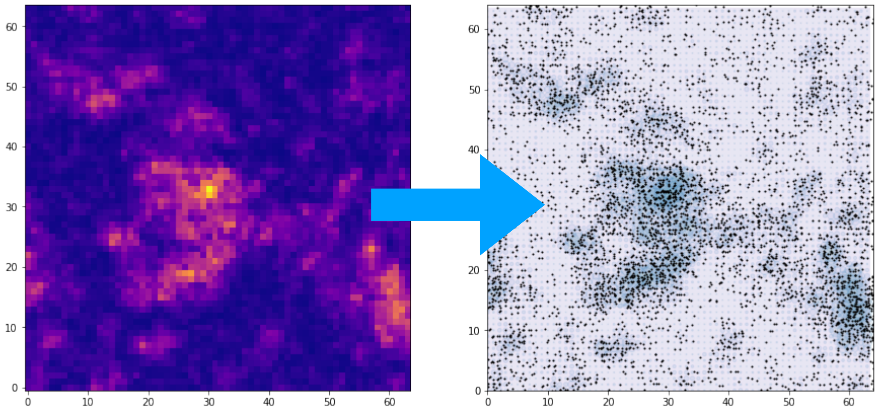


R/R_{eq}

Numerical simulations

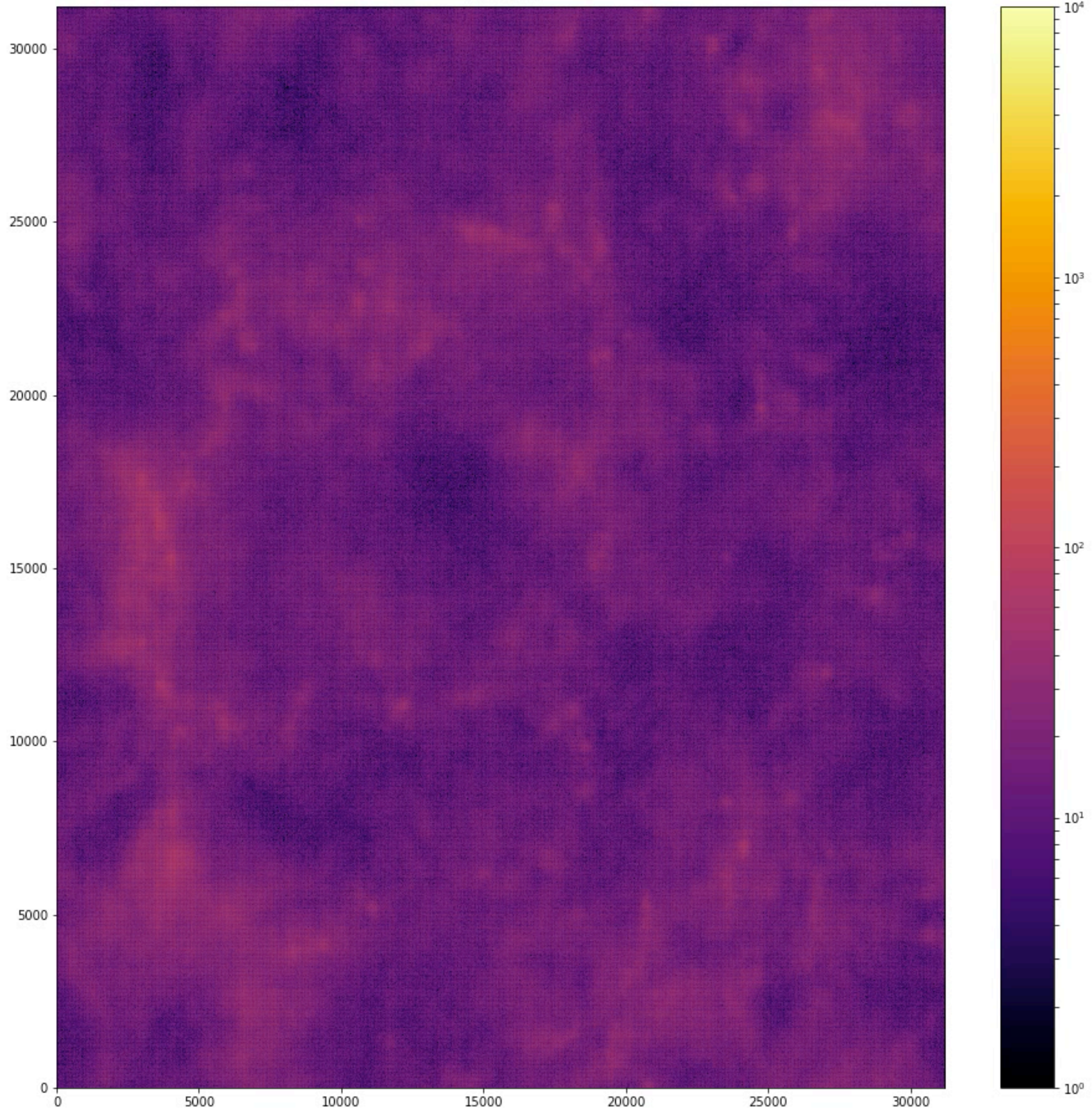
- MCs are not spherically symmetric ... use output of simulations

- Sample densities into particles



- Run N-body gravitational codes

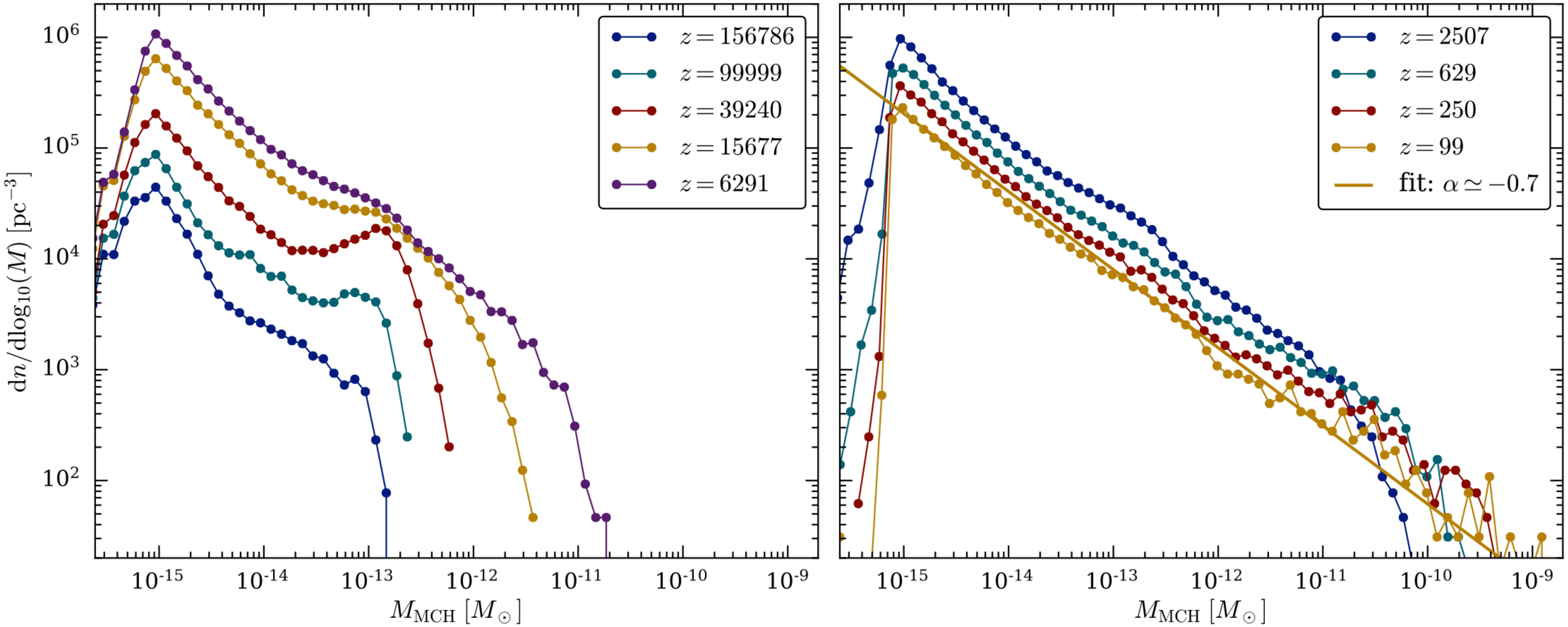
DM density proyection (JR 2018) with Gadget2 (Springer 2005)



Numerical calculations

Eggemeier, JR... 2020

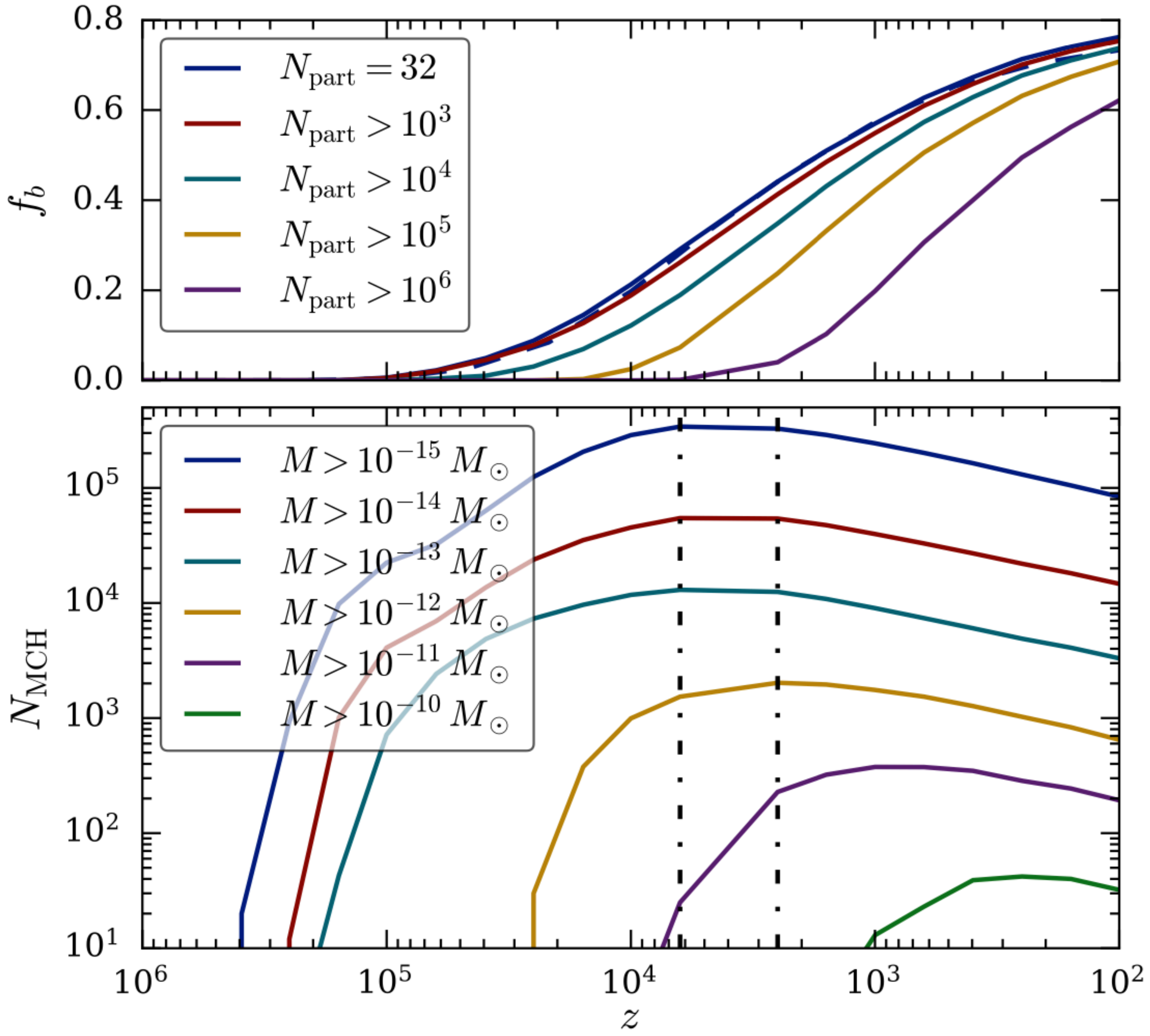
- Starting from results of Numerical simulations of QCD phase transition with strings+DWs ...
- Halo mass function (Mcs/mass/volume)



Filling factor

Eggemeier, JR... 2020

- Most axions are trapped in these high-density Mcs



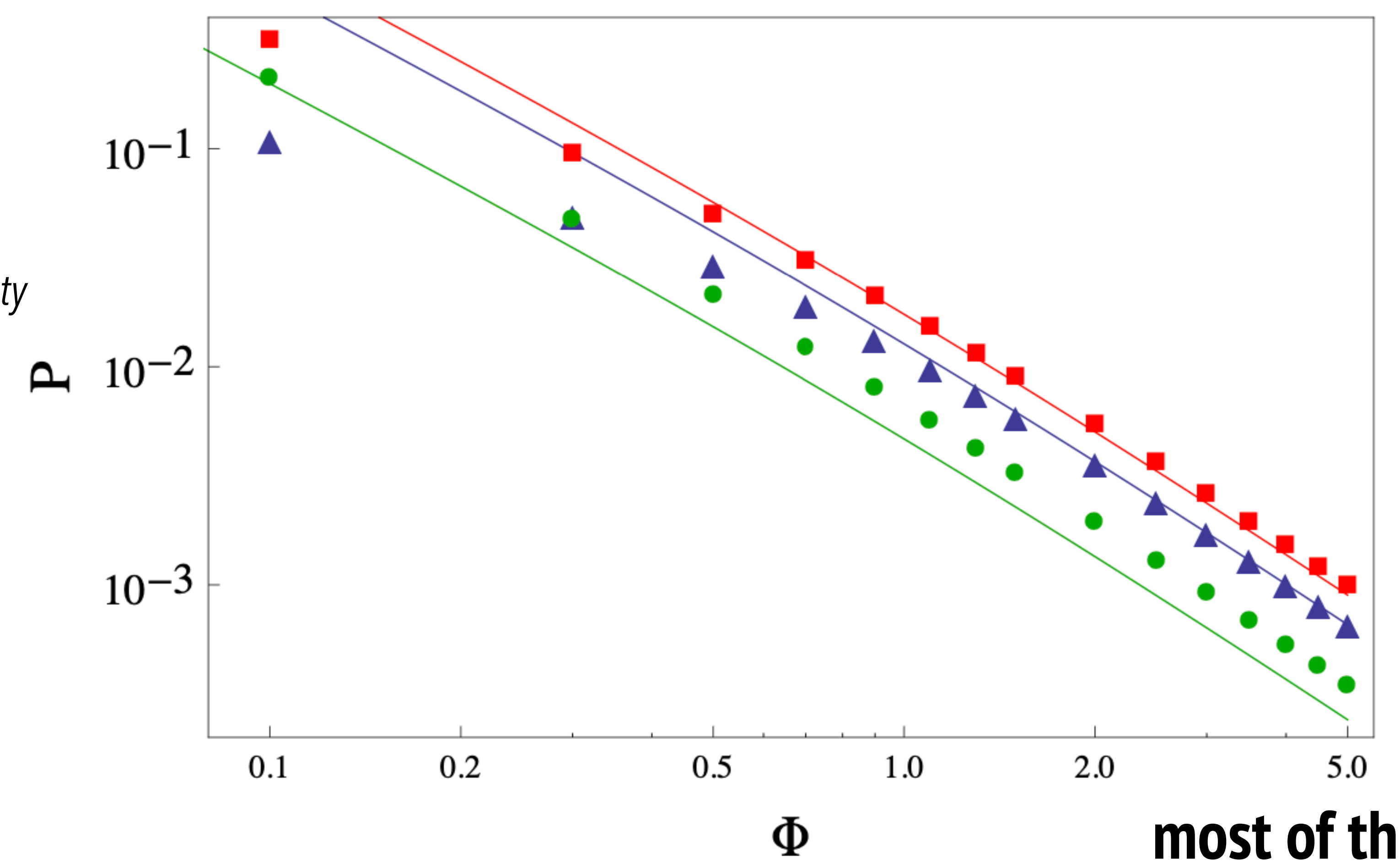
- This leaves very few axions to be discovered!

Survival in the galaxy

Eggemeier, JR... 2020

- Simulations end around z~100 for technical reasons
- Next important event is galaxy formation
- MCs can be disrupted by encoutners with galactic stars

Disruption probability assumes NFW MC profile



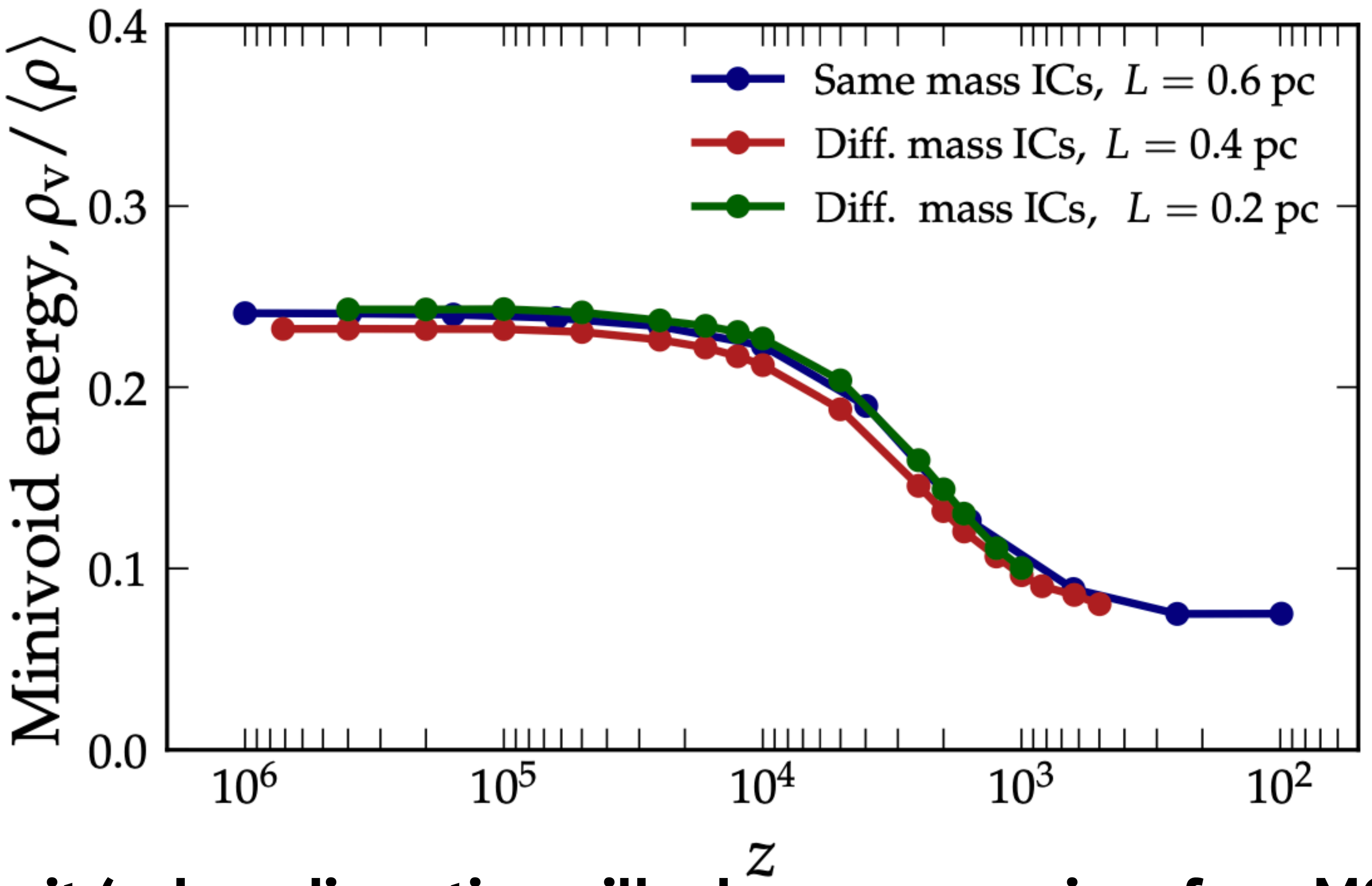
Dokuchaev 17

most of them actually survive!

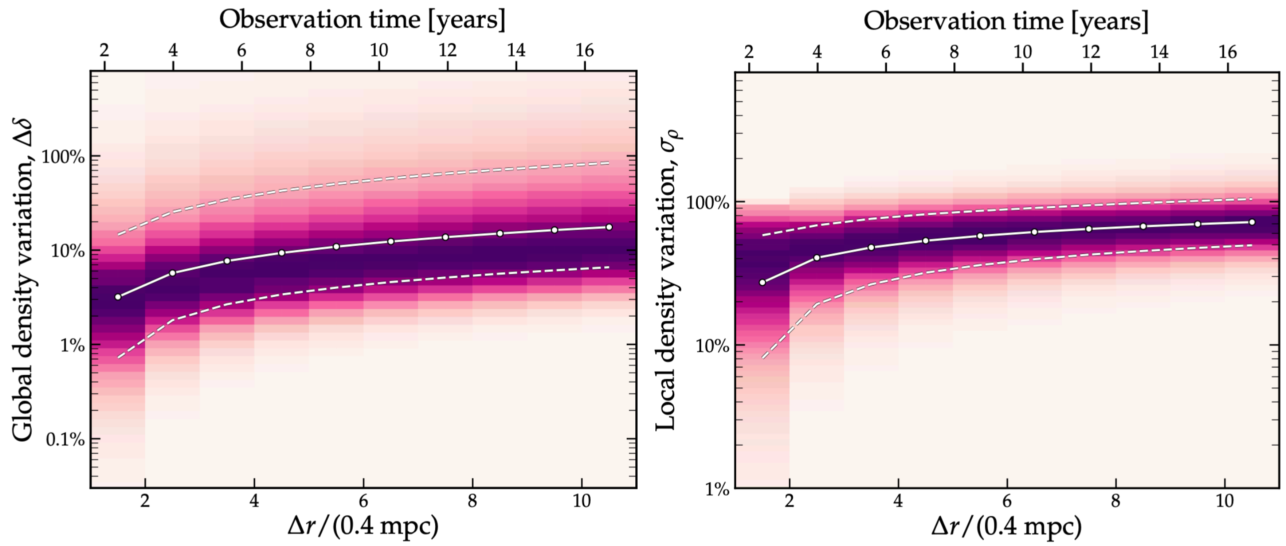
Density in voids

Eggemeier 2022

- The average void density seems to converge around few %

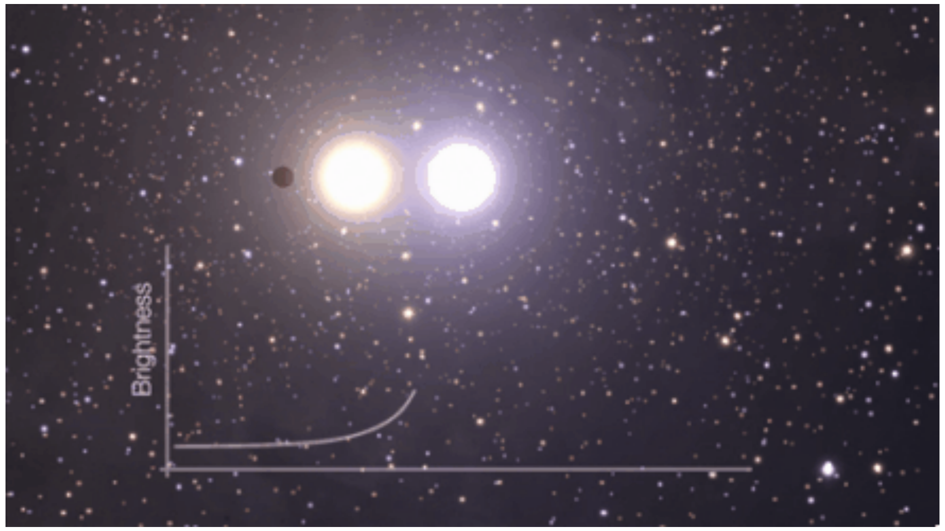


- This is a lower limit (galaxy disruption will release more axions from MCs into voids) that experiments can use

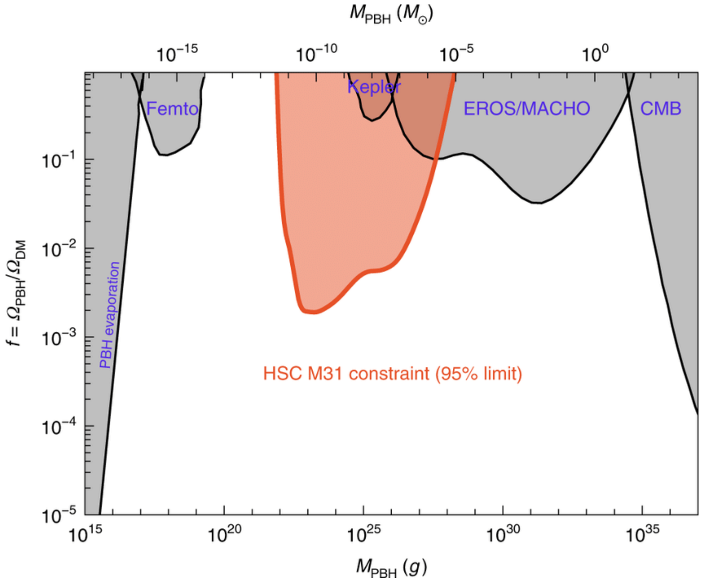


Observing miniclusters?

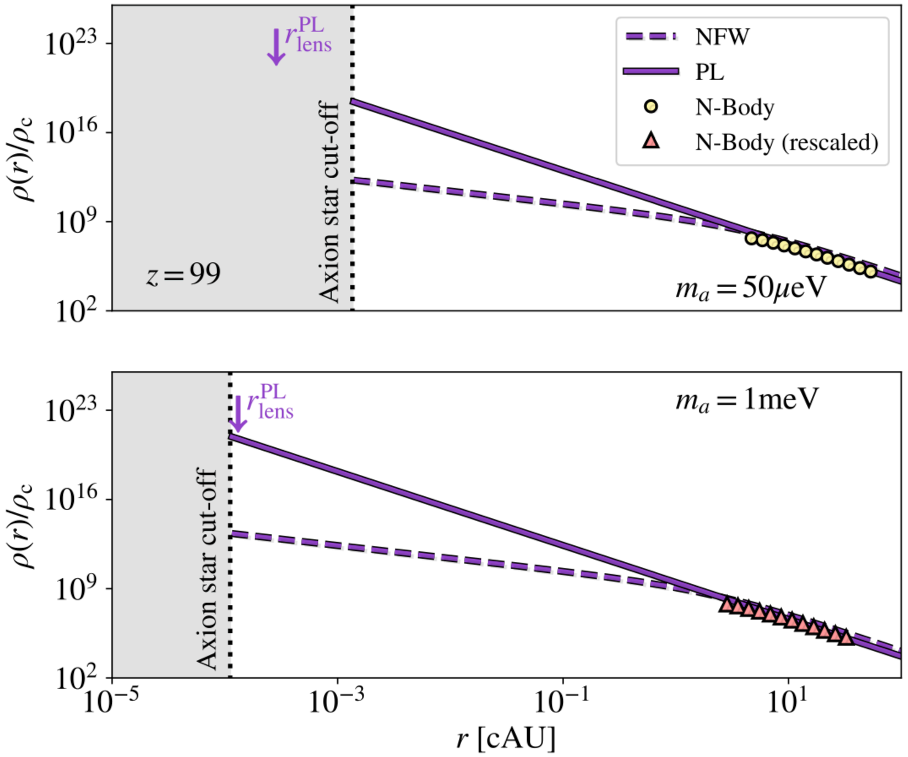
- **Microlensing**

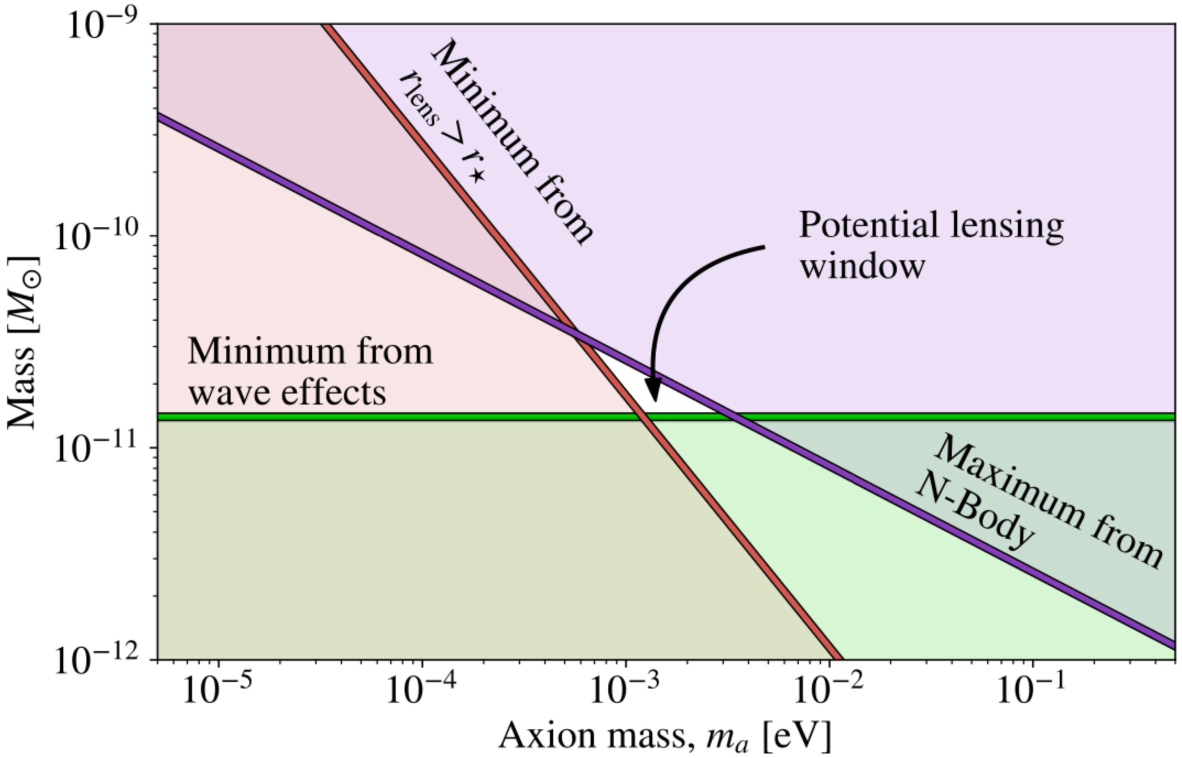


Subaru HSC dedicated search of PHBs along M31



- **Axion MCs appear to be too flufy (simulations do not resolve inner core)**





Ellis 2022

only extreme assumptions offer a window of opportunity!

More pheno

- femtolensing
- minicluster encounters with NSs
- minicluster encounters with the Earth
- Bose-nova formation in miniclusters (and photon burst emission)