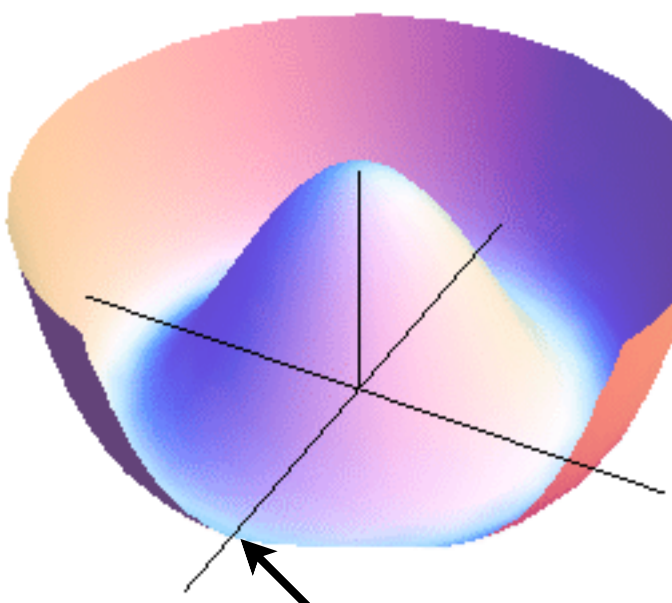
Miniclusters

Javier Redondo + Julia Stadler
(Zaragoza U & MPP)

Axions

- **QCD theta is dynamical** $\theta(t, \mathbf{x}) = a(t, \mathbf{x})/f_a$
- **PQ symmetry not restored, random initial conditions (SMASH)**
- **theta field (at a given point)**



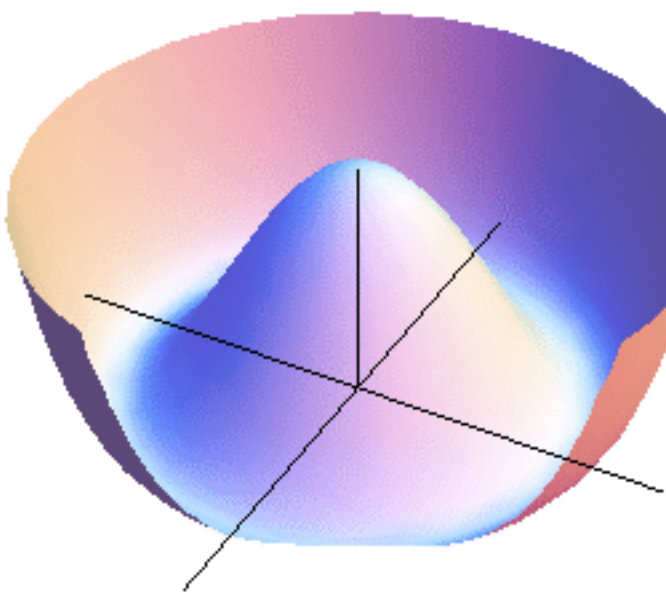
$$\Phi(x) = \rho(x)e^{i\frac{a(x)}{f_a}}$$

CP conserving min.

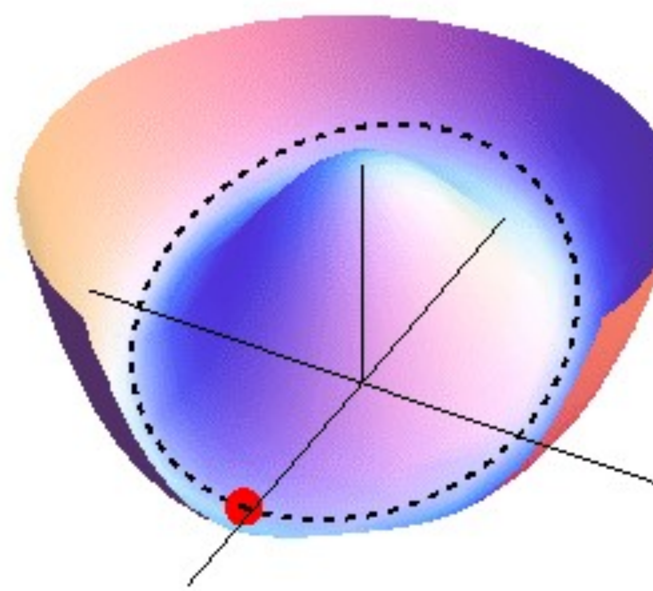
Axions

- **QCD theta is dynamical** $\theta(t, \mathbf{x}) = a(t, \mathbf{x})/f_a$
- **PQ symmetry not restored, random initial conditions (SMASH)**

High T



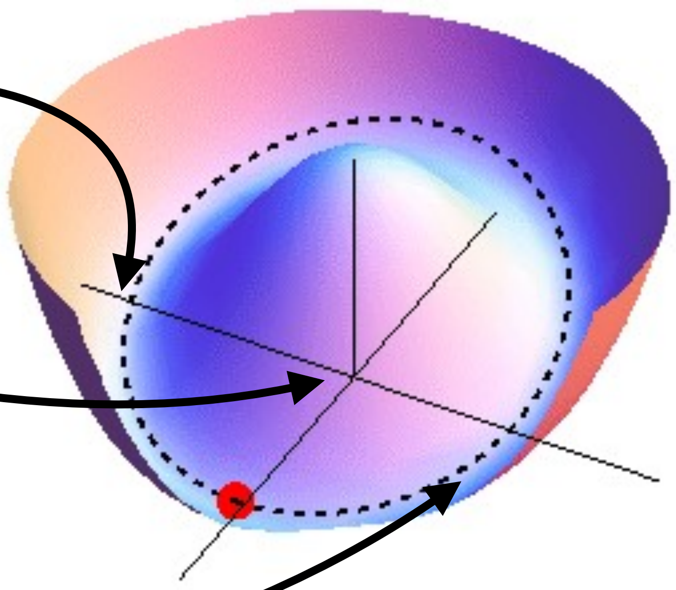
Around T~ QCD



Numerical simulations

- Simulate the full Phi field (topological defects)

$$\ddot{\Phi} - \frac{1}{R^2}\nabla^2\Phi + 3H\dot{\Phi} + \lambda\Phi(|\Phi|^2 - f_A^2) + m_a^2 f_A = 0$$



- Essential theta part

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

- Time scale

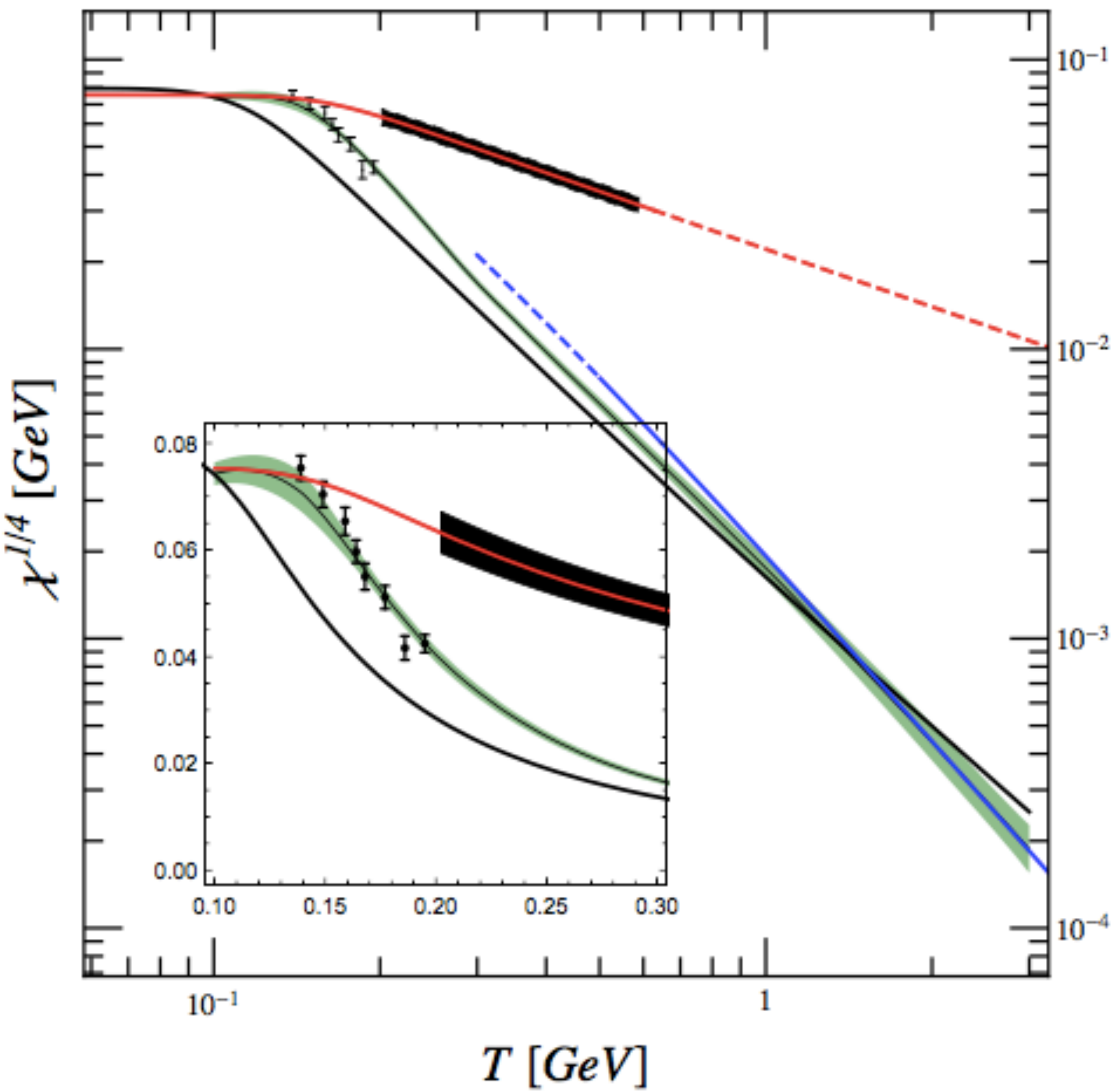
$$3H(T_1) = m_a(T_1) \qquad t_1 \sim \frac{1}{2H_1}$$

- Horizon size (shorter wavelengths deca)

$$L_1 = 2t_1 \sim \frac{1}{H_1}$$

Temperature dependence of axion mass

$$m_a = \sqrt{\chi(T)}/f_a \qquad T_1 \sim 1.5\,\mathrm{GeV}\left(\frac{10^{11}\mathrm{GeV}}{f_a}\right)^{0.16}$$



Lattice QCD 2+1 (T~Tc)
Bonati et al JHEP 1603 (2016) 155

Lattice QCD 2+1
Petreczky at al arXiv:1606.03145

DIGA (analytical) (valid T>>Tc)
Borsany at al PLB 2015

Lattice QCD (DWF) 2+1
Buchoff et al PRD 89 2014

Interacting Instanton Liquid (Model)
Wantz/Shellard PRD 82 2010

Length scales

- Time scale

$$3H(T_1) = m_a(T_1) \qquad t_1 \sim \frac{1}{2H_1}$$

- Horizon size (shorter wavelengths deca)

$$L_1 = 2t_1 \sim \frac{1}{H_1}$$

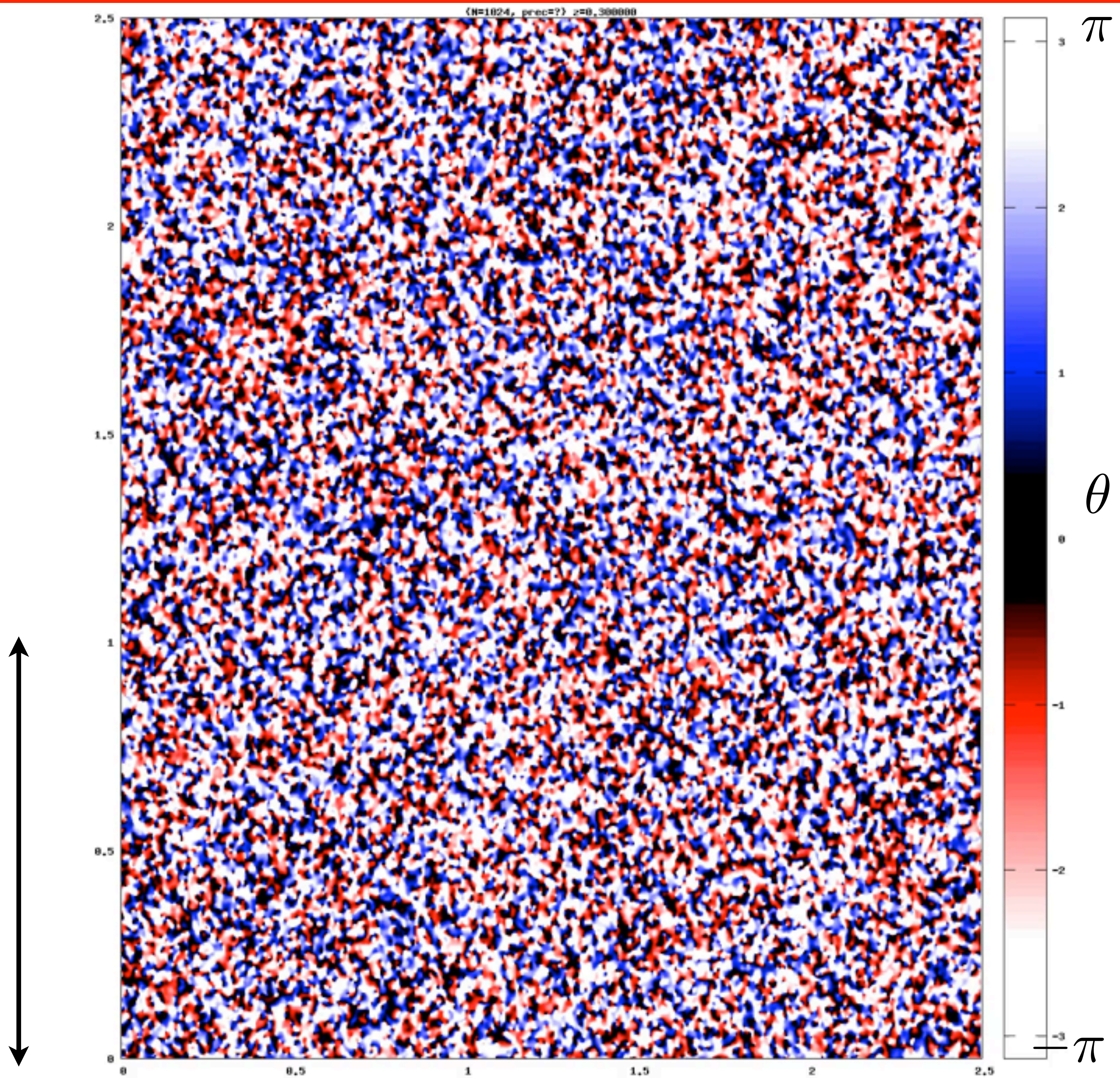
- Full Axion DM in this model $f_A \sim 10^{11}\,\mathrm{GeV}$

$$T_1 \sim 1.5\,\mathrm{GeV}\left(\frac{10^{11}\mathrm{GeV}}{f_a}\right)^{0.16}$$

- Characteristic length scale

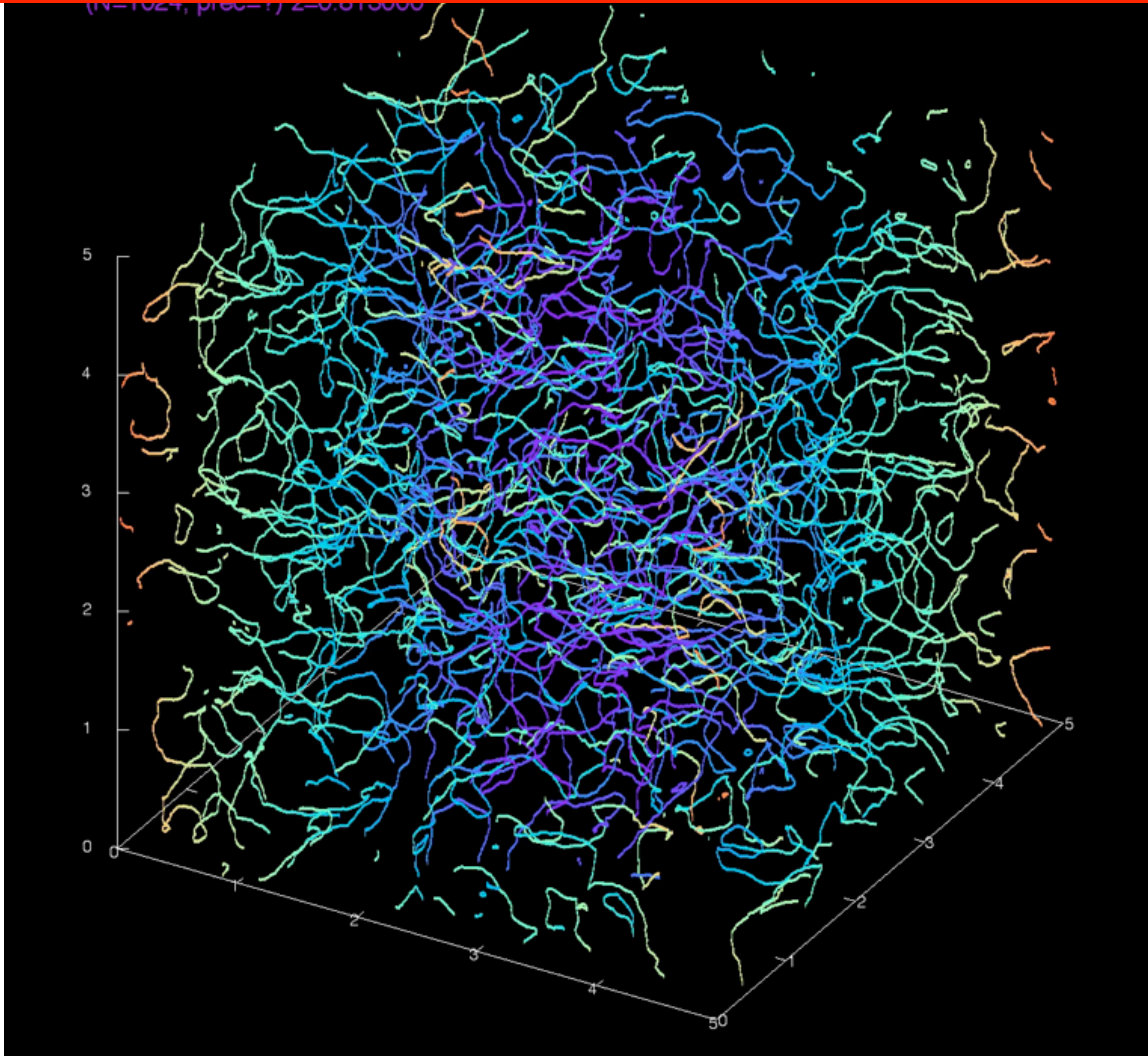
$L \sim 40\,\mathrm{mpc}$ **(comoving)**

SCENARIO B

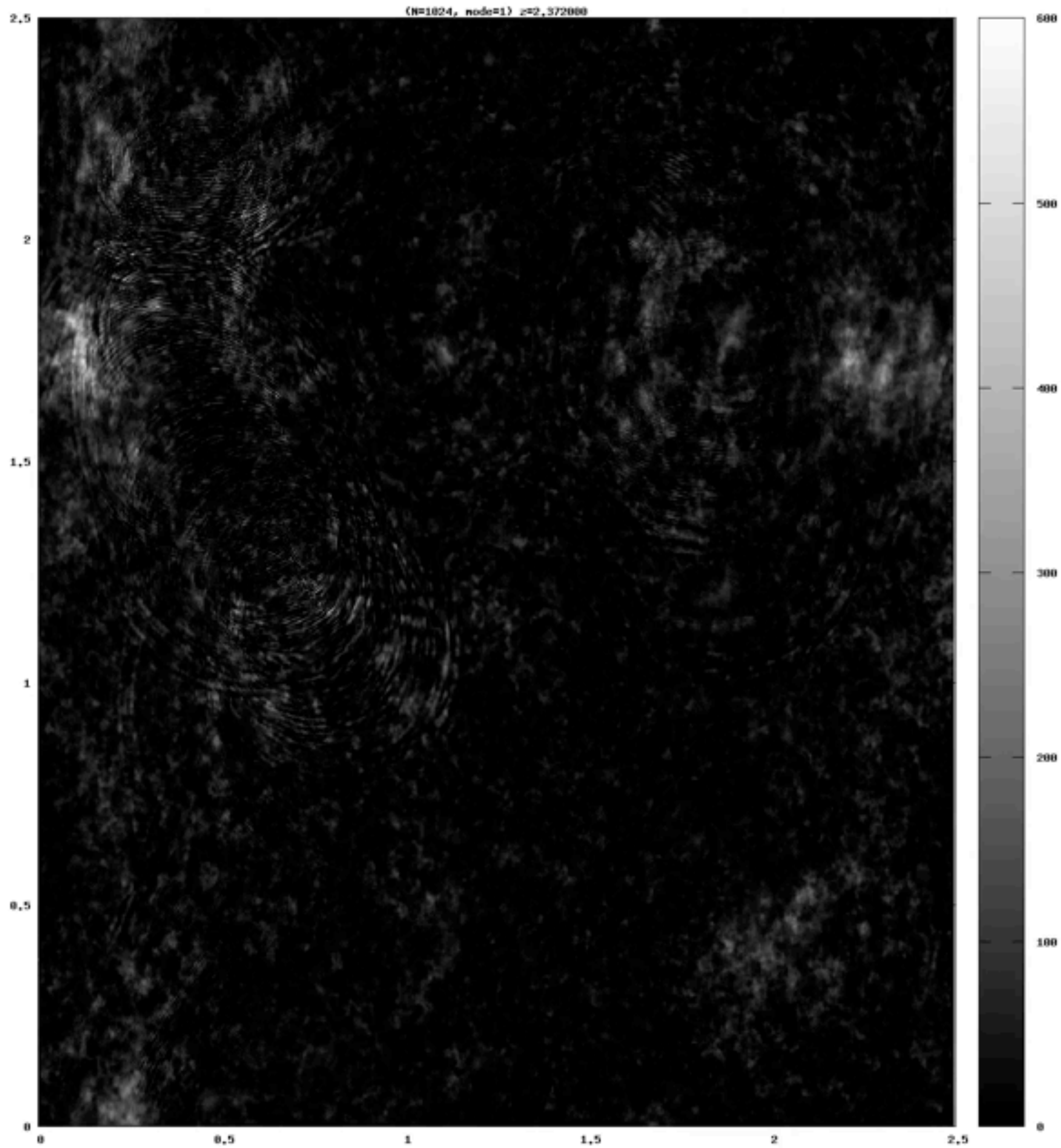


(N=1024, prec=?) z=0.300000
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
2
1
0
-1
-2
-3
π
θ
$-\pi$

Strings



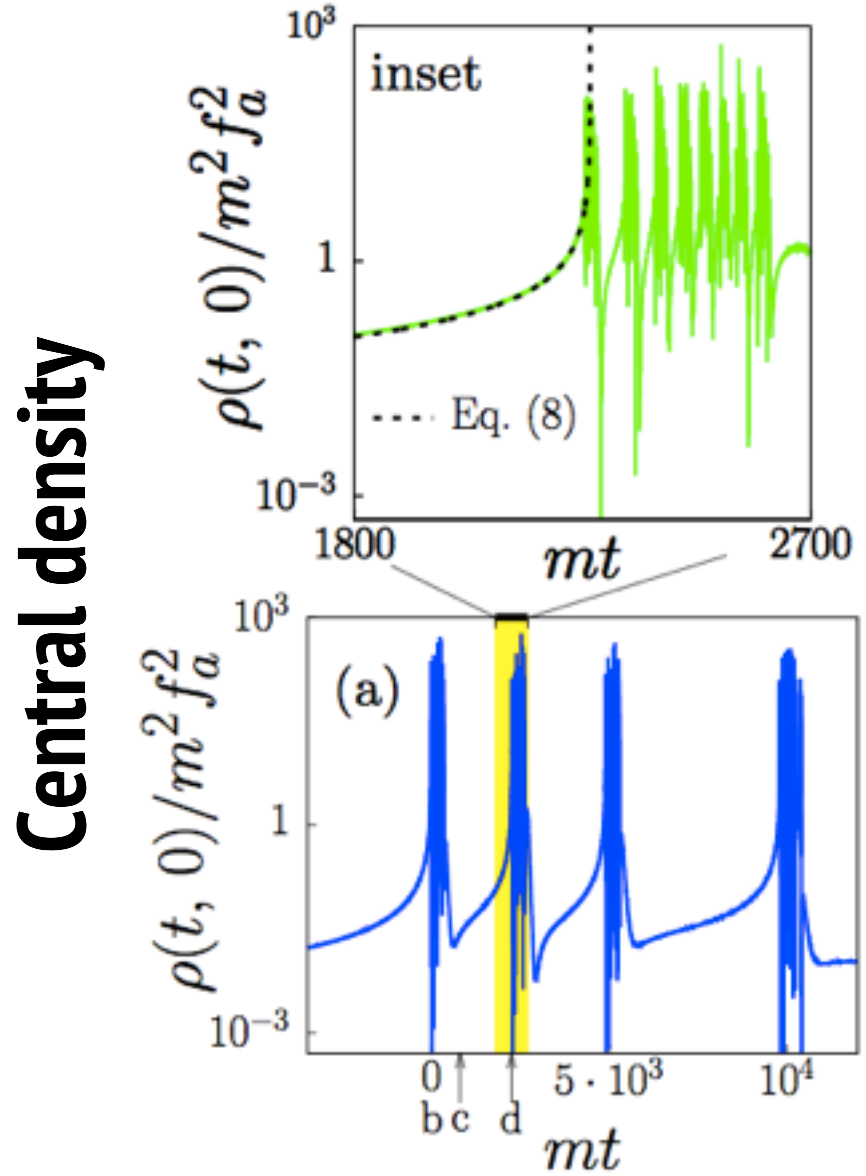
density

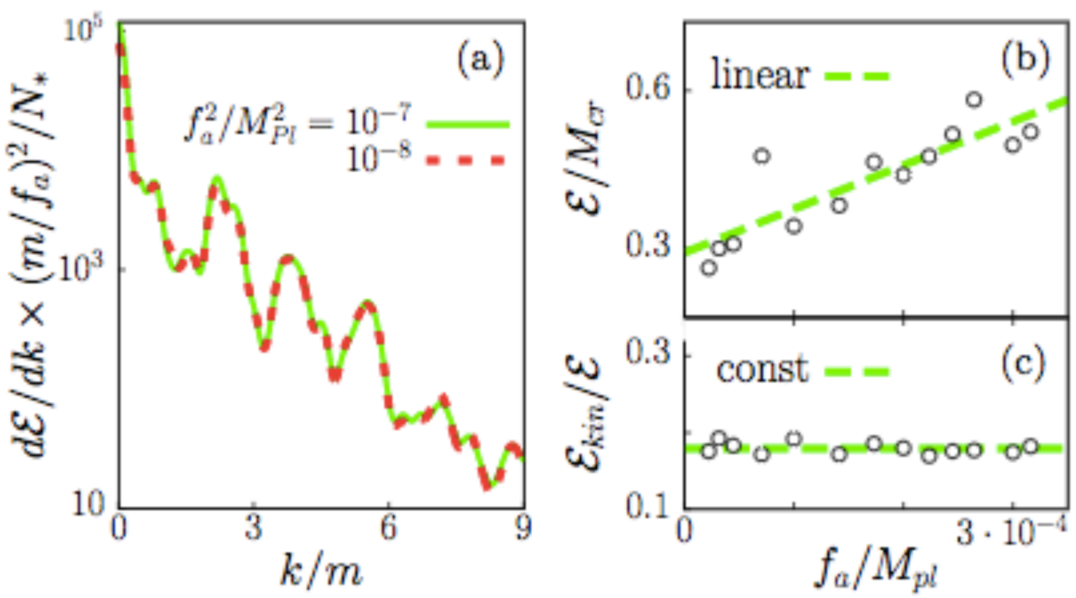


(N=1024, mode=1) z=2.372000
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
600
500
400
300
200
100
0

oscillons (axitons)

- Axion self interactions are attractive -> collapse, bounce, relativistic axion emission





- Impact on dark matter density (oscillons are bound, energy does redshift less inside, but turn DM into DR)

Minicluster gravitational collapse

- regions with overdensity $\Phi = \frac{\delta\rho}{\rho}$ collapse at $z_\Phi \sim z_{\rm eq}(1+\Phi)$

$\Phi > 60$ very dense MCs form bose stars, oscillons -> rel axions

$\Phi < 60$ miniclusters

$$\rho \sim 140\Phi^3(1+\Phi)\rho_a(1+z_{\rm eq})^3$$

$$L_{\rm phys} \lesssim L/(1+z_{\rm eq})\Phi$$

$$L_{\rm phys} \sim {\rm AU}/\Phi$$

$$M \sim 10^{-12} \sim 10^{-10} M_\odot$$

[Virialisation]

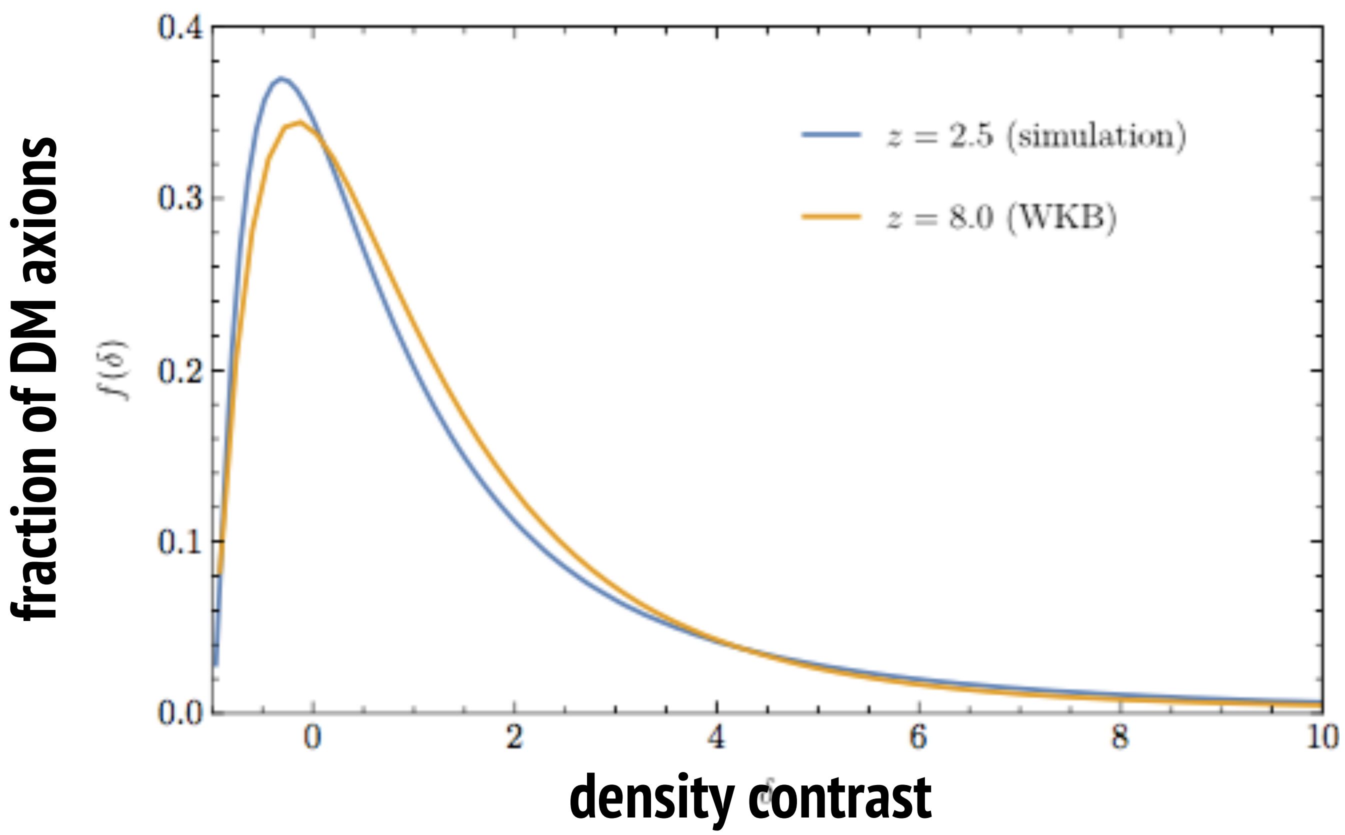
- spherical collapse reduces size ~2 and emits some axions (30%) ?

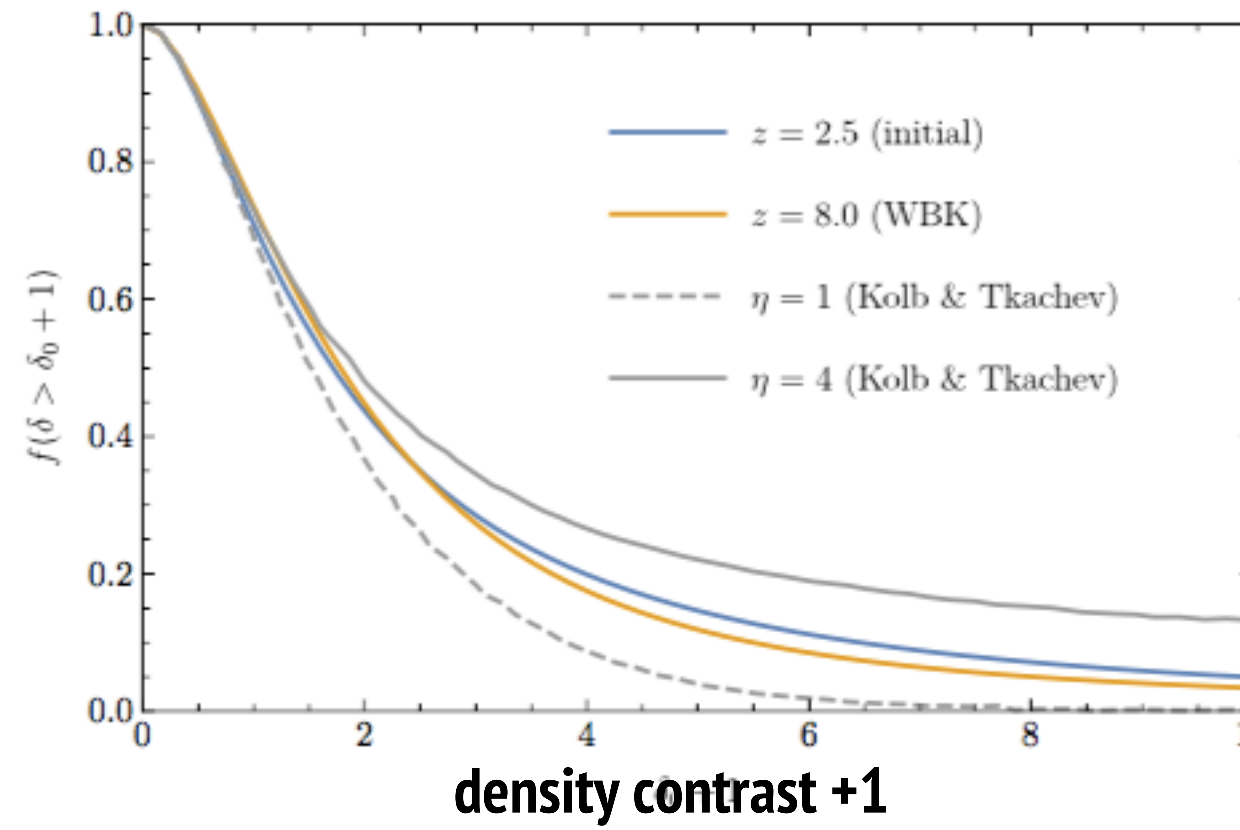
- non spherical $\Phi \sim O(2)$

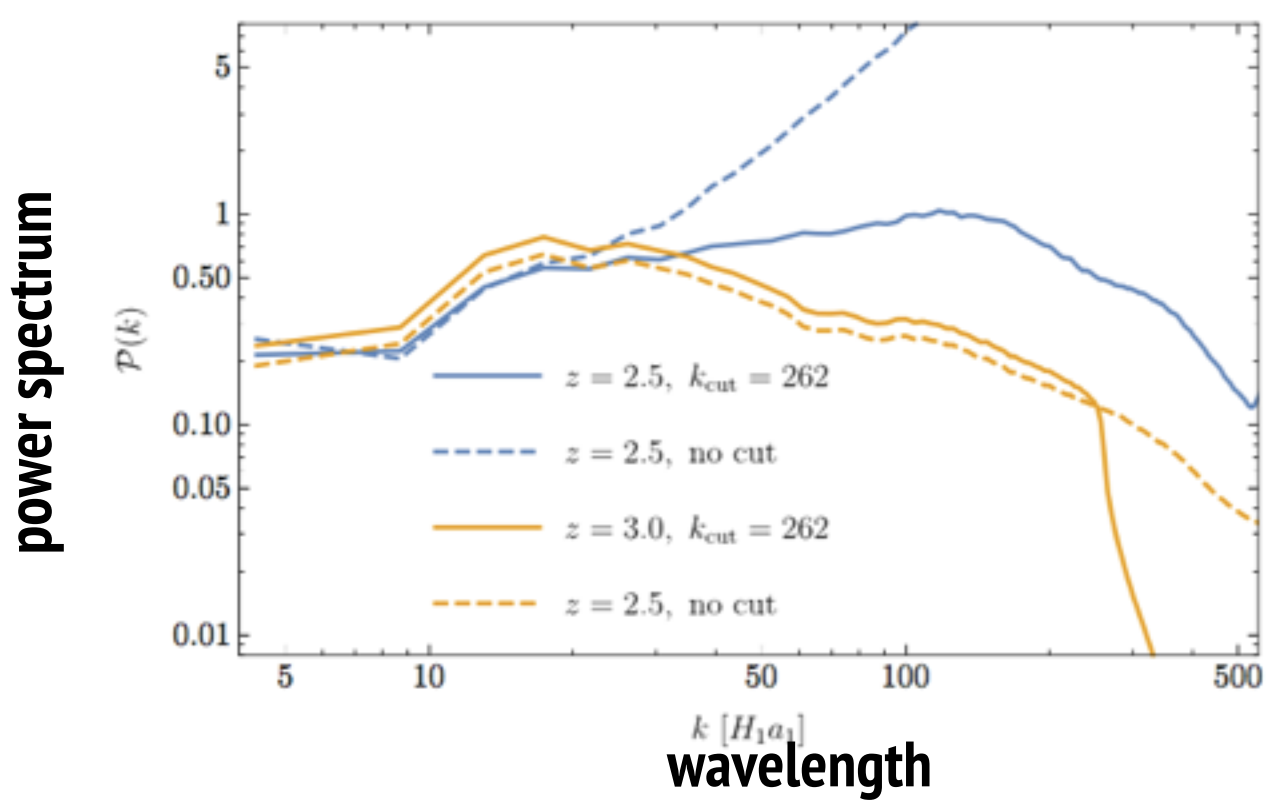
- how many axions ? we do not know!

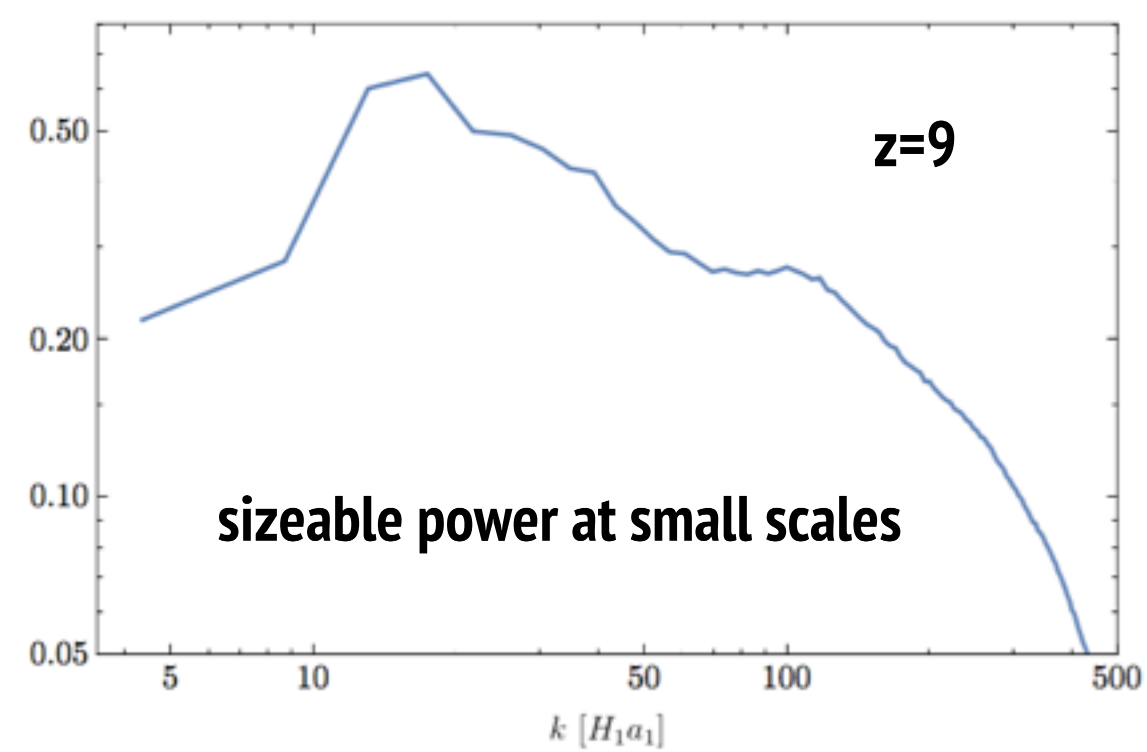
[Collaboration with Jens Niemeyer's group]

first analysis



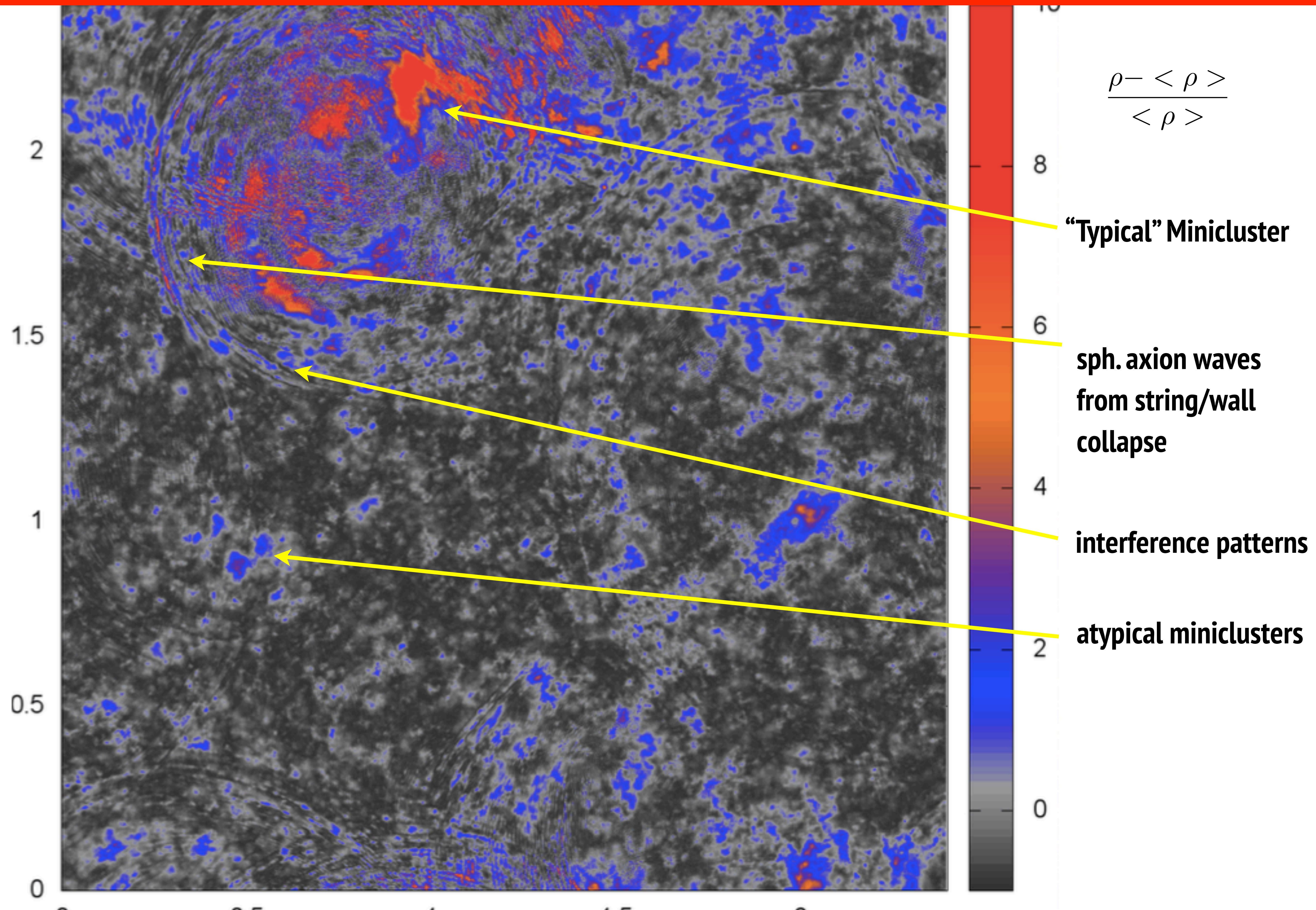






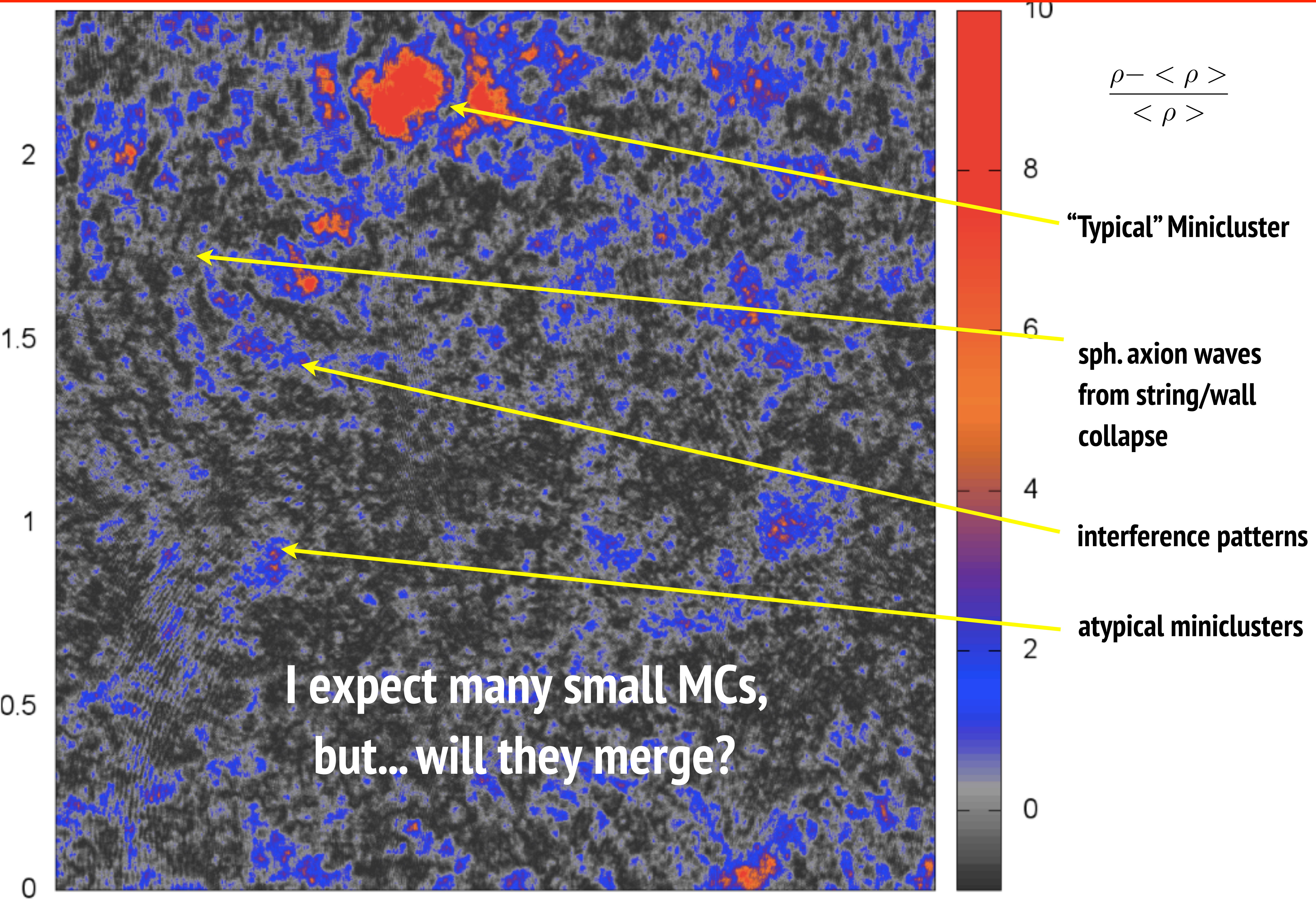
density contrast (end simulation z=2.5)

some axions still relativistic



density contrast (WKB evolved, z=9.2)

axios NR, frozen density



Evolution of MCs

- MCs can form an axion star in the core
- axion star accretes -> maximum mass -> oscillon

    Fast radio bursts ? (not for QCD axions)
    time dependent DM density?

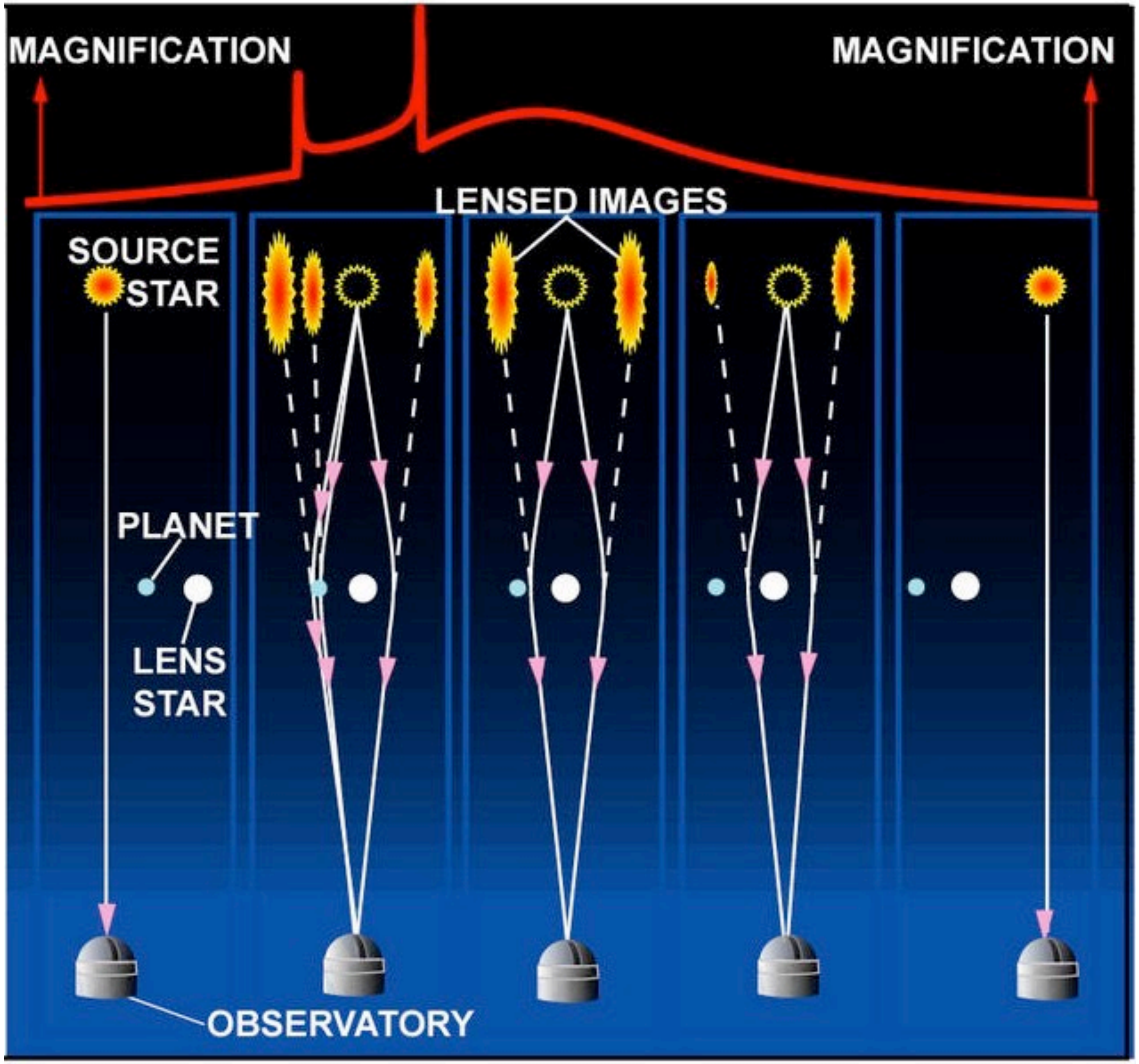
- merging trees?

- MC disruption in star encounters -> tidal streams

- MC disruption in MC encounters -> negligible?

- gas clouds?, GCs? ...

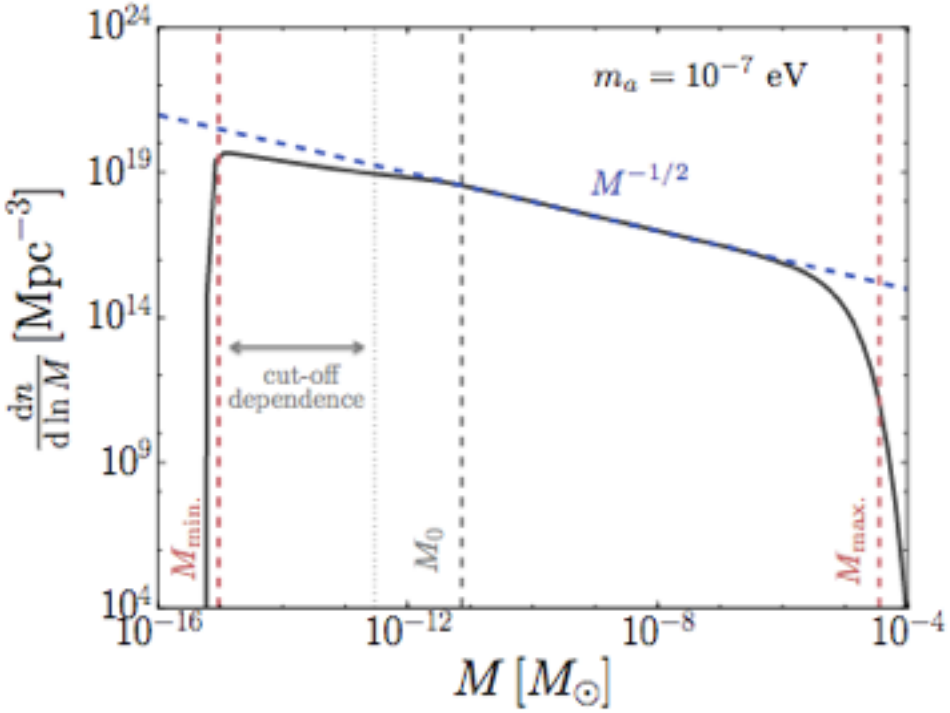
Minicluster Microlensing



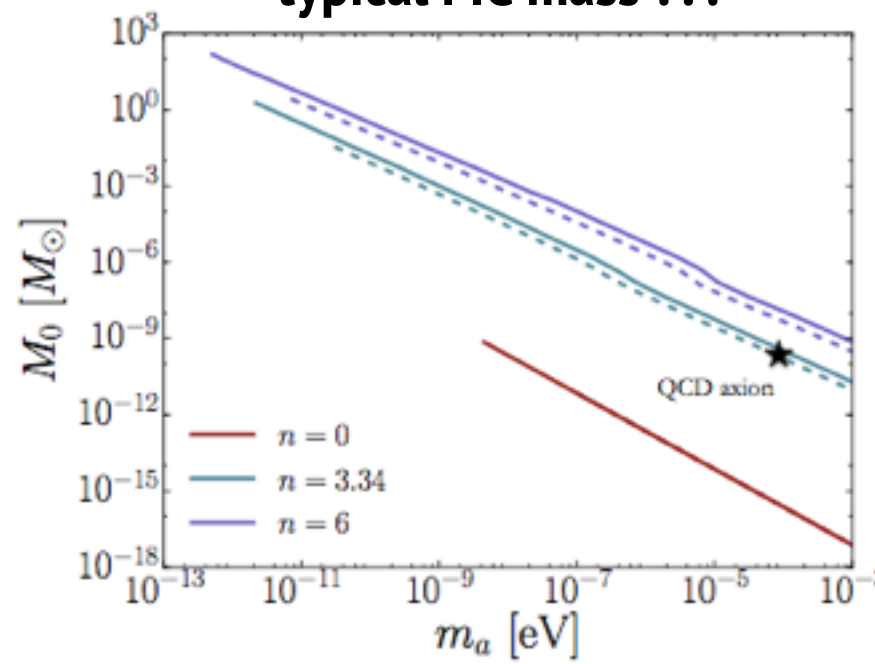
Minicluster Microlensing

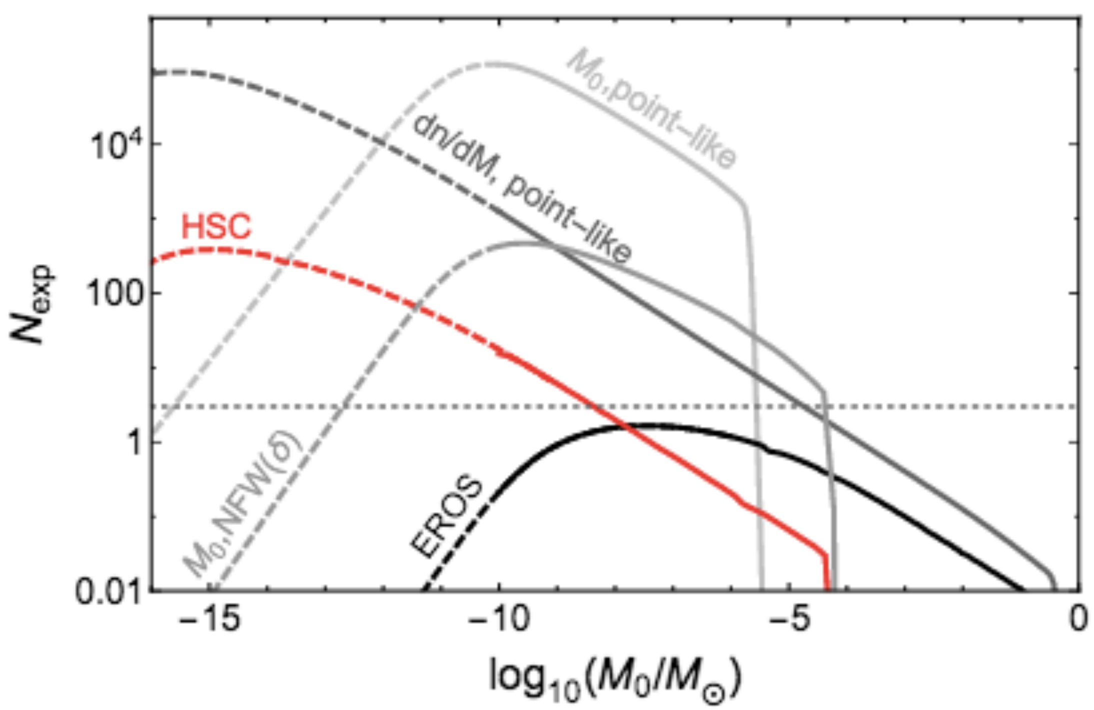
- Fairbairn, Marsh, Quevillon arXiv:1701.04787v1

simplest MC mass function

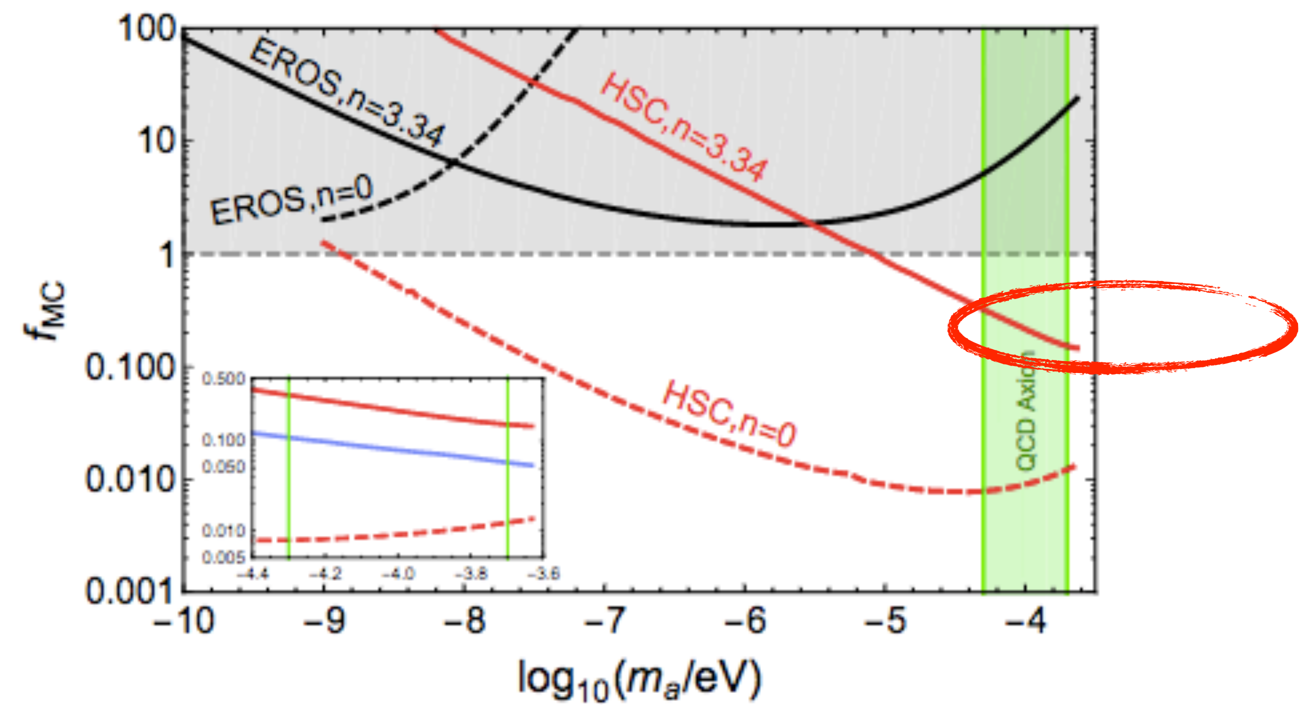


typical MC mass ???





Fraction of DM in miniclusters



No conclusions

- Formation of MCs -> more low mass, more high mass

- Oscillons (collapse axion stars) convert DM -> DR

- Merging, acretion history?

- microlensing potentially powerful

- encounters with the Earth are rare (streams?)

WORK IN PROGRESS