Axion Minicluster

with

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24.11.16

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- ▷ solves the strong CP problem
- ▷ makes up Dark Matter

Axion Minicluster

$\mathcal{O}(1)$ density contrast

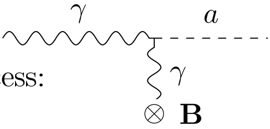
collapse to dense clumps of axions

- ▷ comoving scale ~ 0.02 pc
- ▷ mass $10^{-12} \mathrm{M}_{\odot}$
- ▷ central density $10^{14} \rho_{\mathrm{DM}}$

Axion Haloscopes

source:
http://depts.washington.edu/admx

Primakoff Process:



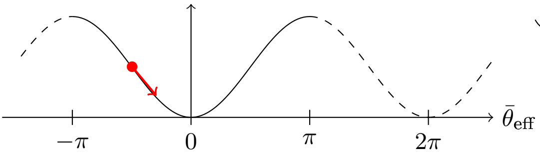
Radiocavity Experiments:
Convert axion DM into a photon signal
[Sikivie (1983)]

- ▷ $P = g_{a\gamma\gamma} \frac{\rho_a}{m_a} B_0^2 V Q$
- ▷ encounters: boost signal
- ▷ voids in the galactic halo: no signal

Content

Peccei Quinn Mechanism

[Peccei, Quinn (1977); Weinberg (1978); Wilczek (1978)]



$$\Delta\mathcal{L}_\theta \to \underbrace{\left(\bar{\theta} - \frac{a(x)}{v_a}\right)}_{\bar{\theta}_{\text{eff}}(x)} \frac{\alpha_s}{8\pi} G_{a\,\mu\nu}\tilde{G}_a^{\mu\nu}$$

- chiral, global, spontaneously broken $U(1)_{\text{PQ}}$
- Axion: Goldstone boson of the $U(1)_{\text{PQ}}$ $\quad \langle\phi\rangle = v_a e^{i\frac{a(x)}{v_a}}$ ($a(x)$ ← axion)
- **KSVZ model** [Kim (1979); Shifman, Vainshtein, Zakharov (1980)]

  New, heavy, electrically neutral quark, charged under $U(1)_{\text{PQ}}$
- **DFSZ model** [Dine,Fischler,Srednicki(1981); Zhitnitsky (1980)]

  Two Higgs doublets, SM quarks and leptons are charged under $U(1)_{\text{PQ}}$

Symmetry Breaking Scales

$$\langle\phi\rangle = v_a e^{i\frac{a(x)}{v_a}}$$

Spontaneous breaking at a large scale v_a

$$V_{\mathrm{s}}(\phi) = \frac{\lambda}{4}\left(|\phi|^2 - v_a^2\right)^2$$

Explicit breaking leads to a $\mathcal{CP}$ conserving theory

$$V(\theta) = f_a^2 m_a^2(T)\left(1 - \cos\left(N_{\mathrm{DW}}\,\theta\right)\right)$$

$$m_a^2(T)\begin{cases}\propto T^{-n} & T \gtrsim 100\ \mathrm{MeV}\\ = m_a(T=0) & T \lesssim 100\ \mathrm{MeV}\end{cases}$$

[Borsanyi et al. (2016); Petreczky et al. (2016); Bonati et al. (2015)]

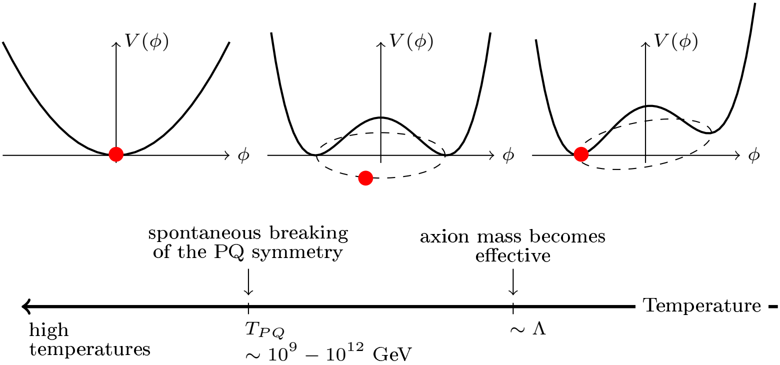
$$\theta(x) \equiv \frac{a(x)}{v_a}$$
$$0 \le \theta \le 2\pi$$

model dependent:

KSVZ: $N_{\mathrm{DW}} = 1$

DFSZ: $N_{\mathrm{DW}} = 6$

Cosmology of the Peccei Quinn Field



Restored PQ symmetry

Flat Axion Potential, Broken PQ Symmetry

CP-conserving Minimum

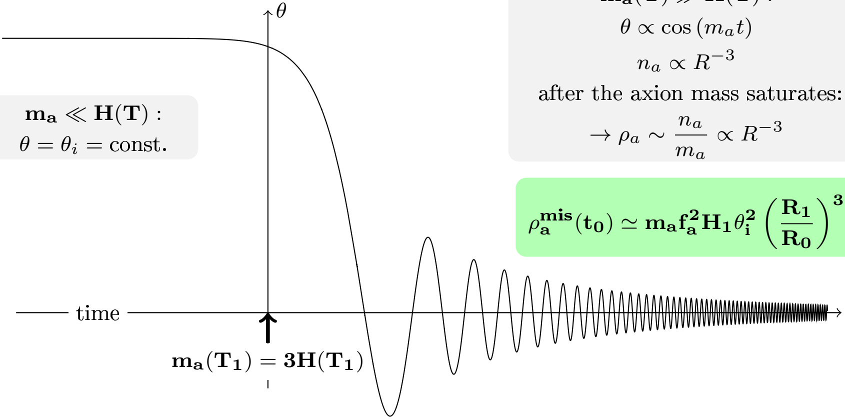
Vacuum Realignment

full equation of motion: $\ddot{\theta} + 3H(t)\dot{\theta} - \frac{1}{R^2(t)}\nabla^2\theta + m_a^2(T)\sin(\theta) = 0$

homogeneous field, small displacement: $\ddot{\theta} + \frac{3}{2t}\dot{\theta} + m_a^2(T)\theta = 0$

$\mathbf{m_a \ll H(T)}$:

$\theta = \theta_i = \text{const.}$



$\mathbf{m_a(T) \gg H(T)}$:

$\theta \propto \cos(m_a t)$

$n_a \propto R^{-3}$

after the axion mass saturates:

$\rightarrow \rho_a \sim \frac{n_a}{m_a} \propto R^{-3}$

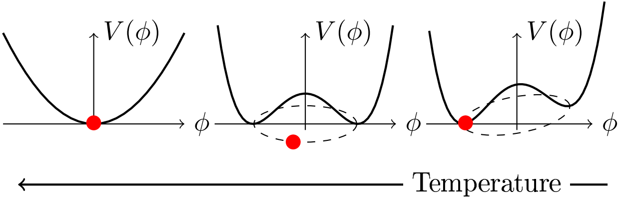
$$\rho_{\mathbf{a}}^{\mathbf{mis}}(\mathbf{t_0}) \simeq \mathbf{m_a f_a^2 H_1}\theta_{\mathbf{i}}^{\mathbf{2}} \left(\frac{\mathbf{R_1}}{\mathbf{R_0}}\right)^{\mathbf{3}}$$

[Preskill, Wise, Wilczek (1983); Abott Sikivie (1983); Dine Fischler (1983)]

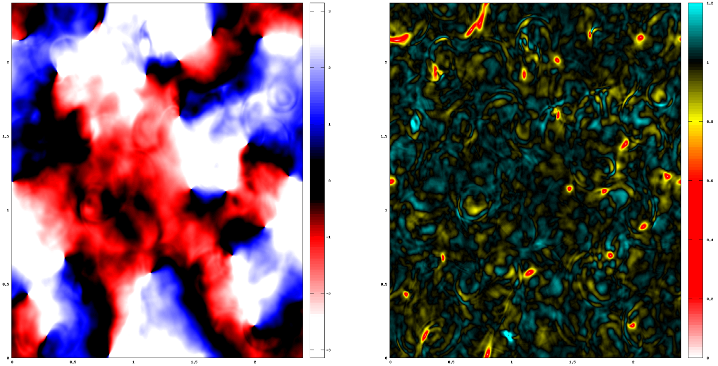
Initial Conditions

- **pre-Inflation Scenario**
  Homogeneous initial value for θ_{i}

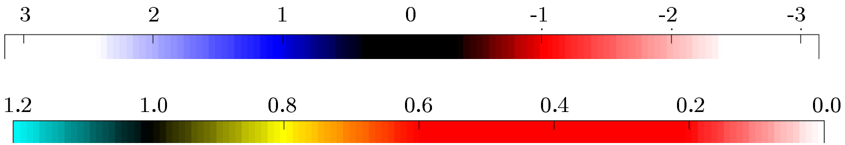
- **post-Inflation Scenario**
  Inhomogeneous θ_i on scales of the Hubble radius at T_1
  $\rightarrow$ average energy density: $\langle \theta_i^2 \rangle = \frac{\pi^2}{3}$
  $\rightarrow$ local energy density: $\mathcal{O}(1)$ variations $\Rightarrow$ **Minicluster**



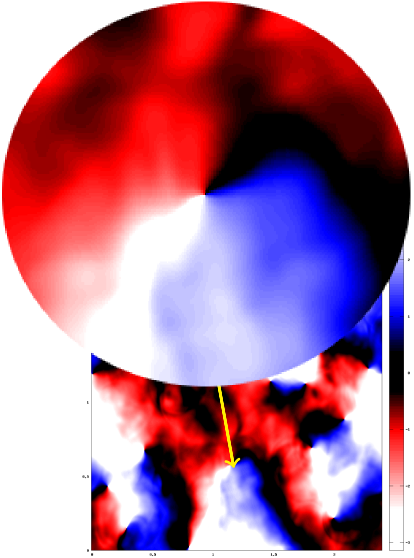
Axion Strings



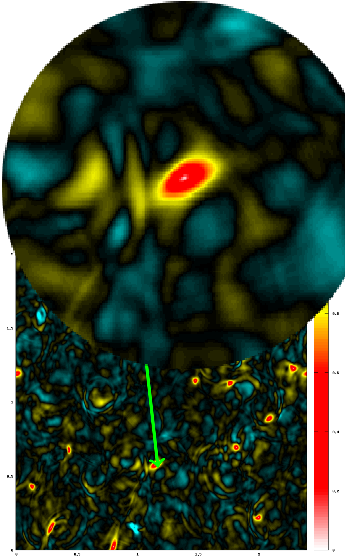
angular component $\theta = a(x)/v_a$ radial component $|\phi|/v_a$



Axion Strings



angular component $\theta = a(x)/v_a$

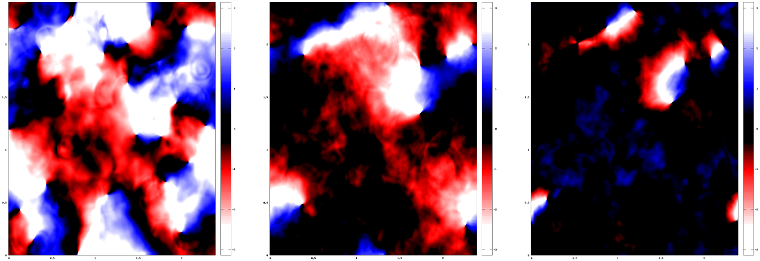


radial component $|\phi|/v_a$

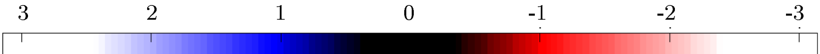
Domain Walls

$$V(\theta) = f_a^2 m_a^2(T)\,(1 - \cos\theta)$$
$$m_a(T_1) = 3H(T_1)$$

- Field configuration, which interpolates between different vacua
- **Domain Wall Problem:** Assume $N_{\mathrm{DW}} = 1$



$R(t)/R_1 = 0.94$ $R(t)/R_1 = 1.0$ $R(t)/R_1 = 1.3$



Simulations

- ▷ Density contrast from misalignment

  [Kolb, Tkachev (1993); Zureck, Hogan, Quinn (2007)]:

- ▷ Significance of contribution from string and wall decay

  [Hiramatsu, Kawasaki, Saikawa, Sekiguchi (2012); Kawasaki, Saikawa, Sekiguchi (2014); Fleury Moore (2015 & 2016)]

- ▷ Do strings and walls add further inhomogeneities?
  On which scales?

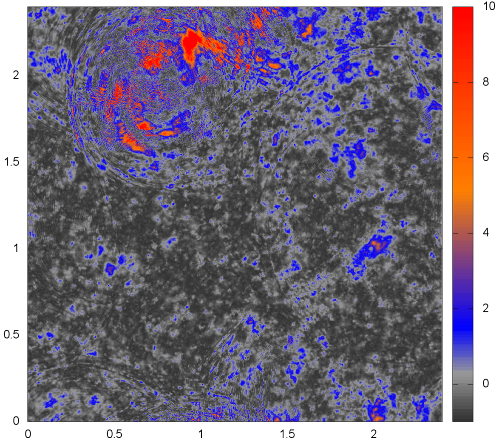
spontaneous PQ breaking potential — axion potential

$$\mu'' - \bar{\nabla}^2 \mu + \bar{\lambda}\, \mu \left(|\mu|^2 - z^2 \right) - 9 z^{n+3} = 0$$

$$z = \frac{R(t)}{R_1} \qquad \bar{\lambda} = \frac{\lambda f_a^2}{H_1^2} \qquad m_a^2 \propto T^{-n}$$

Density Contrast at z = 2.5

(some axions are still relativistic)



$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \rho_{\rm av}}{\rho_{\rm av}}$$

Density Contrast at $z = 2.5$

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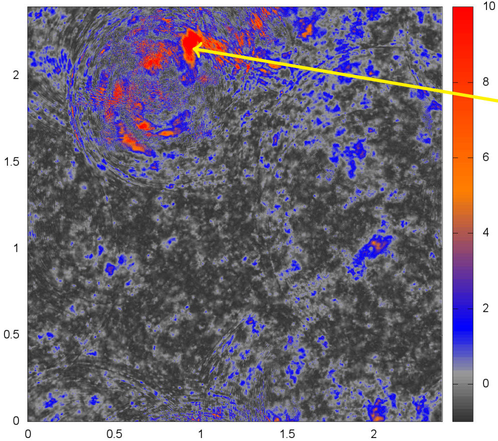

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typical miniclusters

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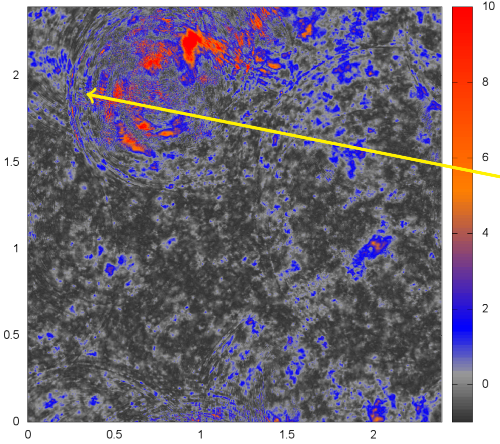

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typical miniclusters

spherical axion waves
from string/wall decay

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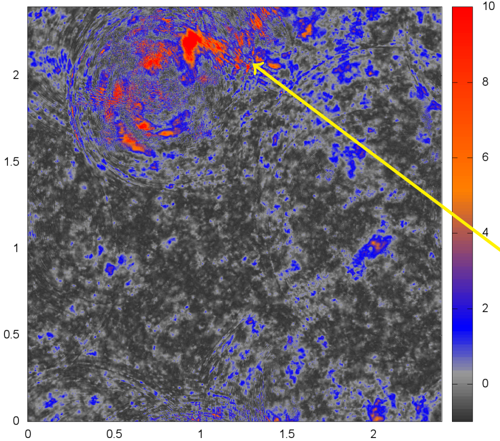

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \rho_{\mathrm{av}}}{\rho_{\mathrm{av}}}$$

typical miniclusters

spherical axion waves
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interference pattern

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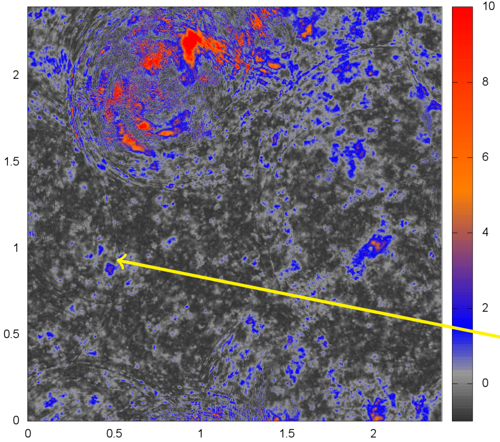


$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \rho_{\text{av}}}{\rho_{\text{av}}}$$

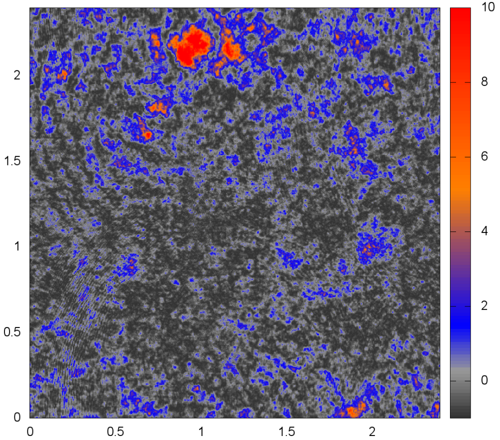
typical miniclusters

spherical axion waves
from string/wall decay

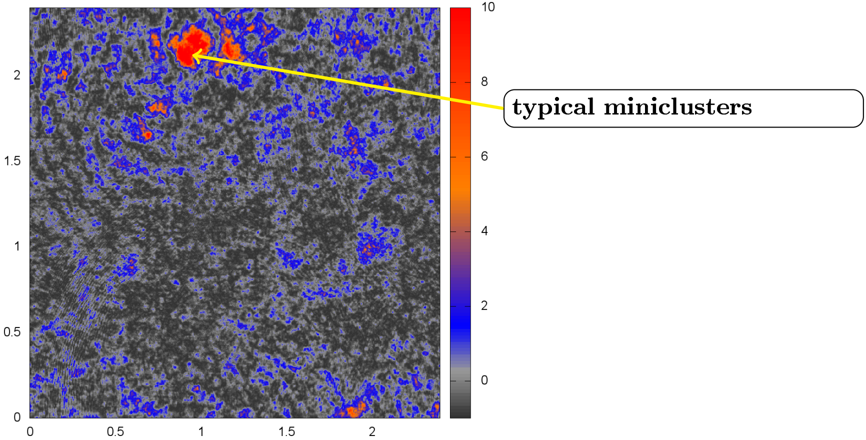
interference pattern

atypical miniclusters
$\mathcal{O}(1)$ fluctuations on small scales

Density Contrast at $z = 9.2$



Density Contrast at z = 9.2



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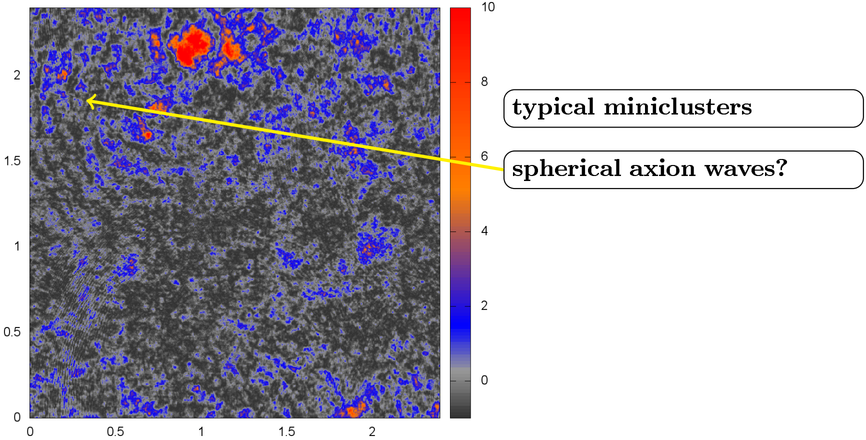
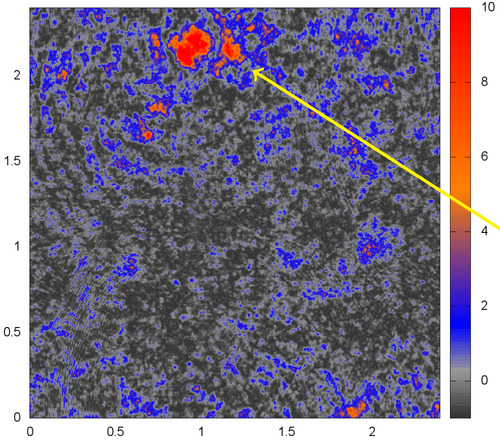


Density Contrast at z = 9.2

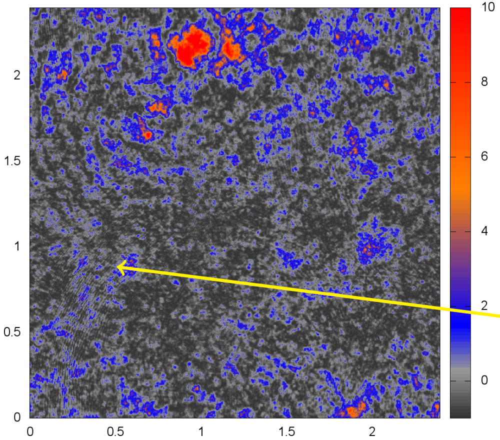


typical miniclusters

spherical axion waves?

interference pattern?

Density Contrast at z = 9.2



typical miniclusters

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Conclusions

- ▷ Numerical simulations for axion density contrast
- ▷ Including misalignment, strings and domain walls
- ▷ String dynamics lead to small Miniclusters, not found before
- ▷ Probably a large hierarchy of Minicluster Masses

To-Do:

- ▷ more simulations
- ▷ virialisation and subsequent evolution
- ▷ observational consequences