Axion dark matter scenarios, parameters, uncertainties ...

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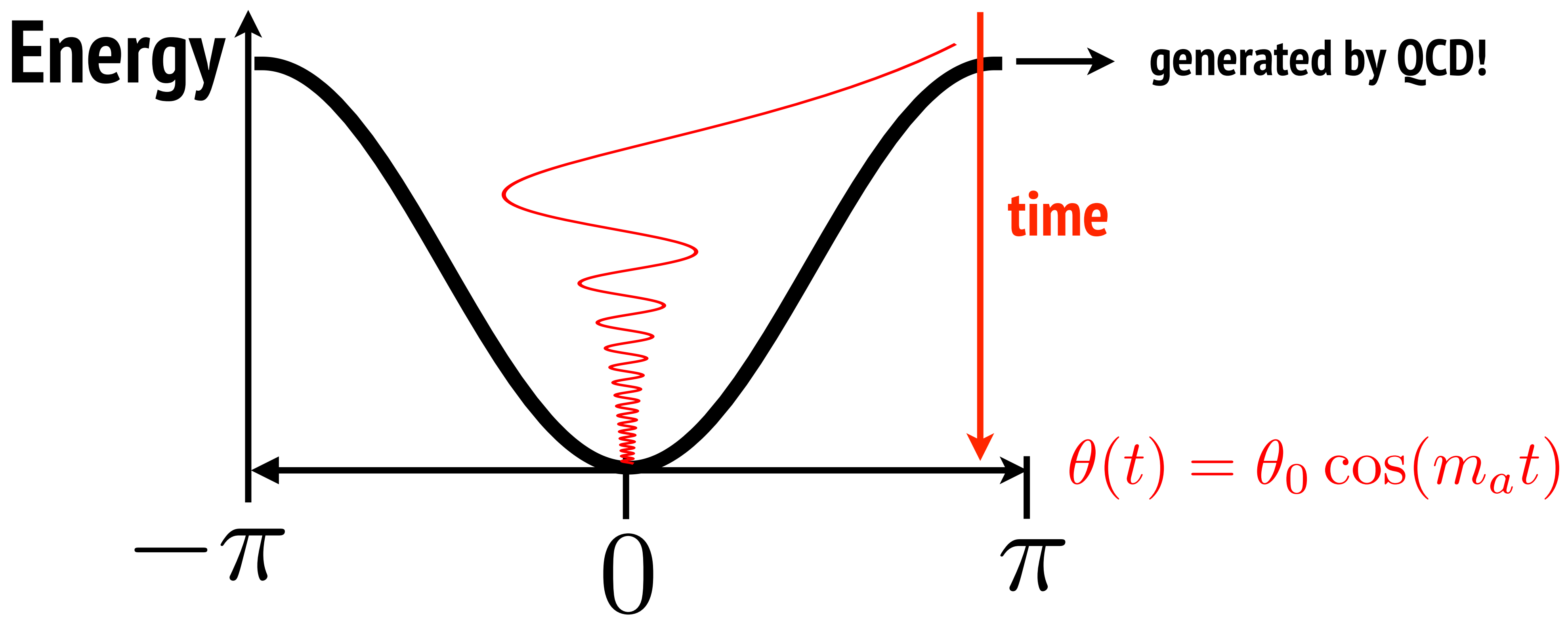
Dark matter

- $\theta(t,\mathbf{x})$ **relaxes to its minimum, overshoots and oscillates**



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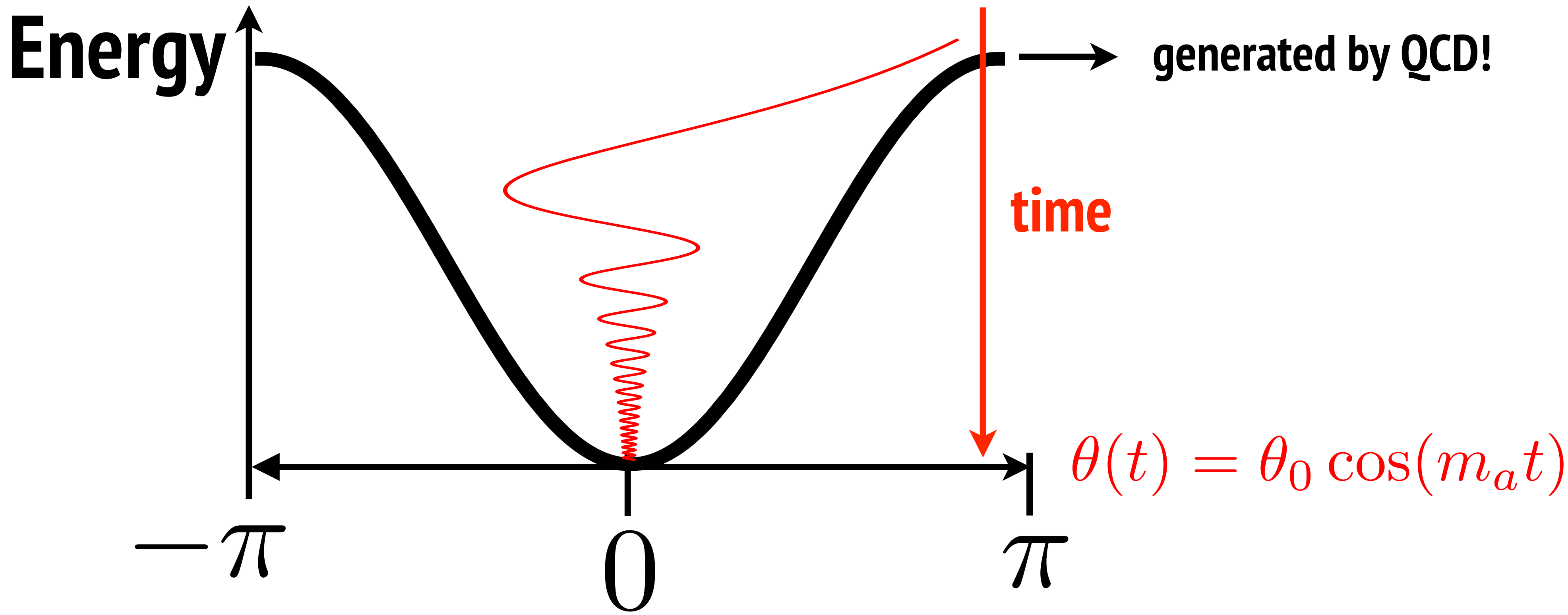
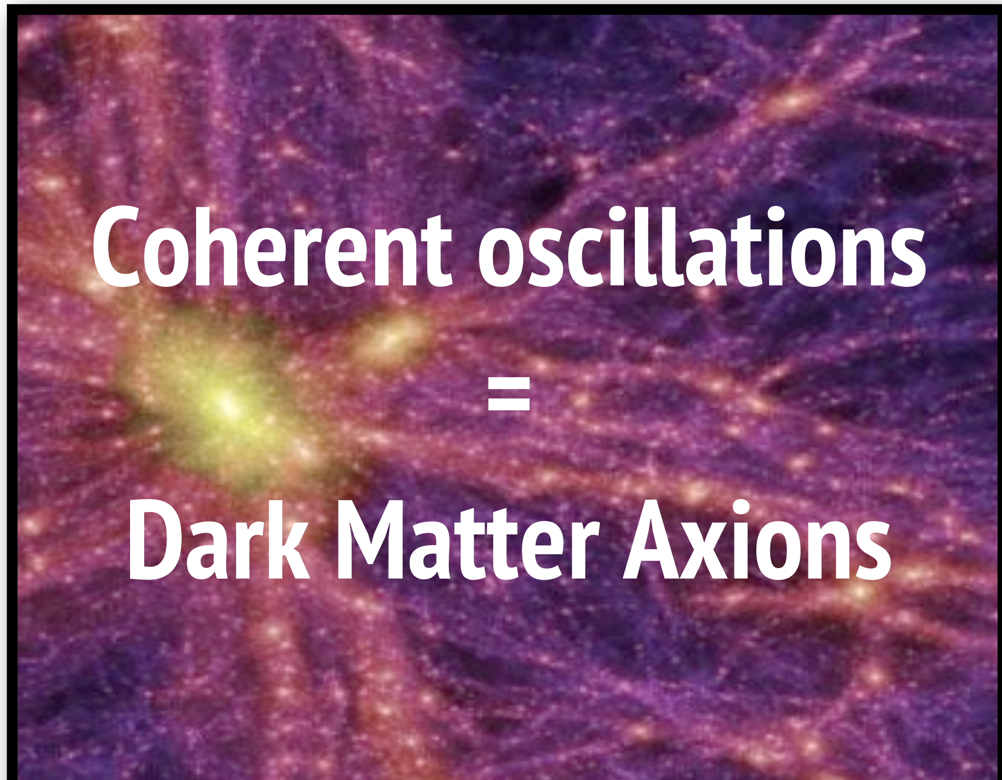




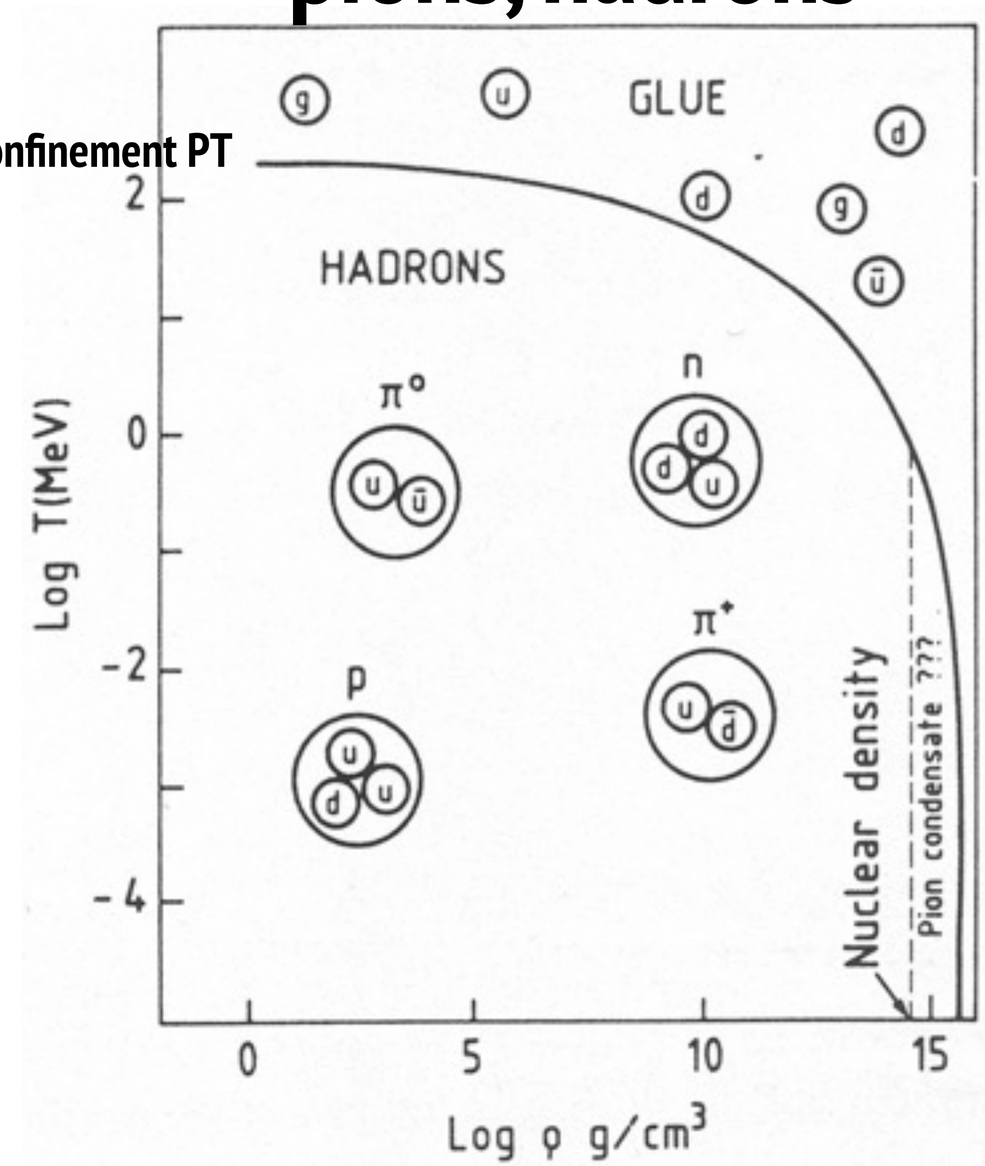
Dark matter

- Non thermal DM production mechanism
- DM abundance depends on <u>initial conditions</u>

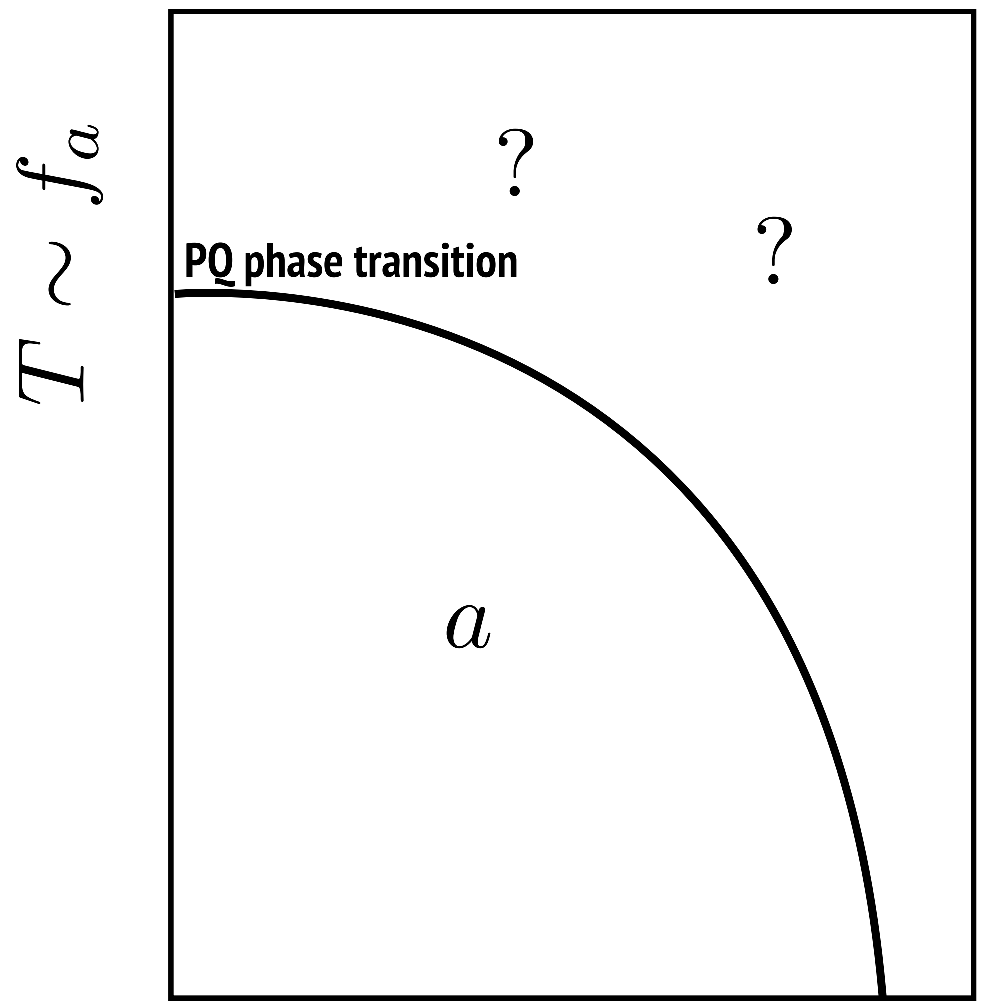
when were axions born?

pions, hadrons

Confinement PT



axions



Dark matter

- Non thermal DM production mechanism
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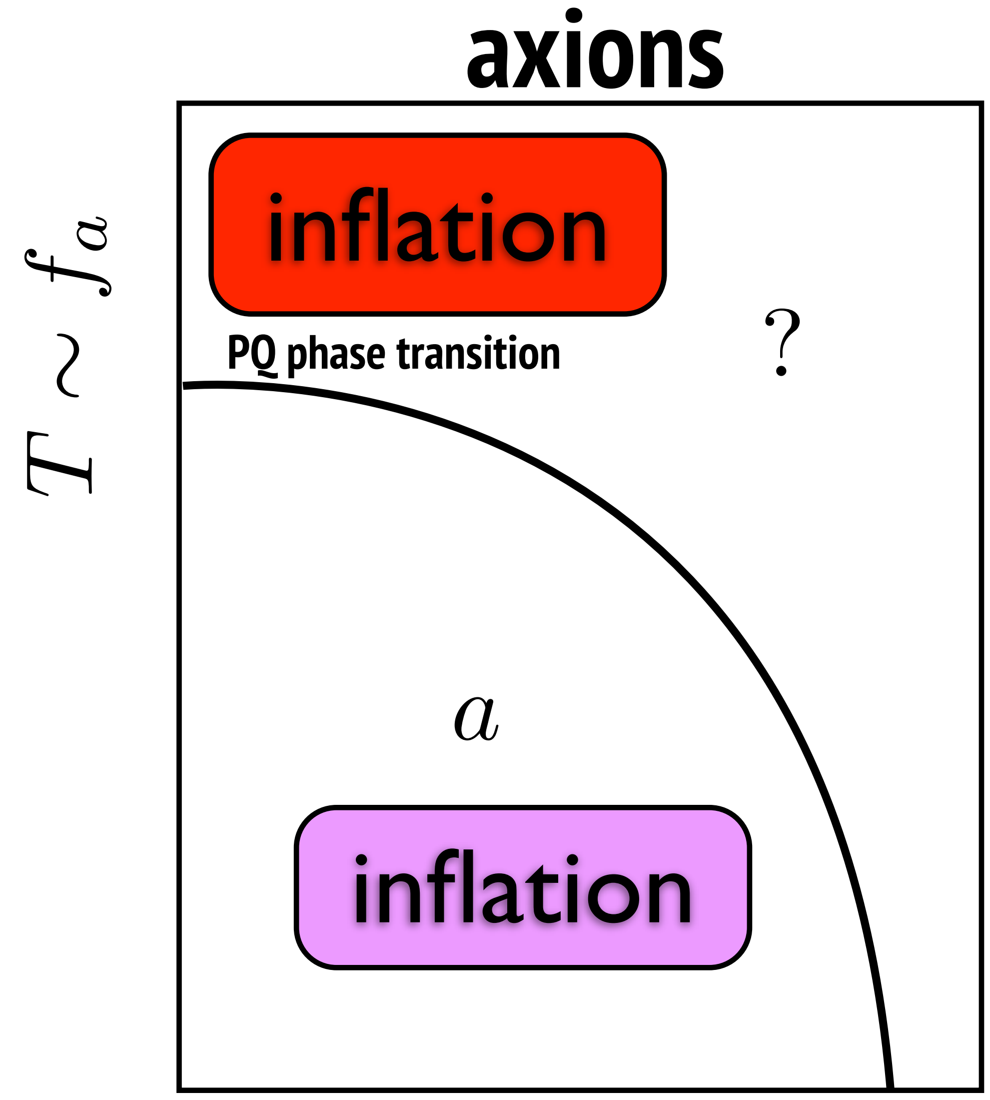
when were axions born?

- Two basic scenarios

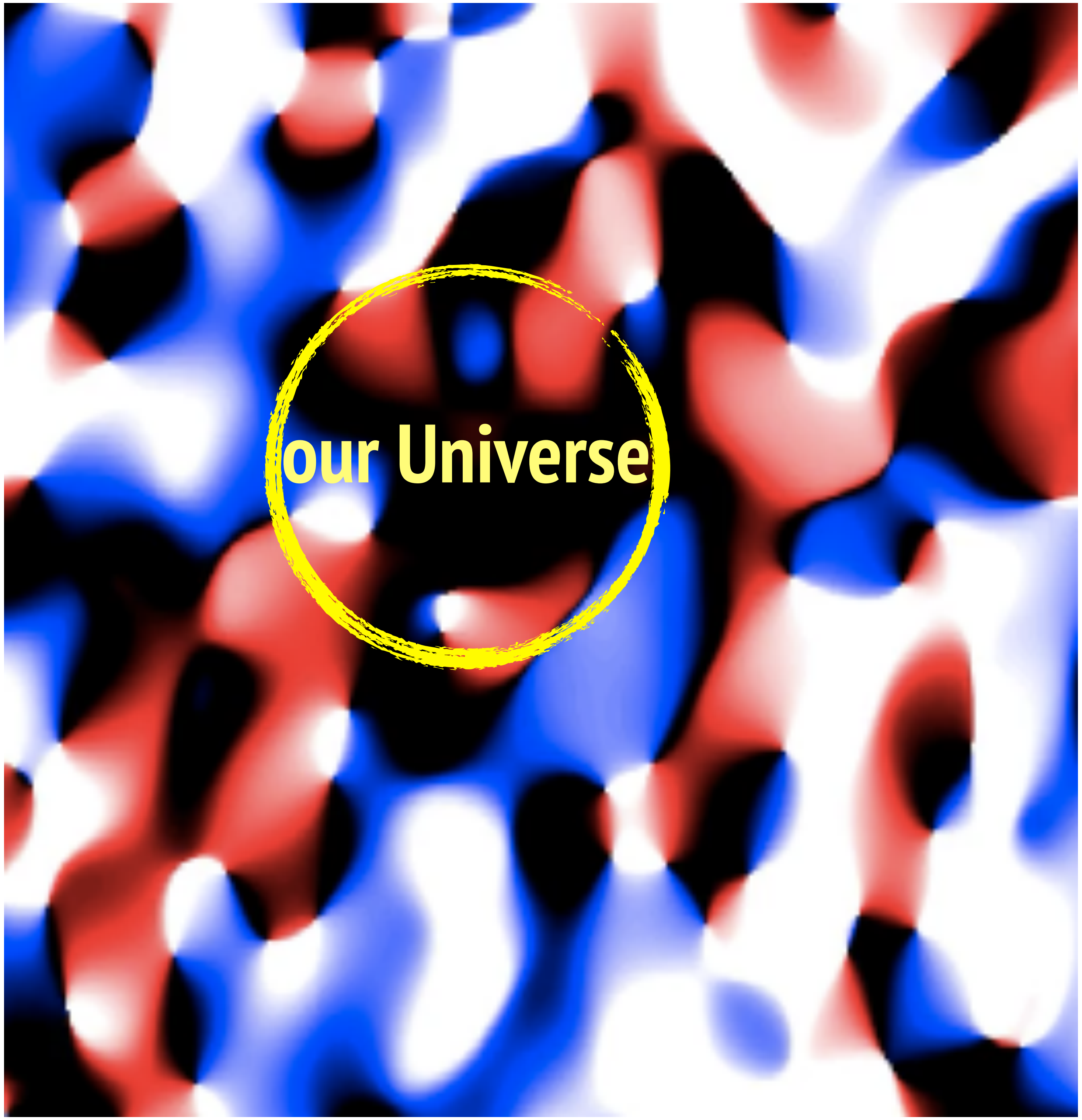
scenario A : inflation happens AFTER PQ phase transition

scenario B : inflation happens BEFORE PQ phase transition



DM in SCENARIO A

π

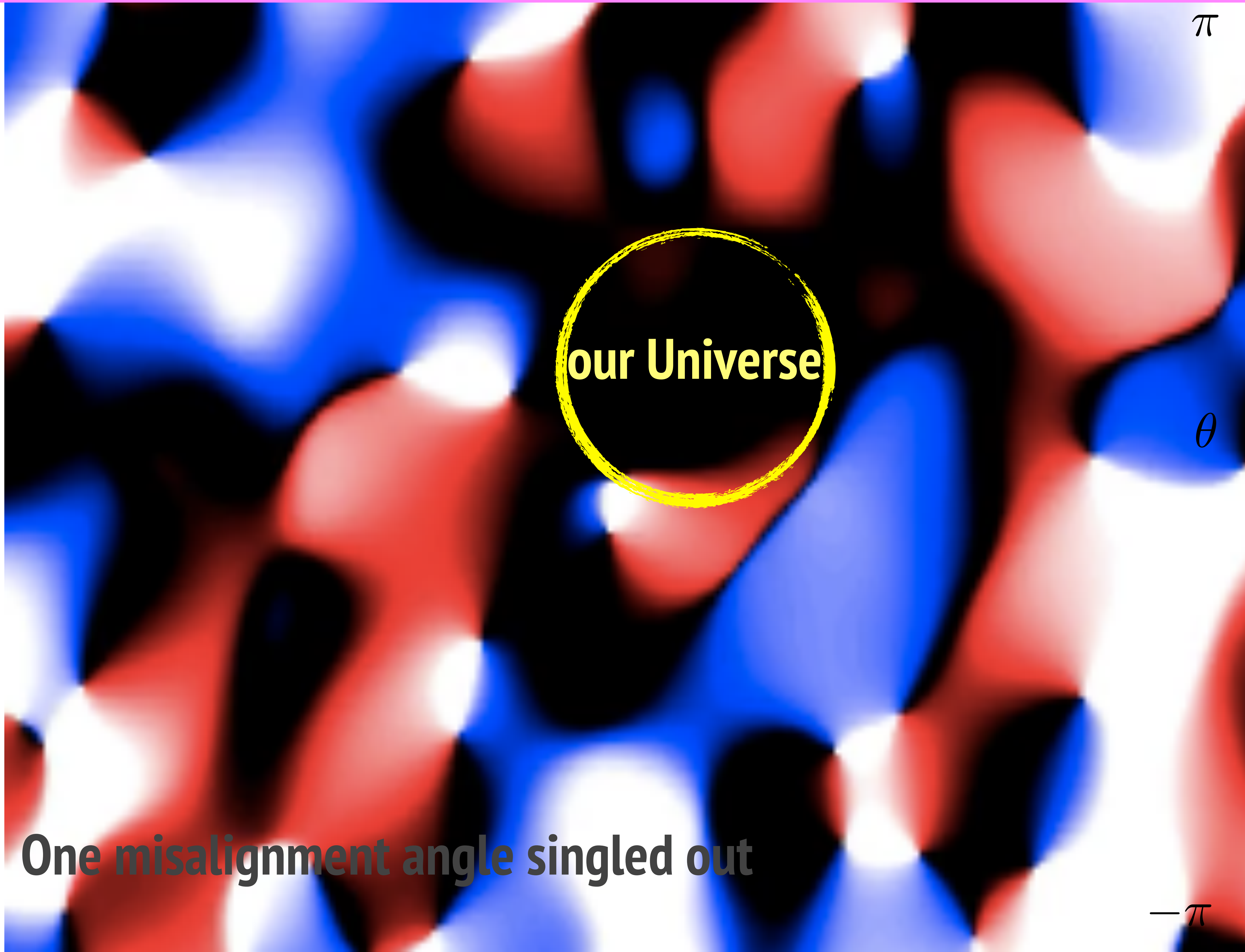


θ

One misalignment angle singled out

$-\pi$

DM in SCENARIO A



DM in SCENARIO A

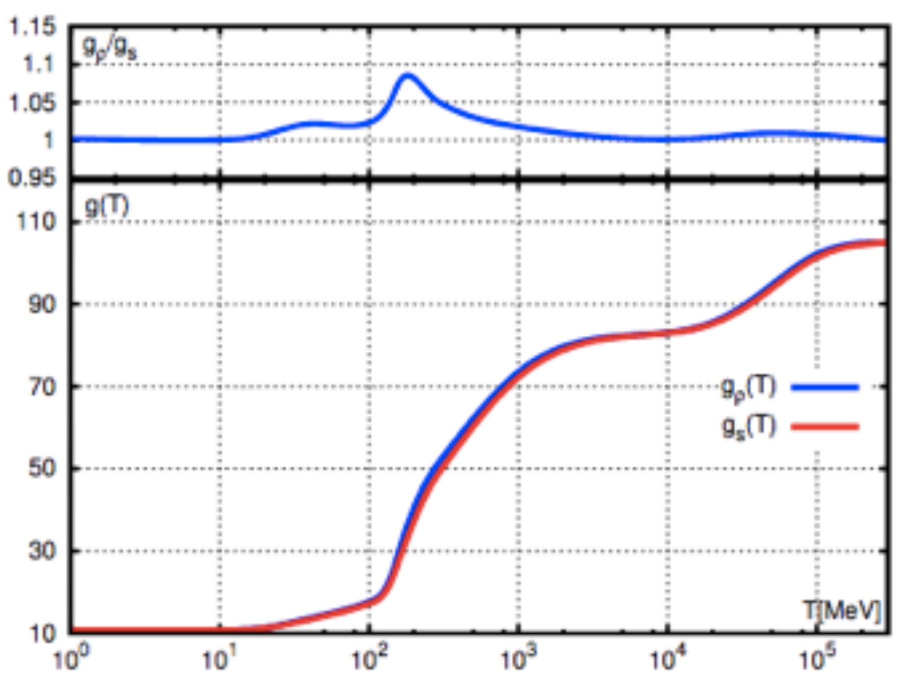
Borsanyi et al, Nature 539 (2016)

- **Homogeneous initial condition** $\theta(t_0, x) = \theta_I$
- **Equations of motion**

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\sin\theta = 0$$

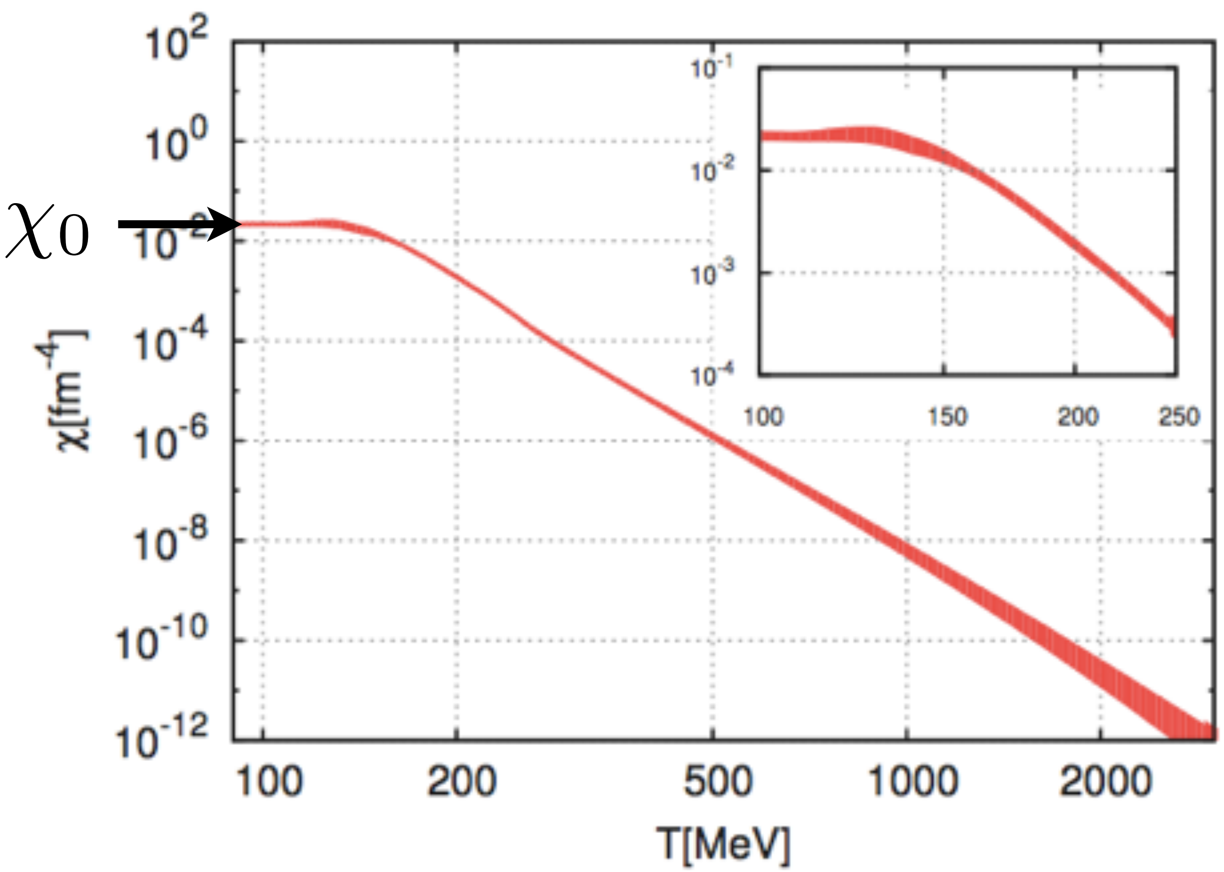
Universe Expansion rate

QCD $m_a^2 f_a^2 = \chi$



SM model only plasma $H \propto \sqrt{g(T)}T^2$

$m_a^2 f_a^2 = \chi_0$



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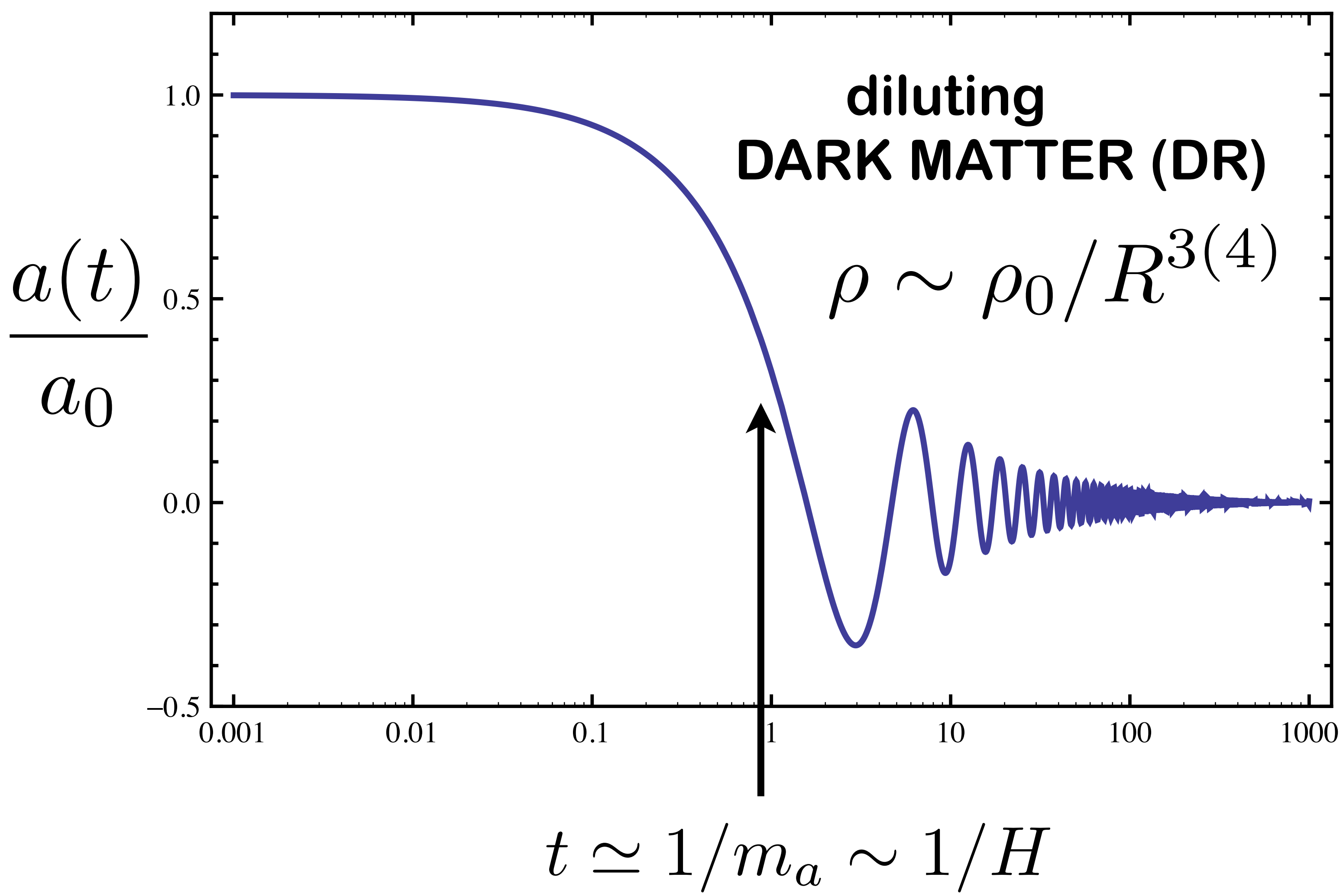

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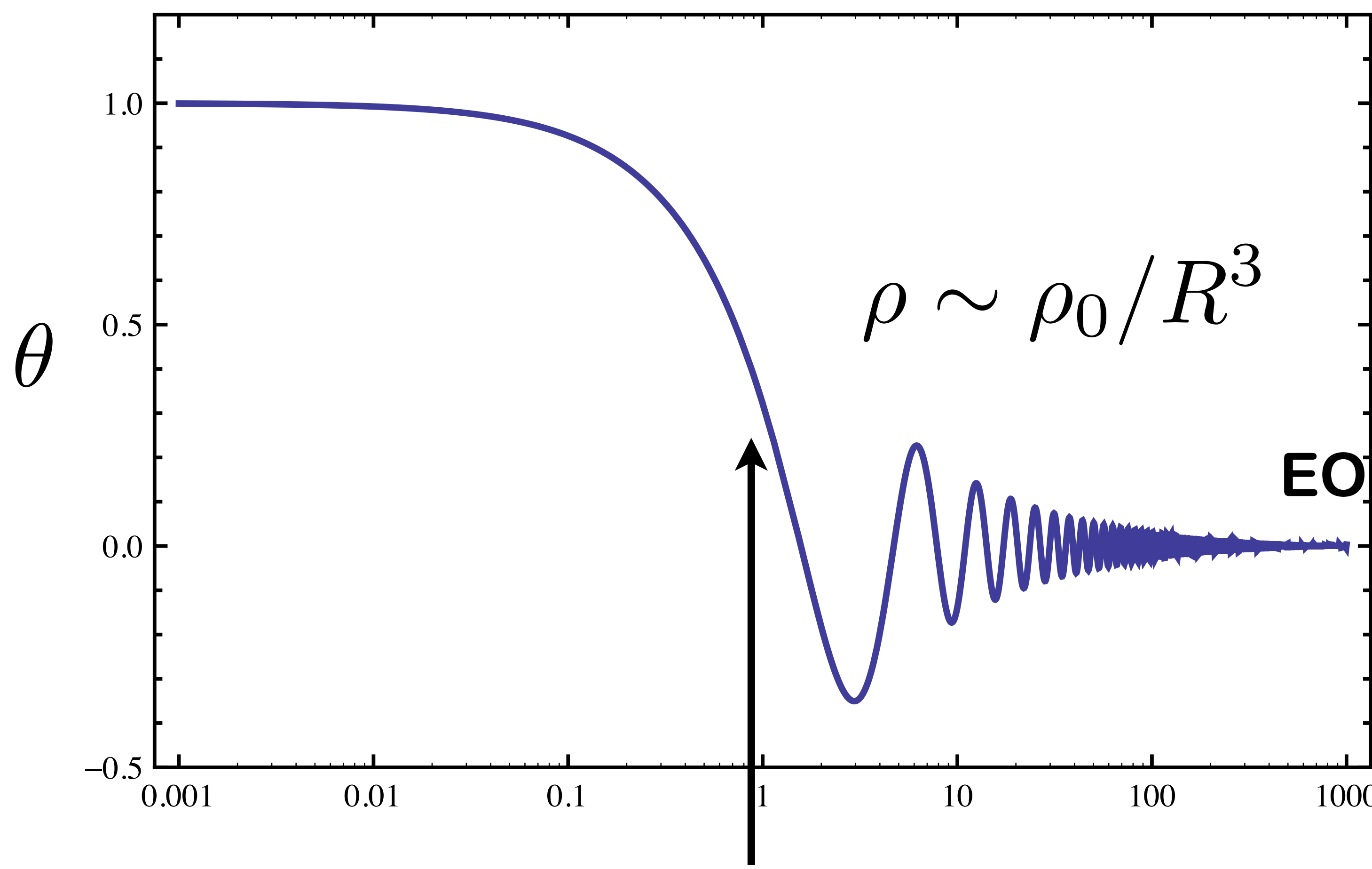
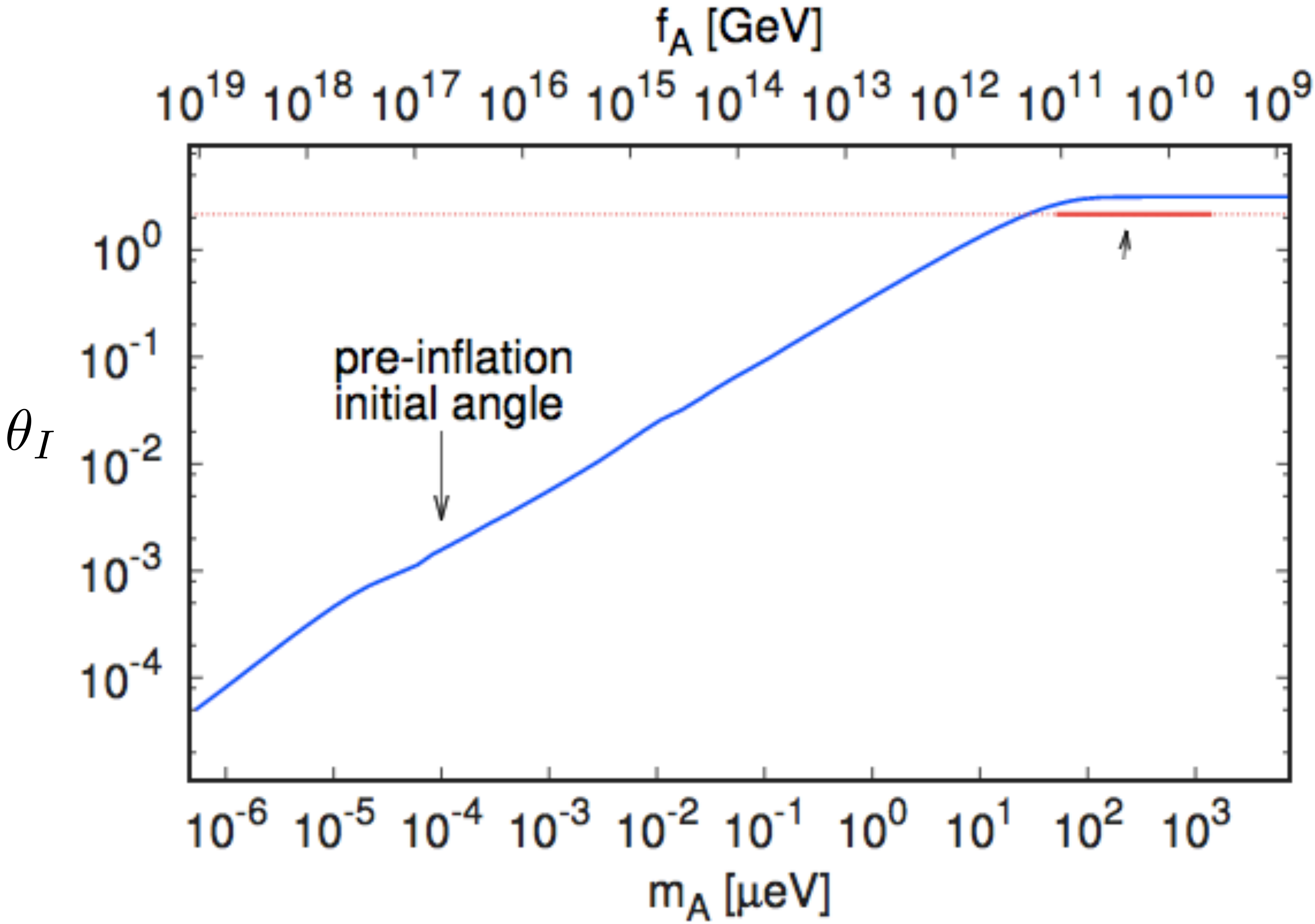


EOS = DARK MATTER

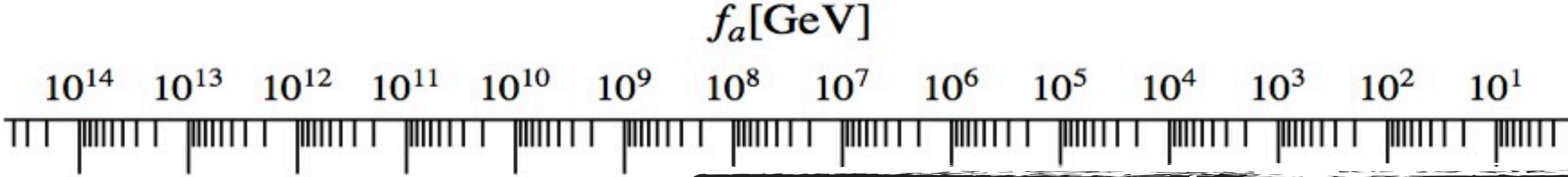
$$t \simeq 1/m_a \sim 1/H$$

DM in SCENARIO A $\Omega_{DM}h^2 = \Omega_a h^2 = 0.12$

- **Absolute uncertainty, any mass has an** $\Omega_a h^2 = 0.12\,\theta_I^2 \left(\frac{6.4\mu\text{eV}}{m_a}\right)^{1.17}$



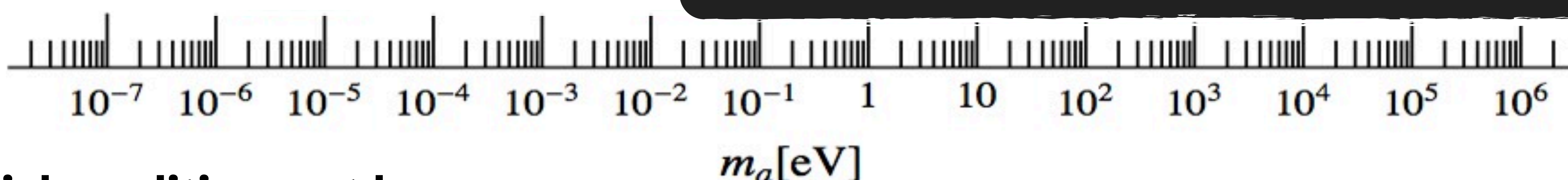
Axion dark matter scenarios



- Axion DM scenarios

$\theta_I < 0.3$ | $\theta_I \in (0.3 - 3)$ | $\theta_I \sim \pi$
tuned (anthropic?) | ok | tuned

Excluded
Astrophysics and cosmo



Initial conditions set by :

SCENARIO A

SCENARIO B

π

- Inflation
- PQ transition
- θ inhomogeneous
- strings
- ...
- relaxation
- ...

θ

- T~QCD $\theta \to 0$
- domain walls

- axion DM

$-\pi$

SCENARIO B

- Inflation
- PQ transition
- θ inhomogeneous
- strings
- ...
- relaxation
- ...

- T~QCD $\theta \to 0$
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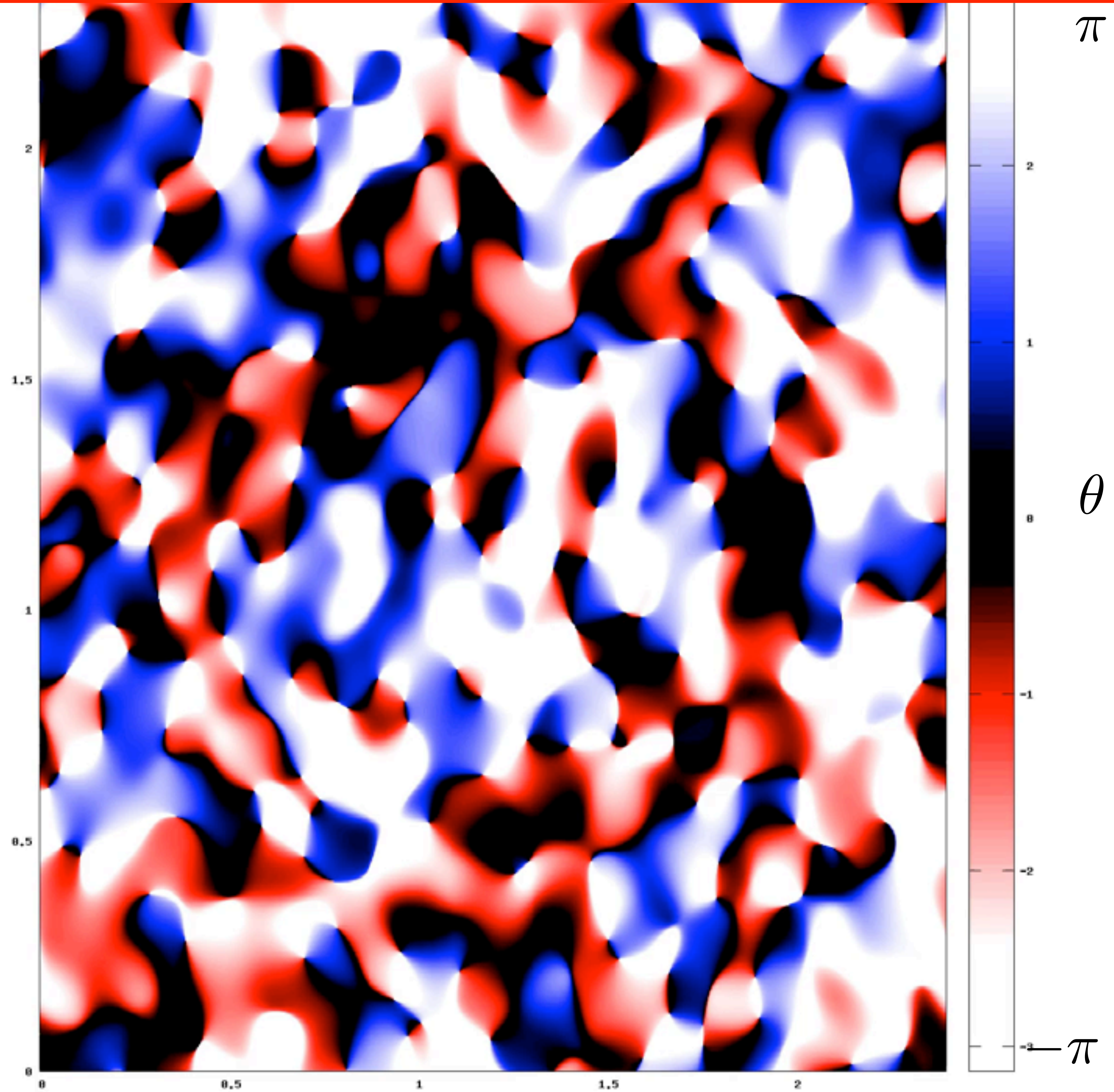
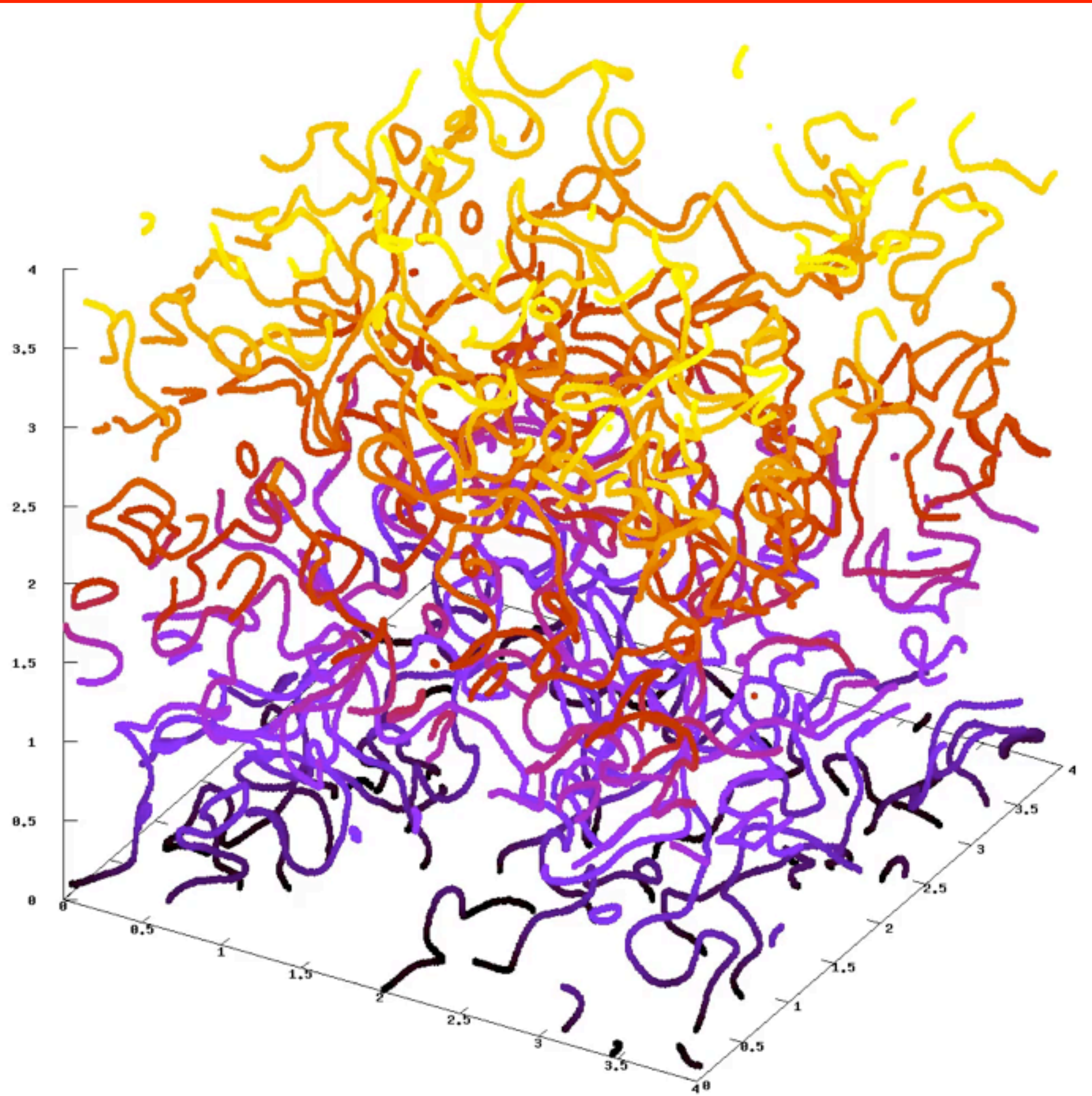
- axion DM



Strings



SCENARIO A $\Omega_{DM}h^2 = \Omega_a h^2 = 0.12$

- Random initial conditions, no θ_I uncertainty
- Uncertainty here is the axion radiation from strings/walls
- Split ... $\Omega_c h^2 = \langle \Omega_c h^2 \rangle_{\theta_I} + \Omega_{a,st} h^2$

$$\langle \Omega_c h^2 \rangle_{\theta_I} = 0.12 \left(\frac{28(2)\mu\text{eV}}{m_a} \right)^{1.165}$$

Energy in string network $\rho_s \simeq \zeta \frac{\pi f_a^2 \log(f_a t)}{t^2}$ **-> axions**

$$\zeta = 1 \pm 0.5$$

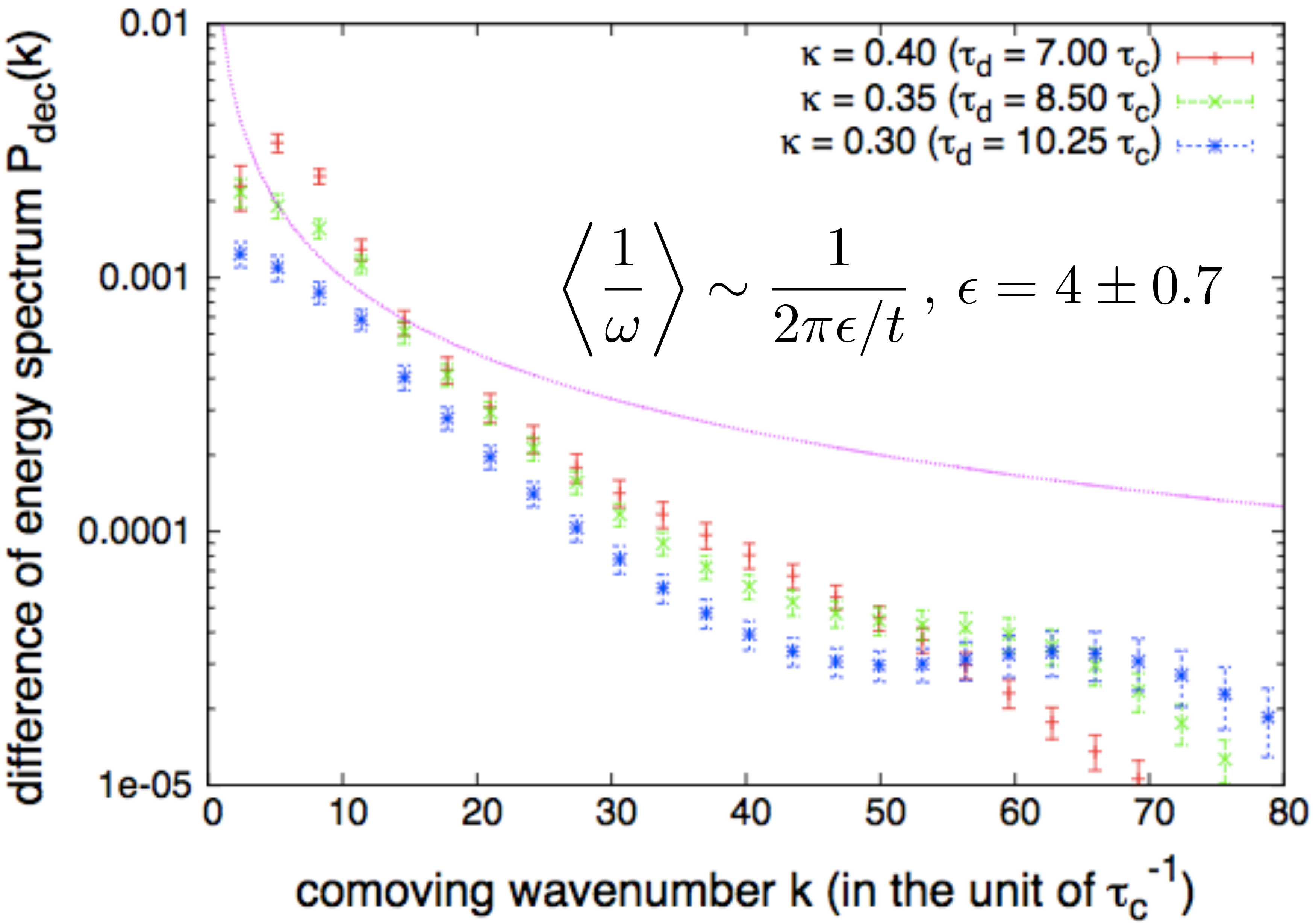
$$\Omega_{a,st} h^2 \propto N_a = \int dt R^3(t) \int d\omega \frac{1}{\omega} \frac{d\rho_{st}}{dt d\omega}$$

radiated axion spectrum

SCENARIO A $\Omega_{DM}h^2 = \Omega_a h^2 = 0.12$

- Spectrum is red

Hiramatsu et al, PRD85 (2012)



$$\Omega_{a,s}h^2 \sim 0.37^{+0.3}_{-0.2}\left(\frac{f_A}{1.92\times 10^{11}}\right)^{1.165}\frac{\ln\left(f_A t_{co}\sqrt{\lambda_\sigma/\zeta}\right)}{50},$$

$$50\,\mu\text{eV} \lesssim m_A \lesssim 200\,\mu\text{eV},$$

SCENARIO A $\Omega_{DM}h^2 = \Omega_a h^2 = 0.12$

$$\Omega_a h^2 = \langle\rangle + \int dt d\omega \frac{1}{\omega}\zeta \ldots$$

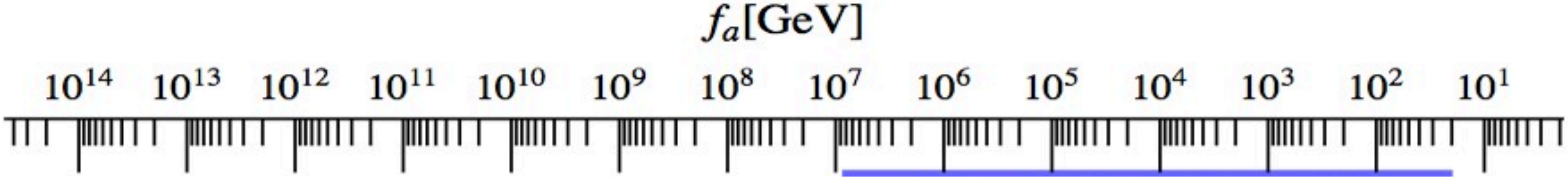
$50\,\mu\mathrm{eV} \lesssim m_A \lesssim 200\,\mu\mathrm{eV},$

- ζ **and** ω **measured from fluffy strings** $f_{a,\mathrm{sim}} \sim 10^{-30} f_a$
- **no hom. patches in the simulation**
- **assume strings do not interact after being radiated ...**

- **alternatively one can compute** $\Omega_a h^2$ **directly from simulations**

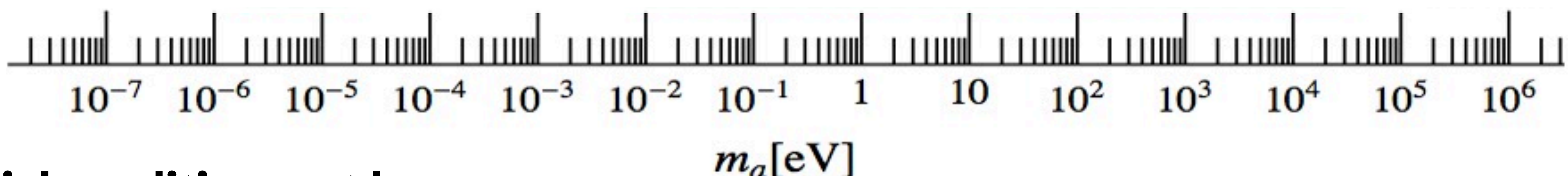
  Moore et al get $m_a \sim 18\,\mu\mathrm{eV}$

Axion dark matter scenarios



- Axion DM scenarios

tuned (anthropic?) | ok | tuned

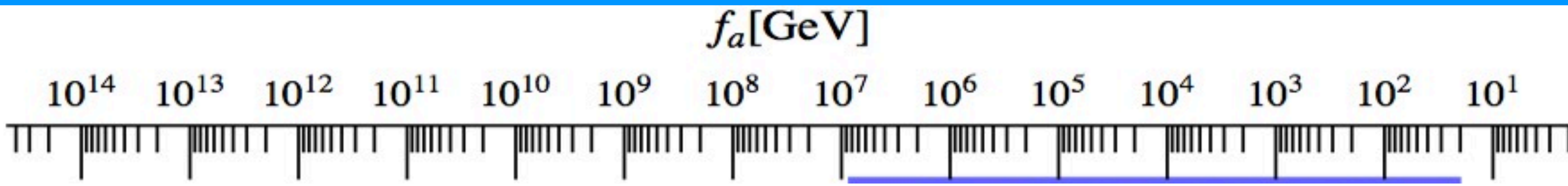


Initial conditions set by :

Inflation smooth

$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$$

Axion dark matter scenarios



- Axion DM scenarios

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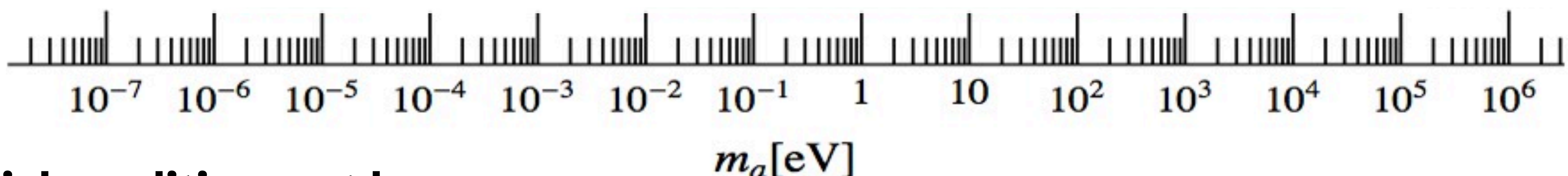
Excluded (too much DM) | ok | sub



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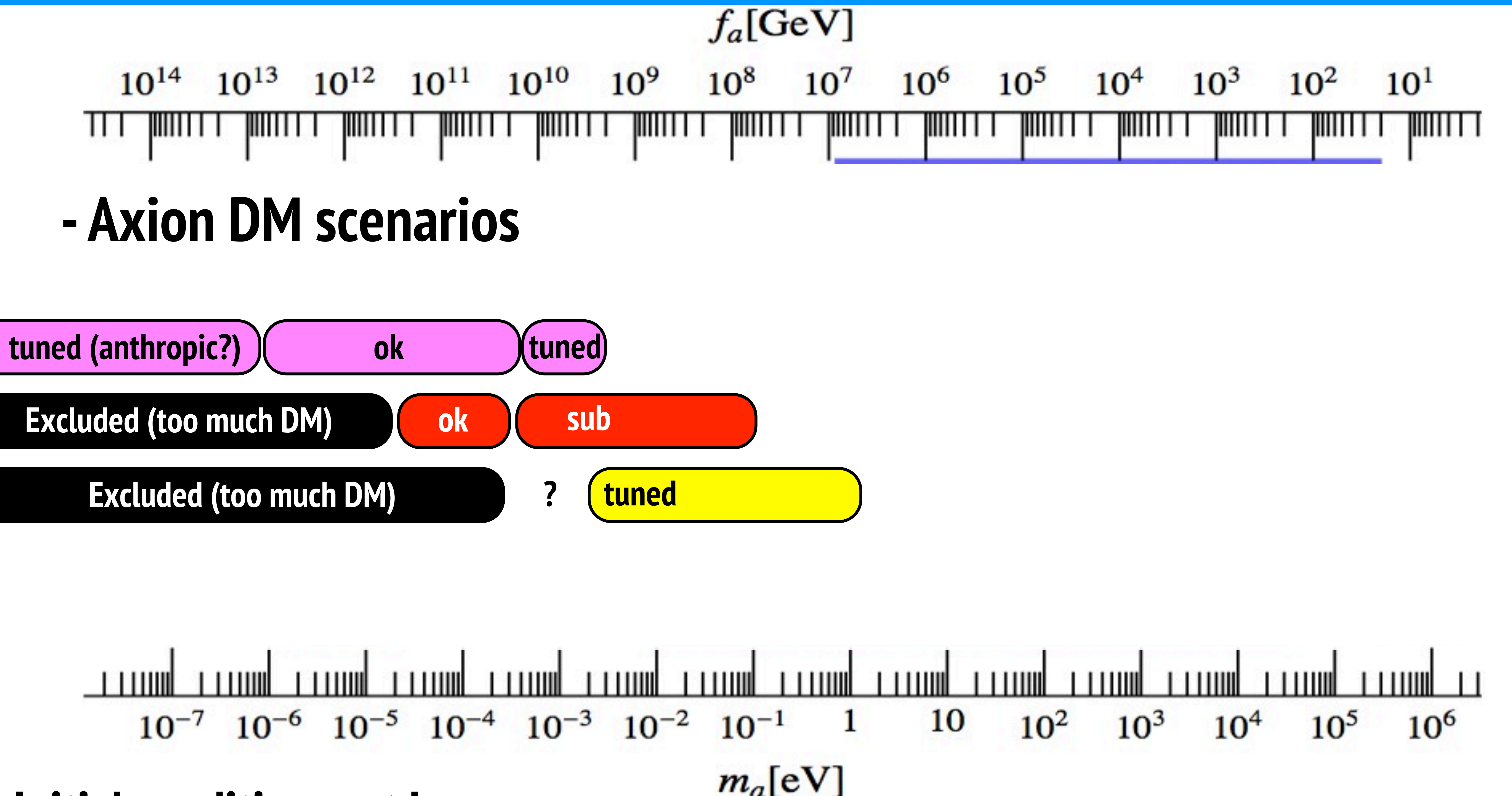
Phase transition (N=1)

strings+unstable DW's

Axion dark matter scenarios

- Axion DM scenarios



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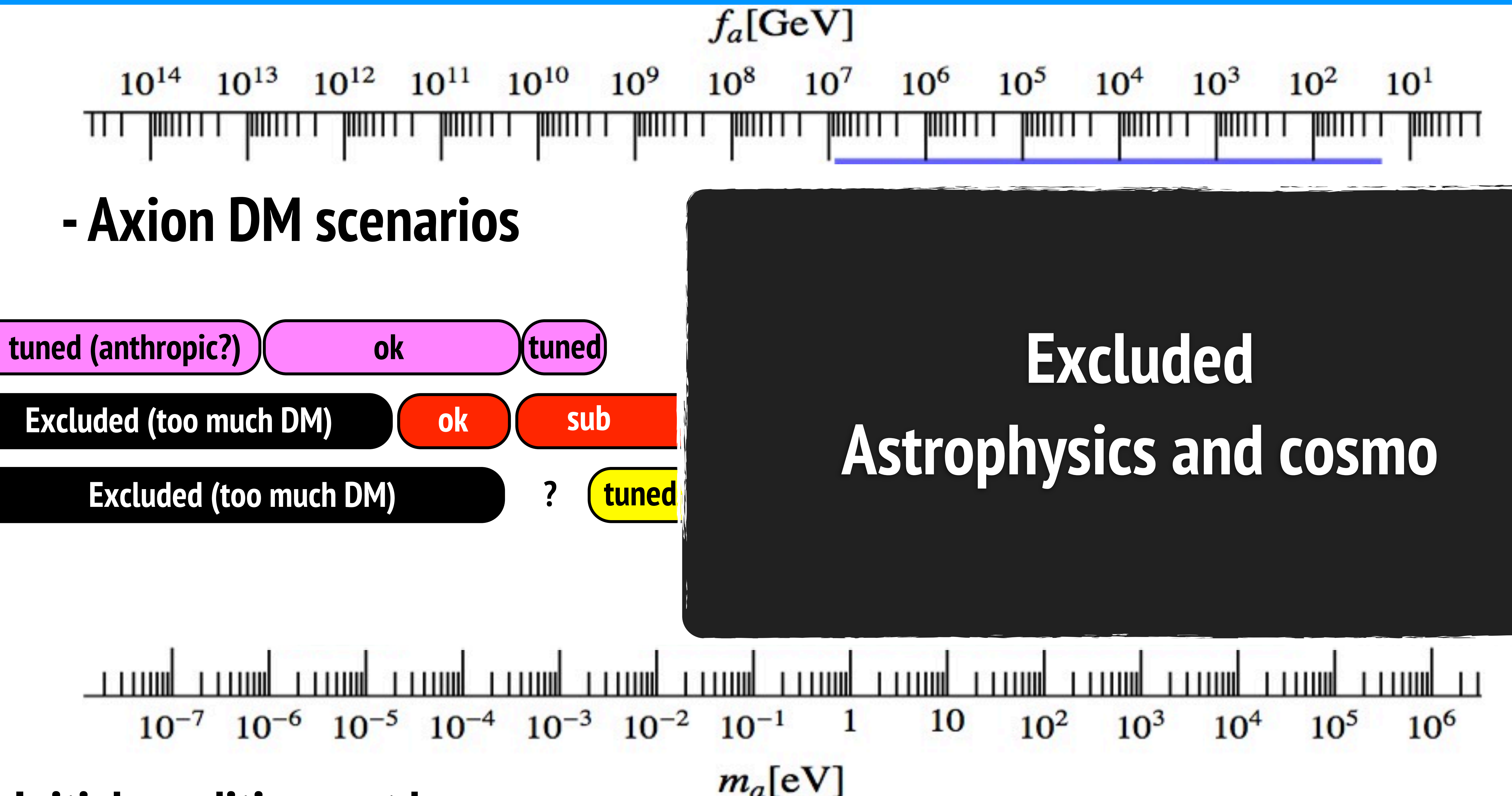
Axion dark matter scenarios



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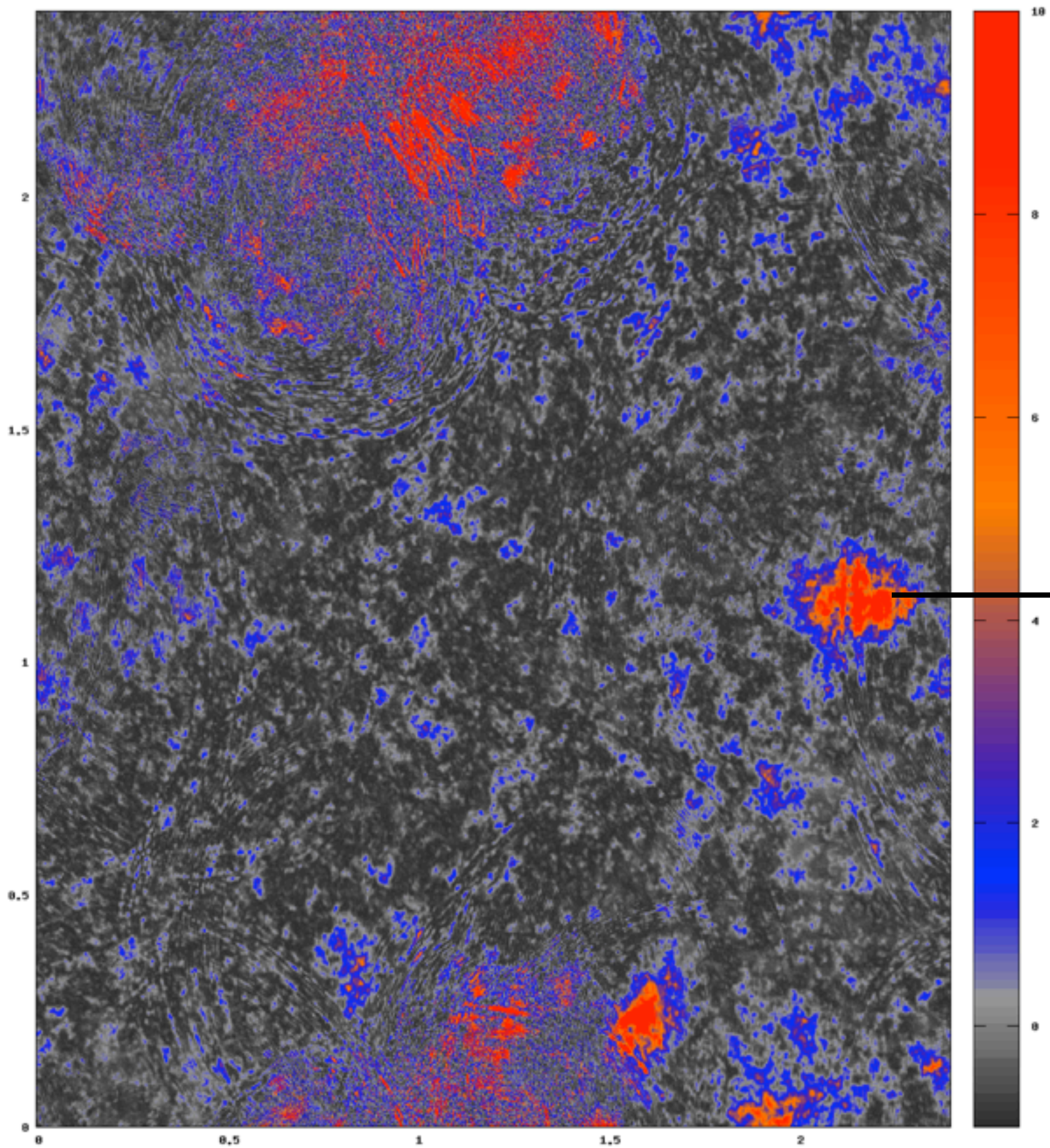
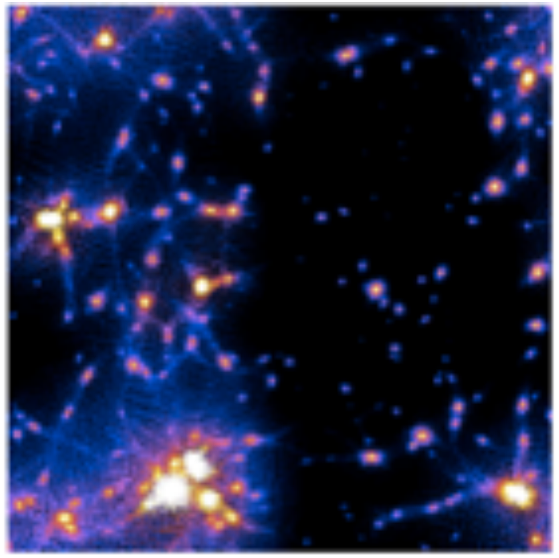
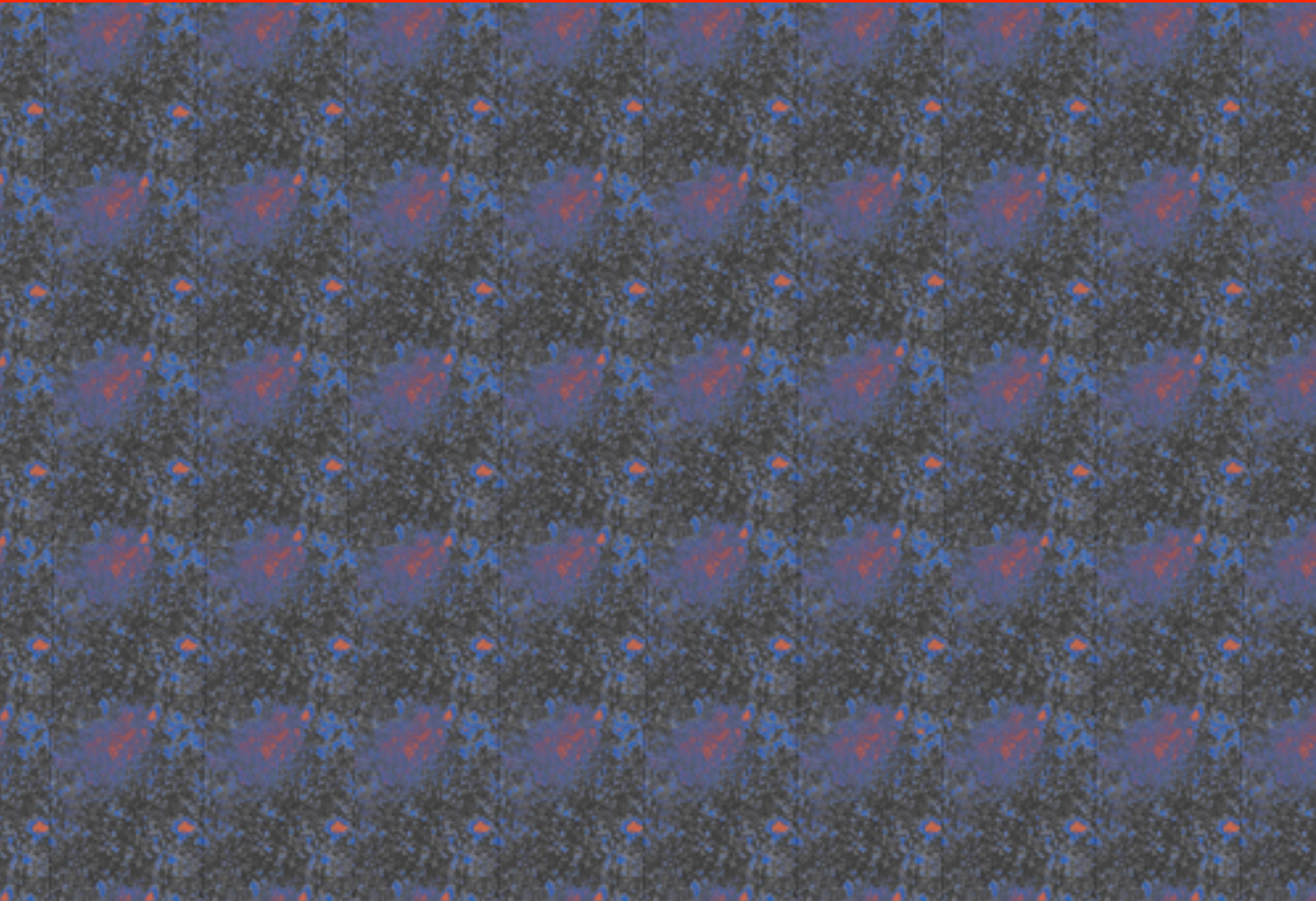
Dark matter density, inhomogeneous at comoving mpc scales



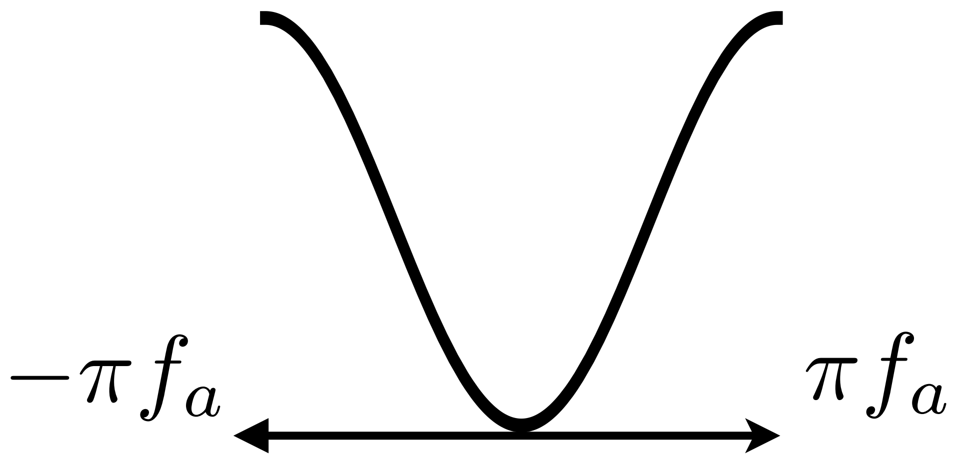
miniclúster seed!



but homogeneous at large scales

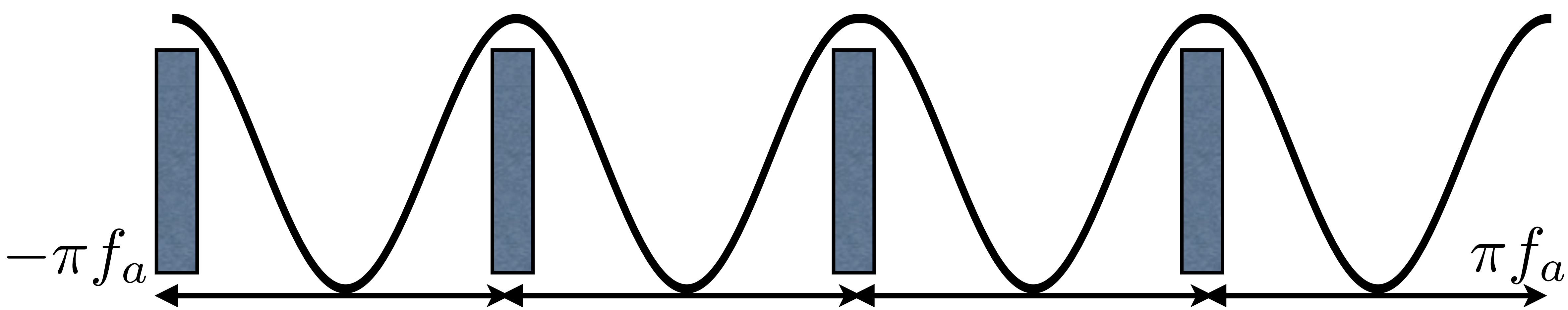


SCENARIO A, N=1



$$\frac{a}{f_a} = N\theta$$

SCENARIO A, N>1, Domain Walls stable-> cosmological disaster



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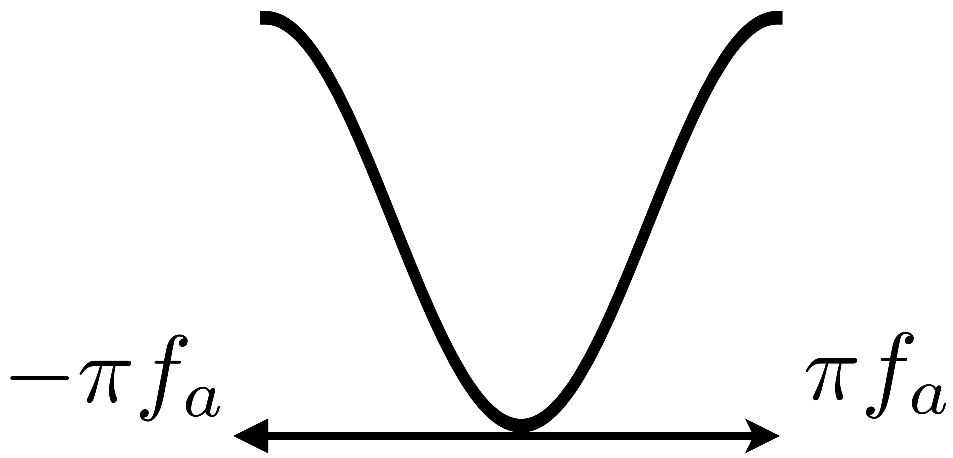
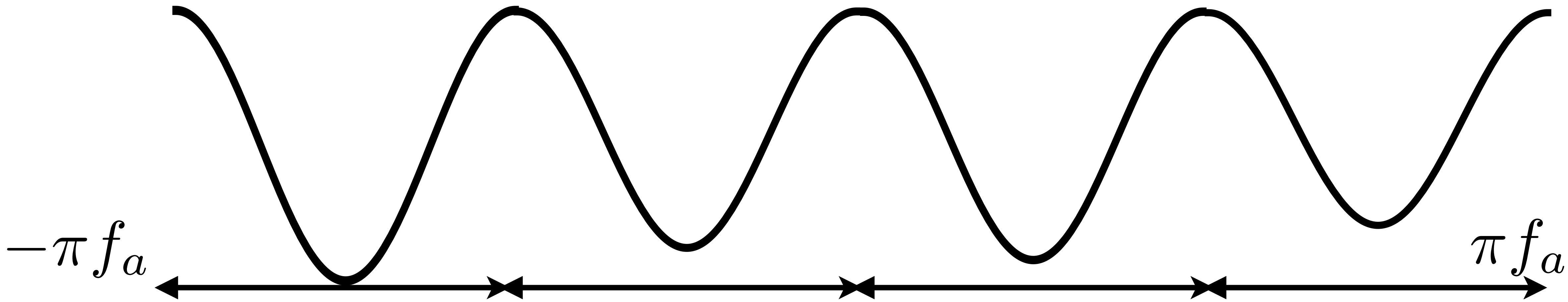
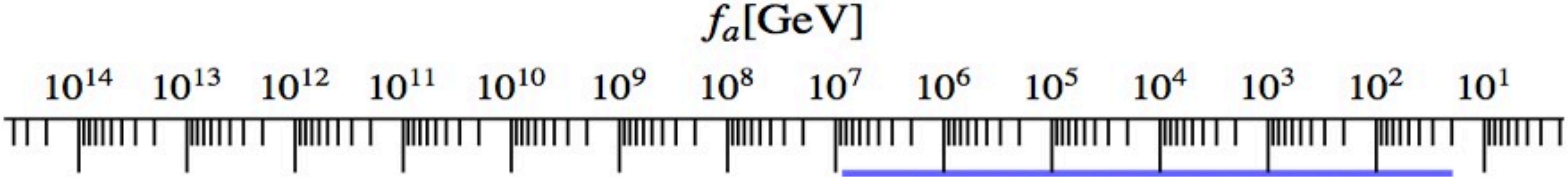


$$\frac{a}{f_a} = N\theta$$

SCENARIO A, N>1, break slightly degeneracy (quantum gravity?)



Axion dark matter scenarios



- Axion DM scenarios

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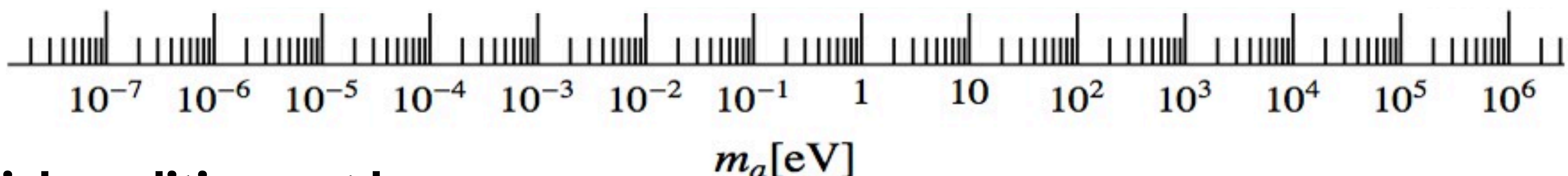

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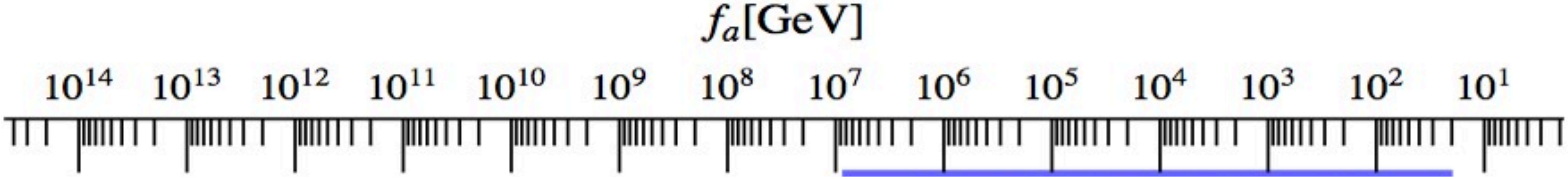

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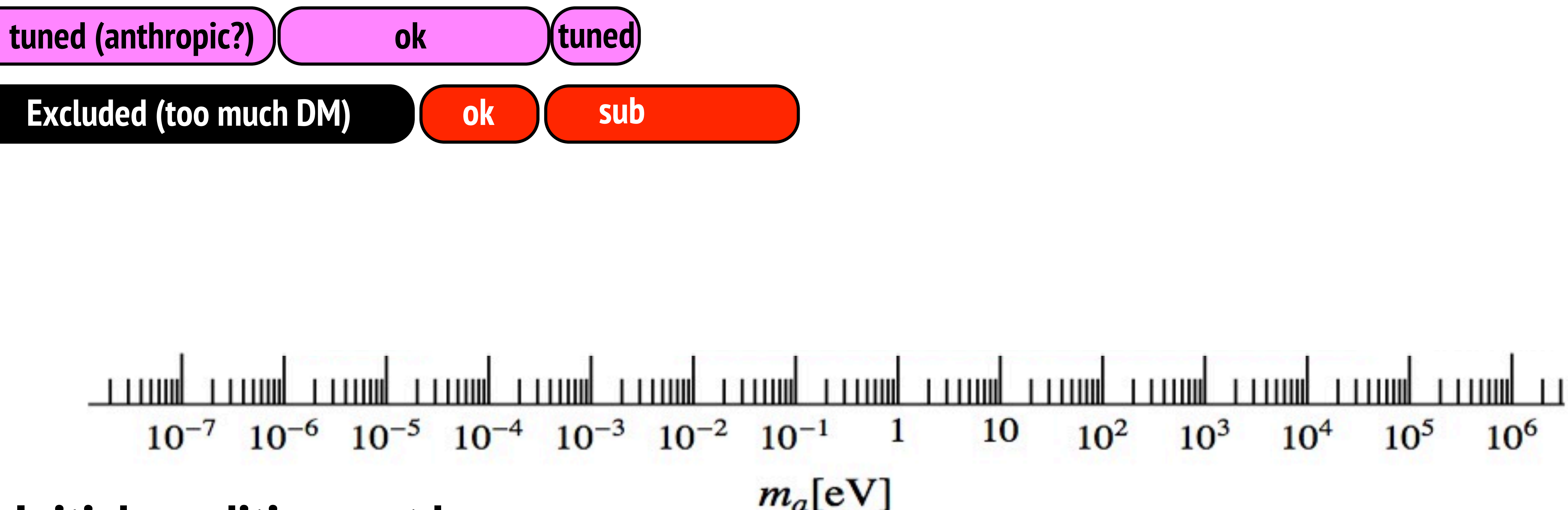

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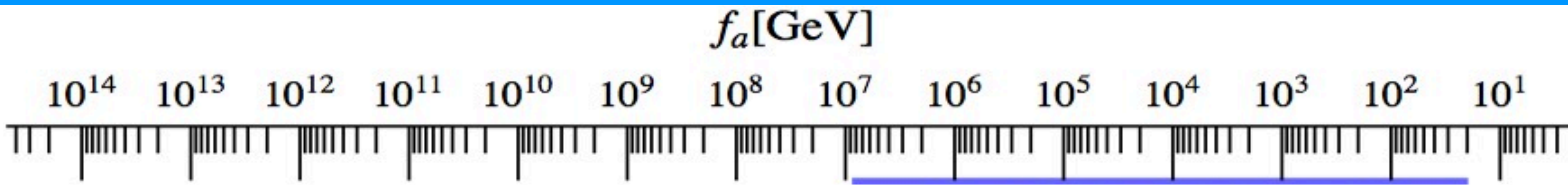
Phase transition (N=1)

strings+unstable DW's

Axion dark matter scenarios



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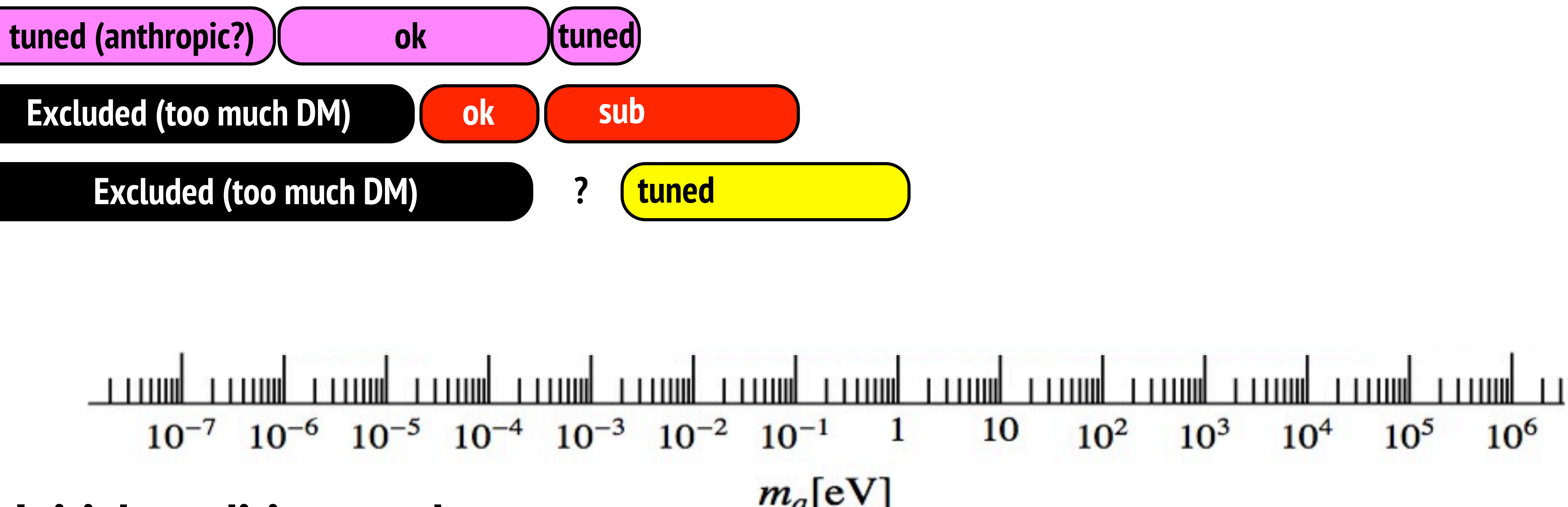

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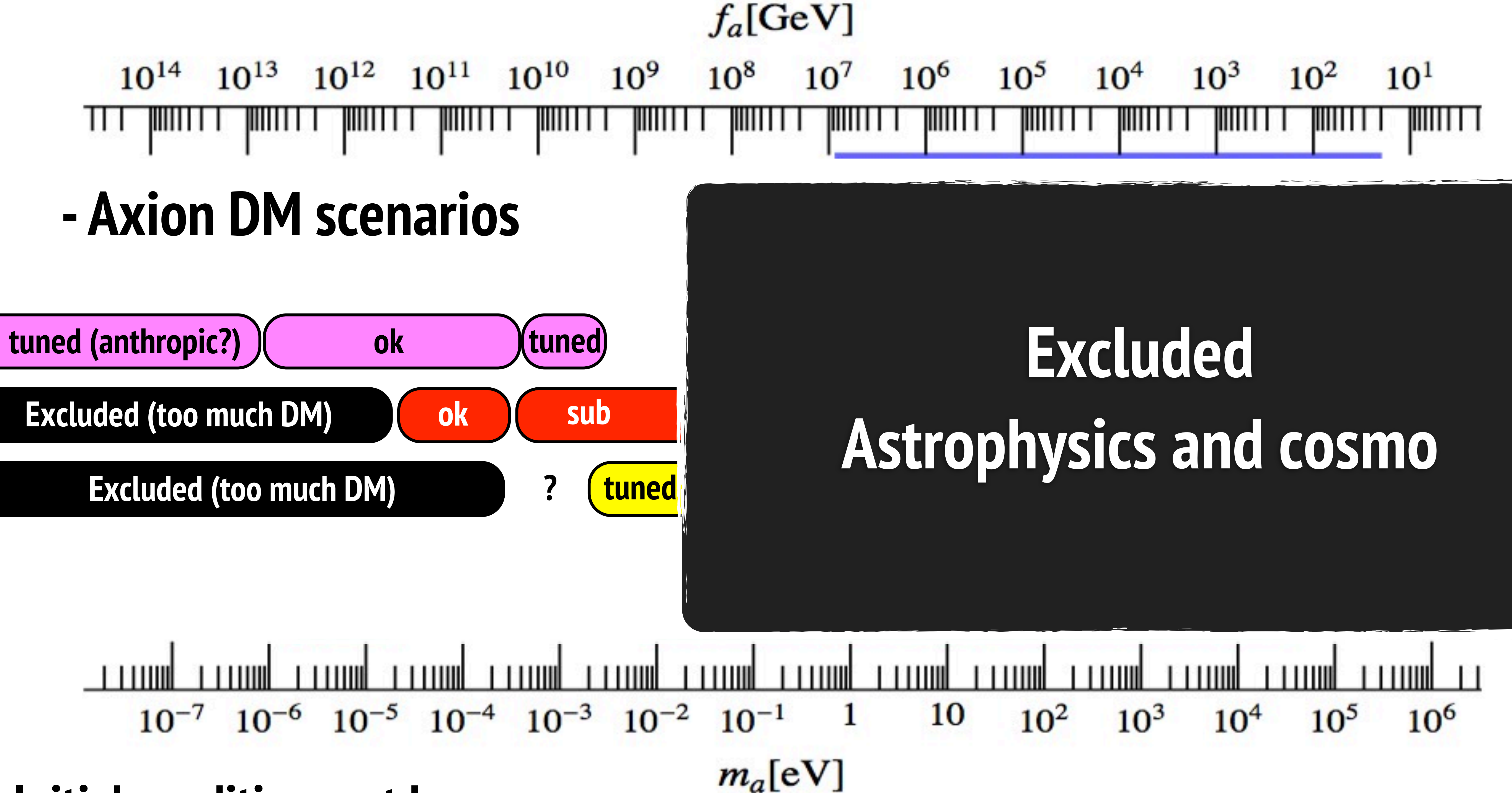
Axion dark matter scenarios

- Axion DM scenarios



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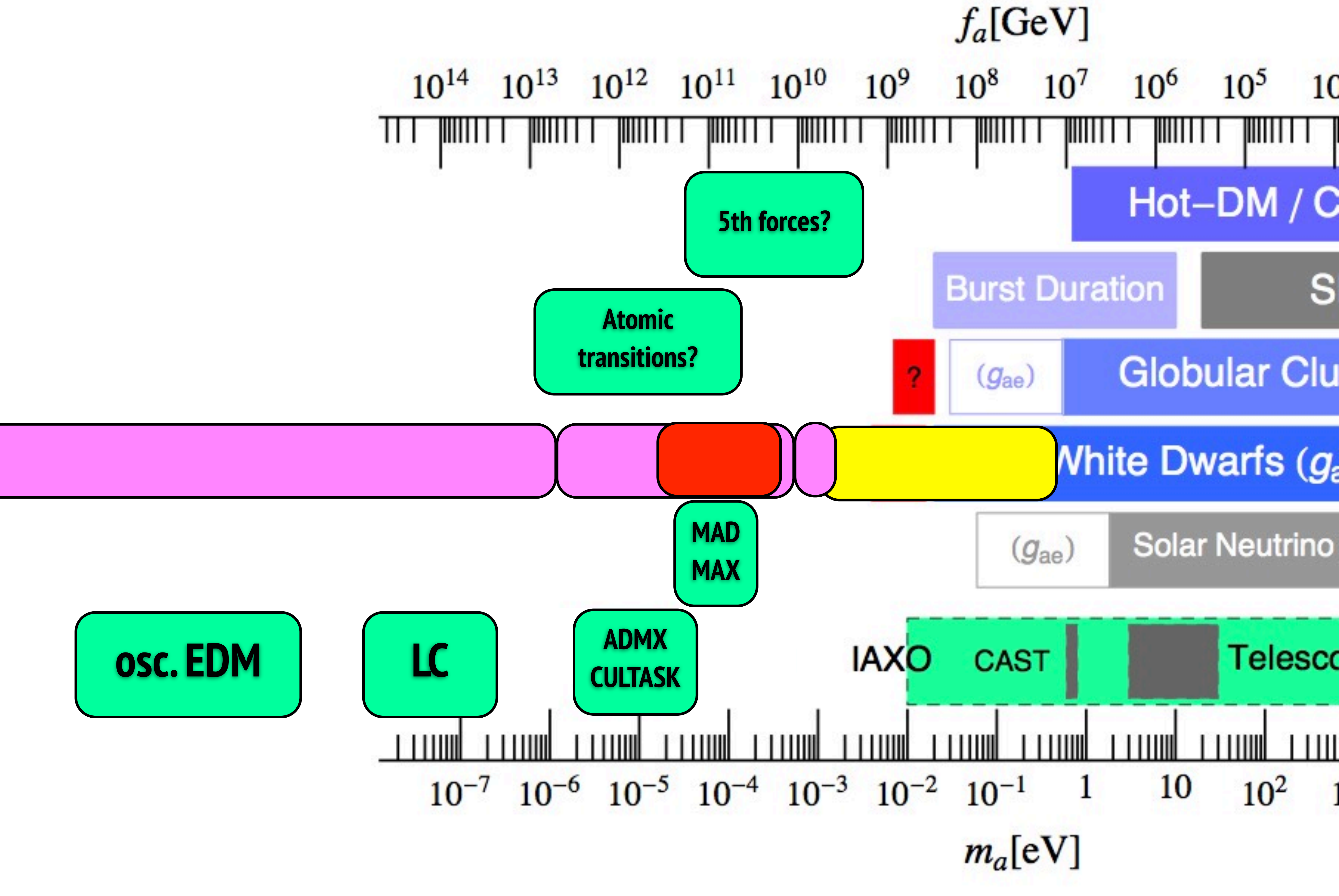
Comparison with experimental target areas



Thank you!!!