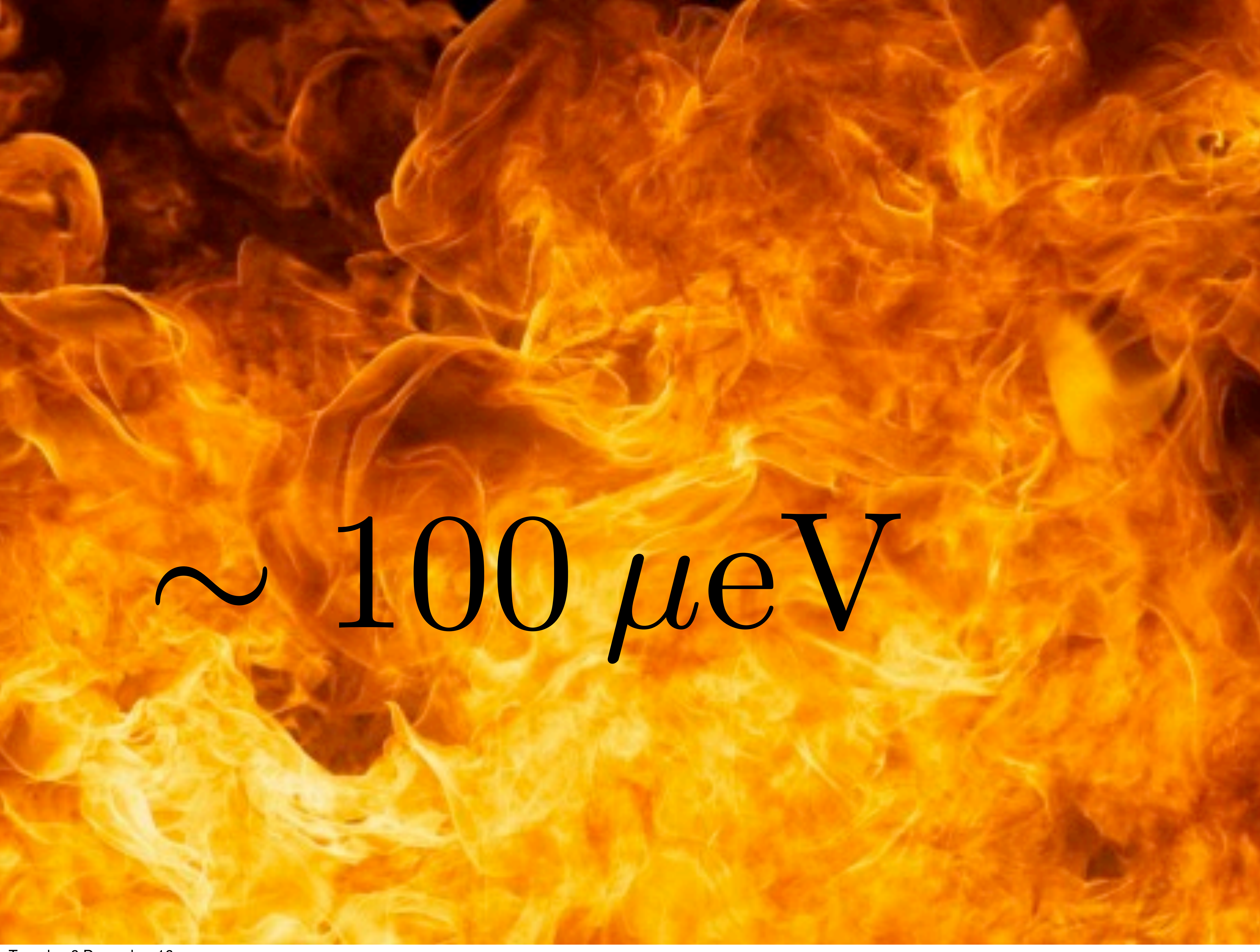
Javier Redondo's

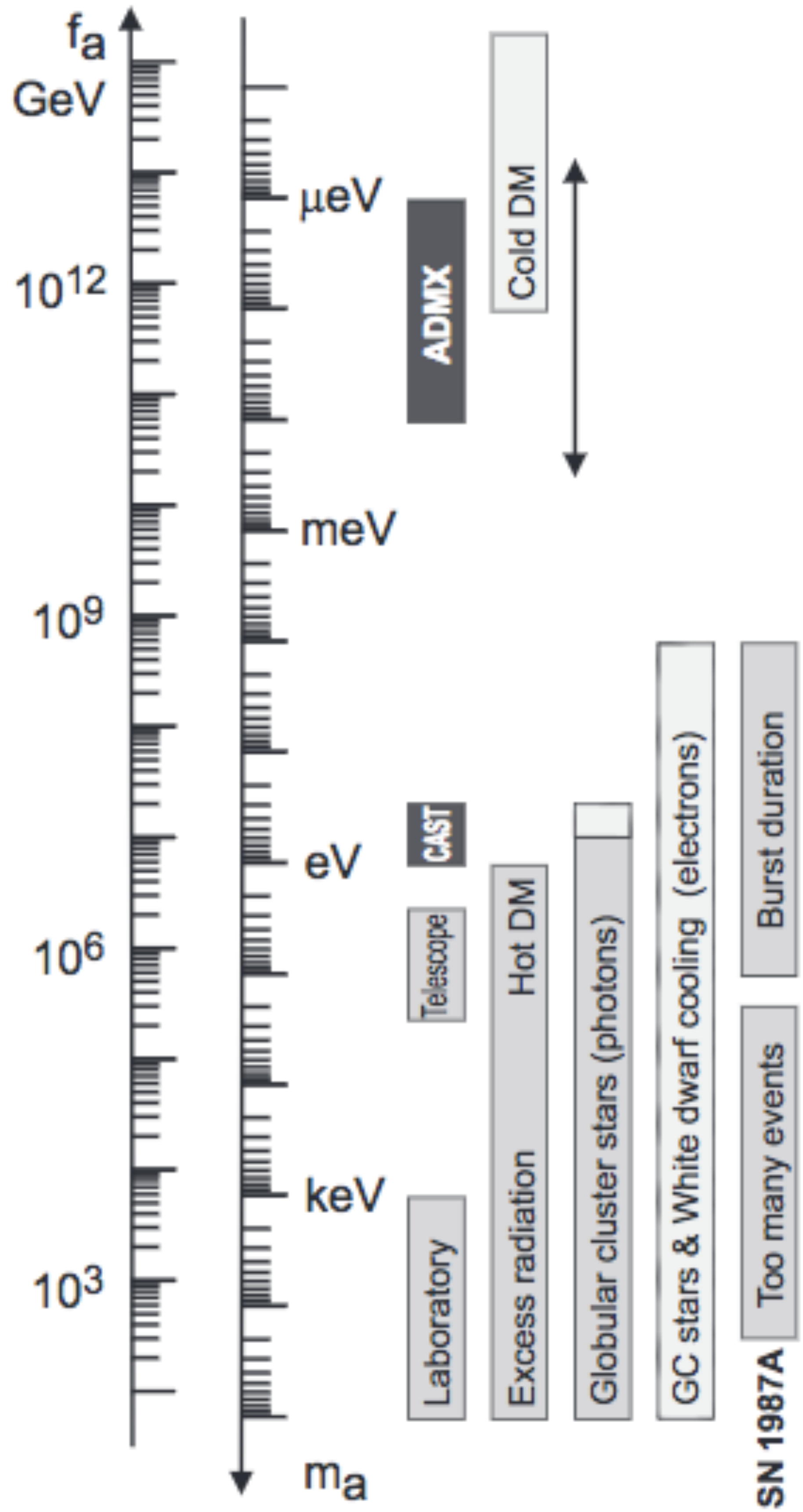
The Axion from Hell

MAX-PLANCK-GESELLSCHAFT

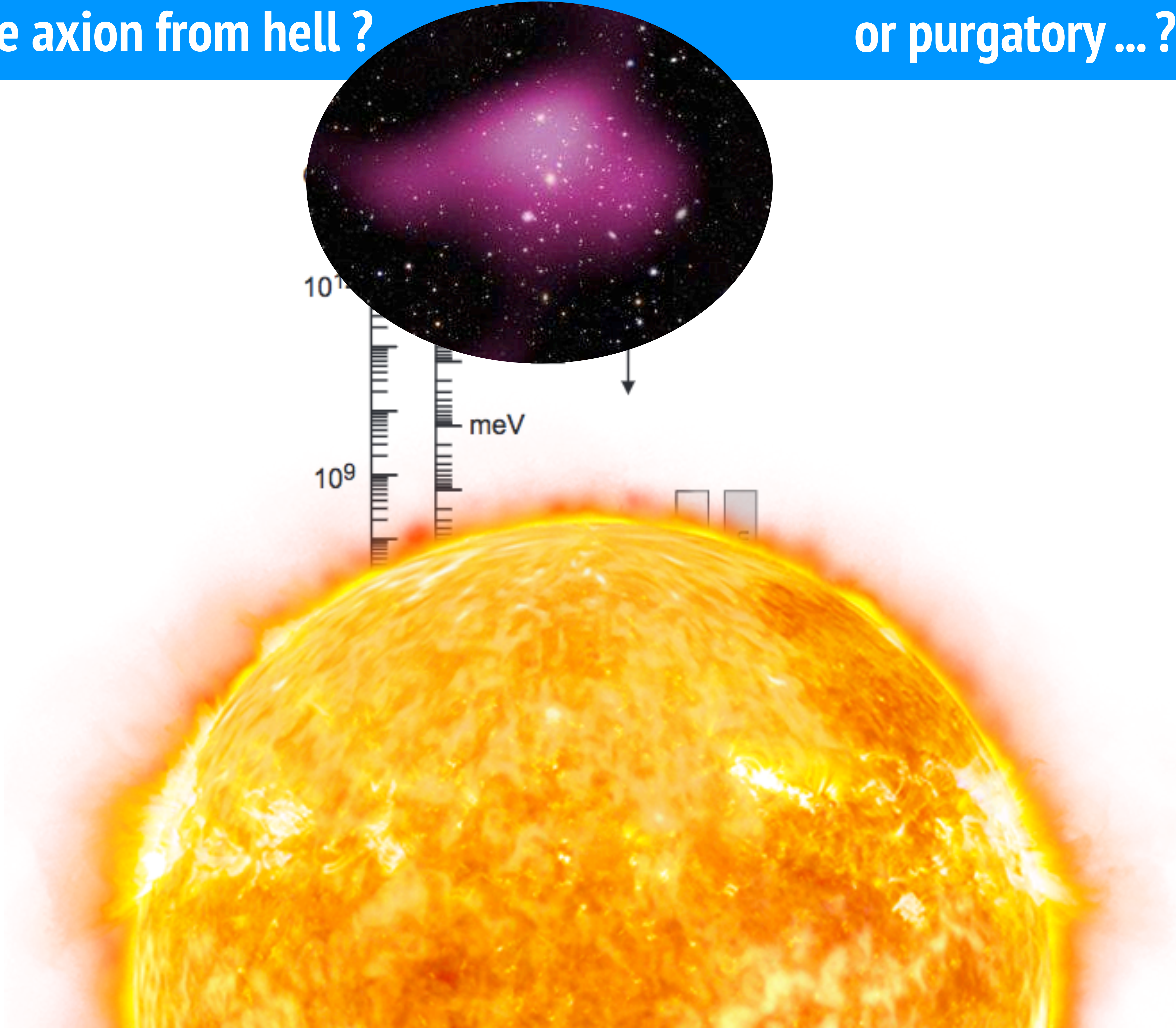


$$\sim 100\ \mu\mathrm{eV}$$

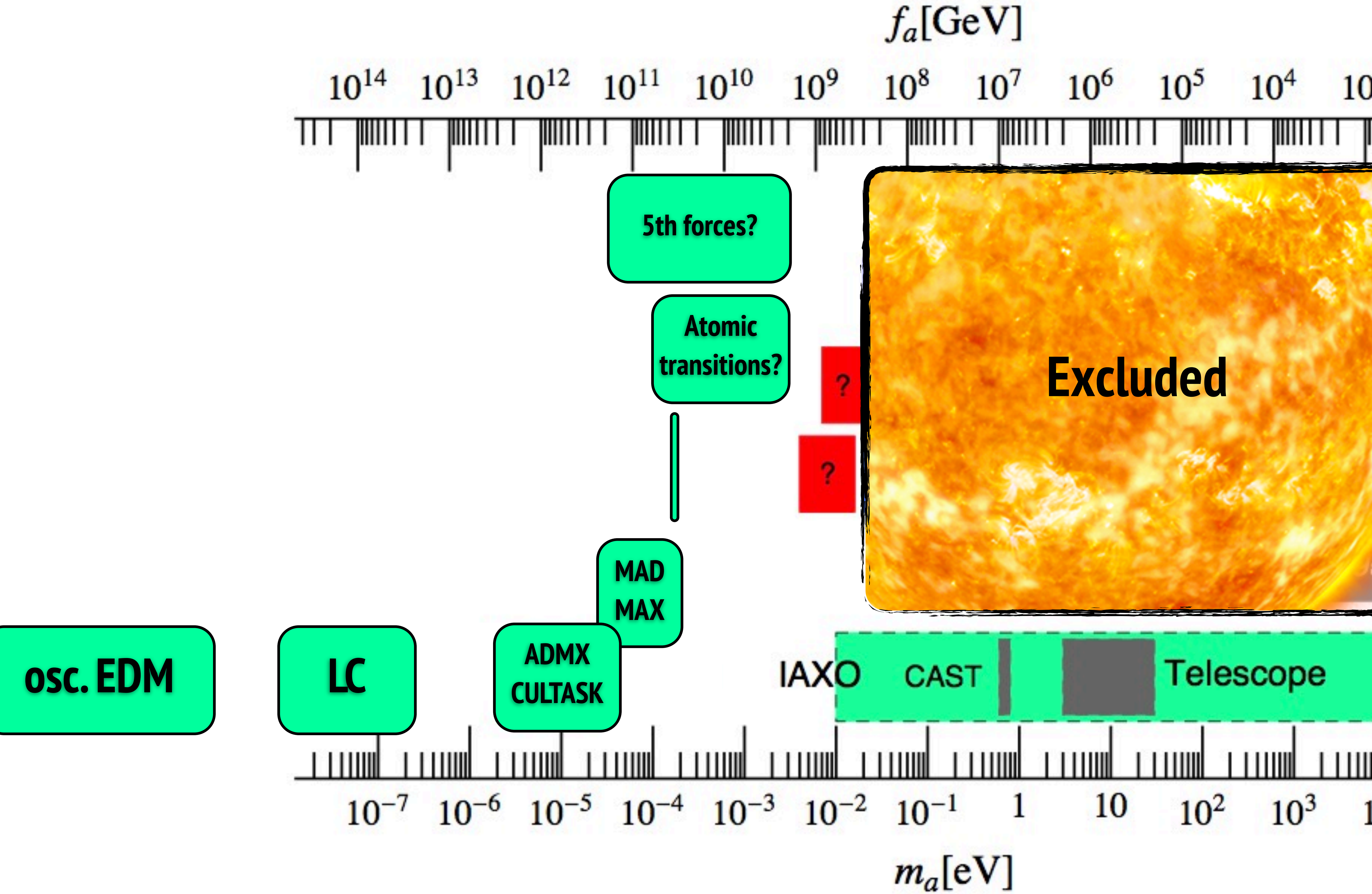
The axion from hell ?



The axion from hell ? or purgatory ... ?

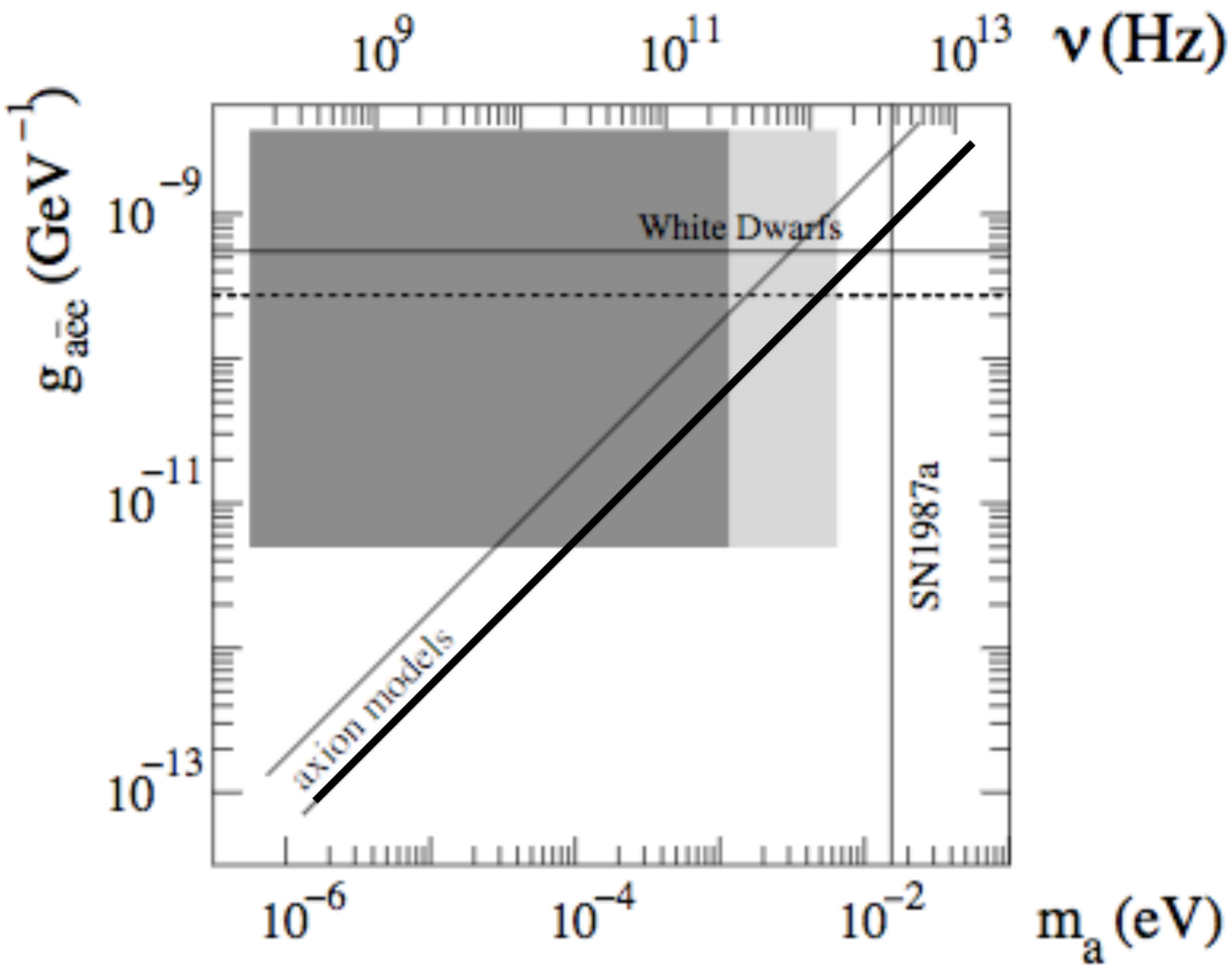


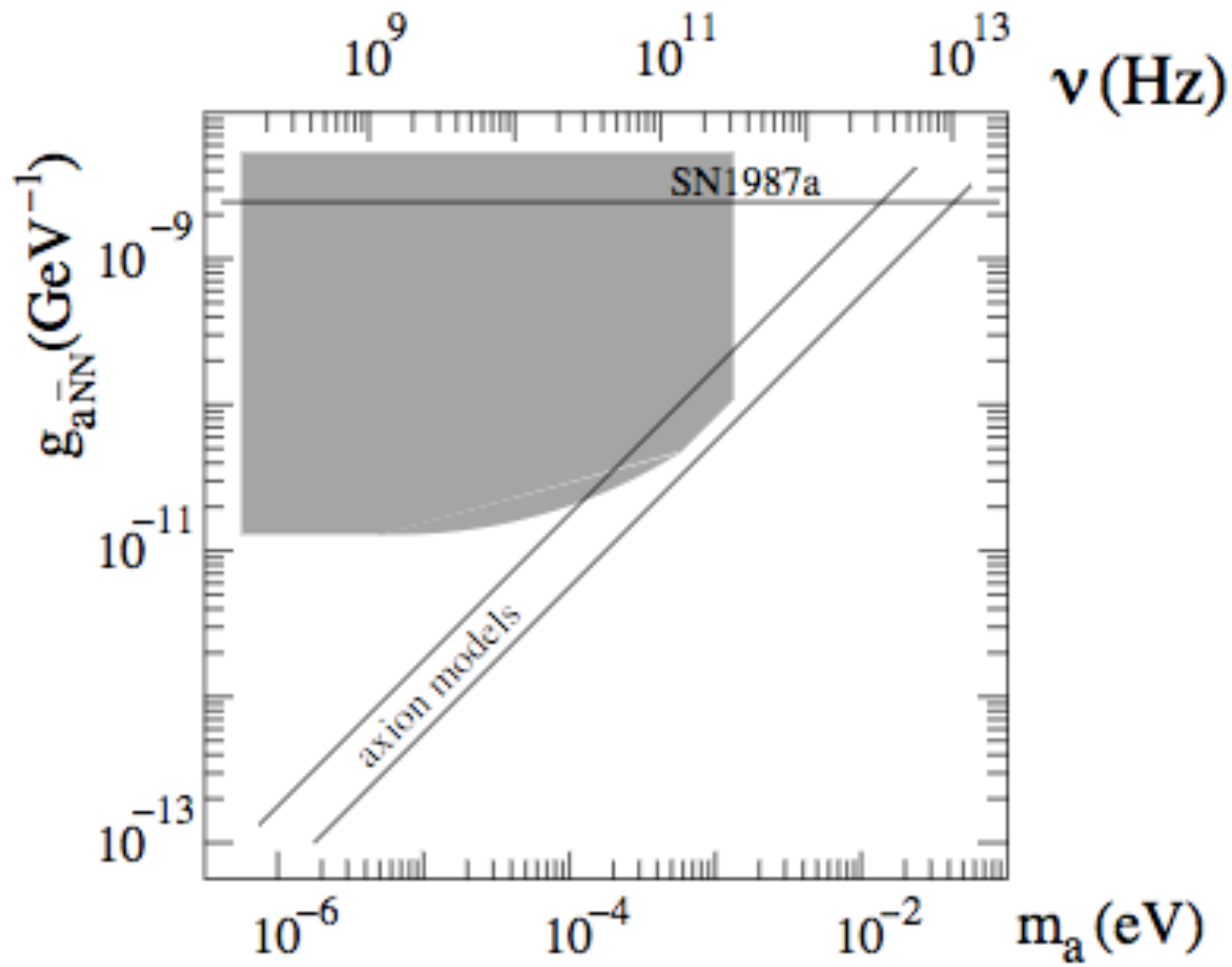
The axion from hell



ATOMIC TRANSITIONS ...

Sikivie PRL 2014

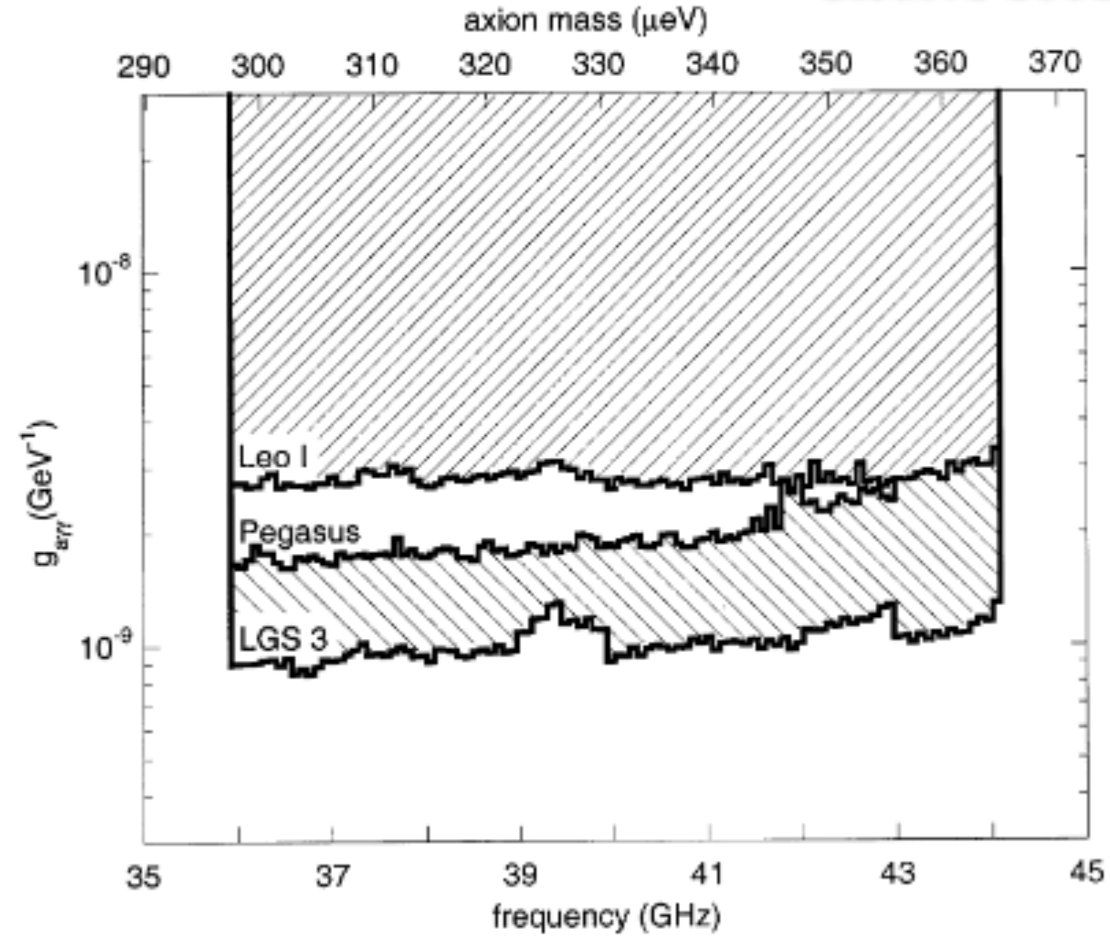




AXION DM DECAY

$$\tau_a = 6.8 \times 10^{24}\left(\frac{0.72}{E/N - 1.95}\right)^2\left(\frac{m_a}{\mathrm{eV}}\right)^{-5}\ \mathrm{s},$$

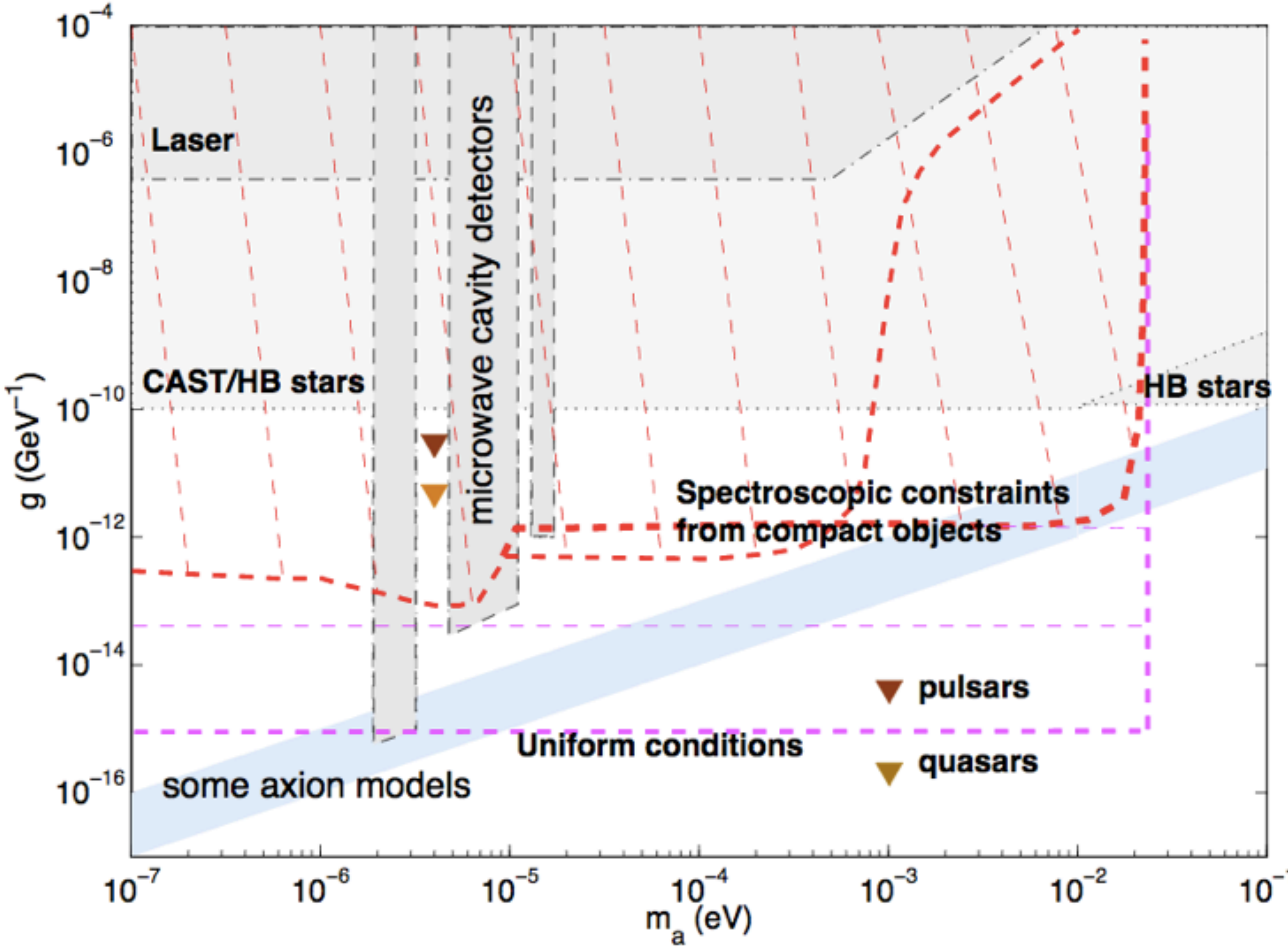
Blout AJ 2001



AXION BAND

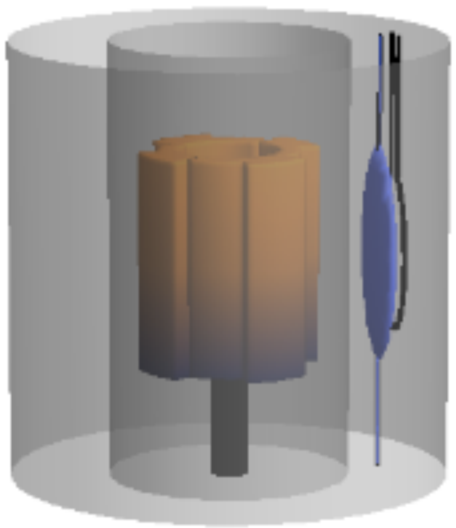
SPECTROSCOPY OF COMPACT STARS

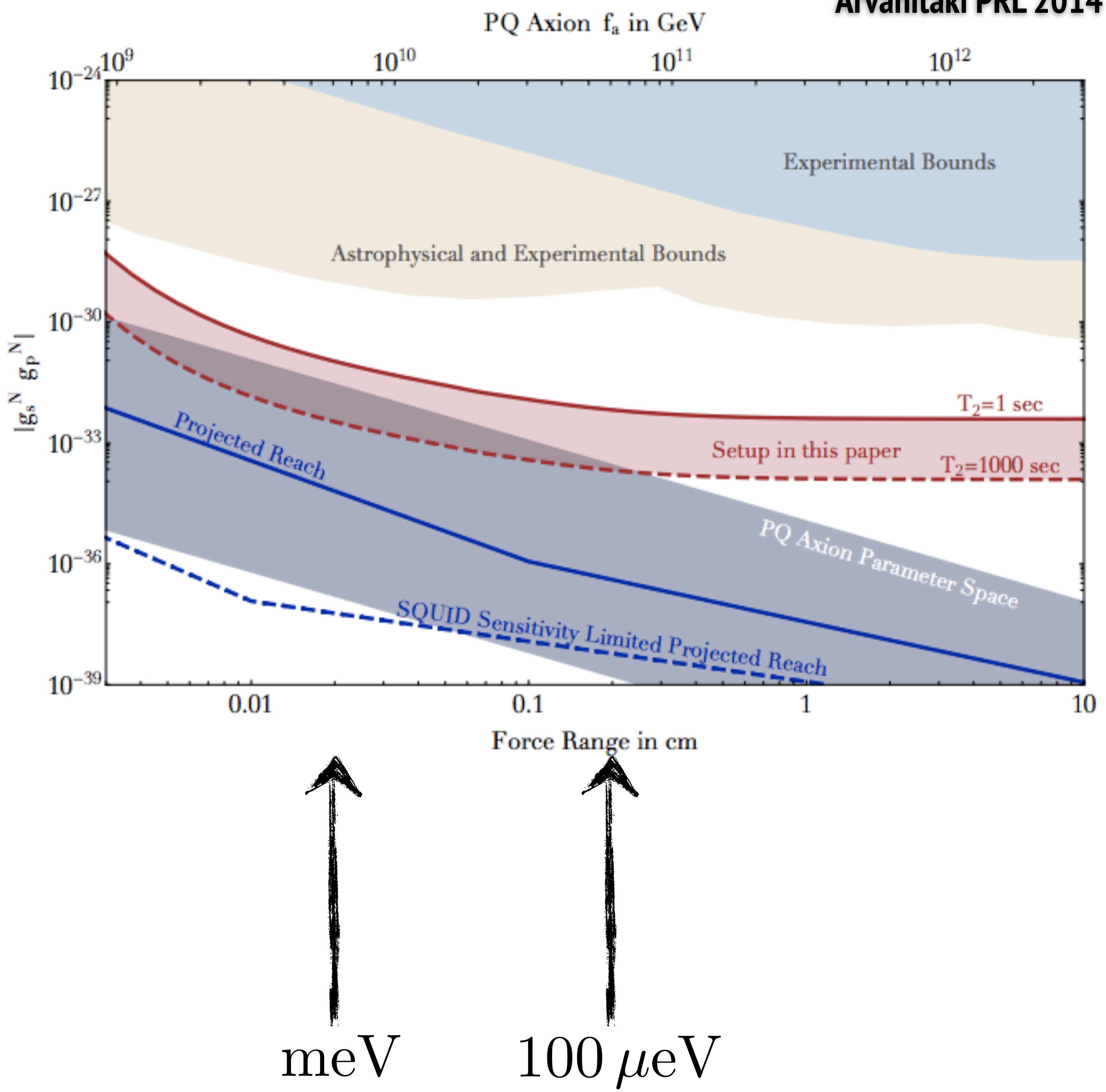
Chelouche ApJ 2008



LONG RANGE FORCES ... SCALAR-SPIN

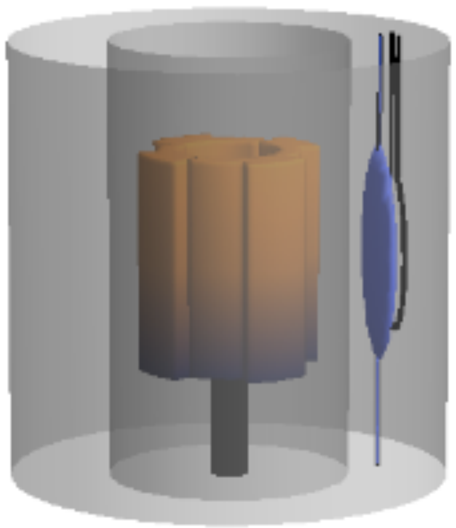
Arvanitaki PRL 2014

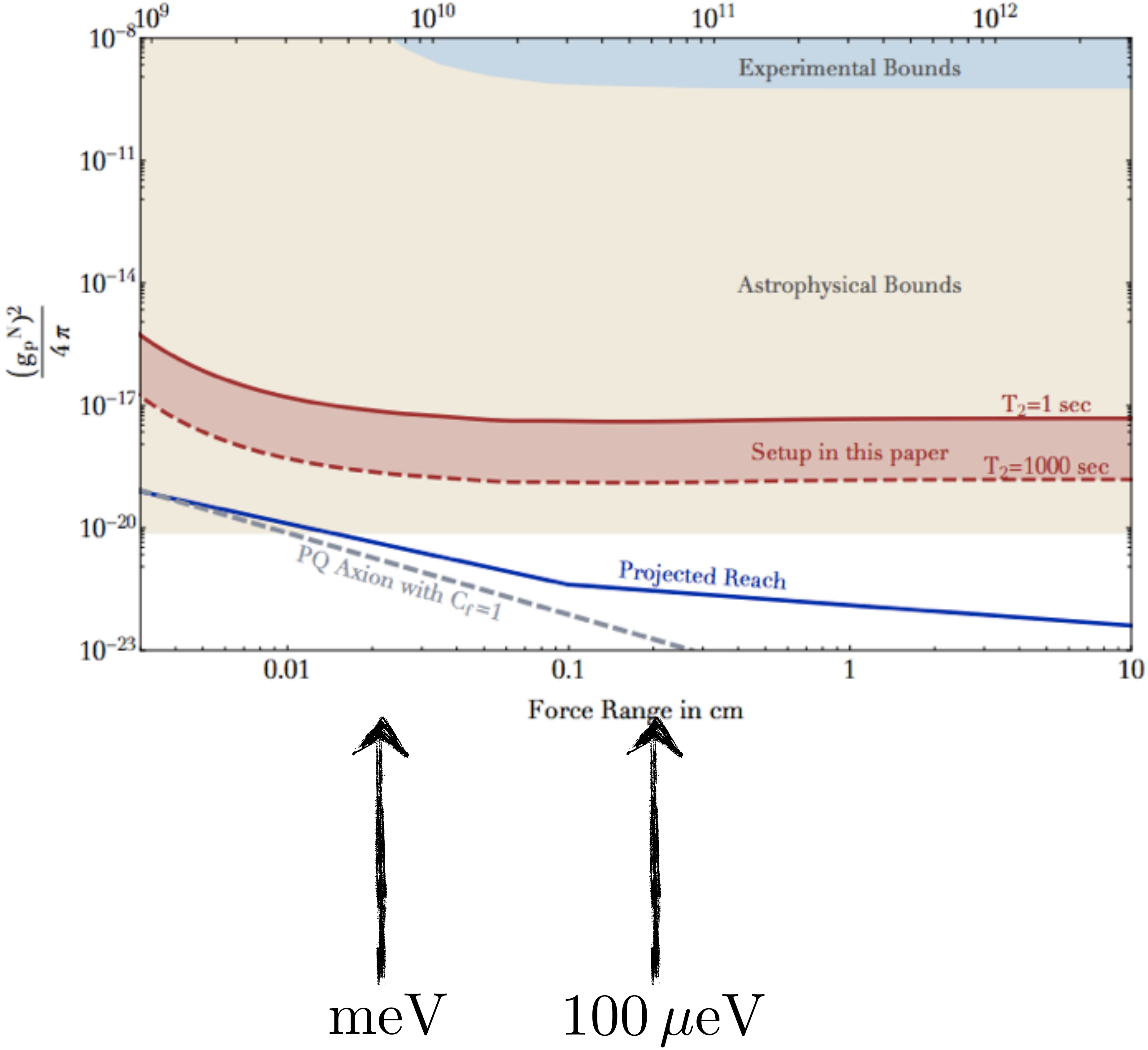




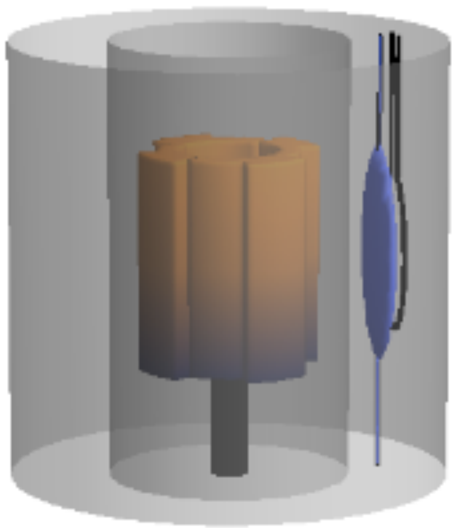
LONG RANGE FORCES ... SPIN-SPIN (P-P)

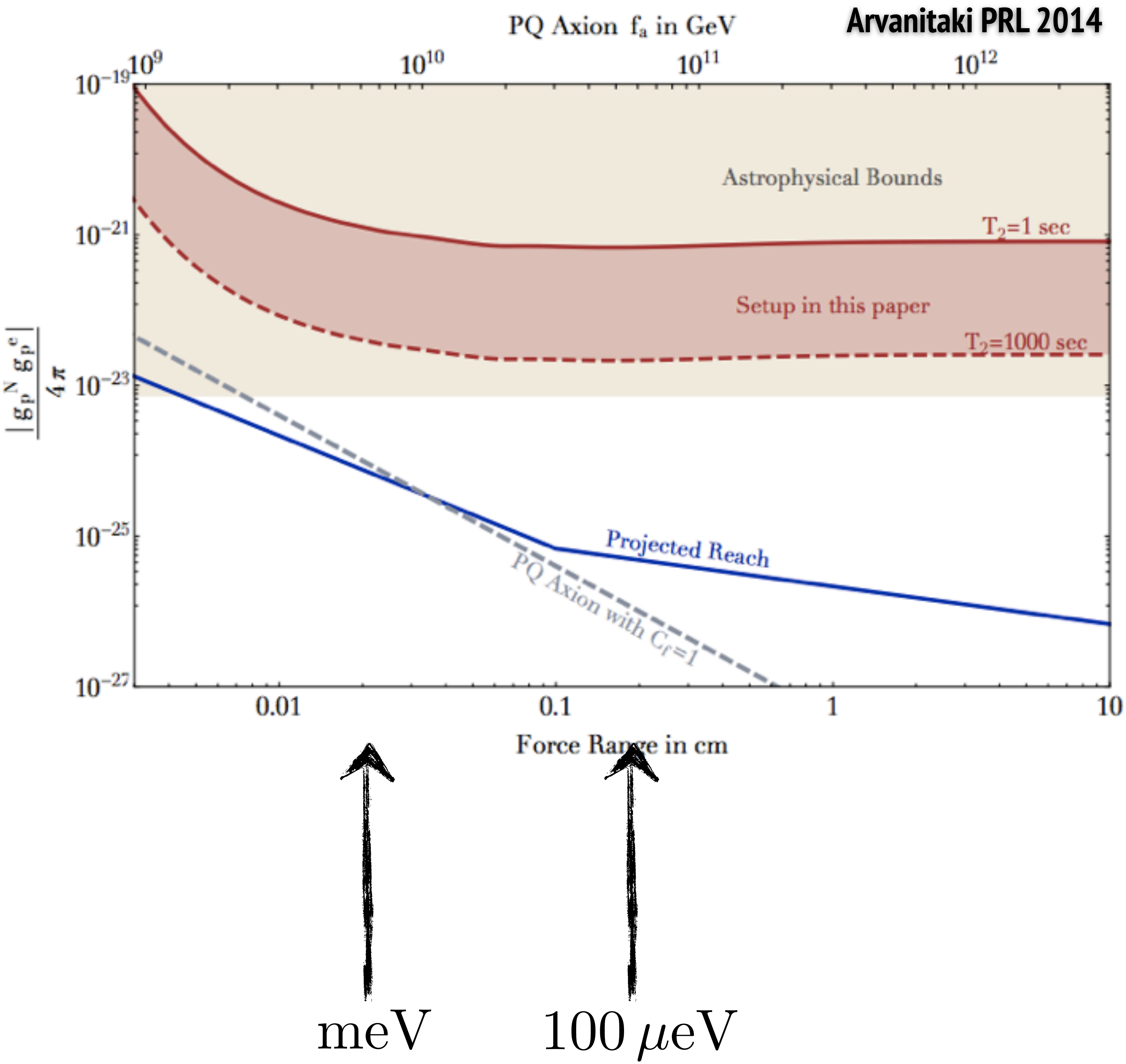
Arvanitaki PRL 2014





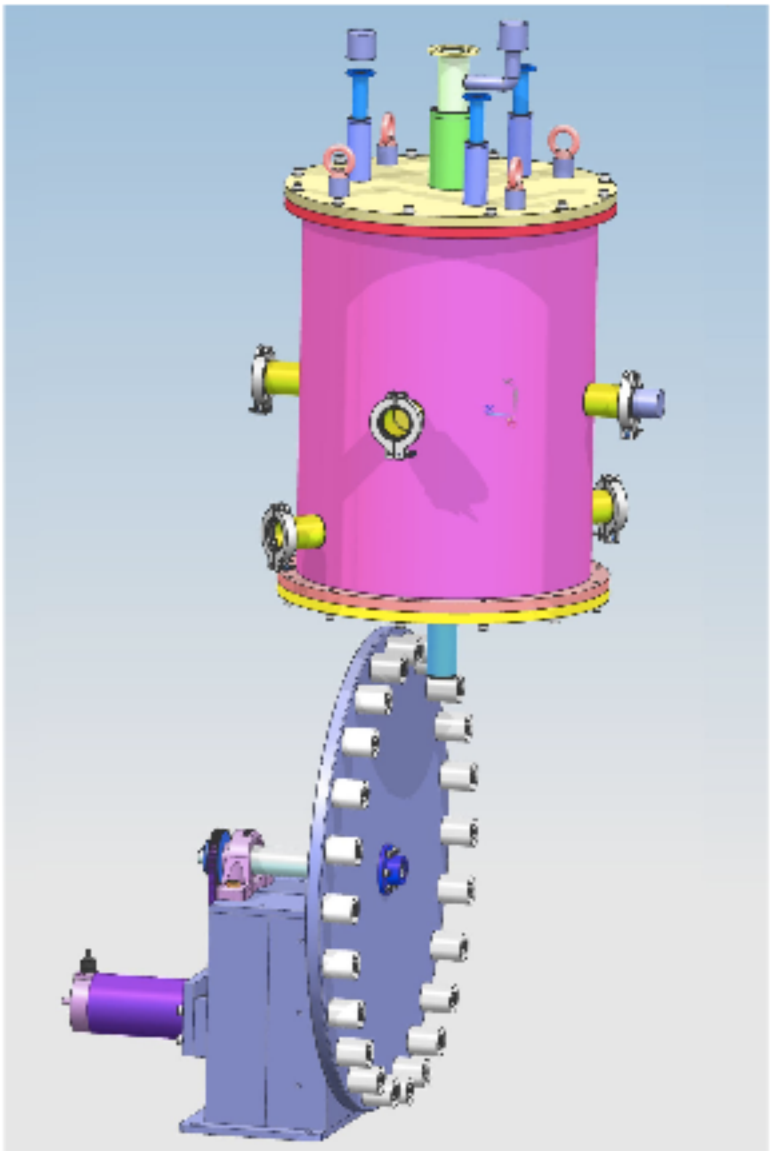
LONG RANGE FORCES ... SPIN-SPIN (e-P)

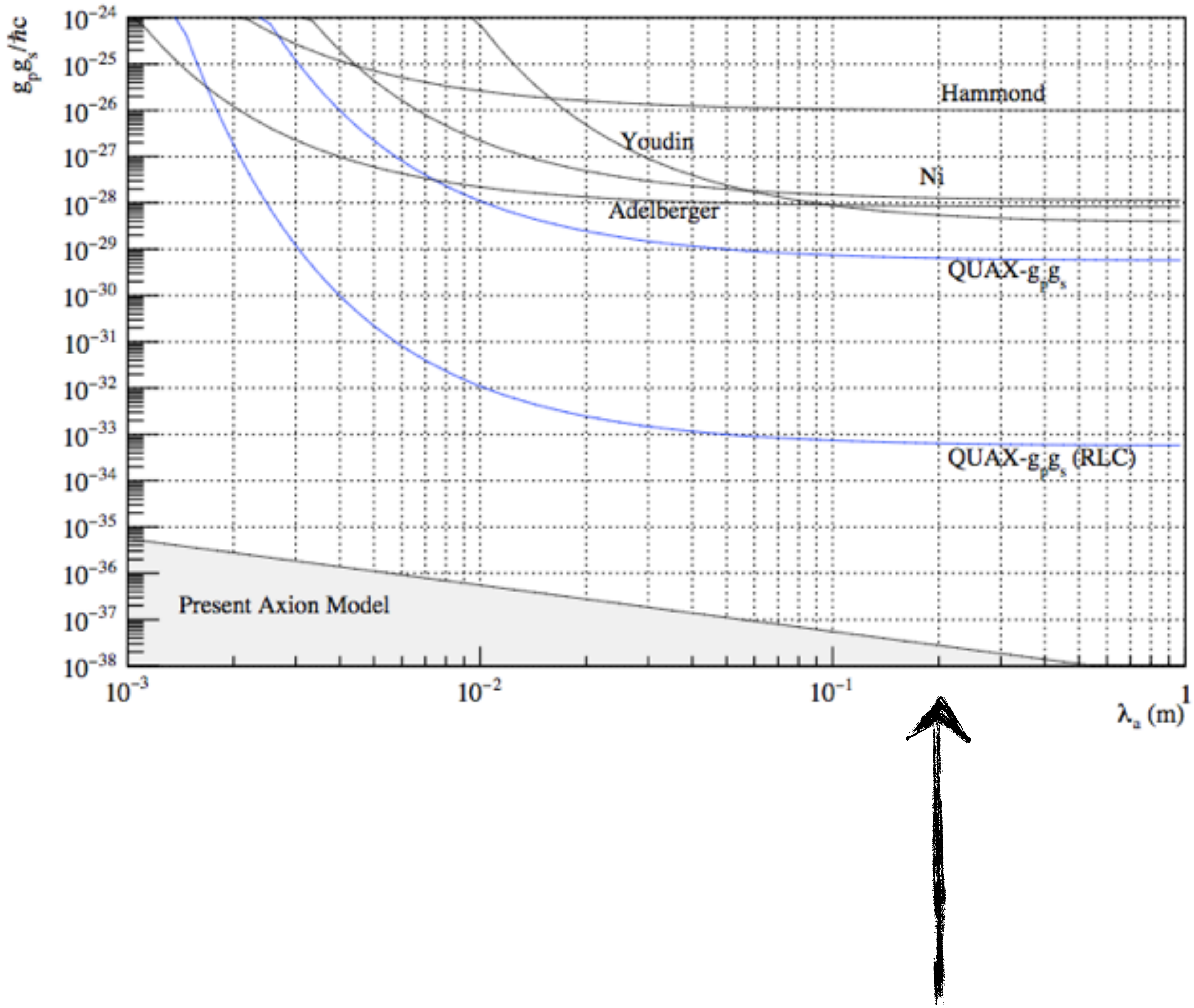




QUAX GNGP ... SCALAR-SPIN

Crescini 1606.04751

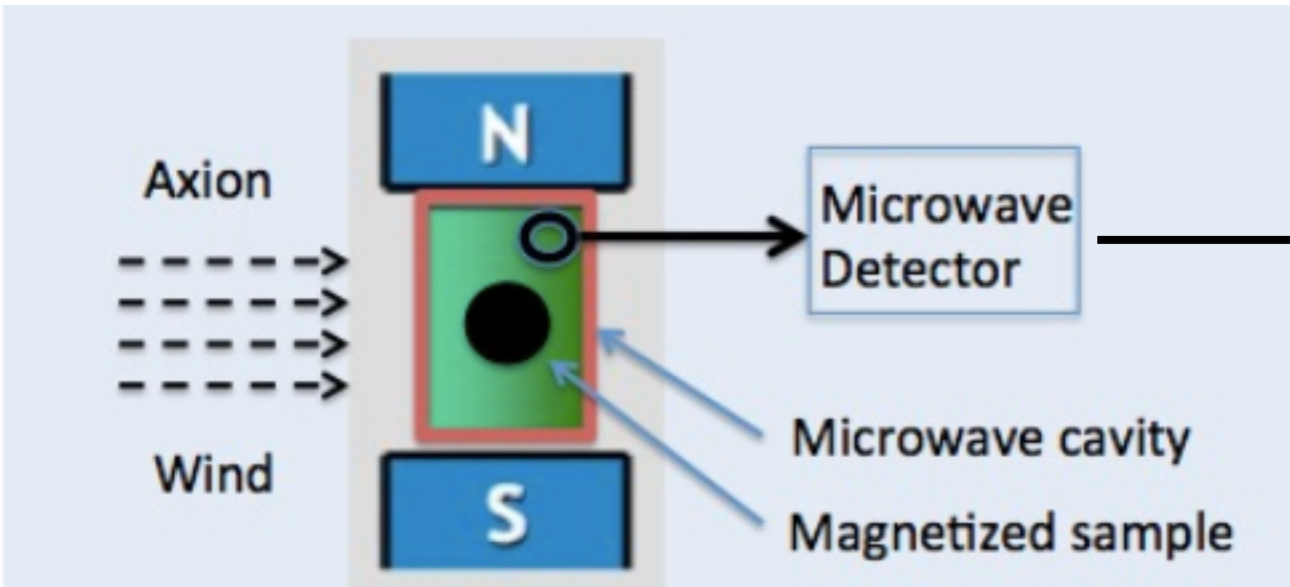




$100\ \mu\mathrm{eV}$

Barbieri 1606.02201

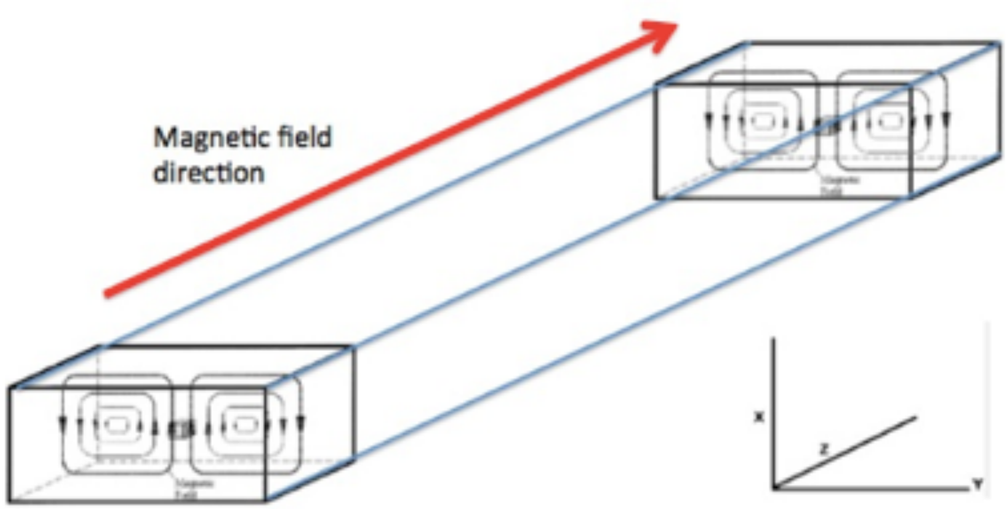
Axion DM wind excites hybrid magnetisation-RF mode



Photon counting rate

$$R_a^* = \frac{1}{2}\gamma^2 B_a^2 \tau n_S V_s =$$

$$= 5.0 \times 10^{-3} \left(\frac{m_a}{2 \cdot 10^{-4}\,\mathrm{eV}}\right)^2 \left(\frac{V_s}{1\ \mathrm{liter}}\right) \left(\frac{n_S}{10^{28}/\mathrm{m}^3}\right) \left(\frac{\tau_{\min}}{10^{-6}\,\mathrm{s}}\right) \mathrm{Hz}.$$

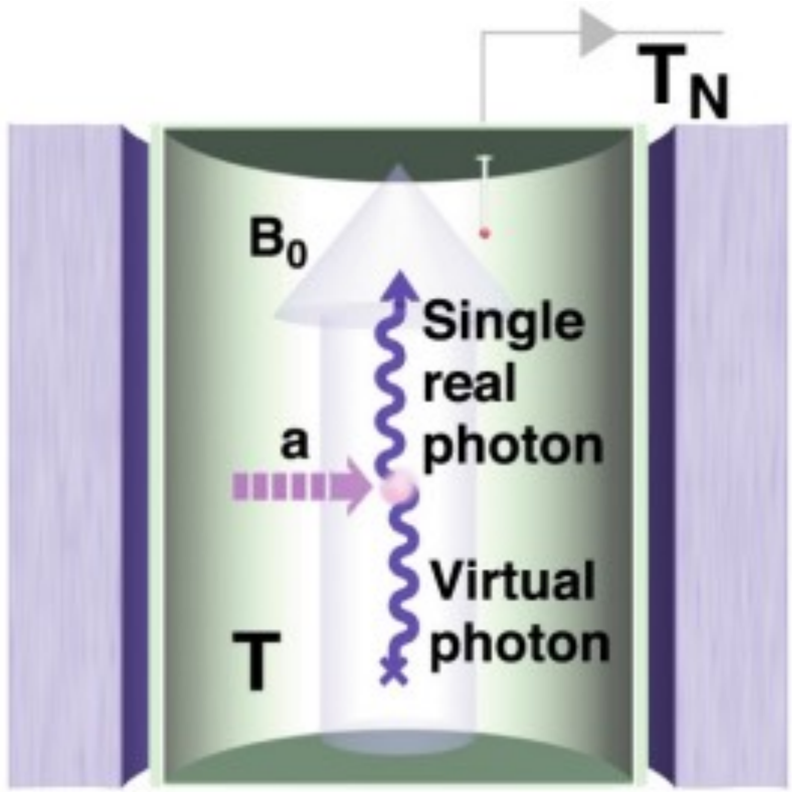


Scannig rate... 200 MHz/year

CAVITY HALOSCOPES

- Haloscope (Sikivie 83)

Sikivie 83



$$P \sim Q|\mathbf{E}_a|^2(V m_a)\mathcal{G}\kappa$$ (ON RESONANCE)

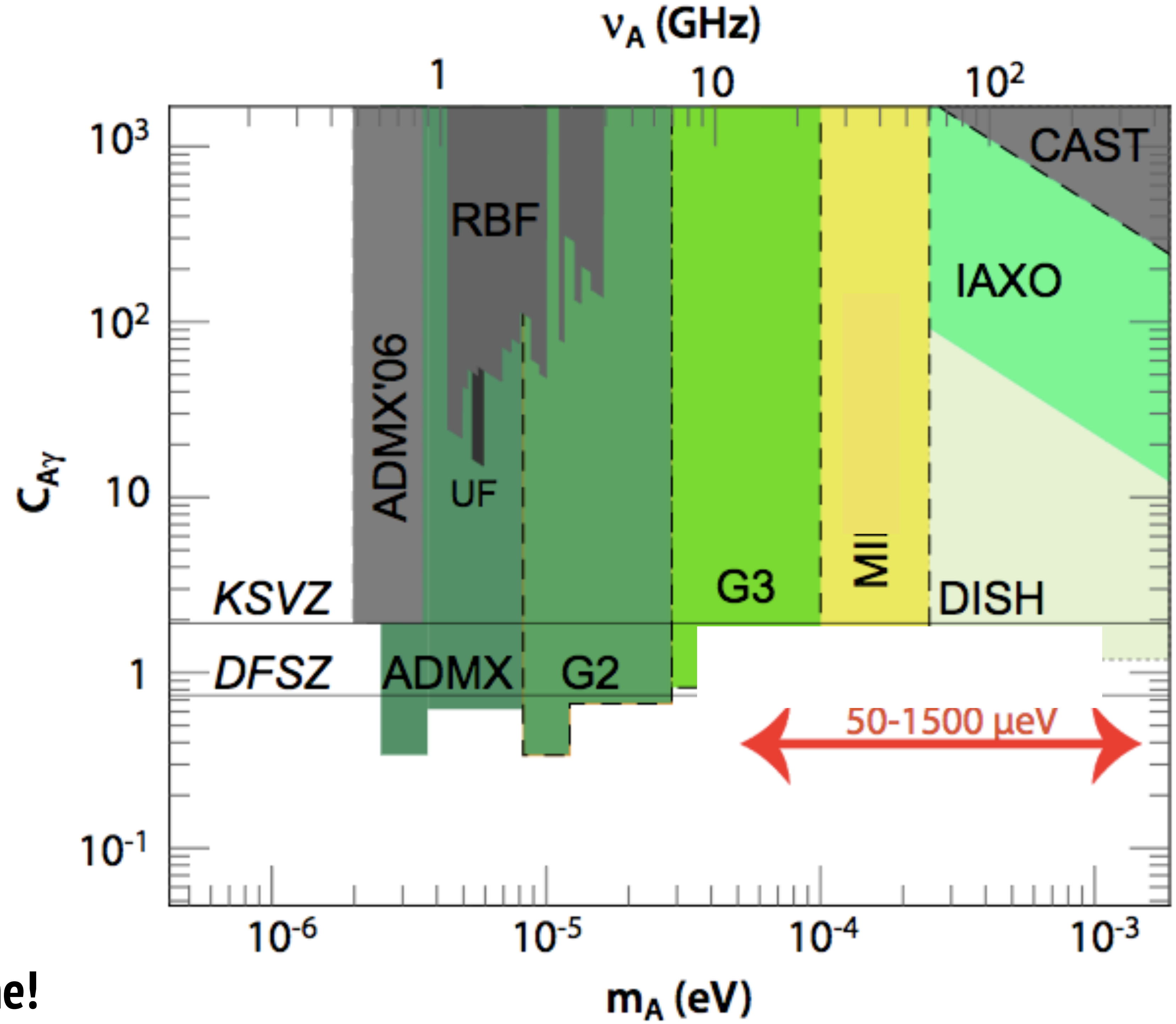
- Naive ADMX scaling (e.g. an ADMX every octave)

- SIGNAL $(V \propto m_a^{-3})$ $\quad P_{\rm out} \propto V m_a \sim \dfrac{1}{m_a^2}$
- NOISE $P_{\rm noise} = T_{\rm sys}\Delta\nu_a \propto m_a^2$
- SIGNAL/NOISE IN $\Delta\nu_a$ OF TIME, T, $\quad \dfrac{S}{N} = \dfrac{P_{\rm out}}{P_{\rm noise}}\sqrt{\Delta\nu_a t}$
- SCANNING RATE $\quad \dfrac{1}{m_a}\dfrac{d\Delta m_a}{dt} \propto \dfrac{C_{A\gamma}^4}{m_a^7}$

CAVITY HALOSCOPES

Borsanyi 2016

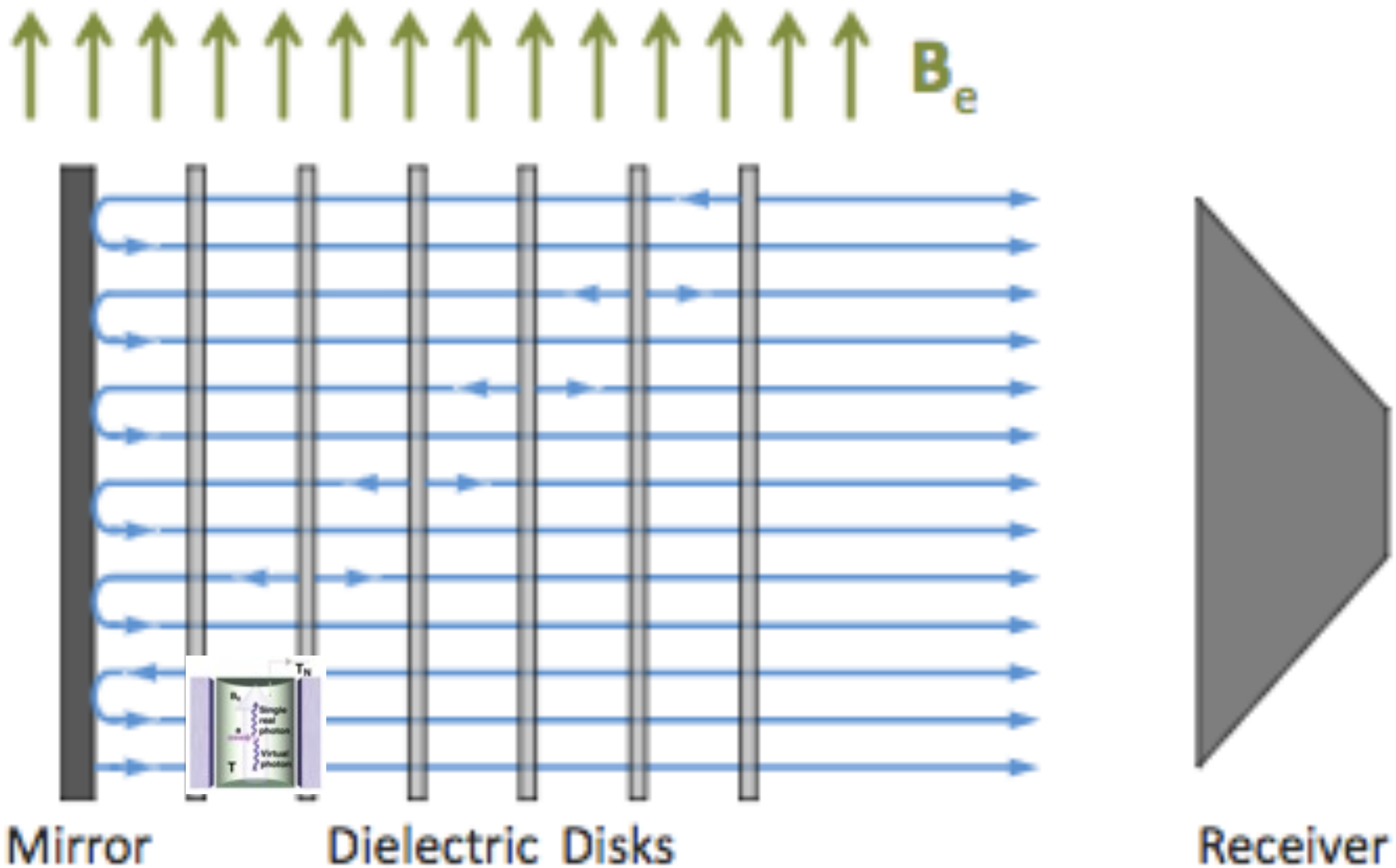
- ADMX (700l) Q=10^5, 8T, 100mK, SQUID, 3 years, 2 chan.
- Gen 2 (ADMXHF, X3, CULTASK) (SCALED) Q=10^6, 20 T, SQL, 3Y,2 CH
- Gen 3 (CULTASK?) (6XSCALED) Q=10^6, 40 T, SQL, 3Y,2 CH



- One should not give up on Volume!

Millar 2016

- maybe with a larger volume ...

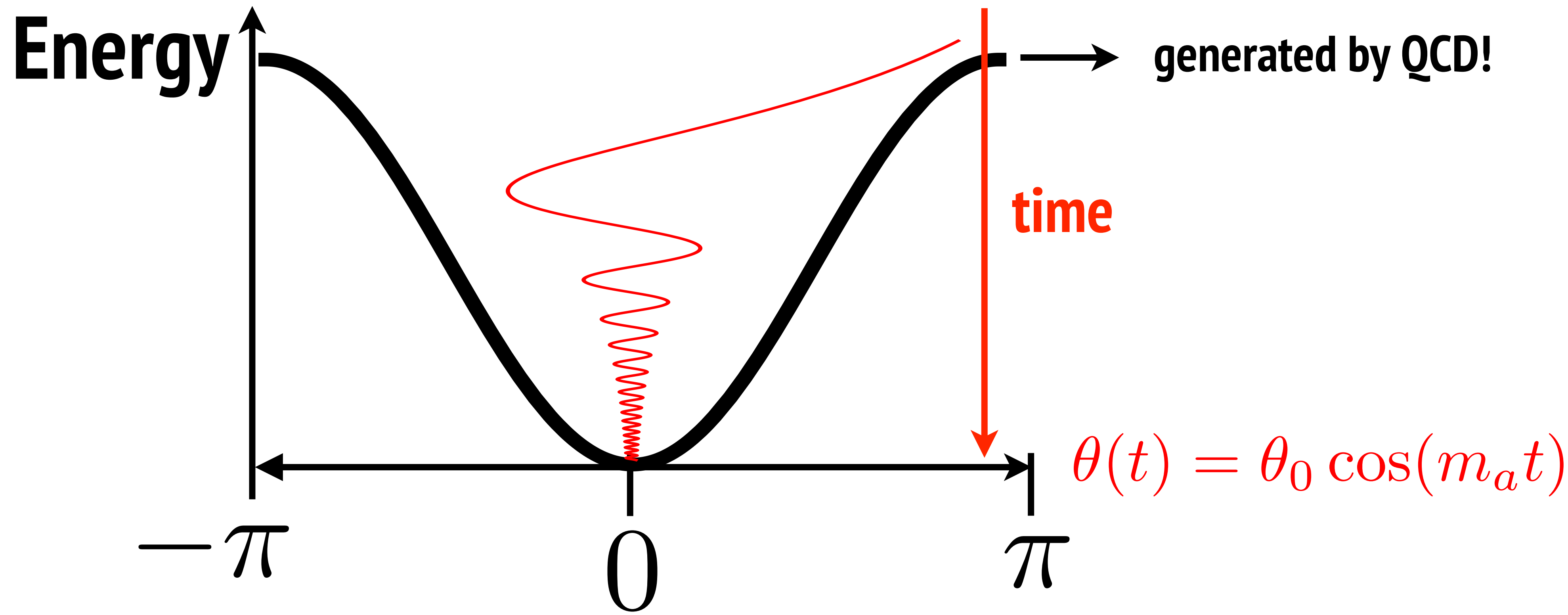


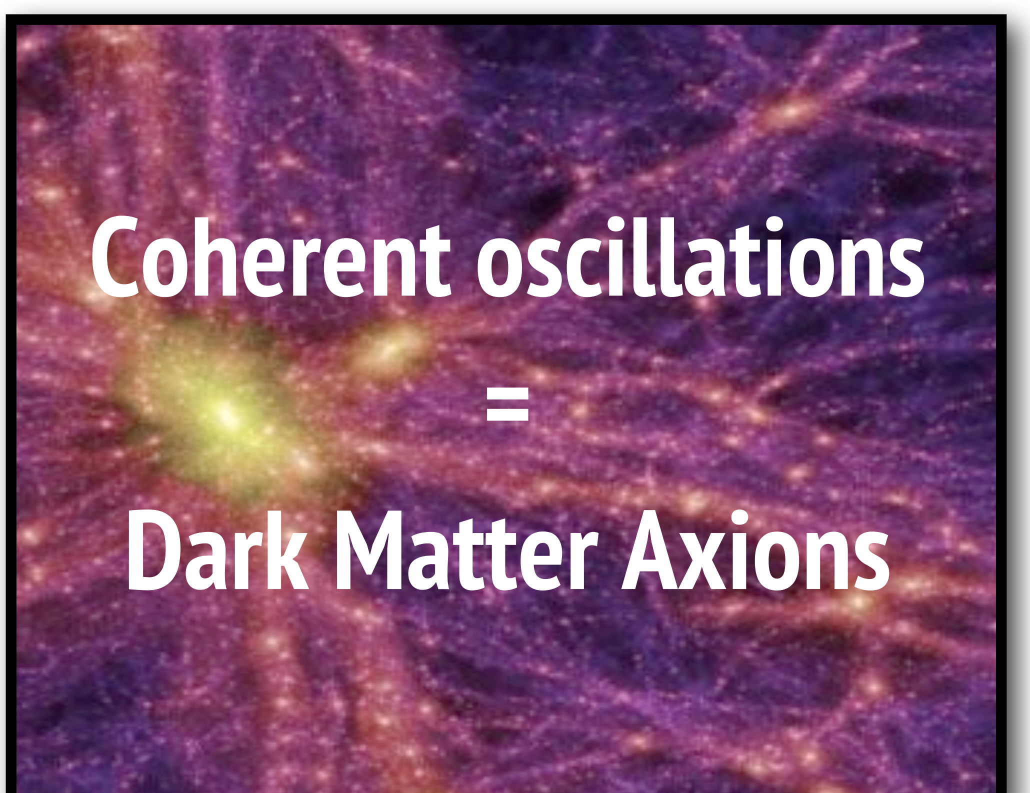
See talks of Millar and Majorovits

$$\text{why} \sim 100\,\mu\text{eV}??$$

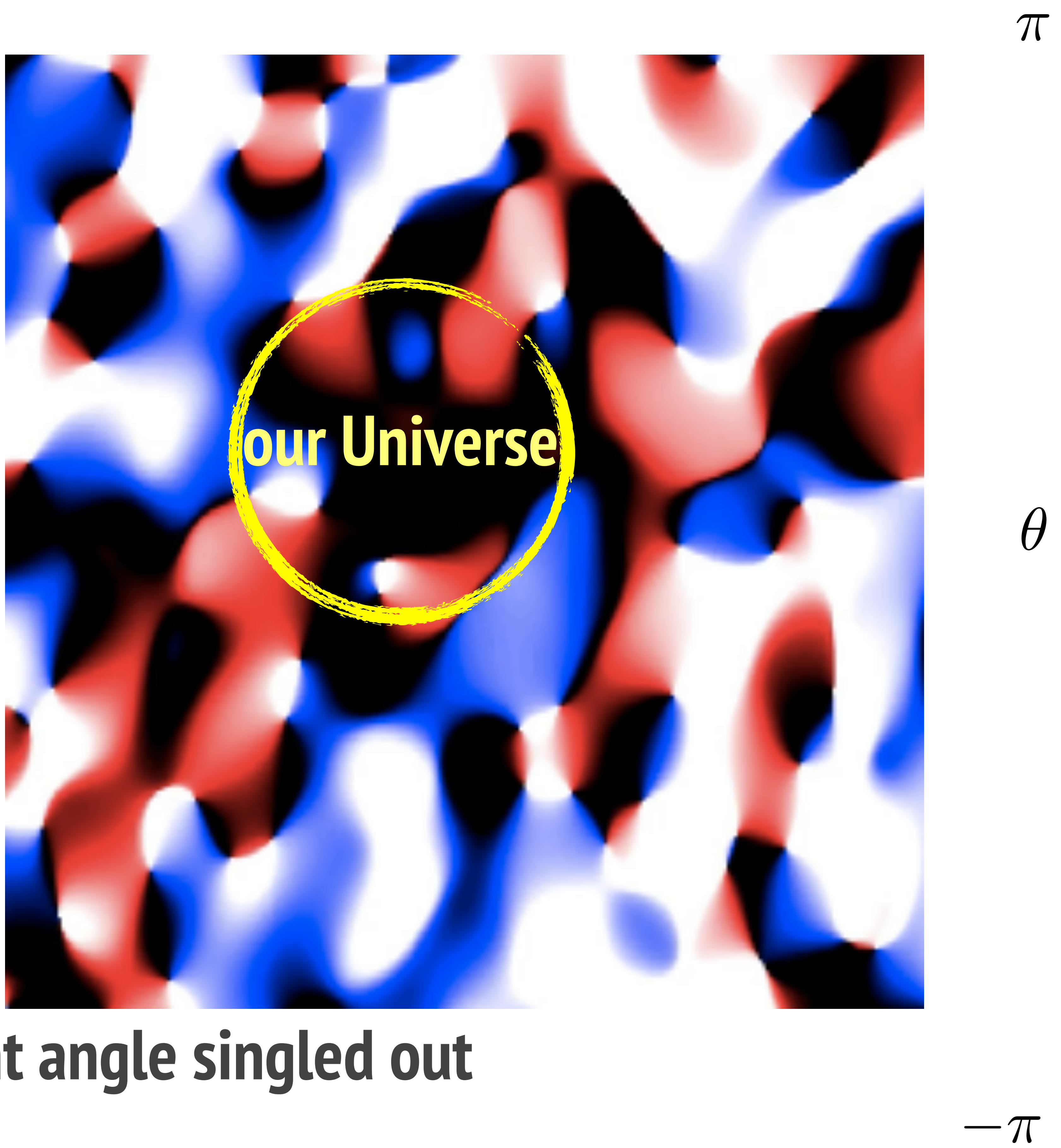
Dark matter

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



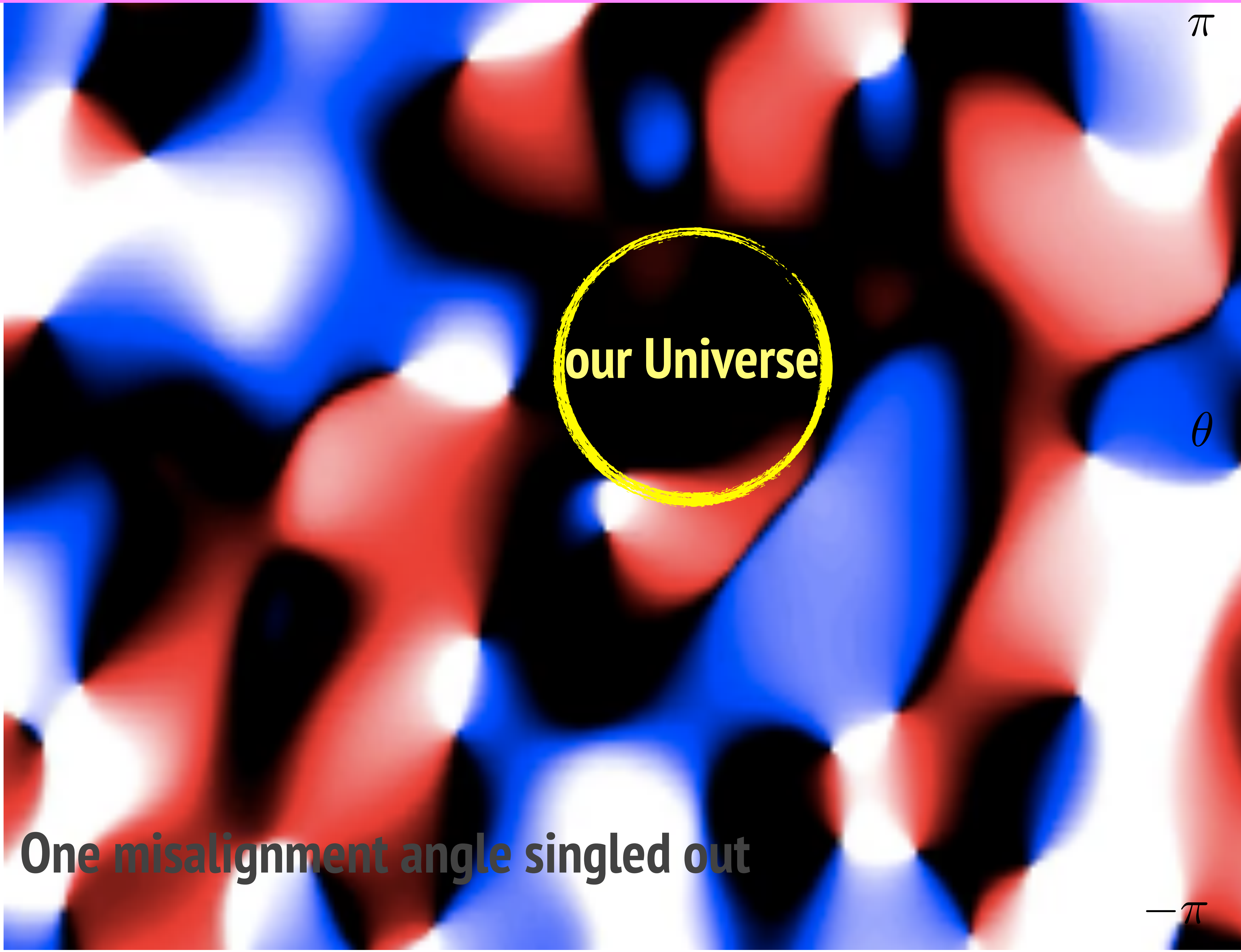


DM in SCENARIO A



One misalignment angle singled out

DM in SCENARIO A



DM in SCENARIO A

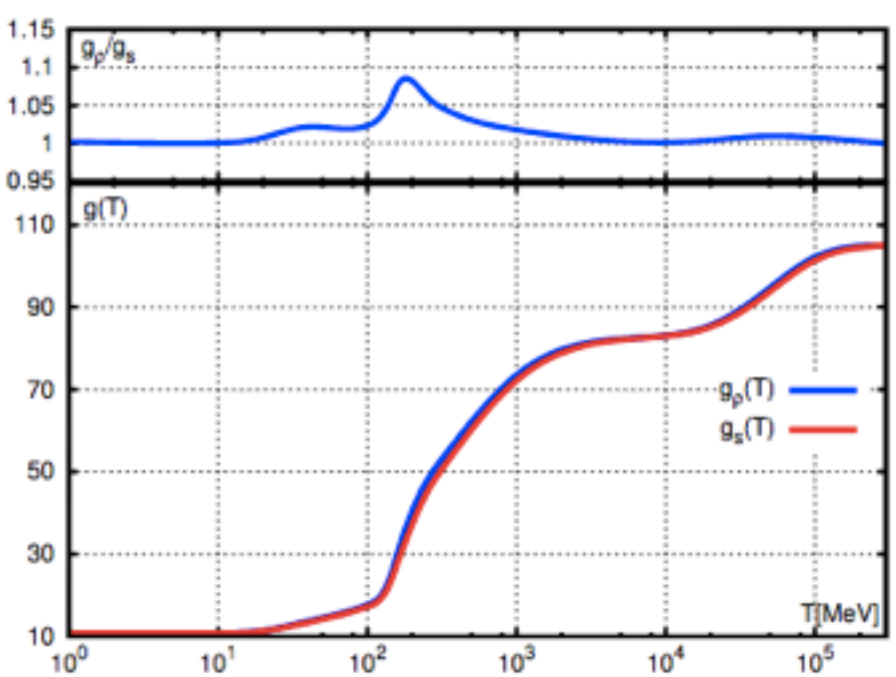
Borsanyi et al, Nature 539 (2016)

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

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

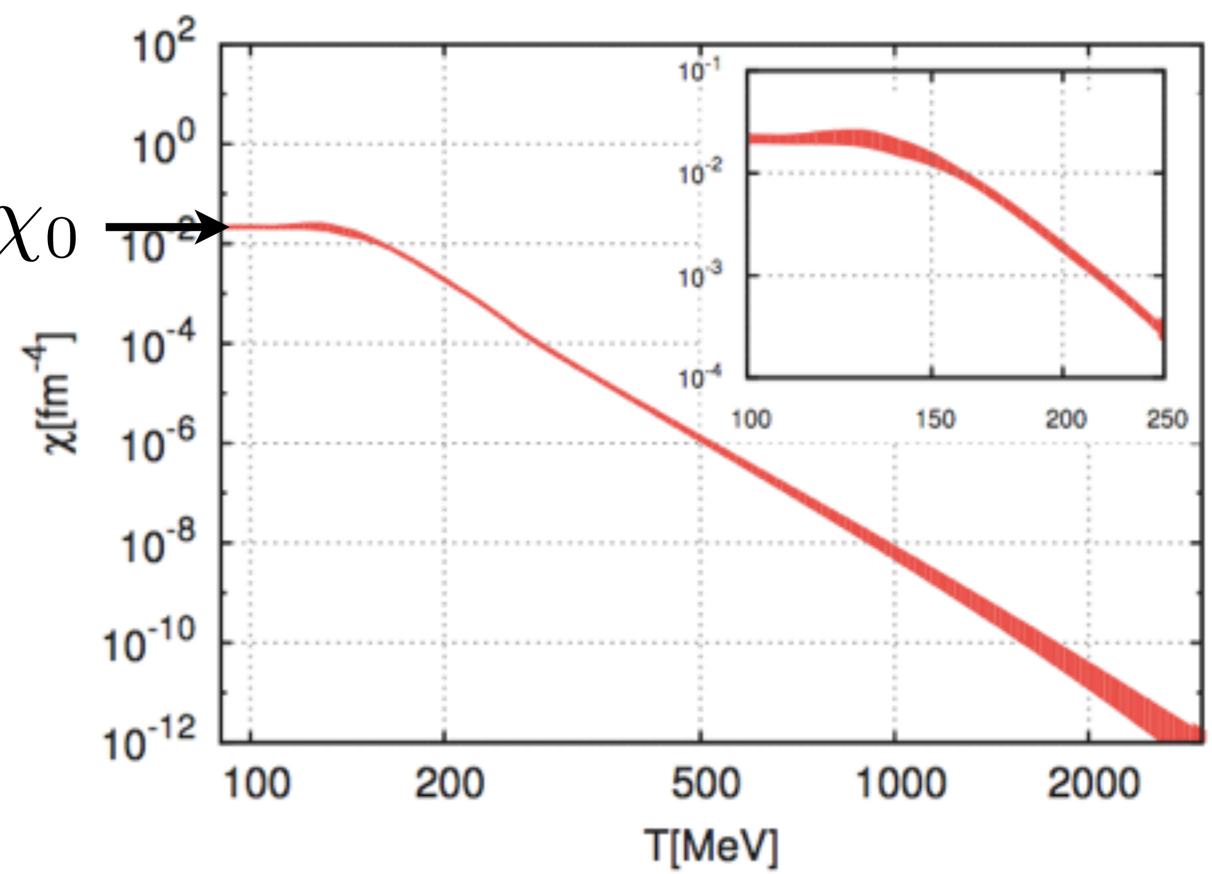
Universe Expansion rate

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



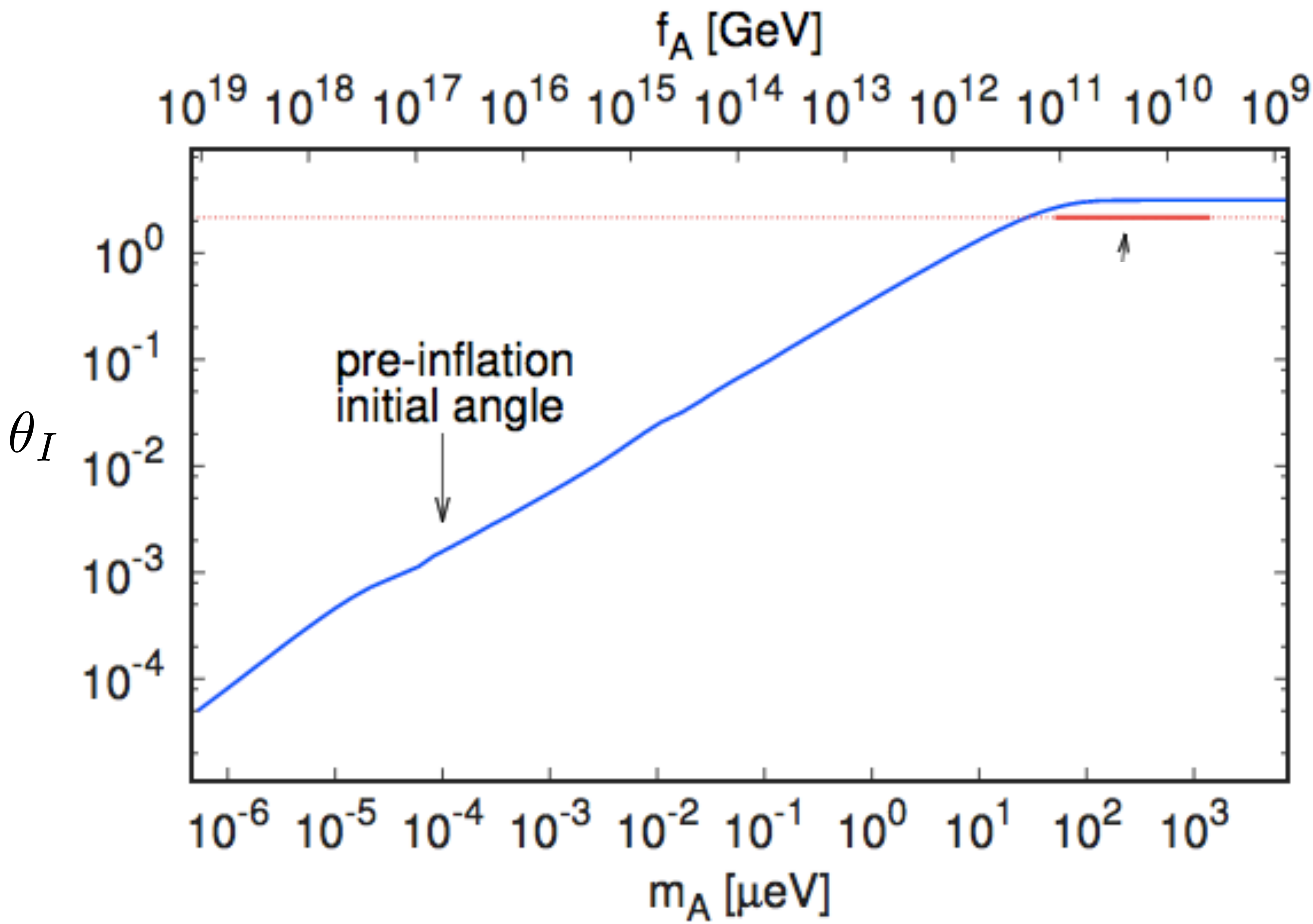
SM model only plasma $H = 1/2t \propto \sqrt{g(T)}T^2$

$m_a^2 f_a^2 = \chi_0$

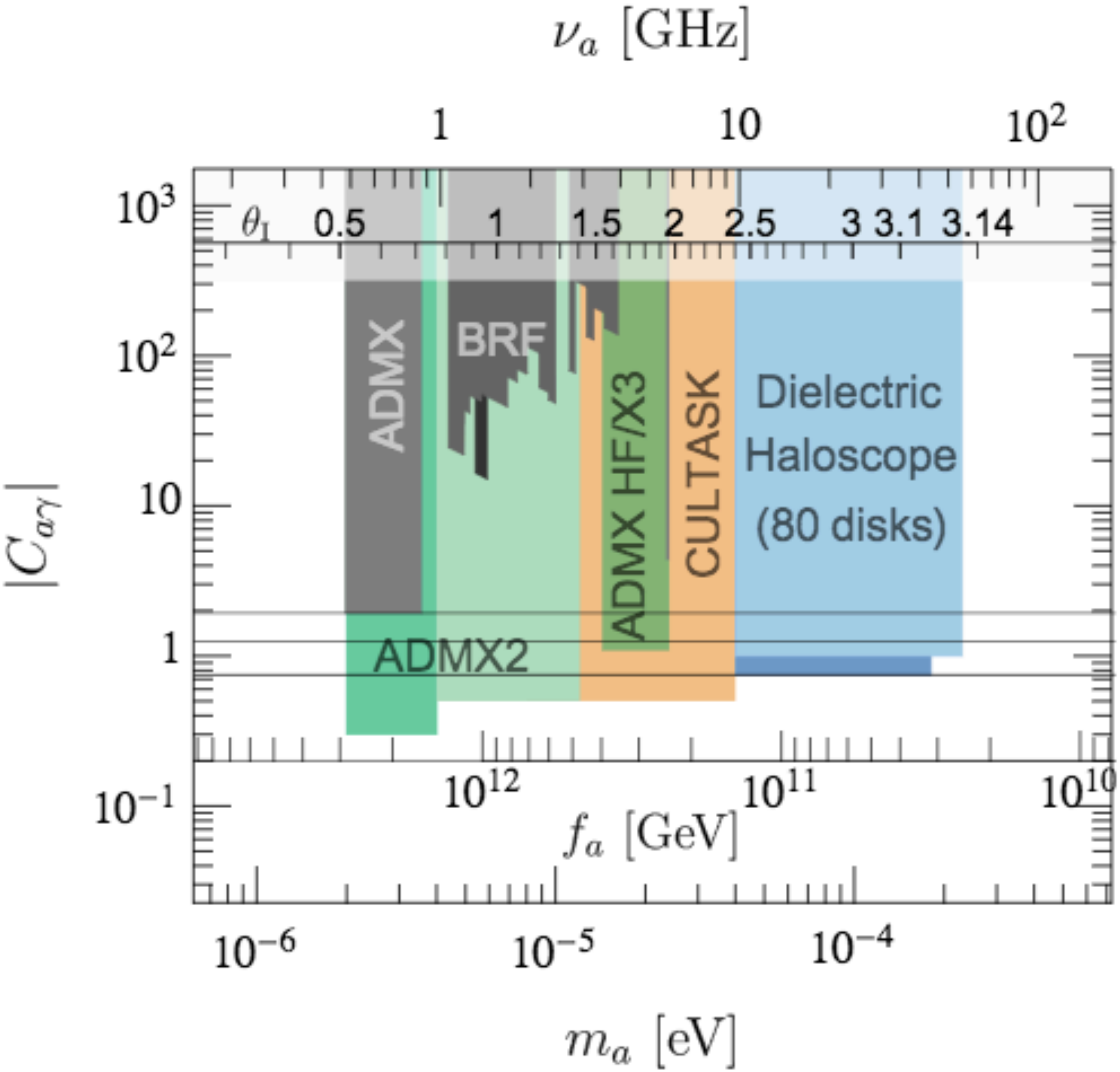


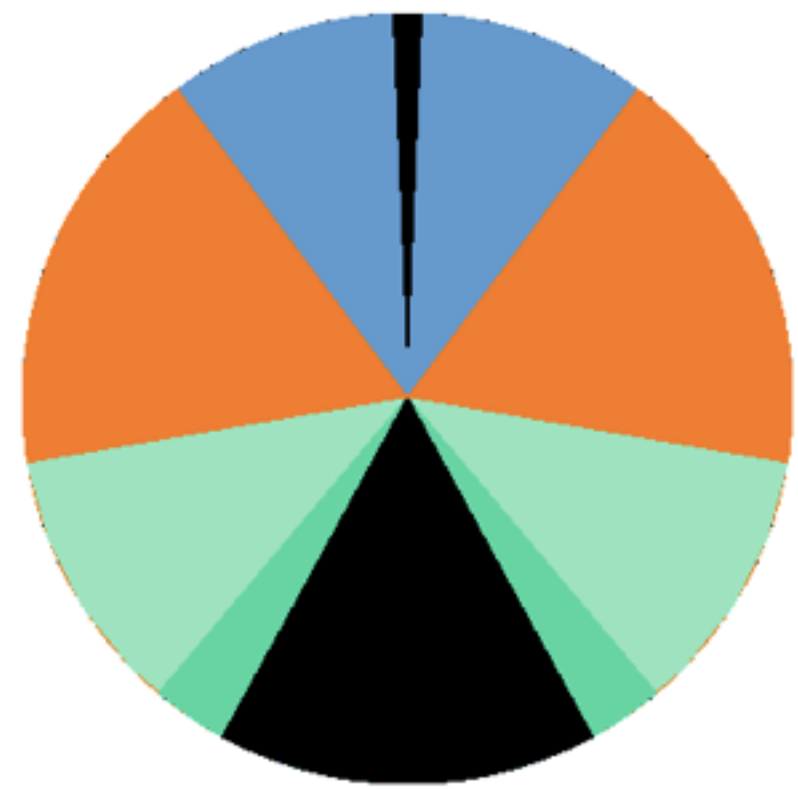
DM in SCENARIO A $\Omega_{DM}h^2 = \Omega_a h^2 = 0.12$

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



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





SCENARIO B

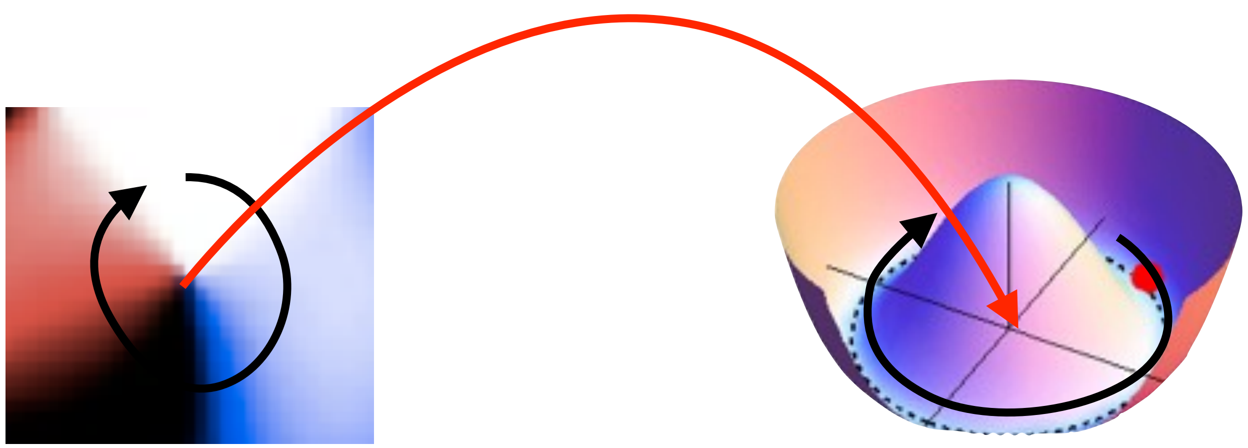
- NO IC UNCERTAINTY $\Omega_c h^2 = 7.9 \times 10^{-4} \left(\frac{100\,\mu\mathrm{eV}}{m_a} \right)^{1.33} \frac{\sqrt{g_{73*}}}{g_{73S}} M$

M from numerical simulations with "random" initial conditions

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

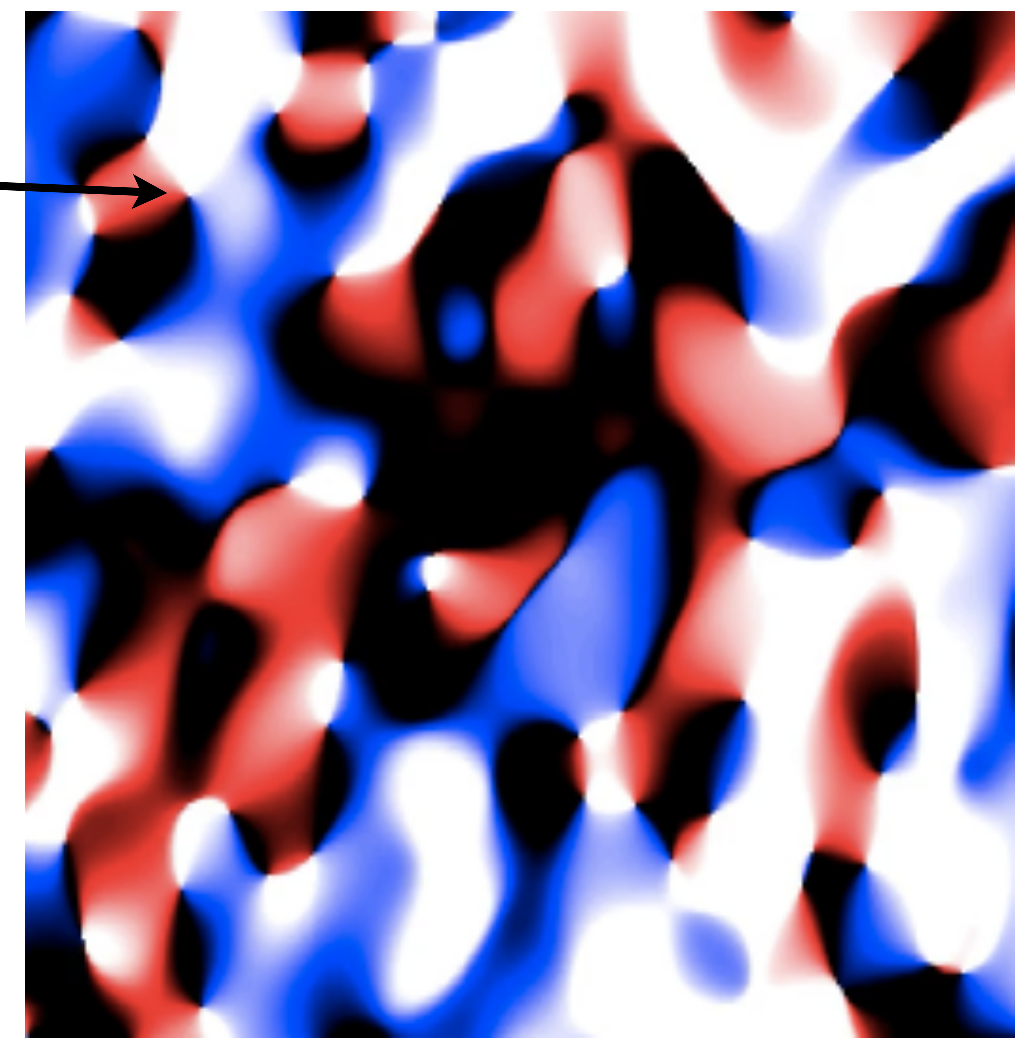
Average over initial conditions

But ... cosmic strings!!!!!



θ

$\phi = \phi_1 + i\phi_2 = |\phi| e^{i\theta}$



$$\ddot{\phi} - \frac{1}{R^2}\nabla^2\phi + 3H\dot{\phi} + \lambda_\phi \phi(|\phi|^2 - f_a^2) - \frac{1}{f_a}\chi = 0$$

SCENARIO B

$$\ddot{\phi} - \frac{1}{R^2}\nabla^2\phi + 3H\dot{\phi} + \lambda_\phi\phi(|\phi|^2 - f_a^2) - \frac{1}{f_a}\chi = 0 \qquad f_a = v = |\phi|$$

ADM units $3H(t_1) = m_a(T(t_1)),$

O(1) Conformal time $\tau = \sqrt{\frac{t}{t_1}} = \frac{R}{R_1} = \frac{R}{R(t_1)},$

O(1) Coordinates $\xi = R_1 H_1 x,$

O(1) Scaled field $\Phi = \frac{\phi}{v}\tau,$

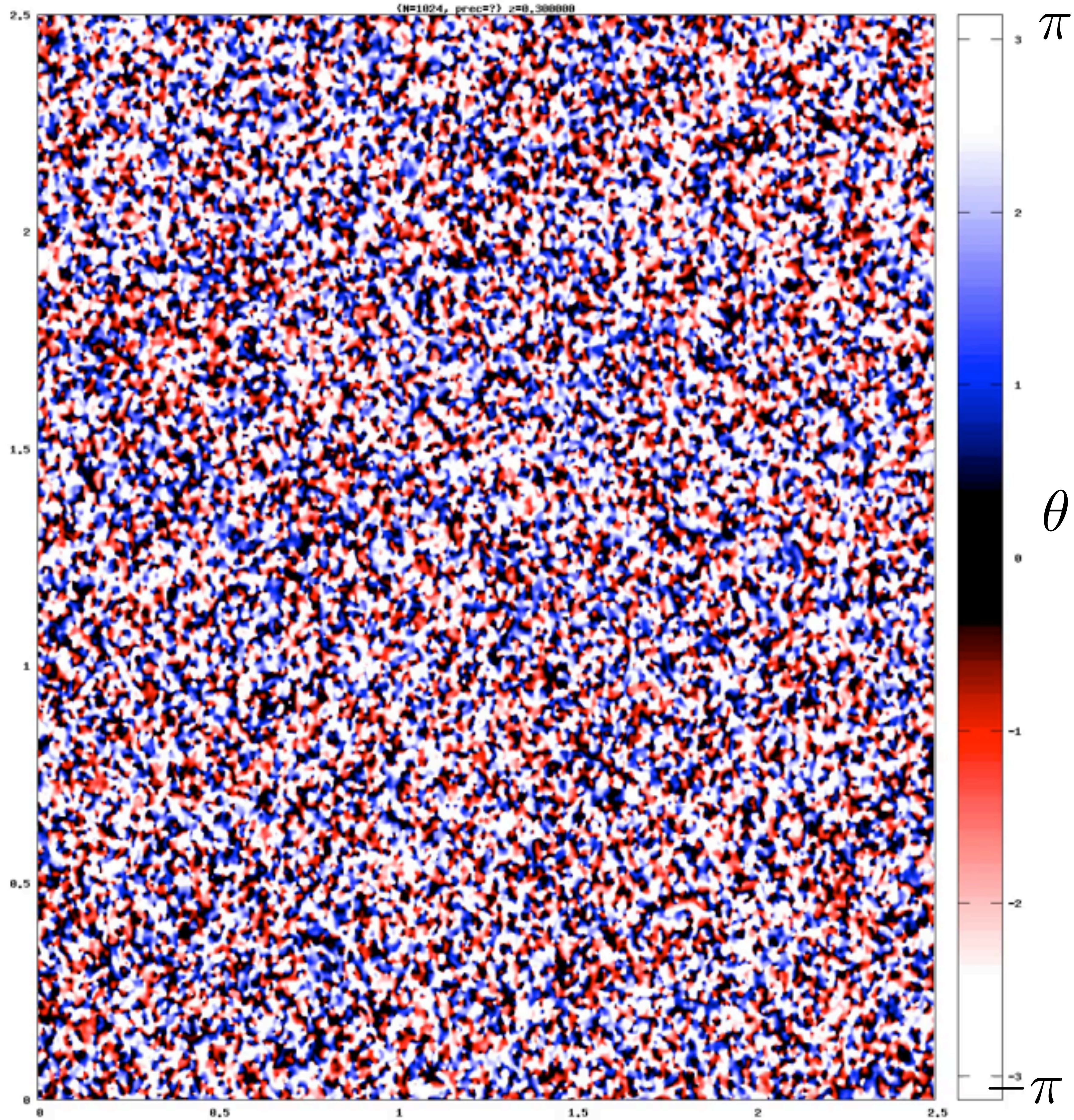
quartic $\lambda = \frac{\lambda_\phi v^2}{H_1^2},$ $\sim 10^{60}$

$$\Phi_{\tau\tau} - \nabla_\xi^2\Phi + \lambda\Phi(|\Phi|^2 - \tau^2) - 9\tau^{n+3} = 0.$$

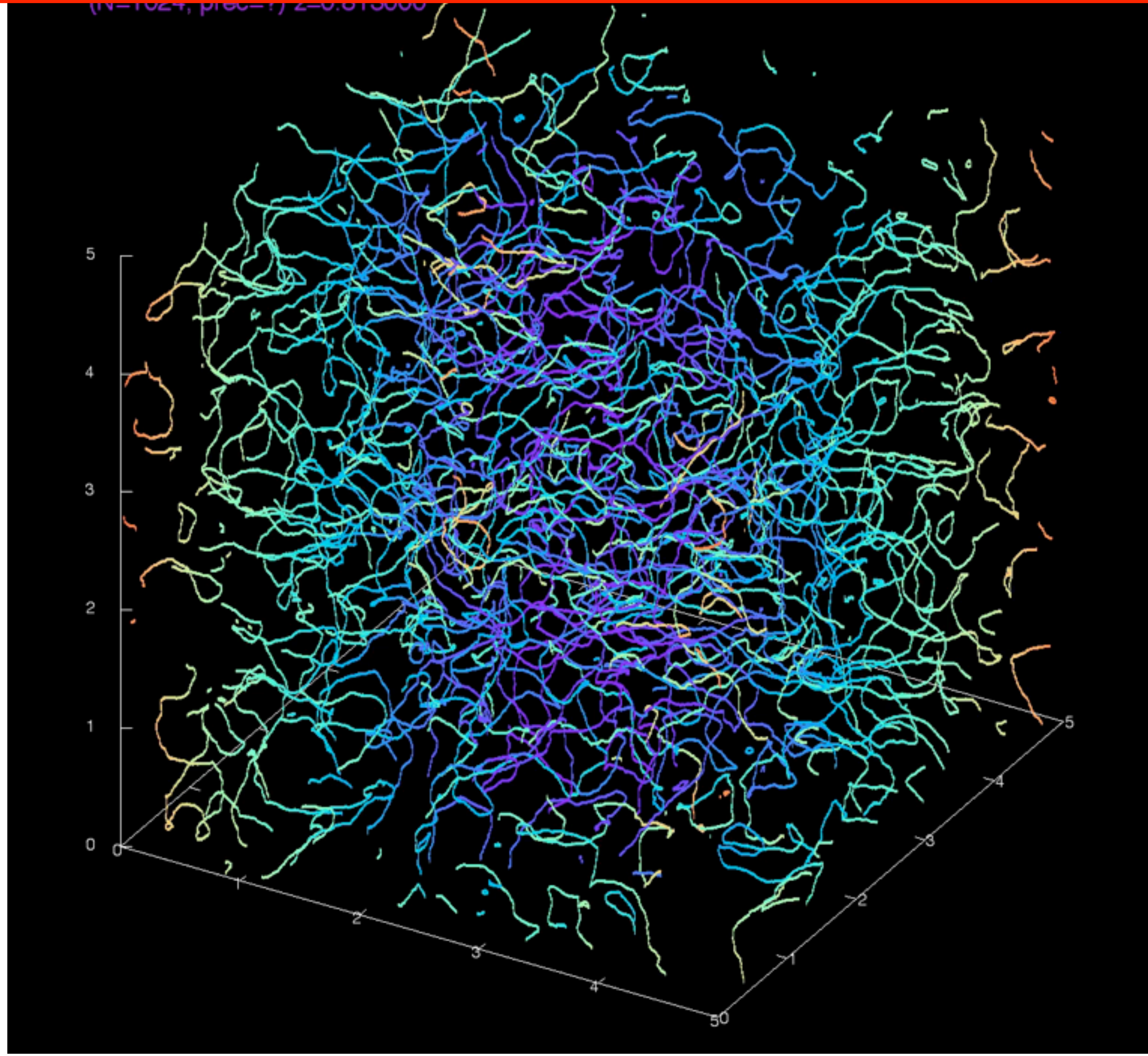
CORE radius $\sim \frac{1}{\sqrt{\lambda}\tau}$

$|\phi| \sim 0$

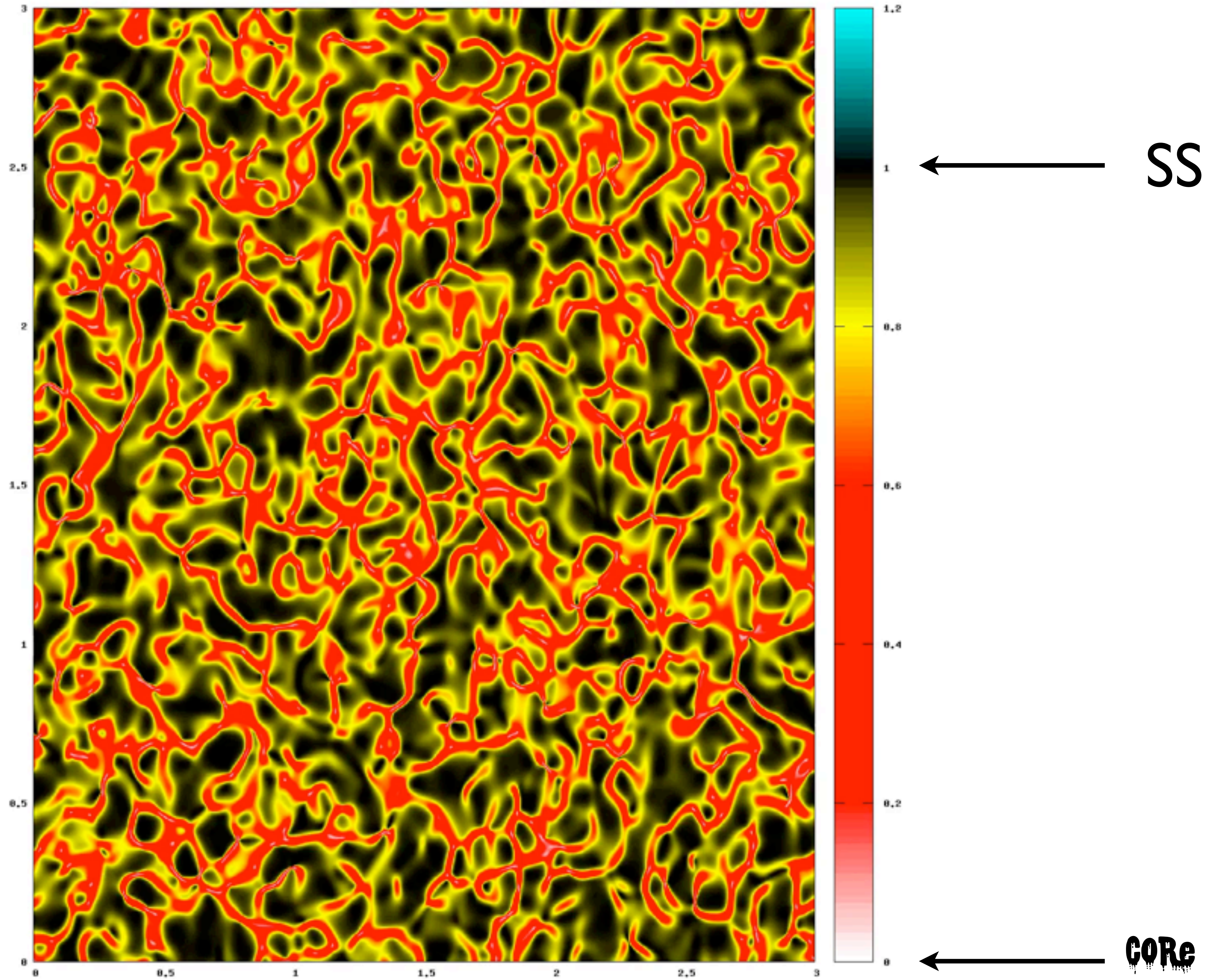
SCENARIO B



Strings

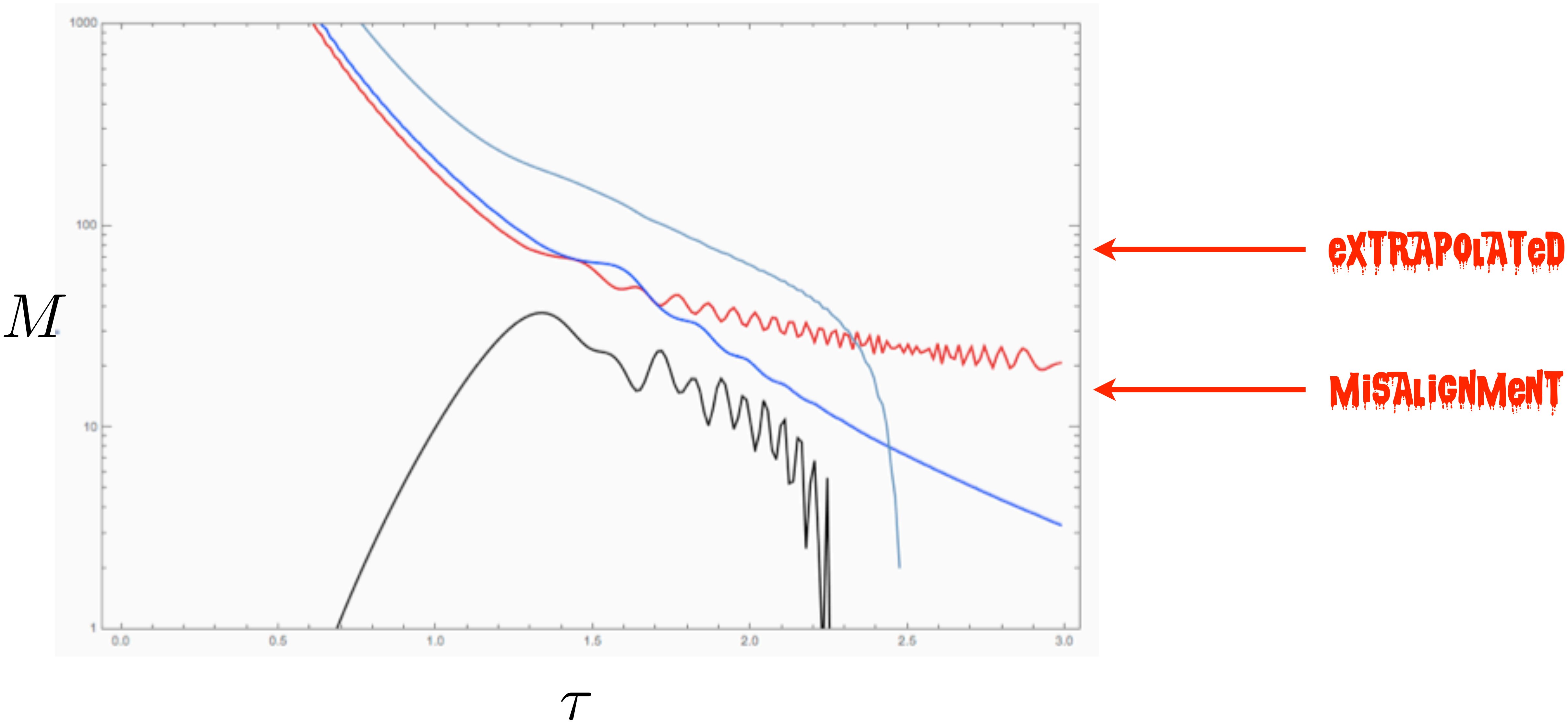


Order parameter



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

MY ~ FIRST RESULTS



STATE OF THE ART

- **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**

$$\zeta = 1 \pm 0.5$$

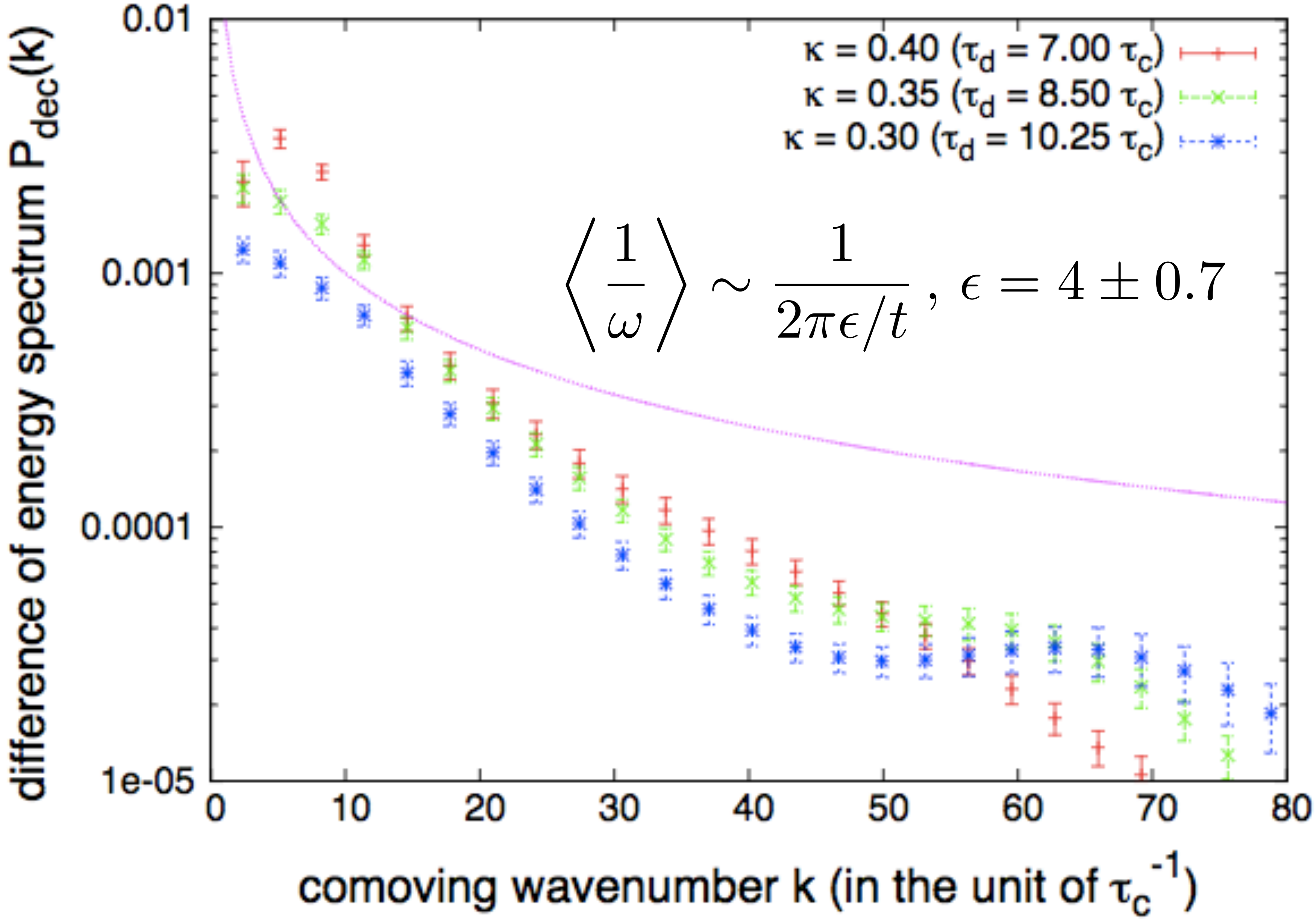
$$\Omega_{a,st} h^2 \propto N_a = \int dt R^3(t) \int d\omega \frac{1}{\omega} \frac{d\rho_{st}}{dt d\omega}$$

radiated axion spectrum

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

- Spectrum is red

Hiramatsu et al, PRD85 (2012)

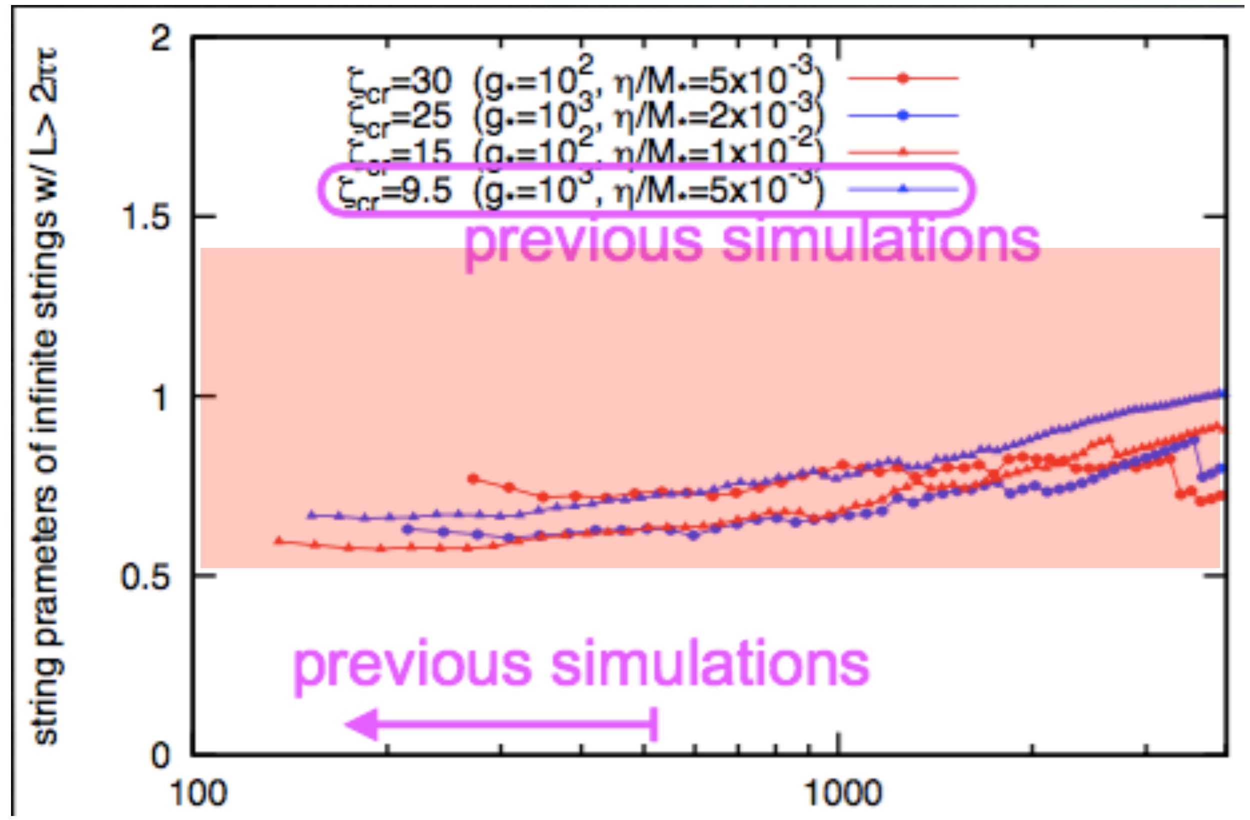


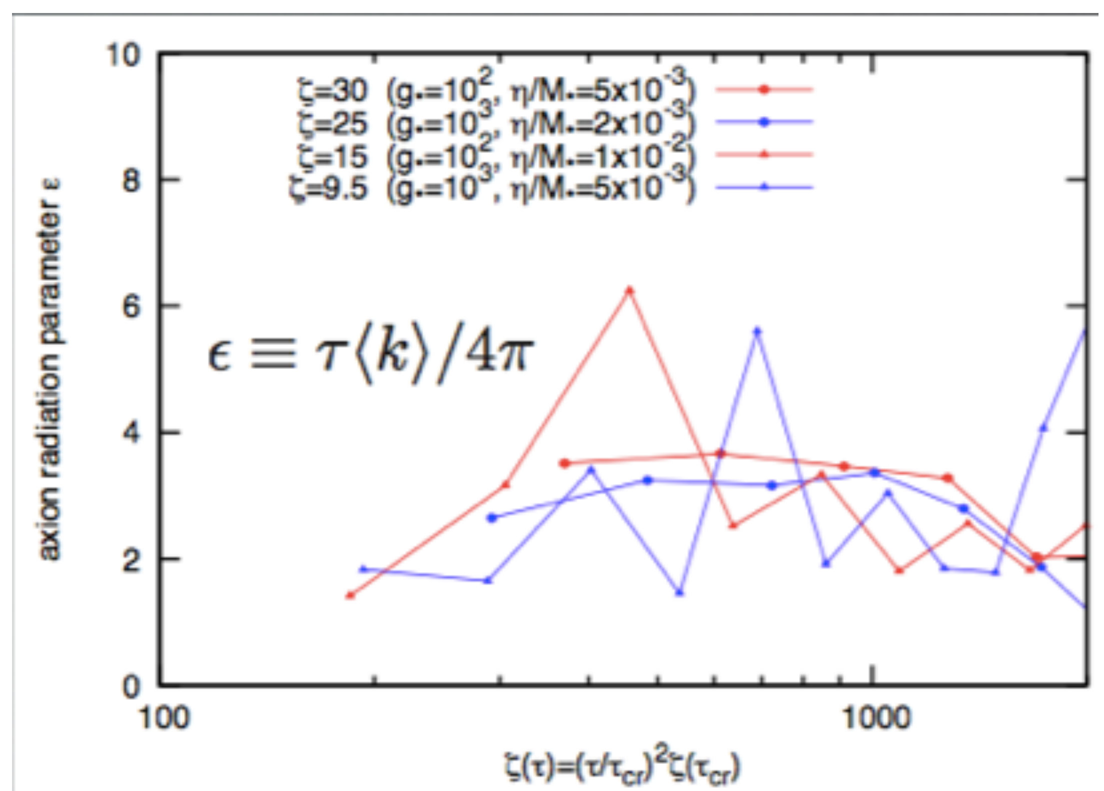
$$\Omega_{a,s}h^2 \sim 0.37^{+0.3}_{-0.2} \left(\frac{f_A}{1.92 \times 10^{11}} \right)^{1.165} \frac{\ln\left(f_A t_{co}\sqrt{\lambda_\sigma/\zeta}\right)}{50},$$

$$m_a = 100^{+100}_{-50}\,\mu\text{eV}$$

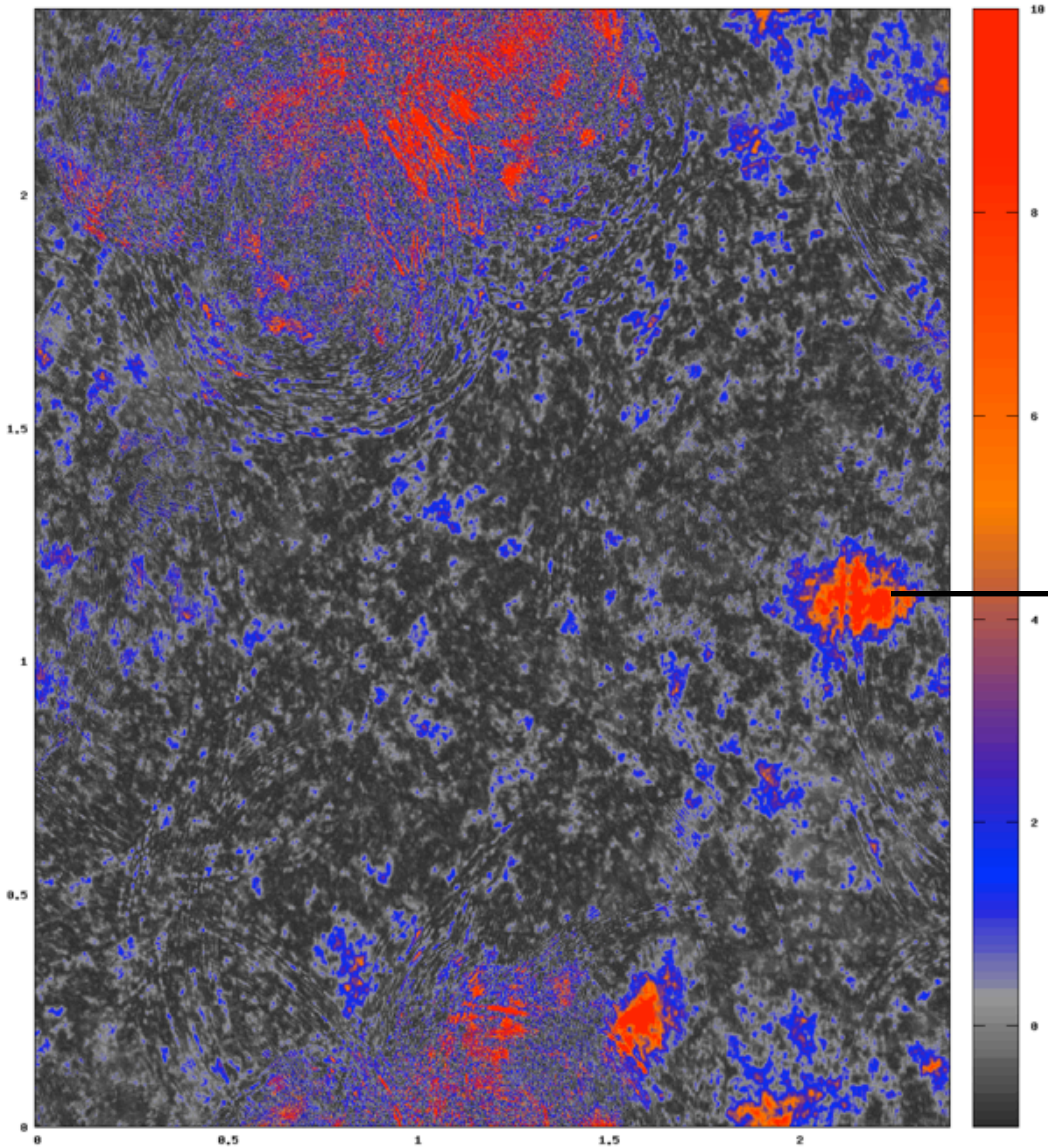
SCENARIO A $\Omega_{DM}h^2 = \Omega_a h^2 = 0.12$

Sekiguchi (HU-CTPU Sapporo Summer Institute) 2016



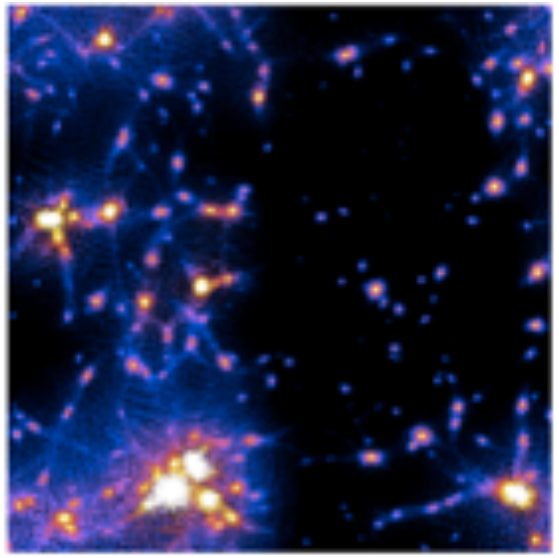


Dark matter density, inhomogeneous at comoving mpc scales



J. STADLER (MTH) 2016

minicluster seed!



FIRST ANALYSIS

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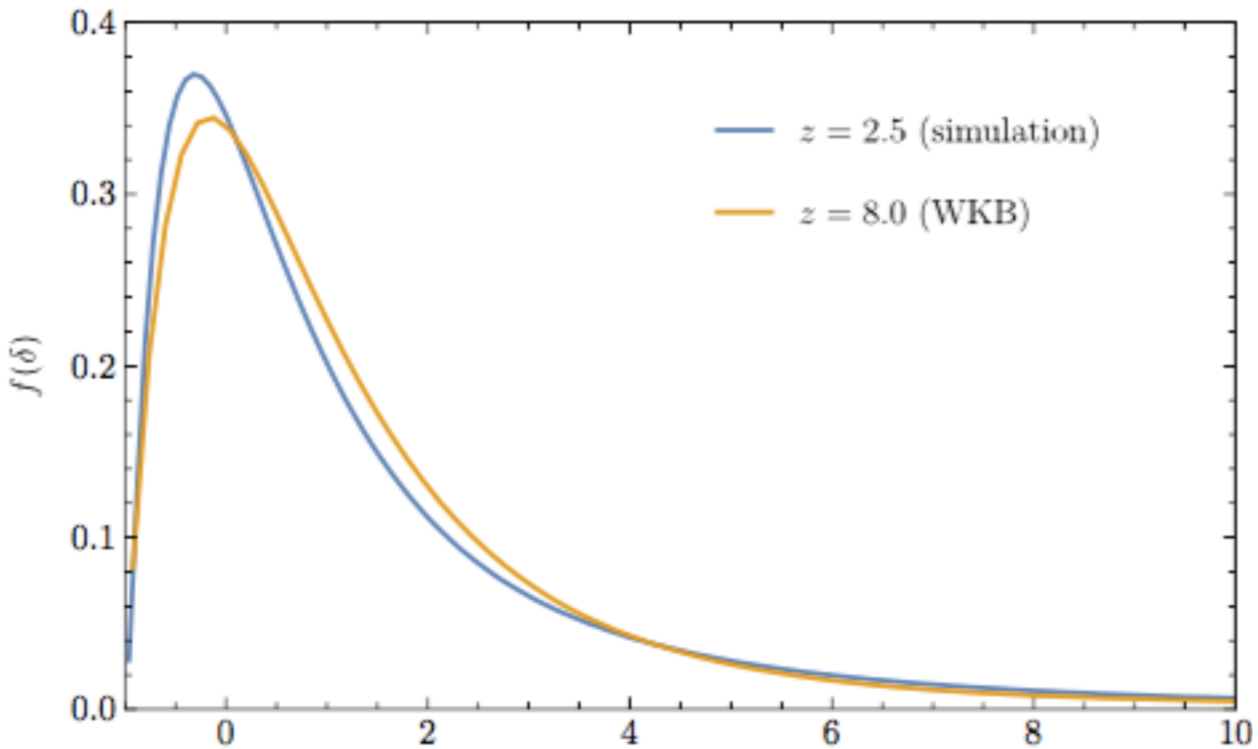
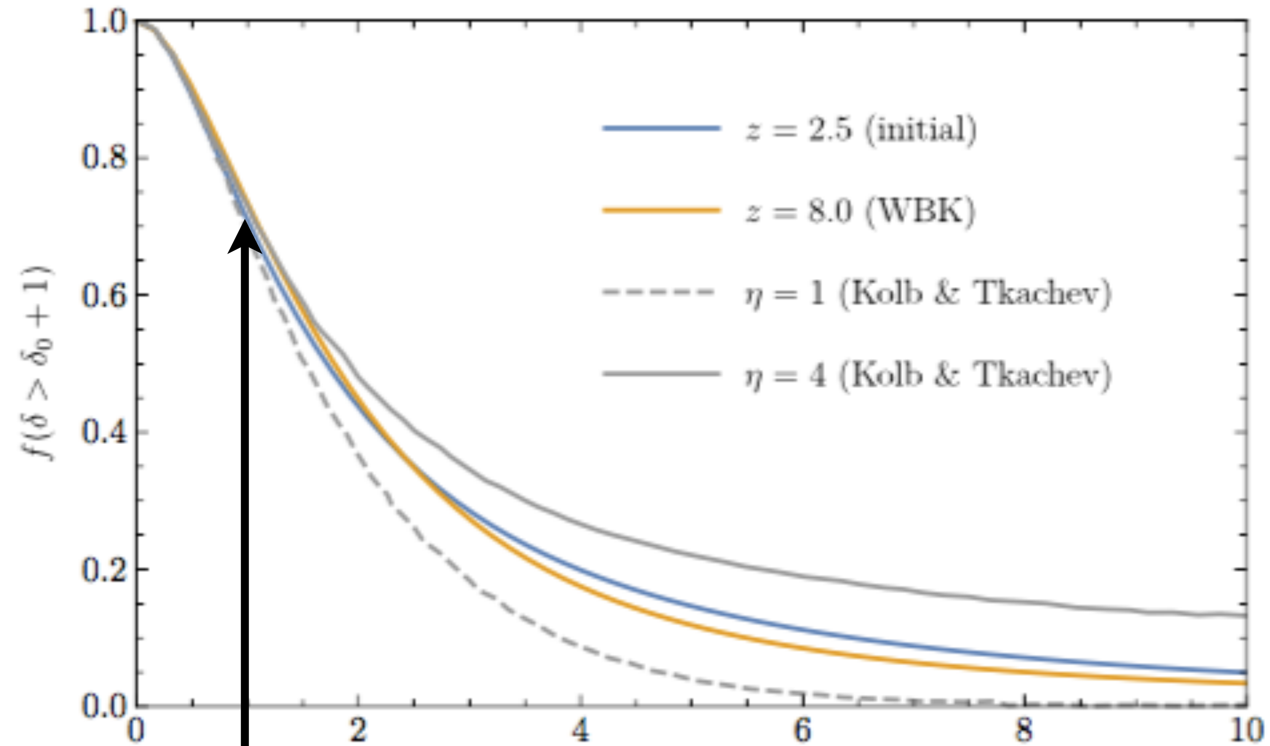
fraction of DM axions



density contrast



density contrast +1

30% – 70% !!!!

YeT TO COMe

- More extensive simulations
- Get the abundance from simulations (controlled extrapolation)

- Controlled Relaxation to DM (lots of radiation)
- Evolve MCs gravitationally (coll. with Niemeyer's group)
- MC/diffuse ratio?
- MC mass/radius distribution
- Astrophysical implications anew

THE AXION FROM HELL IS NOT THAT BAD AFTER ALL...