THE UNIVERSITY OF UTAH

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Axion Cold Dark Matter Revisited

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Based on: Visinelli, Gondolo, arXiv:0903.4377

Axion CDM: Overview

- When is the axion 100% Cold Dark Matter?
- Axion properties
- Axion density today
- Results in axion parameter space

Axion Properties

In 1977 Peccei and Quinn (PQ) proposed to add a $U(1)_{PQ}$ symmetry to solve the strong-CP problem.

The axion is the pseudo Nambu-Goldstone boson originating from the breaking of $U(1)_{PQ}$:

$$L = \ldots + \frac{1}{2}(\partial_\mu a)^2 + \frac{g^2}{32\pi^2}\frac{a(x)}{f_a}\tilde{G}^a_{\mu\nu}G^{\mu\nu}_a + V(\theta)$$

$U(1)_{PQ}$ symmetry spontaneusly breaks at the energy scale f_a.

The axion field is $a(x)$, the misalignment field is $\theta(x) = a(x)/f_a$.

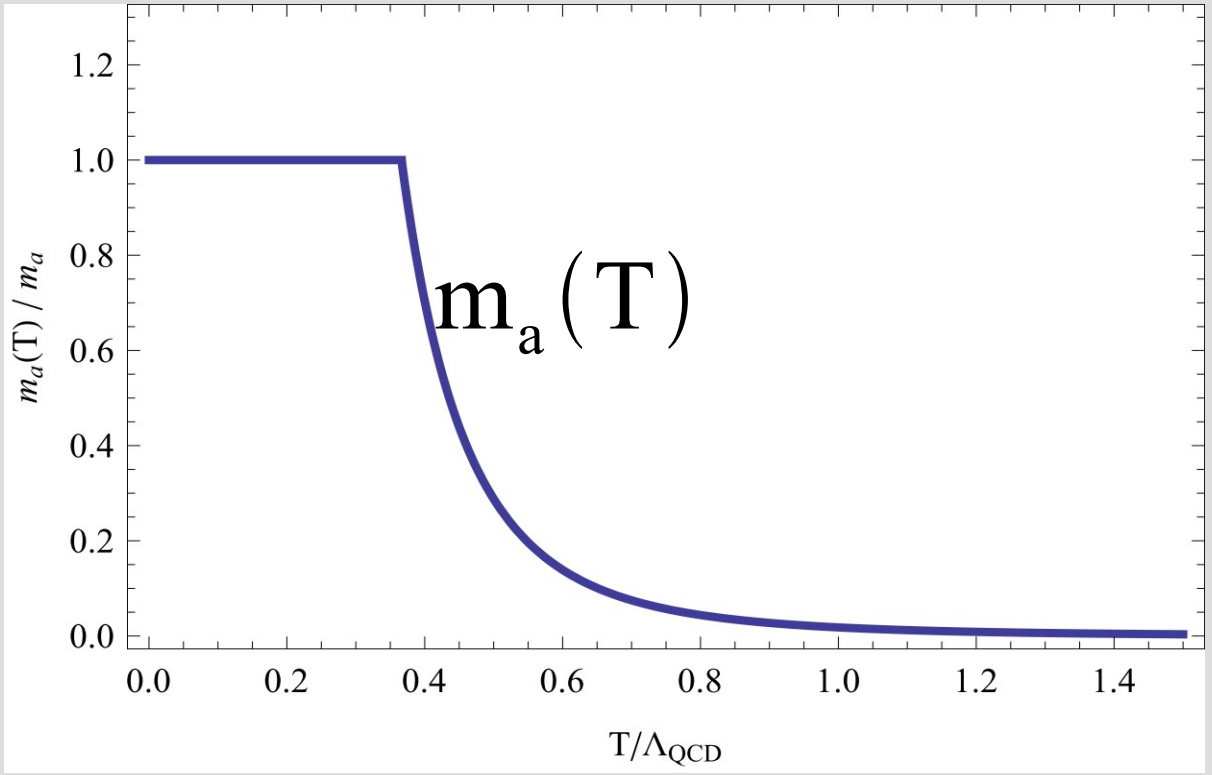
$$V(\theta) = m_a^2 f_a^2 (1 - \cos\theta), \qquad T \sim \Lambda_{QCD}$$

Axion mass

Axion mass depends on temperature

$$m_a(T) = 0.018\, m_a(0) \frac{\Lambda_{QCD}^4}{T^4}, \; T \gg \Lambda_{QCD}$$

$$m_a(0) = 6.2\, \mu eV\, (10^{12}\, GeV / f_a), \; T \ll \Lambda_{QCD}$$



Axion and cosmology

PQ symmetry breaks at $T \sim f_a$;

Different axion physics if $f_a >$ or $< H_I / 2\pi$

Equation of motion in FRW metric:

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

For $\mathrm{T} > 1\,\mathrm{GeV}$ the field is frozen at $\theta = \theta_i = const.$

At T ~ Λ_{QCD} the axion field starts to oscillate.

Axion energy density today

$$\Omega_a h^2 = 0.236 < \theta_i^2 F(\theta_i) > f_{12}^{7/6}, \qquad f_a < 10^{17}\, GeV$$

$$\Omega_a h^2 = 0.0051 < \theta_i^2 F(\theta_i) > f_{12}^{3/2}, \qquad f_a > 10^{17}\, GeV$$

$$f_{12} = f_a / 10^{12}\, GeV$$

Average over one Hubble volume

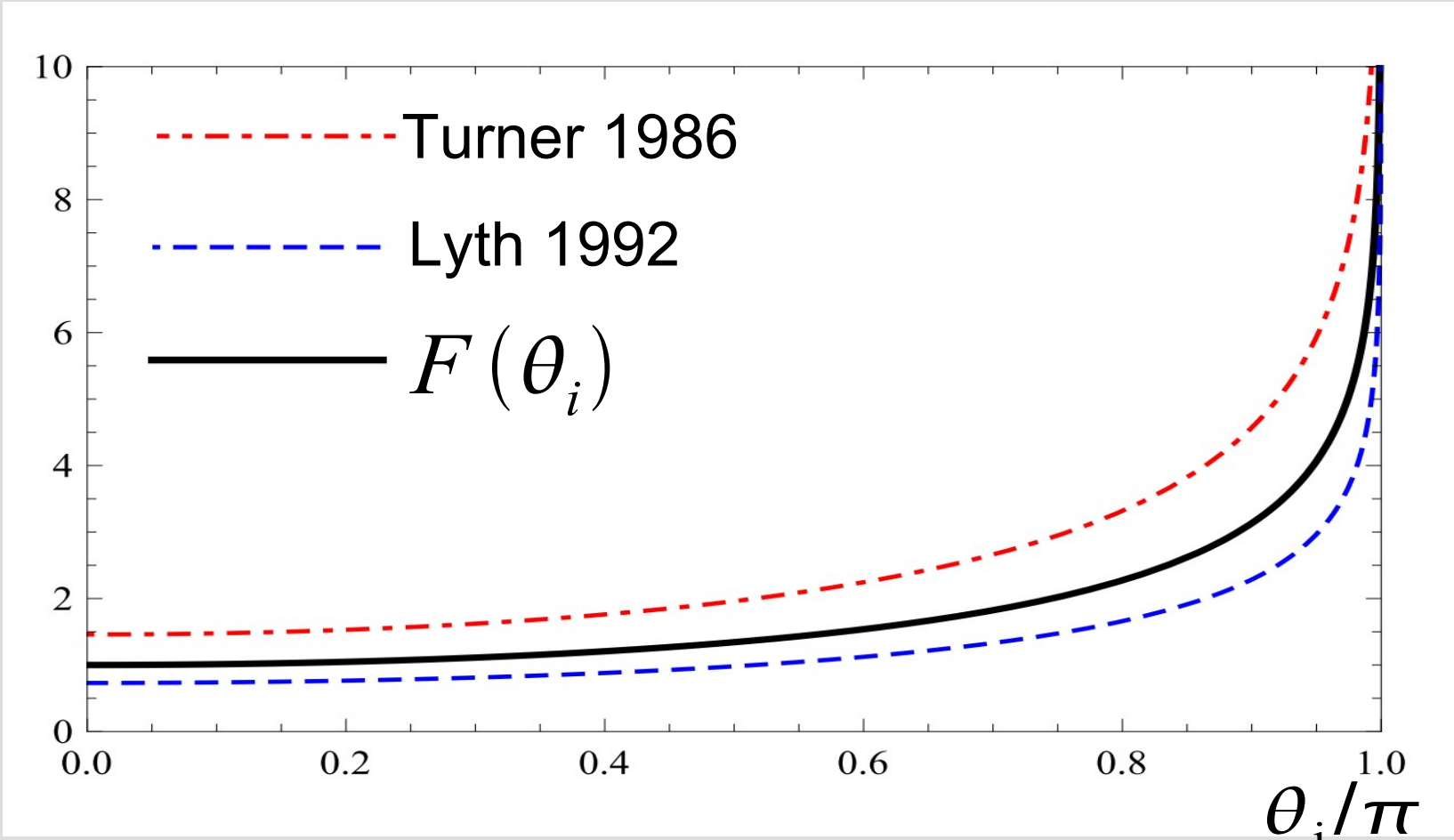
- We impose $\Omega_a h^2 = \Omega_{CDM} h^2 = 0.1131 \pm 0.0034$

- The function $F(\theta_i)$ accounts for anharmonicities in the axion potential

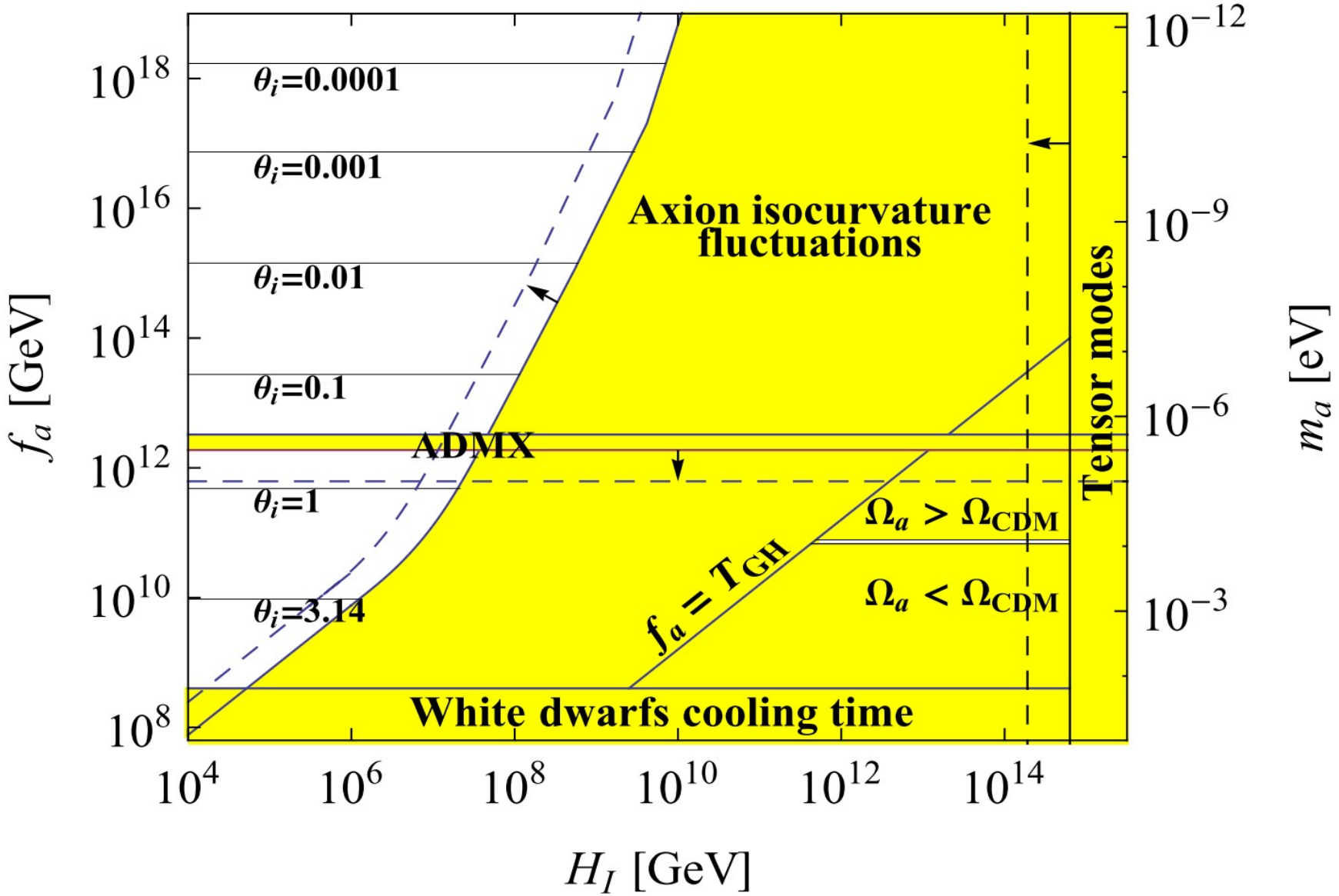
$$\sin\theta_i = \theta_i + \text{anharmonicities}$$

The function $F(\theta_i)$

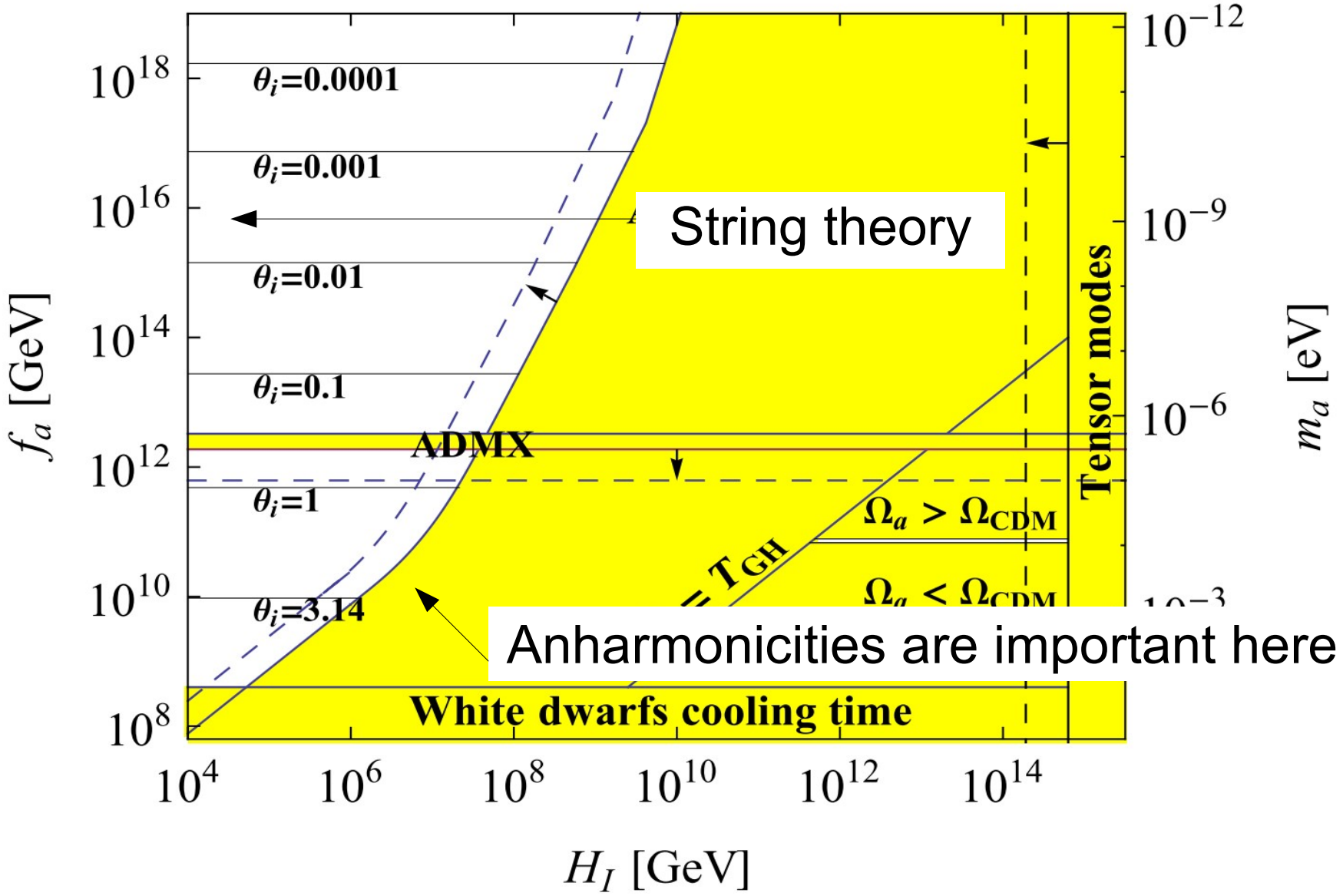
$$F(\theta_i)=\left[\log\left(\frac{e\,\pi^2}{\pi^2-\theta_i^2}\right)\right]^{7/6}$$



Results


θ_i=0.0001
θ_i=0.001
θ_i=0.01
θ_i=0.1
θ_i=1
θ_i=3.14
Axion isocurvature fluctuations
ADMX
Tensor modes
$\Omega_a > \Omega_{CDM}$
$\Omega_a < \Omega_{CDM}$
$f_a = T_{GH}$
White dwarfs cooling time
f_a [GeV]
m_a [eV]
H_I [GeV]
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}

Results


10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
f_a [GeV]
θ_i=0.0001
θ_i=0.001
θ_i=0.01
θ_i=0.1
θ_i=1
θ_i=3.14
ADMX
String theory
Tensor modes
$\Omega_a > \Omega_{CDM}$
$\Omega_a < \Omega_{CDM}$
$T = T_{GH}$
Anharmonicities are important here
White dwarfs cooling time
10^{-12}
10^{-9}
10^{-6}
m_a [eV]
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
H_I [GeV]

Scenario 1:
PQ symmetry breaks after inflation

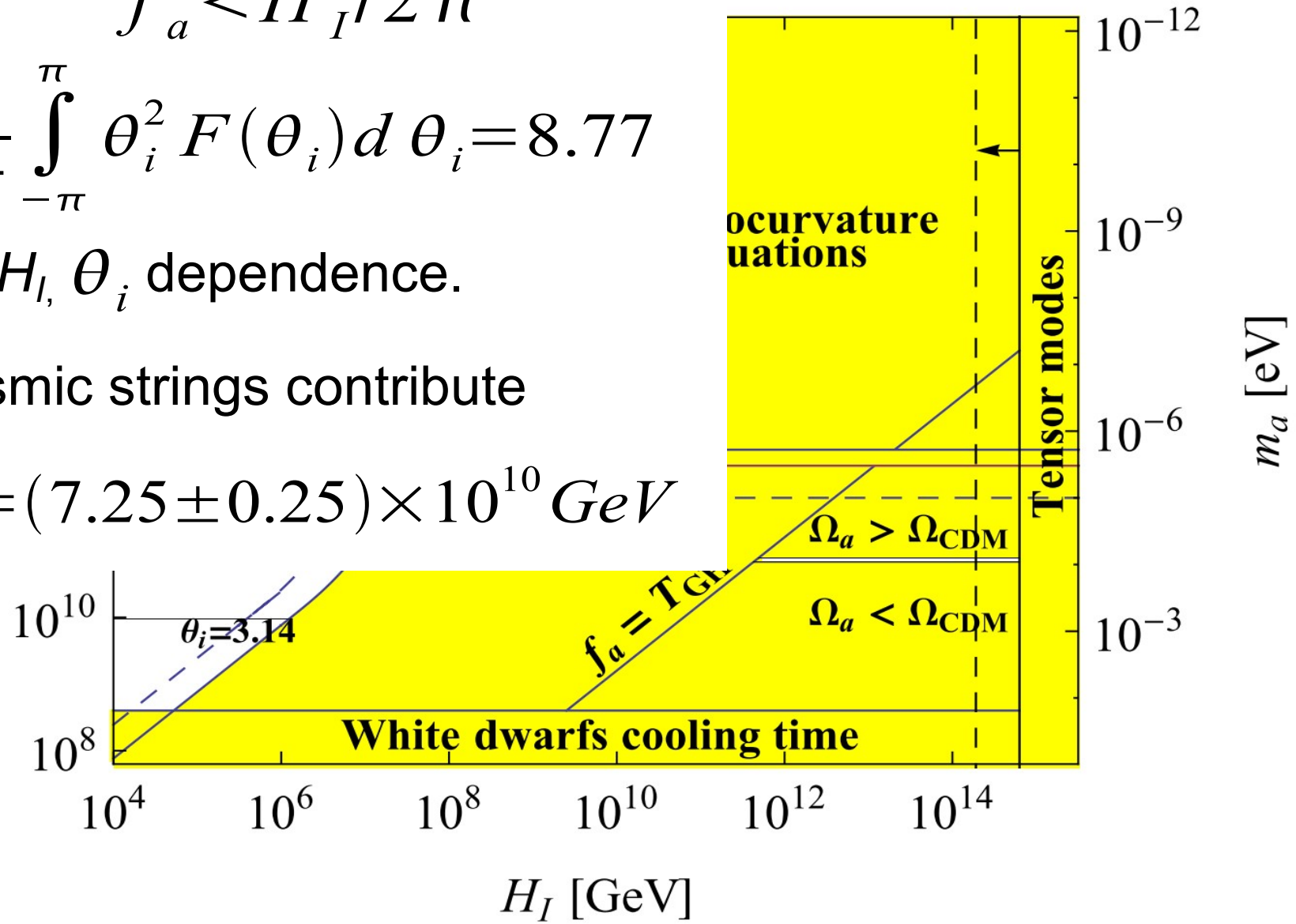
$$f_a < H_I / 2\pi$$

$$\frac{1}{2\pi}\int_{-\pi}^{\pi} \theta_i^2 F(\theta_i) d\theta_i = 8.77$$

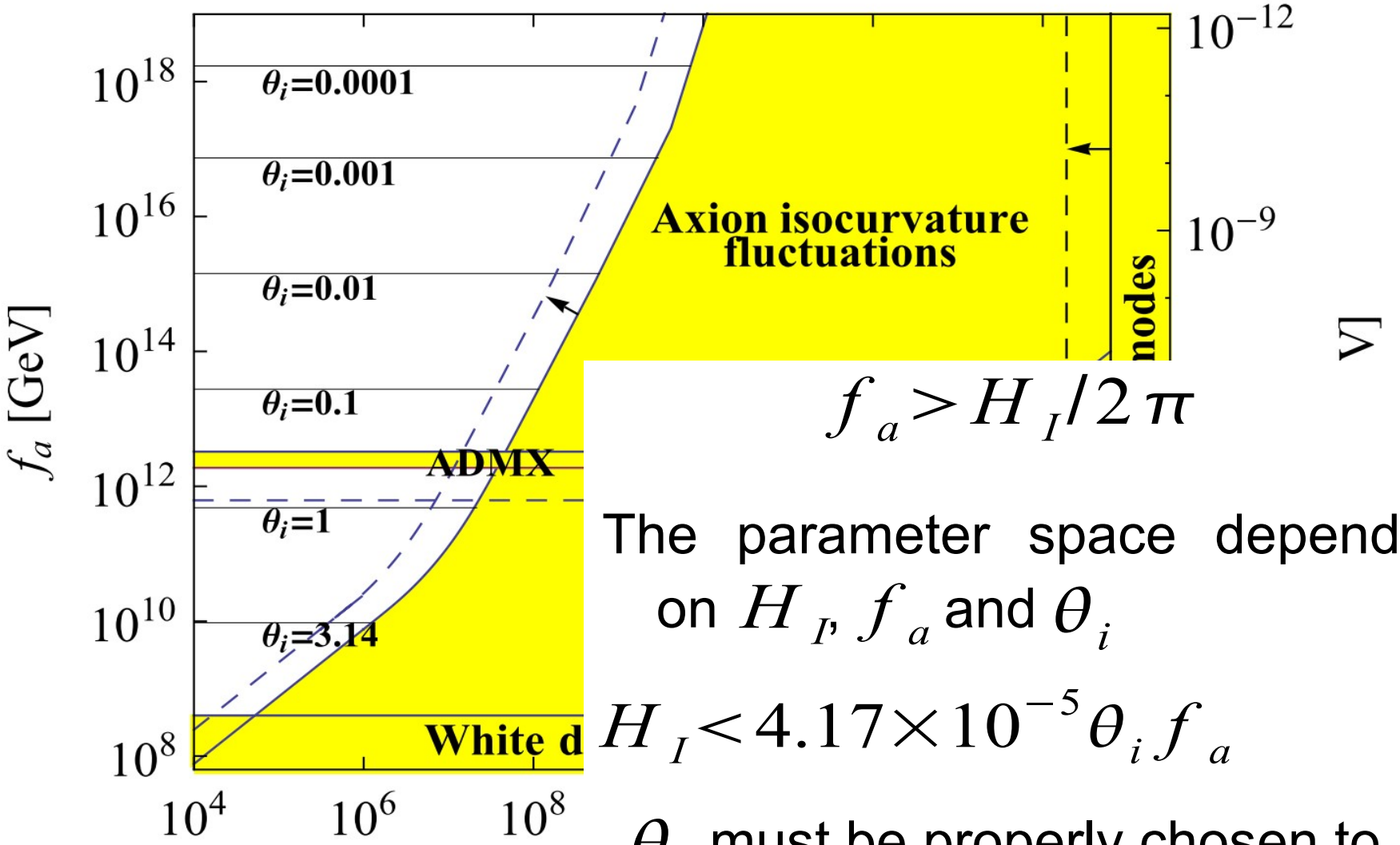
No H_I, θ_i dependence.

Cosmic strings contribute

$$f_a = (7.25 \pm 0.25) \times 10^{10}\, GeV$$



Scenario 1:
PQ symmetry breaks during inflation



$$f_a > H_I / 2\pi$$

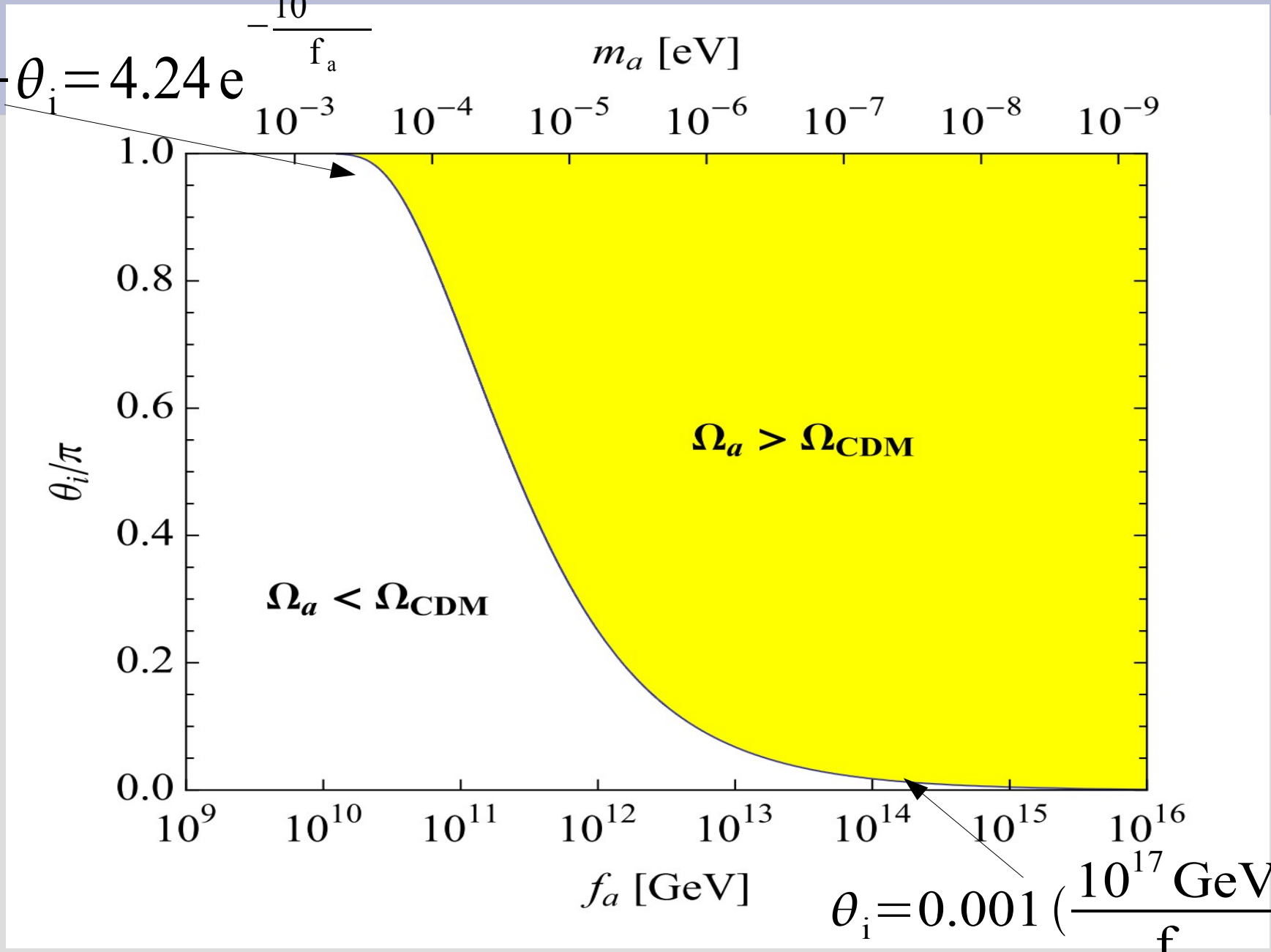
The parameter space depends on H_I, f_a and θ_i

$$H_I < 4.17 \times 10^{-5} \theta_i f_a$$

θ_i must be properly chosen to have axion CDM

f_a vs θ_i in Scenario 2

$$\pi - \theta_i = 4.24\, e^{-\frac{10^{11}\text{GeV}}{f_a}}$$



$$\theta_i = 0.001\,(\frac{10^{17}\,\text{GeV}}{f_a})$$

Discussions and conclusions

- Including anharmonicities, axion can be 100% CDM when:

  1) $m_a = (85 \pm 3)\,\mu\text{eV}$ or $f_a = (7.25 \pm 0.25) \times 10^{10}\,GeV$
  (PQ symmetry breaks after inflation)

  2) specific θ_i for given f_a (PQ symmetry breaks during inflation)

- Scenario 1 can be completely ruled out by more stringent measures of H_I.