

# Axion Cold Dark Matter in Standard and Non-Standard Cosmologies

*Paolo Gondolo*  
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*Visinelli, Gondolo, arxiv:0903.4377, Phys. Rev. D 80, 035024 (2009)*  
*Visinelli, Gondolo, arxiv:0912.0015, Phys. Rev. D 81, 063508 (2010)*



*Luca Visinelli*

# Axion cold dark matter

*When are axions 100% of cold dark matter?*

Study axion parameter space imposing

$$\Omega_a = \Omega_{\text{CDM}} = 0.1131 \pm 0.0034$$

*And update cosmological constraints and include anharmonicities*

# Axions as solution to the strong CP problem

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*The strong CP problem*

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Vacuum potentials  $A_\mu = i\Omega\partial_\mu\Omega^{-1}$  with  $\Omega \rightarrow e^{2\pi in}$  as  $r \rightarrow \infty$

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Why  $\theta$  should be so small is the strong CP problem

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Introducing a  $U(1)_{PQ}$  symmetry replaces

$$\theta_{\text{total}} = \theta + \arg \det M_{\text{quark}}$$

*static CP-violating angle*

$\Rightarrow$

$$\theta(x) = a(x)/f_a$$

*dynamic CP-conserving field*

axion



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New lagrangian  $\mathcal{L}_a = -\frac{1}{2} \partial^\mu a \partial_\mu a + \frac{a}{f_a} \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu} + \mathcal{L}_{\text{int}}(a)$

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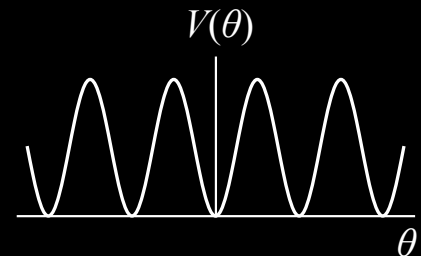
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Before QCD phase transition,  $\langle \theta \rangle$  can be anything

After QCD phase transition, instanton effects generate

$$V(\theta) = m_a^2 f_a^2 (1 - \cos \theta)$$

and  $\langle \theta \rangle = 0$  dynamically





# Axions as dark matter

*Hot*

*Cold*

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## *Hot*

Produced thermally in early universe

*Important for  $m_a > 0.1 eV$  ( $f_a < 10^8$ ), mostly excluded by astrophysics*

## *Cold*

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## Hot

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## Cold

Produced by coherent field oscillations around minimum of  $V(\theta)$

*(Vacuum realignment)*

Produced by decay of topological defects

*(Axionic string decays)*

# Axion cold dark matter parameter space

	$f_a$	Peccei-Quinn symmetry breaking scale
	$N$	Peccei-Quinn color anomaly
	$N_d$	Number of degenerate QCD vacua
Kim-Shifman-Vainshtain-Zakharov Dine-Fischler-Srednicki-Zhitnitski		Couplings to quarks, leptons, and photons
	$H_I$	Expansion rate at end of inflation
	$\theta_i$	Initial misalignment angle
Harari-Sikivie-Hagmann-Chang Davis-Battye-Shellard		Axionic string parameters

*Assume  $N = N_d = 1$  and show results for KSVZ and HSHC string network*

*Thus 3 free parameters  $f_a$ ,  $\theta_i$ ,  $H_I$  and one constraint  $\Omega_a = \Omega_{\text{CDM}}$*

# Cold axion production in cosmology

## *Vacuum realignment*

- Initial misalignment angle  $\theta_i$
- Coherent axion oscillations start at temperature  $T_1$

$$3H(T_1) = m(T_1)$$

Hubble expansion parameter  
*non-standard expansion histories  
differ in the function  $H(T)$*

$T$ -dependent axion mass  
*axions acquire mass through  
instanton effects at  $T < \Lambda \approx \Lambda_{\text{QCD}}$*

- Density at  $T_1$  is  $n_a(T_1) = \frac{1}{2} m_a(T_1) f_a^2 \chi \langle \theta_i^2 f(\theta_i) \rangle$

Anharmonicity correction  $f(\theta)$

*axion field equation has anharmonic terms  $\ddot{\theta} + 3H(T)\dot{\theta} + m_a^2(T) \sin \theta = 0$*

- Conservation of comoving axion number gives present density  $\Omega_a$

# Cold axion production in cosmology

## Axionic string decays

- Energy density ratio (string decay/misalignment)

$$\alpha \equiv \frac{\rho_a^{\text{str}}}{\rho_a^{\text{mis}}} = \frac{\xi \bar{r} N_d^2}{\zeta}$$

(String stretching rate)<sup>-2</sup> →  $\xi \bar{r} N_d^2$

Density enhancement from string decays →  $\xi \bar{r} N_d^2$

Uncertainty in axion spectrum →  $\zeta$

Slow oscillating strings (Davis-Battye-Shellard)

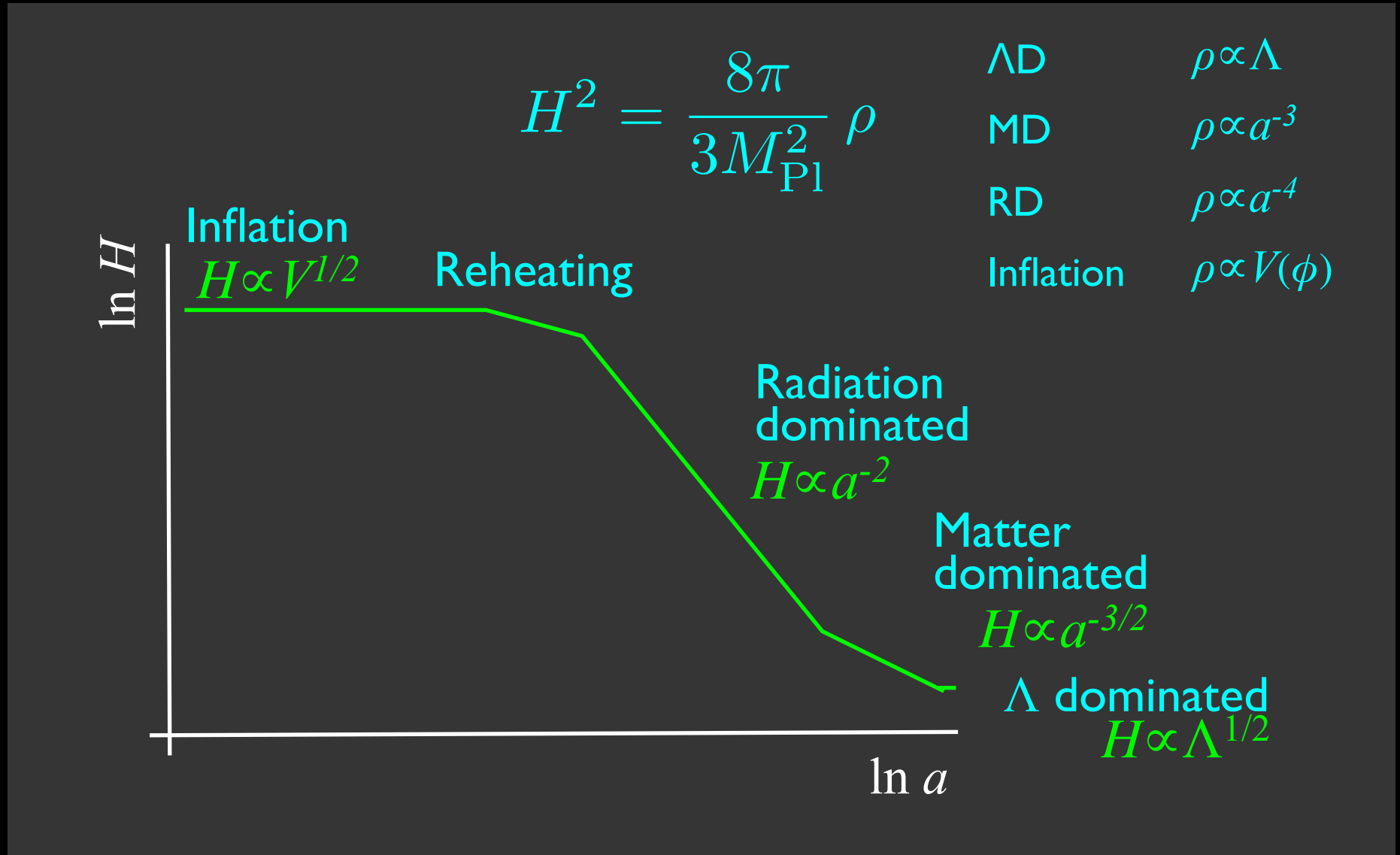
$$\bar{r} = \frac{1-\beta}{3\beta-1} \ln(t_1/\delta)$$

Fast-oscillating strings (Harari-Hagmann-Chang-Sikivie)

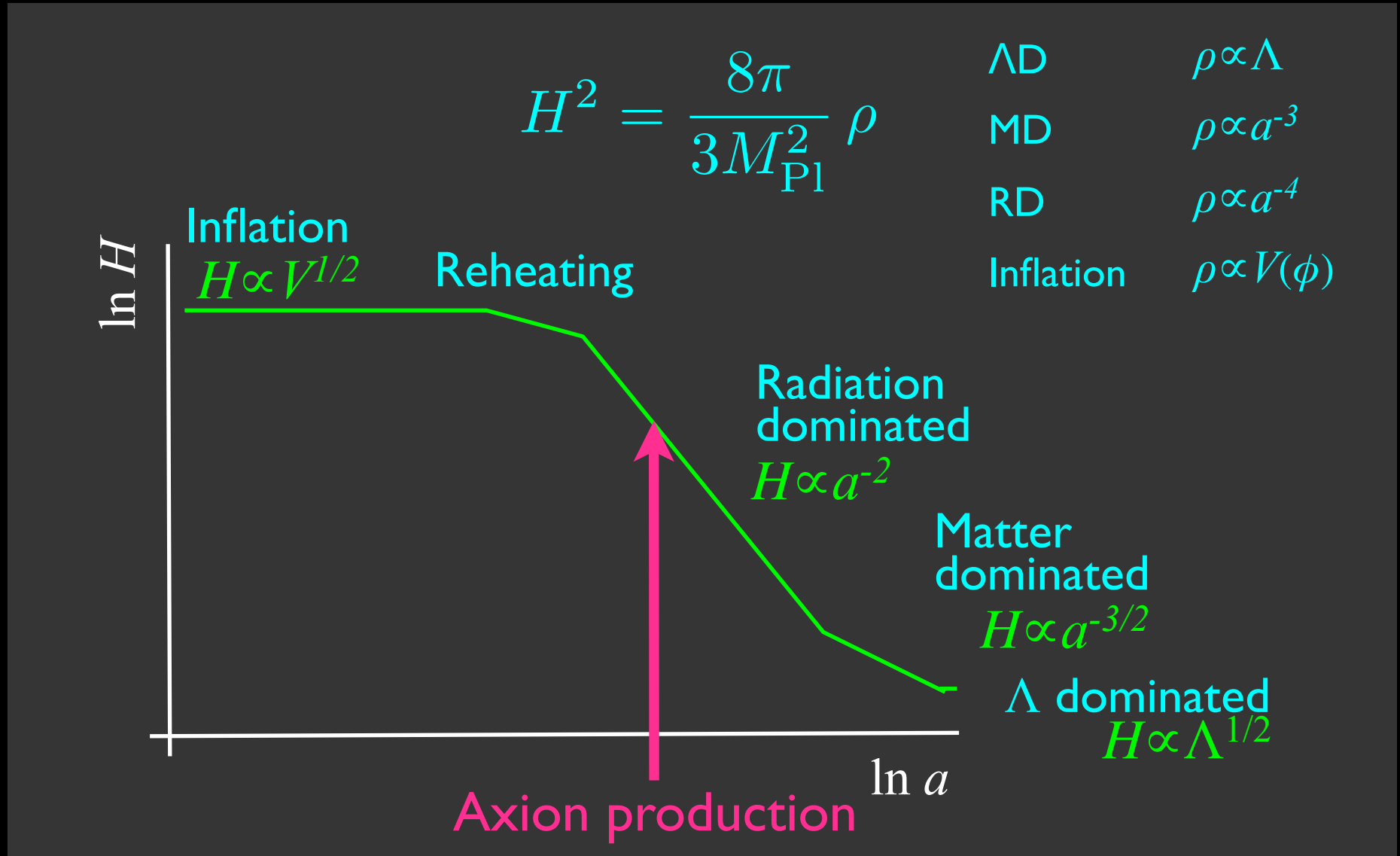
$$\bar{r} = \frac{1-\beta}{3\beta-1} 0.8$$

with  $a(t) \propto t^\beta$

# Standard cosmology

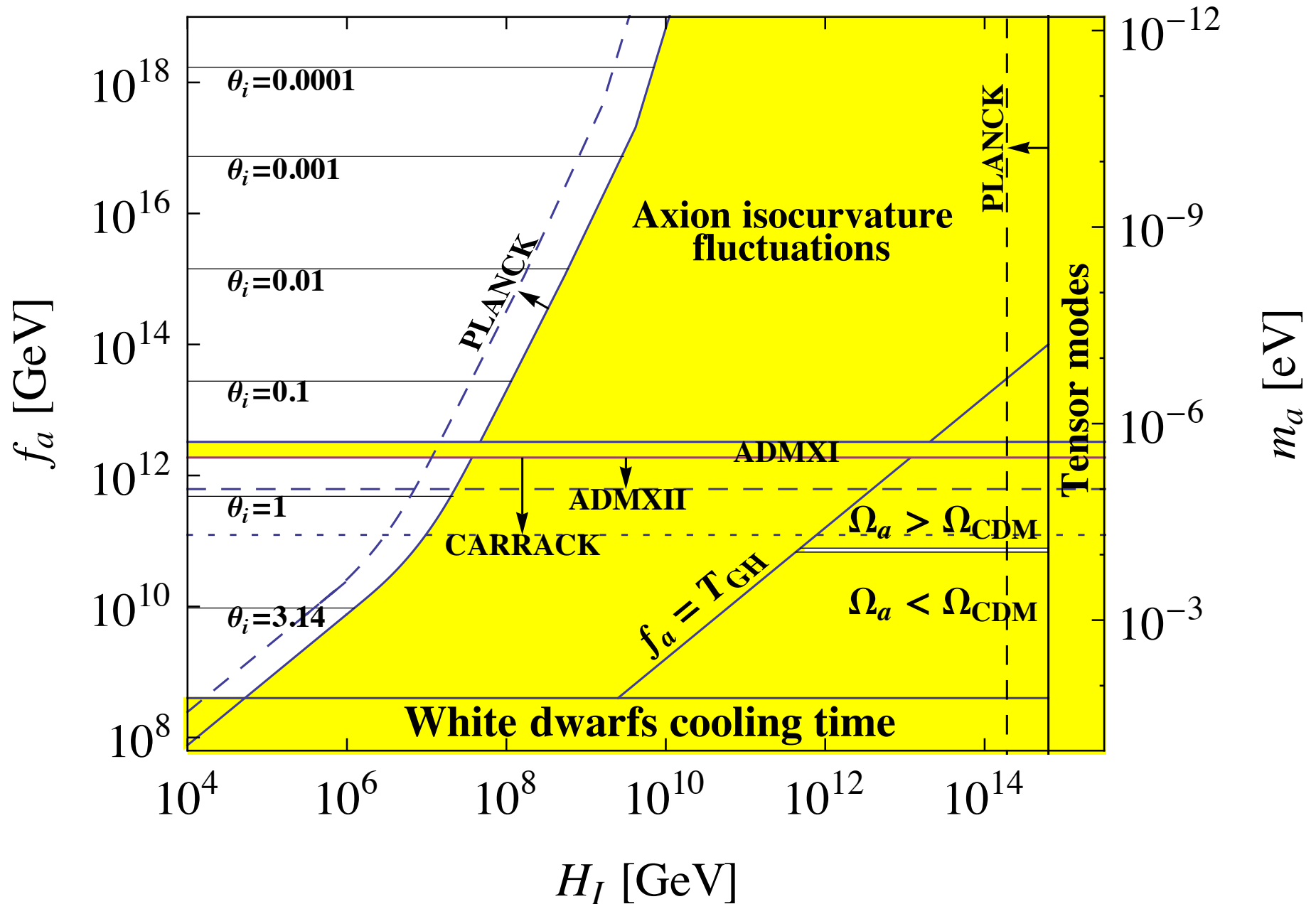


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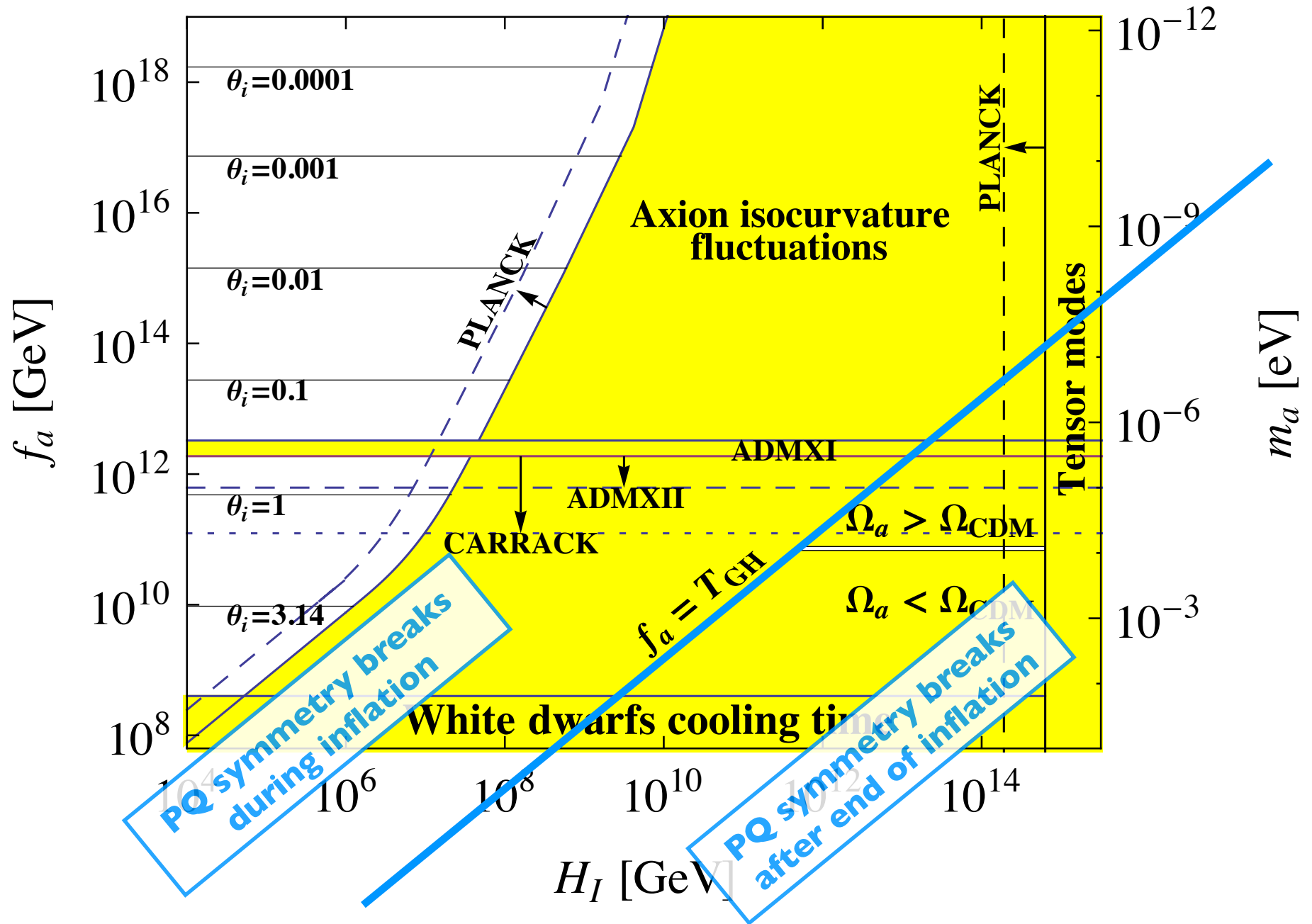




# Axion CDM - Standard cosmology

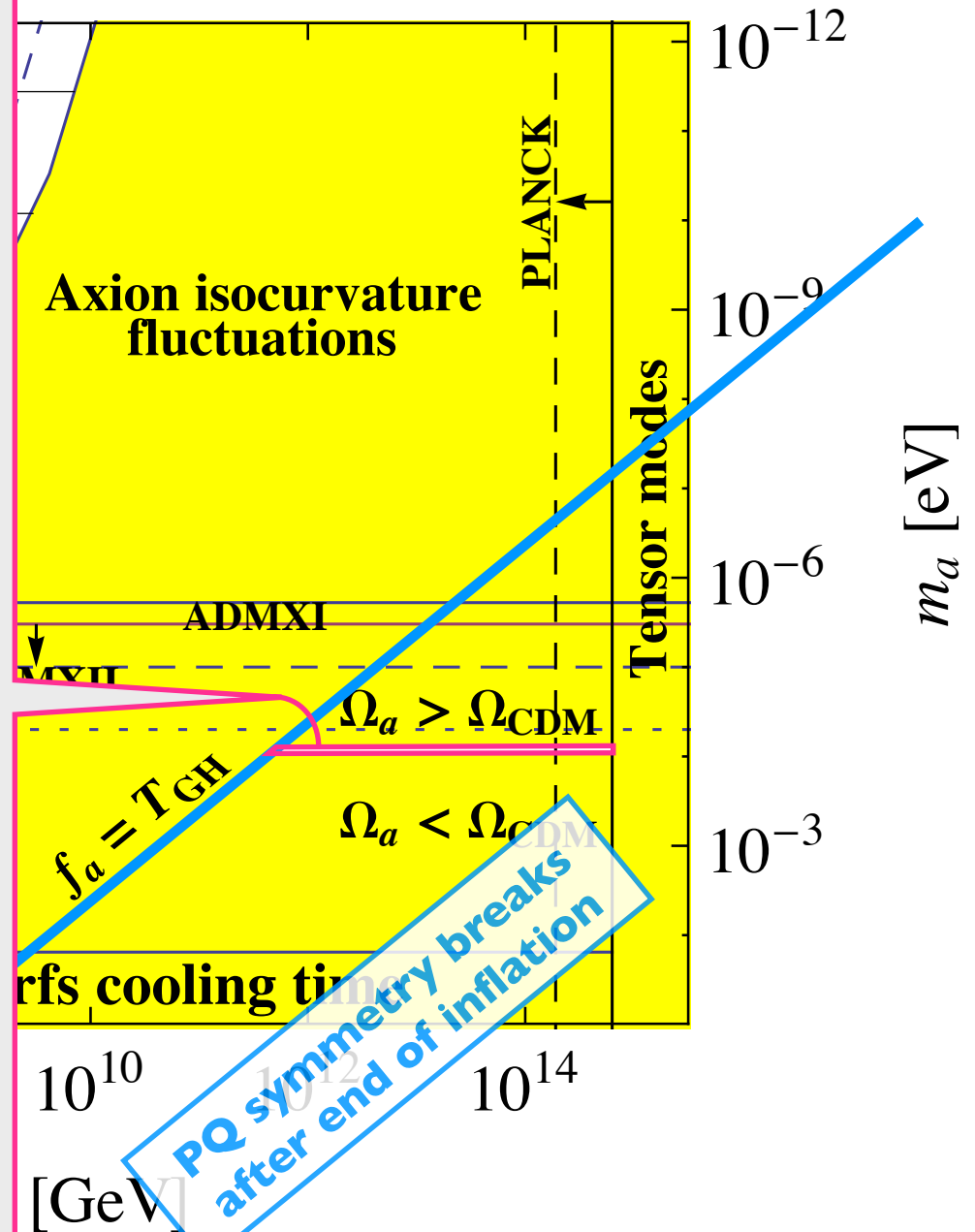


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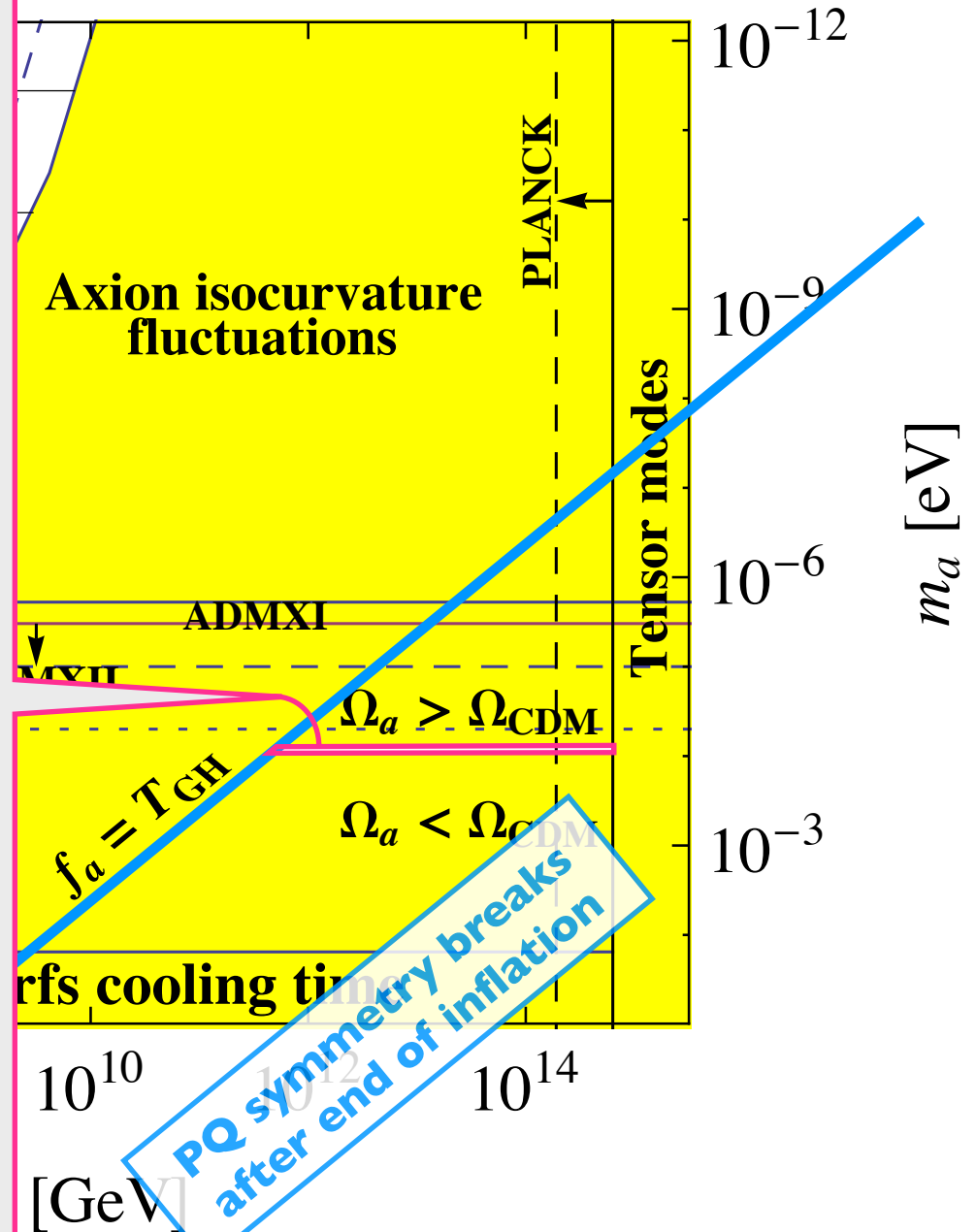
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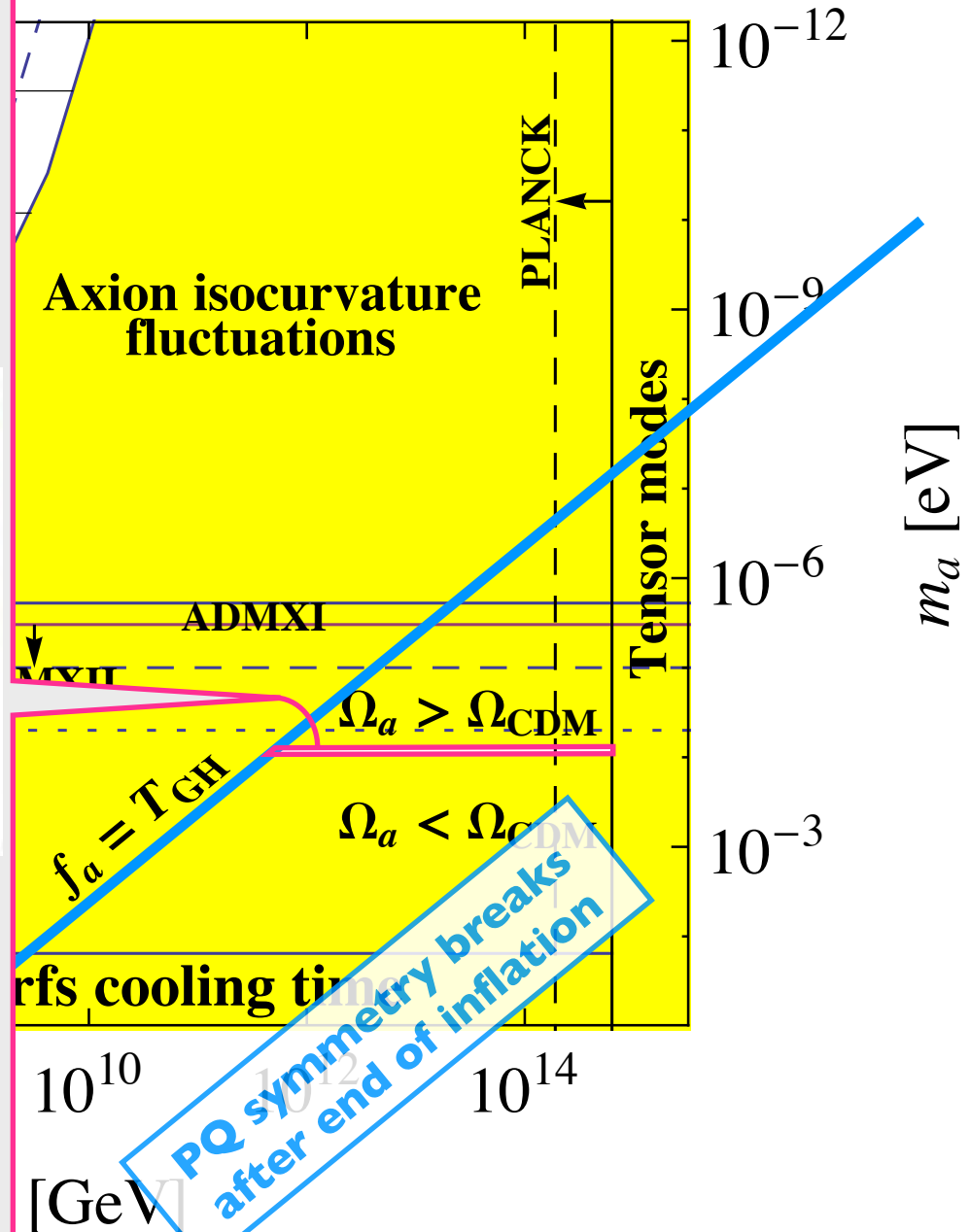
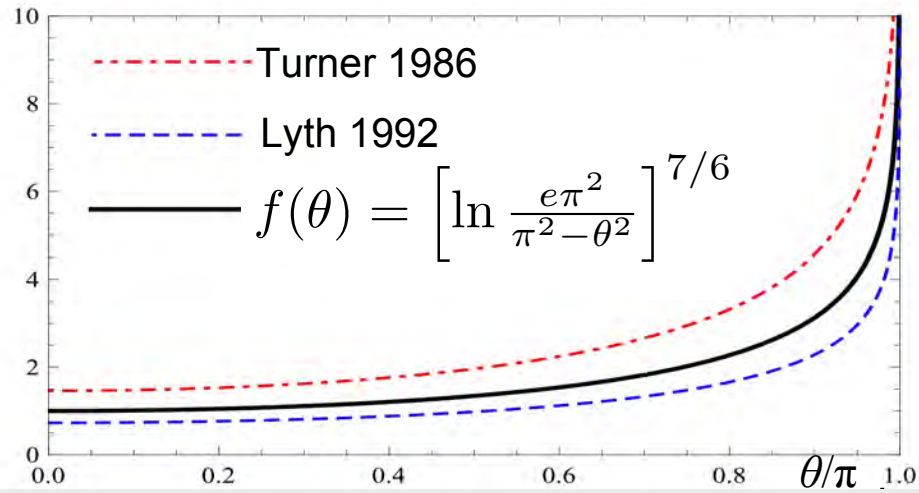
- Average  $\theta_i$  over Hubble volume



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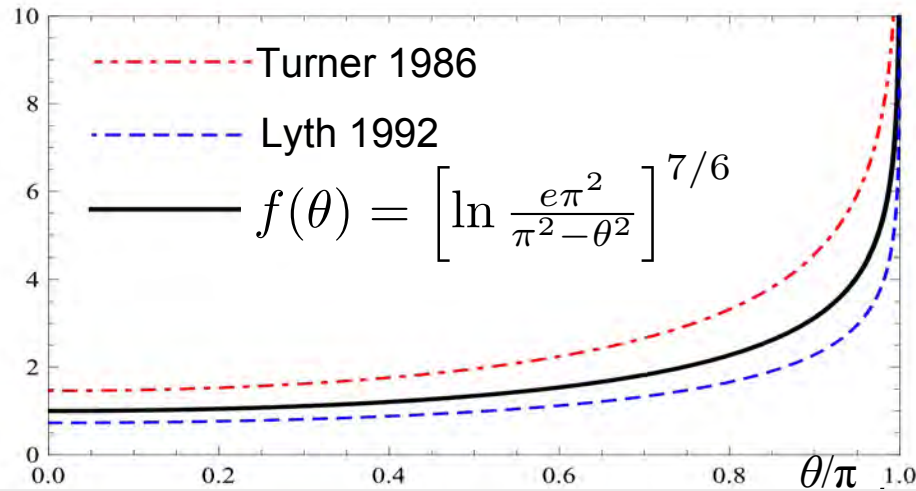
- Average  $\theta_i$  over Hubble volume
- Anharmonicities are important



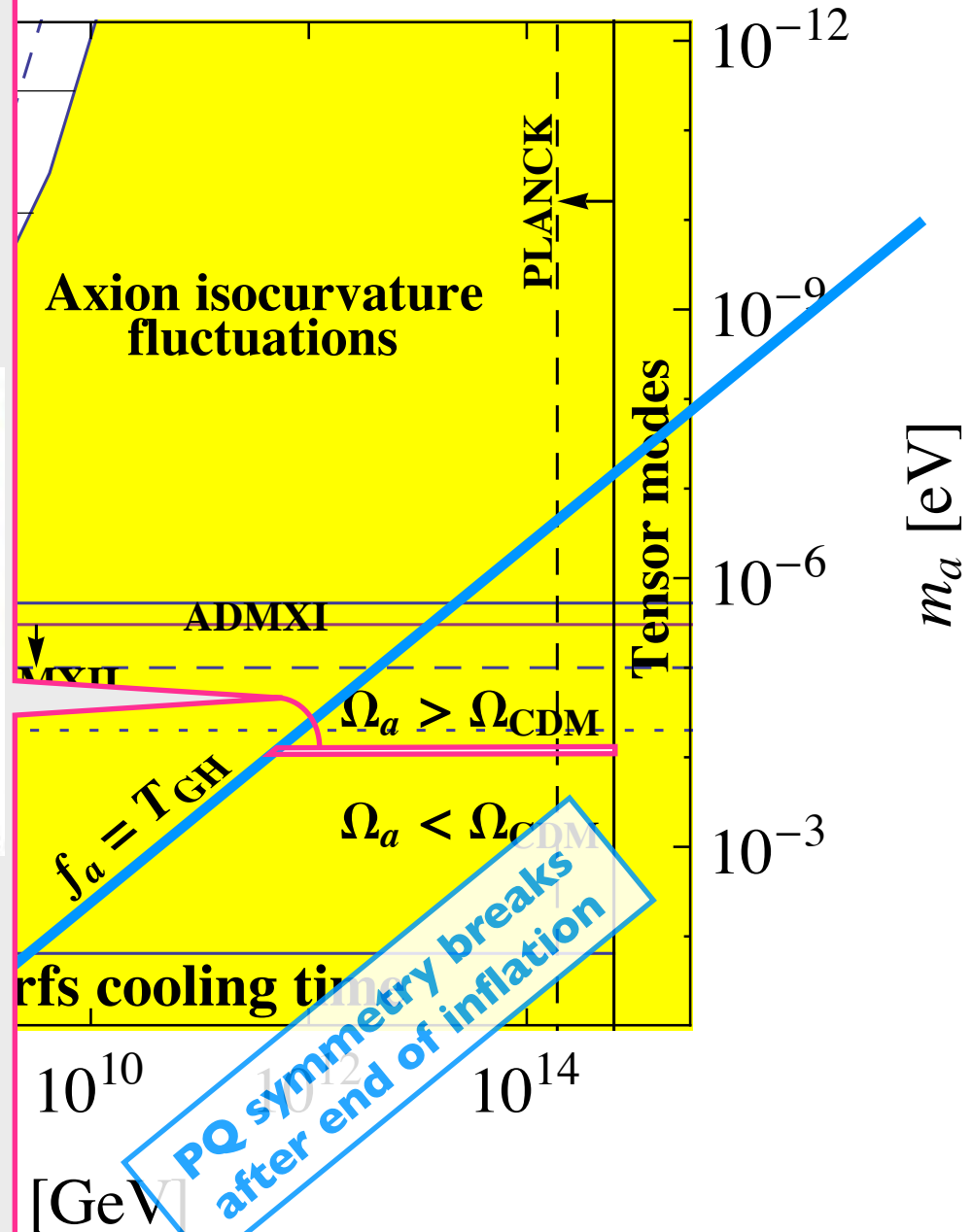
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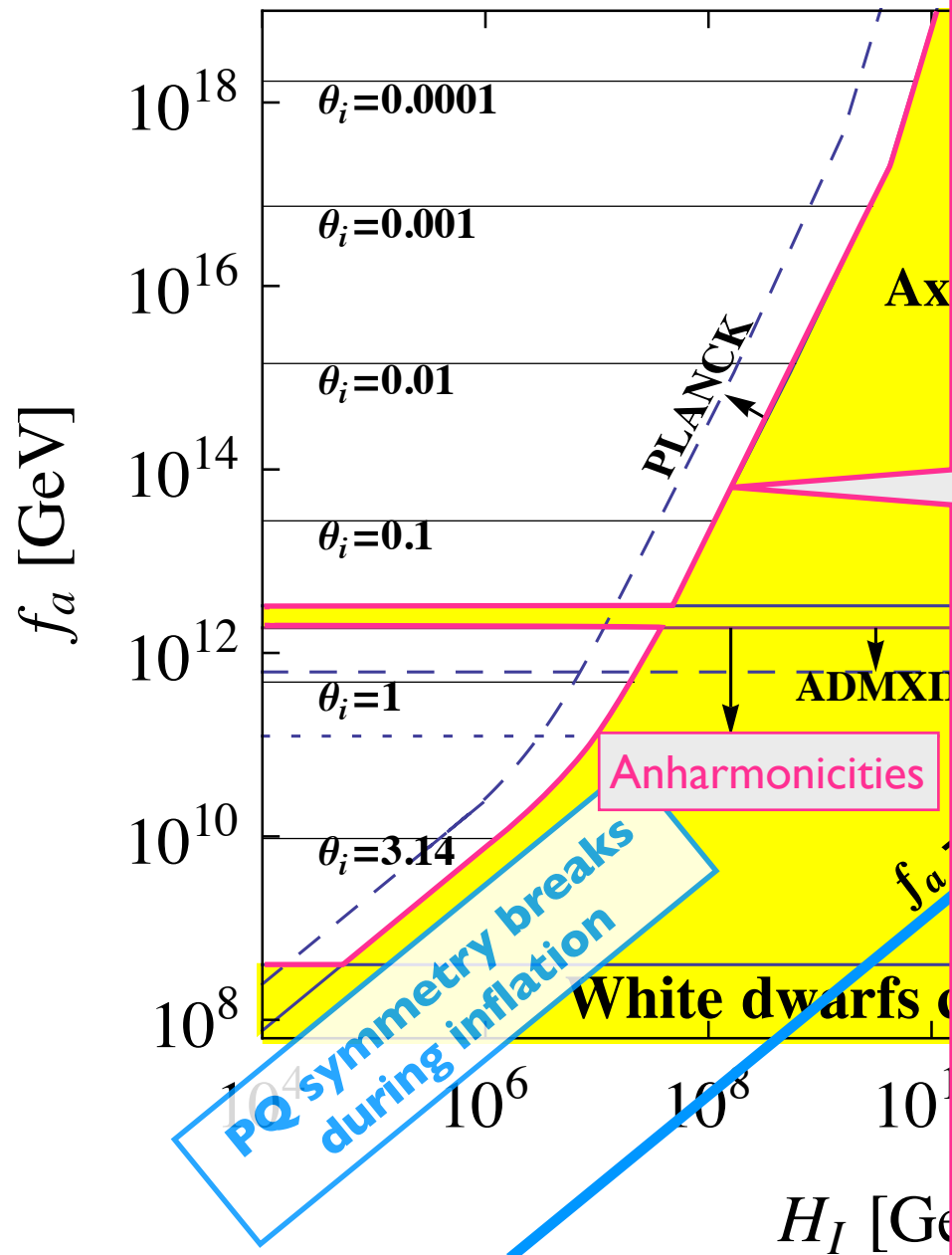
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- String decay contribution is ~16% of vacuum realignment

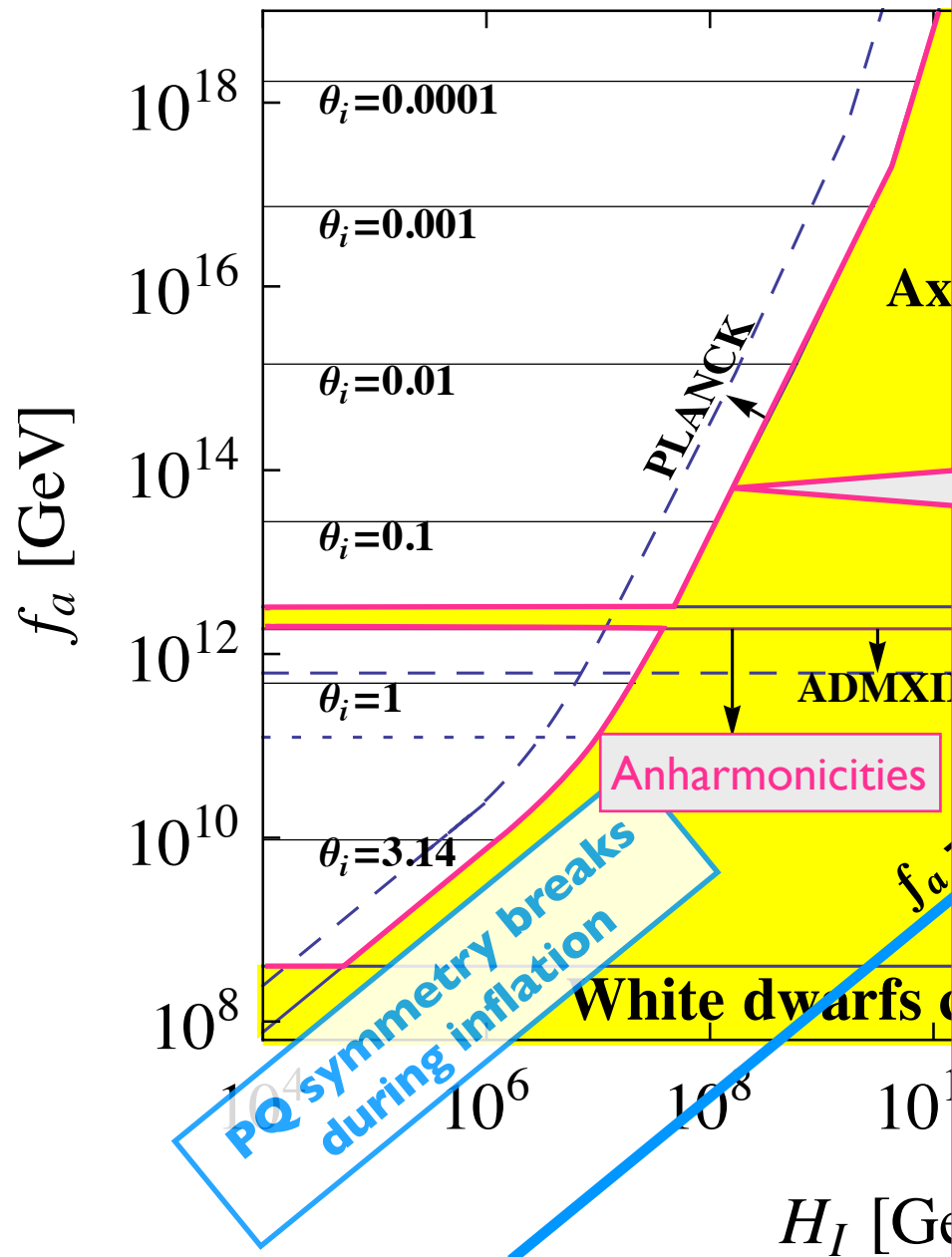


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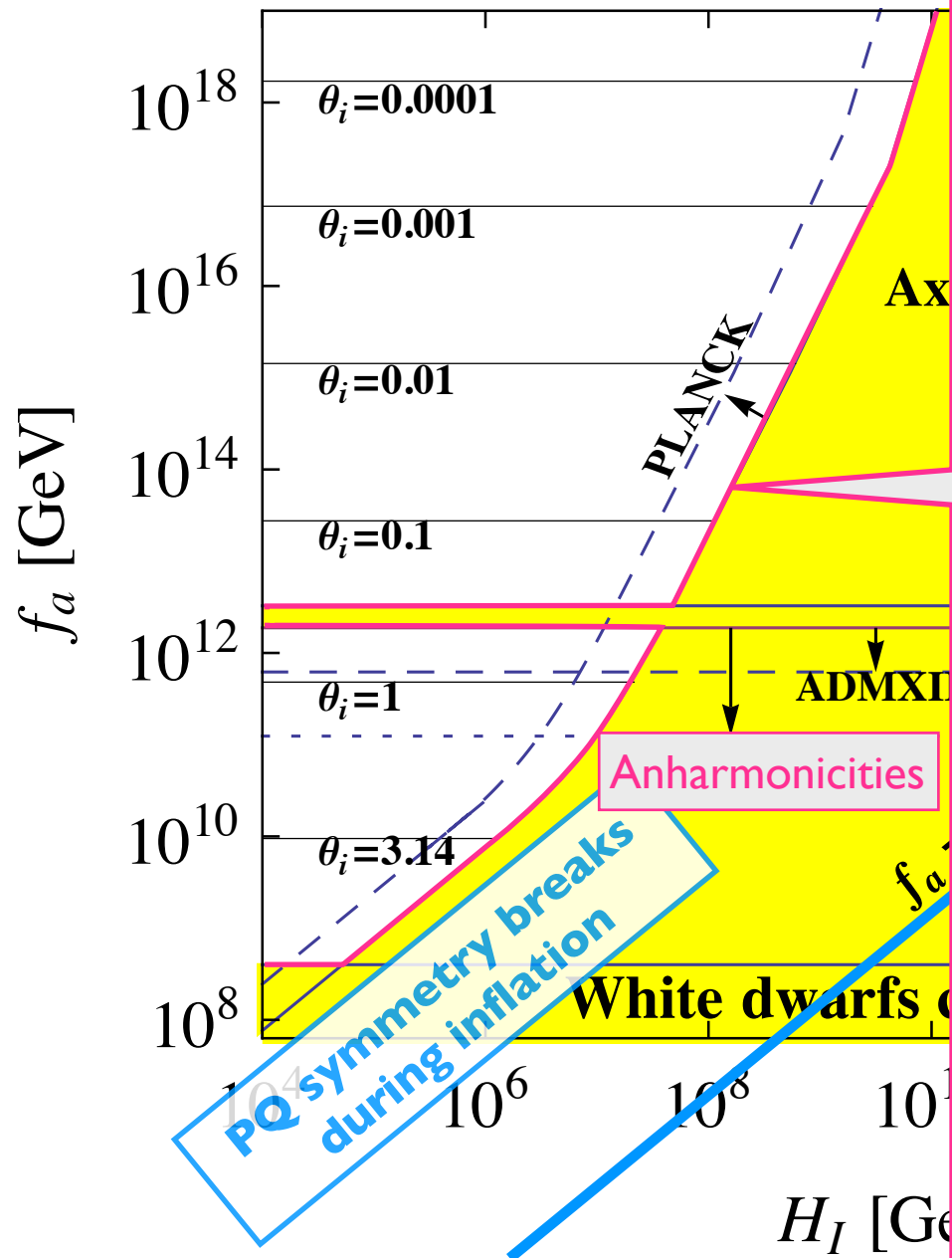


## PQ symmetry breaks during inflation

- Constrained by non-adiabatic fluctuations

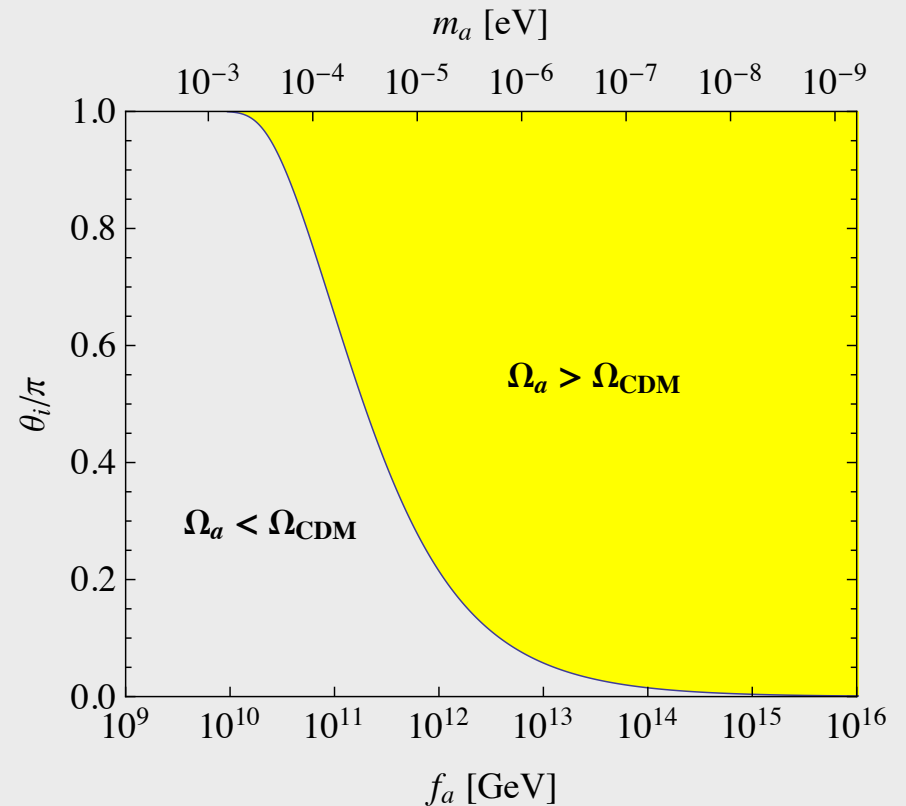


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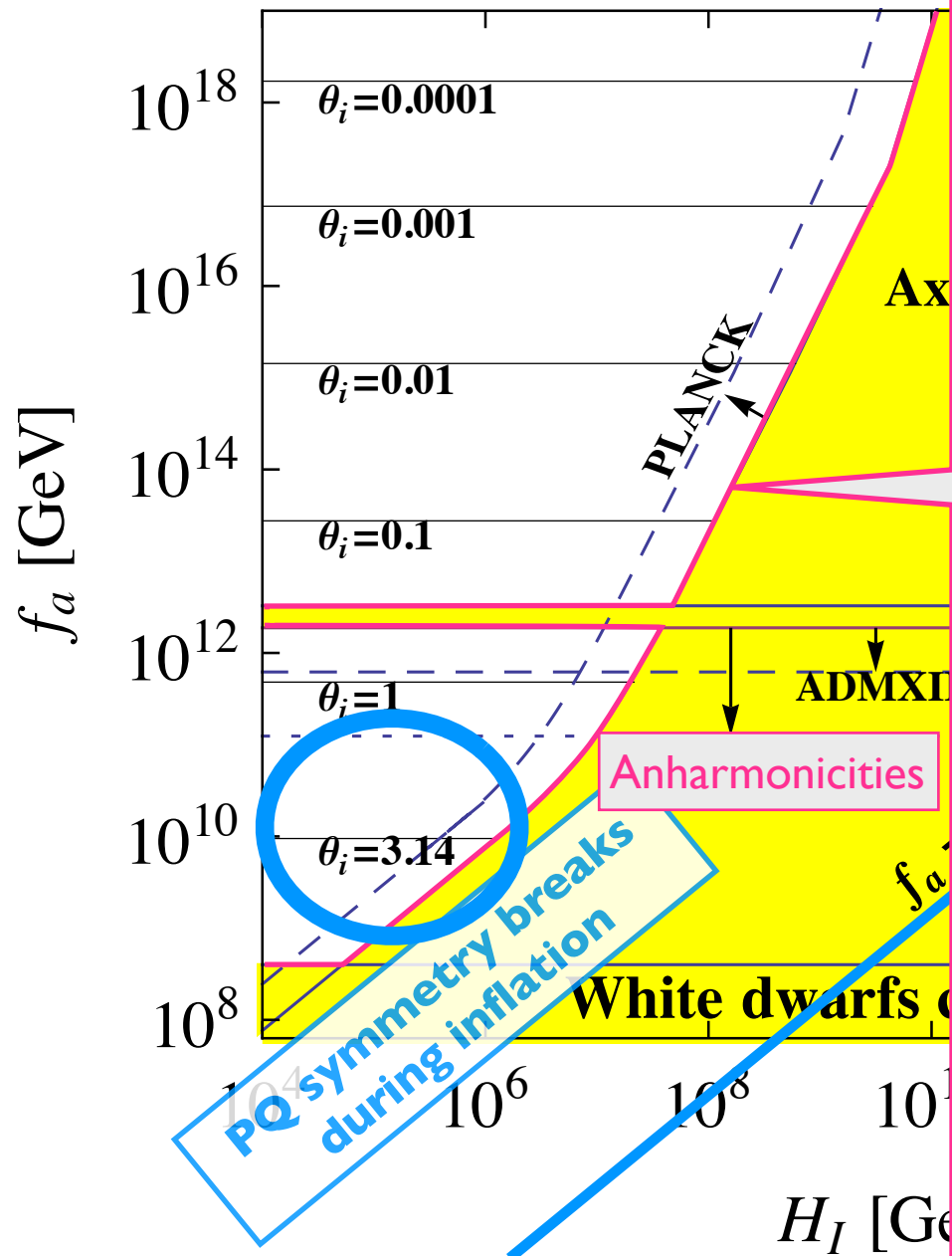


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- Single value of  $\theta_i$  throughout Hubble volume

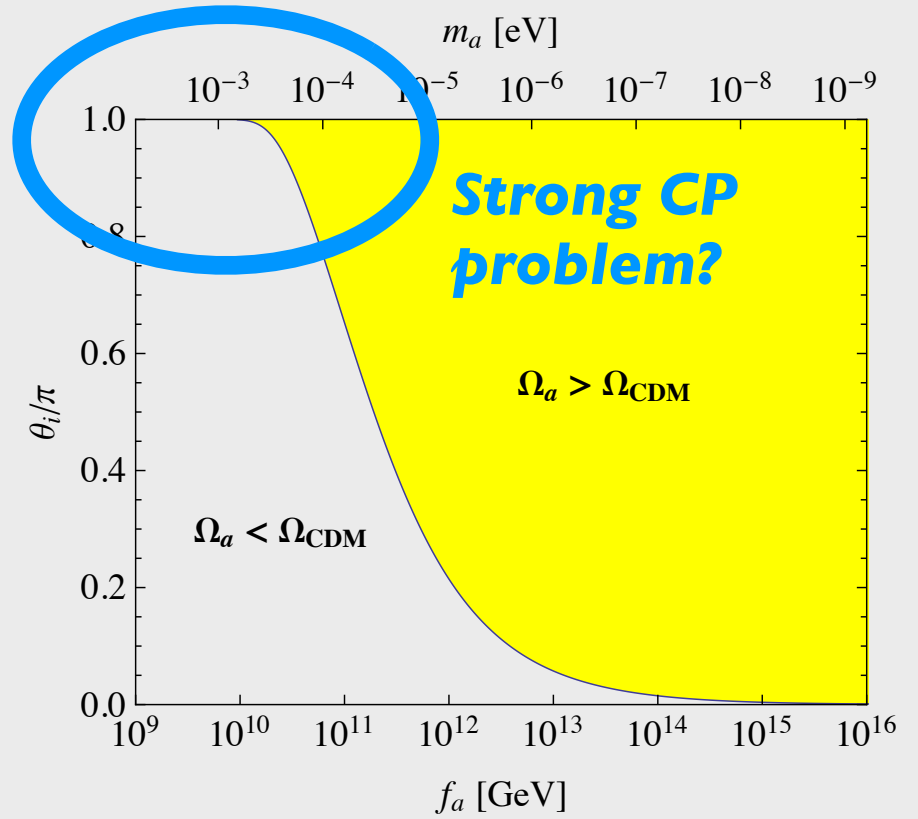


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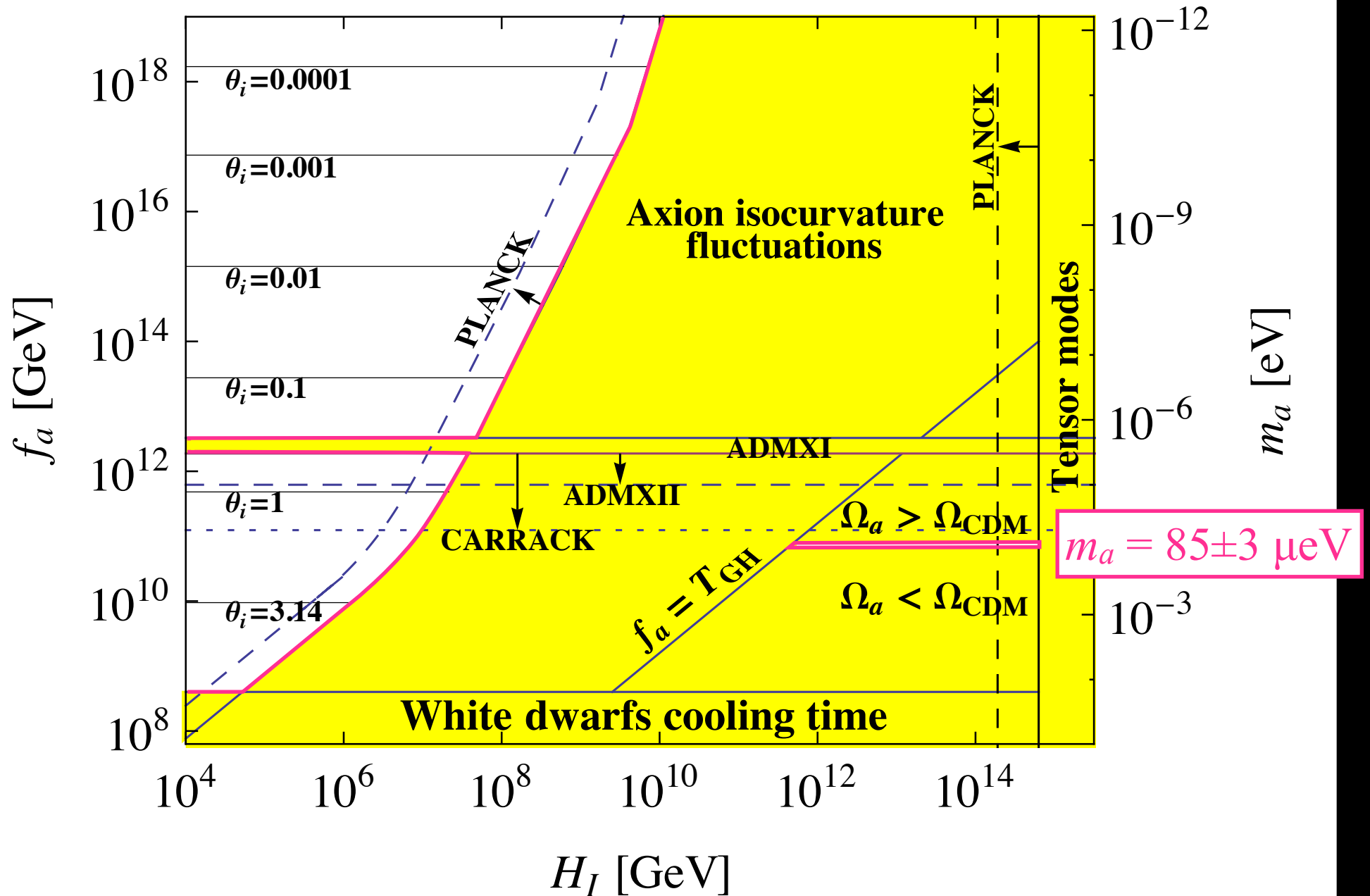


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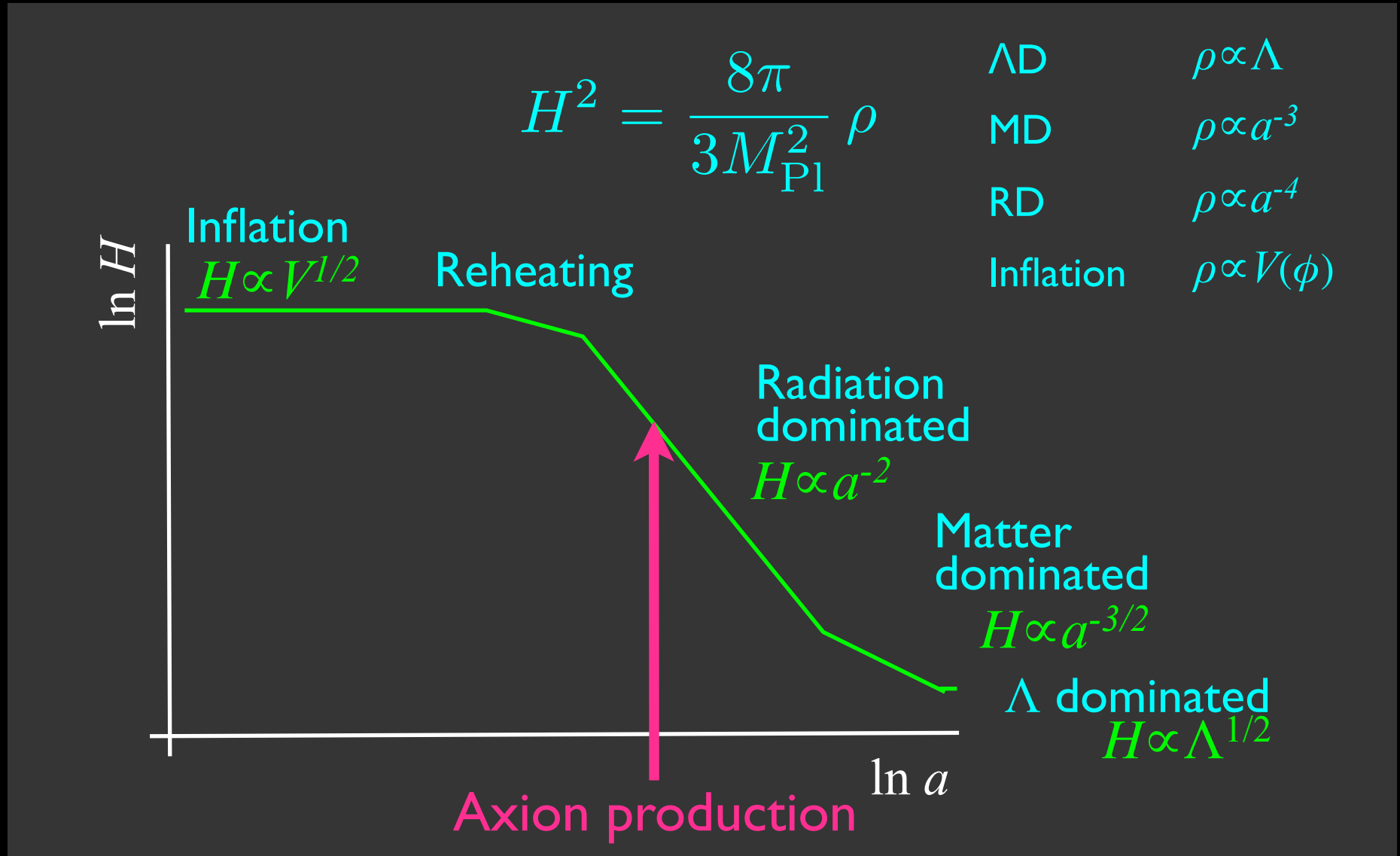
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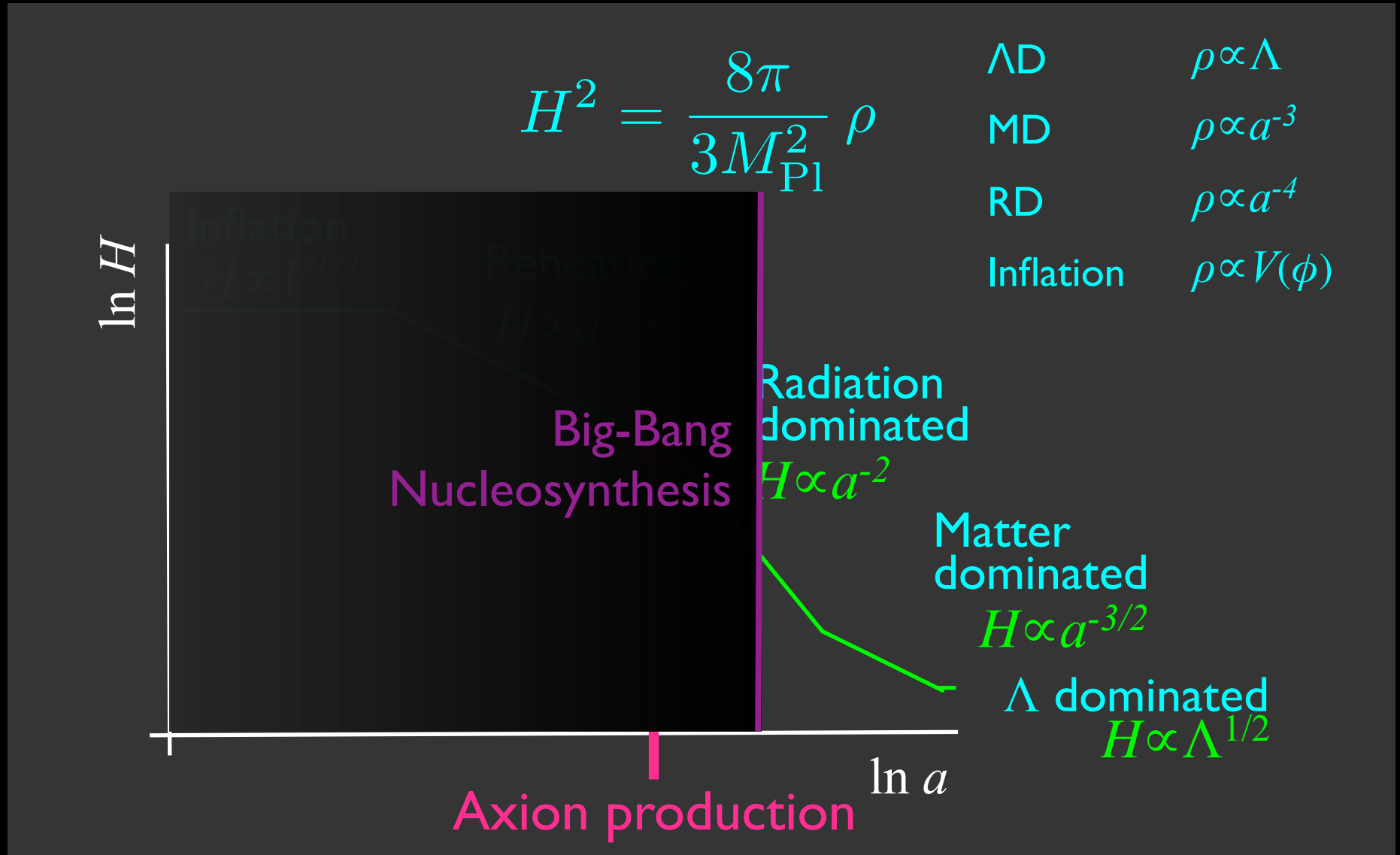
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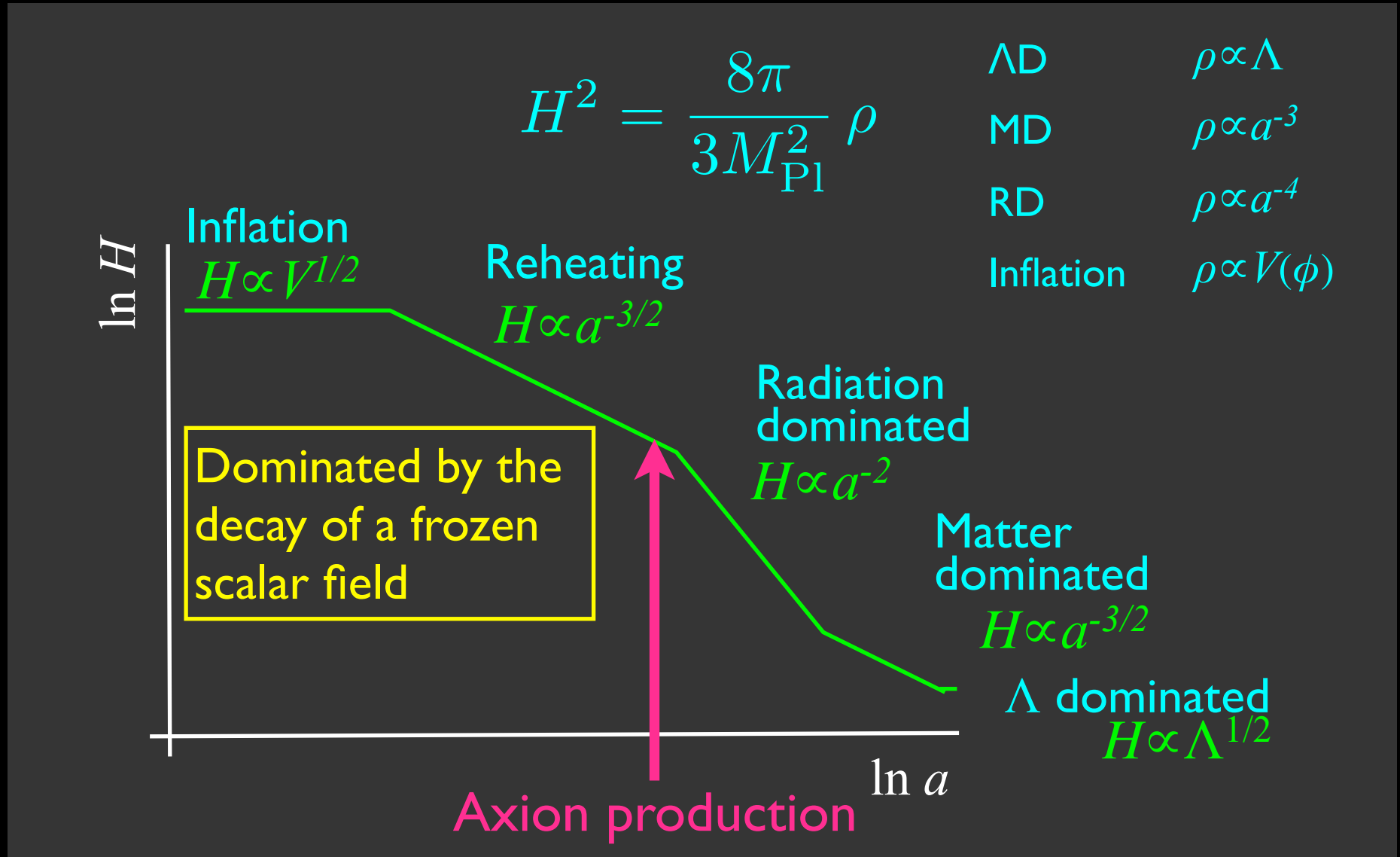
# Standard cosmology



# Non-standard cosmology

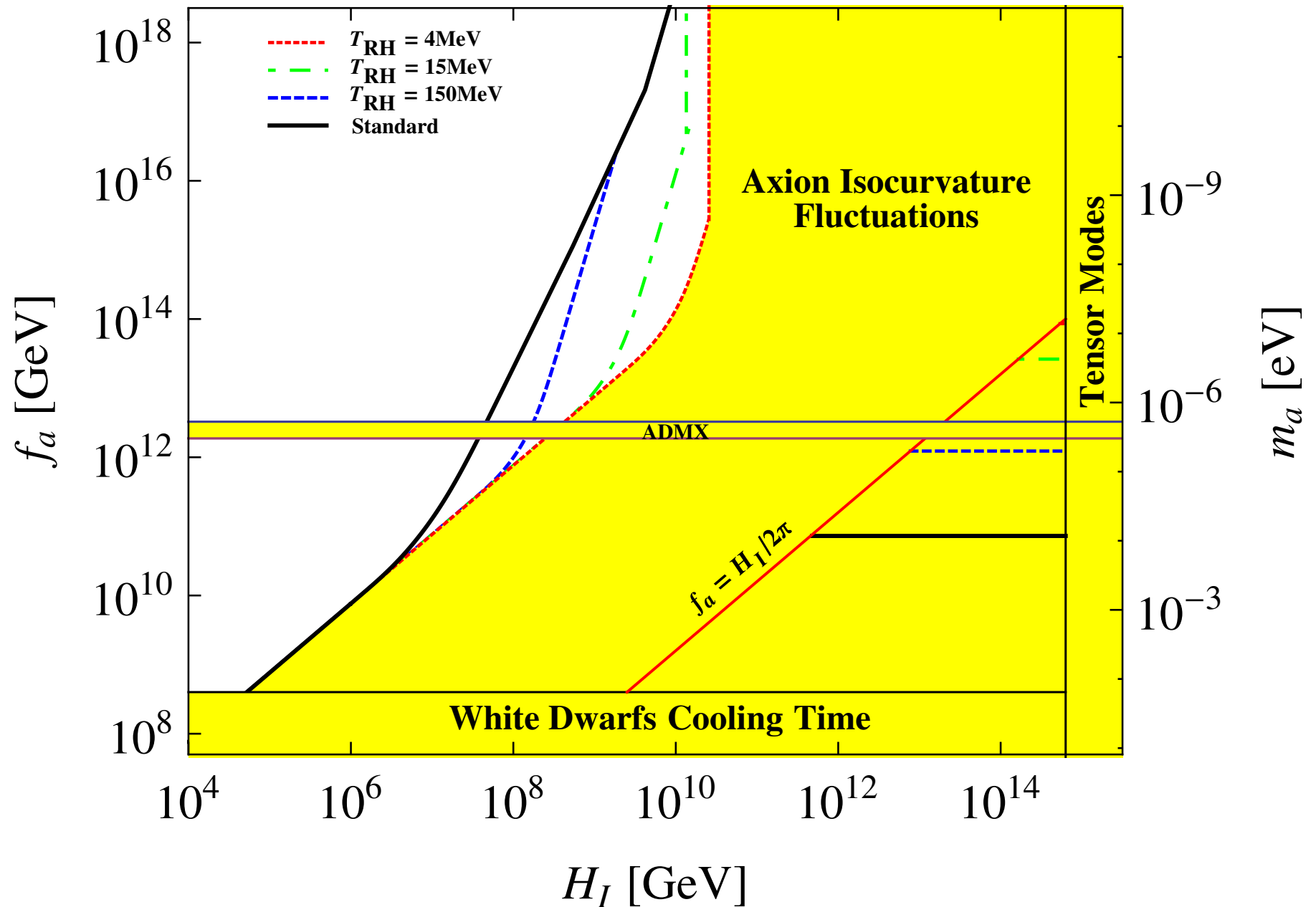


# Low Temperature Reheating cosmology

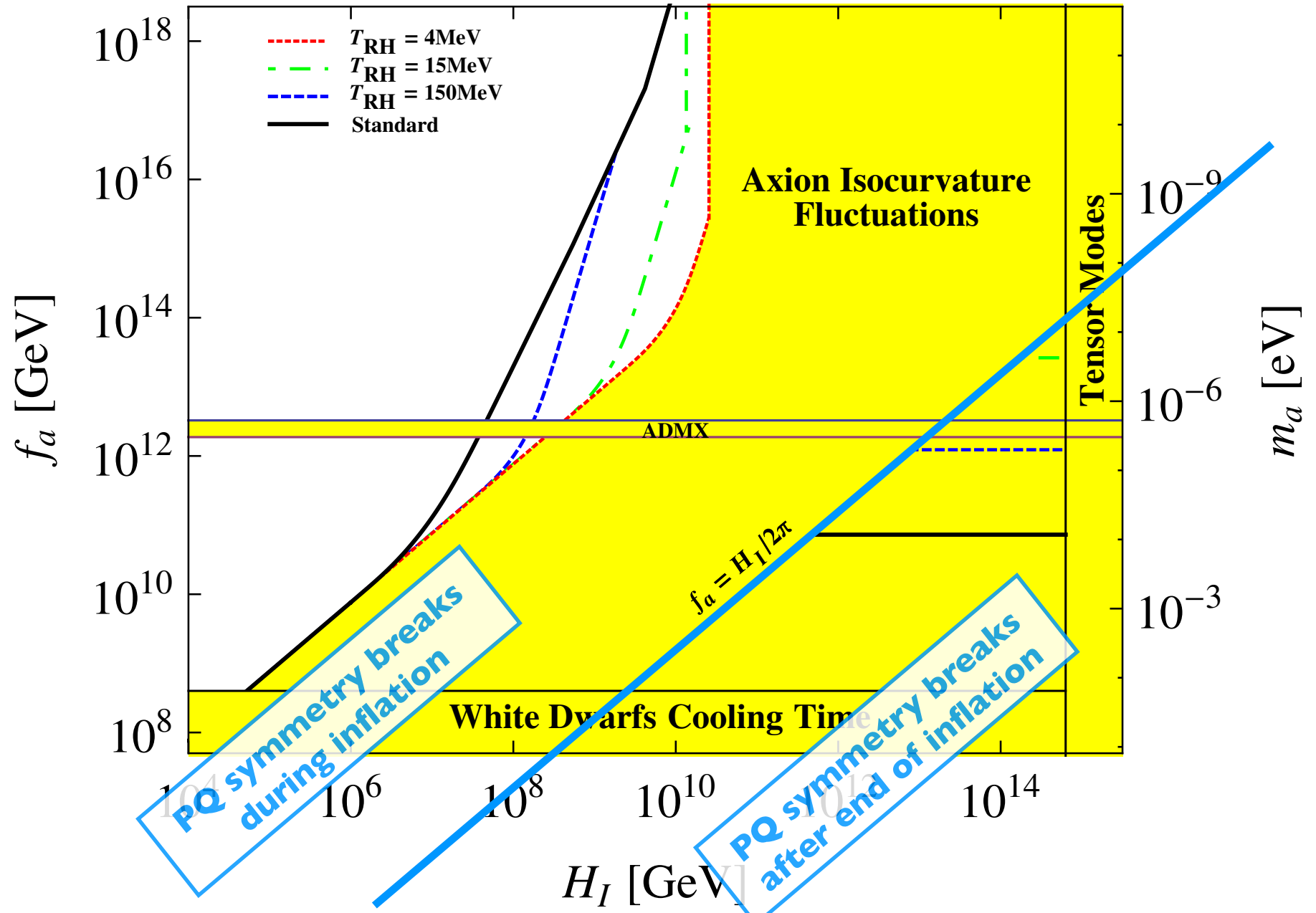


Turner 1983, Scherrer, Turner 1983, Dine, Fischler 1983

# Axion CDM - Low Temp. Reheating cosmology



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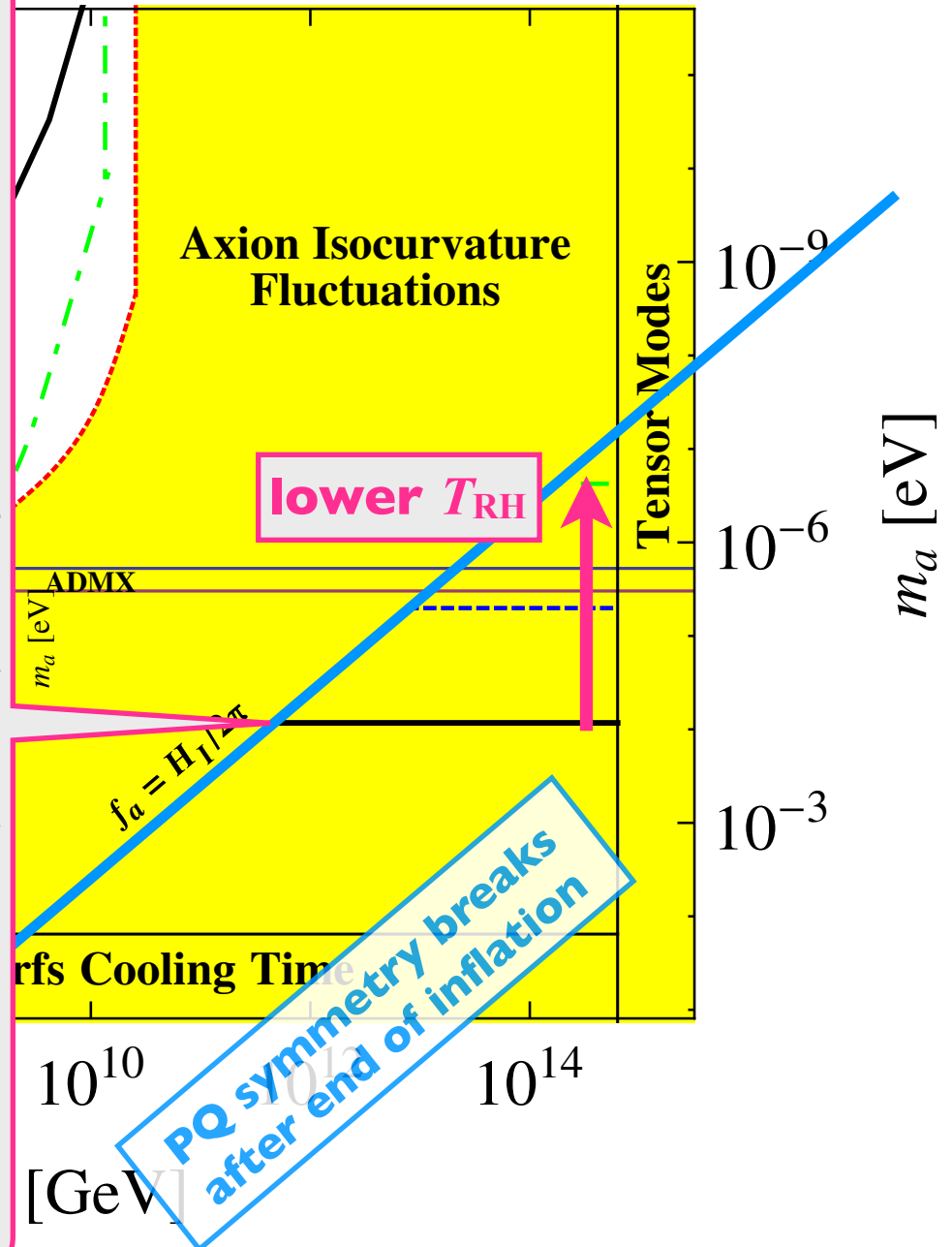
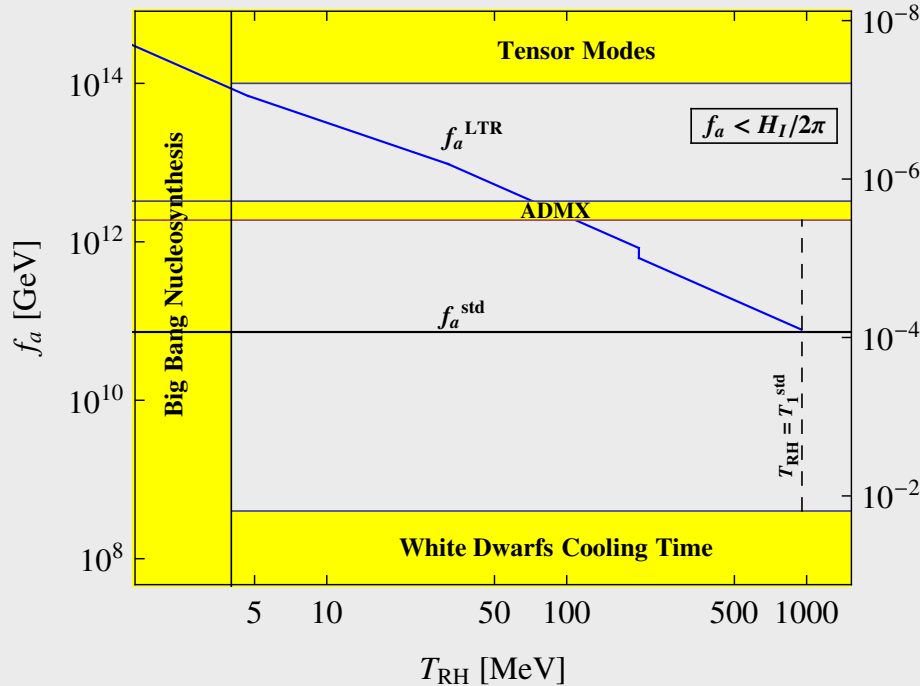




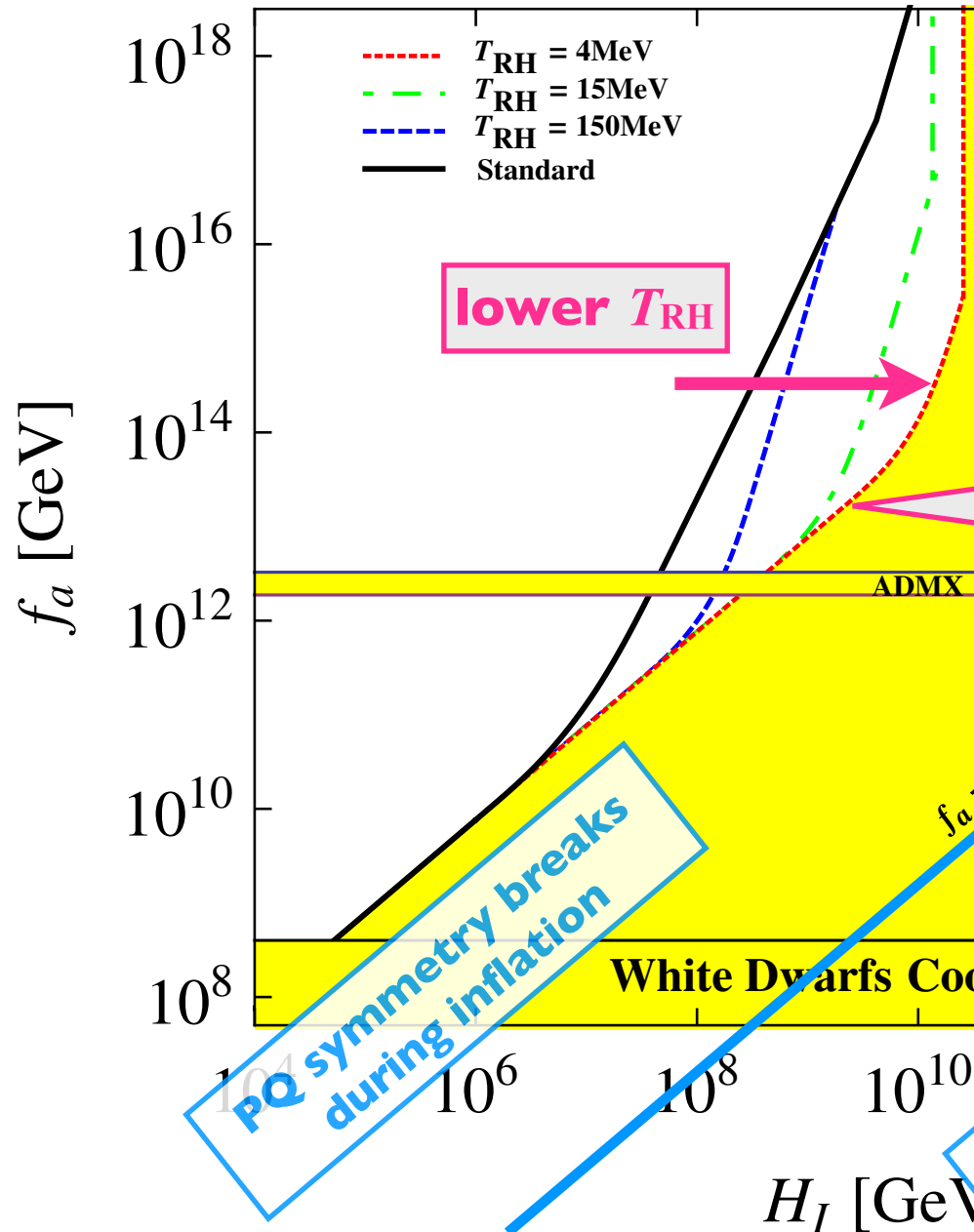
# Axion CDM - Low Temp. Reheating cosmology

**PQ symmetry breaks after end of inflation**

- As  $T_{RH}$  decreases,  $f_a$  must increase and  $m_a$  decrease

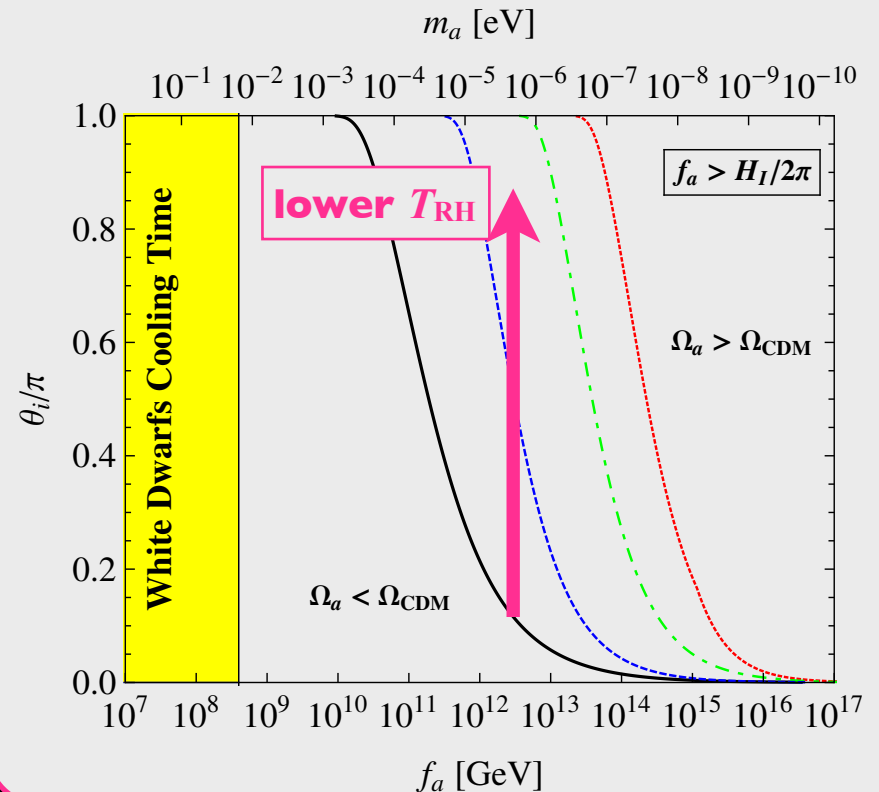


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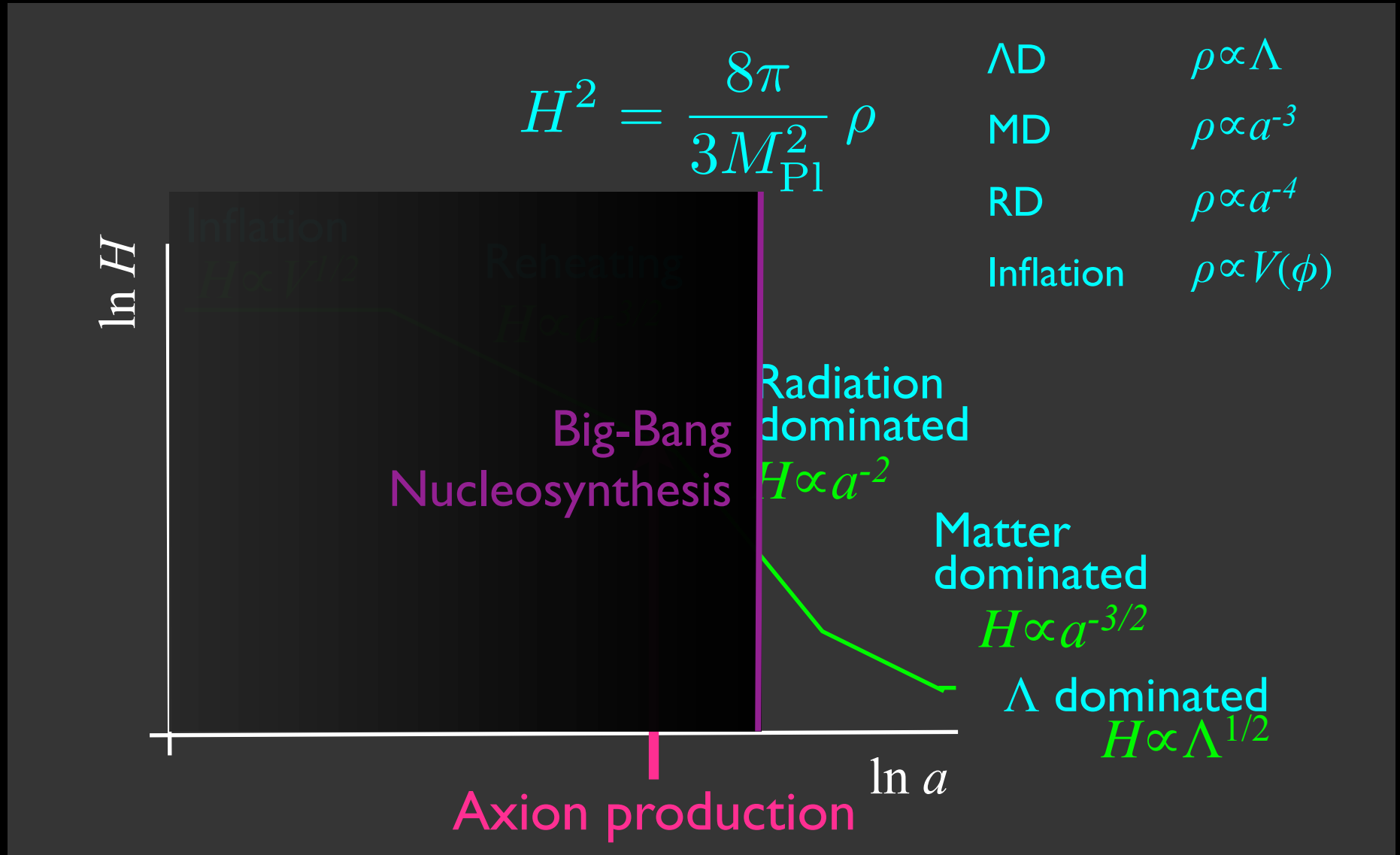


## PQ symmetry breaks during inflation

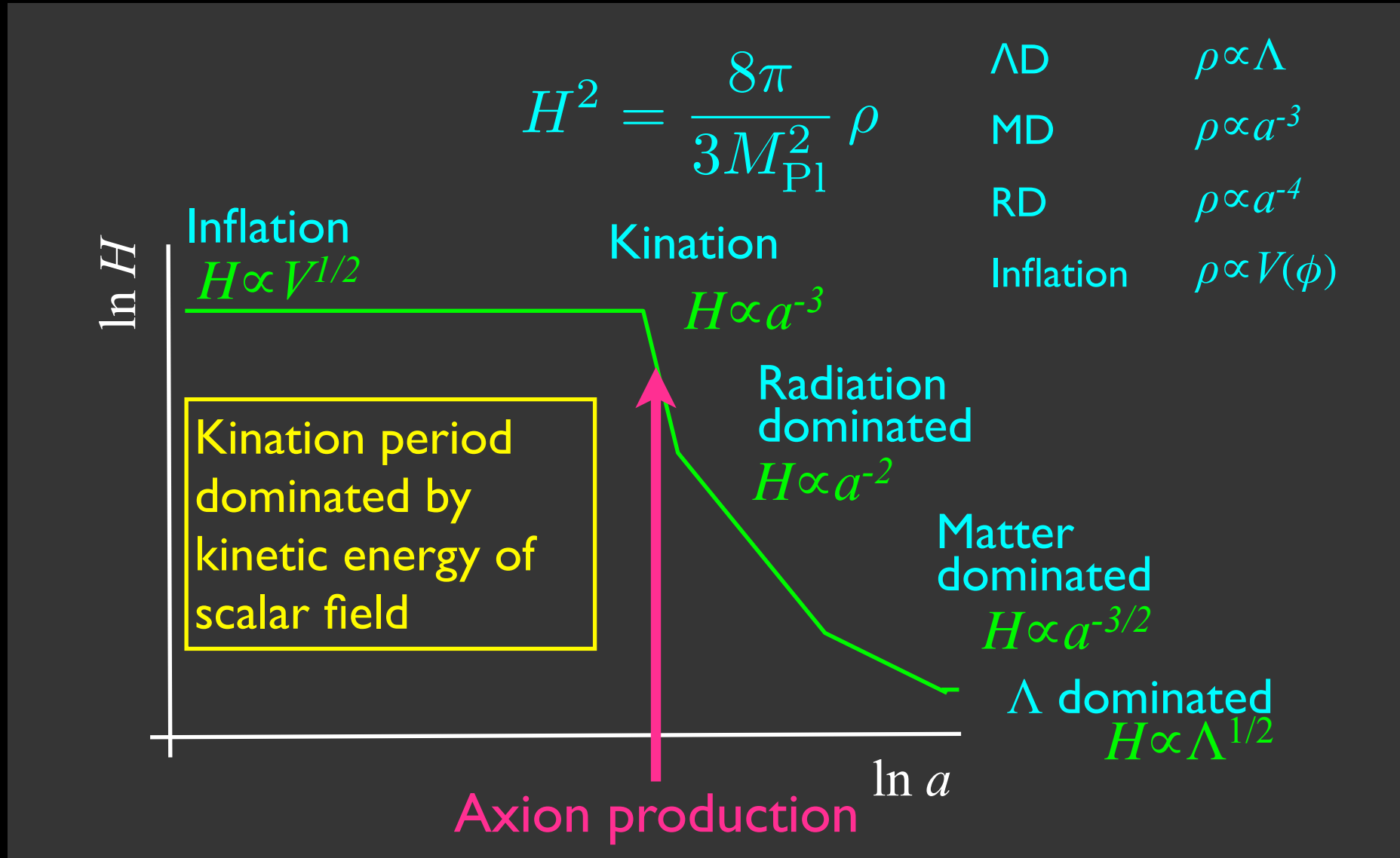
- As  $T_{RH}$  decreases, constraints from non-adiabatic fluctuations become weaker
- And the initial misalignment angle  $\theta_i$  must be larger



# Non-standard cosmology

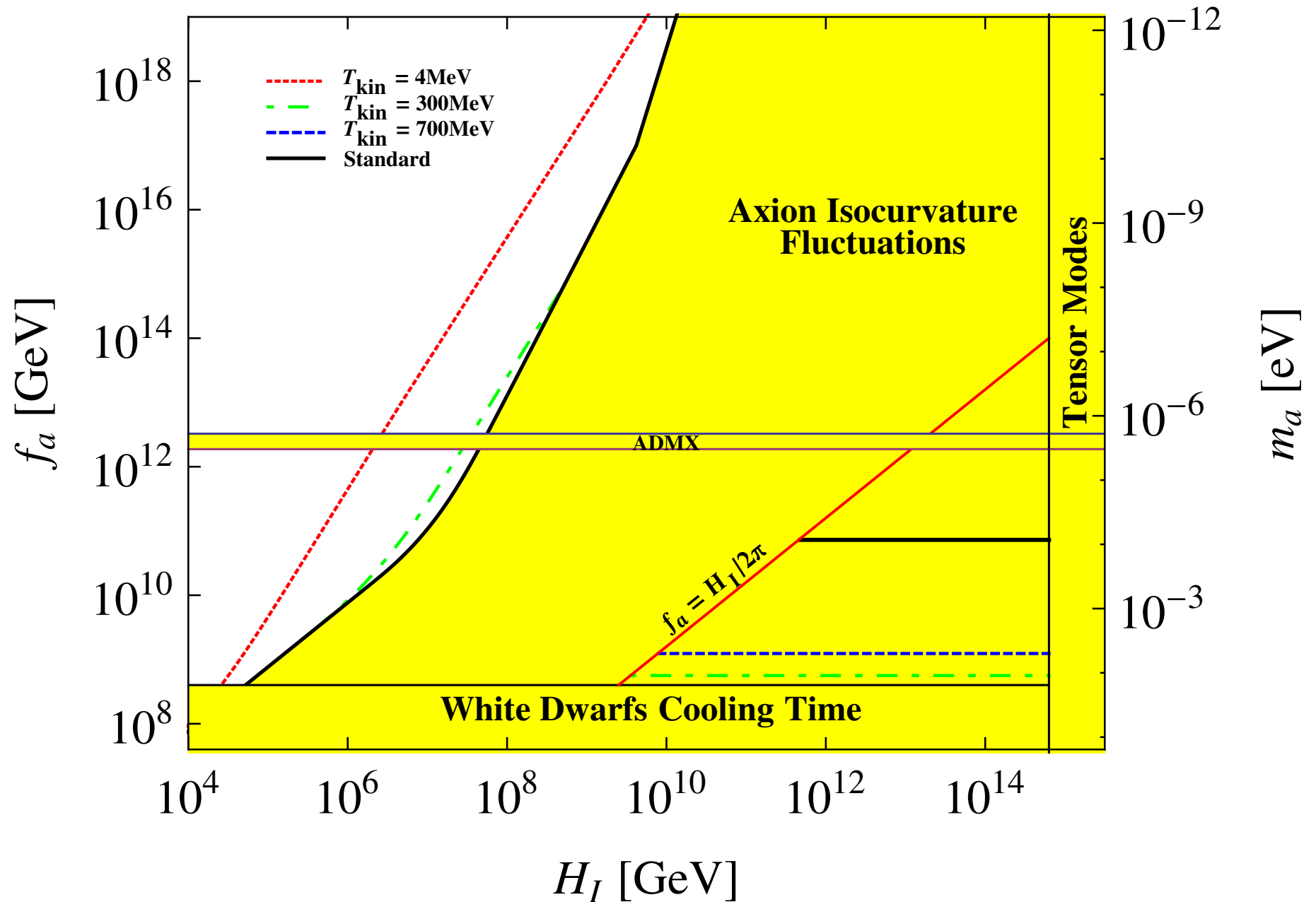


# Kination cosmology

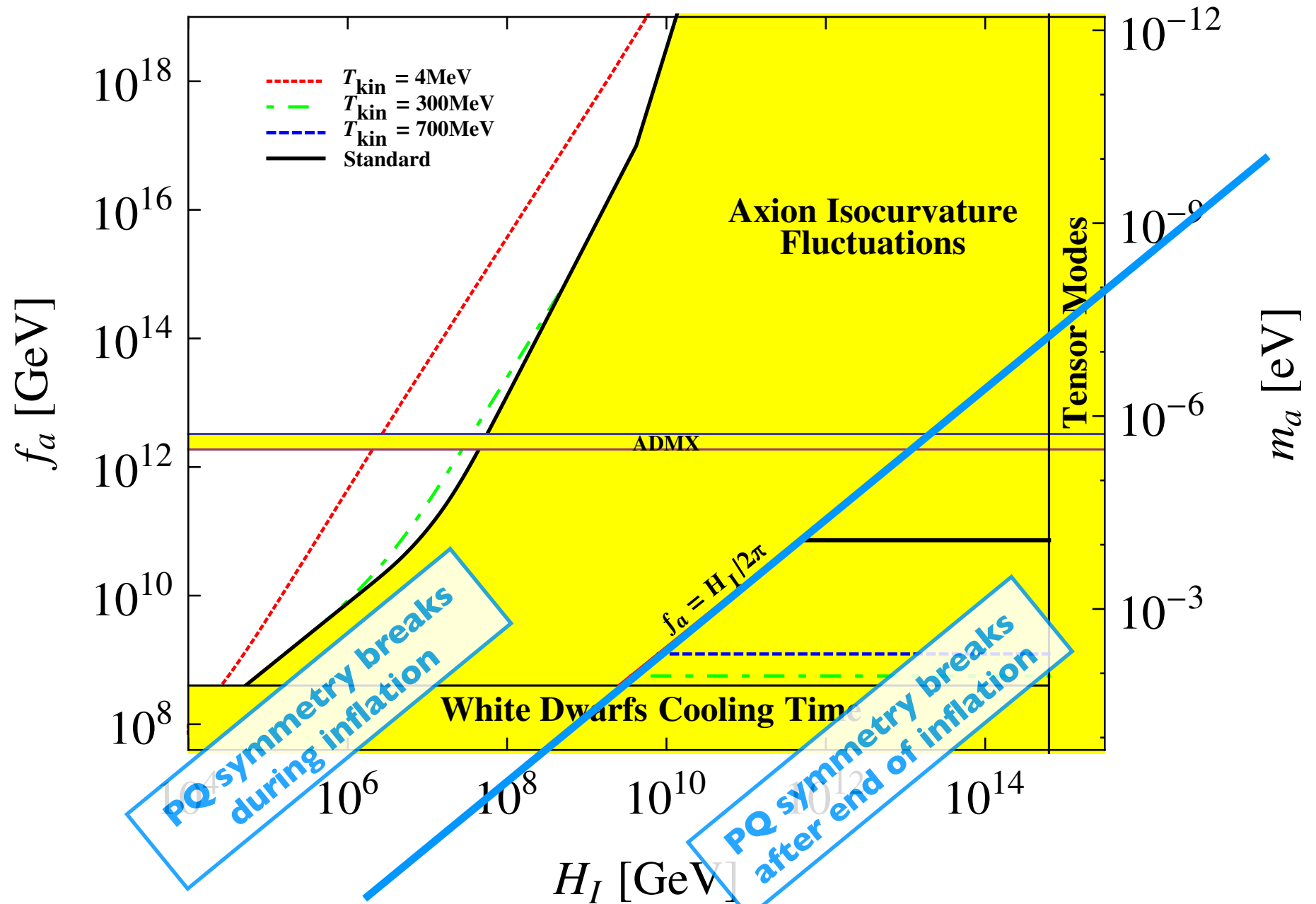


Ford 1987

# Axion CDM - Kination cosmology



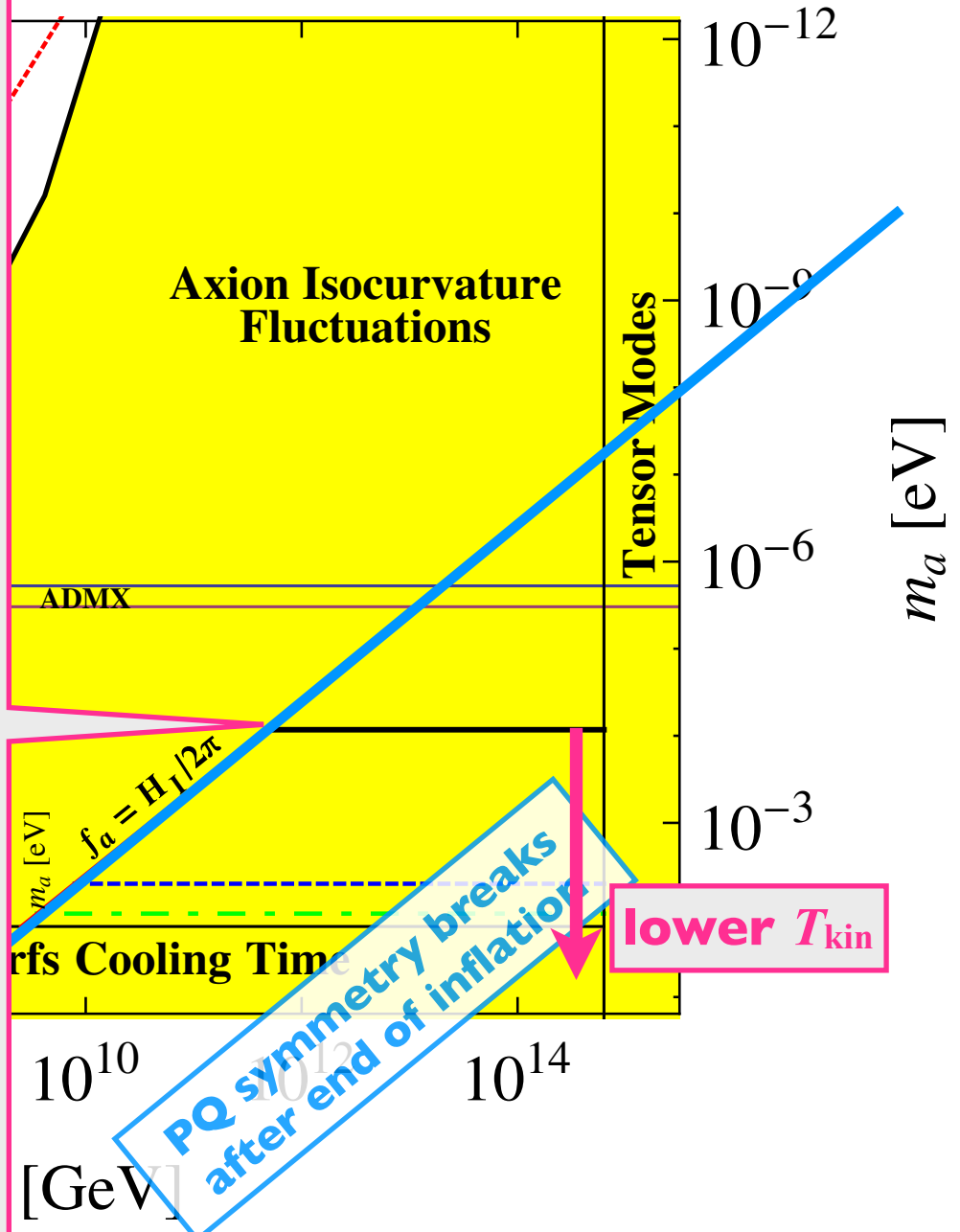
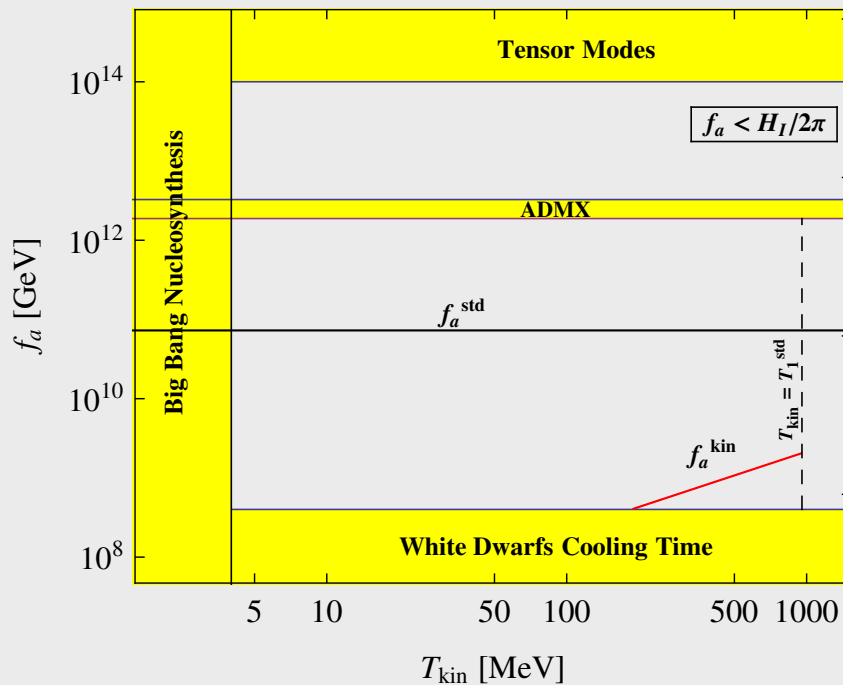
# Axion CDM - Kination cosmology



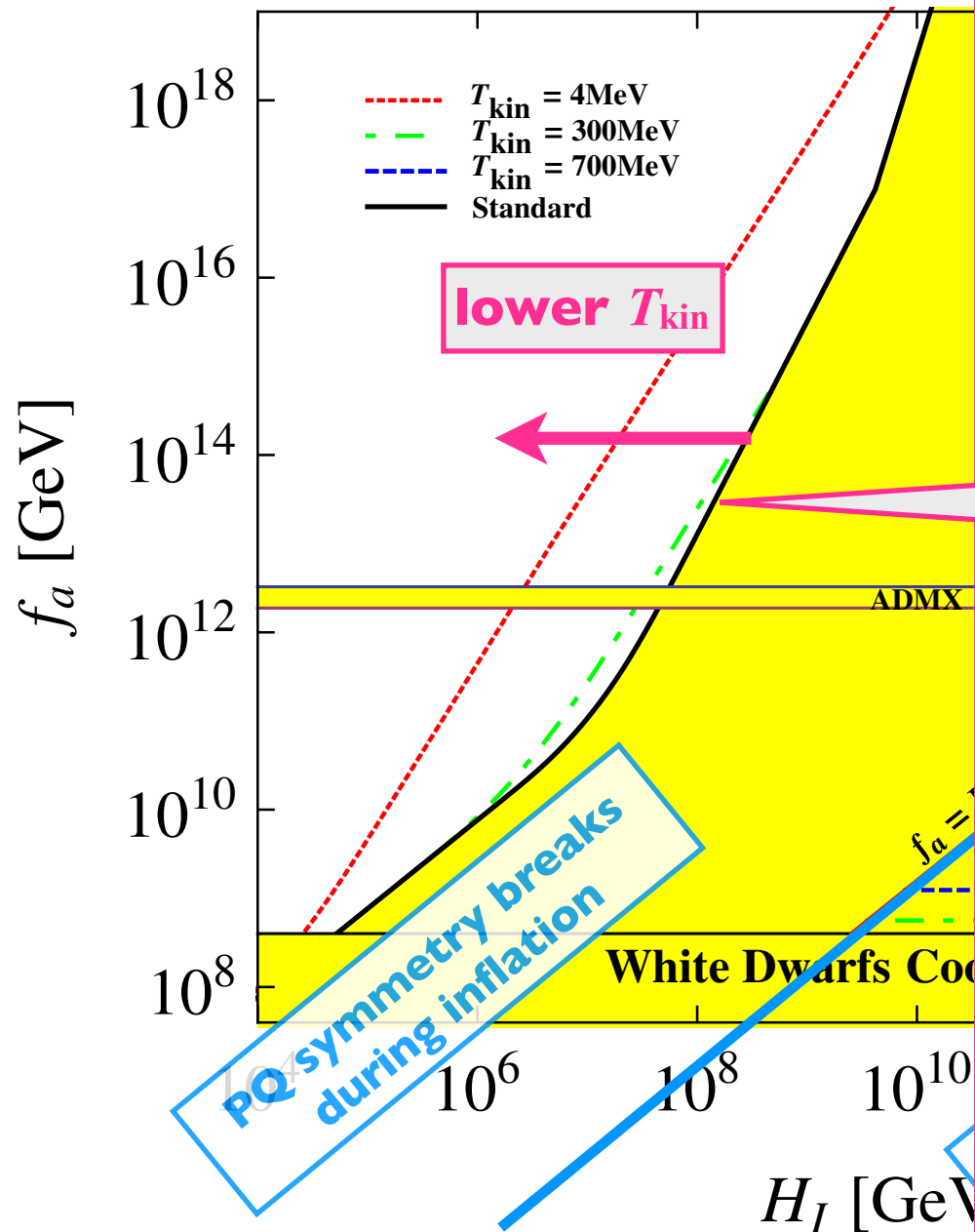
# Axion CDM - Kinination cosmology

*PQ symmetry breaks after end of inflation*

- As  $T_{\text{kin}}$  decreases,  $f_a$  must decrease and  $m_a$  increase
- String decay contribution is  $15 \times$  vacuum realignment

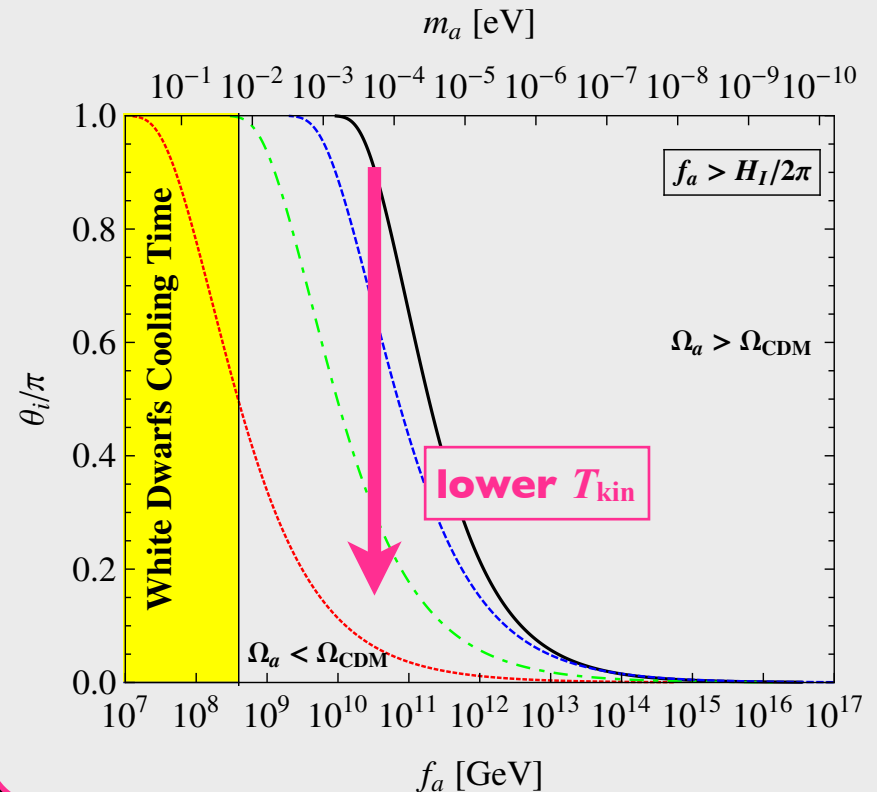


# Axion CDM - Kination cosmology



## PQ symmetry breaks during inflation

- As  $T_{\text{kin}}$  decreases, constraints from non-adiabatic fluctuations become stronger
- And the initial misalignment angle  $\theta_i$  must be smaller





# Conclusions

*For axions to be 100% of cold dark matter....*

- If the Peccei-Quinn symmetry breaks after inflation ends, the axion mass must be  $m_a = 85 \pm 3 \mu\text{eV}$  in standard cosmology
  - much smaller  $m_a$  in LTR cosmology
  - much larger  $m_a$  in kination cosmology
- If the Peccei-Quinn symmetry breaks during inflation, cosmological limits on non-adiabatic fluctuations constrain parameter space and a specific initial misalignment angle  $\theta_i$  must be chosen
  - larger allowed region and larger  $\theta_i$  in LTR cosmology
  - smaller allowed region and smaller  $\theta_i$  in kination cosmology