Axion Cold Dark Matter in Standard and Non-Standard Cosmologies

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Visinelli, Gondolo, arxiv:0903.4377, Phys. Rev. D 80, 035024 (2009)
Visinelli, Gondolo, arxiv:0912.0015

Luca Visinelli

Axion cold dark matter

When are axions 100% of cold dark matter?

Study axion parameter space imposing

$$\Omega_a=\Omega_{\rm CDM}=0.1131+0.0034$$

And update cosmological constraints and include anharmonicities

Axions as solution to the strong CP problem

The strong CP problem

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

Vacuum state $|\theta\rangle = \sum_n e^{-in\theta}\,|0\rangle$

New term in lagrangian $\mathcal{L}_\theta = \theta\,\frac{g^2}{32\pi^2}\,F_a^{\mu\nu}\,\tilde{F}_{a\mu\nu}$

$\mathcal{L}_\theta$ violates P and T but conserves C, thus produces a *neutron electric dipole moment* $d_n \approx e(m_q/M_n^2)\theta$

Experimentally $d_n < 1.1 \times 10^{-26}\,e\mathrm{cm}$ so $\theta < 10^{-9}$–10^{-10}

Why θ should be so small is the strong CP problem

Axions as solution to the strong CP problem

The Peccei-Quinn solution

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

axion

$$\theta_{\text{total}} = \theta + \arg\det M_{\text{quark}} \quad \Rightarrow \quad \theta(x) = a(x)/f_a$$

static CP-violating angle *dynamic CP-conserving field*

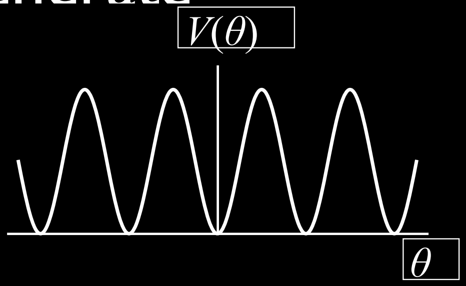
New lagrangian $\mathcal{L}_a = -\frac{1}{2}\partial^\mu a \partial_\mu a + \frac{a}{f_a}\frac{g^2}{32\pi^2} F_a^{\mu\nu} F_{a\mu\nu} + \mathcal{L}_{\text{int}}(a)$

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

Produced thermally in early universe

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

Cold

Produced by coherent field oscillations around mimimum 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-Zhitnistki	Couplings to quarks, leptons, and photons
$H_{\rm I}$	Expansion rate at end of inflation
θ_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, θ_i, $H_{\rm I}$ *and one constraint* $\Omega_a = \Omega_{\rm CDM}$

Cold axion production in cosmology

Vacuum realignment

- Initial misalignment angle θ_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 $T < \Lambda \approx \Lambda_{\rm QCD}$

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

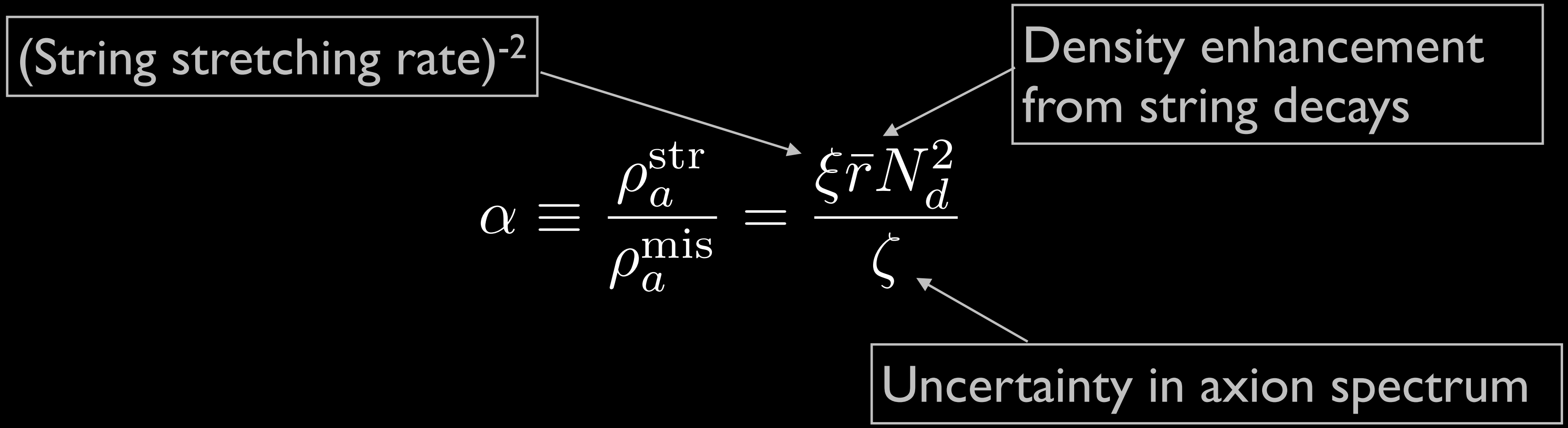
Anharmonicity correction $f(\theta)$
axion field equation has anharmonic terms $\ddot{\theta} + 3H(T)\dot{\theta} + m_a^2(T)\sin\theta = 0$

- Conservation of comoving axion number gives present density Ω_a

Cold axion production in cosmology

Axionic string decays

- Energy density ratio (string decay/misalignment)



(String stretching rate)$^{-2}$

Density enhancement from string decays

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

Uncertainty in axion spectrum

Slow oscillating strings (Davis-Battye-Shellard) $\bar{r} = \frac{1-\beta}{3\beta-1} \ln(t_1/\delta)$

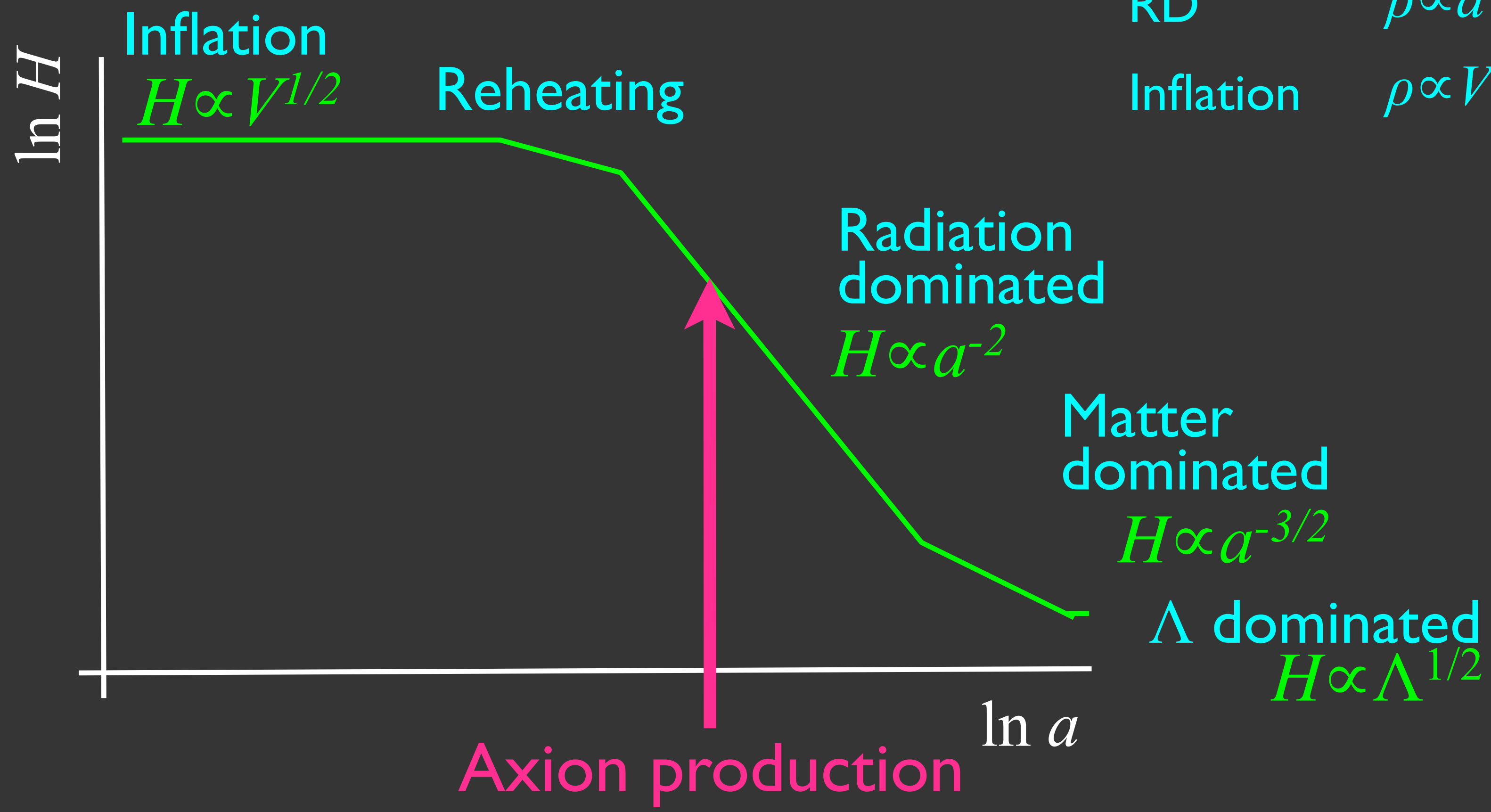
Fast-oscillating strings (Harari-Hagmann-Chang-Sikivie) $\bar{r} = \frac{1-\beta}{3\beta-1}\, 0.8$

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

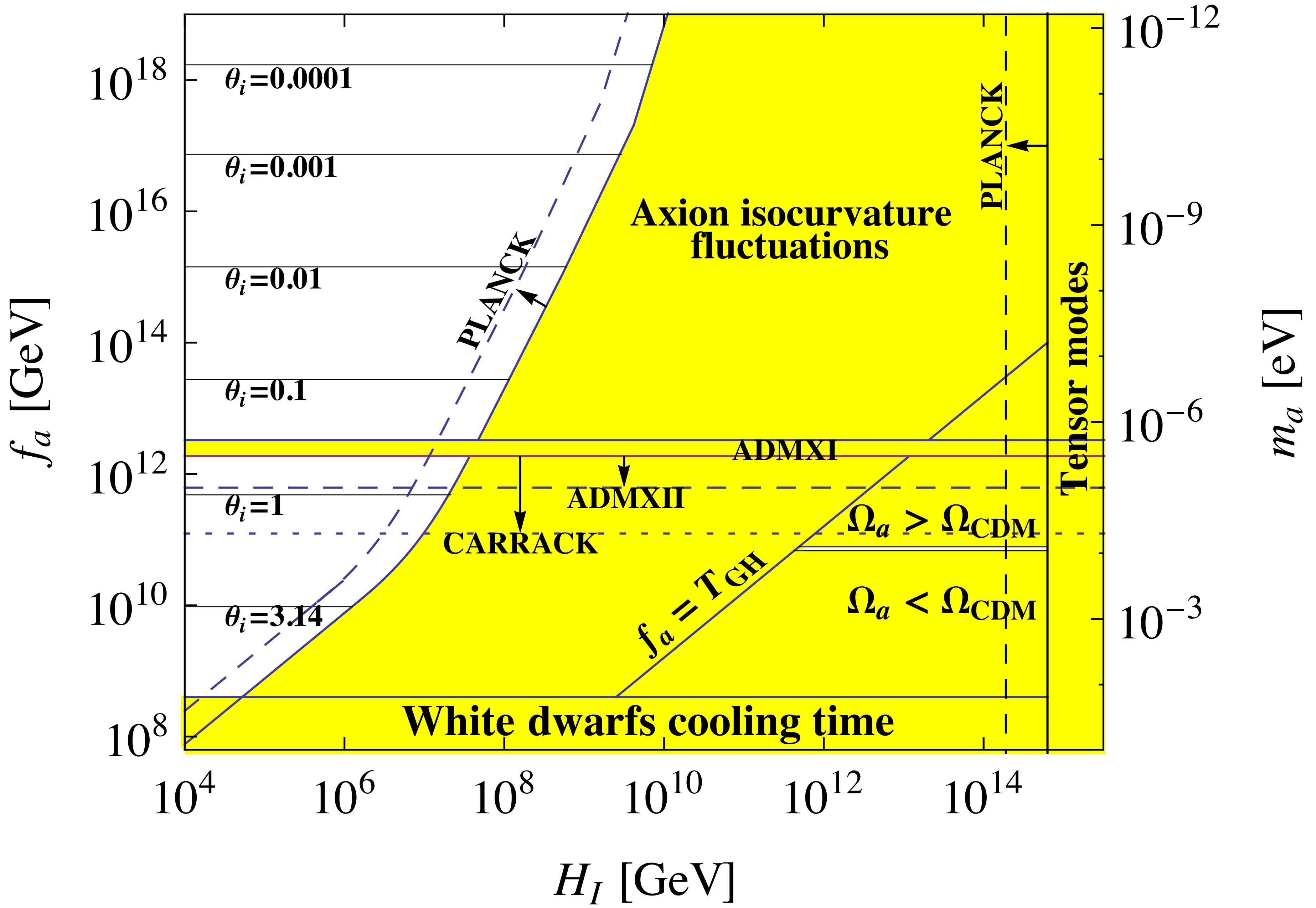
Standard cosmology

$$H^2 = \frac{8\pi}{3M_{\mathrm{Pl}}^2}\rho$$

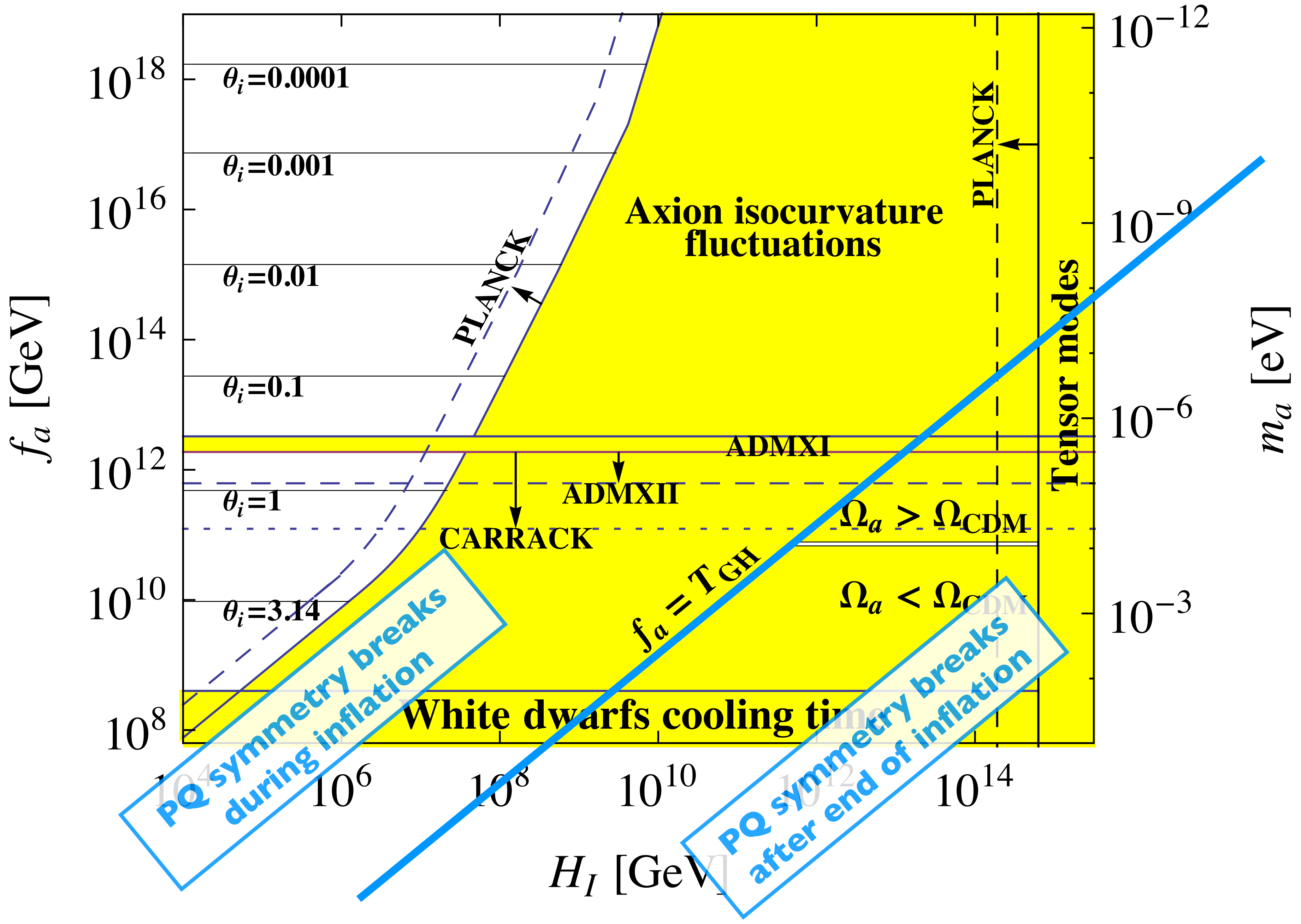
ΛD	$\rho \propto \Lambda$
MD	$\rho \propto a^{-3}$
RD	$\rho \propto a^{-4}$
Inflation	$\rho \propto V(\phi)$



Axion CDM - Standard cosmology



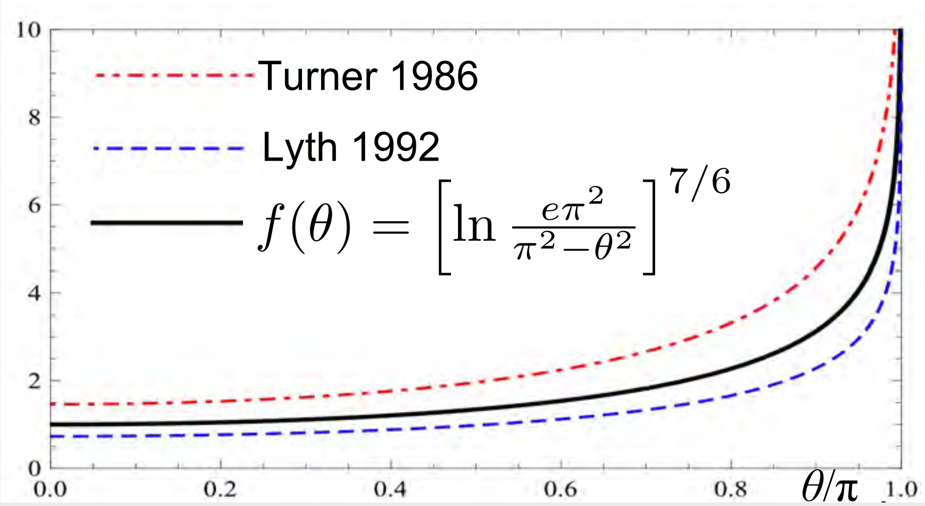
Axion CDM - Standard cosmology



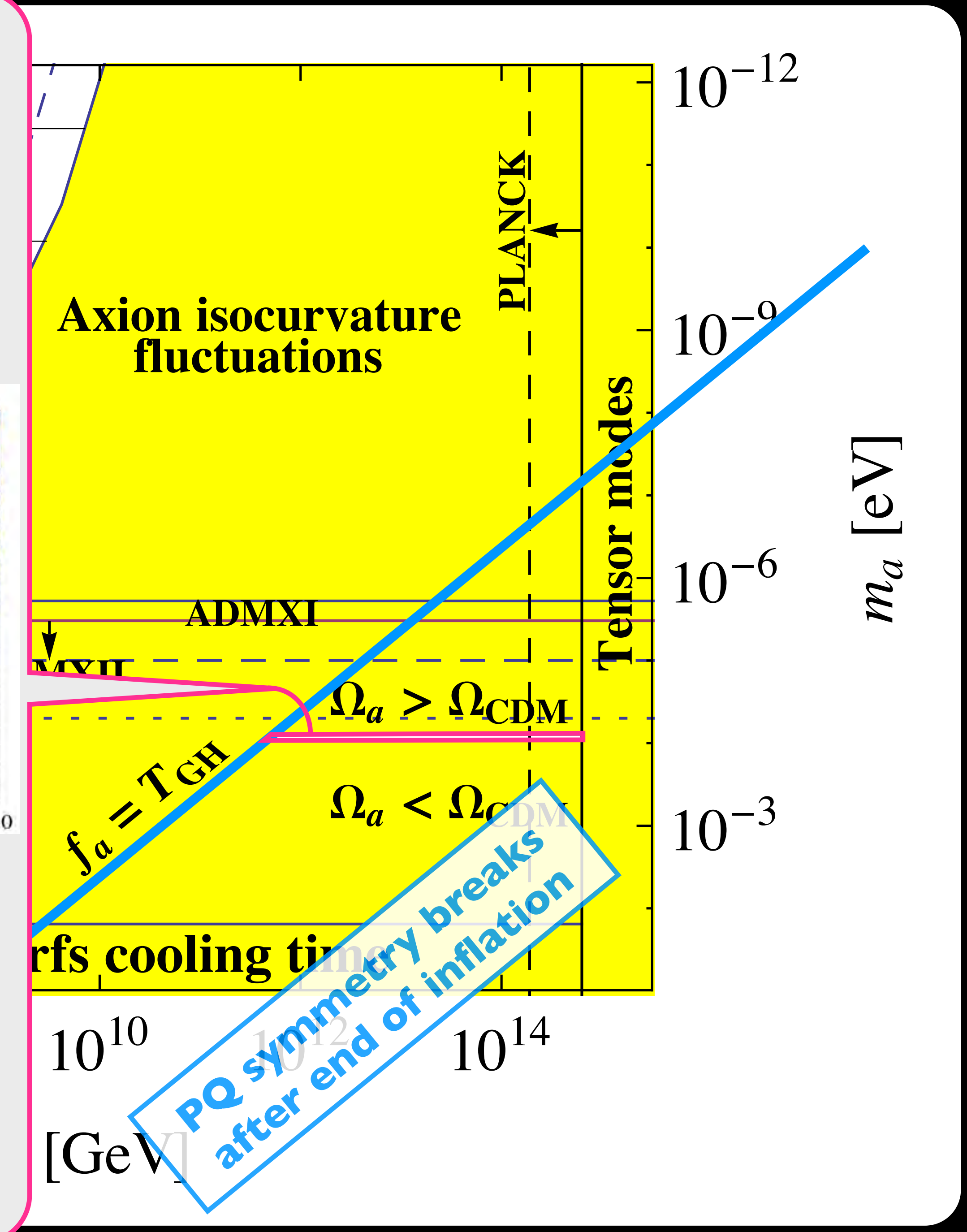
Axion CDM - Standard cosmology

PQ symmetry breaks after end of inflation

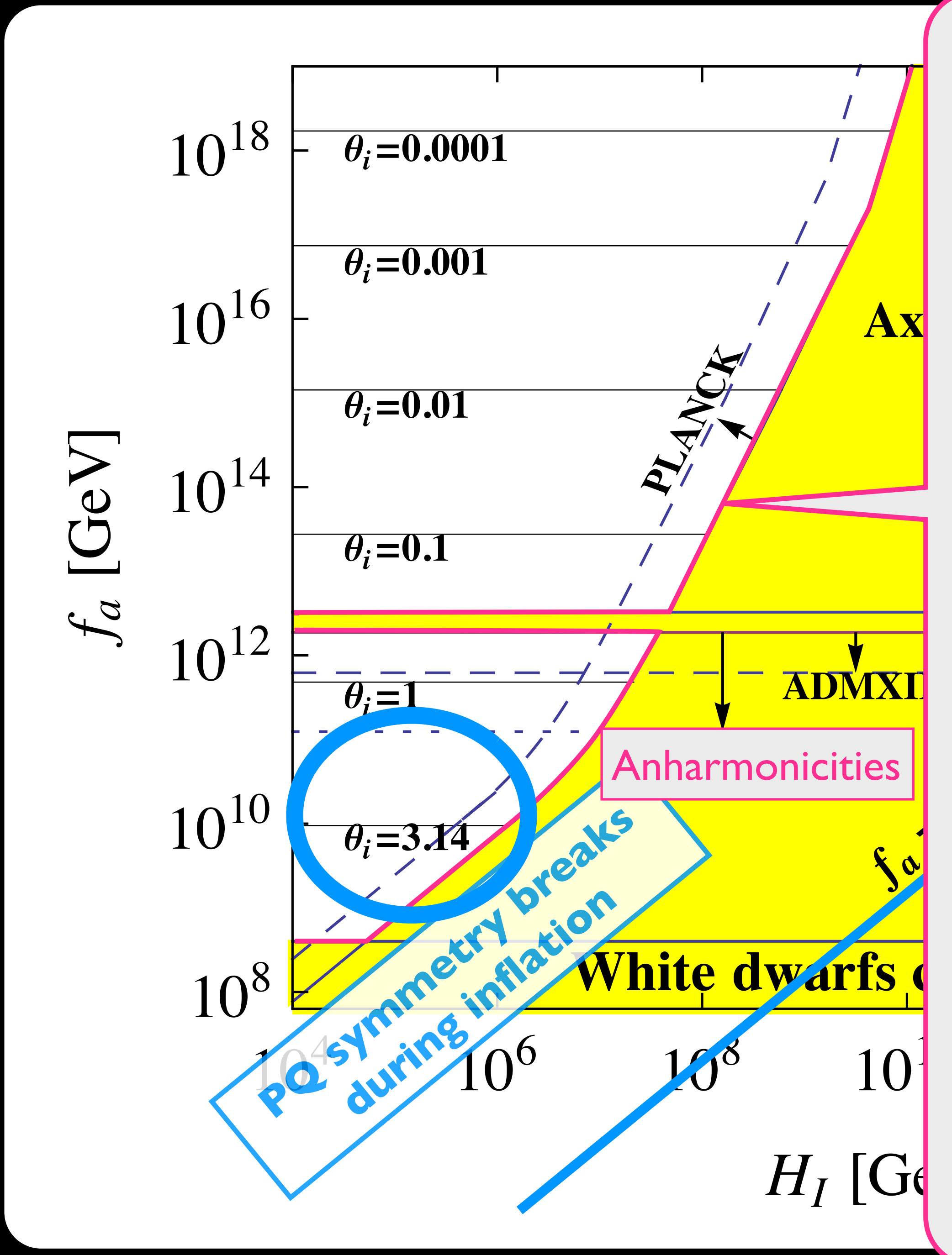
- Average θ_i over Hubble volume
- Anharmonicities are important



- String decay contribution is ~16% of vacuum realignment



Axion CDM - Standard cosmology

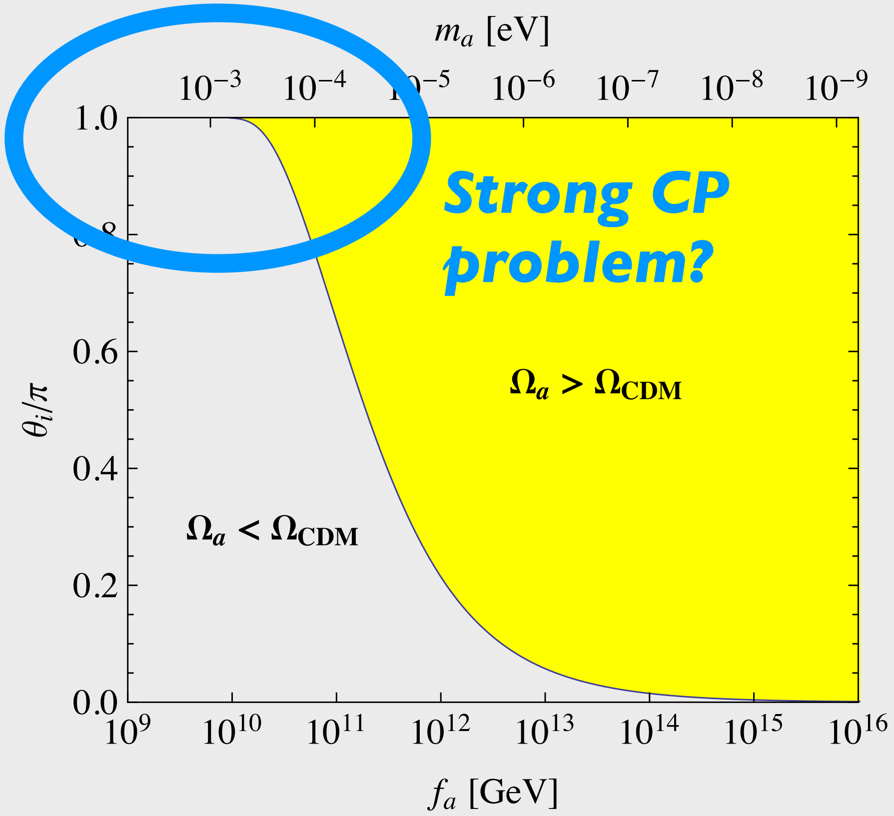


Anharmonicities

PQ symmetry breaks during inflation

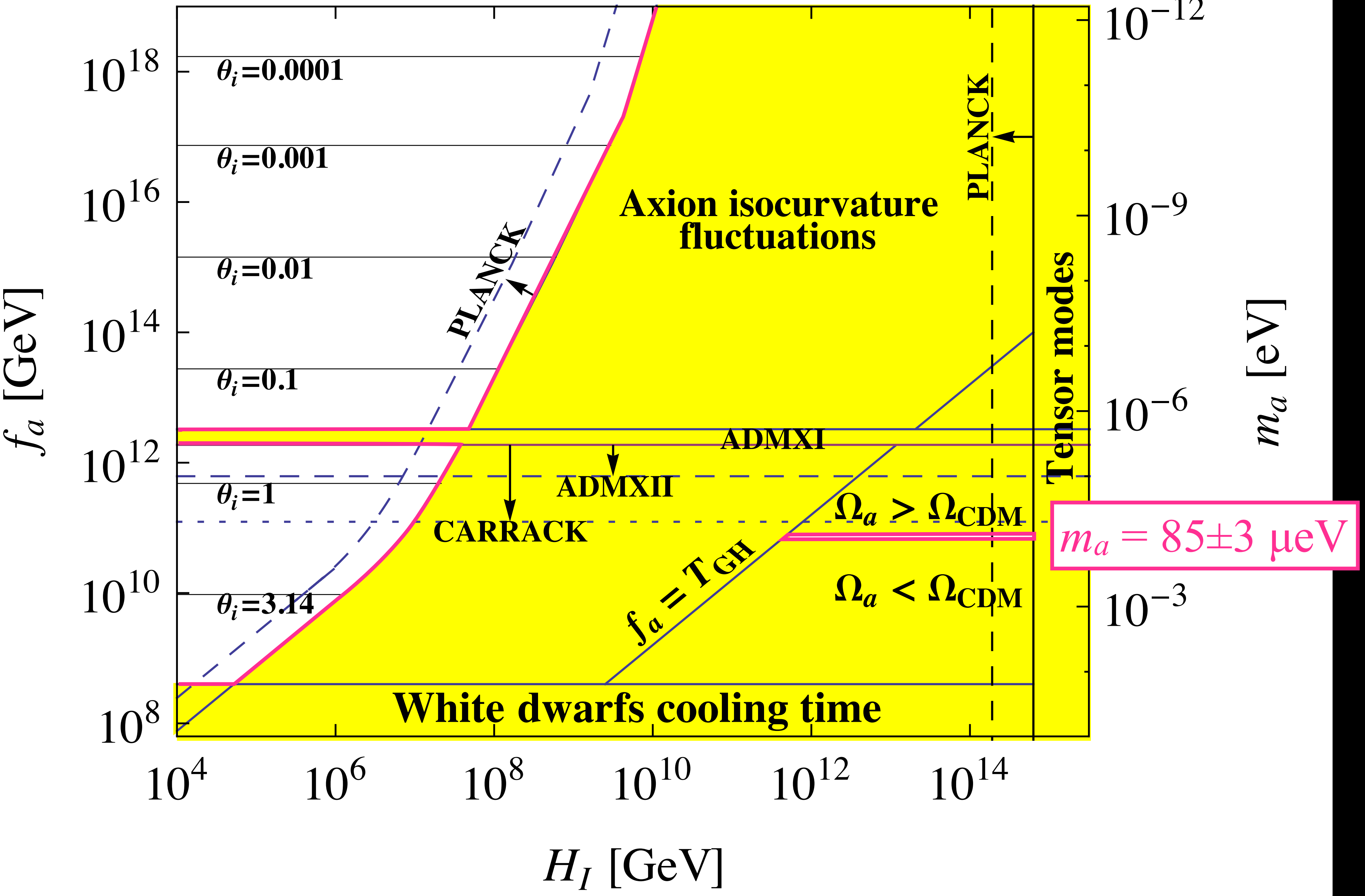
PQ symmetry breaks during inflation

- Constrained by non-adiabatic fluctuations
- Single value of θ_i throughout Hubble volume



Strong CP problem?

Axion CDM - Standard cosmology



Standard cosmology

$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\rho$$

ΛD	$\rho \propto \Lambda$
MD	$\rho \propto a^{-3}$
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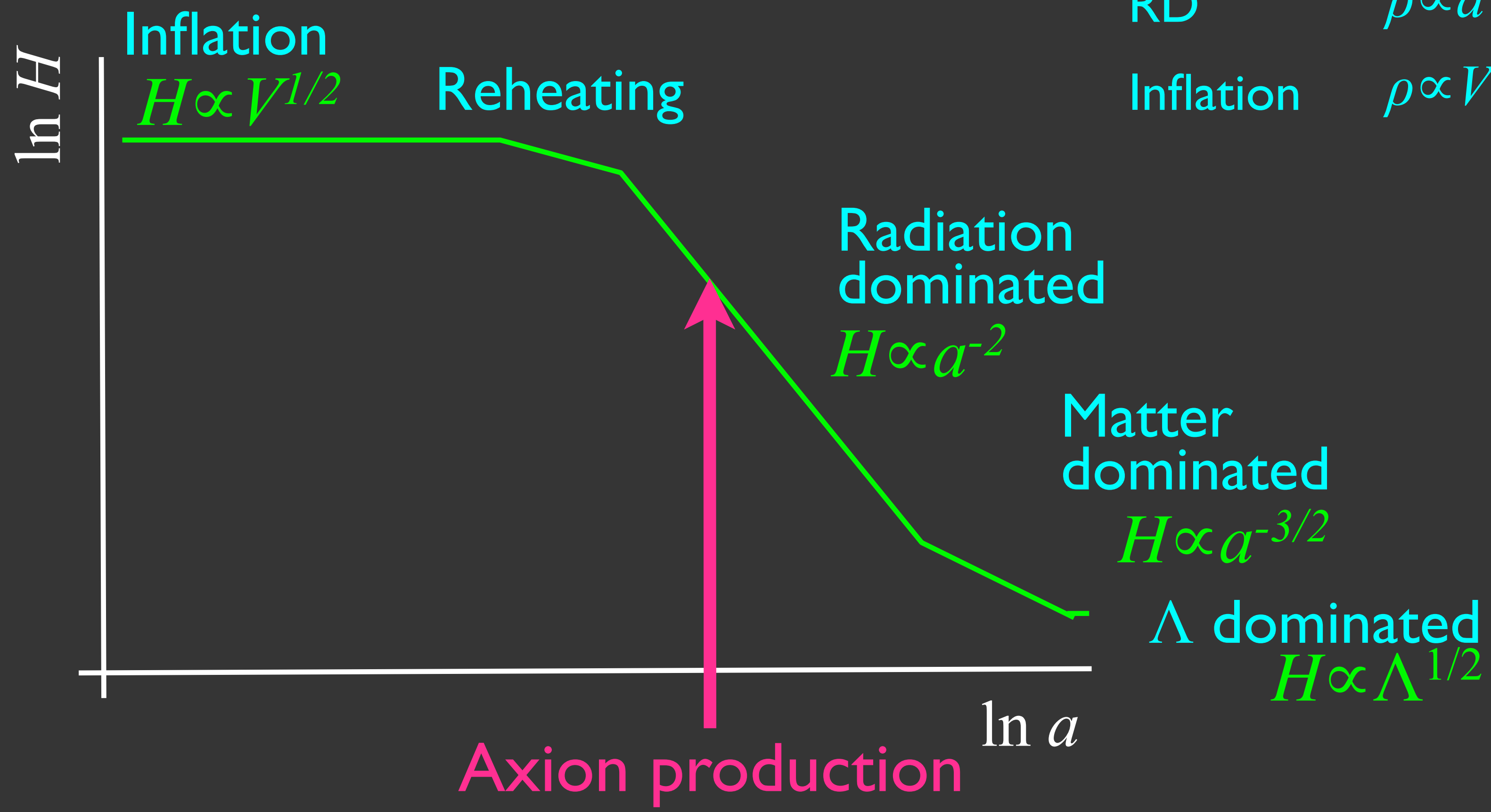
Inflation	$\rho \propto V(\phi)$



Non-standard cosmology

$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\,\rho$$

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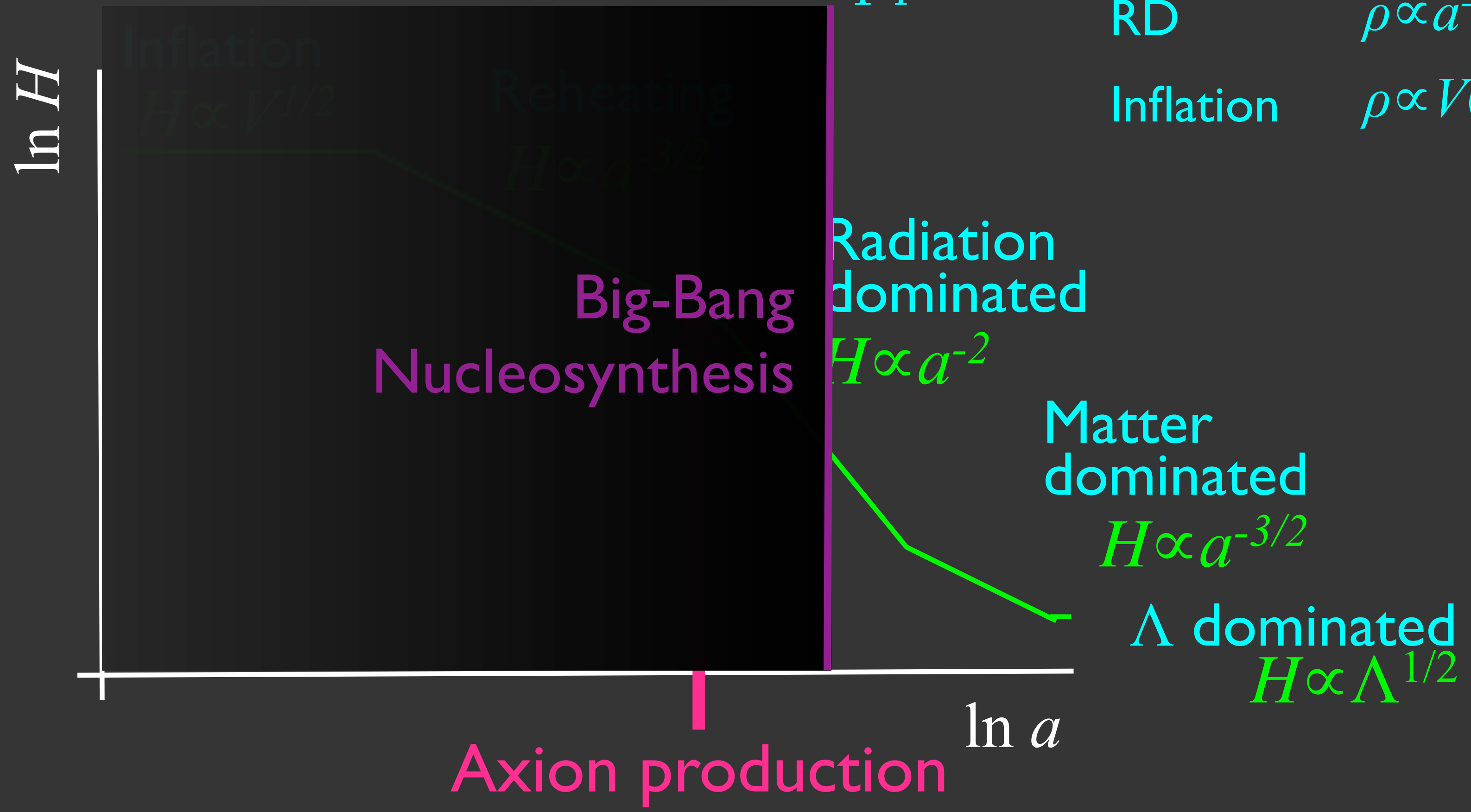

Low Temperature Reheating cosmology

$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\rho$$

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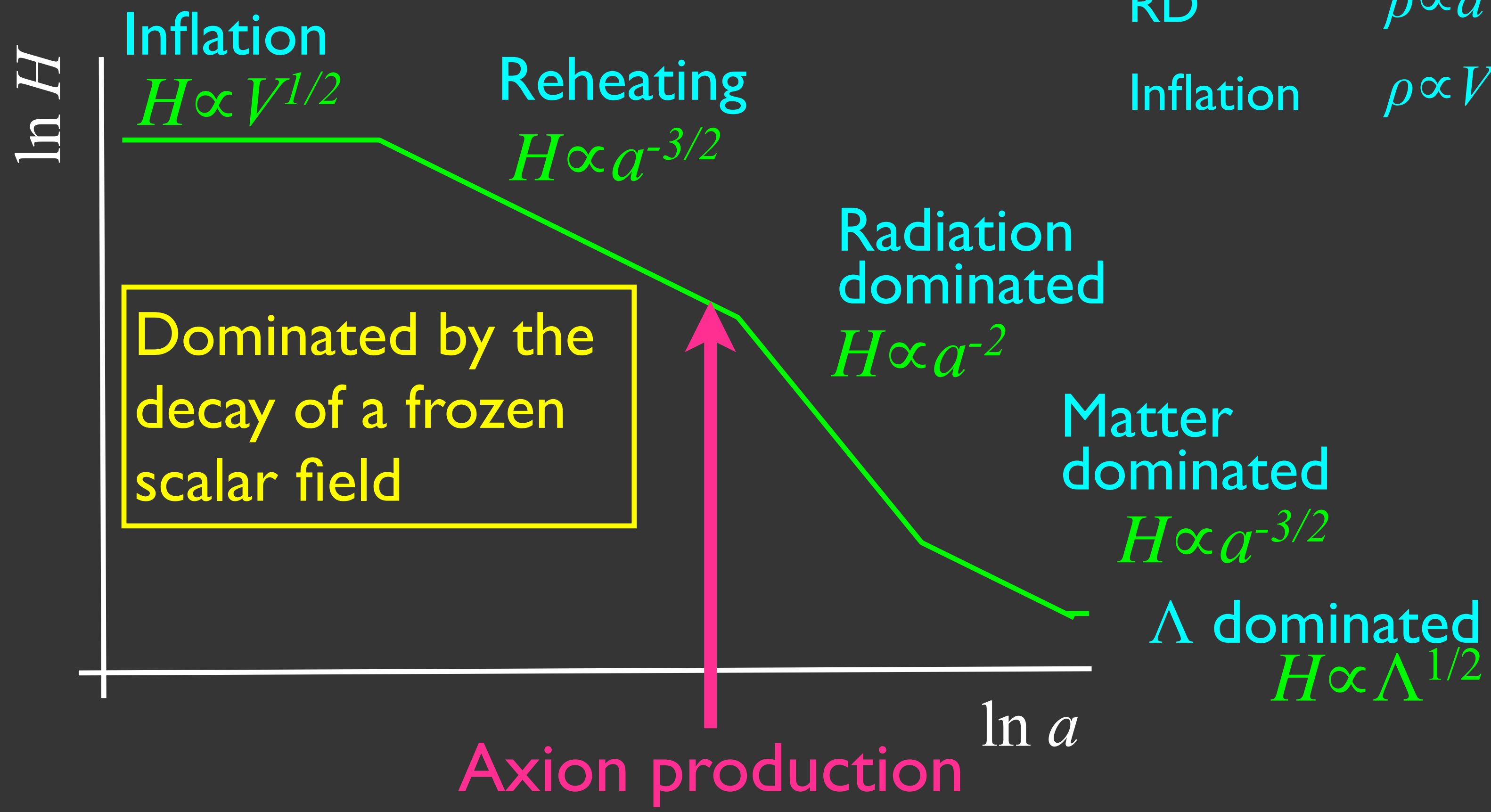


$\ln H$

Inflation
$H\propto V^{1/2}$

Reheating
$H\propto a^{-3/2}$

Dominated by the decay of a frozen scalar field

Radiation dominated
$H\propto a^{-2}$

Matter dominated
$H\propto a^{-3/2}$

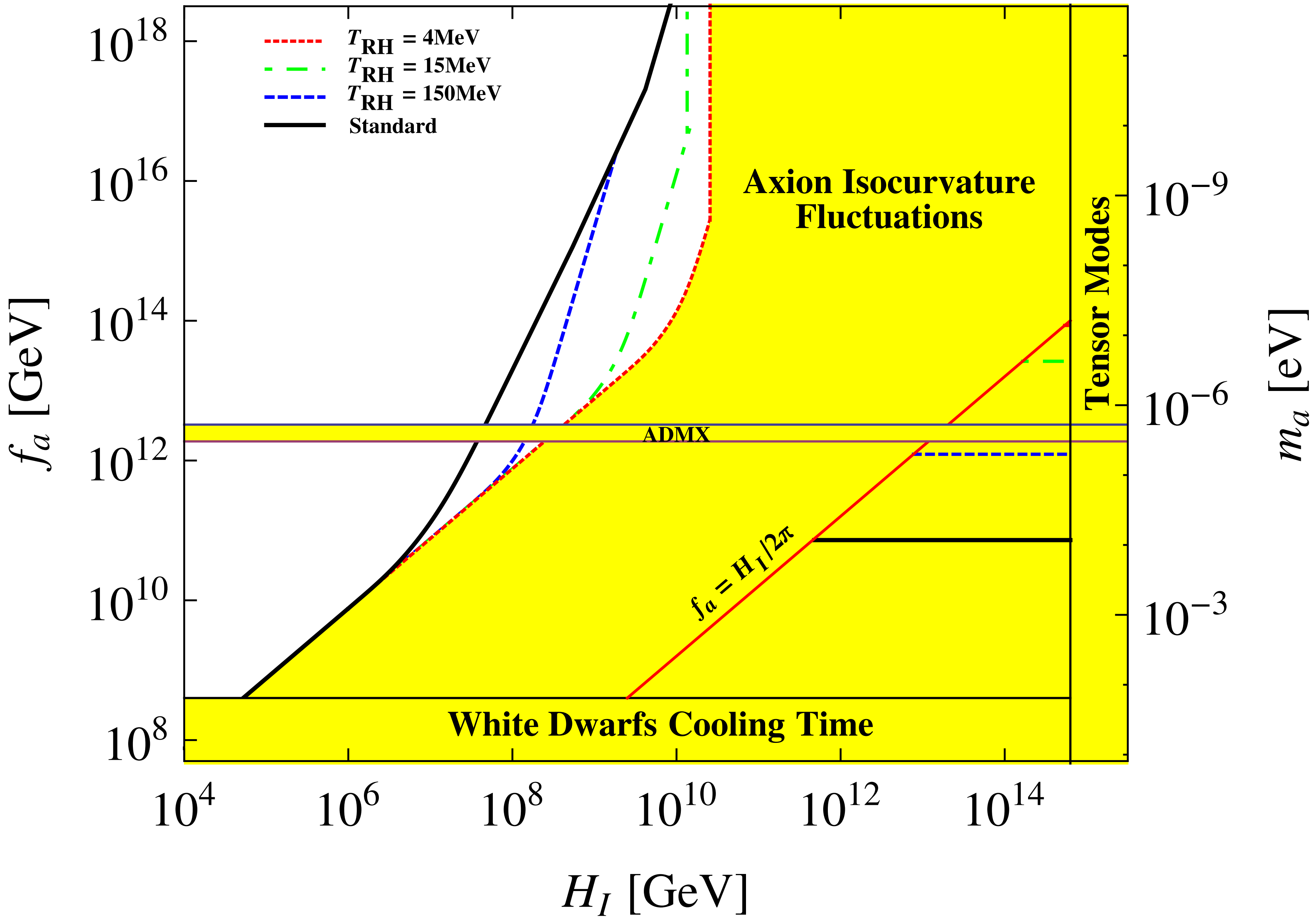
Λ dominated
$H\propto \Lambda^{1/2}$

$\ln a$

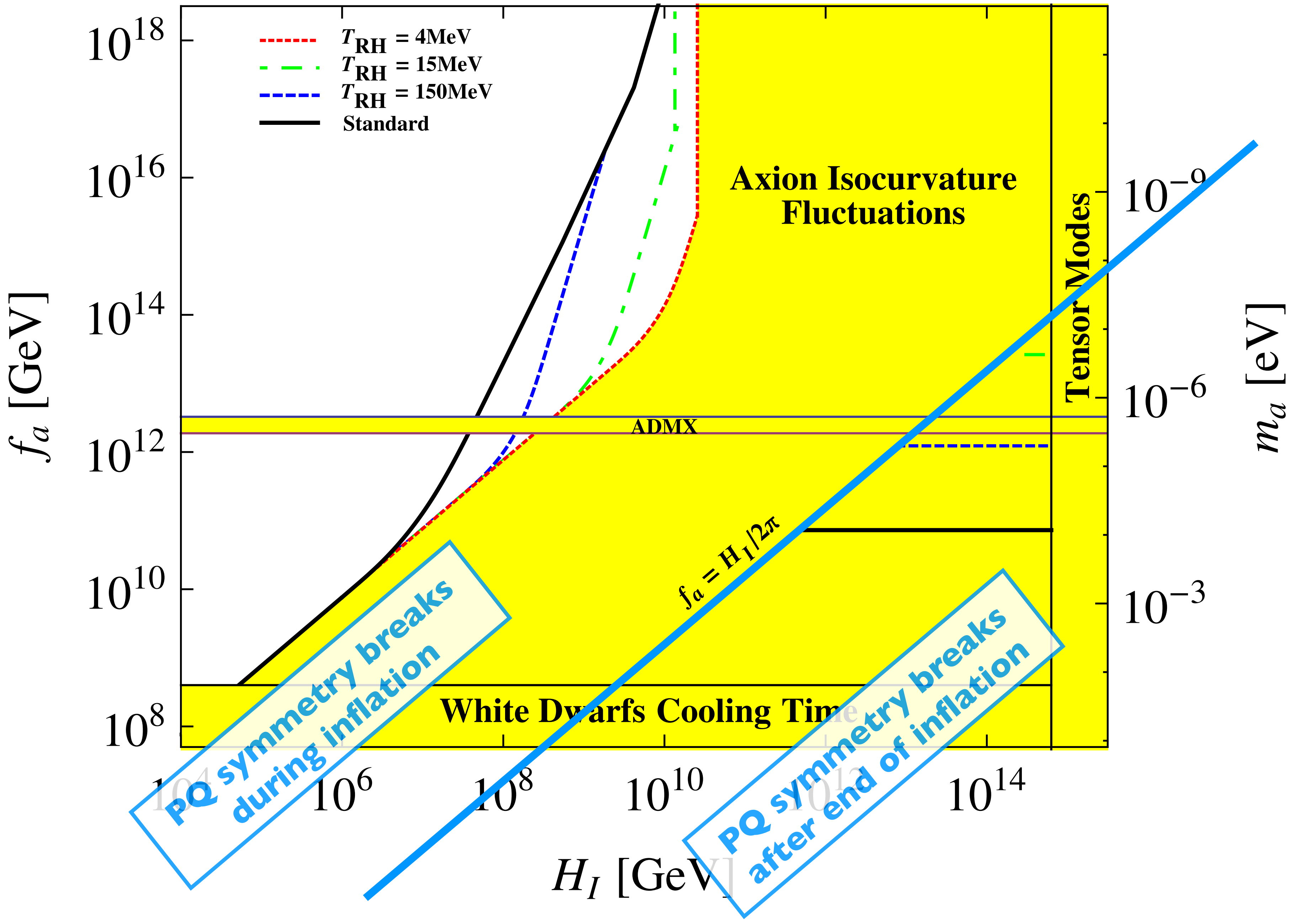
Axion production

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

Axion CDM - Low Temp. Reheating cosmology



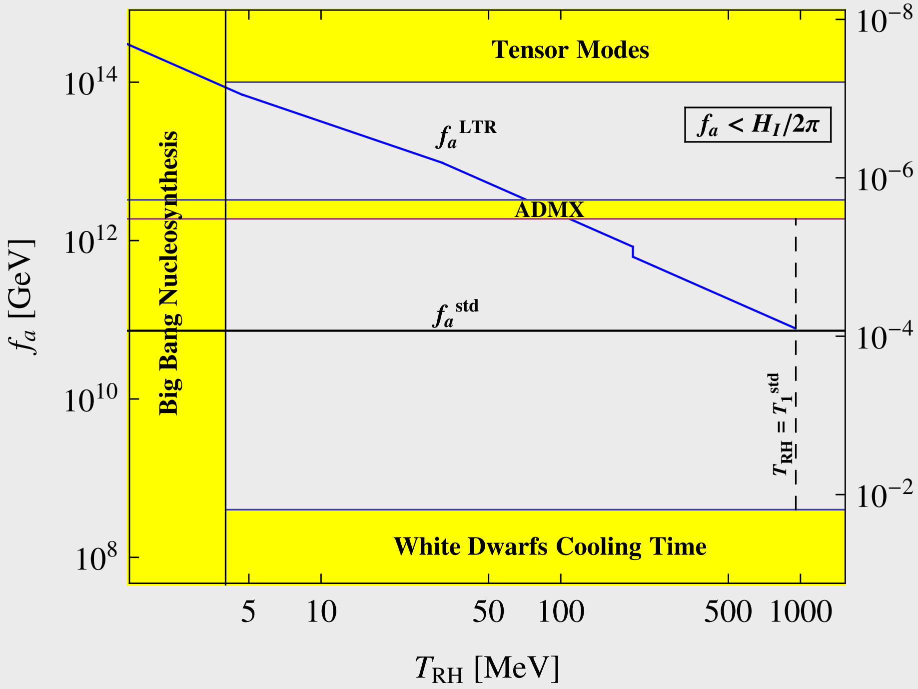
Axion CDM - Low Temp. Reheating cosmology

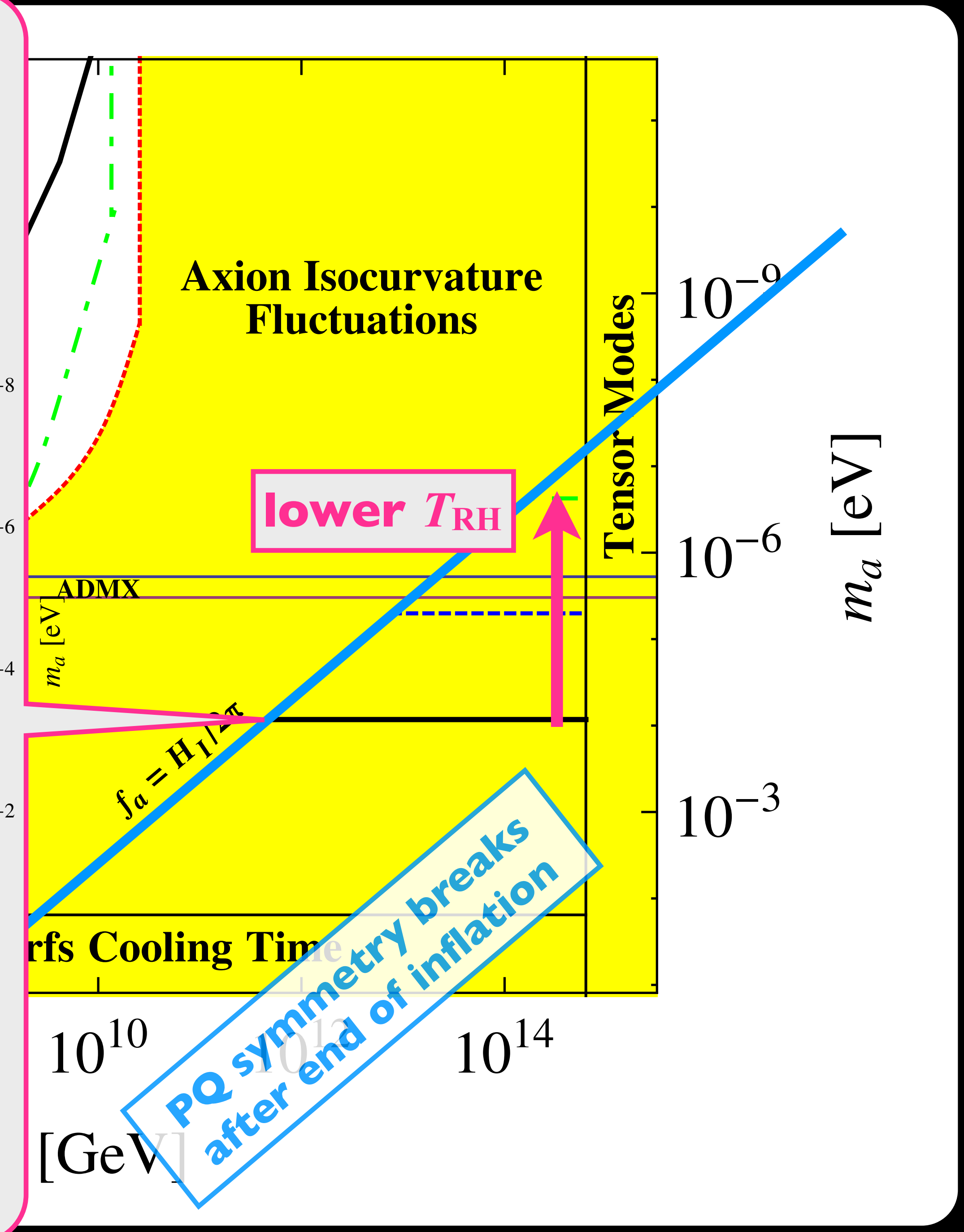


Axion CDM - Low Temp. Reheating cosmology

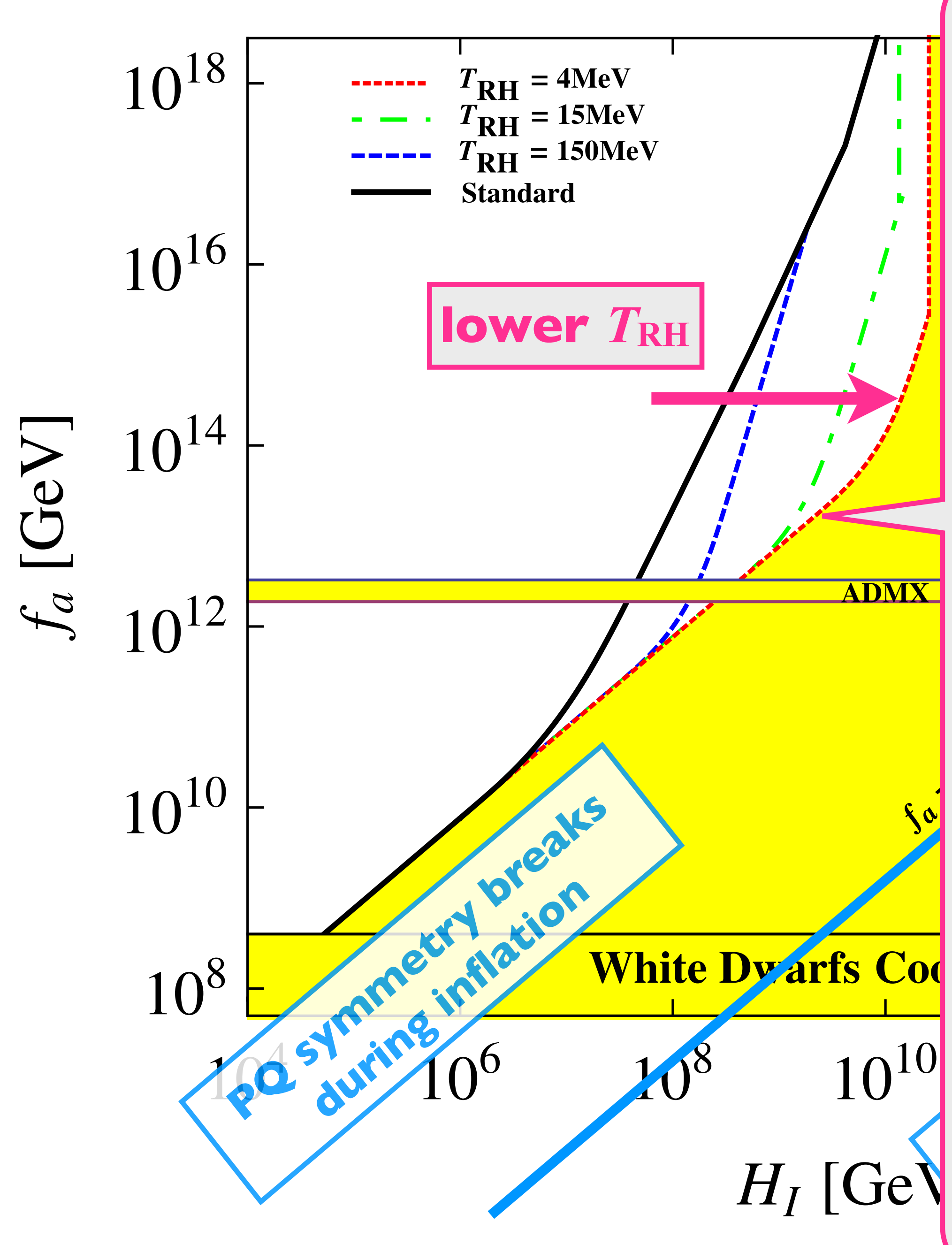
PQ symmetry breaks after end of inflation

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



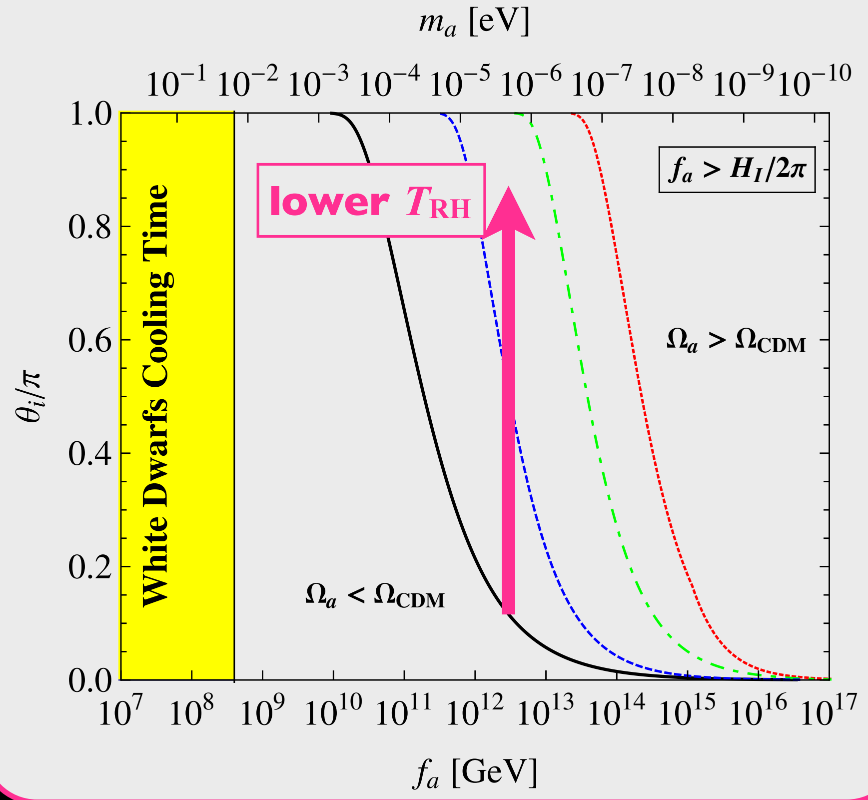


Axion CDM - Low Temp. Reheating cosmology



PQ symmetry breaks during inflation

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



Non-standard cosmology

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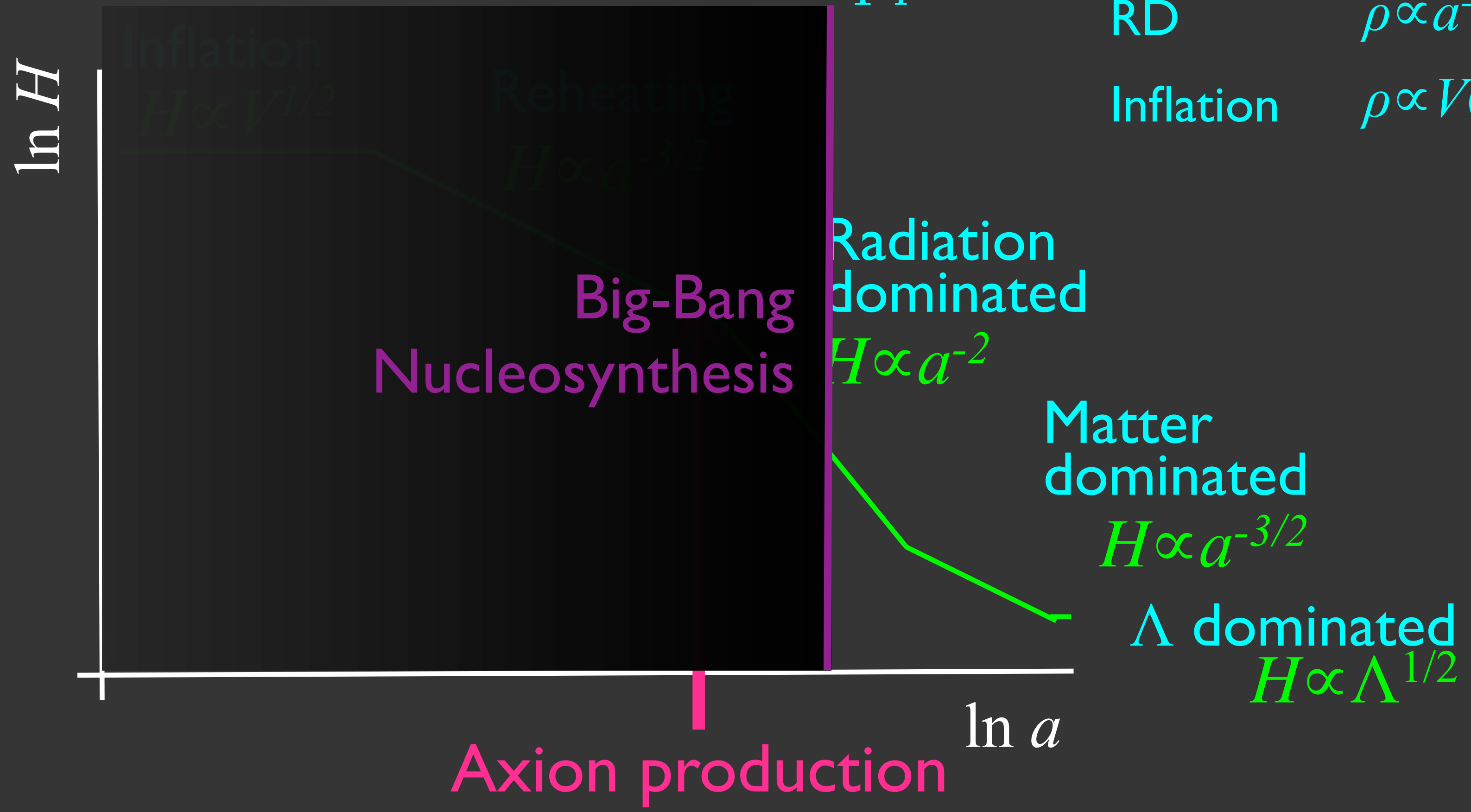
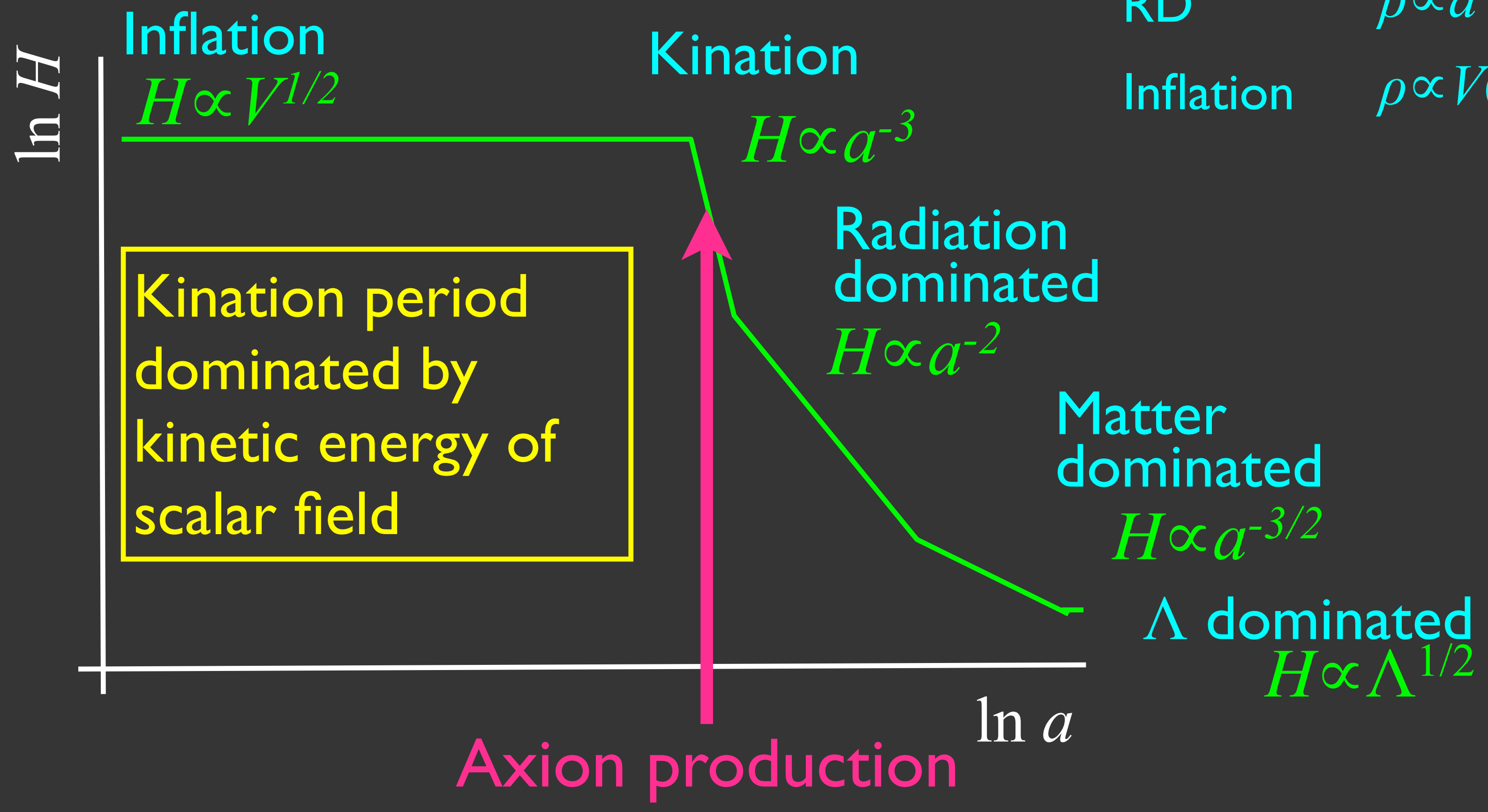


Kination cosmology

$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\rho$$

ΛD	$\rho \propto \Lambda$
MD	$\rho \propto a^{-3}$
RD	$\rho \propto a^{-4}$
Inflation	$\rho \propto V(\phi)$

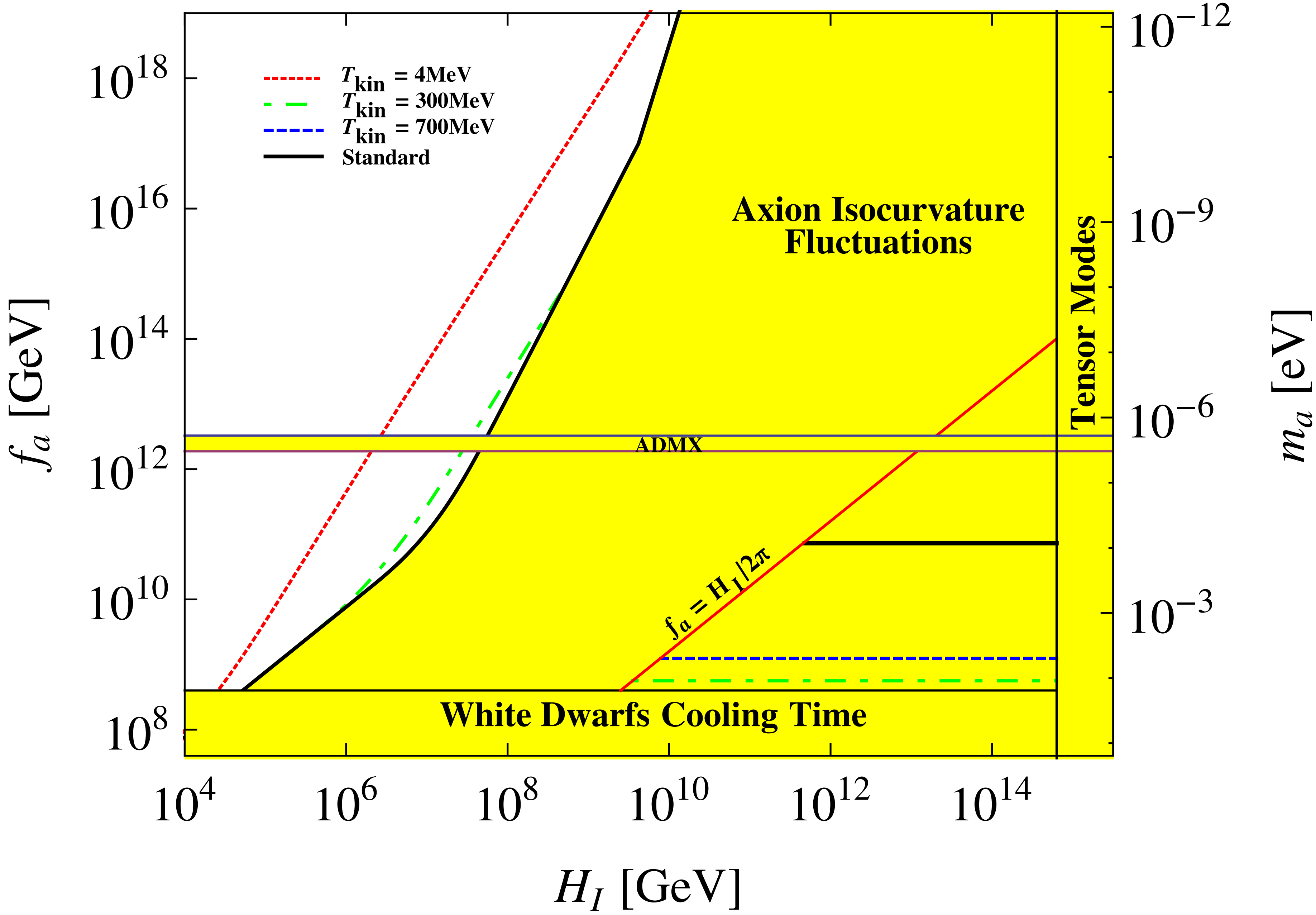


Kination period dominated by kinetic energy of scalar field

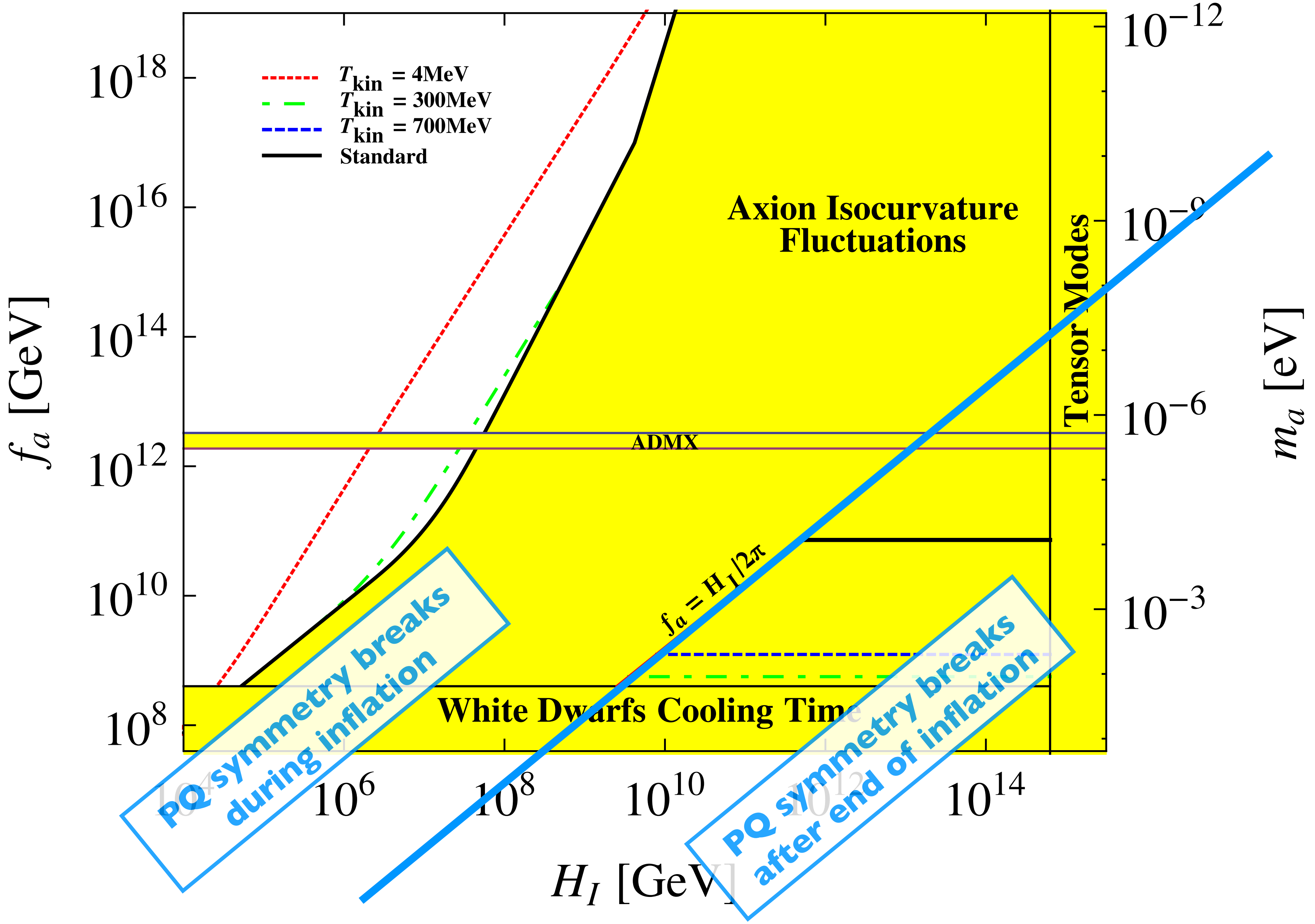
Axion production

Ford 1987

Axion CDM - Kination cosmology



Axion CDM - Kination cosmology



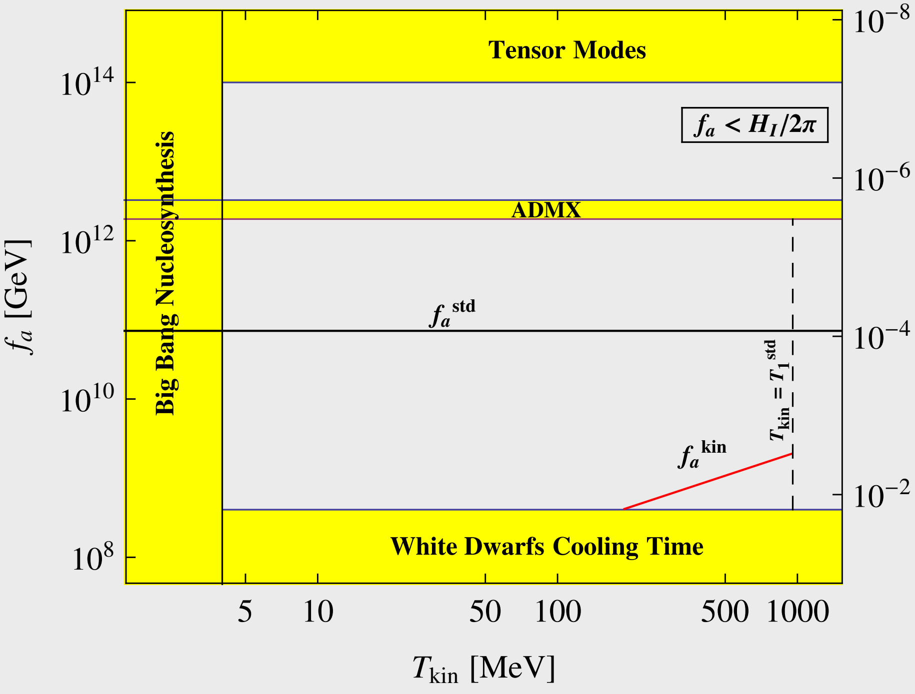
PQ symmetry breaks during inflation

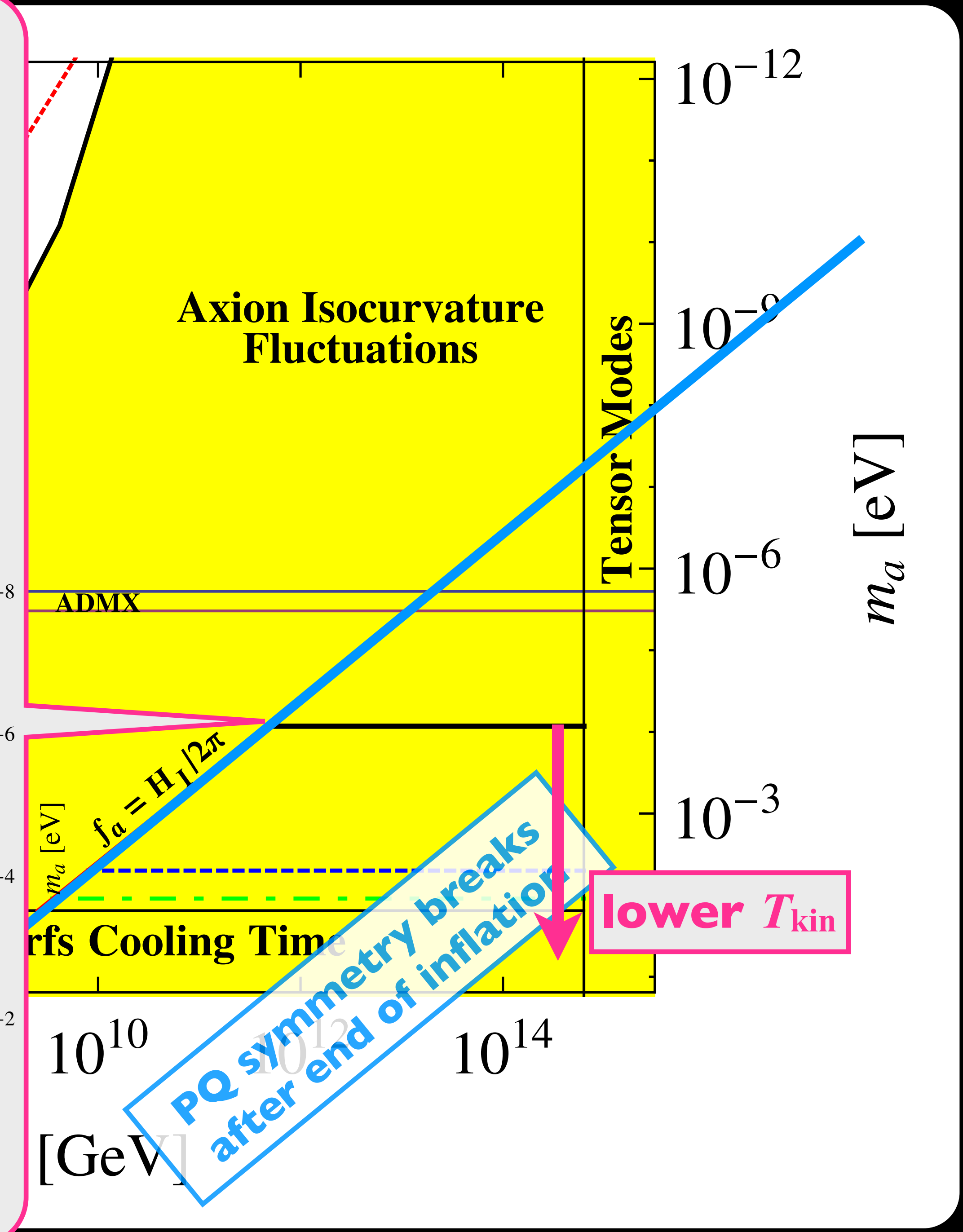
PQ symmetry breaks after end of inflation

Axion CDM - Kination cosmology

PQ symmetry breaks after end of inflation

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

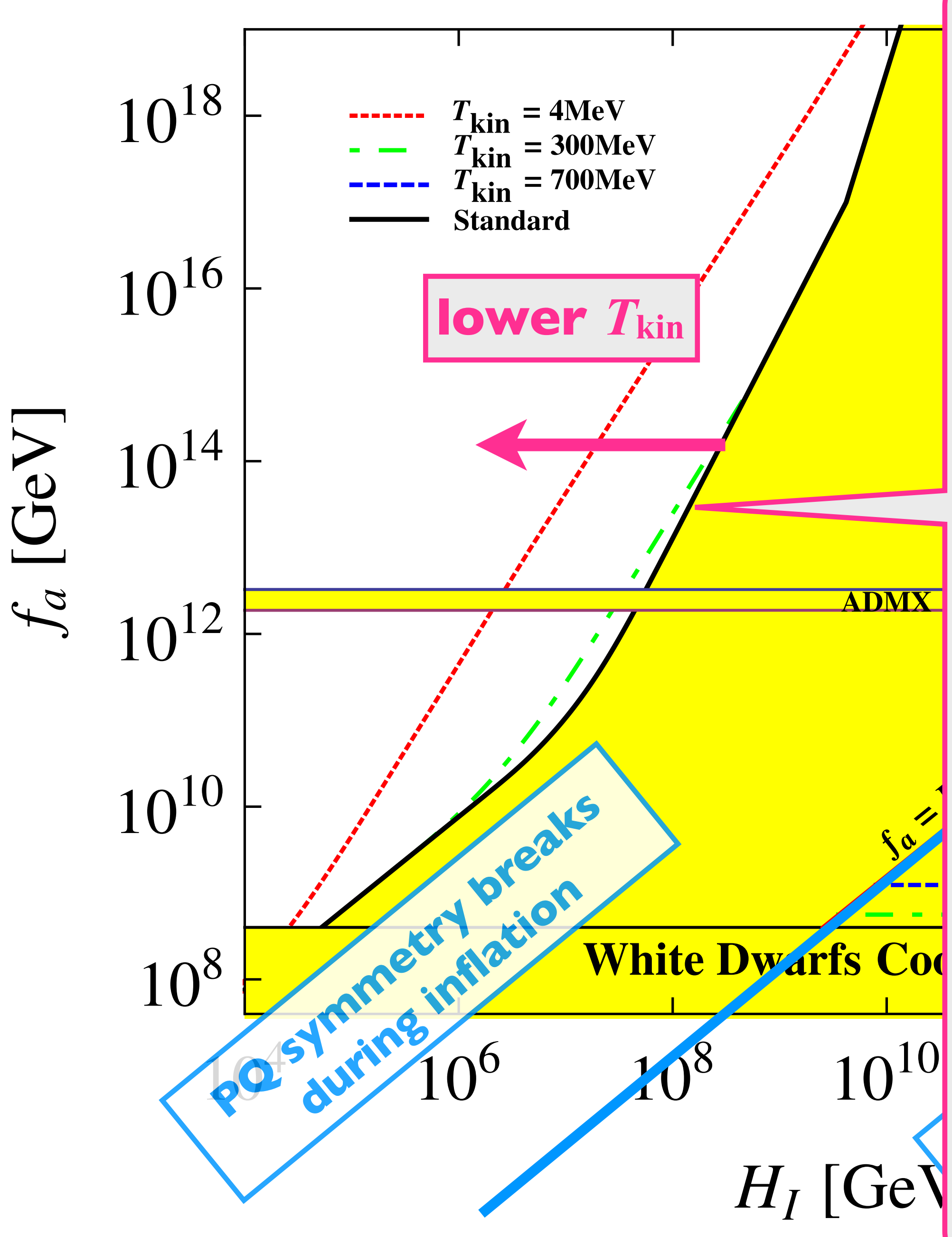




PQ symmetry breaks after end of inflation

lower $T_{\rm kin}$

Axion CDM - Kination cosmology

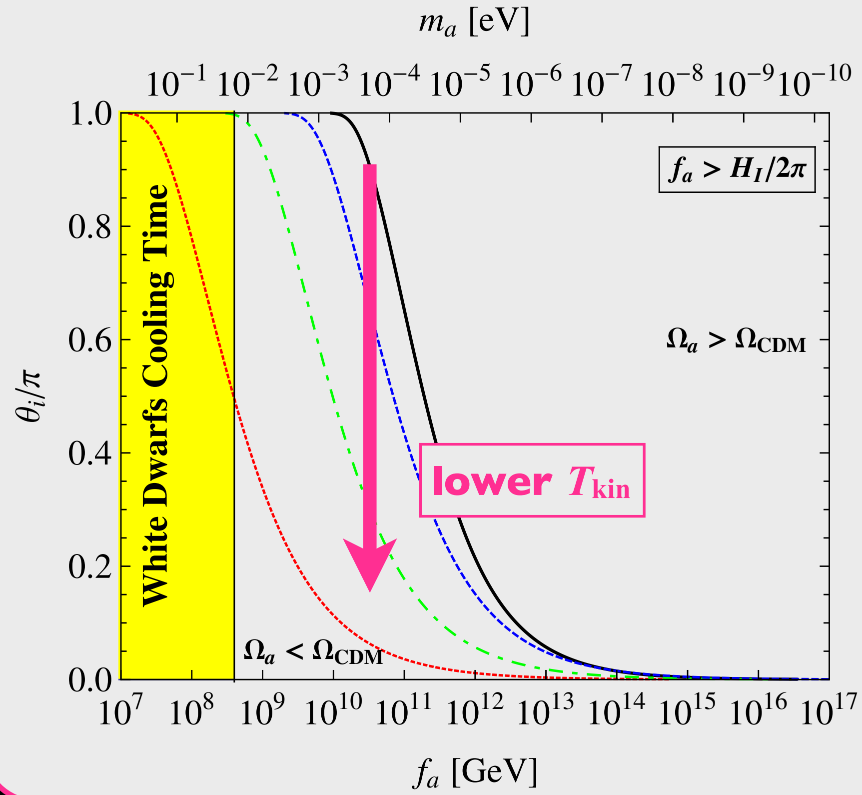


lower $T_{\rm kin}$

PQ symmetry breaks during inflation

PQ symmetry breaks during inflation

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



lower $T_{\rm kin}$

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±3 μeV 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 θ_i must be chosen
  - larger allowed region and larger θ_i in LTR cosmology
  - smaller allowed region and smaller θ_i in kination cosmology