Axion Cold Dark Matter in Non-Standard Cosmologies

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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)

A wider range of masses

Luca Visinelli

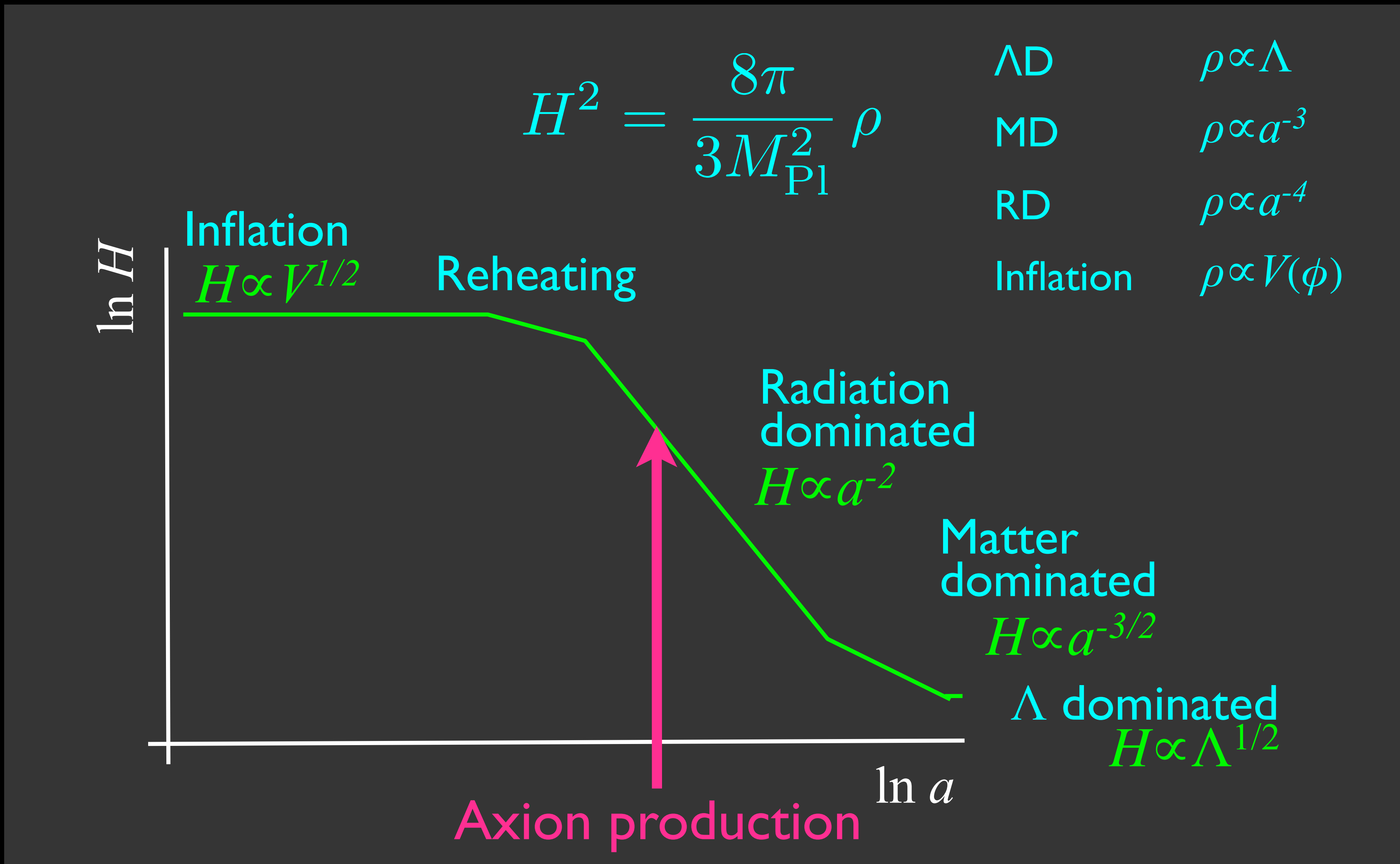
Axion cold dark matter

When are axions 100% of cold dark matter?

Study axion parameter space imposing

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

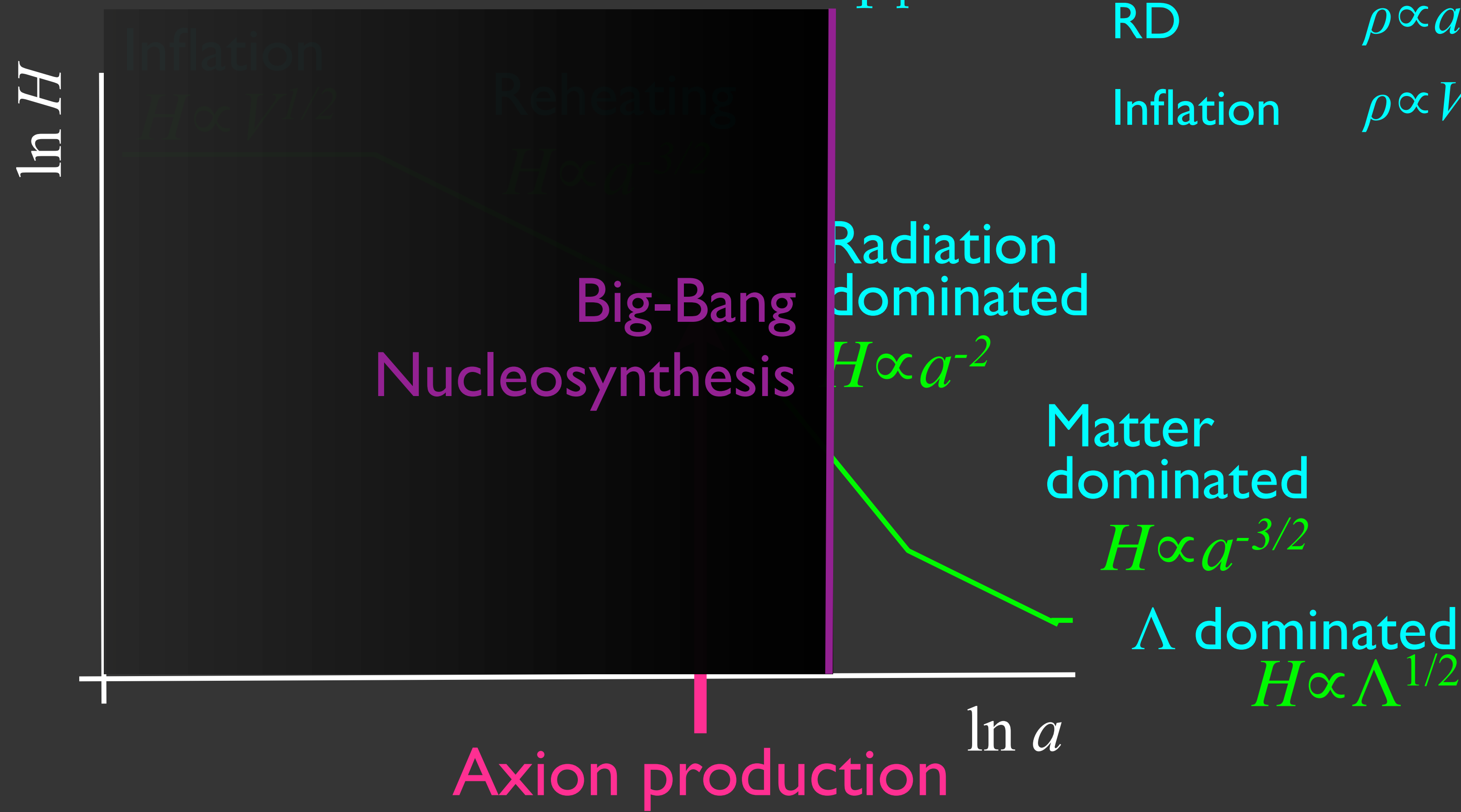
Standard cosmology



Non-standard 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	$\rho \propto V(\phi)$



Non-standard cosmology

Scalar-tensor gravity

Usual metric tensor $g_{\mu\nu}$ + scalar field ϕ with action

$$S_g = \frac{1}{16\pi} \int d^4x \sqrt{-\bar{g}} \, [\bar{\phi}^2 \bar{R} + 4\omega(\bar{\phi}) \bar{g}^{\mu\nu} \partial_\mu \bar{\phi} \partial_\nu \bar{\phi} - 4\bar{V}(\bar{\phi})]$$

(Jordan frame)

For example, Brans-Dicke theory has $\omega(\phi)=\omega$, $V(\phi)=0$

The Friedmann equation has extra terms

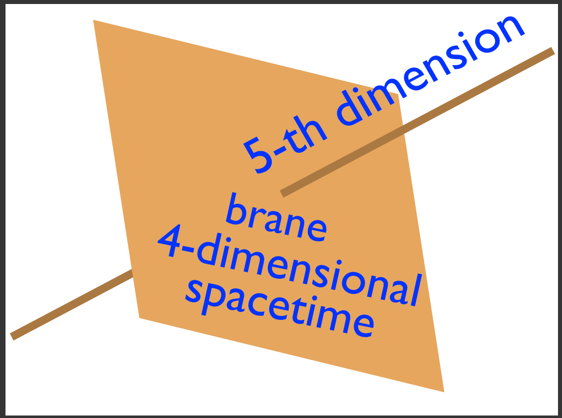
$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2} \left(\rho + \tfrac{1}{2} M_{\rm Pl}^2 \dot{\phi}^2 + V(\phi) \right)$$

(Einstein frame)

Non-standard cosmology

Braneworlds

4-dimensional spacetime embedded in a higher dimensional spacetime



For example, Randall-Sundrum model II

Extra term in the Friedmann equation

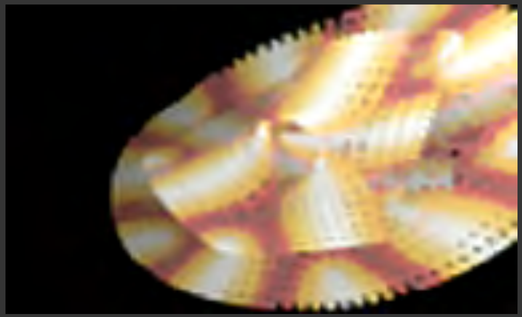
$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\left(\rho + \frac{M_{\rm Pl}^2\rho^2}{96\pi M_5^6}\right)$$

M_5 = Planck's constant in the bulk

Non-standard cosmology

Moduli fields

In string theory, moduli fields parametrize the shape and size of the compactified extra dimensions



Calabi-Yau manifold $z_1^5+z_2^5=1$

J.-F. Colonna, www.lactamme.polytechnique.fr

Moduli fields could dominate the energy of the universe at certain times, with some moduli fields decaying into ordinary and dark matter particles

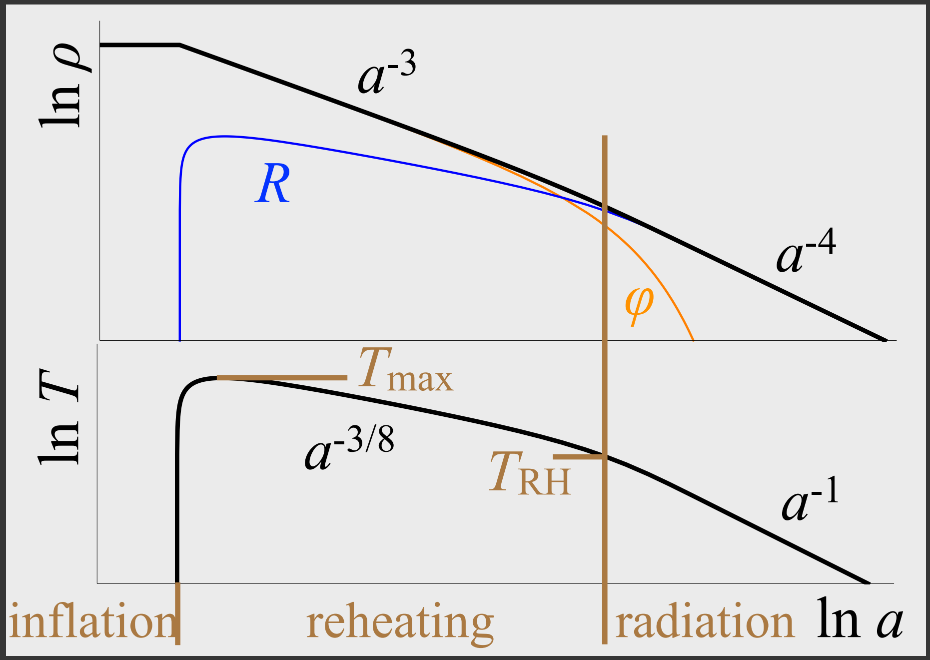
For example, Moroi-Randall and Acharya-Bobkov-Kane-Kumar-Shao

Non-standard cosmology

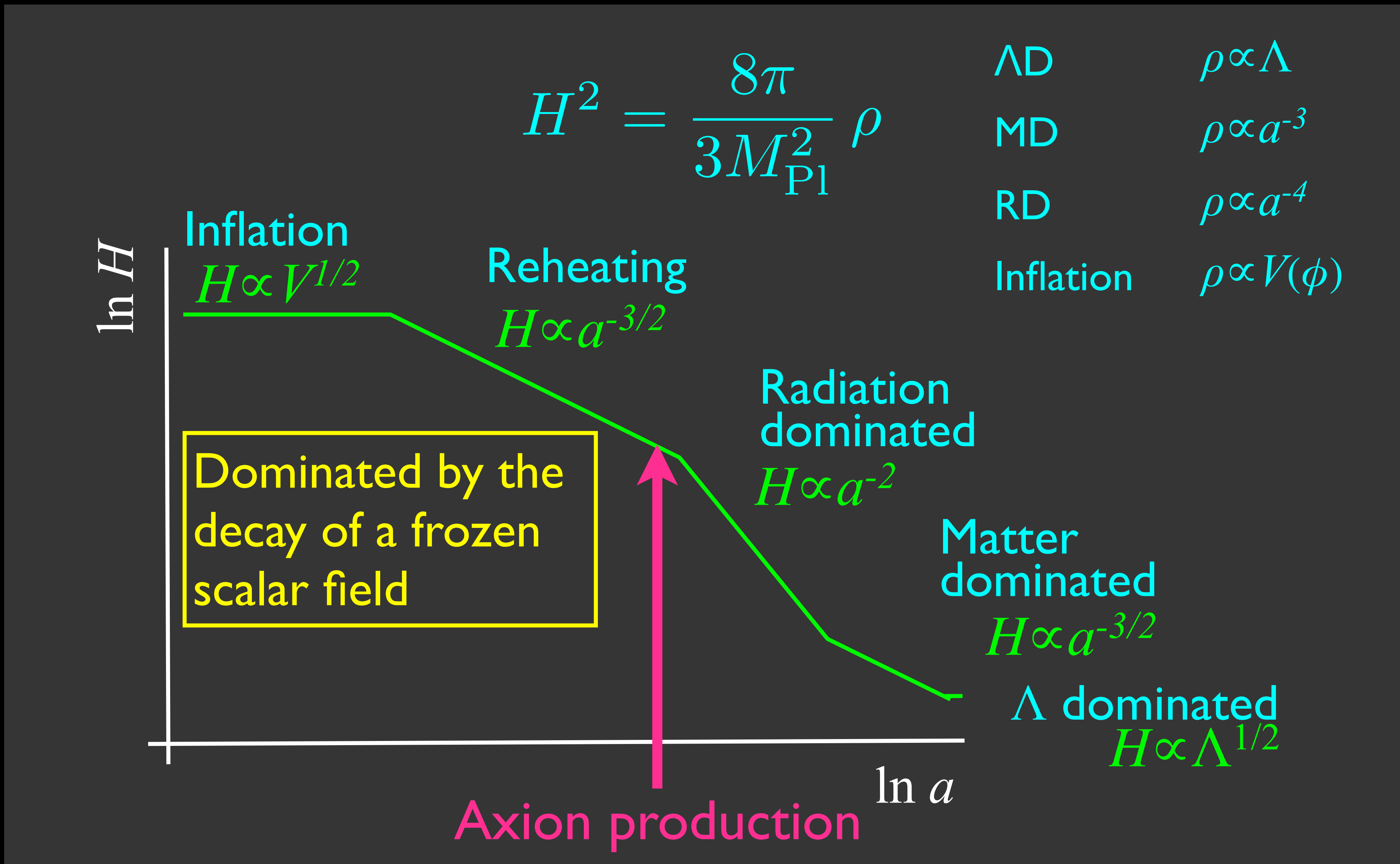
Low temperature reheating

A decaying scalar field is a simple model of reheating at the end of inflation

The reheating temperature could be as low as 4 MeV



Low Temperature Reheating cosmology



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

Kination cosmology

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

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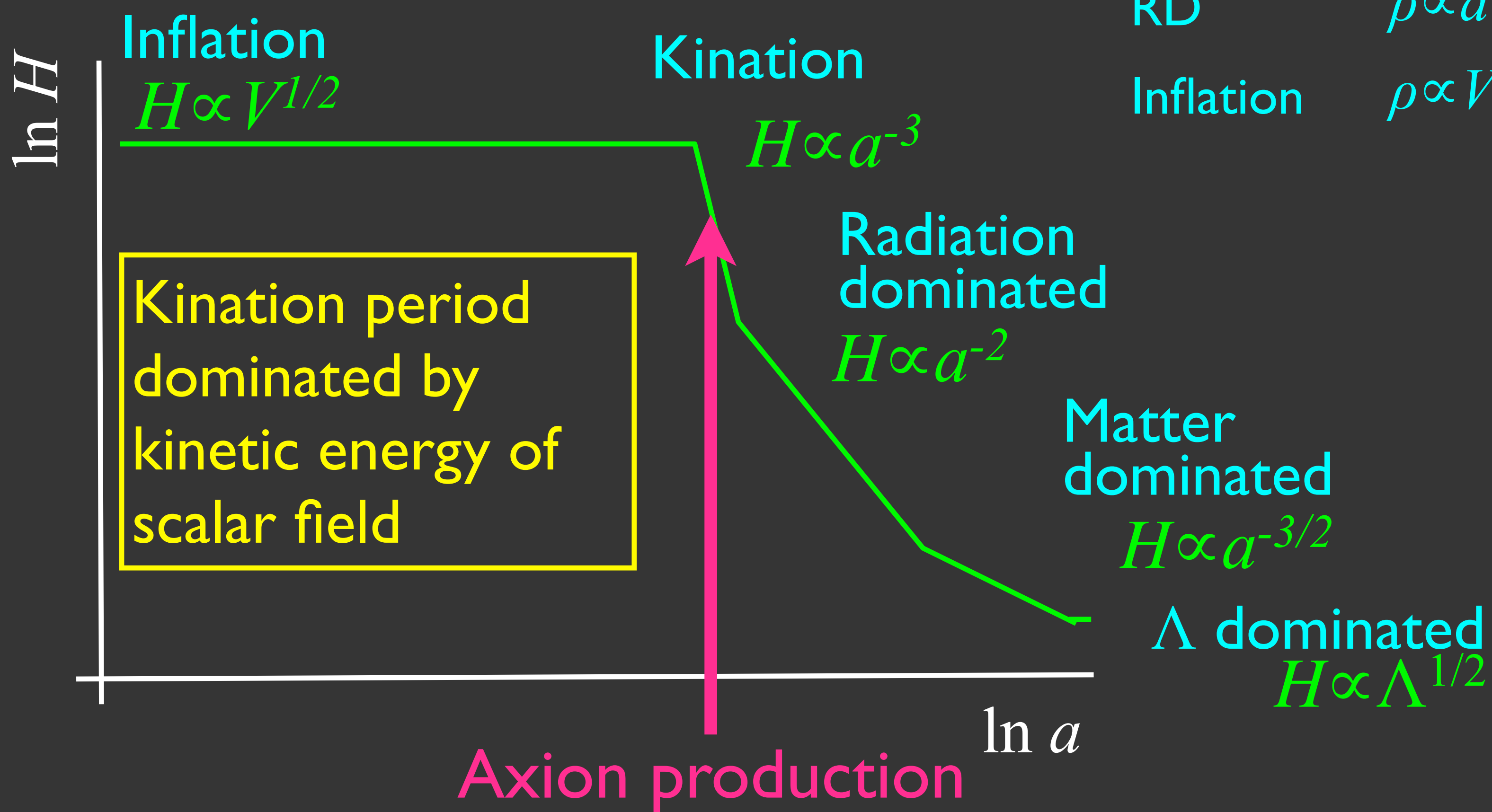

Ford 1987

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_{I}	Expansion rate at end of inflation
θ_i	Initial misalignment angle
Harari-Hagmann-Chang-Sikivie Davis-Battye-Shellard	Axionic string parameters

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

Thus 3 free parameters f_a, θ_i, H_{I} *and one constraint* $\Omega_a = \Omega_{\mathrm{CDM}}$

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

$$\xi = \frac{1}{4c^2}\left(2 - 3\beta + \sqrt{(4c+0)\beta^2 - 12\beta + 4}\right)^2$$

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

$$c = (1 + 2\sqrt{\xi^{\rm std}})/(4\xi^{\rm std})$$

Standard cosmology

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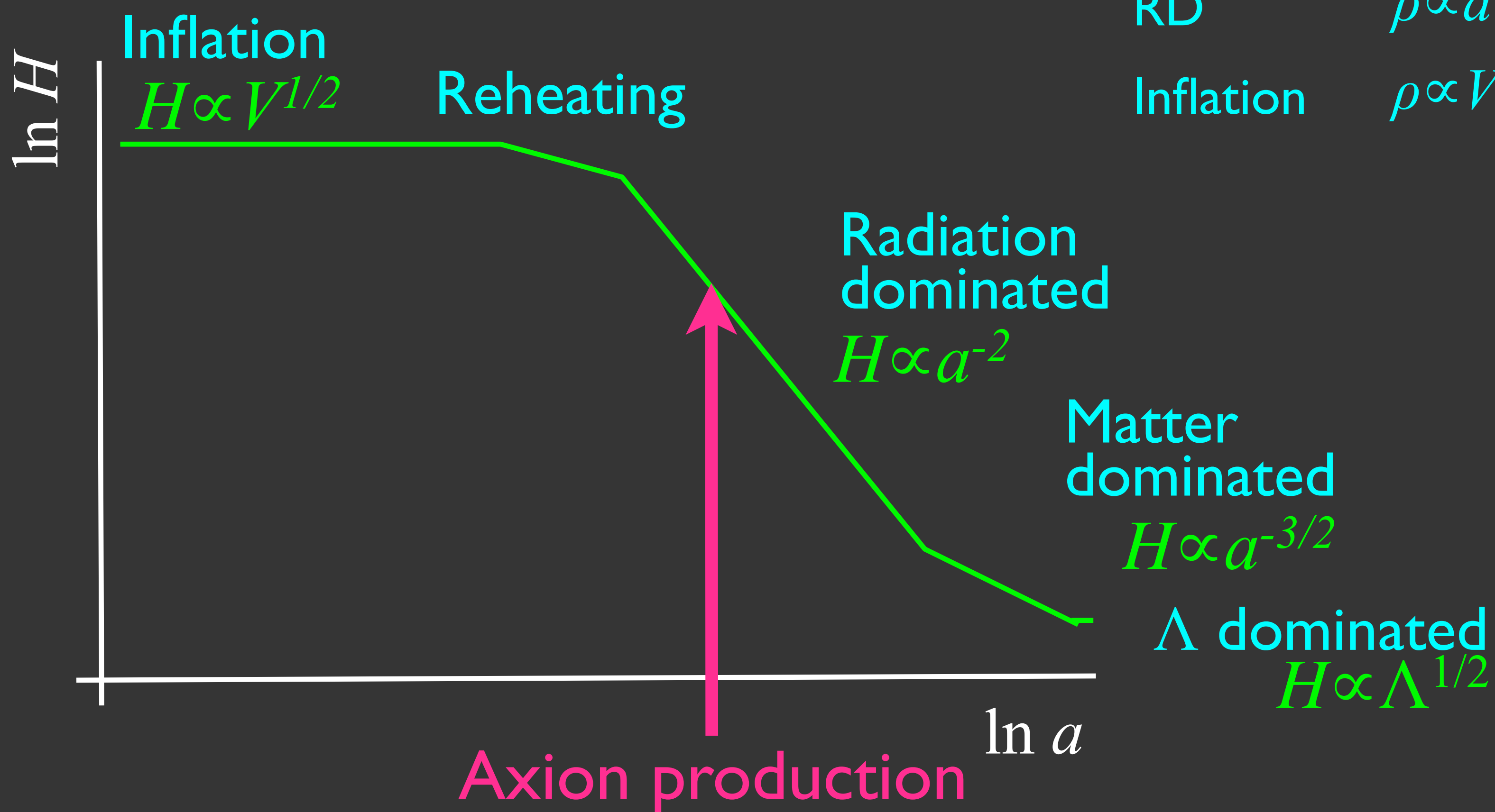
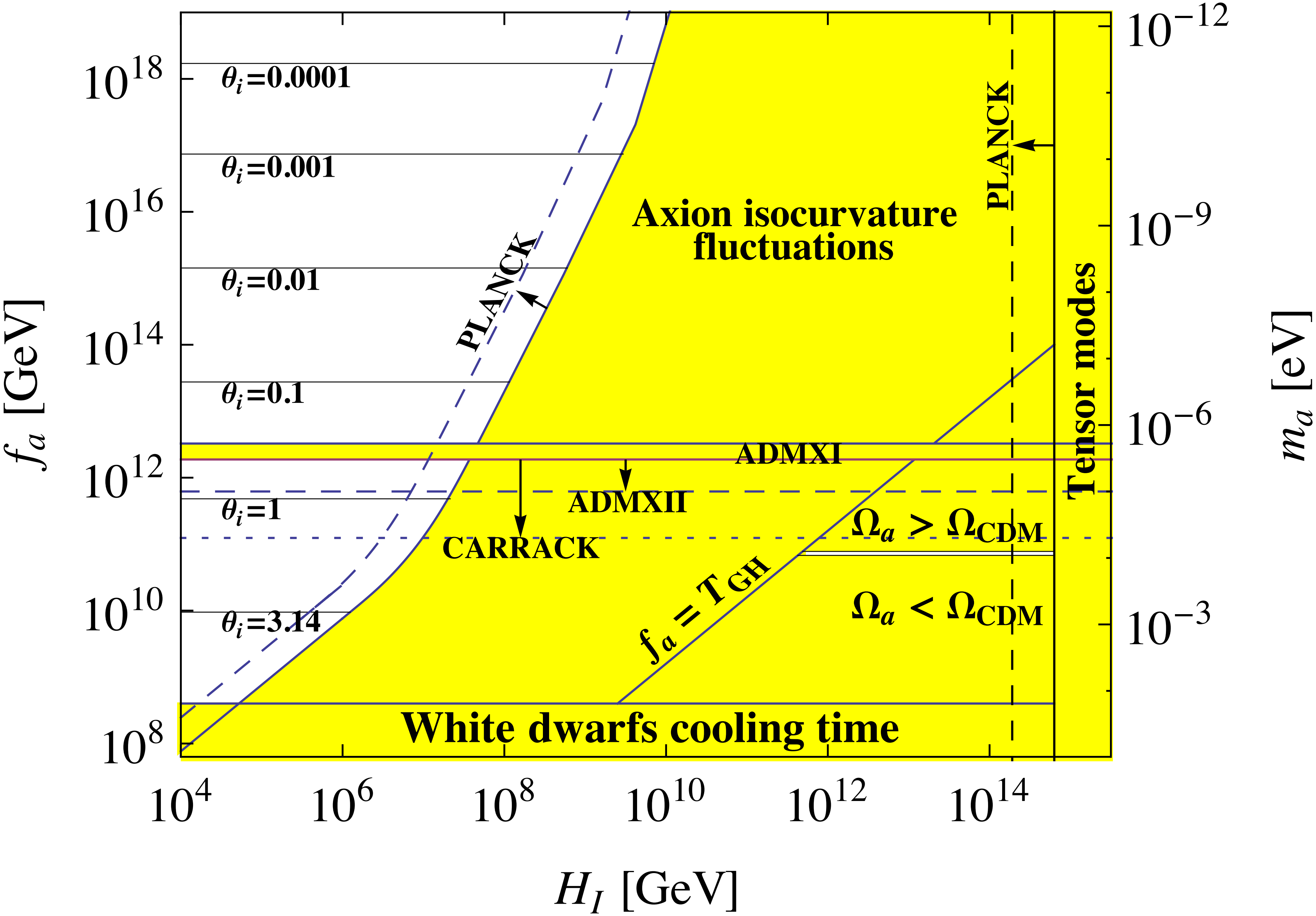
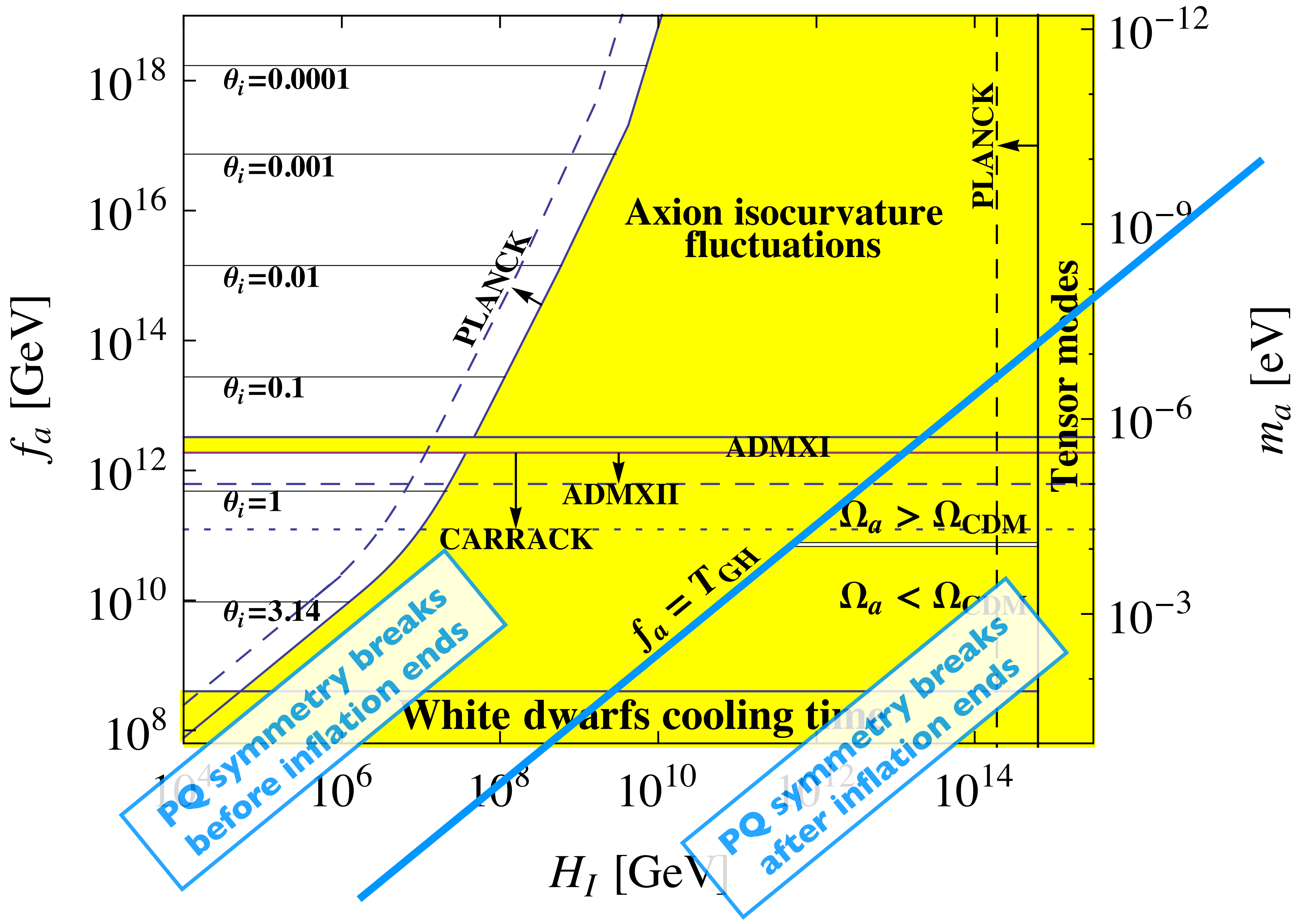


Axion CDM - Standard cosmology



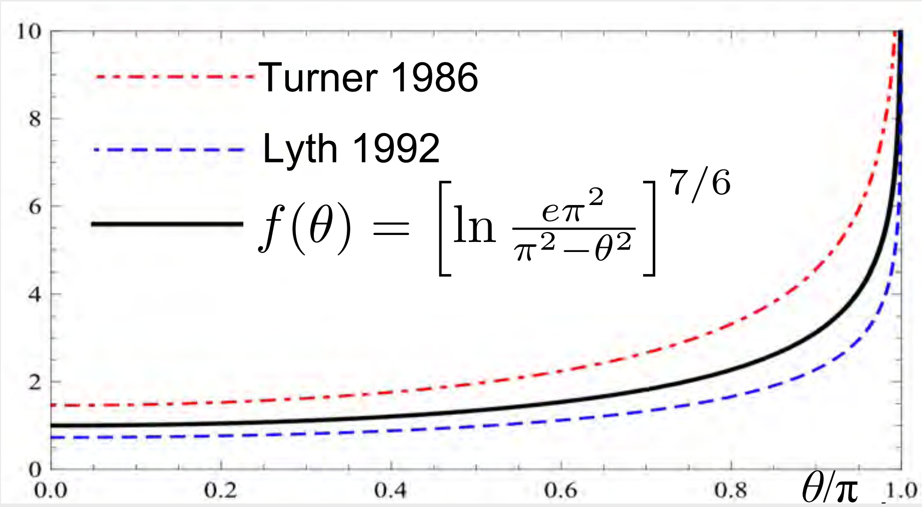
Axion CDM - Standard cosmology



Axion CDM - Standard cosmology

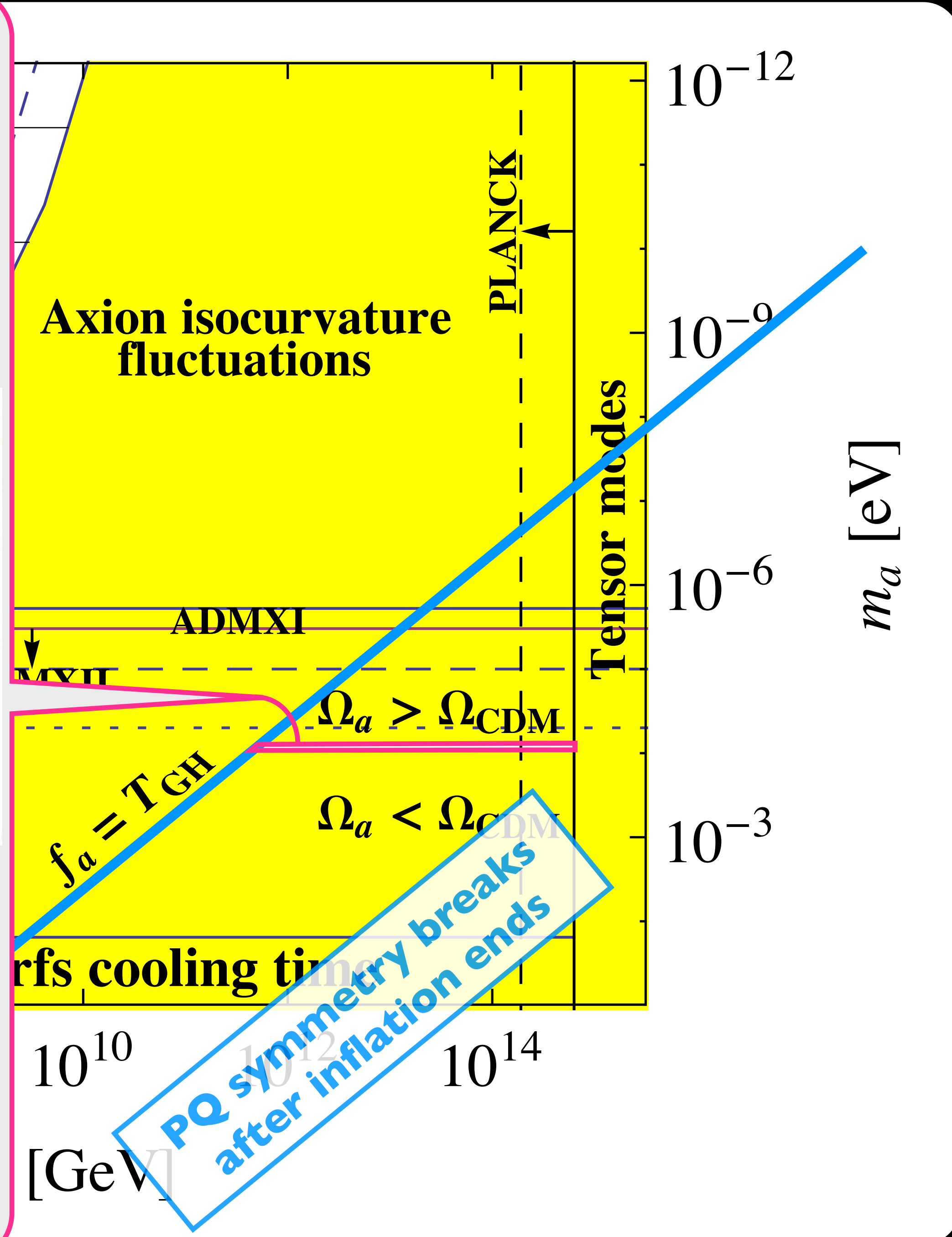
PQ symmetry breaks after inflation ends

- Average θ_i over Hubble volume
- Anharmonicities are important

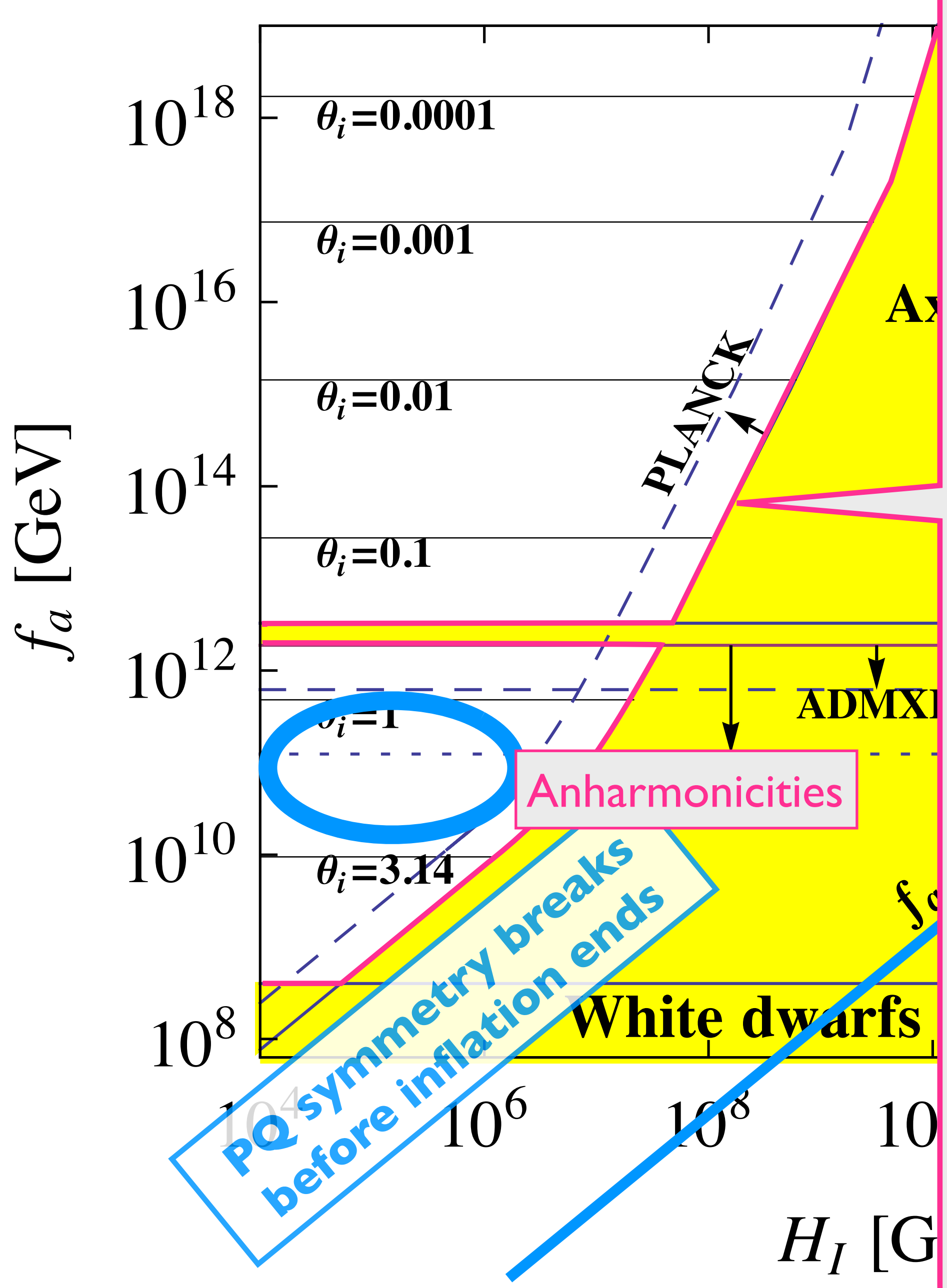


$$\langle \theta_i^2 f(\theta_i) \rangle = (2.96)^2$$

- String decay contribution is ~16% of vacuum realignment



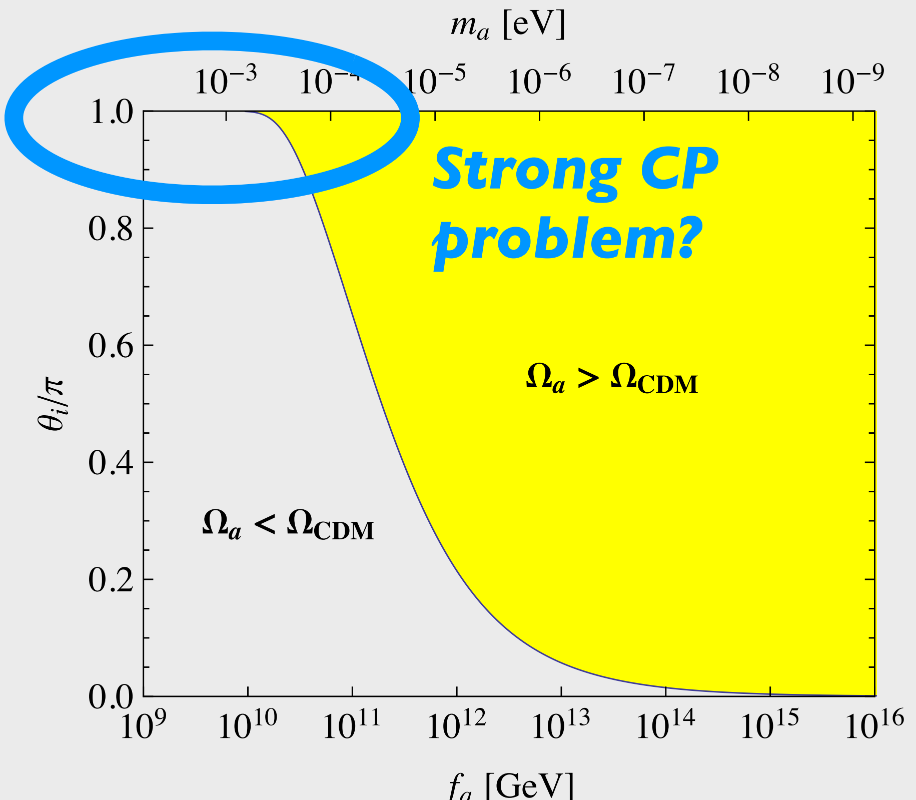
Axion CDM - Standard cosmology



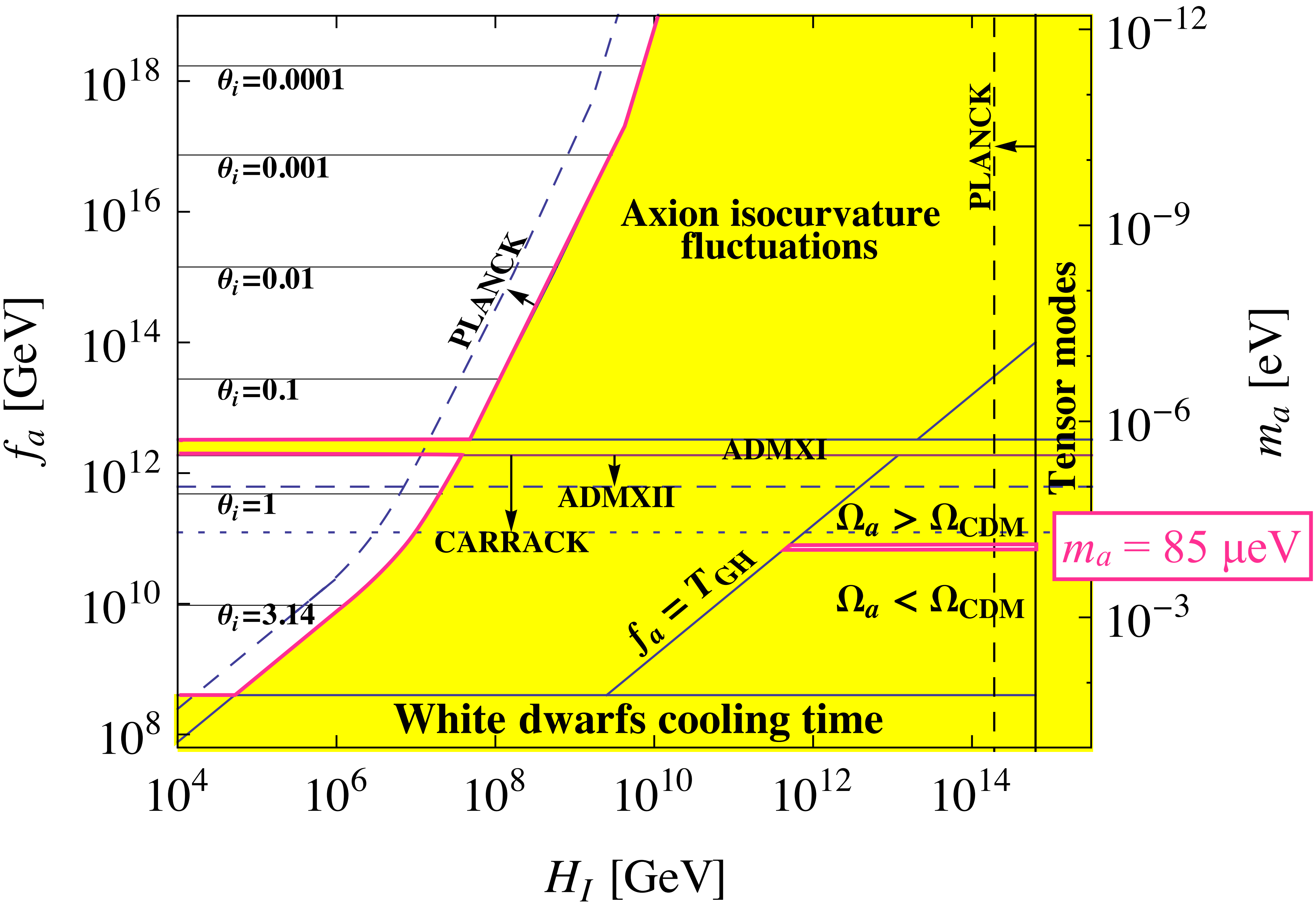
PQ symmetry breaks before inflation ends

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

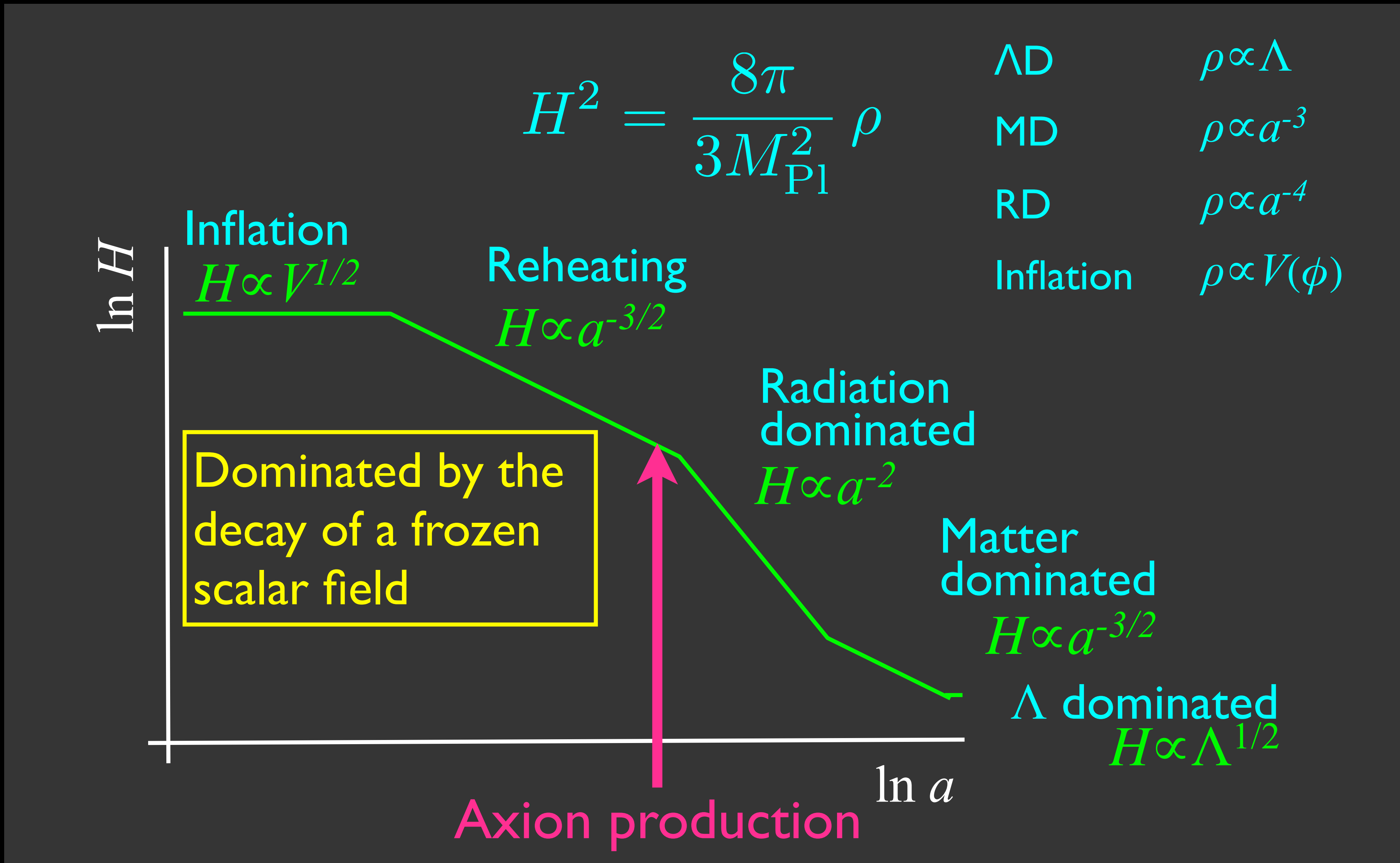
$$\langle \theta_i^2 f(\theta_i) \rangle = \left[\theta_i^2 + \left(\frac{H_I}{2\pi f_a} \right)^2 \right] f(\theta_i)$$



Axion CDM - Standard cosmology

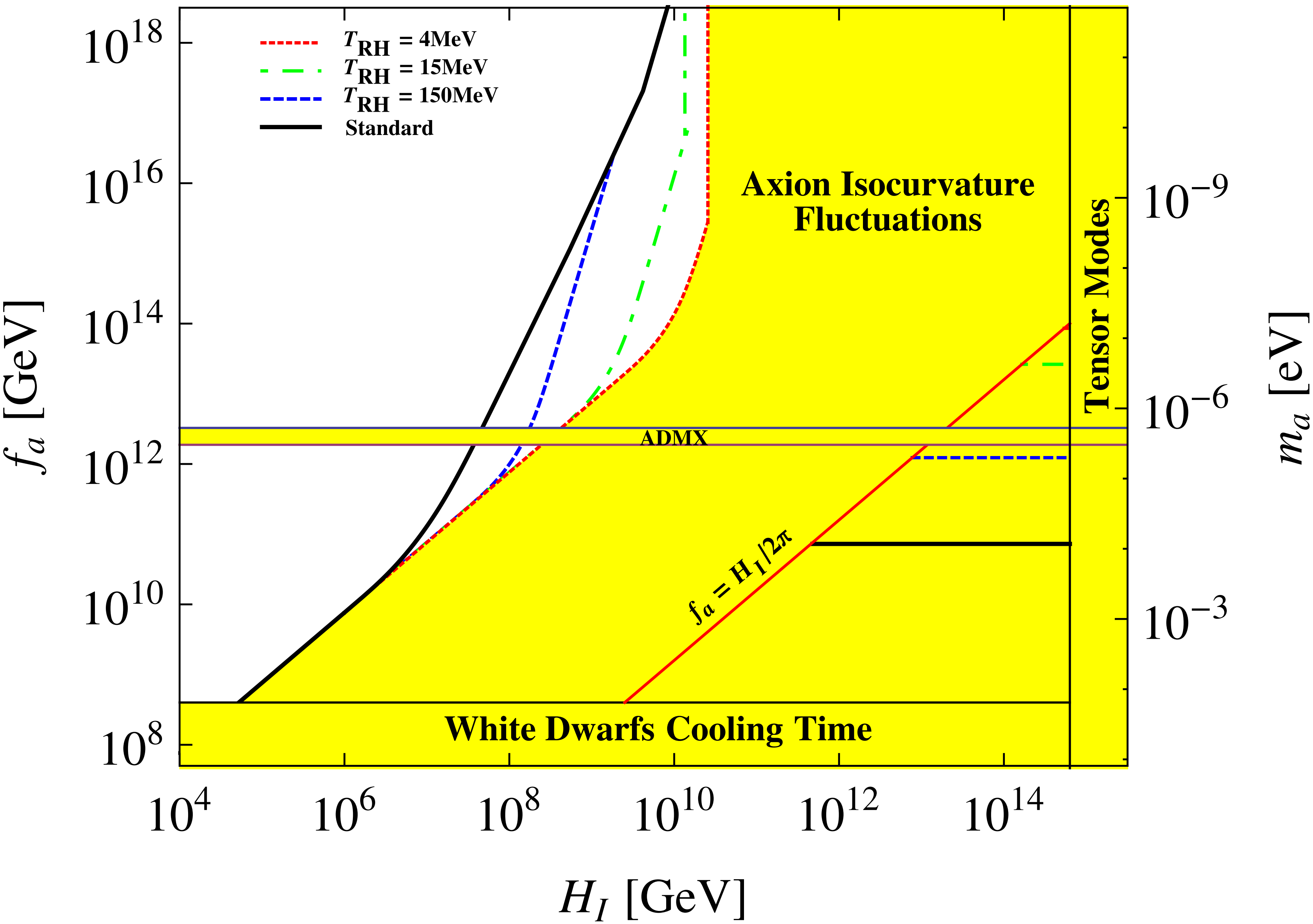


Low Temperature Reheating cosmology

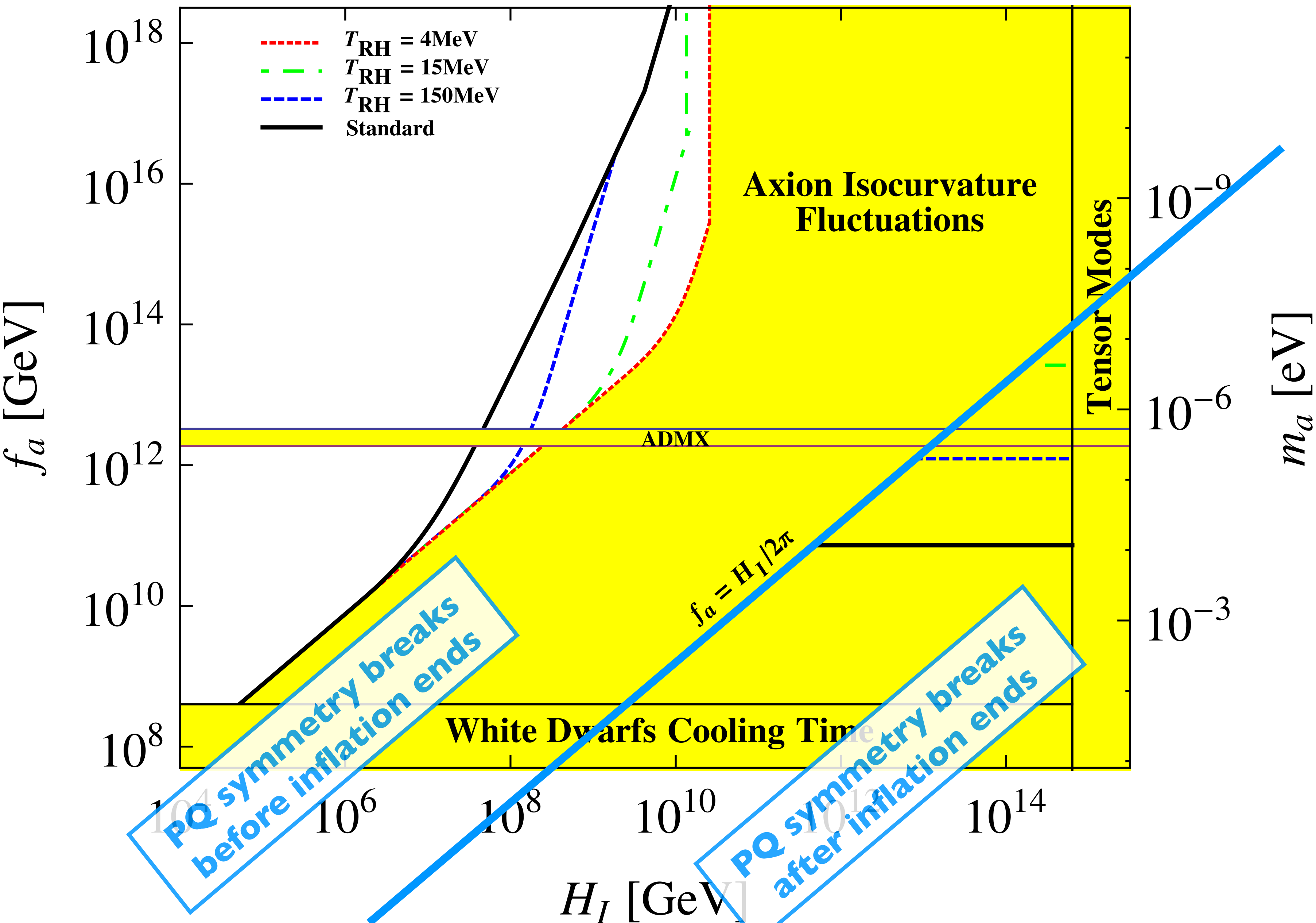


Turner 1983, Scherrer, Turner 1983, Dine, Fischler 1983

Axion CDM - Low Temp. Reheating cosmology



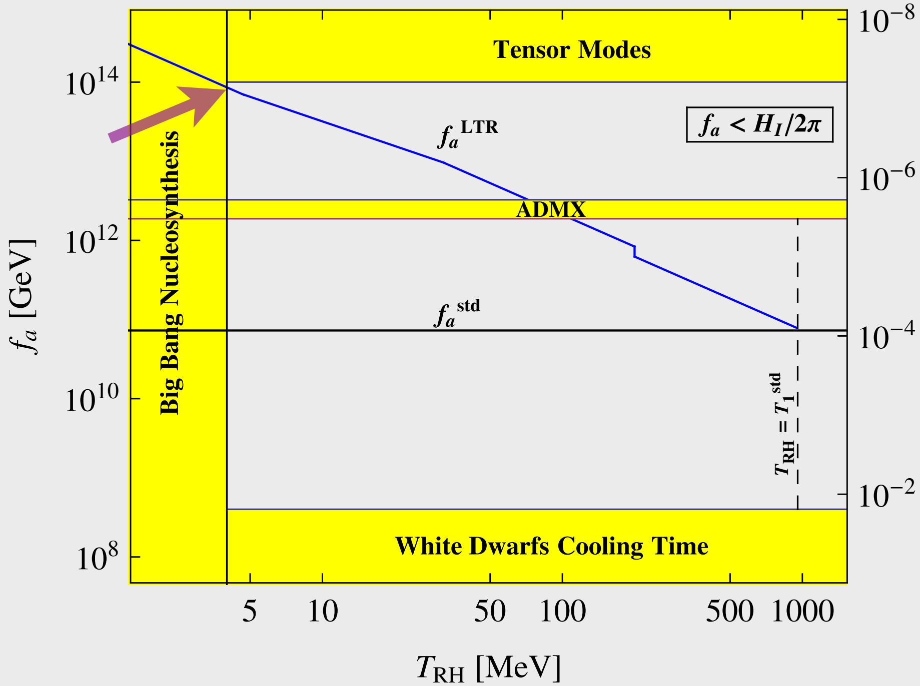
Axion CDM - Low Temp. Reheating cosmology

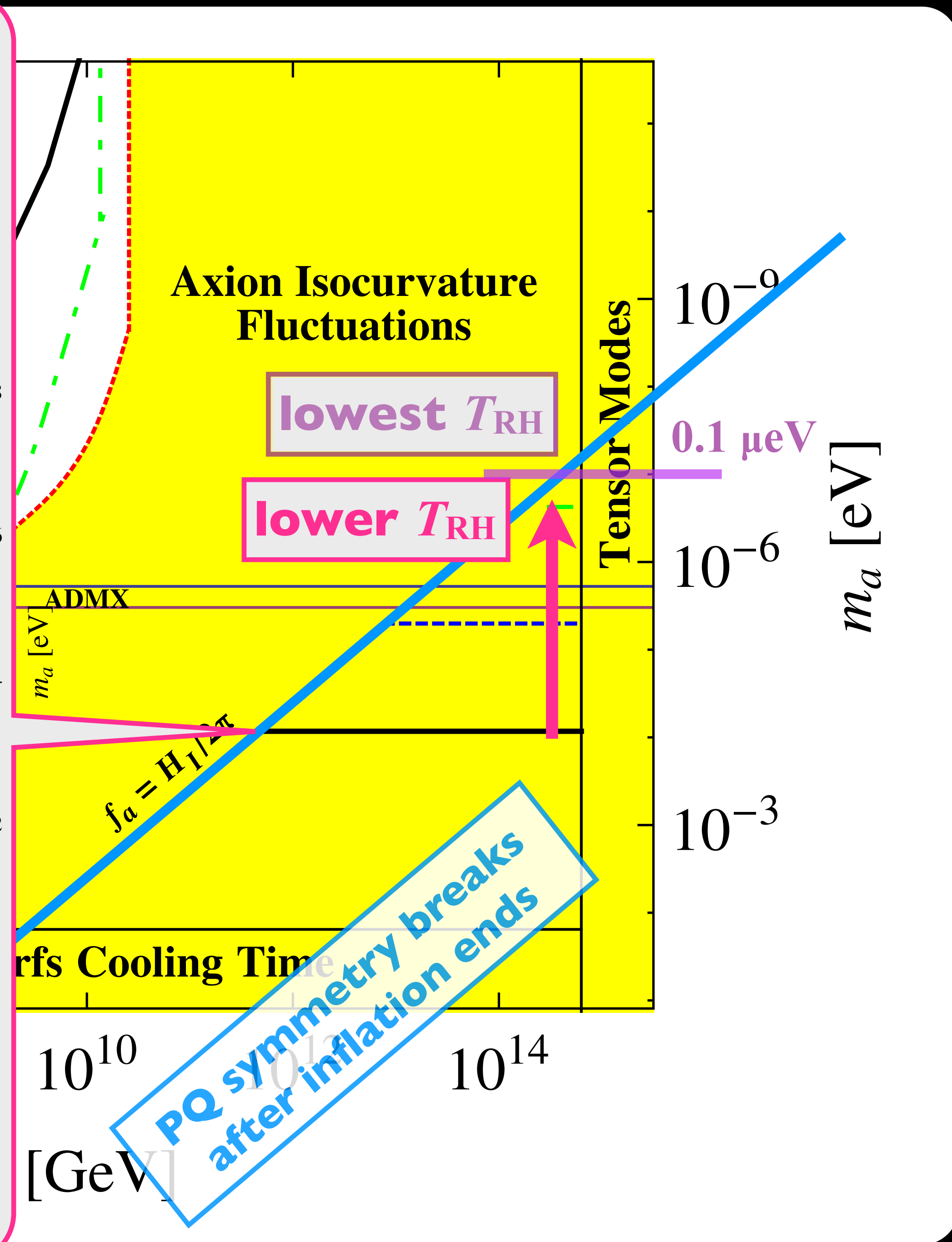


Axion CDM - Low Temp. Reheating cosmology

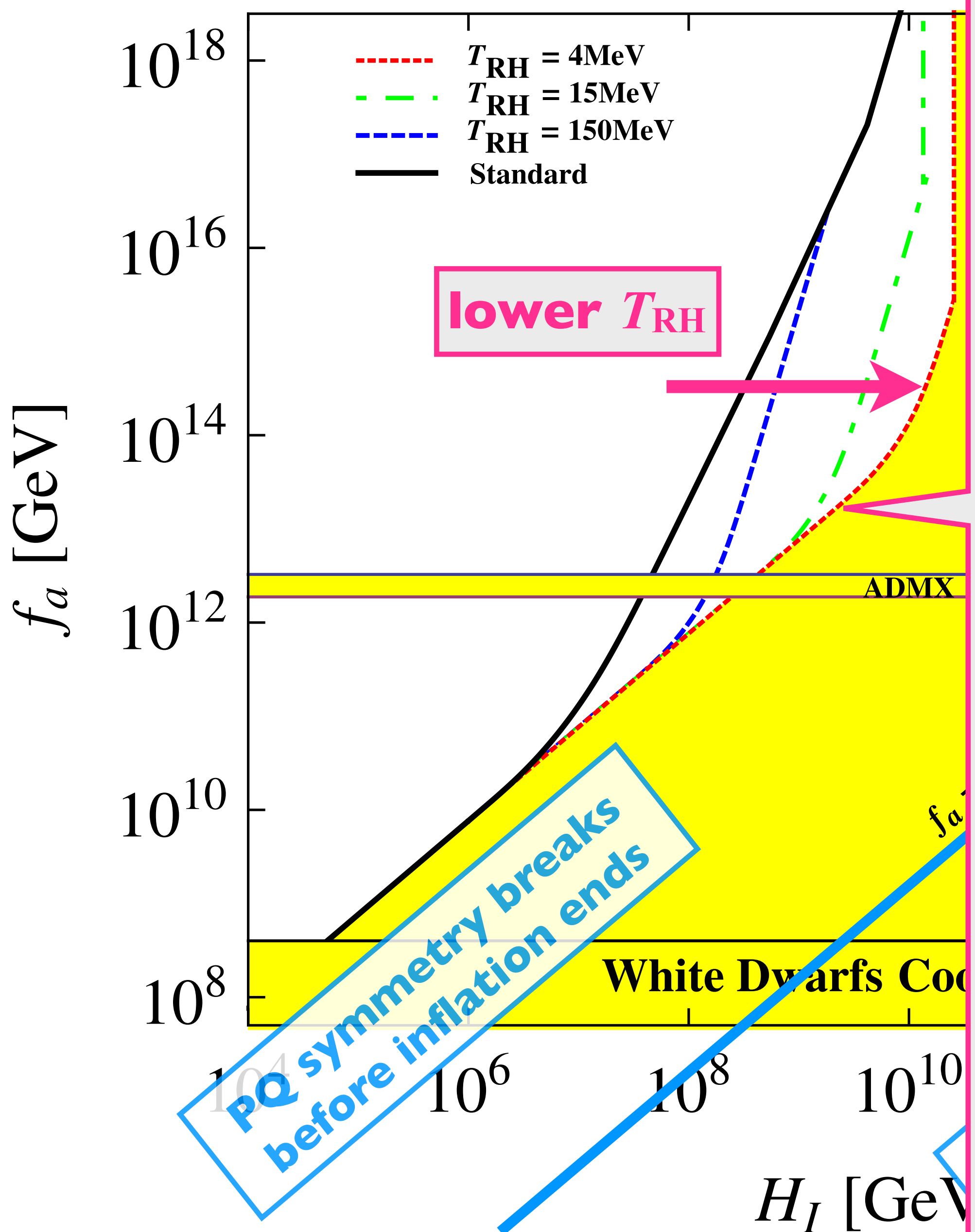
PQ symmetry breaks after inflation ends

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



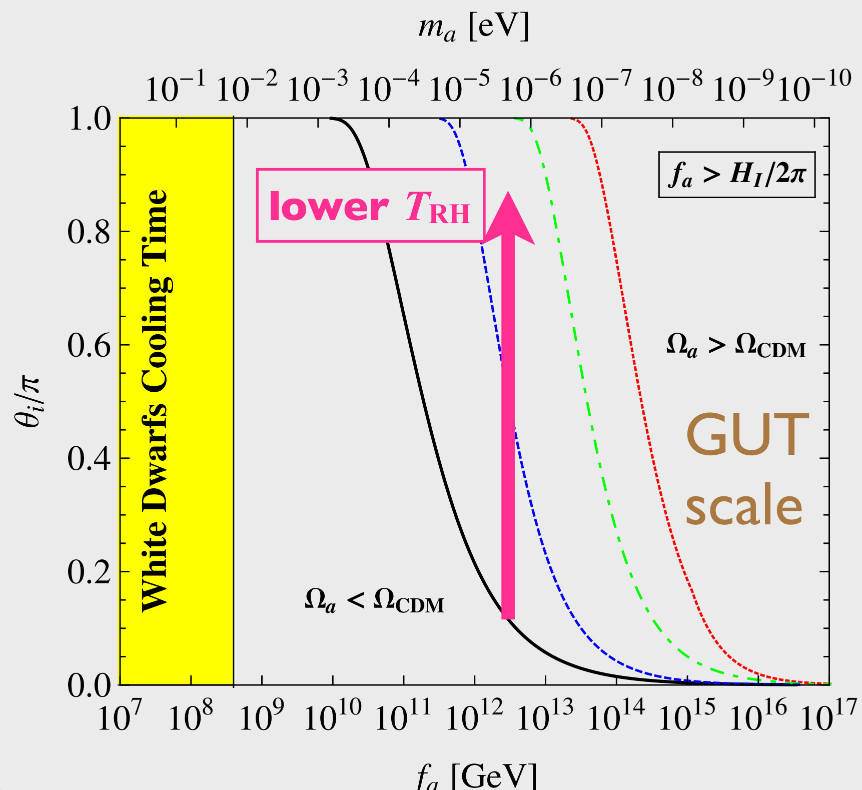


Axion CDM - Low Temp. Reheating cosmology

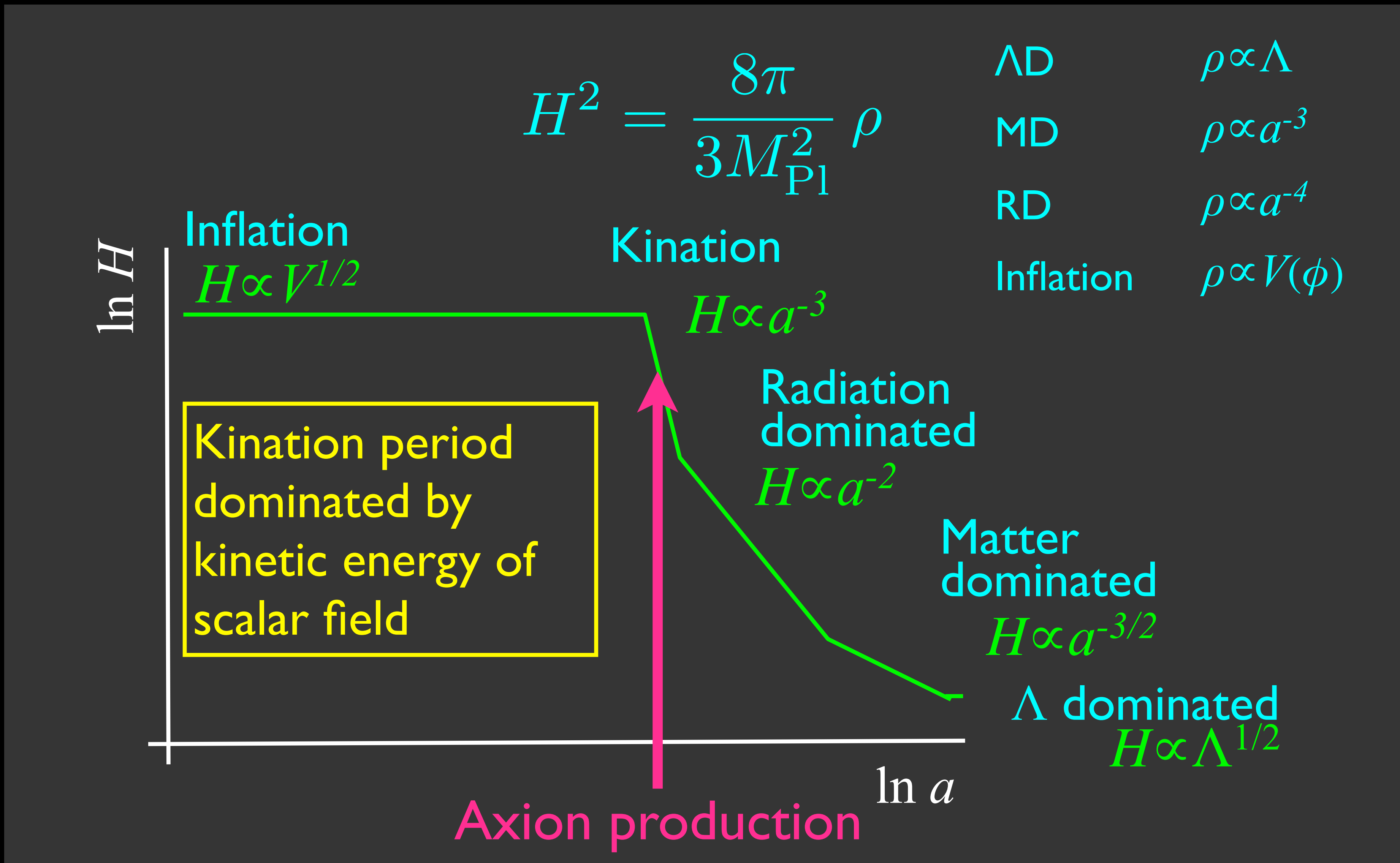


PQ symmetry breaks before inflation ends

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

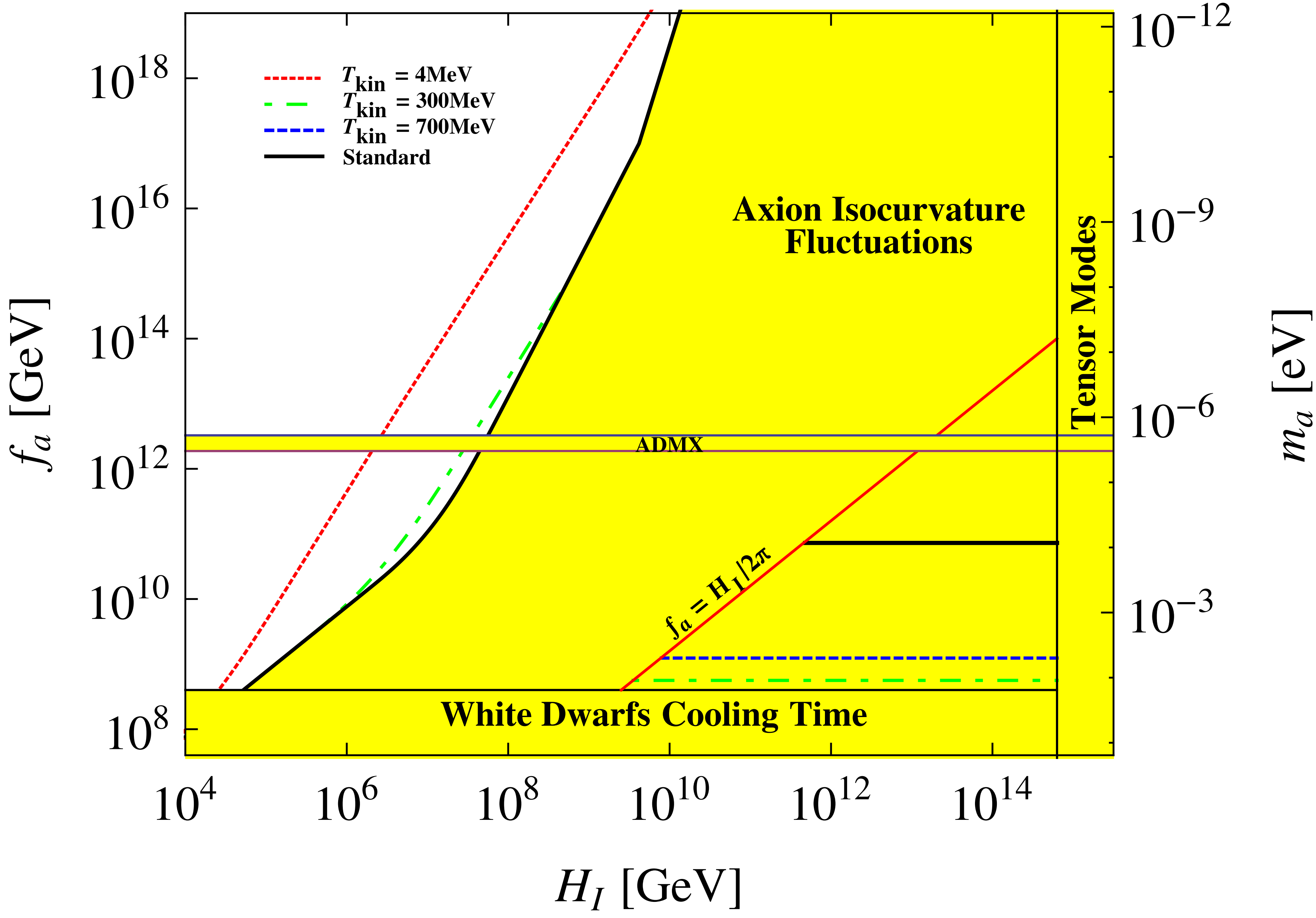


Kination cosmology

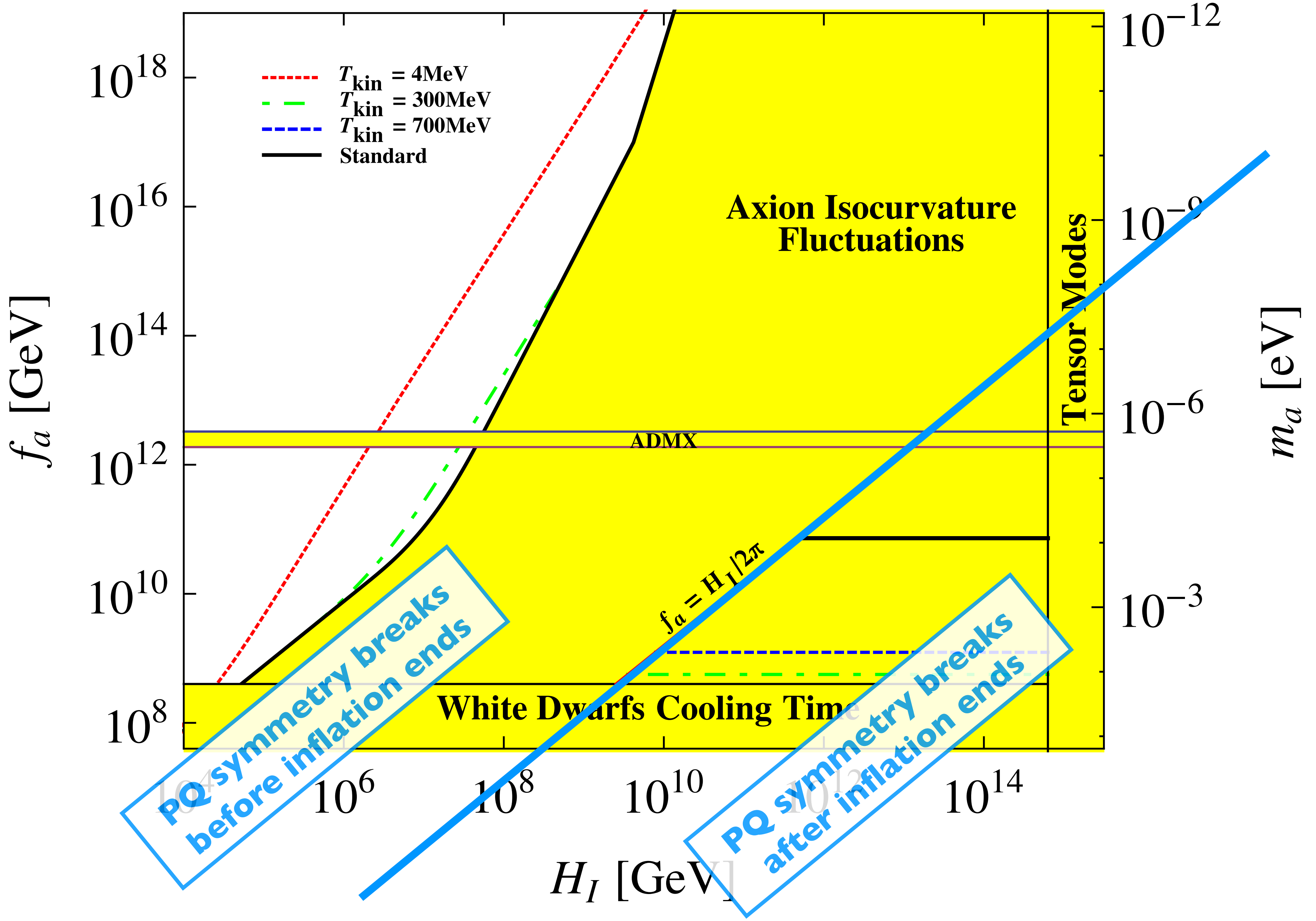


Ford 1987

Axion CDM - Kination cosmology



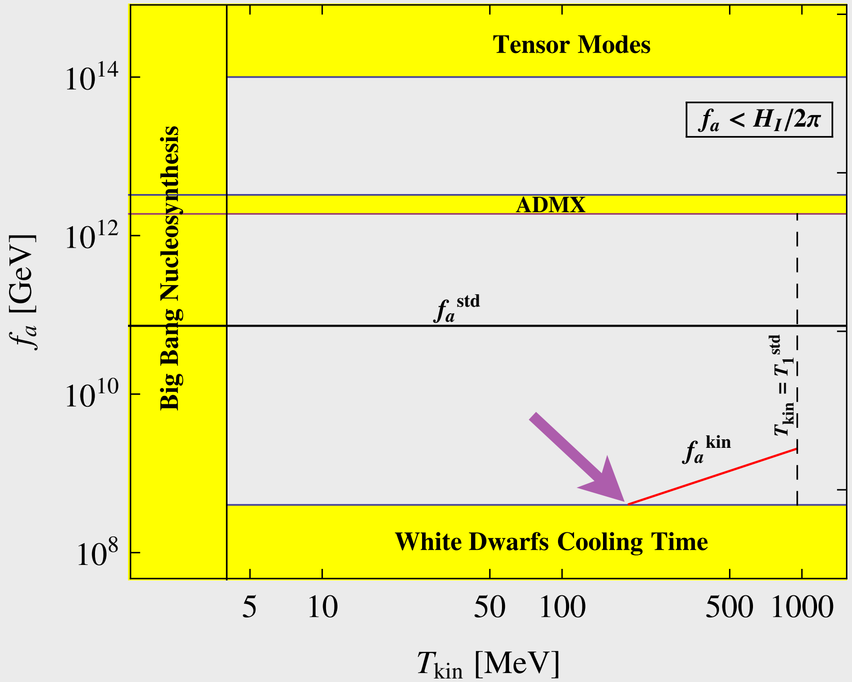
Axion CDM - Kination cosmology

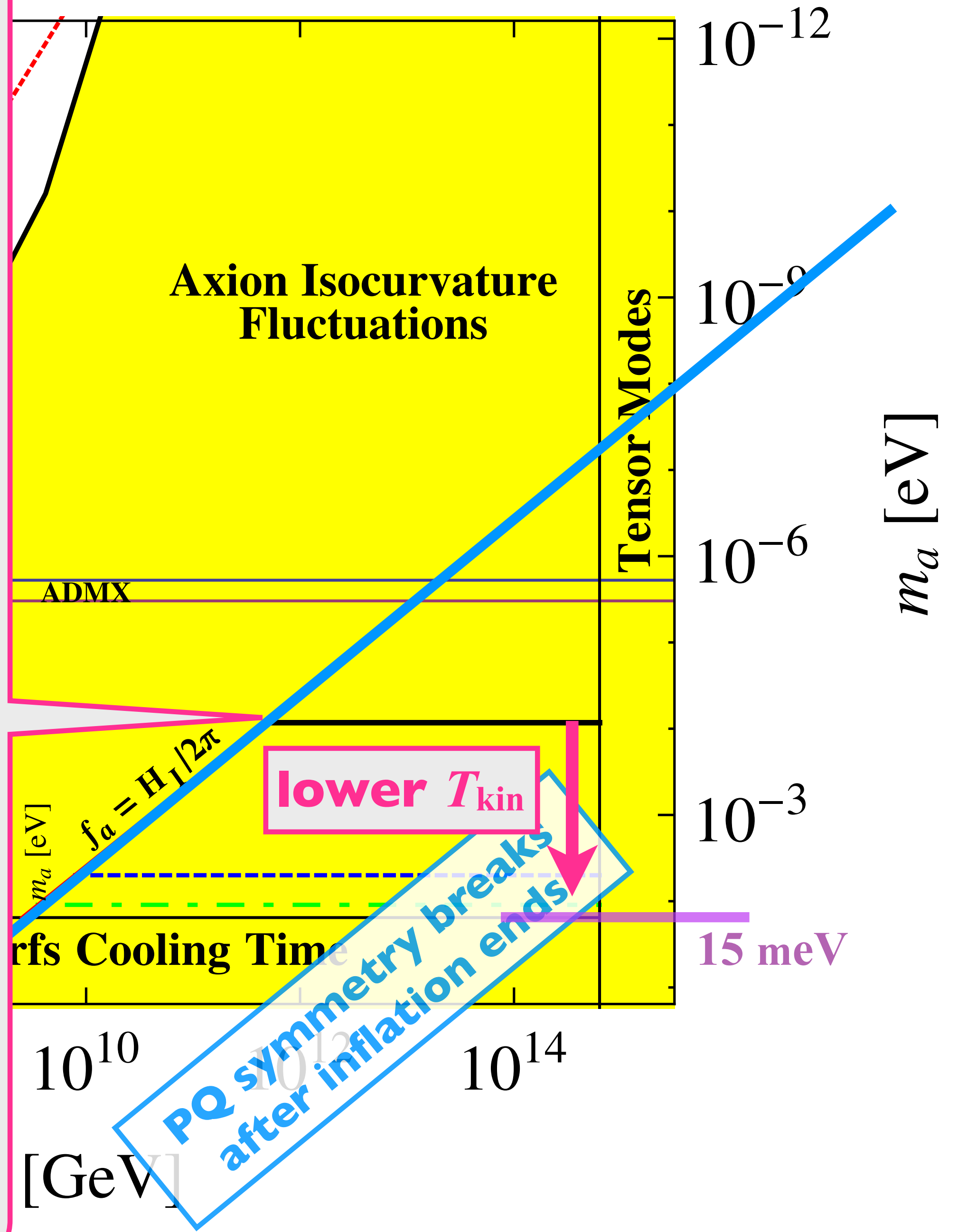


Axion CDM - Kination cosmology

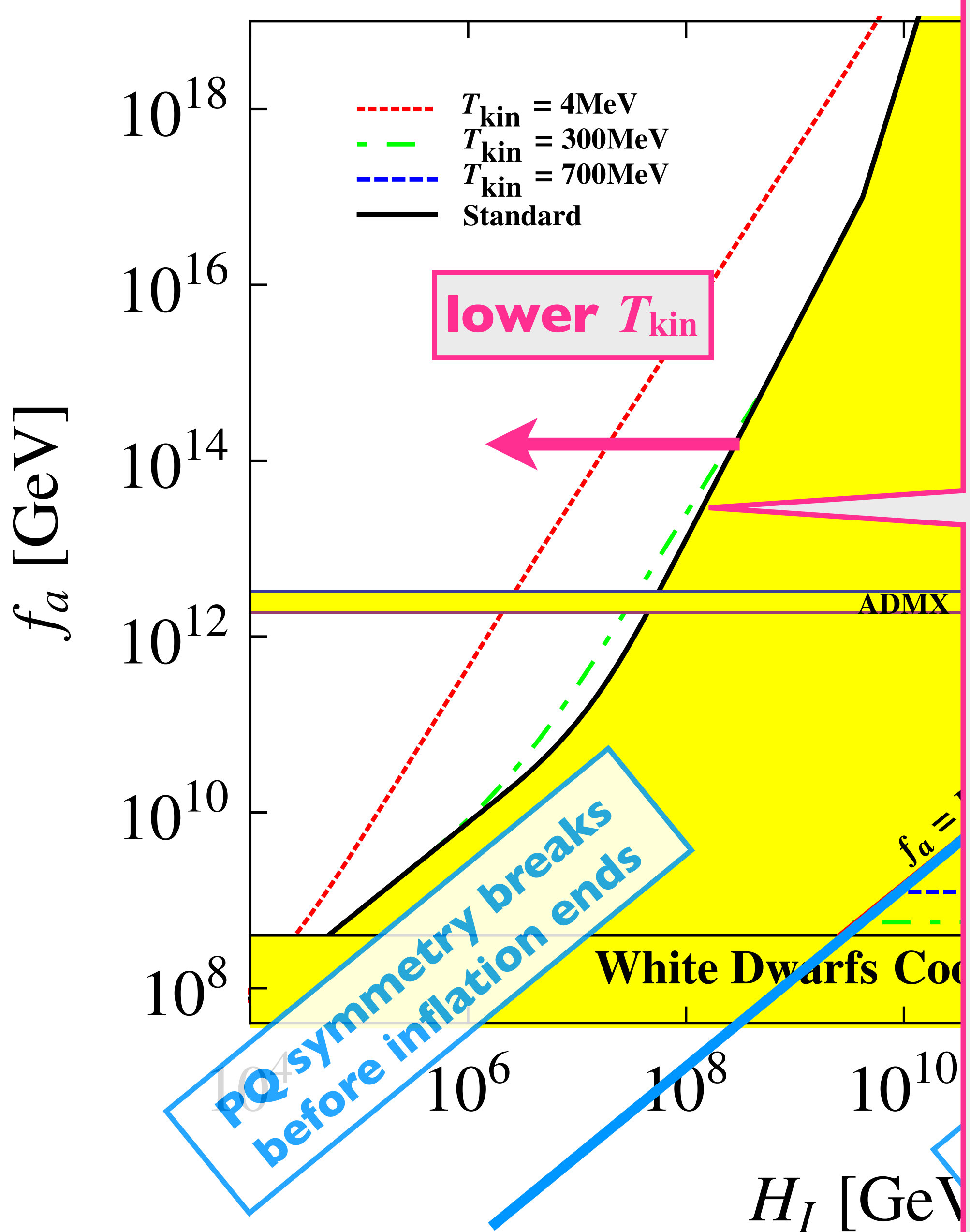
PQ symmetry breaks after inflation ends

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



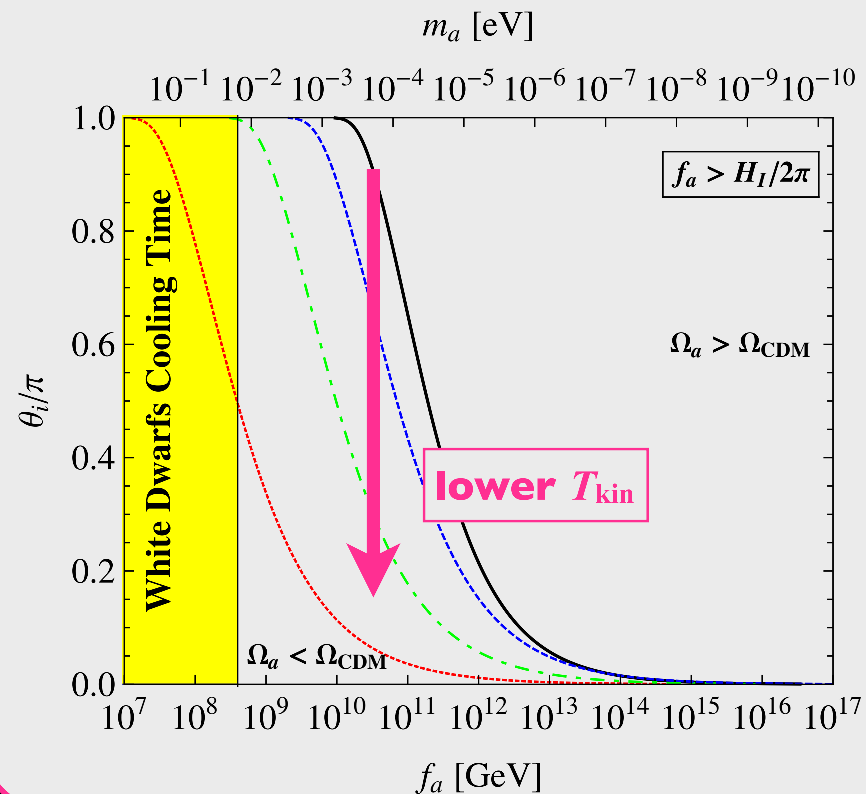


Axion CDM - Kination cosmology



PQ symmetry breaks before inflation ends

- As T_{kin} decreases, constraints from non-adiabatic fluctuations become stronger
- And the required initial misalignment angle θ_i is 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=83 μeV** in standard cosmology
  - much smaller m_a in LTR cosmology
  - much larger m_a in kination cosmology

0.1 μeV<m_a<15 meV

- If the Peccei-Quinn symmetry breaks before inflation ends, an initial misalignment angle θ_i can be chosen for any **m_a<15 meV**
  - larger allowed region and larger θ_i in LTR cosmology
  - smaller allowed region and smaller θ_i in kination cosmology