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Cosmological axion constraints in non-standard thermal histories

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Collaborators: Tristan Smith and Marc Kamionkowski

Outline:

- Cosmological constraints to hot thermal axions
- Non-standard thermal histories
- Constraints in non-standard thermal histories are *significantly* relaxed!
- Future work

Axions

- Axions have a two-photon coupling (Raffelt 1996, Kaplan1985)

$$g_{a\gamma\gamma} = -\frac{3\alpha}{8\pi f_{\rm a}}\xi \quad \xi \equiv \frac{4}{3}\left\{E/N - \frac{2\,(4+r)}{3\,(1+r)}\right\} \quad r = m_u/m_d$$

- Most experimental searches depend on two-photon coupling, e.g. completed telescope search at VLT in *Grin et al., Phys. Rev. D 75, 105018 (2007)*, astro-ph/0611502 and forthcoming more sensitive VLT search. If ξ vanishes, constraints are lifted!

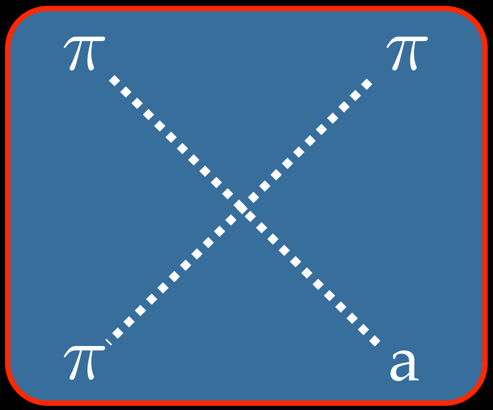
- If $m_{\rm a} \gtrsim 10^{-2}$ eV , axions are produced thermally, yielding sub-dominant cosmological population of Hot axions

$$\Omega_{\rm a} h^2 \simeq \frac{m_{\rm a}}{130\ {\rm eV}}\left(\frac{10}{g_{*{\rm S},{\rm F}}}\right)$$

These can be probed using cosmological tests!

Hot axion production at early times

Axion Production (Chang and Choi 1993):



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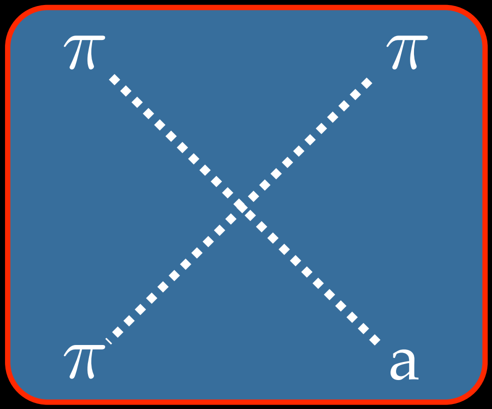

- Axions produced through interactions (standard hadronic axions) between non-relativistic pions in chemical equilibrium with rate

$$\Gamma \sim n_\pi \langle \sigma v \rangle = \frac{T^2 m_{\rm a}^2 (1-r)^2}{9 r f_\pi^4 m_\pi^2} \left(\frac{m_\pi T}{2\pi} \right)^{3/2} e^{-m_\pi/T} \qquad r = m_u/m_d$$

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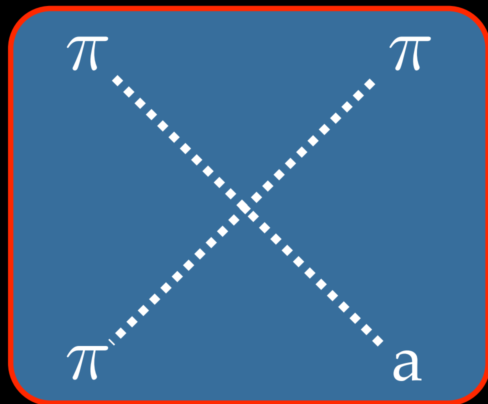

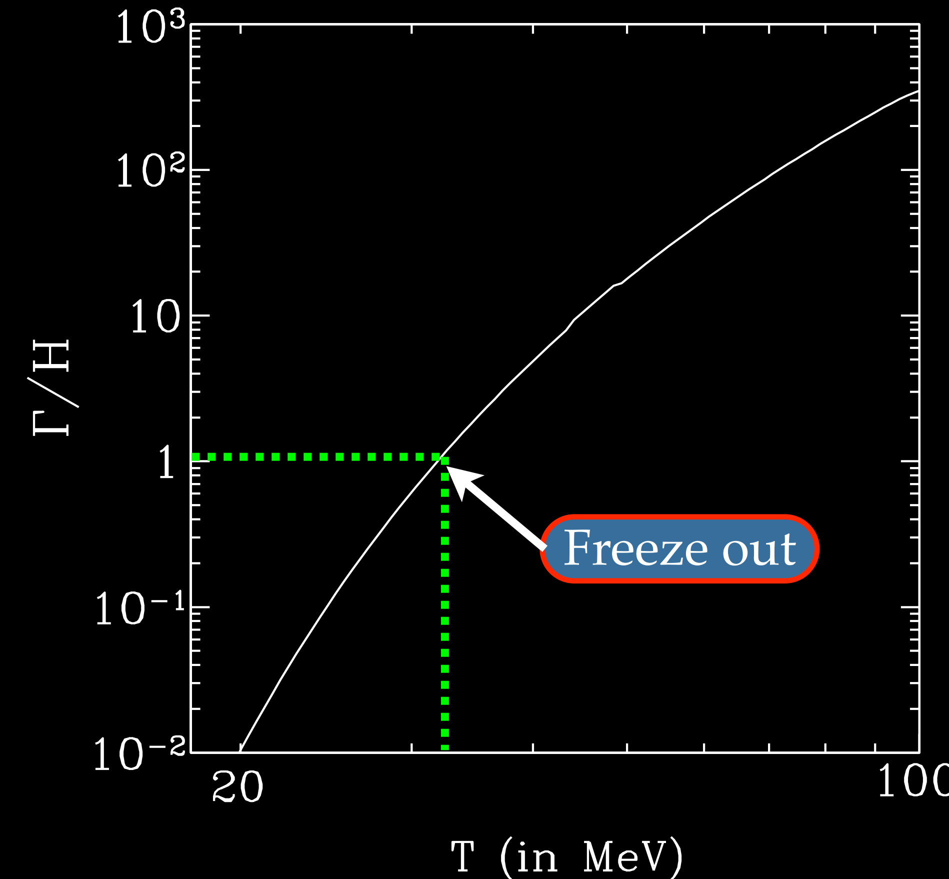

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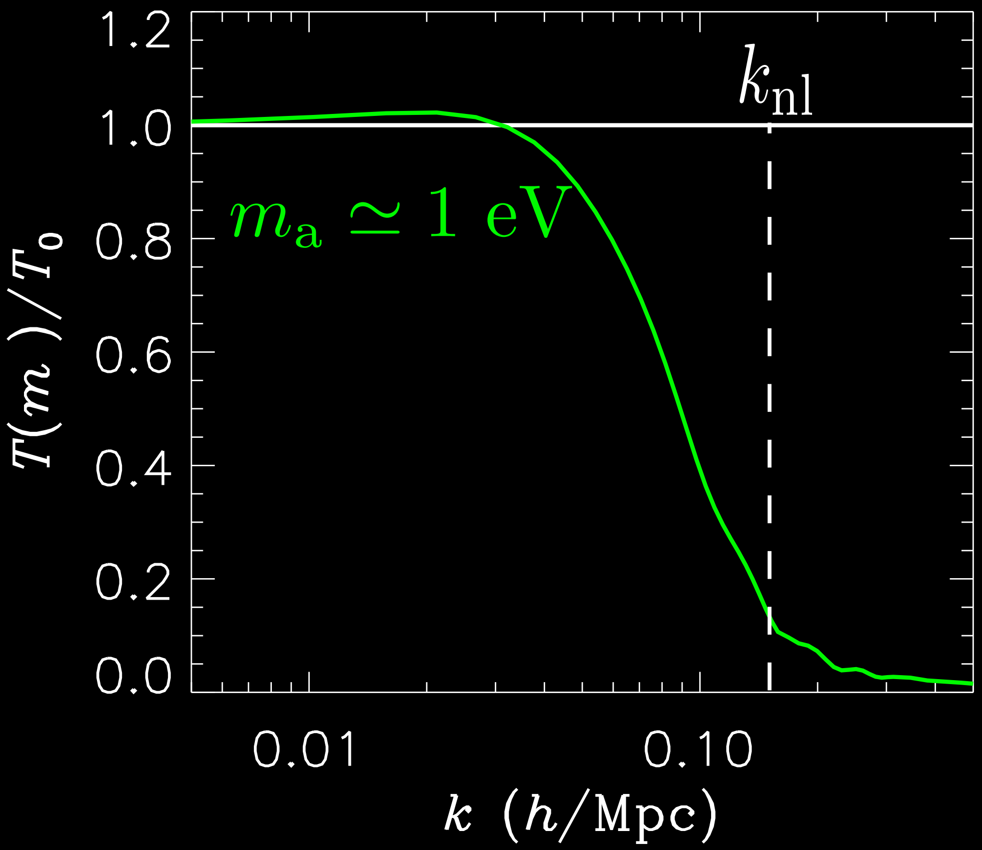
The physics of cosmological axion constraints

- Axions are relativistic at early times, free stream and suppress power by $\Delta P/P \simeq -8\Omega_{\rm a}/\Omega_{\rm m}$ when $\lambda \lesssim \lambda_{\rm fs}$



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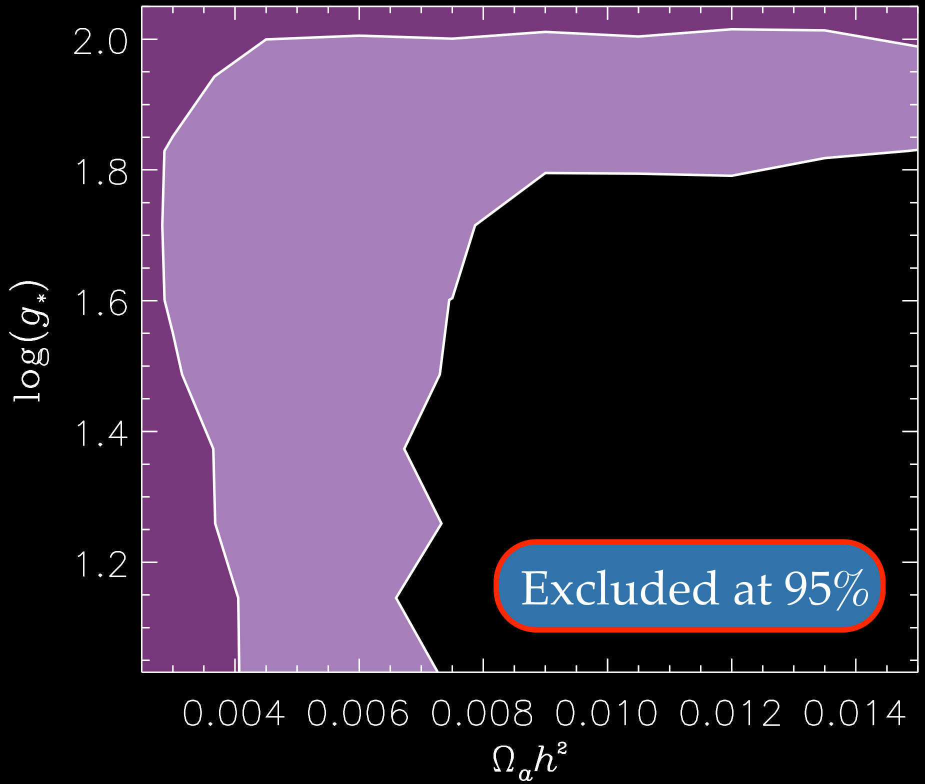

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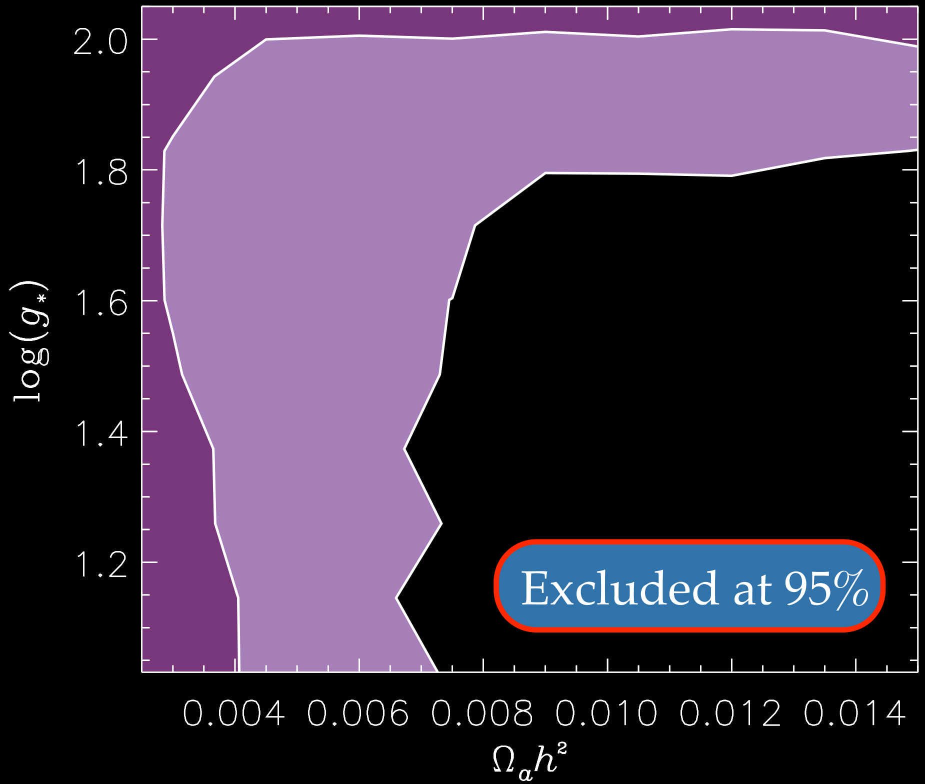

$$\frac{T_{\rm a}}{T_\nu} \simeq \left(\frac{10.75}{g_{*{\rm S},{\rm F}}}\right)^{1/3}$$

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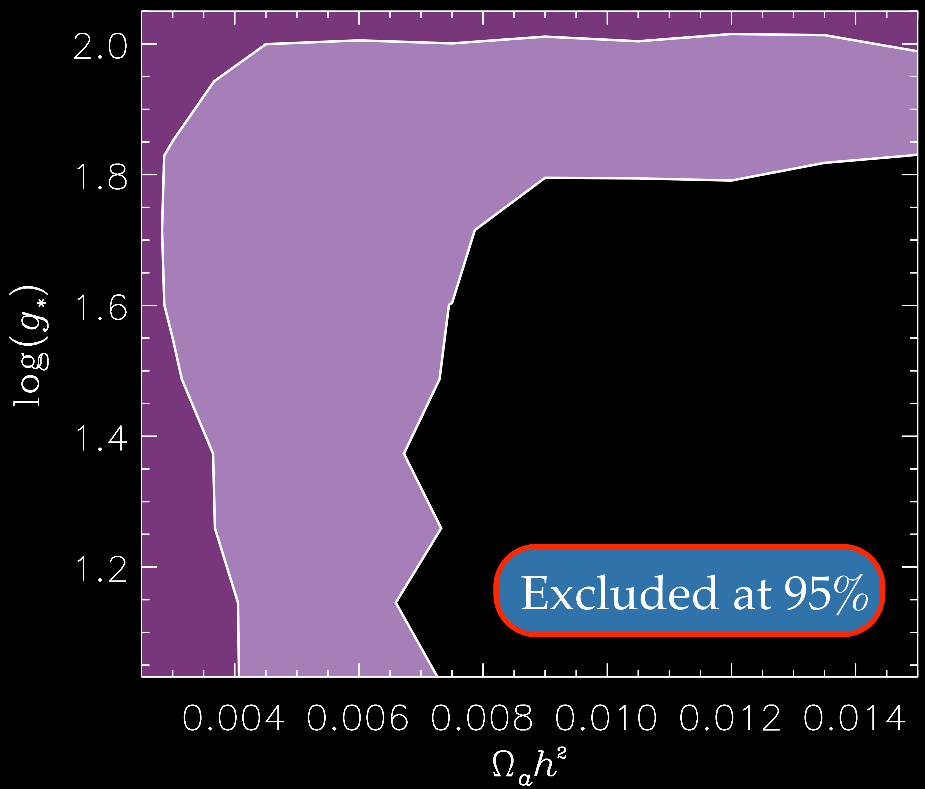

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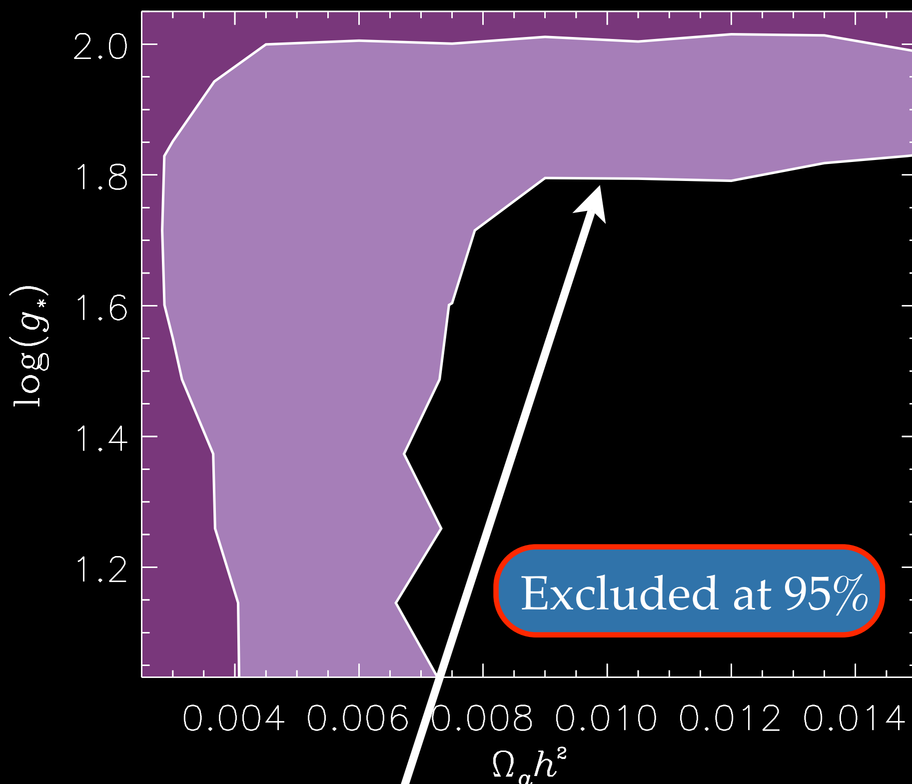


$\lambda_{\rm fs} \rightarrow \lambda_{\rm nl} \simeq 30\ h^{-1}\ {\rm Mpc}$

Low-temperature reheating (LTR)

- We do not know exact thermal history before BBN. BBN is ok if $T_{\rm rh} \gtrsim 4~{\rm MeV}$. Also, harmful relics are washed out for low $T_{\rm rh}$ (Nanopoulos and others).

- Simple model in which $\phi \to$ radiation is responsible for extended reheating phase (Giudice, Kolb, Riotto 2001)

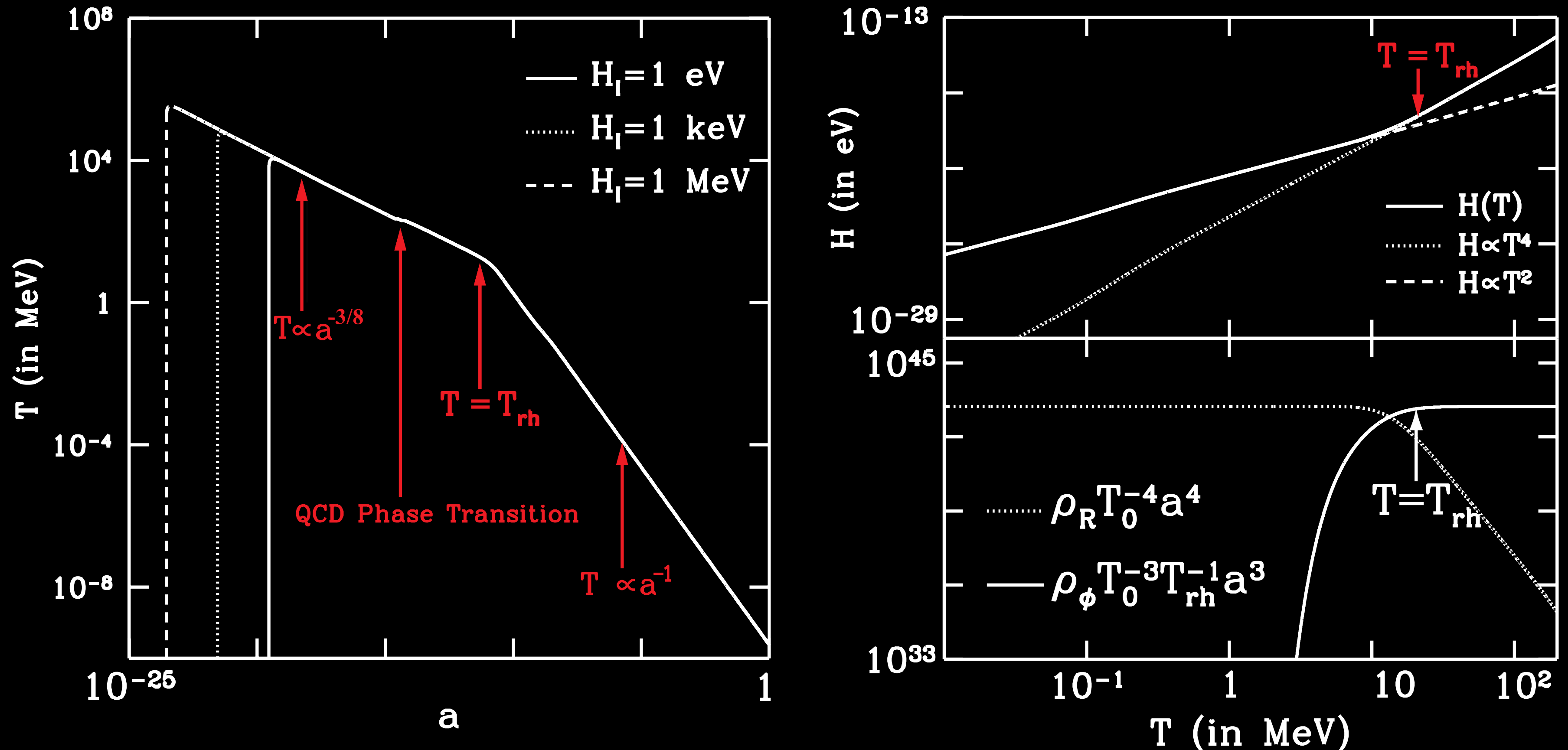
$$\frac{d\rho_{\rm R}}{dt} + 4H\rho_{\rm R} = \Gamma_{\phi}\rho_{\phi} \qquad \frac{d\rho_{\phi}}{dt} + 3H\rho_{\phi} = -\Gamma_{\phi}\rho_{\phi}$$

- Decay products thermalize and entropy generated

$$T = \left[\frac{30}{\pi^2 g_{*}(T)}\right]^{1/4} \rho_{\rm R}^{1/4}$$

- Past work considered effects on other DM candidates and non-thermal axions (Giudice, Yaguna 2007) . *New work: LSS/CMB/total density constraints to hot axions in LTR*

Low-temperature reheating (LTR)



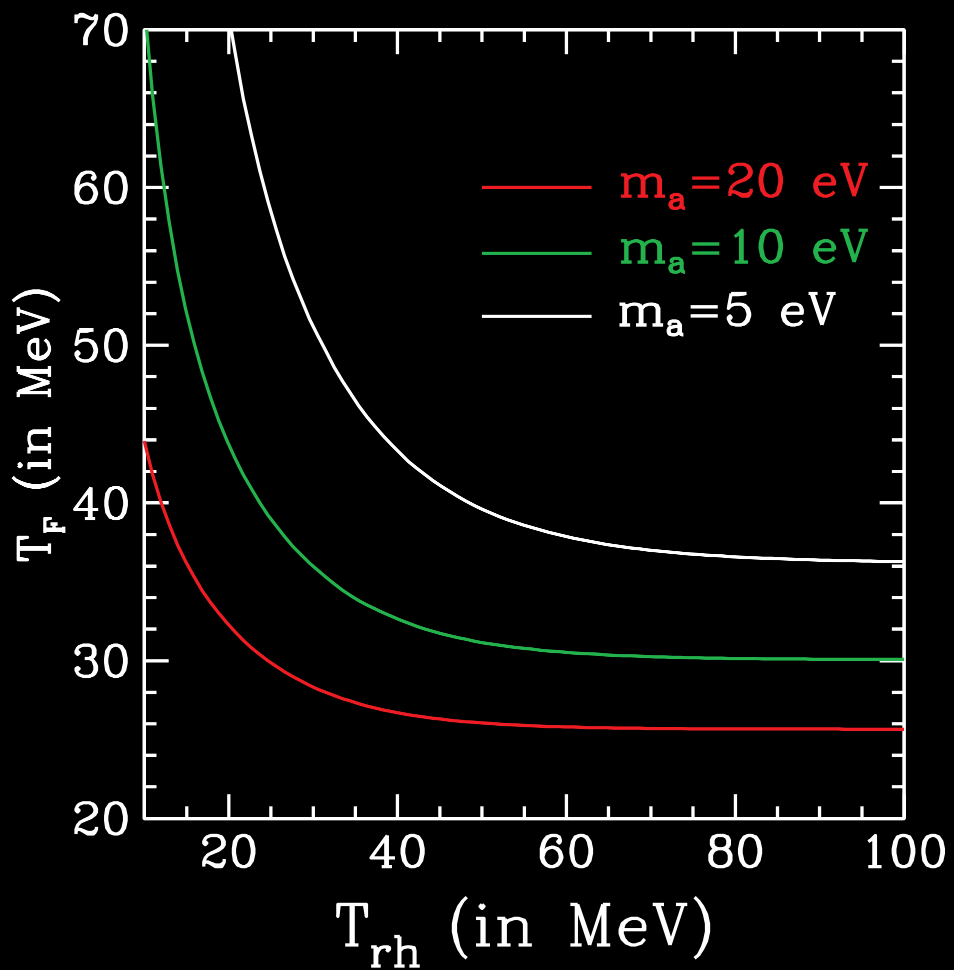
- ✳ Entropy generation slows down temperature decrease

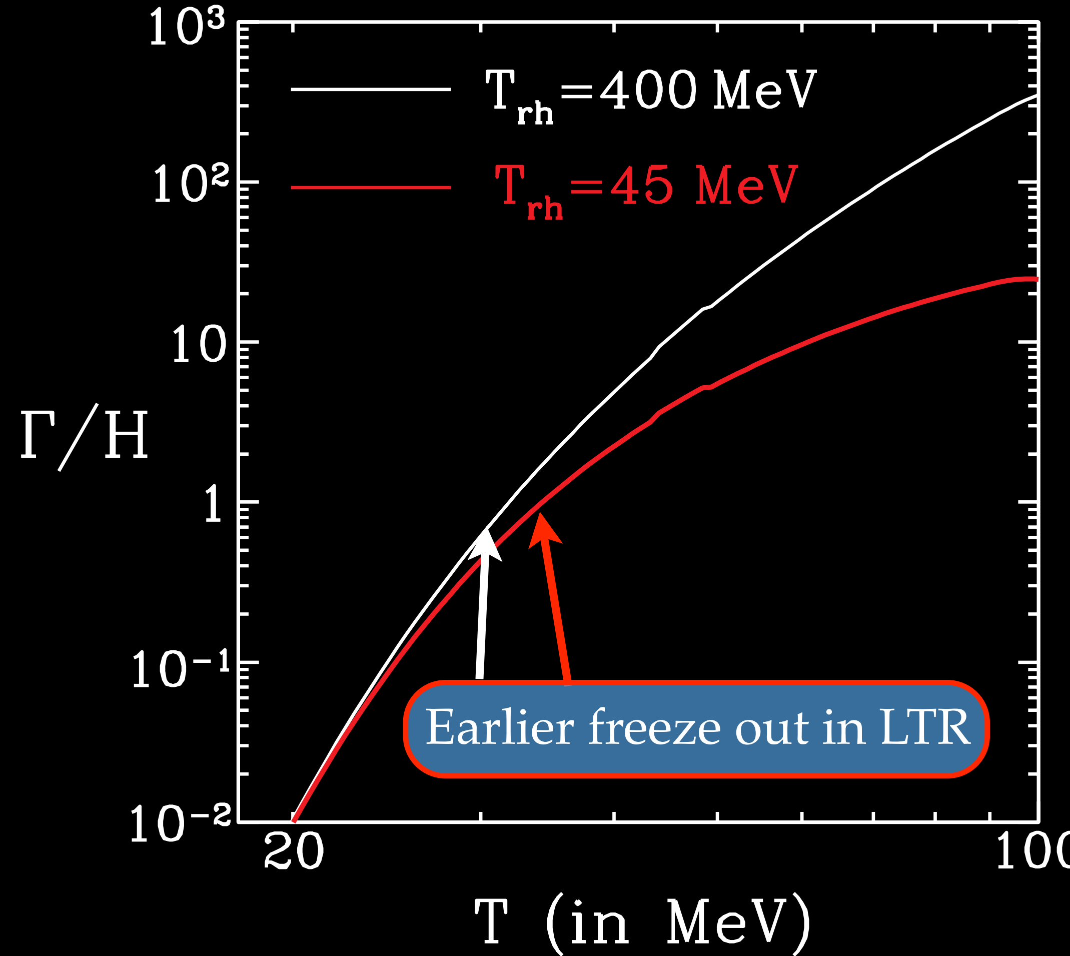
$$T \propto a^{-3/8} \text{ until } T \lesssim T_{\rm rh}, \text{ then } T \propto a^{-1}$$

- ✳ Hubble expansion is faster

$$H \propto T^4 \text{ until } T \lesssim T_{\rm rh}, \text{ then } H \propto T^2$$

Axion freeze out in LTR

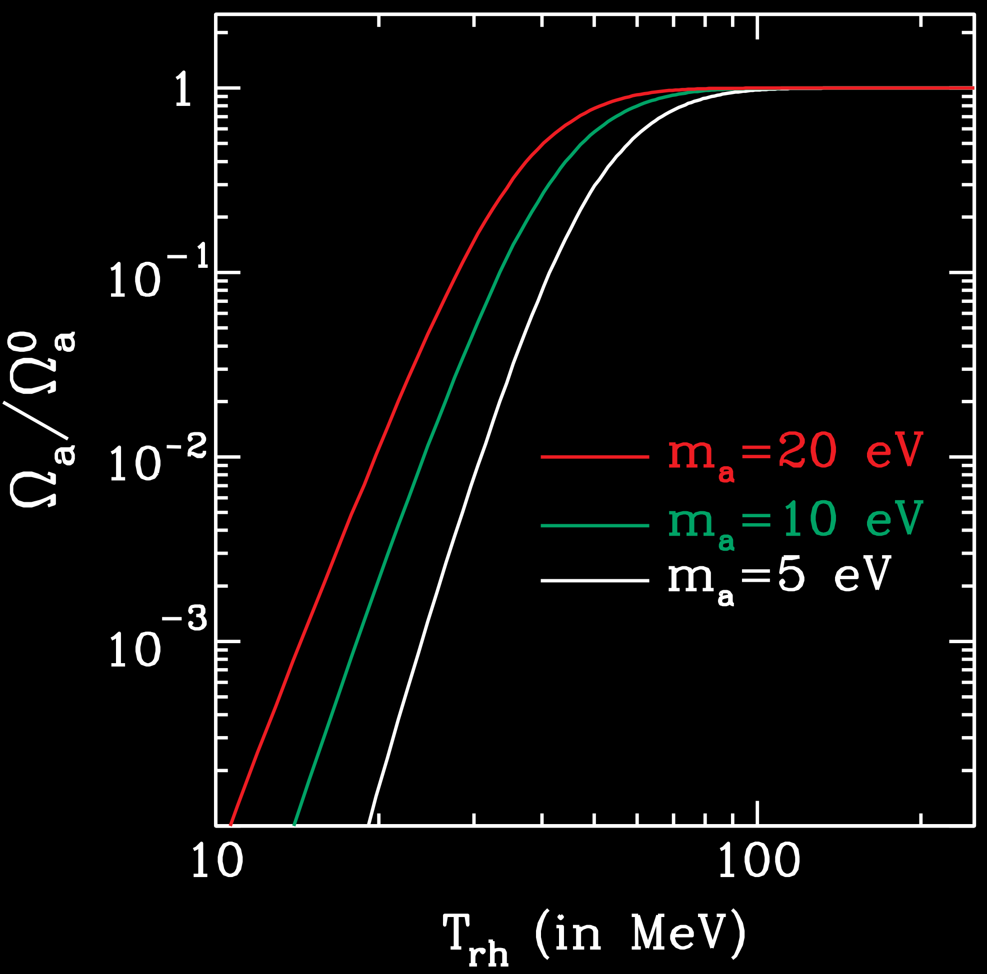




- ✳ Faster expansion: freeze-out is earlier
- ✳ When $T_{\rm rh} \gg T_{\rm F,0}$, standard results are recovered
- ✳ $\Gamma \propto f_{\rm a}^{-2} \propto m_{\rm a}^2$, so more massive axions freeze out later

Axion abundance in LTR

- Higher T_F means higher initial equilibrium abundance
- Entropy generation dramatically suppresses abundances



Axion temperature in LTR

- Entropy generation leads to $T_\mathrm{a} \propto a^{-1}$, while $T_\gamma \propto a^{-3/8}$:

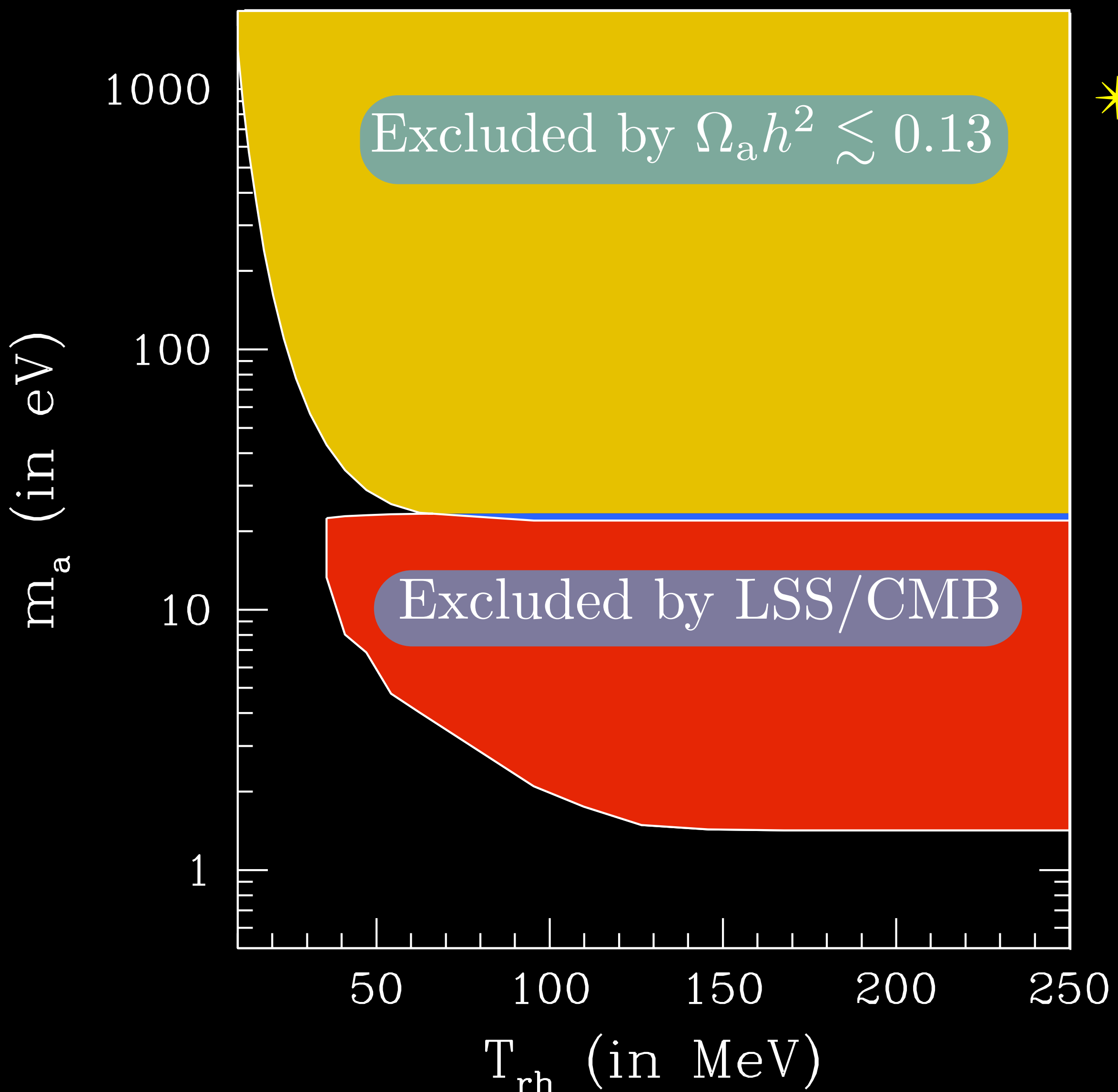
$$\frac{T_\mathrm{a}}{T_\nu} \approx (10.75/g_{*\mathrm{S,F}})^{1/3}, \qquad \text{if } T_\mathrm{F} < T_\mathrm{rh}.$$

$$\frac{T_a}{T_\nu} \simeq \left(\frac{11}{4}\right)^{1/3} \left(\frac{T_\mathrm{rh}}{T_\mathrm{F}}\right)^{5/3} \left(\frac{g^2_{*,\mathrm{RH}}\, g_{*\mathrm{S},0}}{g^2_{*,\mathrm{F}}\, g_{*\mathrm{S},\mathrm{RH}}}\right)^{1/3} \qquad \text{if } T_\mathrm{F} > T_\mathrm{rh}.$$

- Axions non-relativistic earlier: Smaller free-streaming length!

$$\lambda_\mathrm{fs} \simeq \frac{196\ \mathrm{Mpc}}{m_\mathrm{a,eV}} \left(\frac{T_\mathrm{a}}{T_\nu}\right) \left\{1 + \ln\left[0.45 m_\mathrm{a,eV} \left(\frac{T_\nu}{T_\mathrm{a}}\right)\right]\right\}.$$

New constraints in LTR



- $\lambda_{fs}\,(T_{rh}, m_a)$ & $\Omega_a h^2\,(T_{rh}, m_a)$ calculated to trace out allowed region

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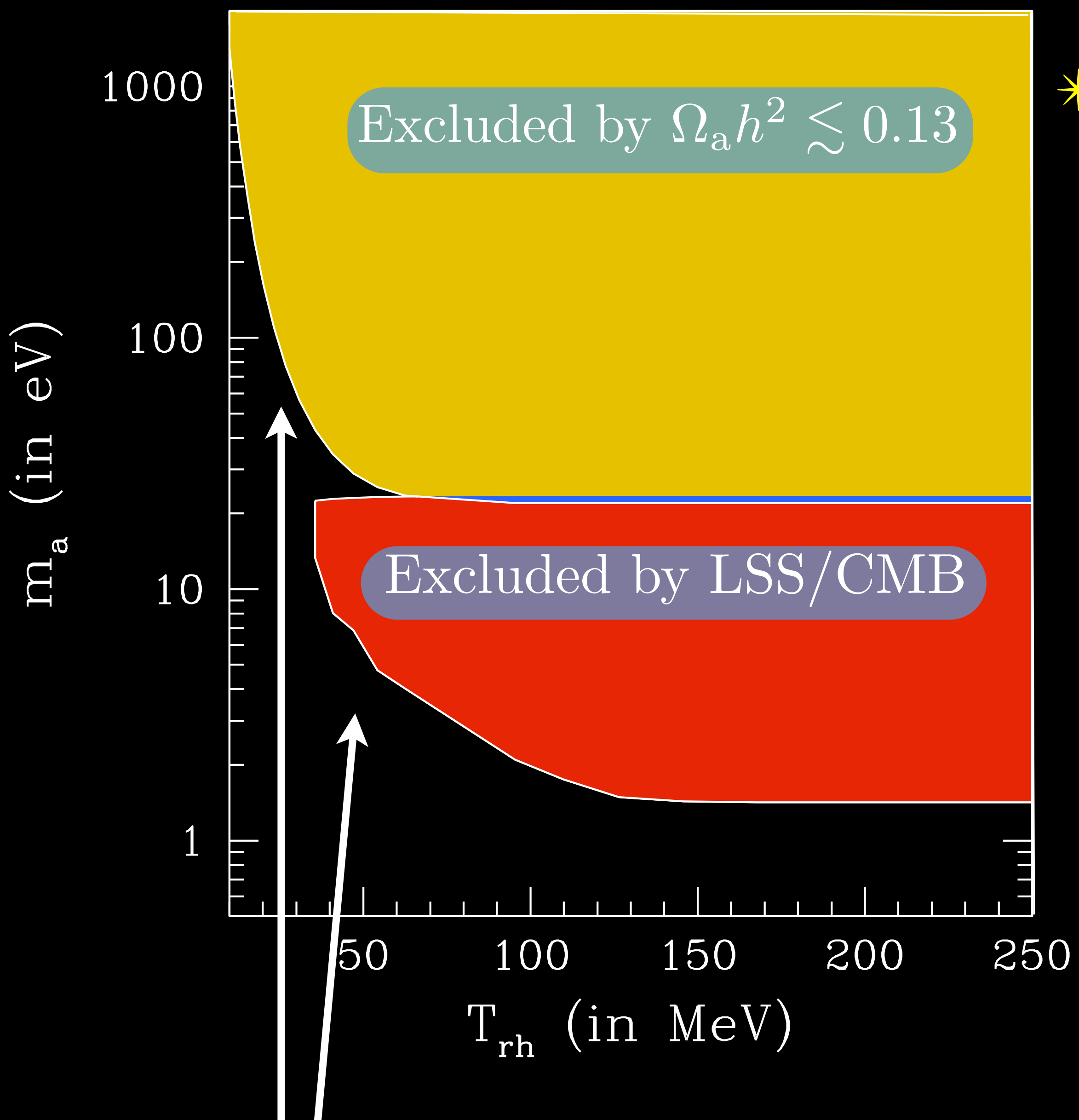
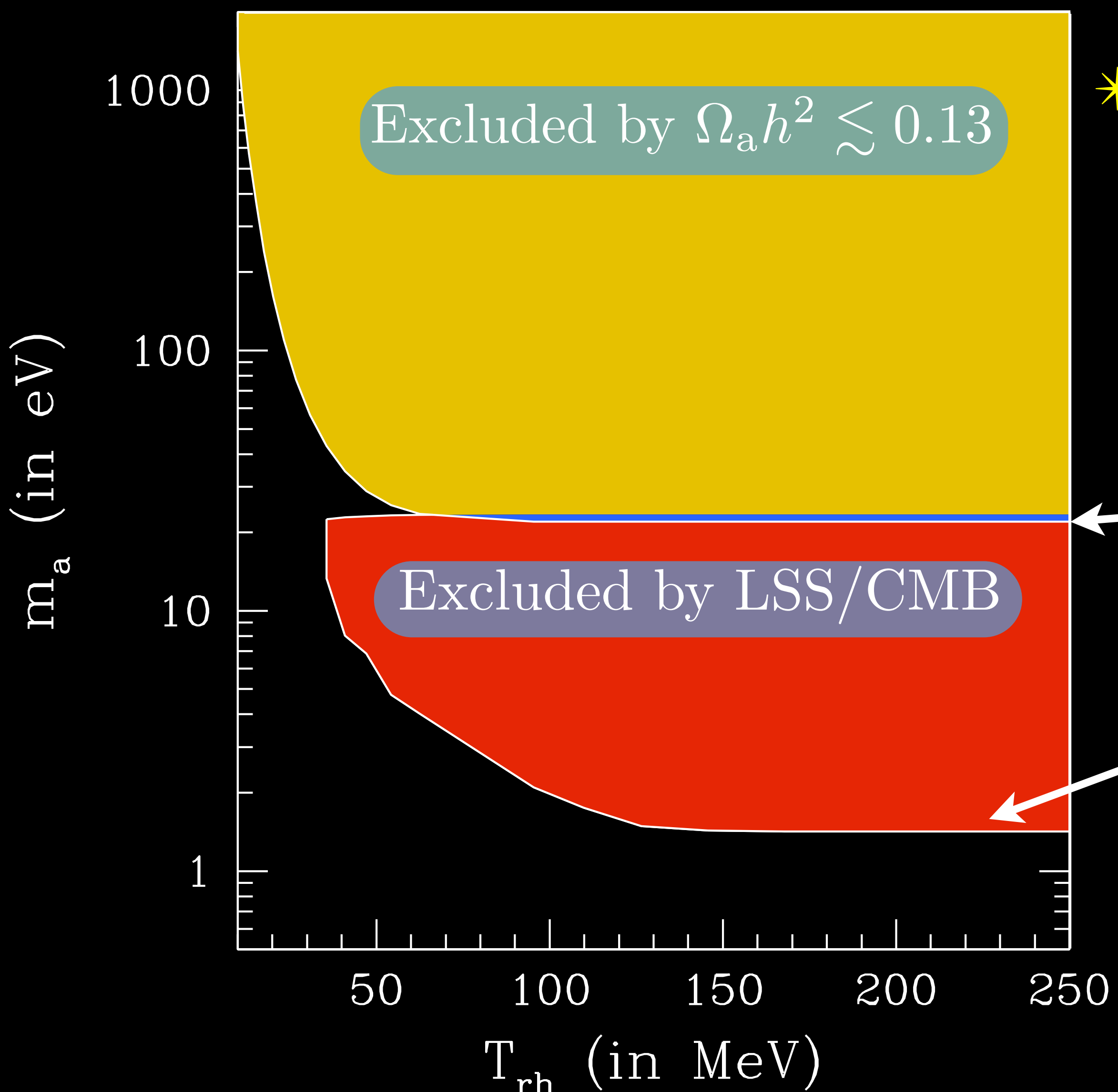


- $\lambda_{fs}(T_{rh}, m_a)$ & $\Omega_a h^2 (T_{rh}, m_a)$ calculated to trace out allowed region

Both constraints loosened as T_{rh} lowered

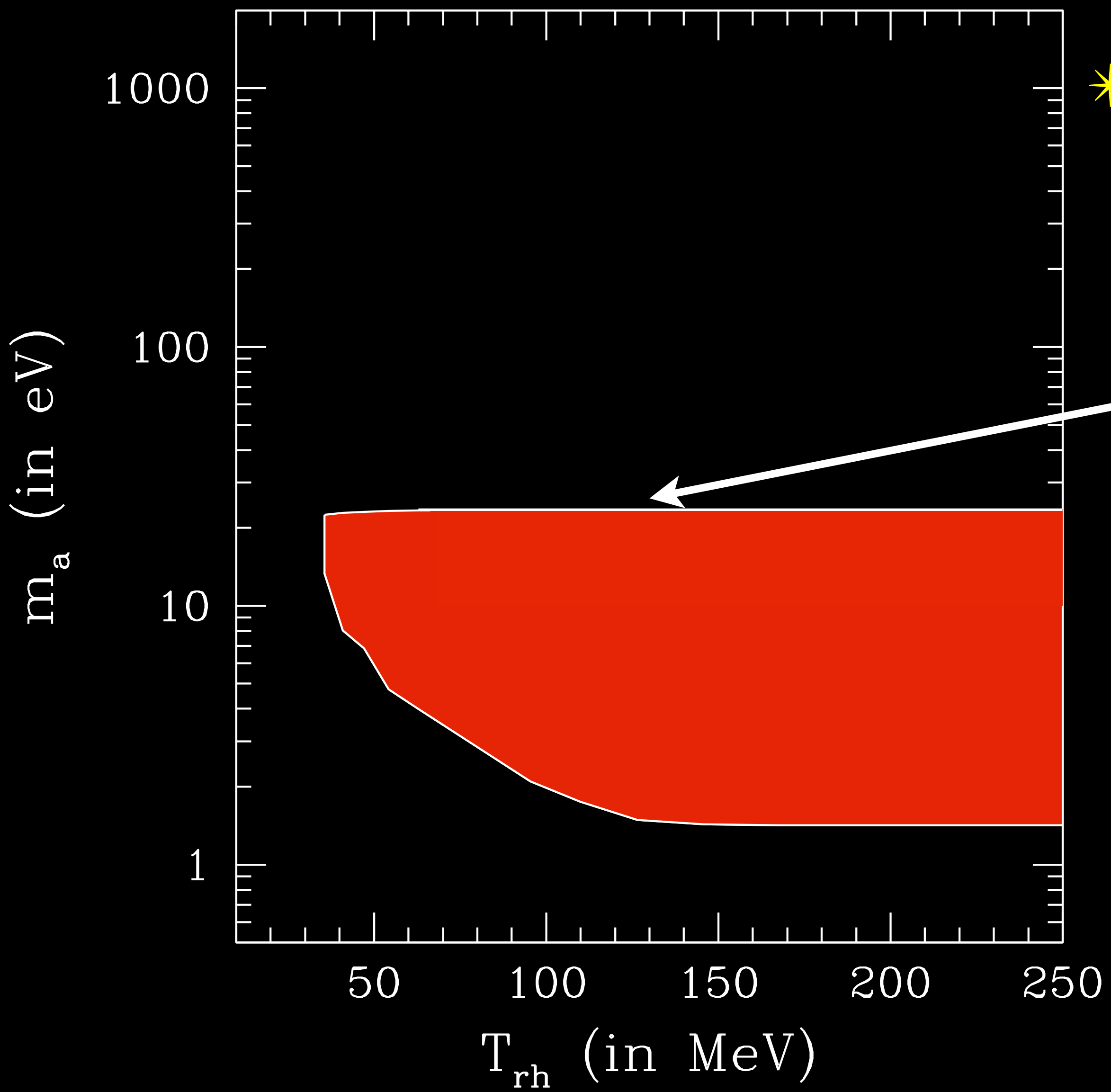
New constraints in LTR



- $\lambda_{fs}(T_{rh}, m_a)$ & $\Omega_a h^2 (T_{rh}, m_a)$ calculated to trace out allowed region

Standard constraints recovered if $T_{rh} \gtrsim 170$ MeV

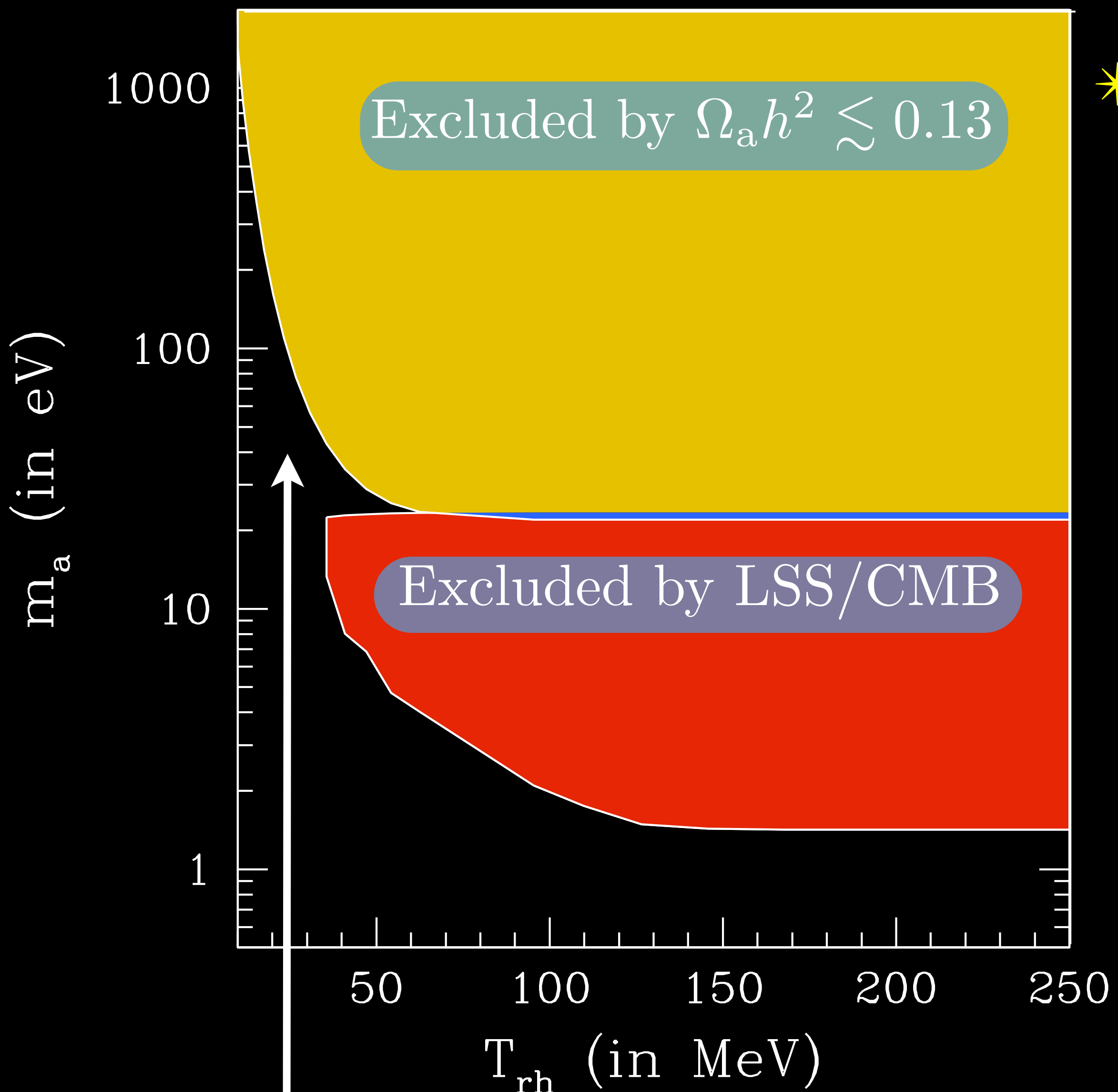
New constraints in LTR



- $\lambda_{fs}(T_{rh}, m_a)$ & $\Omega_a h^2 (T_{rh}, m_a)$ calculated to trace out allowed region

If $m_a \gtrsim 23$ eV , no LSS constraint to `hot axions'

New constraints in LTR



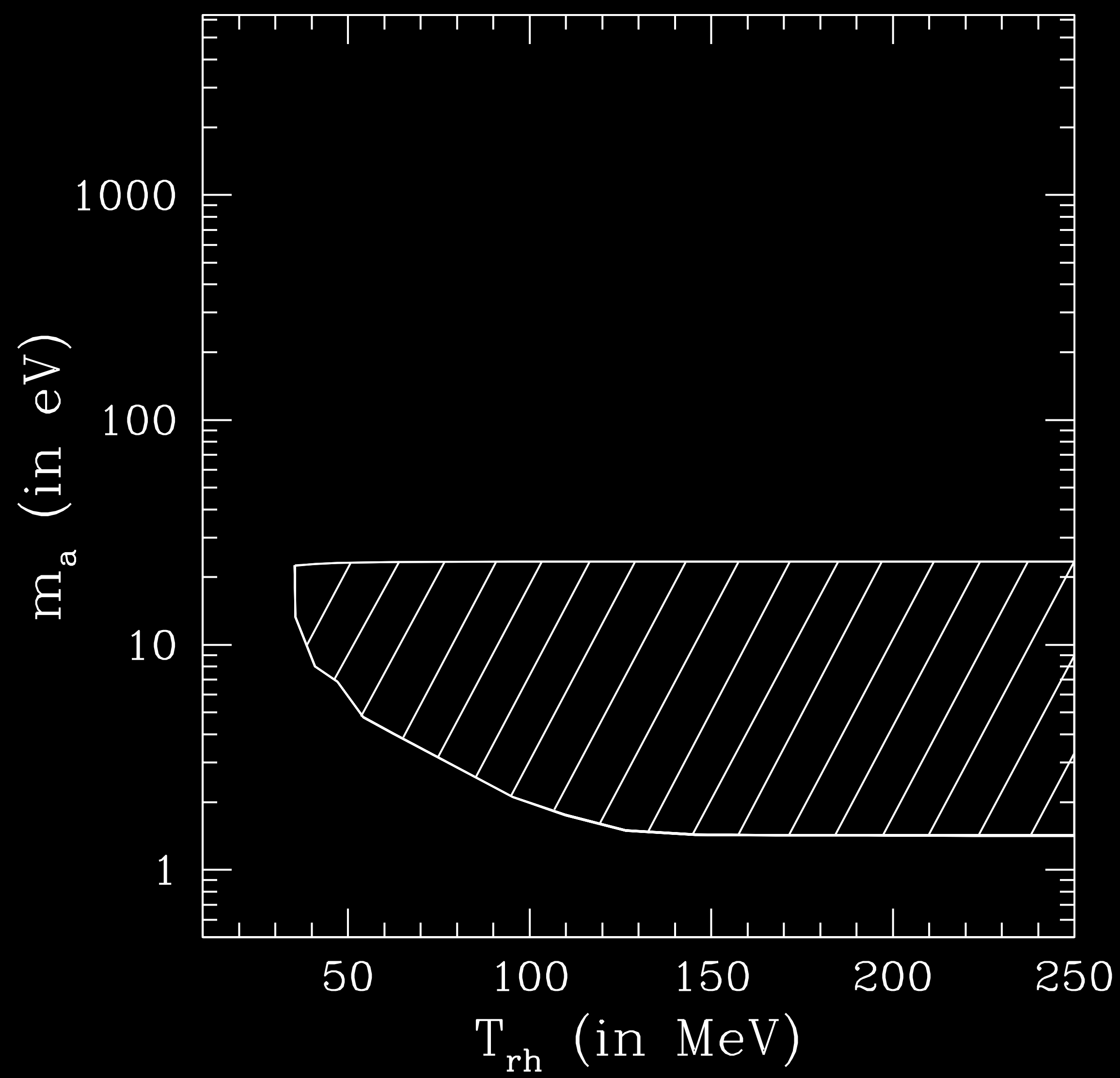
- $\lambda_{fs}\,(T_{rh}, m_a)$ & $\Omega_a h^2\,(T_{rh}, m_a)$ calculated to trace out allowed region

If $T_{rh} \lesssim 35$ MeV, $\lambda_{fs} \lesssim \lambda_{nl}$, LSS constraints completely relaxed

Future surveys

- LSST predicted to reach $\Delta P/P \sim 10^{-2}$ for a sample population similar to SDSS main

- Assuming 21-cm or Lyα observations on very small comoving scales, limits at low reheating temperatures may be improved



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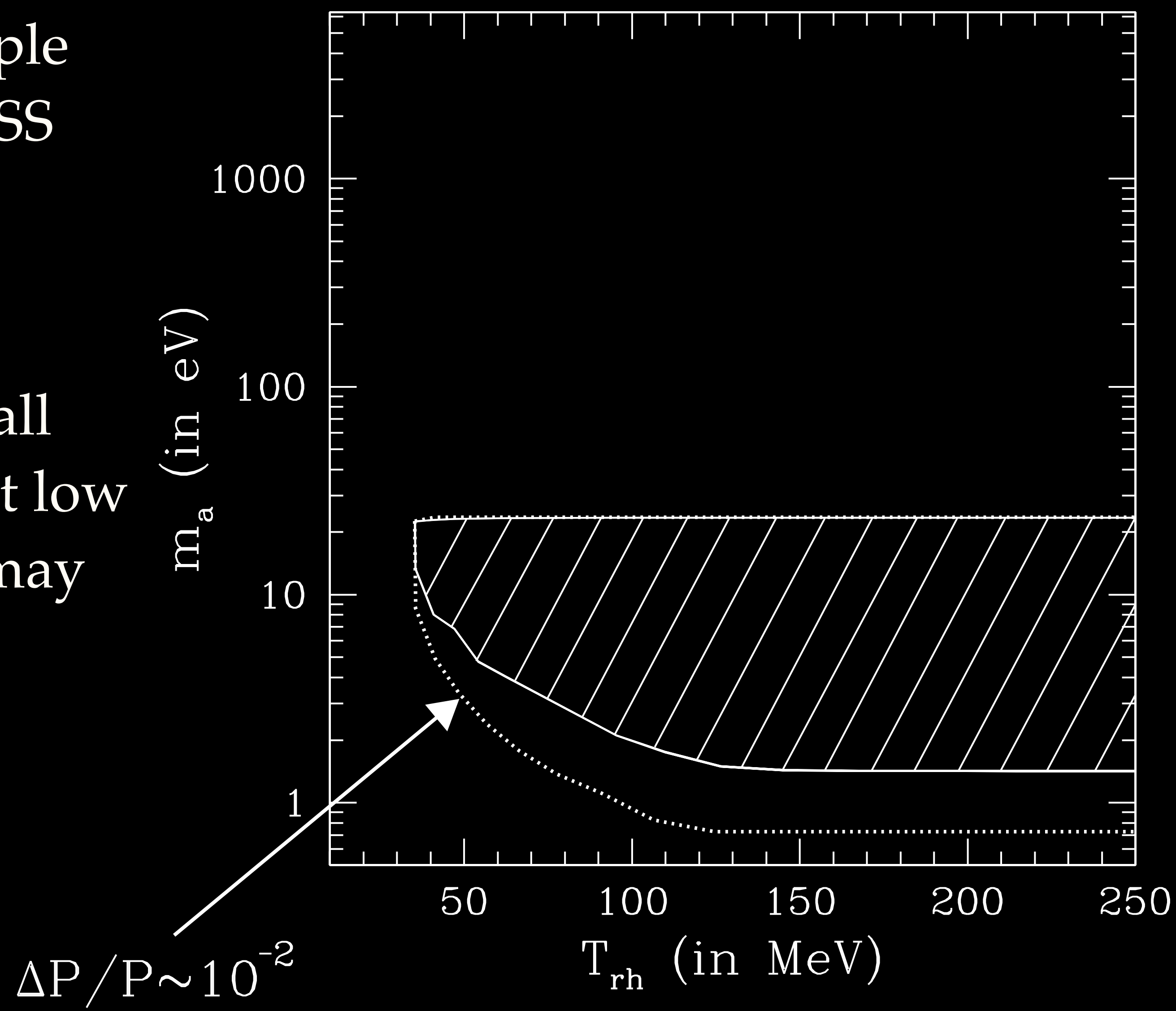

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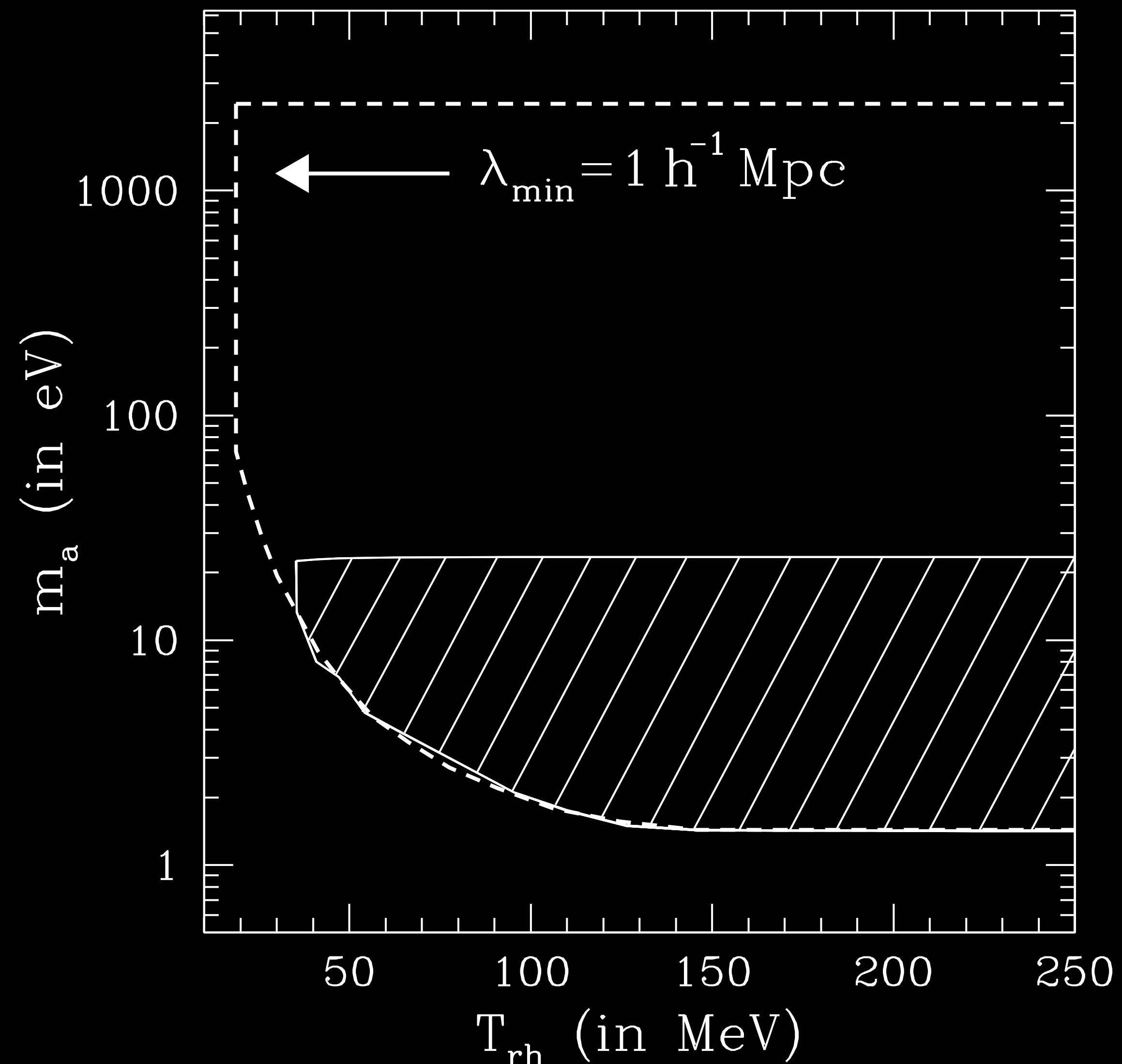
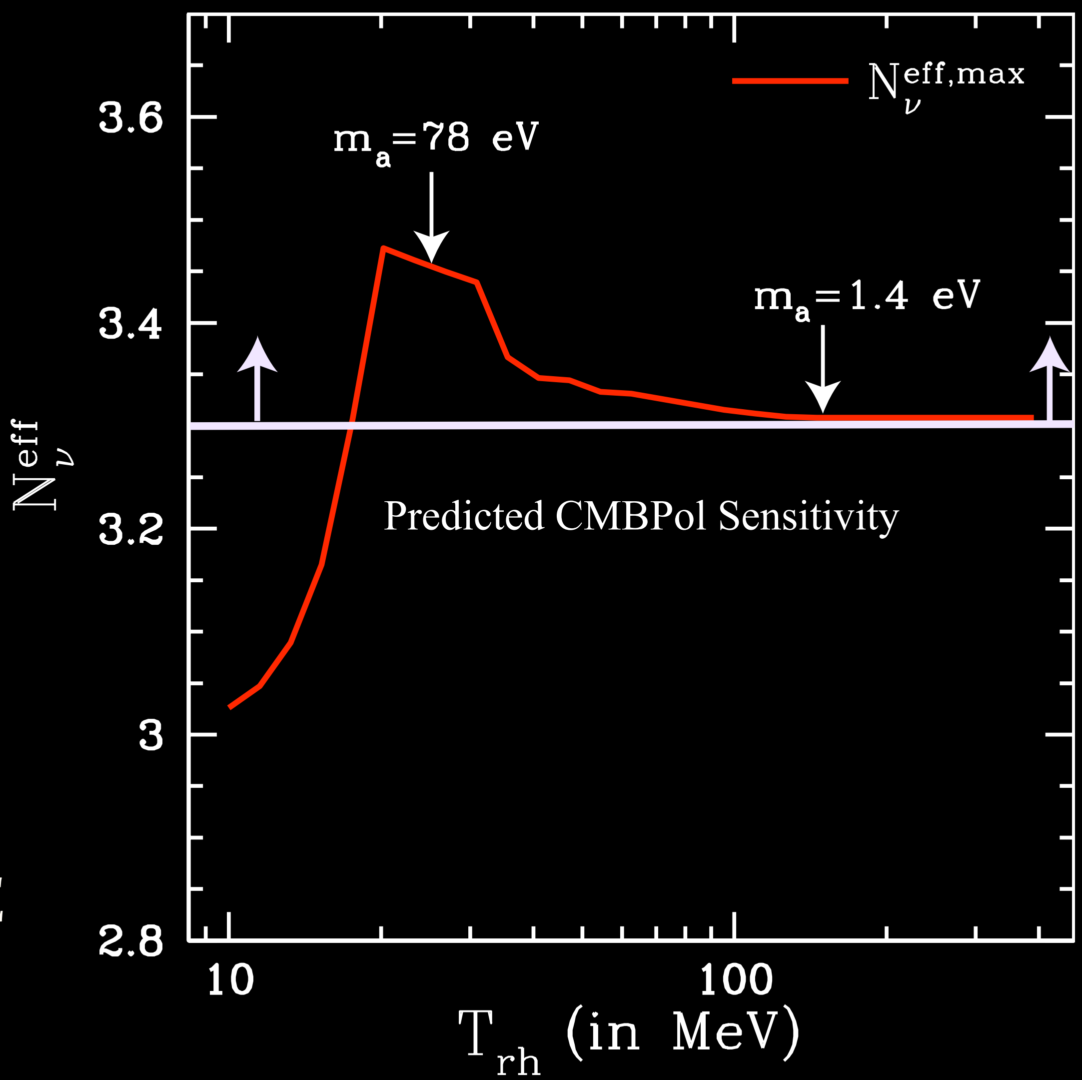


Future limits from abundance of ^{4}He

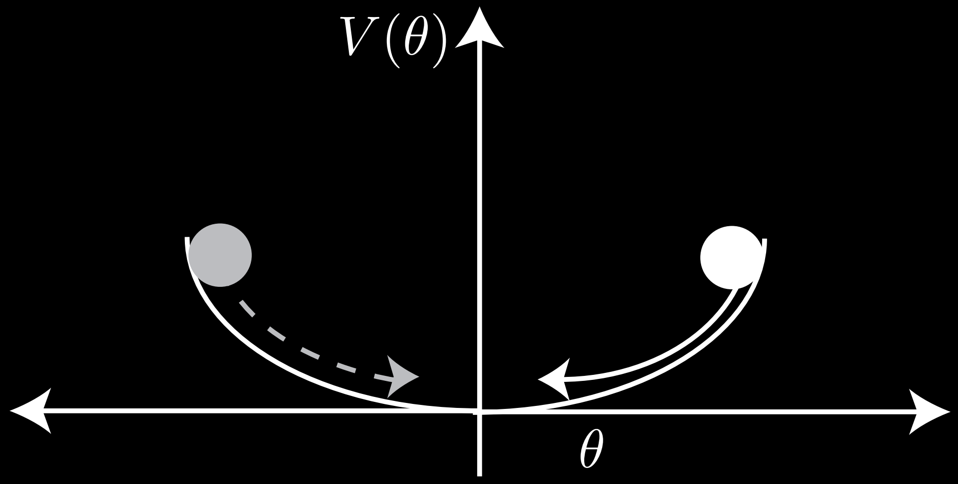
- Axions are relativistic at T~ 1 MeV and contribute to $N_\nu^{\rm eff}$
- Entropy generation suppresses axionic contribution to $N_\nu^{\rm eff}$
- $N_\nu^{\rm eff}$ contributes to $H(T)$ during radiation domination, setting abundance of ^{4}He
- ^{4}He affects CMB TT, TE, and EE spectra: CMBPOL constraints!



Conclusions

- Low-temperature reheating models drastically relax cosmological axion constraints
- Future LSS surveys will extend axion constraints to models with lower $T_{\rm rh}$
- Future CMB experiments may impose additional interesting LTR+axion constraints through helium abundances

2 axion populations: Cold axions



- Before PQ symmetry breaking, θ is generically displaced from vacuum value
- EOM: $\ddot{\overline{\theta}} + 3H\dot{\overline{\theta}} + m_{\mathrm{a}}^2(T)\,\overline{\theta} = 0 \qquad m_{\mathrm{a}}(T) \simeq 0.1 m_{\mathrm{a}}(T=0)\left(\Lambda_{\mathrm{QCD}}/T\right)^{3.7}$
- After $m_{\mathrm{a}}(T) \gtrsim 3H(T)$, coherent oscillations begin, leading to $n_{\mathrm{a}} \propto a^{-3}$
- Relic abundance $\Omega_{\mathrm{a}} h^2 \simeq 0.13 \times g(\theta_0)\left(m_{\mathrm{a}}/10^{-5}\mathrm{eV}\right)^{-1.18}$
- Particles are cold

Subtleties

- Non-equilibrium production
- $T_{\rm F} \gtrsim 200 \text{ MeV}$ necessitates use of different cross sections
- At low values of $m_{\rm a}$, coherent oscillation may become important
- For very low $T_{\rm rh}$, ν may not have time to thermalize, and π may fall out of equilibrium
- All these effects negligible for $T_{\rm rh} \gtrsim 10 \text{ MeV}$ and $m_{\rm a} \gtrsim 0.6 \text{ eV}$

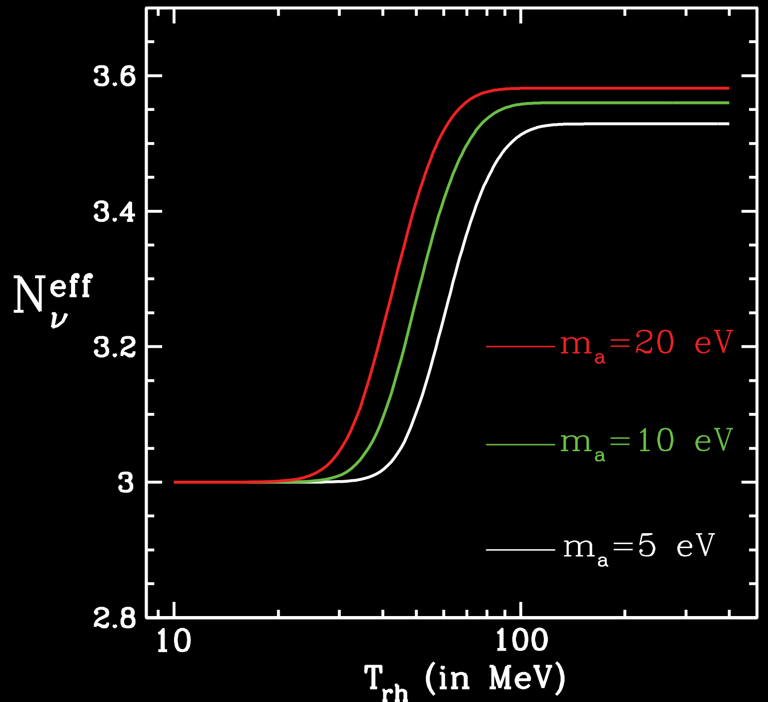
Axionic contribution to pre-BBN radiation energy density in LTR

- Axions are relativistic at T~ 1 MeV and contribute to $N_\nu^{\rm eff}$
- Entropy generation suppresses the axionic contribution to $N_\nu^{\rm eff}$

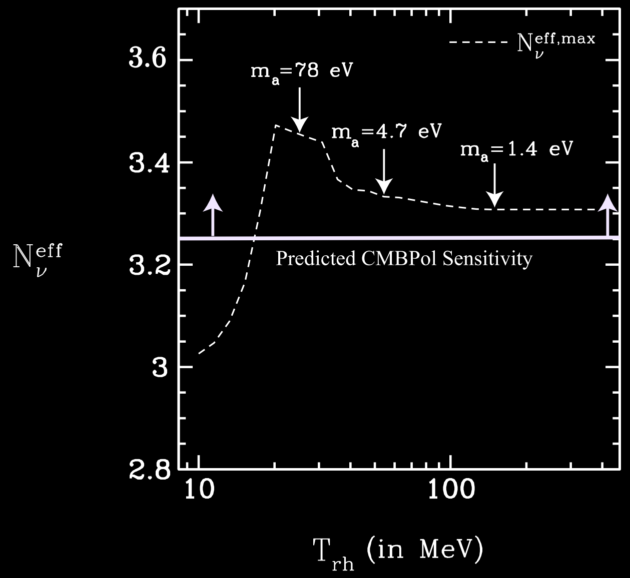
$$N_\nu^{\rm eff} \equiv \left(\frac{\rho_{\rm a}+\rho_\nu}{\rho_\gamma}\right)\left(\frac{8}{7}\right)\left(\frac{11}{4}\right)^{4/3},$$

$$N_\nu^{\rm eff} = 3 + \frac{4}{7}\left(\frac{43}{4}\right)^{4/3}\Psi\left(T_{\rm F}/T_{\rm rh}\right),$$

$$\Psi(y) \sim \begin{cases} \left[g_{*{\rm S},{\rm rh}}\, y^5 \left(\frac{g_{*,{\rm F}}}{g_{*,{\rm rh}}}\right)^2 - 1\right]^{-4/3} & \text{if } y \gg 1, \\ \left[g_{*{\rm S},{\rm F}} - 1\right]^{-4/3} & \text{if } y \ll 1. \end{cases}$$



More details on Helium



- $N_\nu^{\rm eff}$ contributes to $H(T)$ during radiation domination, setting the abundance of $^4\mathrm{He}$:
- For fixed $\eta = \rho_{\rm b}/\rho_\gamma$, $\Delta N_\nu^{\rm eff} = \dfrac{\Delta Y_p}{0.013}$ (Steigman 2007)
- Folding in systematic errors, current measurements yield constraint $N_\nu^{\rm eff} \leq 3.8$
- $Y_{\rm p}$ affects ionization history, and thus CMB TT, TE, and EE spectra

What are axions?

- Axions solve the strong CP problem (Peccei and Quinn 1977, Weinberg 1978, Wilczek 1978)
- Axions interact weakly with SM particles $\Gamma, \sigma \propto \alpha^2$
- Axions have a two-photon coupling (Raffelt 1996, Kaplan 1985)

$$g_{a\gamma\gamma} = -\frac{3\alpha}{8\pi f_\mathrm{a}}\xi \qquad \xi \equiv \frac{4}{3}\left\{E/N - \frac{2\,(4+r)}{3\,(1+r)}\right\} \qquad r = m_u/m_d$$

- Two populations of axions (M. Turner, 1986, 1987):

Cold (nonthermal) axions

$$m_\mathrm{a} \lesssim 10^{-2}\ \mathrm{eV}$$

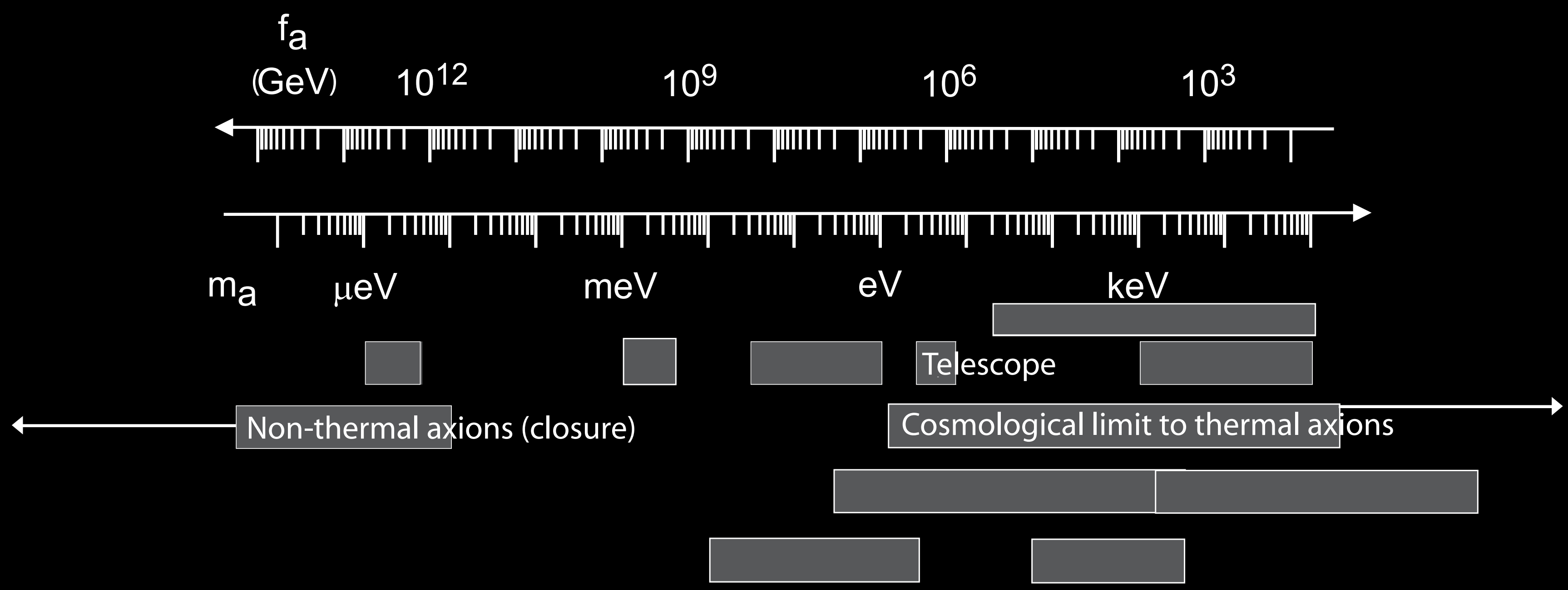
$$\Omega_\mathrm{a} h^2 \simeq 0.13\left(\frac{m_\mathrm{a}}{10^{-5}\ \mathrm{eV}}\right)^{-1.18}$$

Hot (thermal) axions

$$m_\mathrm{a} \gtrsim 10^{-2}\ \mathrm{eV}$$

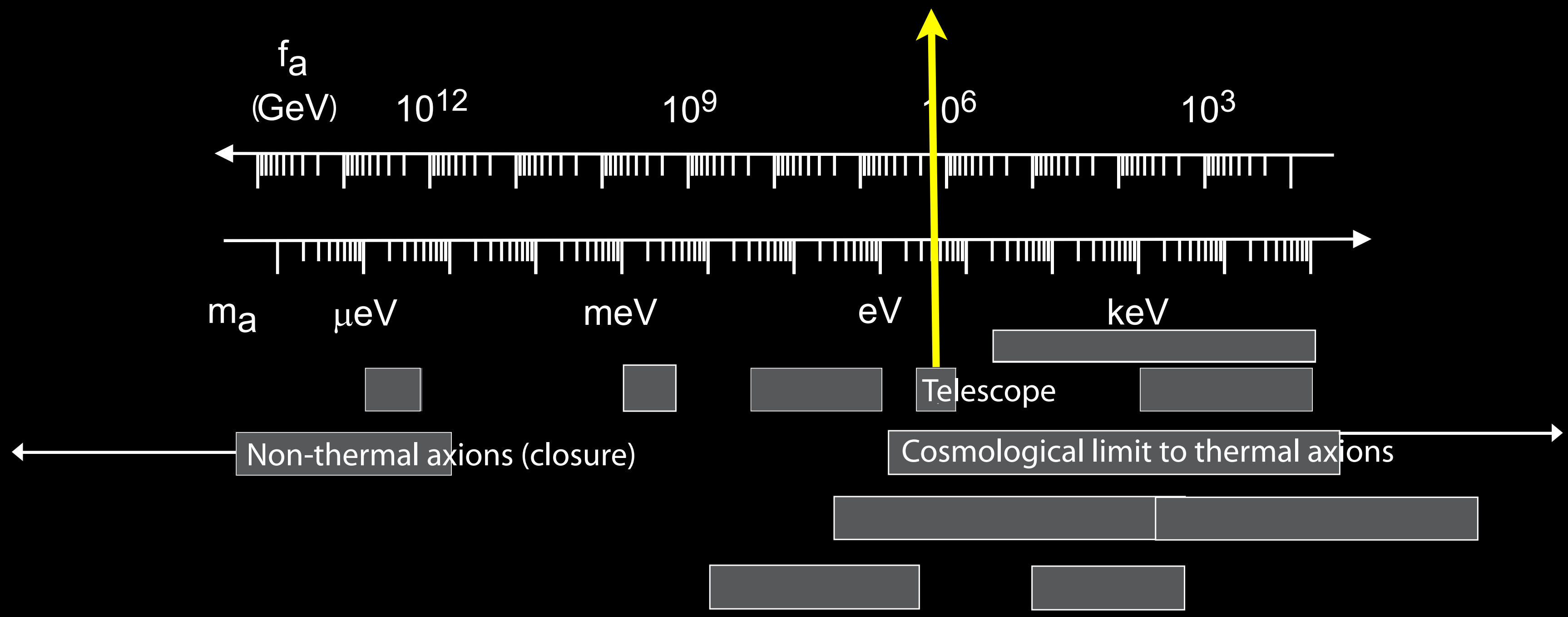
$$\Omega_\mathrm{a} h^2 \simeq \frac{m_\mathrm{a}}{130\ \mathrm{eV}}\left(\frac{10}{g_{*\mathrm{S},\mathrm{F}}}\right)$$

Axions: The big picture



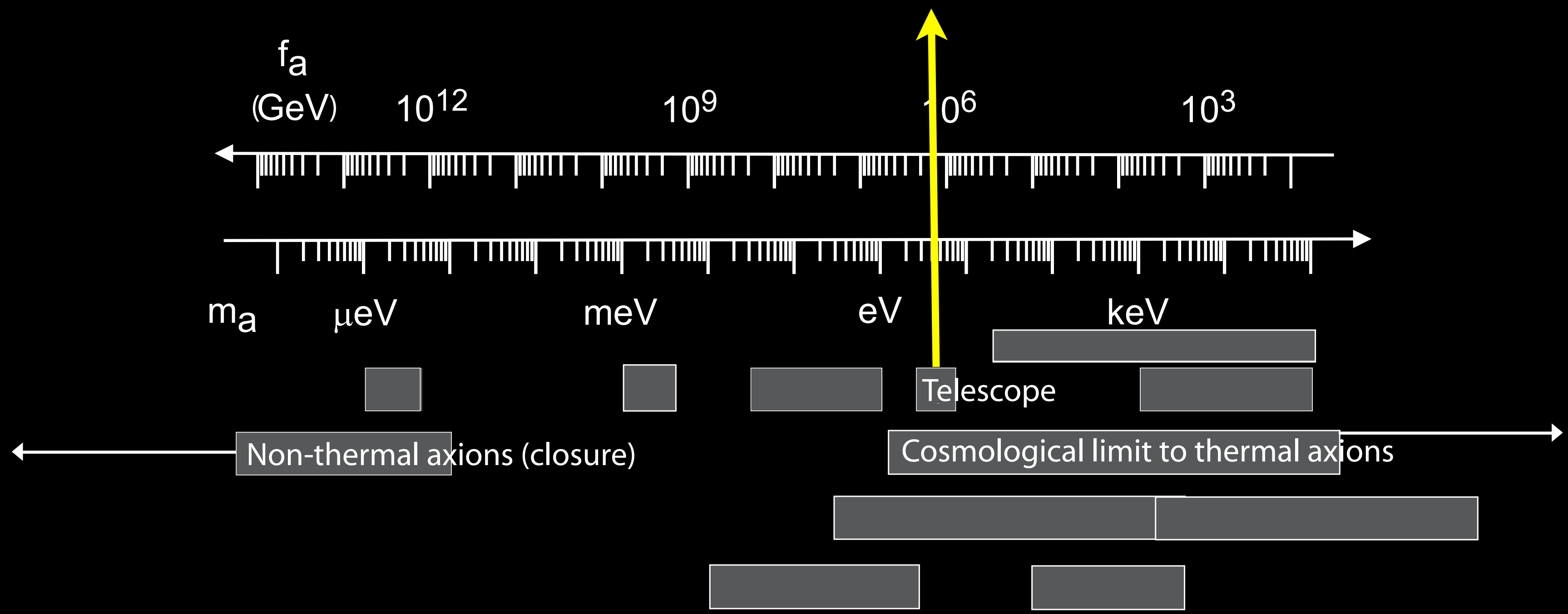
Axions: The big picture

Recent VLT search : Phys. Rev. D 75, 105018 (2007): Grin et al. - *Telescope search for decaying relic axions* (4.5-7.7 eV), arXiv:astro-ph/0611502



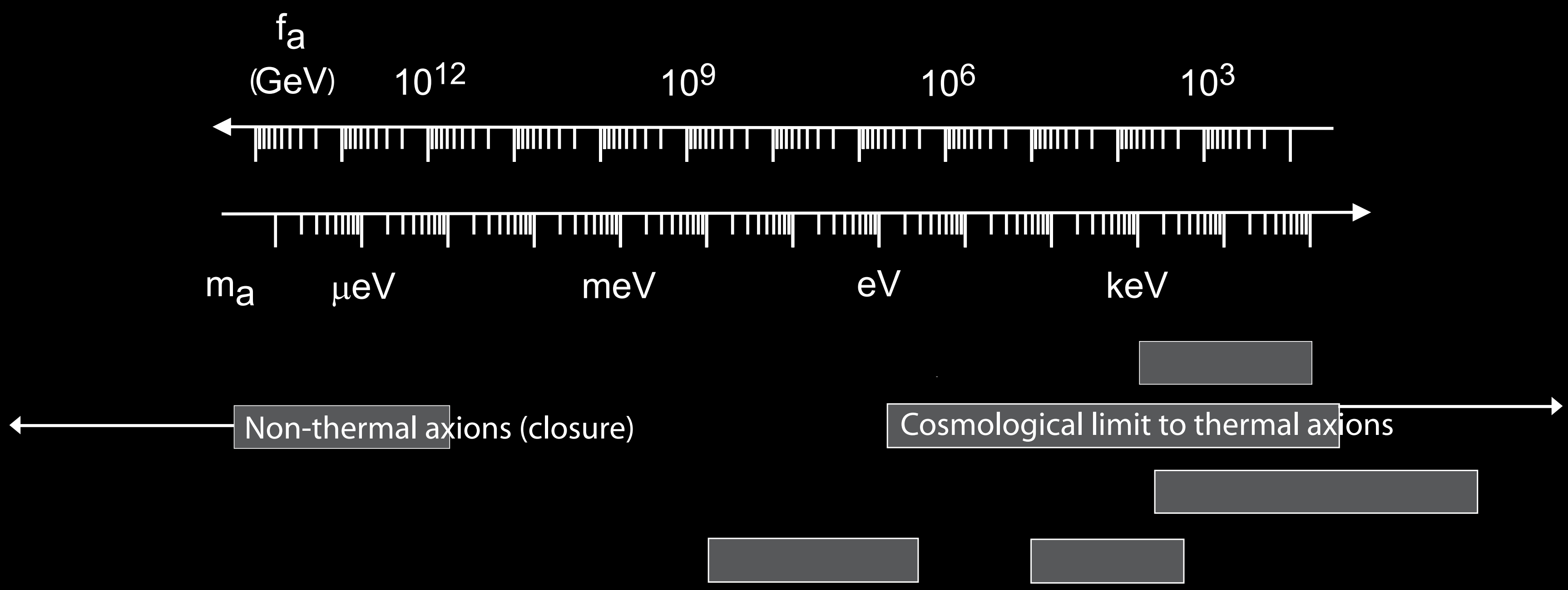
Axions: The big picture

Upcoming VLT search : Grin et al. - *Telescope search for decaying relic axions* (8-20 eV, data recently taken, axion search underway!)



Axions: The big picture

Many astrophysical and experimental constraints to axions depend on two-photon coupling ξ and may be evaded!!



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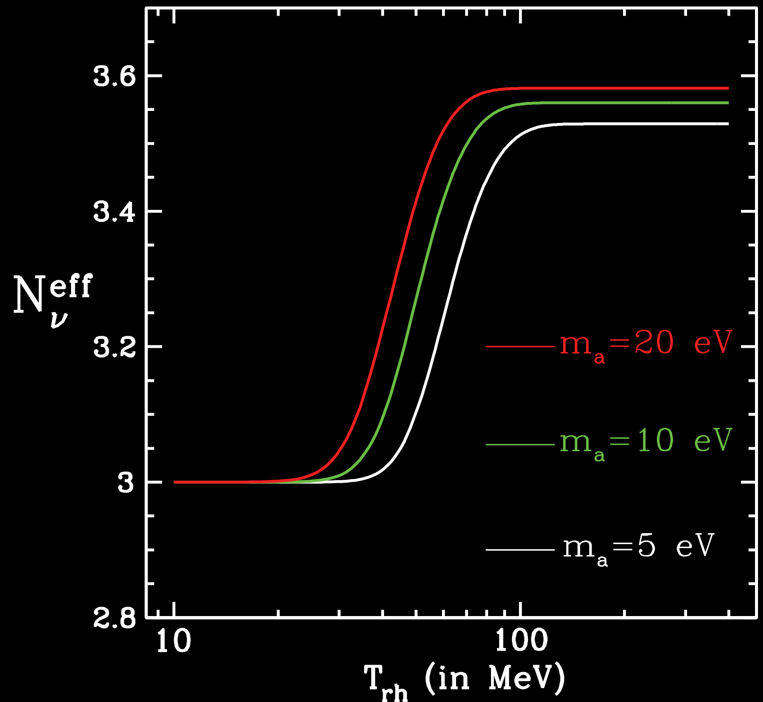

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Kination

- ✴ During a kination epoch (typically pre-BBN), the energy density is dominated by the *kinetic* energy of a scalar field (Joyce 1997)

$$T/V = \dot{\phi}^2/2V(\phi) \gg 1 \rightarrow w = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)} \simeq 1$$

$$\rho \propto a^{-3(1+w)} \qquad H \propto T^3$$

- ✴ Kination could ease along EW baryogenesis and be relevant in quintessential inflation
- ✴ No entropy generation during kination
- ✴ Analysis does not rely on details of kination models, general if

$$H = H_{\rm rad}\left(T/T_{\rm kin}\right) \text{ until } T_{\rm kin}, H = H_{\rm rad} \text{ afterwards}$$

- ✴ Past work considered neutralino abundance in kination models (Profumo and Ullio 2000, Pallis 2005, Gelmini et al. 2006). *New work: LSS/CMB/total density constraints to hot axions in kination models*

Axion abundance in kination

- Higher $T_{\rm F}$ means higher initial equilibrium abundance
- Entropy generation dramatically suppresses abundances
- Kination yields a more modest reduction in $\Omega_{\rm a} h^2$

$$\Omega_{\rm a} h^2 = \frac{m_{\rm a,eV}}{130} \left(\frac{10}{g_{*_{\rm S},{\rm F}}} \right)$$

Axion temperature in LTR/kination

- Entropy generation leads to $T_\mathrm{a} \propto a^{-1}$, while $T_\gamma \propto a^{-3/8}$:

$$\frac{T_\mathrm{a}}{T_\nu} \approx (10.75/g_{*\mathrm{S},\mathrm{F}})^{1/3}, \qquad \text{if } T_\mathrm{F} < T_\mathrm{rh}.$$

$$\frac{T_a}{T_\nu} \simeq \left(\frac{11}{4}\right)^{1/3} \left(\frac{T_\mathrm{rh}}{T_\mathrm{F}}\right)^{5/3} \left(\frac{g^2_{*,\mathrm{RH}}\, g_{*\mathrm{S},0}}{g^2_{*,\mathrm{F}}\, g_{*\mathrm{S},\mathrm{RH}}}\right)^{1/3} \qquad \text{if } T_\mathrm{F} > T_\mathrm{rh}.$$

- Axions non-relativistic earlier: Smaller free-streaming length!

$$\lambda_\mathrm{fs} \simeq \frac{196\ \mathrm{Mpc}}{m_{\mathrm{a,eV}}} \left(\frac{T_\mathrm{a}}{T_\nu}\right) \left\{1 + \ln\left[0.45 m_{\mathrm{a,eV}} \left(\frac{T_\nu}{T_\mathrm{a}}\right)\right]\right\}.$$

- In the kination case, less dramatic changes

$$\frac{T_\mathrm{a}}{T_\nu} \approx (10.75/g_{*\mathrm{S},\mathrm{F}})^{1/3}, \text{ with different } g_{*\mathrm{S},\mathrm{F}}$$

New constraints in LTR

- For kination, new constraints less dramatically different: If $T_{\rm kin} \simeq 10$ MeV, the allowed regions are $m_{\rm a} \lesssim 3.2$ eV and $17 \text{ eV} \lesssim m_{\rm a} \lesssim 26 \text{ eV}$.

- If $T_{\rm kin} \gtrsim 110$ MeV, standard results are recovered.