
# [Cold] Axionic Dark Matter

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Dark Matter Hub Presentation/KICP
4/15/2014

# Outline

- Strong CP Problem, QCD Axion, couplings
- How to make axions in the expanding universe
- Astrophysical Limits
- Lab limits
- Cosmological limits [+BICEP2!]

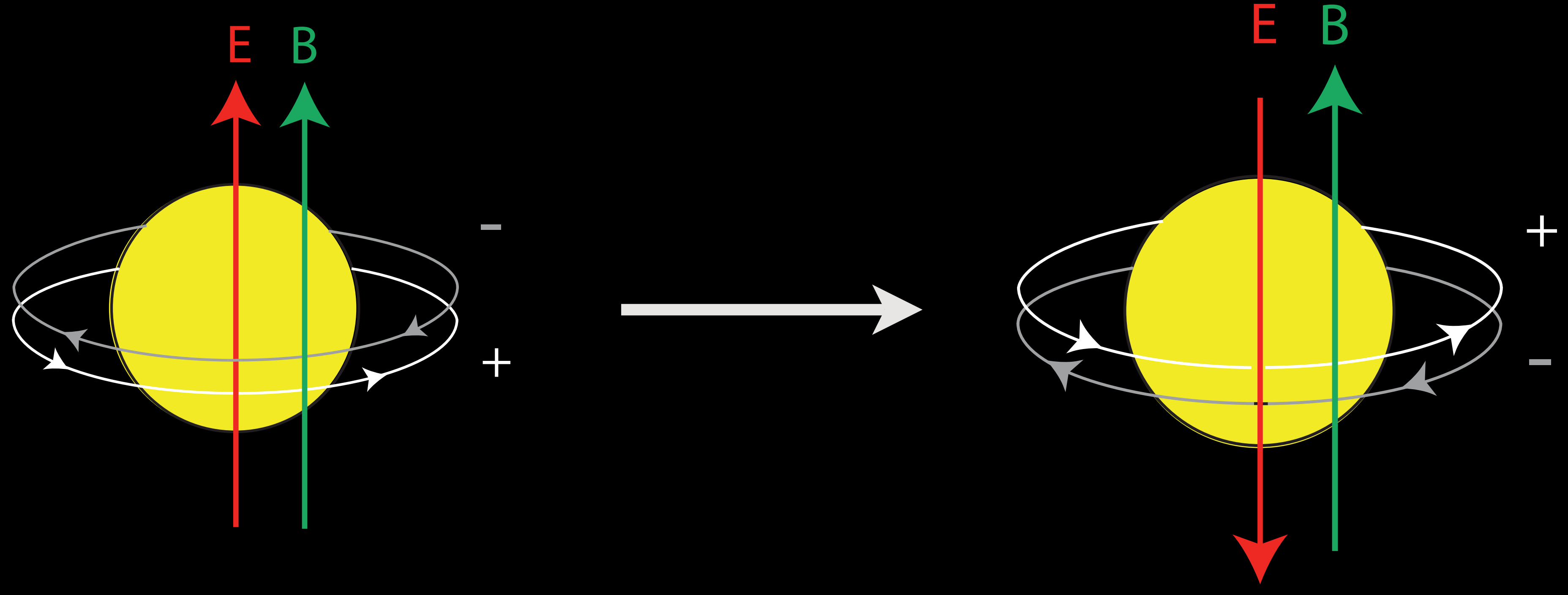
# The strong CP problem

- Strong interaction violates CP through θ -vacuum term

$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G}$$

- Limits on the neutron electric dipole moment are strong. Fine tuning?

$$d_n \simeq 10^{-16}\ \theta\ \text{e cm}$$
$$\theta \lesssim 10^{-10},$$



# Axions solve the strong CP problem

- Strong interaction violates CP through $\theta$ -vacuum term

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- Limits on the neutron electric dipole moment are strong. Fine tuning?

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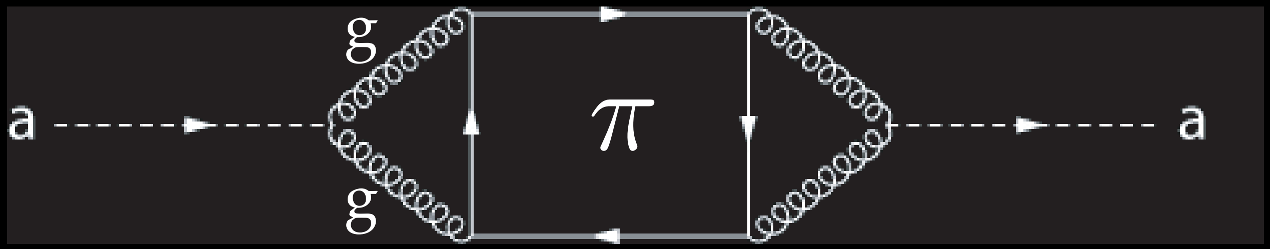
$$\theta \lesssim 10^{-10}$$

- New field (axion) and U(1) symmetry dynamically drive net CP-violating term to 0

$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\rm a}} g^2 G\tilde{G}$$

- Through coupling to pions, axions pick up a mass



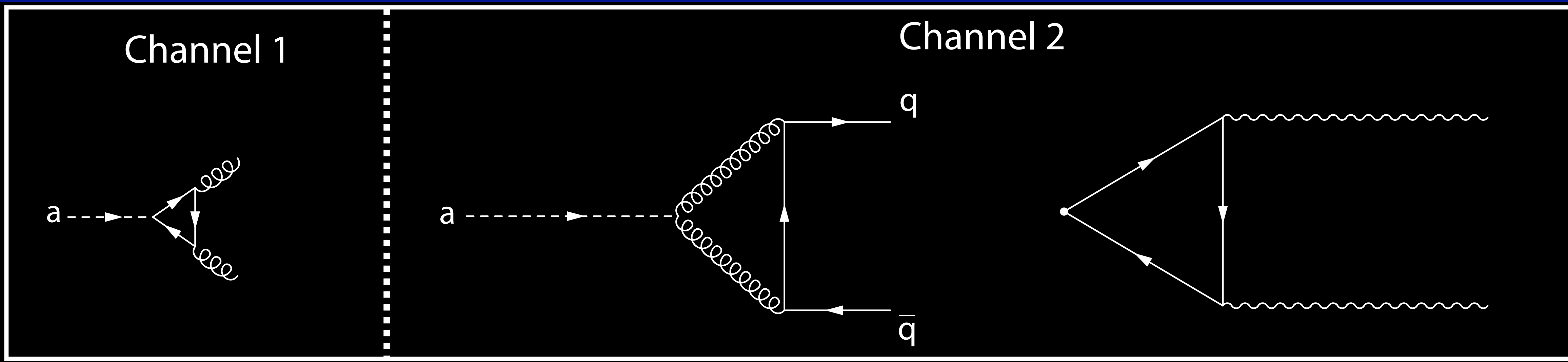

$$\boxed{m_{\rm a} \simeq \frac{m_\pi f_\pi}{f_{\rm a}} \frac{\sqrt{r}}{1+r}}$$

$$r \equiv m_{\rm u}/m_{\rm d}$$

# Axion mass

$$m_a = 6.2\mu\ \mathrm{eV}\left(\frac{10^{12}\ \mathrm{GeV}}{f_\mathrm{a}}\right)$$

# Two-photon coupling of axion




- Axions interact weakly with SM particles $\Gamma, \sigma \sim \alpha^2$

- Axions have a two-photon coupling

$$g_{a\gamma\gamma} = -\frac{3\alpha}{8\pi f_a}\xi$$

$$\xi \equiv \frac{4}{3}\left\{E/N - \frac{2\,(4+r)}{3\,(1+r)}\right.$$

$$r \equiv m_u/m_d$$

$$E = \sum_i Q_i^2$$

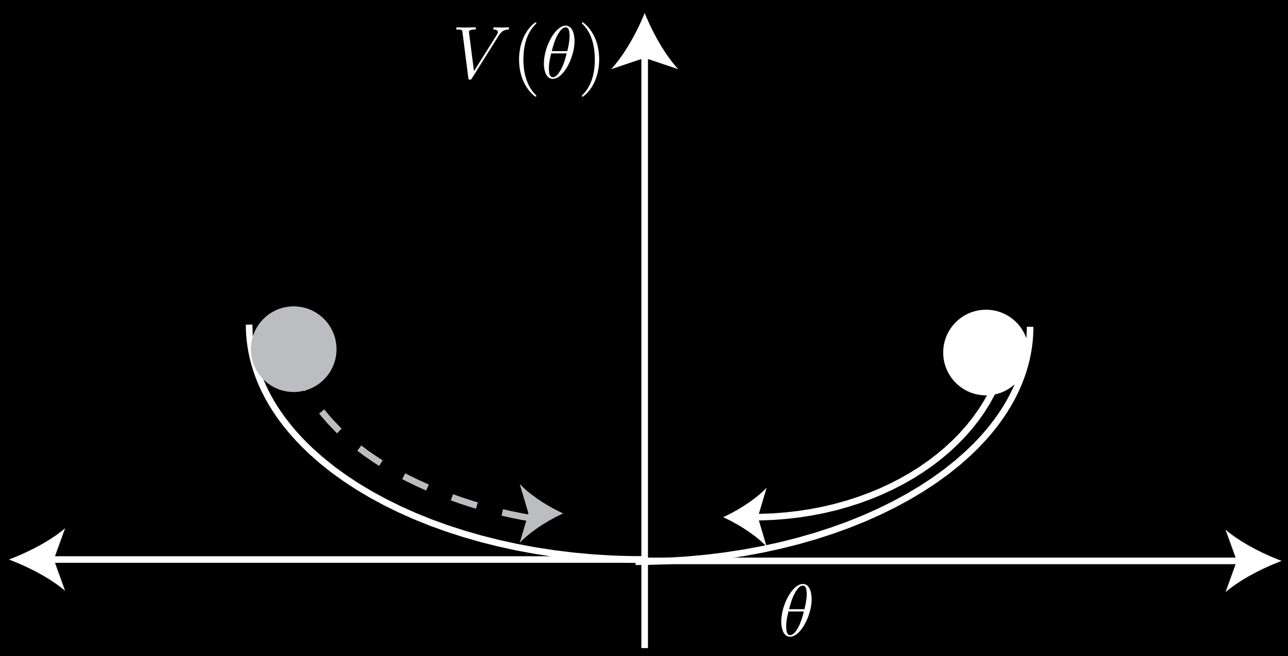
$$N = \sum_i N_i$$

- ξ is model-dependent and may vanish

$$\xi = \tfrac{4}{3}\left\{E/N - 1.92 \pm 0.08\right\}$$

$$\text{KSVZ}: \quad E/N = 0 \ (\text{or } 0)$$
$$\text{DFSZ}: \quad E/N = 8/3$$

# 2 axion populations: Cold axions




- Before PQ symmetry breaking, $\theta$ is generically displaced from vacuum value
- EOM: $\ddot{\bar{\theta}} + 3H\dot{\bar{\theta}} + m_{\rm a}^{2}(T)\,\bar{\theta} = 0$ $\quad m_{\rm a}(T) \simeq 0.1 m_{\rm a}(T=0)\left(\Lambda_{\rm QCD}/T\right)^{3.7}$
- After $m_{\rm a}(T) \gtrsim 3H(T)$, coherent oscillations begin, leading to $n_{\rm a} \propto a^{-3}$
- Axions are cold $p \ll m_a c$

# Dark matter axion abundance

- QCD axion couples to quarks/pions, temp-dependent mass
  - High-temp regime

$$m_{\mathrm{a}} = 0.02 m_{\mathrm{a}}^{(T=0)} \left(\frac{\Lambda_{\mathrm{QCD}}}{T}\right)^4 \quad \text{if } T \gg \Lambda_{\mathrm{QCD}}$$

  - Low-temp regime $m_{\mathrm{a}} = m_{\mathrm{a}}^{(T=0)}$ if $T \lesssim \Lambda_{\mathrm{QCD}}$

$$\boxed{\Omega_{\mathrm{mis}} h^2 = 0.236 \left\langle \theta_i^2 f(\theta_i) \right\rangle \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6}} \quad \text{if } f_a \lesssim 10^{18}\ \mathrm{GeV}$$

$$\boxed{\Omega_{\mathrm{mis}} h^2 = 0.005 \left\langle \theta_i^2 f(\theta_i) \right\rangle \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{3/2}} \quad \text{if } f_a \gtrsim 10^{18}\ \mathrm{GeV}$$

# Anthropic axion window: $f_a > \max\{T_{\mathrm{RH}}, H_{\mathrm{I}}\}$

- Axion field is relatively homogeneous

$$\langle \theta^2 \rangle = \overline{\theta}^2 + \left( \frac{H_I}{2\pi f_a} \right)^2$$

- Abundance

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Misalignment in our Hubble Patch

- Abundance

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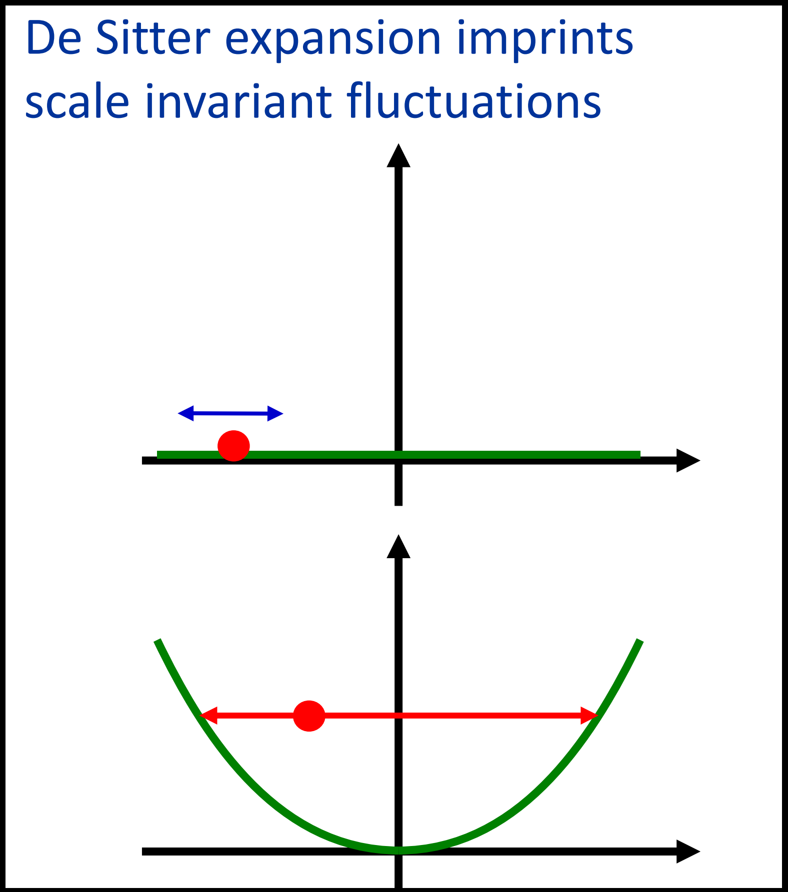
Vacuum fluctuations from inflation




- Abundance

From Raffelt 2012

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$$\langle\theta^2\rangle = \overline{\theta}^2 + \left(\frac{H_I}{2\pi f_a}\right)^2$$

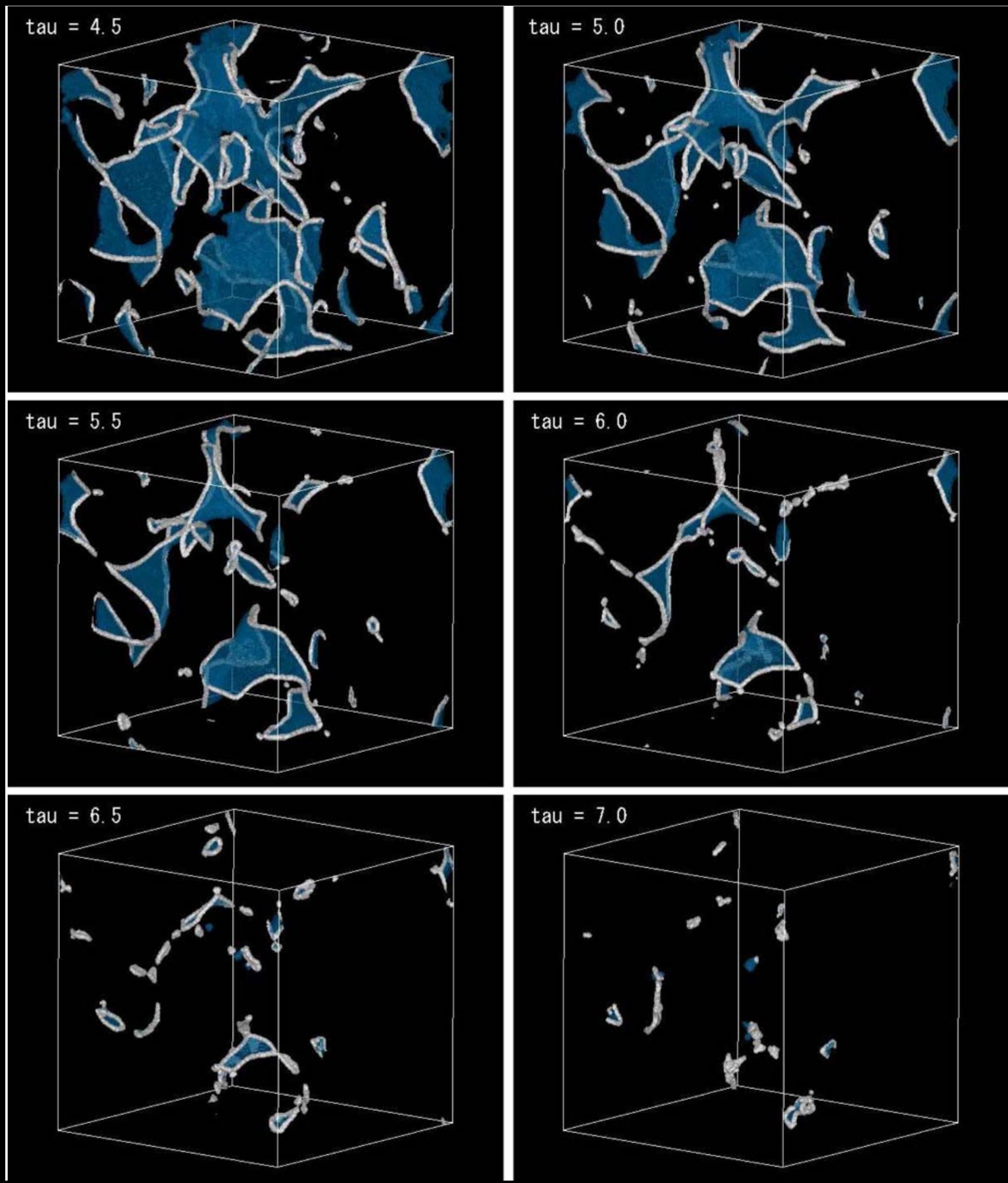
- Abundance

$$\Omega_a h^2 \simeq 0.43\left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6}\theta_i^2$$

$$\Omega_a h^2 \simeq 0.005\left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{3/2}\theta_i^2$$

- $\overline{\theta}$ can be tuned to get DM abundance for many axion masses

# Classic axion window: $f_a < \max\{T_{\mathrm{RH}}, H_{\mathrm{I}}\}$




✳ Axion field is very inhomogeneous

$$\left\langle \bar{\theta}_i^2 \right\rangle = \frac{\pi^2}{6}$$

✳ Defects [domain walls, strings, etc..]

$$\mathcal{O}(1) \lesssim \alpha_{\mathrm{defect}} \lesssim \mathcal{O}(10^2)$$

✳ Abundance

$$\boxed{\Omega_a h^2 \simeq 2.0\,\{1 + f_{\mathrm{defect}}\}\left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6}}$$

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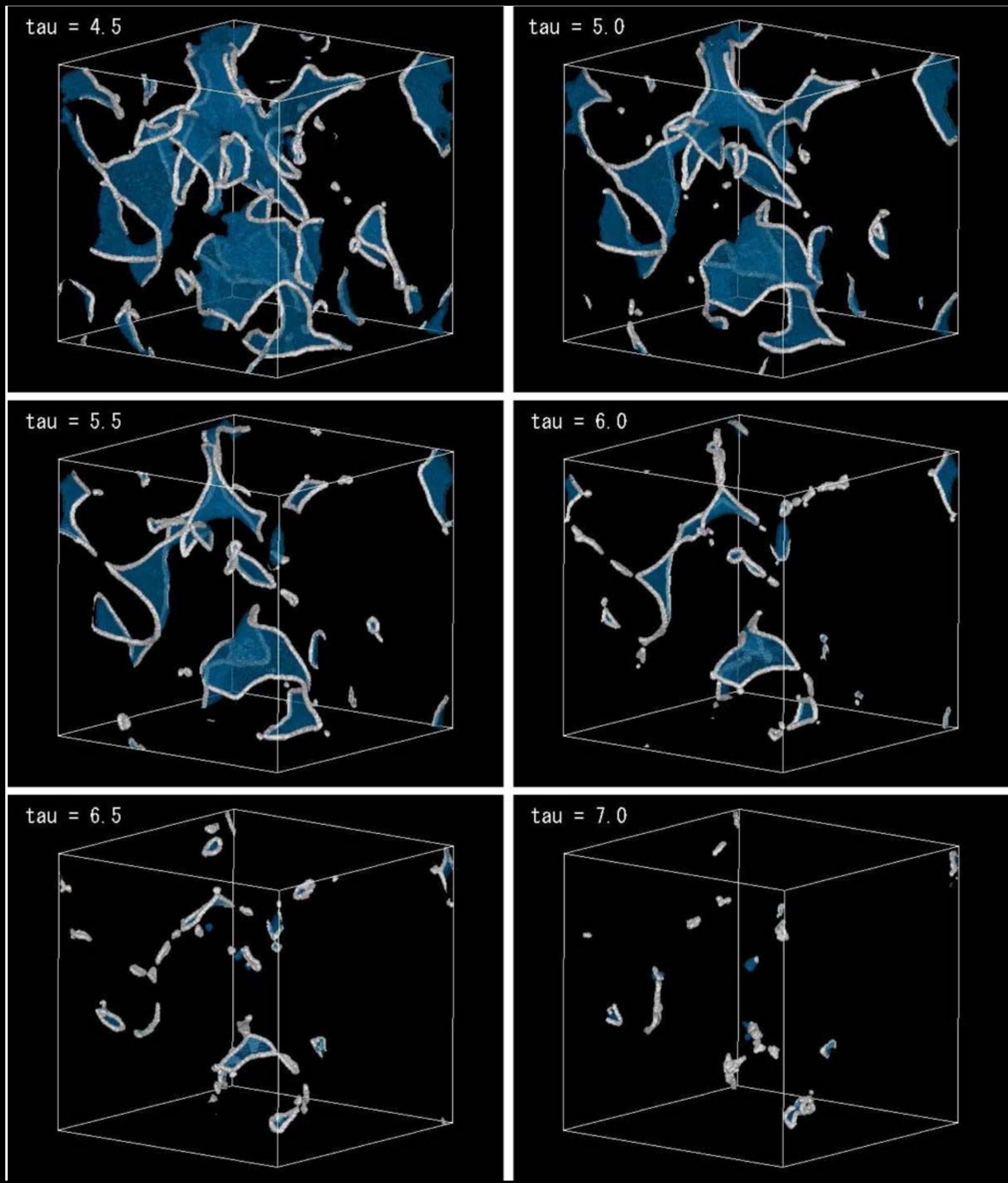
CONTROVERSY!

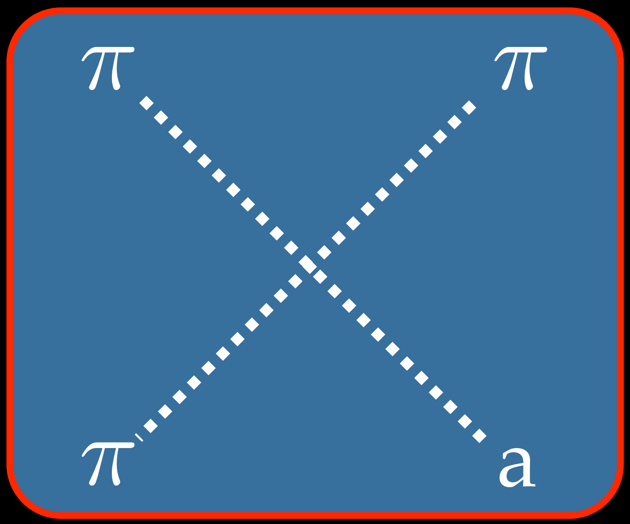



- ✳ Abundance

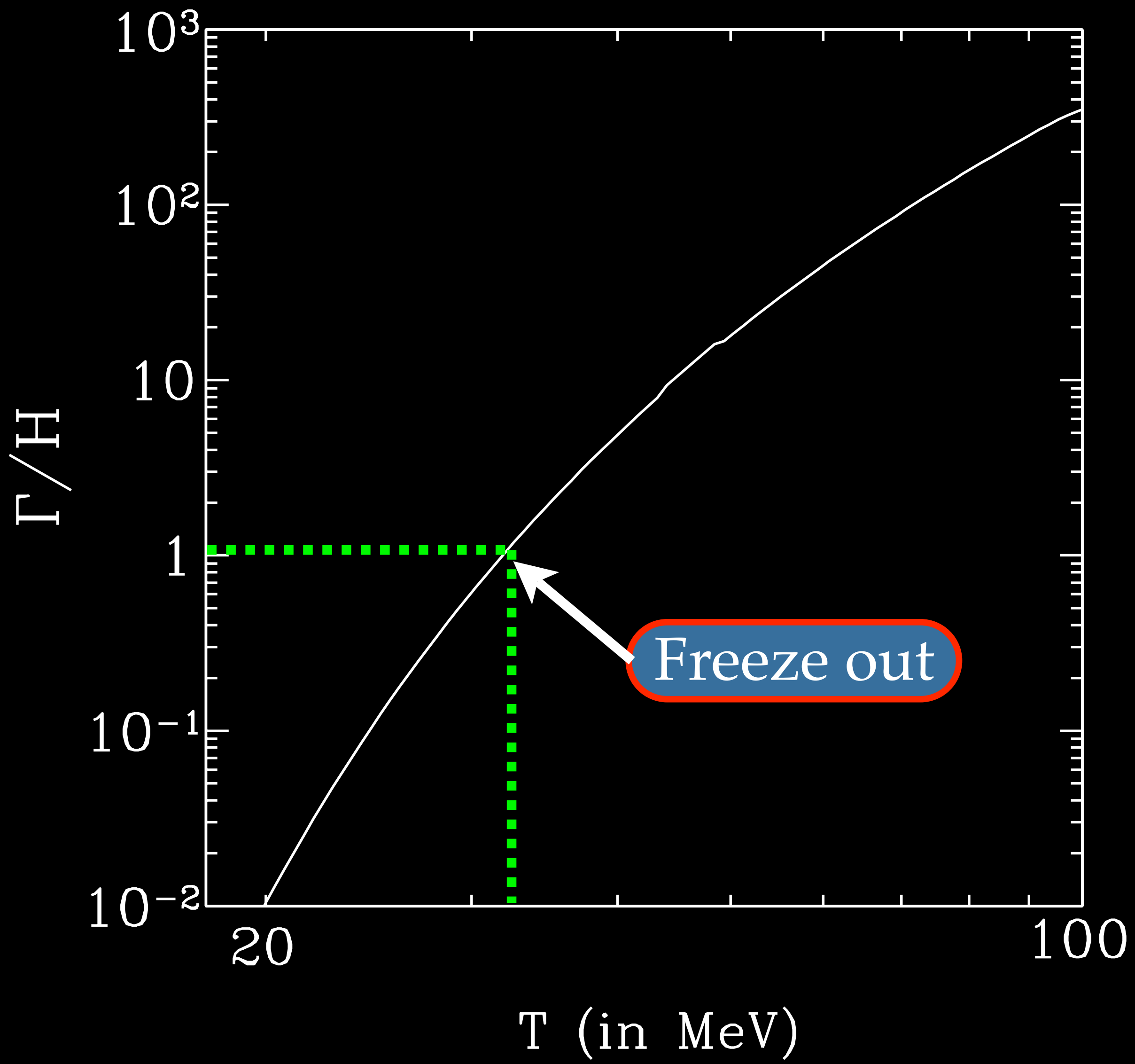
$$\Omega_a h^2 \simeq 2.0\,\{1 + f_{\rm defect}\}\left(\frac{f_a}{10^{12}\ {\rm GeV}}\right)^{7/6}$$

# Hot axion production at early times

Axion Production:




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



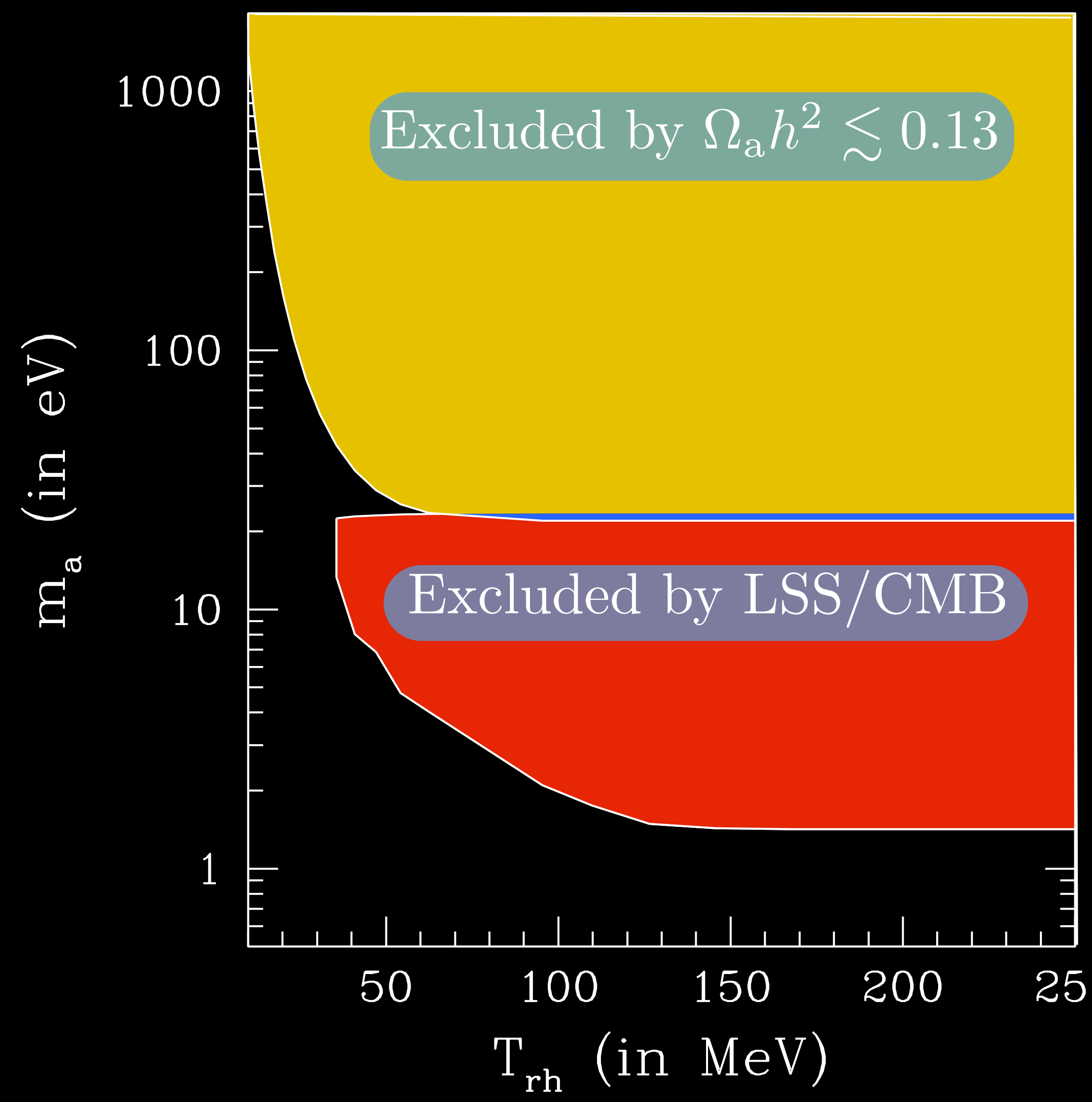

- Axions produced through interactions between non-relativistic pions in chemical equilibrium with rate

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

# Axion hot dark matter

✳ Axion free-streaming length

$$\lambda_{\rm fs} \simeq \frac{196\ {\rm Mpc}}{m_{\rm a,eV}}$$

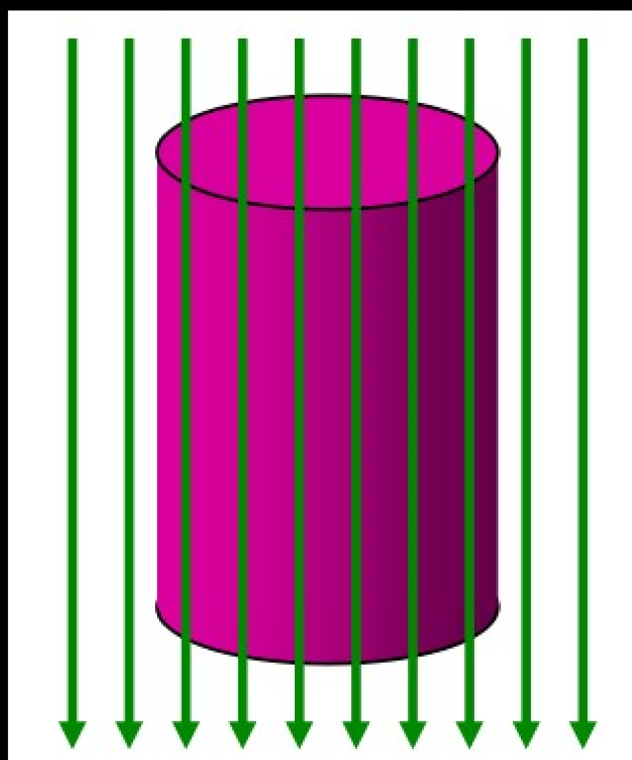


# Yes we can look for the "invisible axion"

# Cavity searches [e.g. ADMX]

Images from Wong 2012

* ✳ Magnetized RF Cavity



* ✳ Axion excites cavity (TEM) modes [cavity must be tuned]

$$E_\gamma = m_\mathrm{a} c^2$$

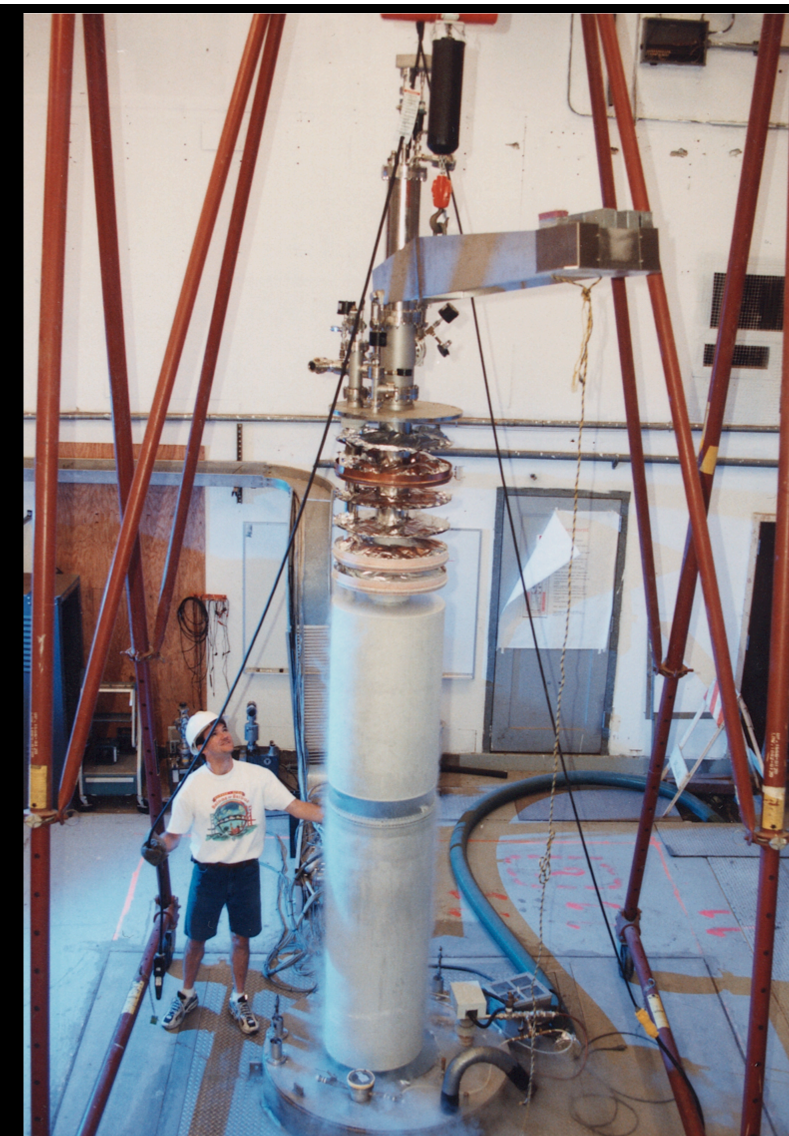
* ✳ Power

Volume

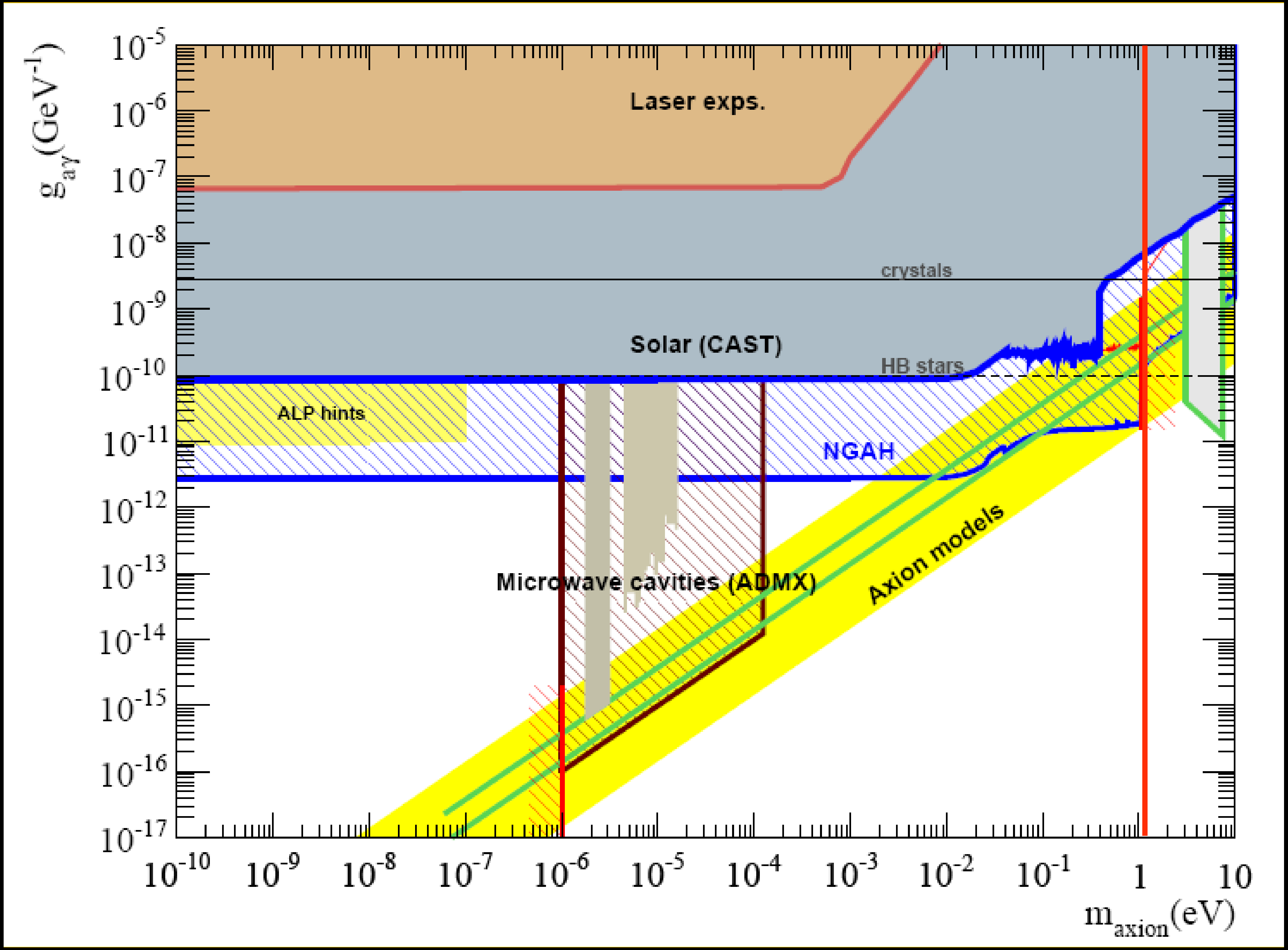
Quality factor

$$\mathrm{Power} = g_{a\gamma}^2 \frac{V B^2 \rho_a Q}{m_a} \sim 10^{-21}\ \mathrm{Watts}$$

Axion energy density



# Cavity limits and context



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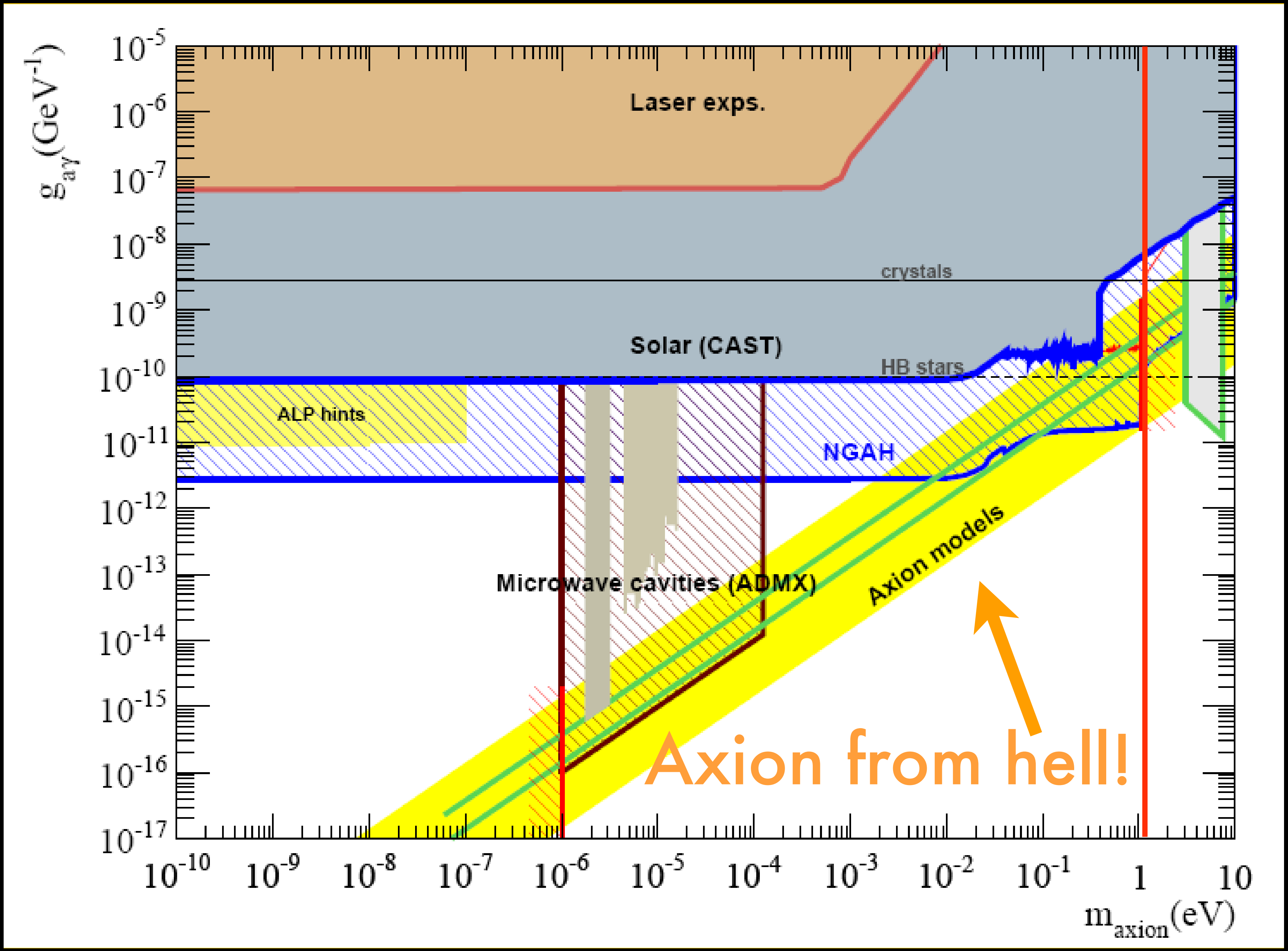

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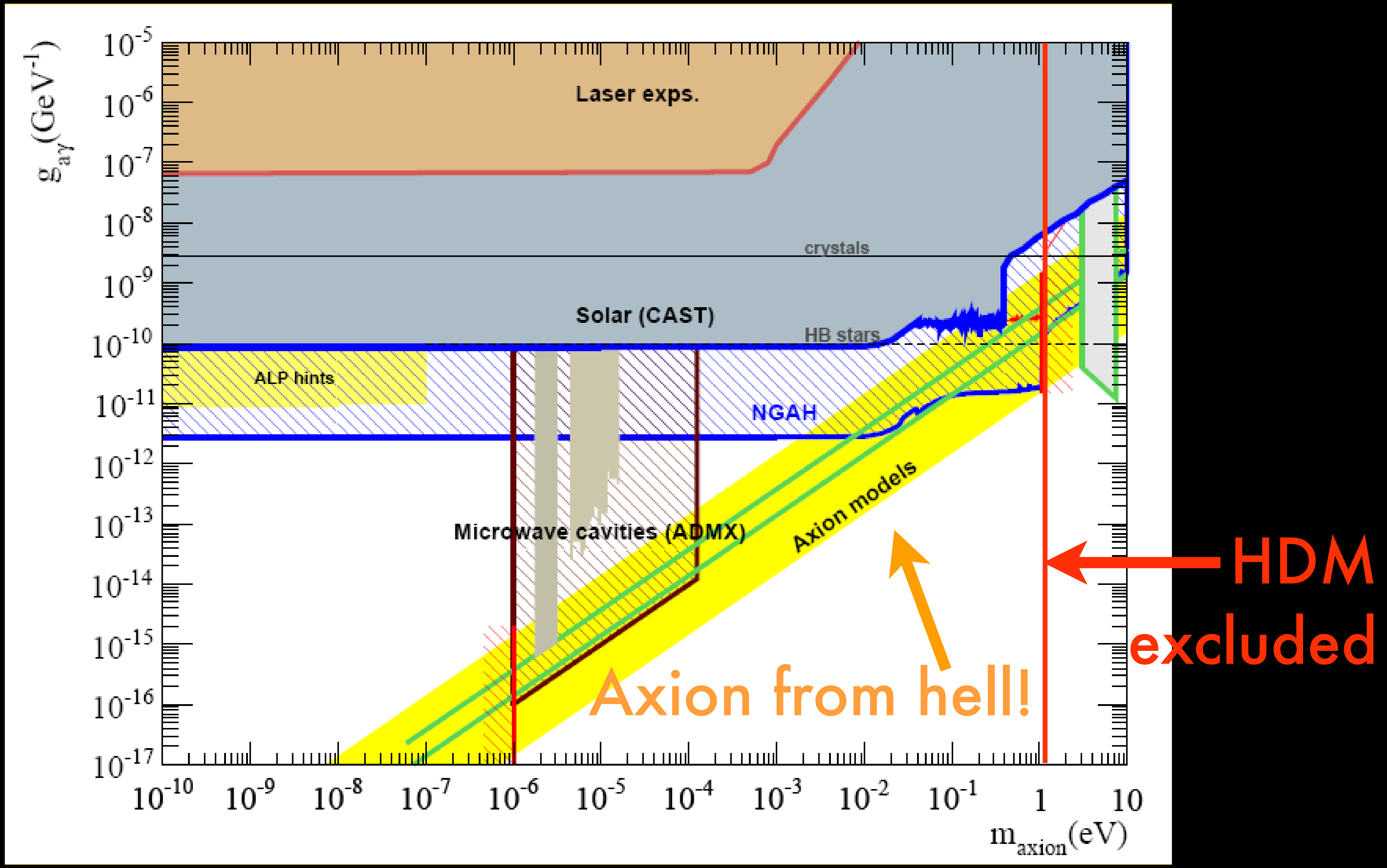
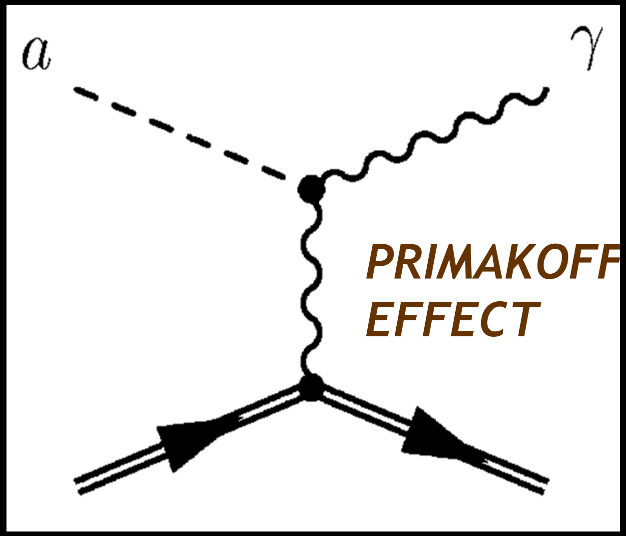
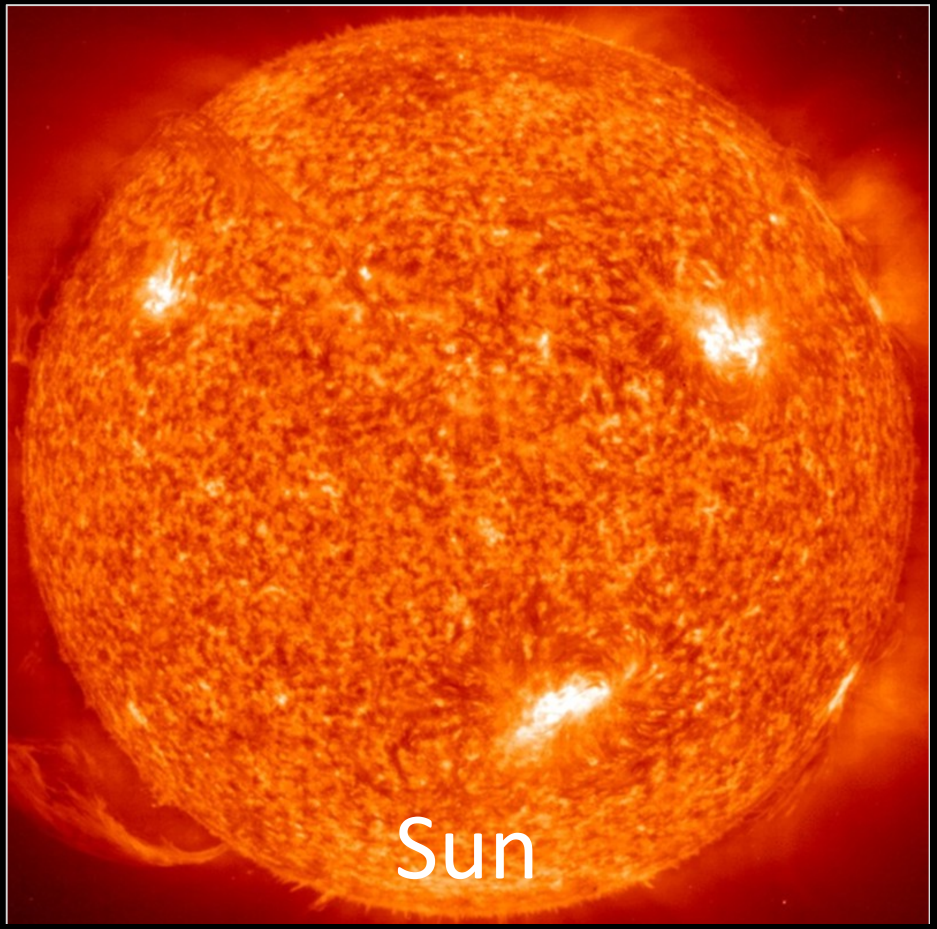


# Making axions in stars, I

- Primakoff process



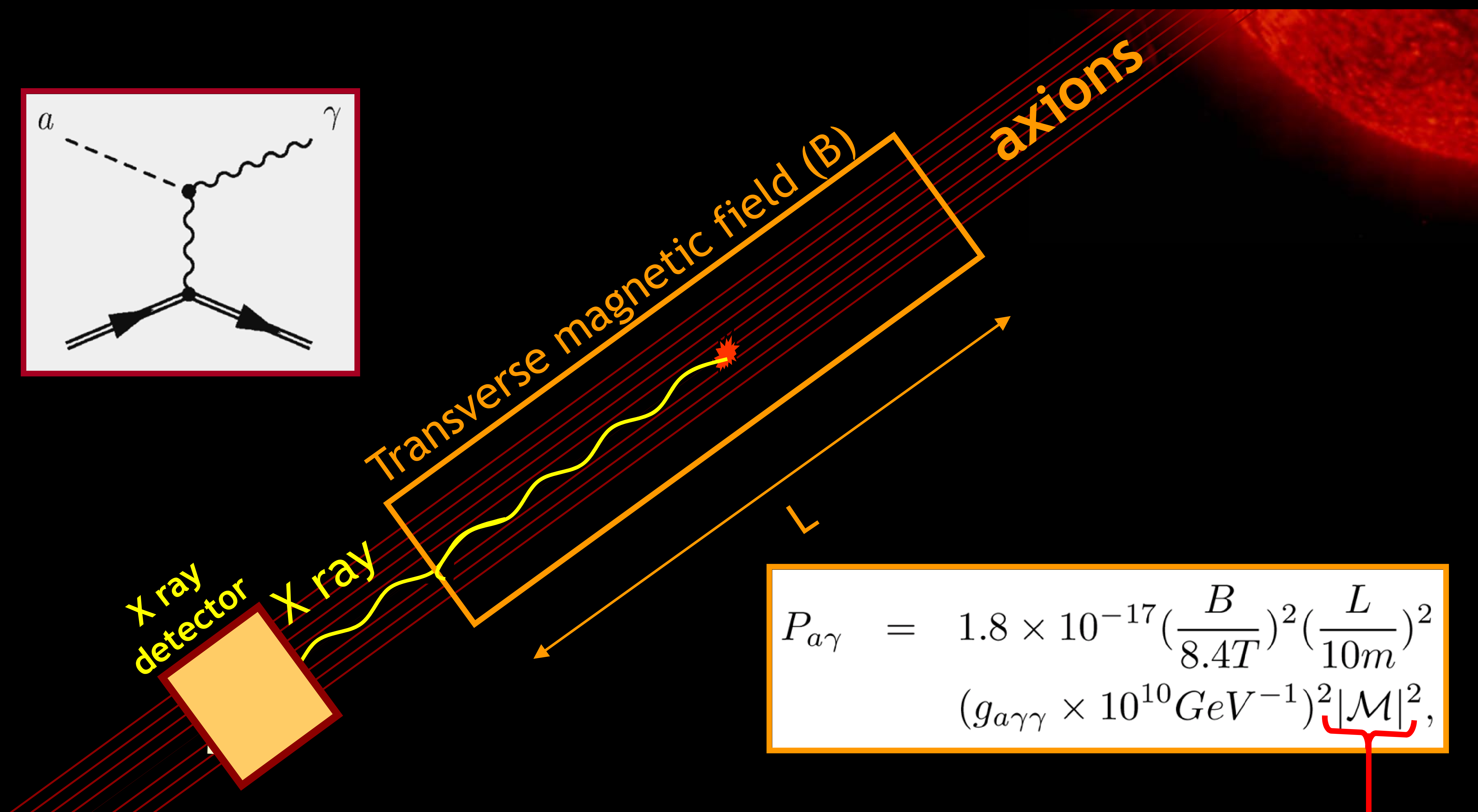




- Lifetime of our own sun/Solar luminosity/helioseismology impose constraint

$$g_{a\gamma\gamma} \lesssim 1 - 3 \times 10^{-9}\ \mathrm{GeV}^{-1}$$

# Axion helioscopes

- Backwards Primakoff process (Sikivie, Zioutas, and many others)




$$P_{a\gamma} = 1.8 \times 10^{-17} \left(\frac{B}{8.4T}\right)^2 \left(\frac{L}{10m}\right)^2 (g_{a\gamma\gamma} \times 10^{10} GeV^{-1})^2 \underbrace{|\mathcal{M}|^2}_{},$$

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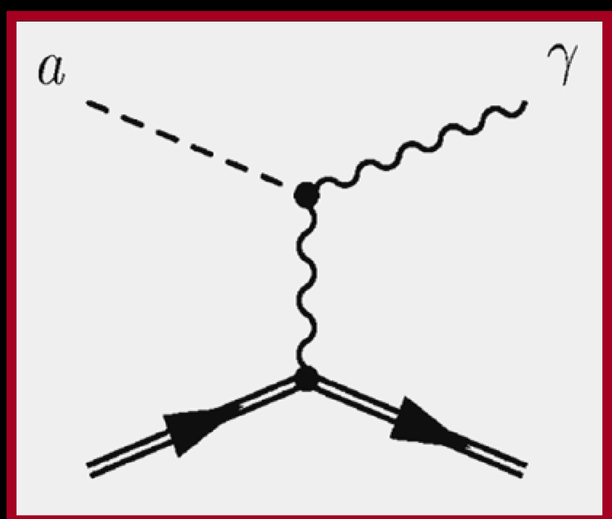


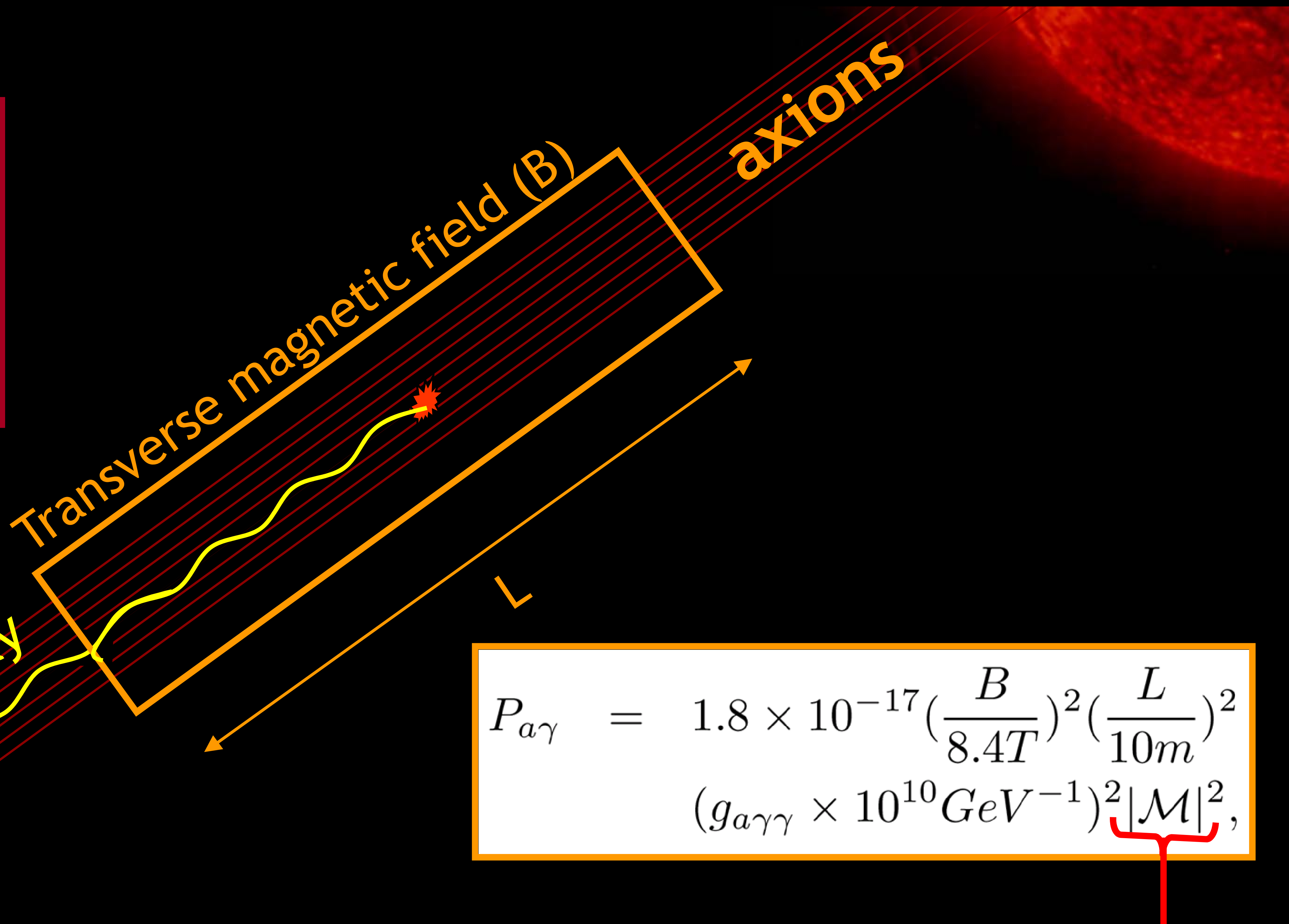


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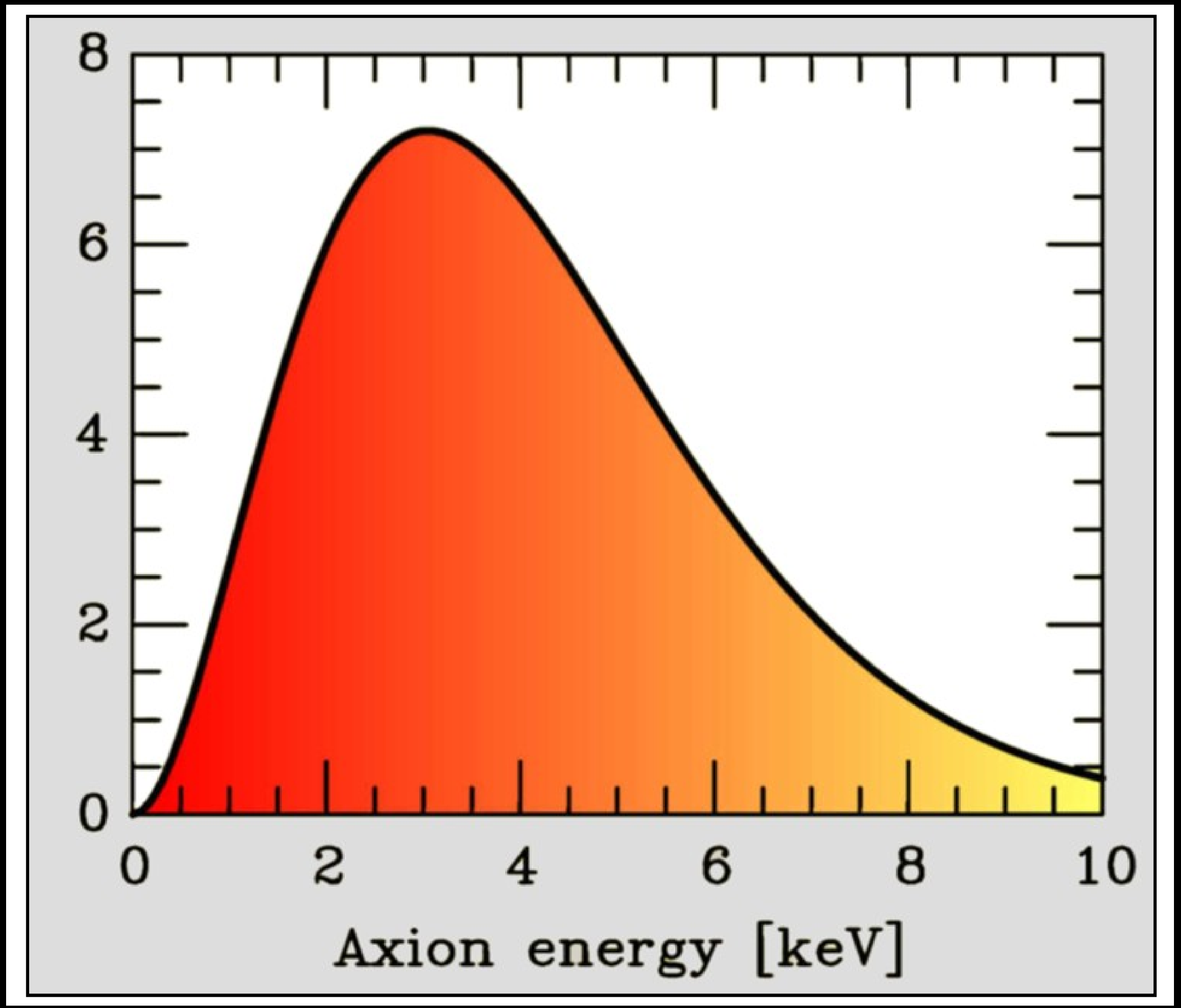
# Axion helioscopes

- Resonance condition

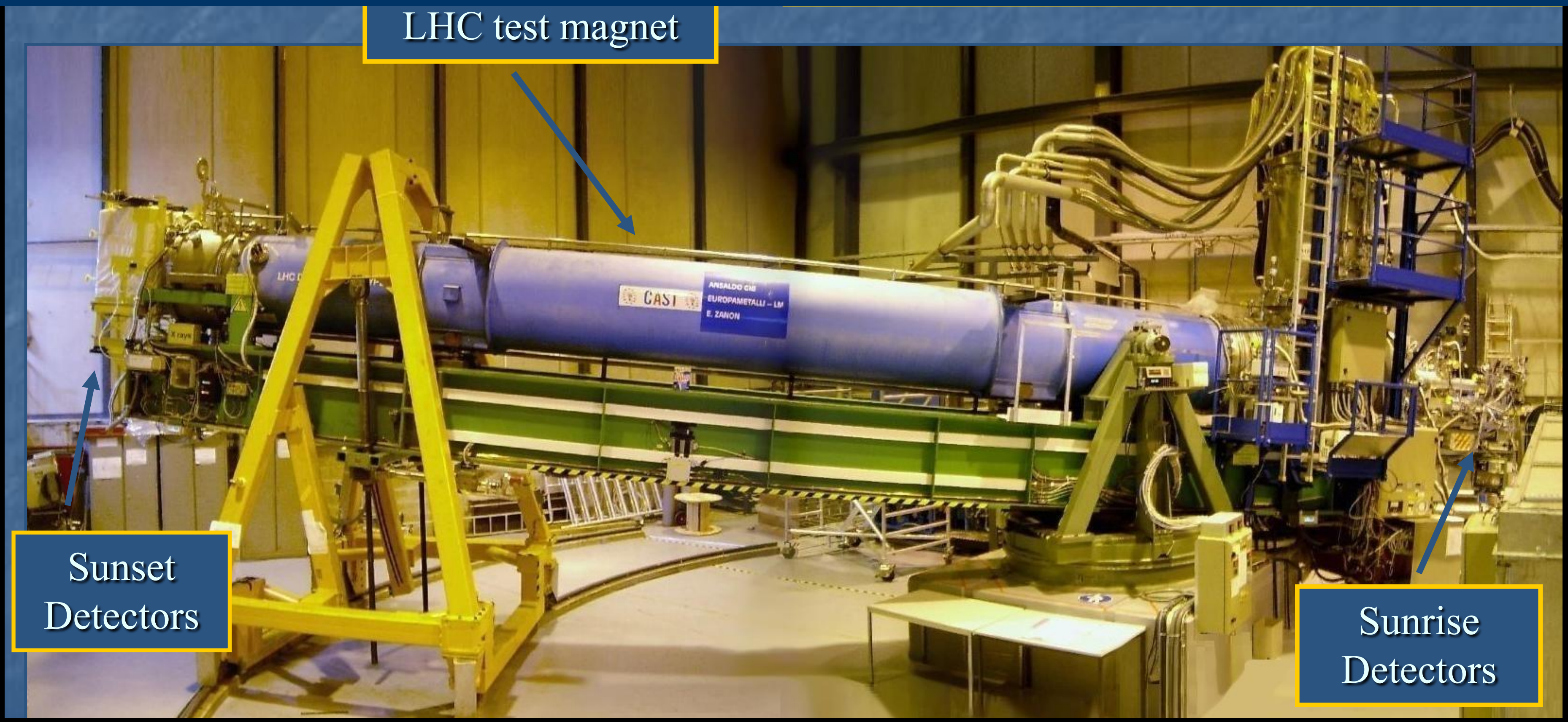
$$qL < \pi \quad \Rightarrow \quad \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}$$

- Broad axion energy spectrum



# CAST/IAXO

- ✴ CAST
  - ➢ LHC test magnet (B=9 T, L=9.26 m)




- ✴ IAXO proposal: 15-20m length magnet, optimized shape [not LHC DUD]

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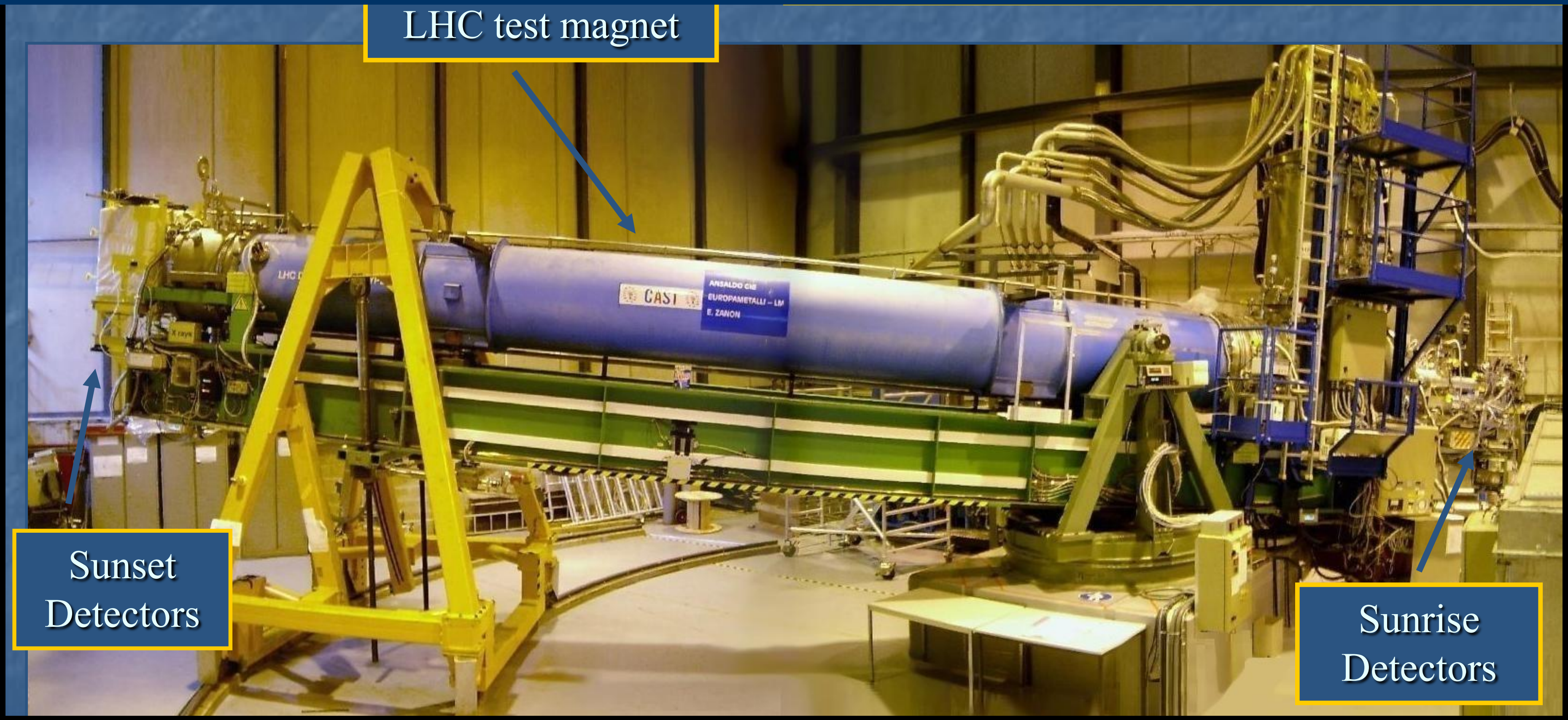


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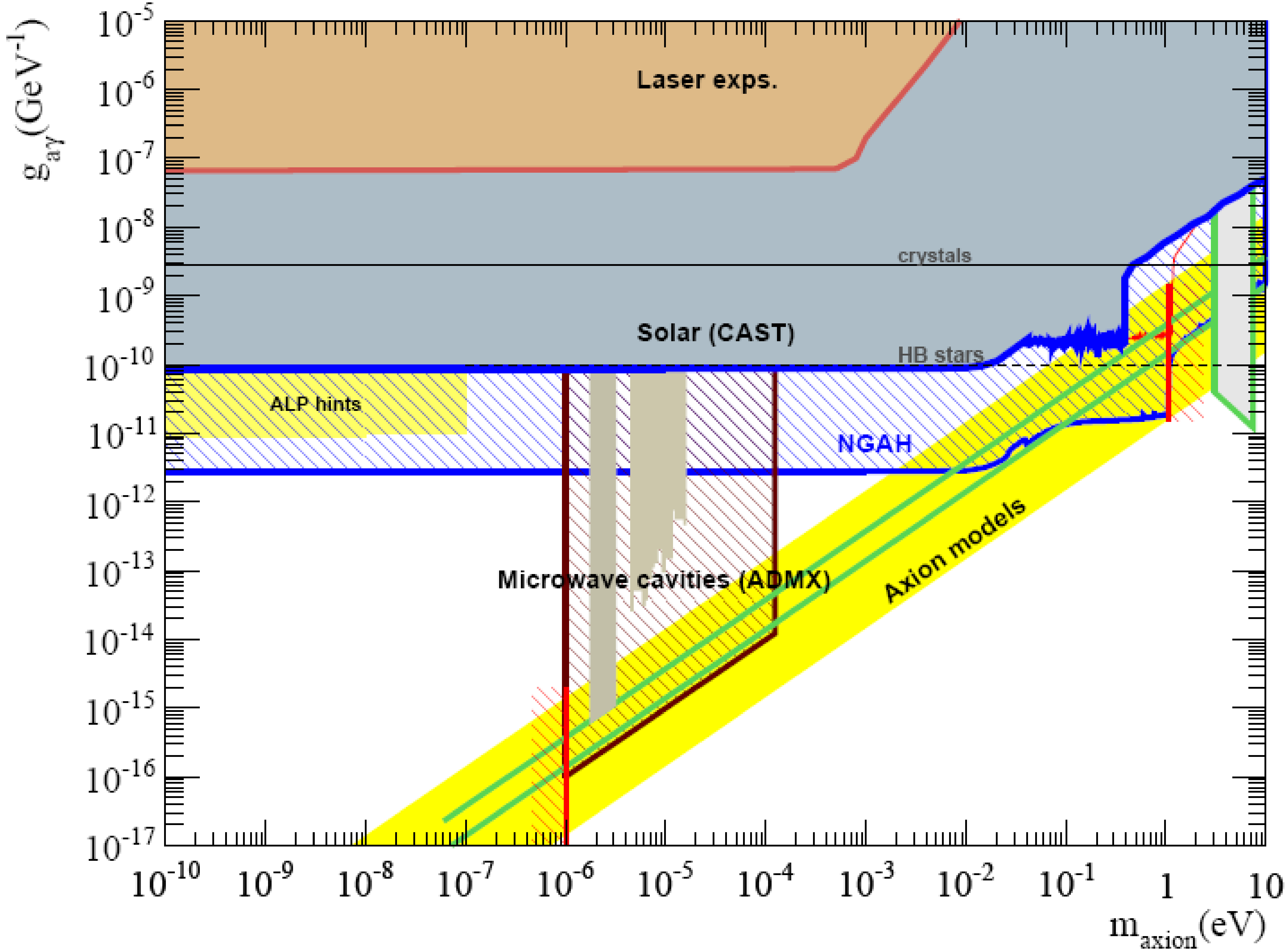
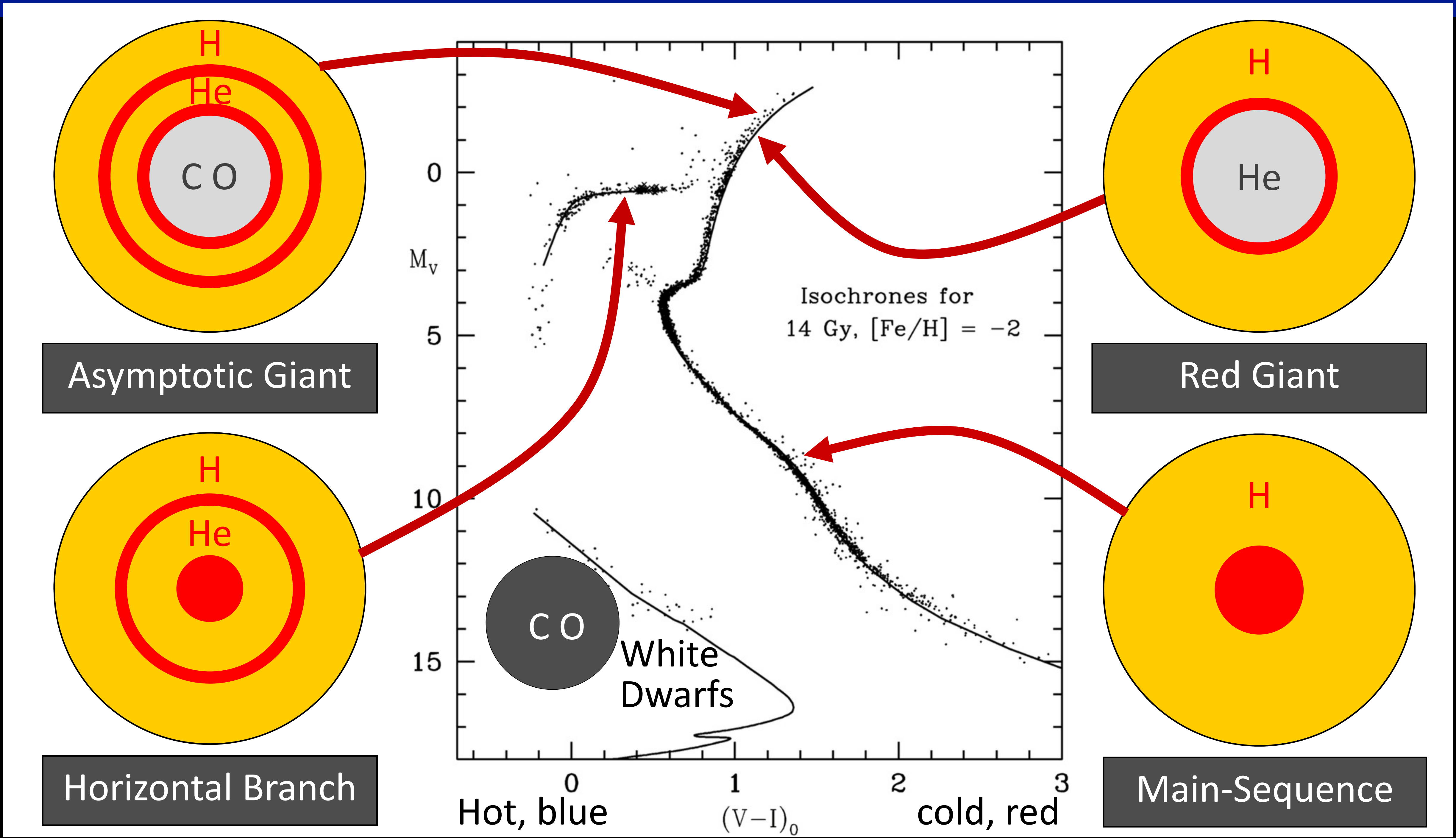
# Limits and horizon



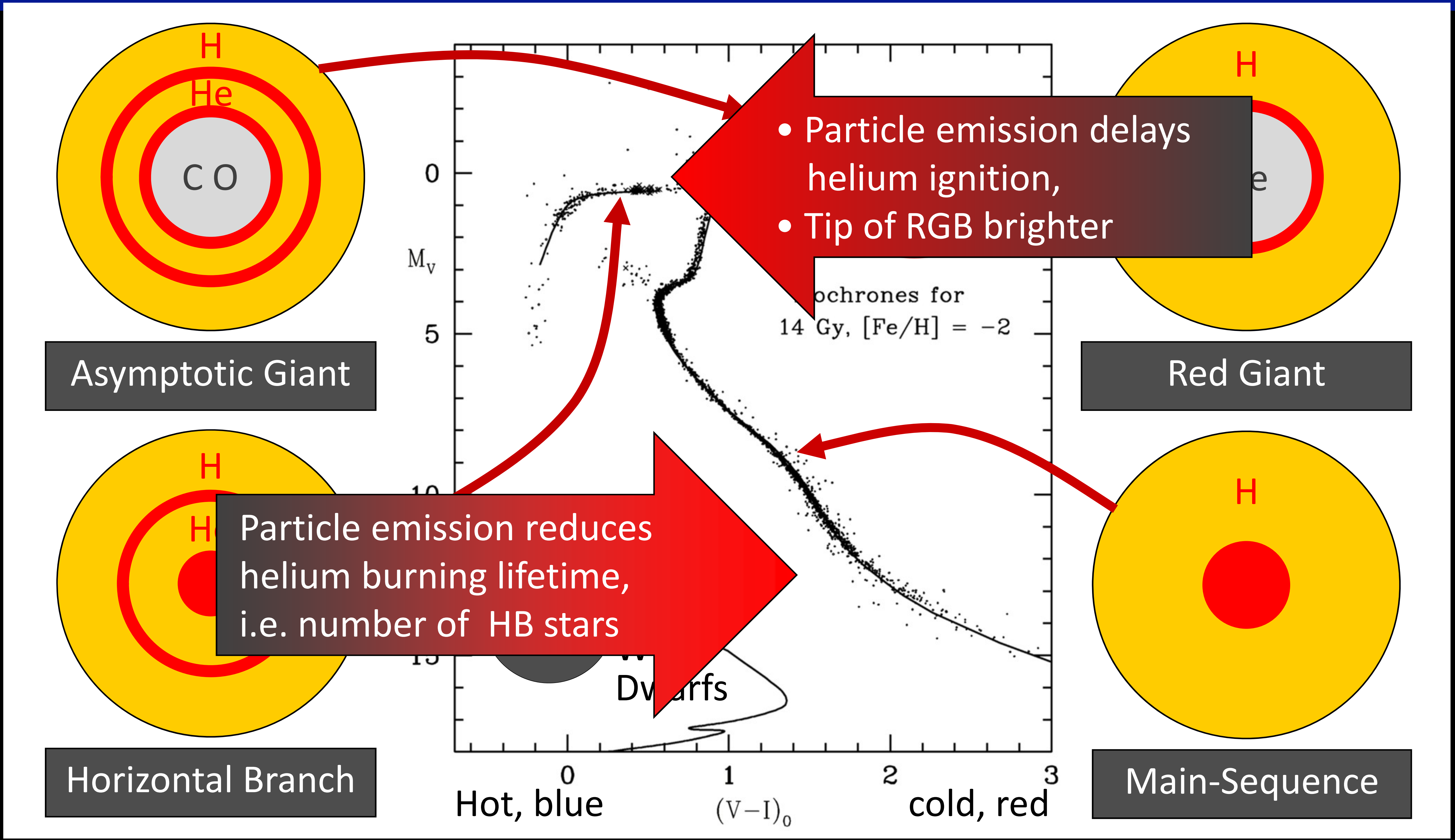
# Making axions in stars, II




From Raffelt 2012

$$g_{a\gamma\gamma} \lesssim 10^{-10}\ \mathrm{GeV}^{-1}$$

# Making axions in stars, II

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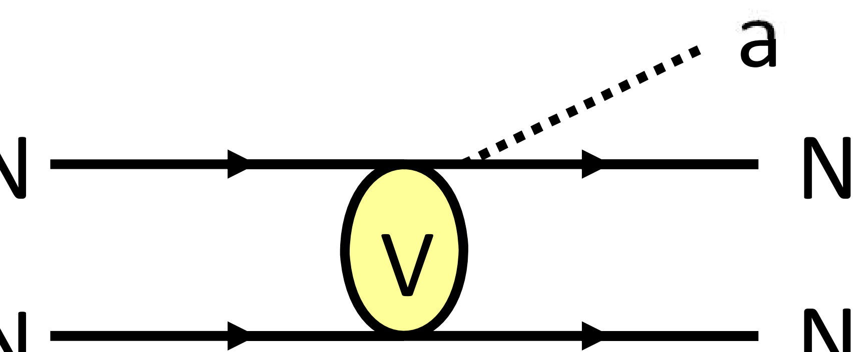
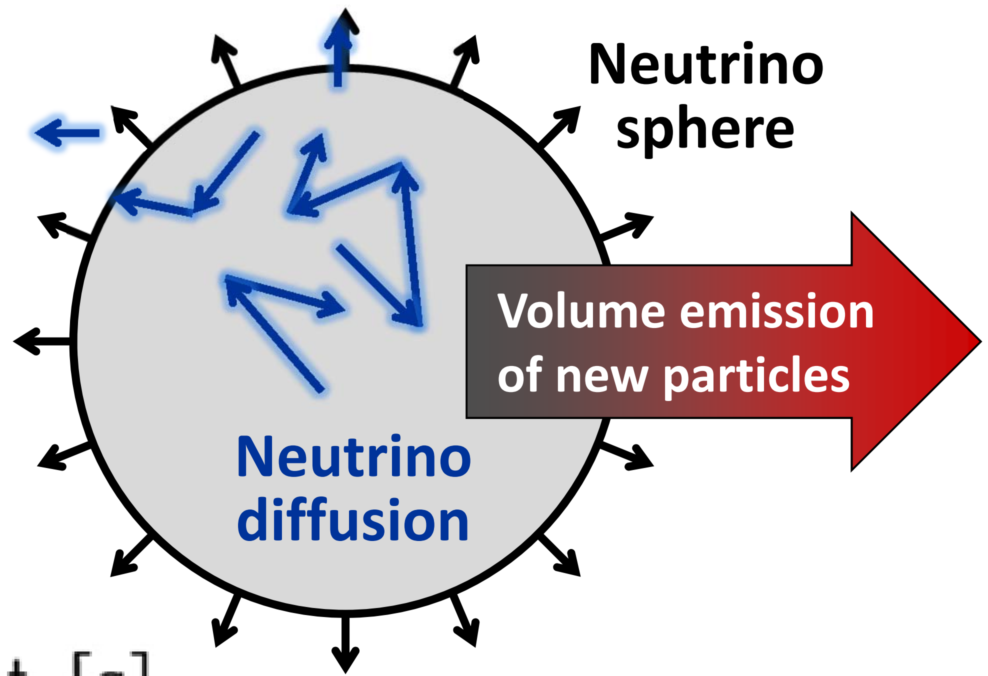
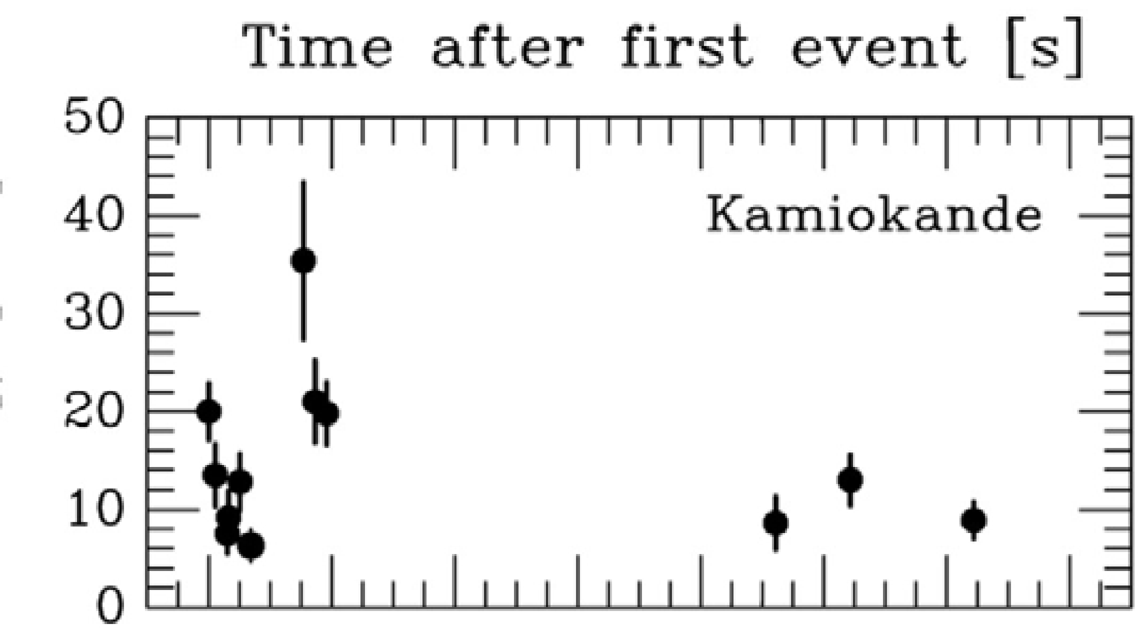
# Making axions in (exploding) stars, III




Nucleon-Nucleon Bremsstrahlung



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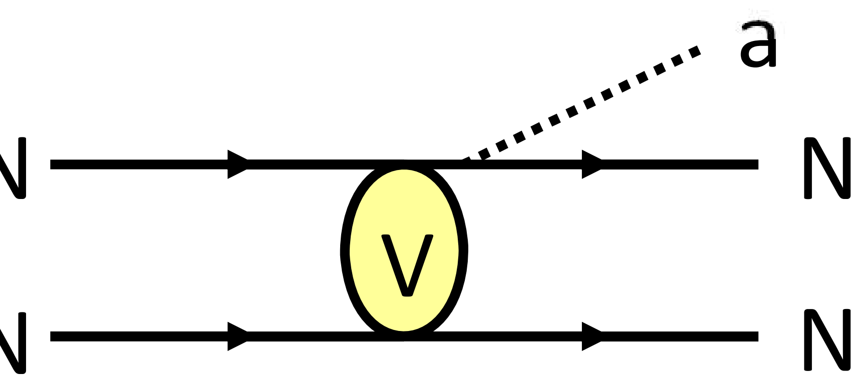


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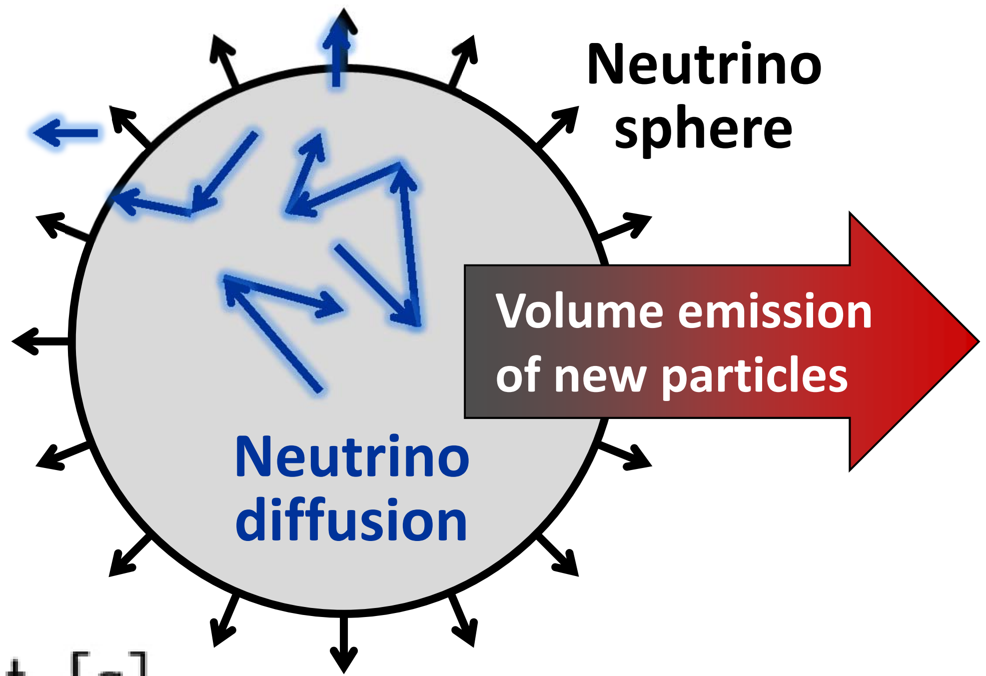


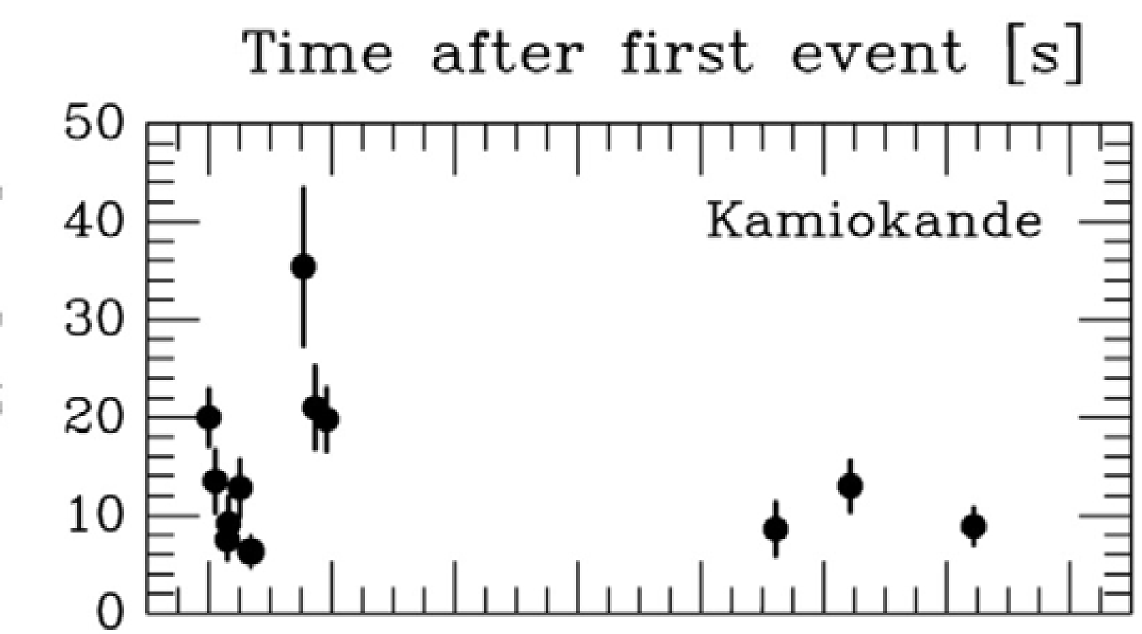

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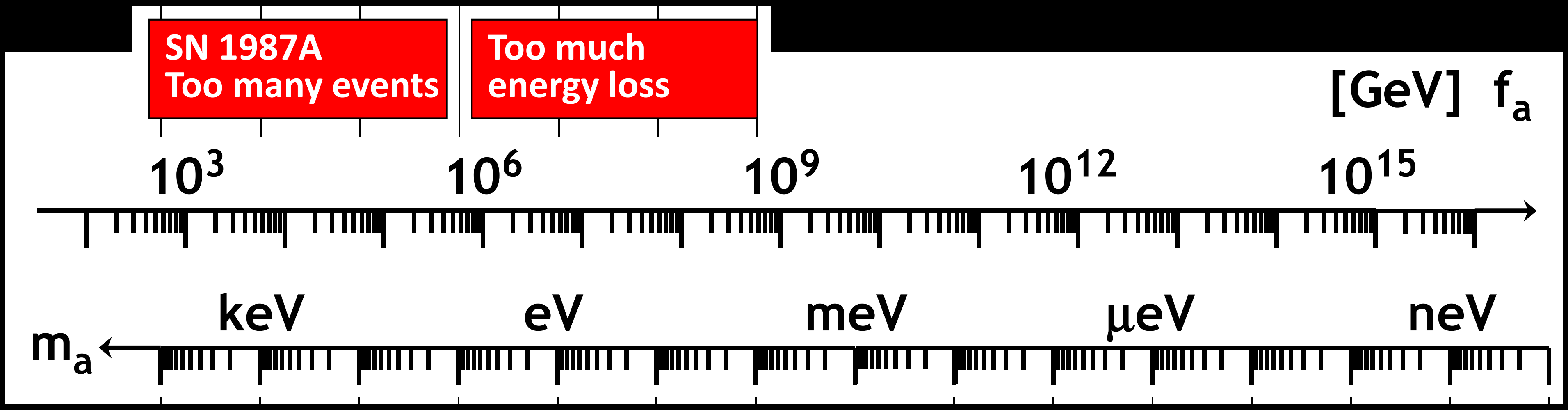
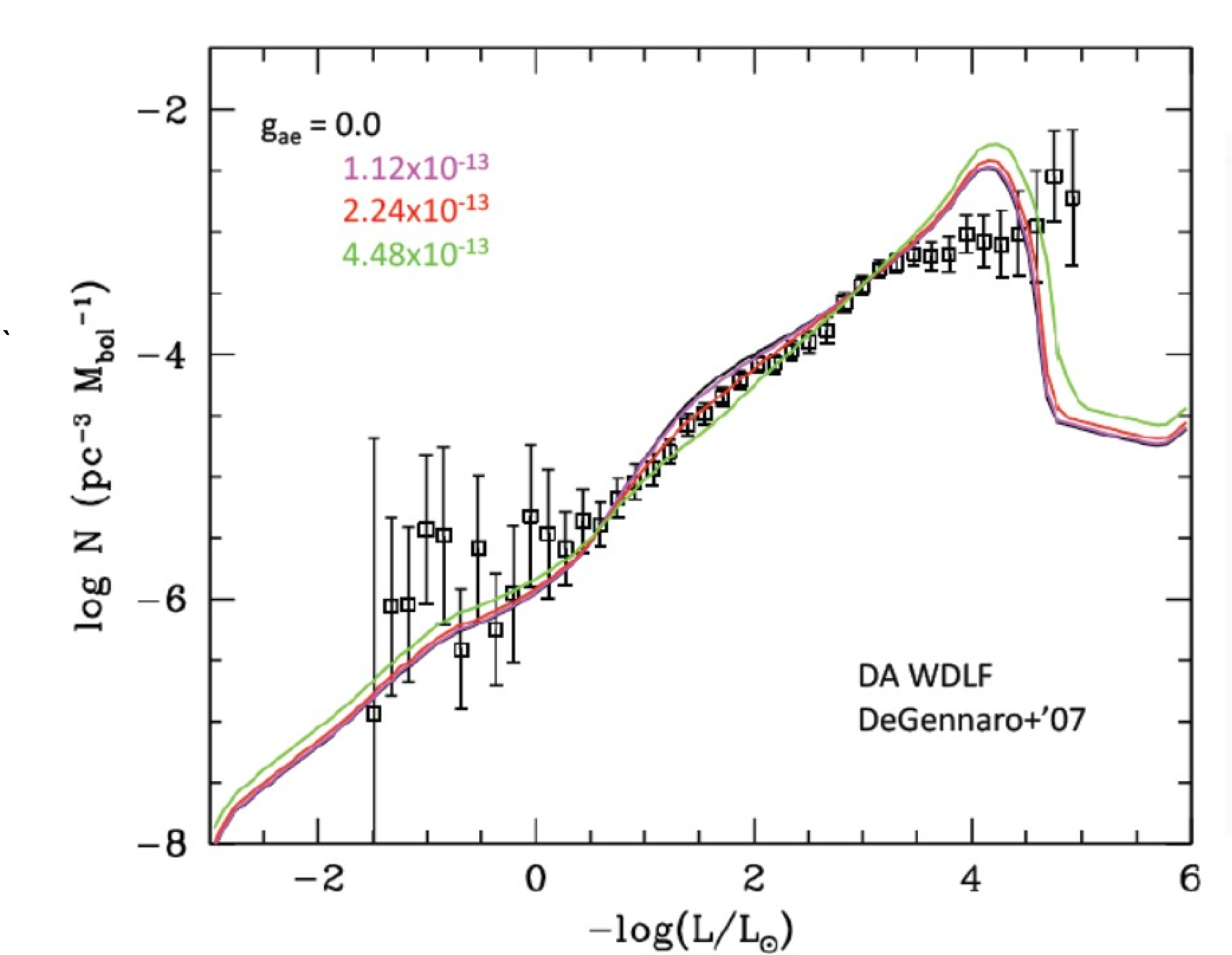
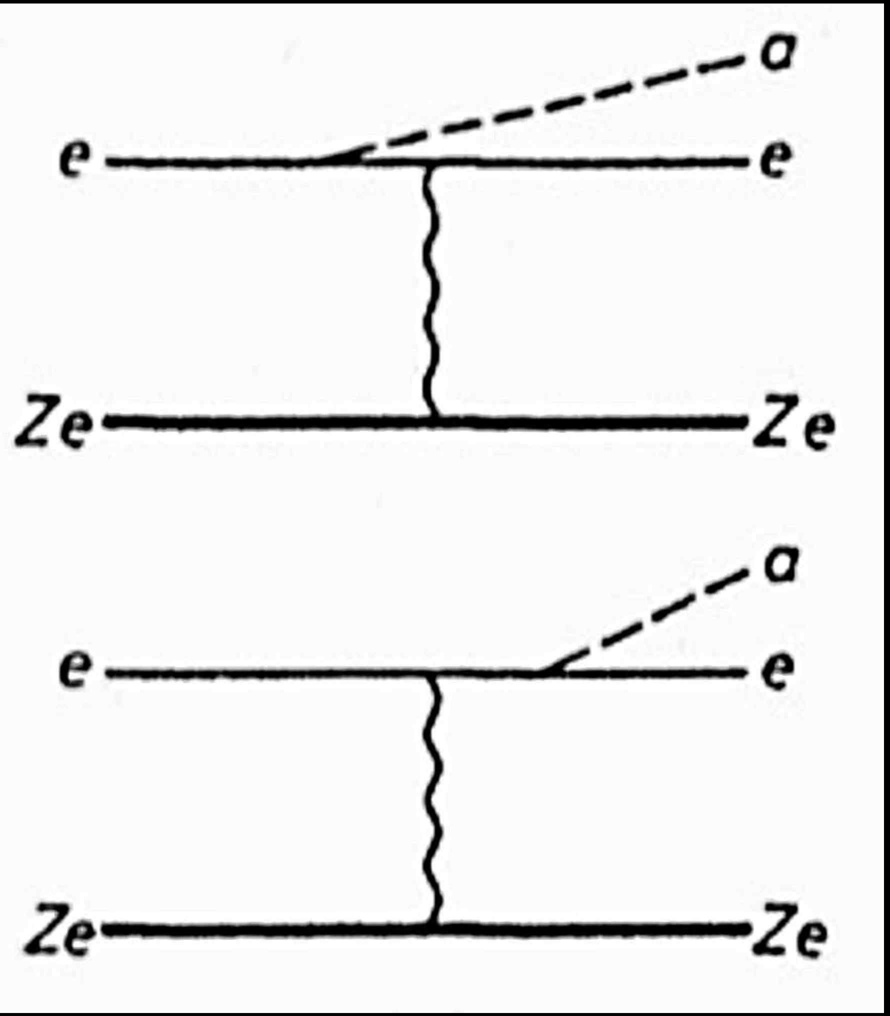


# Making axions in degenerate stars, IV

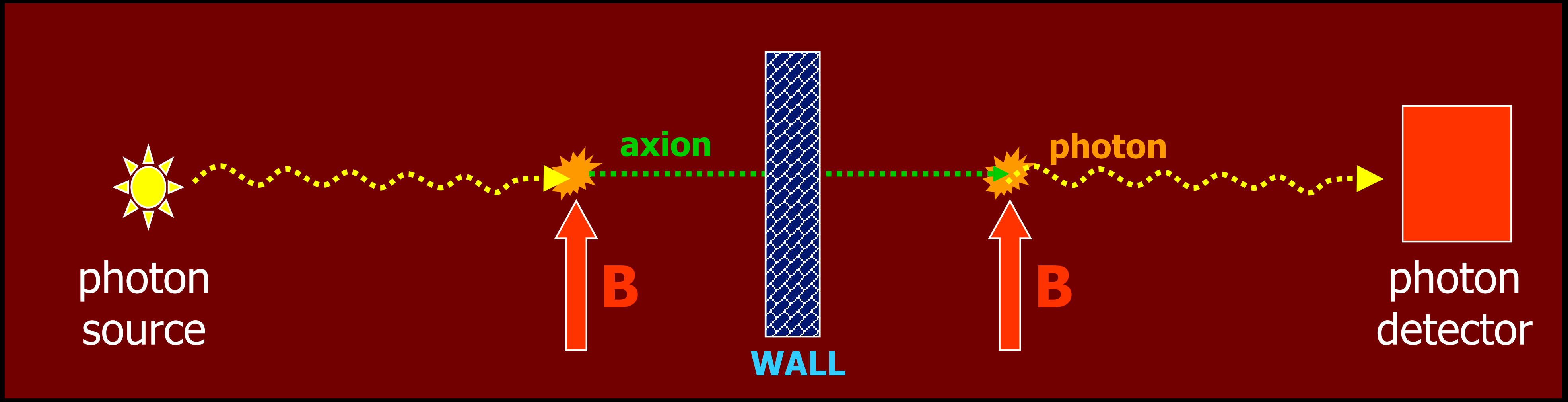
- WDs are remnants of $1\ M_\odot$ main – sequence stars
- Axio-electric coupling provides additional cooling channel



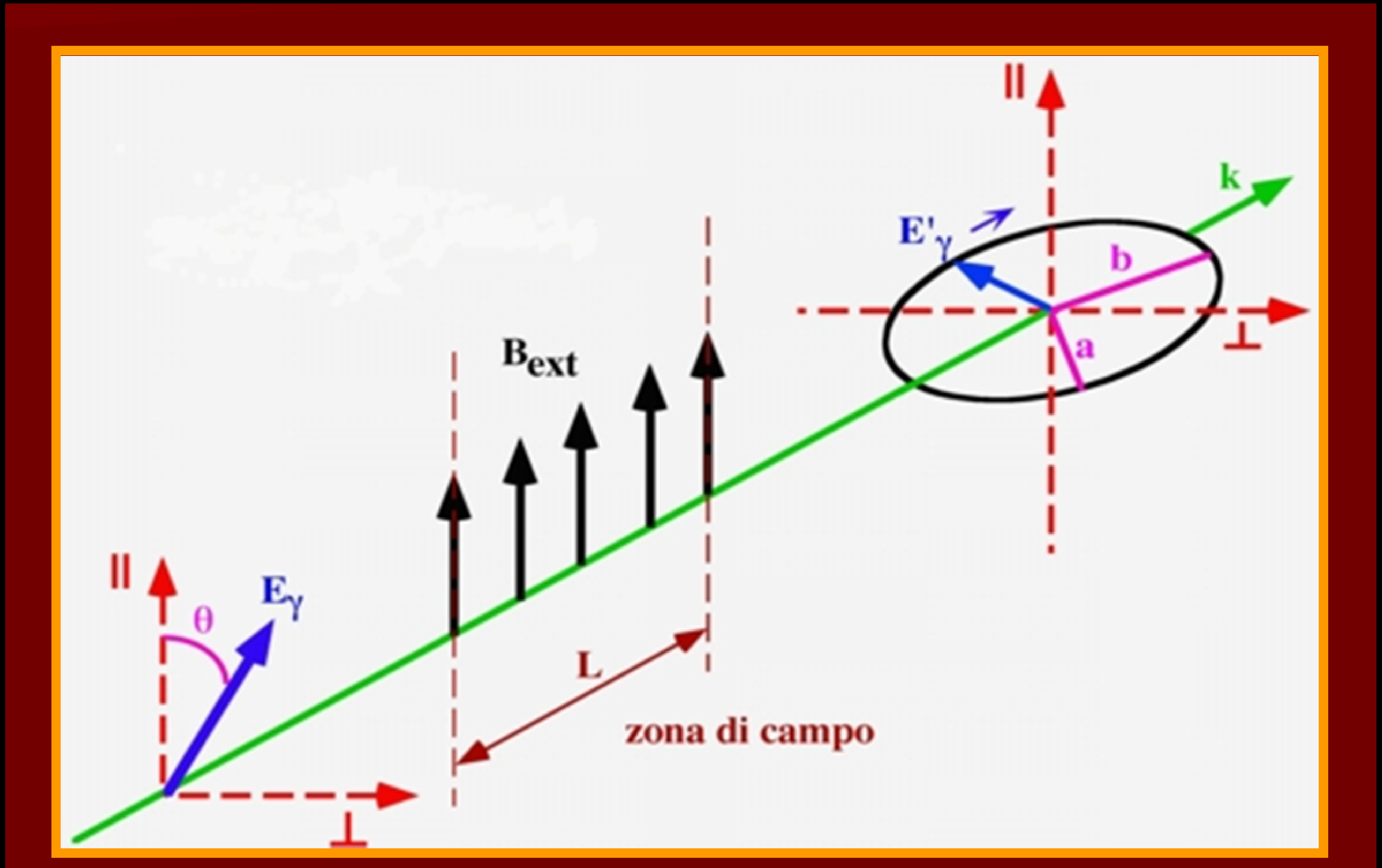



# Laser experiments

## Light shining through walls (e.g. GammeV)



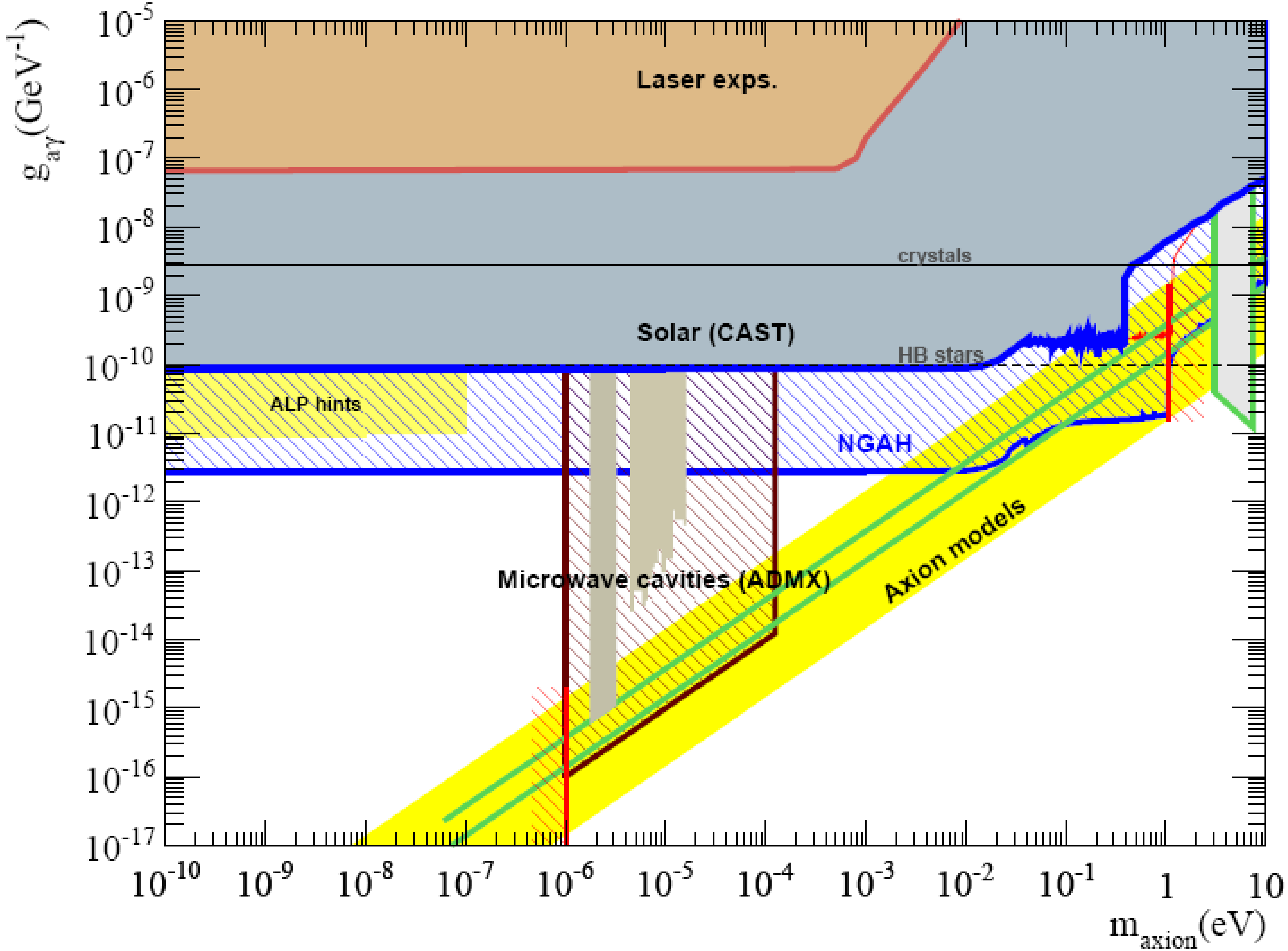

## Polarization experiments (e.g. PVLAS)



# Other methods

- Spectra of magnetic white dwarves **[New]**
- Extragalactic background light
- Pulsating white dwarf seismology **[New]**
- Dimming of gamma-ray blazars **[New]**
- Two-photon decays in galaxy clusters
- Light degrees of freedom at BBN **[New]**
- Helioscope in space **[New]**
- Oscillating electric dipole moments of nucleons **[NEW]**

# Limits and horizon



# Axions carry isocurvature

- If PQ symmetry broken during/before inflation

$$\sqrt{\langle a^2 \rangle} = \frac{H_{\rm I}}{2\pi}$$

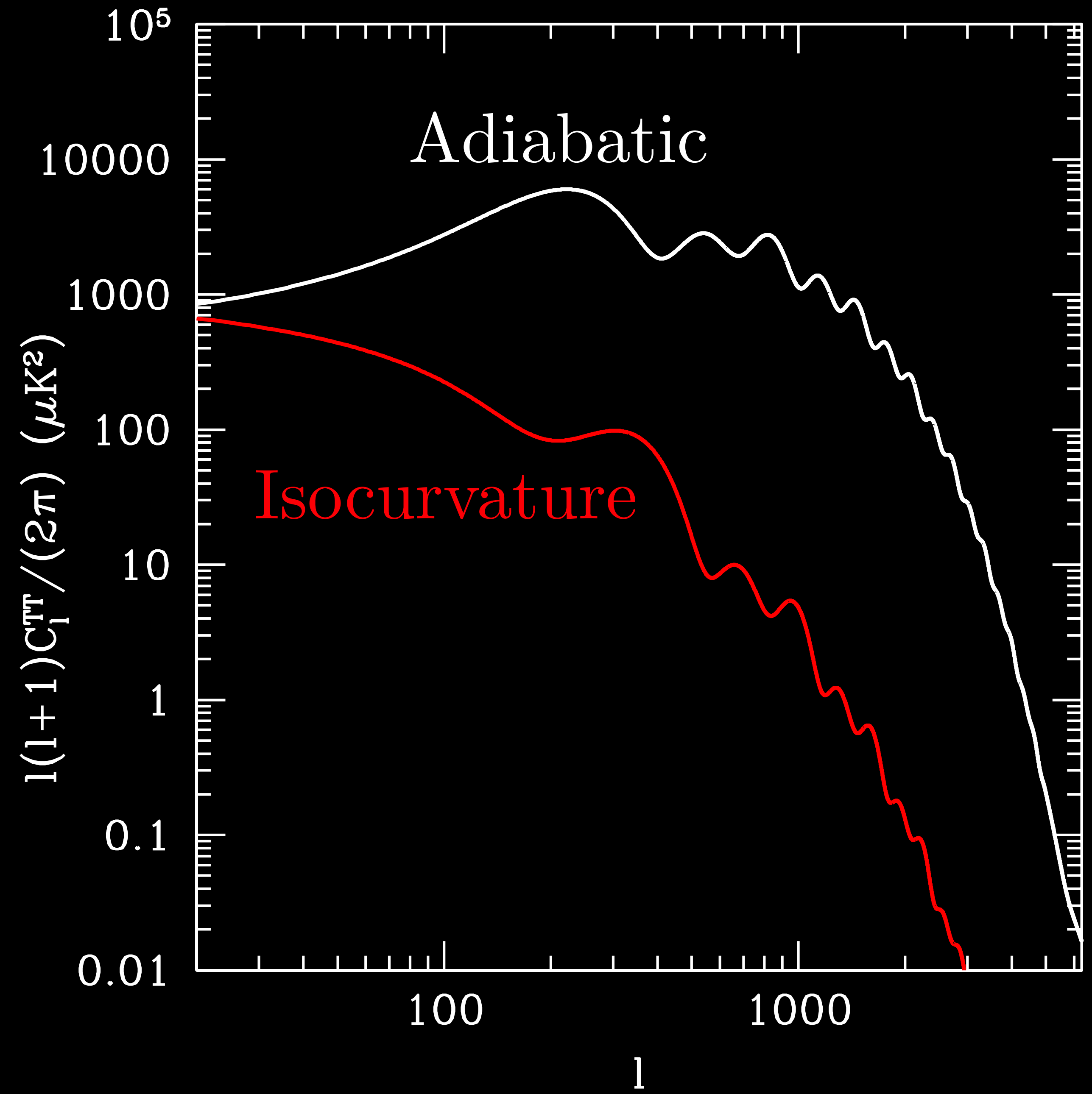
Quantum zero-point fluctuations!

- Subdominant species seed isocurvature fluctuations

$$\zeta \propto \frac{\rho_a}{\rho_{\rm tot}} \frac{\delta\rho_a}{\rho_a} \ll 10^{-5}$$

$$S_{a\gamma} = \frac{\delta n_a}{n_a} - \frac{\delta n_\gamma}{n_\gamma} = \frac{\delta\rho_a}{\rho_a} - \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} \sim 10^{-5}$$

# SACHS WOLFE-EFFECT & POWER SPECTRA



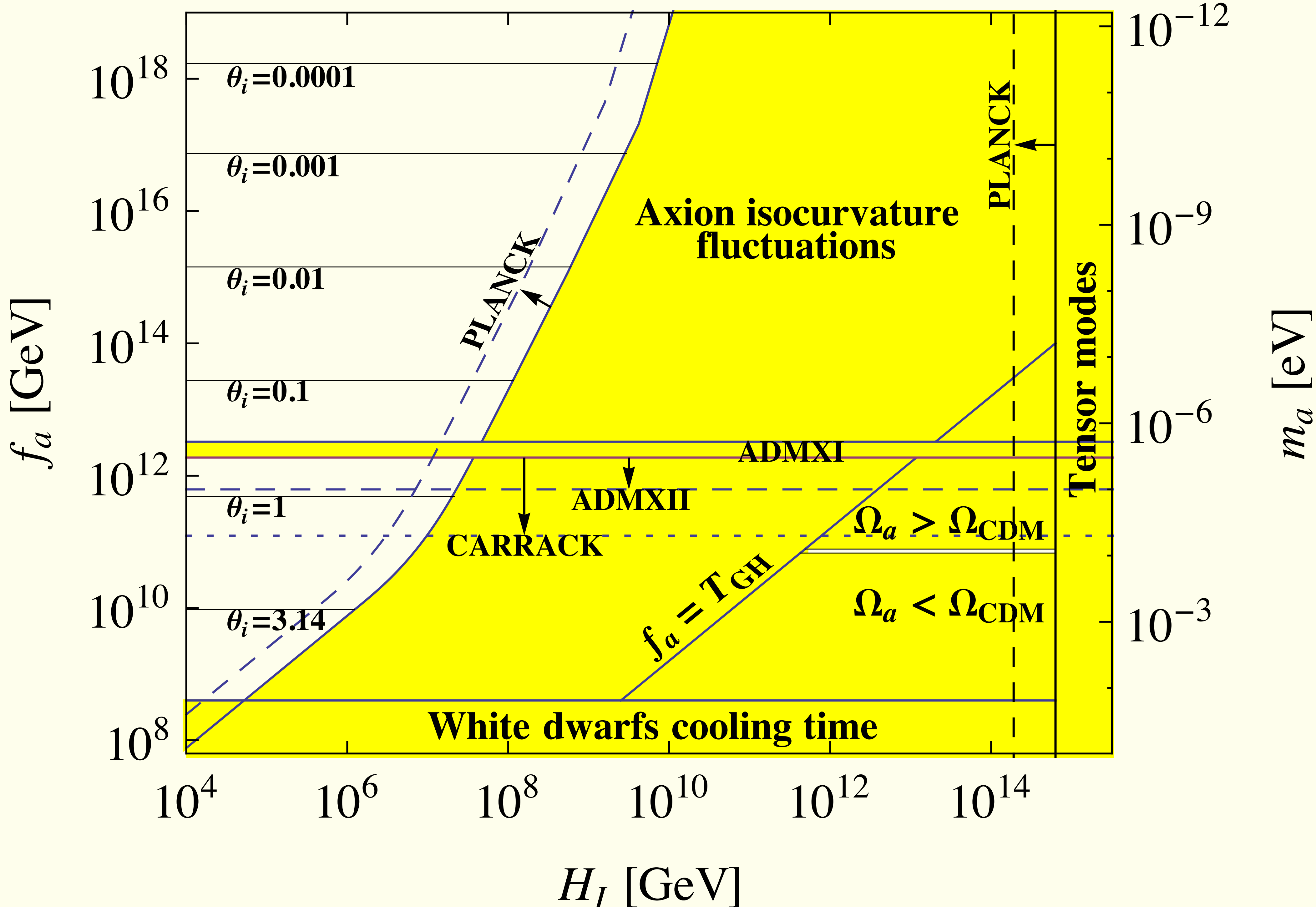

- Planck TT constraints

$$\frac{P_{\rm iso}}{P_{\rm tot}} \lesssim 1.6 \times 10^{-2}$$

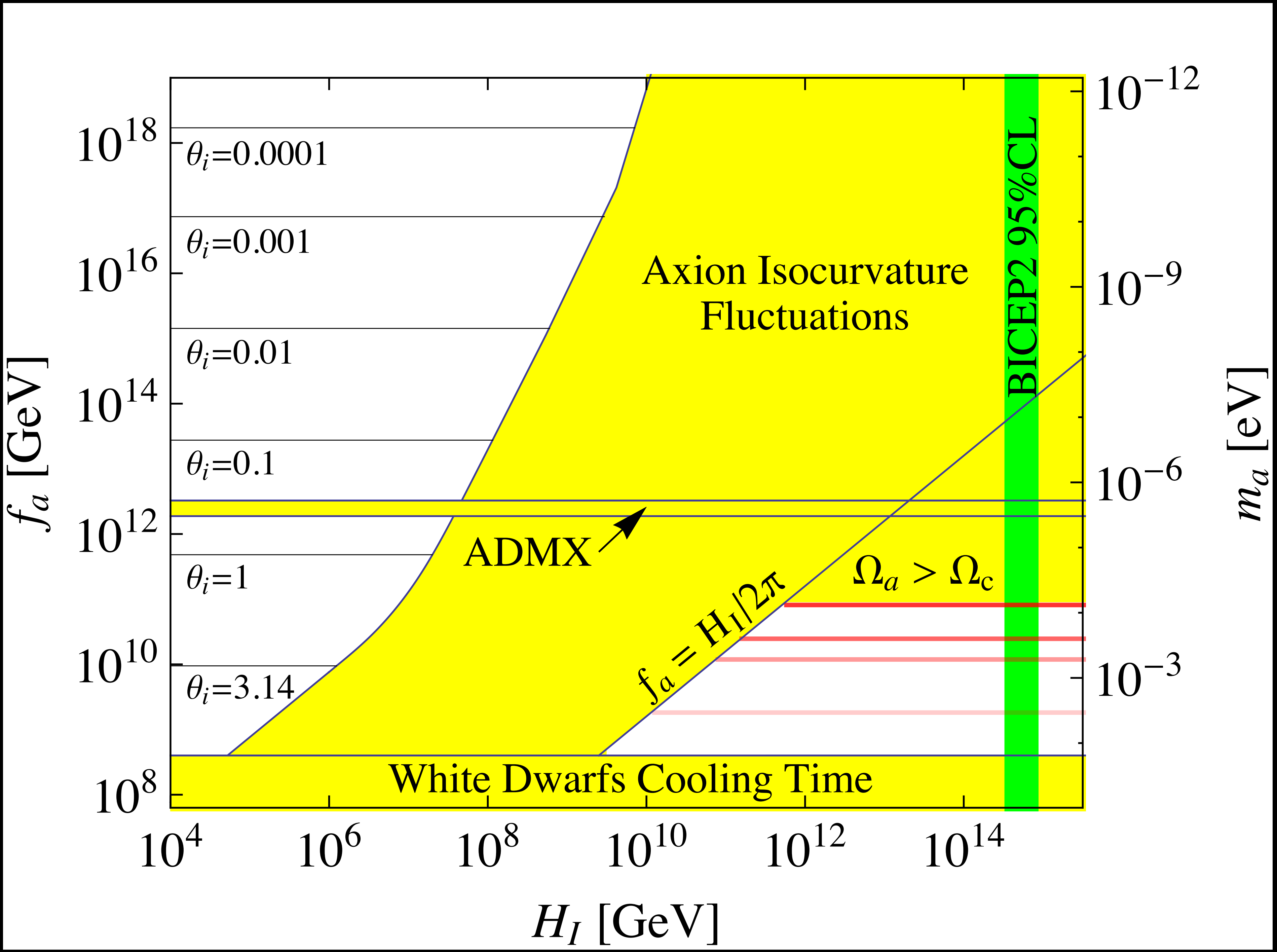
$$\frac{H_I}{f_a \bar{\theta}} \frac{\Omega_a}{\Omega_{\rm d}} \lesssim 4 \times 10^{-5}$$

# LAST AXIONIC STAND BEFORE BICEP2

(Gondolo 2009):
ADMX axions still viable if low-scale inflation
or in classical window

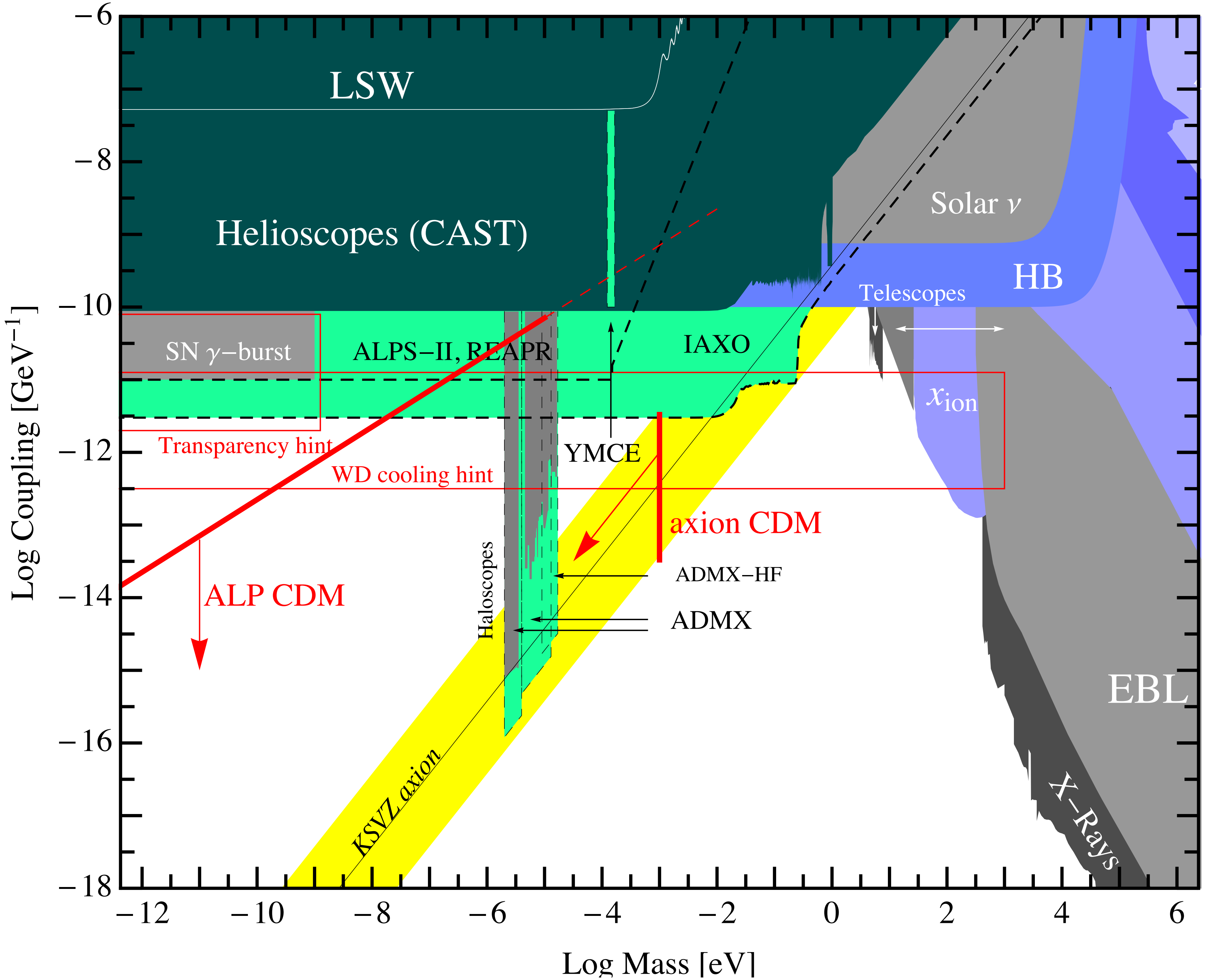


# BICEP2 [inflationary energy scale detected?]




✴ Hard to accomodate QCD axion DM w/o defects! [Marsh +yours truly+others 2014, Gondolo et al. 2014]

# Lay of the land



# A new scale for perturbed scalars

✴ *Perturbations obey*

$$\boxed{\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi} + \left(k^2 + m^2 a^2\right)\delta\phi = -\dot{\phi}_0 \dot{h}/2}$$

✴ *Structure suppressed when*

$$k \gg k_{\mathrm{J}} \sim \sqrt{m\mathcal{H}}$$

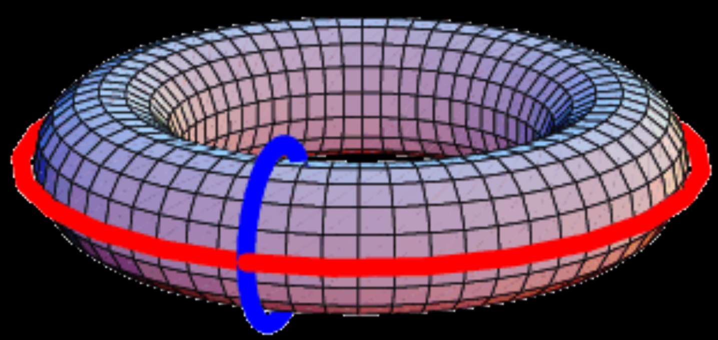
✴ *Scales are very small for QCD axion*

$$\lambda \sim 10^{10}\ \mathrm{cm}$$

What about lighter axions?

# Light axions and string theory

- String theory has extra dimensions: *compactify (6)!*
- Form fields and gauge fields: `Axion’ is KK zero-mode of form field



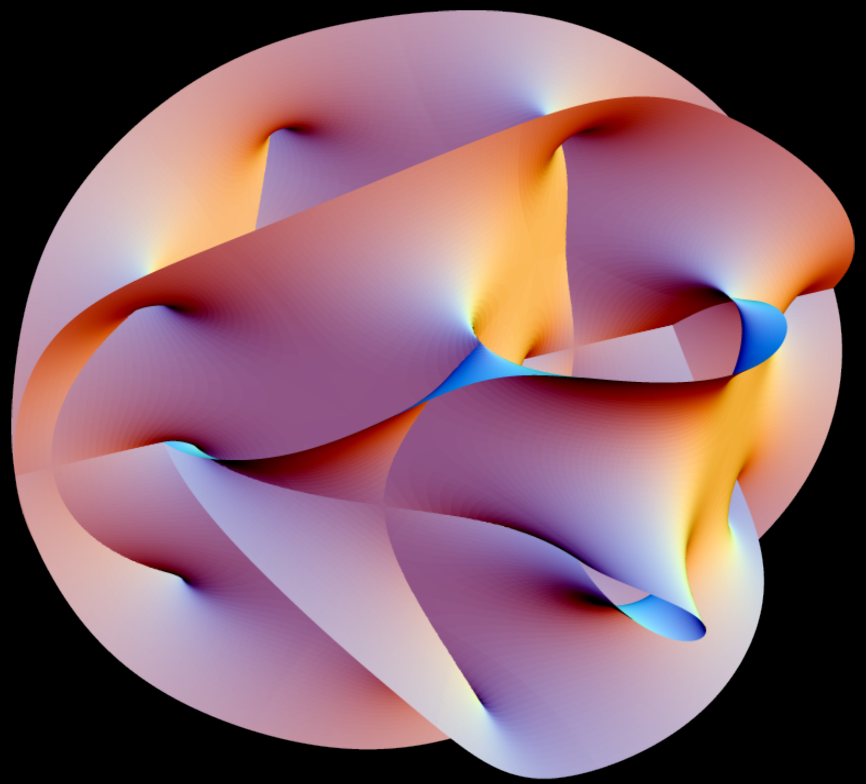
$$\mathcal{L} \propto \frac{aG\tilde{G}}{f_{\mathrm{a}}}$$

# Axiverse! (Arvanitaki et al. 2009)

- ✳ Calabi-Yau manifolds

Many 2-cycles ⟶ Many axions

*Hundreds!*

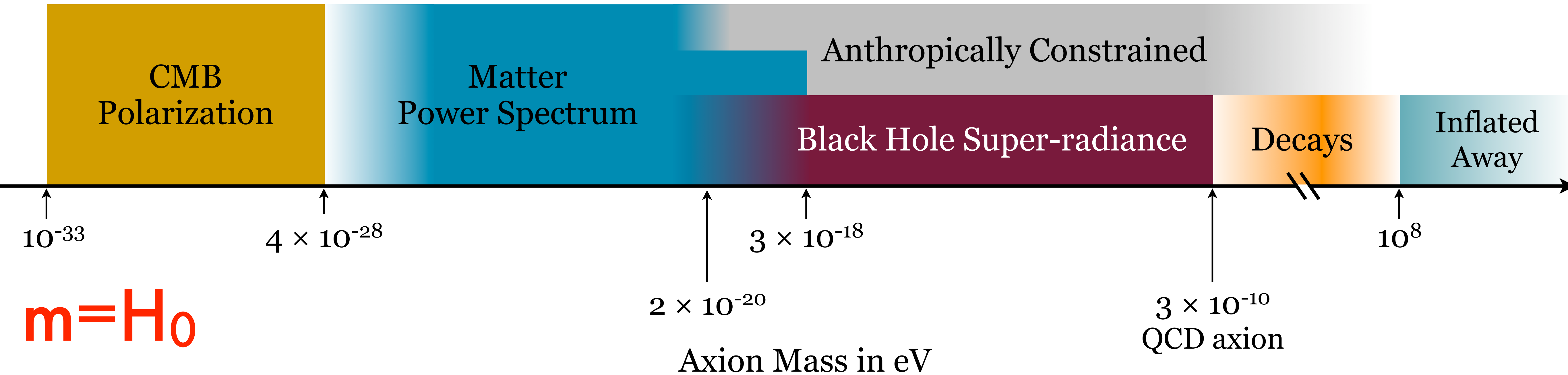


- ✳ Mass from non-perturbative physics (instantons, D-branes)

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-S} \quad f_a \propto \frac{M_{\rm pl}}{S}$$

Many decades in mass covered!

# Axiverse! (Phenomena)




- ***Birefringence (Faraday rotation), model dependent:***

$$\mathcal{L} \propto \frac{a\vec{E}\cdot\vec{B}}{f_a}$$

- ***Decrement in matter power spectrum for***

$$\boxed{k \gg k_{\rm J} \sim \sqrt{m\mathcal{H}}}$$

# Effective fluid approximation

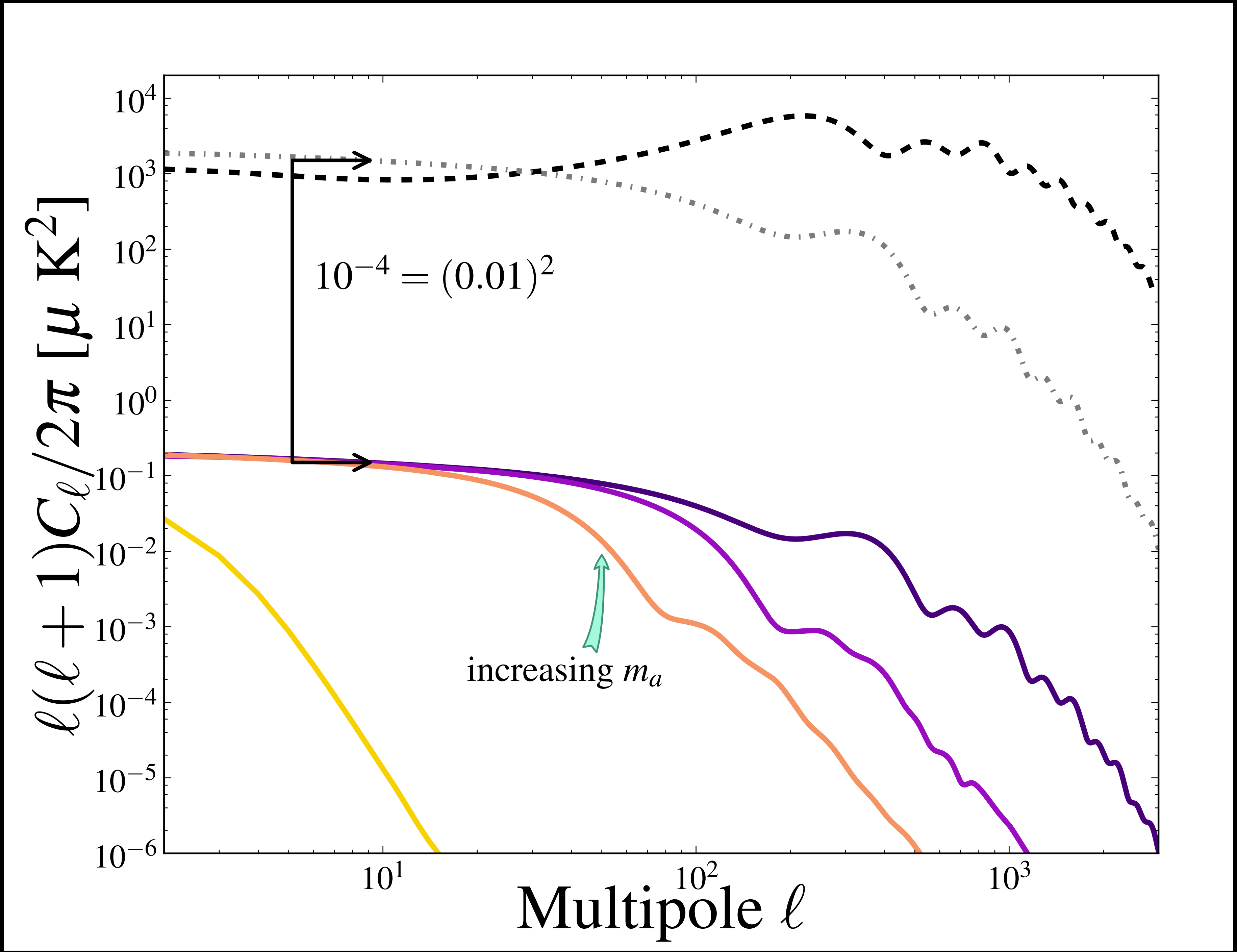
- Computing observables is expensive for $m \gg H_0$:
  - Coherent oscillation time scale

    $$\Delta\eta \sim (ma)^{-1} \ll \Delta\eta_{\mathrm{CAMB}}$$

  - Ansatz $\delta\phi = A_c \Delta_c(k,\eta)\cos(m\eta) + A_s\Delta(k,\eta)\sin(m\eta)$

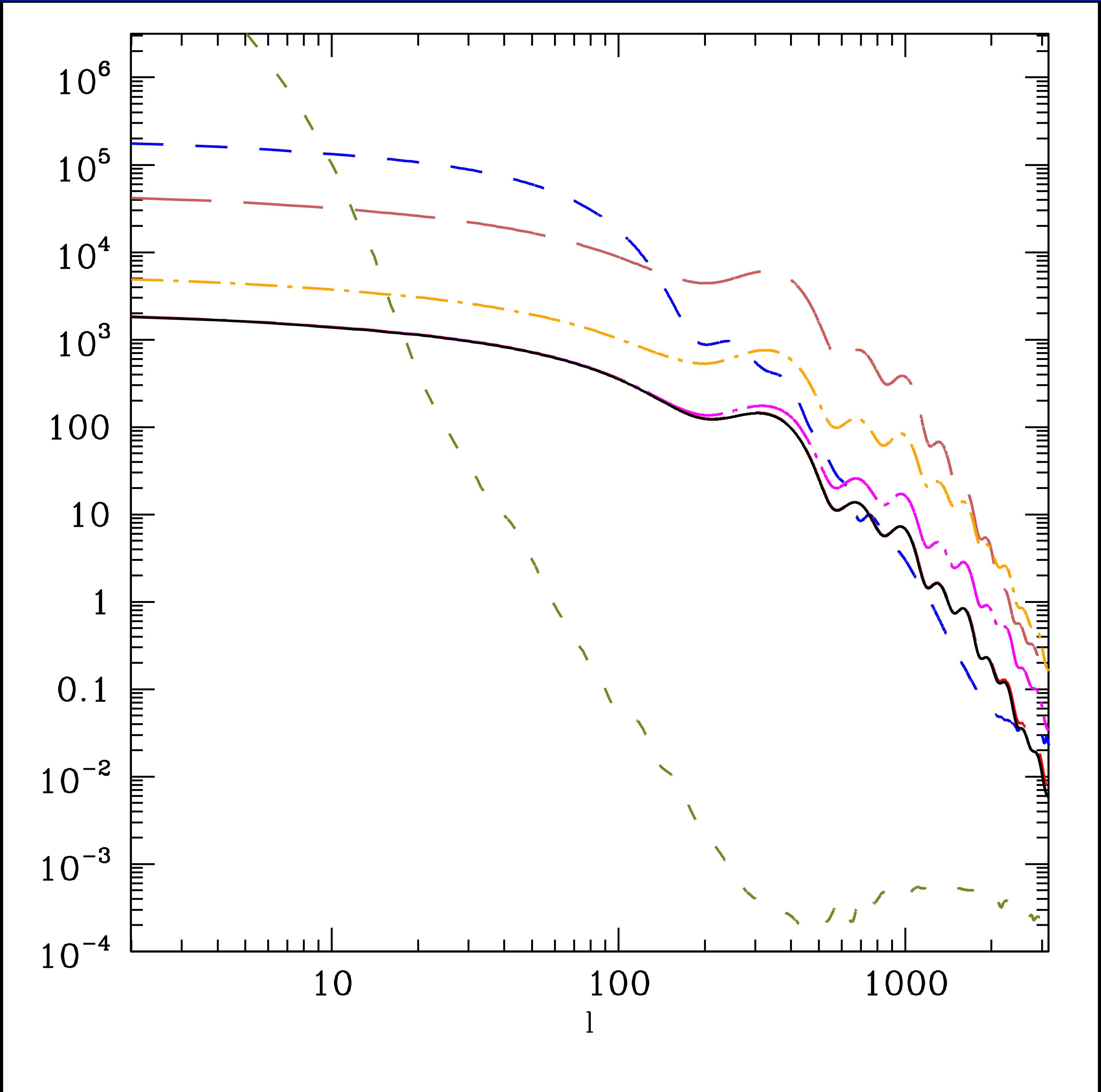
$$\boxed{c_a^2 = \frac{\delta P}{\delta\rho} = \frac{k^2/(4m^2a^2)}{1+k^2/(4m^2a^2)}}$$

# CMB anisotropy power spectra




Power spectra may now be quickly computed for 15 orders of magnitude in axion mass!

# Getting under the hood: The need for numerical care



# Getting under the hood: The need for numerical care

$$\dot{\delta}_a = 3\mathcal{H}\left[w_a - 1\right]\delta_a - (1 + w_a)\left(kv_a + \dot{h}\right)$$

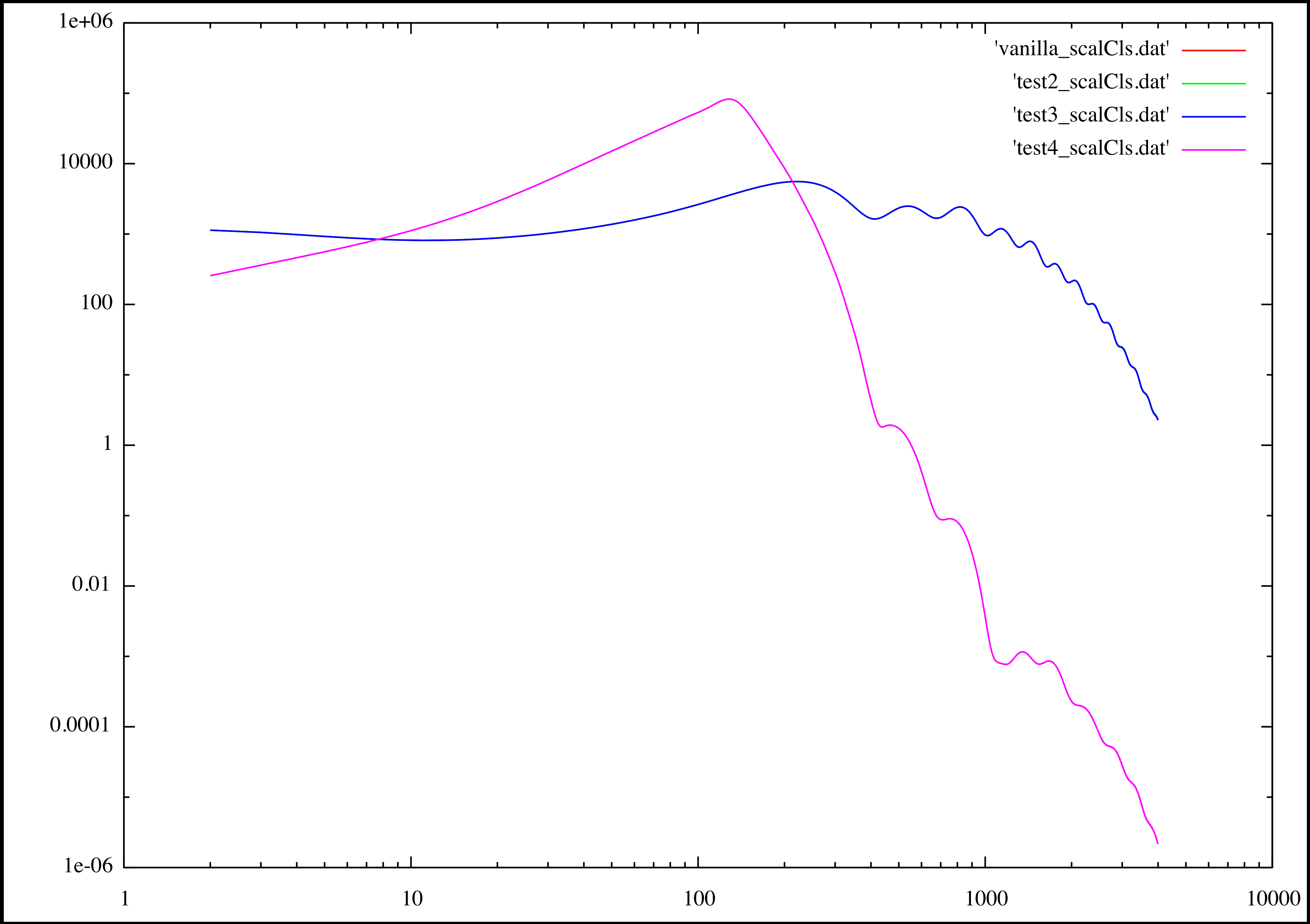
$$\dot{v}_a = -3\mathcal{H}\left[1 - 3w_a\right]v_a - \frac{\dot{w}_a}{(1 + w_w)}v_a + \frac{k\delta_a}{(1 + w_a)}$$

$$\dot{w}_a = -3\mathcal{H}\left(1 + w_a\right)\left[c_{\rm ad}^2 - w_a\right]$$

$$c_{\rm ad}^2 = \frac{\dot{P}_a}{\dot{\rho}_a} = -1 + \frac{2m_a a}{\mathcal{H}}\sqrt{\frac{(1 - w_a)}{(1 + w_a)}}$$

$$\dot{\rho}_a = -3\mathcal{H}\rho_a\left(1 + w_a\right)$$

# Getting under the hood: The need for correct (super-horizon) initial conditions



# Getting under the hood: The need for correct (super-horizon) initial conditions

Synchronous gauge 00-Einstein

$$\dot{h} \propto \eta \left[ \frac{3\delta_{\mathrm{R}}}{a^2} + 3a^2 \mathcal{A} \delta_a \right]$$

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Perrotta and Baccigalupi, astro-ph/9811156

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$$\dot{\delta}_\gamma \simeq -\frac{\dot{h}}{2}$$

NOT KOSHER!

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Solve Eigensystem and expand systematically

$$\frac{d\vec{U}_{\vec{k}}}{d\ln x} = \left(\underline{A}_0 + \underline{A}_1 x + \ldots \underline{A}_n x^n\right) \vec{U}_{\vec{k}}$$

Bucher, Moodley, and Turok, PRD62, 083508, sol'ns can be obtained using this technique, outlined in Doran et al. , astro-ph/0304212

# Matter power spectrum

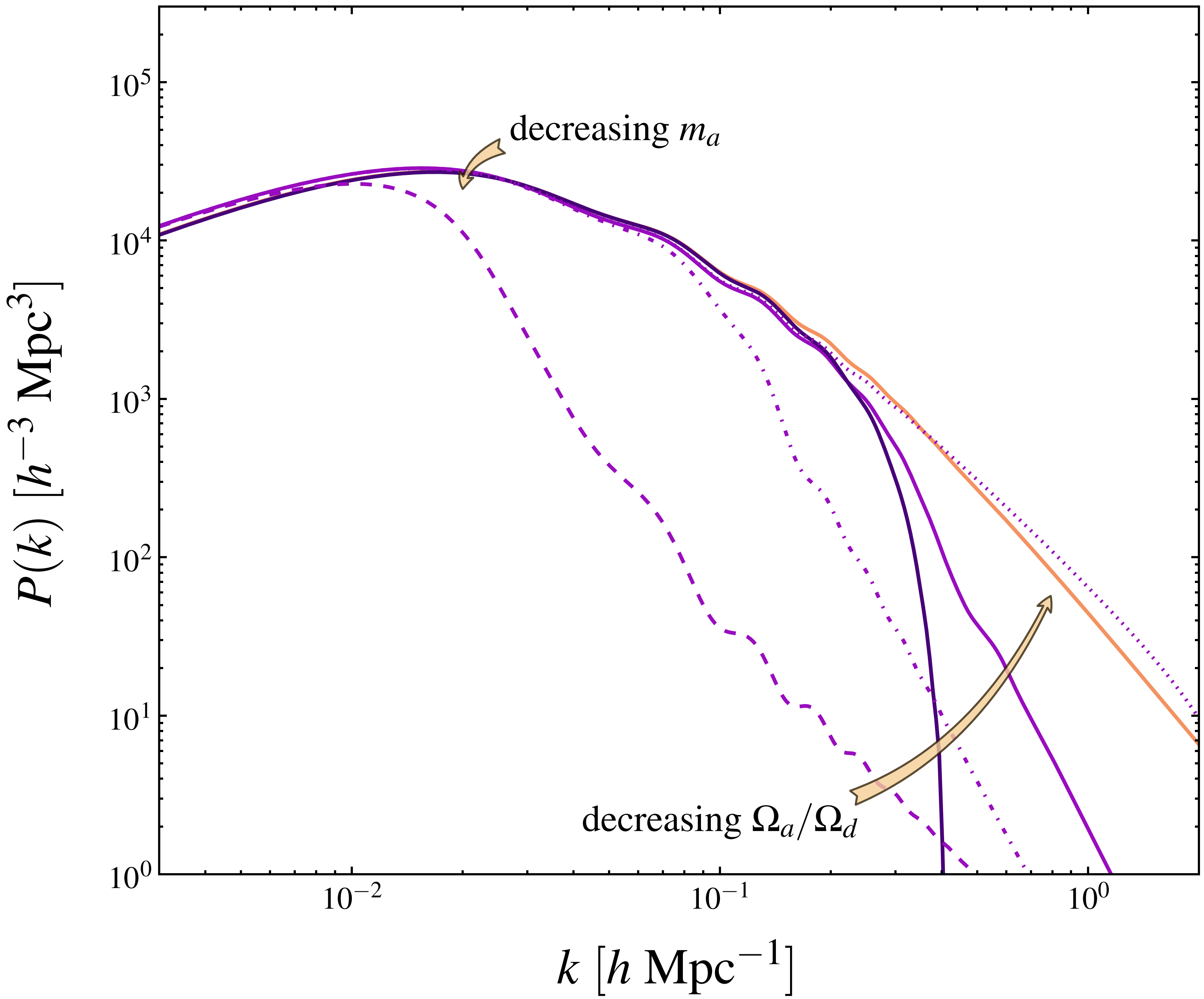
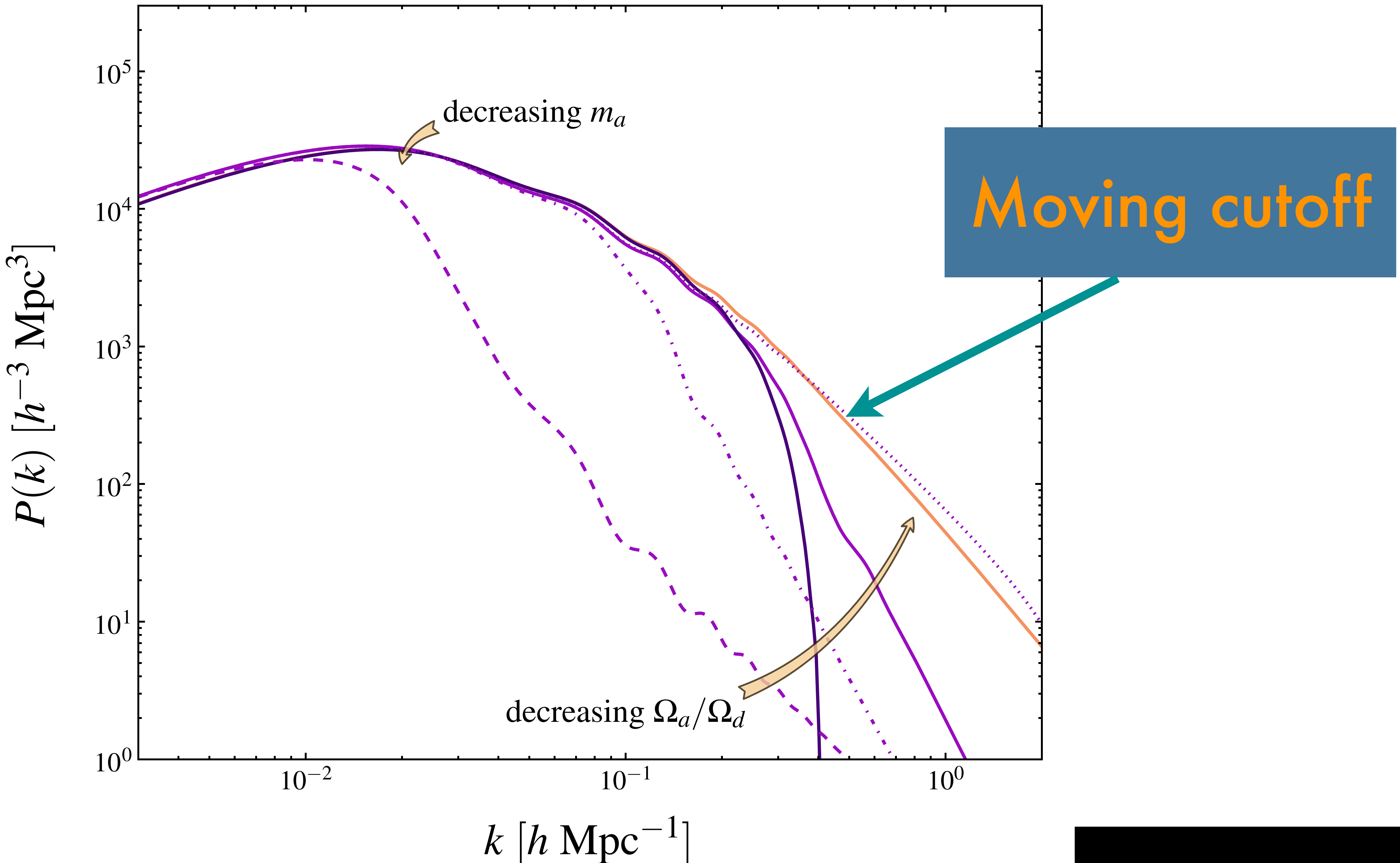



FIG. 1 (color online). Adiabatic matter power spectra, with varying axion mass $m_a = 10^{-28}$, $10^{-26}$, $10^{-25}$, $10^{-23}$ eV at fixed density fraction $\Omega_a/\Omega_d = 0.5$ (dashed) and varying $\Omega_a/\Omega_d = 0.1$, 0.5, 1 at fixed $m_a = 10^{-25}$ eV (solid). Spectra

# Matter power spectrum

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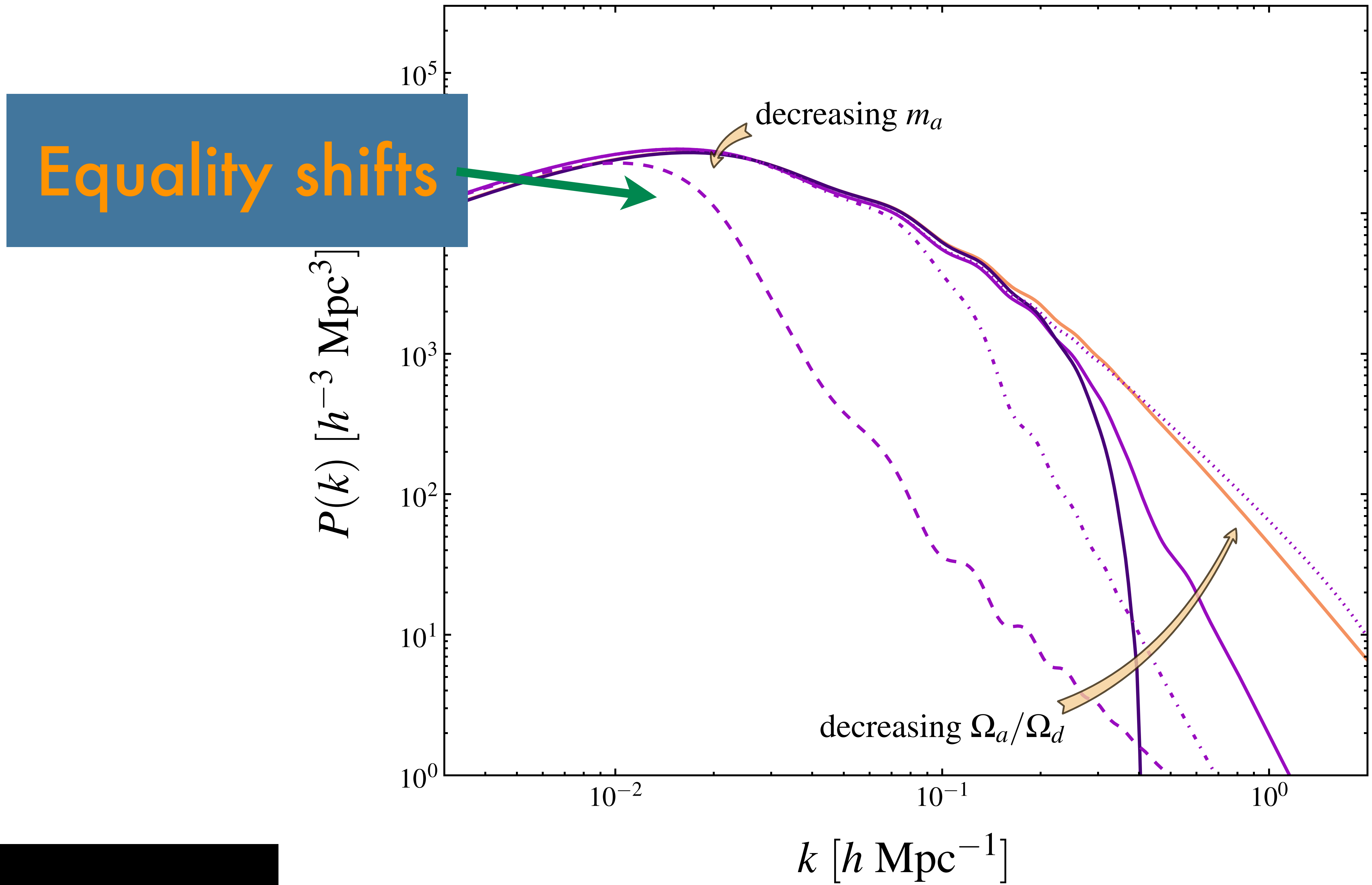


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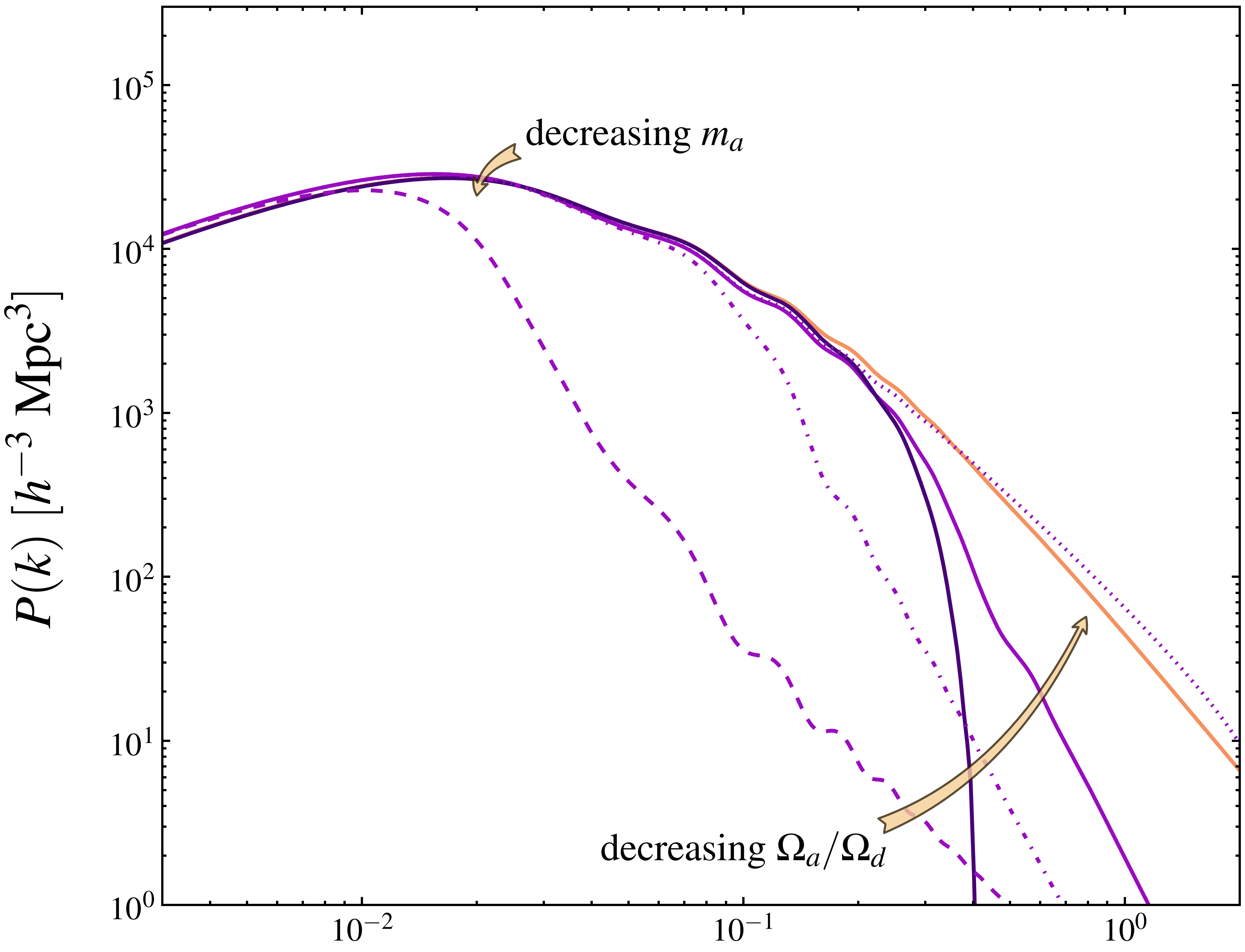


We may now probe ultra-light axions and the axiverse with an MCMC covering 15 orders of magnitude in axion mass

# The axiverse and the scale of inflation

- Tensor mode amplitude set by inflationary energy scale

$$\frac{k^3 P_h}{2\pi^2} = 8\left(\frac{H_{\rm I}/M_{\rm pl}}{2\pi}\right)^2 \qquad \frac{k^3 P_{\rm R}}{2\pi^2} = \frac{1}{2\epsilon}\left(\frac{H_{\rm I}/M_{\rm pl}}{2\pi}\right)^2\left(\frac{k}{k_0}\right)^{n_s-1}$$

$$\frac{k^3 P_S}{2\pi^2} = 4\left(\frac{H_{\rm I}}{2\pi\phi}\right)^2 \qquad \left(\frac{\phi}{M_{\rm pl}}\right)^2 = \frac{6H_0^2\Omega_a}{m_a^2 a_{\rm osc}^3}$$

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$$\boxed{r = 2.3\Omega_d h^2\left(\frac{z_{\rm eq}}{\Omega_m}\right)^{3/4}\left(\frac{\Omega_d}{\Omega_a}\right)\left(\frac{10^{-33}{\rm eV}}{m_a}\right)^{1/2}\left(\frac{\alpha}{1-\alpha}\right)}$$

# The axiverse and the scale of inflation

Komatsu al. 2008/2011 find

$$\boxed{\alpha_{\rm ax} \lesssim 0.1}$$

# The axiverse and the scale of inflation

Komatsu al. 2008/2011 find

$$\alpha_{\mathrm{ax}} \lesssim 0.1$$

$$r = 0.3\left(\frac{\Omega_d/\Omega_a}{100}\right)\left(\frac{10^{-33}\mathrm{eV}}{m_a}\right)^{1/2}$$

Stay tuned for MCMC constraints to the axiverse!

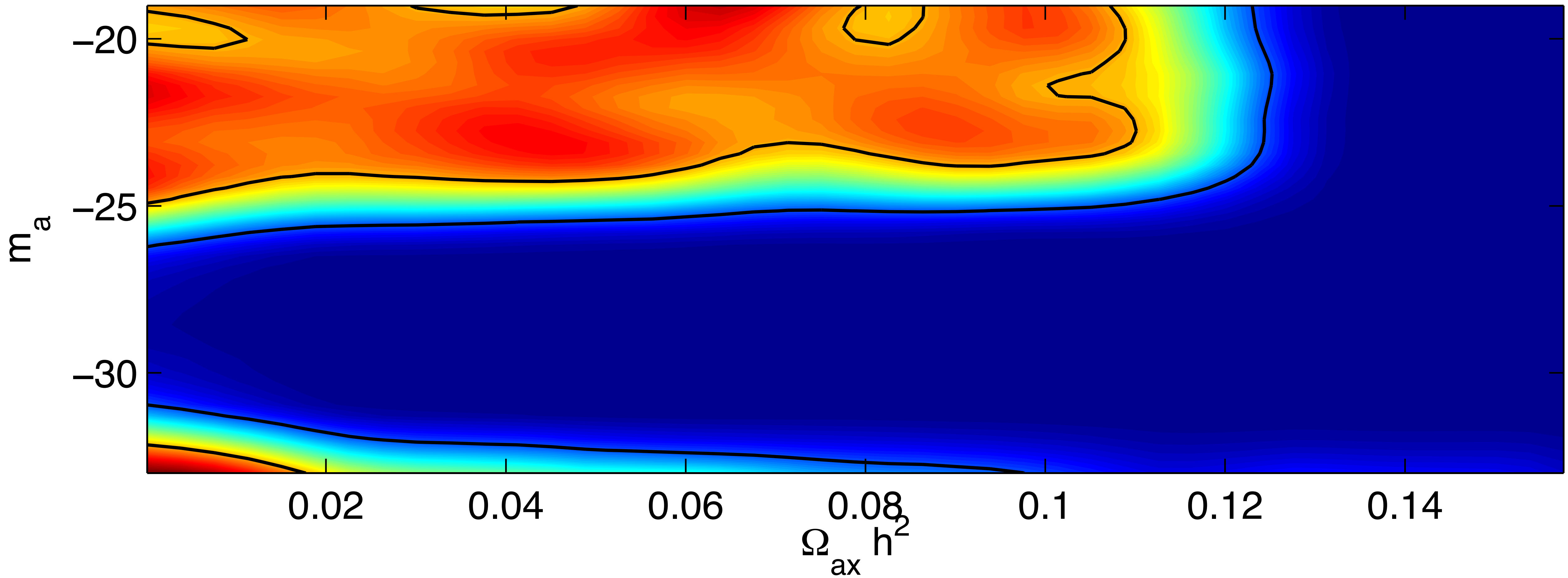
# The axiverse and the scale of inflation

- Compare with (in usual scenario)

$$r \sim 5 \times 10^{-12} \left( \frac{\Omega_{\rm c}}{\Omega_{\rm a}} \right)^{2/7}$$

Komatsu al. 2008/2011

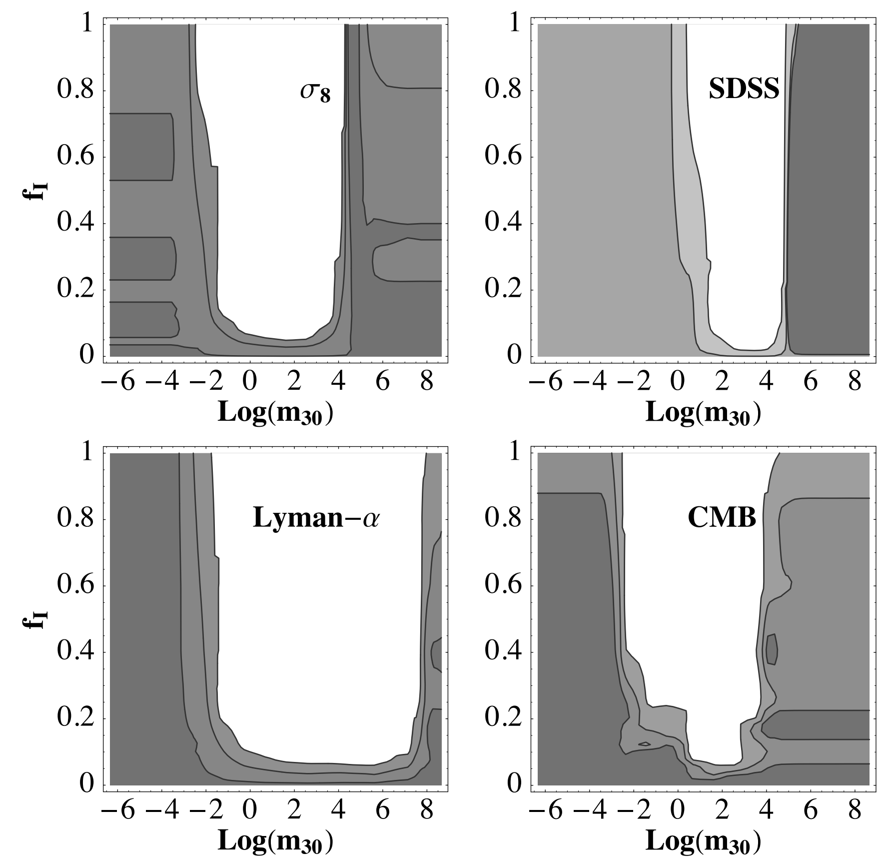
# Preliminary adiabatic results




Convergence and climbing contours required MCMC with nested sampling instead of Metropolis-Hastings!

*Old power spectrum constraints from Amendola and Barbieri, arXiv:hep-ph/0509257*

# Amendola and Barbieri




*Old power spectrum constraints from Amendola and Barbieri, arXiv:hep-ph/0509257*

1) *Grid search*
2) *No isocurvature*
3) *No marginalization over foregrounds*
4) *No lensing, no polarization*
5) *No real Boltzmann code [step in power spectrum, or unclustered DE at low m]*