Axion cold dark matter: two birds with the same stone

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27 Nov 2012, Invisible seminar

Outline

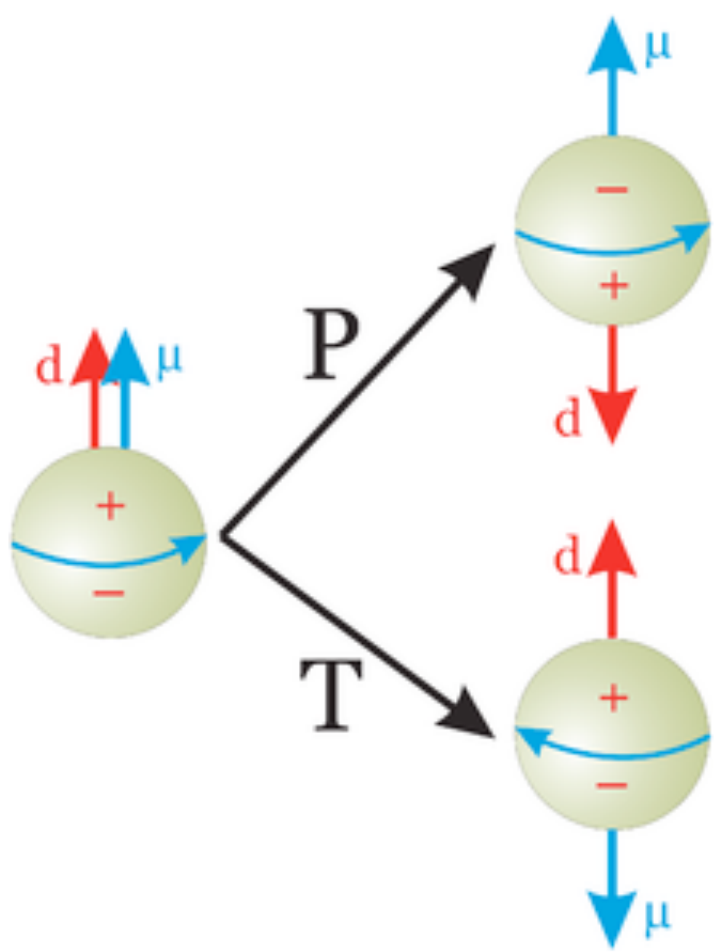
- Strong CP problem
- Strong CP solution: Axions
- Axion Dark matter
- Experimental searches

The Strong CP problem

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \mathrm{tr}\left\{ G_a^{\mu\nu} \widetilde{G}_{a\mu\nu} \right\} \theta$$

$$\theta = \theta_{\rm QCD} + \arg\det \mathcal{M}_q$$

$$\theta_{\rm QCD} \in (-\pi, \pi)$$
$$\arg\det \mathcal{M}_q \sim \mathcal{O}(1)?$$



Prediction:

$$d_n \sim 10^{-15} \theta \, \mathrm{ecm}$$

Non Observation:

$$d_n < 2.6 \times 10^{-26} \, \mathrm{ecm}$$

$\theta \lesssim 10^{-11}$ **Why ?????**

The Strong CP problem: a hint

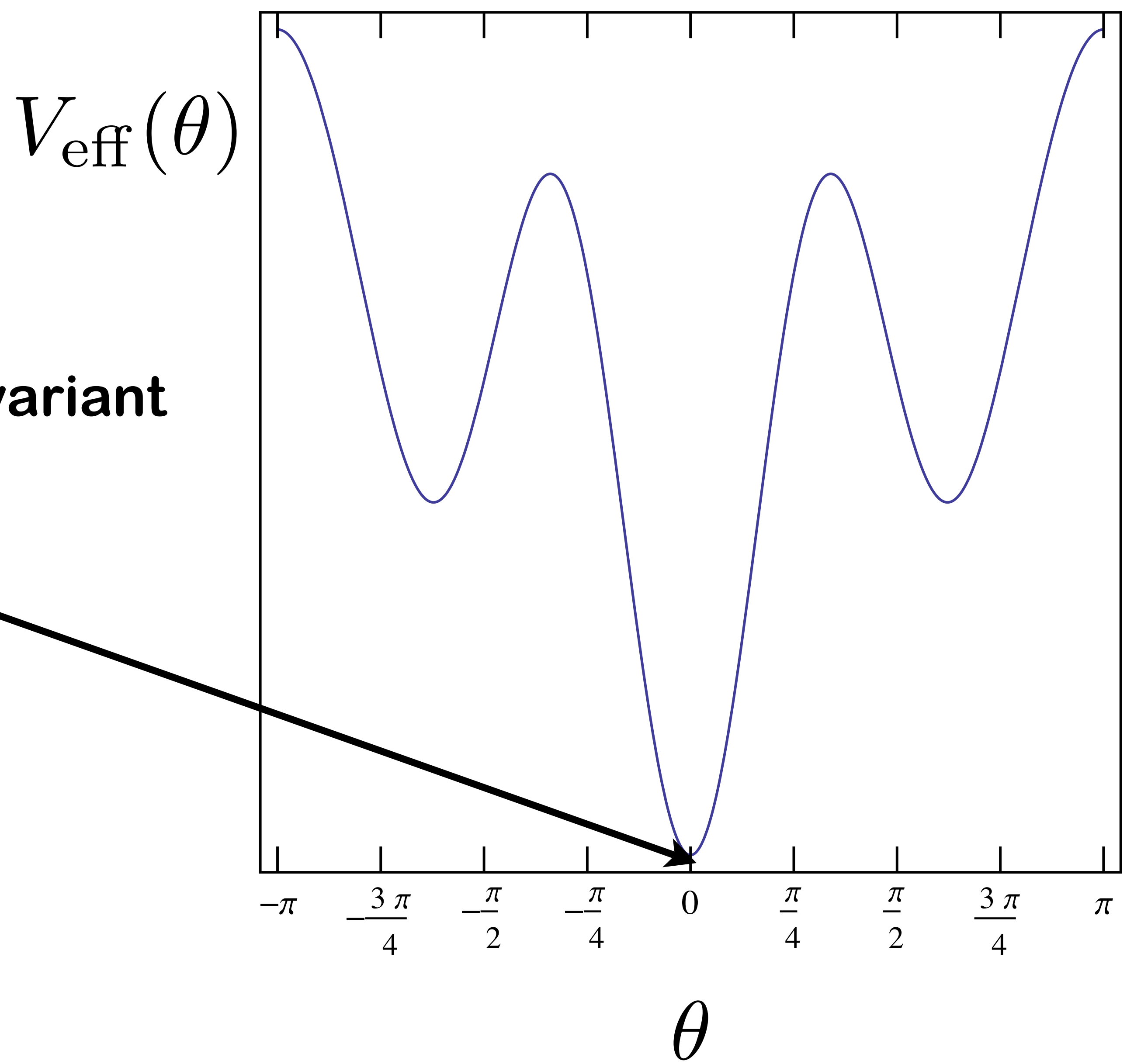
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \mathrm{tr}\left\{ G_a^{\mu\nu} \widetilde{G}_{a\mu\nu} \right\} \theta$$

Consider no quarks

If the rest of the theory is P,T invariant

Minimum at $\theta = 0$

but θ **is not dynamical**



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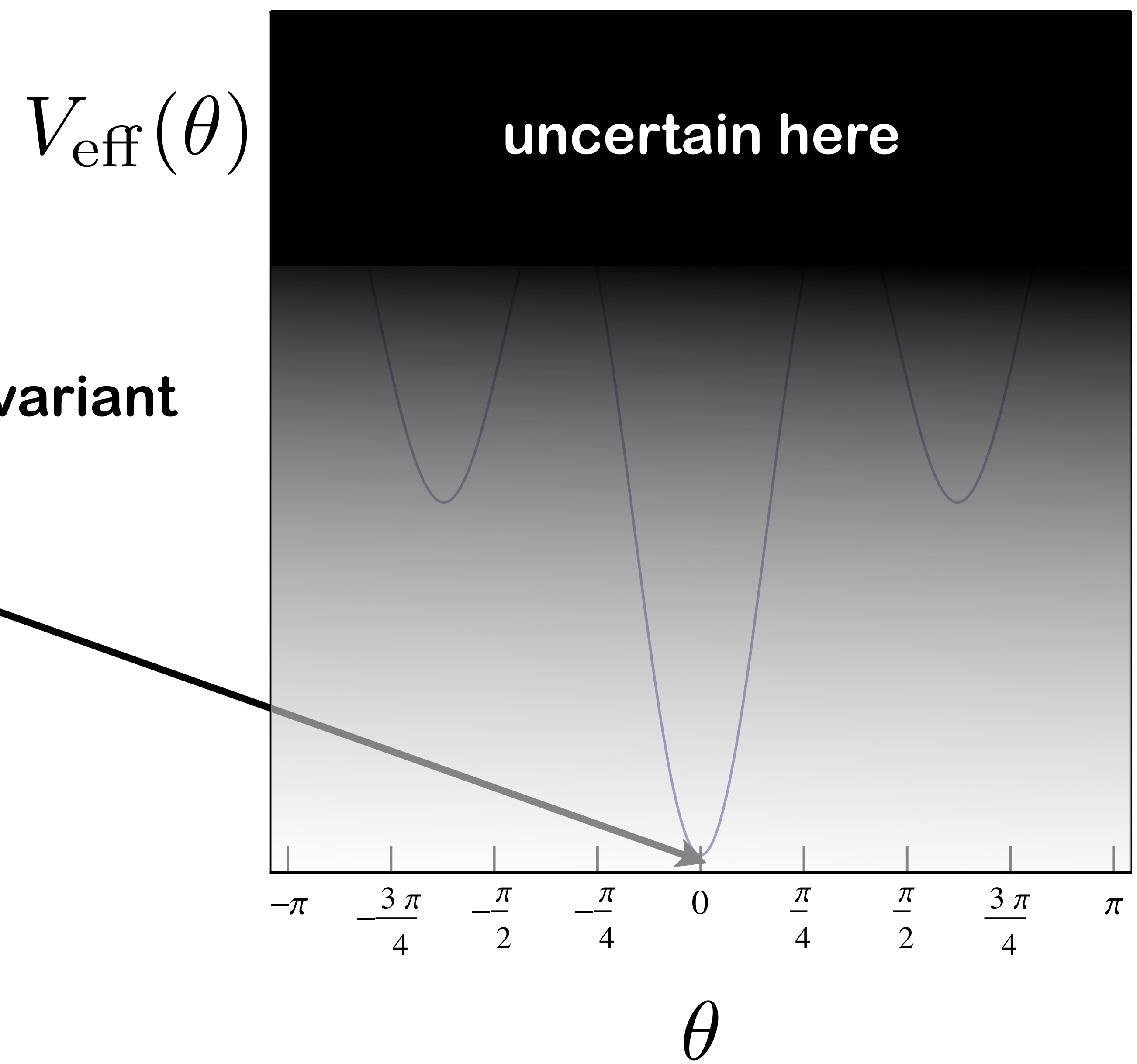

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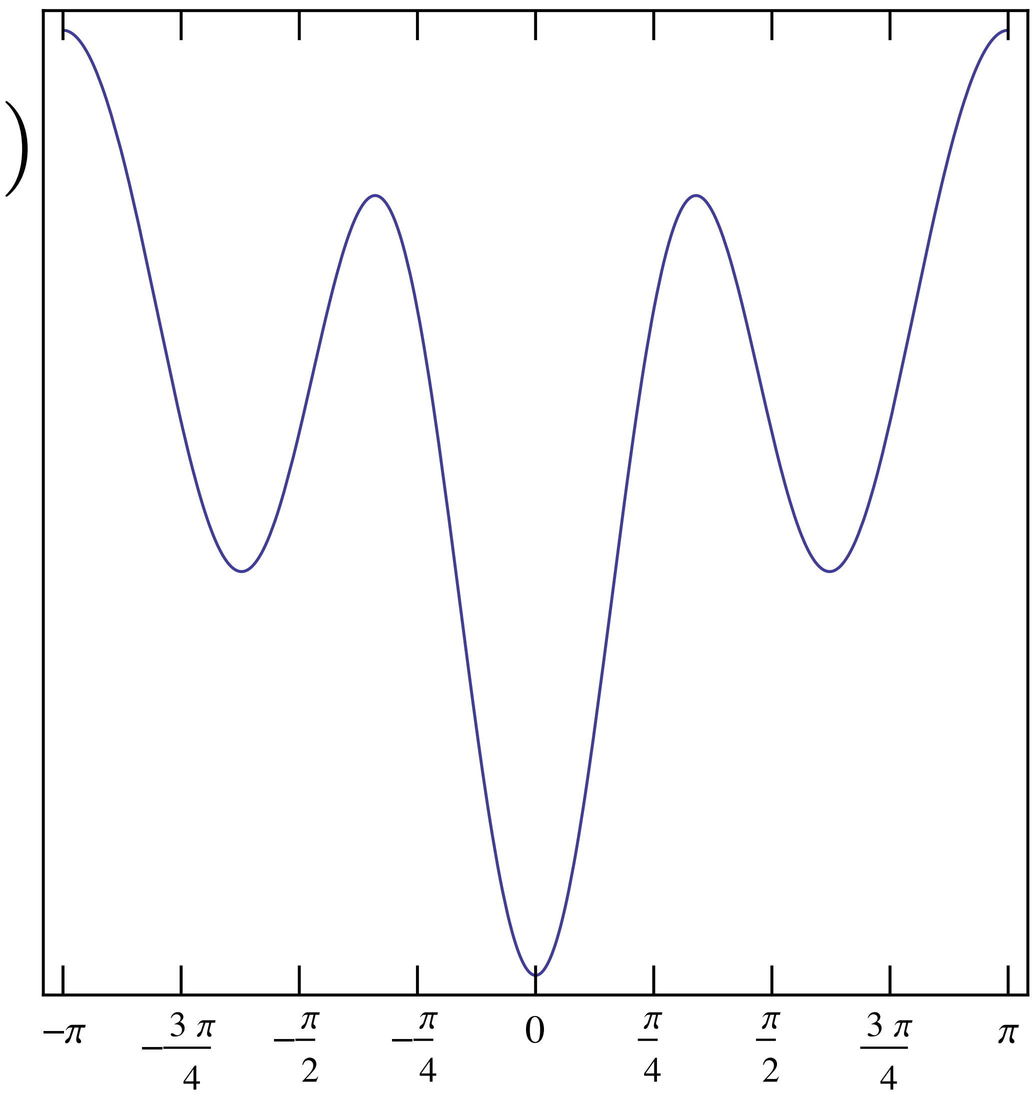
The Strong CP problem: a hint

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \mathrm{tr} \left\{ G_a^{\mu\nu} \widetilde{G}_{a\mu\nu} \right\} \left(\theta + \frac{\eta'}{f_\eta} \right)$$

$V_{\rm eff}(\theta_{\rm eff})$



$$\theta_{\rm eff} = \theta + \langle \eta' \rangle / f_\eta$$

With quarks, low-energy QCD

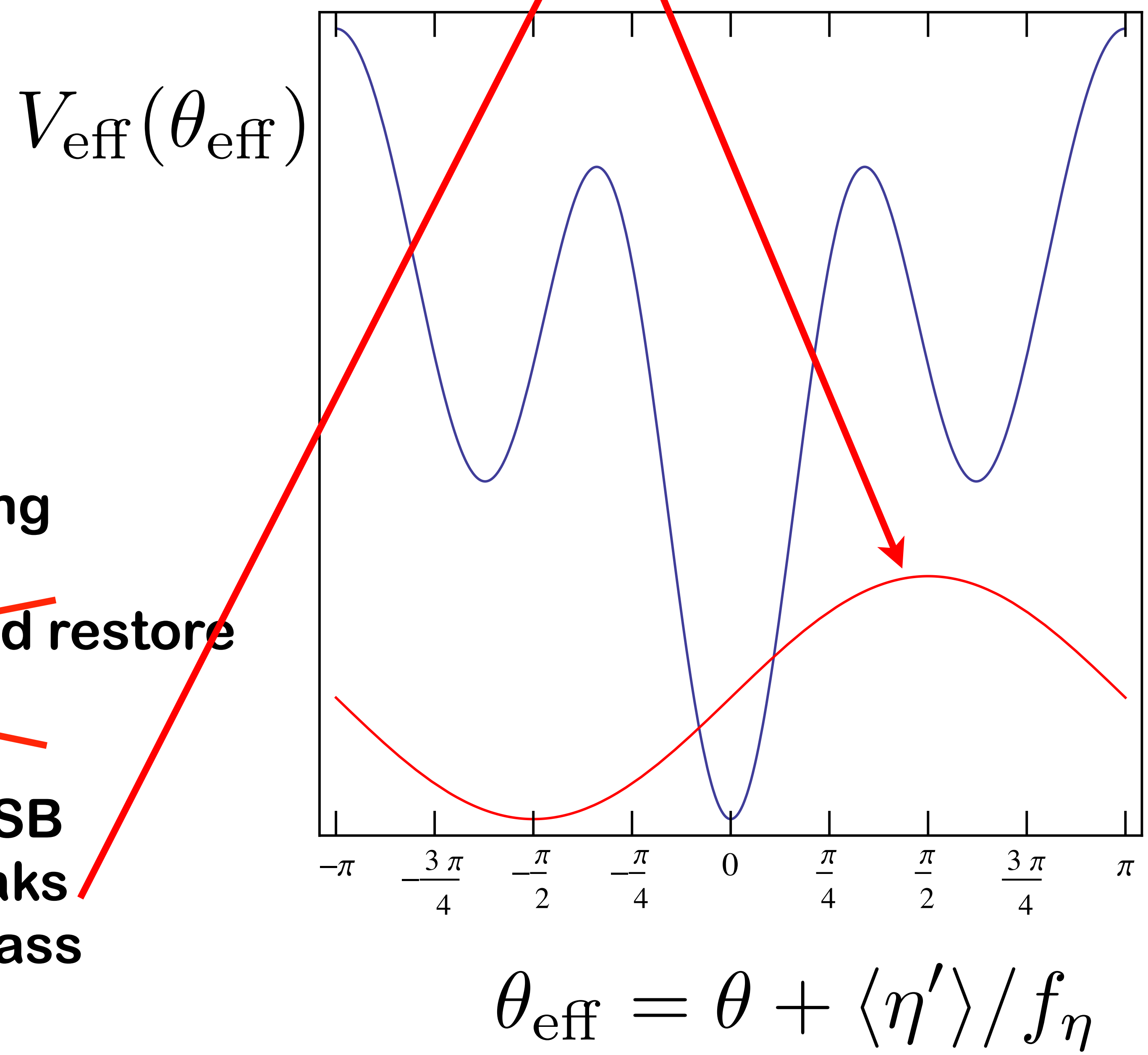
$U(1)_{\rm A}$ **is color anomalous**

η' **has anomalous gg coupling**

can roll down the potential and restore P, T symmetries!!

The Strong CP problem: a hint

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\mathrm{tr}\left\{G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}\right\}\left(\theta + \frac{\eta'}{f_\eta}\right) - \frac{1}{2}m_\pi^2\eta'^2$$



With quarks, low-energy QCD

$U(1)_{\rm A}$ **is color anomalous**

η' **has anomalous gg coupling**

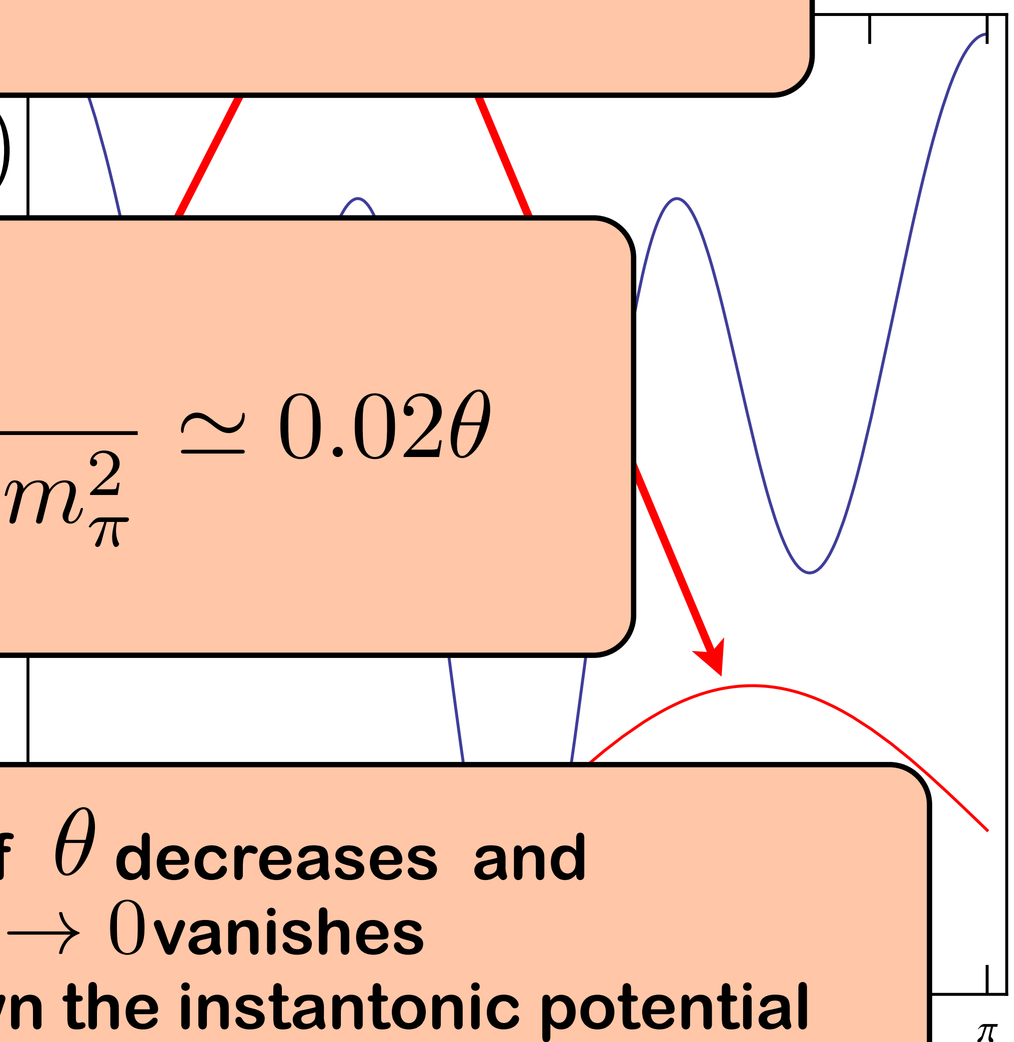
~~**can roll down the potential and restore P, T symmetries!!**~~

Actually cannot because EW SB makes $m_u, m_d \neq 0$ and breaks explicitly $U(1)_{\rm A}$ giving η' mass of the order of the π^0 mass.

The Strong CP problem: a hint

$\mathcal{L}_\theta =$

$$V(\eta') = \frac{1}{2} m_{\eta'}^2 (\eta' + \theta f_\eta)^2 + \frac{1}{2} m_\pi^2 \eta'^2$$



With quarks, low-e

$U(1)_A$ **is color**

η' **has anomalou**

$$\theta_{\text{eff}} = \theta \frac{m_\pi^2}{m_{\eta'}^2 + m_\pi^2} \simeq 0.02\theta$$

~~**can roll down the potential and restore**~~
~~**P, T symm**~~

The effective value of θ decreases and in the limit $m_\pi \to 0$ vanishes since η' can freely roll down the instantonic potential

Actually
makes η
explicitly $U(1)_A$ giving η' a mass of the order of the π^0 mass.

$$\theta_{\text{eff}} = \theta + \langle \eta' \rangle / f_\eta$$

Axion as a solution to the strong CP problem

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\mathrm{tr}\left\{G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}\right\}\left(\theta + \frac{\eta'}{f_\eta} + \frac{\phi}{f_a}\right) - \frac{1}{2}m_\pi^2\eta'^2$$

Add a new field coupling to gg

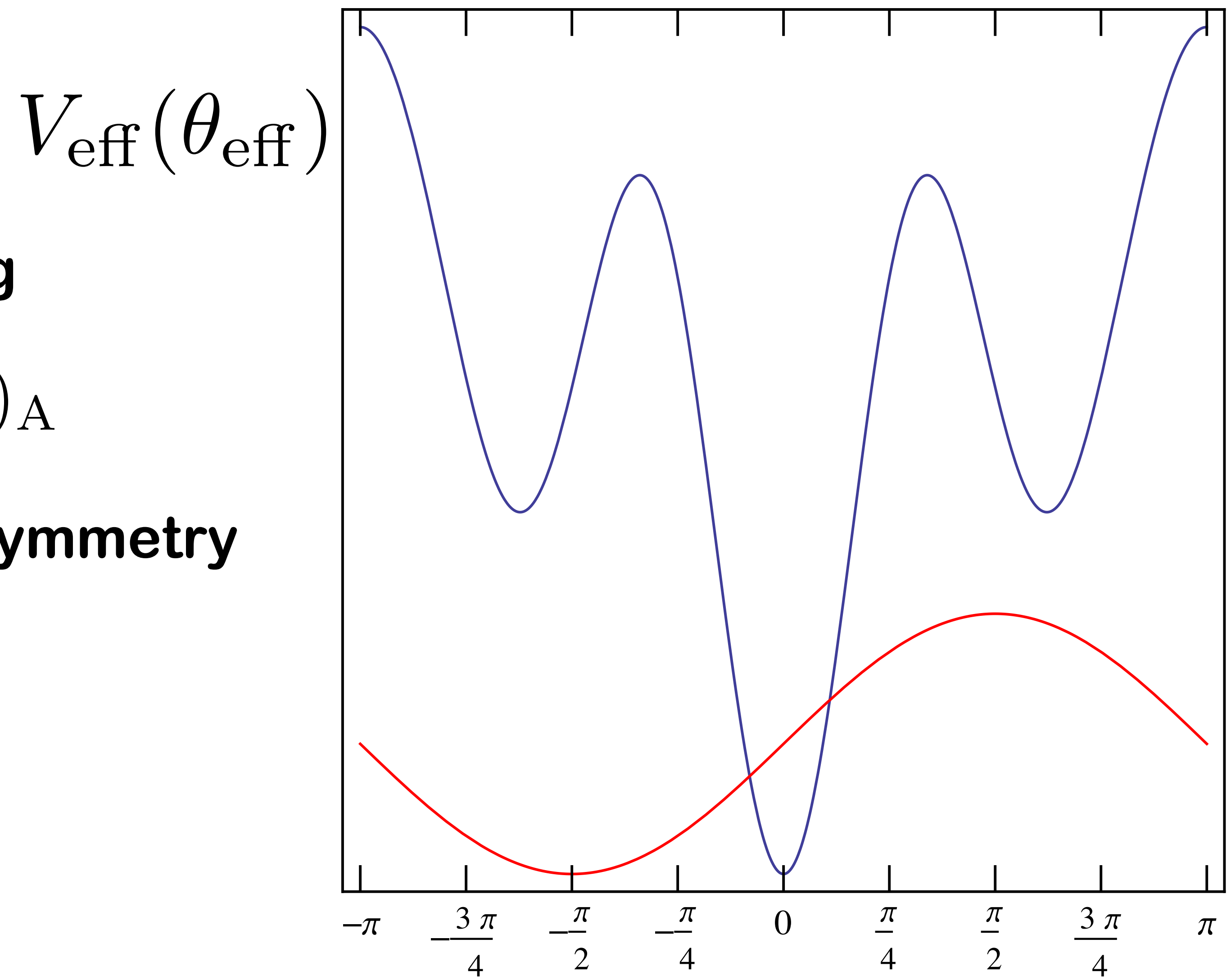
Goldstone of ANOTHER $U(1)_{\mathrm{A}}$

usually called Peccei-Quinn symmetry

$$\langle\eta'\rangle = 0$$

$$\langle\phi\rangle/f_a = -\theta$$

$$\theta_{\mathrm{eff}} = 0!!!!!$$



$$\theta_{\mathrm{eff}} = \theta + \langle\eta'\rangle/f_\eta + \langle\phi\rangle/f_a$$

Axion couplings/mass

(minimal,hadronic model)

$$V(\eta') = \frac{1}{2} m_{\eta'}^2 \left(\eta' + \phi \frac{f_\eta}{f_a} \right)^2 + \frac{1}{2} m_\pi^2 \frac{f_\pi^2}{f_\eta^2} \eta'^2$$

$$a = \phi - \eta' \frac{f_\eta}{f_a}$$

axion = orthogonal to physical η'

$$m_a^2 \simeq m_\pi^2 \left(\frac{f_\pi}{f_a} \right)^2$$

the axion gets a calculable mass

$$m_a \simeq 6\,\mathrm{meV} \frac{10^9\,\mathrm{GeV}}{f_a}$$

And calculable mixings with the neut. ps. mesons

$$\varphi_{a\eta'} \sim f_\eta / f_a$$

$$\varphi_{a\eta} \sim f_\eta / f_a$$

$$\varphi_{a\pi^0} \sim f_{\pi^0} / f_a$$

couplings to hadrons

$$\sim \bar{N} \gamma_\mu \gamma_5 N \frac{\partial^\mu a}{f_a}$$

Axion couplings/mass

In a general model it depends how $U(1)_{\rm PQ}$ is implemented

- Only axion term is in the anomaly -> hadronic axions (KSVZ)

- In the original Peccei-Quinn Model & variants, and DFSZ
the axion is a combination of EW Higgs phases
and therefore axions <u>couple at tree level to leptons as well</u>

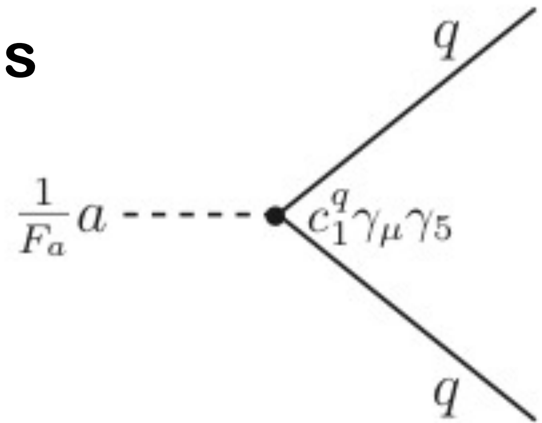
$$L_{\rm Yukawa} = \Gamma^u_{ij}\bar{Q}_{Li}\Phi_1 u_{Rj} + \Gamma^d_{ij}\bar{Q}_{Li}\Phi_2 d_{Rj} + \Gamma^\ell_{ij}\bar{L}_{Li}\Phi_2 \ell_{Rj} + h.c.$$

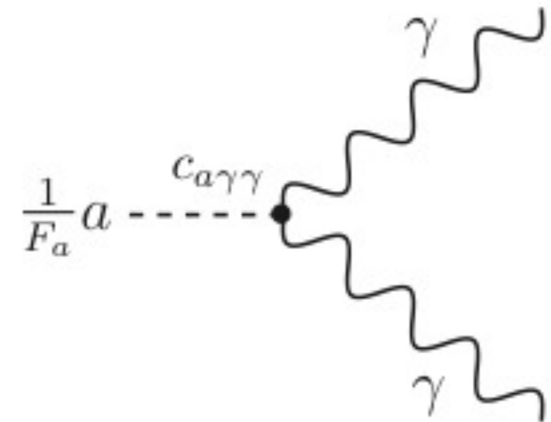
$$\Phi_1 = \frac{v_1}{\sqrt{2}} e^{iax/v_F} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \;\; ; \;\; \Phi_2 = \frac{v_2}{\sqrt{2}} e^{ia/xv_F} \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \qquad x = v_2/v_1$$

However $f_a \sim v_F$ was very soon ruled out,
the only plausible option becaming $f_a \gg v_F$ (INVISIBLE axions)

Axion couplings

Hadronic axions





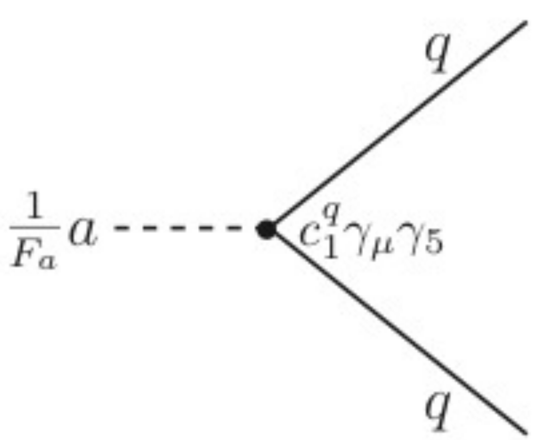
$$c_N(\bar{N}\gamma_\mu\gamma_5 N)\frac{\partial^\mu a}{2f_a} \equiv \frac{c_N m_N}{f_a}\bar{N}\gamma_5 N$$

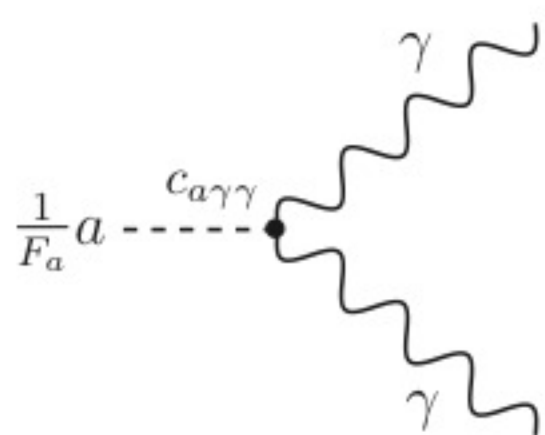
$$\frac{\alpha}{8\pi}(F_{\mu\nu}\widetilde{F}^{\mu\nu})c_{a\gamma\gamma}\frac{a}{f_a}$$

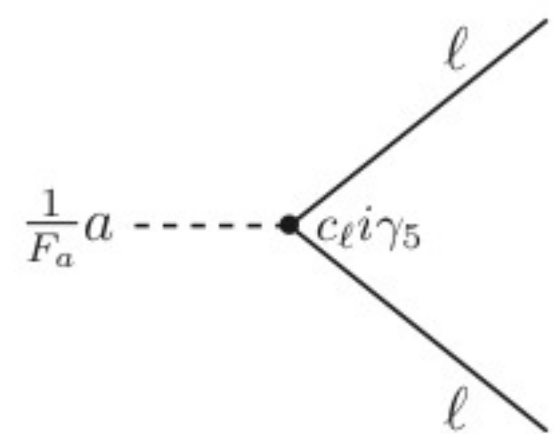
$$g_{aN} = \frac{c_N m_N}{f_a}$$

$$g_{a\gamma} = c_{a\gamma\gamma}\frac{\alpha}{2\pi f_a}$$

Non Hadronic

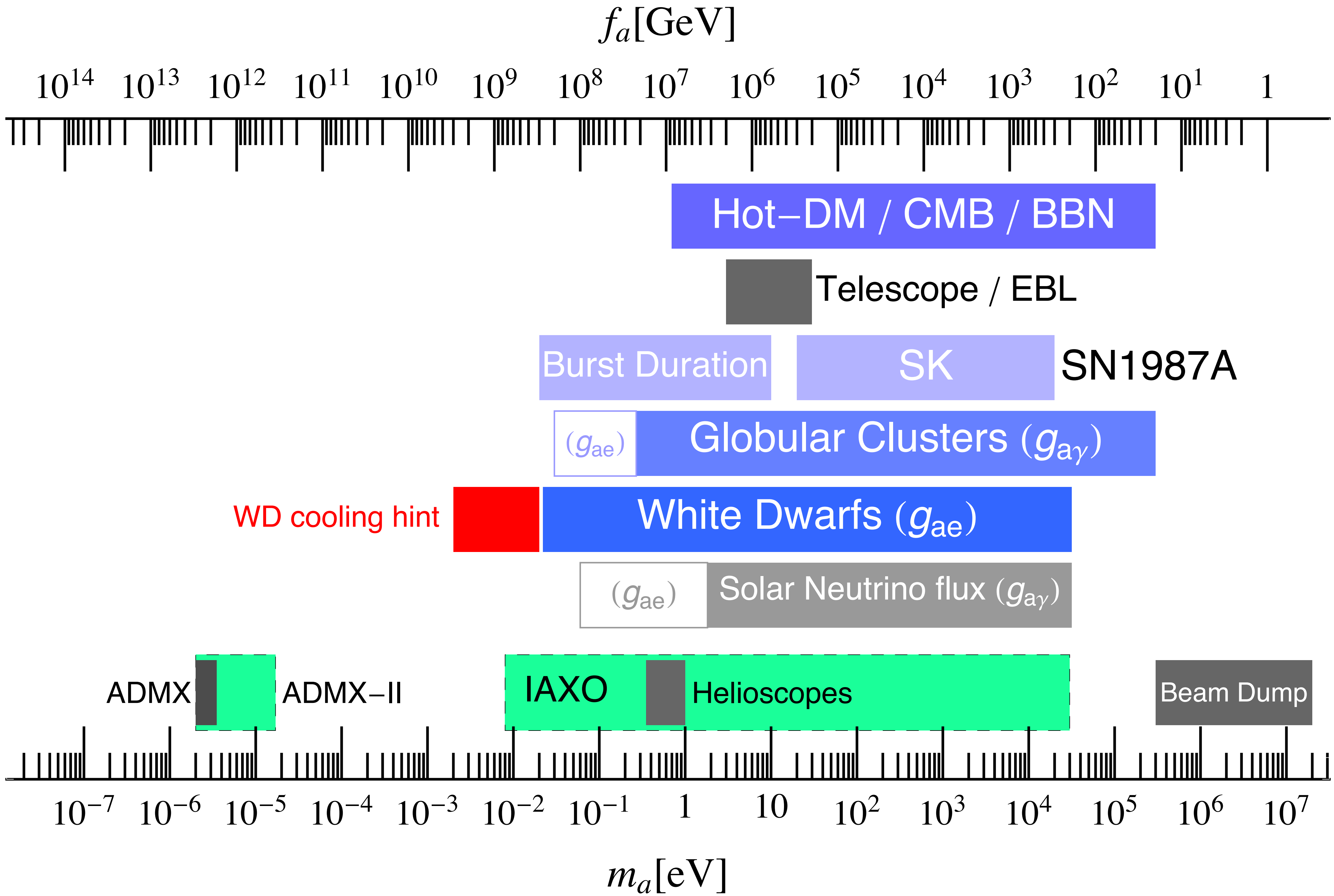






Where we are

Hewett et al. arXiv:1205.2671



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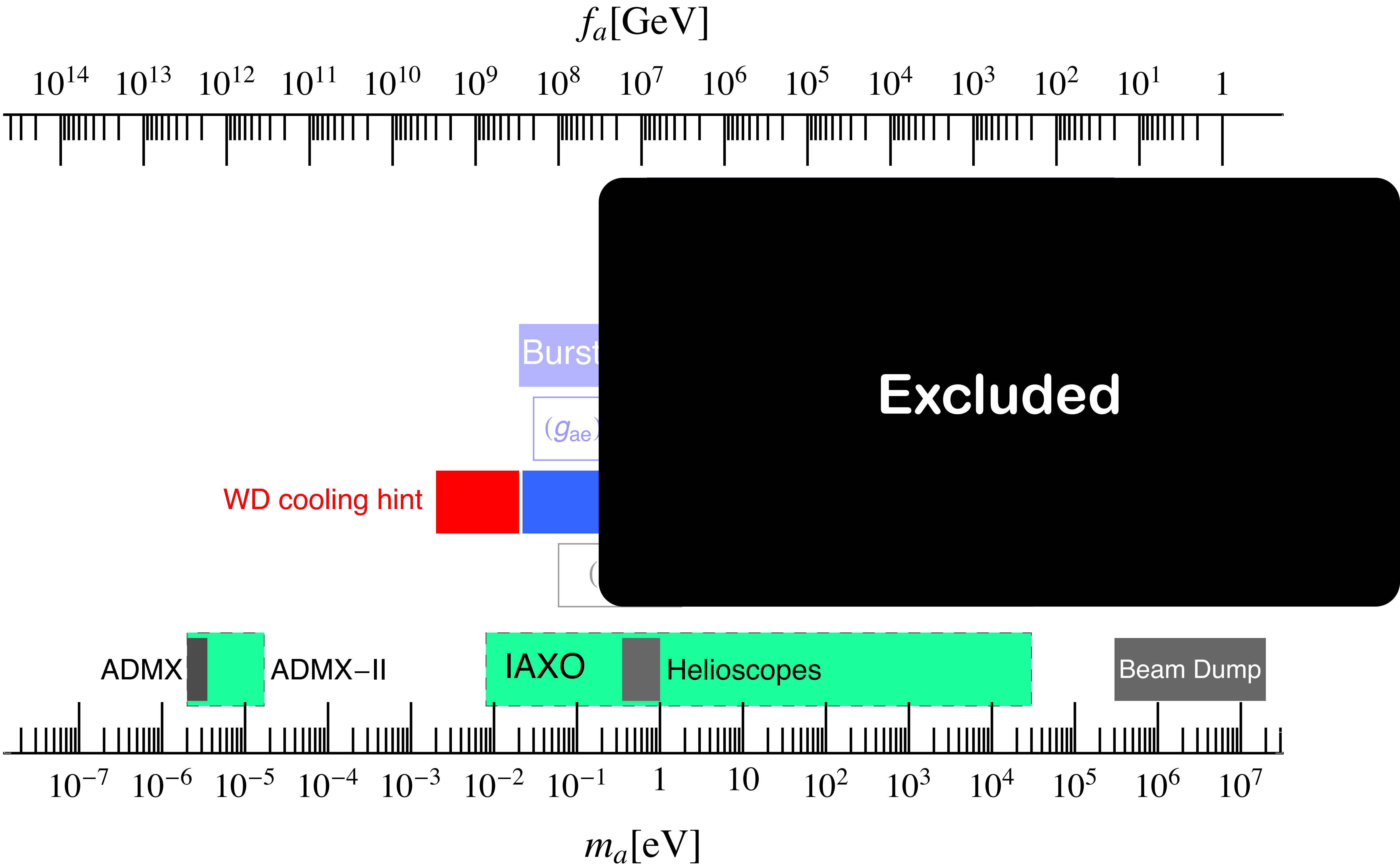

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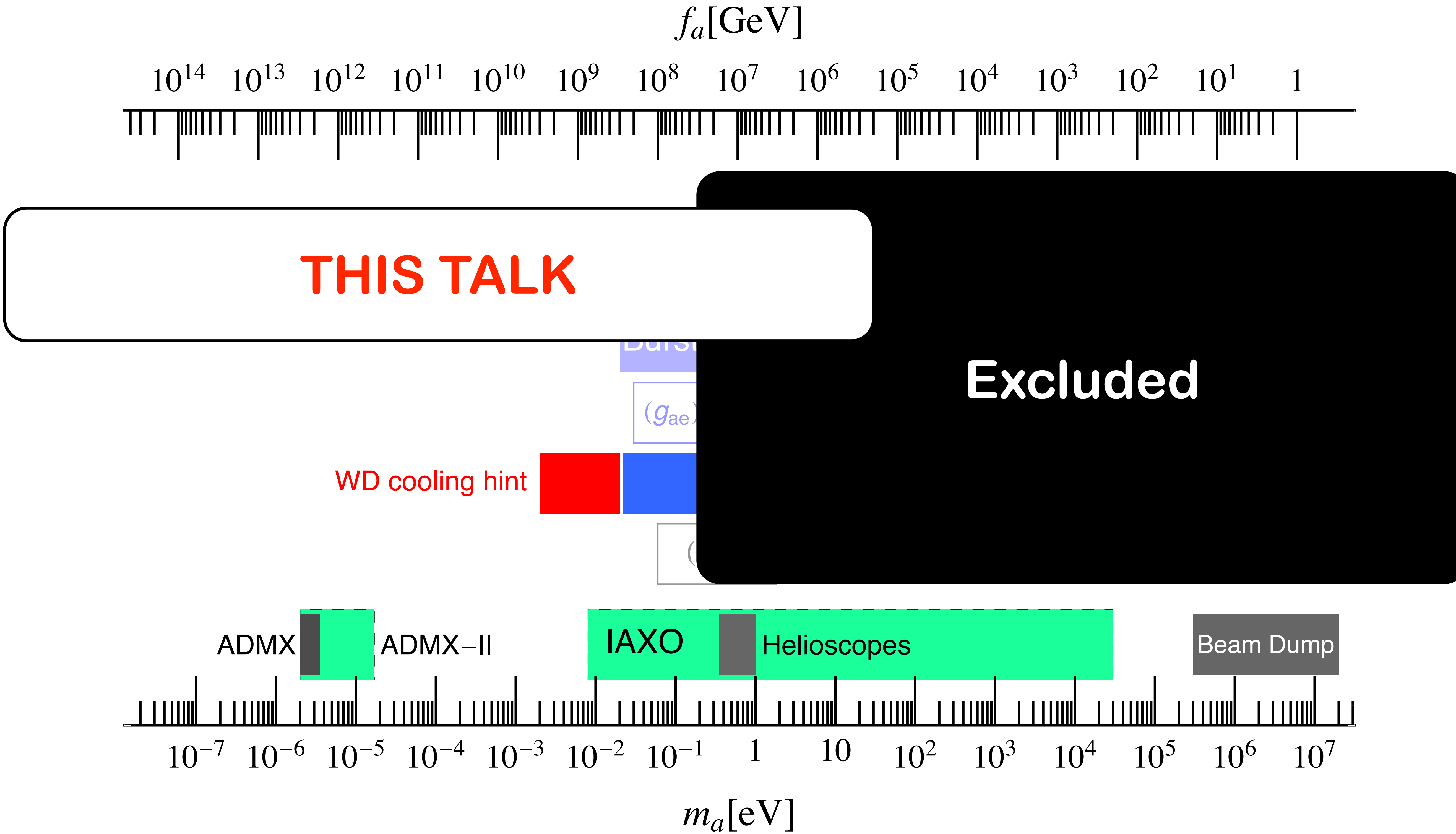

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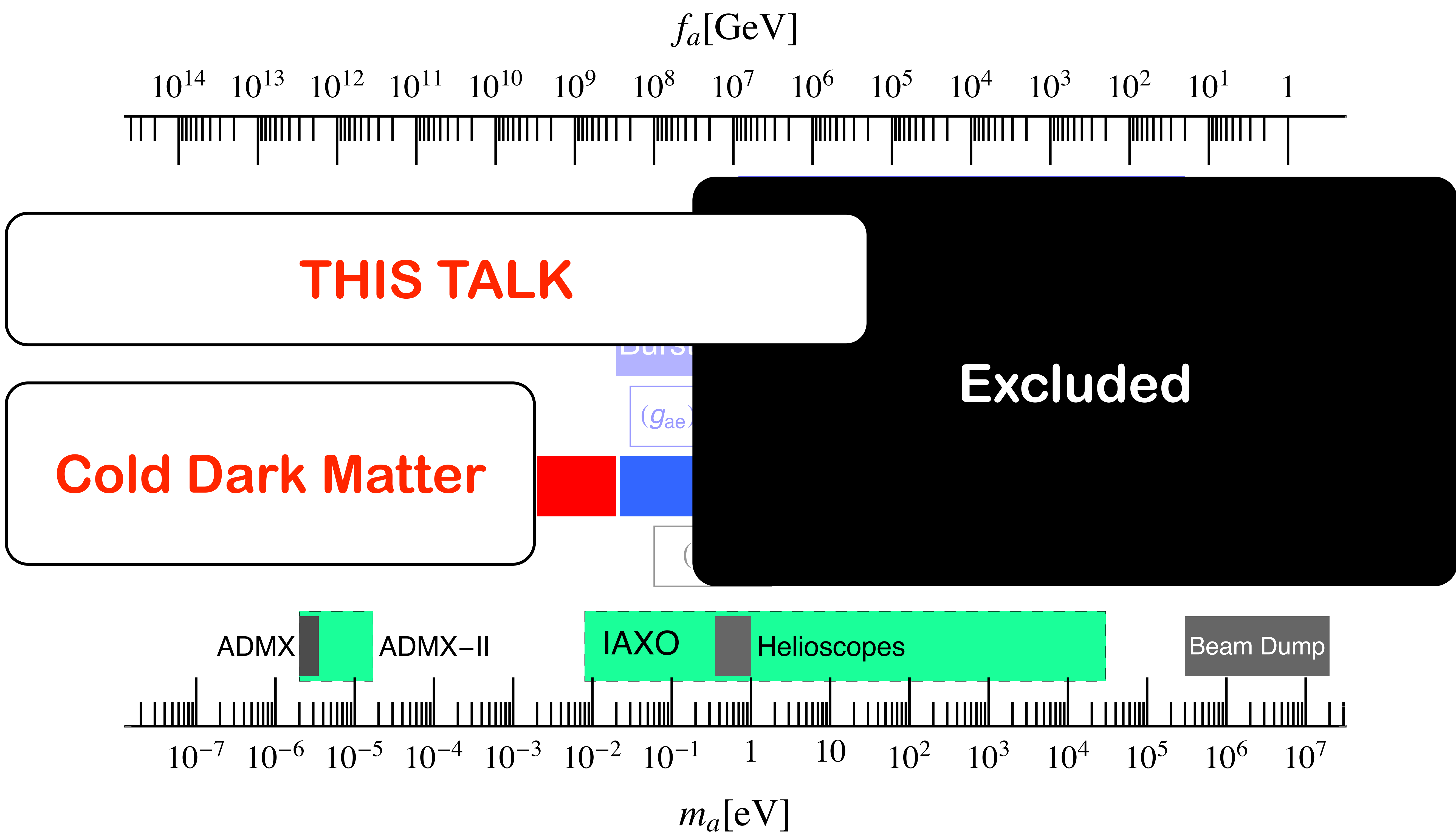

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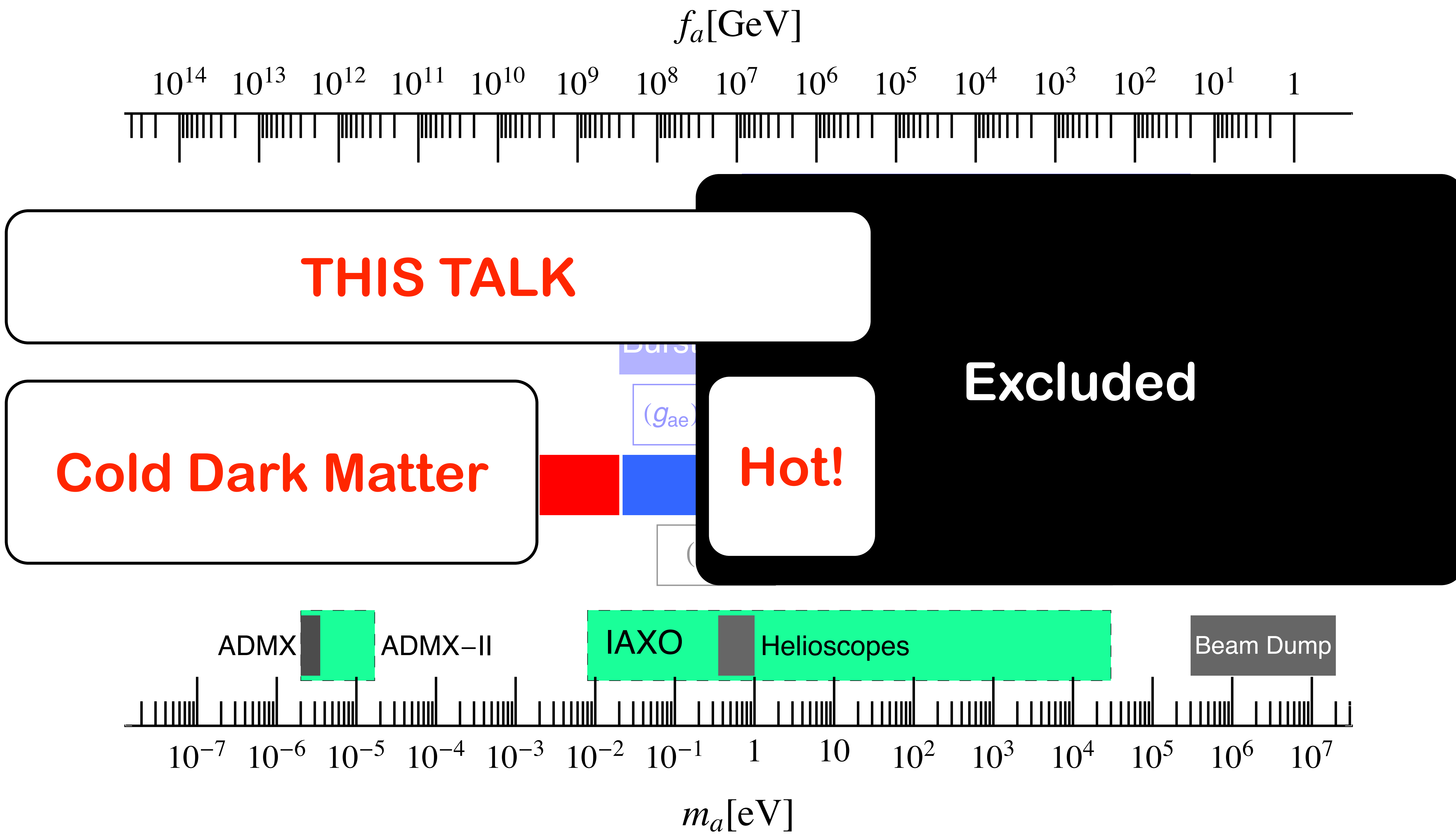
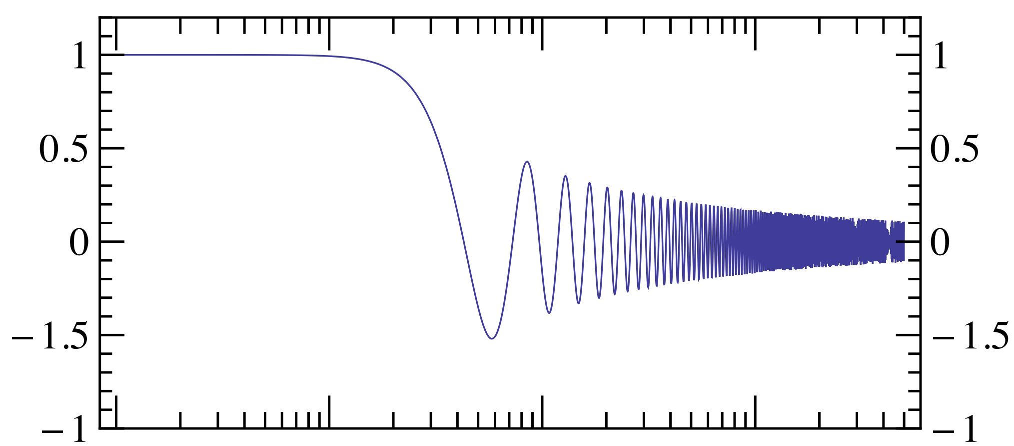
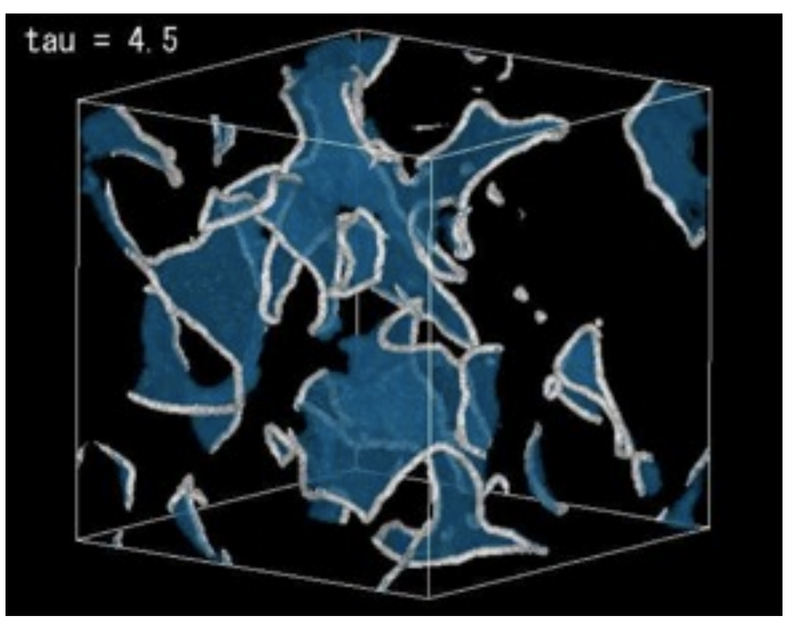


Axion dark matter: production mechanisms

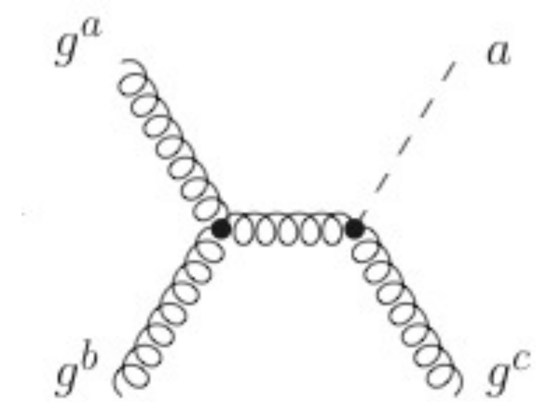
Non thermally (cold)

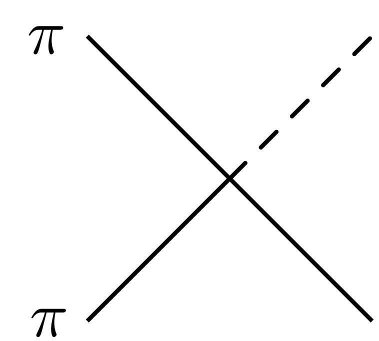
$$\ddot{a} - 3H\dot{a} + m_a^2(T)a = 0$$

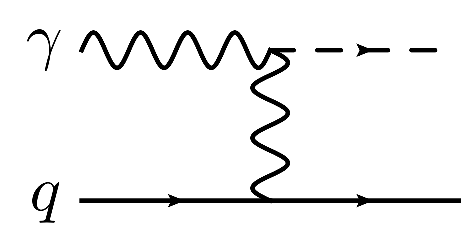




Thermally (hot)

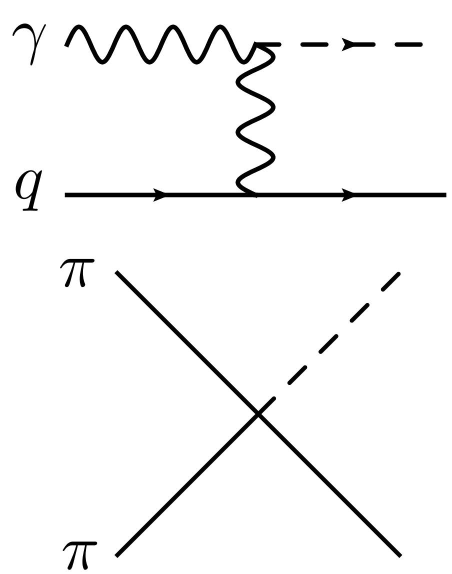






Axion hot Dark Matter (or Dark Radiation)

Axions are thermally produced in the early universe by a number of processes



$$\frac{\Gamma}{H} \propto \frac{T m_{\rm Pl}}{f_a^2}$$

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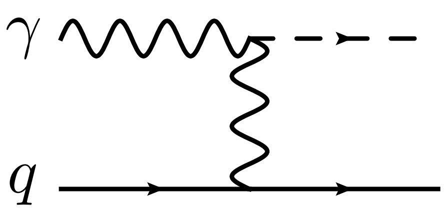

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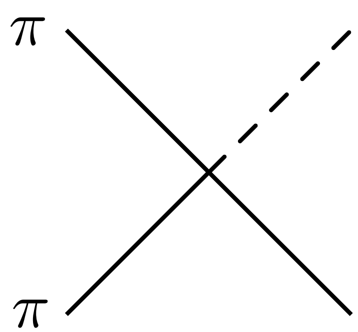

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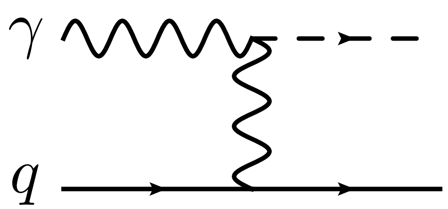
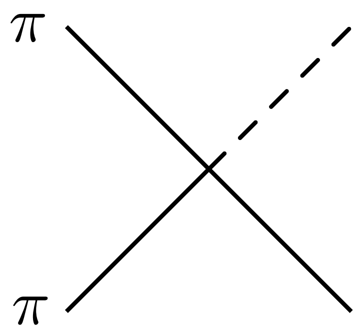


$$\frac{\Gamma}{H} \propto \frac{T m_{\rm Pl}}{f_a^2}$$

Such small mass axions behave as hot DM, which is not favored by observations.



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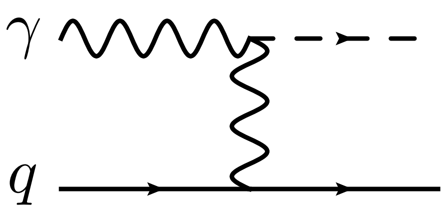

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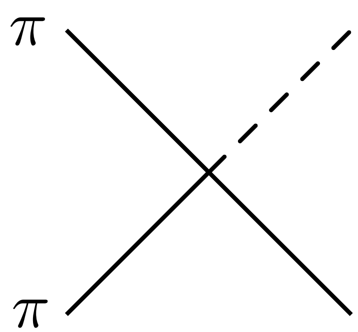

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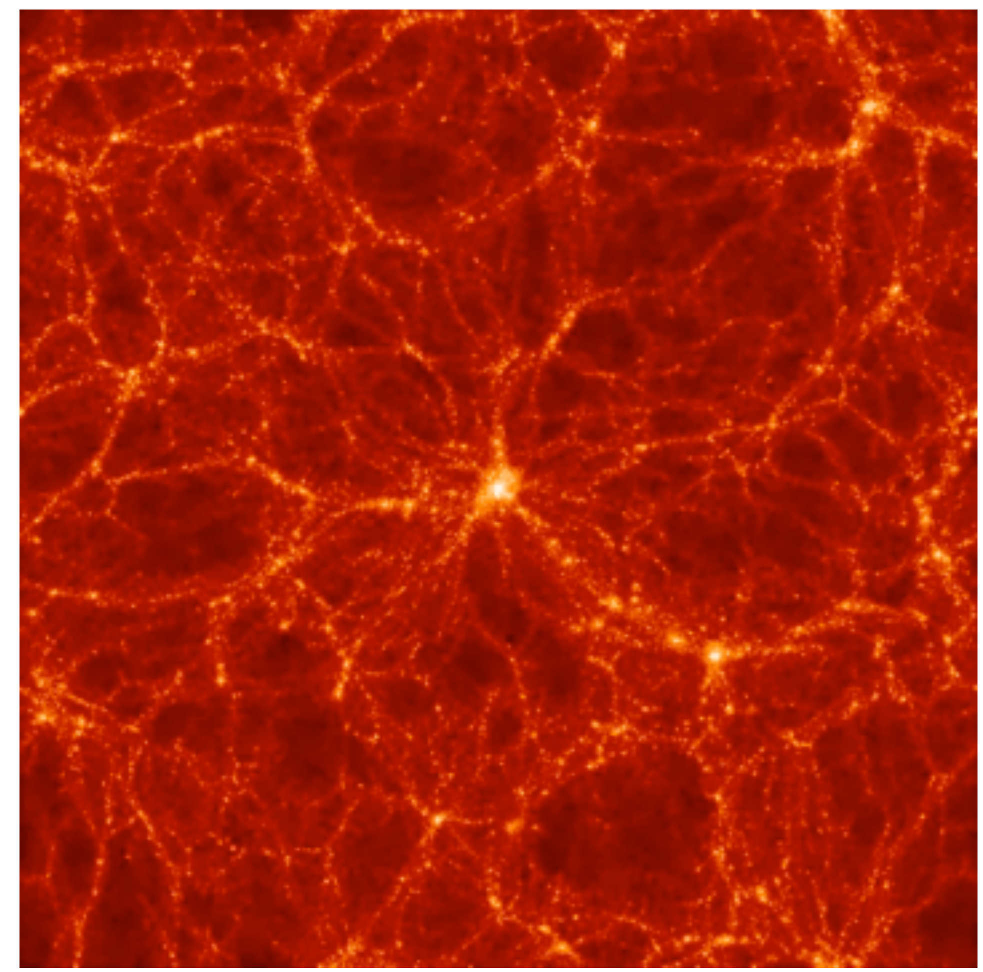

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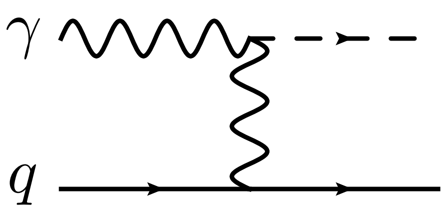

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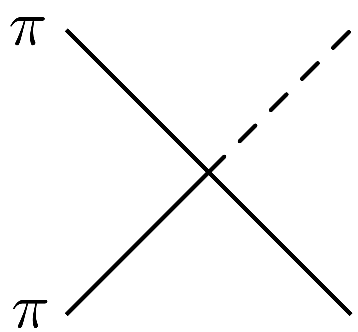

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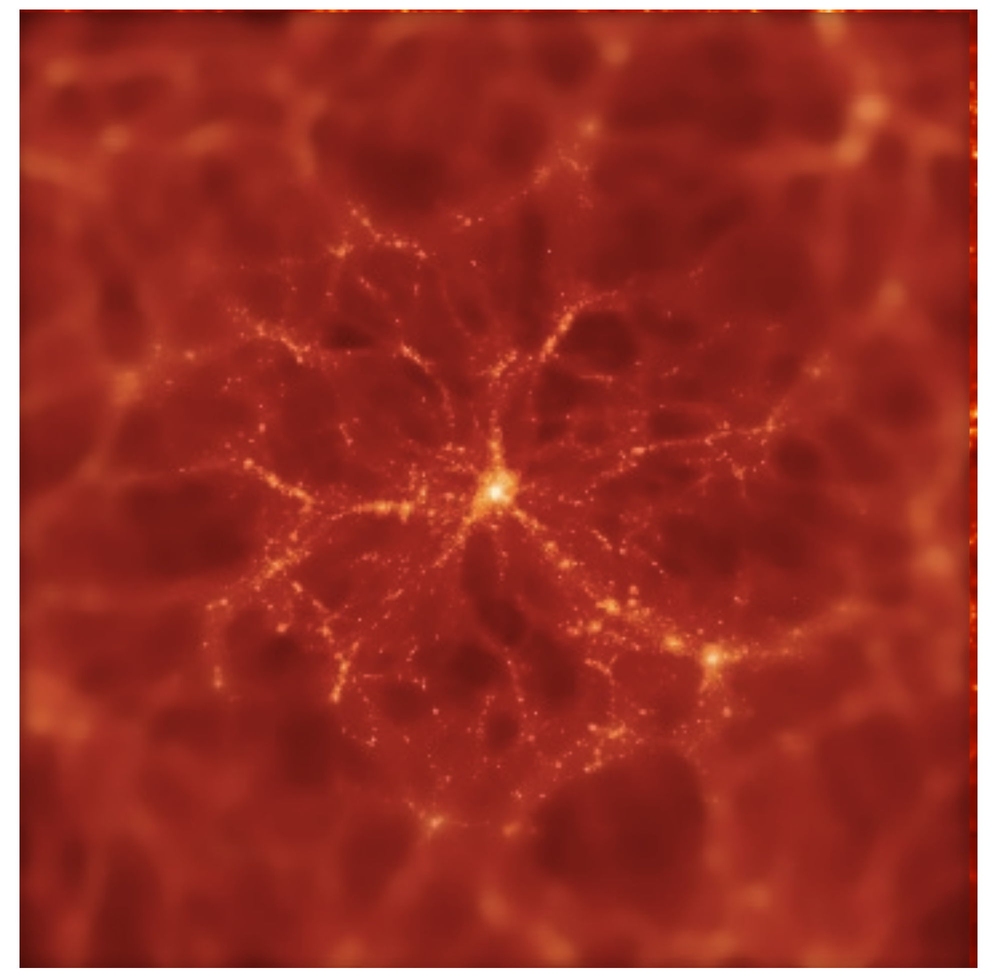

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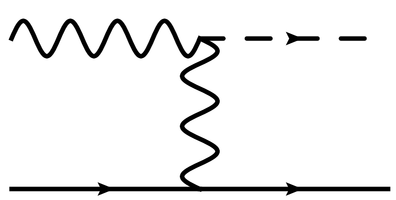

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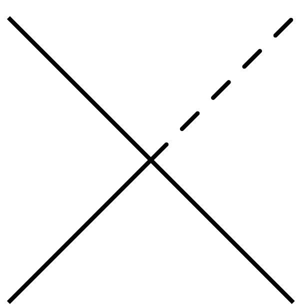

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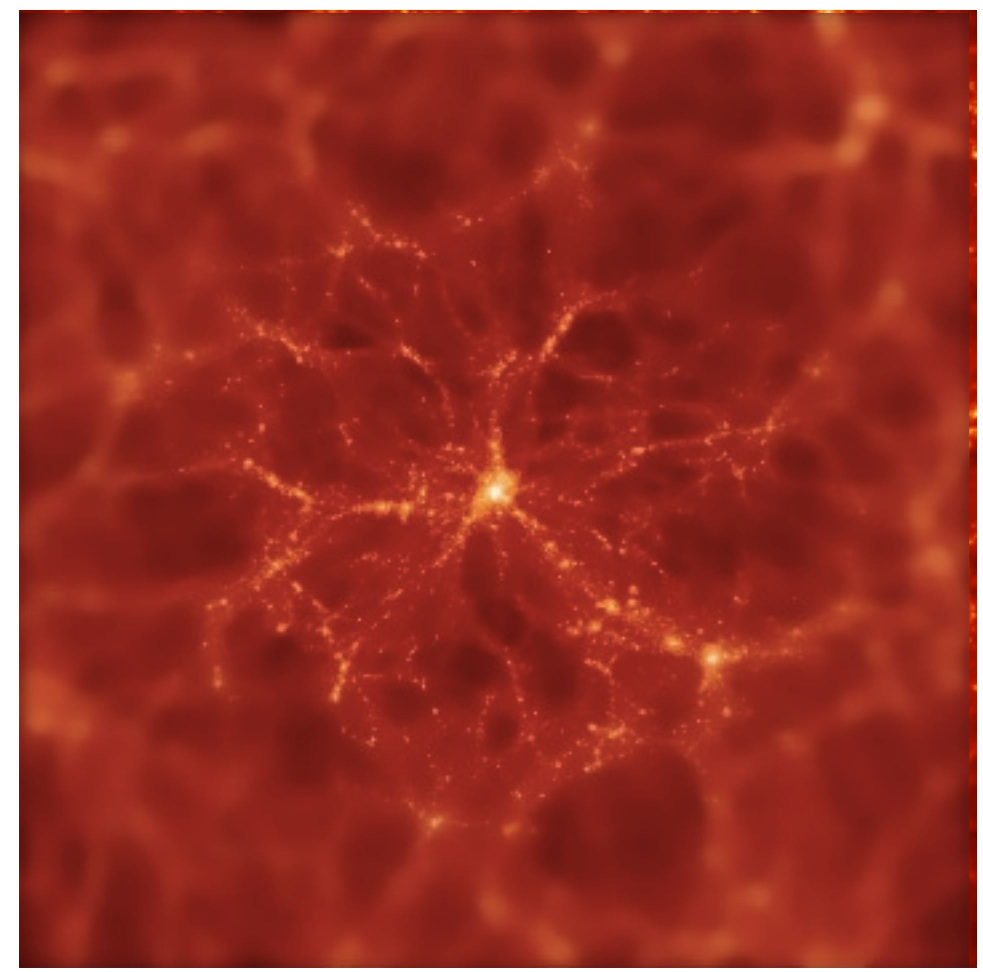

They should be a subdominant component of DM

Hannestad et al. JCAP 1008

$$\frac{\Omega_{{\rm hDM},a}}{\Omega_{\rm DM,obs}} < 0.03 \qquad (m_a < 0.72\,\rm eV)$$

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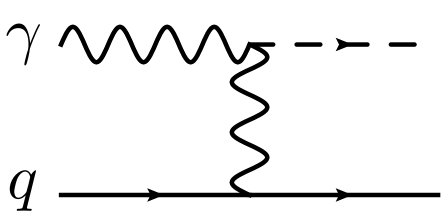

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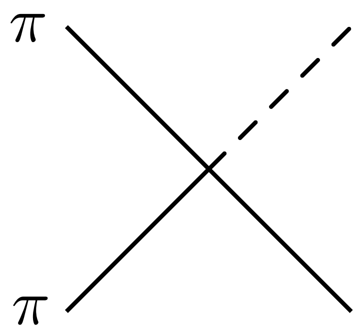

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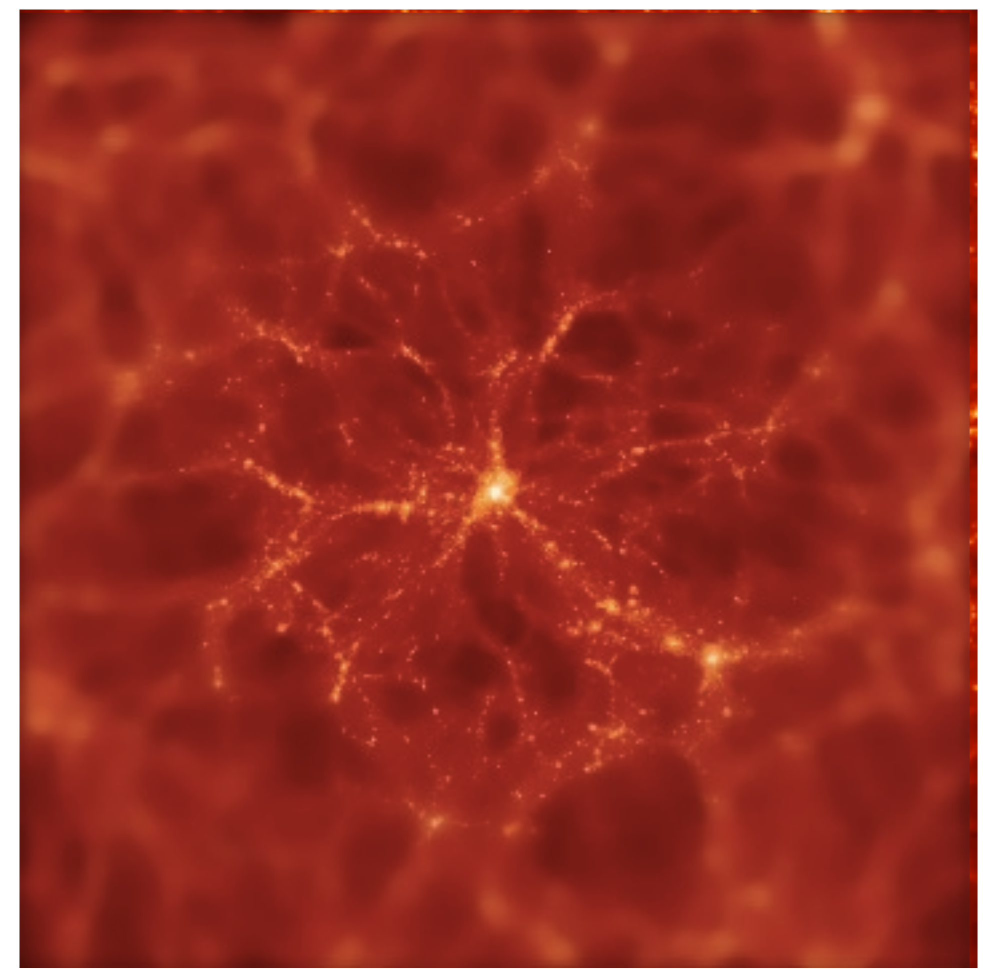

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Sub eV axions or ALPs behave as Dark Radiation but $N_{\rm eff} < 3.9$
(There are however other DR production mechanisms)

Graf and Steffen arXiv:1208.2951,
Takahashi arXiv:1201.4816, Sikivie PRL 108,

Axion cold Dark Matter

Axions (and ALPs) are produced non-thermally by three mechanisms

Realignment mechanism **Cosmic Strings** **Domain Walls**

(Field space) (Position space)

$$\Phi(x) = \rho(x) e^{i \frac{a(x)}{f_a}}$$

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Realignment mechanism

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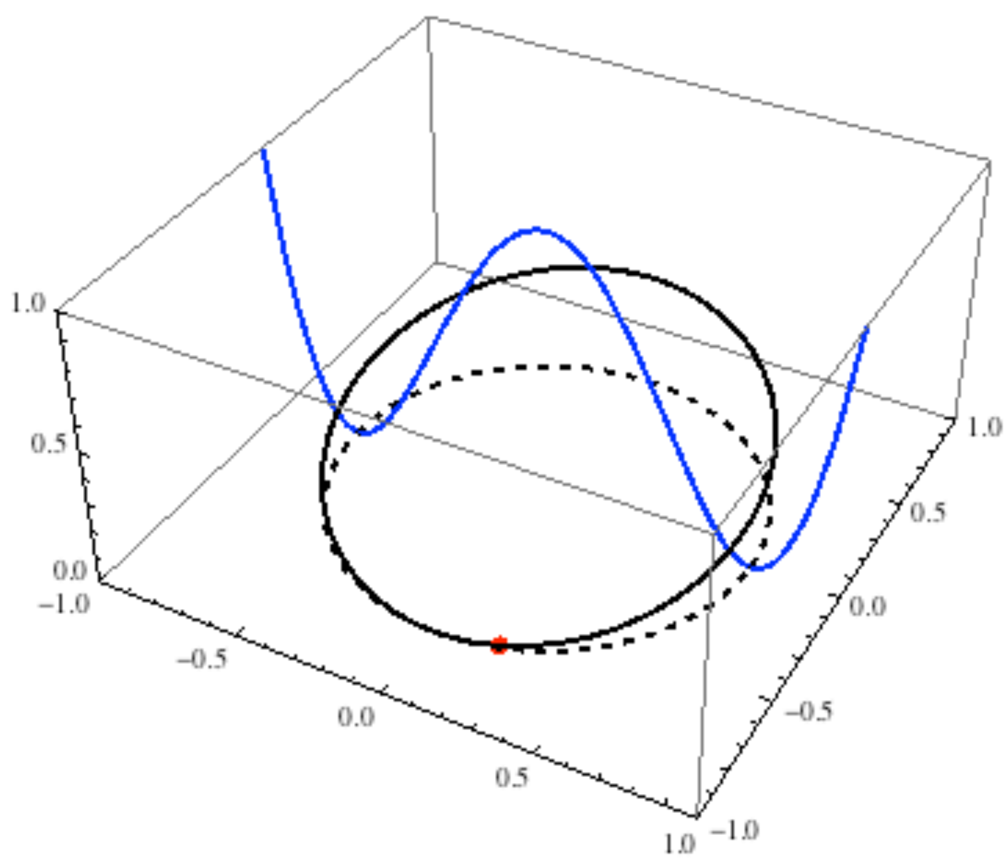

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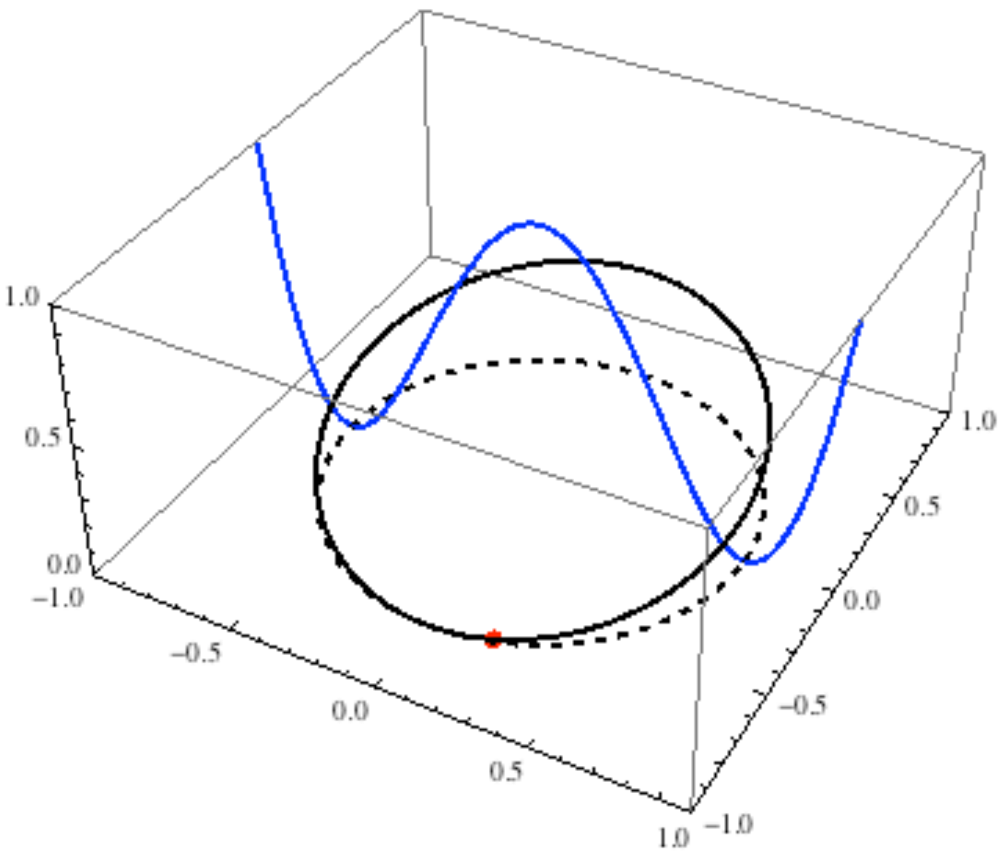

$$\Phi(x) = \rho(x) e^{i\frac{a(x)}{f_a}}$$

$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{40\mu{\rm eV}}{m_a}\right)^{1.184}$$

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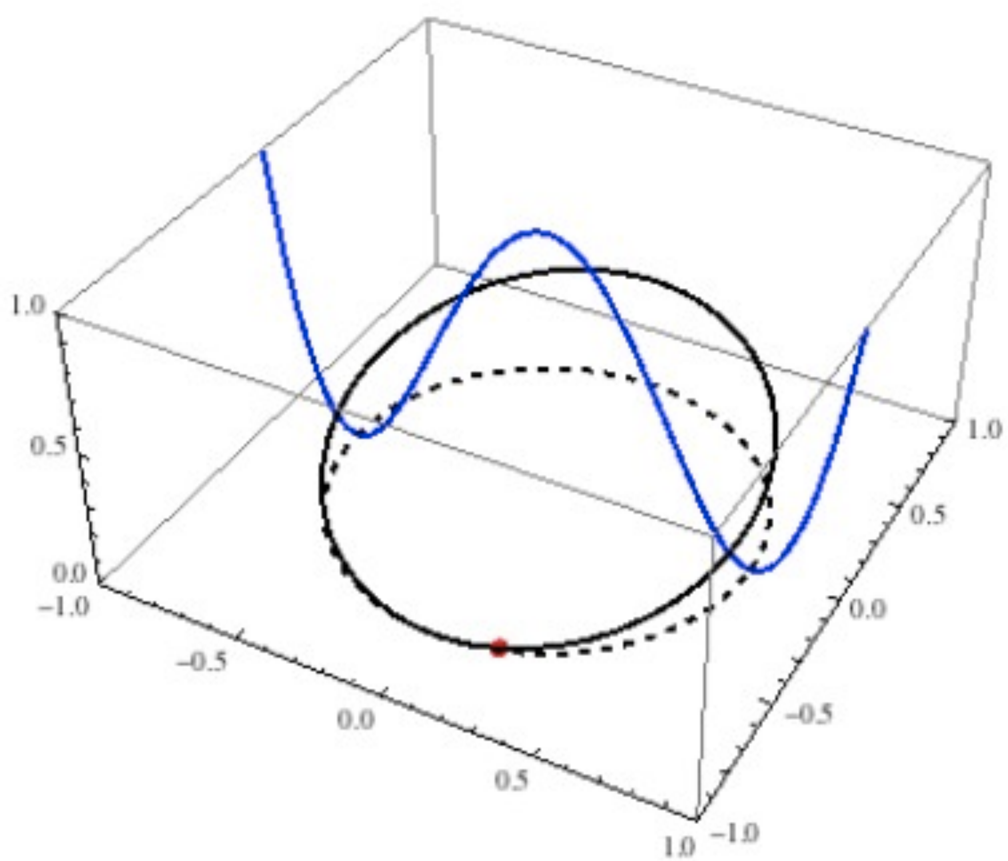
(Position space)

(T>QCD)

(T<QCD)



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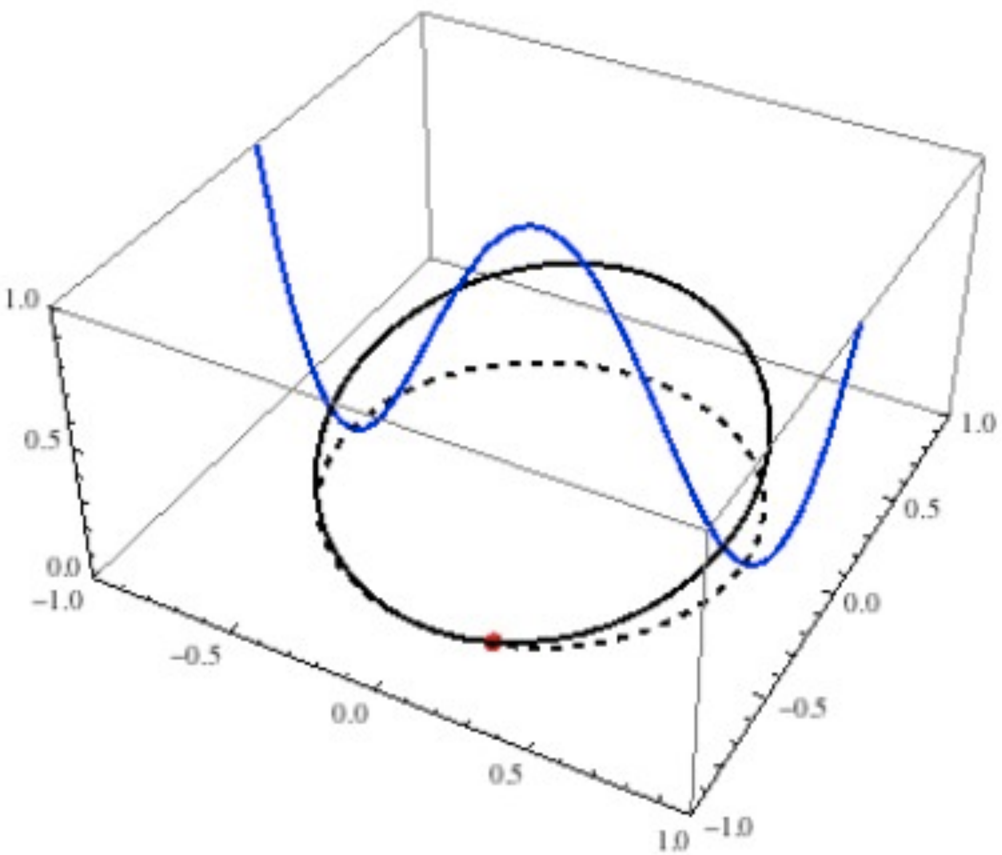

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Cosmic Strings

(Position space)

(T>QCD)

$a = \frac{3\pi}{2}$	$a = \pi$
$a = 0$	$a = \frac{\pi}{2}$

Domain Walls

(T<QCD)

Axion cold Dark Matter

Axions (and ALPs) are produced non-thermally by three mechanisms

Realignment mechanism

Cosmic Strings

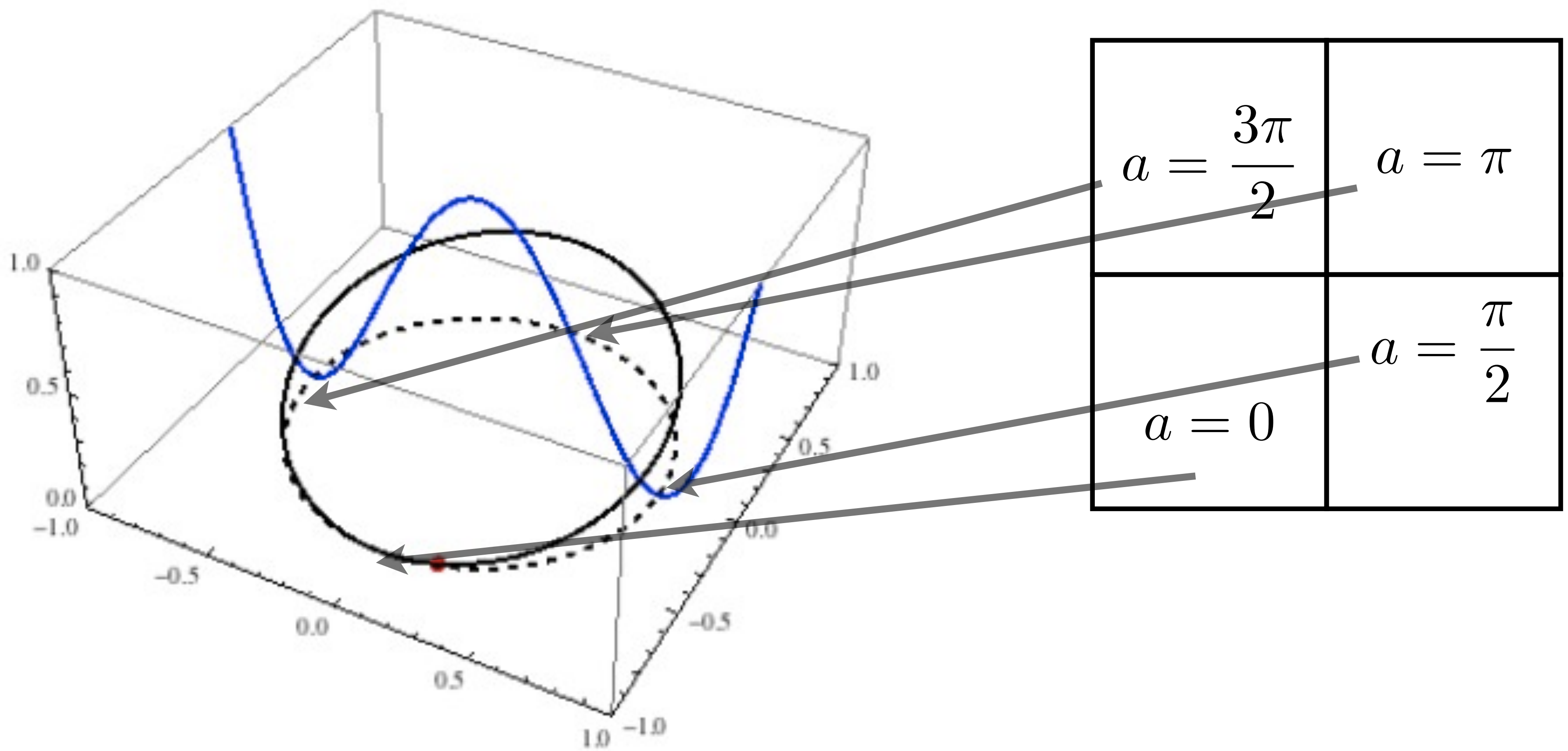
Domain Walls

(Field space)

(Position space)

(T>QCD)

(T<QCD)



$$\Phi(x) = \rho(x) e^{i\frac{a(x)}{f_a}}$$

$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{40\mu\mathrm{eV}}{m_a}\right)^{1.184}$$

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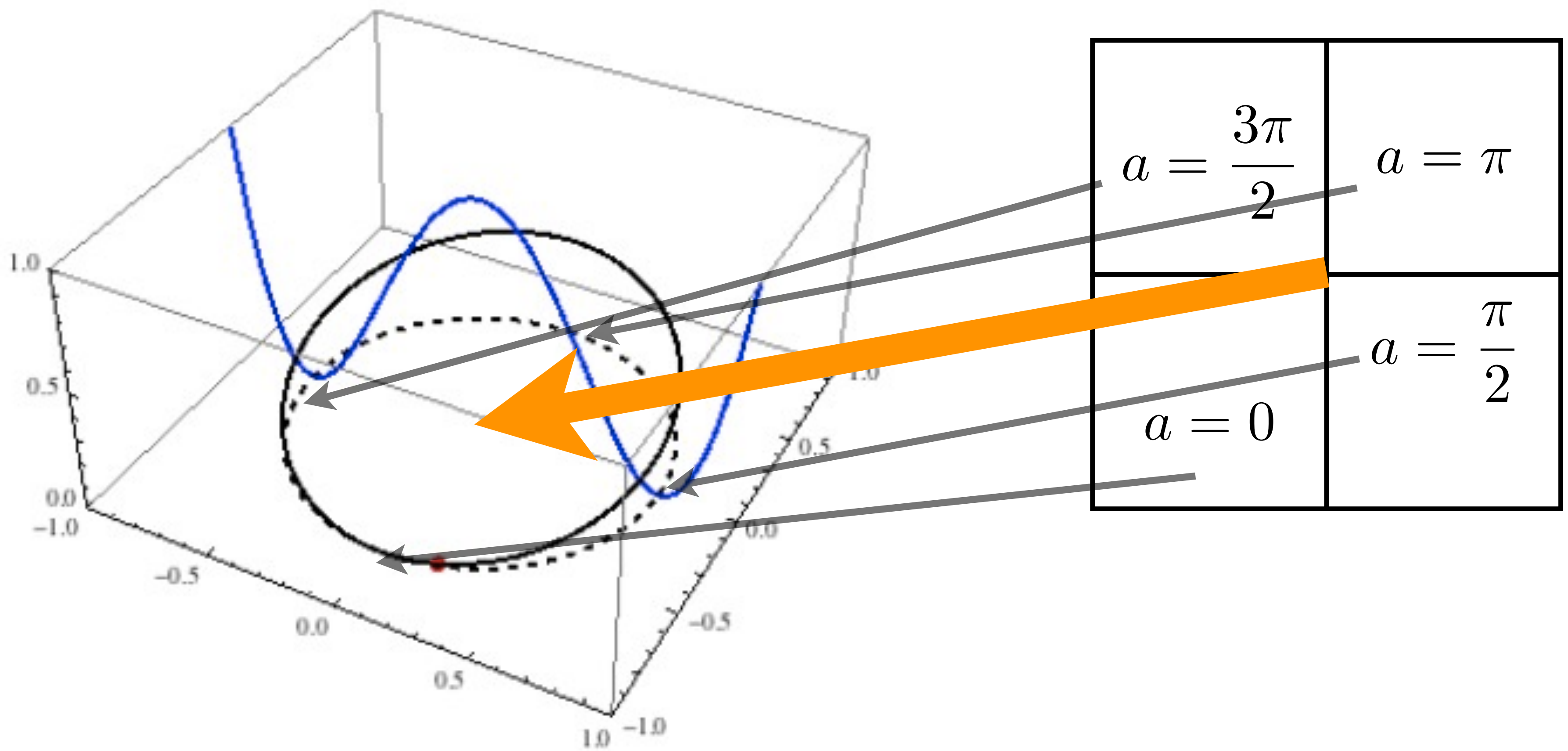

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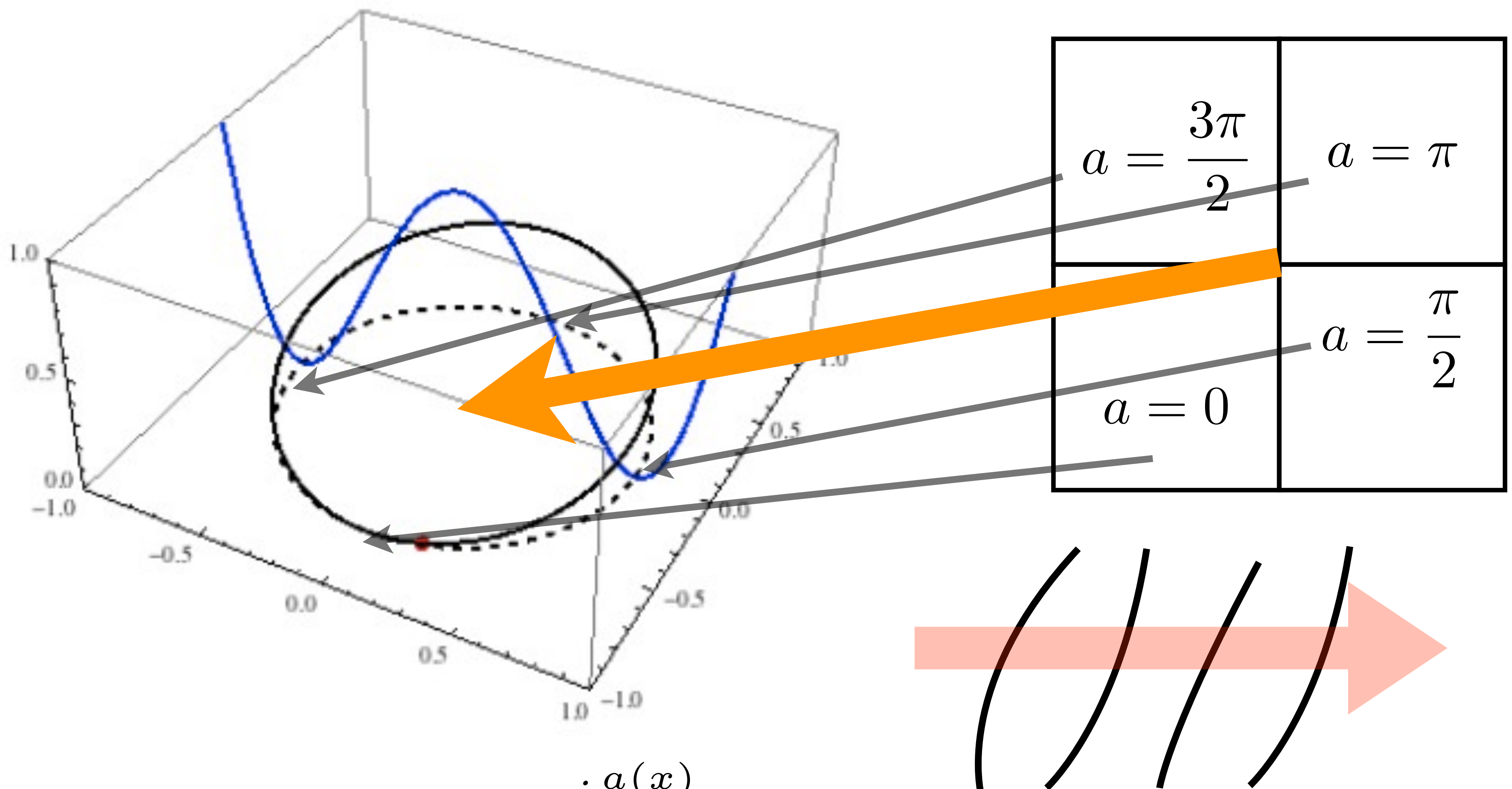

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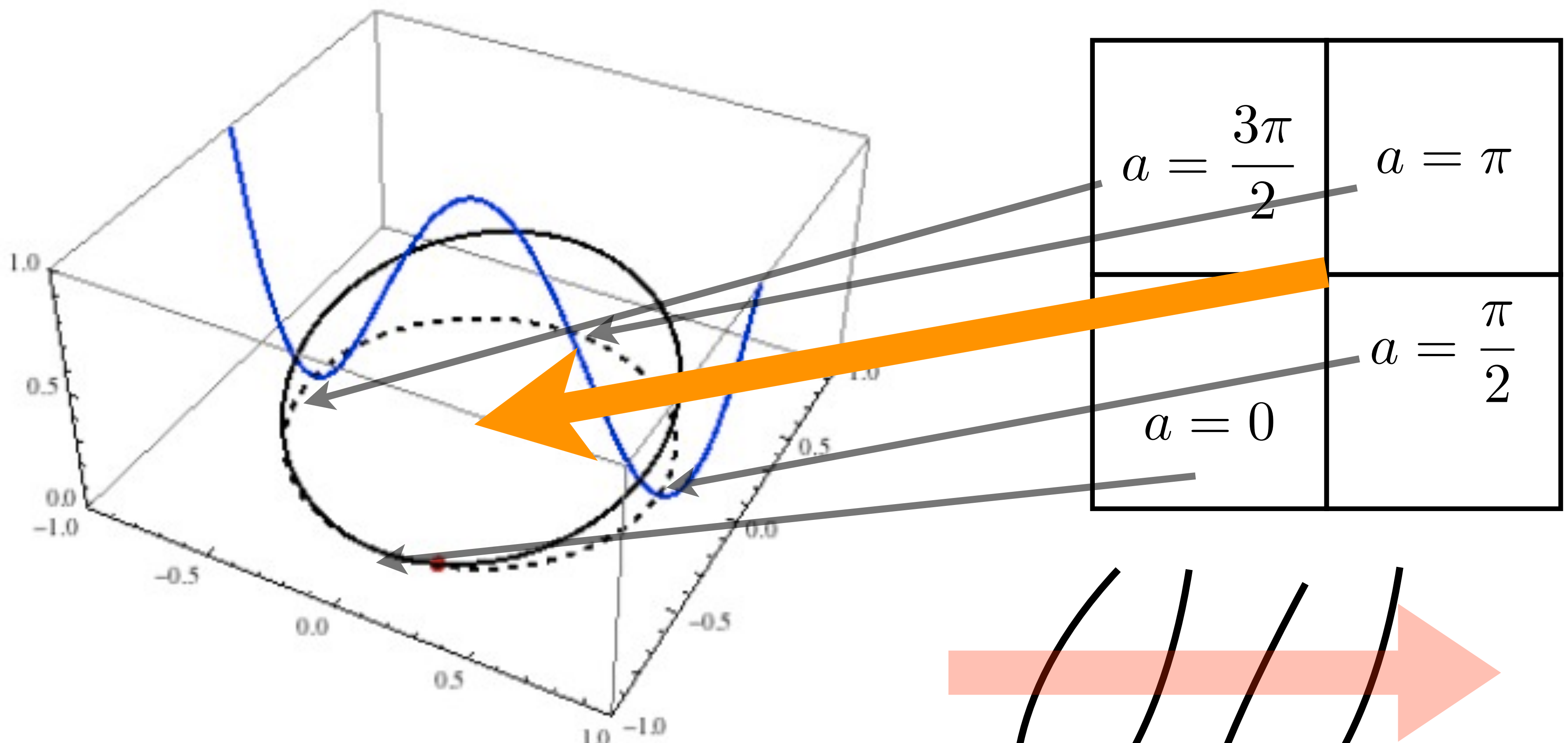

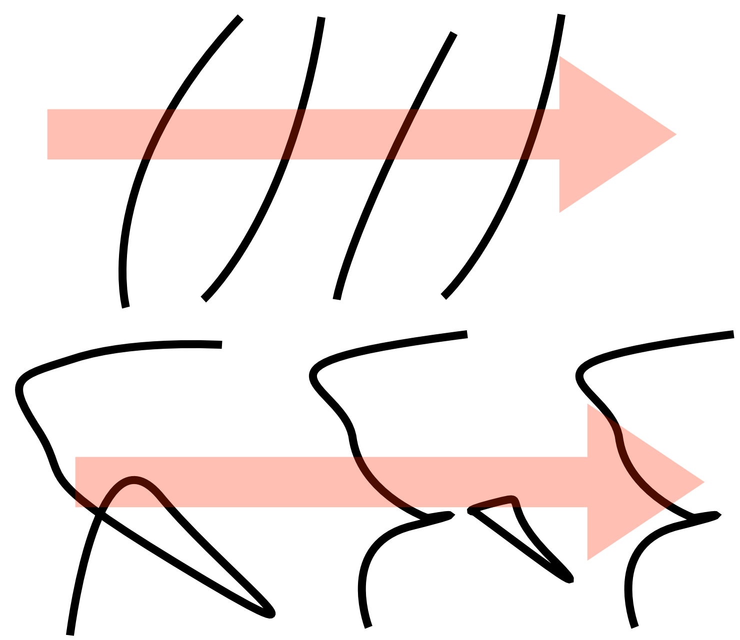

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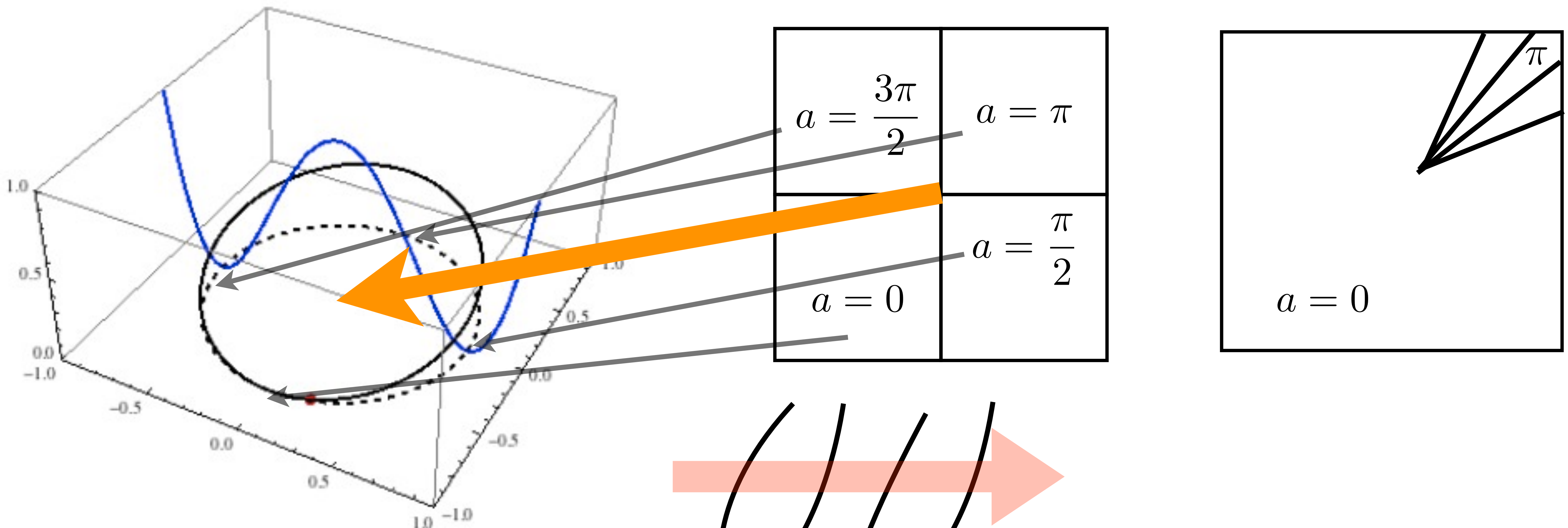

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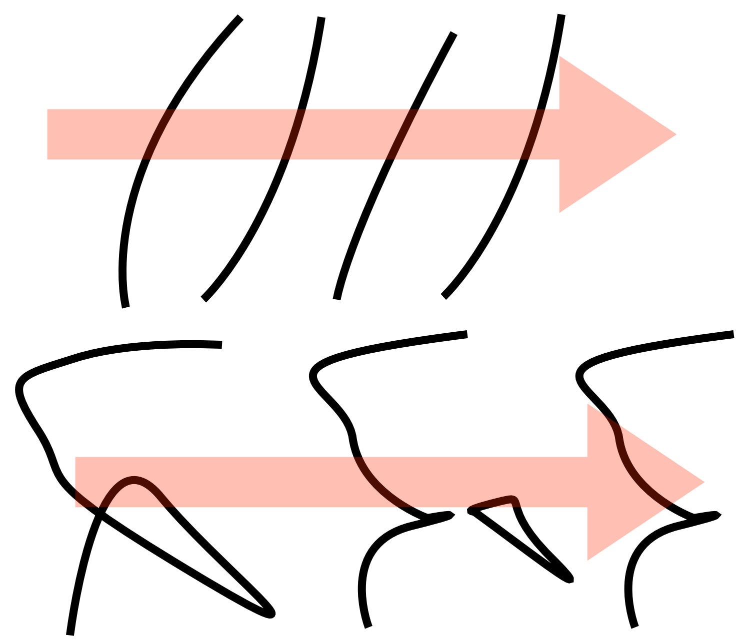

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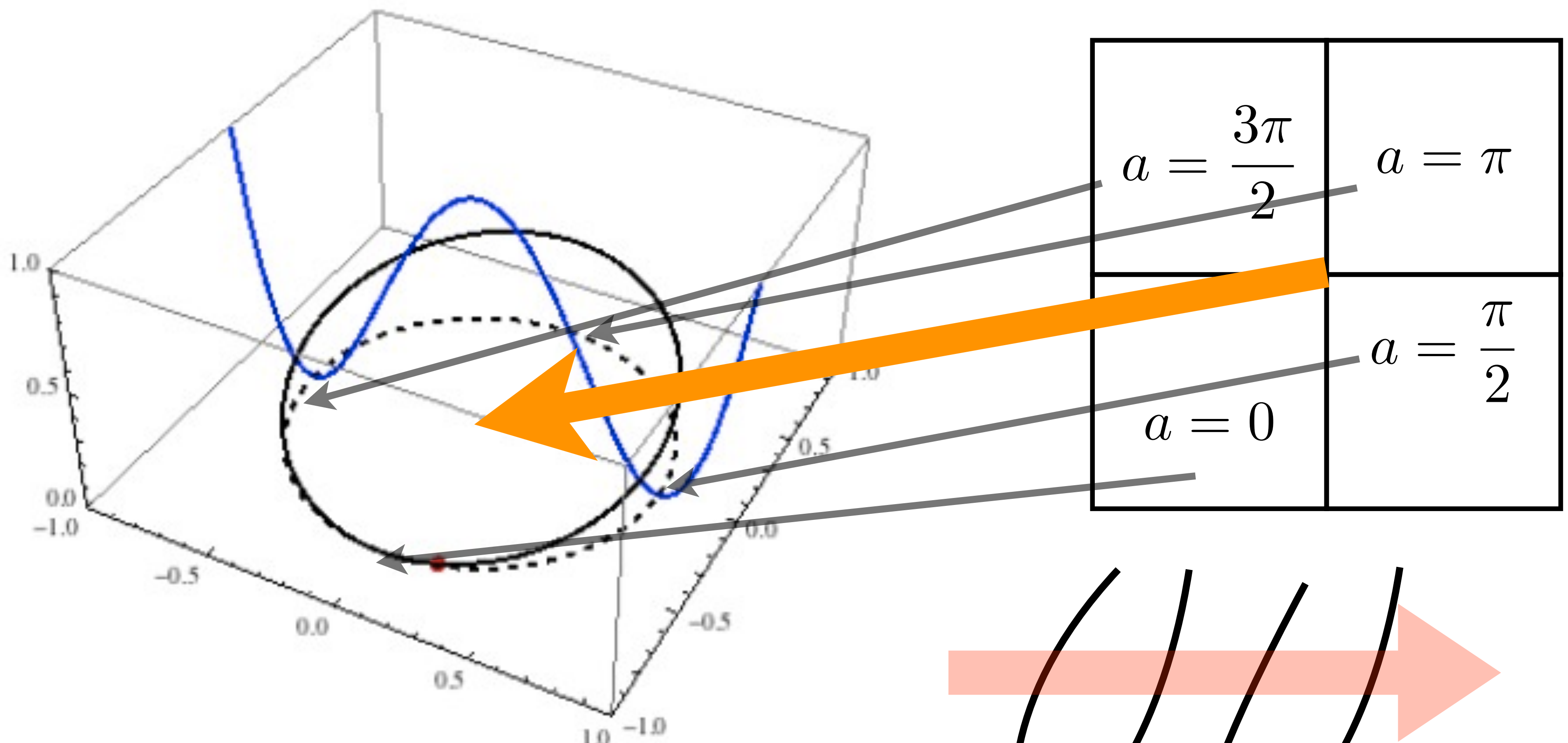

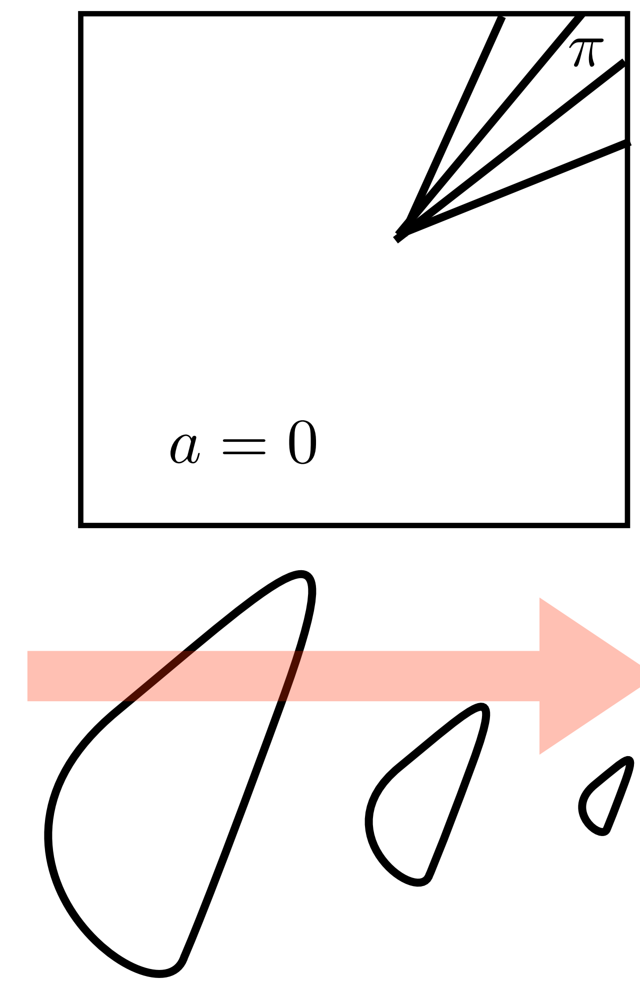

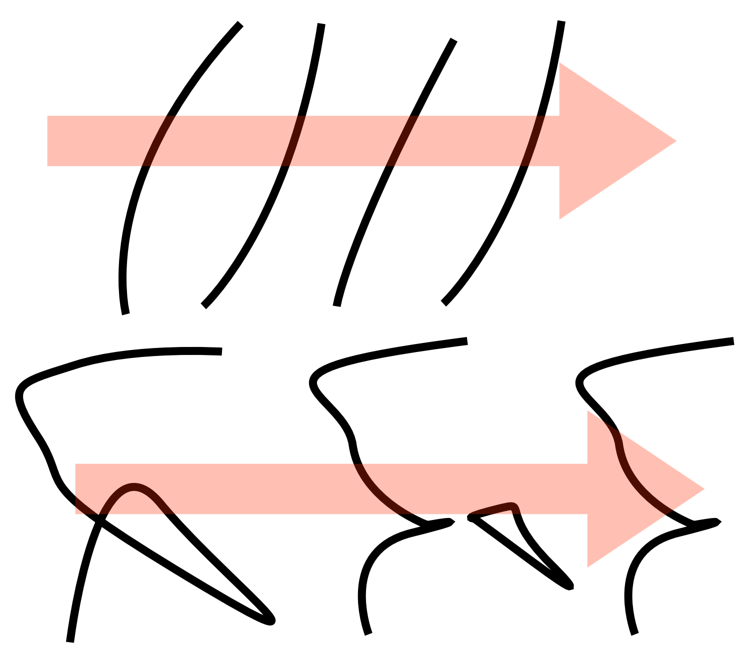

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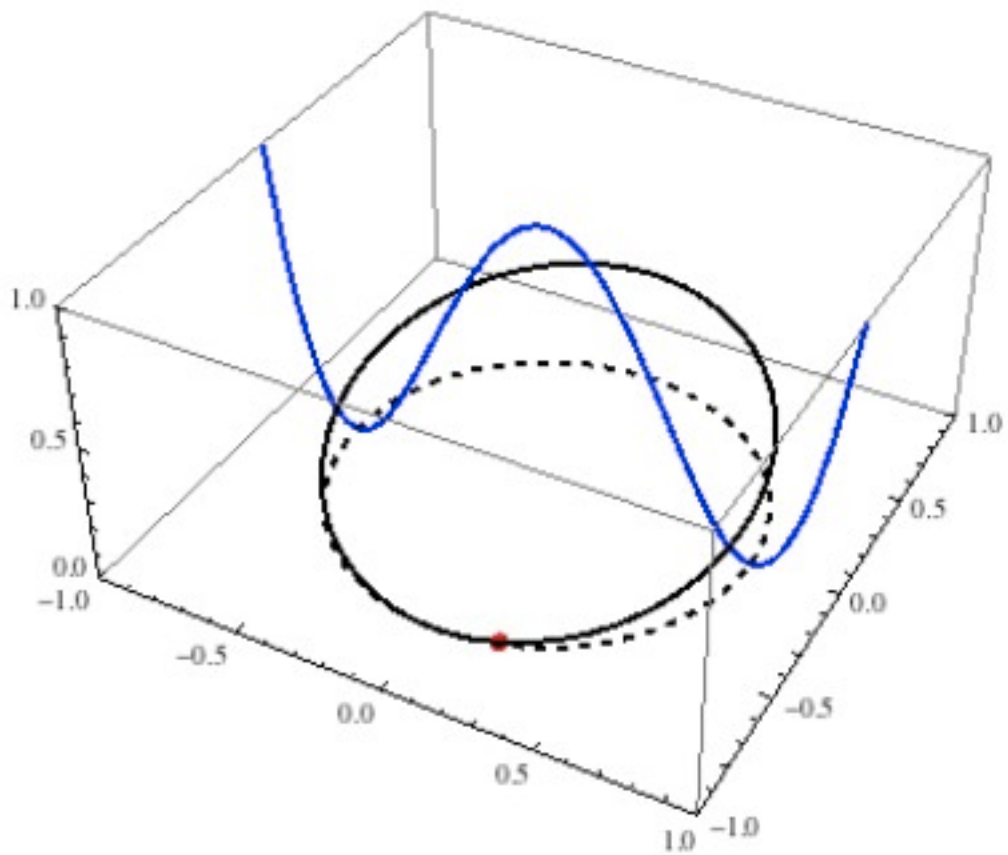

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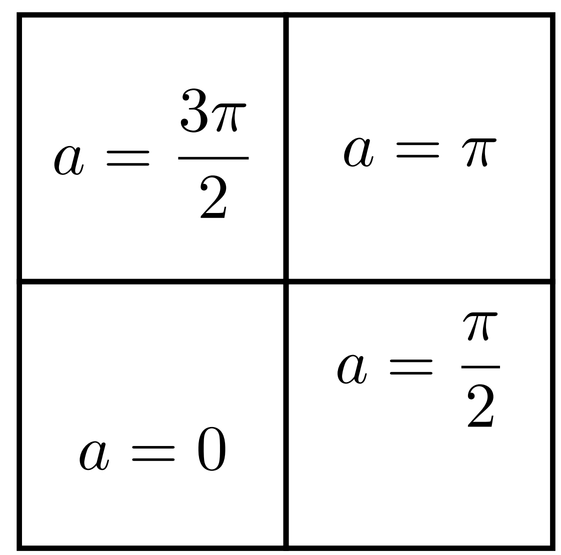

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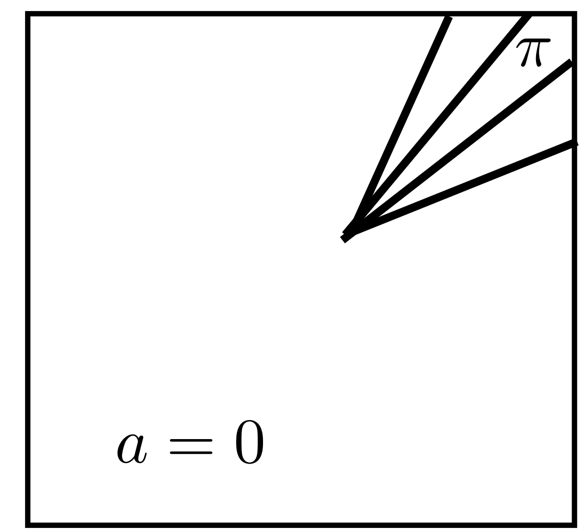

$$\frac{\Omega_{a,DW+ST}}{\Omega_{\rm obs}} \begin{cases} \sim \left(\frac{40\mu{\rm eV}}{m_a}\right)^{1.184} \\ \sim \left(\frac{400\mu{\rm eV}}{m_a}\right)^{1.184} \end{cases}$$

Sikivie, Harari et at.

Shellard, Davis et at.
Kawasaki, Hiramatsu et at

Understanding the behavior $\Omega_{\mathrm{a,cDM}} \propto 1/m_a$

E.o.m. $\ddot{a} + 3H\dot{a} + m_a^2 a = ... \sim 0$

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$$H \ll m_a$$

$$a \sim \frac{\cos m_a t}{R^{3/2}}$$

$$H \gg m_a$$

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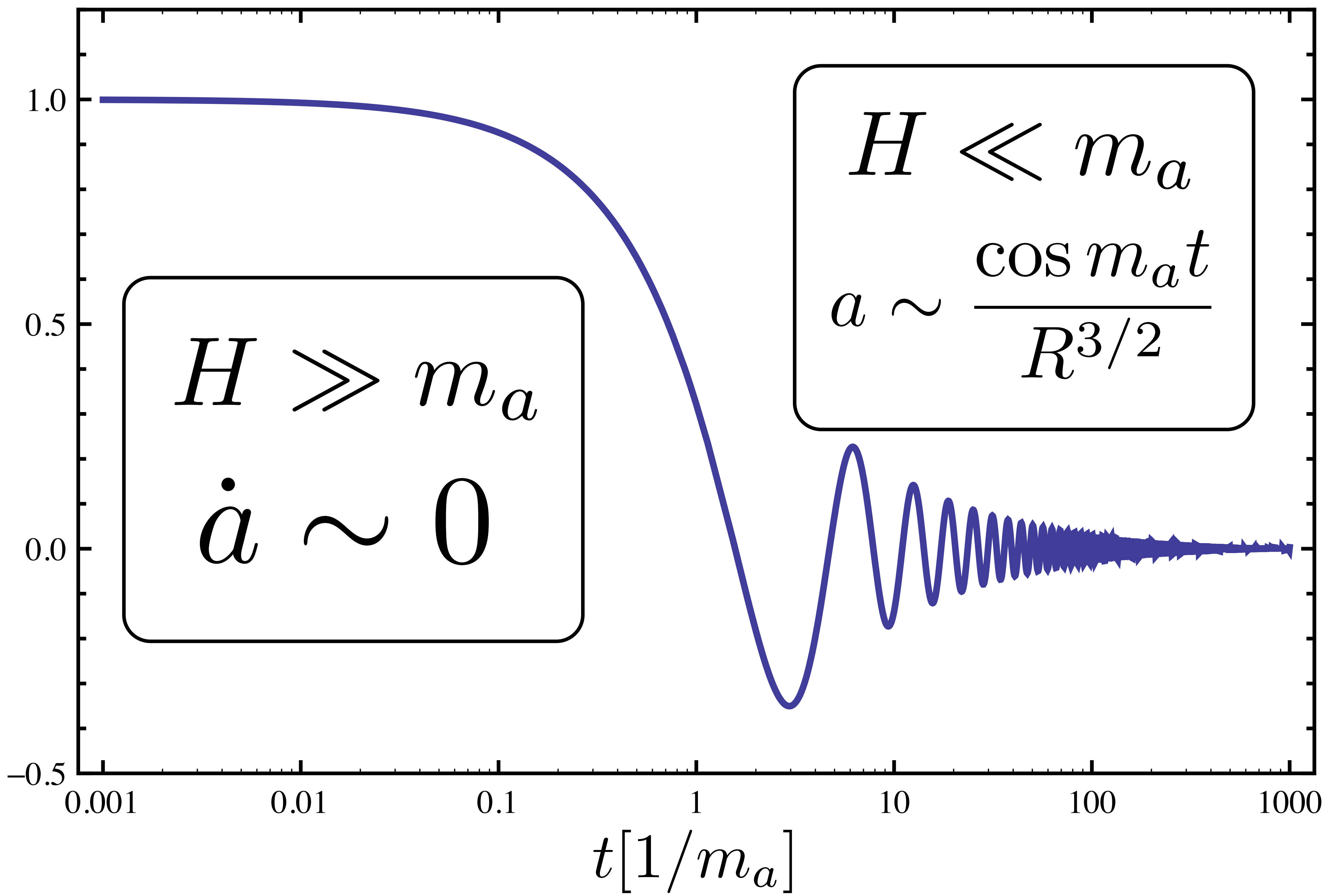

Understanding the behavior $\Omega_{\rm a,cDM} \propto 1/m_a$

comoving axion number conserved

$$\rho_a = \frac{1}{2}(\dot{a})^2 + \frac{1}{2}m_a^2 a^2 \longrightarrow N = \frac{\rho_a R^3}{m_a} = \text{ct.} = \frac{1}{2} m_a R_1^3 a_1^2$$

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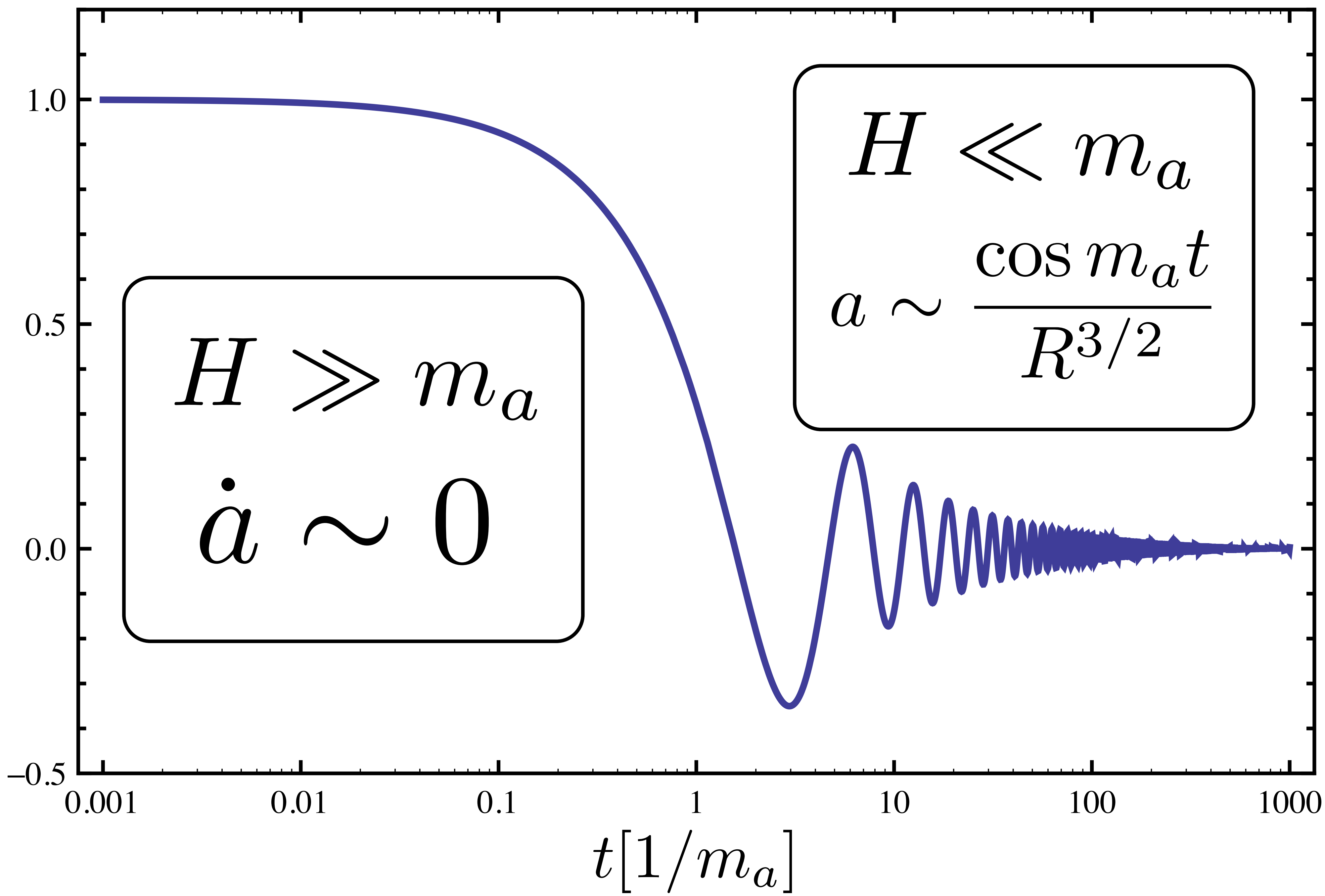
Why so cold?

E.o.m. $\ddot{a} + 3H\dot{a} + m_a^2 a = ... \sim 0$



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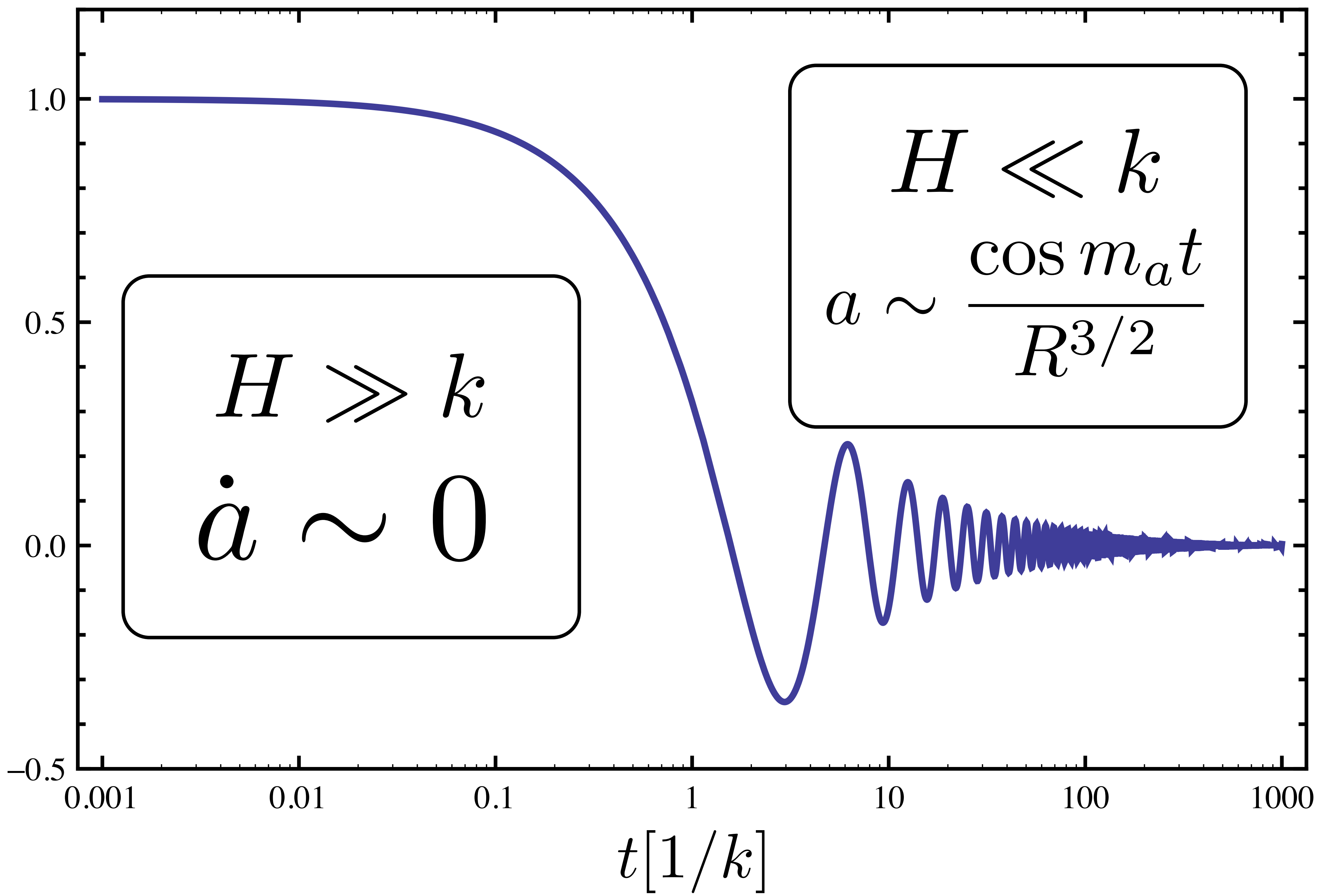

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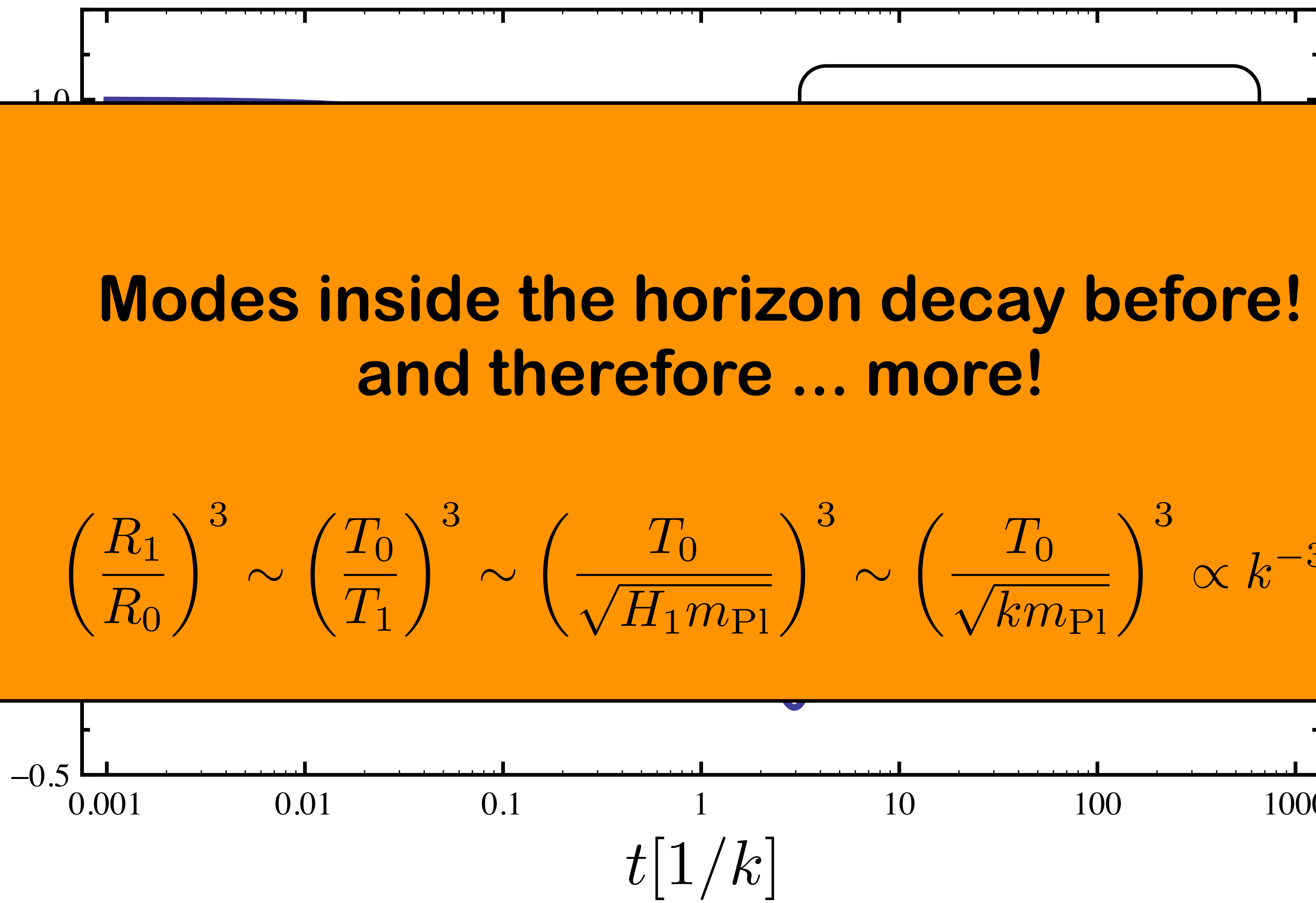


Modes inside the horizon decay before!
and therefore ... more!

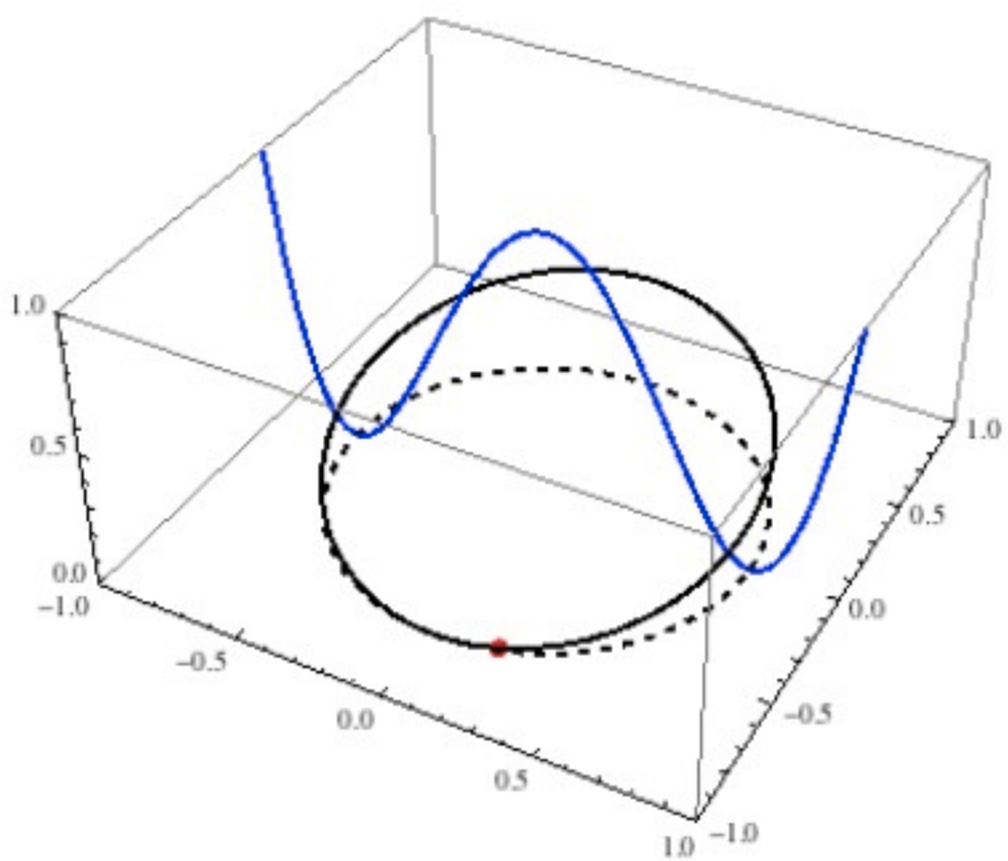
$$\left(\frac{R_1}{R_0}\right)^3 \sim \left(\frac{T_0}{T_1}\right)^3 \sim \left(\frac{T_0}{\sqrt{H_1 m_{\rm Pl}}}\right)^3 \sim \left(\frac{T_0}{\sqrt{k m_{\rm Pl}}}\right)^3 \propto k^{-3/2}$$

Axion cold Dark Matter*

If the Peccei-Quinn phase transition happens before inflation ...

Realignment mechanism

(Field space)



$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \theta_0^2 \left(\frac{12\mu{\rm eV}}{m_a}\right)^{1.184}$$

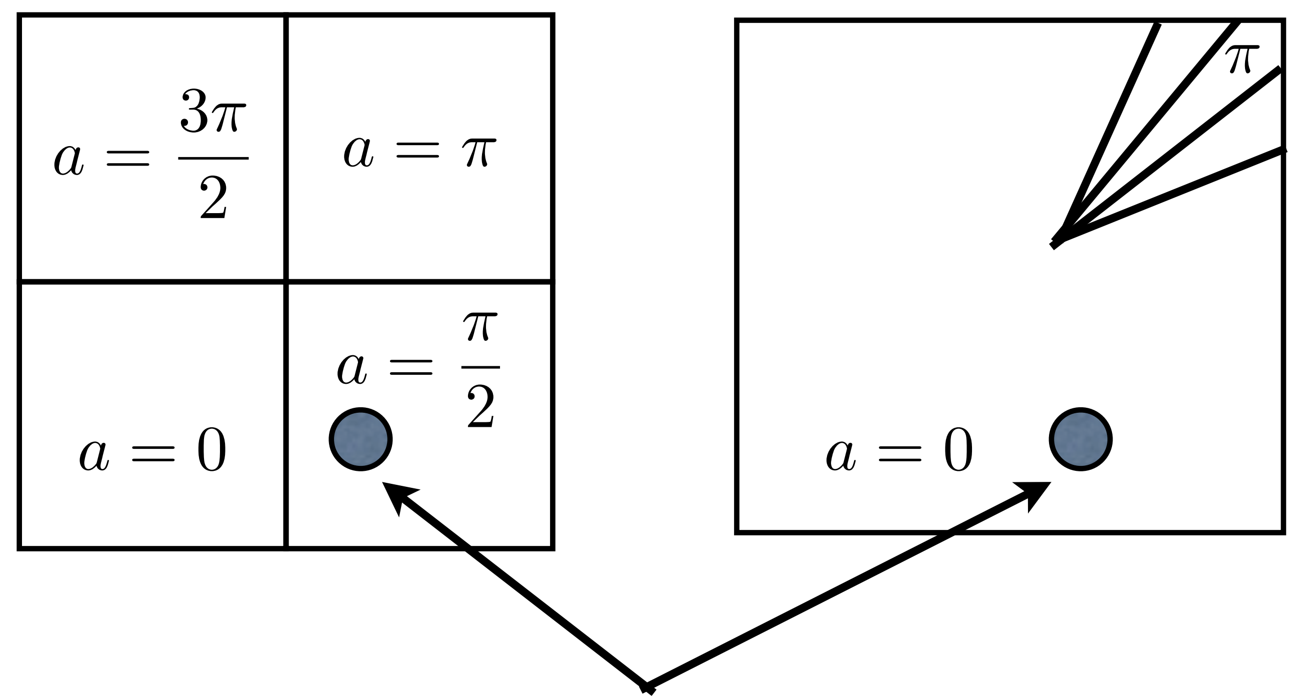
Cosmic Strings

(Position space)

(T>QCD)

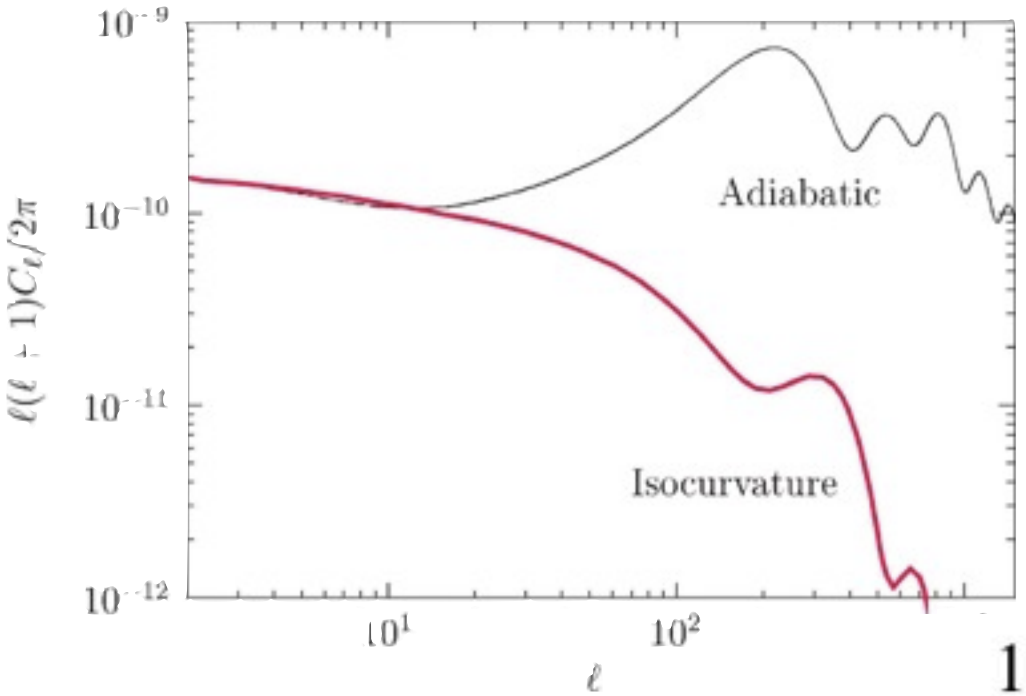
Domain Walls

(T<QCD)

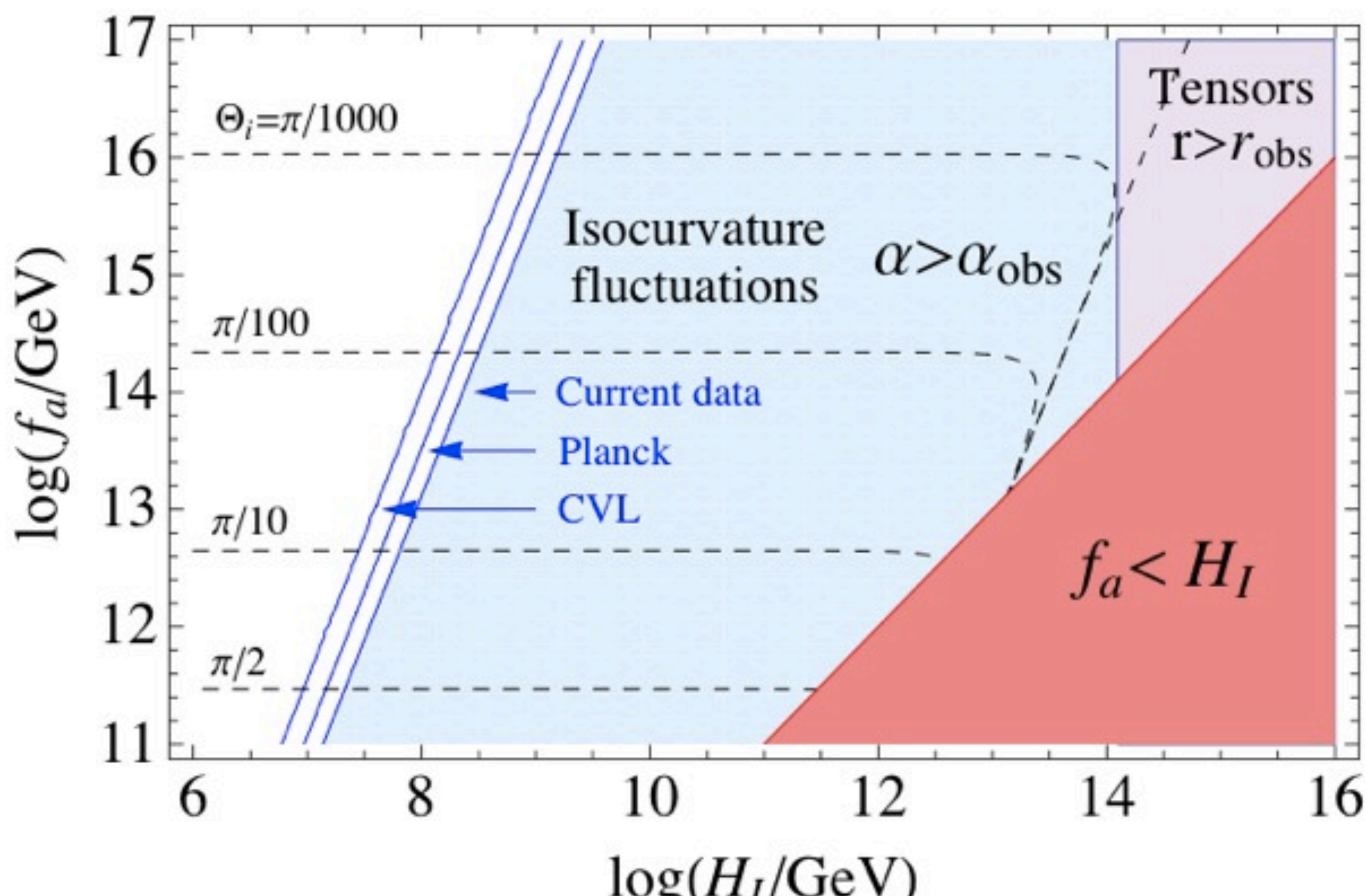


Size of our universe after inflation fits inside one of these domains
- **CSs and DWs are diluted by expansion**
- **Whole universe has 1 initial value for a**

And they imprint ISOCURVATURE perturbations

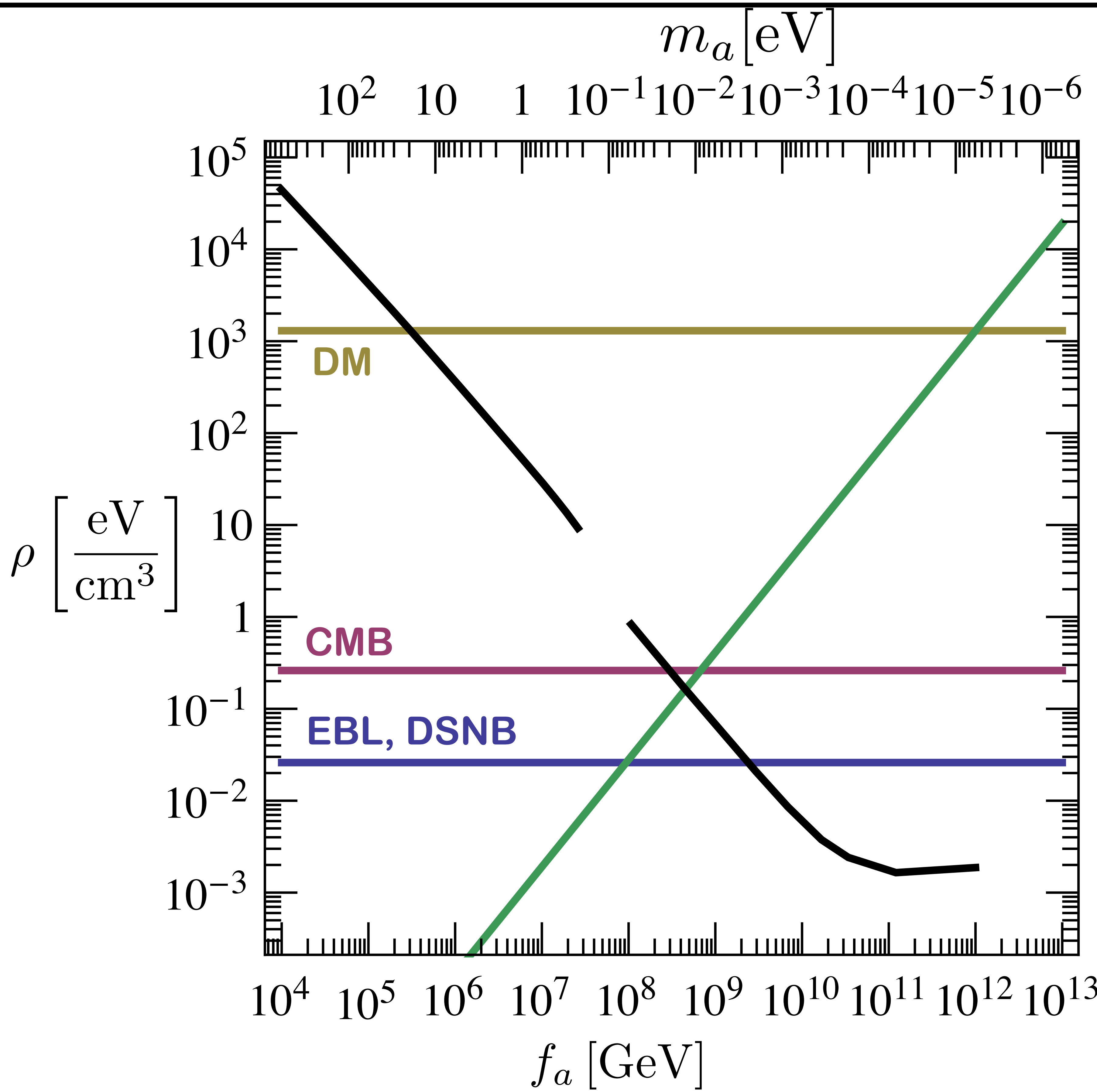


but this depends on H during inflation...



Hamman, Hannestad, Raffelt and Wong JCAP (2009)

Axion energy density today



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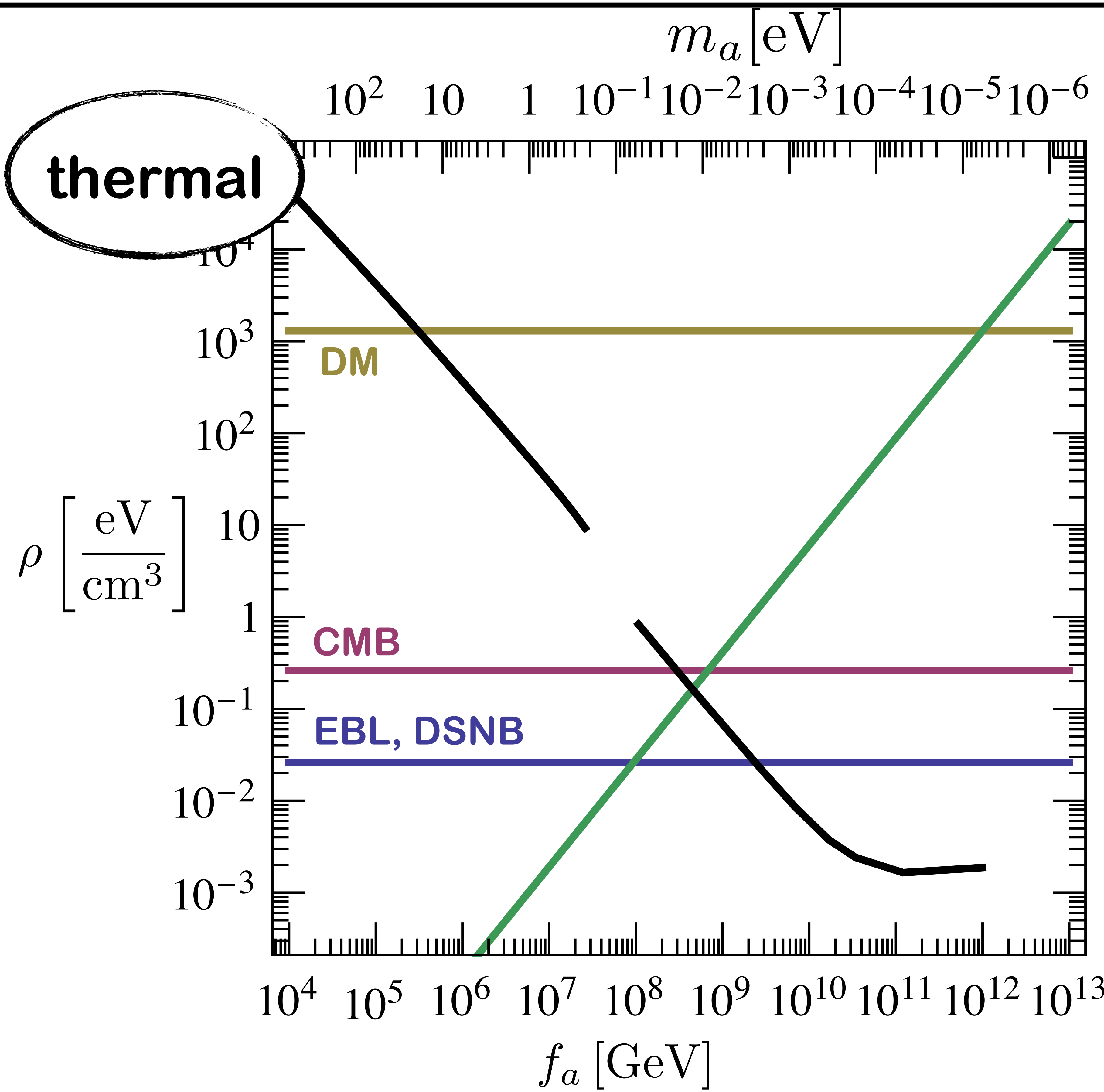

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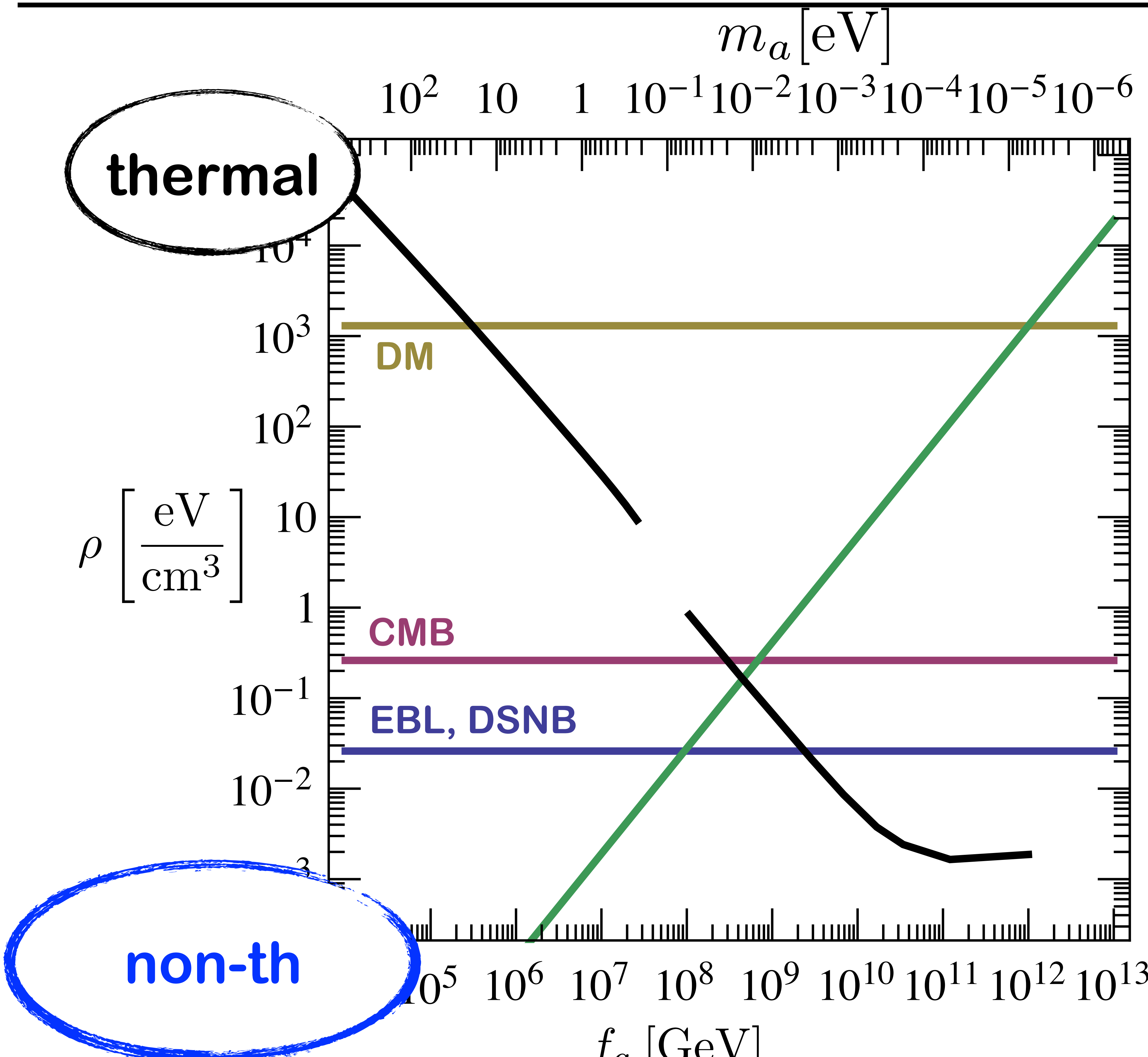

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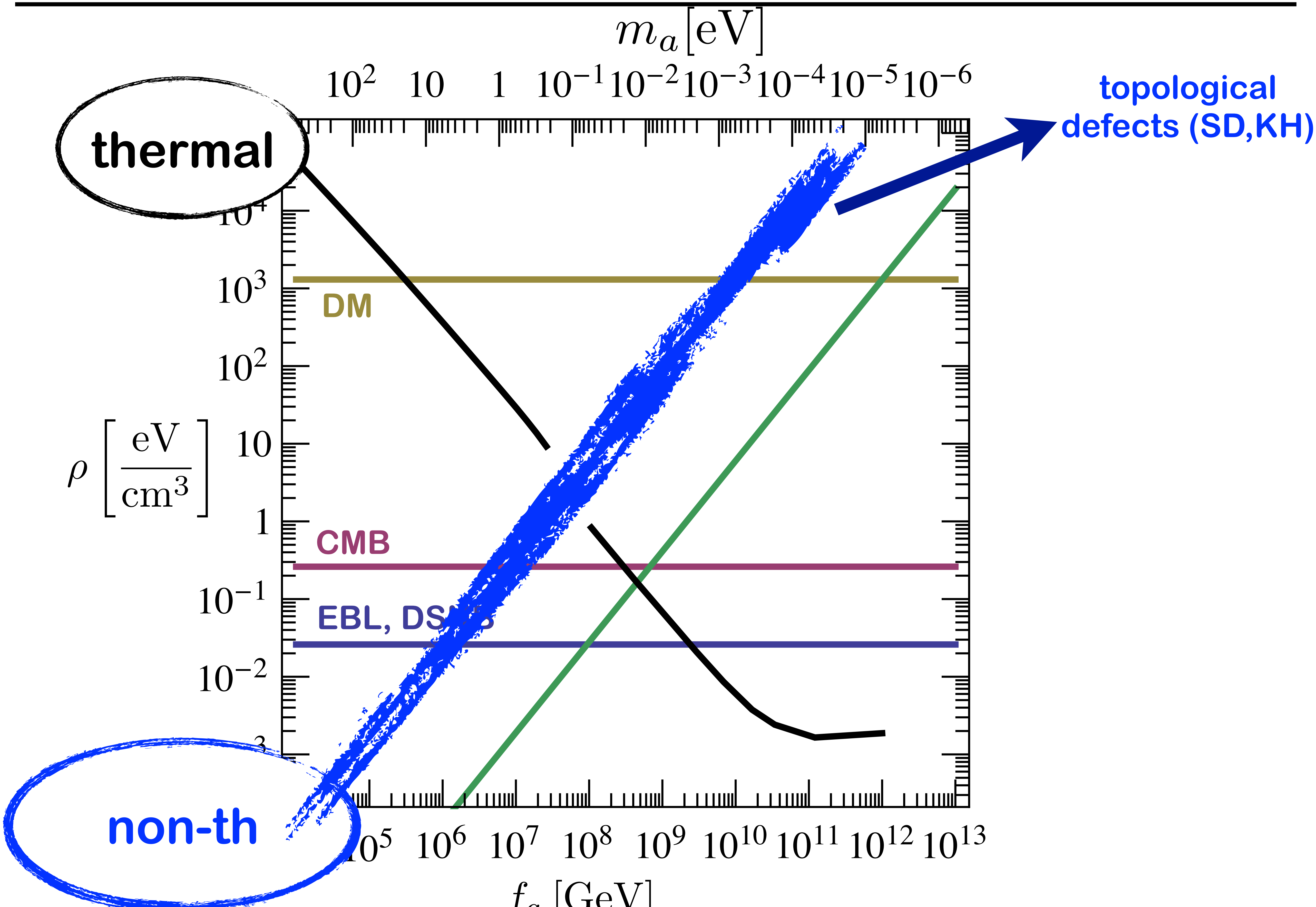

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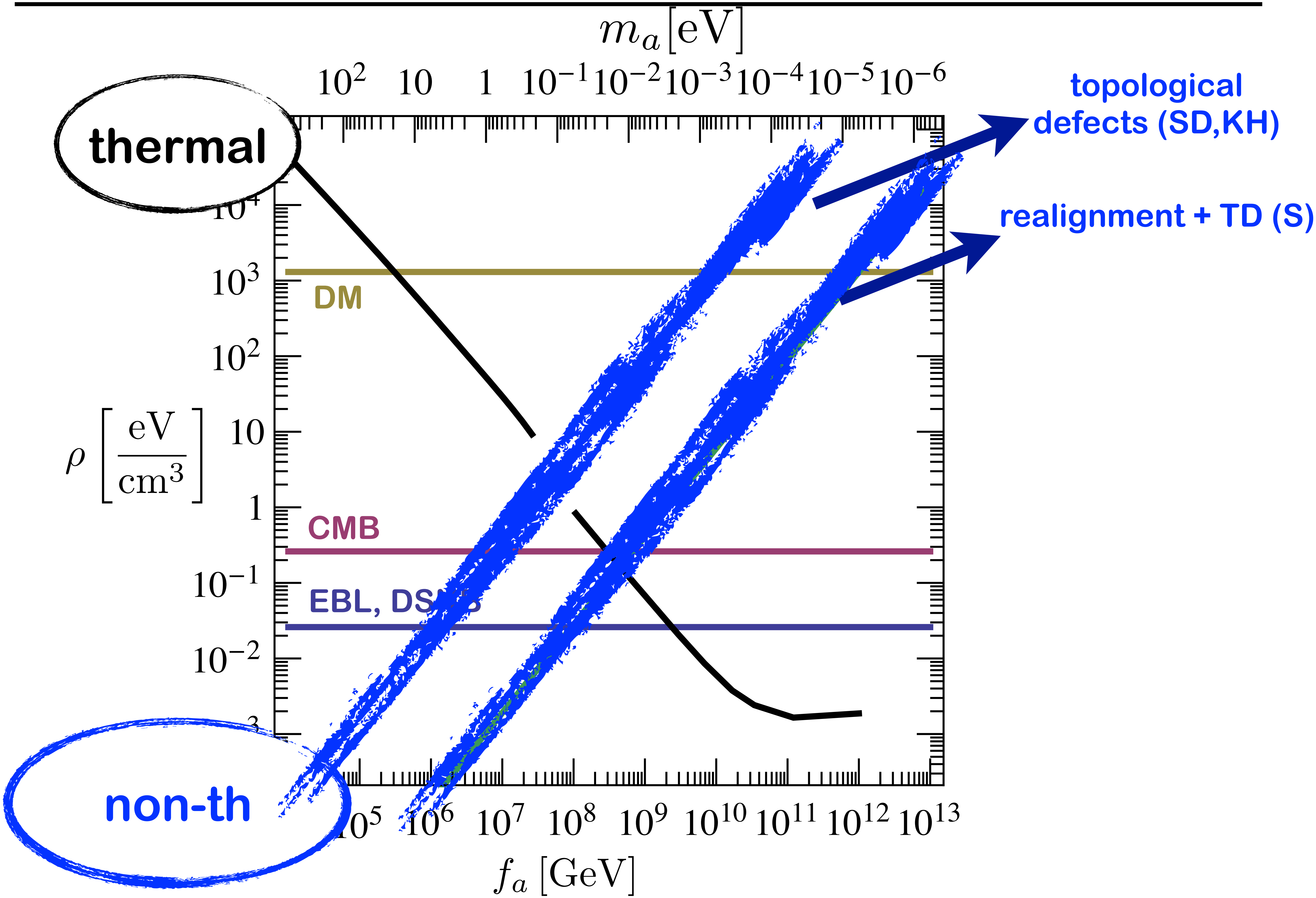

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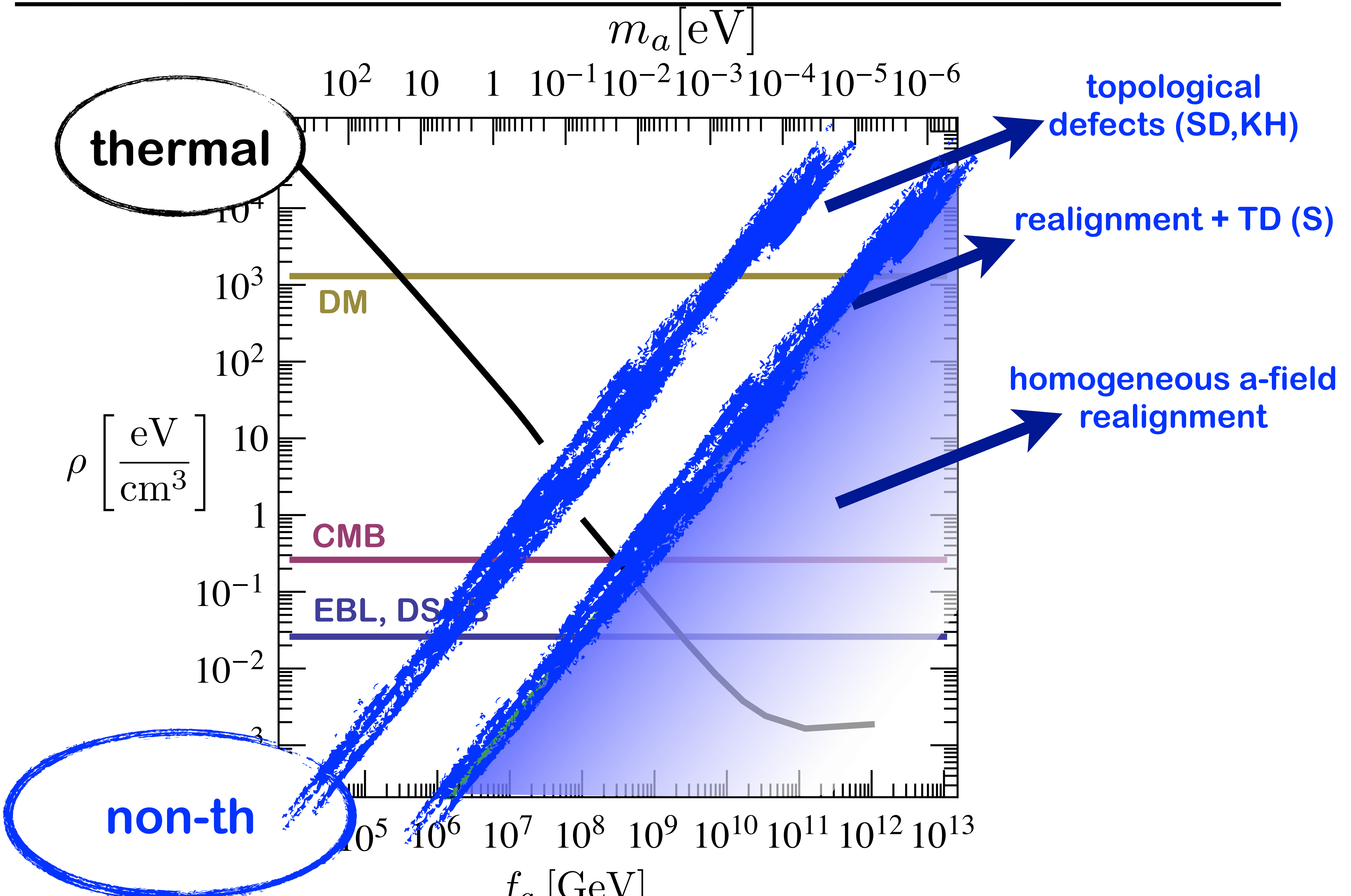
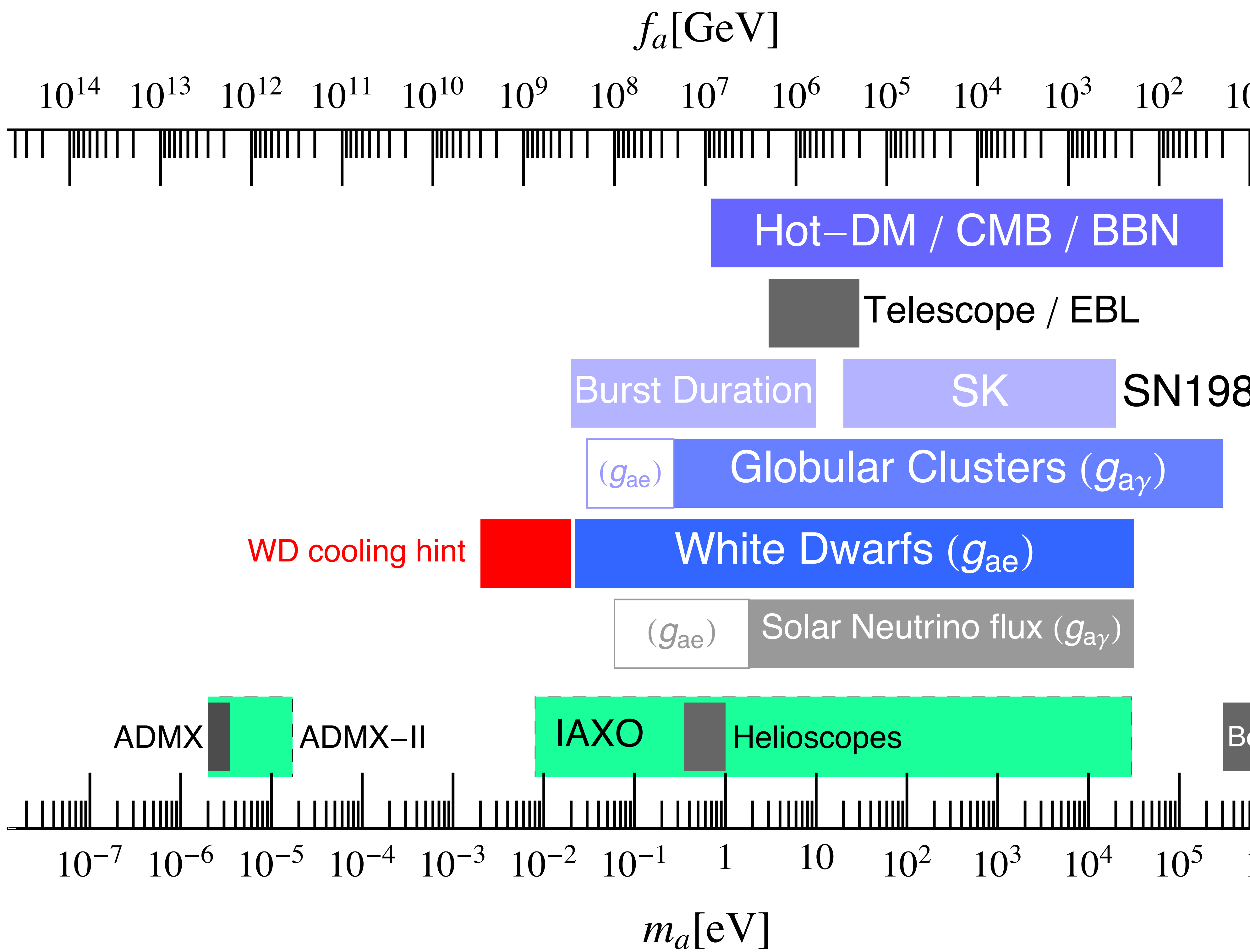


Where we are

Hewett et al. arXiv:1205.2671



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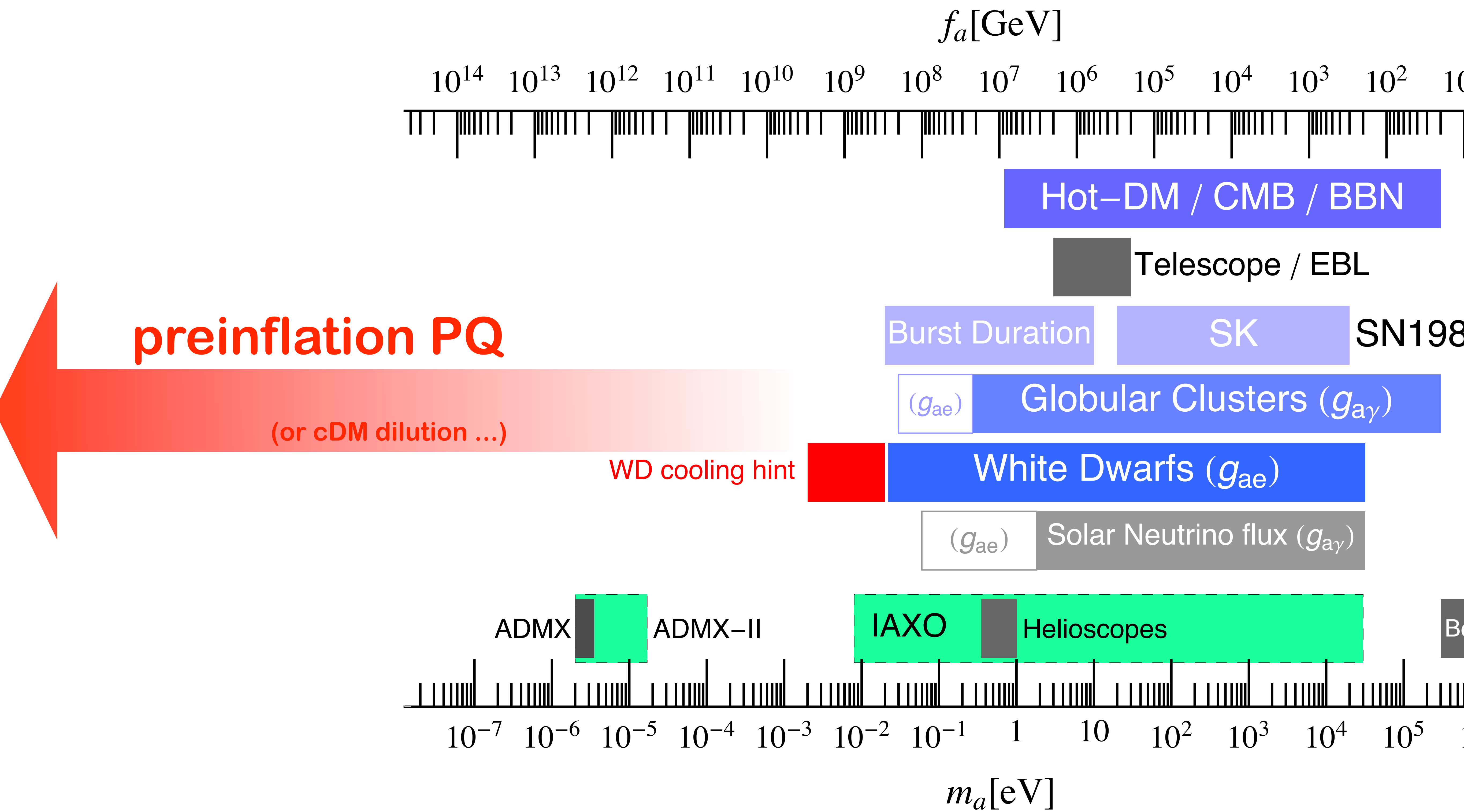

Tuesday, 27, November,2012

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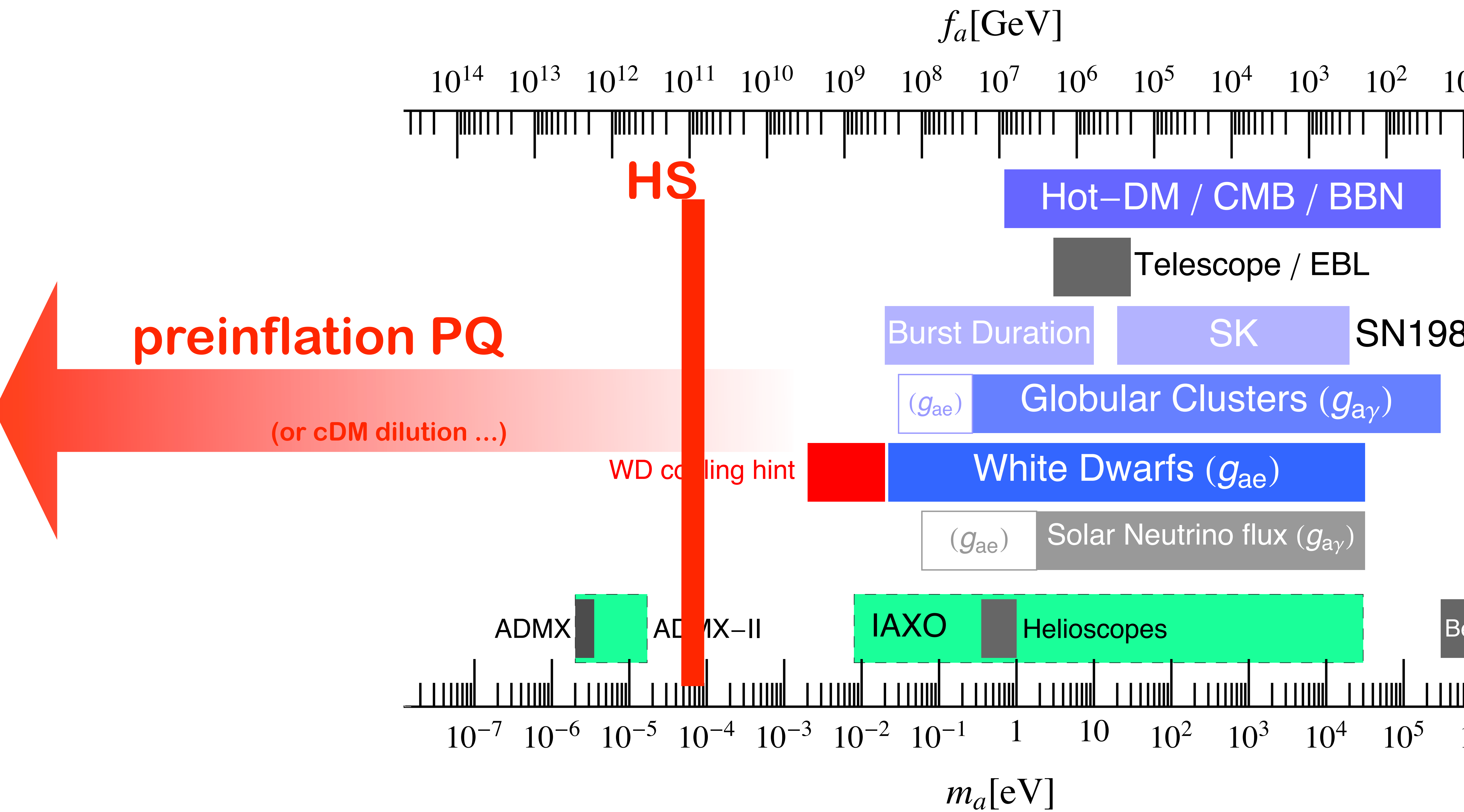

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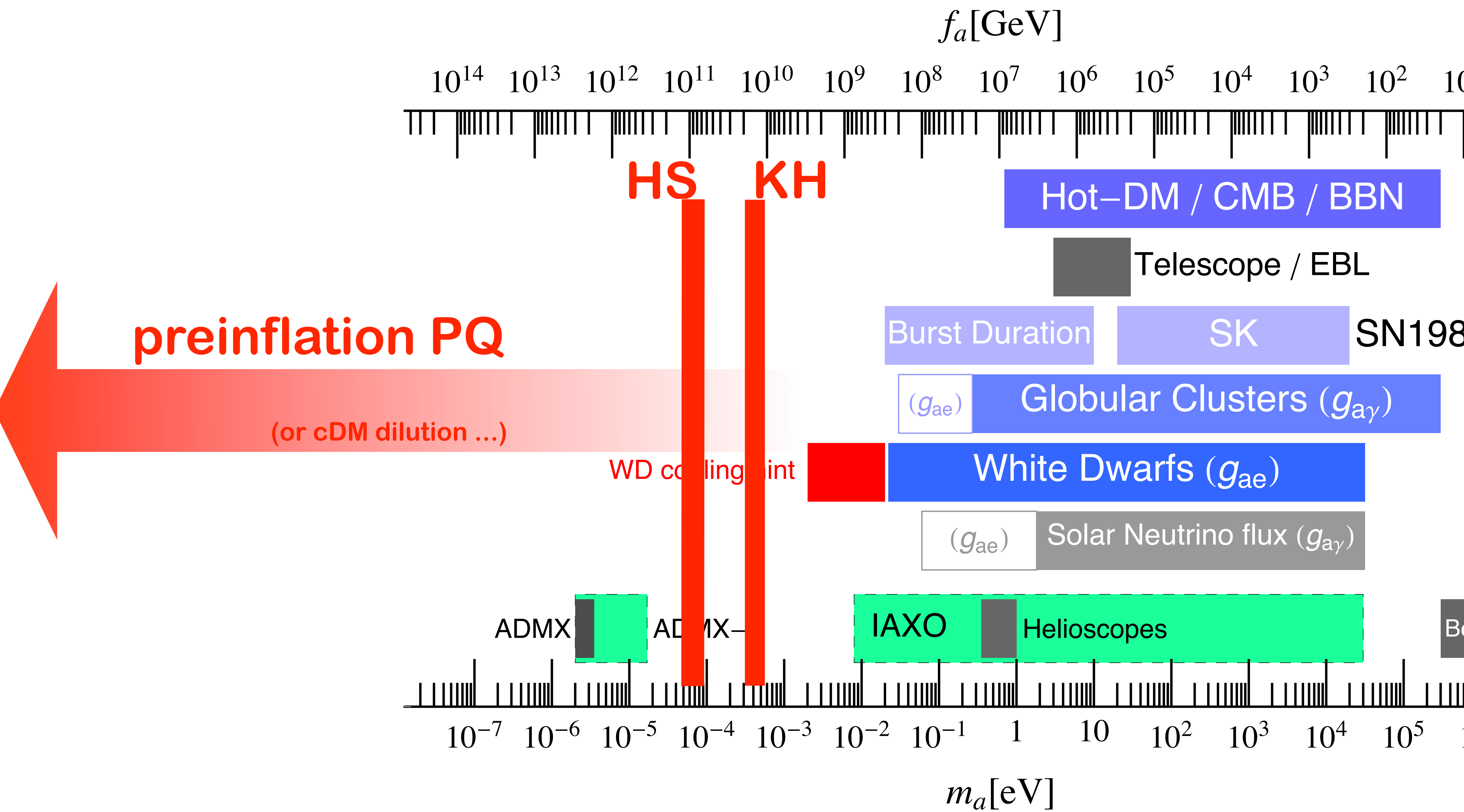

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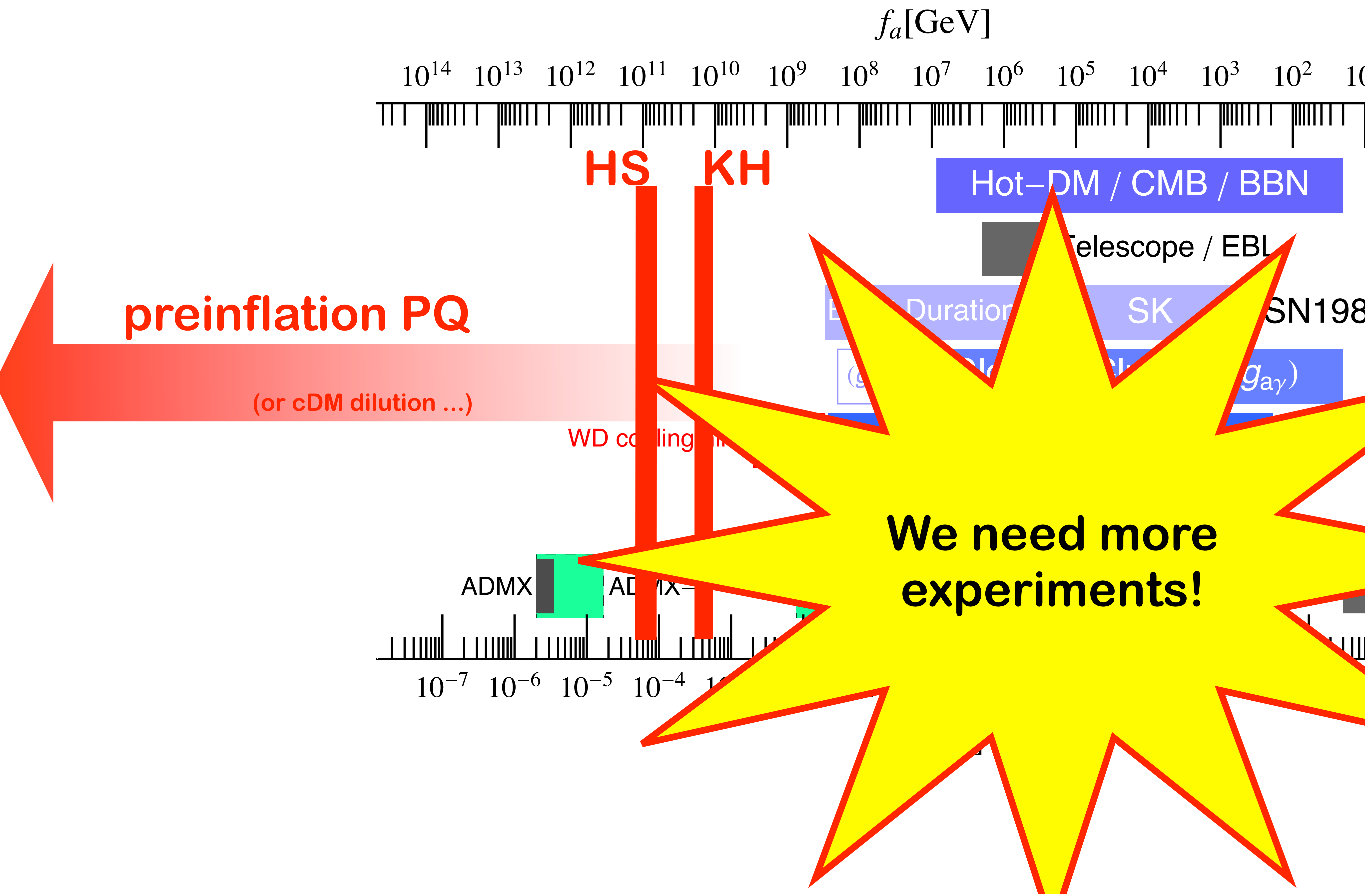
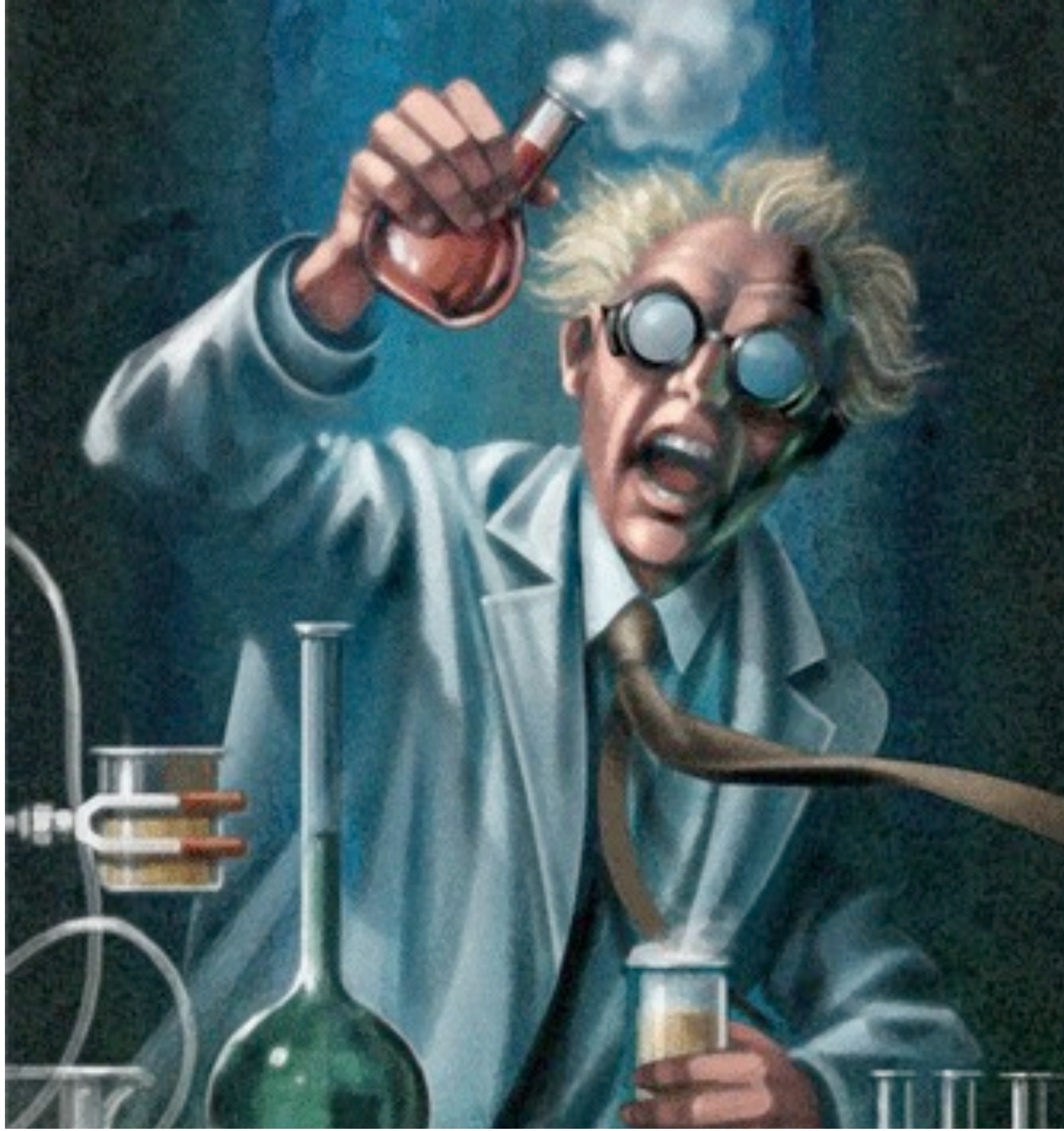


Laboratory



Experimental searches for Axion Cold Dark Matter

How do you search for particles whose interactions are suppressed by $f_a > 10^9 \mathrm{GeV}$?

Experimental searches for Axion Cold Dark Matter

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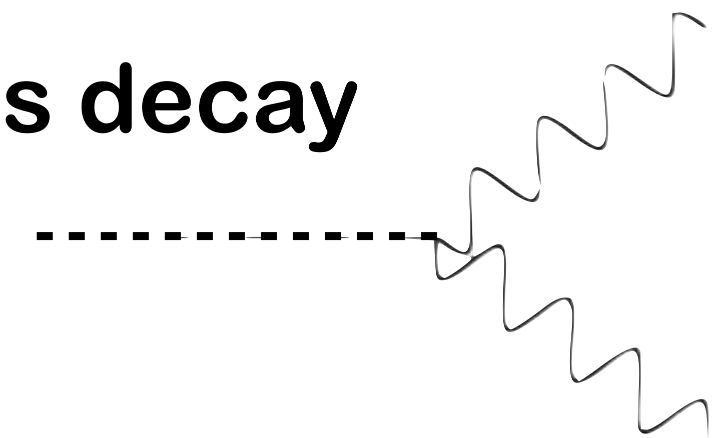
Axions decay



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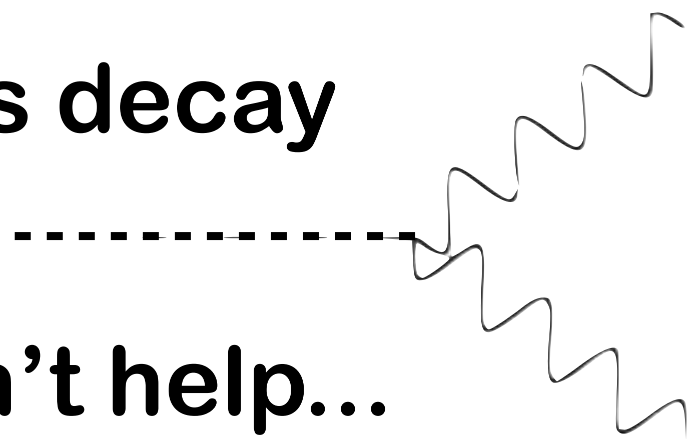

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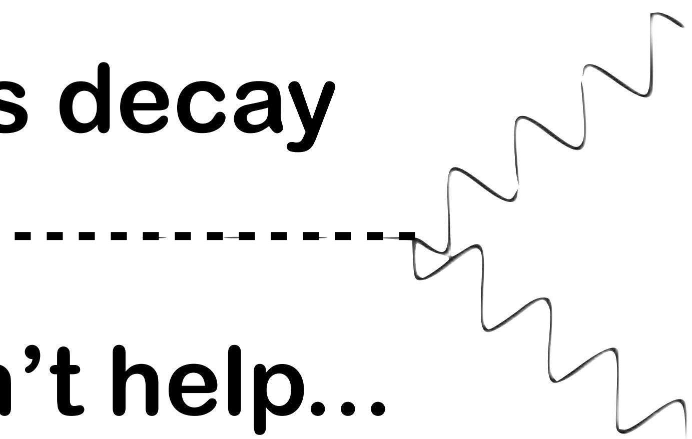

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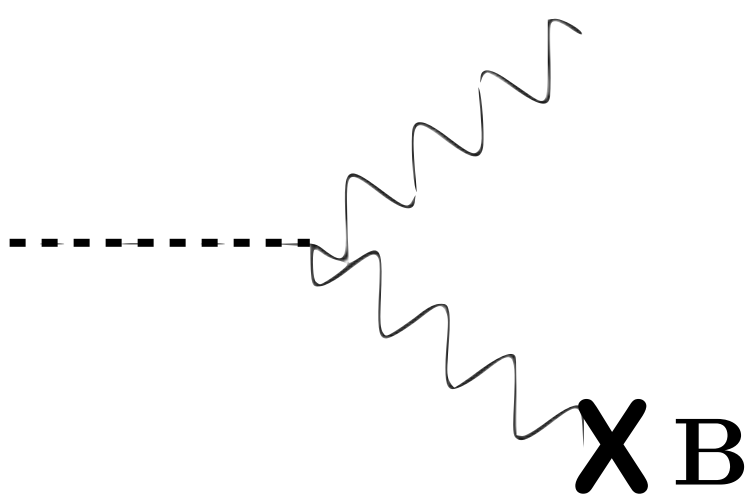
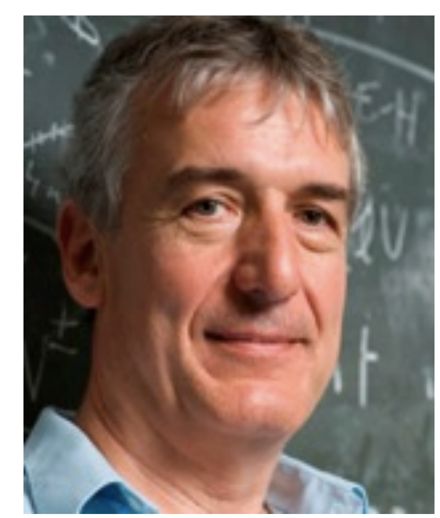
Experimental Tests of the Invisible Axion

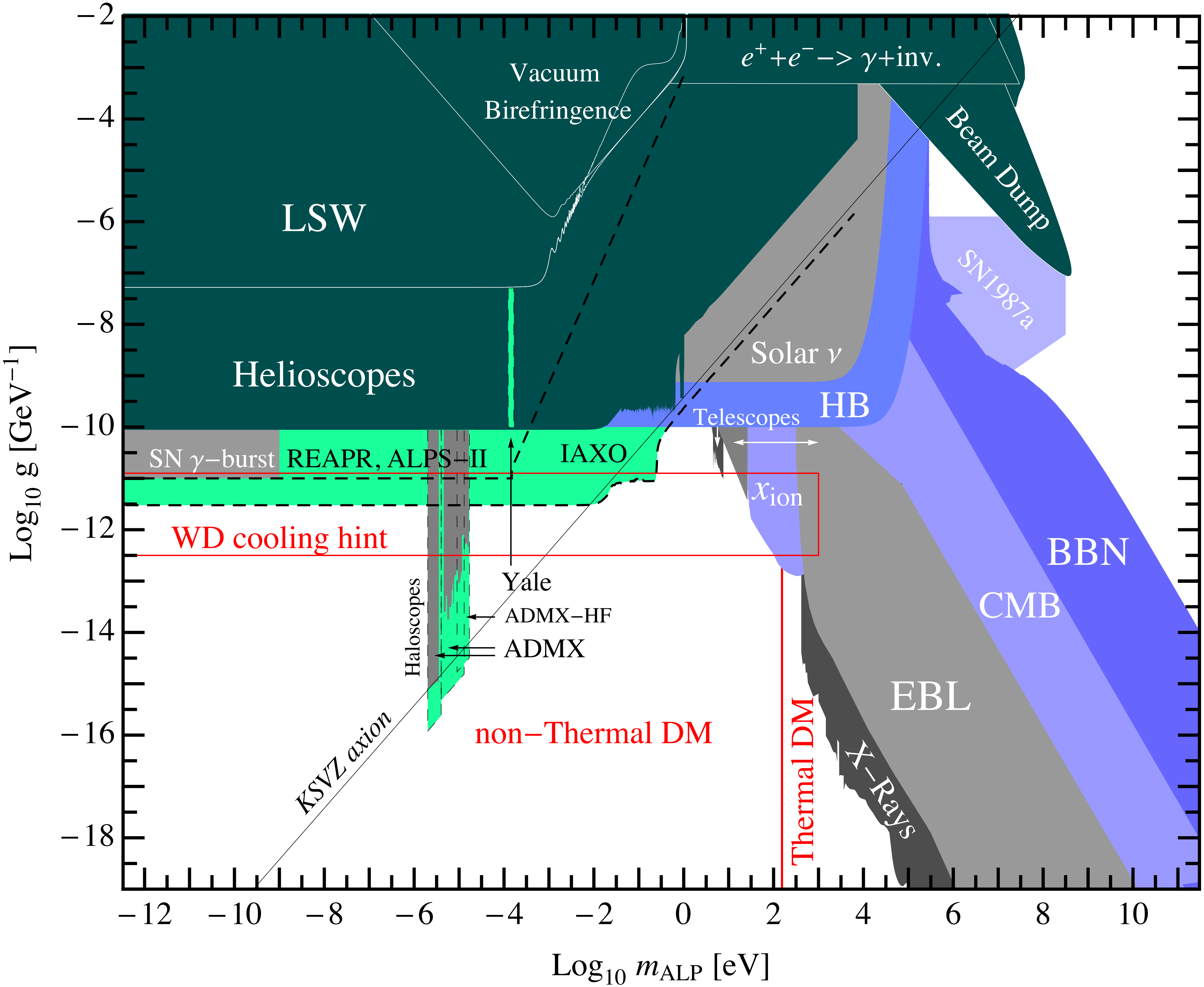
Phys.Rev.Lett. 51 (1983) 1415



Axion-Photon coherent conversion in macroscopic magnetic fields !!



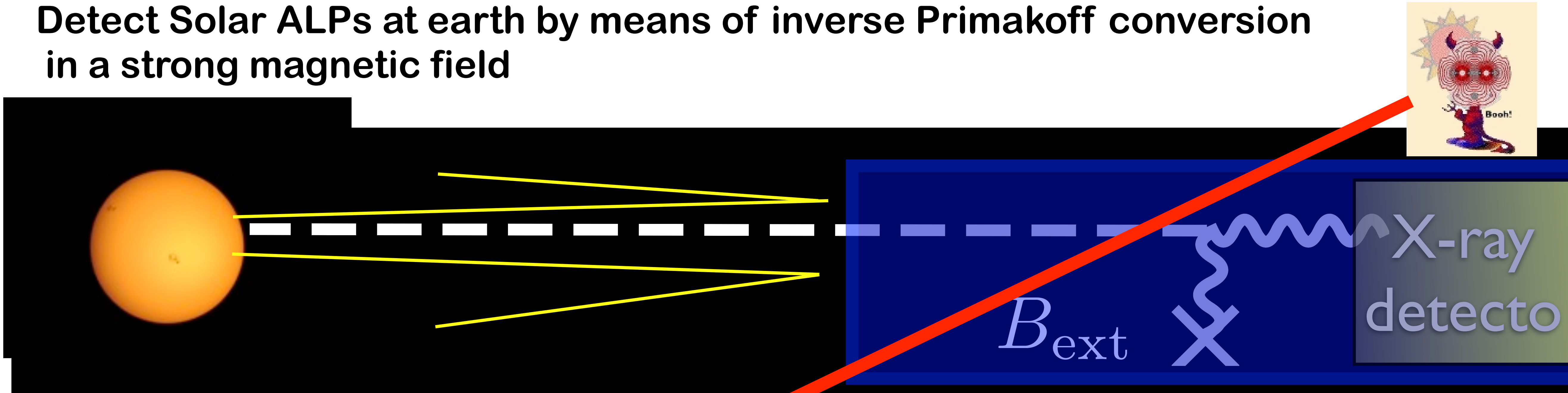
P. Sikivie

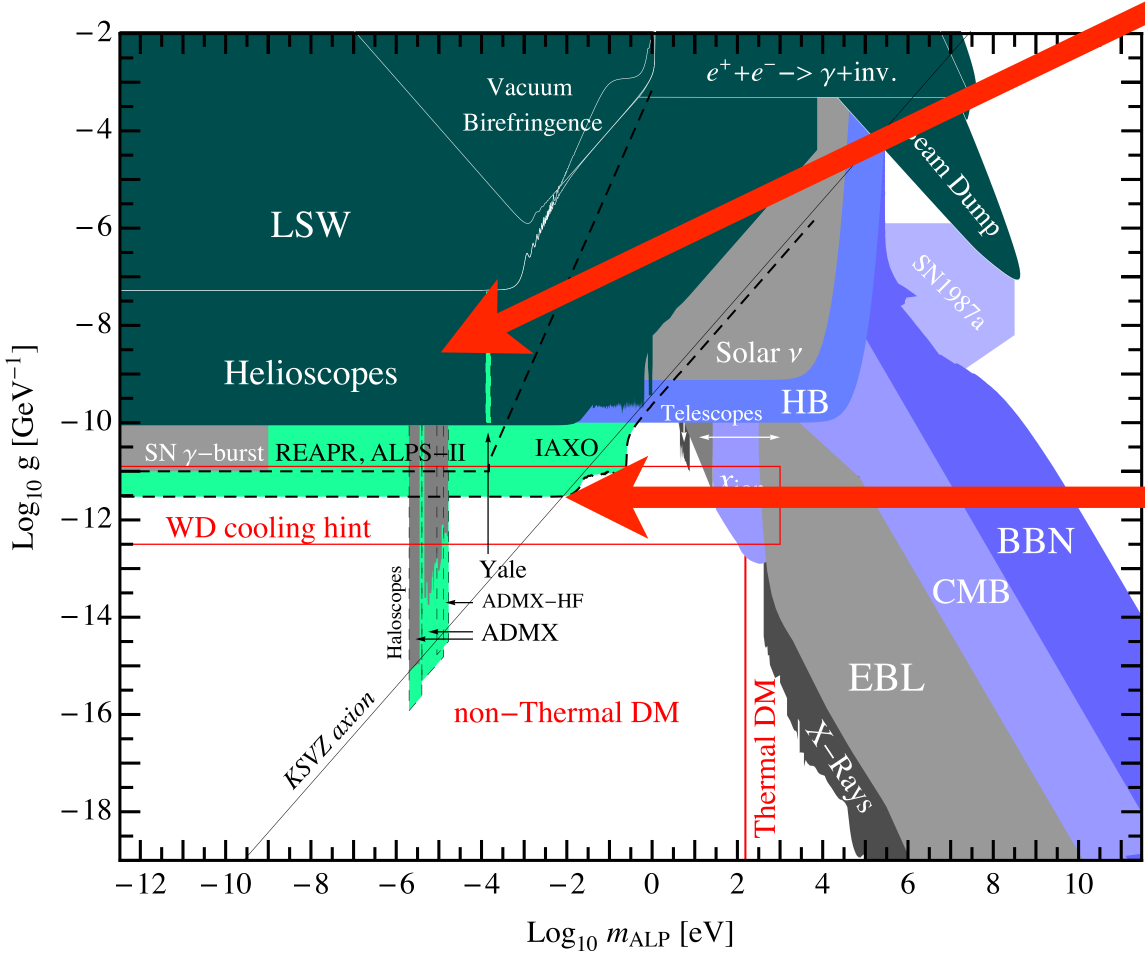


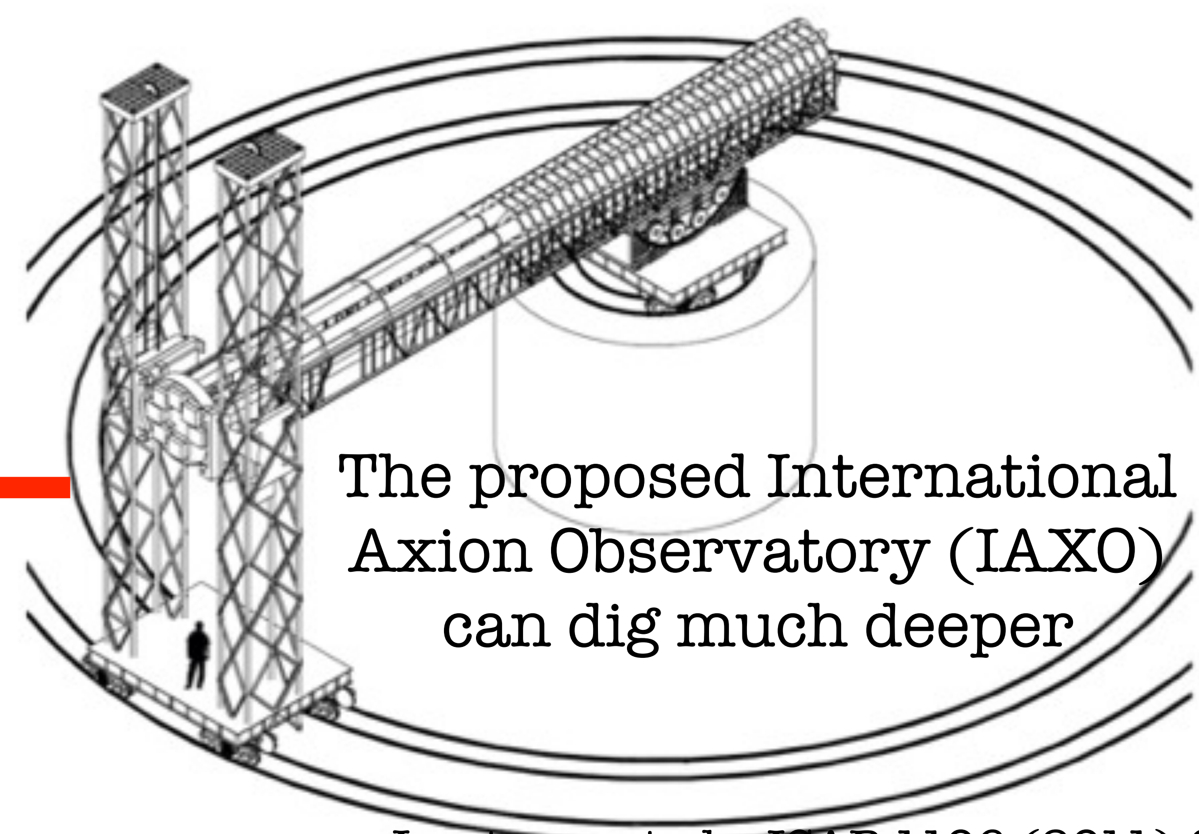
LSW
Vacuum Birefringence
$e^+ + e^- -> \gamma$+inv.
Beam Dump
Helioscopes
SN1987a
Solar ν
HB
Telescopes
SN γ−burst
REAPR, ALPS−II
IAXO
x_{ion}
WD cooling hint
Yale
ADMX−HF
ADMX
Haloscopes
BBN
CMB
EBL
non−Thermal DM
Thermal DM
X−Rays
KSVZ axion
$\mathrm{Log}_{10}\, g\ [\mathrm{GeV}^{-1}]$
$\mathrm{Log}_{10}\, m_{ALP}$ [eV]

HELIOSCOPES

Detect Solar ALPs at earth by means of inverse Primakoff conversion in a strong magnetic field





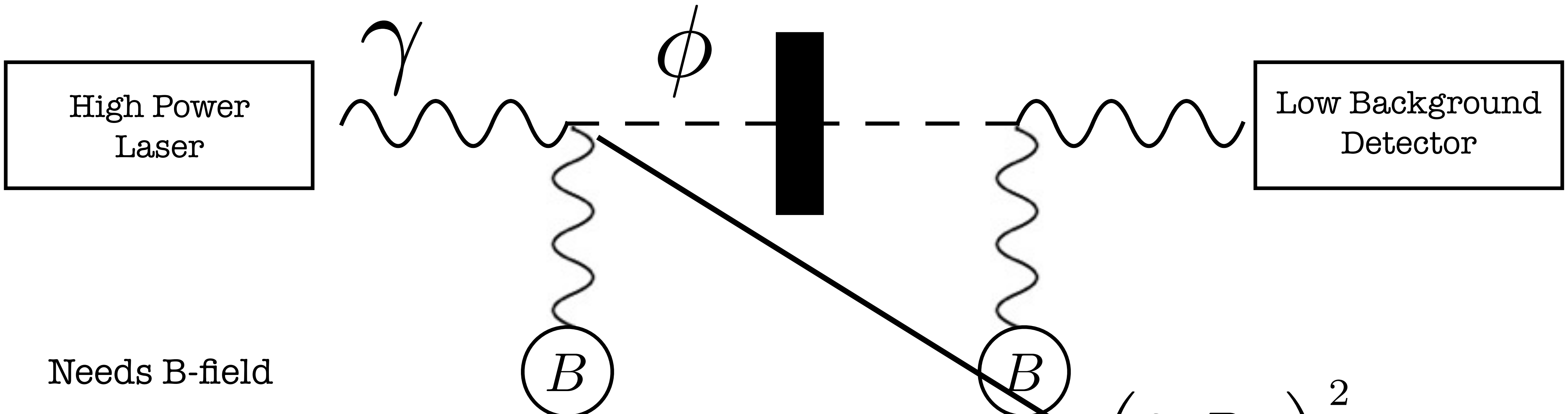


The proposed International Axion Observatory (IAXO) can dig much deeper

Irastorza et al. JCAP 1106 (2011) 013

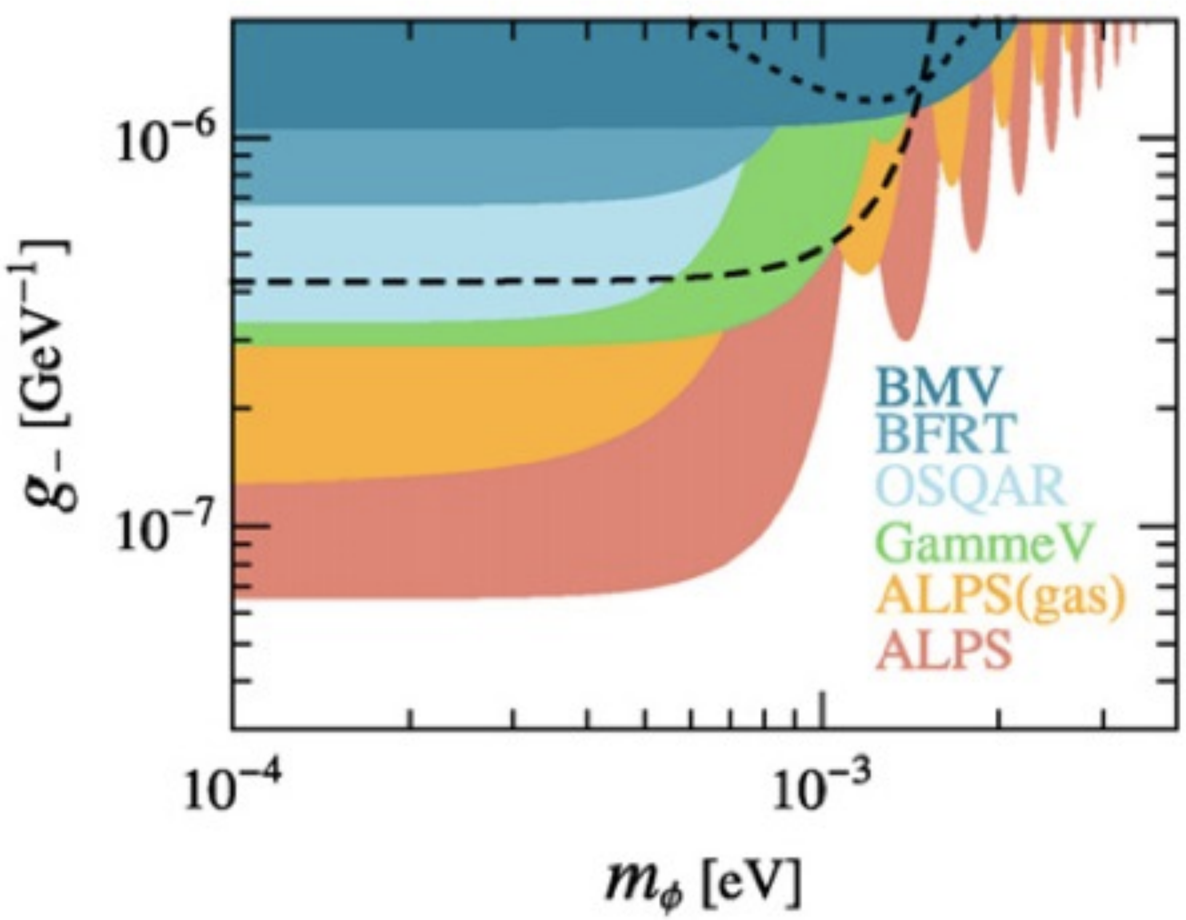
Laboratory Experiments

Laser shining through walls (LSW)



Needs B-field

$$P(\gamma \to \phi) = \left(\frac{2gB\omega}{m_\phi^2}\right)^2 \times \sin^2 \frac{m_\phi^2 L}{4\omega}$$



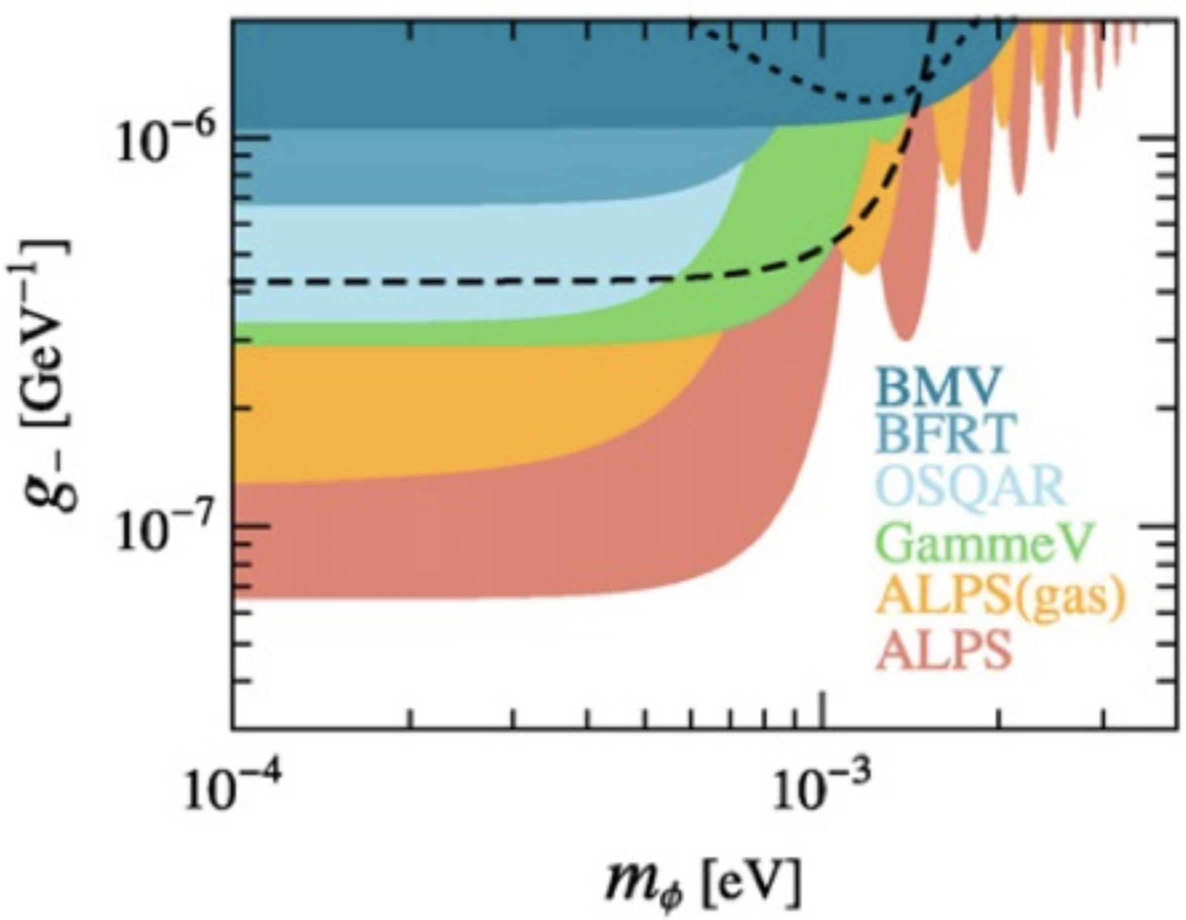
Ehret et al. 2010

Laboratory Experiments

Higl
L

Need

$$P(\gamma \to \phi) = \left(\frac{2gB\omega}{m_\phi^2}\right) \times \sin^2 \frac{m_\phi^2 L}{4\omega}$$



ALPS DESY

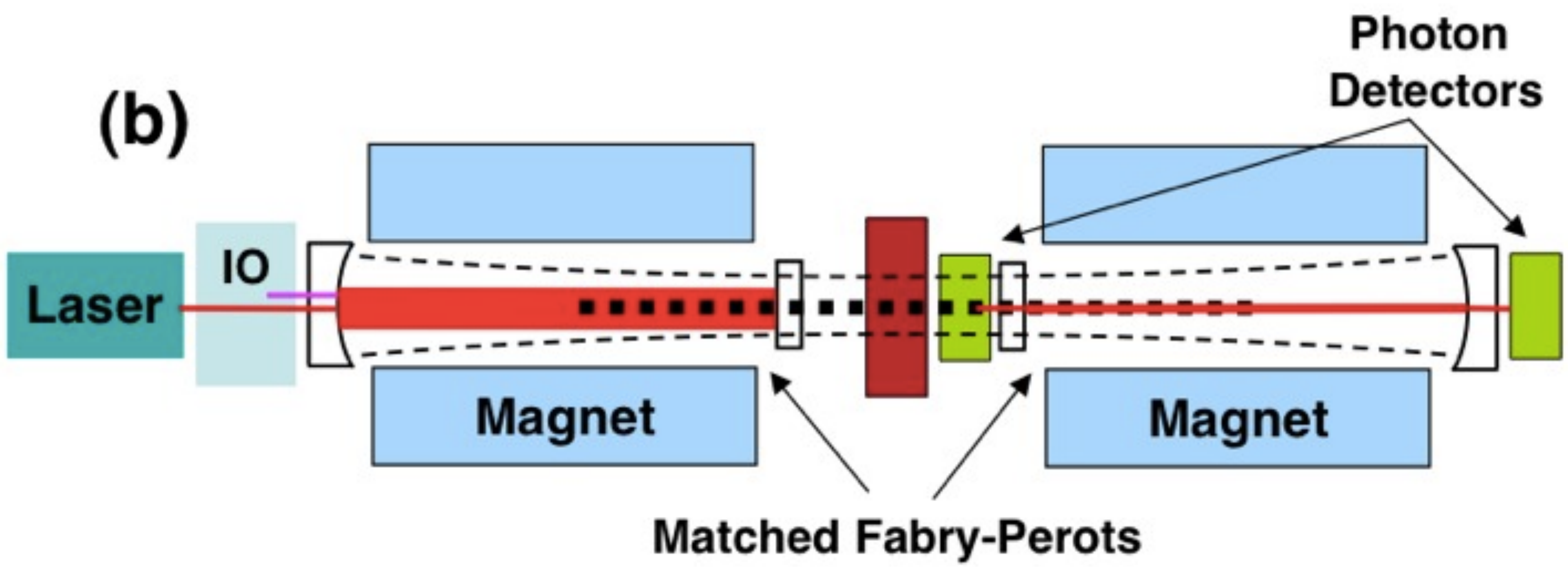
Ehret et al. 2010

Next Generation of LSW

Hoogeveen 91, Sikivie 2009

Much longer experiments + 2nd resonant cavity

$O(100\ \mathrm{m})$ $Q \sim 10^5$

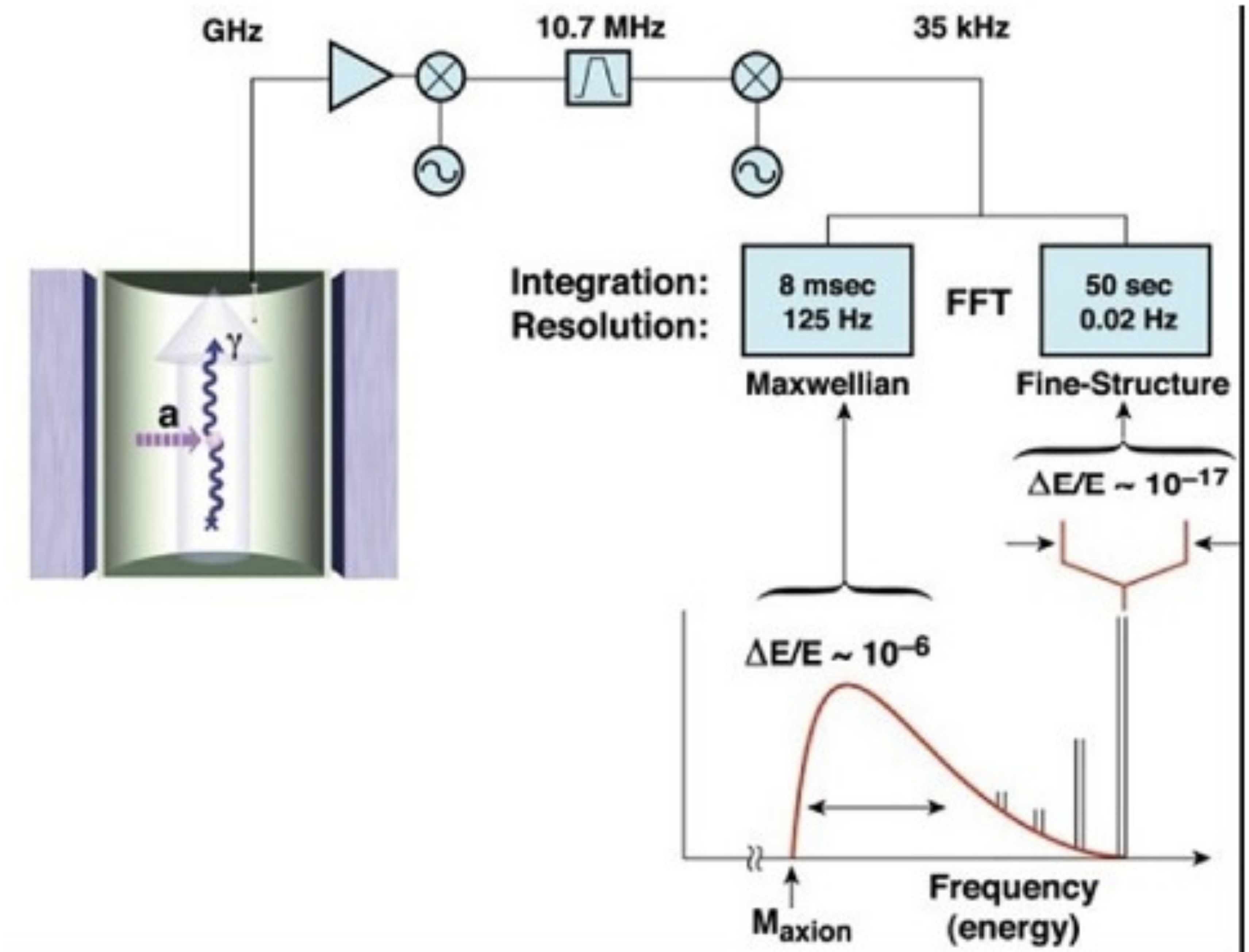


Two competing groups:
ALPS II @ DESY vs. Fermilab

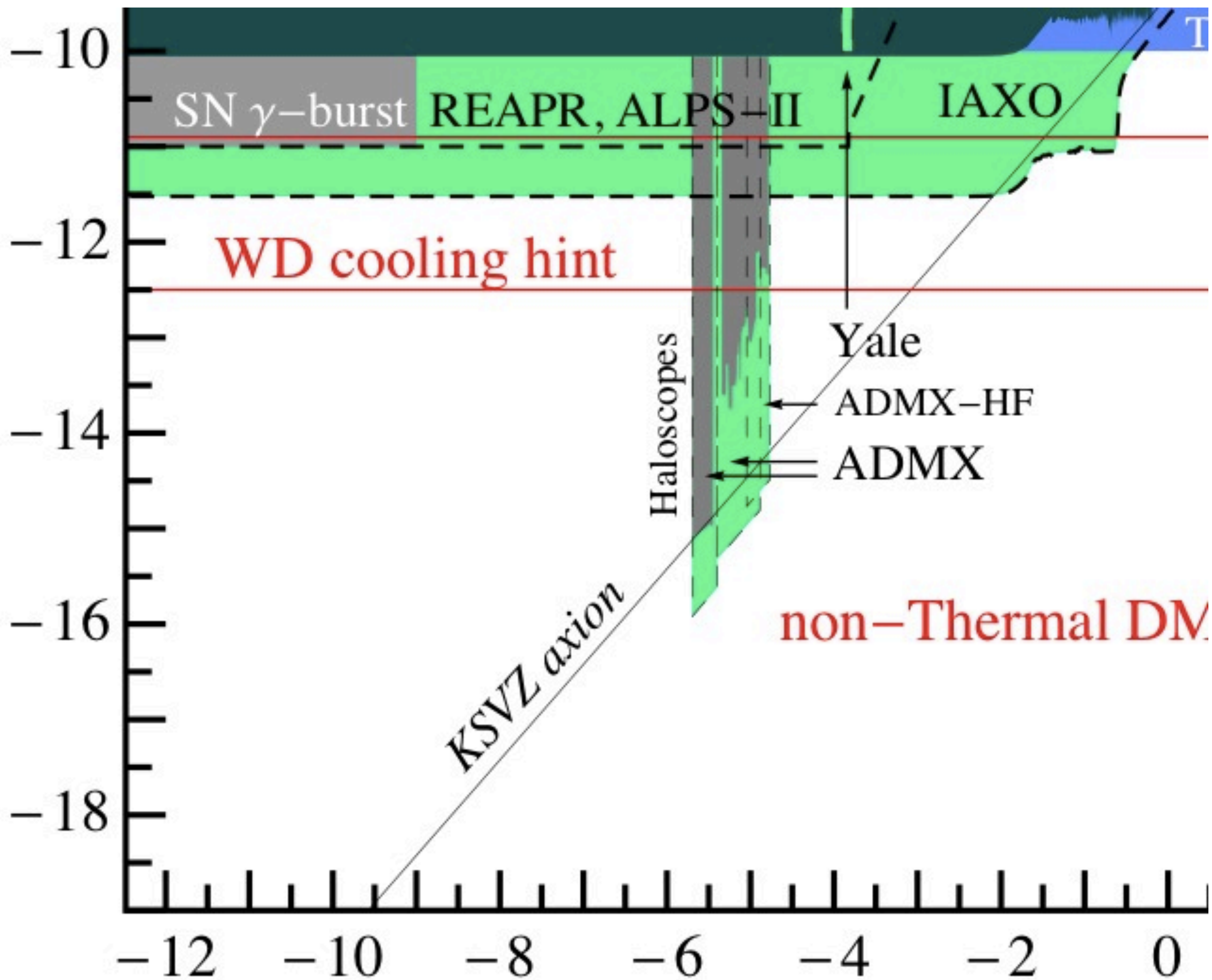
Cavity experiments (Haloscopes)

Axions excite electromagnetic waves in a cavity

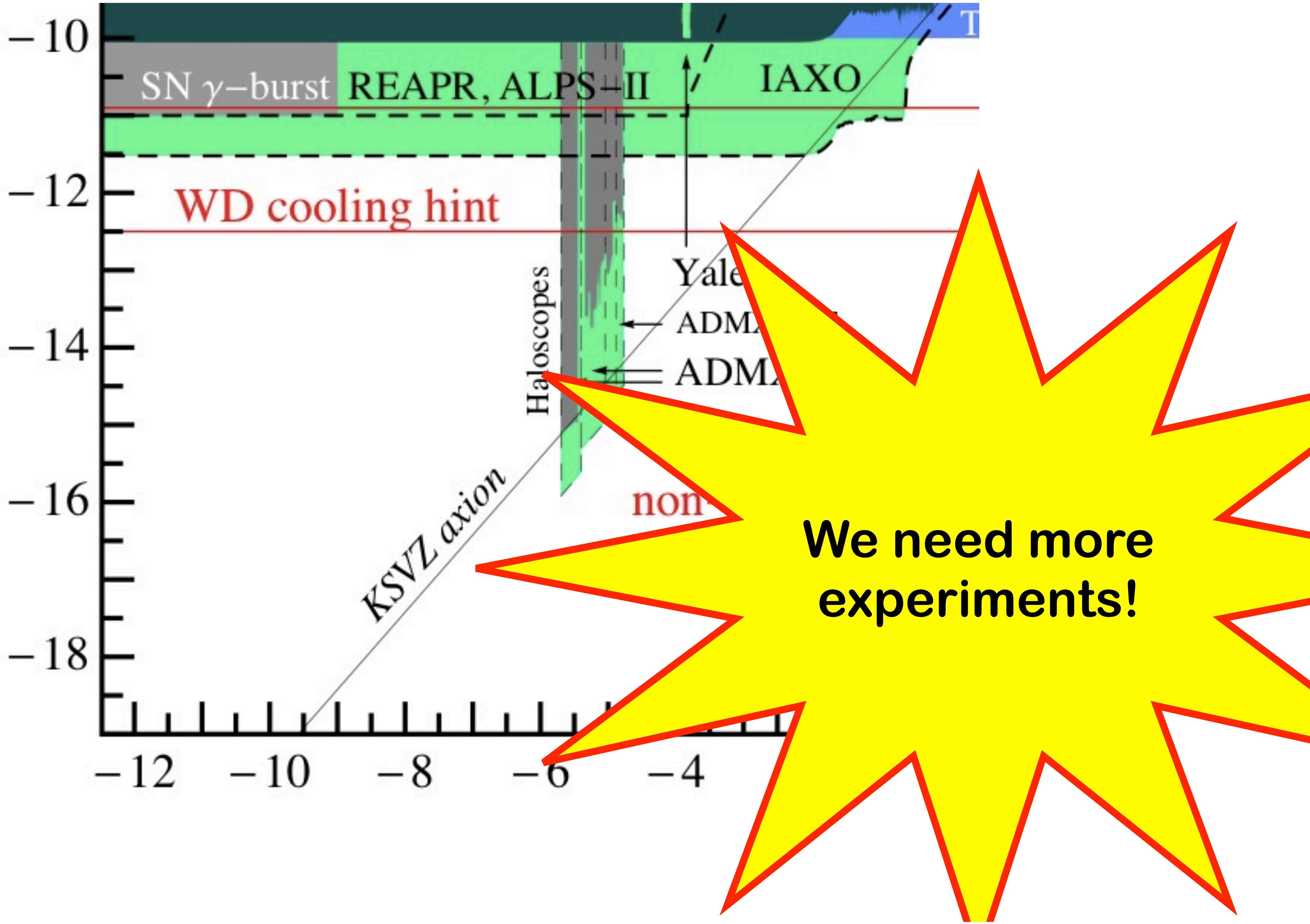
$$\omega \sim m_a$$



Cavity experiments (Haloscopes)



Cavity experiments (Haloscopes)



Conclusions

- Invite me again to know more about experiments

- Dynamical mechanism to solve Strong CP implies

  detectable cold Dark Matter axions

- Different cosmologies/uncertainties

  large range of masses to scan

- Powerful but insufficient ongoing experiments

  many more are to come!

The End

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27 Nov 2012, Invisible seminar