ALP cold dark matter

Javier Redondo (LMU & MPP München)

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LMU
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
ARNOLD SOMMERFELD CENTER FOR THEORETICAL PHYSICS
MAX-PLANCK-GESELLSCHAFT

Outline

- Strong CP problem and axions

- axion-like particles BSM

- Axion (WISPy) cold dark matter

- axion - photon mixing

- radiation from a magnetised mirror

- cavity experiments

- dish antennas

The Strong CP problem

- Topological term in QCD cannot be neglected (‘t Hooft) (explains eta’ mass)

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

Violates P and T (and thus CP, since CPT is conserved)

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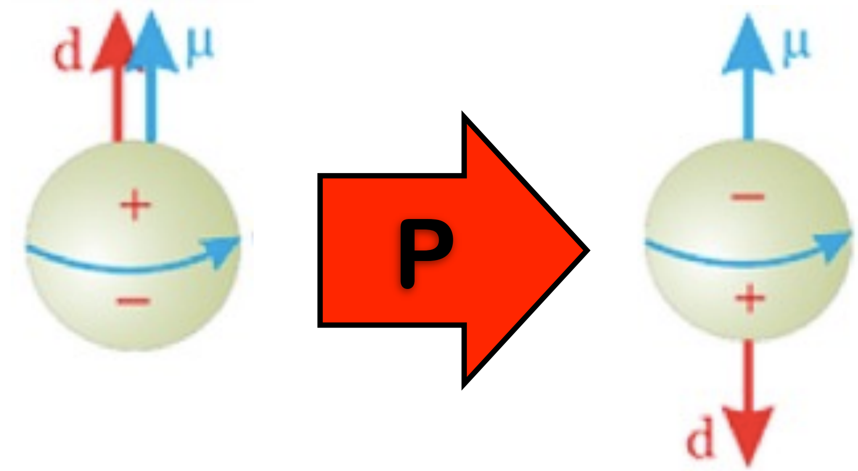

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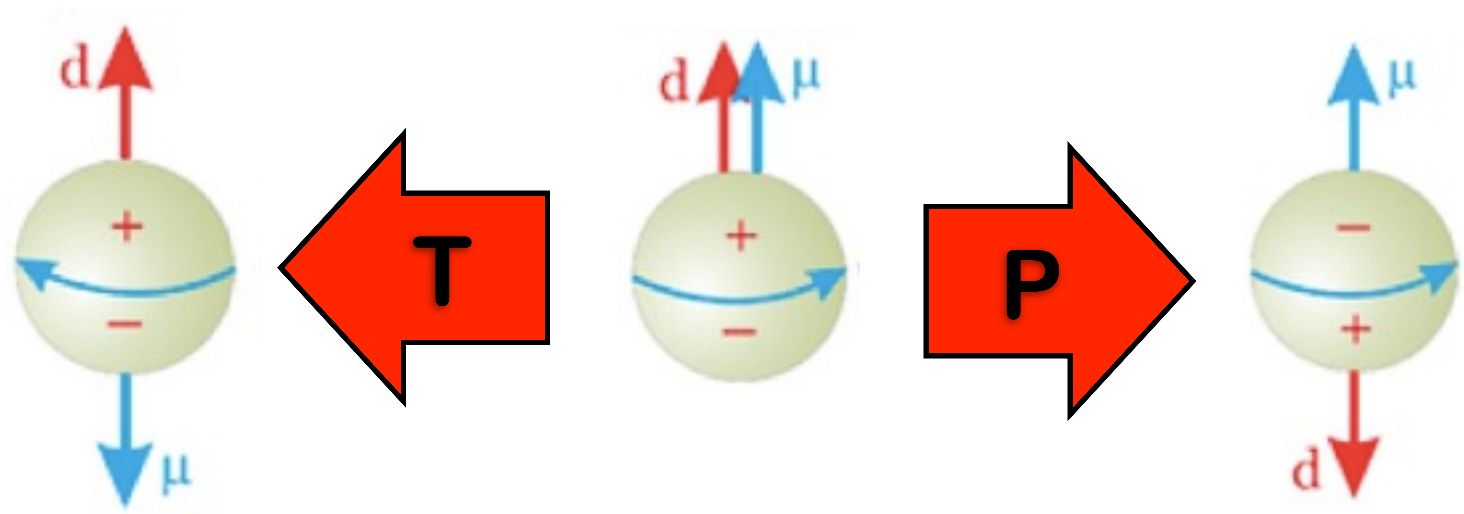

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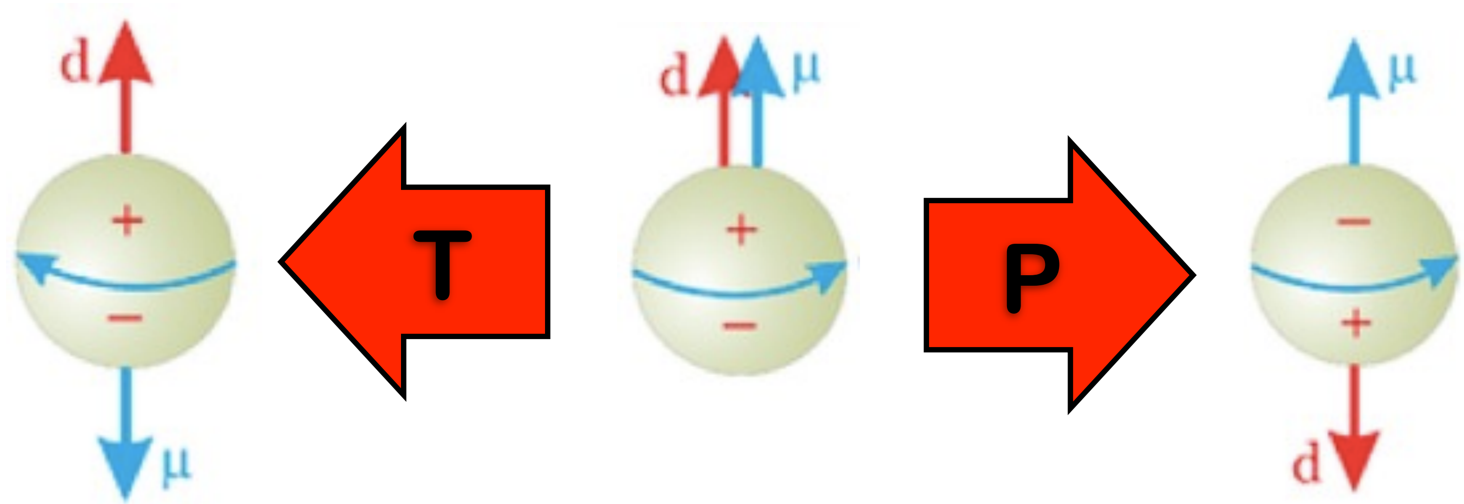

Prediction is $d_n \sim 10^{-15} \theta\, \mathrm{ecm}$ **but ... Experiments do not find it**

Experimental limit

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

$\theta \lesssim 10^{-11}$

Why ?????

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

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Axions!

Quinn, PRL'77
Weinberg PRL '78
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took two nobel prizes to realize that this implies a NEW PARTICLE

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(Energy scale at which the U(1) is spontaneously broken)

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$$f_a$$

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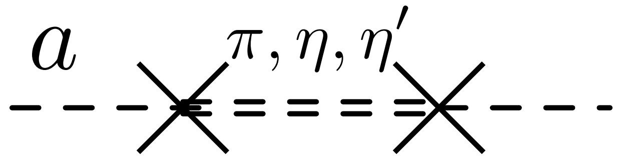
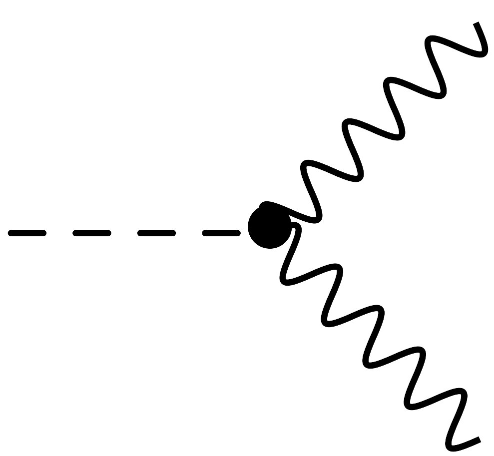


$$m_a \simeq 6\,\mathrm{meV}\,\frac{10^9\,\mathrm{GeV}}{f_a}$$



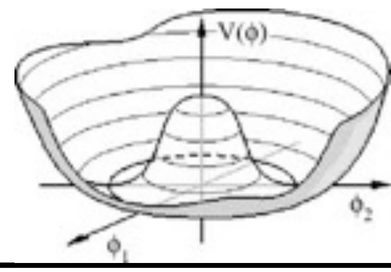
$$\frac{\alpha}{8\pi}(F_{\mu\nu}\widetilde{F}^{\mu\nu})c_{a\gamma\gamma}\frac{a}{f_a}$$

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

0^-

pseudo Goldstone bosons

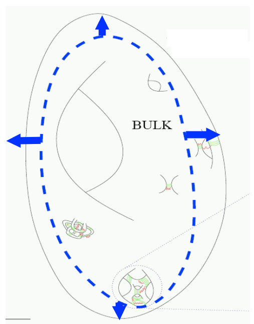
Global continuous symmetry spontaneously broken at high energy scale M



$\pi^0\ \eta'\ \eta\ a$ **MAJORONS** **R-AXION** **FAMILONS**

String 'axions'

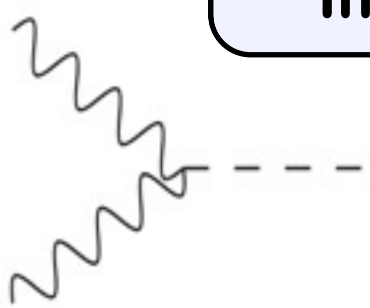
Sizes and deformations of extra dimensions, gauge couplings



DILATONS **RADION** **MODULI**

String Axiverse!
O(100) candidates!

Important remark!



$g \sim \alpha/2\pi M$? $\text{mass}\, m_\phi$

but QCD axions... $m_a \simeq 6\,\text{meV}\frac{10^9\,\text{GeV}}{f_a}$

Axion-like particles (ALPs) BSM 0^-

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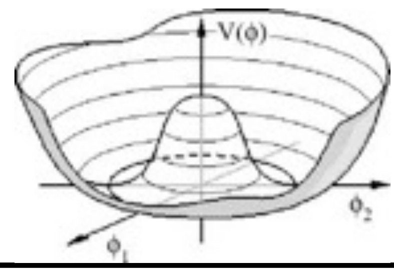

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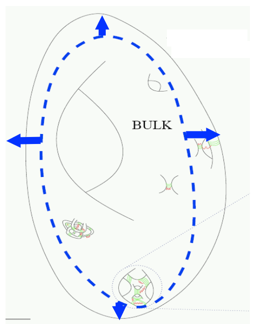

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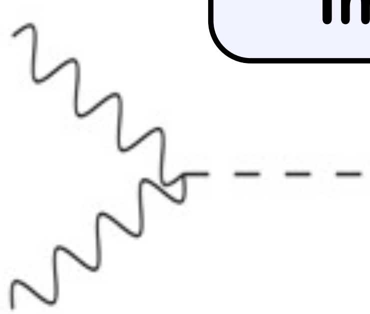

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Axion cold dark matter

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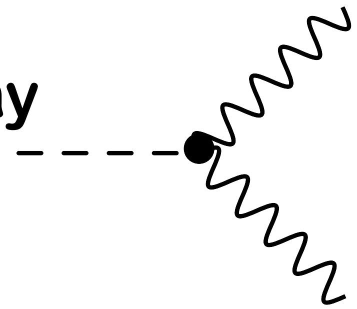
- **Axions decay**



$$\tau \sim \frac{1}{g_{a\gamma}^2 m_a^3} \propto \frac{1}{m_a^5}$$

only low mass axions can be DM!

Axion cold dark matter

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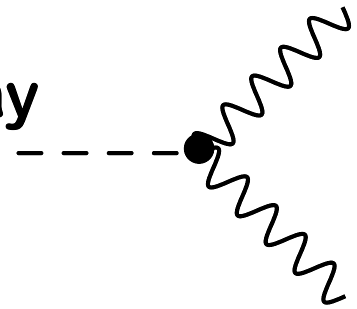

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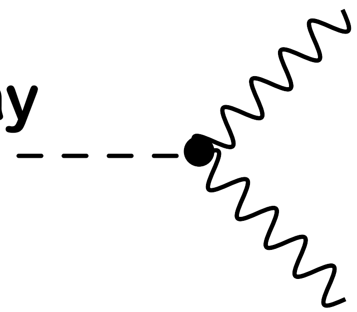

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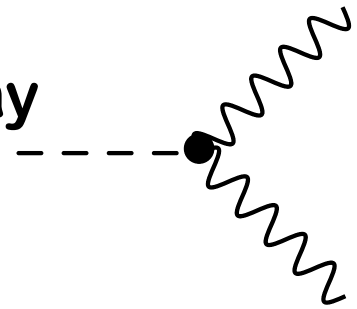
- Axions decay  $\tau \sim \frac{1}{g_{a\gamma}^2 m_a^3} \propto \frac{1}{m_a^5}$ **only low mass axions can be DM!**

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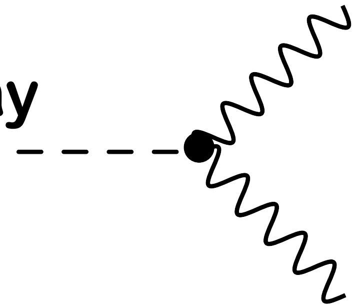

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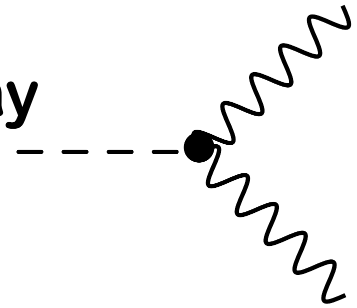
- Axions decay  $$\tau \sim \frac{1}{g_{a\gamma}^2 m_a^3} \propto \frac{1}{m_a^5}$$ **only low mass axions can be DM!**

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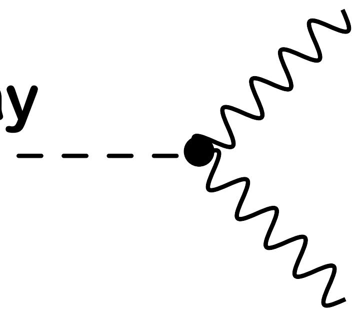
- Axions decay  $$\tau \sim \frac{1}{g_{a\gamma}^2 m_a^3} \propto \frac{1}{m_a^5}$$ **only low mass axions can be DM!**

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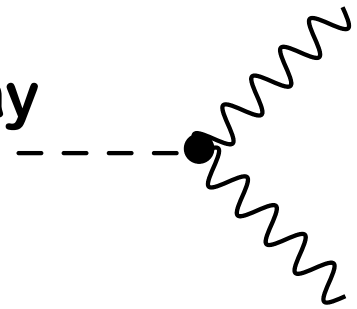
- Axions decay  $$\tau \sim \frac{1}{g_{a\gamma}^2 m_a^3} \propto \frac{1}{m_a^5}$$ only low mass axions can be DM!

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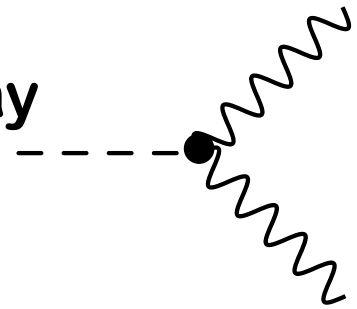

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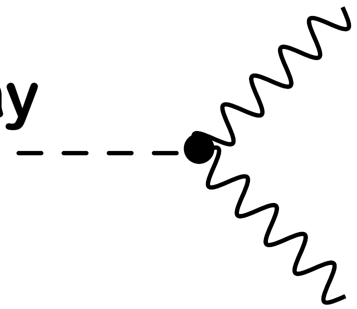
- Axions decay  $\tau \sim \frac{1}{g_{a\gamma}^2 m_a^3} \propto \frac{1}{m_a^5}$ **only low mass axions can be DM!**

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$\cancel{m_a \sim \mathrm{eV}???}$

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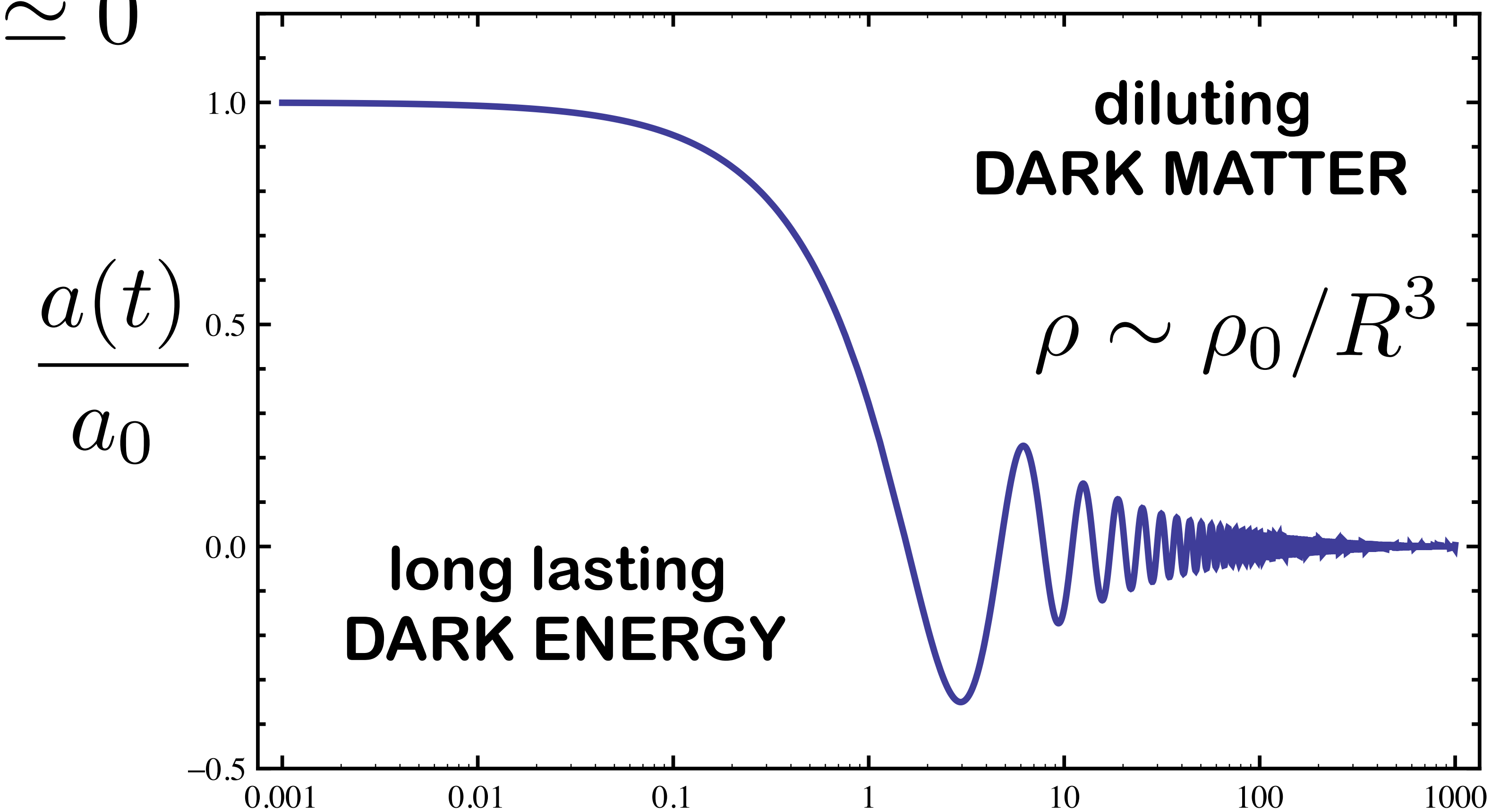
$$\boxed{\frac{a(t_0)}{f_a} \in (-\pi, \pi)}$$

At PQ phase transition

the lonely scalar field evolution

$$\ddot{a} + 3H\dot{a} + (k^2 + V'(a)) \simeq 0$$



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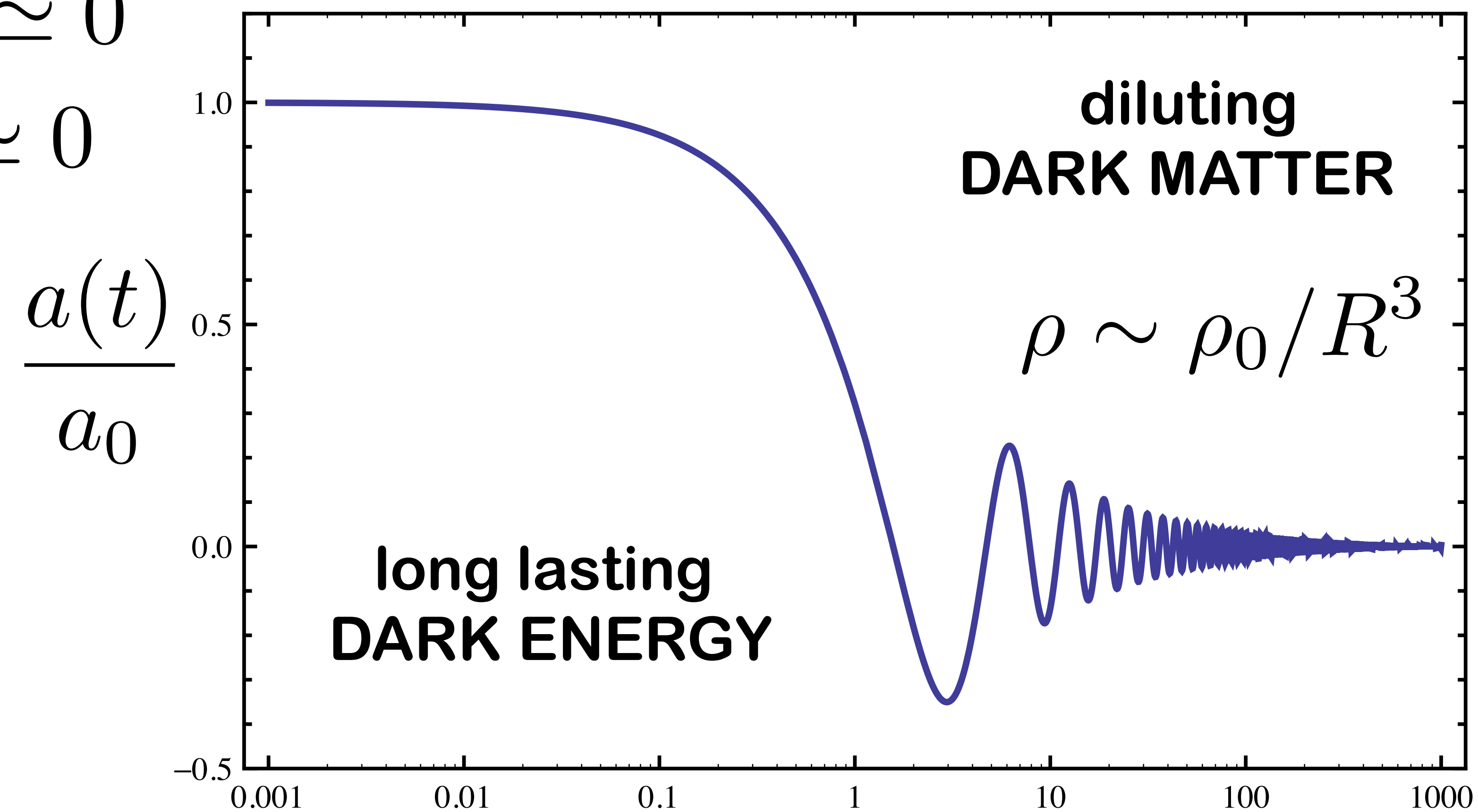
$$\ddot{a} + 3H\dot{a} + (k^2 + m_a^2)a \simeq 0$$



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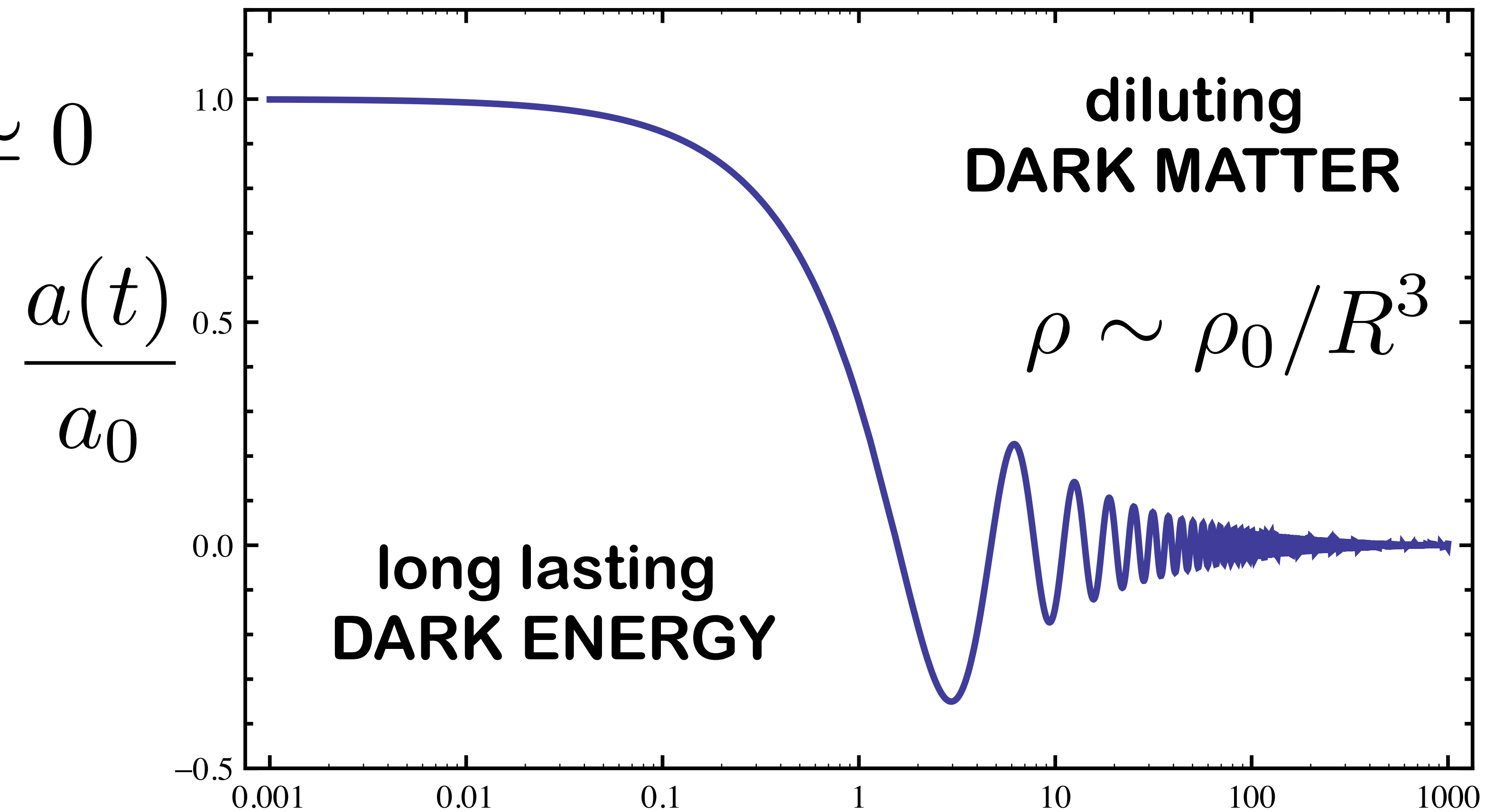

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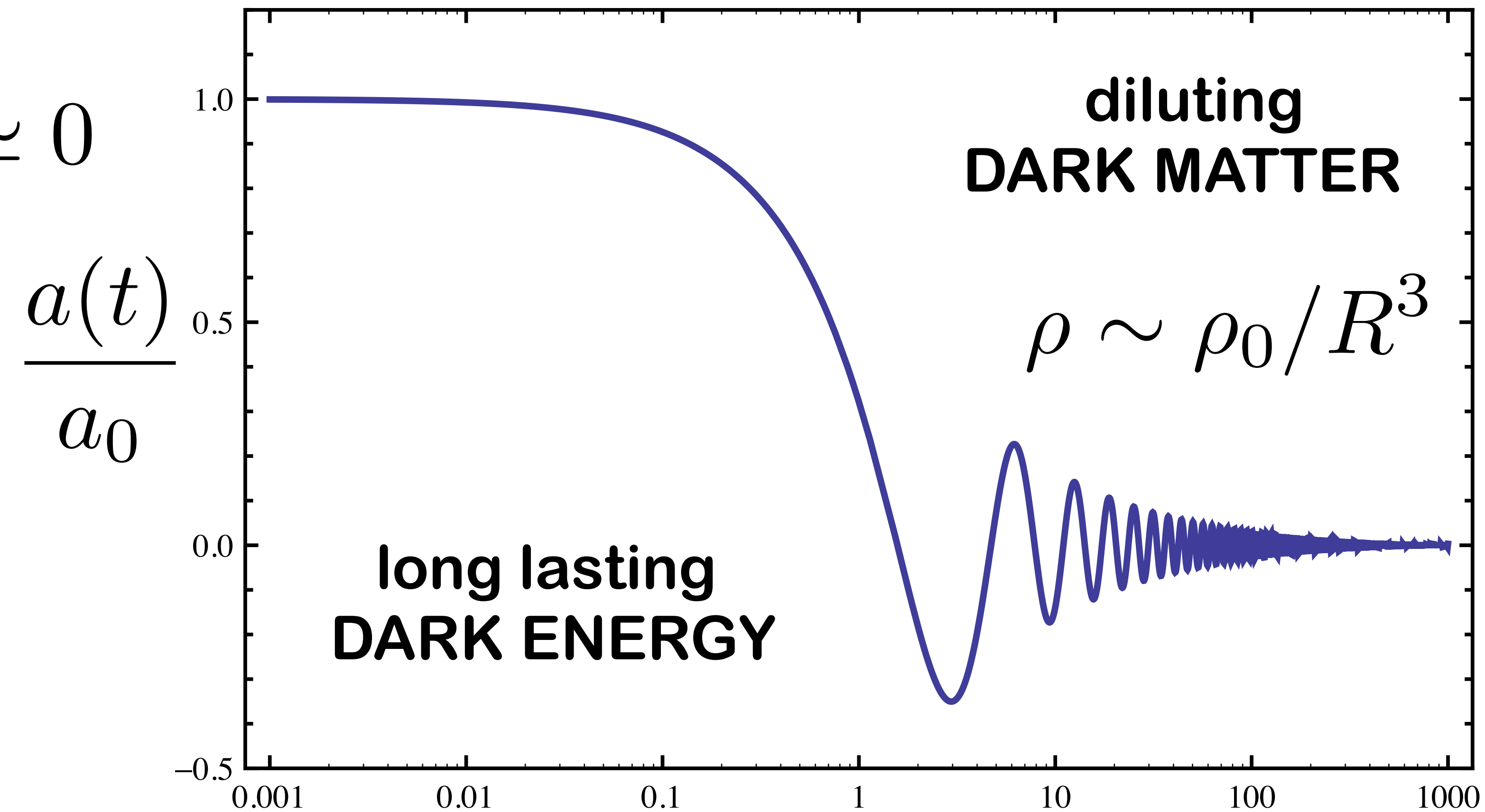

this time is given by

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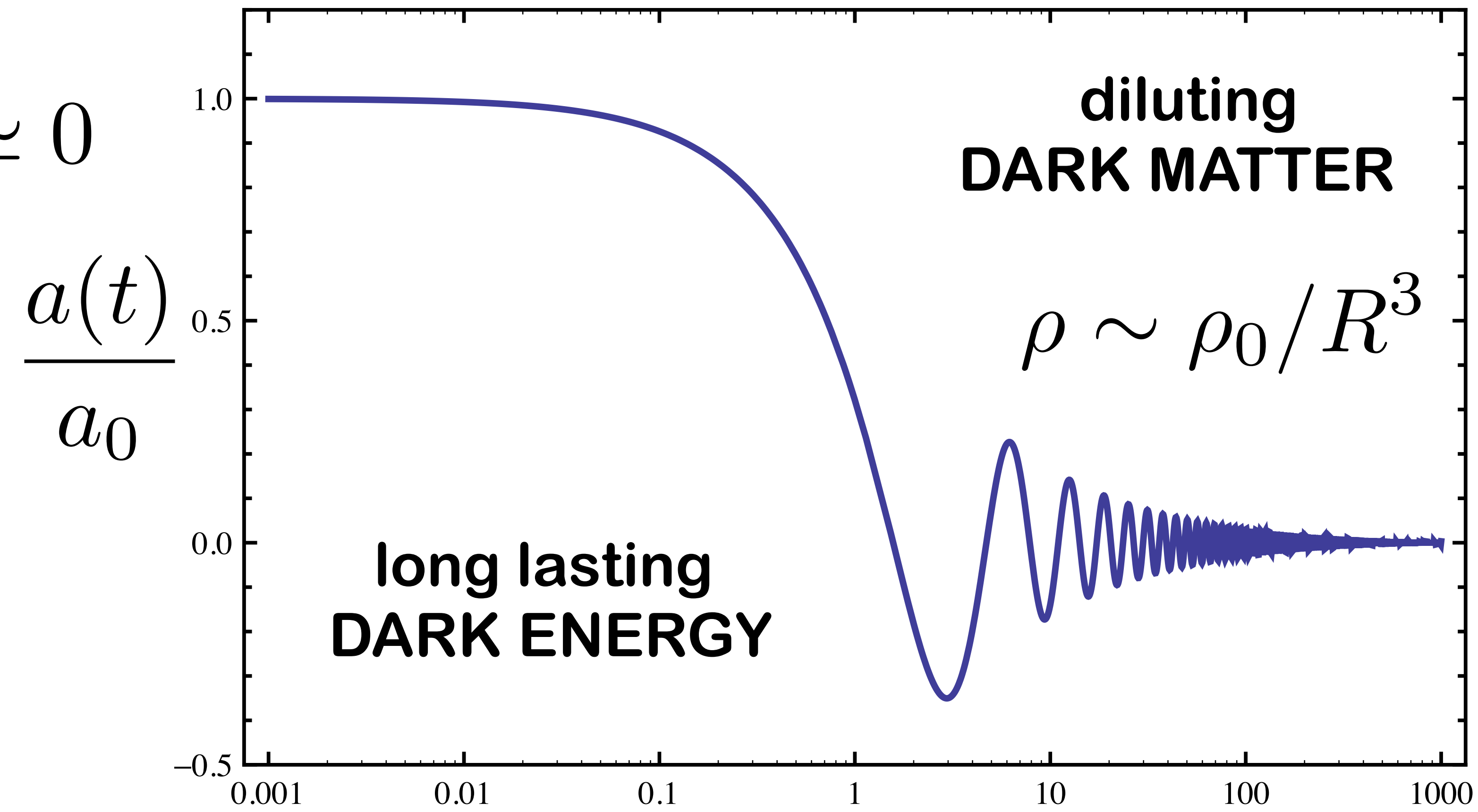

short wavelengths (hotter axions)
start being diluted earlier!
and thus more

this time is given by

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Axion cold Dark Matter

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

Realignment mechanism

(Field space)

Cosmic Strings

(Position space)

Domain Walls

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

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

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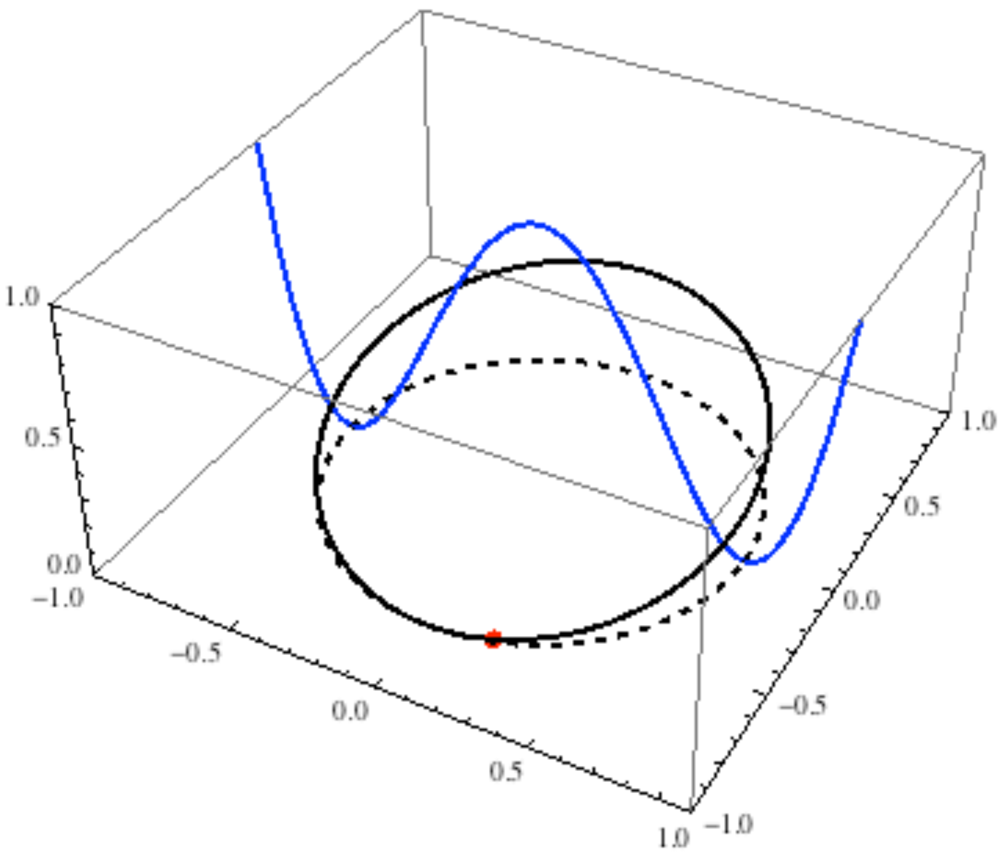

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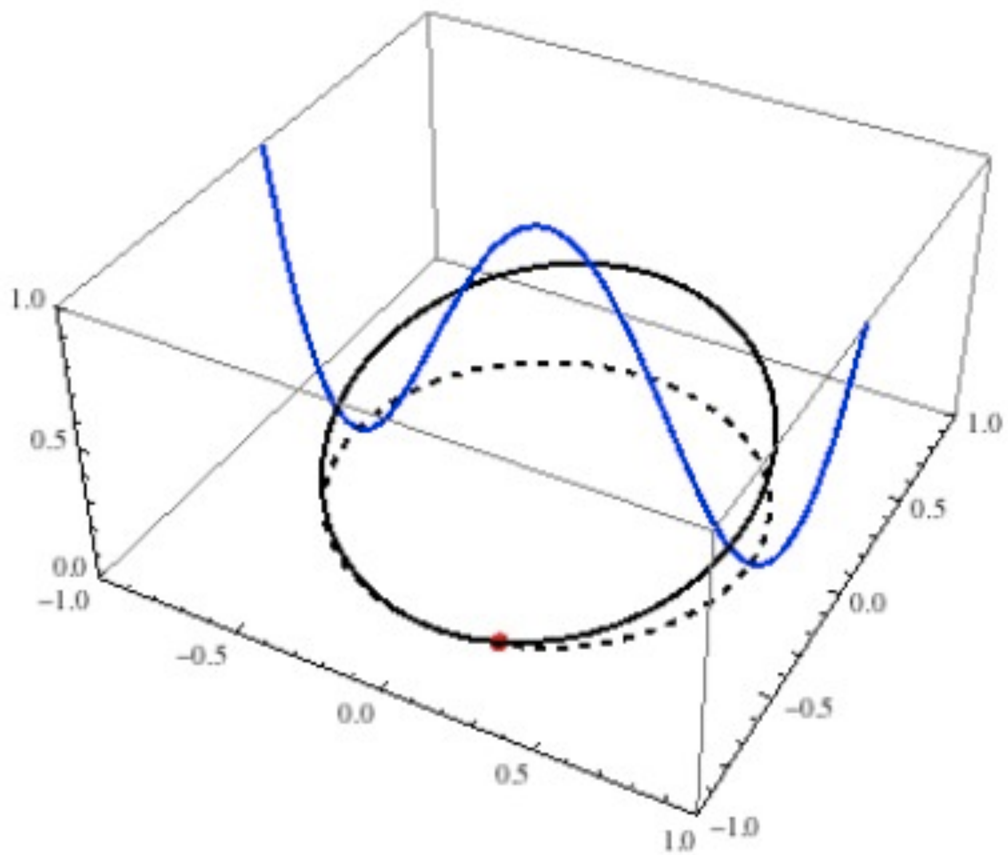

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(T>QCD)

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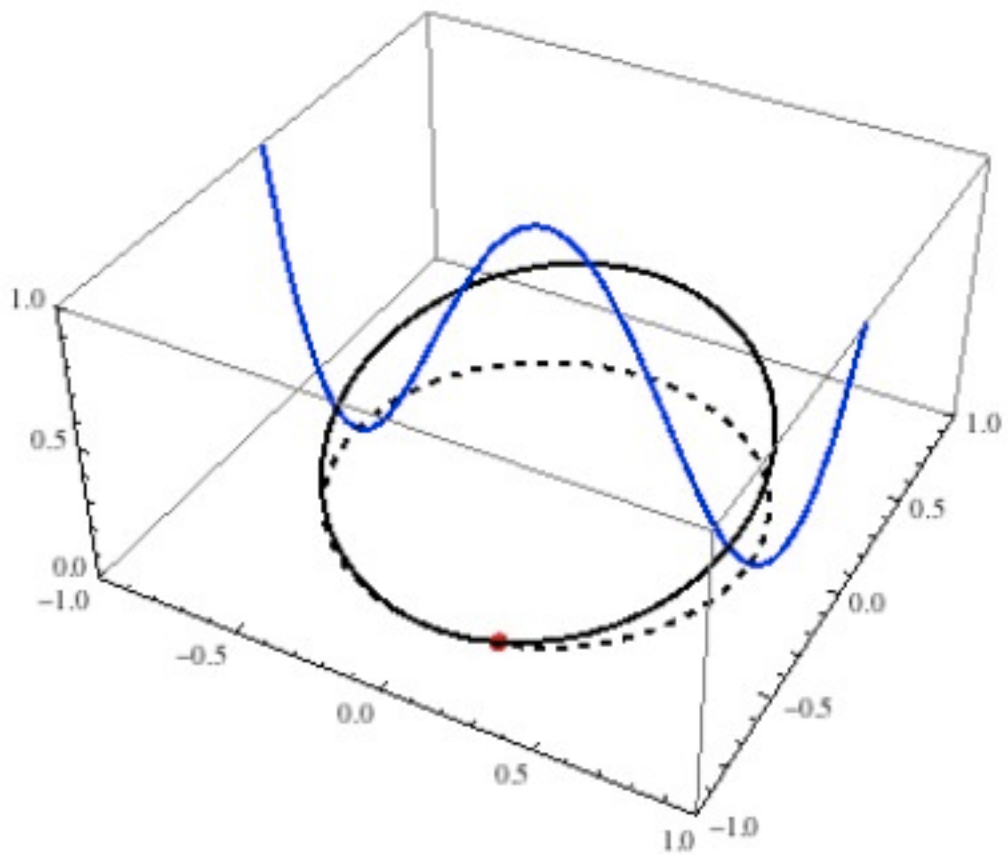

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Cosmic Strings

(Position space)

(T>QCD)

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

Domain Walls

(T<QCD)

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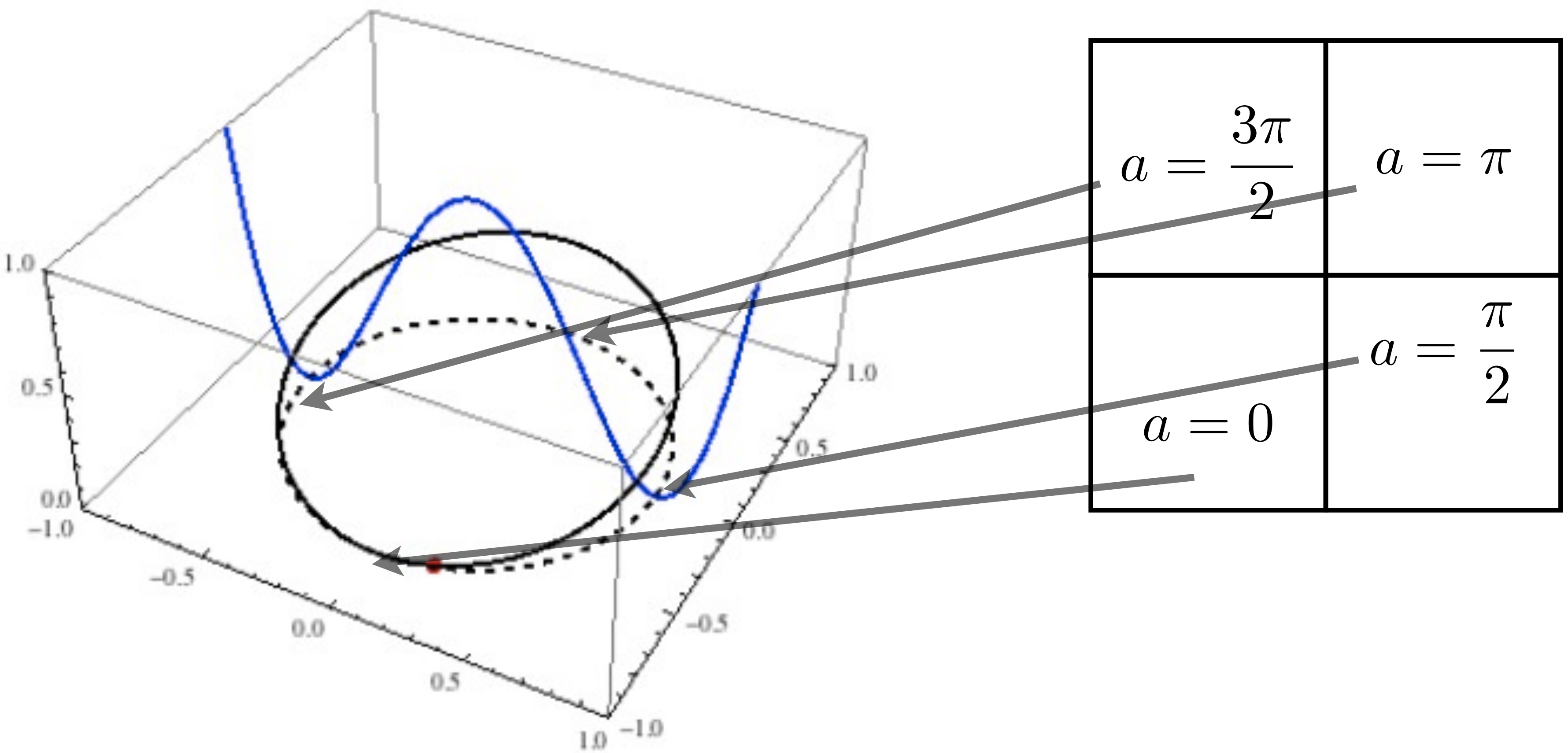

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$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{40\mu\text{eV}}{m_a}\right)^{1.184}$$

Axion cold Dark Matter

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

Realignment mechanism

Cosmic Strings

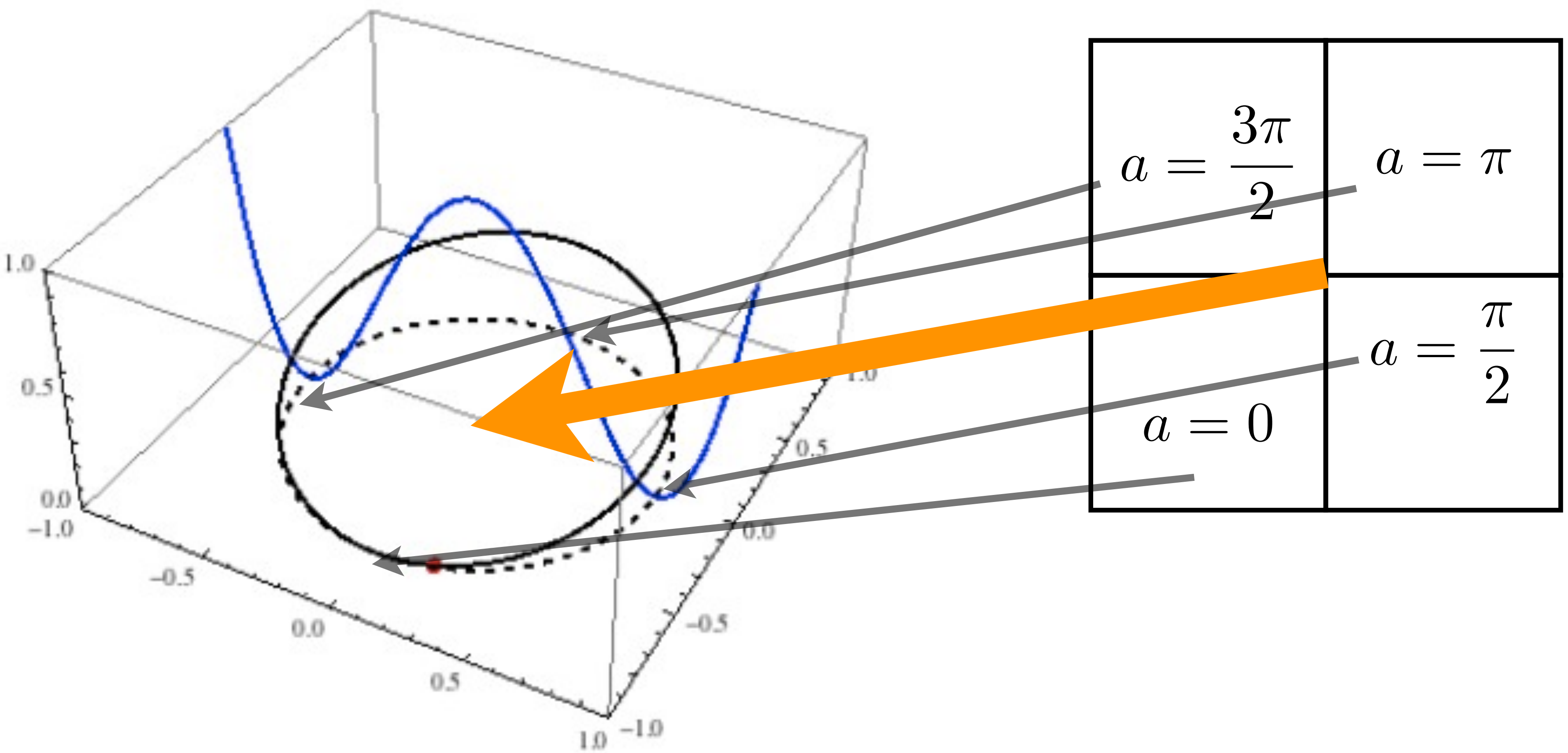
Domain Walls

(Field space)

(Position space)

(T>QCD)

(T<QCD)



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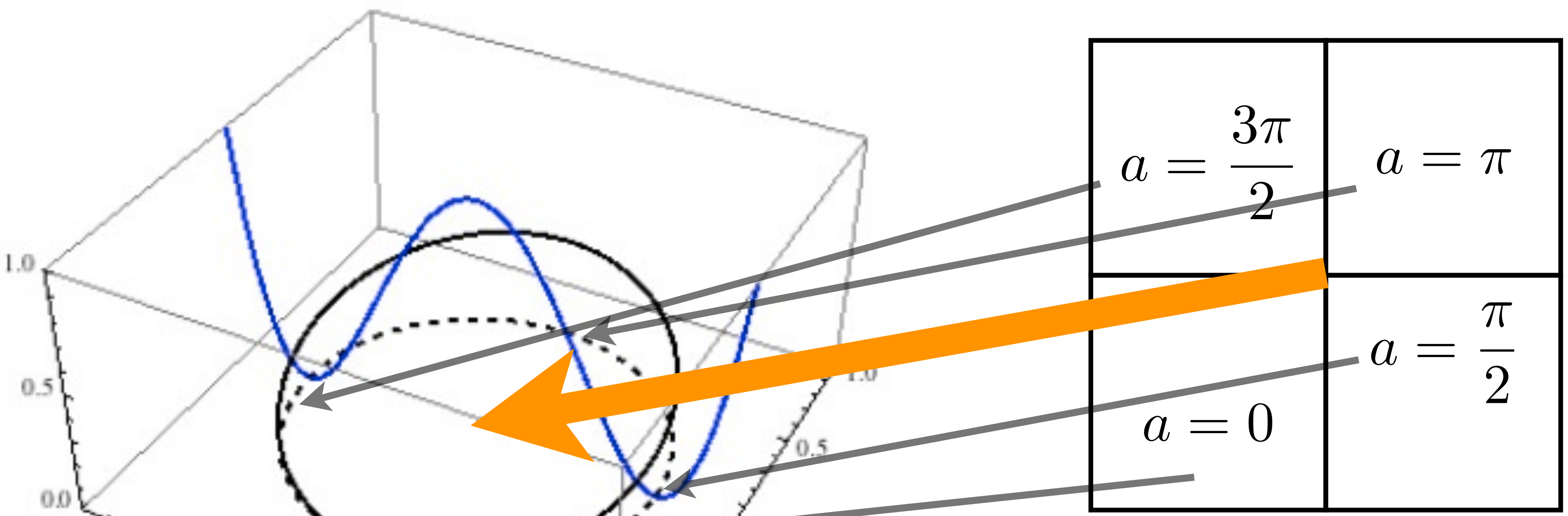

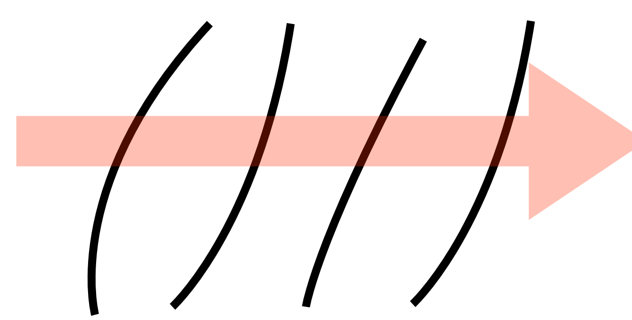

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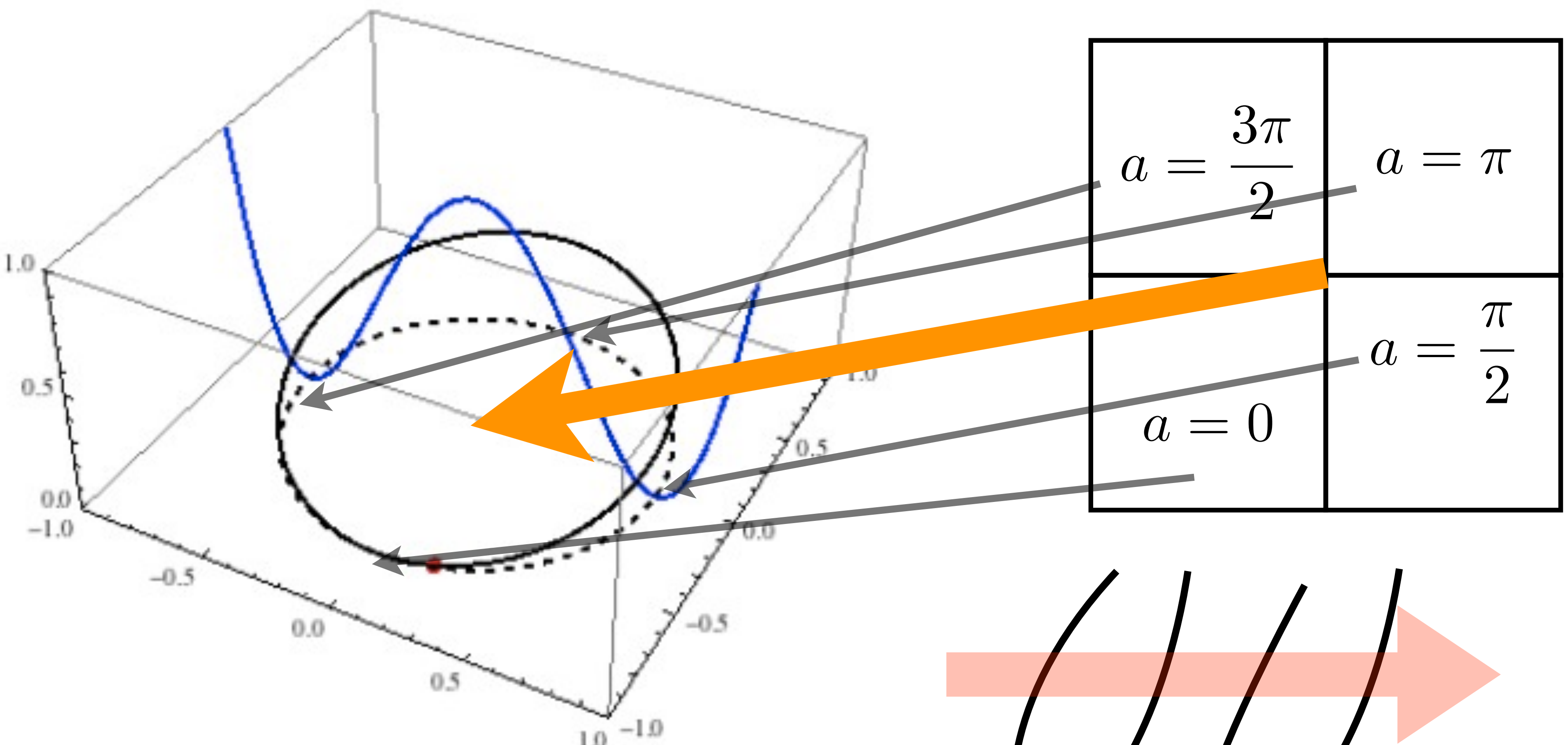

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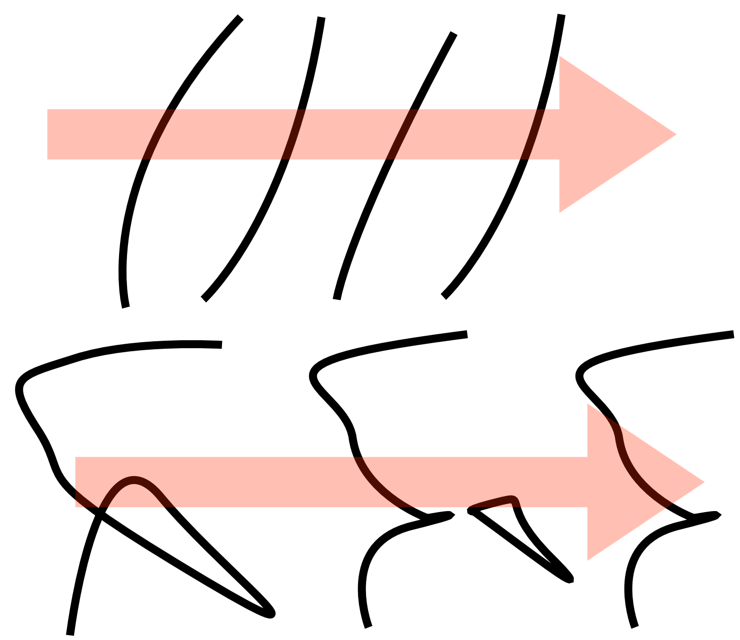

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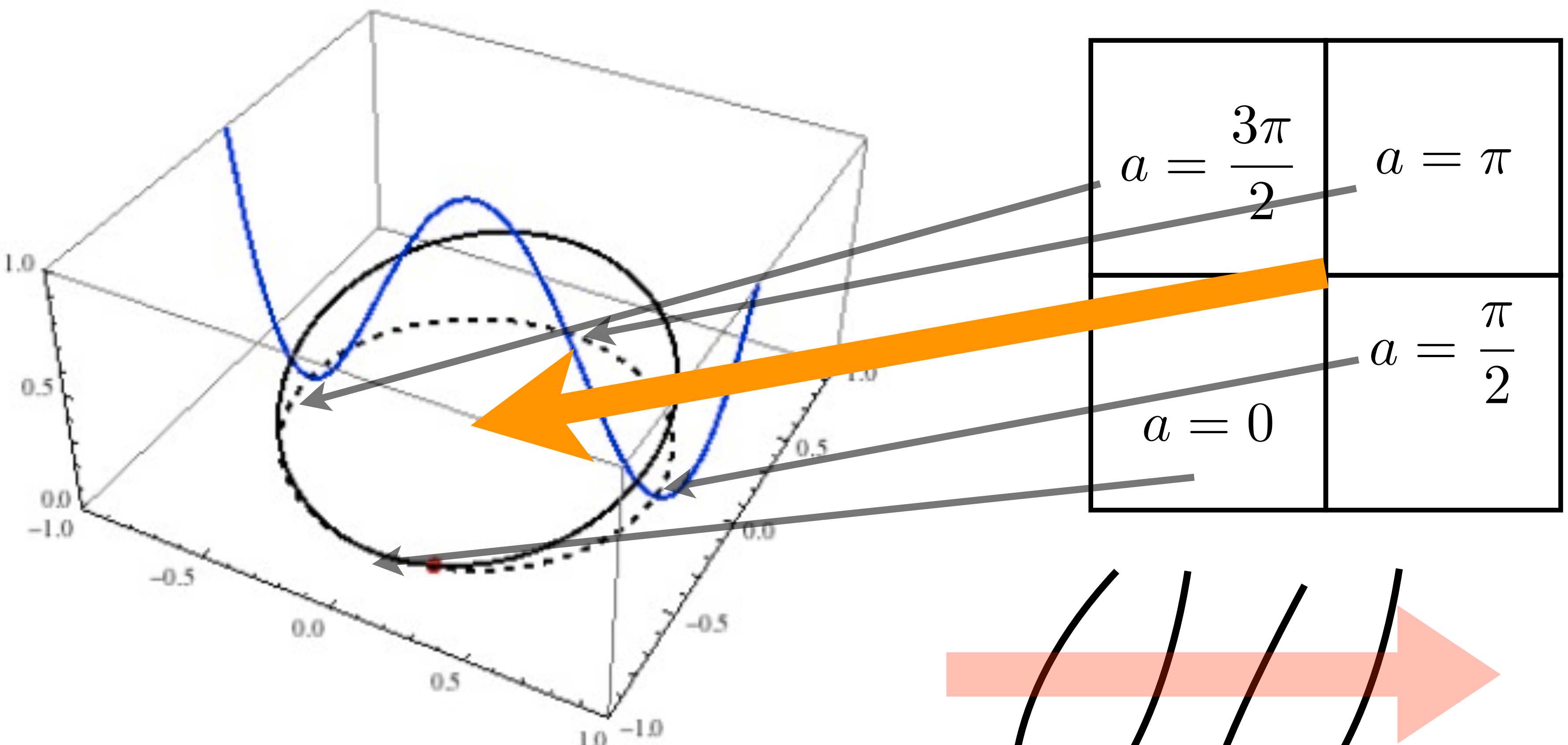

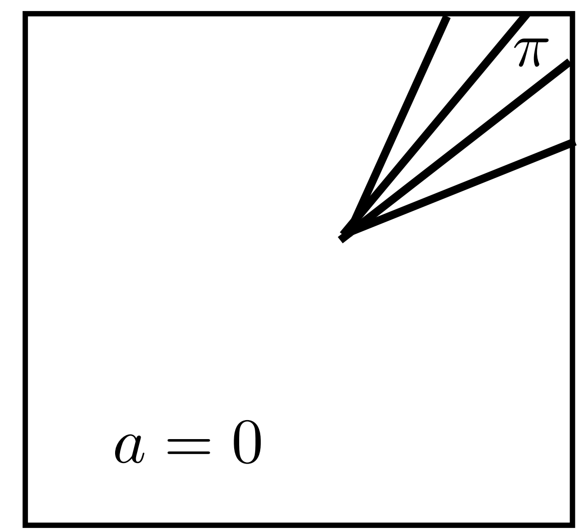

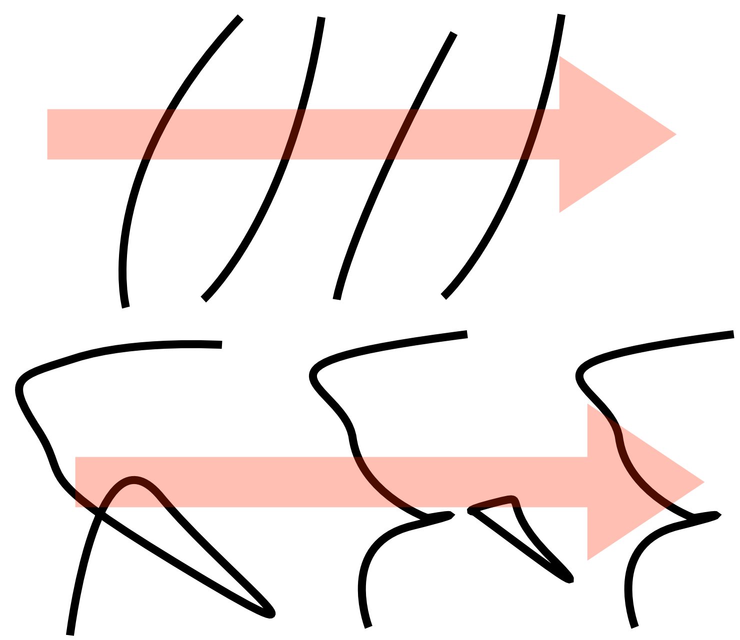

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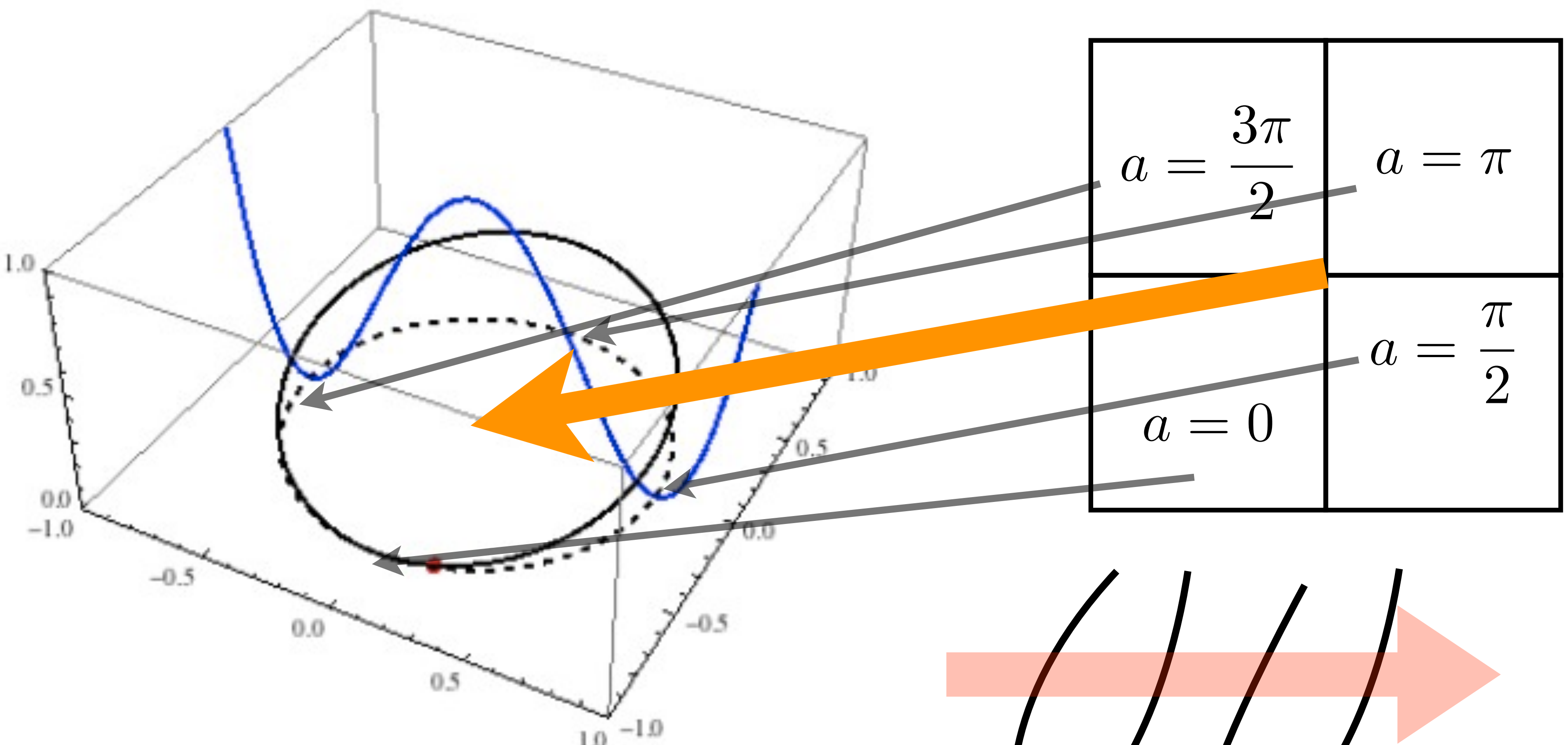

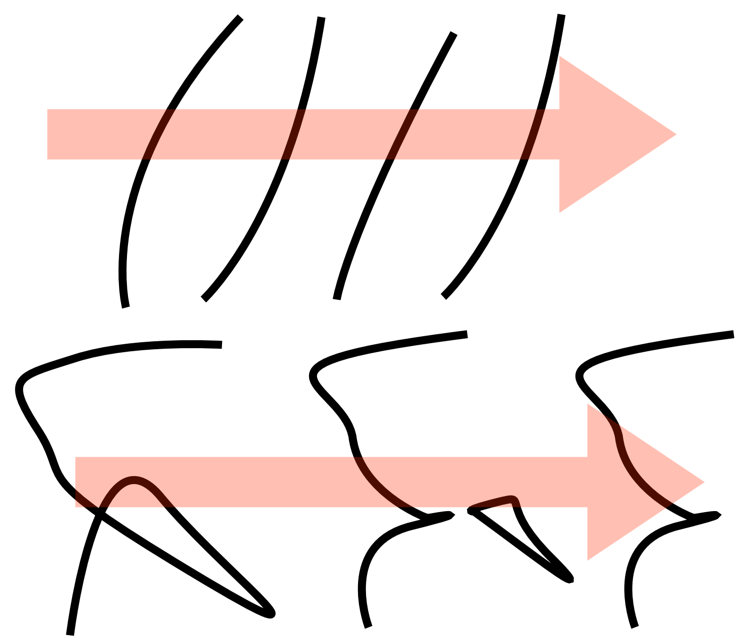

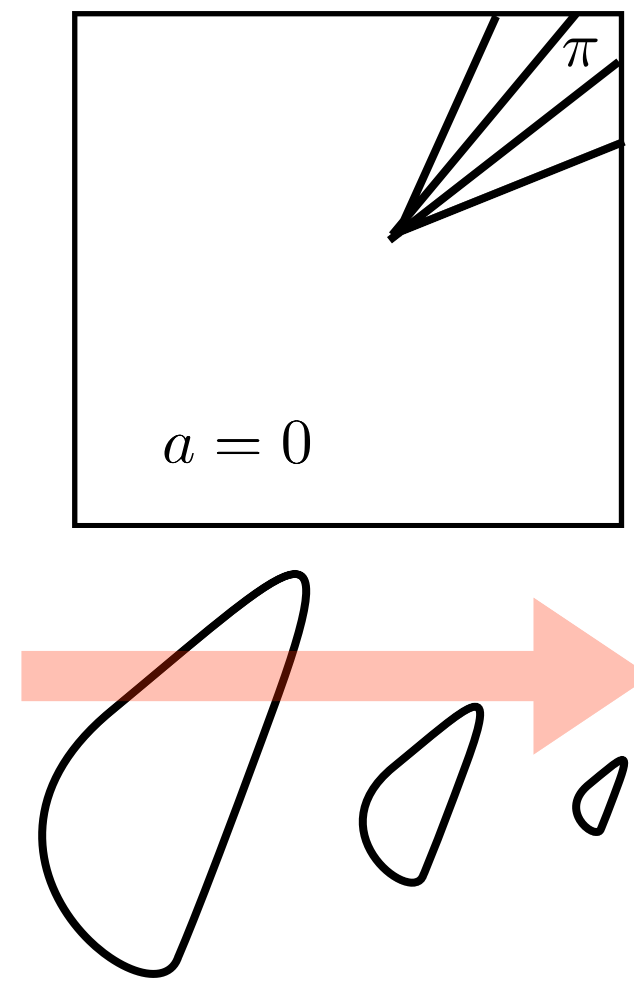

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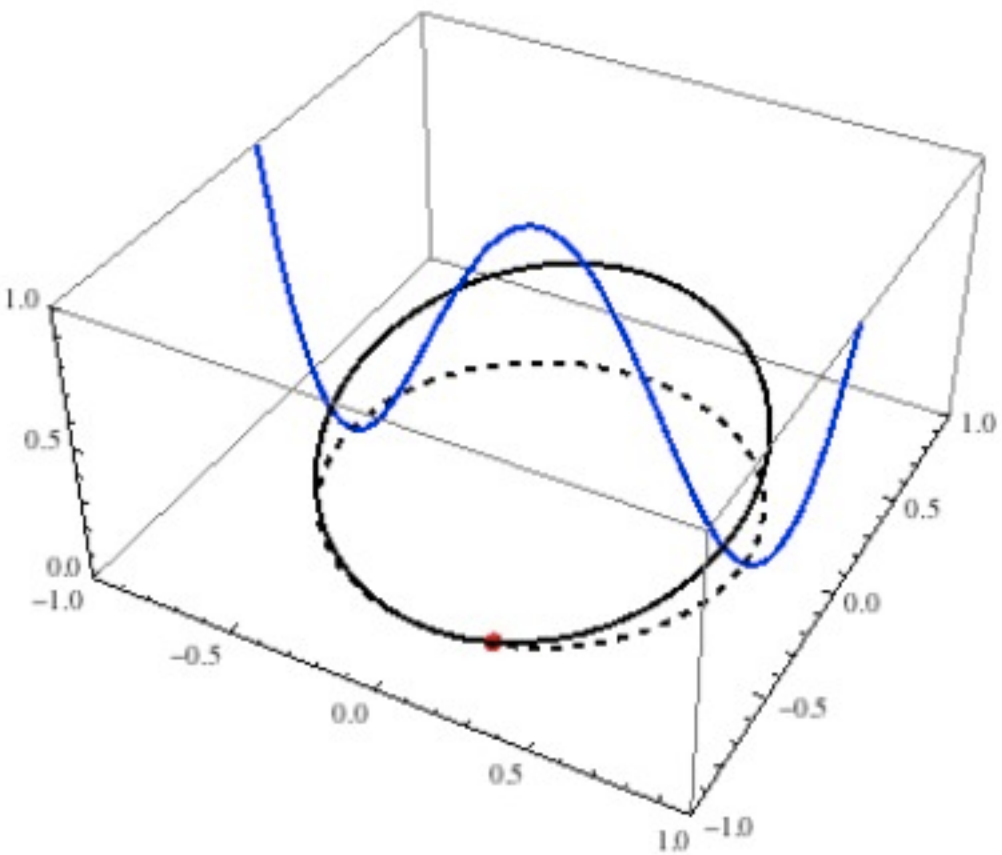

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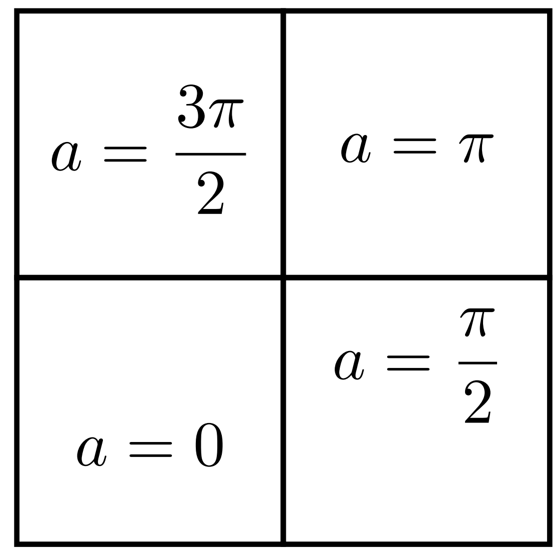

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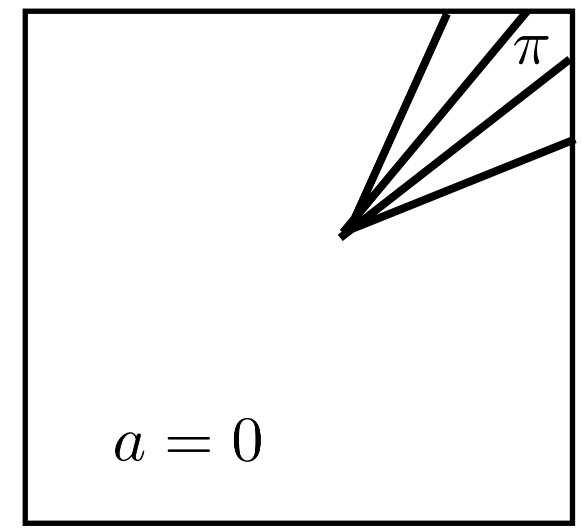


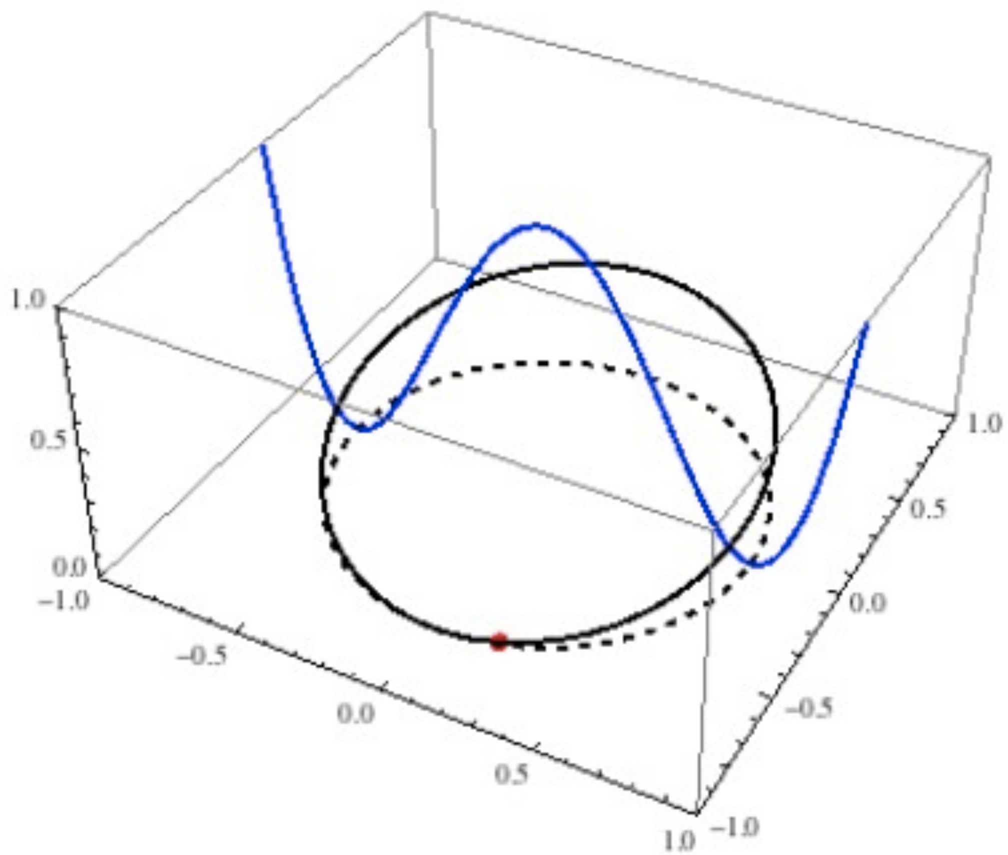
$$\frac{\Omega_{a,DW+ST}}{\Omega_{\rm obs}} \begin{cases} \sim \left(\frac{40\mu\text{eV}}{m_a}\right)^{1.184} & \text{Sikivie, Harari et at.} \\ \sim \left(\frac{400\mu\text{eV}}{m_a}\right)^{1.184} & \text{Shellard, Davis et at. Kawasaki, Hiramatsu et at} \end{cases}$$

Axion cold Dark Matter*

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

Realignment mechanism

(Field space)



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

Cosmic Strings

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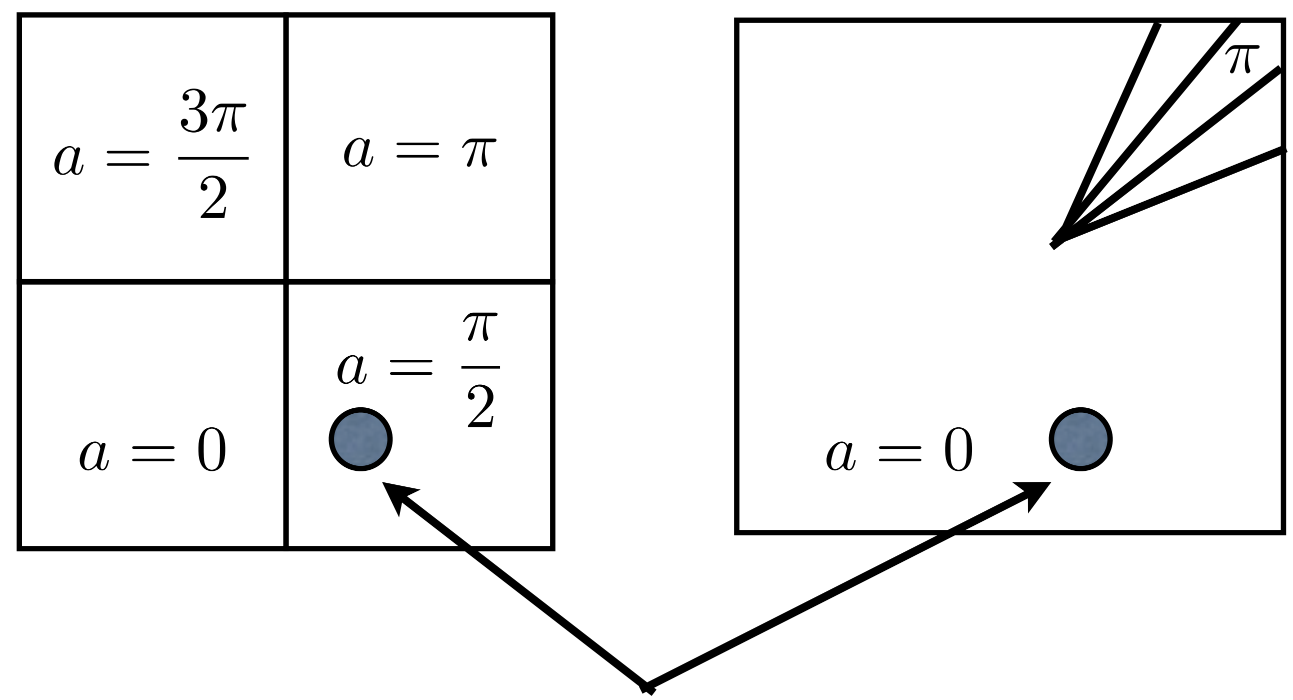
(T>QCD)

Domain Walls

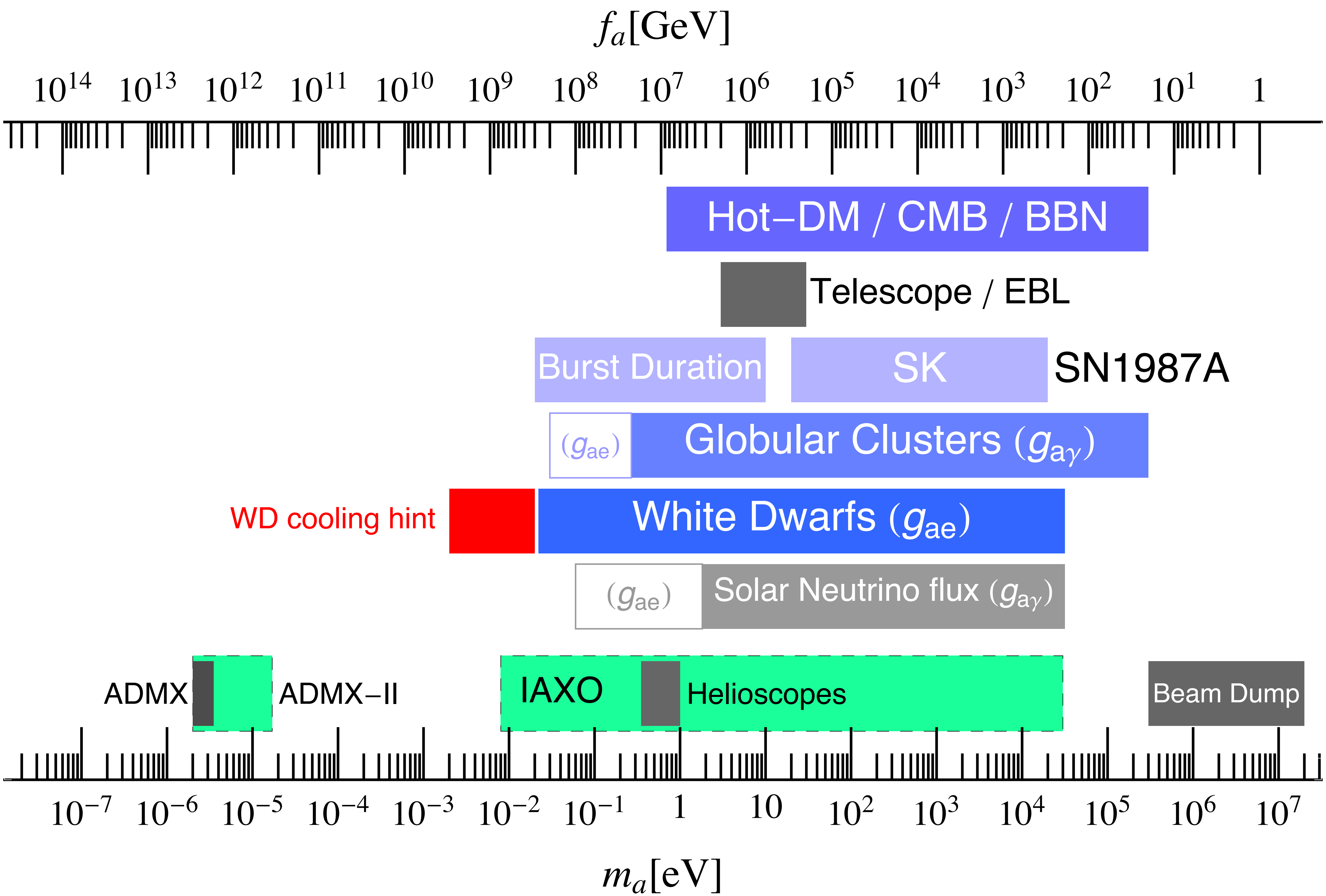
(T<QCD)



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

Where axion CDM lies??

Hewett et al. arXiv:1205.2671 [hep-ex]



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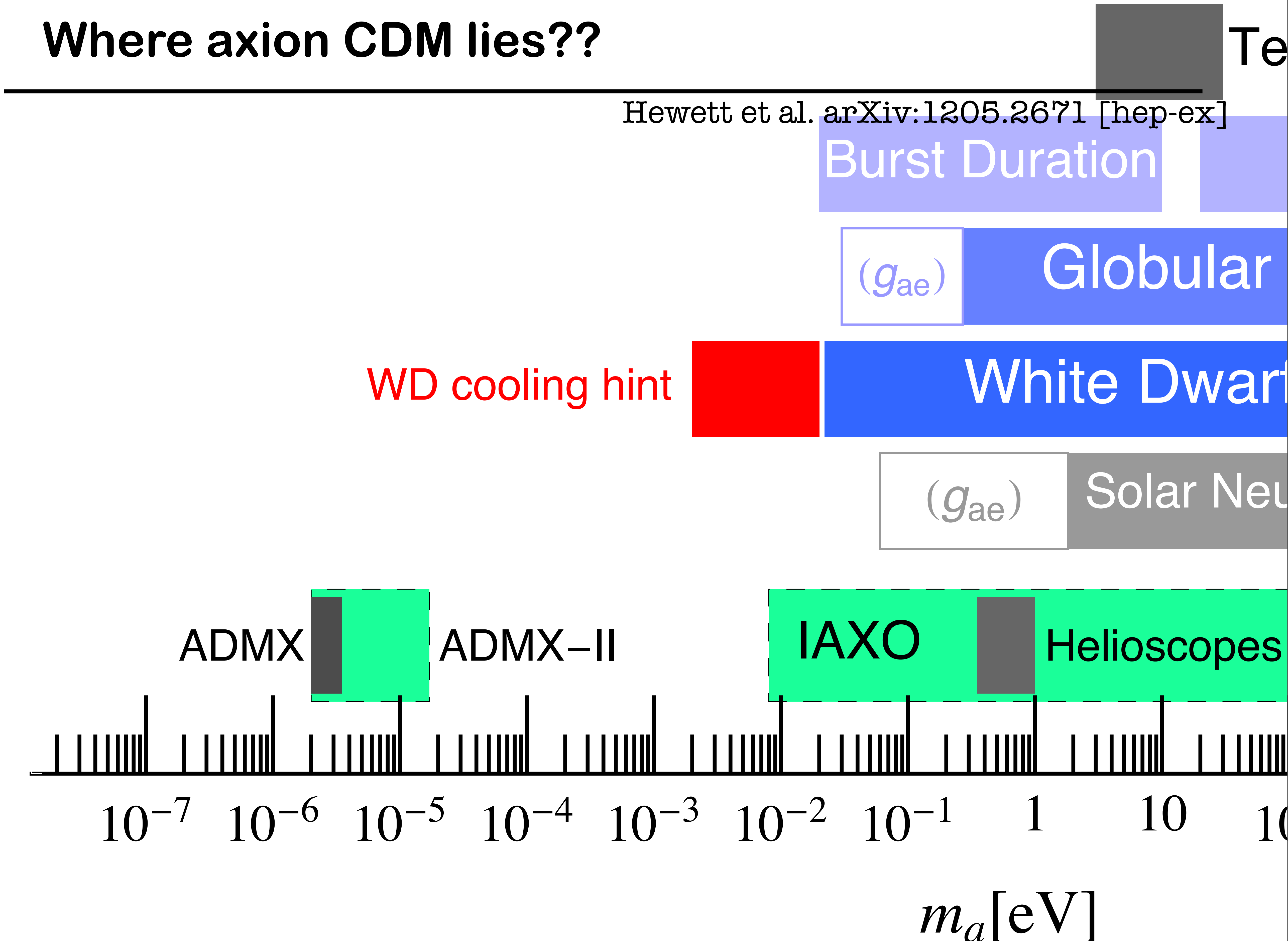

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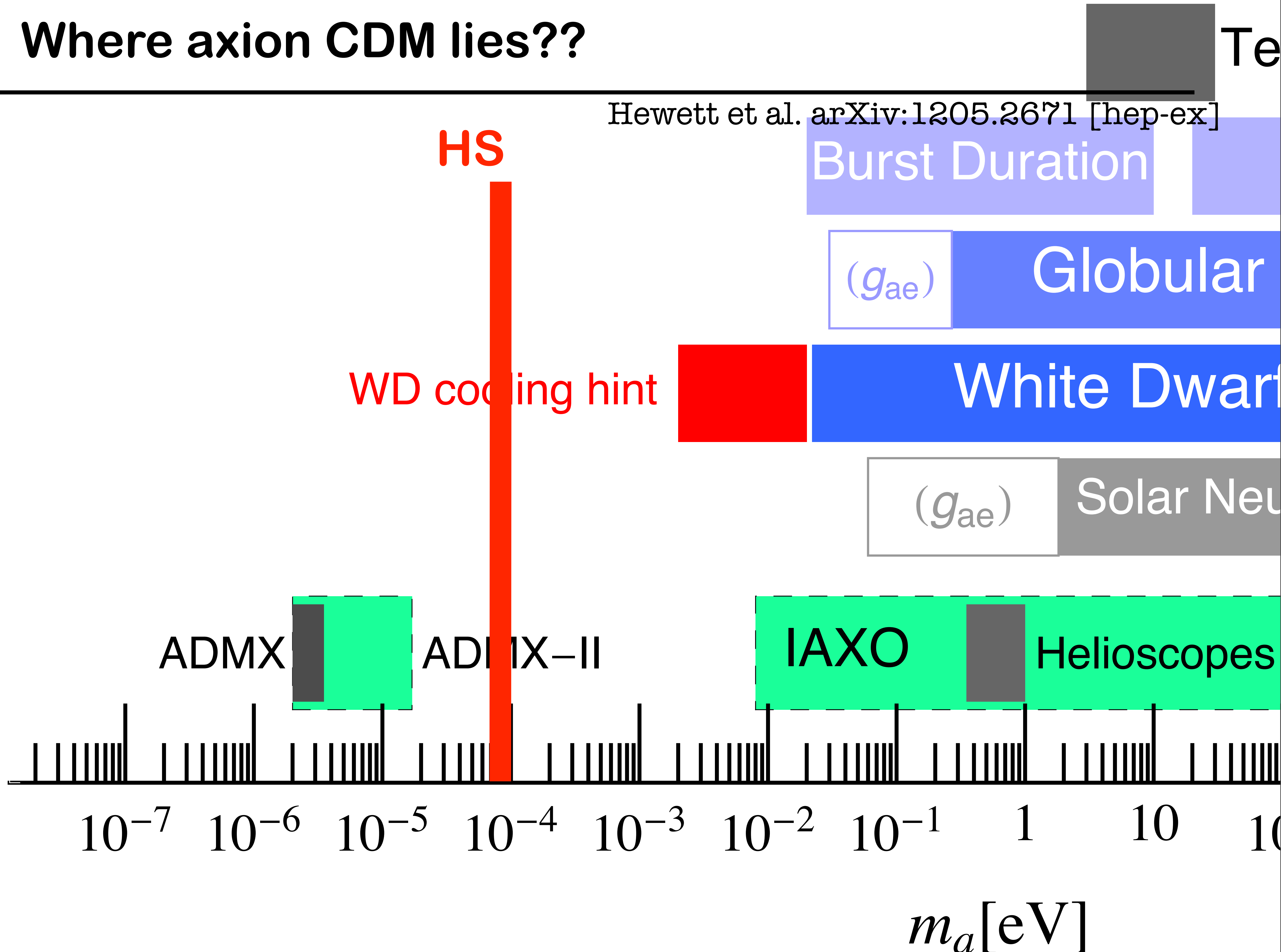

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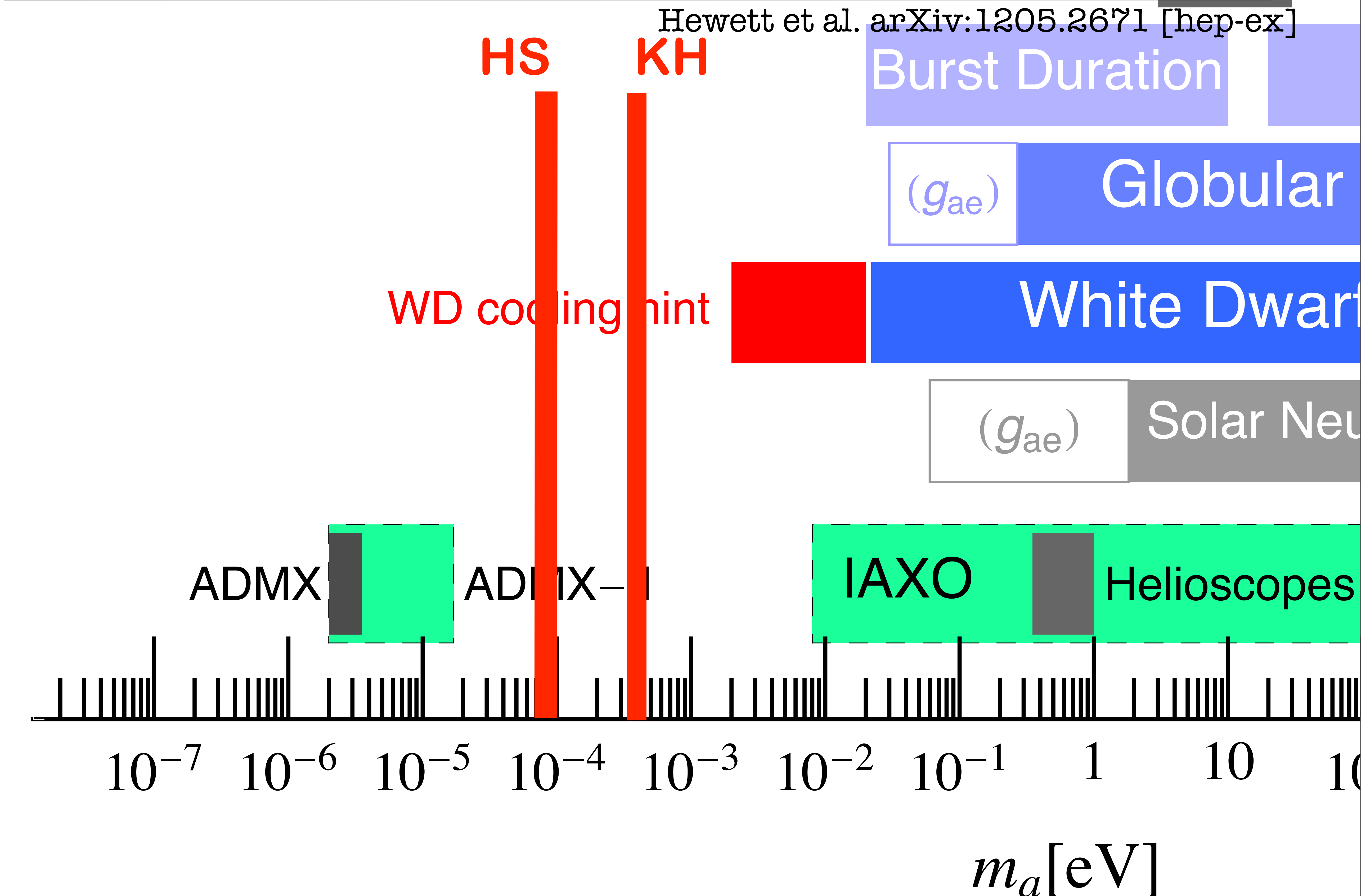

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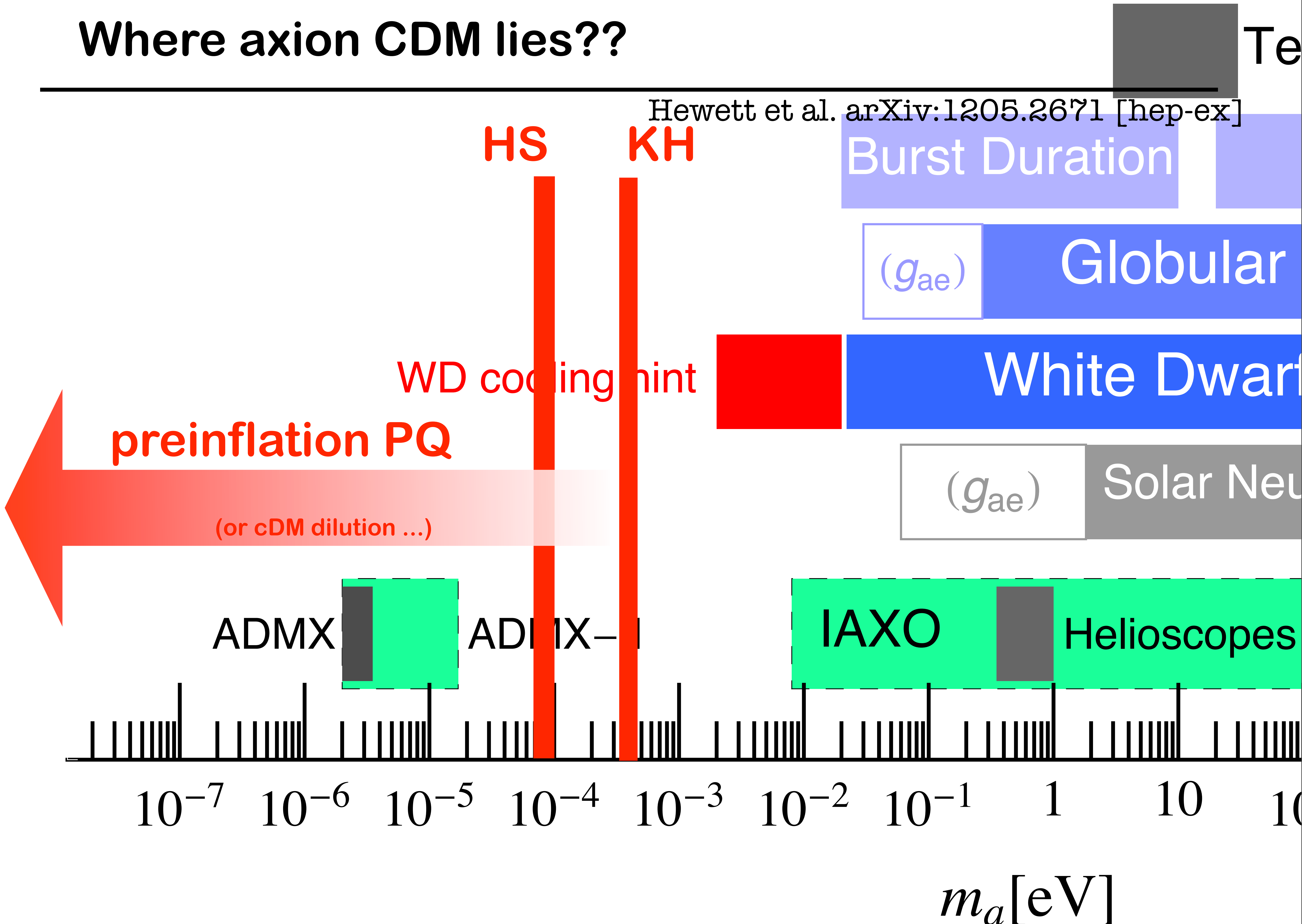
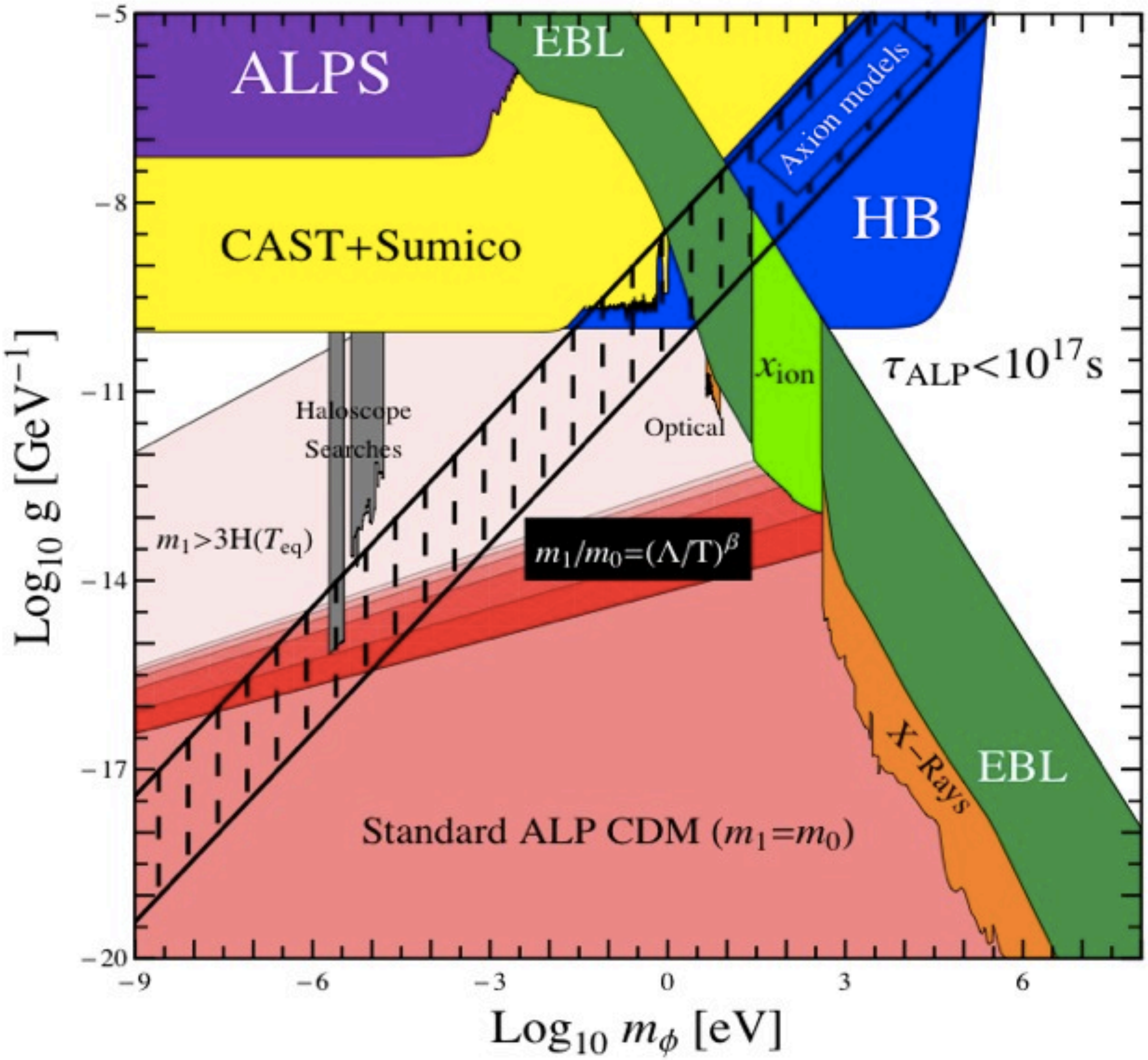


WISPy cold dark matter

Arias et al, JCAP 1206



Detecting axion (ALP) cold dark matter

axion - photon mixing in a magnetic field

Raffelt, PRD'88

$$\mathcal{L}_I = \frac{g_{a\gamma}}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu} a = -g_{a\gamma} \mathbf{B} \cdot \mathbf{E}\, a$$

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Raffelt, PRD'88

- In a magnetic field one photon polarization Q-mixes with the axion

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Not axions, nor photons are propagation eigenstates!

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$$\chi \sim \frac{g_{a\gamma}|\mathbf{B}|}{m_a}$$

radiation from a mirror

Horns et al, arXiv:1212.2970, accepted in JCAP

$$E_a = \omega_a \chi \cos(\omega_a t + kz).$$

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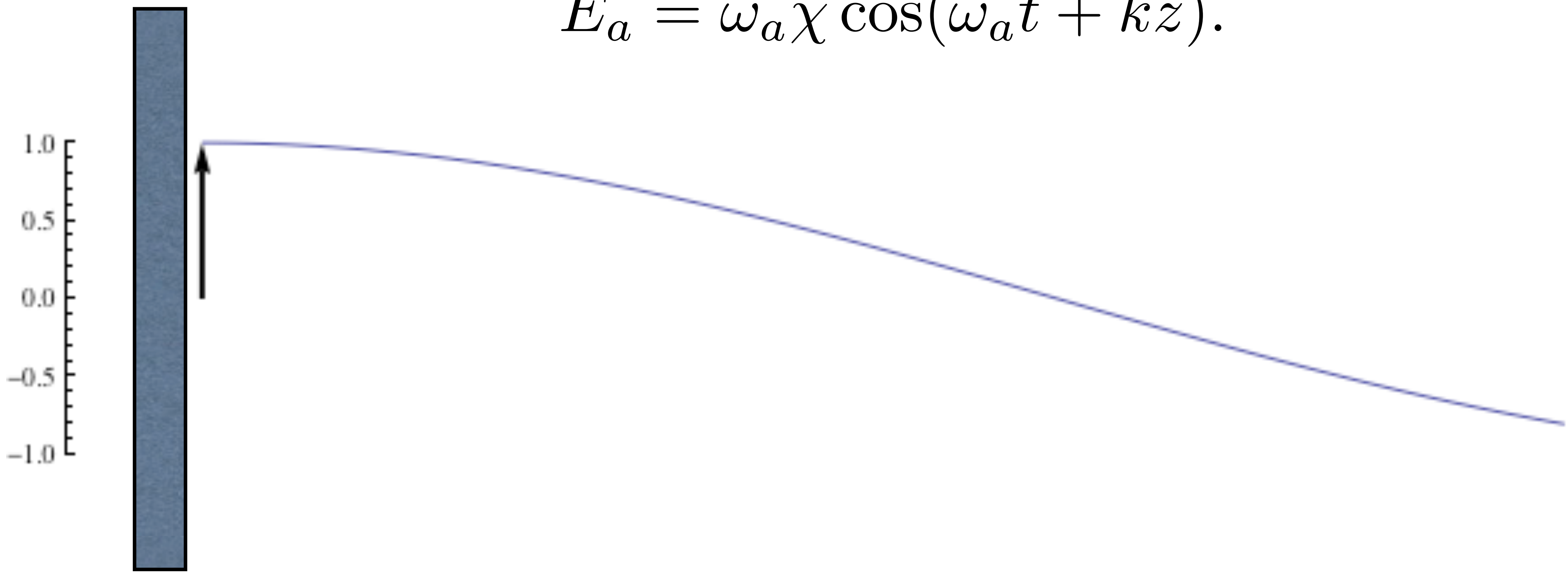

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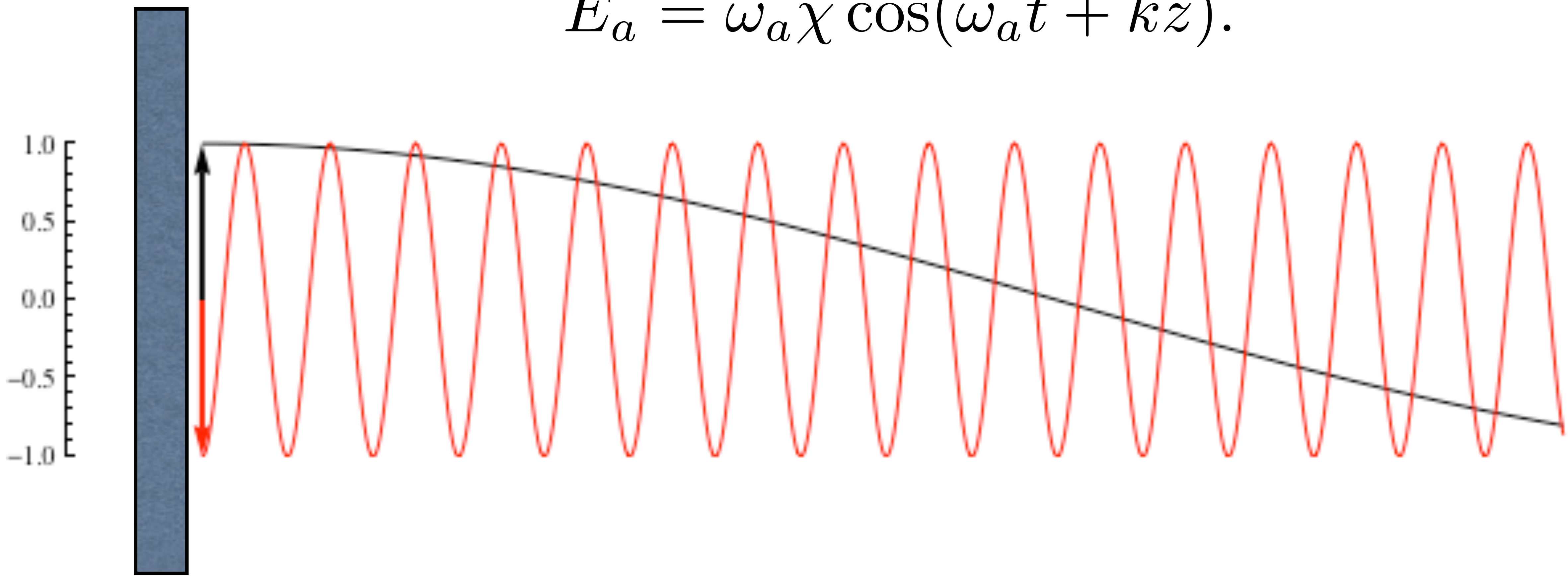

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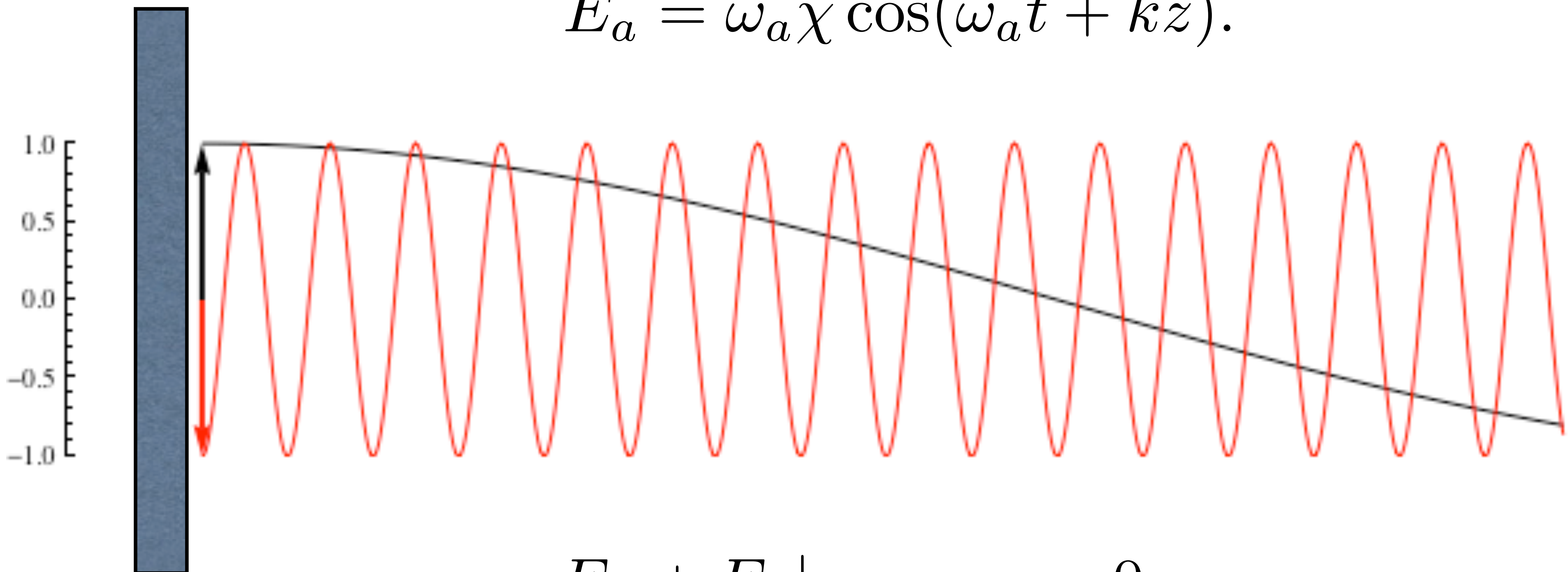

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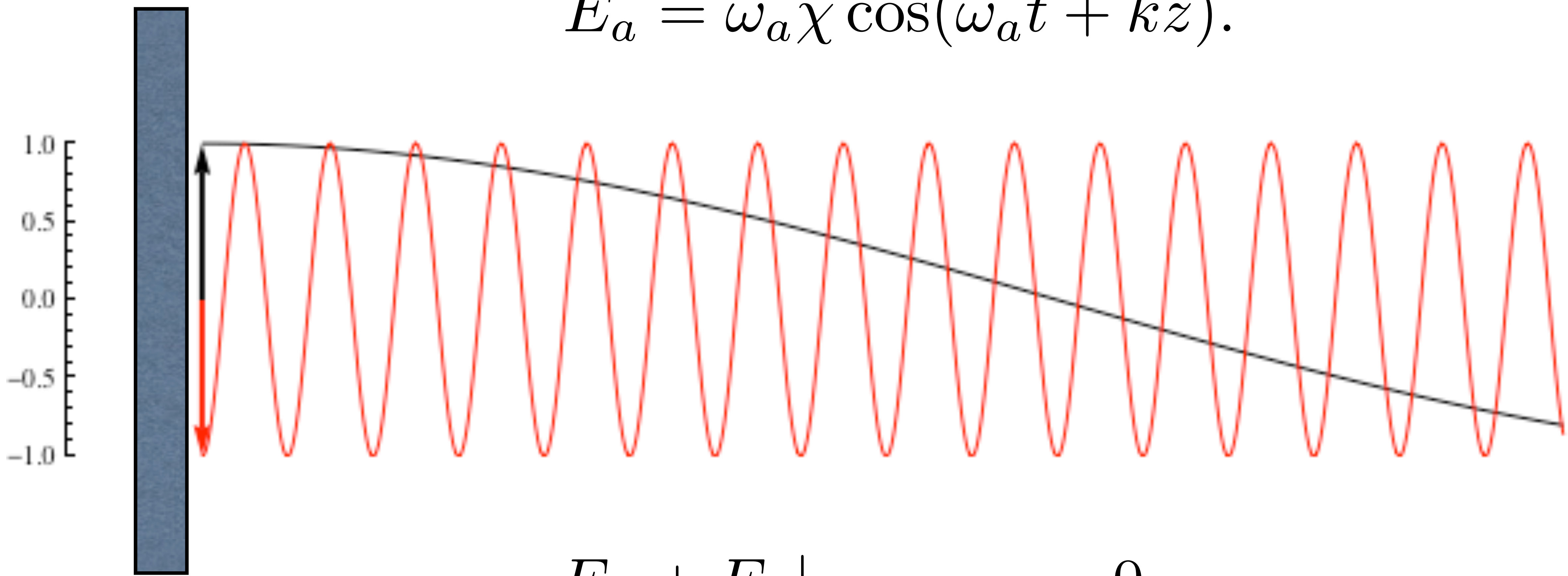

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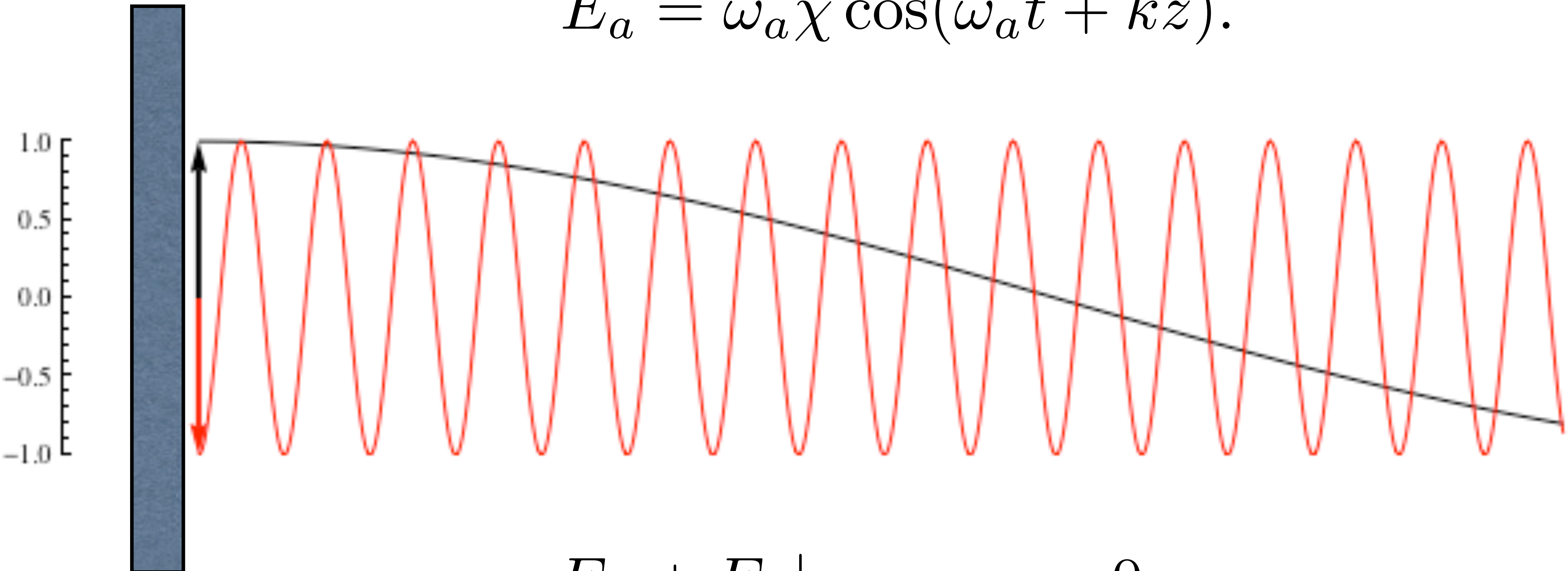

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radiation from a mirror

Horns et al, arXiv:1212.2970, accepted in JCAP

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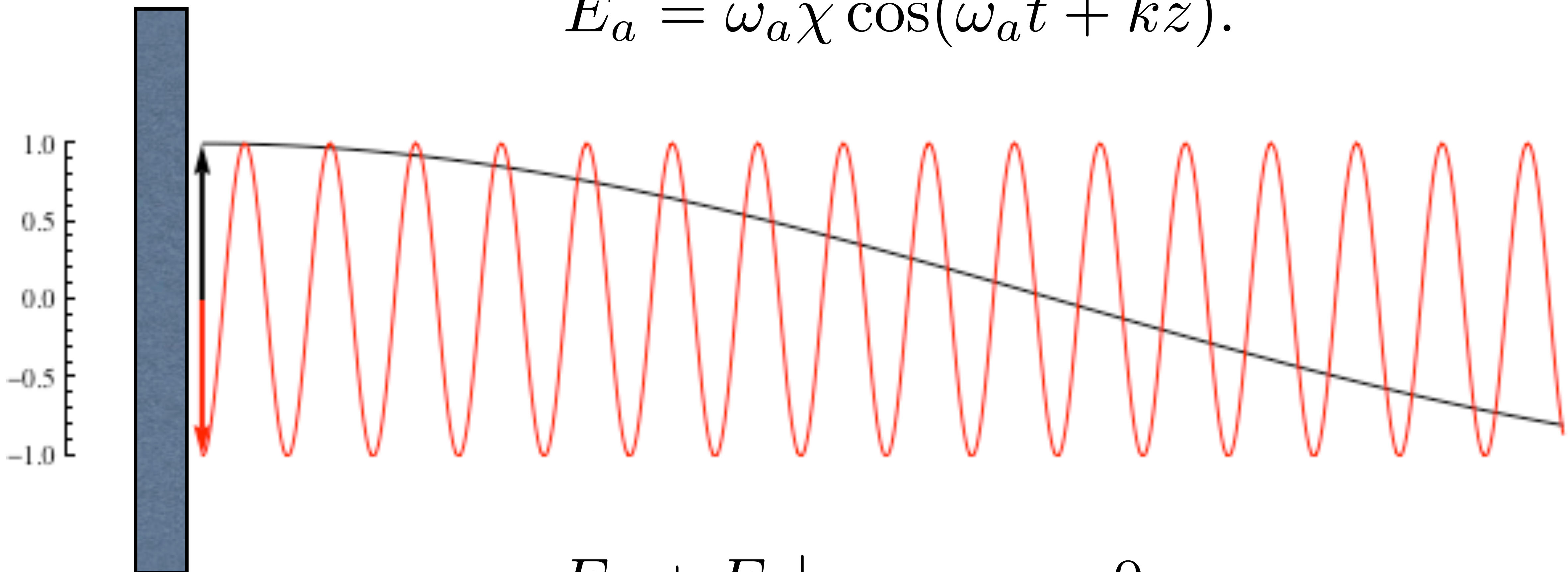

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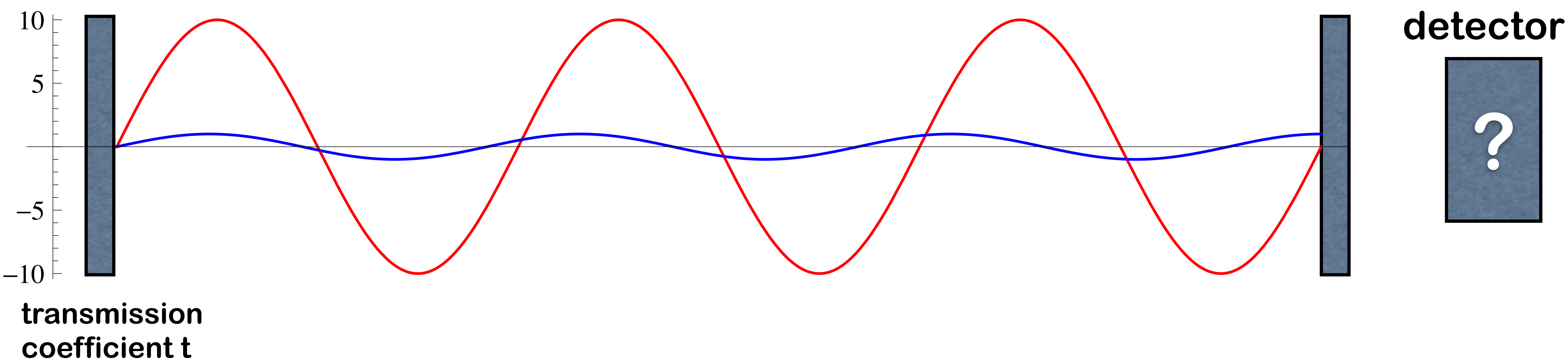
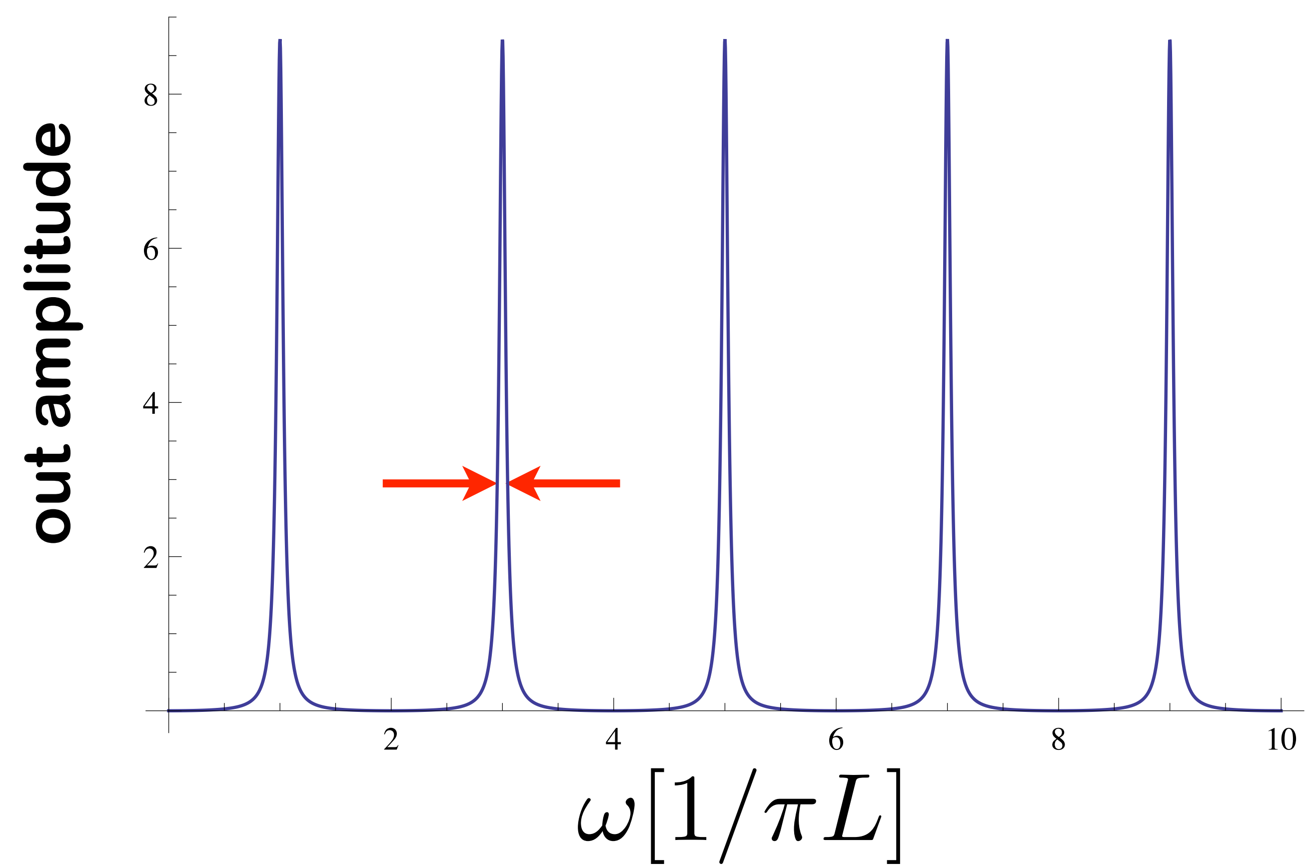
**Note: measuring these photons,
we measure the TOTAL DM energy,
DM mass and the velocity distribution!
also with directional sensitivity!
Irastorza et al. 2012**

cavity searches (haloscopes)

Sikivie PRL ‘83

- Use two facing mirrors (simplistic resonant cavity in 1D)





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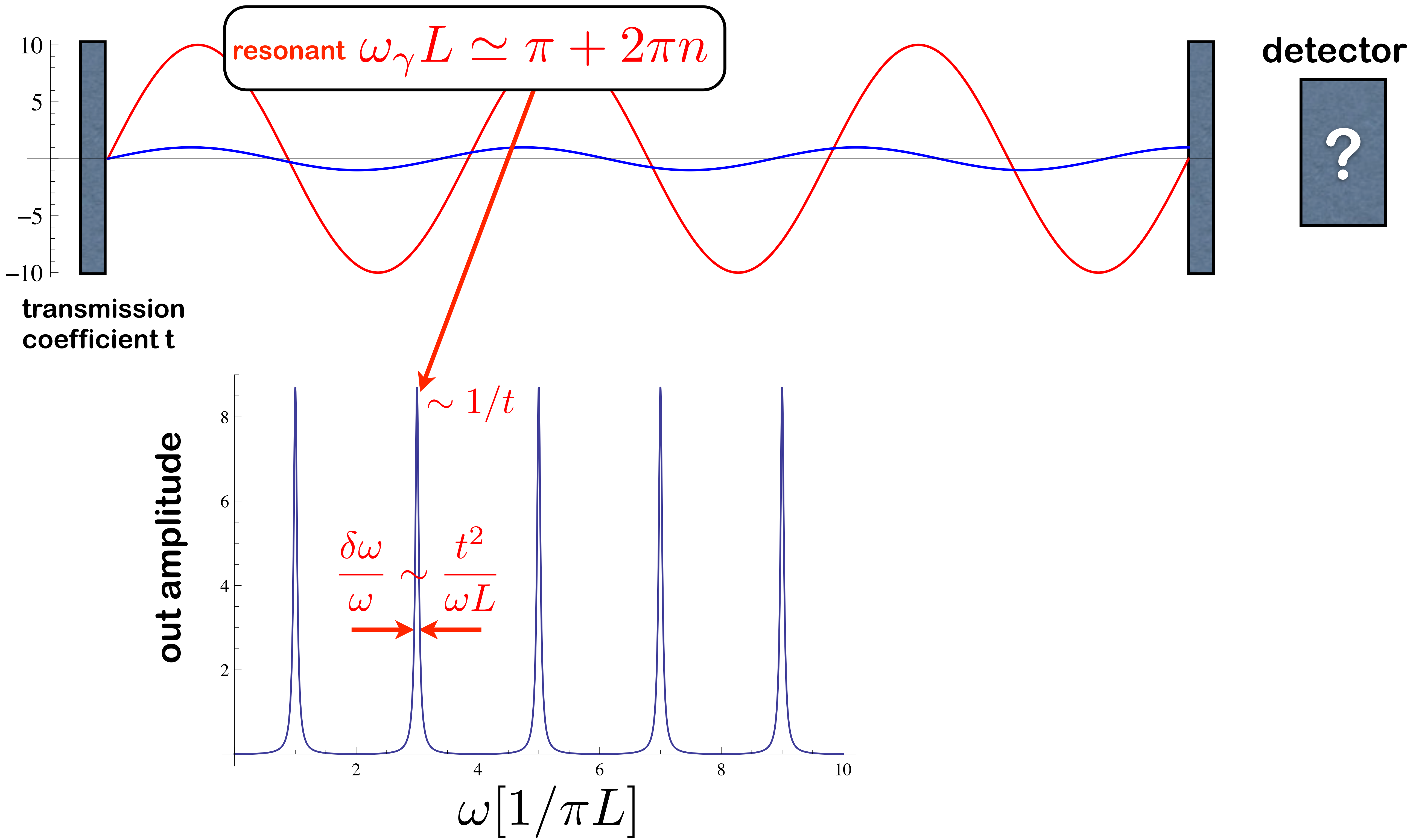

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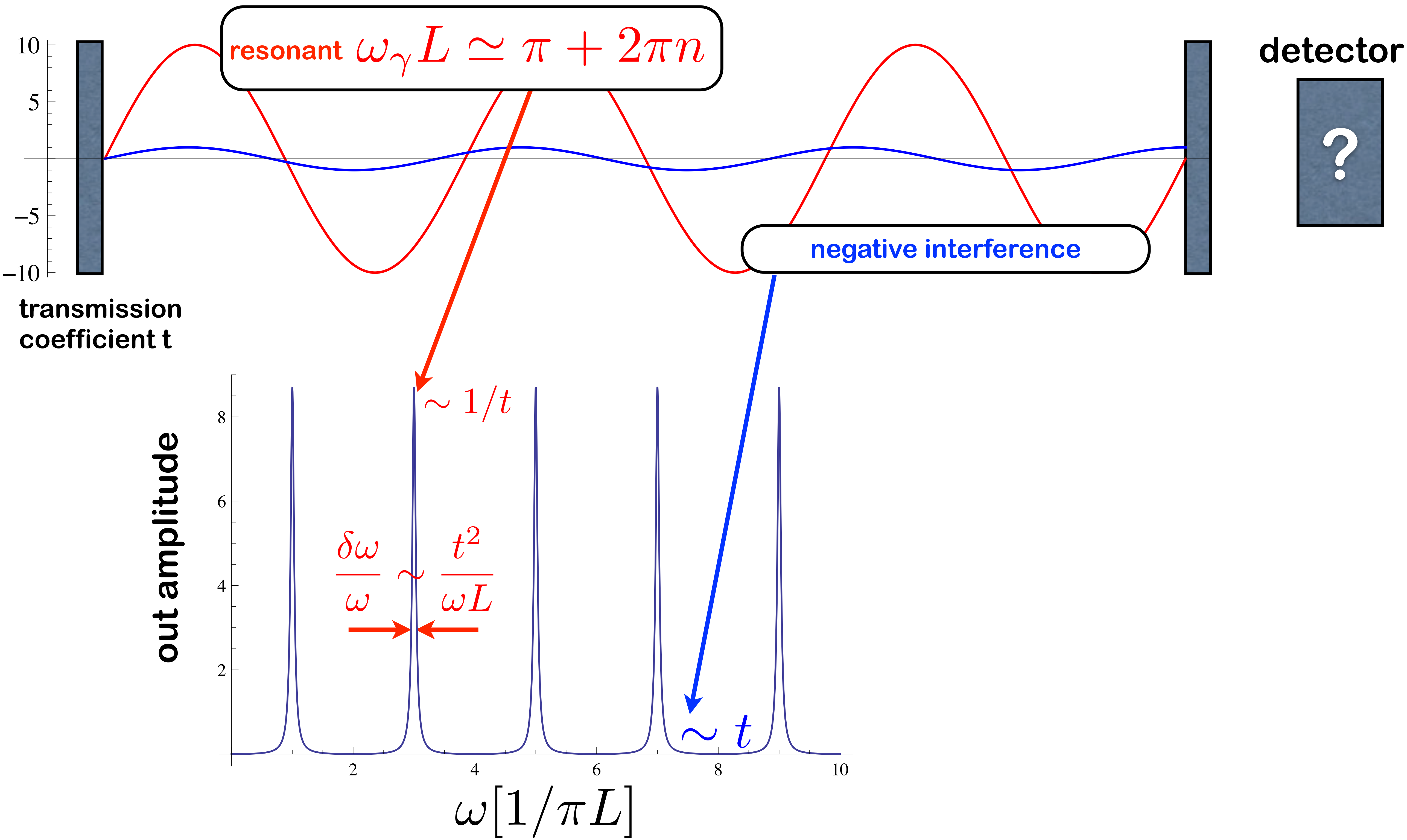

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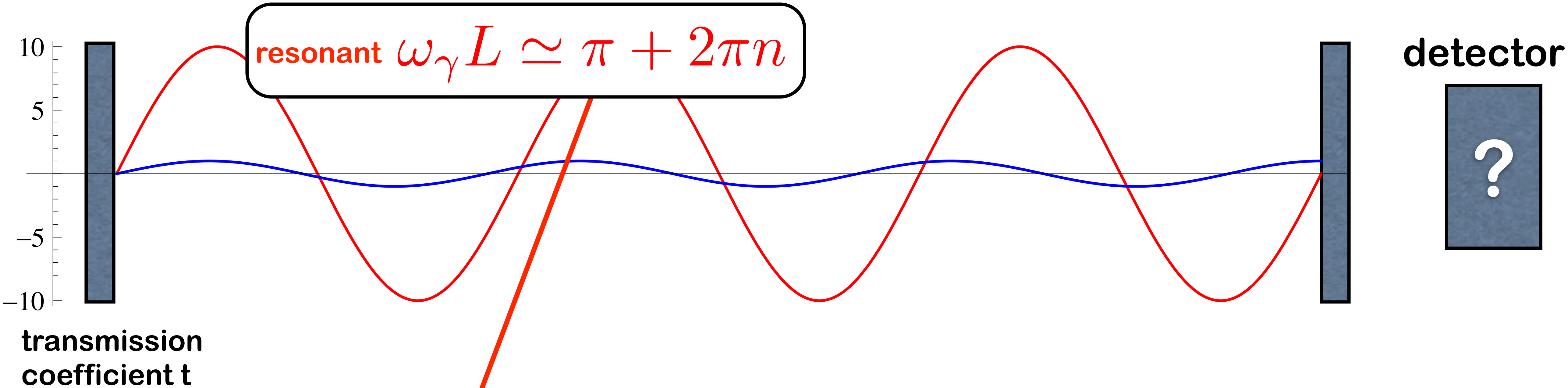

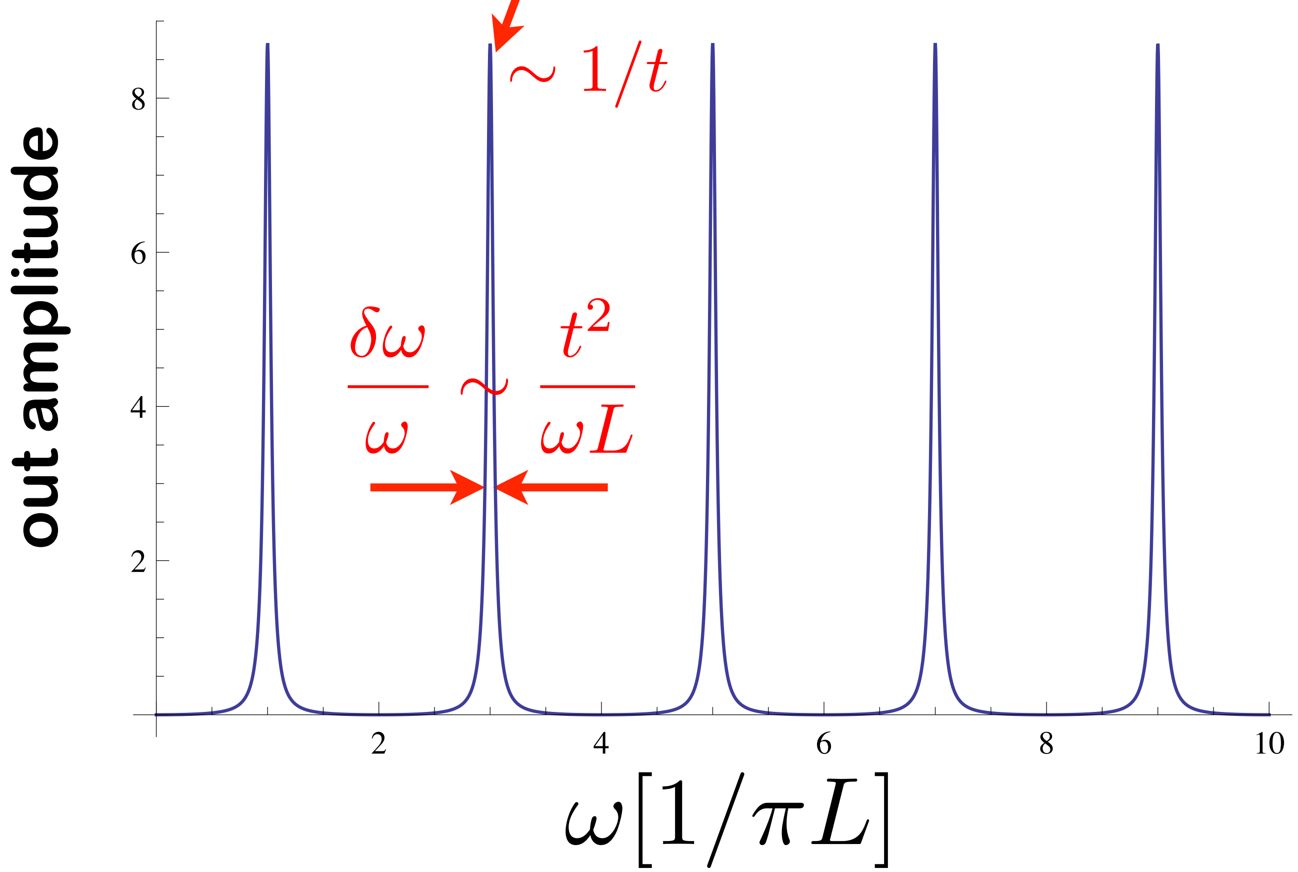

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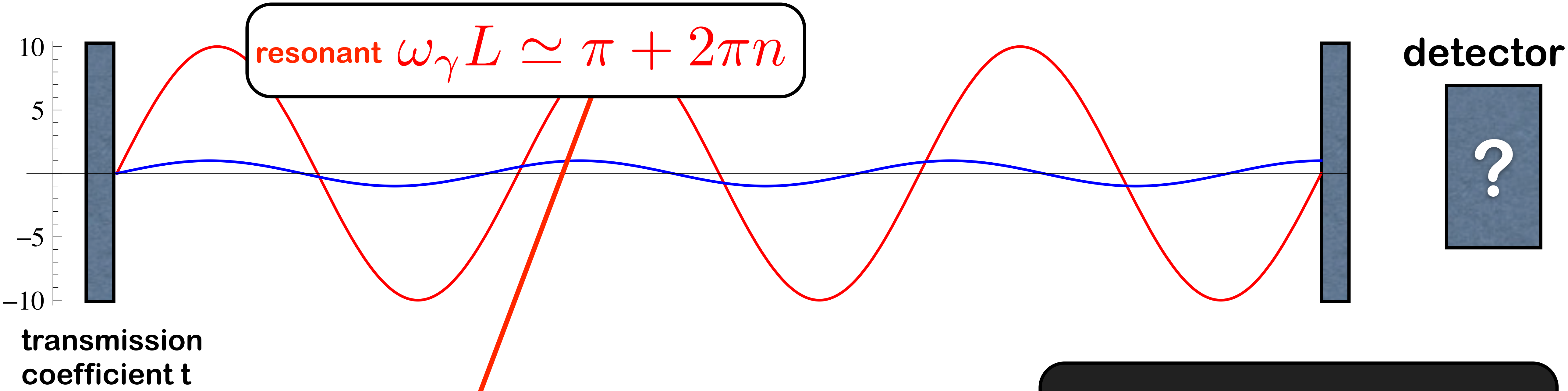

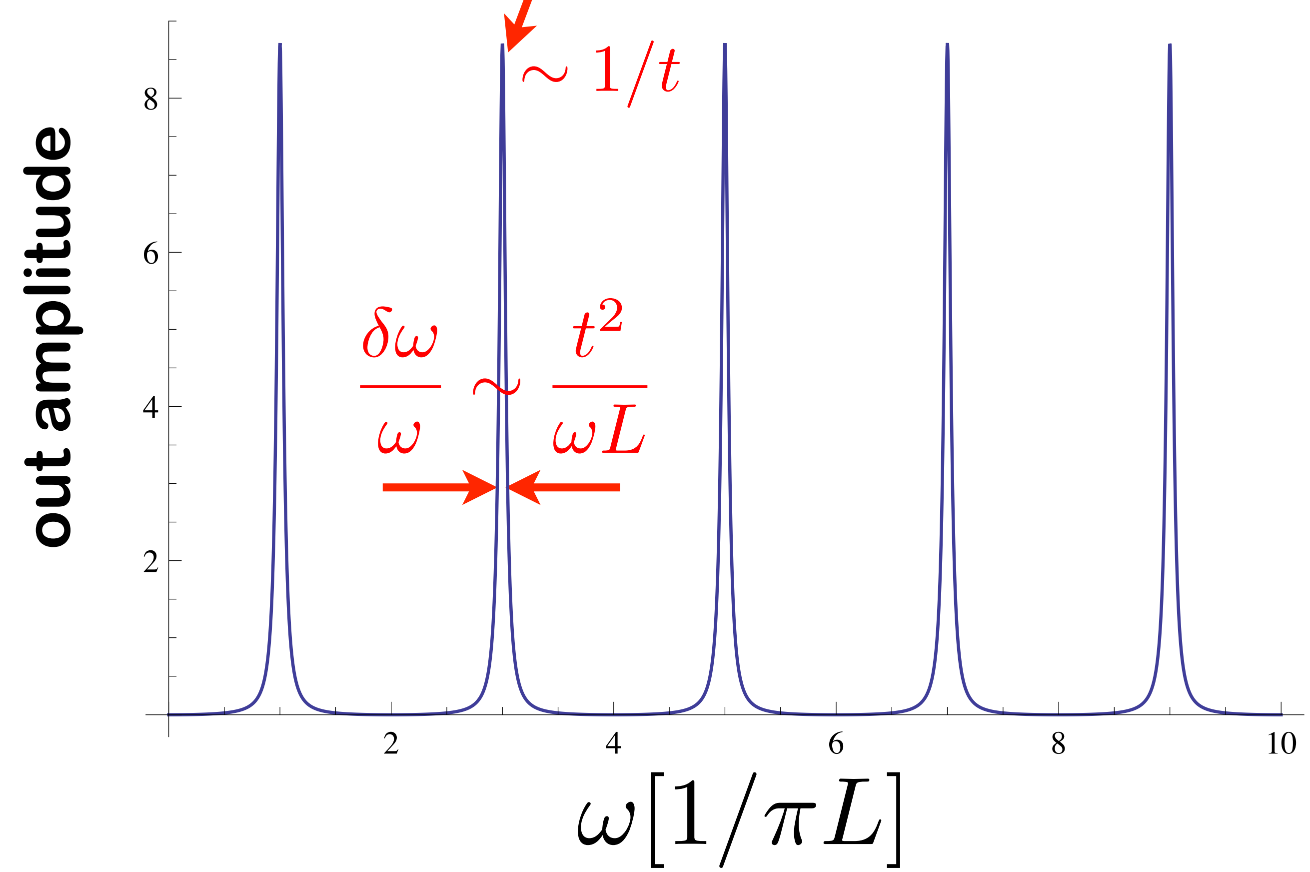

dark matter distribution

$$\frac{\delta\omega}{\omega} \sim \frac{v^2}{2} \sim 10^{-6}$$

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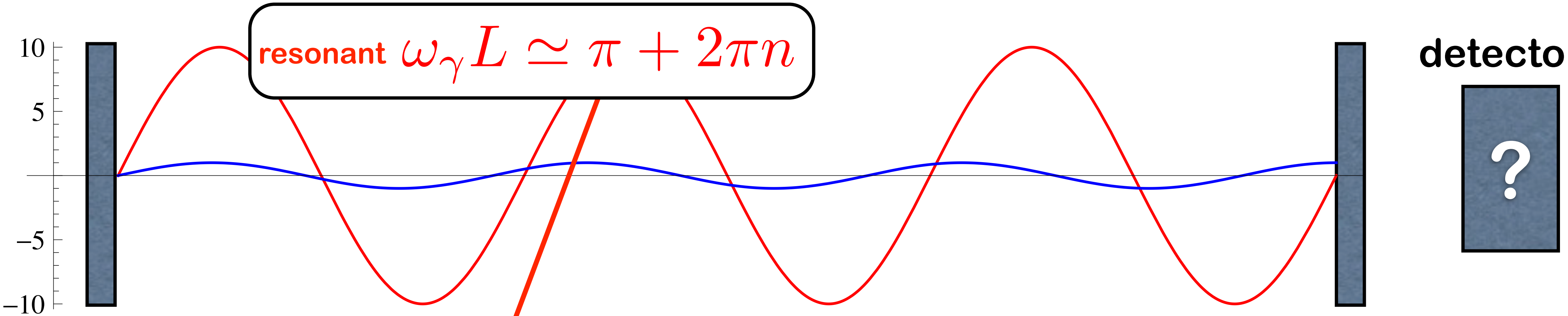

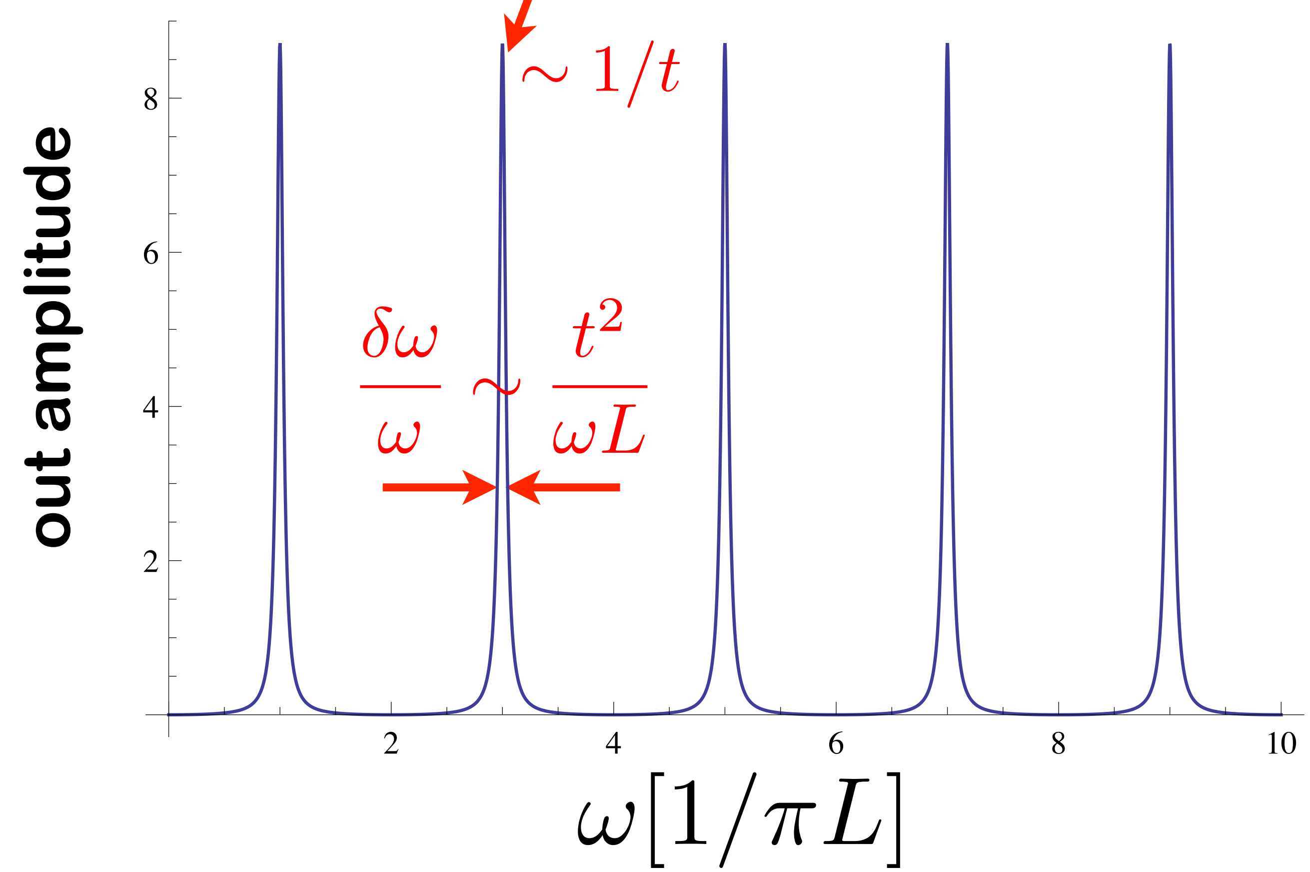

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chose

$$m_a L = \pi$$

$1/t$ **large**

$$t^2 \sim 10^{-6}$$

cavity searches (haloscopes)

- Understanding the out Power

$$P_{\rm out} = {\rm Area}\,|E_\gamma^{out}|^2 = {\rm Area}\,|\frac{1}{t}E_\gamma^{in}|^2 = {\rm Area}\,|\frac{1}{t}E_a^{in}|^2 =$$

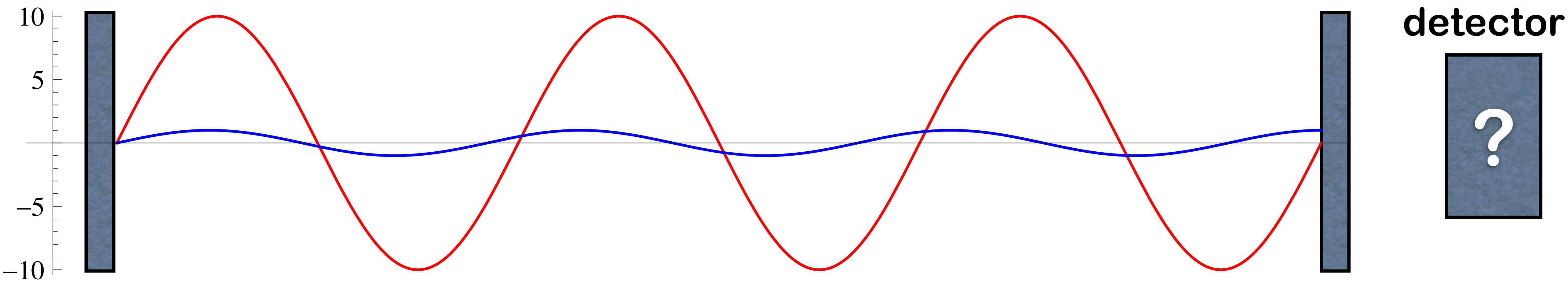
$$ {\rm Area}\,\frac{1}{t^2}\chi^2|\omega_a a|^2 = {\rm Area}\,\frac{1}{t^2}\frac{g^2B^2}{m_a^2}\rho_{\rm CDM}$$

$$m_a L = \pi \to {\rm Area} = \frac{m_a {\rm Volume}}{\pi}$$

$$P_{\rm out} = \boxed{\frac{{\rm Volume}\times m_a}{\pi}} \times \boxed{\frac{1}{[t^2 \sim \delta v^2]}} \times \boxed{\left[\chi \sim \frac{gB}{m_a}\right]^2} \times \boxed{\rho_{\rm CDM}}$$

cavity searches and ALPS-II

- This is the same principle used in the REGENERATION CAVITY OF ALPS-II



- In the HALOSCOPE experiment the coherence in time of the signal comes from the fact that axions are non-relativistic (in the zero-k limit they are standing waves)

- In the ALPS-II (relativistic axions) regeneration cavity, the coherence in time has to be provided by an amazingly stable feeding-laser (and it is ensured if the production cavity is resonant)

cavity searches II: the real thing...

http://www.phys.washington.edu/groups/admx/home.html

$$L = \pi / m_a ?$$

**Once you have the right cavity ...
the only problem is signal/noise**

$$\frac{S}{N} = \frac{P_{\rm out}}{P_{noise}} = \frac{P_{\rm out}}{T_S}\sqrt{\frac{\rm time}{\rm Bandwidth}}$$

measurement time vs. different measurements

ADMX is now fighting to cool down the cavity/amplifier to liquid 3He

the definitive experiment! ... ???

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- Problem! We don't know the axion mass!!!!!!!!! $L = \pi/m_a?$

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$$L_0,\, L_0 + \delta,$$

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slow scan, adjusting the length!

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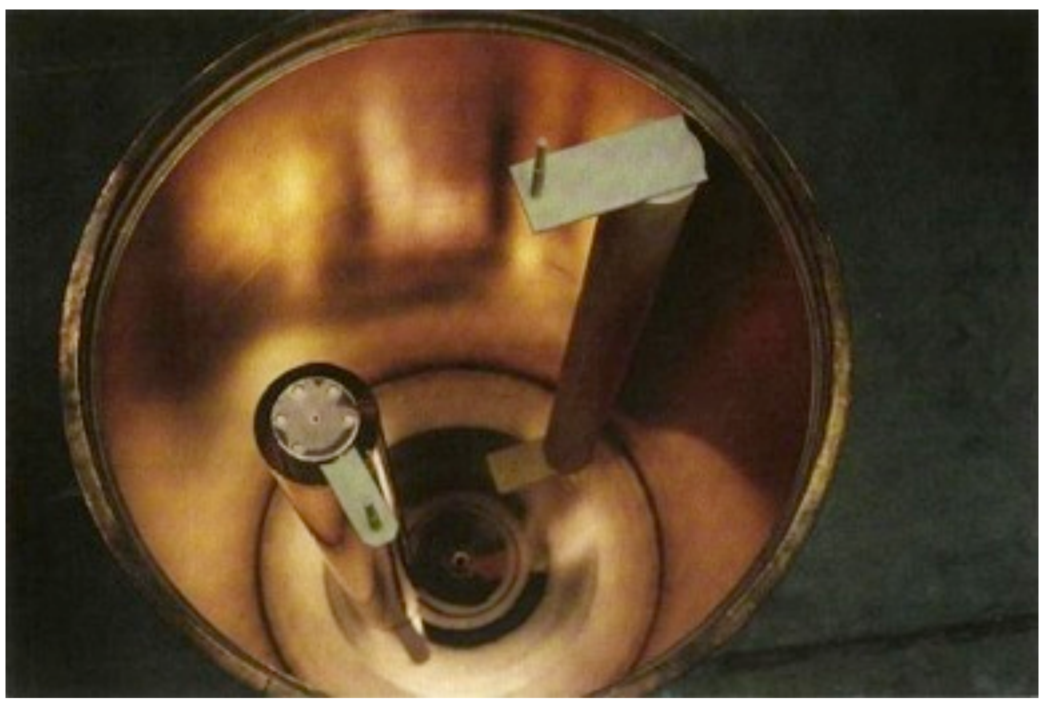
- Axion DM eXperiment ADMX (Washington U.) ... (the 3D version is more complex)



8T field, 1mL,0.5mD

$$m_a \sim 1/L \sim \mu\mathrm{eV}$$

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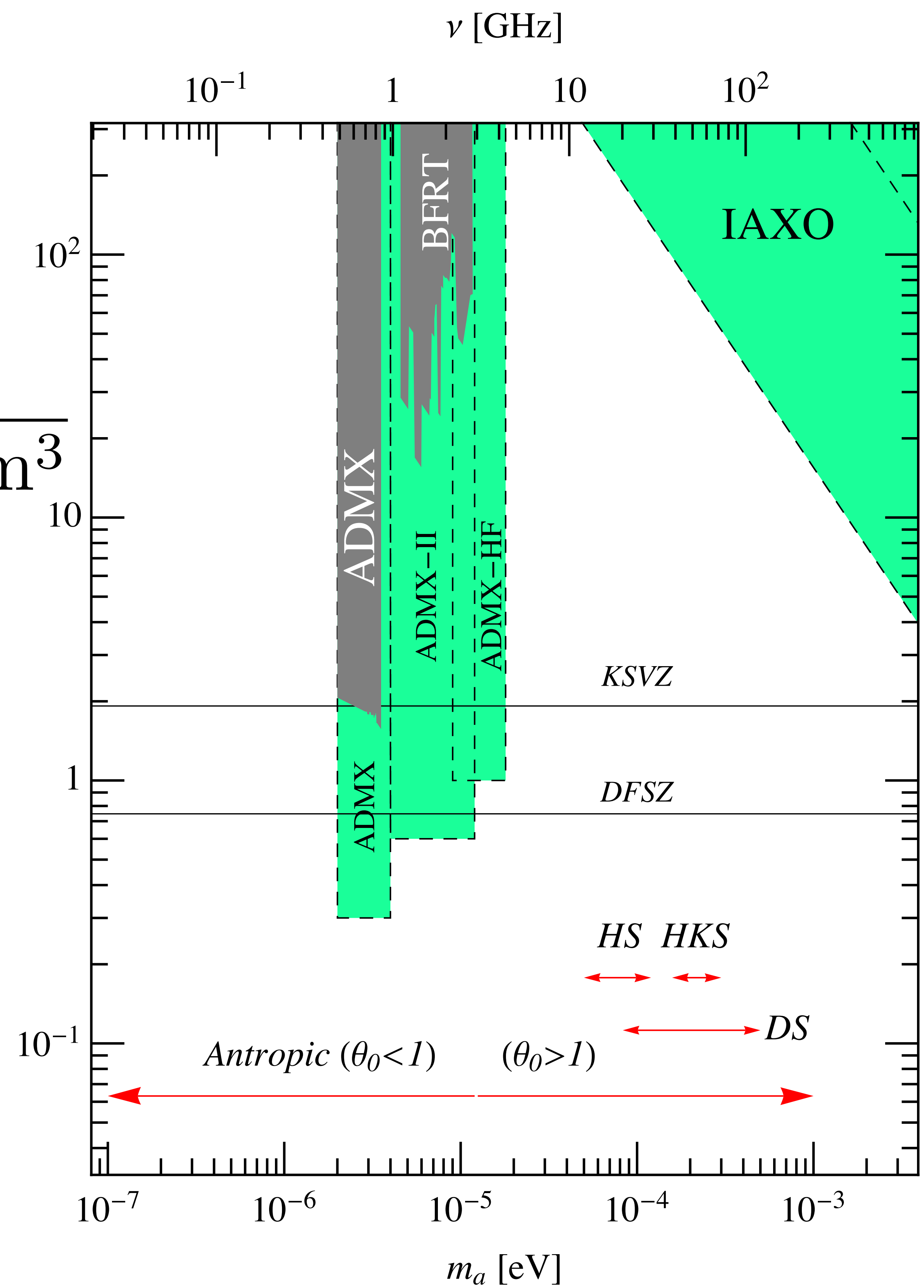
cavity searches II: ADMX and relatives

$$c_{a\gamma\gamma} \times \frac{\rho_{\rm CDM}}{0.3{\rm GeV}/{\rm cm}^3}$$



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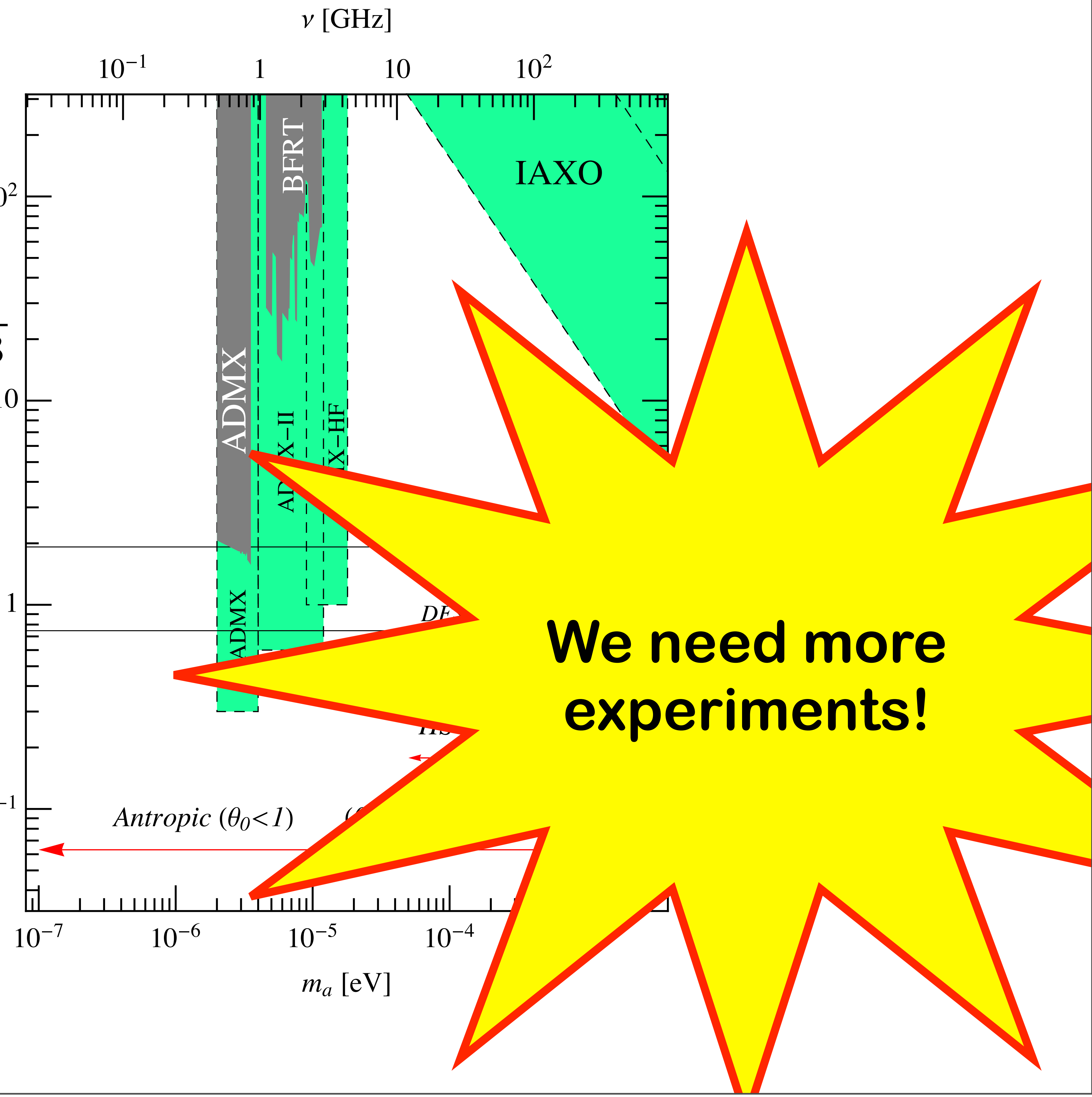
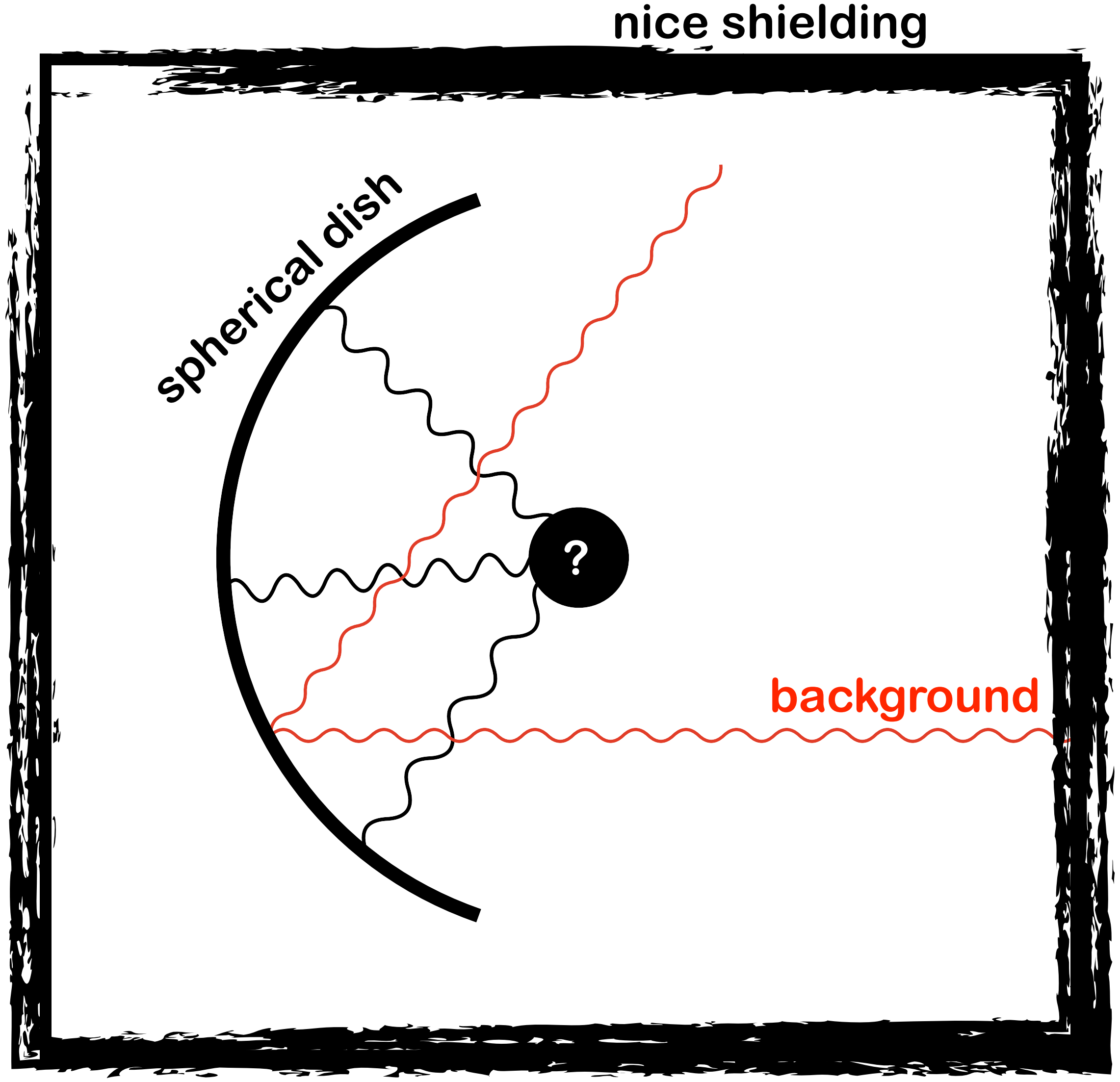


dish antenna searches (broadband!)

Horns et al, arXiv:1212.2970



- Mirror radiation is perpendicular to the mirror's surface (emitted coherently from the surface!)

- concentrate emission using a spherical dish antenna!

Comparing both methods...

$$P_{\rm center} \approx A_{\rm dish}\langle|\mathbf{E}_{{\rm DM},||}|^2\rangle \sim \chi^2 \rho_{\rm CDM} A_{\rm dish}$$

$$P_{\rm resonant\ cavity} = \kappa\chi^2 m_a \rho_{\rm CDM} Q V_{\rm cavity} \mathcal{G}_0(\alpha')^2 .$$

$$\frac{P_{\rm center}}{P_{\rm cavity}} \sim \frac{A_{\rm dish} m_a^2}{10^6}$$

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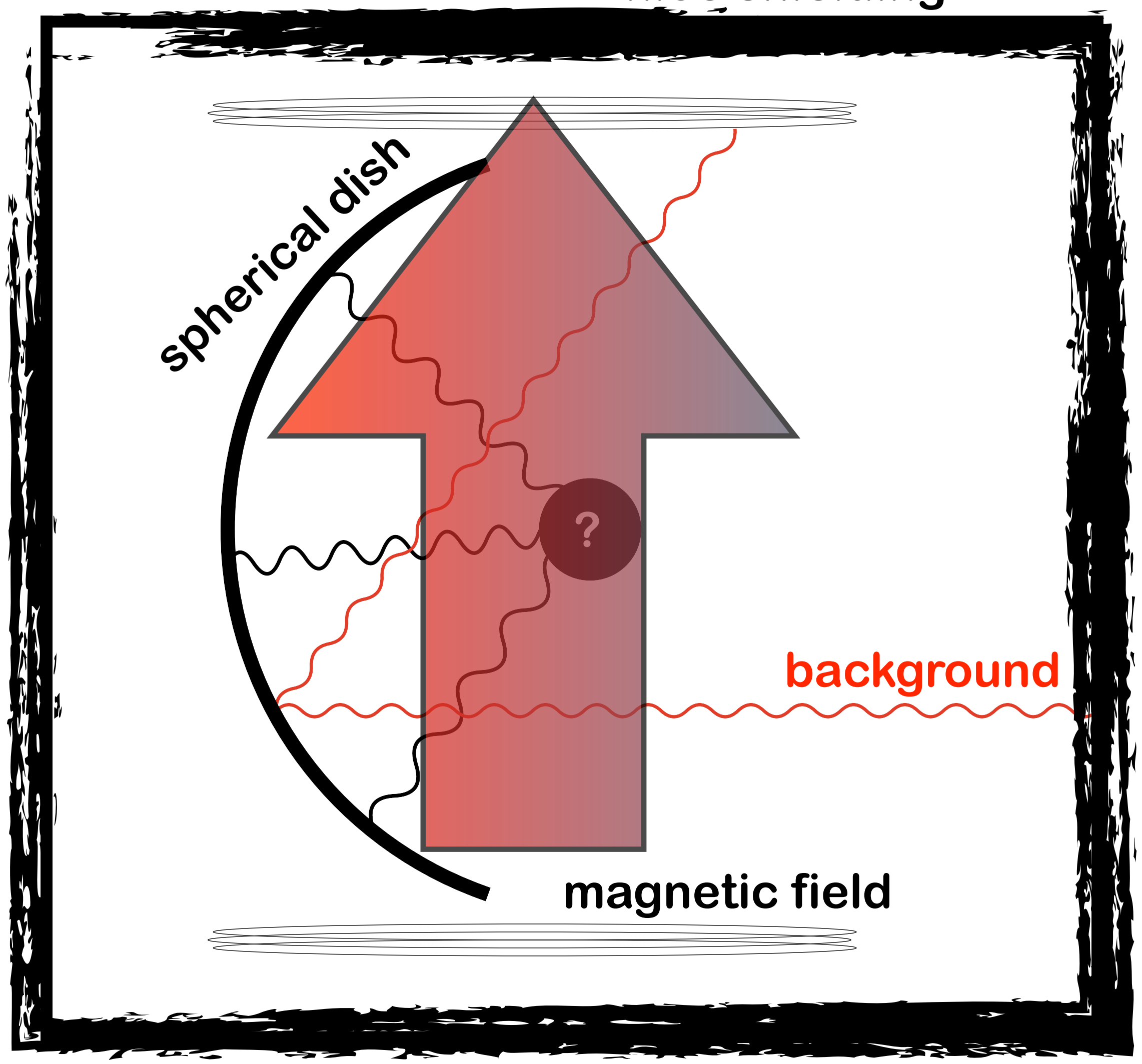

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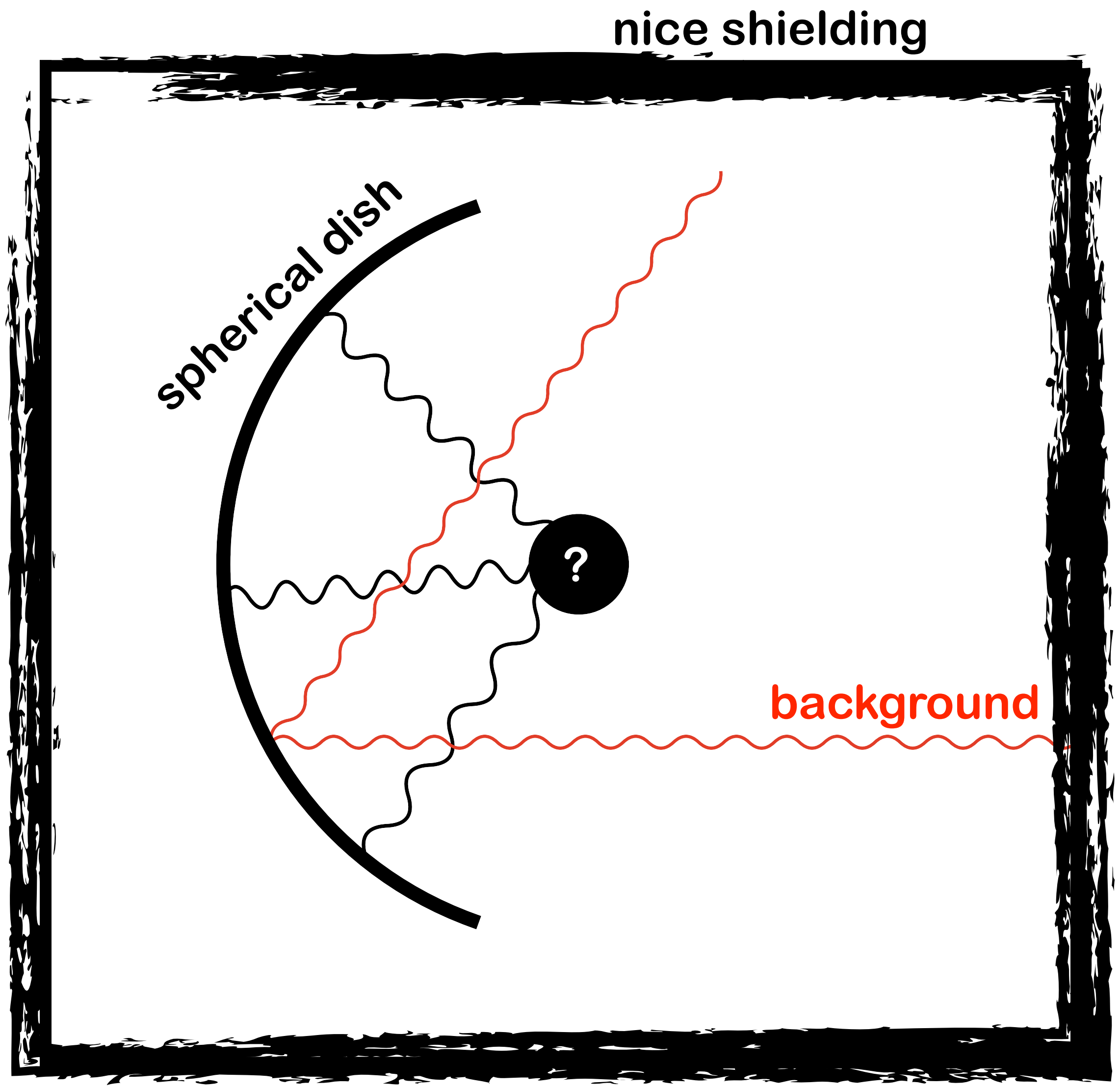

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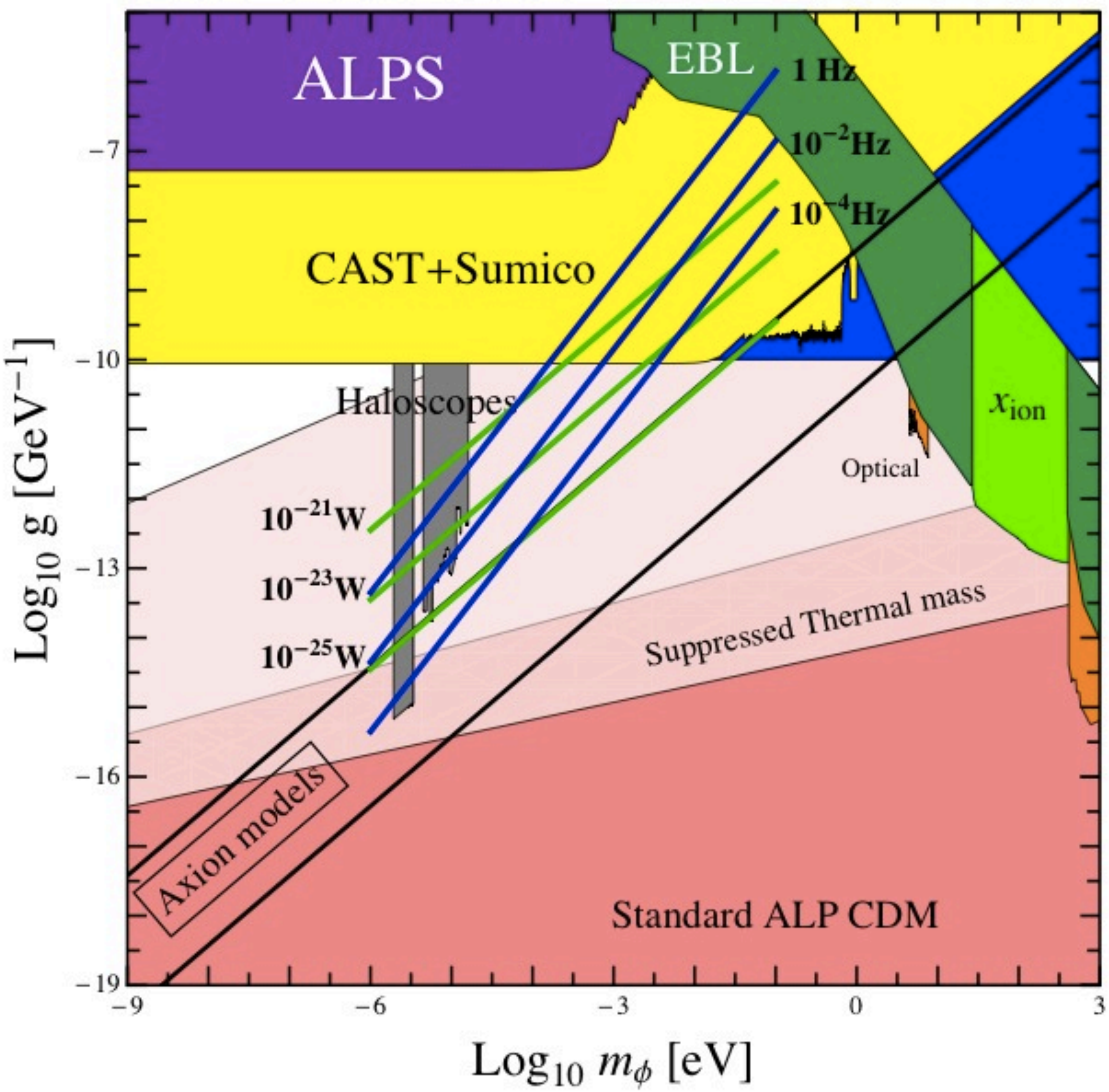


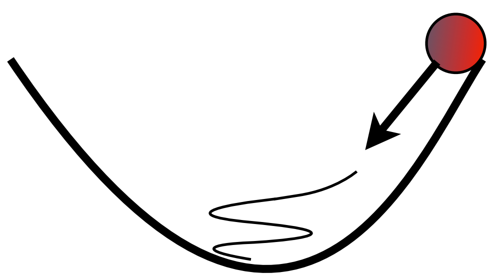
1 m^2 dish
5T magnet

to take home

- No nEDM, dark matter is there... axions?
- WISPy cold dark matter
- cavity experiments (ADMX) hunt in the micro-eV
- new experiments!
- higher masses are motivated, but difficult!
- new broadband proposal with dish antennas

Light Dark Matter: non-thermal relics

Any light boson features the realignment mechanism (like axions)



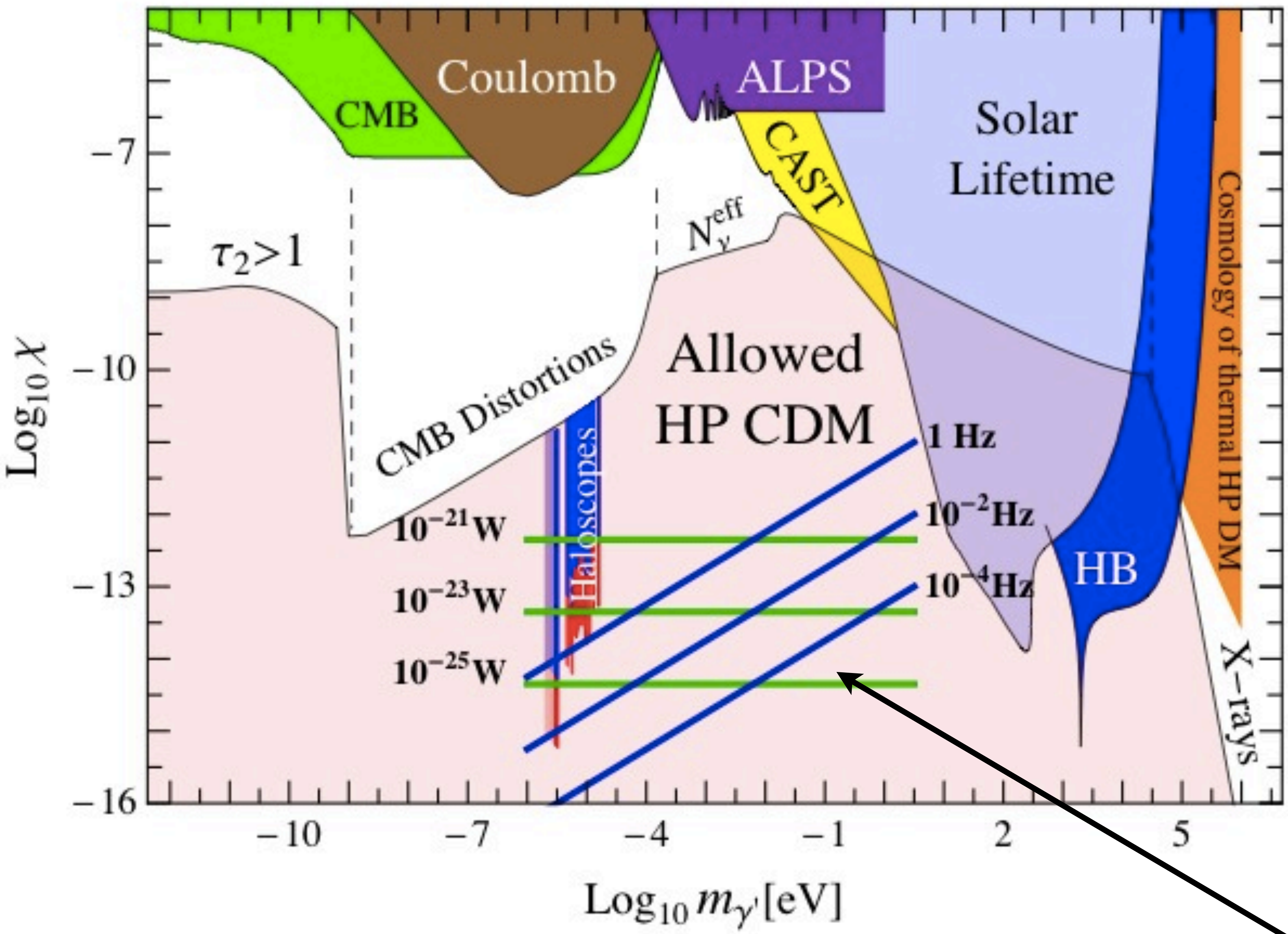
Hidden photons can be also Cold Dark Matter

Nelson et al, PRD84 ; Arias et al, JCAP 1206

dish antenna searches (broadband!)

Horns et al, arXiv:1212.2970

kinetic mixing



HP mass

1 m^2 dish
5T magnet