Searching for axion Dark Matter

Jun 7th 2013,
IPhT, Saclay

Javier Redondo (LMU, MPP Munich)

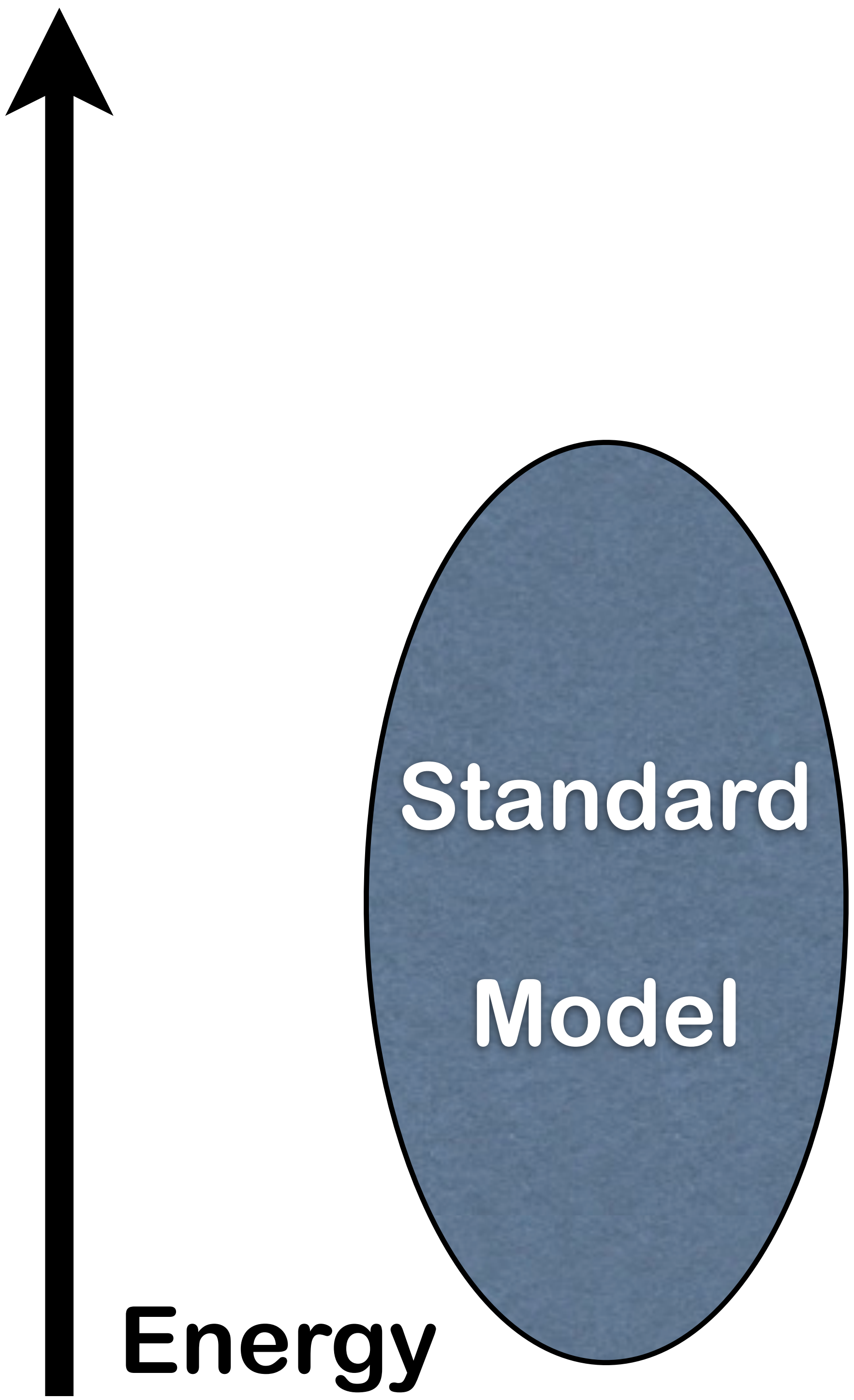
Outline

- Invitation: BSM at low energies and strong CP

- Axions and WISPs as dark matter

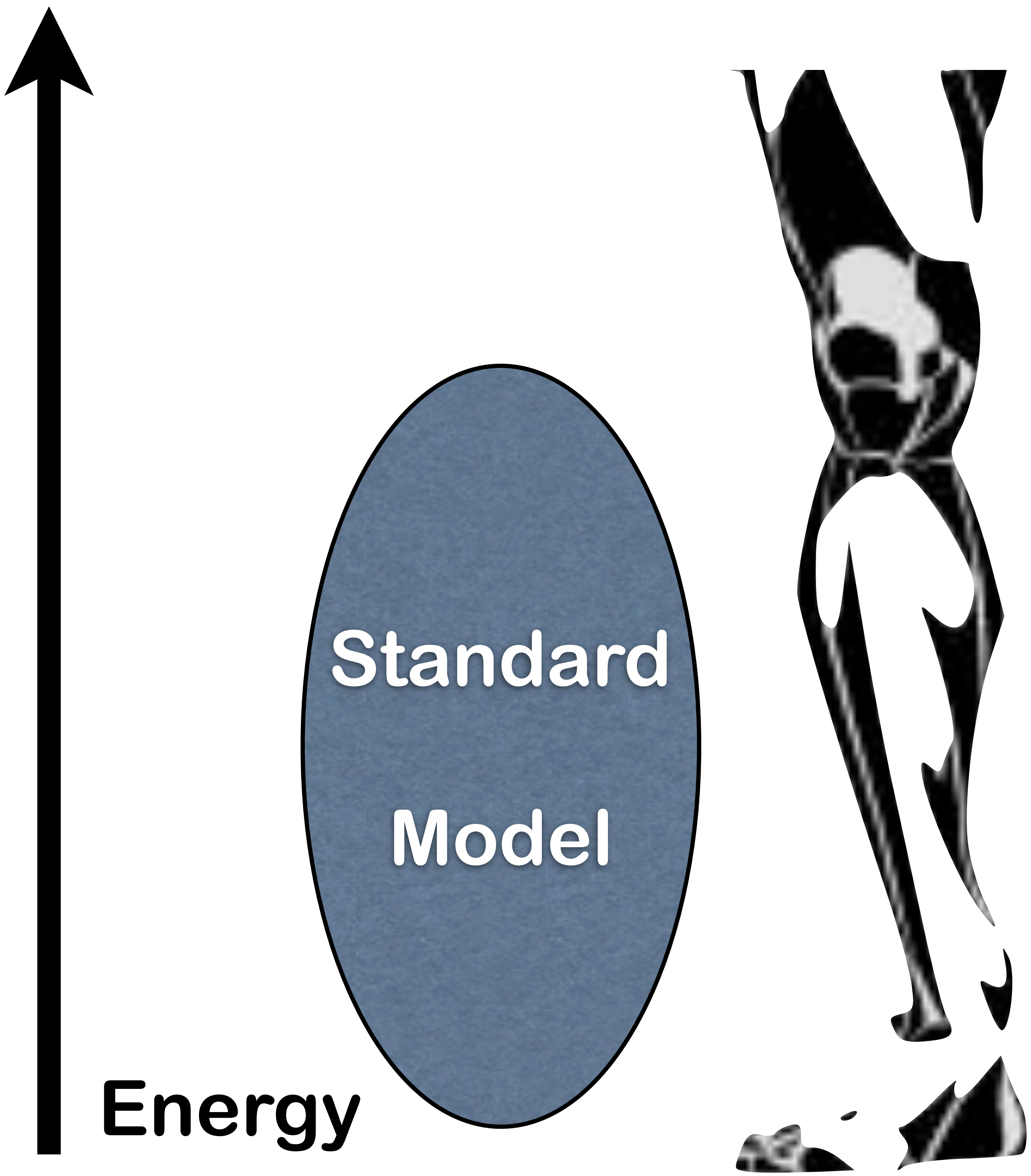
- Searching for axion dark matter

Beyond the SM ... at low energies



Describes extremely well fundamental physics (at low energies)

Beyond the SM ... at low energies

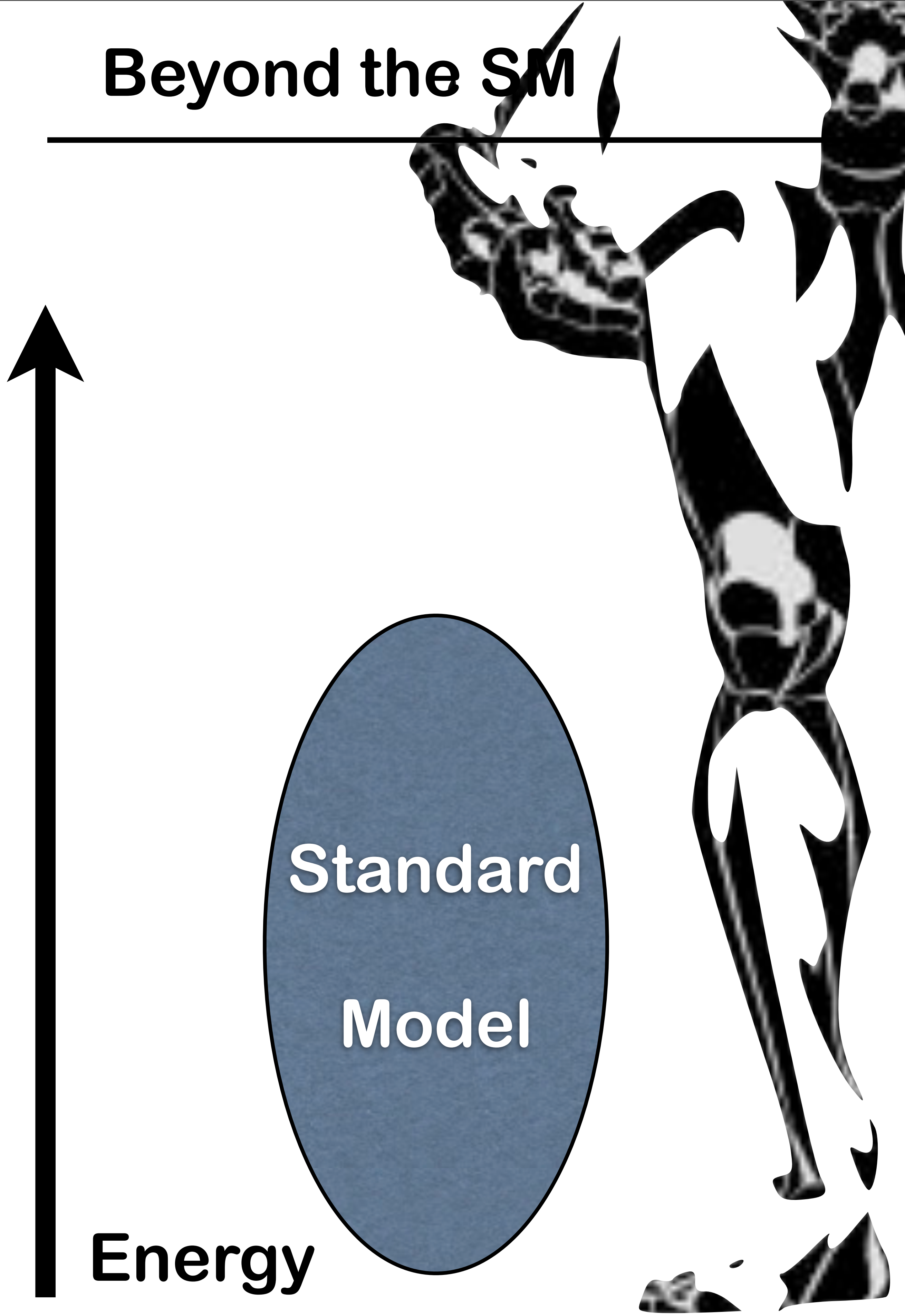


Describes extremely well fundamental physics (at low energies)

but feels certainly

INCOMPLETE

Beyond the SM ... at low energies

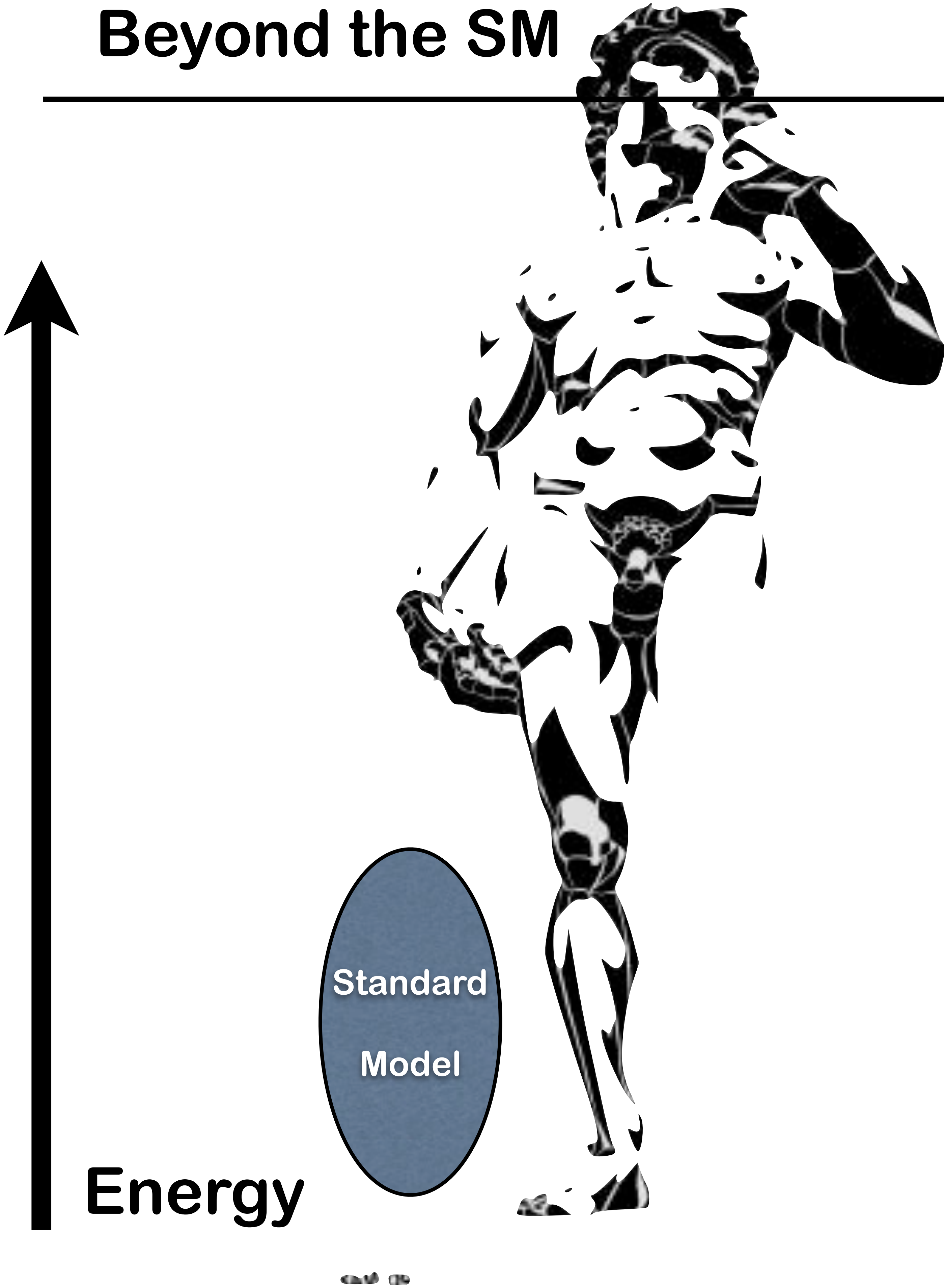


Answers are awaiting in the

high energy frontier

where more symmetric beautiful theories arise

Beyond the SM ... at low energies



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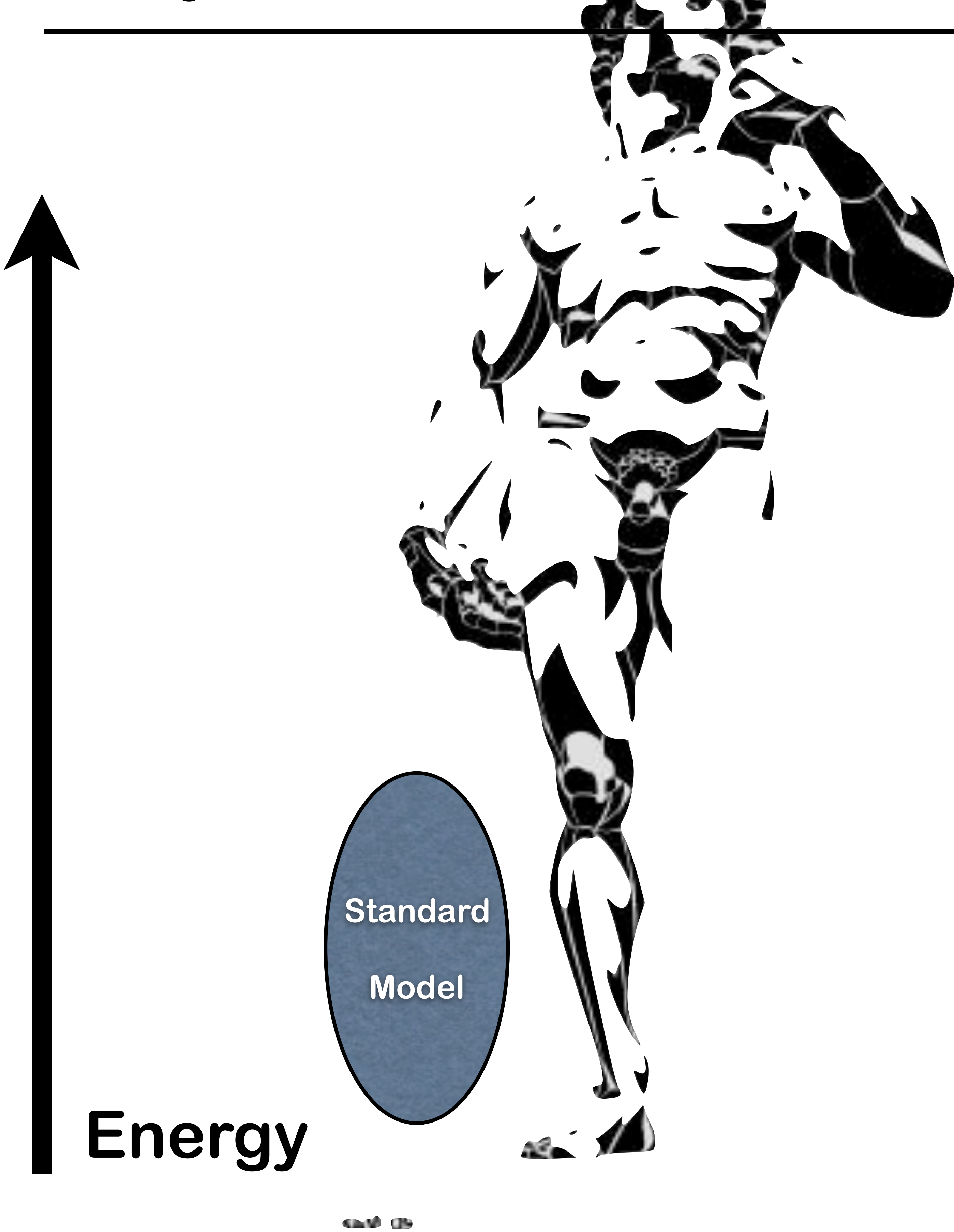

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Beyond the SM ... at low energies

Energy

Answers are awaiting in the

high energy frontier

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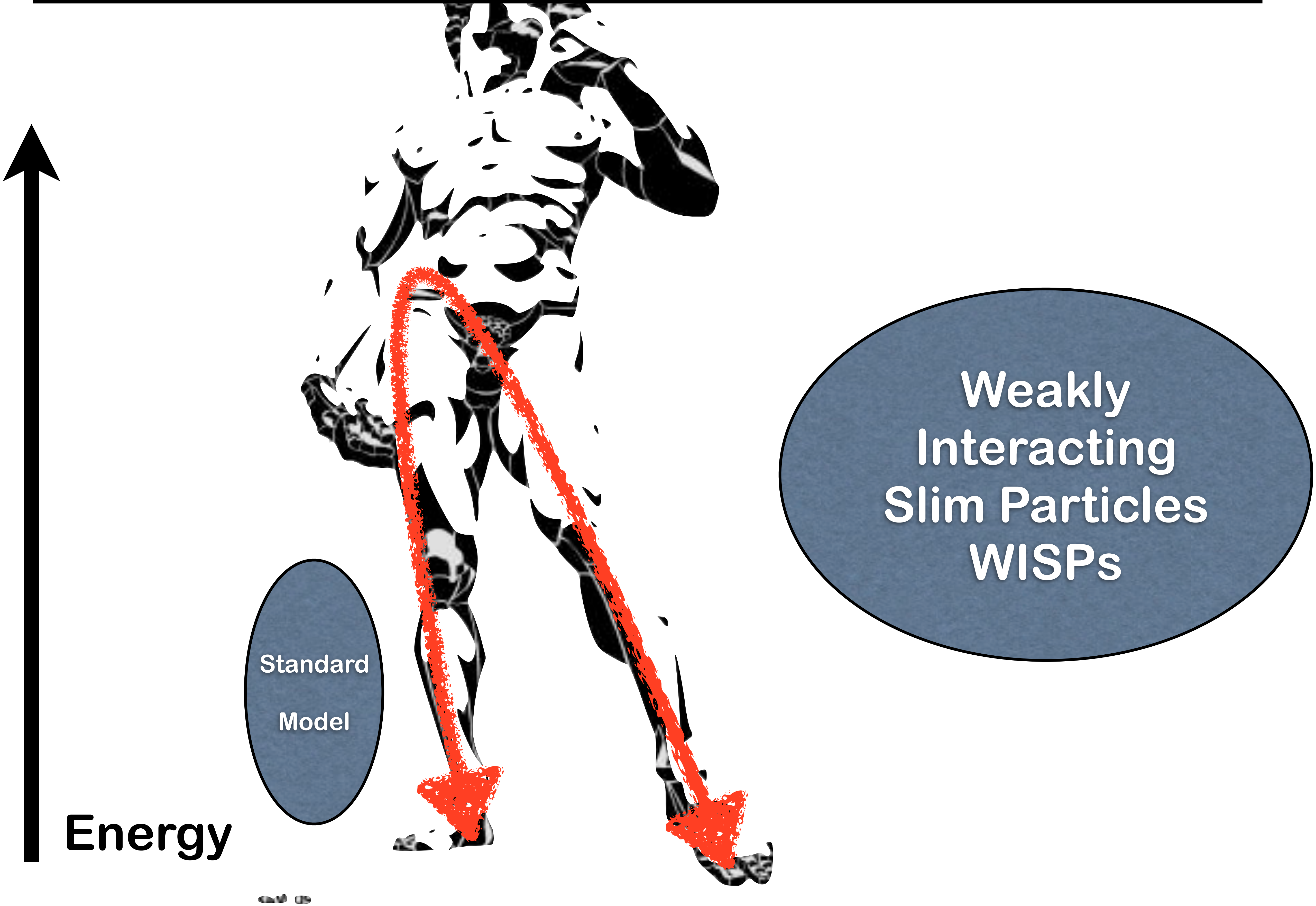
... and can imply physics at low energies

Beyond the SM ... at low energies

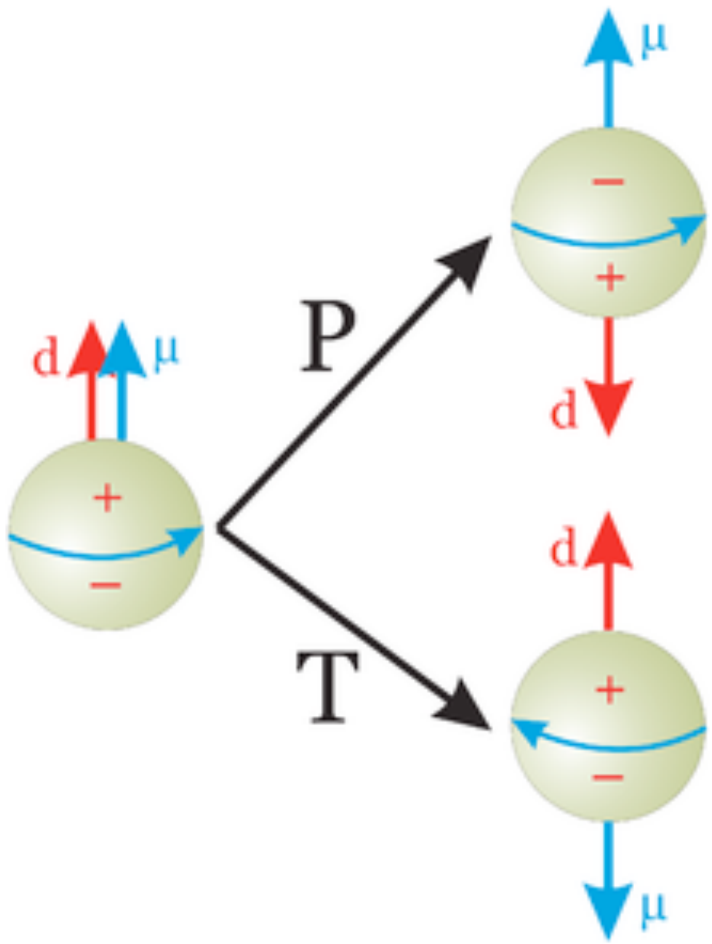


The paradigmatic example: Strong CP problem

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

Violates P and T

neutron EDM



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

Prediction:

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

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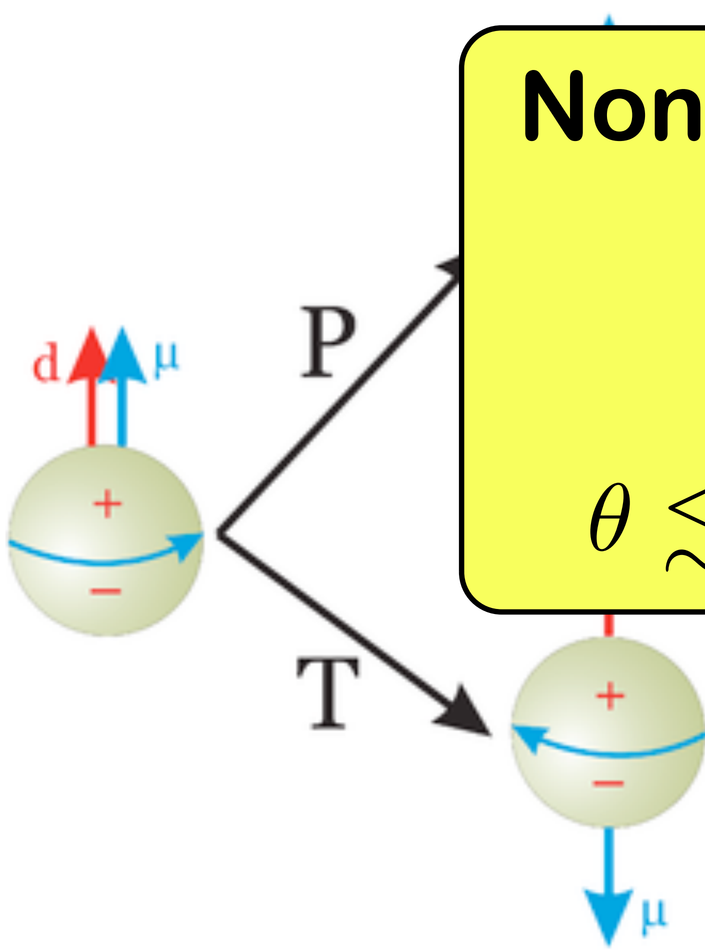


Non Observation:

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

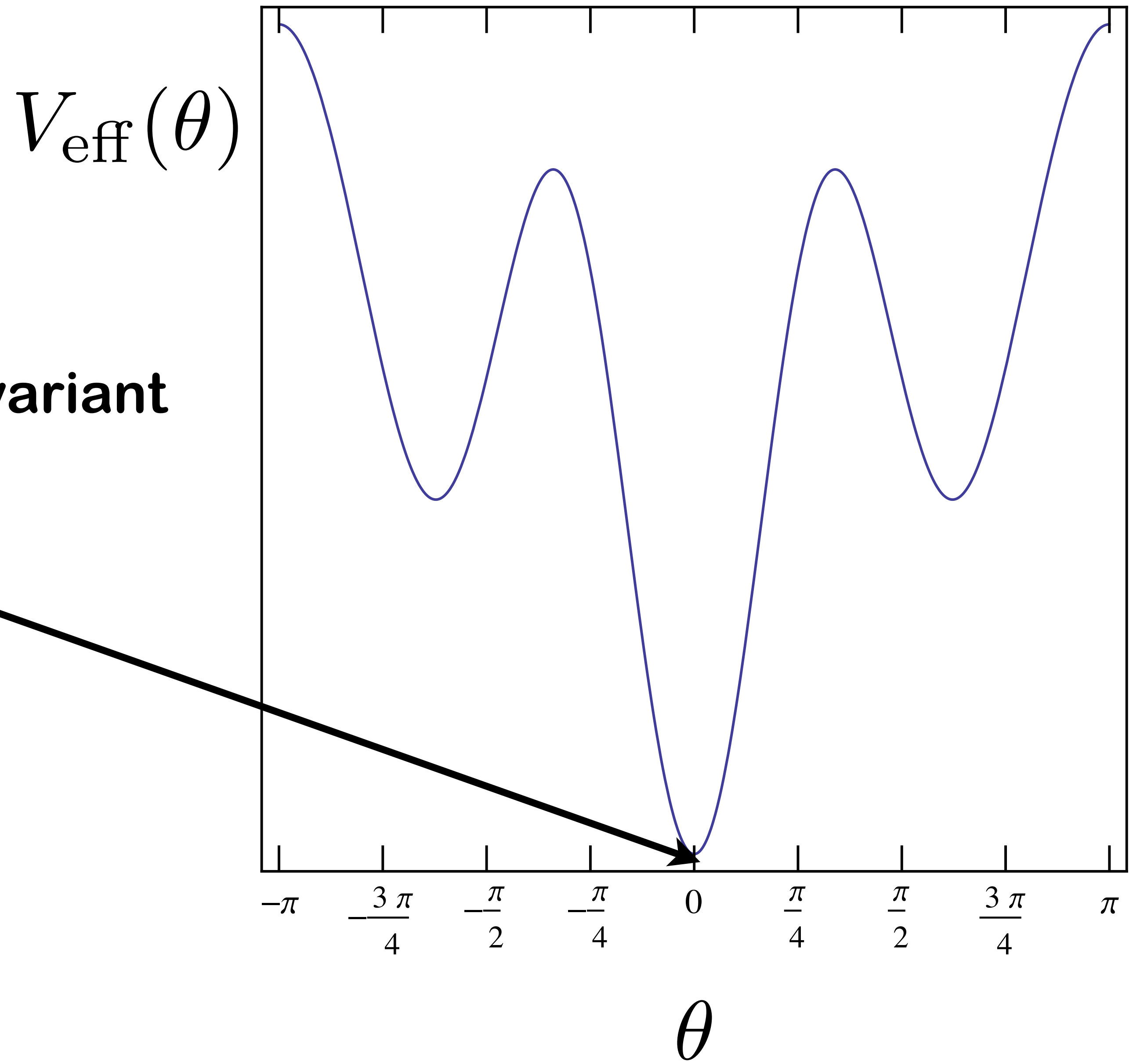
$\theta \lesssim 10^{-11}$ **Why ?????**

Prediction:

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

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

The Strong CP problem: a hint

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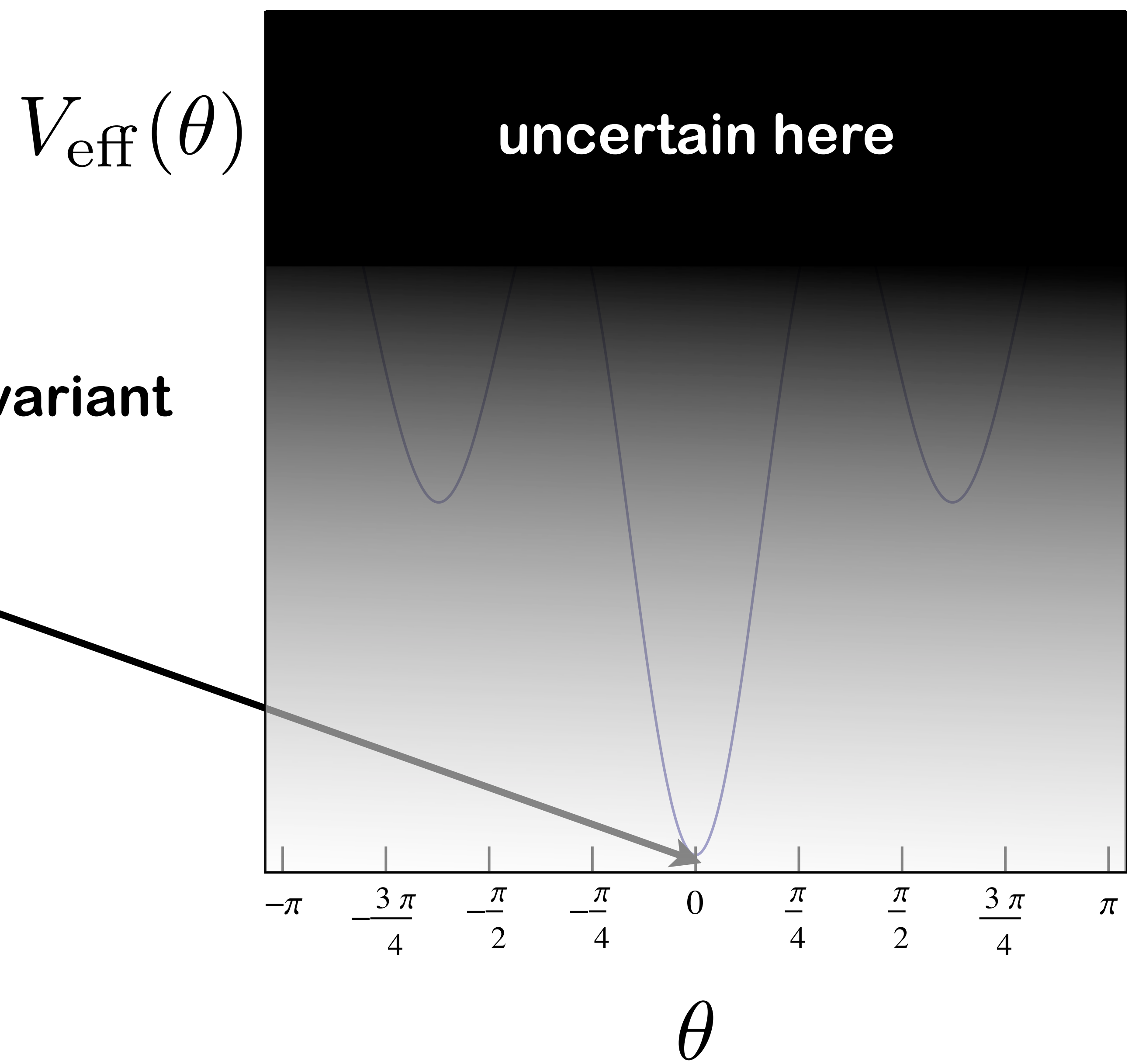


The Strong CP problem: a hint

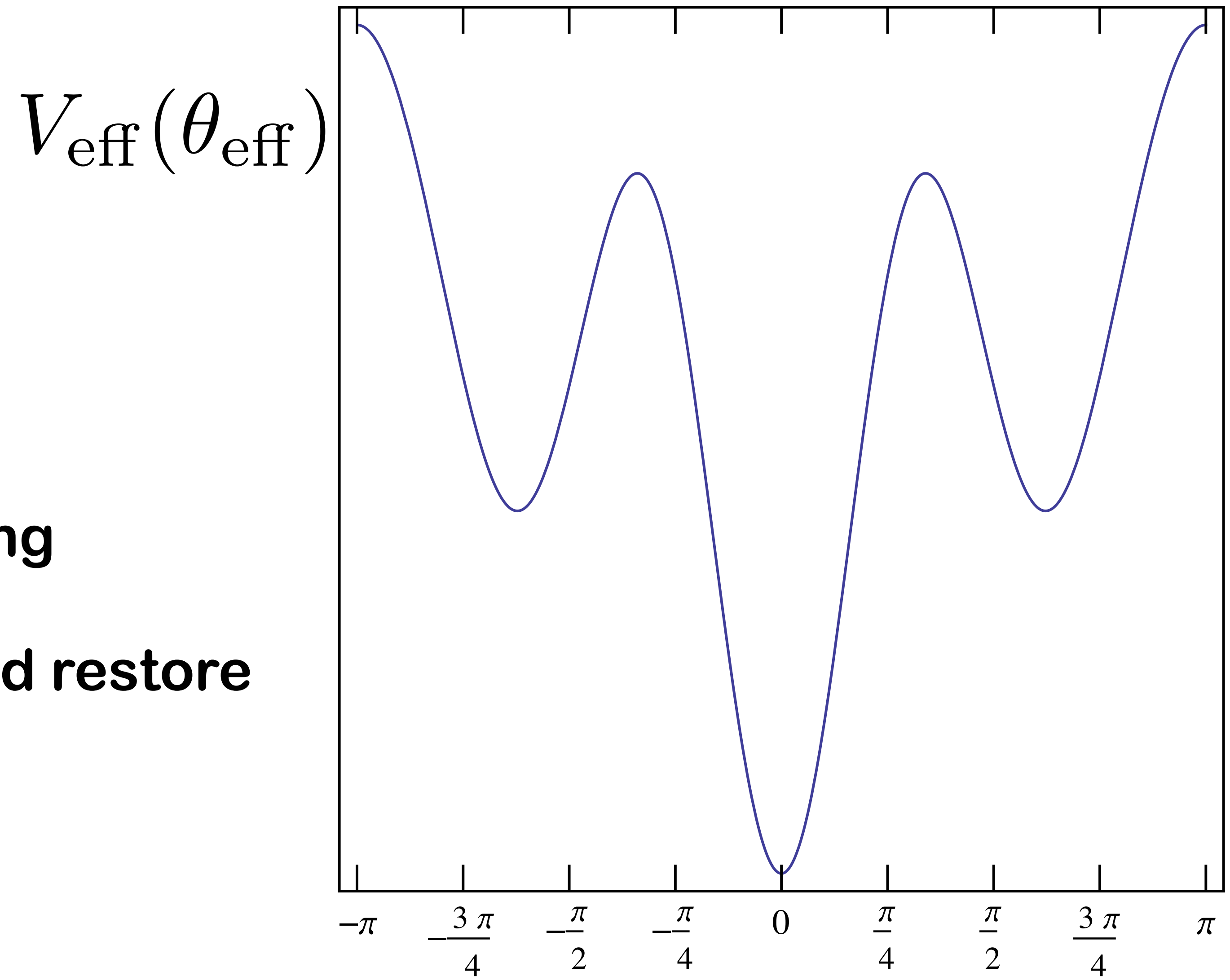
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\mathrm{tr}\left\{G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}\right\}\left(\theta + \frac{\eta'}{f_\eta}\right)$$

With quarks, low-energy QCD

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

η' **has anomalous gg coupling**

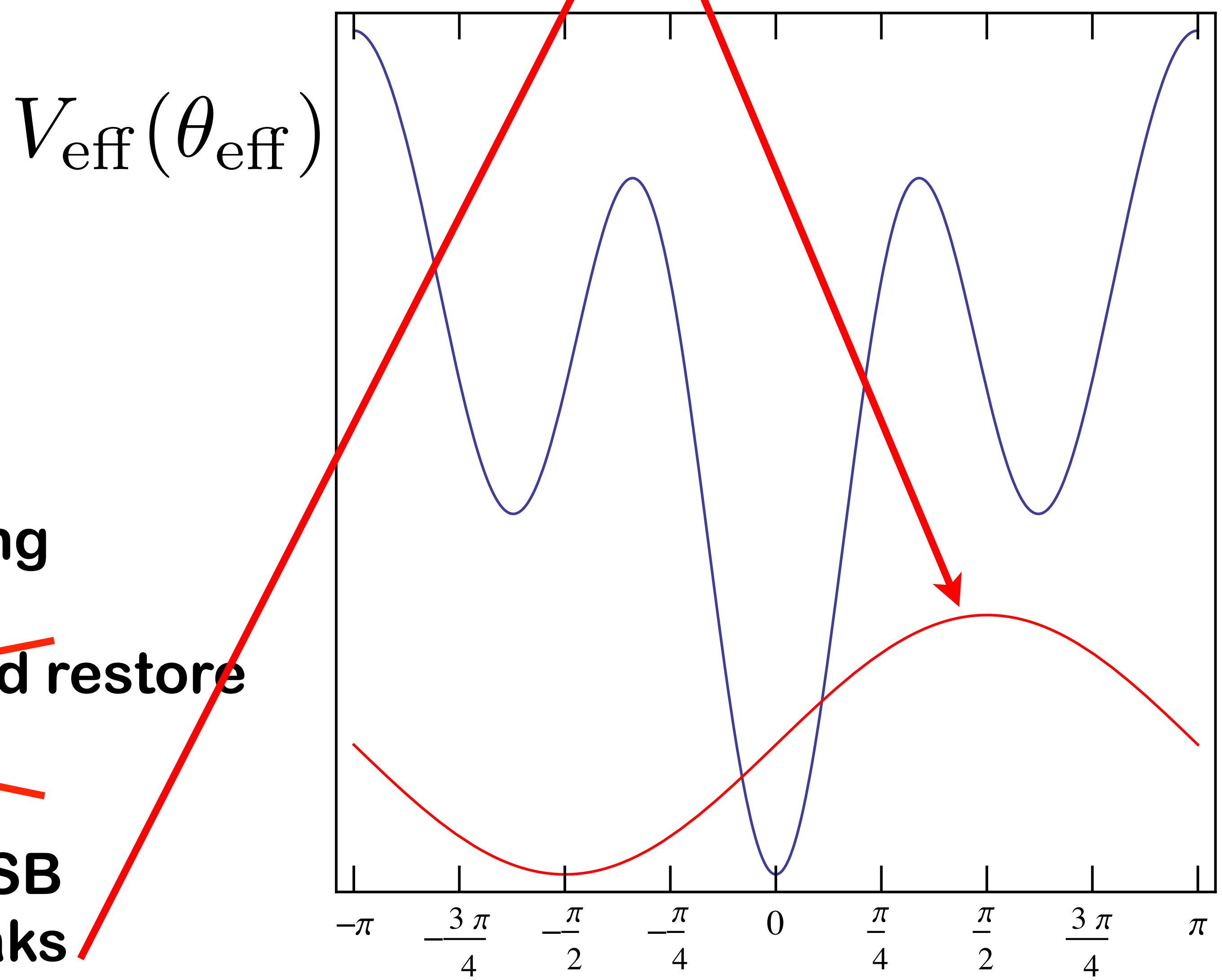
can roll down the potential and restore P, T symmetries!!



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

The Strong CP problem: a hint

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



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With quarks, low-energy QCD

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

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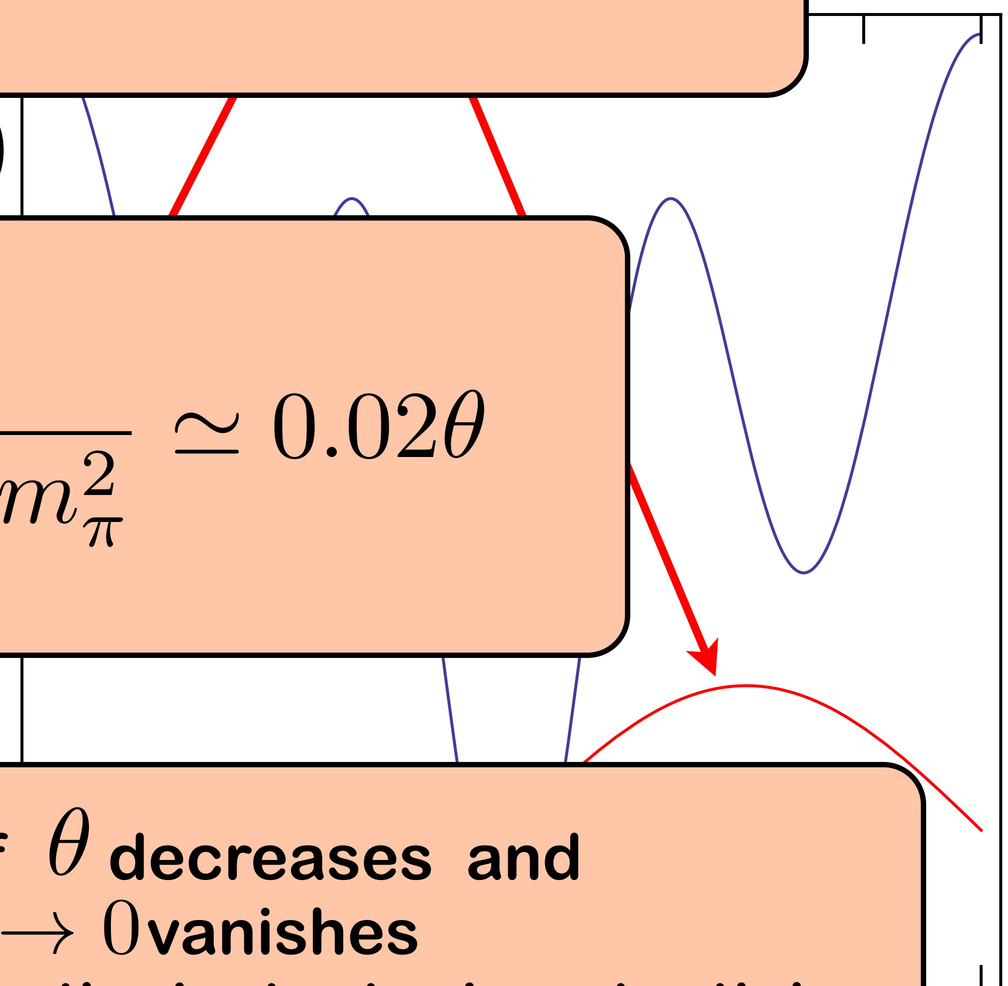
~~**can roll down the potential and restore P, T symmetries!!**~~

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

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

η' **has anomalou**

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

~~**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

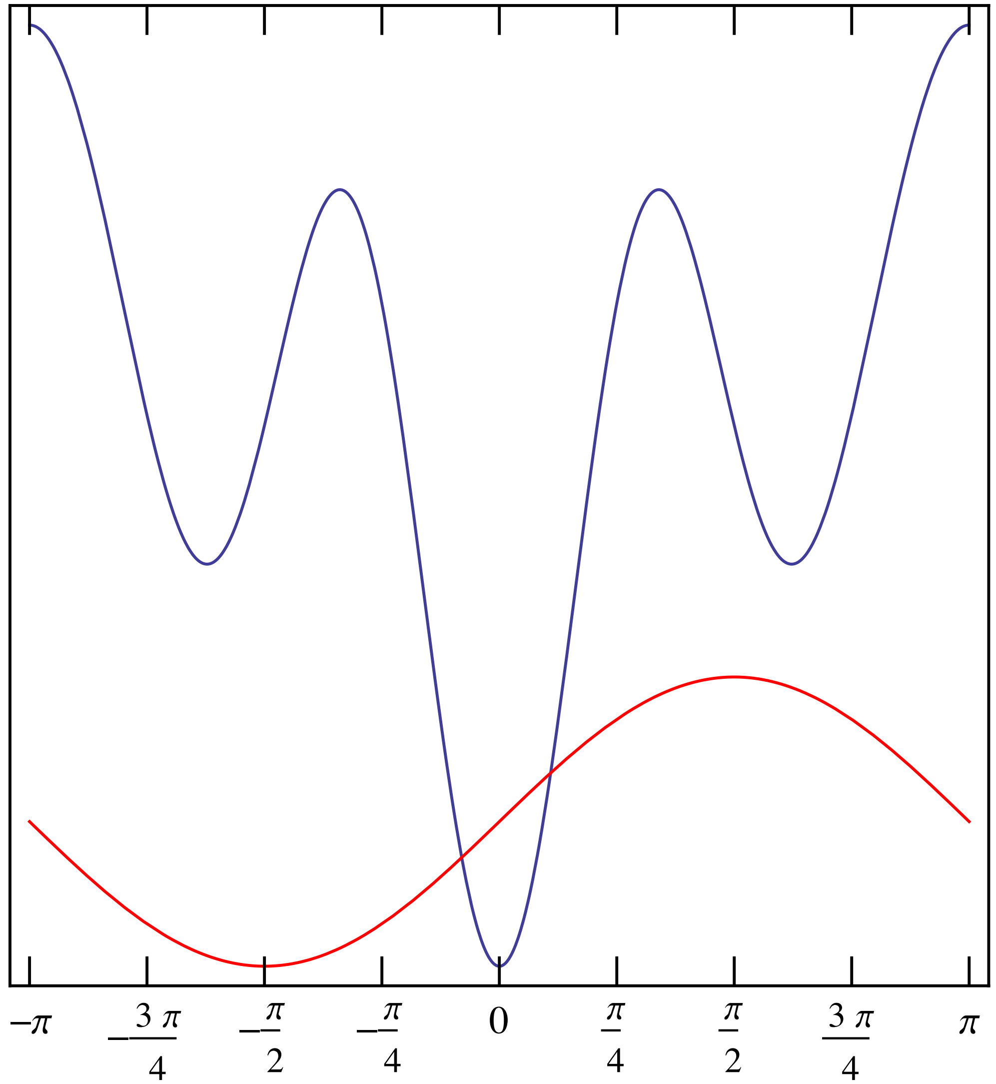
Actually
makes η
explicitly $U(1)_{\rm A}$ giving η' a mass of the order of the π^0 mass.

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

Axion as a solution to the strong CP problem

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

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



Add a new field coupling to gg

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

usually called Peccei-Quinn symmetry

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

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

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

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

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 mixes with QCD mesons and gets mass and couplings

Mass

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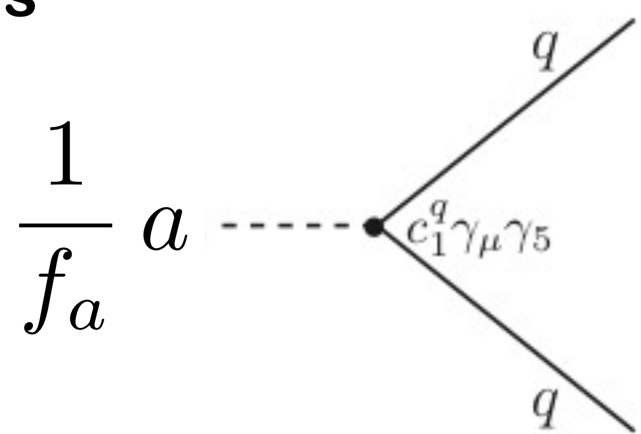
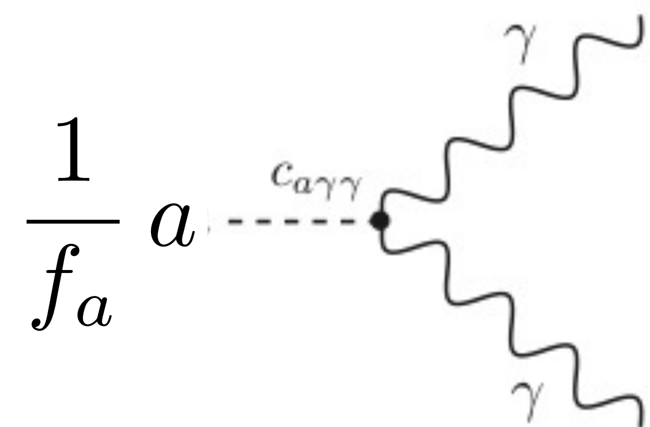
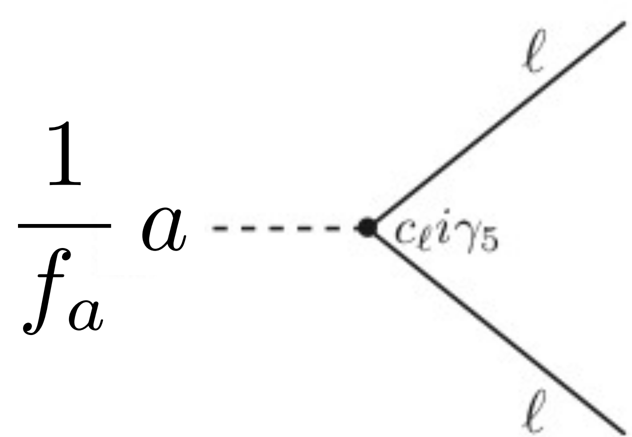
Bare models





Extended models also feature couplings to leptons



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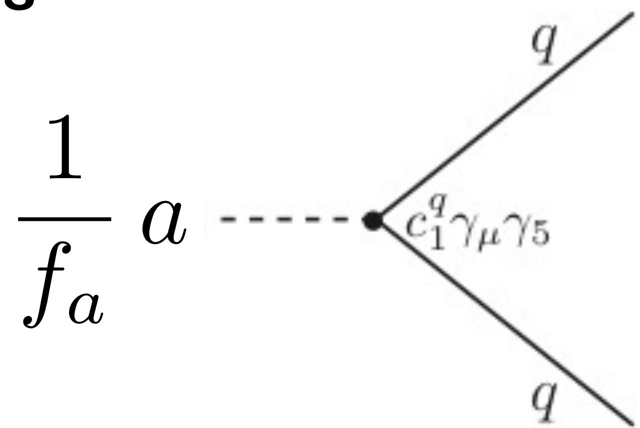

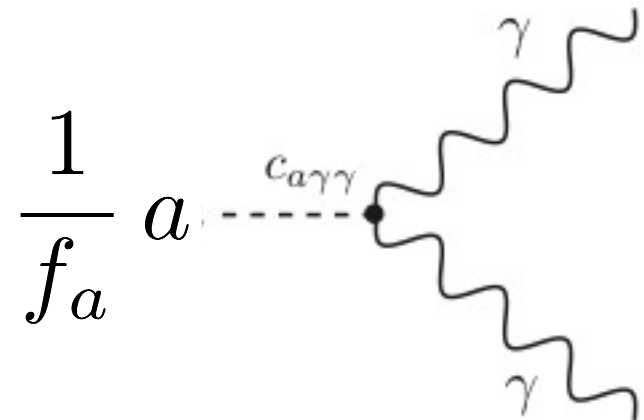

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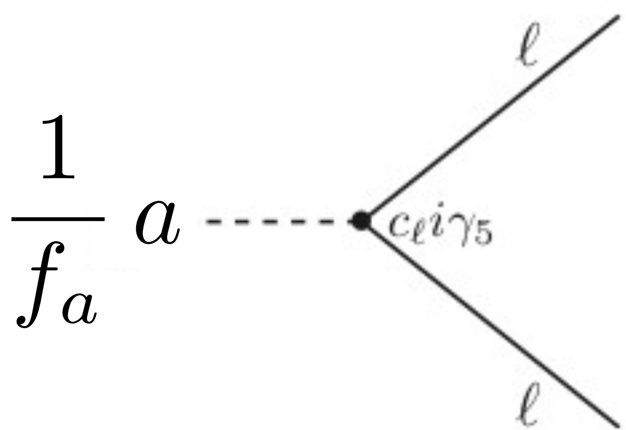

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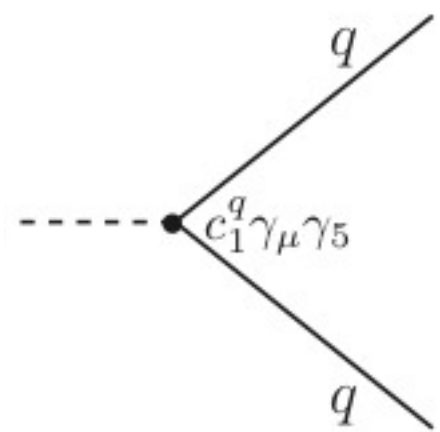
$$\frac{1}{f_a}\, a$$



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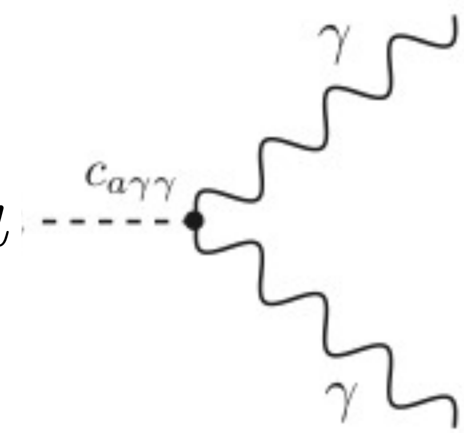

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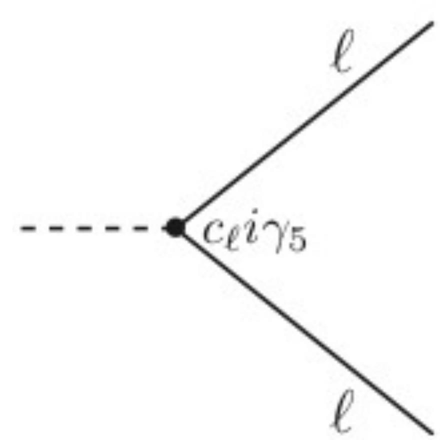

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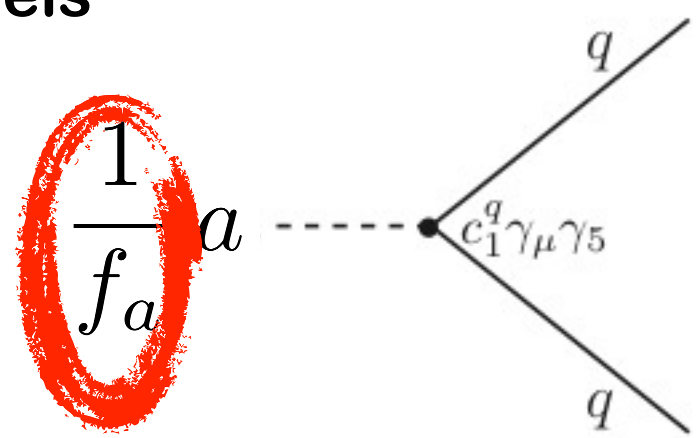

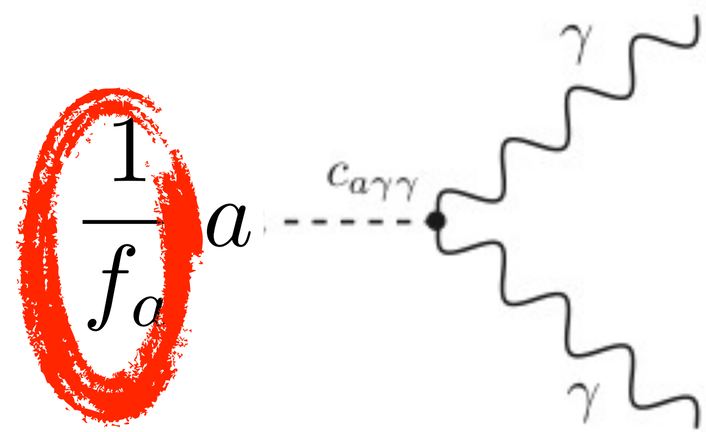

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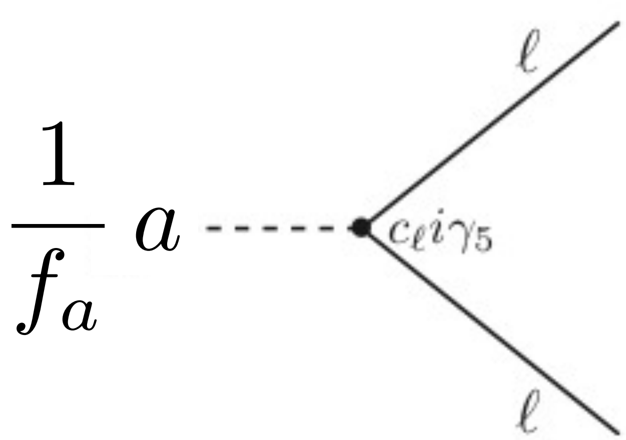

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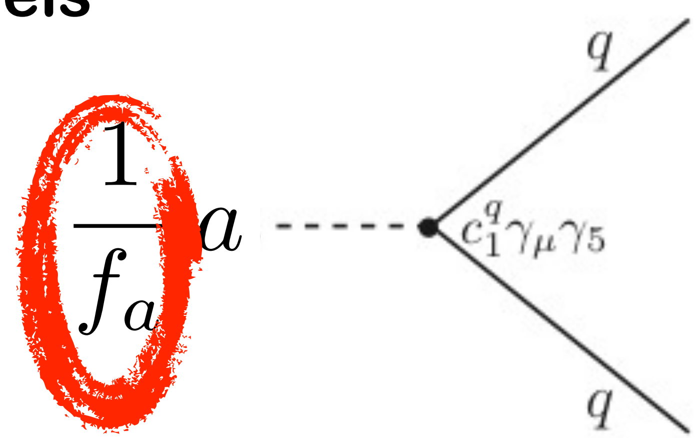

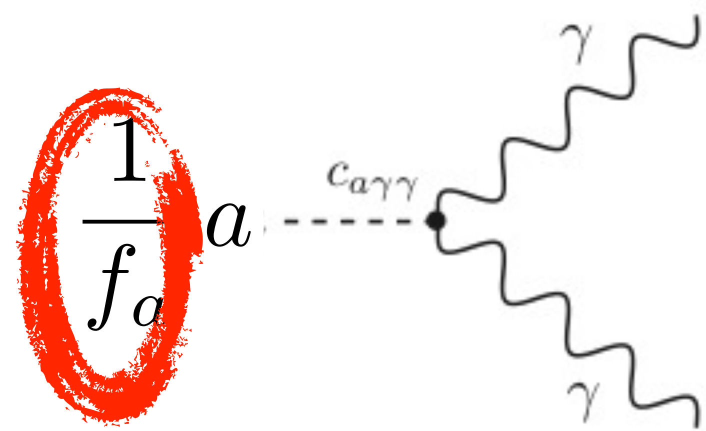

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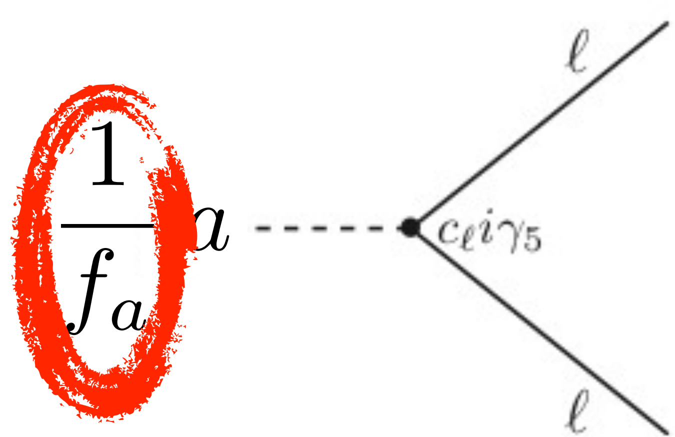

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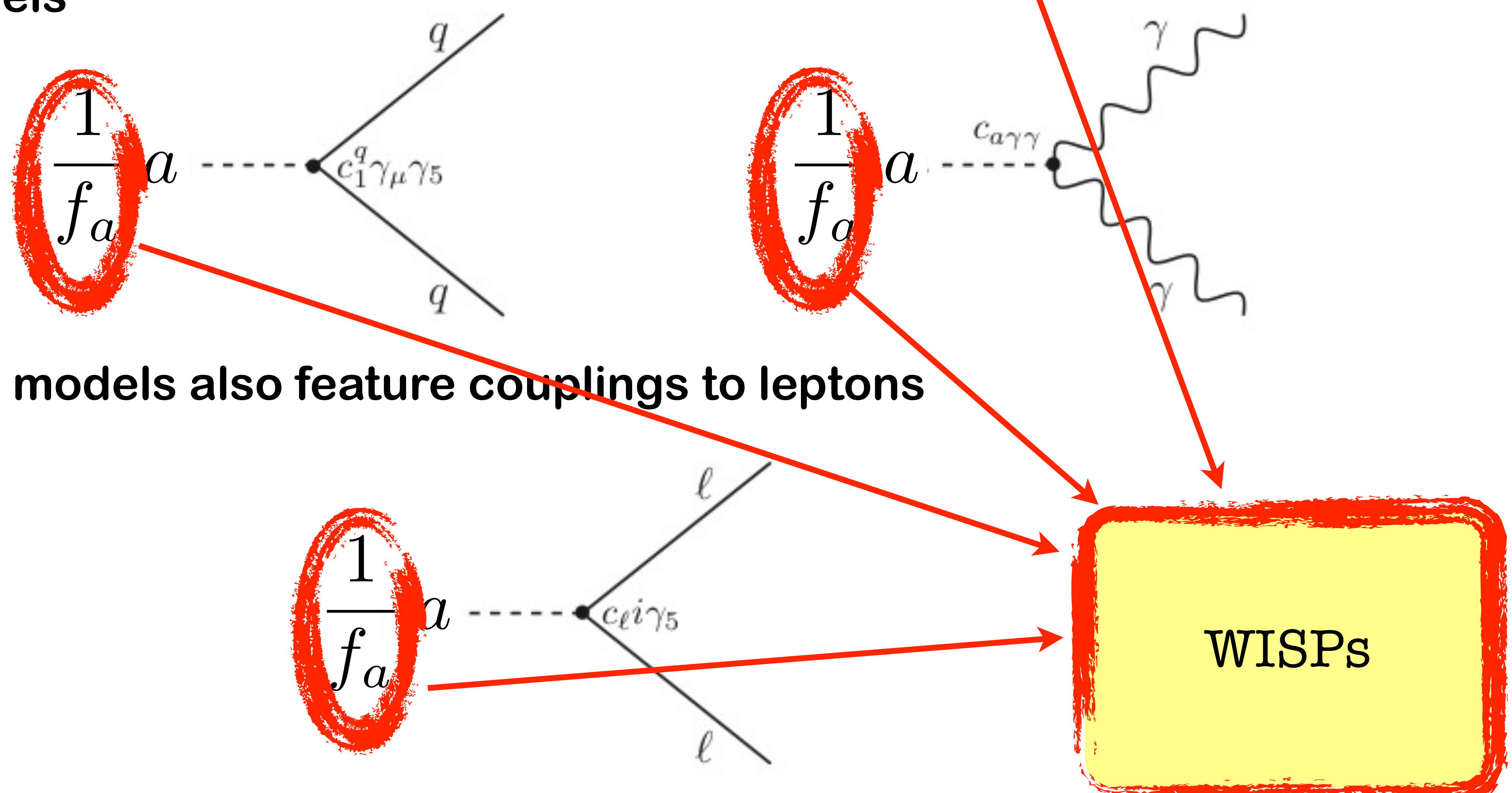

Axion mixes with QCD mesons and gets mass and couplings

Typical from Nambu-Goldstone Bosons

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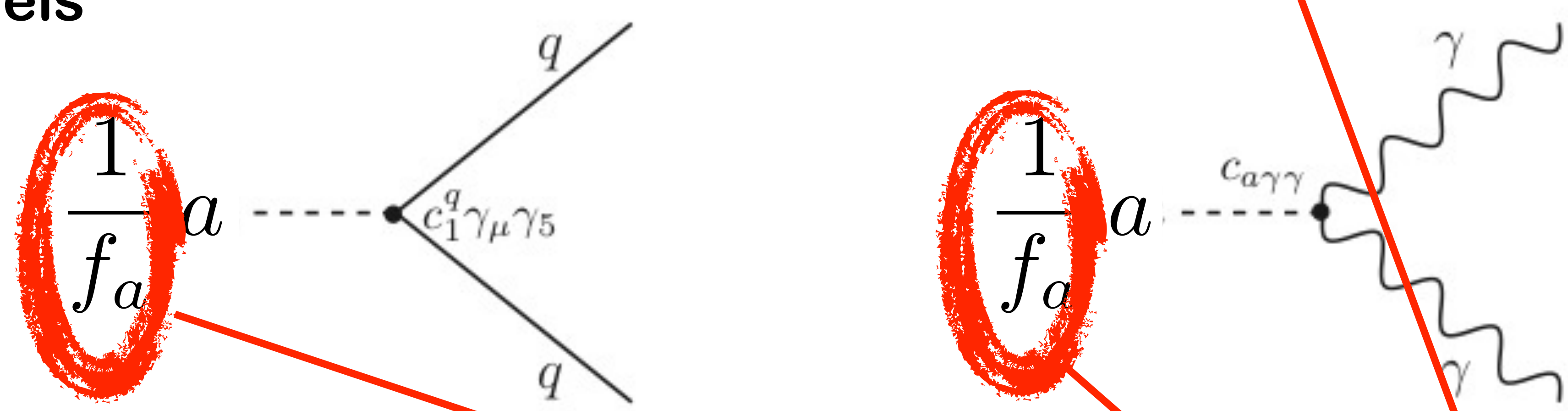

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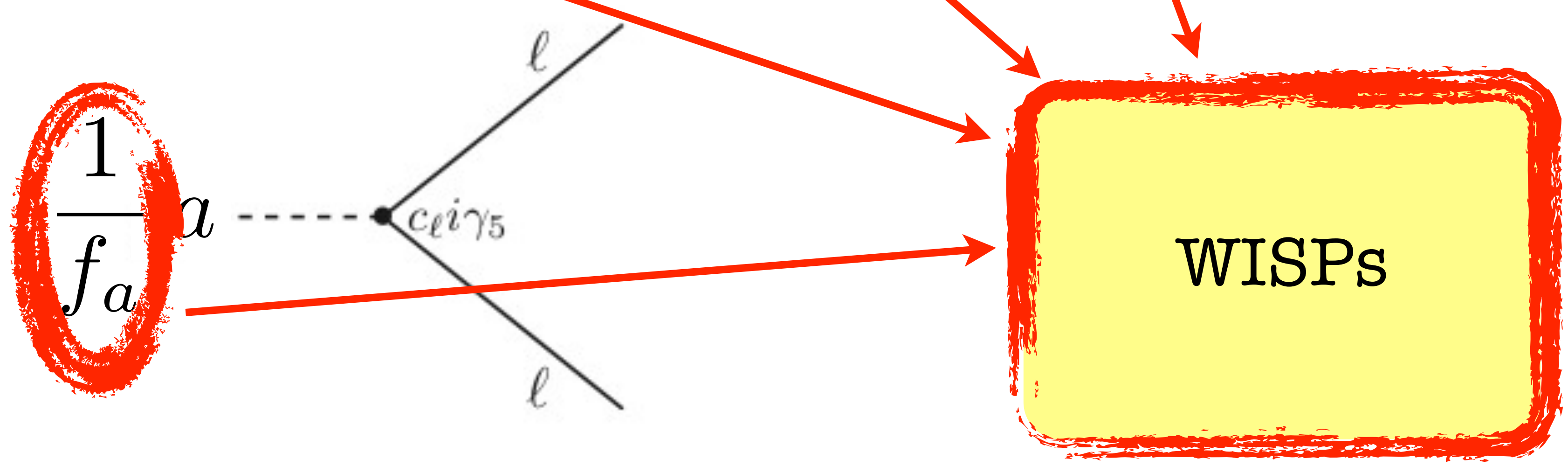
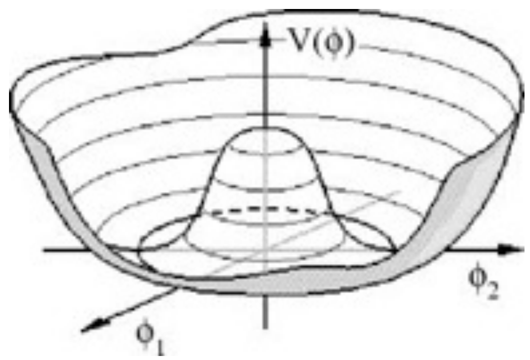


Axion-like particles (ALPs) 0^{-}

pseudo Goldstone bosons

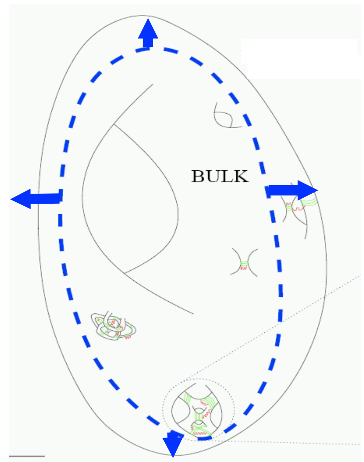
Global continuous symmetry spontaneously broken at high energy scale M



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

String 'axions'

Sizes and deformations of extra dimensions, gauge couplings



DILATONS RADION MODULI Axiverse!

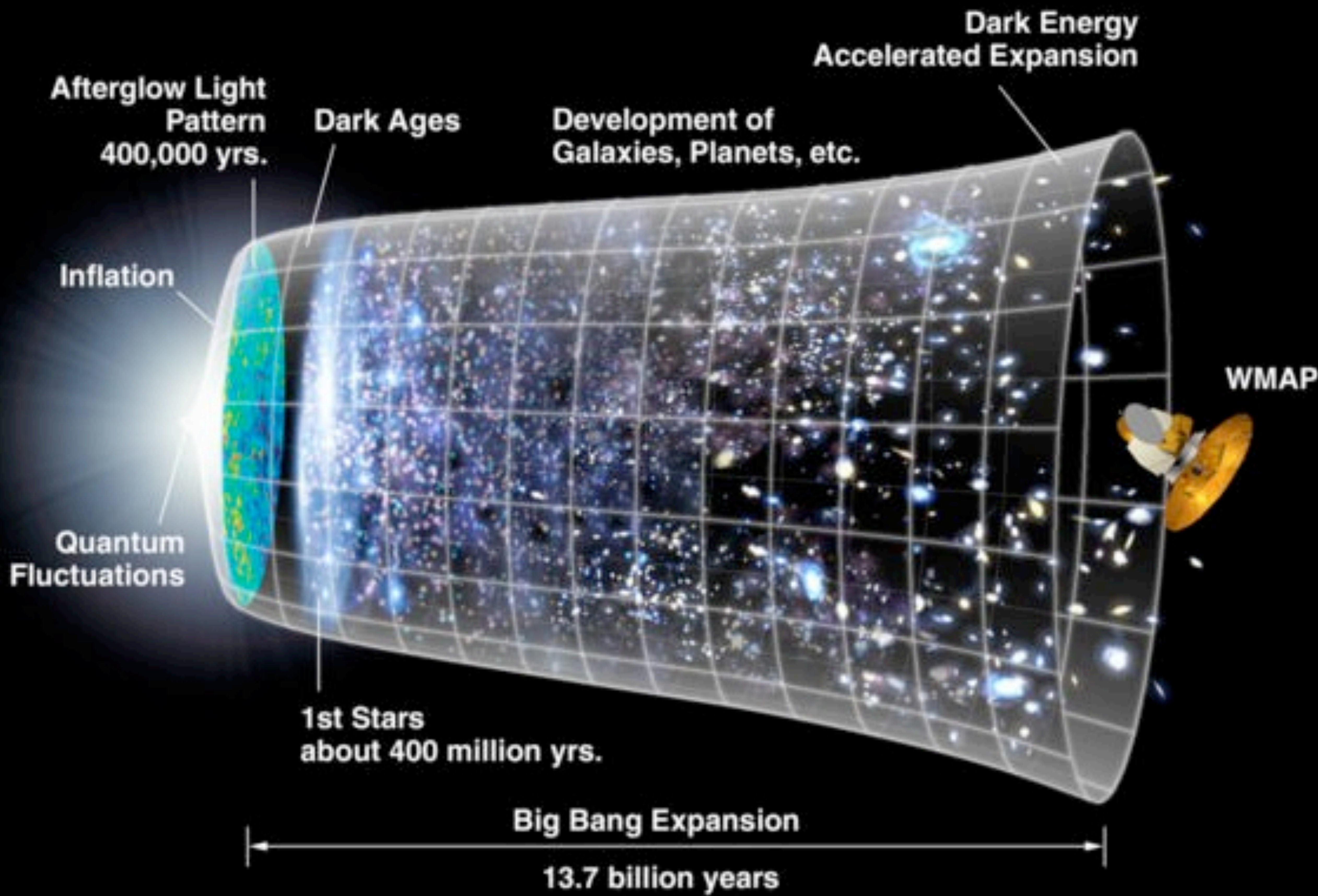
Supersymmetry/supergravity

EACH GAUGE GROUP HAS ITS OWN AXION

$$\mathrm{Re}(f(\Phi)) \int \sqrt{g} F_{\mu\nu} F^{\mu\nu} + \frac{i}{2} \mathrm{Im}(f(\Phi)) \int \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

$$\frac{1}{g^2} \int \sqrt{g} F_{\mu\nu} F^{\mu\nu} + i\theta \int \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

Cosmology



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Energy content of the Universe today

Two unidentified substances make most of it!

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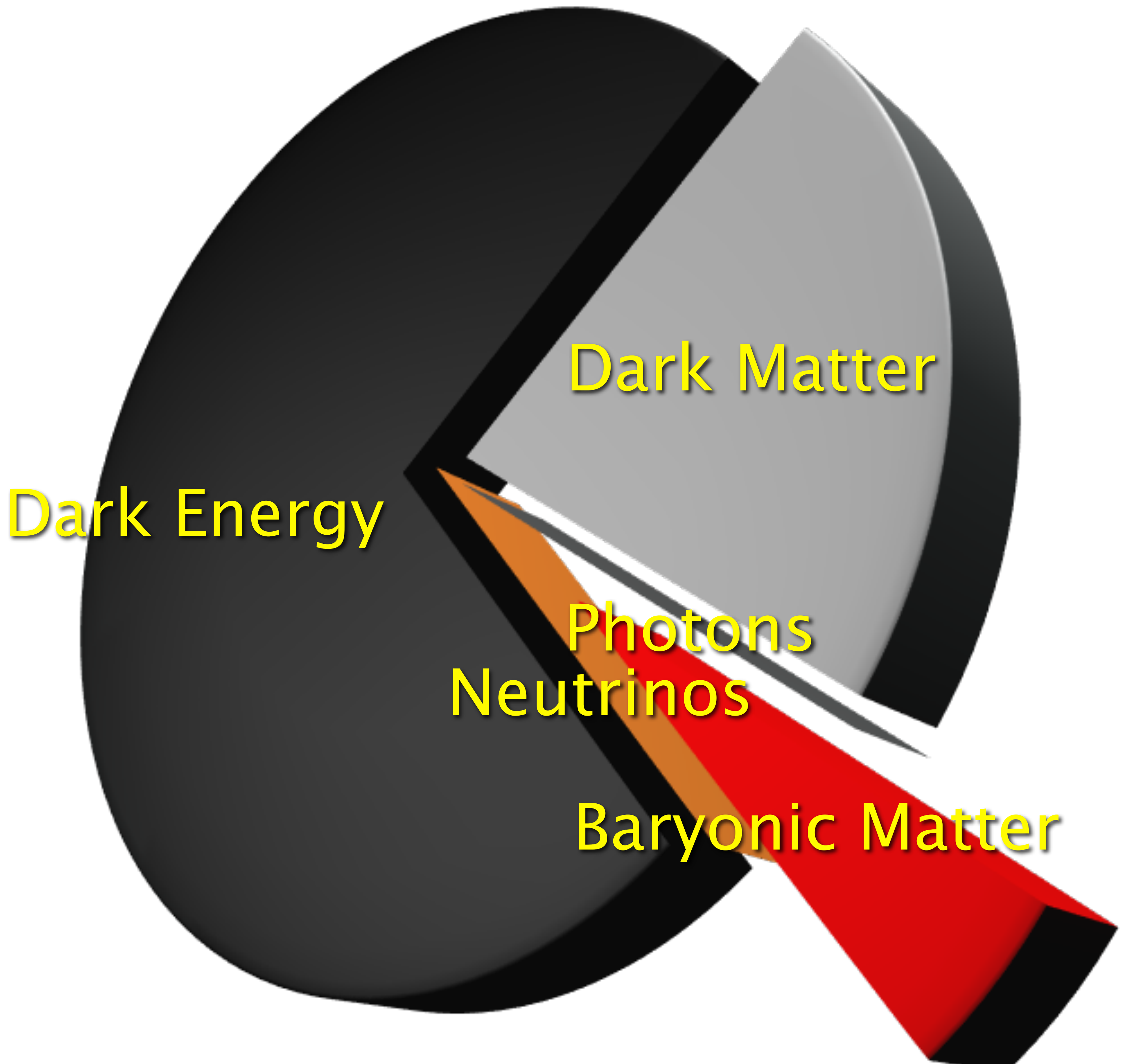

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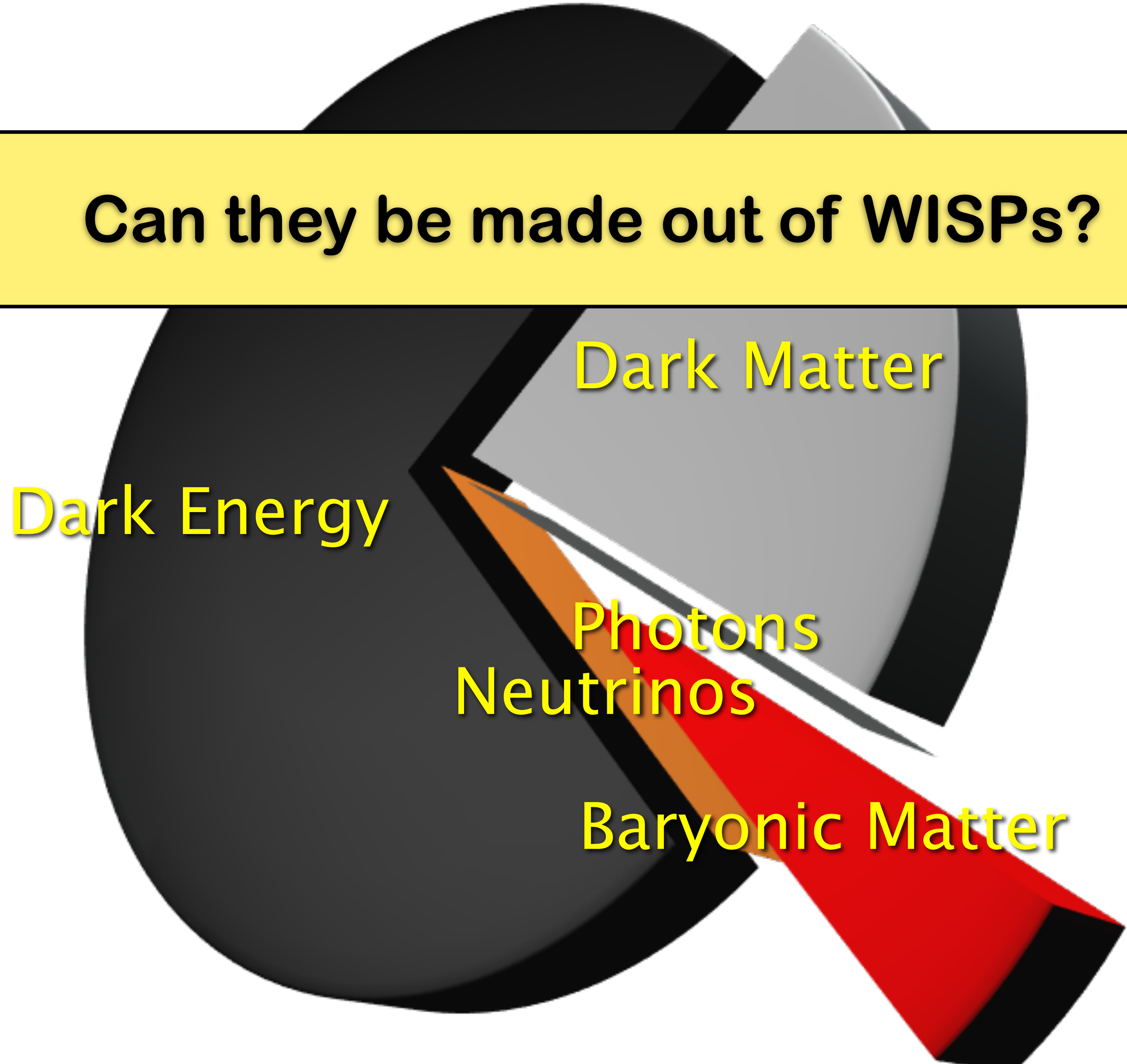
Can they be made out of WISPs?



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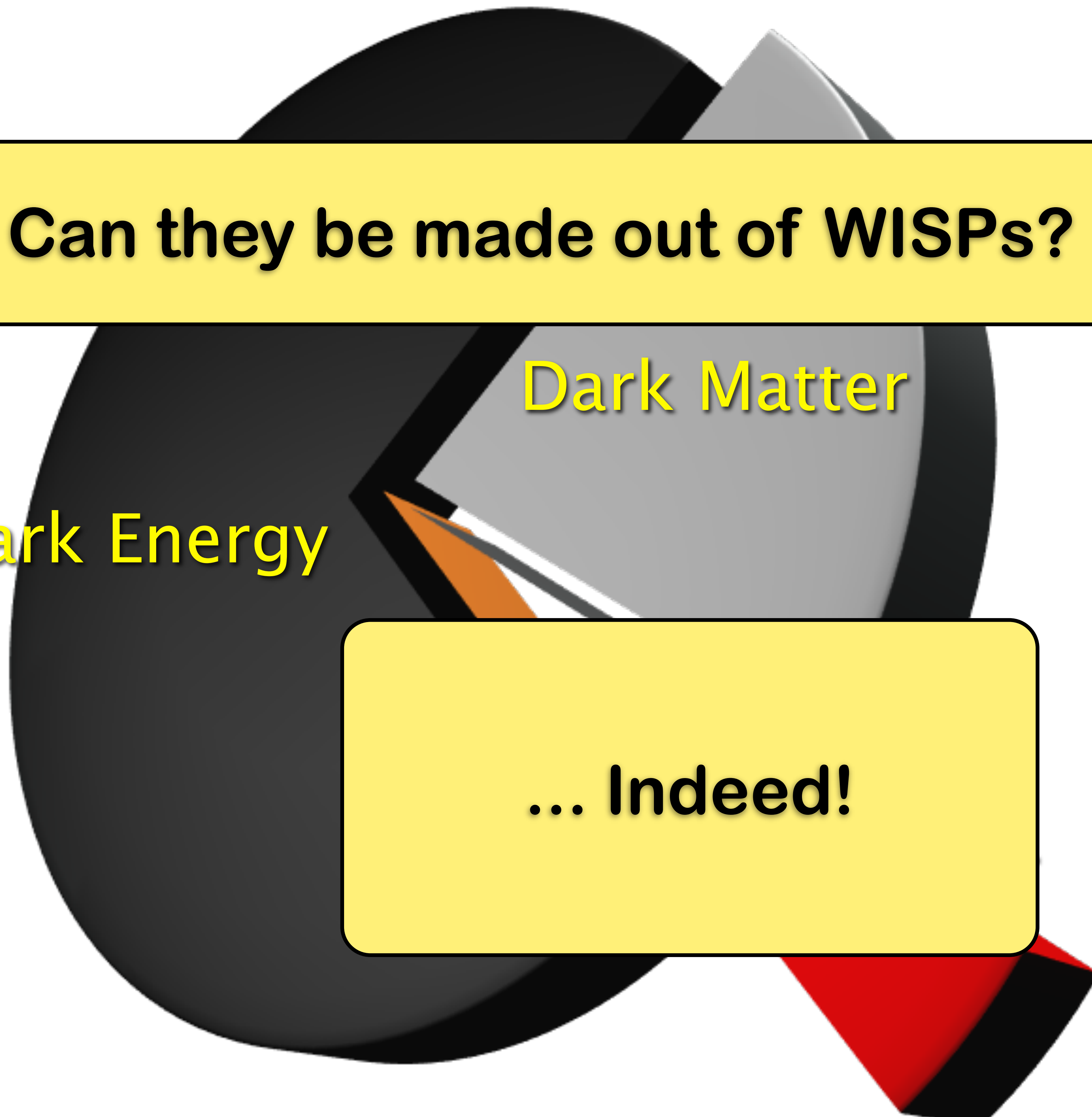

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... Indeed!

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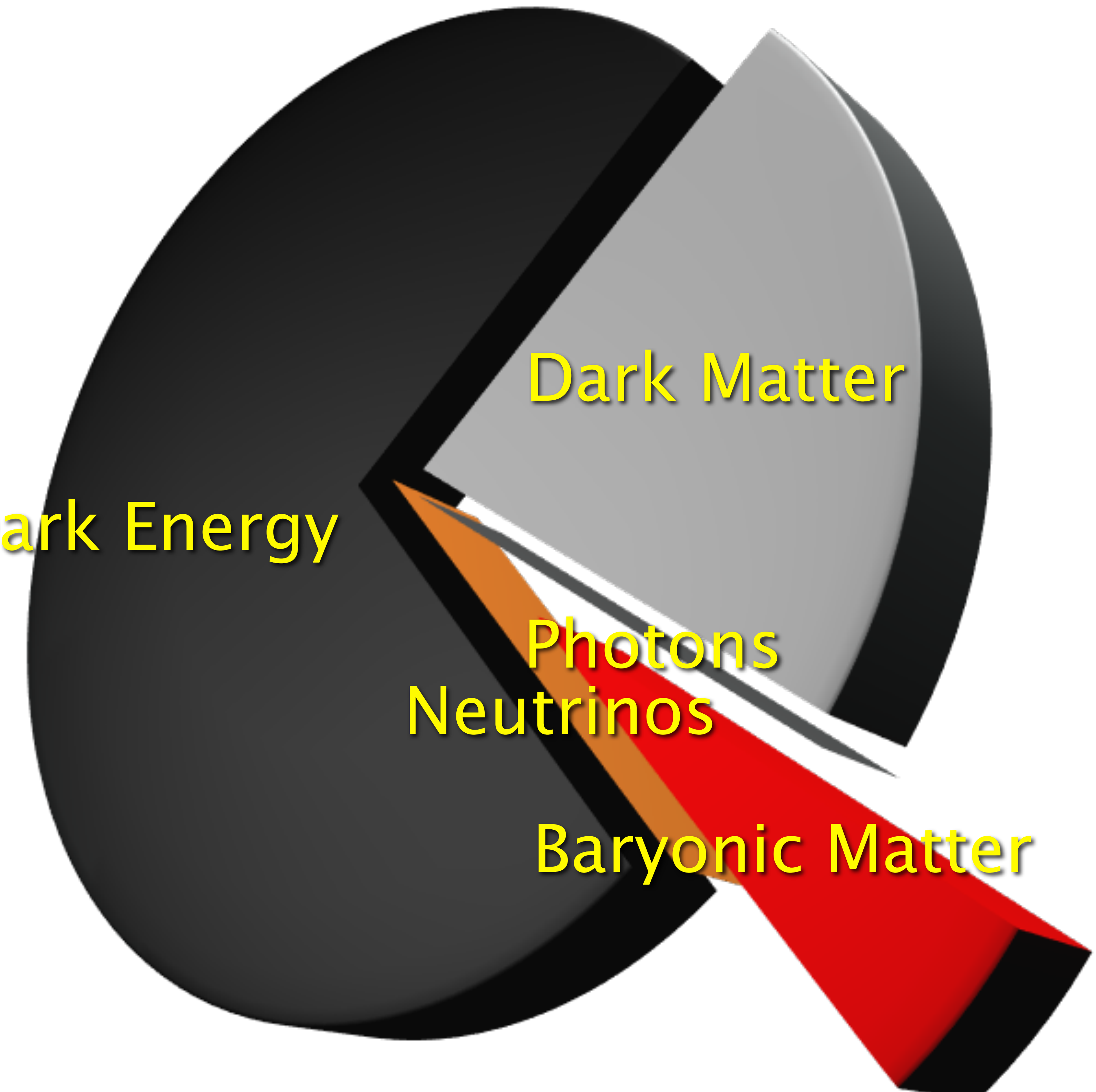

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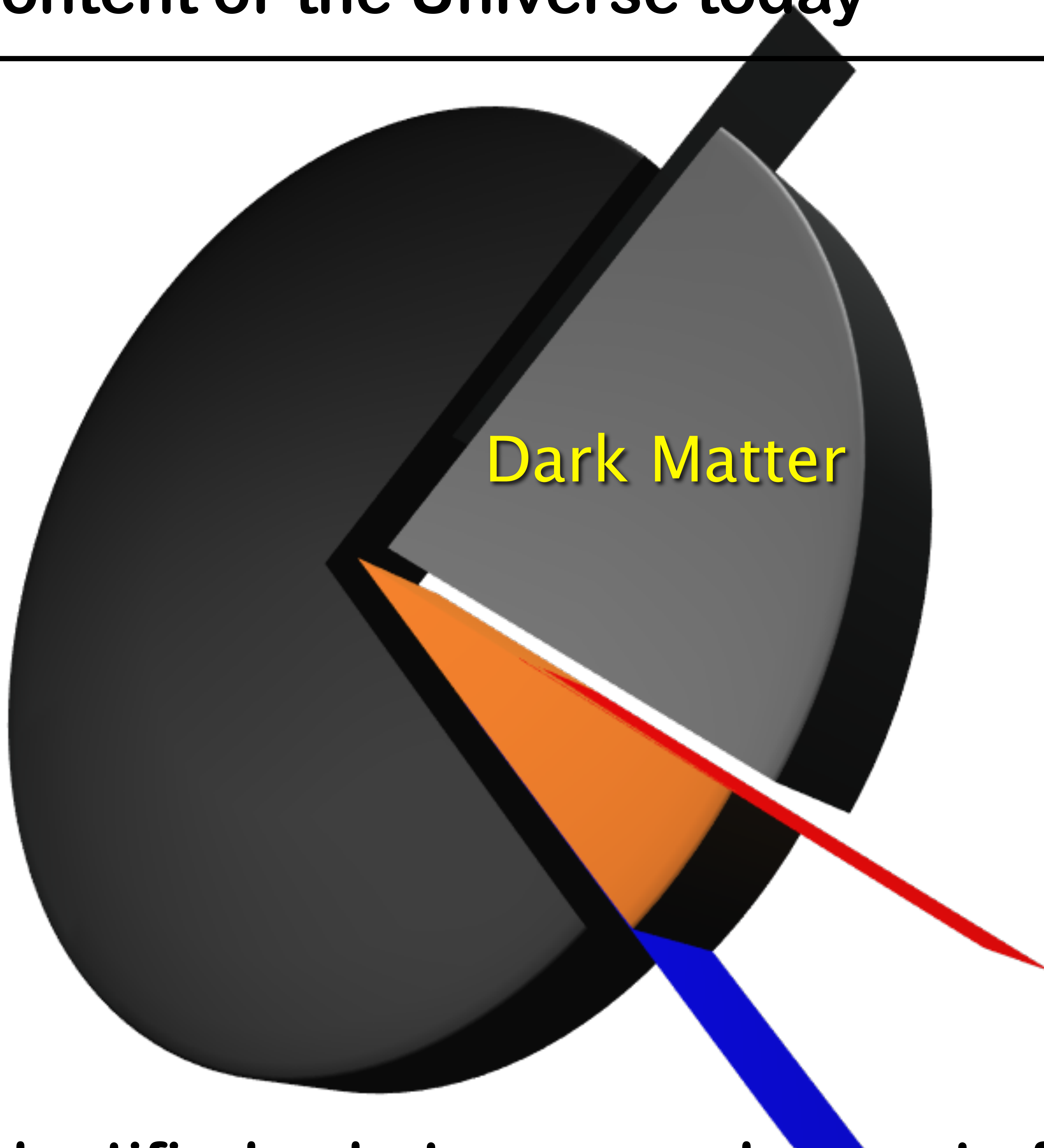

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Energy content of the Universe today

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What do we know about Dark Matter particles?

Basically only what the name suggests:

- Dark -

in the sense that they interact very weakly with SM particles.

(and among themselves)

- Matter -

in the sense that are non-relativistic

(most of them)

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mmmm...

WISPy Dark matter is generically COLD!

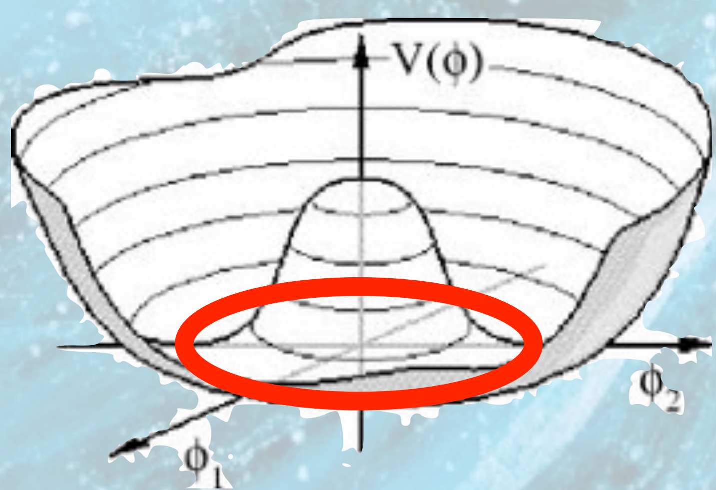
- Hot relics (velocities T/mass ~ 0.23 meV/mass)

$$v \sim \frac{T}{m}$$

- WISPs don't thermalize -> initial conditions ?

$$v \sim \frac{H}{m} \qquad H = \frac{\dot{R}}{R} \sim \frac{T^2}{M_{\rm Pl}} \ll T \quad ({\rm RD})$$

Let's understand it

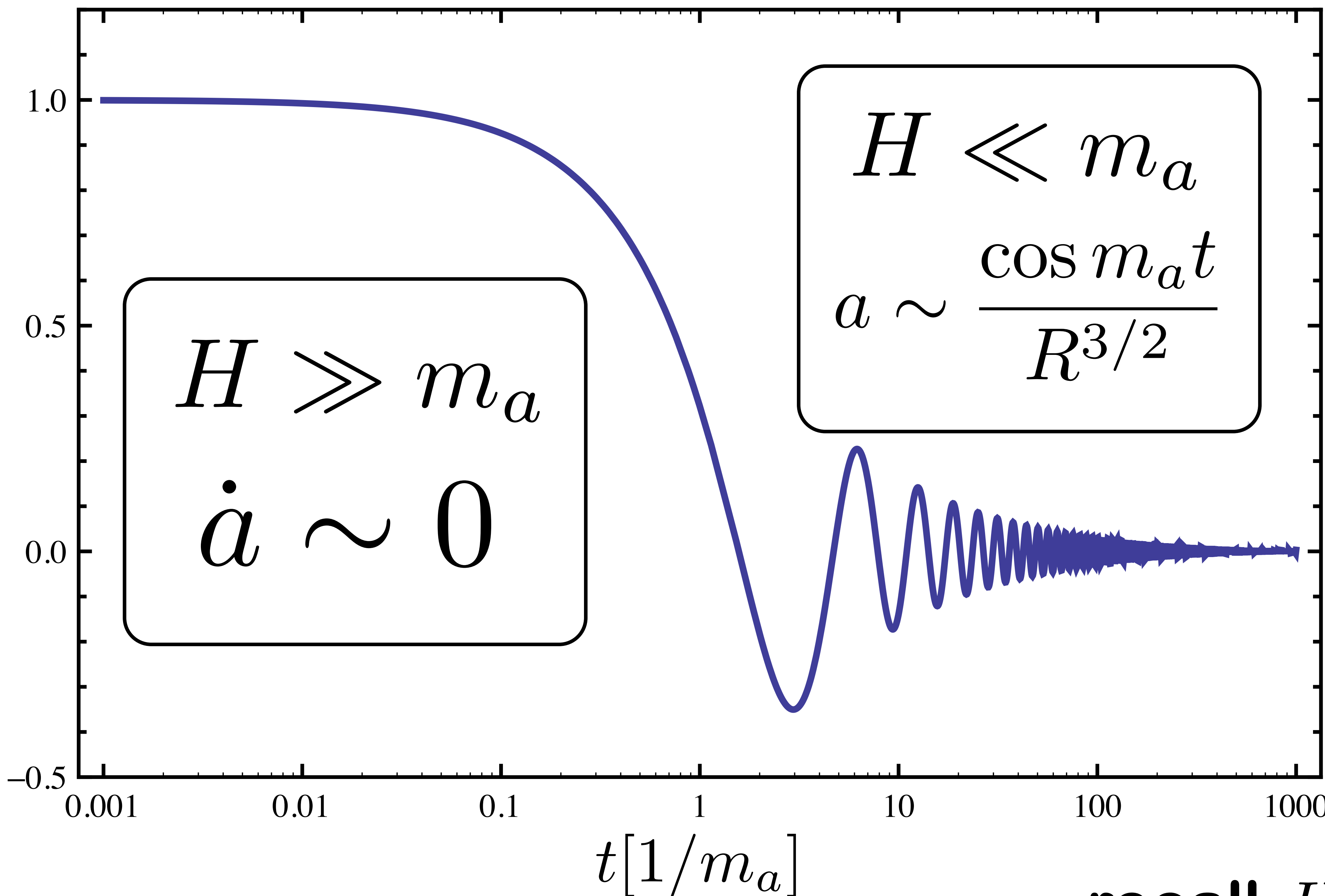


$$a \in (-\pi f_a, \pi f_a)$$

$$a(x) = \int \frac{d^3\mathbf{k}}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{x}} a_k$$

WISPy Dark matter is generically COLD!

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



recall $H \sim 1/t$

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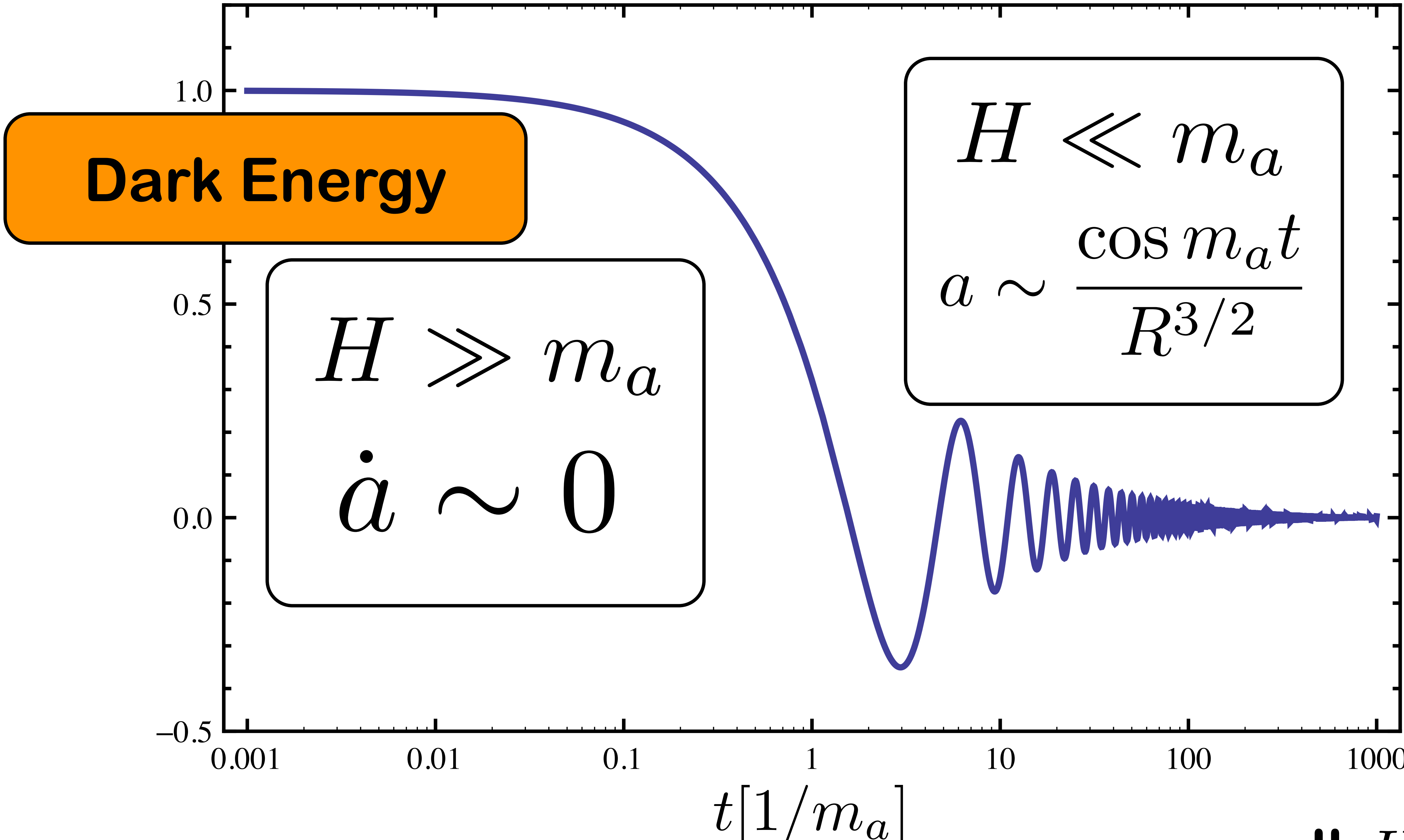

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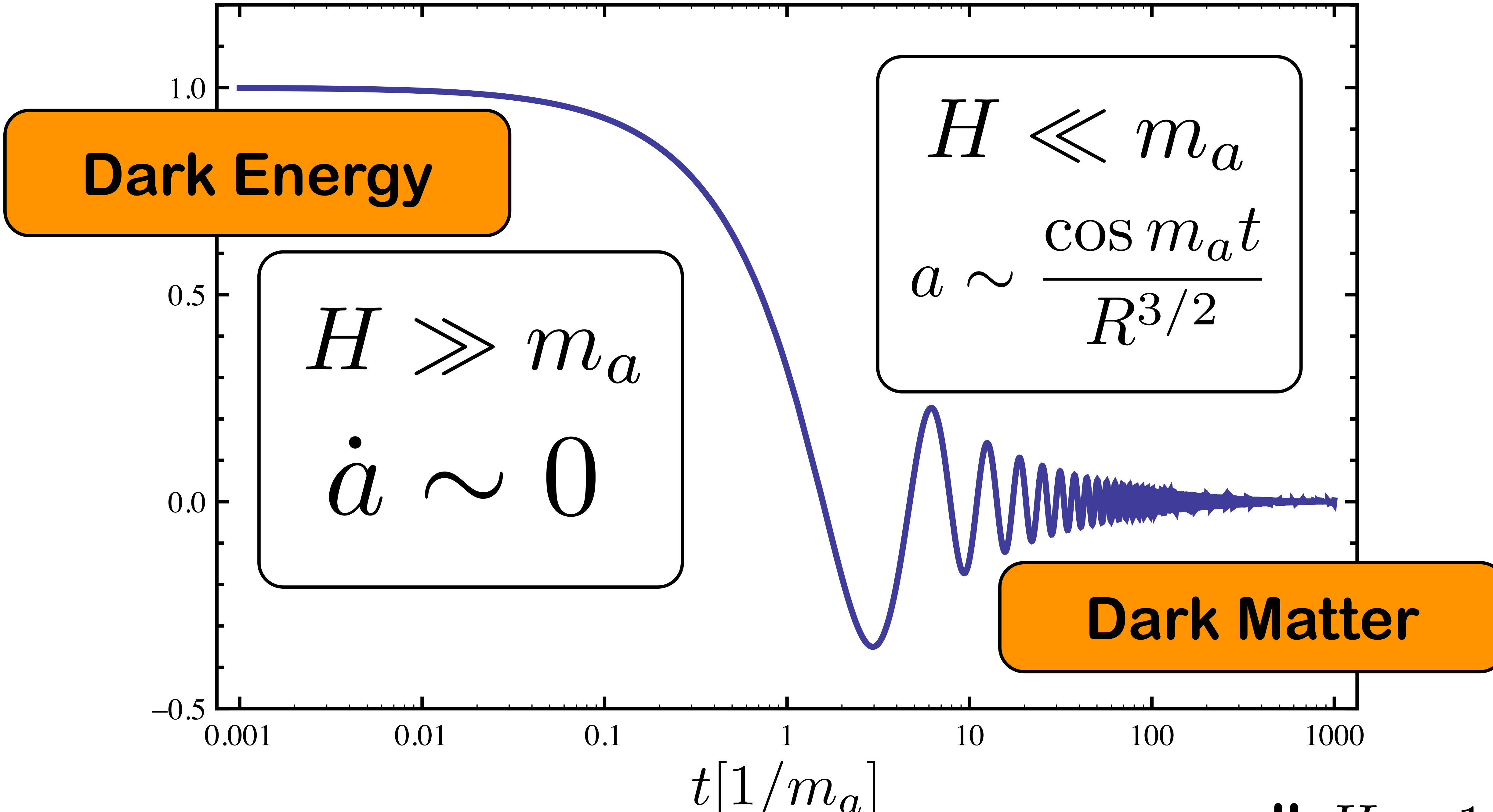

recall $H \sim 1/t$

Relic abundance of WISPy Dark matter

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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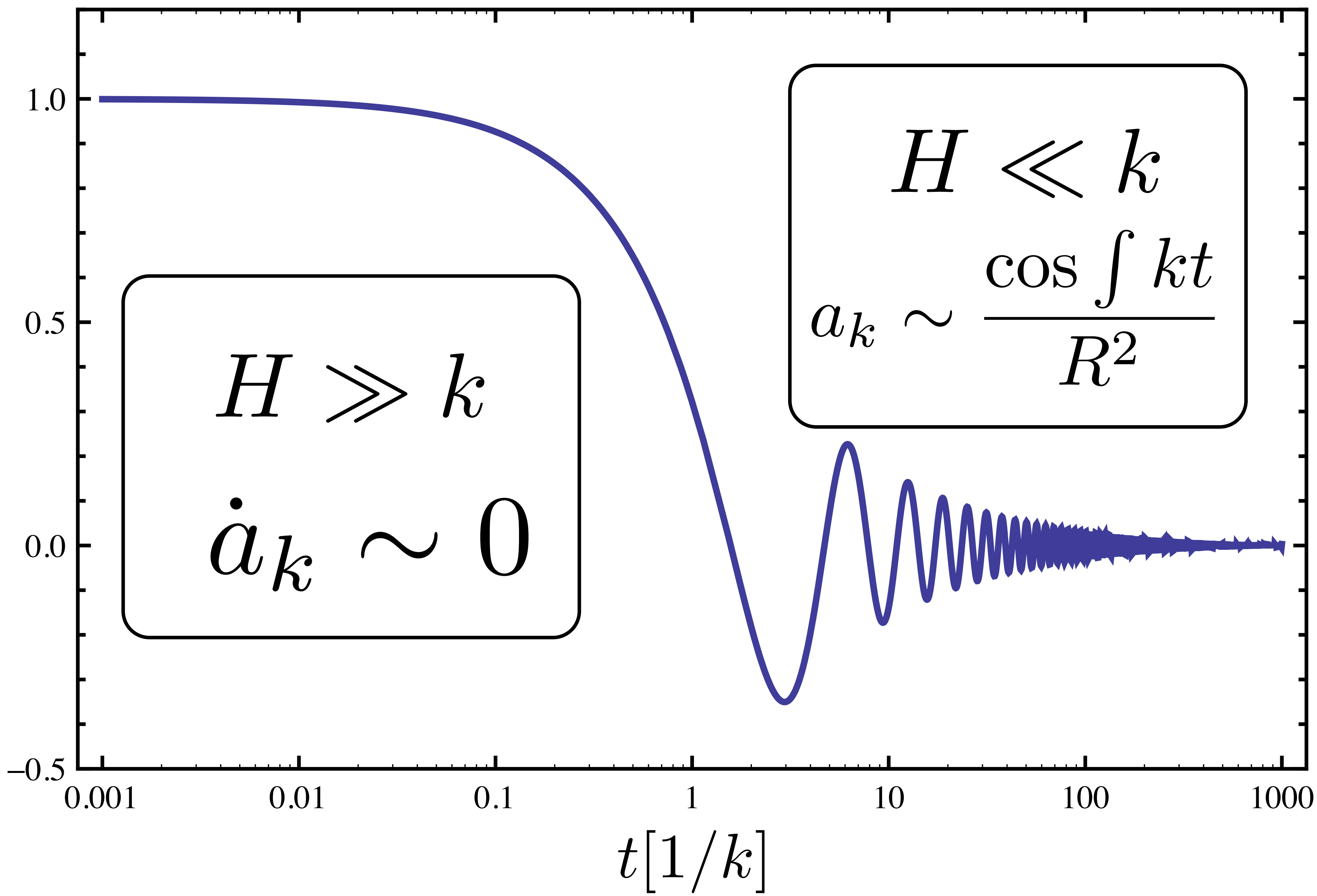
Why so cold?

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



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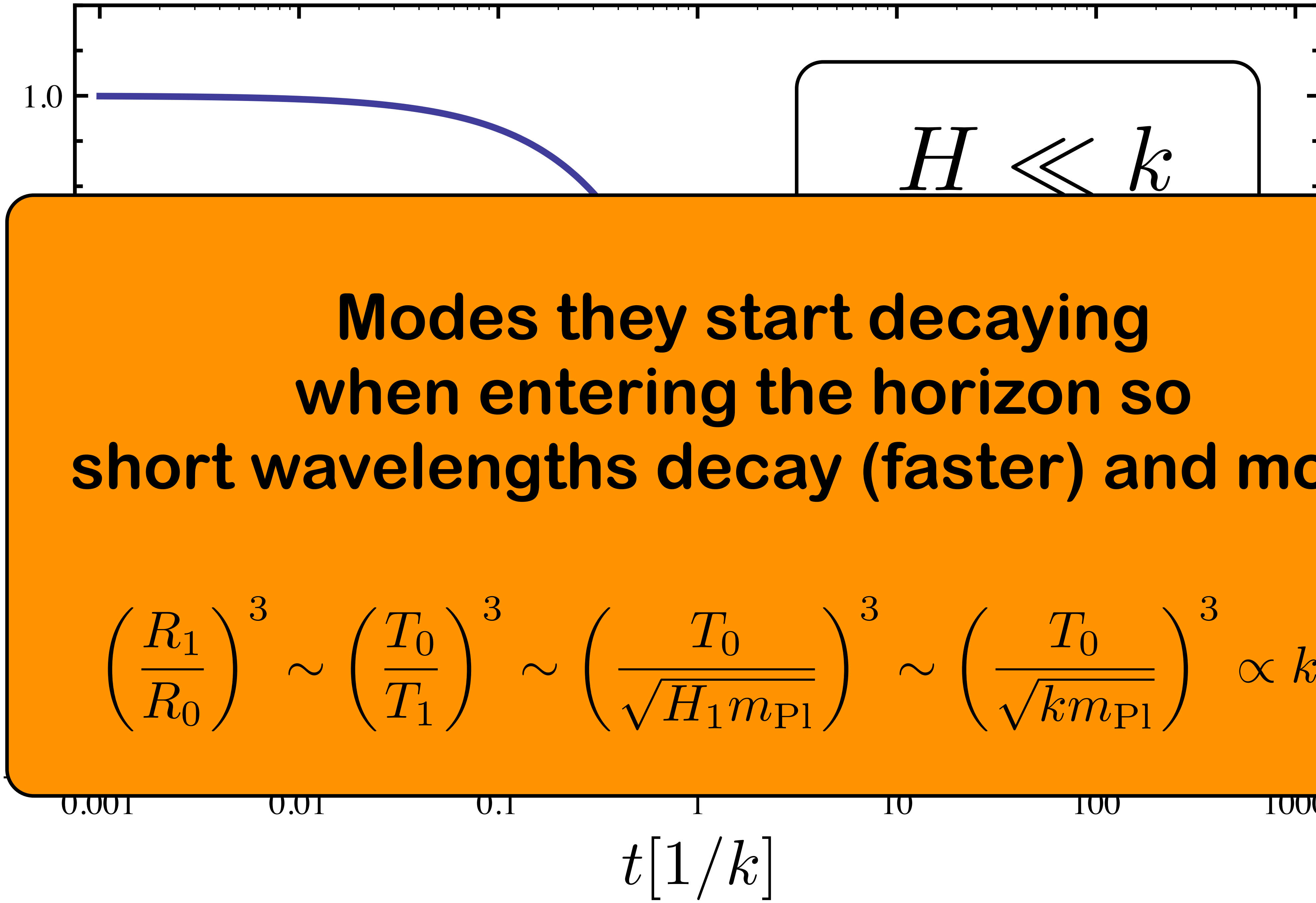


Modes they start decaying when entering the horizon so short wavelengths decay (faster) and more!

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

Relic abundance of WISPy Dark matter

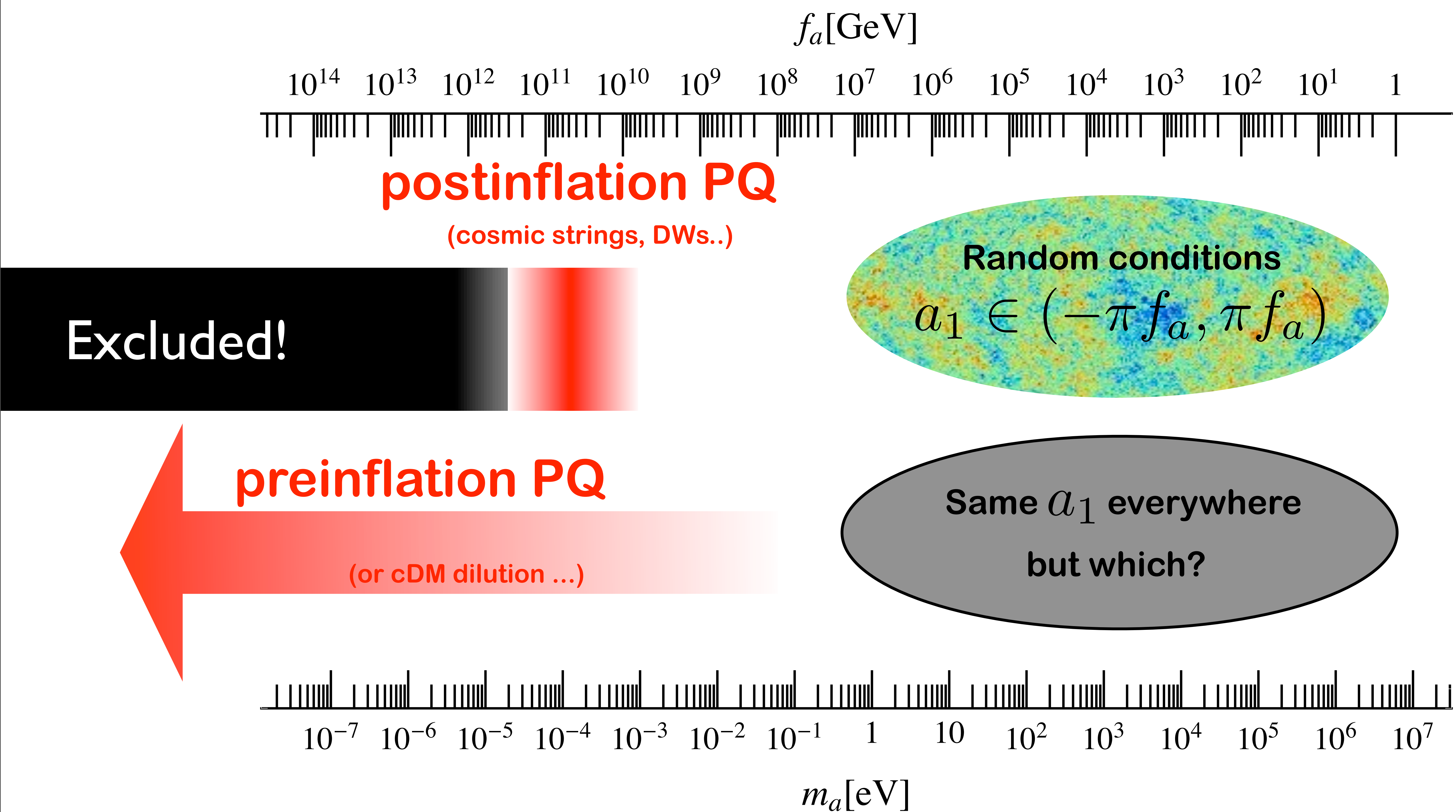
- Simplest scenario:

$$\rho_{a,0} \simeq 1.17\,\frac{\mathrm{keV}}{\mathrm{cm}^3} \times \sqrt{\frac{m_a}{\mathrm{eV}}}\left(\frac{a_1}{4.8\times 10^{11}\,\mathrm{GeV}}\right)^2 \mathcal{F},$$

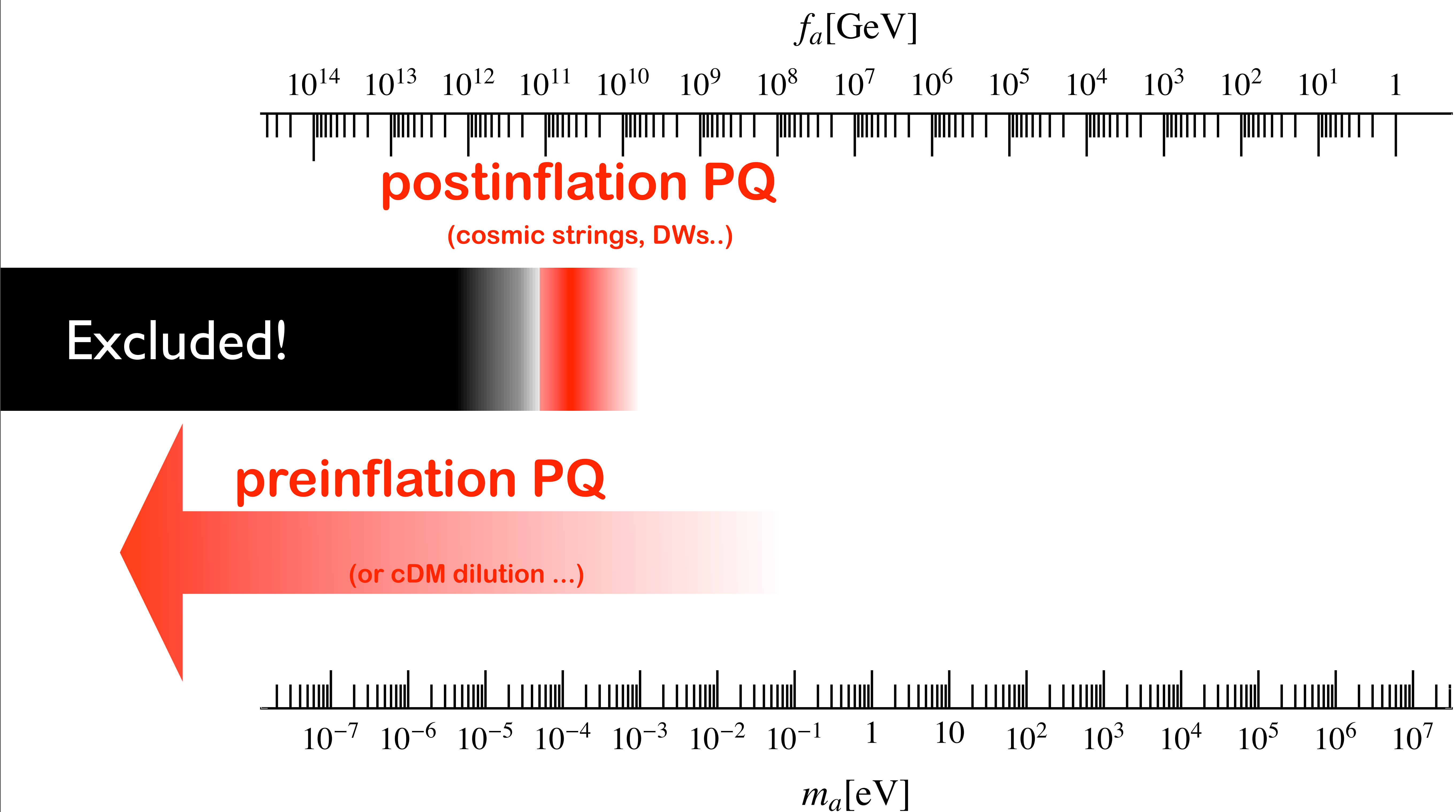
recall $\rho_{\mathrm{CDM}} = 1.17(6)\dfrac{\mathrm{keV}}{\mathrm{cm}^3}$

- Initial amplitude, physics at <u>very high energies</u>
- WISPy DM opens a window to HEP

Full axion cold dark matter: two scenarios



+ Bounds on axions (and prospects)



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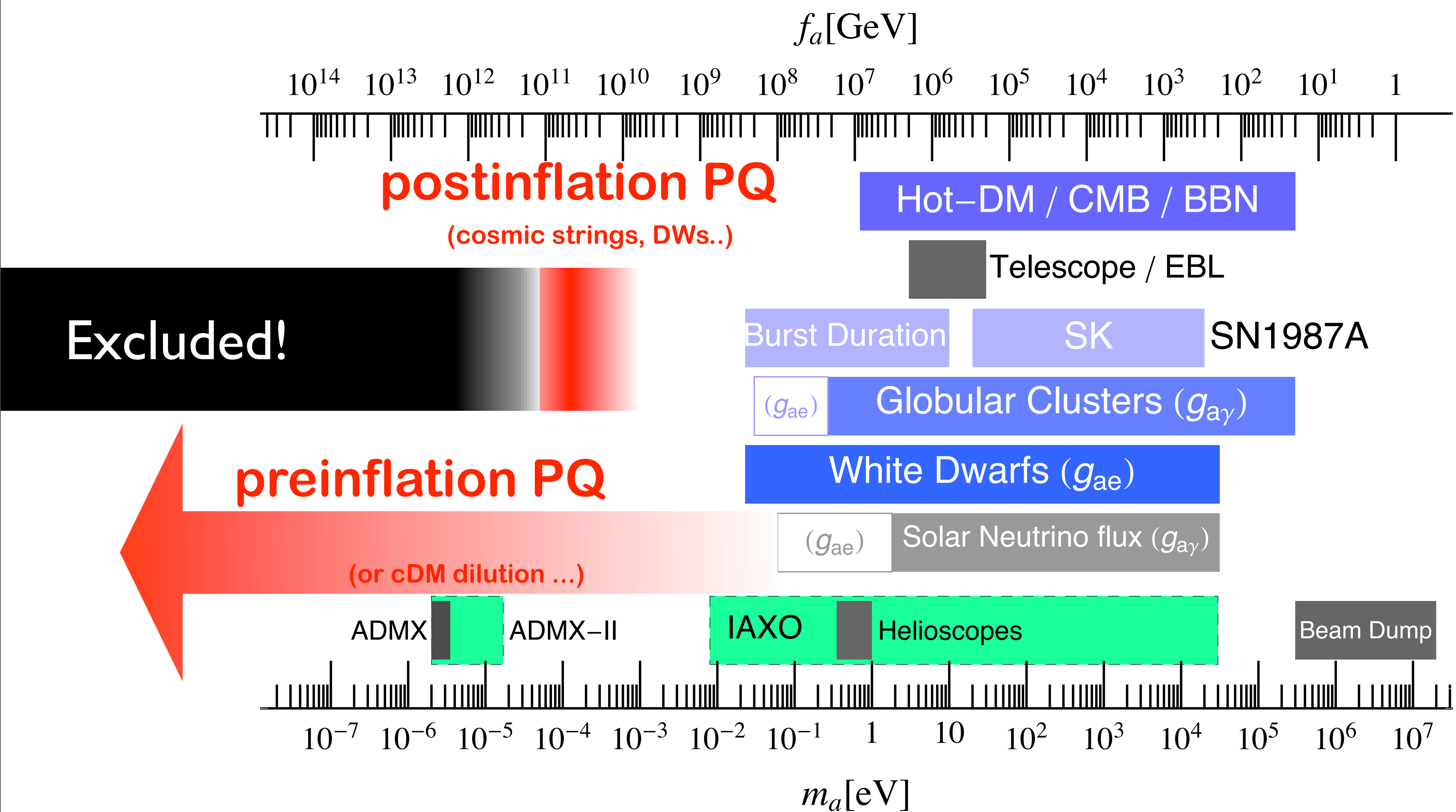
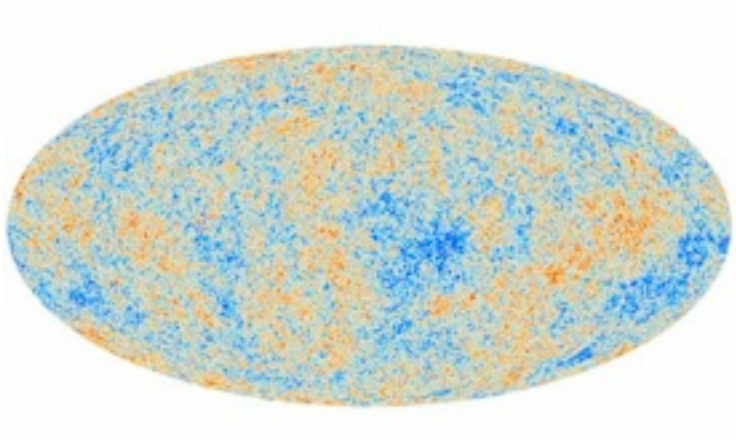
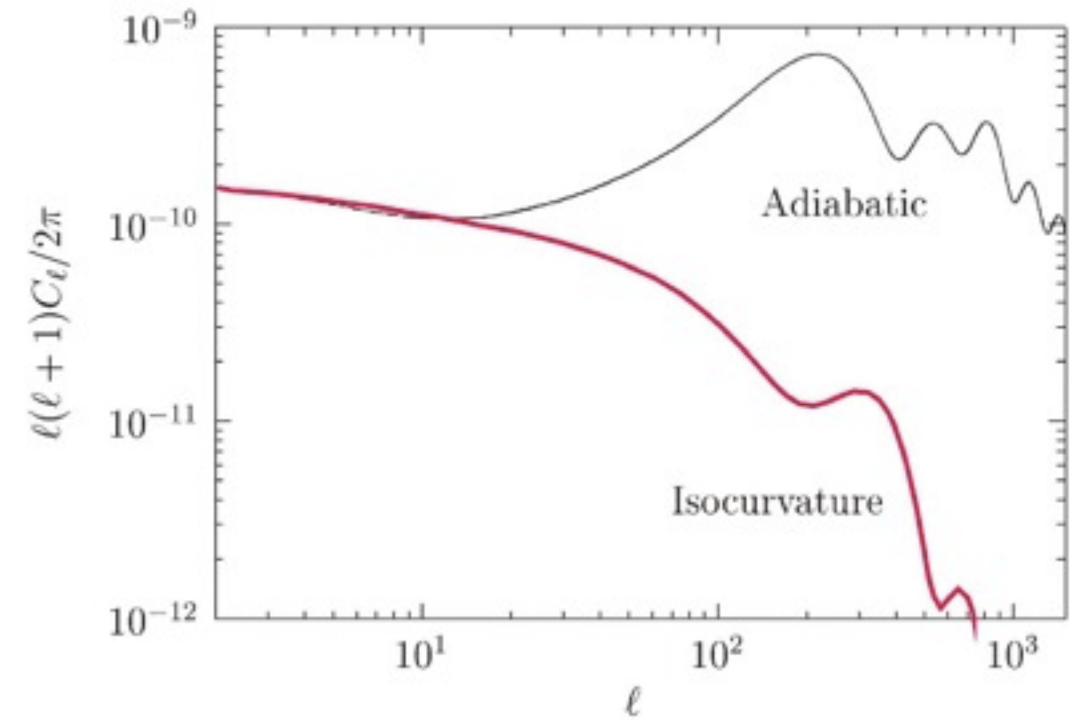


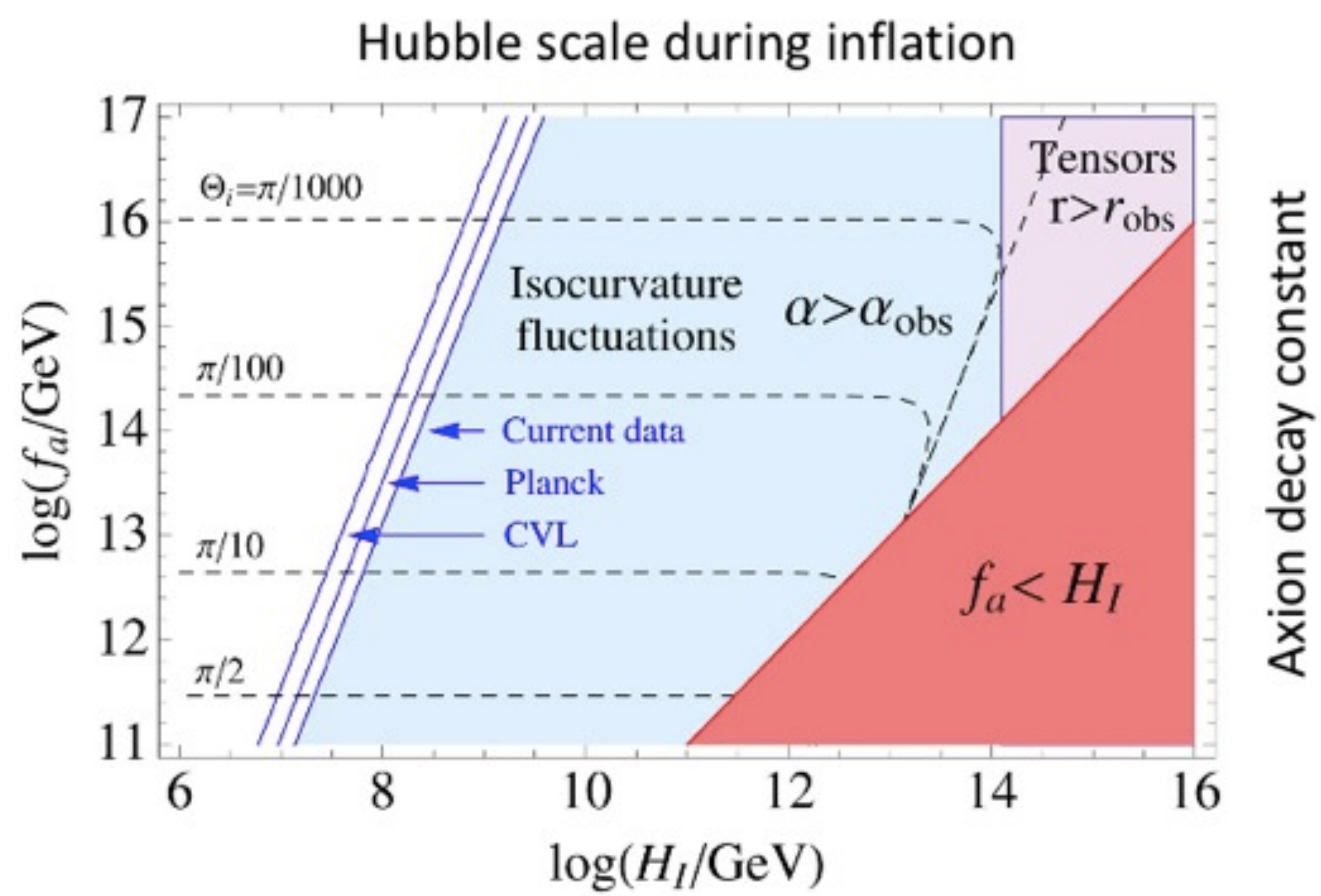
ISOCURVATURE perturbations in the CMB



Fourier



but this depends on H during inflation...



Avoiding isocurvature

massless field fluctuations (canonically normalised field) are huge !!

$$\delta a^2 \simeq \frac{H_I^2}{4\pi^2}$$

Two solutions (C. Germani et al arXiv:1304.7270)

Small HI — **Axion-like inflation + non-minimal gravity K-coupling**

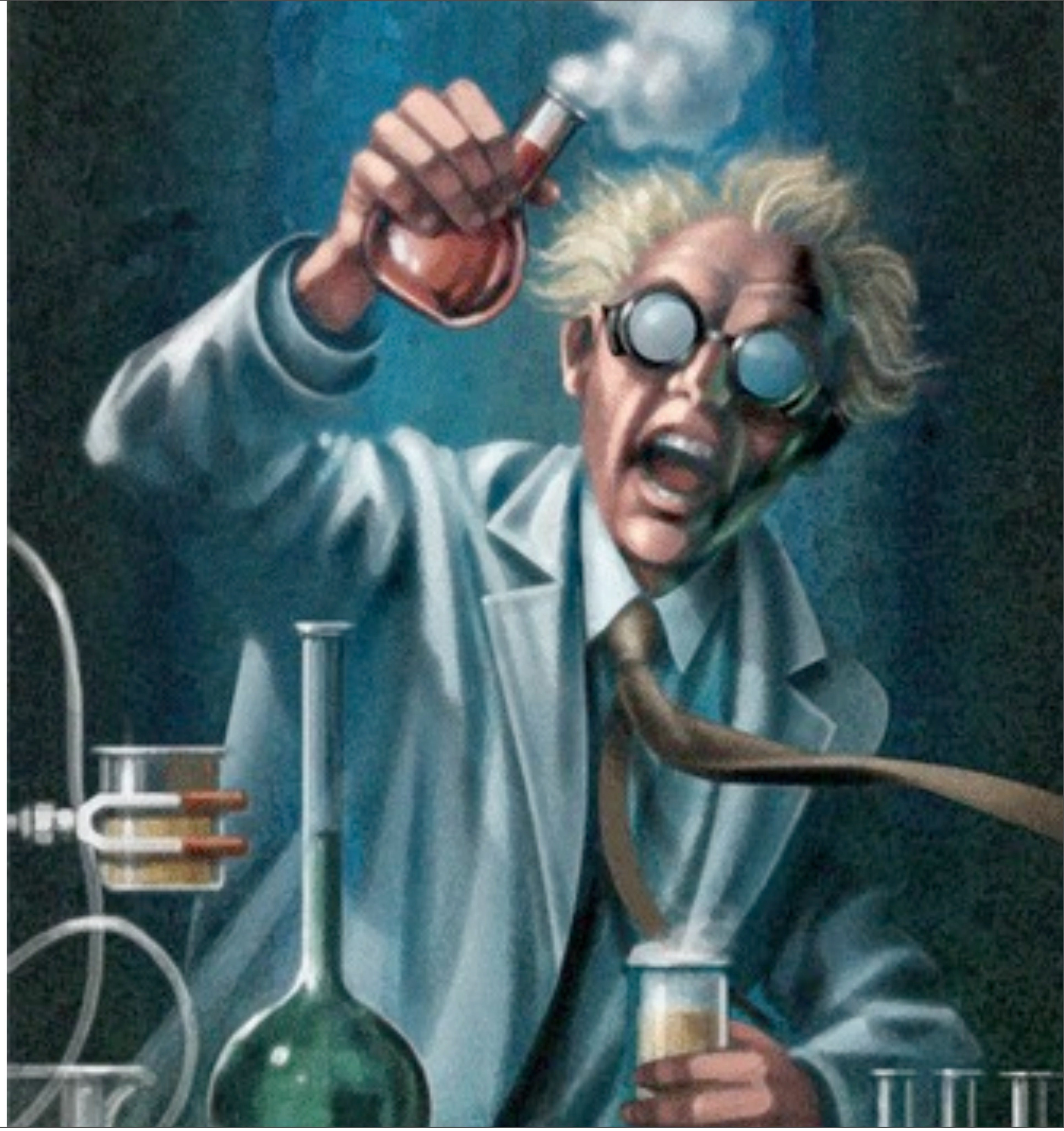
$$V(A) = \Lambda^4 \cos(A/f_A) \qquad \left(1 + \frac{G_{\mu\nu}}{M^2}\right)(\partial^\mu A)(\partial^\nu A)$$

single field models have negligible non-gaussianities

Suppress fluctuations — **non-minimal gravity K-coupling of axion field itself**

$$\left(1 + \frac{G_{\mu\nu}}{M_a^2}\right)(\partial^\mu a)(\partial^\nu a) \sim \left(1 + \frac{3H_I^2}{M_a^2}\right)(\partial^\mu a)(\partial^\nu a) \qquad \delta a^2 \simeq \frac{M_a^2}{4\pi^2}$$

Laboratory



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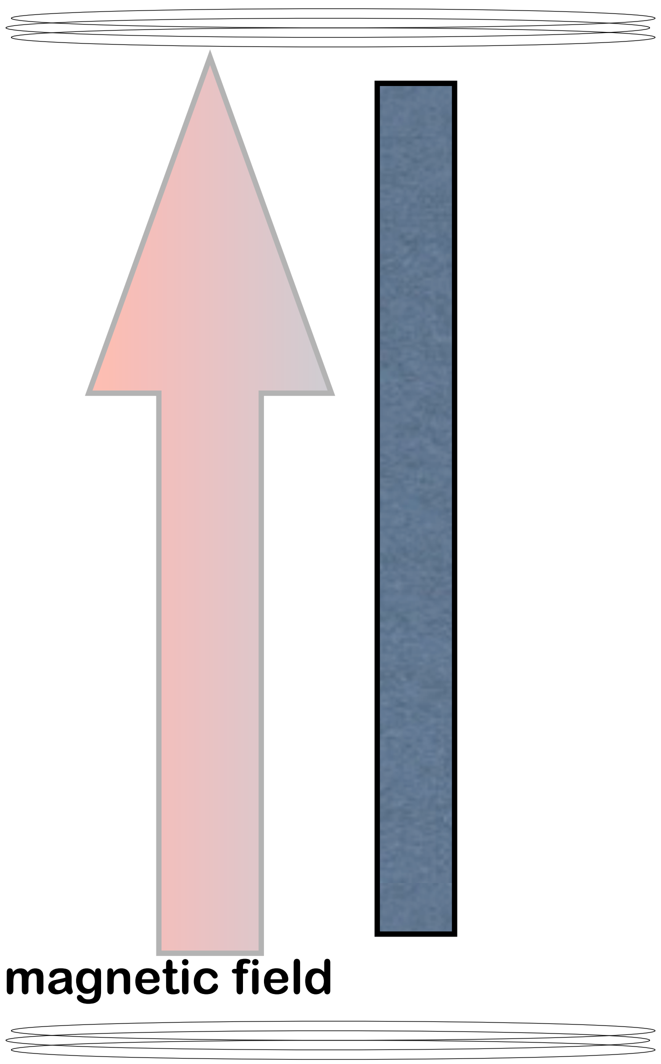
$$\chi \sim \frac{g_{a\gamma}|\mathbf{B}|}{m_a}$$

Radiation from a magnetised mirror

JR et al , JCAP04(2013)016



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

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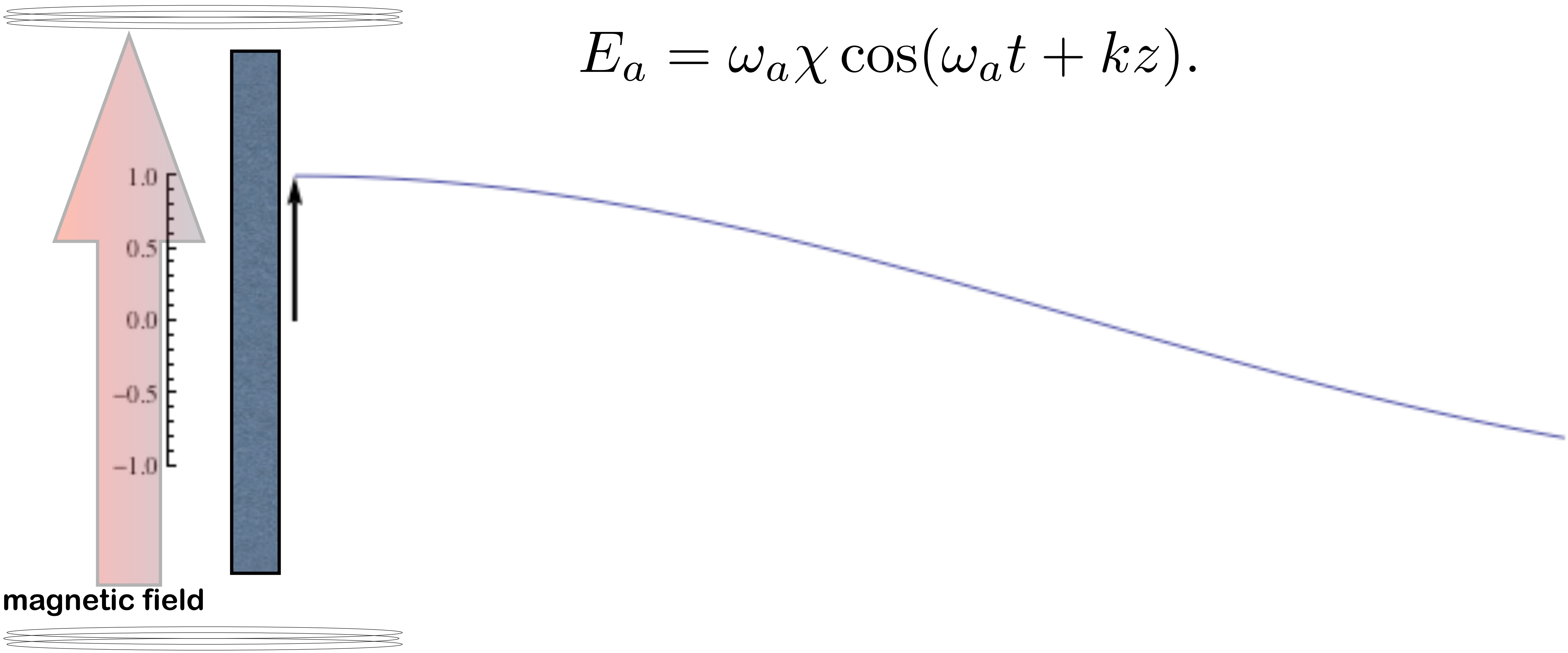

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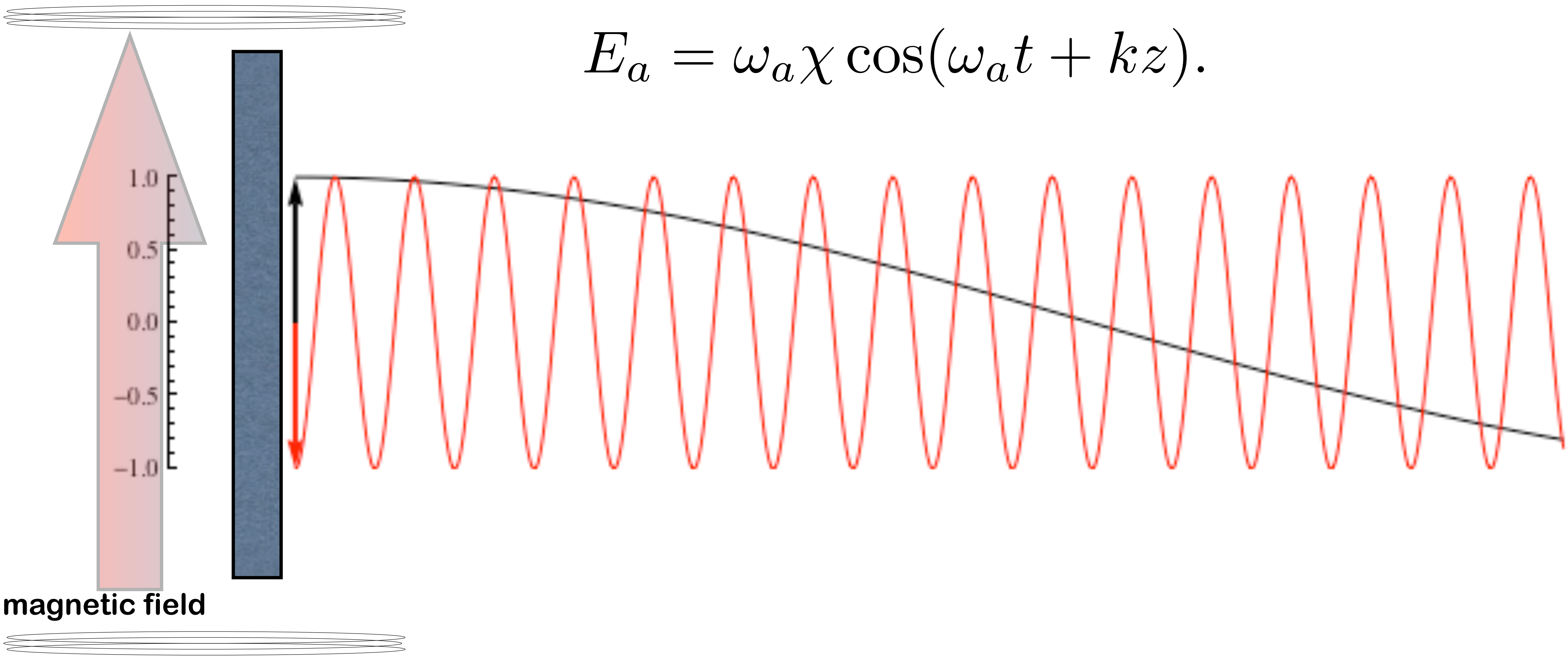

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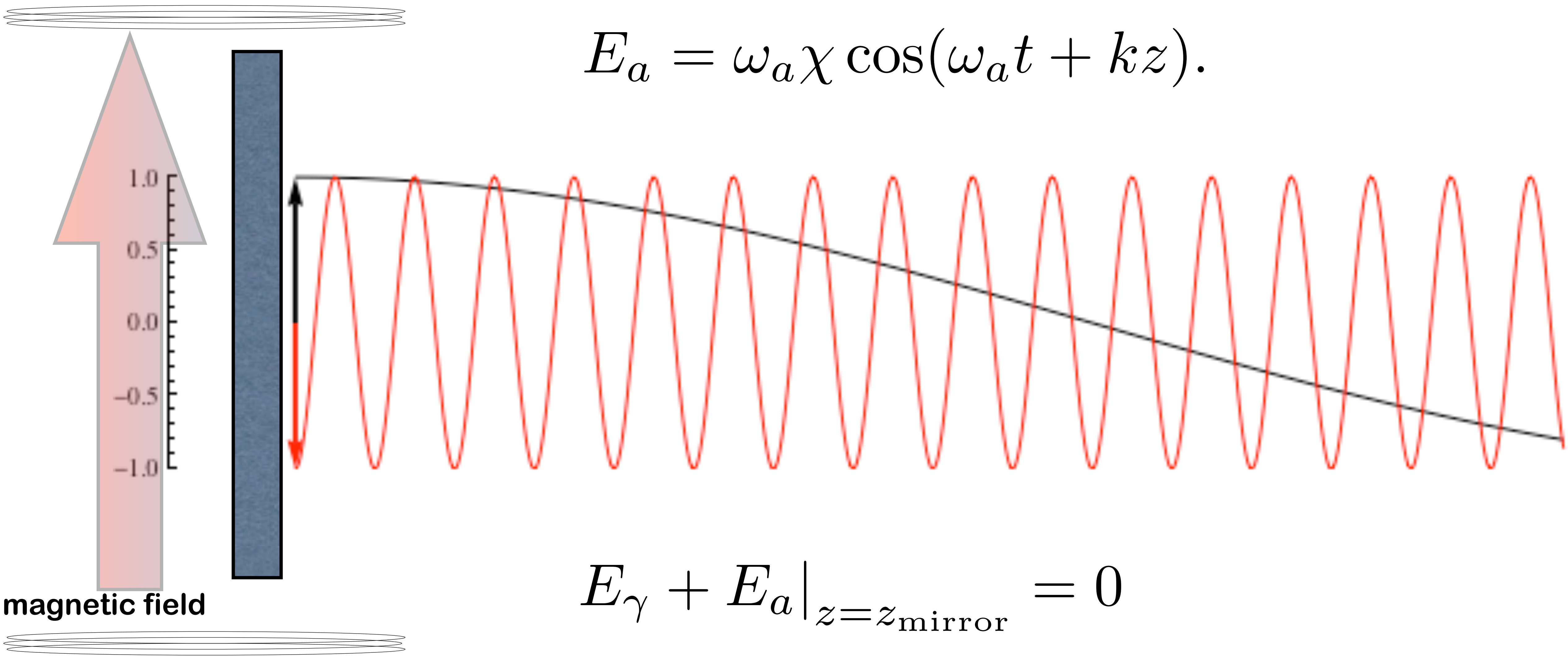

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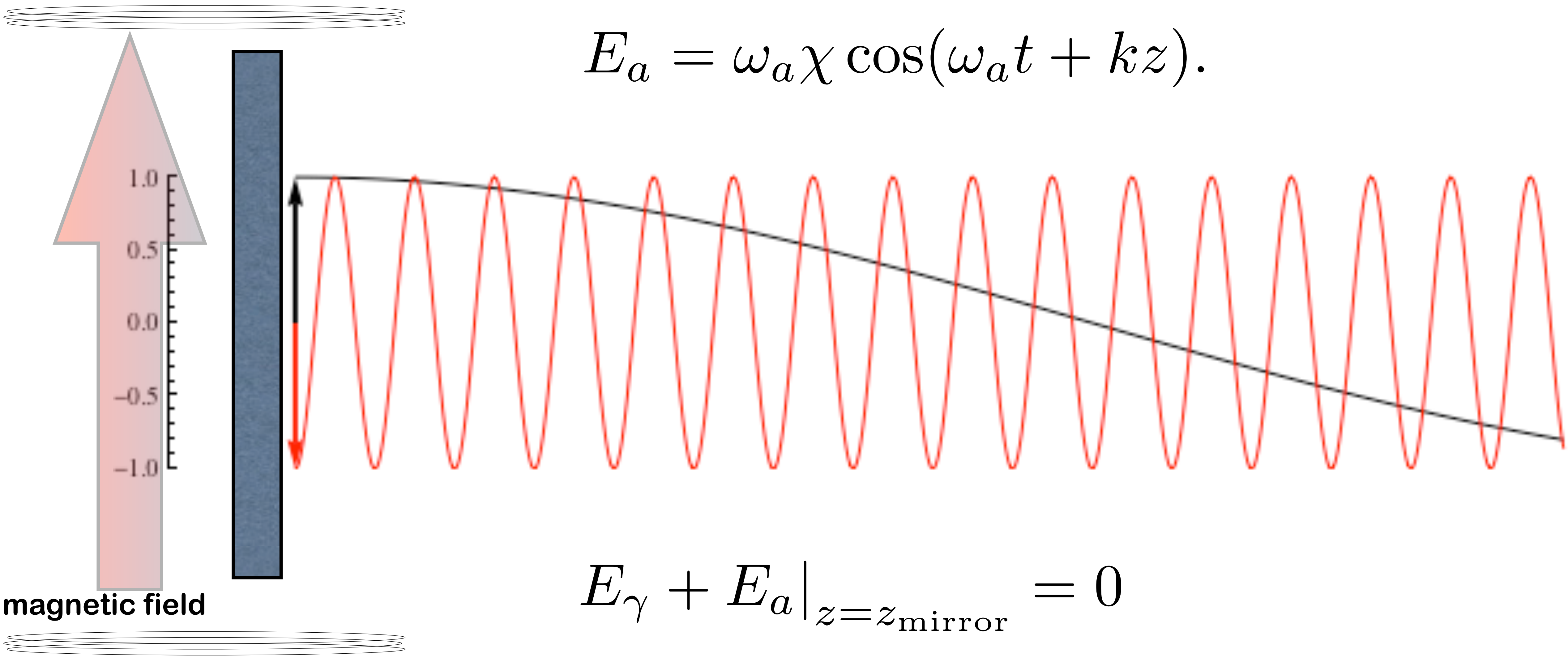

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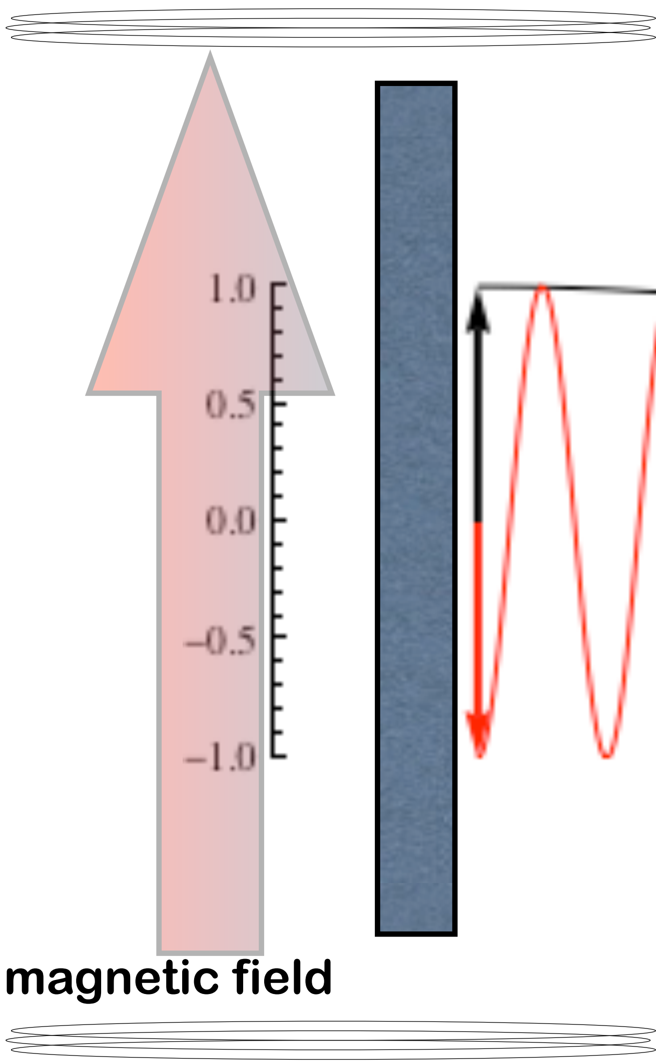

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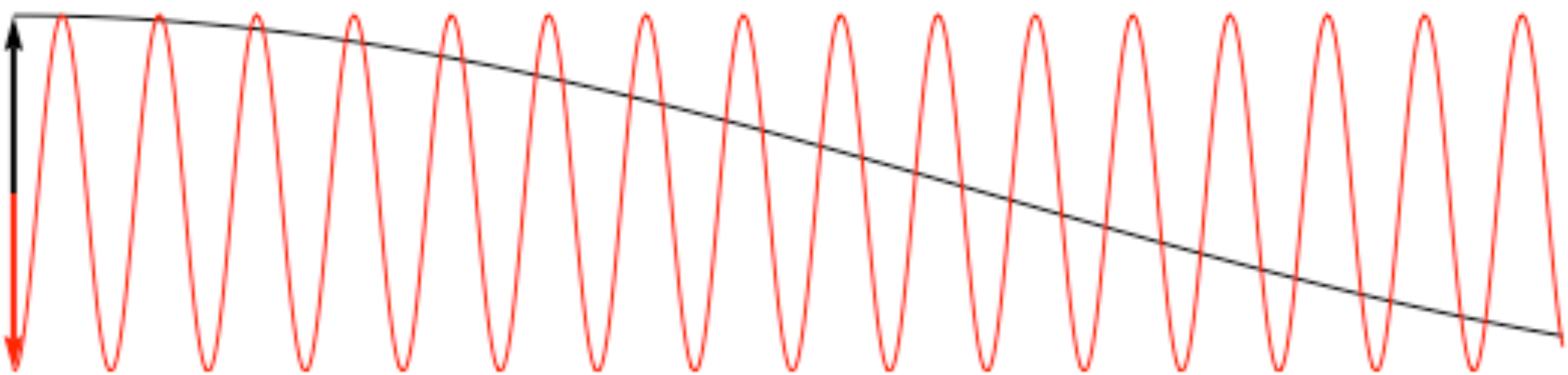

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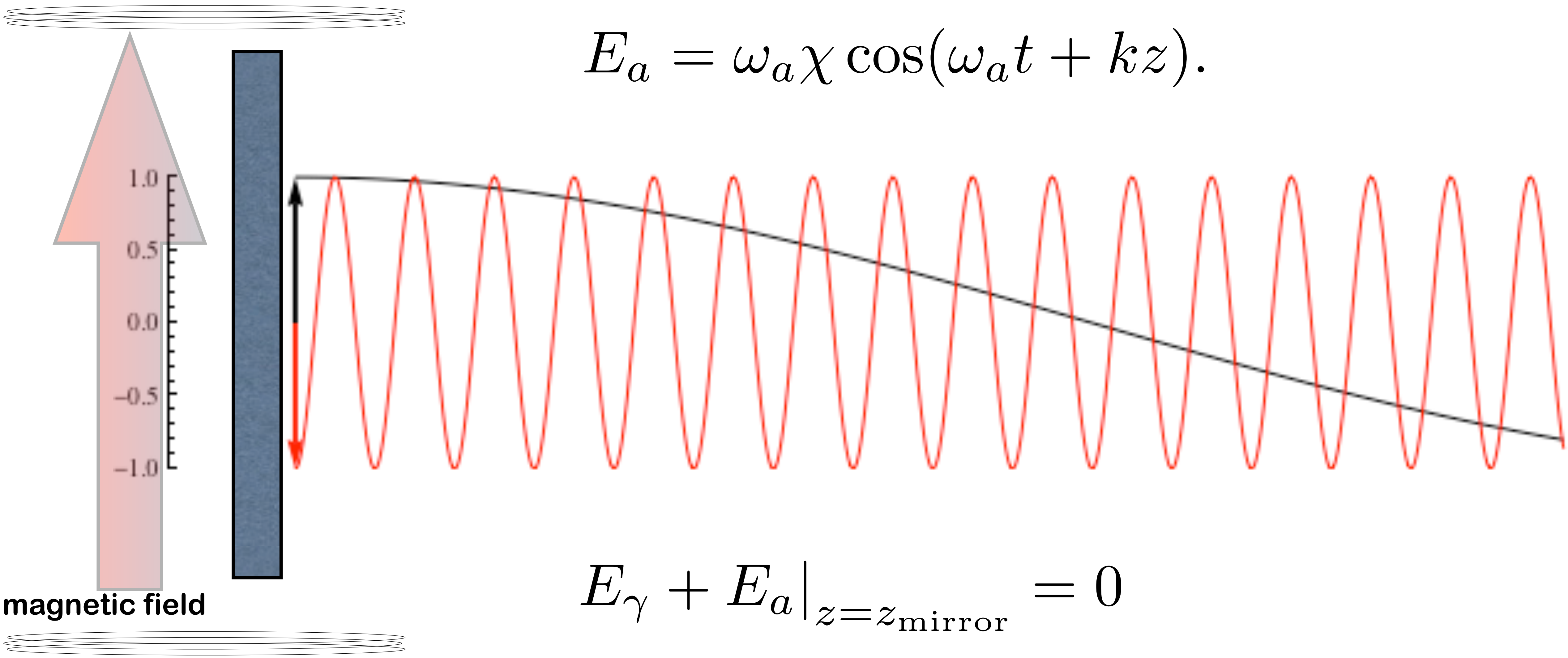

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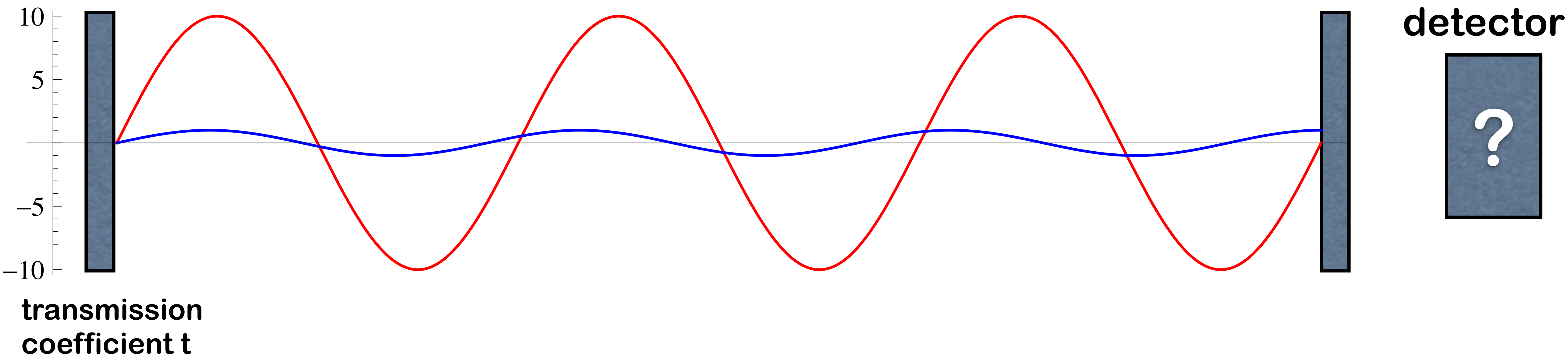
Photons radiated from the mirror with $\omega_\gamma = \omega_a = m_a(1 + v^2/2)$

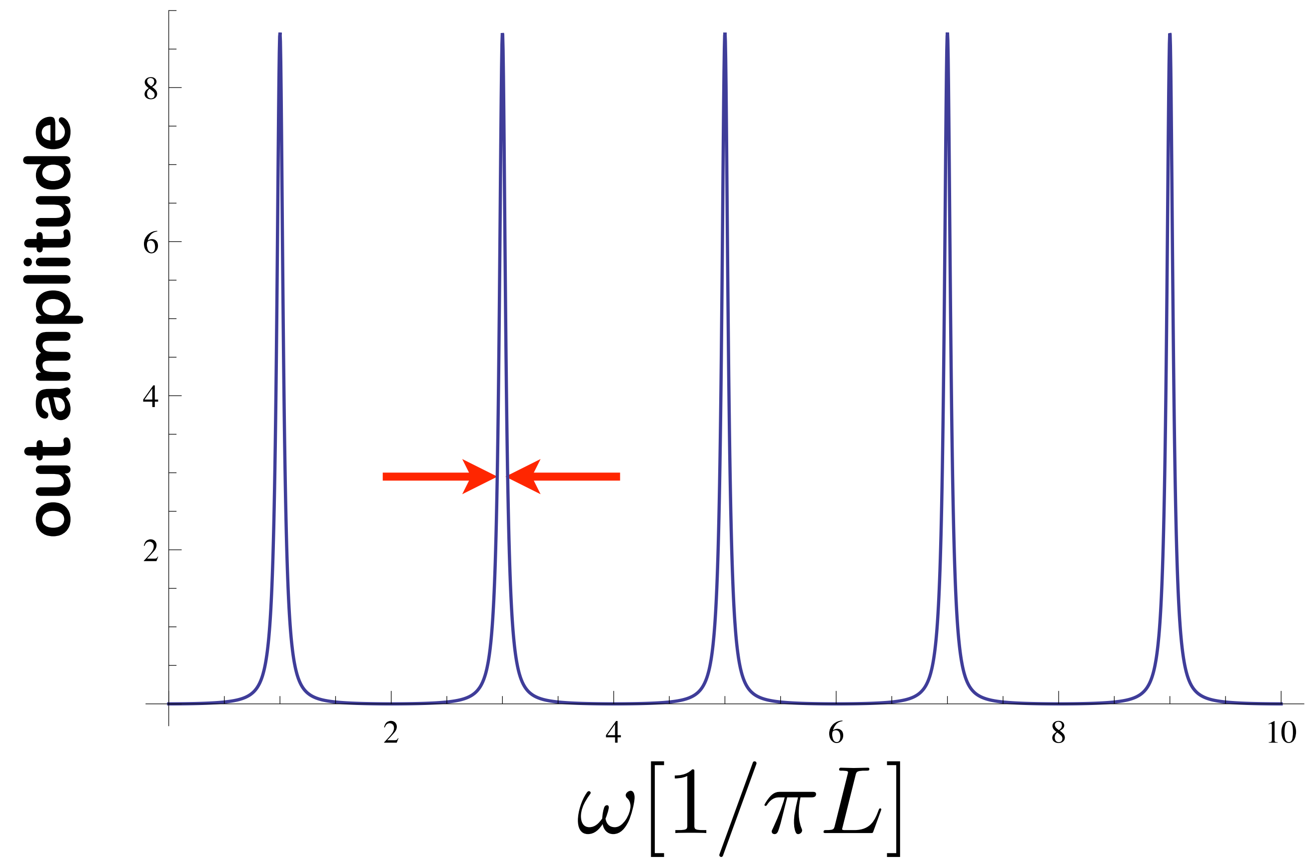
**Note: measuring these photons,
we measure the TOTAL DM energy,
DM mass and the velocity distribution!
also with directional sensitivity!**

Cavity searches (haloscopes)

Sikivie PRL '83

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





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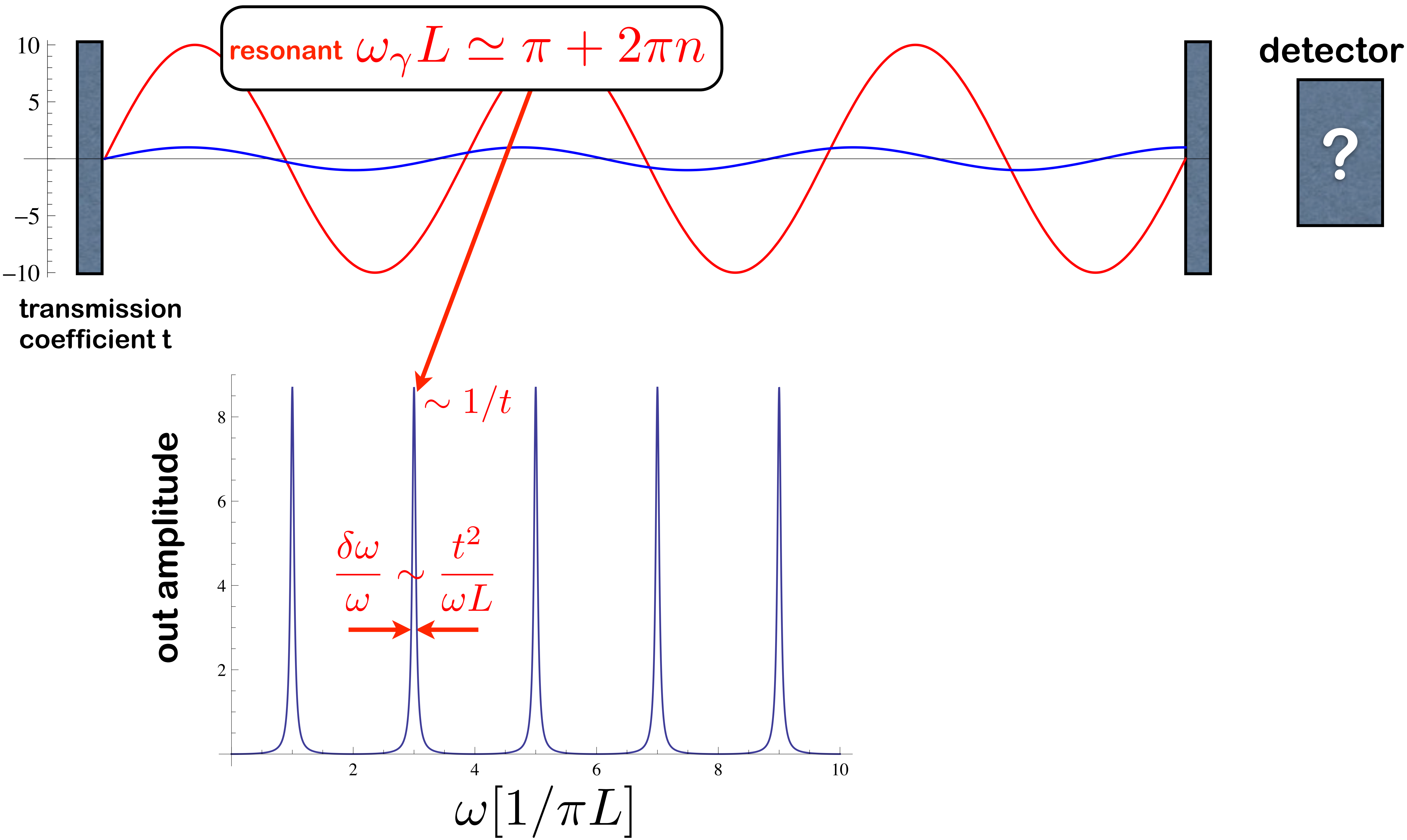

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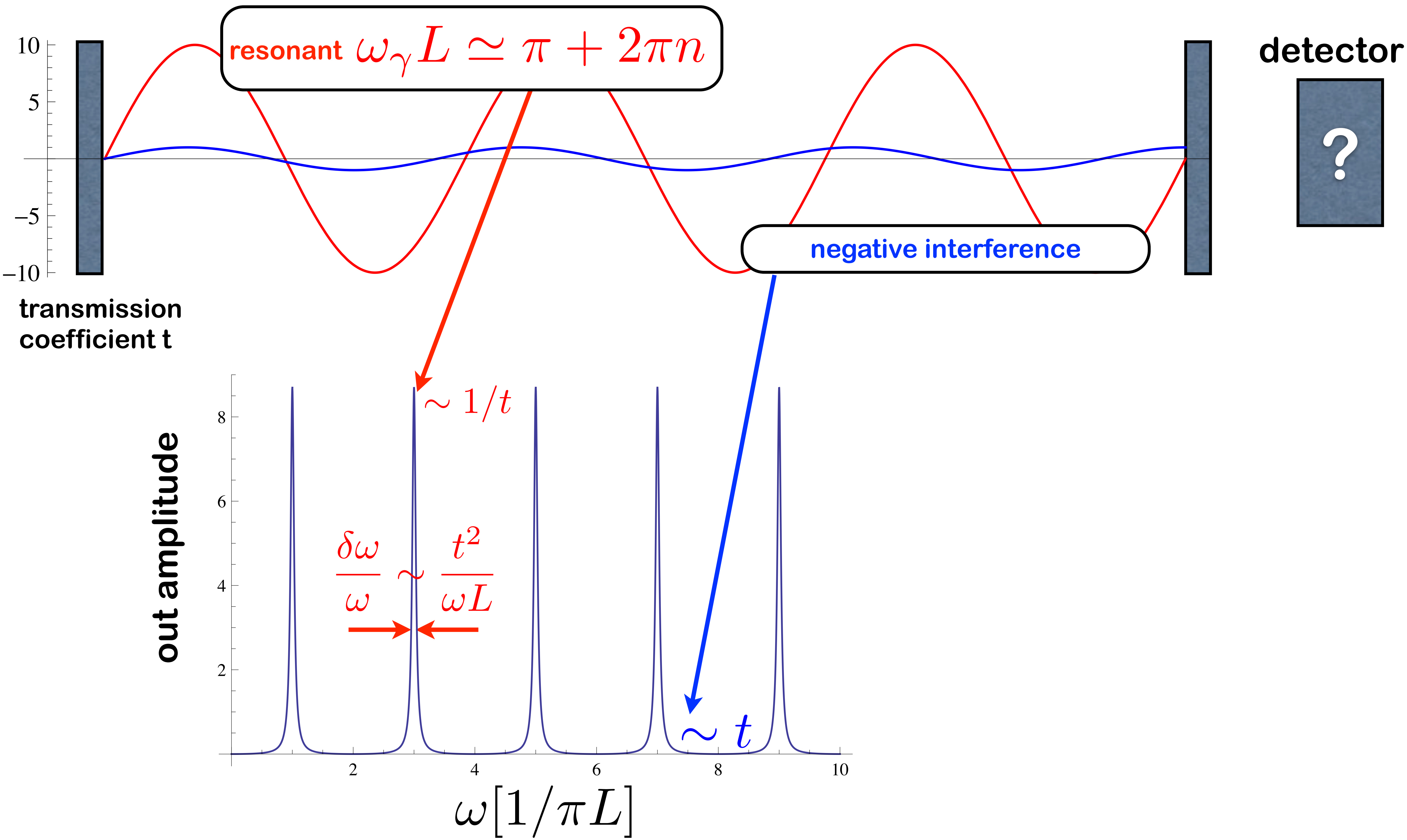

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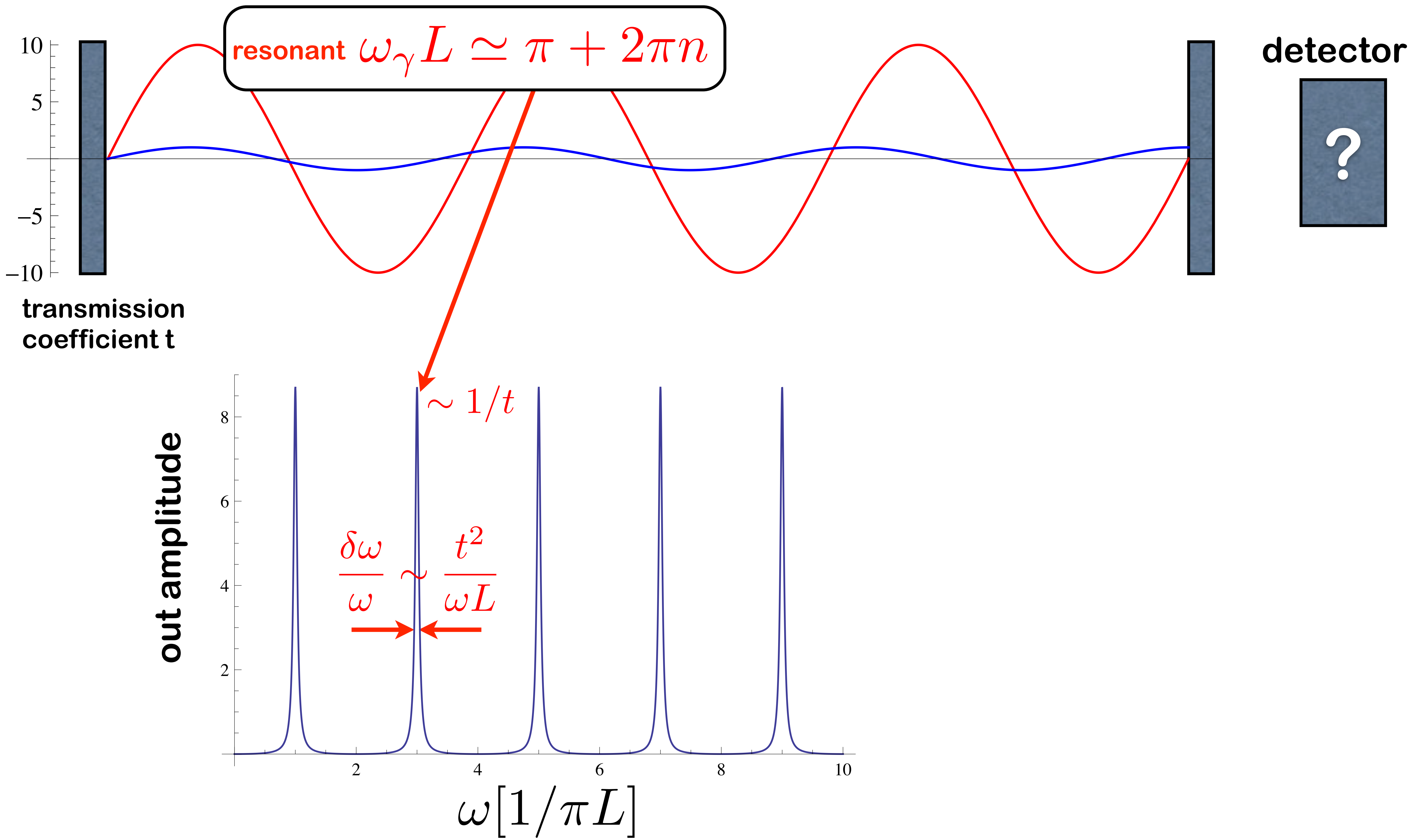

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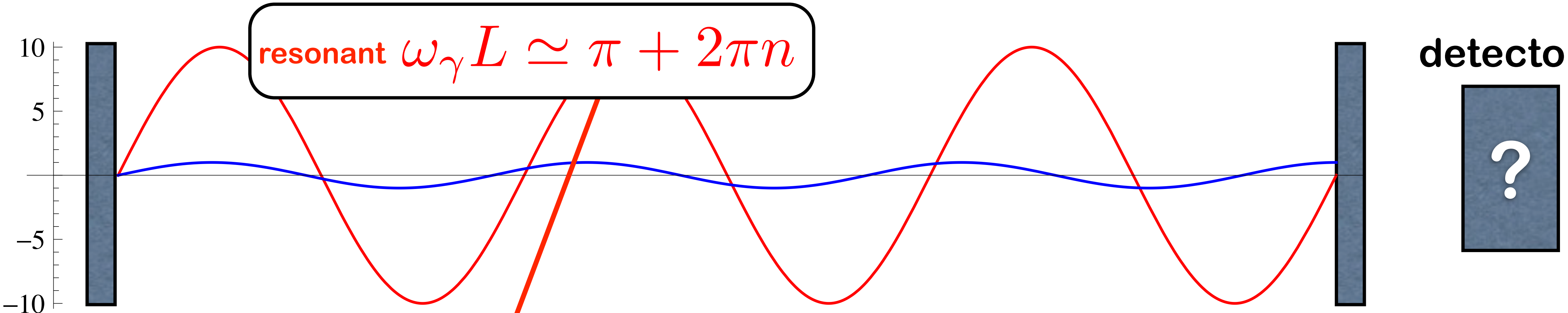
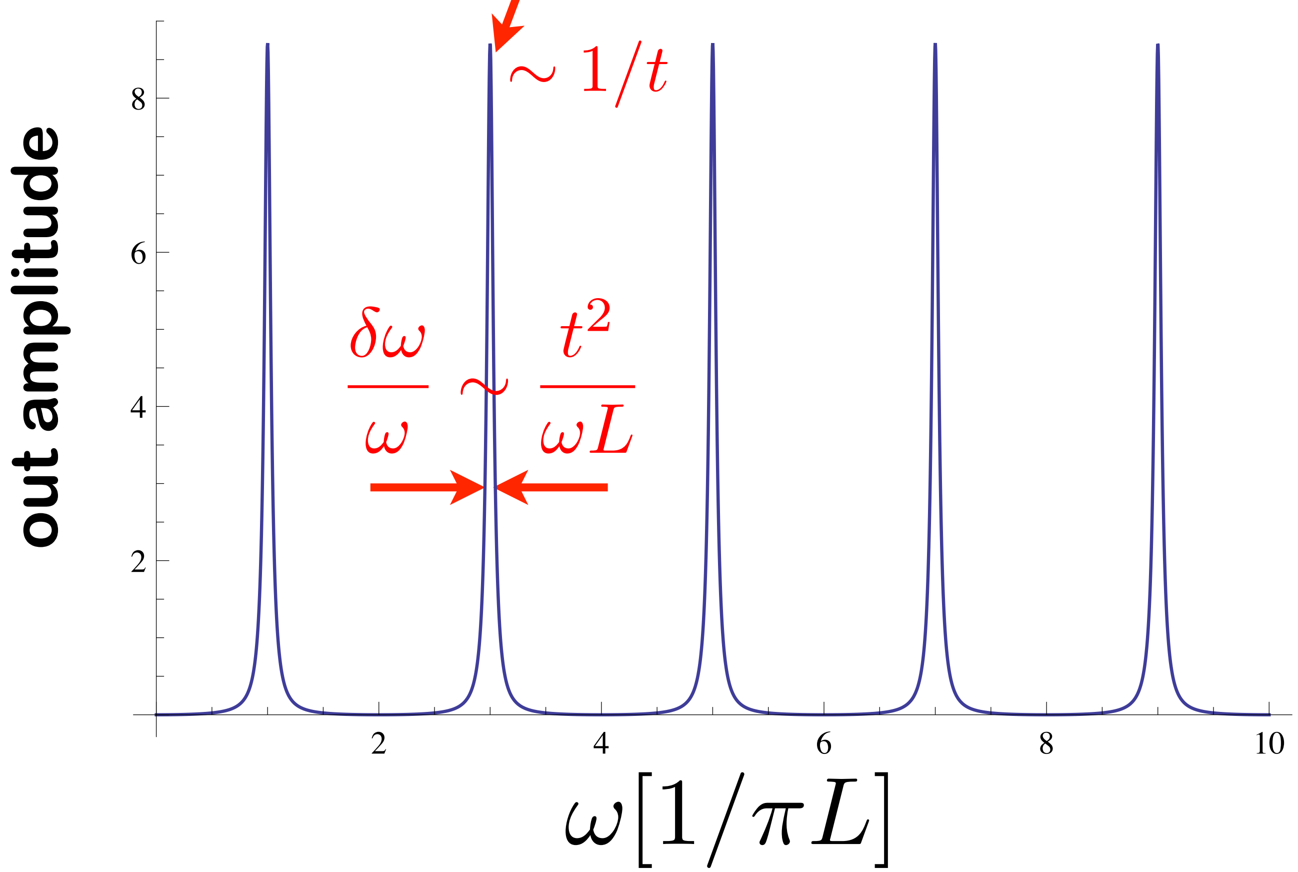


transmission coefficient t



dark matter distribution

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

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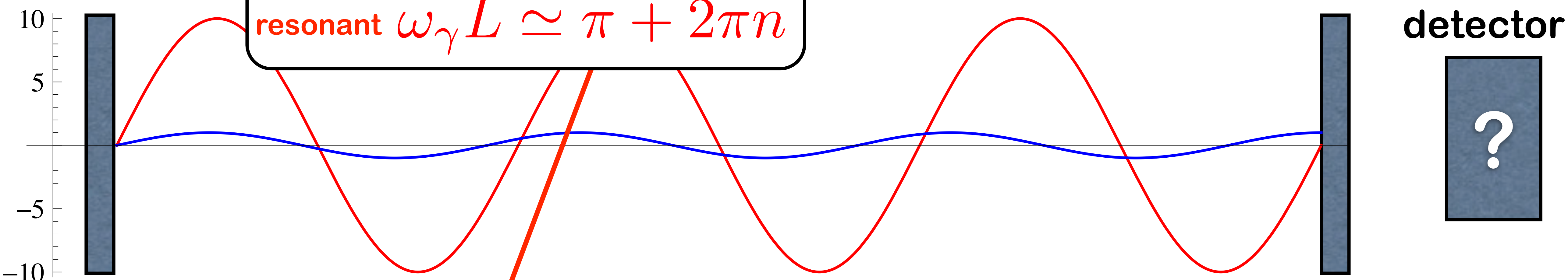
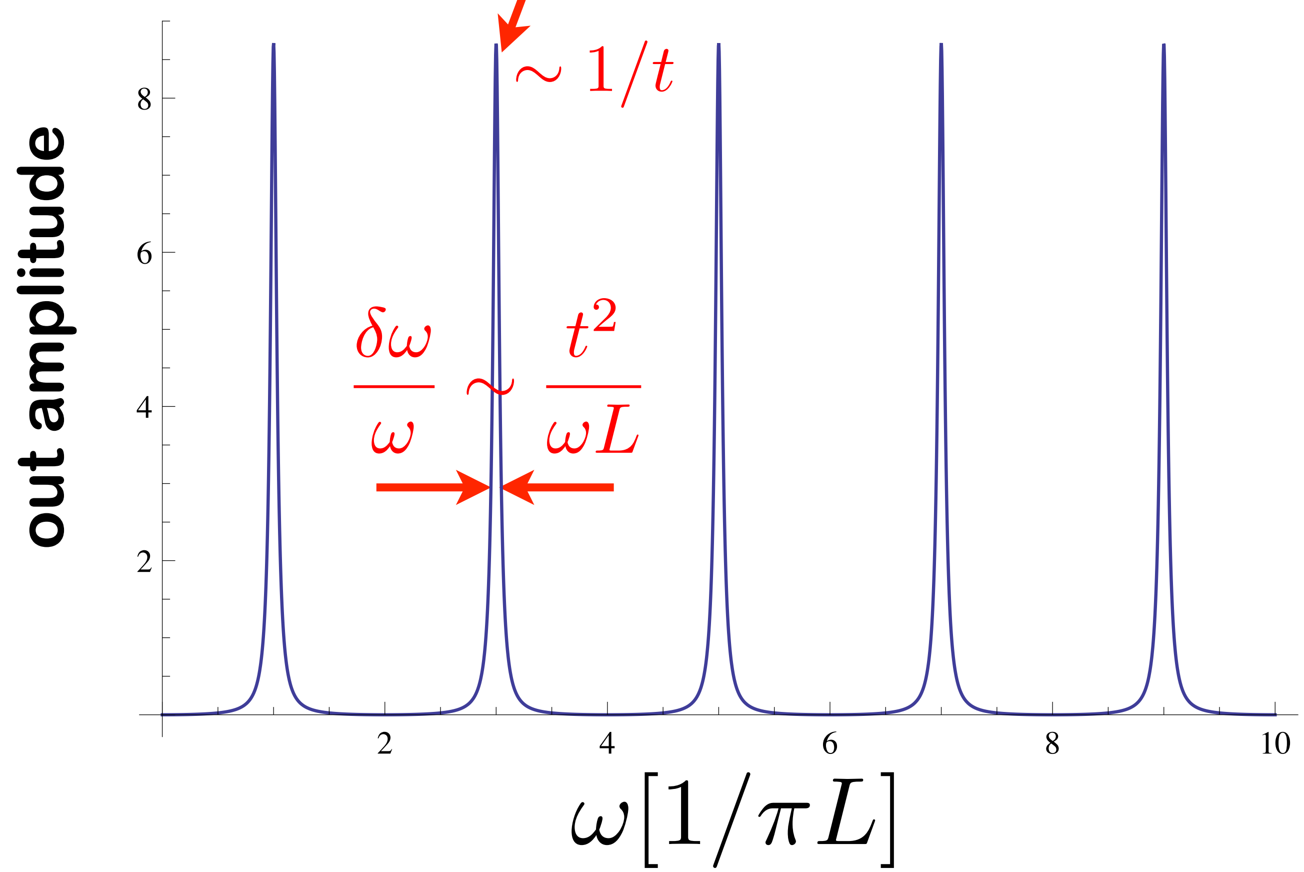
- Use two facing mirrors (simplistic resonant cavity in 1D)

resonant $\omega_\gamma L \simeq \pi + 2\pi n$



transmission coefficient t



dark matter distribution

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

chose

$$m_a L = \pi$$

$1/t$ **large**

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

Cavity searches (haloscopes)

- **Understanding the out Power**

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

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

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

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

Cavity searches II: the real thing...

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

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

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$L_0,$

Cavity searches II: the real thing...

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$$L_0, L_0 + \delta,$$

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

$$L_0, L_0 + \delta, L_0 + 2\delta,$$

Cavity searches II: the real thing...

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

$$L_0,\, L_0 + \delta,\, L_0 + 2\delta,\; etc...$$

slow scan, adjusting the length!

Cavity searches II: the real thing...

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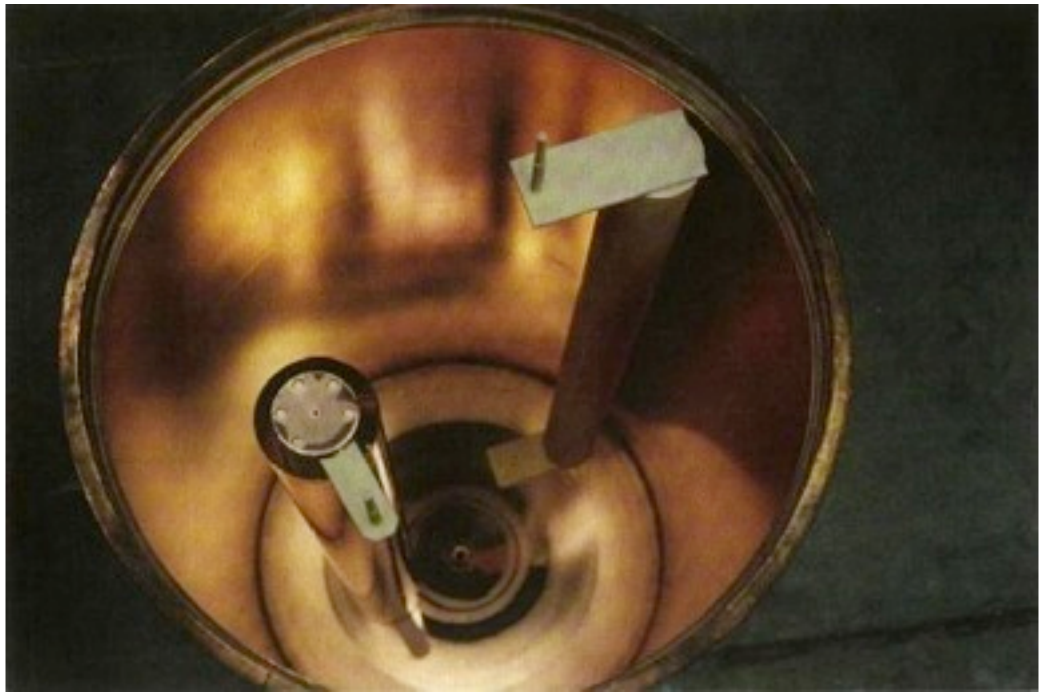
slow scan, adjusting the length!

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



8T field, 1mL,0.5mD

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

Cavity searches II: the real thing...

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

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

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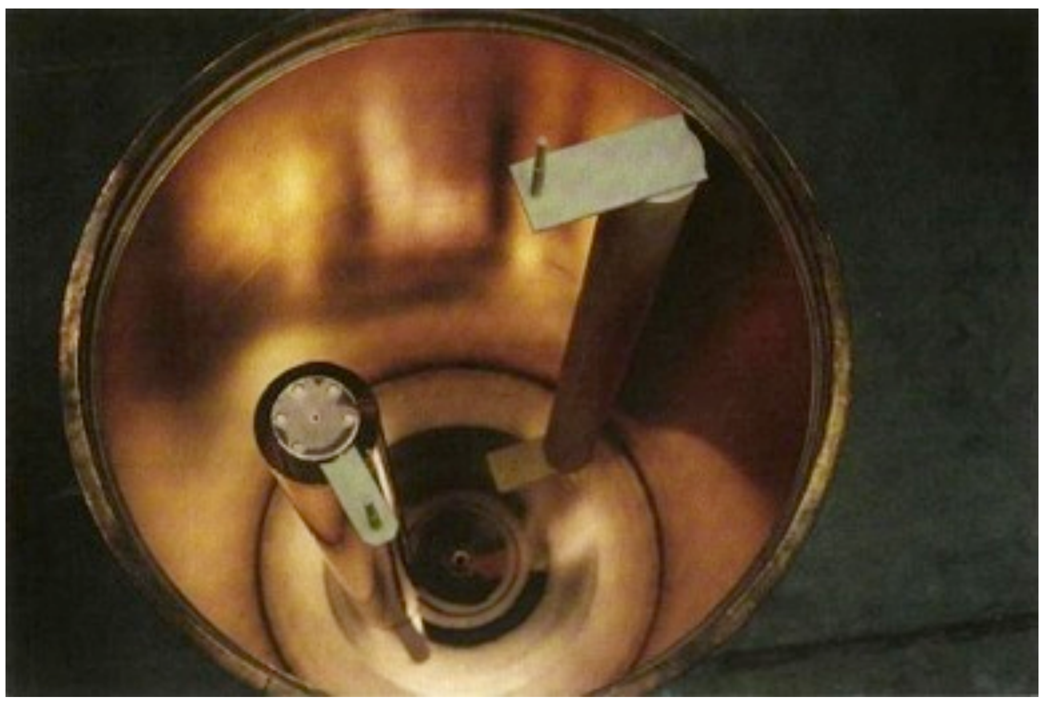


8T field, 1mL,0.5mD

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

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

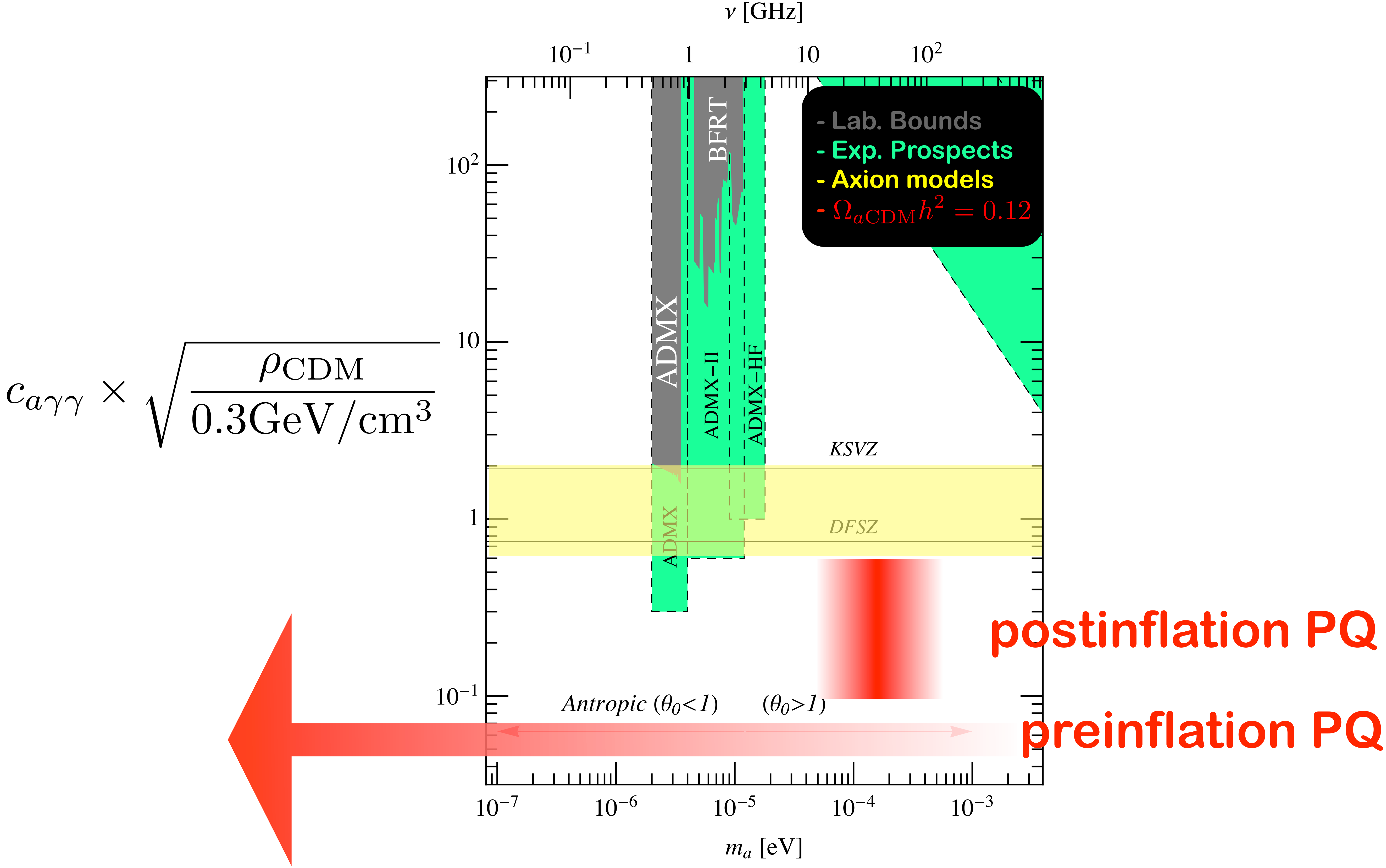
$$\frac{S}{N} = \frac{P_{\rm out}}{P_{noise}} = \frac{P_{\rm out}}{T_S}\sqrt{\frac{\rm time}{\rm Bandwidth}}$$

measurement time vs. different measurements

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

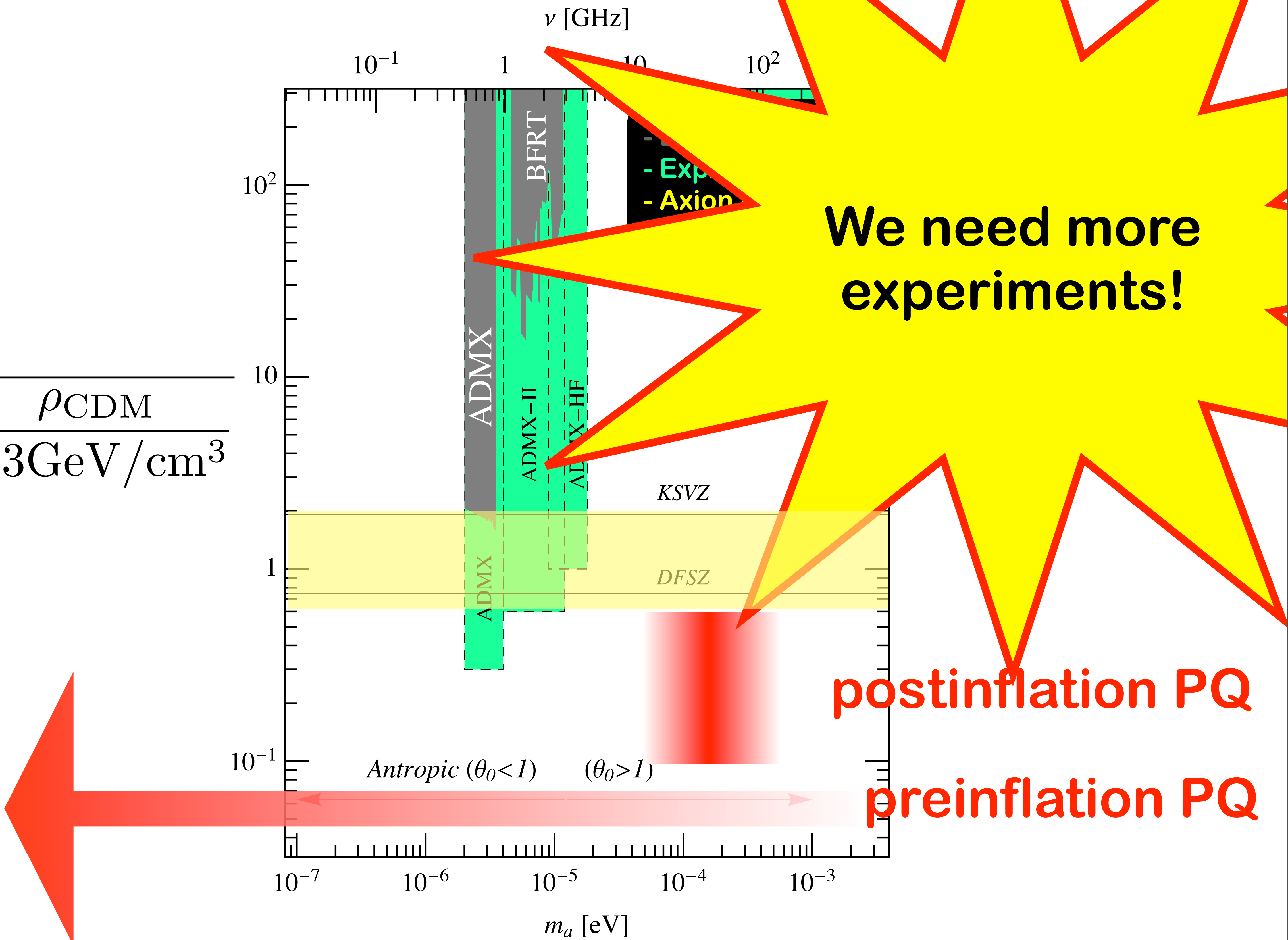
the definitive experiment! ... ???

Cavity searches II: ADMX and relatives



Cavity searches II: ADMX and relatives

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

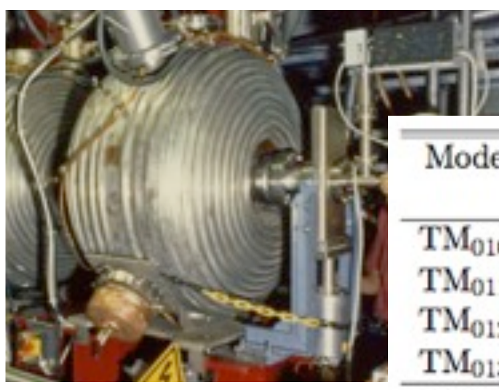


Cavity searches III: lower masses

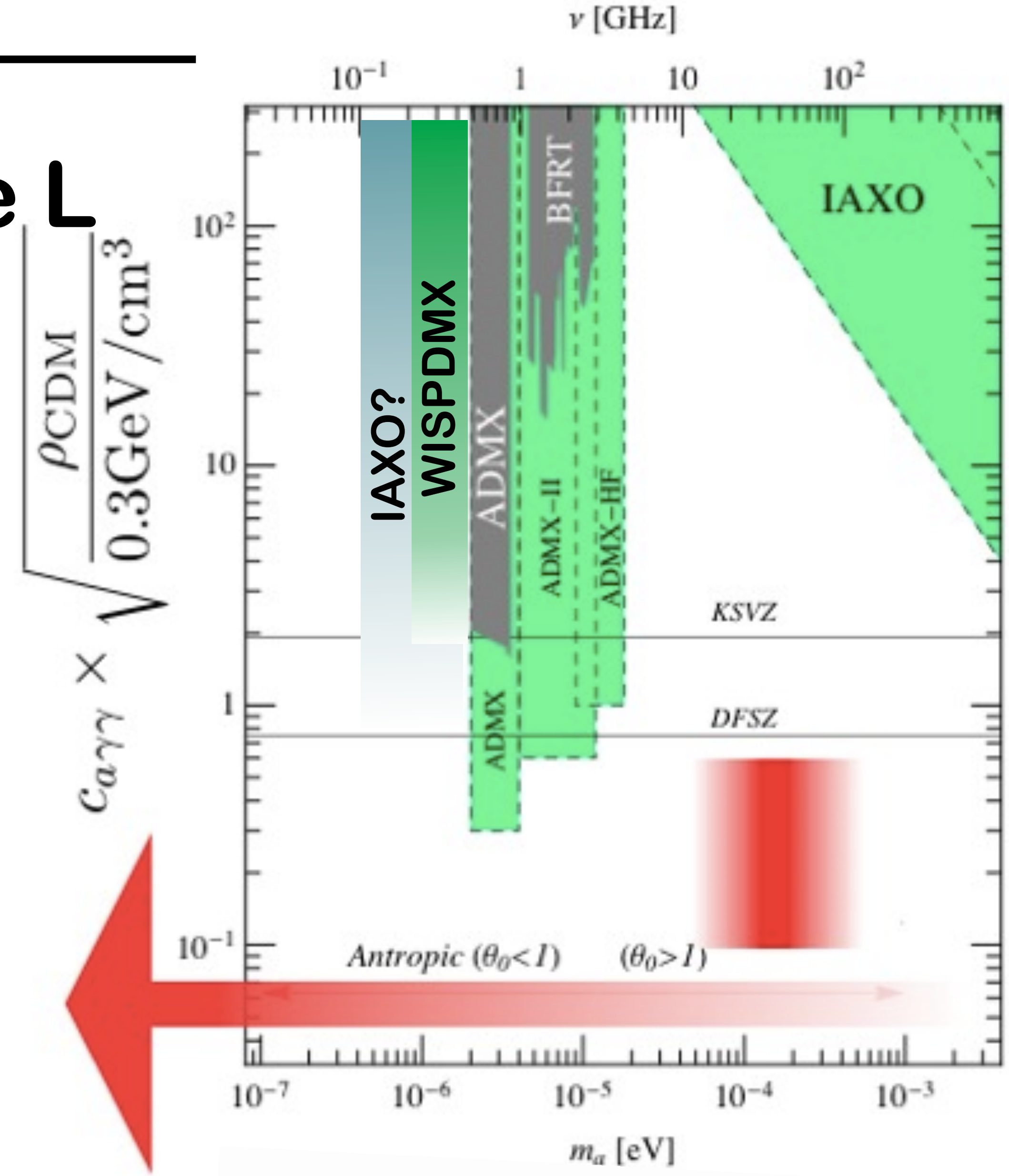
- **Larger signal but needs large L**

$$P \sim 10^{-23}\, W \left(\frac{\mu\text{eV}}{m_a}\right)^2$$

- **WISPDMX @ DESY (ALPS)**

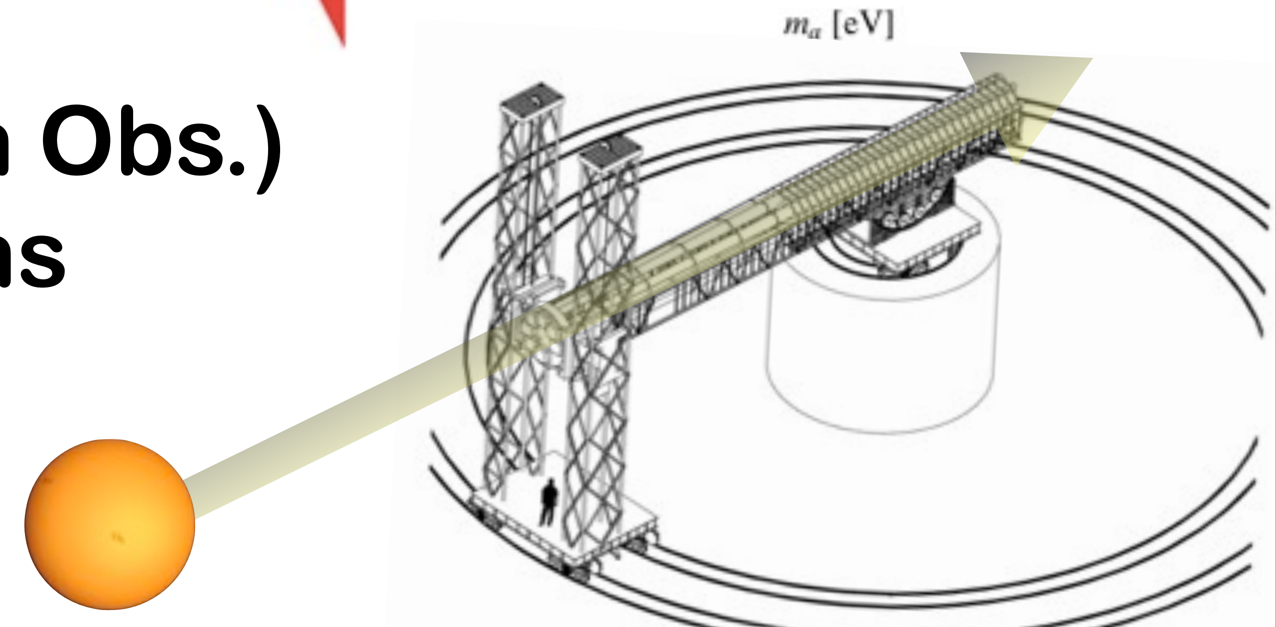


Mode	ν [MHz]	Q_0	Mode	ν [MHz]	Q_0
TM_{010}	199	53360	TM_{014}	579	122500
TM_{011}	295	44830	TM_{015}	707	60950
TM_{012}	433	47450	TM_{016}	765	105070
TM_{013}	524	47710	TM_{017}	832	102230



- **IAXO (International Axion Obs.) main focus on solar axions**

  - B~ 5 T,
  - L~ 20 m
  - A~ 6 m^2



~~Cavity~~ searches III: much lower masses

Graham & Rajendran

$$\frac{\alpha_s}{8\pi} G\widetilde{G}\theta \to d_n \sim 10^{-15}\theta \, \mathrm{ecm}$$

$$\begin{aligned} \frac{\alpha_s}{8\pi} G\widetilde{G}\left(\frac{a}{f_a}\right) \quad &\to \quad 10^{-15}\frac{a(t)}{f_a}\,\mathrm{e\,cm} \\ &\sim \quad 10^{-15}\frac{\sqrt{\rho_{\mathrm{CDM}}}\cos(m_a t)}{m_a f_a}\,\mathrm{e\,cm} \sim 10^{-15}\frac{\sqrt{\rho_{\mathrm{CDM}}}\cos(m_a t)}{m_\pi f_\pi}\,\mathrm{e\,cm} \\ &\sim \quad 10^{-34}\cos(m_a t)\,\mathrm{e\,cm} \end{aligned}$$

oscillating EDM of the neutron!! .... NOOOOOO

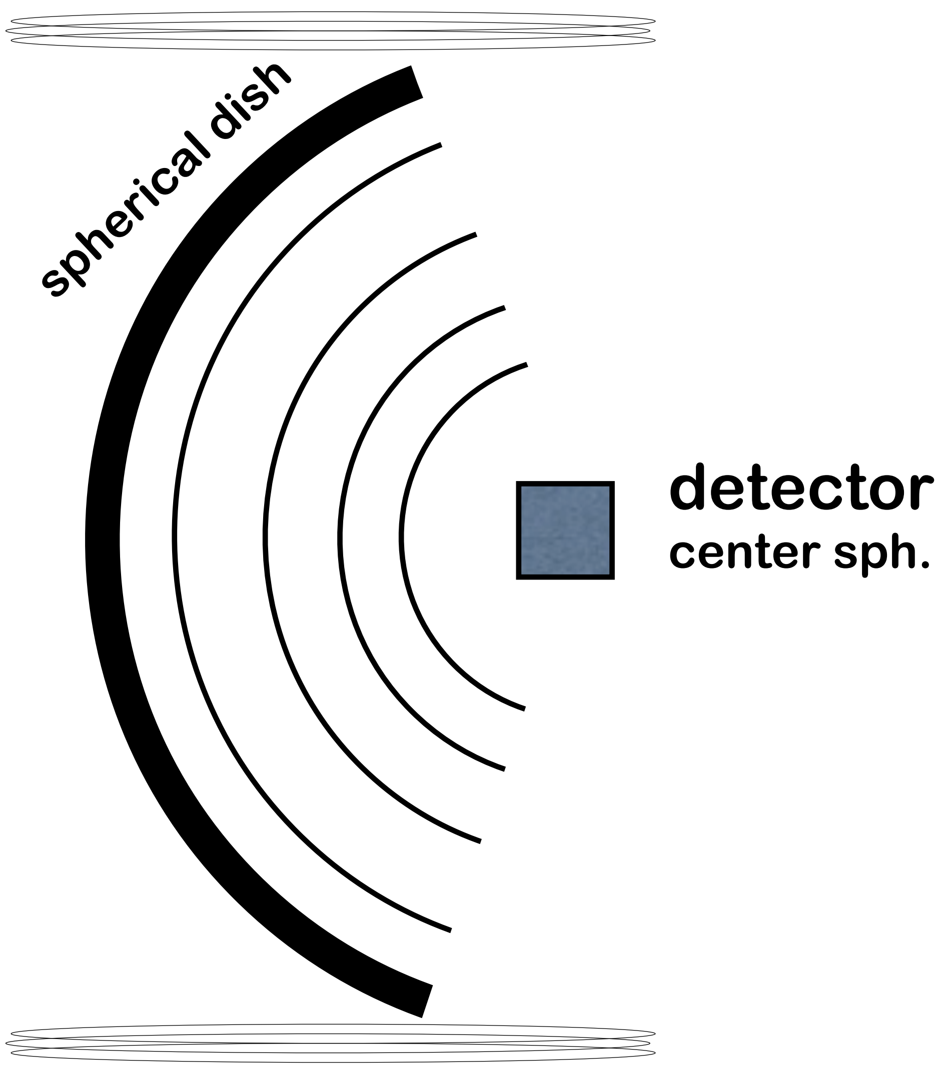
The state coupling to GG is $\eta'_{\mathrm{phys}} = \eta' + \phi\frac{f_\eta}{f_a}$

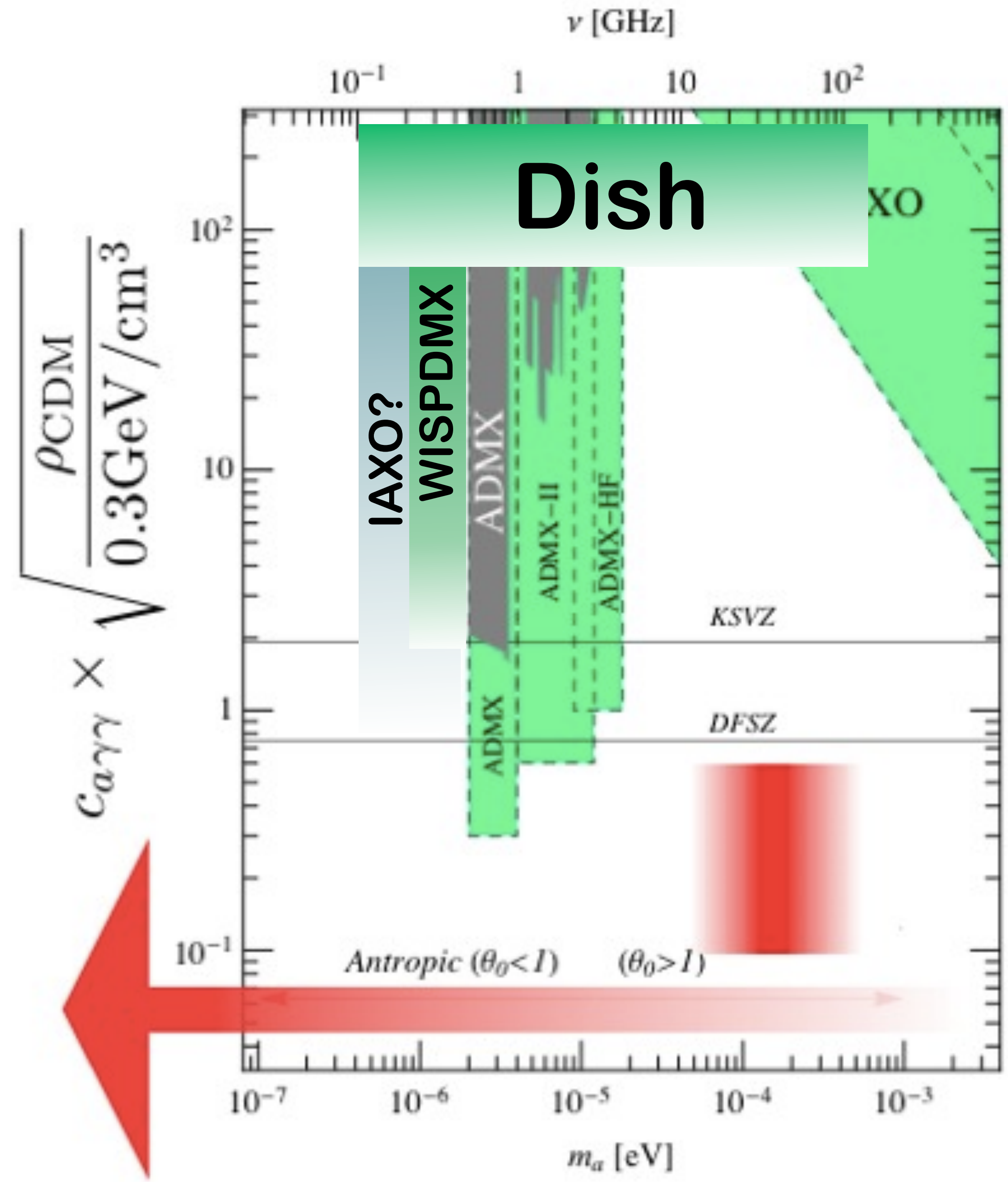
and the DM is $a = \phi - \eta'\frac{f_\eta}{f_a}$

and is decoupled from GG (up to small corrections)

Dish antenna searches (broadband!)

JR et al , JCAP04(2013)016





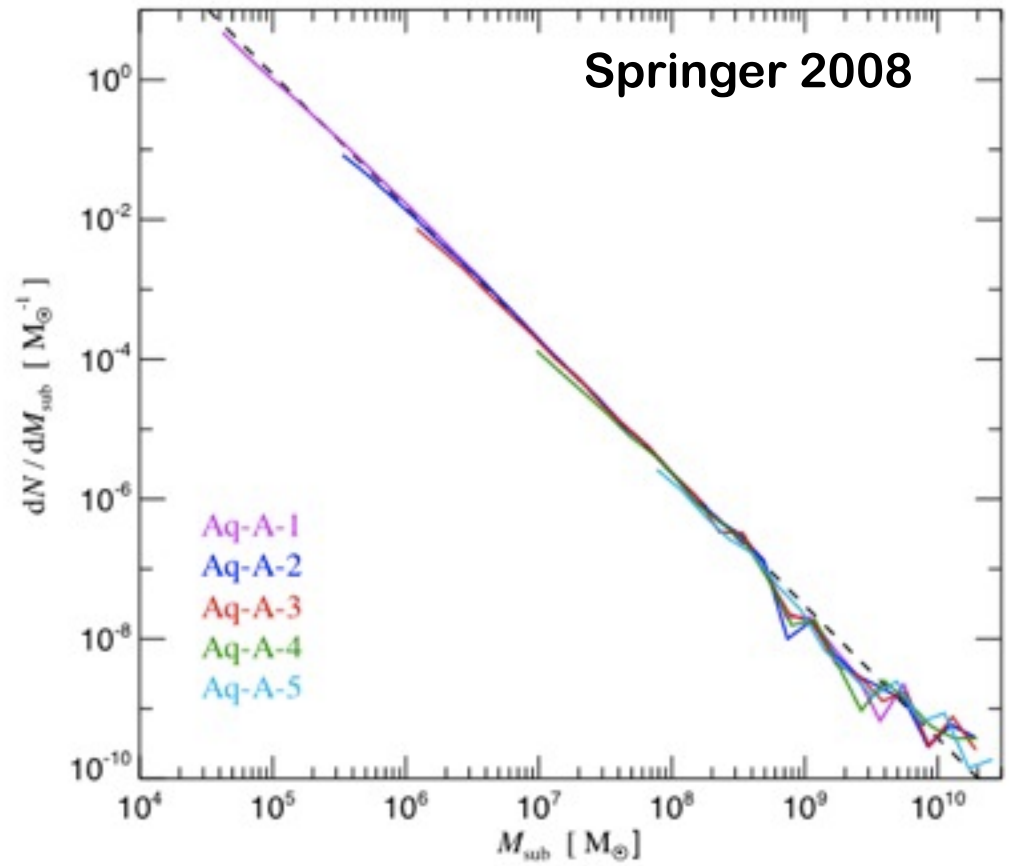
$$P_{\rm center} \approx A_{\rm dish}\langle|\mathbf{E}_{\rm DM,||}|^2\rangle \sim \chi^2 \rho_{\rm CDM} A_{\rm dish}$$

Comparing (1 m^2, B=5 T, B=10^-23 W) with an ideal cavity search

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

But measuring all range at a time!

DM substructures ?



- Cold dark matter clumps

(axions=standard + miniclusters)

- Cavity experiments miss encounters

They are likely looking at the wrong freq.

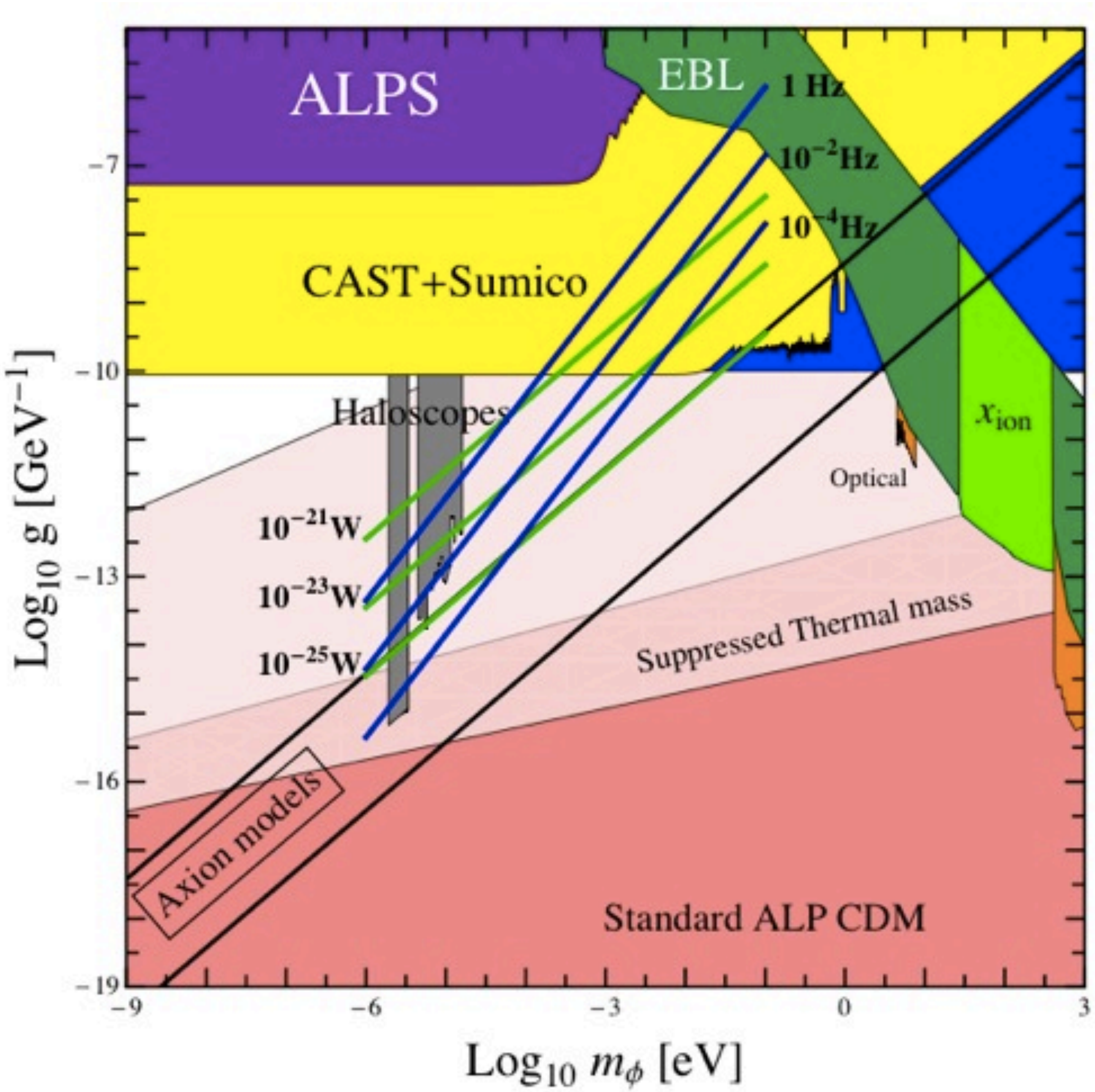
- Broadband Dish search not (10^4 boost req.)

Work in progress!

Generic Axion-like particles

JR et al , JCAP04(2013)016

much more promising!



1 m^2 dish
5T magnet

mass and coupling unrelated

Conclusions

- Extensions of the SM might well accommodate WISPs

The Strong CP problem cries for an axion

- The mysteries of cosmology can be solved by WISPs

Dark Matter, (Dark Radiation, Dark Energy)

- WISPs can be searched experimentally

New Axion/ALP/HP cold dark matter experiments !!!
Next generation experiments (ALPS-II, IAXO?)