
Axion Cold Dark Matter
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May 16th 2013,
ICTP

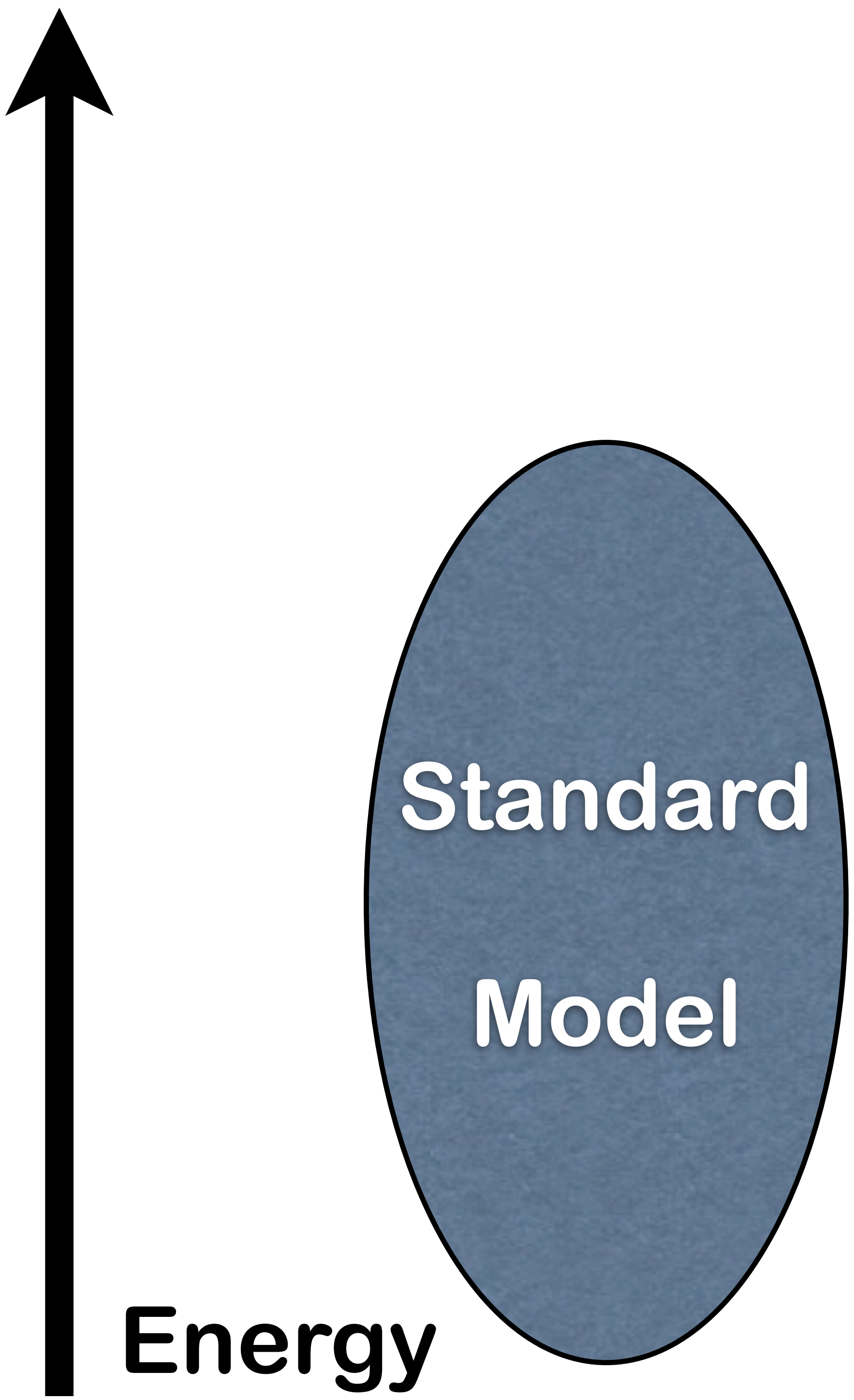
# Outline

- 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

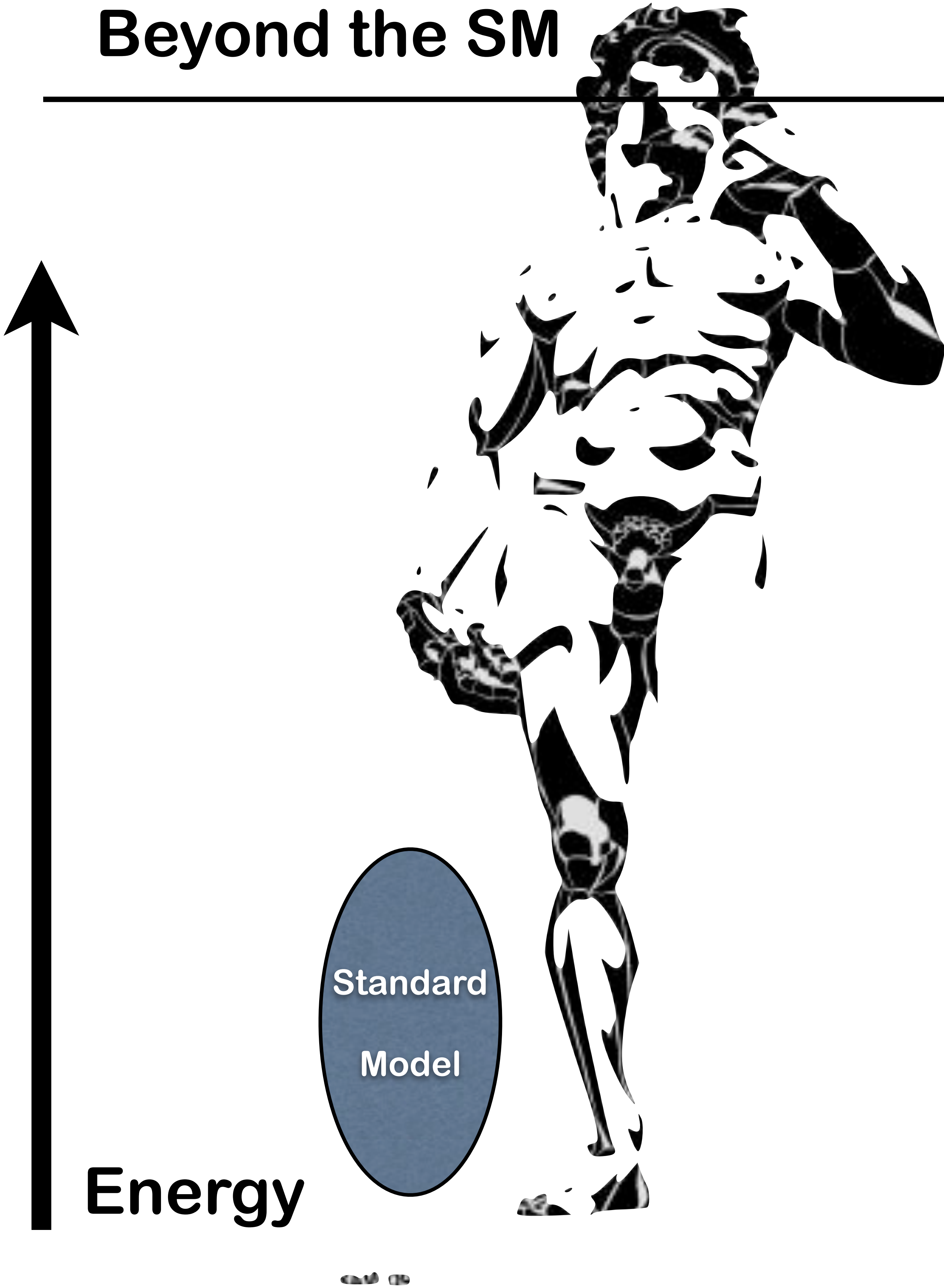



**Describes extremely well fundamental physics (at low energies)**

**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


Energy

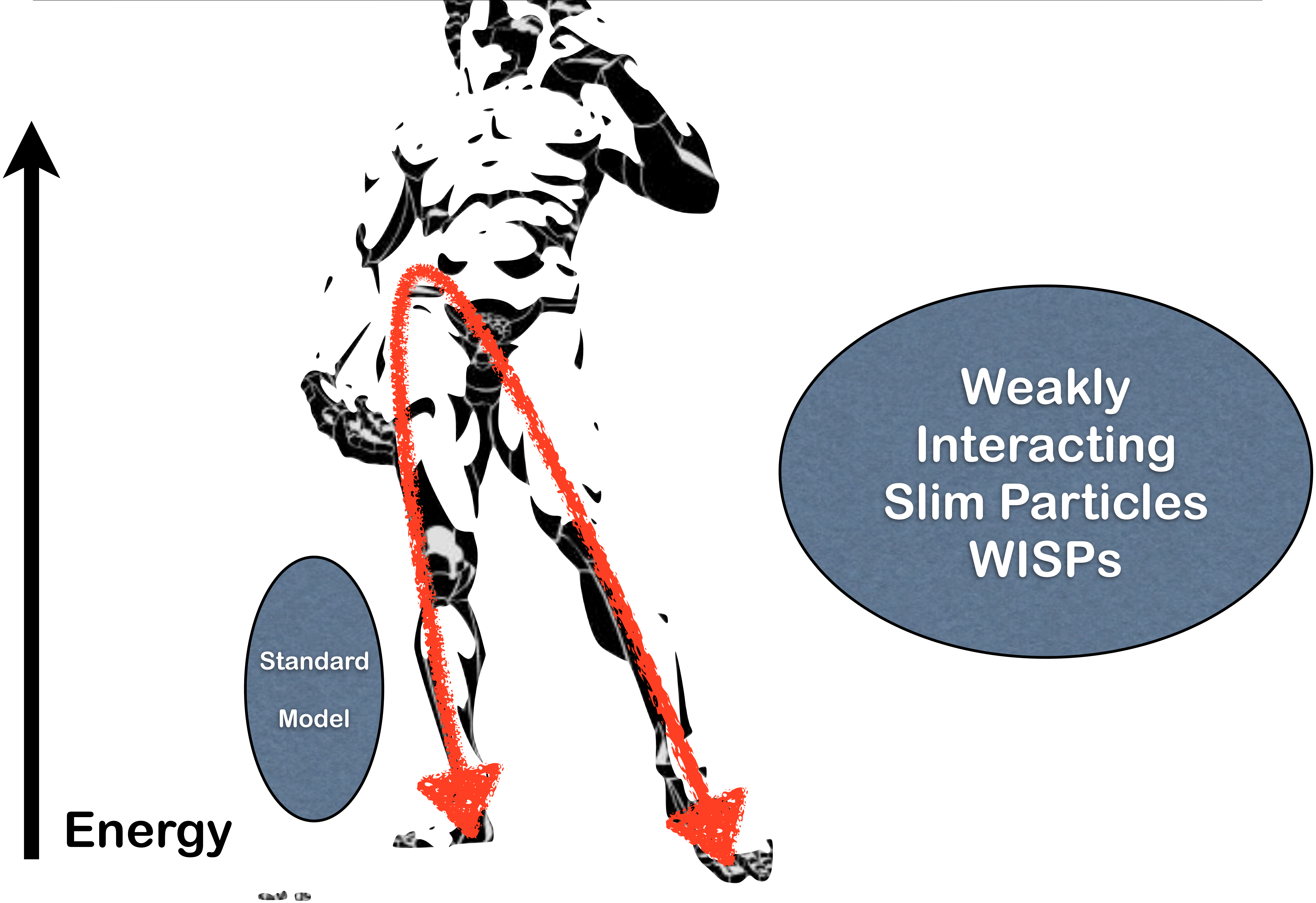
**Answers are awaiting in the**

**high energy frontier**

**where more symmetric beautiful theories arise**

**... and can imply physics at low energies**

# Beyond the SM ... at low energies



# The paradigmatic example: Strong CP problem

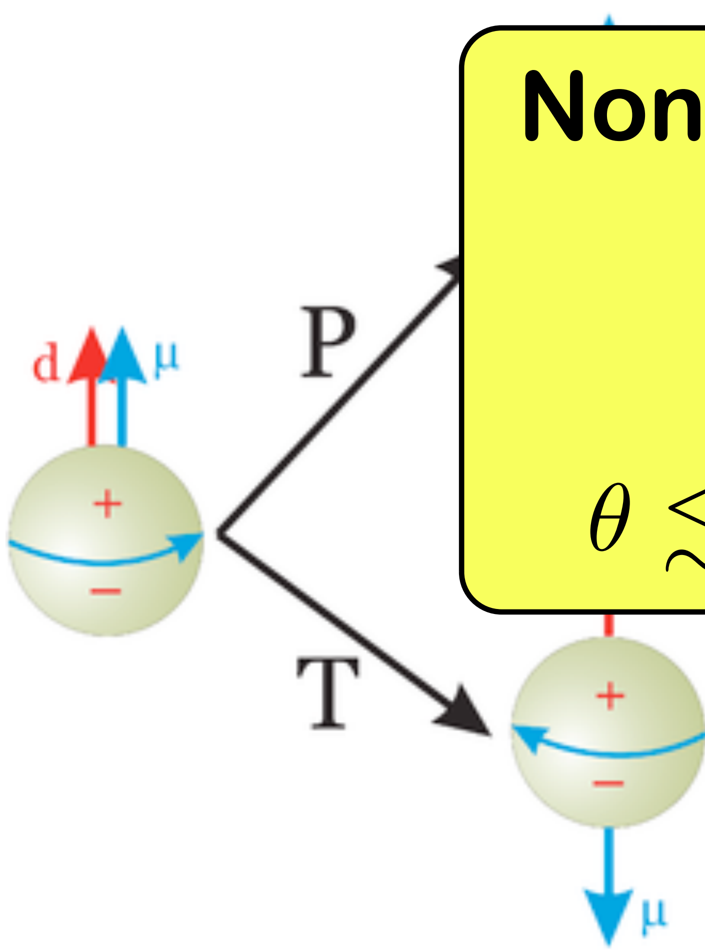
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \mathrm{tr}\left\{ G_a^{\mu\nu} \widetilde{G}_{a\mu\nu} \right\} \theta$$

**Violates P and T**

$$\theta_{\mathrm{QCD}} \in (-\pi, \pi)$$

$$\arg\det M_q \sim \mathcal{O}(1)?$$

**neutron EDM**




**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

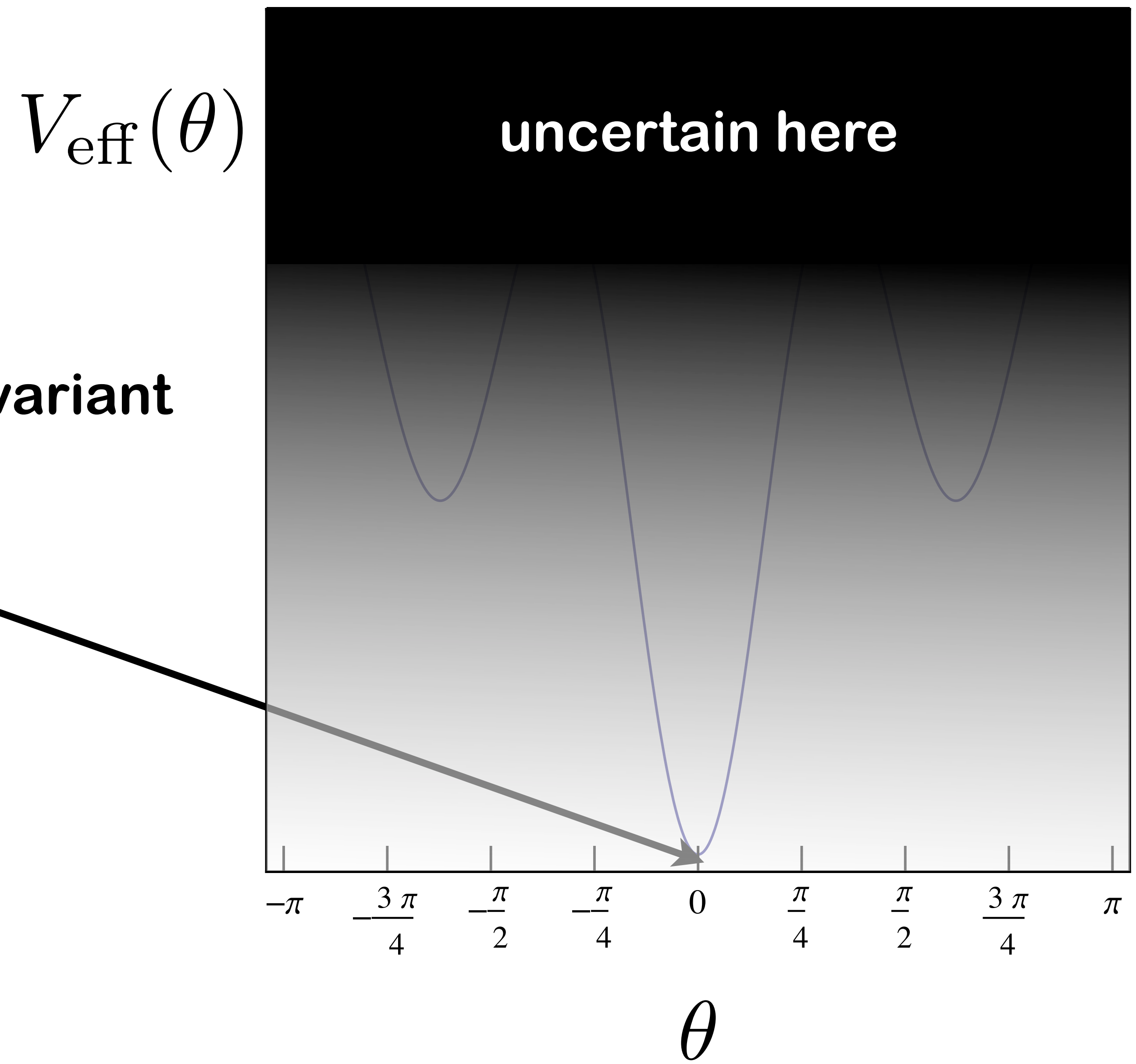
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\mathrm{tr}\left\{G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}\right\}\theta$$

**Consider no quarks**

**If the rest of the theory is P,T invariant**

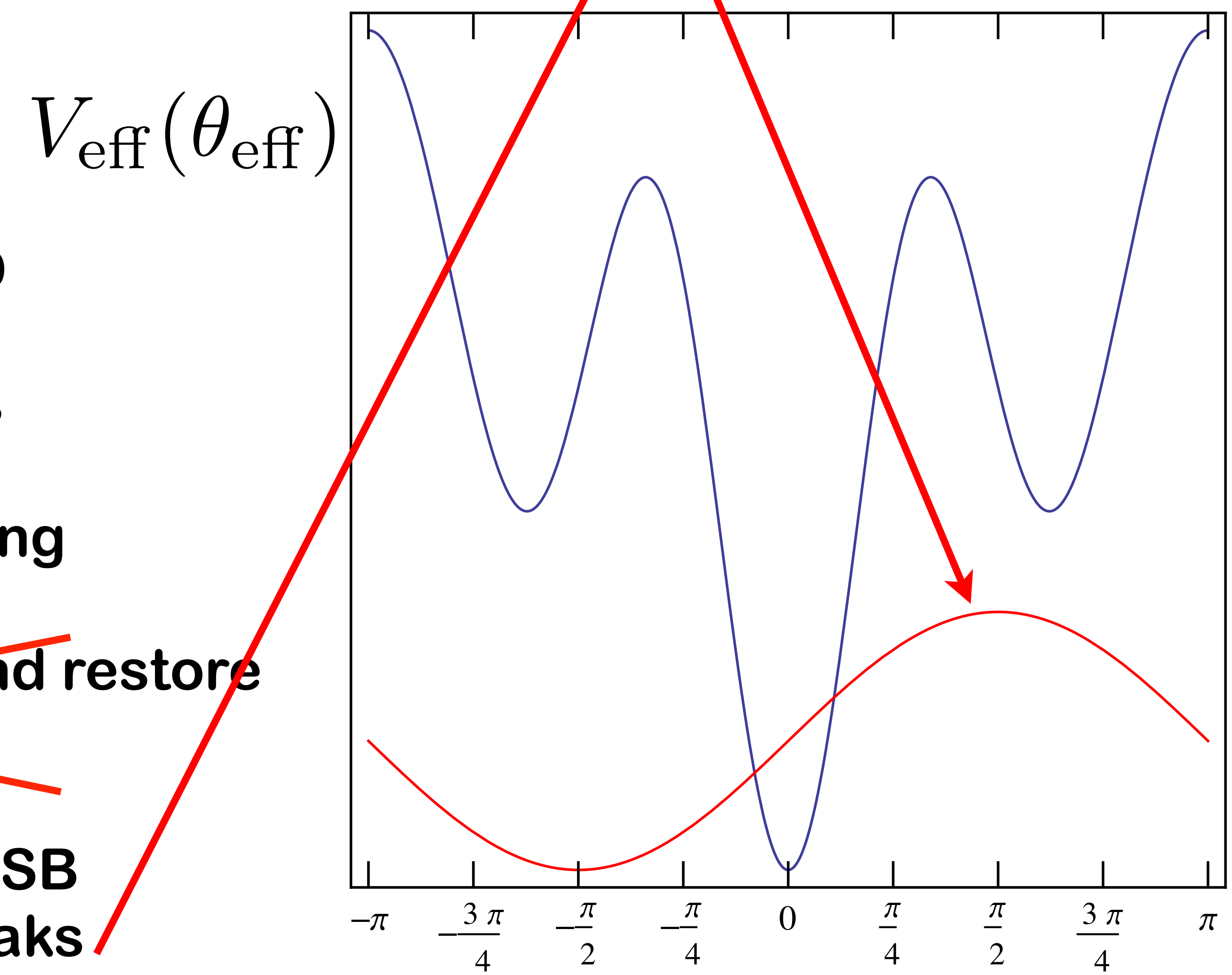
## Minimum at $\theta = 0$

**but $\theta$ is not dynamical**



# The Strong CP problem: a hint

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




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

**With quarks, low-energy QCD**

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

$\eta'$ **has anomalous gg coupling**

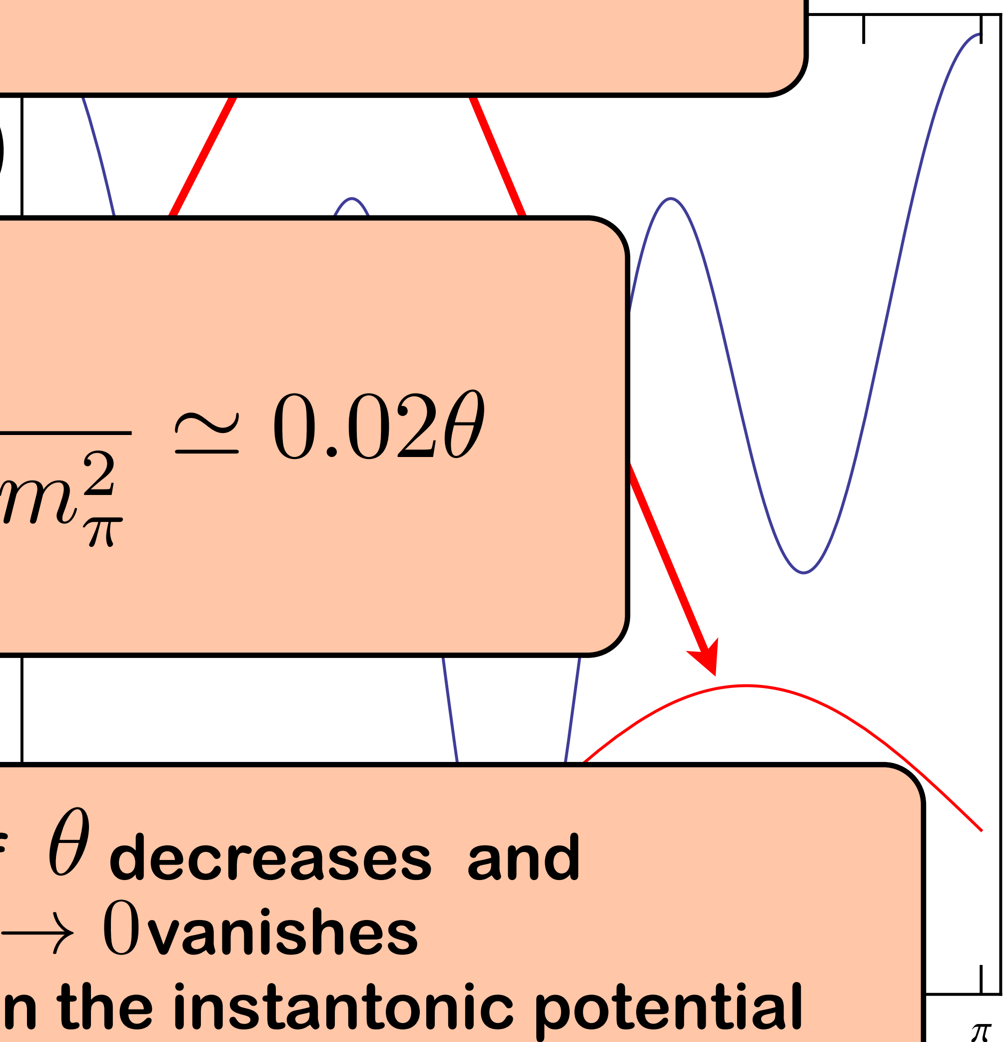
~~**can roll down the potential and restore P, T symmetries!!**~~

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

$\eta'$ **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 sym**~~

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

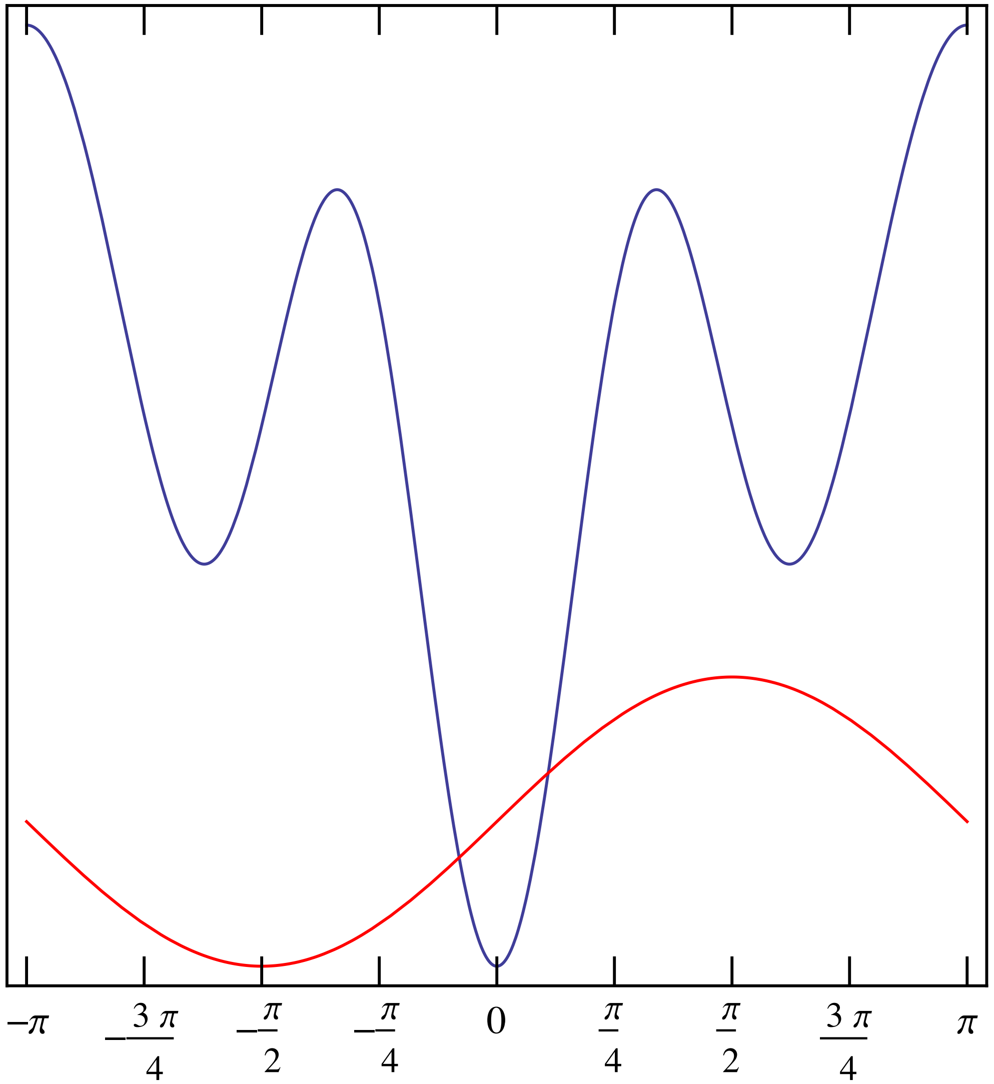
**Actually**
**makes $m$**
**explicitly $U(1)_{\rm A}$ giving $\eta'$ a mass**
**of the order of the $\pi^0$ mass.**

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

# 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** $\eta'$

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

**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**

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

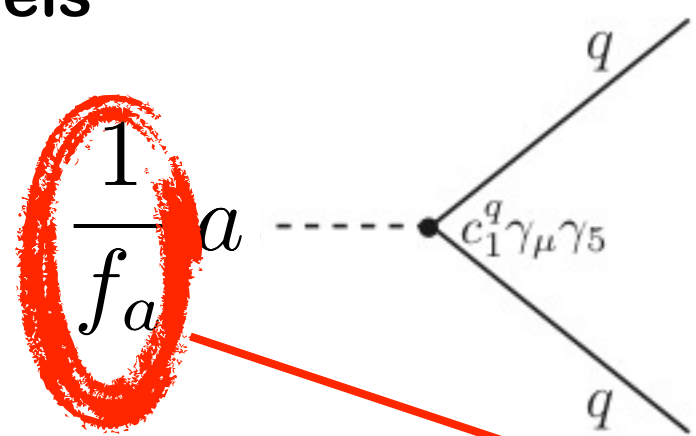
# Axion mixes with QCD mesons and gets mass and couplings

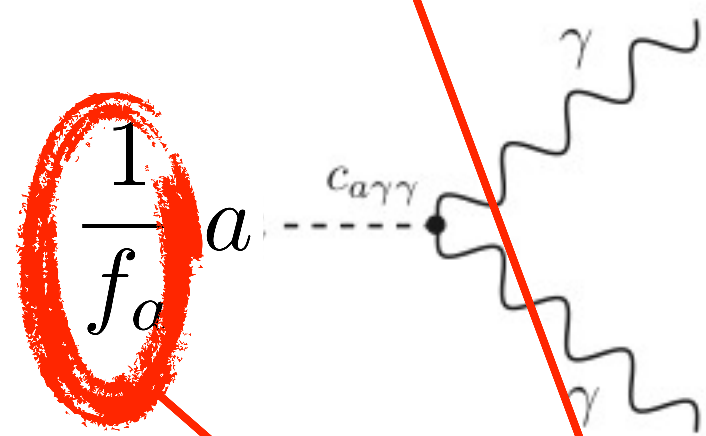
## Typical from Nambu-Goldstone Bosons

### Mass

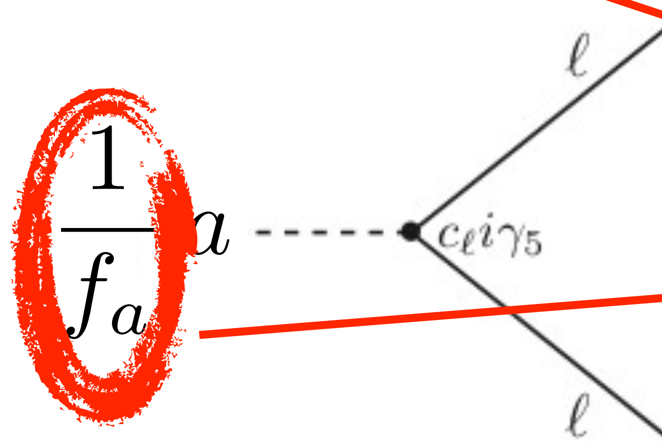
$$m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6\ \mathrm{meV}\,\frac{10^9\,\mathrm{GeV}}{f_a}$$

**Bare models**




**Extended models also feature couplings to leptons**

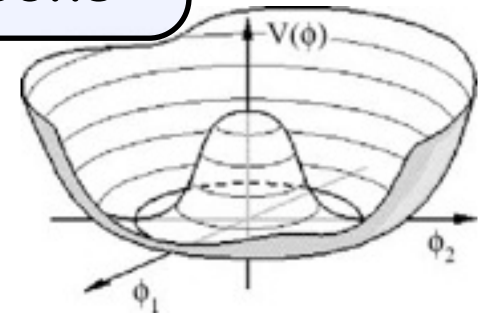



# Weakly interacting slim particles (WISPs)

## Axion-like particles (ALPs) $0^-$

**pseudo Goldstone bosons**

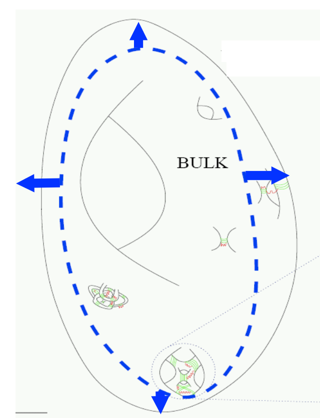
Global continuous symmetry
spontaneously broken at
high energy scale f




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

**String ‘axions’**

Sizes and deformations of
extra dimensions,
gauge couplings

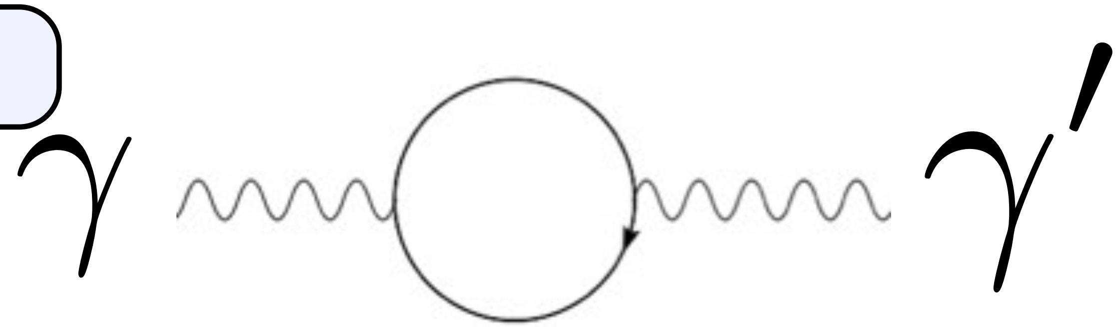



DILATONS RADION MODULI

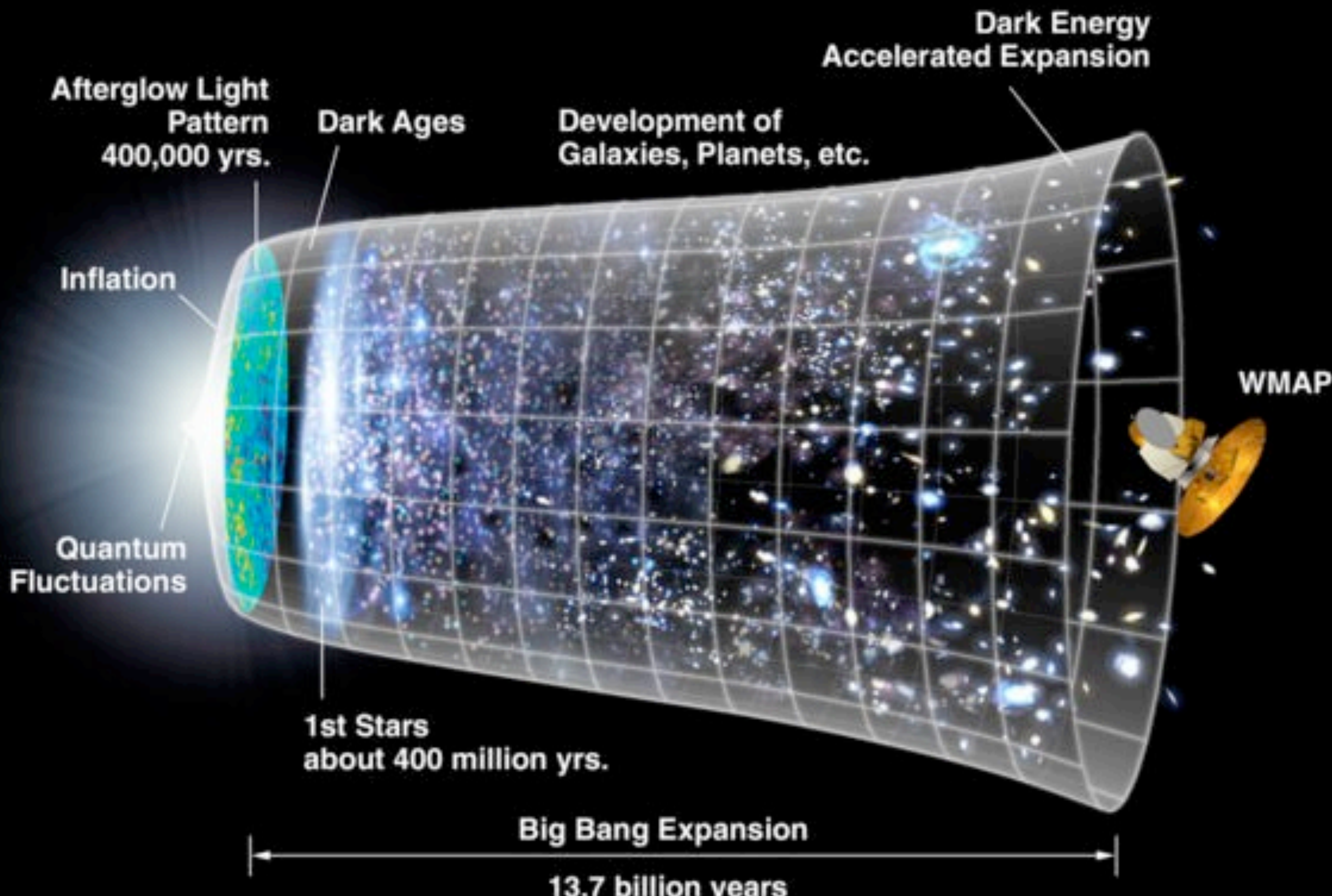
## Gauge bosons

**Hidden (Dark) Photons, paraphotons**

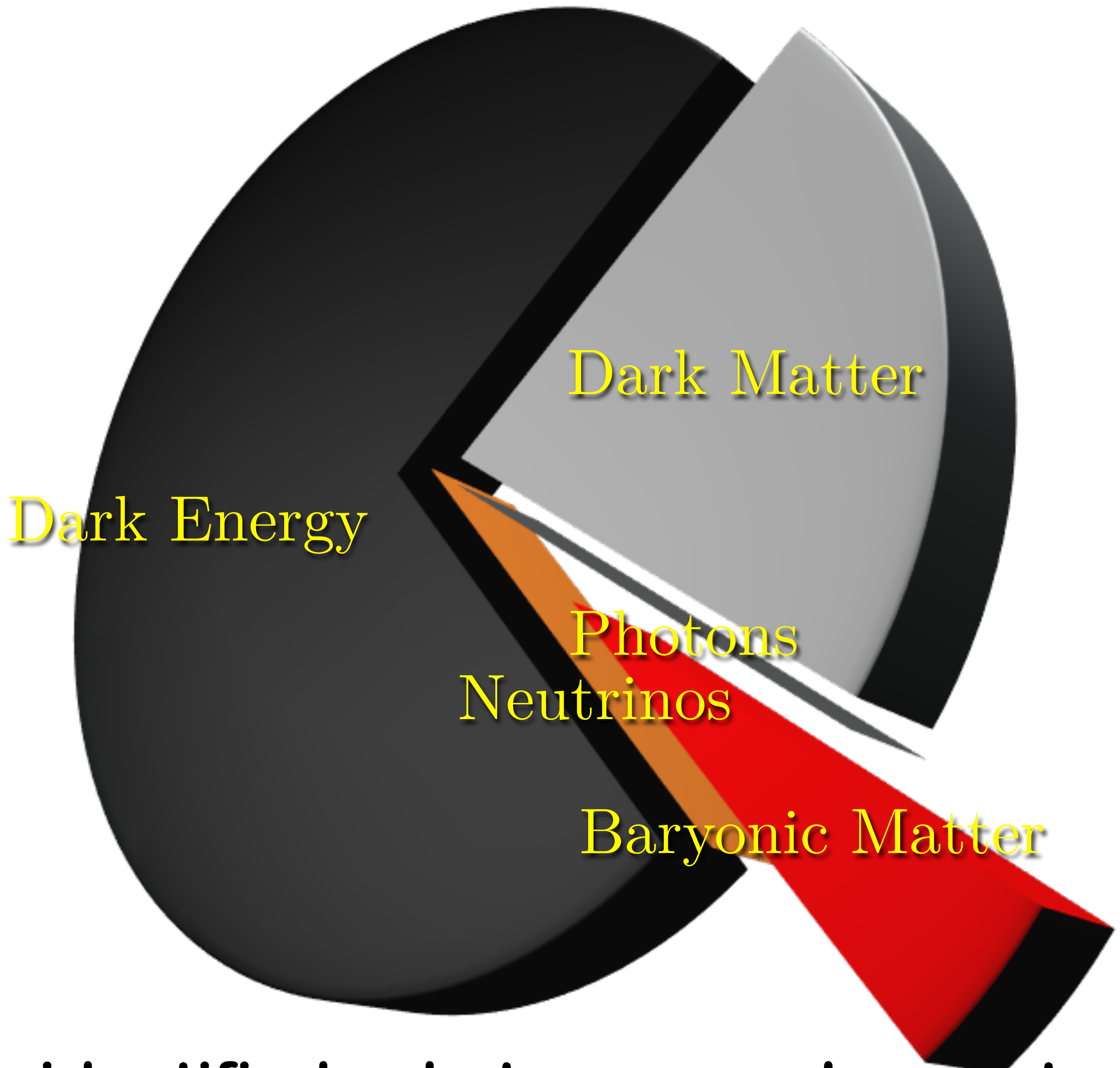
- Extra U(1) factors ubiquitous in string theory
- Hidden sectors required sor SUSY breaking
- Stueckelberg or HIggs masses ...



# Cosmology

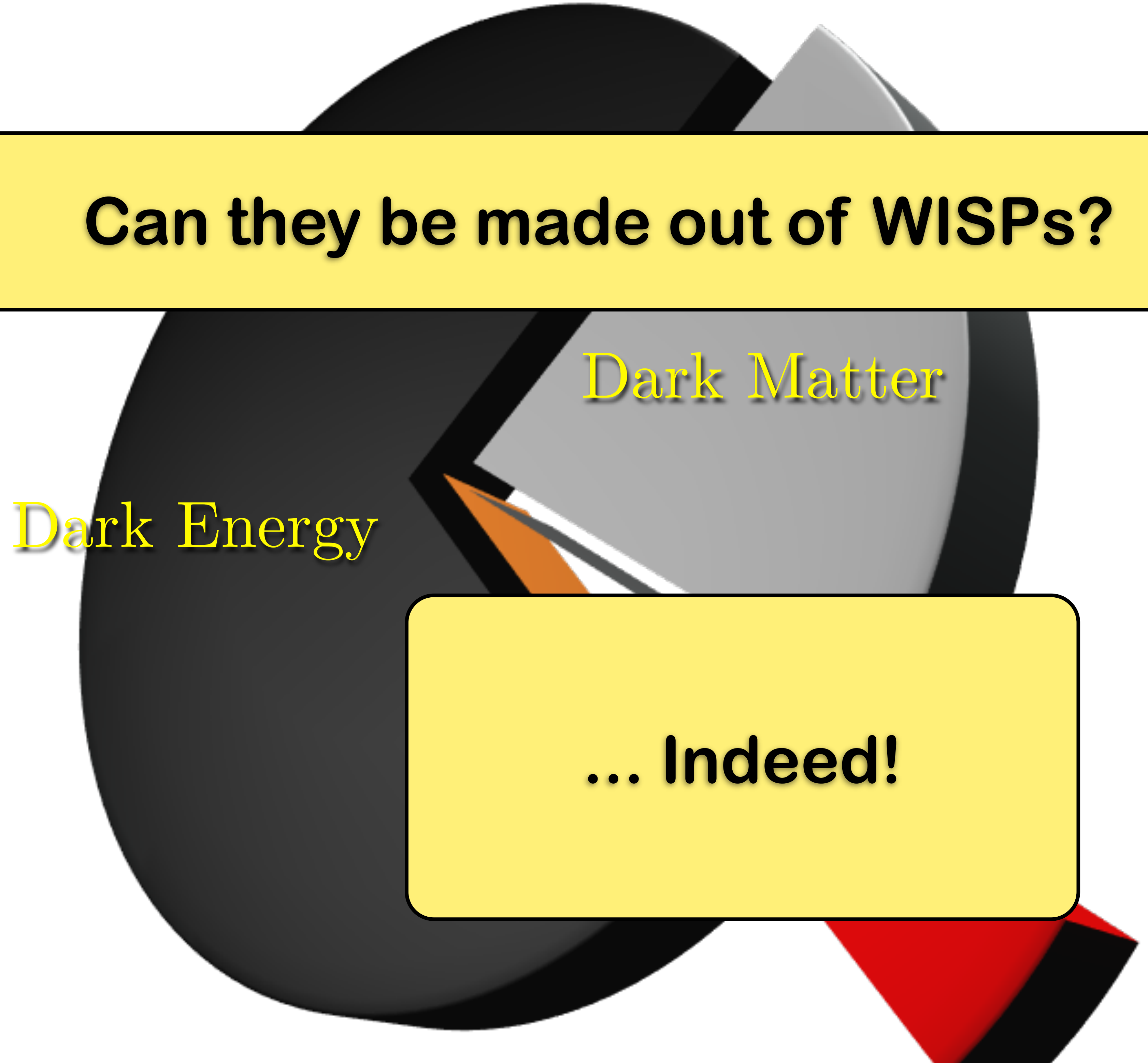

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

# Energy content of the Universe today




**Two unidentified substances make most of it!**

# Energy content of the Universe today




**Two unidentified substances make most of it!**

# 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)

very WISPy

**- Matter -**

in the sense that are
non-relativistic

(most of them)

mmm...

# WISPy Dark matter is generically COLD!

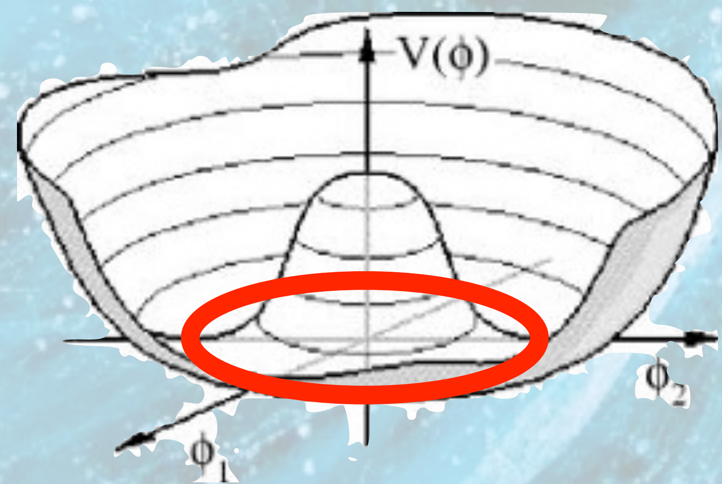
- Hot relics  (velocities T/mass ~ 0.23 meV/mass)

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

- 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

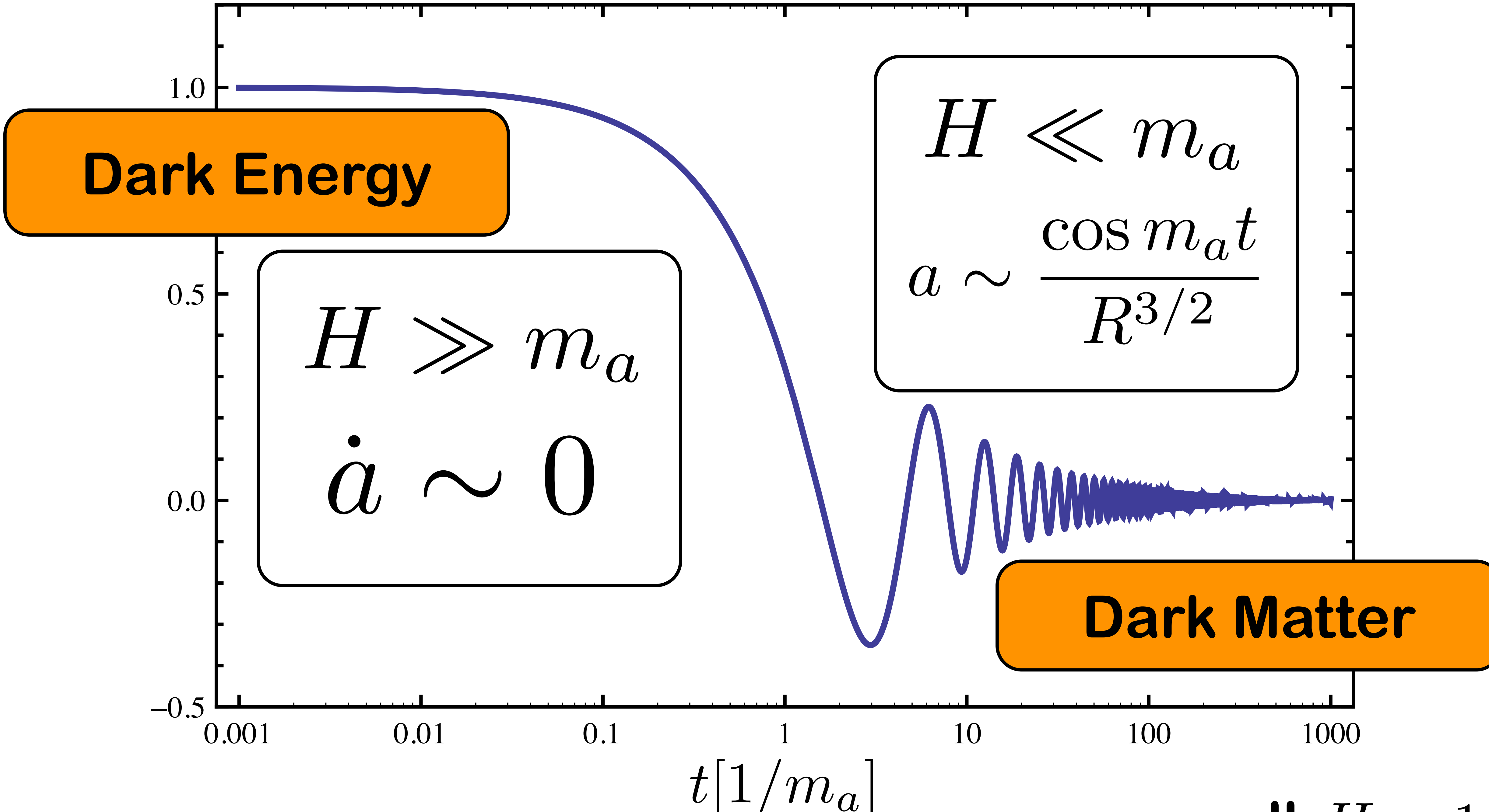



$$a \in (-\pi f_a, \pi f_a)$$

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

# WISPy Dark matter is generically COLD!

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




**recall** $H \sim 1/t$

# Relic abundance of WISPy Dark matter

**comoving axion number conserved**

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

$$\rho_a(t_0) = m_a \frac{N}{R_0^3} = \frac{1}{2} m_a^2 a_1^2 \left(\frac{R_1}{R_0}\right)^3$$

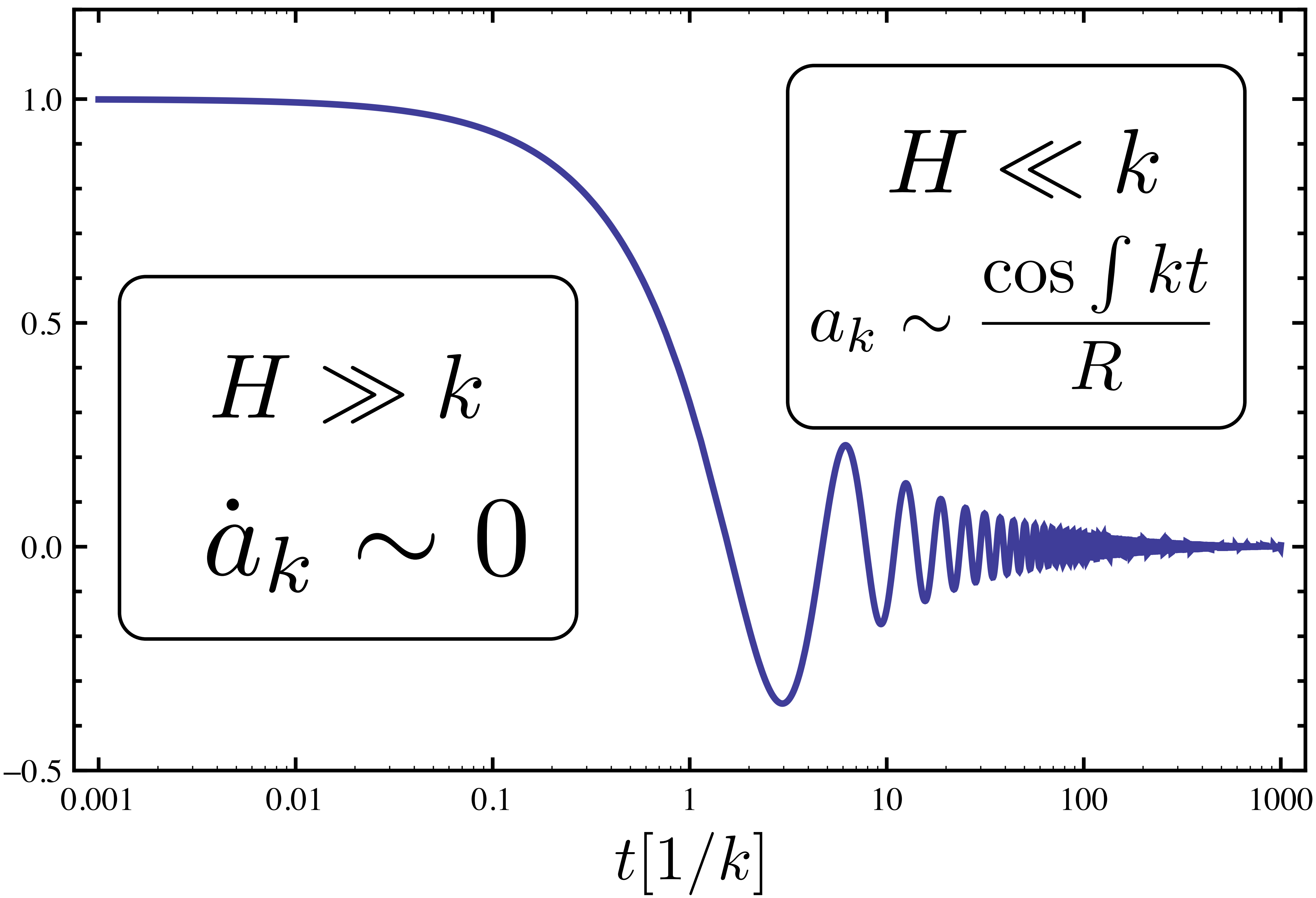
$$\left(\frac{R_1}{R_0}\right)^3 \sim \left(\frac{T_0}{T_1}\right)^3 \sim \left(\frac{T_0}{\sqrt{H_1 m_{\rm Pl}}}\right)^3 \sim \left(\frac{T_0}{\sqrt{m_a m_{\rm Pl}}}\right)^3 \propto m_a^{-3/2}$$

$$a_1 \sim f_a \qquad\qquad f_a \propto 1/m_a$$

$$\rho_a(t_0) \propto \sqrt{m_a} f_a^2 \quad \propto m_a^{-3/2}$$

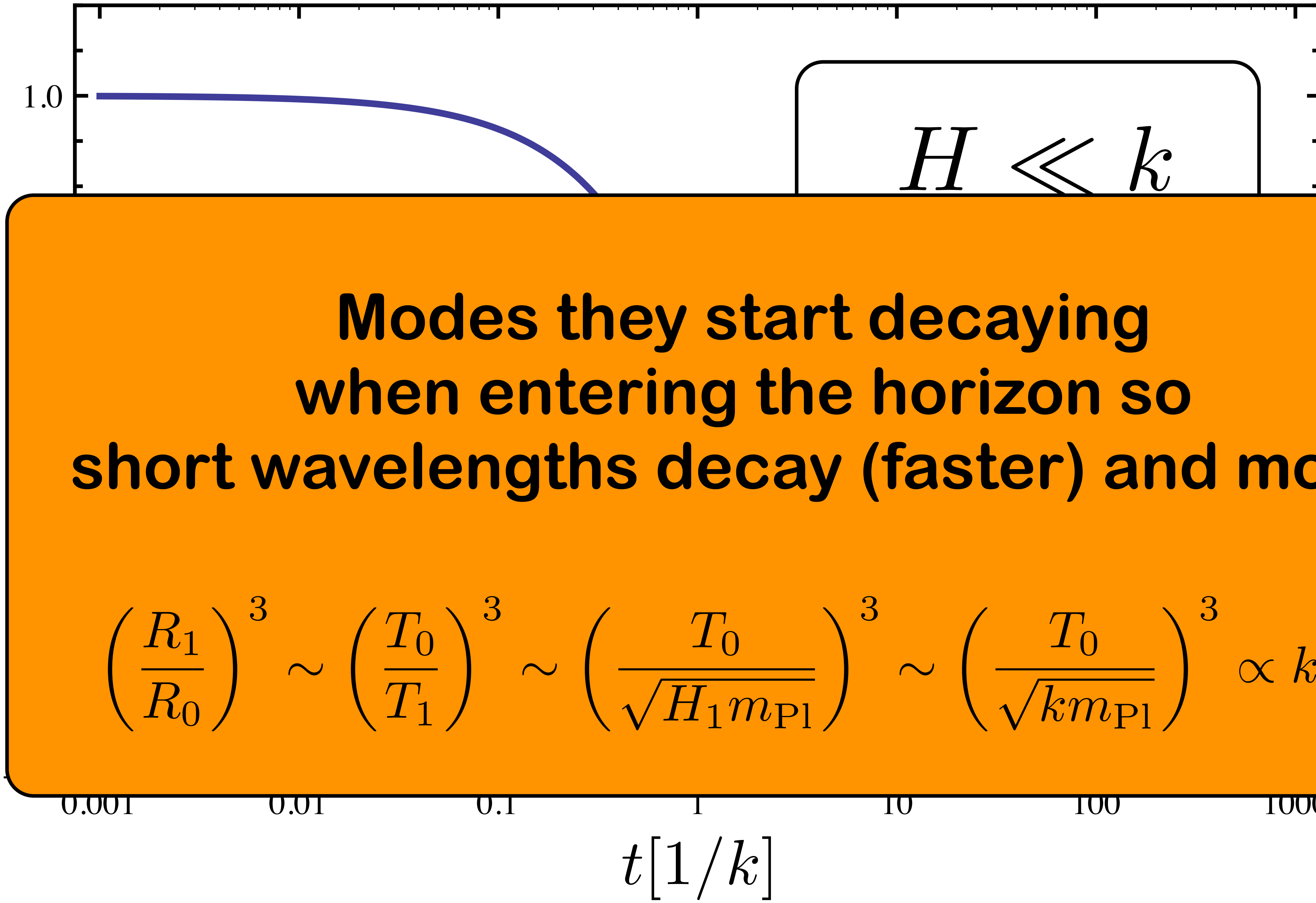
# Why so cold?

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



# Why so cold?

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




**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

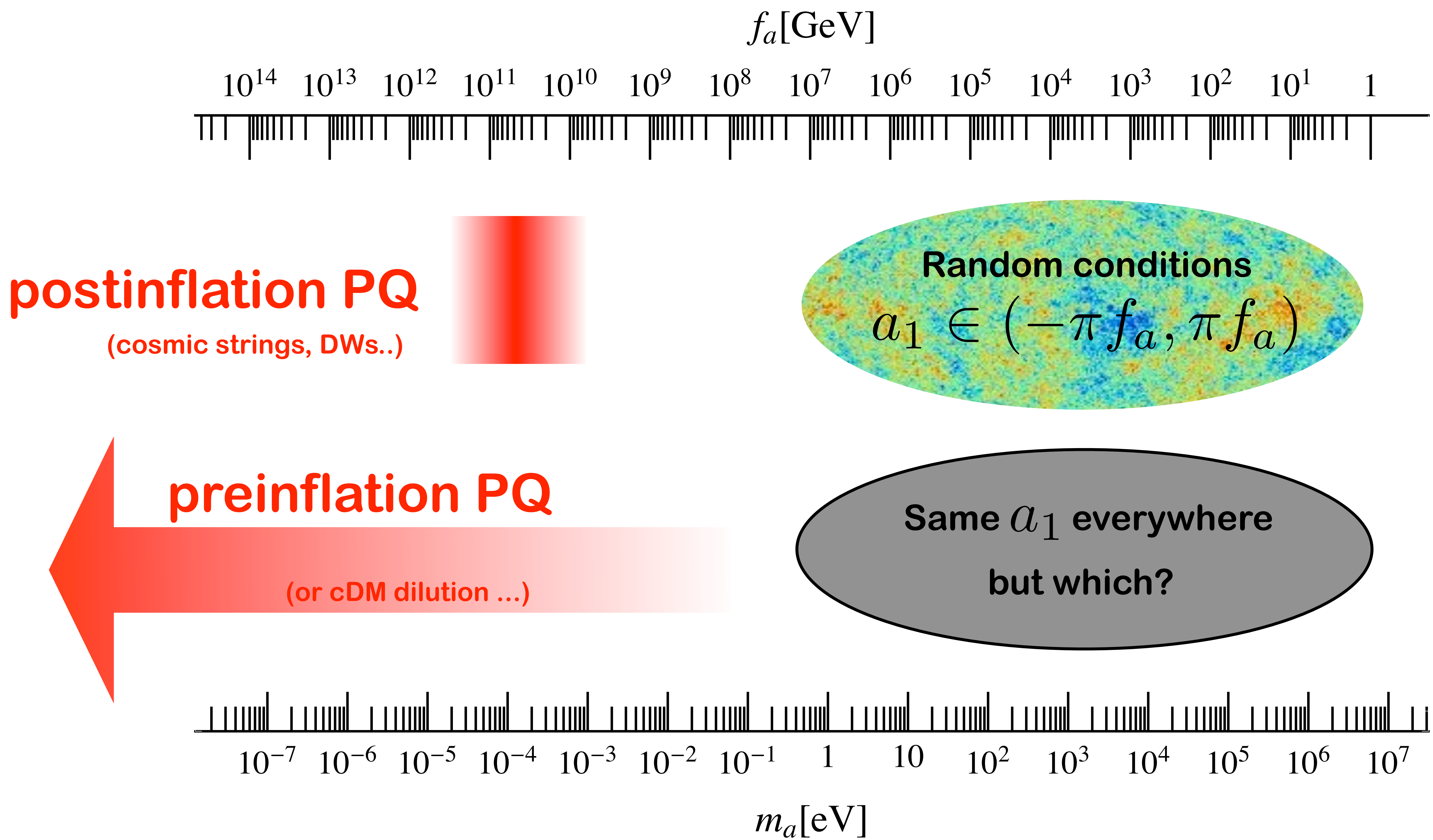
## - Simplest scenario:

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

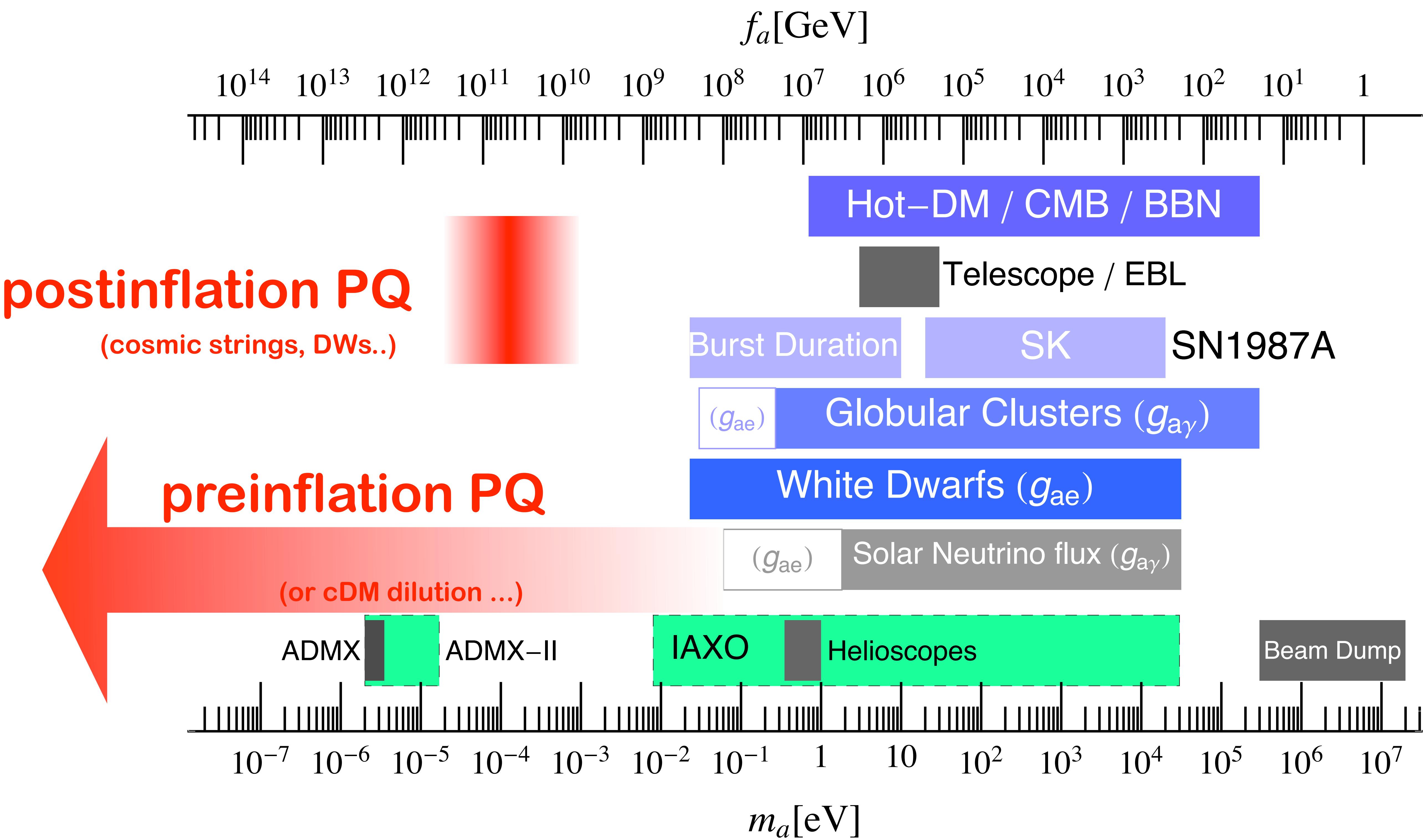
**recall** $\rho_{\mathrm{CDM}} = 1.17(6) \frac{\mathrm{keV}}{\mathrm{cm}^3}$

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

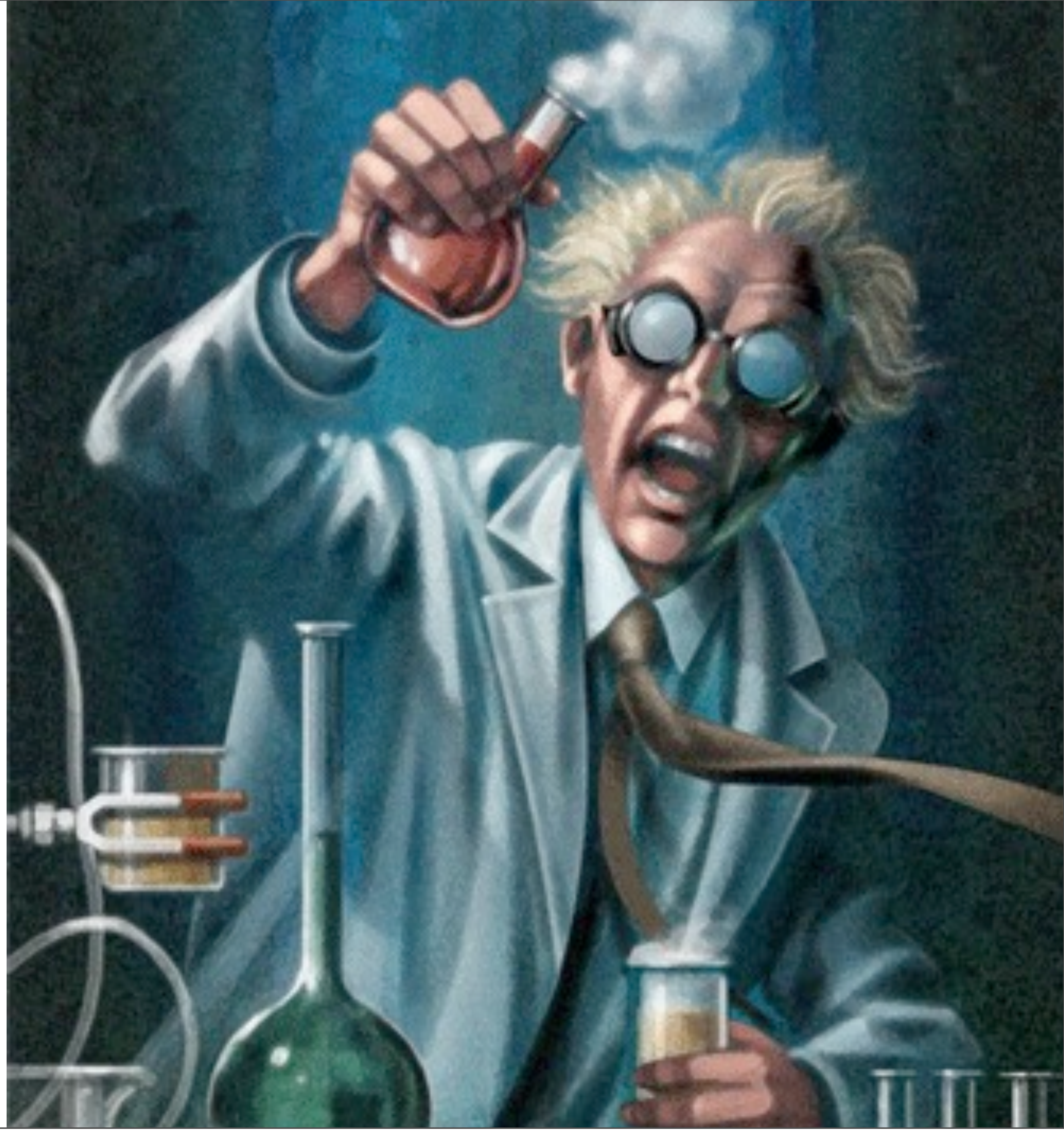
# Full axion cold dark matter: two scenarios



# + Bounds on axions (and prospects)



Laboratory



# Axion - photon mixing in a magnetic field

Raffelt, PRD'88

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

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

Not axions, nor photons are propagation eigenstates!

- Equations of motion can be easily diagonalised

$$\left[(\omega^2 - k^2)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & -g_{a\gamma}|\mathbf{B}|\omega \\ -g_{a\gamma}|\mathbf{B}|\omega & m_a^2 \end{pmatrix}\right]\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}.$$

- Dark matter solution $v = \frac{k}{\omega}$ ; $\omega \simeq m_a(1 + v^2/2 + ...)$

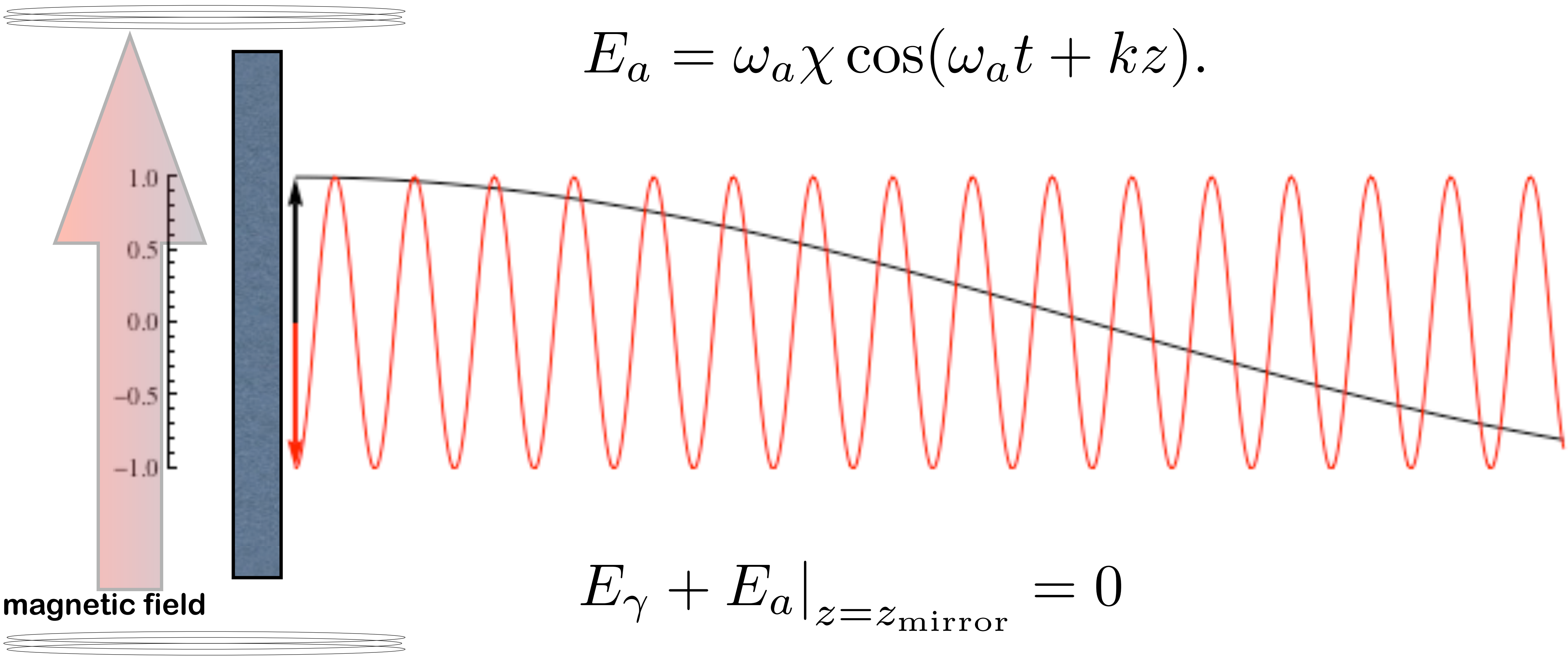
$$\left.\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix}\right|_{\mathrm{DM}} \propto \begin{pmatrix} \boxed{-\chi} \\ 1 \end{pmatrix} \exp(-i(\omega t - kz)).$$

It has a small E field!

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

# Radiation from a magnetised mirror

JR et al , JCAP04(2013)016




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

$$E_\gamma + E_a\big|_{z=z_{\rm mirror}} = 0$$

$$E_\gamma = -\omega_a \chi \cos(\omega_\gamma (t - z)).$$

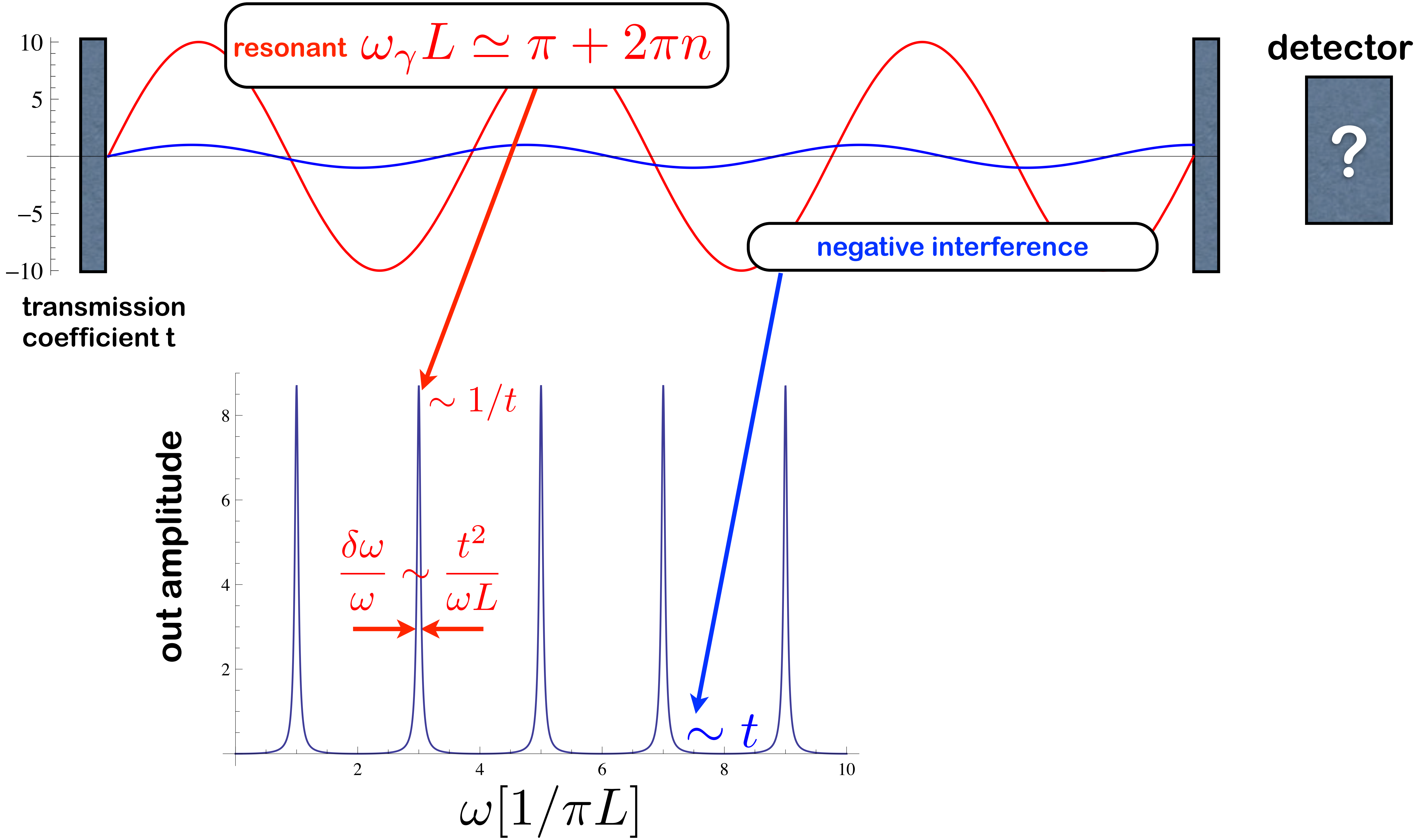
**Photons radiated from the mirror with** $\omega_\gamma = \omega_a = m_a(1 + v^2/2)$

**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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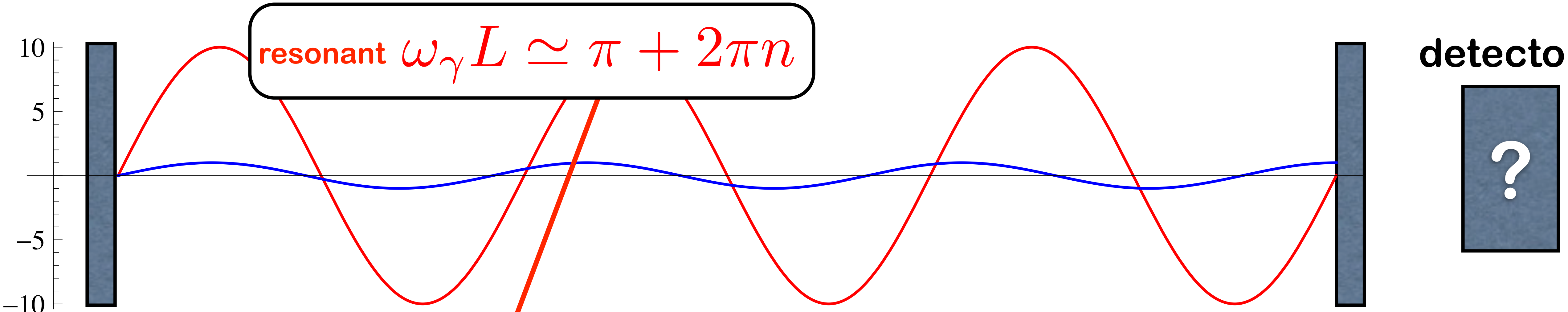
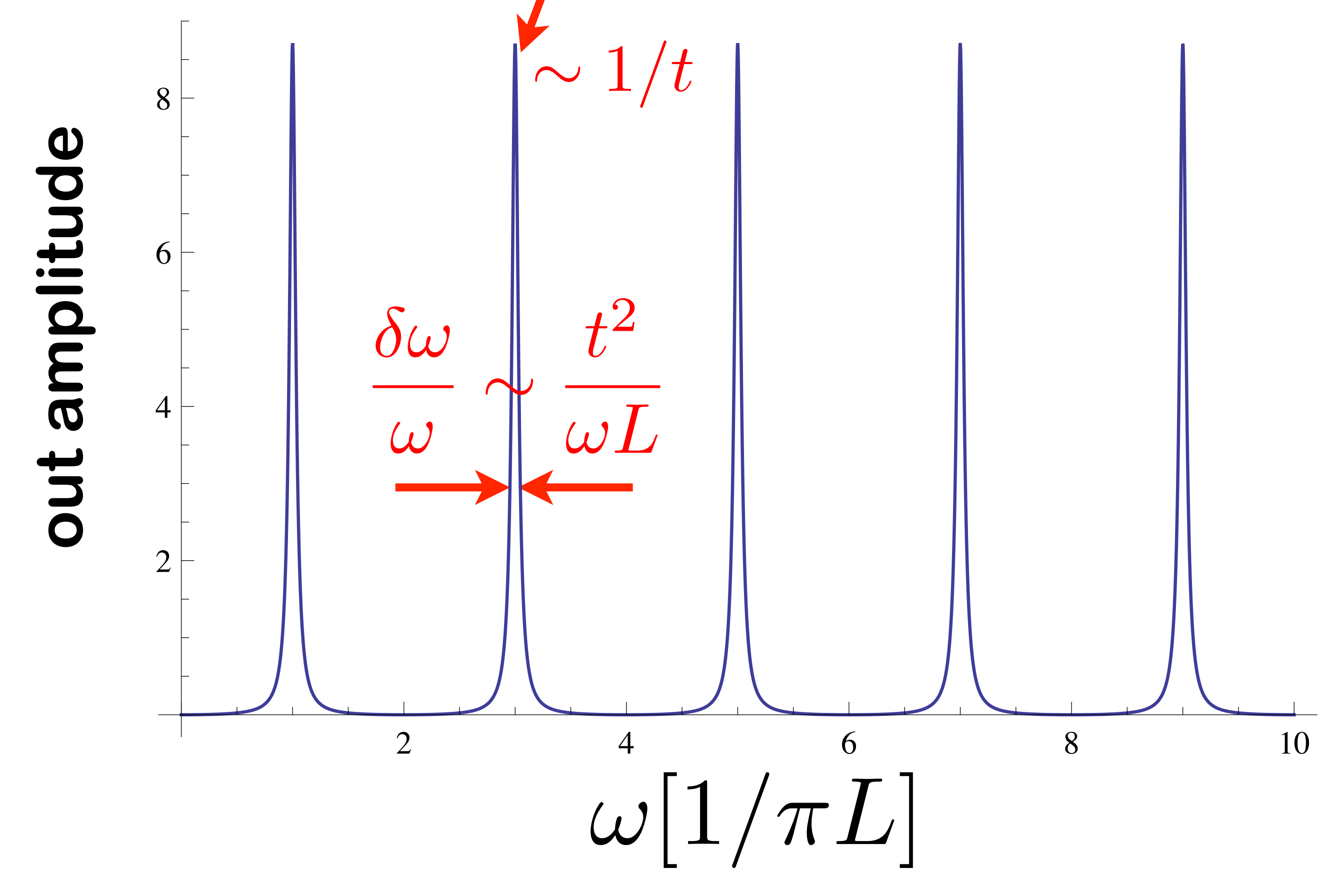



transmission coefficient t




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**

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

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

$$m_a L = \pi \rightarrow \text{Area} = \frac{m_a \text{Volume}}{\pi}$$

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

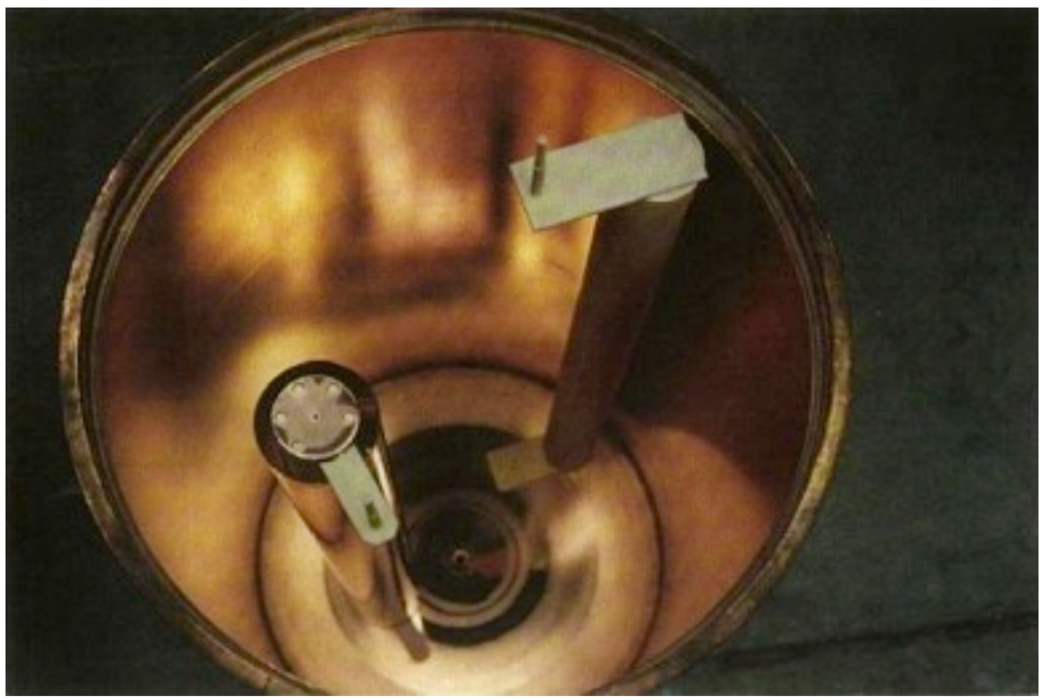
# Cavity searches II: the real thing...

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

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

$L_0, L_0+\delta, L_0+2\delta,\ etc...$ **slow scan, adjusting the length!**

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



**8T field, 1mL,0.5mD**

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

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

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

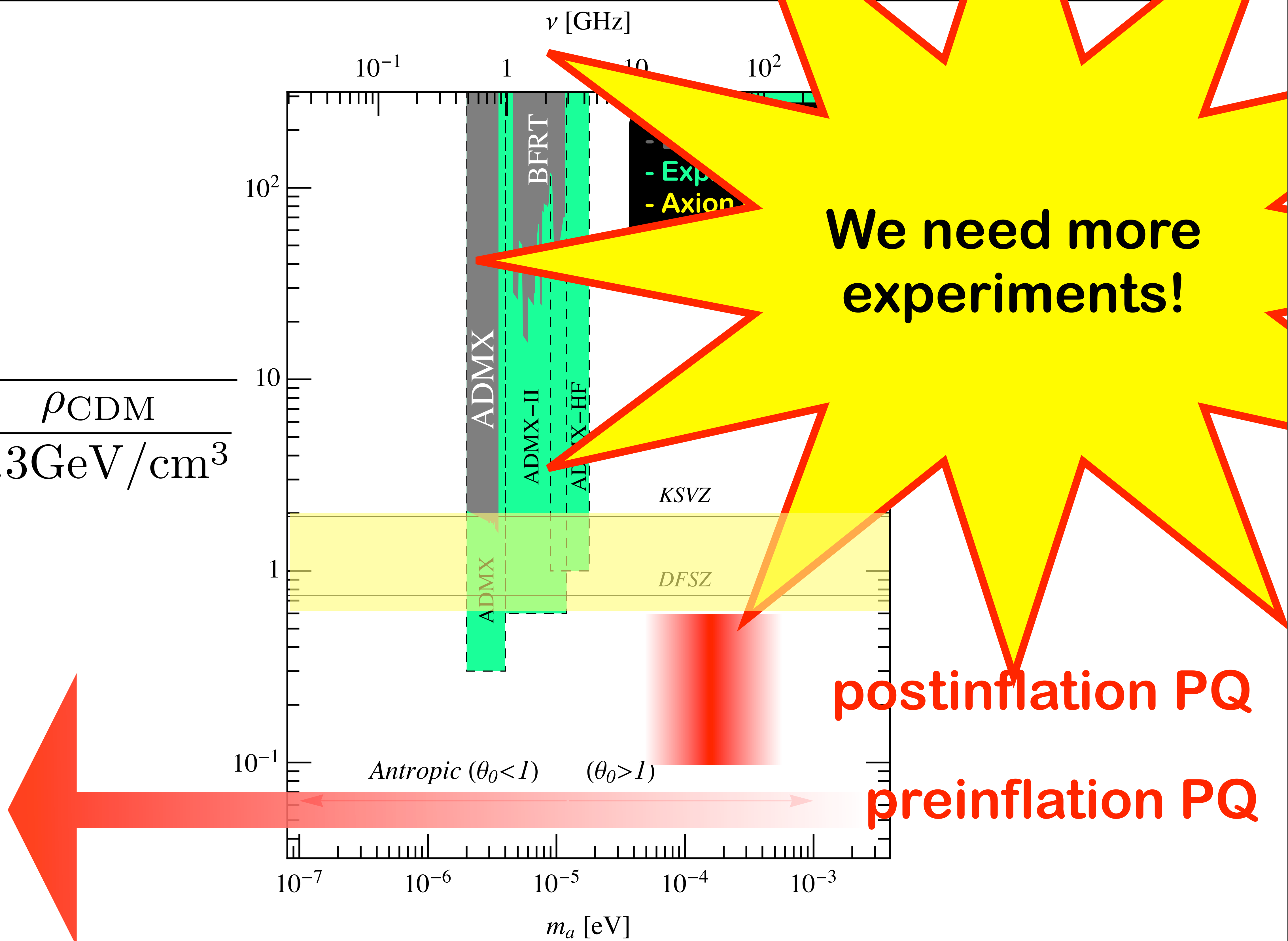
**measurement time vs. different measurements**

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

**the definitive experiment! ... ???**

# Cavity searches II: ADMX and relatives

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

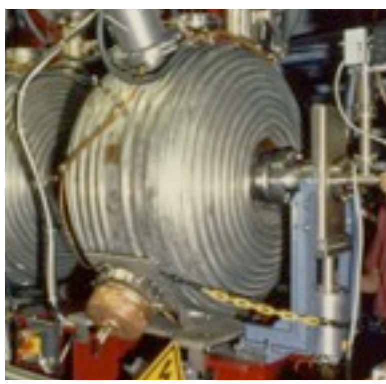


# Cavity searches III: lower masses

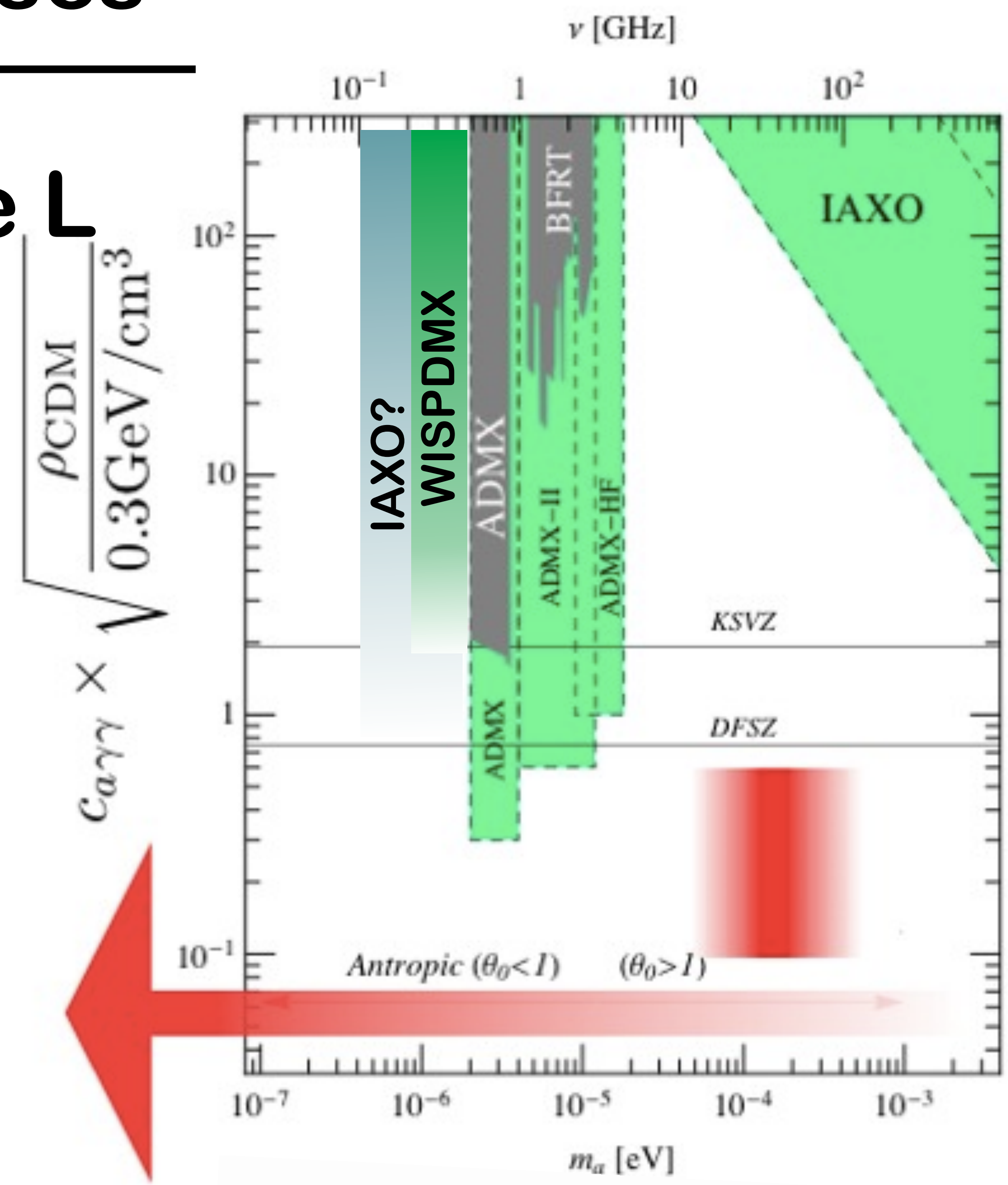
- **Larger signal but needs large L**

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

- **WISPDMX @ DESY (ALPS)**

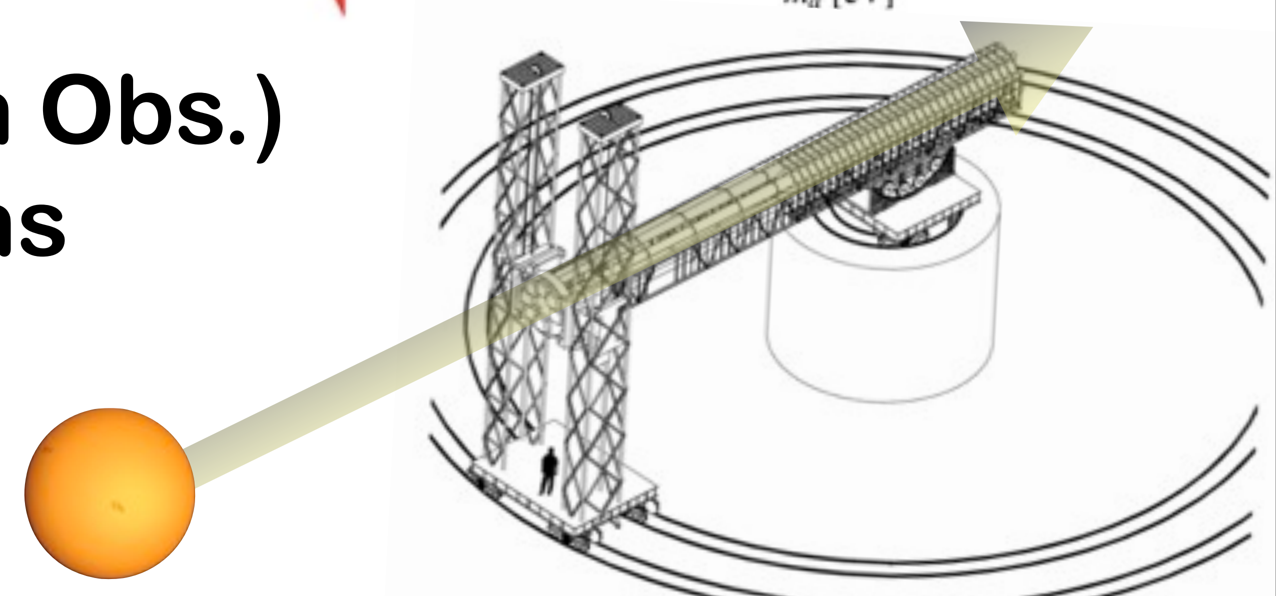


| Mode | $\nu$ [MHz] | $Q_0$ | Mode | $\nu$ [MHz] | $Q_0$ |
|---|---|---|---|---|---|
| $TM_{010}$ | 199 | 53360 | $TM_{014}$ | 579 | 122500 |
| $TM_{011}$ | 295 | 44830 | $TM_{015}$ | 707 | 60950 |
| $TM_{012}$ | 433 | 47450 | $TM_{016}$ | 765 | 105070 |
| $TM_{013}$ | 524 | 47710 | $TM_{017}$ | 832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



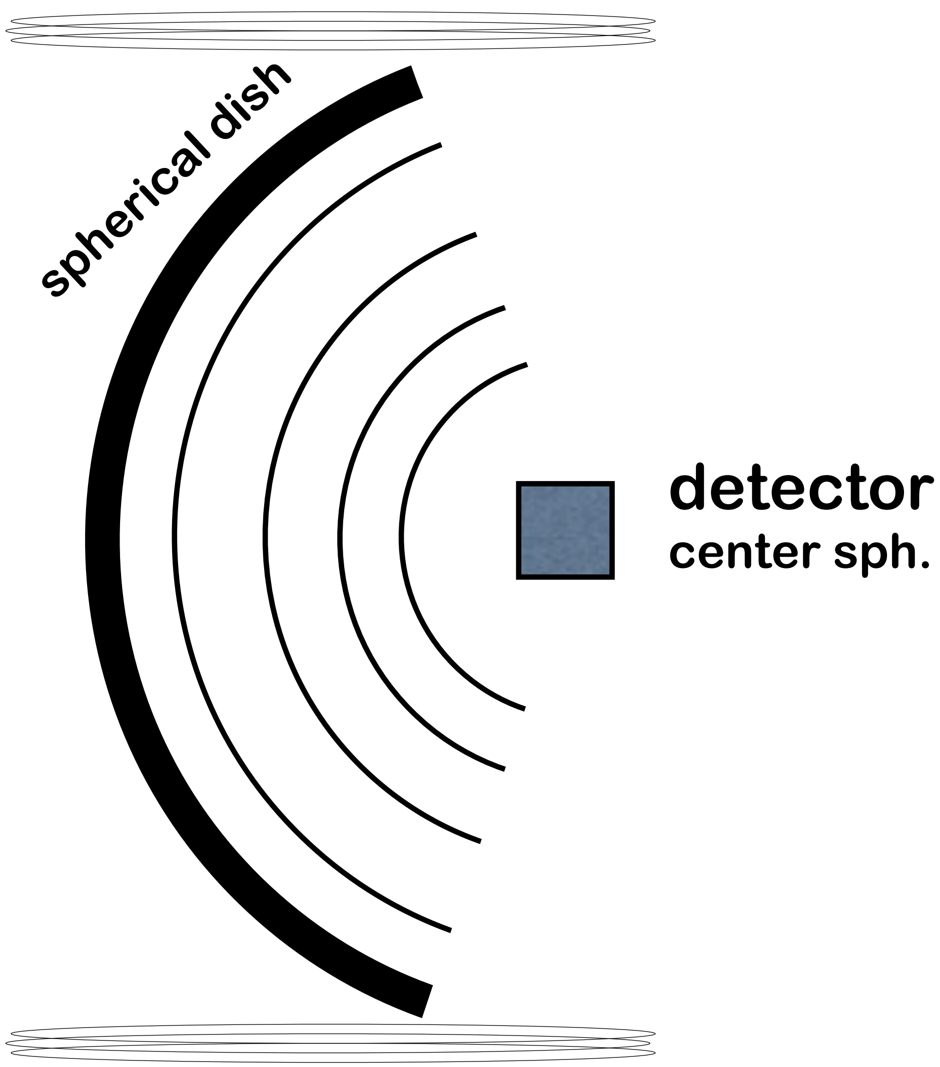

- **IAXO (International Axion Obs.) main focus on solar axions**

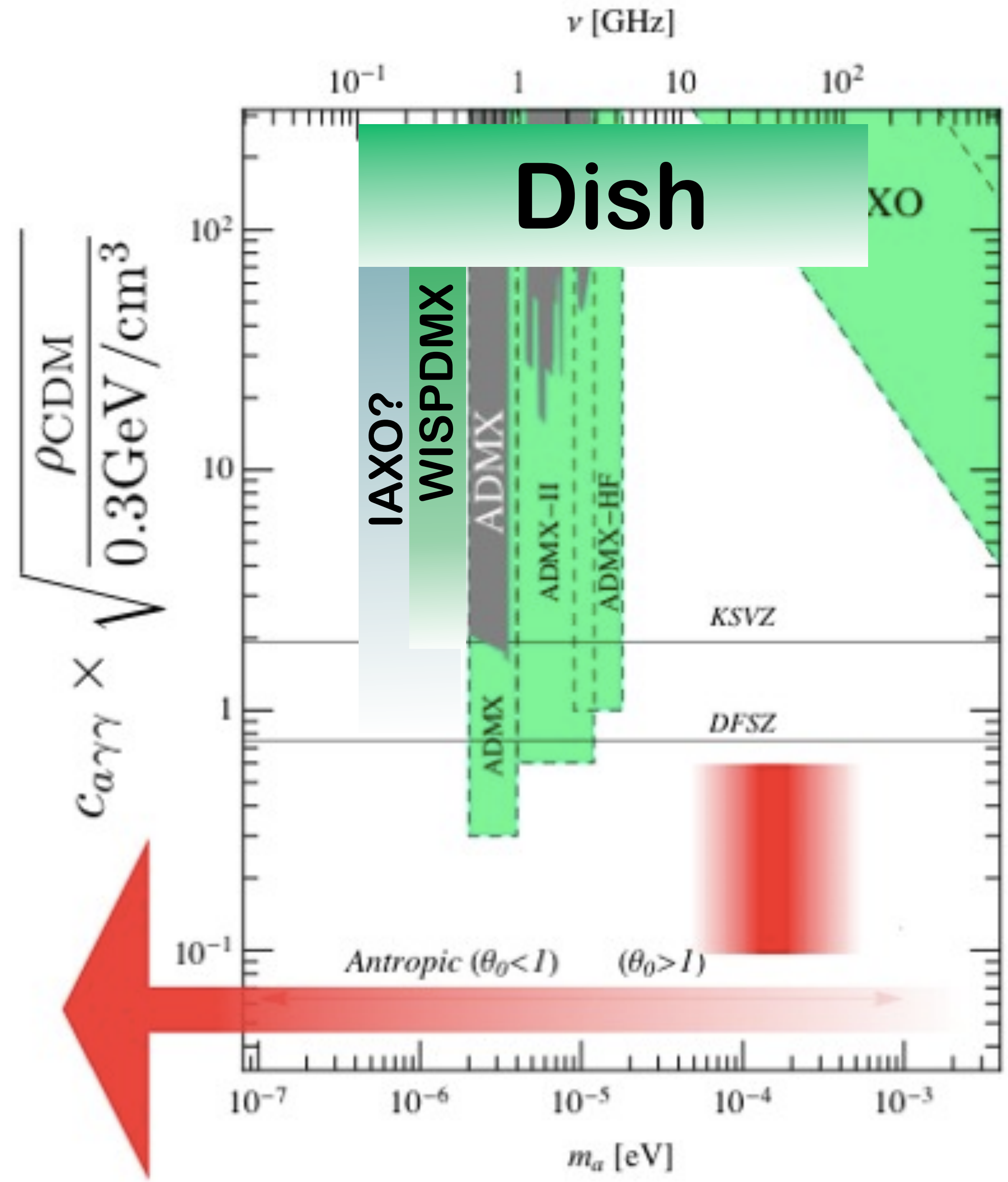
  - B~ 5 T,
  - L~ 20 m
  - A~ 6 m$^2$



# Dish antenna searches (broadband!)

JR et al , JCAP04(2013)016



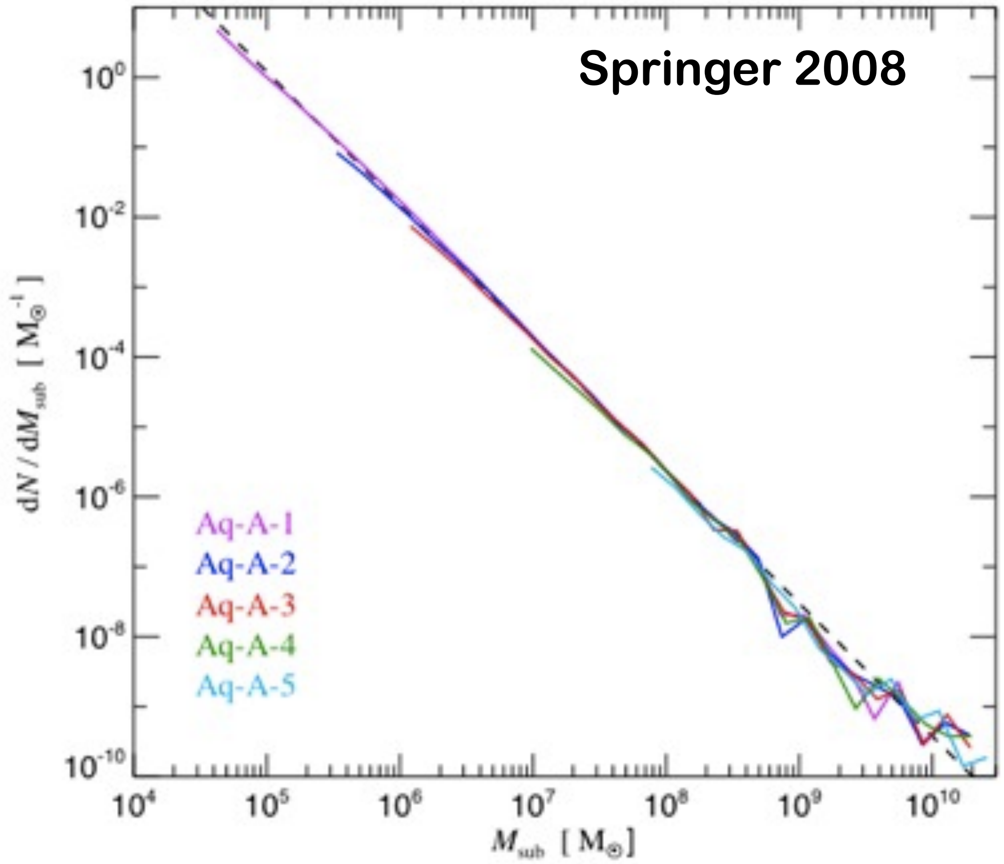

$$P_{\rm center} \approx A_{\rm dish}\langle|\mathbf{E}_{\rm DM,||}|^2\rangle \sim \chi^2 \rho_{\rm CDM} A_{\rm dish}$$

**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.

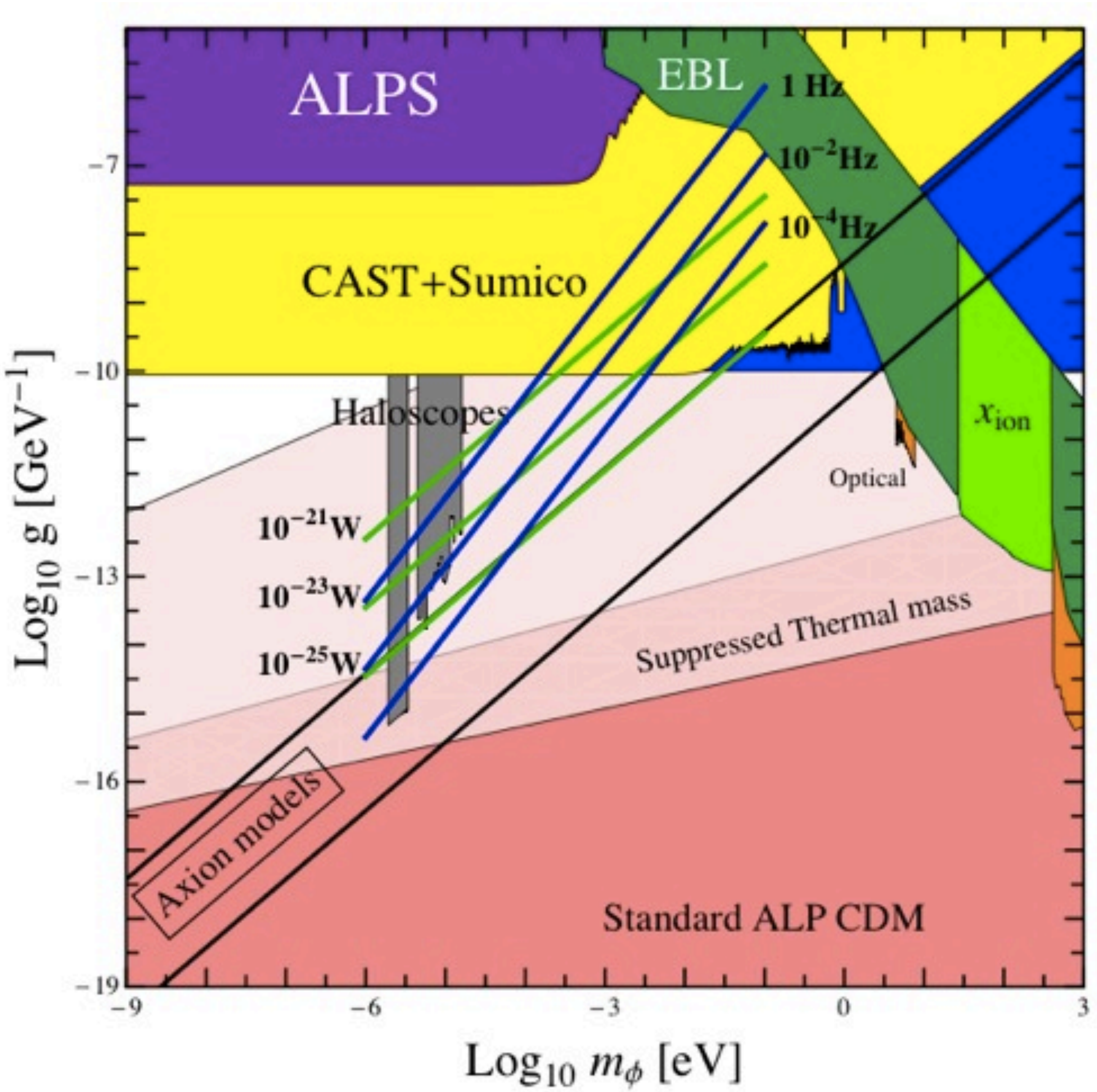
- Broadband Dish search not ($10^4$ boost req.)

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?)