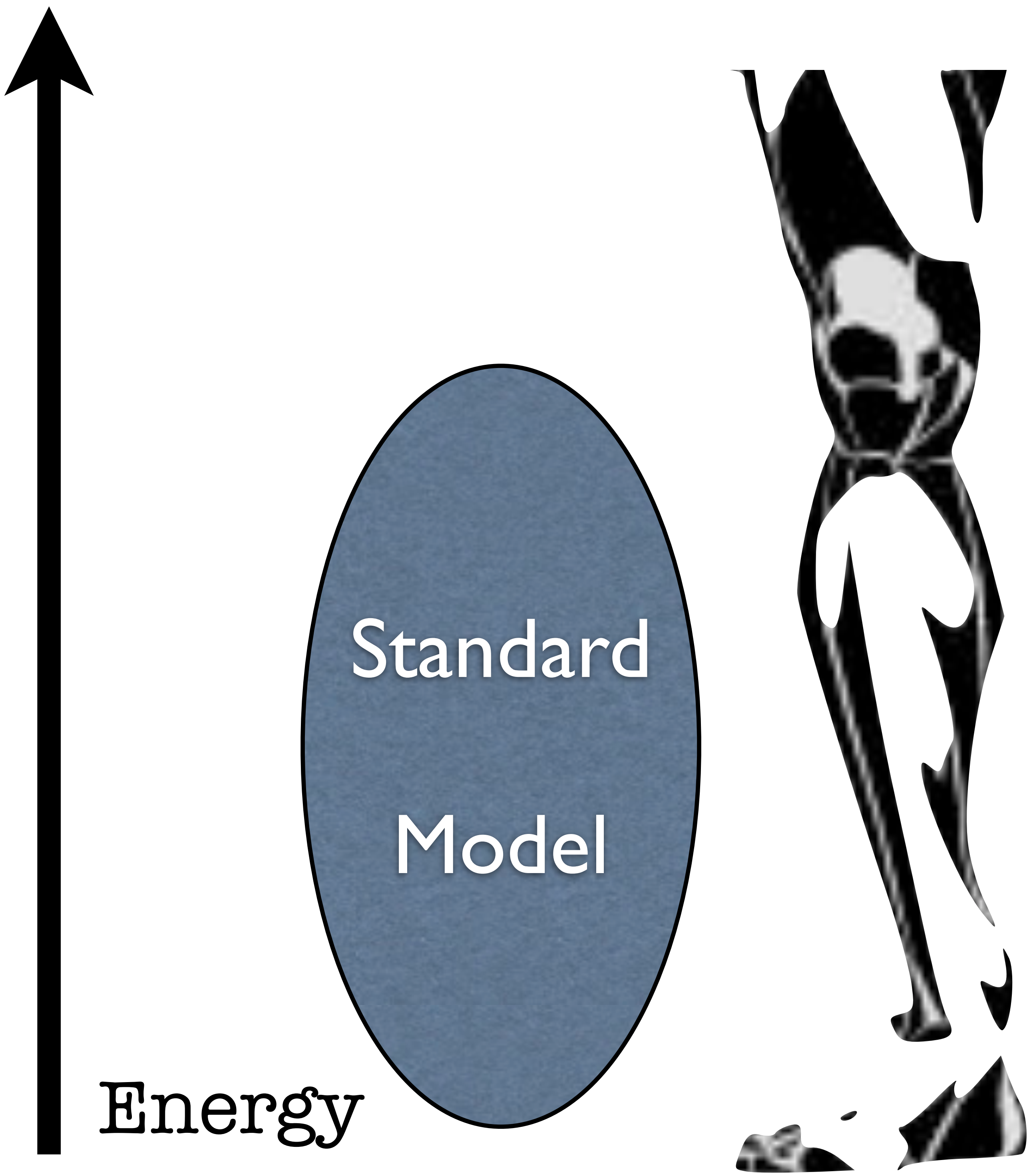
WISPy Cold Dark Matter

Heretic contribution to Vistas in axions:
A Roadmap for Theoretical and Experimental Axions Physics through 2025

Javier Redondo, MPP München

Beyond the SM ... at low energies

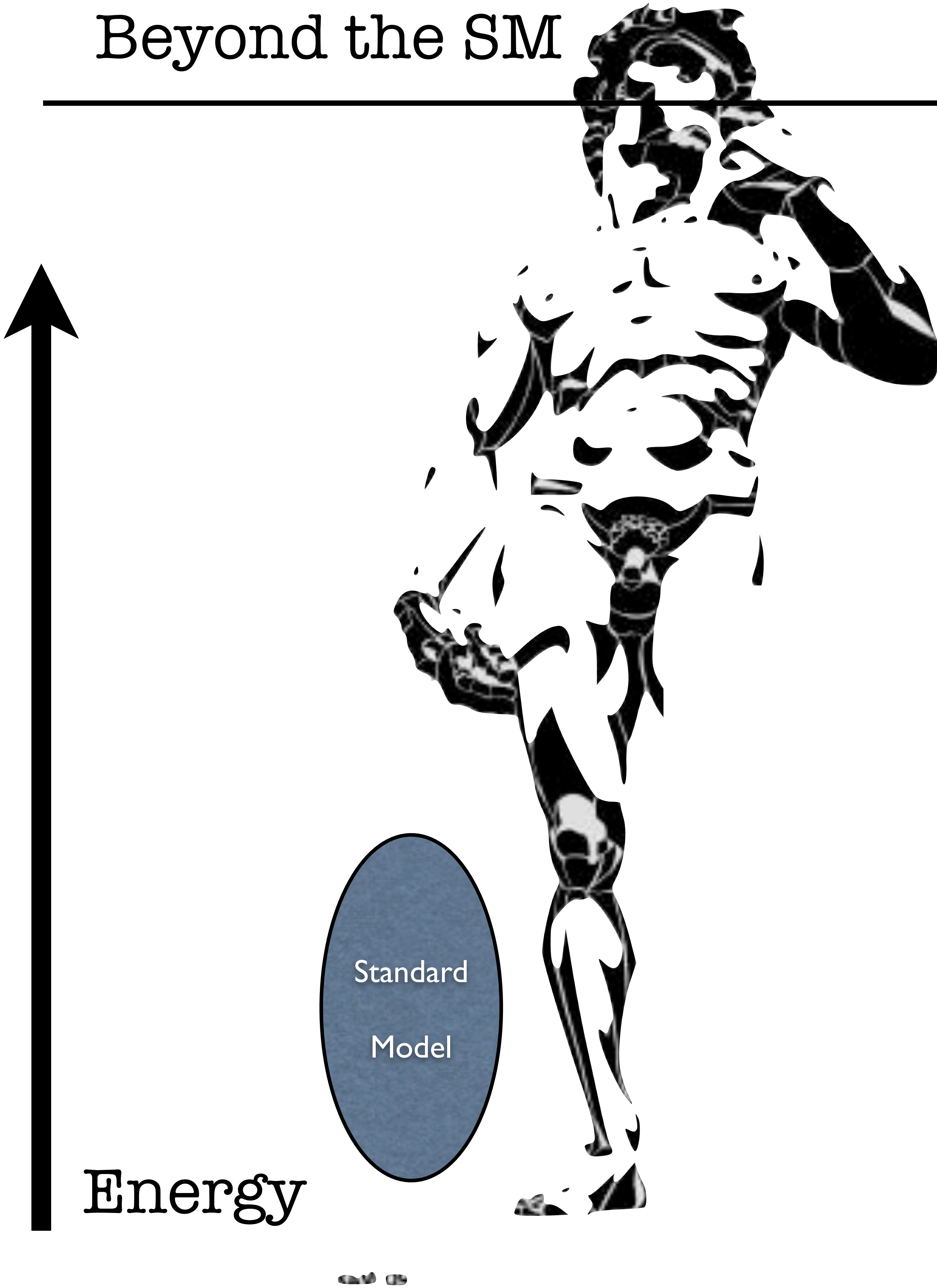


Describes extremely well fundamental physics (at low energies)

but feels certainly

INCOMPLETE

Beyond the SM ... at low energies

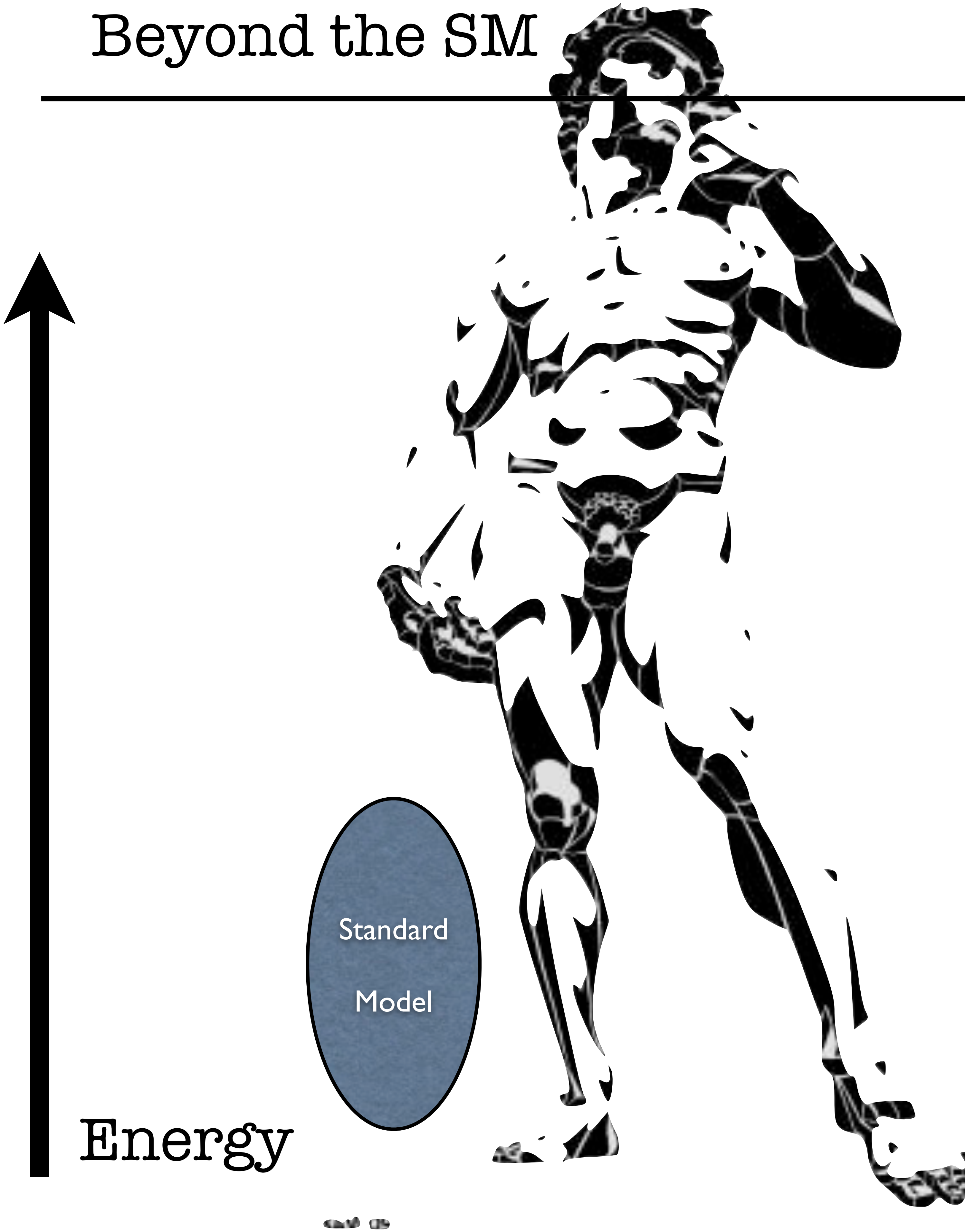


Answers are
awaiting in the

high energy frontier

where more symmetric
beautiful theories arise

Beyond the SM ... at low energies



Answers are awaiting in the

high energy frontier

where more symmetric beautiful theories arise

... and often imply physics at low energies

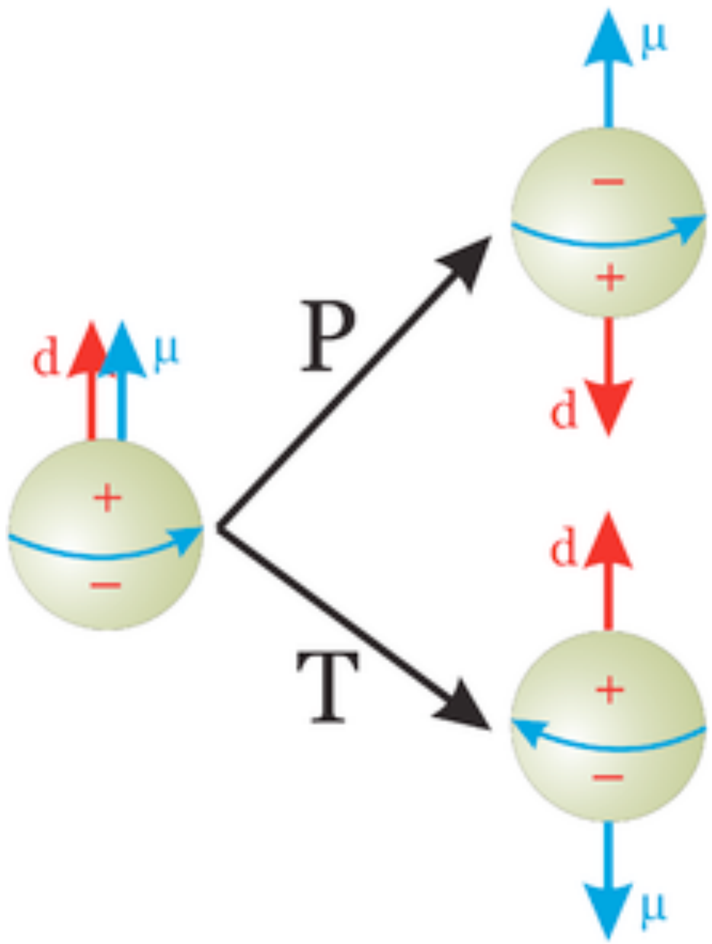
Beyond the SM ... at low energies

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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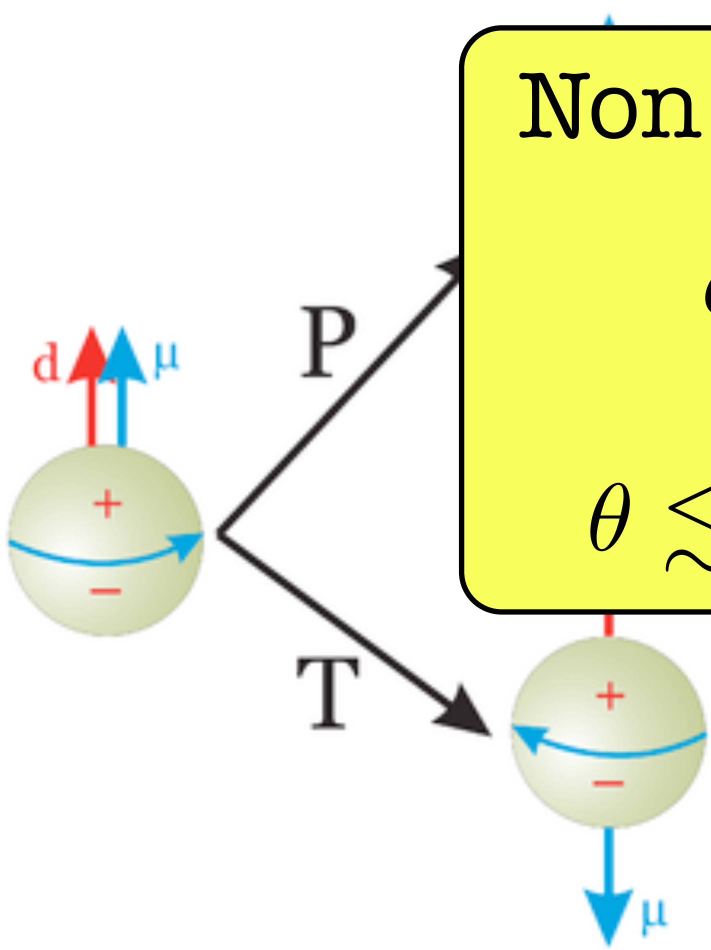

Non Observation:

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

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

Prediction:

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

Peccei-Quinn symmetry and the axion

Introduce a new axial global color-anomalous symmetry, which is spontaneously broken at a high energy scale, >>> TeV

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⇒ Massless Goldstone Boson: the axion

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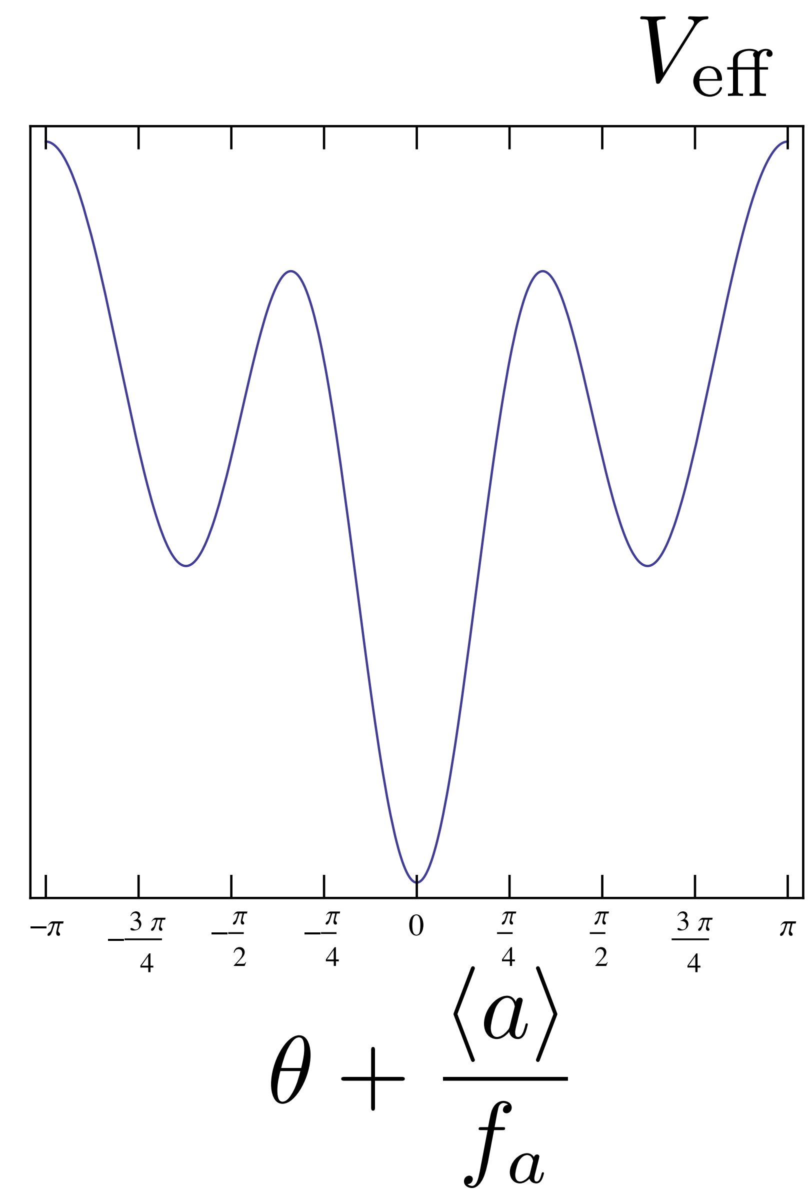
➡ Massless Goldstone Boson: the axion

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

Free parameter → θ

The QCD induced potential is minimized for ...

$$\theta_{\mathrm{eff}} = \theta + \frac{\langle a \rangle}{f_a} = 0$$



Peccei-Quinn symmetry and the axion

Introduce a new axial global color-anomalous symmetry, which is spontaneously broken at a hig…

The axions adjusts its v.e.v. to cancel the effects of any theta!

…n

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

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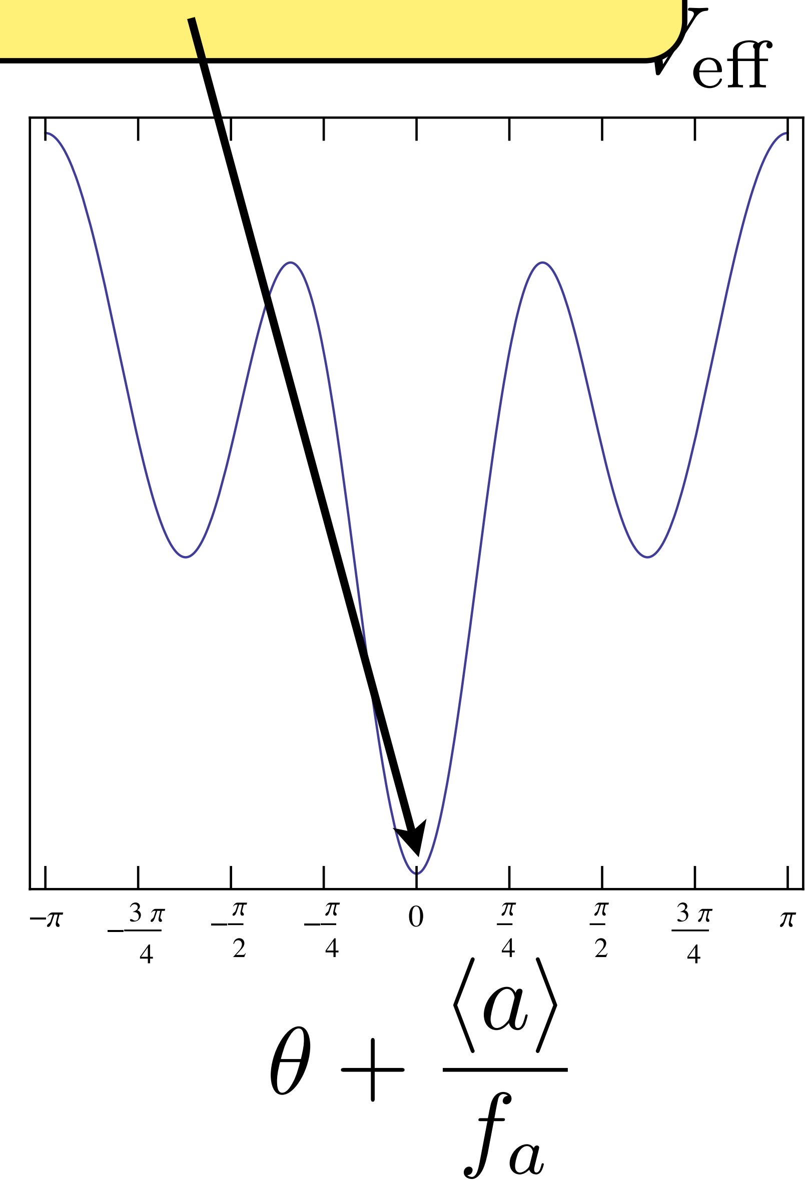


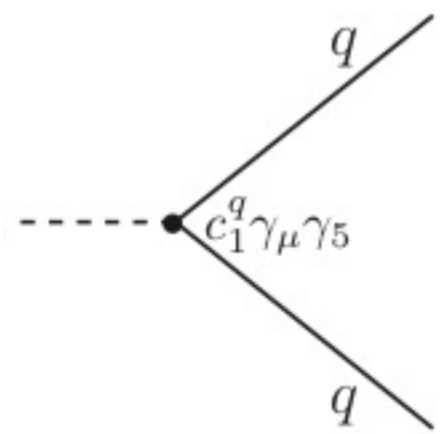
Axion mixes with QCD mesons and gets mass and couplings

Mass

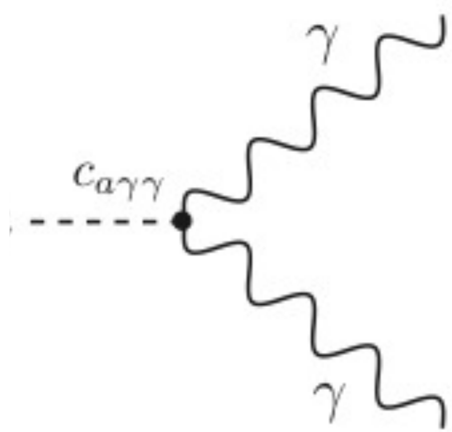
$$m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6 \text{ meV} \frac{10^9 \text{GeV}}{f_a}$$

Bare models

$\frac{1}{f_a} a$

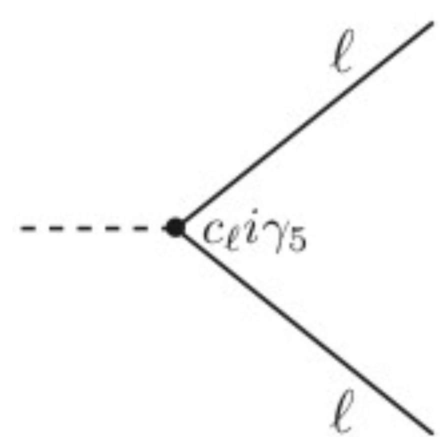


$\frac{1}{f_a} a$



Extended models also feature couplings to leptons

$\frac{1}{f_a} a$



Axion mixes with QCD mesons and gets mass and couplings

Typical from Nambu-Goldstone Bosons

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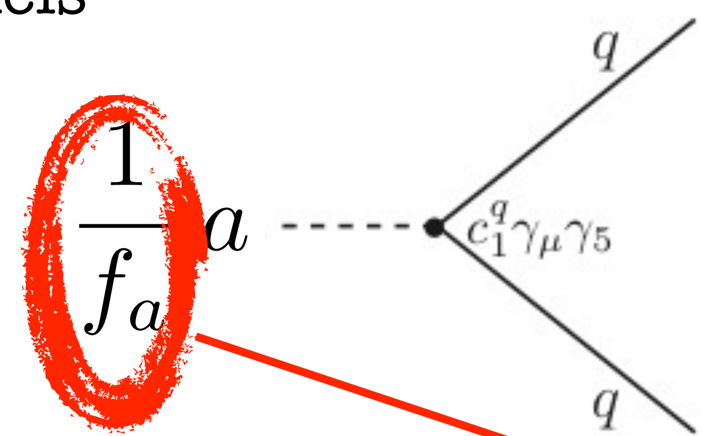

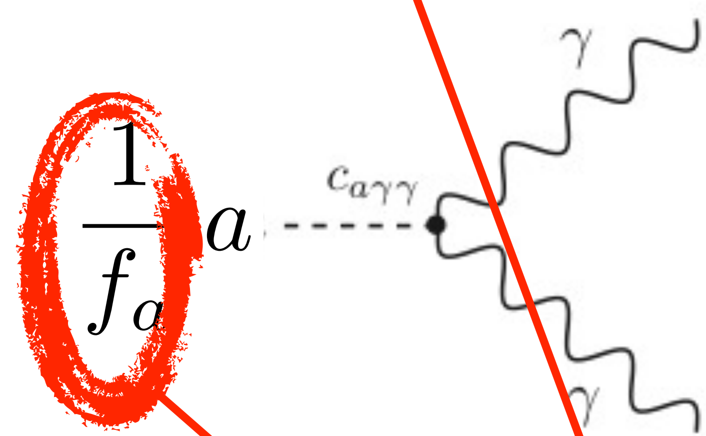

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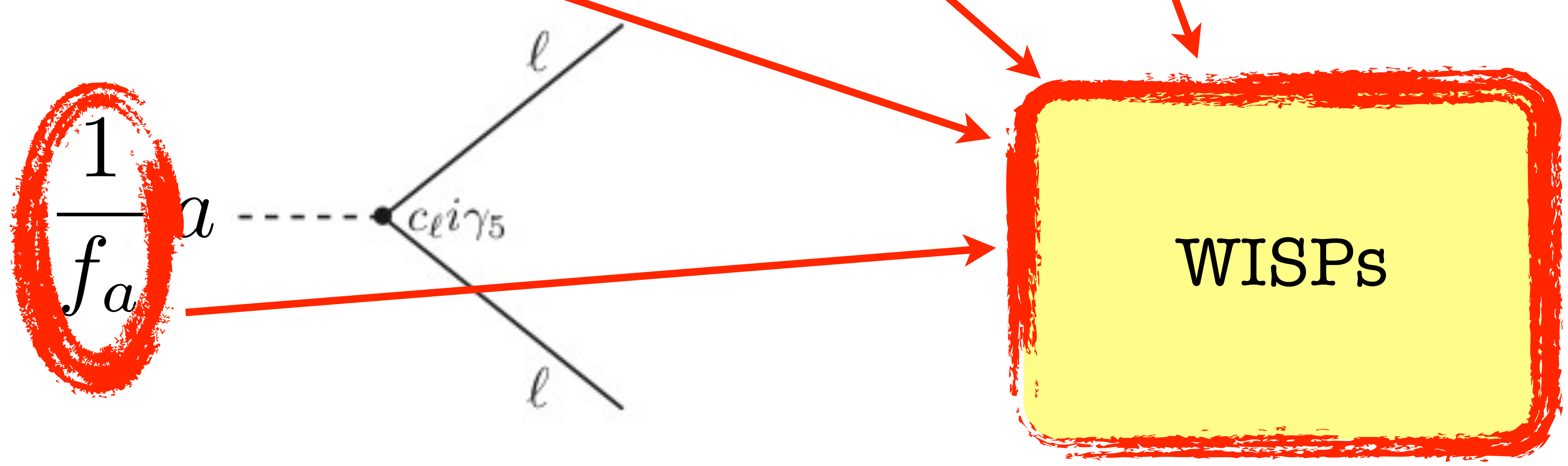
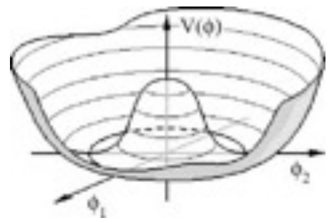


Axion-like particles (ALPs) 0^{-}

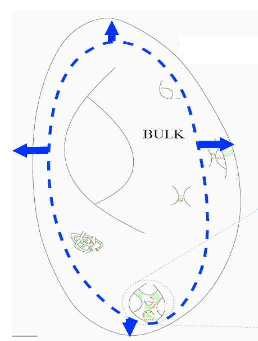
pseudo Goldstone bosons

Global continuous symmetry spontaneously broken at high energy scale M



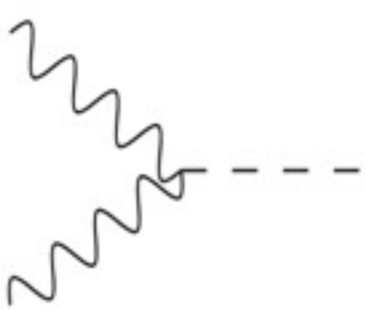
String 'axions'

Sizes and deformations of extra dimensions, gauge couplings



Reference model (this talk)

$$\mathcal{L} = \mathcal{L}_{\rm free} + \frac{g}{4} F_{\mu\nu}\widetilde{F}^{\mu\nu}\phi$$



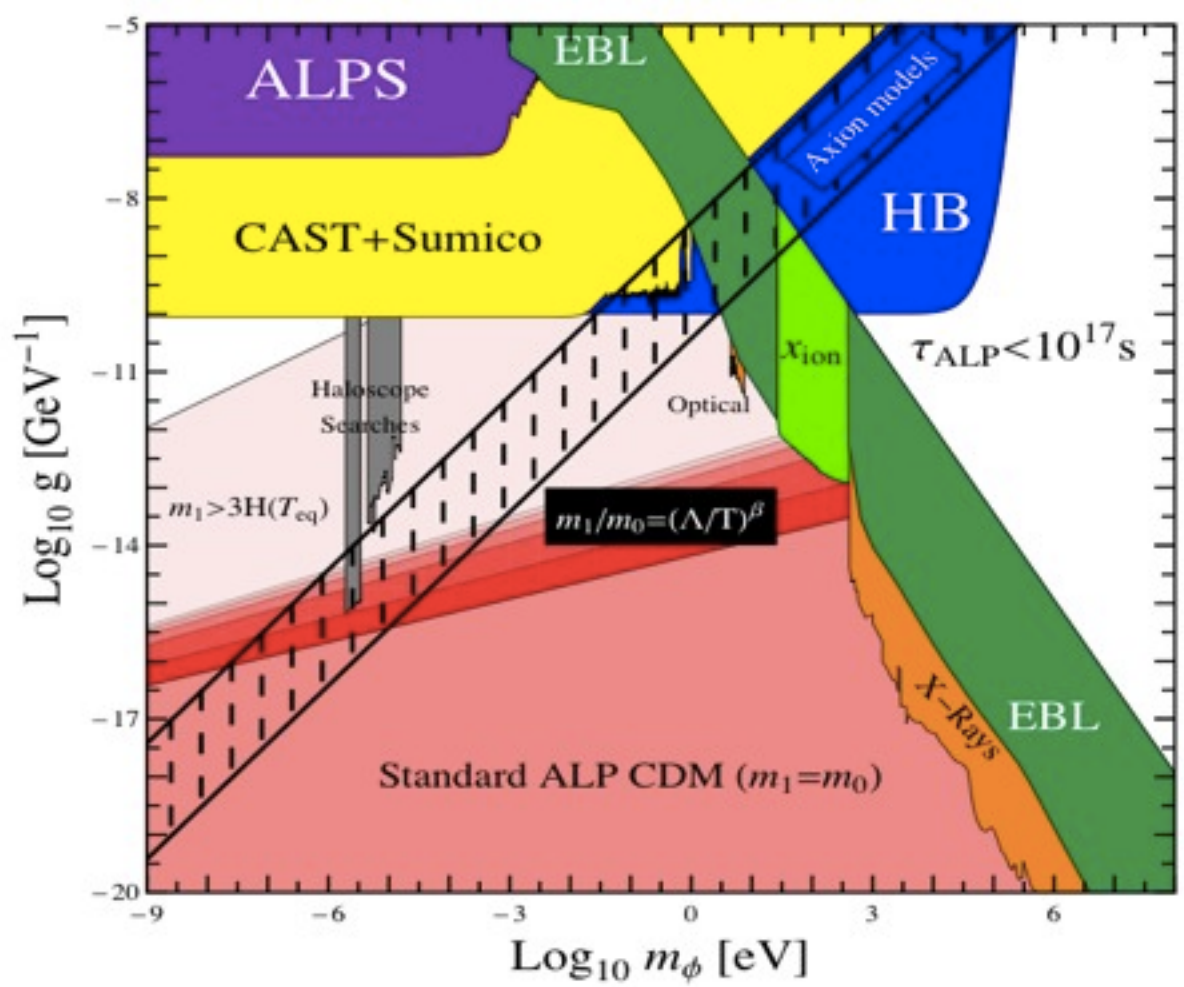
$g \sim \alpha/2\pi M$

independent

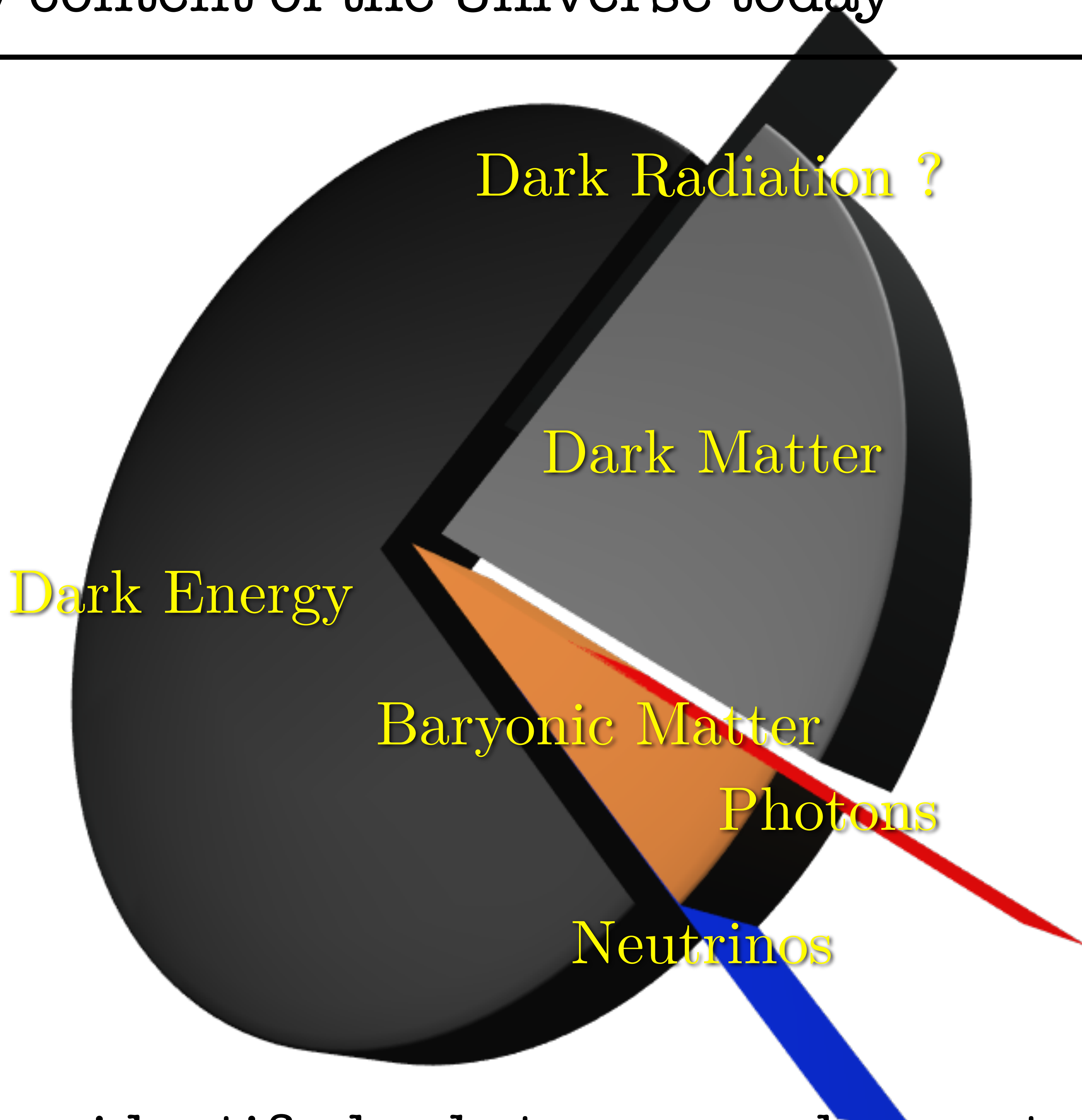
mass m_ϕ

π^0 η' η a MAJORONS R-AXION FAMILONS

DILATONS MODULI RADION

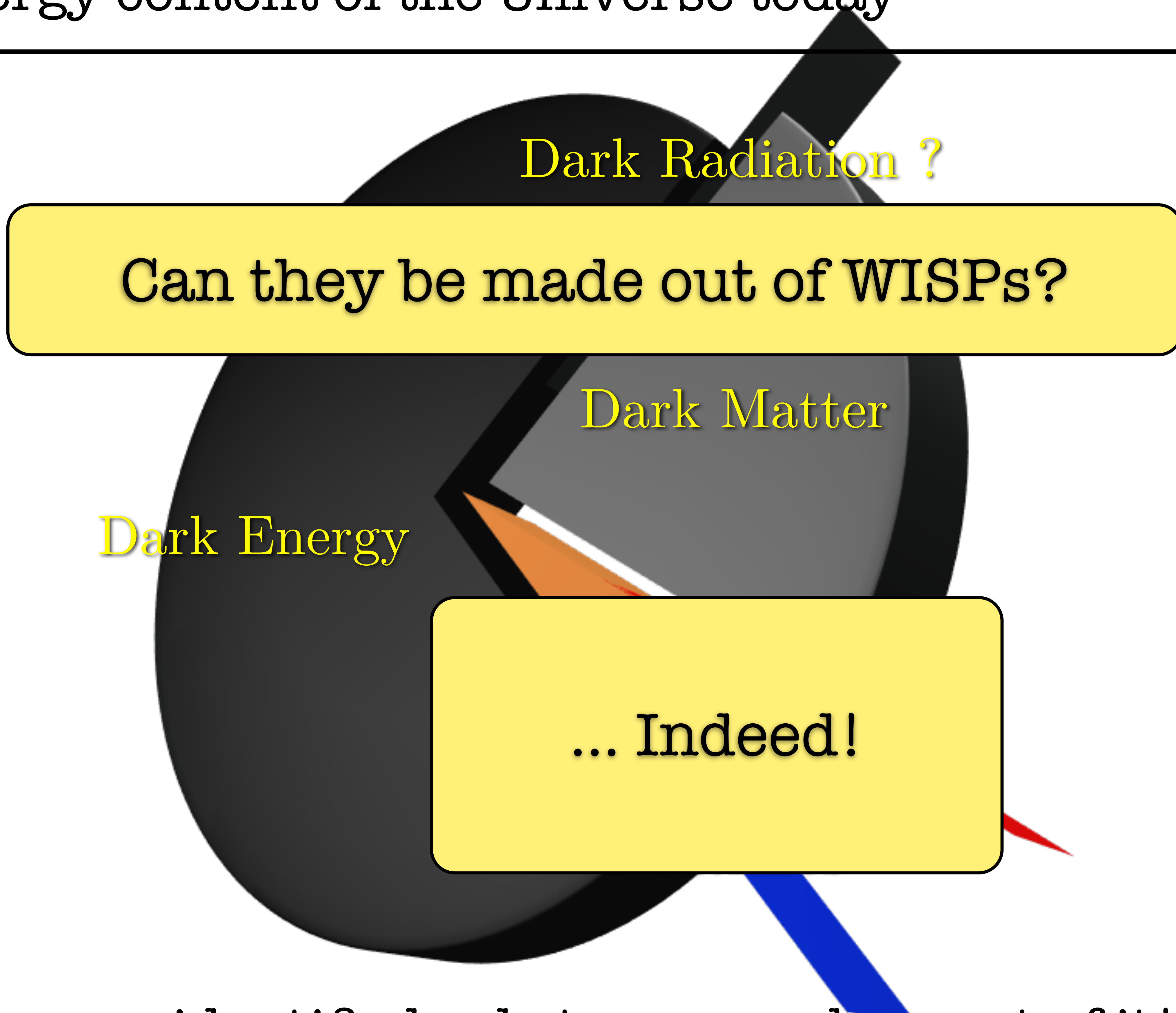


Energy content of the Universe today



Three unidentified substances make most of it!

Energy content of the Universe today



Three unidentified substances make most of it!

Energy content of the Universe today

Three 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 <u>interact very weakly</u> with SM particles.

(and among themselves)

- Matter -

in the sense that are <u>non-relativistic</u>

(most of them)

What do we know about Dark Matter particles?

Basically only what the name suggests:

- Dark -

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(and among themselves)

Very WISPy

- Matter -

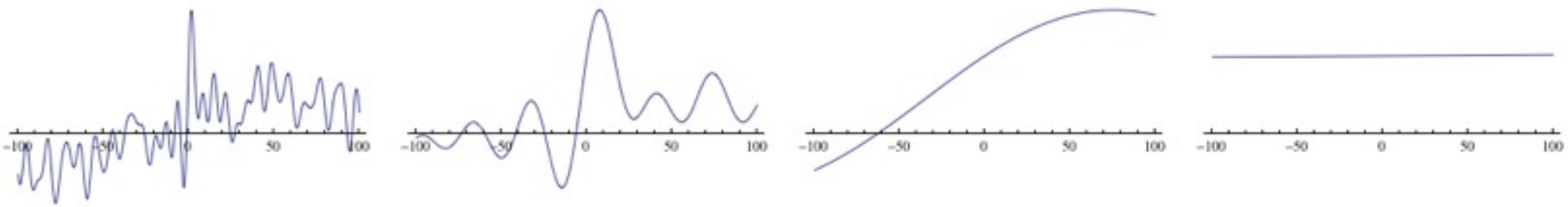
in the sense that are non-relativistic

(most of them)

mmm...

WISPy Dark matter is generically COLD!

During Inflation inhomogeneities in bosonic fields are stretched out.
Fields become ultra-homogeneous (ultra COLD!)

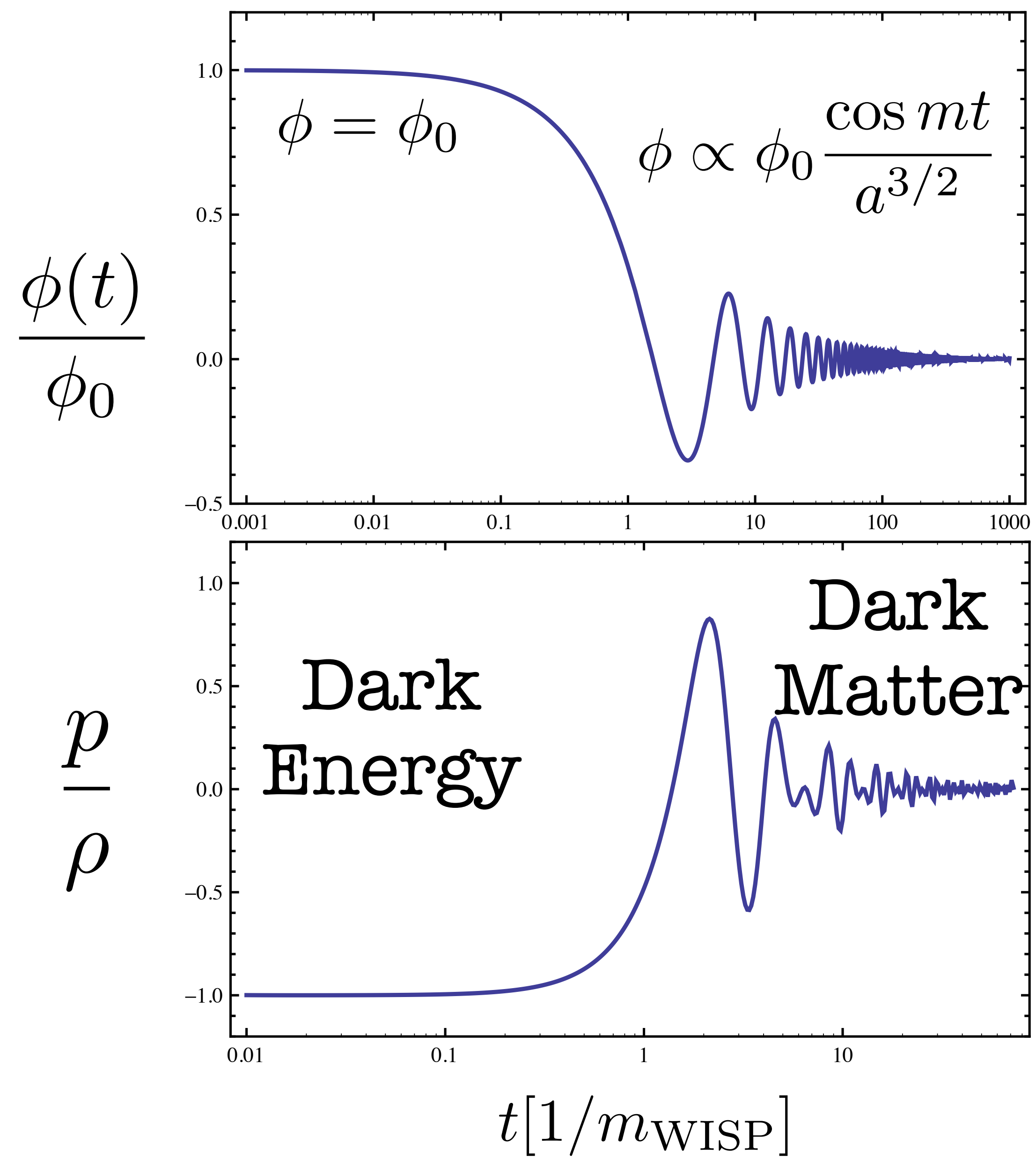


Afterwards:

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = \text{(very weak interactions)}$$

Evolution of homogeneous WISP field in expanding universe

Equation of state



Right amount of WISPy Dark matter

In the simplest ALP/HP models:

$$\rho_{\phi,0} \simeq 1.17\,\frac{\mathrm{keV}}{\mathrm{cm}^3} \times \sqrt{\frac{m_\phi}{\mathrm{eV}}}\left(\frac{\phi_0}{4.8\times 10^{11}\,\mathrm{GeV}}\right)^2 \mathcal{F},$$

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

The most important factor is the initial amplitude
it requires physics at <u>very high energies</u> at play

(Detecting WISPy DM opens a window to HEP!!!)
in a sense...

But this model only testable if BECss and forms caustic rings (See P. Sikivie's talk)

One more level of complication

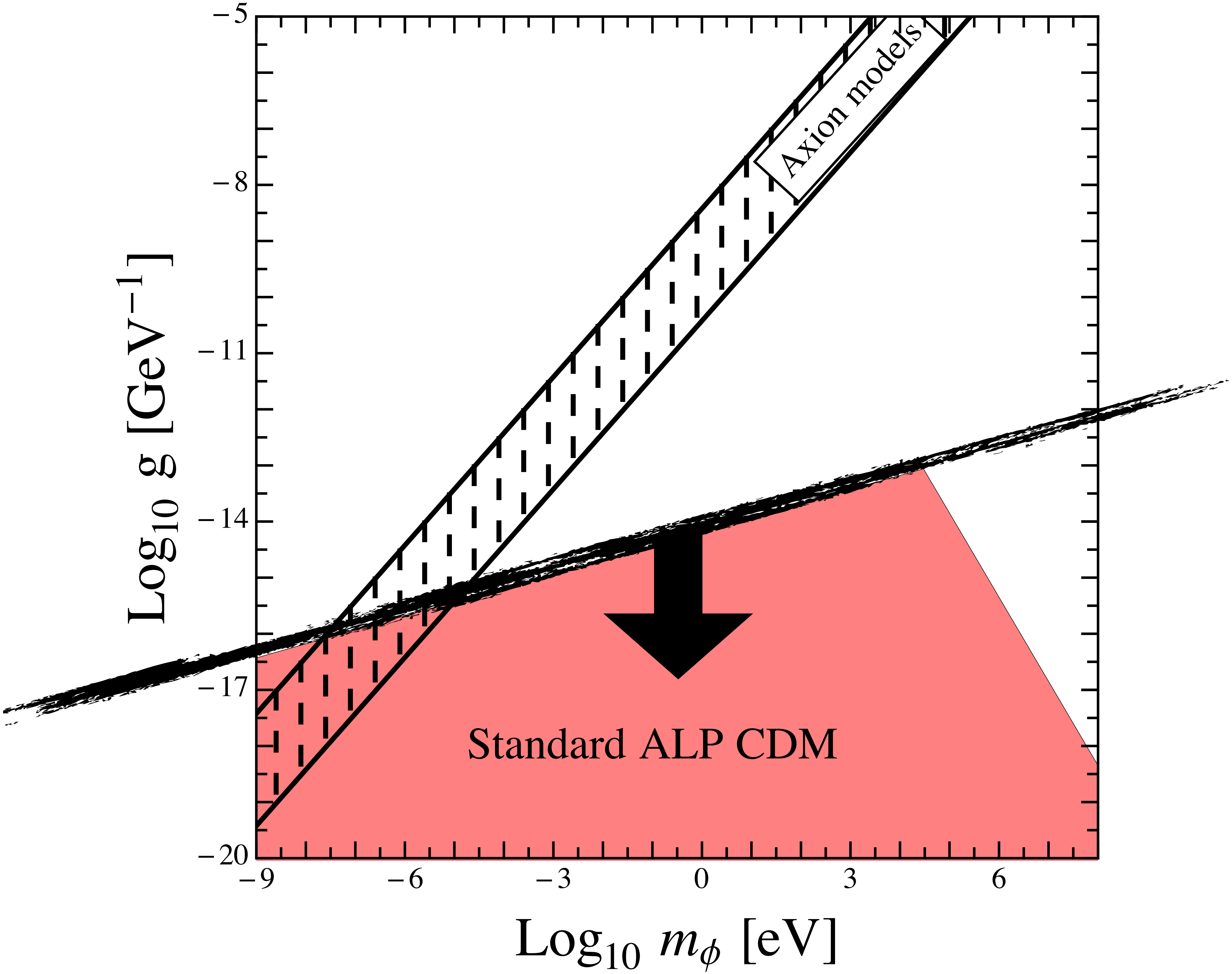
Consider an ALP with a two photon coupling

$$\mathcal{L} = \mathcal{L}_{\rm free} + \frac{g}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu} \phi \qquad g \equiv \frac{\alpha}{2\pi} \frac{1}{f_\phi} \mathcal{N} \qquad \mathcal{N} \sim O(1)$$

Since the coupling is 1/f and the v.e.v. is O(f) we can relate the DM abundance with coupling

$$\phi_0 \in (-\pi f_\phi, \pi f_\phi) \qquad \phi_0 < \frac{\alpha \mathcal{N}}{2} \frac{1}{g}$$

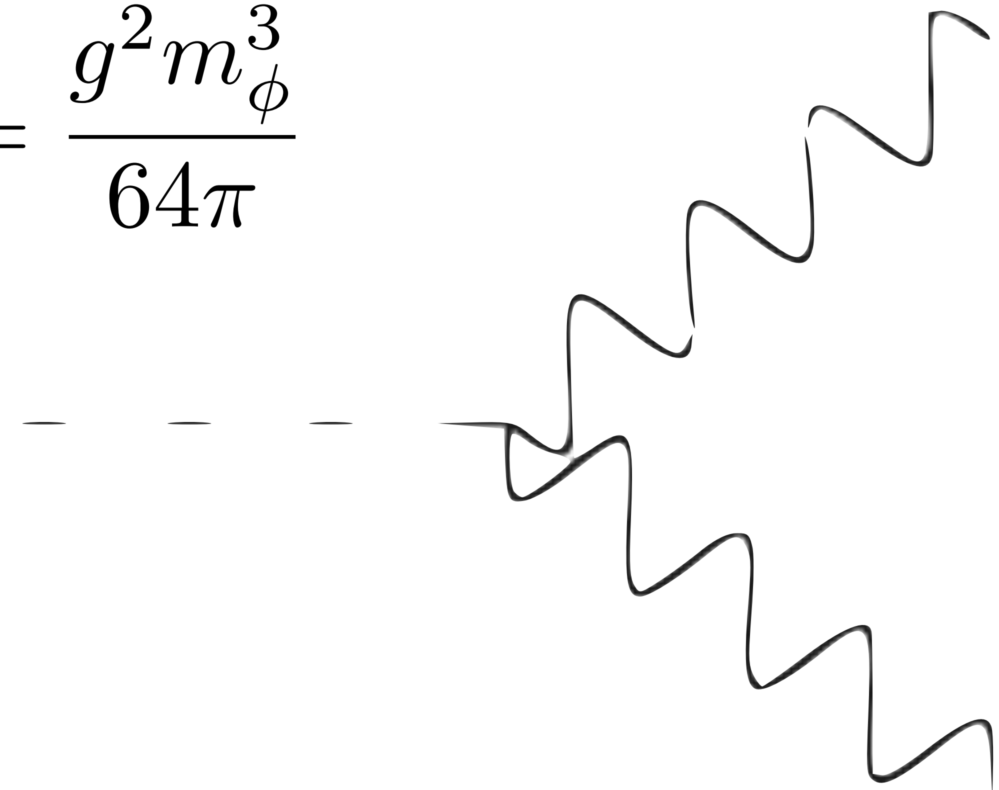
$$\rho_{\phi,0} \lesssim 1.17 \, \frac{\rm keV}{\rm cm^3} \times \sqrt{\frac{m_\phi}{\rm eV}} \left(\frac{0.8 \times 10^{-14} \, {\rm GeV}^{-1}}{g} \right)^2 \mathcal{F} \mathcal{N}^2,$$

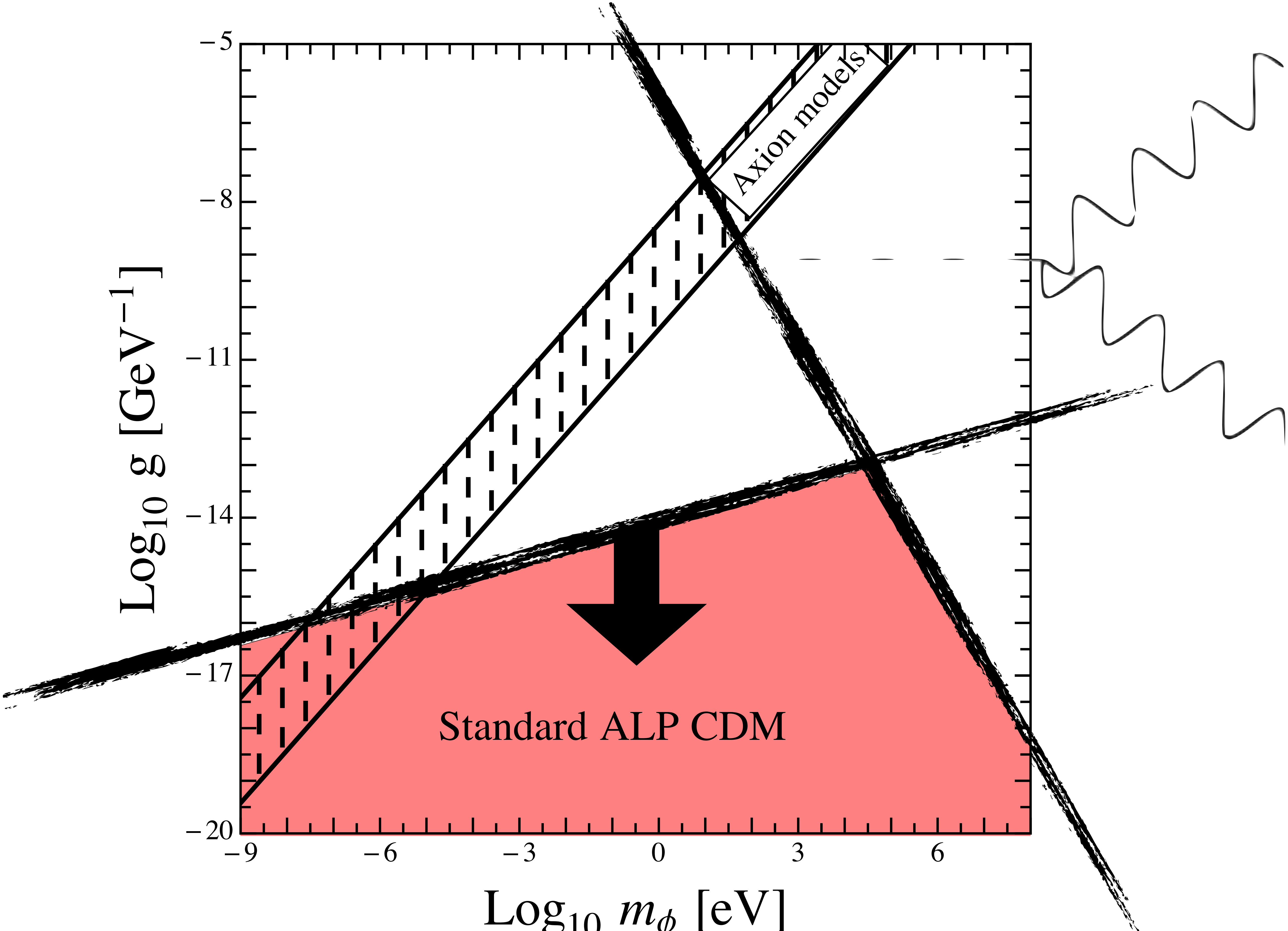


Axion models
Standard ALP CDM
Log$_{10}$ g [GeV^{-1}]
Log$_{10}$ m_ϕ [eV]
−5
−8
−11
−14
−17
−20
−9
−6
−3
0
3
6

But ALPs decay

$$\Gamma = \frac{g^2 m_\phi^3}{64\pi}$$





−5
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−9
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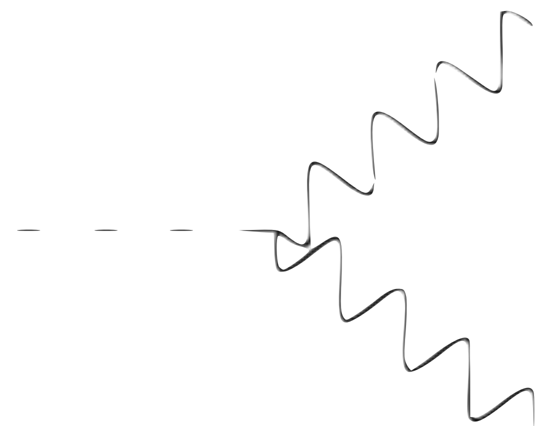
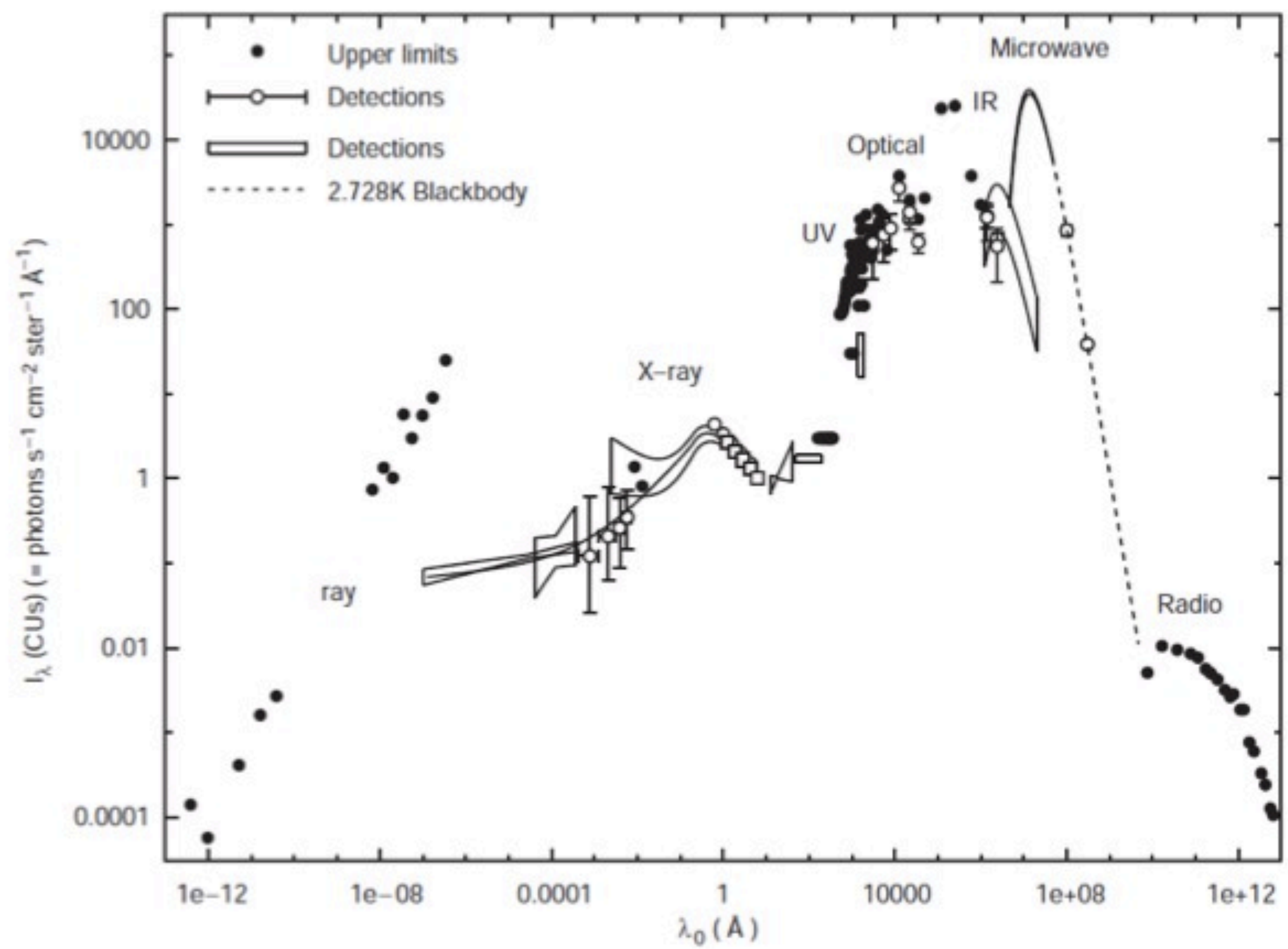
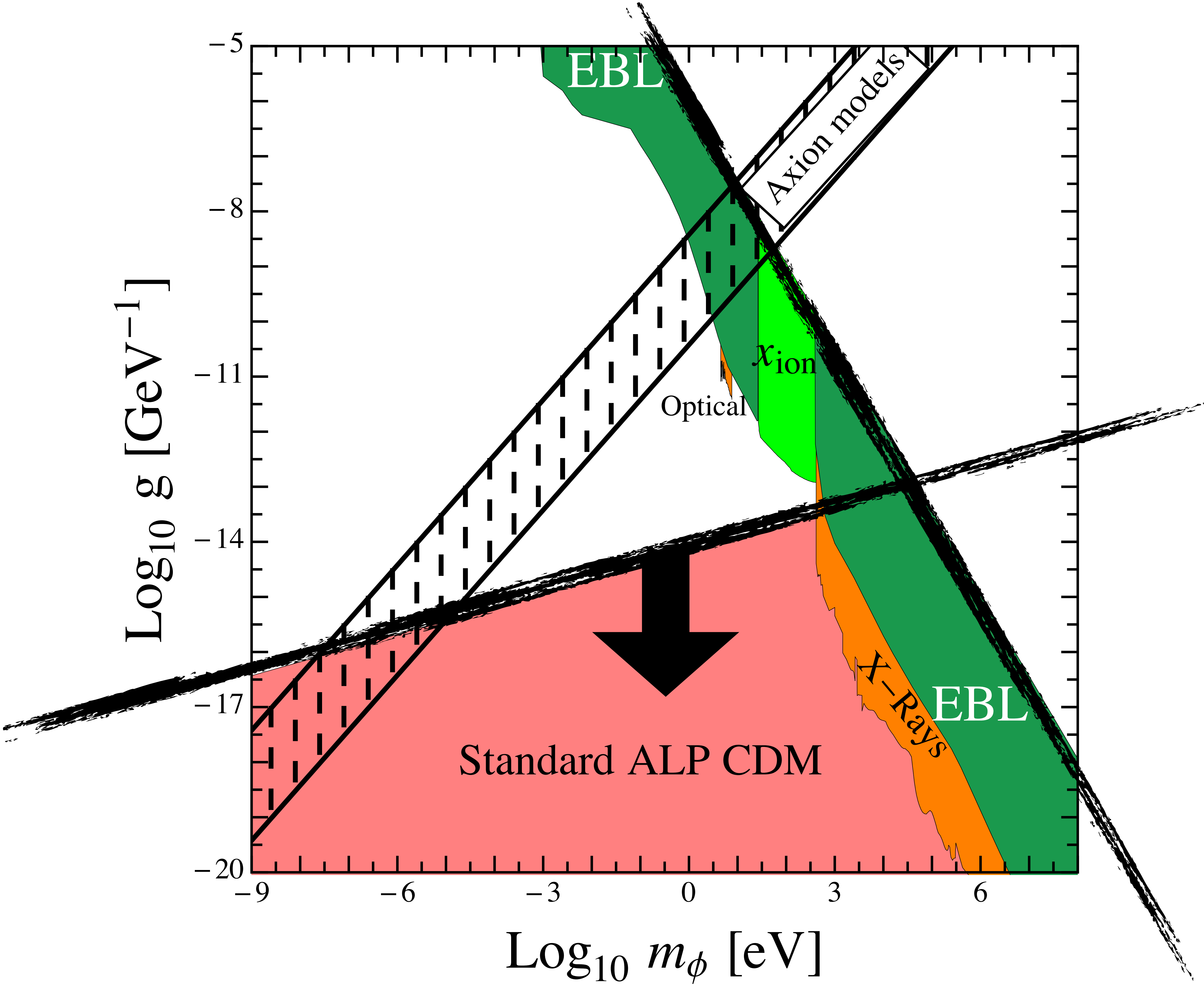
Log10 g [GeV−1]
Log10 mϕ [eV]
Axion models
Standard ALP CDM

But ALPs decay and we don't see the photons...

$$\Gamma = \frac{g^2 m_\phi^3}{64\pi}$$







EBL
Axion models
$x_{\rm ion}$
Optical
X–Rays
EBL
Standard ALP CDM
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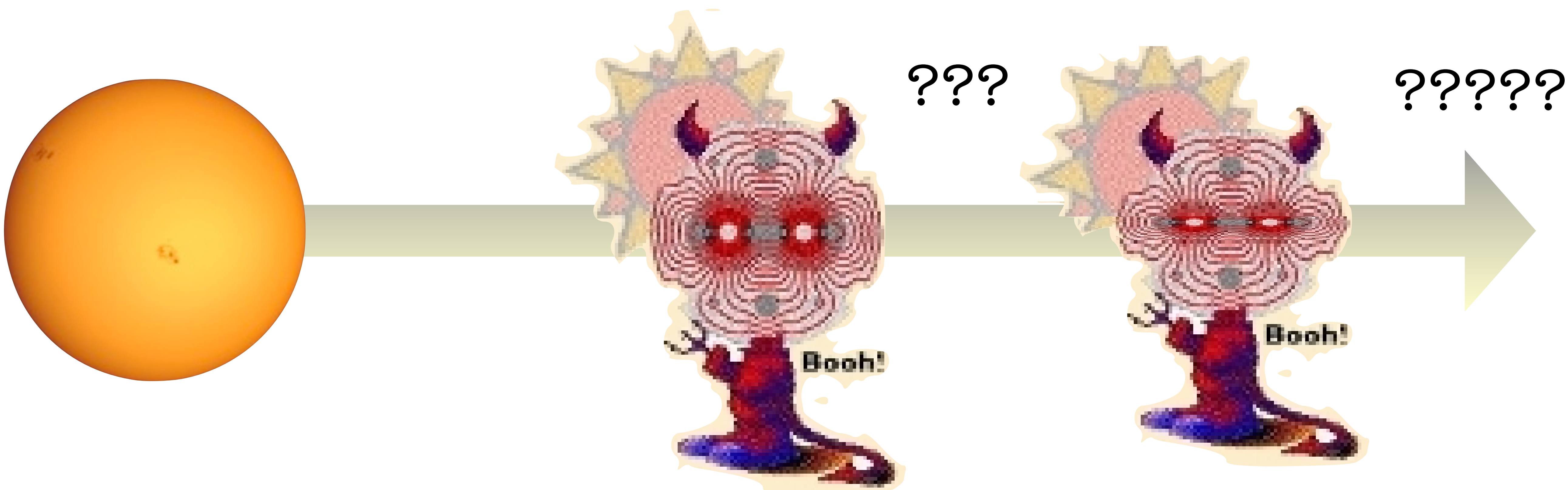
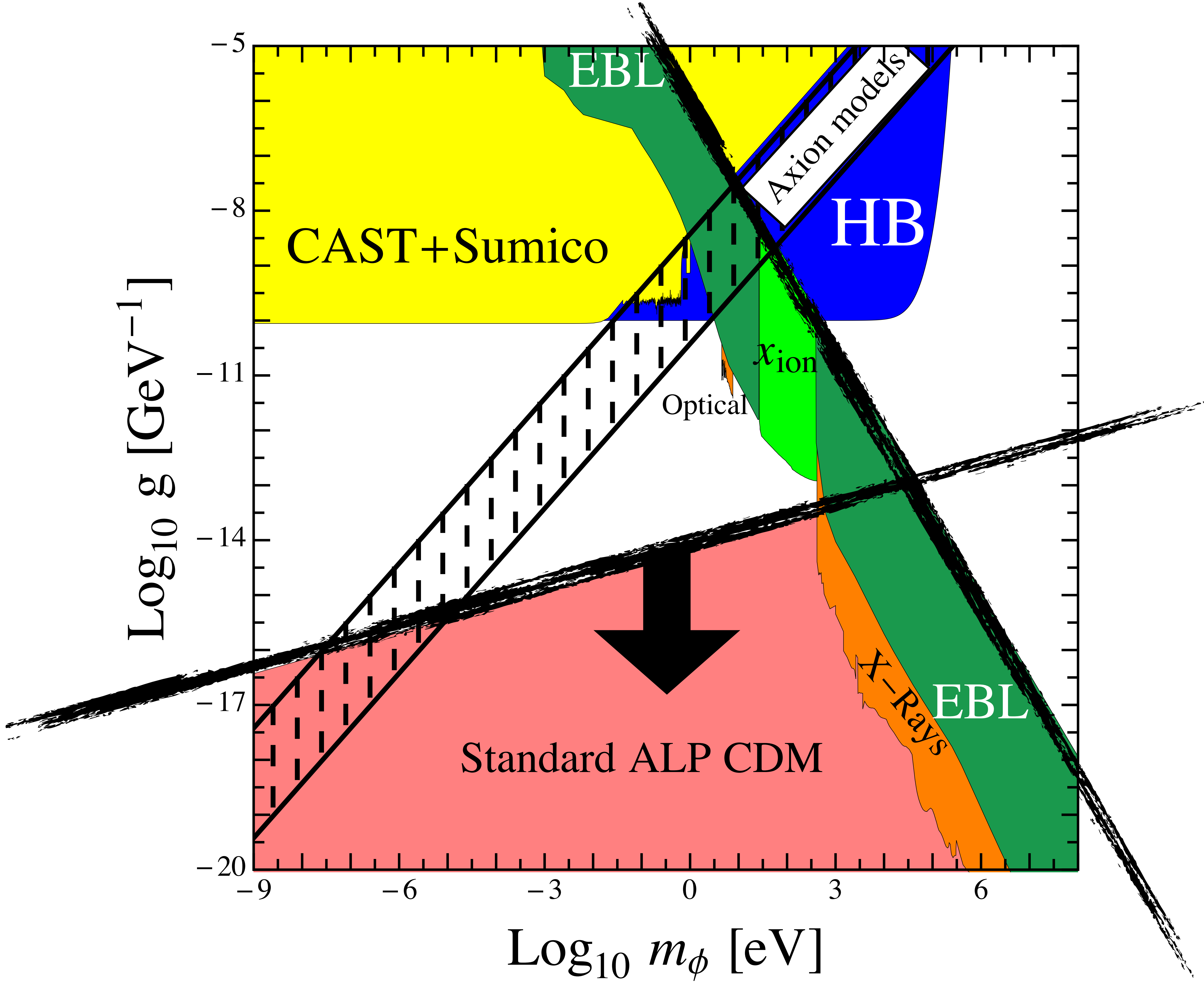
$\mathrm{Log}_{10}\ g\ [\mathrm{GeV}^{-1}]$
$\mathrm{Log}_{10}\ m_\phi\ [\mathrm{eV}]$

And they are radiated from stars

And CAST and SUMICO do not see them




EBL
Axion models
HB
CAST+Sumico
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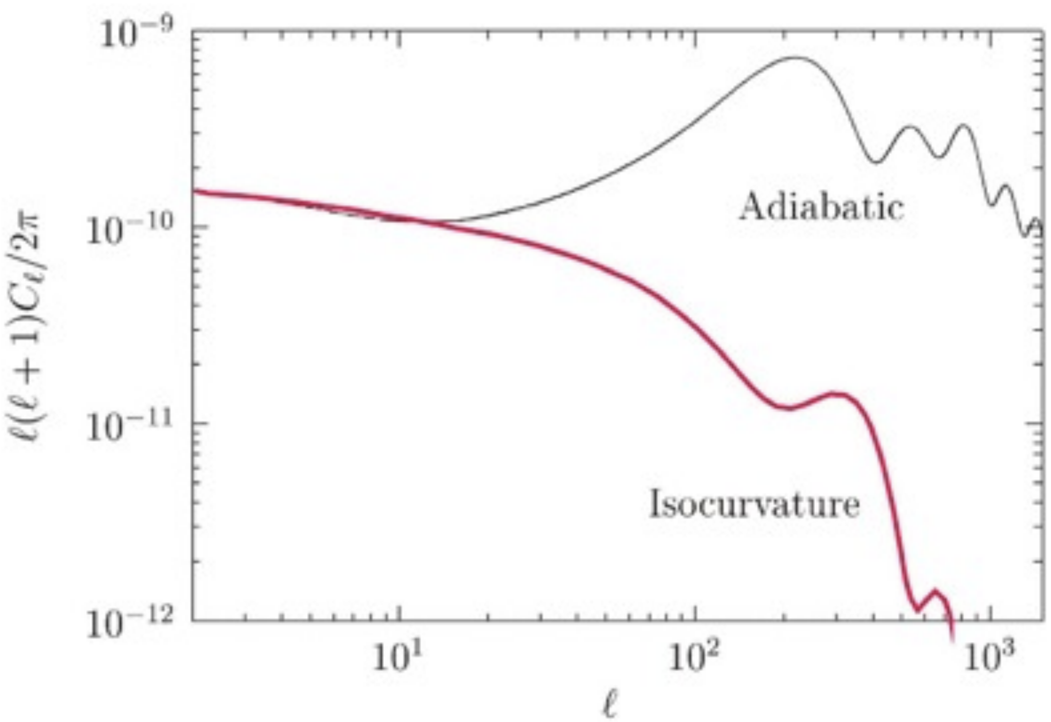
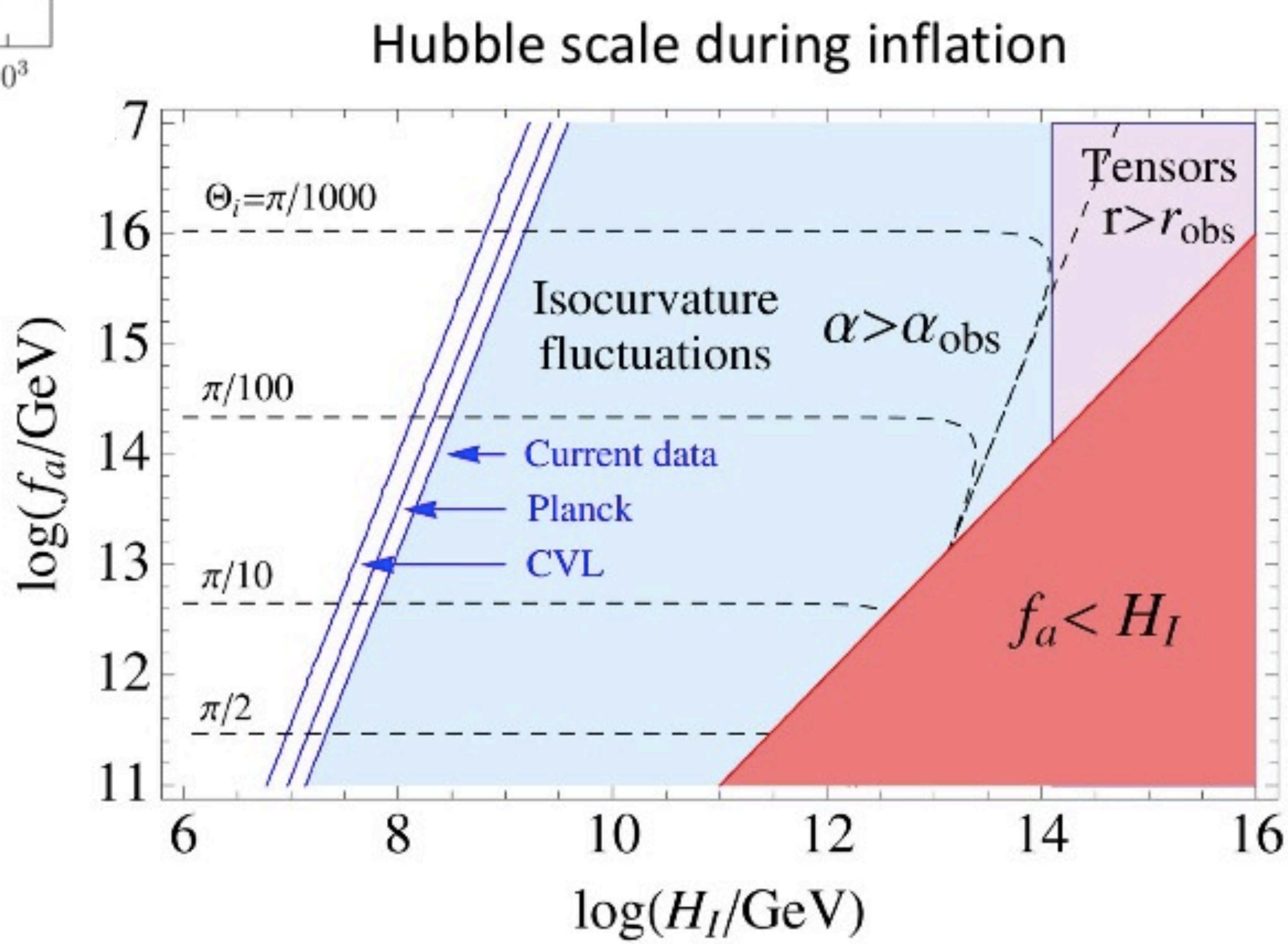
ANd they imprint ISOCURVATURE perturbations



but this depends on H during inflation...

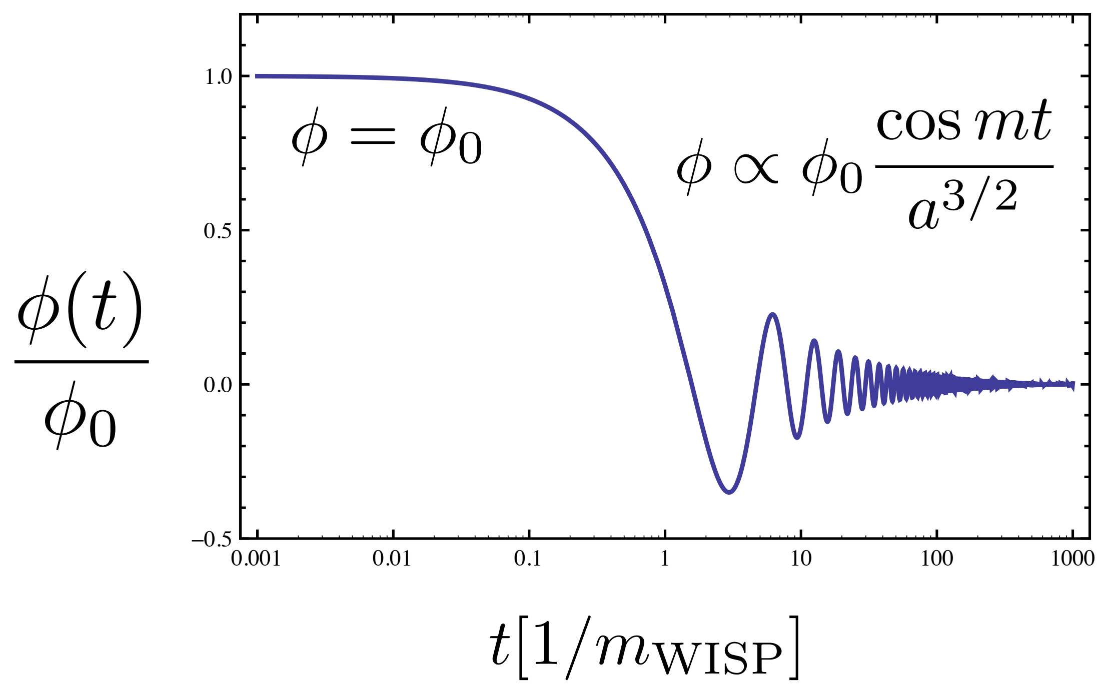


Standard ALP CDM not soooo promising for det.

Situation can change much if thermal mass

$$m = m(T)$$

Damping of the oscillations starts when $m_1 \sim 3H$

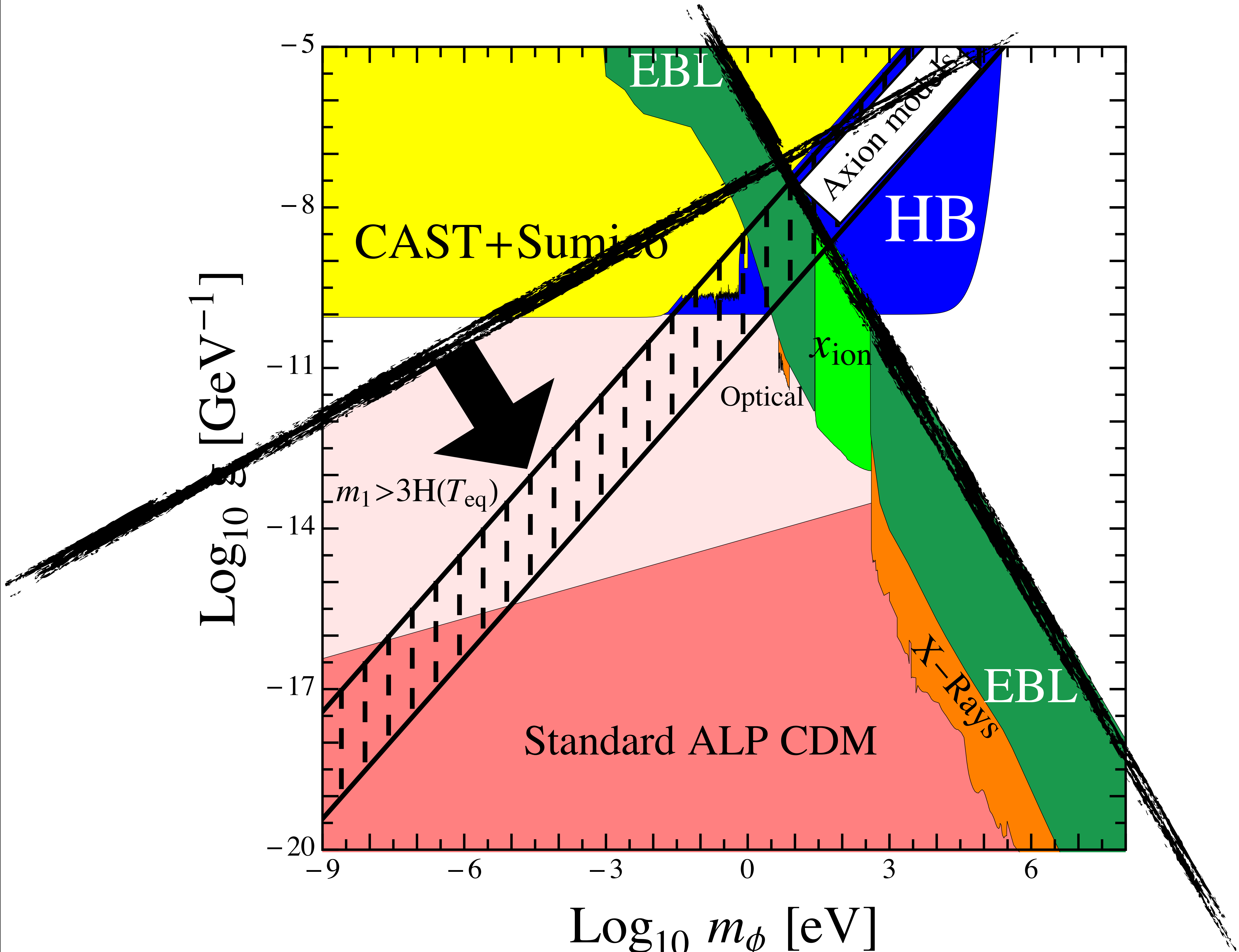


$$\rho_{\phi,0} \simeq 1.17 \frac{\rm keV}{\rm cm^3} \times \sqrt{\frac{m_0}{\rm eV}} \sqrt{\frac{m_0}{m_1}} \left(\frac{\phi_0}{4.8 \times 10^{11}\,{\rm GeV}}\right)^2 \mathcal{F},$$

How small can be m_1 ??

If we want the ALP to behave as CDM after standard Matter-Radiation equality $T_{\rm eq} \sim 1.3\,{\rm eV}$

$$m_0 > m_1 > 3H_{\rm eq} = 1.8 \times 10^{-27}\,{\rm eV}$$



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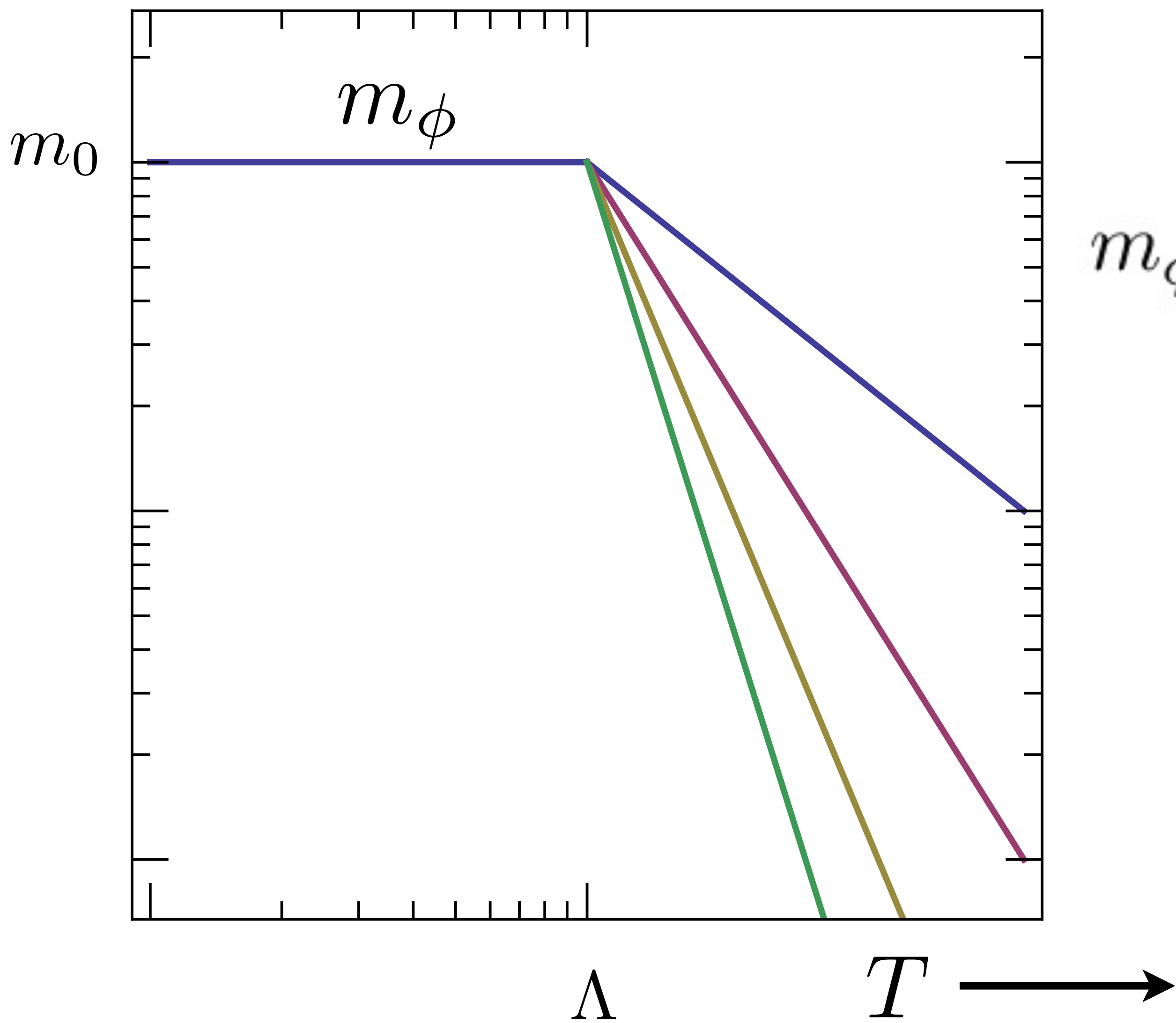
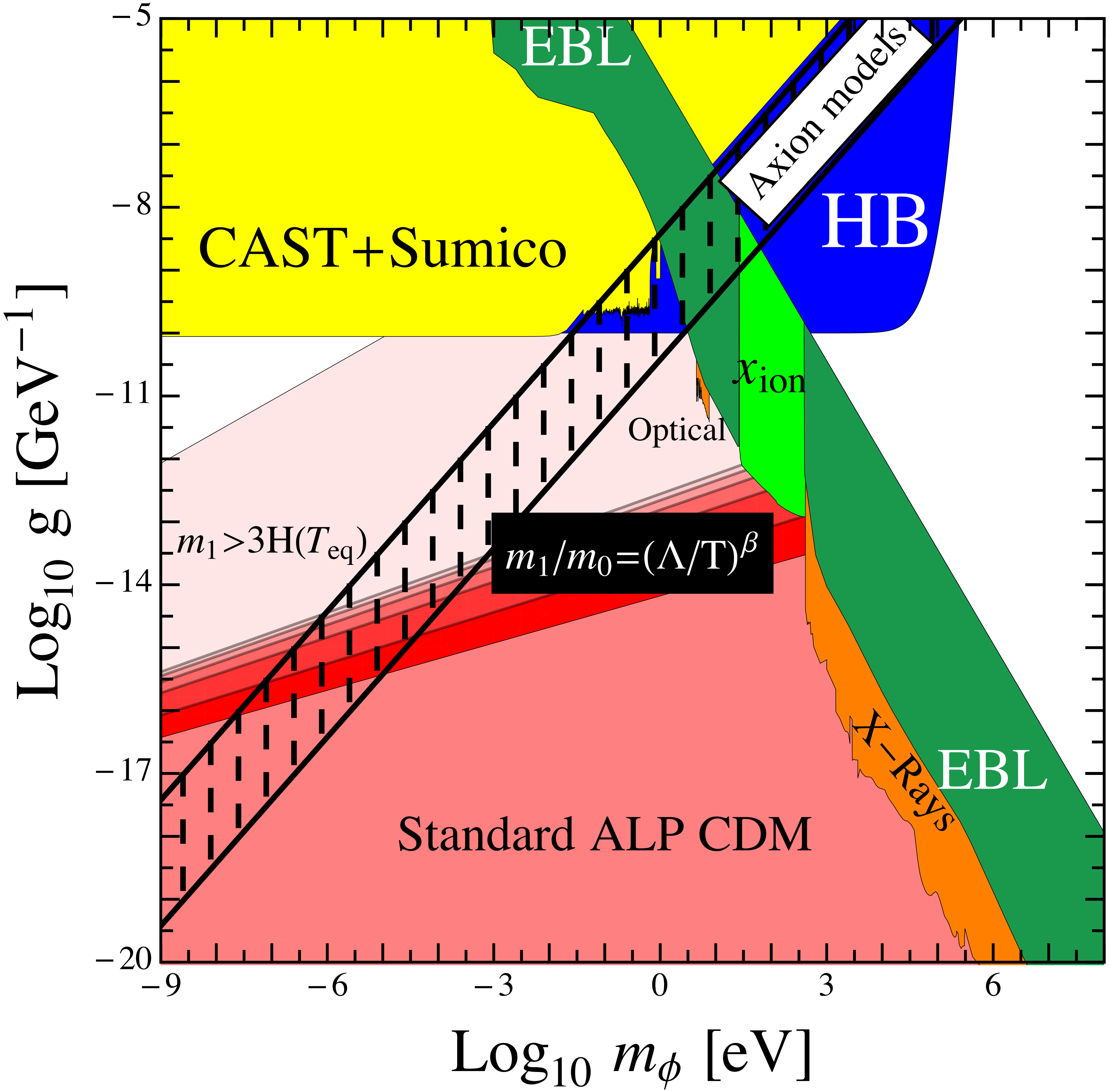
It is however kind of difficult to build such models

Instantonic-like potentials (like for the axion)



$$m_\phi \simeq \begin{cases} \frac{\Lambda'^2}{f_\phi} \equiv m_0 & \text{for } T \ll \Lambda, \\ m_0 \left(\frac{\Lambda''}{T}\right)^\beta & \text{for } T \gg \Lambda. \end{cases}$$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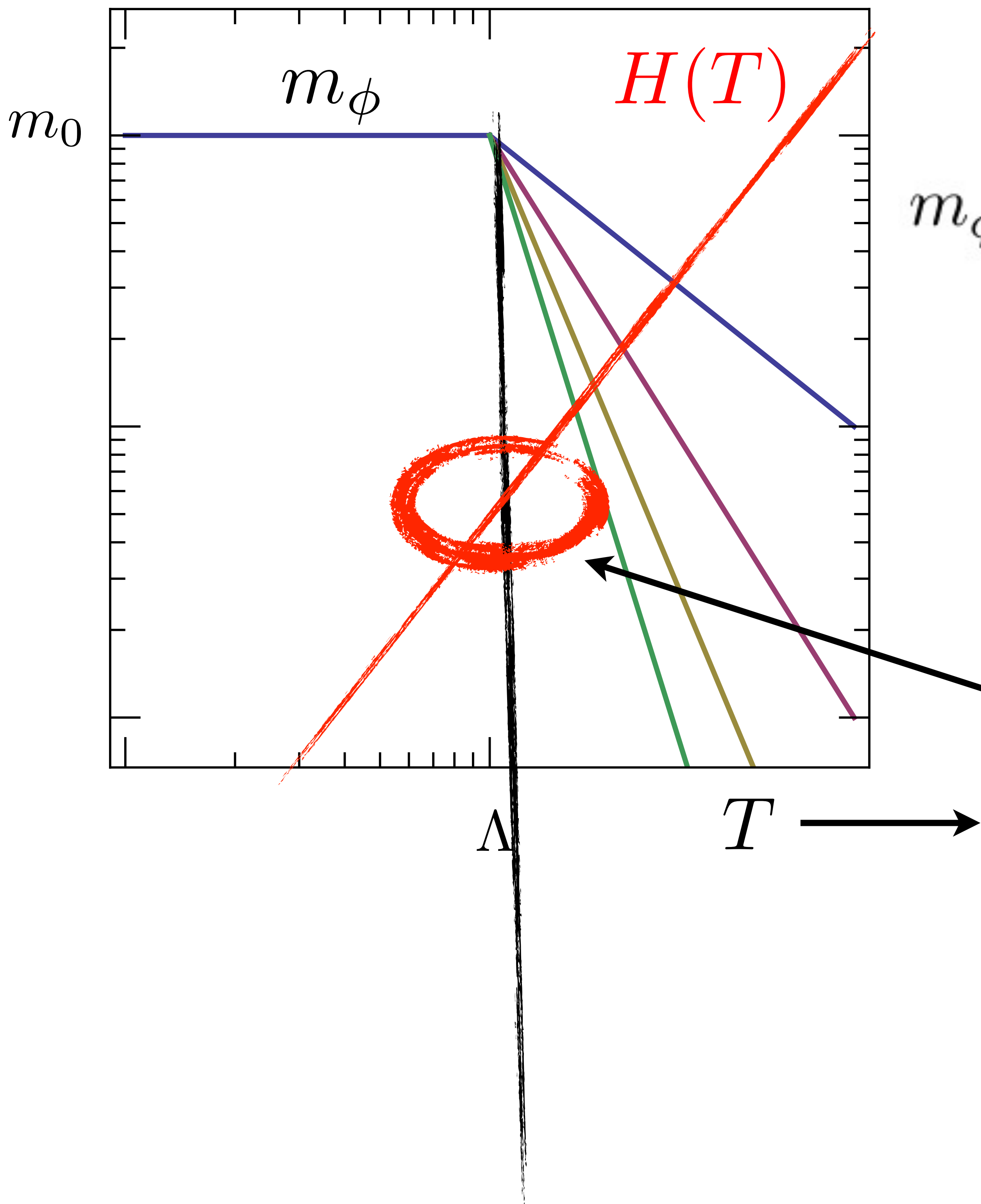

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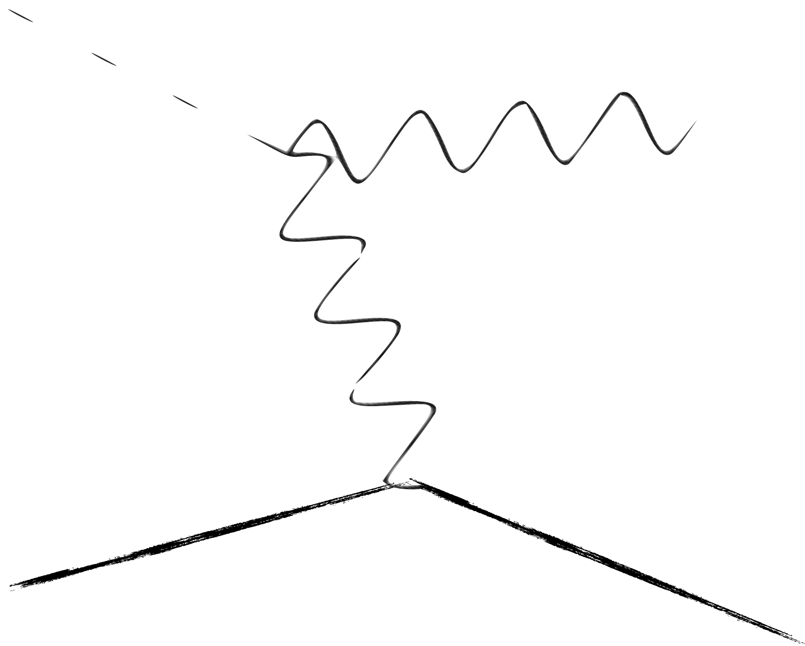
$$T_1 \gtrsim \Lambda$$

Thermalization of ALP CDM I



Primakoff process very effective at high T ...

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

If ALP energy $E_a \sim T$

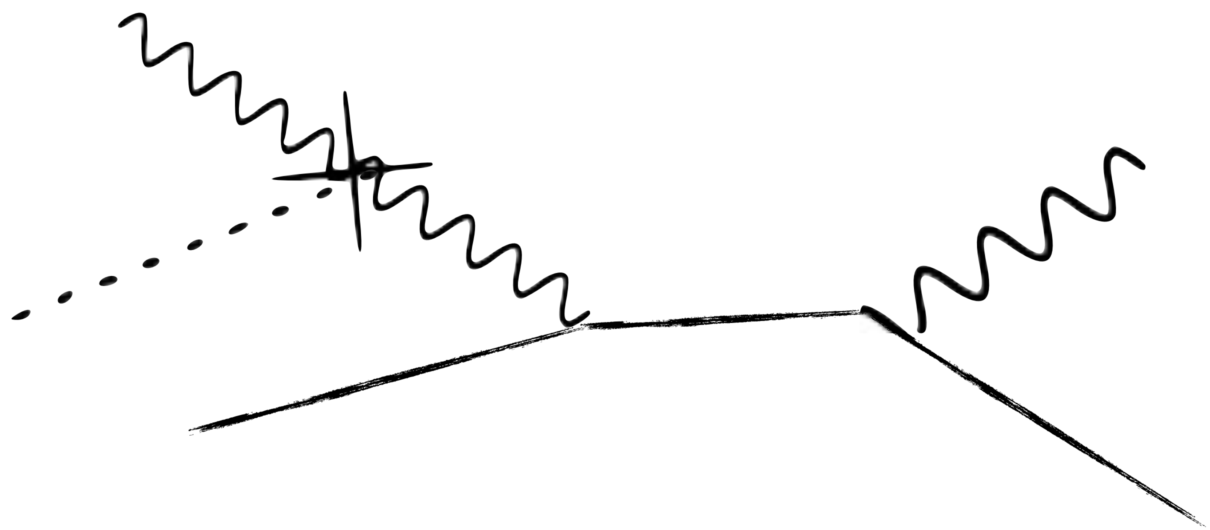
When ALP energies $E_a = m_a \ll T$
the COM energy is not sufficient to produce a plasmon!

$$s = m_e^2 + m_a^2 + 2E_e m_a > (m_e + m_\gamma)^2$$

$$E_e > \frac{2m_e m_\gamma + m_\gamma^2}{2m_a} \gg T$$

Exponentially suppressed!

Thermalization of ALP CDM II



Add other photon in the initial state ...

$$d\Gamma_{\phi C} = \frac{1}{2m_\phi}\Gamma_C(\omega)|\mathcal{M}(\gamma\phi \to \gamma^*)|^2 \frac{1}{(2\omega m_\phi)^2 + (\omega\Gamma_C(\omega))^2} dn_\gamma(\omega)$$
$$= g^2 m_\phi \beta^2 \frac{\omega^2 \Gamma_C(\omega)}{(2\omega m_\phi)^2 + (\omega\Gamma_C(\omega))^2} dn_\gamma(\omega)$$

$$\Gamma_{\phi C} \sim g^2 T^3 \frac{m_\phi}{\langle \Gamma_C \rangle}$$

To still find a suppression $\sim \frac{m_a}{T}$

which makes it irrelevant in the region shown :-)

$$\phi F\widetilde{F} \sim (\partial_\mu \phi) K^\mu = m_\phi K_0$$

Thermalization of ALP CDM III

Primordial Magnetic fields trigger $\phi \leftrightarrow \vec{E}$

And Electric fields are amazingly damped, due to the huge conductivity of the primordial plasma

$$\sigma \sim \frac{T}{\alpha}$$

However, the conductivity also enters into the mixing matrix... and highly suppresses mixing

Eff. mixing... $$\frac{(2gB\omega)^2}{(m_\phi^2 - \omega_{\rm P}^2)^2 + (\omega\sigma)^2}$$

Thermalization of ALP CDM III

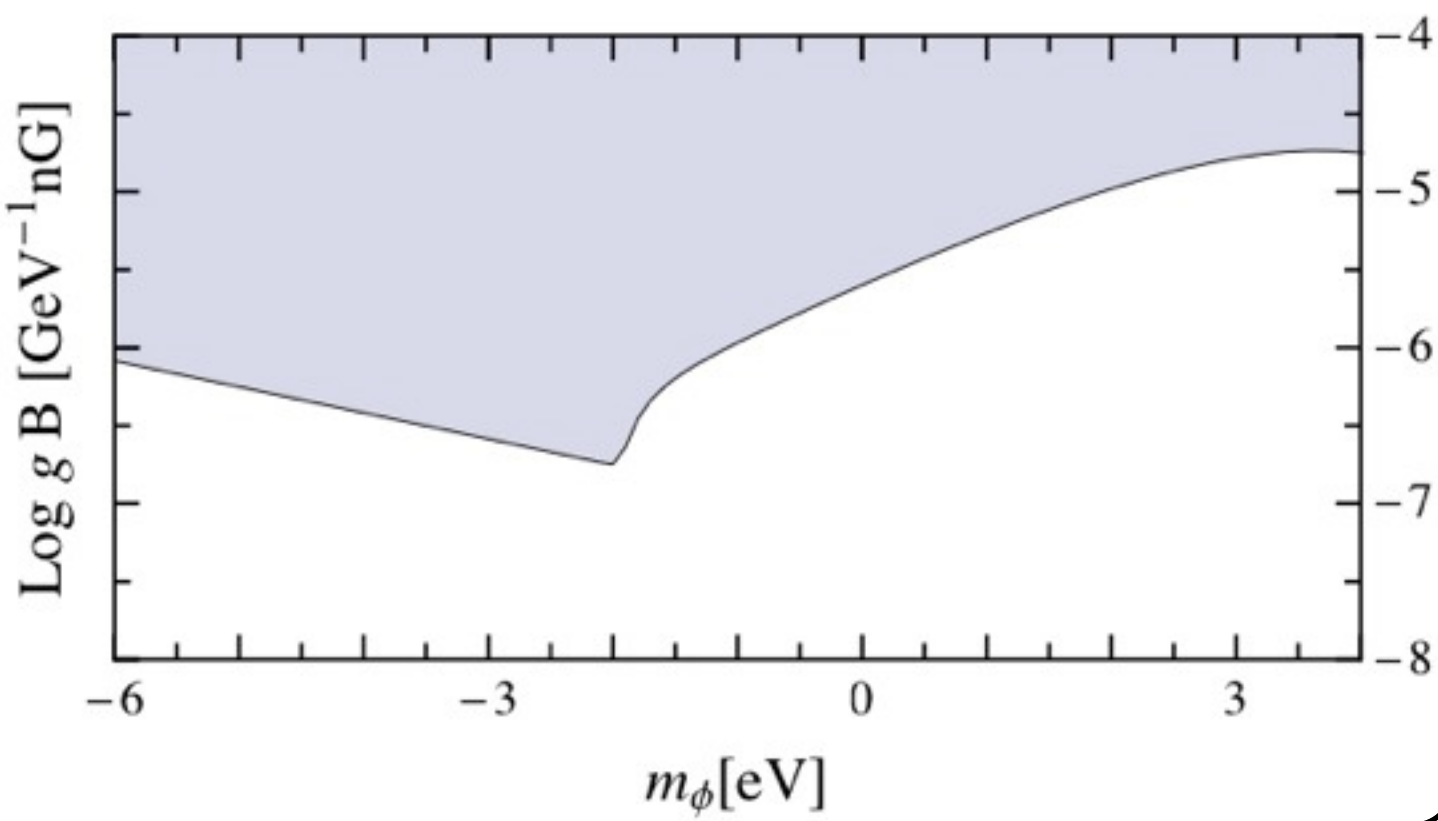
Primordial Magnetic fields trigger $\phi \leftrightarrow \vec{E}$

but very big fields (or very primordial) required

high T constraint (if $B \propto T^2$)

$$\left(\frac{g}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B_0}{3\mathrm{nG}}\right)^2 \frac{T_B}{10^9\,\mathrm{GeV}} \lesssim 1$$

res. oscillations



And what if $T_R > f_\phi$??

Different causally connected regions diff.

$$\phi_0 \in (-\pi f_\phi, \pi f_\phi)$$

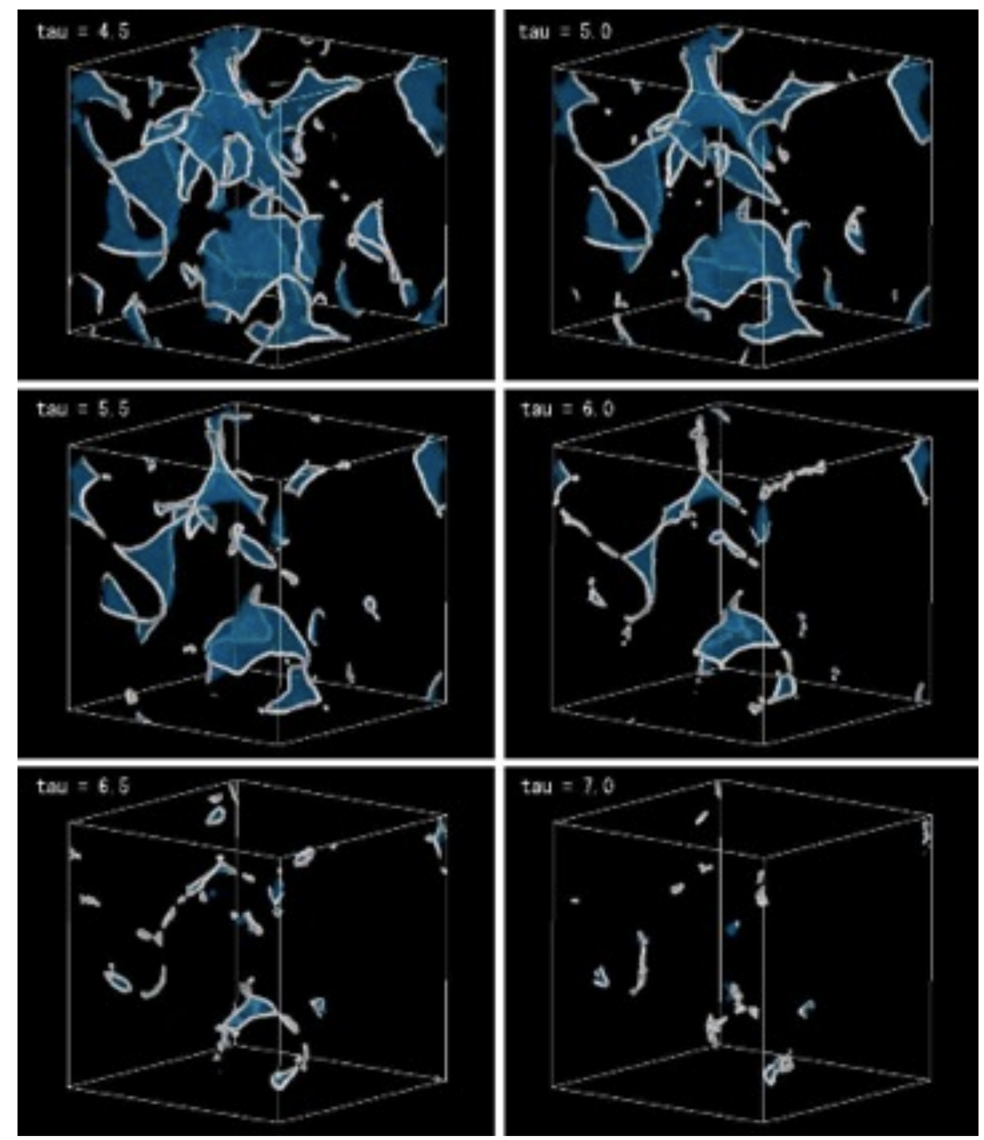
As long as $m_\phi \ll H(T_R)$ the ALP does not know where its minimum is ... (we don't need $m_\phi(T_R) = 0$)

Leads to Cosmic Strings

(decay into ALP DM)

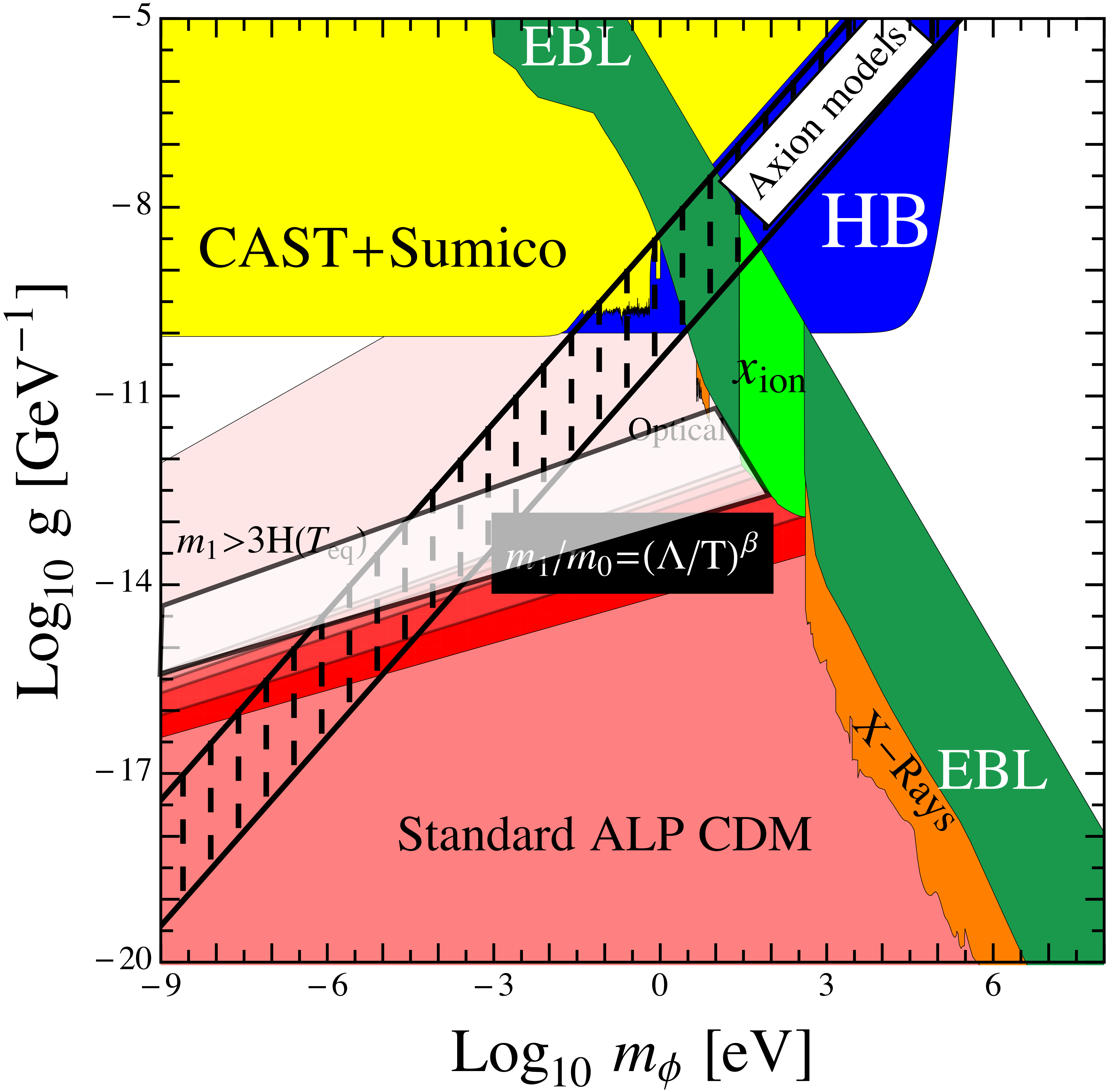
and plausibly Domain Walls!

decay if SYM is exp. Broken
(remind about axions...)

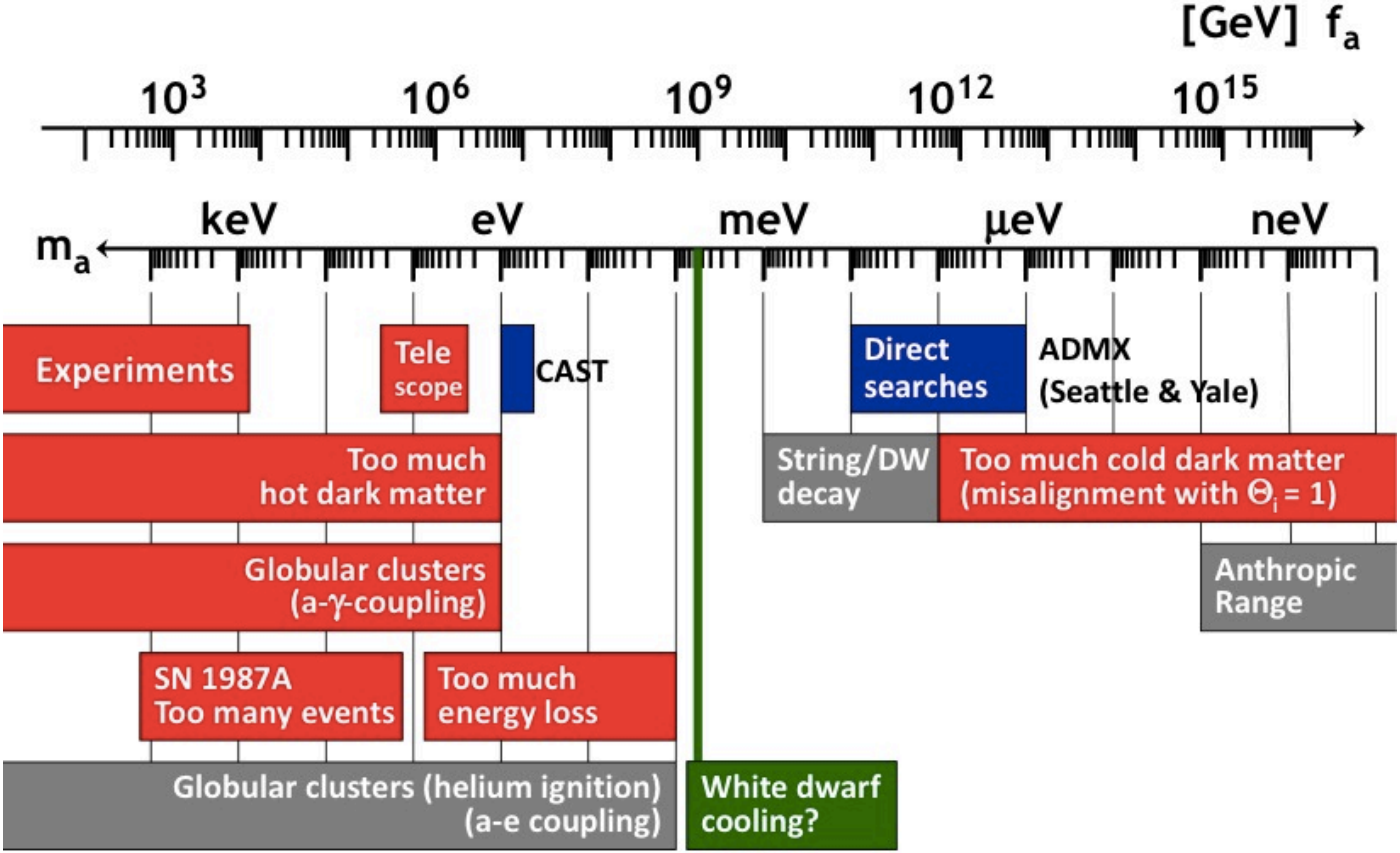


dominant contribution to DM?

Smaller f_ϕ are preferred -> stronger couplings

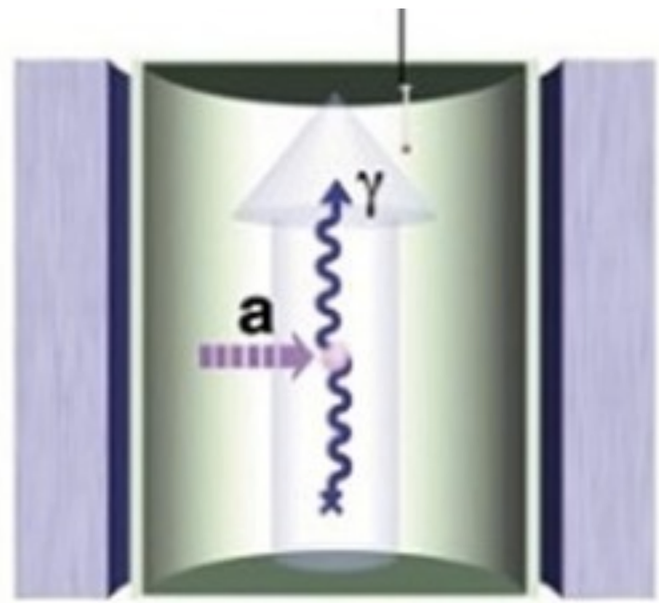


Axion Bounds and Searches



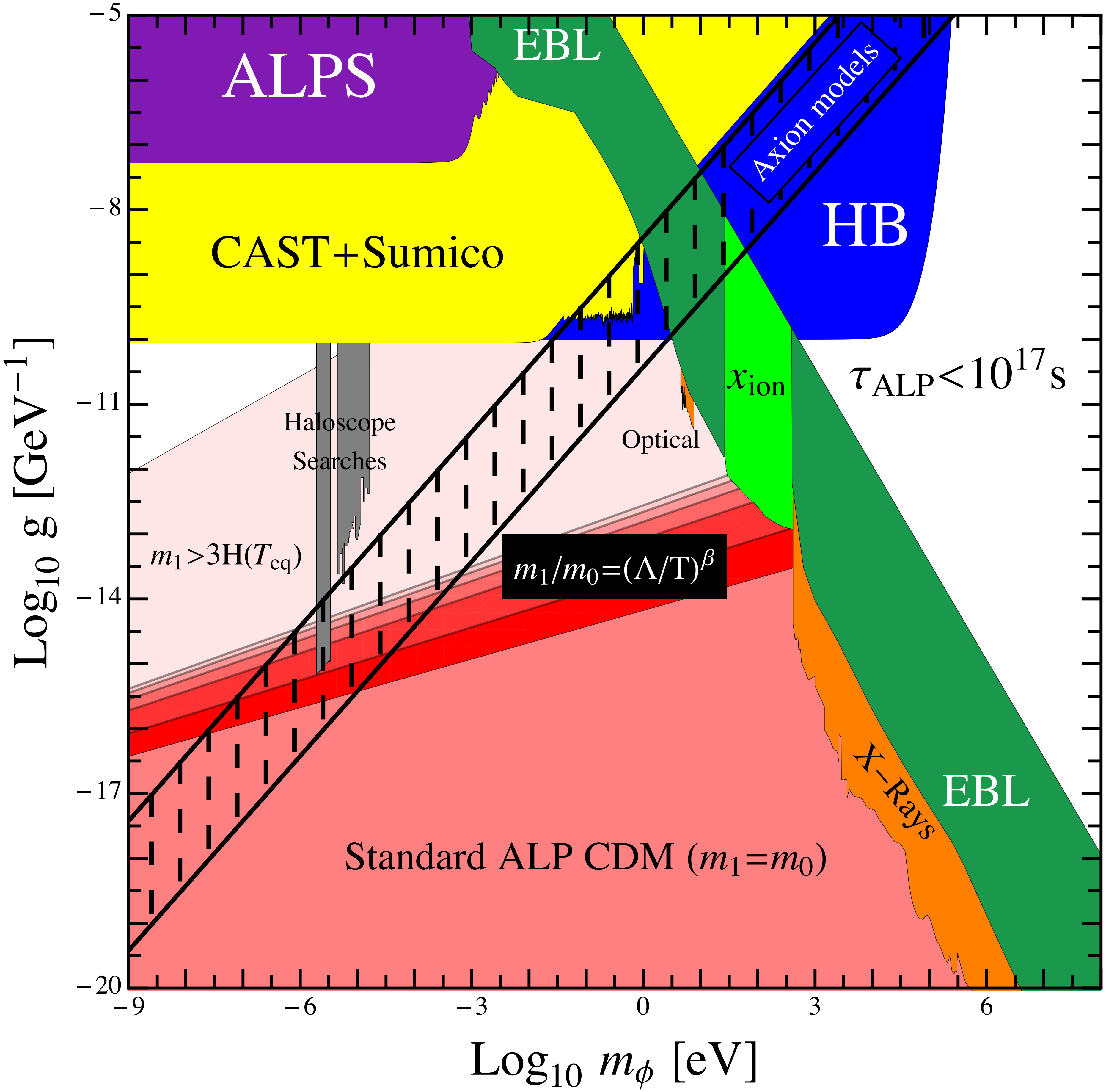
Cavity experiments

(are sensible in a wider range than previously expected)



- ADMX, ADMX-II, and HF (Yale)
- Proposed at DESY, CERN
- IAXO
- UWA

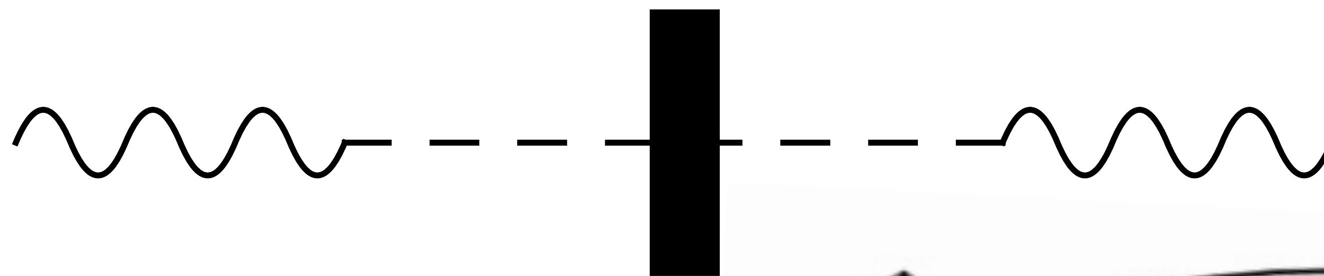
They seem too few for such a wealth of possibilities !!!!!!!!!!!!



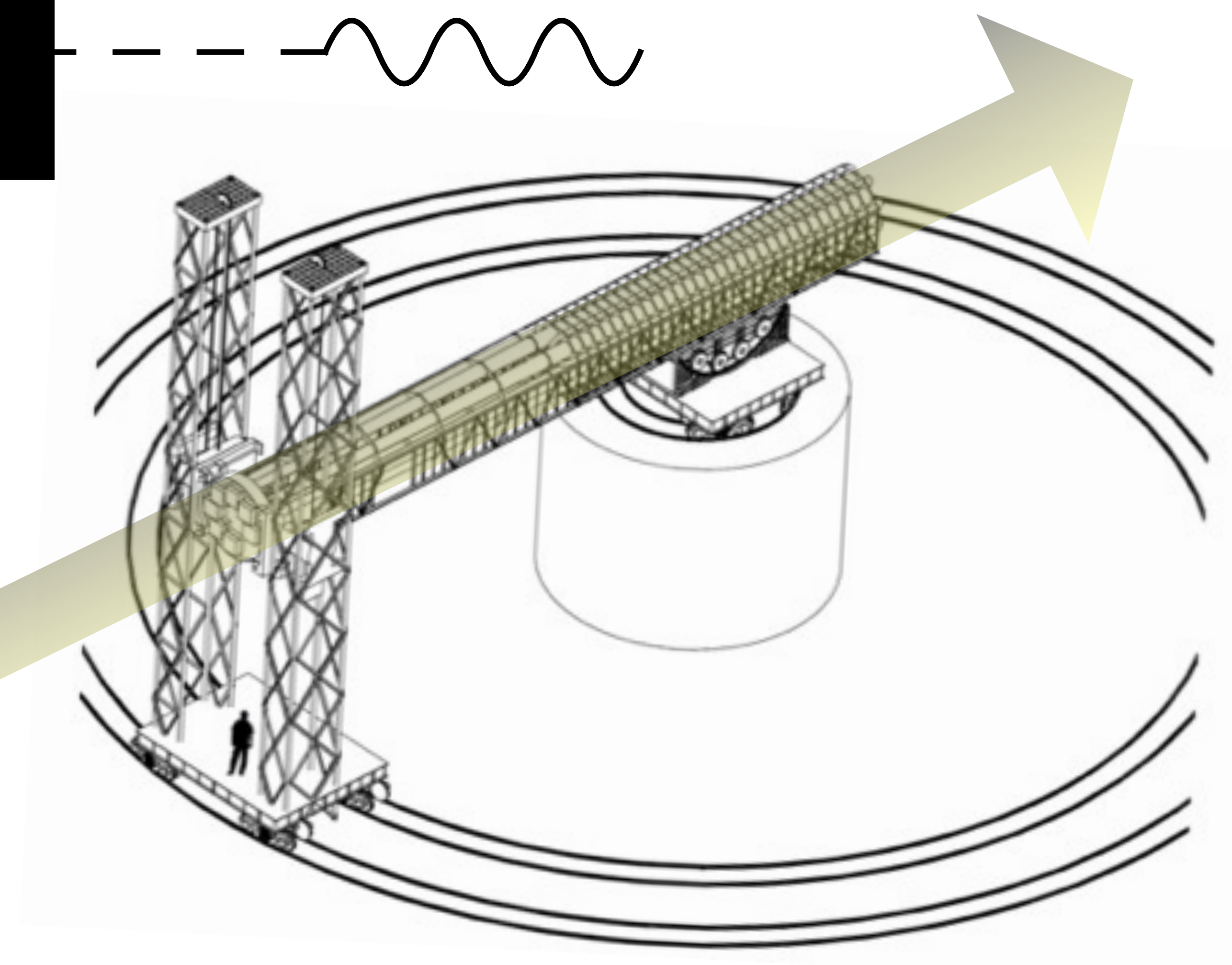
ALPS
EBL
Axion models
HB
CAST+Sumico
$\tau_{\rm ALP}<10^{17}$s
$x_{\rm ion}$
Haloscope
Searches
Optical
$m_1>3{\rm H}(T_{\rm eq})$
$m_1/m_0=(\Lambda/{\rm T})^{\beta}$
X-Rays
EBL
Standard ALP CDM ($m_1=m_0$)
−5
−8
−11
−14
−17
−20
−9
−6
−3
0
3
6
$\mathrm{Log}_{10}\ g\ [\mathrm{GeV}^{-1}]$
$\mathrm{Log}_{10}\ m_\phi\ [\mathrm{eV}]$

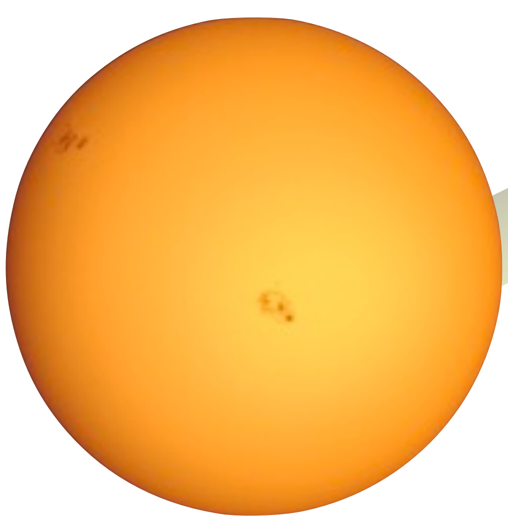
Other experiments are sensible to WISPy ALP DM

- Light Shinning through walls (REAPR, ALPS II)

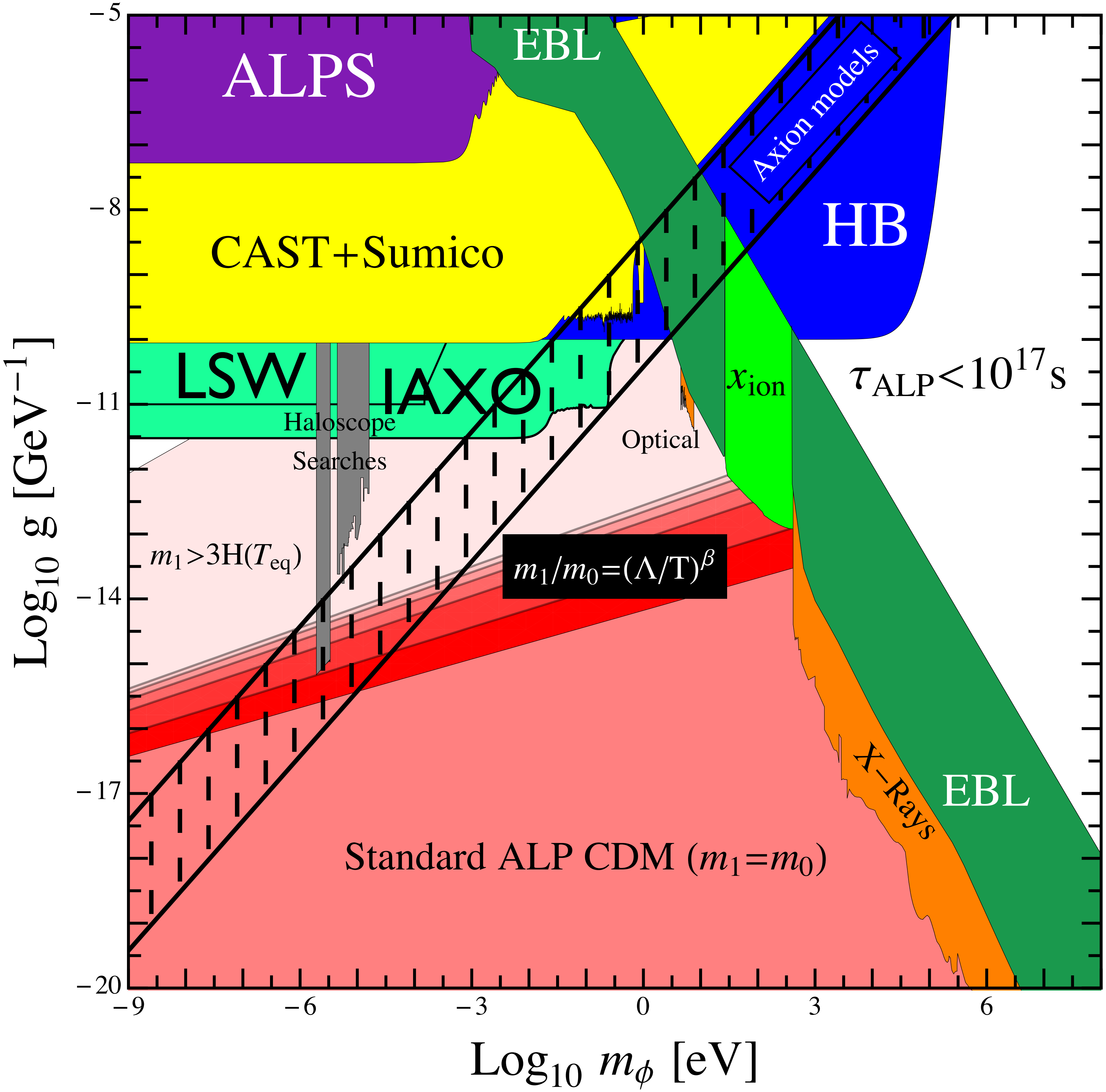


- IAXO





- 5th forces ? (still don’t know...)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Local U(1)'s: Hidden Photons & kinetic mixing

Extra U(1) symmetries are ubiquitous BSM (for instance in String Theory)

If the corresponding Hidden photon does not couple to SM particles ->
HIDDEN PHOTON

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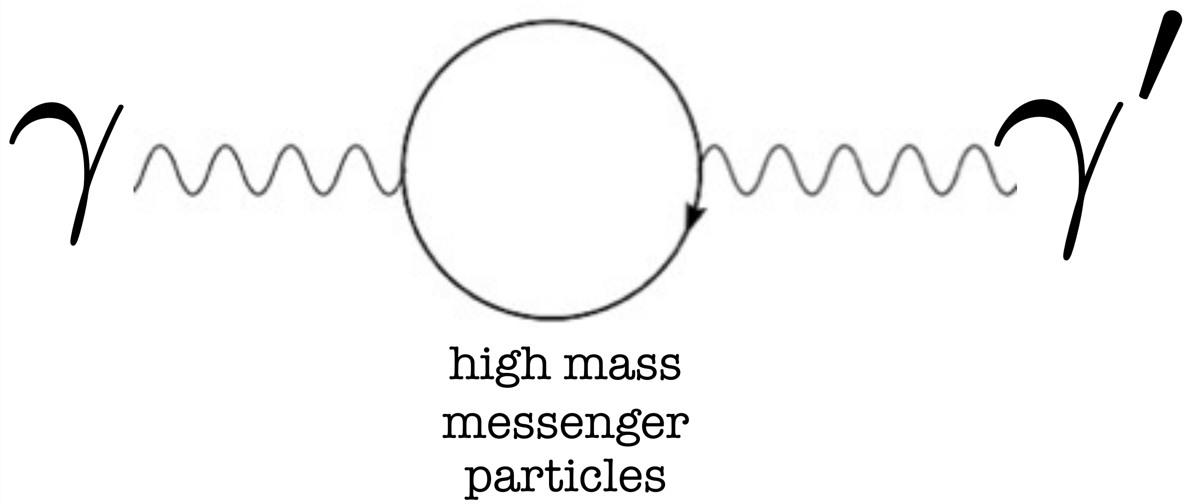

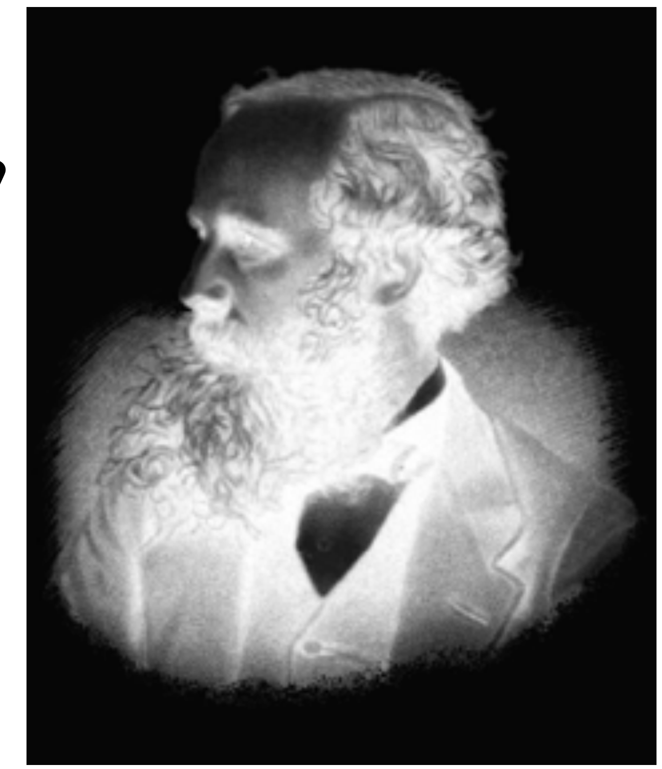

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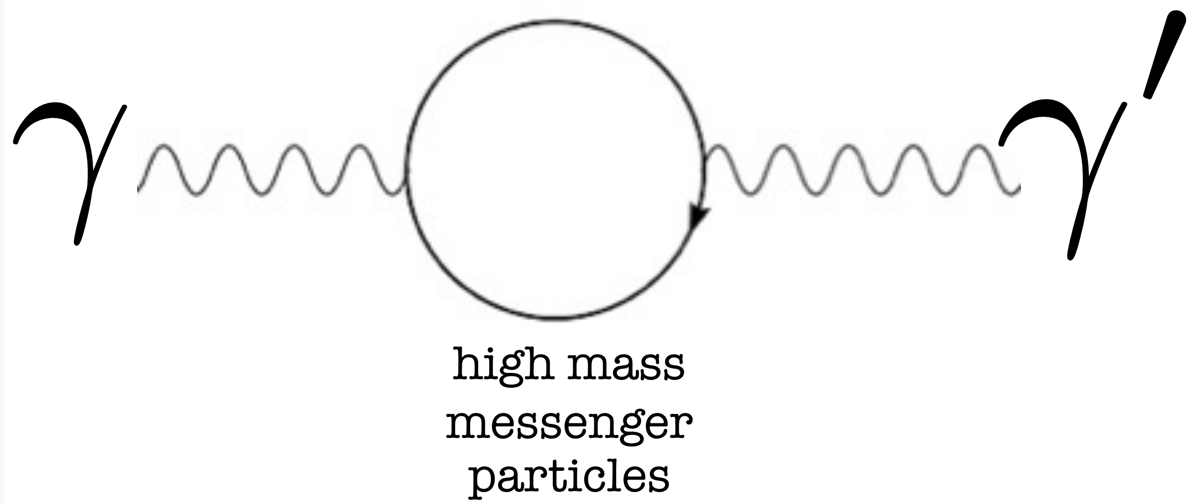
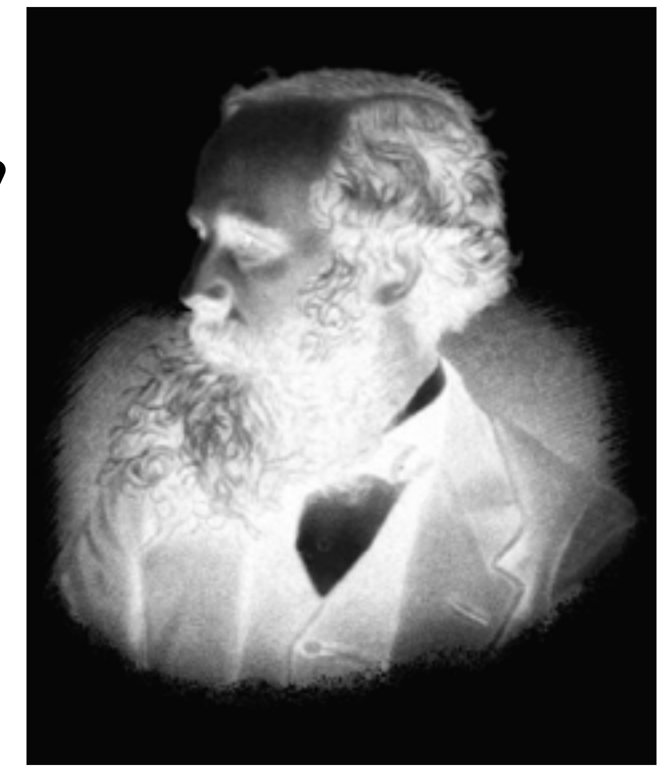




Kinetic mixing is the most relevant interaction at low energies

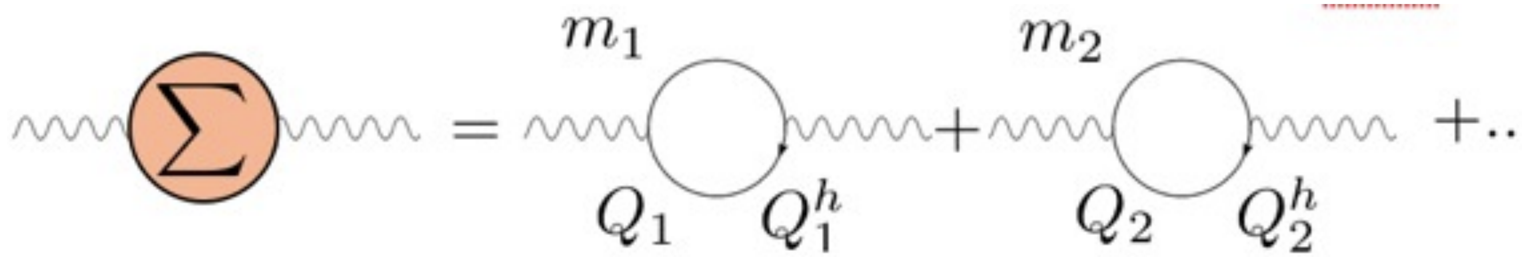
$$\mathcal{L}_I = -\frac{1}{2}\chi F_{\mu\nu} B^{\mu\nu}$$

Size of kinetic mixing

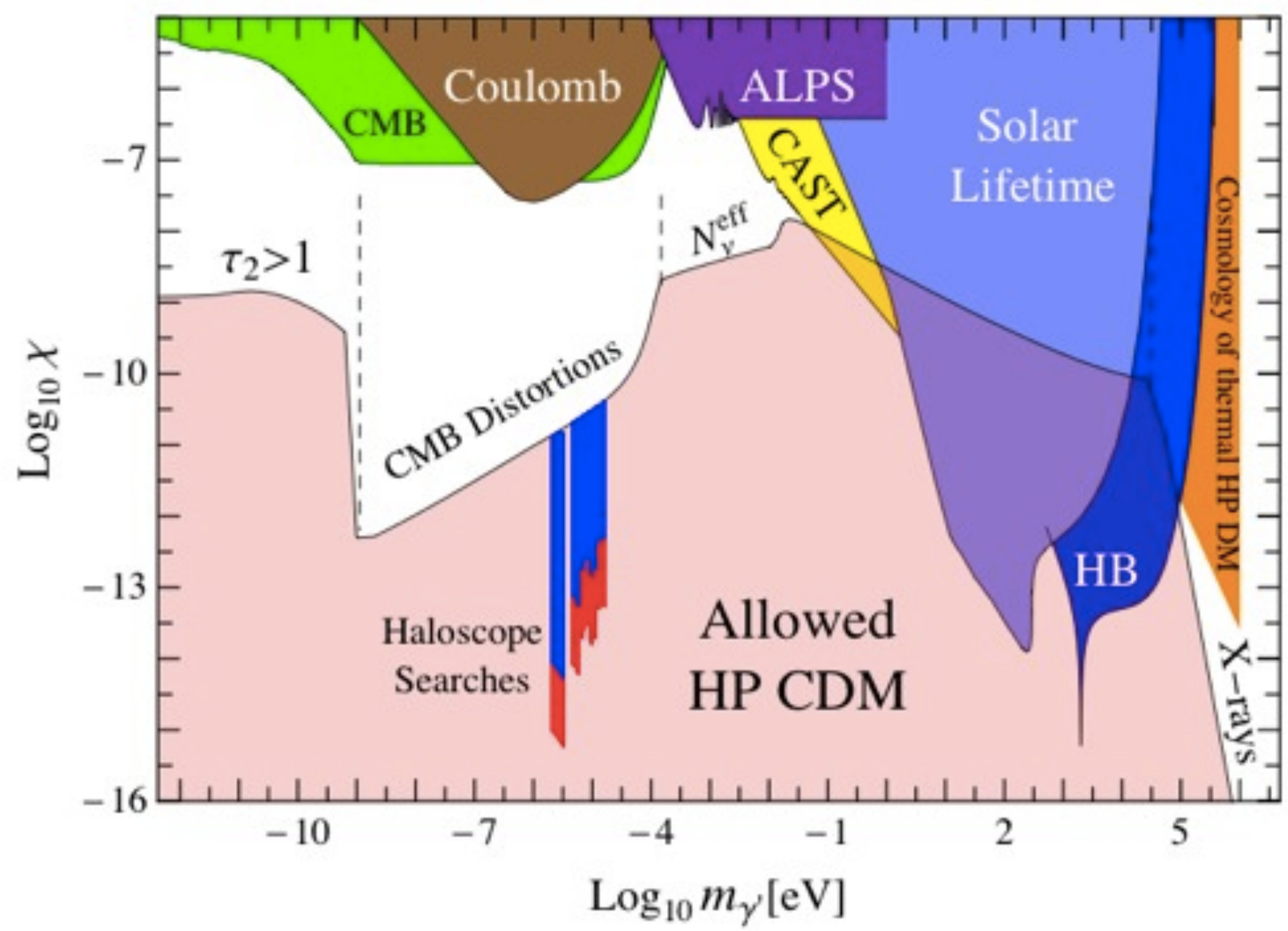
Natural size: radiative correction $\chi \sim \frac{e g_h}{16\pi^2} \log \frac{m}{\mu} \sim 10^{-3}$

But can be much smaller !!!!
if hyperweak hidden gauge coupling
or cancelations between contributions

natural value
not soooo small!



Again a huge parameter space to explore, even in the minimal case!

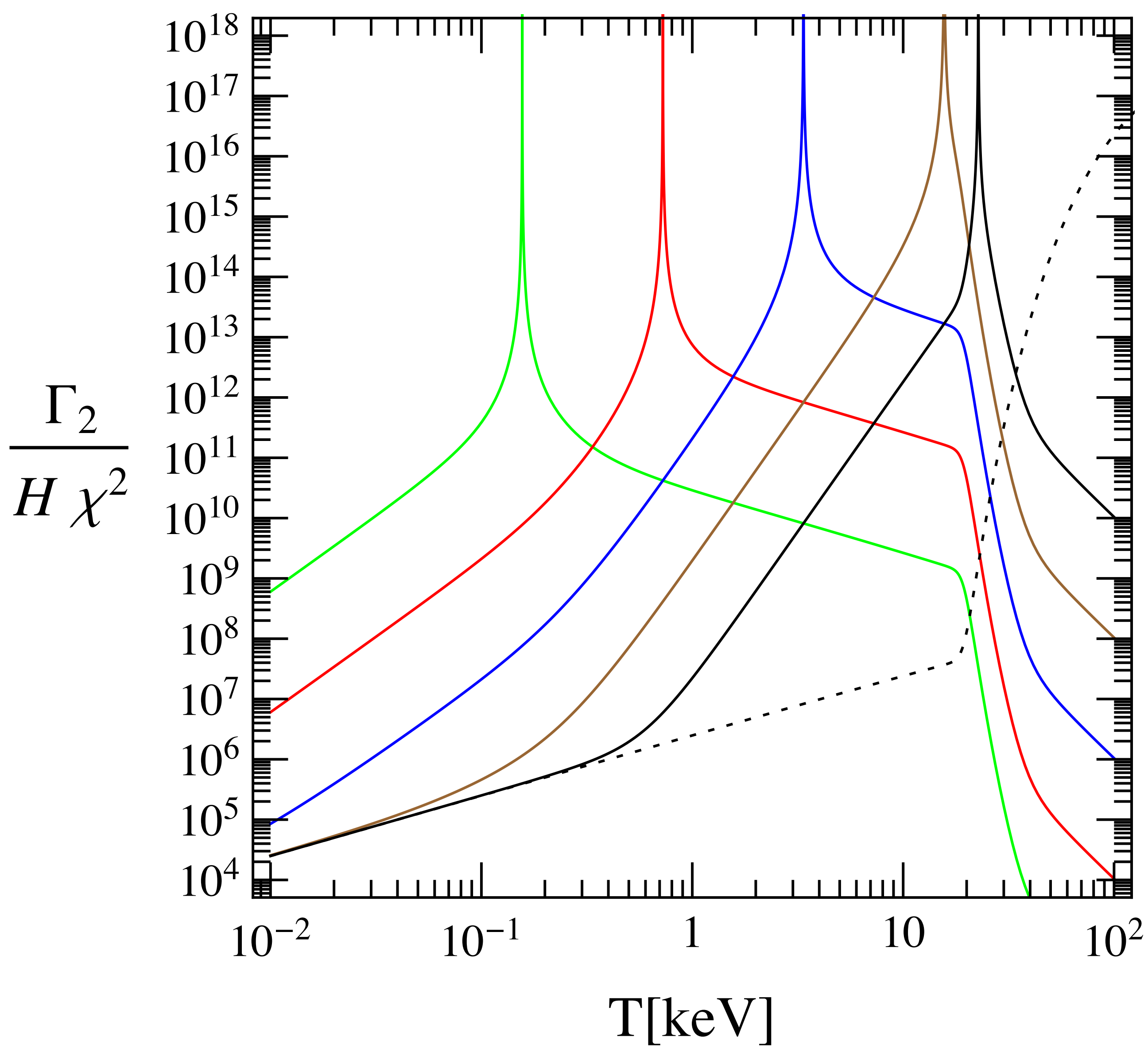


Crucial Differences

- The initial value of amplitude is not bounded!

- No phase transitions (no CSs, DWs ... well...)

- HPs mix directly with Photons (no need for B) (resonance transitions can evaporate HP CDM)

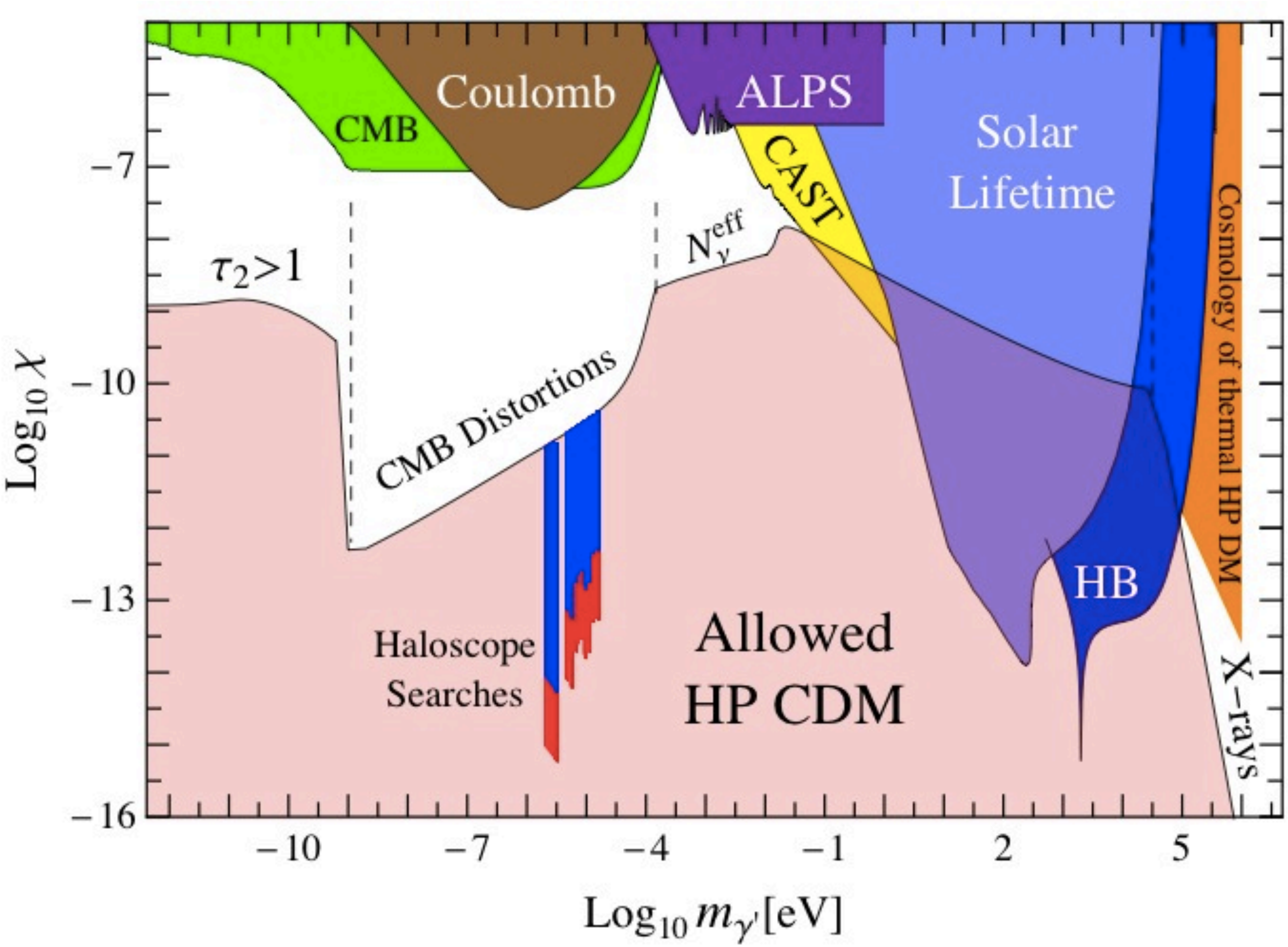


- Small E field in the universe

- ADMX-lie exps. do not need B field

WISPy Dark matter: Example II (Hidden Photon)

Nelson & Scholtz, Arias et al.



Conclusions

- Extensions of the SM might well accommodate WISPs

The Strong CP problem cries for an axion

- Cosmology cries for WISPs!

Dark Matter, (Dark Radiation, Dark Energy)

- Astrophysics shouts WISP loud!

White dwarfs, Universe transparency

- WISPs can be searched experimentally

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