WISPy Cold Dark Matter

May 7th 2012,
MPIK, Heidelberg

Javier Redondo, MPP München

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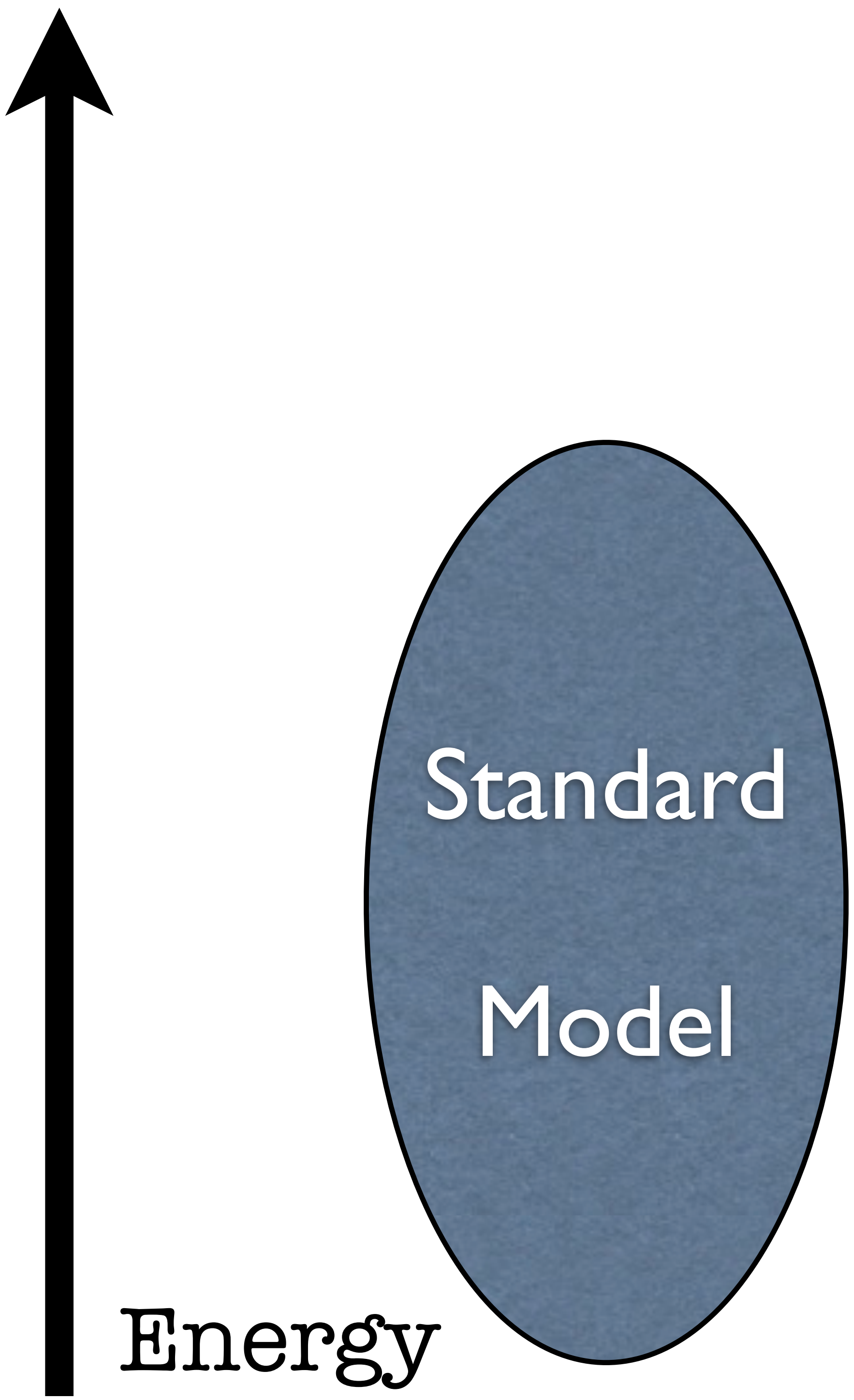
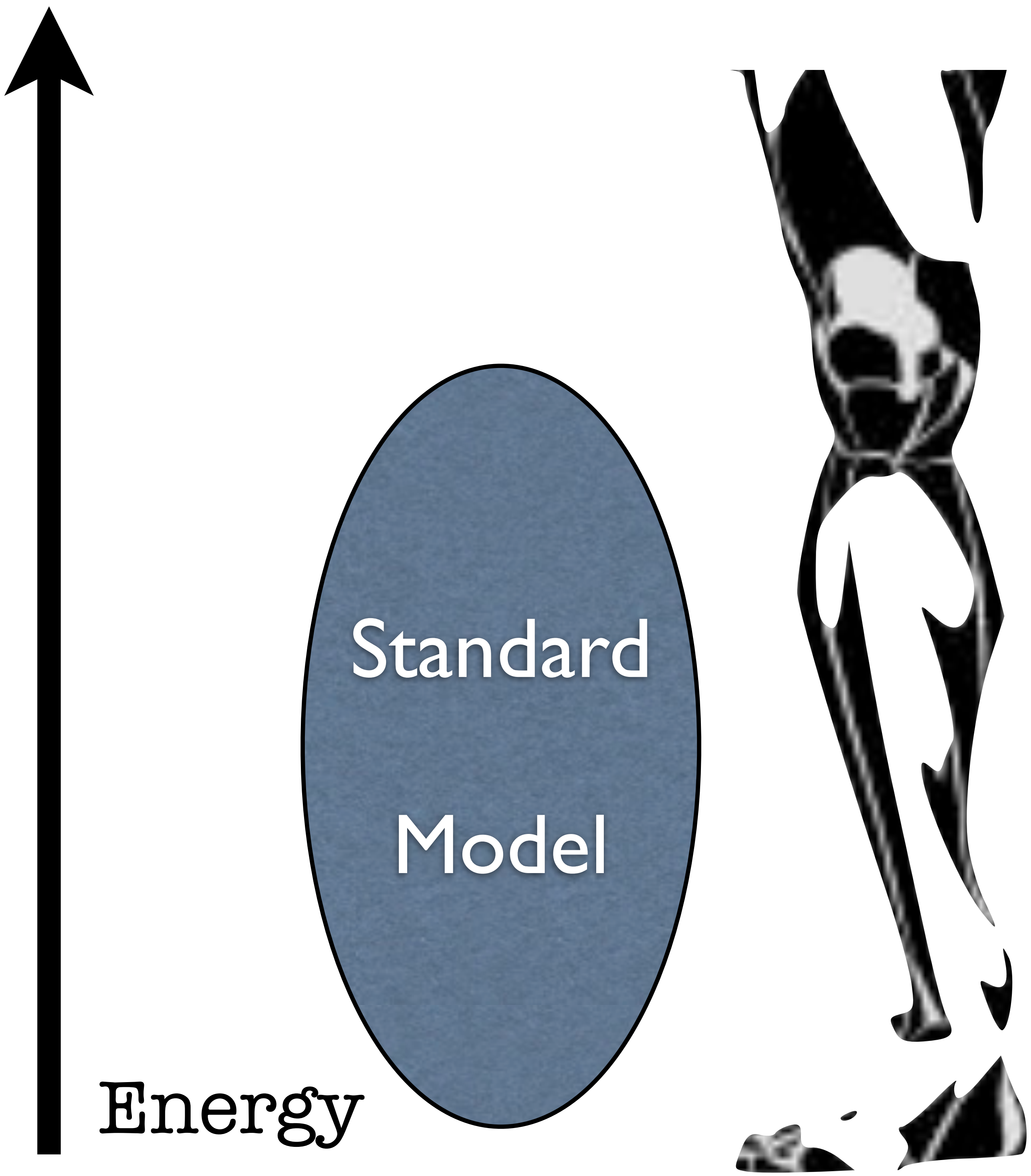


Describes
extremely well
fundamental physics
(at low energies)

Beyond the SM … at low energies

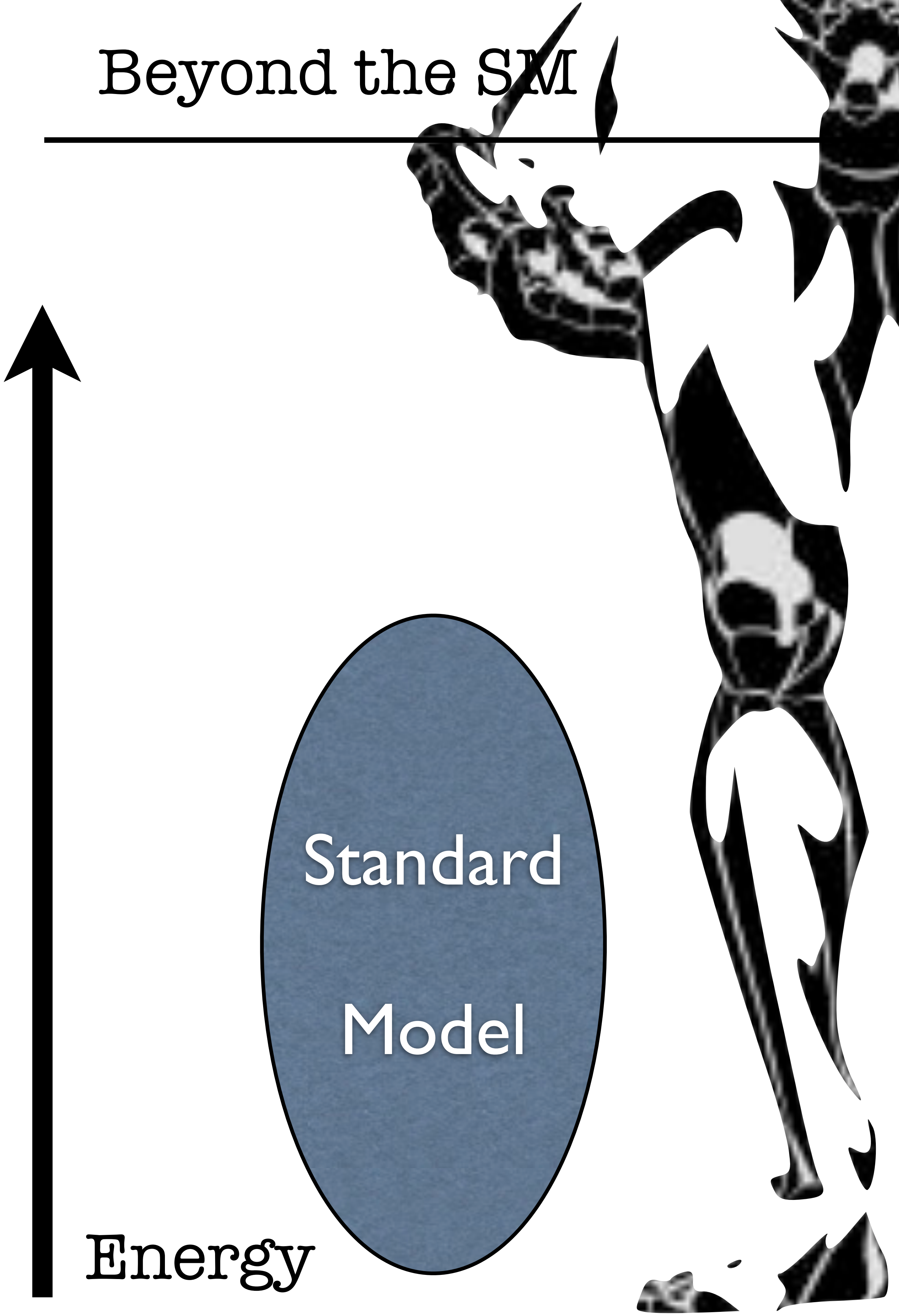


Describes extremely well fundamental physics (at low energies)

but feels certainly

INCOMPLETE

Beyond the SM ... at low energies

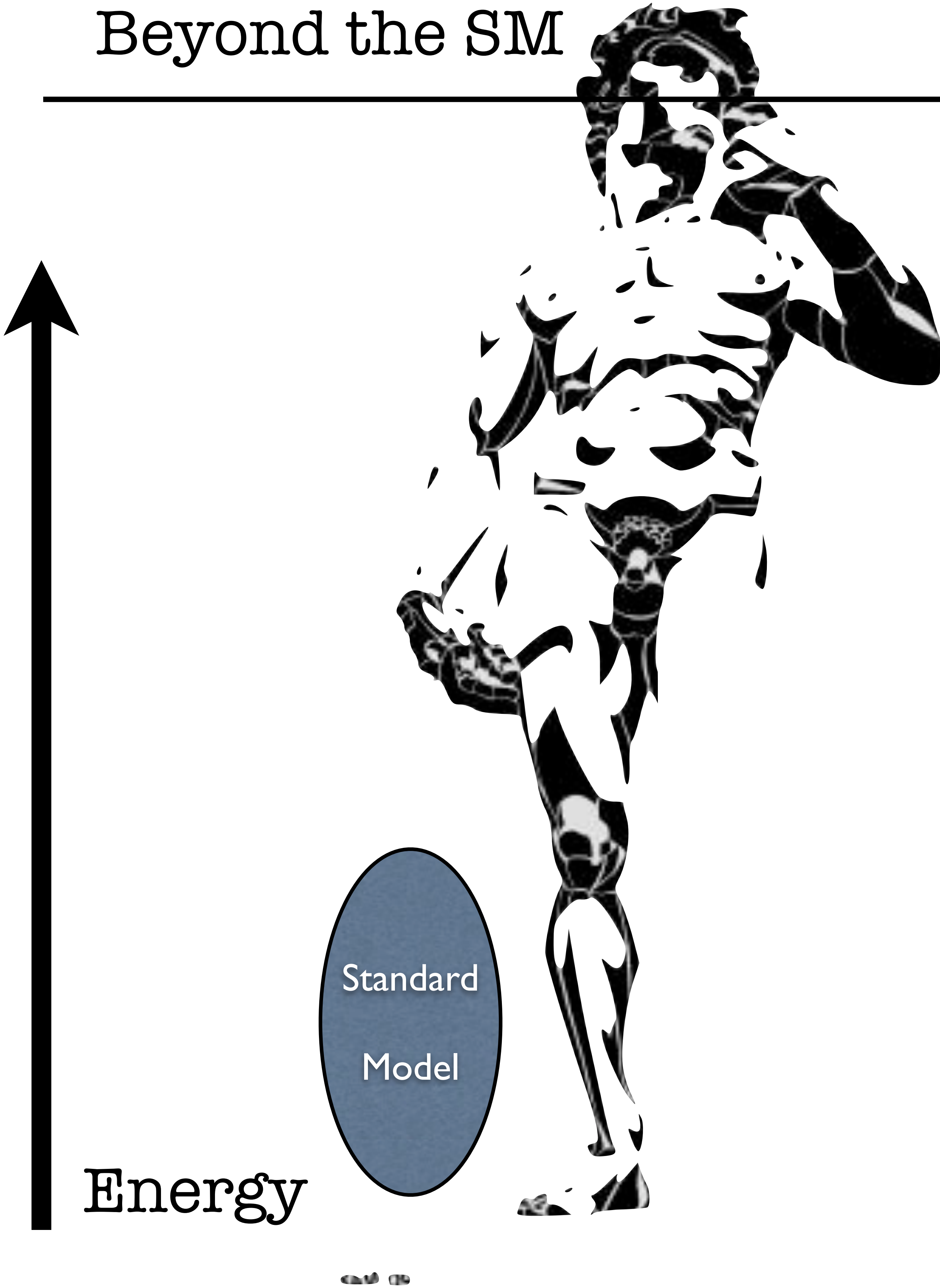


Answers are awaiting in the

high energy frontier

where more symmetric beautiful theories arise

Beyond the SM … at low energies



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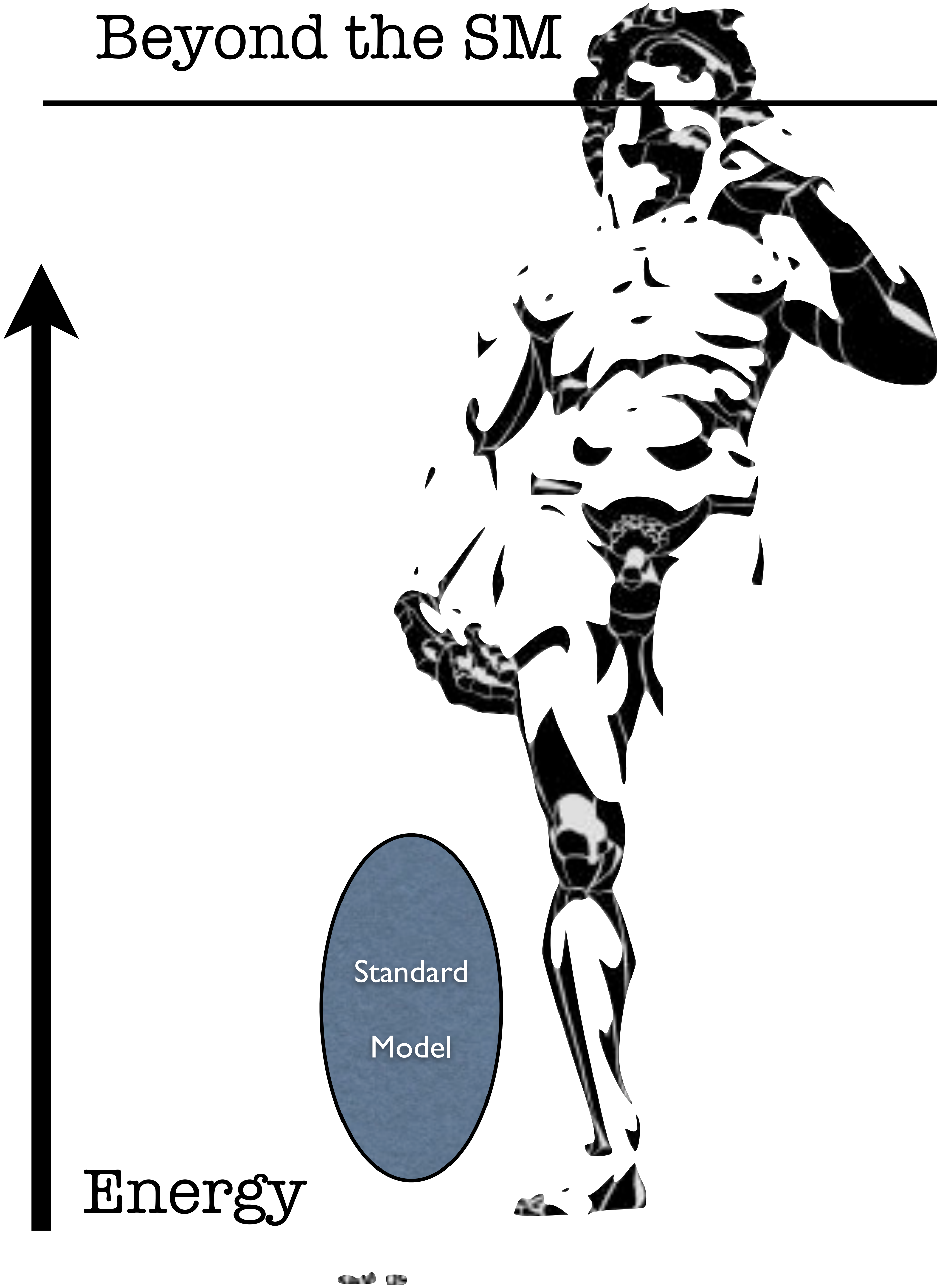

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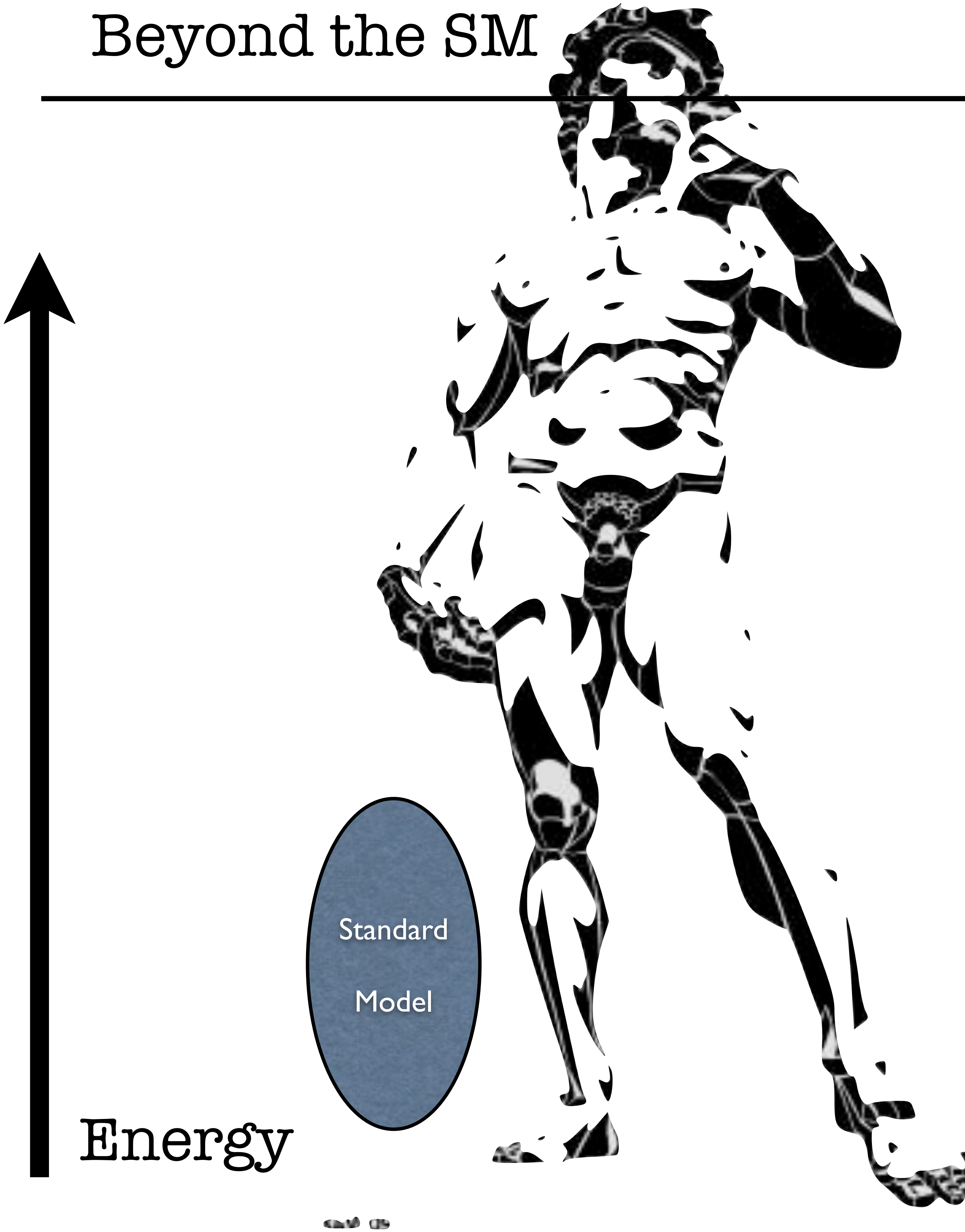


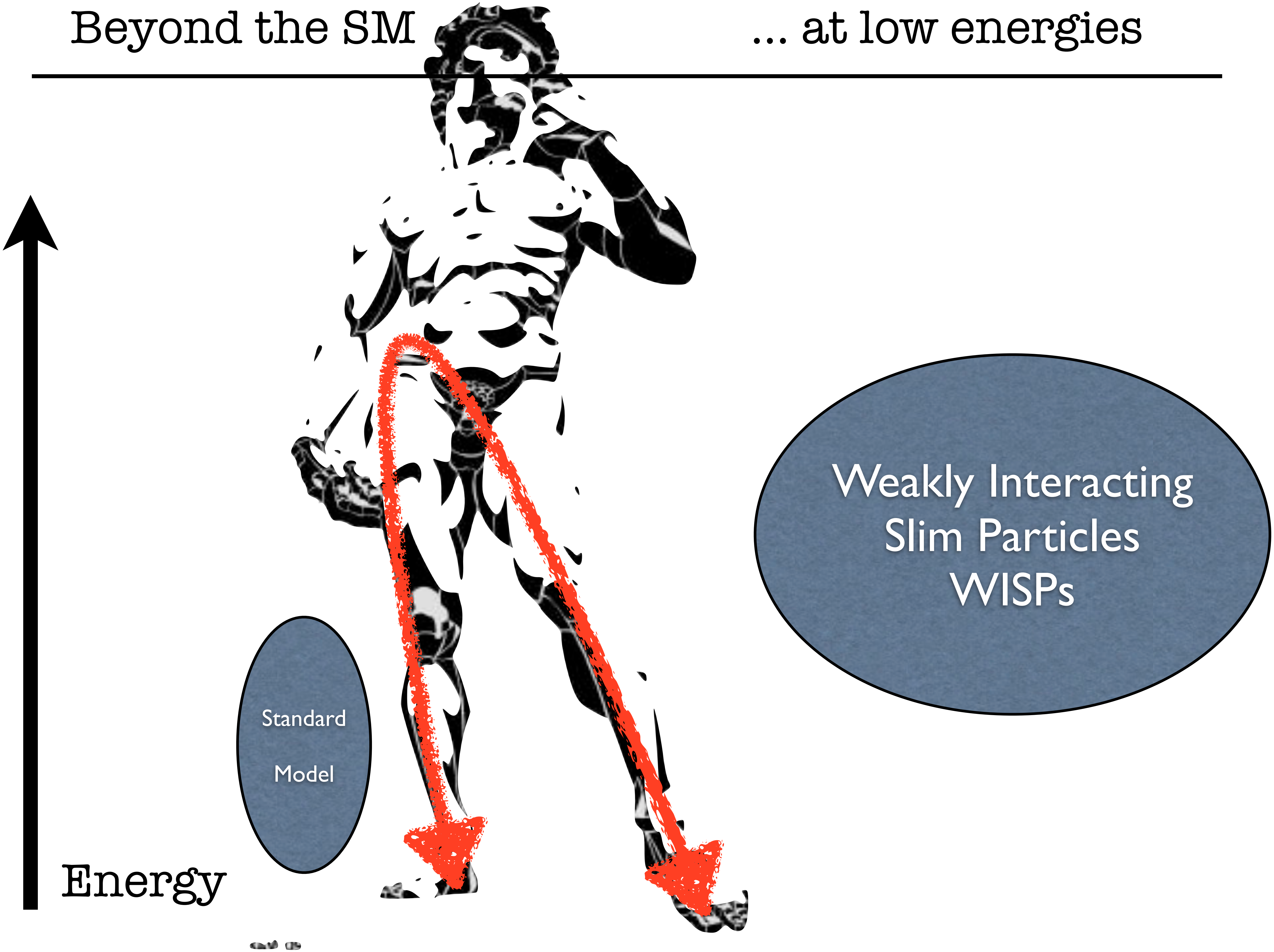
Answers are awaiting in the

high energy frontier

where more symmetric beautiful theories arise

... and often imply physics at low energies

Beyond the SM ... at low energies

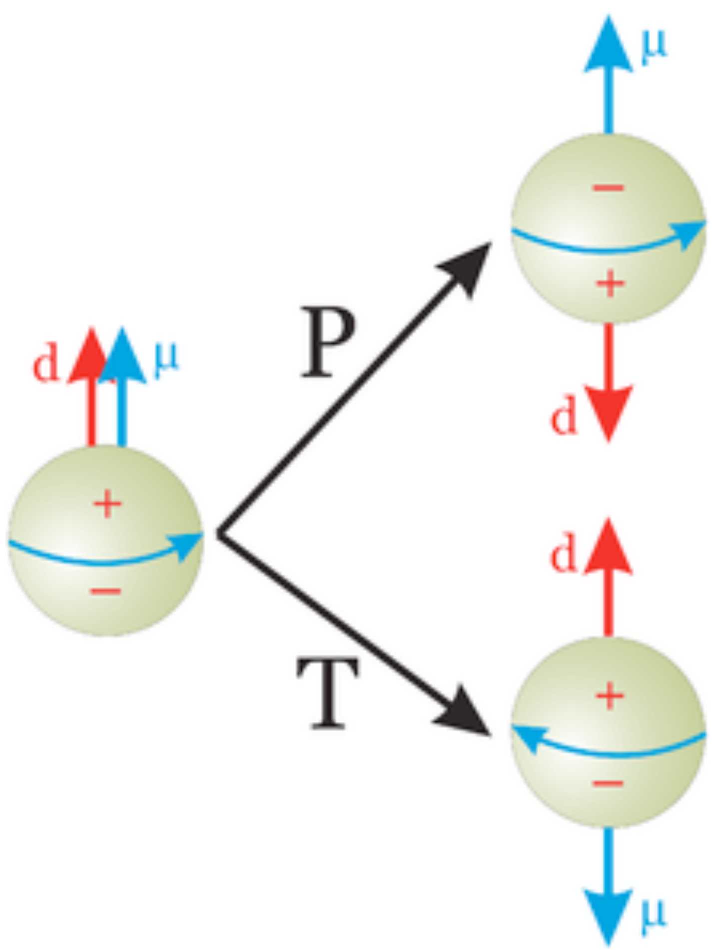


The paradigmatic example: Strong CP problem

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

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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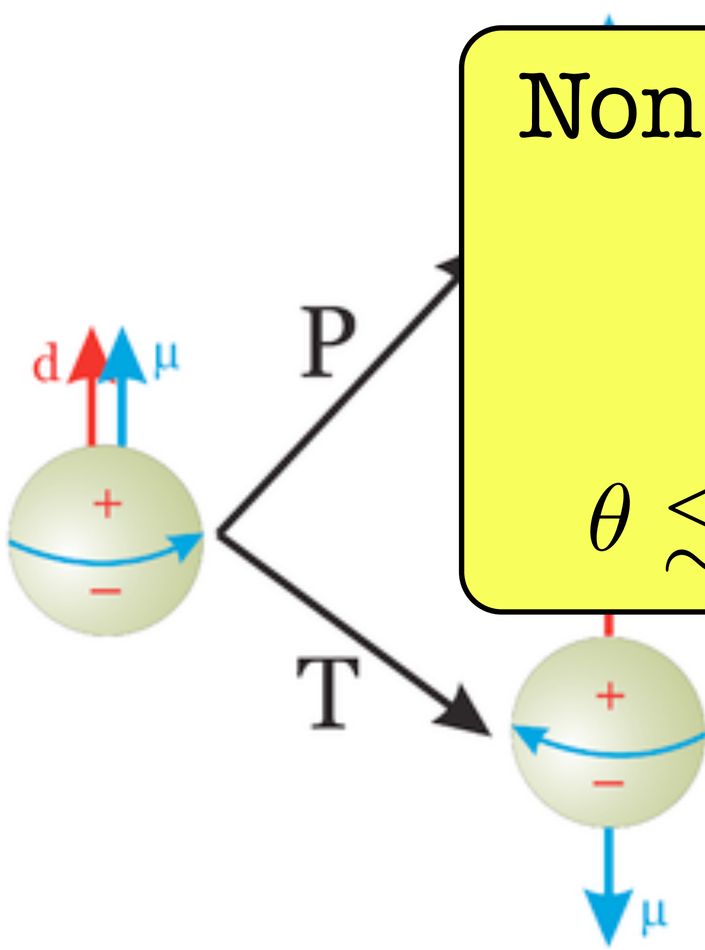

Non Observation:

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

$\theta \lesssim 10^{-11}$ 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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$\Rightarrow$ Massless Goldstone Boson: the axion

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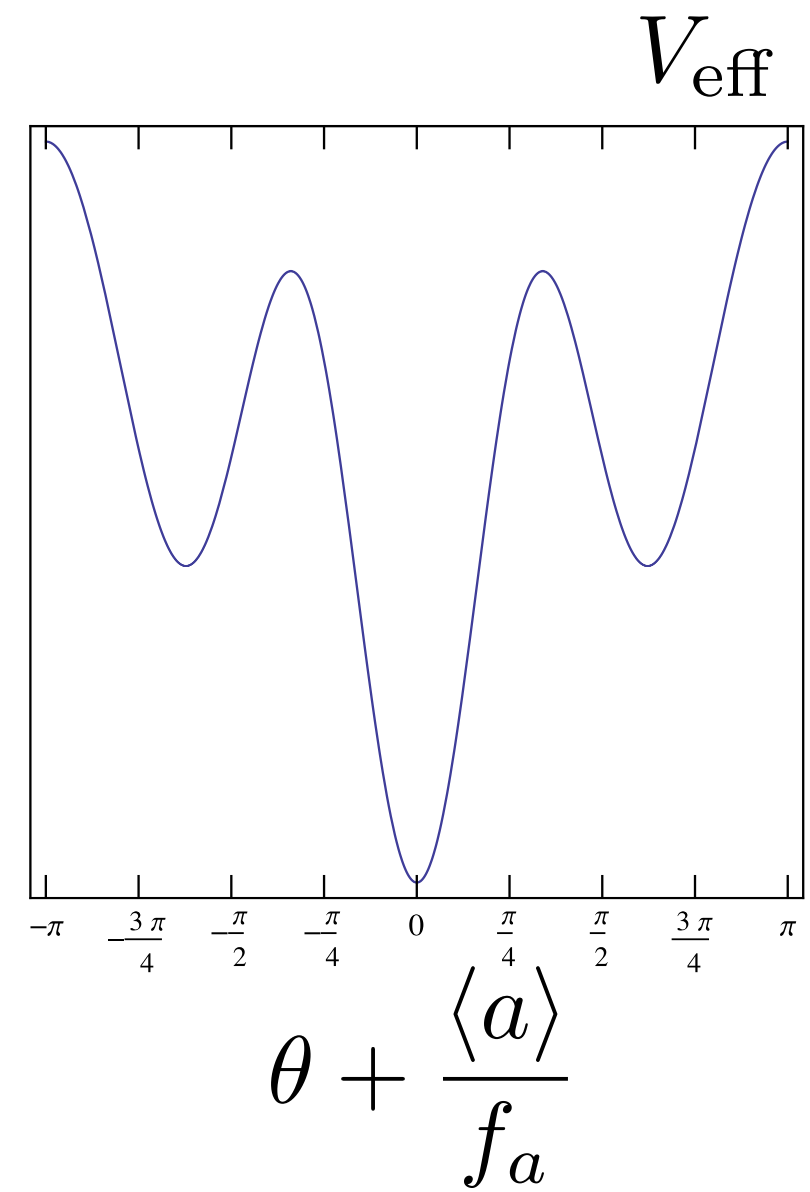
Massless Goldstone Boson: the axion

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

Free parameter

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

V_{eff}

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

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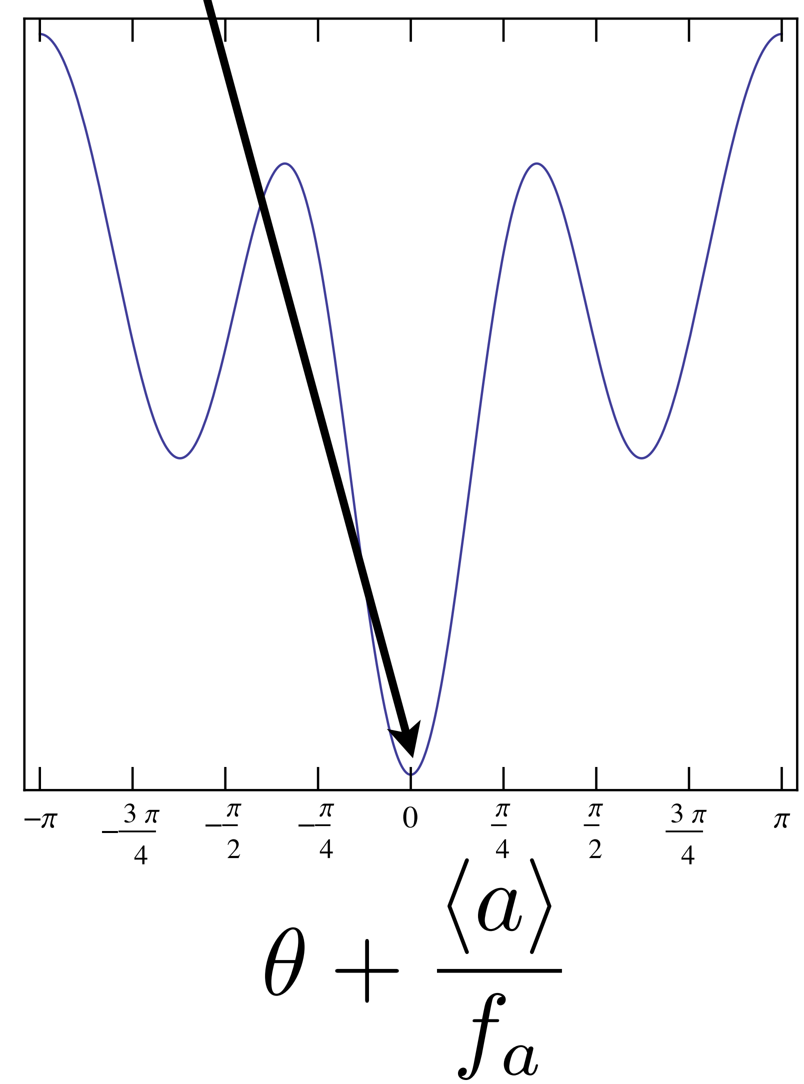


The QCD induced potential is minimized for ...

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

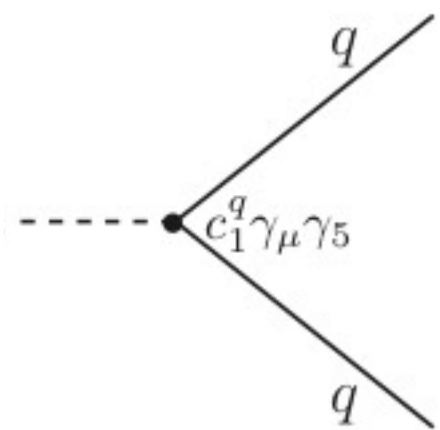
Axion mixes with QCD mesons and gets mass and couplings

Mass

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

Bare models

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



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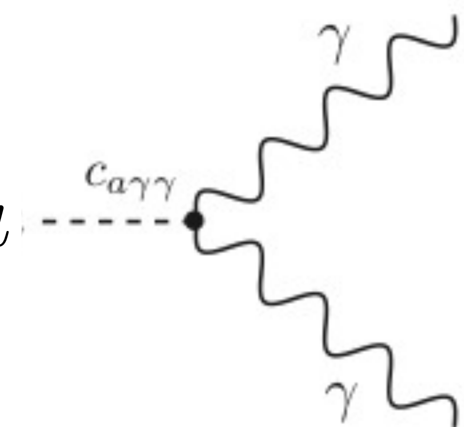

Extended models also feature couplings to leptons

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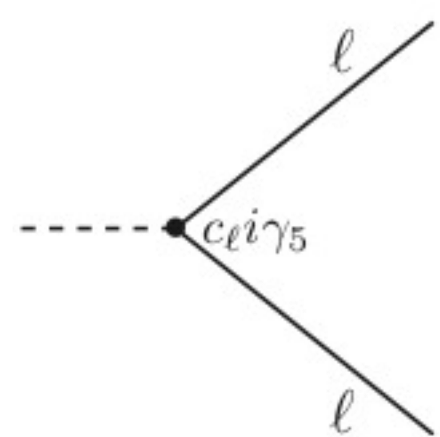

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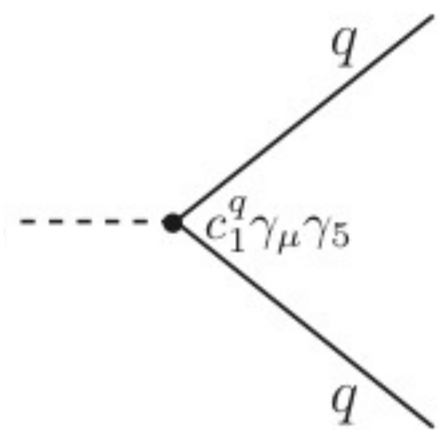
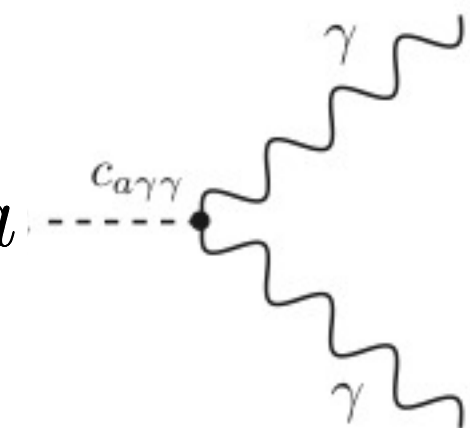
$\frac{1}{f_a}\, a$ 

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

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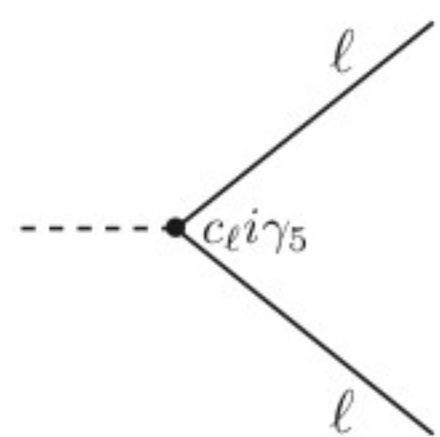
$\frac{1}{f_a}\, a$ 

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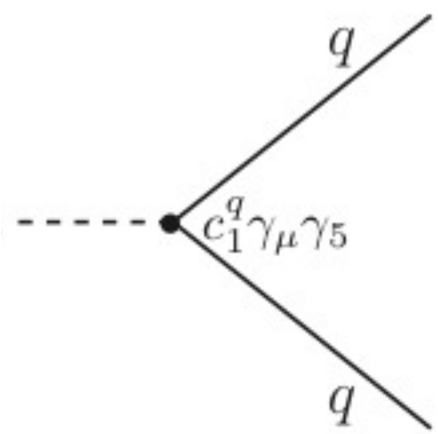

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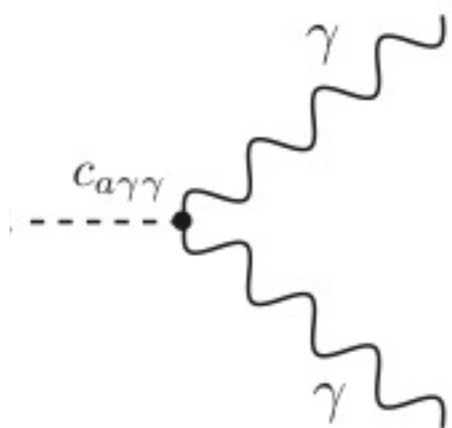

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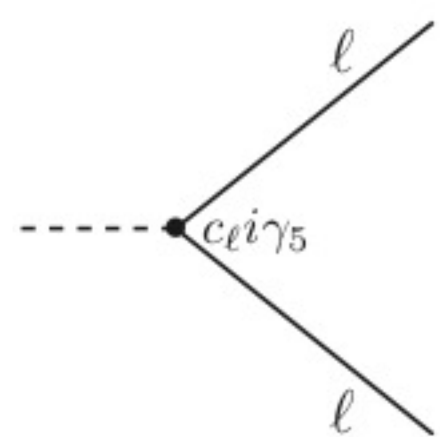

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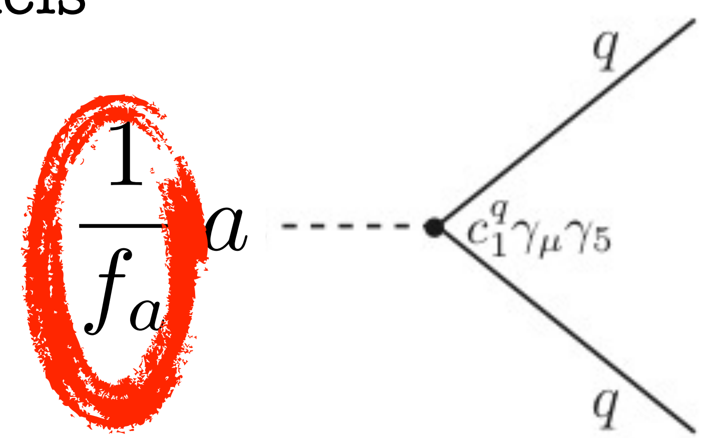

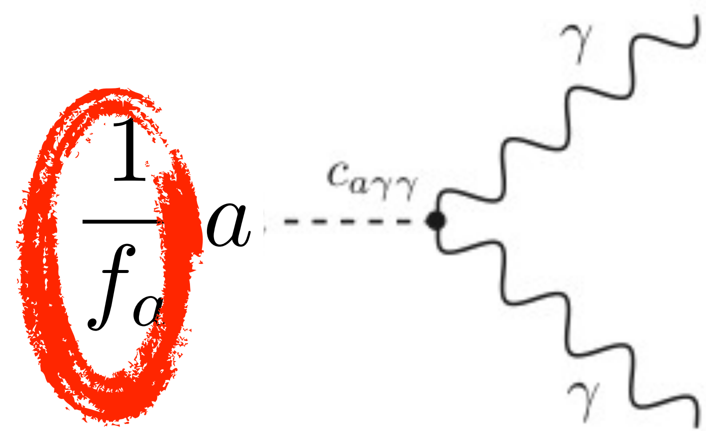

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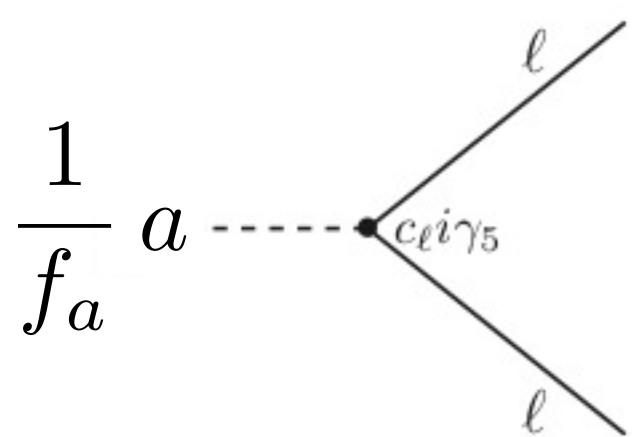

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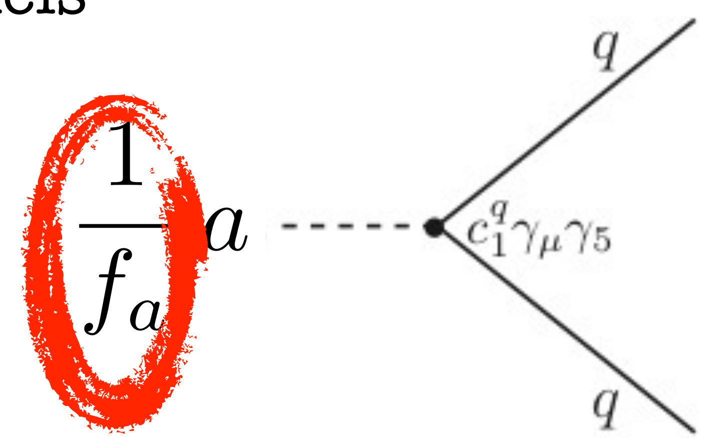

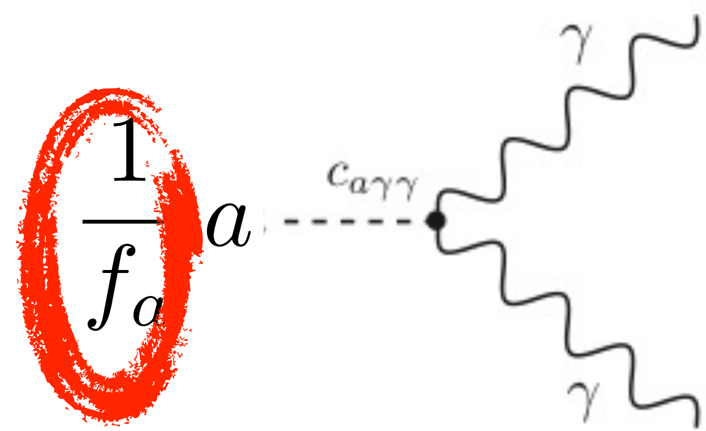

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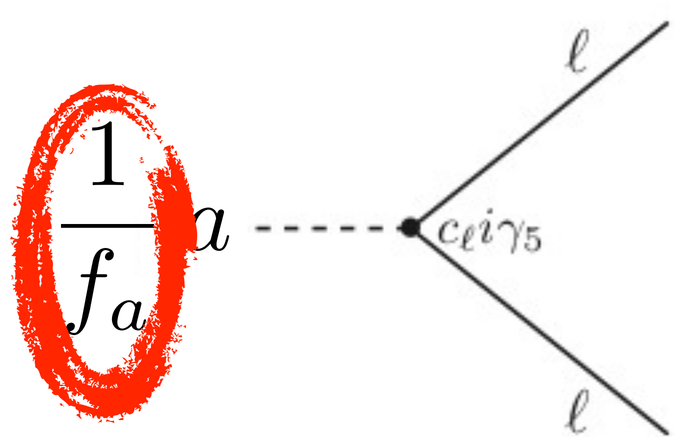

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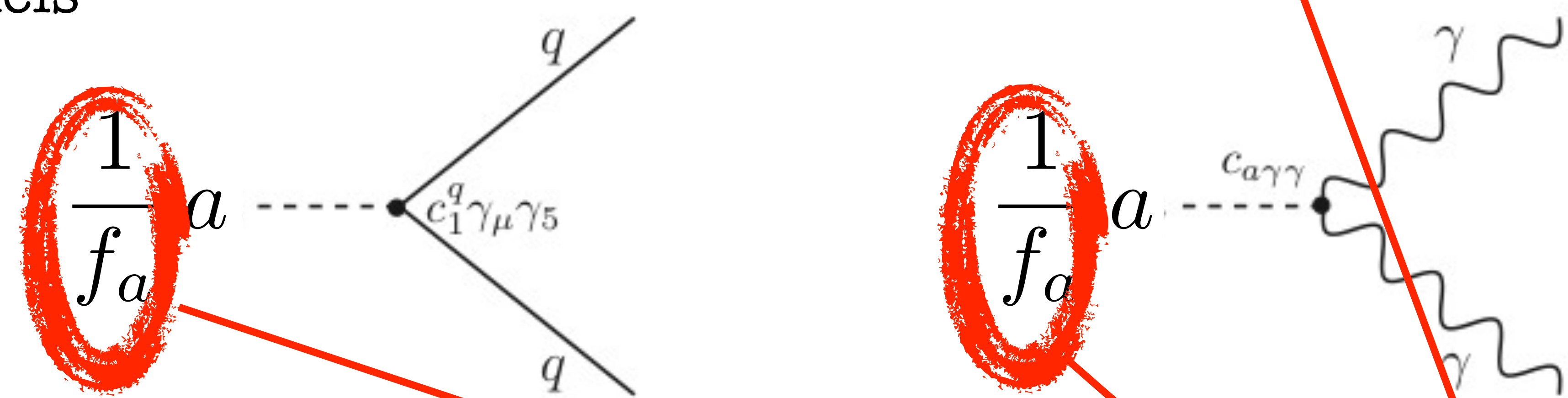

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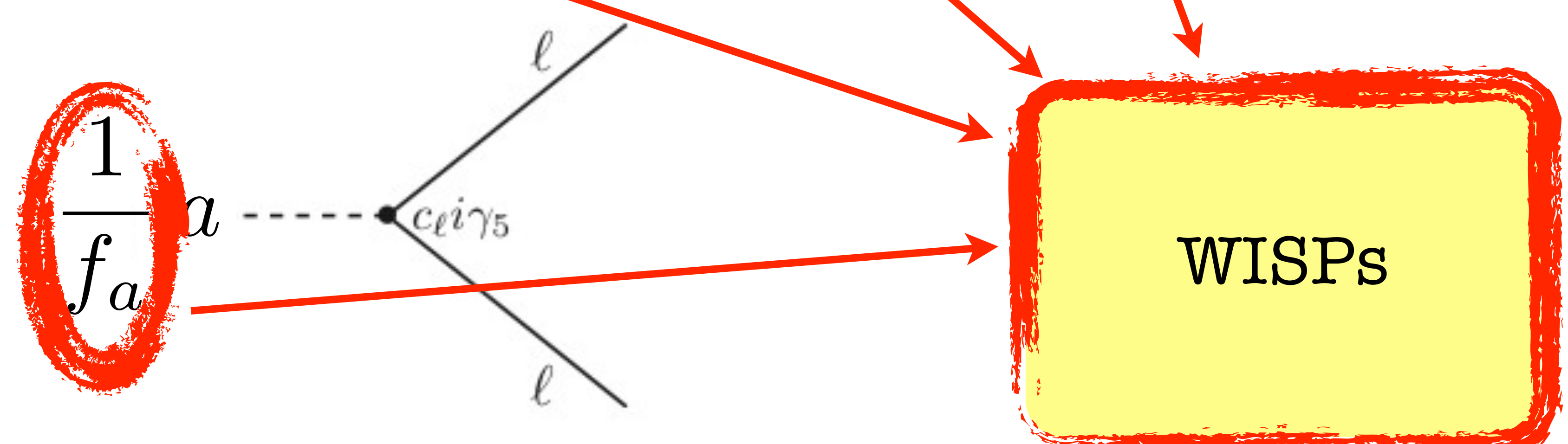

Axion mixes with QCD mesons and gets mass and couplings

Typical from Nambu-Goldstone Bosons

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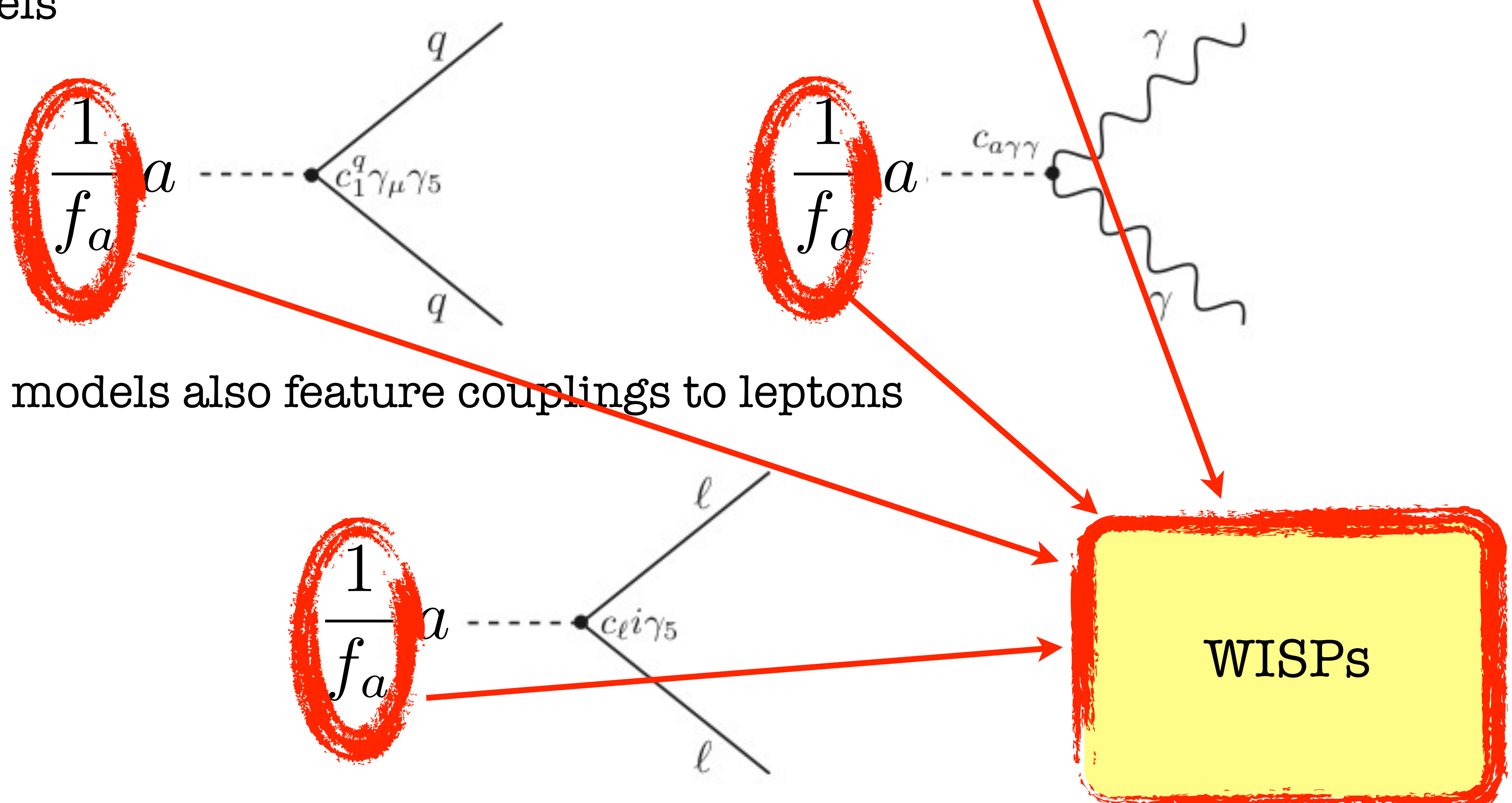
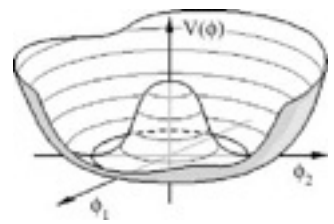


Axion-like particles (ALPs) 0^-

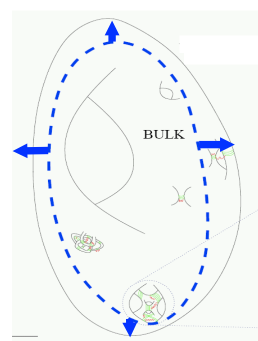
pseudo Goldstone bosons

Global continuous symmetry spontaneously broken at high energy scale M



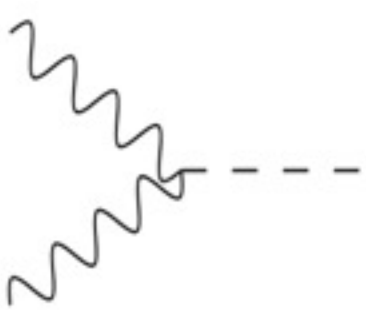
String 'axions'

Sizes and deformations of extra dimensions, gauge couplings



Reference model (this talk)

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



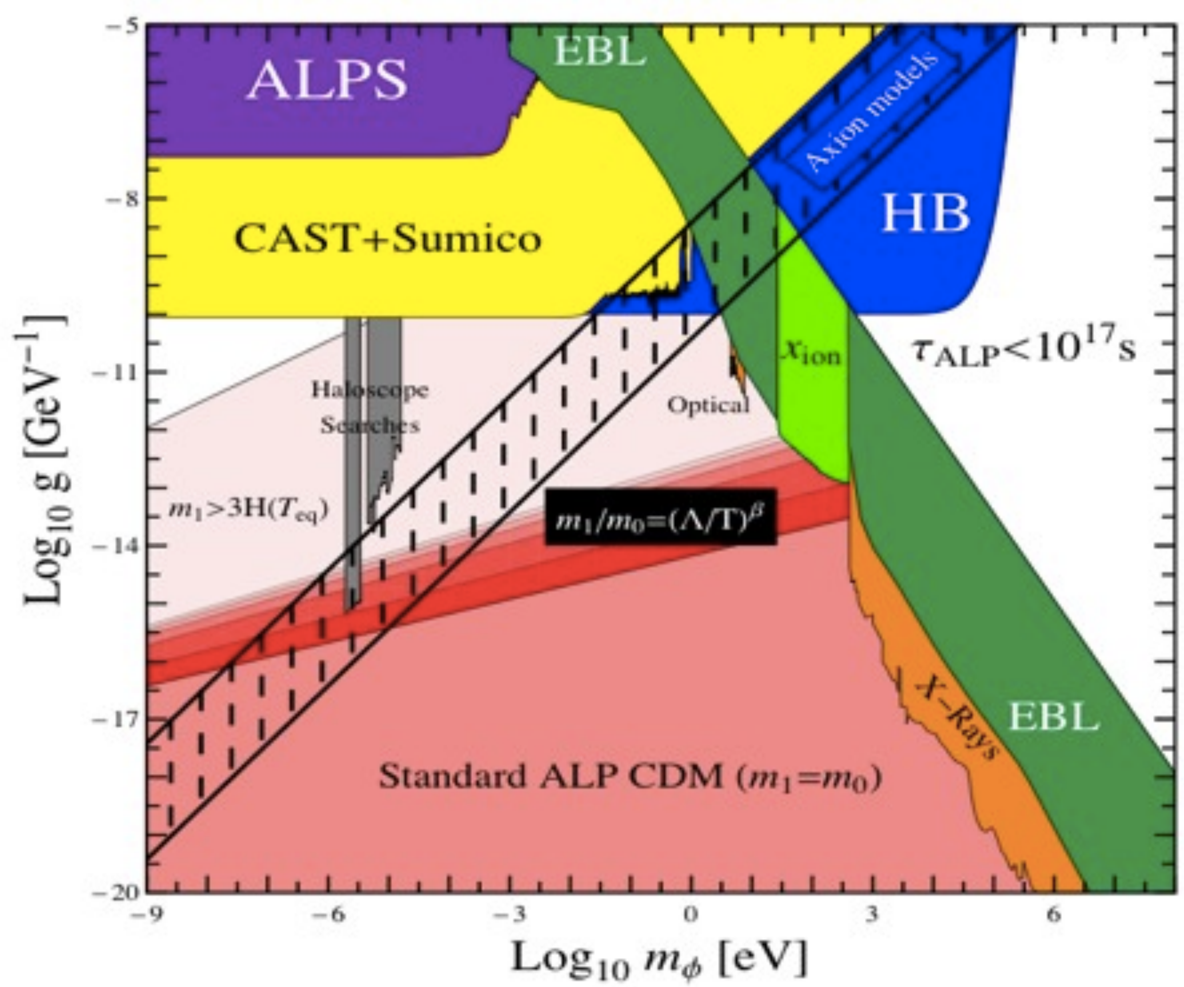
$g \sim \alpha/2\pi M$

independent

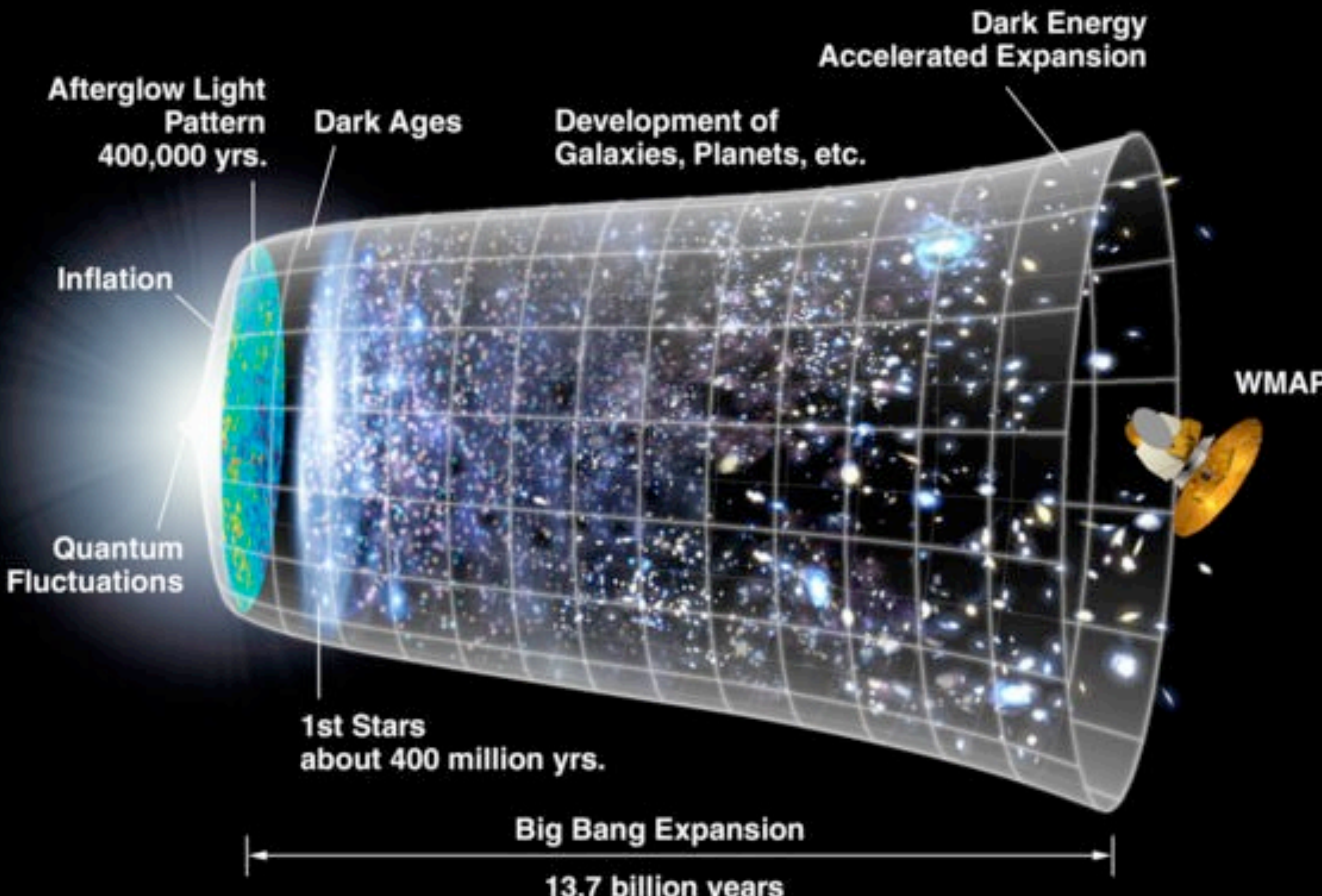
mass m_ϕ

π^0 η' η a MAJORONS R-AXION FAMILONS

DILATONS RADION MODULI



Cosmology

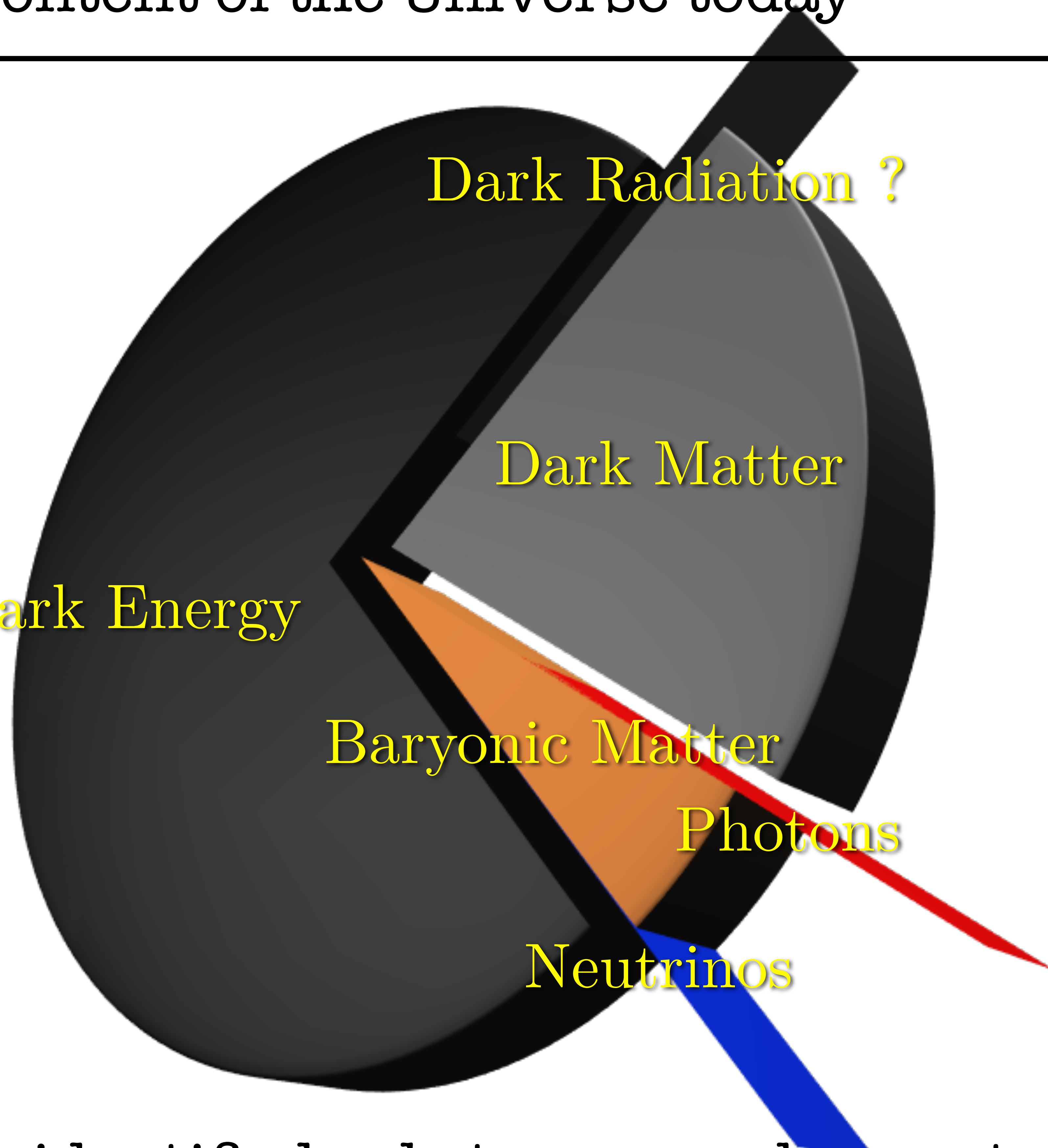


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Energy content of the Universe today

Three unidentified substances make most of it!

Energy content of the Universe today



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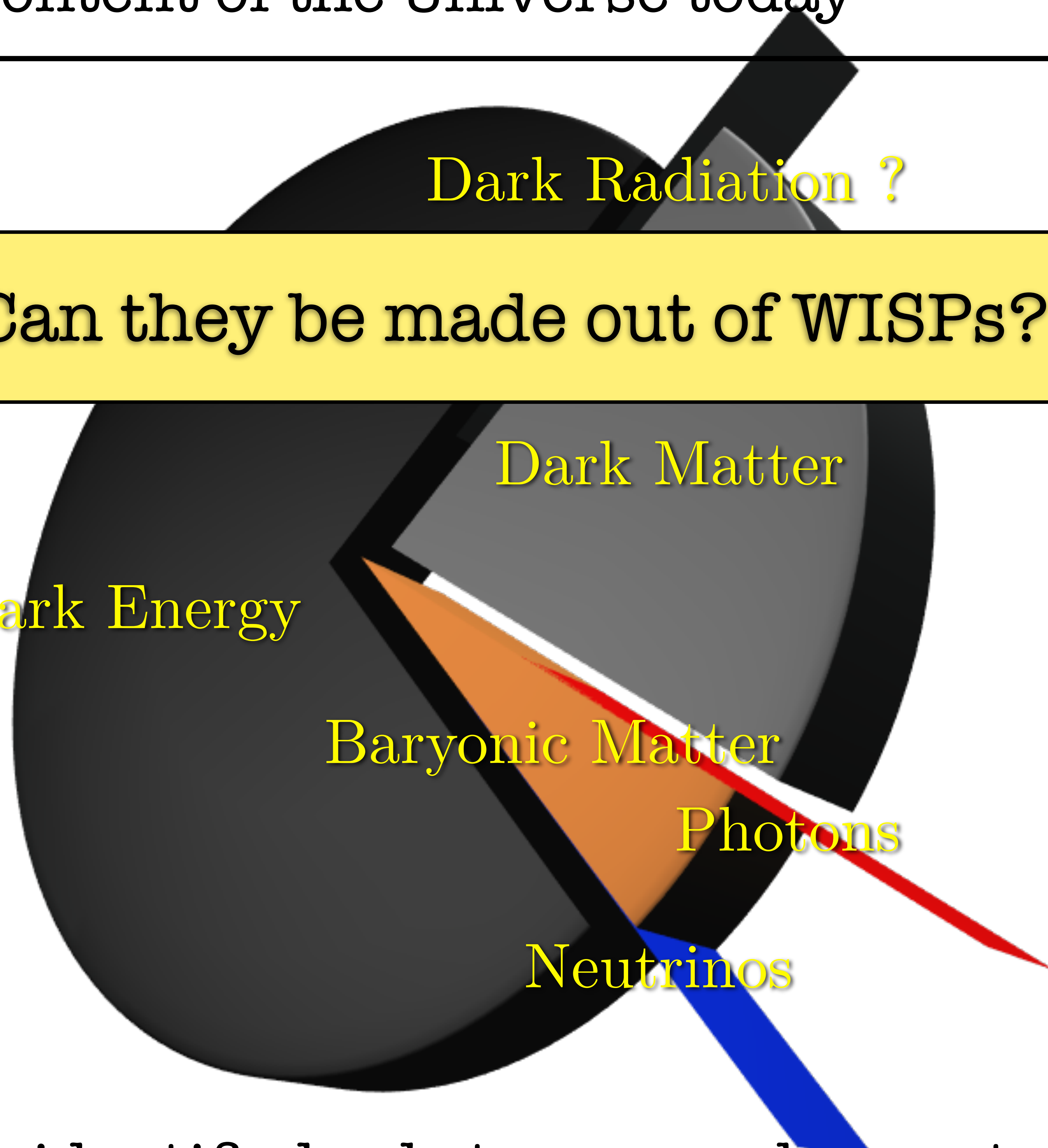

Can they be made out of WISPs?

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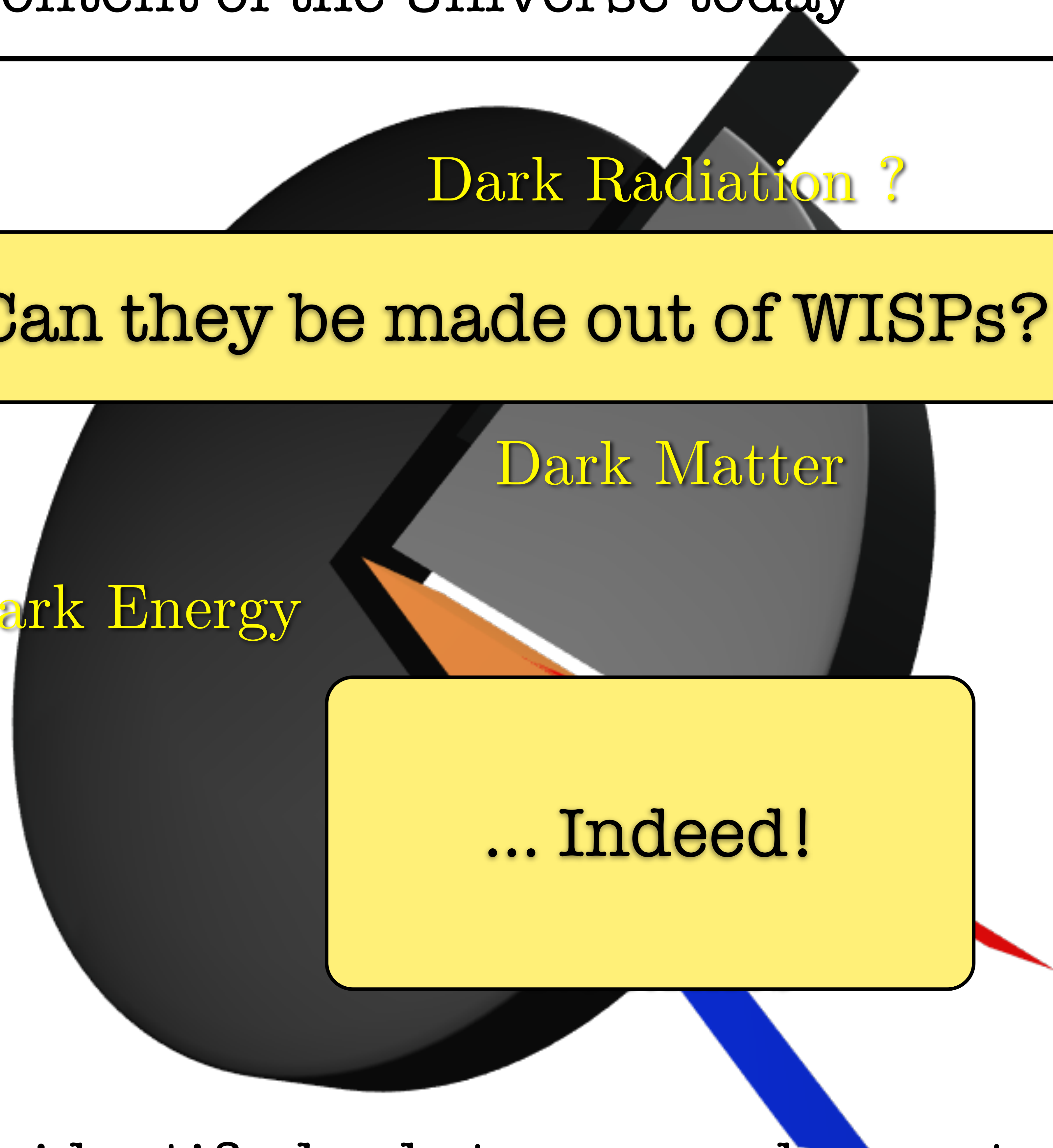

Can they be made out of WISPs?

... Indeed!

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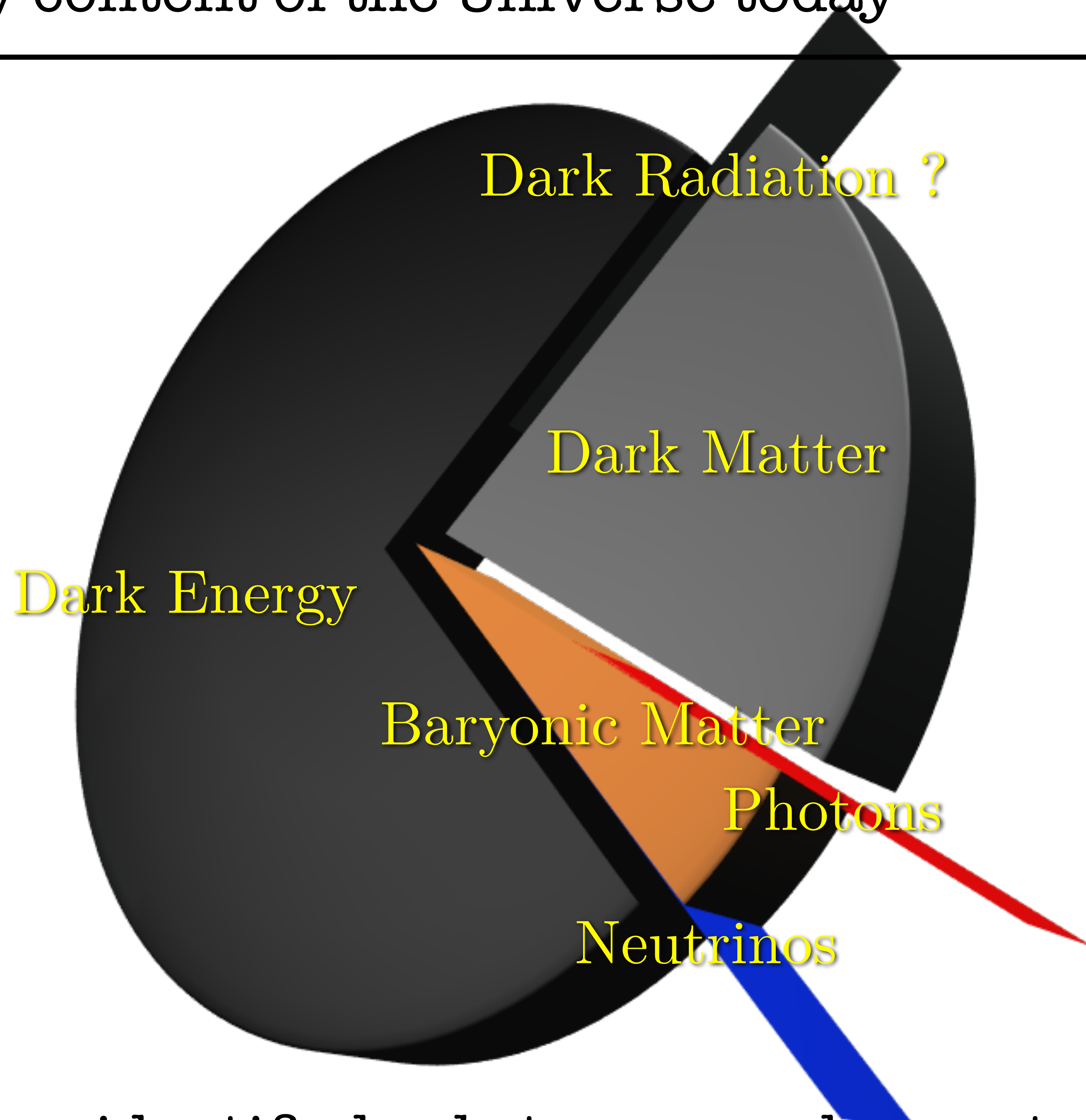

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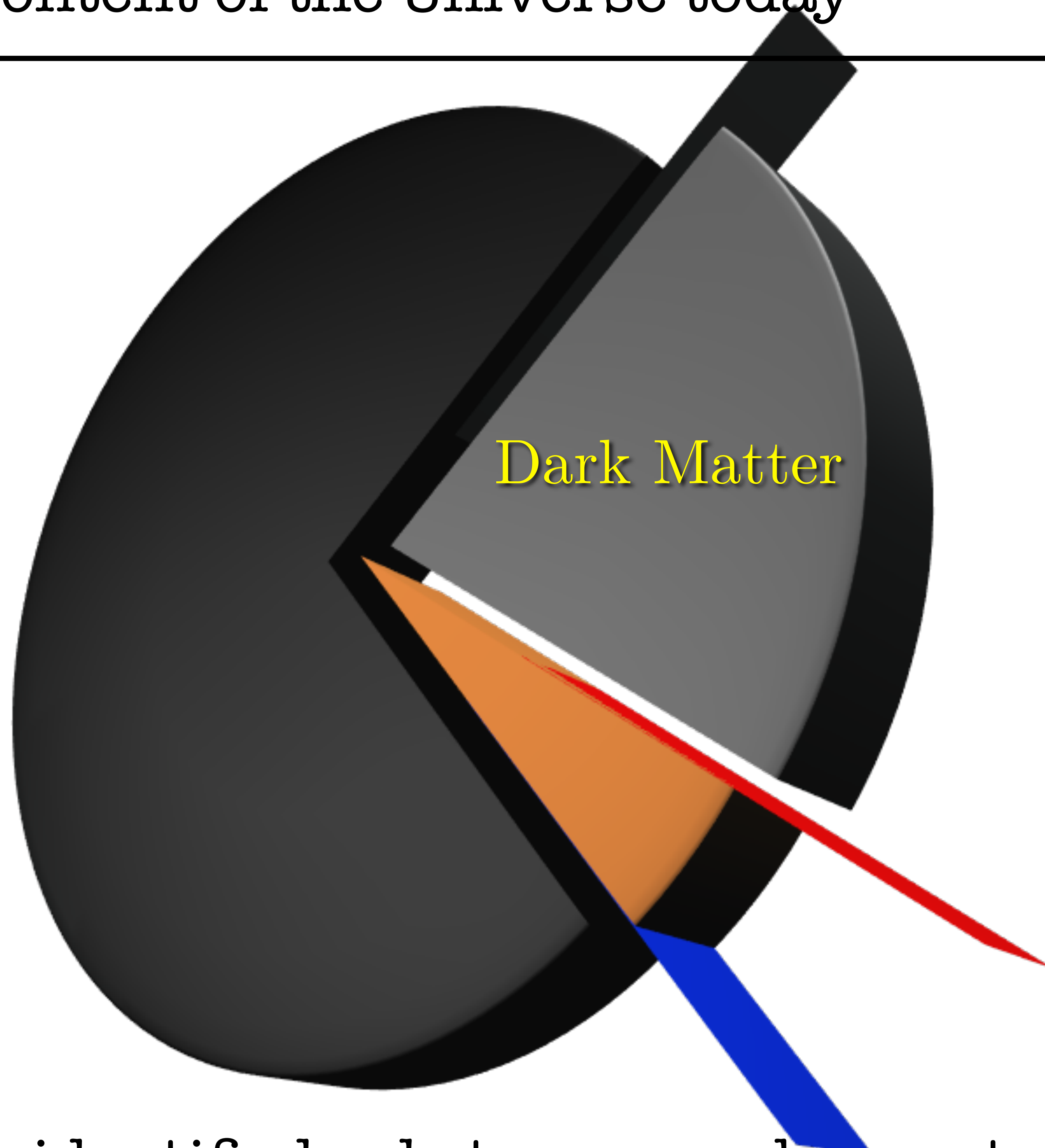

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Energy content of the Universe today

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
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(most of them)

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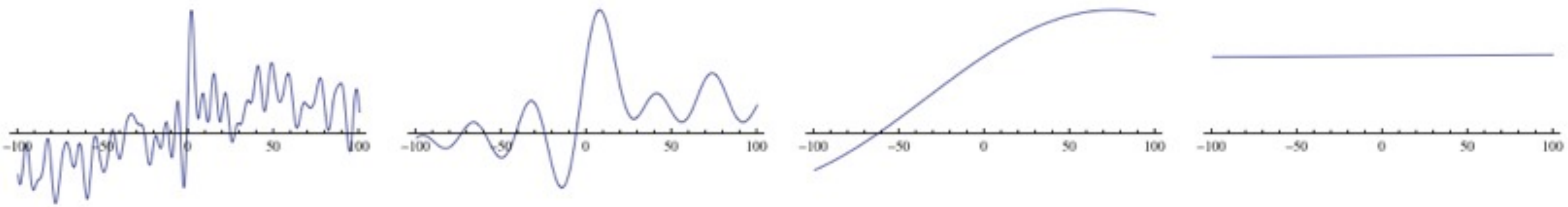
mmm...

WISPy Dark matter is generically COLD!

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

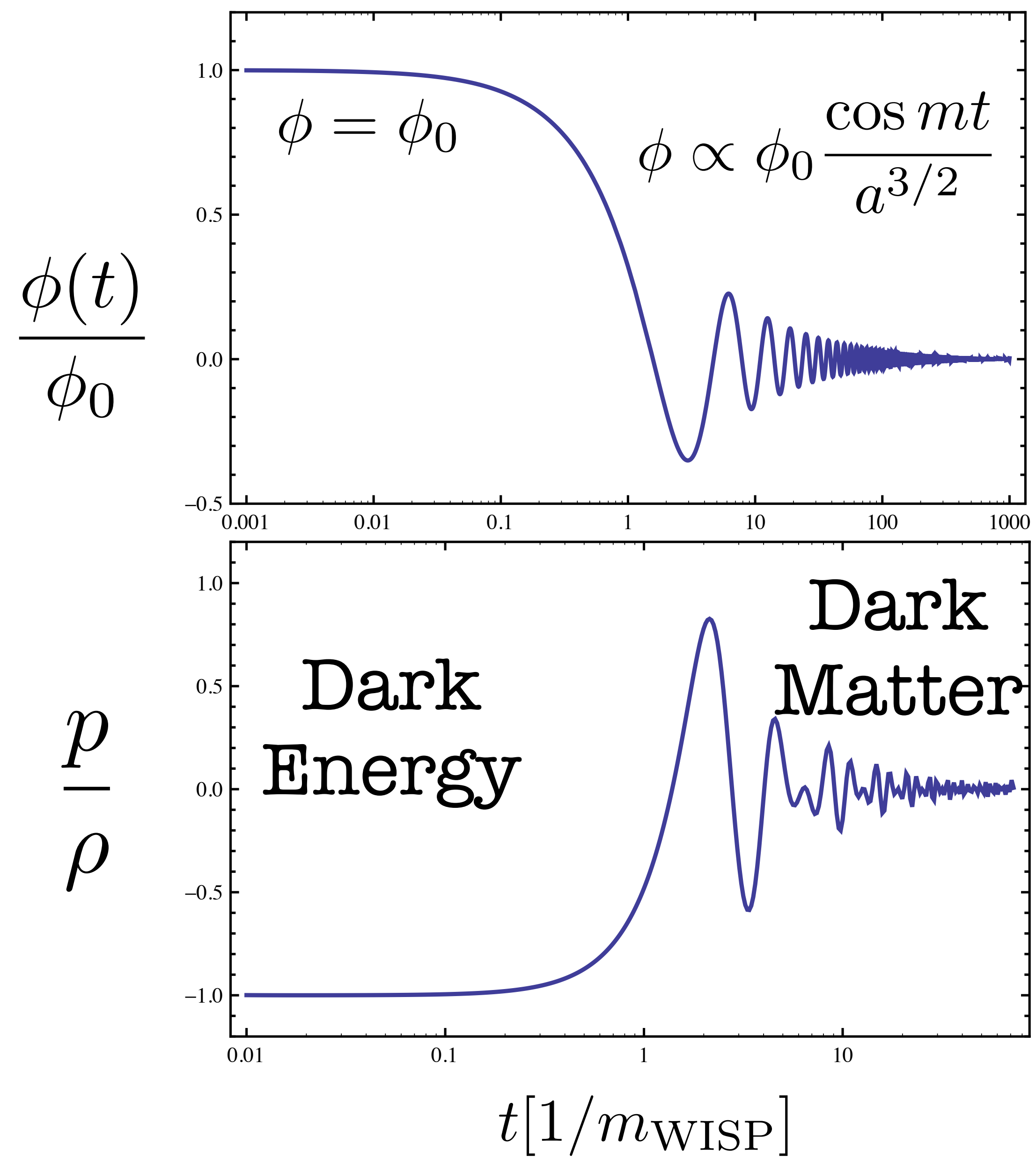


Afterwards:

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

Evolution of homogeneous WISP field
in expanding universe

Equation of state



Right amount of WISPy Dark matter

In the simplest ALP/HP models:

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

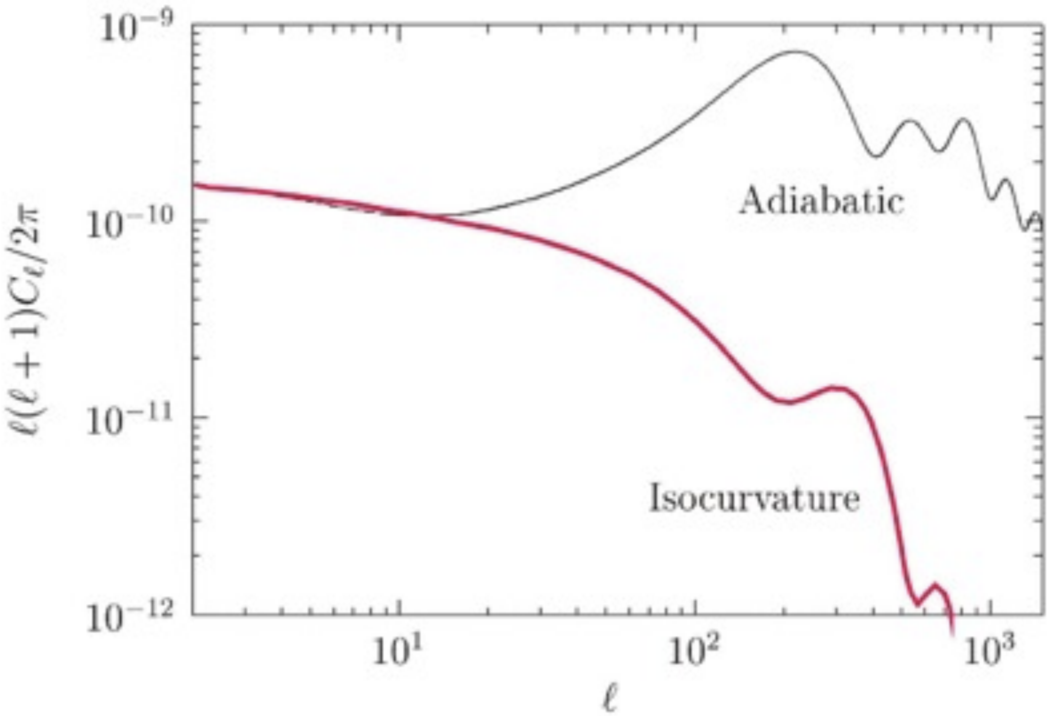
recall $\rho_{\mathrm{CDM}} = 1.17(6)\,\frac{\mathrm{keV}}{\mathrm{cm}^3}$

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

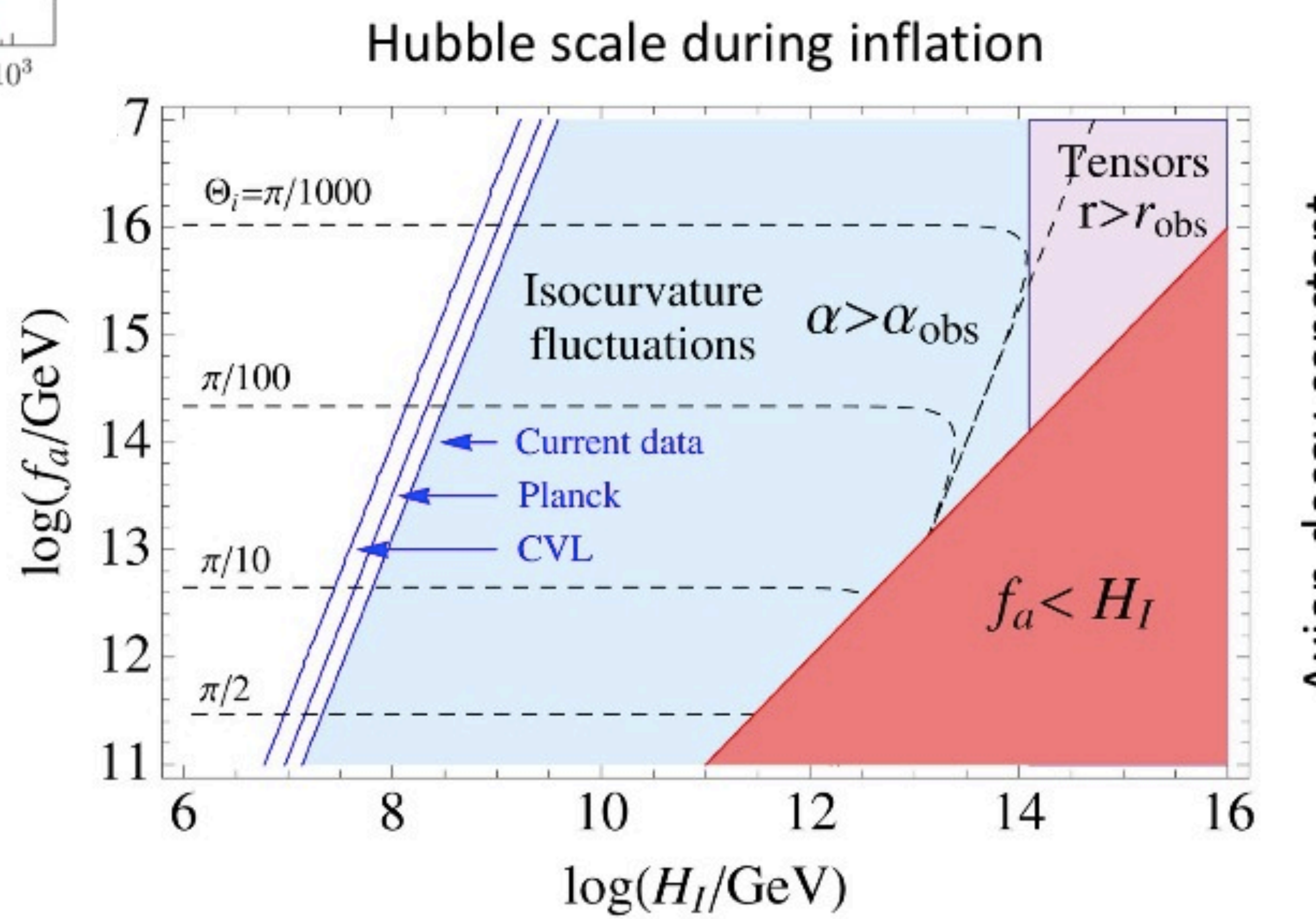
(Detecting WISPy DM opens a window to HEP!!!)
in a sense...

But this model is not very testable... unless
- Isocurvature perturbations
- ALPs form a BECs through gravity int. (Sikivie's 2009)

And they imprint ISOCURVATURE perturbations



but this depends on H during inflation...



One more level of complication

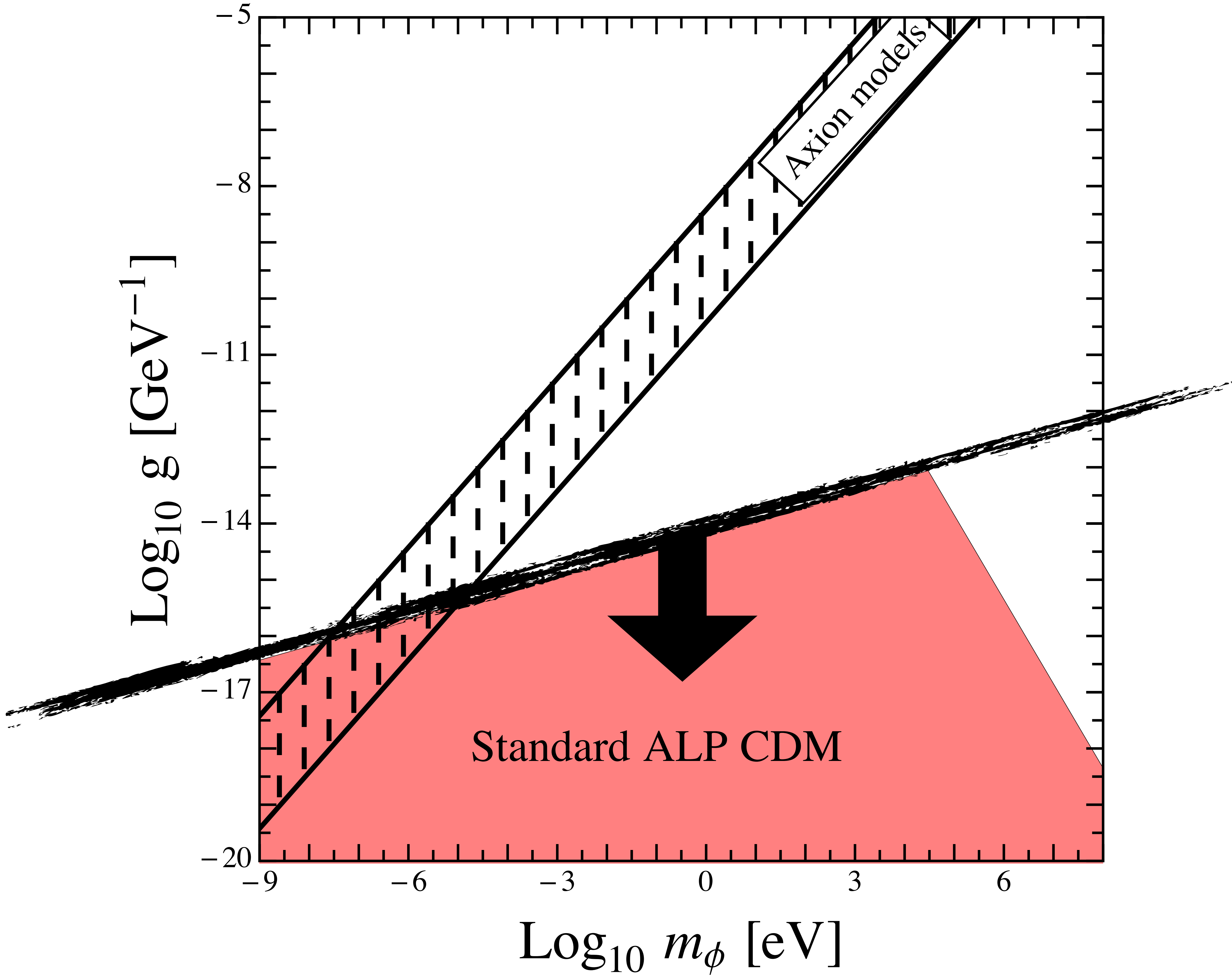
Consider an ALP with a two photon coupling

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

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

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

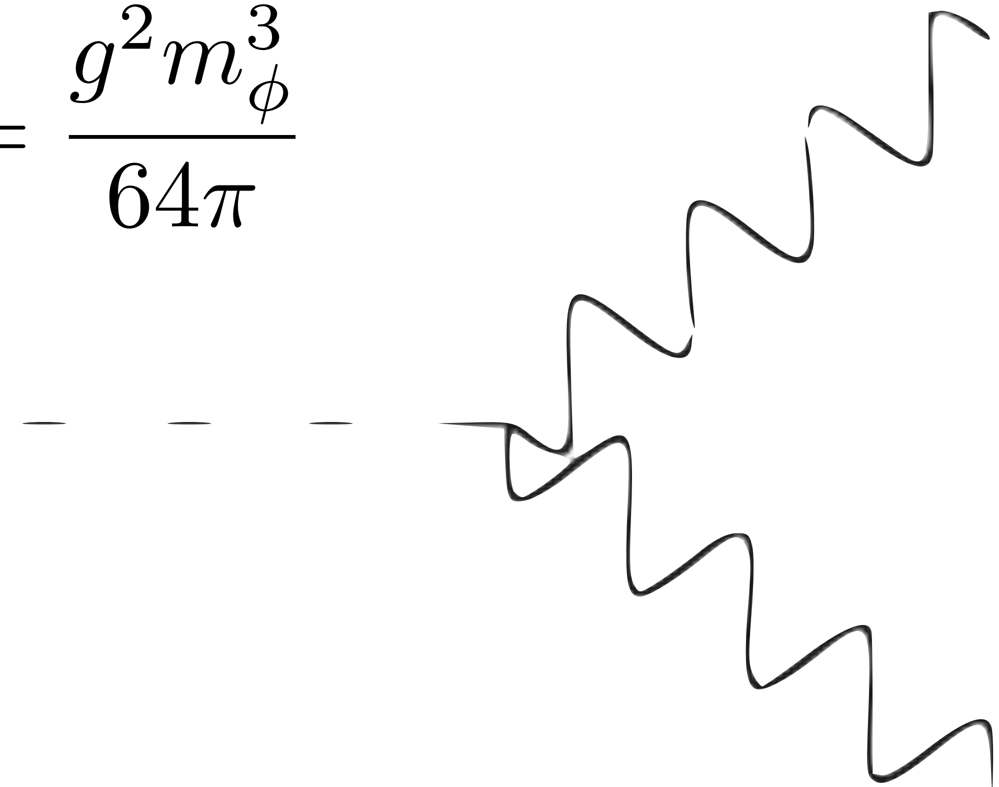
$$\rho_{\phi,0} \lesssim 1.17 \, \frac{\text{keV}}{\text{cm}^3} \times \sqrt{\frac{m_\phi}{\text{eV}}} \left(\frac{0.8 \times 10^{-14} \, \text{GeV}^{-1}}{g} \right)^2 \mathcal{F} \mathcal{N}^2,$$

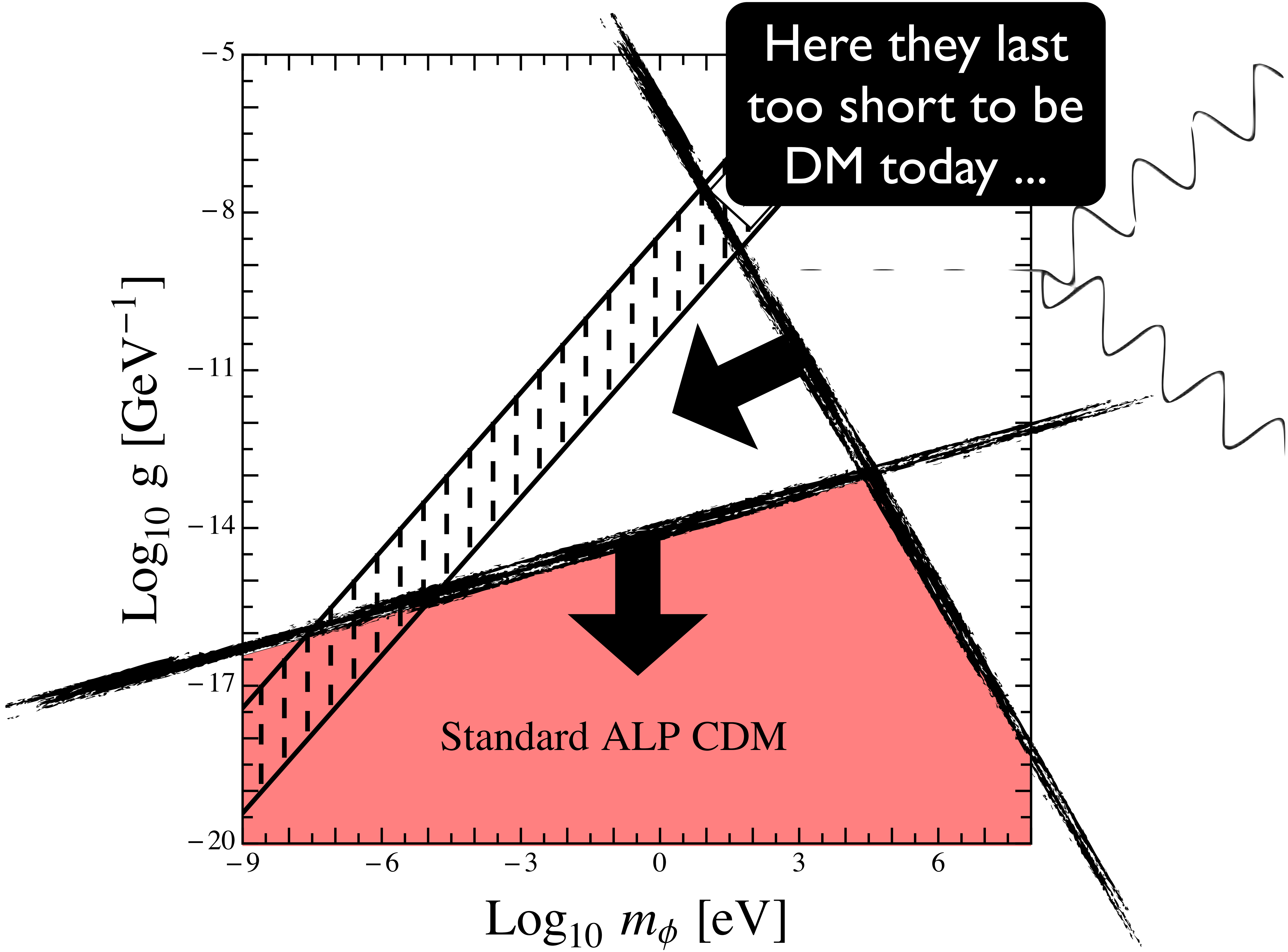


Axion models
Standard ALP CDM
$\mathrm{Log}_{10}\ g\ [\mathrm{GeV}^{-1}]$
$\mathrm{Log}_{10}\ m_\phi\ [\mathrm{eV}]$
−5
−8
−11
−14
−17
−20
−9
−6
−3
0
3
6

But ALPs decay

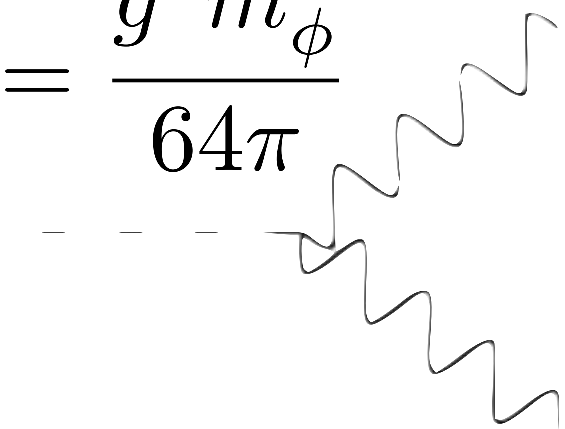
$$\Gamma = \frac{g^2 m_\phi^3}{64\pi}$$




Here they last too short to be DM today ...
Standard ALP CDM
−5
−8
−11
−14
−17
−20
−9
−6
−3
0
3
6
Log$_{10}$ g [GeV^{-1}]
Log$_{10}$ m_ϕ [eV]

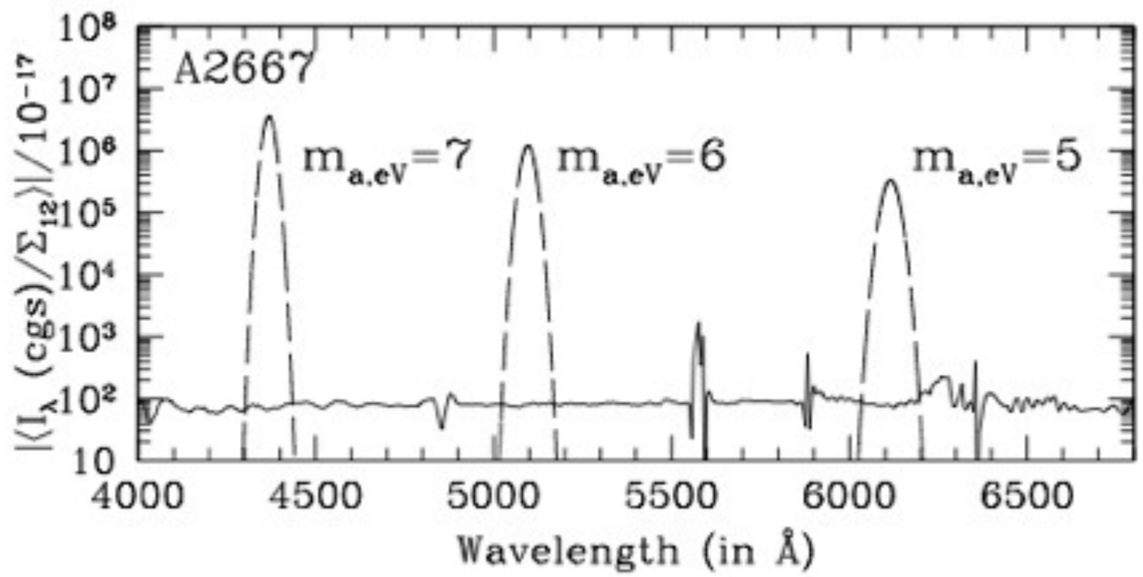
But ALPs decay and we don't see the photons...

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

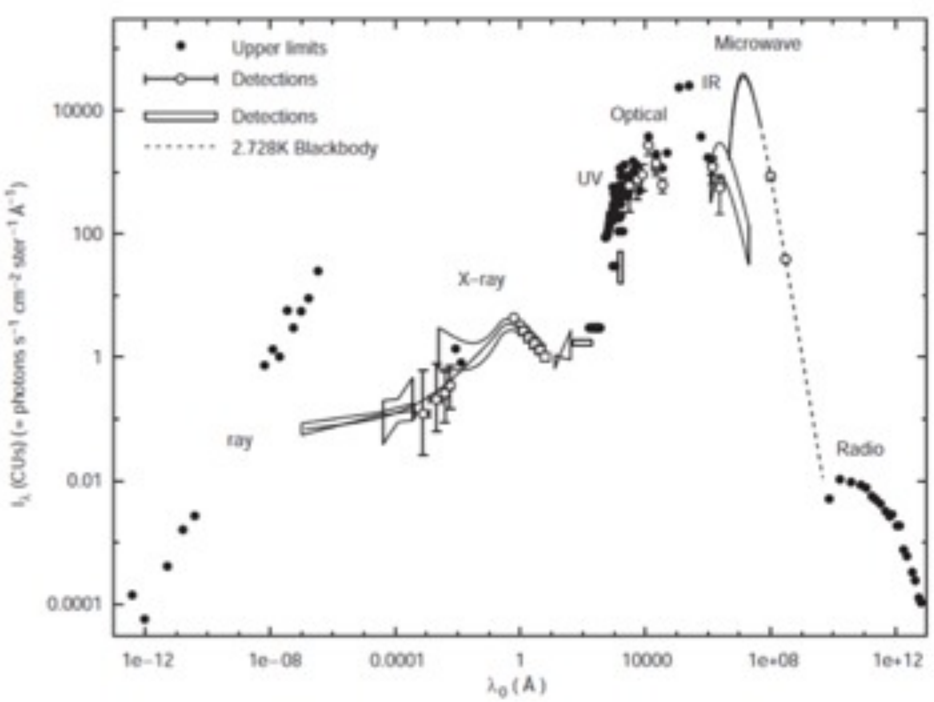


monochromatic line at

$$\lambda = 2\frac{2\pi}{m_\phi}$$



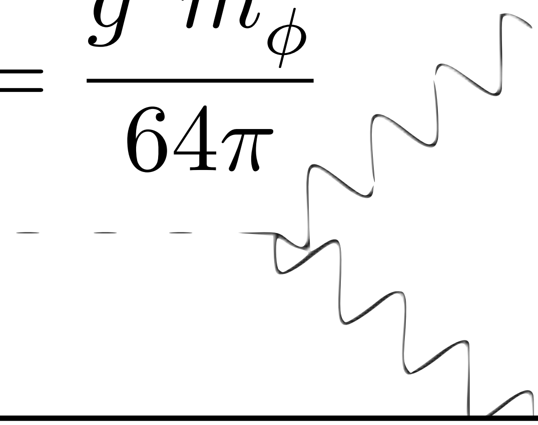
Galactic emission in the vis.
(Ressell 91, Grin 2007)



Extragalactic Background Light
(Overduin & Wesson)

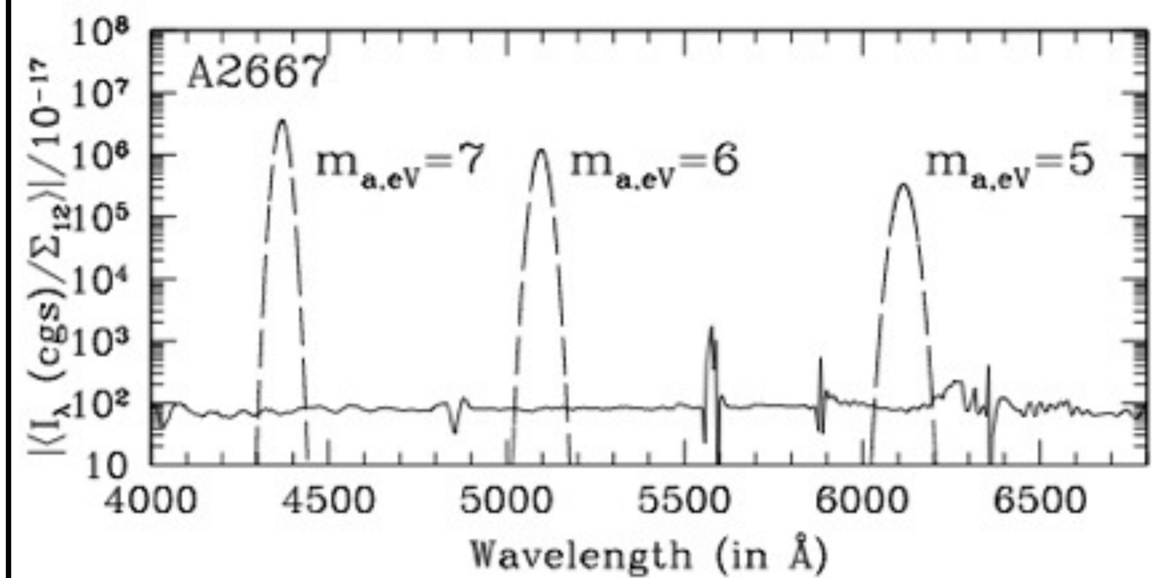
But ALPs decay and we don't see the photons...

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

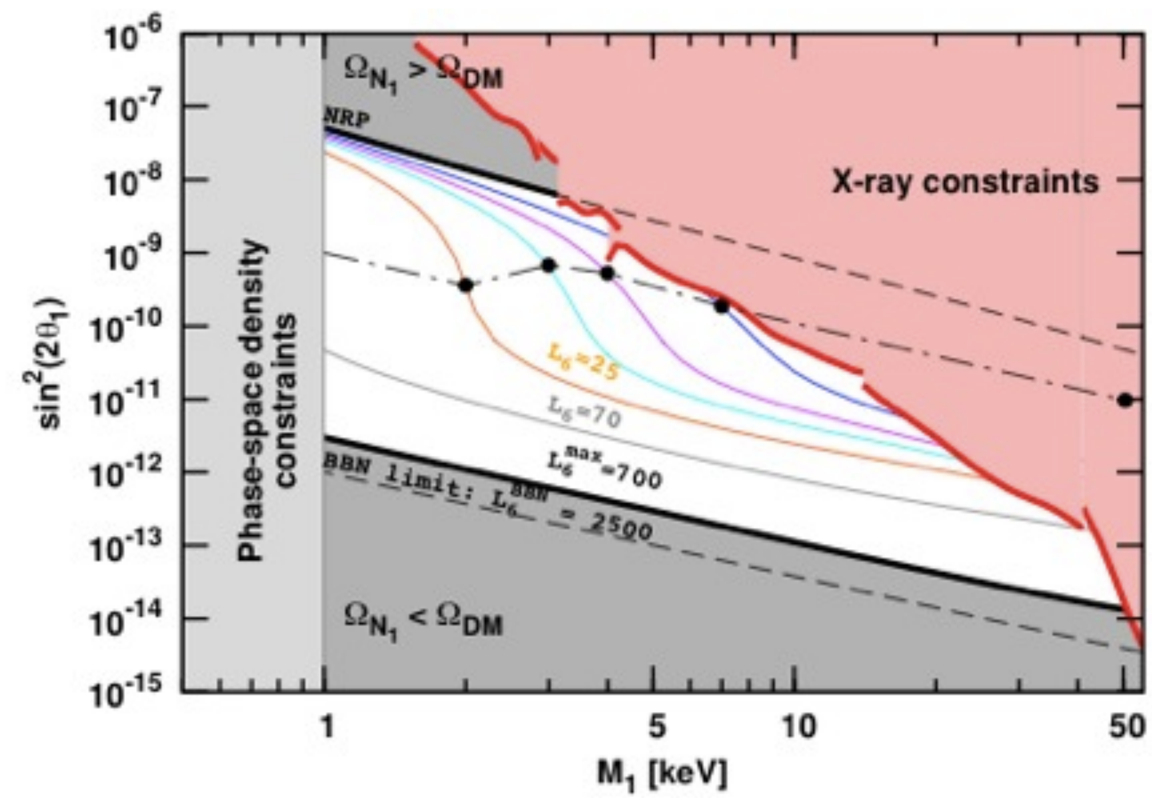


monochromatic line at

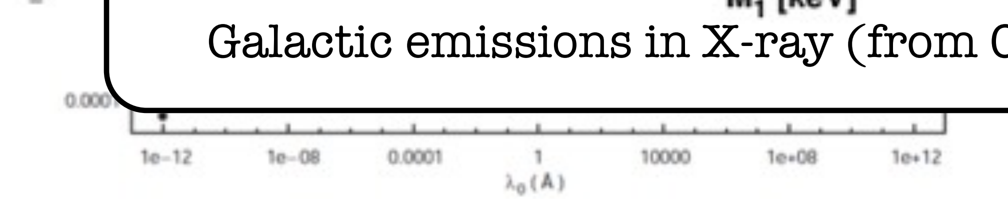
$$\lambda = 2\frac{2\pi}{m_\phi}$$



Galactic emission in the vis.
(Ressell 91, Grin 2007)



Galactic emissions in X-ray (from 0901.0011)



Extragalactic Background Light
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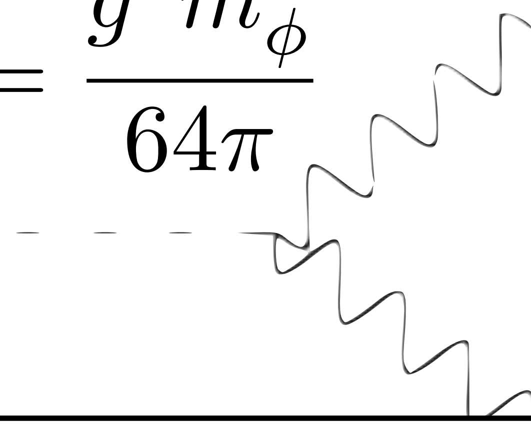
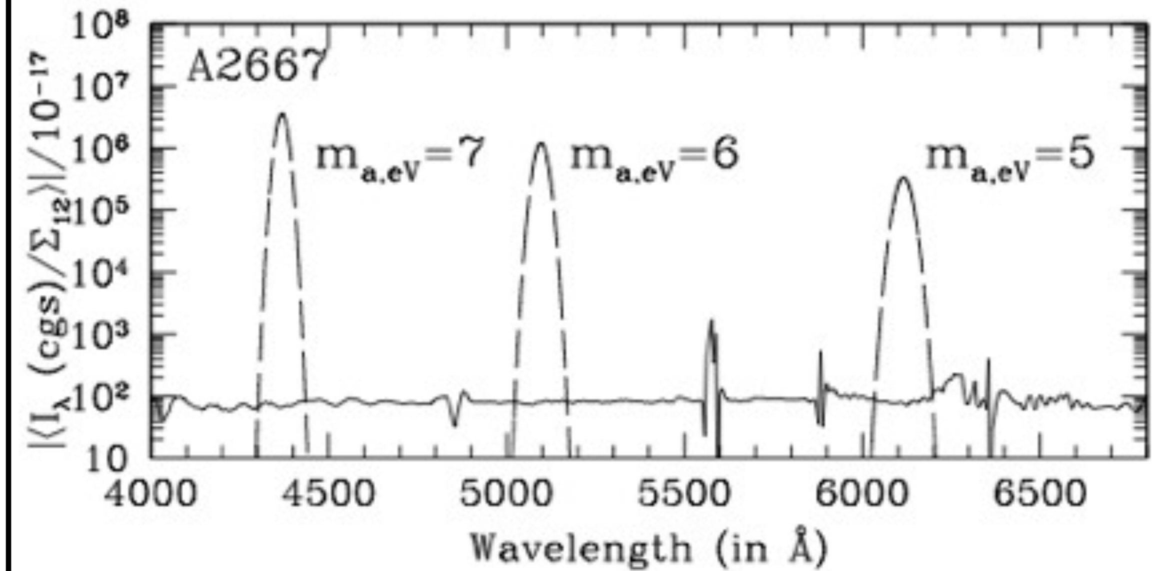
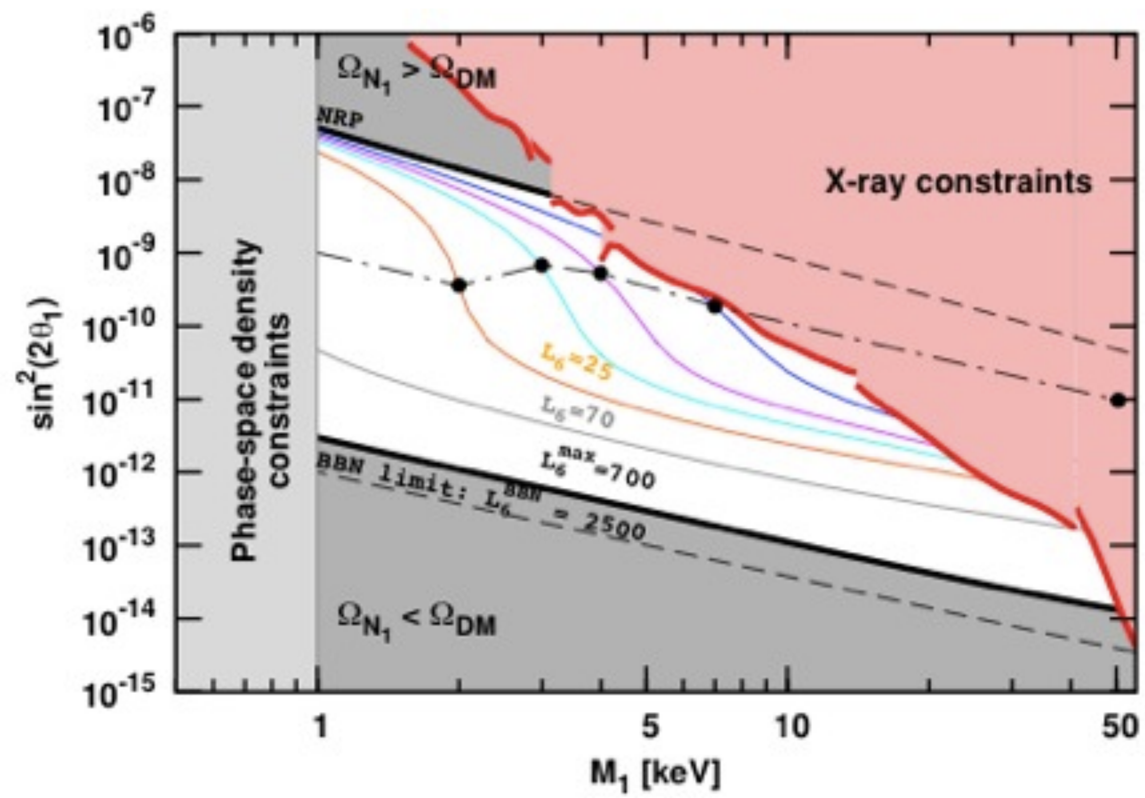


monochromatic line at

$$\lambda = 2\frac{2\pi}{m_\phi}$$



Galactic emission in the vis.



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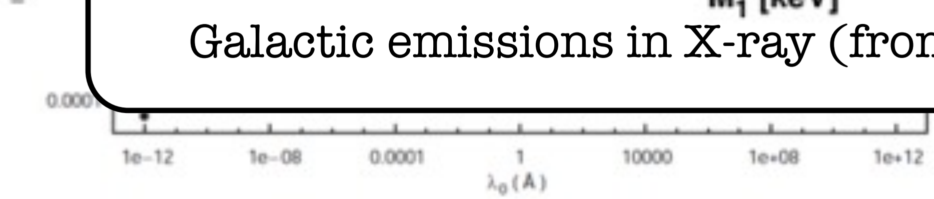

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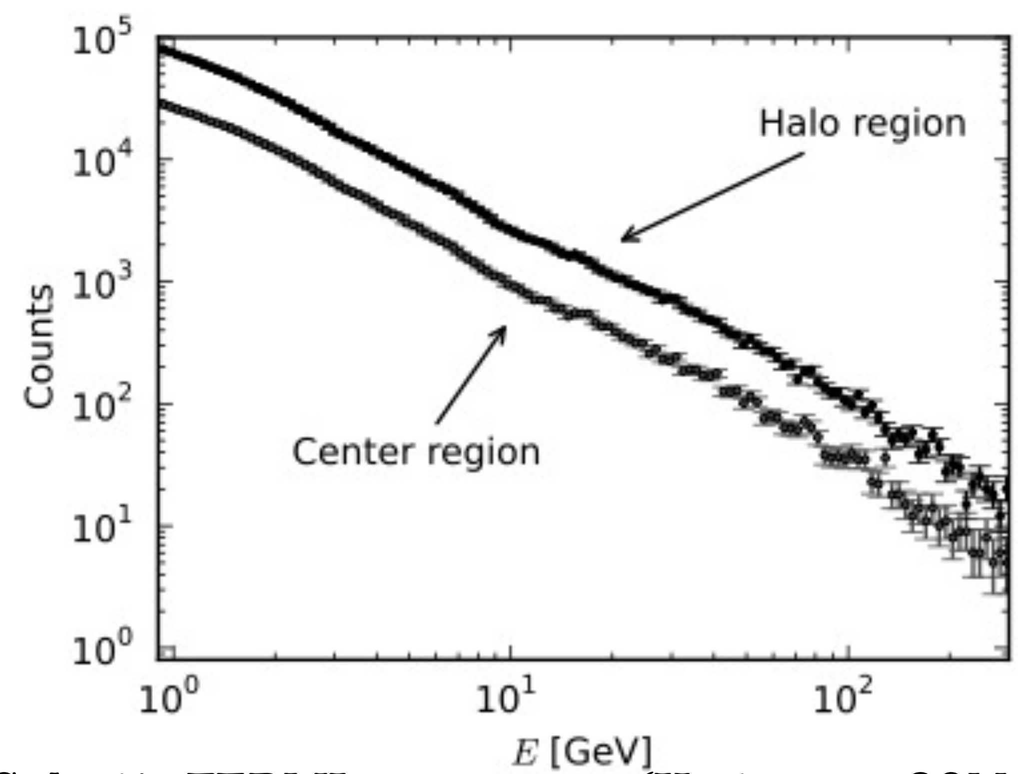
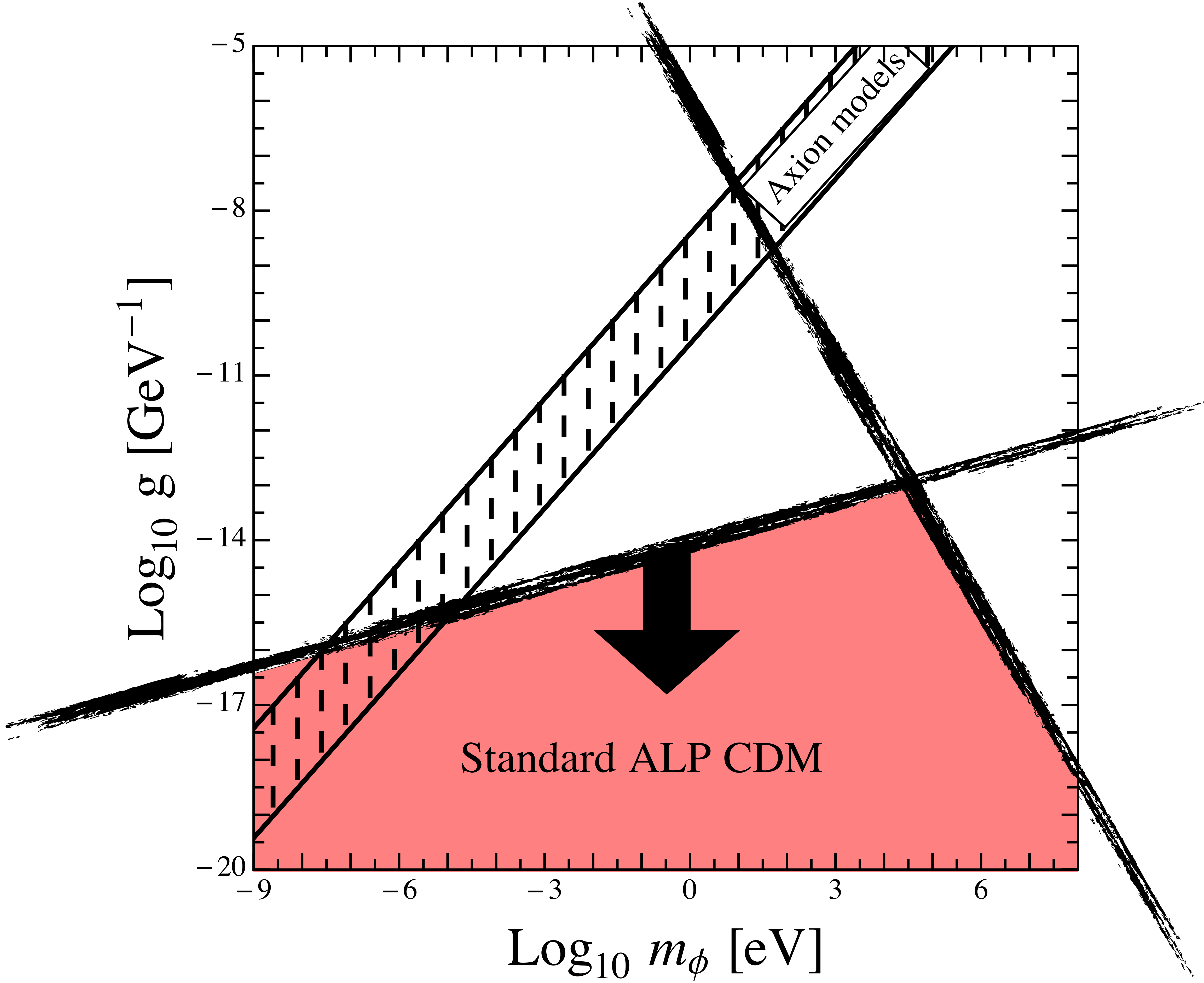
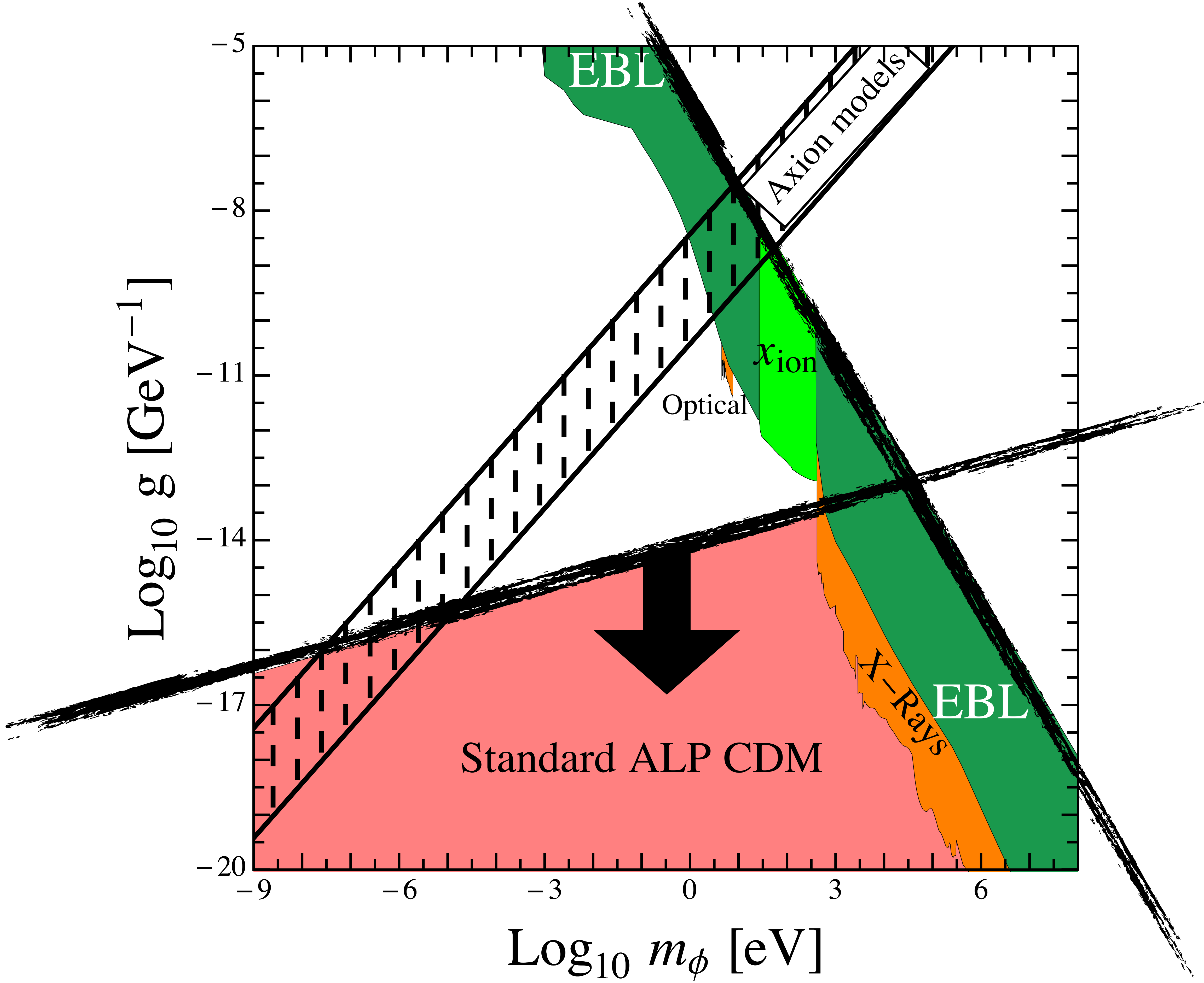


Galactic FERMI gamma-ray (Vertongen 2011)


Axion models
Standard ALP CDM
−5
−8
−11
−14
−17
−20
−9
−6
−3
0
3
6
Log10 g [GeV−1]
Log10 mϕ [eV]



EBL
Axion models
$x_{\rm ion}$
Optical
X-Rays
EBL
Standard ALP CDM
-5
-8
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-14
-17
-20
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-6
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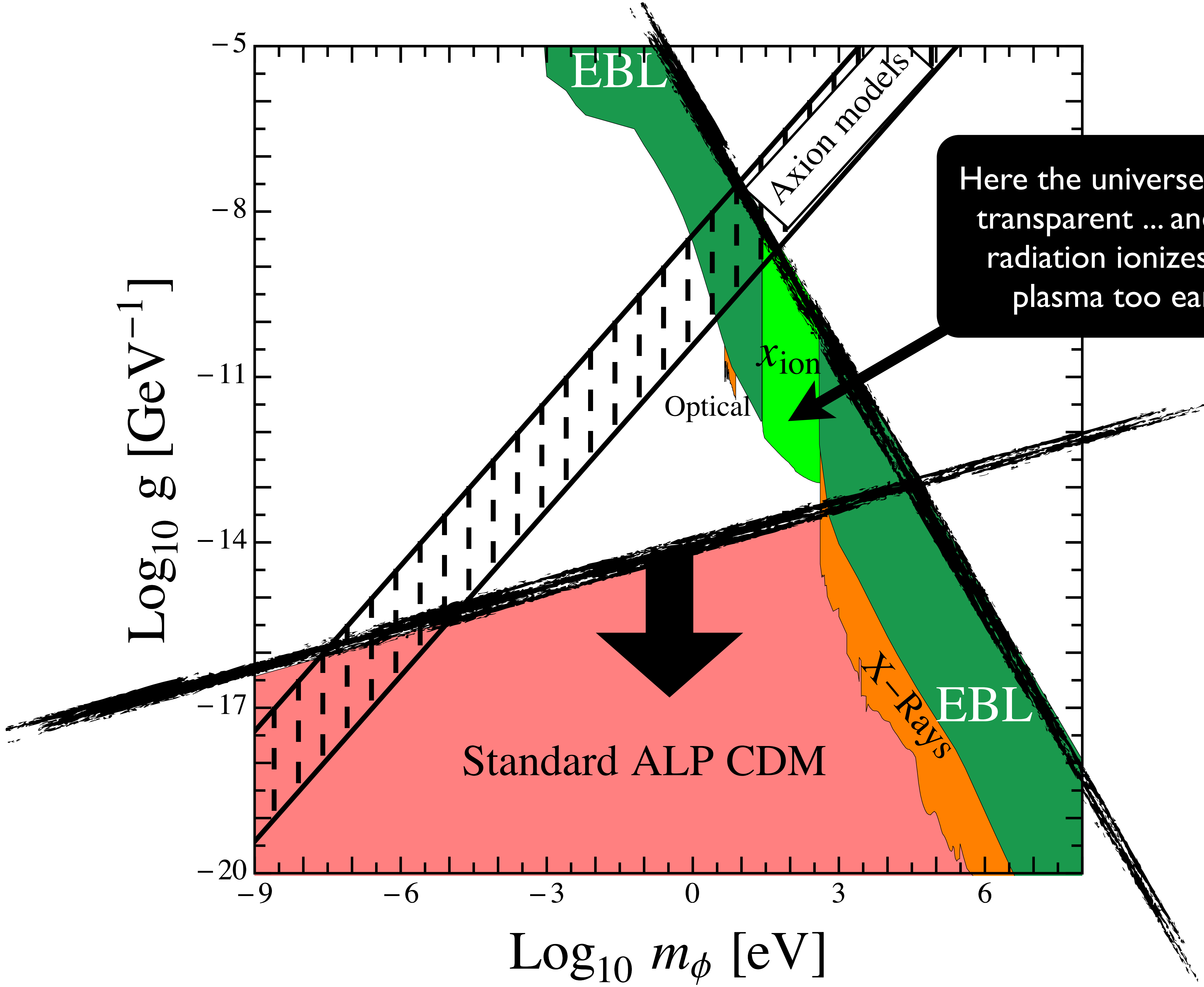
0
3
6
$\mathrm{Log}_{10}\ g\ [\mathrm{GeV}^{-1}]$
$\mathrm{Log}_{10}\ m_\phi\ [\mathrm{eV}]$



EBL
Axion models
Here the universe is not transparent ... and UV radiation ionizes the plasma too early
$x_{\rm ion}$
Optical
X-Rays
EBL
Standard ALP CDM
-5
-8
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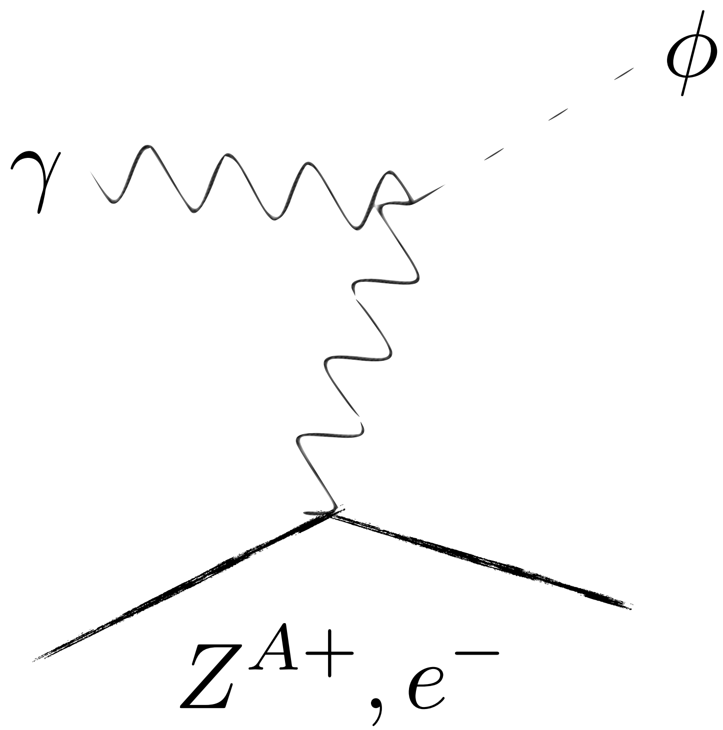
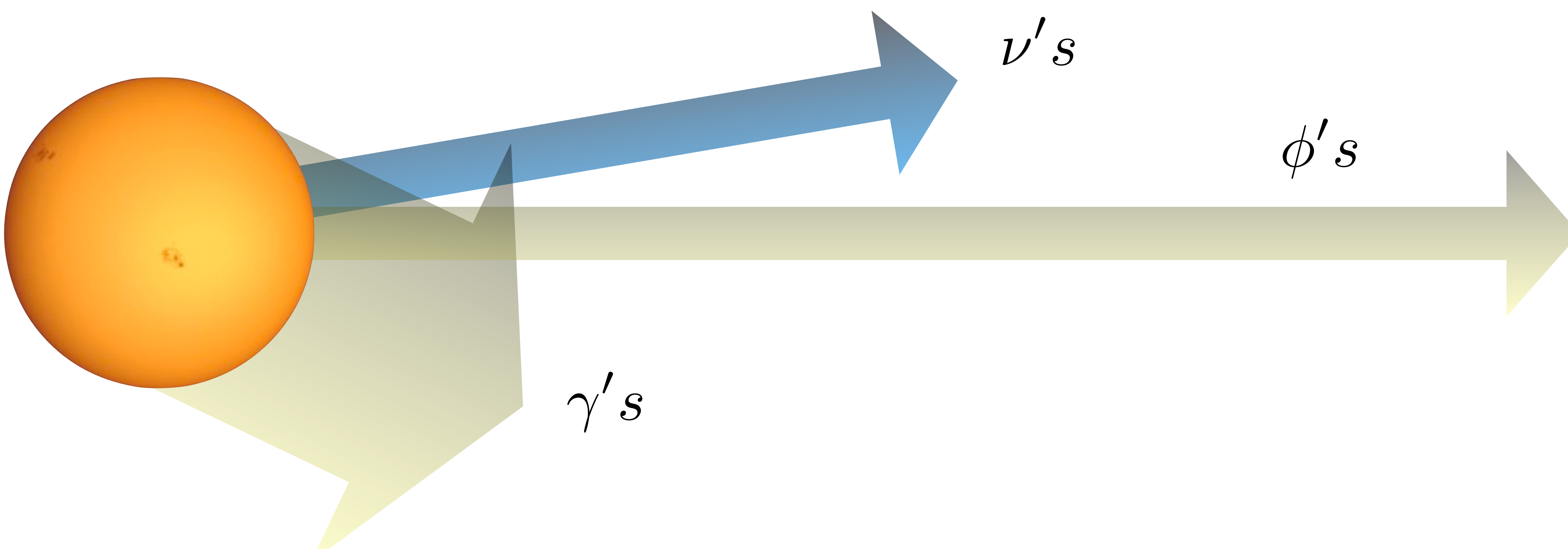
6
$\mathrm{Log}_{10}\, g\ [\mathrm{GeV}^{-1}]$
$\mathrm{Log}_{10}\, m_\phi\ [\mathrm{eV}]$

And they are radiated from stars



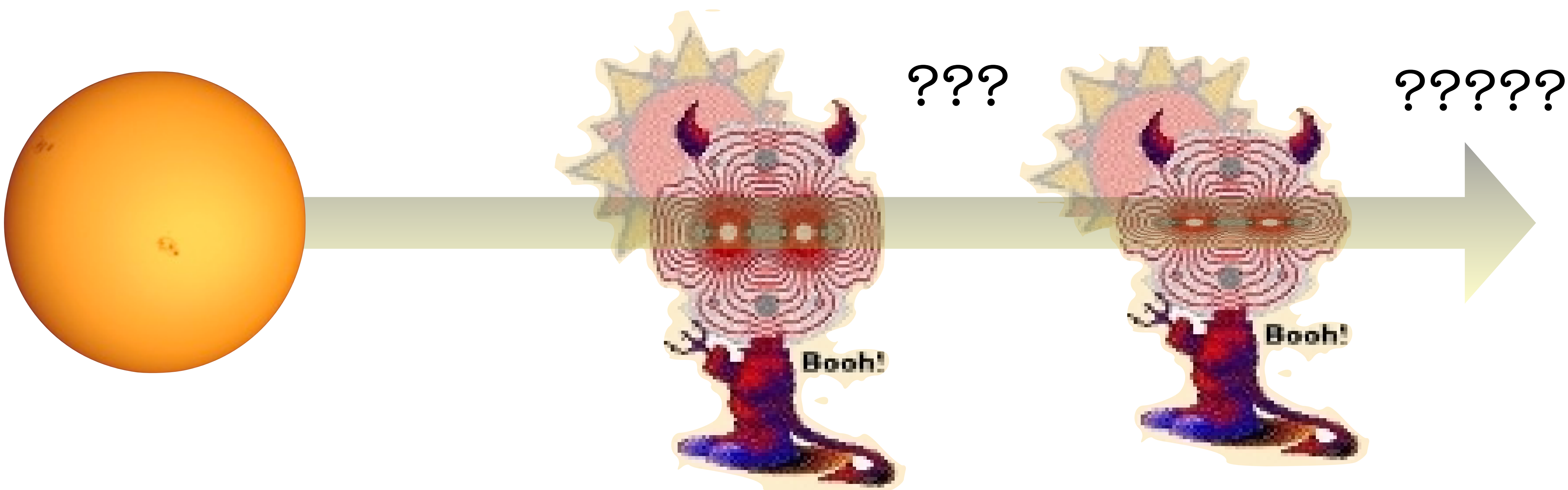
(Primakoff process)

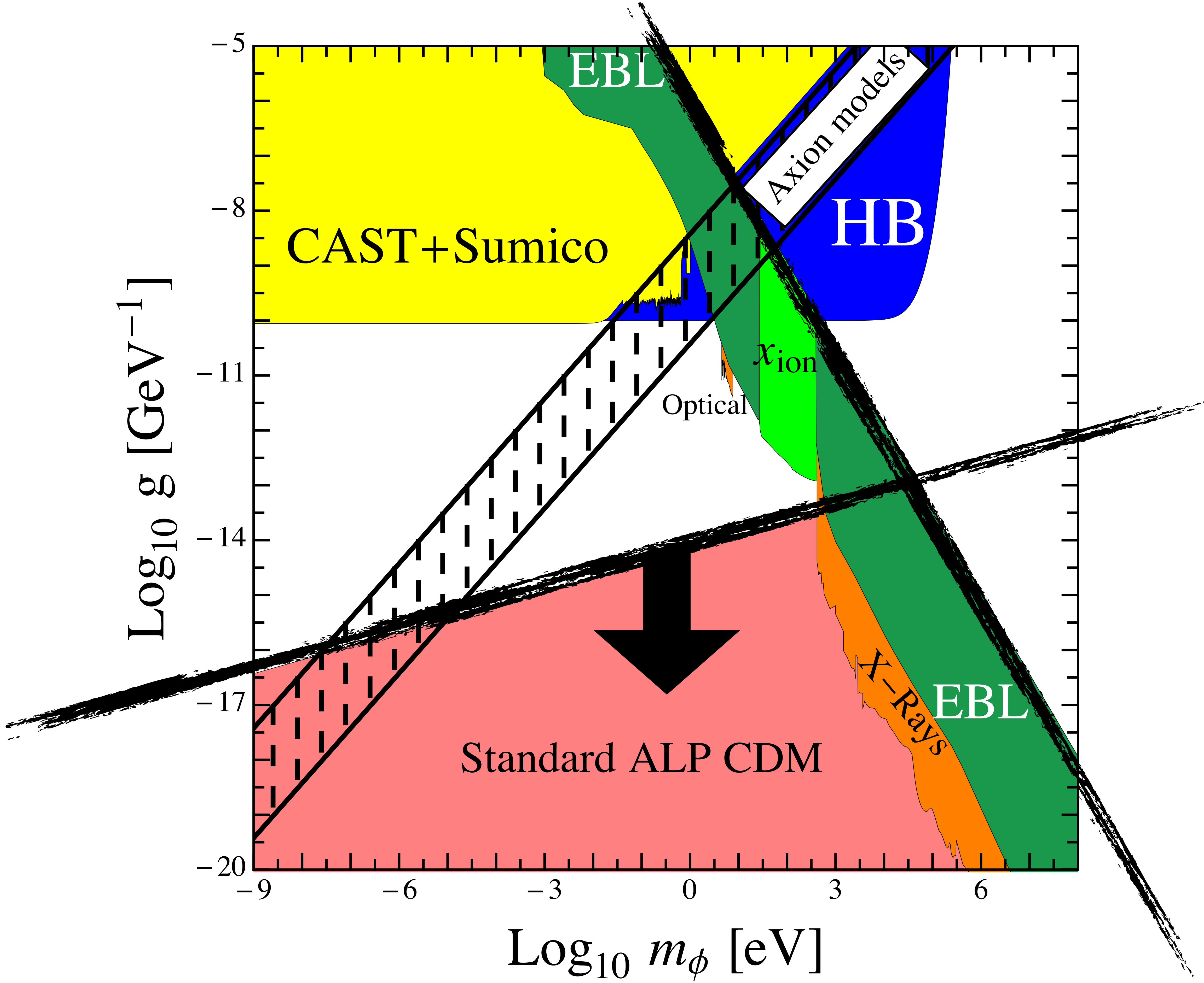
This accelerates the nuclear reactions that power the star, and increases the speed of stellar evolution (most of the times) which is relatively well understood!



And CAST and SUMICO do not see them

Experiments looking for solar axions (see later) didn't found a trace so far...

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CAST+Sumico
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0
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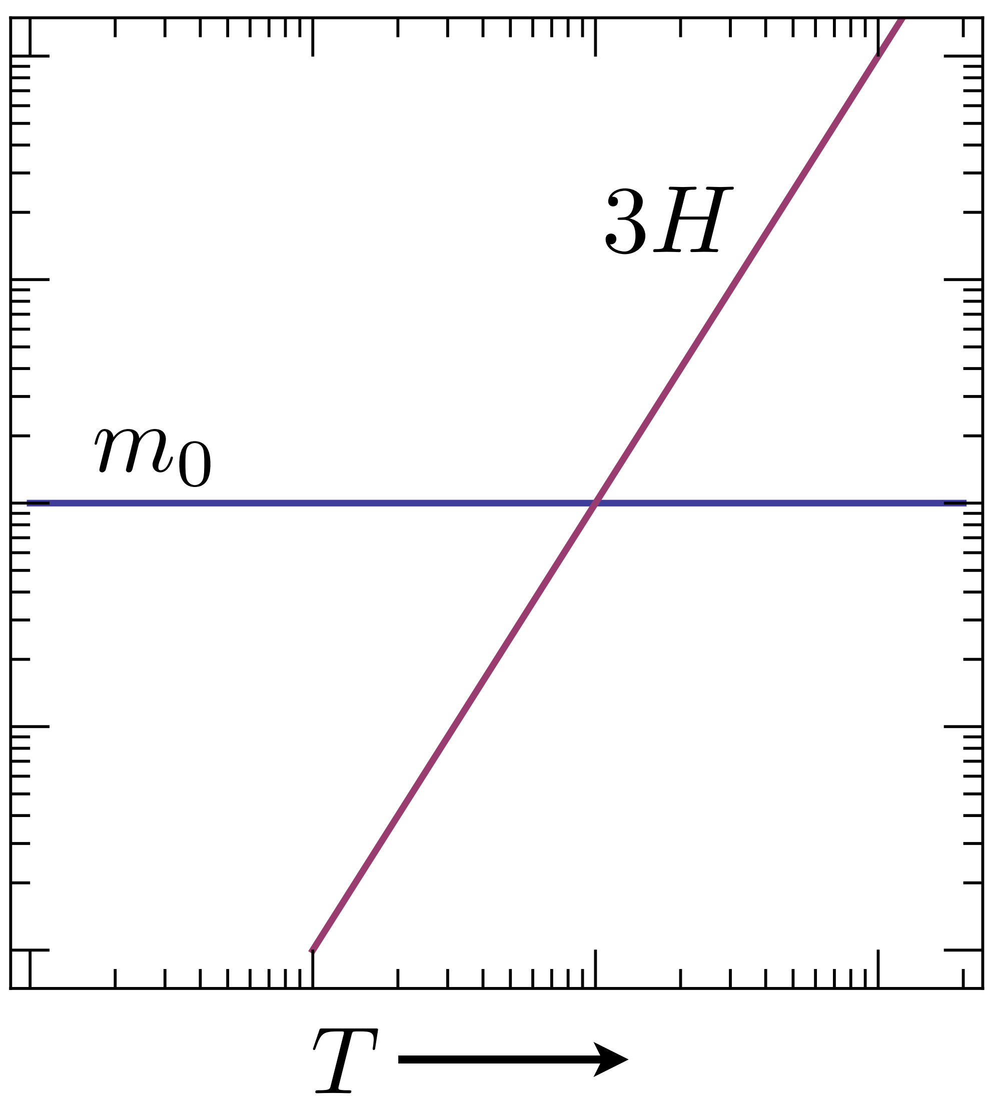
$\mathrm{Log}_{10}\ m_\phi\ [\mathrm{eV}]$

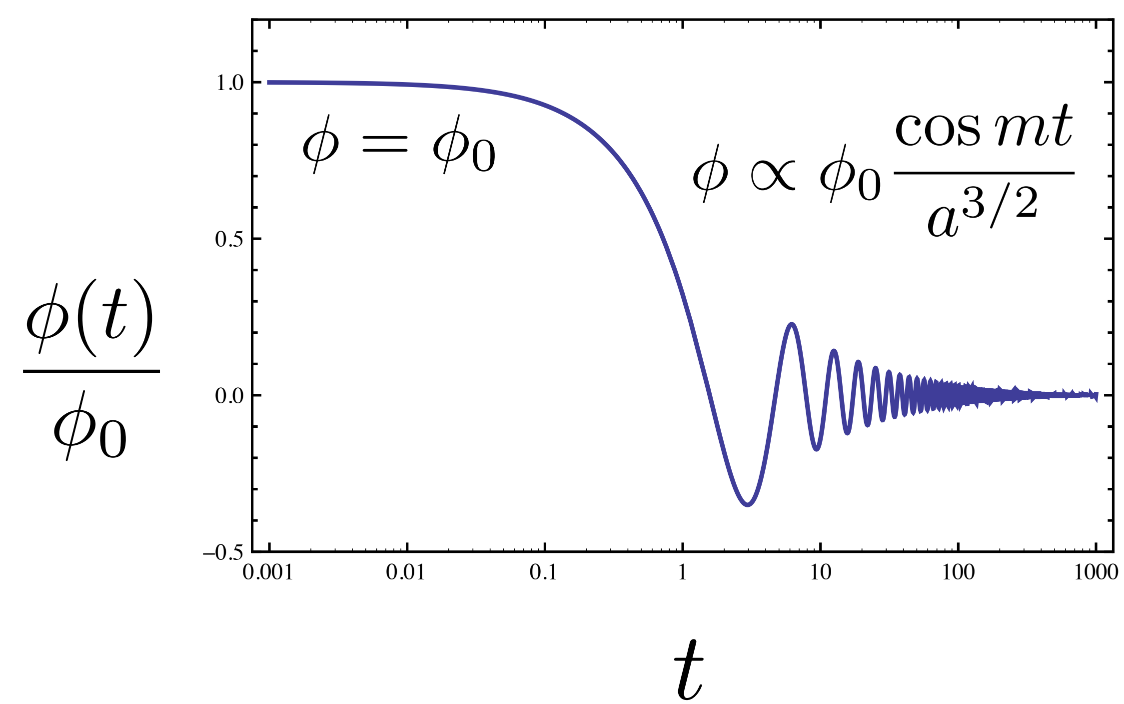
Standard ALP CDM not soooo promising for det.

Situation can change much if thermal mass

$$m = m(T)$$

Damping of the oscillations starts when $m(T_1) \sim 3H(T_1)$





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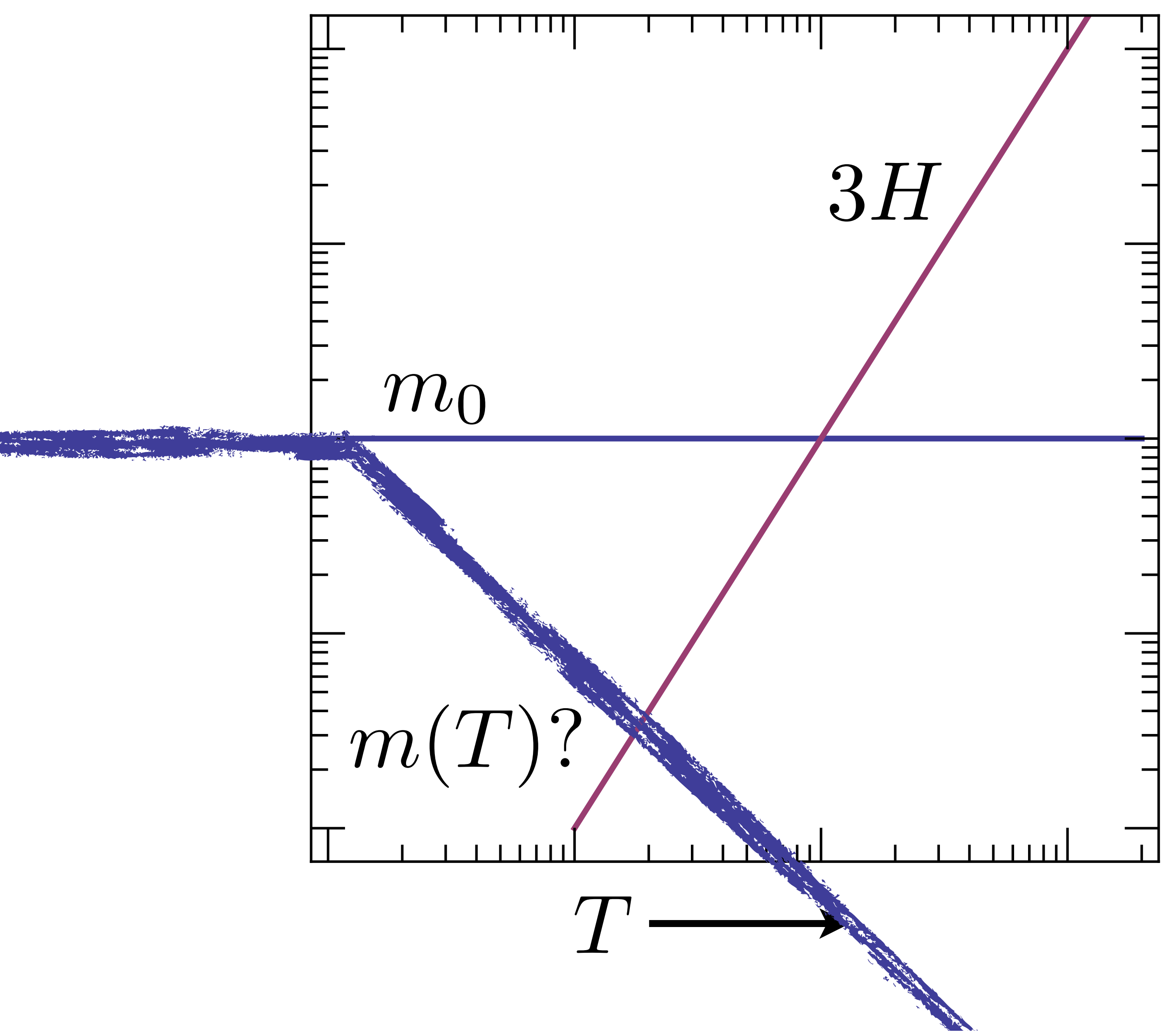

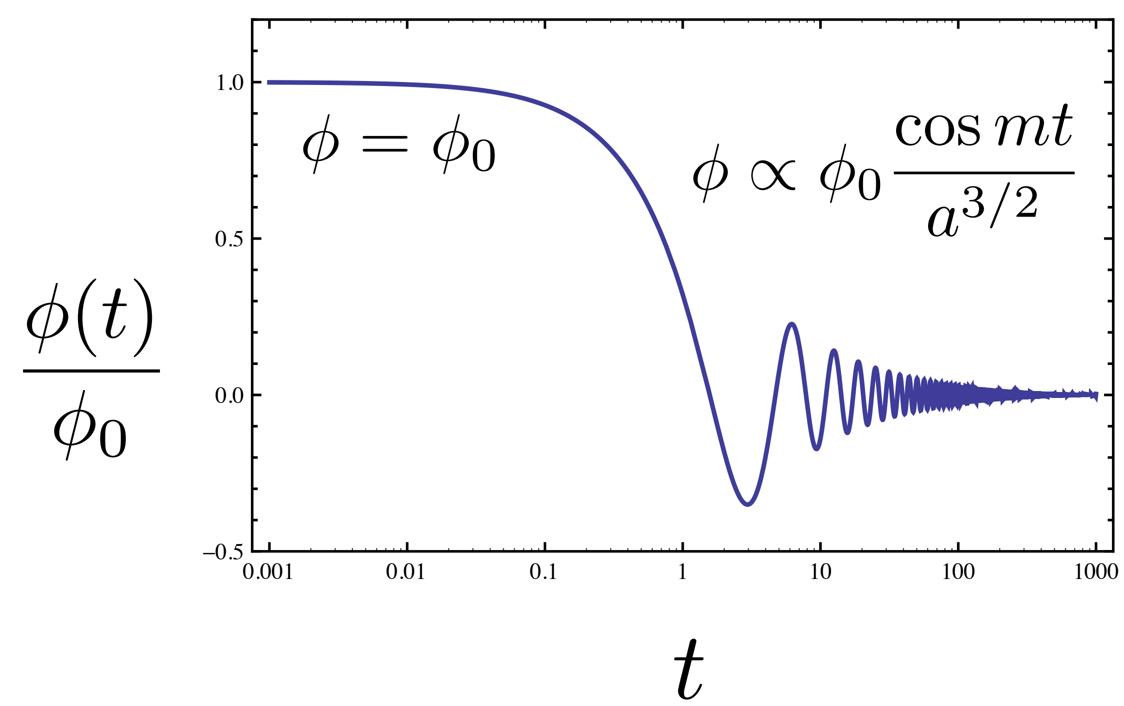

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$$m(T_1) \equiv m_1$$

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

(Assuming adiabatic evolution of number density)

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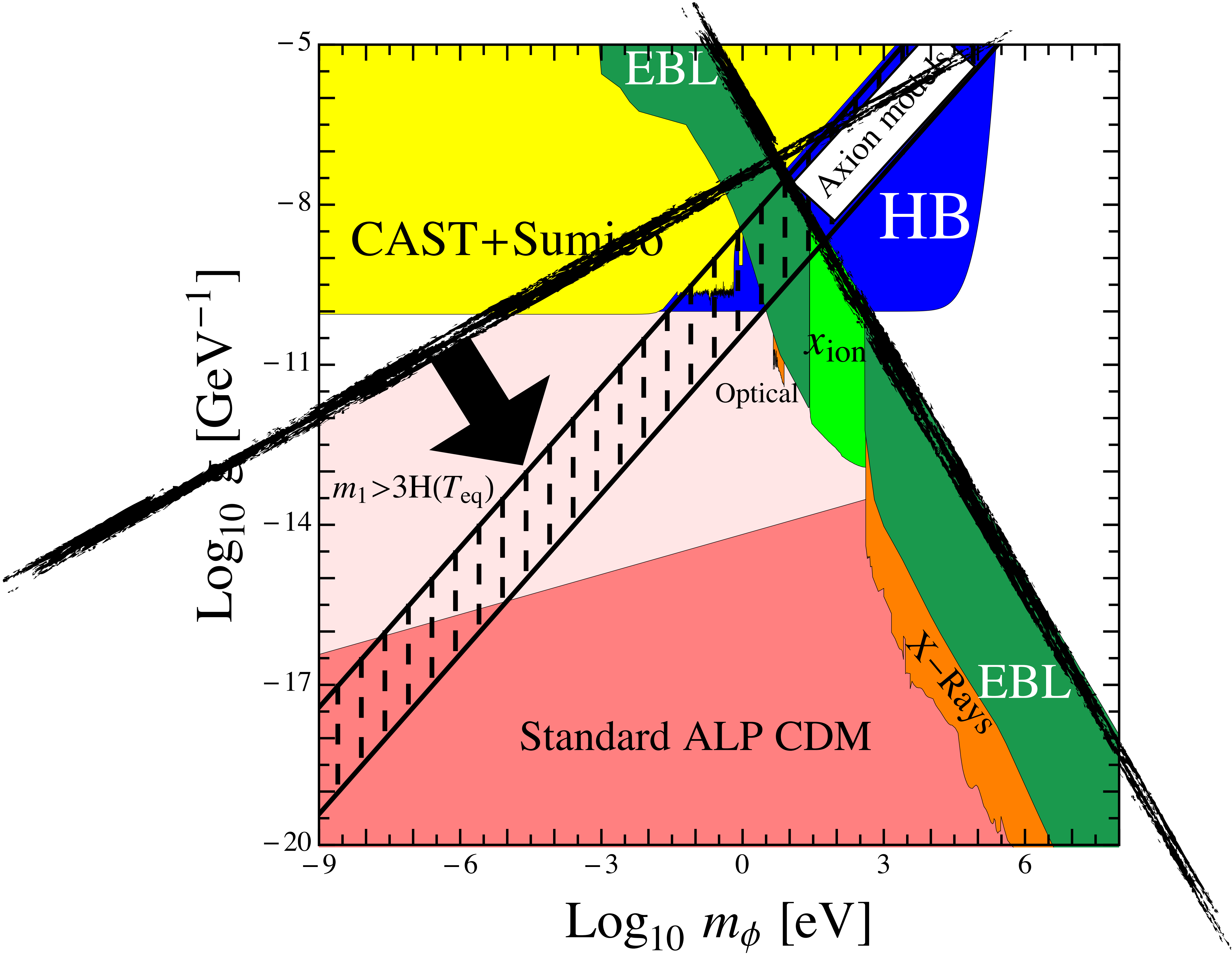
(Assuming adiabatic evolution of number density)

How small can be m_1 ??

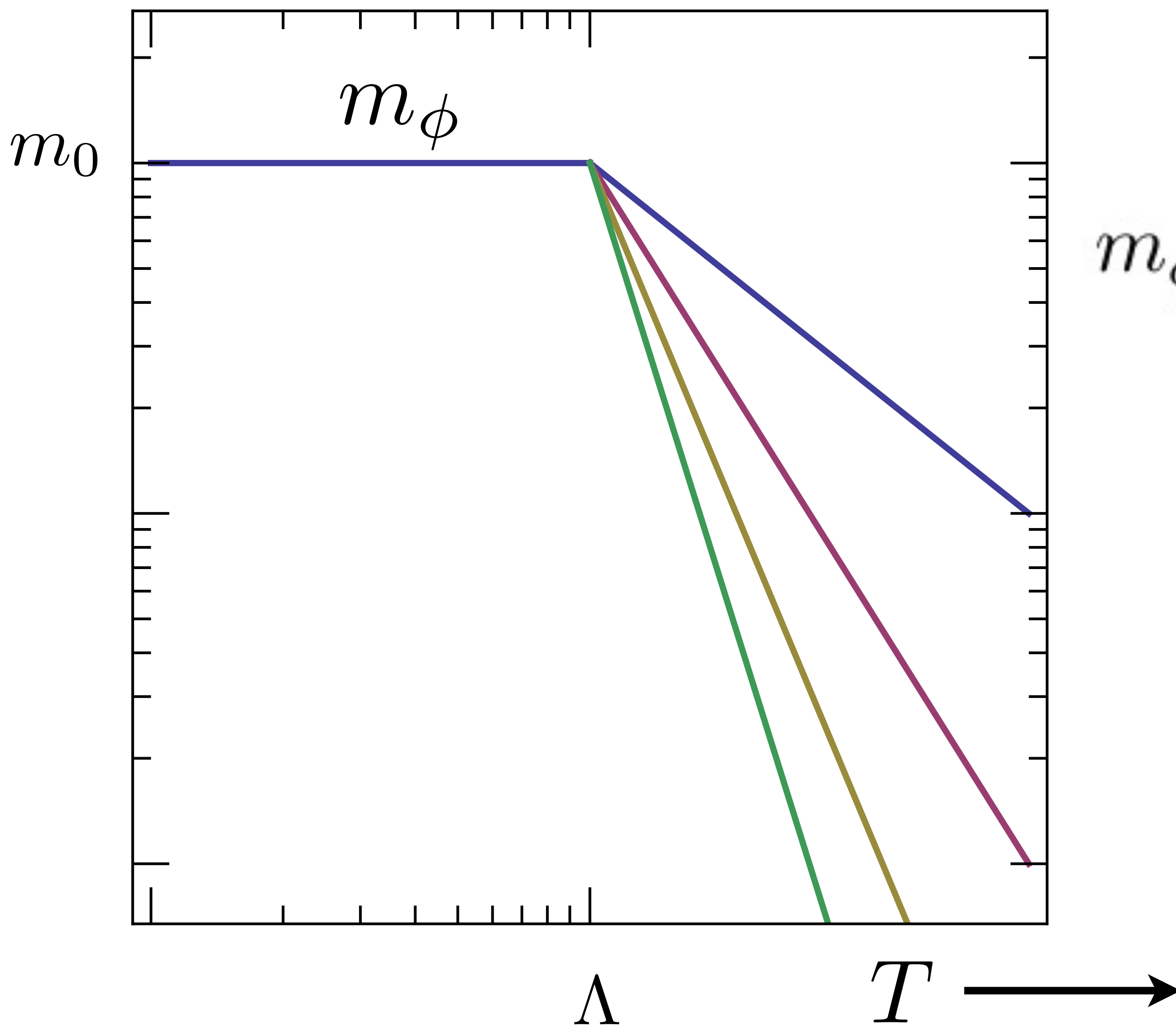
If we want the ALP to behave as CDM after standard Matter-Radiation equality $T_{\rm eq} \sim 1.3\,{\rm eV}$

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

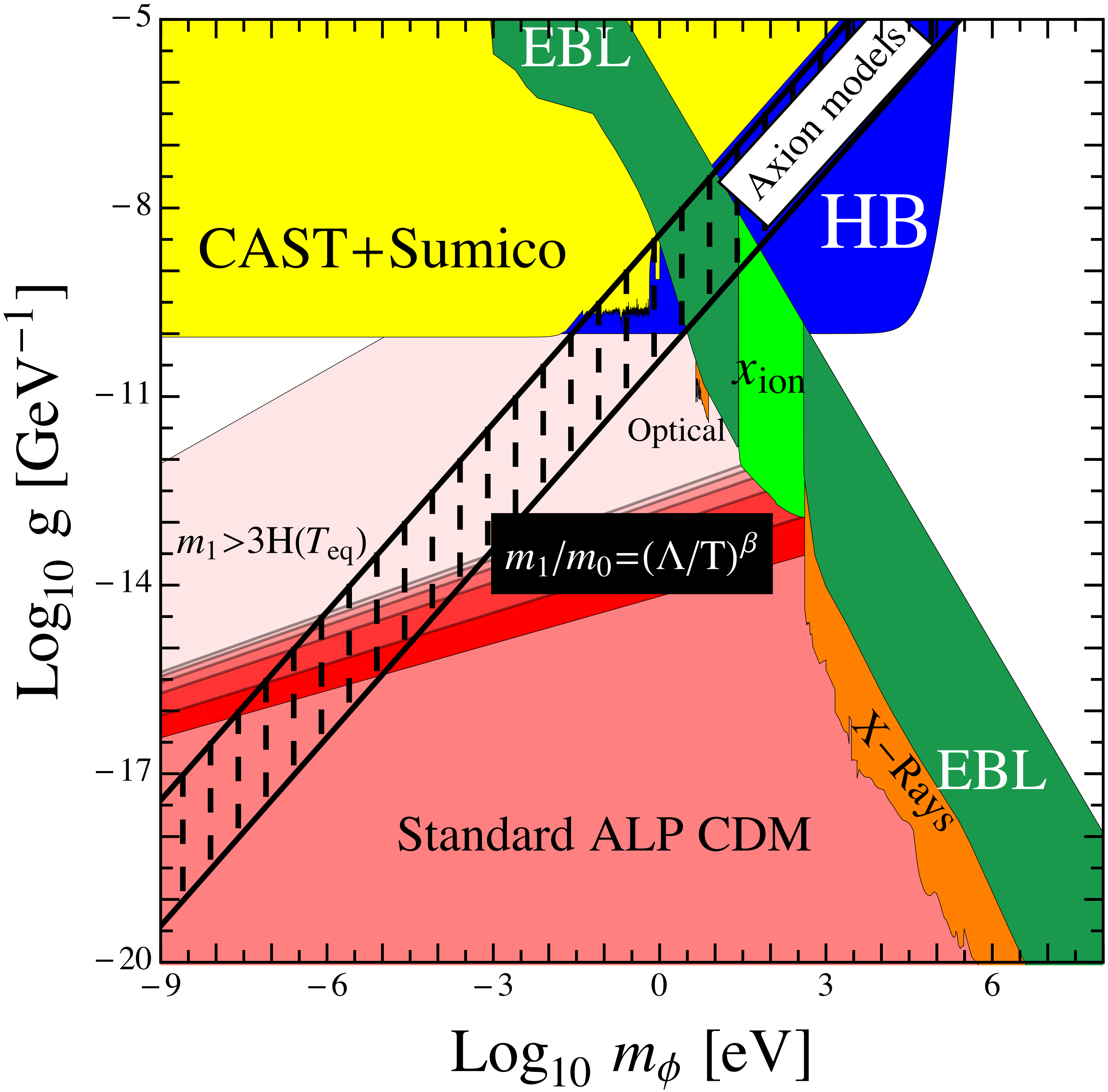

EBL
CAST+Sumico
Axion models
HB
$x_{\rm ion}$
Optical
$m_1 > 3H(T_{\rm eq})$
Standard ALP CDM
X-Rays
EBL
$\mathrm{Log}_{10}\, g\ [\mathrm{GeV}^{-1}]$
$\mathrm{Log}_{10}\, m_\phi\ [\mathrm{eV}]$
−5
−8
−11
−14
−17
−20
−9
−6
−3
0
3
6

It is however to saturate this bound

Instantontic-like potentials (like for the axion)



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


EBL
CAST+Sumico
Axion models
HB
$x_{\rm ion}$
Optical
$m_1>3\mathrm{H}(T_{\rm eq})$
$m_1/m_0=(\Lambda/\mathrm{T})^\beta$
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Standard ALP CDM
$\mathrm{Log}_{10}\, g\ [\mathrm{GeV}^{-1}]$
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−5
−8
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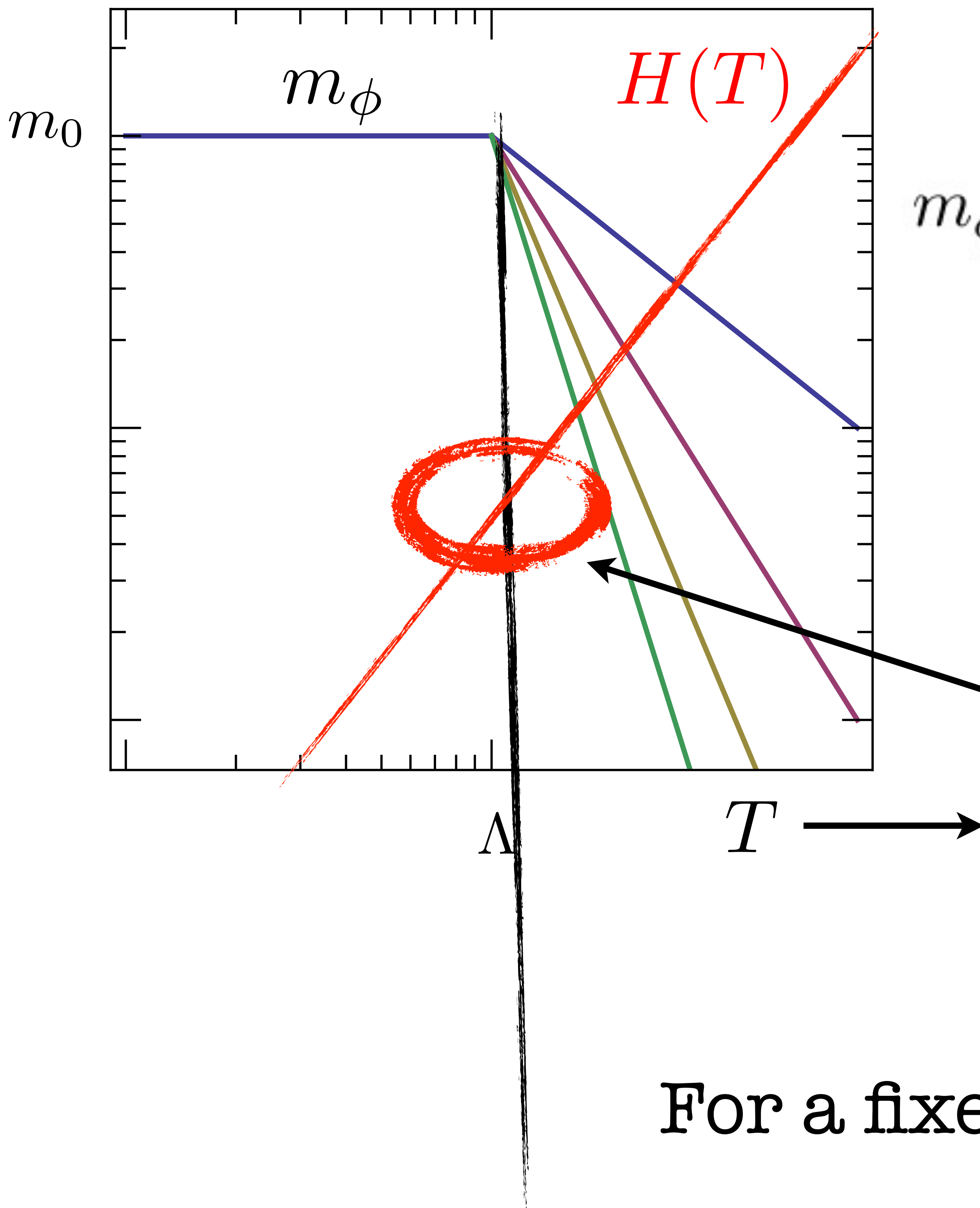
3
6

It is however kind of difficult to build such models

Instantonic-like potentials (like for the axion)



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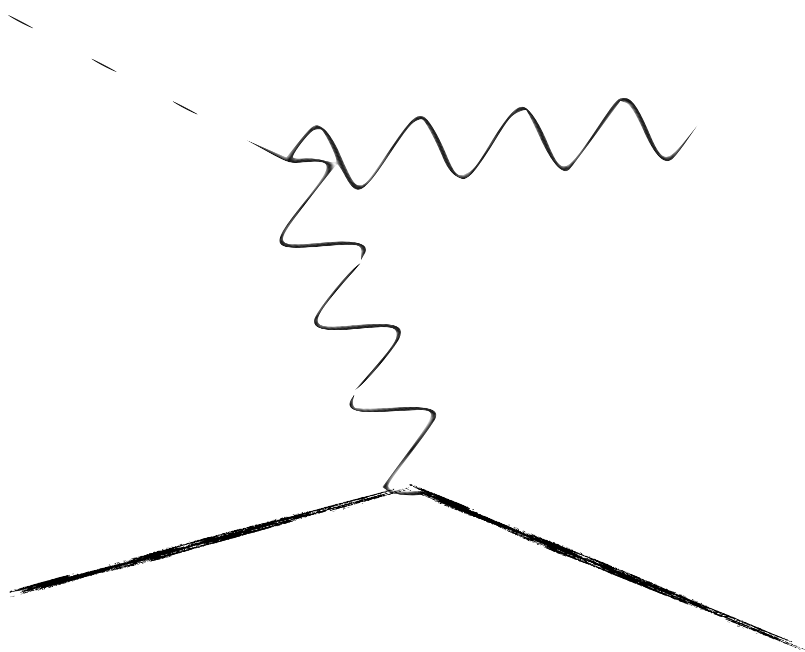
$$T_1 \gtrsim \Lambda$$

For a fixed $m_0, \beta \to \infty$ does not help

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 $E_a \sim T$

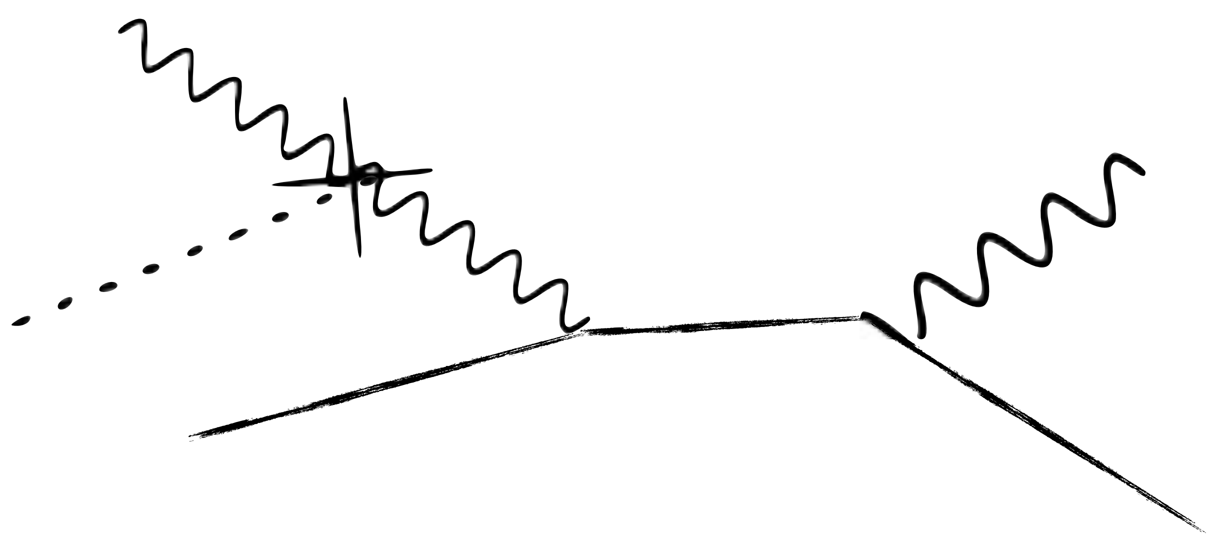
When ALP energies $E_a = m_a \ll T$
the COM energy is not sufficient to produce a plasmon!

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

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

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 $\phi \leftrightarrow \vec{E}$

$$\mathcal{L} \ni \frac{g}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu} \phi = -g \vec{\mathbf{B}} \cdot \vec{\mathbf{E}} \phi = (gB) E_{||} \phi$$

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

$$M^2 = \begin{pmatrix} i m_\phi \sigma & g B m_\phi \\ g B m_\phi & m_\phi^2 \end{pmatrix} \quad \rightarrow \theta_{\rm eff} \sim \frac{(2 g B m_\phi^2)^2}{(m_\phi^2 - \omega_{\rm P}^2)^2 + (m_\phi^2 \sigma)^2}$$

Thermalization of ALP CDM III

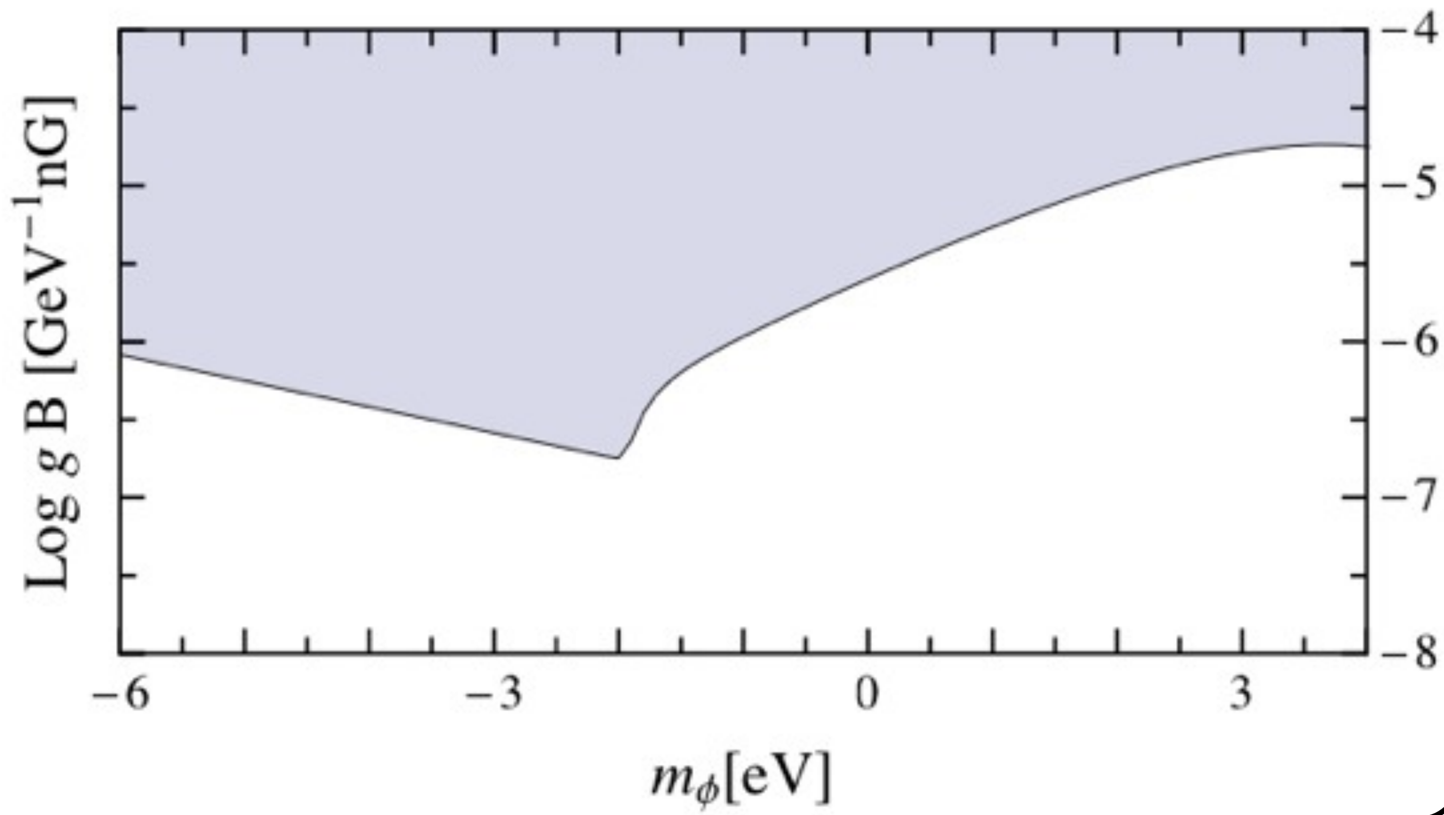
Primordial Magnetic fields trigger $\phi \leftrightarrow \vec{E}$

but very big fields (or very primordial) required

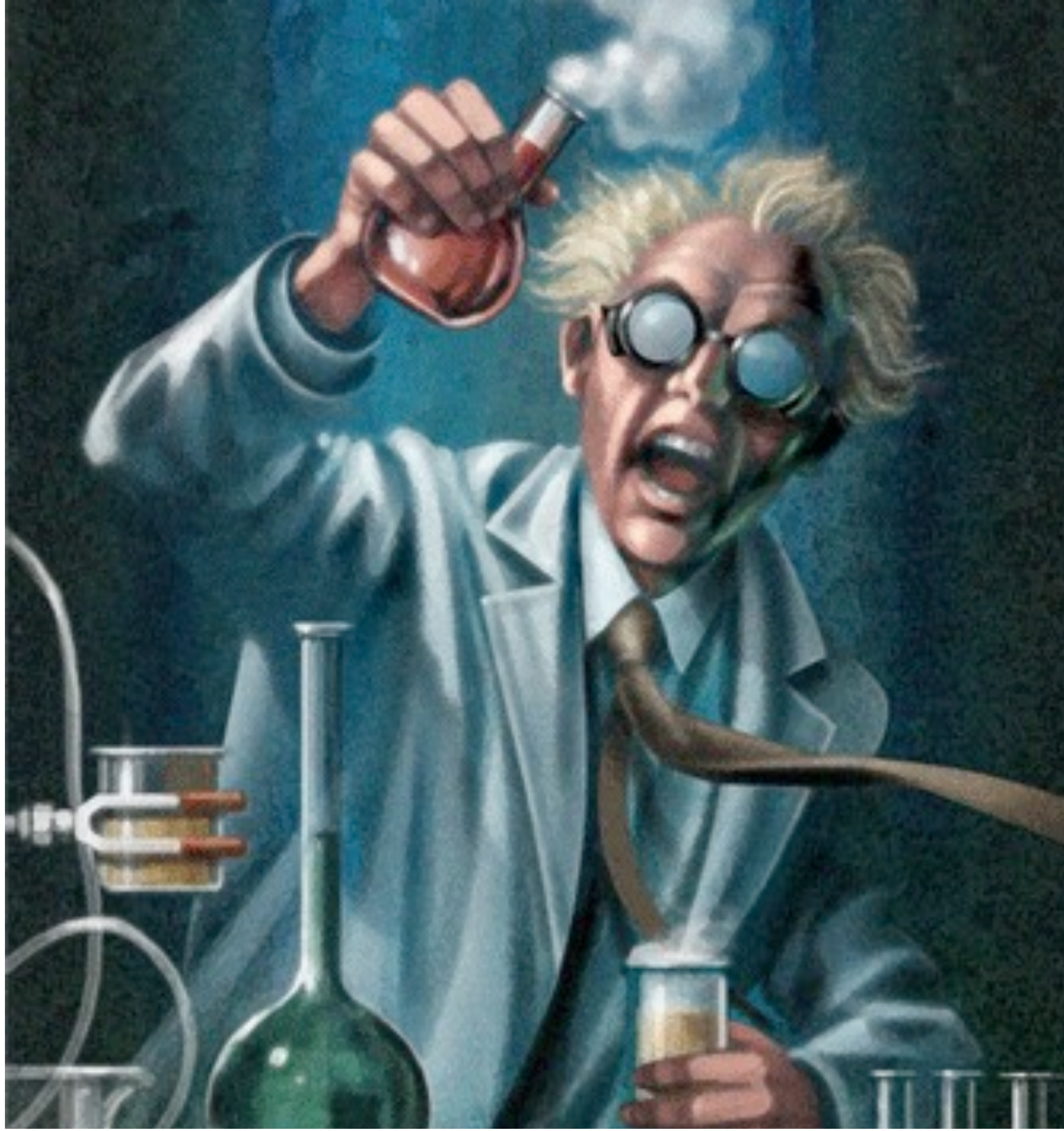
high T constraint
(if $B \propto T^2$)

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

res. oscillations



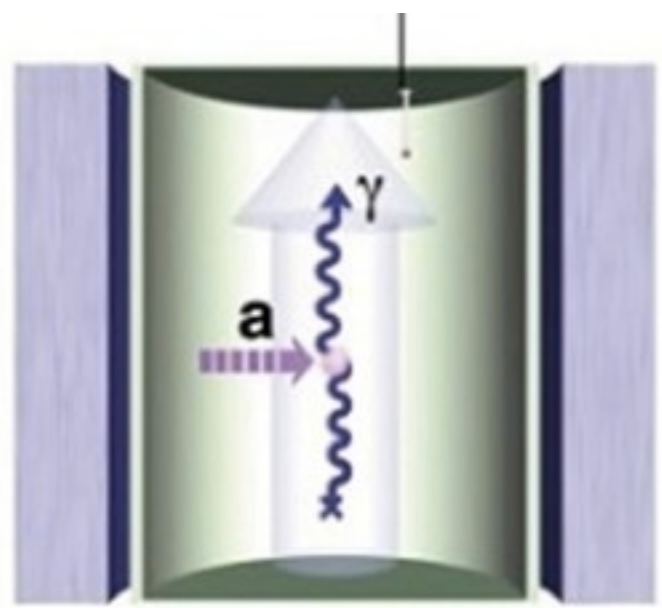
Laboratory



Laboratory Experiments

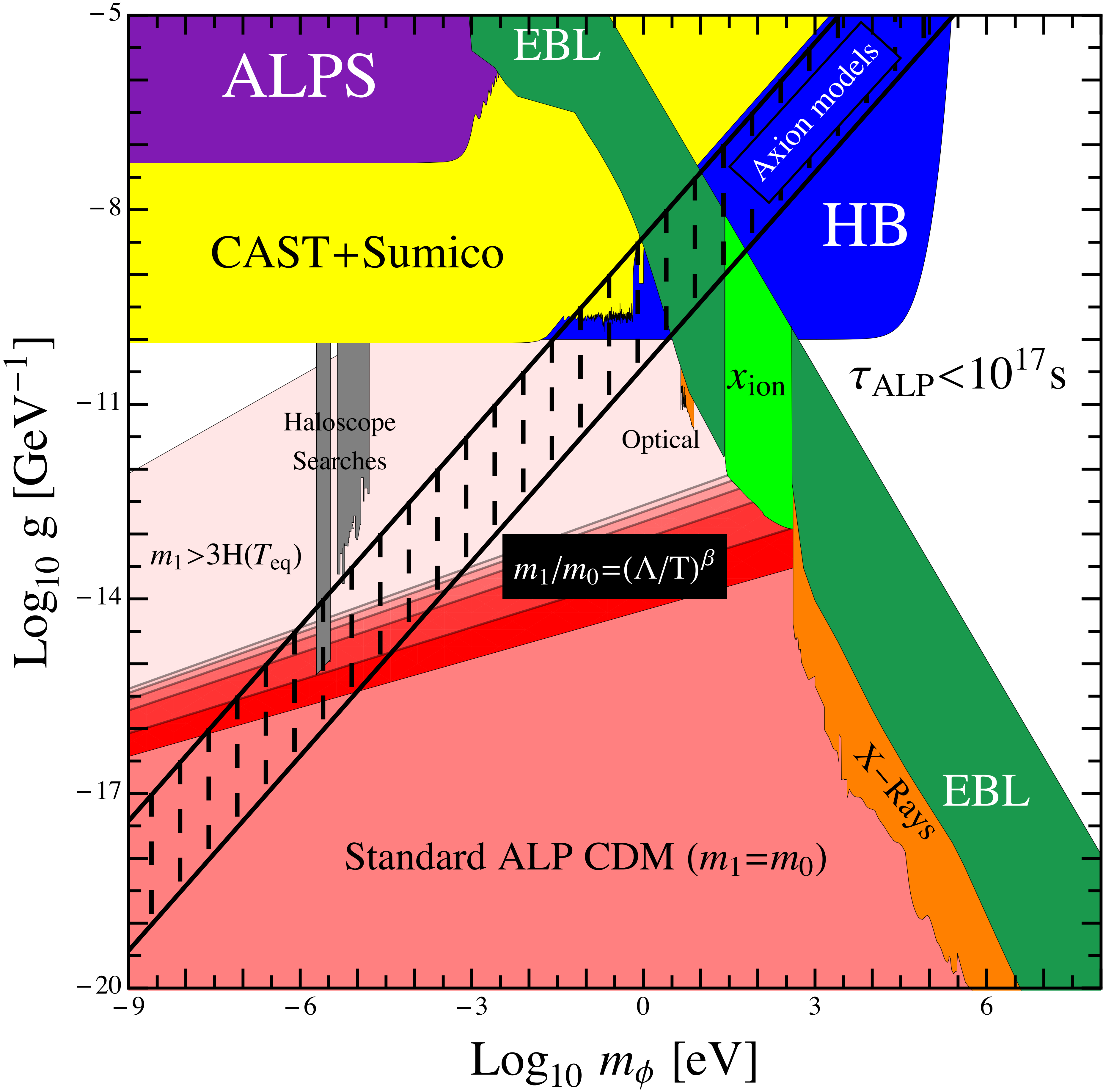
Cavity experiments looking for ALP CDM

based on $\phi \leftrightarrow \vec{E}$ mixing in a magnetic field (detect a tiny electric field, oscillating at fixed frequency $\omega \simeq m_\phi$)



- 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
$\tau_{ALP}<10^{17}$s
x_{ion}
Haloscope Searches
Optical
$m_1>3H(T_{eq})$
$m_1/m_0=(\Lambda/T)^\beta$
X-Rays
EBL
Standard ALP CDM ($m_1=m_0$)
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Log_{10} m_ϕ [eV]
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−20
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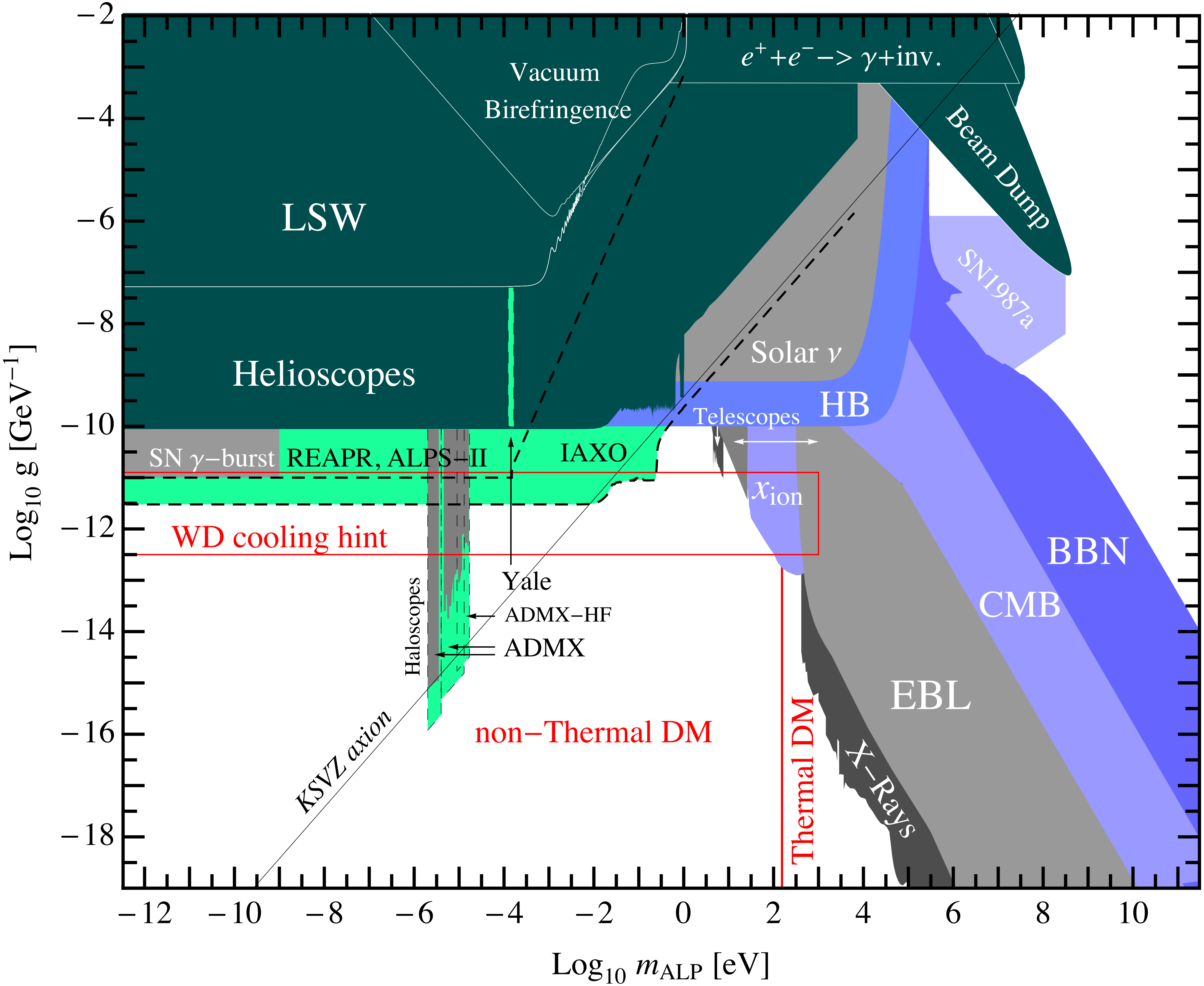
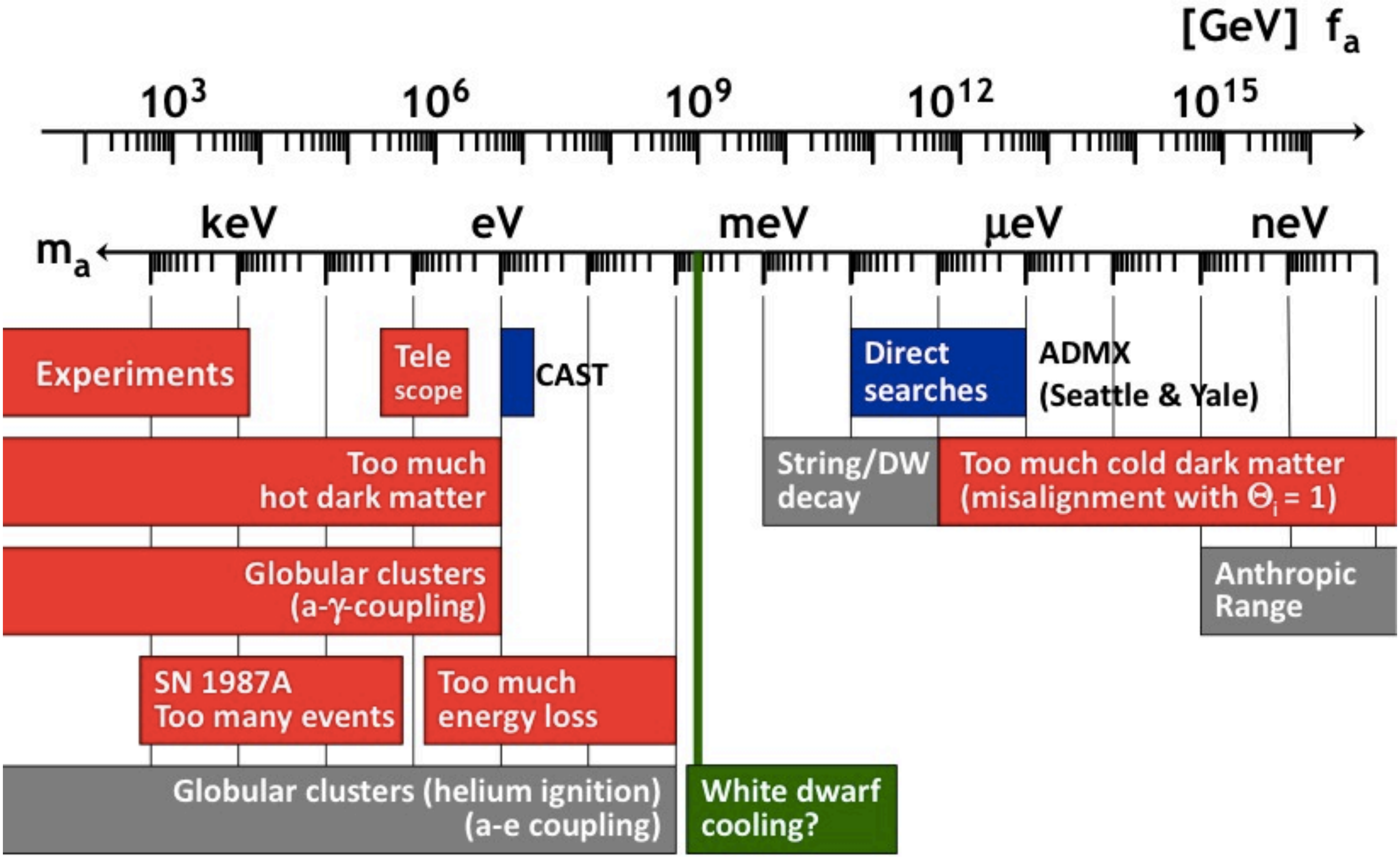
−6
−3
0
3
6



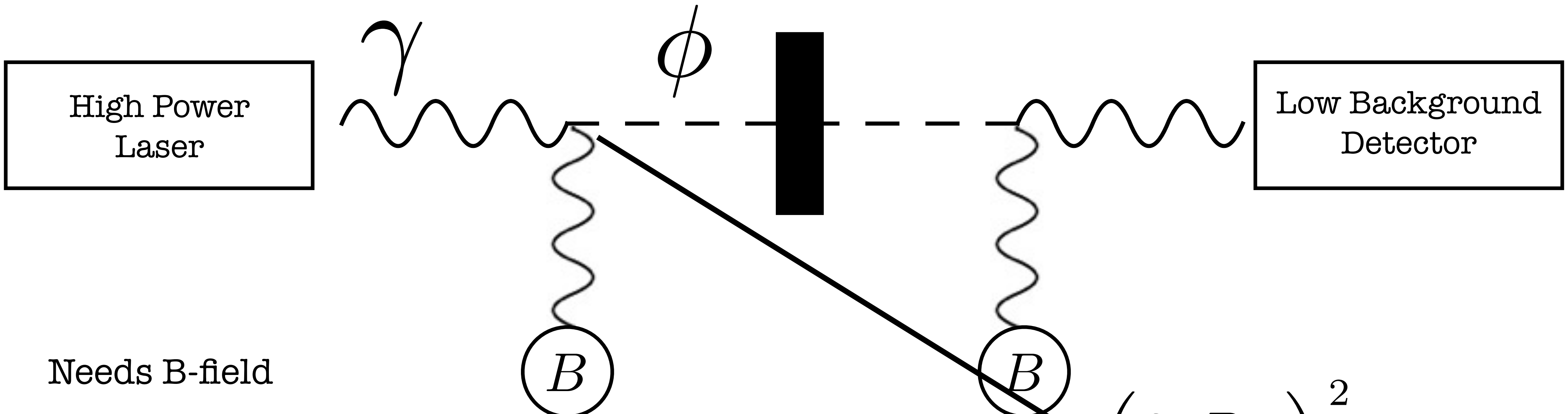
LSW
Vacuum Birefringence
$e^+ + e^- -> \gamma$+inv.
Beam Dump
Helioscopes
SN1987a
Solar ν
HB
Telescopes
SN γ−burst
REAPR, ALPS−II
IAXO
x_{ion}
WD cooling hint
Yale
ADMX−HF
ADMX
Haloscopes
BBN
CMB
EBL
X−Rays
Thermal DM
non−Thermal DM
KSVZ axion
Log$_{10}$ g [GeV^{-1}]
Log$_{10}$ m_{ALP} [eV]

Axion Bounds and Searches



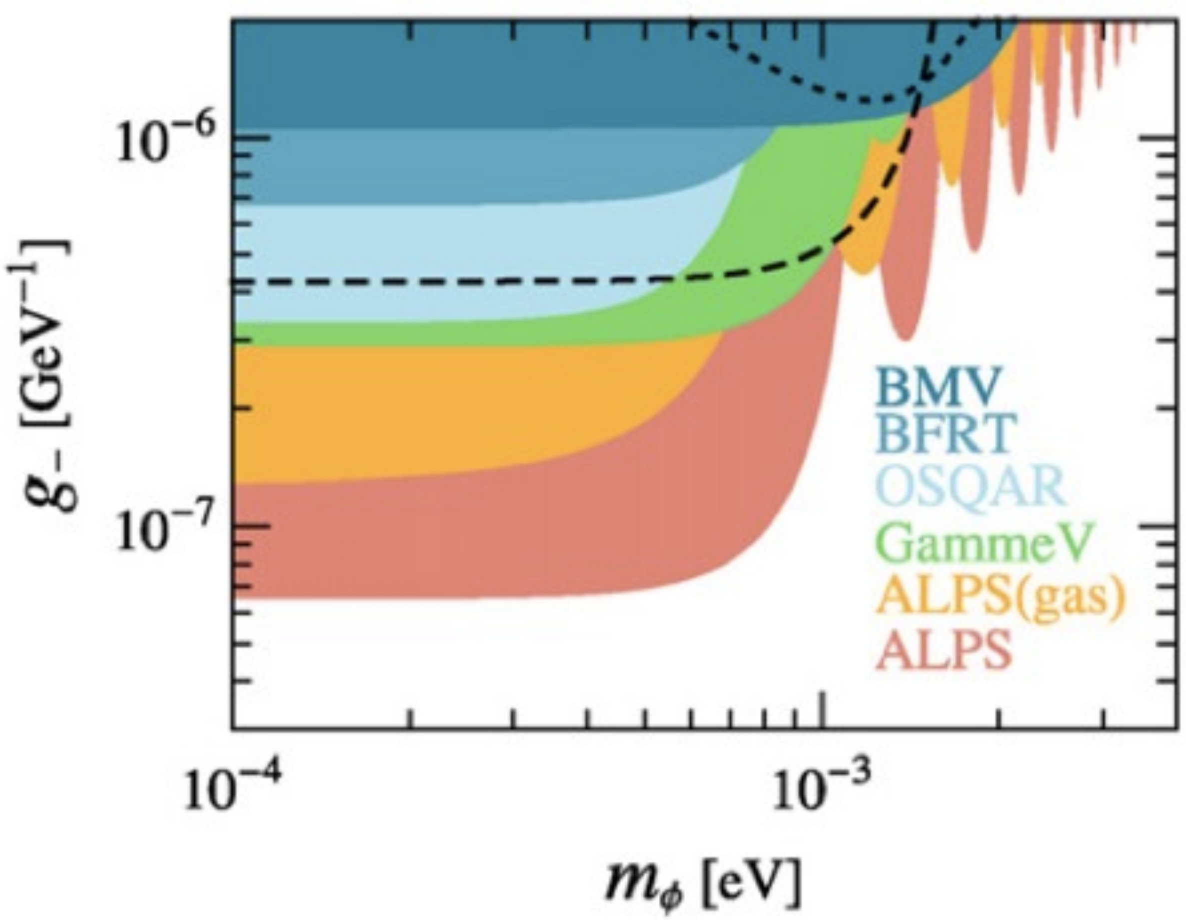
Laboratory Experiments (just an important sample)

Laser shining through walls (LSW)



Needs B-field

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



ALPS DESY

Ehret et al. 2010

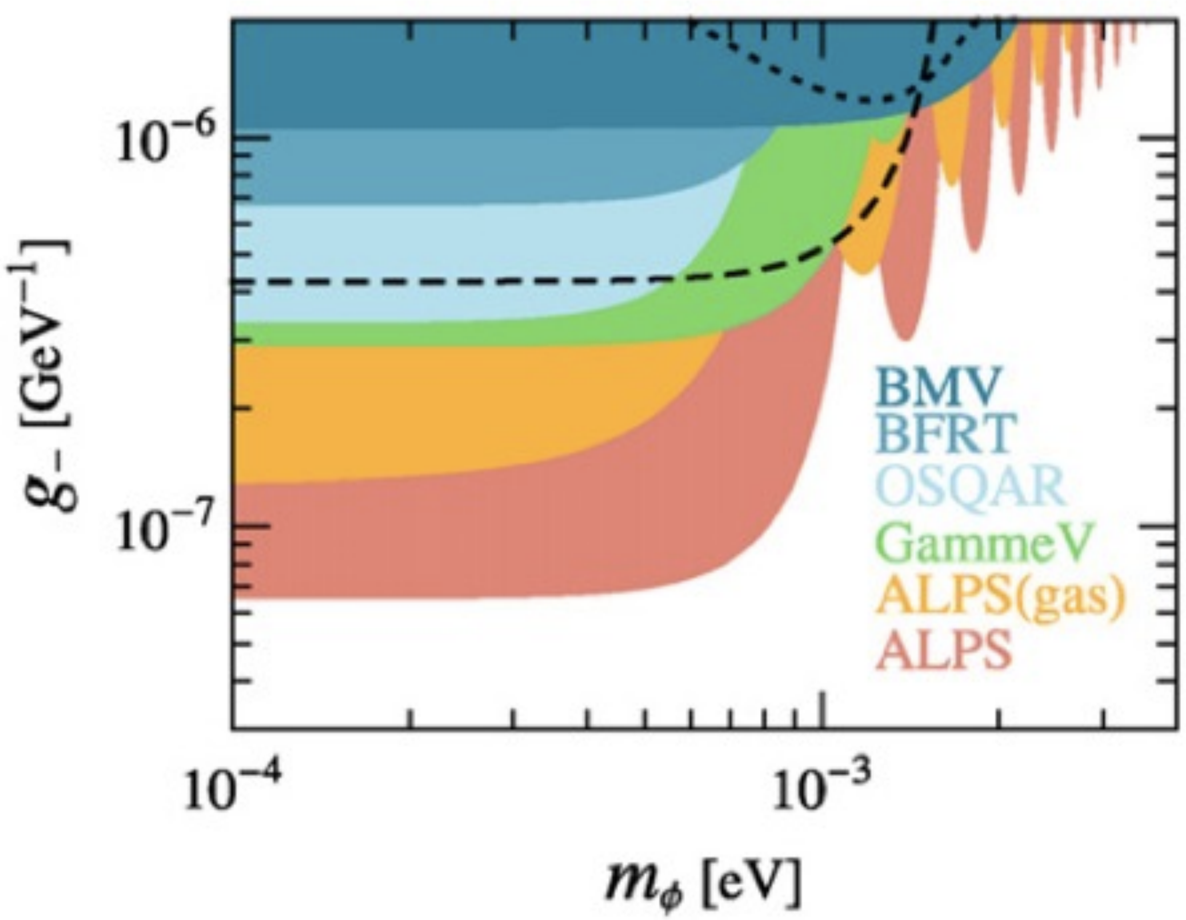
Laboratory Experiments (just an important sample)

Laser

High
L

Need

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



ALPS

DESY

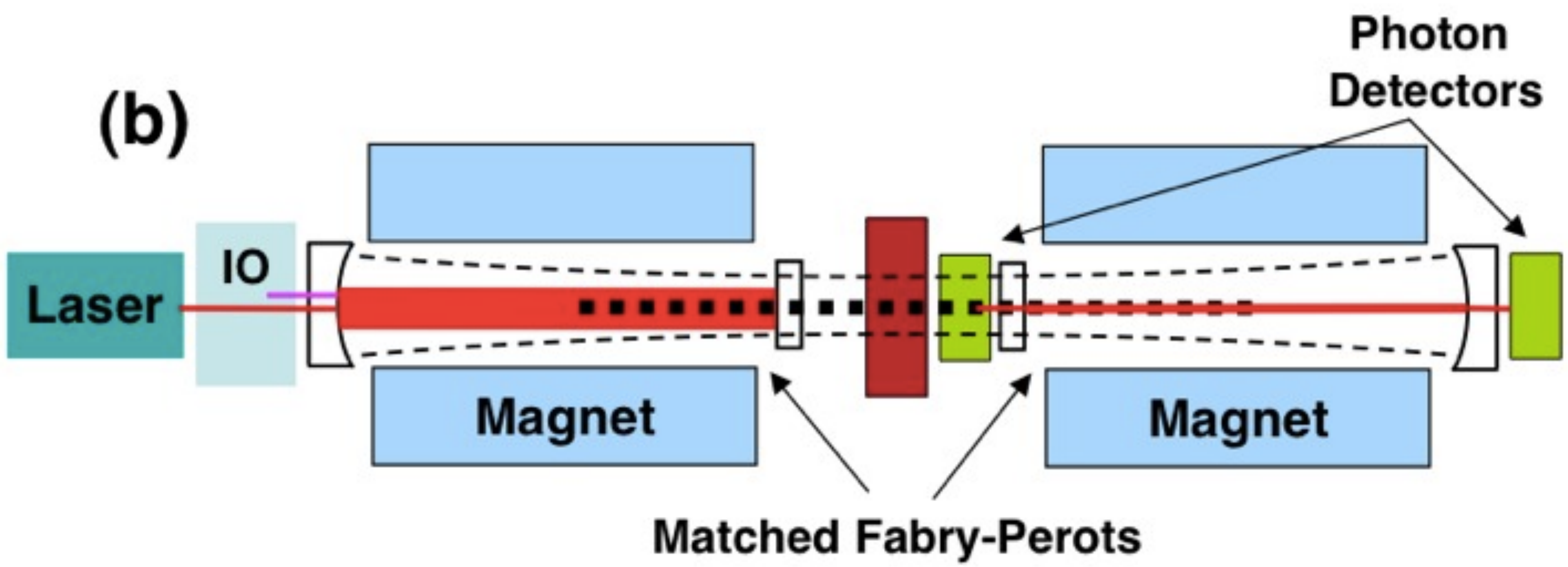
Ehret et al. 2010

Next Generation of LSW

Hoogeveen 91, Sikivie 2009

Much longer experiments + 2nd resonant cavity

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



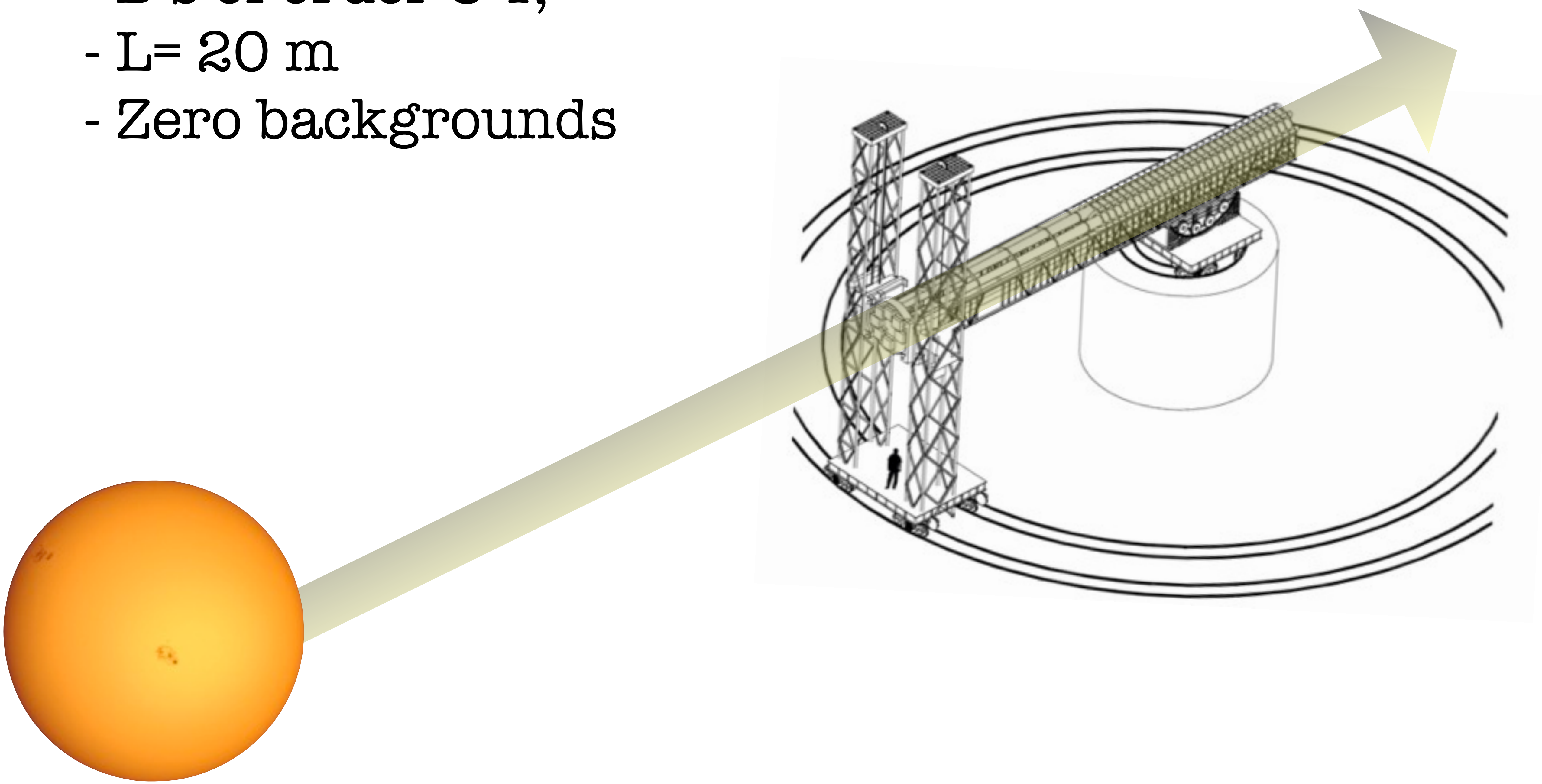
Two competing groups:

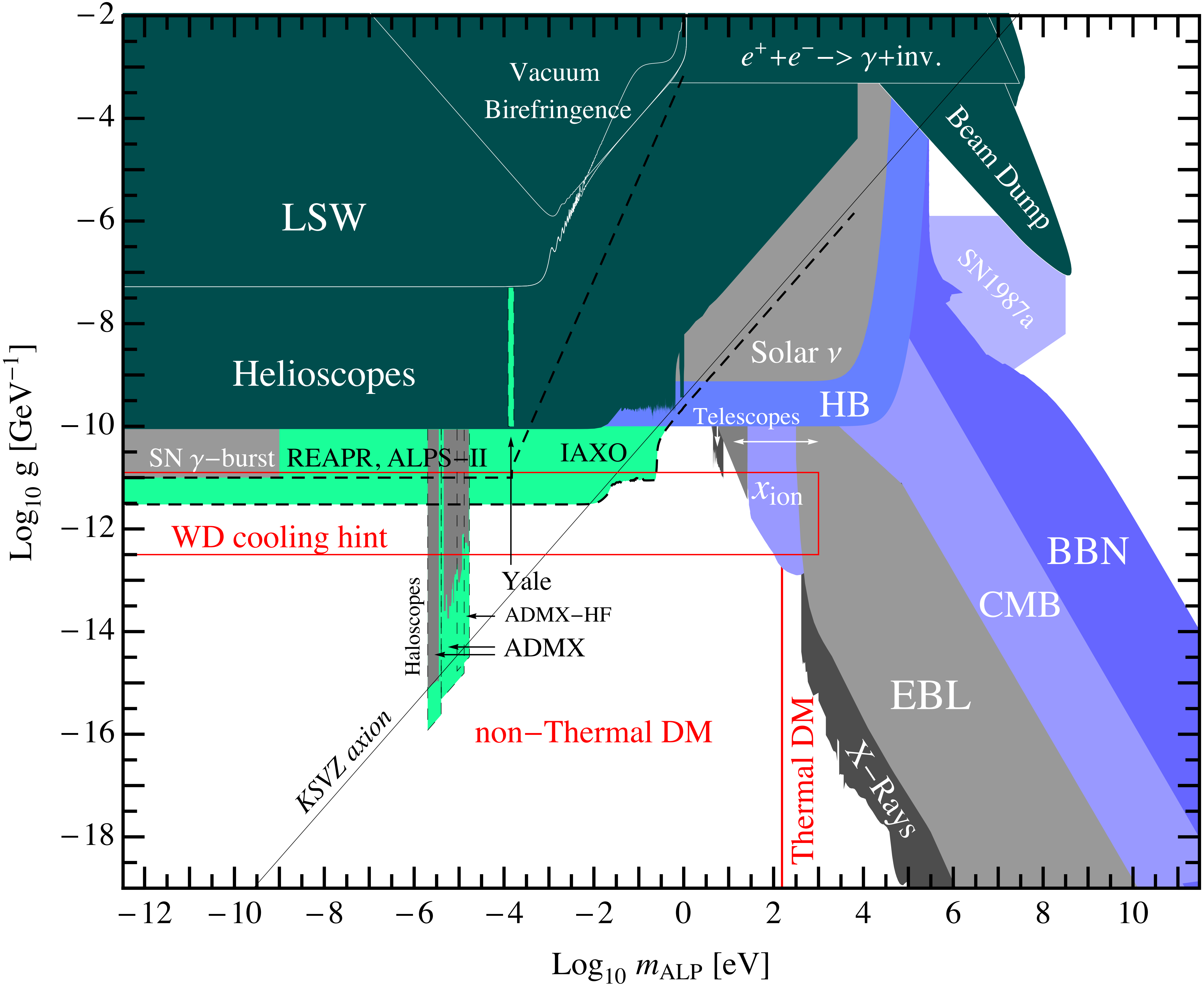
ALPS II @ DESY vs. Fermilab

Other experiments are sensible to ALPs

- International Solar observatory

  - B's of order 5 T,
  - L= 20 m
  - Zero backgrounds





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Birefringence
$e^+ + e^- \rightarrow \gamma + \text{inv.}$
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non−Thermal DM
KSVZ axion
Thermal DM
X−Rays
$\mathrm{Log}_{10}\, g\ [\mathrm{GeV}^{-1}]$
$\mathrm{Log}_{10}\, m_{\mathrm{ALP}}$ [eV]

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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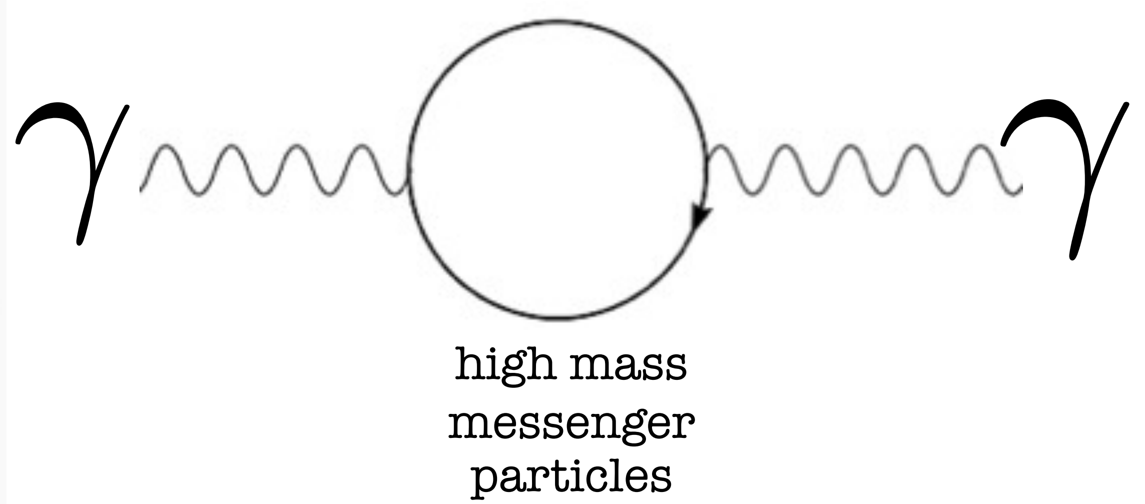

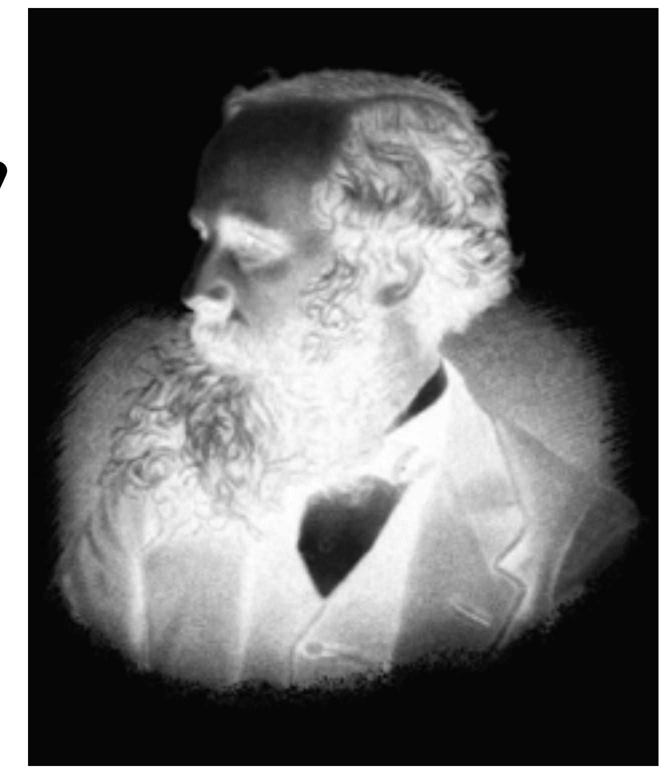

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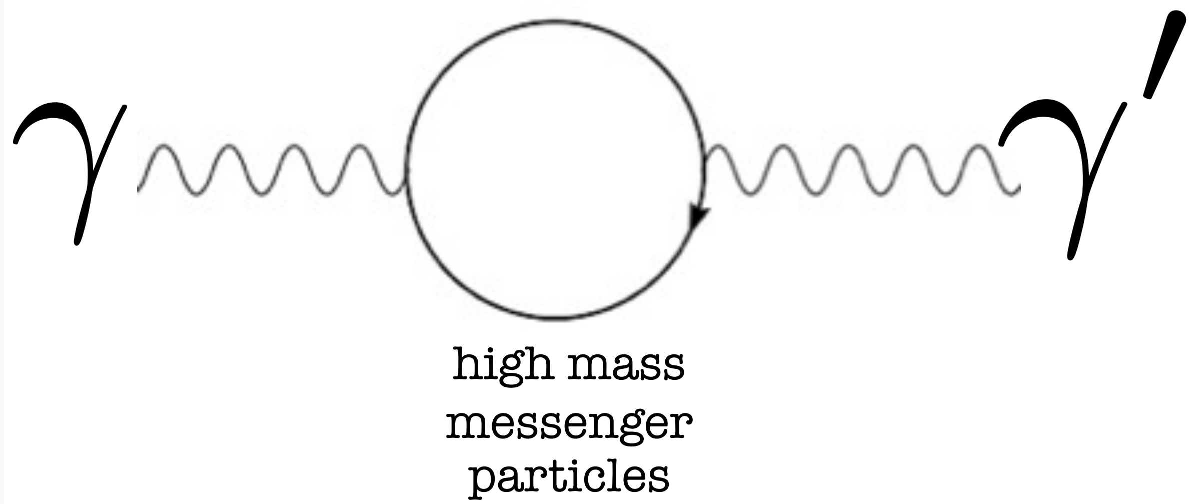
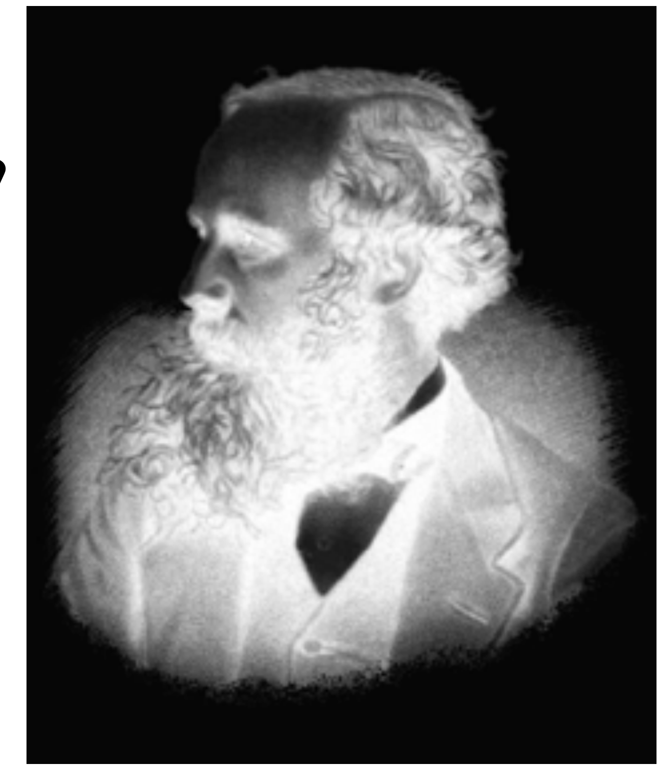
If the corresponding Hidden photon does not couple to SM particles ->
HIDDEN PHOTON





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

$$\chi \sim \frac{e g_h}{16\pi^2} \log \frac{m}{\mu} \sim 10^{-3}$$

natural value
not soooo small!

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

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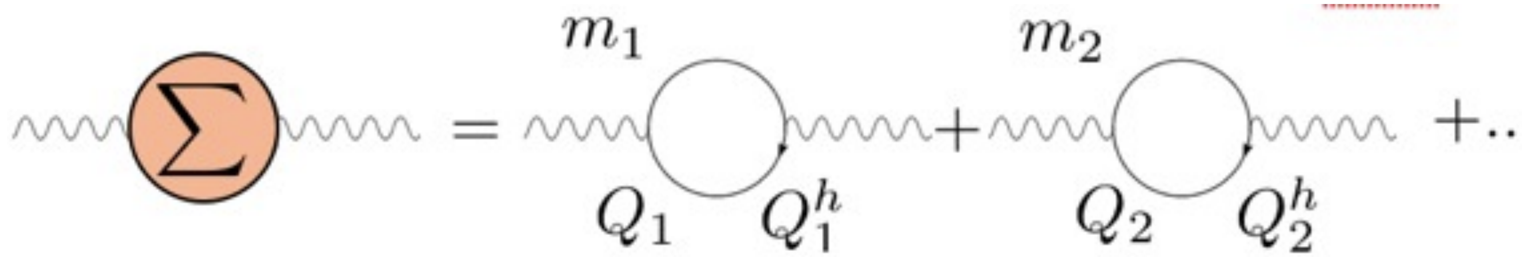

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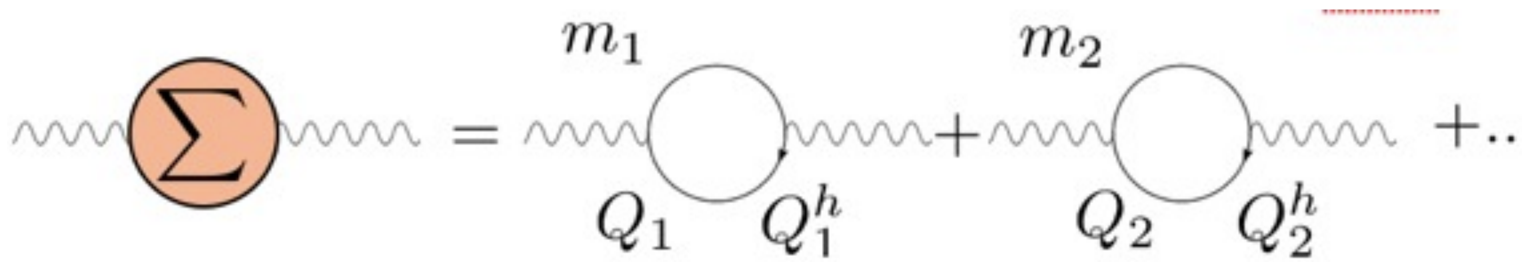
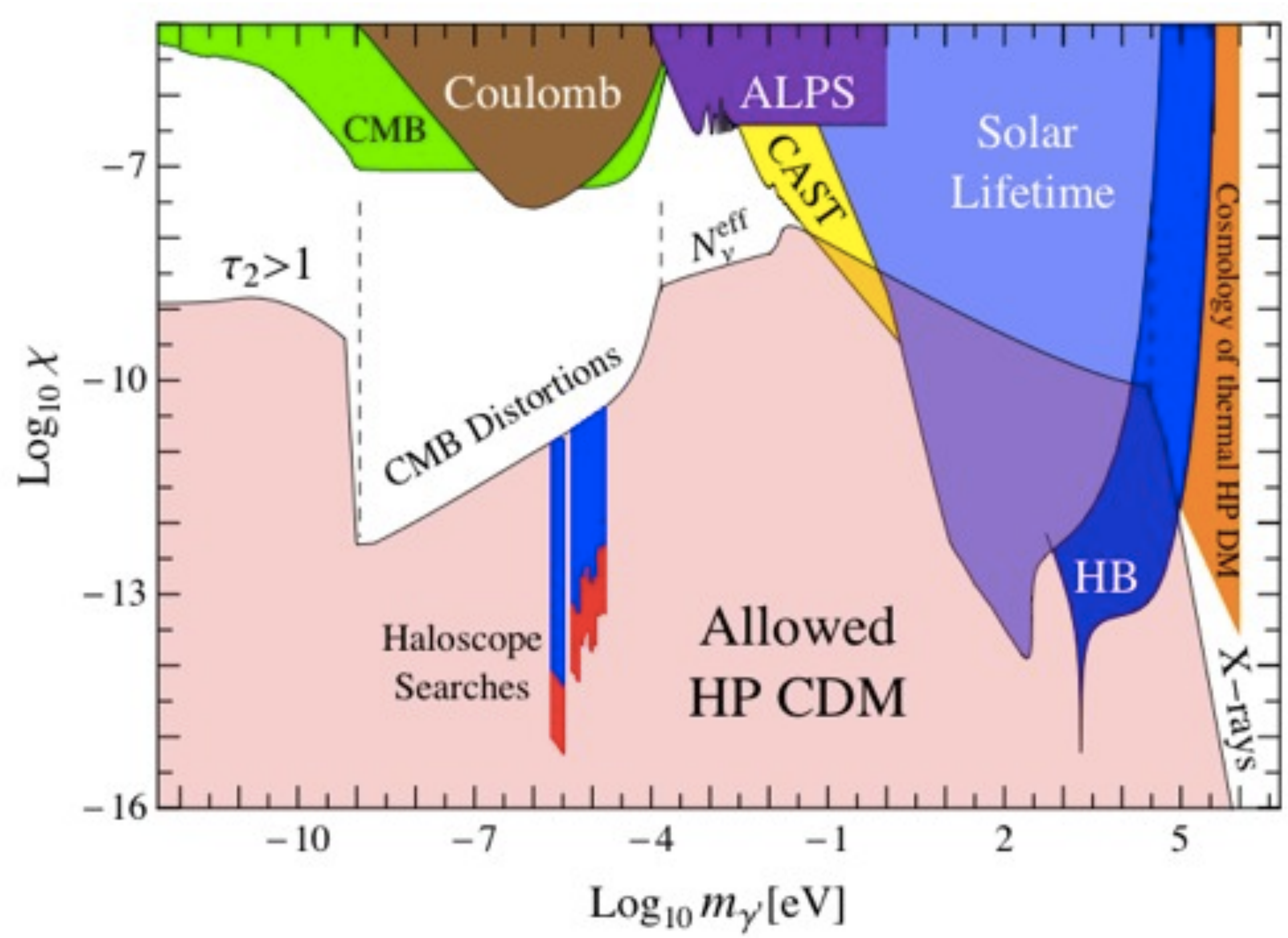


Again a huge parameter space to explore, even in the minimal case!



Crucial Differences

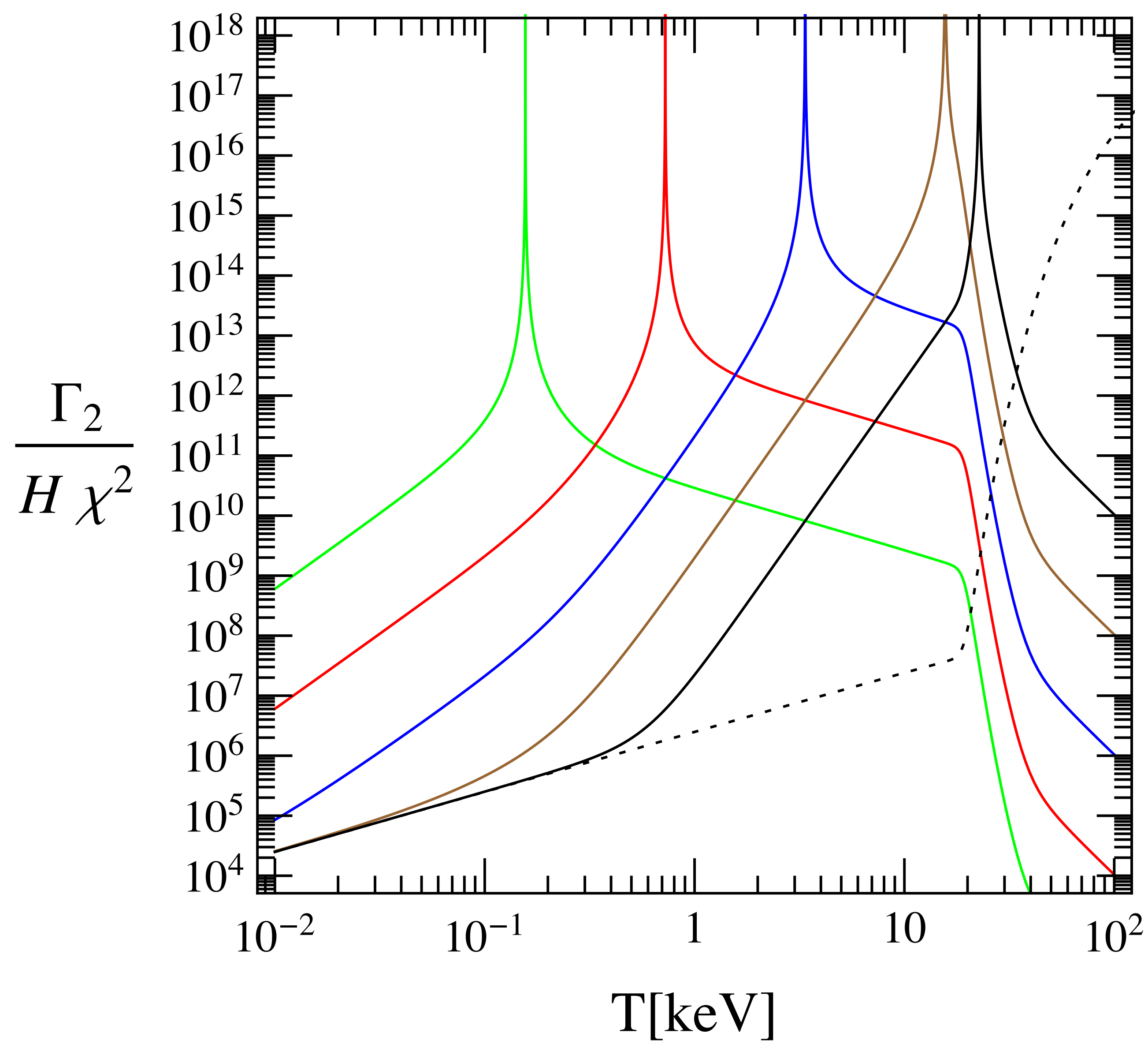
- The initial value of amplitude is not bounded!

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

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

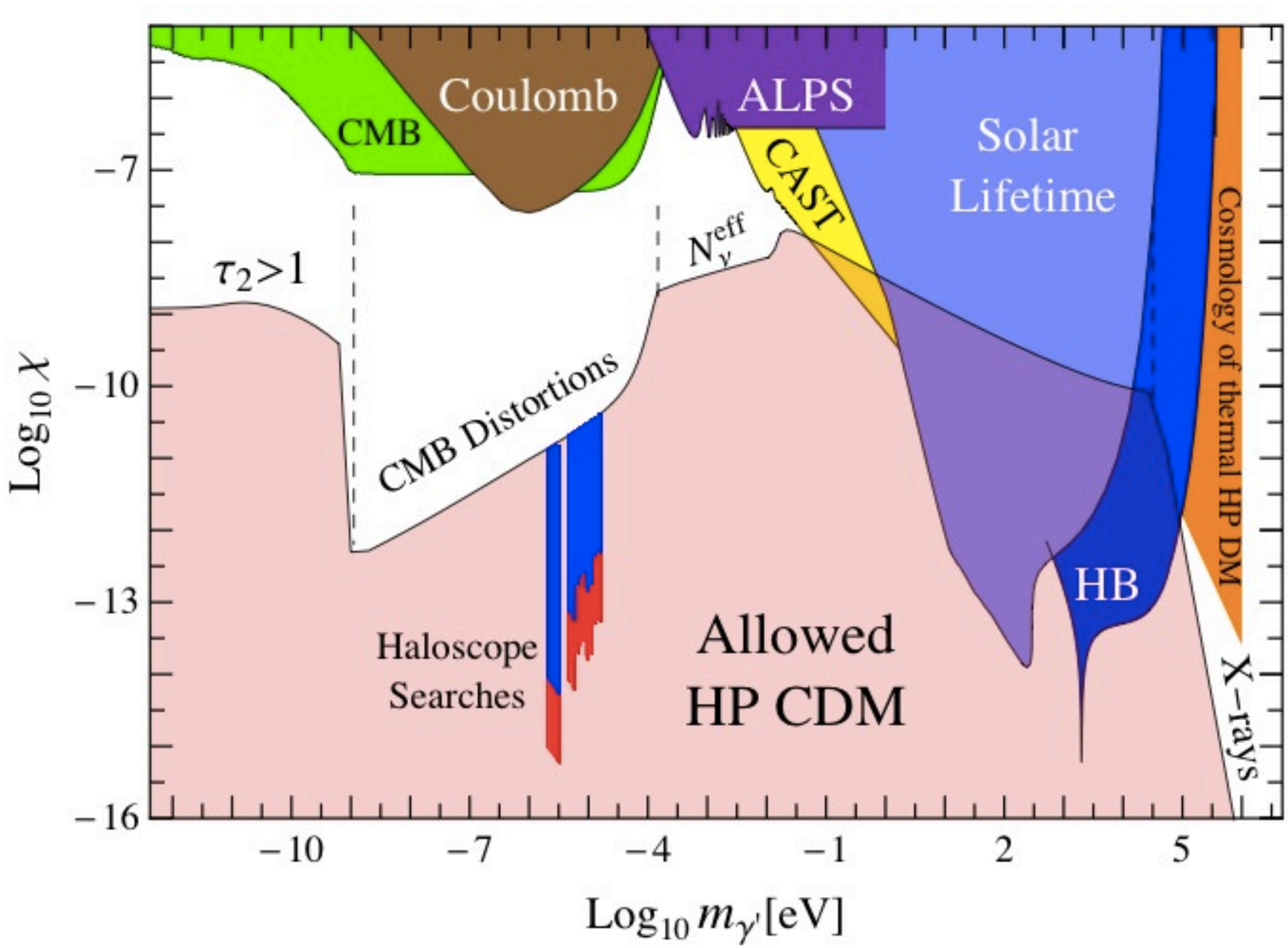
- Small E field in the universe

- 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)

- WISPs can be searched experimentally

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