WISPy cold dark matter

8th Patras Workshop on axions, WIMPS and WISPs
Hyatt Regency & Fermilab, Chicago 23/07/2012

Javier Redondo, MPP München

8th Patras Workshop on Axions, WIMPs & WISPs
July 18 - 22, 2012 • Hyatt Regency, Chicago, Illinois (USA)
http://axion-wimp.desy.de/
Programme
The physics case for WIMPs, Axions, WISPs
Searches for Hidden Sector Photons
Signals from astrophysical sources
Direct and Indirect searches for Dark Matter
Indirect and Direct searches for Axions and WISPs
New theoretical developments
Review of collider experiments
Scalar Dark Energy, theory and experiment
Harrison HOTEL PARK FREE
TORCO
U.S. DEPARTMENT OF ENERGY
Office of Science
Fermilab
Fermi Research Alliance LLC
UF FLORIDA
Jefferson Lab
URA
Yale

n-th Patras Workshop on axions, WIMPs and WISPs

Why bother?

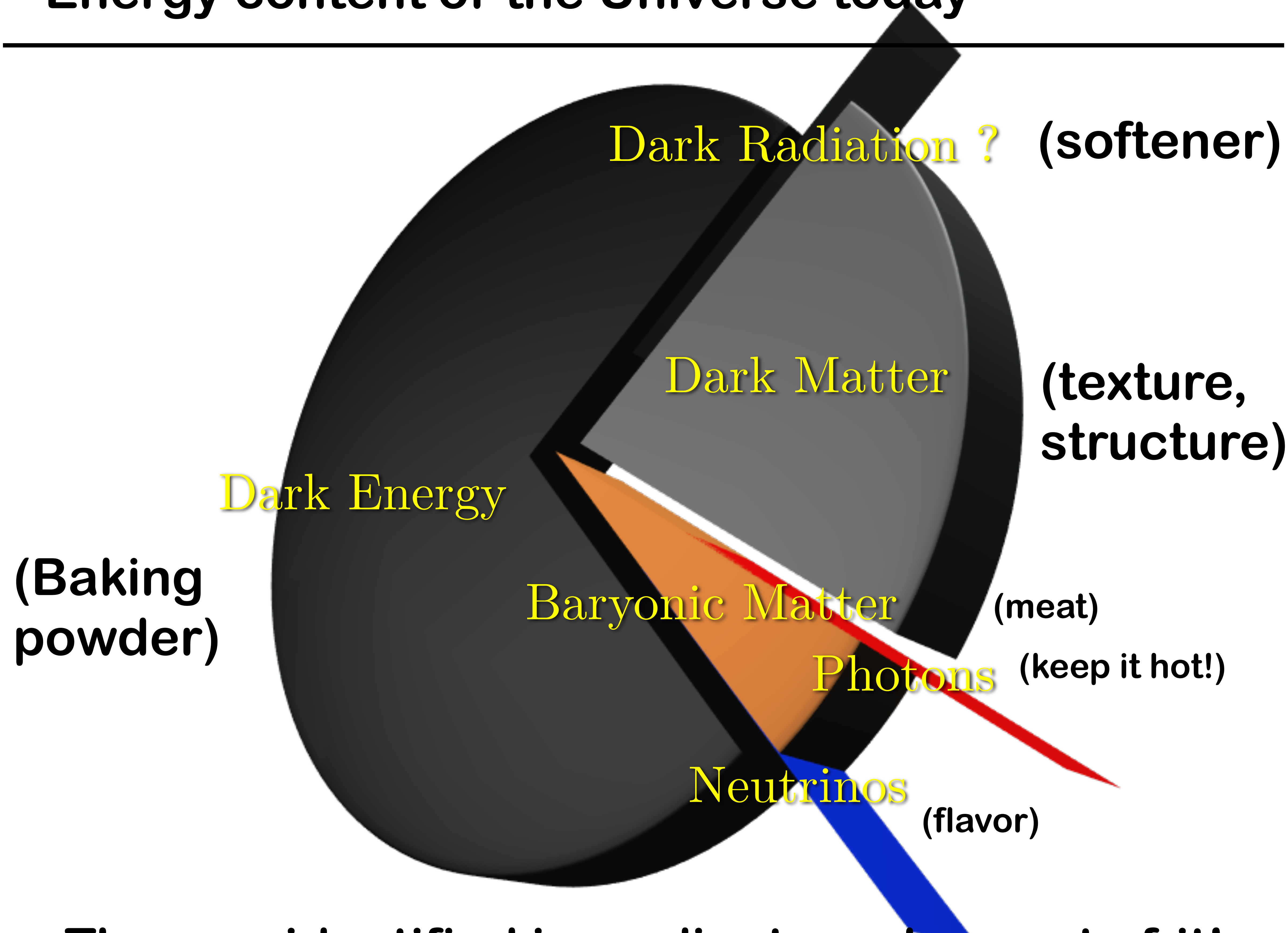
- generic predictions of HE completions of the SM

- strong CP problem & axions

- hints from astrophysics

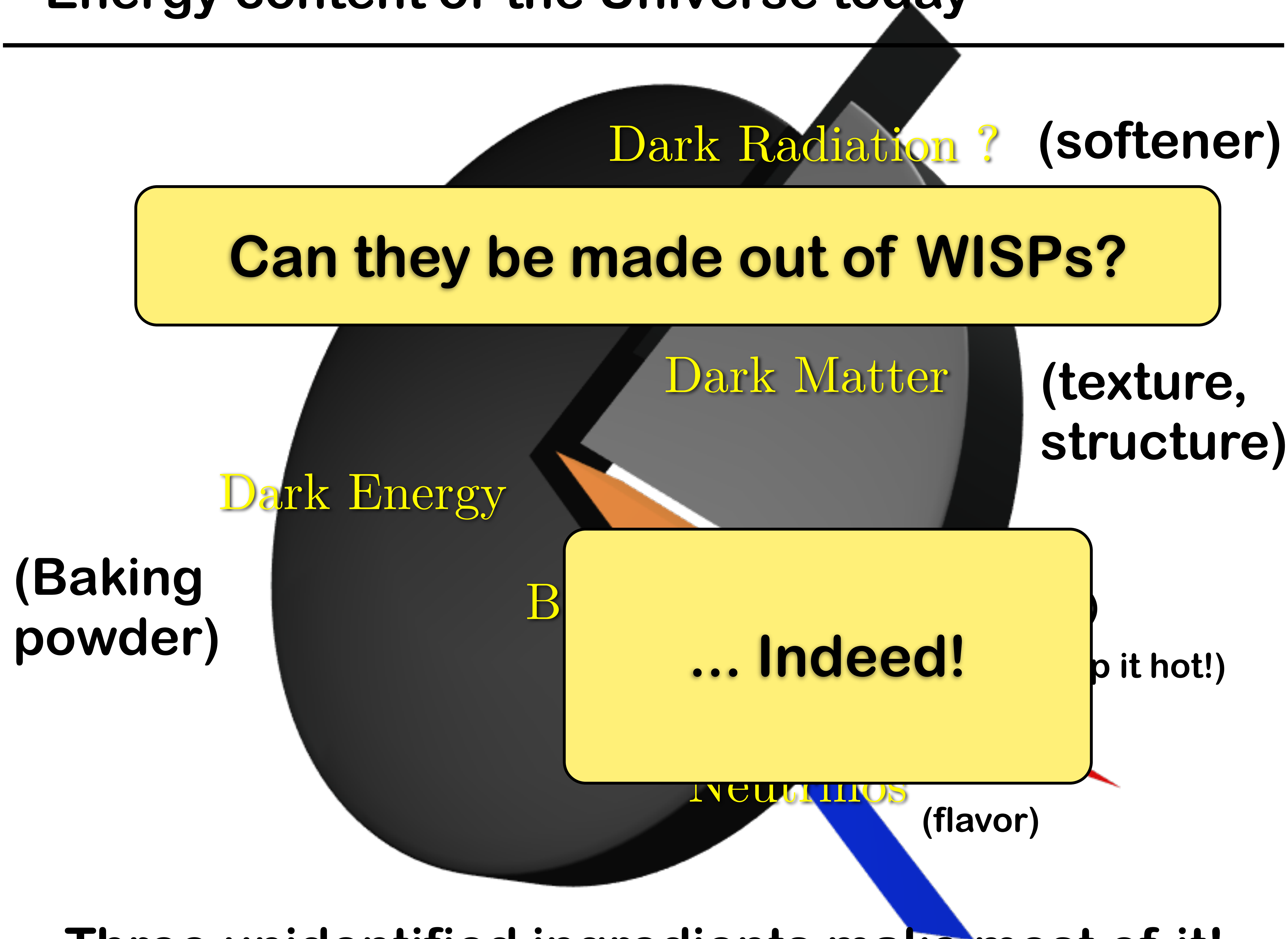
- and ... cosmology ... Dark matter !!!!!!!!

Energy content of the Universe today



Three unidentified ingredients make most of it!

Energy content of the Universe today



Three unidentified ingredients 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)

Very WISPy

- Matter -

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

(most of them)

mmm...

Axion cold Dark Matter

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

Realignment mechanism **Cosmic Strings** **Domain Walls**

(Field space) (Position space)

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

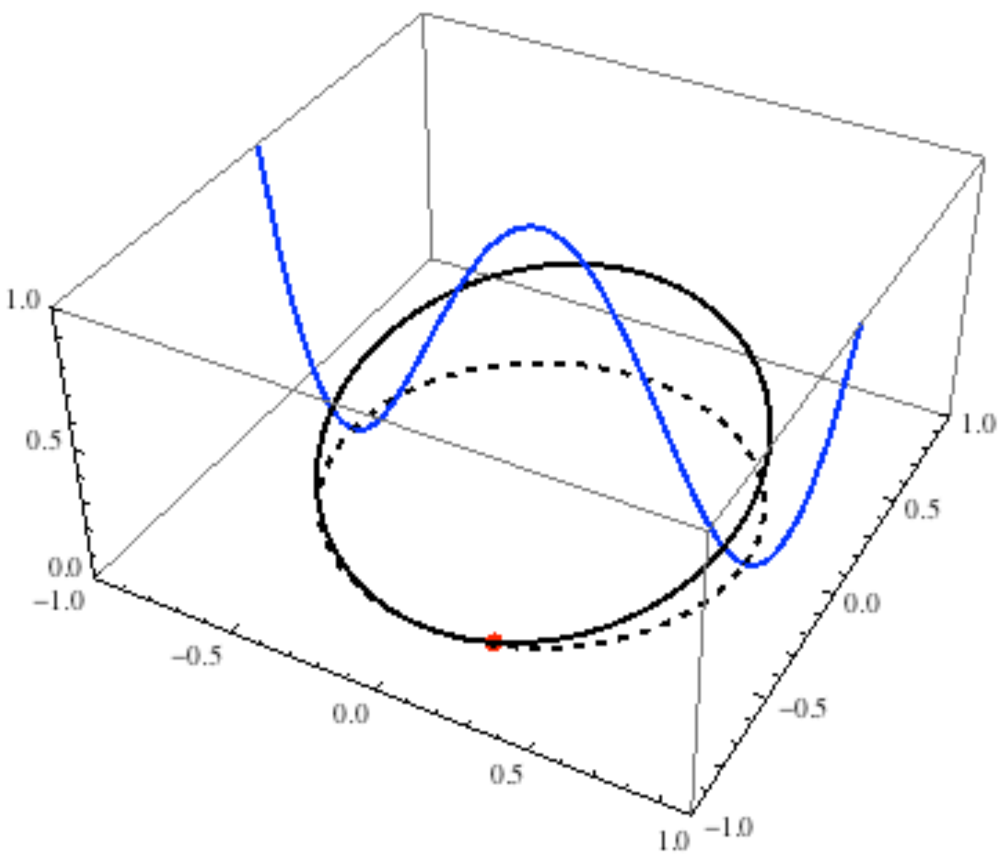
$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{40\mu{\rm eV}}{m_a}\right)^{1.184}$$

Axion cold Dark Matter

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

Realignment mechanism **Cosmic Strings** **Domain Walls**

(Field space) **(Position space)**



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

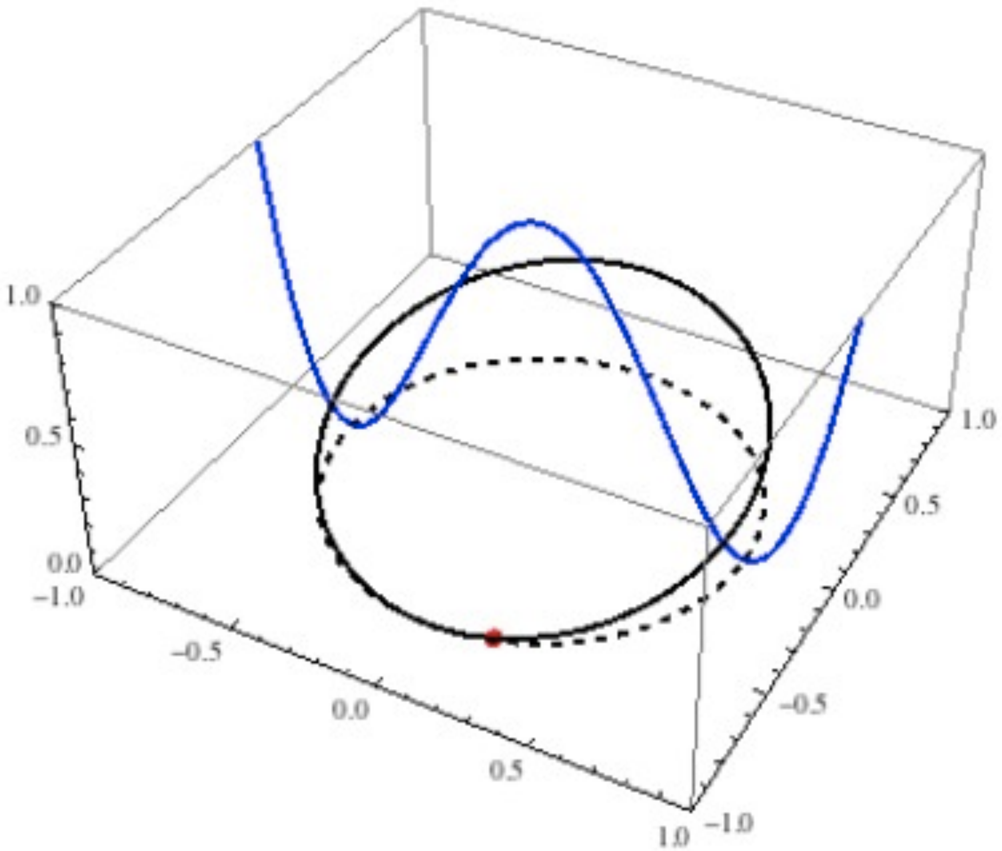
$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{40\mu\mathrm{eV}}{m_a}\right)^{1.184}$$

Axion cold Dark Matter

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

Realignment mechanism

(Field space)



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

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

Cosmic Strings

(Position space)

(T>QCD)

Domain Walls

(T<QCD)

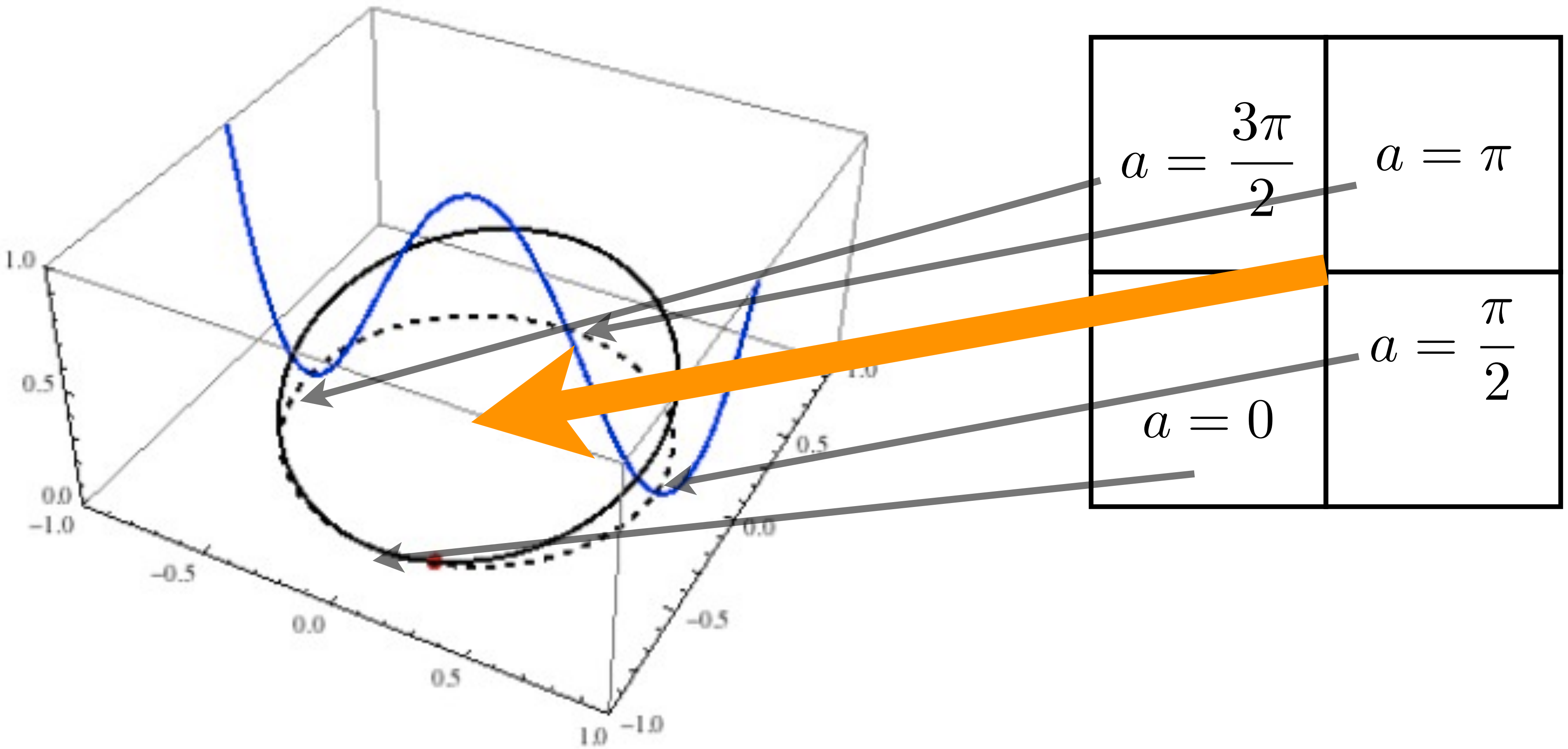
Axion cold Dark Matter

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

Realignment mechanism | **Cosmic Strings** | **Domain Walls**

(Field space) (Position space)

(T>QCD) (T<QCD)



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

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

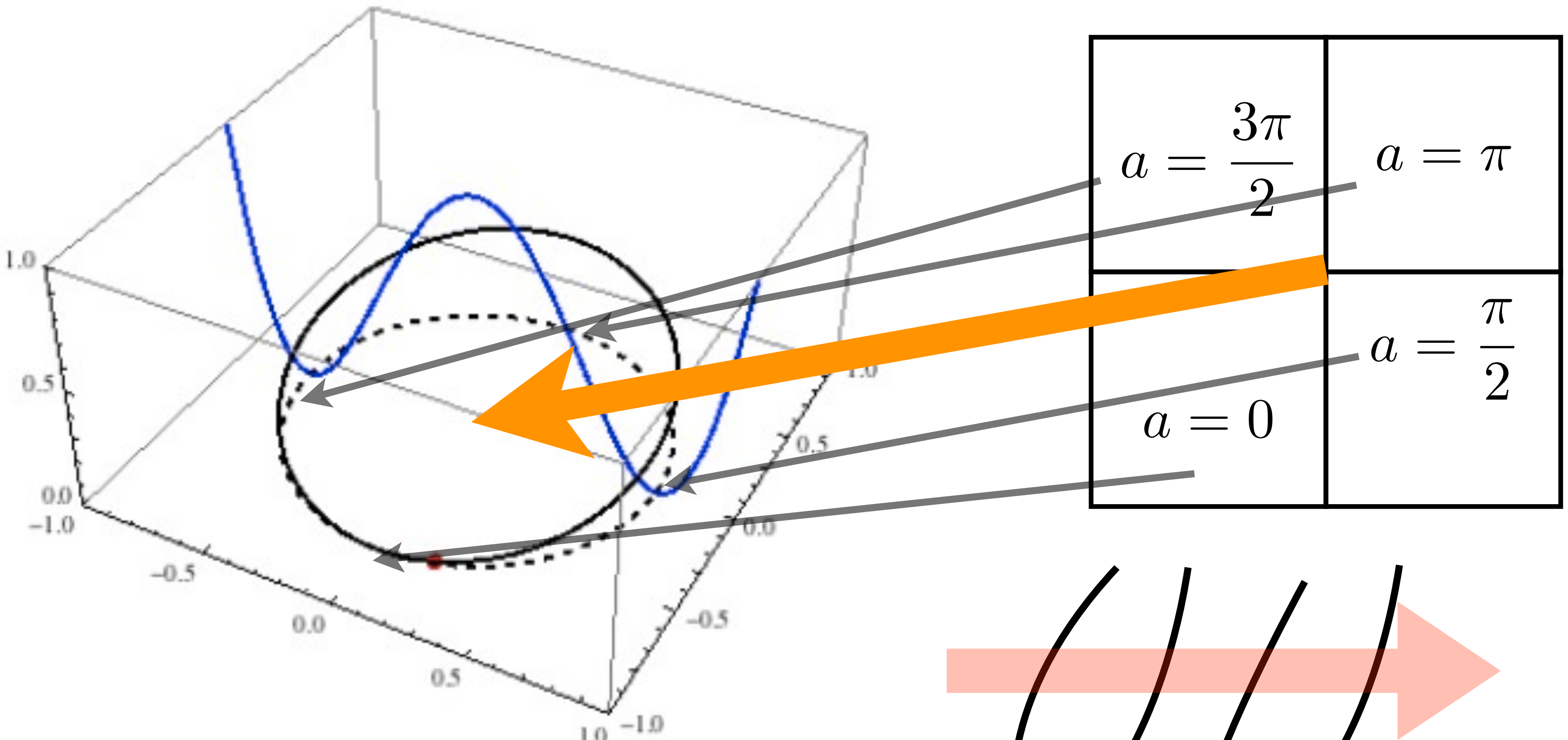
Axion cold Dark Matter

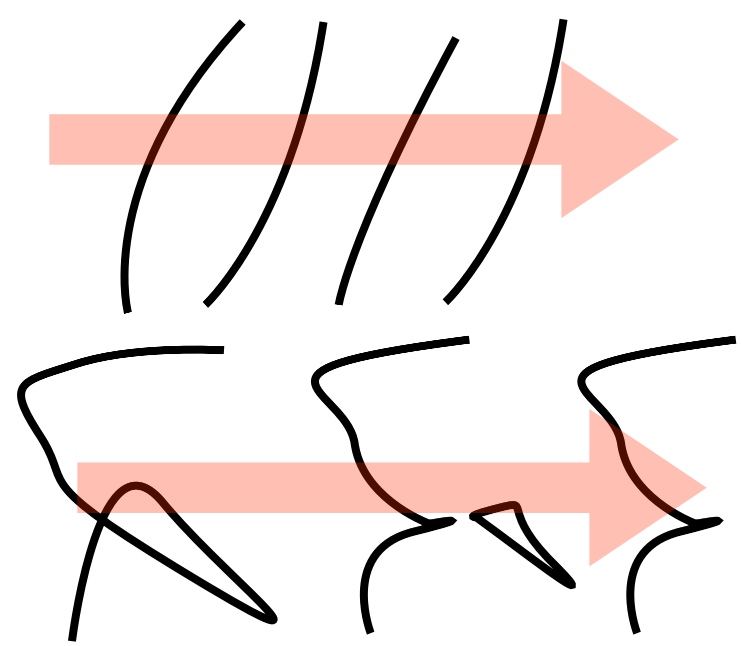
Axions (and ALPs) are produced non-thermally by three mechanisms

Realignment mechanism | **Cosmic Strings** | **Domain Walls**

(Field space) (Position space)

(T>QCD) (T<QCD)





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

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

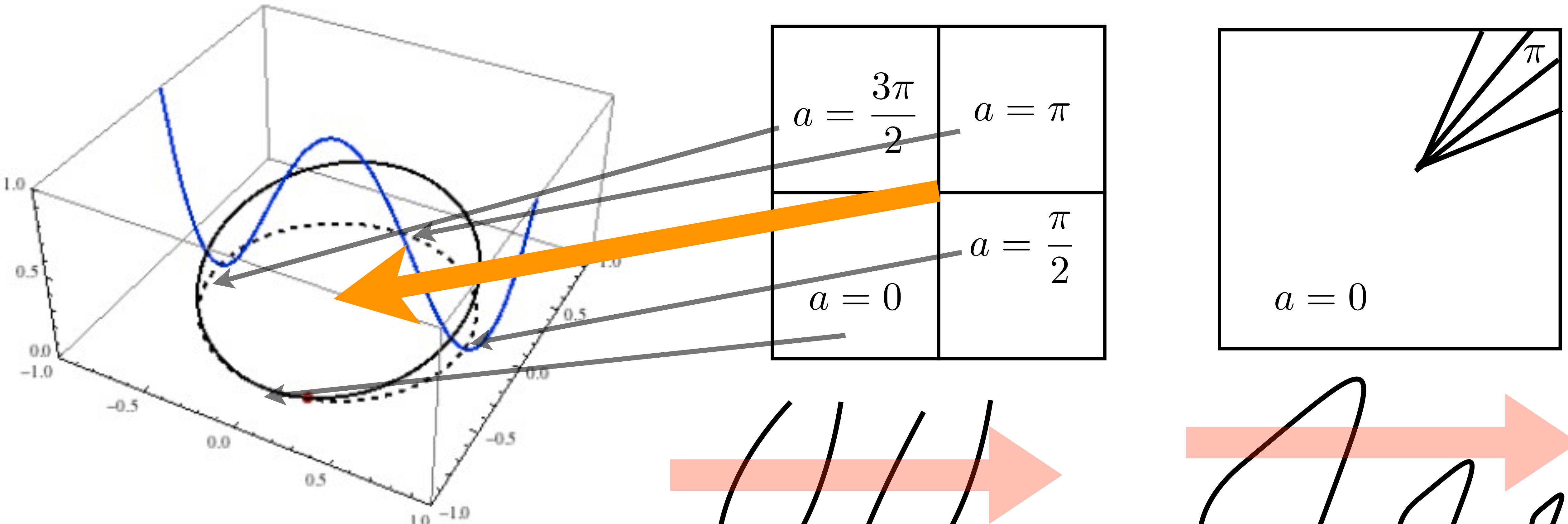
Axion cold Dark Matter

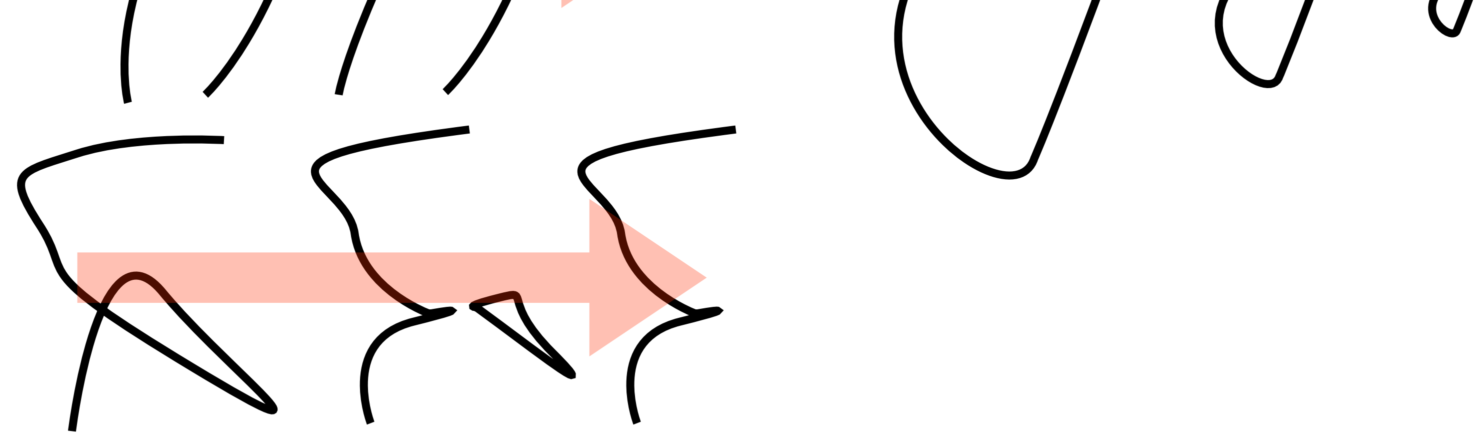
Axions (and ALPs) are produced non-thermally by three mechanisms

Realignment mechanism | **Cosmic Strings** | **Domain Walls**

(Field space) (Position space)

(T>QCD) (T<QCD)





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

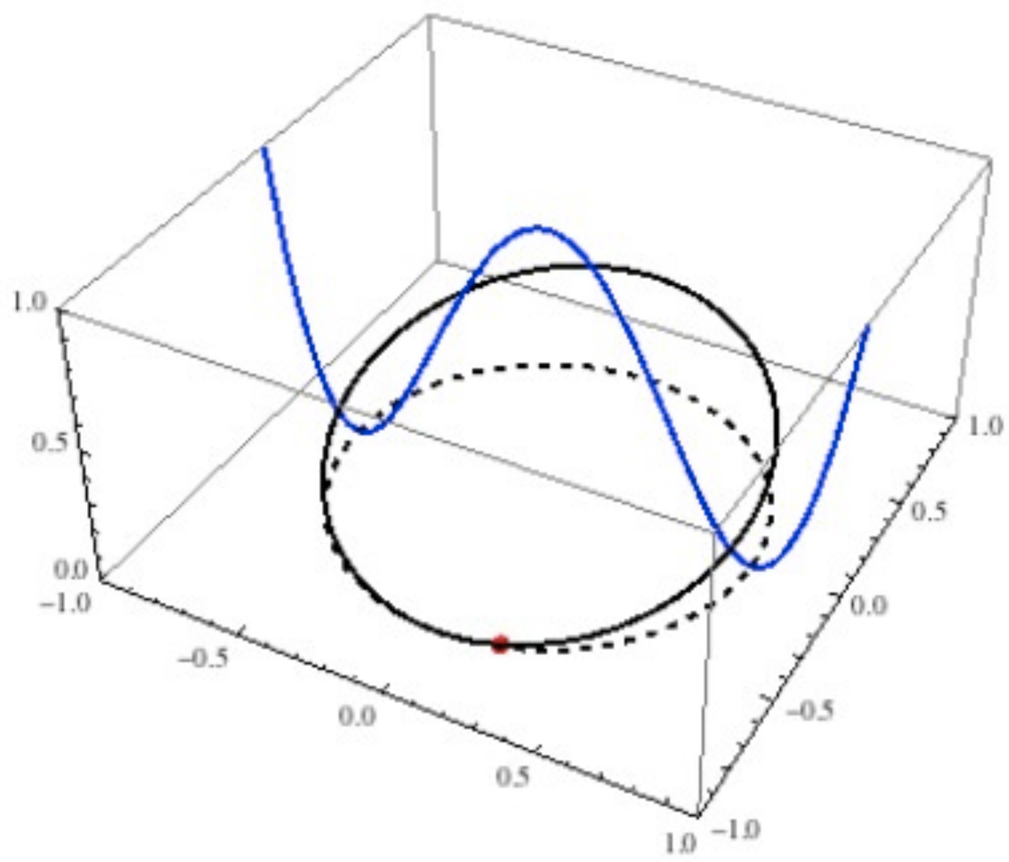
$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{40\mu\mathrm{eV}}{m_a}\right)^{1.184}$$

Axion cold Dark Matter

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

Realignment mechanism

(Field space)

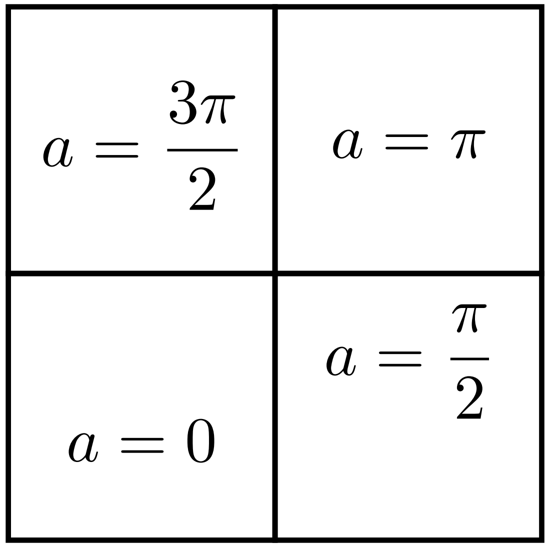


$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{40\mu{\rm eV}}{m_a}\right)^{1.184}$$

Cosmic Strings

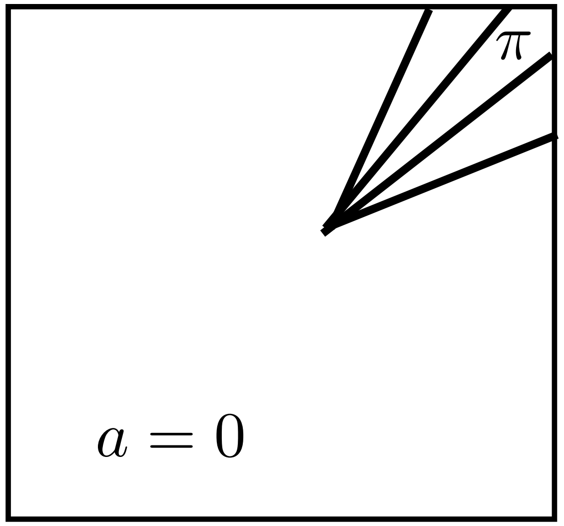
(Position space)

(T>QCD)



Domain Walls

(T<QCD)



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

Sikivie, Harari et at.

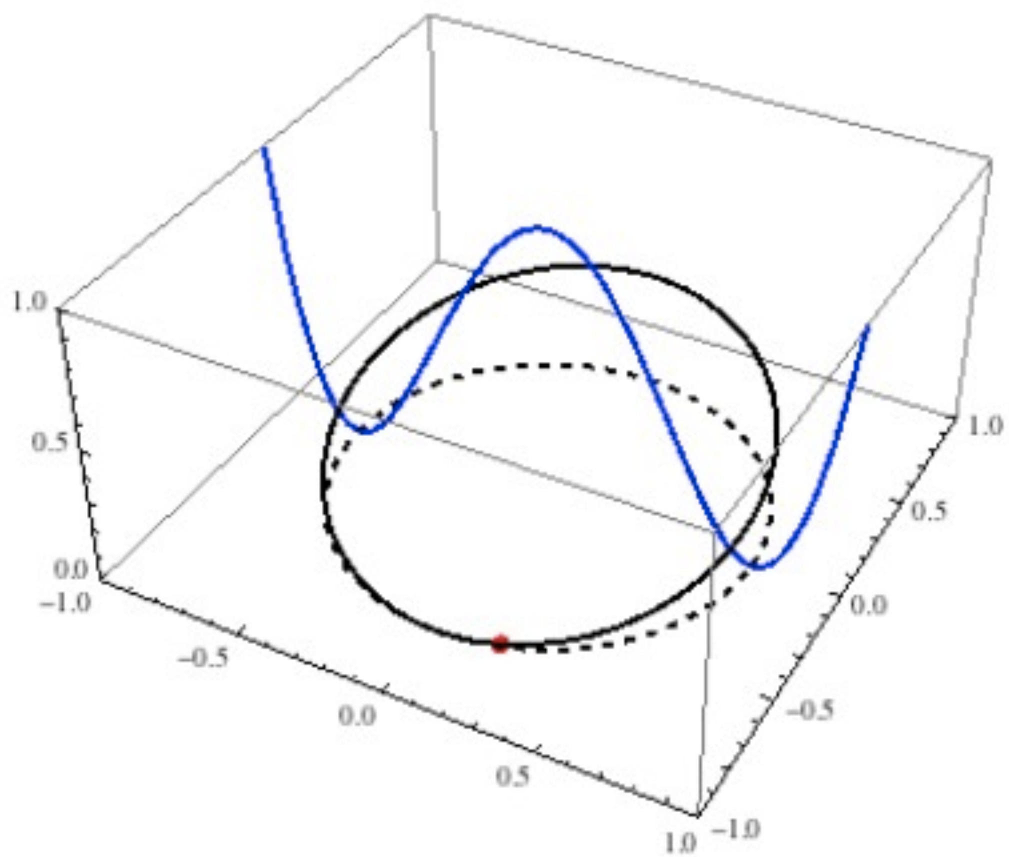
Shellard, Davis et at.
Kawasaki, Hiramatsu et at

Axion cold Dark Matter*

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

Realignment mechanism

(Field space)



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

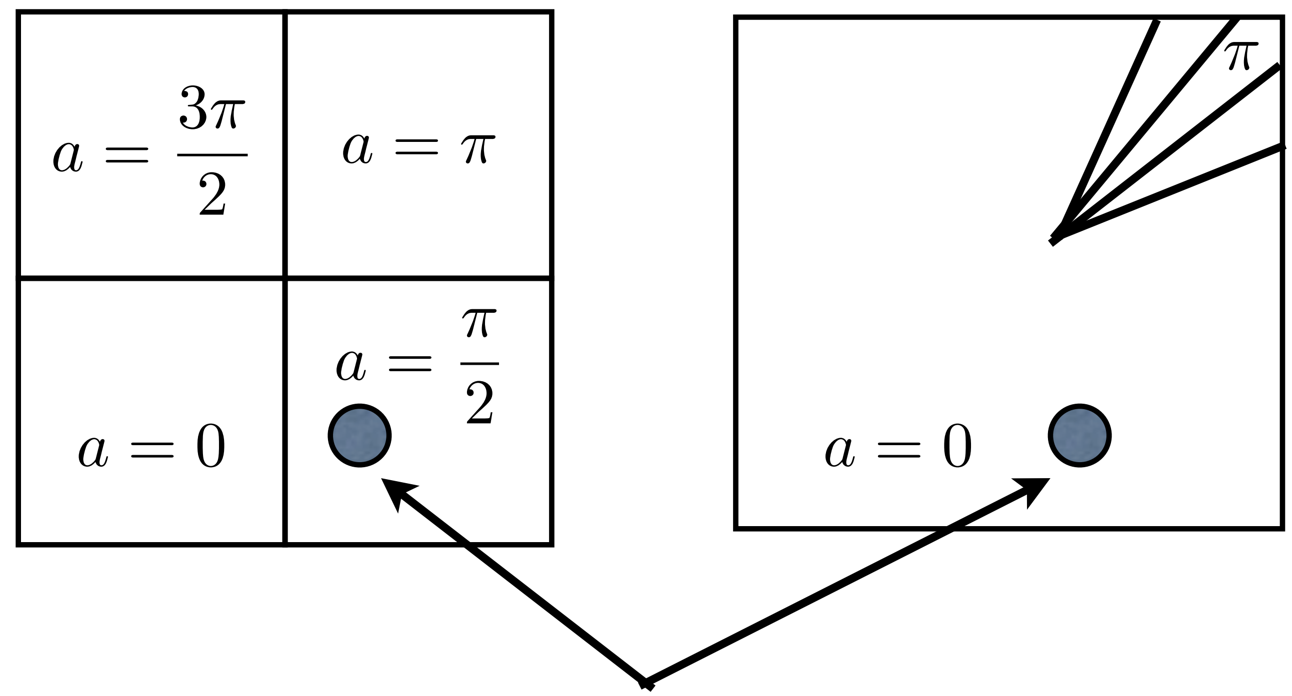
Cosmic Strings

(Position space)

(T>QCD)

Domain Walls

(T<QCD)



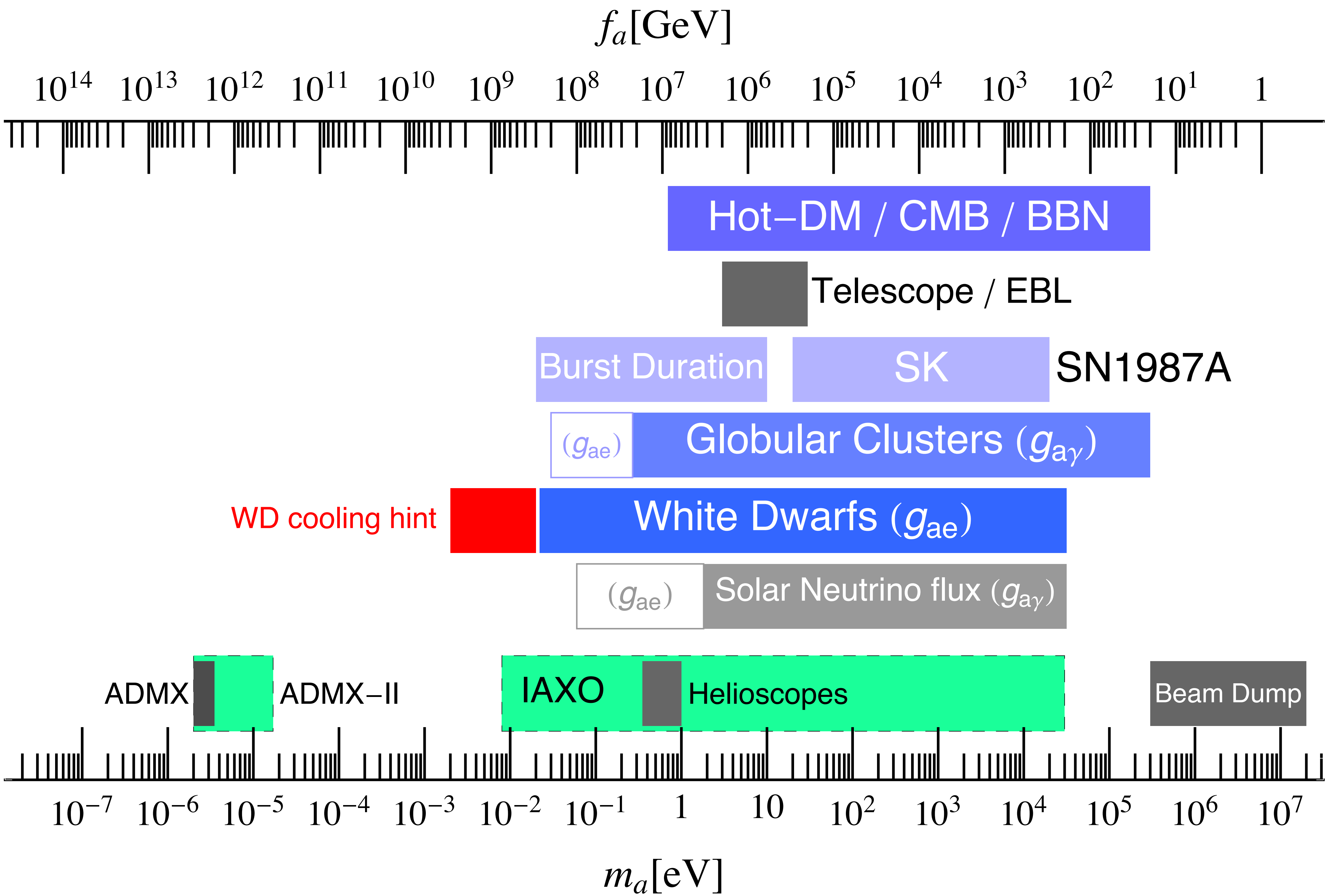
Size of our universe after inflation fits inside one of these domains

- CSs and DWs are diluted by expansion

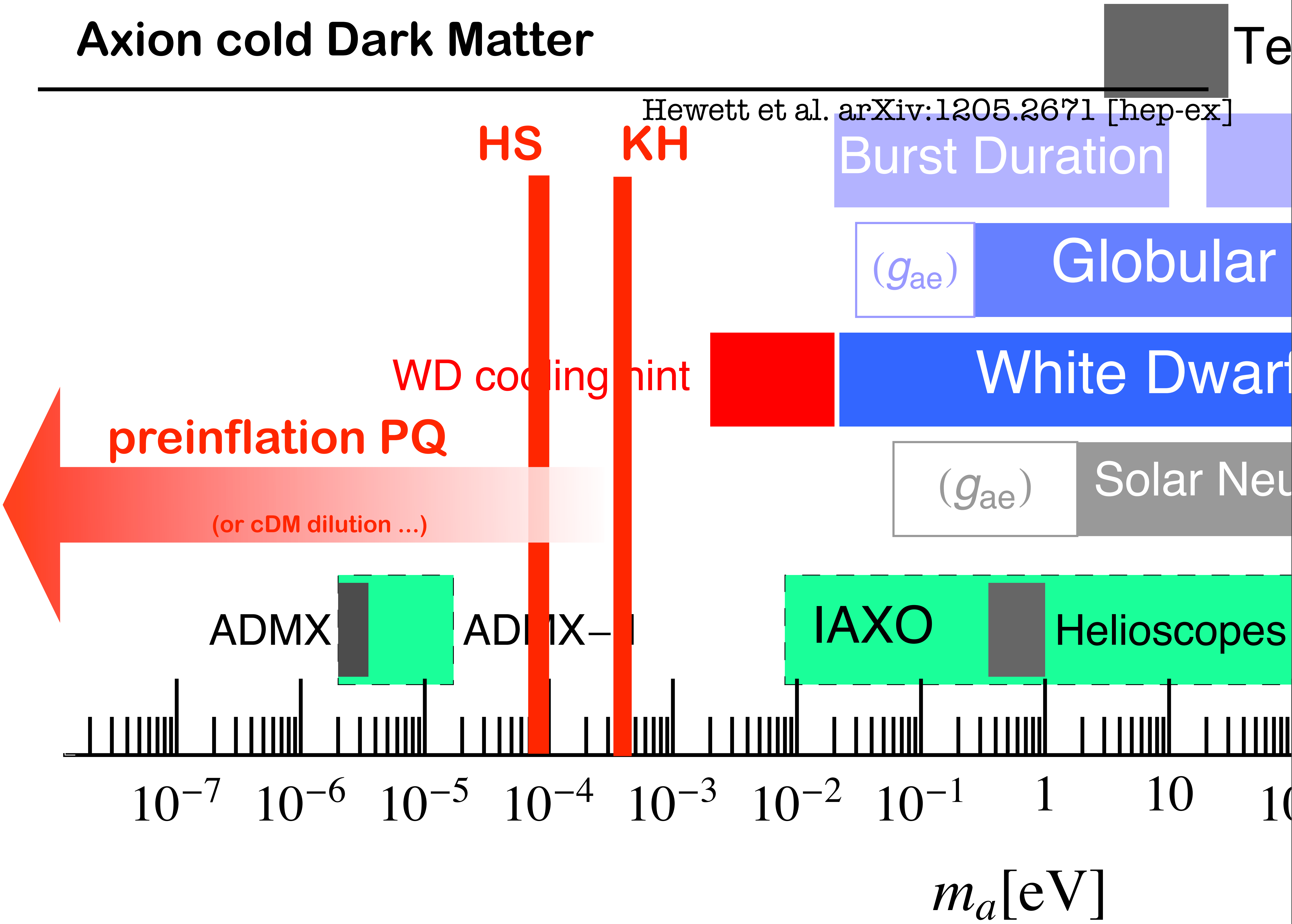
- Whole universe has 1 initial value for a

Axion cold Dark Matter

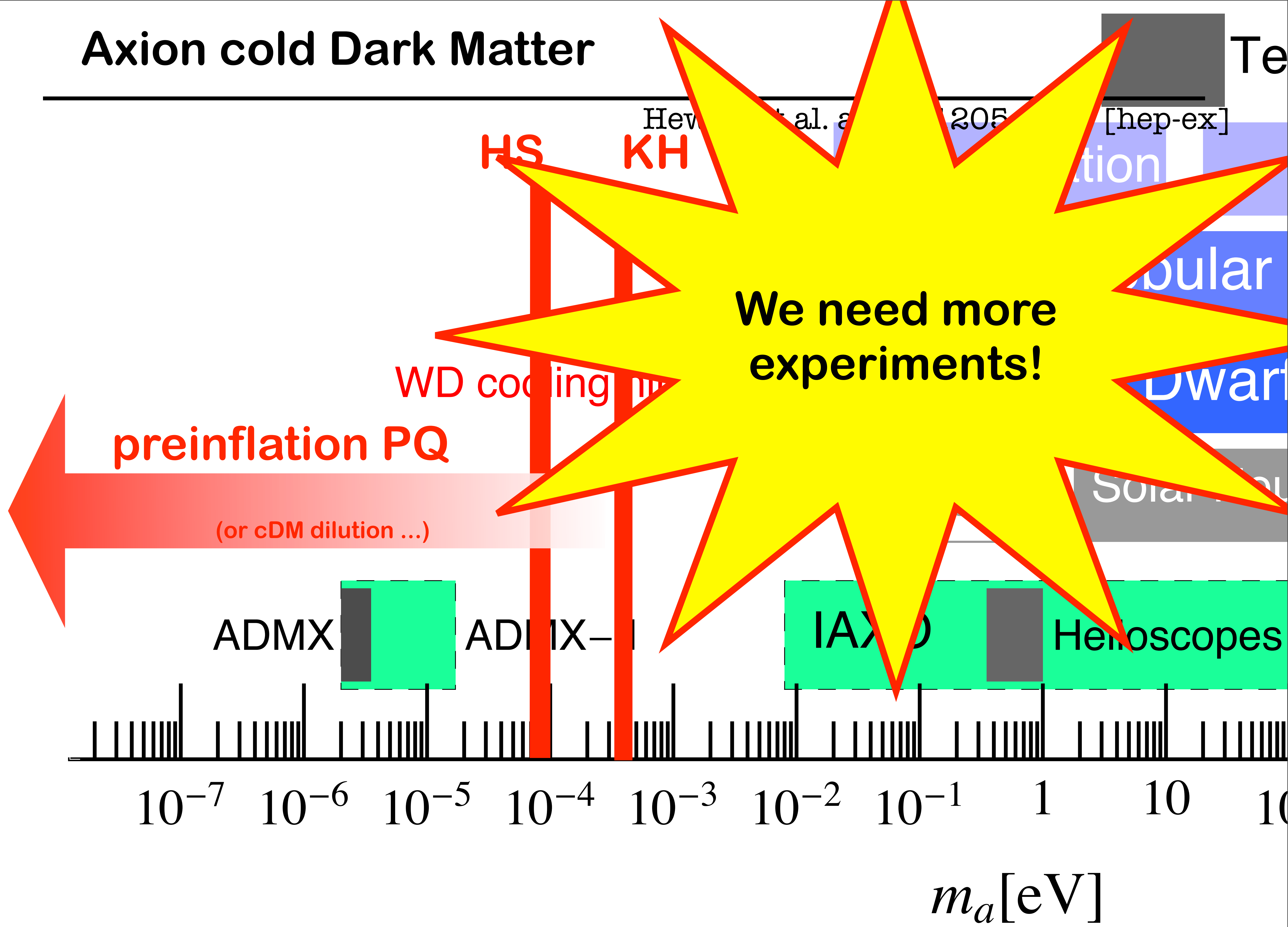
Hewett et al. arXiv:1205.2671 [hep-ex]



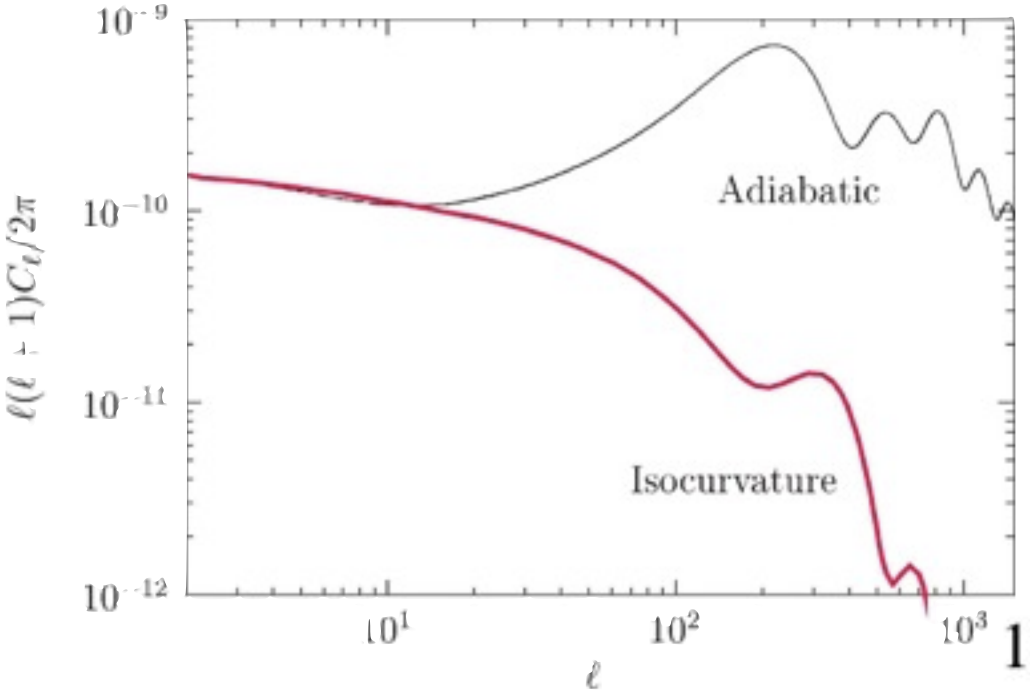
Axion cold Dark Matter



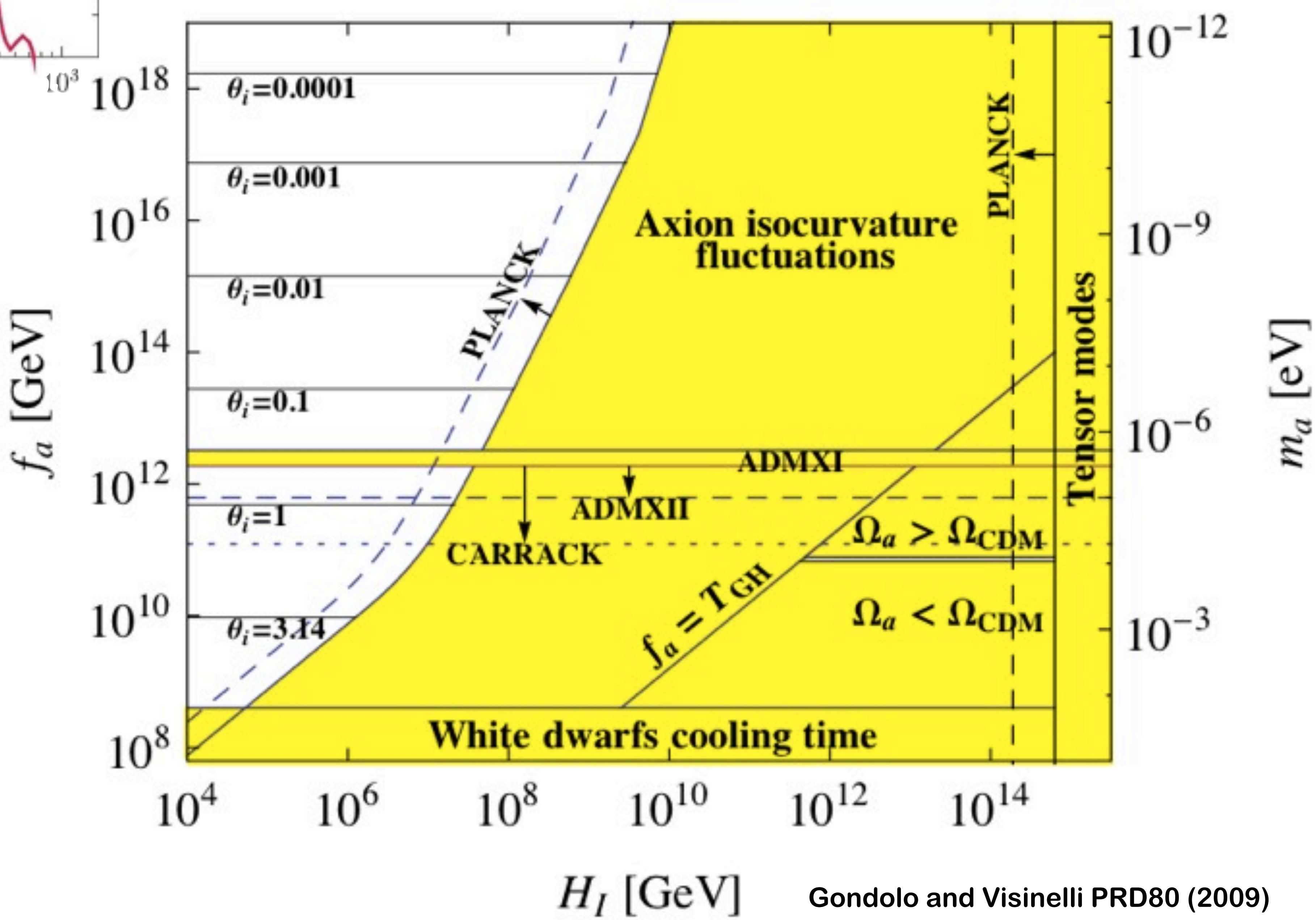
Axion cold Dark Matter



And they imprint ISOCURVATURE perturbations



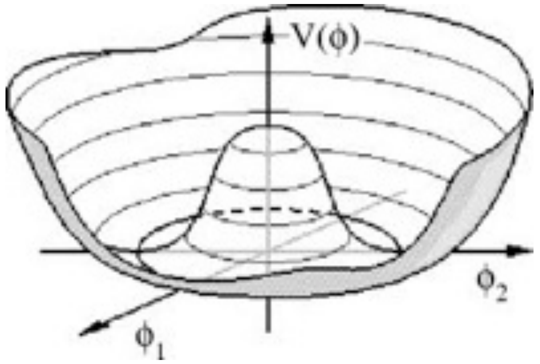
but this depends on H during inflation...



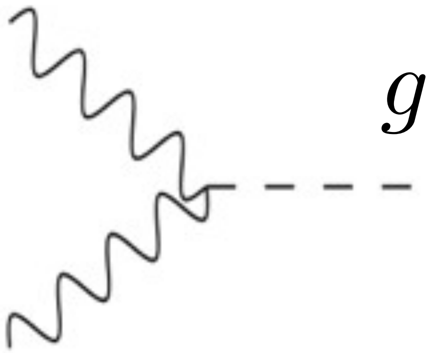
Gondolo and Visinelli PRD80 (2009)

Theory provides us with ALP candidates

pseudo Nambu Goldstone bosons



Global continuous symmetry spontaneously broken at high energy scale M implies a low mass particle (Nambu-Goldstone boson) with weak couplings



$$g \sim \frac{\alpha}{2\pi M}$$

Existing examples: $\pi^0, \eta, \eta', \ldots$

Hypothetical fancies: axion, majoron, R-axion, familons, and a loooong etc.

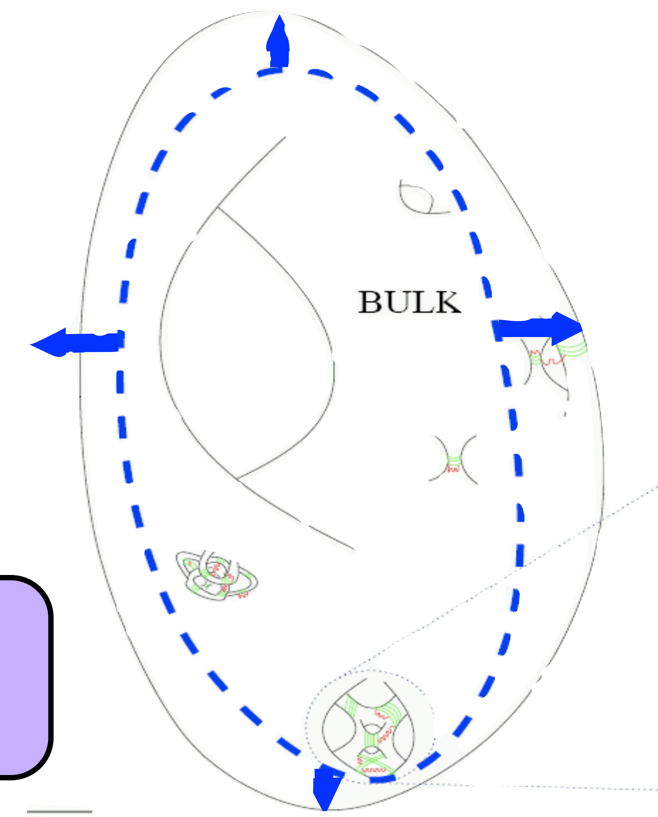
stringy ‘axions’ & string Axiverse

Arvanitaki, Dimopoulos Phys.Rev. D81 (2010)

Scalars and pseudoscalars that govern the sizes and deformations of extra dimensions, gauge couplings,etc... (typically there are O(100) of these)

$$g \sim \frac{\alpha}{2\pi M_{\rm string}}$$

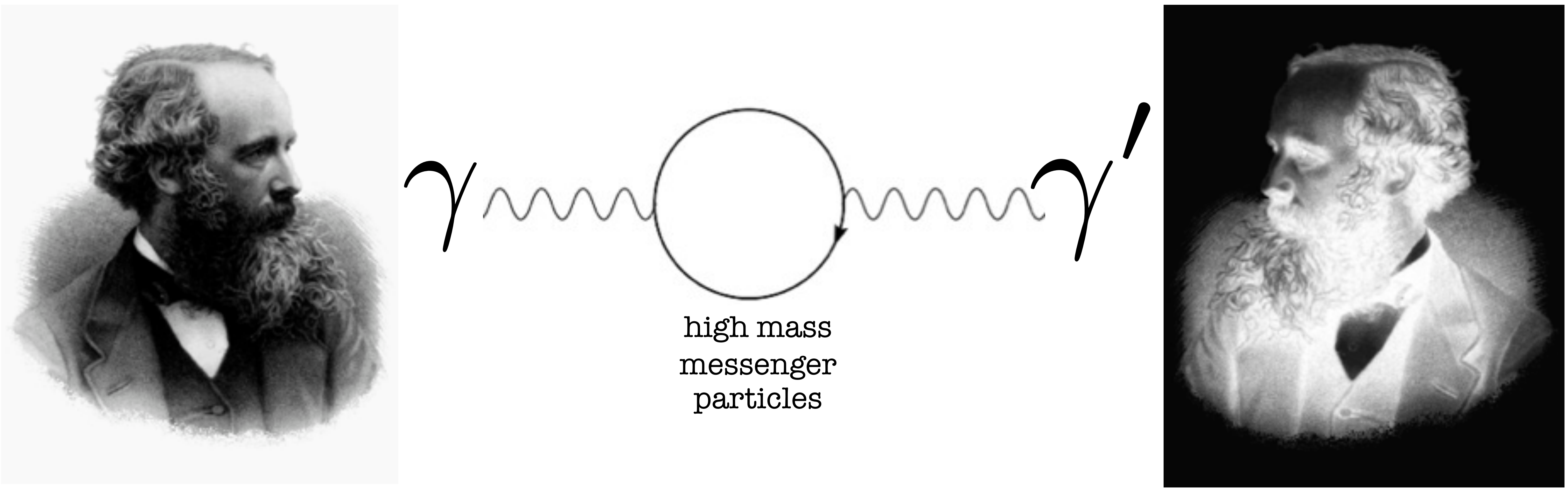
Moduli, Radion, Dilatons



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



Kinetic mixing is the most relevant interaction at low energies

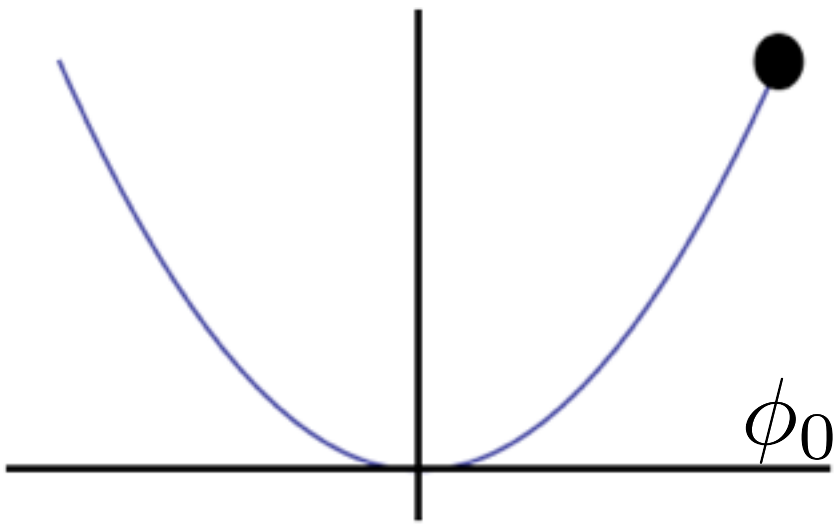
$$\mathcal{L}_I = -\frac{1}{2}\chi F_{\mu\nu} B^{\mu\nu}$$

Right amount of WISPy Dark matter

In the simplest ALP/HP models:

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 + ...$$

with an initial value ϕ_0



$$\frac{\Omega_\phi}{\Omega_{\rm CDM}} = \sqrt{\frac{m_\phi}{\rm eV}} \left(\frac{\phi_0}{4.8 \times 10^{11}\, {\rm GeV}} \right)^2 \mathcal{F},$$

Physics at <u>very high energies</u> at play!!!

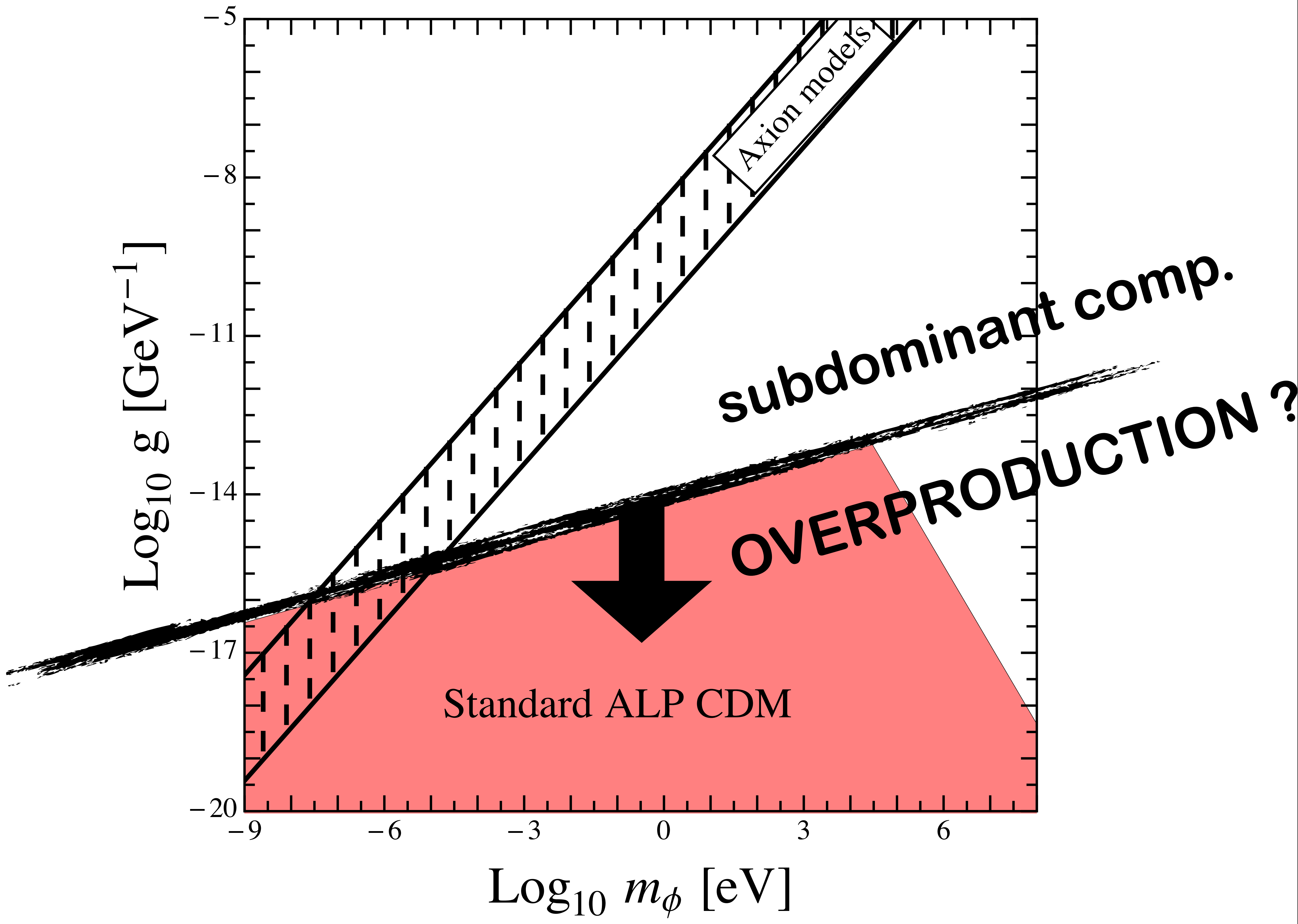
ALPs in the $m_\phi - g$ plane

Consider an ALP with a two photon coupling

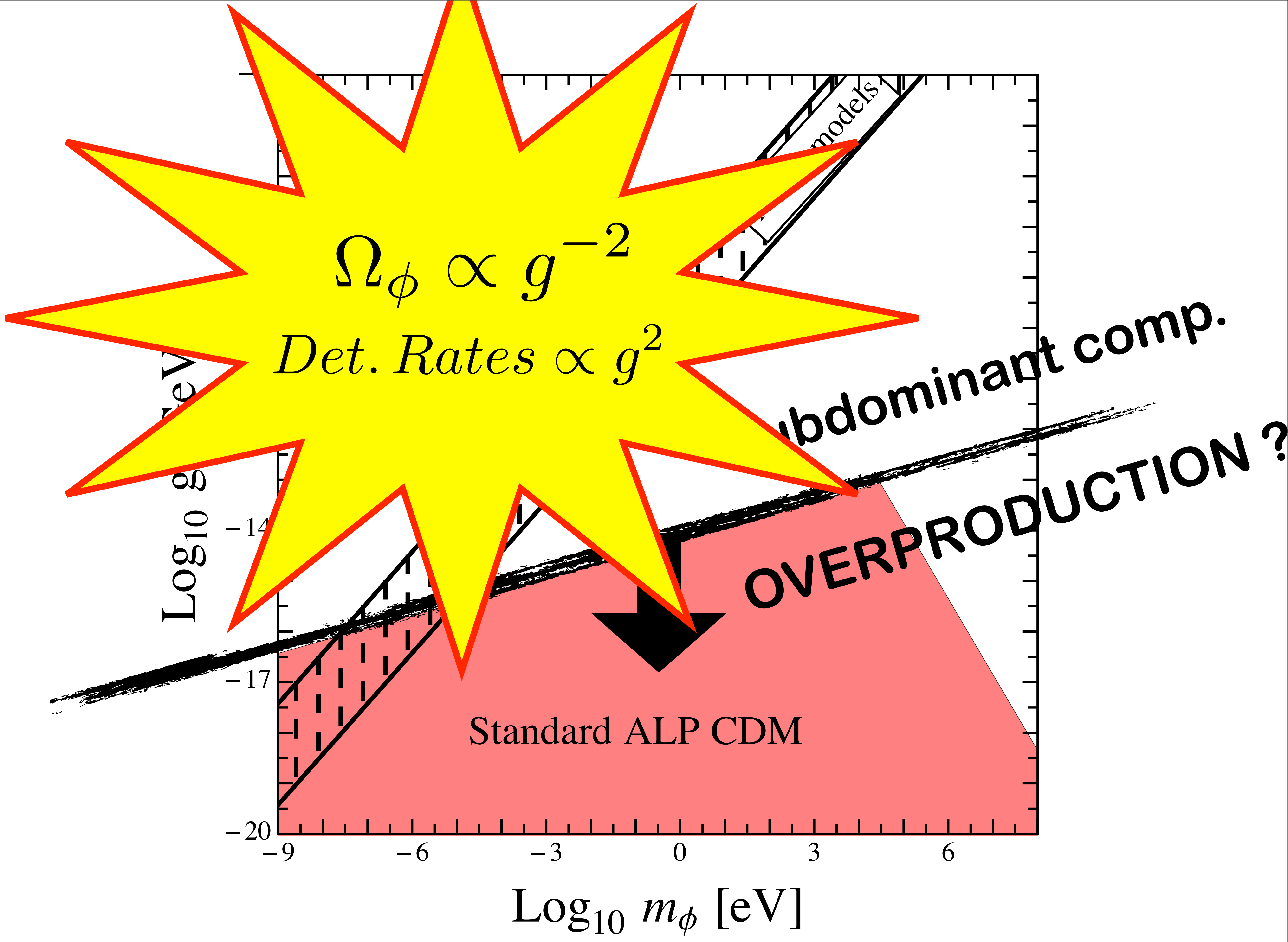
$$\mathcal{L} = \mathcal{L}_{\rm free} + \frac{g}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu} \phi \qquad g \equiv \frac{\alpha}{2\pi} \frac{1}{f_\phi} \mathcal{N} \qquad \mathcal{N} \sim O(1)$$

Since the coupling is $1/f_\phi$ and initial value is $O(f_\phi)$ we can relate the DM abundance with the coupling

$$\frac{\Omega_\phi}{\Omega_{\rm CDM}} \lesssim \sqrt{\frac{m_\phi}{\rm eV}} \left(\frac{0.8 \times 10^{-14}\,{\rm GeV}^{-1}}{g} \right)^2 \mathcal{F} \mathcal{N}^2$$



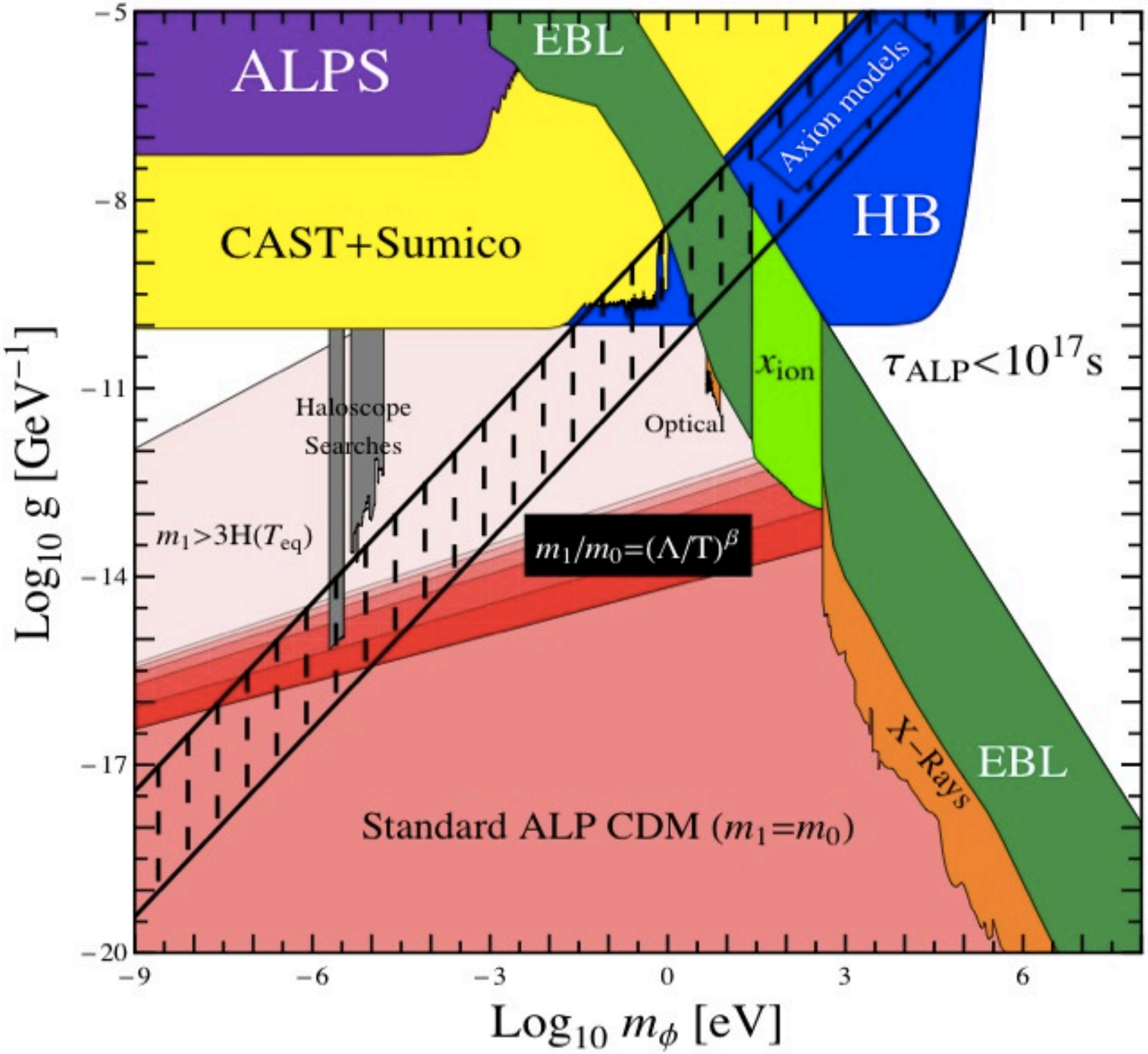
Axion models
subdominant comp.
OVERPRODUCTION ?
Standard ALP CDM
Log10 g [GeV−1]
Log10 mφ [eV]
−5
−8
−11
−14
−17
−20
−9
−6
−3
0
3
6



$\Omega_\phi \propto g^{-2}$
$Det.\,Rates \propto g^2$
models
ubdominant comp.
OVERPRODUCTION ?
Standard ALP CDM
-14
-17
-20
-9
-6
-3
0
3
6
$\mathrm{Log}_{10}\, m_\phi$ [eV]

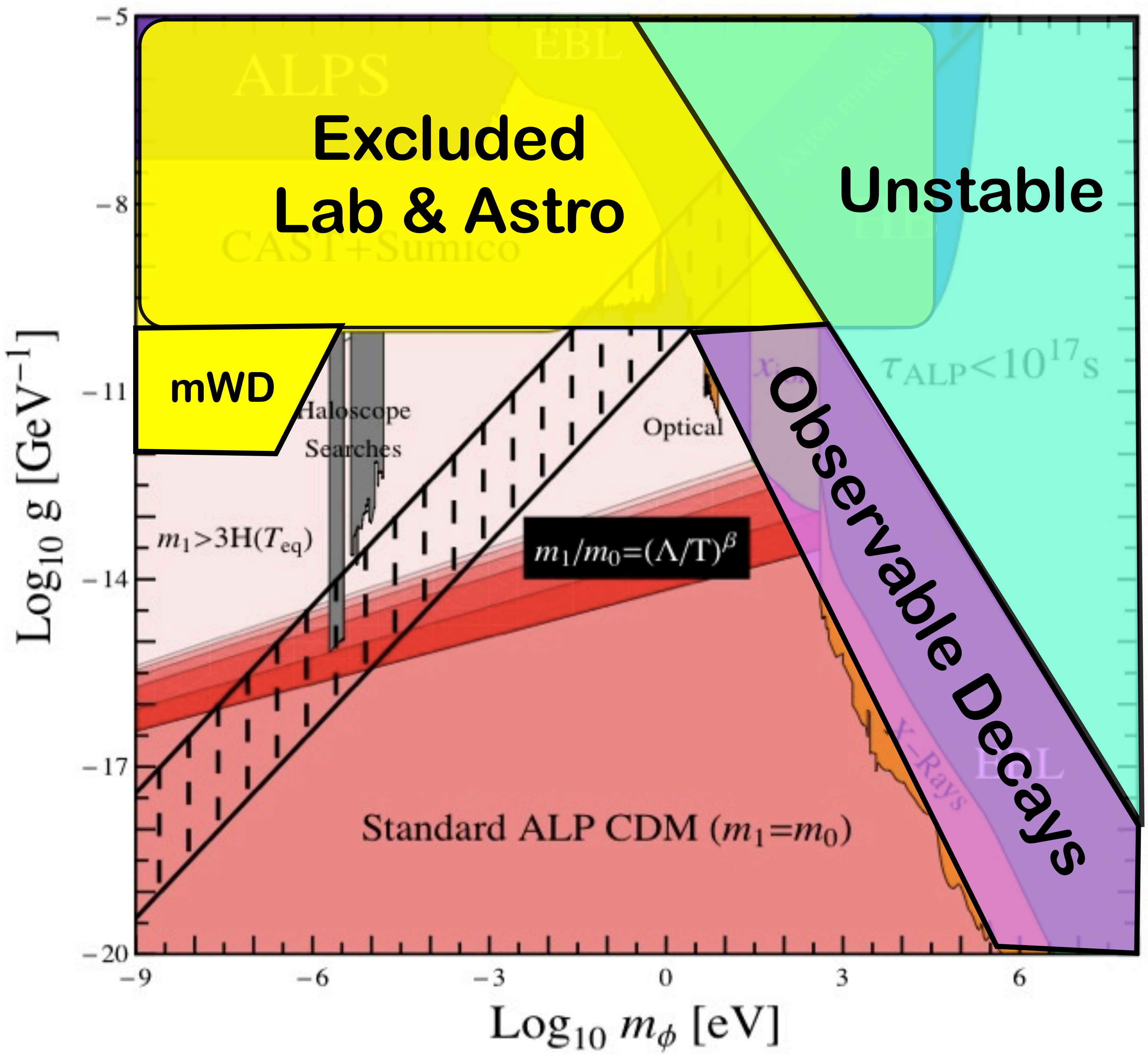
WISPy Dark matter: Axions and ALPs

Arias et al. JCAP06 (2012) 013



WISPy Dark matter: Axions and ALPs

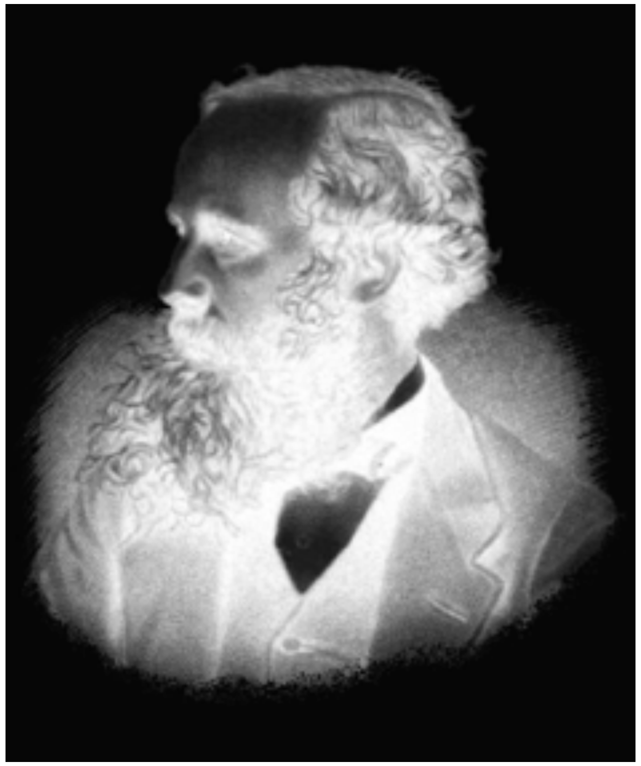
Arias et al. JCAP06 (2012) 013



Hidden Photon cDM

Nelson and Scholtz PRD 84 (2011)

The initial field value of A' has, in principle, nothing to do with the coupling χ

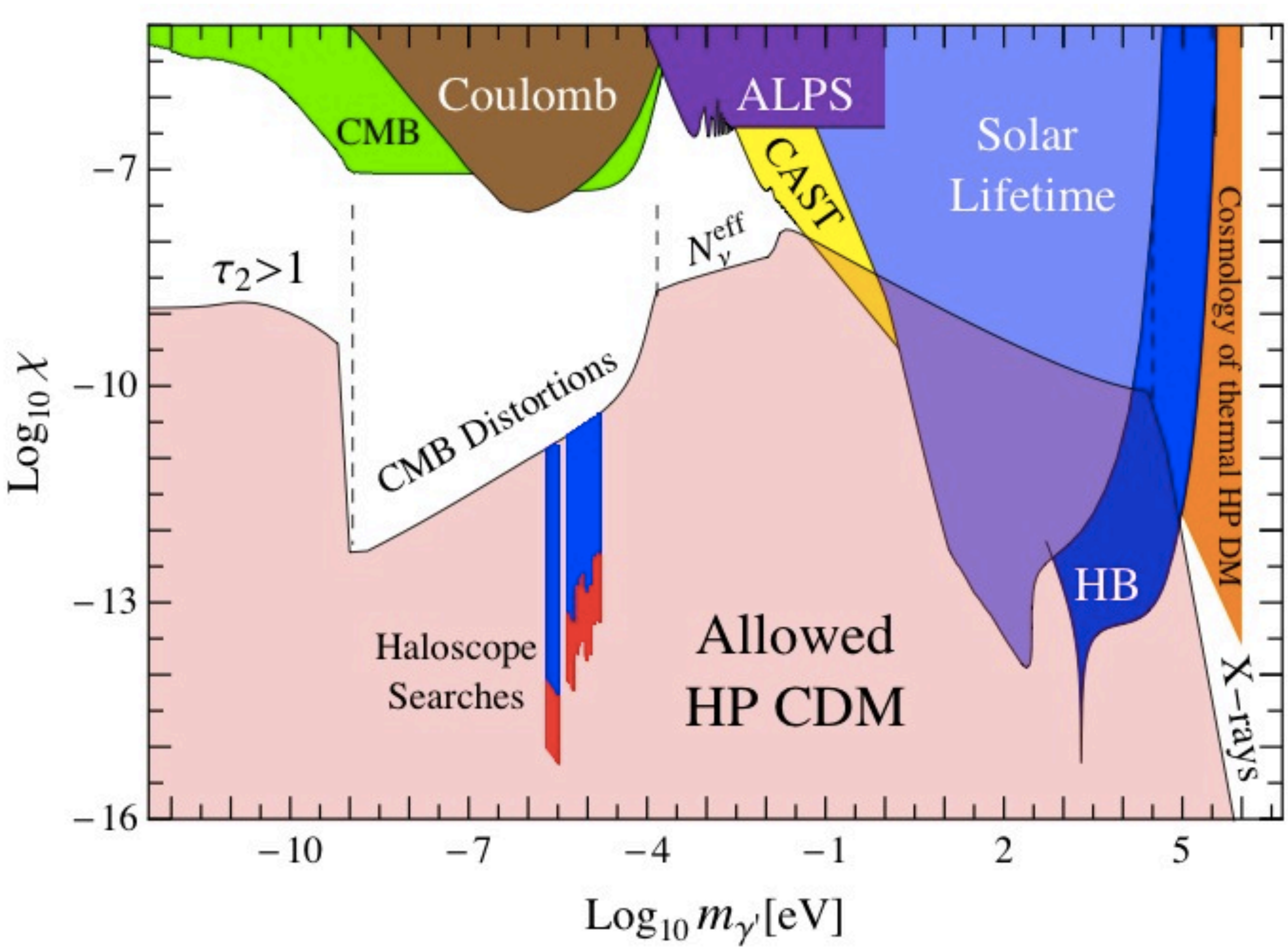


In the following... let's assume it takes the right value

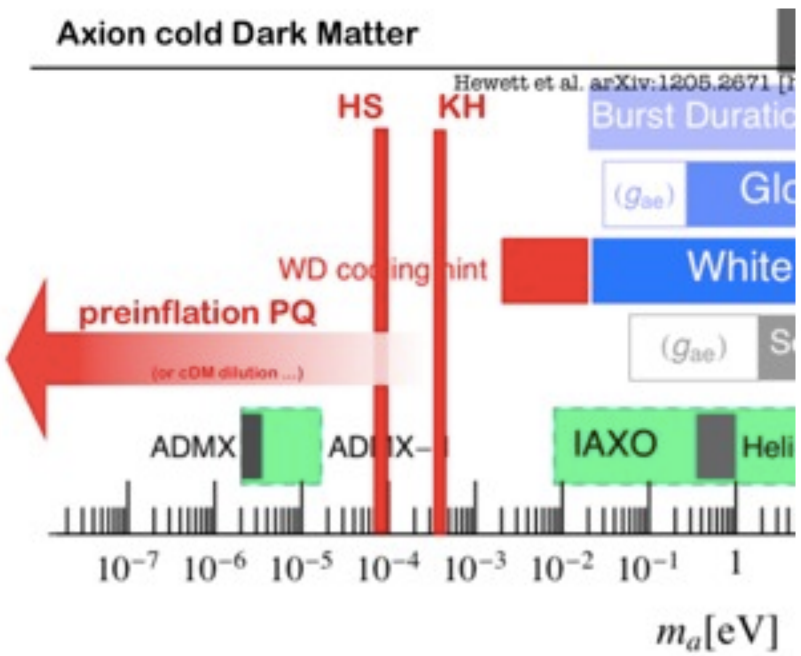
Hidden Photon cDM

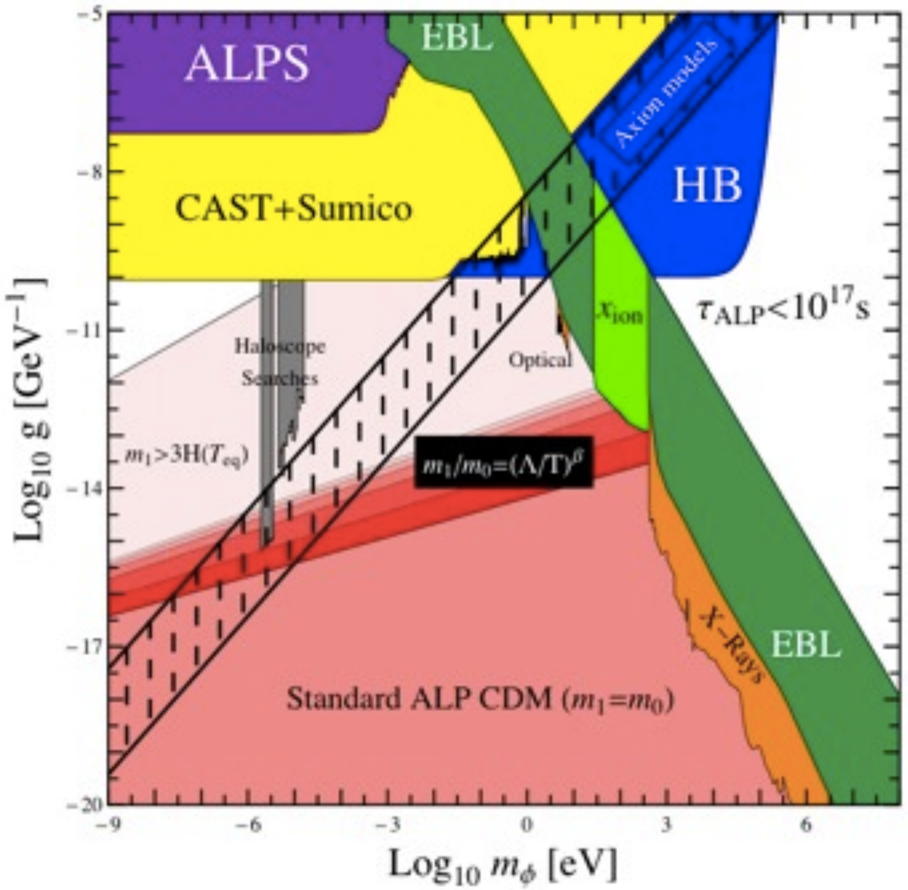
Nelson and Scholtz PRD 84 (2011)

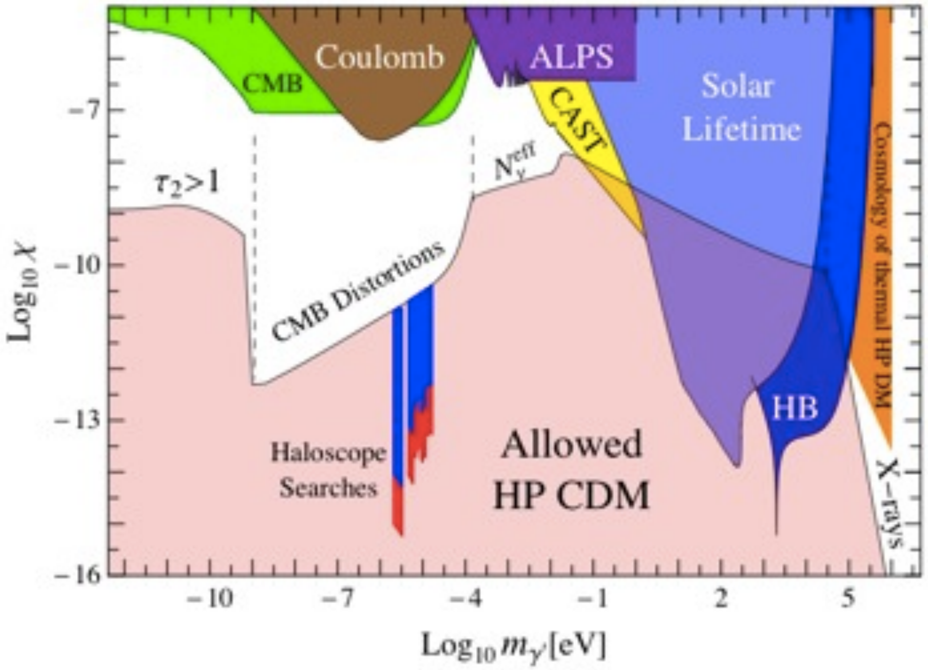
Arias et al. JCAP06 (2012) 013



Plenty of parameter space to explore!!!





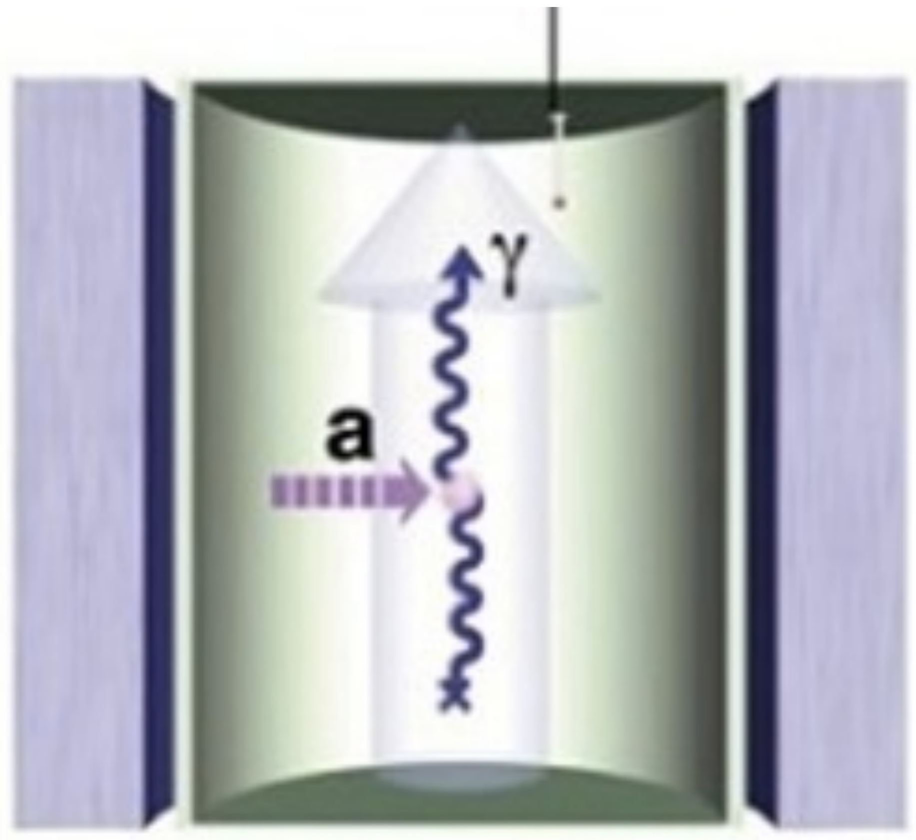


MSG1 = Indirect searches can explore it and provide candidates!

- Helioscopes CAST, TSHIPS and IAXO,
- LSW like ALPSII and REAPR, or MW-LSW@ CERN

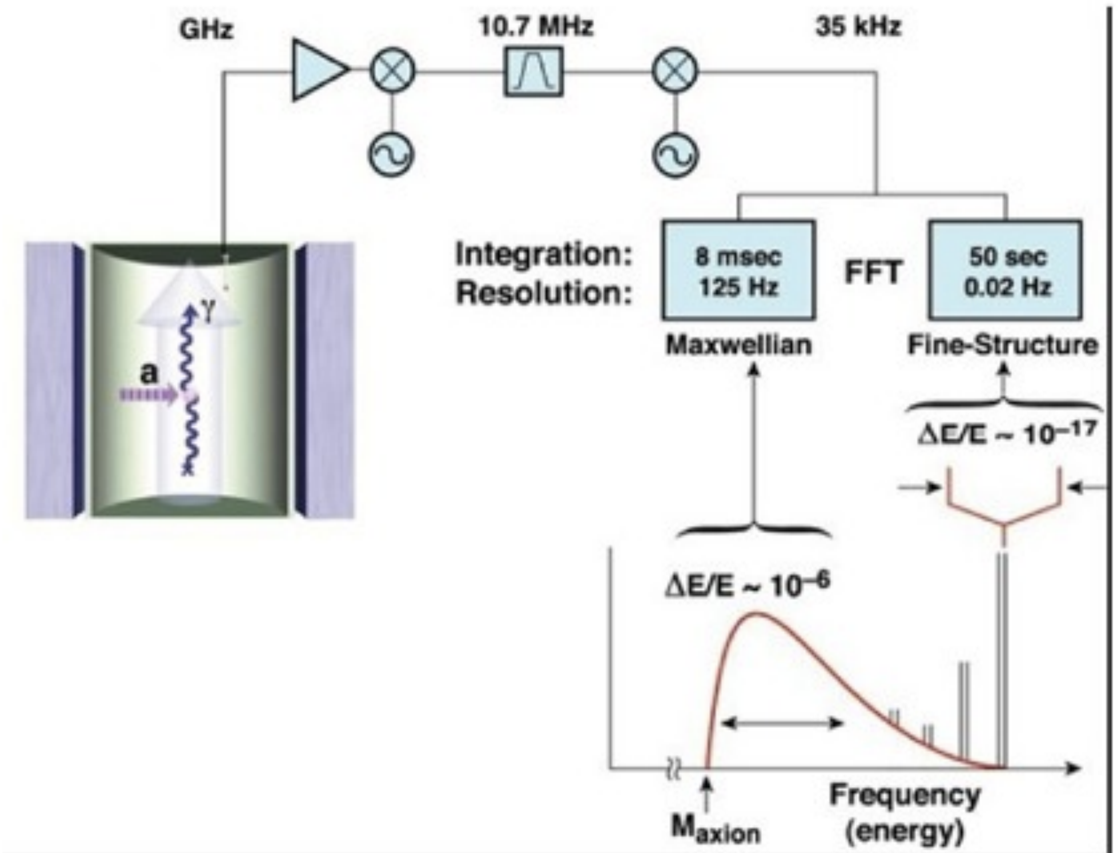
MSG2 = Direct searches ADMX, HF, Yale ...
europe entering the game @ DESY, TS...

Experiments for WISPy cold dark matter



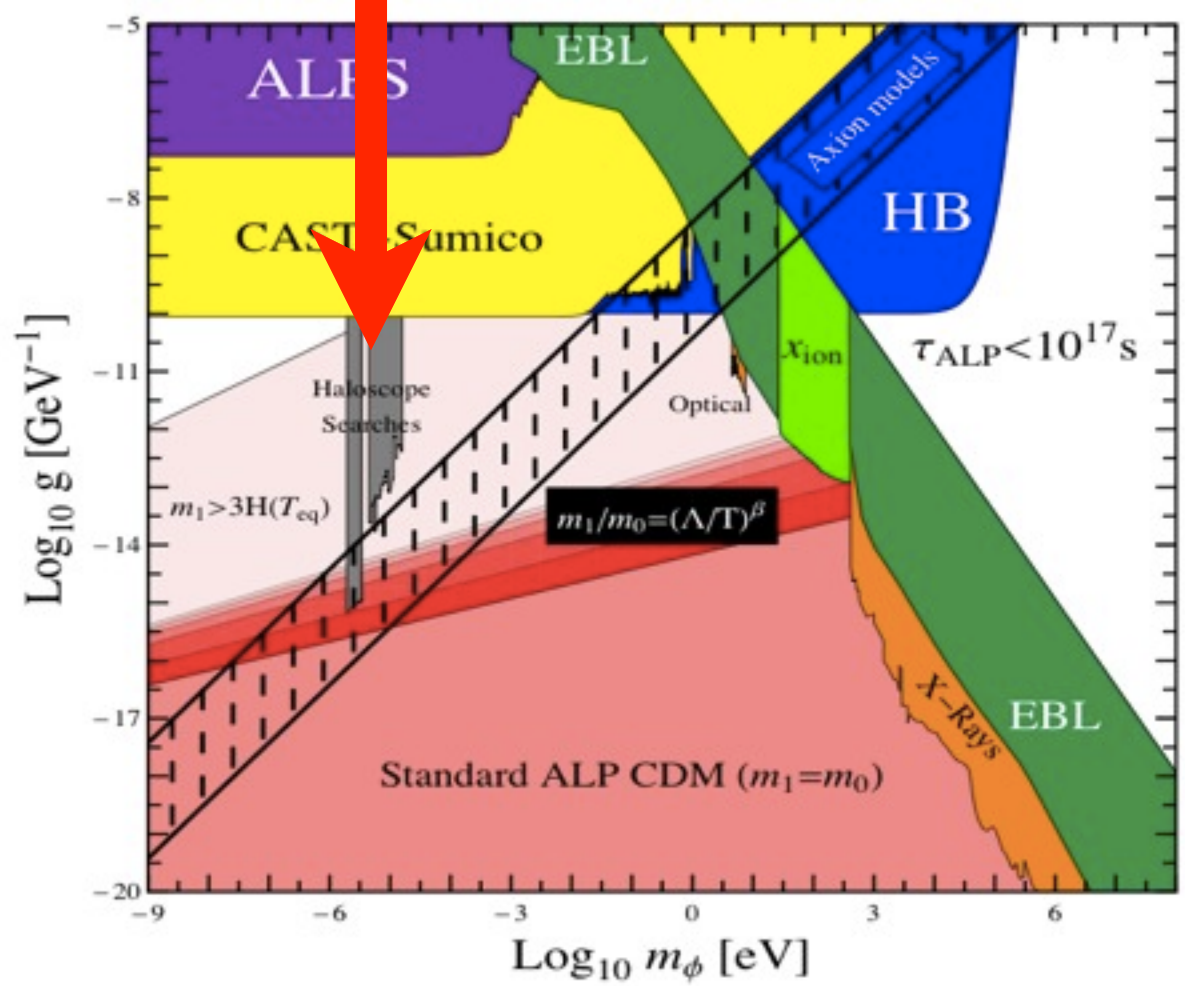
Thanks Pierre and the ADMX group!

WISPy Dark Matter detection with microwave cavities

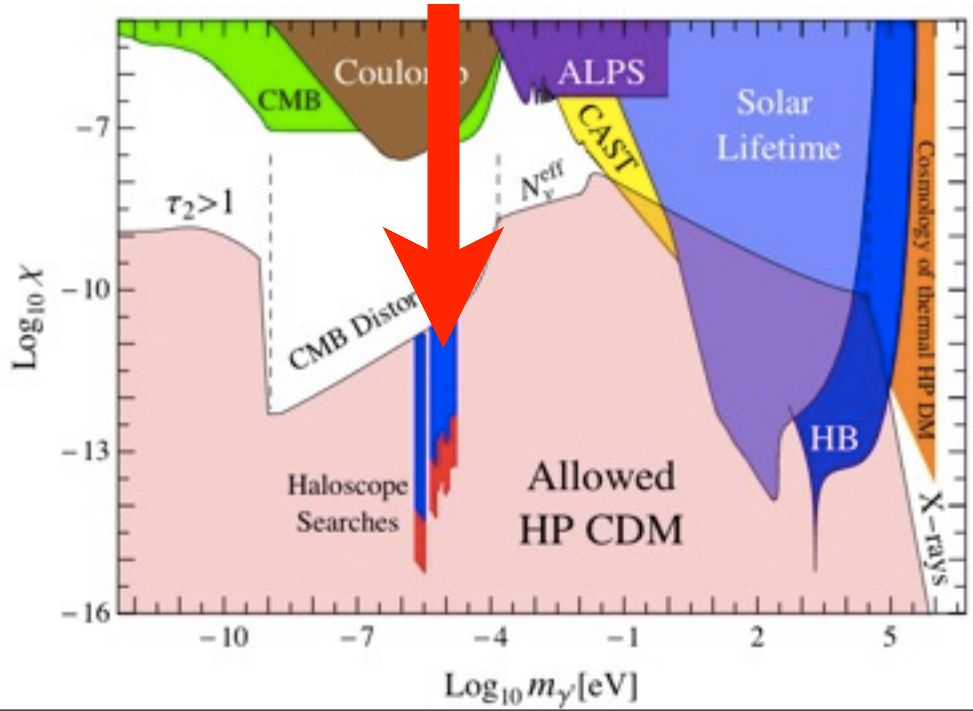


Pioneer Experiments looking for axions

ADMX, BRFT

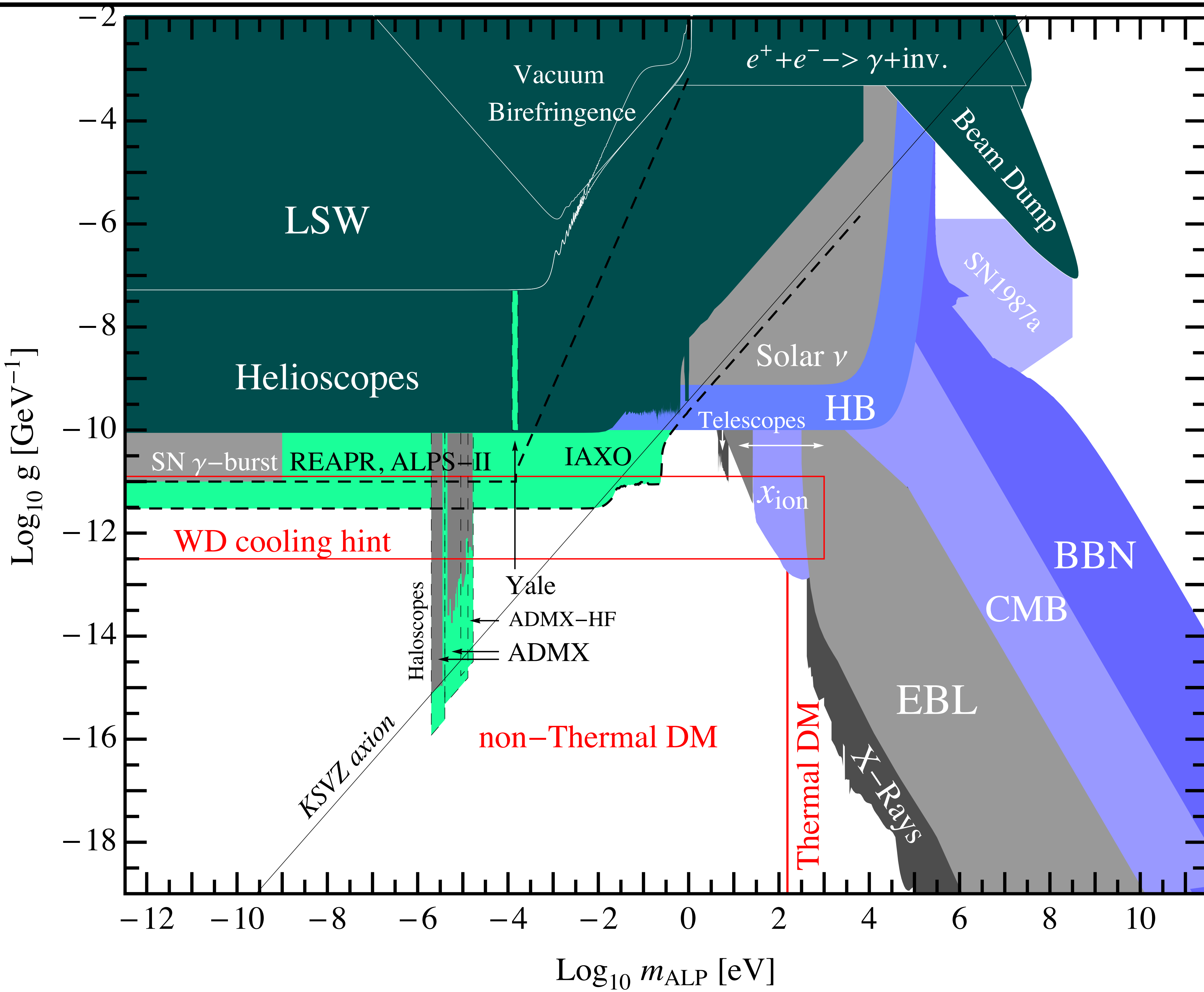


Are sensitive also to HPs



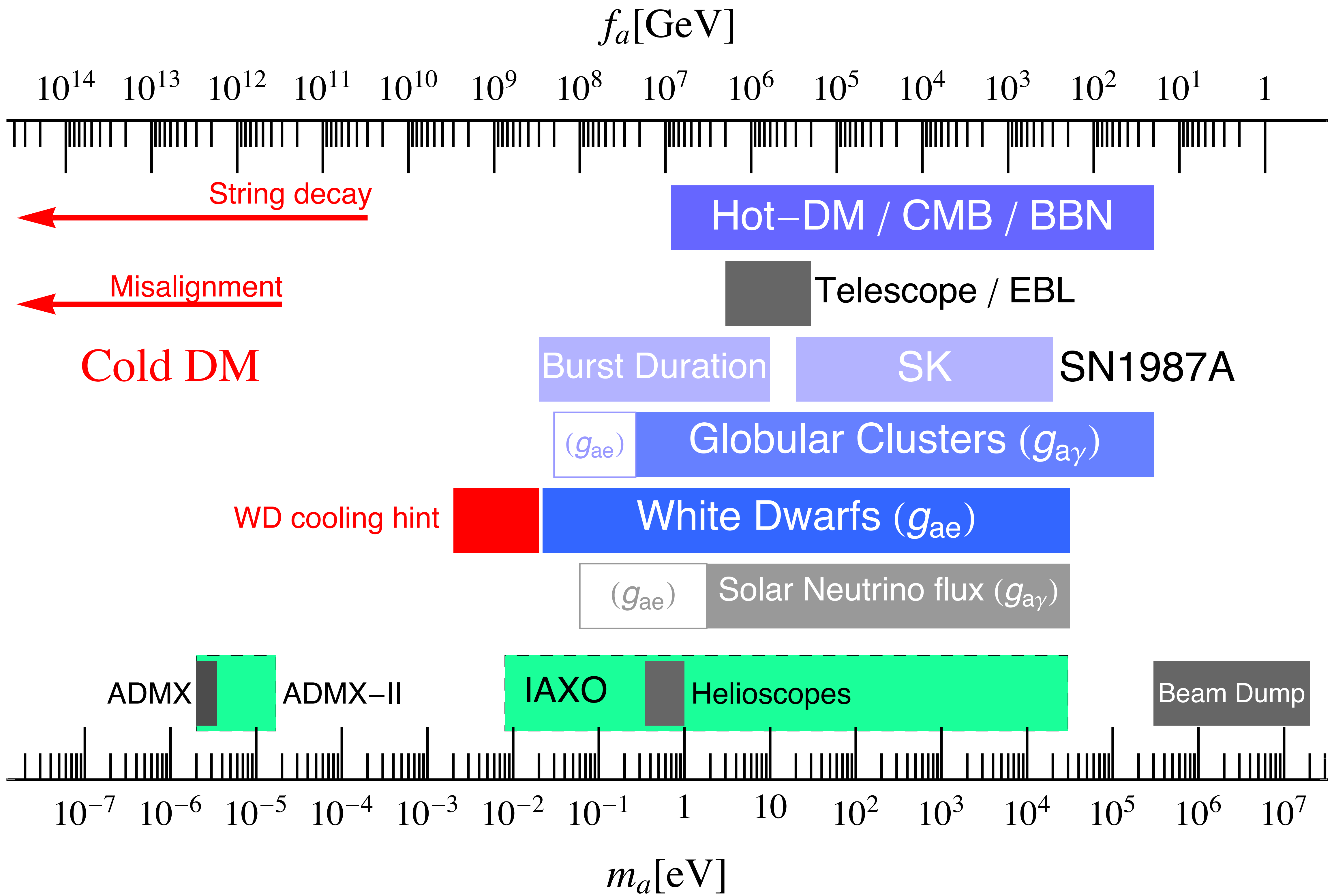
Prospects plots (Intensity frontier report)

arXiv:1205.2671



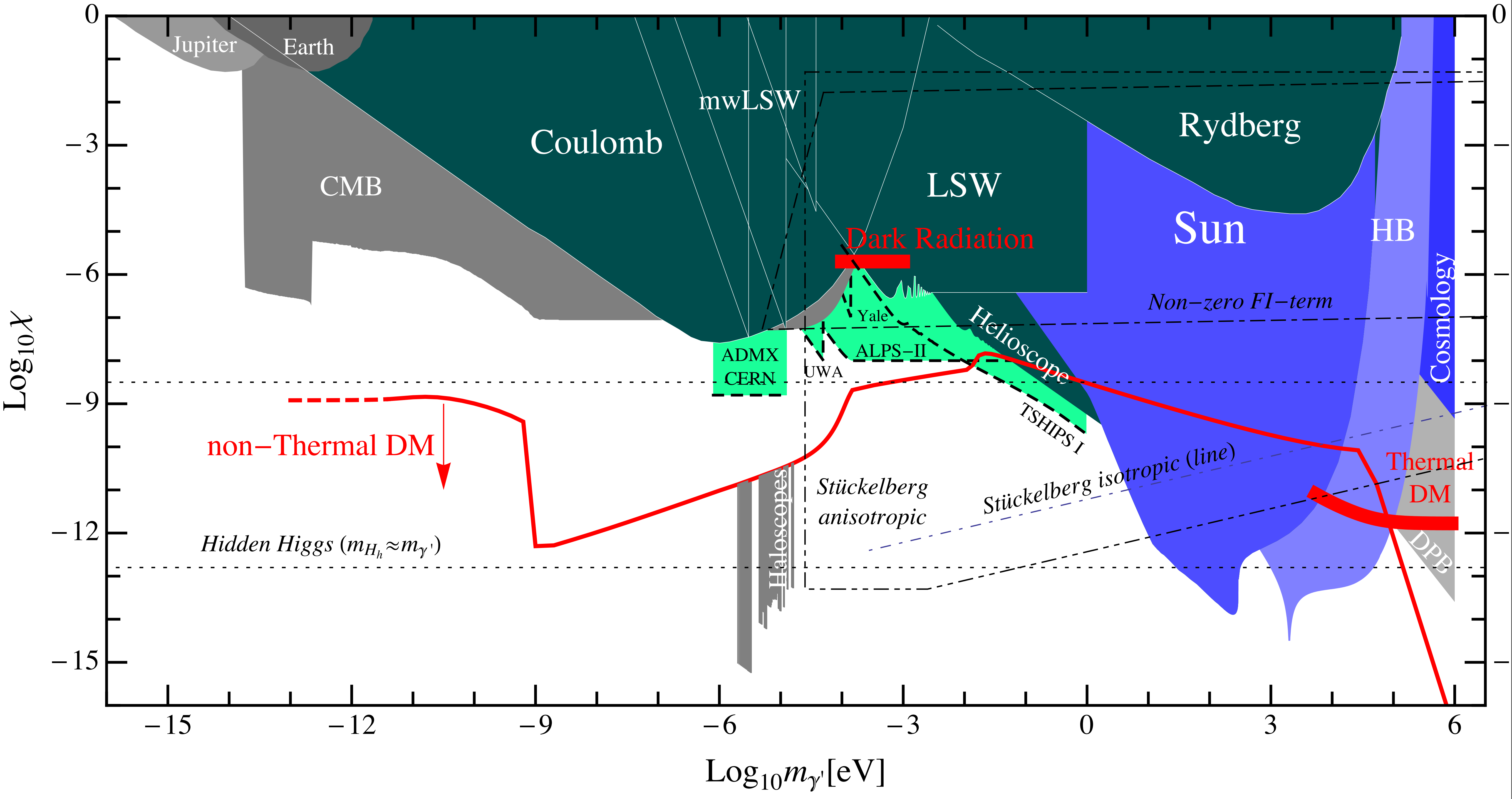
Prospects plots (Intensity frontier report)

arXiv:1205.2671



Prospects plots (Intensity frontier report)

arXiv:1205.2671



New Ideas/techniques (must be pursued!)

- Oscillating EDMs

Graham, Rajendran PRD84 (2011)

- ALP searches with toroidal, dipole, wiggler magnets

Baker et al. PRD85 (2012)

- HP searches with antennas.

Horns, Jaeckel, Lindner, Lobanov, Redondo, Ringwald, In prep.

- and more to come!

Conclusions

- Chicago rocks

- WISPs appear in well motivated extensions of the SM

- WISPy cold Dark Matter is a natural possibility

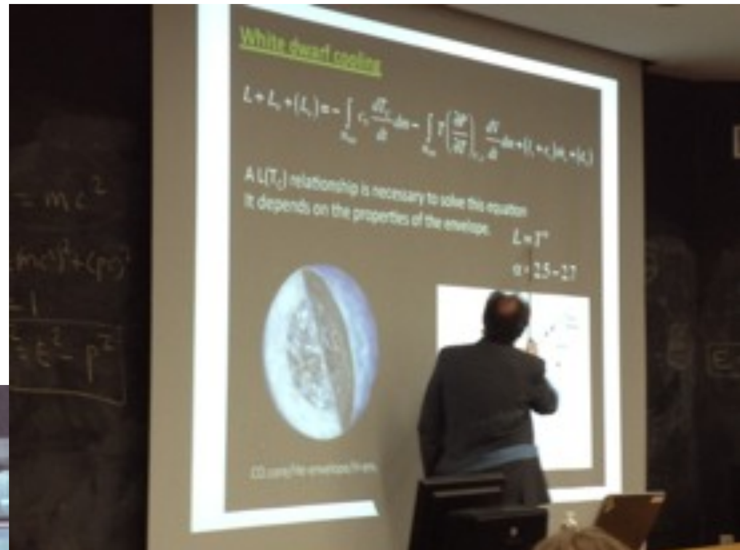
- Indirect searches will provide WISP cDM candidates

- Direct cDM searches with cavities must be strengthen and

- New ideas pursued

Apologies

to those whose relevant work wasn't mentioned



it was a busy week...

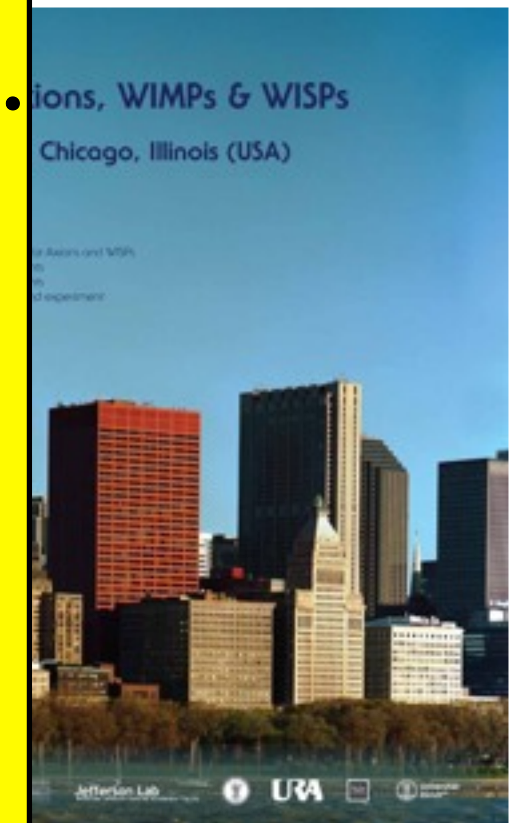
Thanks

To the organizers/speakers

To the city of Chicago

Thanks

To the org



To the cit

where you can

find everything ...