WISPy Cold Dark Matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

J. Jaeckel[**]

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[**]Heidelberg University, [z]CERN, [†]IPPP Durham, *DESY,
[y]MPIfR Bonn, [x]U. Zaragoza, [xx]Paris LPTHE, [0]ITP Jena

WISPy Cold Dark Matter

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Weakly interacting sub-eV particle

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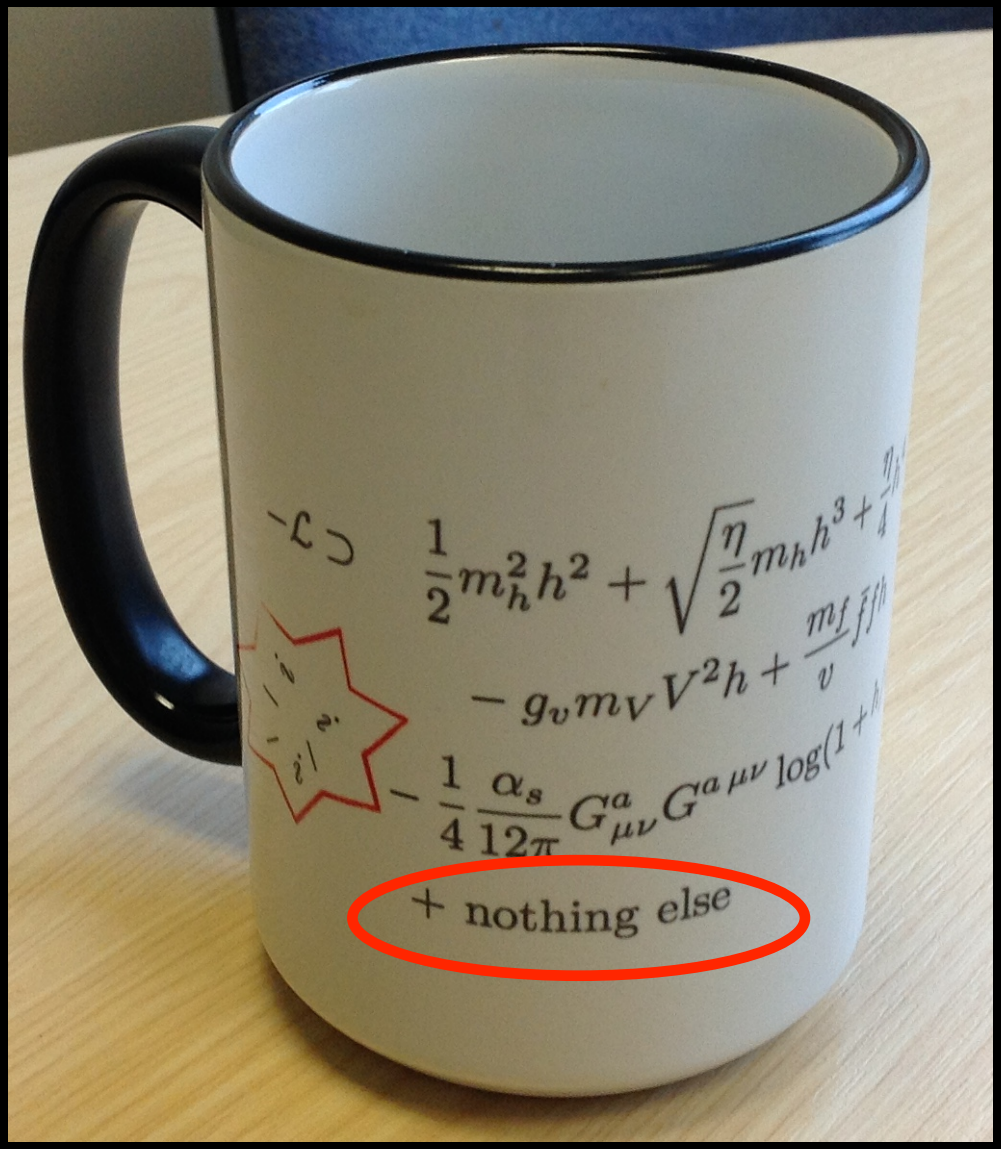
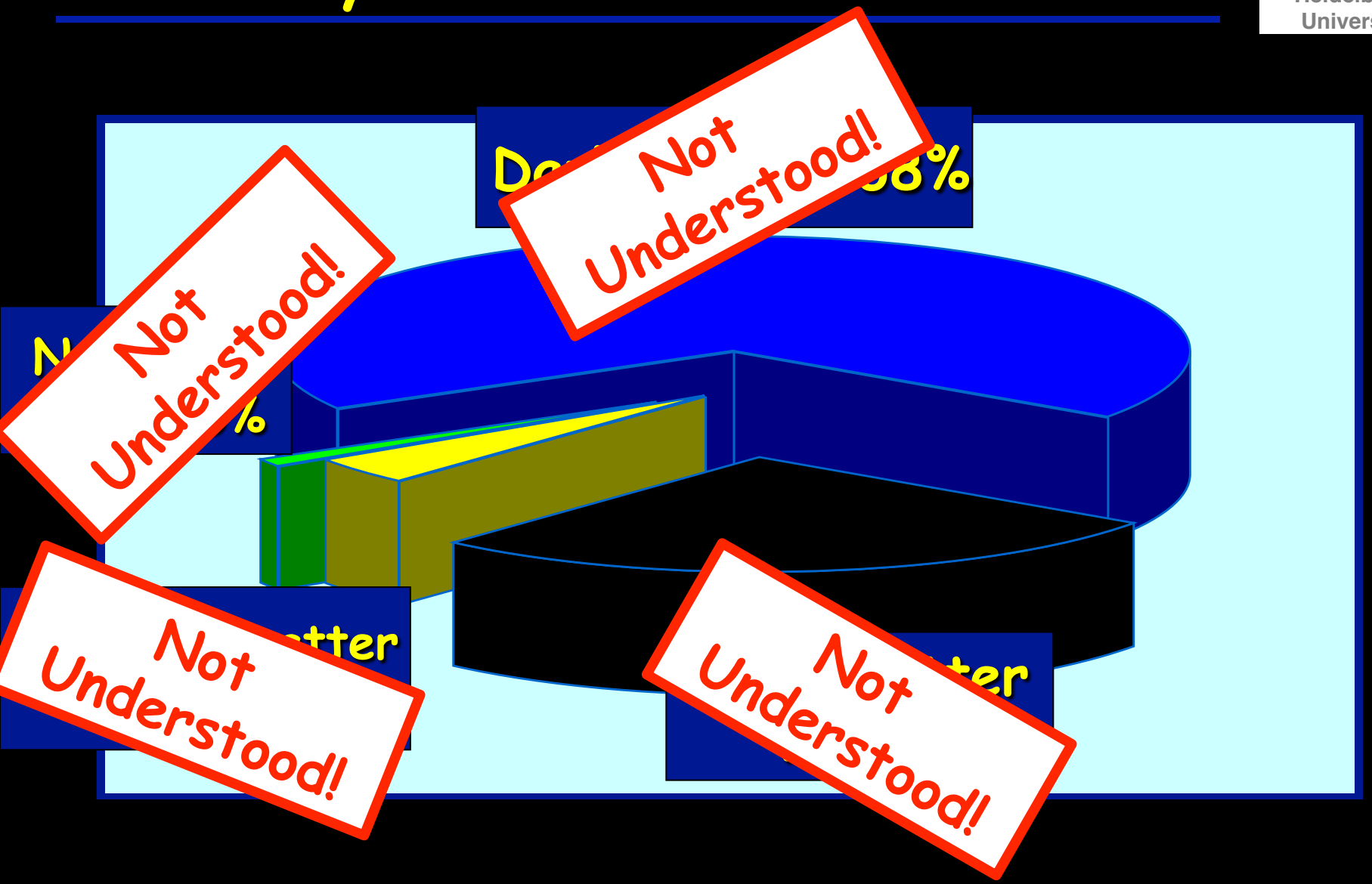

$-\mathcal{L} \supset \frac{1}{2}m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta_h}{4}$
$- g_v m_V V^2 h + \frac{m_f}{v} \bar{f} f h$
$- \frac{1}{4}\frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1+h$
+ nothing else

Inventory of the Universe



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Where is the New Physics?

Exploring is (at least) 2 dimensional

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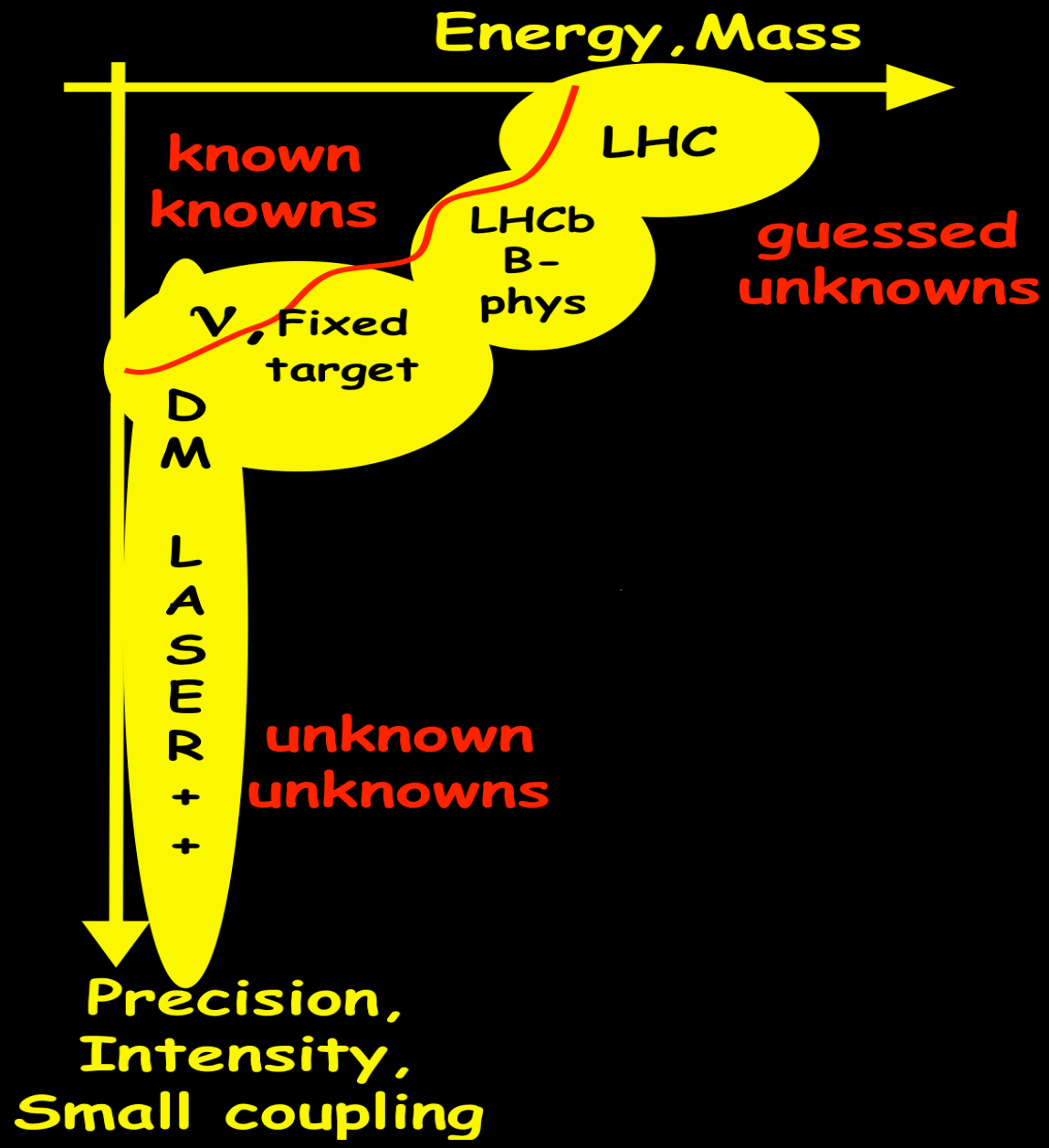

Exploring is (at least) 2 dimensional

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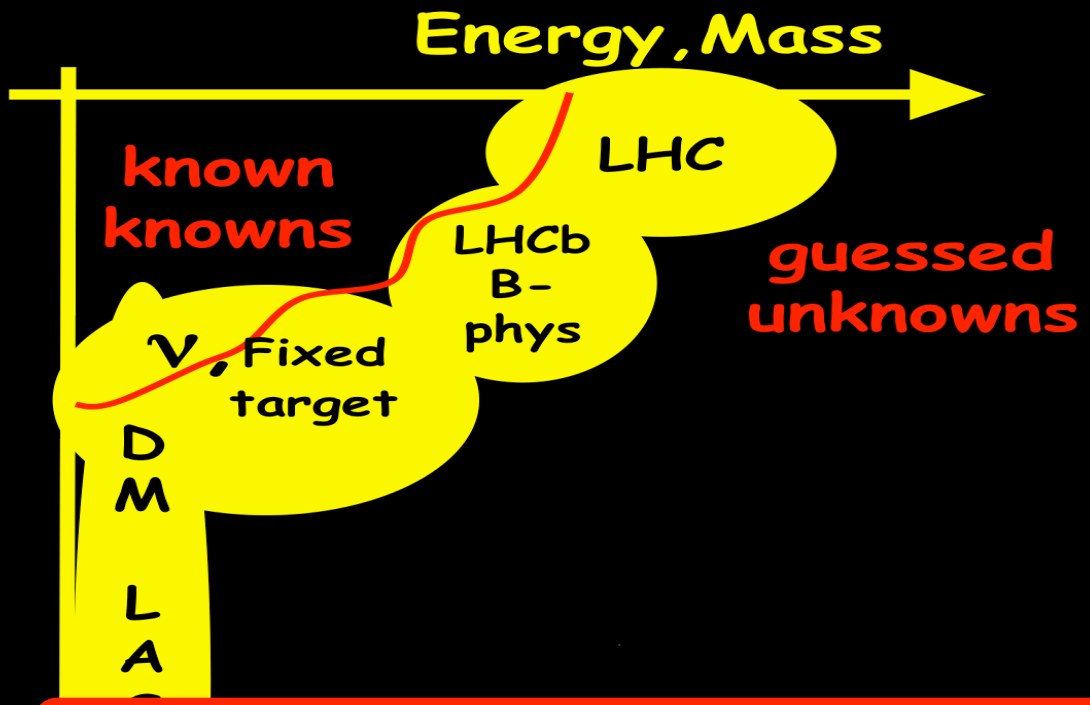

THE DARK SECTOR!!!

Precision,
Intensity,
Small coupling

Example WISPs:
Axion(-like particles)

A dirty little secret...

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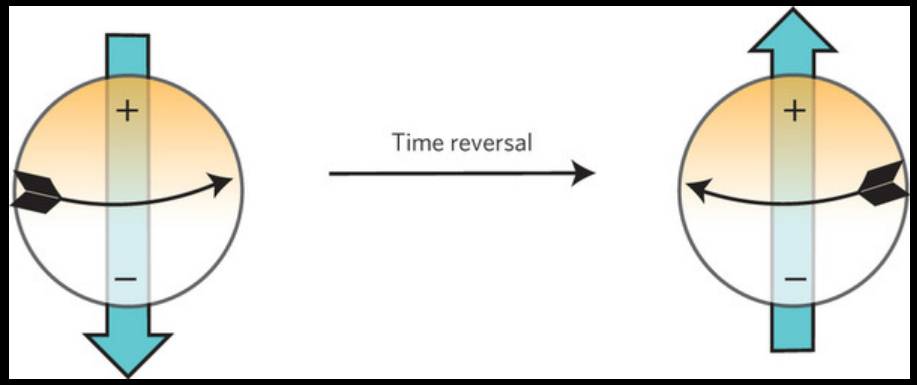
$$S = \int d^4x \left[-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu} + 1\bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right]$$

$$\text{“} \sim \theta \vec{E} \cdot \vec{B} \text{”}$$

- The θ-term violates time reversal (T=CP)!
- Connected to strong interactions!

➡ Electric dipole moment of the neutron!



Not found
➔ θ~0!!!

The axion solution to the strong CP problem

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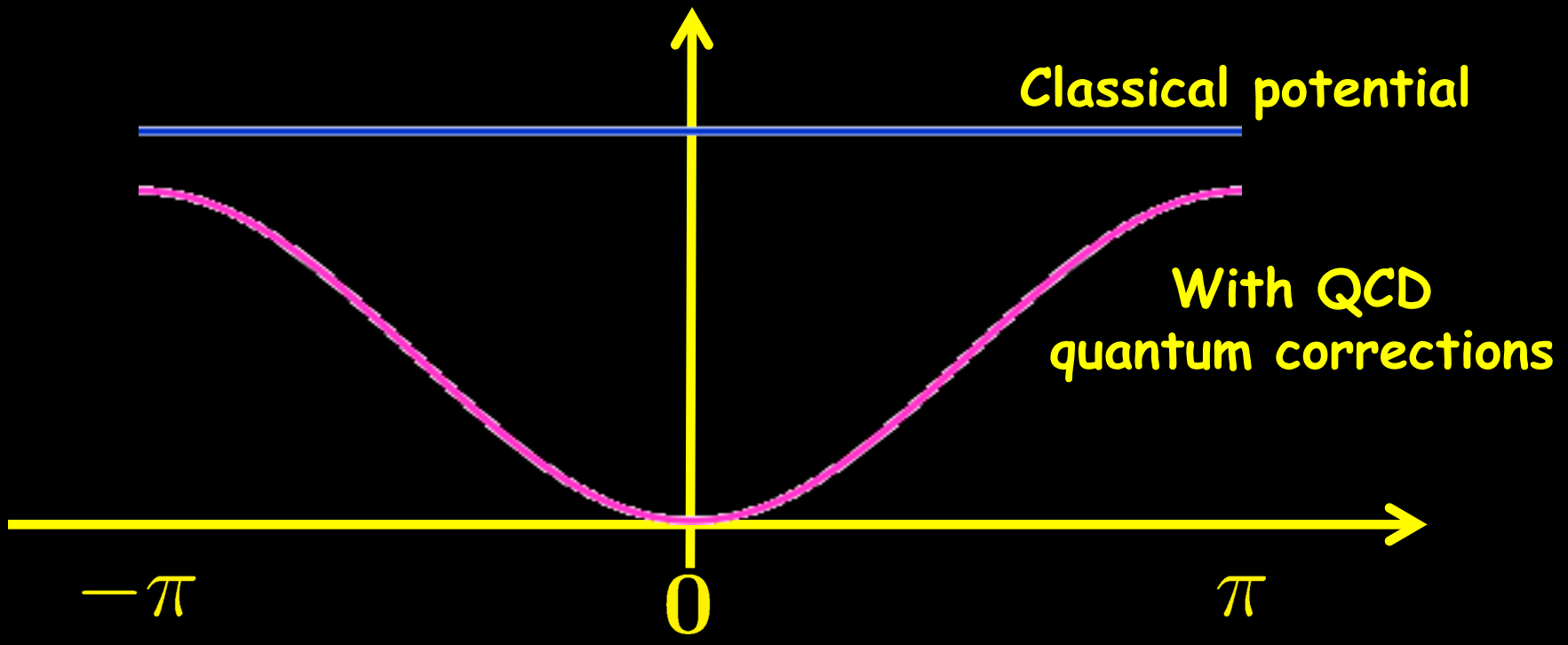
- Make θ dynamical ➔ it can change its value



The axion solution to the strong CP problem

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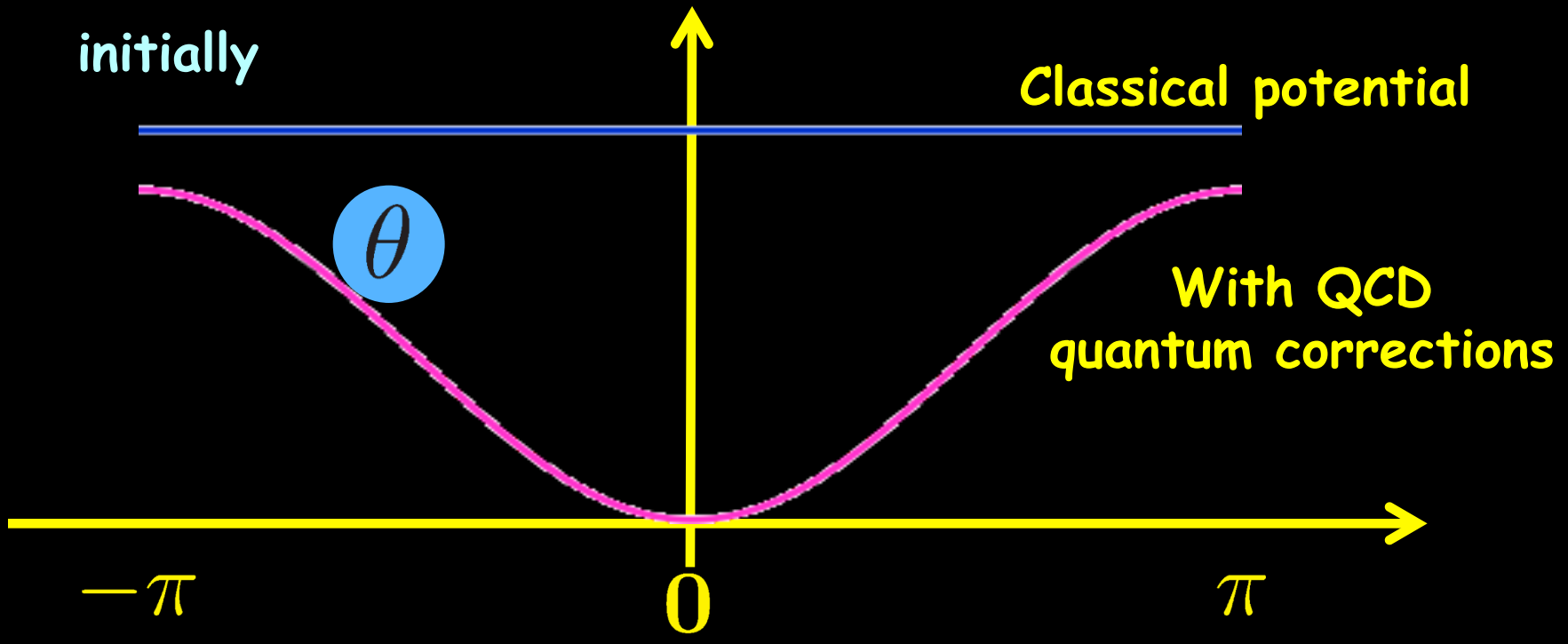

The axion solution to the strong CP problem

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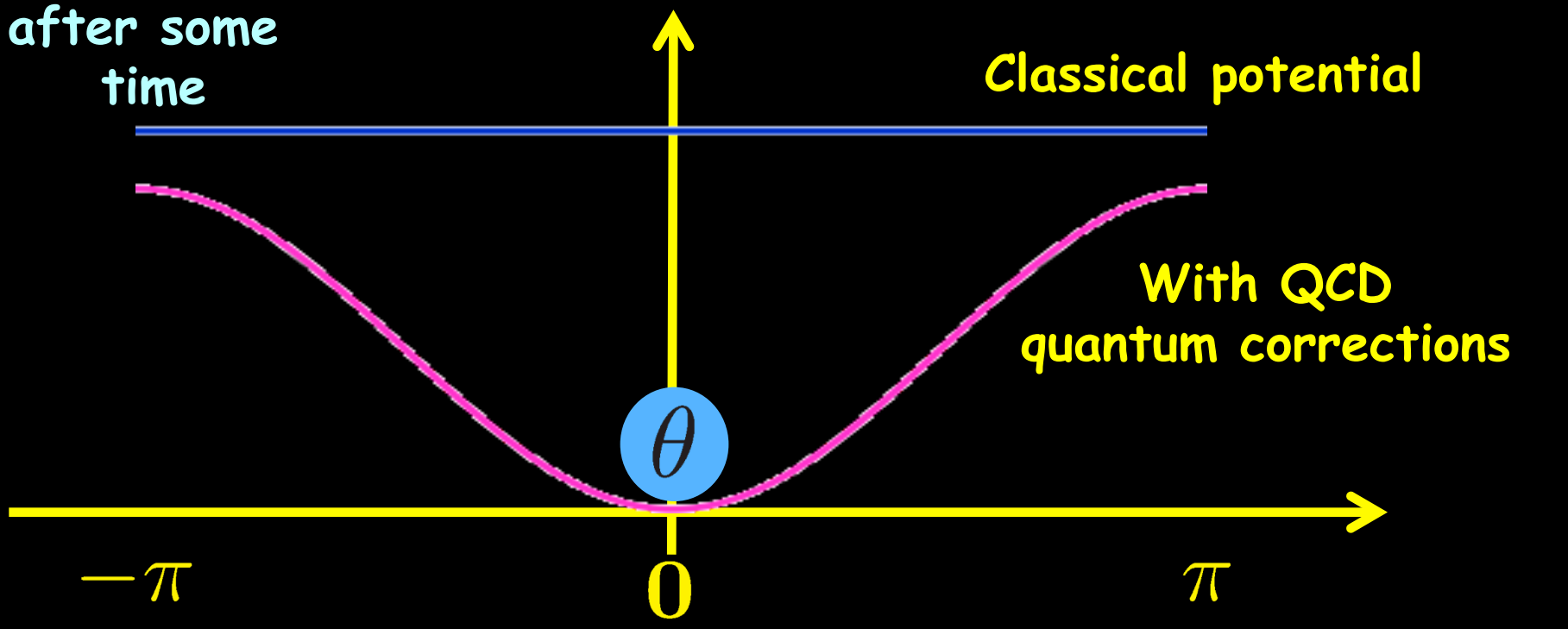

➔ QCD likes to be CP conserving (if we allow it)

The axion solution to the strong CP problem

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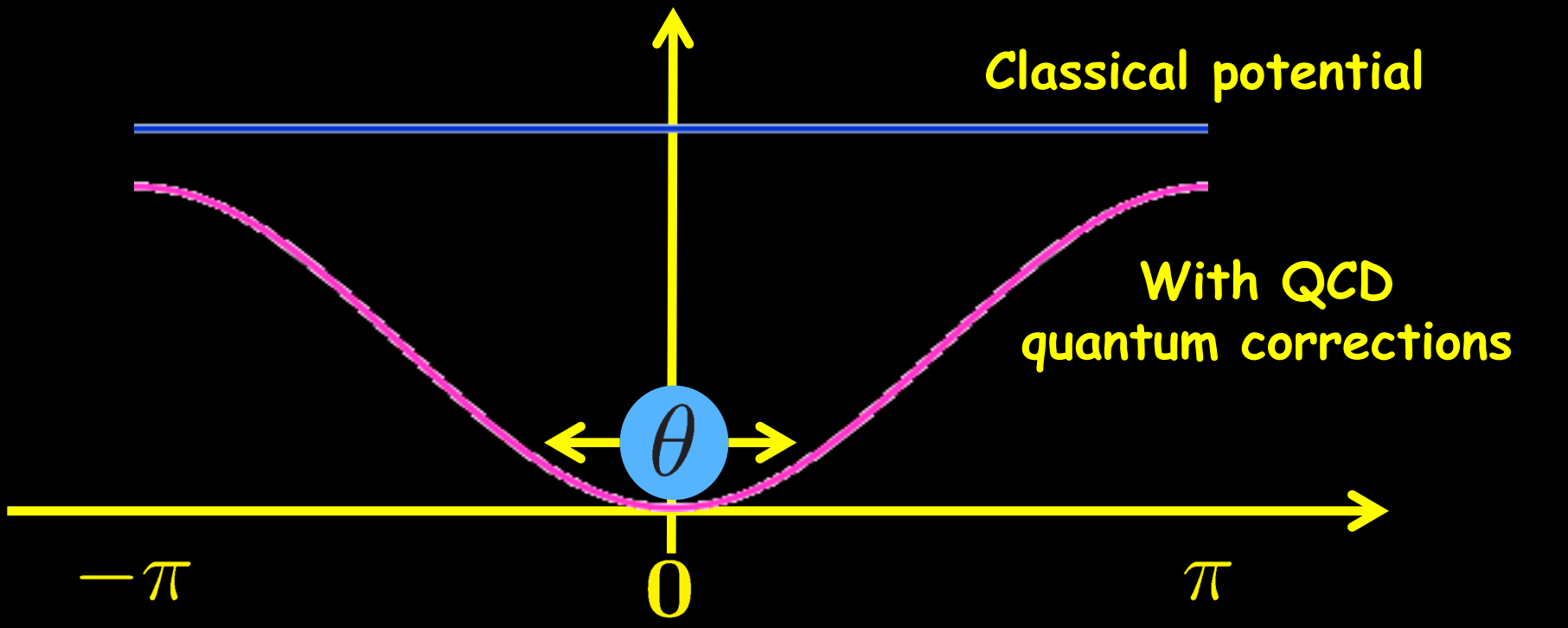
- Make θ dynamical ➔ it can change its value



➔ Can still move

➔ new particle = axion

Axion also couples to two photons

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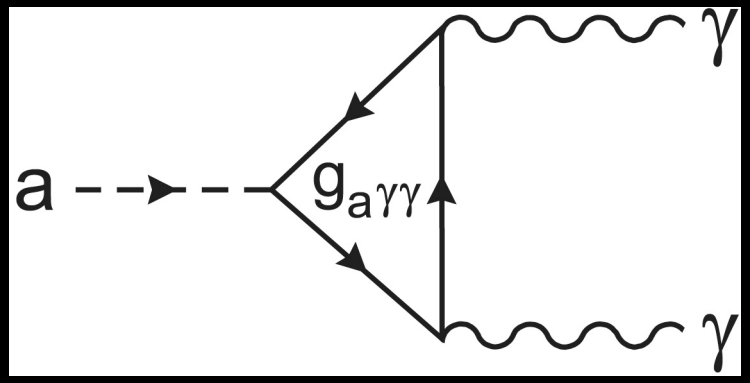

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a - m^2 a^2 - \frac{1}{4}g_{a\gamma\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu} + \ldots$$

Coupling to two photons

Very very weak $g_{a\gamma\gamma} \sim \dfrac{\alpha}{2\pi\, f_a}$

Because: Very large

Axion-like Particles

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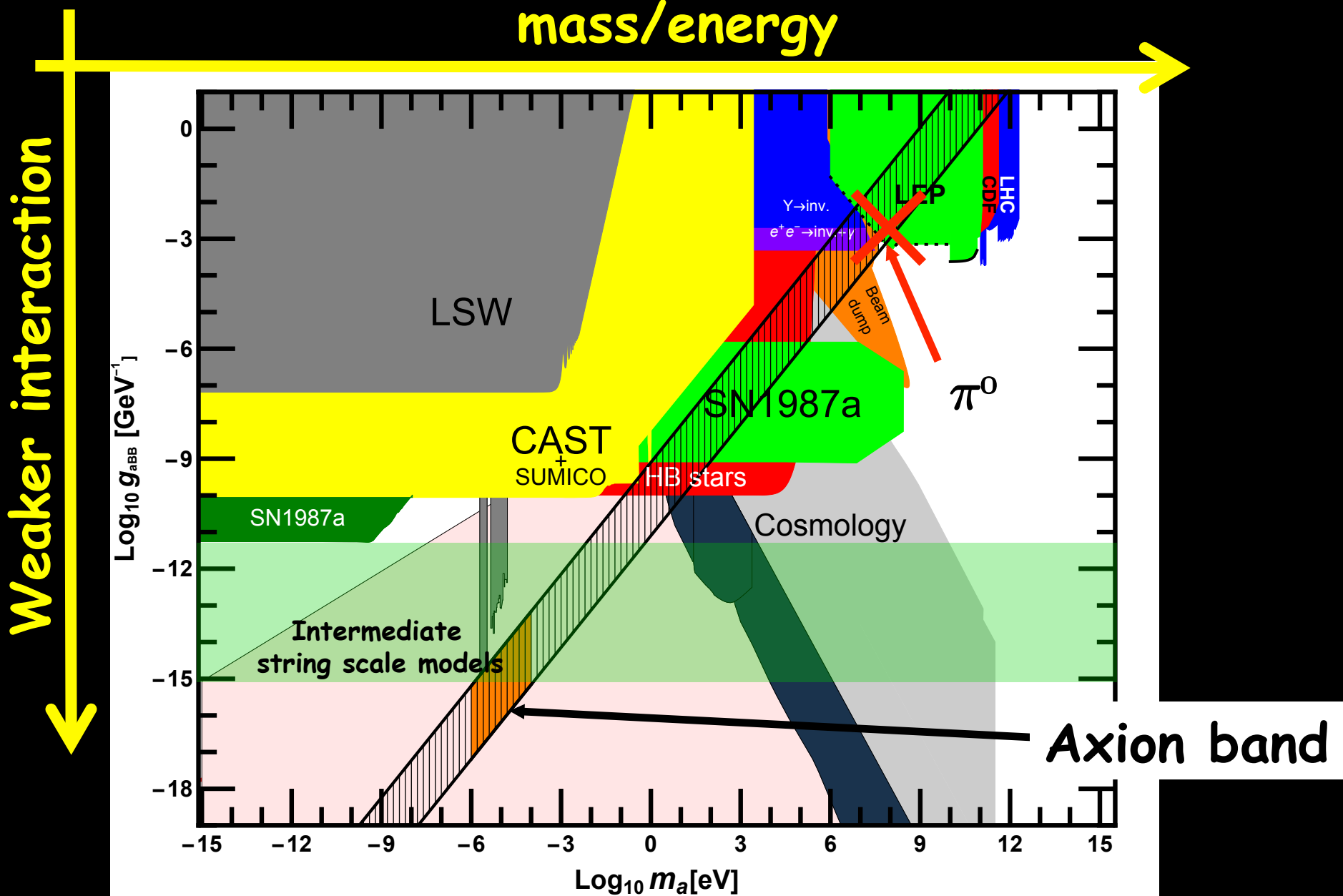

Dark Matter(s)

Can Dark Matter be WISPy?

(Weakly Interacting Sub-eV Particley)

Slim

Properties of Dark Matter

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- Dark matter is dark, i.e.
  it doesn't radiate!
  (and also doesn't absorb)

➔ very, very weak interactions with light and with ordinary matter

➔ Exactly the property of WISPs

Exploring is (at least) 2 dimensional

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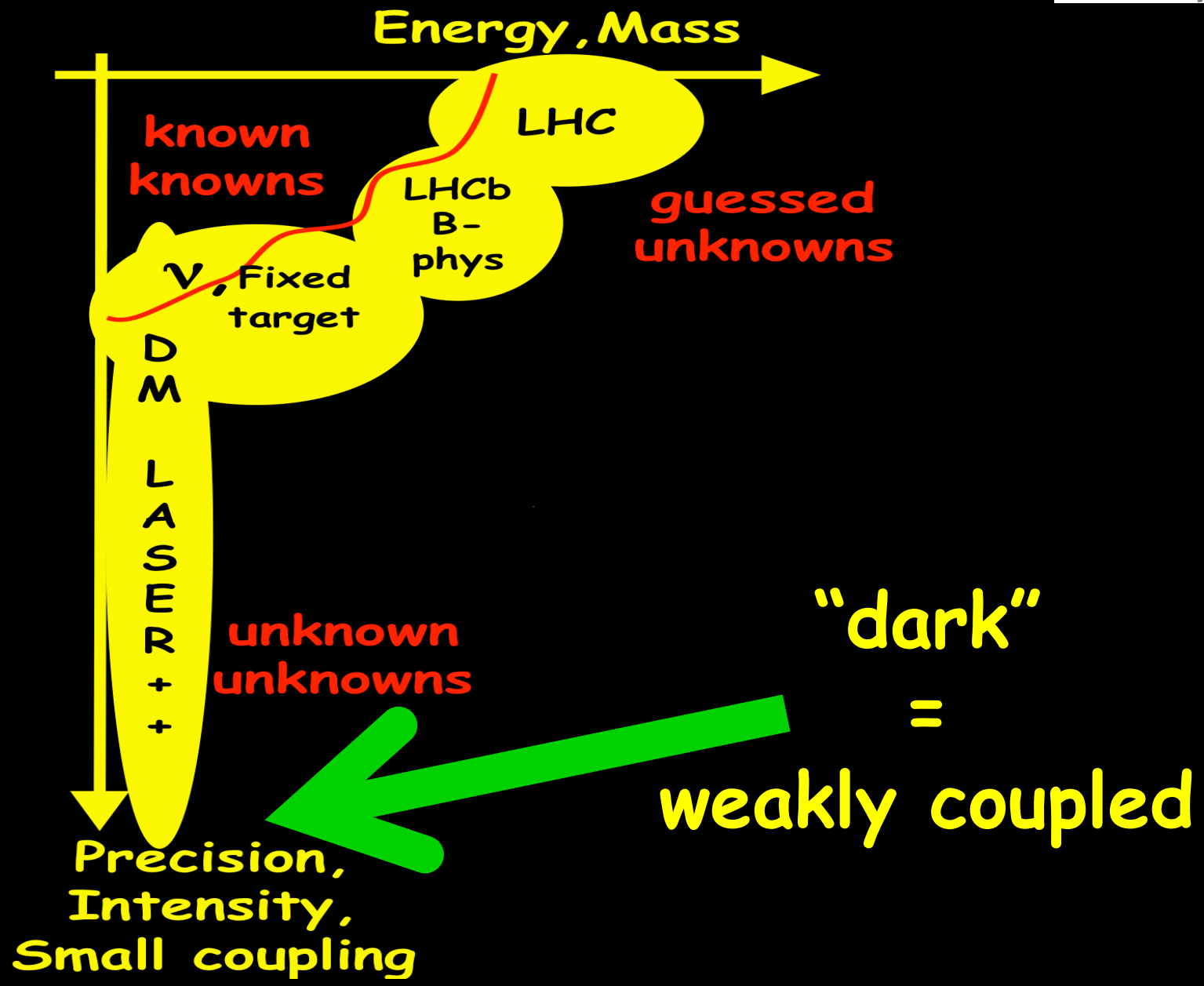

A common prejudice

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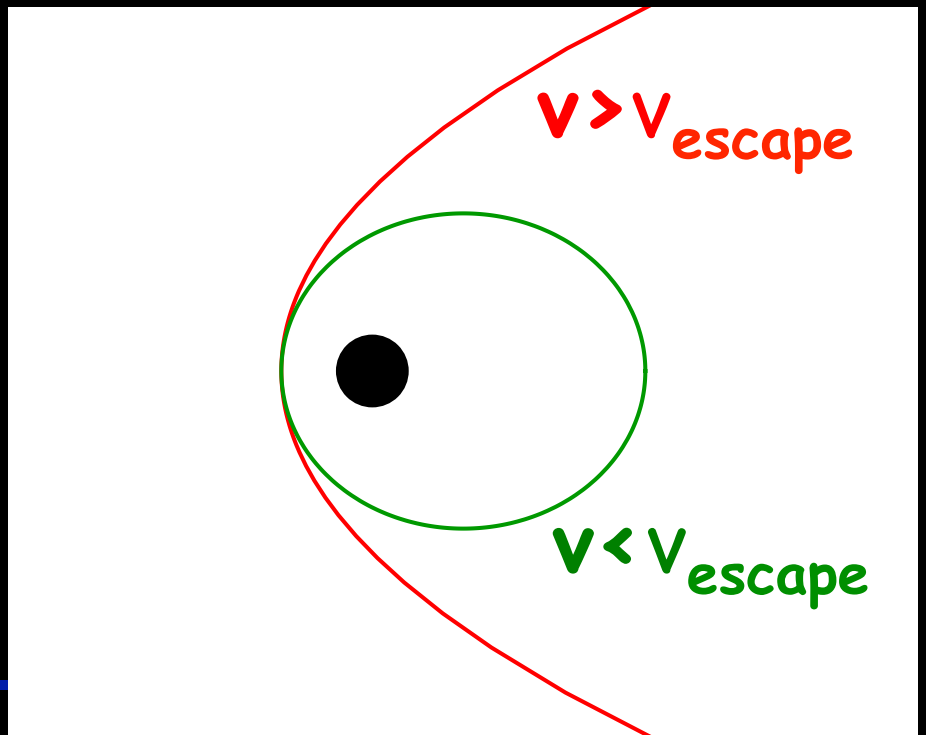
- Dark Matter has to be heavy: $m_{\rm DM} \gtrsim {\rm keV}$.

- Prejudice based on thermal production!
  and/or fermionic DM!

Both assumptions give minimal velocity

➔ galaxy,
i.e. structure,
formation inhibited!



Weakly interacting sub-eV DM

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- Has to be non-thermally (cold!!!) produced

  ➡ See misalignment mechanism 

- Bosonic!

  ➡ Axion(-like particles)
  Hidden Photons 

Dark matter has to be heavy…

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Dark matter has to be heavy $m_{\rm DM} \gtrsim {\rm keV}$?

Dark matter has to be heavy…

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SUPERCOLD DARK MATTER

The axion has no clue where to start

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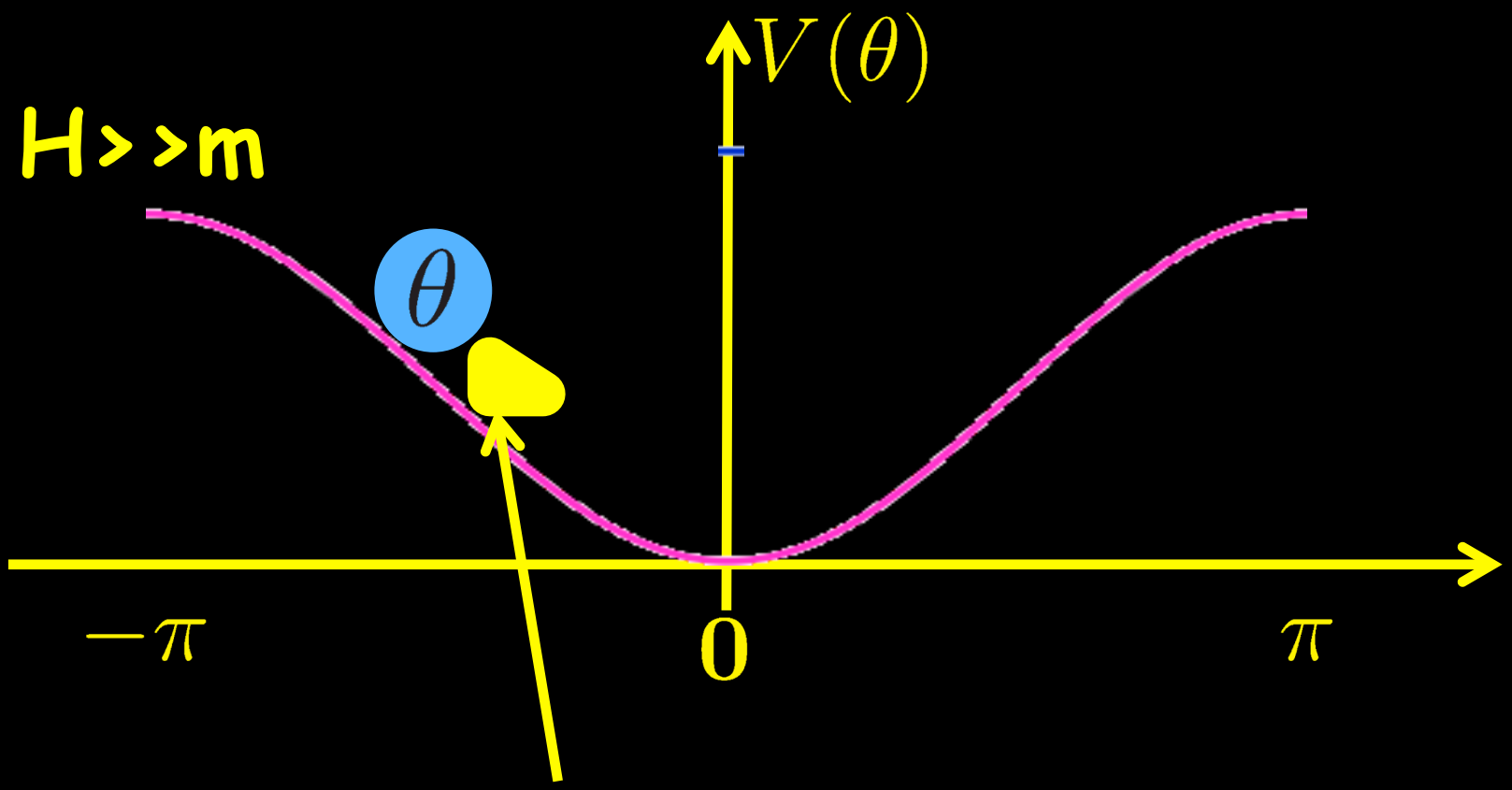

Field is stuck because of Hubble "breaking"

The axion has no clue where to start

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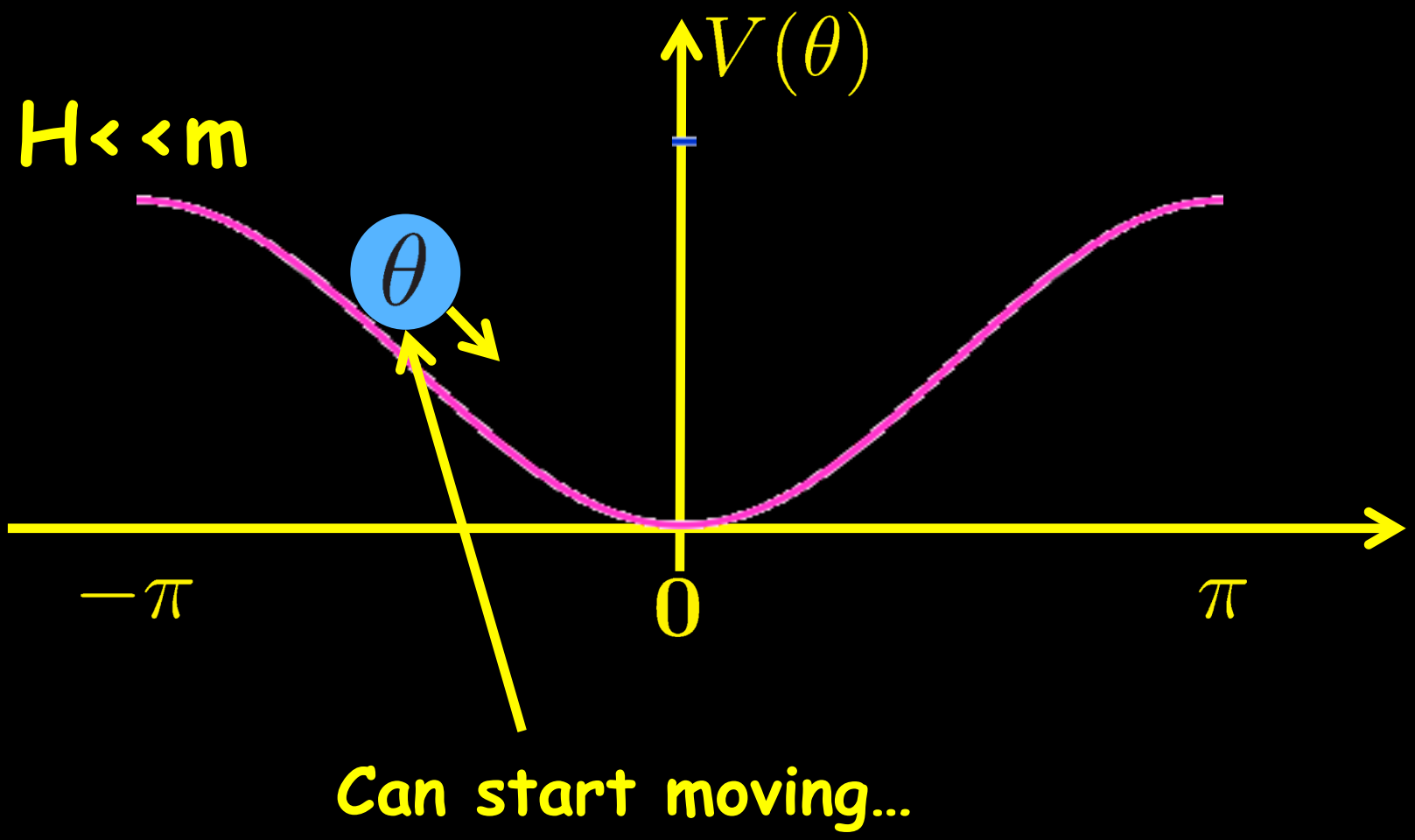

The axion solution to the strong CP problem

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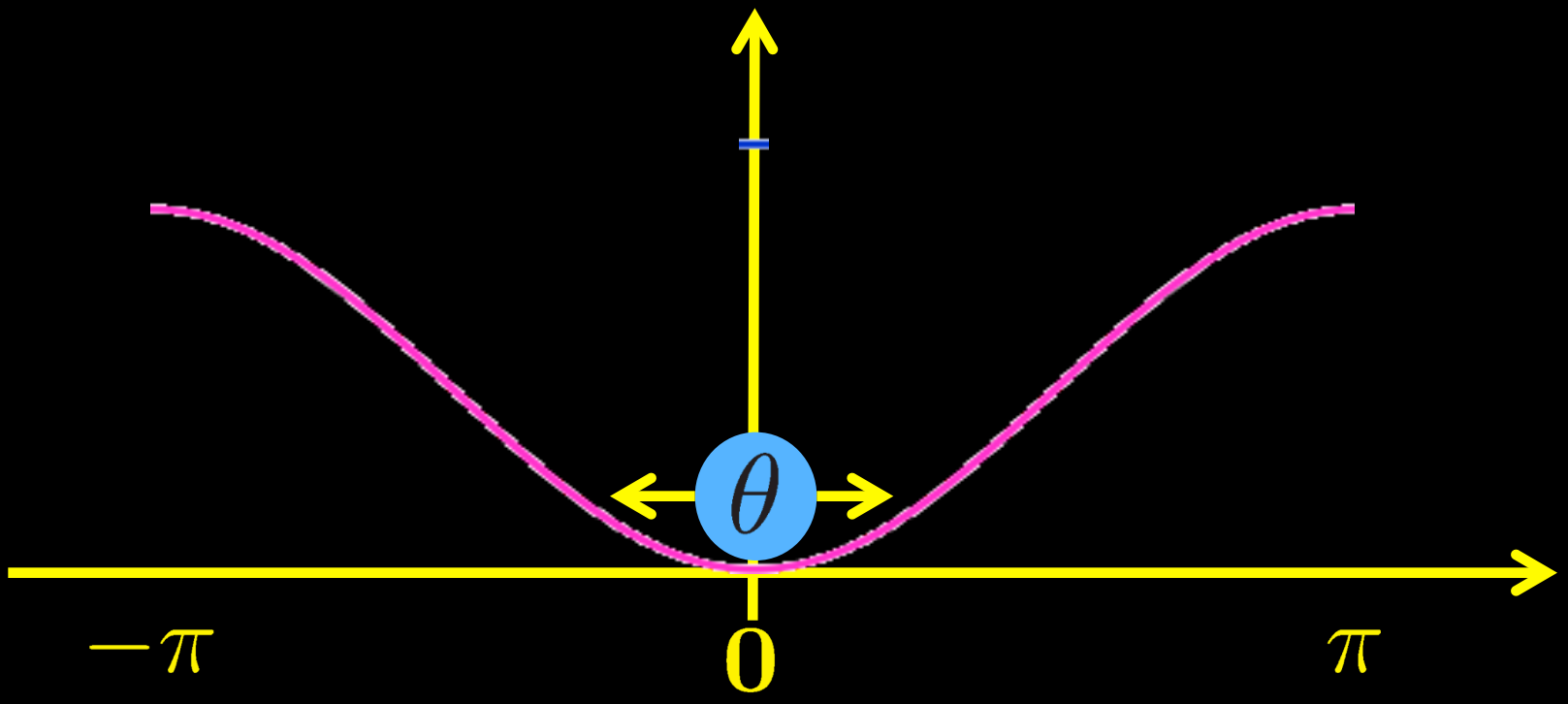

➔ Oscillations contain energy
➔ behave like non-relativistic particles (T=0)

Why Cold? Inflation!

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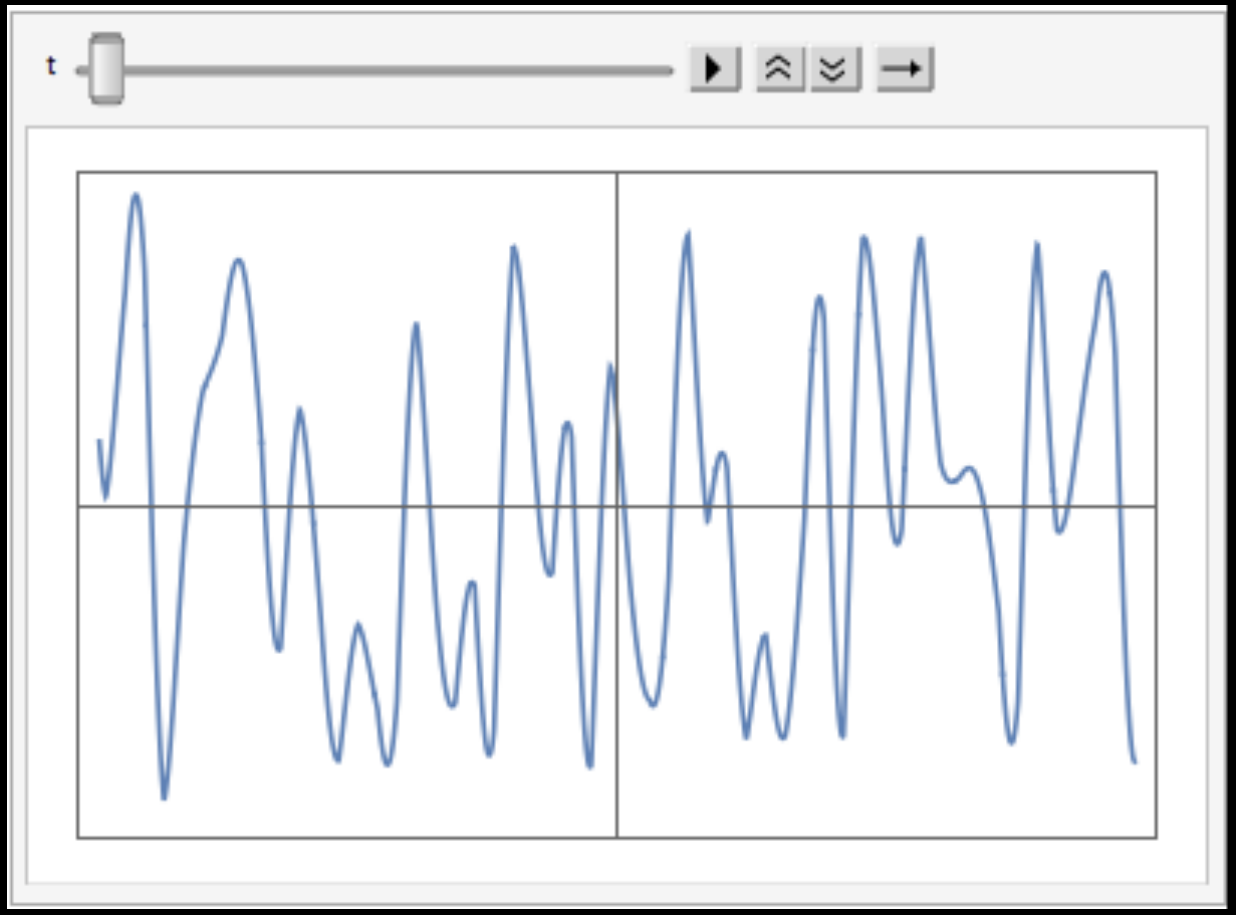
Field value



space

$$velocity \sim \frac{p}{m} \sim \frac{\hbar}{m}\frac{d}{dx} \to 0$$

Axion(-like particle) Dark Matter

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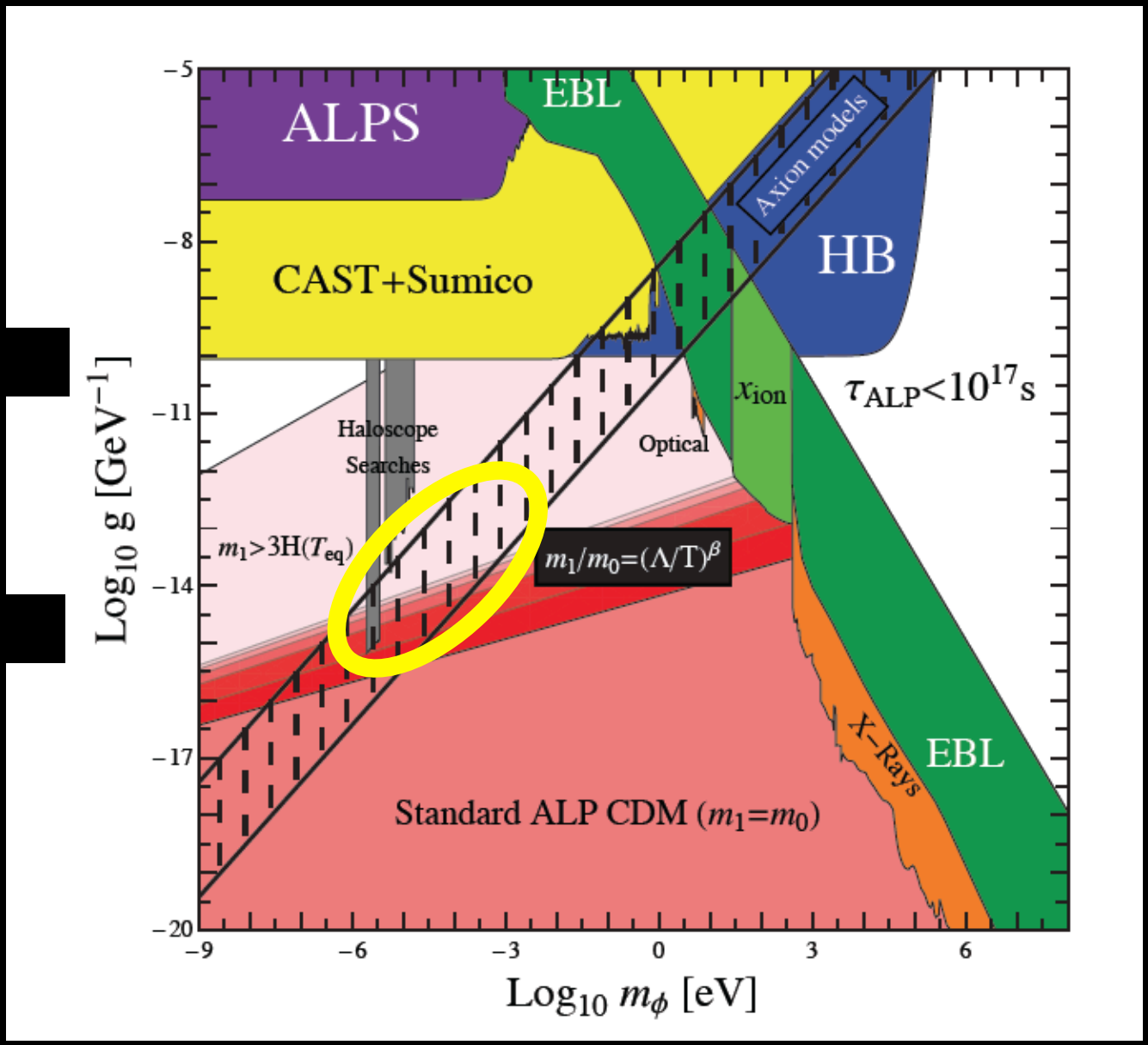
~10^7 GeV

~10^{12} GeV



Detecting WISPy DM

Use a plentiful source of axions

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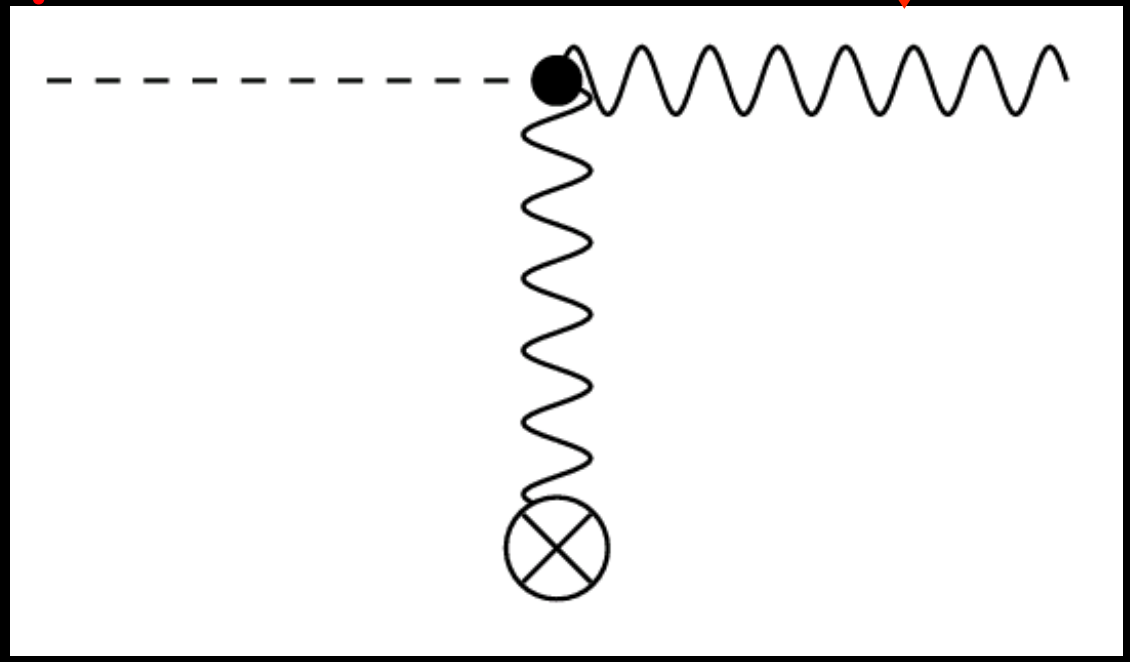
- Photon Regeneration

Photon
(amplified in resonator)



axion
(dark matter)

Signal: Total energy of axion

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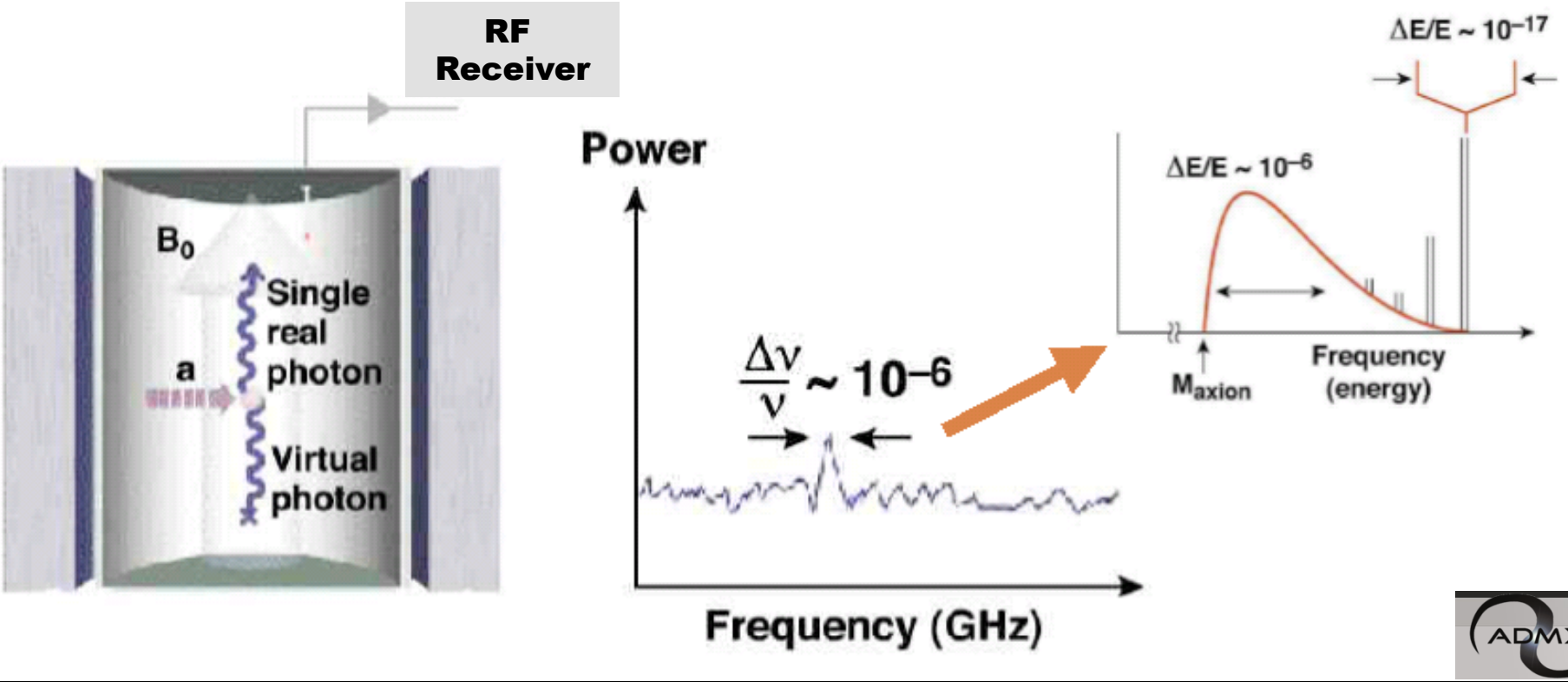

$$h\nu = m_a c^2 [1 + \mathcal{O}(\beta^2 \sim 10^{-6})]$$

Virial velocity in galaxy halo!

An extremely sensitive probe!!!

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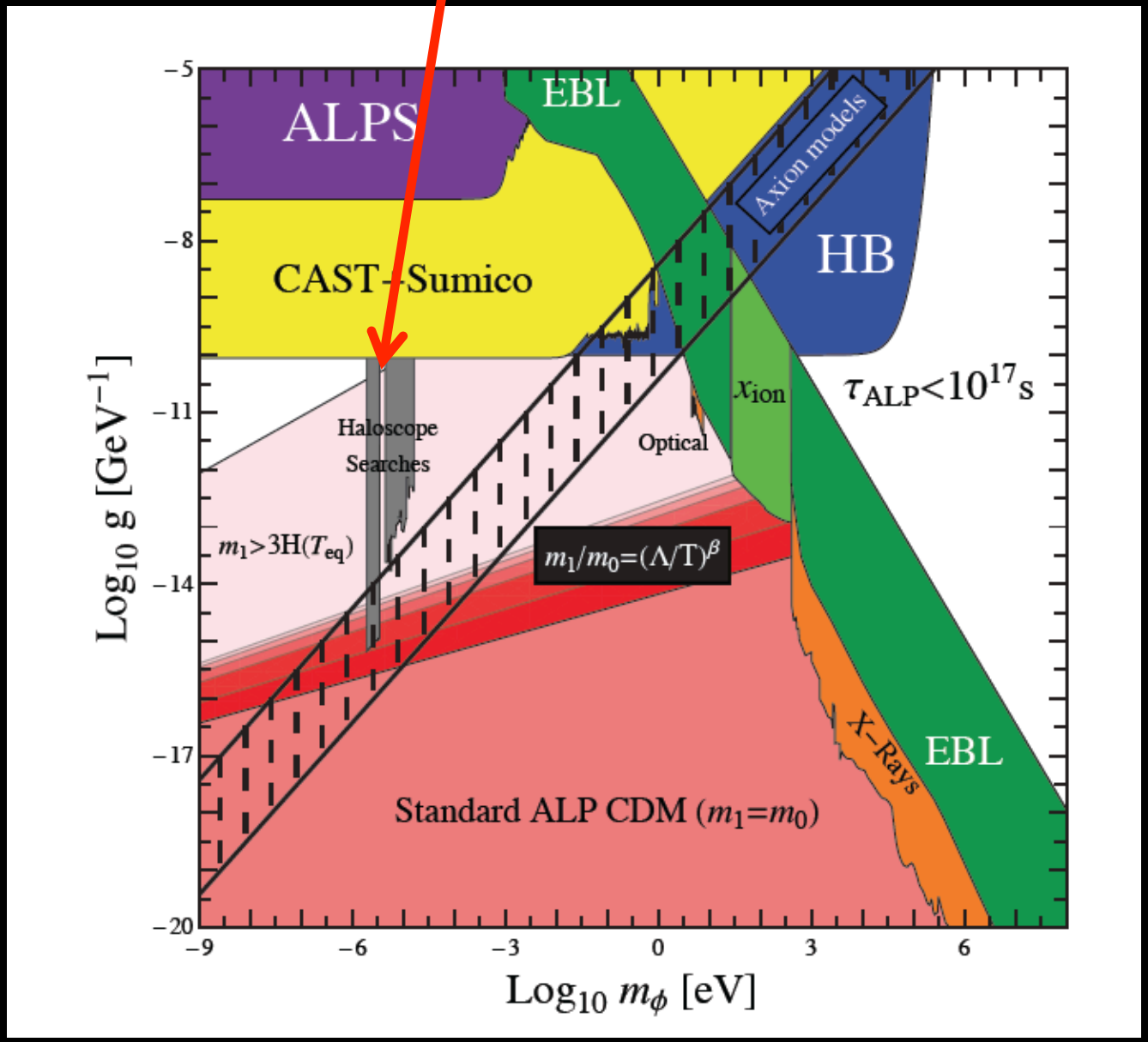

Electricity from Dark Matter ;-).

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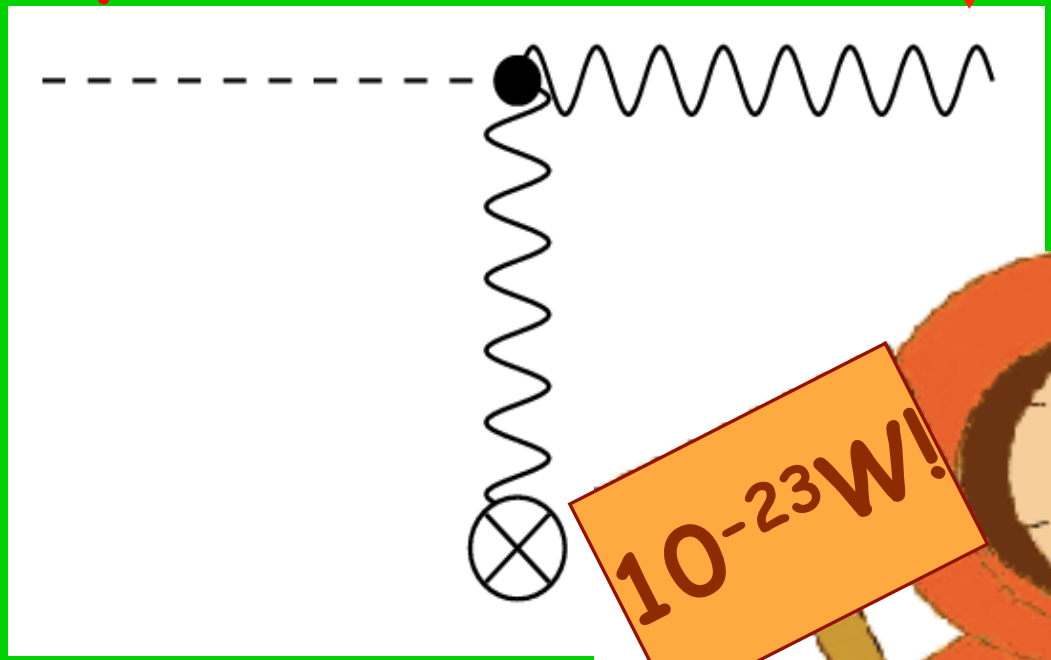
- Photon Regeneration

Photon
(amplified in resonator)

axion
(dark matter)



Really sustainable Energy

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- Galaxy contains (6-30)x10^{11} solar masses of DM

  ➔ (3-15)x10^{43} TWh

@100000 TWh per year (total world today)

  ➔ 10^{38} years ☺

DM power

ρ*v~300 MeV/cm^3*300km/s~10 W/m^2

compared to 2W/m^2 for wind

A discovery possible any minute!

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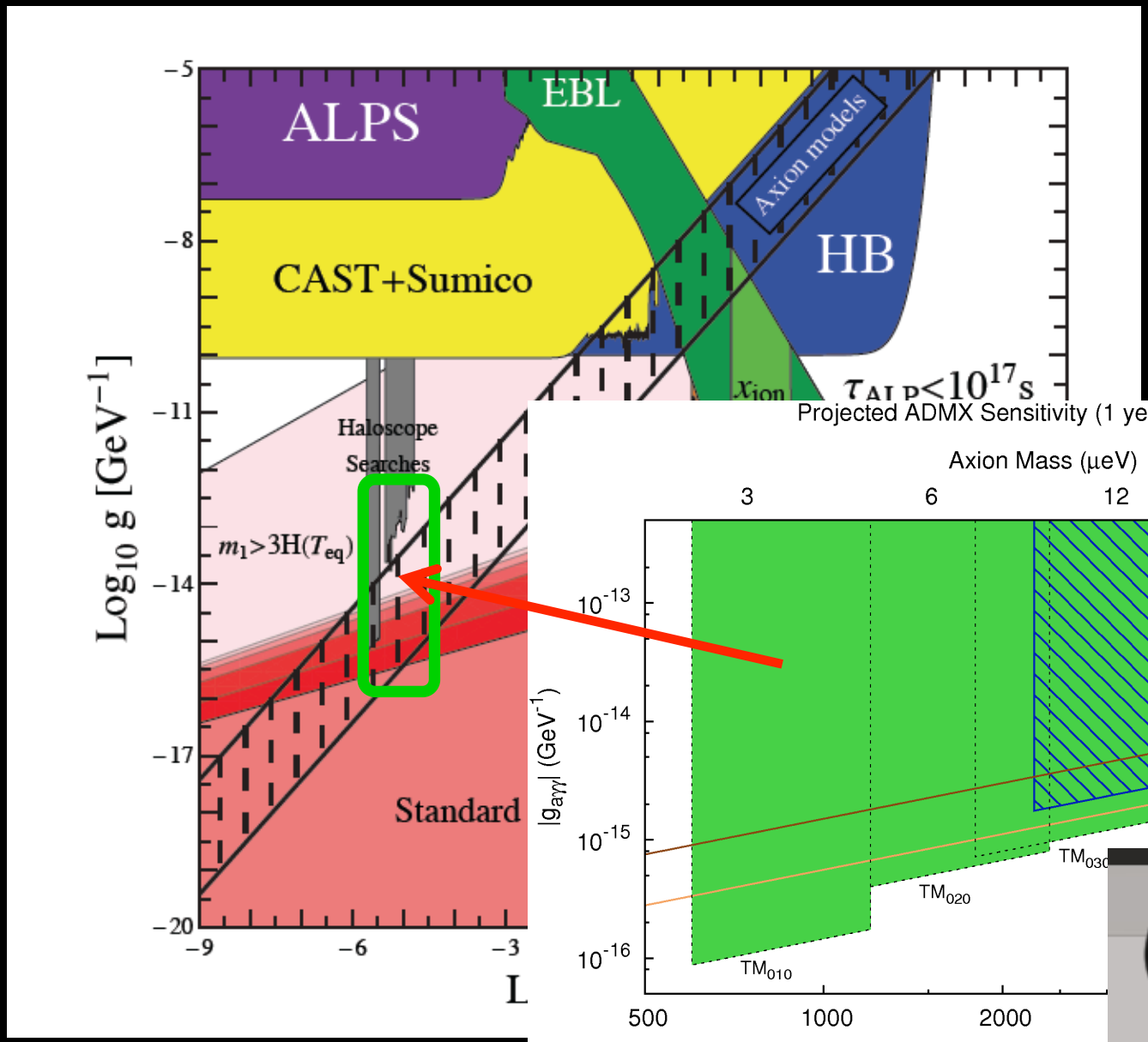

Encircling the axion...

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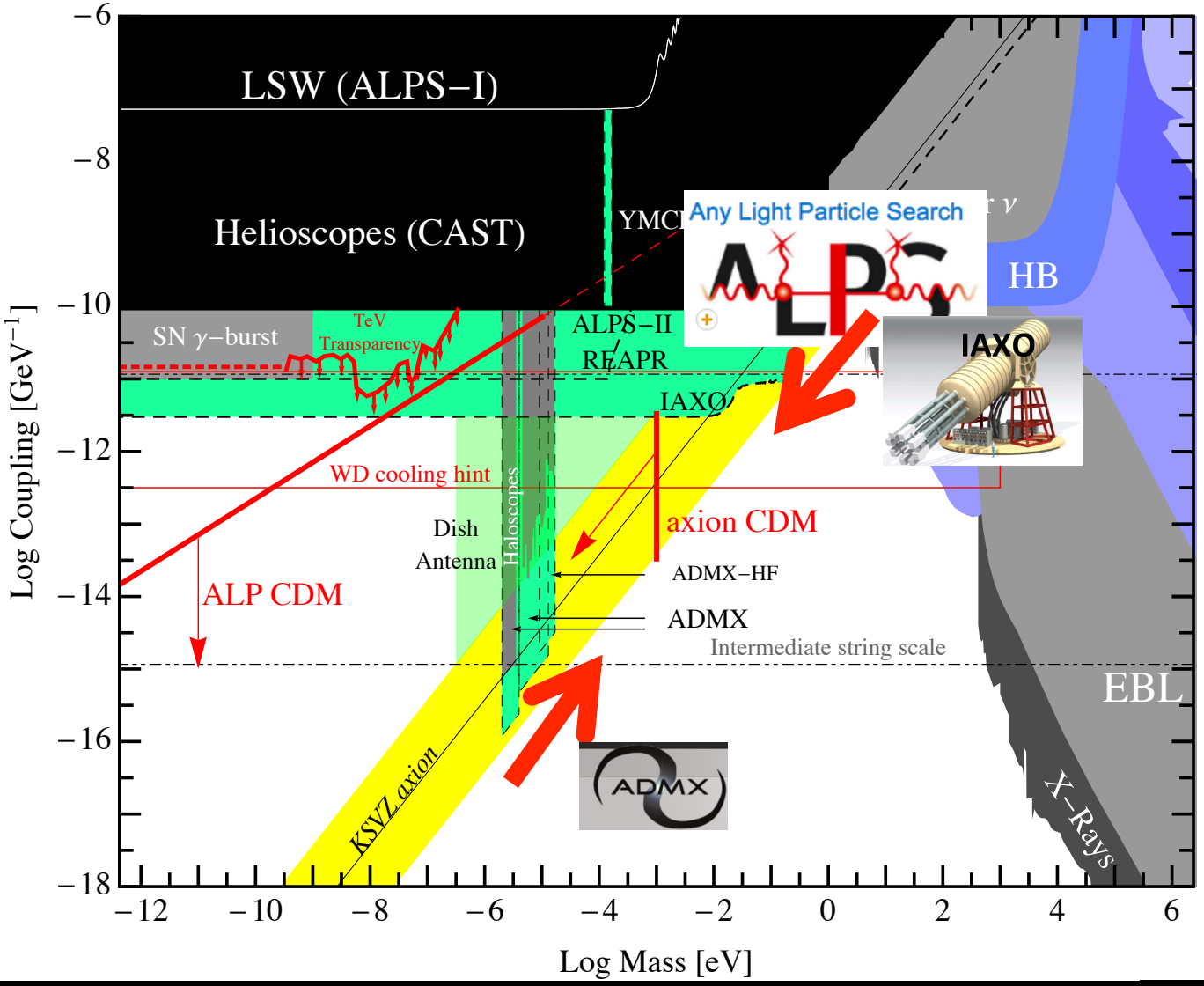

Beyond ALPs

Hidden photons

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- Photon Regeneration

Photon
(amplified in resonator)

Hidden photon

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} F^{\mu\nu}_{(\text{A})} F_{(\text{A})\mu\nu} - \frac{1}{4} F^{\mu\nu}_{(\text{B})} F_{(\text{B})\mu\nu} + \frac{\chi}{2} F^{\mu\nu}_{(\text{A})} F_{(\text{B})\mu\nu},$$

„Our" U(1) | „Hidden" U(1) | Mixing

+ Mass $\mathcal{L}_{\text{mass}} = \frac{1}{2} m^2_{\gamma'} X^\mu X_\mu$

Also for hidden photons!!!

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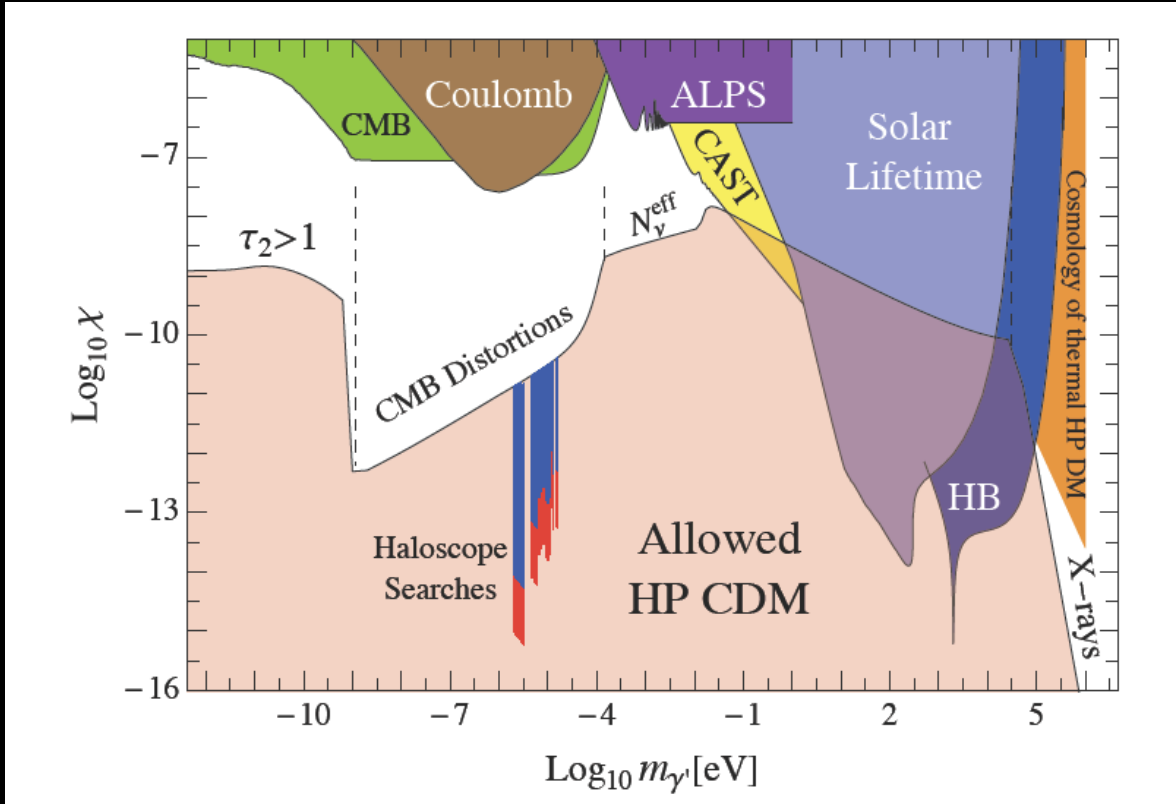
- There are other very light DM candidates
- E.g

  extra (hidden) U(1) bosons=hidden photons!!!



@ DESY + Bonn: WISPDMX

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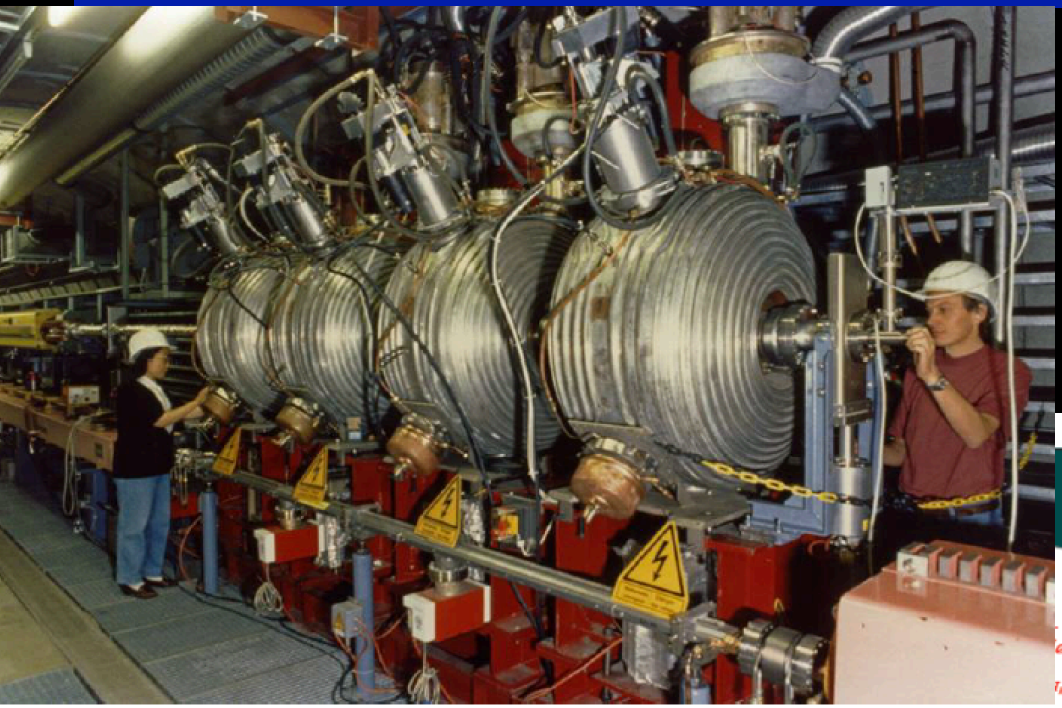

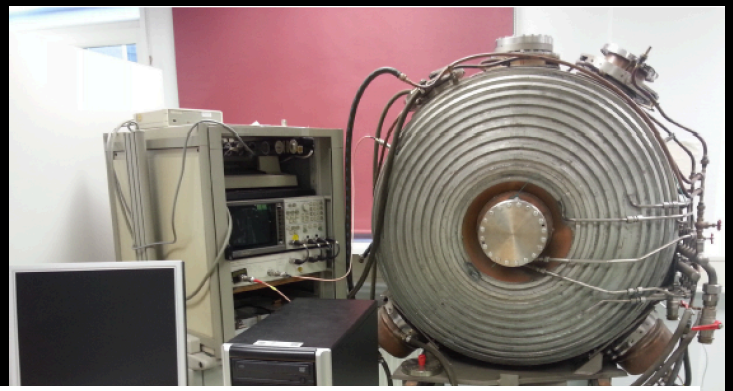

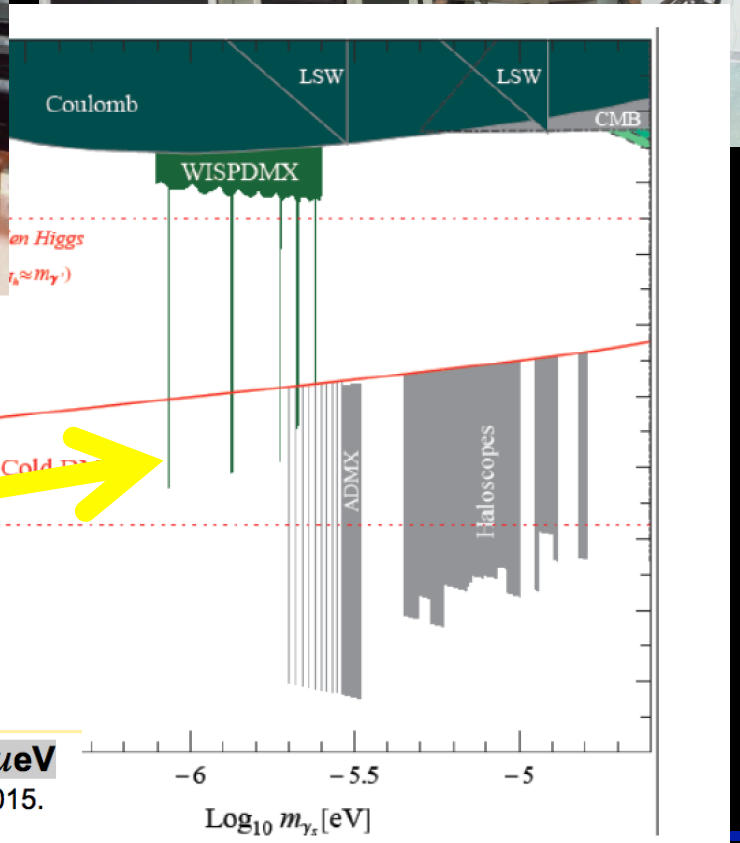

New Results!

1. **WISPDMX: A haloscope for WISP Dark Matter between 0.8-2 μeV**
   Le Hoang Nguyen, Dieter Horns, Andrei Lobanov, Andreas Ringwald. Nov 10, 2015.
   DESY-15-185
   e-Print: arXiv:1511.03161 [physics.ins-det] | PDF

Broadband Search Strategy

Dark Matter Antenna

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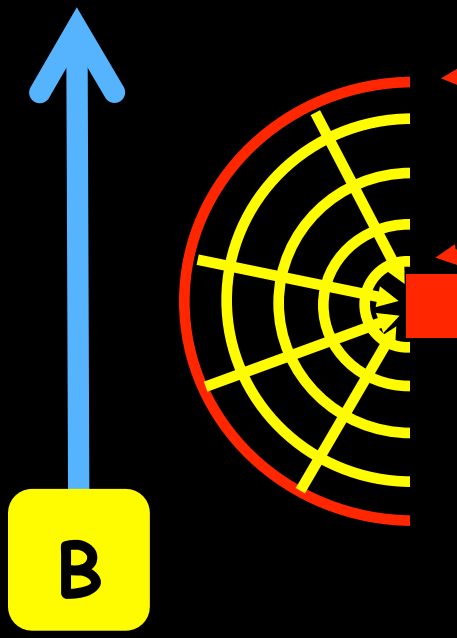
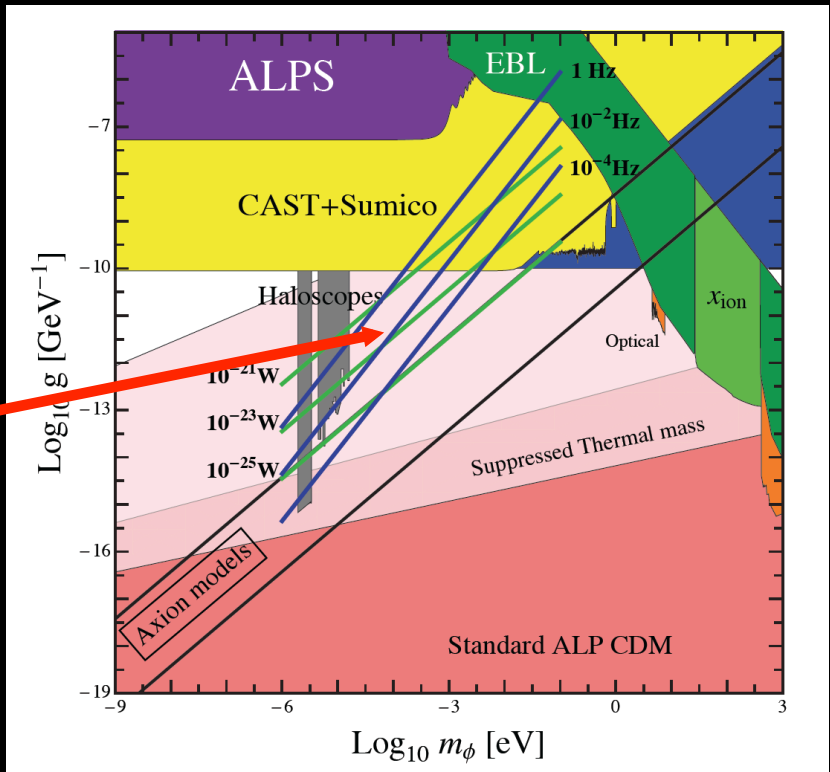


Antenna converts axion->photon

Radiation concentrated in center

Detector

Probes here;
very sensitive!!



The FUNK Experiment

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Recycle Auger mirror

Detector

First Results

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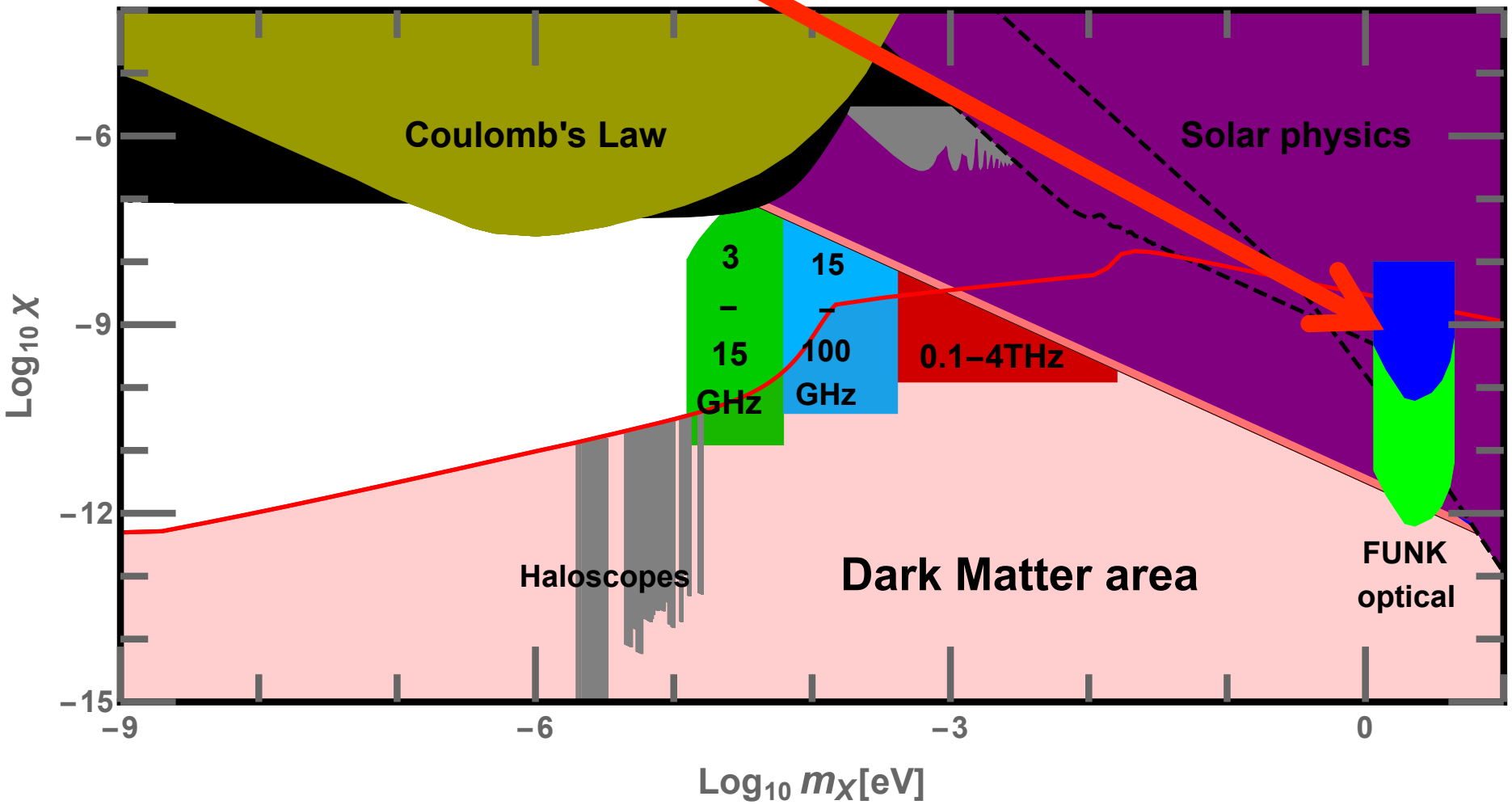

Upgrade: The PMT 9000(+107)

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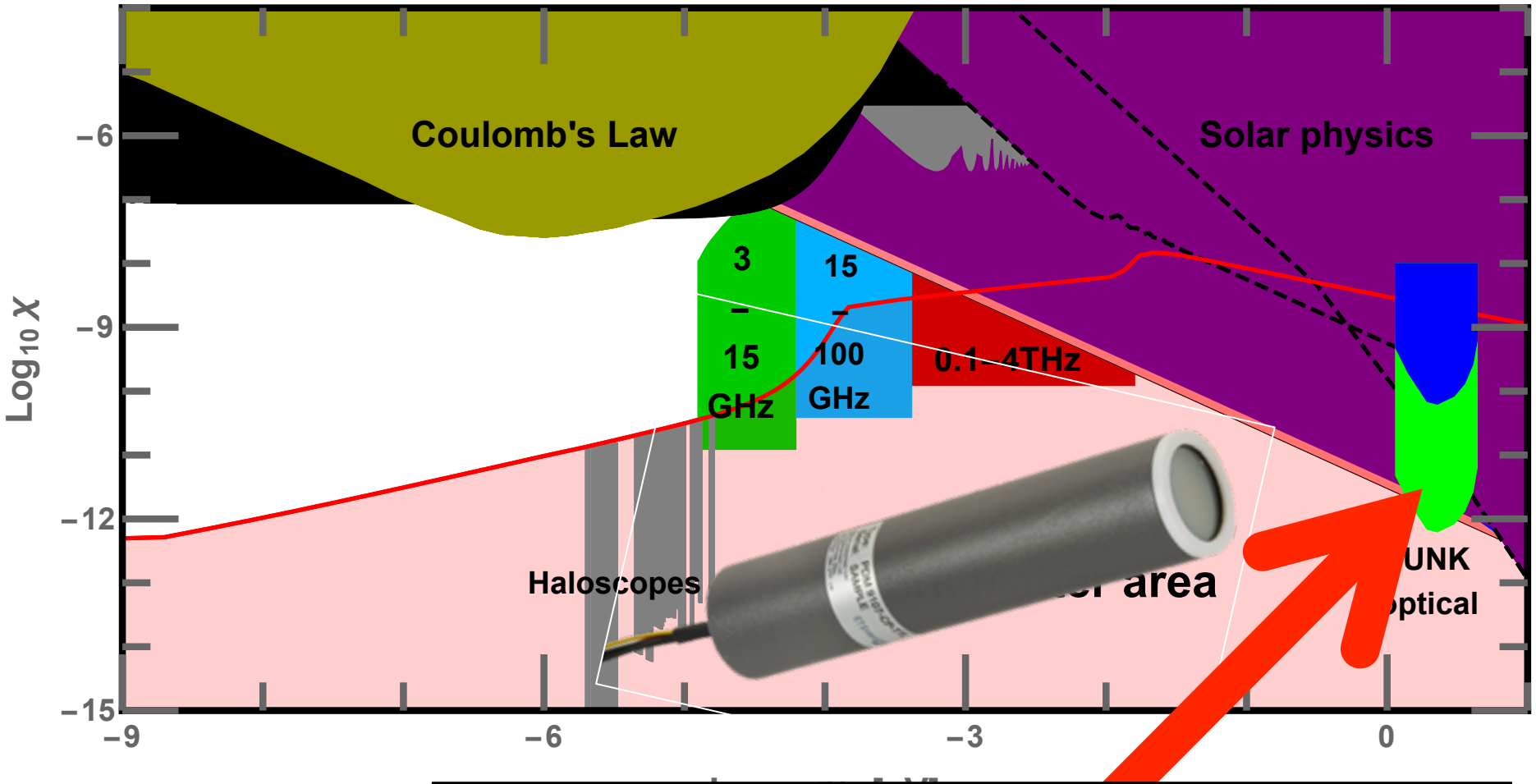

Discovery Potential ☺!!!

The next years ➔ Lower frequency

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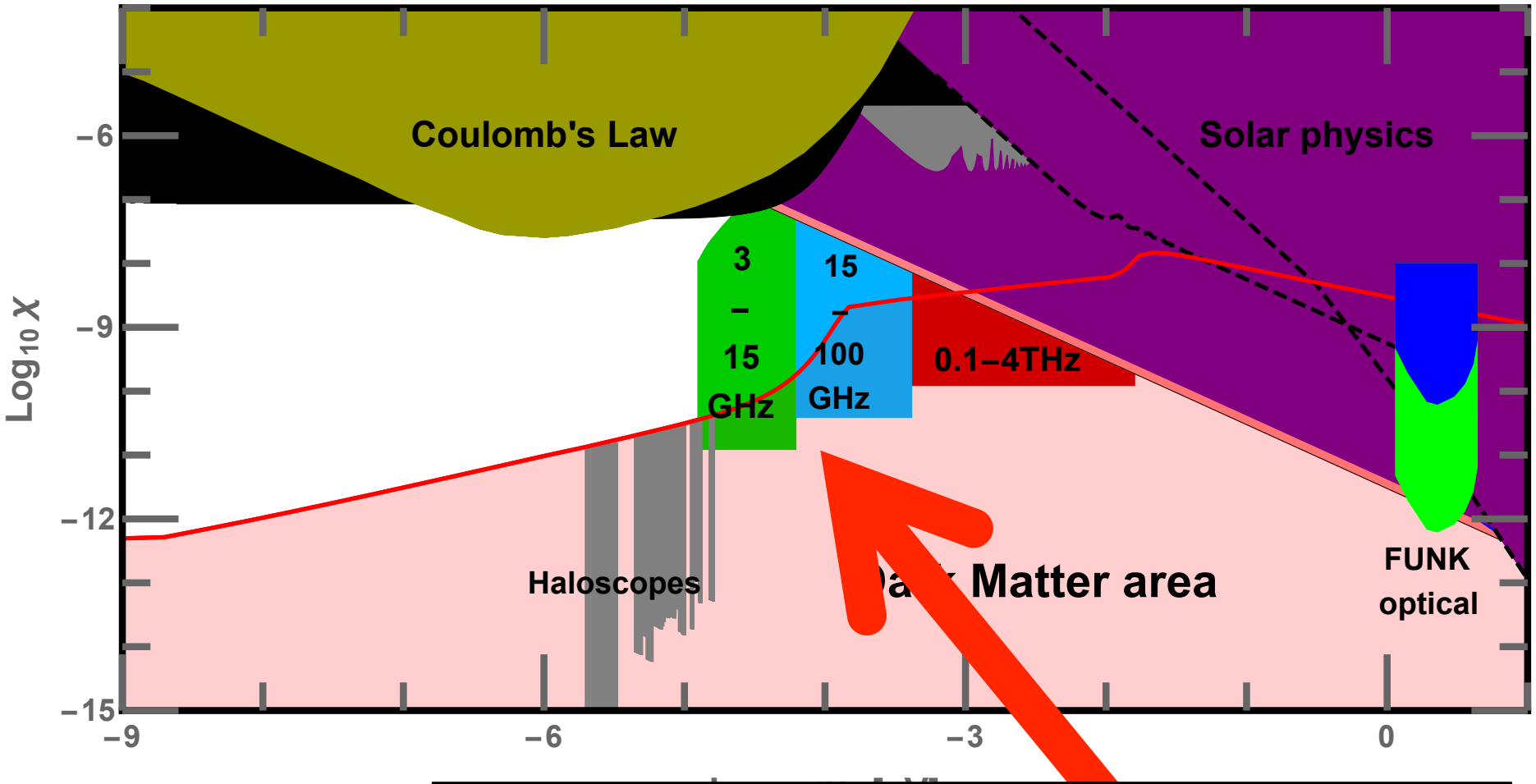

Discovery Potential ☺!!!

A Dream for ~~Astrology~~ ehhm Astronomy

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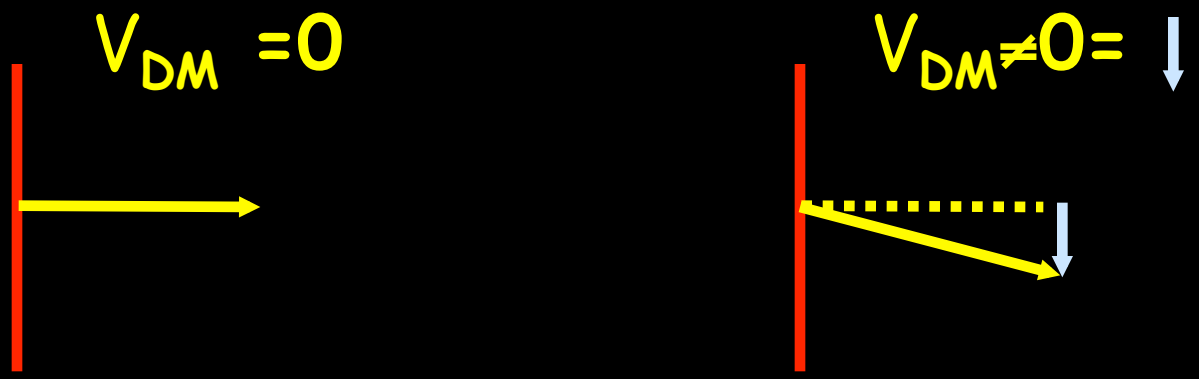
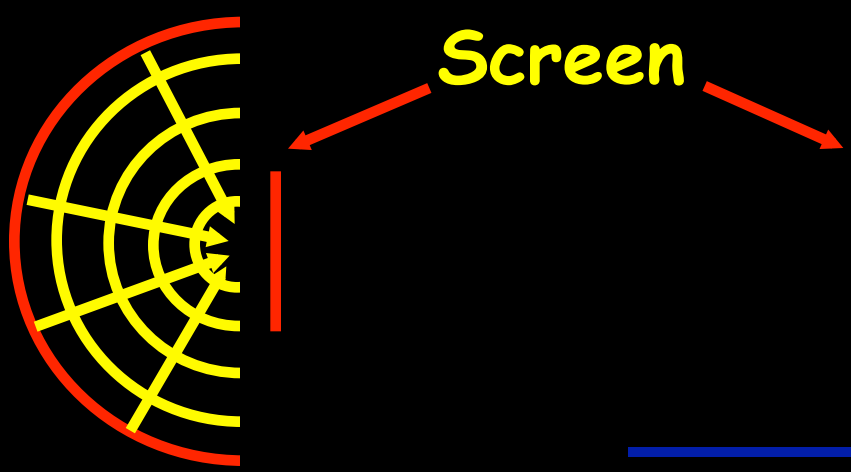
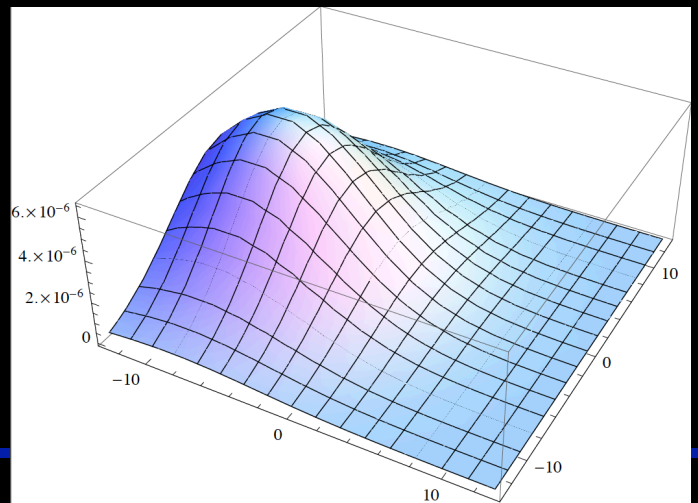
- Emission from moving dark matter



- A picture of the DM-velocity distribution





New couplings:
A spin experiment

Looking for oscillating dipoles

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- **Remember:**

  Axion field controls electric dipole moment:

$$d_e \sim \theta \sim \frac{a}{f_a}$$

- **Dipole moments follow the oscillating axion field**

  ➔ Tiny oscillating electric dipole

$$d_e \sim 10^{-35} e\,\mathrm{cm}\cos(m_a t)$$

New Observables for Direct Detection of Axion Dark Matter
Peter W. Graham, Surjeet Rajendran (Stanford U., ITP). Jun 25, 2013. 13 pp.
Published in **Phys.Rev. D88 (2013) 035023**
DOI: 10.1103/PhysRevD.88.035023
e-Print: arXiv:1306.6088 [hep-ph] | PDF

In an electric field

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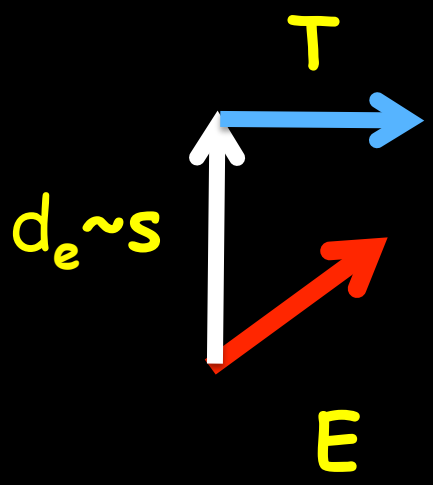

Energy in an elecxtric field

$$H = -\mathbf{d} \cdot \mathbf{E} = -c_E \mathbf{s} \cdot \mathbf{E}.$$

Torque tries to tilt dipole moment/spin

$$\mathbf{T} = \mathbf{d} \times \mathbf{E} = c_E \mathbf{s} \times \mathbf{E}.$$

Dealing with oscillation

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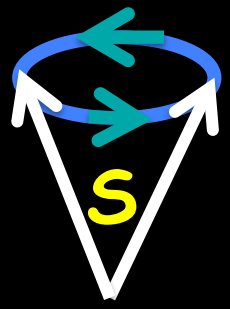
Problem: the dipole moment is rapidly oscillating ~m_a

➔ Danger of cancellation

Solution: Rotate spin to compensate

➔ Use Spin Precession in magnetic field

$$\omega_L = 2\mu B$$



Resonance when $\omega_L = m_a$

Modification of Xenon EDM

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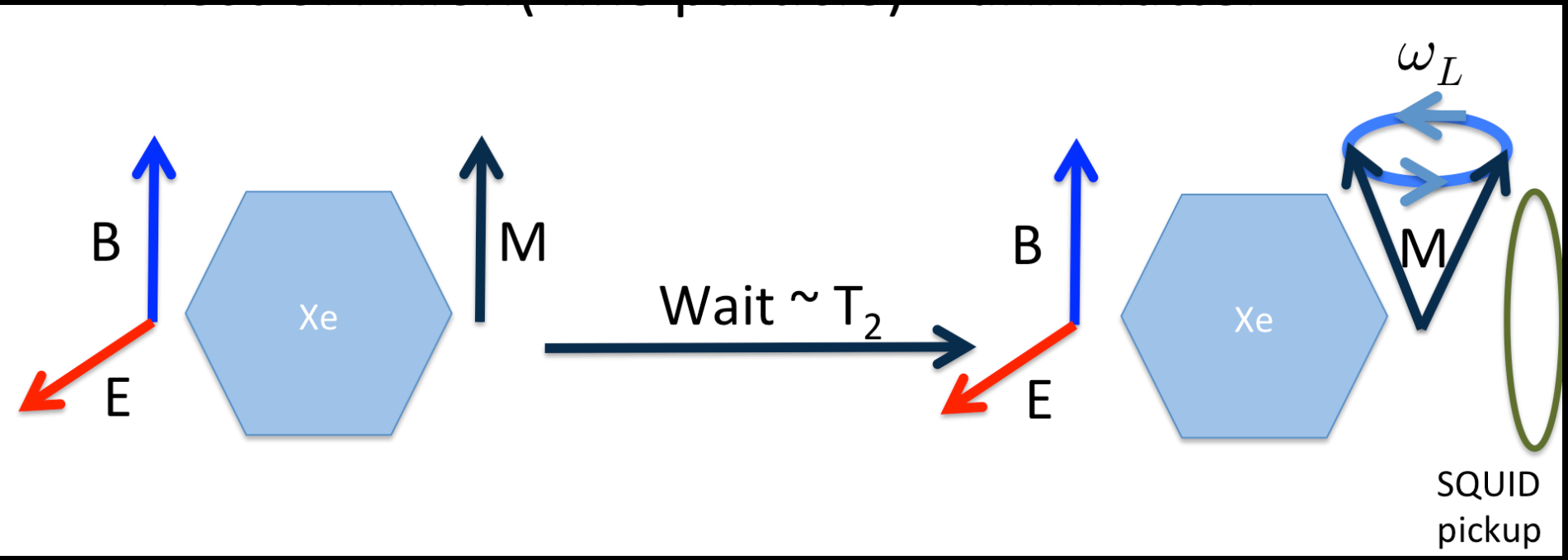
Modification of Xenon EDM experiment to be sensitive to time varying nuclear EDM



Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)
Dmitry Budker (UC, Berkeley & LBNL, NSD), Peter W. Graham (Stanford U., ITP), Micah Ledbetter (Unlisted, US, CA), Surjeet Rajendran (Stanford U., ITP), Alex Sushkov (Harvard U., Phys. Dept.).
Published in **Phys.Rev. X4 (2014) no.2, 021030**
DOI: 10.1103/PhysRevX.4.021030
e-Print: arXiv:1306.6089 [hep-ph] | PDF

Sensitivity

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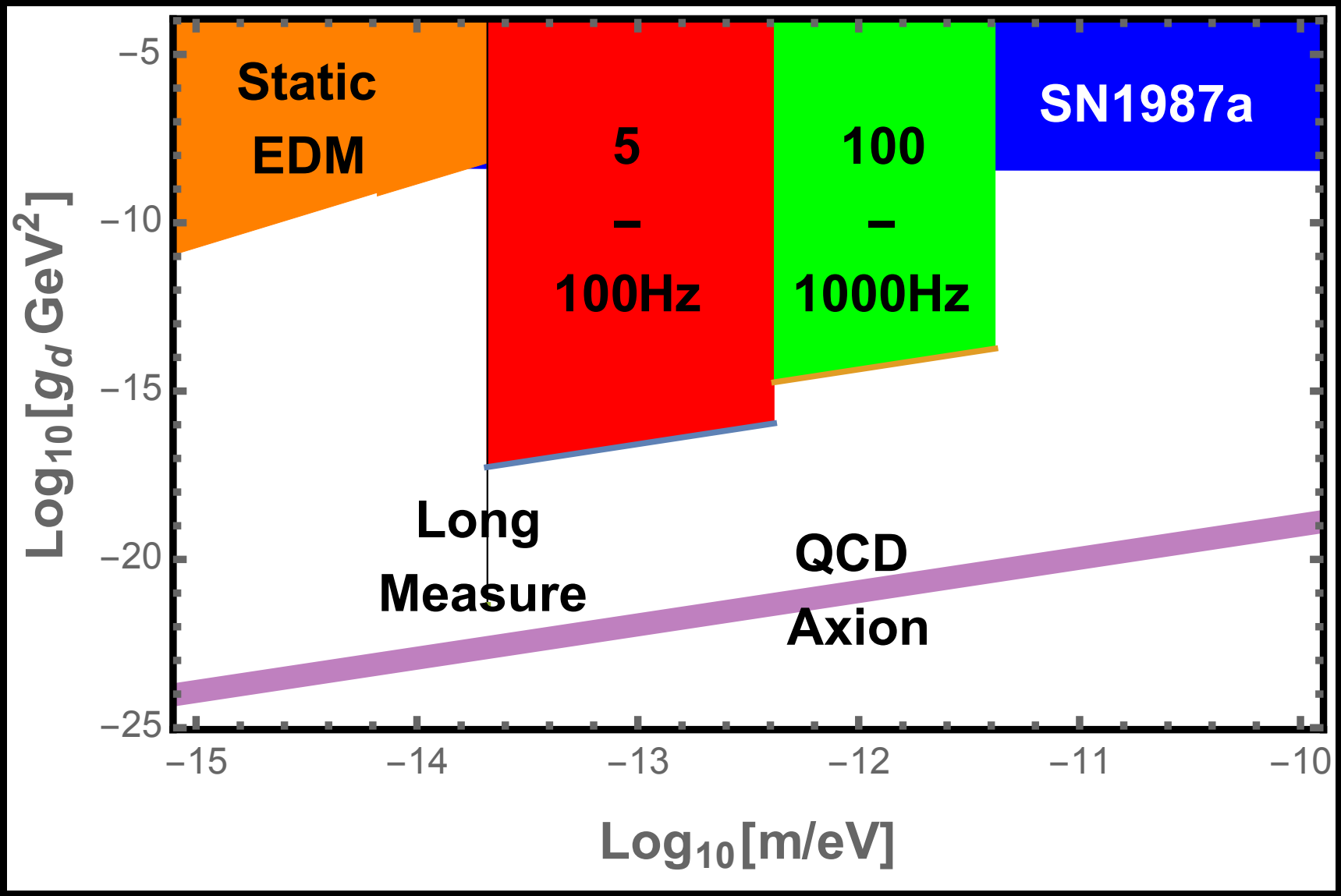

Going Monodromic

Axion Monodromy

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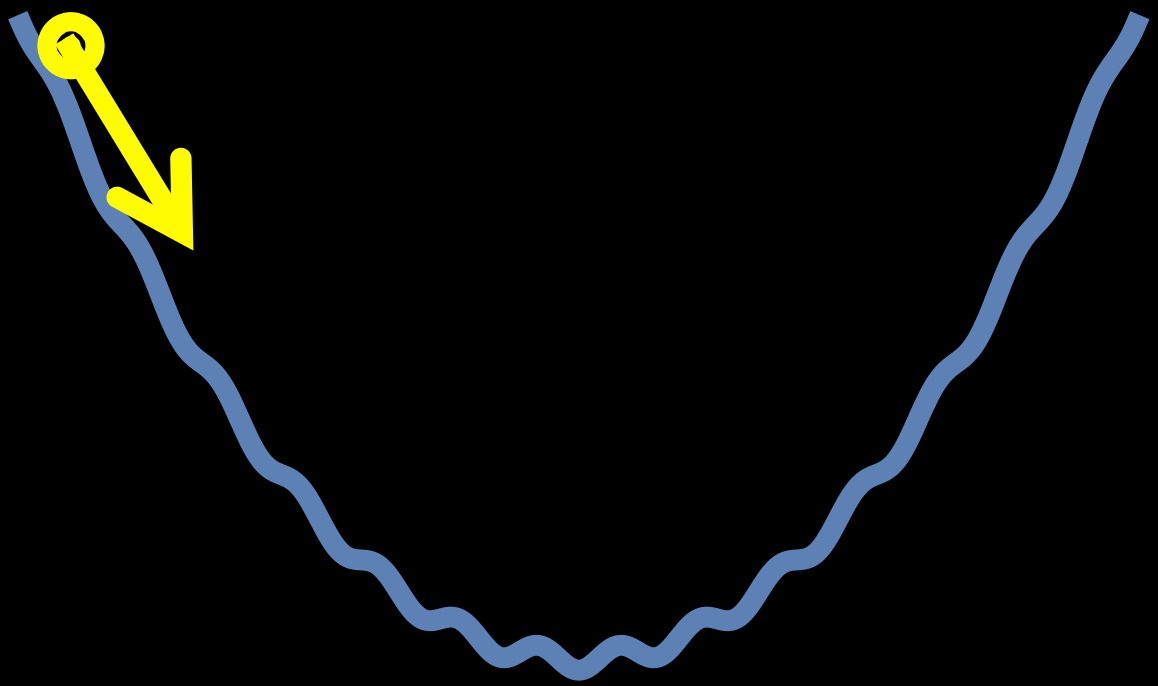
- Allows for extended field range

$$V(\phi) = \frac{1}{2} m^2 \phi^2 + \Lambda^4 \left(1 - \cos\left(\frac{\phi}{2\pi f}\right)\right)$$



Advantages

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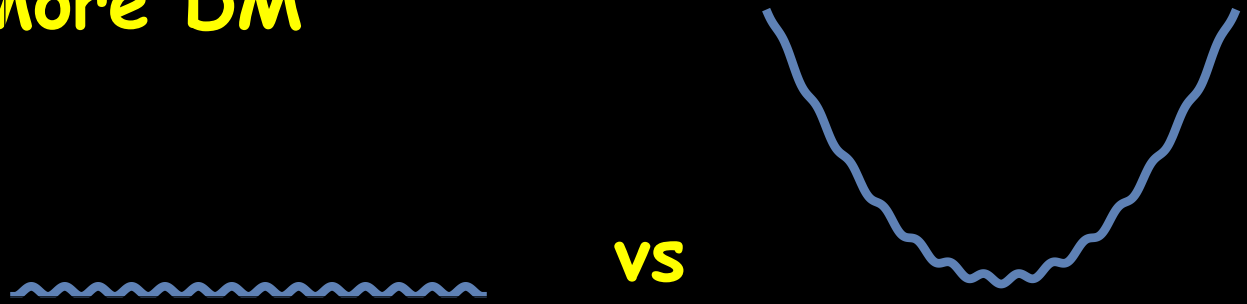
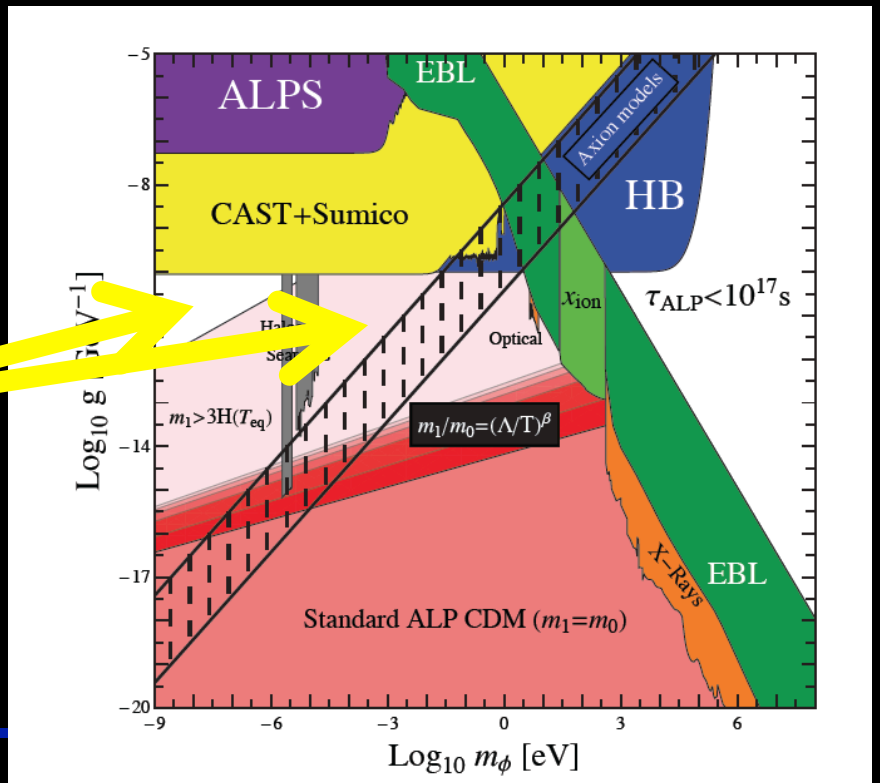
- Allows to start with higher energy density
  ➔ More DM



vs

Models
in this region!



Interesting Phenomena??

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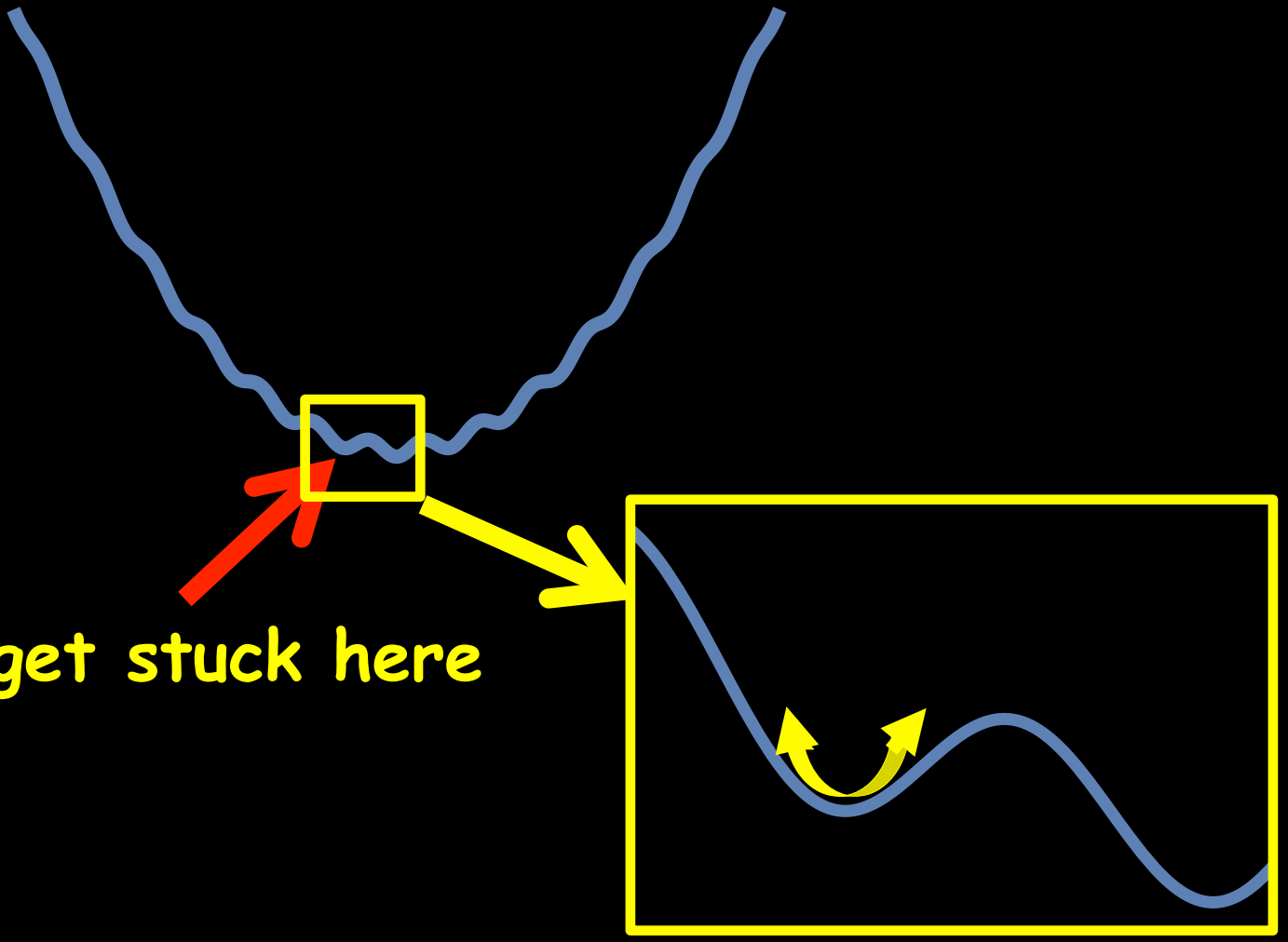

Oscillations like DM!

Interesting Phenomena??

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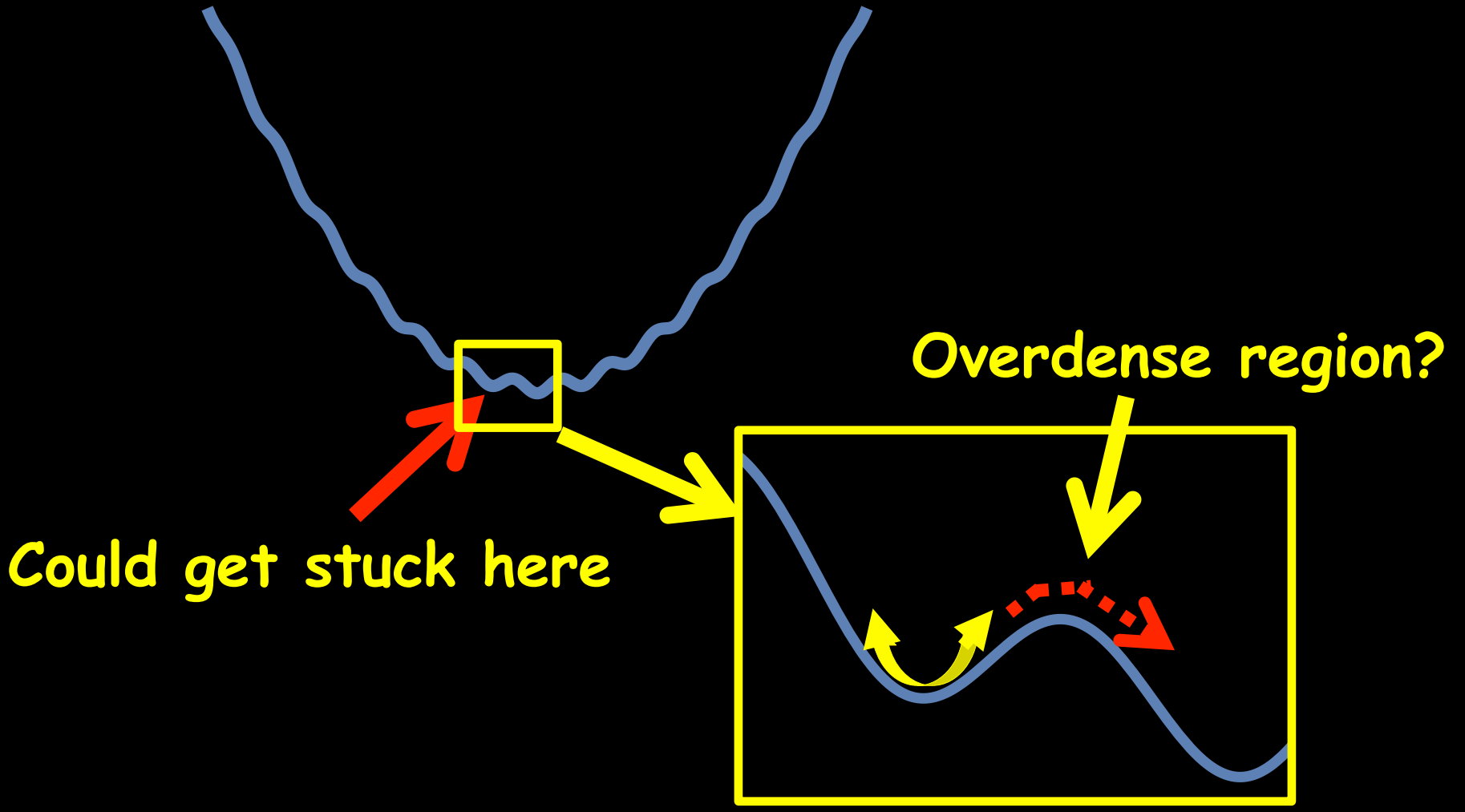

$$amplitude \sim \sqrt{DM density}$$

Interesting Phenomena??

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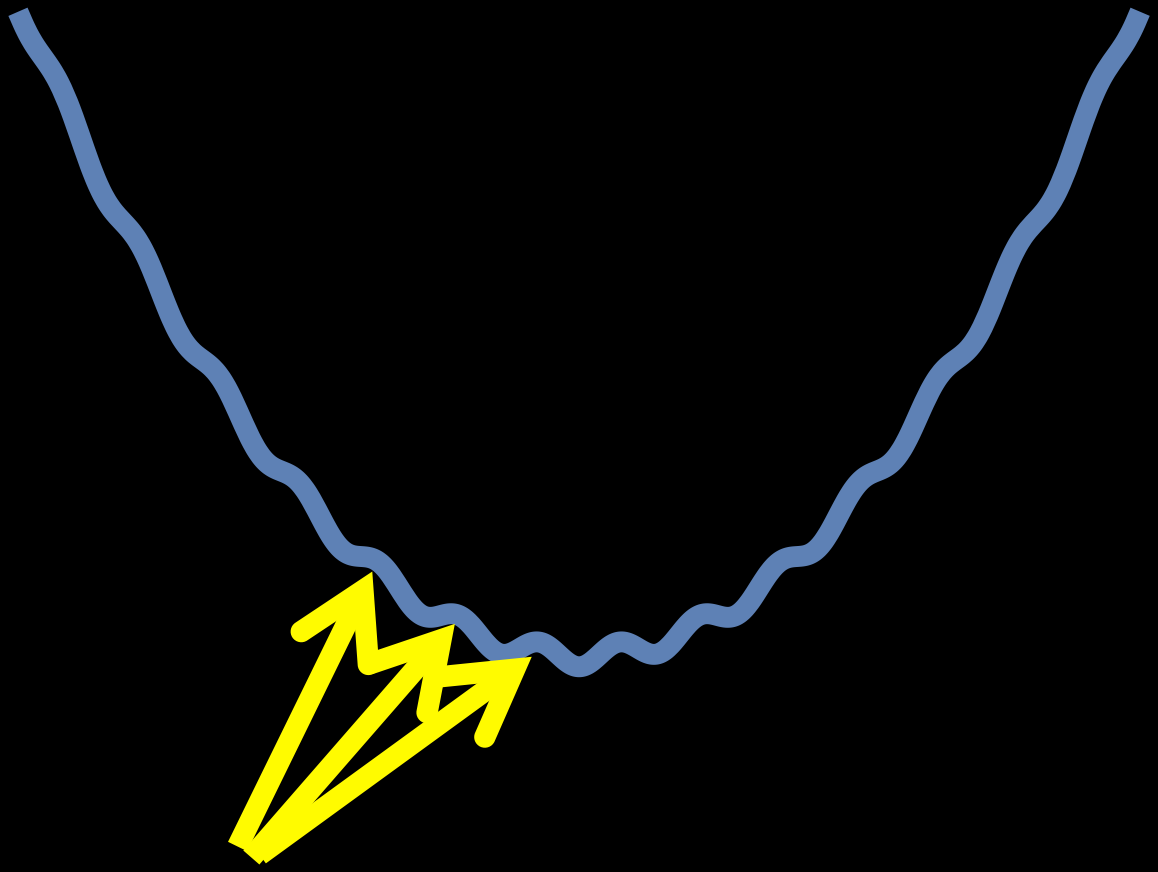

Regions with "negative mass"

Instability ➔ Particle Production with p≠0?!?

Running through walls

A WISPy Domain Wall

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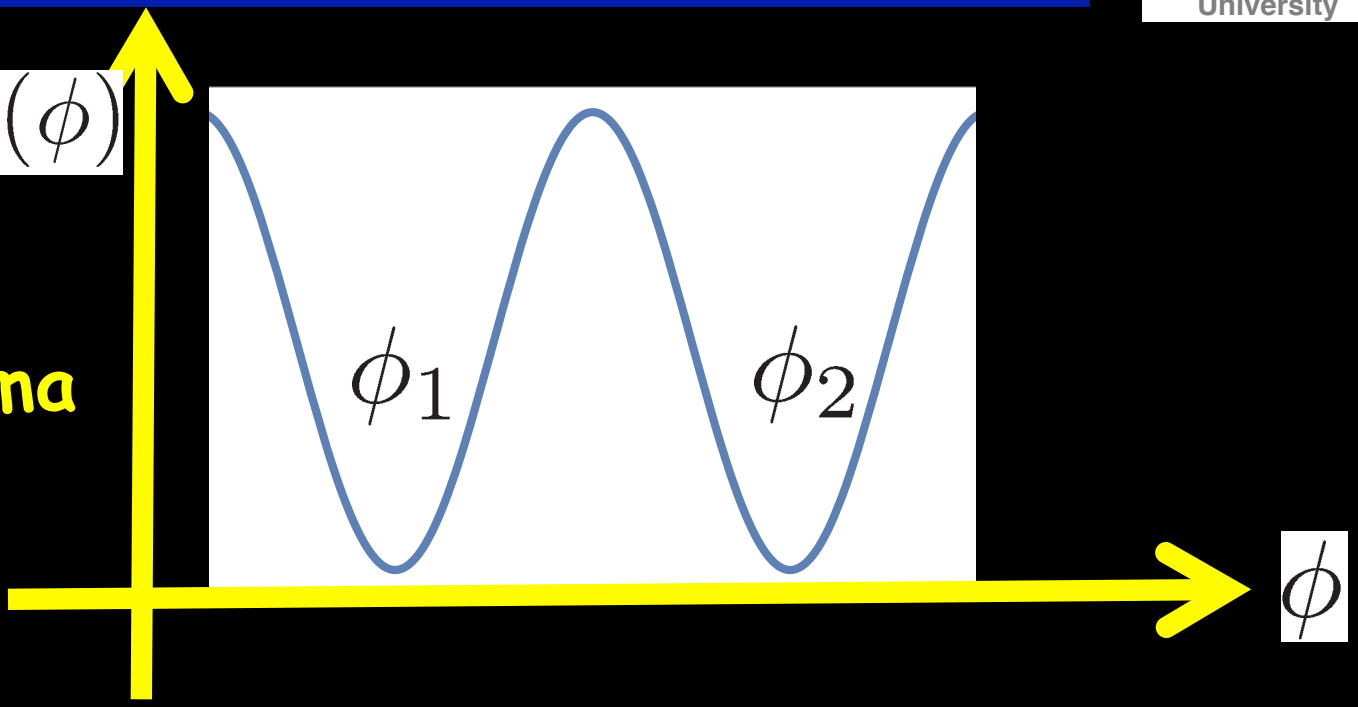
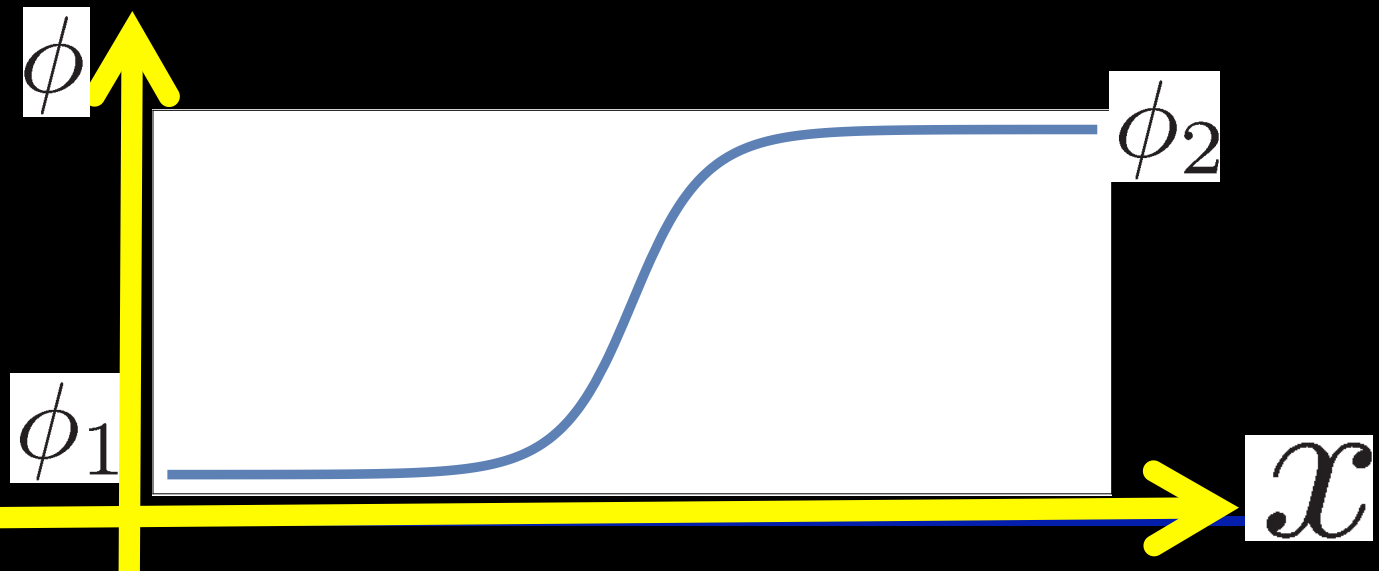
Potential with two minima



Domain wall from side 1 To side 2



A WISPy Domain Wall

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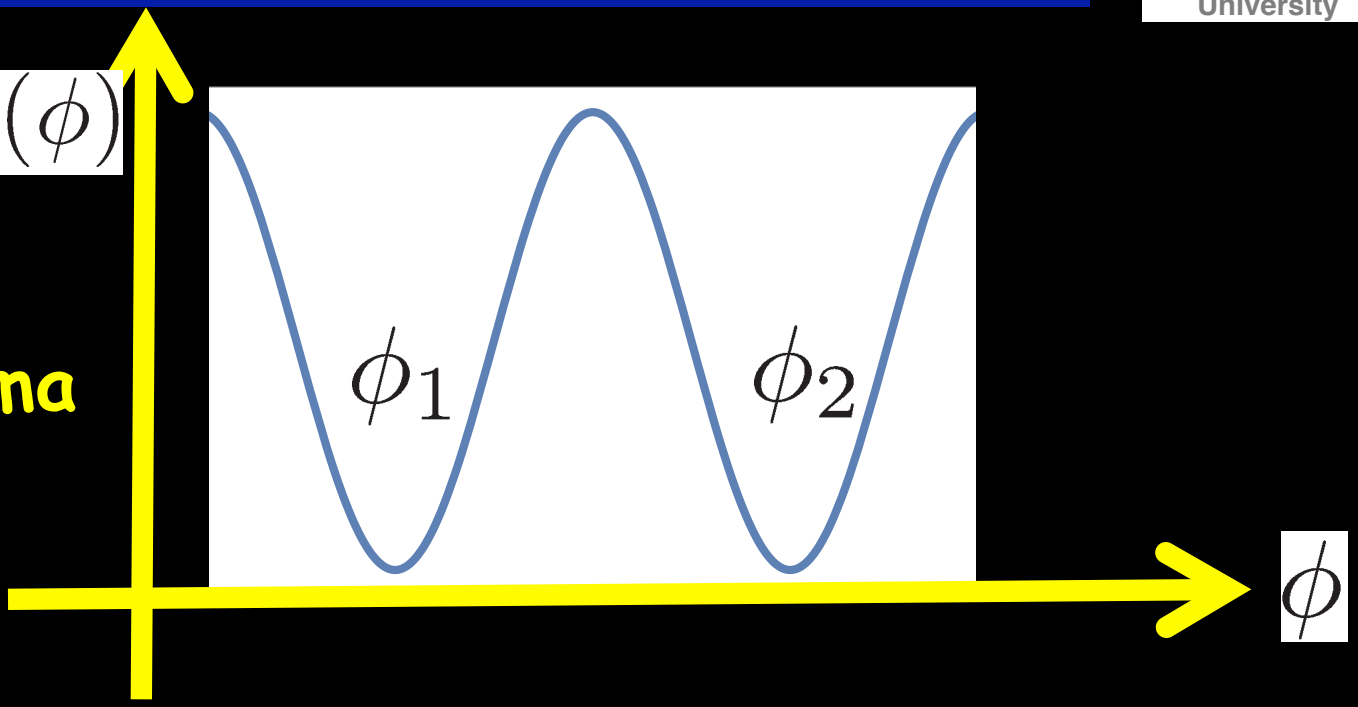
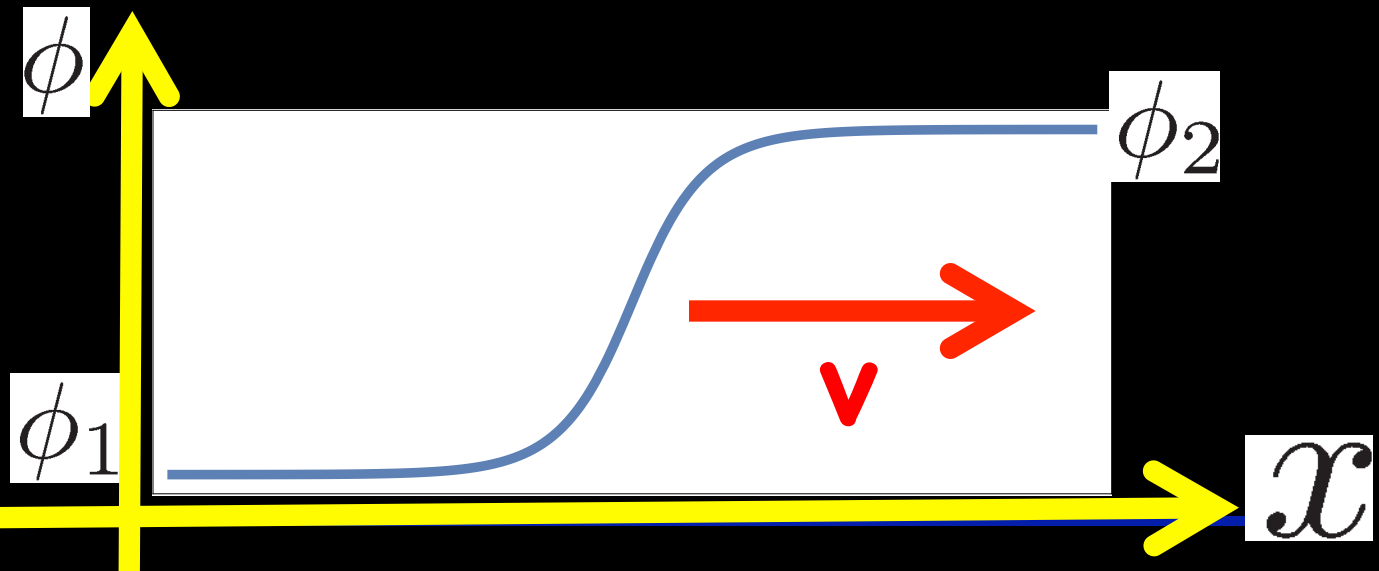
Potential with two minima



Domain wall from side 1 To side 2



aLIGO

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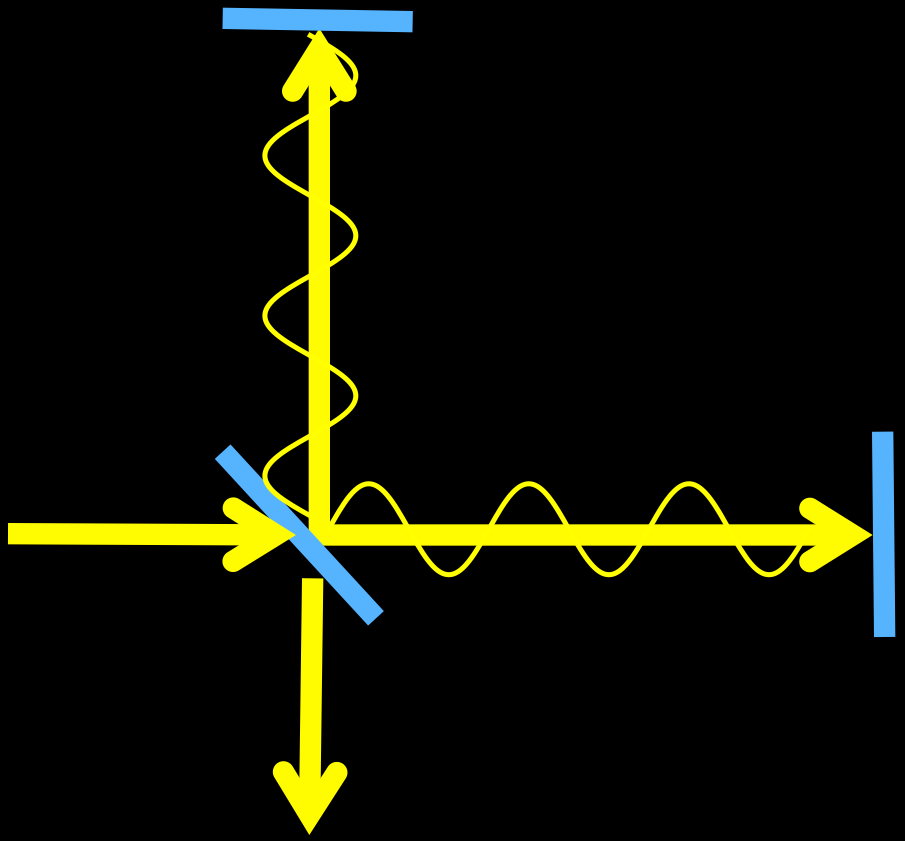
- Has detected gravitational waves!!
- Is an Interferometer



Interference pattern

Causing a phase shift

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- Interaction inside wall creates photon mass

$$\mathcal{L}_A = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} m_{0,\gamma}^2 \sin^2\left(\frac{N_A \phi}{f}\right) A^\mu A_\mu$$

aLIGO

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- Has detected gravitational waves!!
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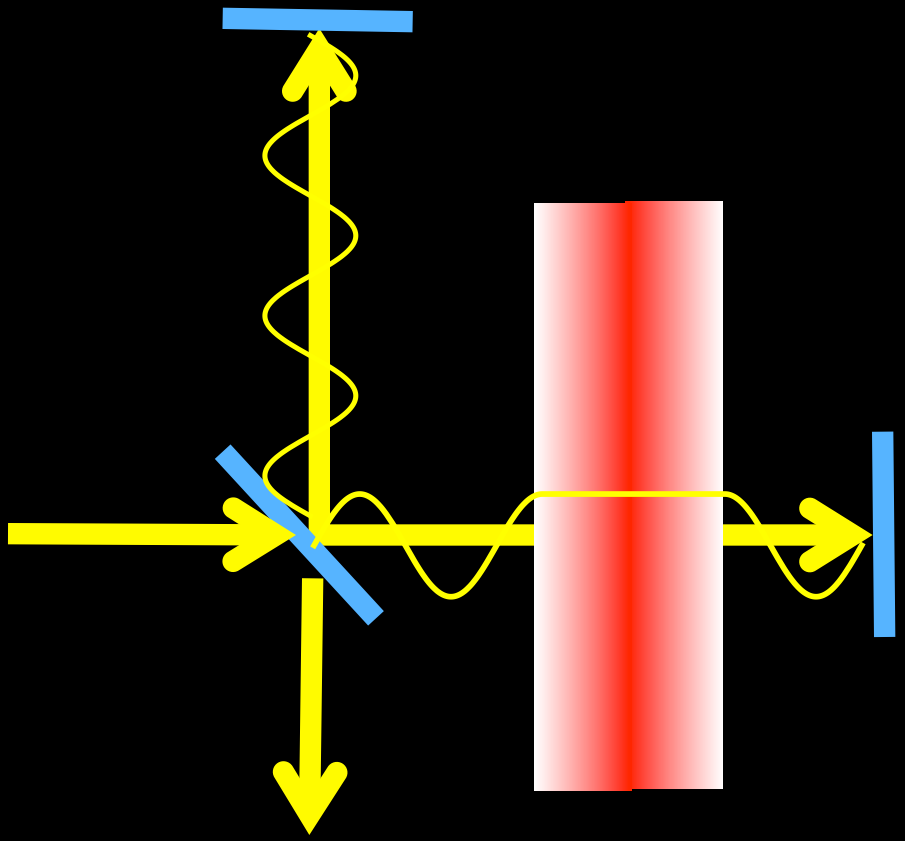

Interference pattern changed

Signal shapes

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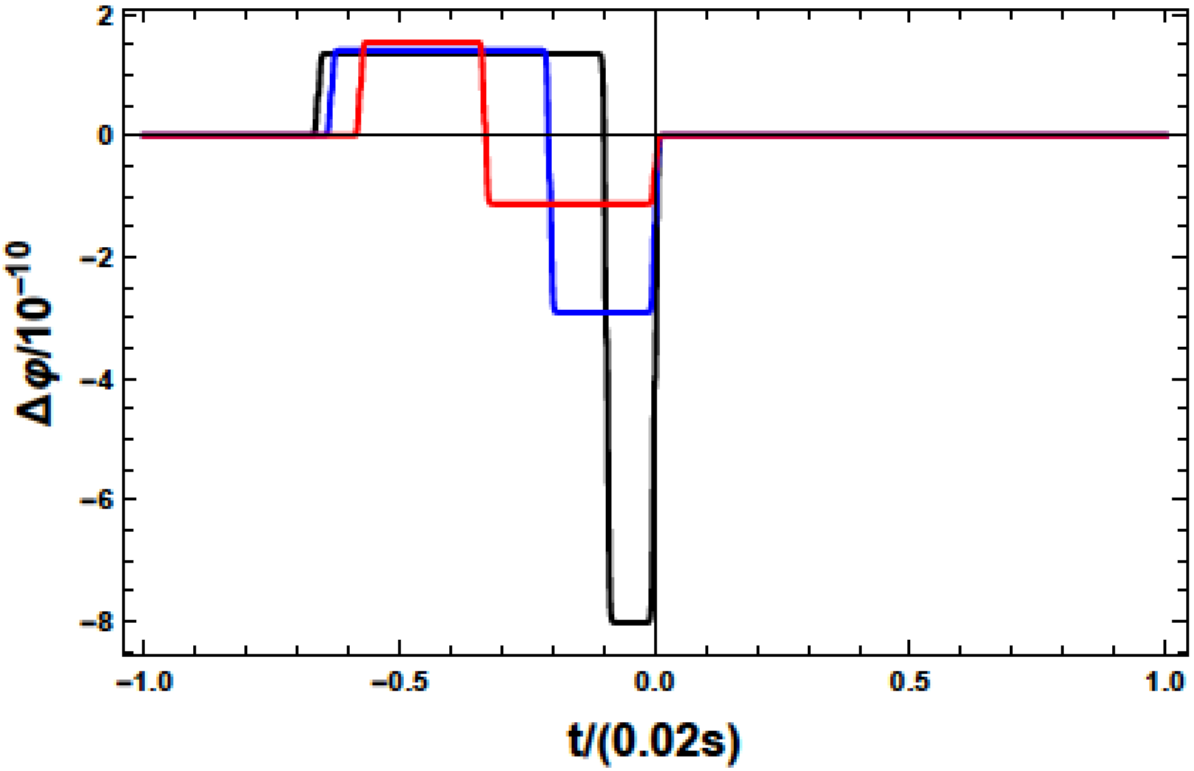

FIG. 6: $L = 4000\,\mathrm{m}$, $\omega \approx 1\,\mathrm{eV}$, $m = 10\,\mathrm{neV}$, $m_{\gamma,0} = 1\,\mathrm{neV}$, $N_A/N_\phi = 1$, $\alpha = \pi/2.2, \pi/2.5, \pi/3$ (black, blue, red), v chosen such that signal has roughly a length of $0.02\mathrm{s} \sim 1/(50\,\mathrm{Hz})$ this corresponds to $v = 1 \times 10^{-3}$.

Signal shapes

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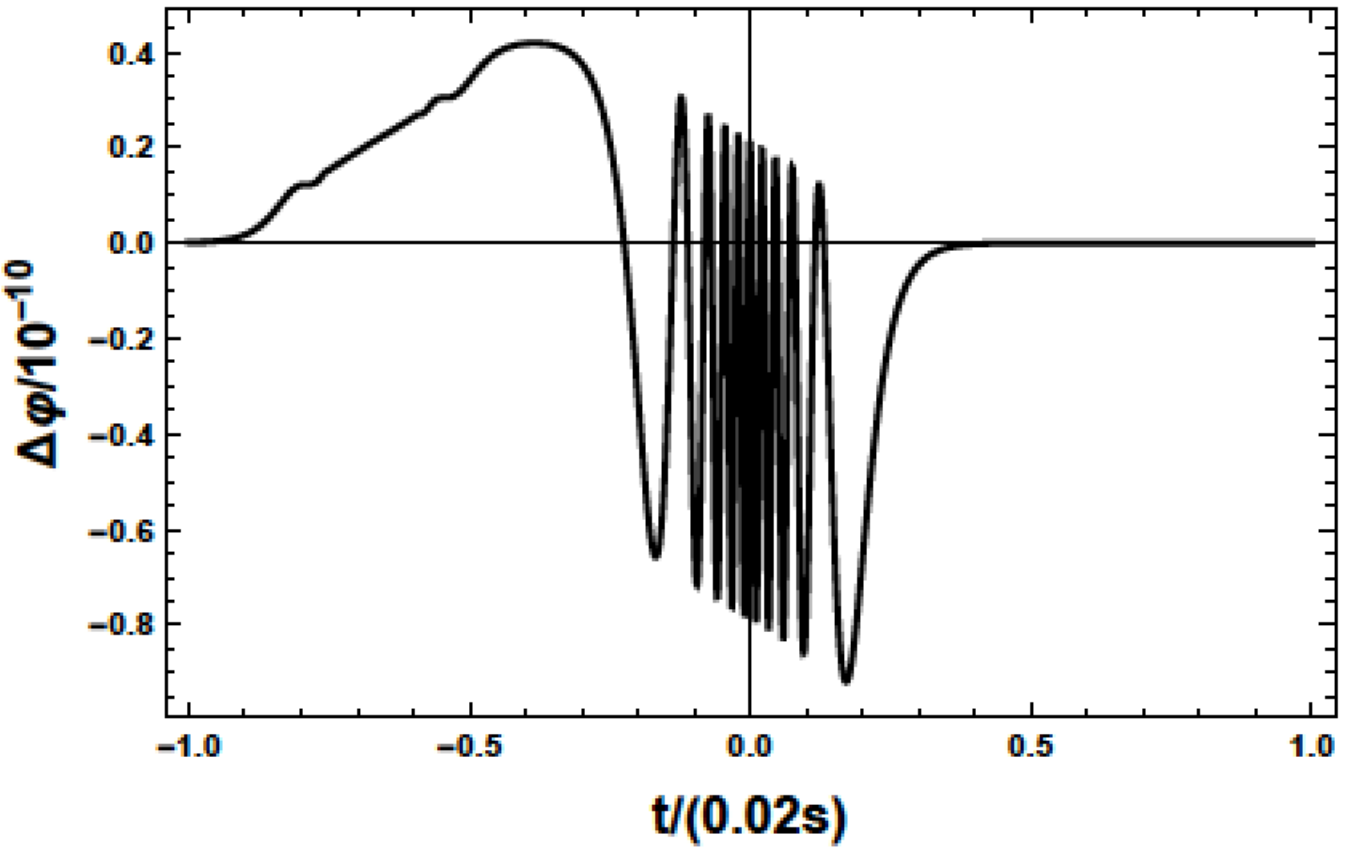

FIG. 8: As in Fig. ?? but $m_{\gamma,0} = 0.1\,\mathrm{neV}$, $N_A/N_\phi = 5$, $m = 0.5\,\mathrm{neV}$, $\alpha = \pi/2$ and $v = 1 \times 10^{-3}$.

How to distiguish from grav waves?

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- velocity<<c
- $v \sim 10^{-3}$

➔ Time difference between two sites
~few seconds

➔ Need careful analysis strategies

Conclusions

Conclusions

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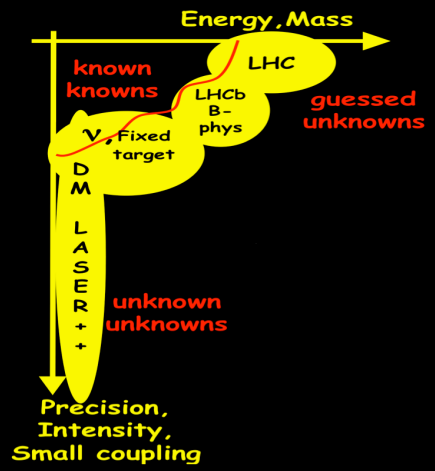
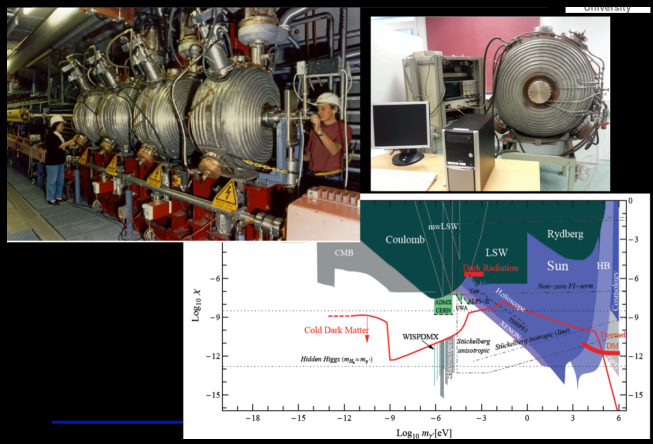
- Good Physics Case for Axions and WISPs

  ➡ explore `The Low Energy Frontier'

- Low energy experiments complementary to accelerators!



- Dark Matter may be WISPy ☺
  - ➔ New Search opportunities!
  - ➔ Searches ongoing!
  - ➔ Crazy things to explore!



Hidden sector