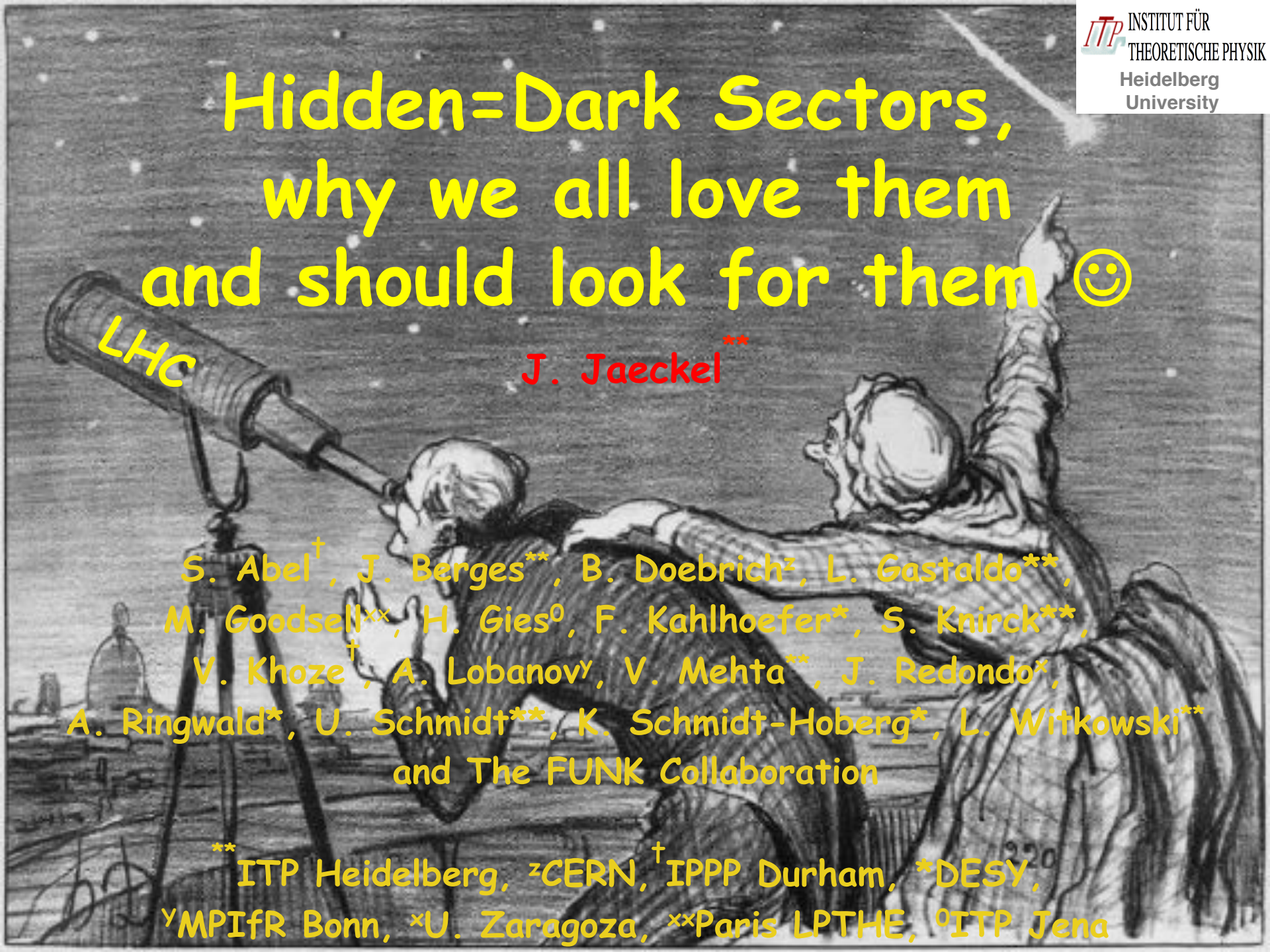


Hidden=Dark Sectors, why we all love them and should look for them ☺

J. Jaeckel[**]

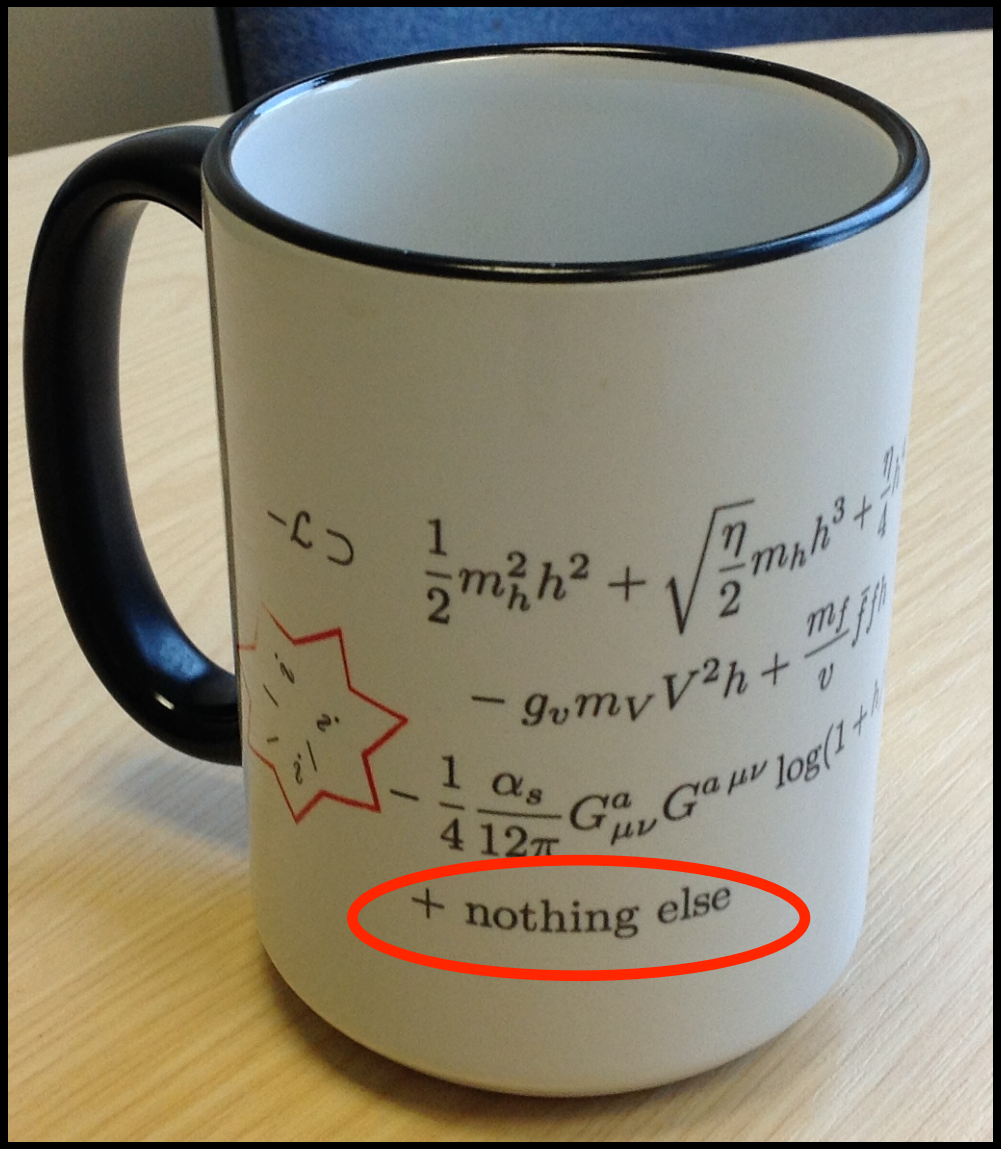
S. Abel[†], J. Berges[**], B. Doebrich[z], L. Gastaldo[**], M. Goodsell[xx], H. Gies[0], F. Kahlhoefer[*], S. Knirck[**], V. Khoze[†], A. Lobanov[y], V. Mehta[**], J. Redondo[x], A. Ringwald[*], U. Schmidt[**], K. Schmidt-Hoberg[*], L. Witkowski[**]
and The FUNK Collaboration

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

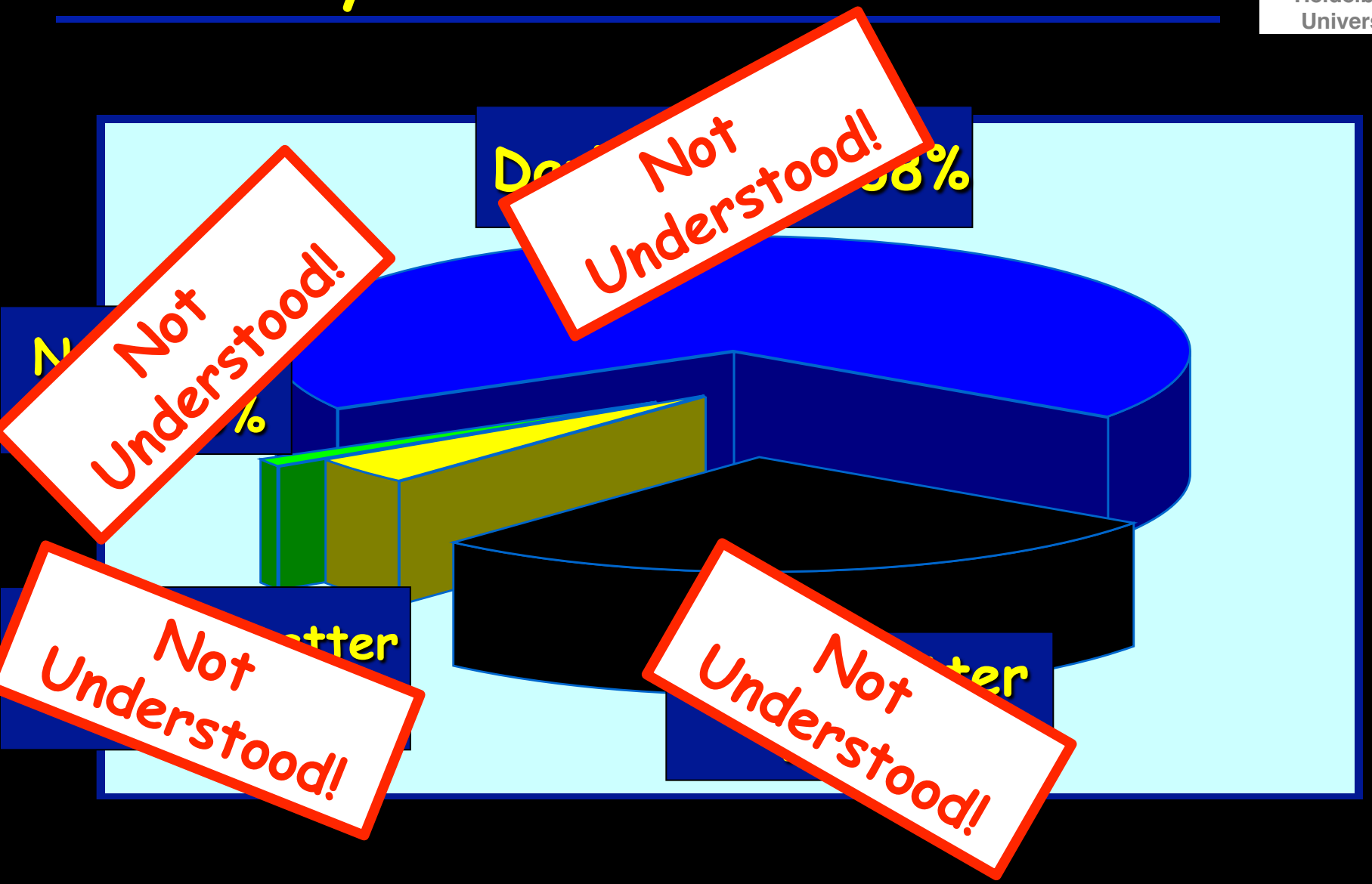
We need...

Physics beyond the Standard Model

No no no!!!!!!!!


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

Inventory of the Universe



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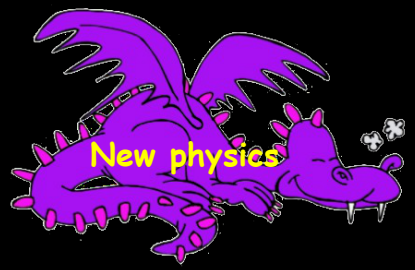
Where does it hide?



Exploring is (at least) 2 dimensional

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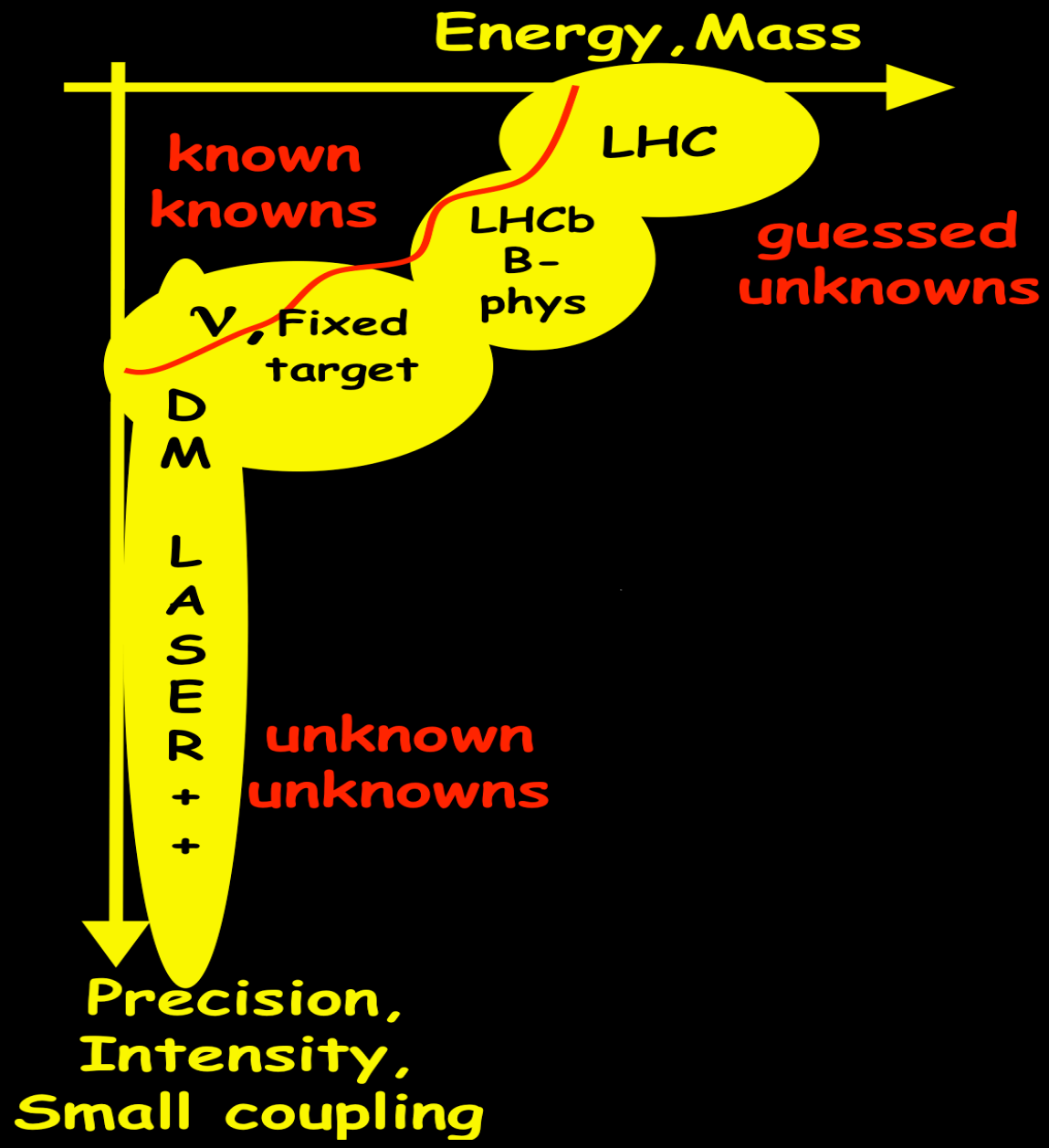

Exploring is (at least) 2 dimensional

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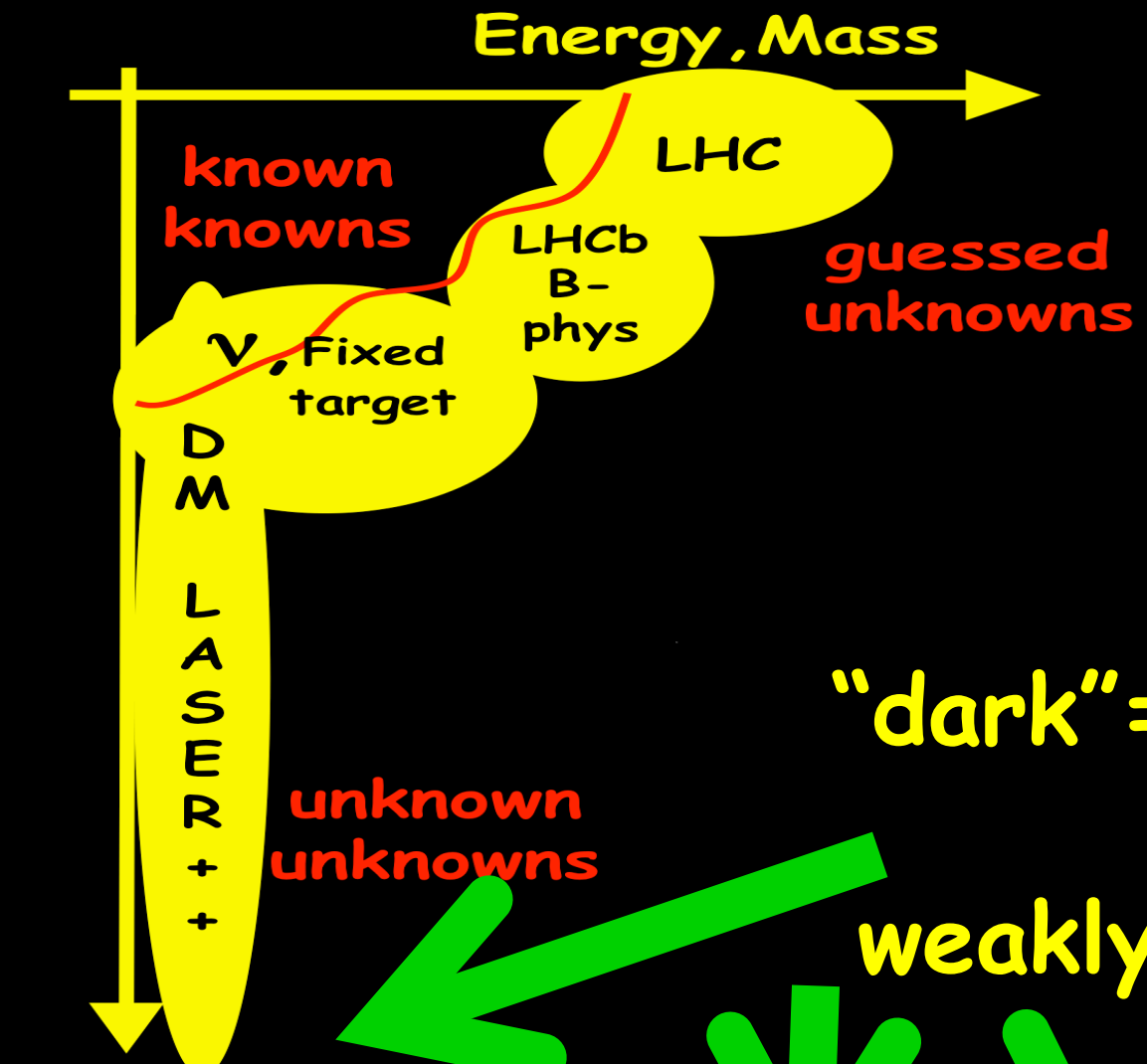

"dark"="hidden"
=
weakly coupled

Theories for hidden sectors...

Get a map for exploration…
there is room for finding dragons

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Get a map for exploration… there is room to find dragons

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Theories for exploration…

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- Columbus used a calculation by D'Ailly:

  Canary Island ←→ Japan ~ 4500 km

  Reality: 20000km

- Sometimes it helps to be optimistic ;-).

Theories for exploration…

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- Perhaps a better example…

- The theory of a southern continent to "balance" the northern ones…

➔ James Cook discovered Australia.
(though not quite as big as expected)

The "theory" was #$%@.
But: Who can argue with these results ☺

Hope for light Particles?

YES!

Coincidences?

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- Neutrino masses:

$$m_\nu \sim \mathrm{meV}$$

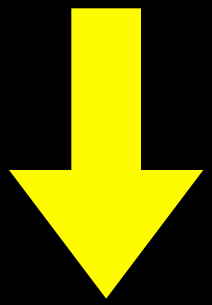
- Dark Energy scale:

$$\rho_\Lambda \sim (\mathrm{meV})^4$$

- Energy density of the Universe:

$$\rho_{\mathrm{today}} \sim (\mathrm{meV})^4$$

Large scale



Small coupling

Example: Axion coupling

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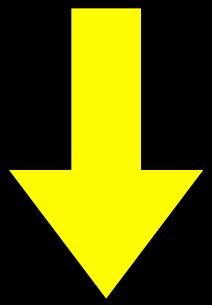
- Effective higher dimensional coupling

$$\mathcal{L}_{Int} = -\frac{1}{4} g a F^{\mu\nu} \tilde{F}_{\mu\nu} = -g a \mathbf{E} \cdot \mathbf{B}$$

- Small coupling for large axion scale:

Small → $g \sim \frac{\alpha}{2\pi f_a}$ ← Large

Large scale



Small mass

Example: Axion See-Saw

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- The axion mass is small, too!

Small → $m_a \sim \frac{m_\pi f_\pi}{f_a}$ ← Large

Example: Axion See-Saw

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- The axion mass is small, too!

Small → $m_a \sim \frac{m_\pi f_\pi}{f_a}$ ← Large

Pseudo-Goldstone Boson!

Example: Axion See-Saw

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- The axion mass is small, too!

$$m_a \sim \frac{m_\pi f_\pi}{f_a}$$

$$\sim 0.6\,\mathrm{meV}\left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right)$$

Sub-eV mass

Large scale

Very Weakly Interacting Sub-favorite scale Particles

WISPs

from

String Theory

Axion(-like particles)

String theory: Moduli and Axions

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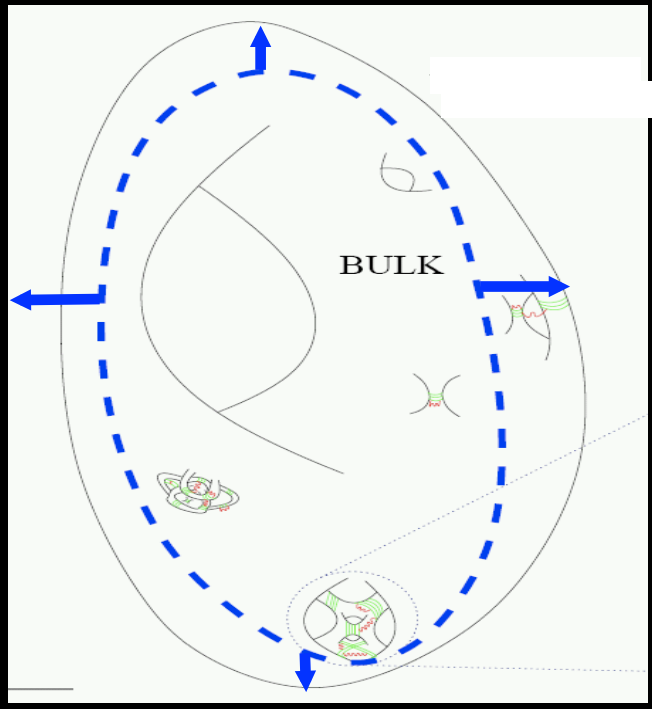
- String theory needs Extra Dimensions

Must compactify

- Shape and size deformations correspond to fields:
  Moduli (WISPs) and Axions
  Connected to the fundamental scale, here string scale



WISPs candidates

Axions and Moduli

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- Gauge field terms

$$\mathcal{L} = \frac{1}{g^2} F^2 + i\theta F\tilde{F}$$

+ Supersymmetry/supergravity

$$\mathcal{L} = \mathrm{Re}[f(\Phi)] F^2 + \mathrm{Im}[f(\Phi)] F\tilde{F}$$

Scalar ALP/moduli coupling + pseudoscalar ALP coupling

Axions and Moduli

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- Gauge couplings always field dependent (no free coupling constants)

- Axions + Moduli always present in String theory

Masses and Couplings

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- "Axion scale" related to fundamental scale

$$f_a \sim \frac{M_P}{\text{Volume}^x} \sim M_s \left(\frac{M_s}{M_P}\right)^y$$

- If QCD axion: m_a fixed

- However, if not QCD axion

$$m_{\text{ALP}} \sim \frac{\Lambda^2}{f_a}$$

(nearly) arbitrary

Axion-like Particles

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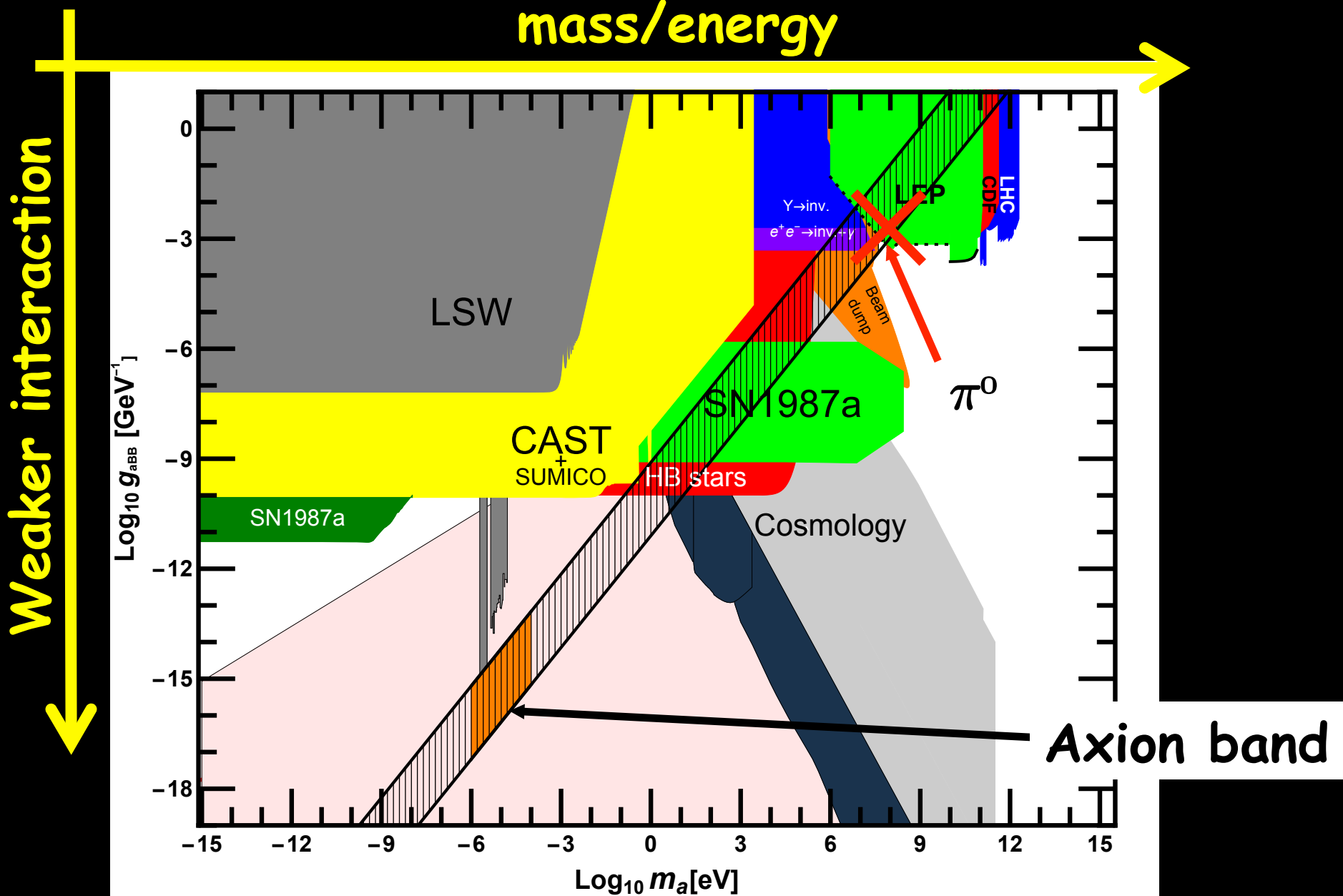

Axion-like Particles

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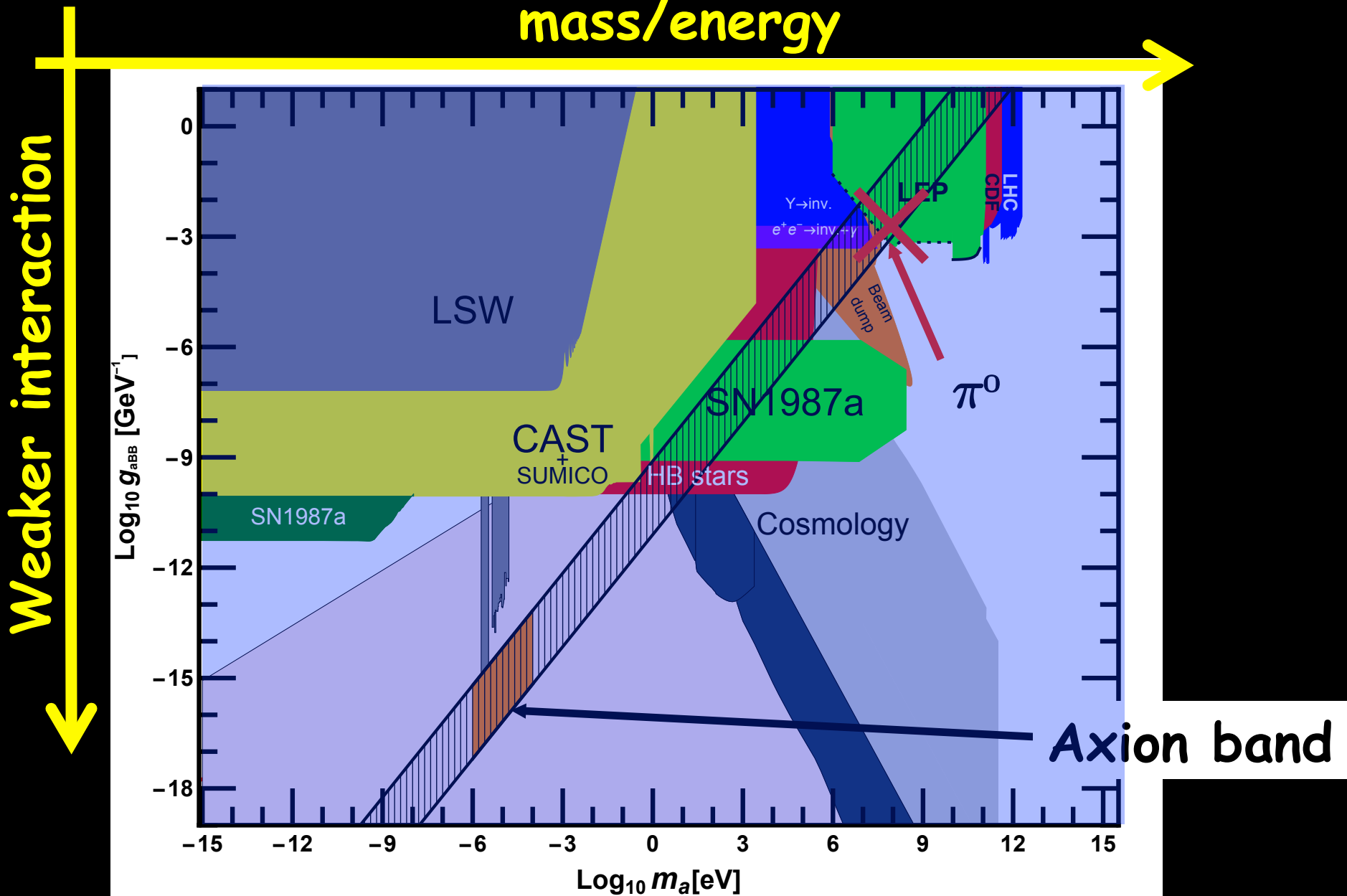

Axion-like Particles

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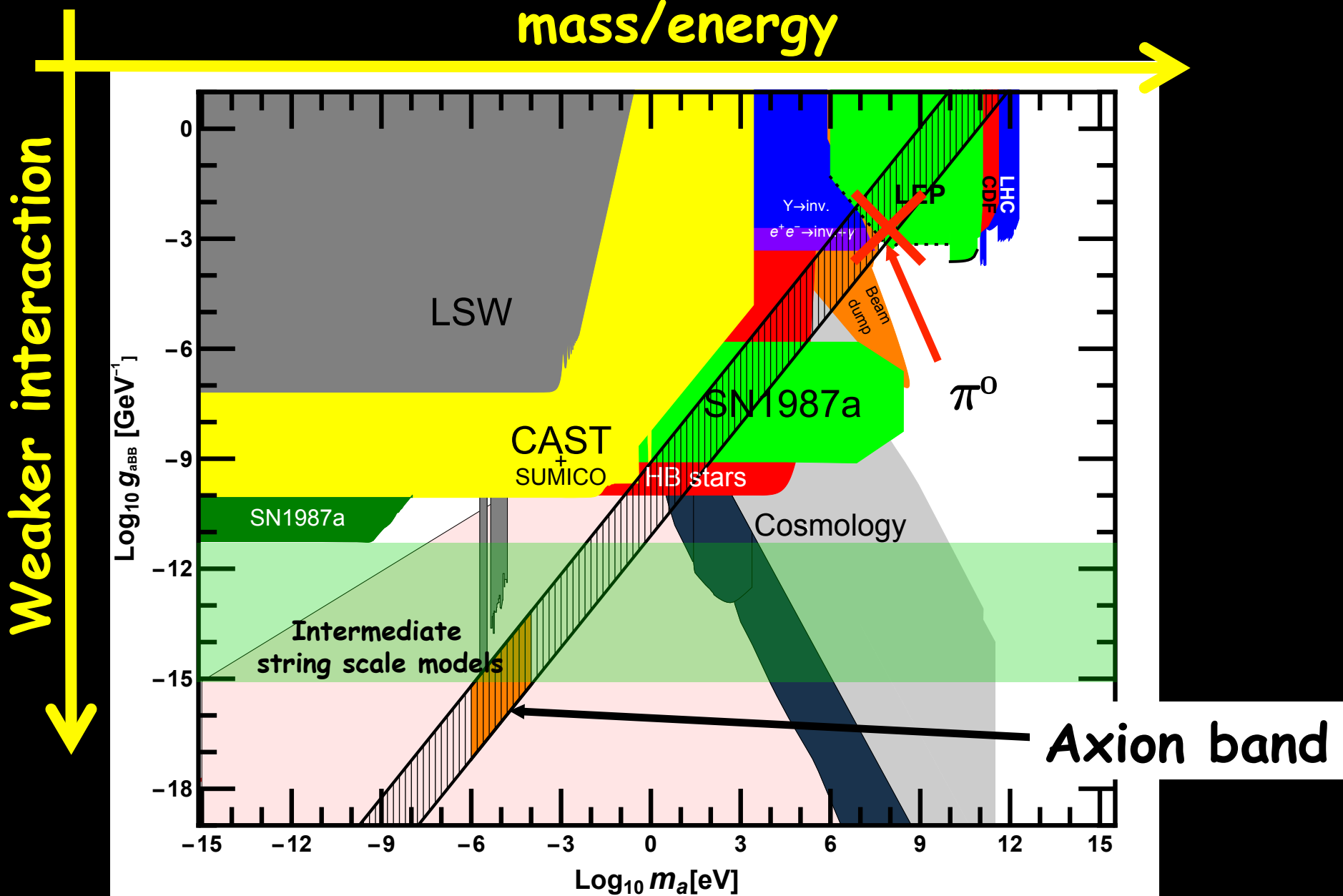

Hidden Photons

+

Hidden Matter

String theory likes extra gauge groups

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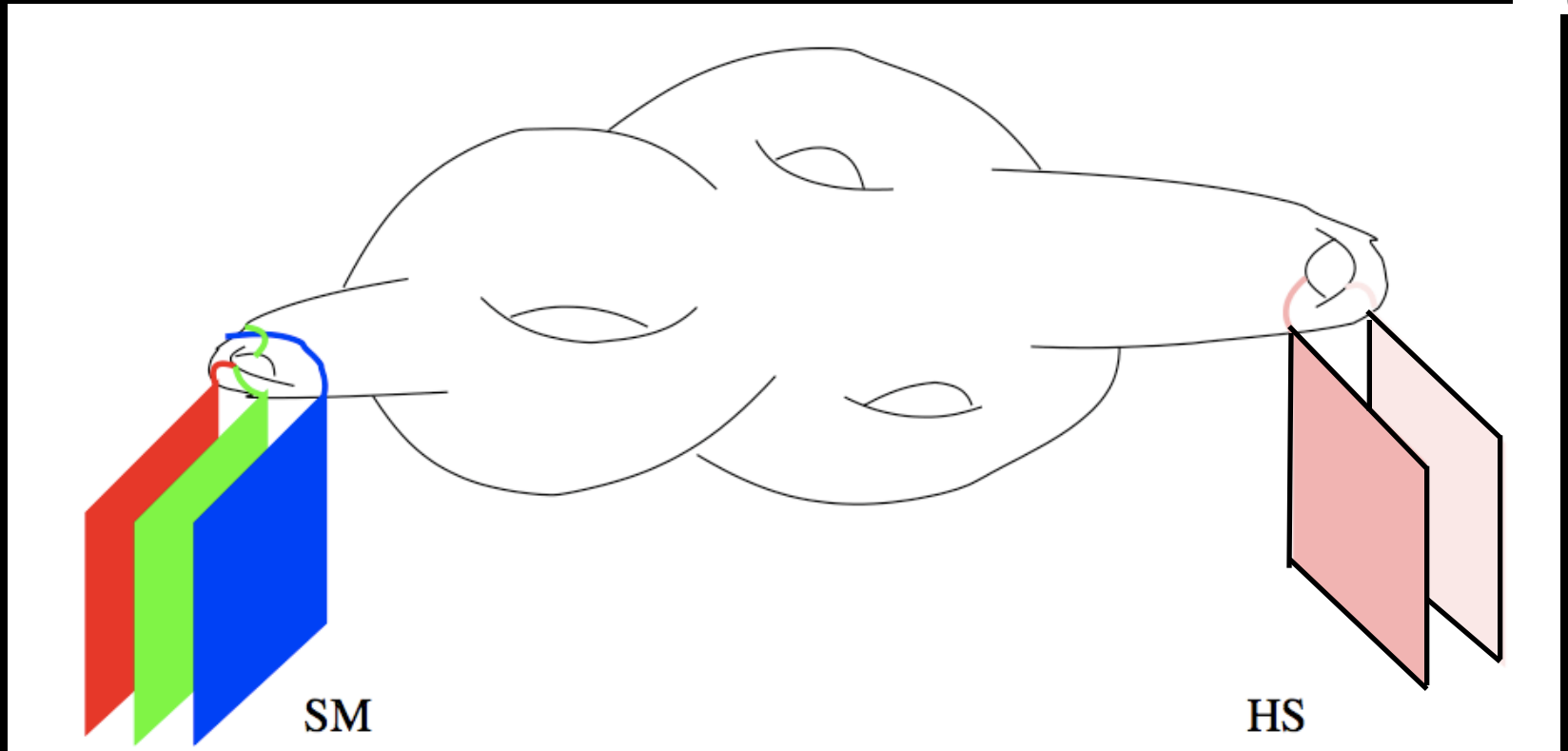

$U(A) \times U(B) \times U(C)$

$U(A) \times U(B)$

➡ Many extra U(1)s!

➡ Candidates for WISPs

How coupled?

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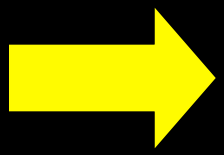
- Kinetic mixing

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

„Our" U(1) | „Hidden" U(1) | Mixing

- Mass

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



photon – hidden photon oscillations
Light shining through walls, fixed targets etc..

Hidden by distance

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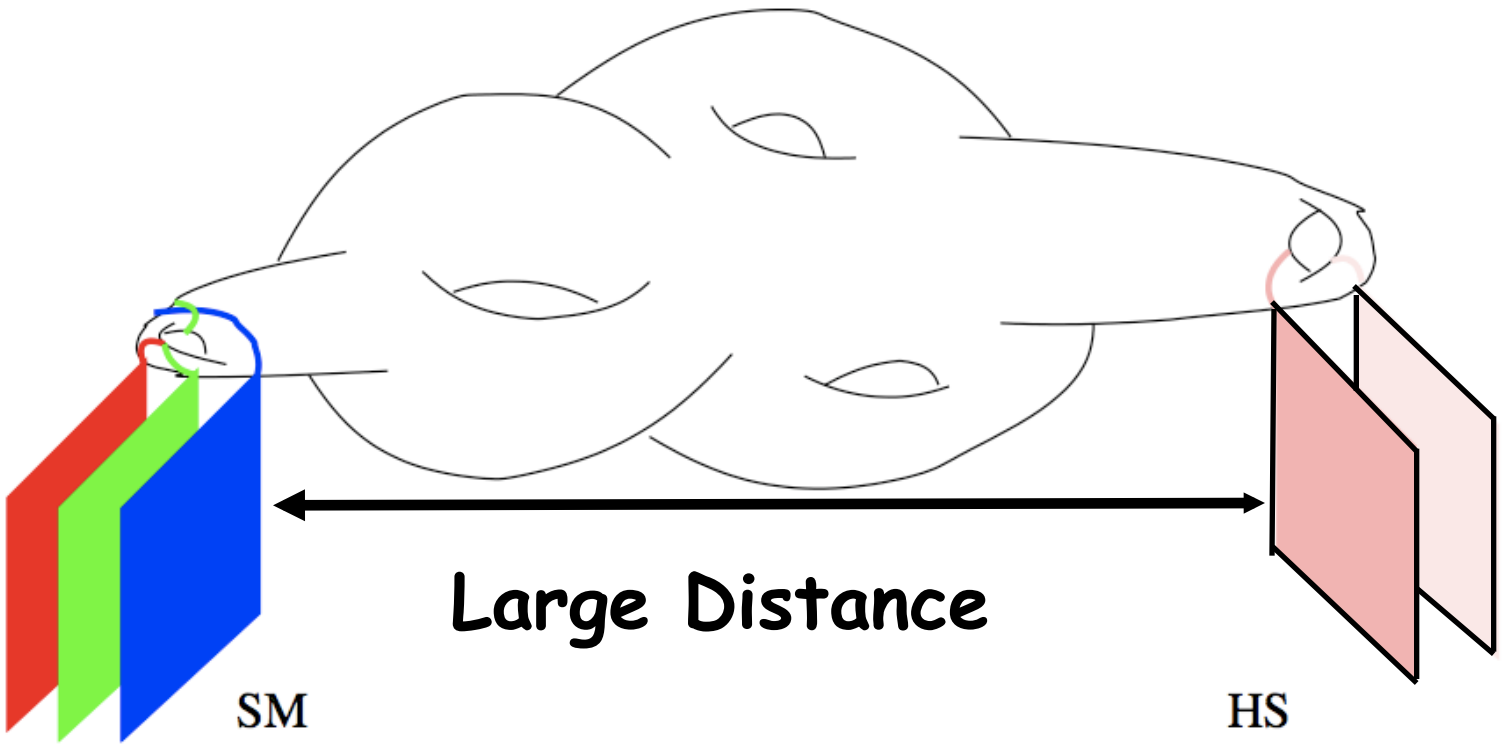

$U(A) \times U(B) \times U(C)$

$U(A) \times U(B)$

$$\chi \sim \frac{g_s}{8\pi} \frac{1}{Volume^x}$$

$$g_{\rm hid} \sim 1$$

Hidden by weakness

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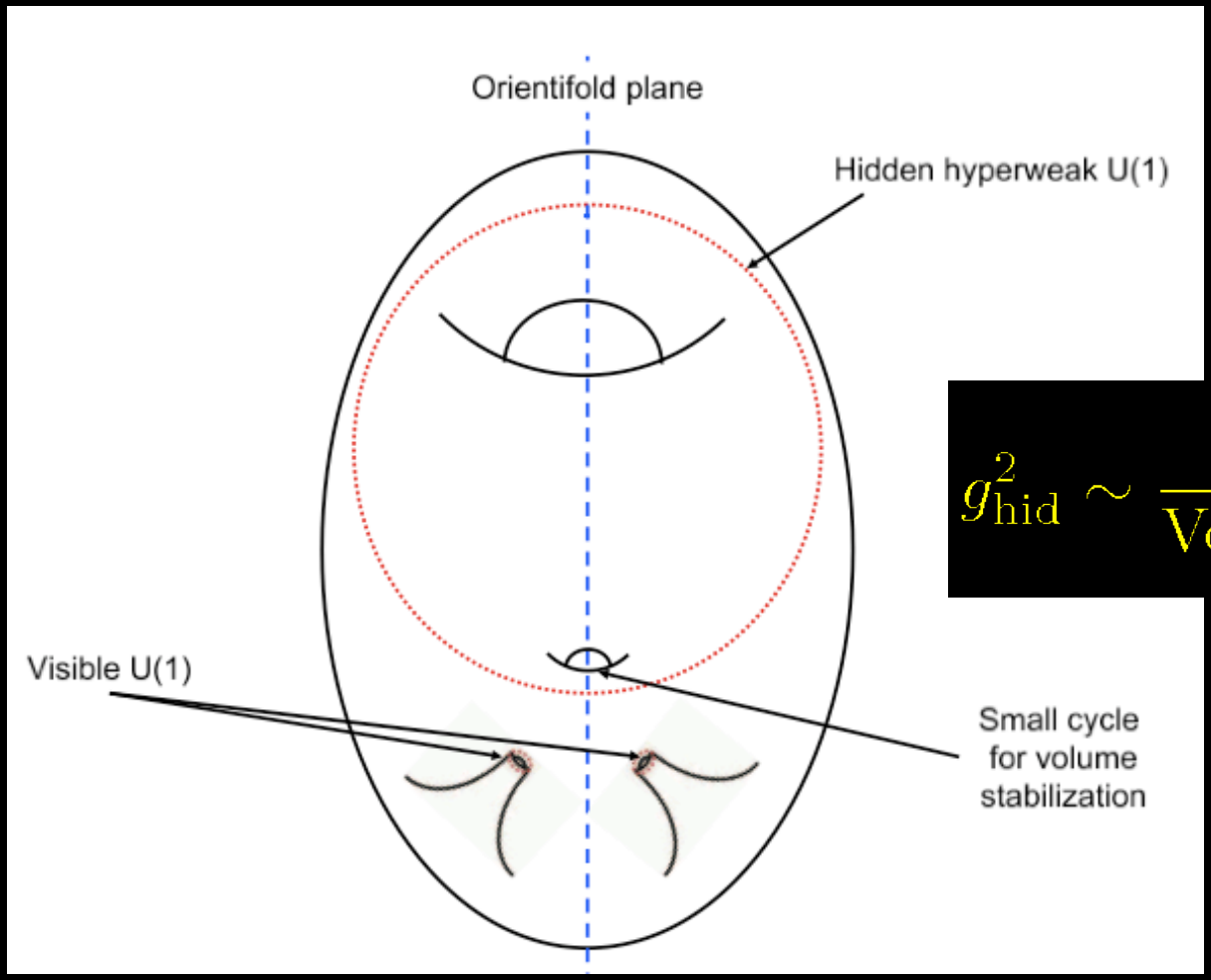

$$g^2_{\rm hid} \sim \frac{2\pi g_s}{\rm Volume^x} \sim \left(\frac{M_s^2}{M_P^2}\right)^x \ll 1$$

$$\chi \sim \frac{g_{\rm vis} g_{\rm hid}}{16\pi^2} \sim \frac{2\pi g_s}{\rm Volume^{x/2}} \sim \left(\frac{M_s^2}{M_P^2}\right)^{x/2} \ll 1$$

Masses

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- Higgs and Stueckelberg mechanism possible

- Example: Stueckelberg

$$(m_{\gamma'}^{\mathrm{Stueck}})^2 \simeq \frac{g_s}{2}\left(\frac{4\pi}{g_s^2}\frac{M_s^2}{M_P^2}\right)^z$$

$$\simeq \frac{g_s}{2}\frac{M_s}{\mathrm{Volume}^z}, \qquad z = \frac{1}{3}, 1.$$

Hidden Photons, All over the place

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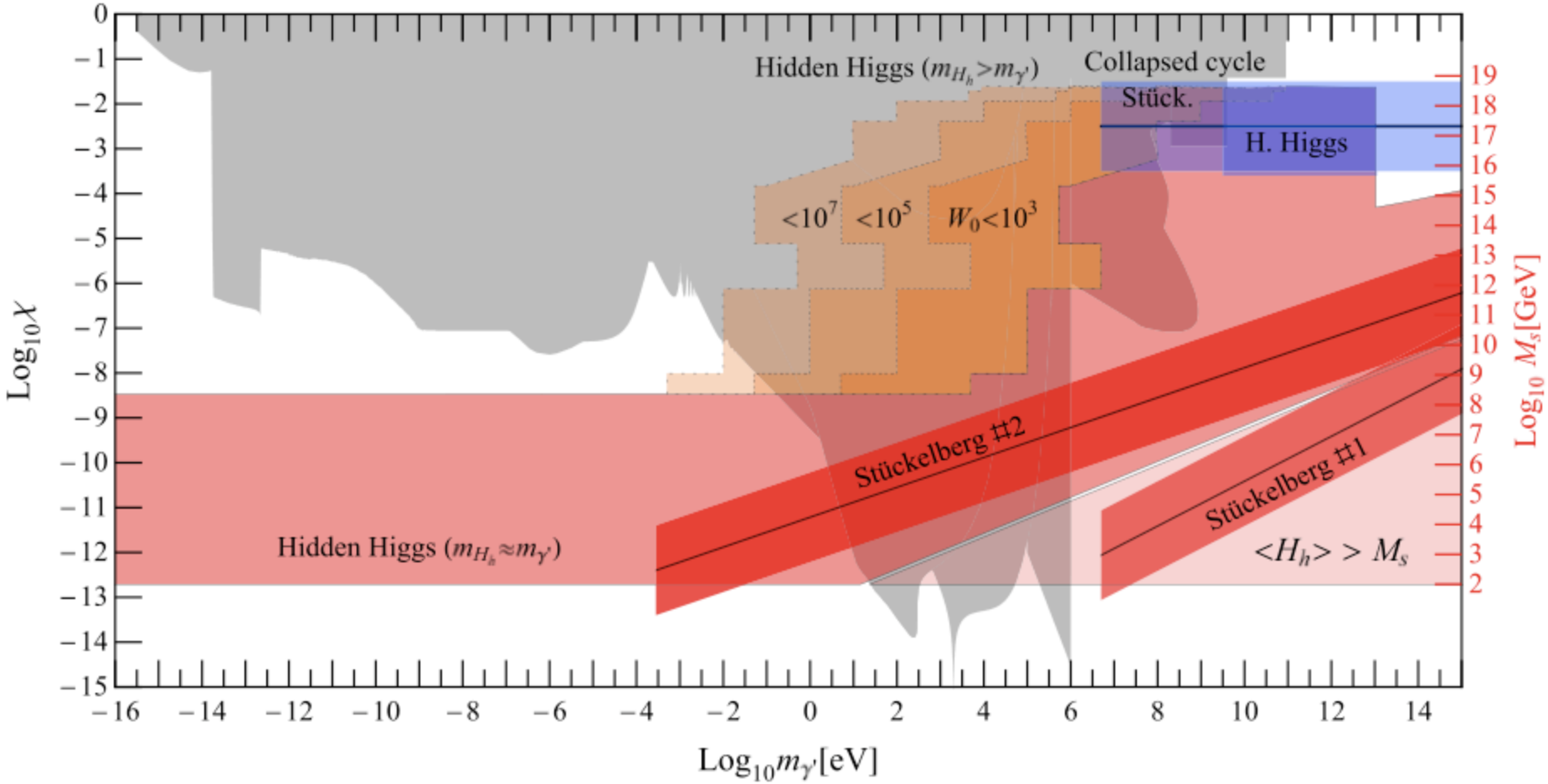

Hidden Photons: Back to Experiment

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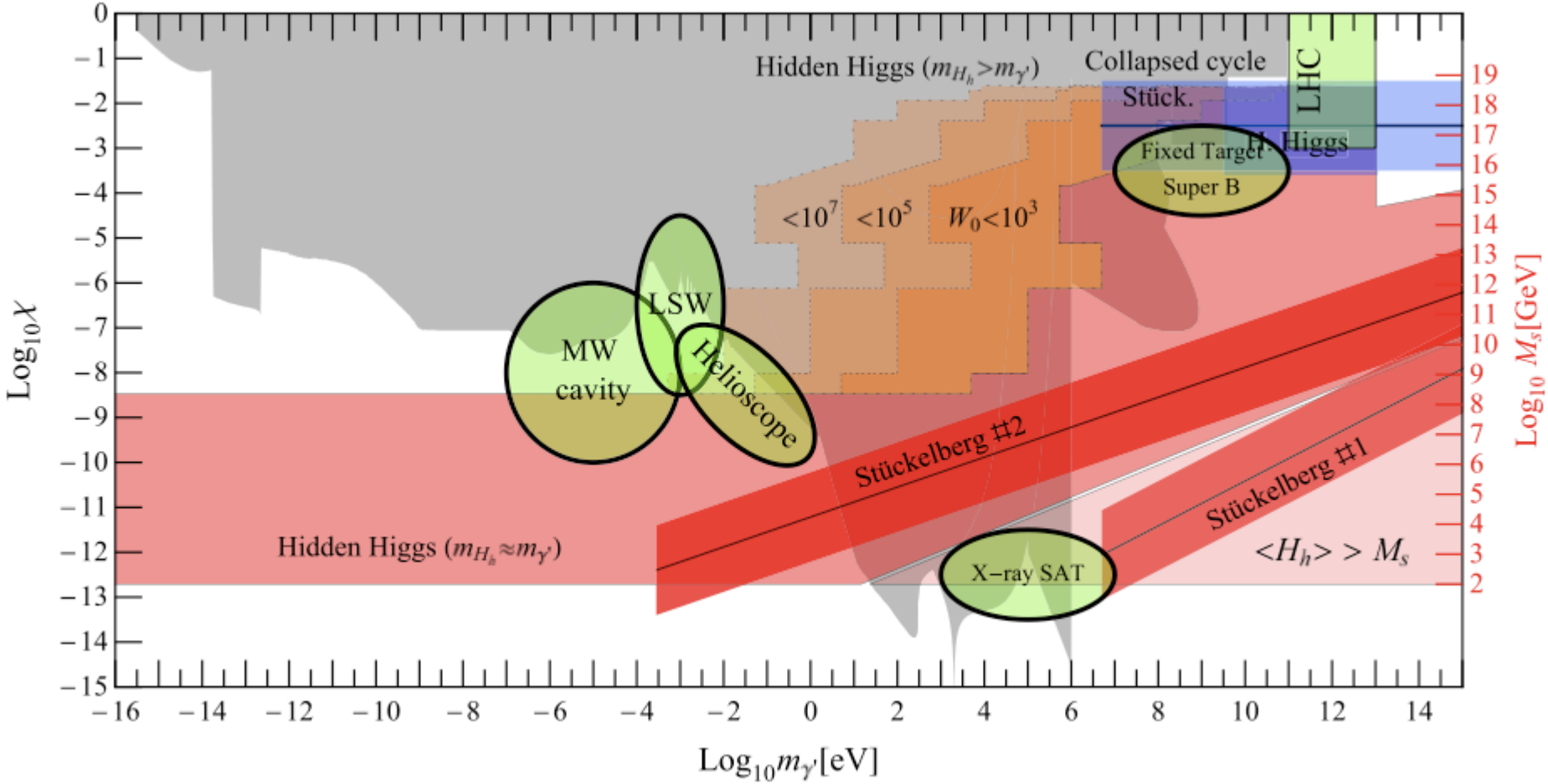

String theory likes extra matter

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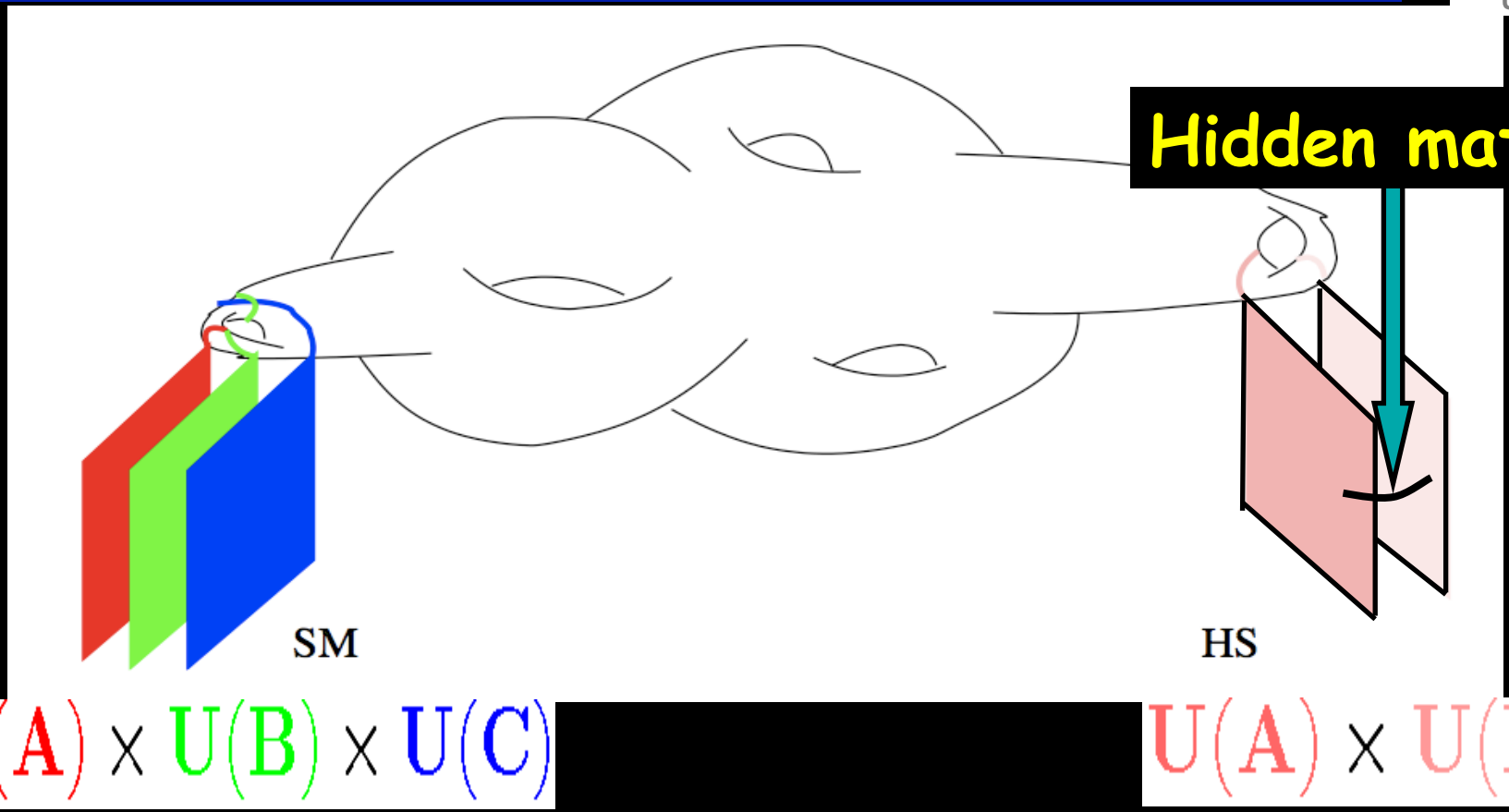

➡ Hidden sector matter

➡ Appears to be minicharged

How coupled?

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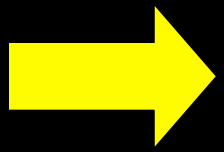
- Kinetic mixing

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

„Our" U(1) | „Hidden" U(1) | Mixing

+ Matter $\mathcal{L}_{\text{int}} = g_{\text{hid}} \bar{h} \gamma_\mu X^\mu h$



U(1) massless:
Particles with small electric charges
U(1) massive:
Very weakly coupled dark particles
(e.g. dark matter messenger models)

Minicharged particles…

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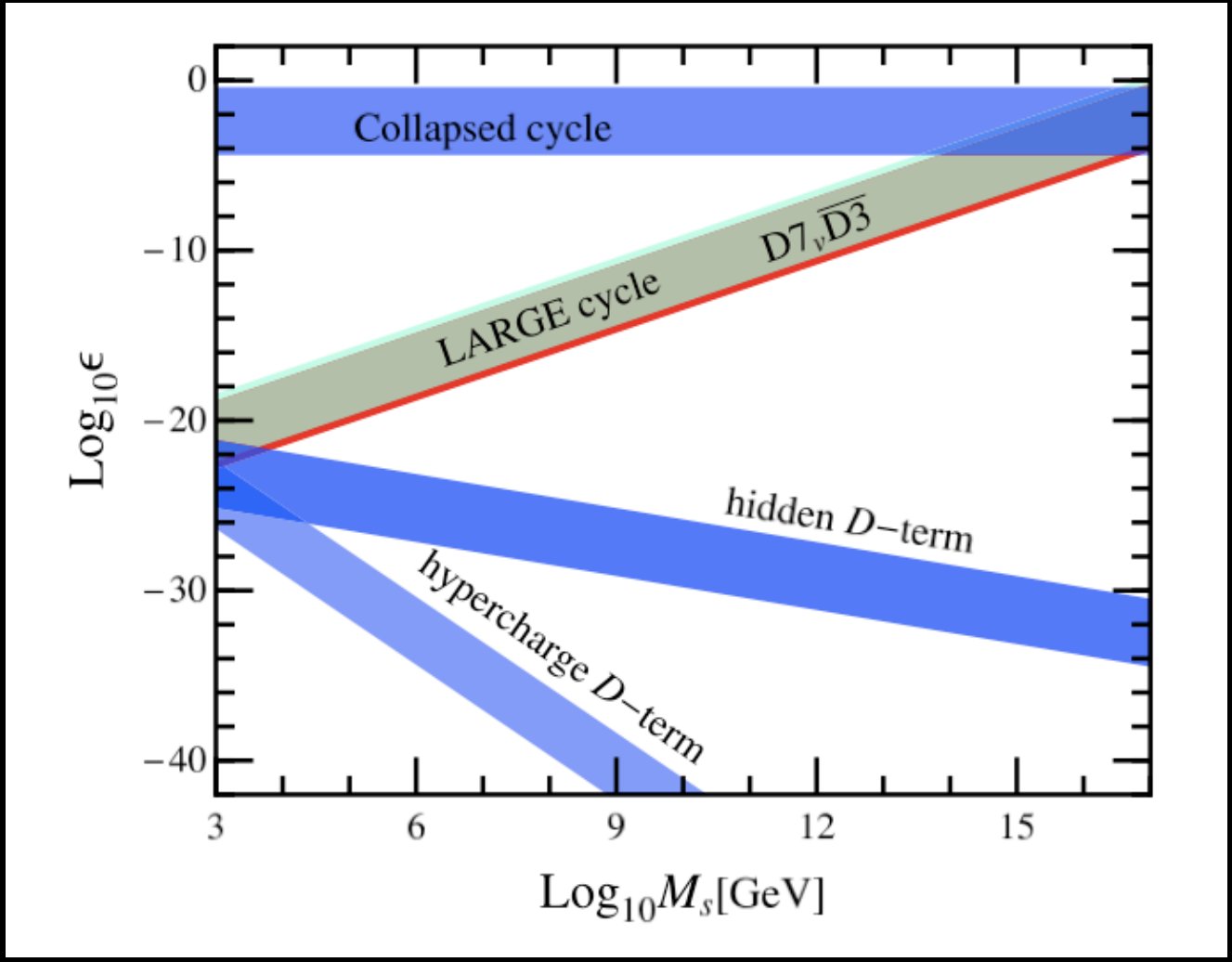

Phenomenological reasons for Hidden Sectors

Many Uses

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- Gamma ray transparency of Universe
- Energy Loss in Stars
- (g-2) of the muon
- Supersymmery breaking and the hierarchy problem
- Dark Matter (and indications from astrophysics)
- Dark Energy
- Many more….

Dark Matter(s)

Answering the big questions...

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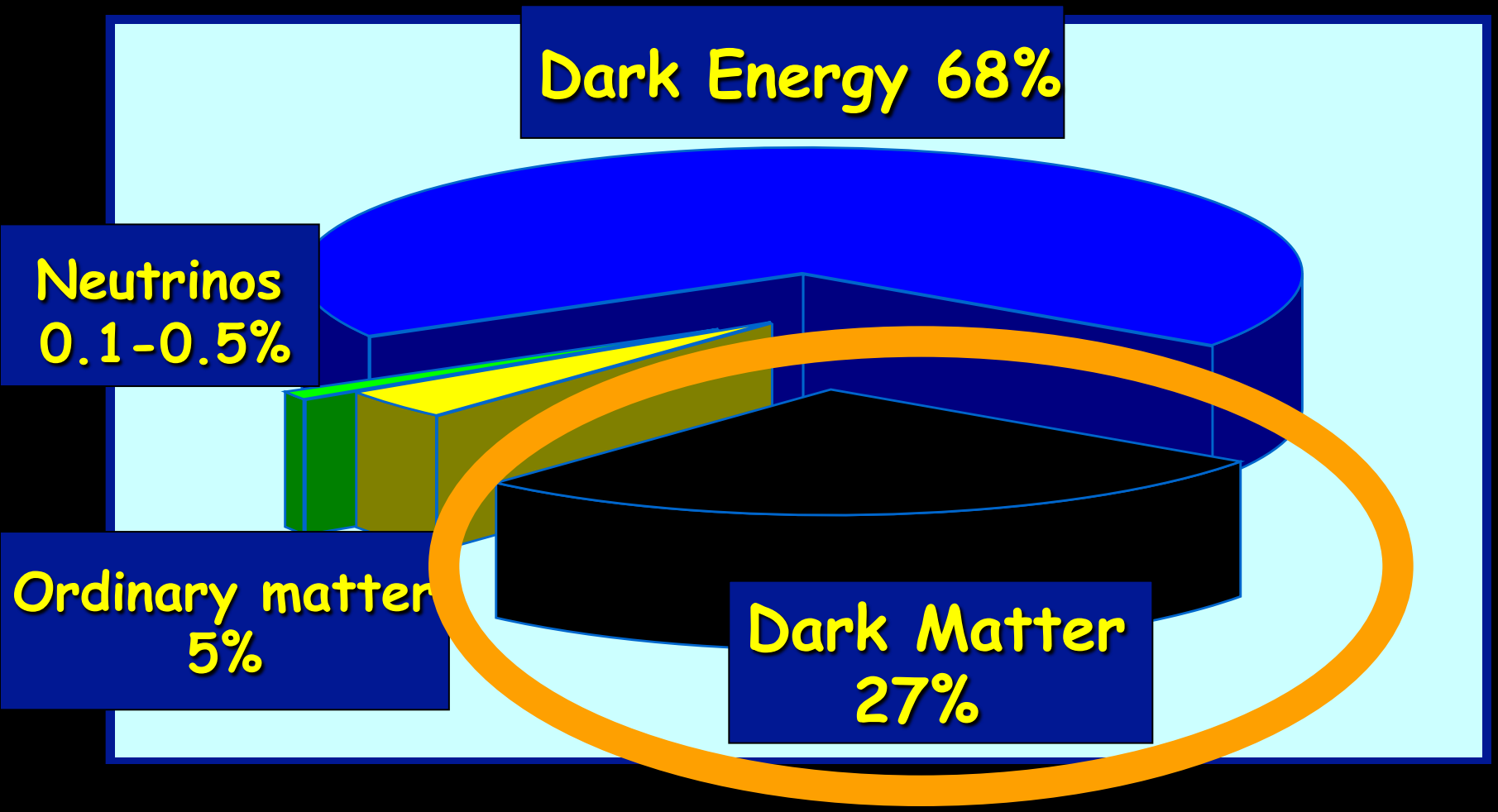

The axion has no clue where to start

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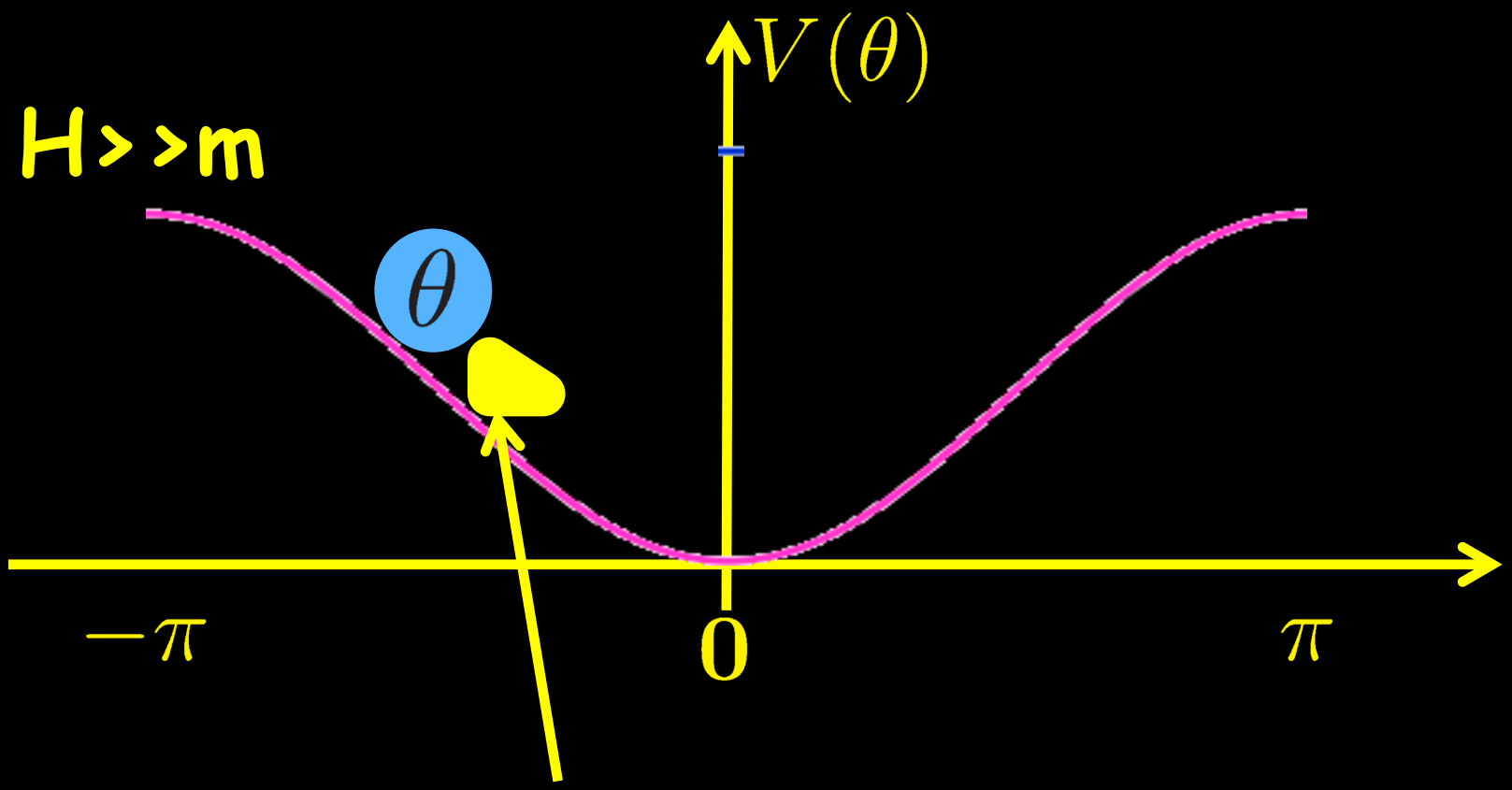

Field is stuck because of Hubble "breaking"

The axion has no clue where to start

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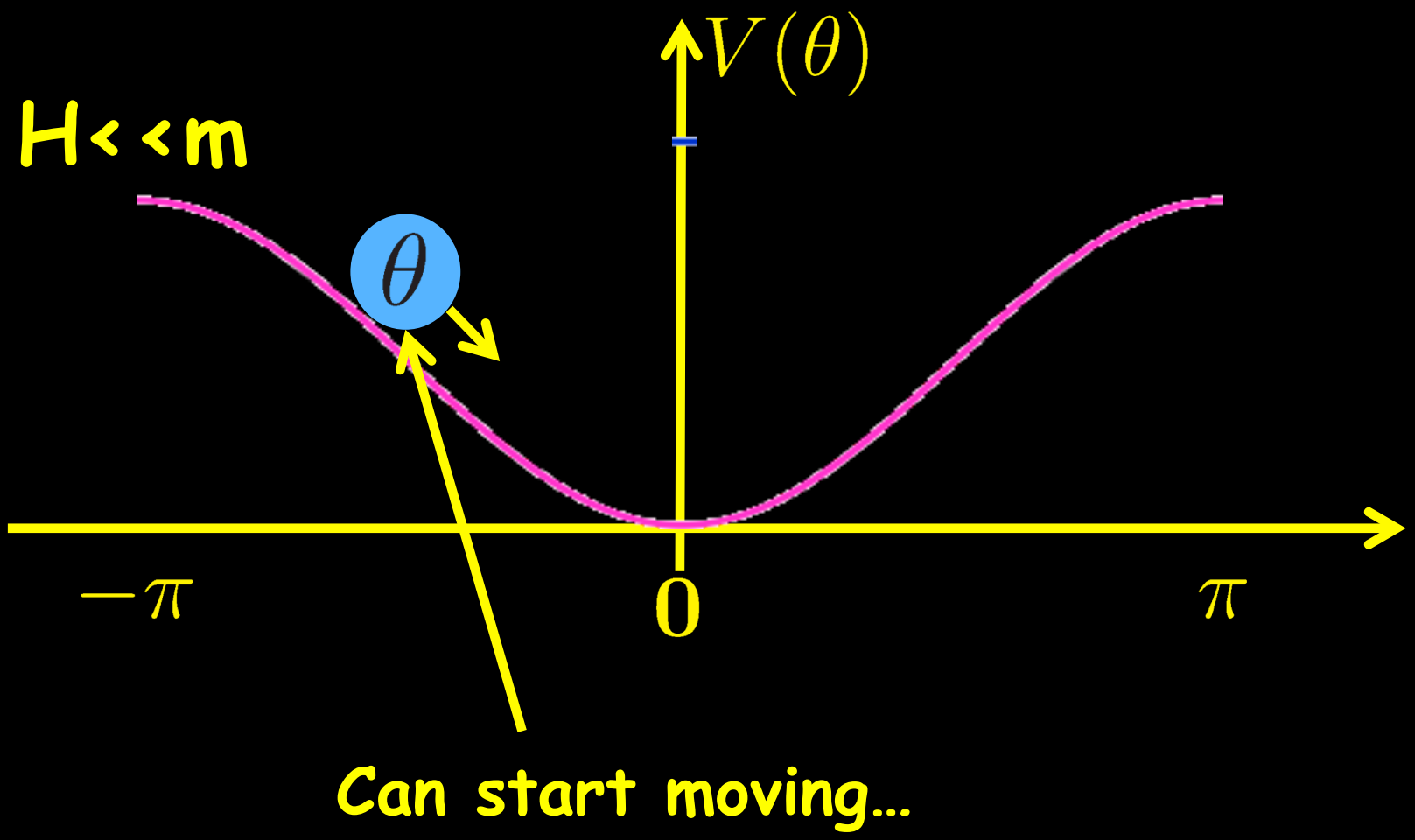

The axion solution to the strong CP problem

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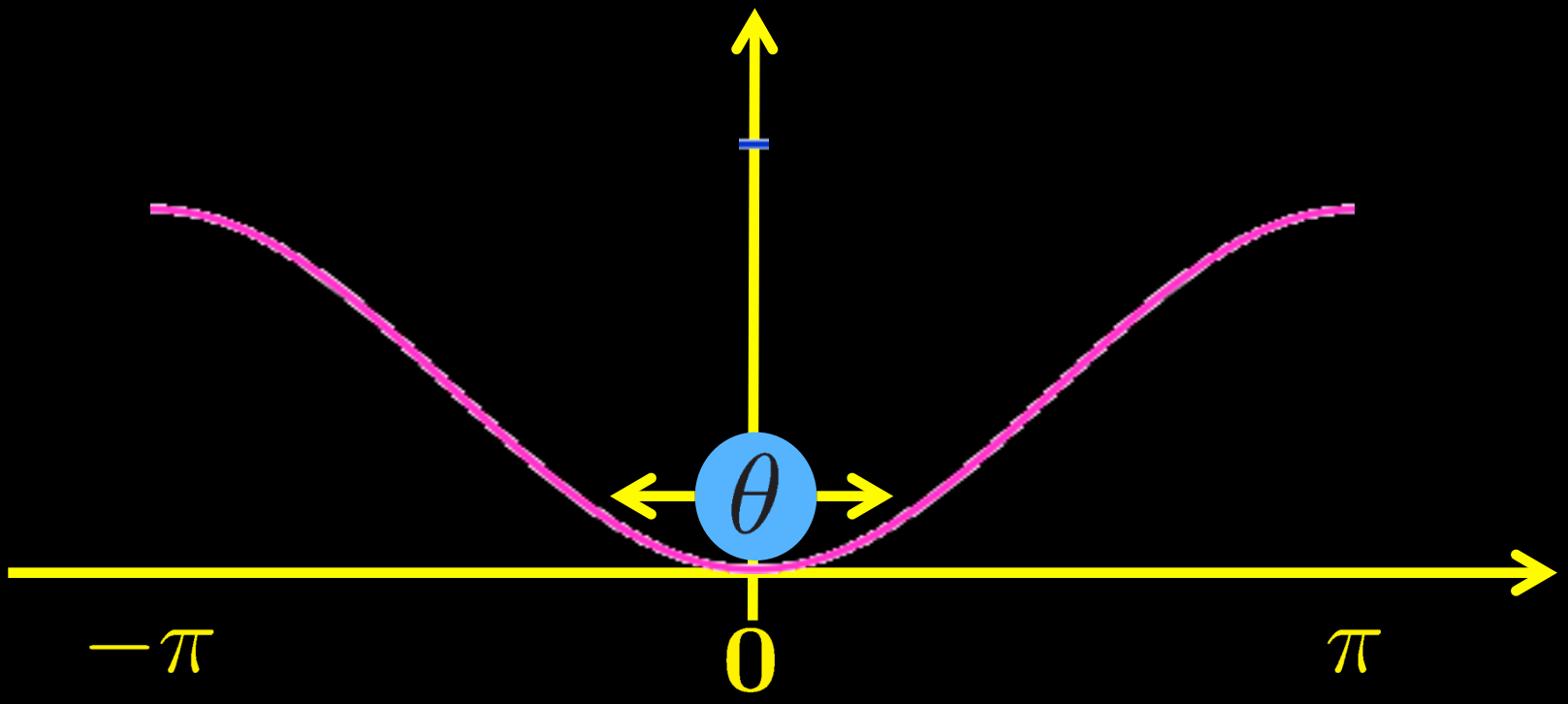

➔ Oscillations contain energy
➔ behave like non-relativistic particles (T=0)

Axion(-like particle) Dark Matter

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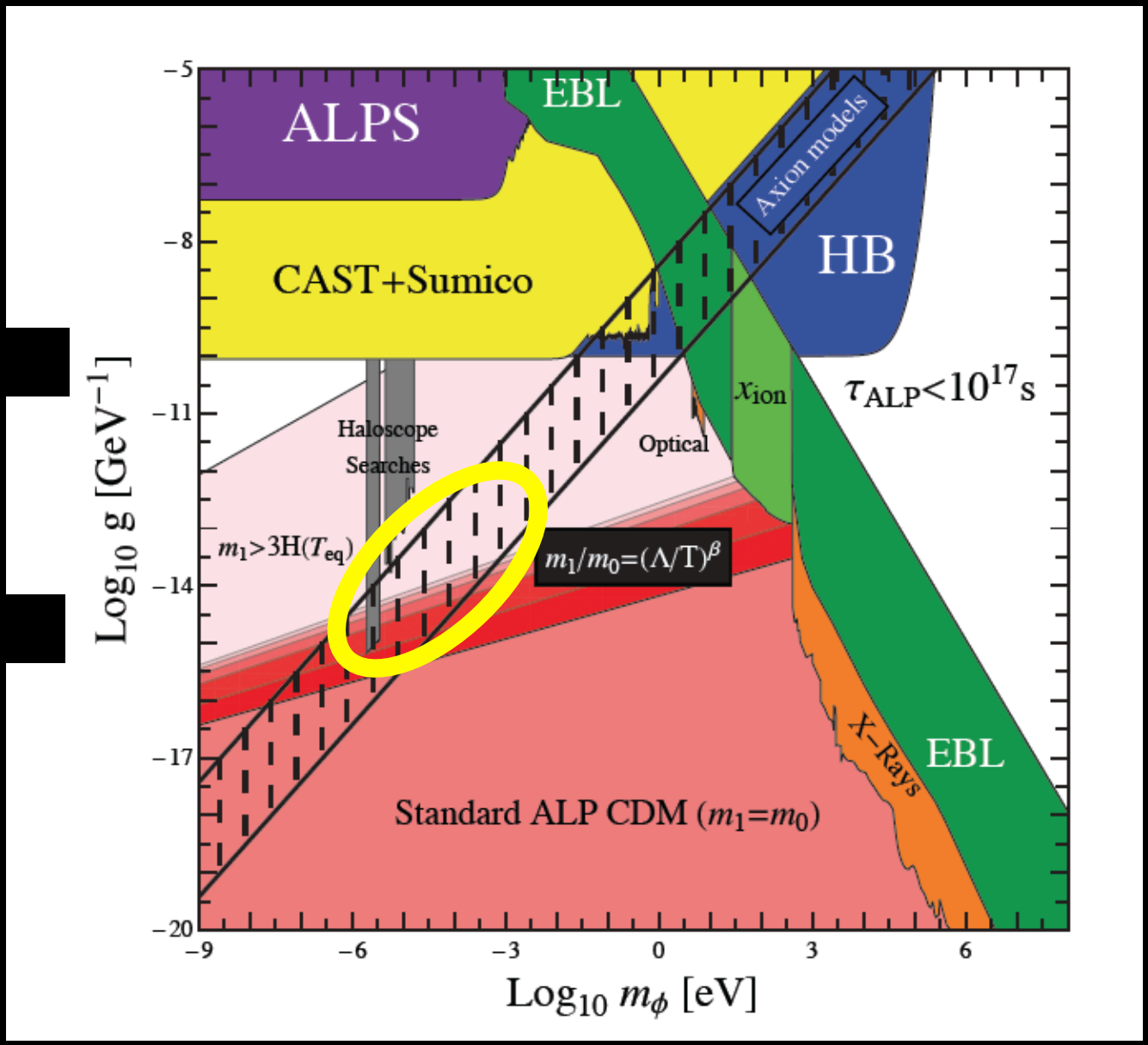
~10^7 GeV

~10^{12} GeV



Detecting WISPy DM

Use a plentiful source of axions

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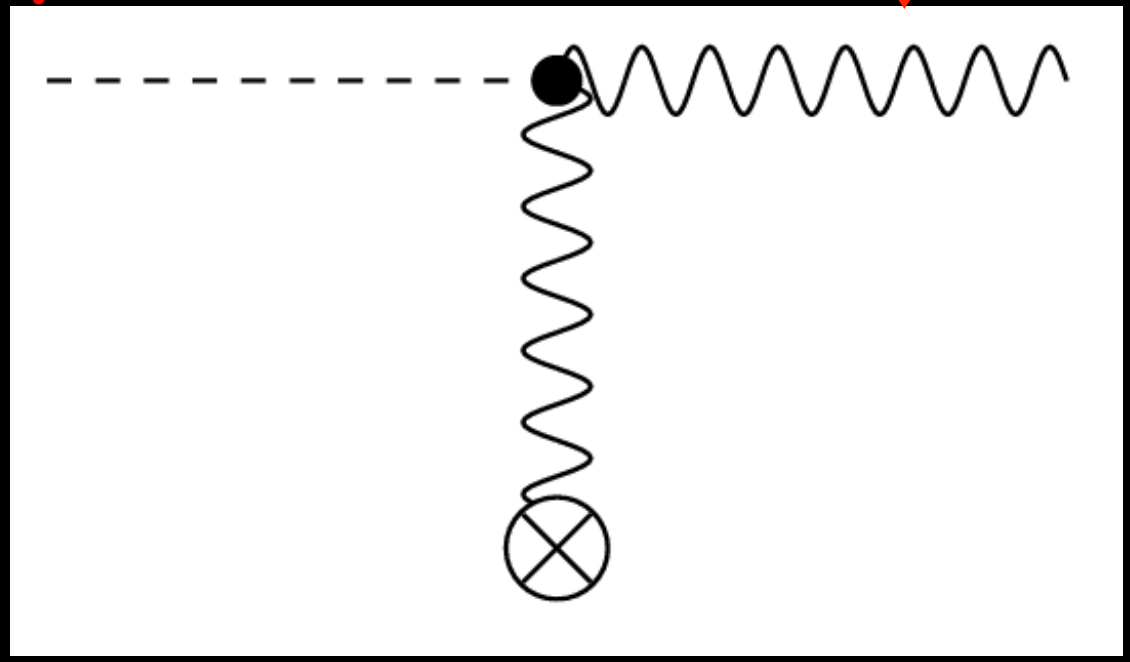
- Photon Regeneration

Photon
(amplified in resonator)



axion
(dark matter)

Signal: Total energy of axion

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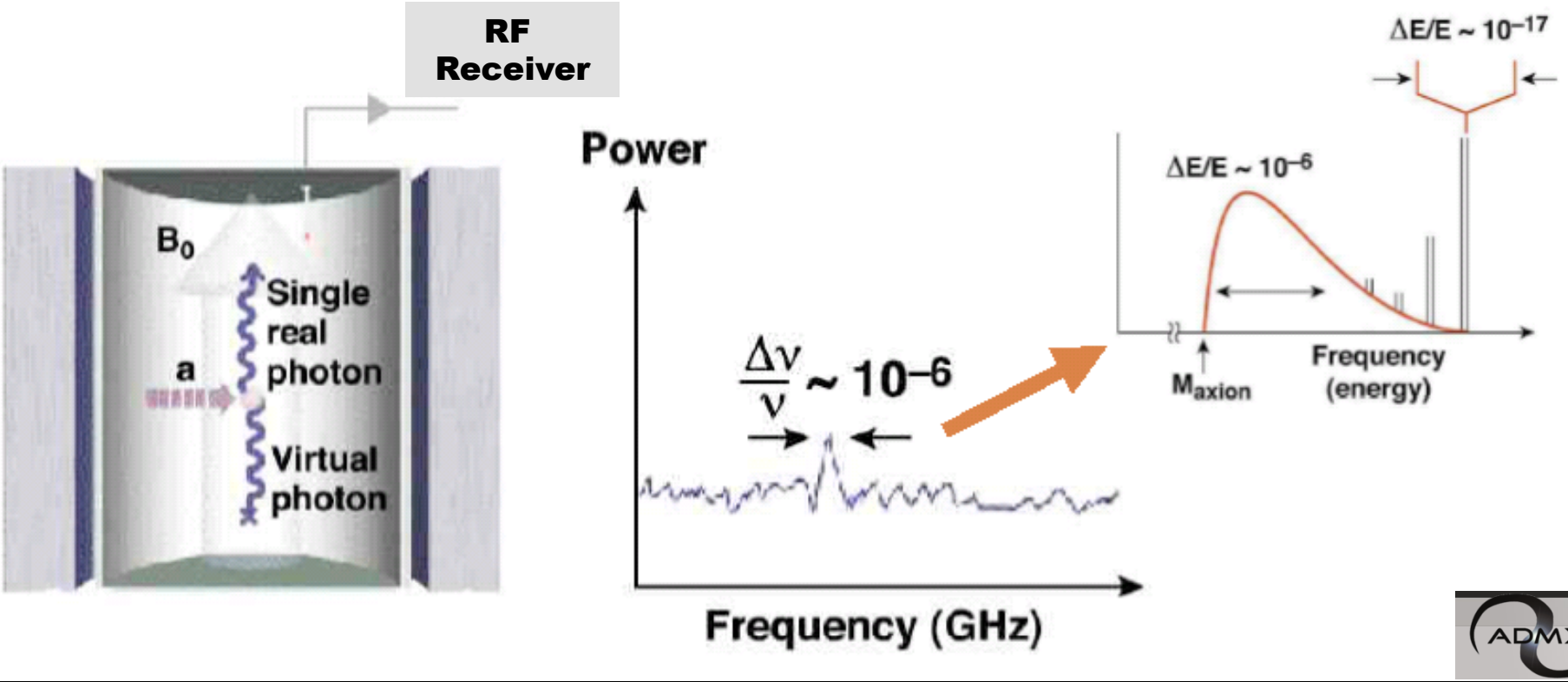

$$h\nu = m_a c^2 [1 + \mathcal{O}(\beta^2 \sim 10^{-6})]$$

Virial velocity in galaxy halo!

An extremely sensitive probe!!!

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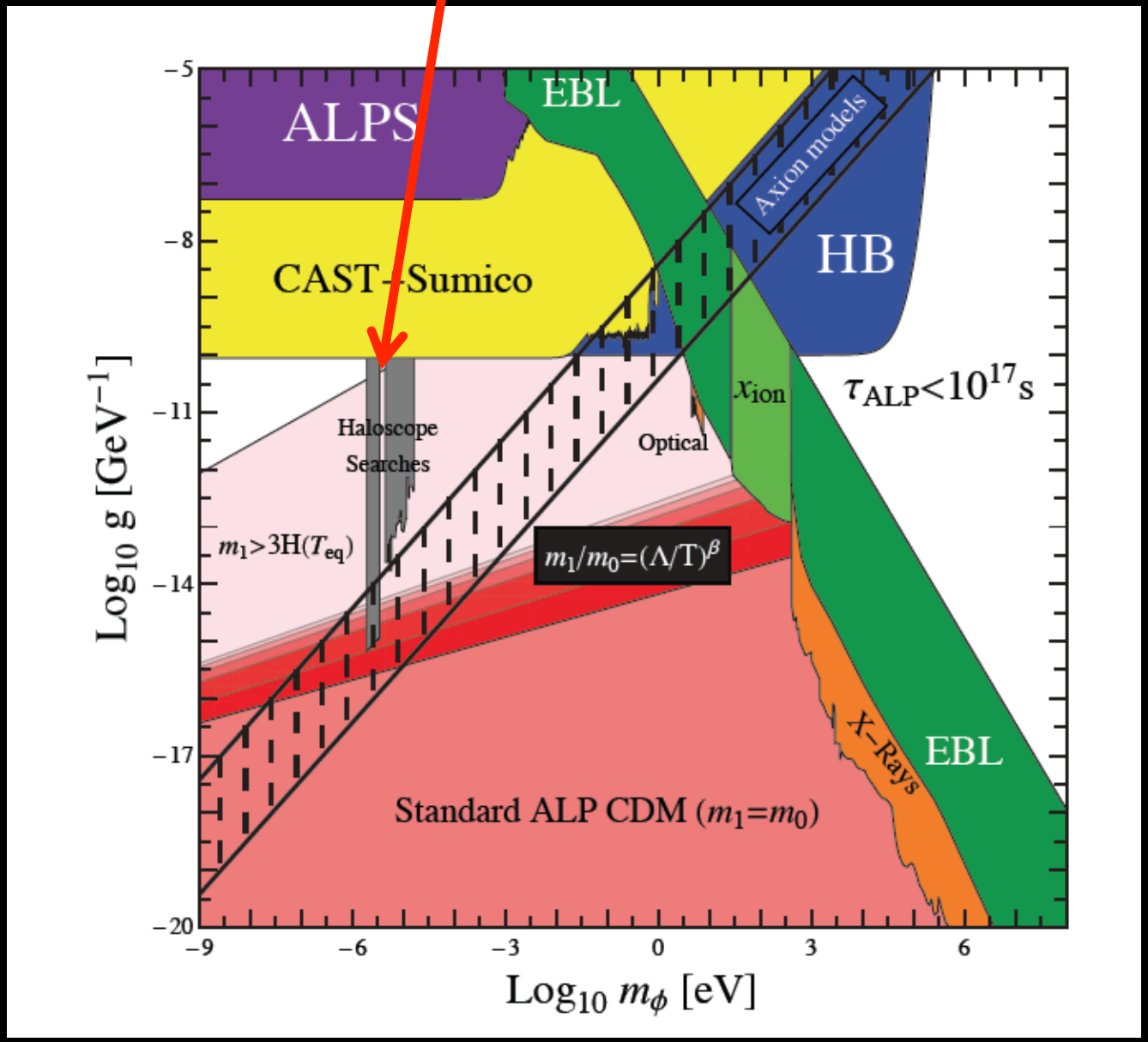

A discovery possible any minute!

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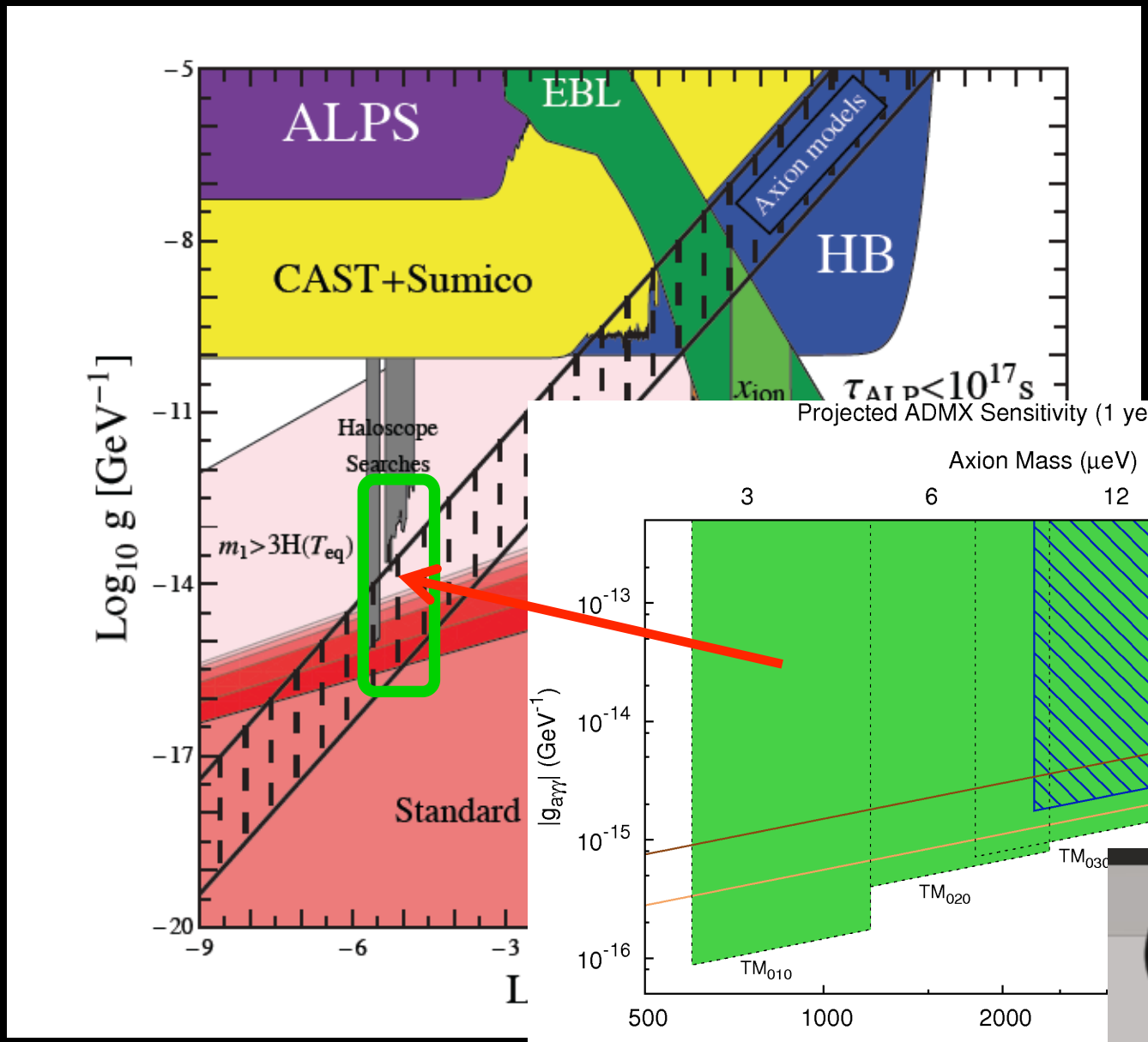

Electricity from Dark Matter ;-).

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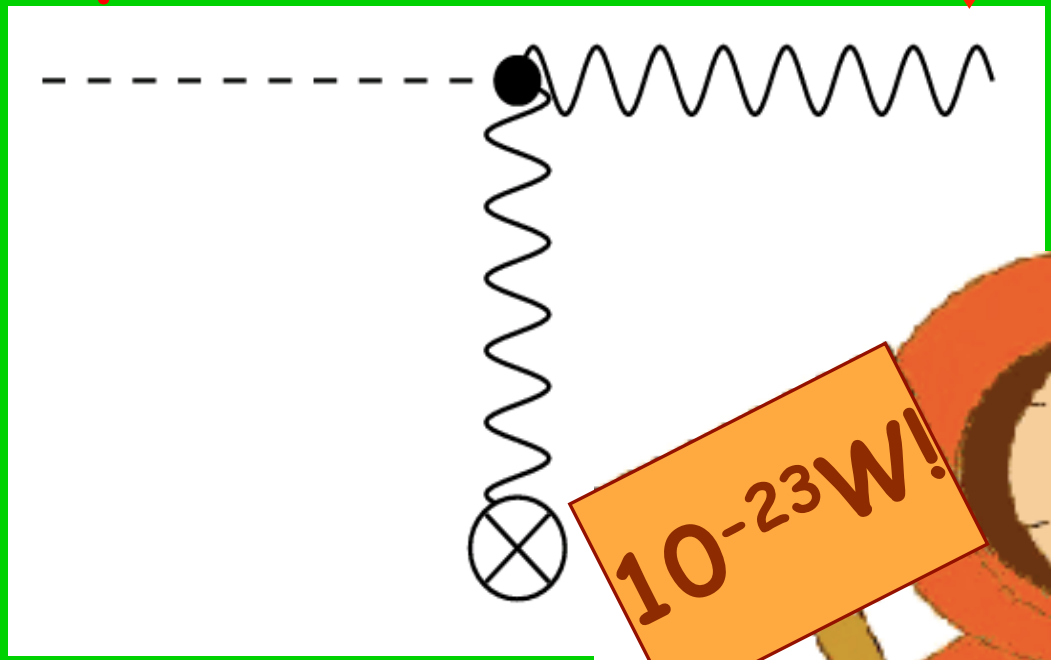
- Photon Regeneration

Photon
(amplified in resonator)

axion
(dark matter)



Encircling the axion…

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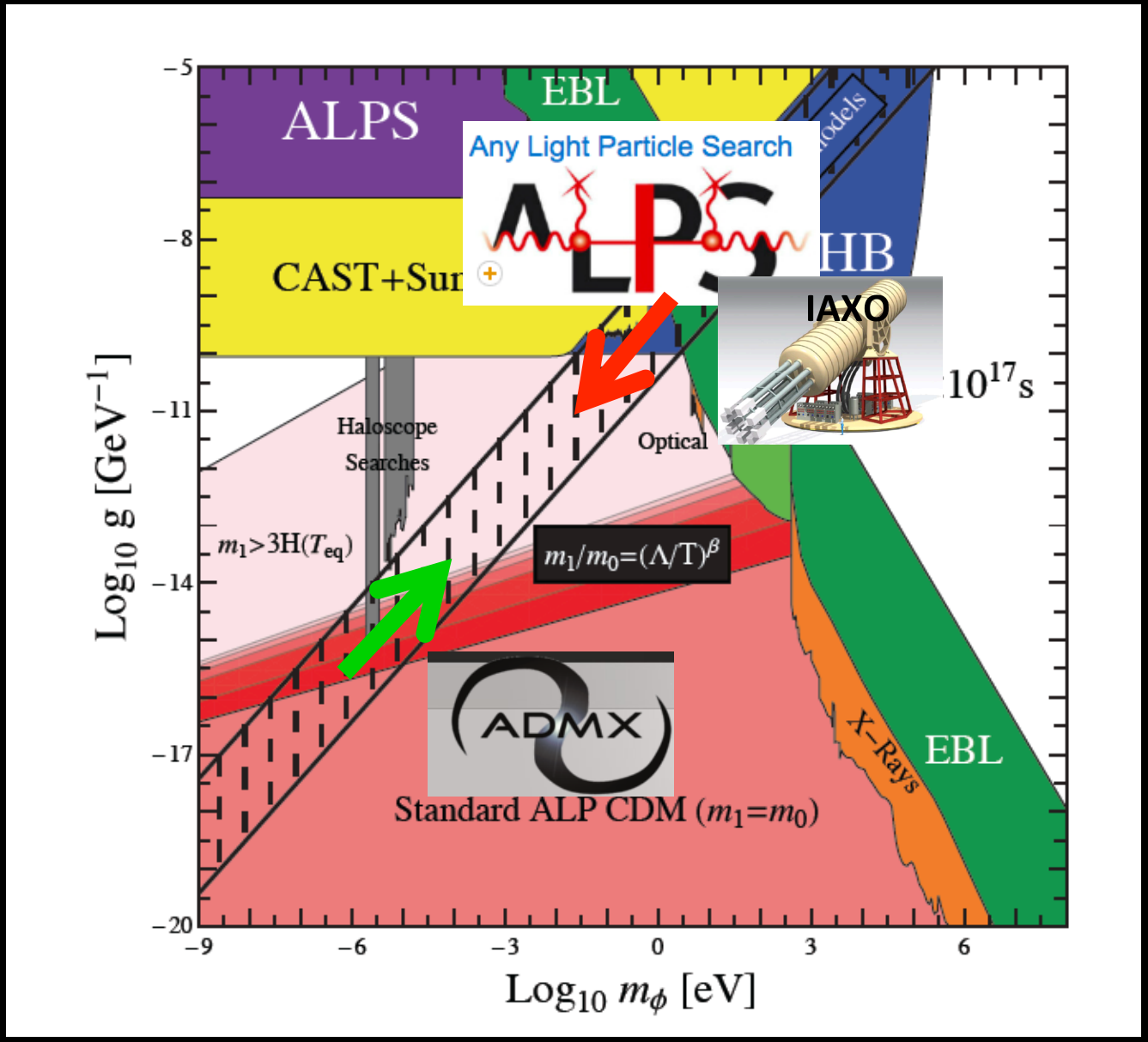

Broadband Search Strategy

Dark Matter Antenna

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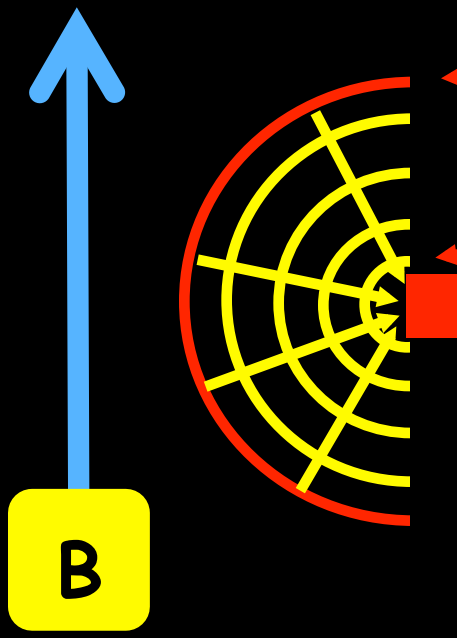
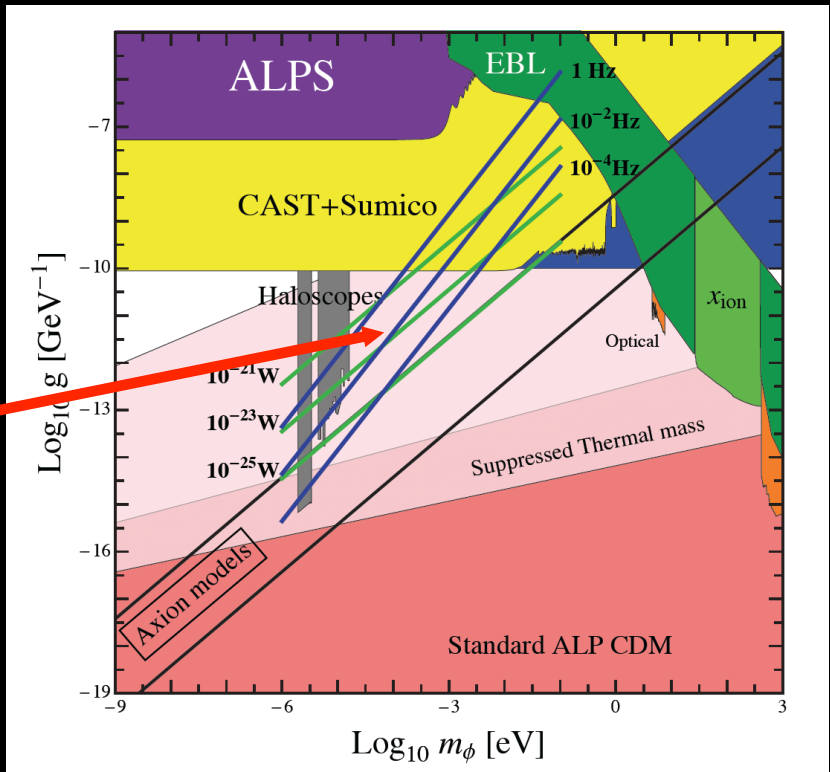


Antenna converts axion->photon

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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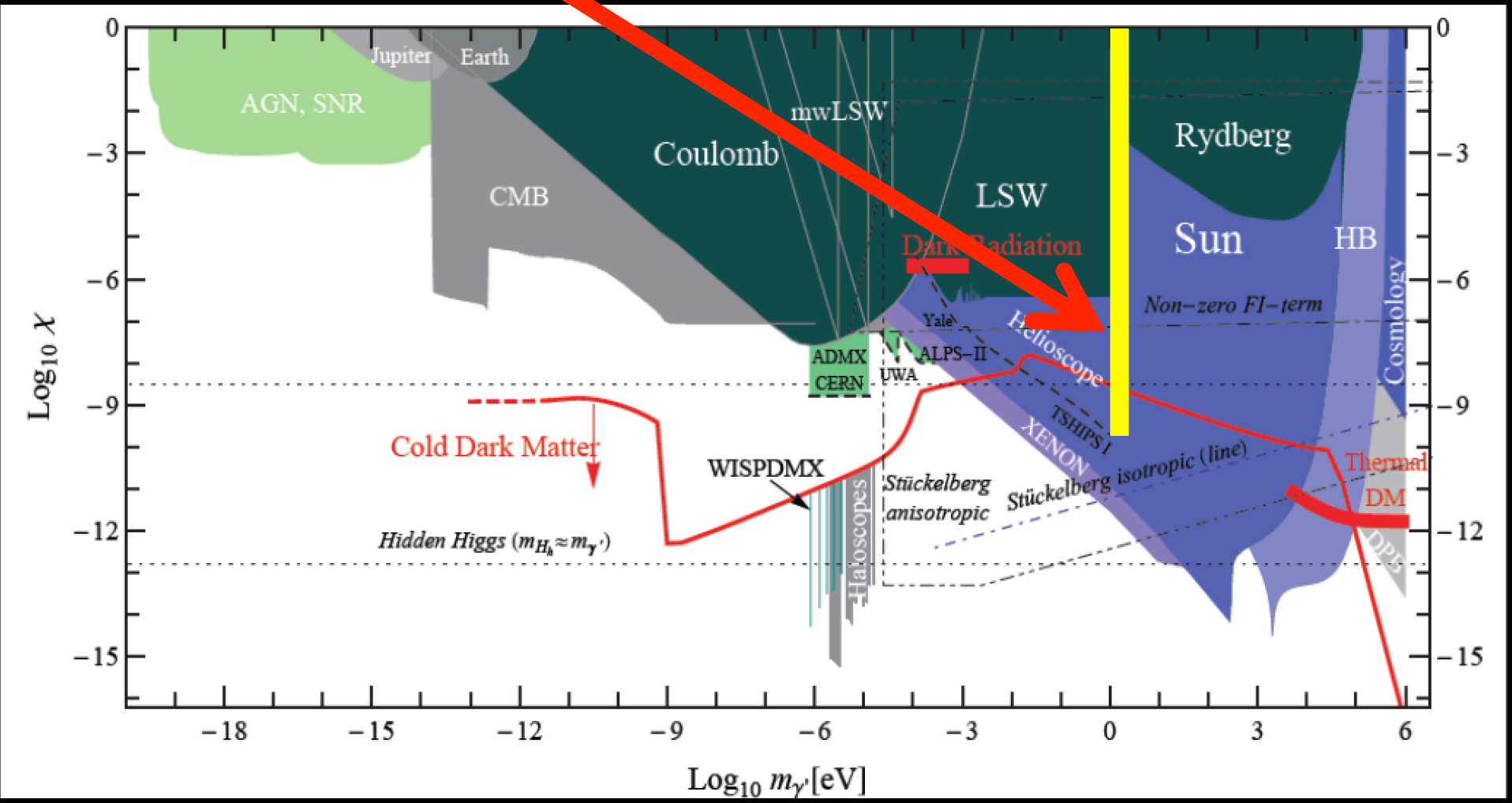

Upgrade: The PMT 9000(+107)

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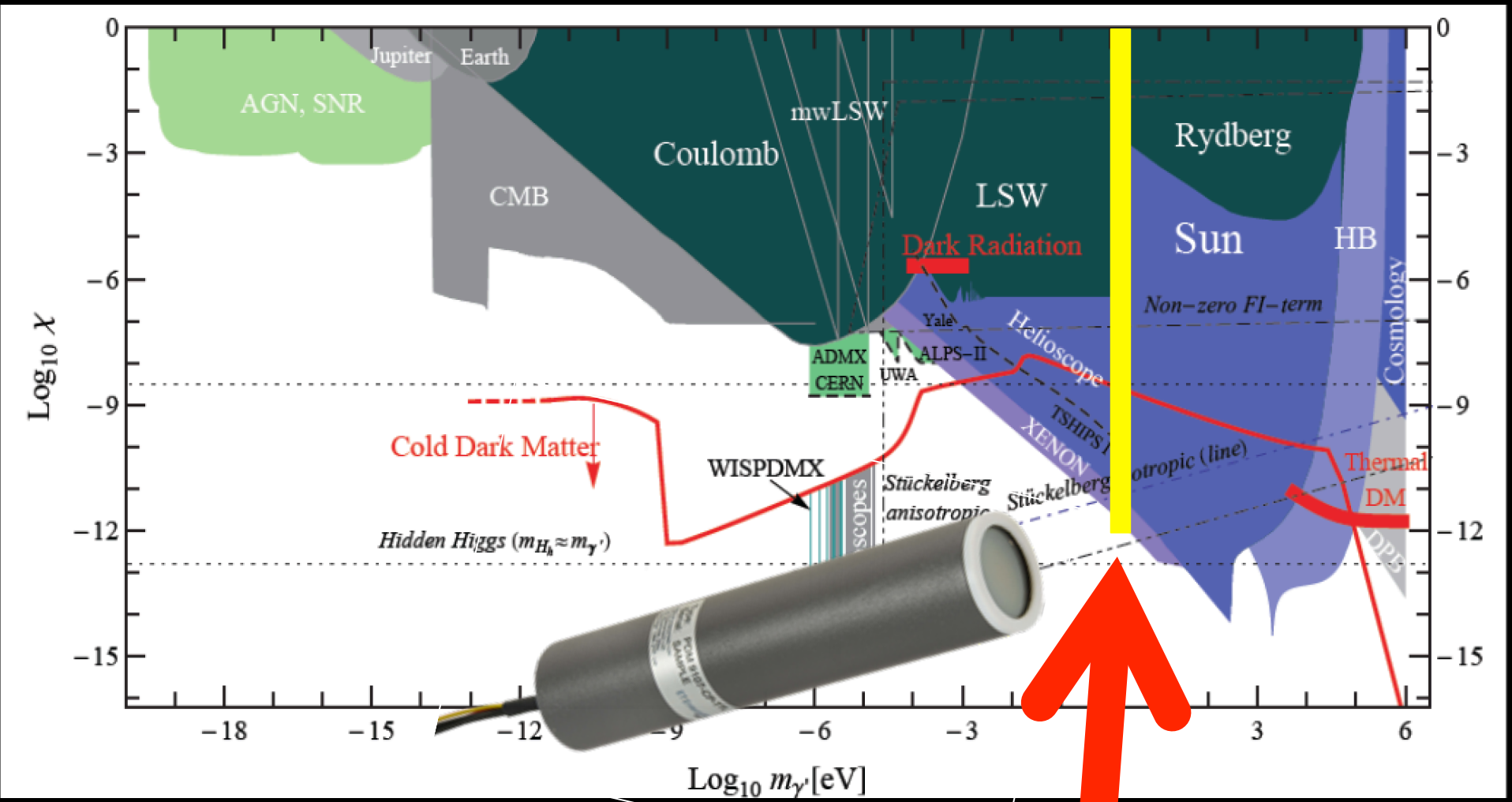

Discovery Potential ☺!!!

A Dream for ~~Astrology~~ ehhm Astronomy

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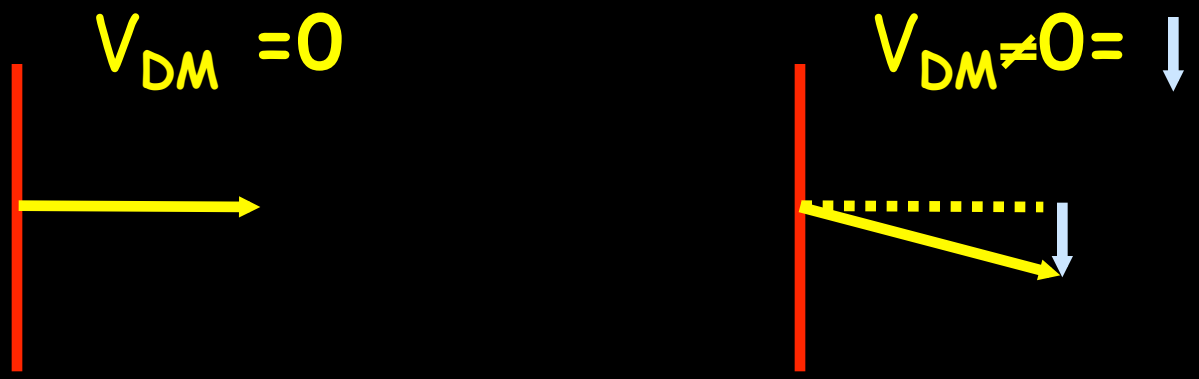
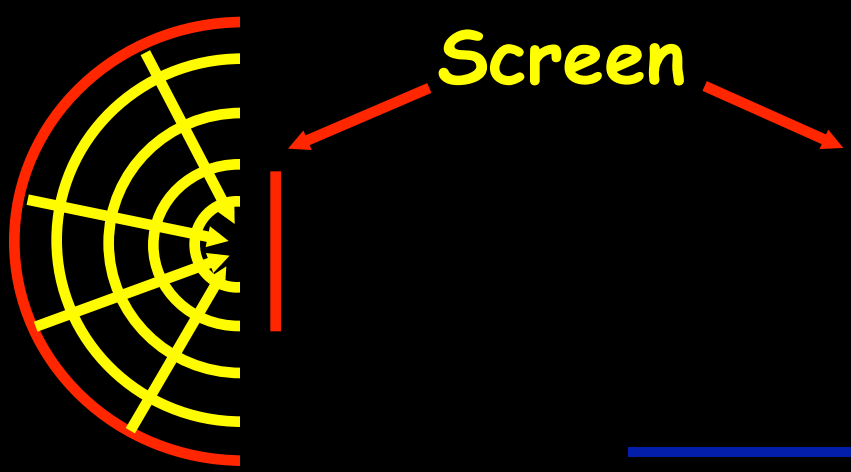
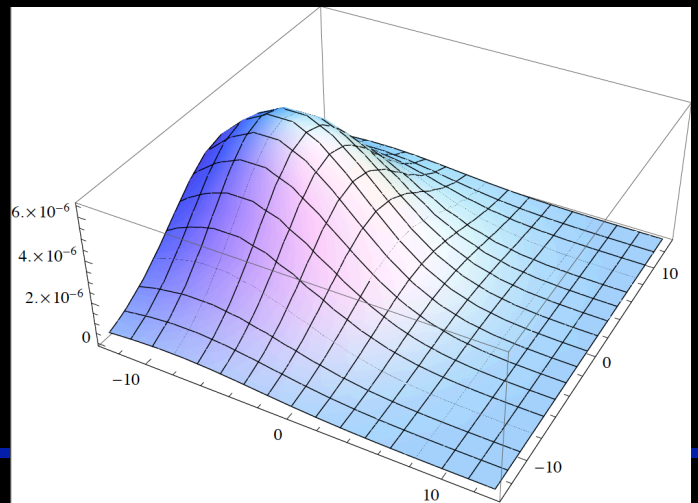
- Emission from moving dark matter



- A picture of the DM-velocity distribution





Going Ultimate… MADMAX

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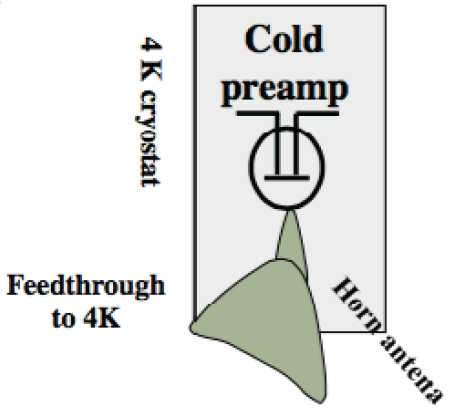
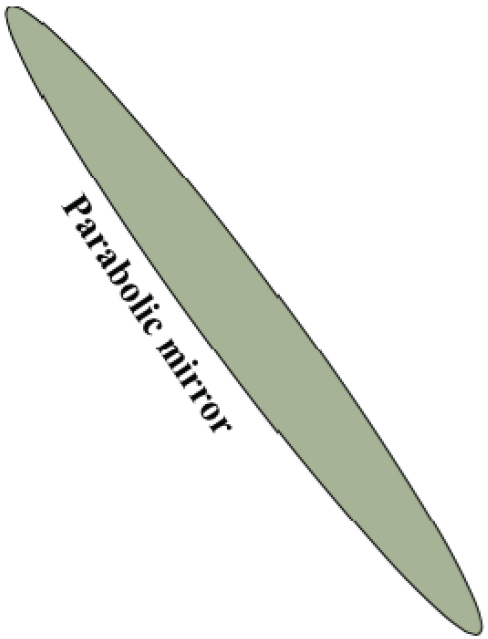
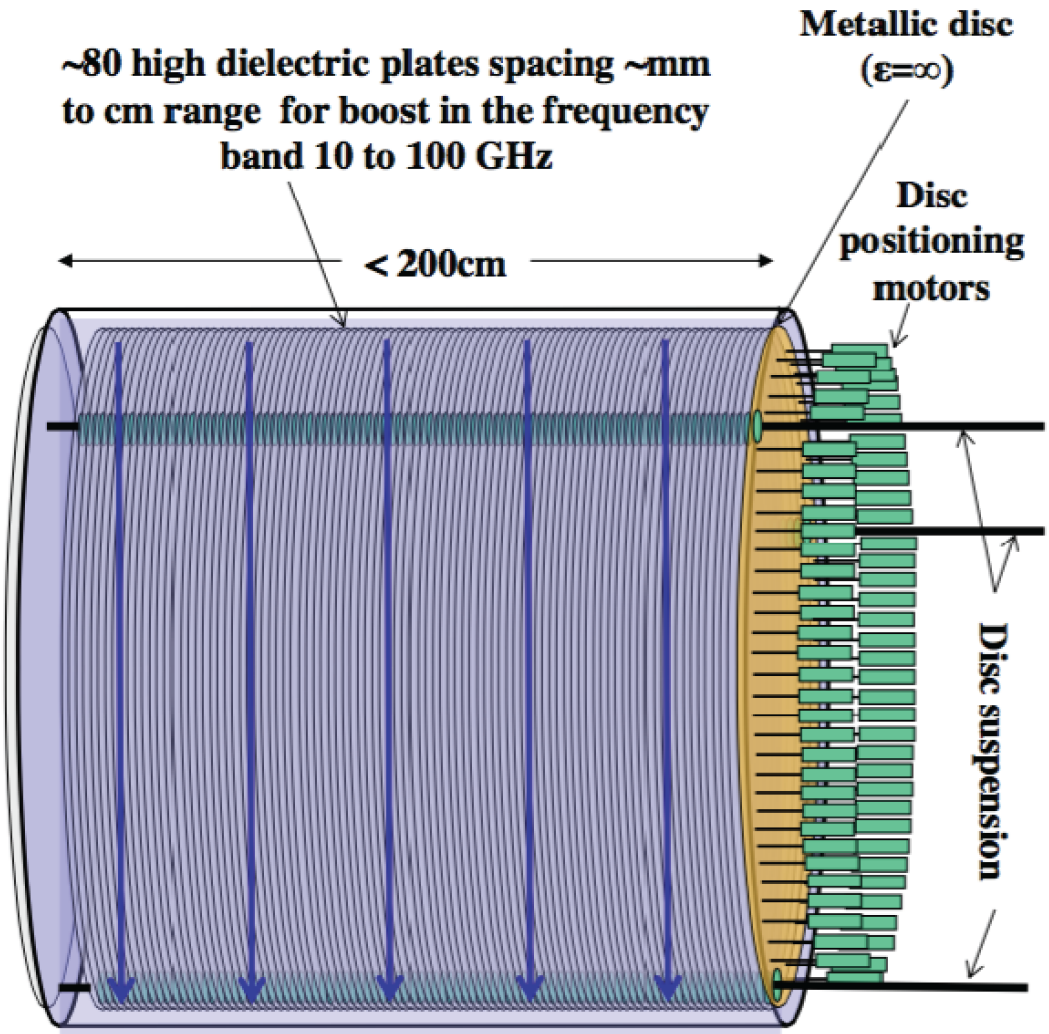
Experimental idea

+J. Redondo, +++







Going Monodromic

Axion Monodromy

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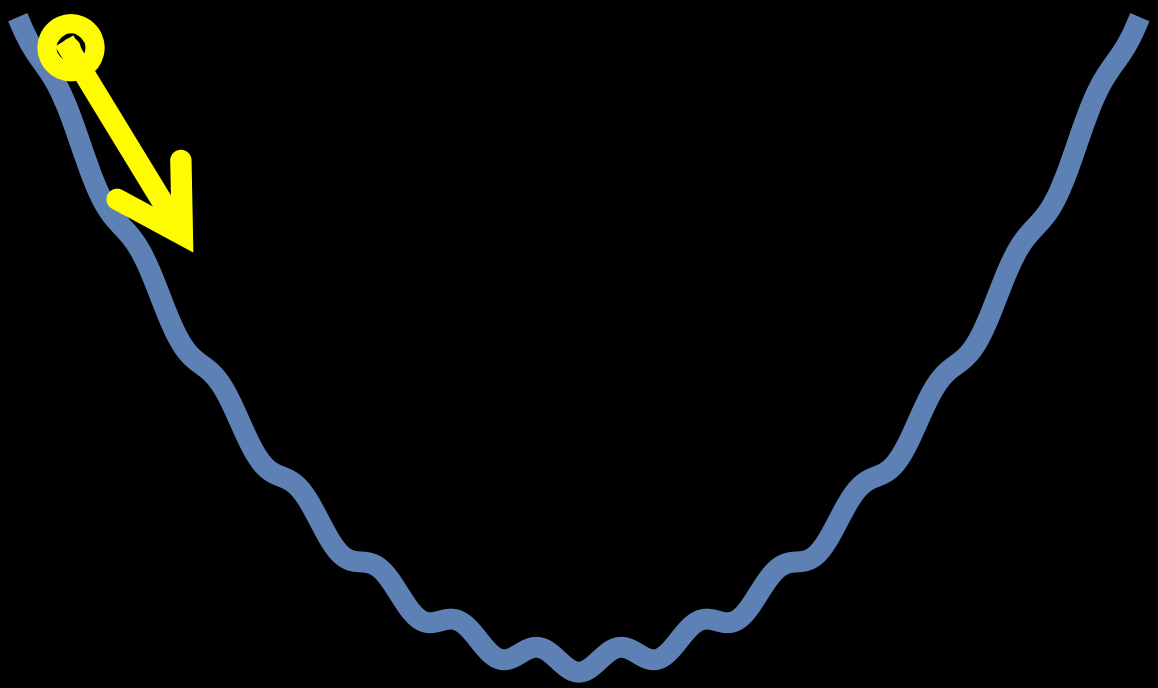
- Allows for extended field range

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



Advantages

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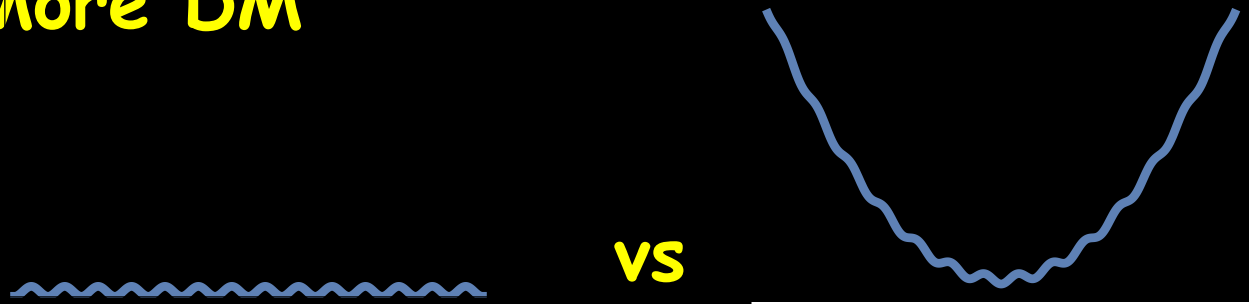
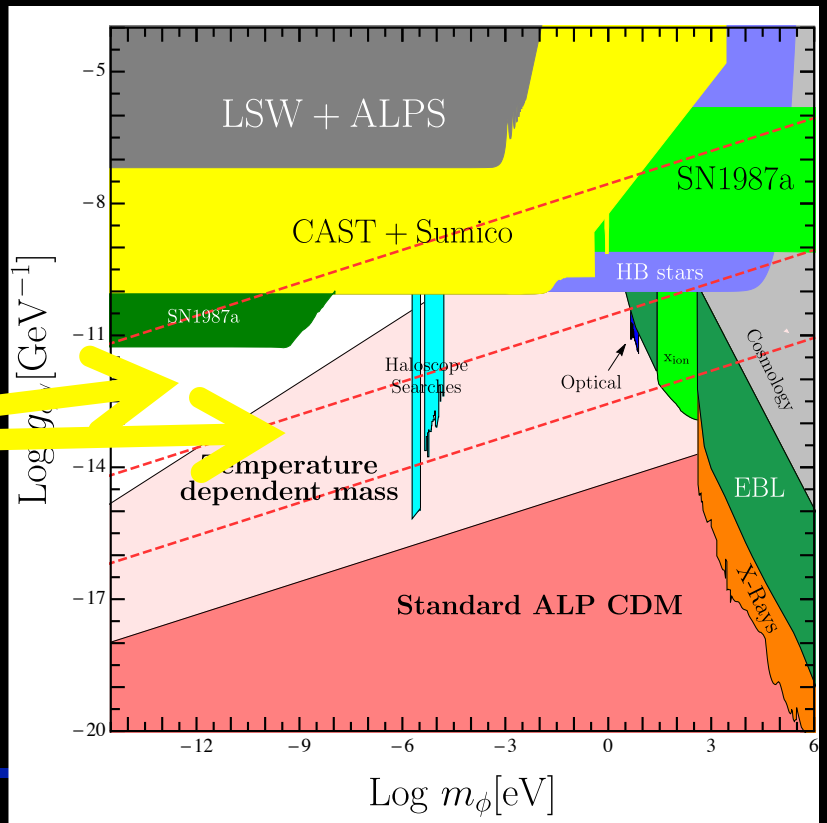
- Allows to start with higher energy density
  ➔ More DM



vs

Models
in this region!



Interesting Phenomena??

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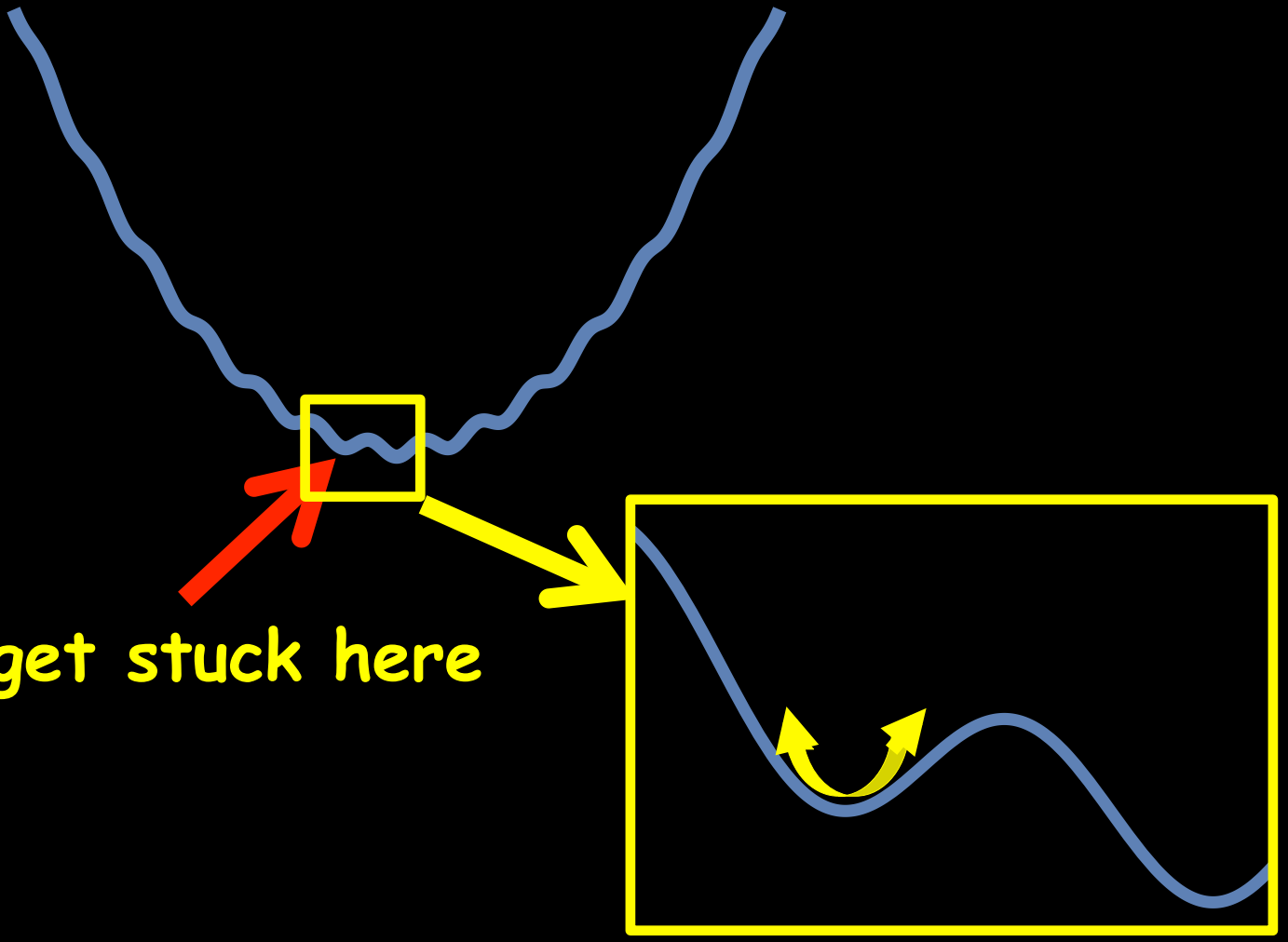

Oscillations like DM!

Interesting Phenomena??

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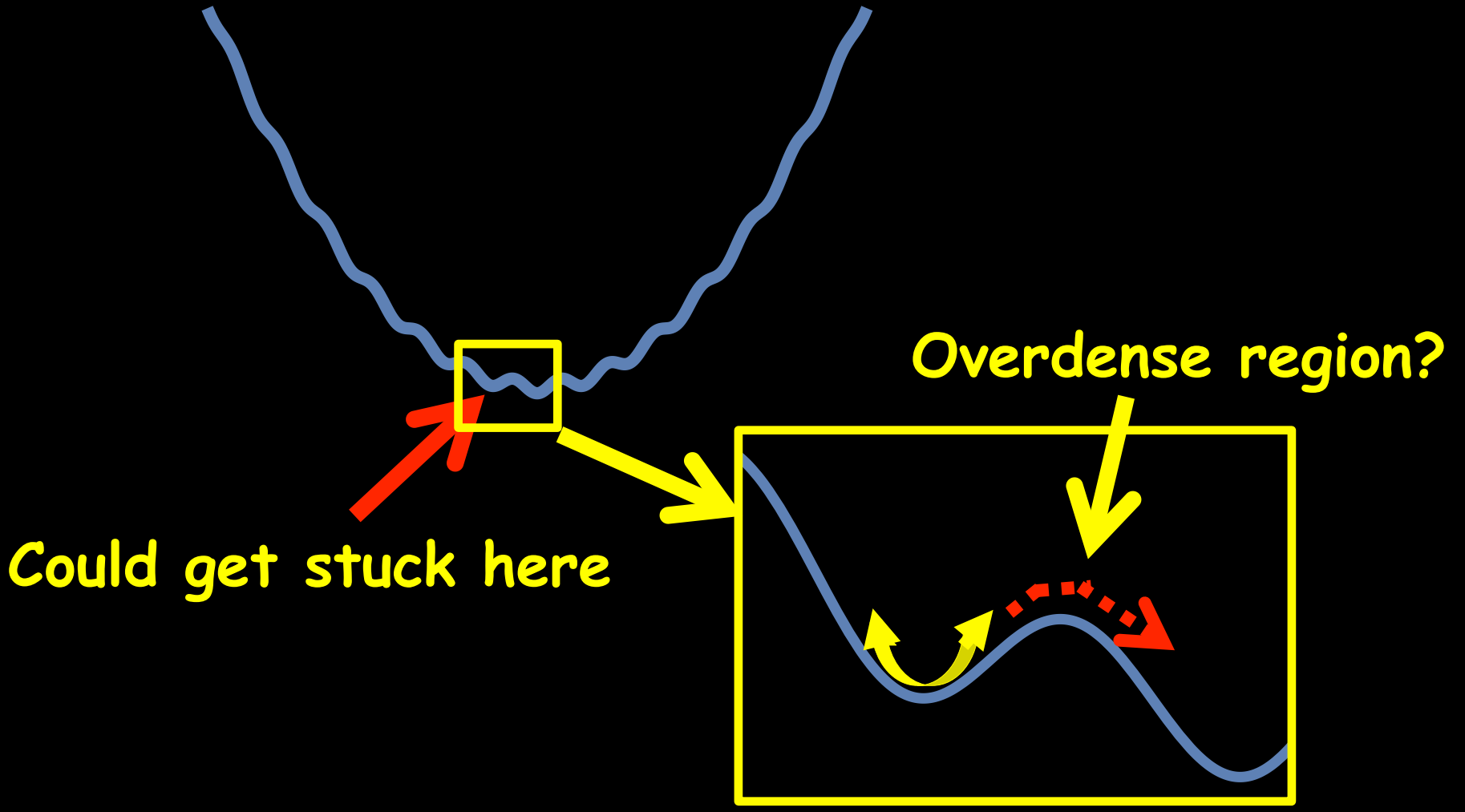

$$amplitude \sim \sqrt{DM density}$$

Interesting Phenomena??

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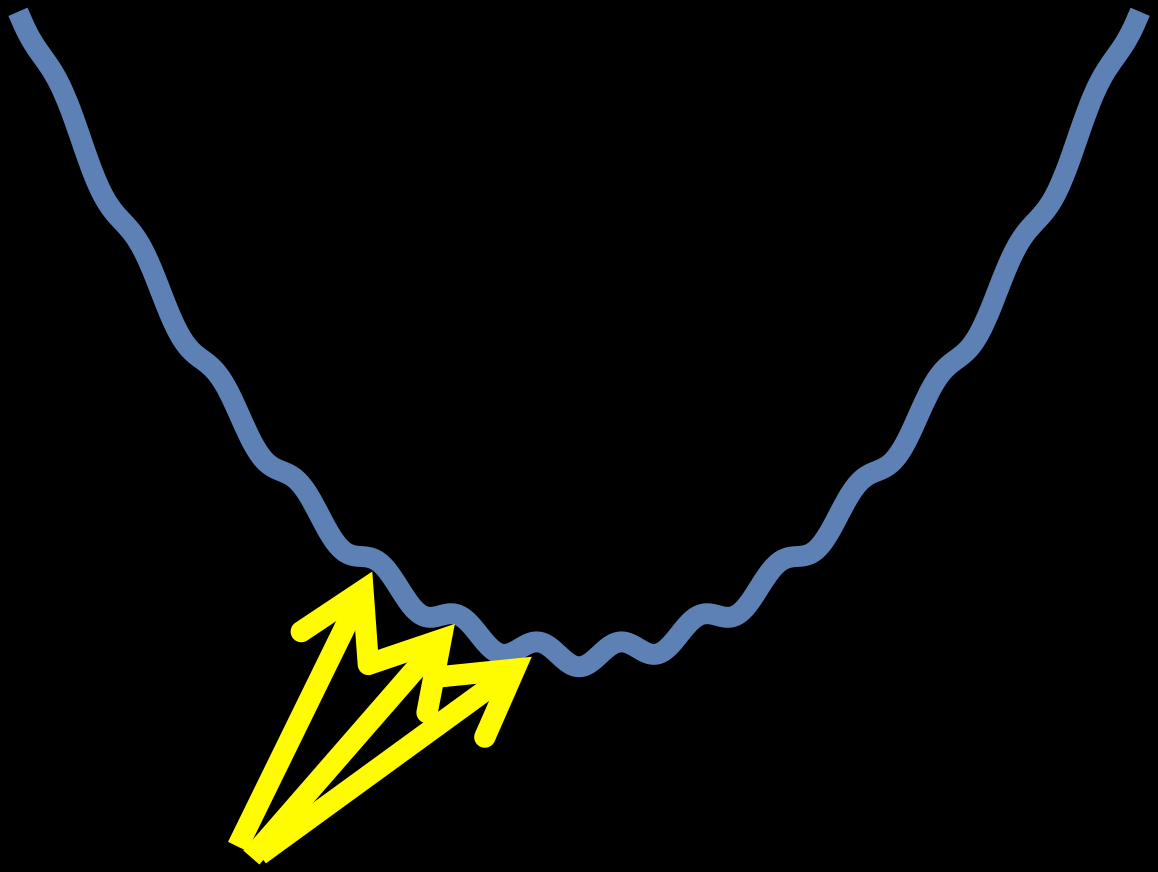

Regions with "negative mass"

Instability ➔ Particle Production with p≠0?!?

Very rapid particle production…

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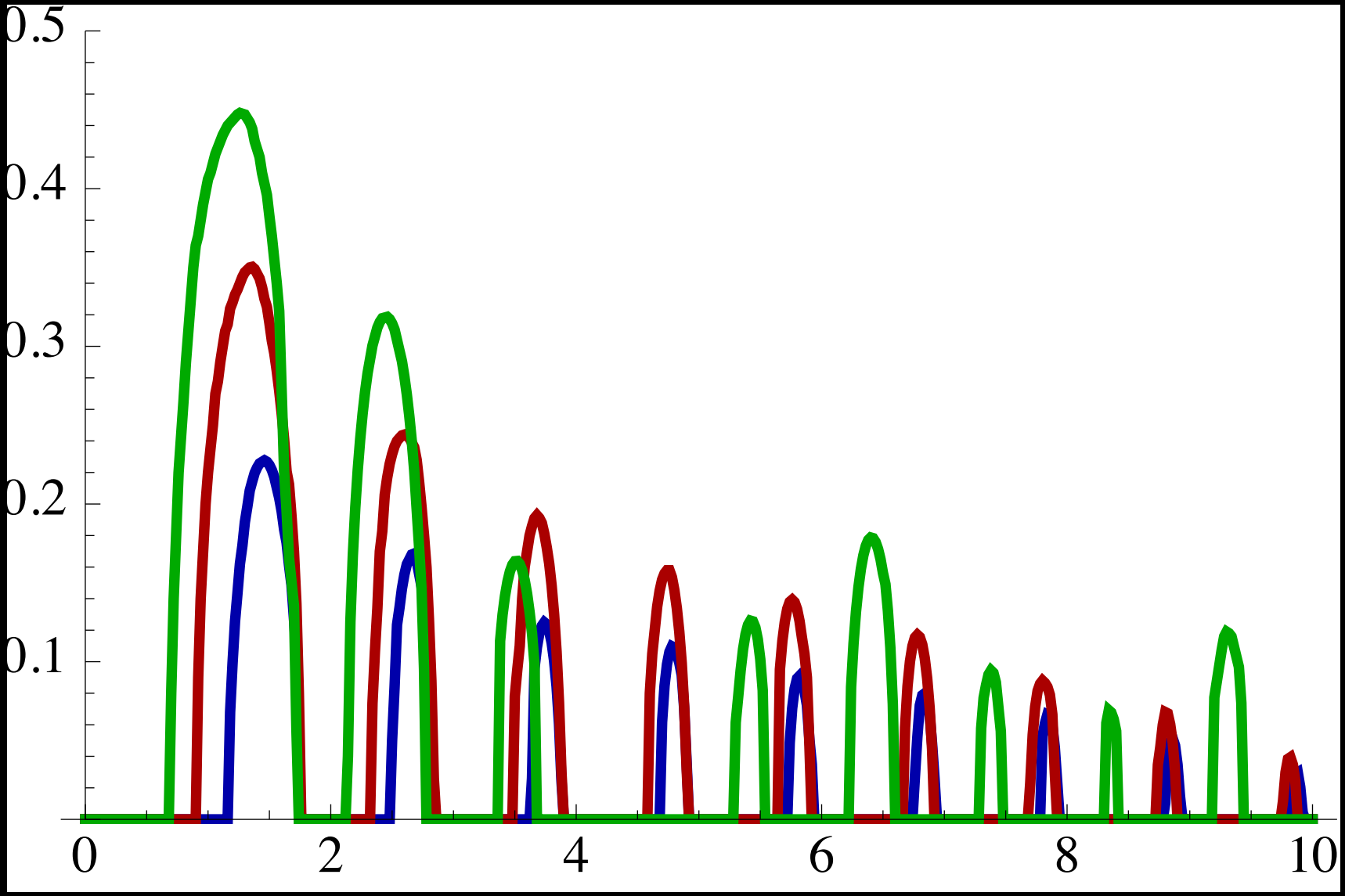

Conclusions

Conclusions

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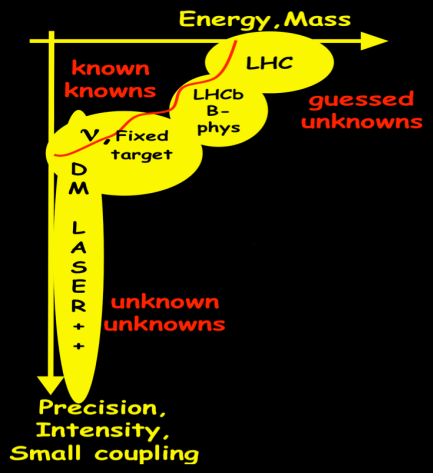
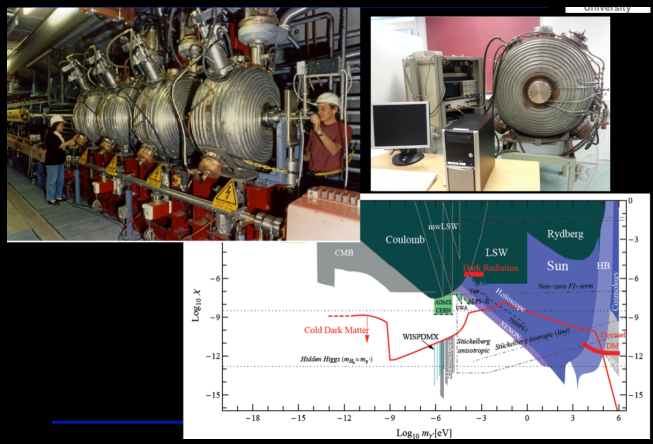
- Good Physics Case for Hidden Sectors

  ➡ 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!

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