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Axions

–

Motivated by the Strong Interactions, Perfect for Cosmology

J. Jaeckel[**]

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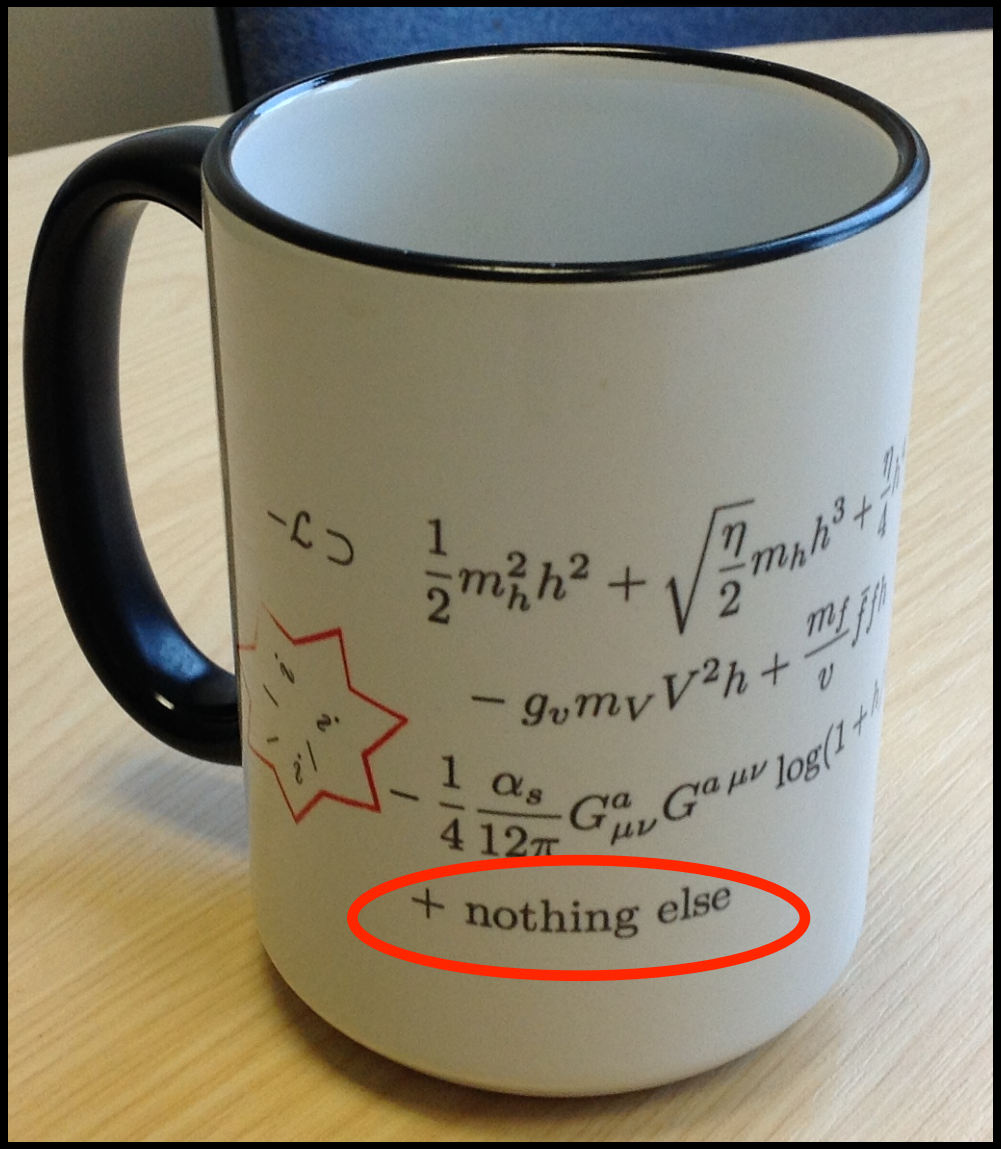
V. Khoze[†], A. Lobanov[y], J. Redondo[x],
A. Ringwald[*], U. Schmidt[**], K. Schmidt-Hoberg[*]
and The FUNK Collaboration

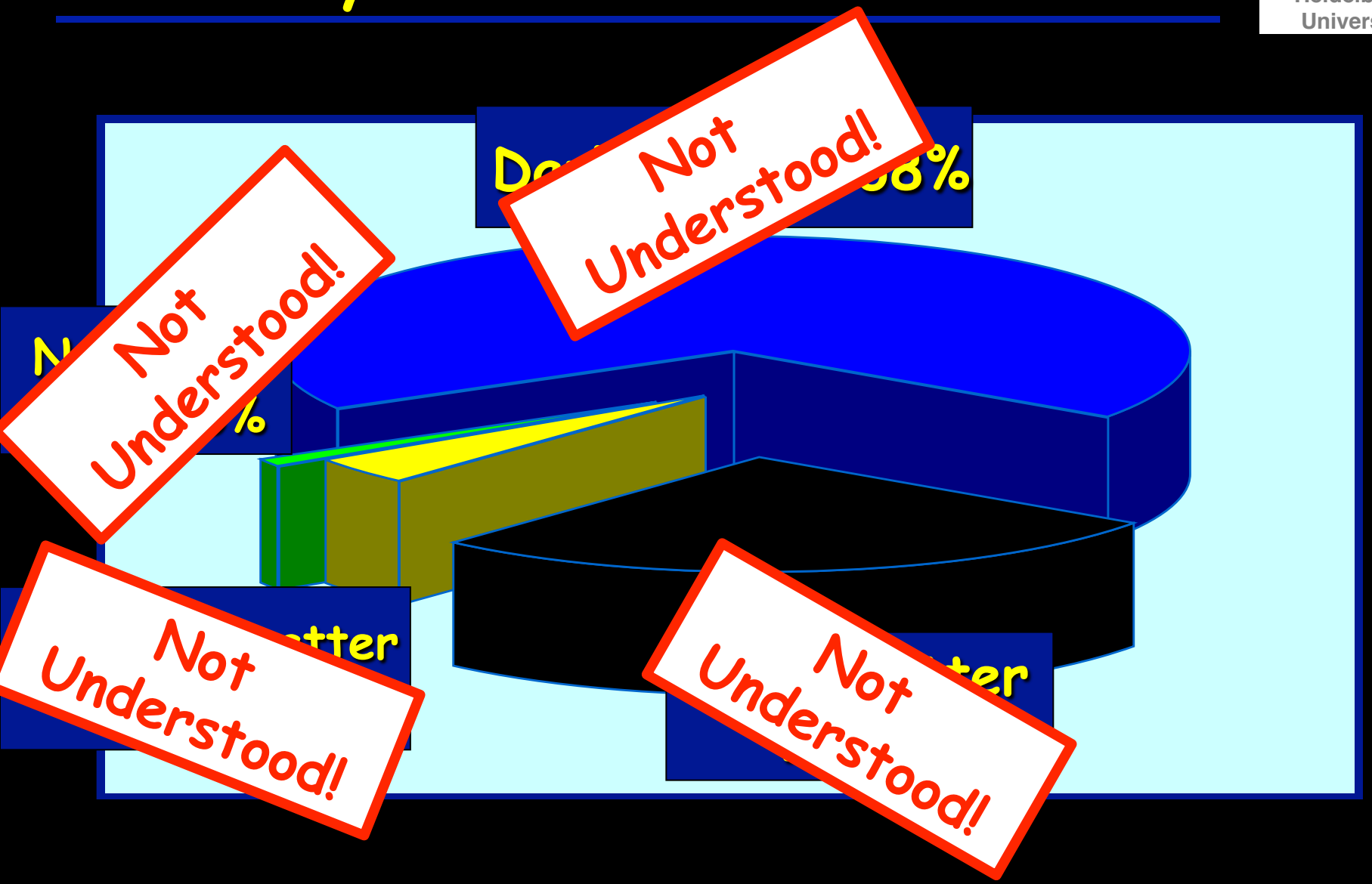
[**]Heidelberg U., [z]CERN, [†]IPPP Durham, [*]DESY, [y]MPIfR Bonn, [x]U. Zaragoza, [xx]Paris LPTHE, [0]ITP Jena, [*x]RWTH Aachen

We need...

Physics beyond the Standard Model


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

Inventory of the Universe



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Where does it hide?

New physics

Exploring is (at least) 2 dimensional

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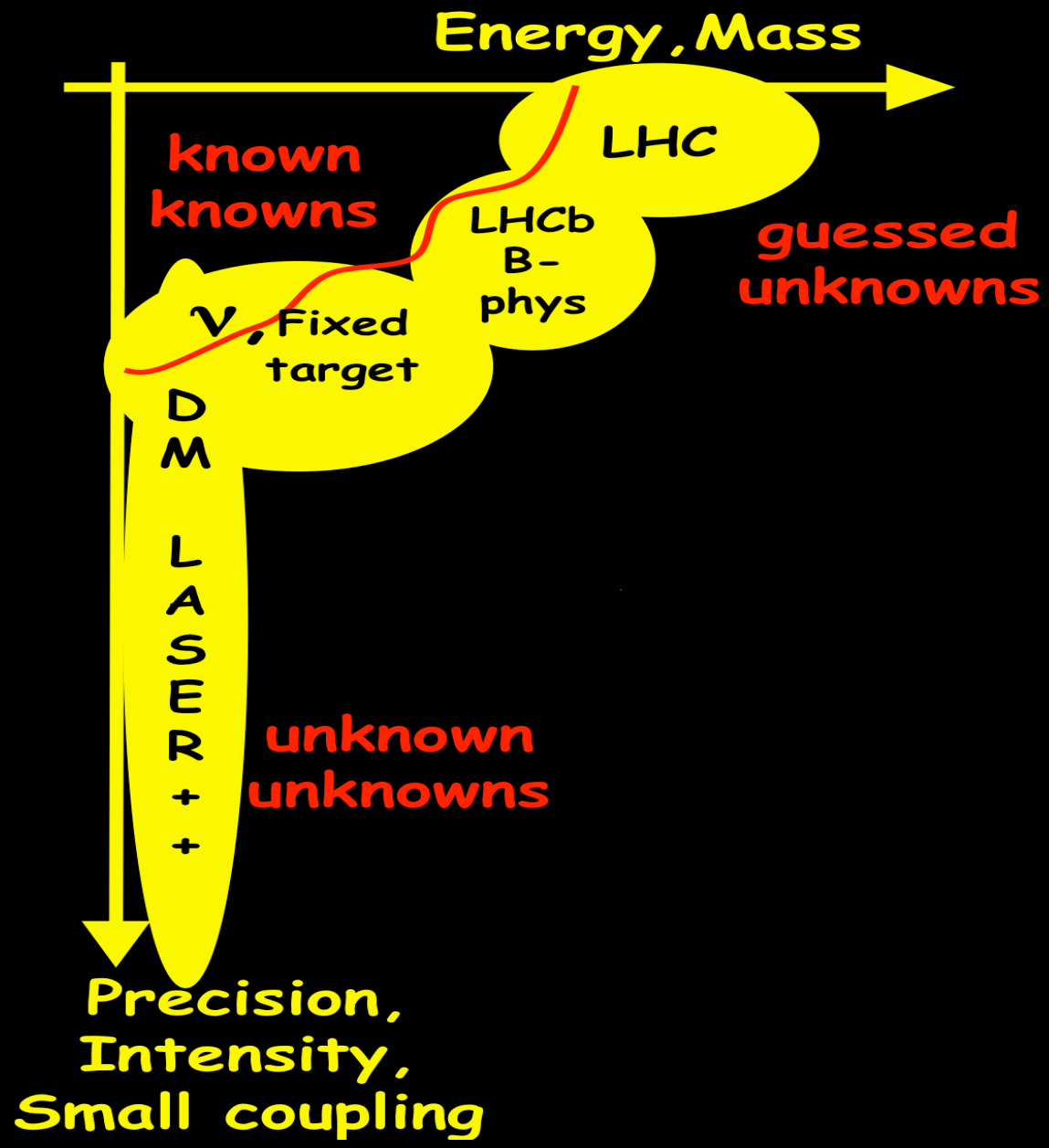

Exploring is (at least) 2 dimensional

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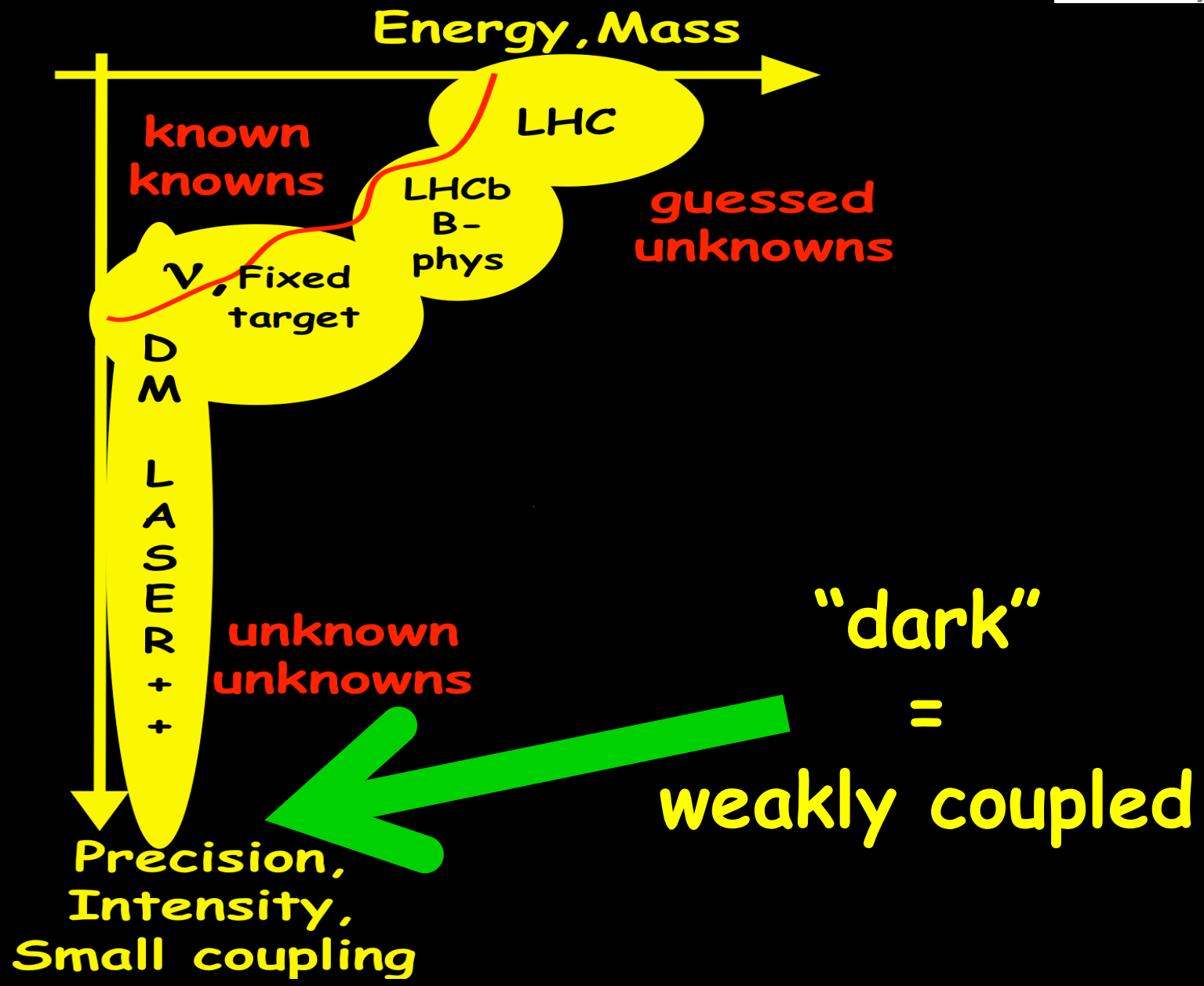

What are Axions?
And why do we need them?

A „visible“ Hint for new Physics

The strong CP Problem

A dirty little secret...

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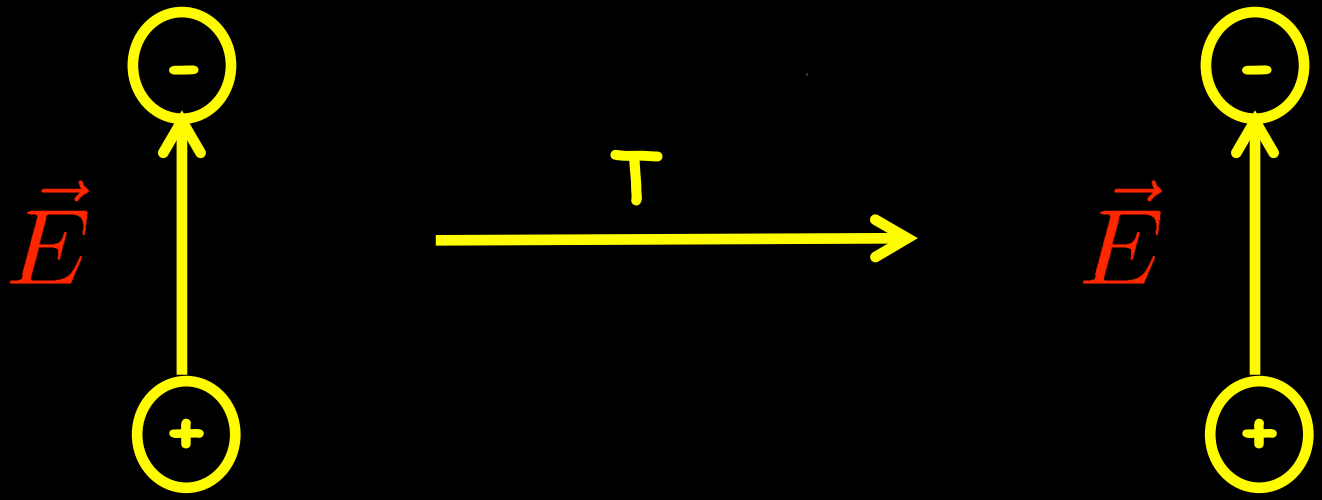
$$S = \int d^4x \left[-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu} + 1\bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right]$$

$$\text{"} \sim \theta \vec{E} \cdot \vec{B} \text{"}$$

- The θ-term violates time reversal (T=CP)!



A dirty little secret...

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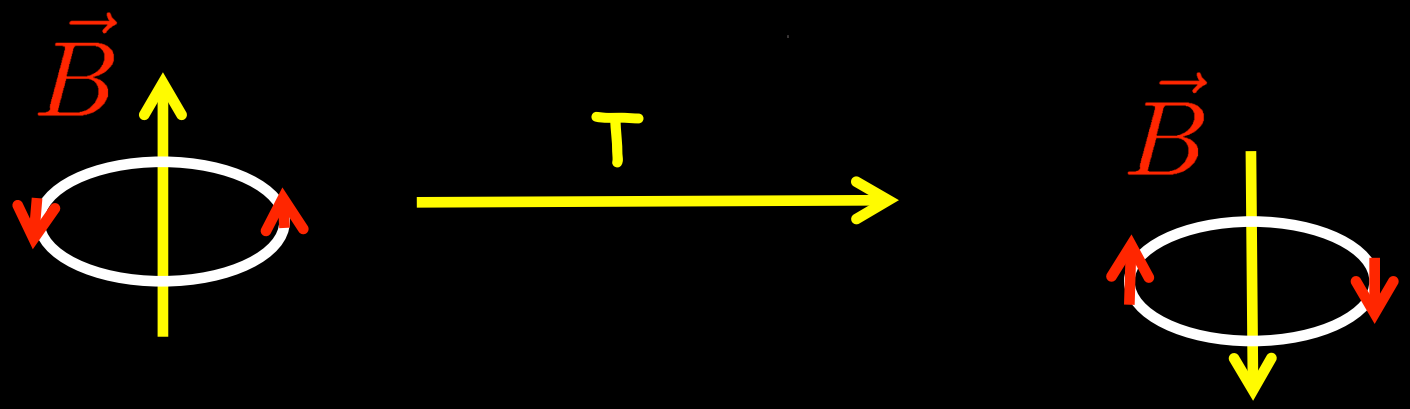

A dirty little secret...

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$$\text{"} \sim \theta \vec{E} \cdot \vec{B} \text{"}$$

- The θ-term violates time reversal (T=CP)!

T=CP

$$\vec{E} \longrightarrow \vec{E}$$

$$\vec{B} \longrightarrow -\vec{B}$$

$$\vec{E} \cdot \vec{B} \longrightarrow -\vec{E} \cdot \vec{B}$$

A dirty little secret...

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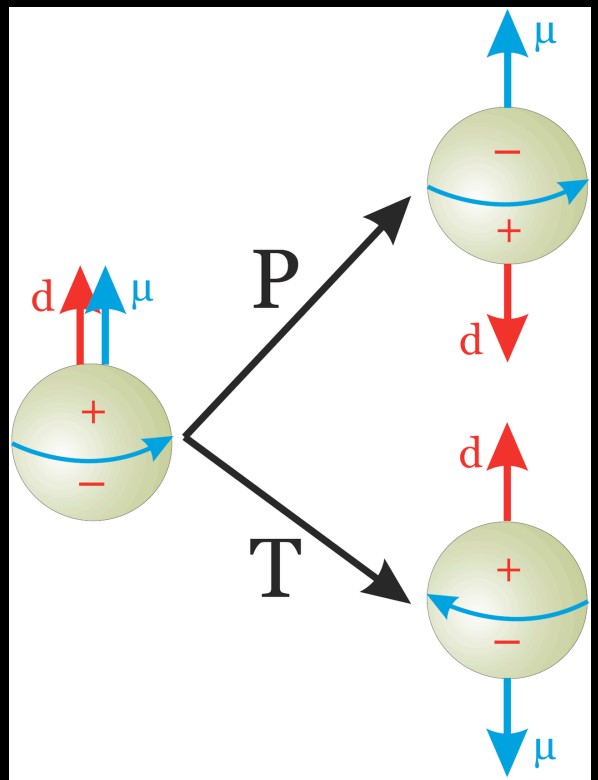
$$S = \int d^4x \left[-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu} + 1\bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right]$$

$$\text{"} \sim \theta \vec{E} \cdot \vec{B} \text{"}$$

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

➡ **Electric dipole moment of the neutron!**



https://en.wikipedia.org/wiki/Neutron_electric_dipole_moment

Measure neutron electric dipole moment

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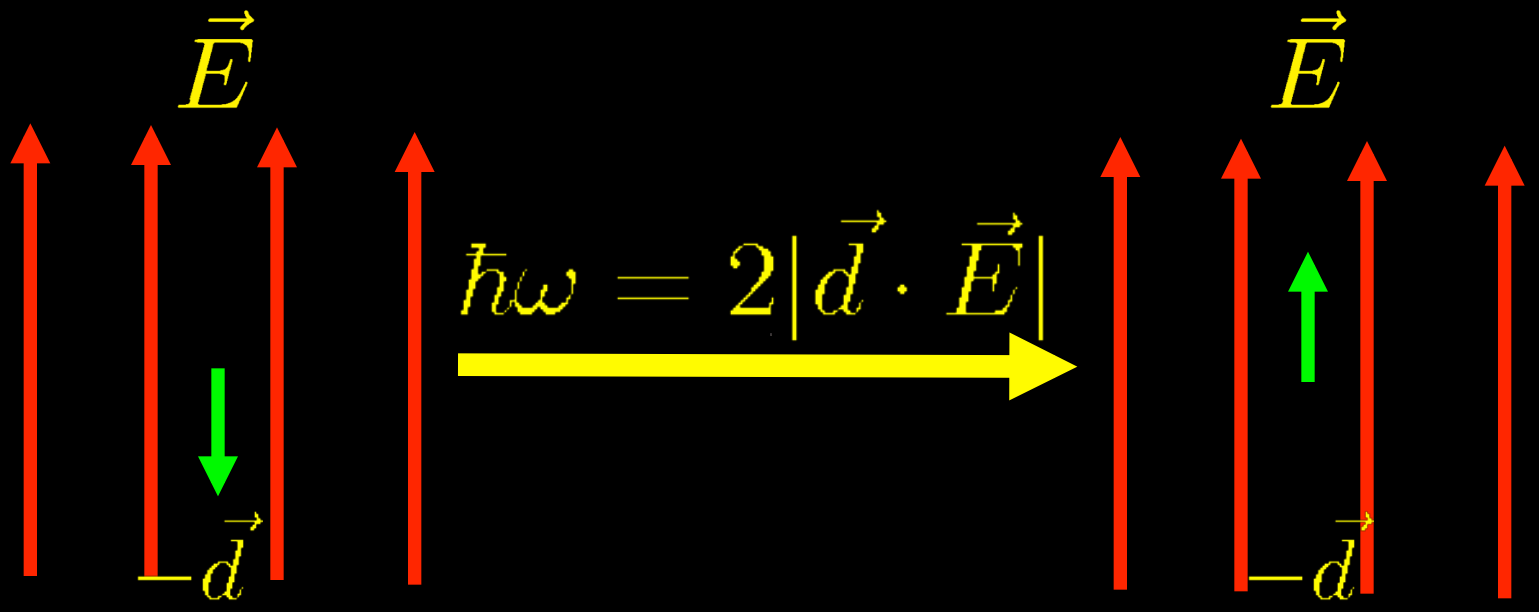
- θ would cause neutron EDM ➡ Experiment



➡ Measure transition frequency.

No neutron electric dipole moment...

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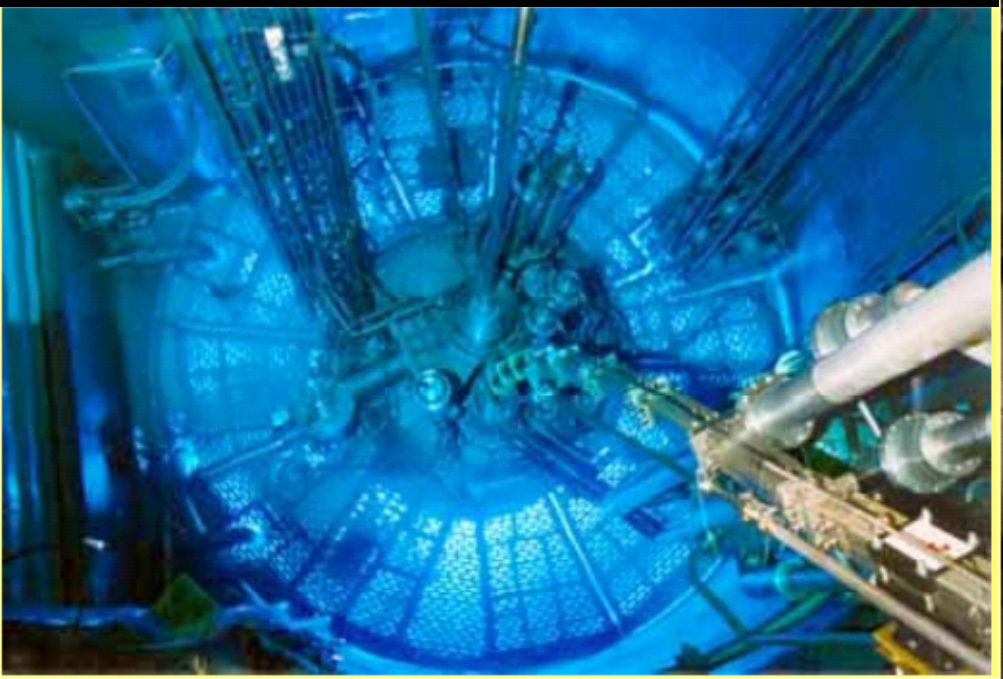

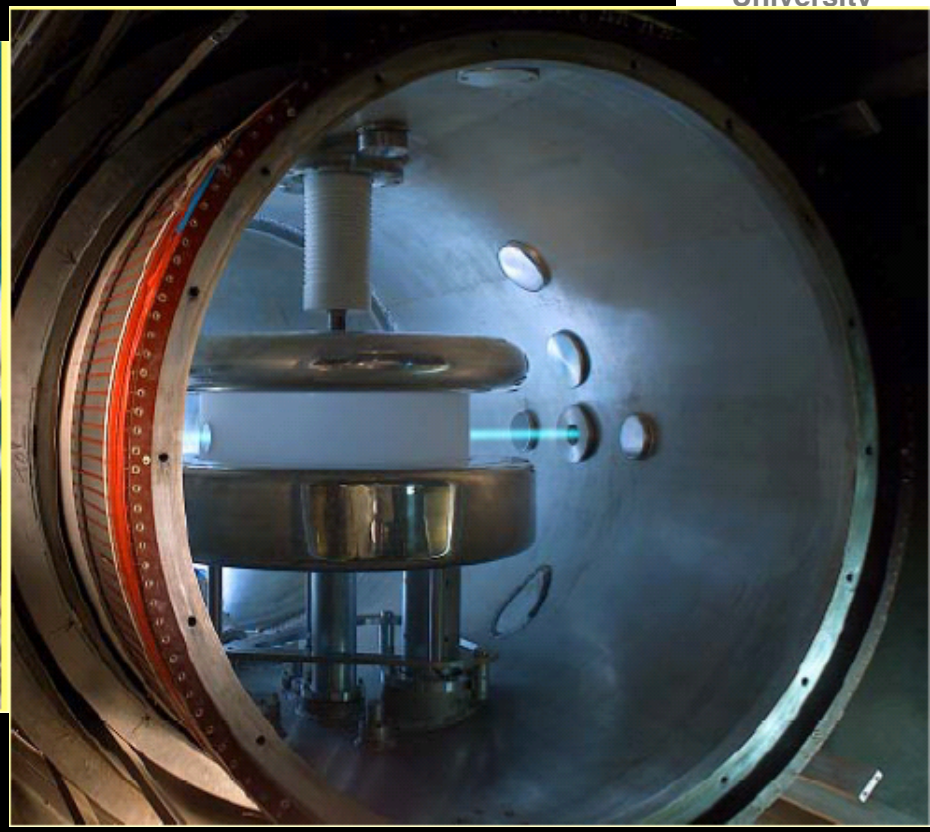

RAL-Sussex-ILL EDM collaboration

$$|\vec{d}| < 3\,10^{-26} e\,cm$$
$$= 3\,10^{-13} e\,fm$$

What do we expect?

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- Two mass scales in the game:

$$m_q \sim 1 - 10\,\mathrm{MeV}$$

$$\Lambda_{\mathrm{QCD}} \sim 300\,\mathrm{MeV}$$

$$d_n \sim e \times \mathrm{length} \times \theta \sim \mathrm{e} \times \frac{\mathrm{m_q}}{\Lambda^2_{\mathrm{QCD}}} \times \theta$$

$$\sim (1 - 10) \times 10^{-16}\, e\,\mathrm{cm}\,\theta$$

"Argument" EDM Blackboard

Implications

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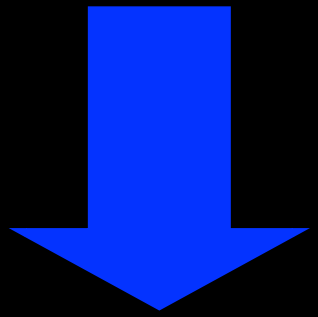
- Detailed calculation gives

$$|\vec{d}| \sim 1 - 10 \times 10^{-16} e\, cm\, \theta$$

$$\Rightarrow \quad |\theta| < 3\, 10^{-9}$$

$$\Rightarrow \quad \text{Extremely unnatural!}$$



Strong CP Problem

The axion solution
to the strong CP problem

In pictures…

The axion solution to the strong CP problem

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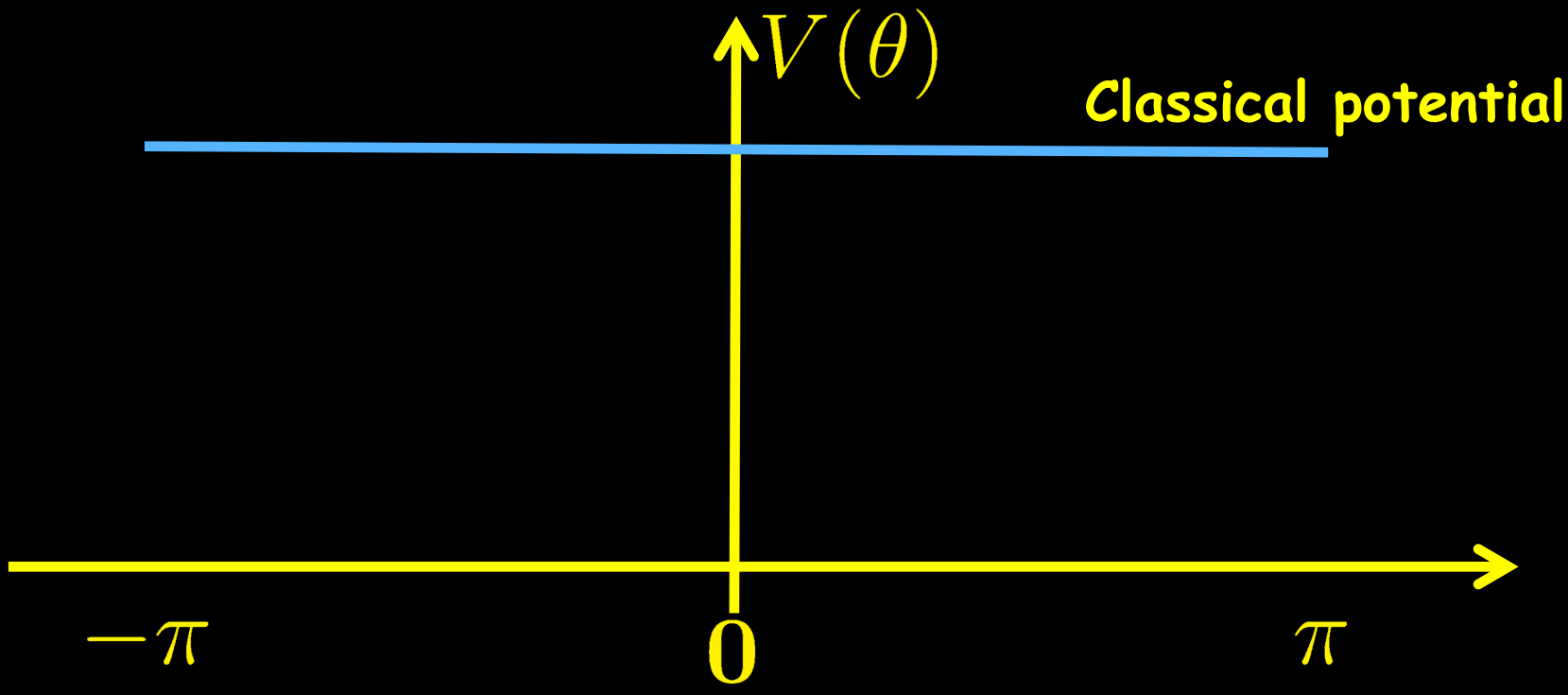
- Make θ dynamical ➔ it can change its value



The axion solution to the strong CP problem

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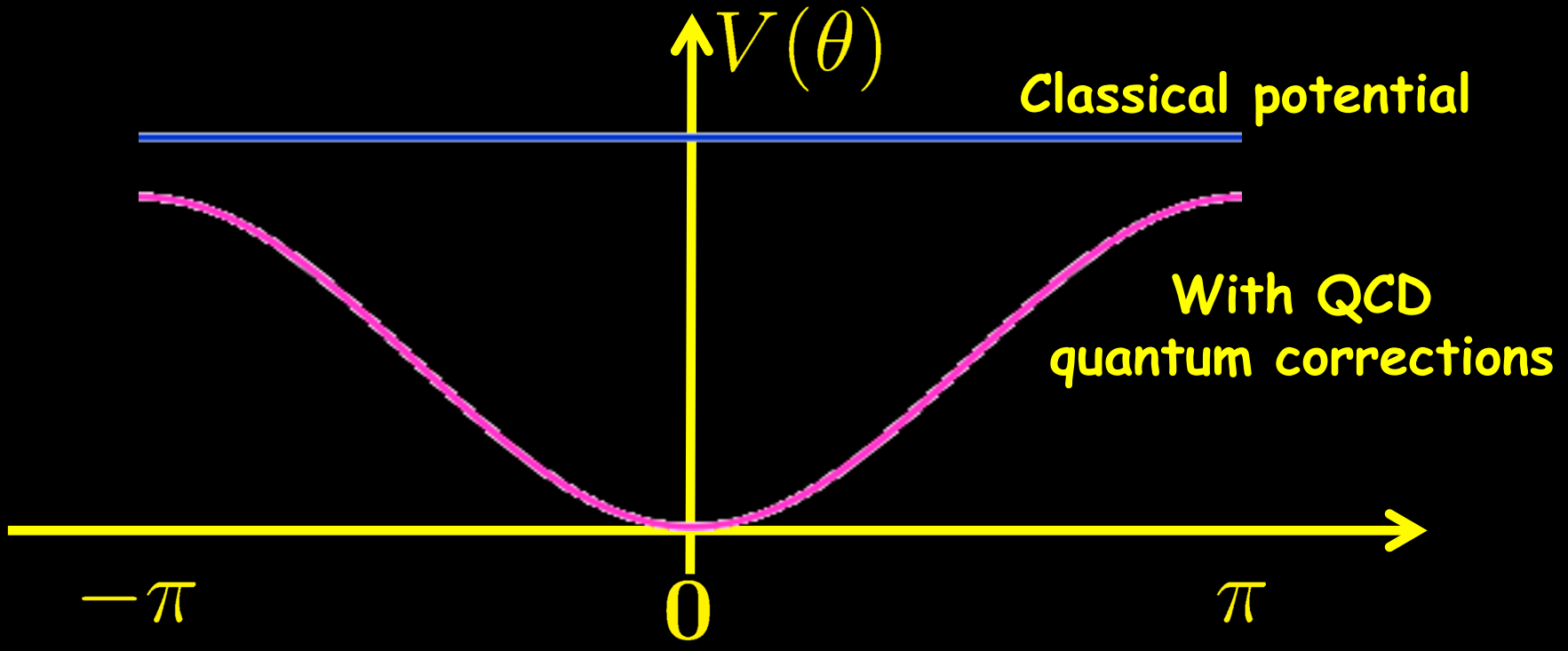

The axion solution to the strong CP problem

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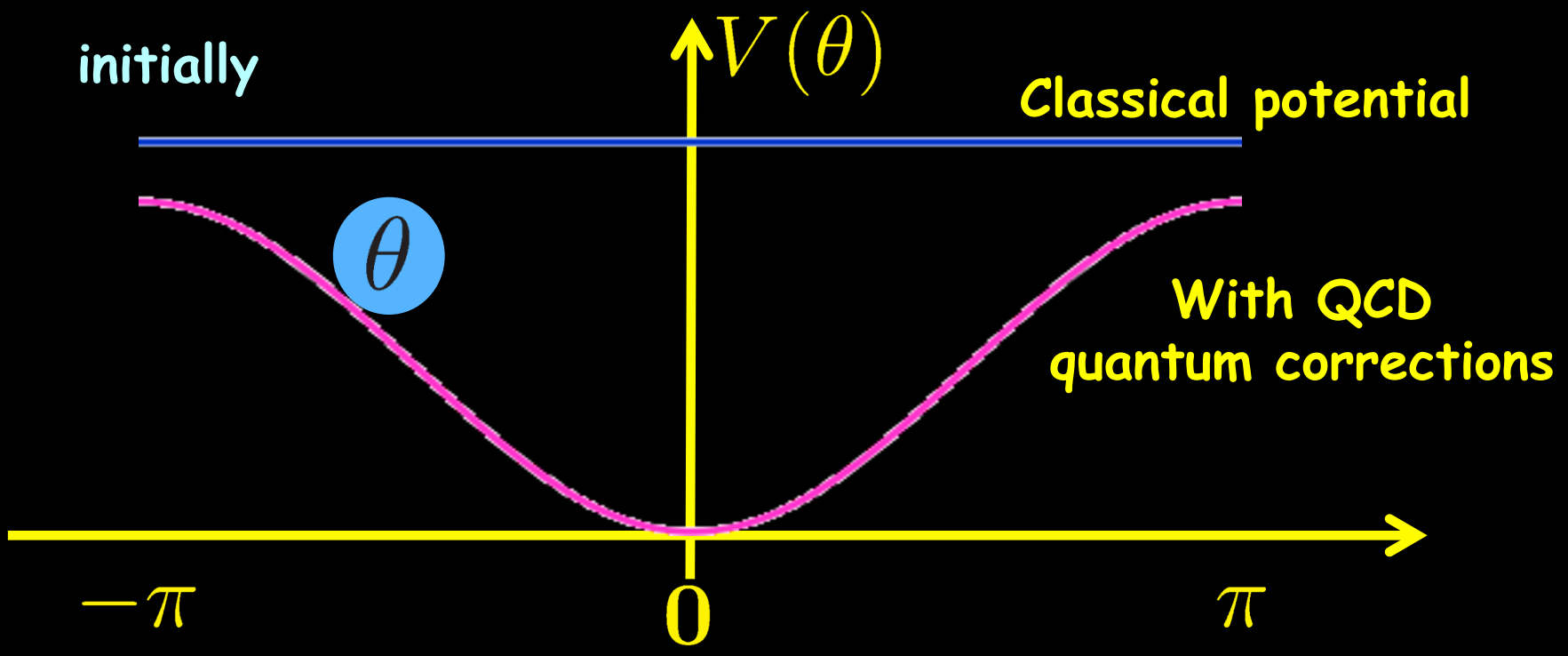

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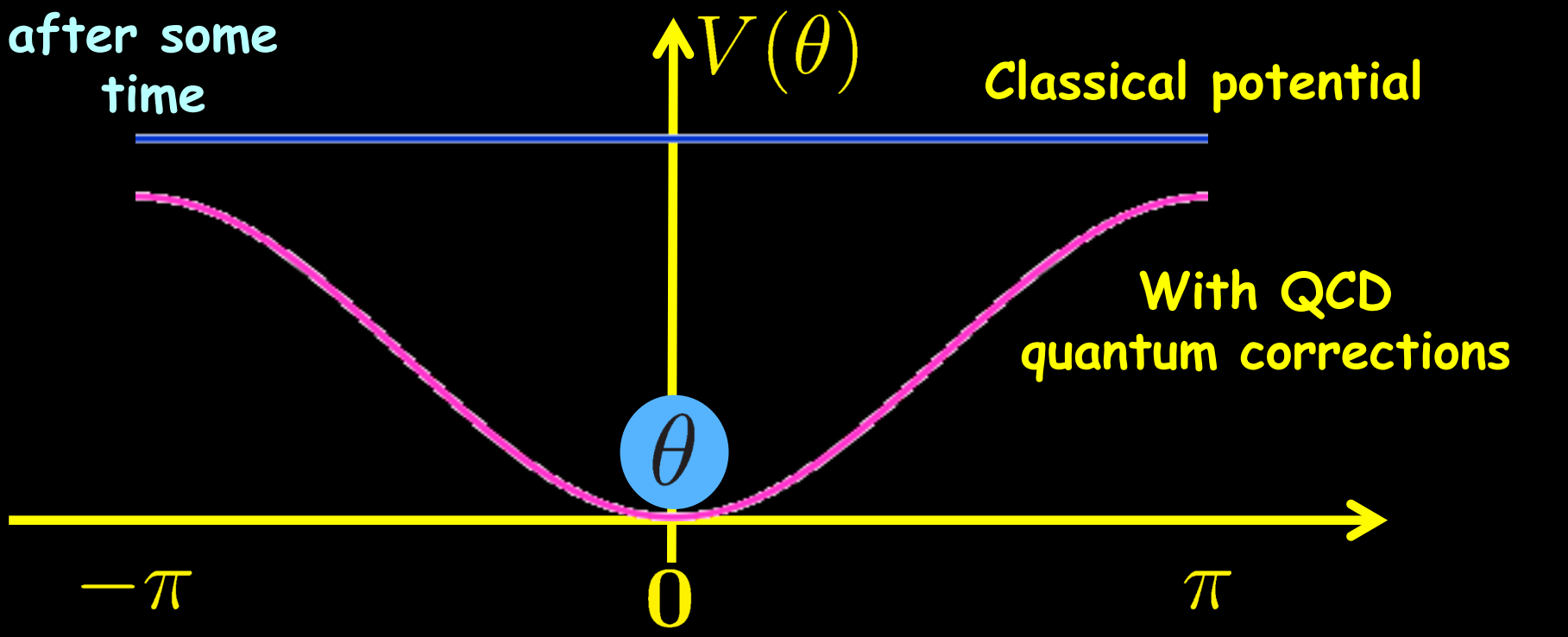

➔ QCD likes to be CP conserving (if we allow it)

The axion solution to the strong CP problem

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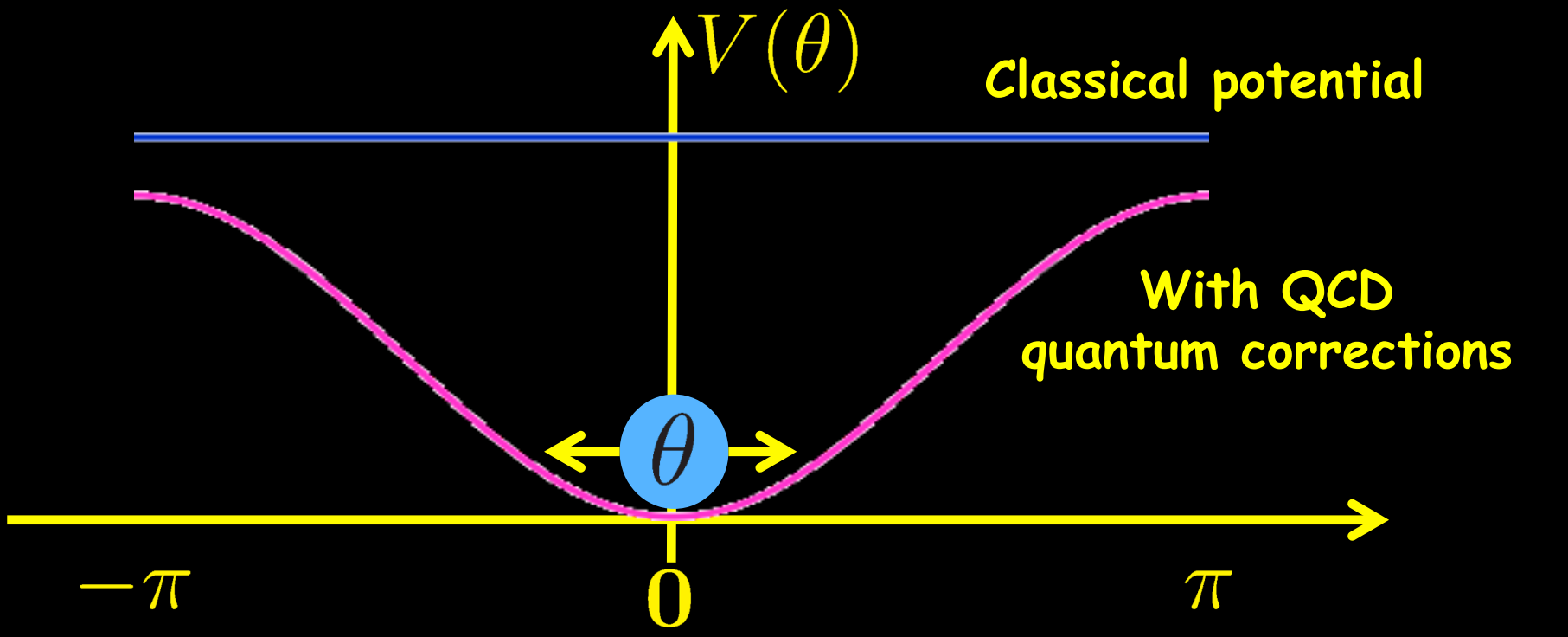
- Make θ dynamical ➔ it can change its value



➔ Can still move

➔ new particle = axion

Axions

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- Classical flatness from symmetry
- Quantum corrections are small
- New light particle: The Axion
  (it's a Weakly Interacting Sub-eV Particle)

Dark matter candidate

Good motivation
for axion/WISP experiments

In Equations…

A Dynamical θ

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- Idea:
  - Make θ a dynamical degree of freedom
  - Let θ have no tree level potential
  - Let θ have only derivative couplings
- Then:

$$\begin{aligned}
\exp\left(-\int_x V(\theta)\right) &= \left|\int \mathcal{D}A_\mu \exp\left(-S_{eff}[\phi, A^\mu]\right) \exp\left(-i\theta \frac{g^2}{32\pi^2}\int_x G^{\mu\nu}\tilde{G}_{\mu\nu}\right)\right| \\
&\leq \int \mathcal{D}A_\mu \left|\exp\left(-S_{eff}[\phi, A^\mu]\right) \exp\left(-i\theta \frac{g^2}{32\pi^2}\int_x G^{\mu\nu}\tilde{G}_{\mu\nu}\right)\right| \\
&\leq \int \mathcal{D}A_\mu \exp\left(-S_{eff}[\phi, A^\mu]\right) \\
&\leq \exp\left(-\int_x V[0]\right)
\end{aligned}$$

A Dynamical θ

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- Idea:
  - Make θ a dynamical degree of freedom a.
  - Let θ have no tree level potential
  - Let θ have only derivative couplings

- Canonically normalize $\theta = a/f_a$

$$\Rightarrow V[a/f_a = \theta = 0] \leq V[\theta] \;\; \forall\theta$$

$\Rightarrow \theta = a/f_a$ will evolve to $a = \theta = 0$

$\Rightarrow$ CP is conserved

What is a?

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- Properties:
  - Let a be a dynamical degree of freedom.
  - Let a have no tree level potential
  - Let a have only derivative couplings

  - $a/f_a \in [0, 2\pi]$ since

$$\frac{g^2}{32\pi^2}\int d^4x G_{\mu\nu}\tilde{G}^{\mu\nu} = n \in \mathbb{Z}$$

→ a is Goldstone boson of a U(1) symmetry → Axion!

Peccei-Quinn Symmetry

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- Toy model:

$$\mathcal{L} = -\frac{1}{4}F^2 + 1\bar{\psi}D_\mu\gamma^\mu\psi - |\partial_\mu\phi|^2 - \mu^2|\phi|^2 - \lambda|\phi|^4$$
$$+\bar{\psi}\left(Y\phi\frac{1+\gamma_5}{2} + Y^\star\phi^\star\frac{1-\gamma_5}{2}\right)\psi$$

- U(1): $\phi \rightarrow \exp(i\beta)\phi$

$$\psi \rightarrow \exp\left(-i\frac{\beta}{2}\gamma_5\right)\psi$$

- If $\mu^2<0$ we have SSB

➡ Phase is Goldstone ➡ Use it as Axion

The Coupling to $F\tilde{F}$ ($G\tilde{G}$ analog)

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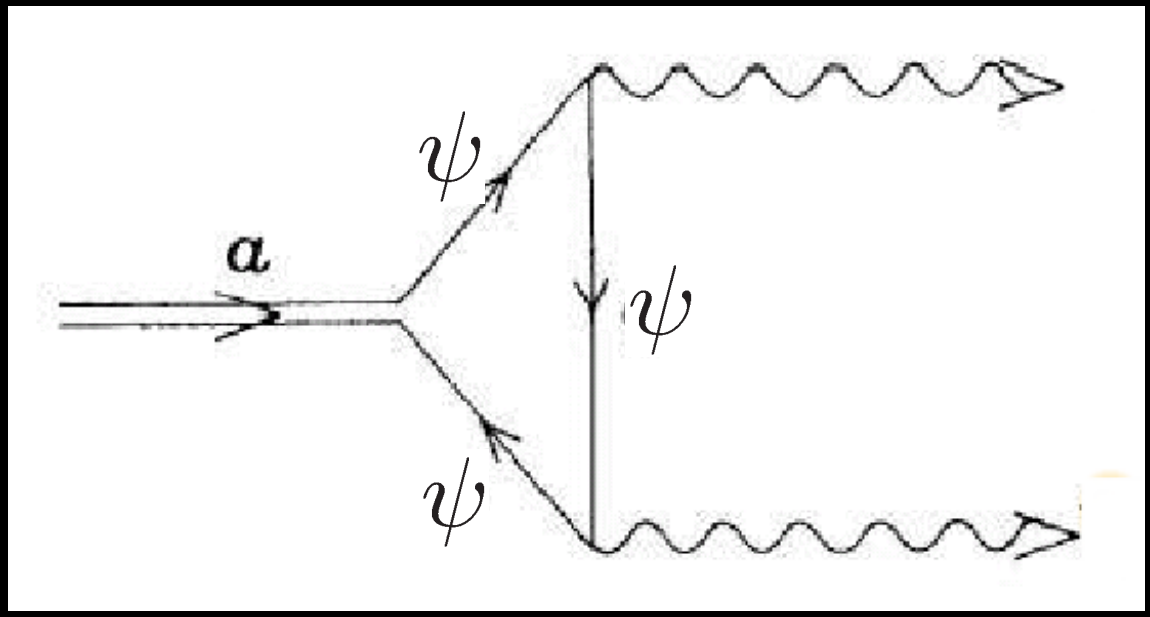
- A diagram



- And a dimensional argument:

$$g \sim \frac{1}{\text{mass}} \sim \frac{1}{f_a}$$

The Coupling to $F\tilde{F}$

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- **Adler-Bell-Jackiw anomaly**

$$\partial_\mu j^\mu = \frac{g^2}{16\pi^2} F^{\mu\nu}\tilde{F}_{\mu\nu}$$

- **Chiral rotations not a good symmetry: it is anomalous**

$$d\mu' = \mathcal{D}\psi'\mathcal{D}\bar{\psi}' = d\mu \exp\left(-\frac{i}{4}\int_x \frac{\beta}{2}\frac{e^2}{8\pi^2} Tr F^{\mu\nu}\tilde{F}_{\mu\nu}\right)$$

$$\psi' = \exp\left(-i\frac{\beta}{2}\gamma_5\right)\psi \qquad = \frac{a}{f_a}$$

The Coupling to $F\tilde{F}$

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- **Adler-Bell-Jackiw anomaly**

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$$\mathcal{L} \supset -\frac{1}{4}\frac{\alpha}{4\pi f_a} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

The mass of the Axion

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- $U(1)_{PQ}$ is not exact. It's anomalous!

➡ Goldstone ➡ Pseudogoldstone

- Dimensional considerations
  - SSB scale $\sim f_a$
  - Quark masses $\sim m_q$
  - QCD scale $\sim \Lambda_{\mathrm{QCD}} \sim f_\pi$

➡ PseudoGoldstone mass $m_a^2 = \dfrac{m_u m_d}{(m_u + m_d)^2} \dfrac{m_\pi^2 f_\pi^2}{f_a^2}$

One can actually calculate the potential

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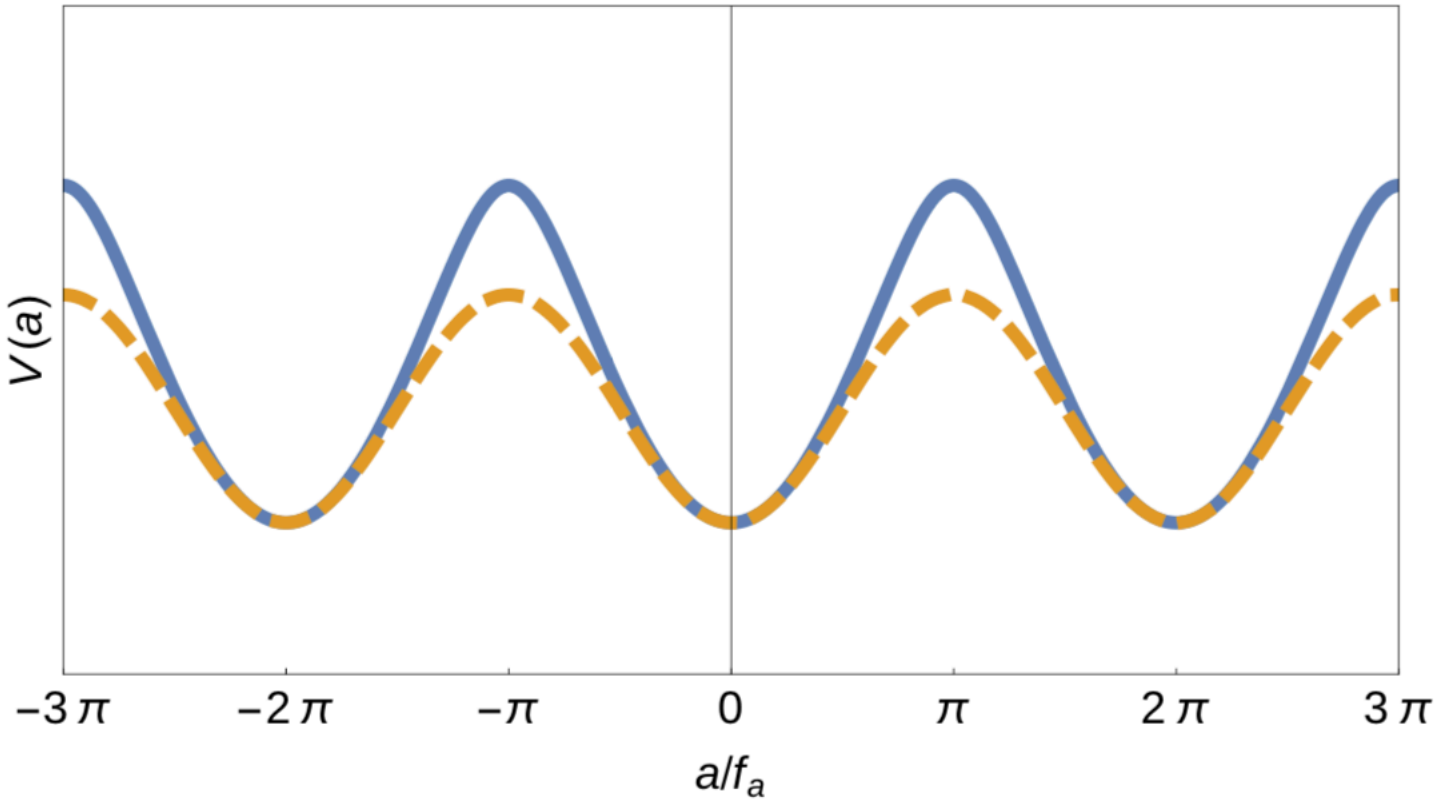
$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a}\right)}$$

The QCD axion, precisely

Giovanni Grilli di Cortona[a], Edward Hardy[b], Javier Pardo Vega[a,b] and Giovanni Villadoro[b]



"Argument"
Topological Suszeptibility

The ``topological'' axion mass

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$$\frac{d^2}{d\theta^2}\exp\left(-\int_x V(\theta)\right) = \frac{d^2}{d\theta^2}\exp\left(-V(\theta)\mathcal{V}\right)$$
$$= \left(-V''(\theta)\mathcal{V} + (V'(\theta)\mathcal{V})^2\right)\exp(-V(\theta)\mathcal{V})$$

➔ Evaluate at a=0 (minimum)
normalize V(0)=0

$$= -V''(\theta)\mathcal{V}$$
$$= -m_a^2 f_a^2 \mathcal{V}$$

The axion mass

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$$\exp\left(-\int_x V(\theta)\right) = \int \mathcal{D}A_\mu \exp\left(-S_{eff}[\phi, A^\mu]\right) \exp\left(-i\theta \frac{g^2}{32\pi^2} \int_x G^{\mu\nu}\tilde{G}_{\mu\nu}\right)$$
$$= \int \mathcal{D}A_\mu \exp\left(-S_{eff}[\phi, A^\mu]\right) \exp\left(-i\theta Q\right)$$

$$\frac{d^2}{d\theta^2} \exp\left(-\int_x V(\theta)\right) = \int \mathcal{D}A_\mu (-iQ)^2 \exp\left(-S_{eff}[\phi, A^\mu]\right) \exp\left(-i\theta Q\right)$$
$$= -\langle Q^2 \rangle$$
$$= -\mathcal{V}\chi_{top}$$

➔ $m_a^2 f_a^2 = -\chi_{top}$

Axion-like Particles

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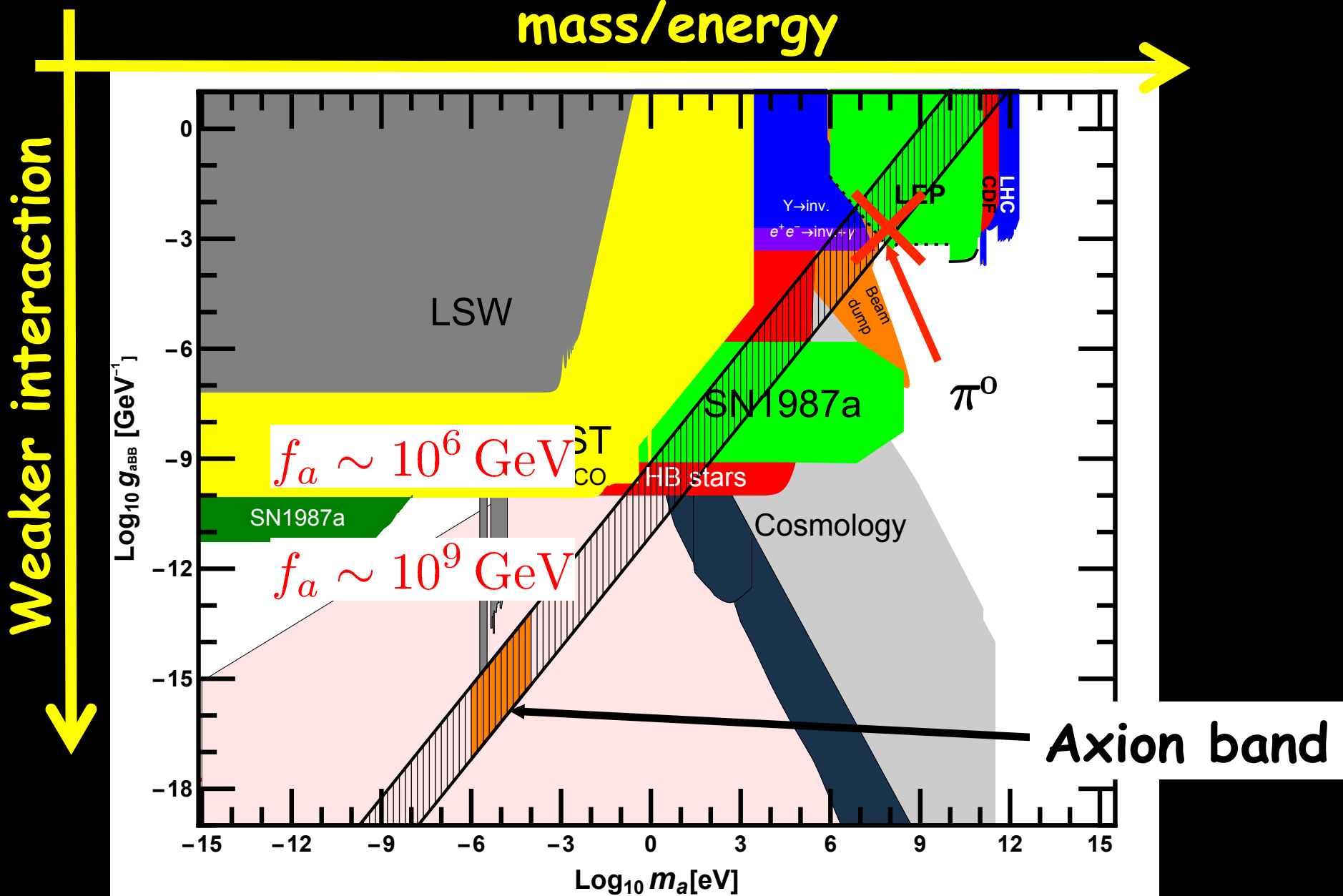

How to find the Axion…

Exploring fundamental high energy physics…

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- The direct approach: MORE POWER

LHC, Tevatron + ILC,CLIC

- Detects most things within energy range
- E.g. may find SUSY particles, WIMPs etc.

But…

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- May miss very weakly interacting matter (Axions, WIMPs, WISPs…)
- Current maximal energy few TeV

- Man it's DANGEROUS…

But…

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- May miss very weakly interacting matter (Axions, WIMPs, WISPs…)
- Current maximal energy few TeV

- Or much much more horrifying:

No signal above background!

The Power of Low Energy Experiments

Complementary approaches

Light shining through walls

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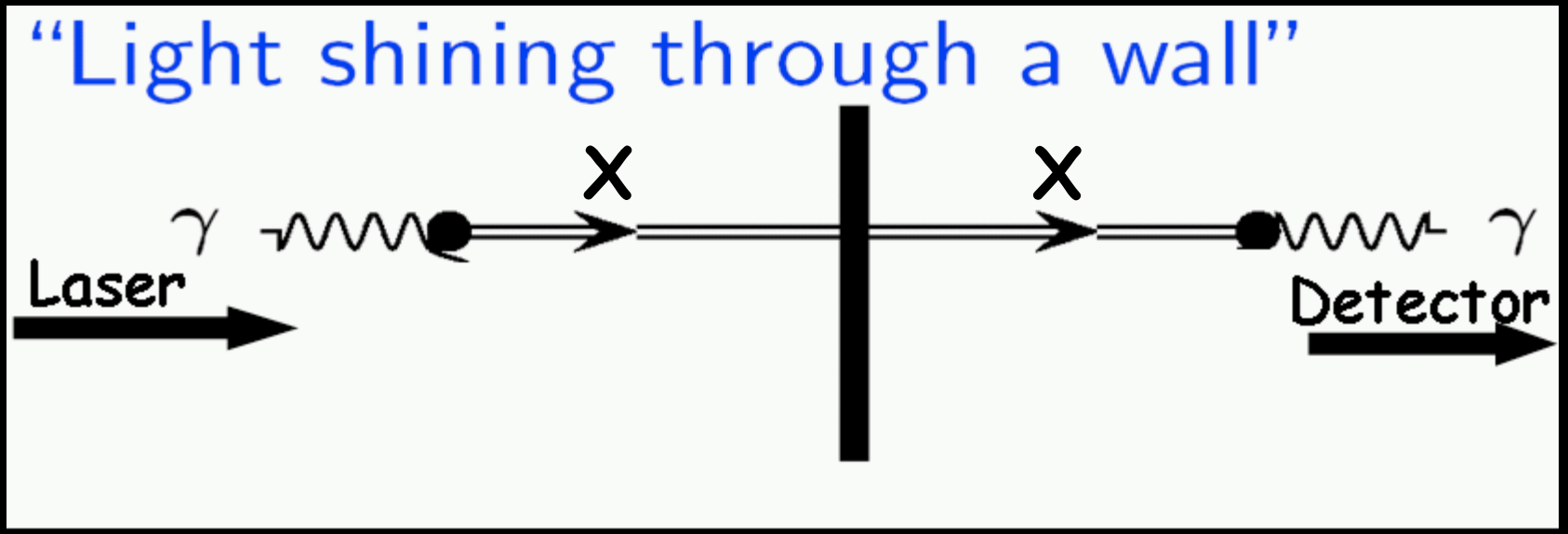

Light shining through walls

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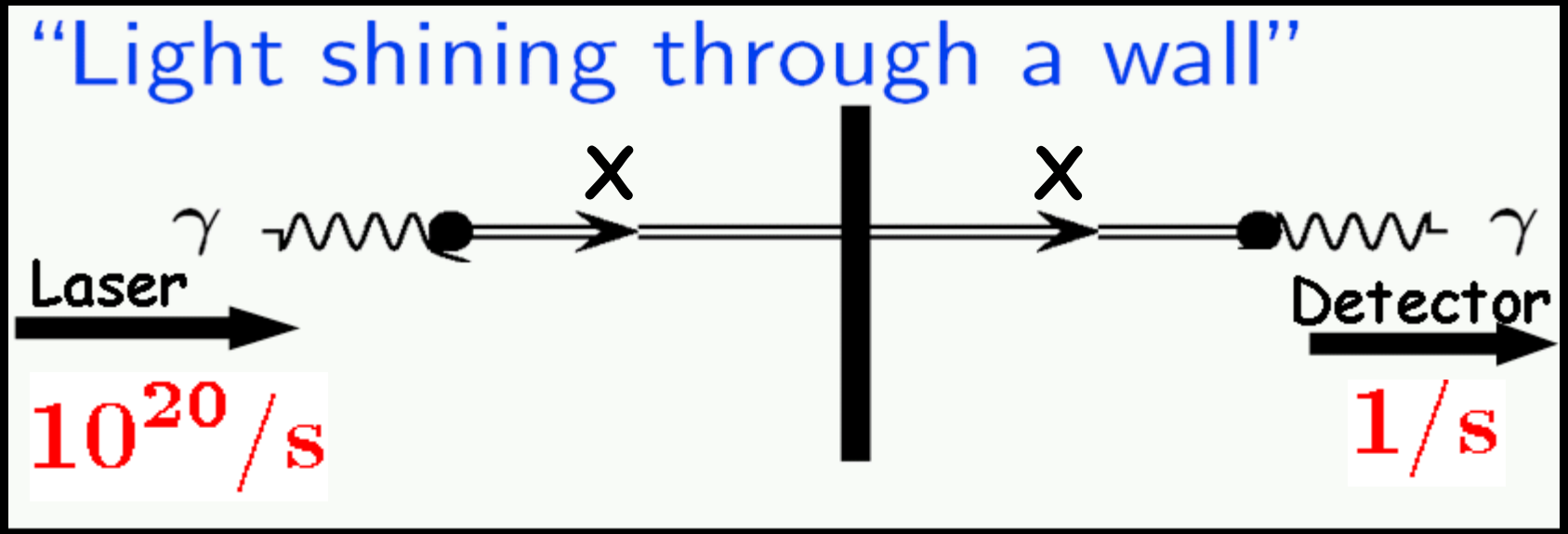

- Test $P_{\gamma\to X\to\gamma} \lesssim 10^{-20}$

- Enormous precision!
- Study extremely weak couplings!

Photons coming through the wall!

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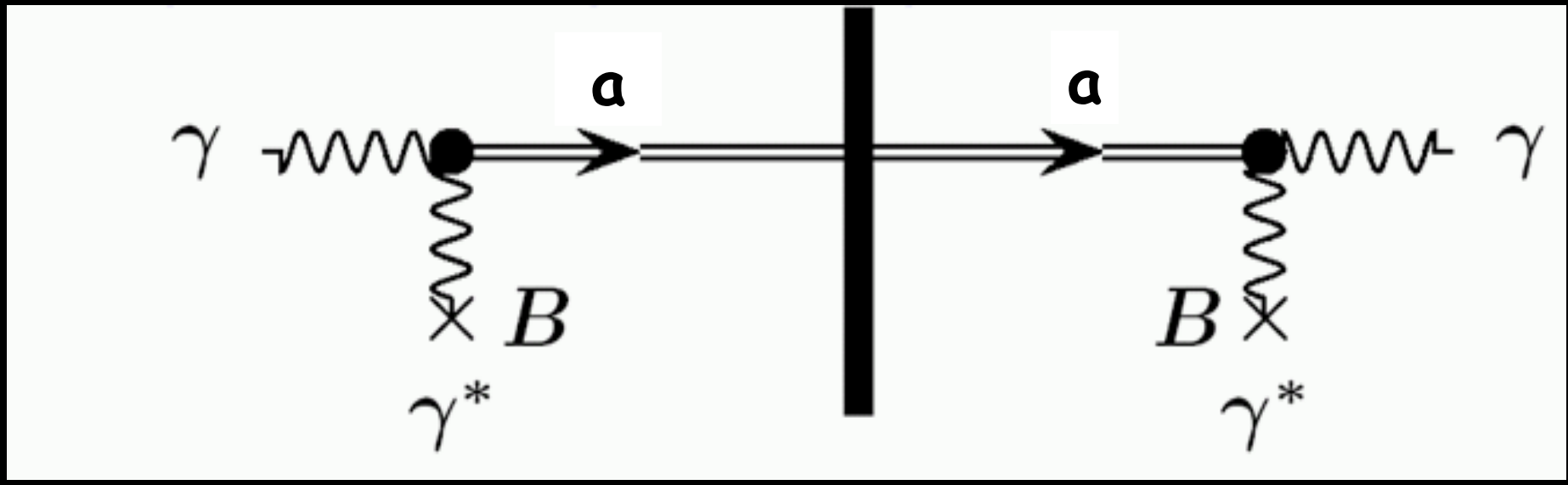
- It could be Axion(-like particle)s!
- Coupling to two photons: $\frac{1}{M} a \tilde{F} F \sim \frac{1}{M} a \vec{E} \cdot \vec{B}$



$$P_{\gamma \to a \to \gamma} \sim N_{\text{pass}} \left(\frac{BL}{M} \right)^4$$

Light Shining Through Walls

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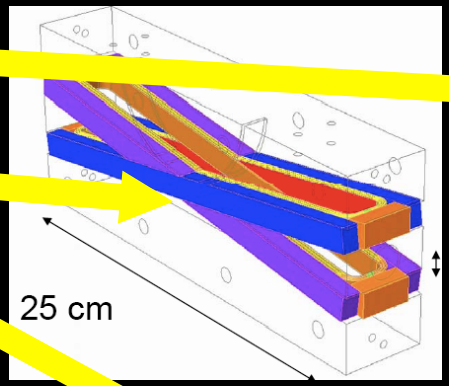
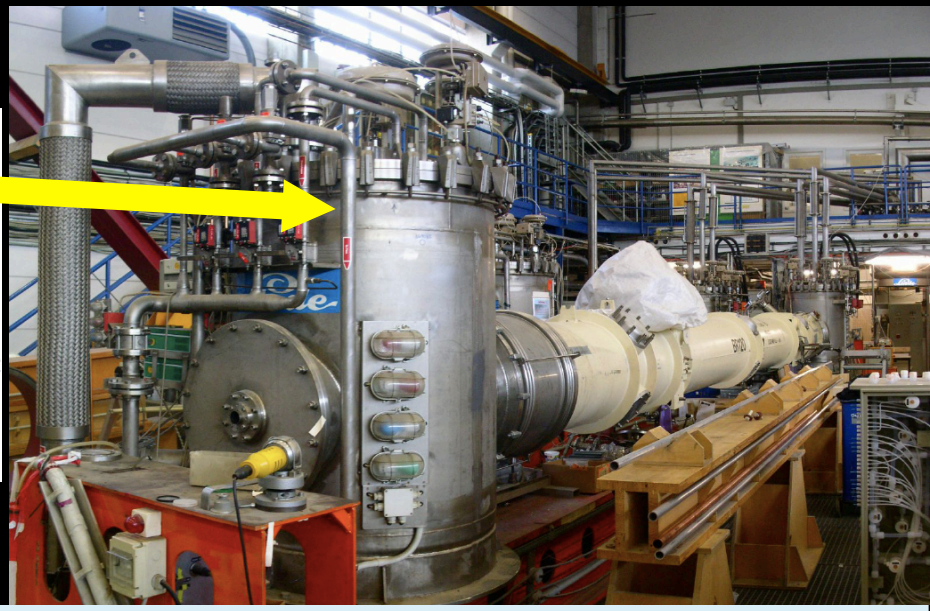
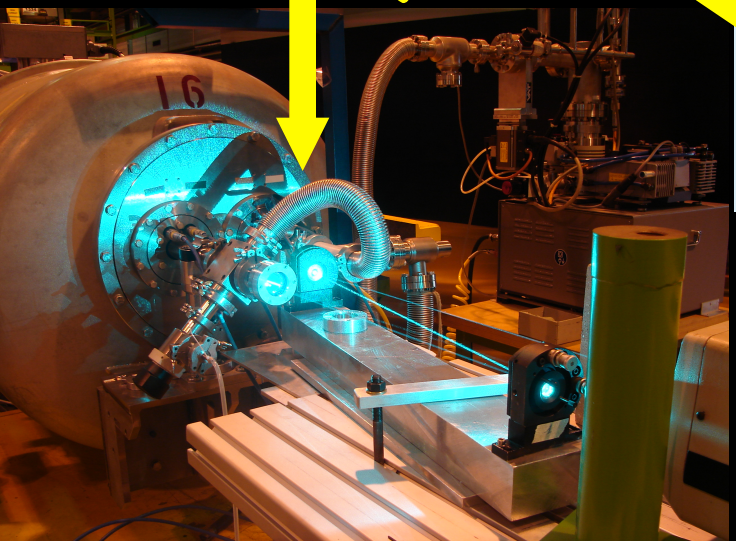
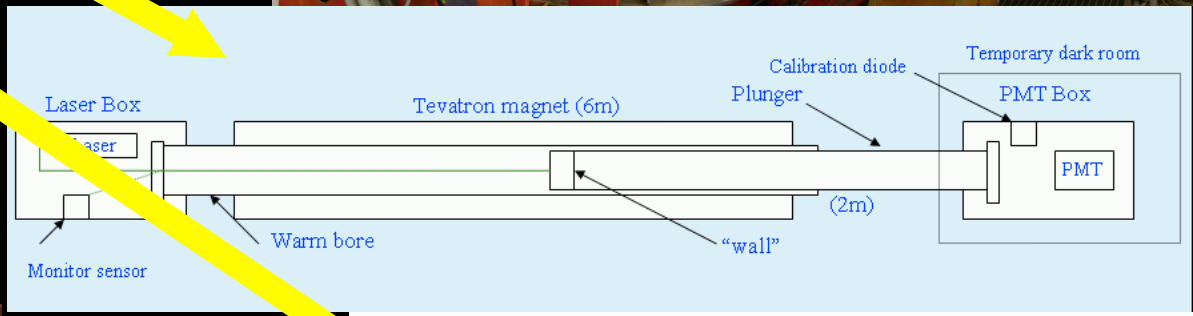
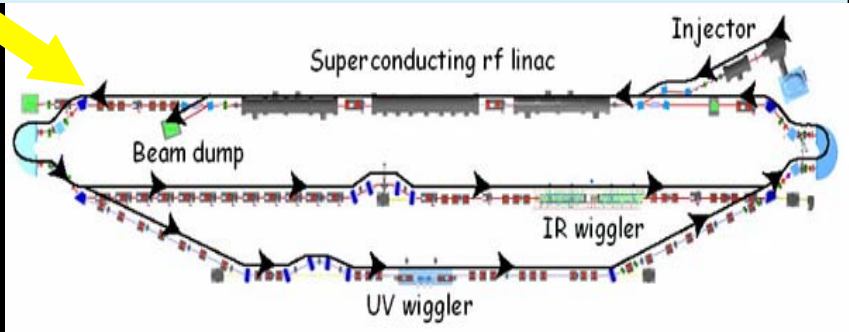
- A lot of activity
  - ALPS
  - BMV
  - GammeV
  - LIPPS
  - OSQAR











Small coupling, small mass

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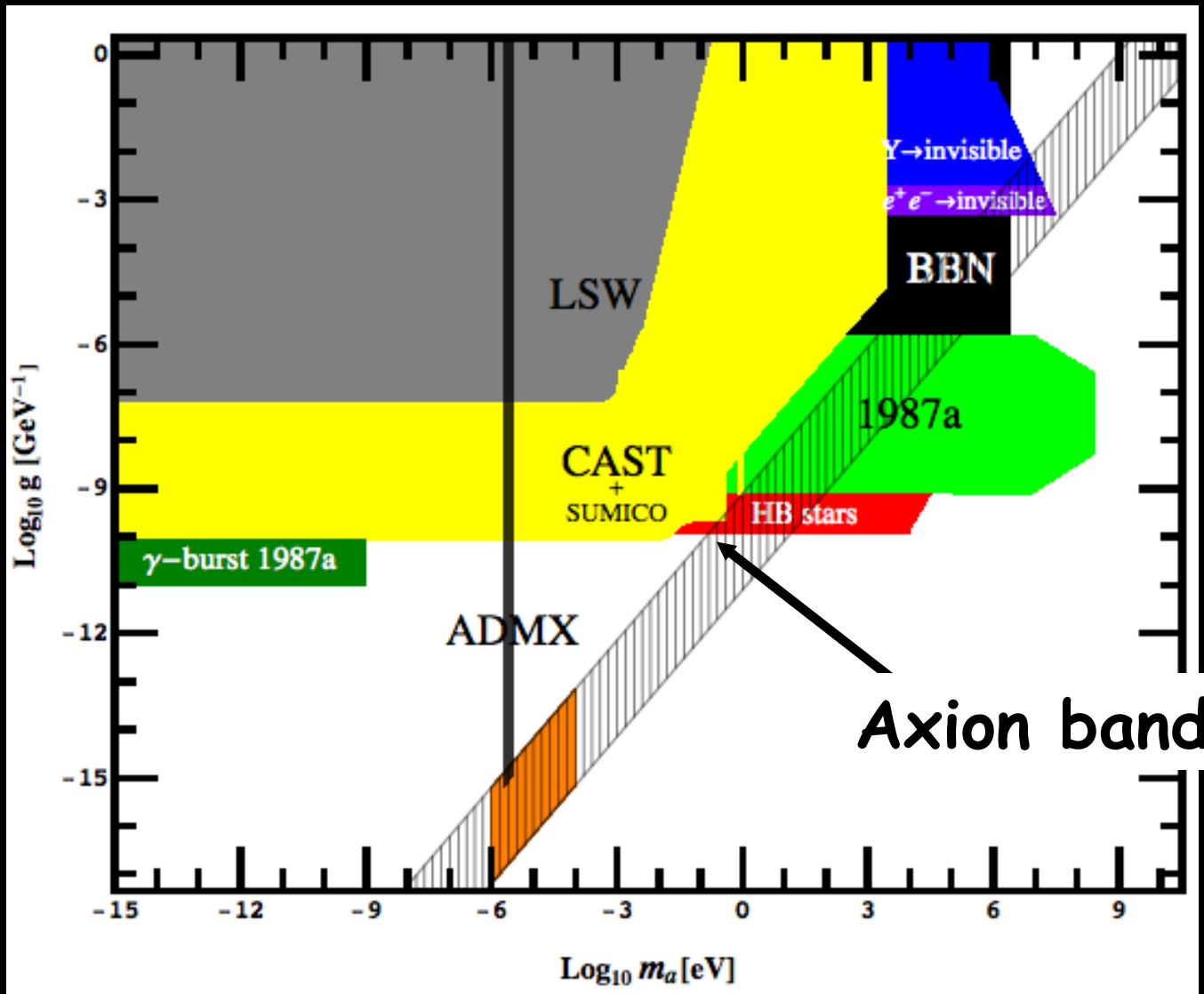
mass/energy

Weaker interaction



Interlude:
Think and make life hard for experimentalists…

Energy loss in stars.

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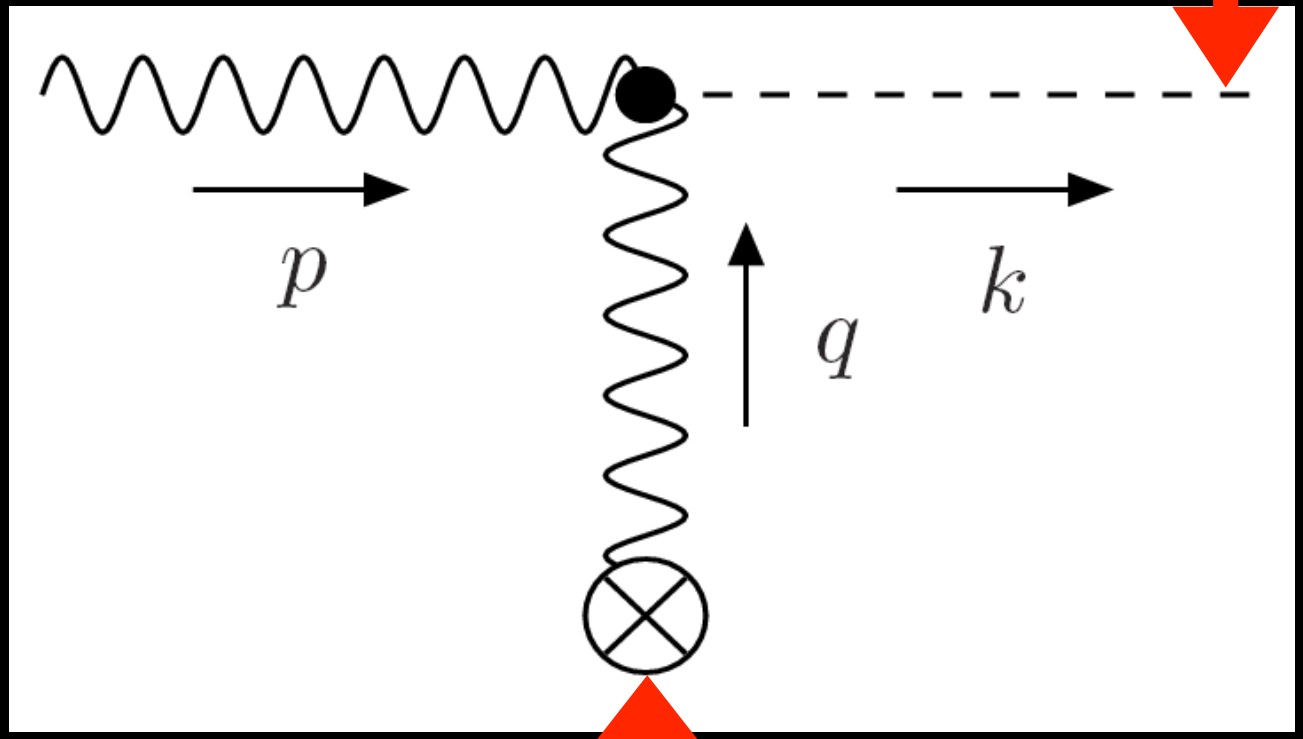
- Primakoff process (in the sun)

ALP (leaving the sun)



Photon (plasma)

Ion or electron

We would freeze...

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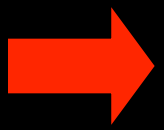
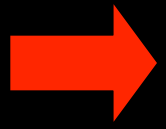
- If the coupling g is too large the sun would have died long ago.
- Why?

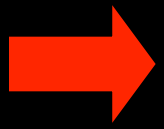
  Axions can leave the sun without further interaction (in contrast to photons)



Large energy loss from axion emission



Sun burns fuel faster



Sun would have died long ago

A (Very) Moderate Bound

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- Without ALPs sun has fuel for about 10^{10} years
- Energy loss via ALPs:

- Sun Lifetime with ALPs

$$L_a \approx 1.7\,10^9 (g\,10^4 \mathrm{GeV})^2 L_\gamma$$

- Pretty sure sun has been around for more than 10 years

$$t_{sun} \sim 10\,years \times (g\,10^4 \mathrm{GeV})^{-2}$$

$$\Rightarrow \quad g \leq 10^{-4} \mathrm{GeV}^{-1}$$

A Real killer bound

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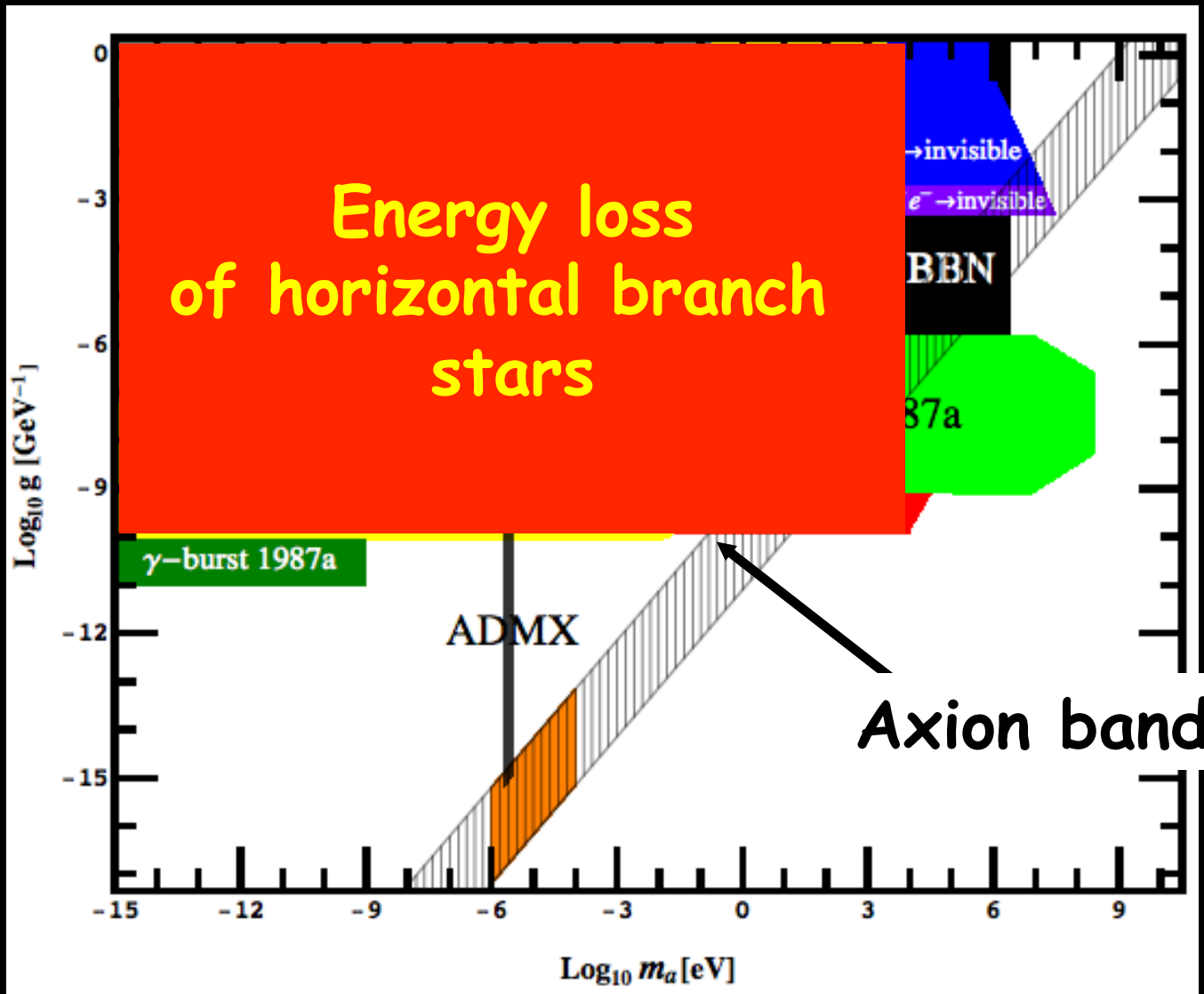
mass/energy

Weaker interaction



Back to experiments…

Helioscopes

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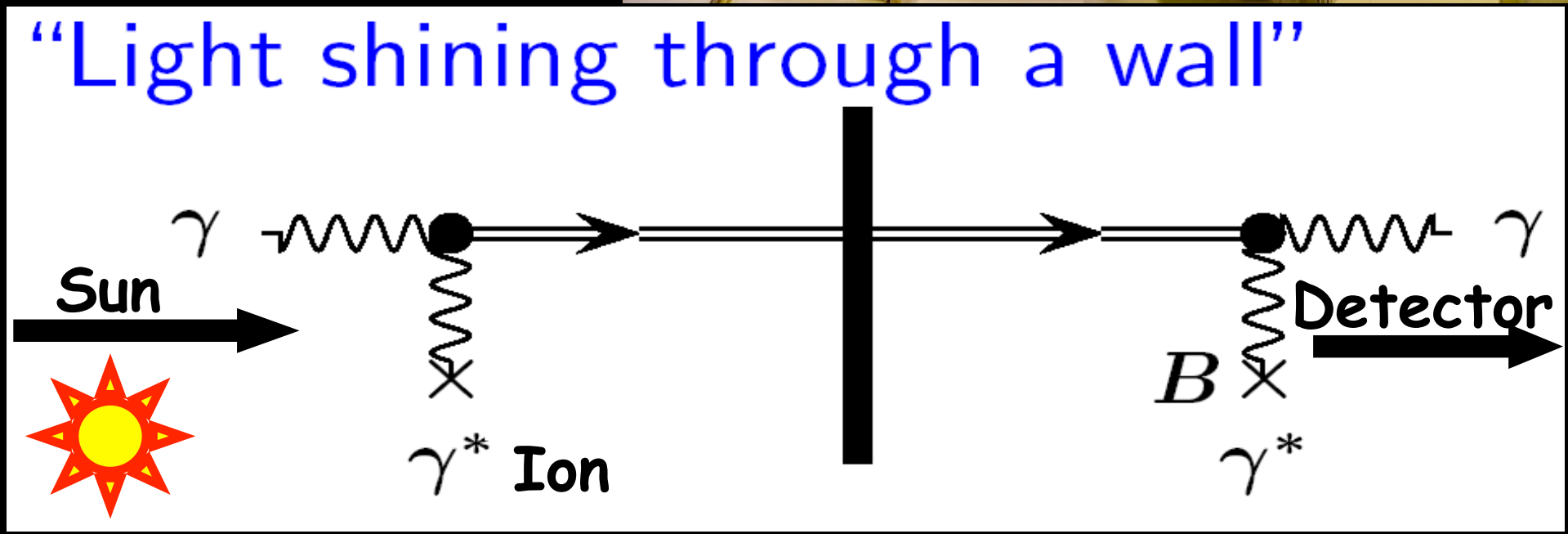
CAST@CERN
SUMICO@Tokyo

SHIPS@Hamburg



Sensitivity

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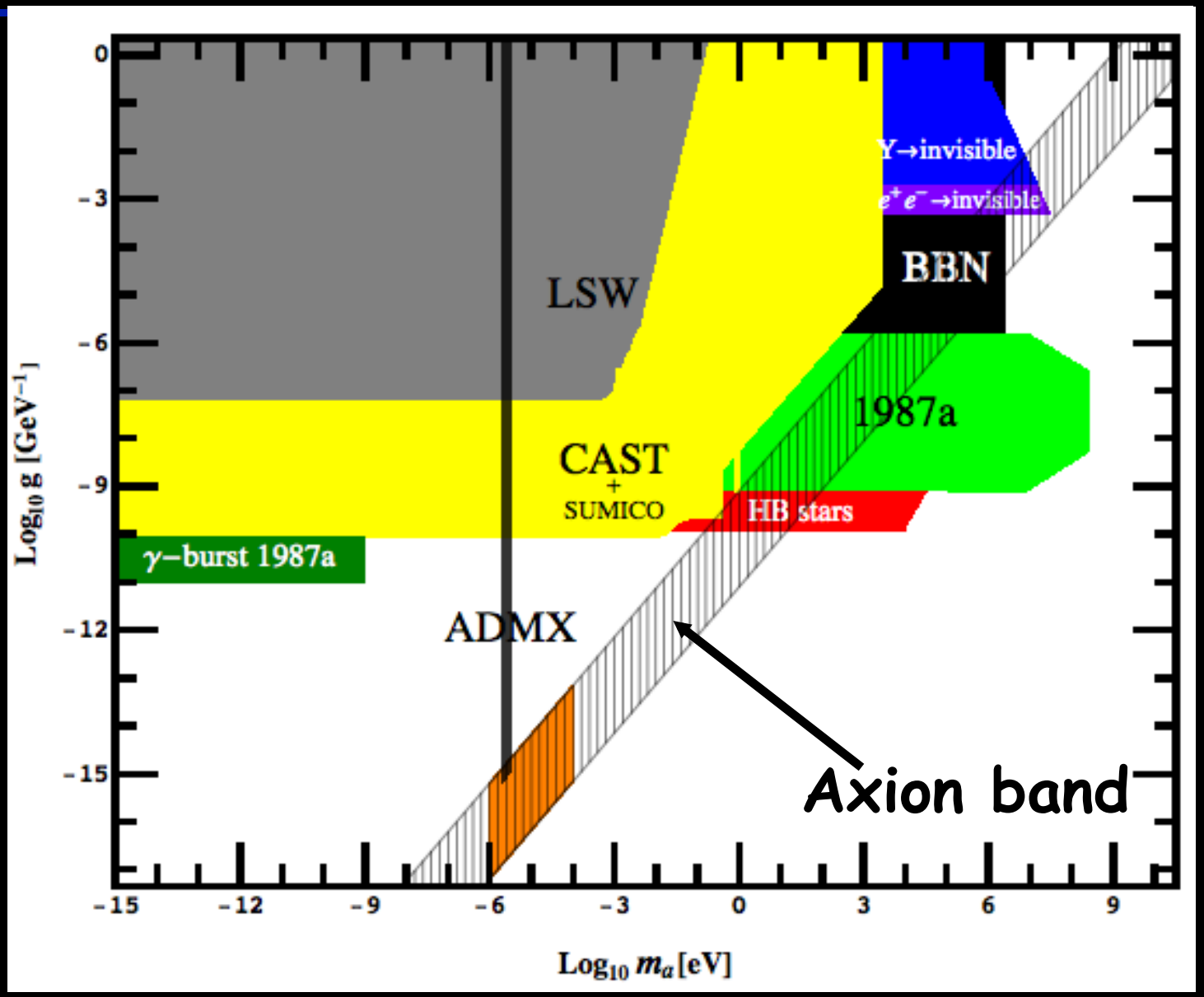

Going to the future: IAXO

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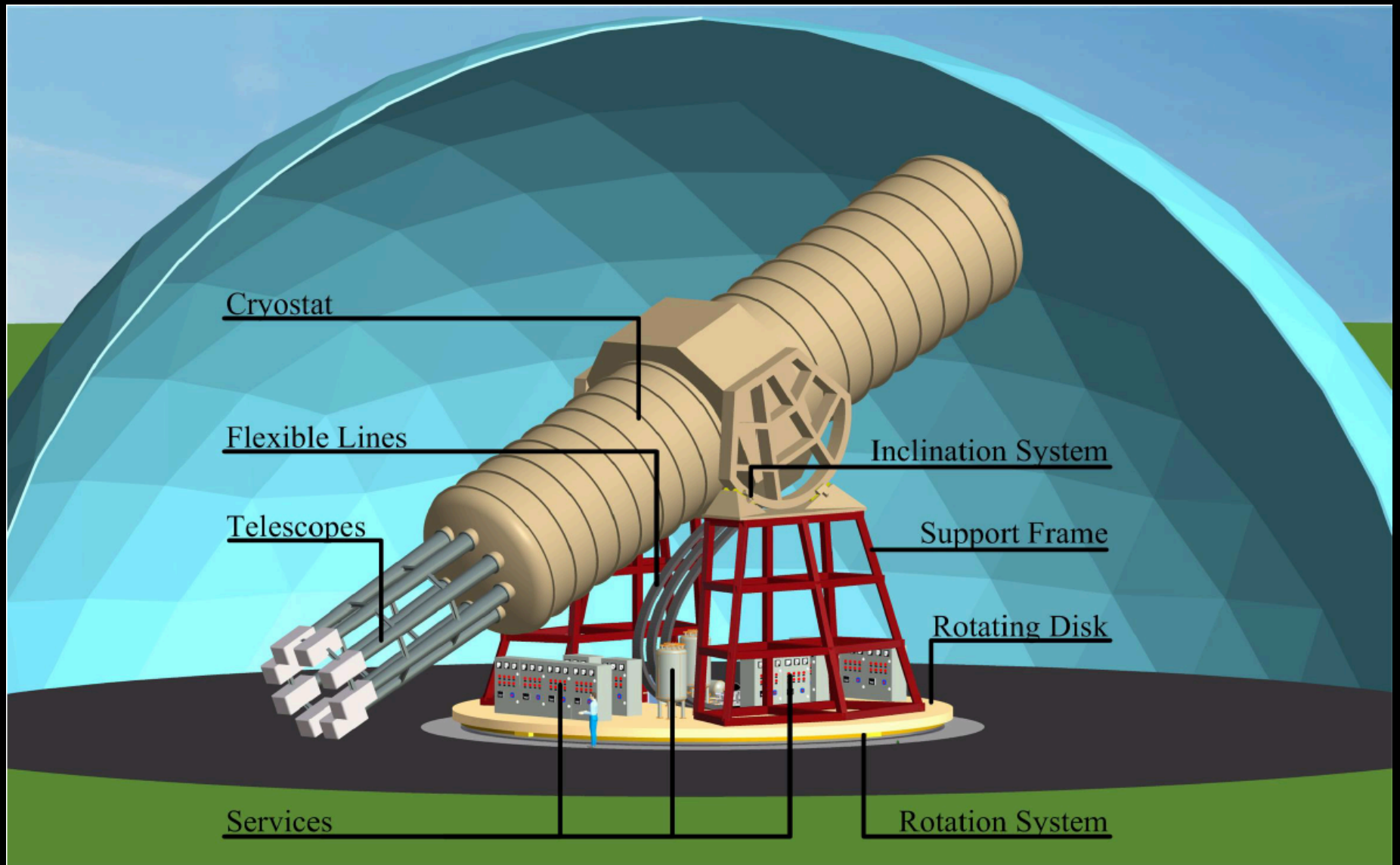
The International Axion Observatory



An interesting area…

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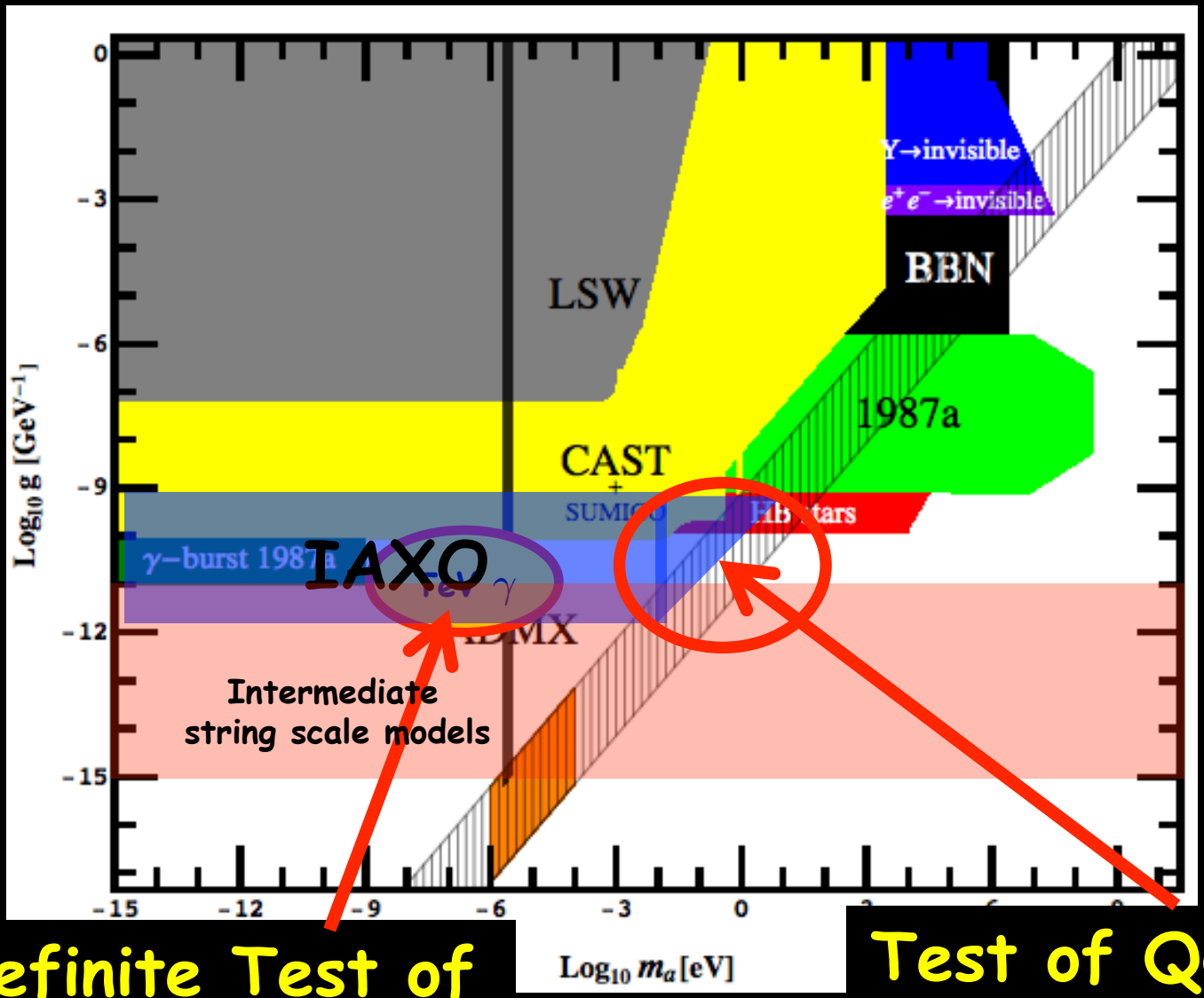

Definite Test of TeV transparency

Test of QCD axion
+ white dwarf anomaly

WISPS=Weakly interacting sub-eV particles

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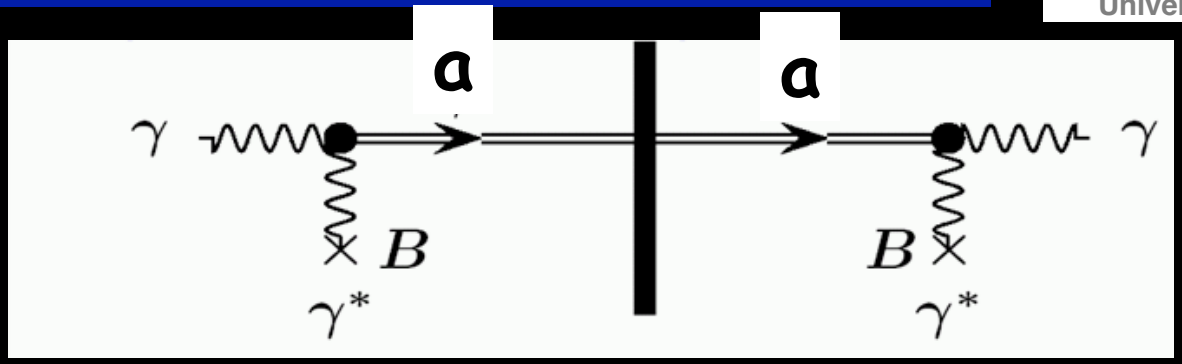
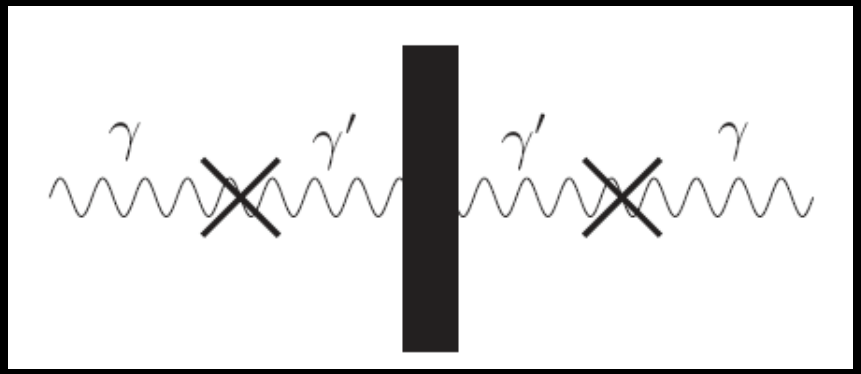
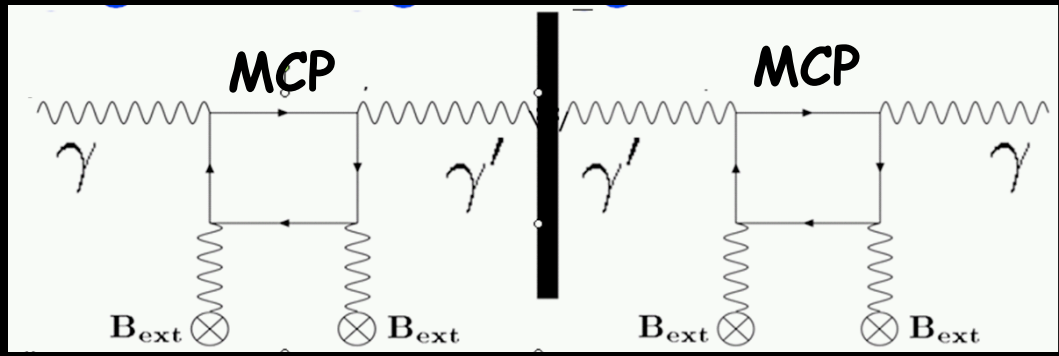
- Axions



- Massive hidden photons (without B-field) =analog ν-oscillations



- Hidden photon + minicharged particle (MCP)



Axions and ALPs
from
String Theory

String theory

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- Attempt to unify SM with gravity
- New concept: strings instead of point particles

String theory: Moduli and Axions

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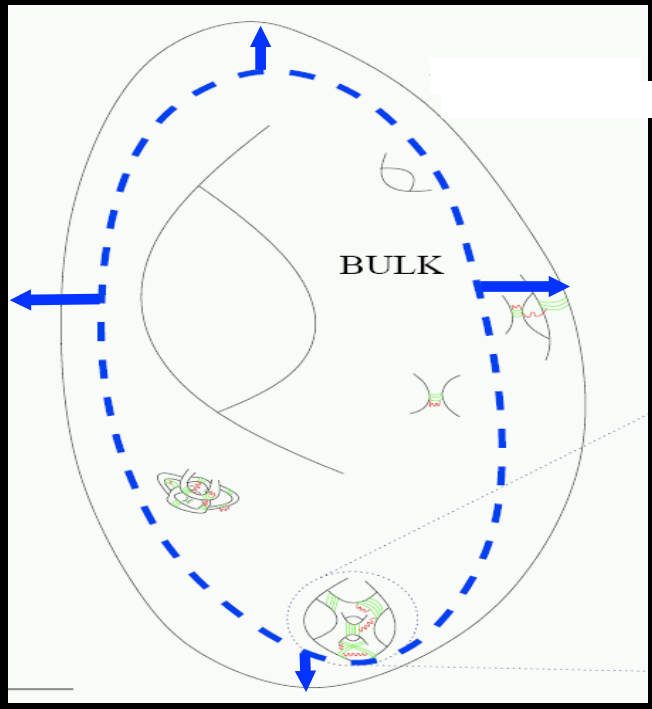
- String theory needs Extra Dimensions

↓

Must compactify

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



↓

Axion/ALP candidates

Axion (like particles): Where are we?

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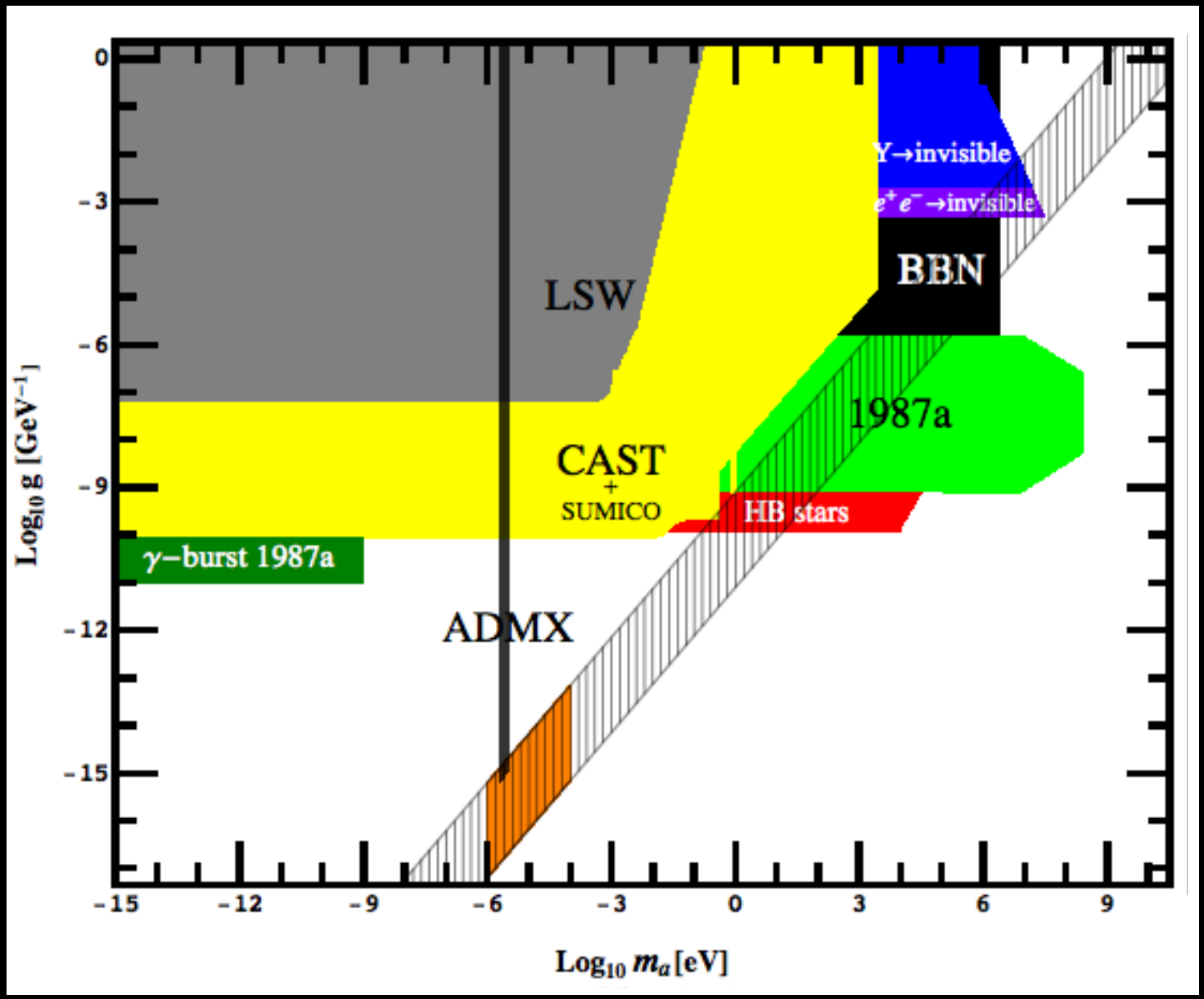

Axions and Moduli

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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): Where are we?

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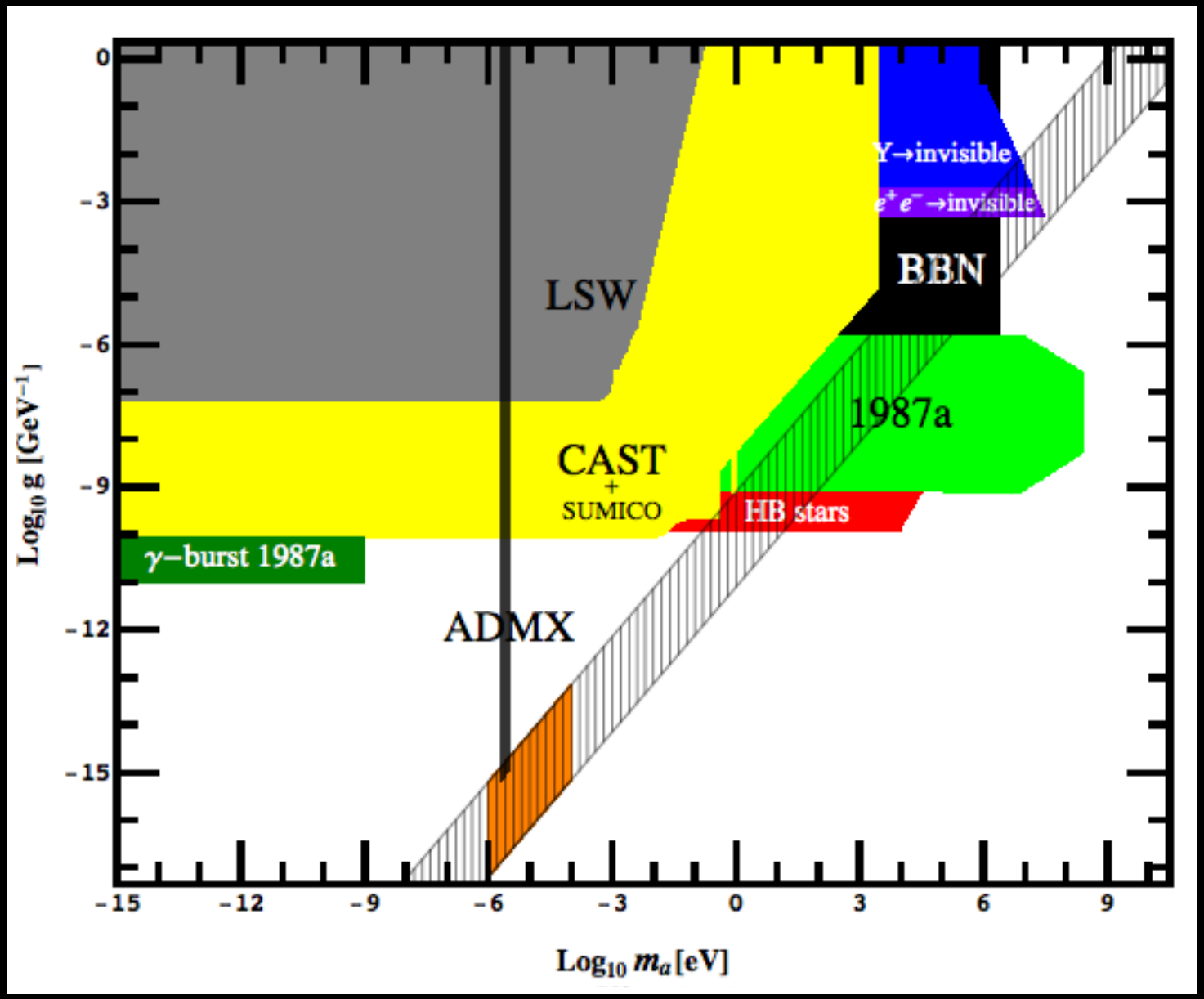

Axion (like particles): Where are we?

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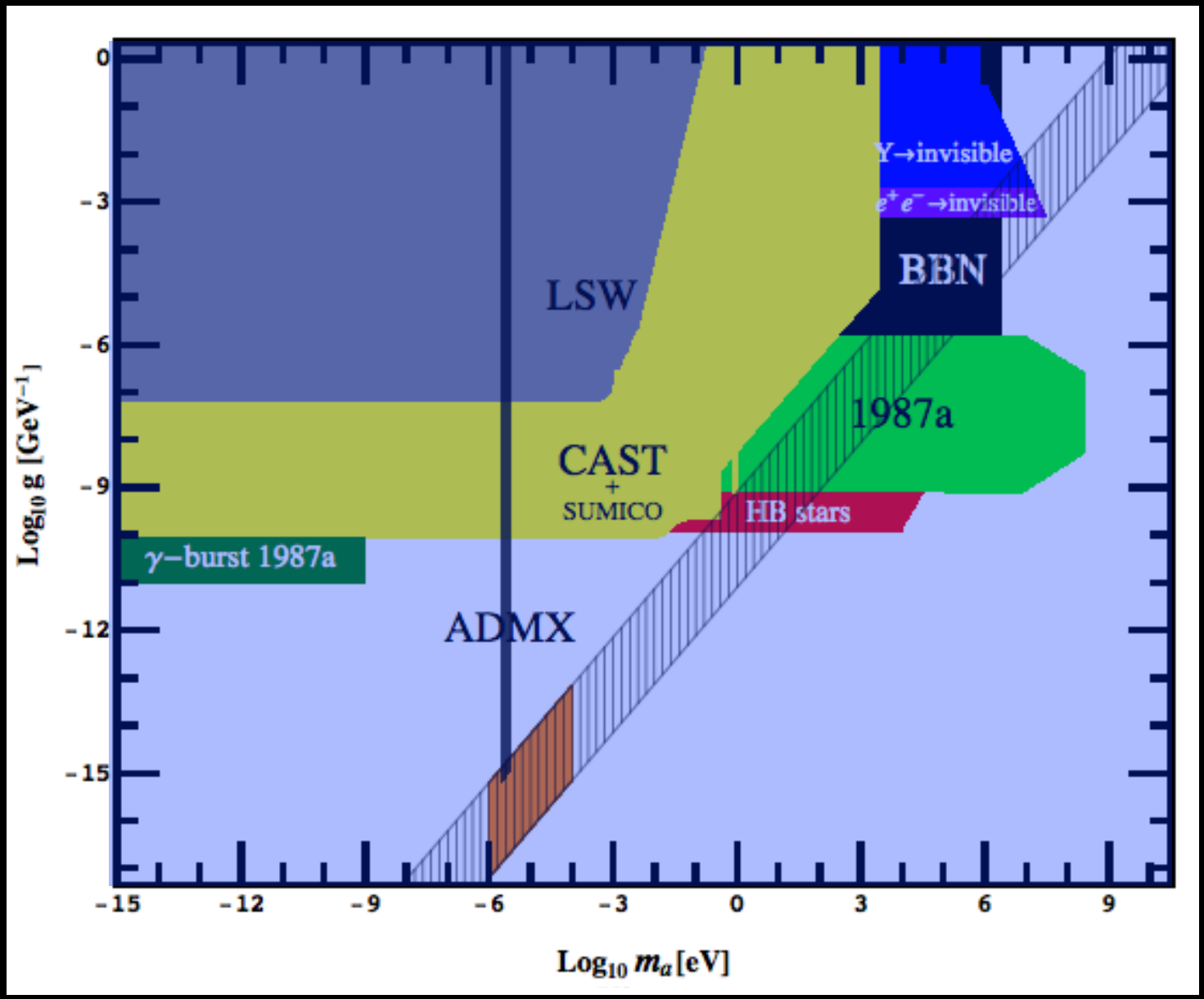

Axion (like particles): Where are we?

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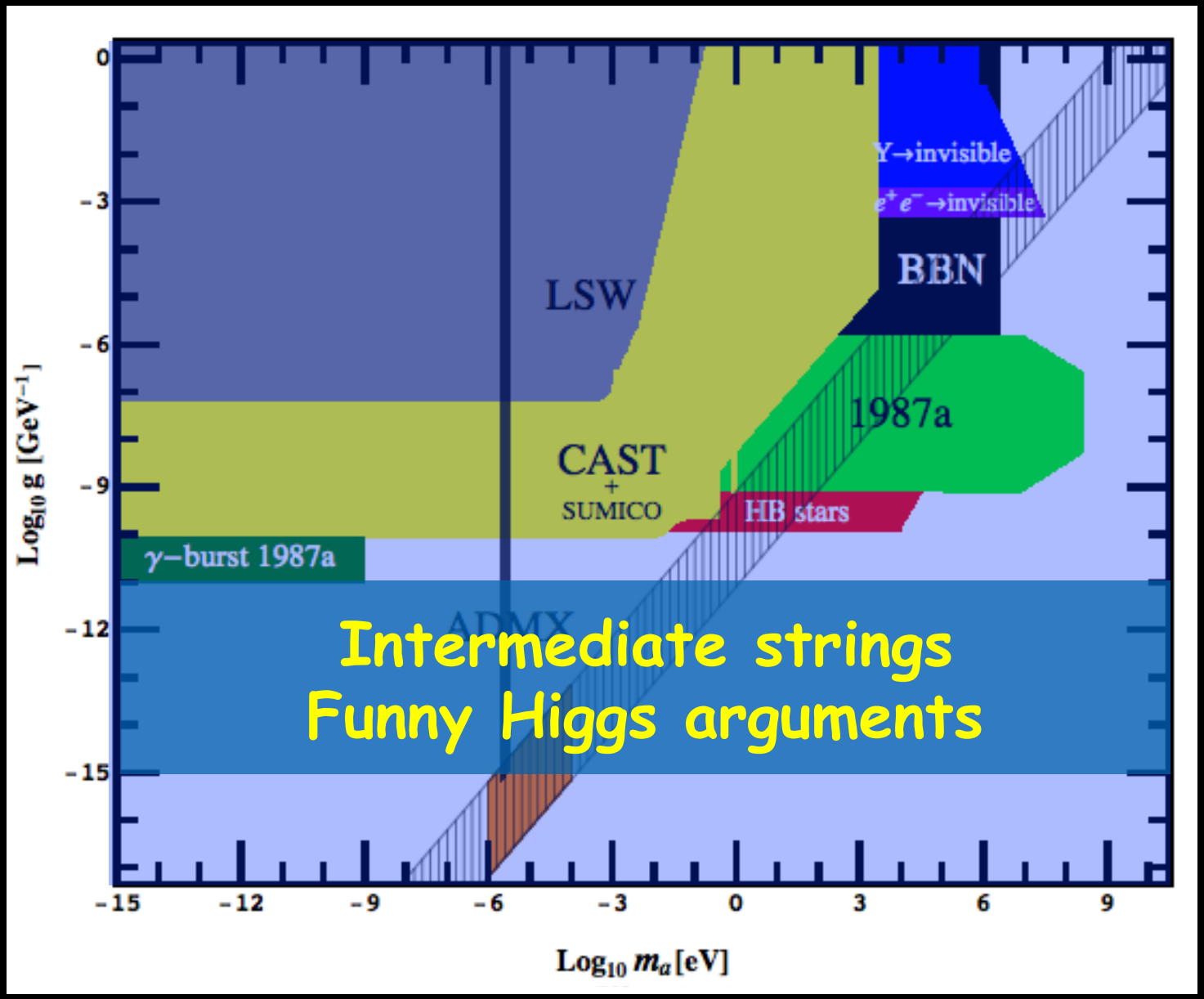

Dark Matter(s)

Can Dark Matter be Axiony/WISPy?

(Weakly Interacting Sub-eV Particley)

Slim

Properties of Dark Matter

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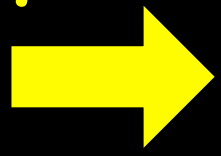
- Dark matter is dark, i.e.
  it doesn't radiate!
  (and also doesn't absorb)

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

➔ Exactly the property of Axions/WISPs



Exploring is (at least) 2 dimensional

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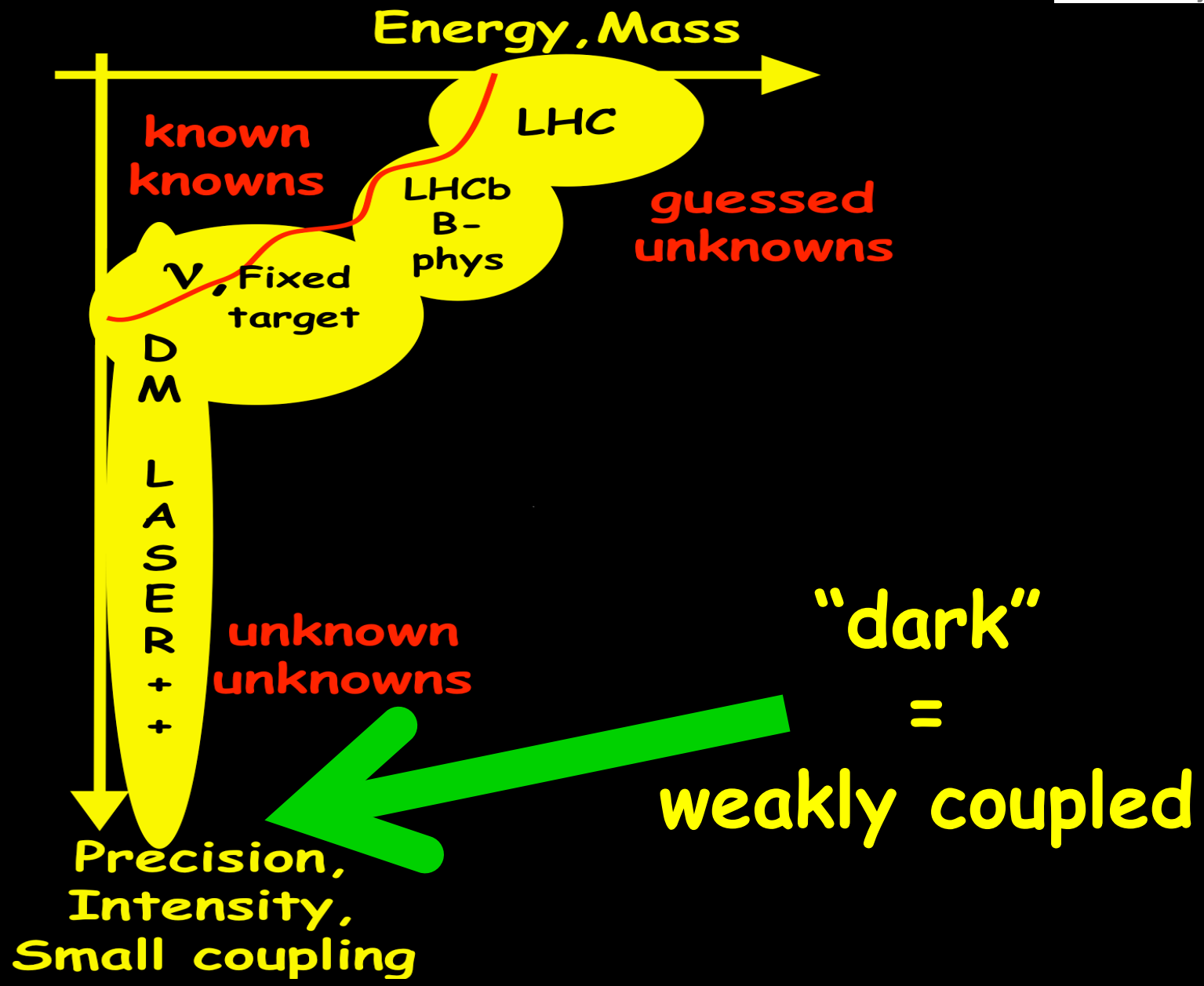

A common prejudice

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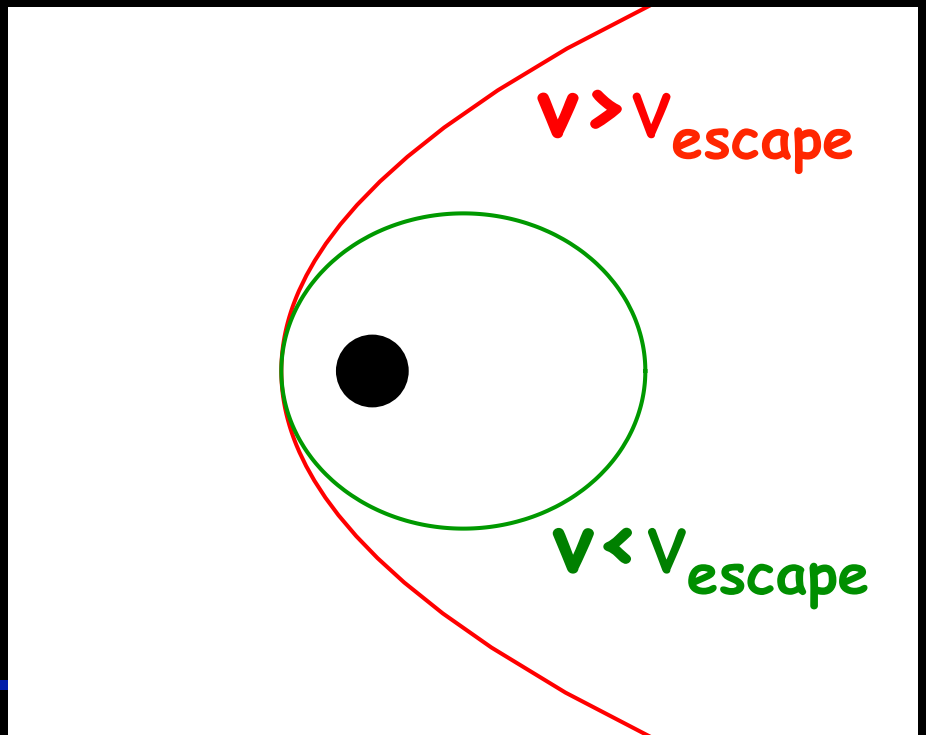
- Dark Matter has to be heavy: $m_{\rm DM} \gtrsim {\rm keV}$.

- 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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Heidelberg University

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

Myth Busted

SuperCold Dark Matter

The axion has no clue where to start

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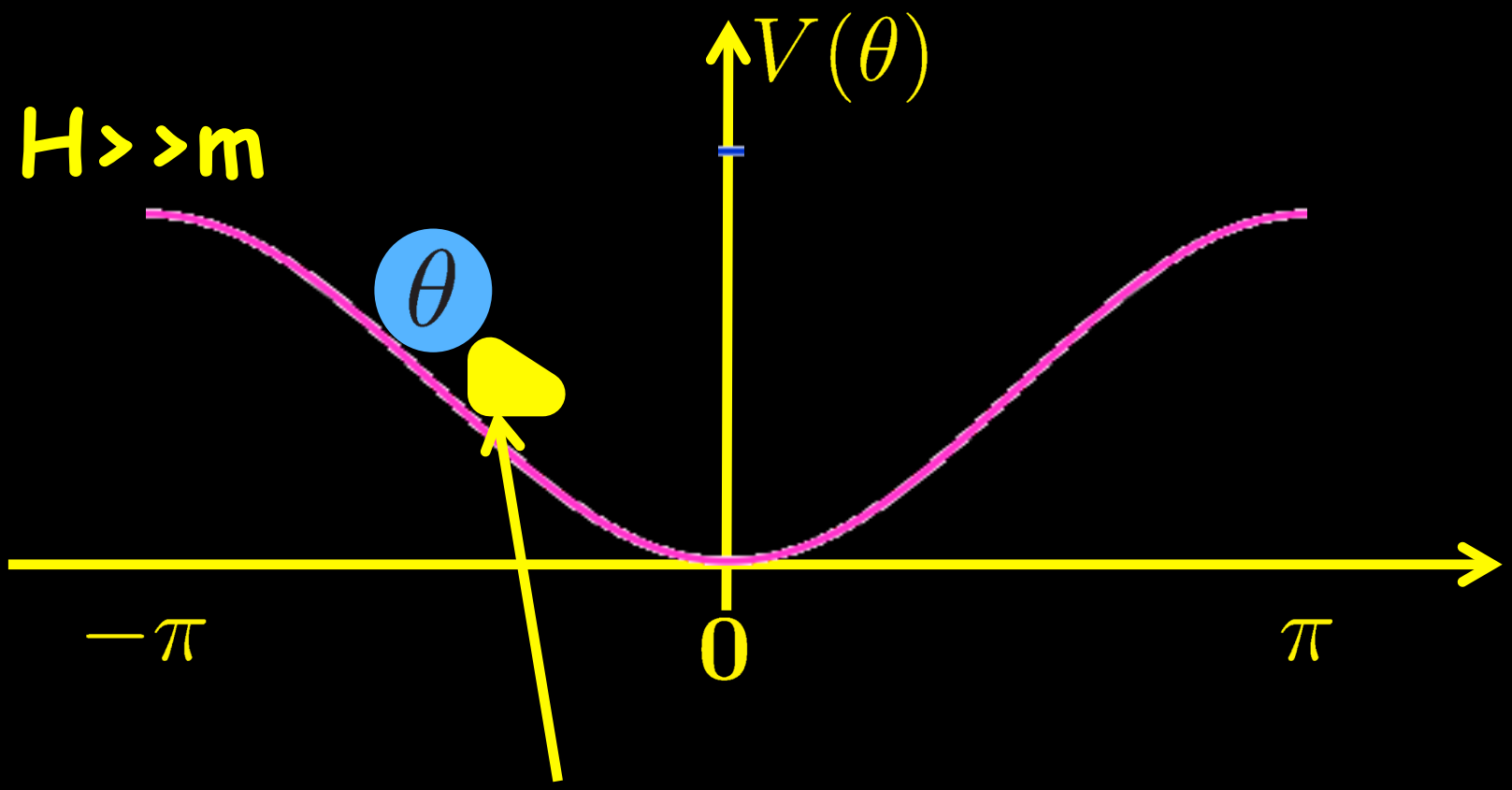

Field is stuck because of Hubble "breaking"

The axion has no clue where to start

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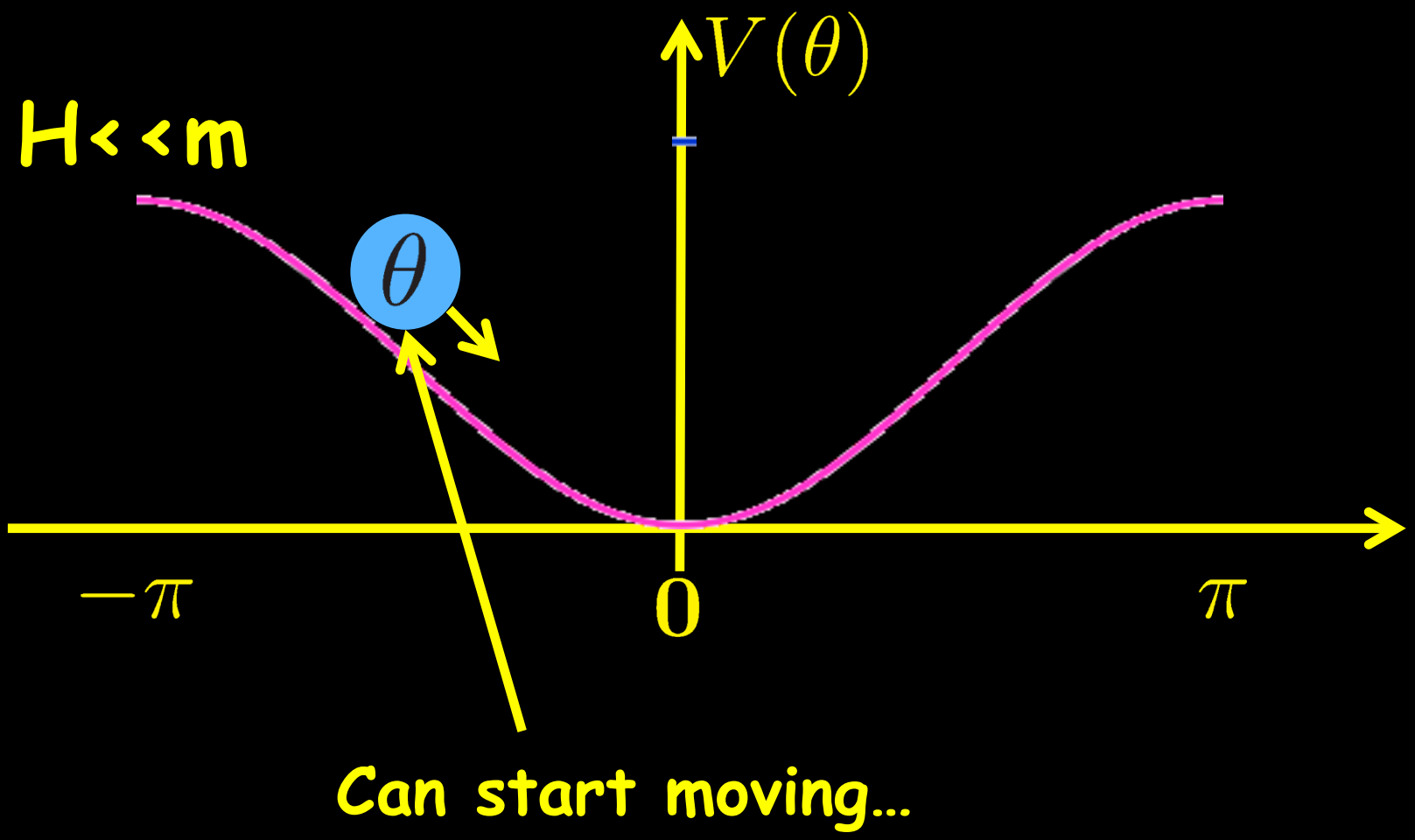

The axion solution to the strong CP problem

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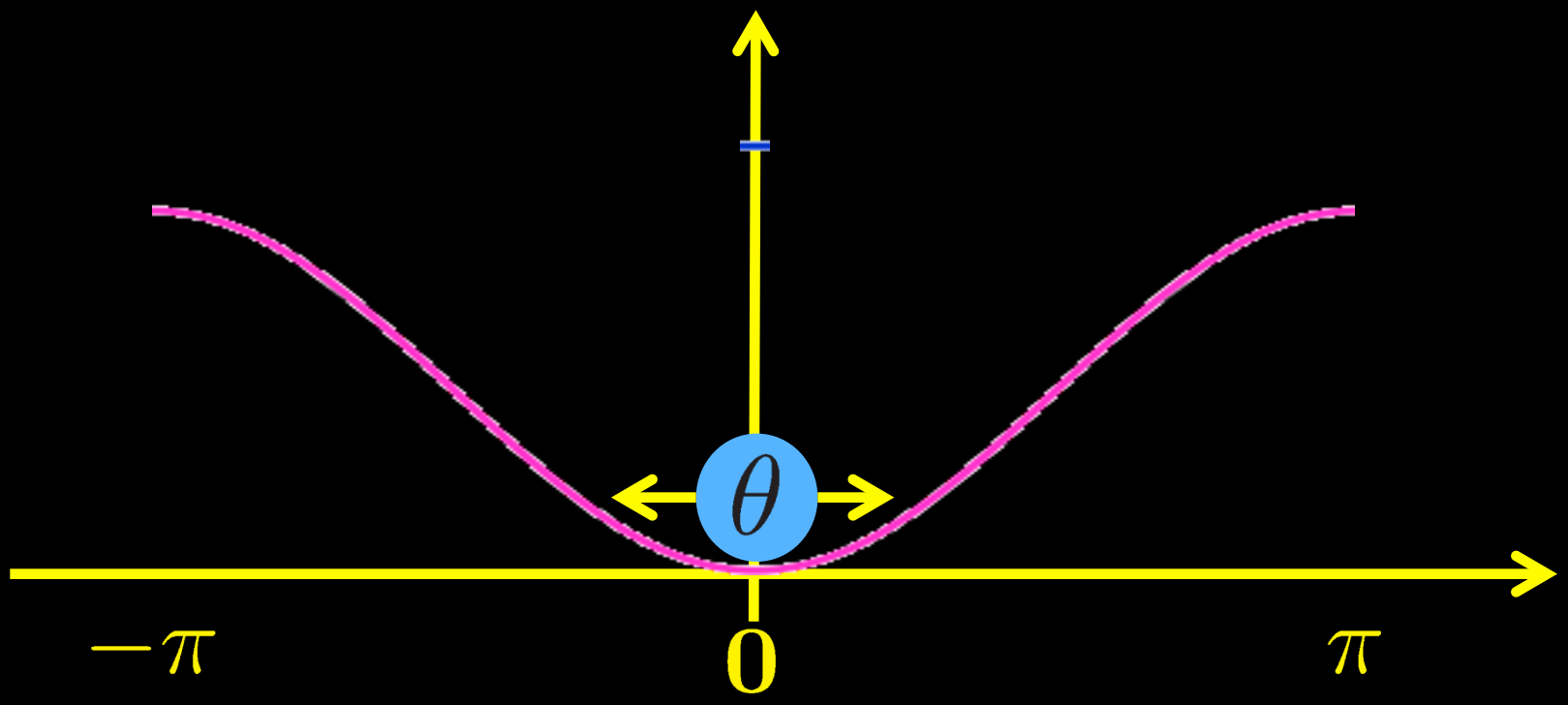

➔ Oscillations contain energy
➔ behave like non-relativistic particles (T=0)

Axion Dark Matter

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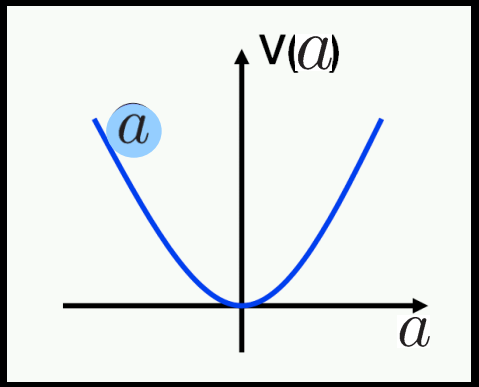
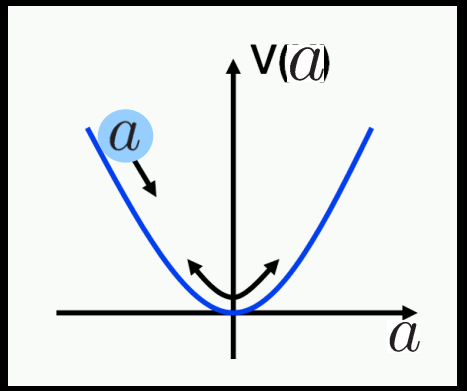
$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0 \qquad H = \frac{\dot{R}(t)}{R(t)}$$

- $H \gg m_a$ ➔ overdamped oscillator



- $H \ll m_a$ ➔ damped oscillator



$$\rho_a(t) = \frac{\rho_{ini}}{R^3(t)}$$ ➔ Dark Matter

Why Cold? Inflation!

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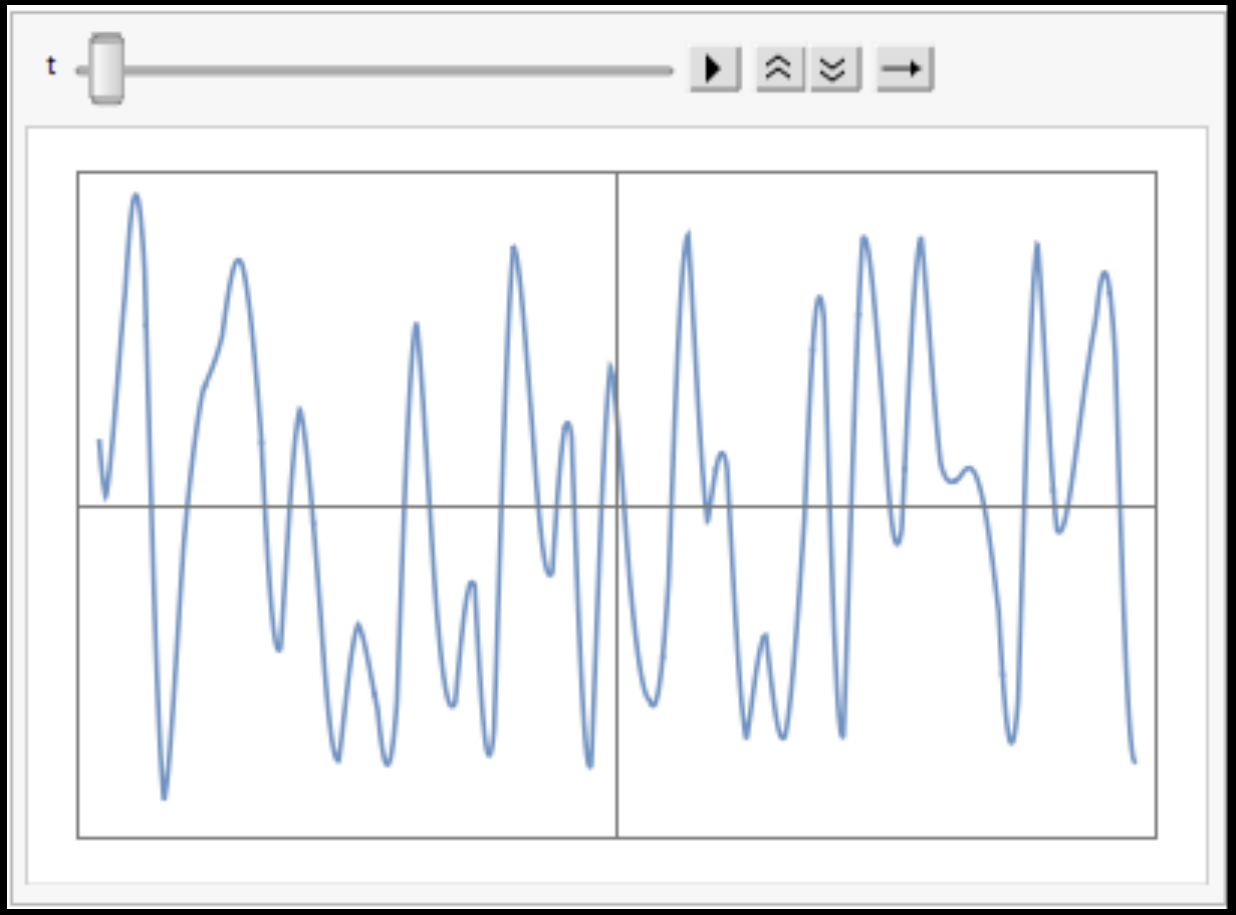
Field value



space

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

Axion(-like particle) Dark Matter

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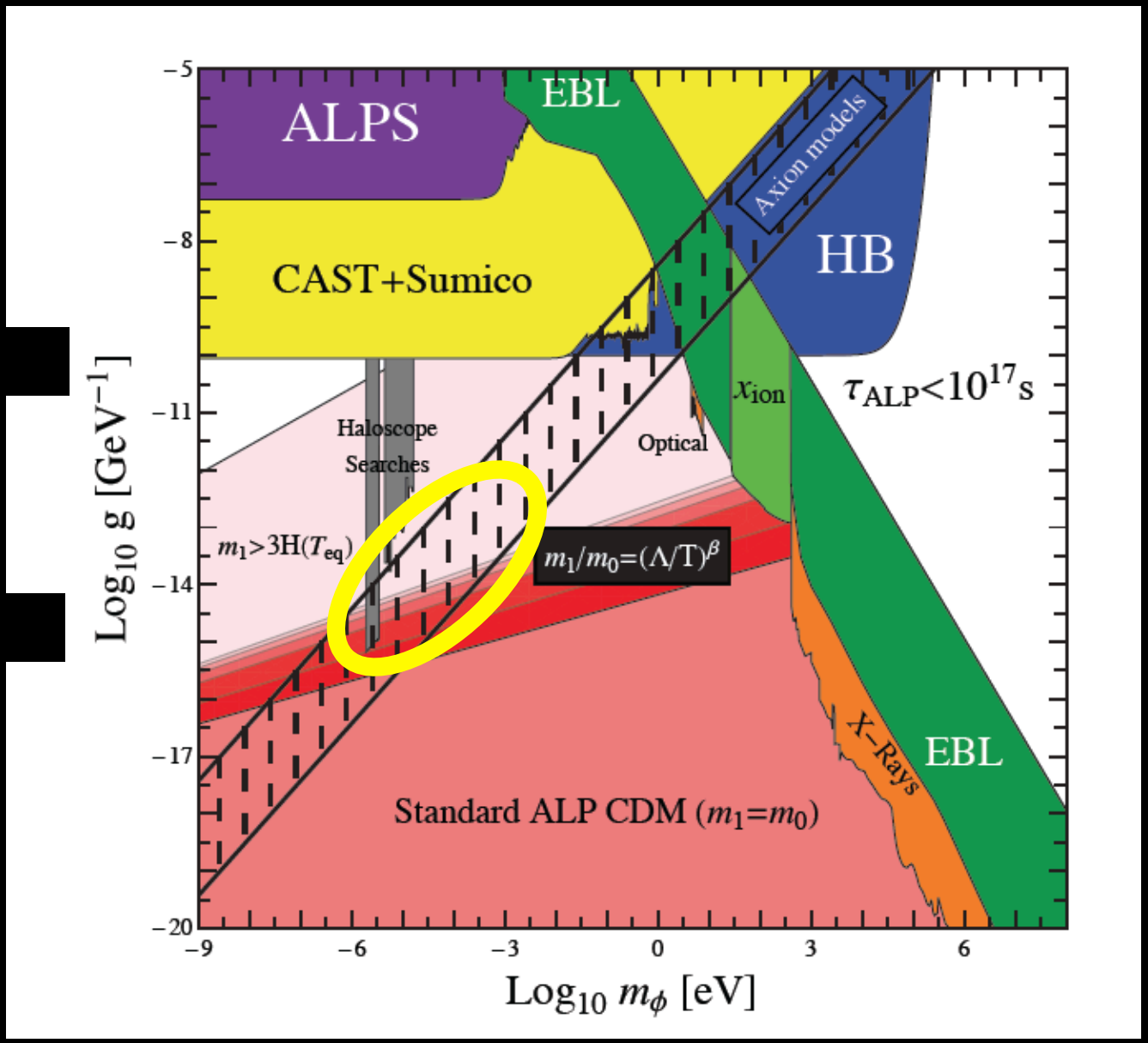
~10^7 GeV

~10^{12} GeV



Detecting Axiony/WISPy DM

Use a plentiful source of axions

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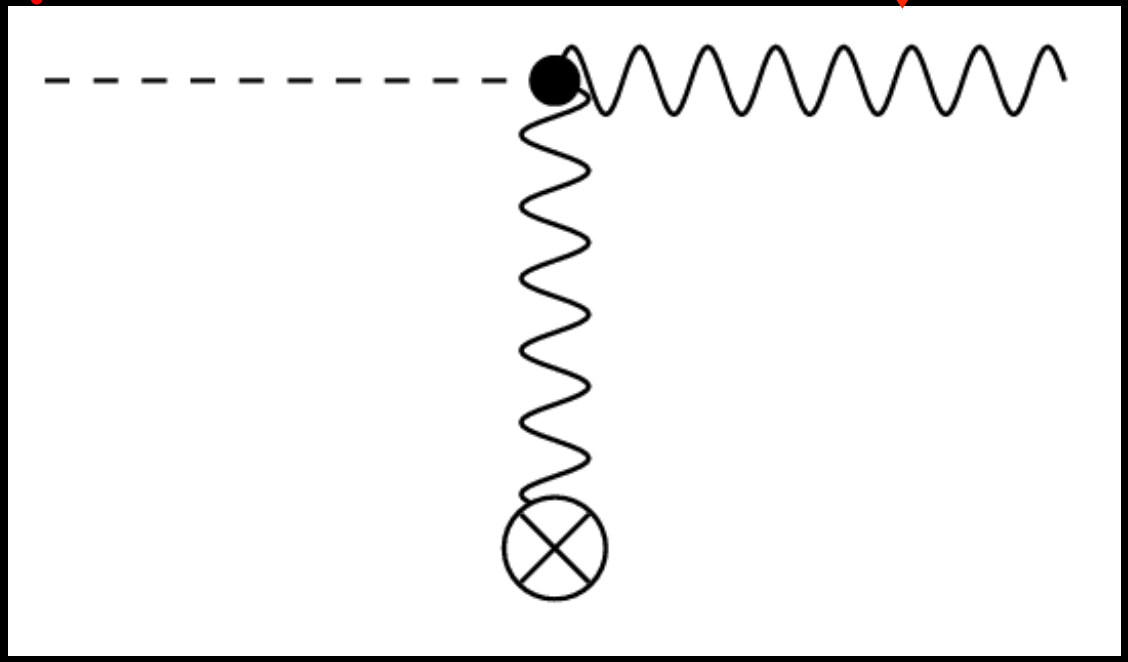
- Photon Regeneration

Photon
(amplified in resonator)

axion
(dark matter)



Signal: Total energy of axion

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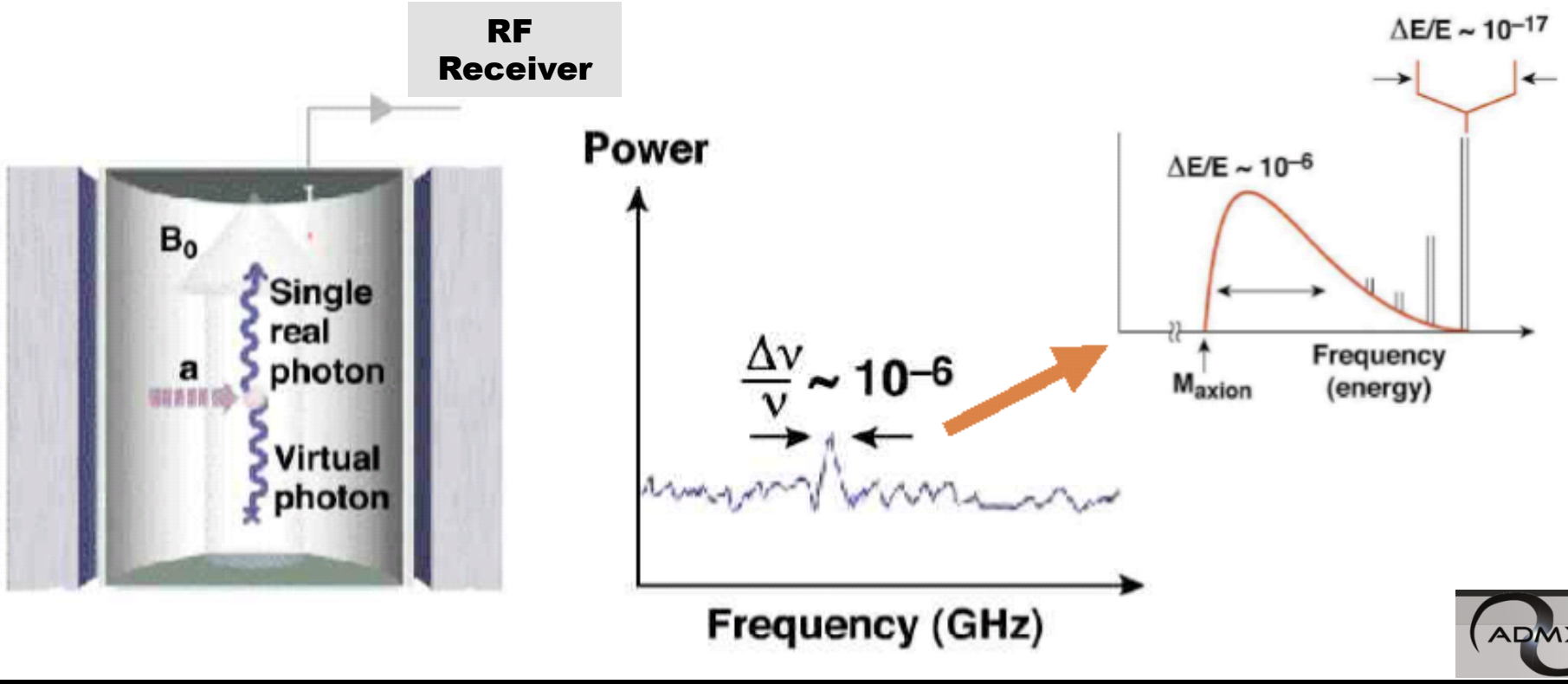

$$h\nu = m_a c^2 [1 + \mathcal{O}(\beta^2 \sim 10^{-6})]$$

Virial velocity in galaxy halo!

An extremely sensitive probe!!!

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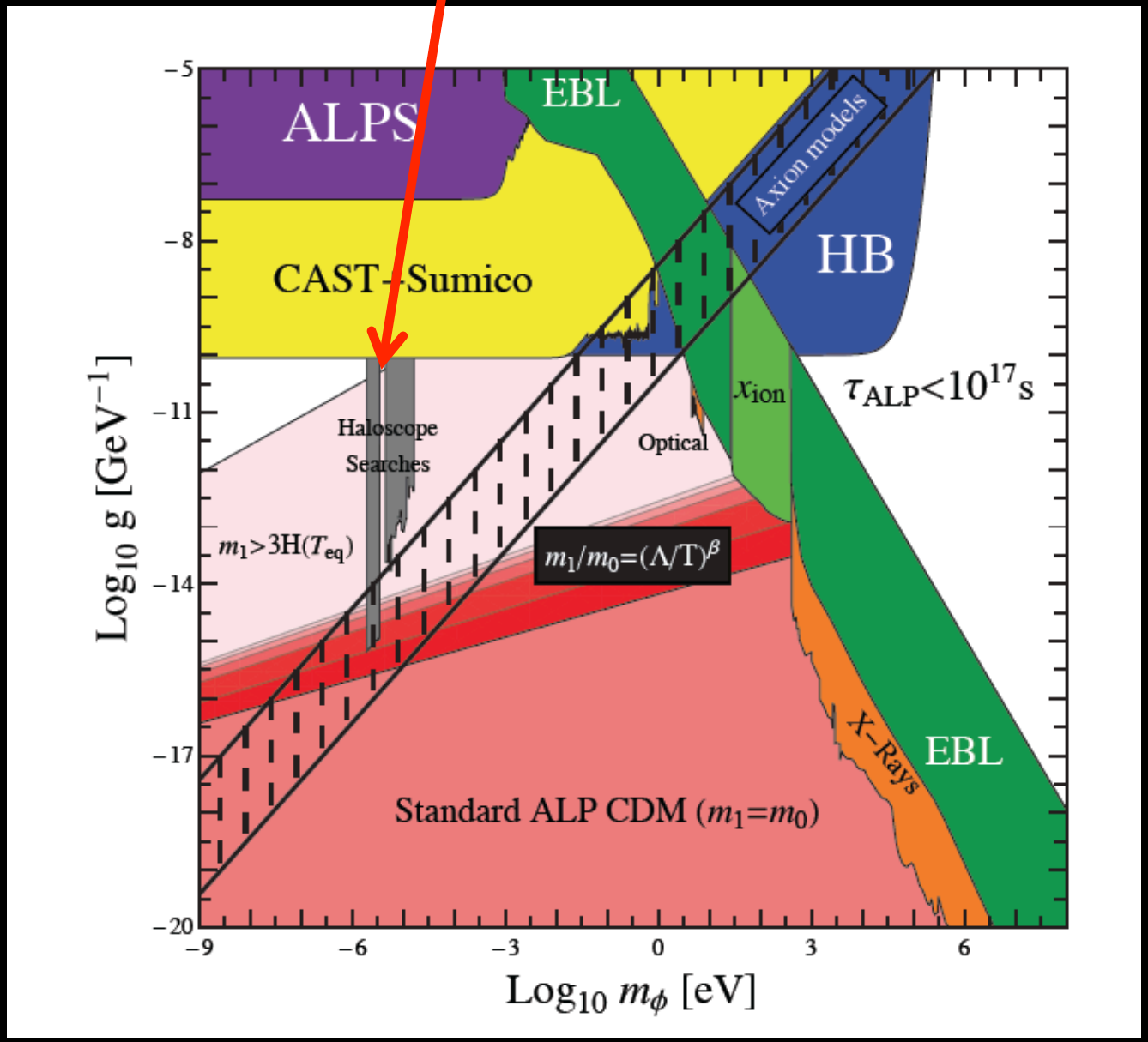

A discovery possible any minute!

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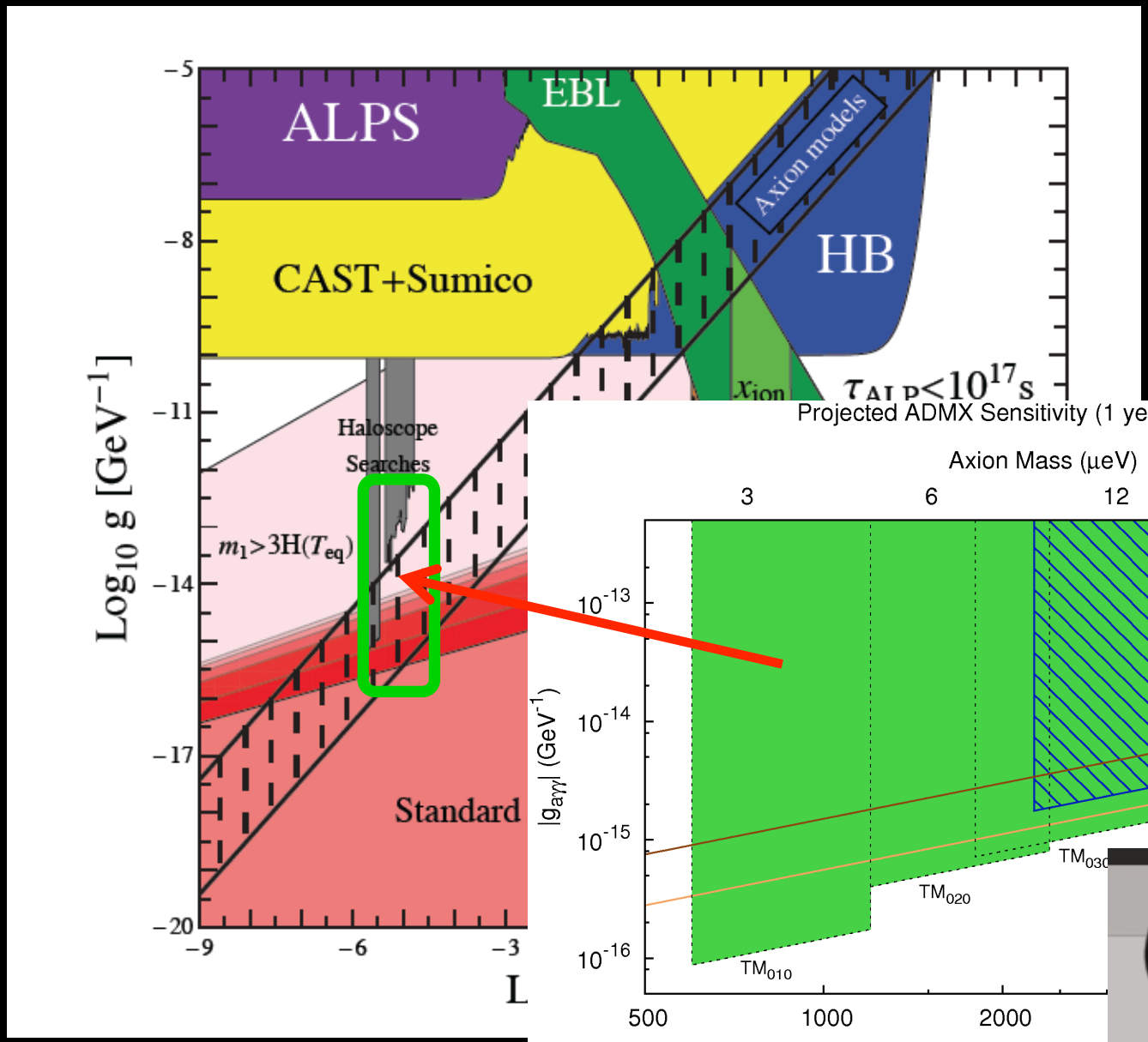

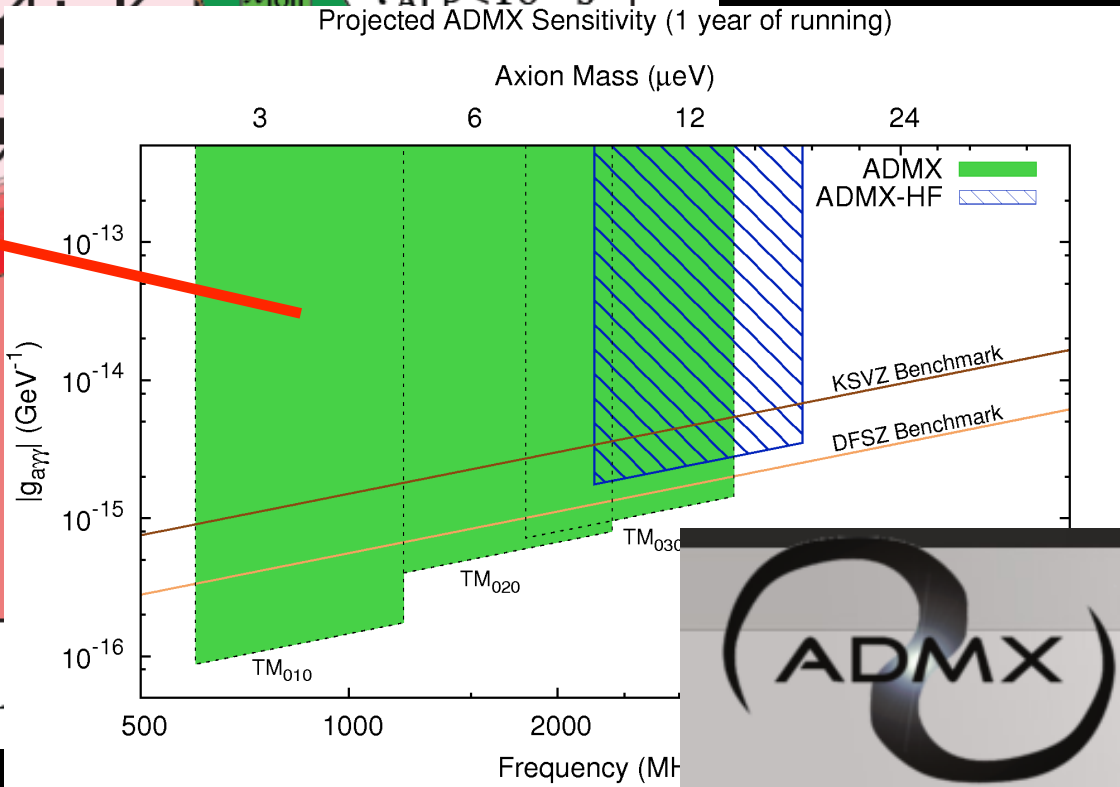

Encircling the axion…

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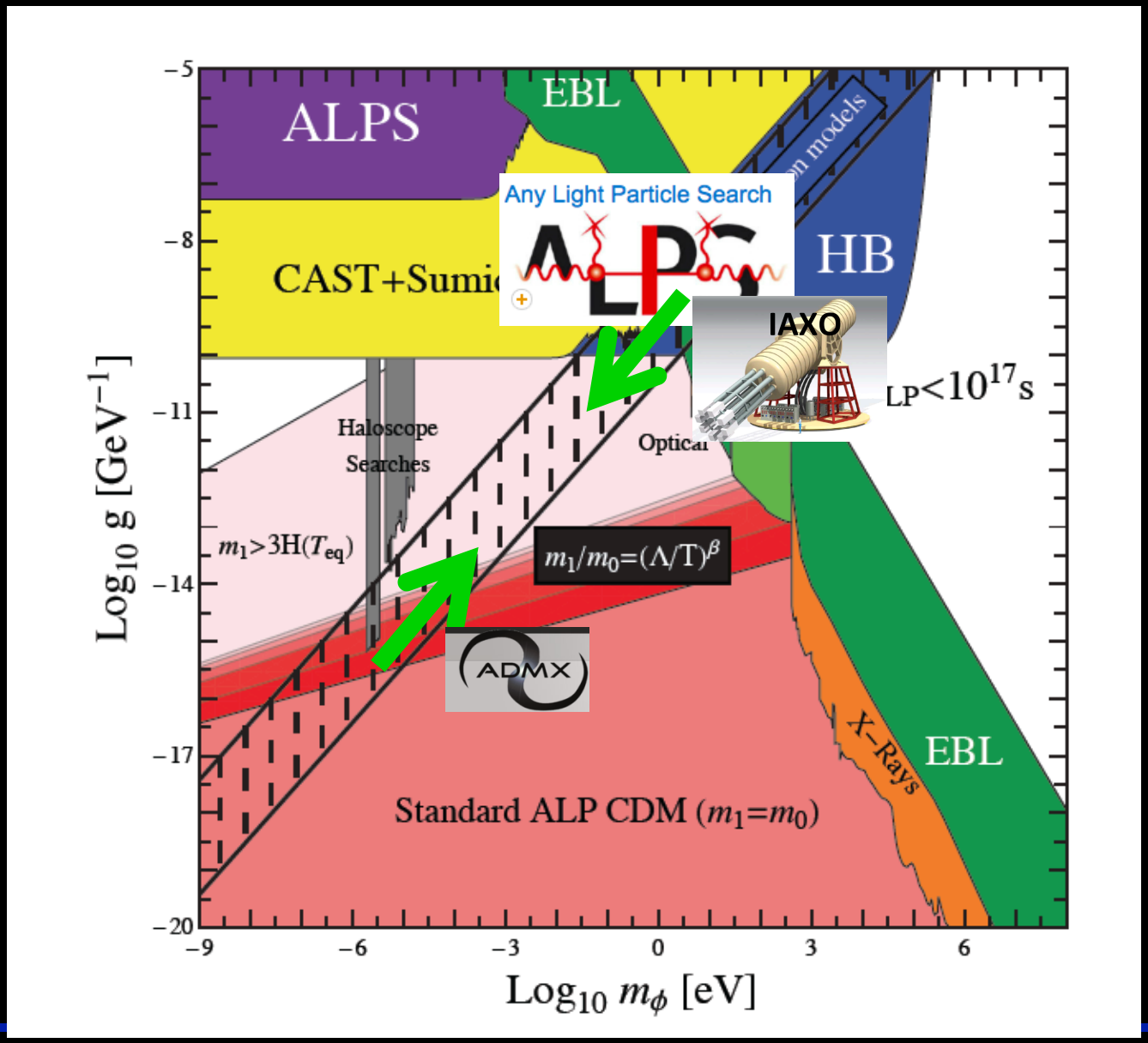

Electricity from Dark Matter ;-).

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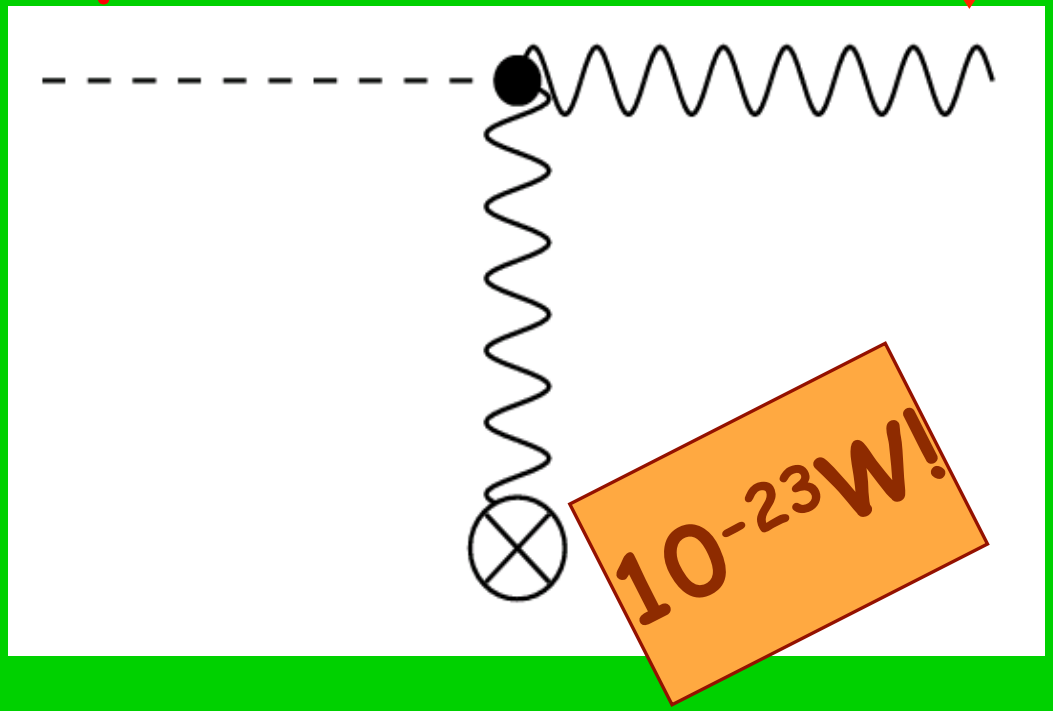
- Photon Regeneration

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

Broadband Search Strategy

Dark Matter Antenna

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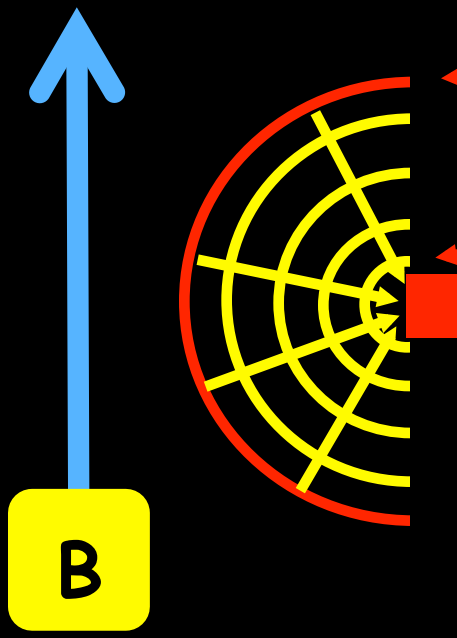
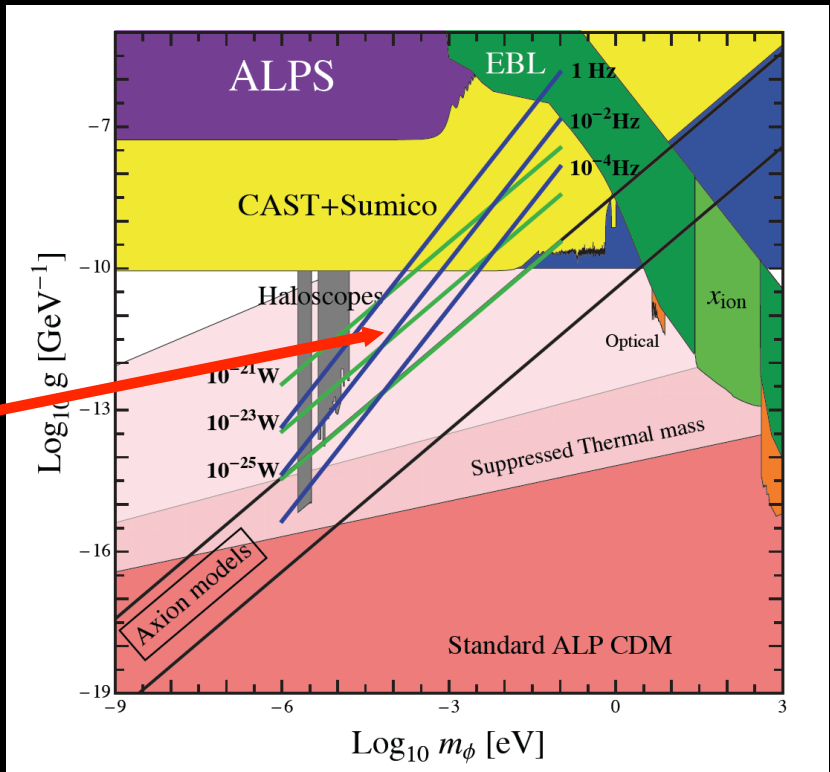


Antenna converts axion->photon

Radiation concentrated in center

Detector

Probes here;
very sensitive!!



The FUNK Experiment

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Recycle Auger mirror

First Results

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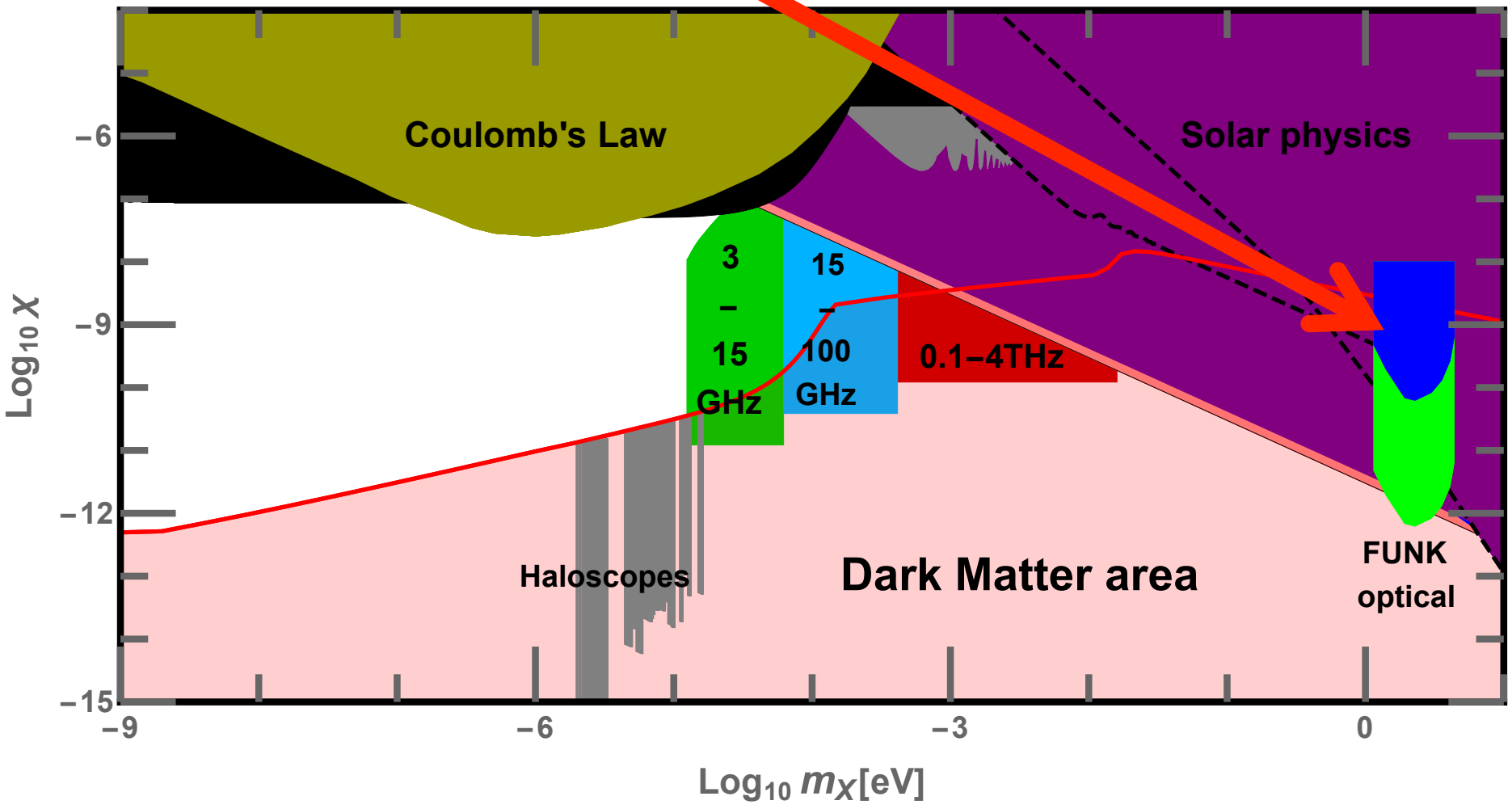

Upgrade: The PMT 9000(+107)

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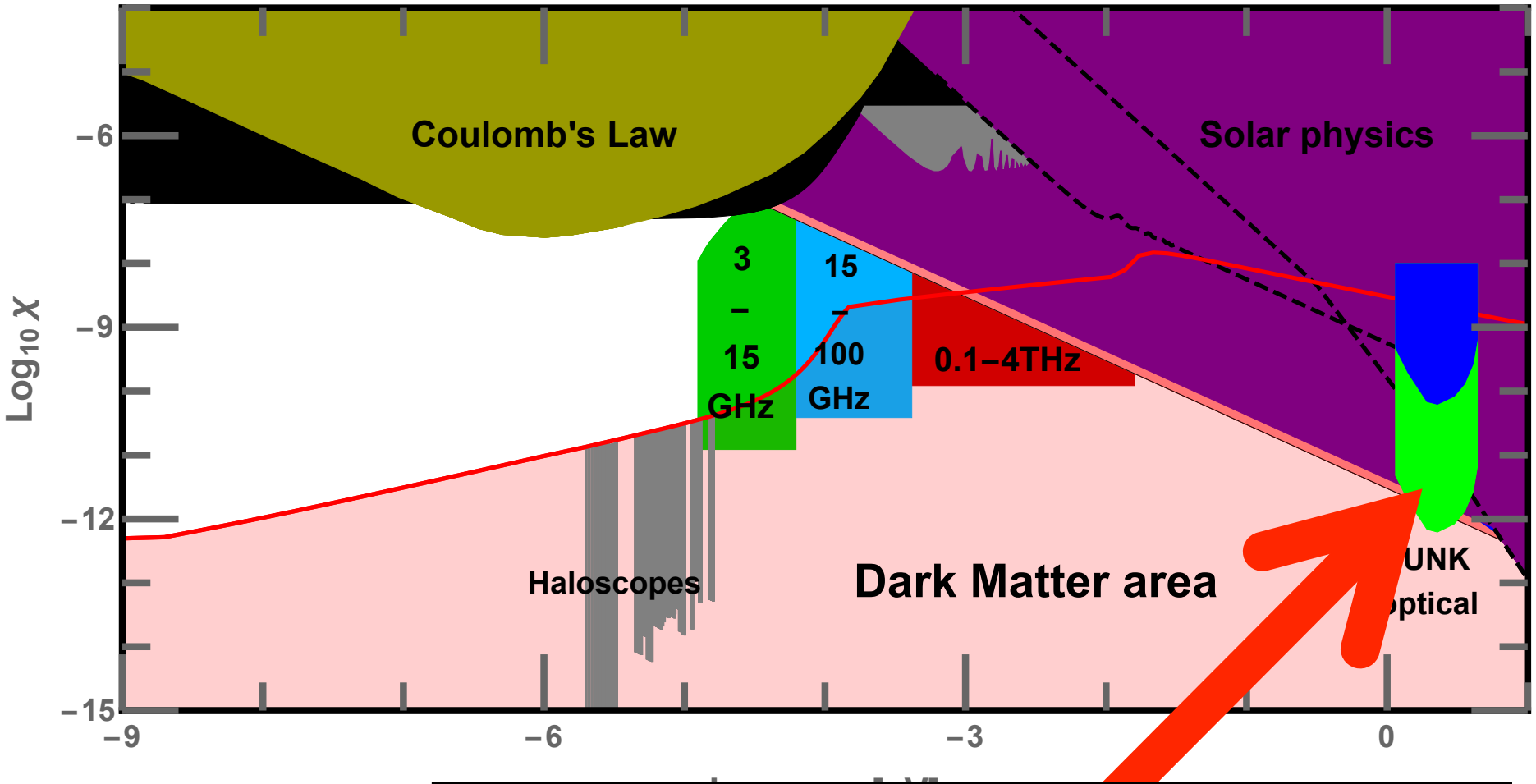

Discovery Potential ☺!!!

The next years ➔ Lower frequency

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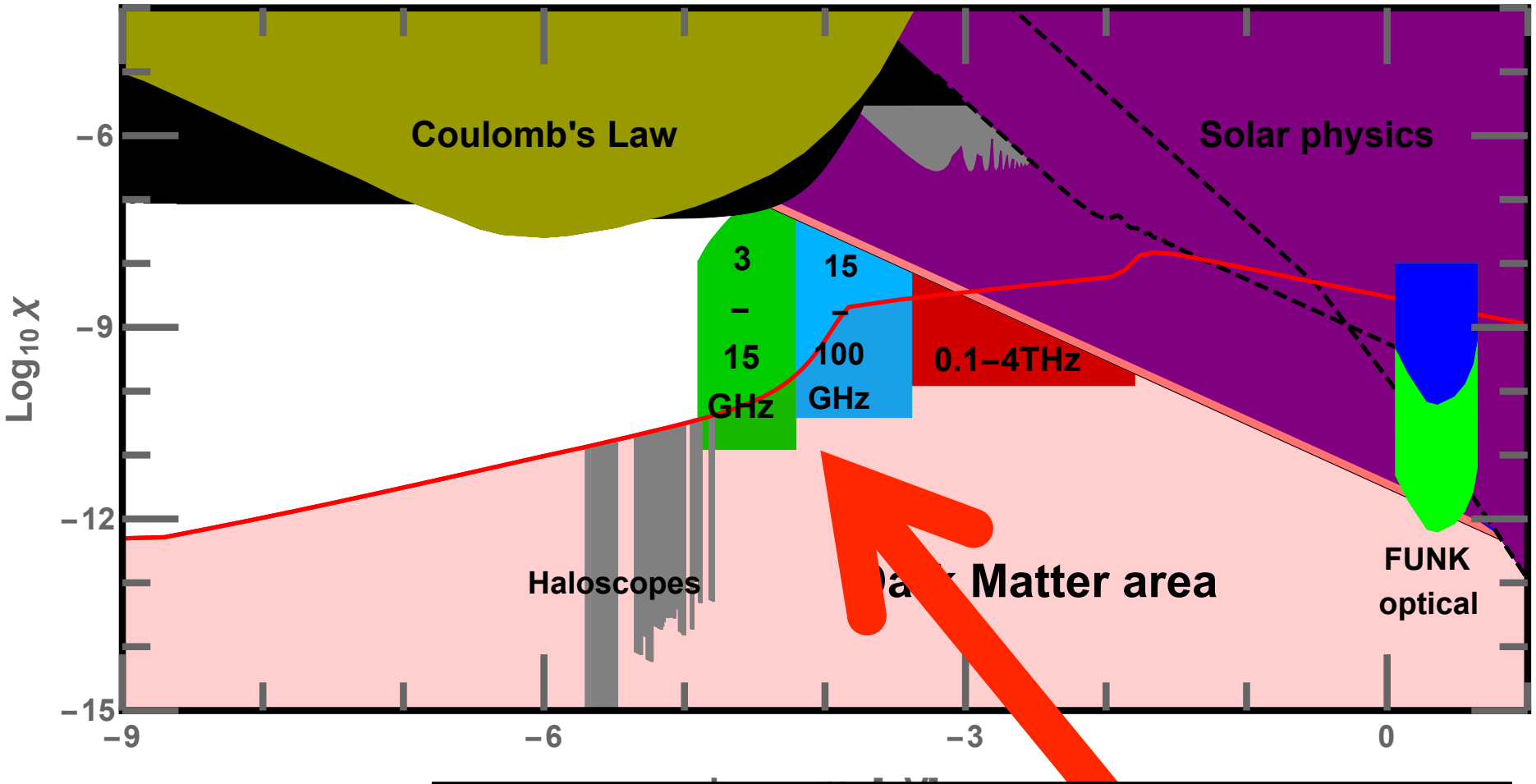

Discovery Potential ☺!!!

A Dream for ~~Astrology~~ ehhm Astronomy

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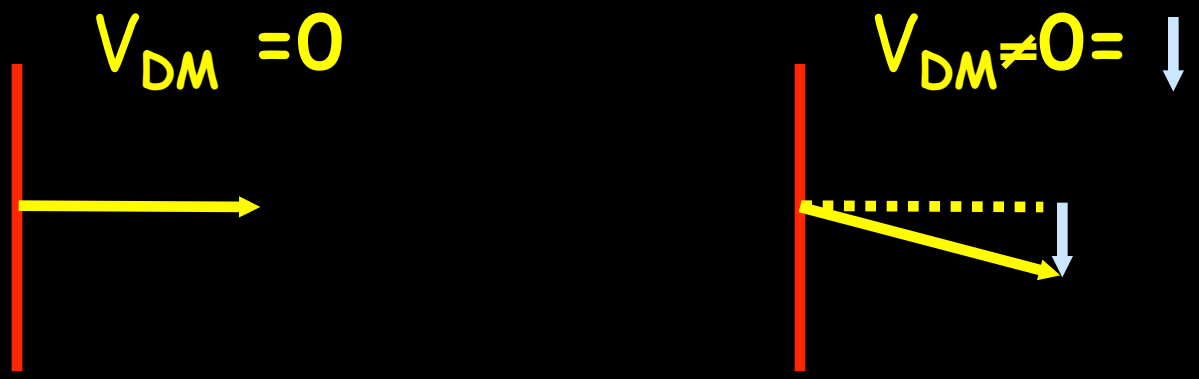
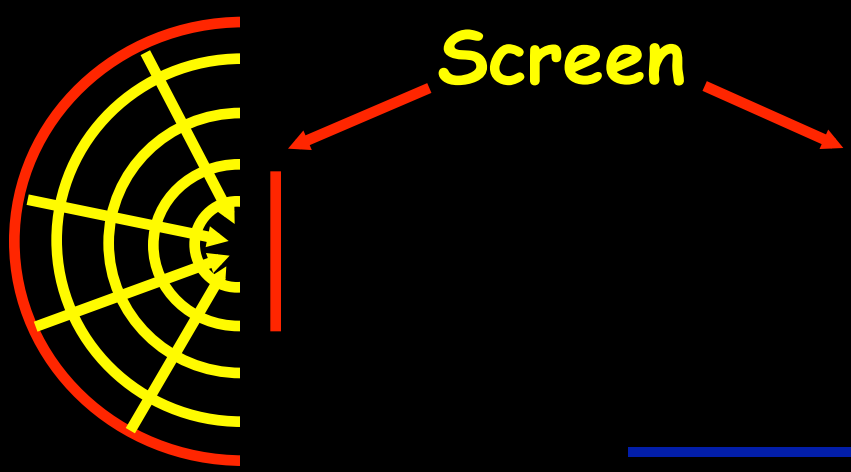
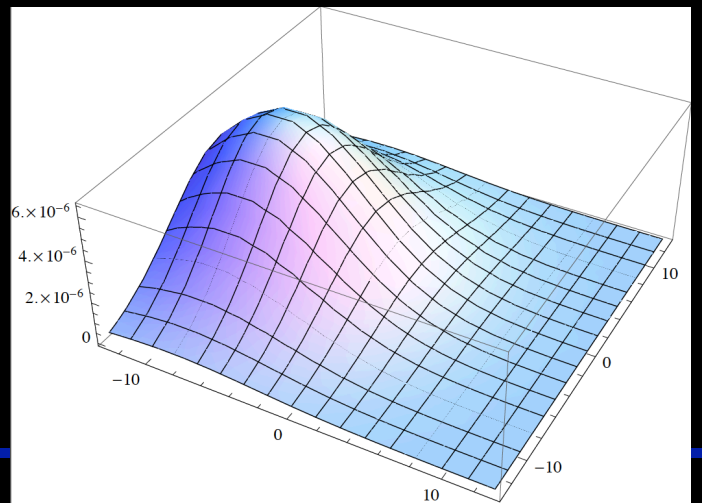
- Emission from moving dark matter



- A picture of the DM-velocity distribution





Going Mad(Max)

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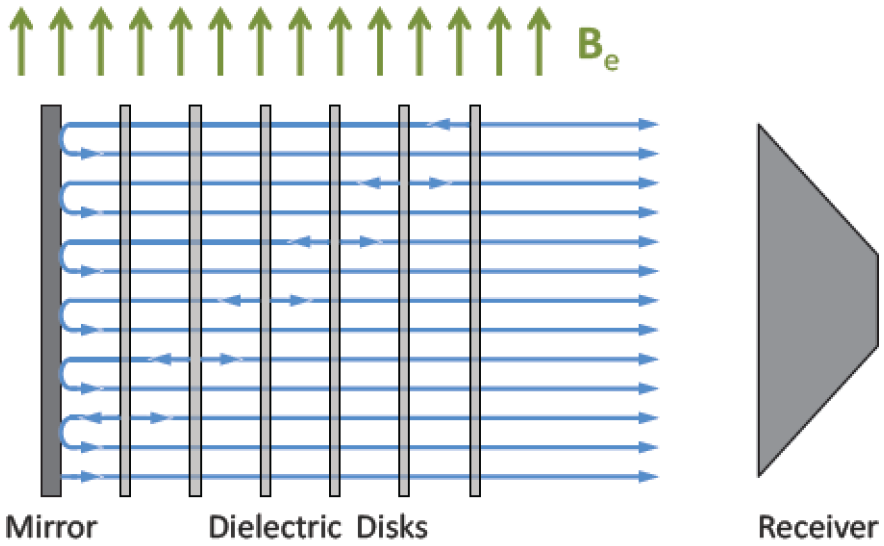
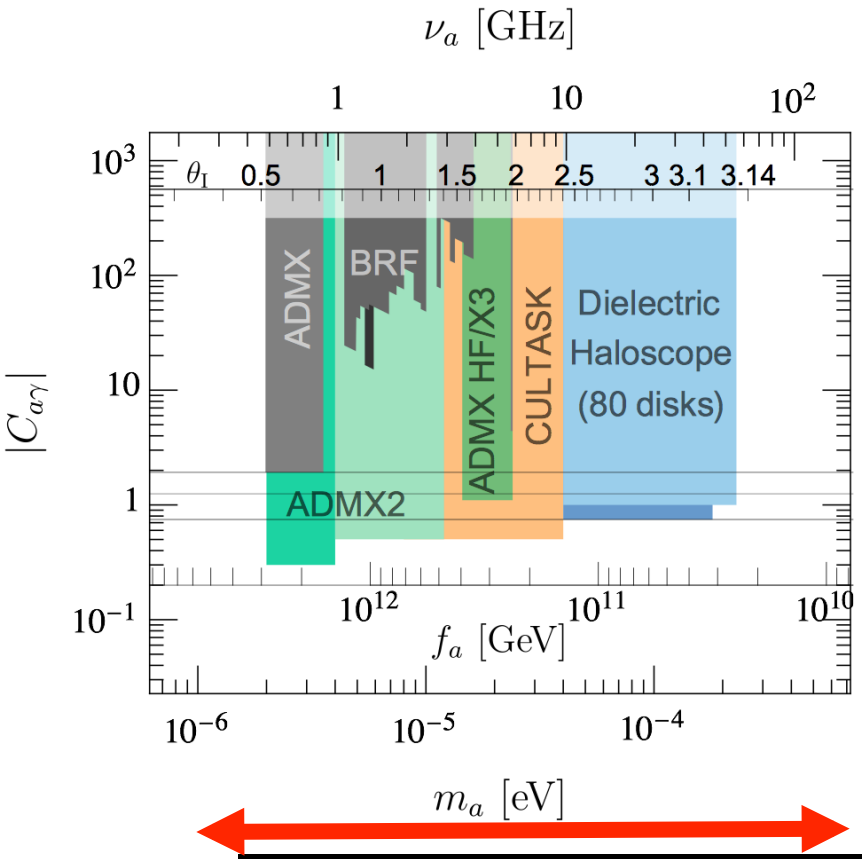
Ambitious new project at MPP





Dielectric Haloscopes: A New Way to Detect Axion Dark Matter

The MADMAX Working Group: Allen Caldwell, Gia Dvali, Bela Majorovits, Alexander Millar, Georg Raffelt, Javier Redondo, Olaf Reimann, Frank Simon, Frank Steffen

Natural DM

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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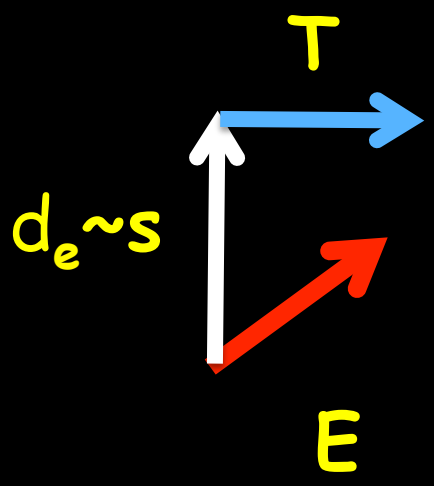

Energy in an elecxtric field

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

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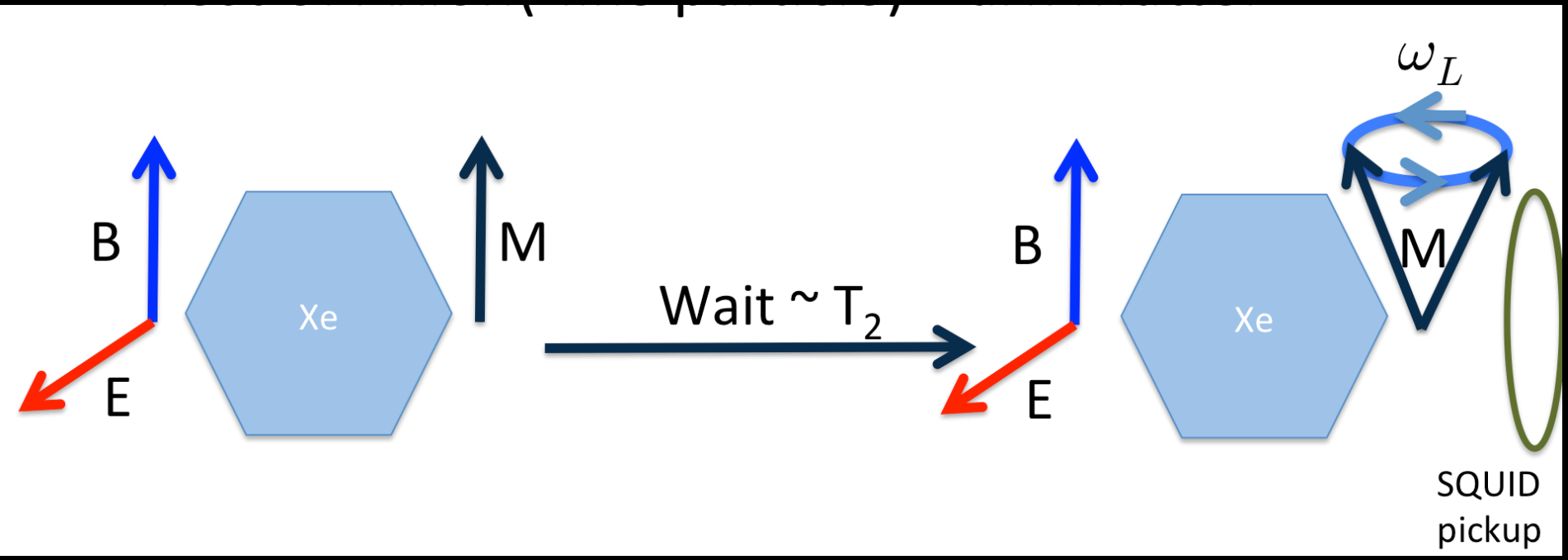
Modification of Xenon EDM experiment to be sensitive to time varying nuclear EDM



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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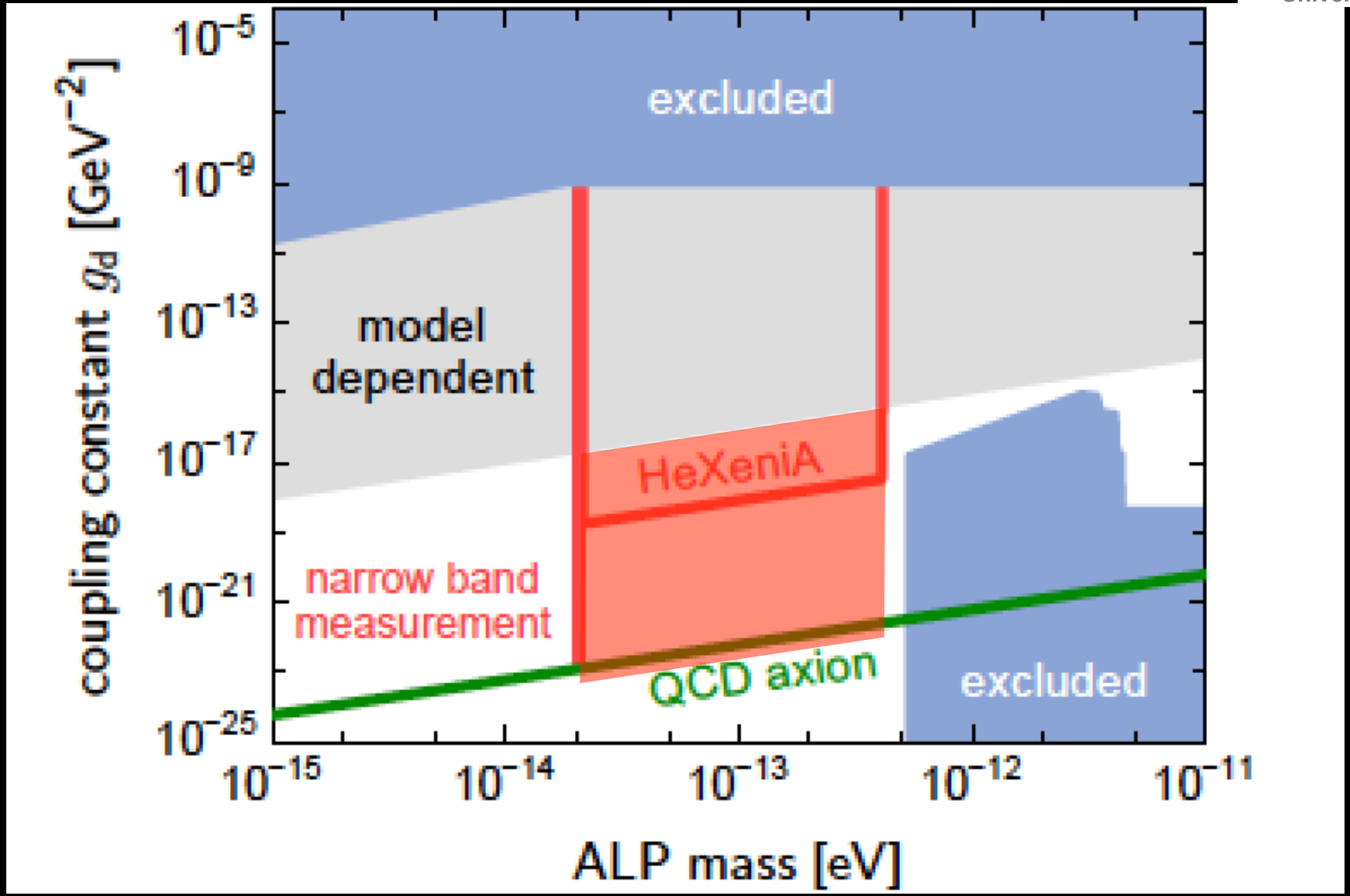

Many more experiments…

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- Abracadabra
- Alps
- Ariadne
- Casper
- Cultask
- EDM ring
- Haystac
- Iaxo
- Organ
- Sensei
- Quax
- …

Conclusions

Conclusions

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- Good Physics Case for Axions and WISPs
  → explore `The Low Energy Frontier'
- Low energy experiments test energy scales much higher than accelerators
  → Complementary!
- May provide information on hidden sectors and thereby into the underlying fundamental theory
- Dark Matter may be WISPy ☺
  → New cool Experiments underway.