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Axions
–
Motivated by the Strong Interactions, Perfect for Cosmology

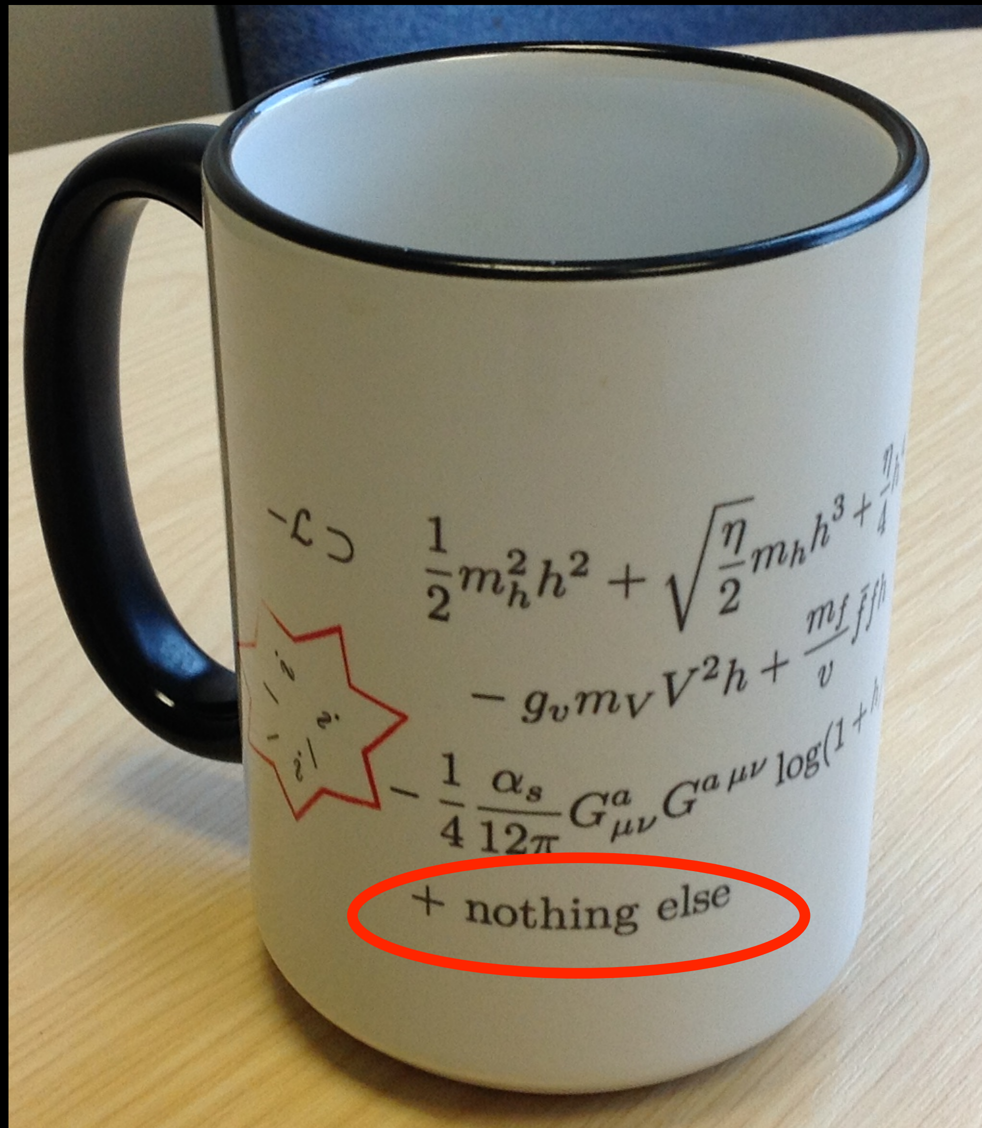
J. Jaeckel[**]

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

[**]ITP Heidelberg, [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



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

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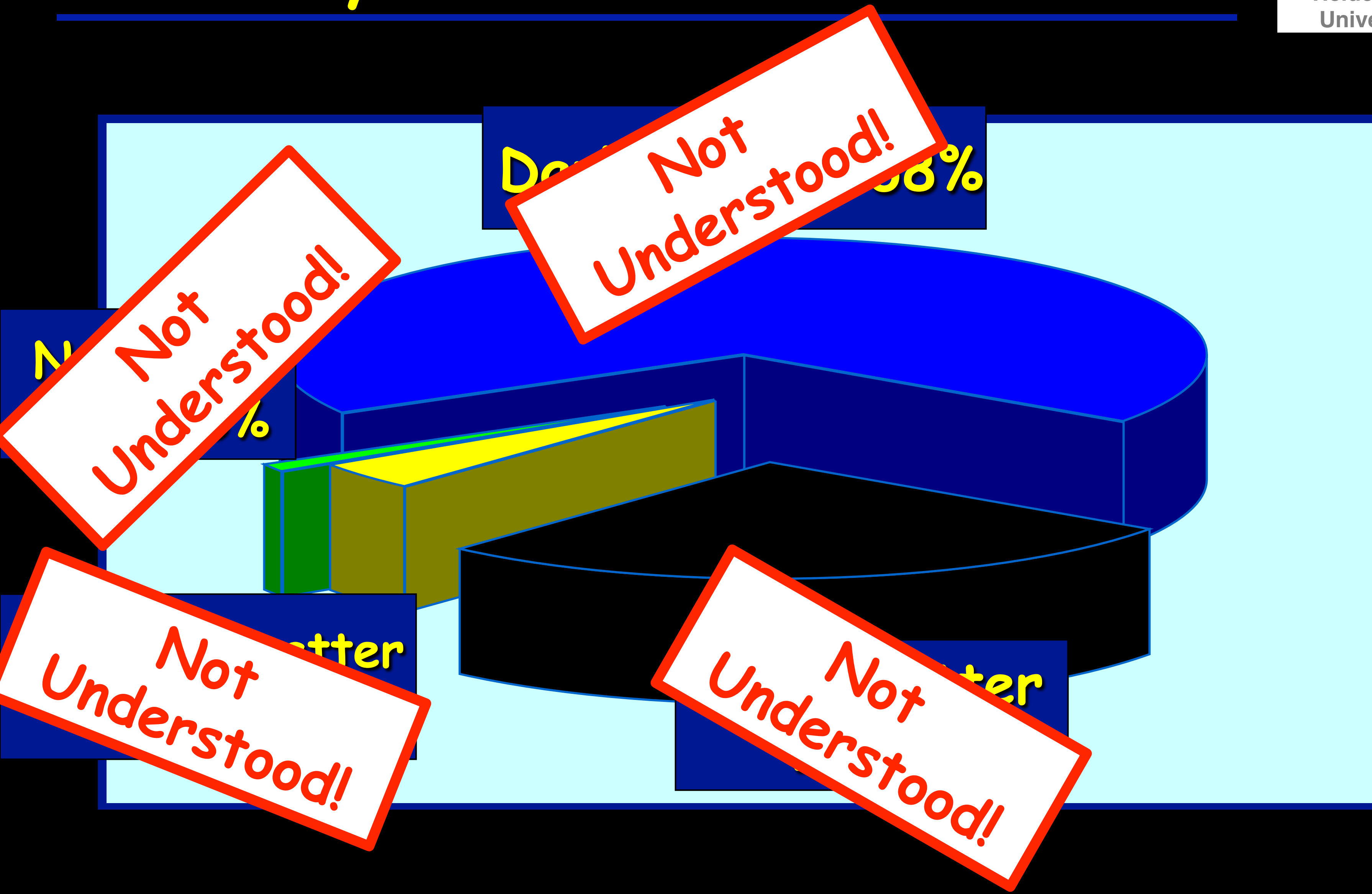
Inventory of the Universe



Where does it hide?

New physics

Exploring is (at least) 2 dimensional

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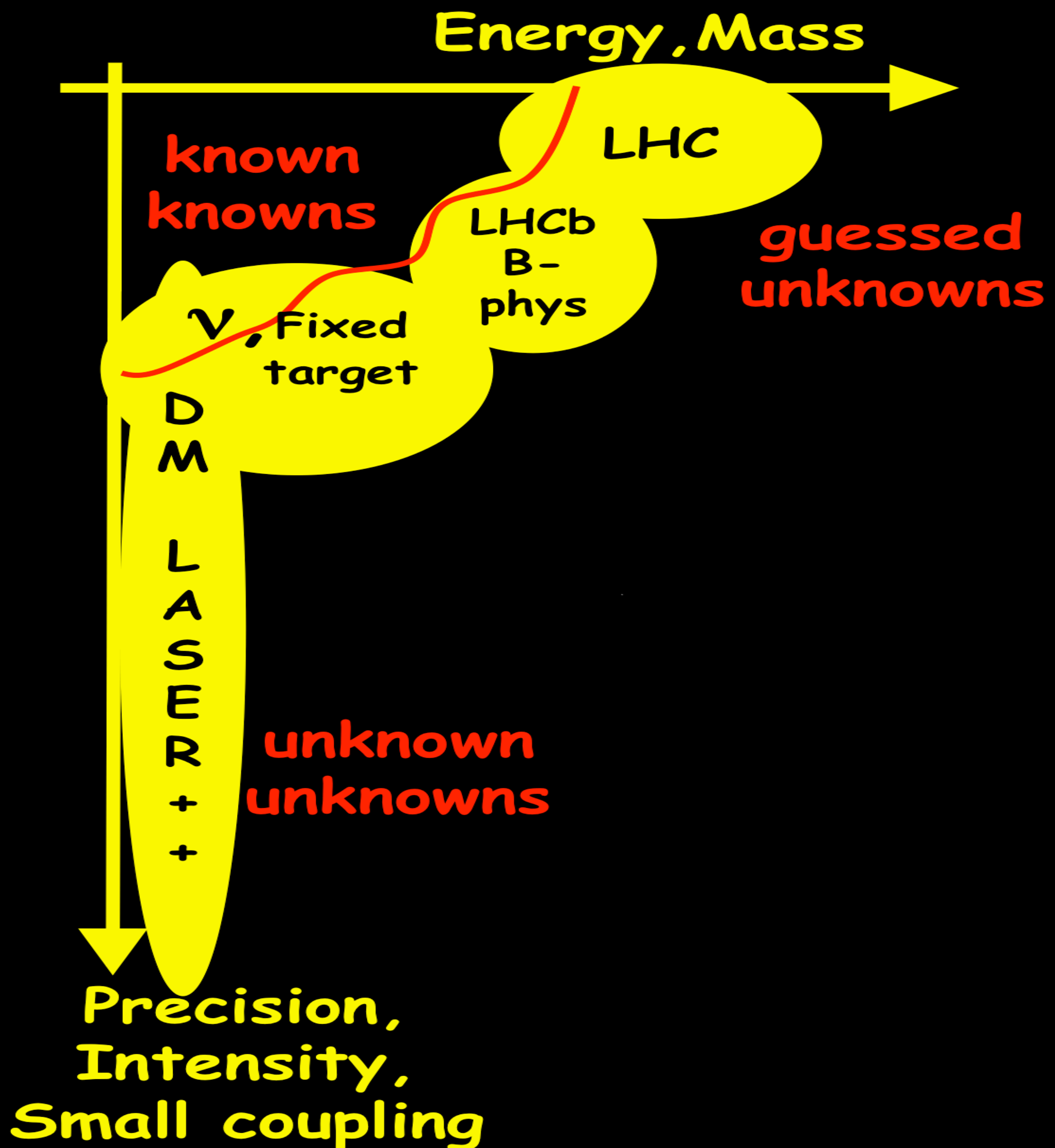

Exploring is (at least) 2 dimensional

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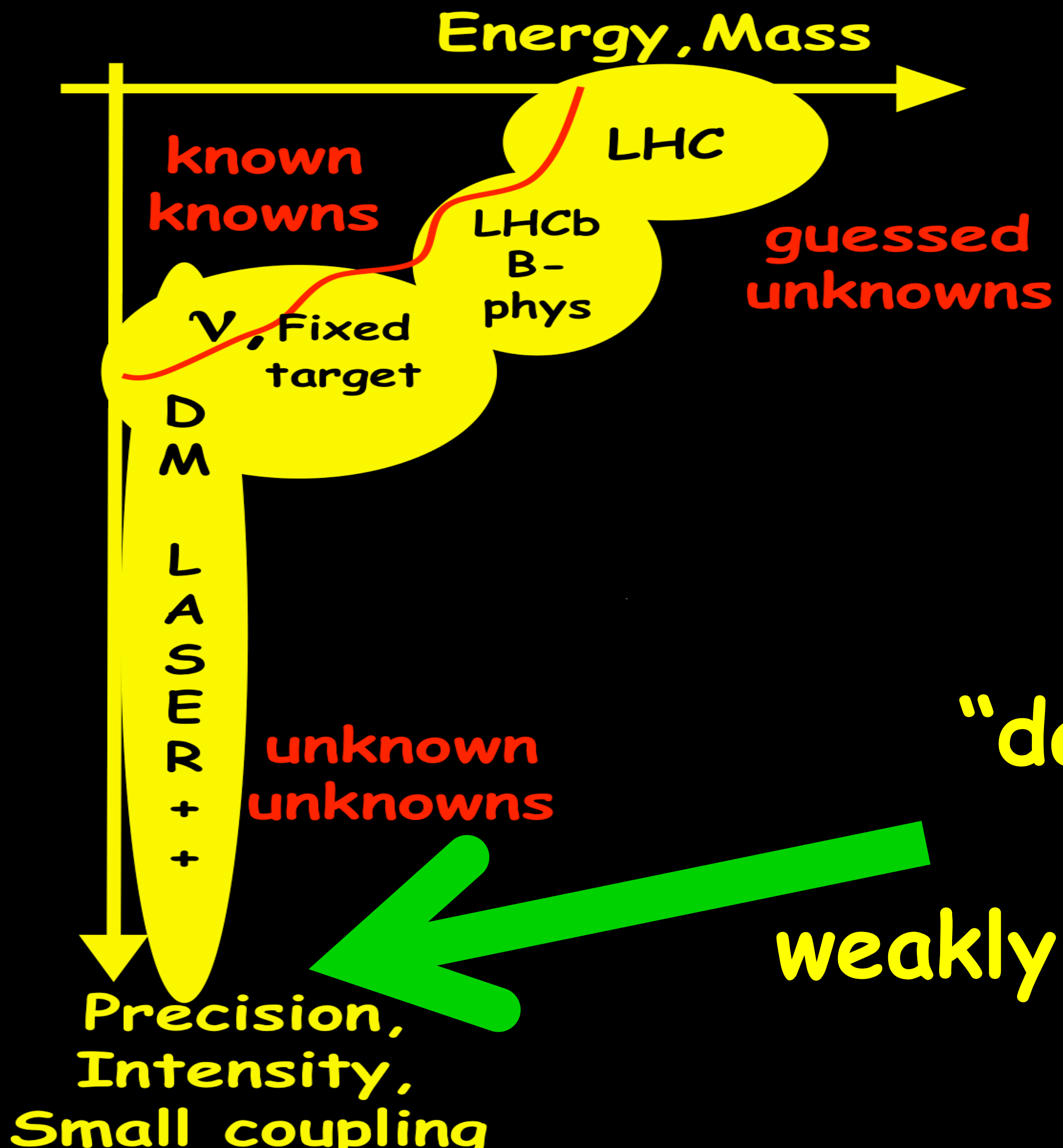

"dark" = weakly coupled

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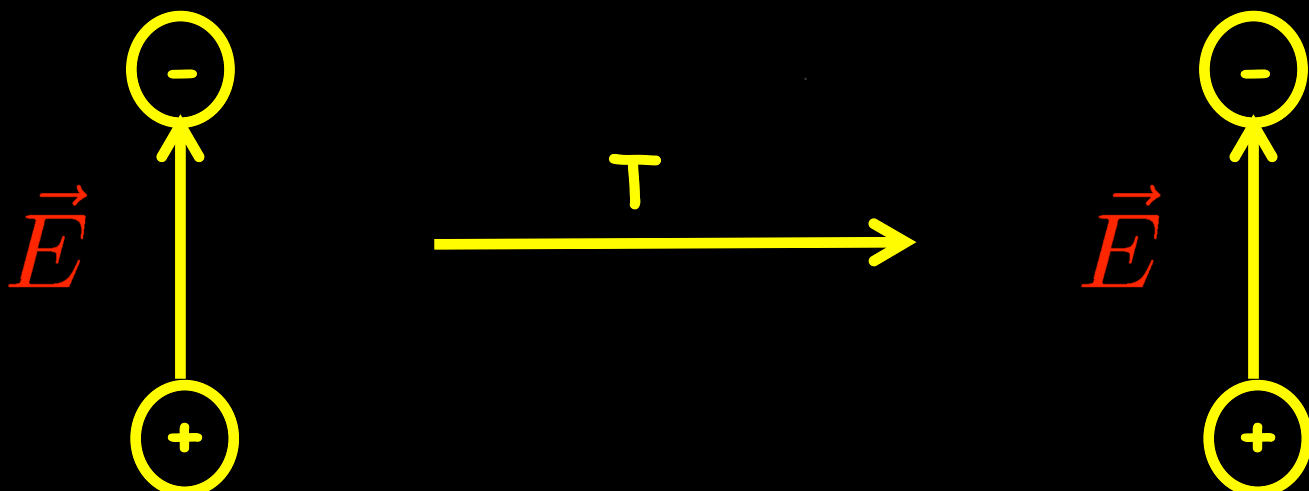
$$S = \int d^4x \left[-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu} + i\bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right]$$

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

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



A dirty little secret...

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

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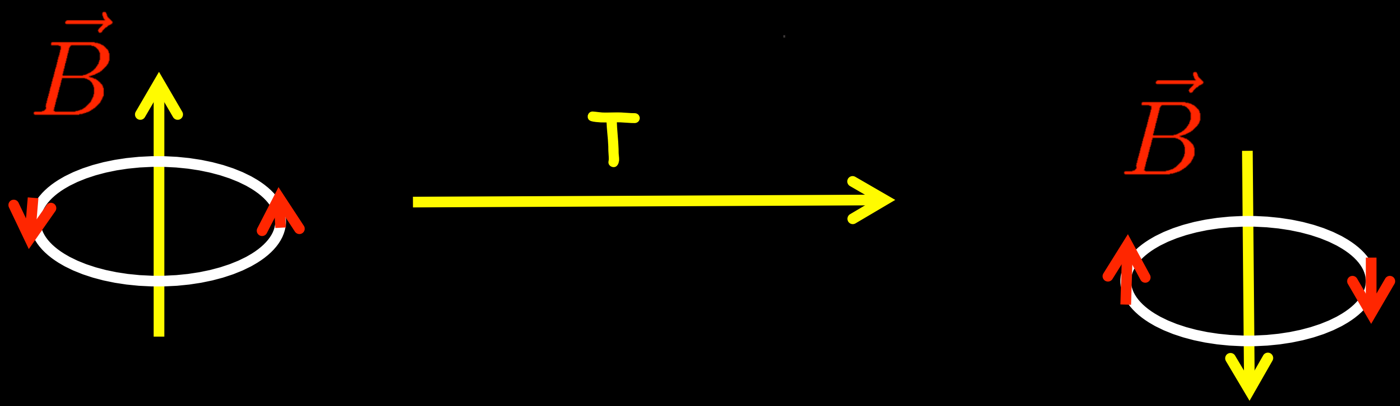

A dirty little secret...

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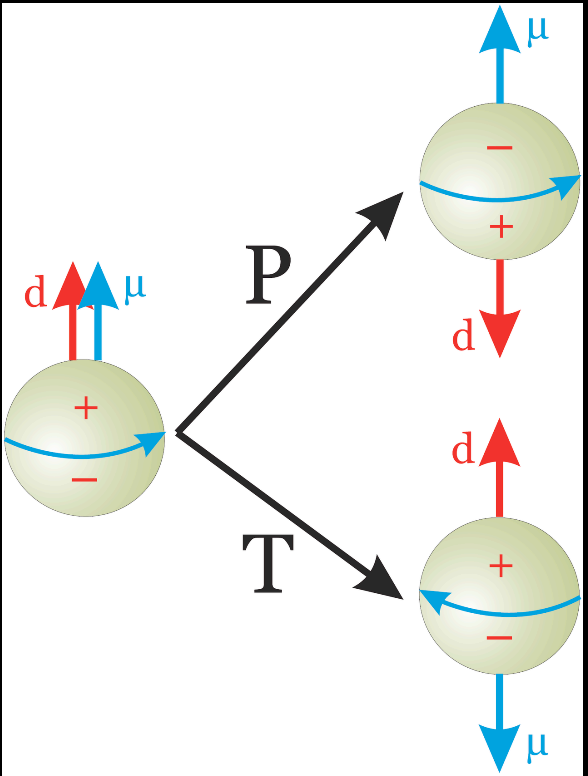
$$S = \int d^4x \left[-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu} + \imath \bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right]$$

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

- 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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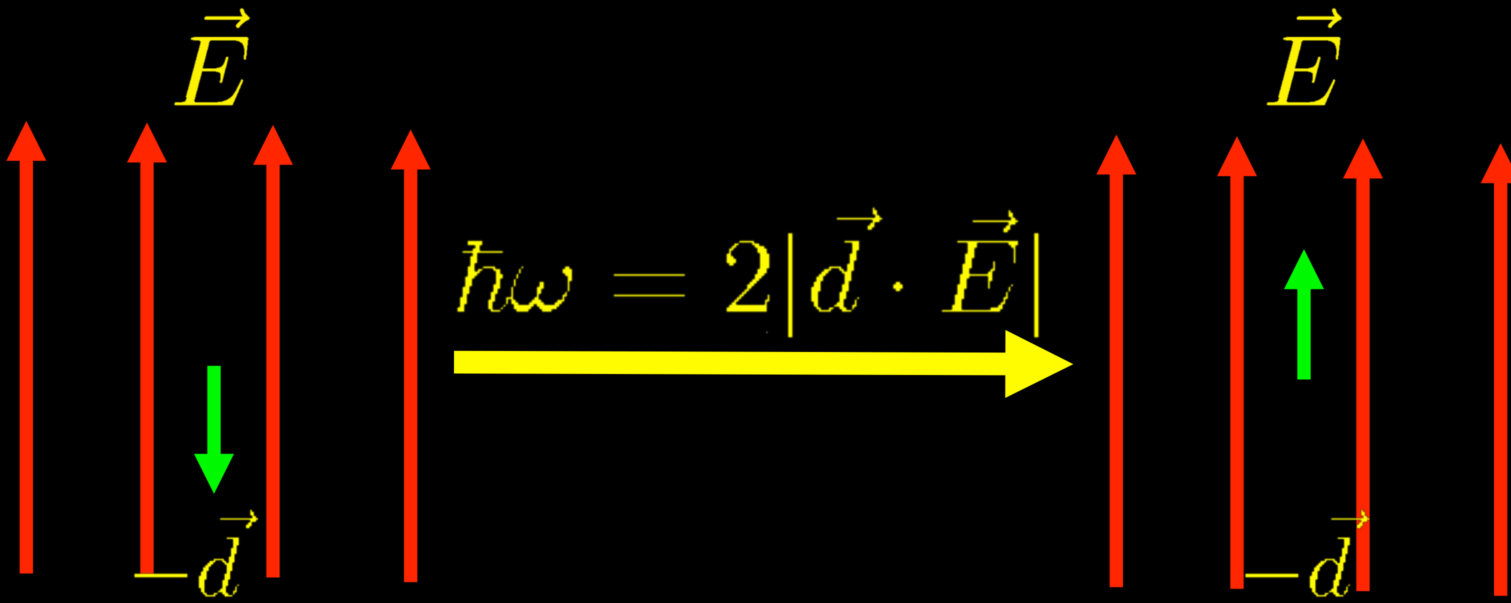
- θ would cause neutron EDM ⟶ Experiment



⟶ Measure transition frequency.

No neutron electric dipole moment...

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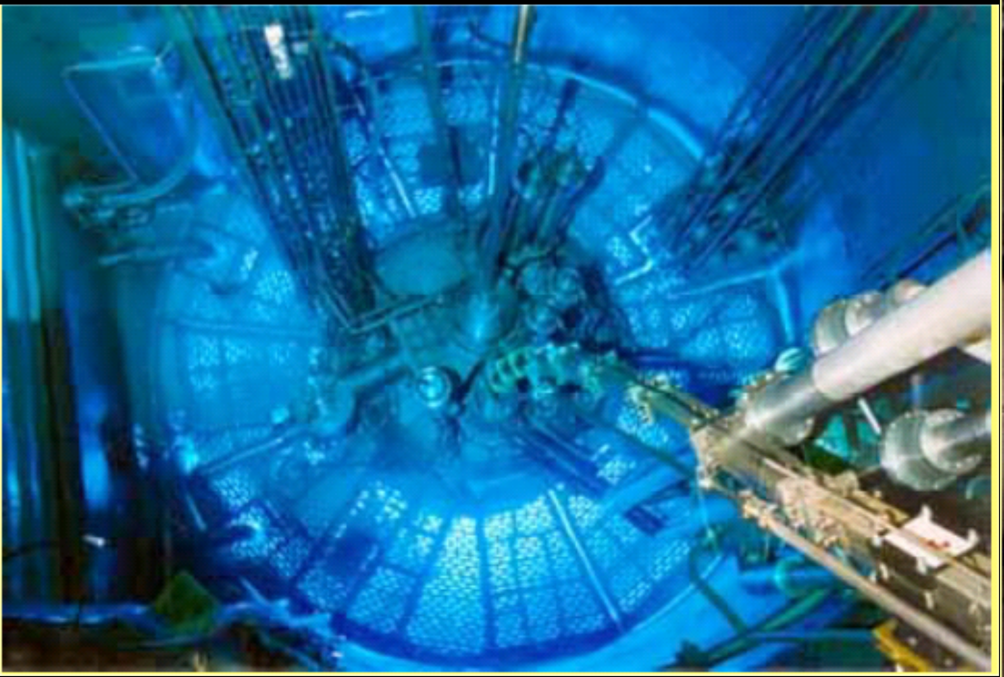
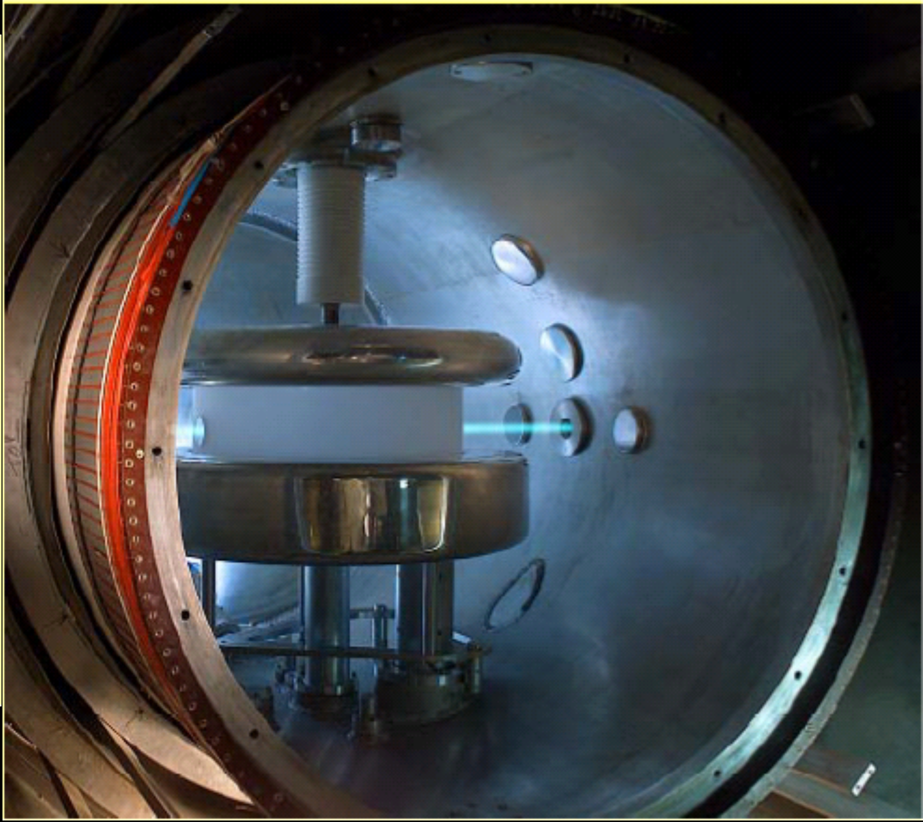


RAL-Sussex-ILL EDM collaboration



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

What do we expect?

- 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

- Detailed calculation gives

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

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

⇒ **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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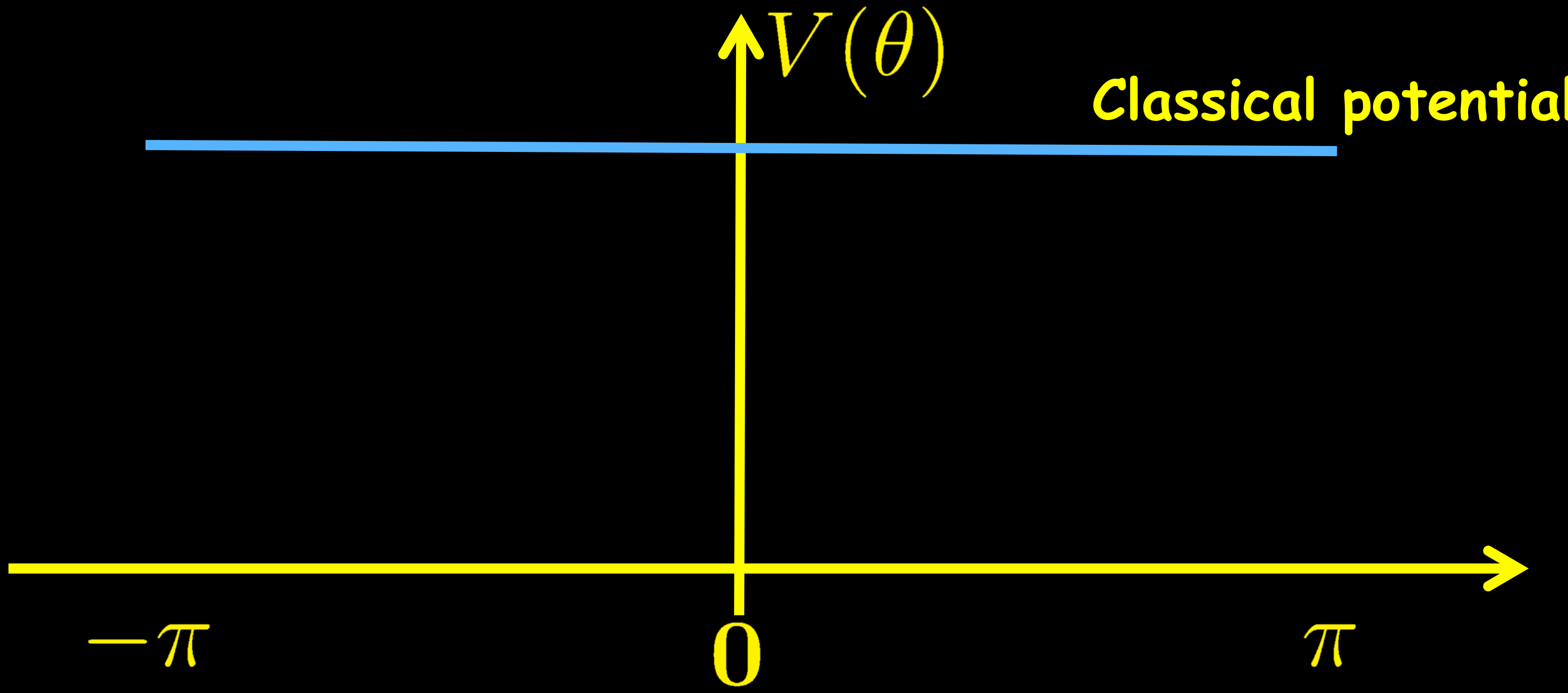
- Make θ dynamical → it can change its value



The axion solution to the strong CP problem

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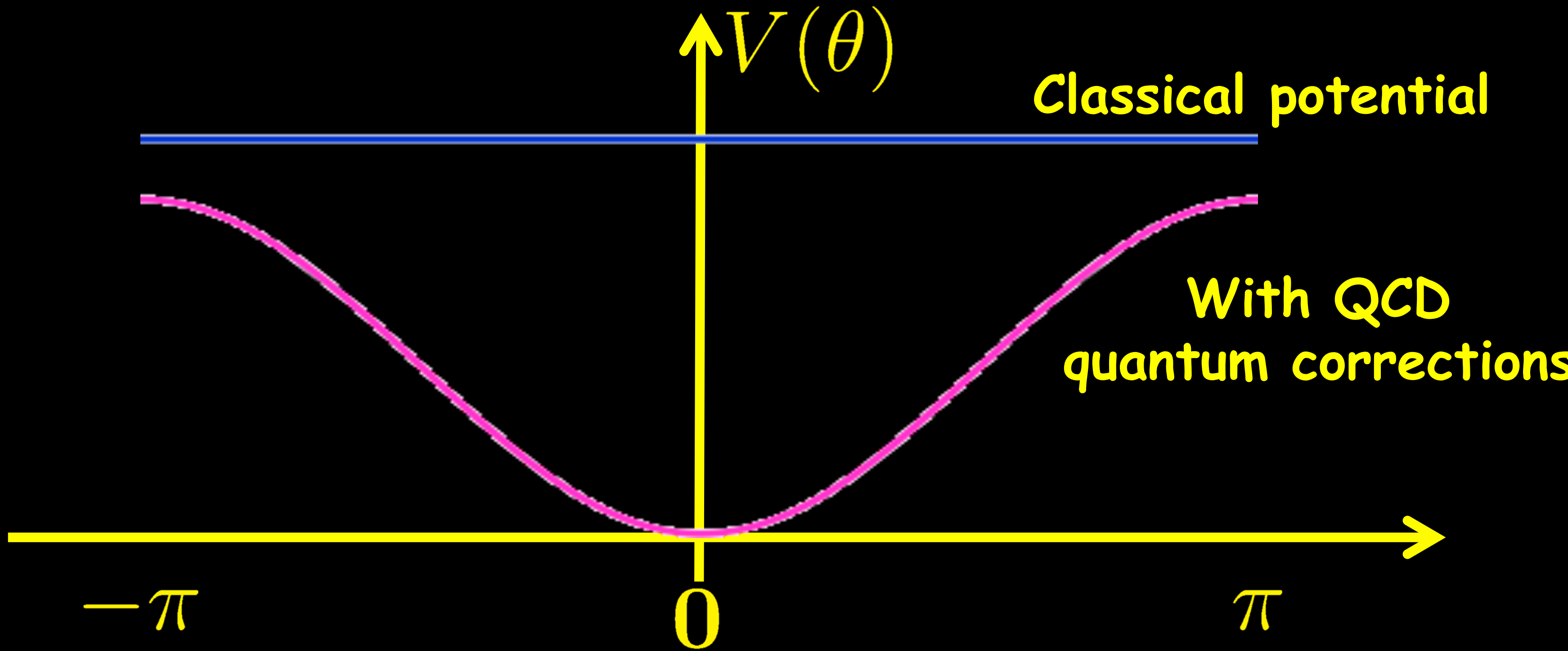
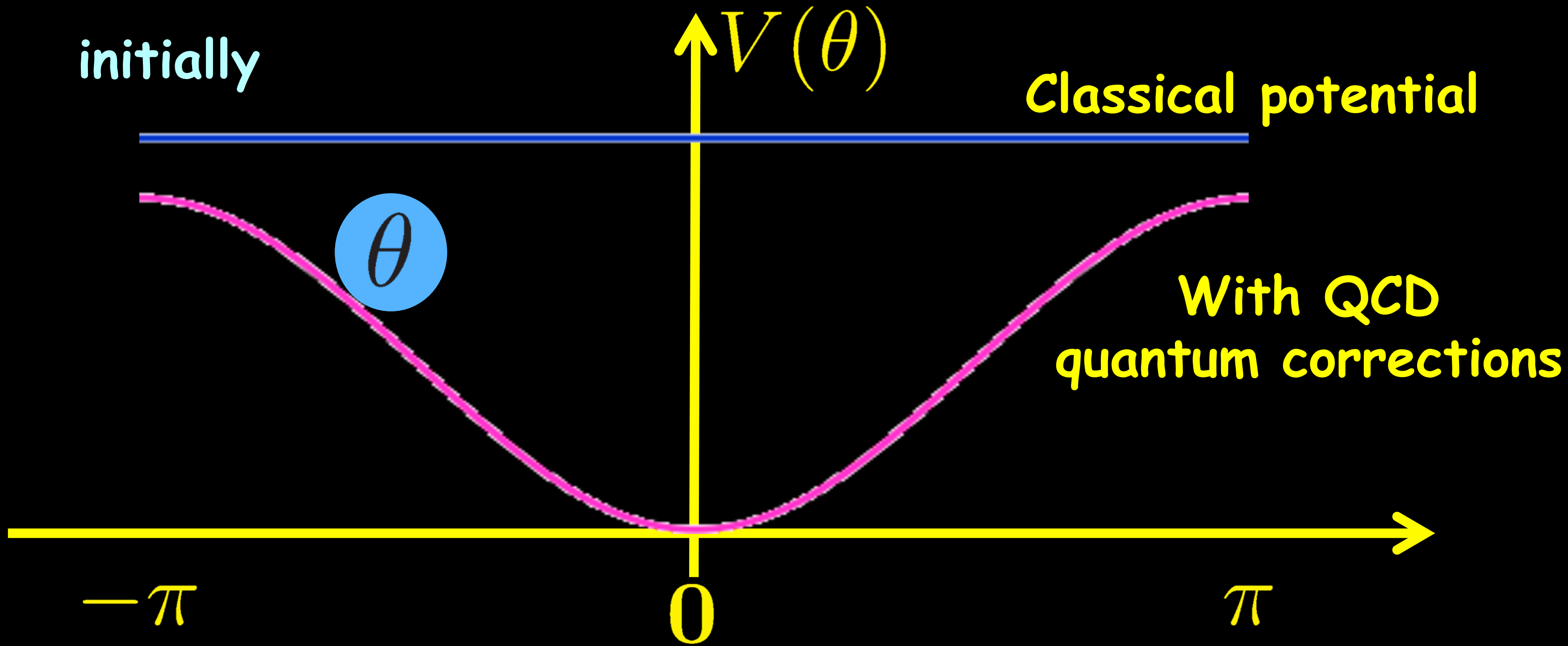
- Make θ dynamical → it can change its value



The axion solution to the strong CP problem

- Make θ dynamical → it can change its value



The axion solution to the strong CP problem

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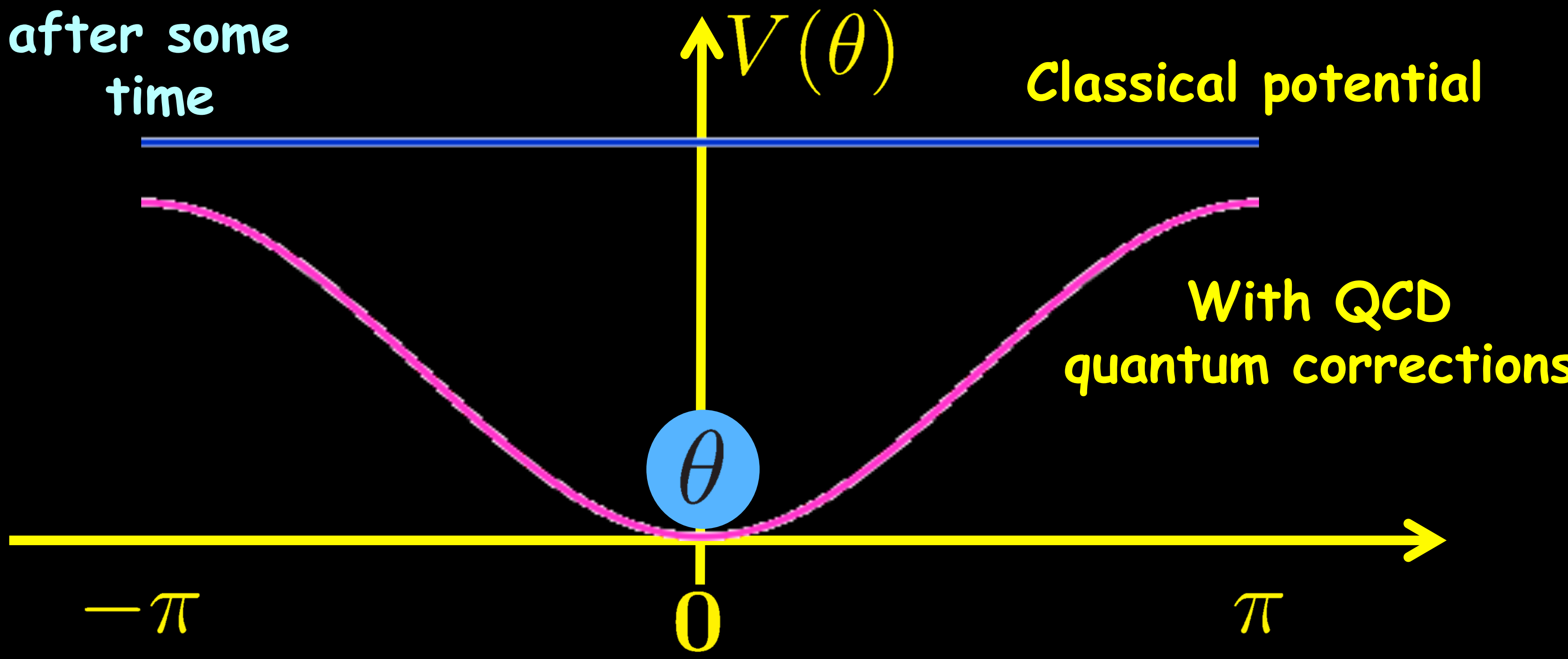
- Make θ dynamical ➔ it can change its value



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

The axion solution to the strong CP problem

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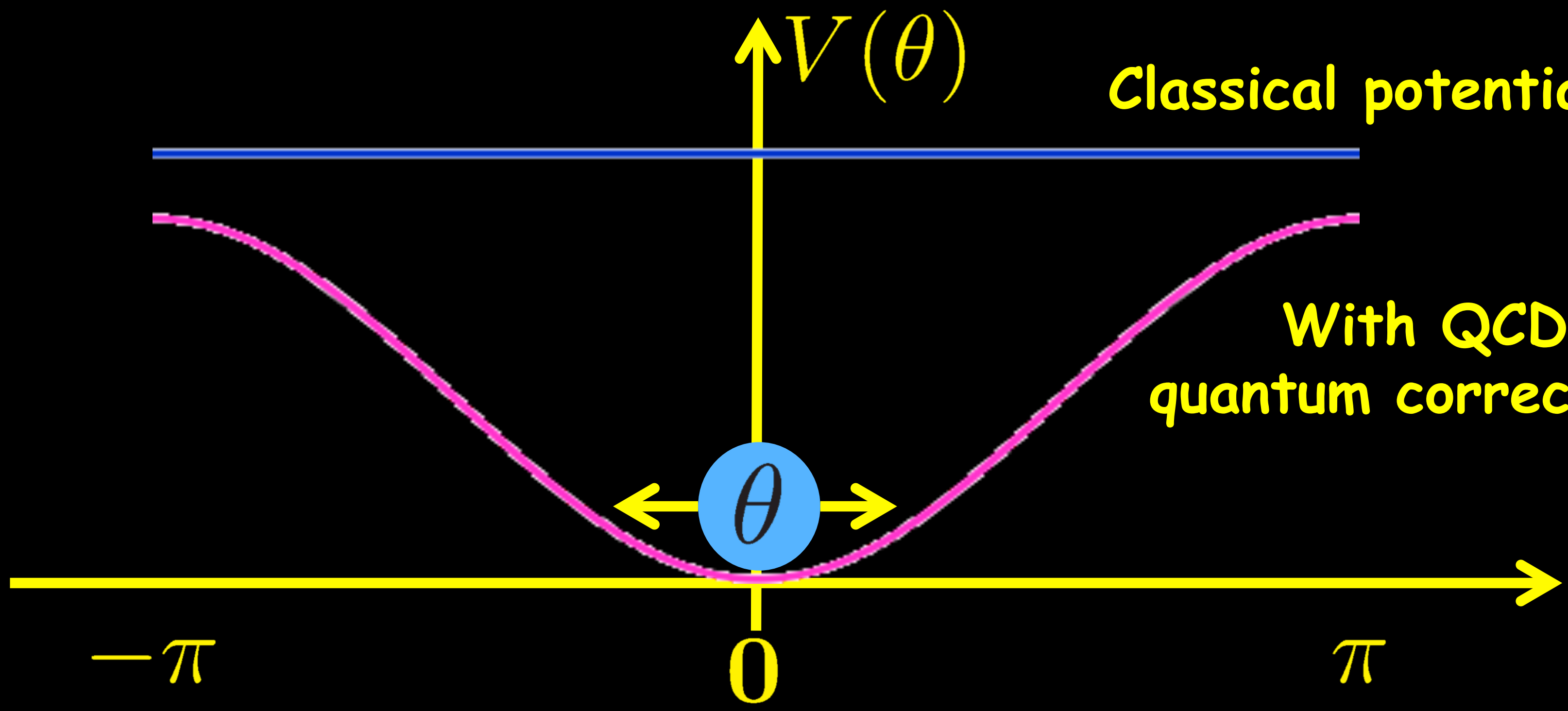
- Make θ dynamical ➔ it can change its value



➔ 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

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

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

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

$$\leq \int \mathcal{D}A_\mu \exp\left(-S_{eff}[\phi, A^\mu]\right)$$

$$\leq \exp\left(-\int_x V[0]\right)$$

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 $\theta = a/f_a$

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

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

⇒ CP is conserved

What is a?

- 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:**

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

- **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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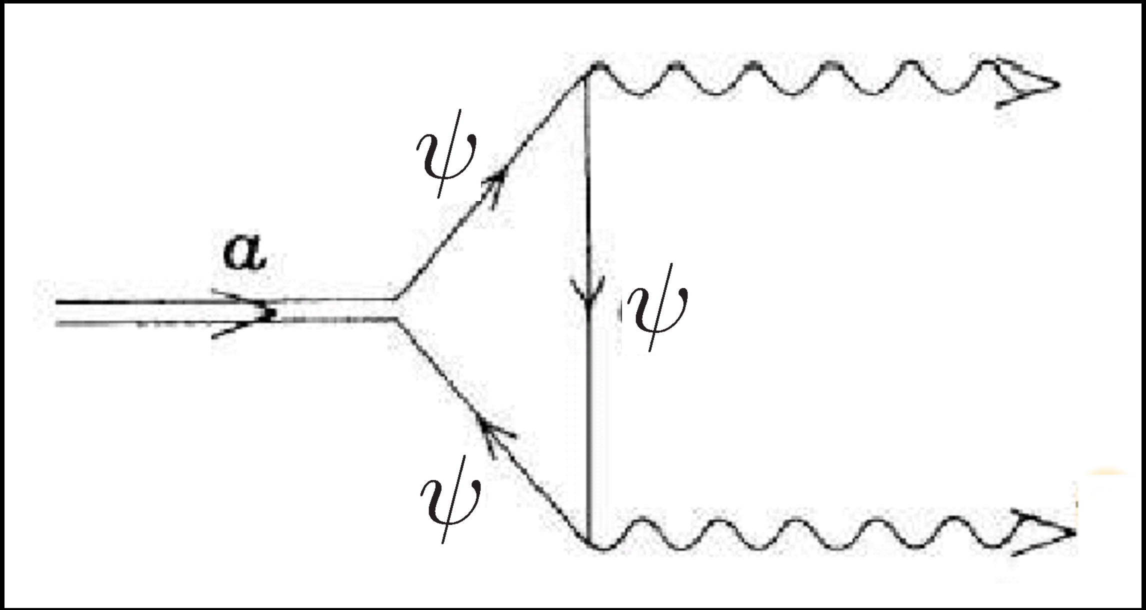
- A diagram



- And a dimensional argument:

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

The Coupling to $F\tilde{F}$

- **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**

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

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

$$\frac{\beta}{2} = \frac{a}{f_a}$$

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

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

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

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 $m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}$

One can actually calculate the potential

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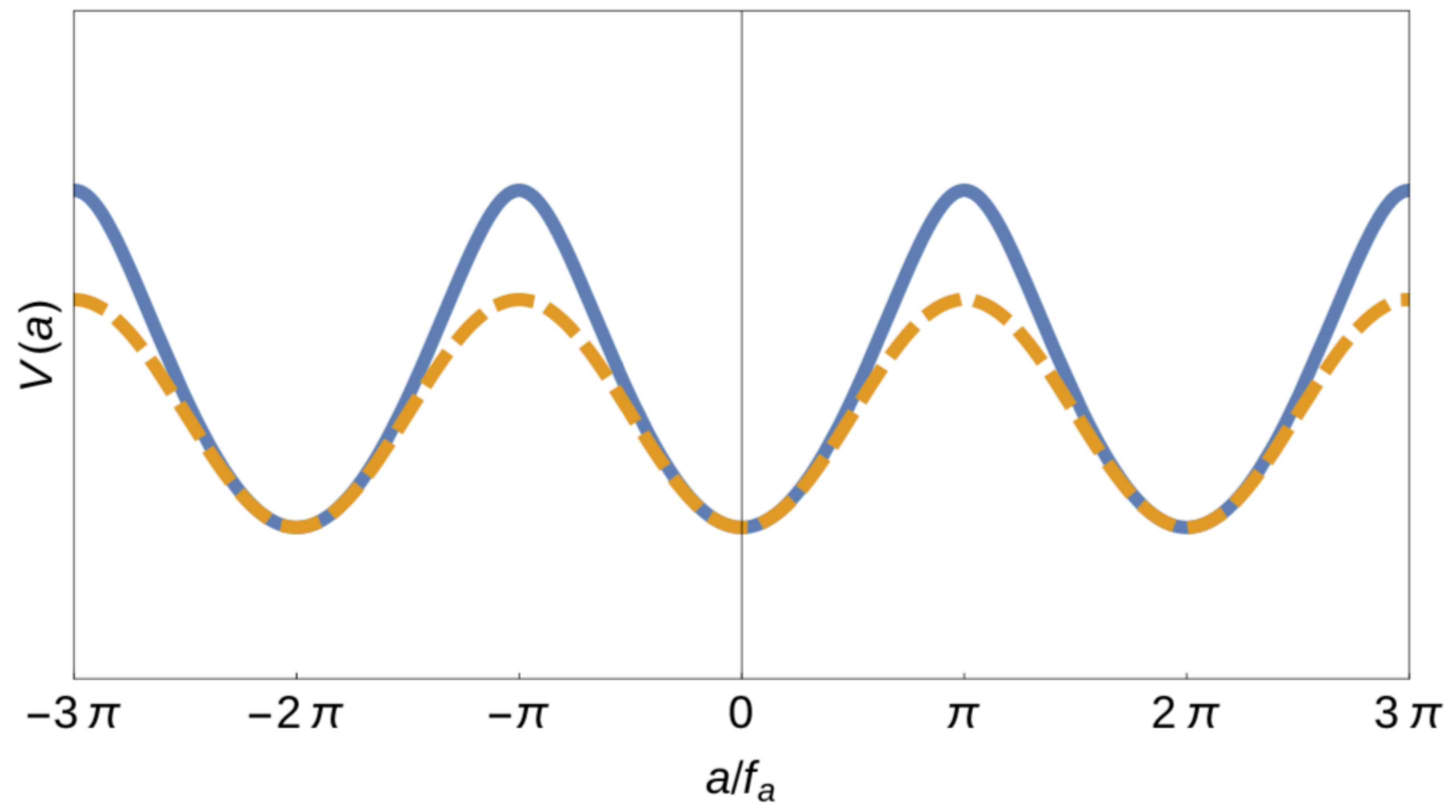
$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a}\right)}$$

The QCD axion, precisely

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



“Argument”
Topological Susceptibility

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

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

$$= \int \mathcal{D}A_\mu \exp\left(-S_{eff}[\phi, A^\mu]\right) \exp\left(-i\theta Q\right)$$

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

$$= -\langle Q^2 \rangle$$

$$= -\mathcal{V}\chi_{top}$$

➔ $$m_a^2 f_a^2 = -\chi_{top}$$

Axions and Axion-like Particles

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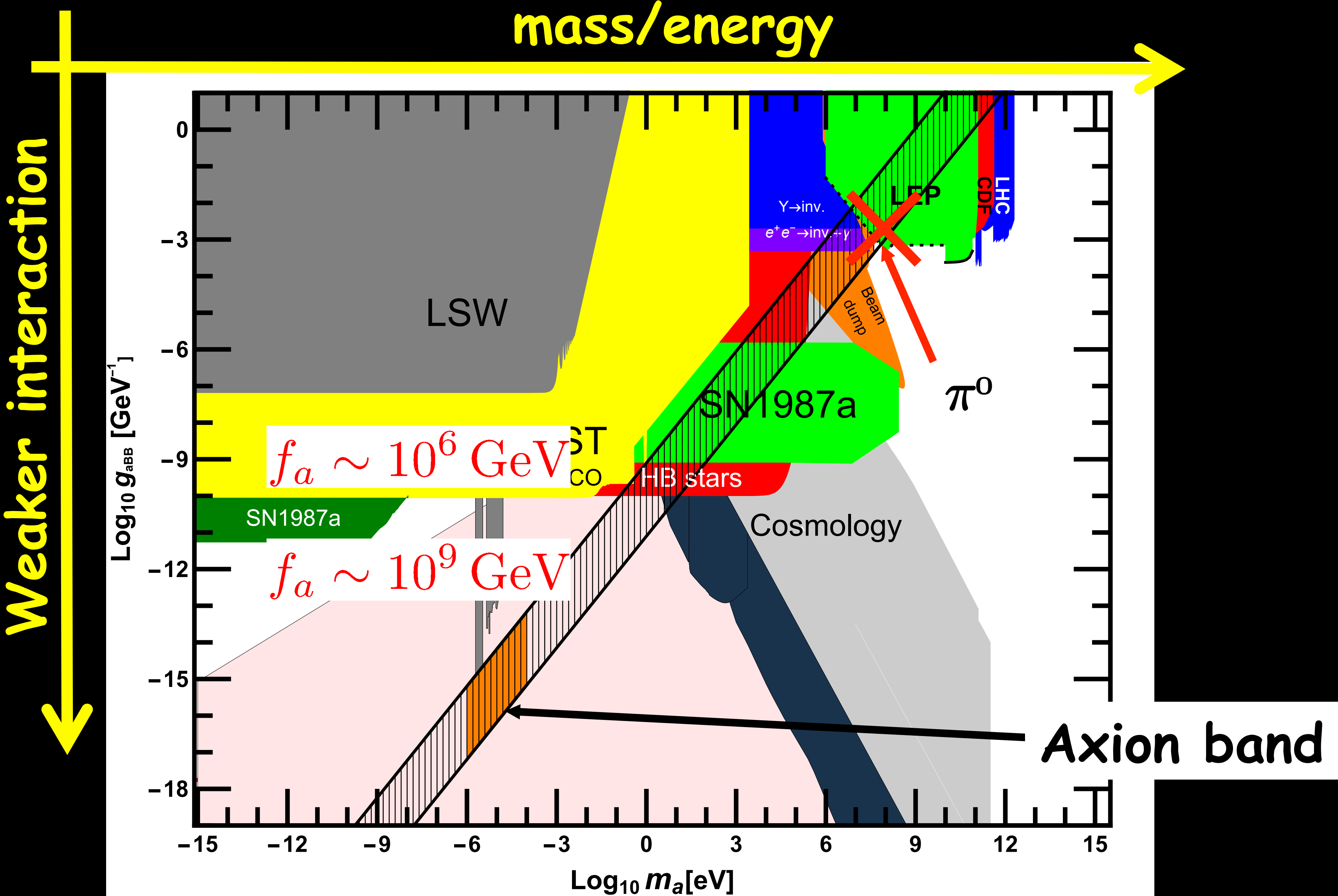

Add on
to yesterday's tutorial

Topology of U(1) vs SU(3)

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Topological concepts in gauge theories
Frieder Lenz (Erlangen - Nuremberg U., Theorie III). 2001. 83 pp.
Published in **Lect.Notes Phys. 659 (2005) 7-98**
FAU-TP3-04-3
DOI: 10.1007/978-3-540-31532-2_2
Conference: C01-09-24.6
e-Print: **hep-th/0403286** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Consider inequivalent pure gauge vacua

$$\mathbf{A} = \frac{1}{ig} U(\mathbf{x}) \nabla U^{\dagger}(\mathbf{x}).$$

$$U(\mathbf{x}) \to \text{const.} \quad \text{for } |\mathbf{x}| \to \infty.$$

Toward a theory of the strong interactions
Curtis G. Callan, Jr.* and Roger Dashen
Institute for Advanced Study, Princeton, New Jersey 08540
David J. Gross†
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 26 August 1977)

$$U(\mathbf{x}) : \; S^3 \longrightarrow S^3$$

$$\pi_3(S^3) = \mathbb{Z}$$

For U(1)

$$U(\mathbf{x}) : \quad S^3 \to S^1$$

$$\pi_3(S^1) = 0$$

How to find the Axion…

Exploring fundamental high energy physics…

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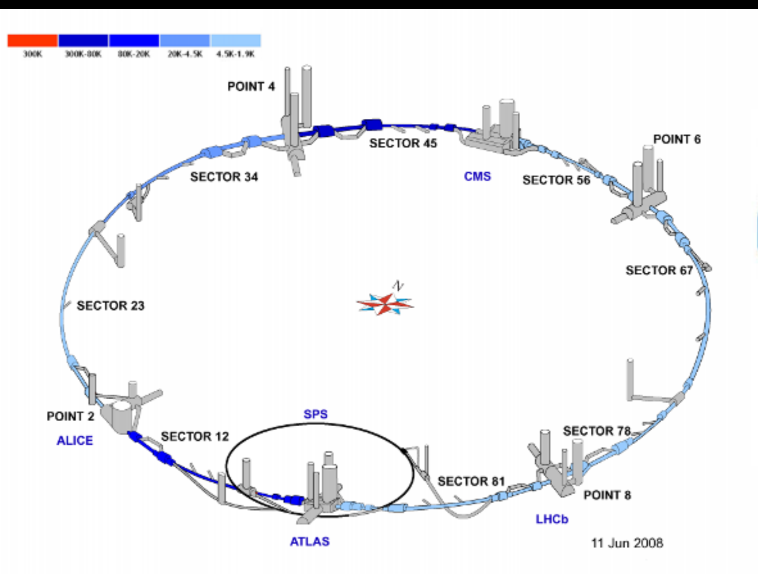
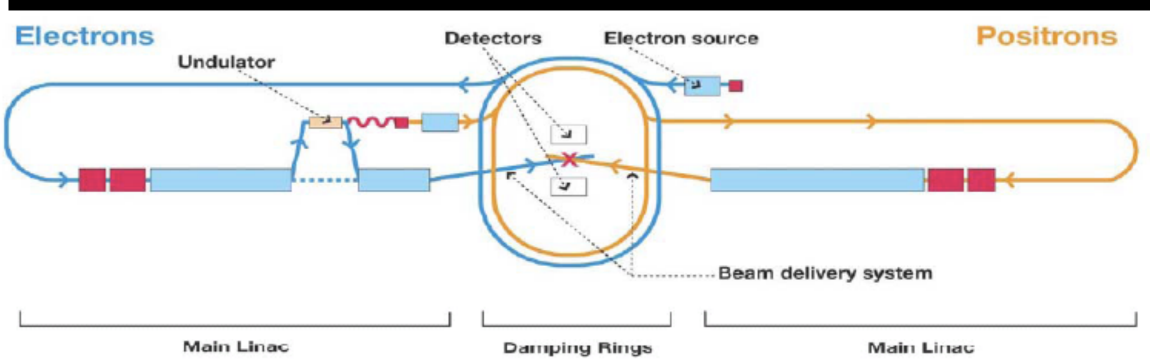
- The direct approach: MORE POWER

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

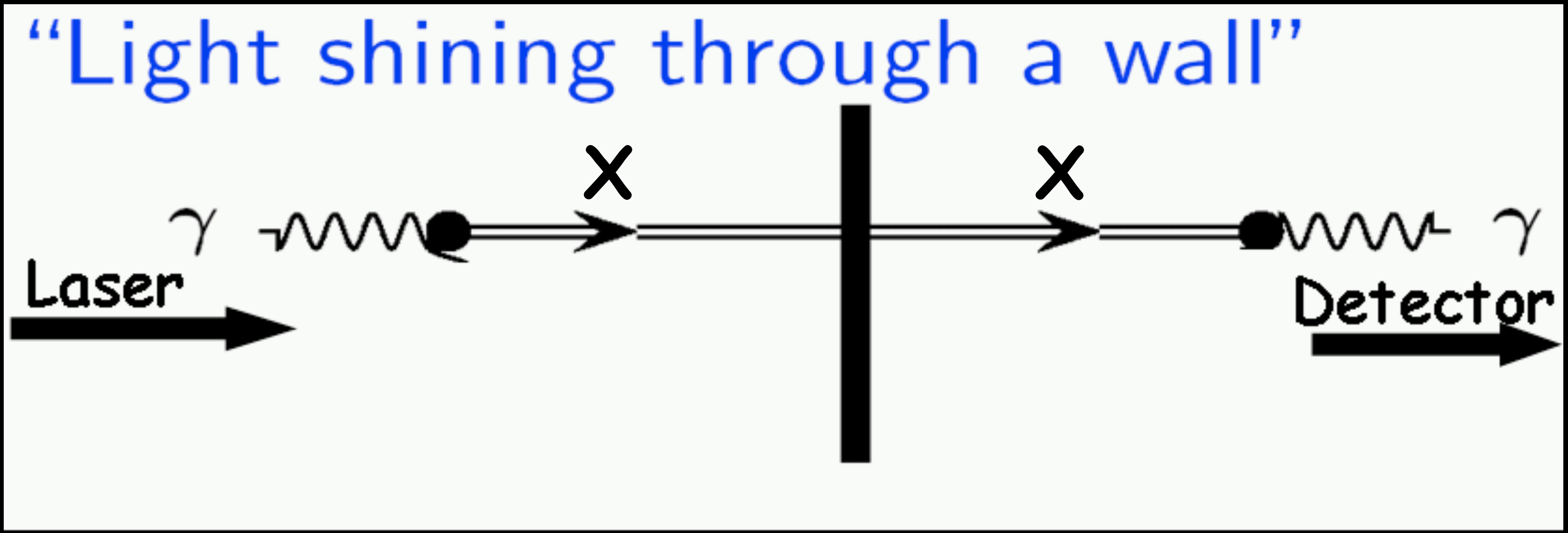
- Or much much more horrifying:

No signal above background!

The Power of Low Energy Experiments

Complementary approaches

Light shining through walls



Light shining through walls

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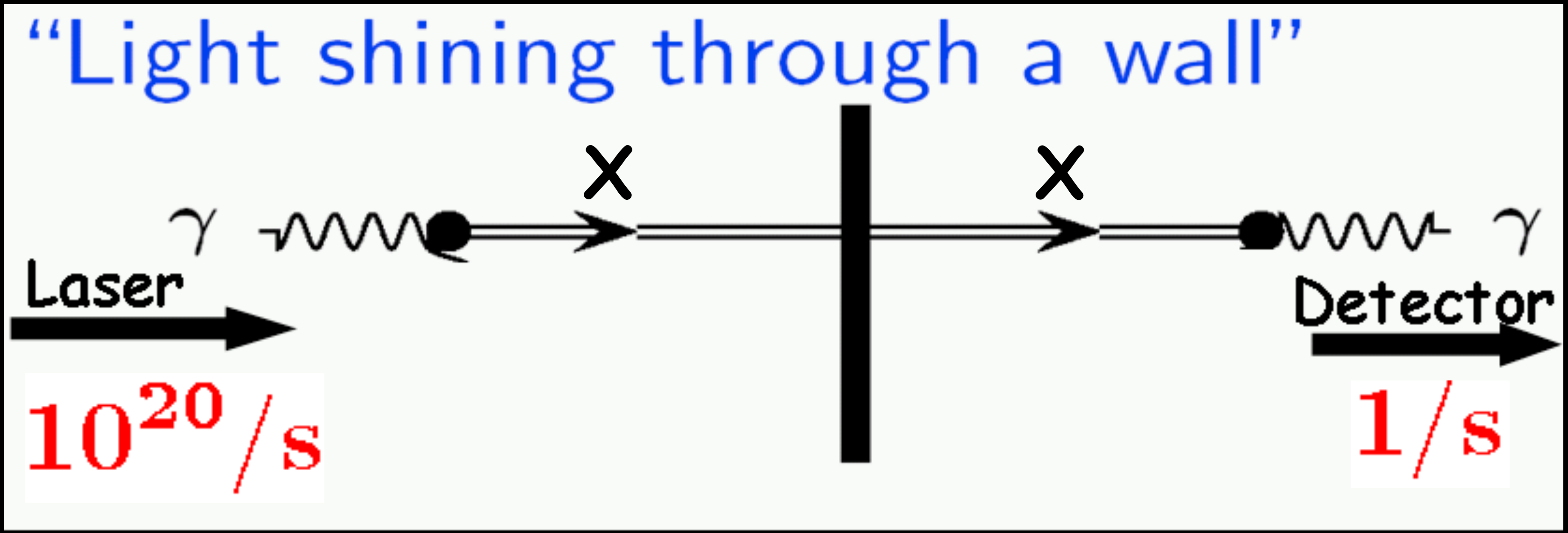
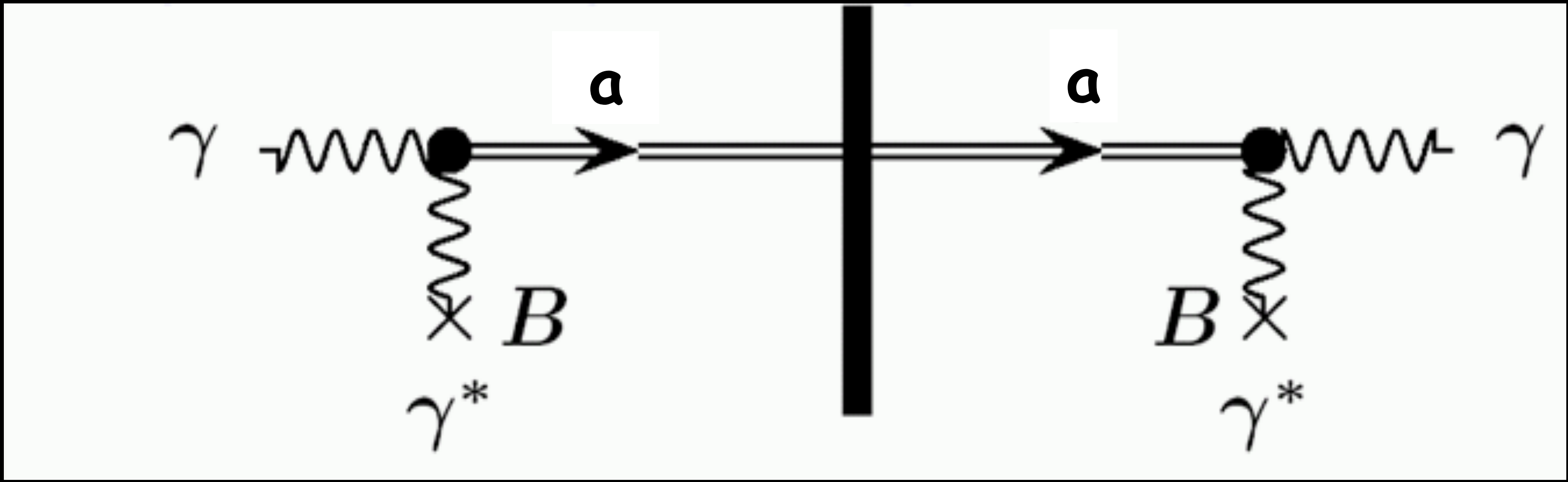


- Test $P_{\gamma\to X\to\gamma} \lesssim 10^{-20}$

- Enormous precision!
- Study extremely weak couplings!

Photons coming through the wall!

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



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

Light Shining Through Walls

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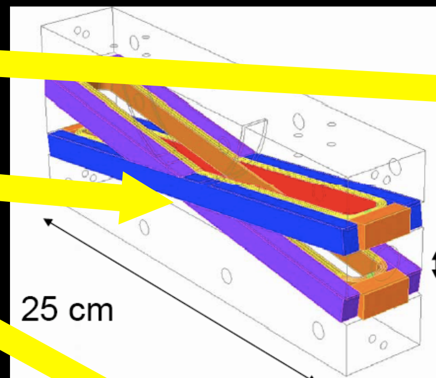
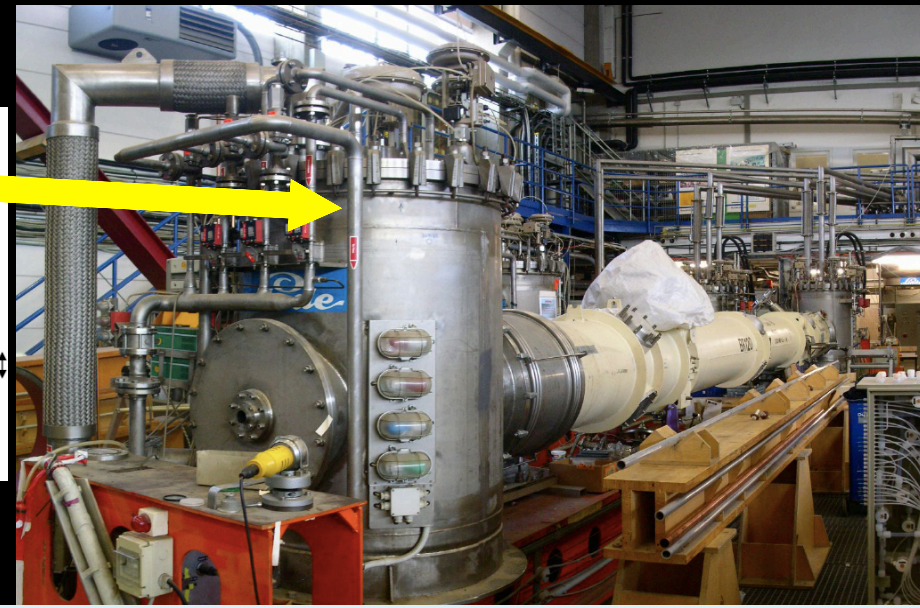
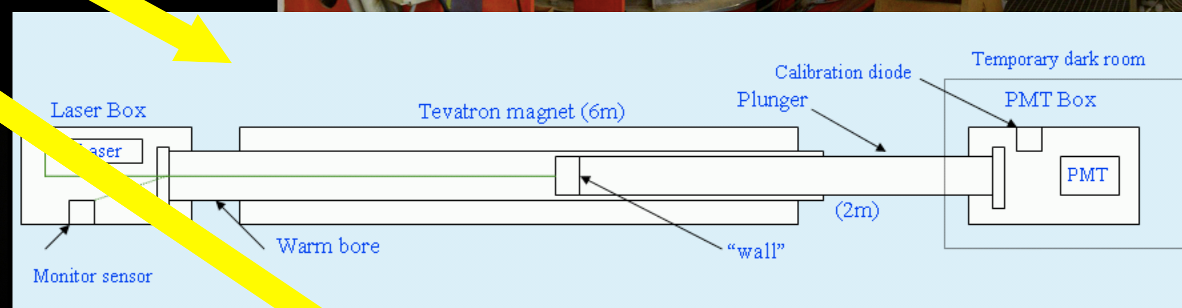
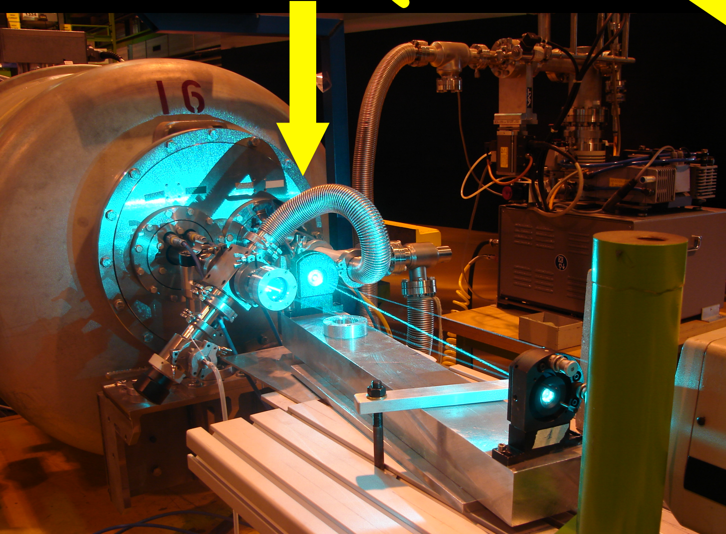
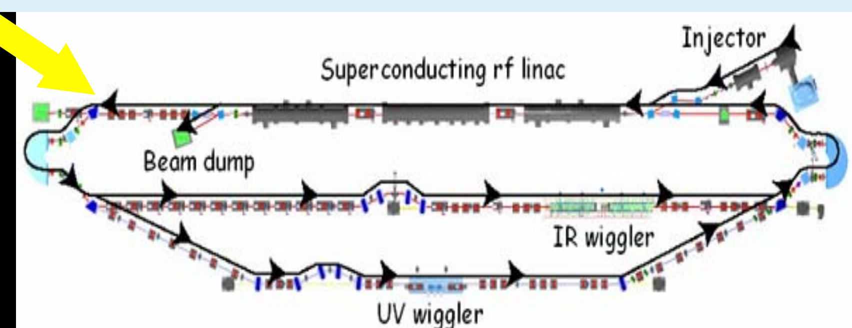
- A lot of activity
  - ALPS
  - BMV
  - GammeV
  - LIPPS
  - OSQAR











Small coupling, small mass

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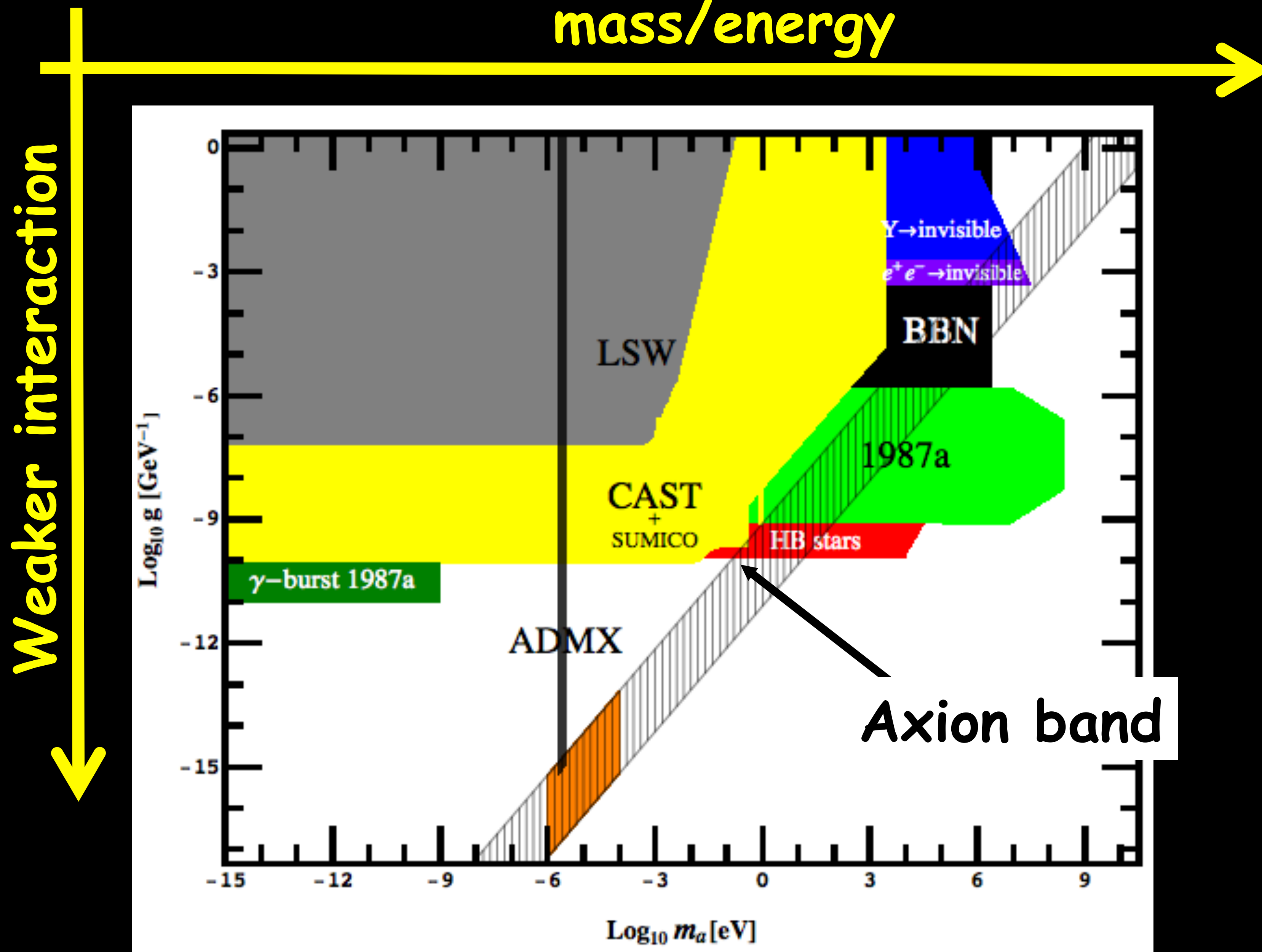
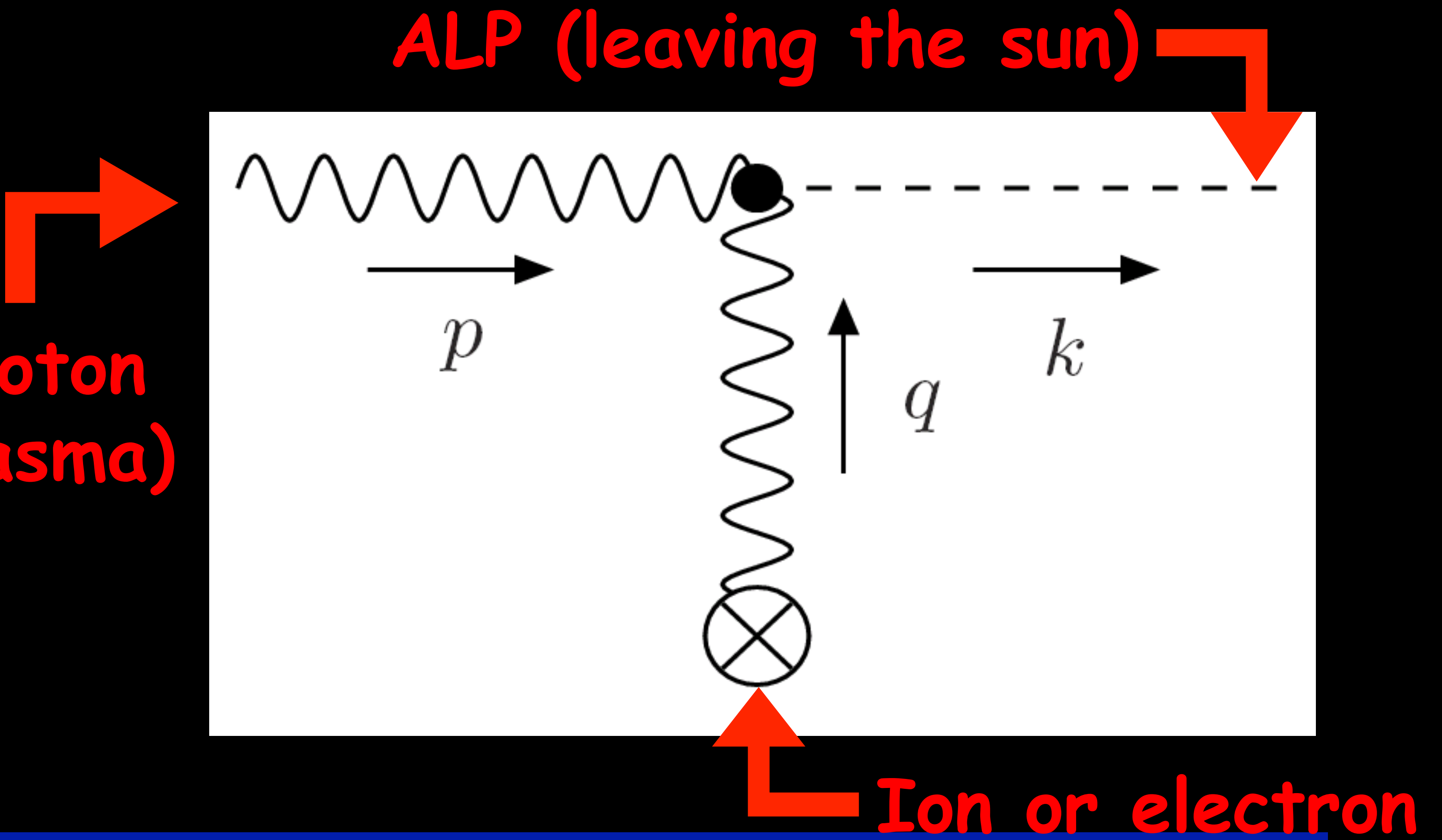


Interlude:
Think and make life hard for experimentalists…

Energy loss in stars.

- Primakoff process (in the sun)



We would freeze...

- 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:

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

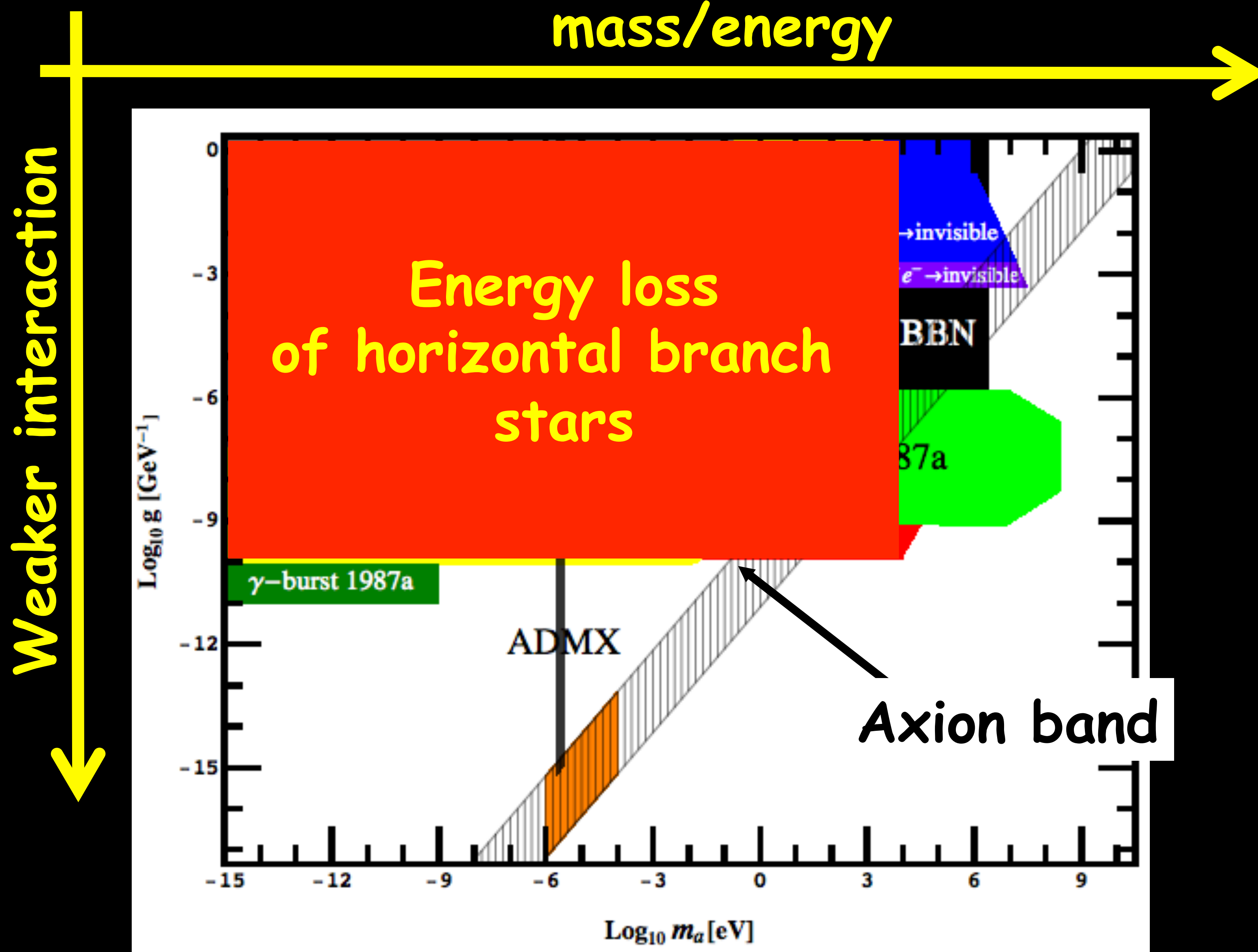
- Sun Lifetime with ALPs

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

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

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

A Real killer bound

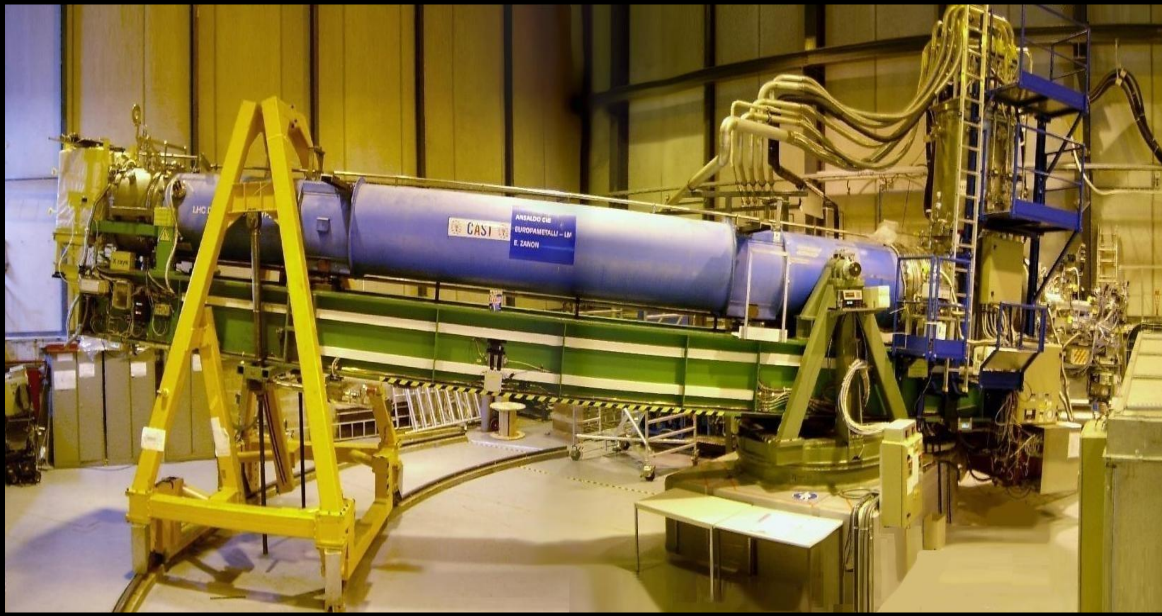


Back to experiments…

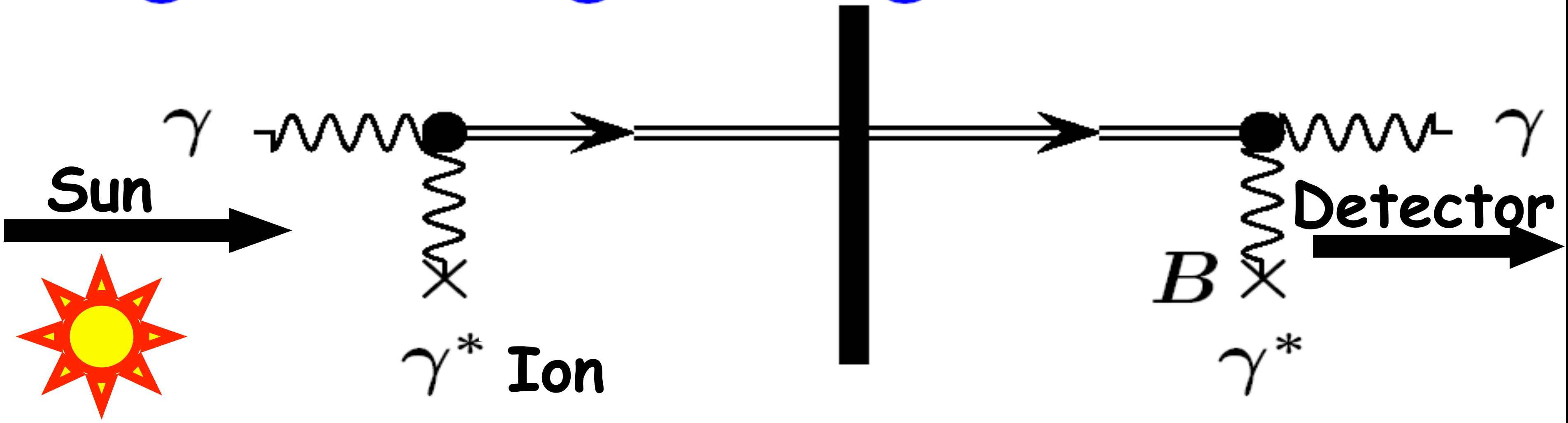
Helioscopes

CAST@CERN
SUMICO@Tokyo

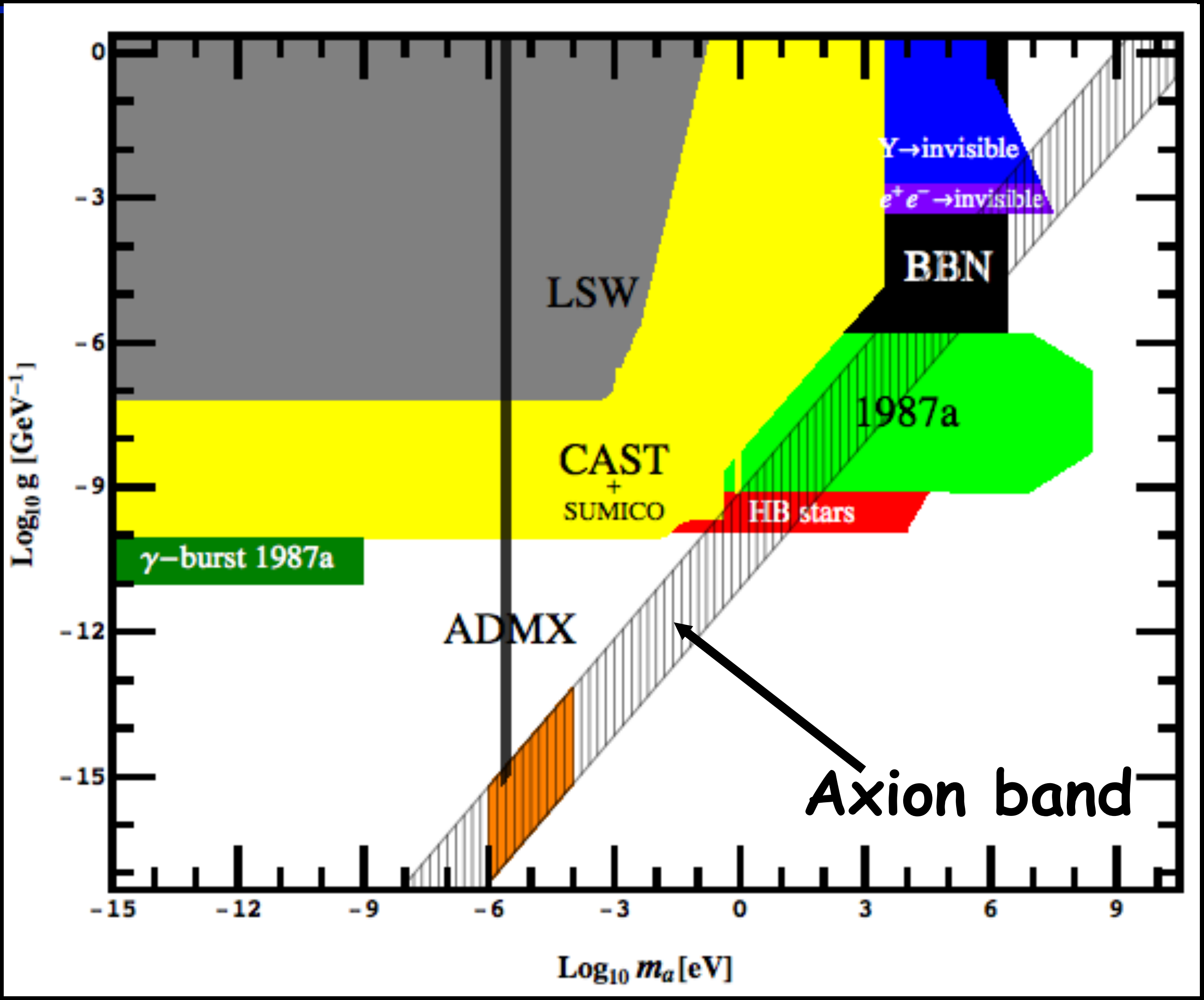
SHIPS@Hamburg



"Light shining through a wall"



Sensitivity



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Going to the future: IAXO

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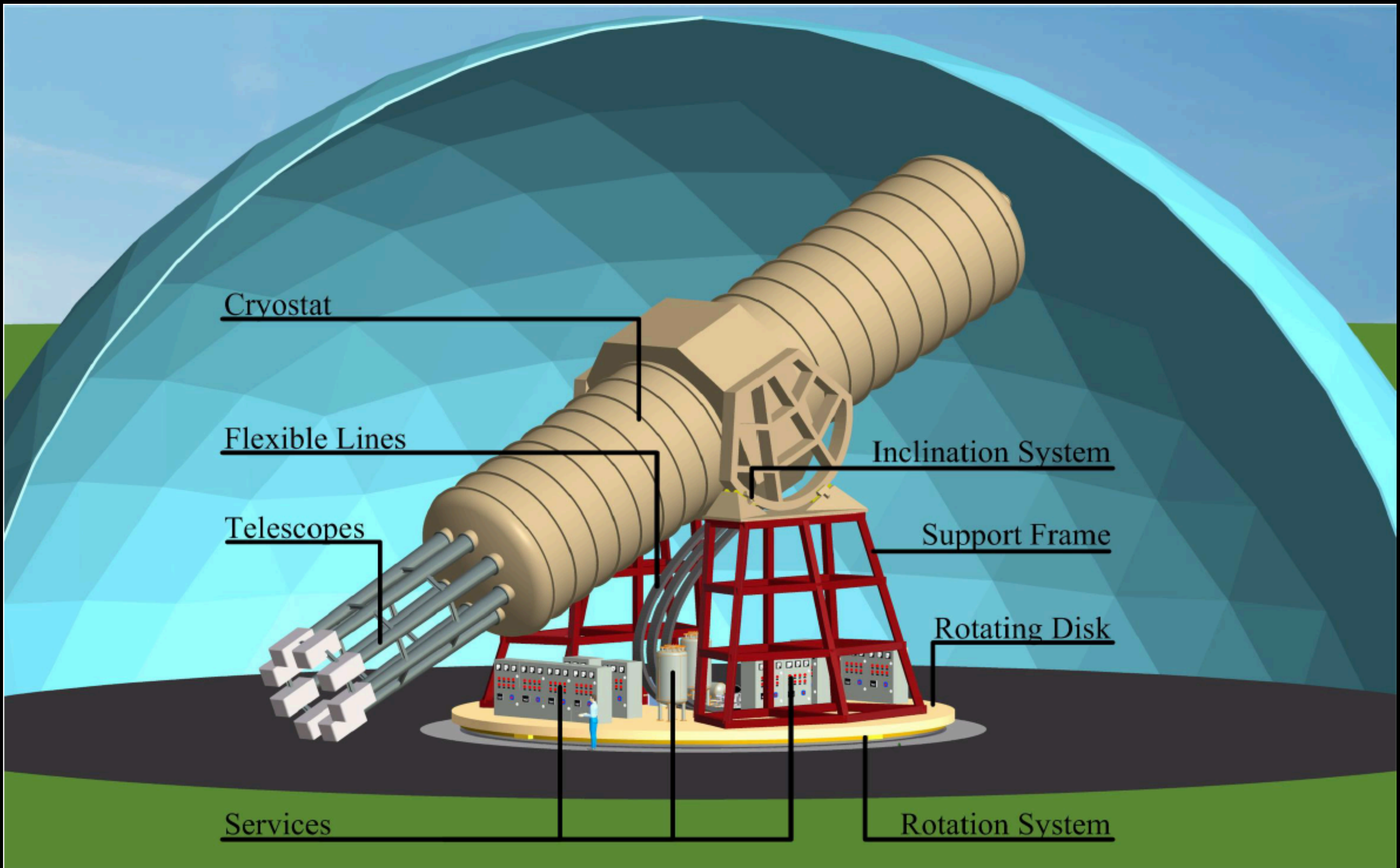
The International Axion Observatory



An interesting area...

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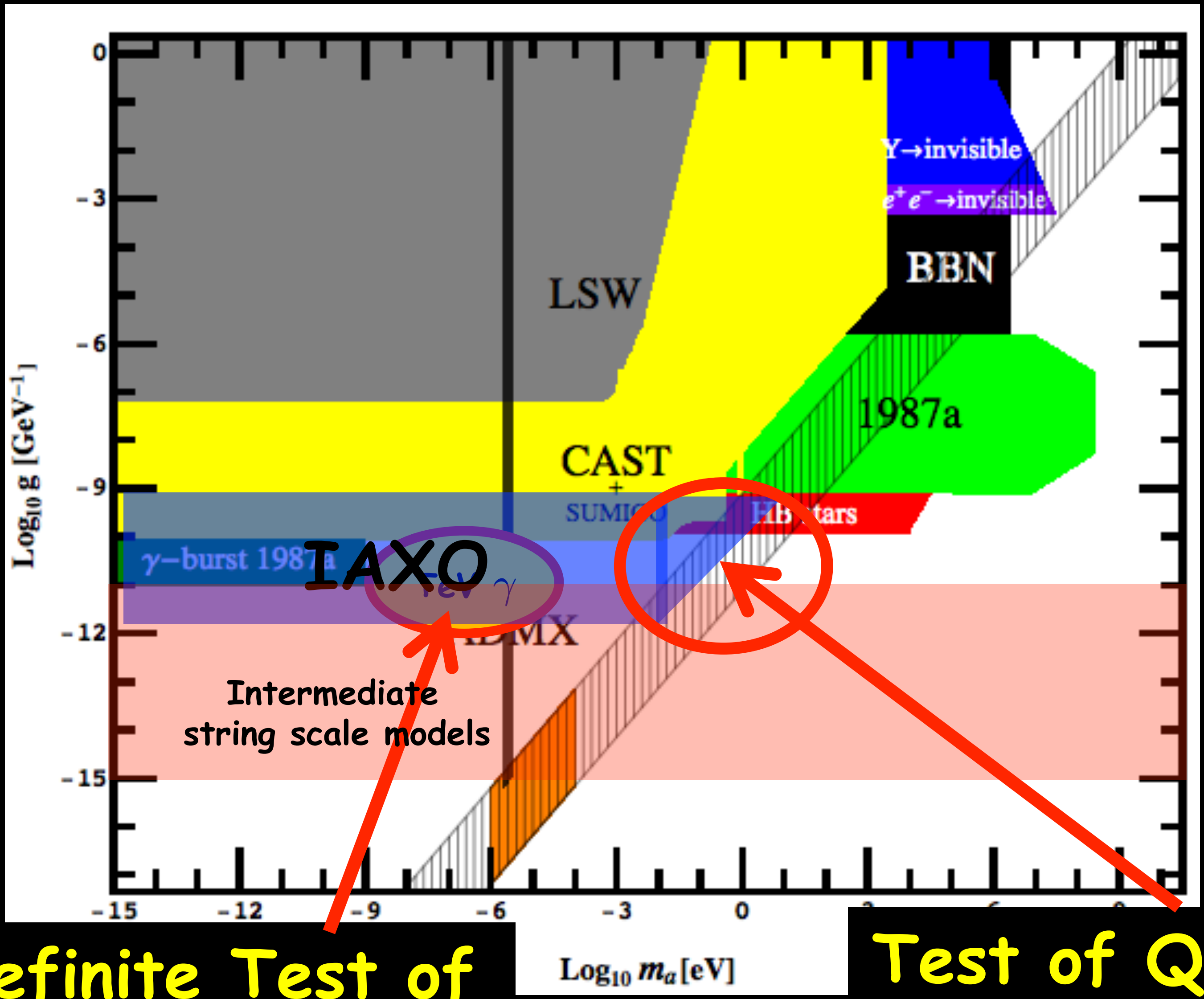

Definite Test of TeV transparency

Test of QCD axion + white dwarf anomaly

WISPS=Weakly interacting sub-eV particles

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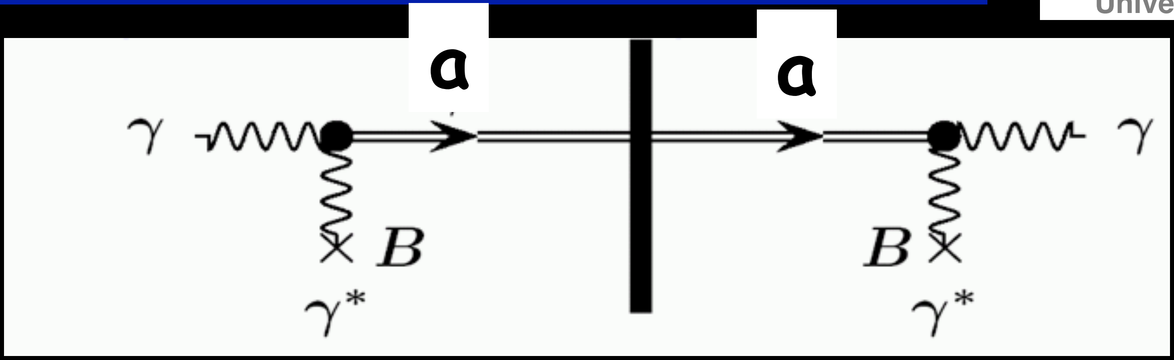
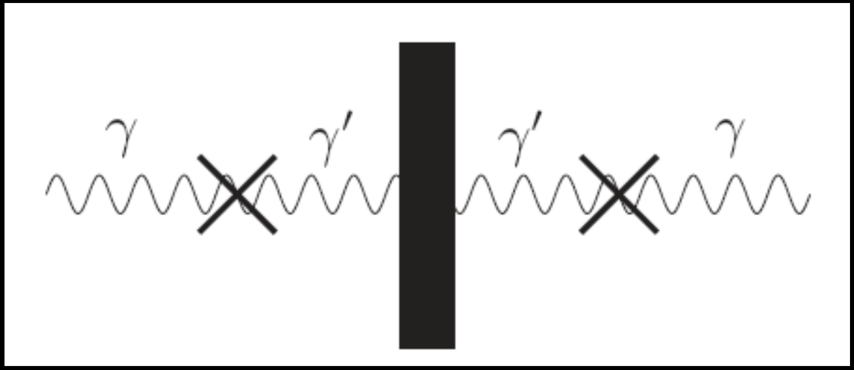
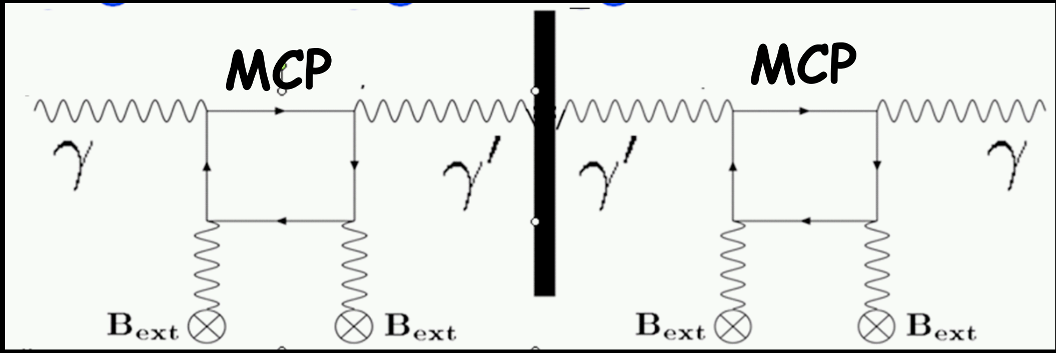
- Axions



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



- Hidden photon + minicharged particle (MCP)



Dark Matter(s)

Can Dark Matter be Axiony/WISPy?

(Weakly Interacting Sub-eV Particley)

Slim

Properties of Dark Matter

- 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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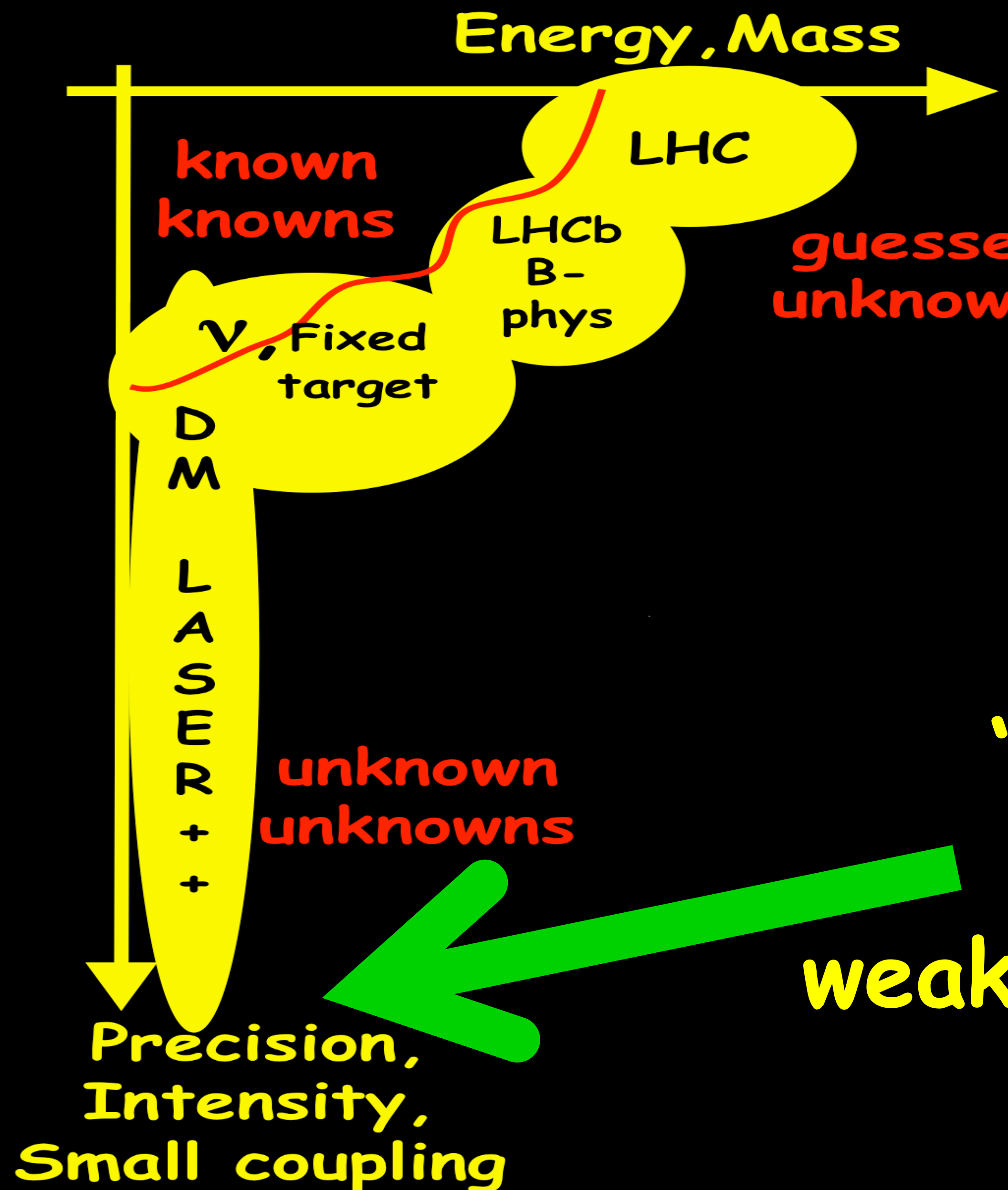


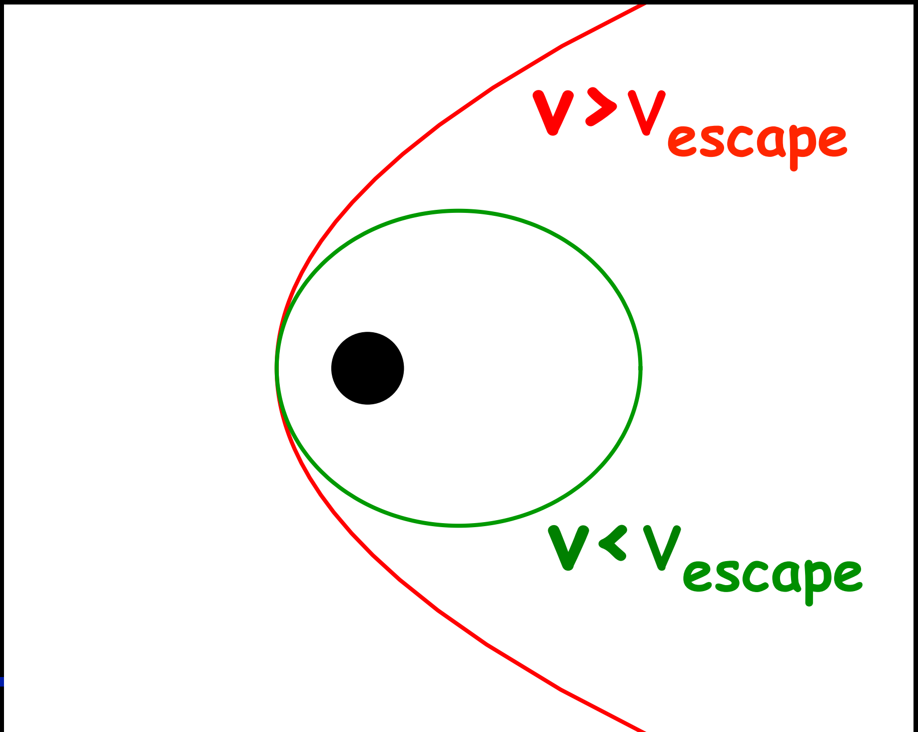
"dark" = weakly coupled

A common prejudice

- 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…

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

Dark matter has to be heavy...

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Dark matter has … avy $m_{\mathrm{DM}} \gtrsim \mathrm{keV}$?

Myth Busted

SuperCold Dark Matter

The axion has no clue where to start

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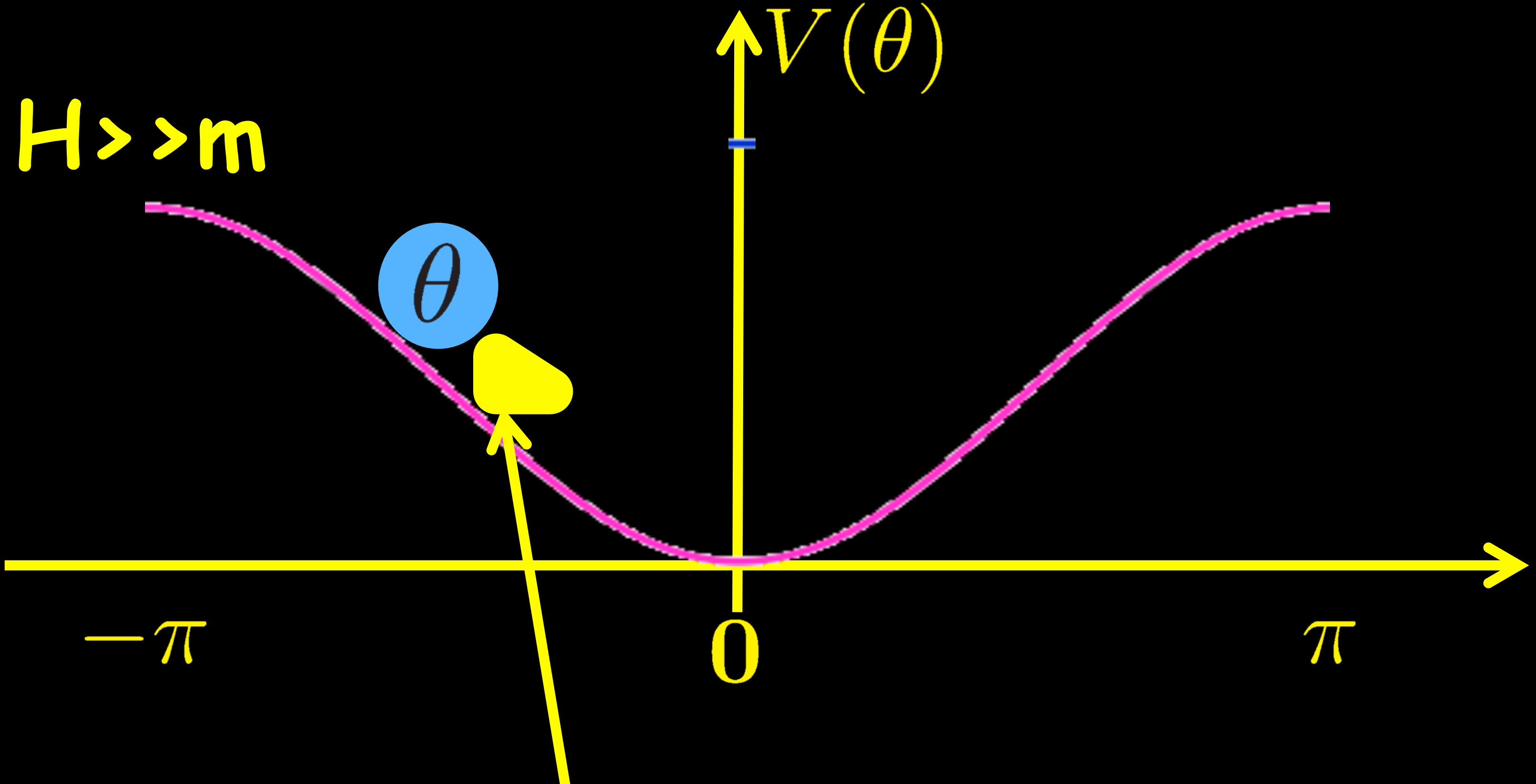

Field is stuck because of Hubble "breaking"

The axion has no clue where to start

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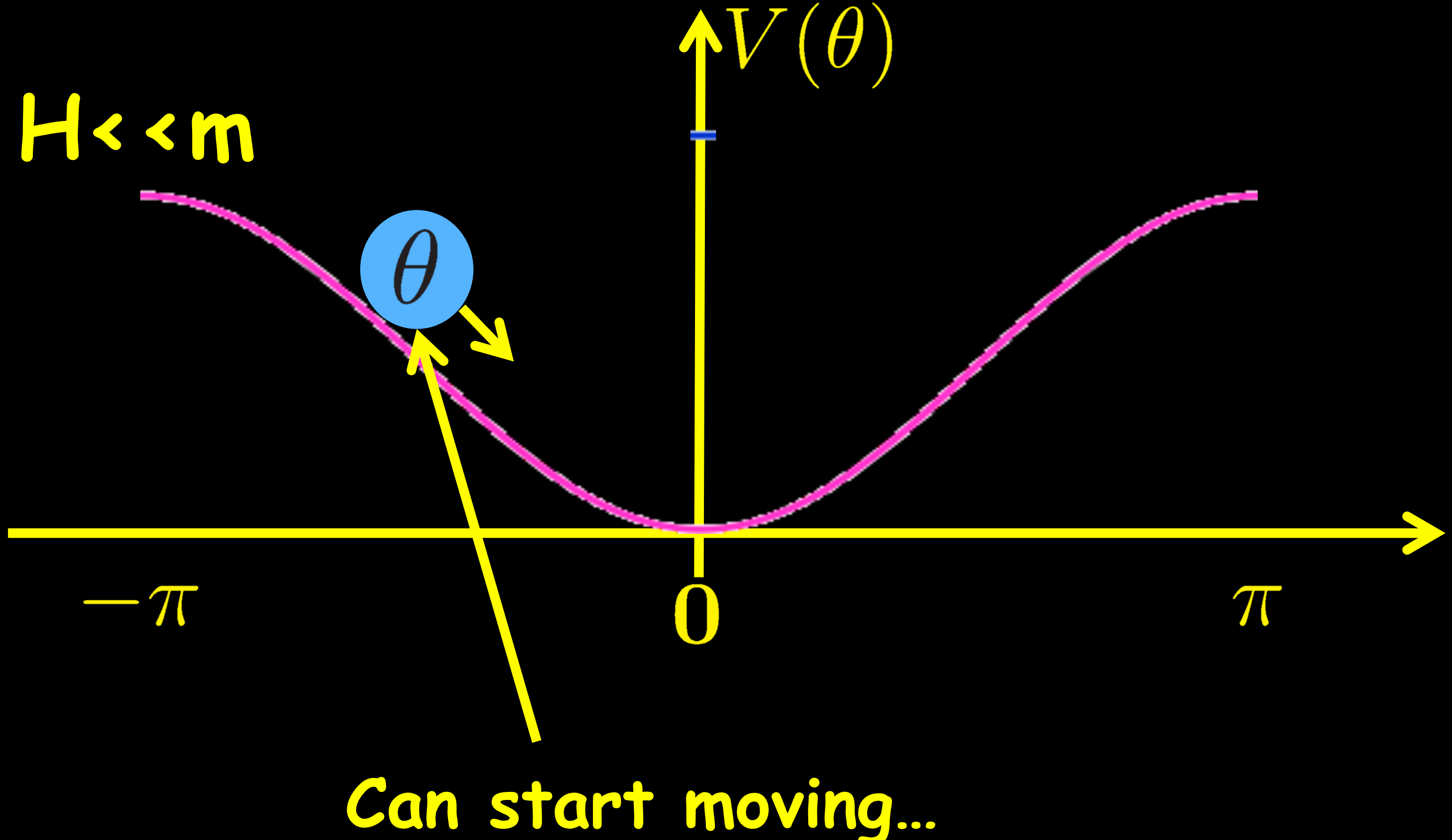

The axion solution to the strong CP problem

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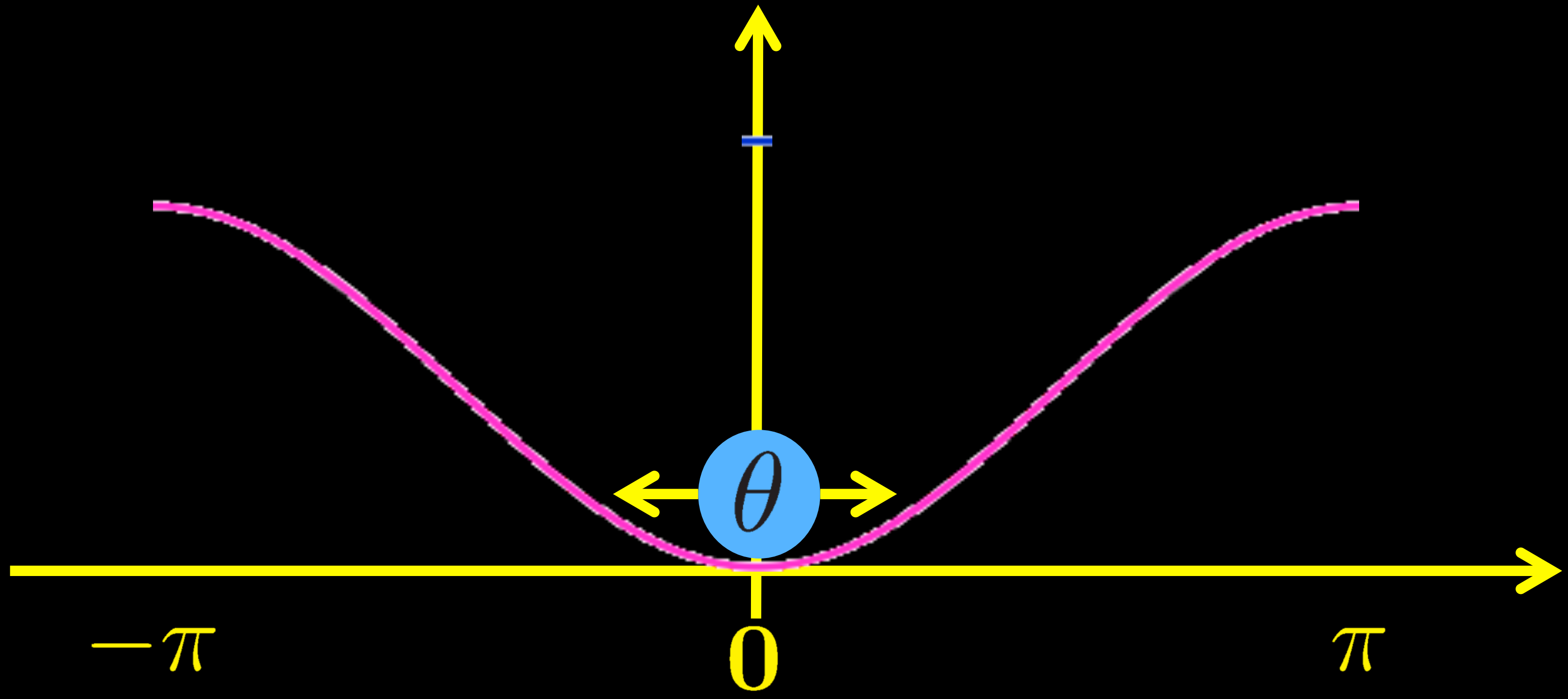

➔ Oscillations contain energy
➔ behave like non-relativistic particles (T=0)

Axion Dark Matter

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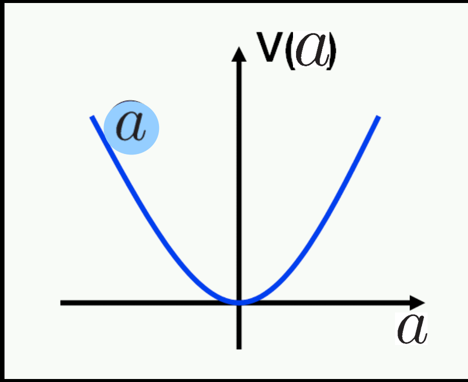
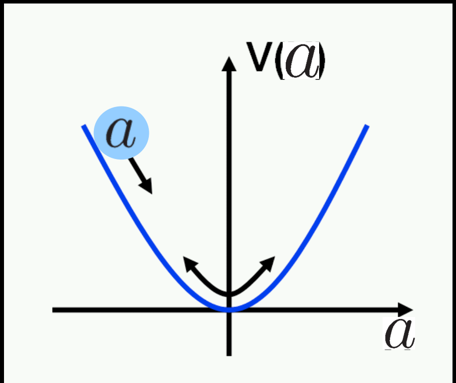
$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0 \qquad H = \frac{\dot{R}(t)}{R(t)}$$

- $H \gg m_a$ → 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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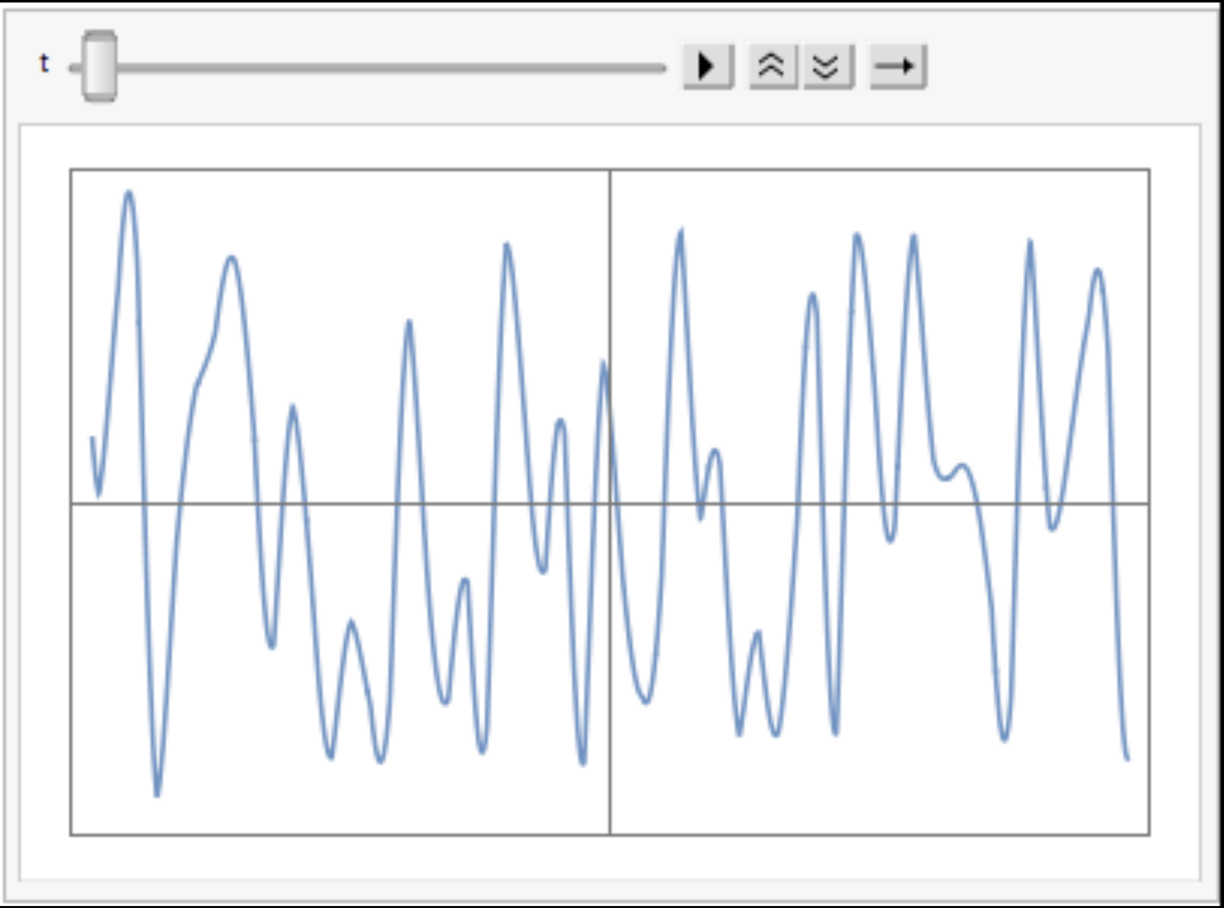
Field value



space

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

Axion(-like particle) Dark Matter

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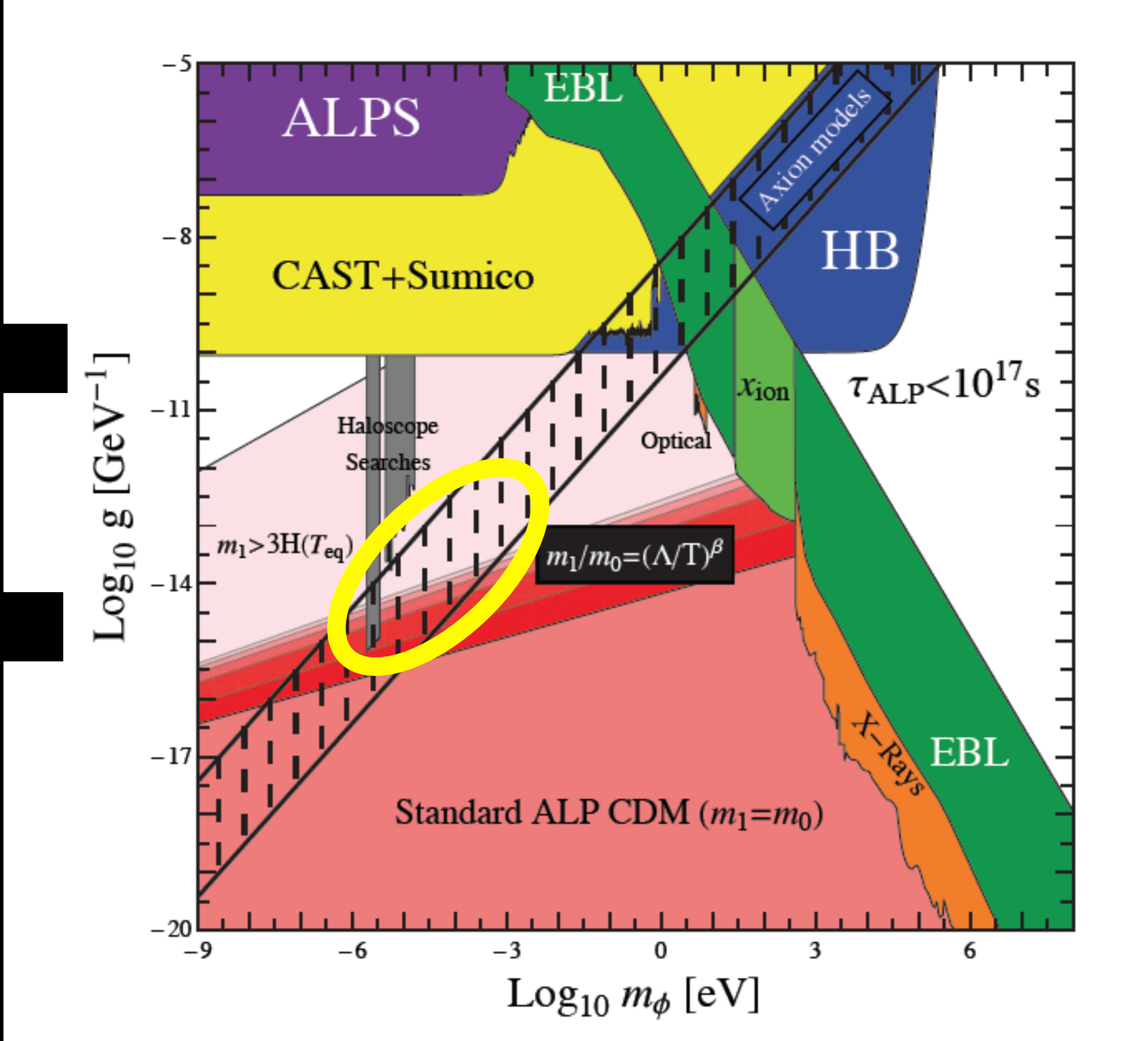
~10^7 GeV

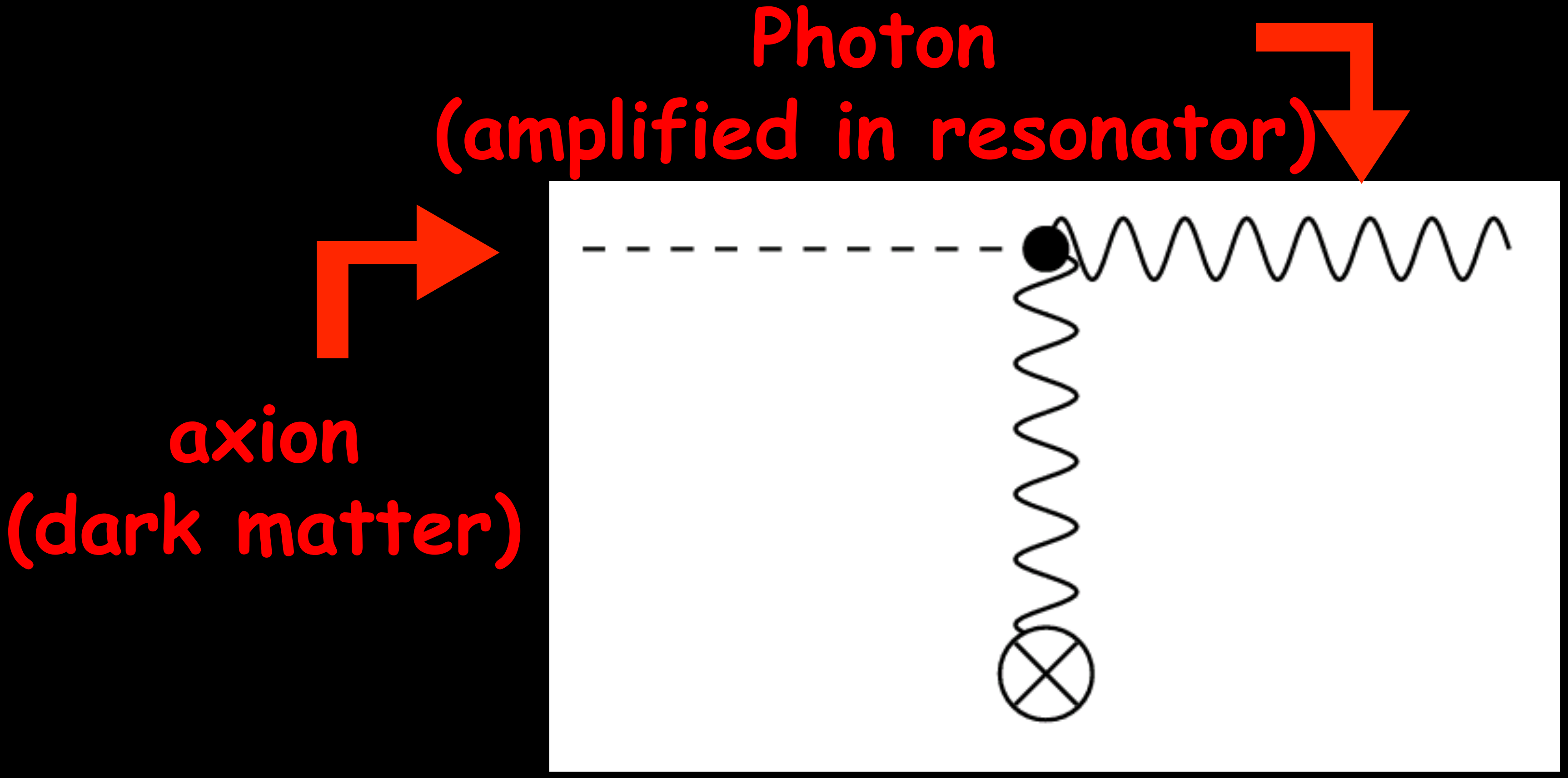
~10^{12} GeV



Detecting Axiony/WISPy DM

Use a plentiful source of axions

- Photon Regeneration



Signal: Total energy of axion

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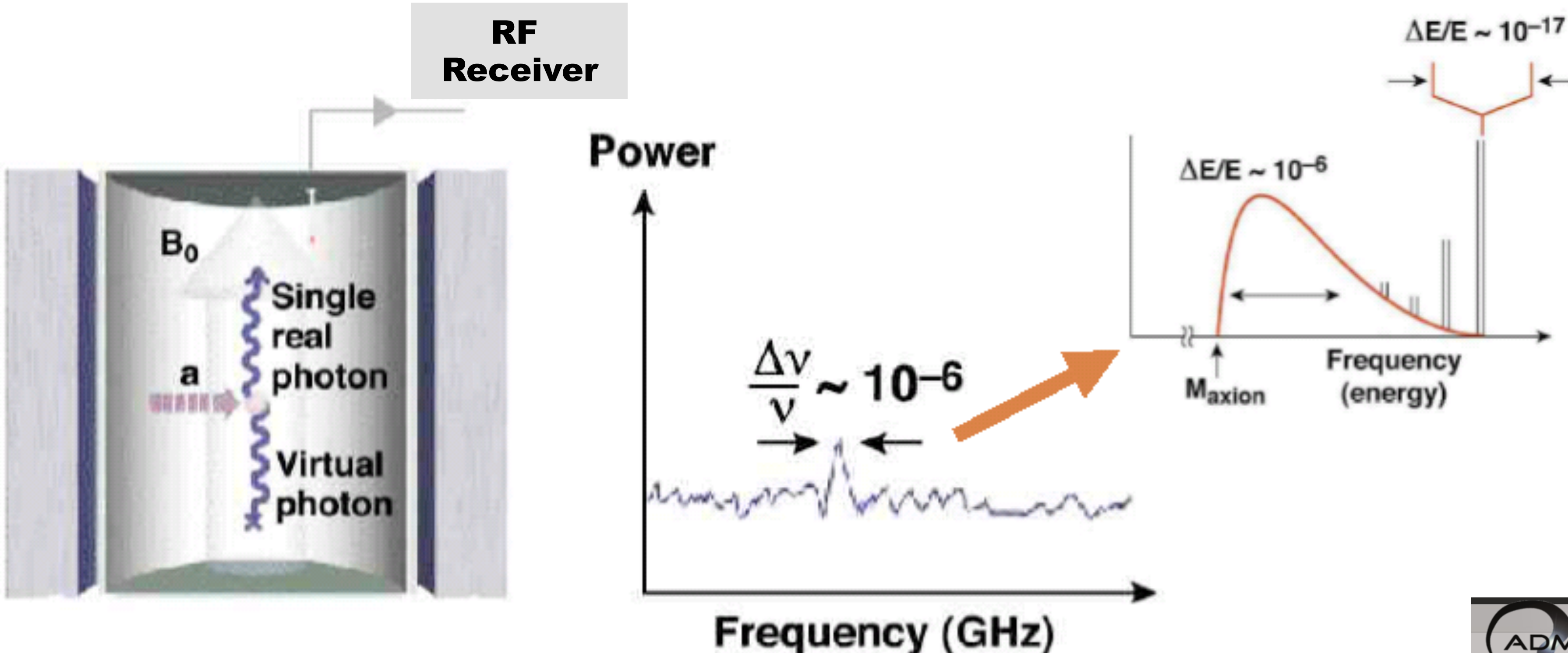
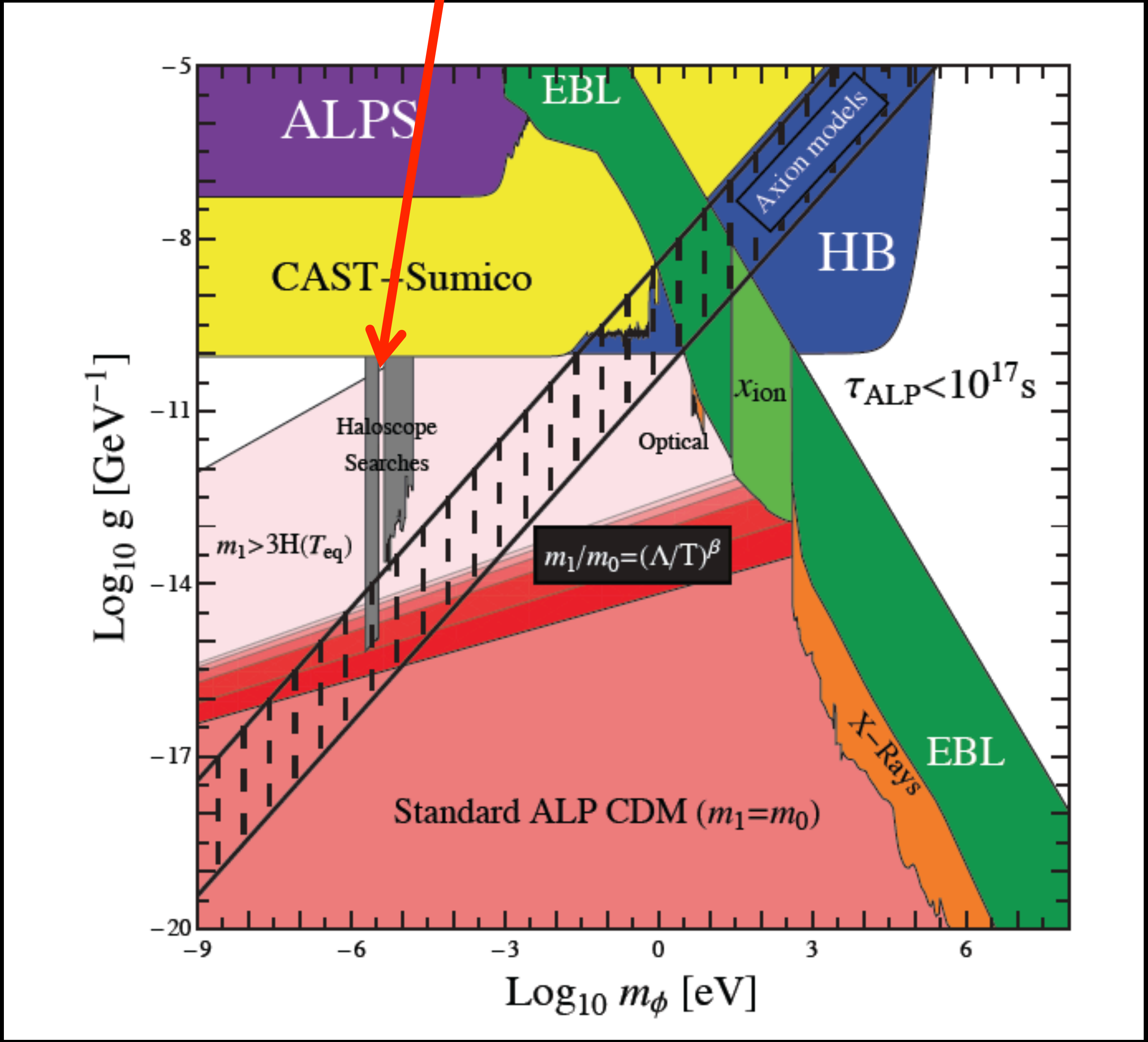


ADMX

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

Virial velocity in galaxy halo!

An extremely sensitive probe!!!



A discovery possible any minute!

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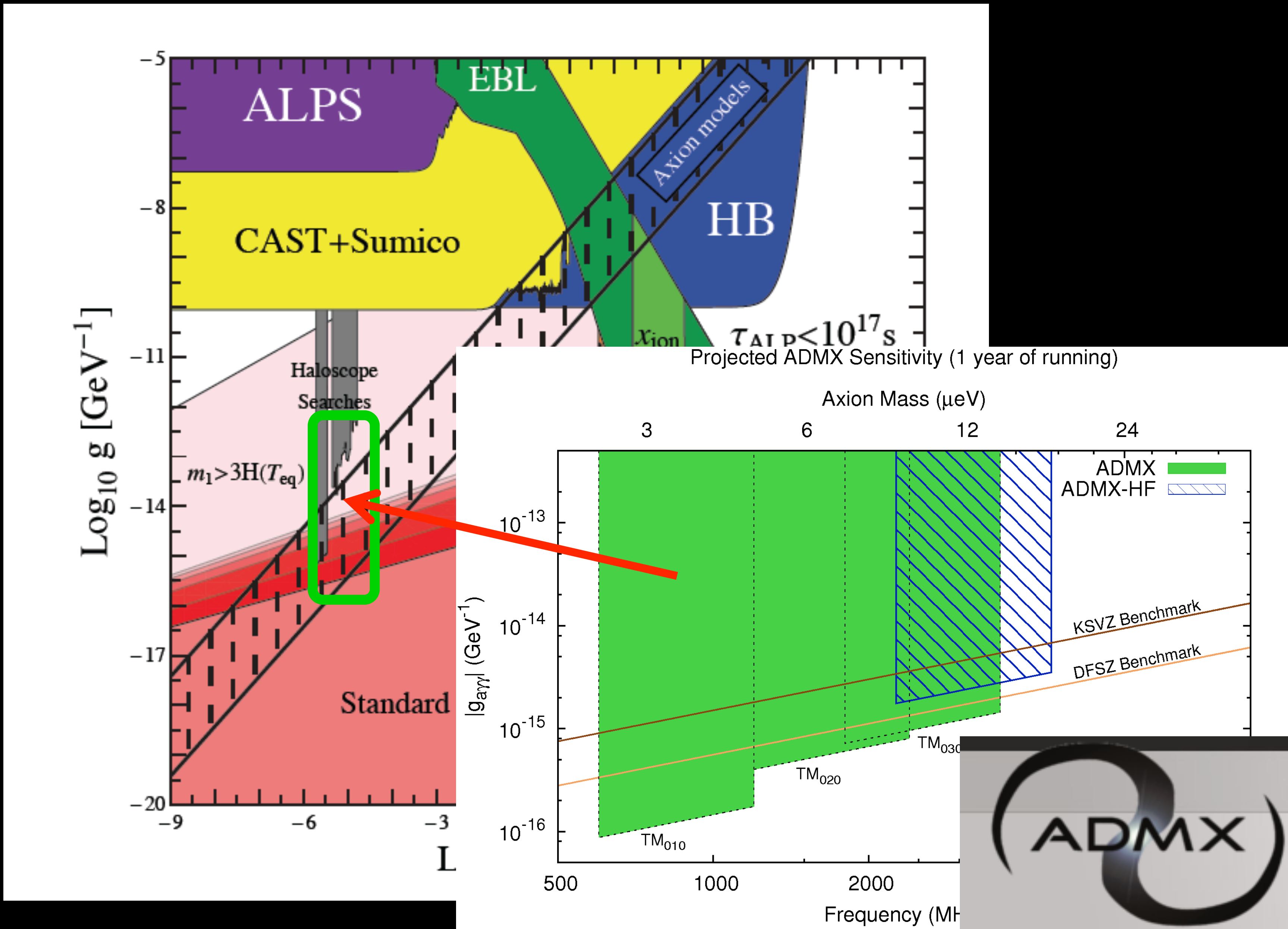

Encircling the axion…

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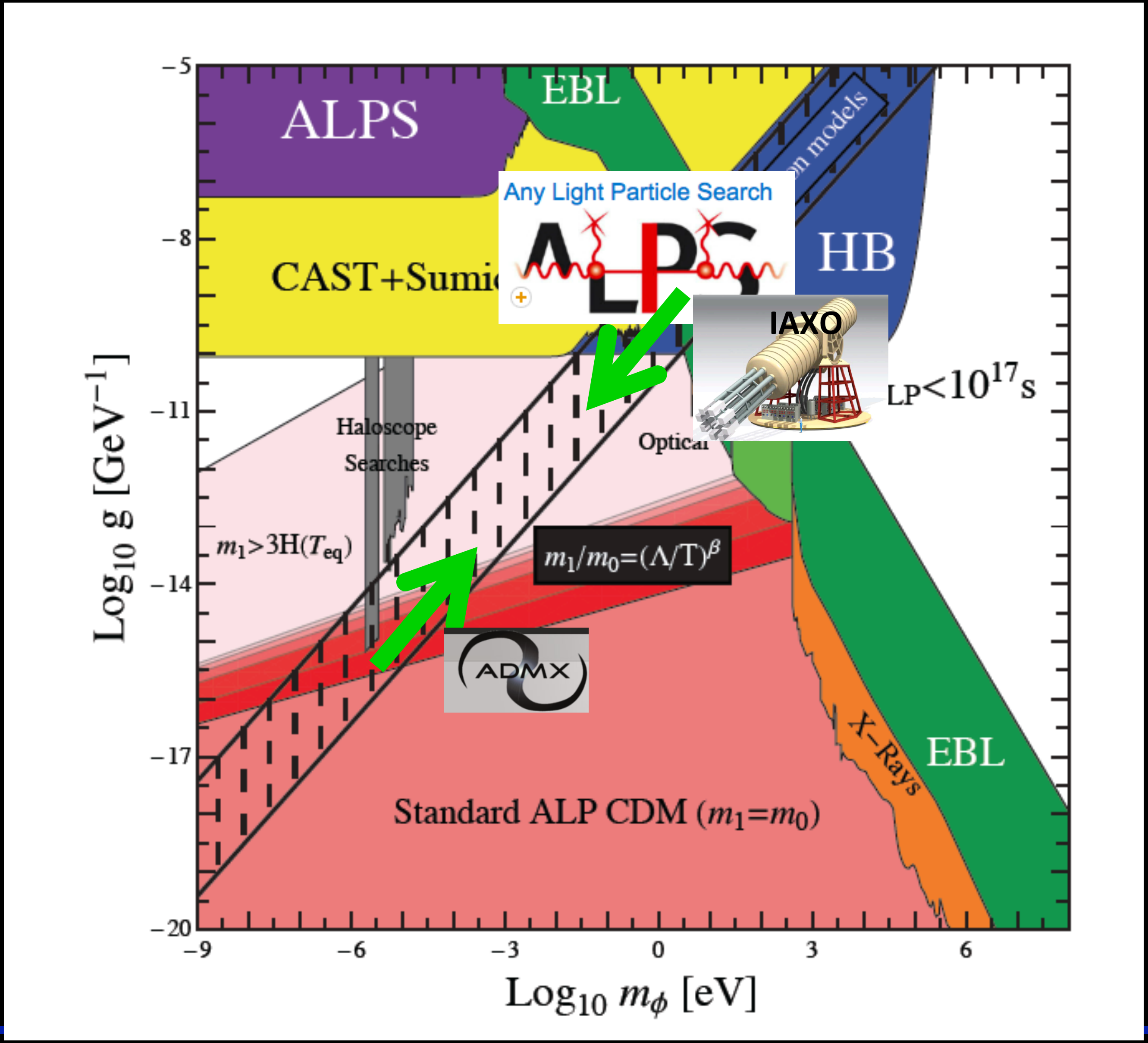
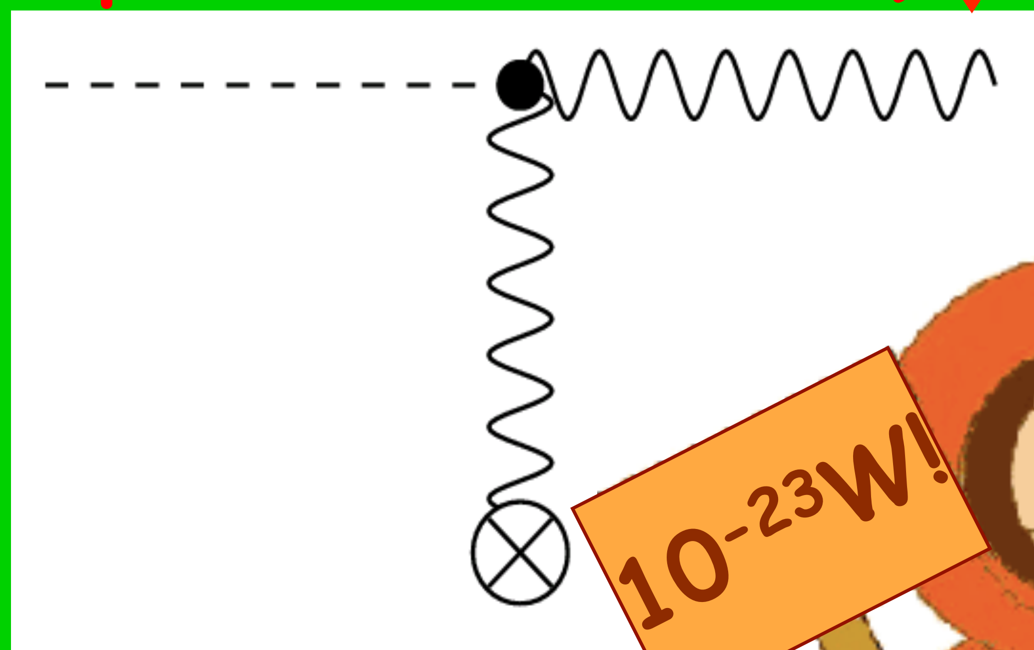


Electricity from Dark Matter ;-).

• Photon Regeneration

Photon
(amplified in resonator)

axion
(dark matter)



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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


Dark Matter
Dark Matter

Broadband Search Strategy

Dark Matter Antenna

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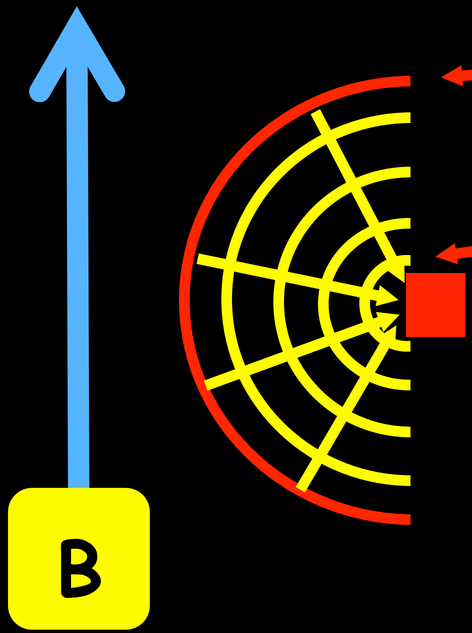
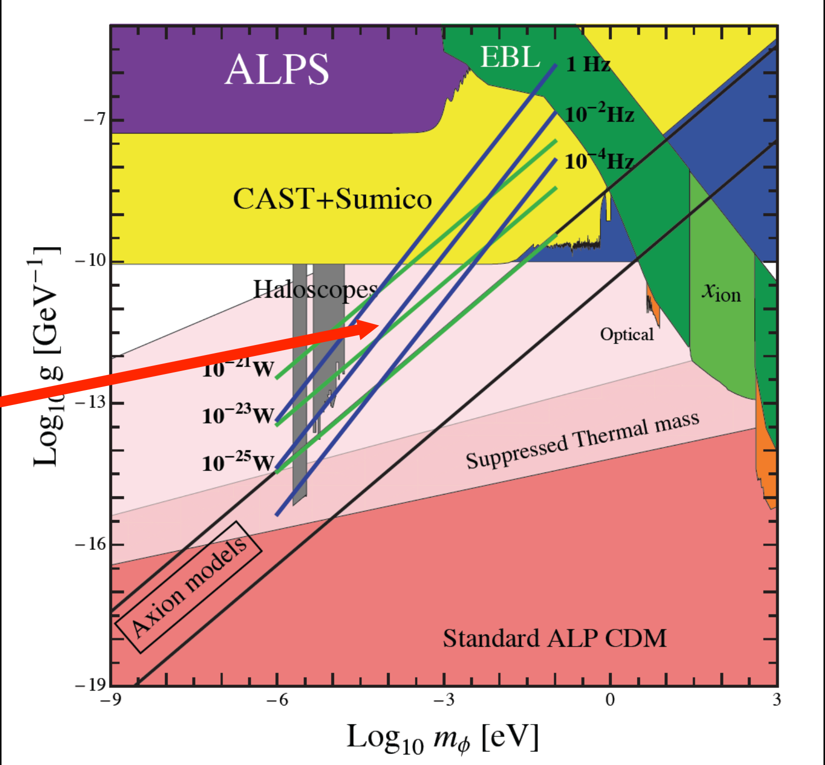


Antenna converts axion->photon

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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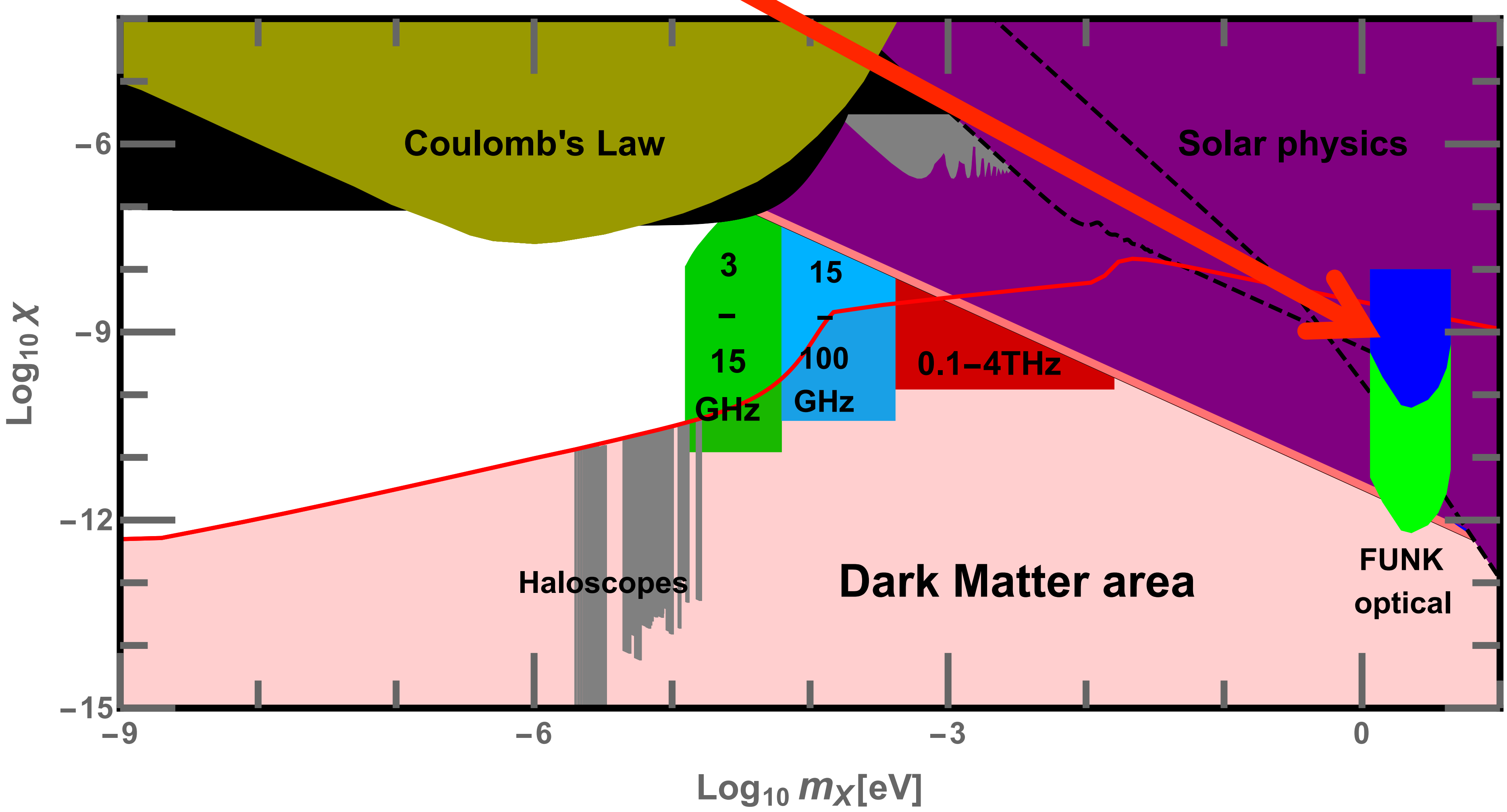

Upgrade: The PMT 9000(+107)

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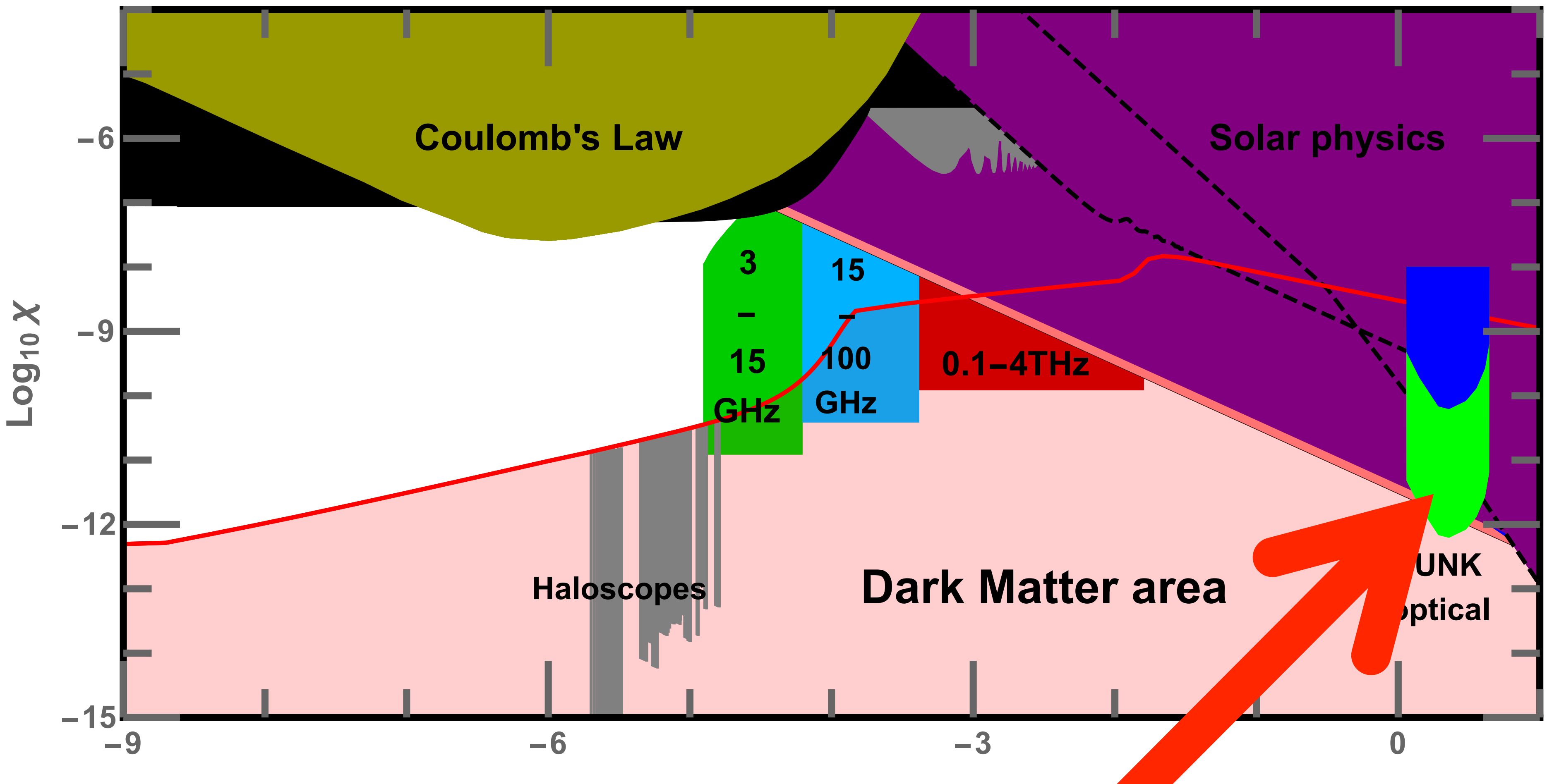

Discovery Potential ☺!!!

The next years ➔ Lower frequency

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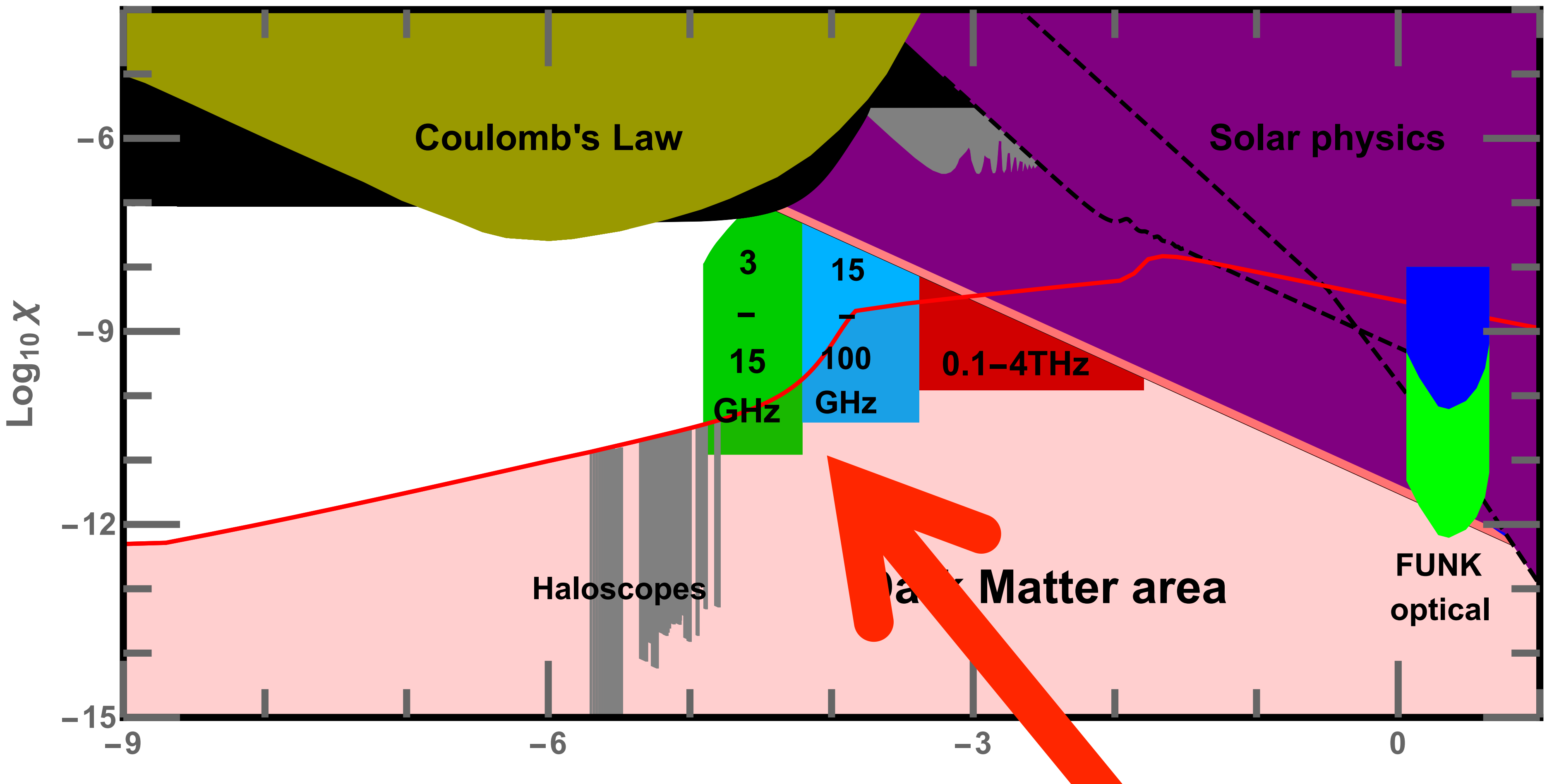
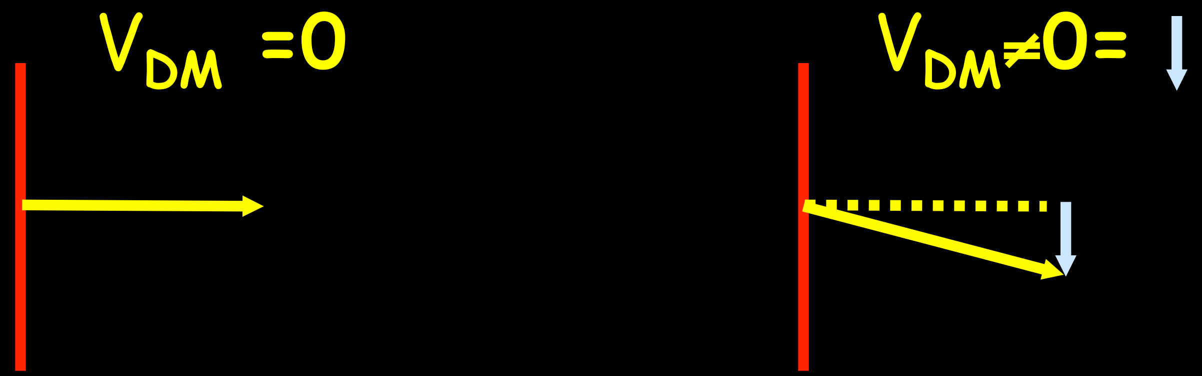


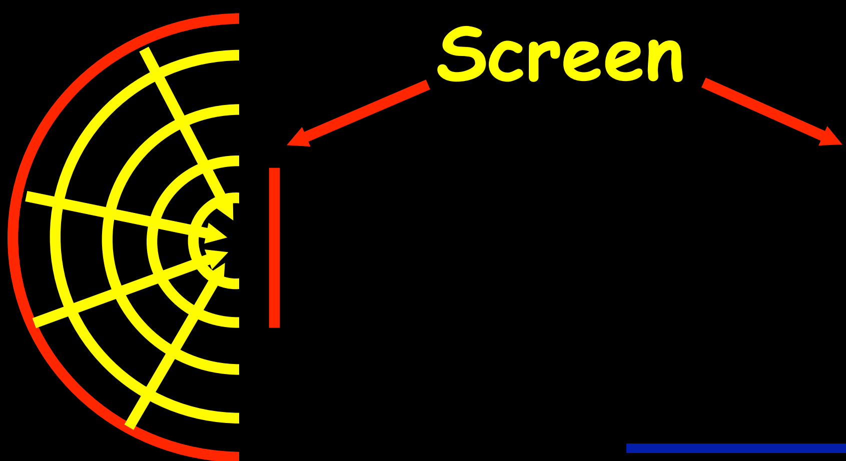
Discovery Potential ☺!!!

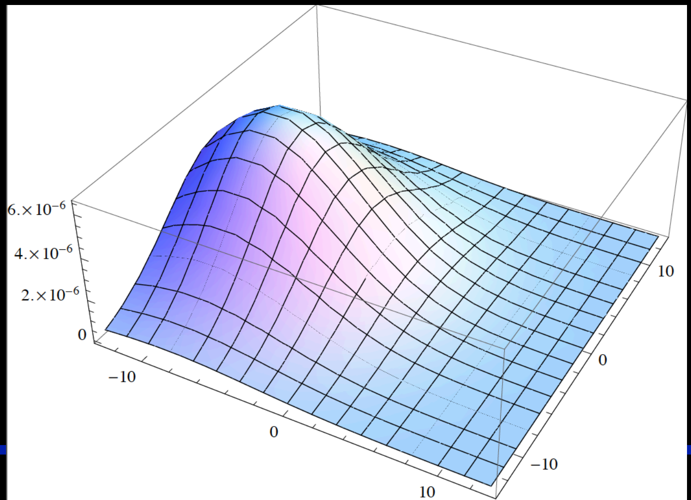
A Dream for ~~Astrology~~ ehhm Astronomy

- Emission from moving dark matter



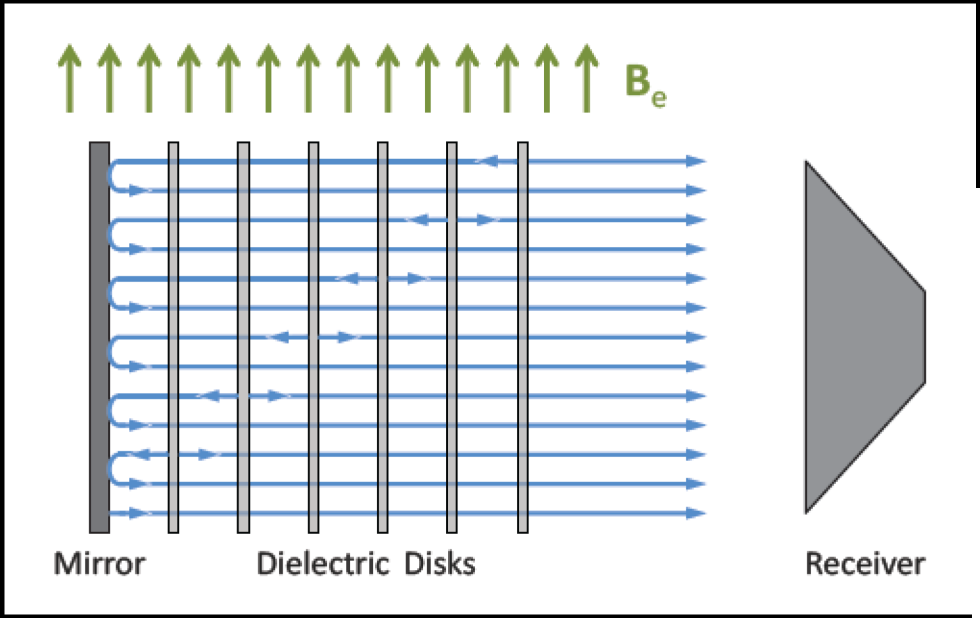
- A picture of the DM-velocity distribution

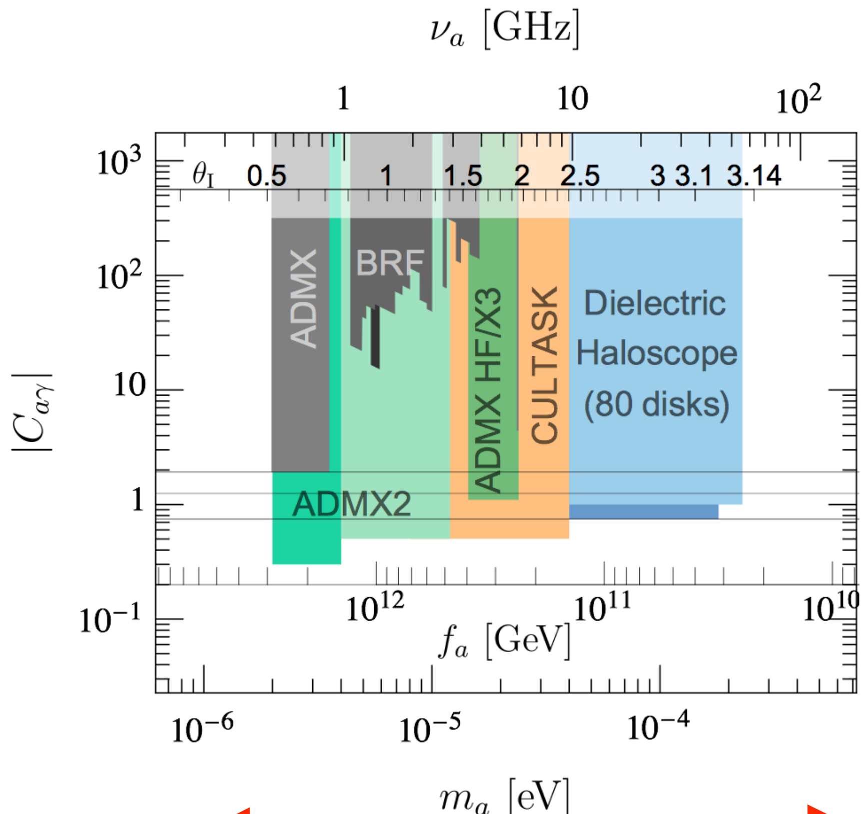




Going Mad(Max)

Ambitious new project at MPP





Natural DM

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

Many more experiments…

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

Conclusions

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Conclusions

- 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.