Intro to Axions

Particle Physics @ Low Energies

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], 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

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This used to be a funny slide.

Where we want to go…

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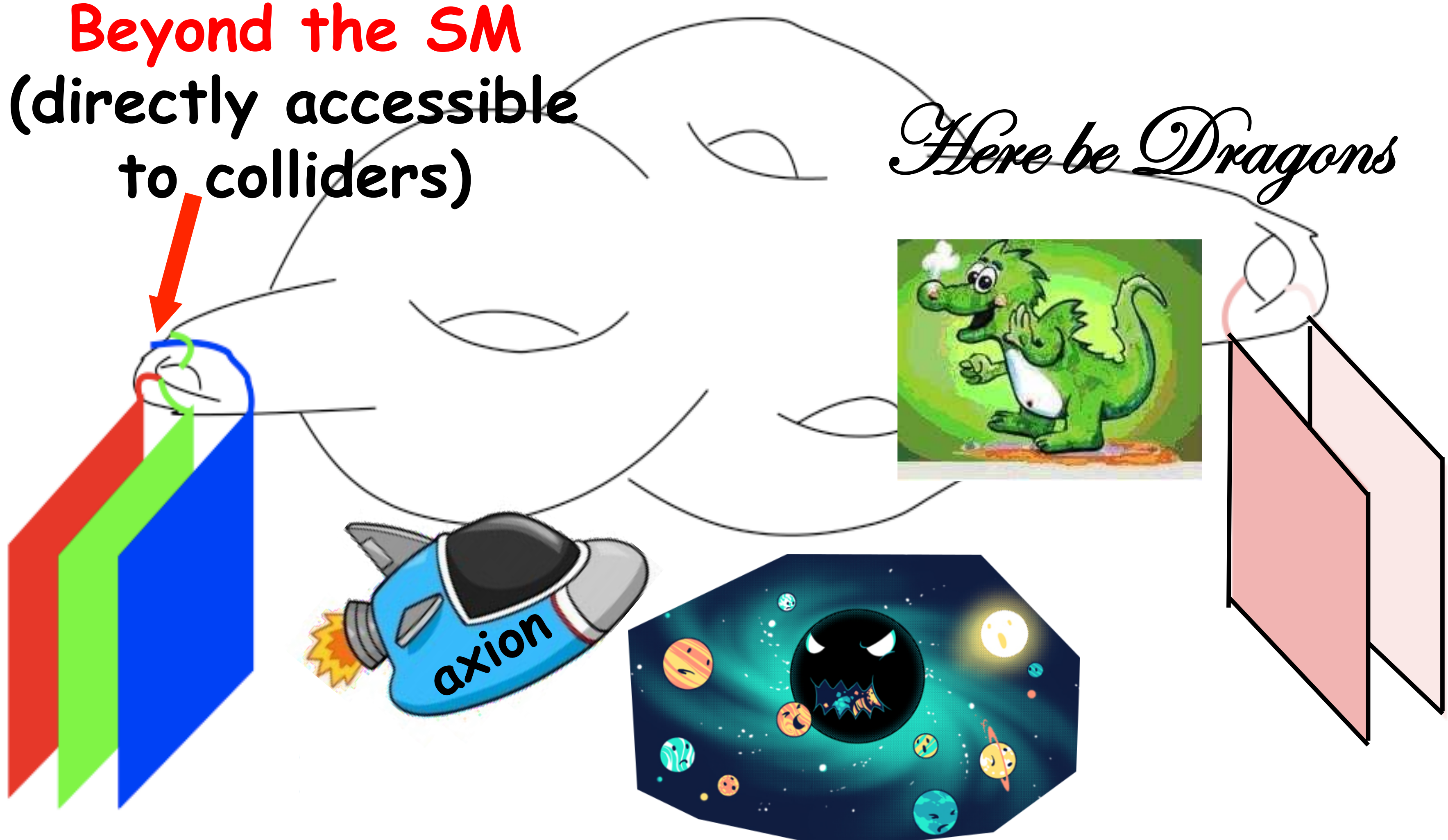
The Standard Model

+

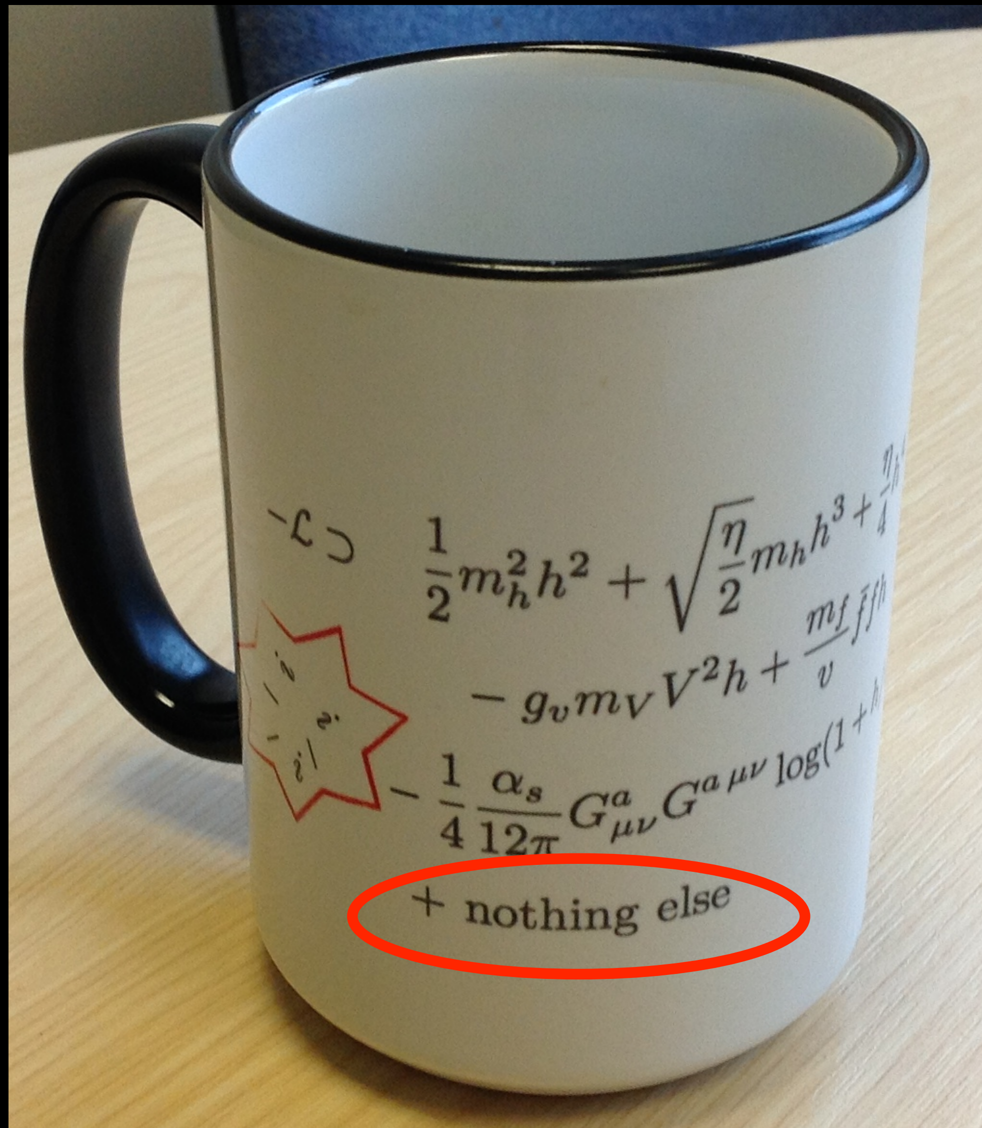
Beyond the SM
(directly accessible to colliders)

The Hidden Sector



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

Inventory of the Universe

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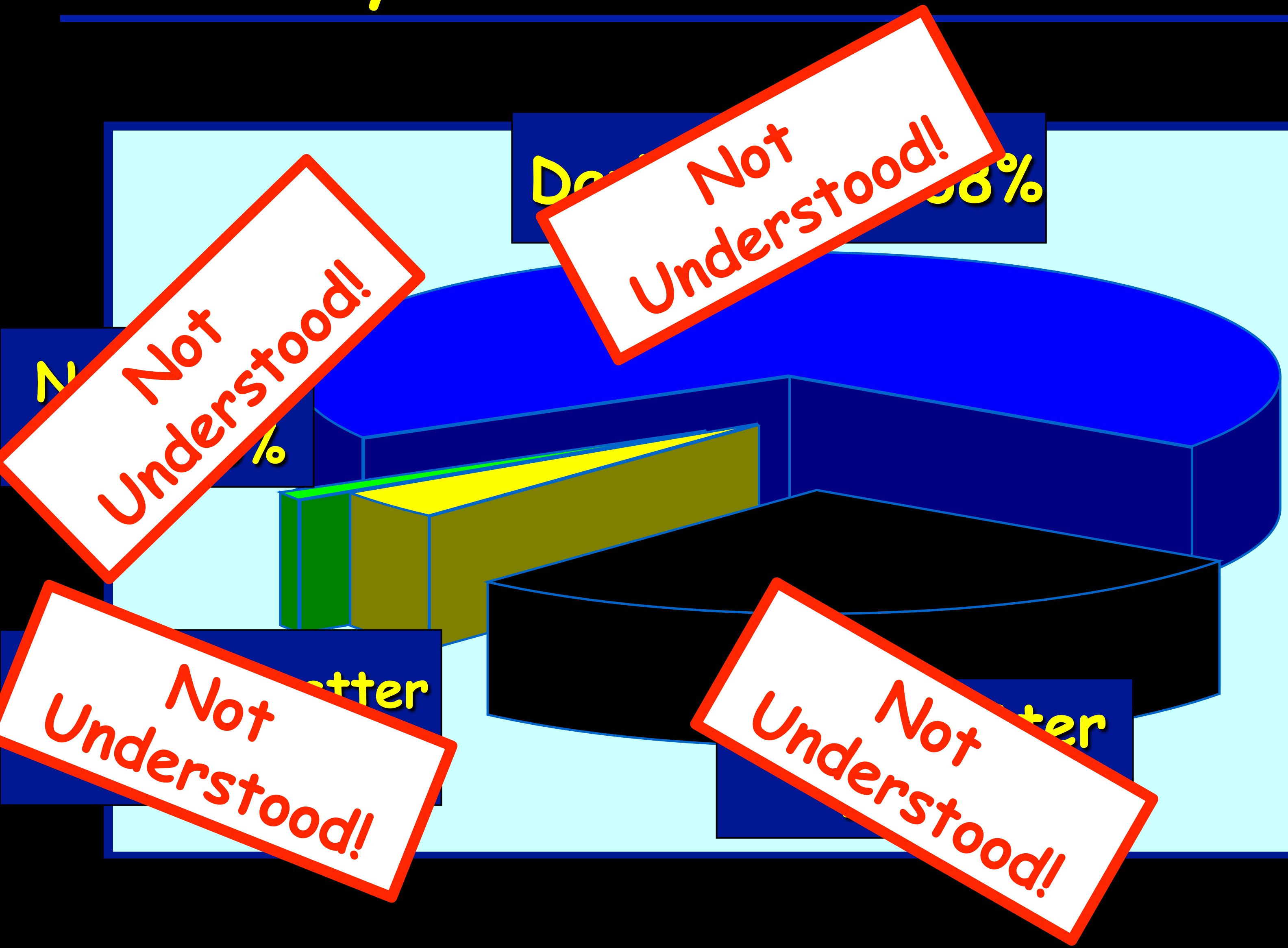
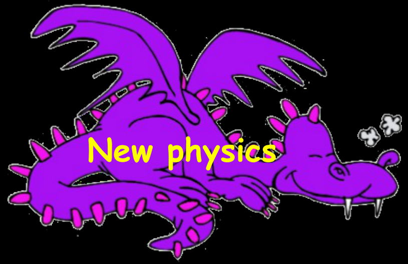
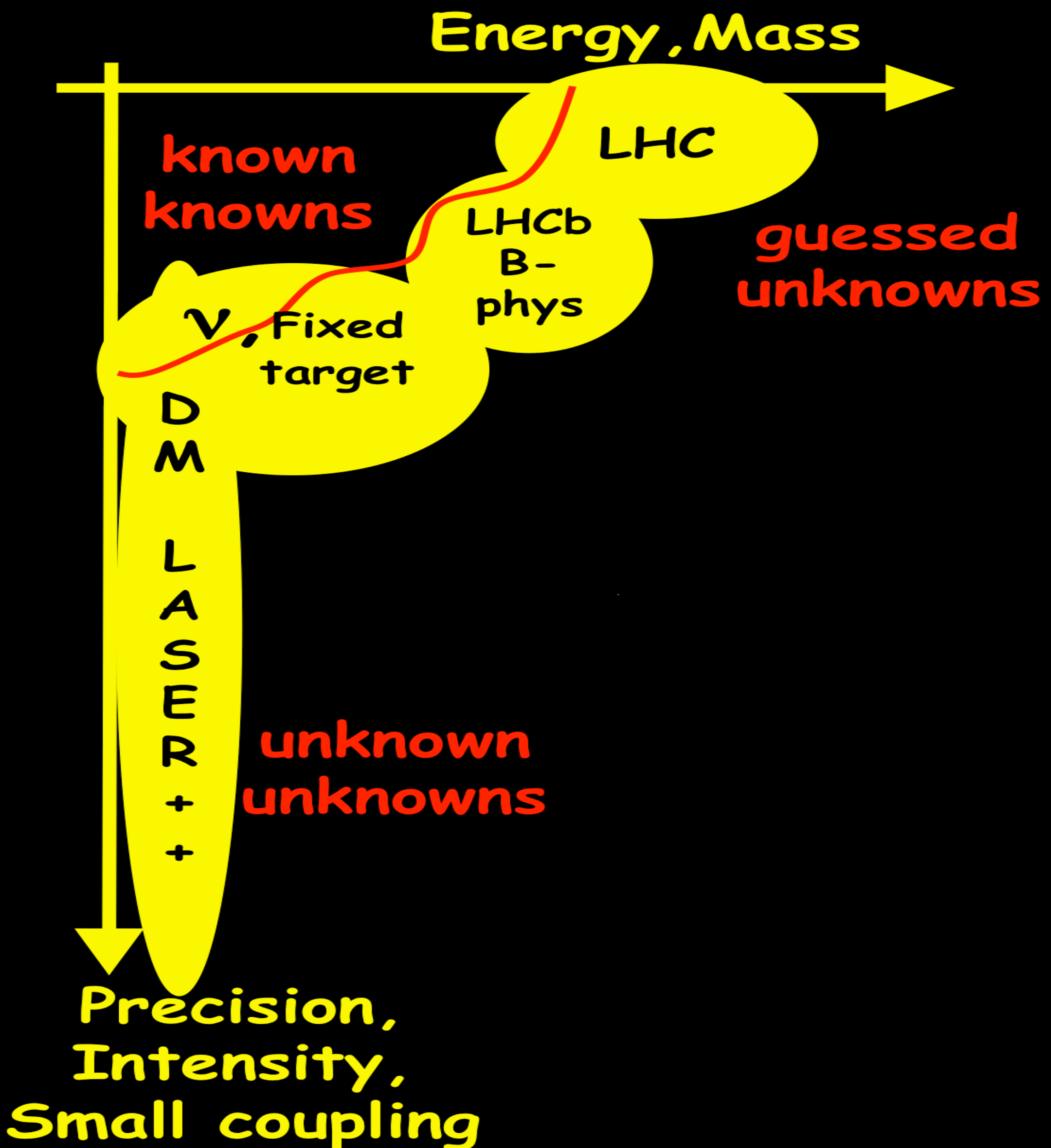


Where does it hide?



Exploring is (at least) 2 dimensional



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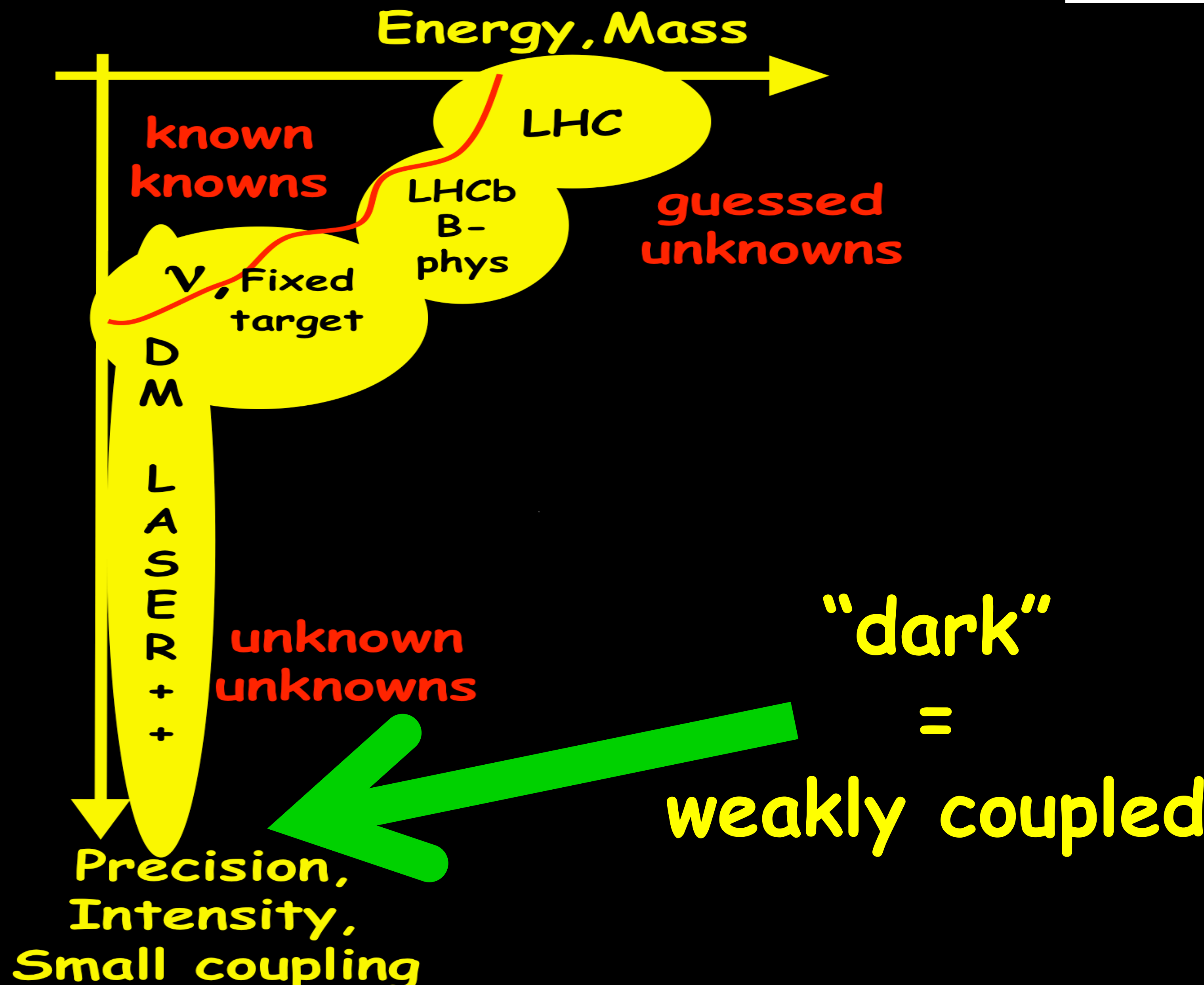

What are Axion?

And why do we need them?

A „visible" Hint for new Physics

The strong CP Problem

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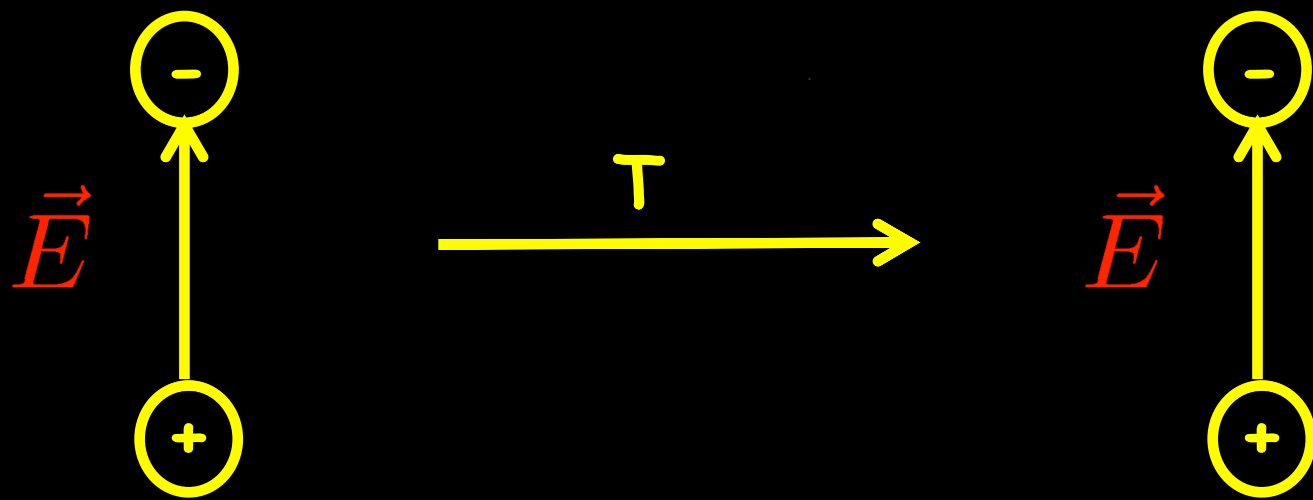
A dirty little secret...

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

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

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



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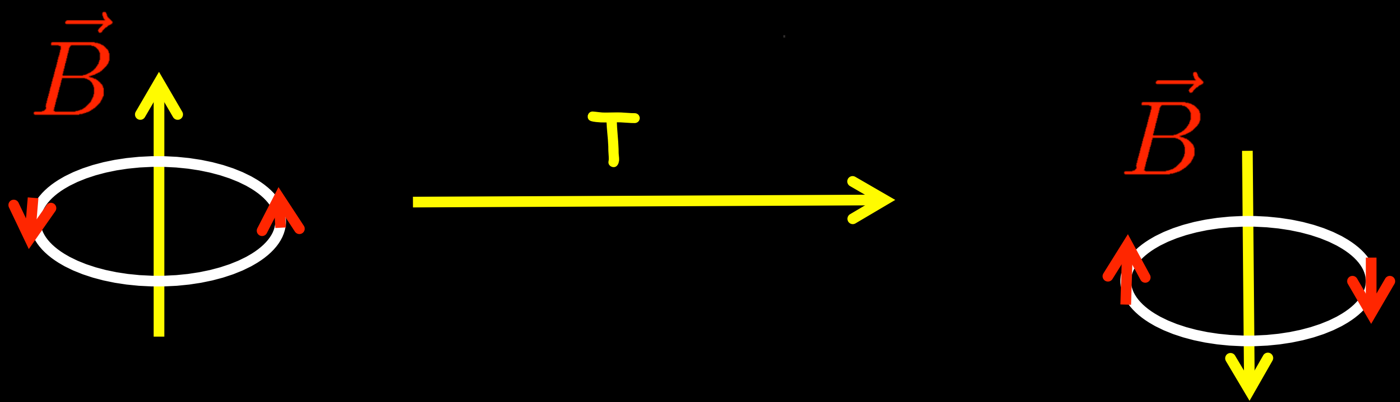

A dirty little secret...

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

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

$$\vec{E} \xrightarrow{CP} \vec{E}$$

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

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

A dirty little secret...

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A dirty little secret...

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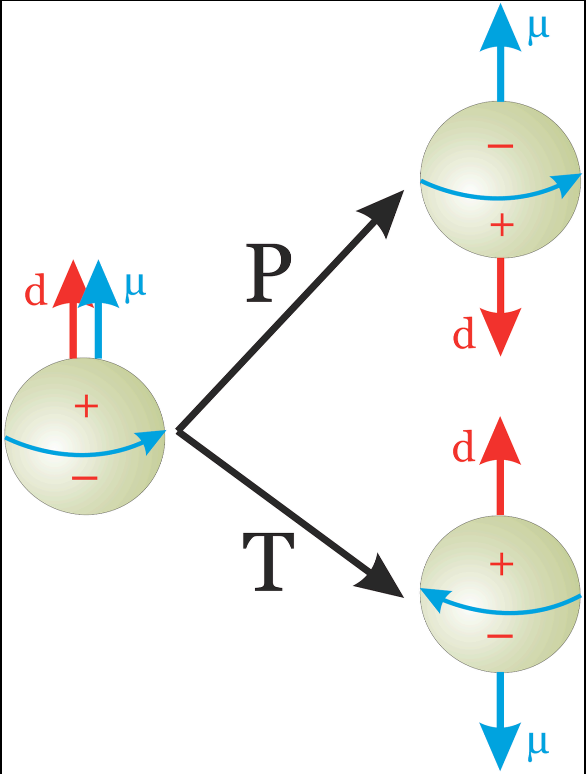
$$\text{"} \sim \theta \vec{E} \cdot \vec{B} \text{"}$$

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

⇨ Electric dipole moment of the neutron!



Measure neutron electric dipole moment

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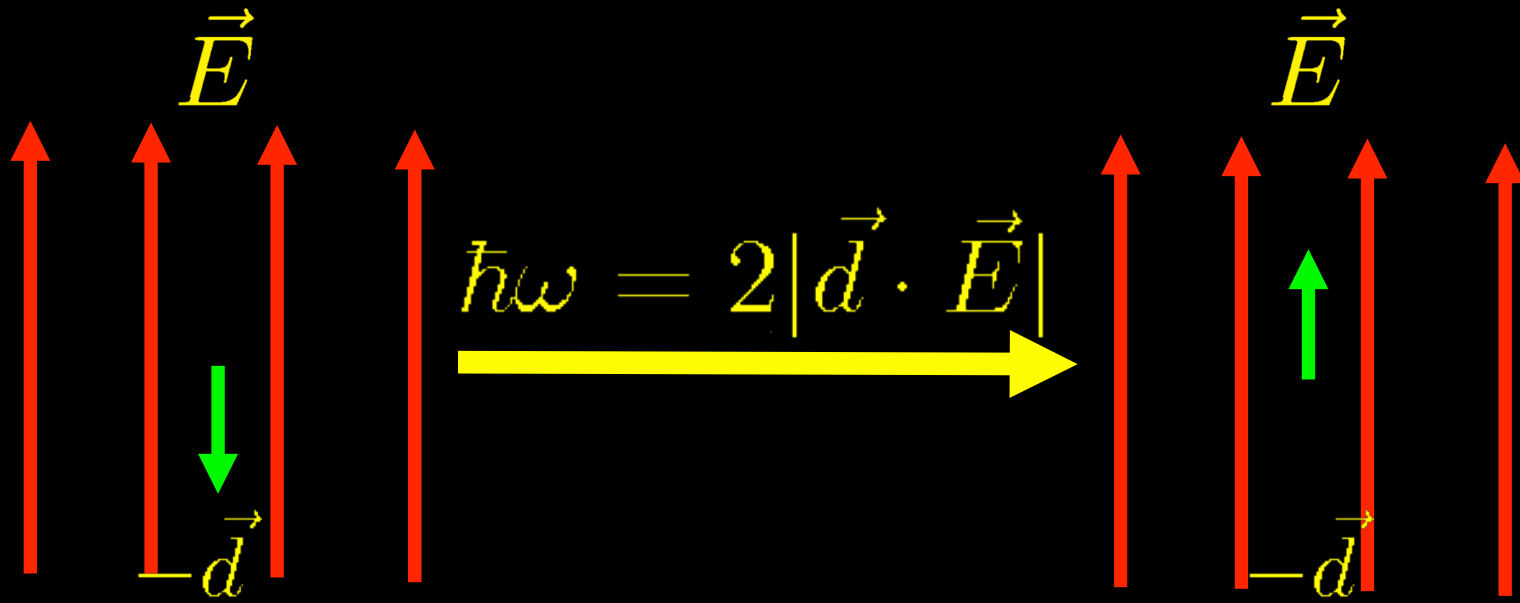
- θ would cause neutron EDM ➡ Experiment



➡ Measure transition frequency.

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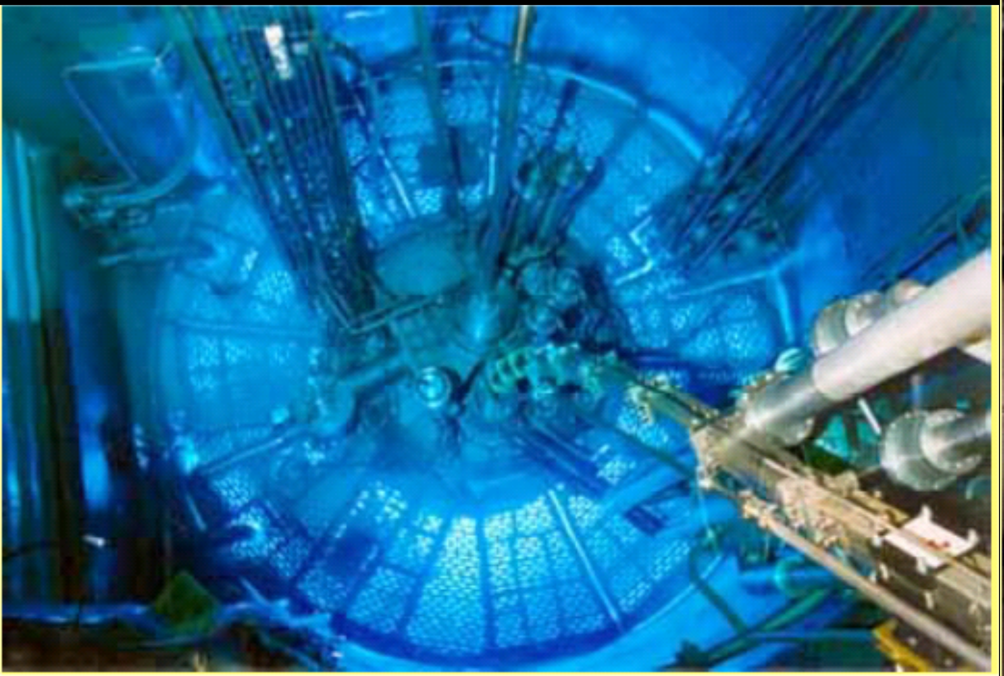
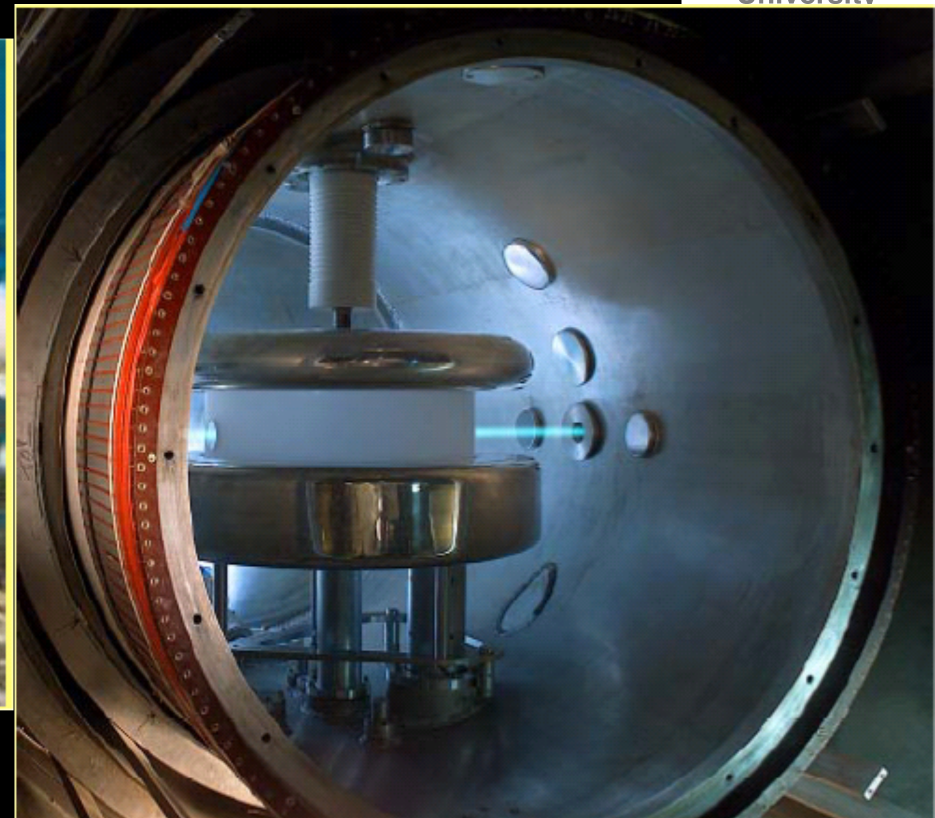
No neutron electric dipole moment...





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

What do we expect?

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- **Two mass scales in the game:**

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

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

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

$$\sim (3 - 30) \times 10^{-16}\, e\,\mathrm{cm}\,\theta$$

Implications

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- Detailed calculation gives

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

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

$\Rightarrow$ **Extremely unnatural!**

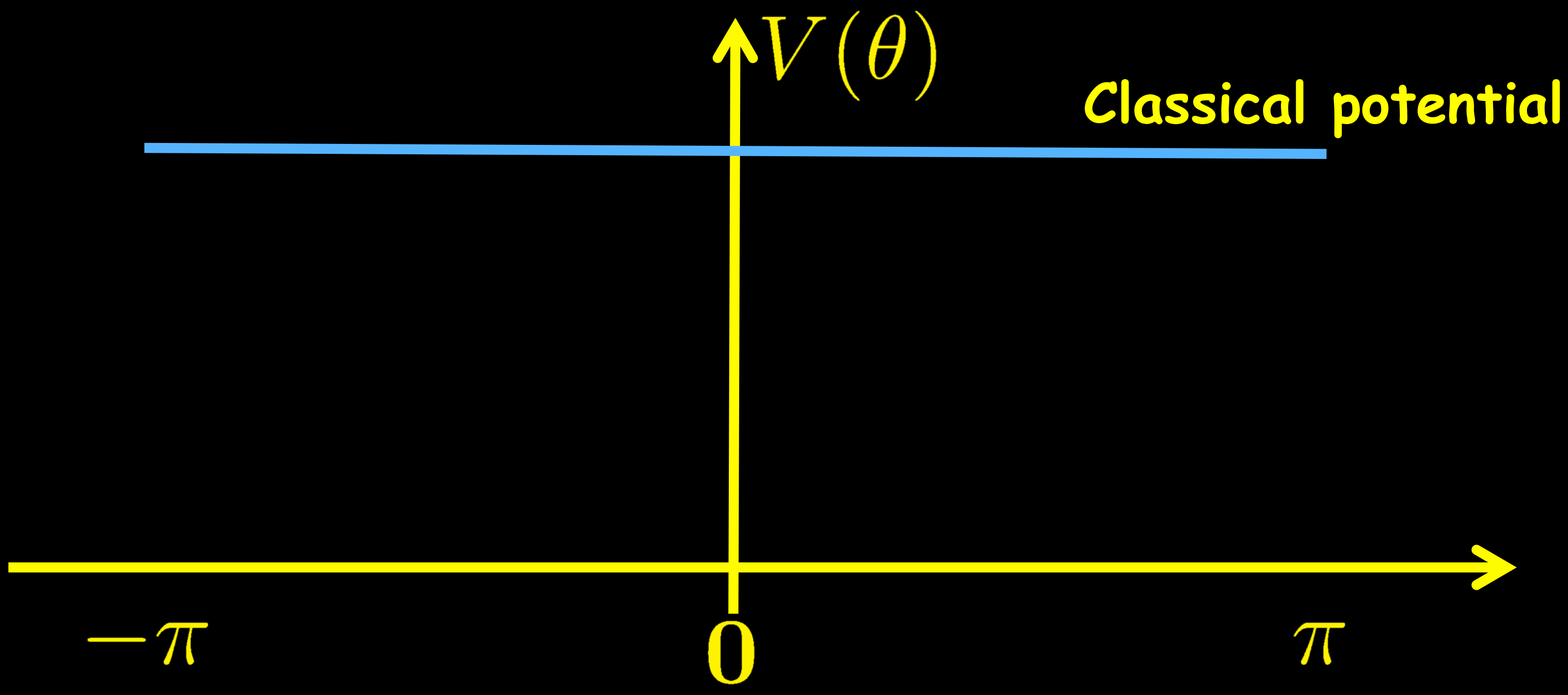
Strong CP Problem

The axion solution
to the strong CP problem

In pictures…

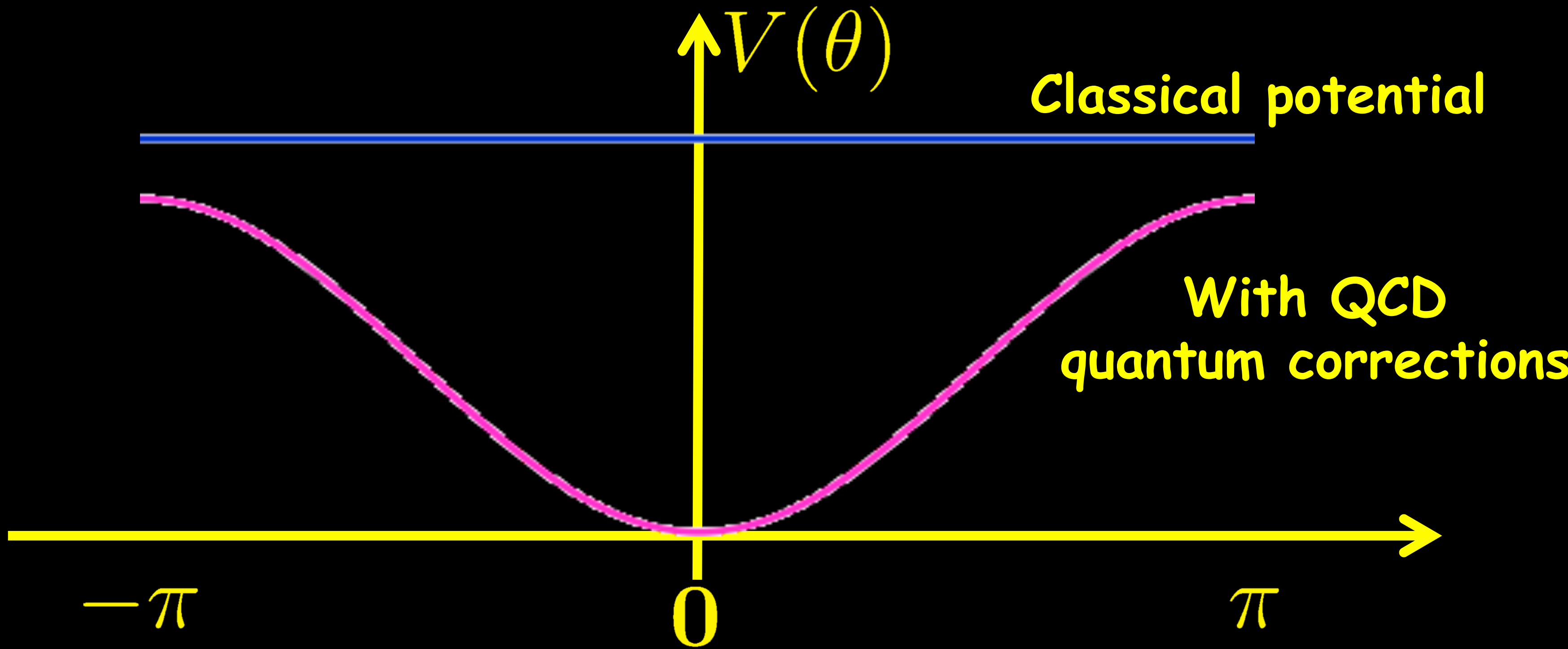
The axion solution to the strong CP problem

- Make θ dynamical → it can change its value



The axion solution to the strong CP problem

- Make θ dynamical → it can change its value



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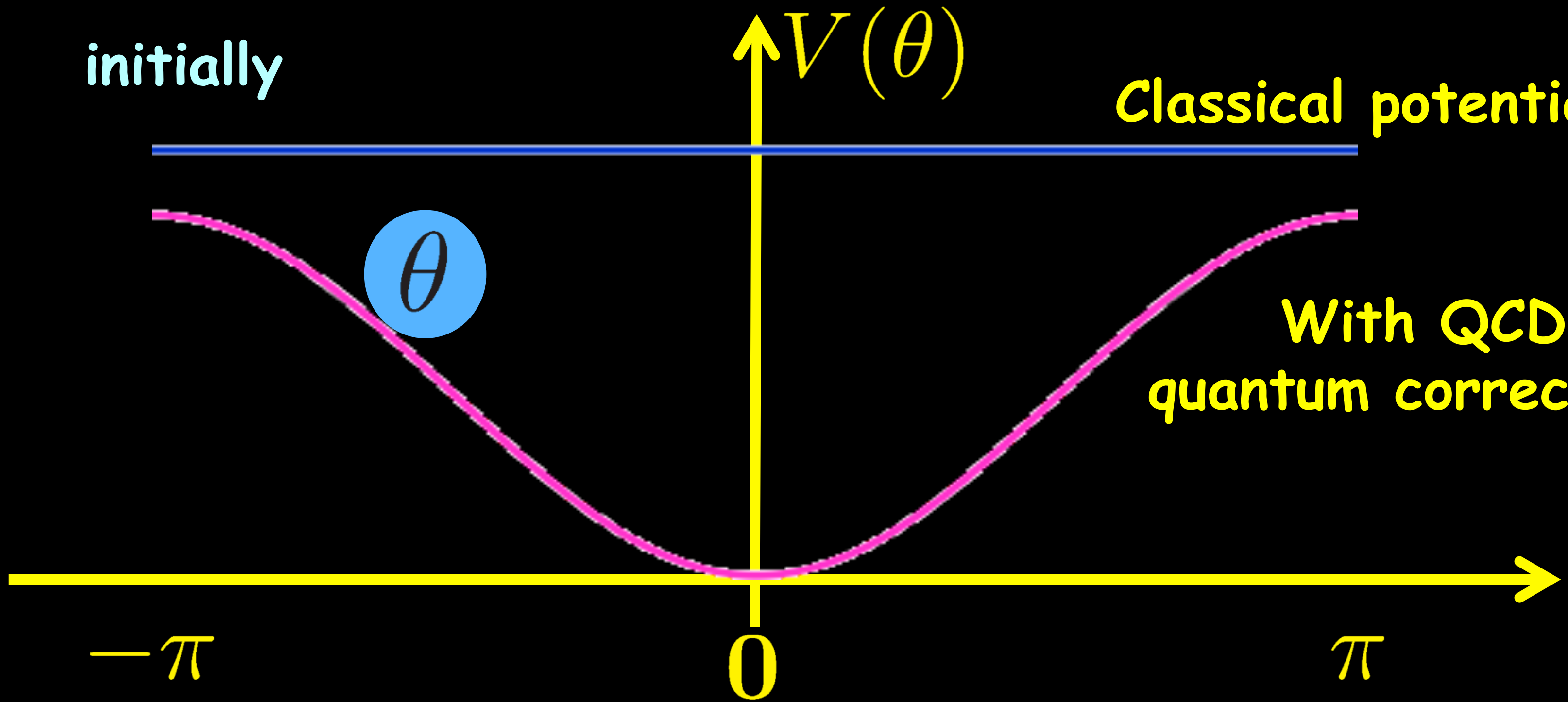
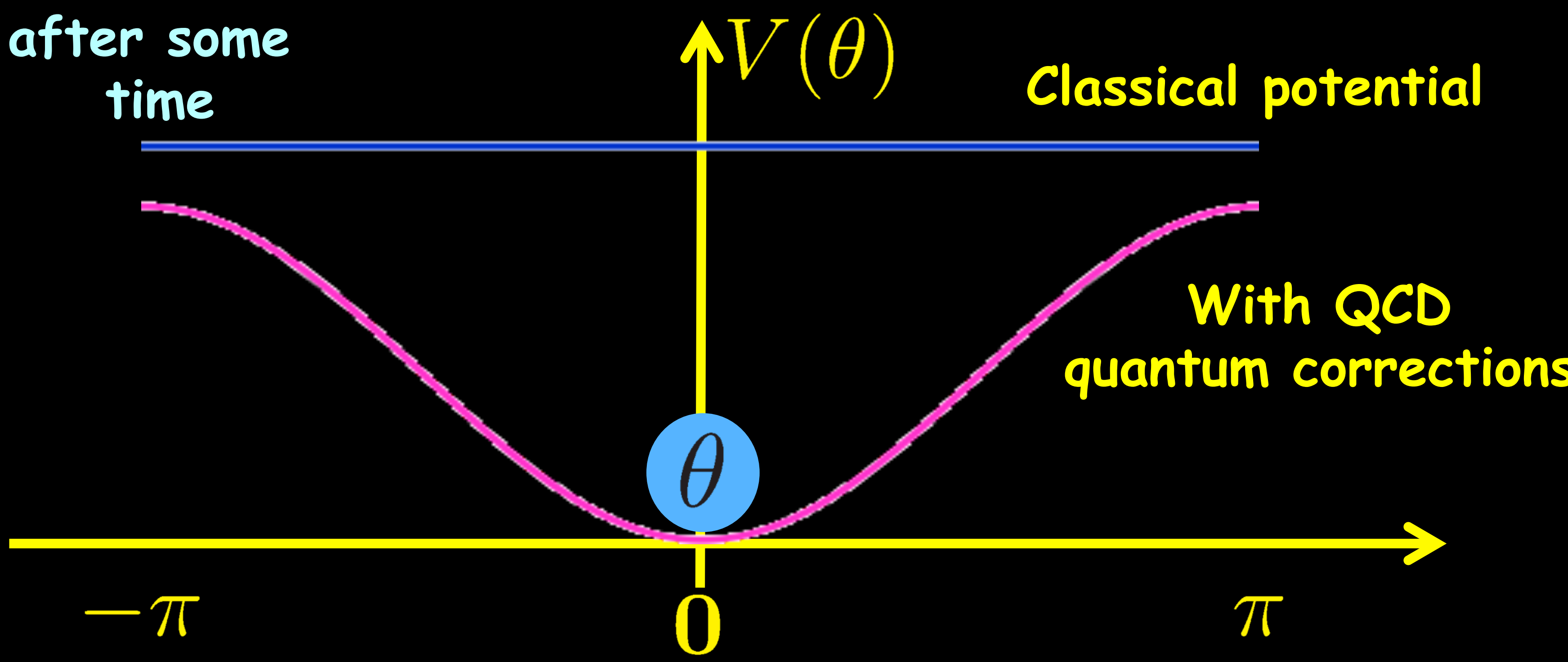


The axion solution to the strong CP problem

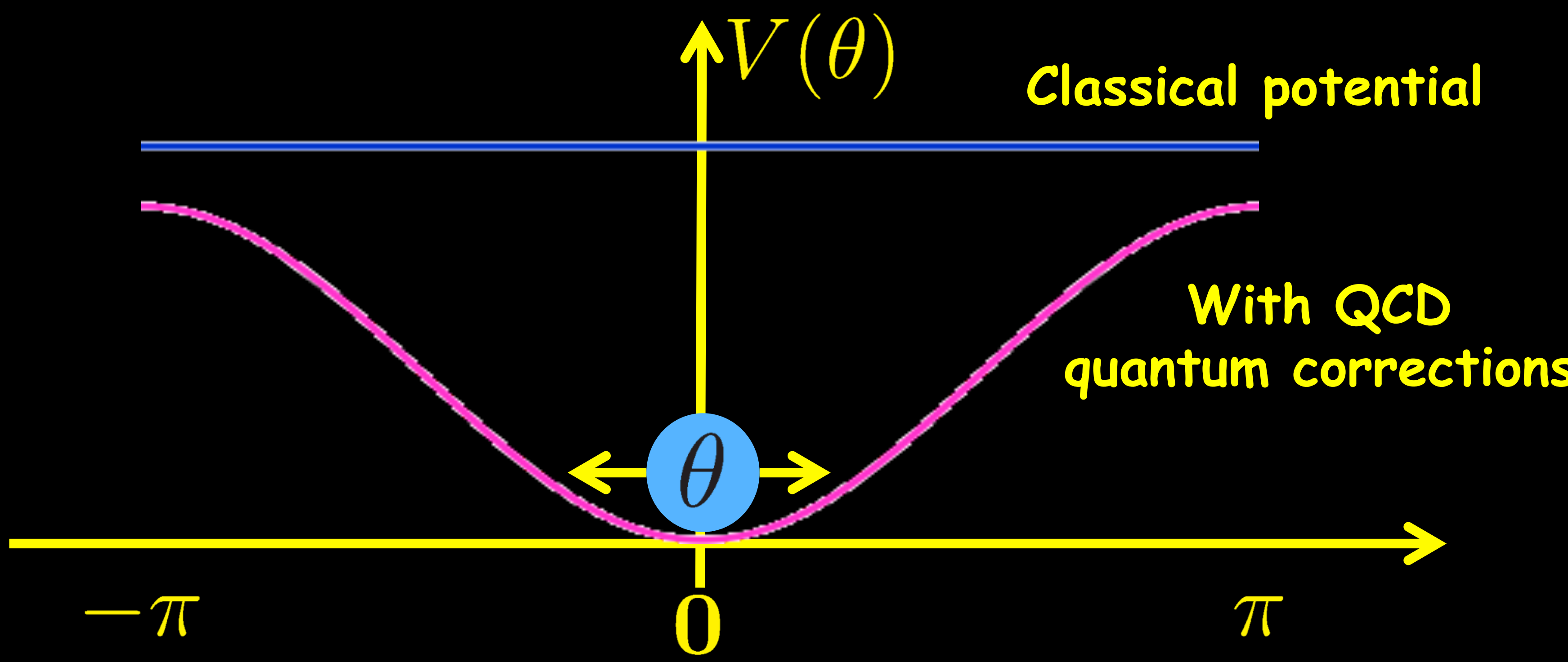
- Make θ dynamical ➔ it can change its value



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

The axion solution to the strong CP problem

- Make θ dynamical ➔ it can change its value



➔ Can still move

➔ new particle = axion

Axions

- 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 a
  - Let a have no tree level potential
  - Let a have only derivative couplings
- **Then:**

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

A Dynamical θ

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

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

⇒ θ=a will evolve to a=θ=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∈[0,2π] since

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

⇒ 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):** $\phi \rightarrow \exp(i\beta)\phi$

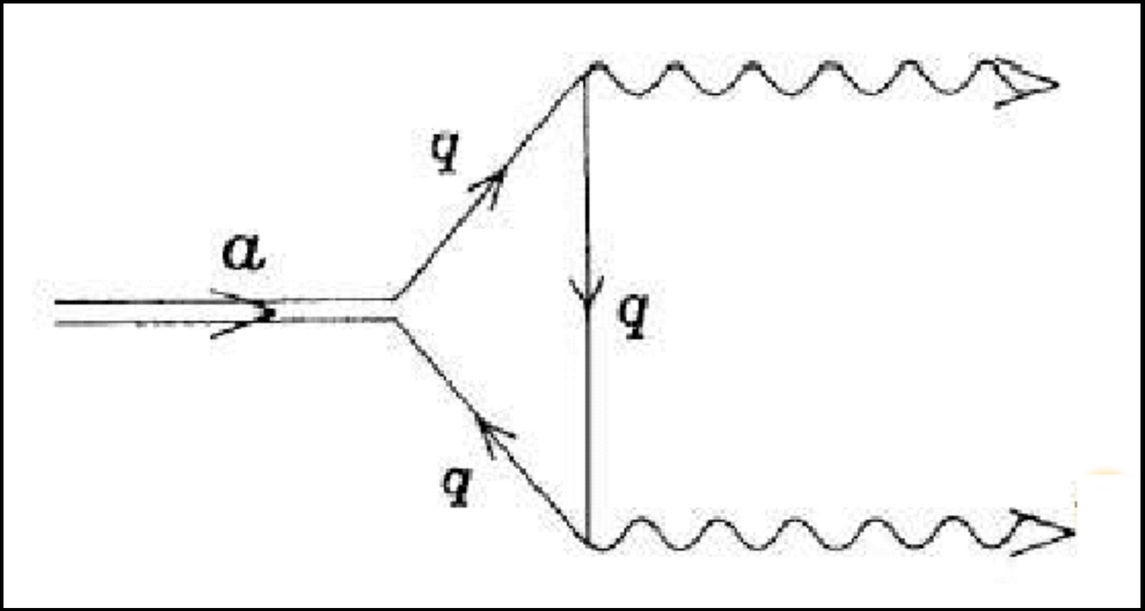
$$\psi \rightarrow \exp\left(-i\frac{\beta}{2}\gamma_5\right)\psi$$

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

⇒ Phase is Goldstone ⇒ Use it as Axion

The Coupling to $G\tilde{G}$ and $F\tilde{F}$

- 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**

$$d\mu' = \mathcal{D}\psi' \mathcal{D}\bar{\psi}' = d\mu \exp\left(-1 \int_x \frac{\beta}{2} \frac{1}{8\pi^2} Tr F^{\mu\nu} \tilde{F}_{\mu\nu} \right)$$

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

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

The Coupling to $F\tilde{F}$

- **Adler-Bell-Jackiw anomaly**

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

The mass of the Axion

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

⇒ Goldstone → Pseudogoldstone

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

⇒ PseudoGoldstone mass $m_a^2 \sim \frac{m_\pi^2 \Lambda_{QCD}^2}{f_a^2}$

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Axion-like Particles

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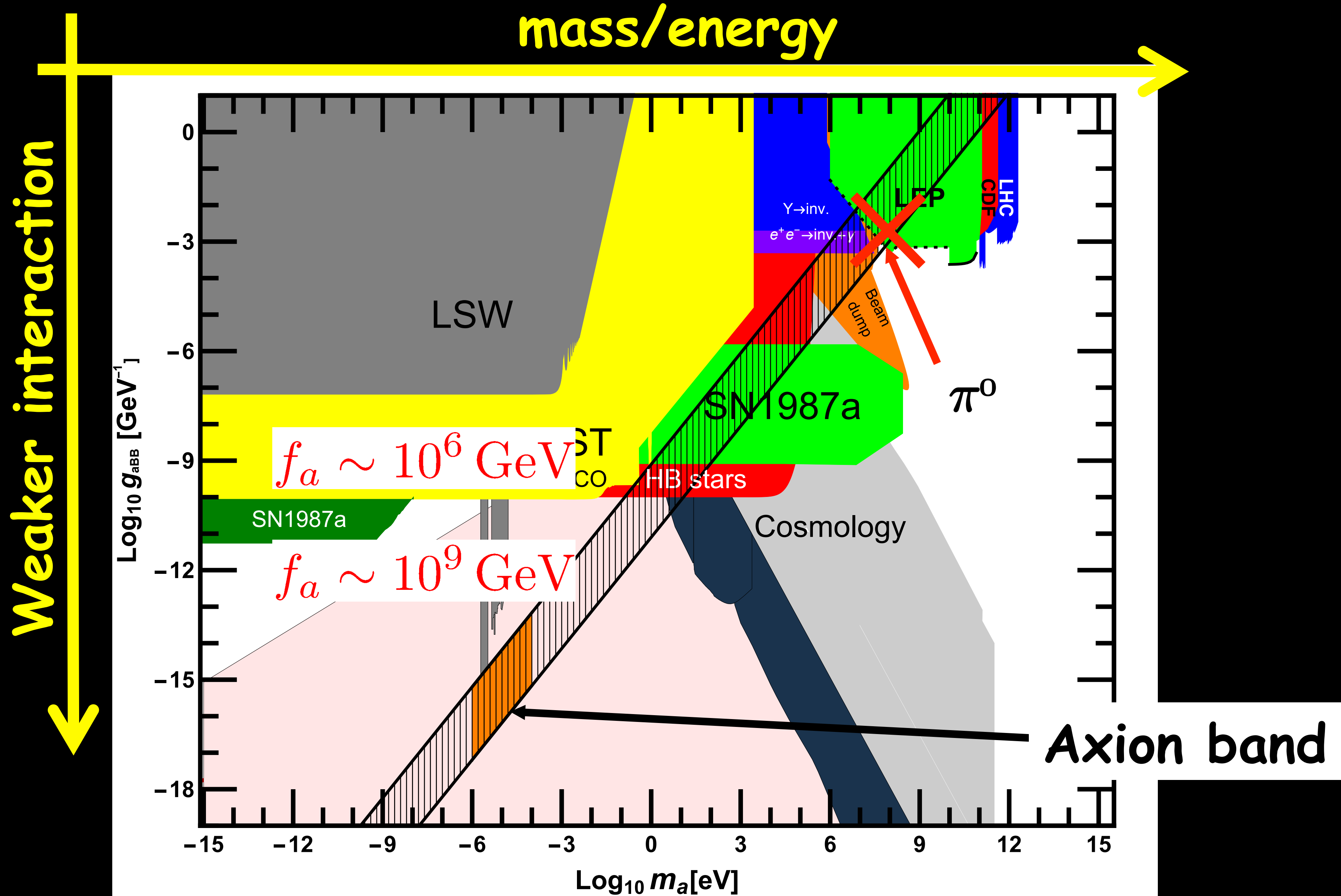

Axion-like Particles

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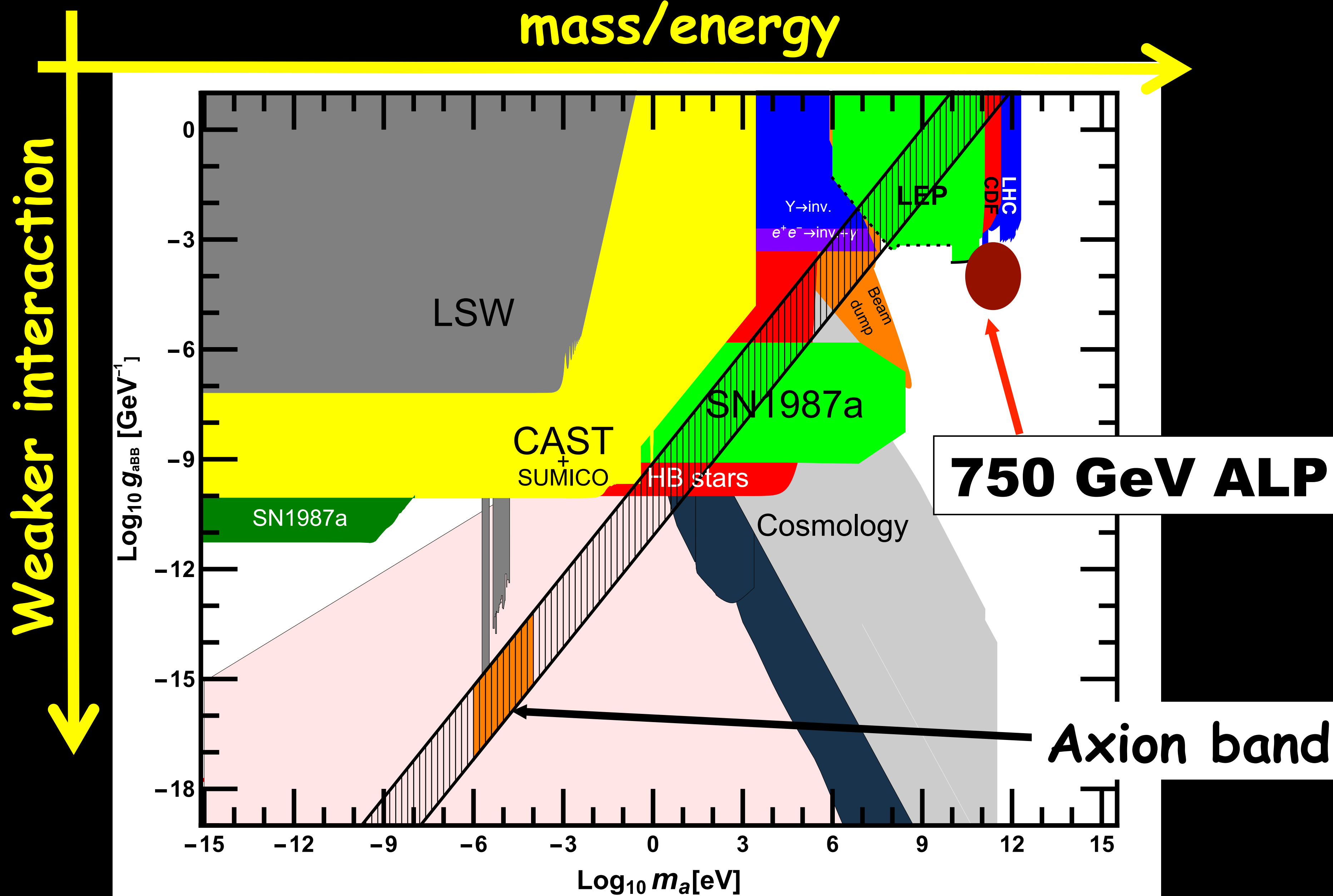

Axion-like Particles

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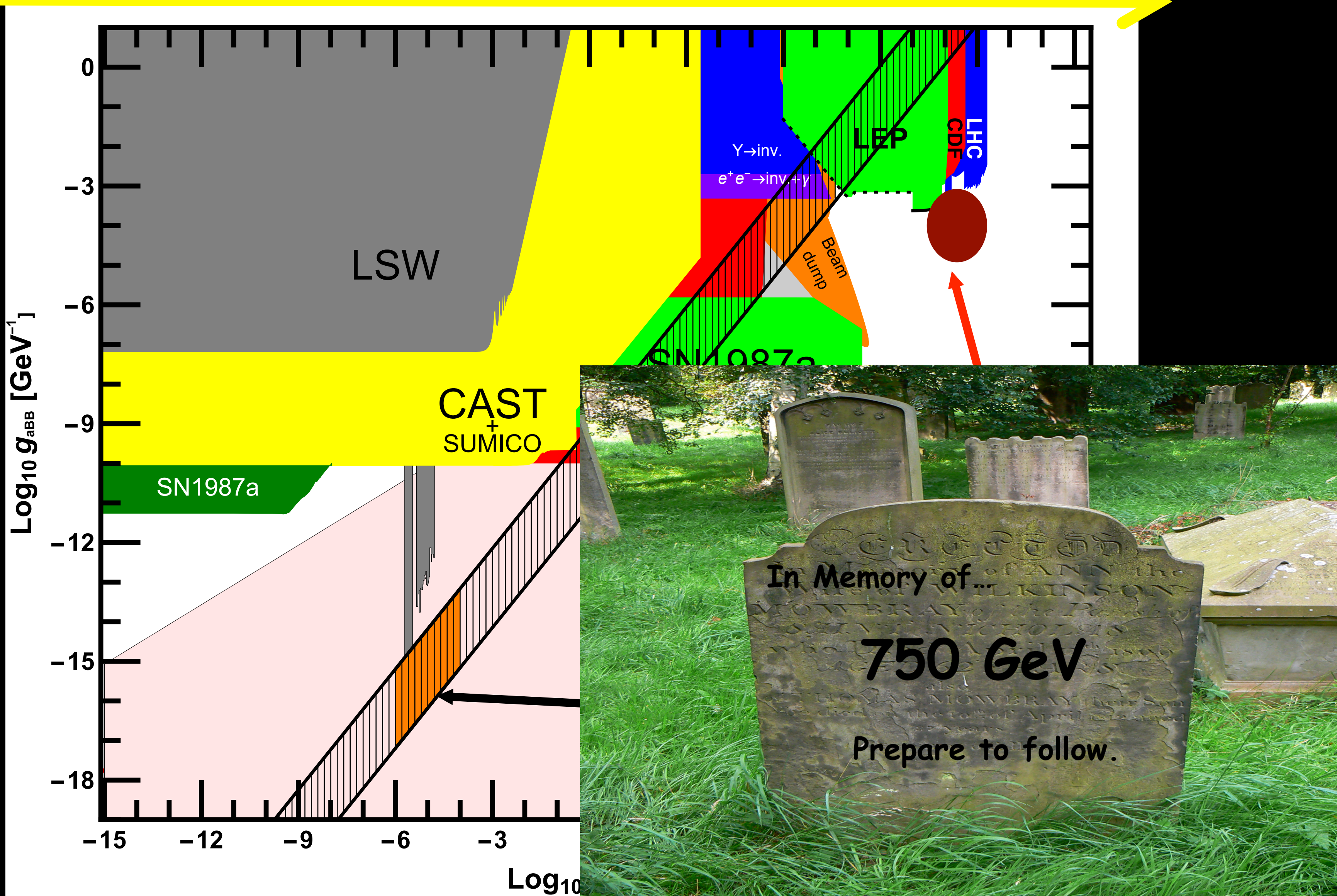
mass/energy

Weaker interaction

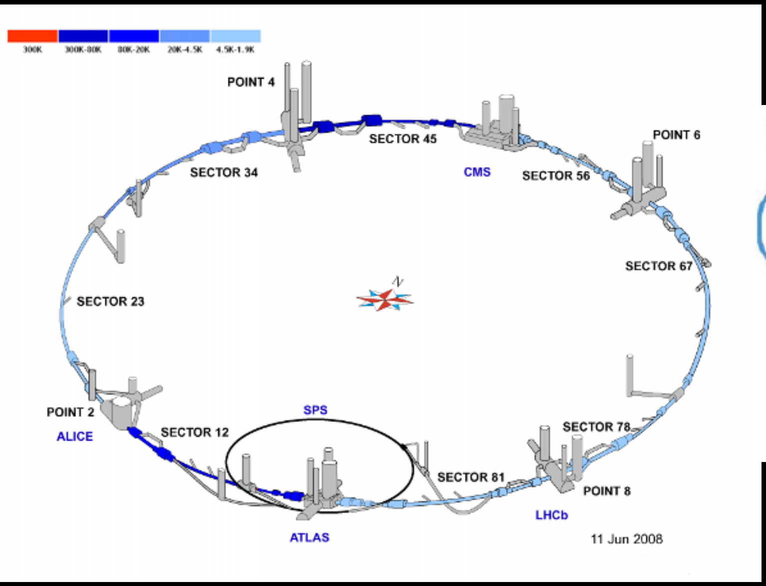


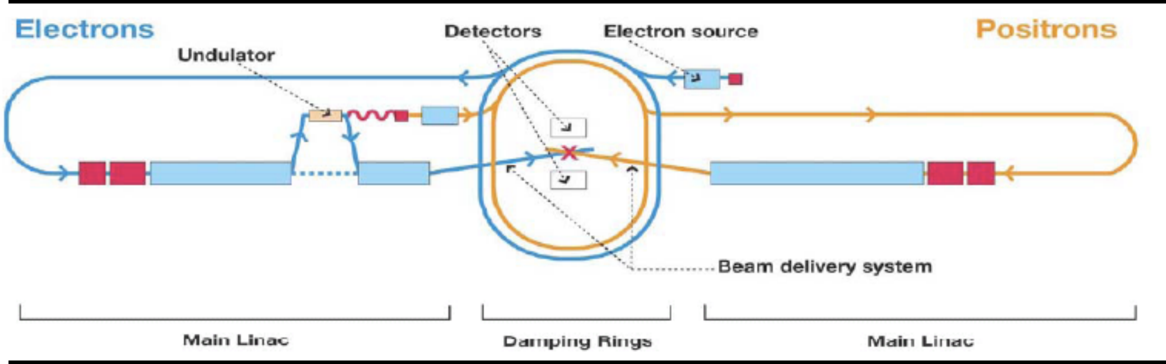
How to find the Axion…

Exploring fundamental high energy physics…

- 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

But…

- May miss very weakly interacting matter (Axions, WIMPs, WISPs…)
- Current maximal energy few TeV
- Man it's DANGEROUS…

☺

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But…

- 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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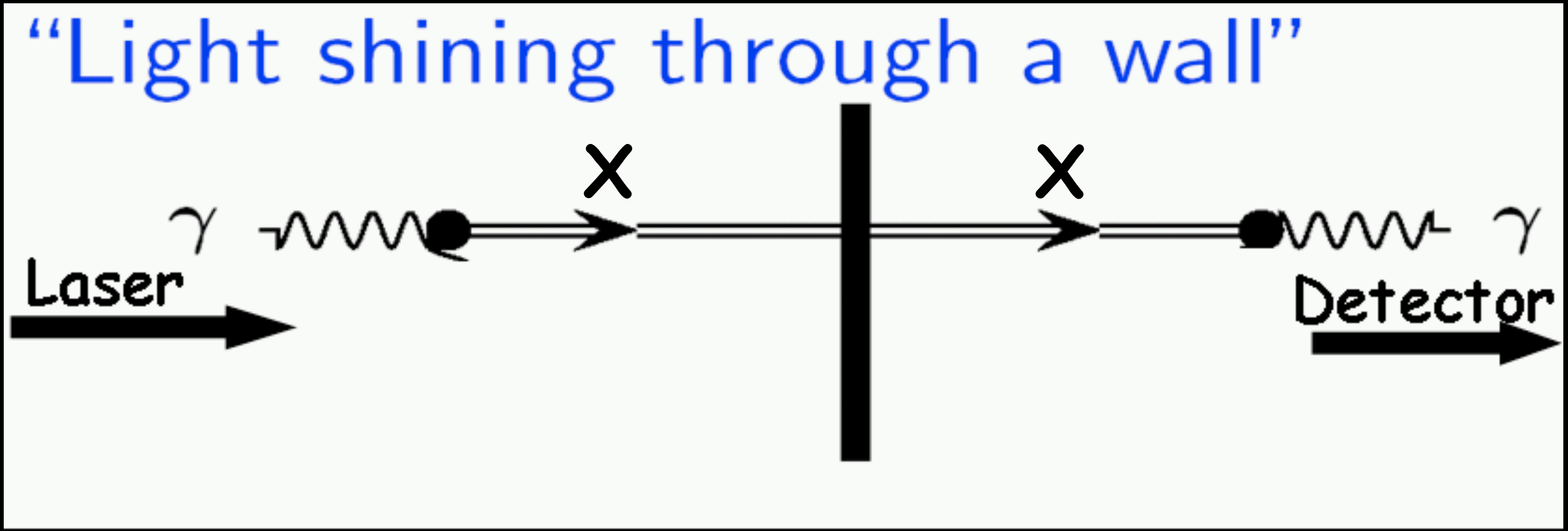
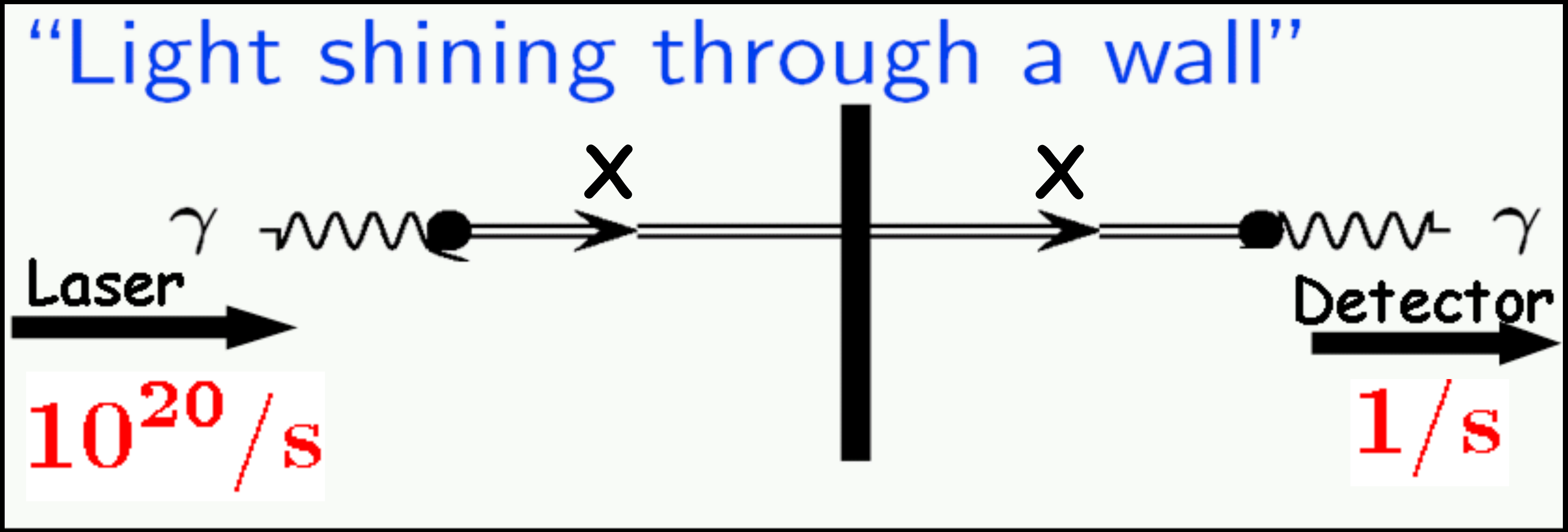


Light shining through walls



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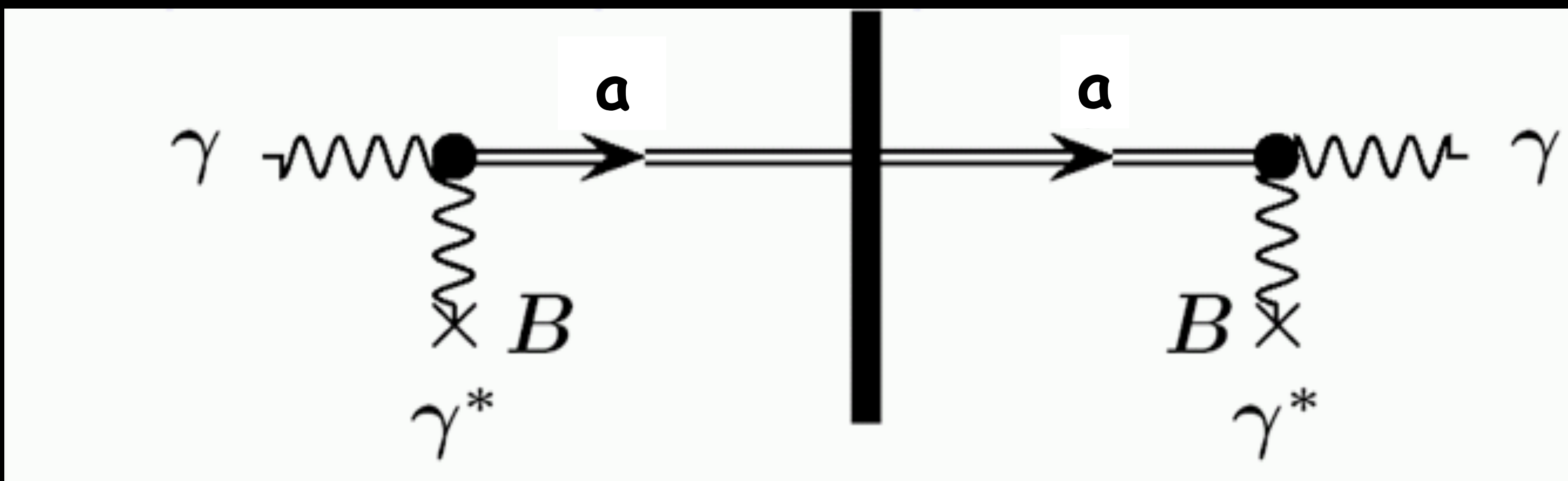
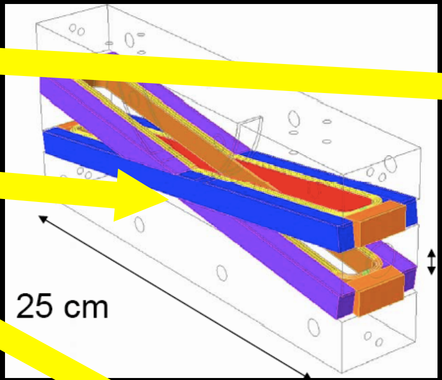
- It could be Axion(-like particle)s!
- Coupling to two photons: $\frac{1}{M} a\tilde{F}F \sim \frac{1}{M} a\vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$

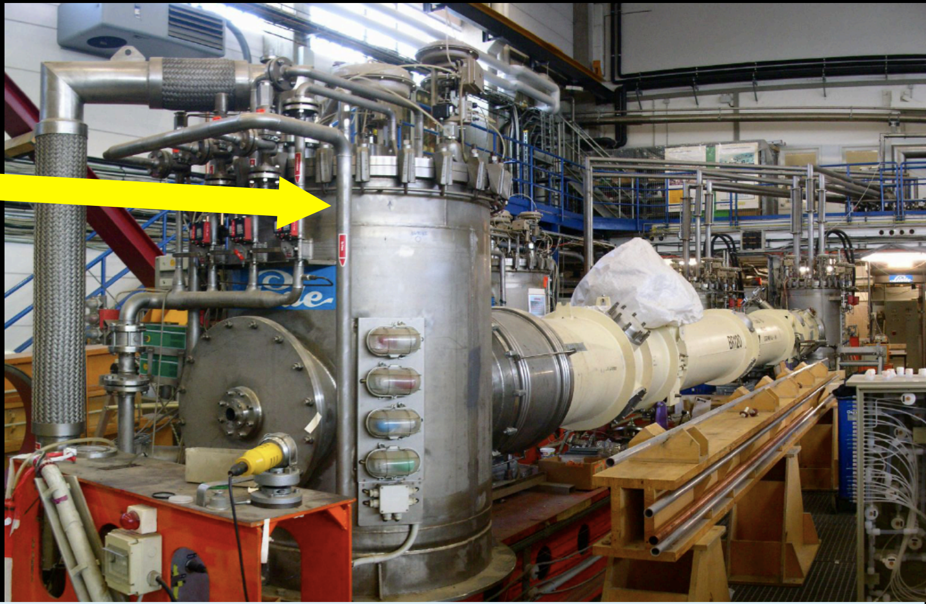


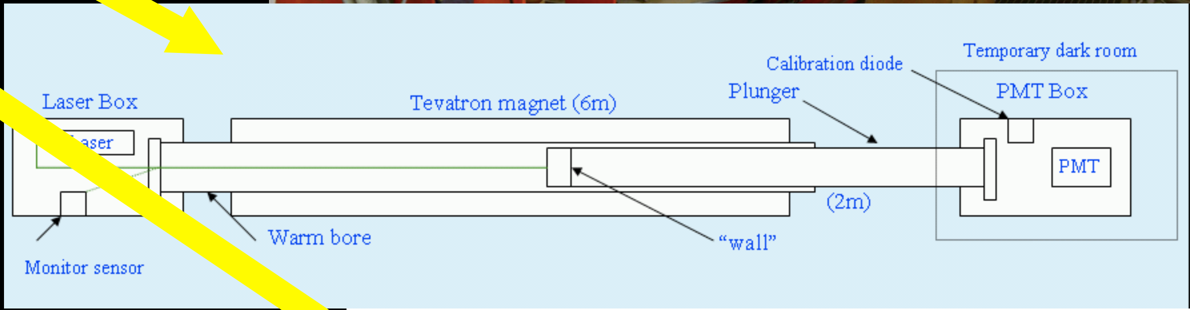
$$P_{\gamma\to a\to\gamma} \sim N_{\text{pass}} \left(\frac{BL}{M}\right)^4$$

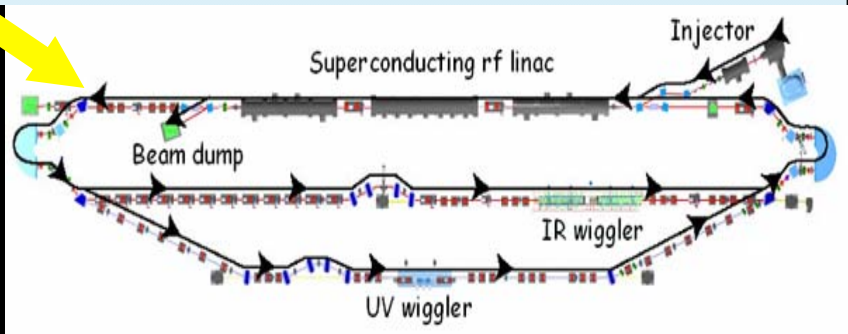
Light Shining Through Walls

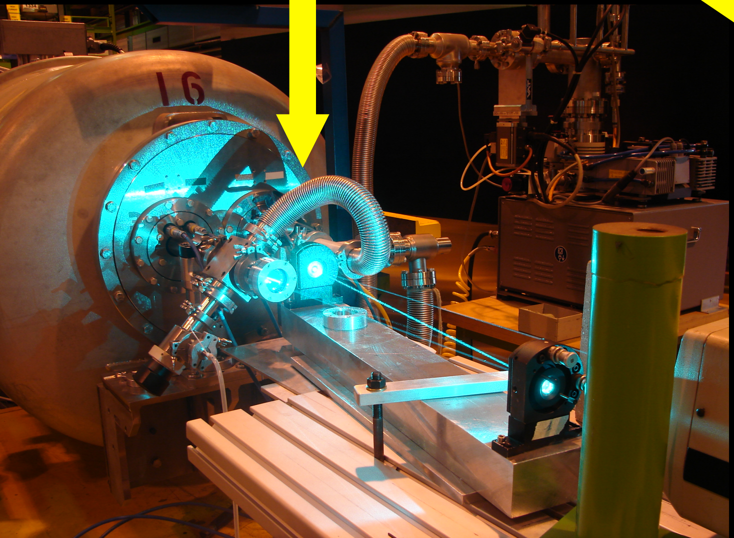
- A lot of activity
  - ALPS
  - BMV
  - GammeV
  - LIPPS
  - OSQAR











Small coupling, small mass

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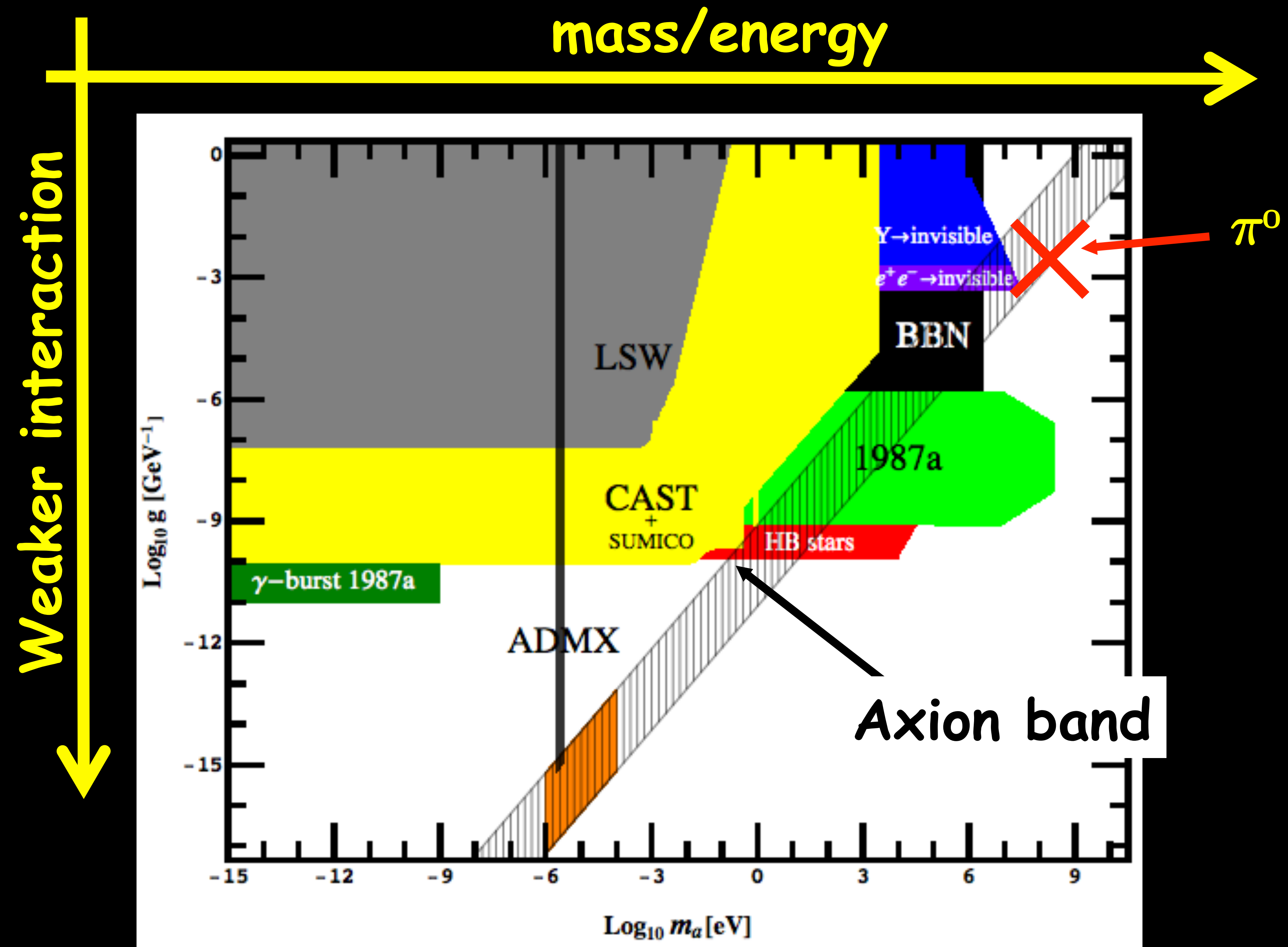

Helioscopes

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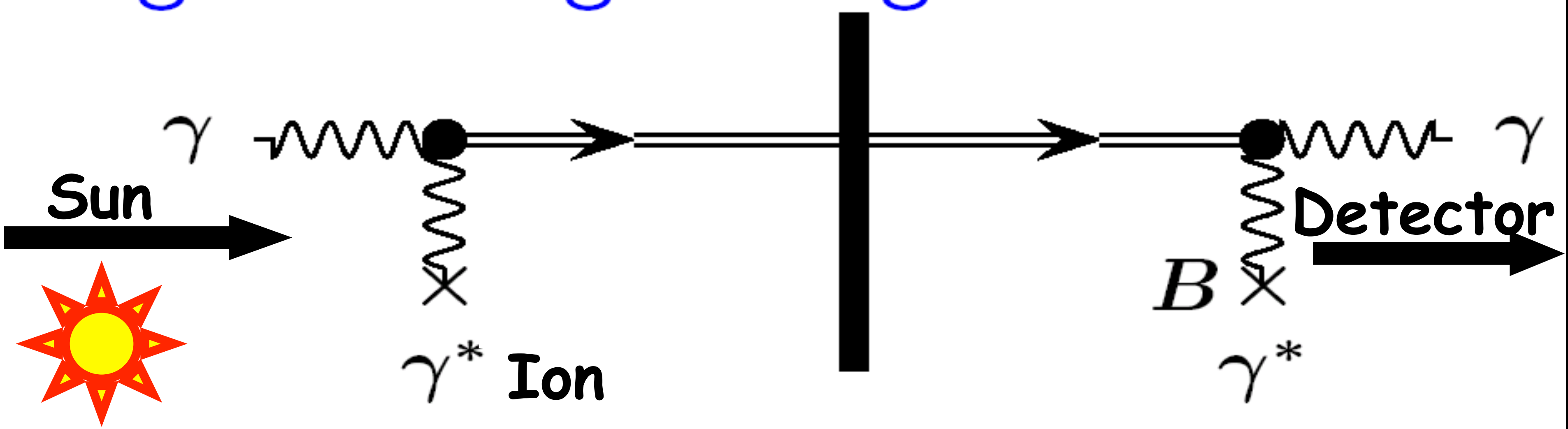
CAST@CERN
SUMICO@Tokyo

SHIPS@Hamburg

"Light shining through a wall"



Sensitivity

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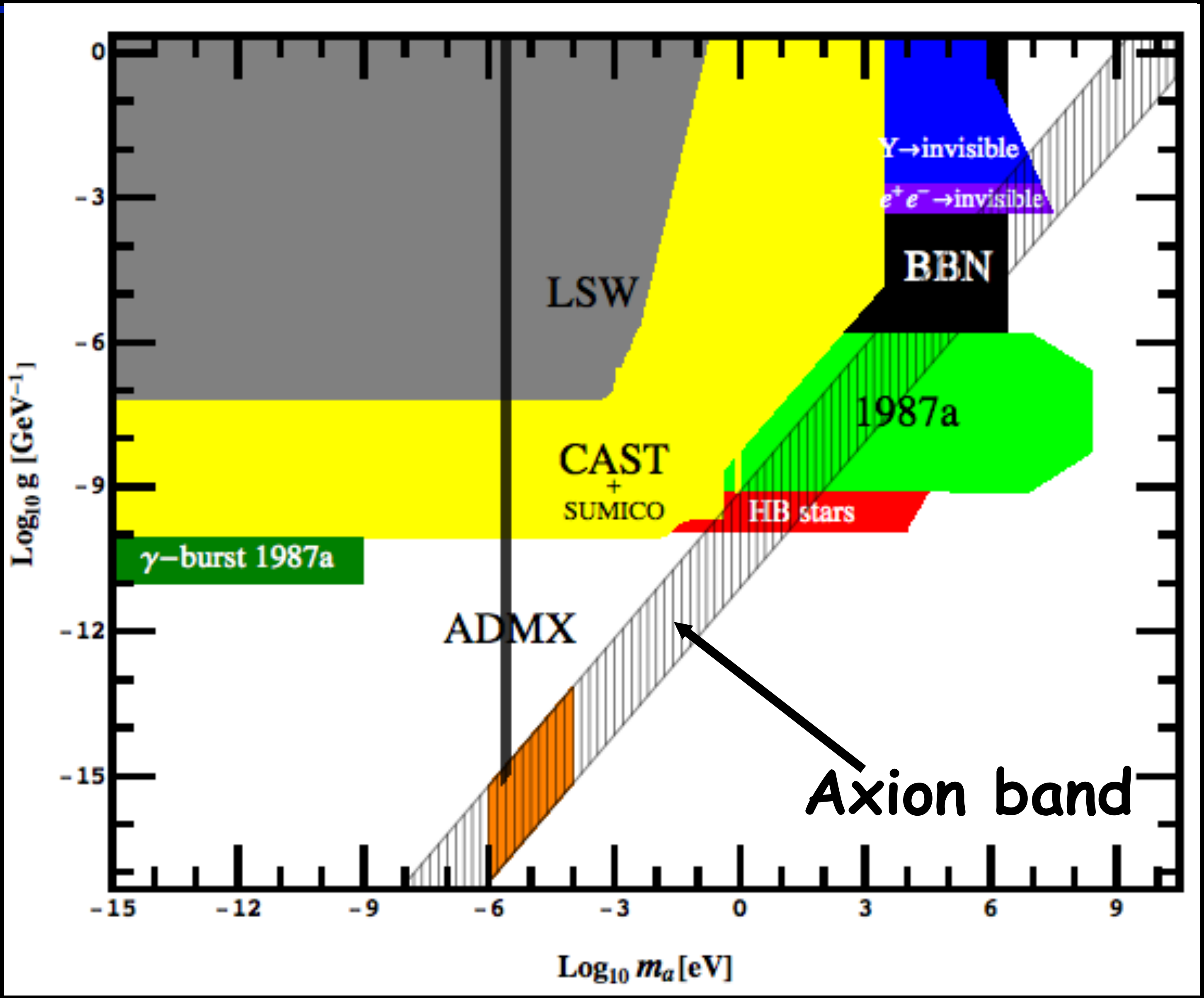
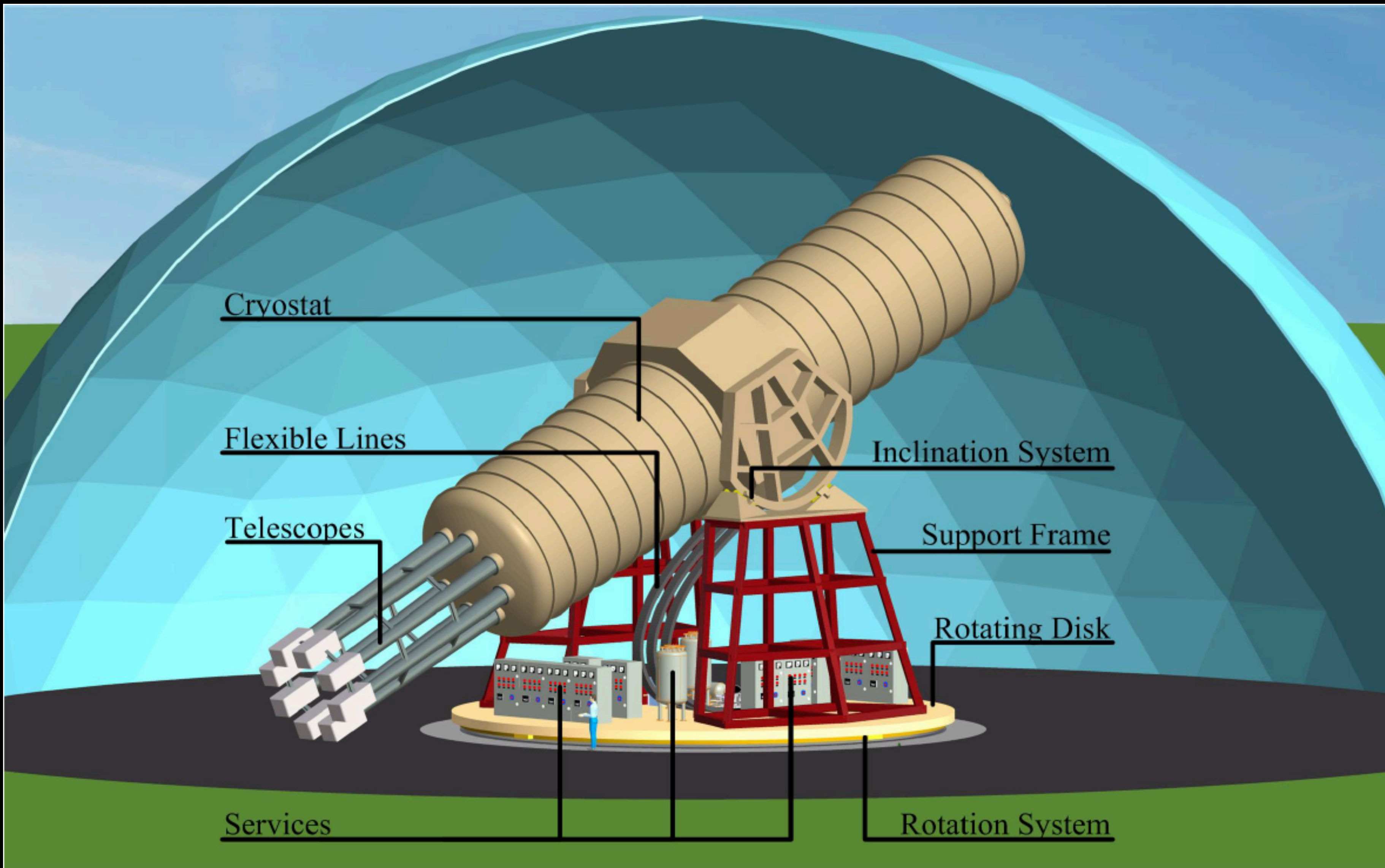


Going to the future: IAXO

The International Axion Observatory



An interesting area...

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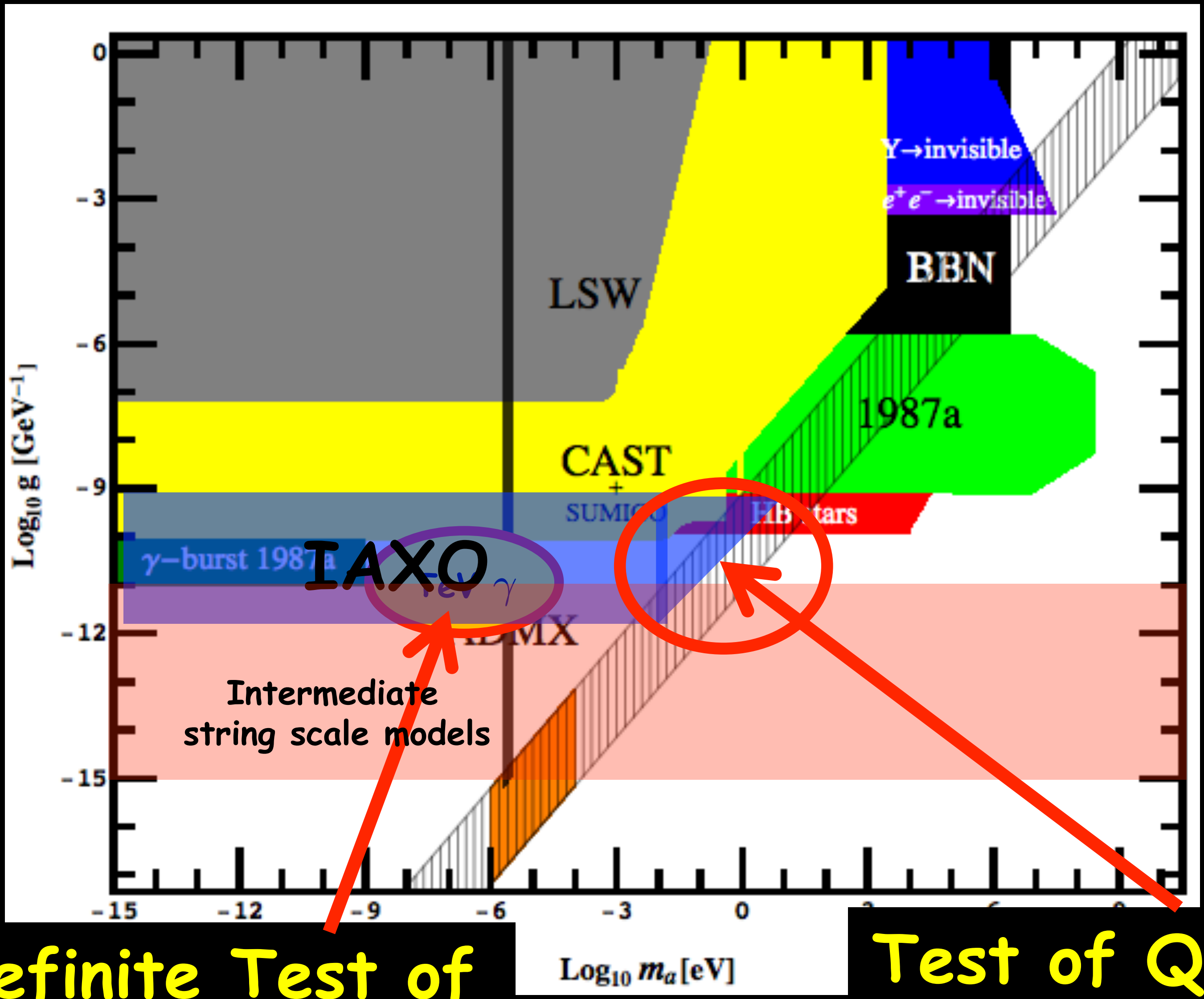
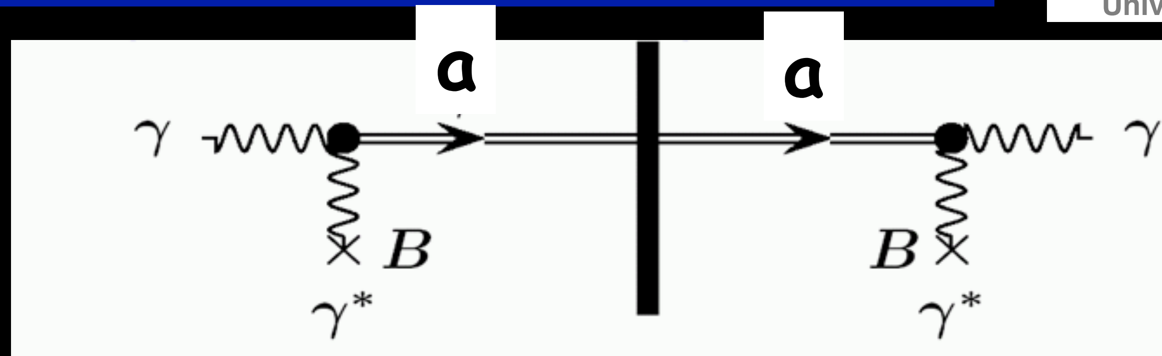


Definite Test of TeV transparency

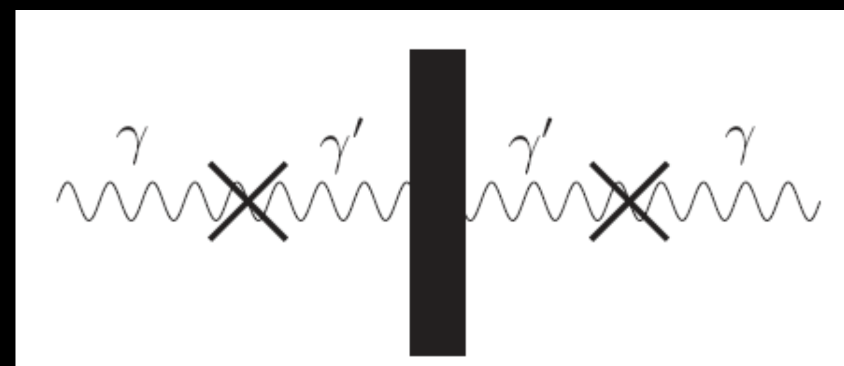
Test of QCD axion
+ white dwarf anomaly

WISPS=Weakly interacting sub-eV particles

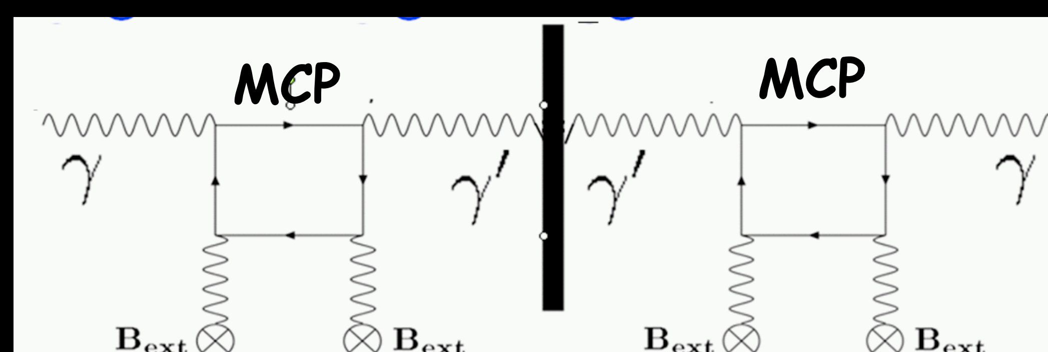
- Axions



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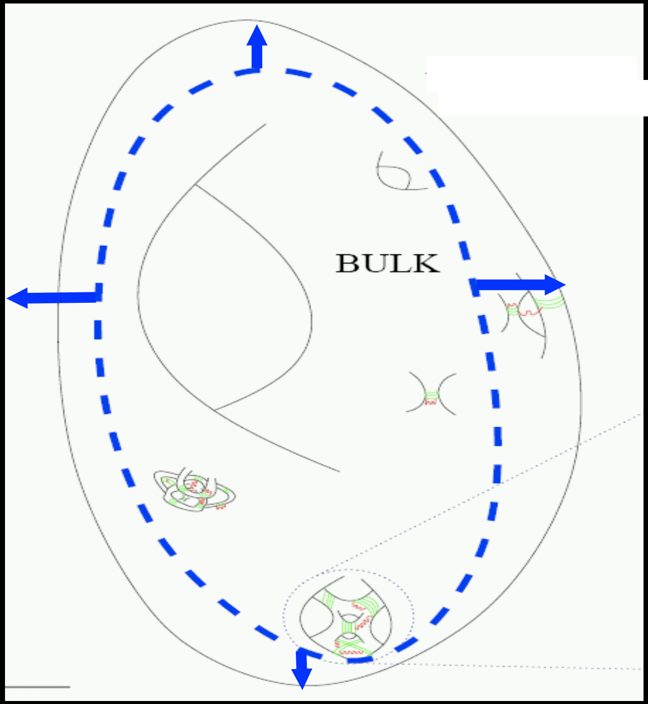
- Attempt to unify SM with gravity
- New concept: strings instead of point particles

String theory: Moduli and Axions

- 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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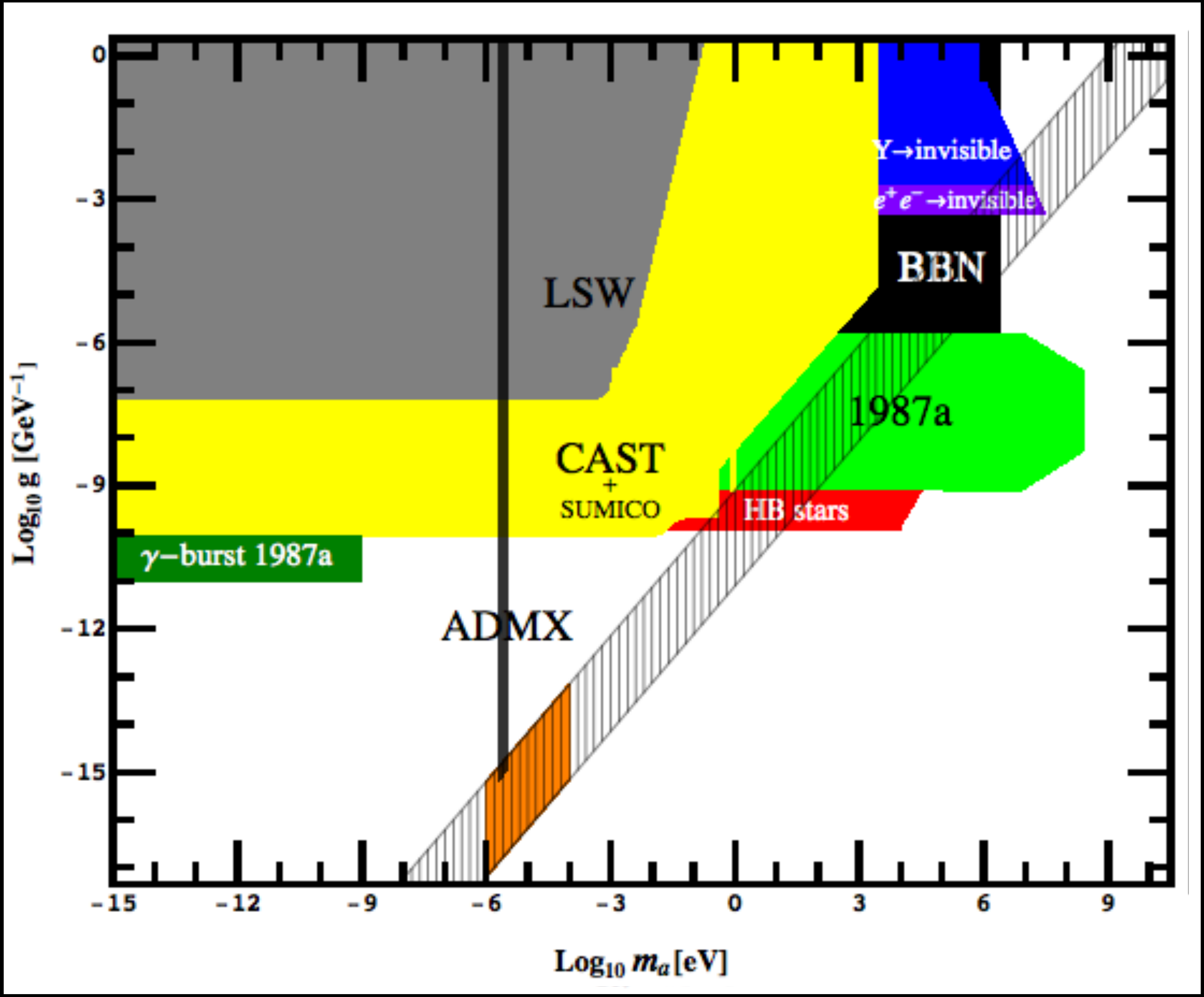

Axions and Moduli

- 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

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

- If QCD axion: m_a fixed

- However, if not QCD axion

$$m_{\mathrm{ALP}} \sim \frac{\Lambda^2}{f_a}$$ (nearly) arbitrary

Axion (like particles): Where are we?

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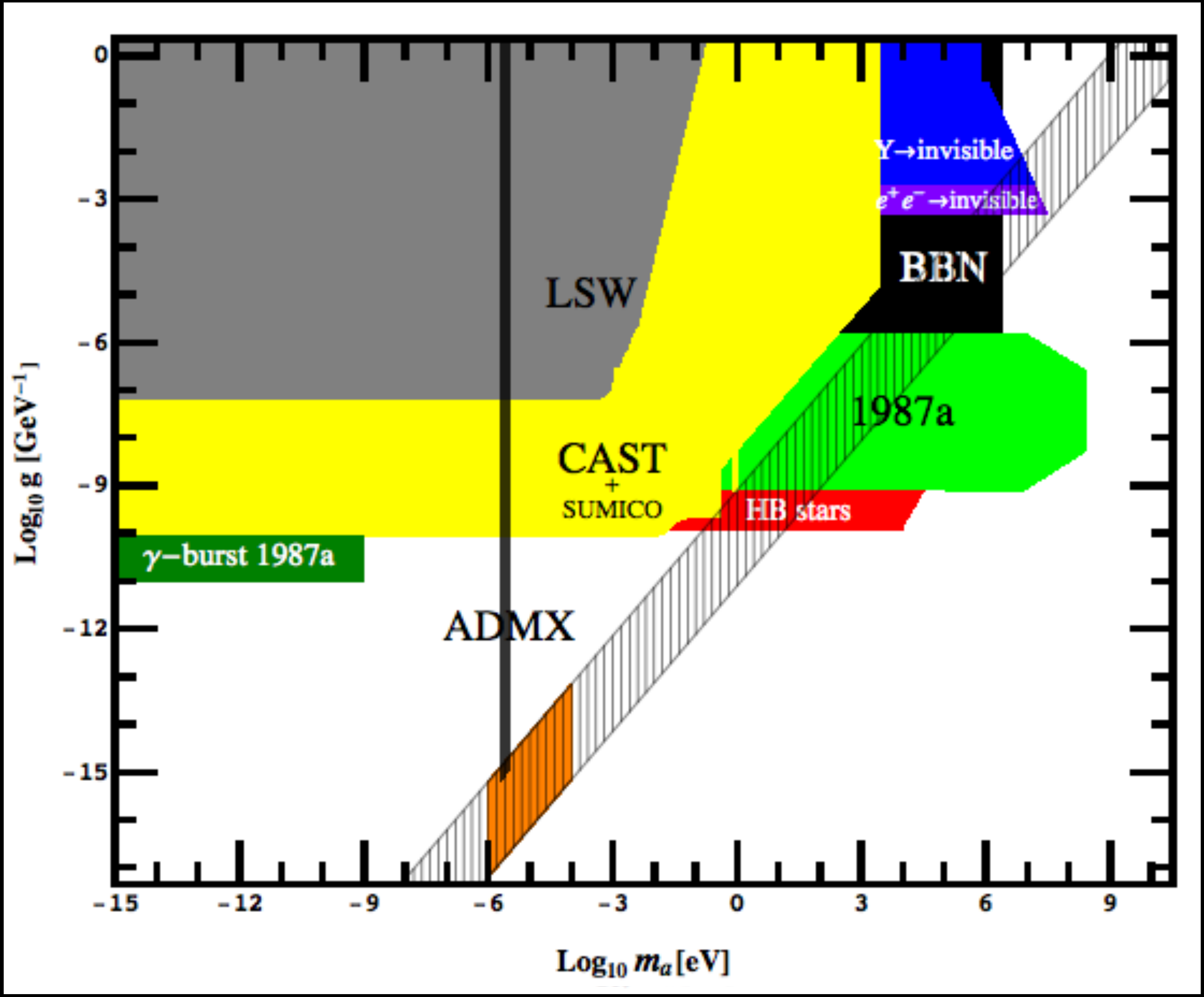

Axion (like particles): Where are we?

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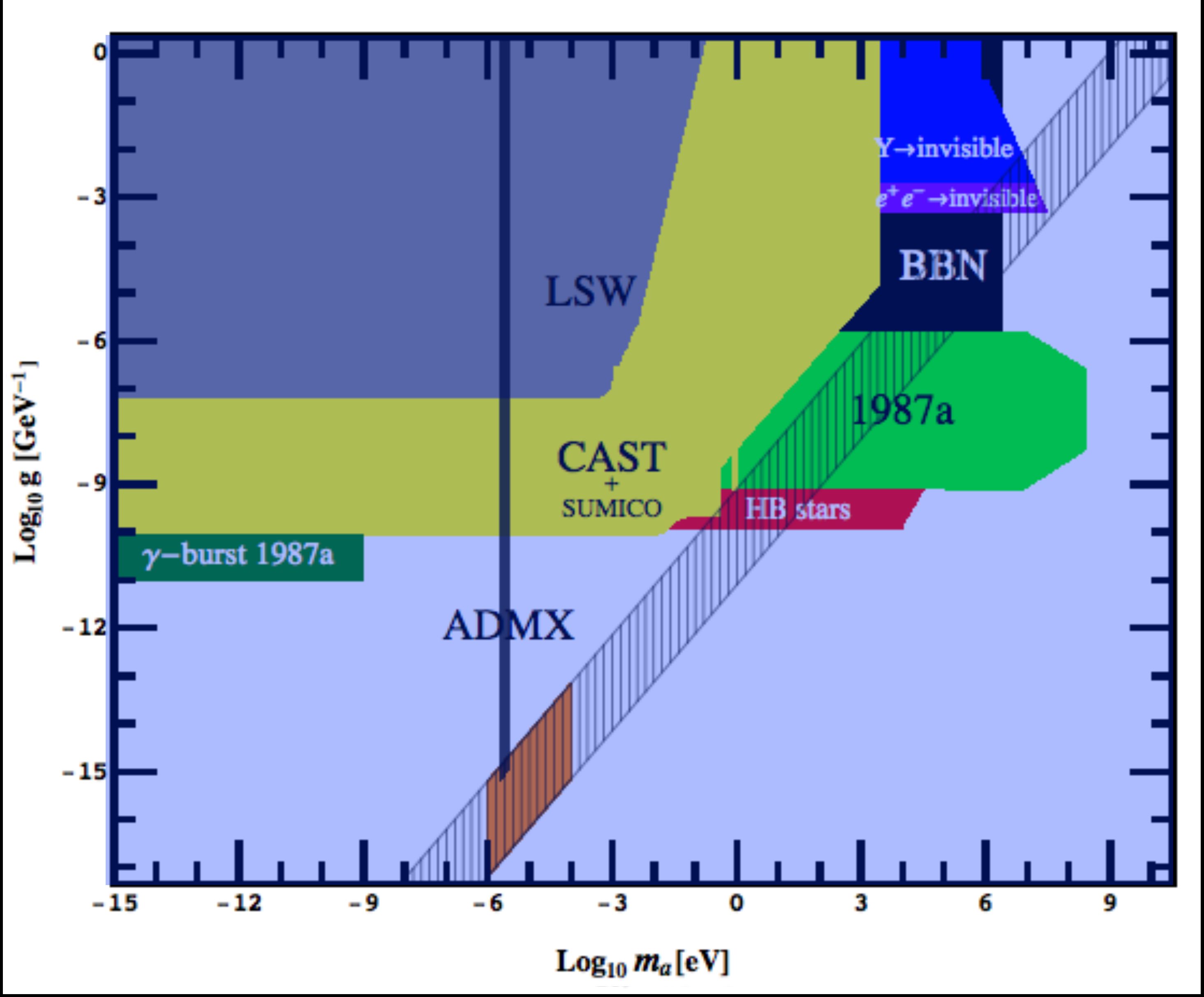

Axion (like particles): Where are we?

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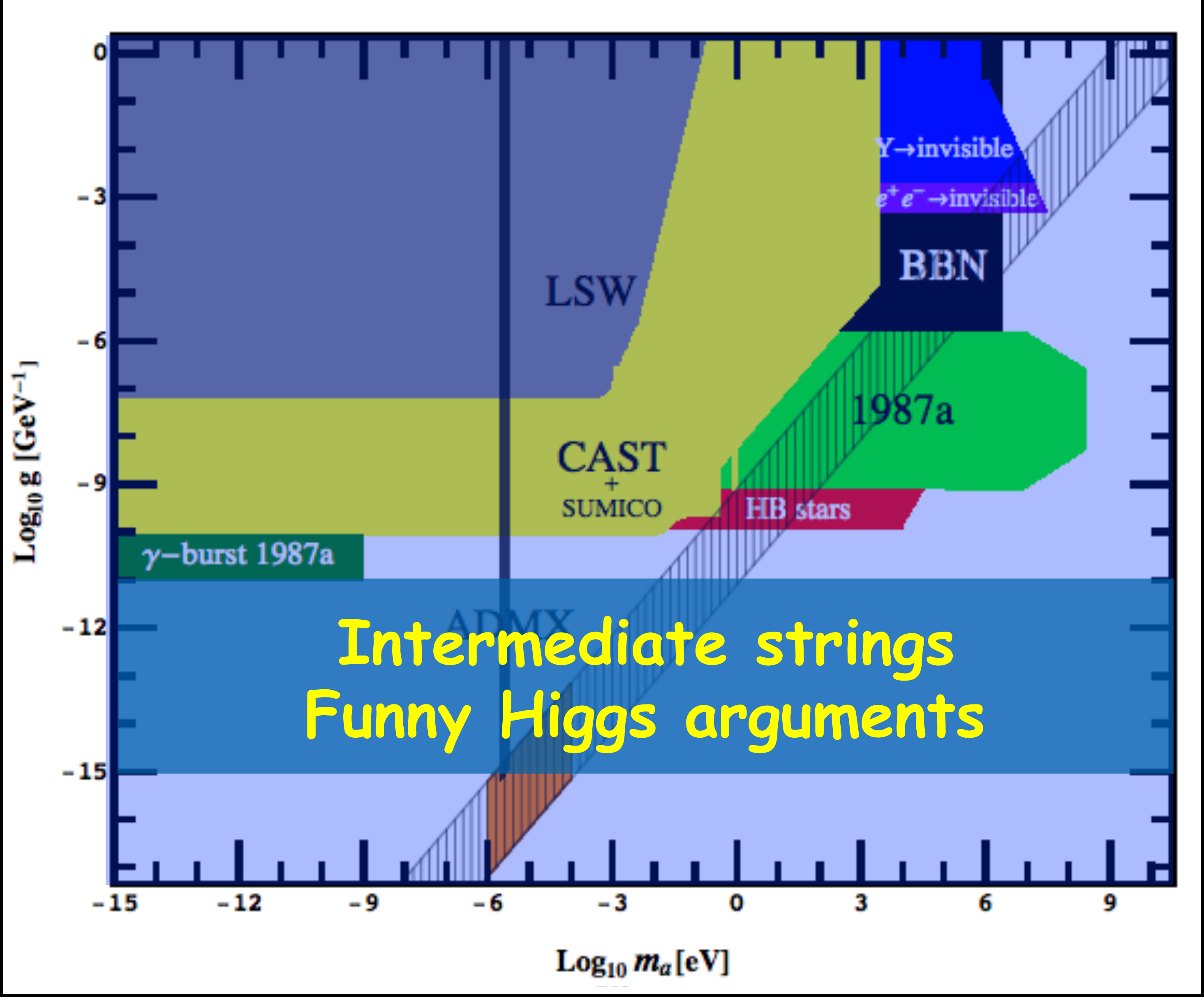

Dark Matter(s)

Can Dark Matter be Axiony/WISPy?

(Weakly Interacting Sub-eV Particley)

Slim

Properties of Dark Matter

- 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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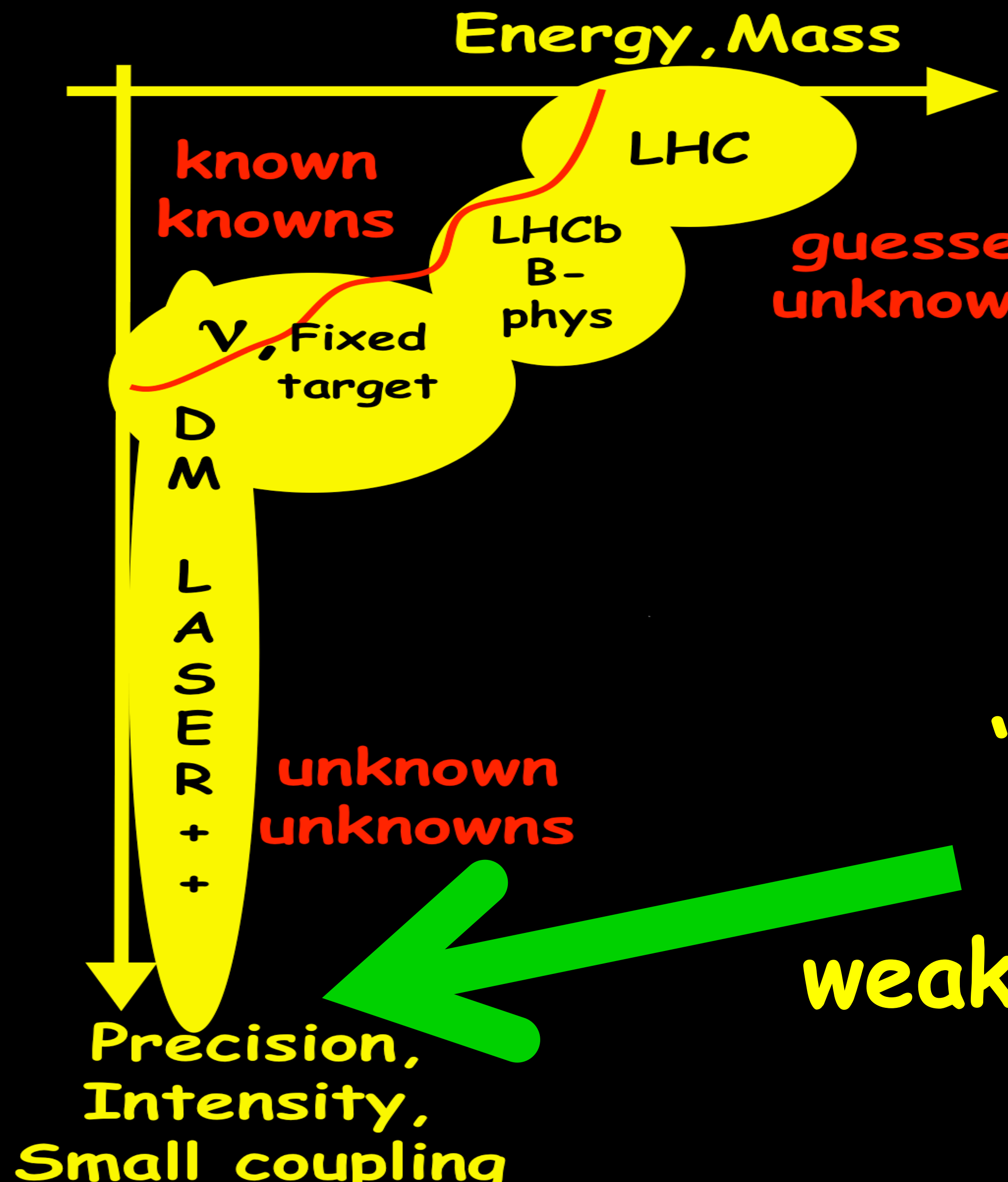


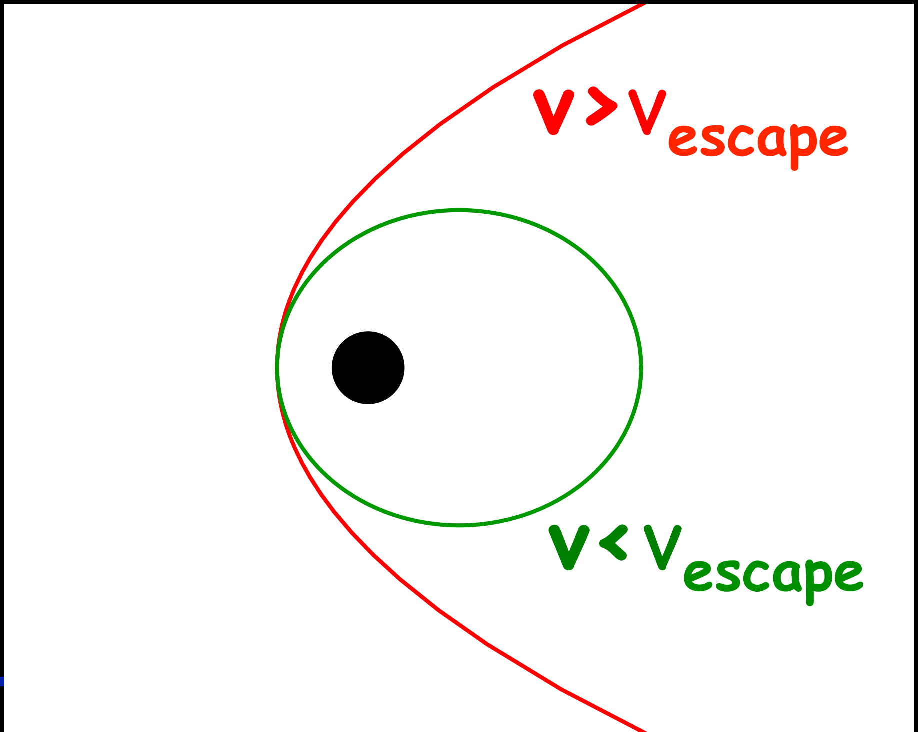
"dark"
=
weakly coupled

A common prejudice

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

- 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 $m_{\mathrm{DM}} \gtrsim \mathrm{keV}?$

Dark matter has to be heavy...

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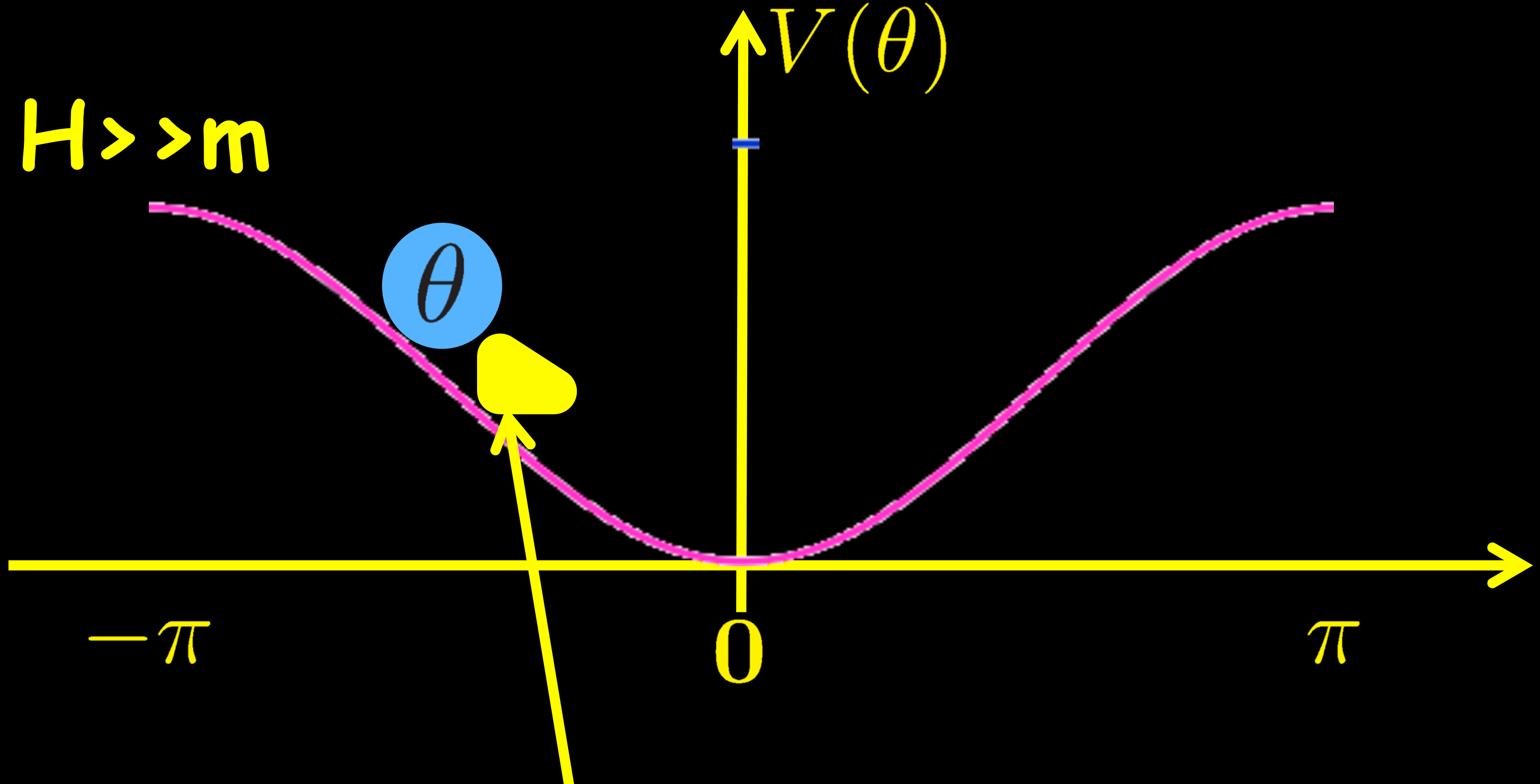
Dar

keV?

SUPERCOLD DARK MATTER

The axion has no clue where to start

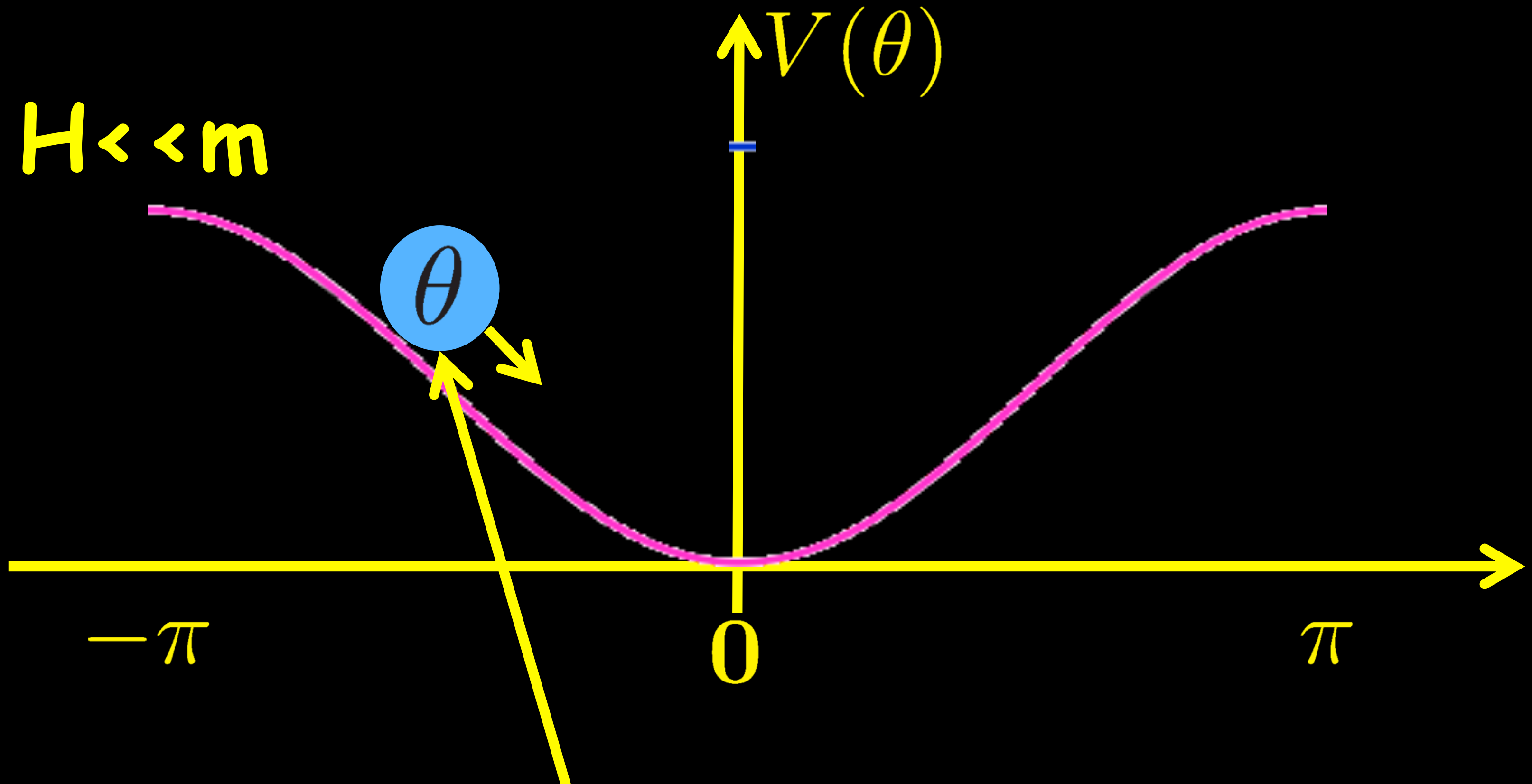
$H >> m$



Field is stuck because of Hubble "breaking"

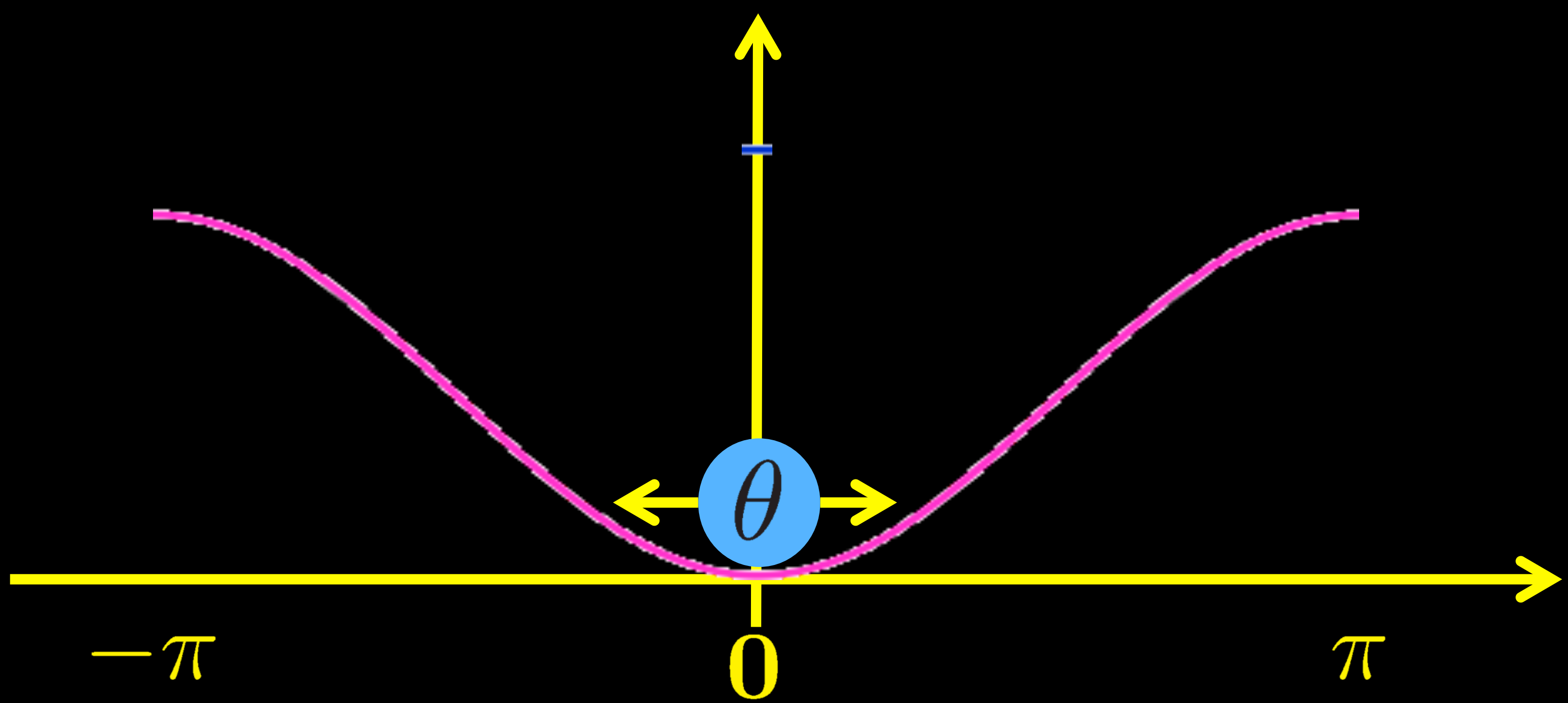
The axion has no clue where to start

H<<m



Can start moving...

The axion solution to the strong CP problem



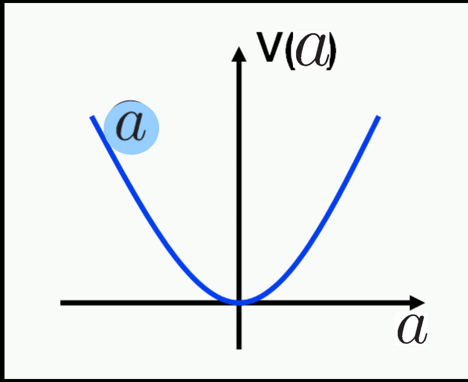
➔ Oscillations contain energy

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

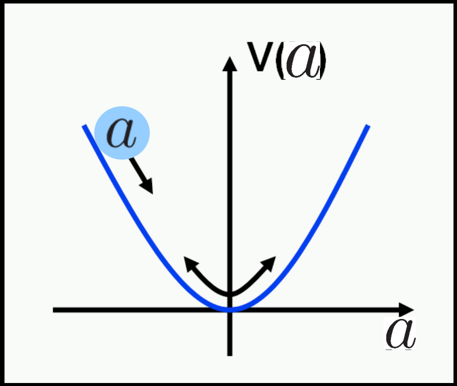
Axion Dark Matter

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

- $H \gg m_a$ → overdamped oscillator



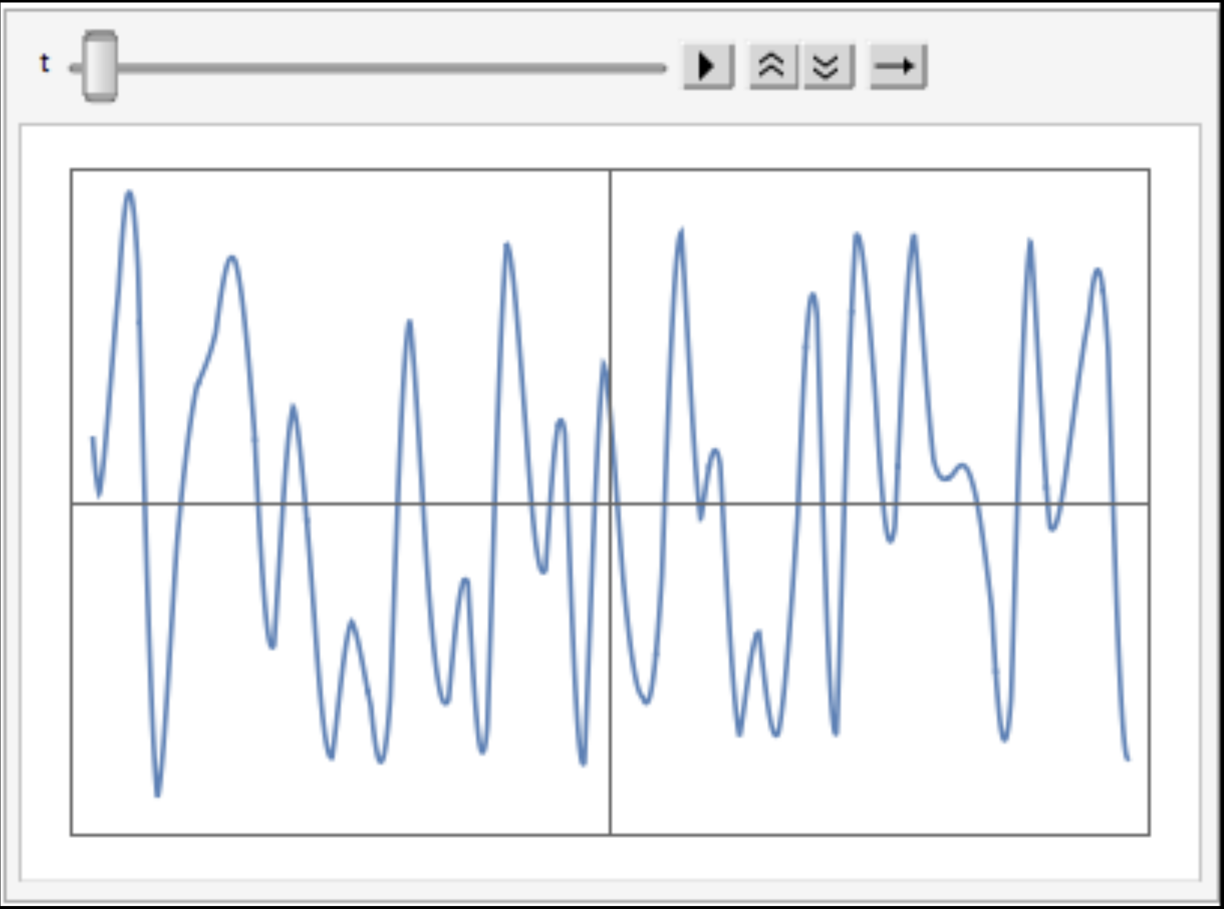
- $H \ll m_a$ → damped oscillator



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

Why Cold? Inflation!

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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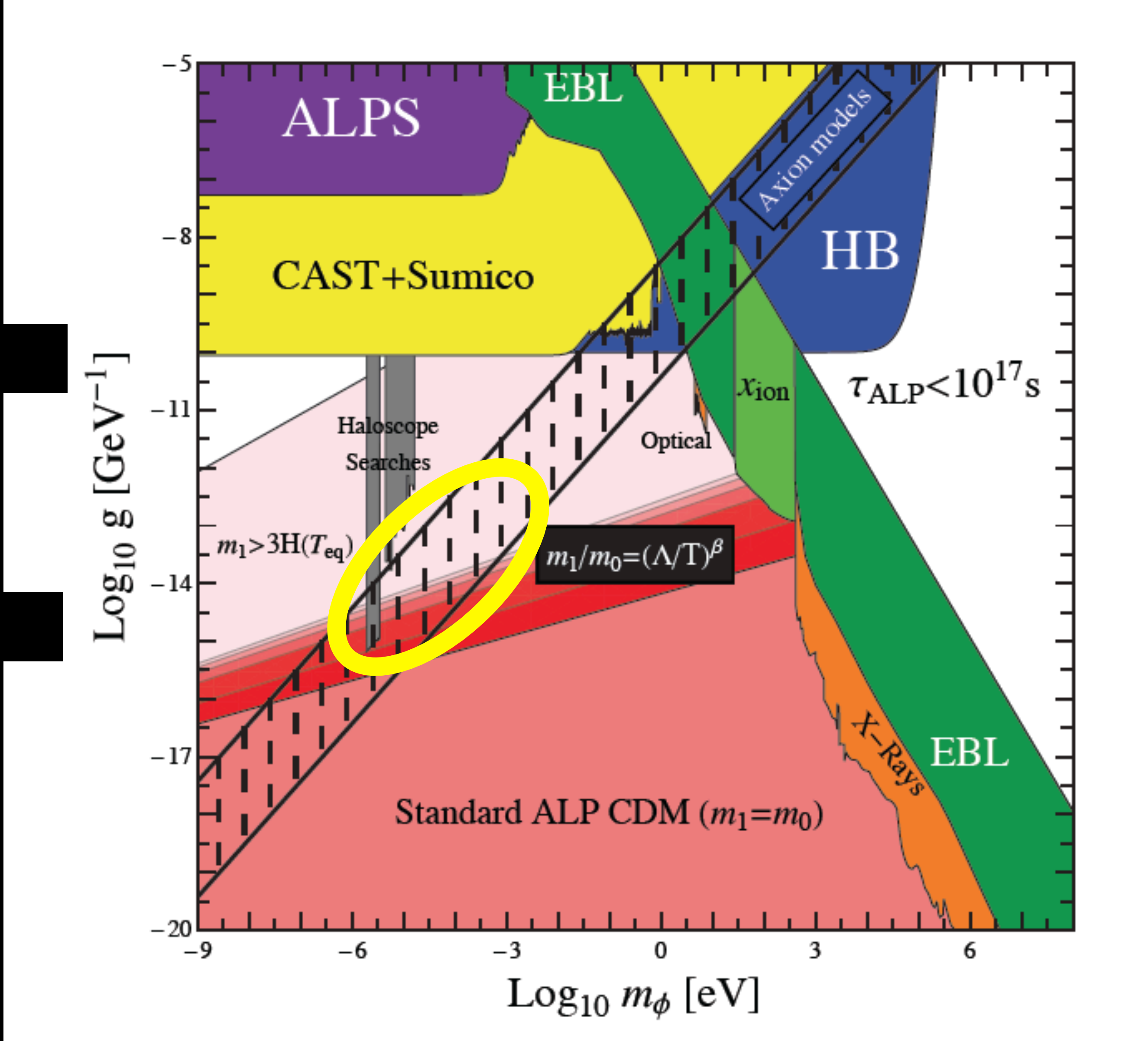
~10^7 GeV

~10^{12} GeV



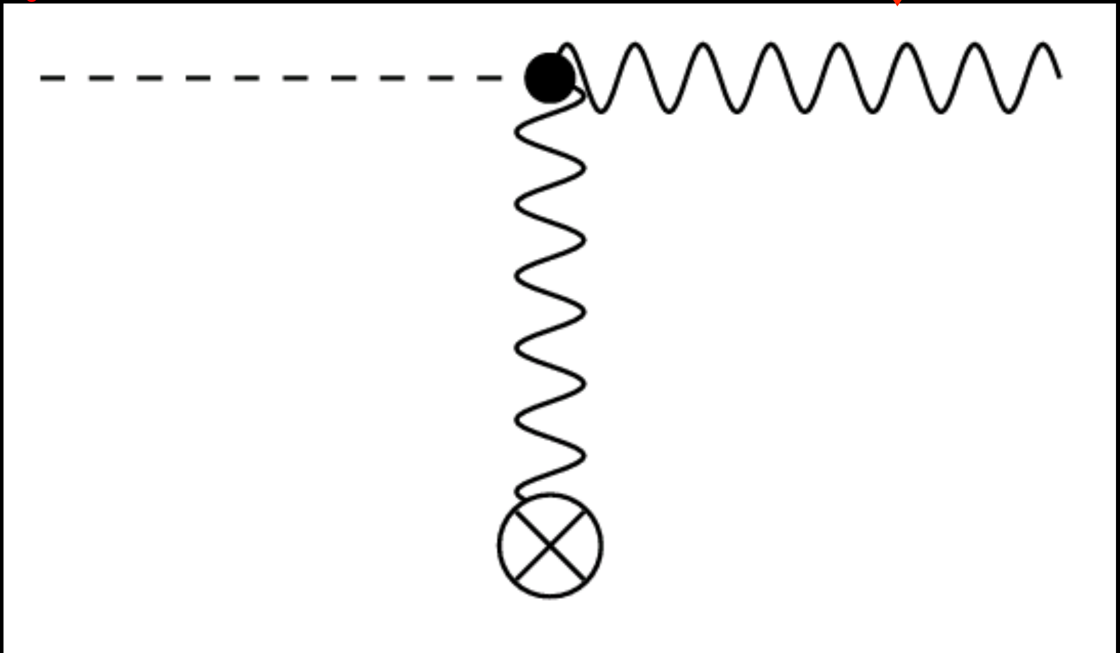
Detecting Axiony/WISPy DM

Use a plentiful source of axions

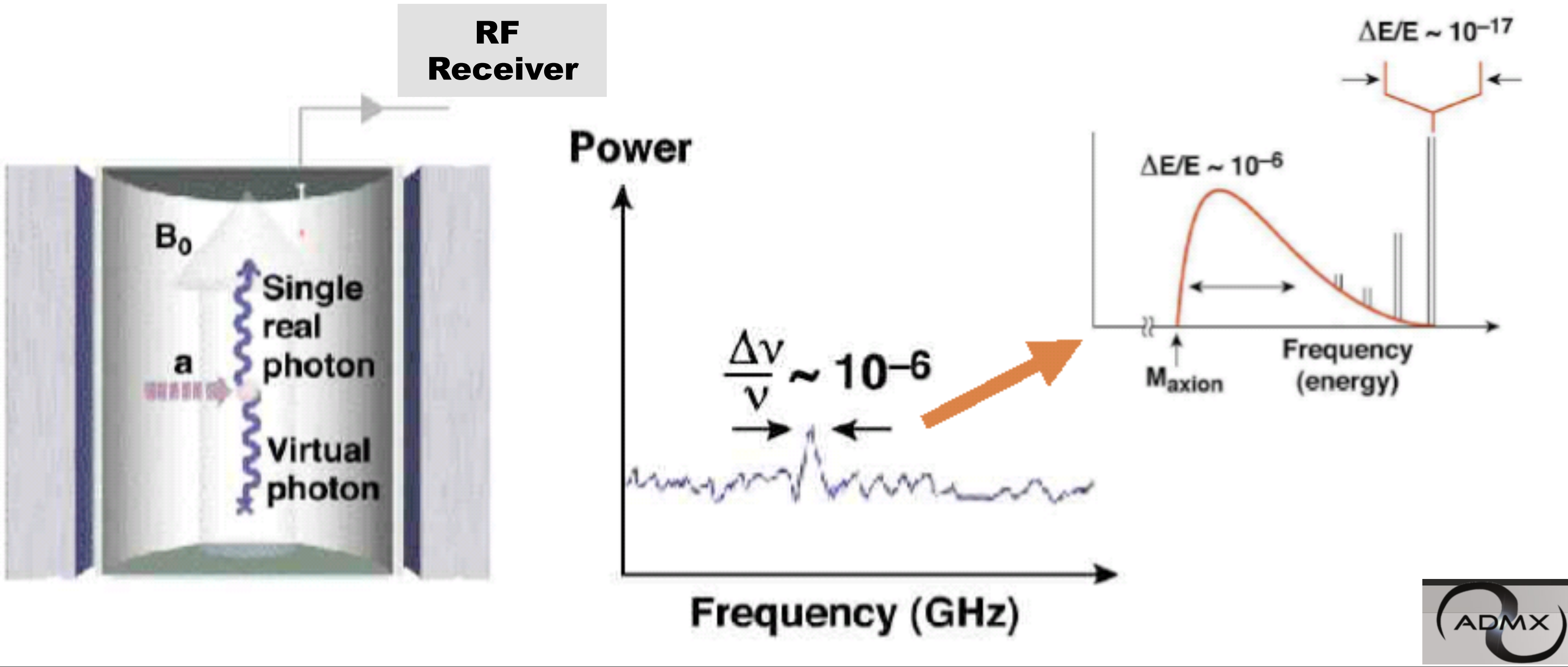
- Photon Regeneration

Photon
(amplified in resonator)

axion
(dark matter)



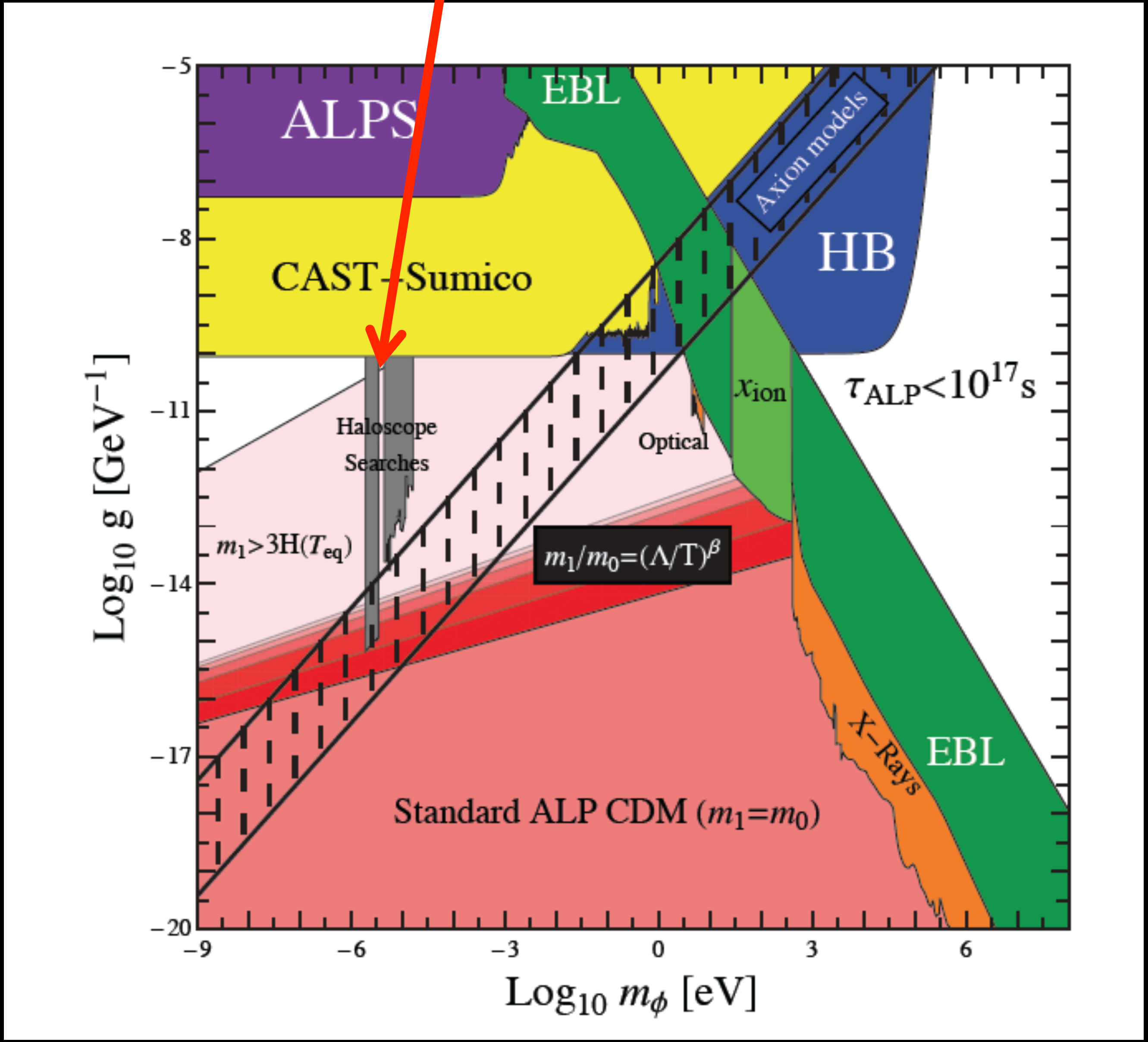
Signal: Total energy of axion



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

Virial velocity
in galaxy halo!

An extremely sensitive probe!!!



A discovery possible any minute!

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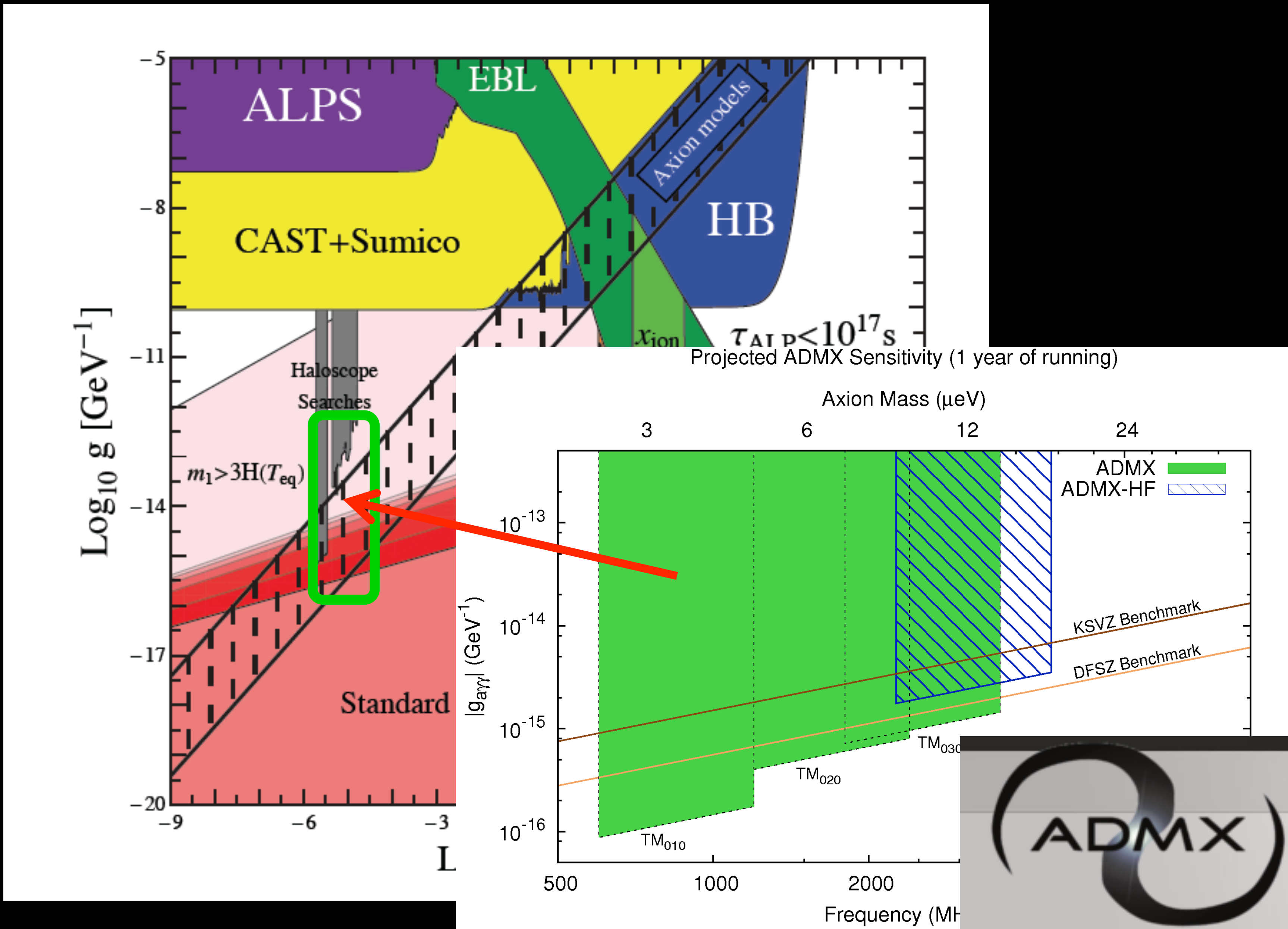
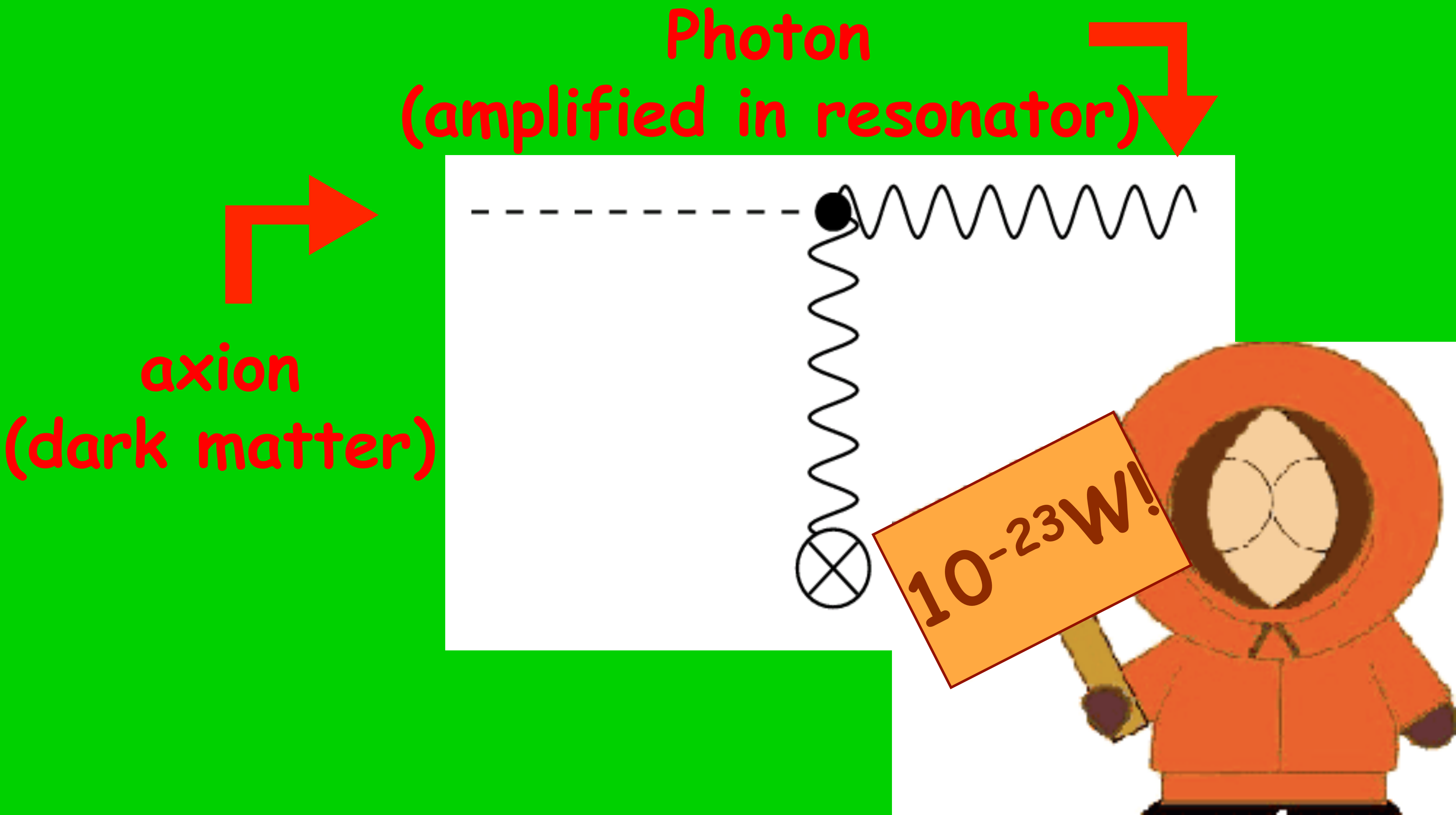


Electricity from Dark Matter ;-).

- Photon Regeneration



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Really sustainable Energy

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

➔ (3-15)x10^{43} TWh

@100000 TWh per year (total world today)

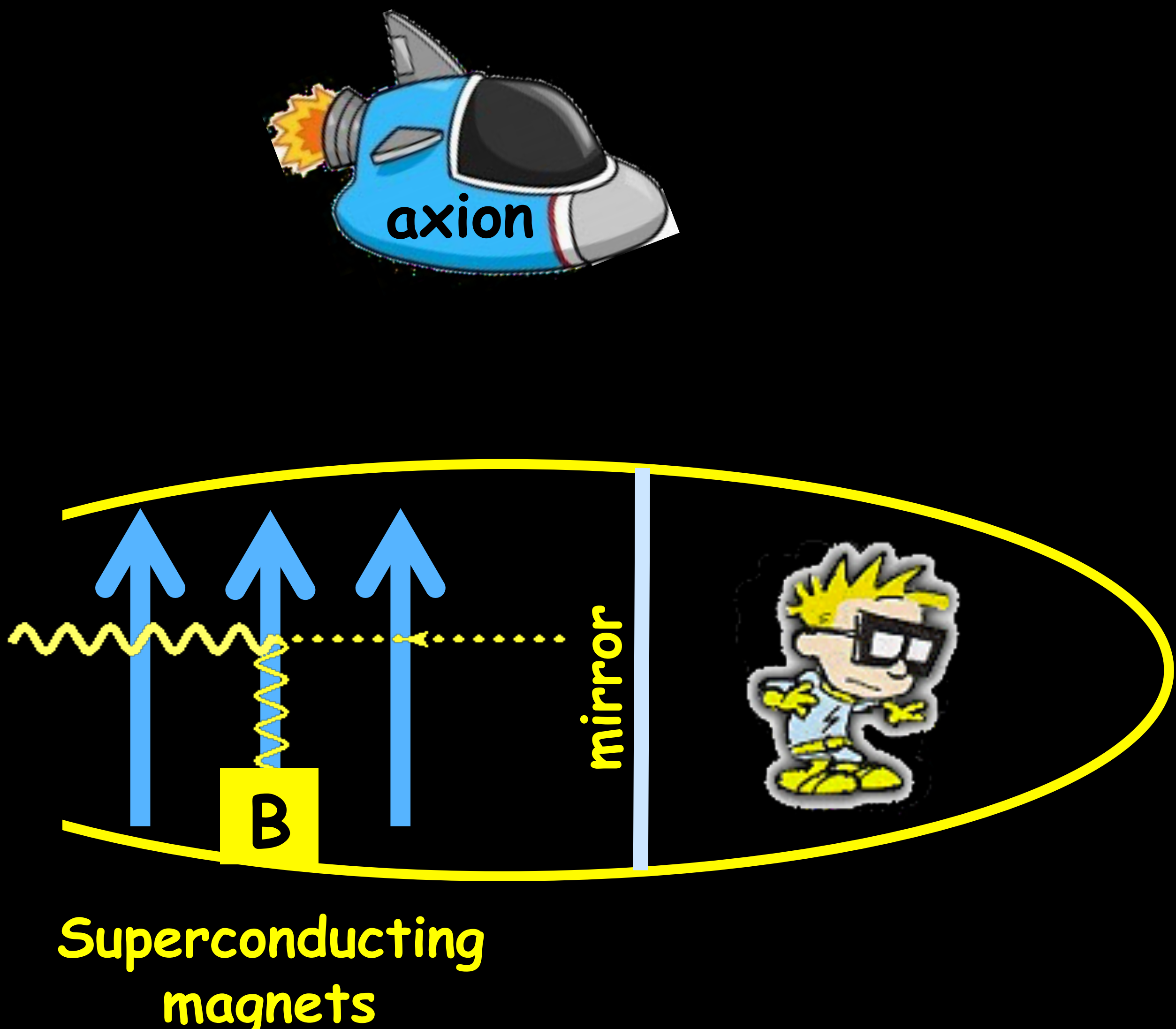
➔ 10^{38} years ☺

DM power

ρ*v~300 MeV/cm^3*300km/s~10 W/m^2

compared to 2W/m^2 for wind

How "the axion" works



Encircling the axion…

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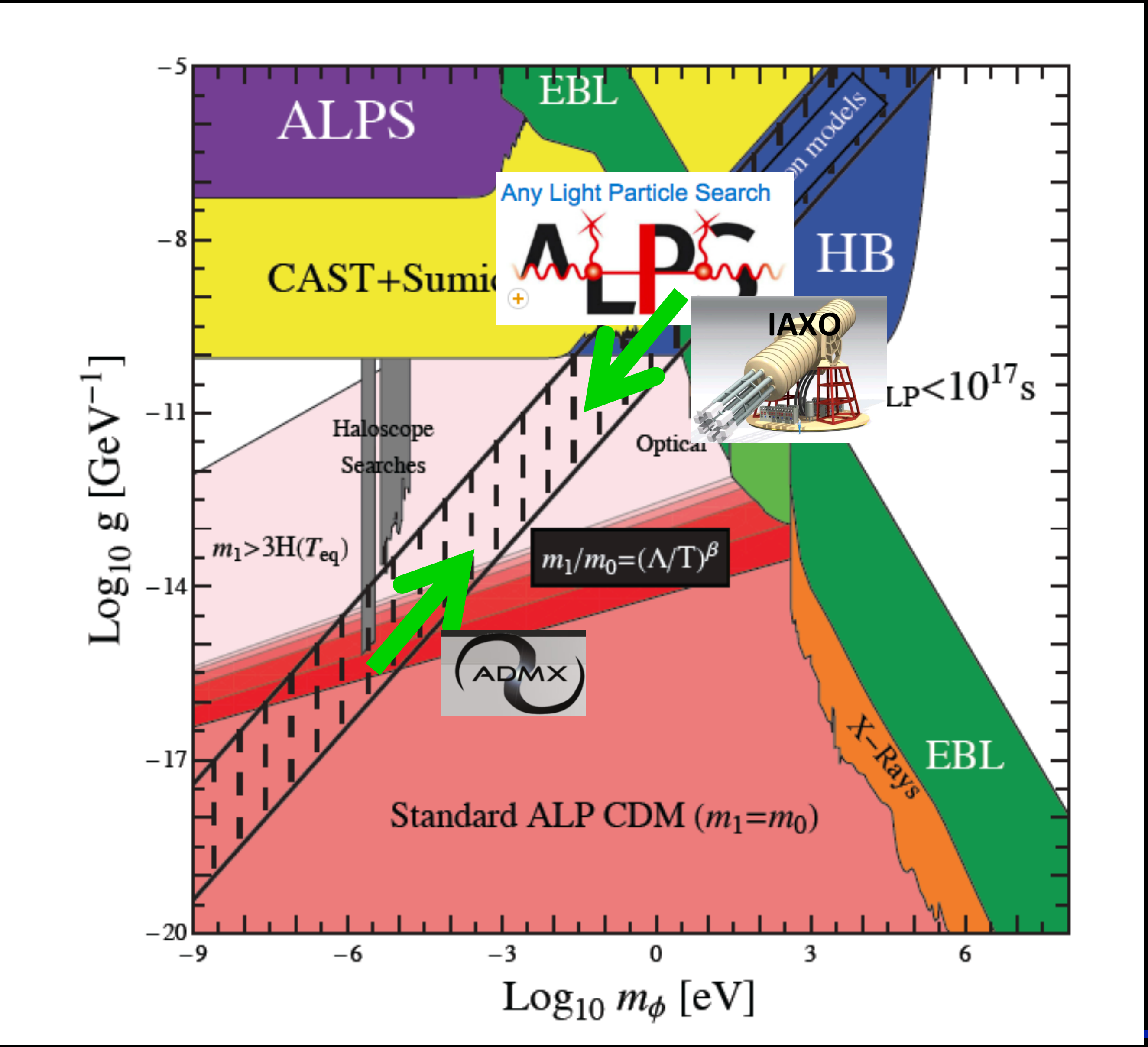

Broadband Search Strategy

Dark Matter Antenna

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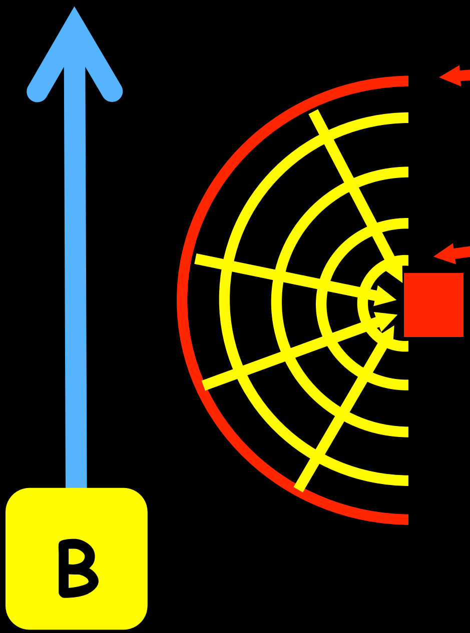
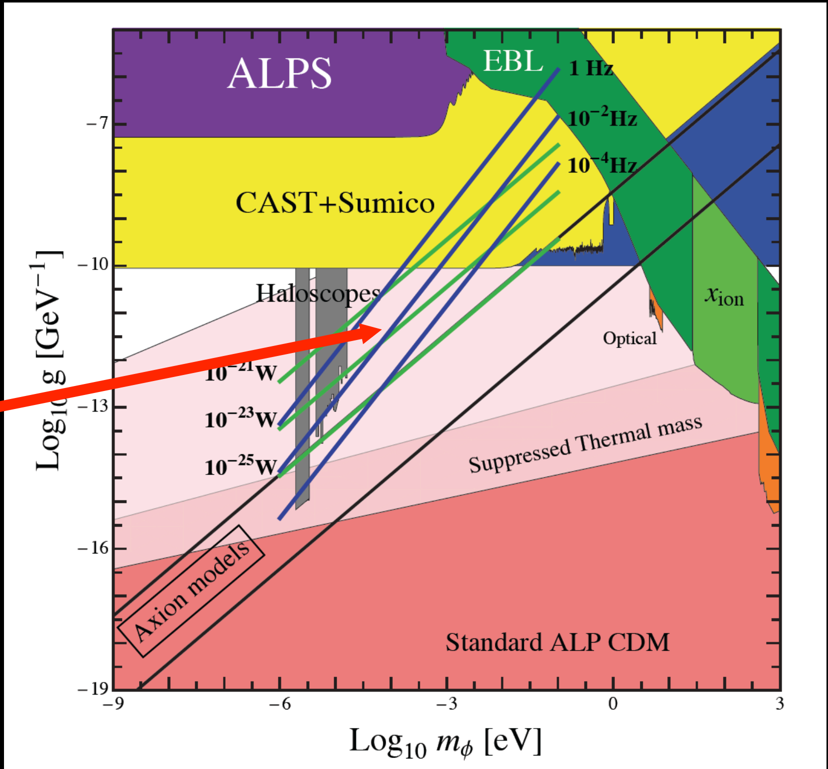


Antenna converts axion->photon

Radiation concentrated in center

Detector

Probes here;
very sensitive!!



The FUNK Experiment

Recycle Auger mirror

Detector

First Results

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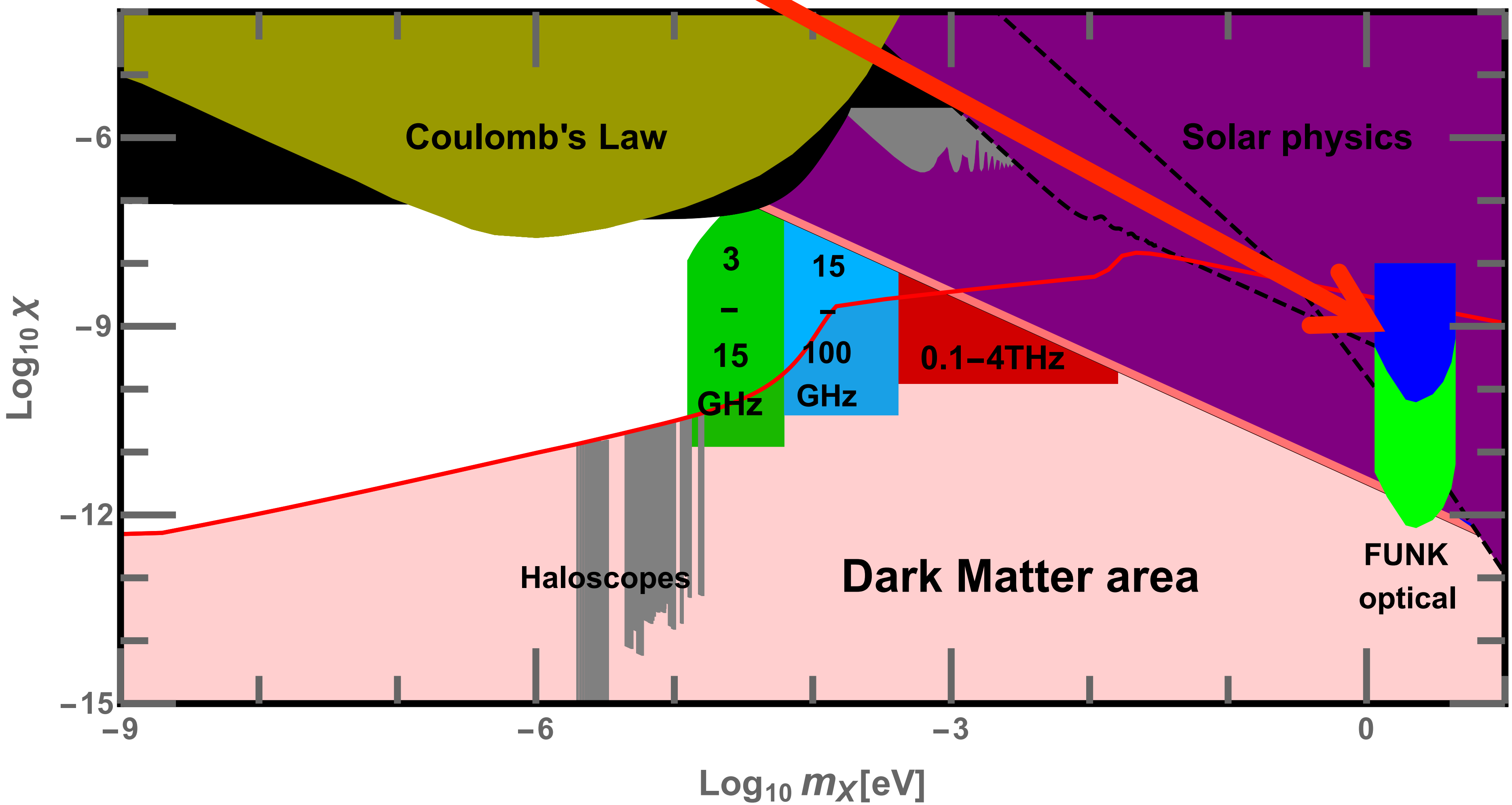
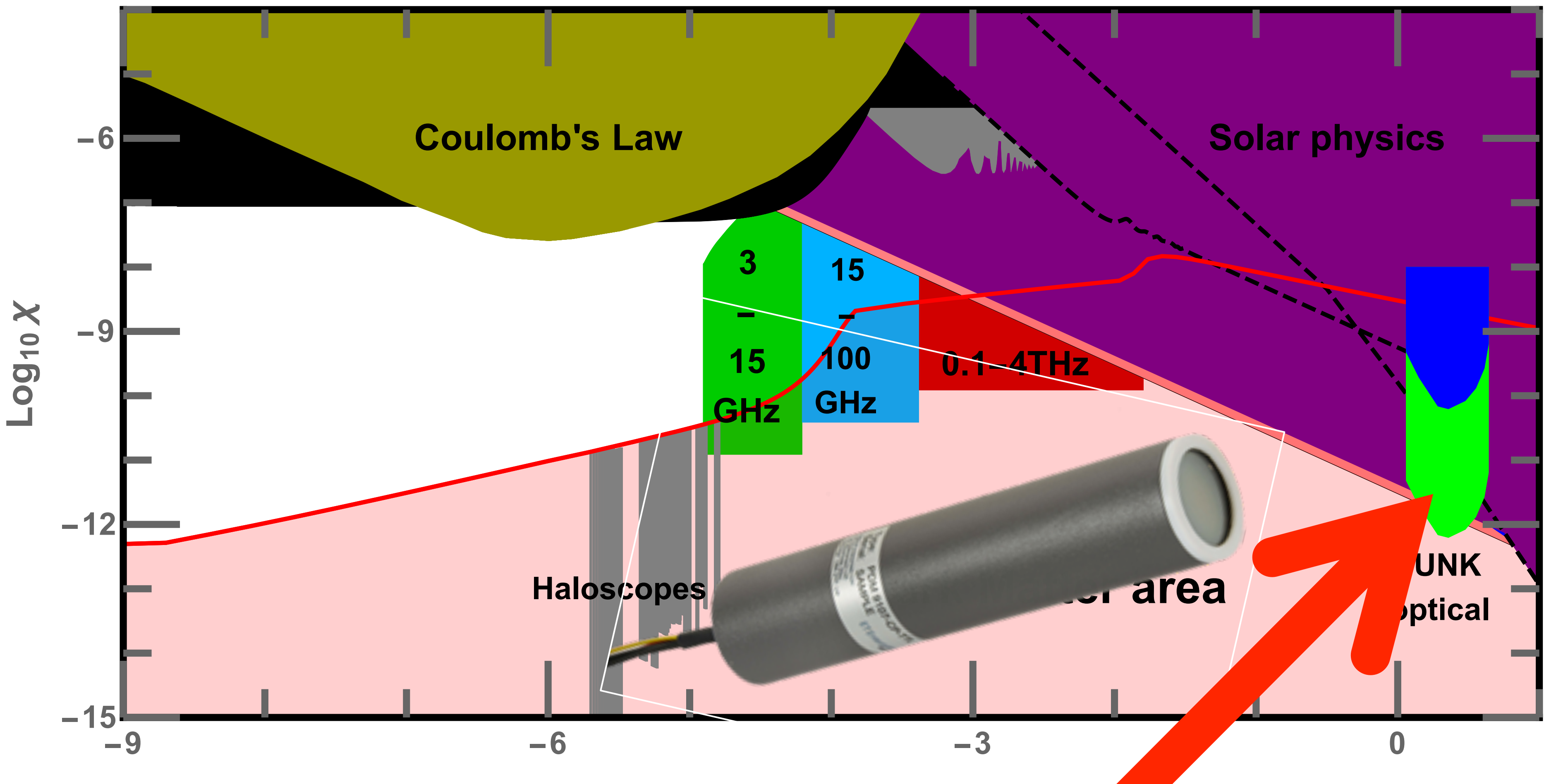


Upgrade: The PMT 9000(+107)



Discovery Potential ☺!!!

The next years → Lower frequency

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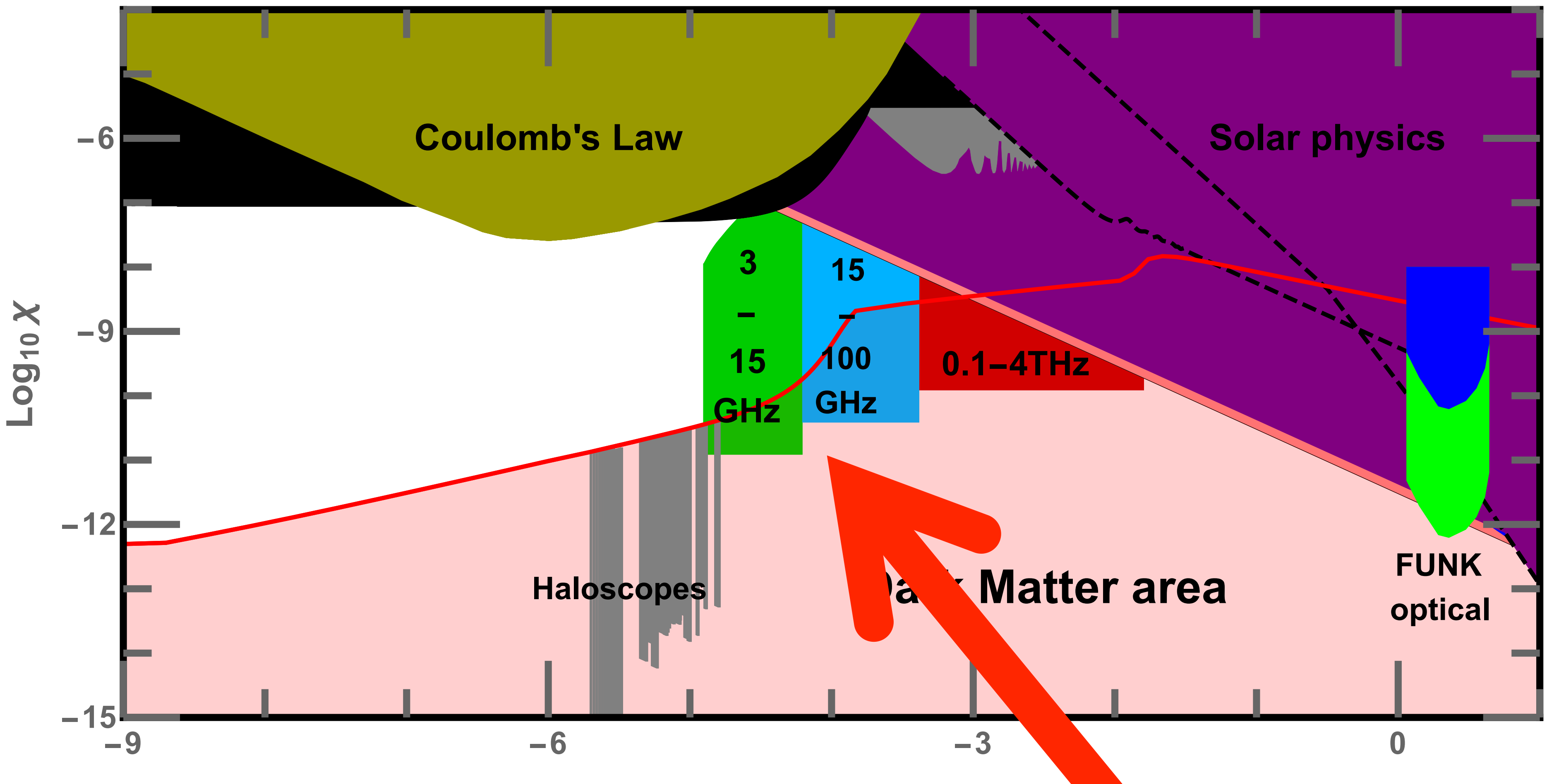

Discovery Potential ☺!!!

A Dream for ~~Astrology~~ ehhm Astronomy

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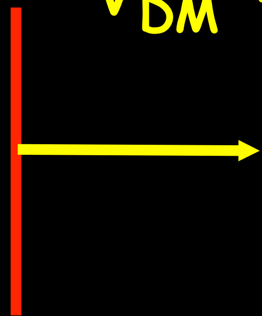
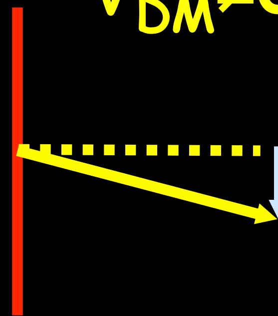
- Emission from moving dark matter

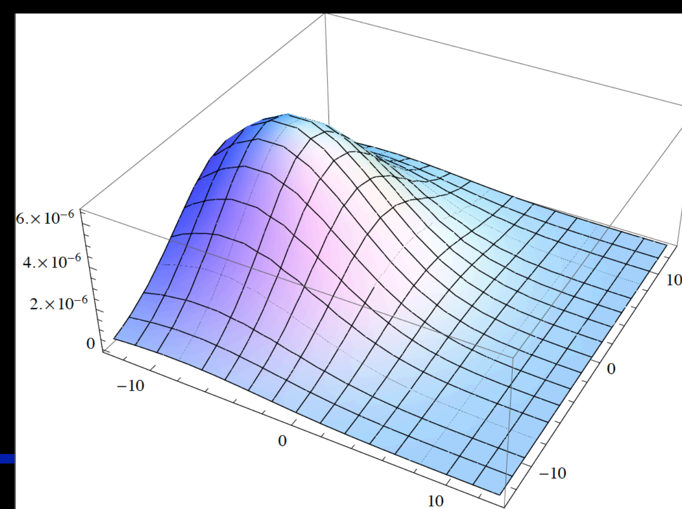
$V_{DM}=0$ $\qquad\qquad$ $V_{DM}\neq 0=$ ↓





- A picture of the DM-velocity distribution

Screen



New couplings:
A spin experiment

Looking for oscillating dipoles

- 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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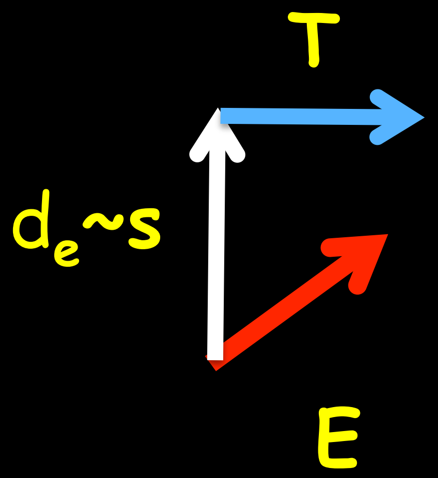


Energy in an elecxtric field

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

Torque tries to tilt dipole moment/spin

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

Dealing with oscillation

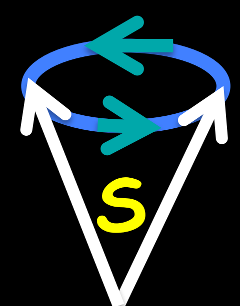
Problem: the dipole moment is rapidly oscillating ~m_a

→ Danger of cancellation

Solution: Rotate spin to compensate

→ Use Spin Precession in magnetic field

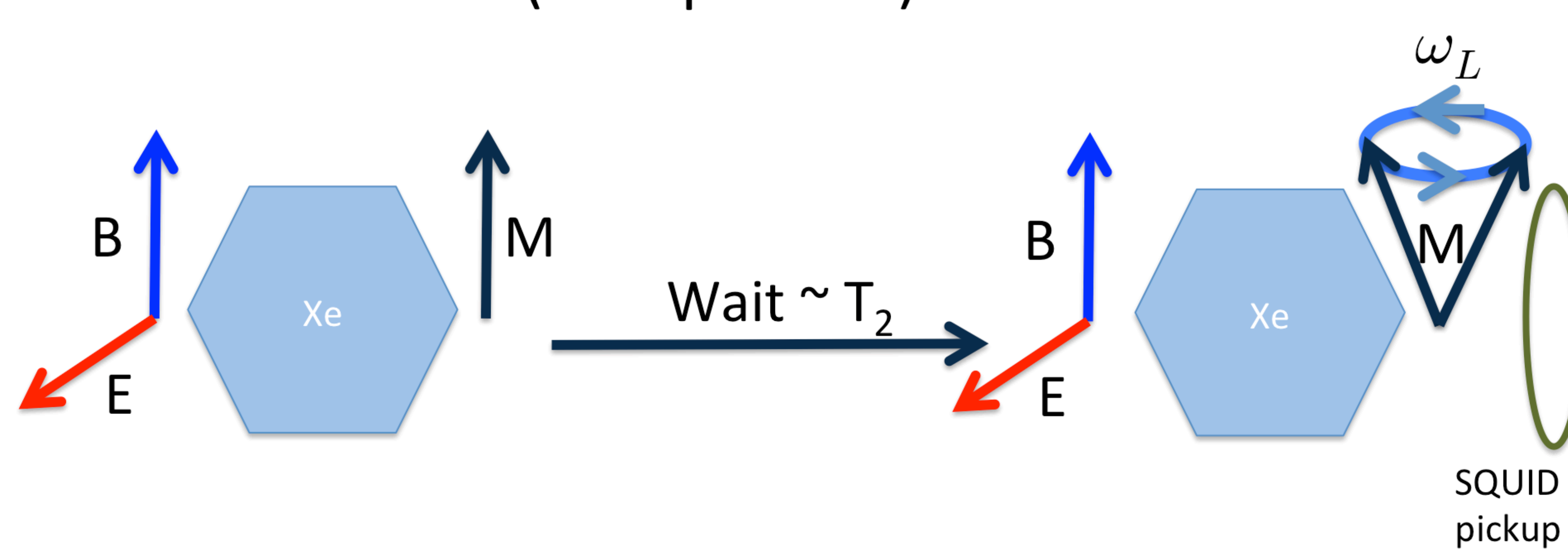
$$\omega_L = 2\mu B$$



Resonance when $\omega_L = m_a$

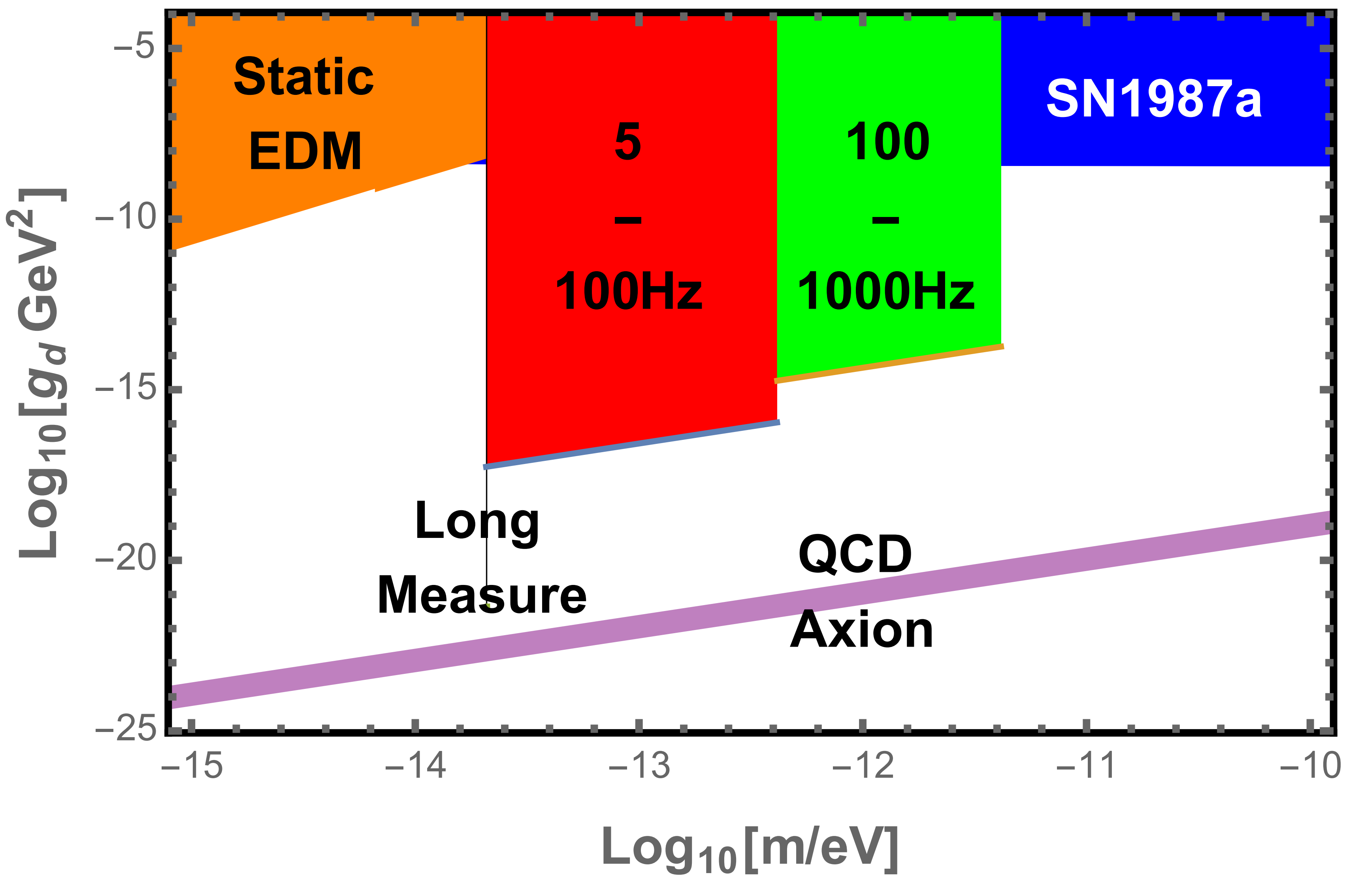
Modification of Xenon EDM

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

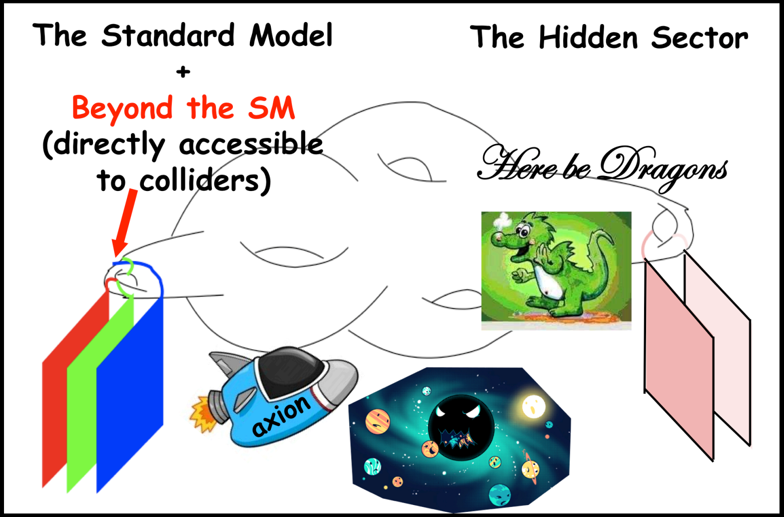
Sensitivity



Conclusions

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.


Axions
and
Hidden sector
a

Beyond ALPs

Hidden photons

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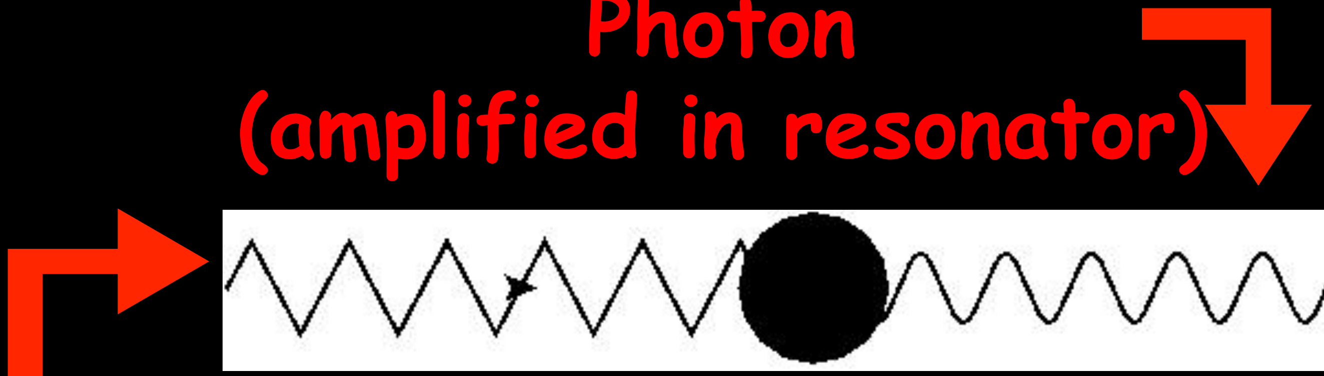
- **Photon Regeneration**

Photon
(amplified in resonator)



Hidden photon

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

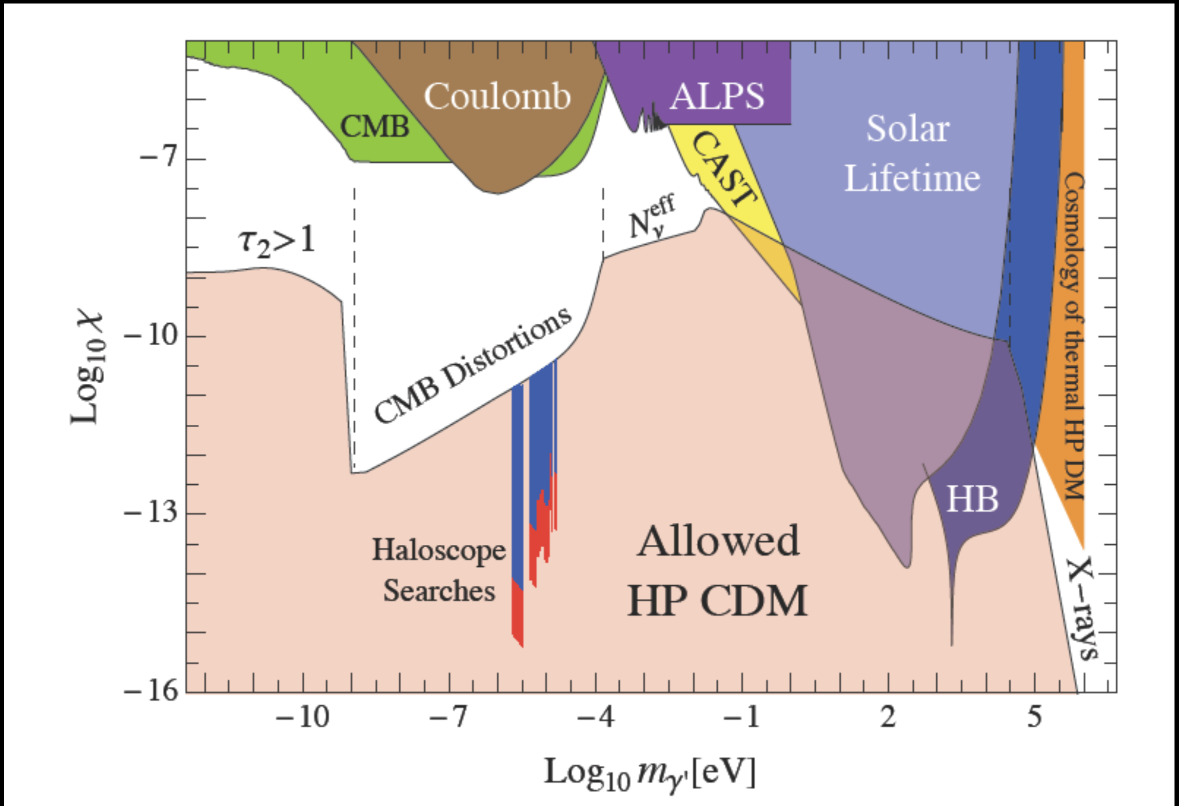
„Our" U(1) „Hidden" U(1) Mixing

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

Also for hidden photons!!!

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

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



@ DESY + Bonn: WISPDMX

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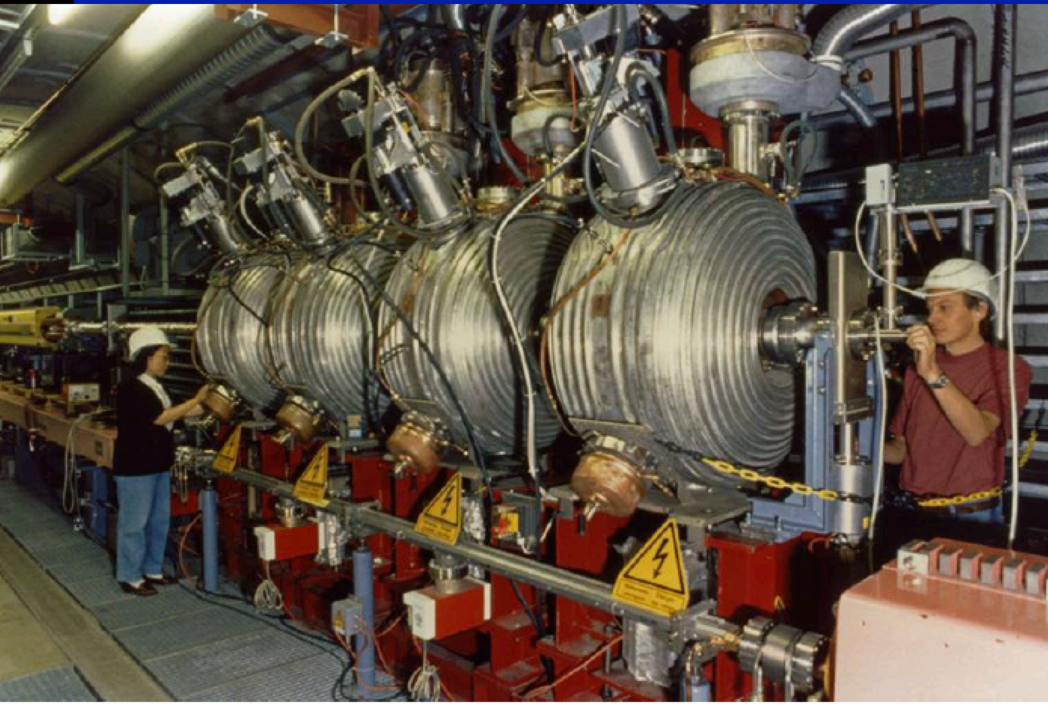

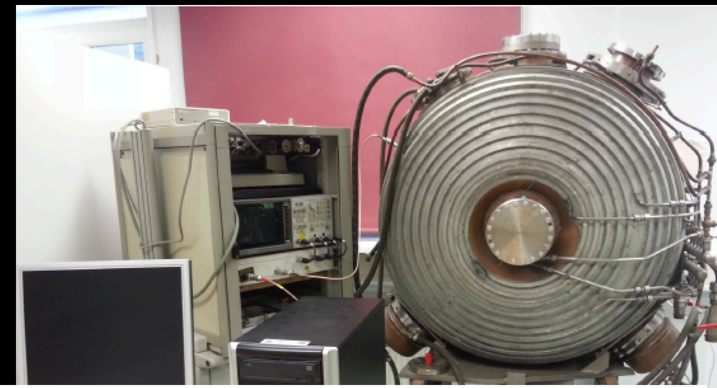

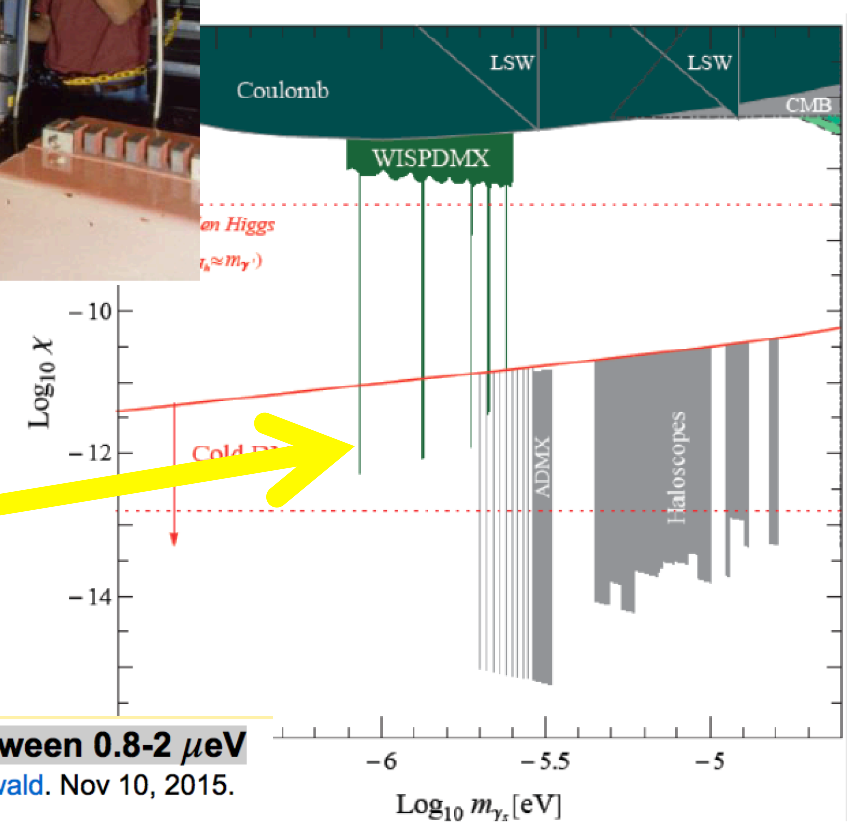

New Results!

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