INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

Axions

–

Motivated by the Strong Interactions, Perfect for Cosmology

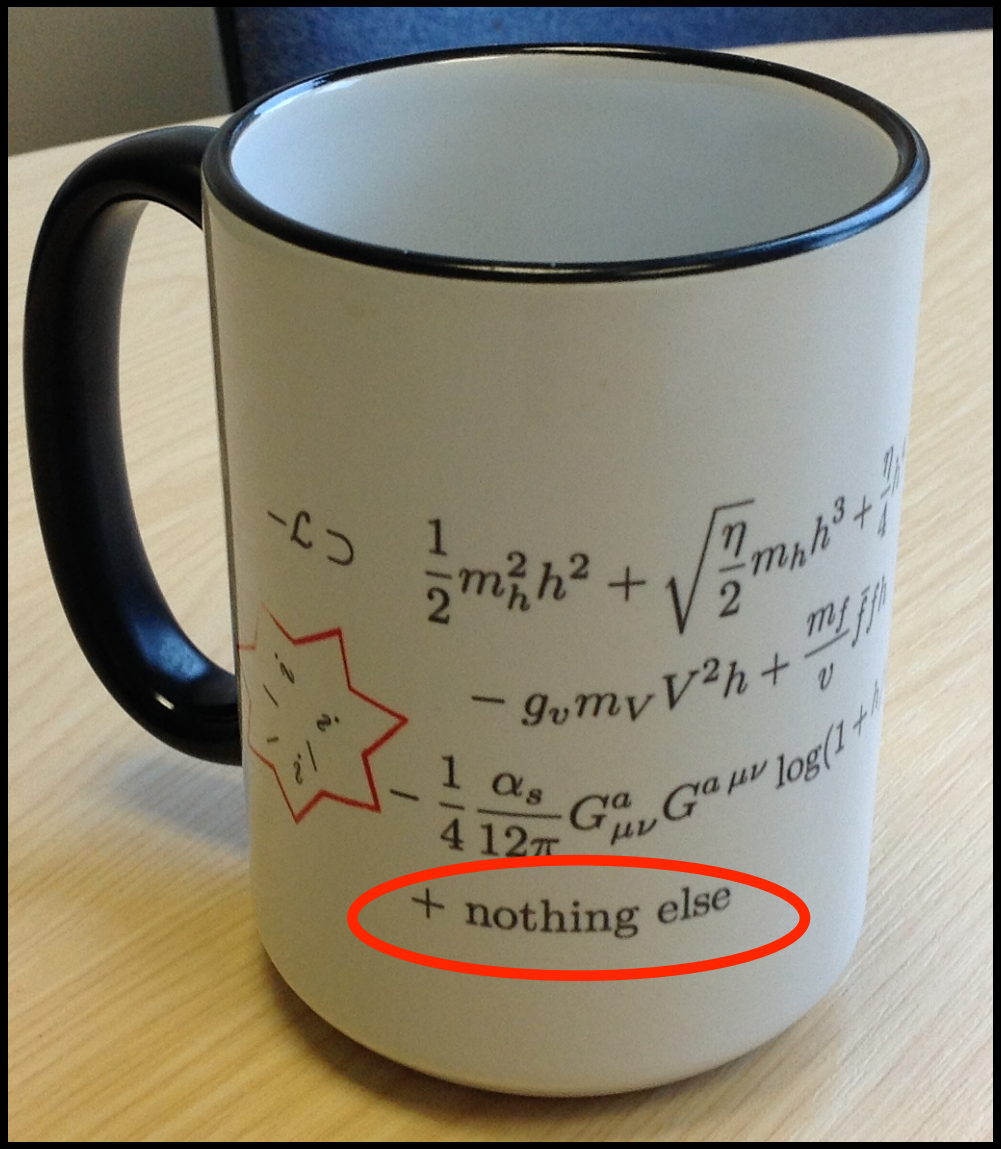
J. Jaeckel[**]

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

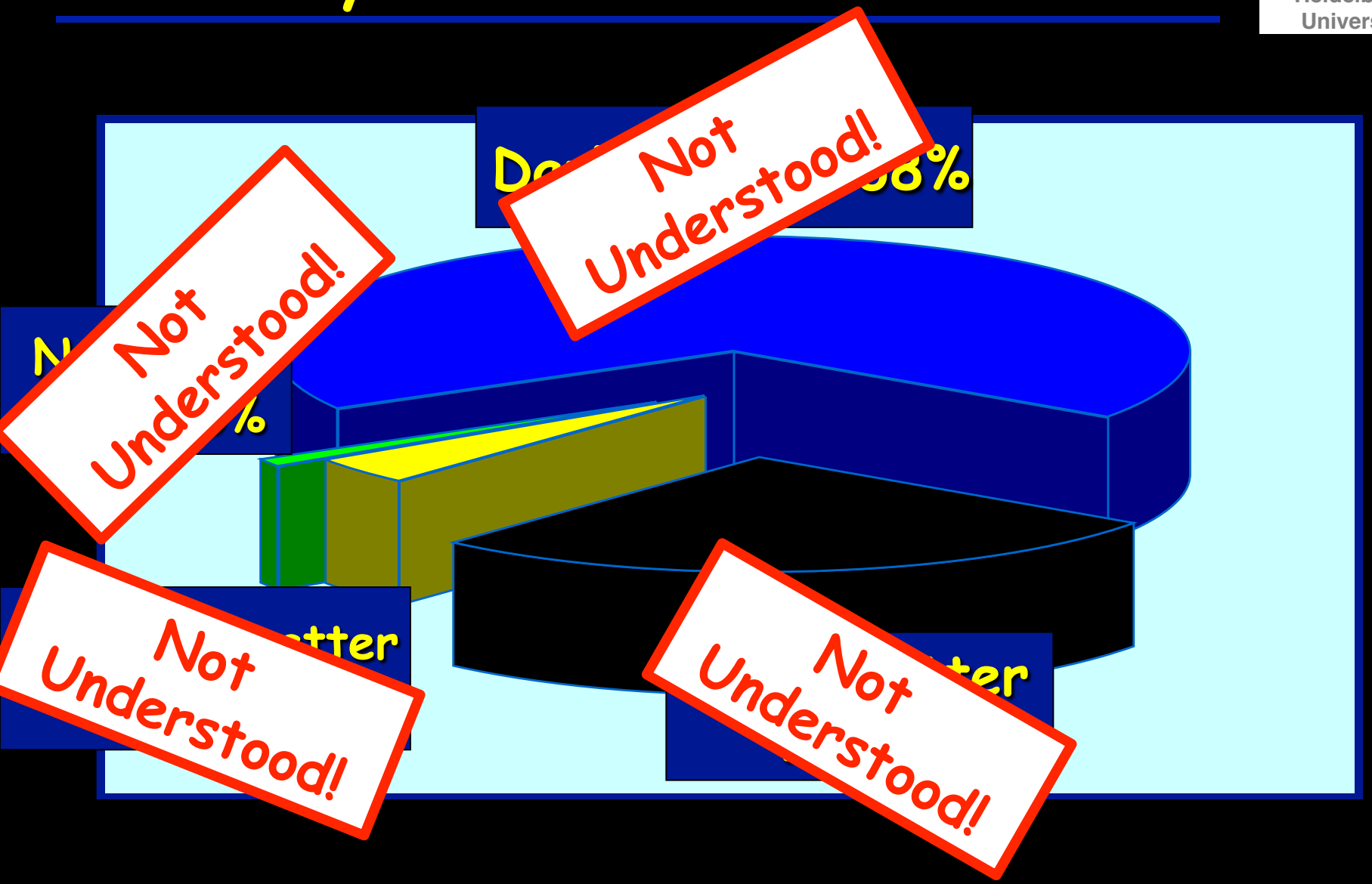
[**]ITP Heidelberg, [z]CERN, [†]IPPP Durham, *DESY,
[y]MPIfR Bonn, [x]U. Zaragoza, [xx]Paris LPTHE, [0]ITP Jena

We need...

Physics beyond the Standard Model


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

Inventory of the Universe



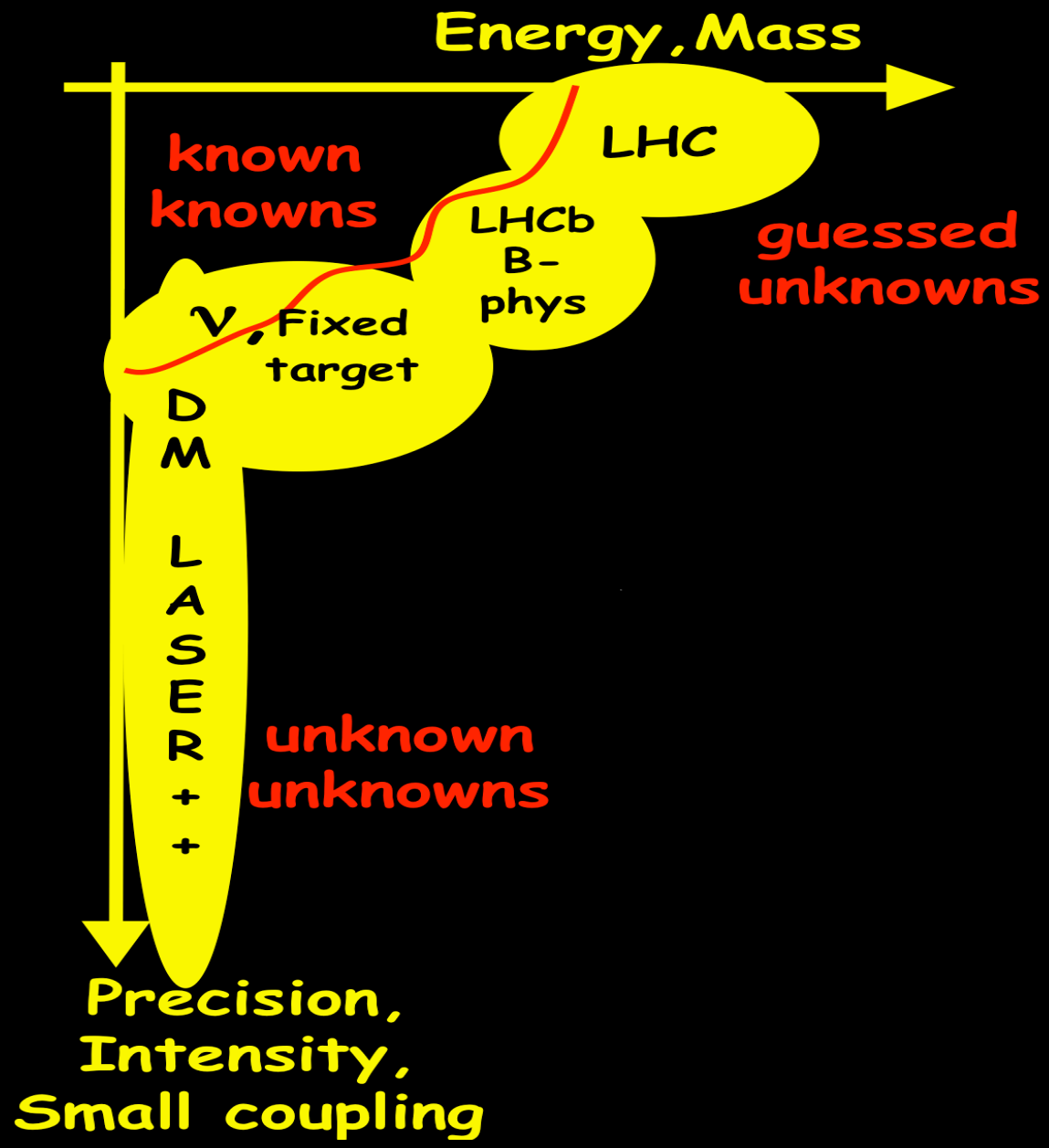
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

Where does it hide?

New physics

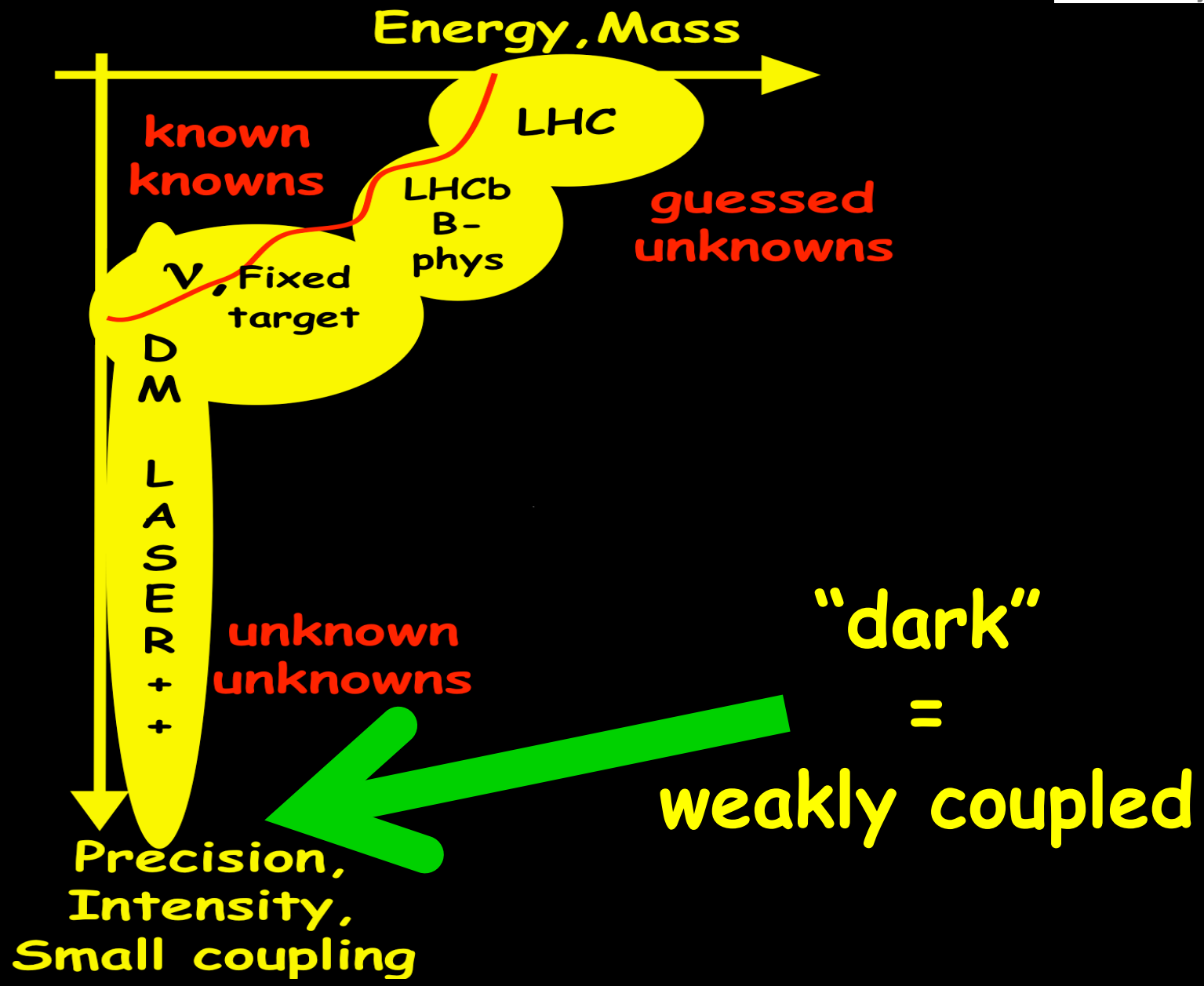
Exploring is (at least) 2 dimensional

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Exploring is (at least) 2 dimensional

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



What are Axion?
And why do we need them?

A „visible“ Hint for new Physics

The strong CP Problem

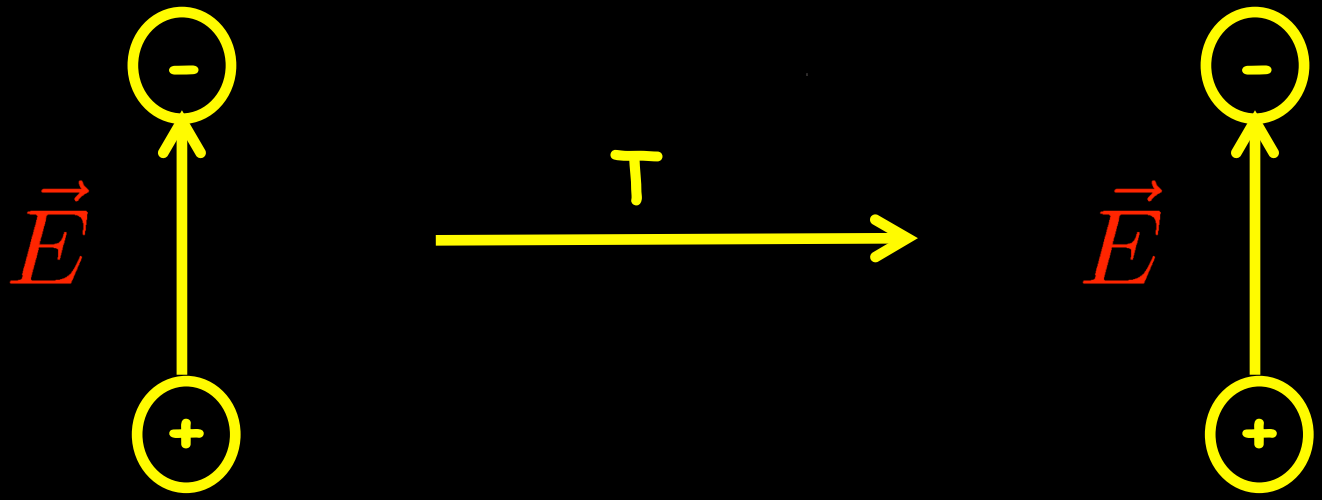
A dirty little secret...

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

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

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



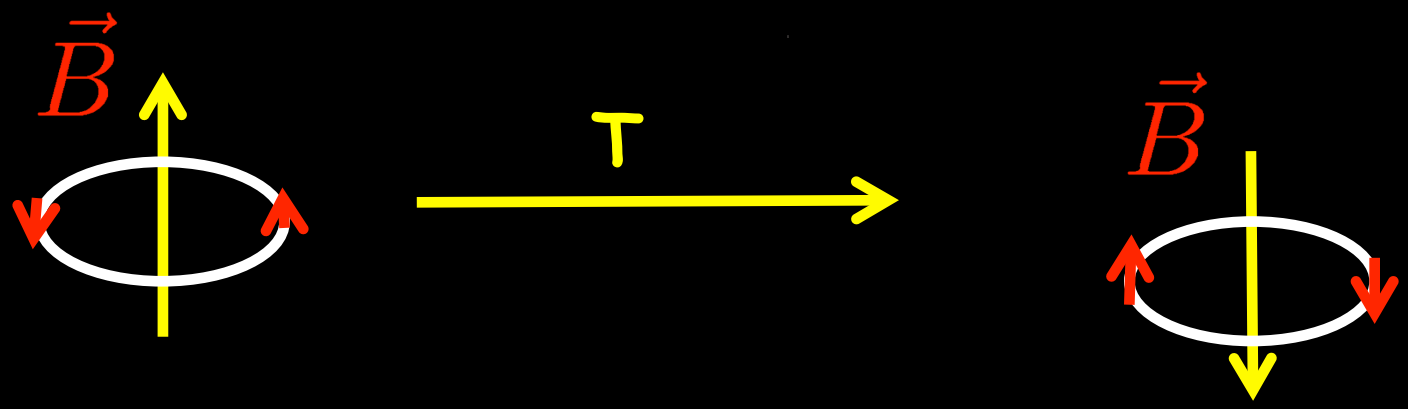
A dirty little secret...

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

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

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



A dirty little secret...

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

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

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

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...

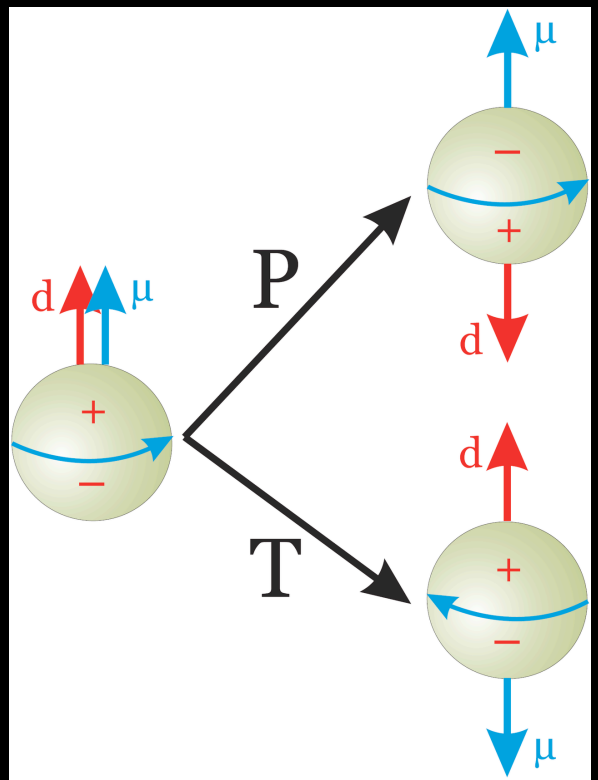
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

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

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

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

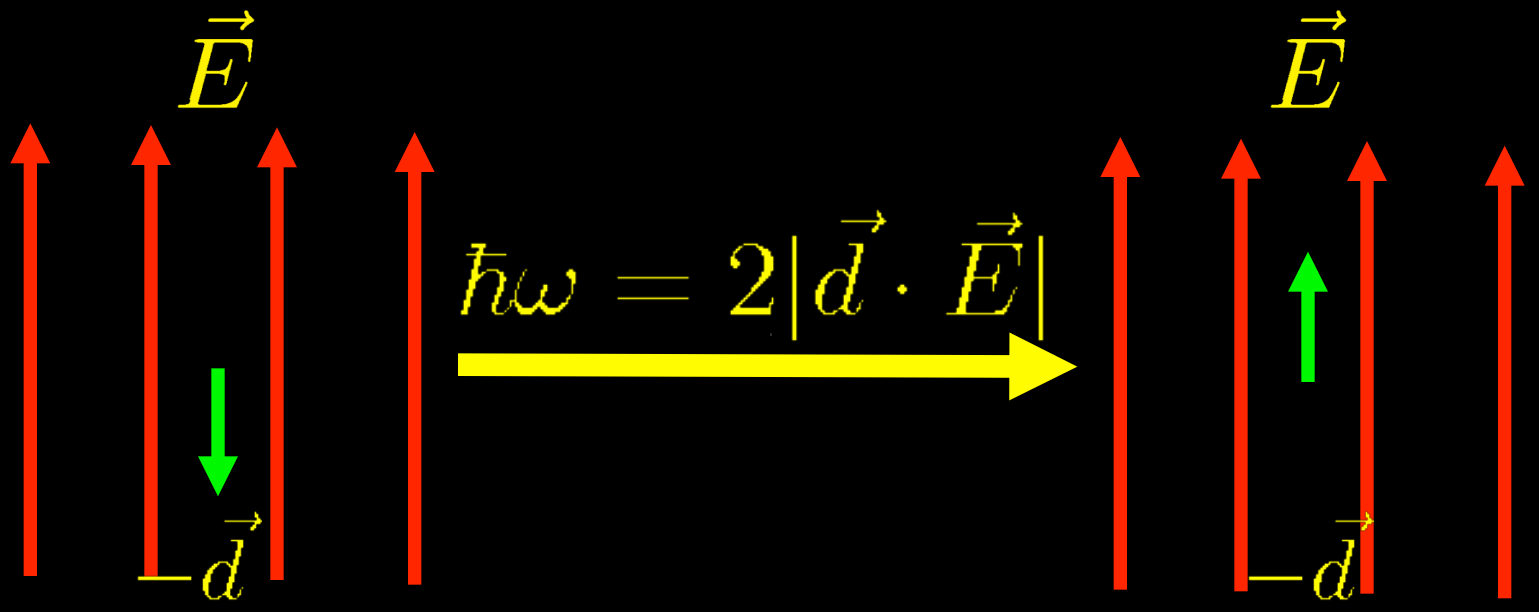


https://en.wikipedia.org/wiki/Neutron_electric_dipole_moment

Measure neutron electric dipole moment

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

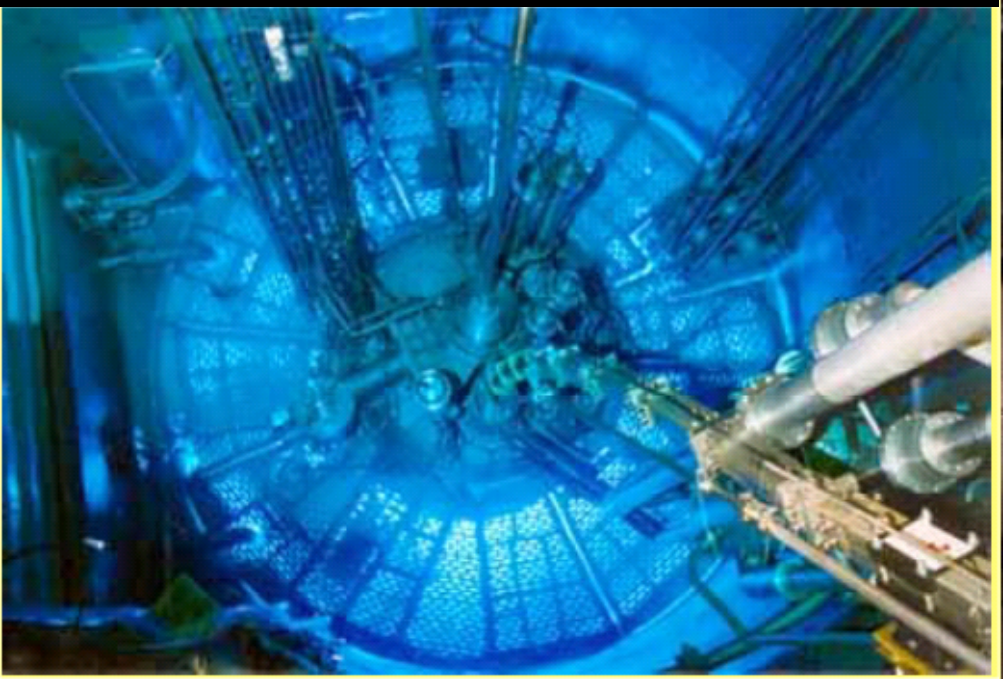
- θ would cause neutron EDM ➡ Experiment



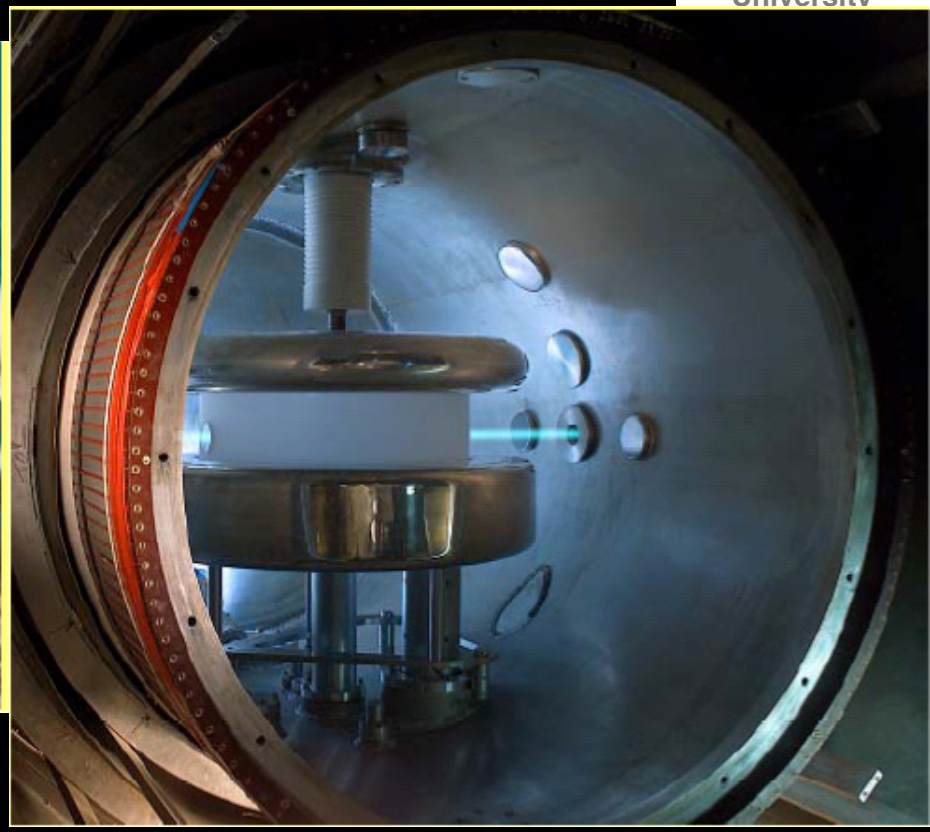
➡ Measure transition frequency.

No neutron electric dipole moment...

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



RAL-Sussex-ILL EDM collaboration



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

What do we expect?

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- Two mass scales in the game:

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

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

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

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

"Argument" EDM Blackboard

Implications

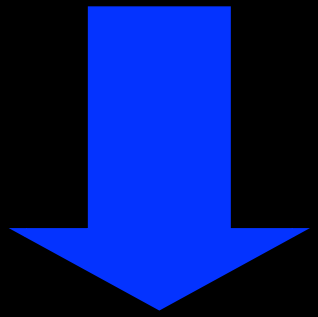
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- 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

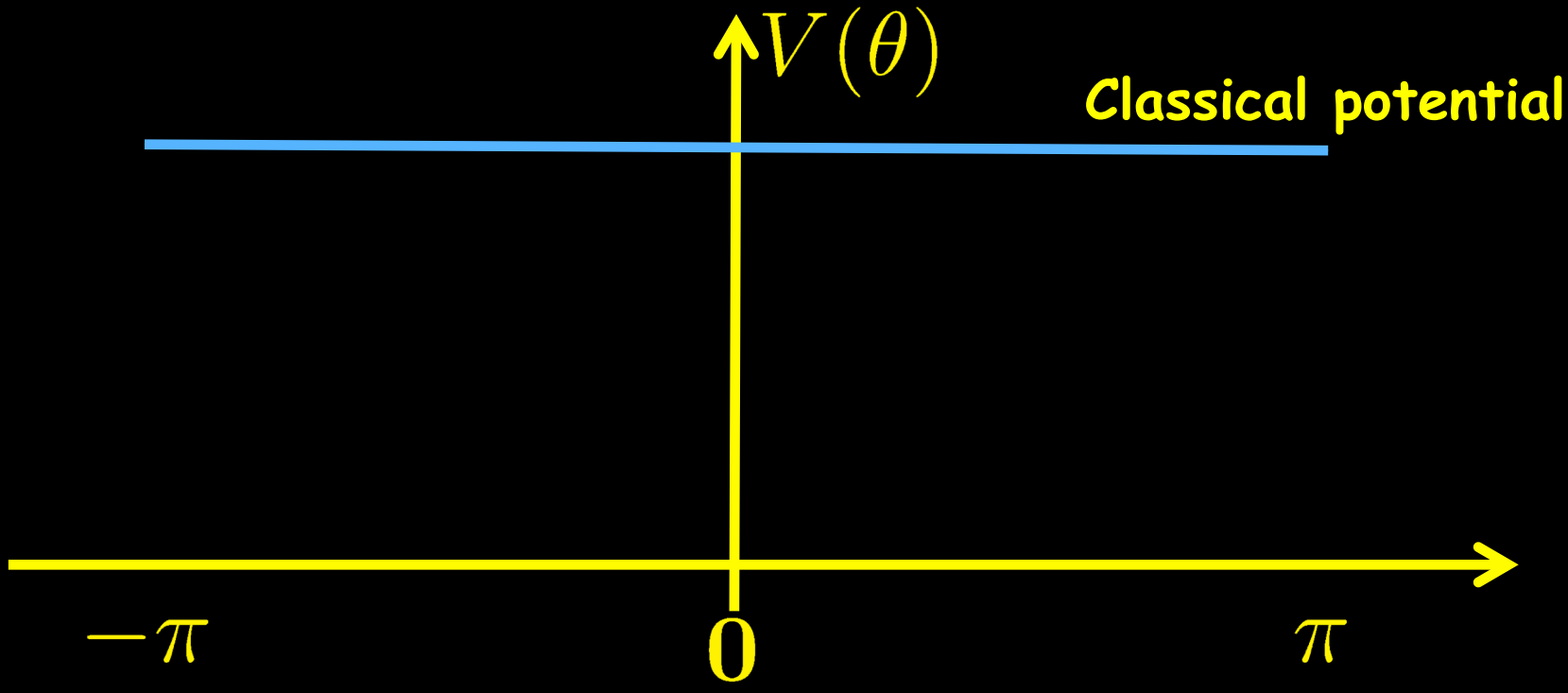
The axion solution
to the strong CP problem

In pictures…

The axion solution to the strong CP problem

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

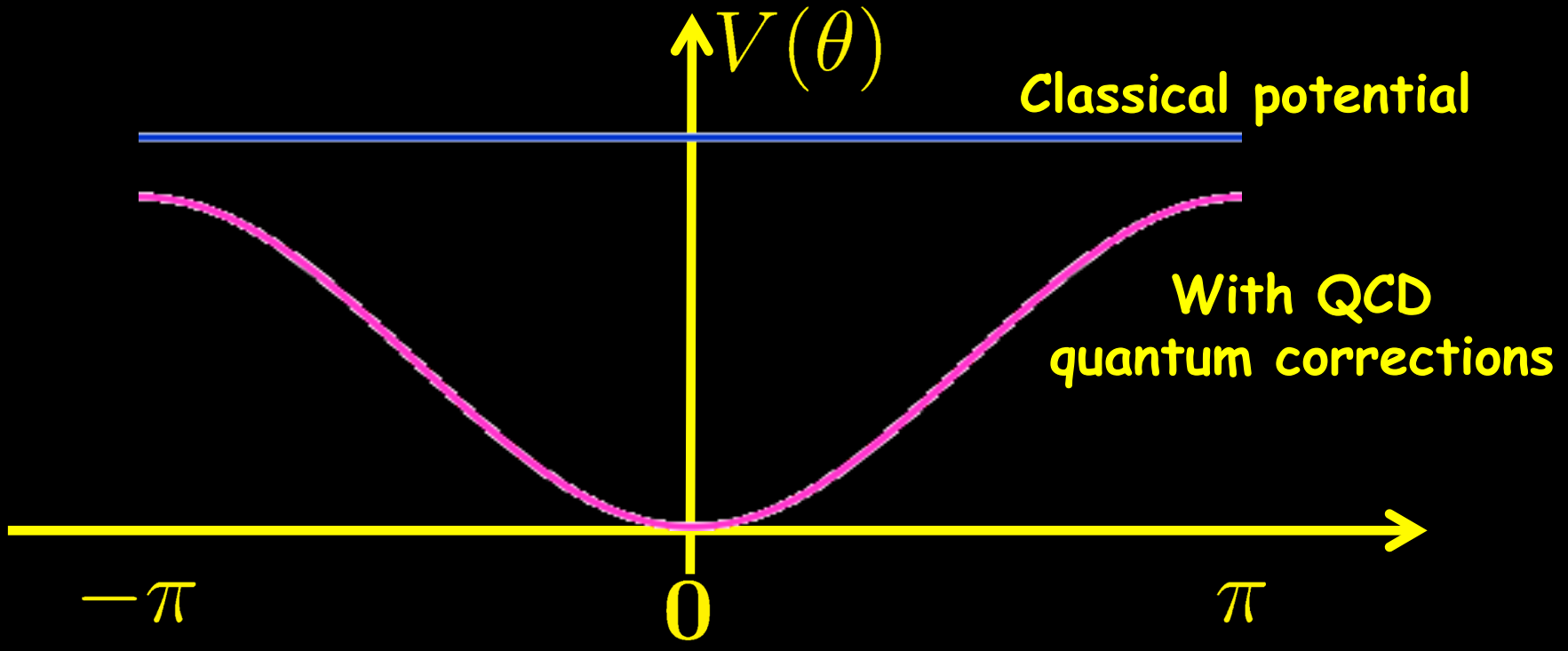
- Make θ dynamical ➔ it can change its value



The axion solution to the strong CP problem

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

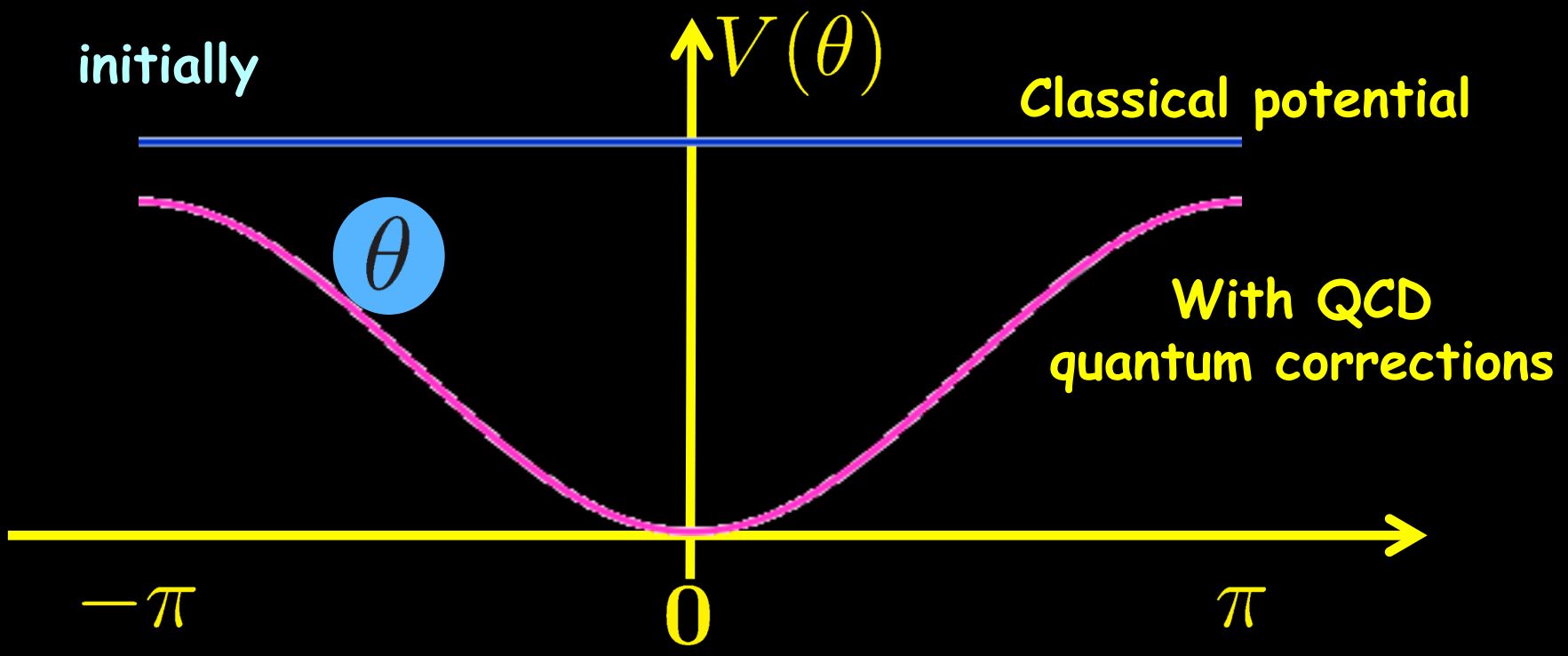
- Make θ dynamical ➔ it can change its value



The axion solution to the strong CP problem

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

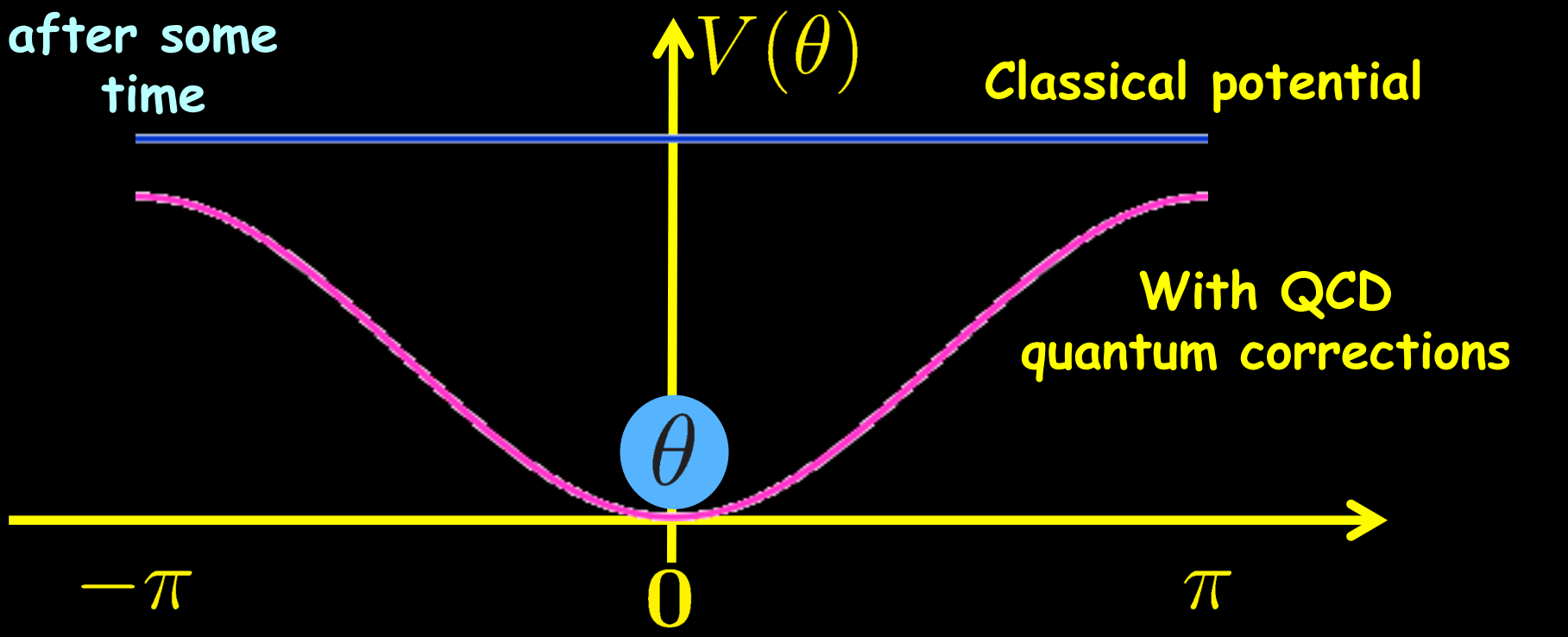
- Make θ dynamical ➔ it can change its value



The axion solution to the strong CP problem

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- Make θ dynamical ➔ it can change its value

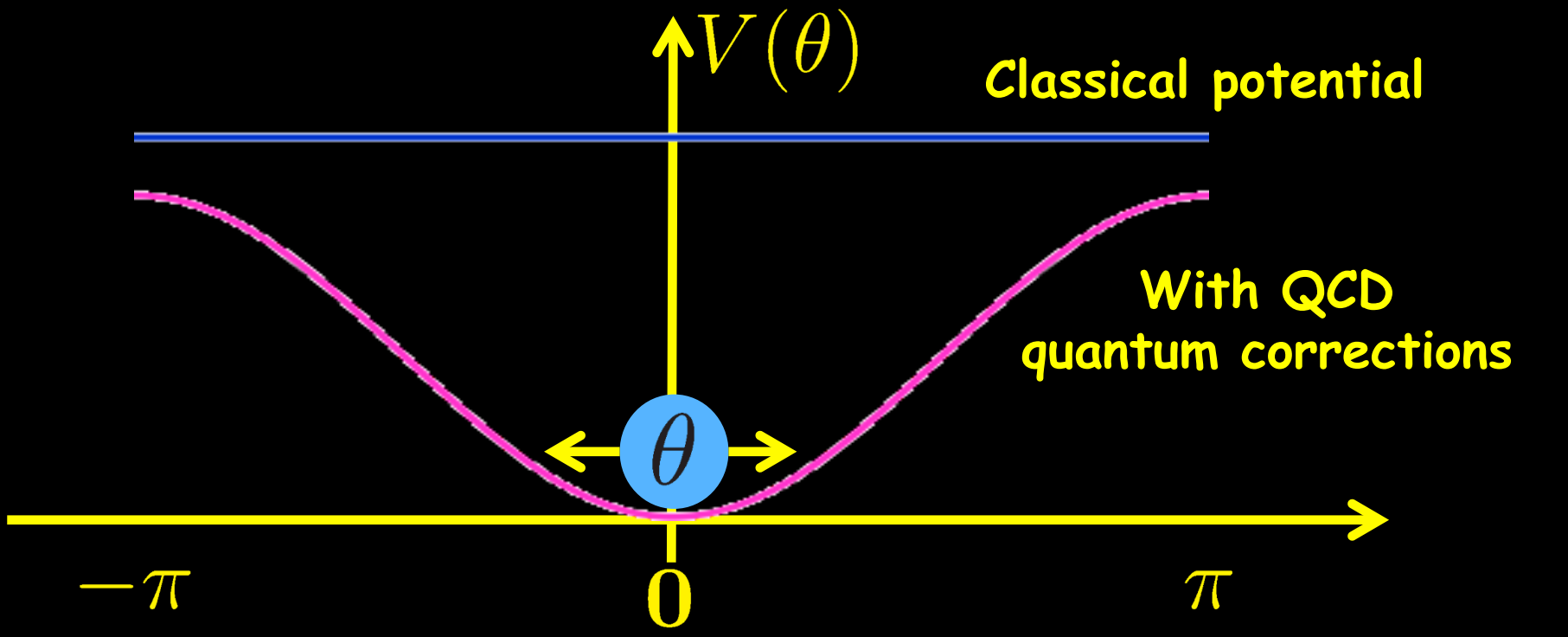


➔ QCD likes to be CP conserving (if we allow it)

The axion solution to the strong CP problem

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- Make θ dynamical ➔ it can change its value



➔ Can still move

➔ new particle = axion

Axions

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- 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

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

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

A Dynamical θ

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

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

$\Rightarrow$ θ=a will evolve to a=θ=0

$\Rightarrow$ CP is conserved

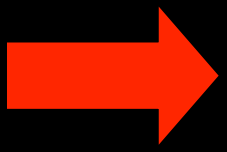
What is a?

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

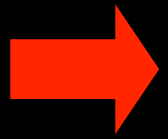
- Properties:
  - Let a be a dynamical degree of freedom.
  - Let a have no tree level potential
  - Let a have only derivative couplings

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

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



a is Goldstone boson of a U(1) symmetry



Axion!

Peccei-Quinn Symmetry

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

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

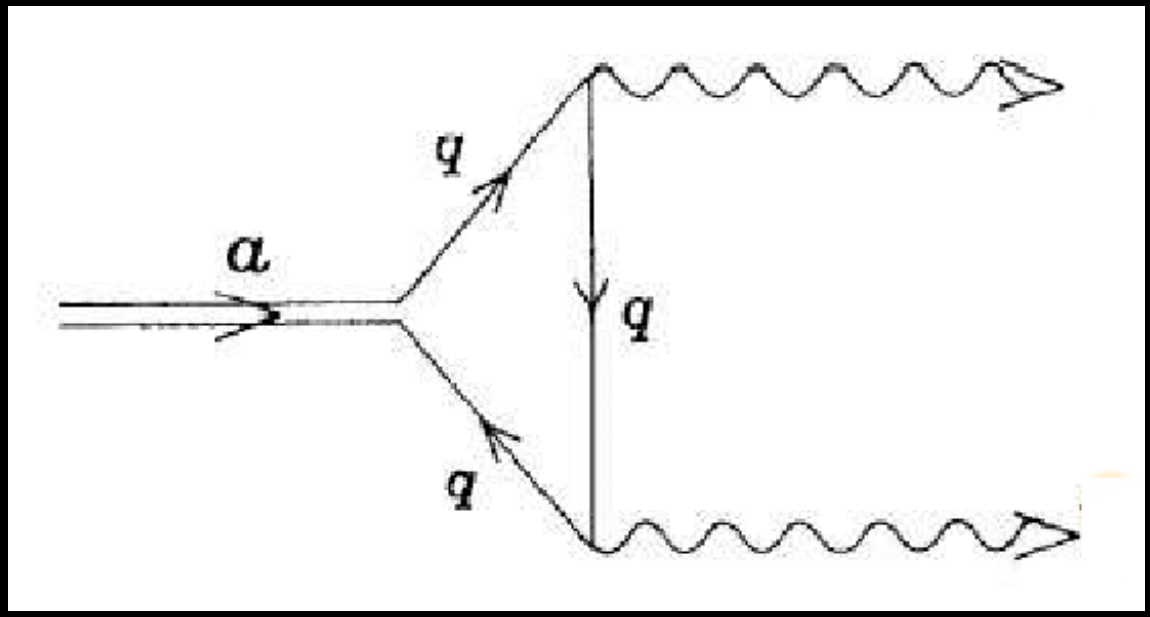
- If $\mu^2<0$ we have SSB

➡ Phase is Goldstone ➡ Use it as Axion

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

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- A diagram



- And a dimensional argument:

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

The Coupling to $F\tilde{F}$

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- **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 $F\tilde{F}$

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- **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

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

➡ Goldstone ➡ Pseudogoldstone

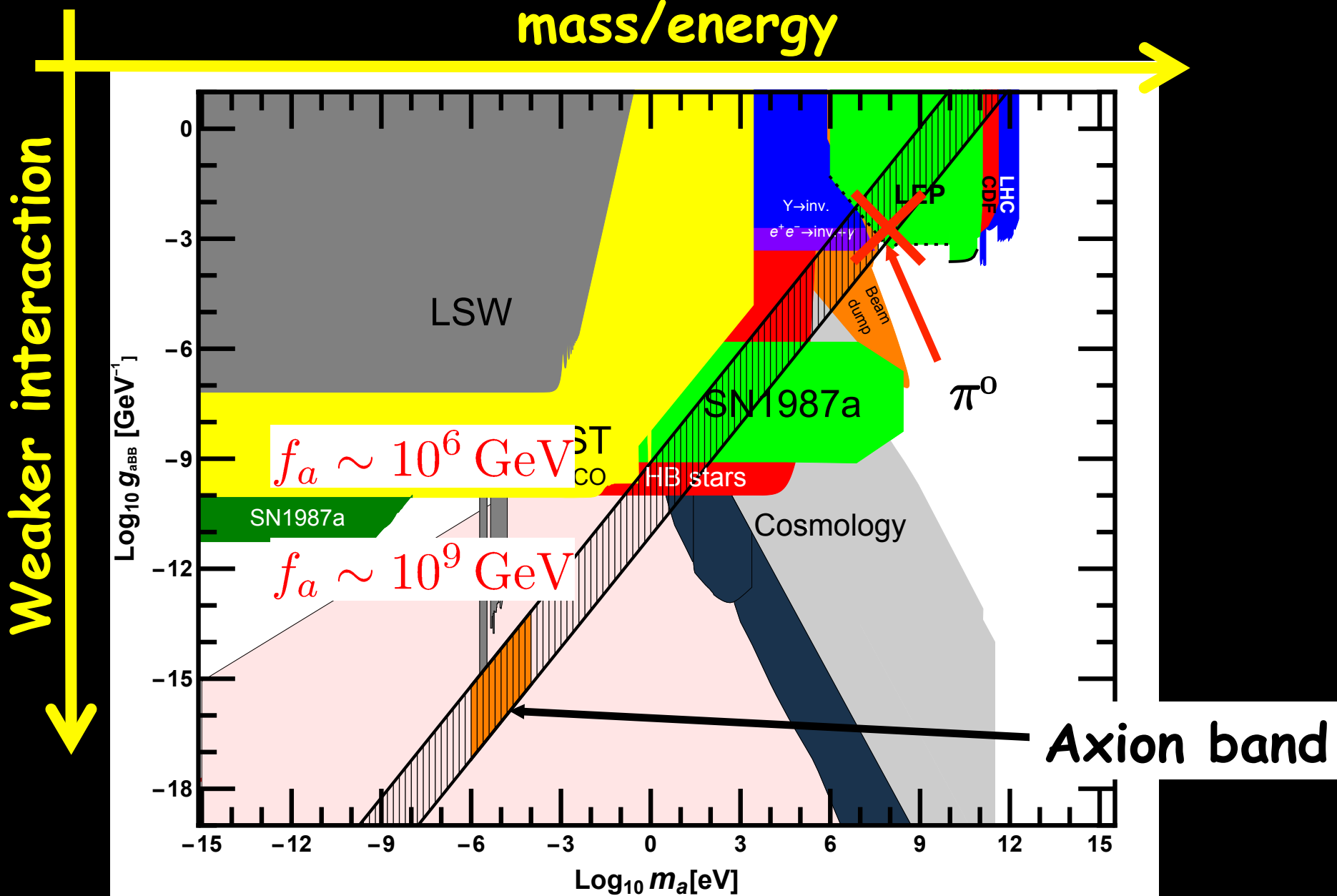
- Dimensional considerations
  - SSB scale $\sim f_a$
  - Quark masses $\sim m_q \sim m_\pi$
  - QCD scale $\sim \Lambda_{\mathrm{QCD}} \sim f_\pi$

➡ PseudoGoldstone mass $m_a^2 \sim \dfrac{m_\pi^2 f_\pi^2}{f_a^2}$

"Argument"
Topological Suszeptibility on blackboardl

Axion-like Particles

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



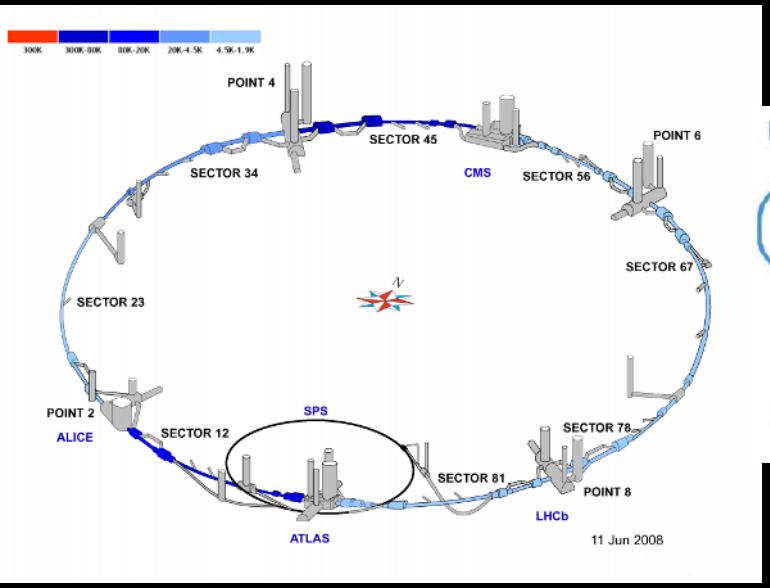
How to find the Axion…

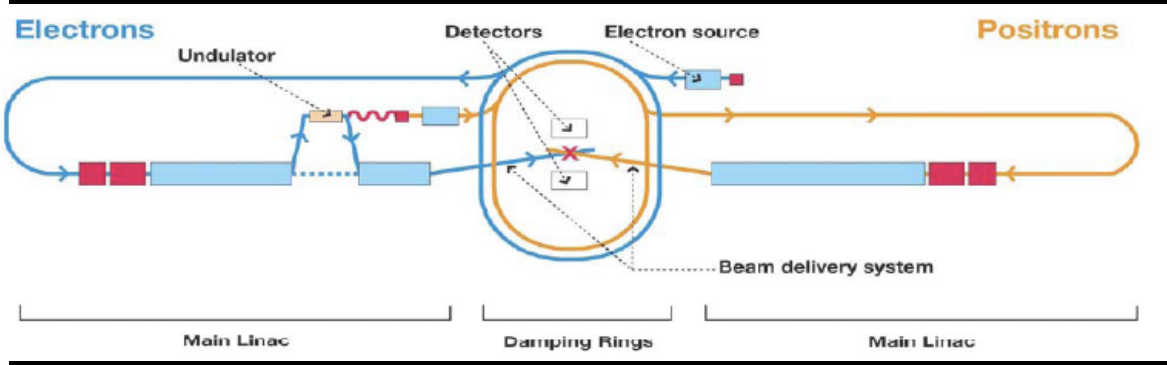
Exploring fundamental high energy physics…

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- The direct approach: MORE POWER

LHC, Tevatron + ILC,CLIC





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

But…

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

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

But…

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

- Man it's DANGEROUS…

But…

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

- Or much much more horrifying:

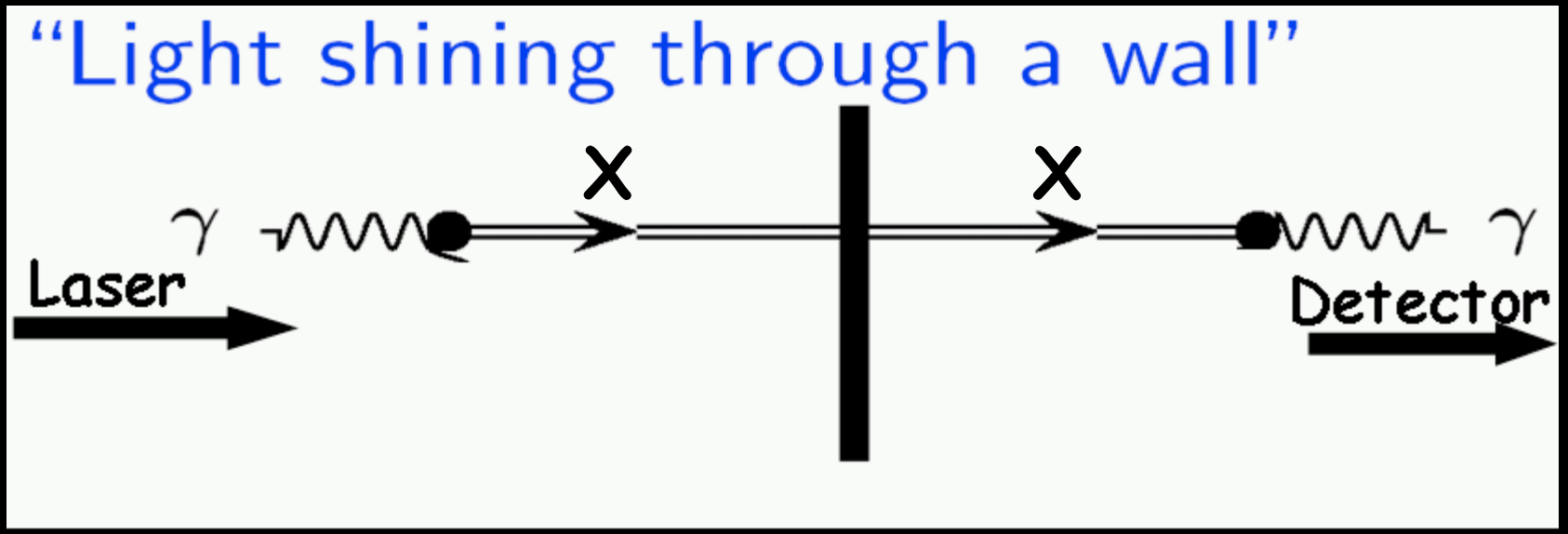
NO SIGNAL ABOVE BACKGROUND!

The Power of Low Energy Experiments

Complementary approaches

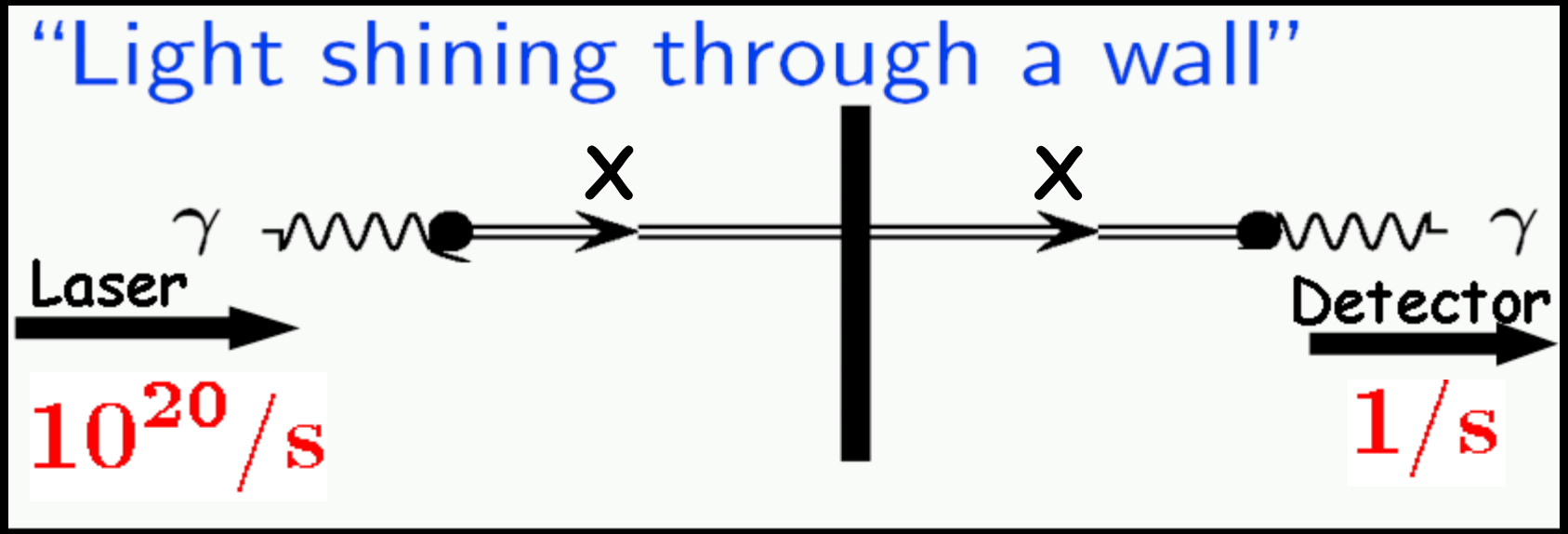
Light shining through walls

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Light shining through walls

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



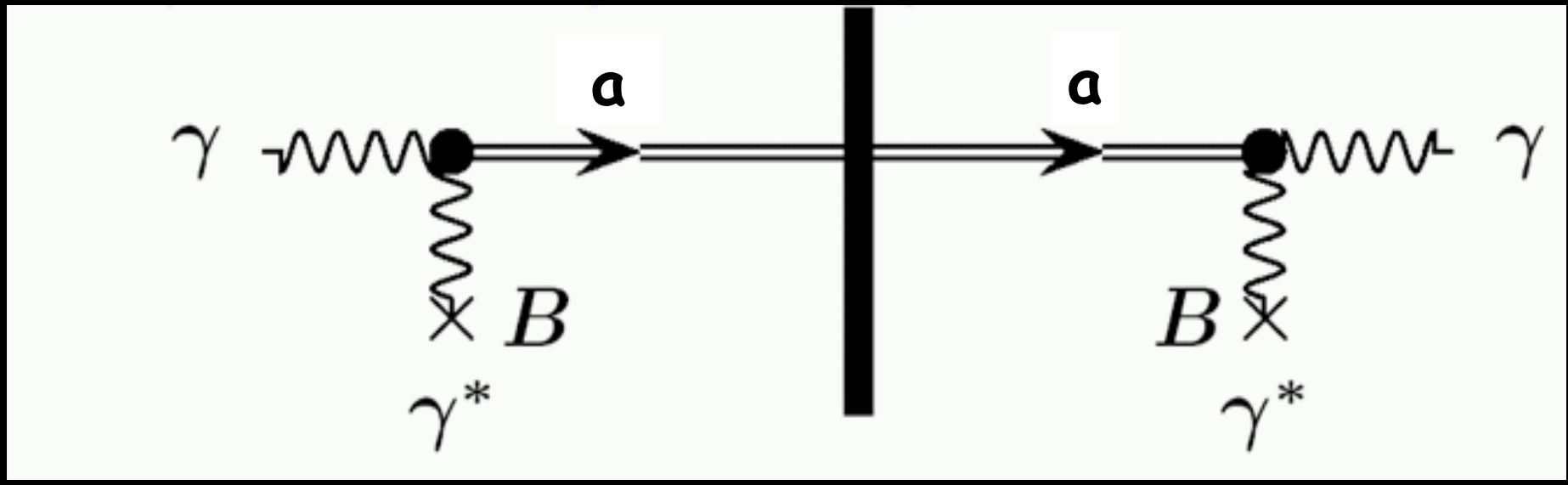
- Test $P_{\gamma\to X\to\gamma} \lesssim 10^{-20}$

- Enormous precision!
- Study extremely weak couplings!

Photons coming through the wall!

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

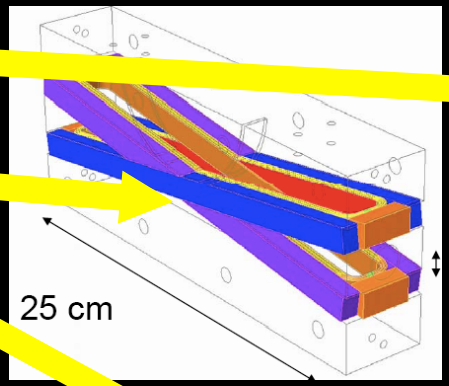


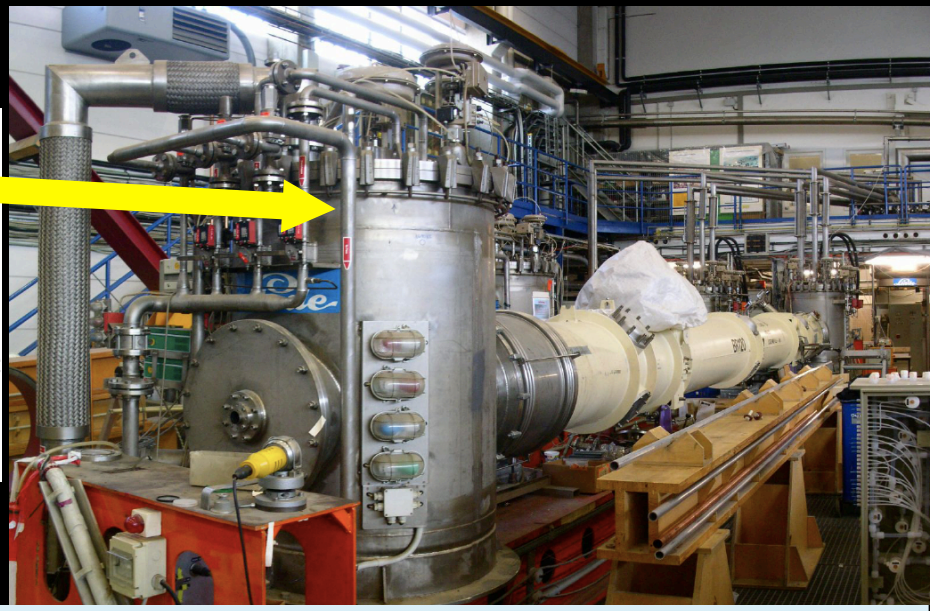
$$P_{\gamma \to a \to \gamma} \sim N_{\text{pass}} \left(\frac{BL}{M} \right)^4$$

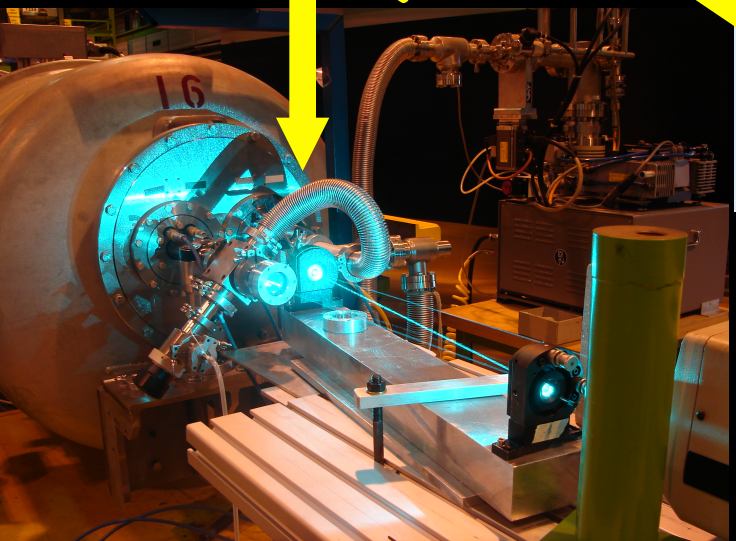
Light Shining Through Walls

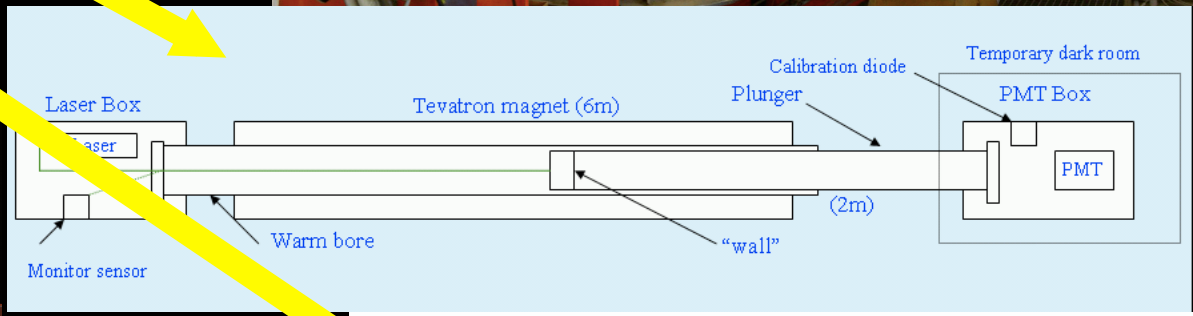
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

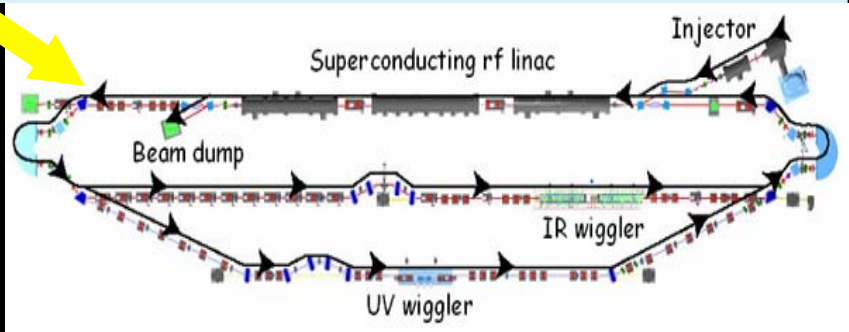
- A lot of activity
  - ALPS
  - BMV
  - GammeV
  - LIPPS
  - OSQAR









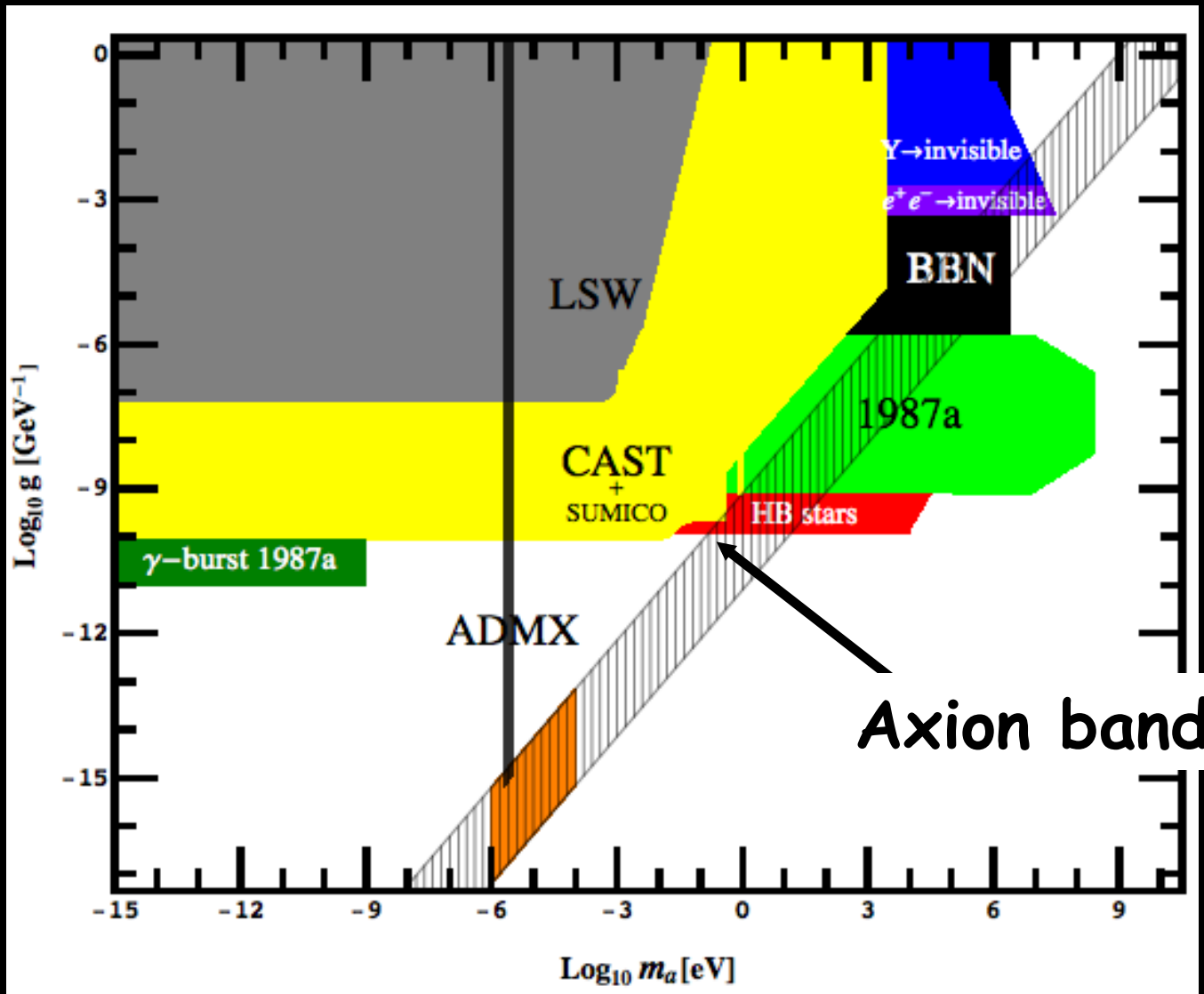


Small coupling, small mass

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

mass/energy

Weaker interaction

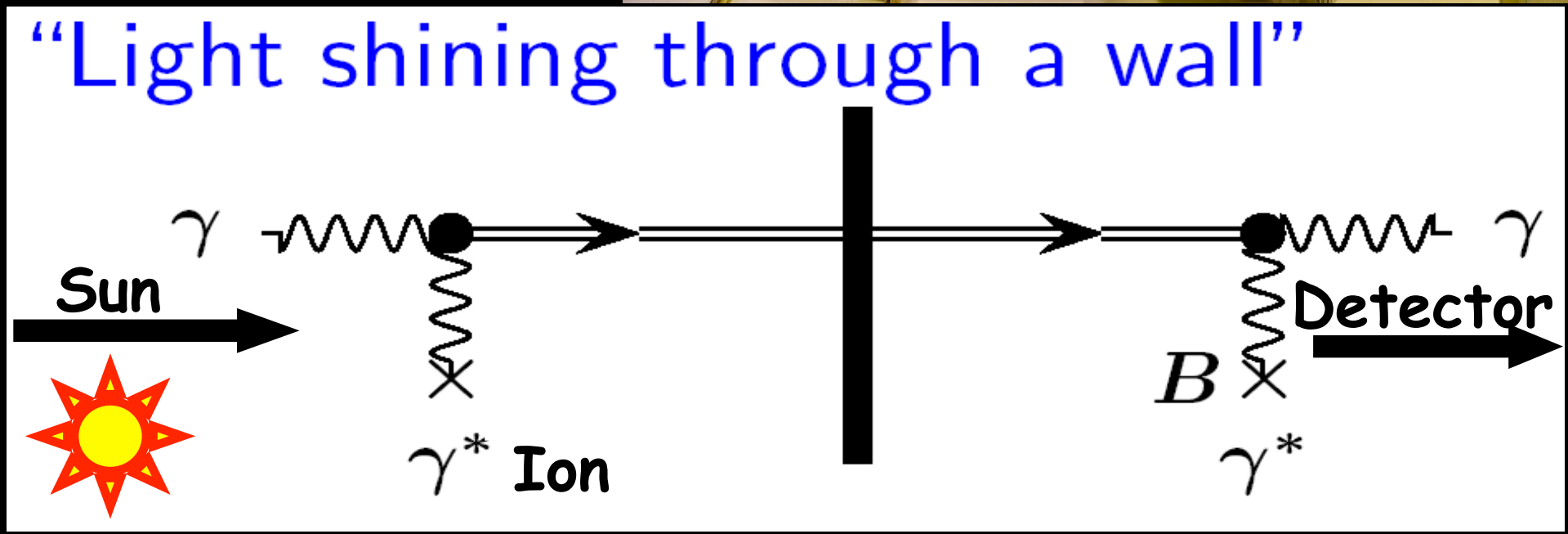


Helioscopes

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

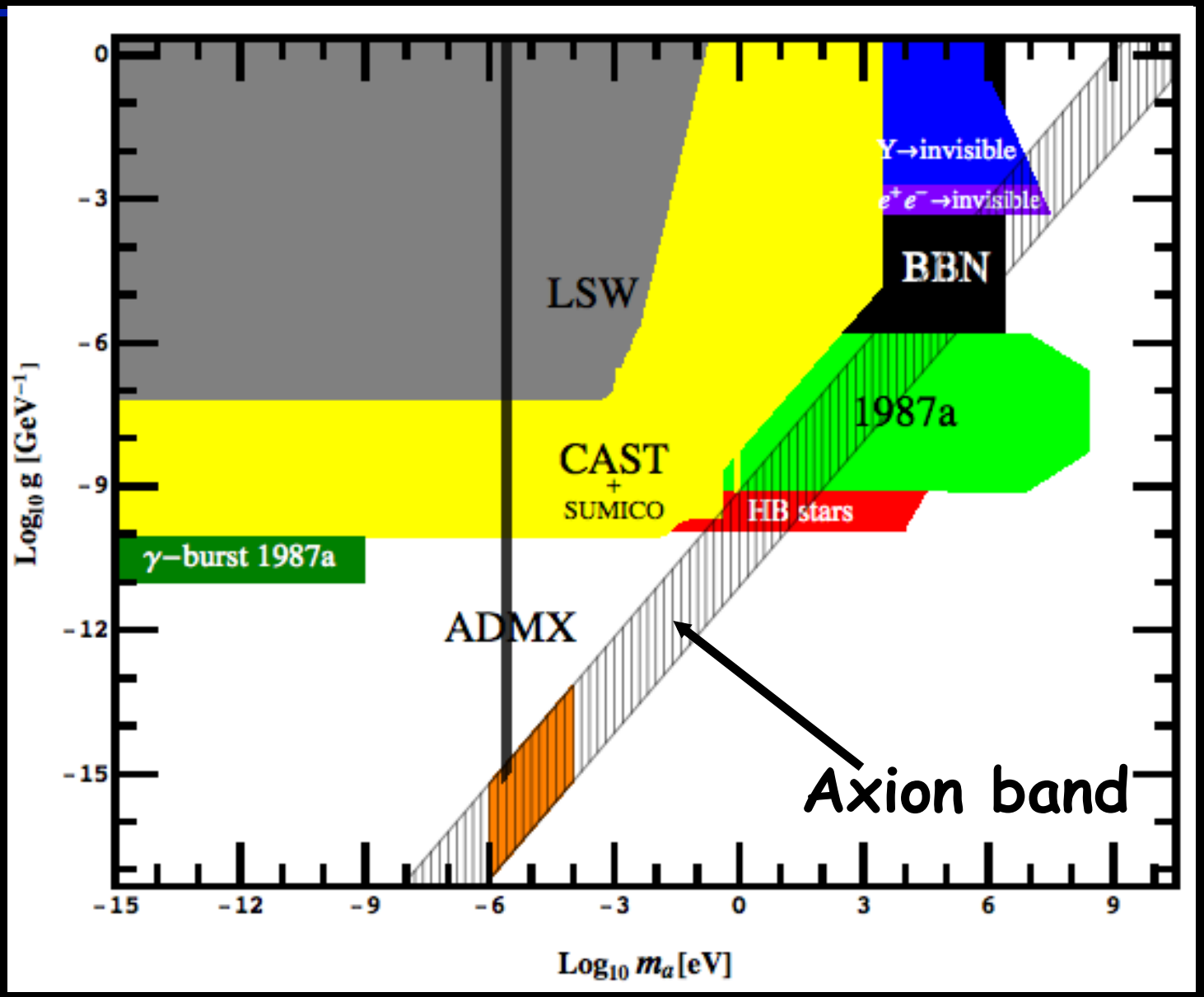
CAST@CERN
SUMICO@Tokyo

SHIPS@Hamburg



Sensitivity

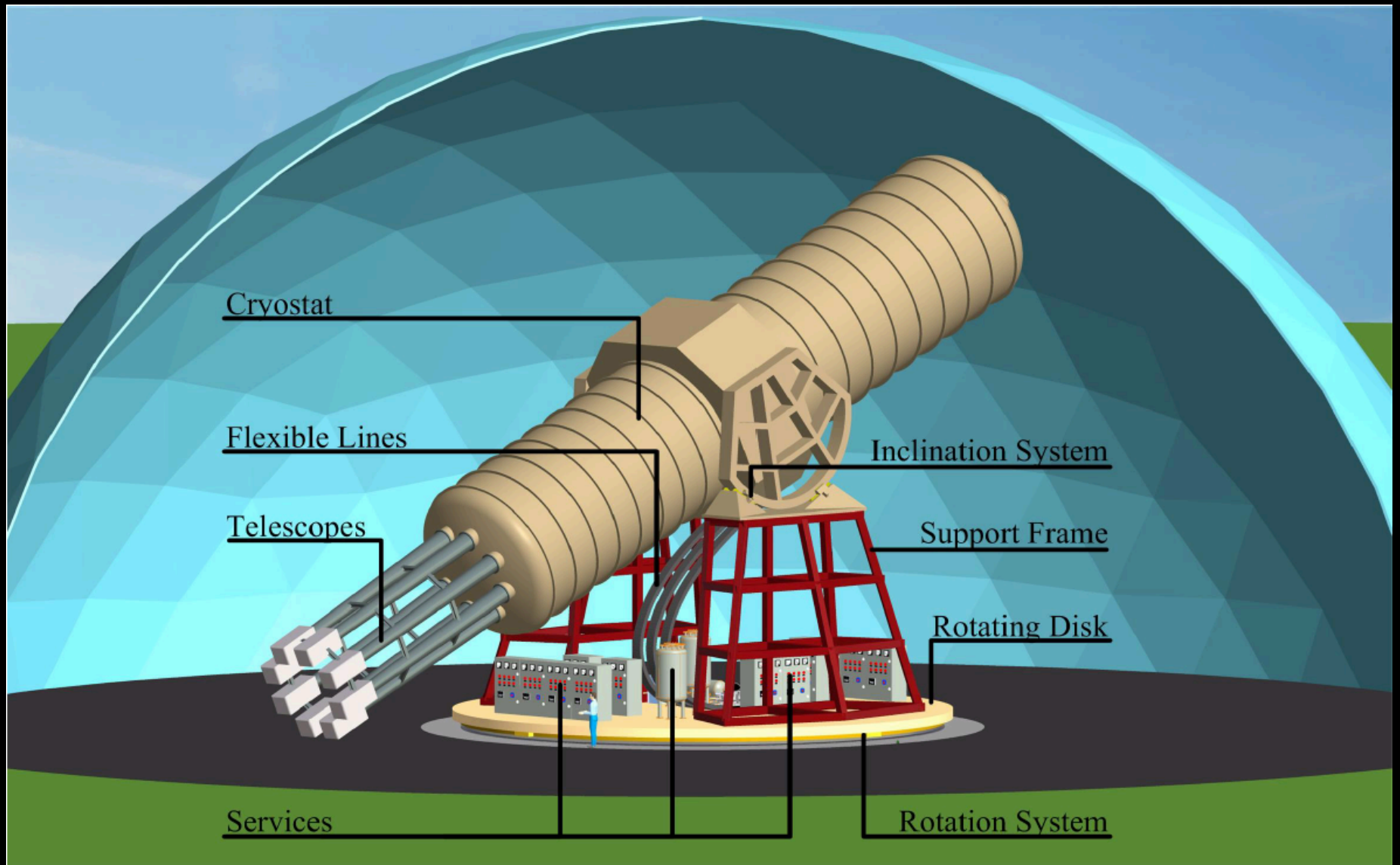
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Going to the future: IAXO

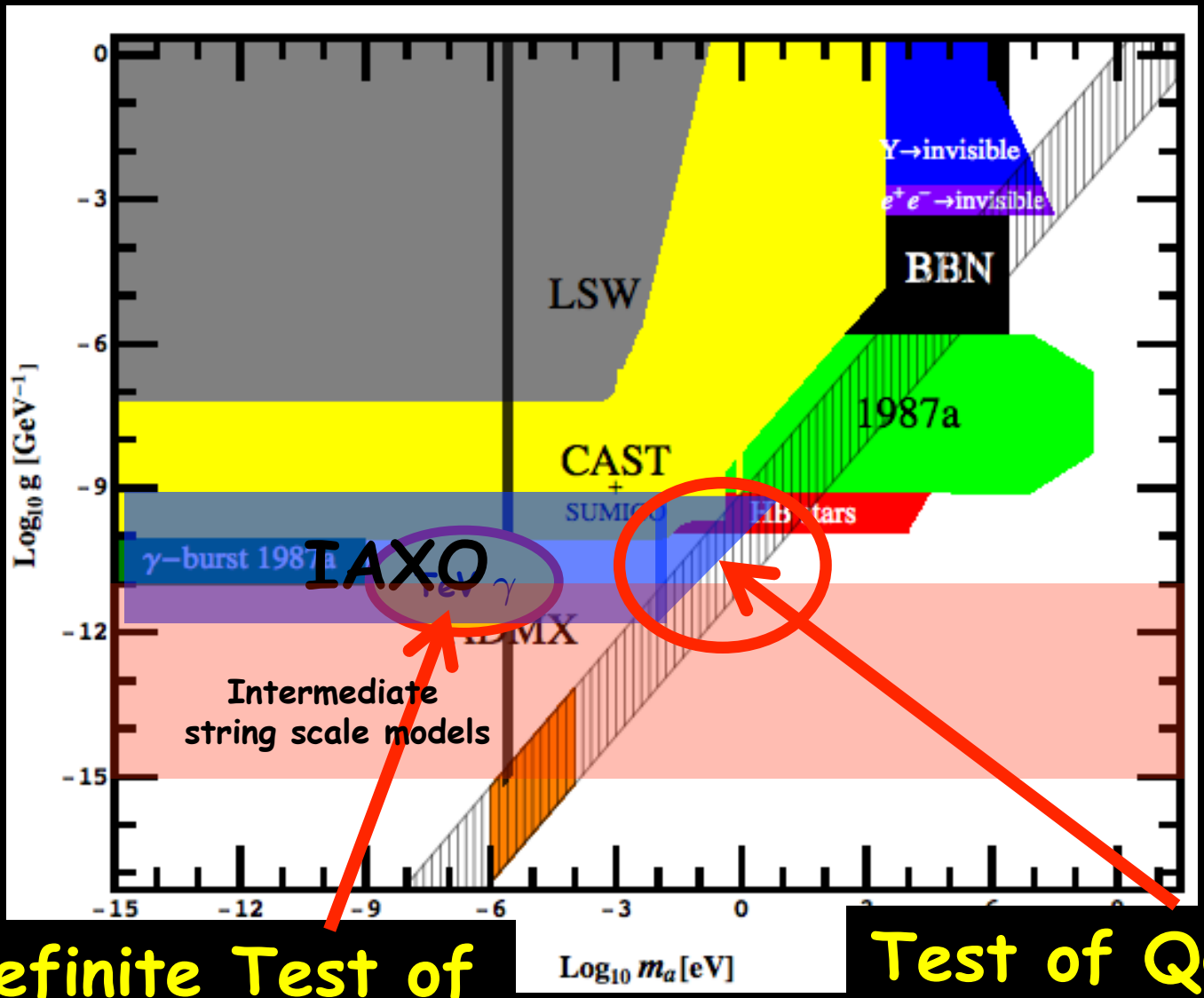
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

The International Axion Observatory



An interesting area…

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



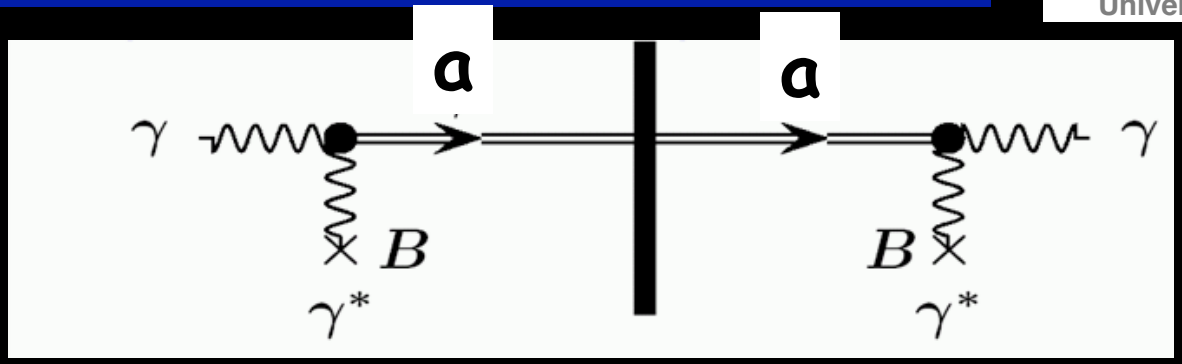
Definite Test of TeV transparency

Test of QCD axion + white dwarf anomaly

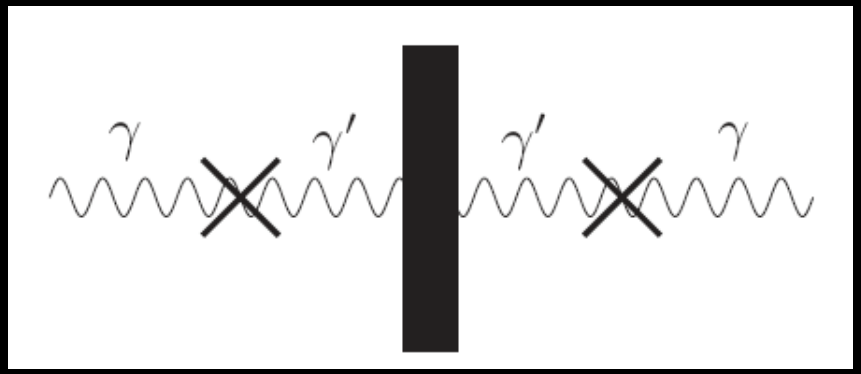
WISPS=Weakly interacting sub-eV particles

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

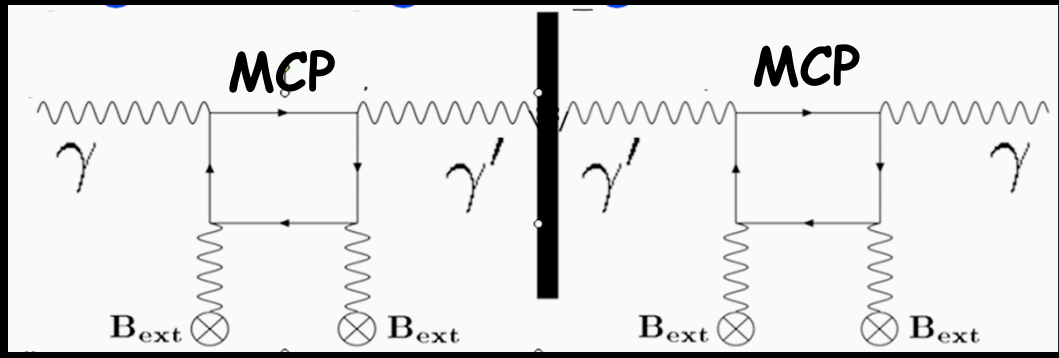
- Axions



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



- Hidden photon + minicharged particle (MCP)



Axions and ALPs
from
String Theory

String theory

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

String theory: Moduli and Axions

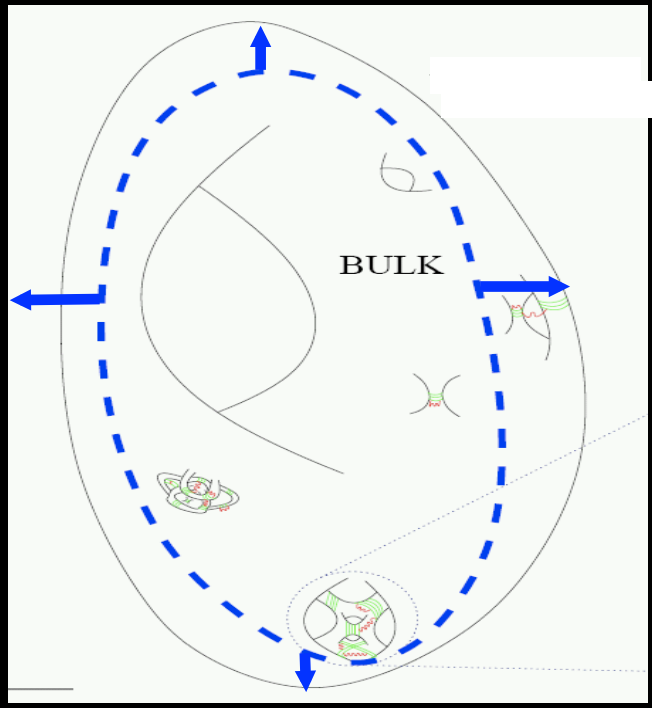
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- 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

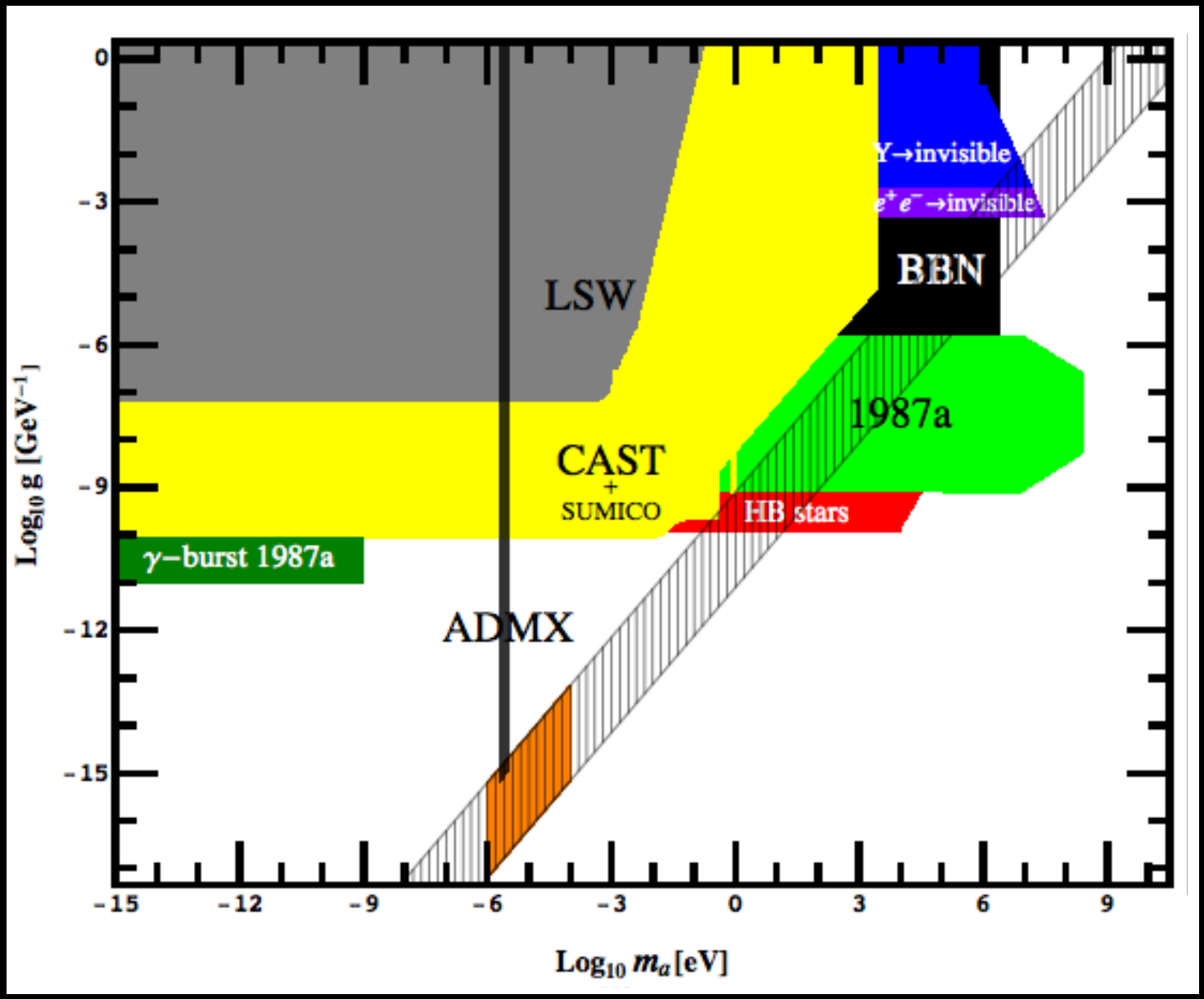


↓

Axion/ALP candidates

Axion (like particles): Where are we?

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Axions and Moduli

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- 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

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

- Axions + Moduli always present in String theory

Masses and Couplings

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- "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

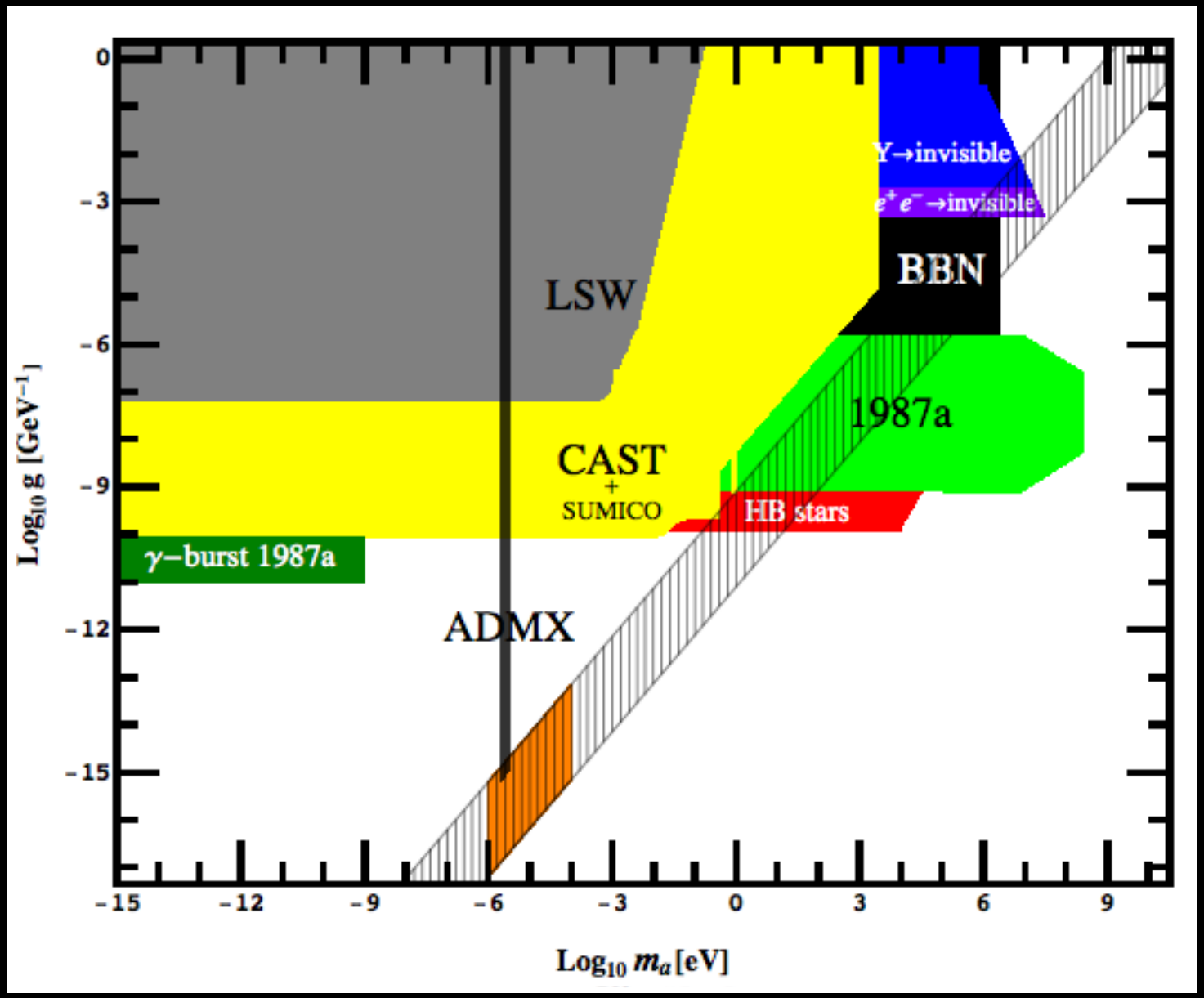
- However, if not QCD axion

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

(nearly) arbitrary

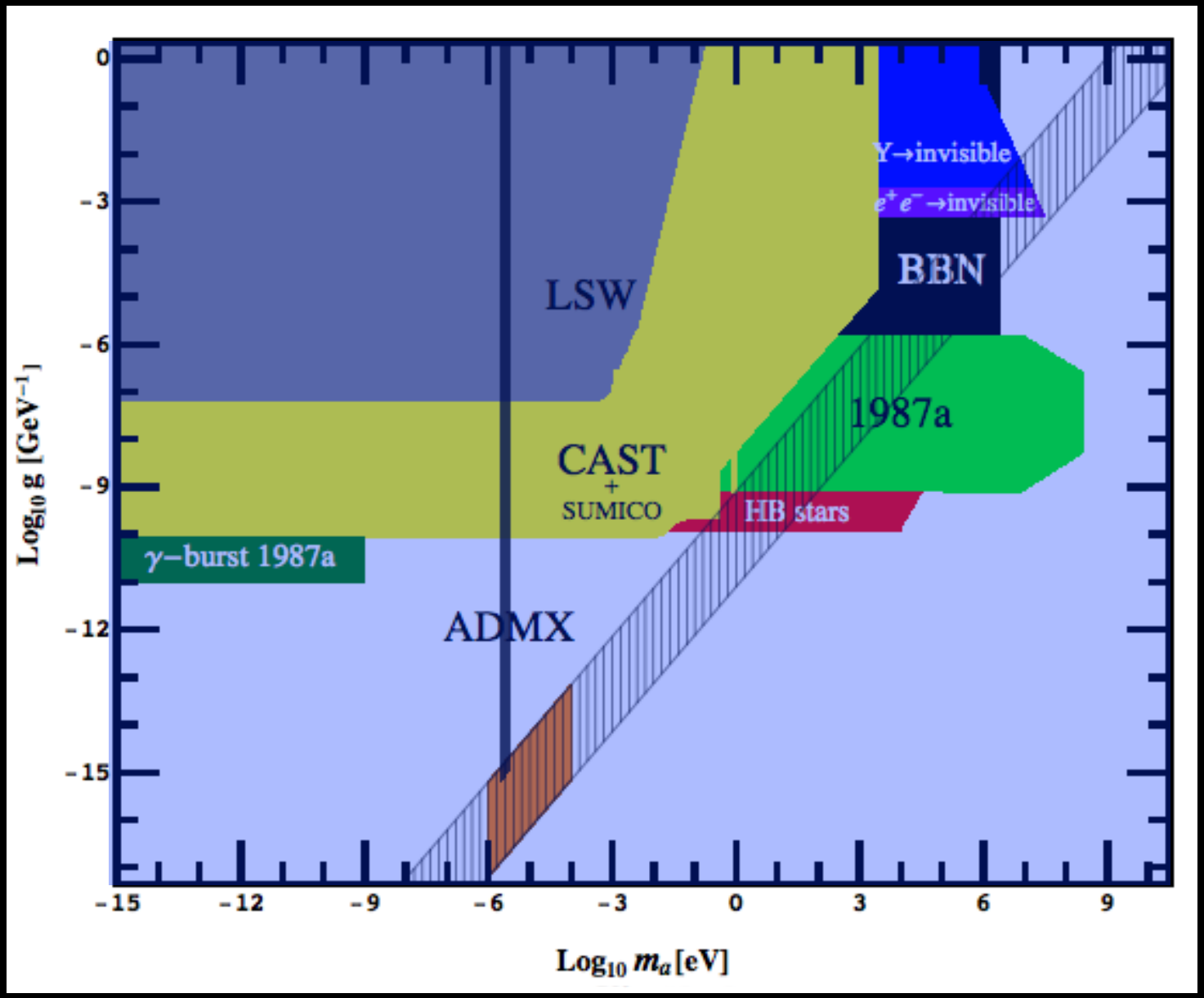
Axion (like particles): Where are we?

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



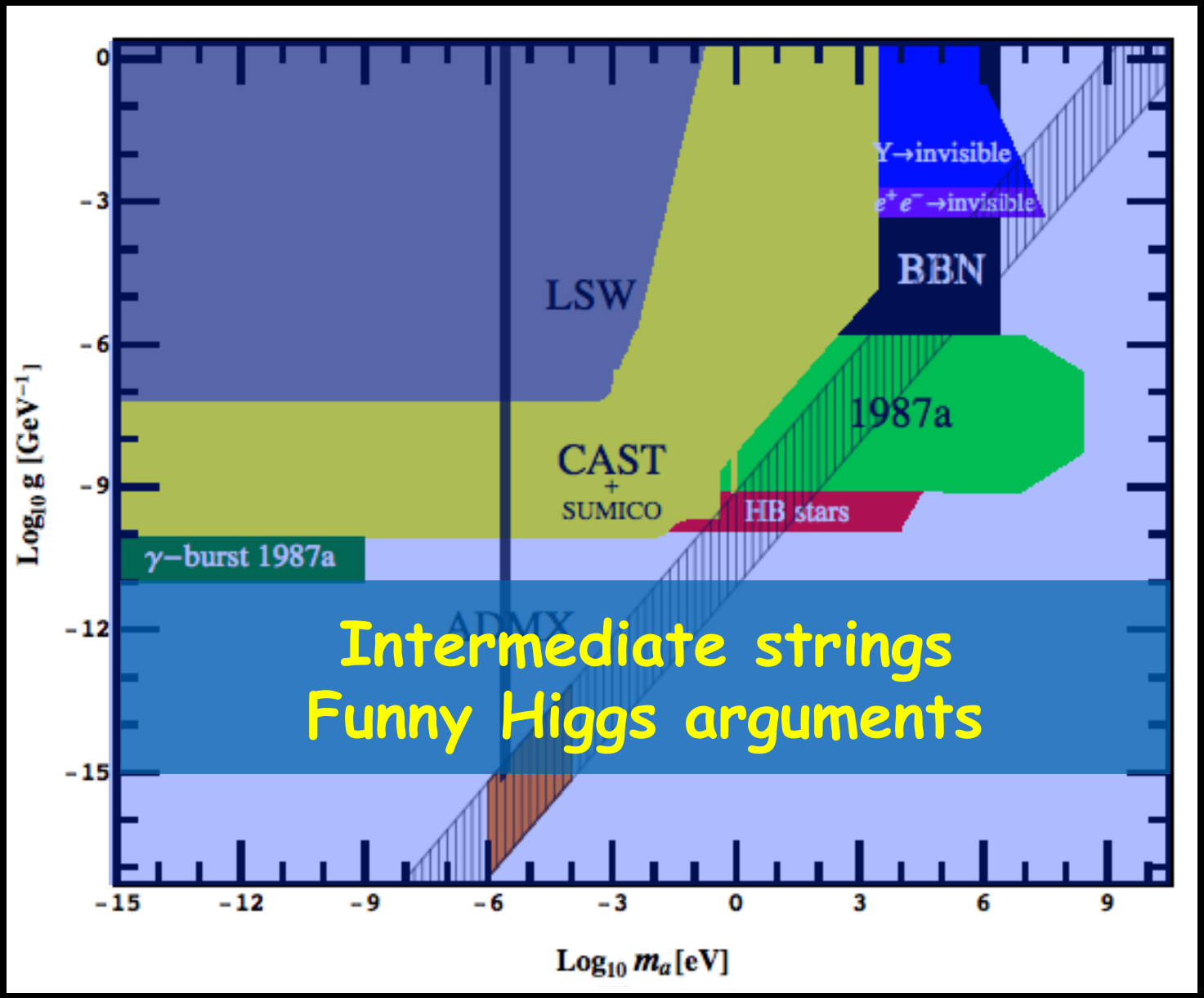
Axion (like particles): Where are we?

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Axion (like particles): Where are we?

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Dark Matter(s)

Can Dark Matter be Axiony/WISPy?

(Weakly Interacting Sub-eV Particley)

Slim

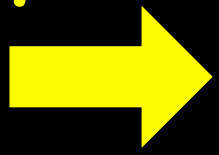
Properties of Dark Matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

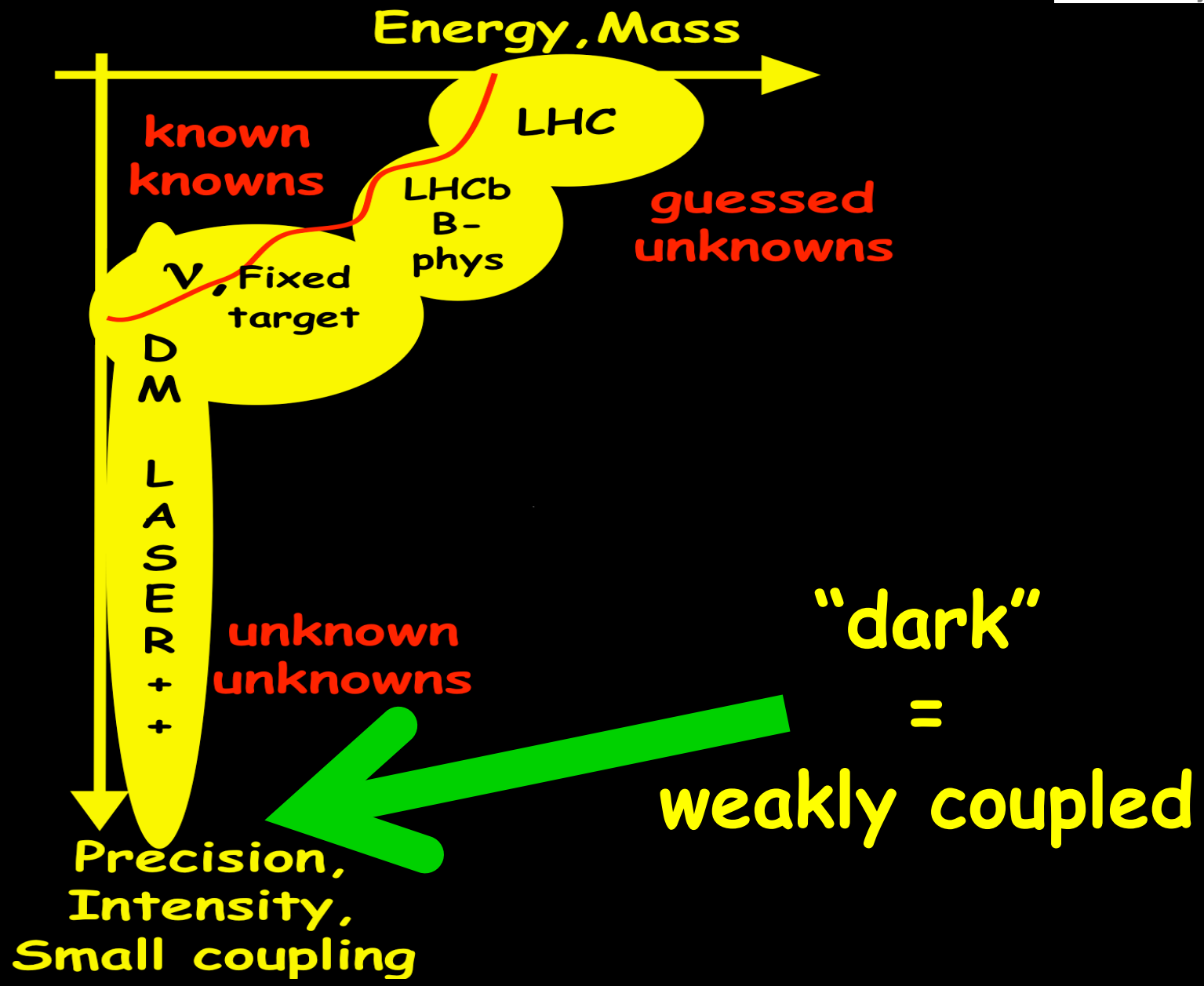
➔ very, very weak interactions with light and with ordinary matter

➔ Exactly the property of Axions/WISPs



Exploring is (at least) 2 dimensional

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



A common prejudice

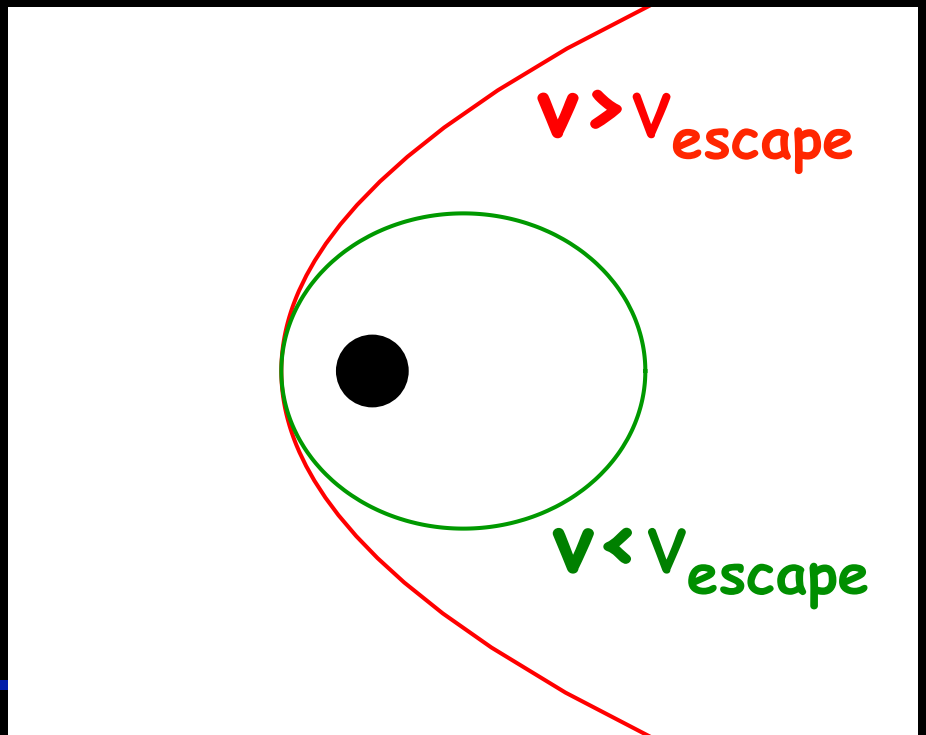
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- 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

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

  ➡ See misalignment mechanism 

- Bosonic!

  ➡ Axion(-like particles)
  Hidden Photons 

Dark matter has to be heavy…

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

Dark matter has to be heavy…

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

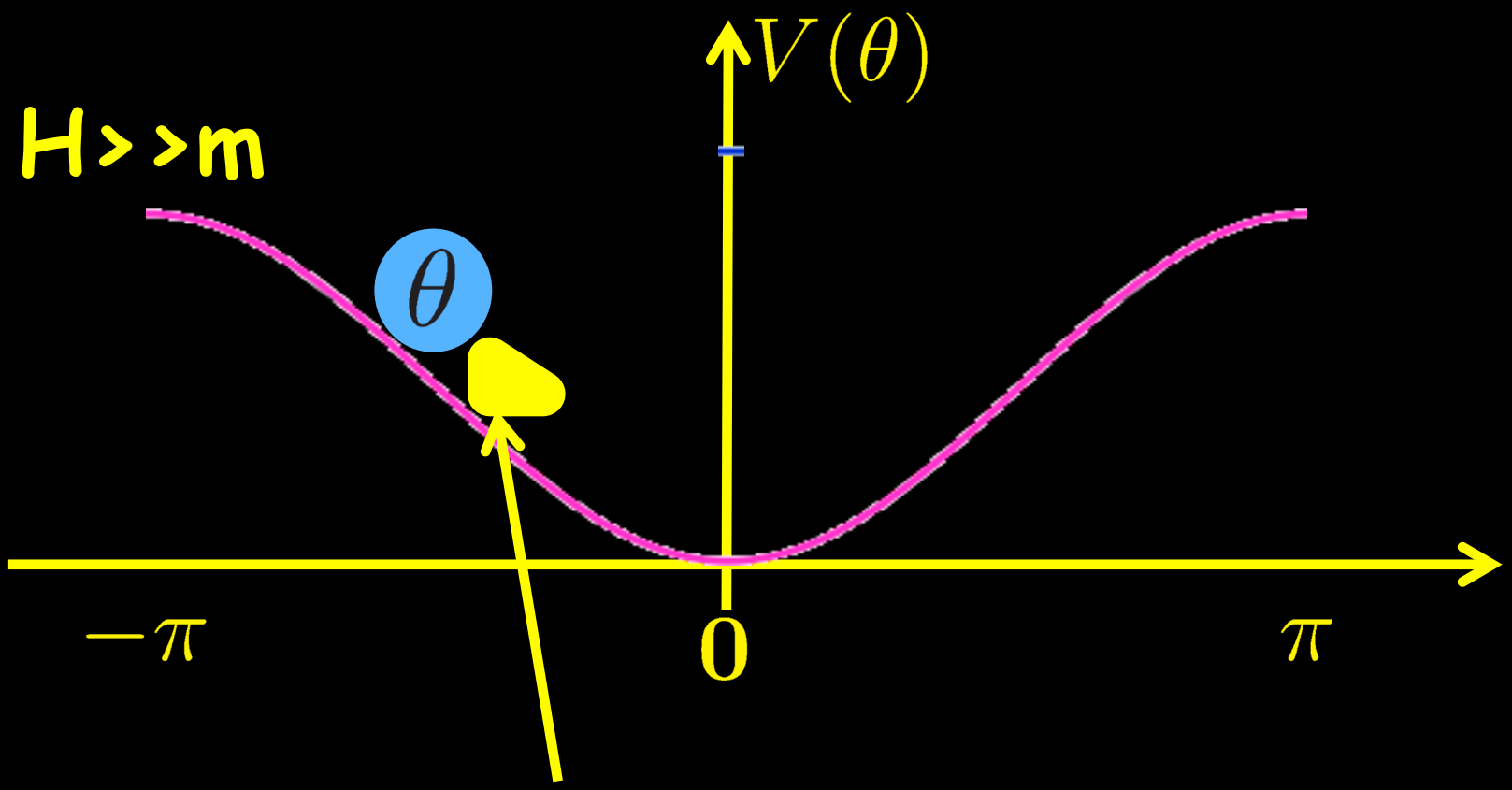
Dark matter has to be heavy $m_{\rm DM} \gtrsim {\rm keV}$?

Myth Busted

SUPERCOLD DARK MATTER

The axion has no clue where to start

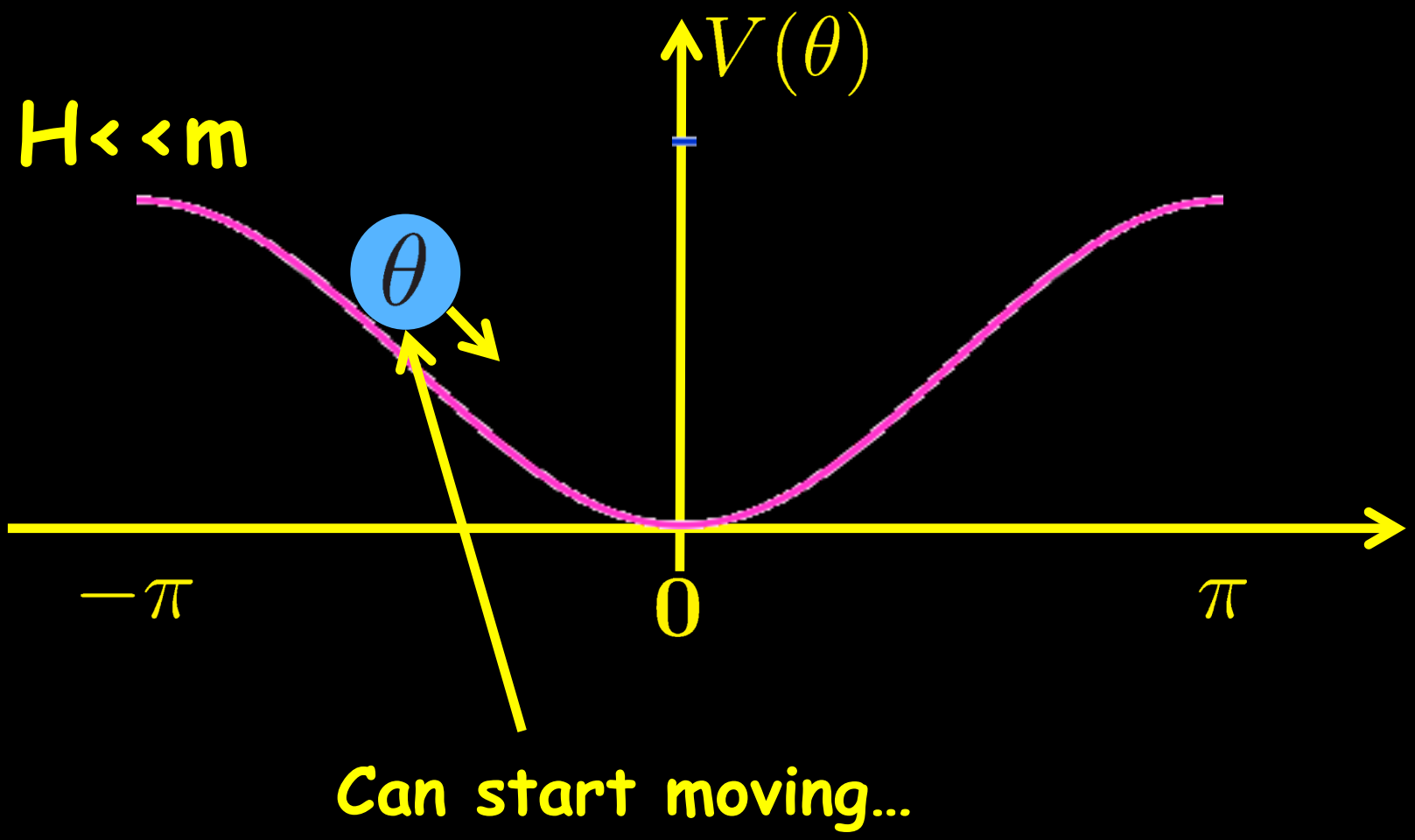
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Field is stuck because of Hubble "breaking"

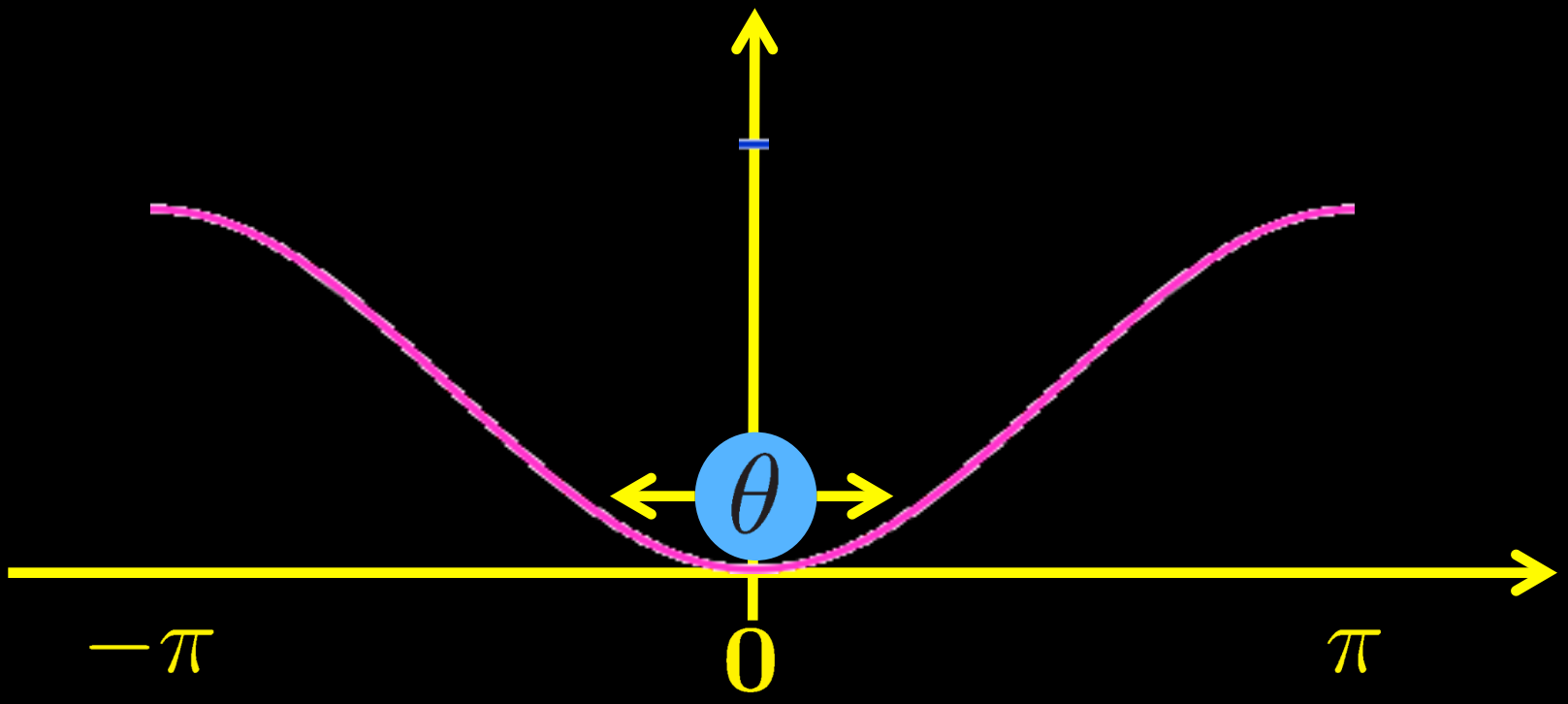
The axion has no clue where to start

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



The axion solution to the strong CP problem

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



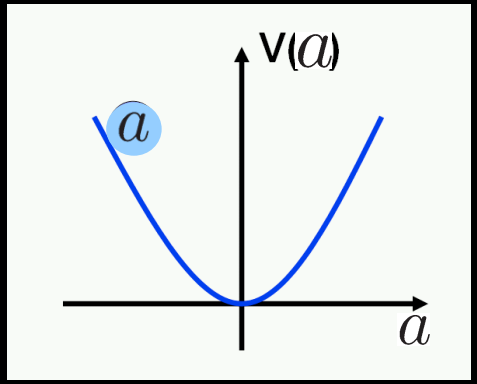
➔ Oscillations contain energy
➔ behave like non-relativistic particles (T=0)

Axion Dark Matter

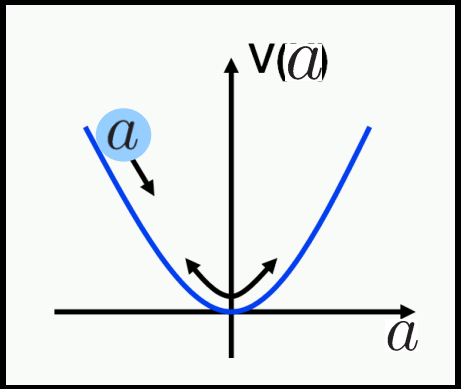
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

- $H \gg m_a$ ➔ overdamped oscillator



- $H \ll m_a$ ➔ damped oscillator

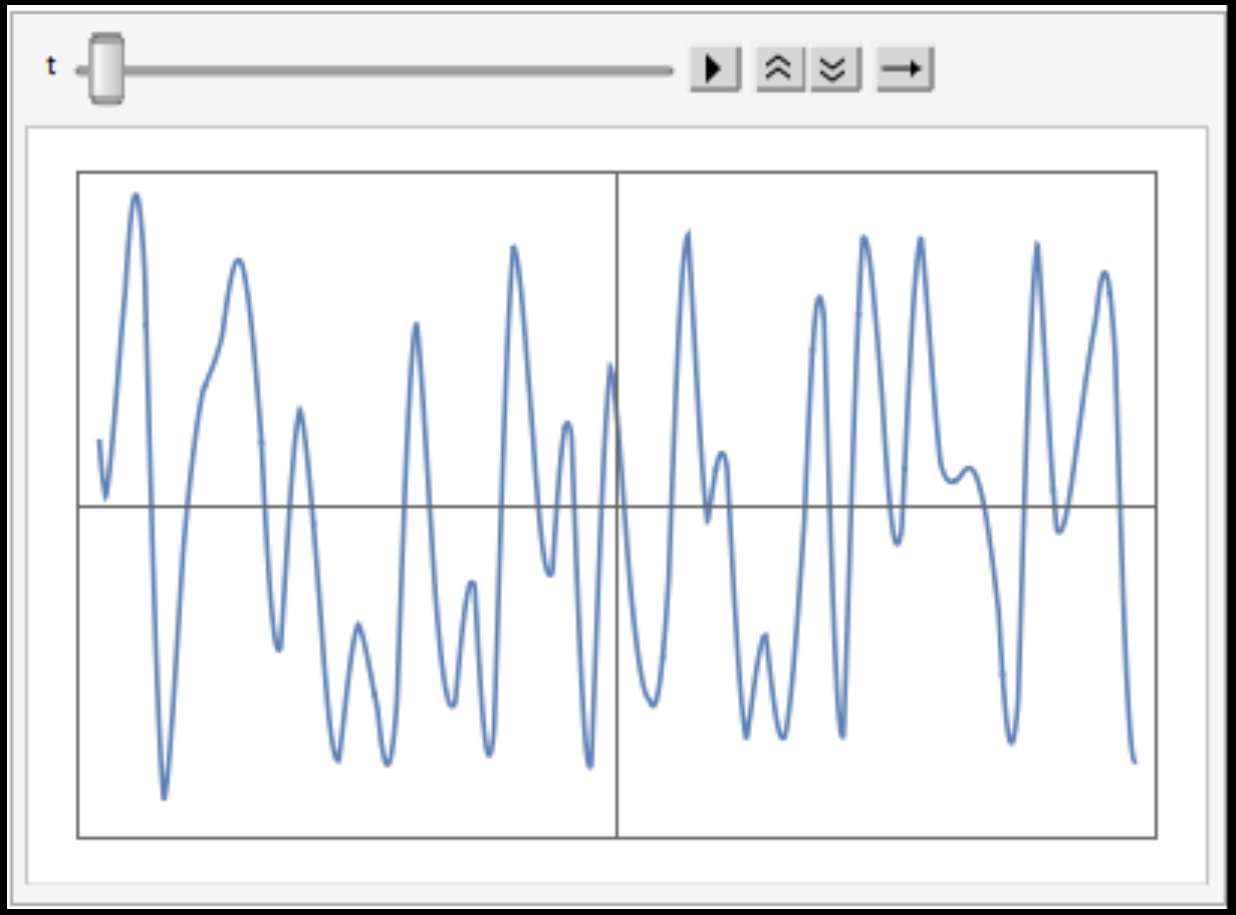


$$\rho_a(t) = \frac{\rho_{ini}}{R^3(t)}$$ ➔ Dark Matter

Why Cold? Inflation!

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

Field value



space

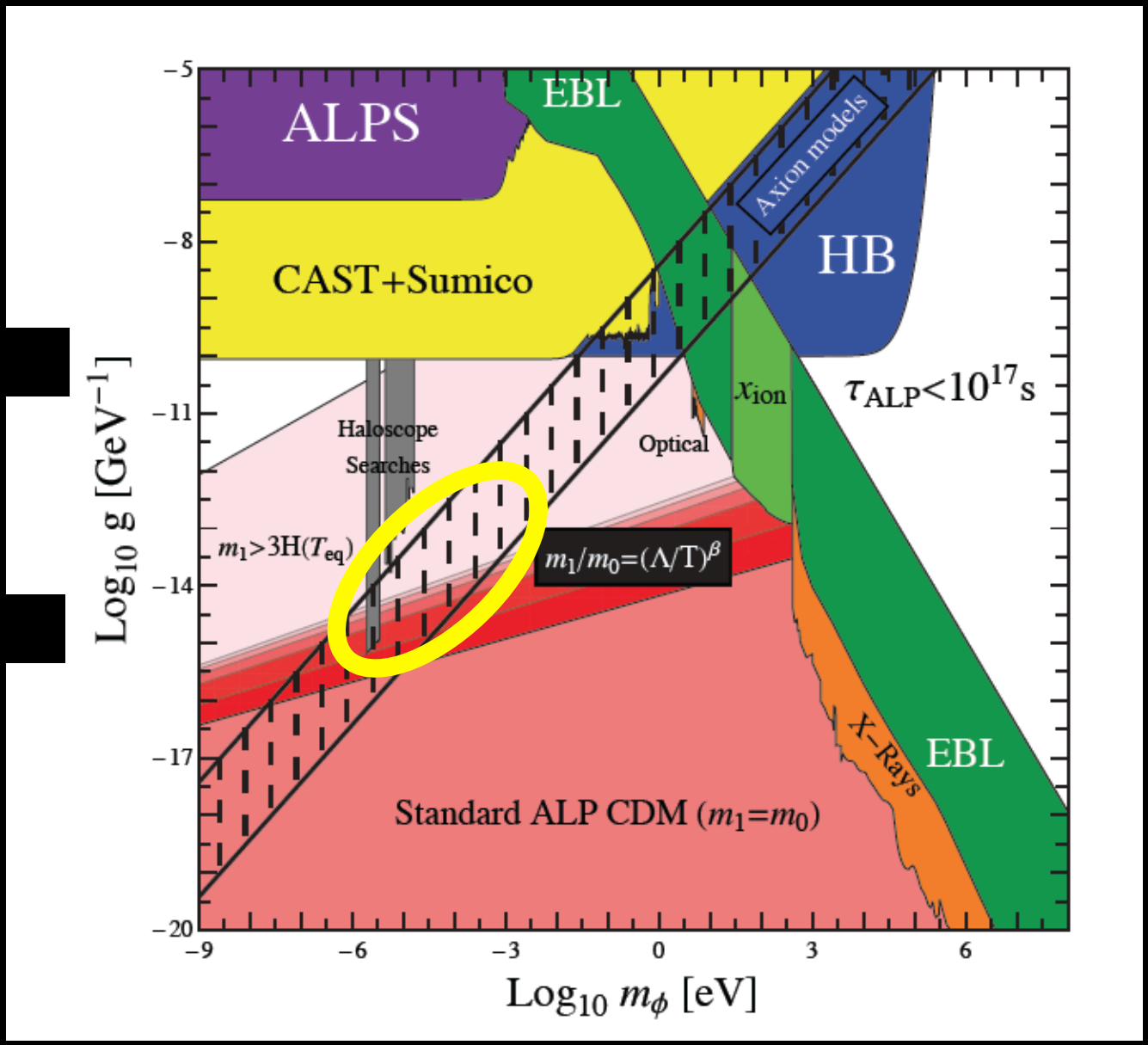
$$velocity \sim \frac{p}{m} \sim \frac{\hbar}{m}\frac{d}{dx} \to 0$$

Axion(-like particle) Dark Matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

~10^7 GeV

~10^{12} GeV



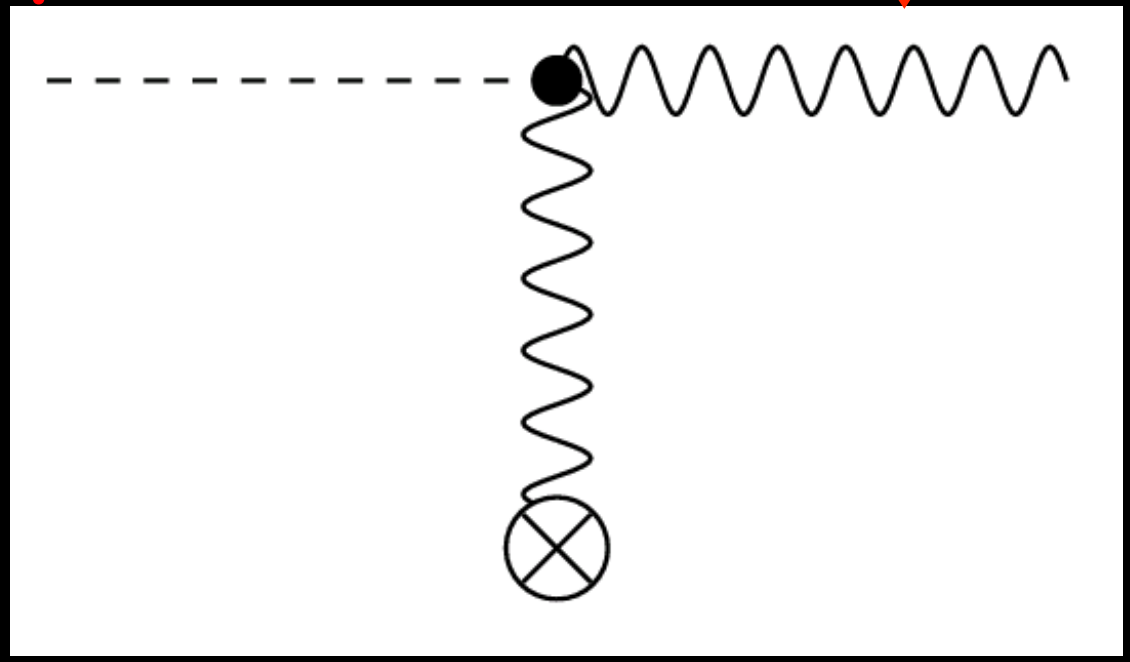
Detecting Axiony/WISPy DM

Use a plentiful source of axions

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- Photon Regeneration

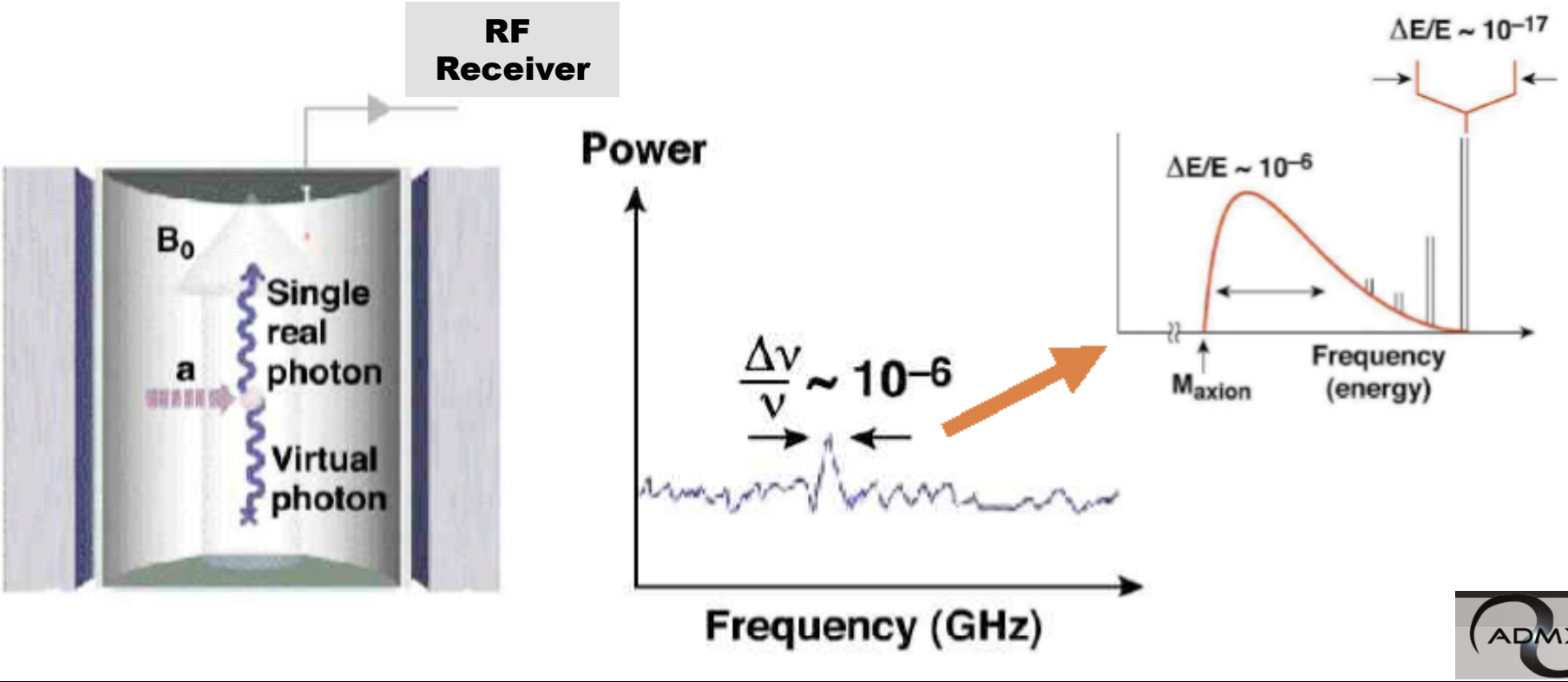
Photon
(amplified in resonator)



axion
(dark matter)

Signal: Total energy of axion

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

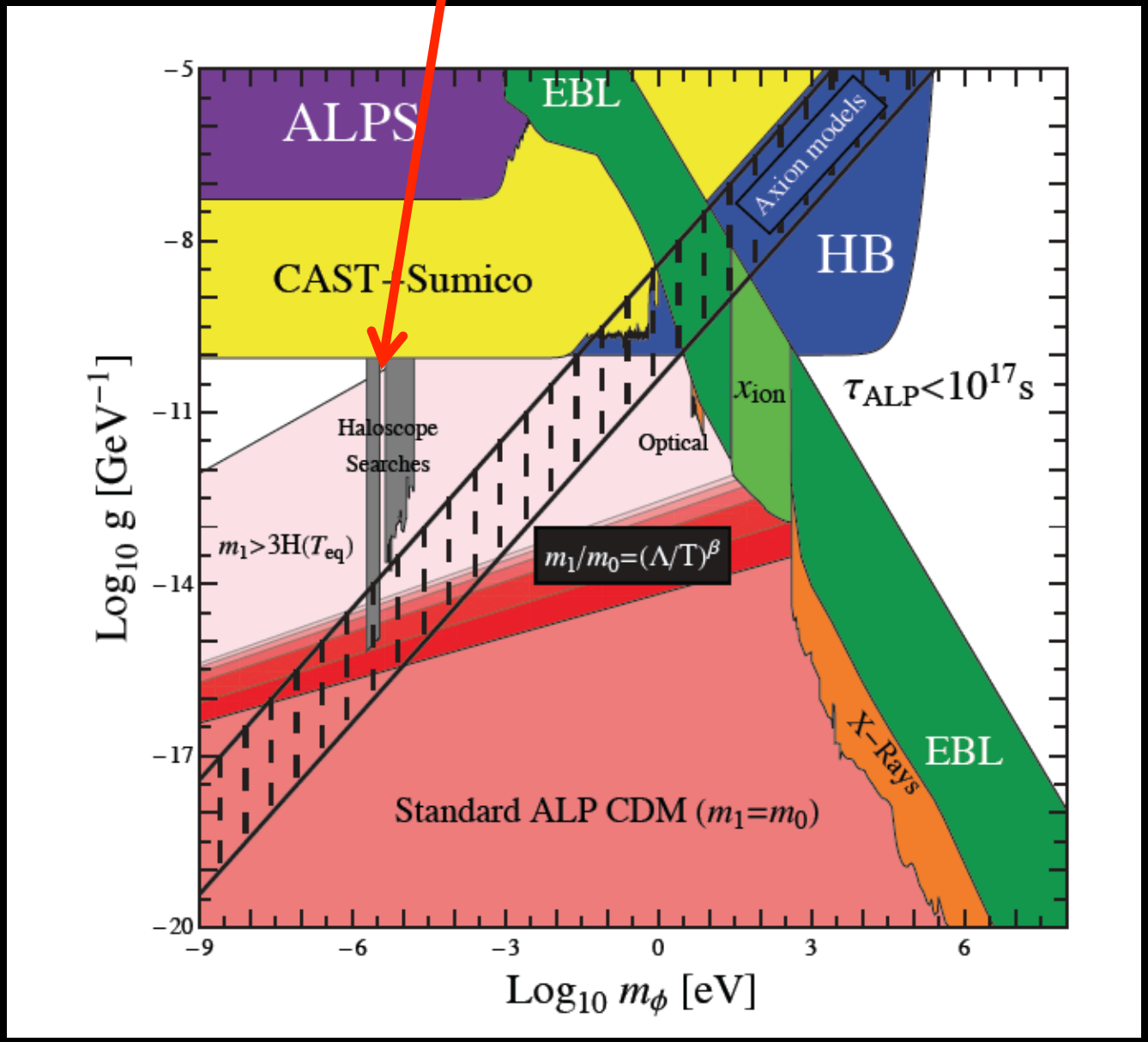


$$h\nu = m_a c^2 [1 + \mathcal{O}(\beta^2 \sim 10^{-6})]$$

Virial velocity in galaxy halo!

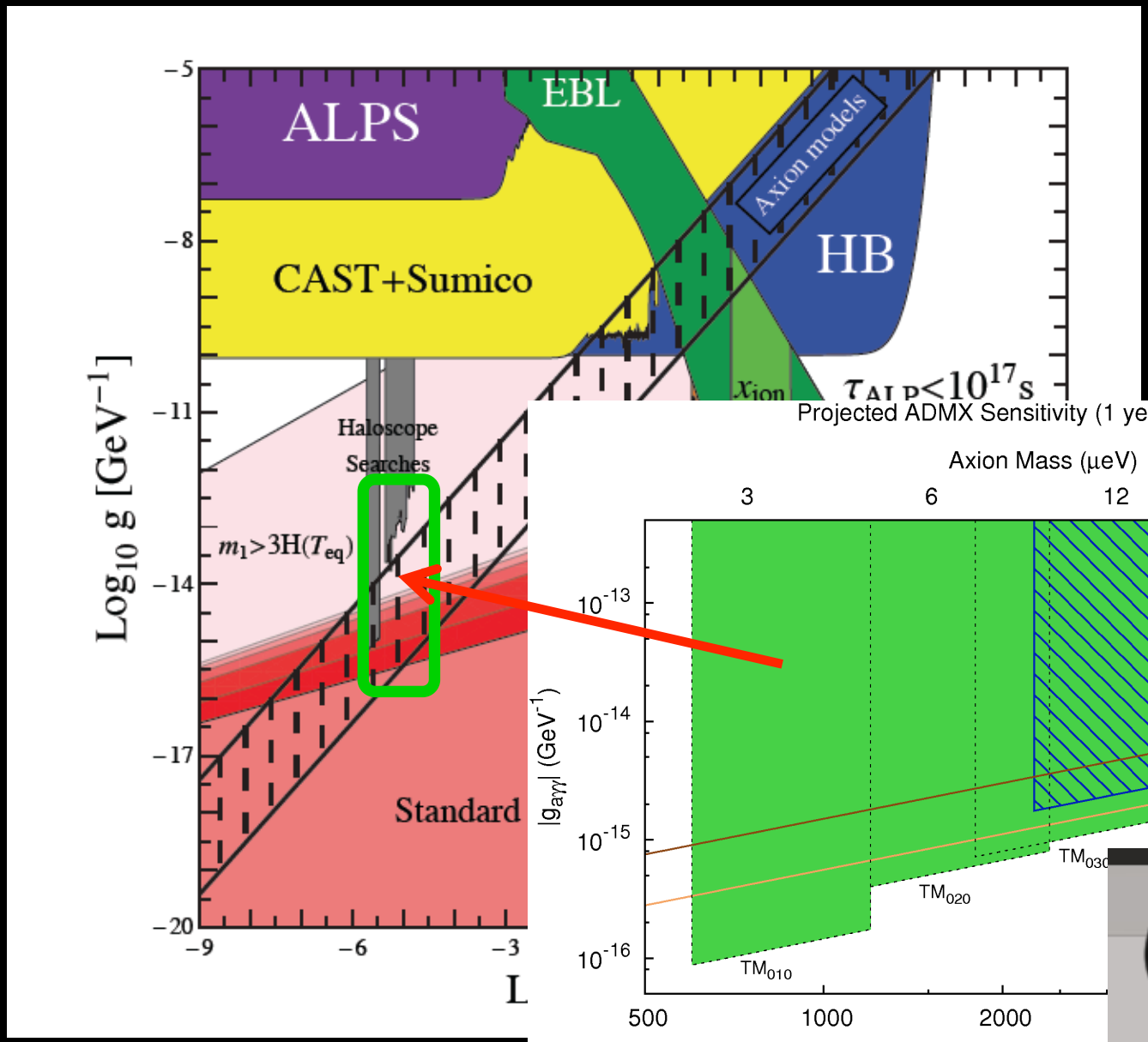
An extremely sensitive probe!!!

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



A discovery possible any minute!

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



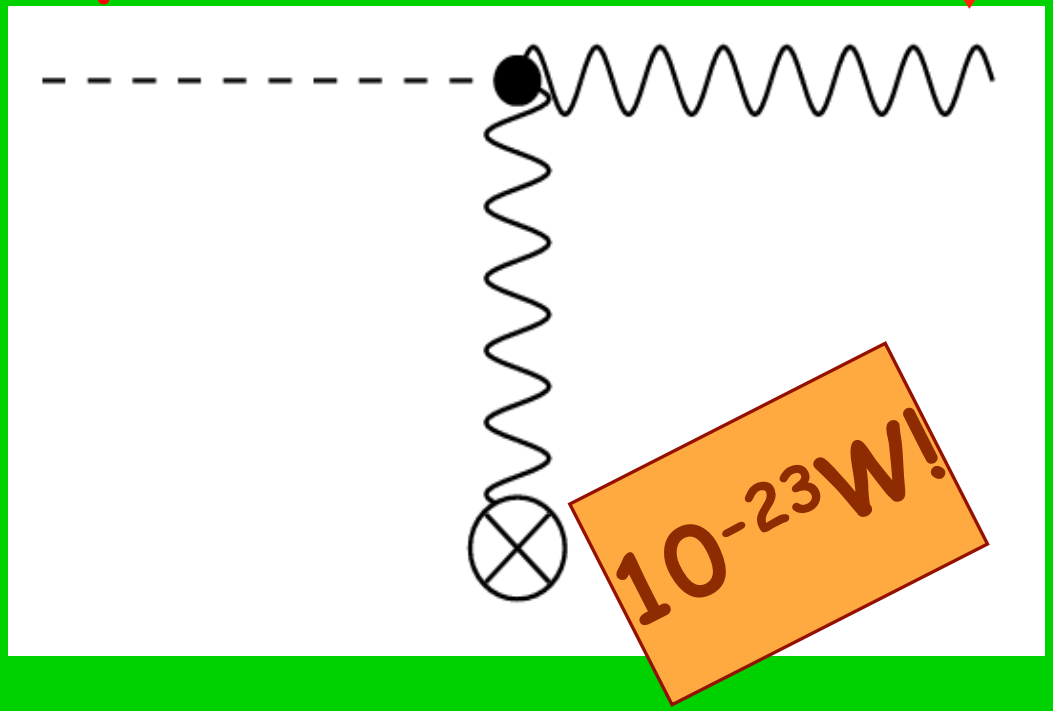
Electricity from Dark Matter ;-).

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- Photon Regeneration

Photon
(amplified in resonator)

axion
(dark matter)



Really sustainable Energy

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- 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 ☺

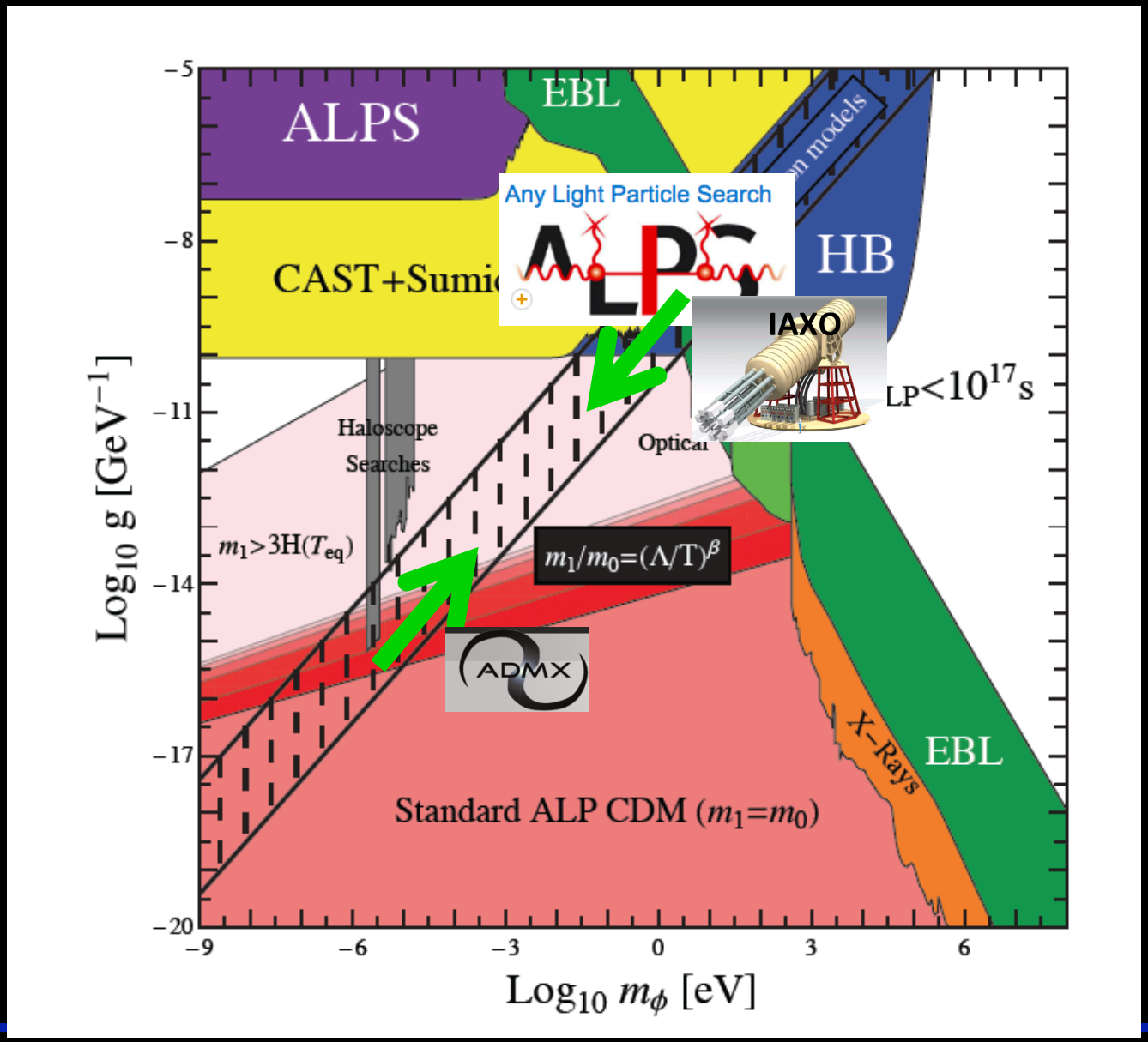
DM power

ρ*v~300 MeV/cm^3*300km/s~10 W/m^2

compared to 2W/m^2 for wind

Encircling the axion…

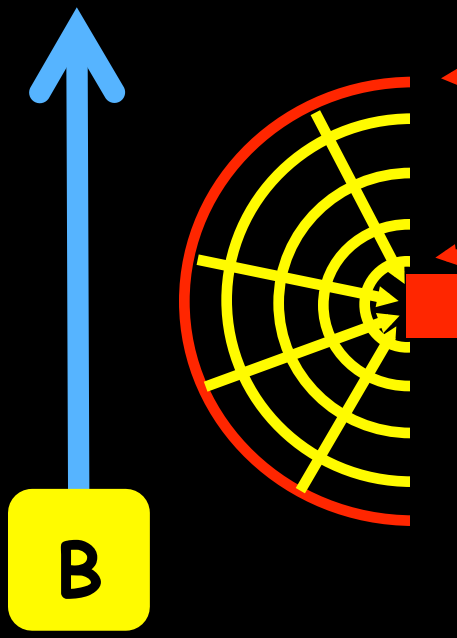
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Broadband Search Strategy

Dark Matter Antenna

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

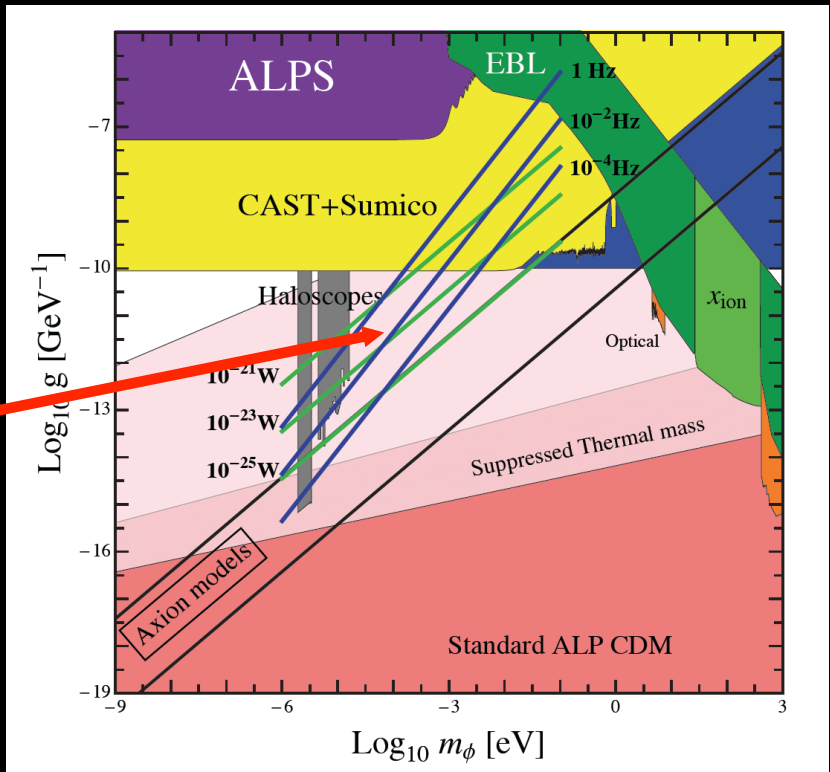


Antenna converts axion->photon

Radiation concentrated in center

Detector

Probes here;
very sensitive!!



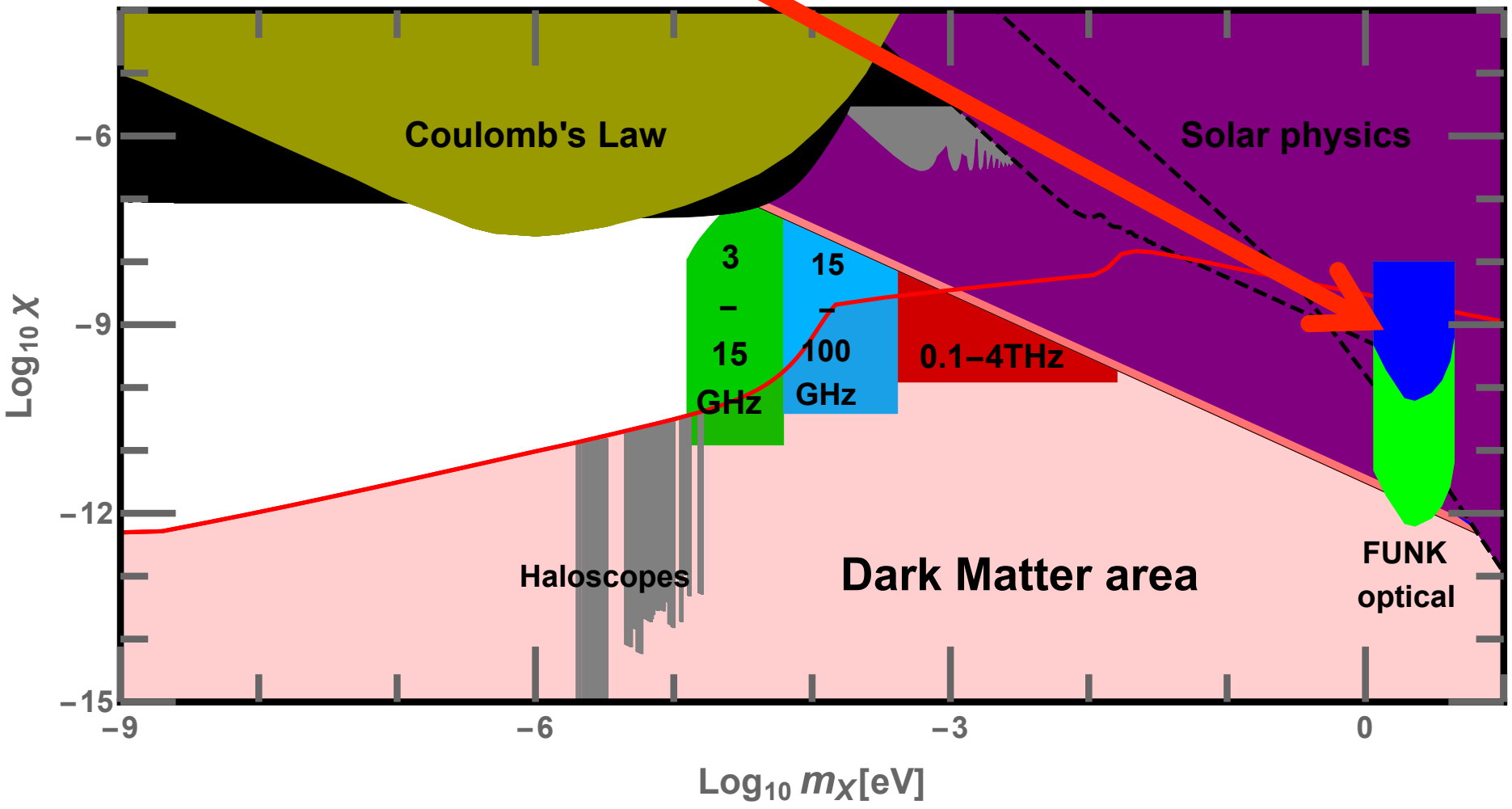
The FUNK Experiment

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

Recycle Auger mirror

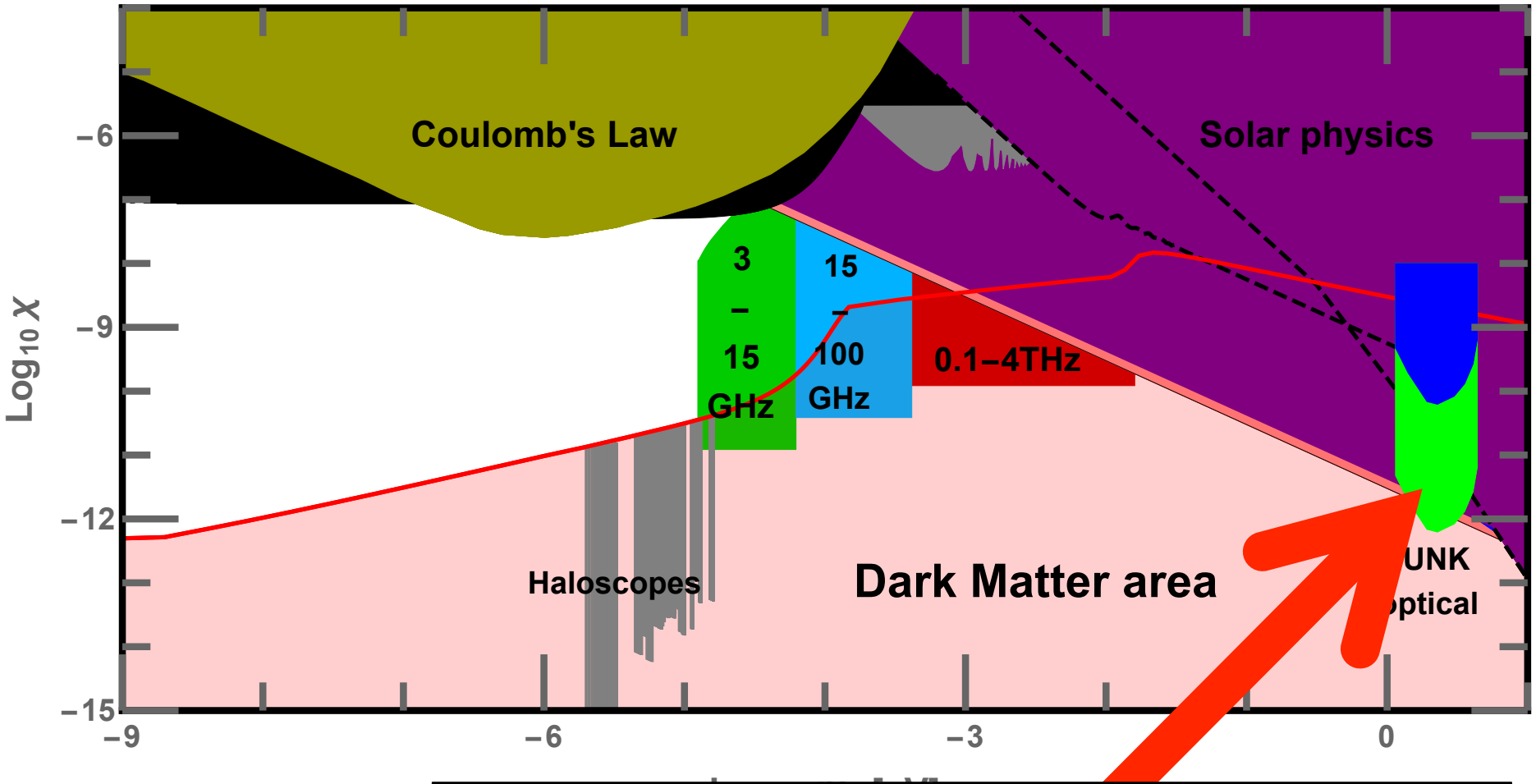
First Results

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Upgrade: The PMT 9000(+107)

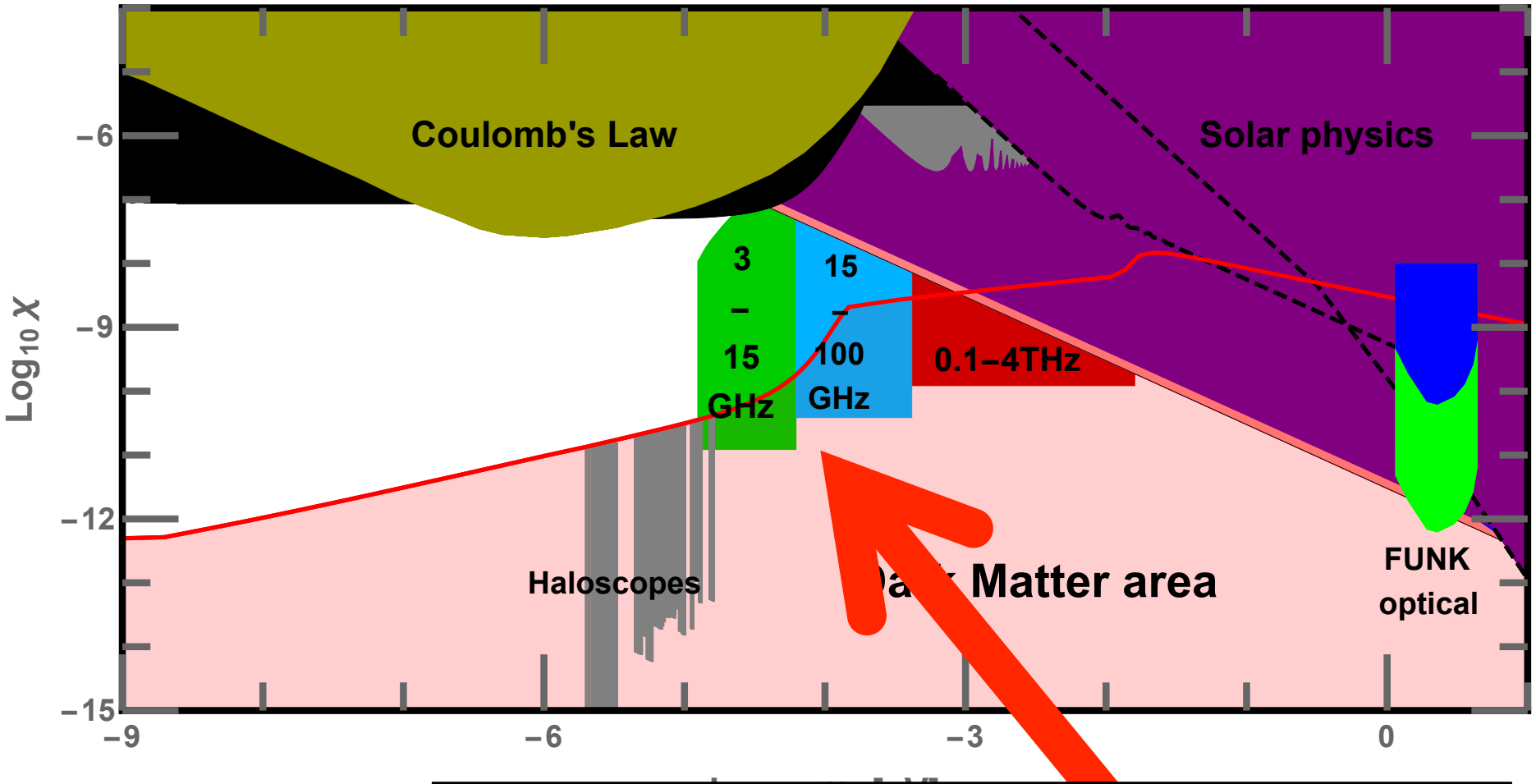
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Discovery Potential ☺!!!

The next years ➔ Lower frequency

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

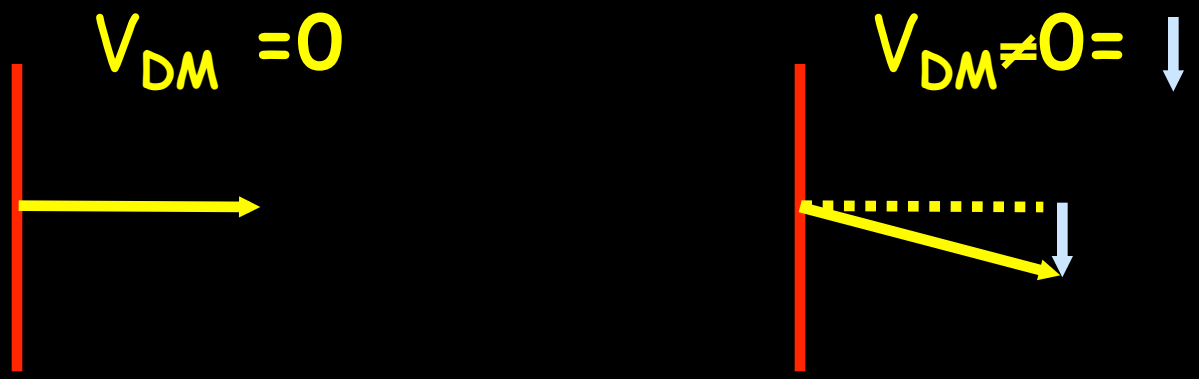


Discovery Potential ☺!!!

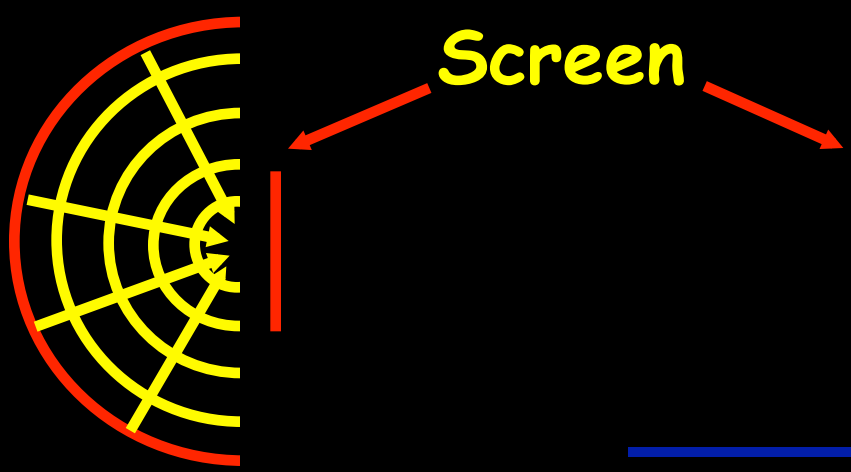
A Dream for ~~Astrology~~ ehhm Astronomy

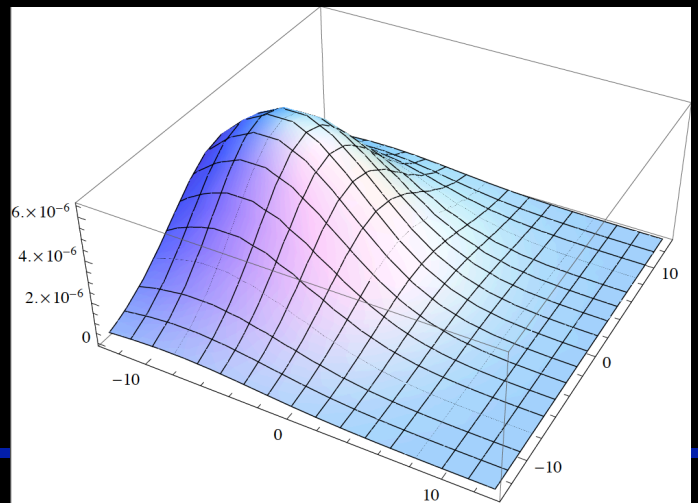
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- Emission from moving dark matter



- A picture of the DM-velocity distribution





New couplings:
A spin experiment

Looking for oscillating dipoles

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- **Remember:**

  Axion field controls electric dipole moment:

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

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

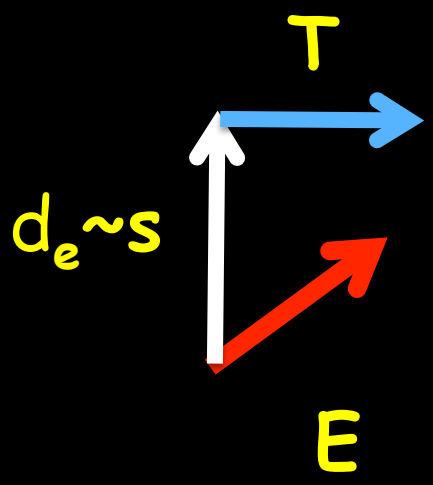
  ➔ Tiny oscillating electric dipole

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

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

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



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

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

Problem: the dipole moment is rapidly oscillating ~m_a

➔ Danger of cancellation

Solution: Rotate spin to compensate

➔ Use Spin Precession in magnetic field

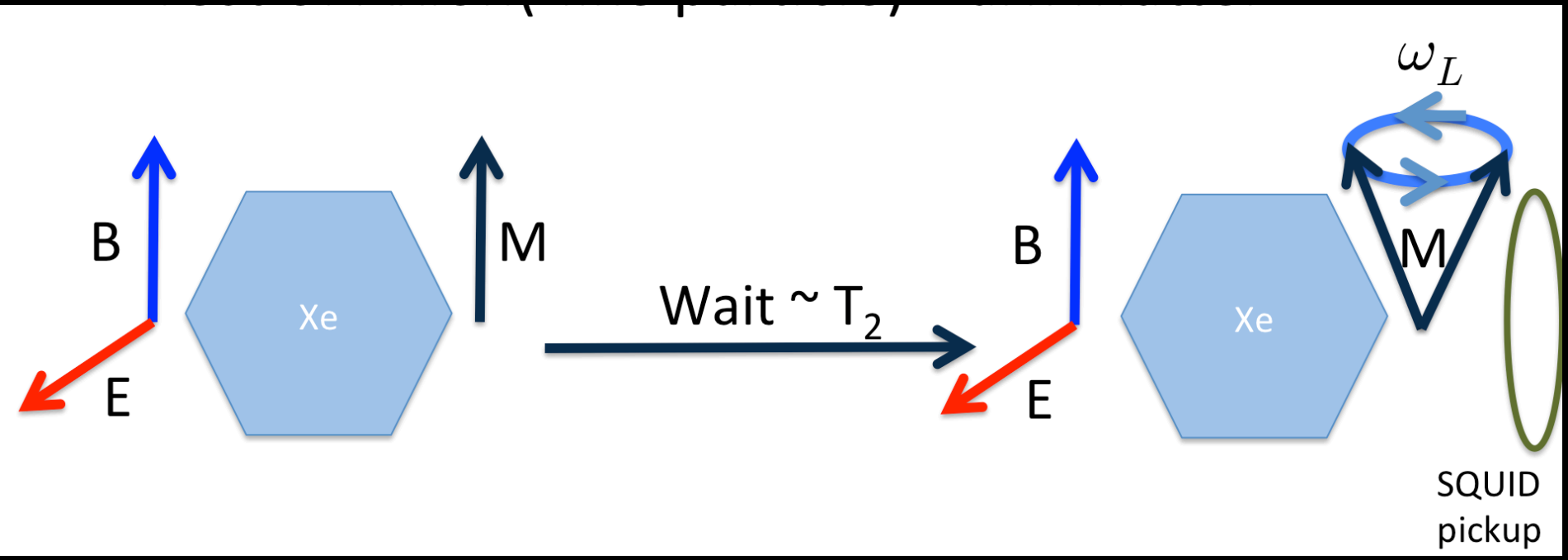
$$\omega_L = 2\mu B$$

Resonance when $\omega_L = m_a$

Modification of Xenon EDM

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

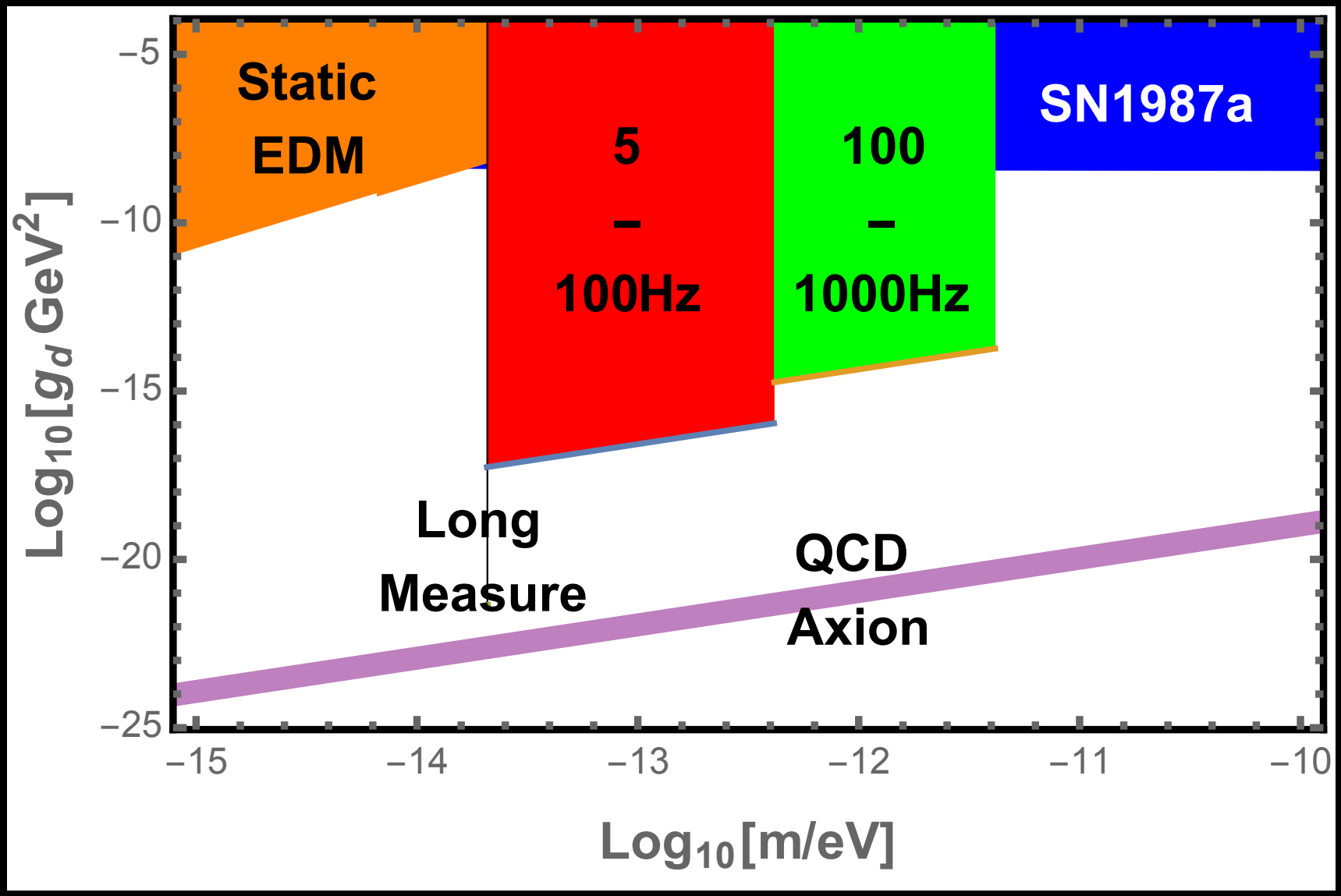
Modification of Xenon EDM experiment to be sensitive to time varying nuclear EDM



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

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Conclusions

Conclusions

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- 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.