Cleaning up the Dishes – Axions and the strong CP Problem

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What is “Axion”?

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Media & Entertainment

Business

Medical & Chemistry

Energy & Power

Or something more mundane?

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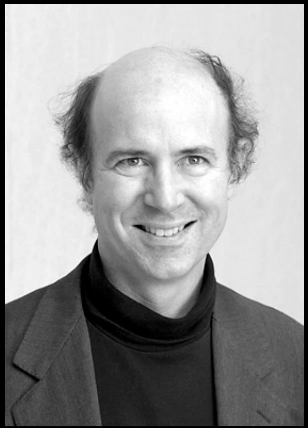
Today's Topic

The CP Cleaner of QCD

F. Wilczek
Julius-Wess-Award 2008



AXION – The Grease Stripper
Cleaning product by the
Colgate-Palmolive Company

Nobel lecture 2004:

"I named them after a laundry detergent,
since they clean up a problem
with an axial current."

So what is an "Axion"?

Let's look for some professional help:

Collins English Dictionary	**A hypothetical neutral elementary particle postulated to account for certain conservation laws in the strong interaction.**
Webster's New World Dictionary	**A hypothetical subatomic particle thought to be a lightweight, electrically neutral boson essential to the strong interaction.**
DUDEN	**Online nicht gefunden :-(**

What is an "Axion"?

Not so bad ...:

Wikipedia
The Free
Encyclopedia

The axion is a hypothetical elementary particle postulated by the Peccei–Quinn theory in 1977 to resolve the strong CP problem in quantum chromodynamics (QCD).
If axions exist and have low mass within a specific range, they are of interest as a possible component of cold dark matter.

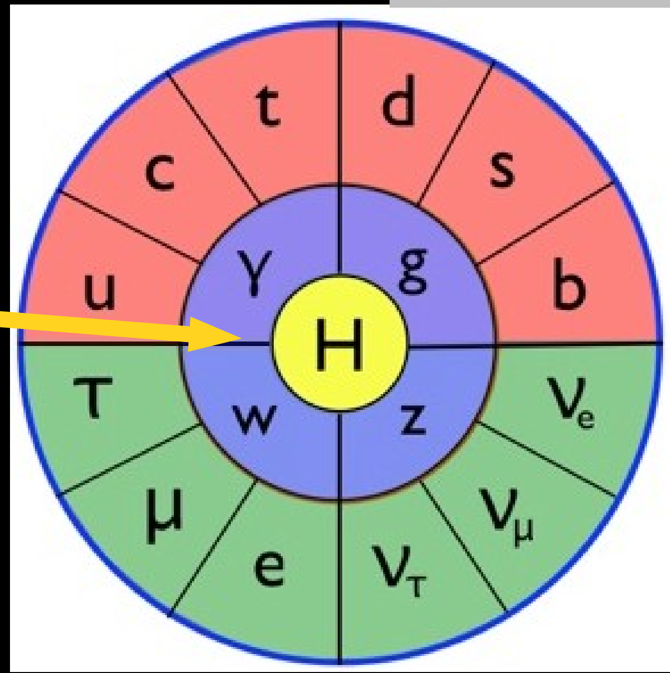
Axions are subatomic particles, which are
- ➔ hypothetical
- ➔ elementary
- ➔ light
- ➔ helpful for the strong force
- ➔ candidates for dark matter

Why do we need an "Axion"?

CERN
main auditorium

CERN, July 2012
Centre piece of the Standard Model cake has been found: the Higgs boson!

Symmetry Magazine



We know everything!

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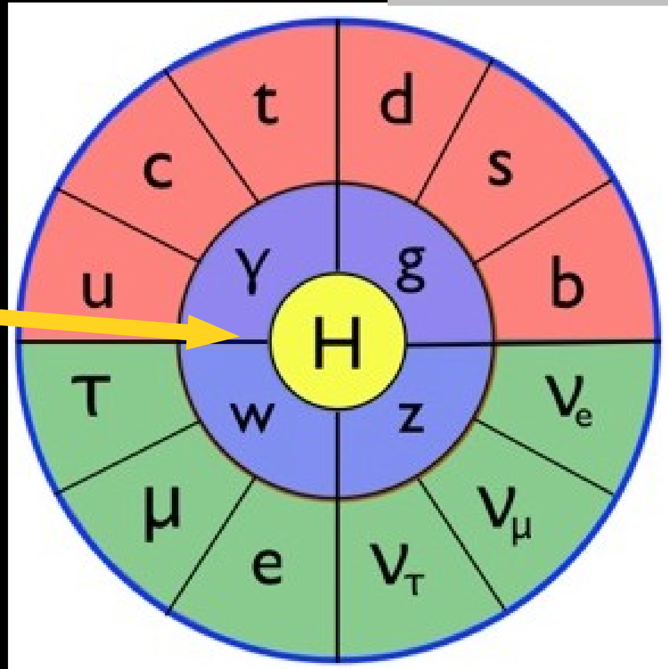
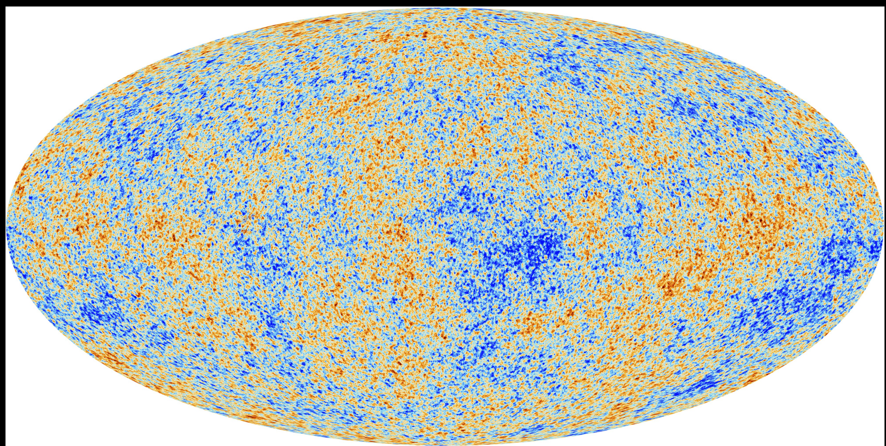
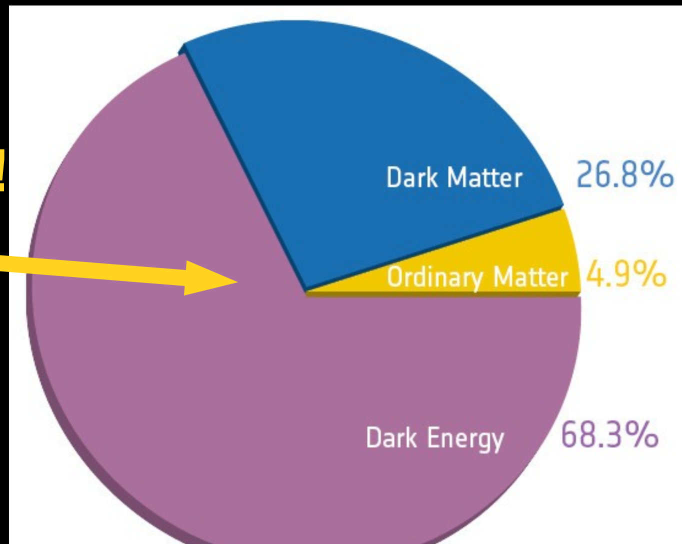


CERN
main auditorium

We know everything!



ESA 2015
Only 4.9 % ordinary matter in the universe!



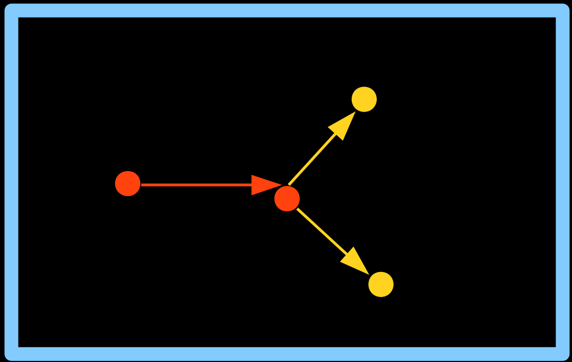
ESA/Planck 2015

Universe
cosmic microwave background

We still know nothing!

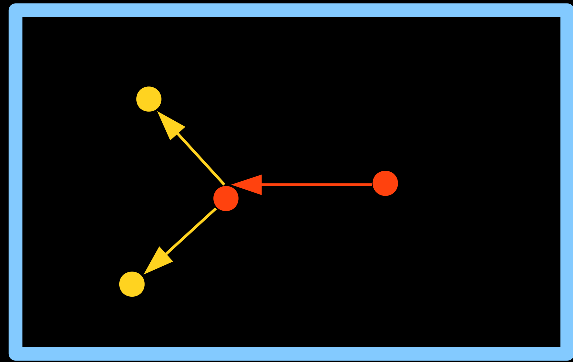
Discrete Symmetries

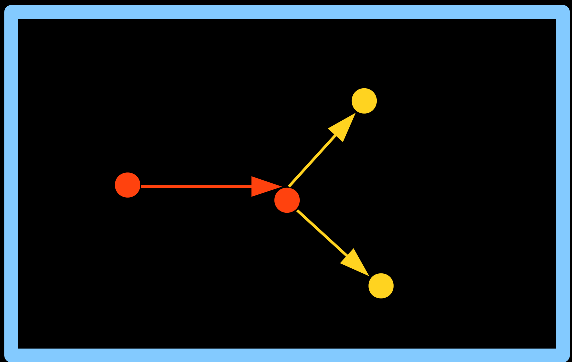
Is nature invariant, i.e. symmetric, under these transformations?



Spatial inversion

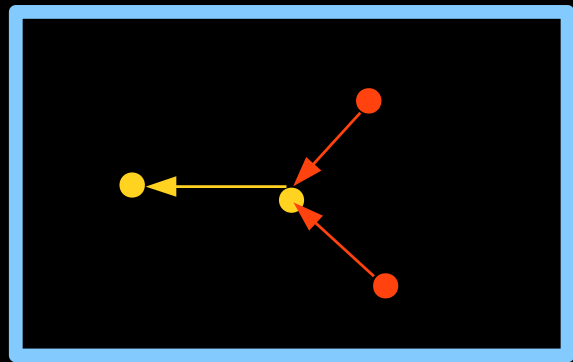
P

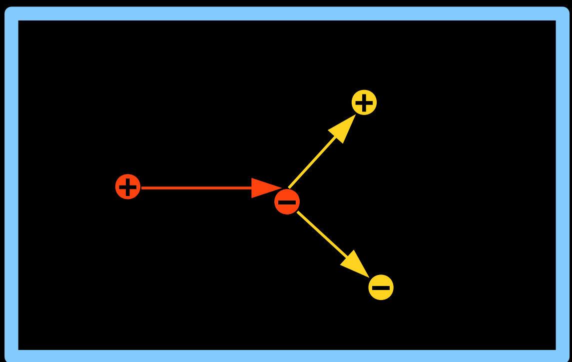




Time reversal

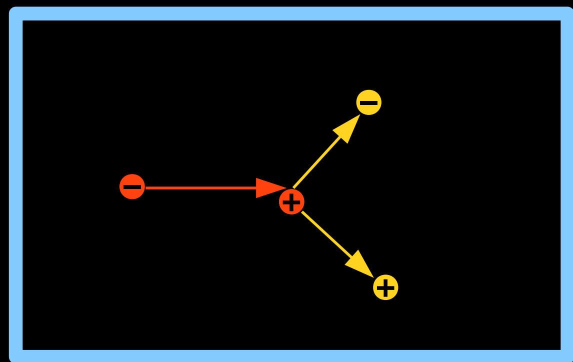
T





Charge conjugation

C



Discrete Symmetries

Is nature invariant, i.e. symmetric, under these transformations?

The answer is: No, not all!
→ Our universe differentiates between left and right.
More precisely:

- OK for gravity & electromagnetism, but WRONG for weak interactions!
  - β decay, Wu et al. 1956 → maximal P violation
    → only left-handed neutrinos … except for their small mass (→ Katrin?)
  - Neutral K decays, Fitch, Cronin, et al. 1964 → small CP violation
    → whole physics field measures this today with B mesons (→ Belle II)
- What is still valid?
  - Very general assumptions → CPT invariance
  - BUT: Must have CP violation → matter universe (Sakharov condition)
- What about the strong / nuclear force (QCD)?

QCD and C, P, T Invariance

Lorentz-scalar in QED $$-\frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu} = \frac{1}{2}\left(\vec{E}^2 - \vec{B}^2\right)$$ OK

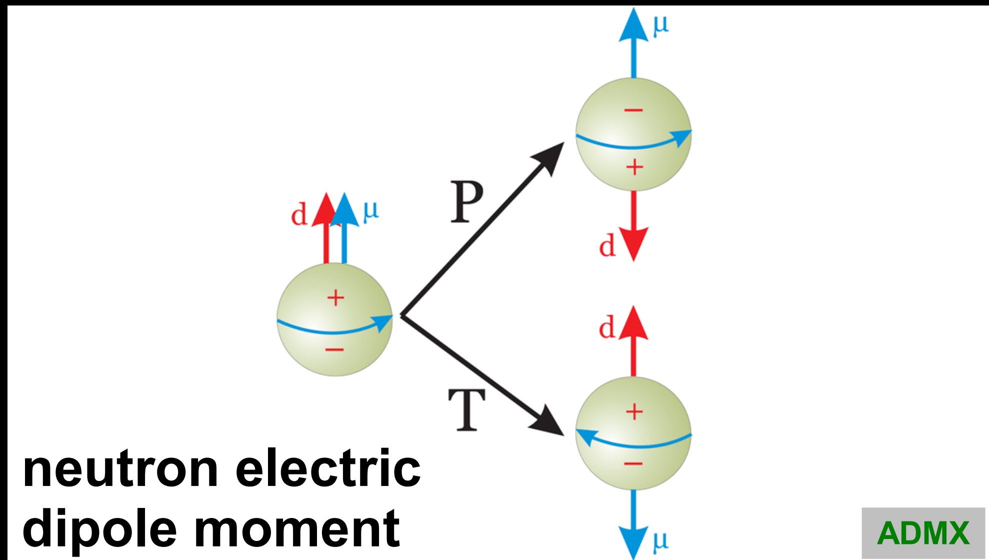
No effect, since surface term with QED fields → 0 at ∞ $$-\frac{1}{4}\mathcal{F}_{\mu\nu}\tilde{\mathcal{F}}^{\mu\nu} = \left(\vec{E}\cdot\vec{B}\right)$$ $\not{P}$, $\not{T}$

The case of QCD

Dual tensor: $$\tilde{\mathcal{F}}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\mathcal{F}_{\rho\sigma}$$

If all $m_q > 0$, possible term of

$$\theta\frac{g_s^2}{32\pi^2}\mathcal{G}^A_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}_A$$ →



should have effect, because of degenerate nonperturbative QCD vacuum with phase 0 ≤ θ ≤ 2π.

Neutron EDM

Including weak CP violating effects → $\bar{\theta}\frac{g_s^2}{32\pi^2}\mathcal{G}^A_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}_A$

where $0 \leq \bar{\theta} \leq 2\pi$

NMR measurement with spin-polarised, trapped (t ≈ 150s), ultracold neutrons (v < 7 m/s → total reflection)
B ≈ 1 μT, E ≈ 10 kV/cm

$$h\nu_{\uparrow\uparrow} = |2\mu_n B + 2d_n E|$$

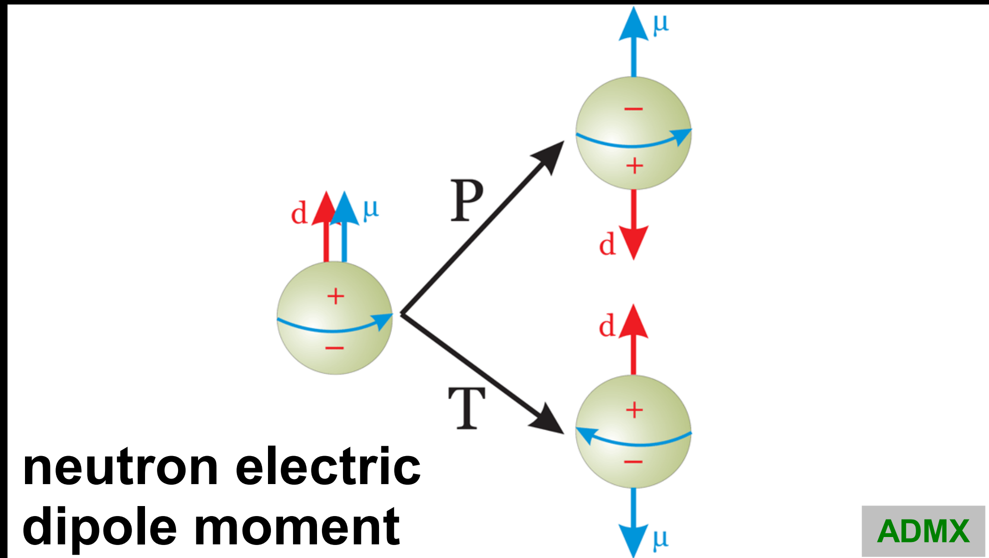
$$h\nu_{\uparrow\downarrow} = |2\mu_n B - 2d_n E|$$

Measure change in spin precession frequency between E parallel and anti-par.

$$-\delta\nu = 4d_n E/h$$

$$d_n < 2.9 \cdot 10^{-26} e\text{cm}$$

Best limit → $\bar{\theta} < 10^{-10}$ **!!**



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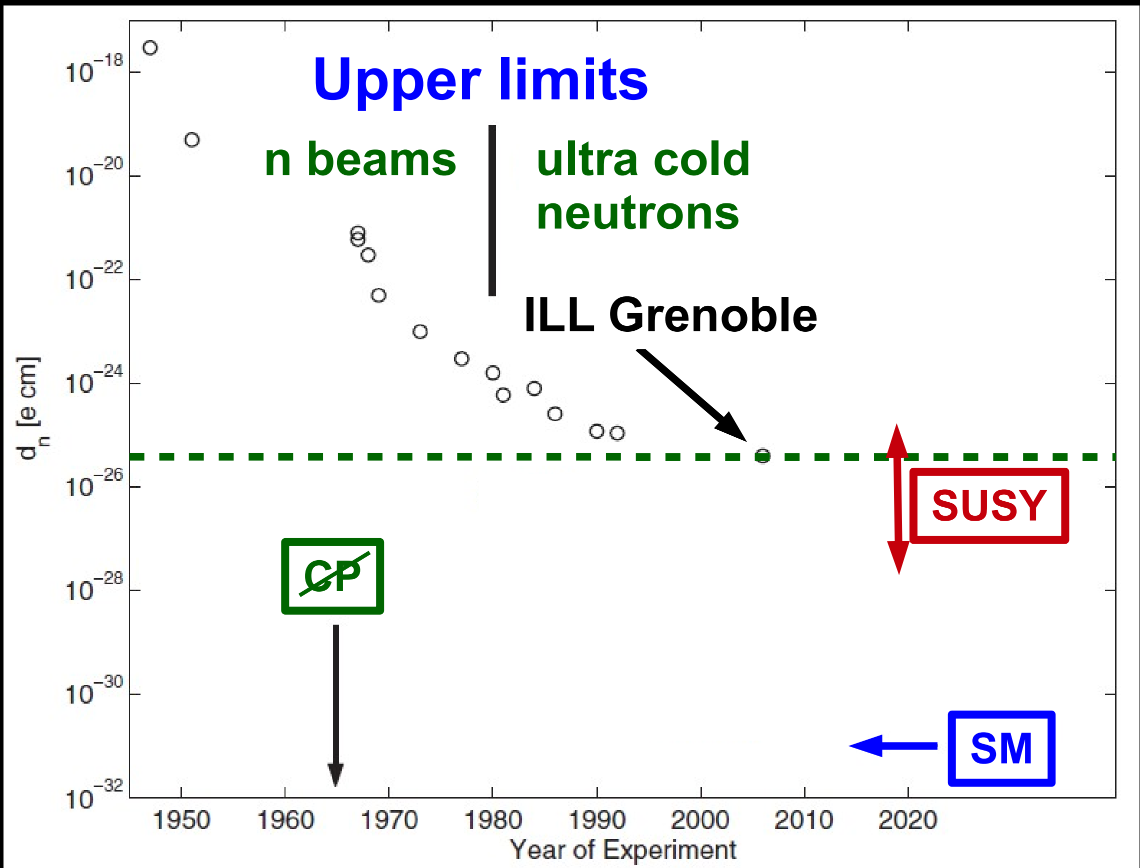

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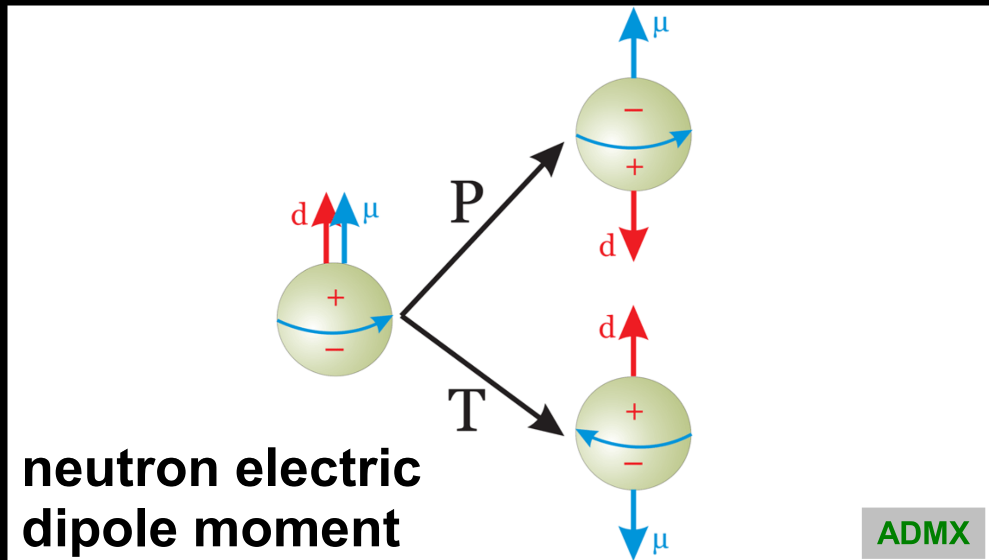

J. Phys. G, 2009, 36, 104002

Pool Table Analogy

QCD conserves CP invariance

Gravity

Perfectly symmetric

P. Sikivie, Physics Today, 12/1996;
arXiv:hep-ph/9506229

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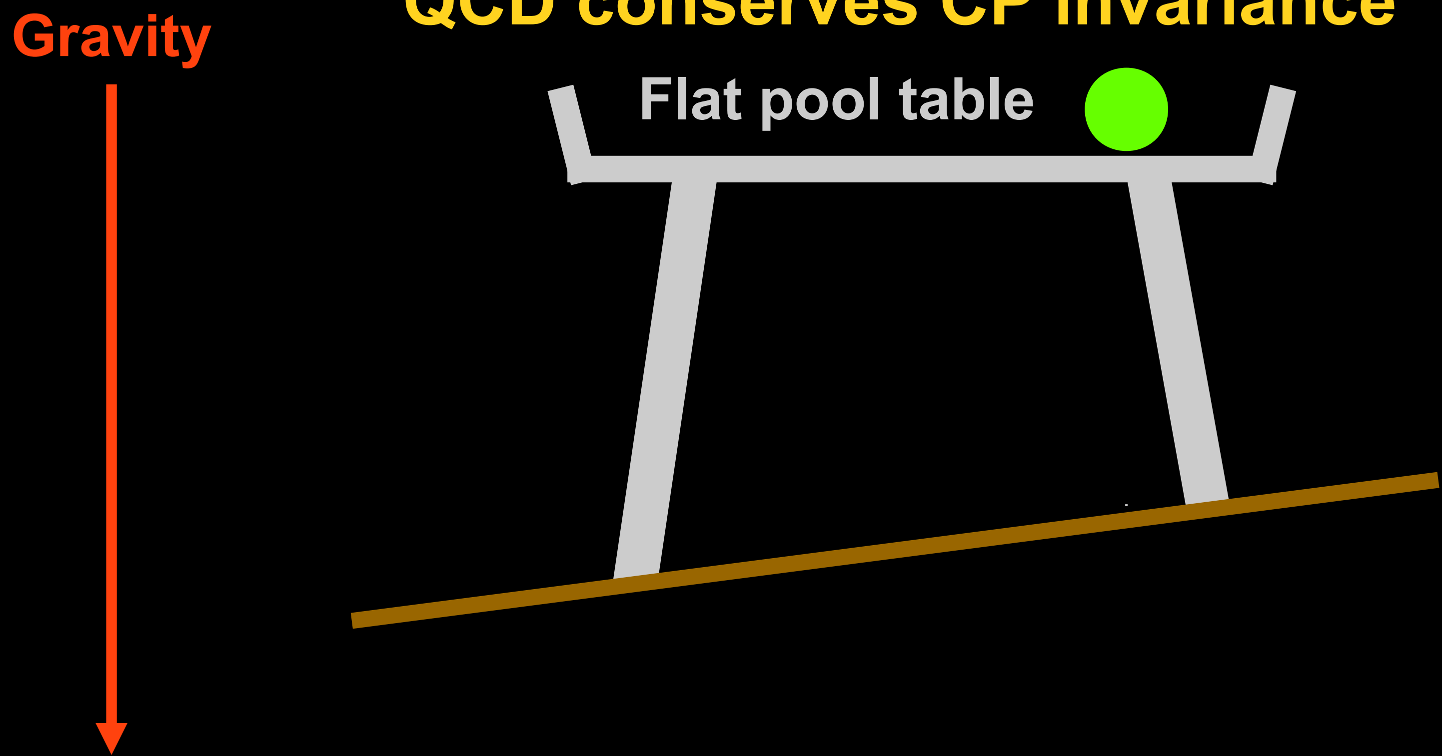
QCD conserves CP invariance



Perfectly symmetric relative to gravity

But why ...?

Floor inclined → broken symmetry

By accident?
Everywhere?
→ perfect tuning ...

P. Sikivie, Physics Today, 12/1996;
arXiv:hep-ph/9506229

Pool Table Analogy

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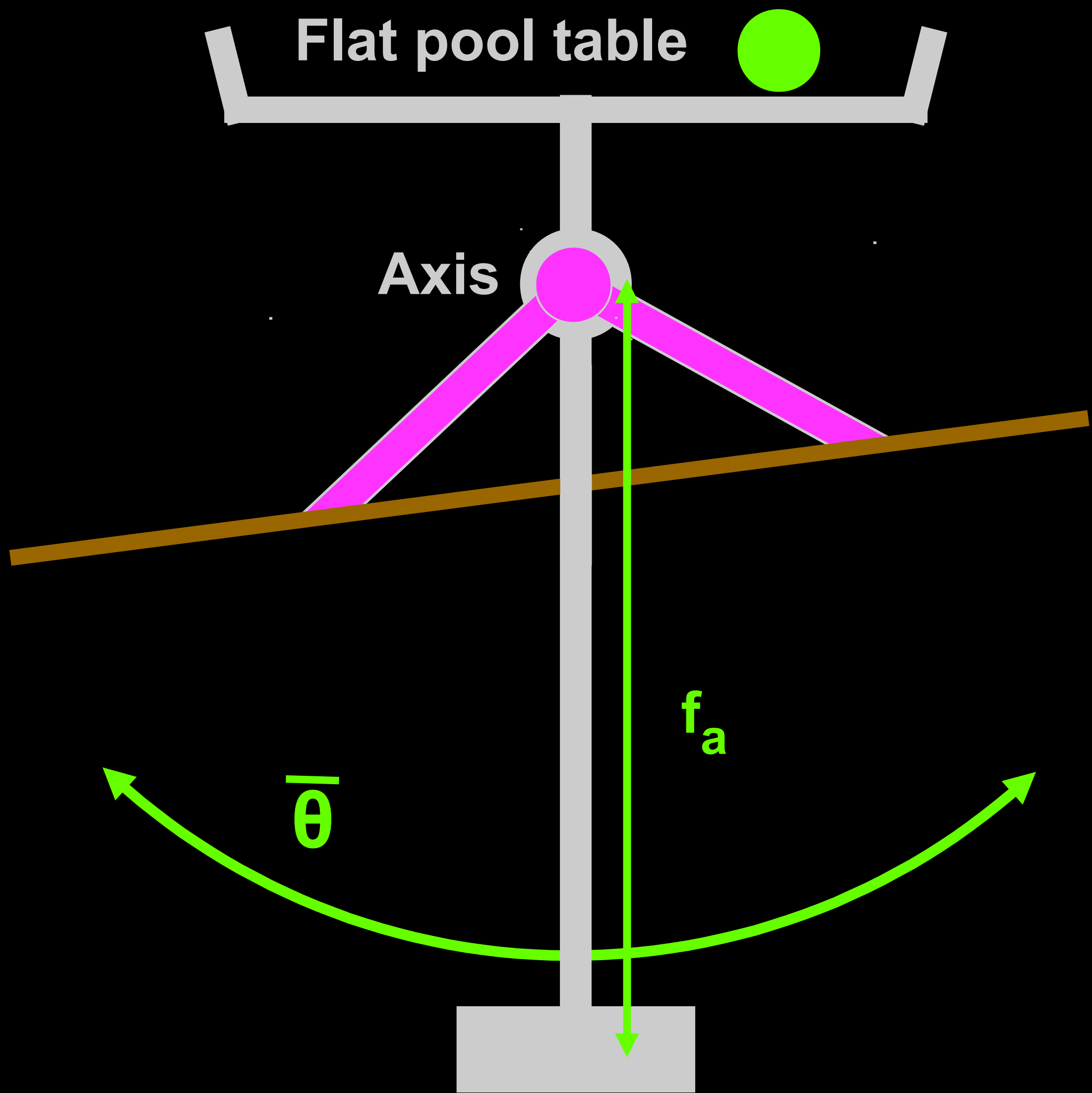
Gravity



Perfectly symmetric relative to gravity

Floor inclined → broken symmetry

Symmetry restored dynamically … at the cost of potential oscillations

New degree of freedom → Axion

P. Sikivie, Physics Today, 12/1996; arXiv:hep-ph/9506229

Peccei-Quinn Mechanism (1977)

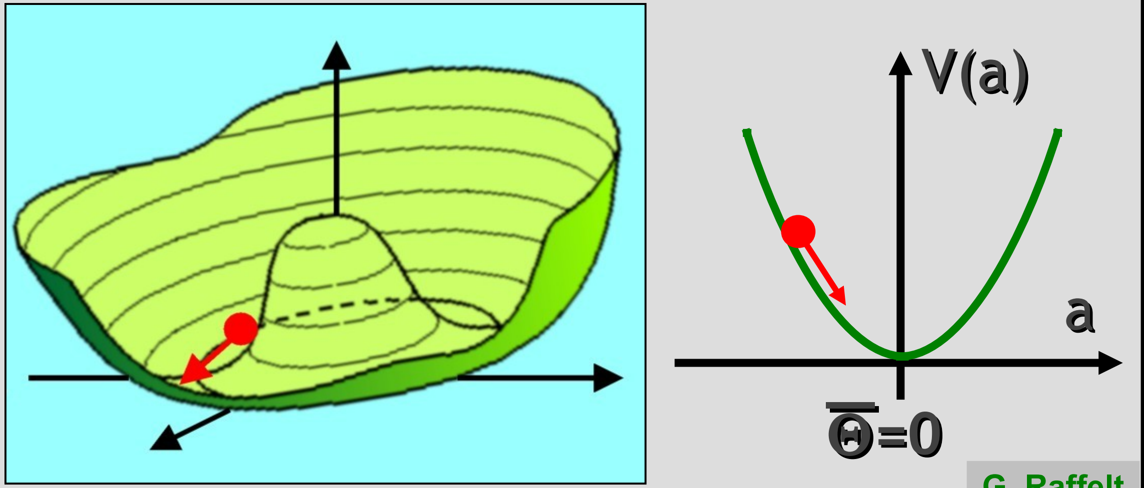
Repeat successful recipes →
Similar to Brout-Englert-Higgs mechanism!

Postulate global $U(1)_{PQ}$ chiral symmetry, spontaneously broken at scale f_a

- **Dynamically generated CP violating term restores QCD CP invariance**
- **Axions as resulting pseudoscalar bosons (Wilczek, Weinberg, 1978)**

$E \approx \Lambda_{QCD} \approx f_\pi \ll f_a$

- $U_{PQ}(1)$ explicitly broken by QCD vacuum effects
- Mexican hat tilts
- Axions acquire a mass



G. Raffelt

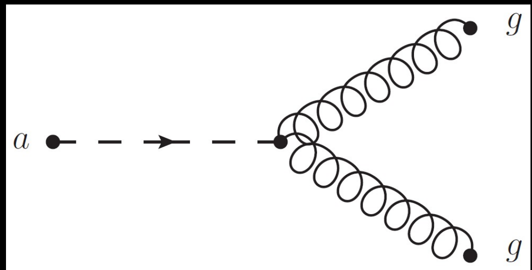
Mexican-hat potential → minimum at θ = 0

Axion Properties

Reinterpretation $\bar{\theta} \rightarrow \frac{a(x)}{f_a}$ → **pseudo-scalar axion field** → **PQ scale, axion decay constant**

Original PQWW axion suggestion quickly excluded by experiment ... $f_a \sim (\sqrt{2}G_F)^{-1/2} \approx 247\,\mathrm{GeV}$

Axions effectively couple to gluons



→ **axions mix with π^0**
→ **properties scale**

$$m_a f_a \sim m_\pi f_\pi$$
$$\approx 140\,\mathrm{MeV} \cdot 100\,\mathrm{MeV}$$

Peccei, Quinn, PRL 1977, 38, 1440; PRD 1977, 16, 1791; Wilczek, PRL 1978, 40, 279; Weinberg, PRL 1978, 40, 223.

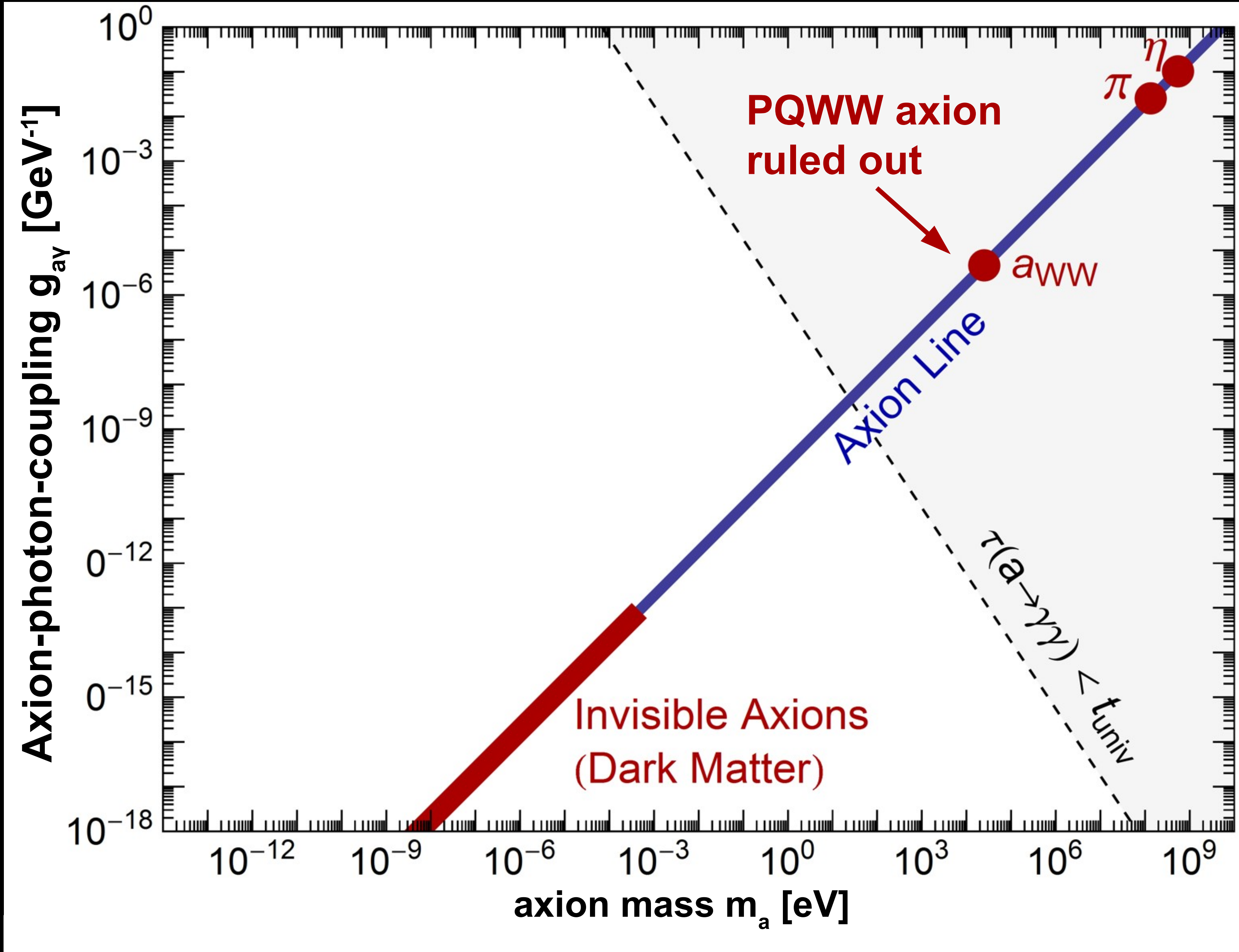
Axion Parameter Space

How can we find/ exclude axions In this plane?

Two parameters:
axion mass m_a

axion-γ-coupling
$g_{a\gamma} \sim 1/f_a$

$m_a f_a \sim m_\pi f_\pi$



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Two alternatives not in contradiction with experiment:
KSVZ (Kim-Shifman-Vainshtein-Zakharov)
DFSZ (Dine-Fischler-Srednicki-Zhitnitskii)

KSVZ Axion, PRL 1979, 43,103; NPB 1980, 166, 493.
DFSZ Axion, SJNP 1980, 31, 260; PLB 1981, 104, 199.

$$m_a \lesssim 10\,\mathrm{meV}$$

A. Vainshtein
Julius-Wess-Award 2014

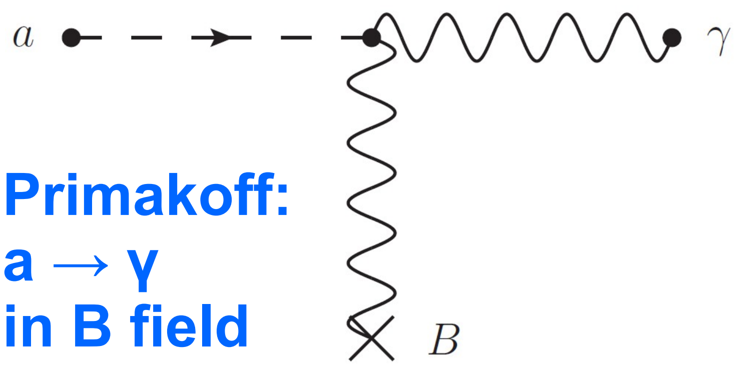
→ Low Energy Physics!
ALPs: axion-like particles:
WEAKLY INTERACTING AND LIGHT!

Cosmic Axions – Haloscopes

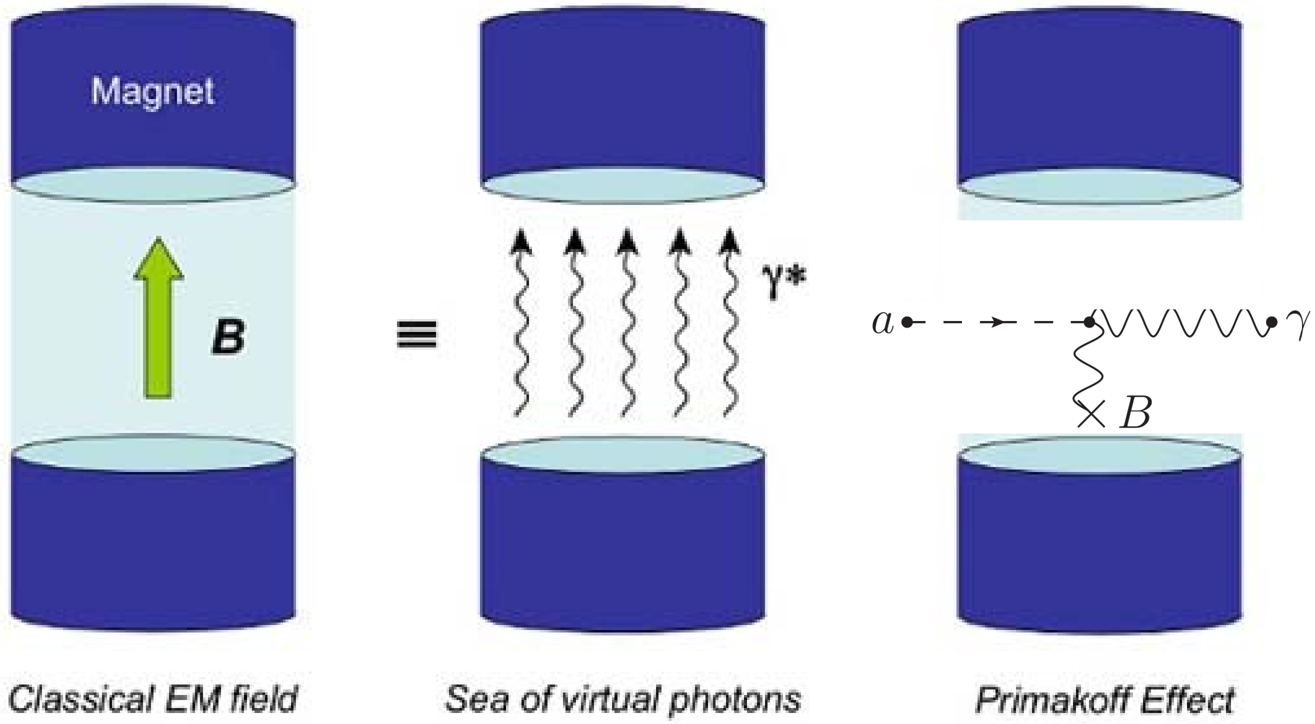
Cosmic mass window

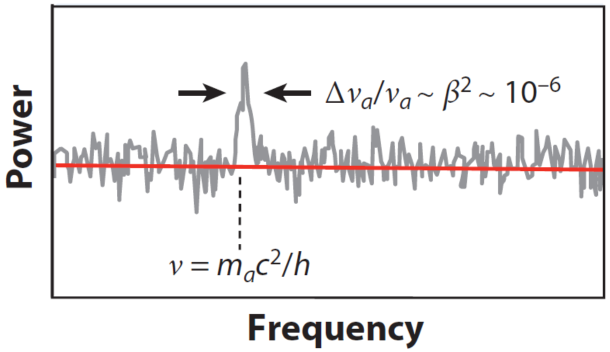
$m_a \approx 1$ μeV - 10meV
$v_a \approx 300$ km/s
$\rightarrow E_a \approx (1\pm 10^{-6})\ m_a$
$P_{sig} \approx 10^{-22}$ W

Microwave resonators (Sikivie 1983) of very high quality Q ~ 10^5



Primakoff:
a → γ
in B field





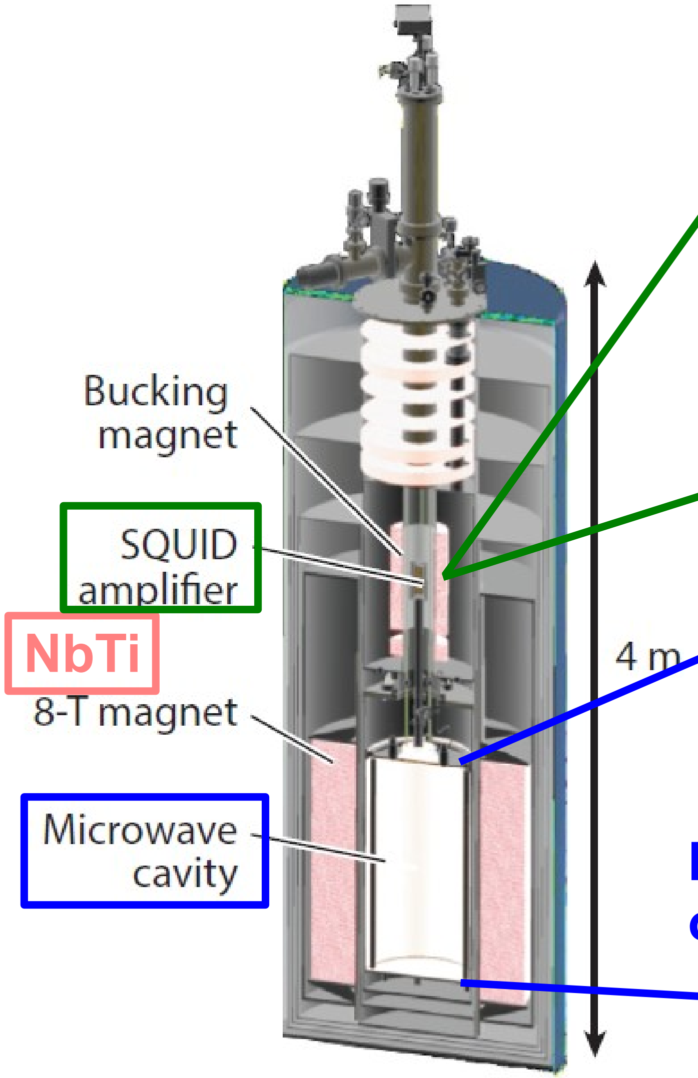
← FFT

Tune cavity to resonant frequency $\omega \sim m_a$ (bandpass)

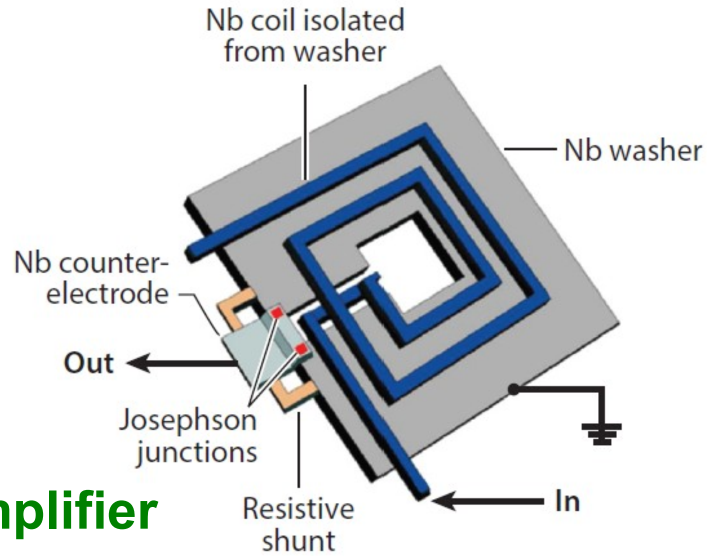
Adapted from ADMX
Graham et al., ARNPS 2015, 65, 485.

A Dark Matter eXperiment (ADMX)

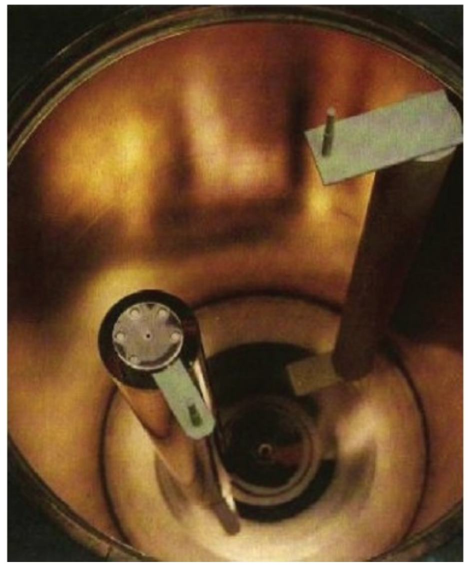
ADMX microwave resonator
(1 GHz ~ 4 μeV)



low-noise SQUID amplifier



high-purity Co on steel resonator



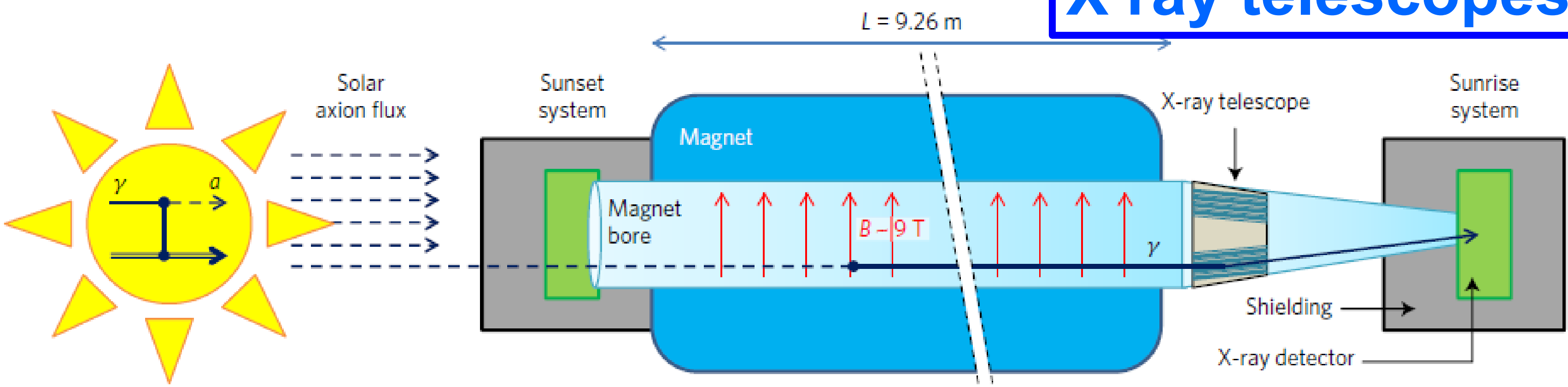
Update, R&D:
- **cooling 25mK**
- **SC film coated cavities**
- **squeezed vac. states as in GEO/LIGO**

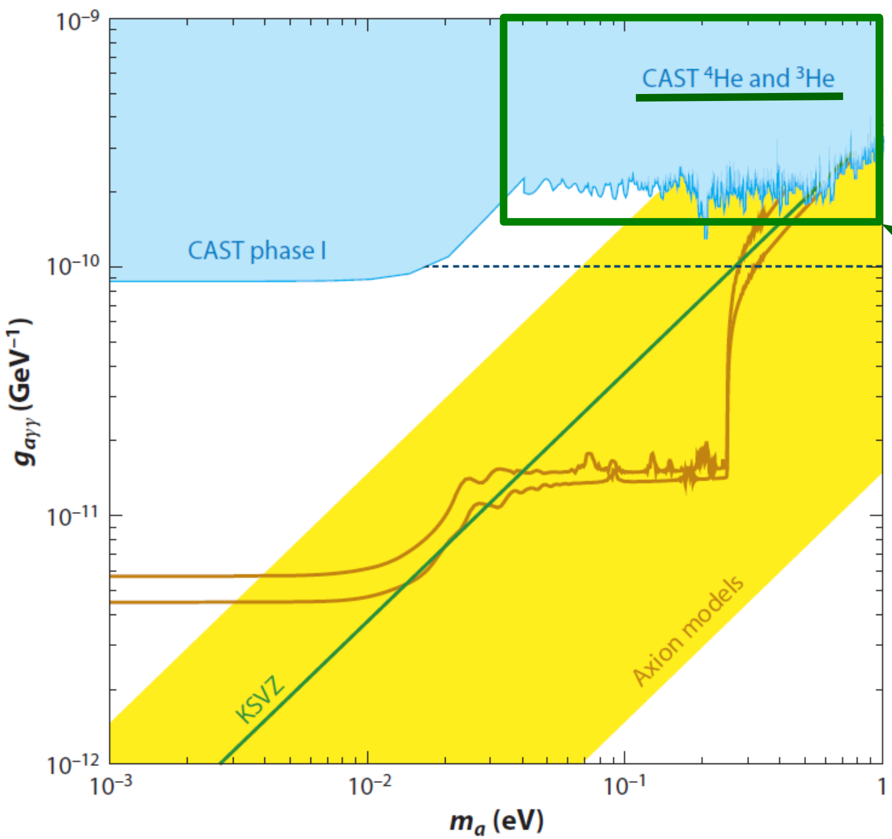
ADMX; Graham et al., ARNPS 2015, 65, 485.

Solar Axions – Helioscopes

E_a, keV's

X ray telescopes





Transition depends on coherence length

$$P_{a\to\gamma} = \left(g_{a\gamma} B \frac{\sin(qL/2)}{q}\right)^2$$

$$q = m_a^2/2E$$

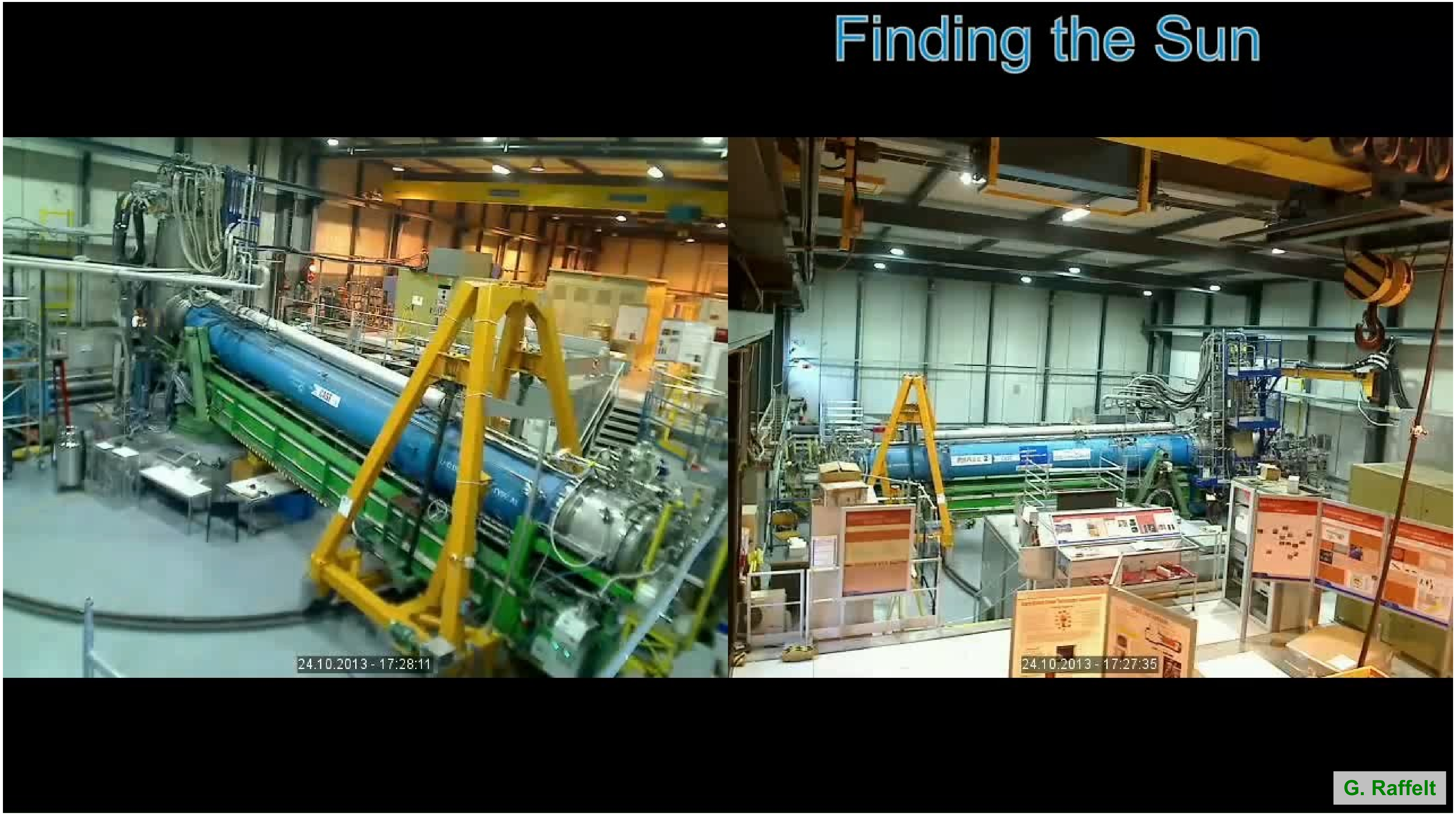
In vacuum: $m_a \lesssim 0.02\,\mathrm{eV}$

Filling vacuum with ^{4}He and ^{3}He to extend to higher masses
→ reaches yellow QCD axion band!

Here: CERN Axion Solar Telescope (CAST)
Uses LHC magnet prototype!

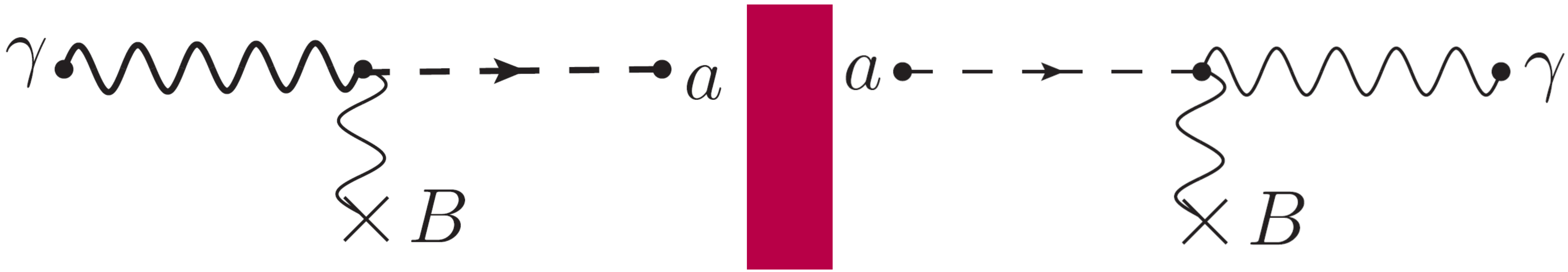
CAST, Nat. Phys. 2017.
Graham et al., ARNPS 2015, 65, 485.

Solar Tracking with CAST



Lab Axions – LSW

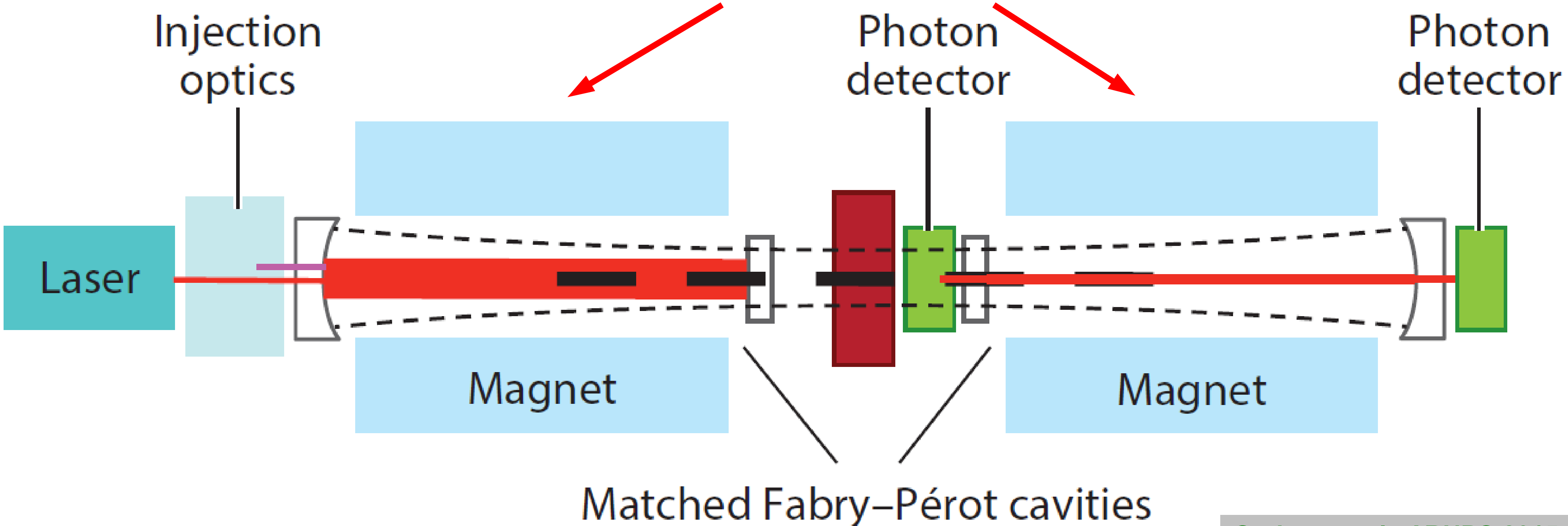
Light shines through walls (LSW)



Injection side

Aligned?
Same tune?

Detection side



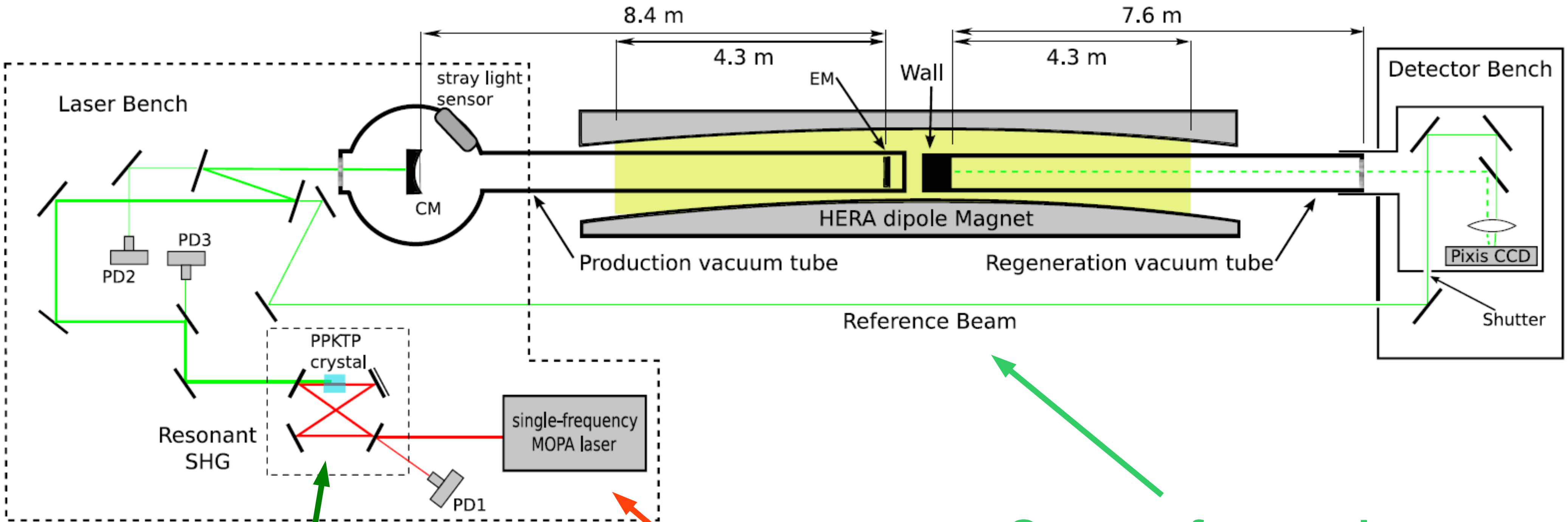
Graham et al., ARNPS 2015, 65, 485.

Any Light Particle Search

$m_a \approx 10^{-8} - 10^{-3}$ eV

Example: ALPS at DESY

Uses HERA dipoles



Nonlinear optical crystal
→ frequency doubling

Infrared laser
λ = 1064 nm

Green reference beam
λ = 532 nm

ALPS-II

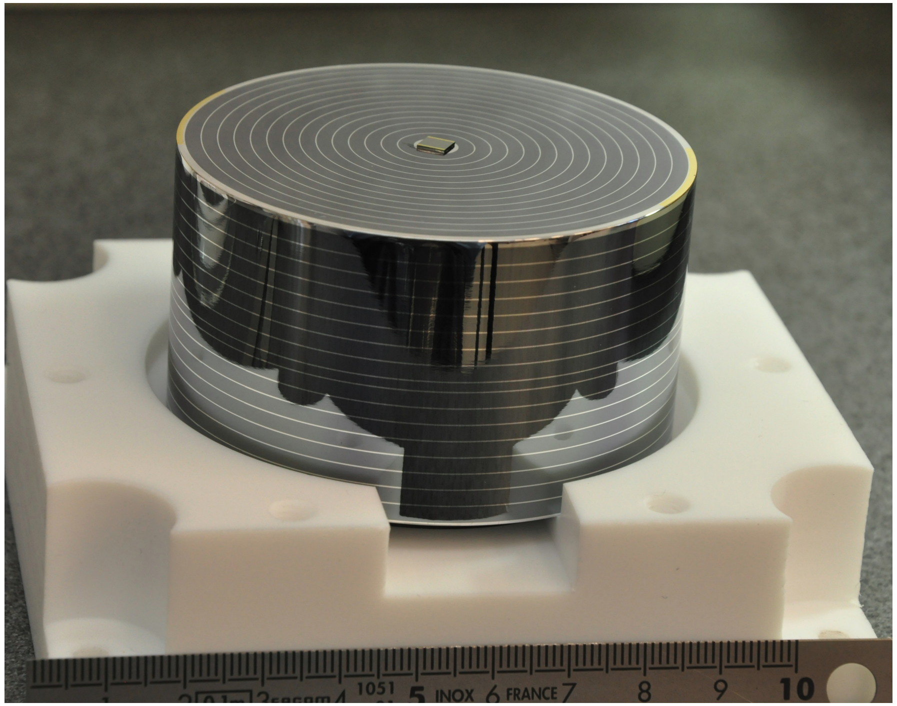
Edelweiss

$m_a \approx 10^0 - 10^3$ eV

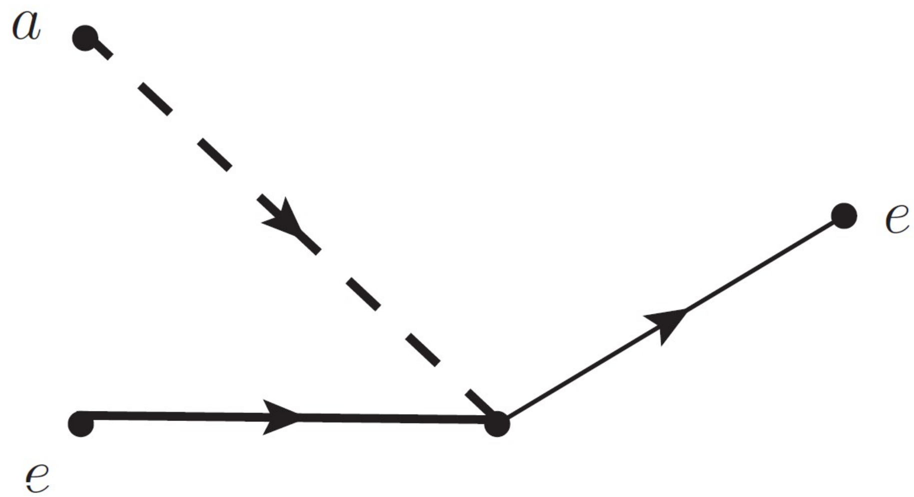
Designed for WIMPs to detect N recoils (Weakly Interacting Massive Particles)

Situated in underground lab of Modane

Uses Germanium monocrystals in radiation-poor environment at 18 mK



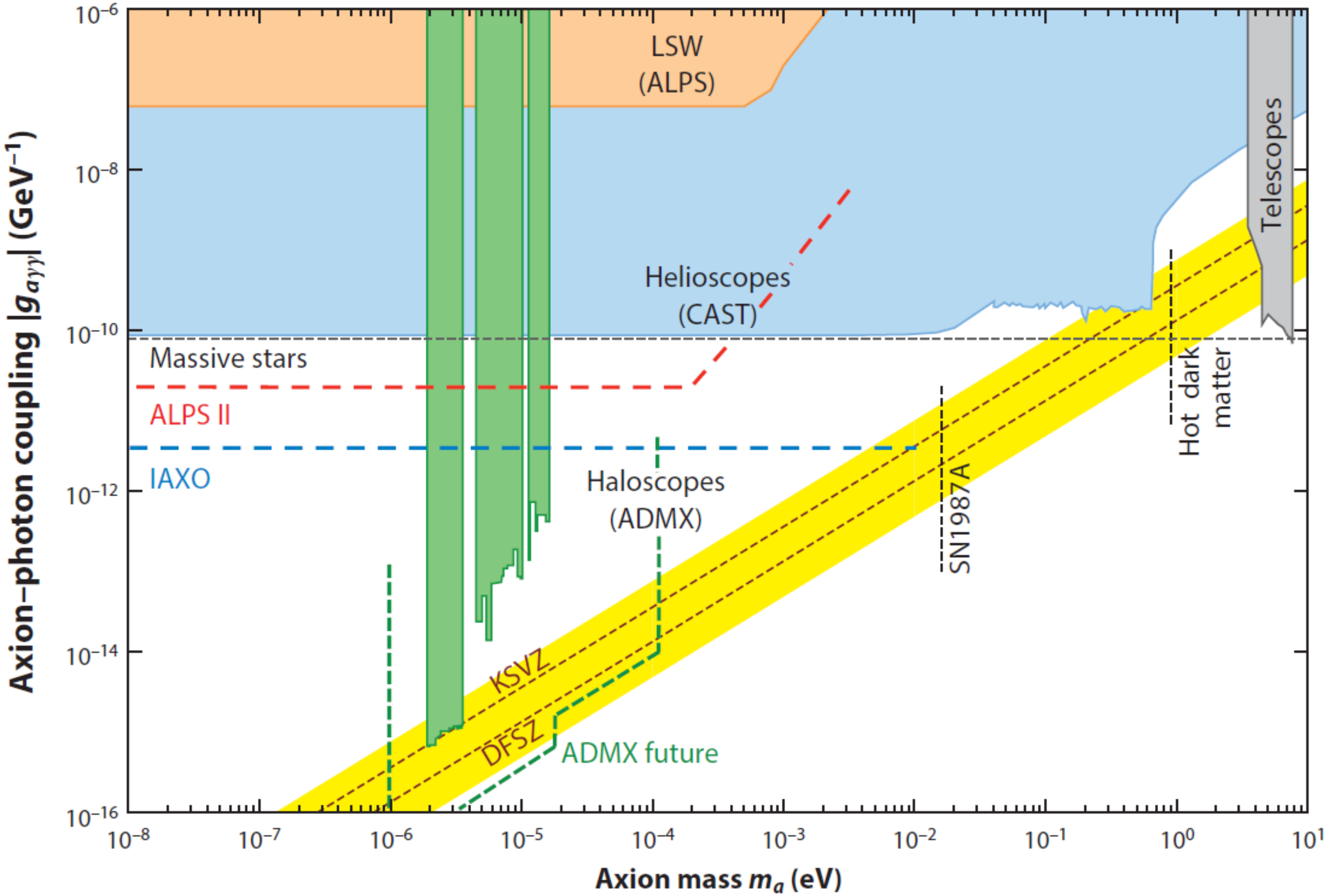
Can detect Primakoff and axioelectric effect



Measure electron recoils
→ searched also for DM and solar axions.

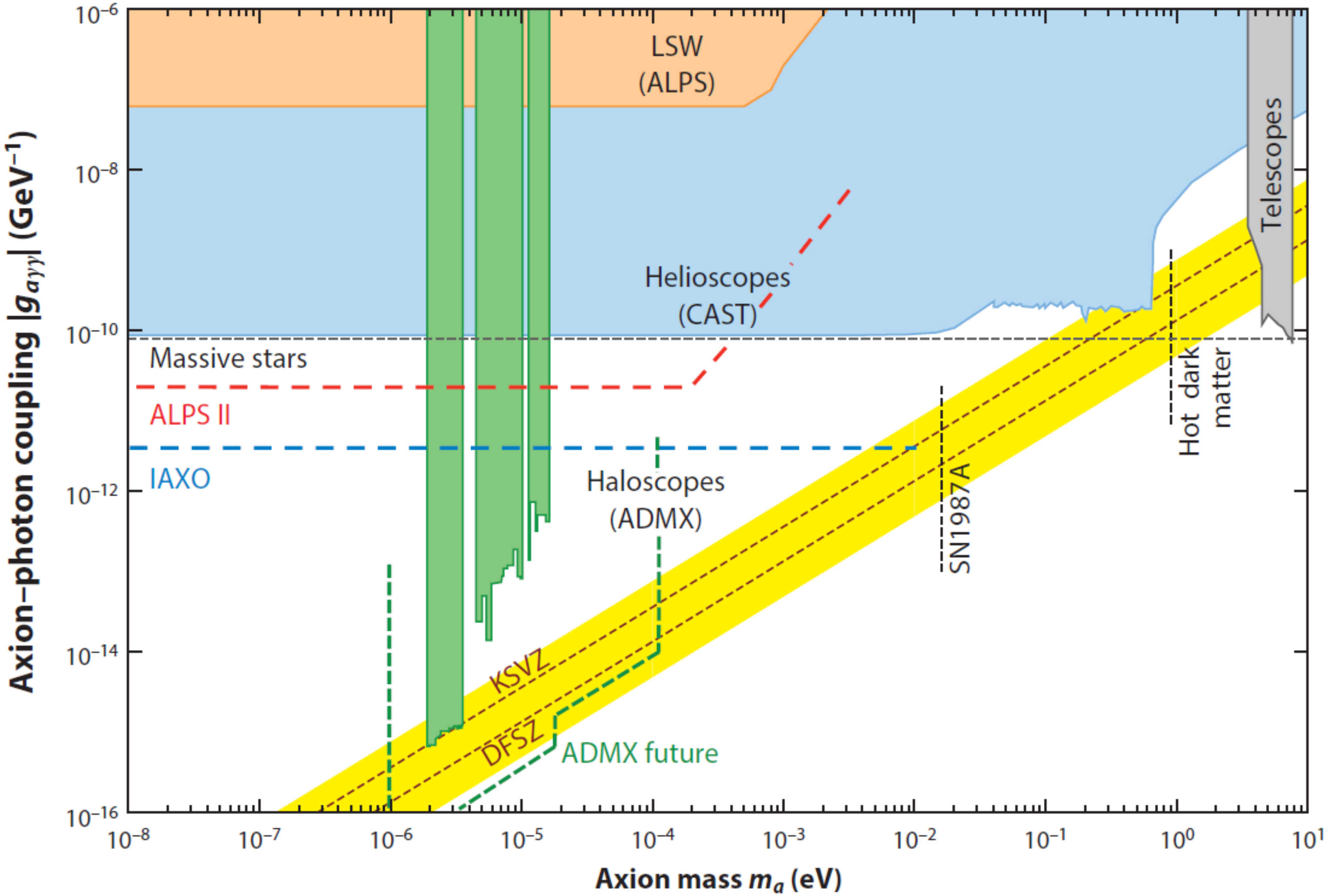
Edelweiss, JCAP 2013, 1311, 067.

Outlook



- **Axions are promising objects to study fundamental physics questions**
- **Innovative technologies are required for their hunt**

Outlook



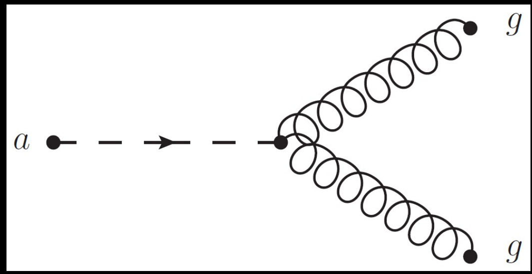
Vielen Dank für Ihre Aufmerksamkeit

Backup

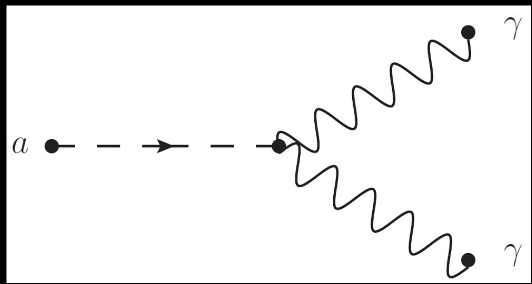
For the latest News

Axion Interaction

Gluon coupling (effective)

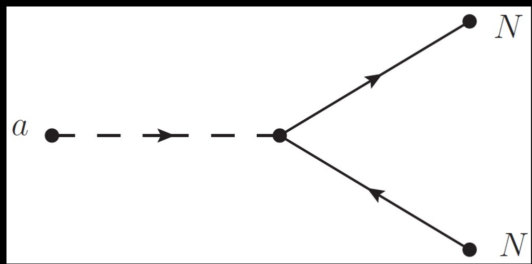


Photon coupling (effective)

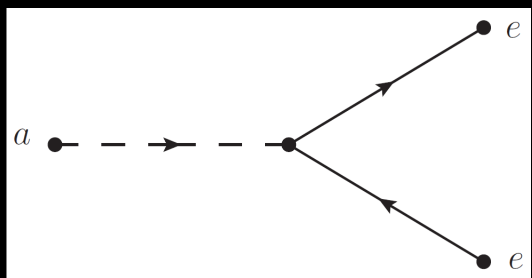


Detection of axion-photon conversion:
Primakoff-effect
→ Let's bring light to dark matters

Nucleon coupling (axial vector)



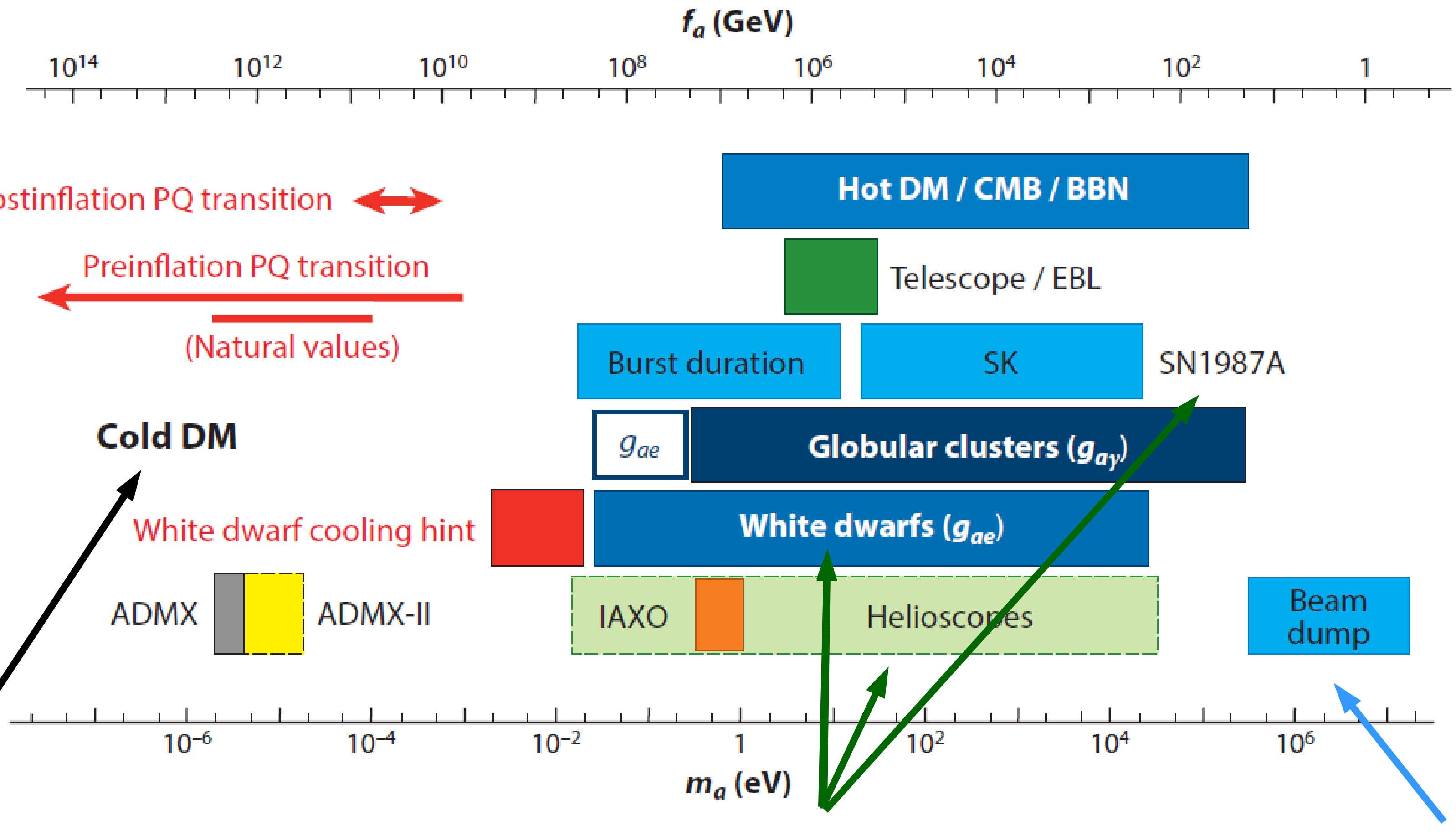
Electron coupling (optional)



Detection of axion-electron scattering:
Axio-electric effect

Axion Limits

Astrophysical limits on axion mass and decay constant



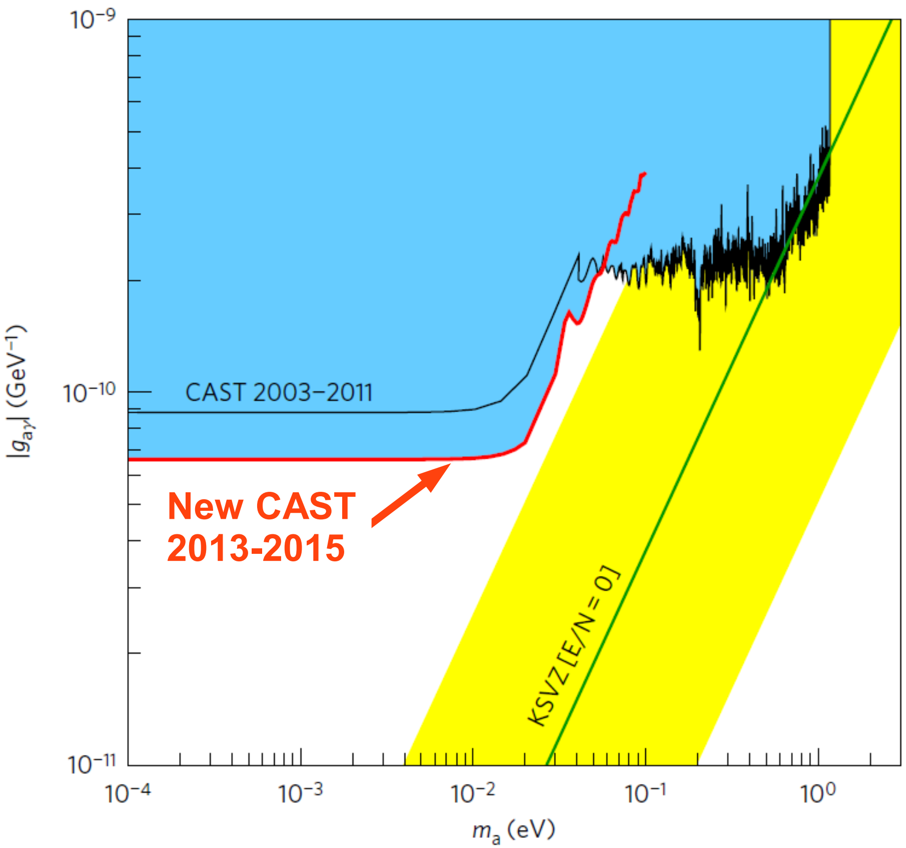
Cosmic/relic axions **Solar/stellar axions** **Beams, laser**

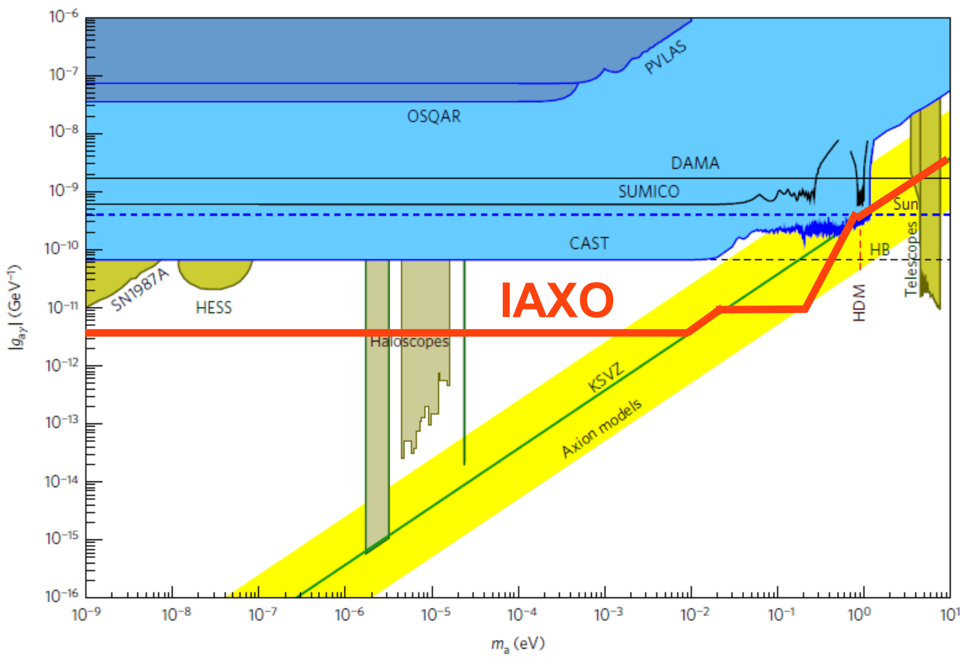
Graham et al., ARNPS 2015, 65, 485.

CAST & IAXO Reach

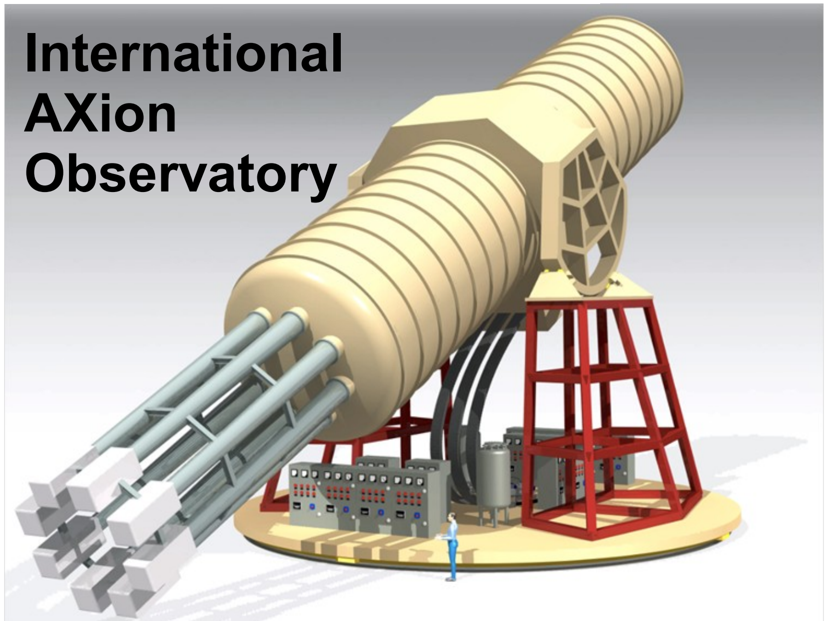
Latest solar axion results from CAST 2013-2015

In vacuum but with improved Xray telescope & low noise MicroMega detectors
→ prototypes for IAXO



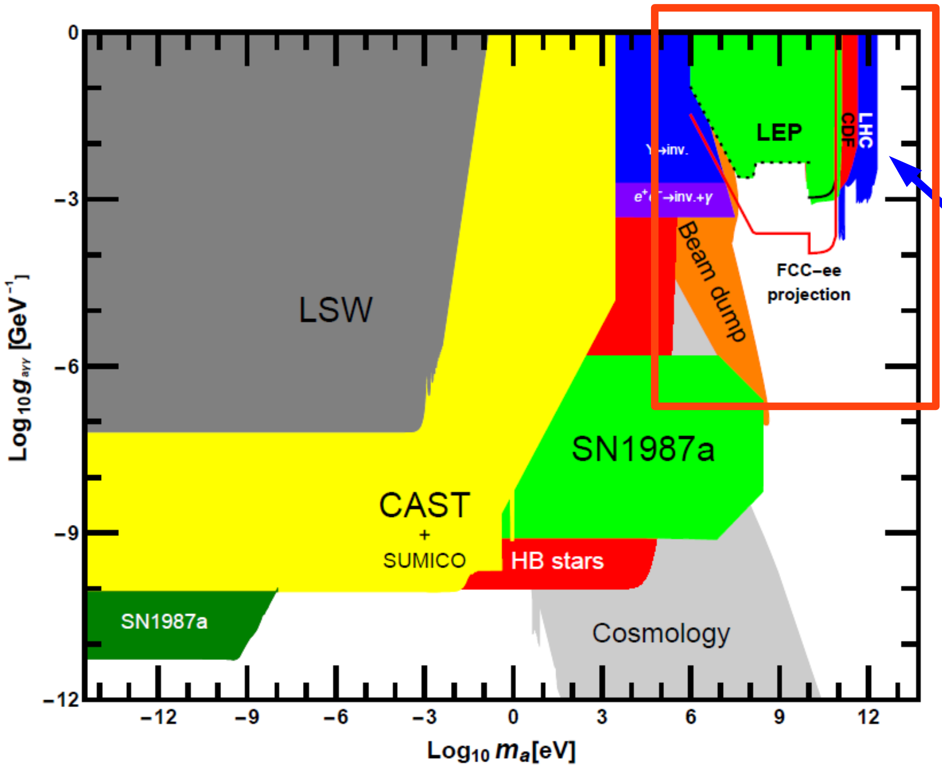


Reach of IAXO project



CAST, Nat. Phys. 2017.
IAXO letter of intent

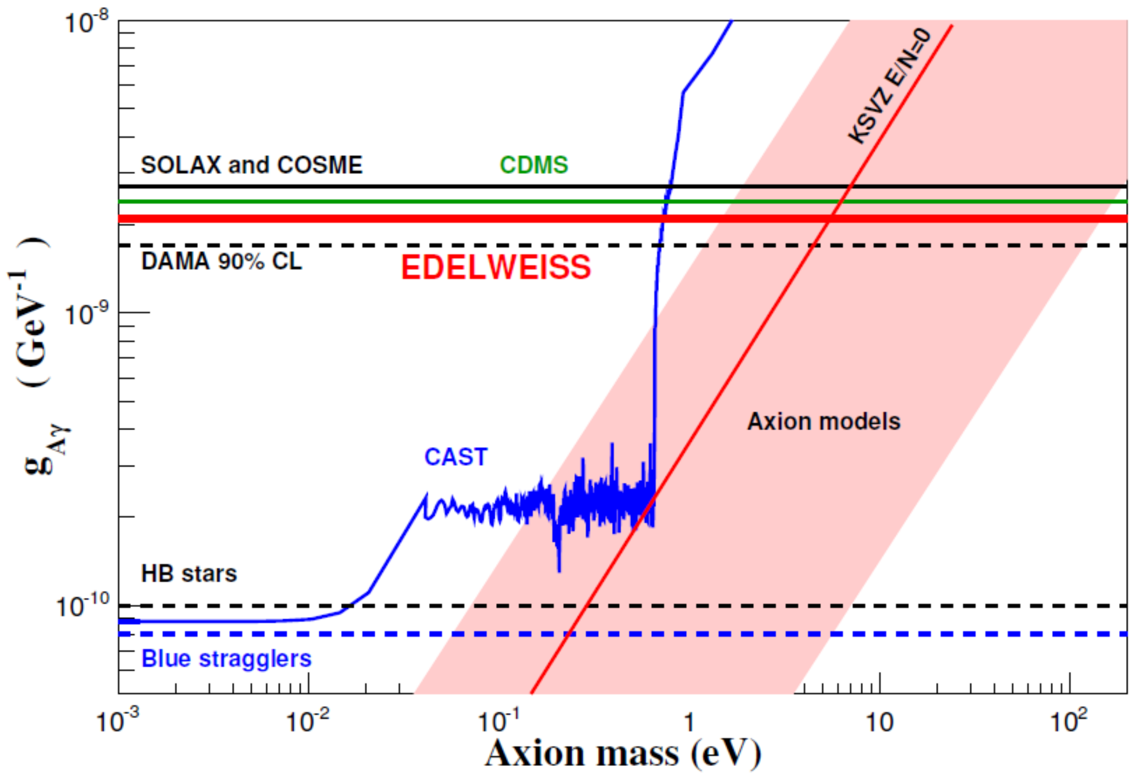
Even more Axion Limits



First searches for appearance behind beam dumps:
PS & SPS at CERN, SIN &PSI in Switzerland, ...

LHC

→ at the high end of the axion mass scale



Edelweiss axion limits