Axions

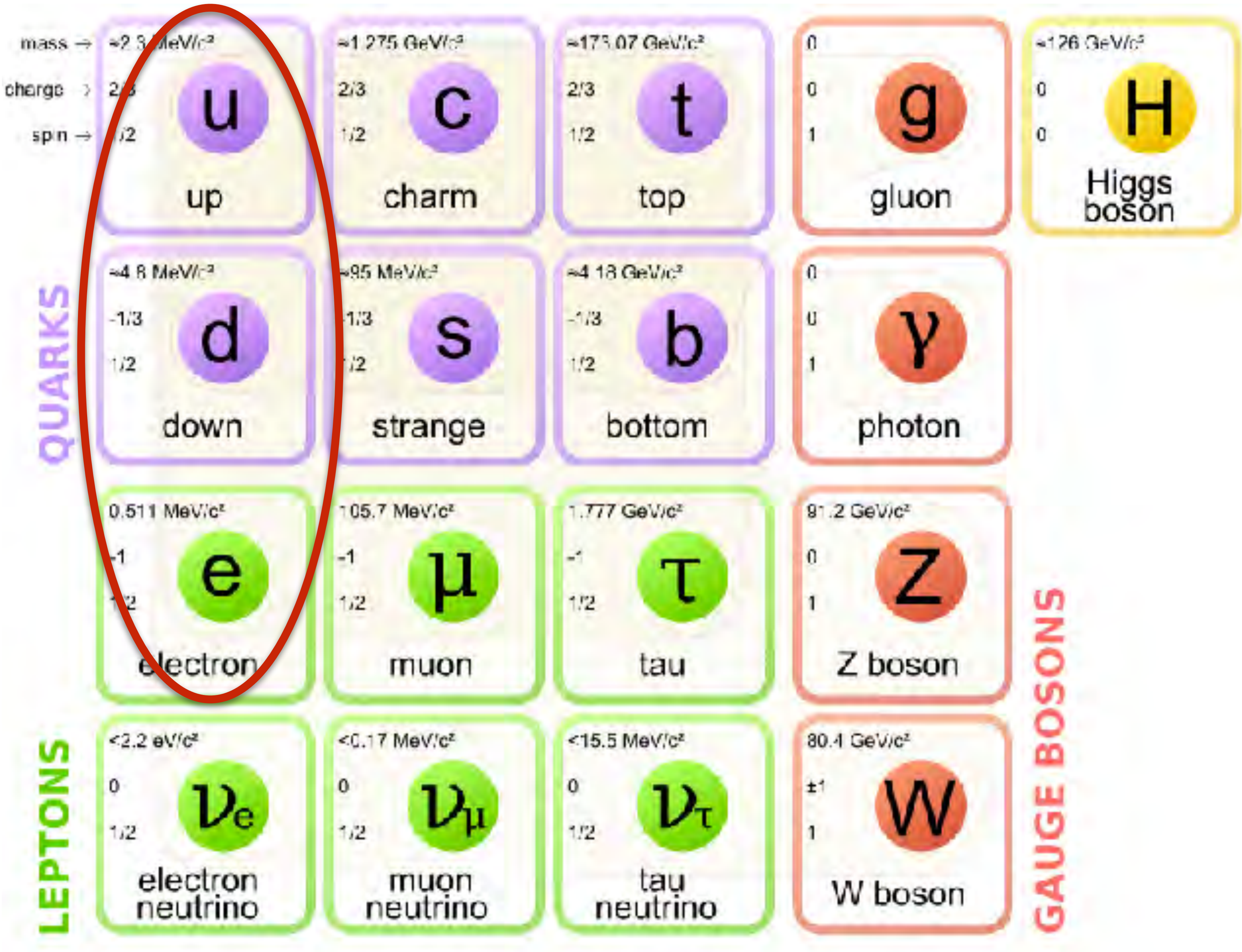
Alexander Schmidt

axions?

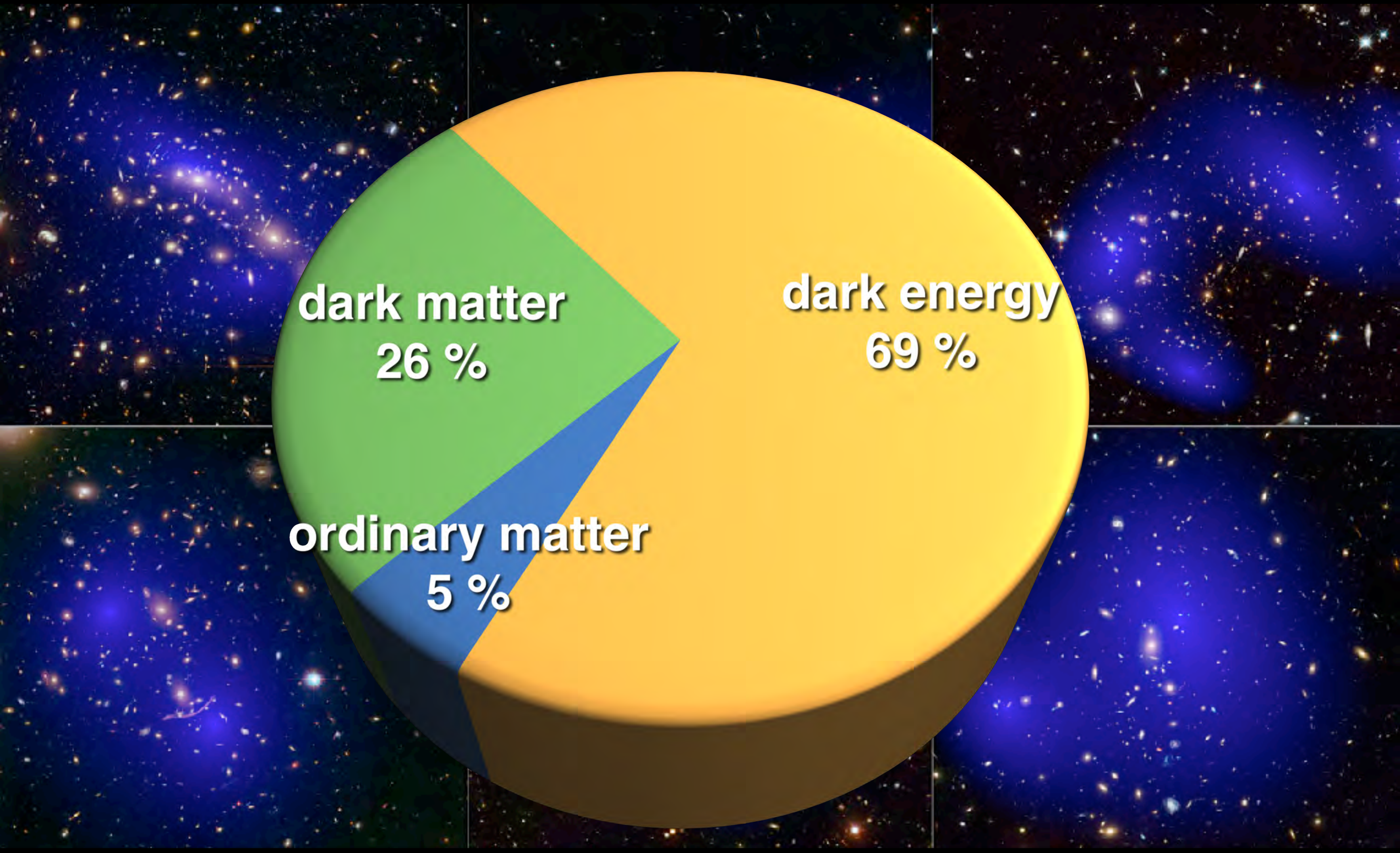
AXION
energy

the big picture

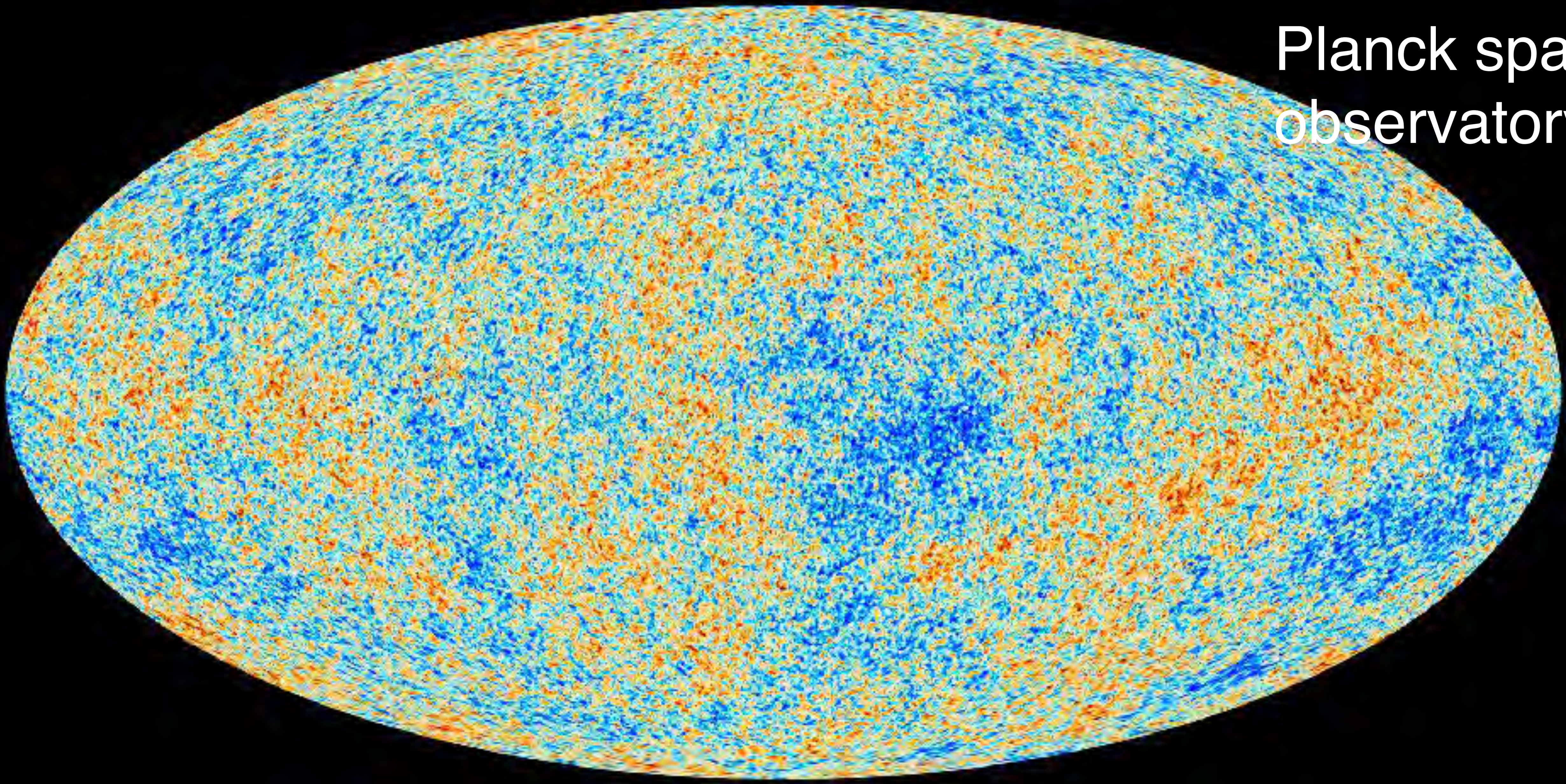
- confirmed again and again by all experiments:



- makes incredibly precise predictions about:
  - properties of particles
  - interactions between particles
  - ➡ production cross sections
  - ➡ decay rates of particles


dark matter
26 %
dark energy
69 %
ordinary matter
5 %

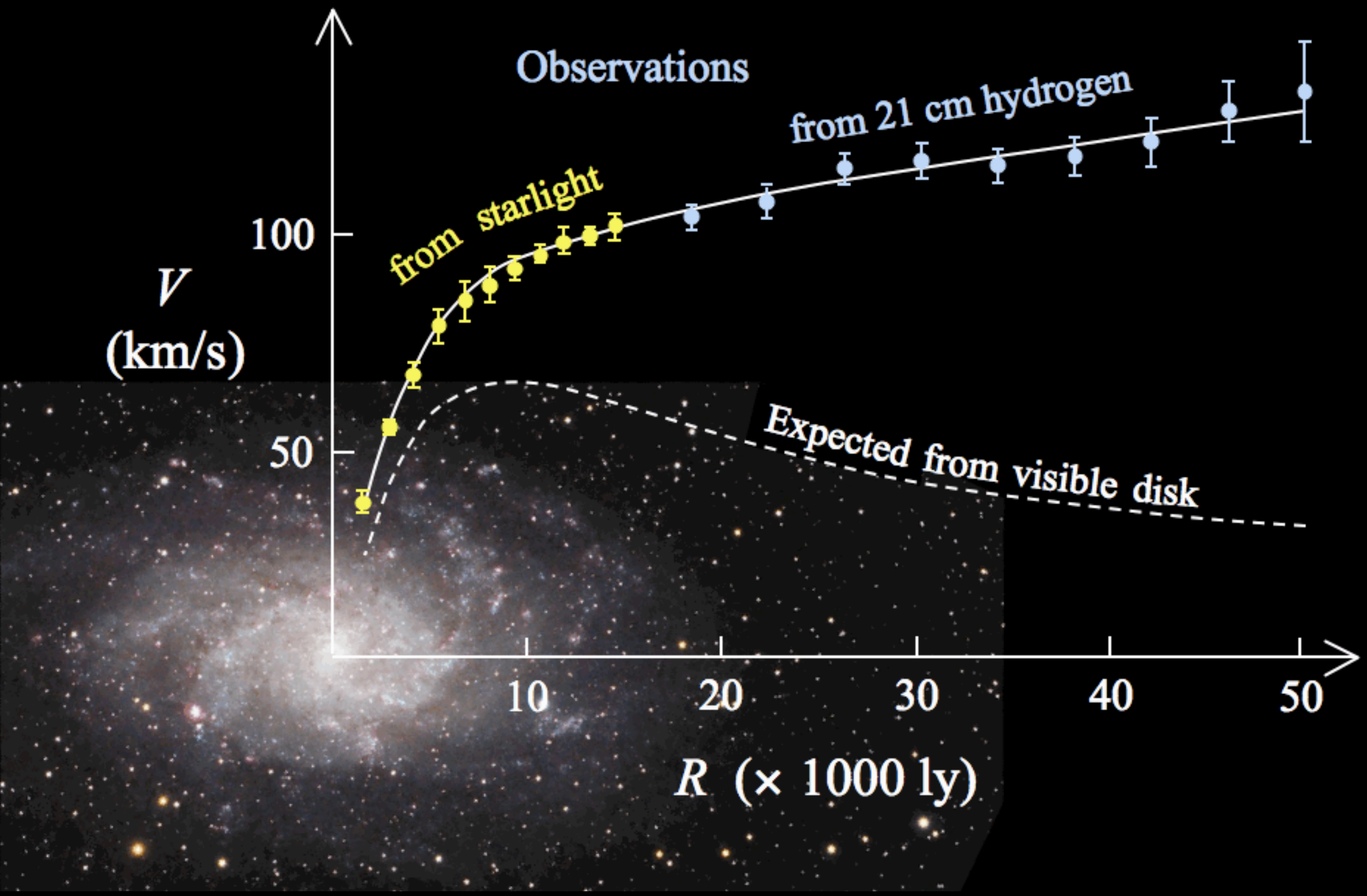
cosmic microwave background



anisotropy distribution constrains cosmological models:

- expansion of the universe
- dark matter
- structure formation

indications for dark matter



dark matter candidates

WIMPs

- weakly interacting **massive** particles
- predicted by supersymmetry
- very large experimental efforts

subjective plausibility: 50%

Axions

- ultra-**light** particles
- predicted by Peccei-Quinn theory
- large experimental efforts

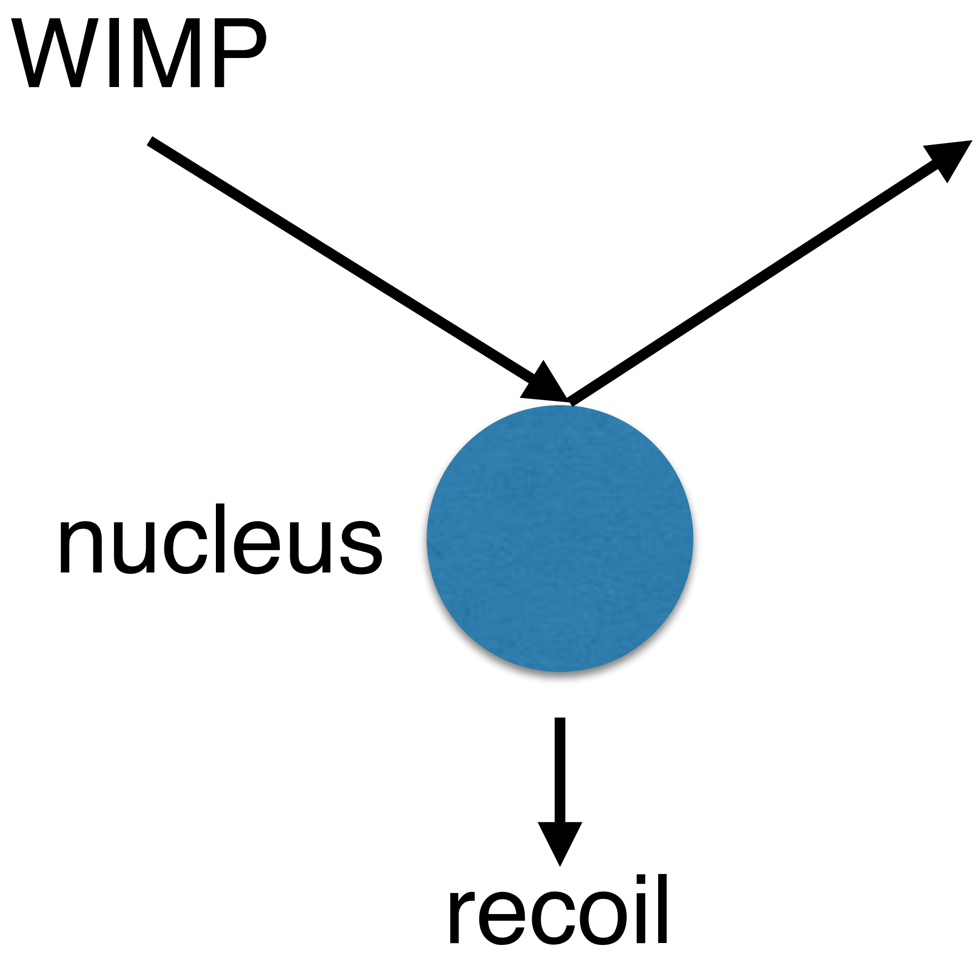
subjective plausibility: 45%

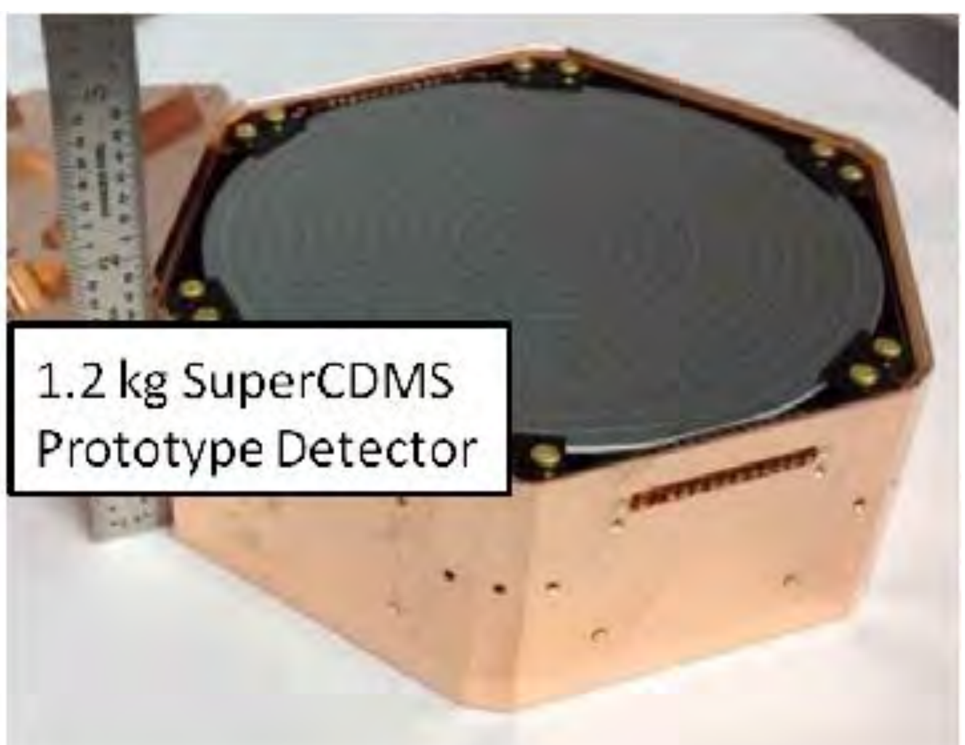
other:

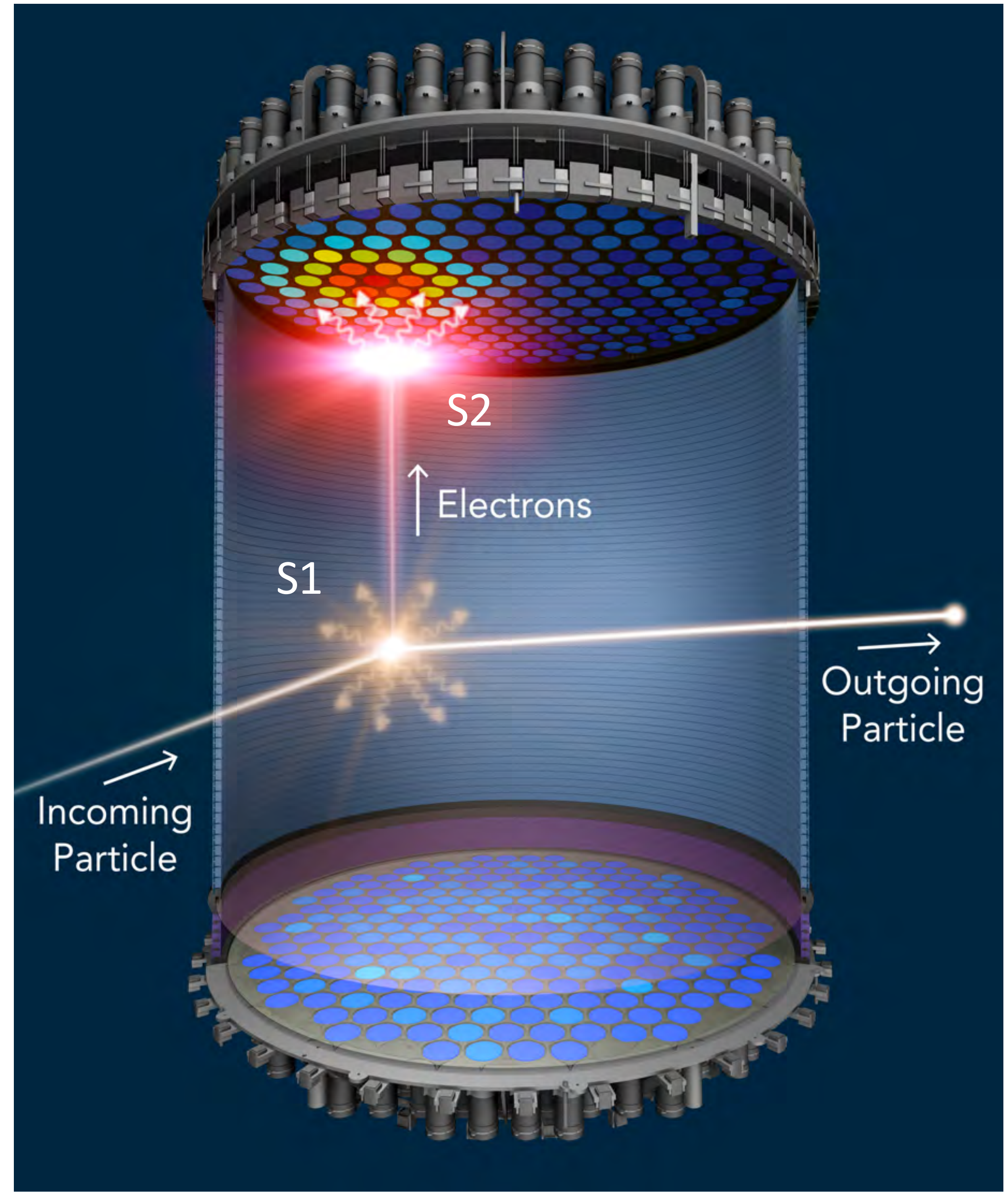
- modified Newtonian dynamics (MOND)
- massive compact halo objects (MACHO)

subjective plausibility: 5%

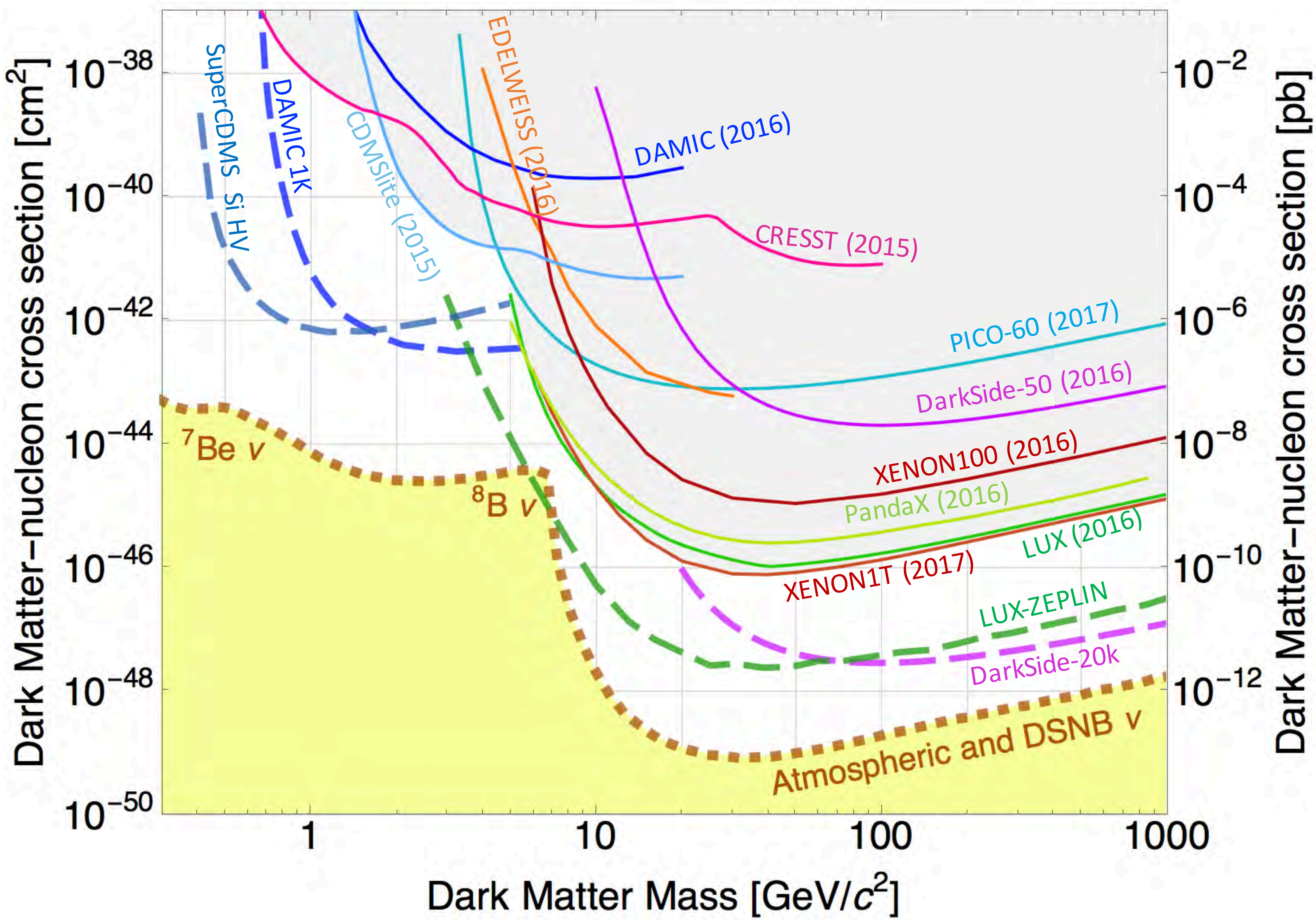
direct search for WIMPs







search for WIMPs



dark matter candidates

WIMPs

- weakly interacting **massive** particles
- predicted by supersymmetry
- very large experimental efforts

subjective plausibility: 25%

Axions

- ultra-**light** particles
- predicted by Peccei-Quinn theory
- large experimental efforts

subjective plausibility: 70%

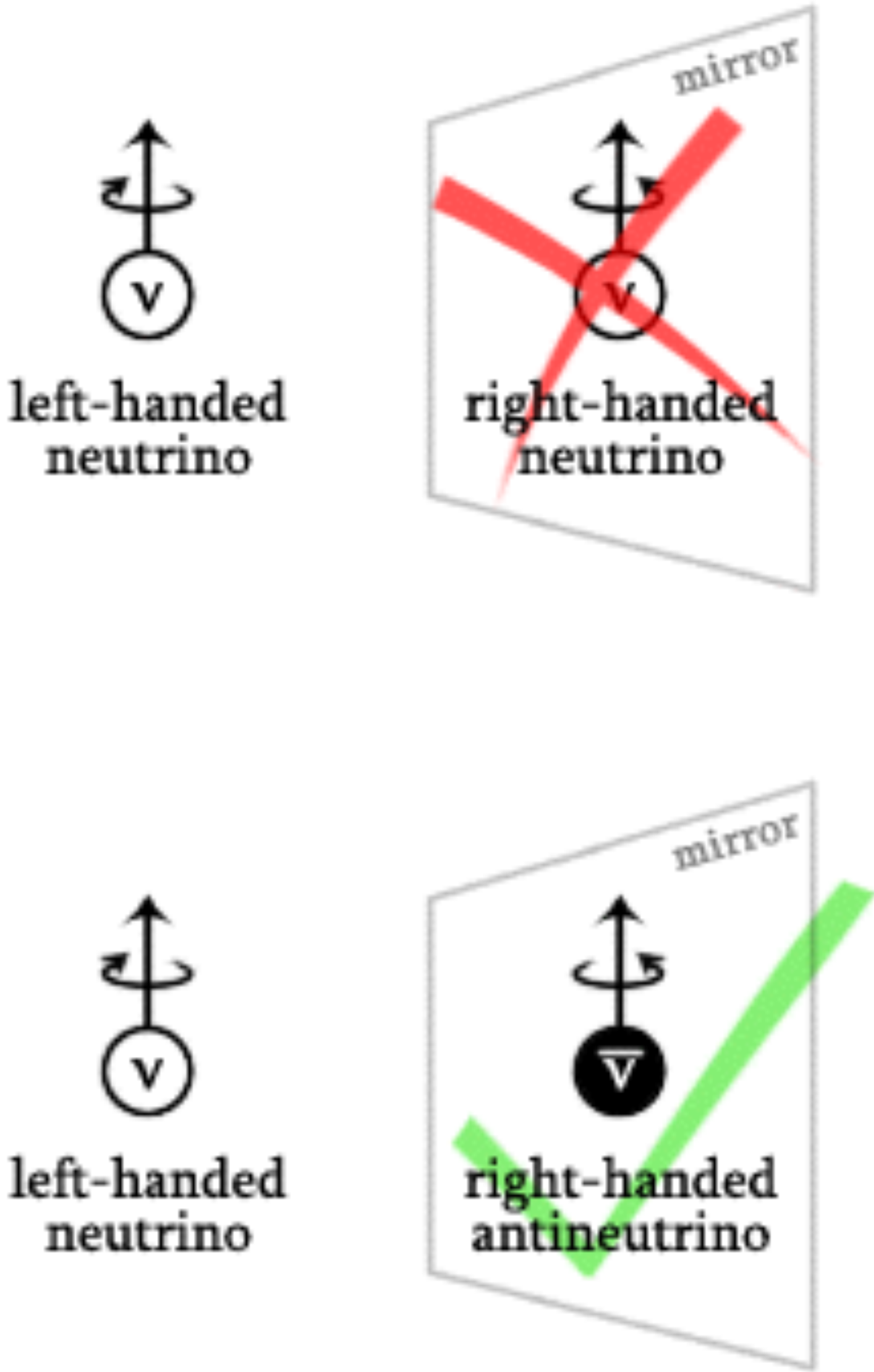
other:

- modified Newtonian dynamics (MOND)
- massive compact halo objects (MACHO)

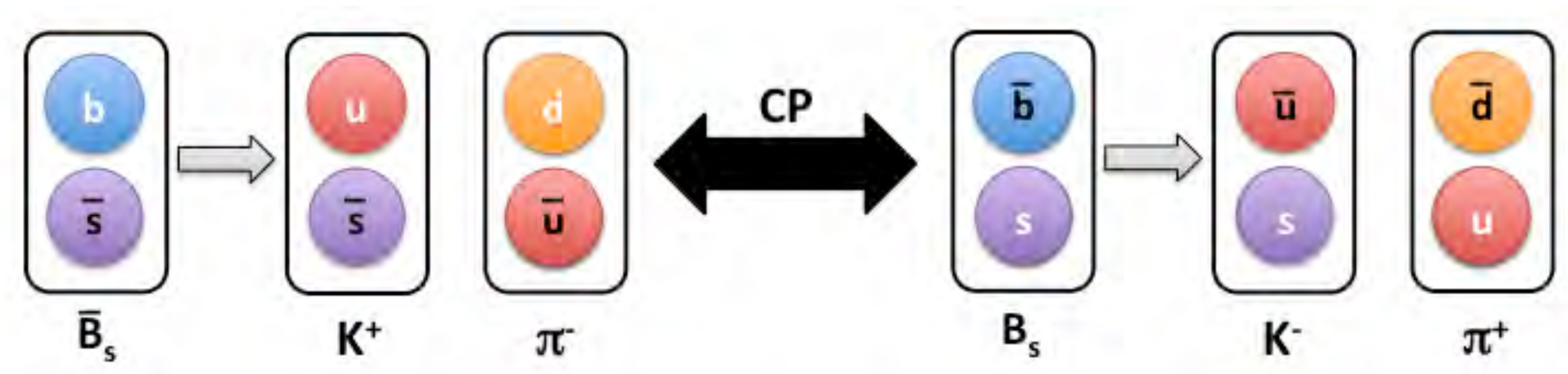
subjective plausibility: 5%

P violation

- **maximum** parity (P) violation in weak interaction
- well established in theory
- CP is the **true symmetry**



CP violation



- decay rates **differ** at percent level
- CP symmetry is violated
- well established in EWK theory
- CPT is the **true symmetry**

strong CP problem

- CP violation
  - **not** established in strong interaction

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} \tilde{G}^{a\mu\nu} G^a_{\mu\nu}$$

- CP violating term
- θ is arbitrary angle
- gluon field

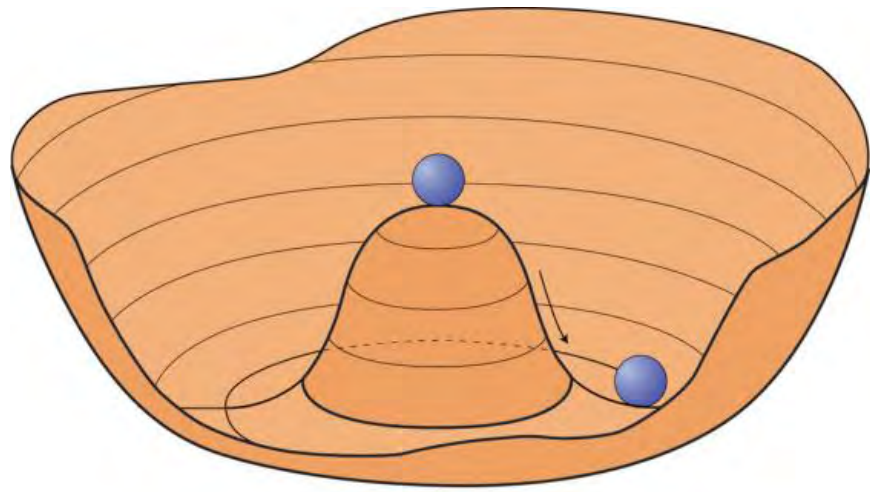
- why is $\theta == 0$?

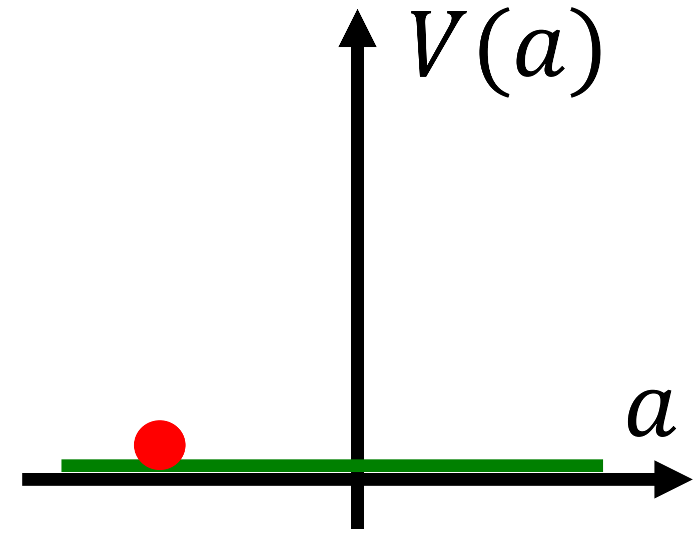
- possible solution:
  - θ is a new scalar field
  - minimum of QCD potential occurs at $\theta == 0$

the axion in the early universe

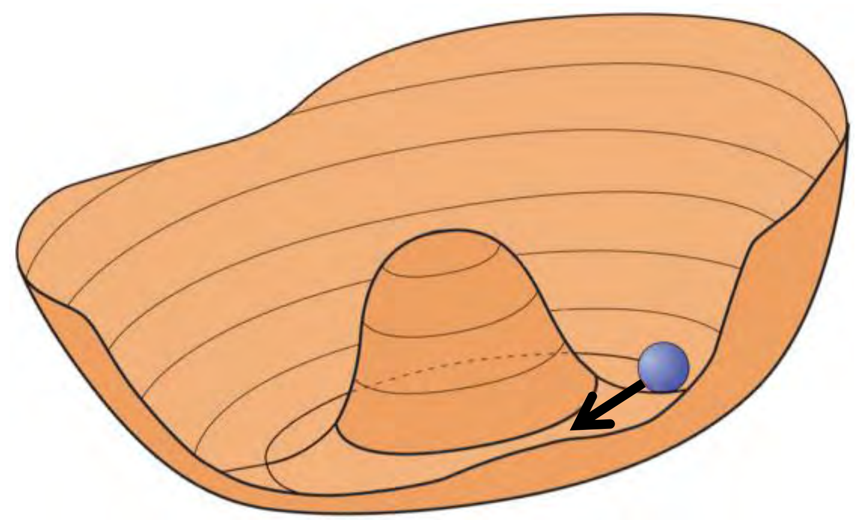
pictures from G. Raffelt (MADMAX workshop 2016)

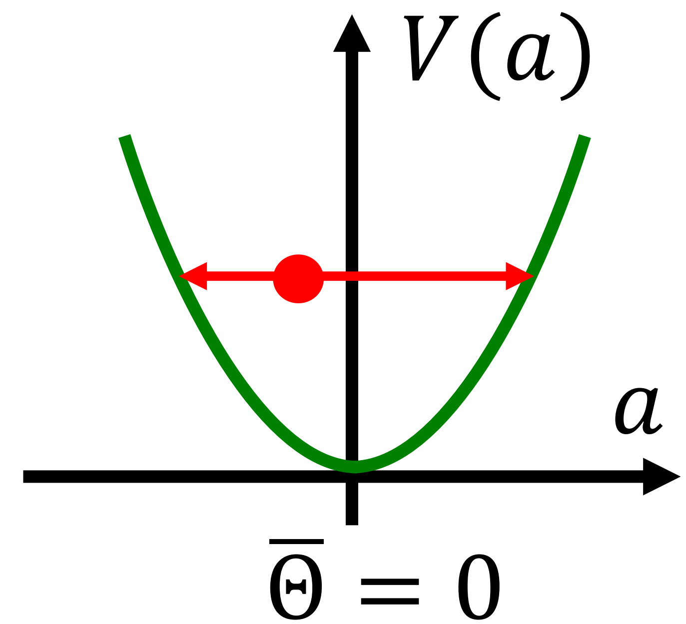
- new $U(1)_{PQ}$ symmetry breaks at high scale f_a





- potential changes shape when universe cools down (T~1GeV)
- axion acquires mass
- field starts oscillating
- expected density compatible with DM

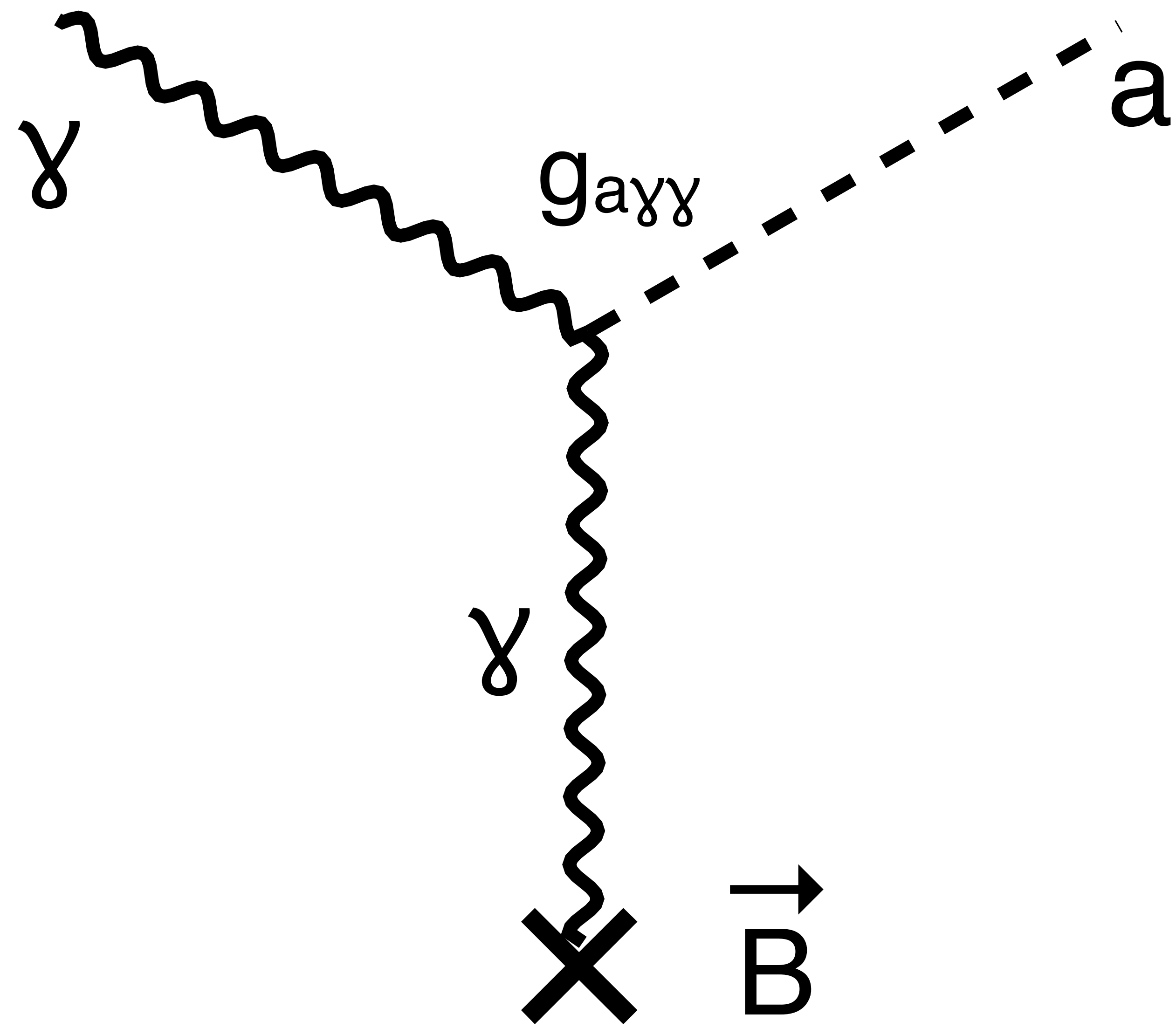




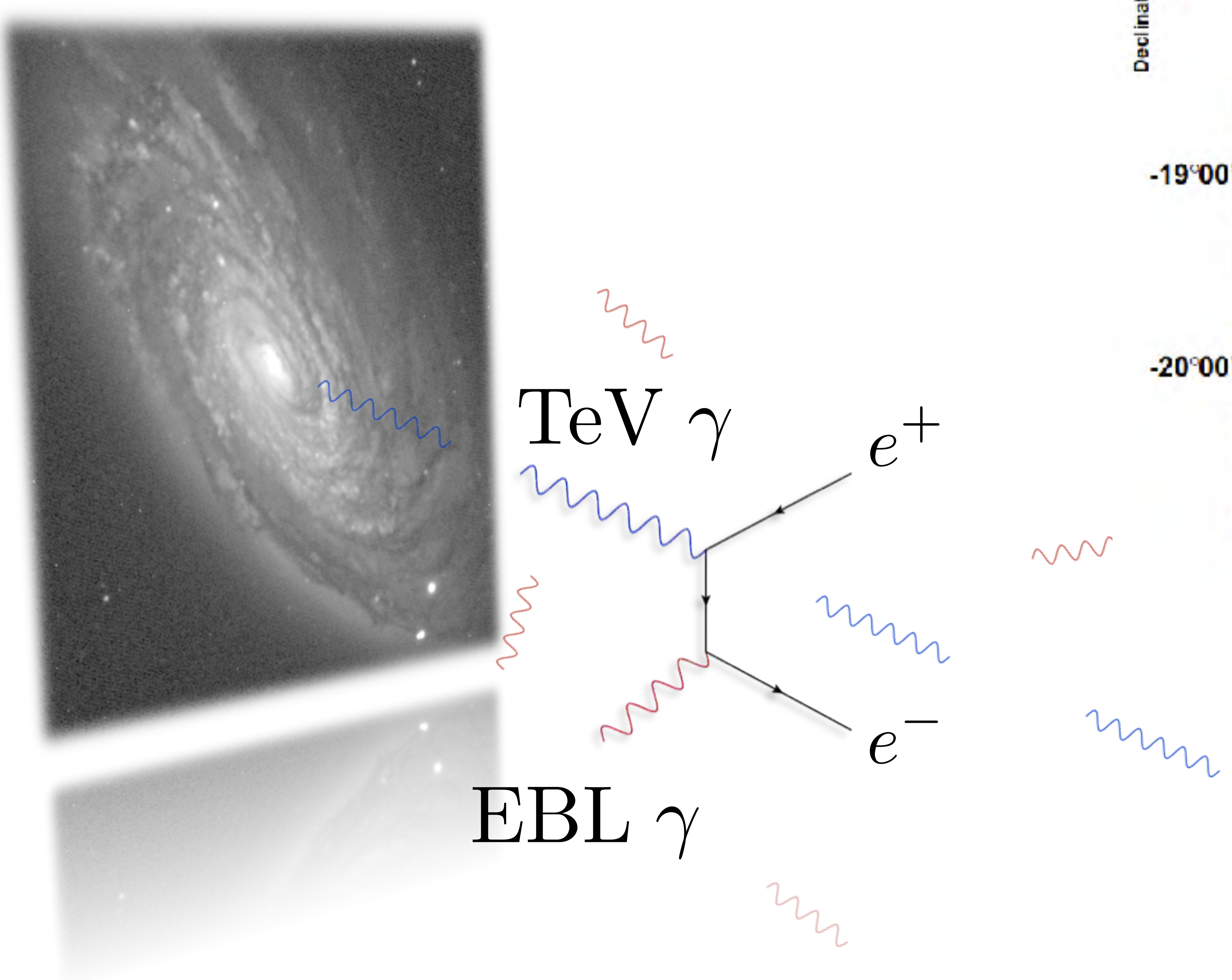
axions born from vacuum realignment

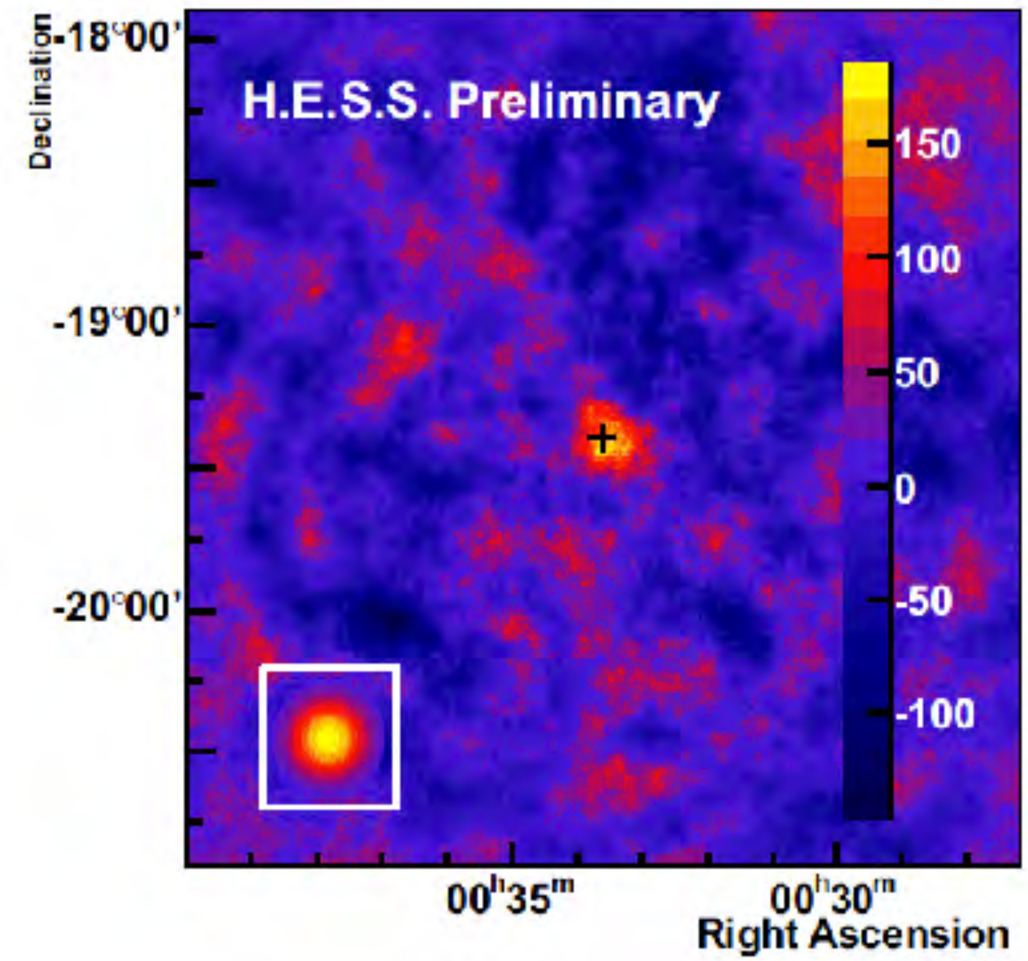
axion couplings predicted

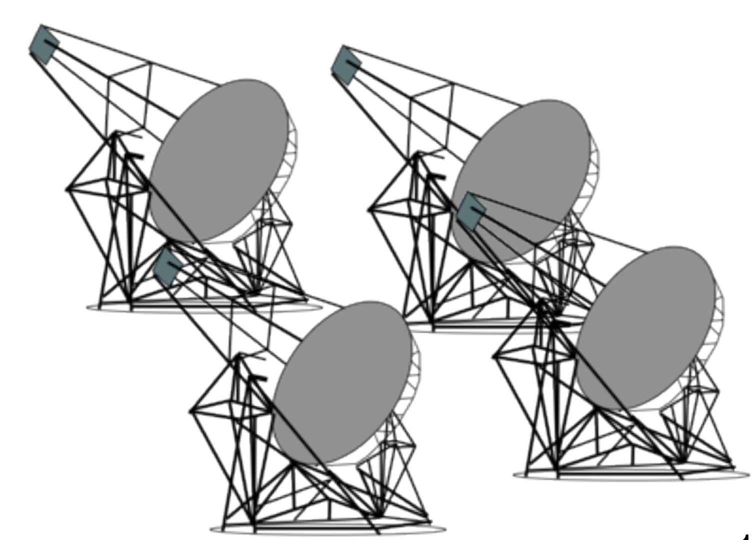
- **Axion-photon coupling**



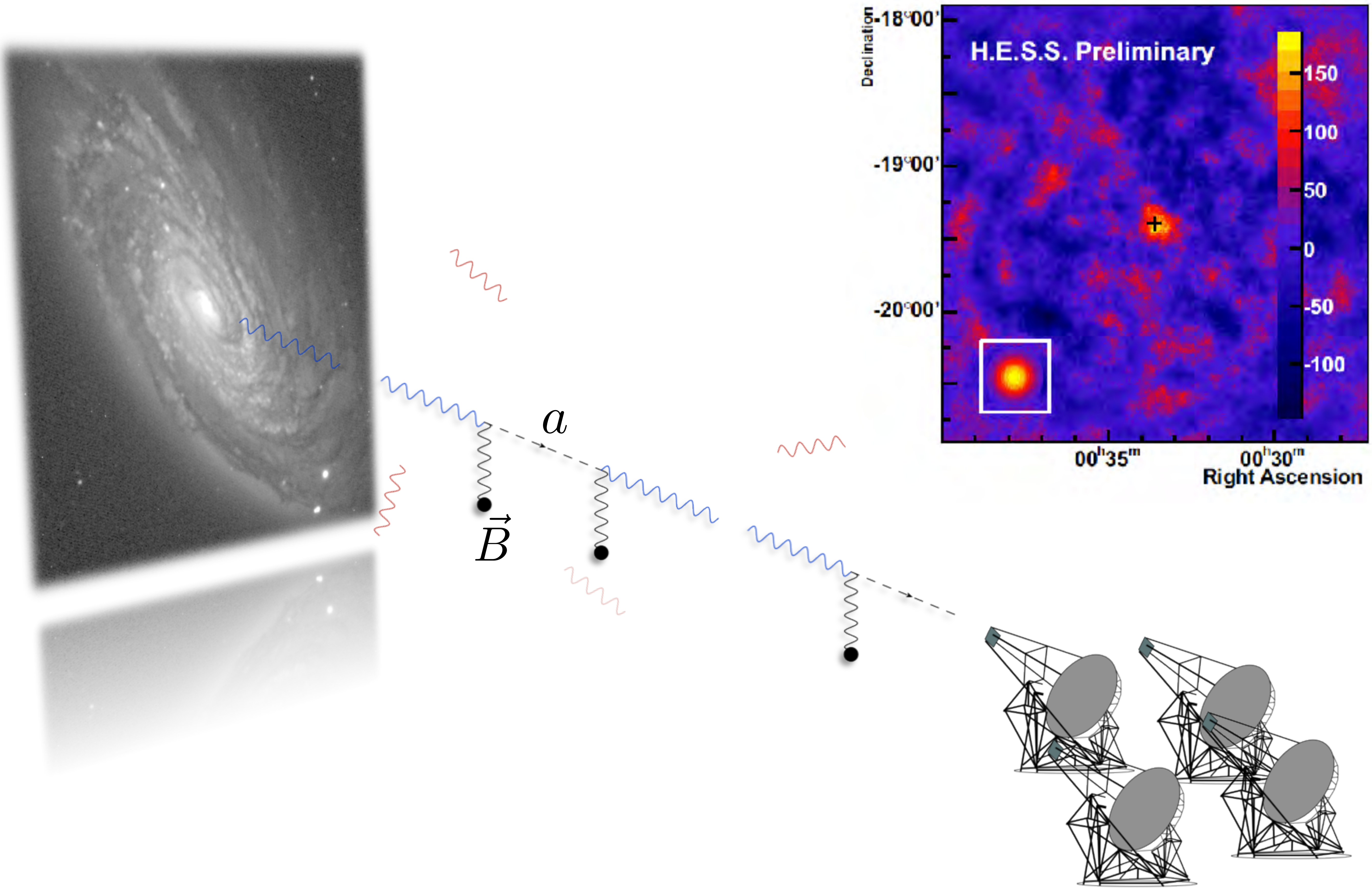
transparency of the universe



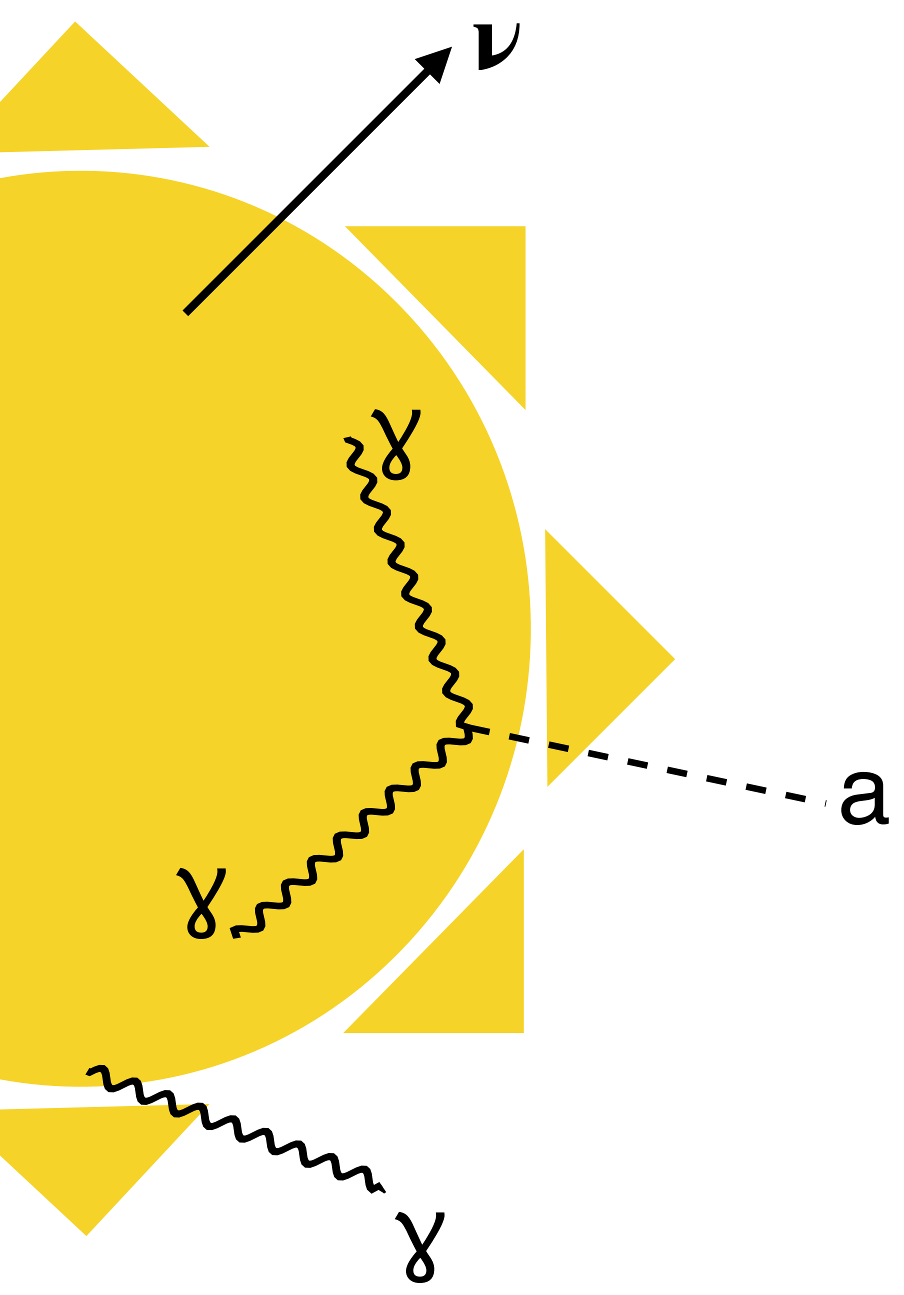




transparency of the universe



stellar cooling



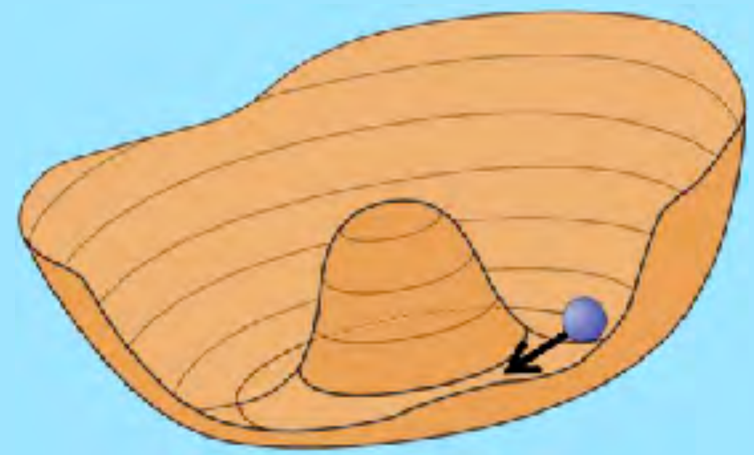
- excessive cooling in different types of stellar objects:
  - white dwarfs, red giants, …
- single observation not statistically significant
  - combination is significant
- straight forward explanation with axions
  - hypothetical axion emission

axions solve many problems simultaneously

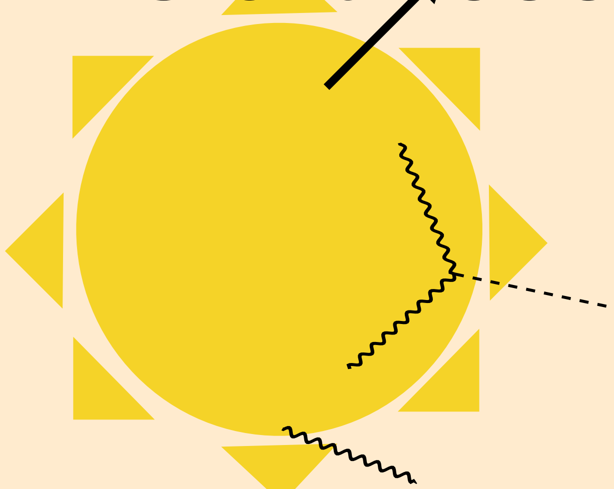
- **strong CP problem**

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} \tilde{G}^{a\mu\nu} G^a_{\mu\nu}$$

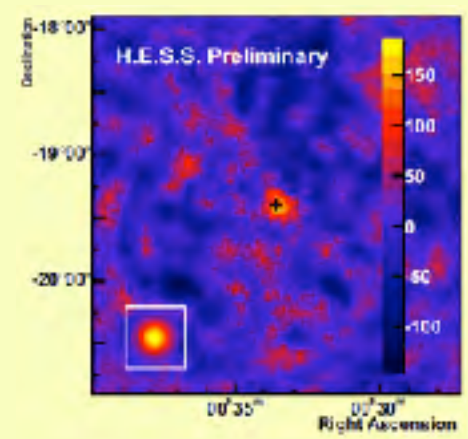
- **dark matter**



- **stellar cooling**

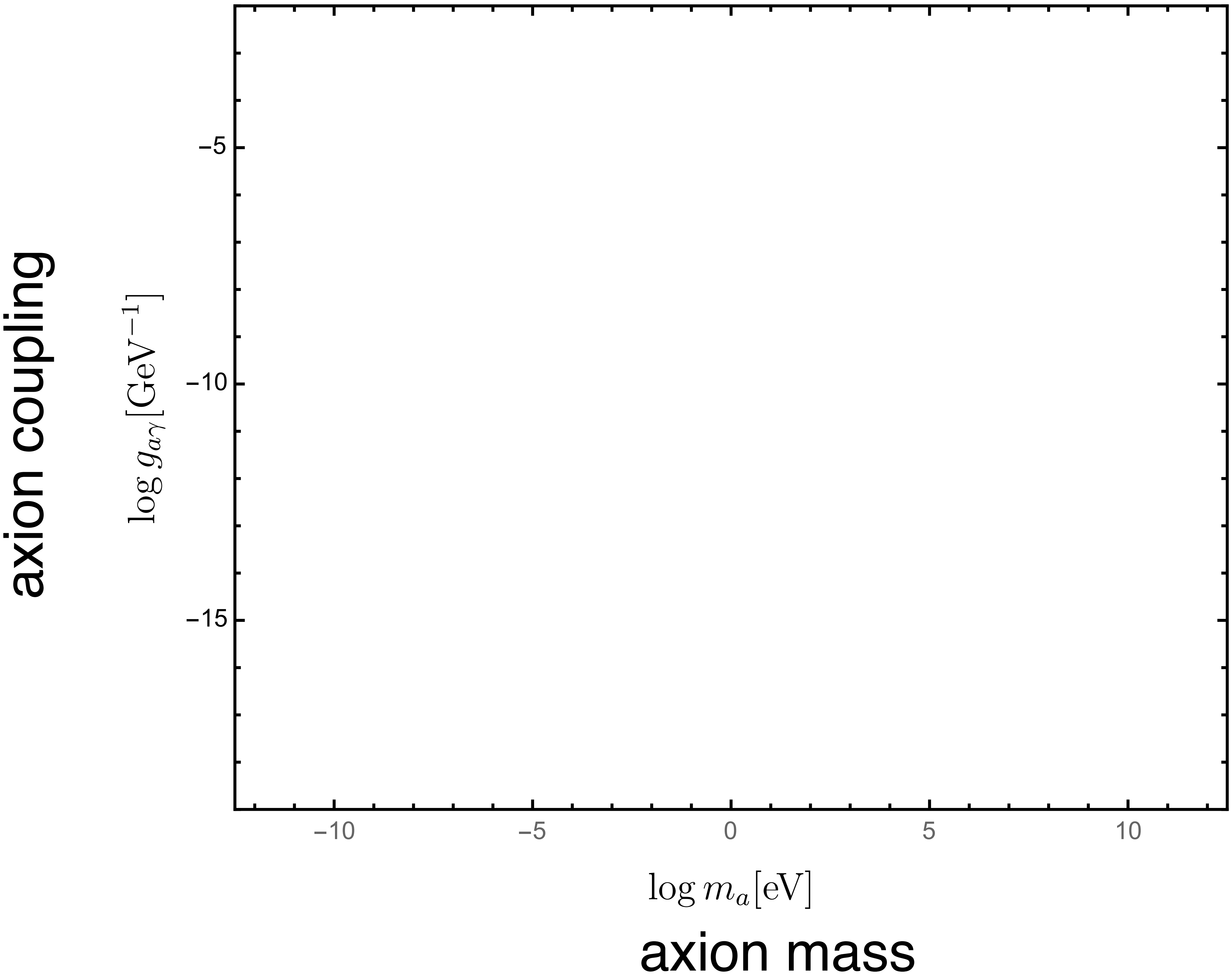


- **transparency**

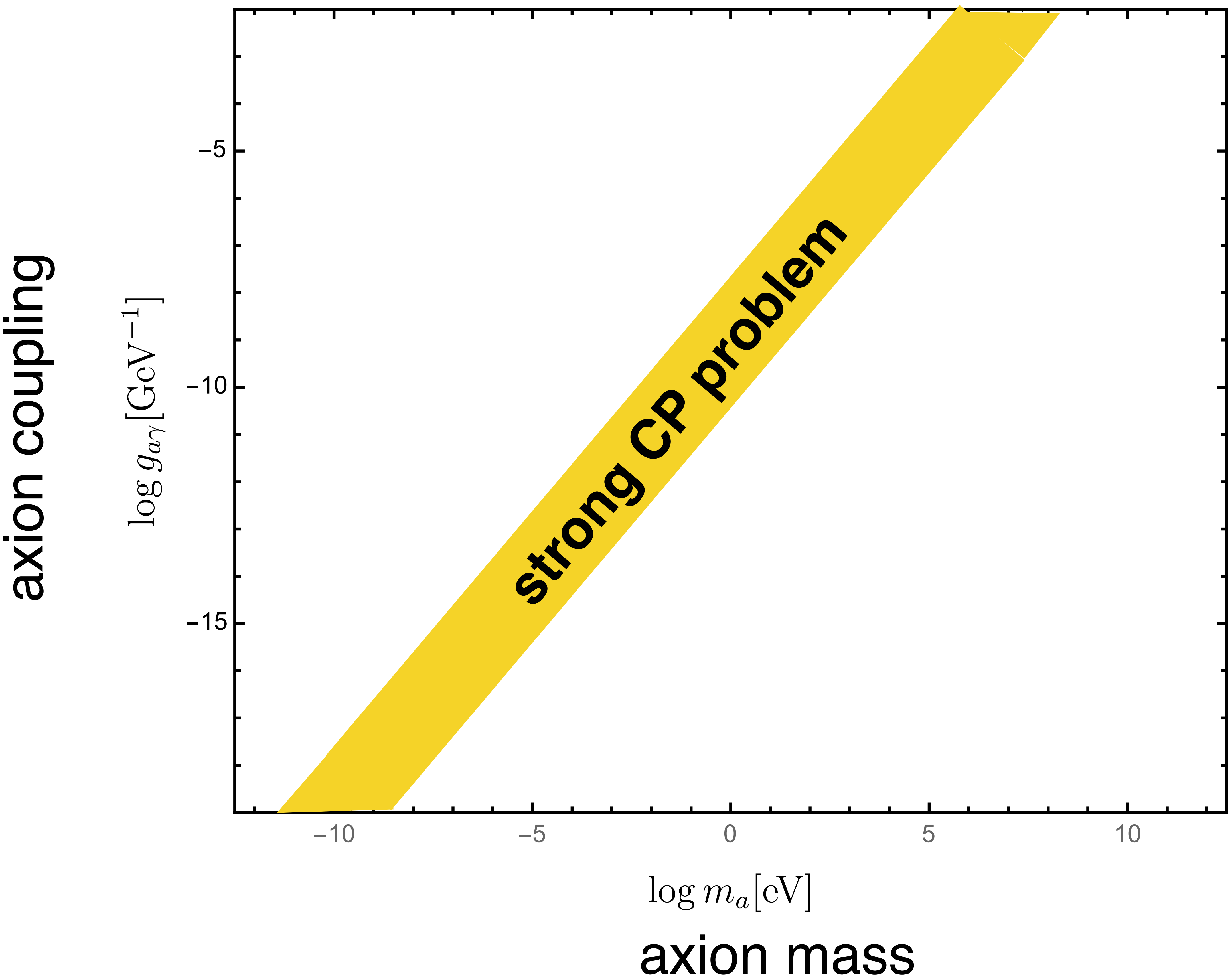


and it’s not a new concept! Higgs!

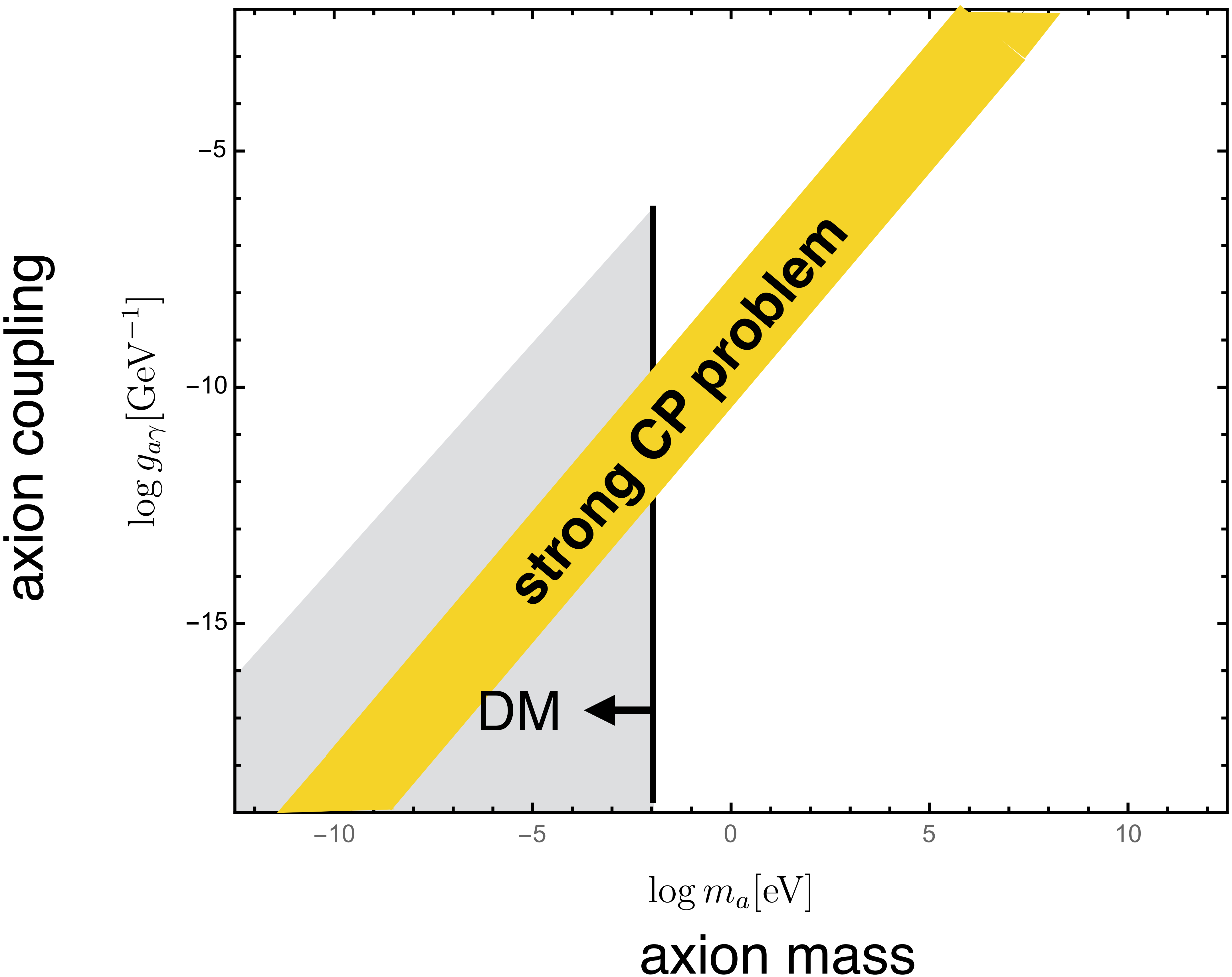
where to search for axions



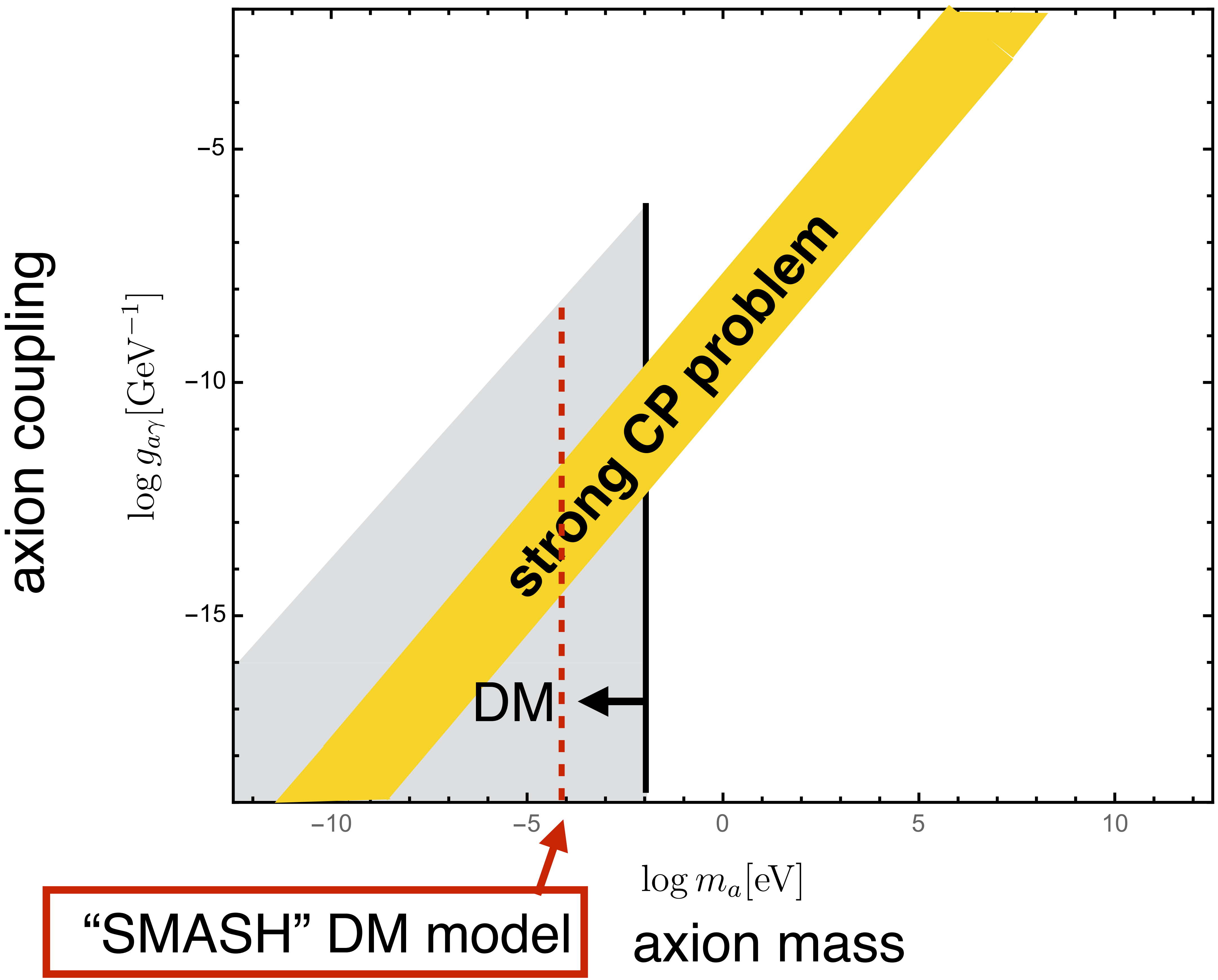
where to search for axions



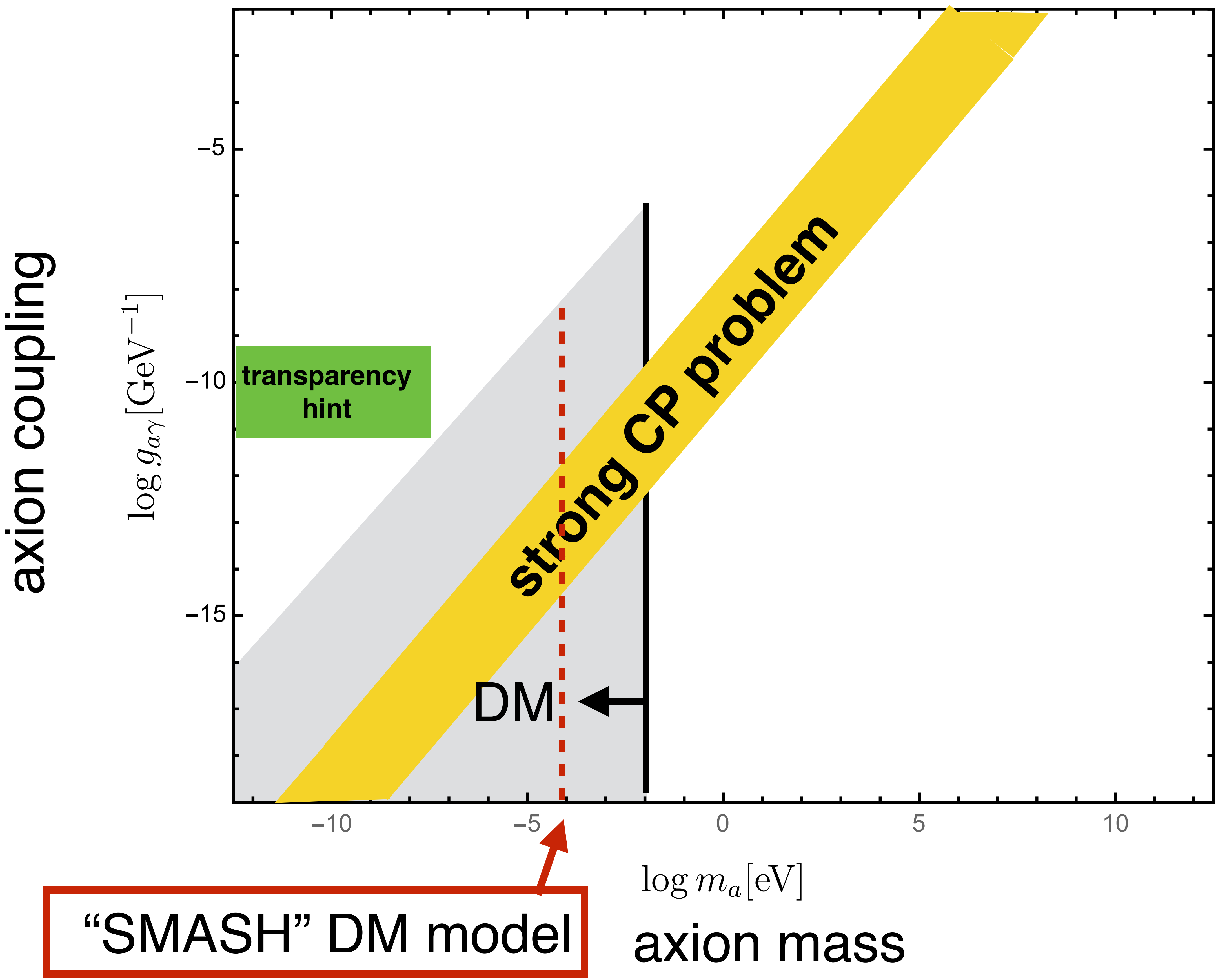
where to search for axions



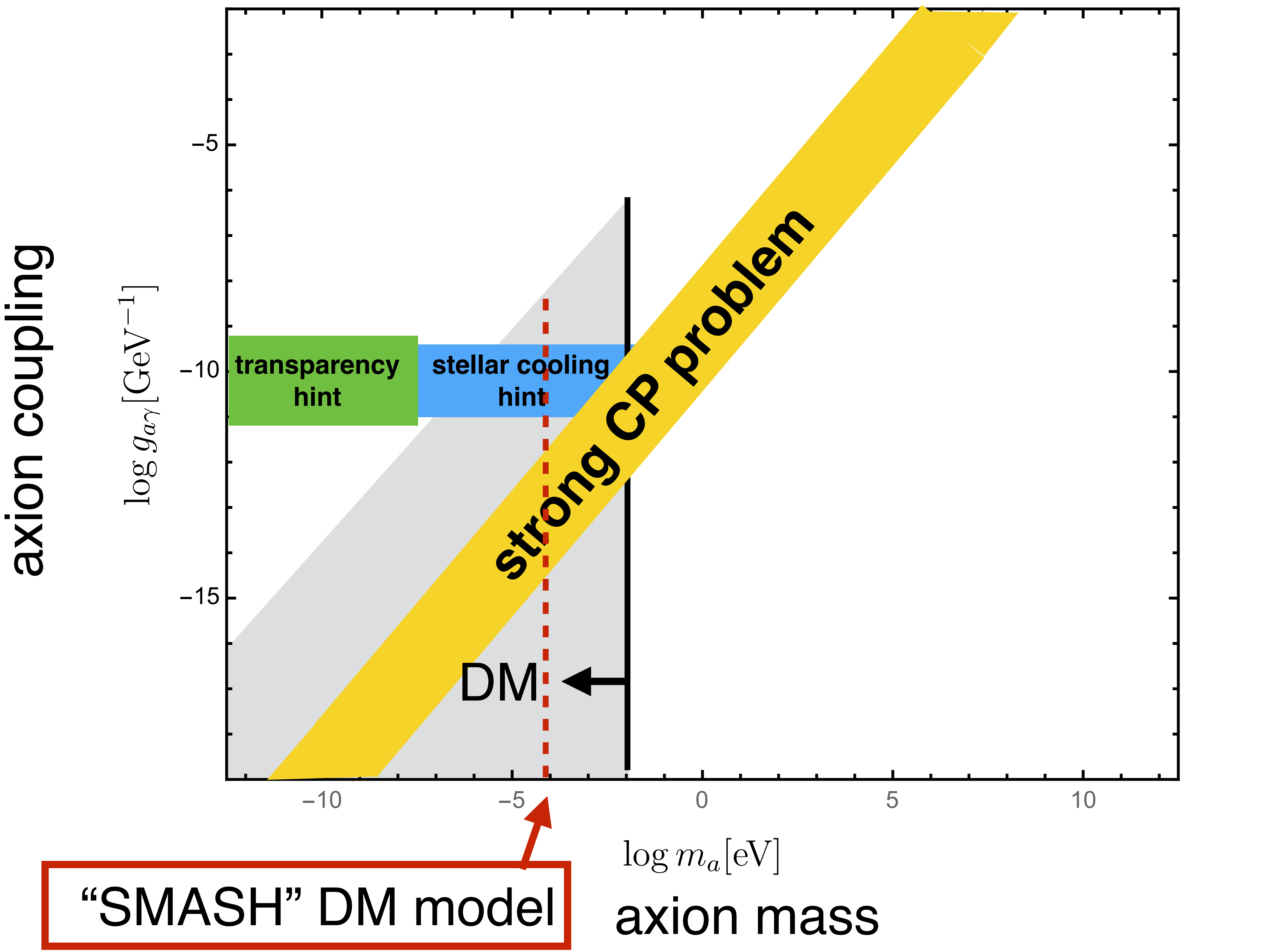
where to search for axions



where to search for axions



where to search for axions

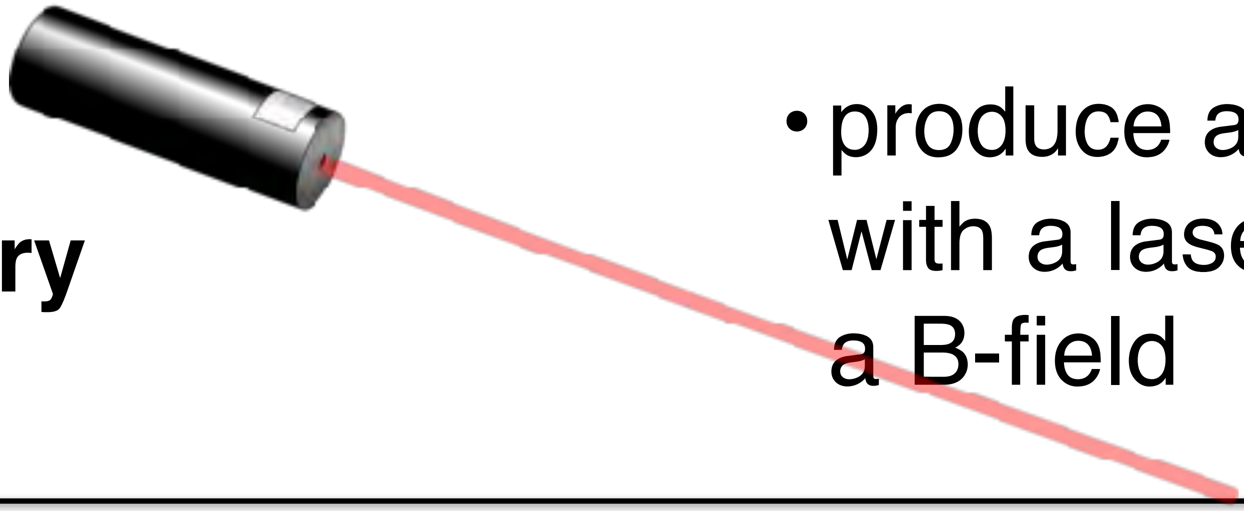


how to search for axions

- **helioscope**

- search for axions emitted by the sun

- **laboratory**

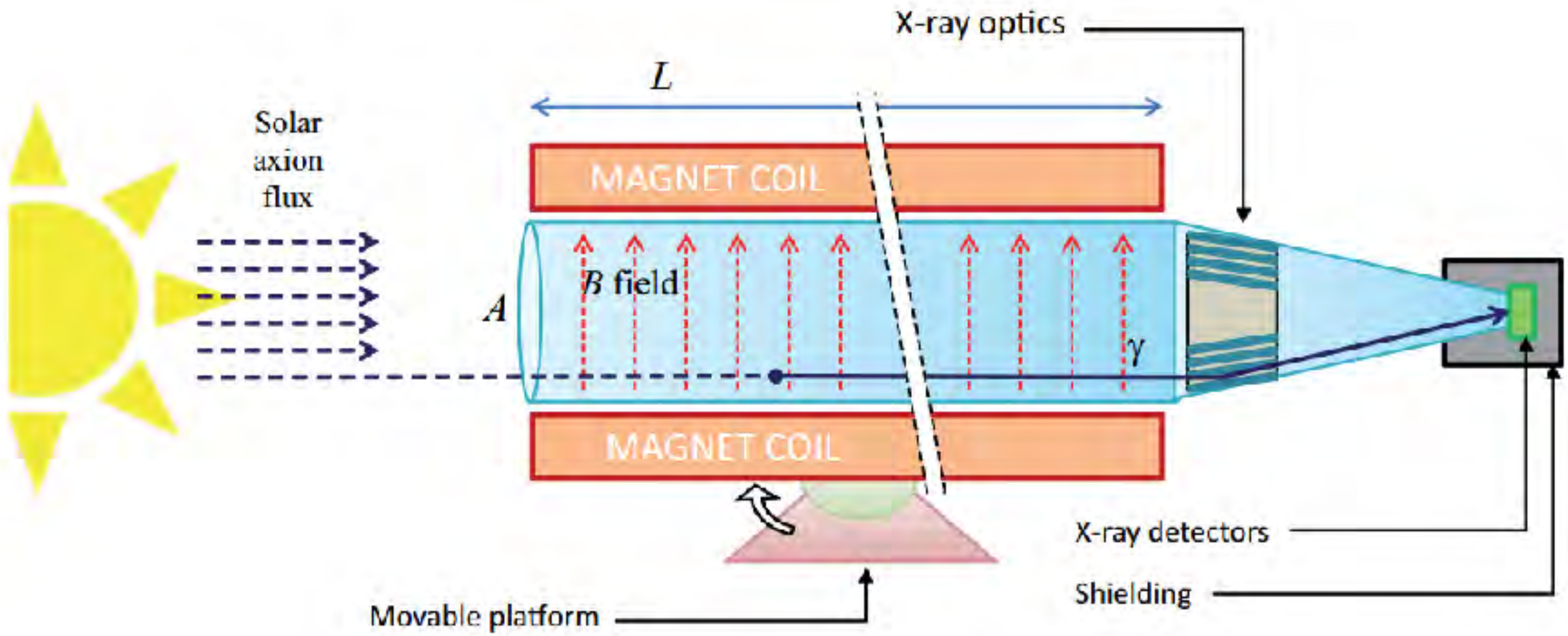


- produce axions with a laser and a B-field

- **haloscope**

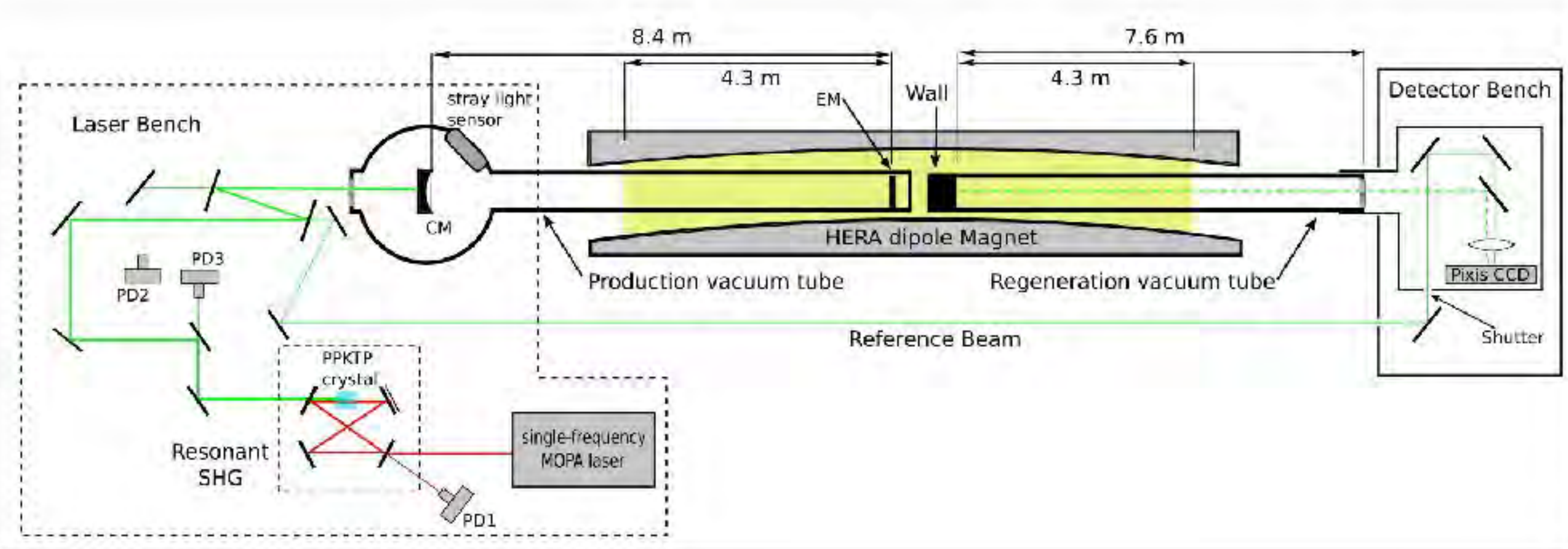
- find axions in the galactic DM halo

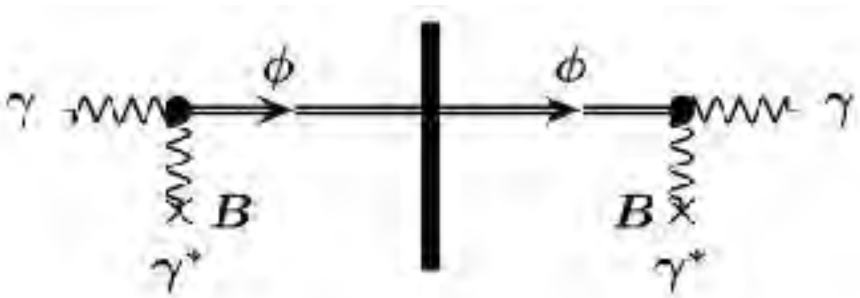
helioscope: “CAST”



- in operation since 2003

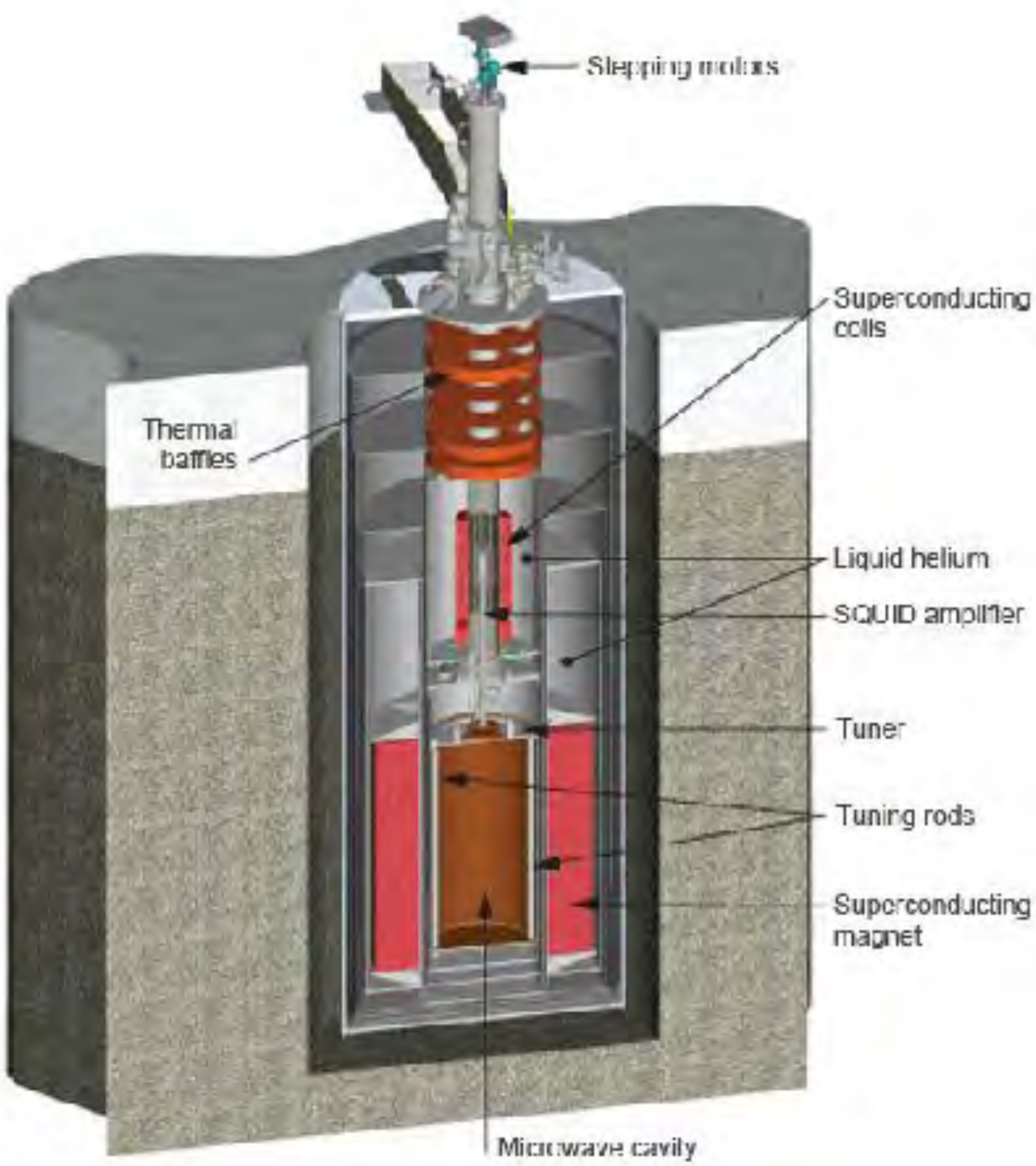
laboratory: “ALPS”



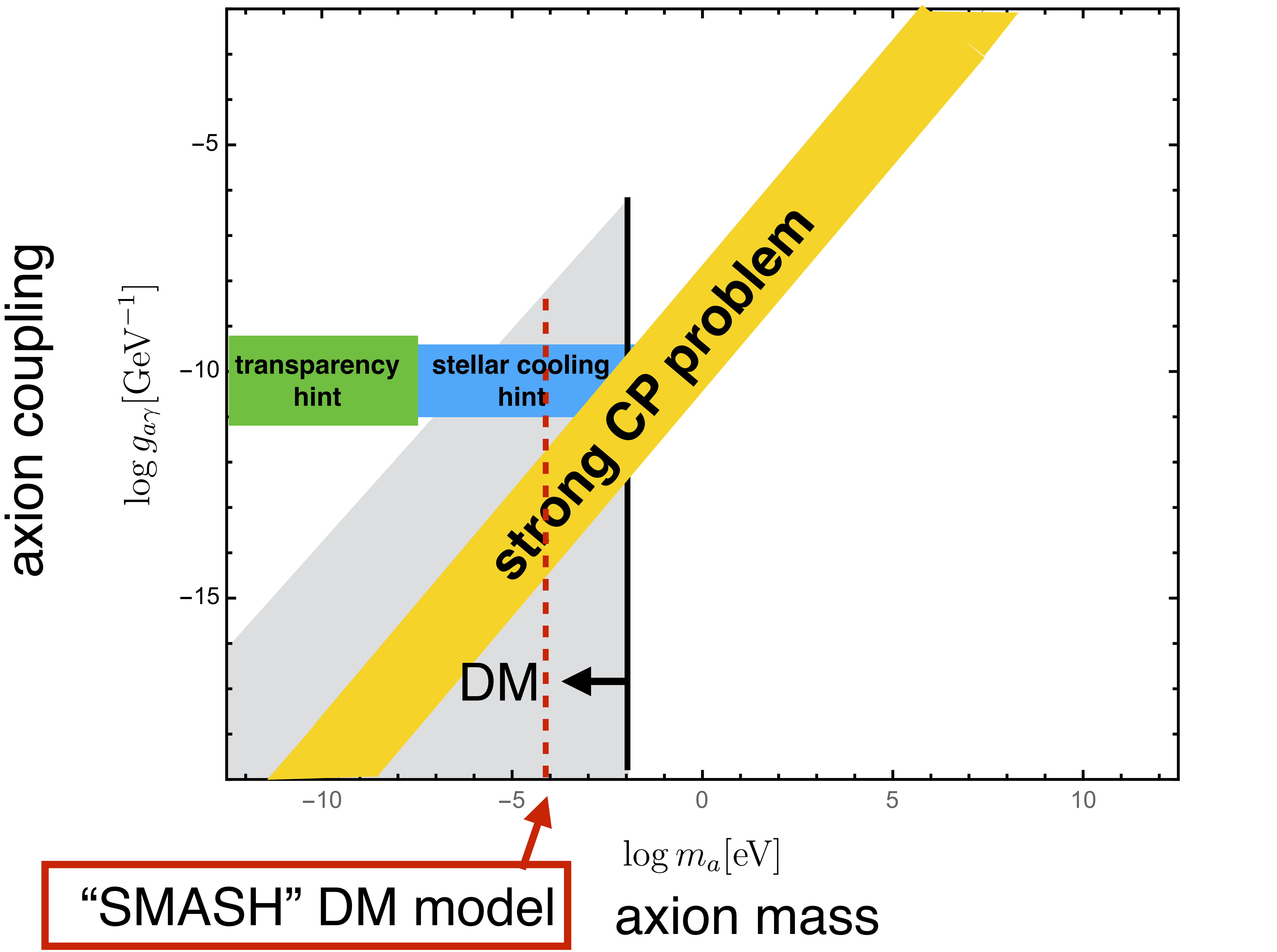


haloscope: “ADMX”

- the galactic DM halo is …here!
- axions in a B field emit photons
  - too weak to detect directly
- enhanced with resonator

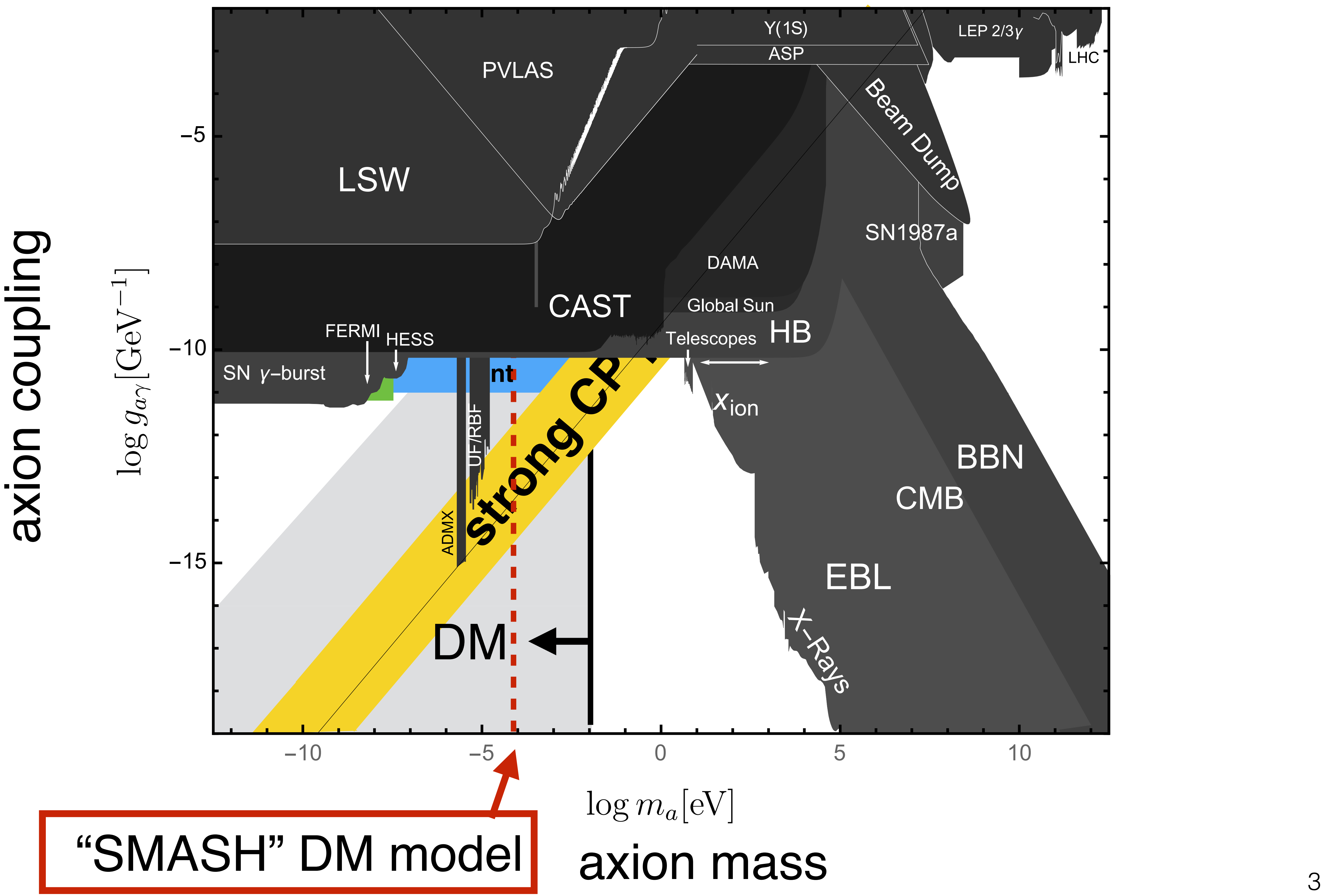


current constraints



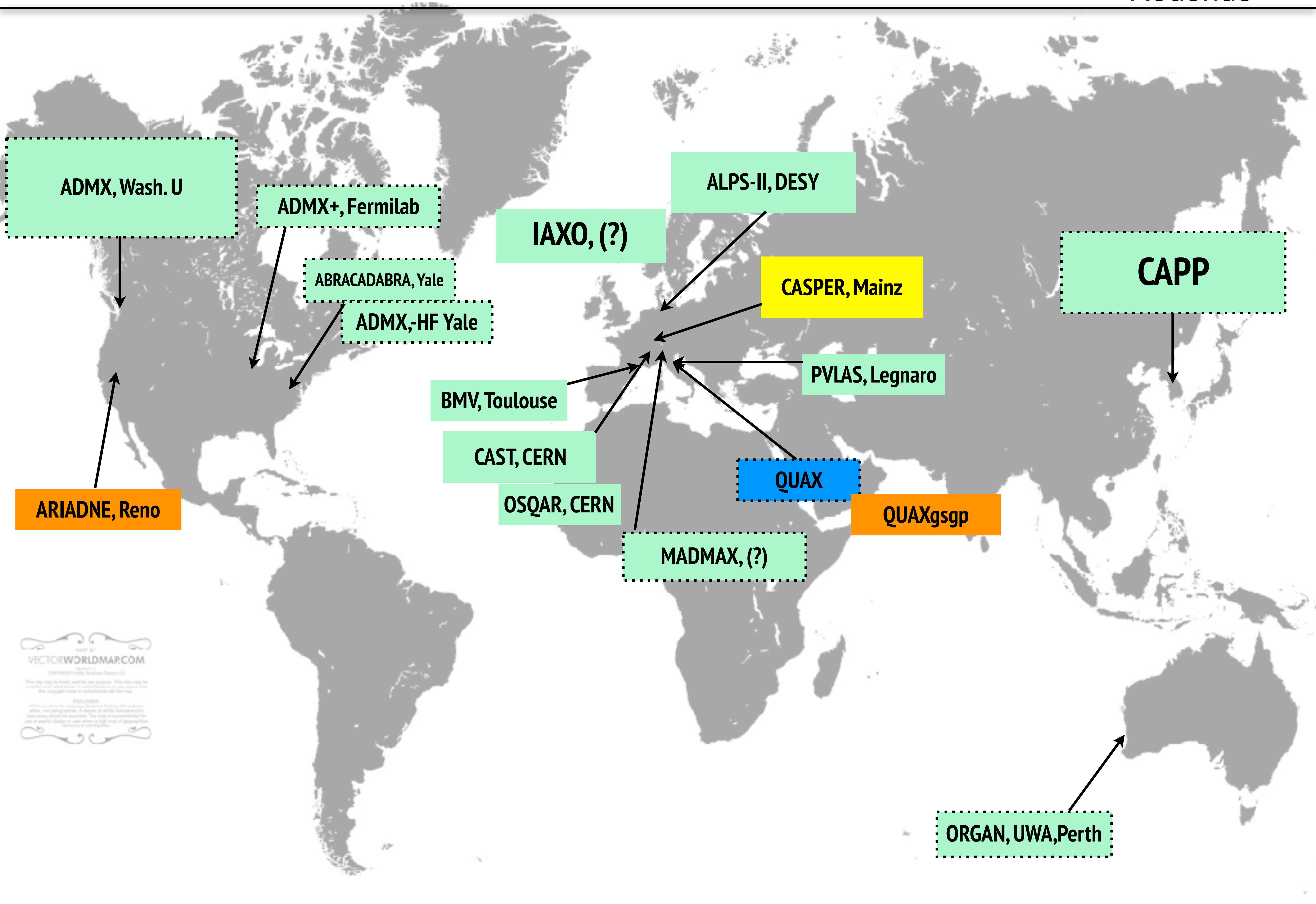
current constraints

plot with support
from J. Redondo



future experiments

map from J. Redondo

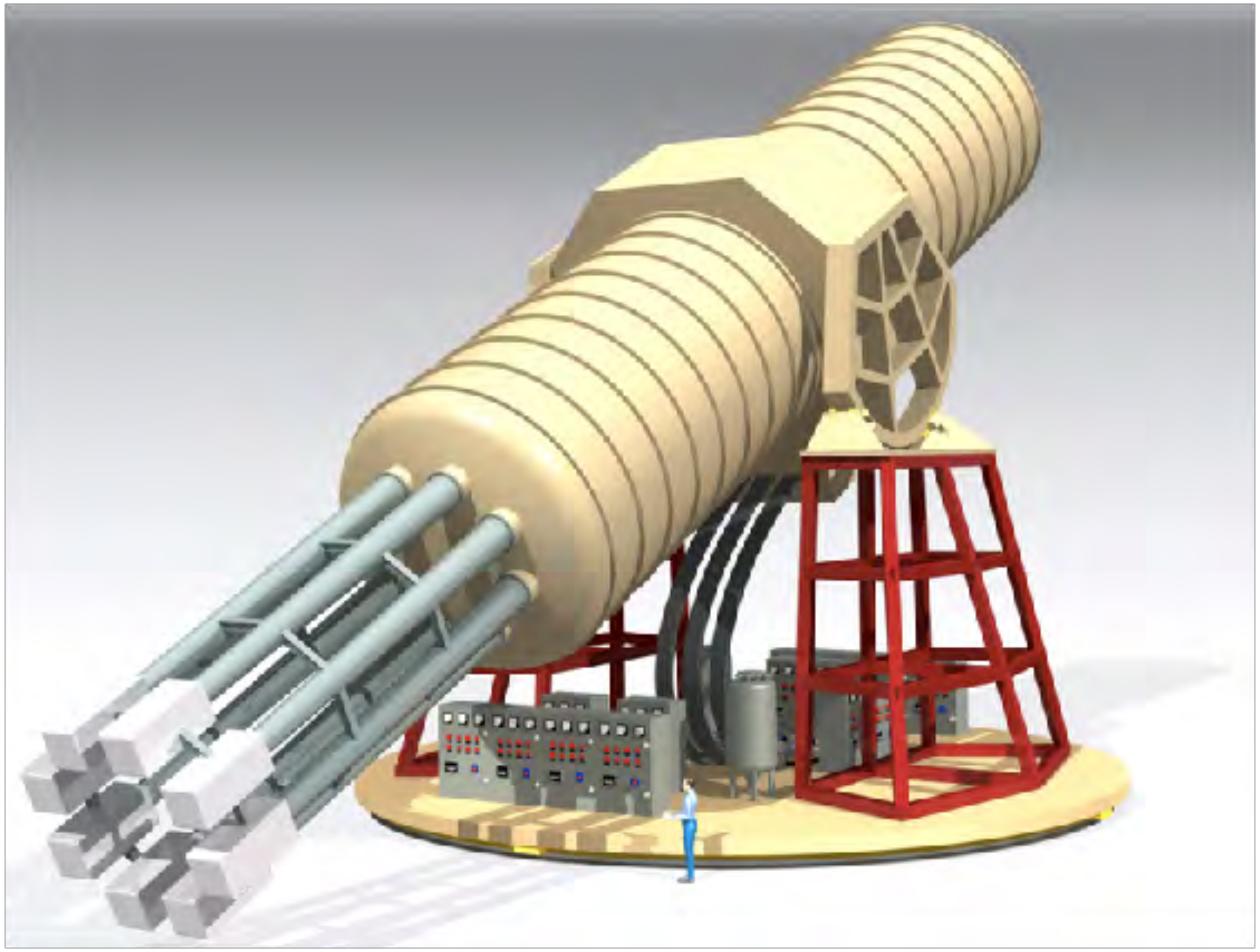


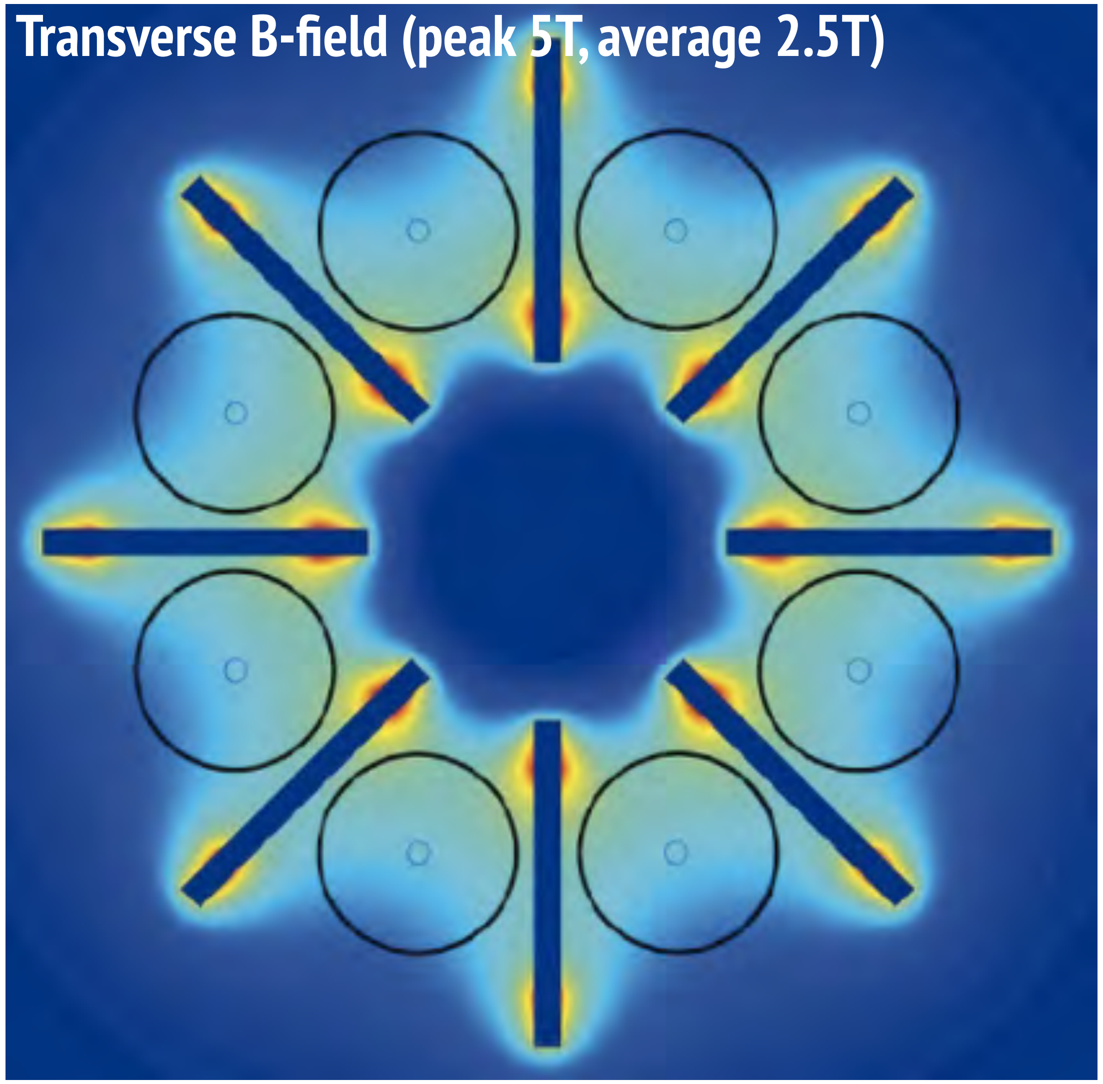
future experiments

CERN-SPSC-2013-022

- IAXO: next generation helioscope
  - larger, stronger magnet
- when and how not yet clear

- more than one order of magnitude improvement over CAST



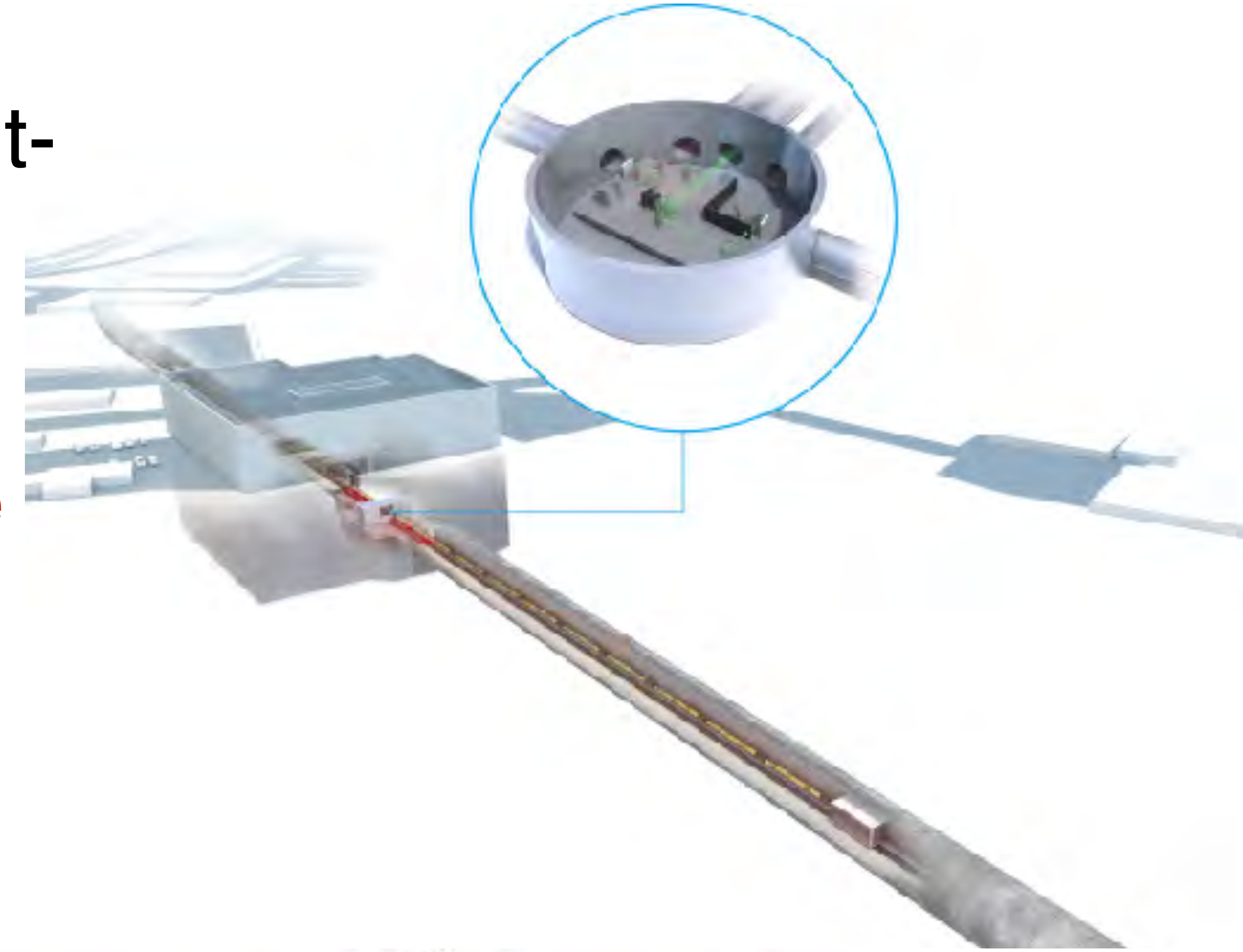


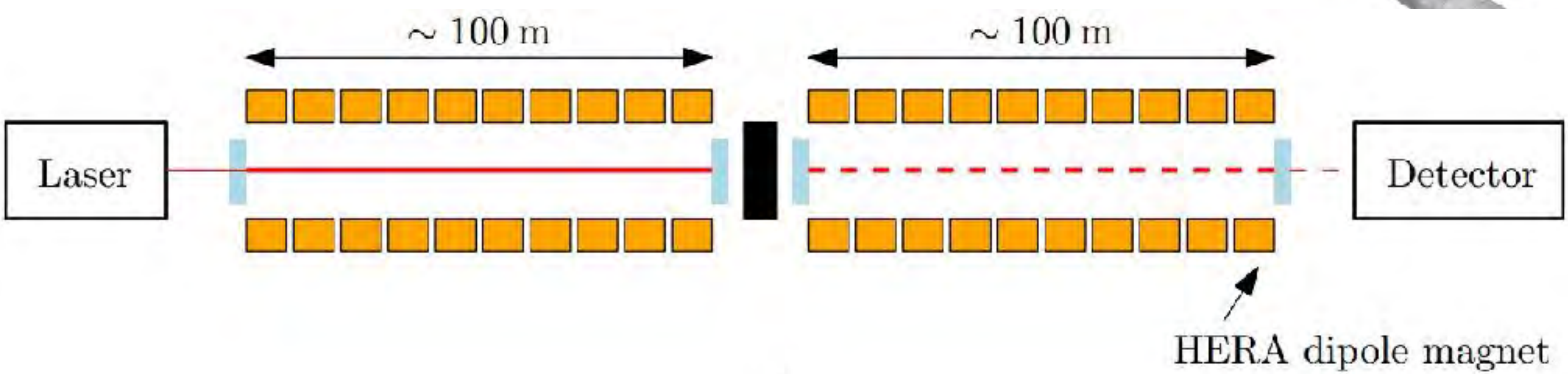
future experiments

arXiv:1302.5647

- ALPS-II: next generation light-shining-through-the-wall
  - more magnets, better laser, better detector
  - resonator in regeneration volume

- clear schedule at DESY
  - several stages: ALPS II a-c
  - factor 3000 improvement

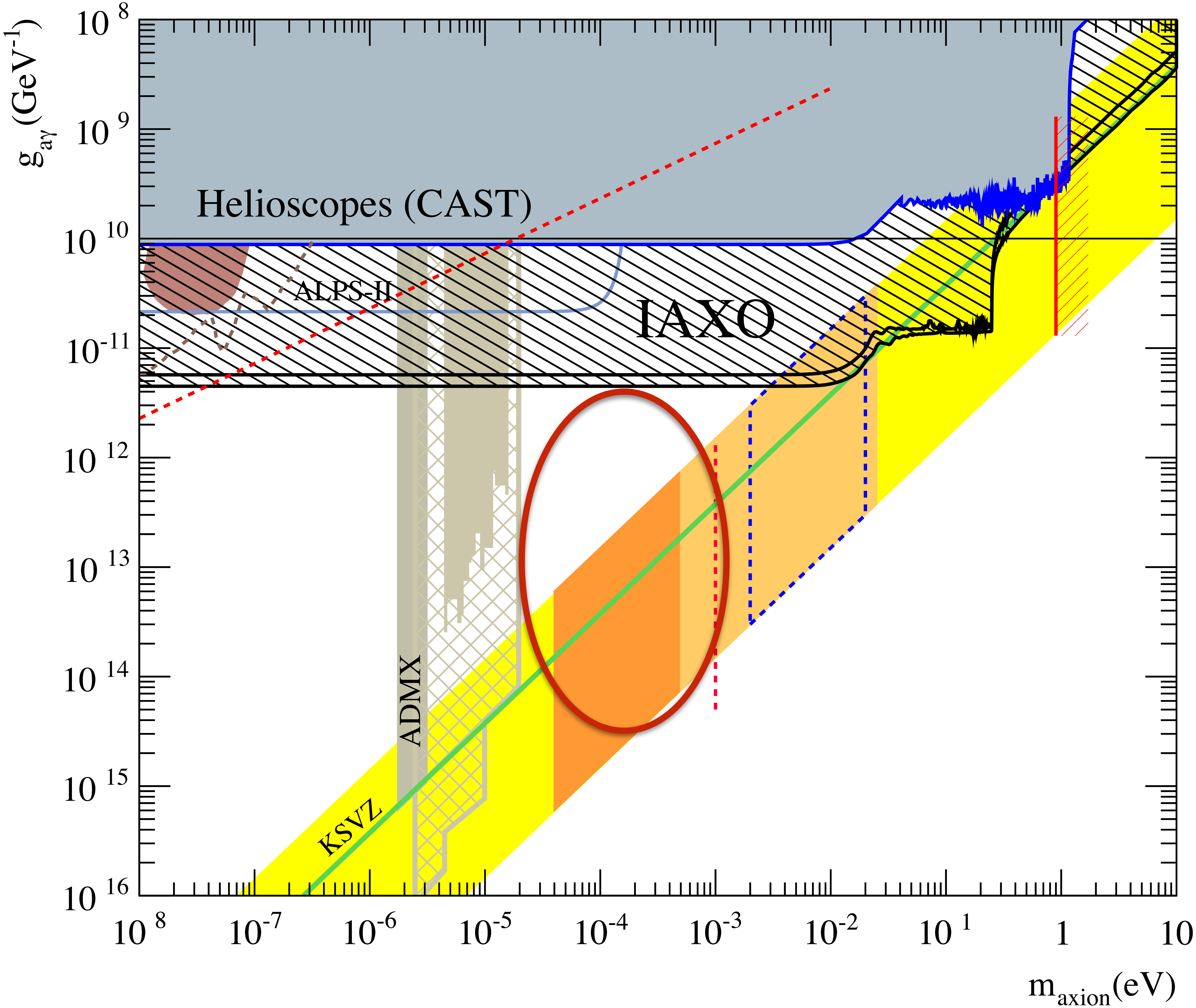




ALPS-IIc

future experiments

plot from talk of
J. Redondo



dielectric haloscope

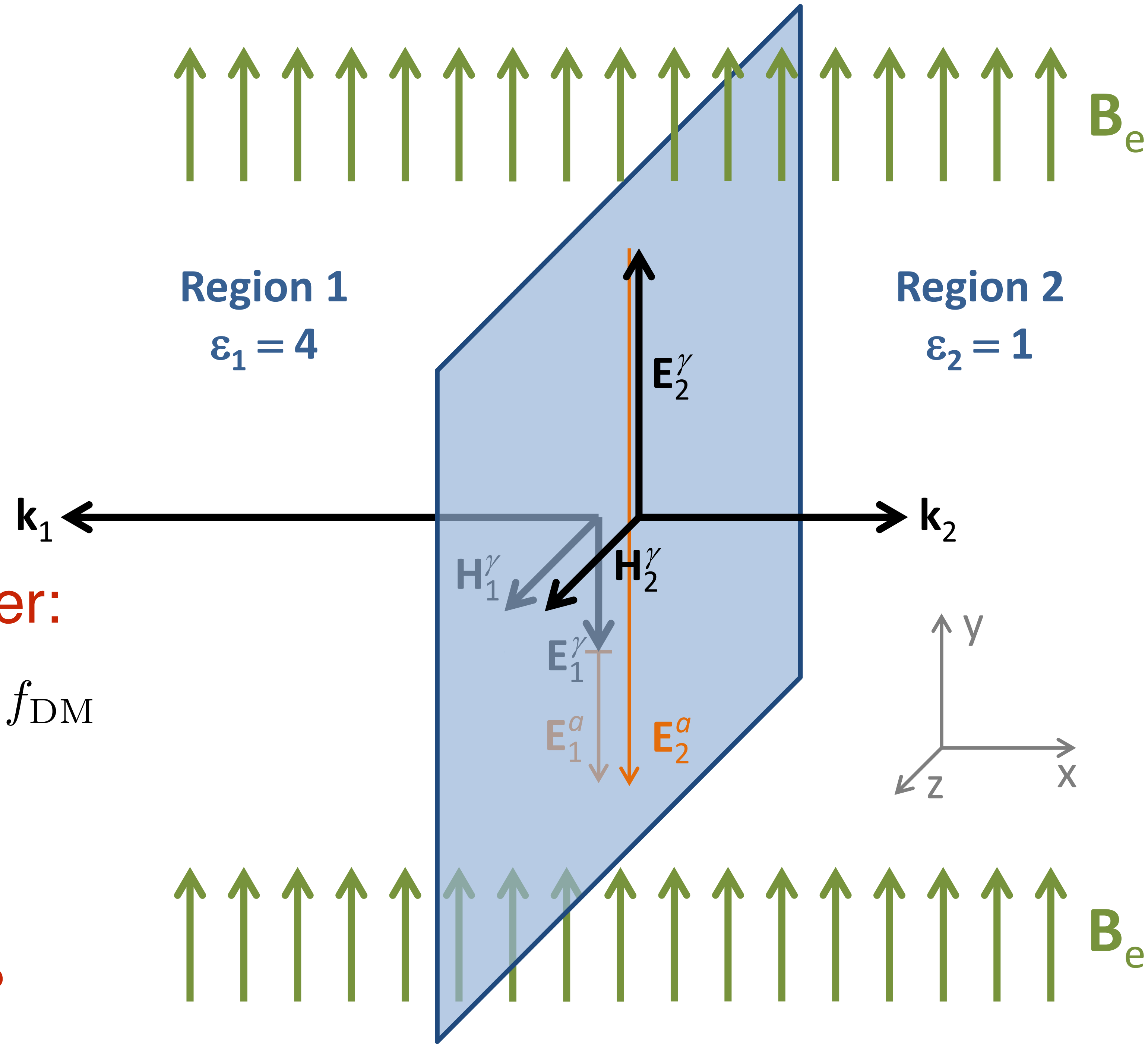
axion DM modifies maxwell equations:

- EM radiation emitted at dielectric transition region
- power emission by one layer:

$$\frac{P}{A} = 2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_e}{10\mathrm{T}}\right)^2 C_{a\gamma}^2 f_{\mathrm{DM}}$$

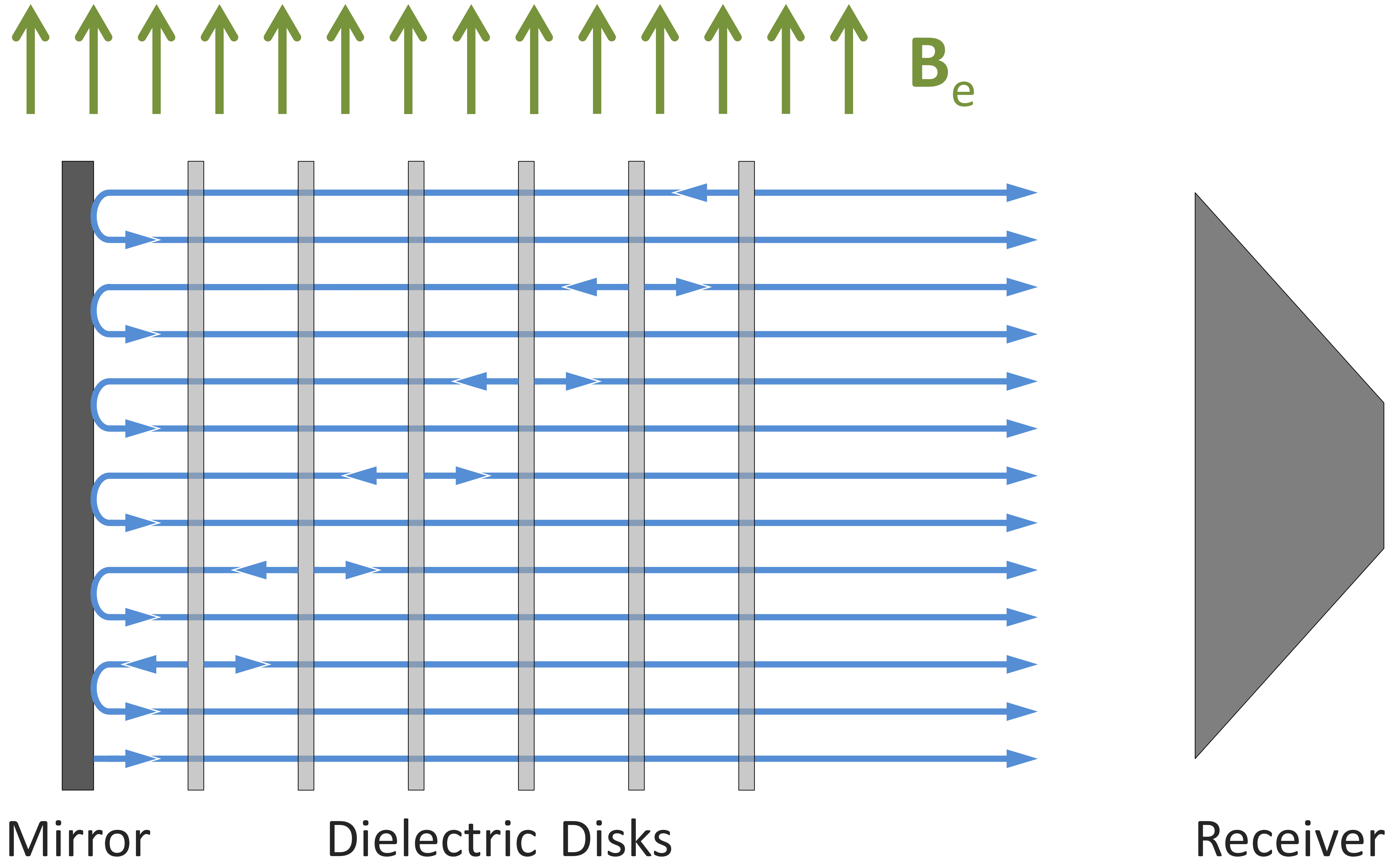
- too small to detect?
- stronger field? larger area?

➡resonator



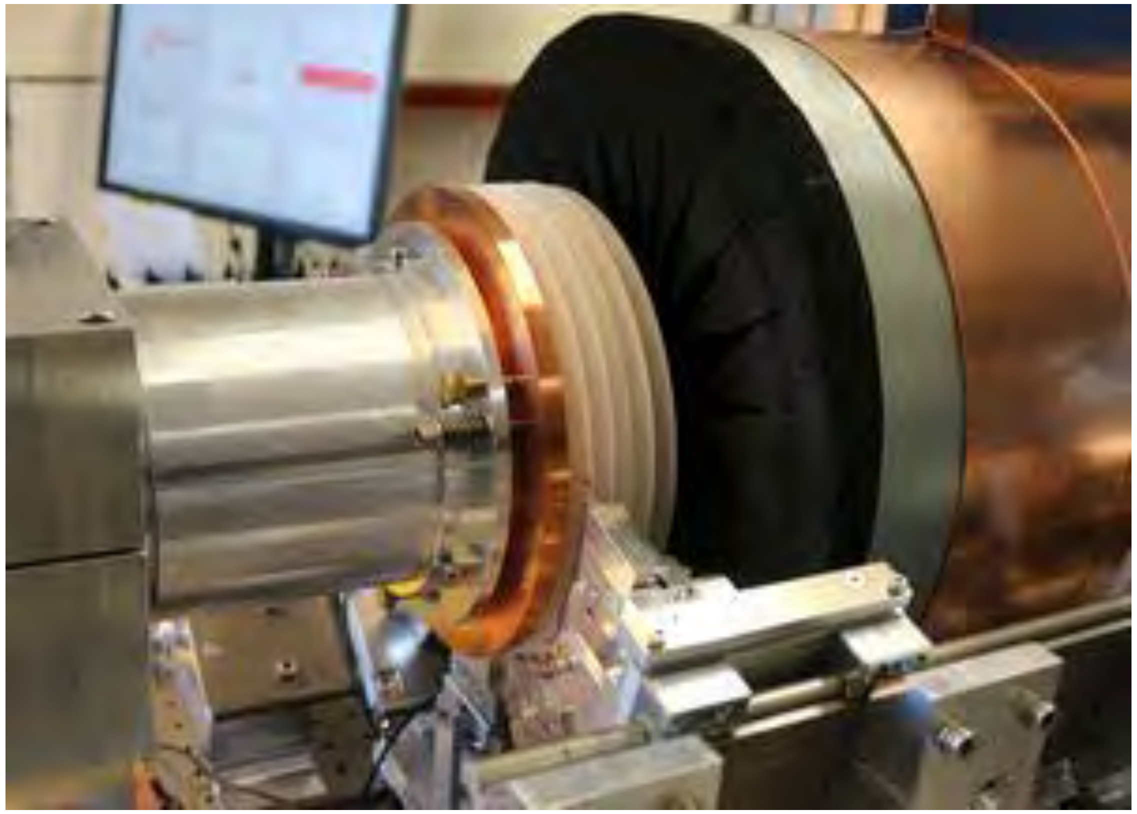
dielectric haloscope

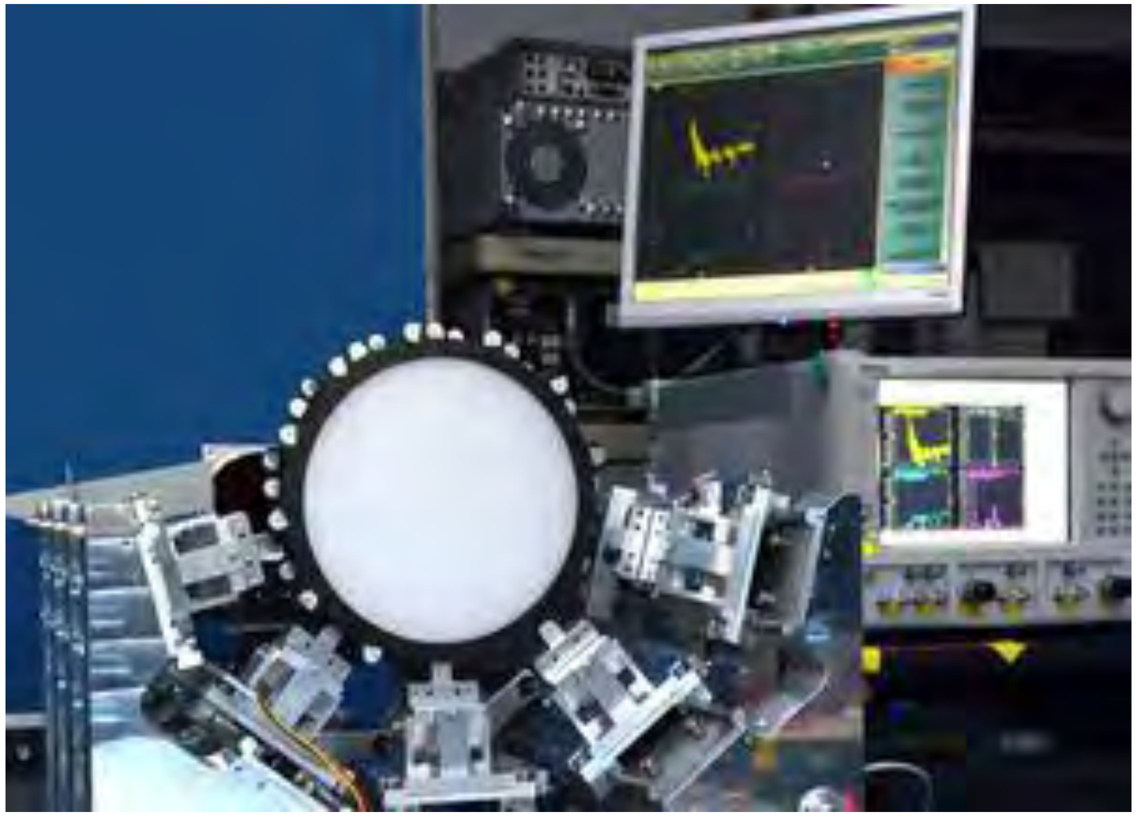
- resonator: multiple layers



MADMAX experiment

- MADMAX: magnetized dish and mirror axion experiment:
  - dark matter axion search in region 50 - 400 μeV
  - multiple dielectric layers in strong B field
  - overcome limitations from microwave cavities

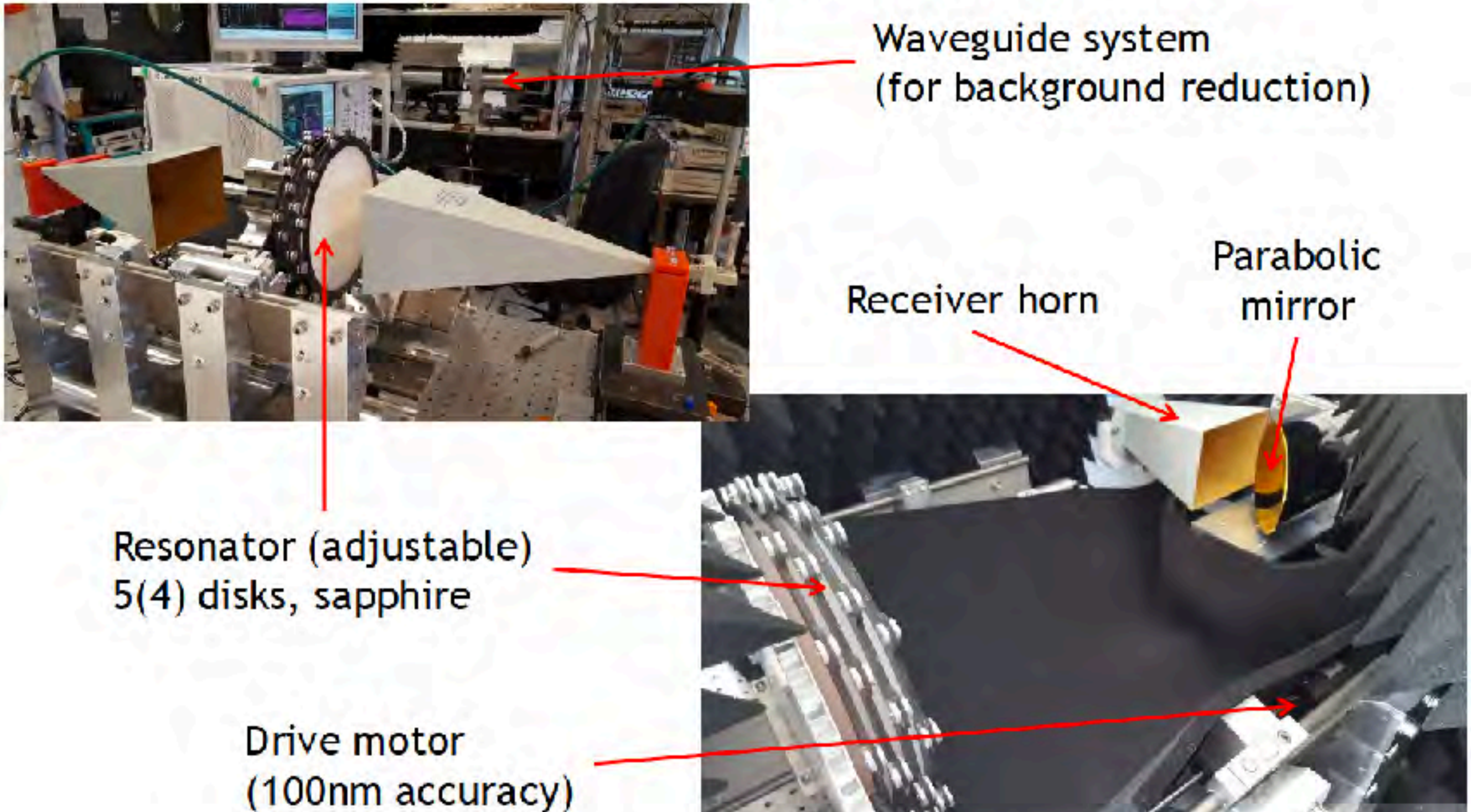




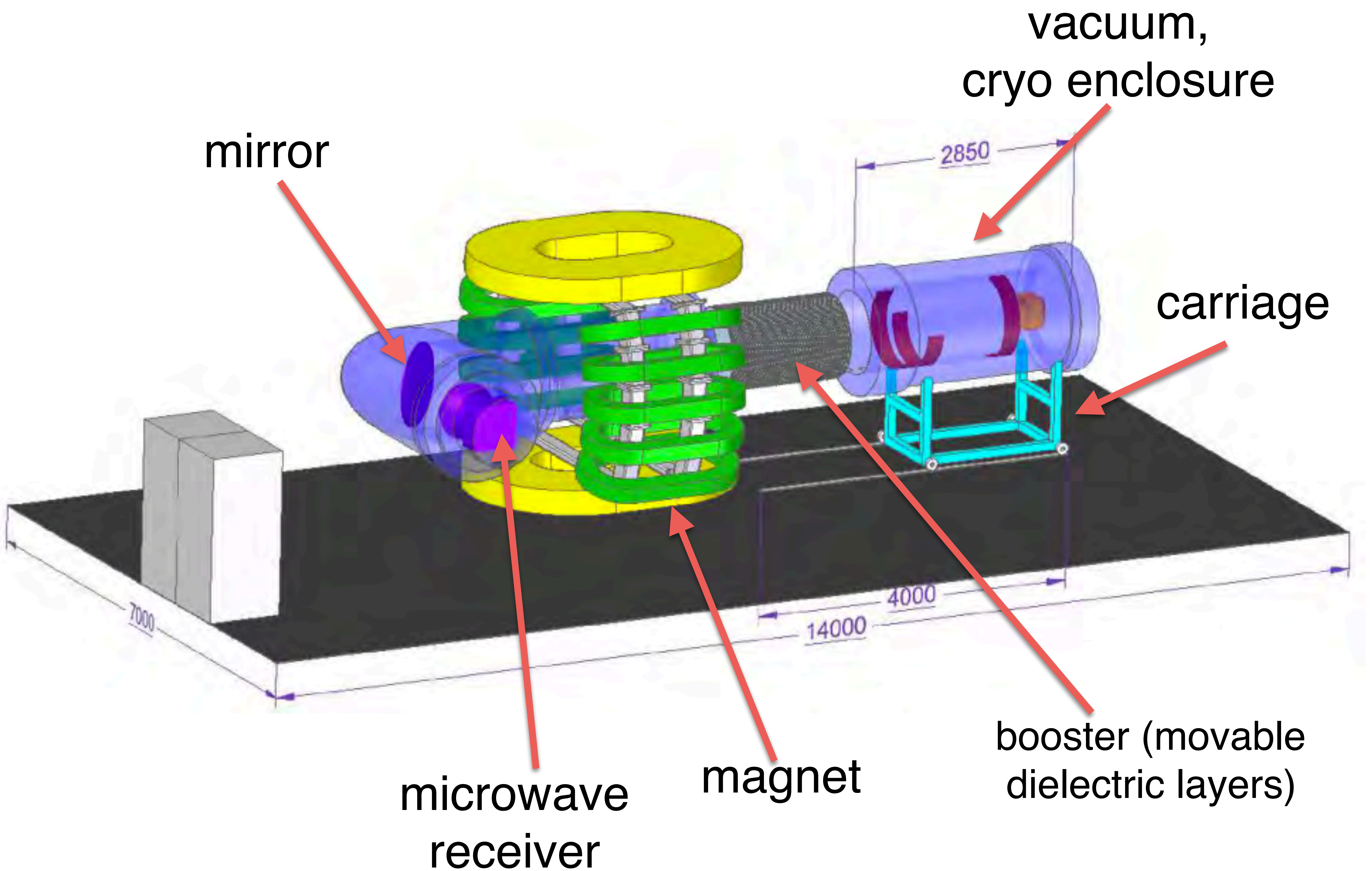
test setup in Munich

O. Reimann / MPP

- The real device (200mm sapphire disks):



MADMAX prototype plan



MADMAX experiment

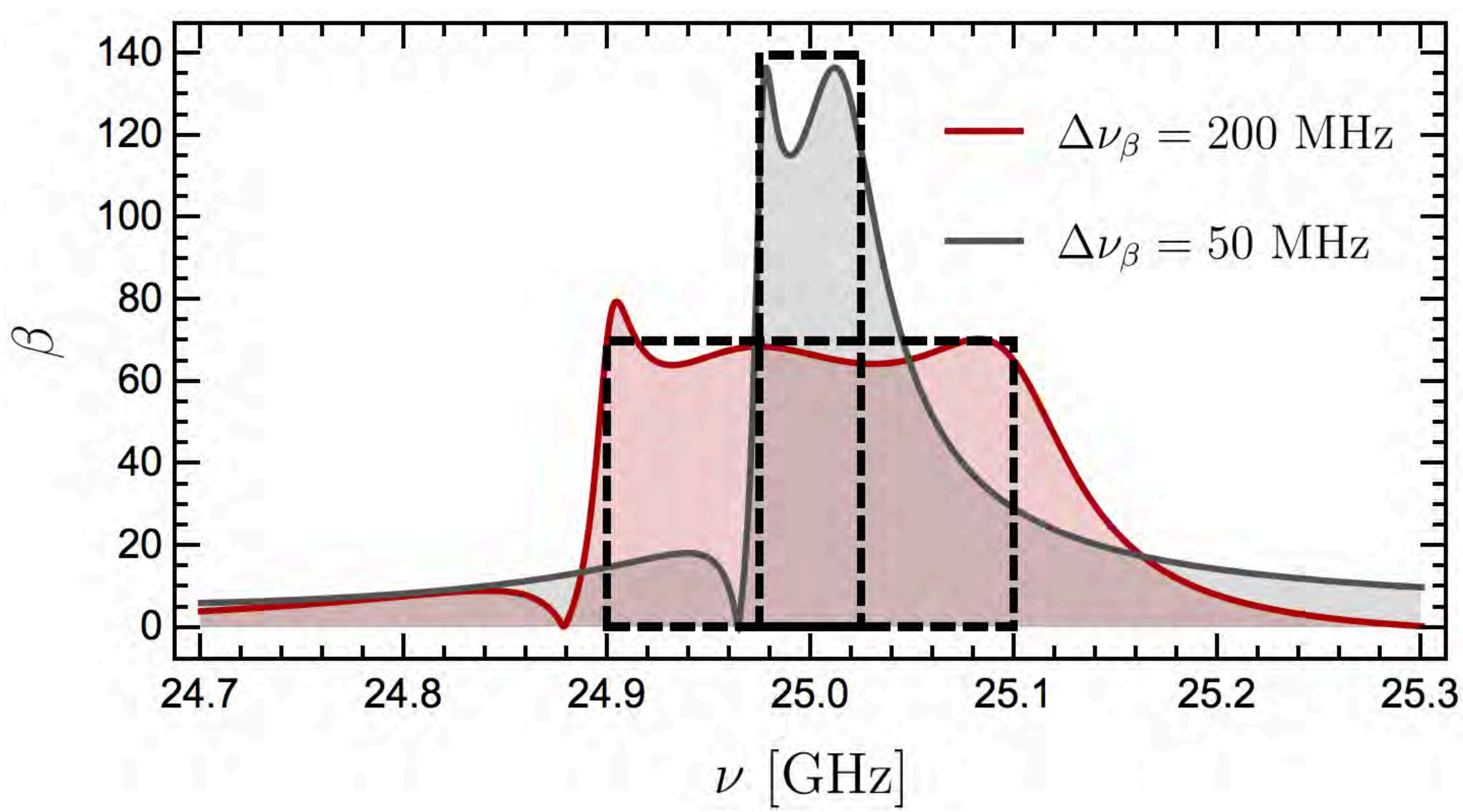
arXiv:1612.07057

operating principle

- equidistant layers:
  - large boost, good S/N
  - narrow frequency range
  - frequent disk -repositioning required
- slight misalignment of layers:
  - smaller boost, worse S/N
  - broad frequency range
  - less repositioning

→trade-off for optimal sensitivity

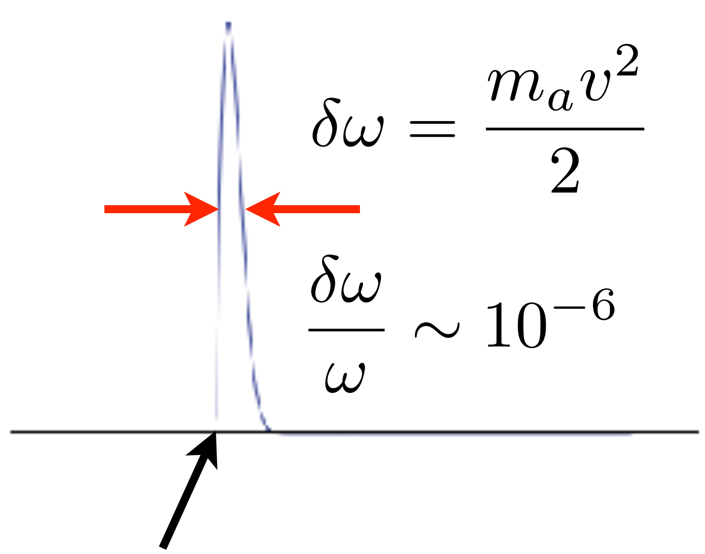
- all disks need individual high-precision adjustment



MADMAX experiment

- challenges:
  - huge and strong magnet (never built before)
  - large, thin dielectric media to be moved around with high precision (in vacuum, strong field)
  - tiny signal, unknown frequency
  - is DM here or out there?
  - coherence:

$$\omega \simeq m_a(1 + v^2/2 + ...)$$



$$\delta\omega = \frac{m_a v^2}{2}$$

$$\frac{\delta\omega}{\omega} \sim 10^{-6}$$

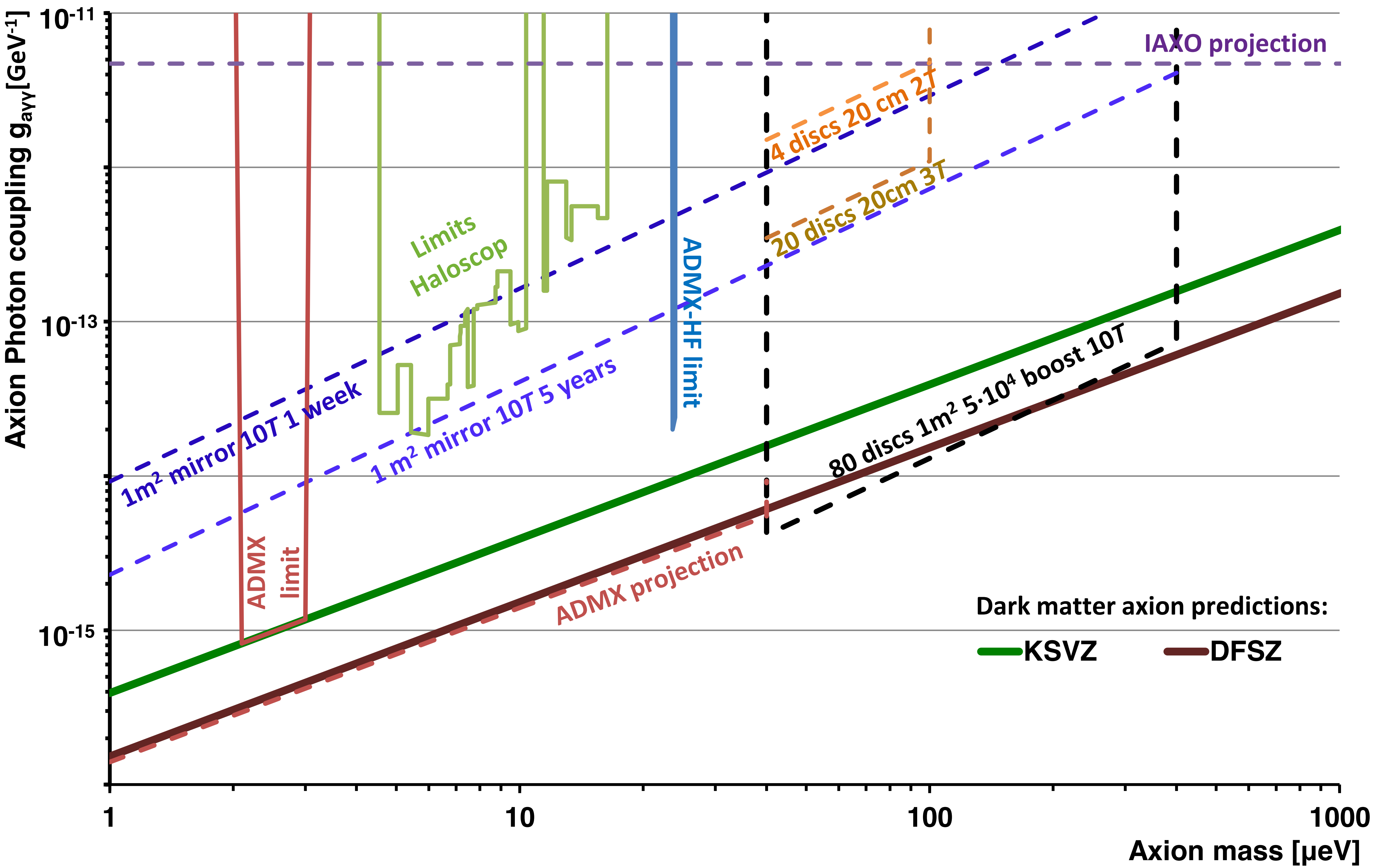
m_a

coherence length

$$\delta L \sim \frac{1}{\delta p} \sim 20\mathrm{m}\left(\frac{10^{-5}\mathrm{eV}}{m_a}\right)$$

MADMAX experiment

plot from MADMAX white paper



MADMAX white paper

- UHH & DESY have signed the MADMAX white paper:

A new experimental approach to probe QCD Axion Dark Matter in the mass range above 40 μeV

The MADMAX interest group:
P. Brun[a] A. Caldwell[b] L. Chevalier[a] G. Dvali[b,c] E. Garutti[d] C. Gooch[b] A. Hambarzumjan[b] S. Knirck[b] M. Kramer[e] H. Krüger[f] T. Lasserre[a] A. Lindner[f] B. Majorovits [b,1] C. Martens[f] A. Millar[b] G. Raffelt[b] J. Redondo [g,2] O. Reimann[b] A. Schmidt[d] F. Simon[b] F. Steffen[b] G. Wieching[e]

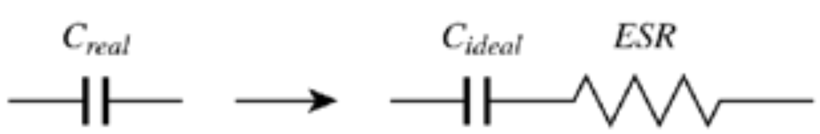
- madmax website:
https://www.mpp.mpg.de/forschung/astroteilchenphysik-und-kosmologie/madmax-suche-nach-axionen-als-dunkler-materie/

dielectric material

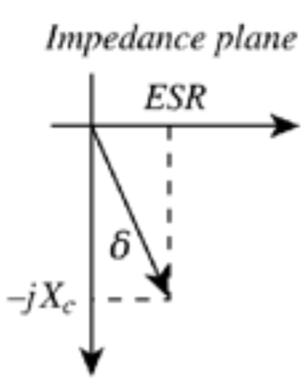
- **Problem**: find the ideal dielectric material to obtain
  - high boost factors
  - over a large surface

- ideal dielectric has:
  - High dielectric constant ($\varepsilon > 10$) for large axion/photon conversion factor
  - Low loss ($\tan \delta < 10^{-5}$) in order to reduce photon loss

real dielectric = ideal capacitor + equivalent series resistance (ESR)

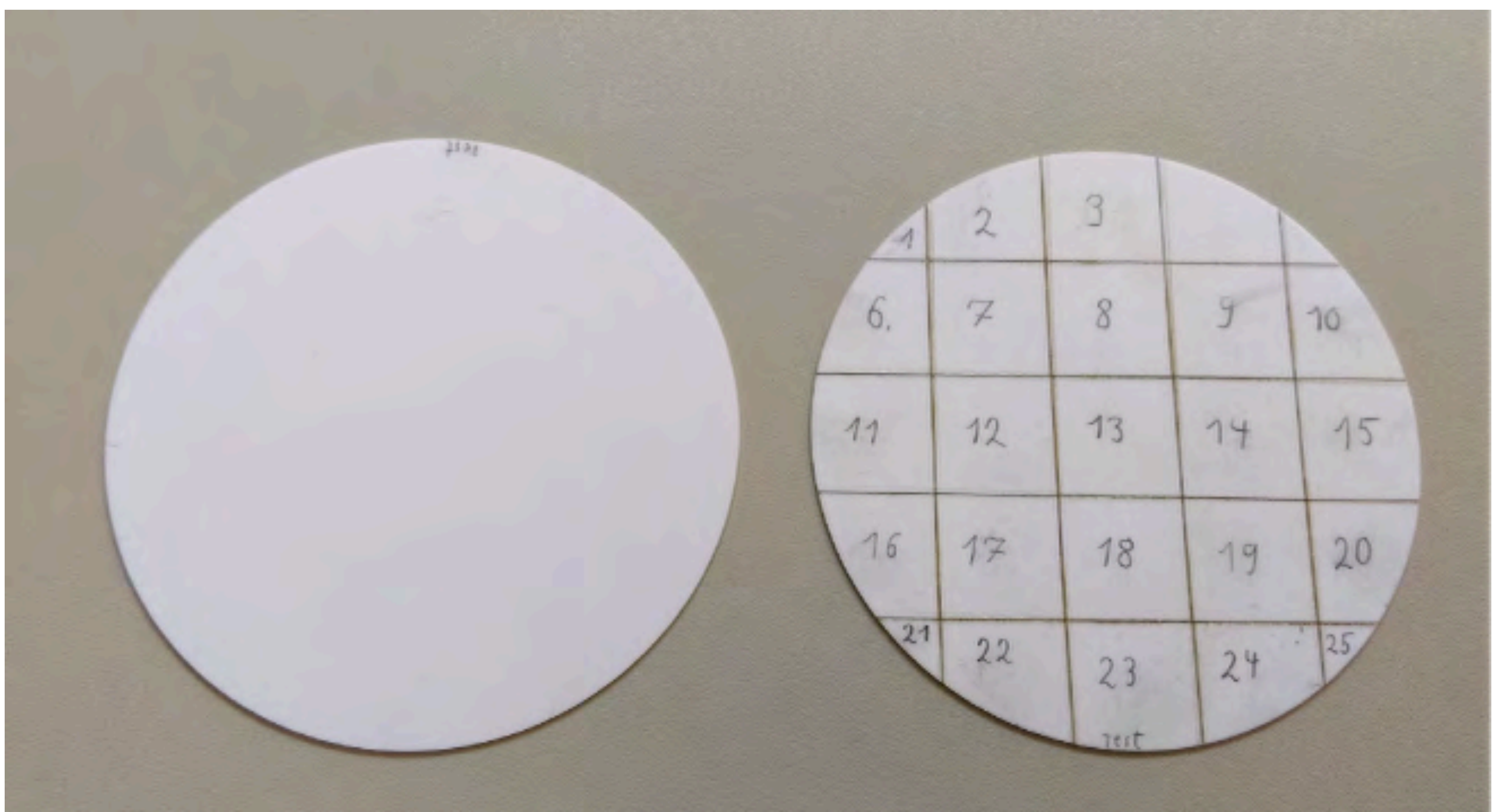


ESR should be minimum, i.e. tan δ should be small



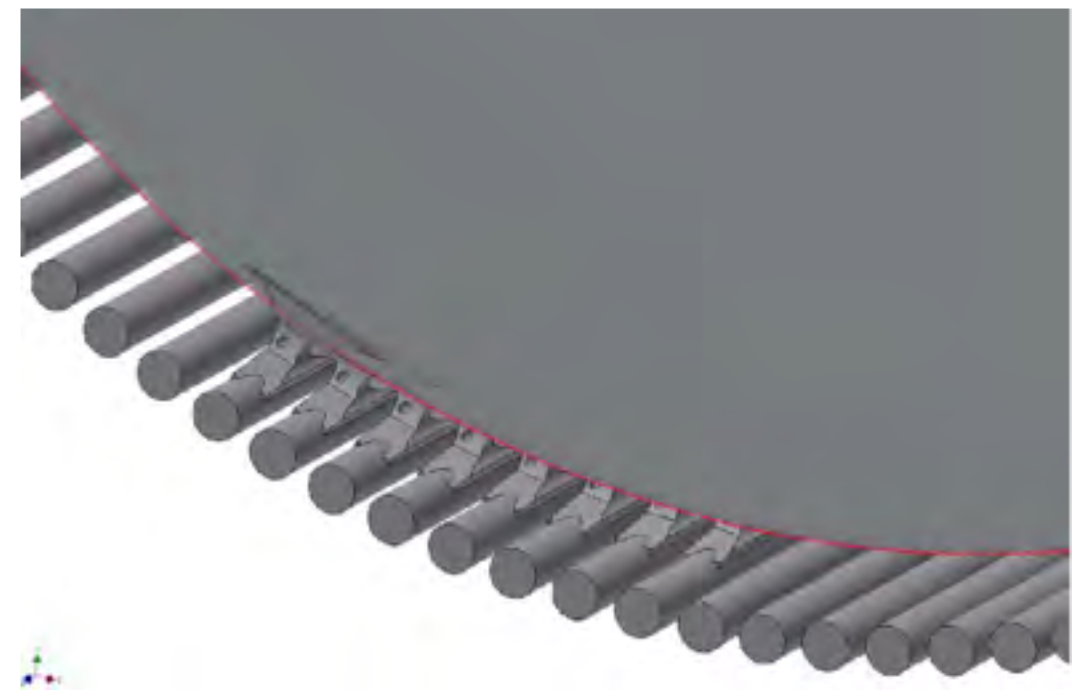
test of dielectric disk tiling

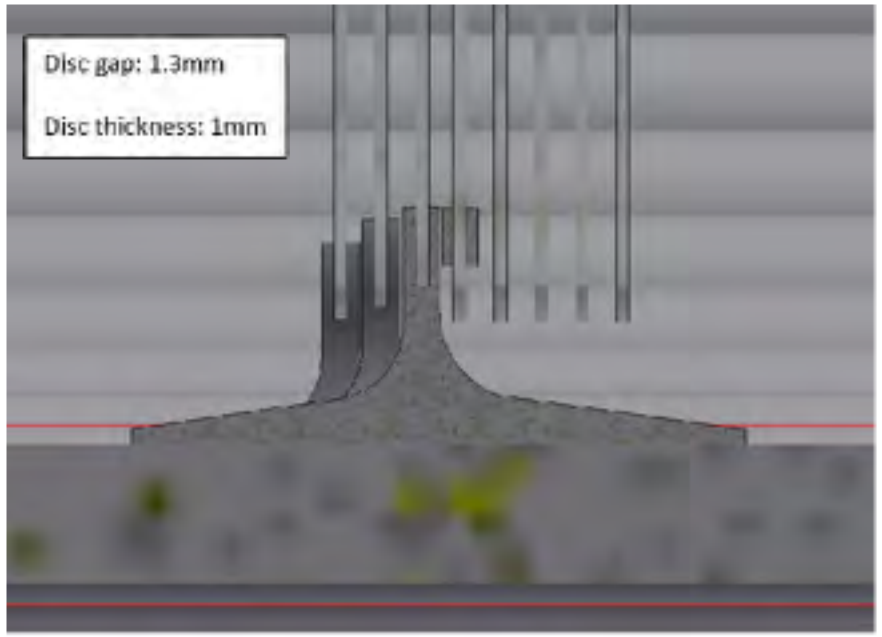
- 1 m^2 dielectric crystals cannot be grown (today)
- Solution: tiling
  - how to cut dielectric crystals ? (bridle)
  - how to glue ?
  - how to test dielectric properties after glueing ?



ideas for disk positioning system

- sliding rods to support & adjust position
- 3-points fixation / disc, 80 discs
- variable discs distance 1-20 mm
- rod movement ~ 1.6 m





goals of prototype in HH

- Test the scaling of the test system at MPP Munich to a full 80 discs booster system
- Test the mechanical alignment system
- Investigate behaviour of different dielectric material in a cryogenic environment
  - (and with high magnetic field)
- Check the agreement of simulations & measurements, including boost factor, transmissivity and reflectivity
- Study the required precision and stability of the mechanical alignment system and flatness of disc surface
- First test with a 4 T magnet
- First physics run with reduced sensitivity to obtain exclusion limits on Axion models

summary

> *"There are viable theories and there are natural and elegant theories.*
> *However, all viable, natural and elegant theories contain dark-matter axions"* — Ann Nelson

- three types of experiments searching for axions:
  - helioscopes
  - haloscopes
  - light-shining-through-wall
- all experiments will experience dramatic improvements in the coming years
  - better magnets, better detectors, better ideas
- the region where axions solve both QCD and DM problems will **soon be covered by MADMAX**

more

SFB Lectures

14 Jul 2017 DESY Hamburg (Room 2, Building 2a), 14:30	Axel Lindner: Axion/ALPs in Experiments [indico]
7 Jul 2017 DESY Hamburg (Room 2, Building 2a), 14:30	Andreas Ringwald: Axion/ALPs in Astrophysics and Cosmology [indico]
30 Jun 2017 DESY Hamburg (Room 2, Building 2a), 14:30	Andreas Ringwald: Axion/ALPs in Particle Physics [indico]

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