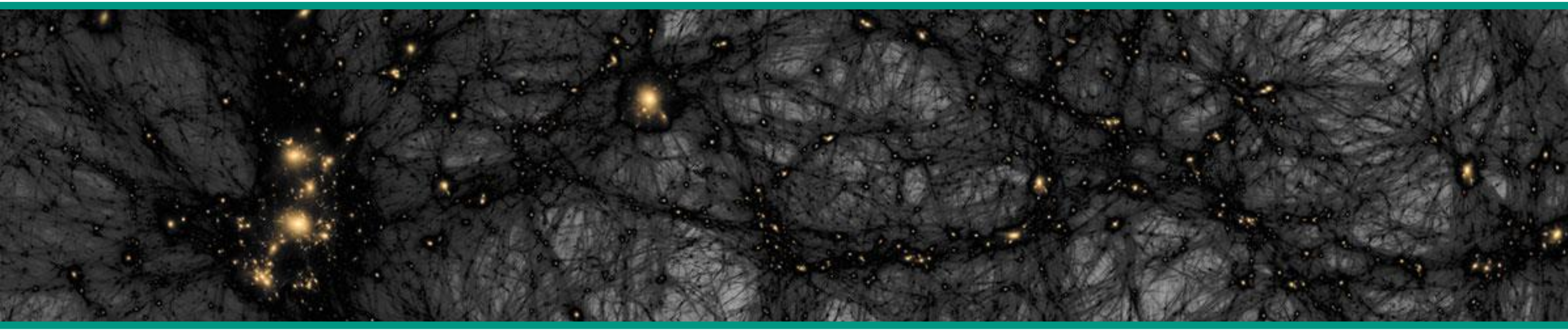
Astroparticle physics I – Dark Matter

WS22/23 Lecture 21 Feb. 15, 2023



Recap of Lecture 20

- **Axions: a non-thermal $\boldsymbol{WISP}$ as a ´totally different´ $\boldsymbol{DM}$ – candidate**

  - **axions** introduced to solve the **strong $\boldsymbol{CP}$ – problem**: a light pseudo-scalar

  - **mass $\boldsymbol{m_a}$** depends on (unknown) **scale $\boldsymbol{f_a}$** of spontaneous breaking of $\boldsymbol{U(1)_{PC}}$

  - broad mass range possible: $\boldsymbol{m_a = \mu eV \ldots meV}$ (latest: $\boldsymbol{m_a = 40 \ldots 180\ \mu eV}$)

  - extension: $\boldsymbol{ALP}$s = $\boldsymbol{A}$xion-$\boldsymbol{L}$ike-$\boldsymbol{P}$articles, do not solve $\boldsymbol{QCD}$ –/$\boldsymbol{DM}$ – problem

  - axions form a **Bose-Einstein condensate** in the galactic $\boldsymbol{DM}$ – halo

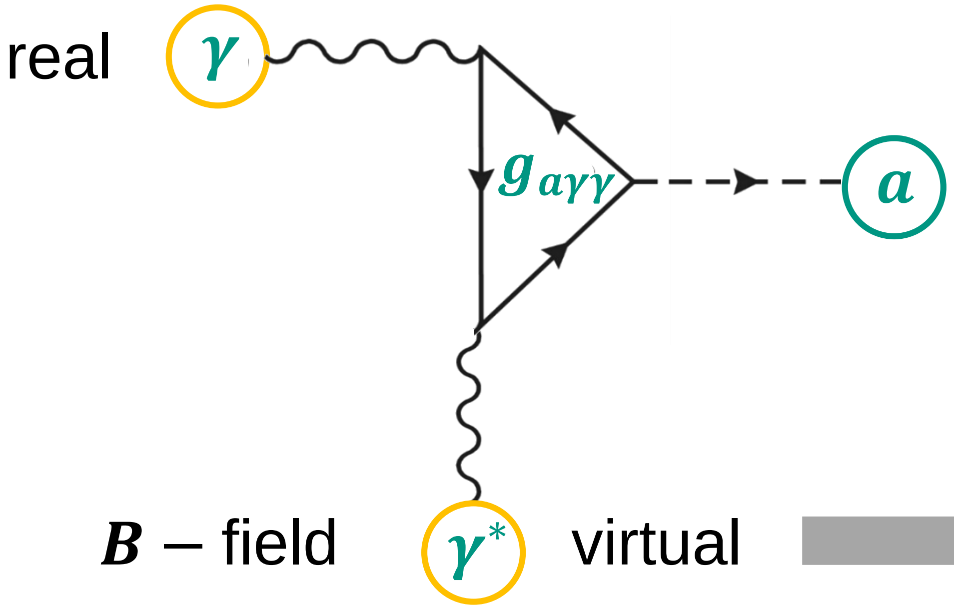
  - various astrophysical limits: $\boldsymbol{CDM}$ –requirement, $\boldsymbol{SN - \nu}$ –pulse: $\boldsymbol{m_a < 16\ meV}$

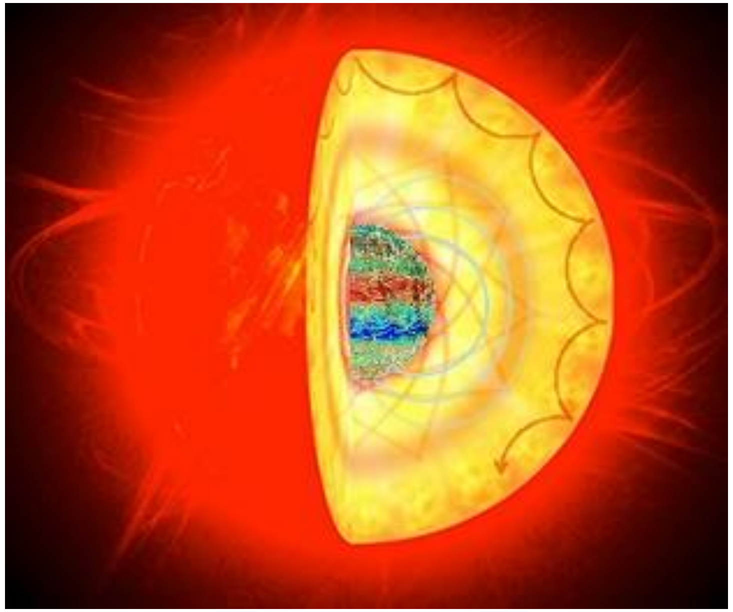
Generating axions via the Primakoff effect

- A ´natural´ process to generate axions: here - in a magnetized plasma

  - for axion emission: will occur in magnetized plasma state from **virtual photons** γ^* to transform **real photons** γ (from the plasma) into axions via Primakoff effect

  - axions then leave the solar interior without further interaction & can be detected



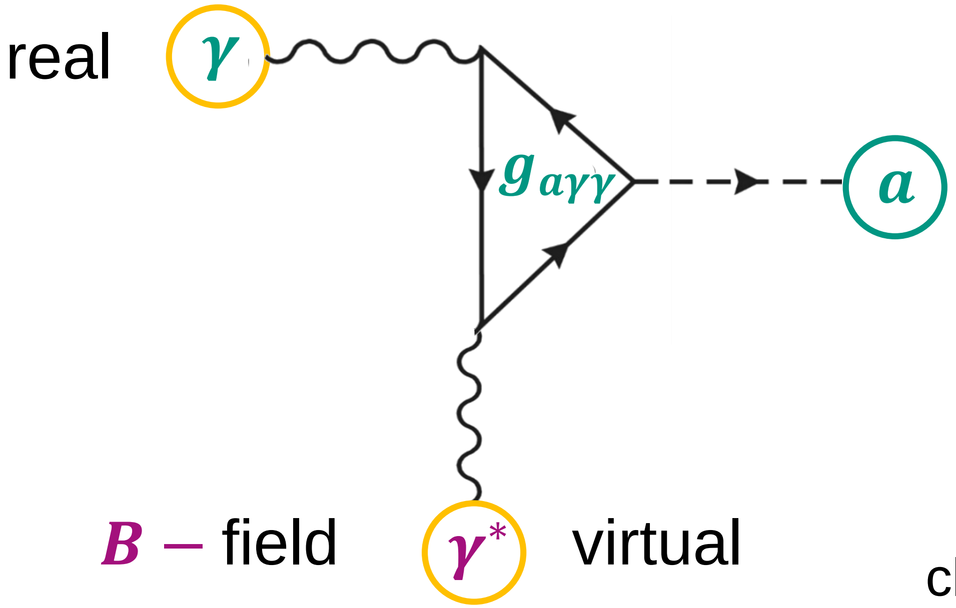


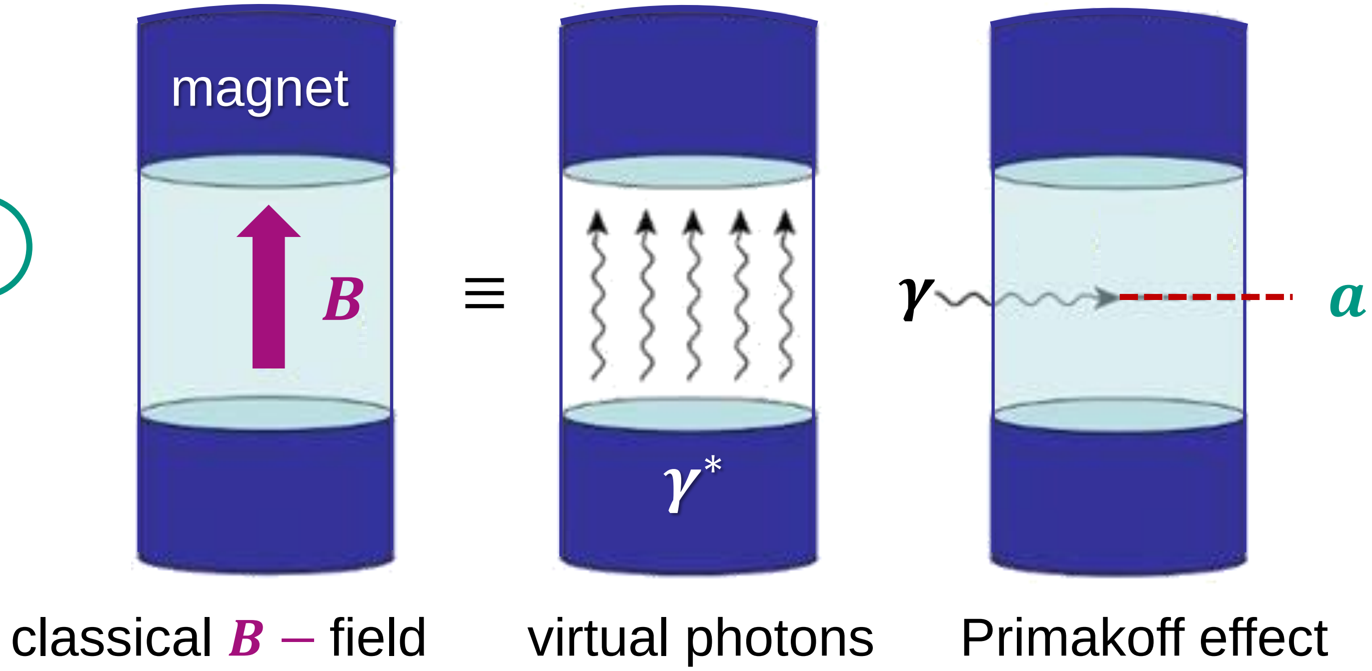
example: **magnetised plasma** in the solar interior

Generating axions via the Primakoff effect

- **A** **coherent** **process to generate axions: here - we use a** **magnet**

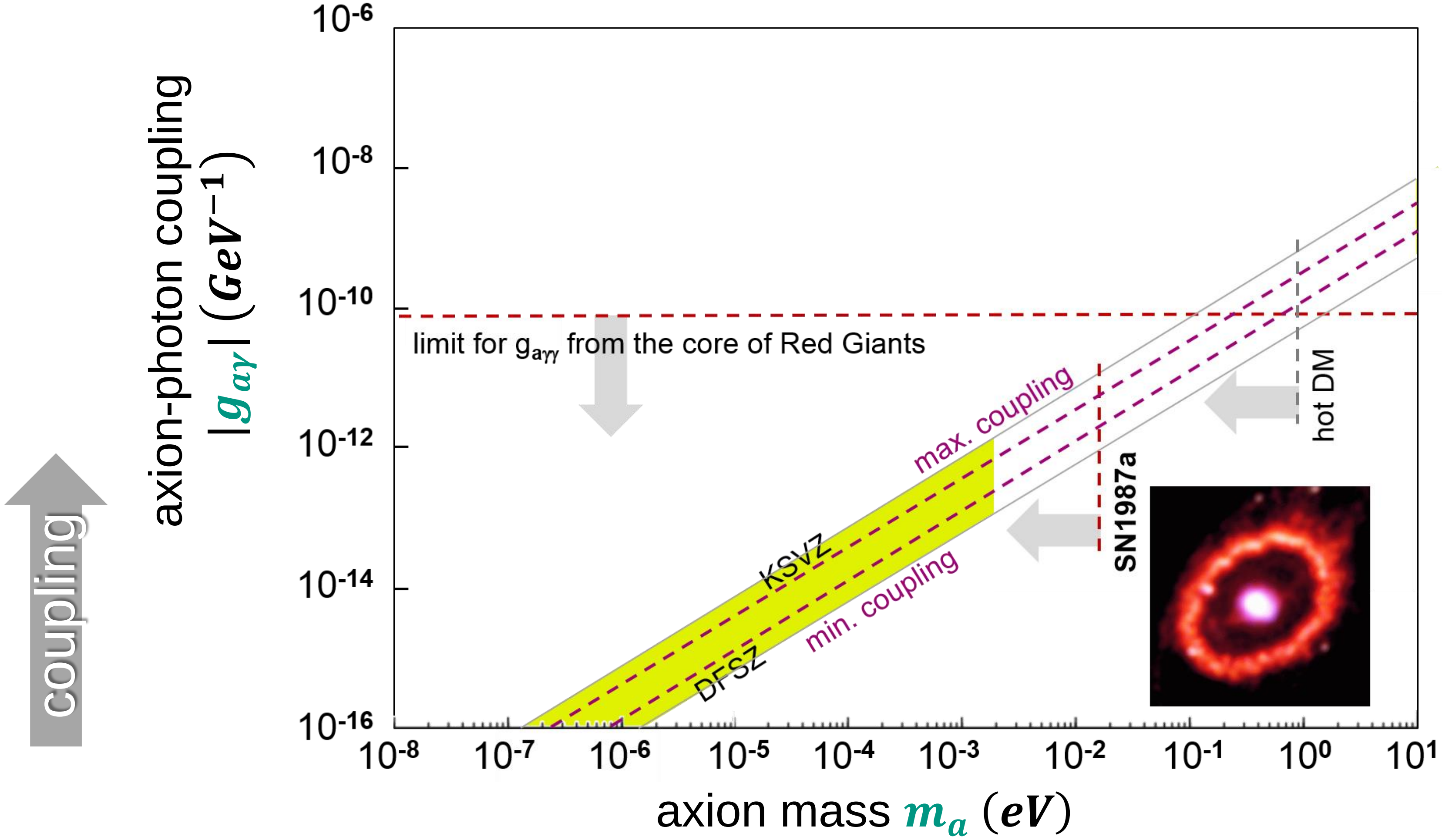
  - the stronger the $\boldsymbol{B}$ – field (lab: up to $\mathbf{10}\ \boldsymbol{T}$) the more **virtual photons** $\boldsymbol{\gamma^*}$ we have to transform **real photons** $\boldsymbol{\gamma}$ into axions





The axion plot: mass m_a *vs.* coupling $g_{a\gamma\gamma}$

- **Experimental limits on axion parameters compared to theoretical estimates**



…OK, in principle it´s like the $WIMP$ plot we know…

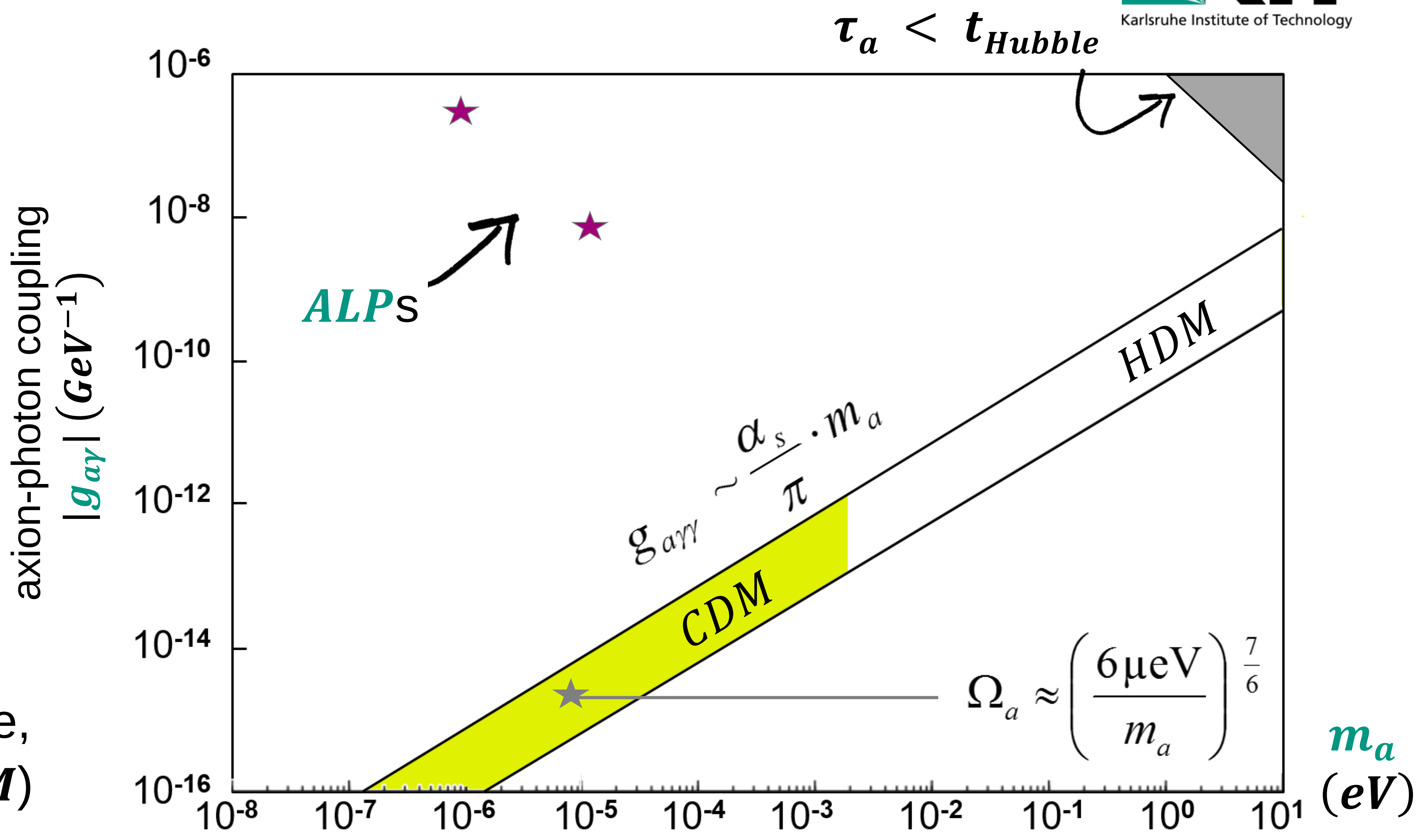
mass

Axion plot: parameters for QCD – axions

- QCD – axions

- **expected parameter regions** form an allowed band

- beyond:
  ALPs ★
  Axion Like Particles
  (no CP – relevance, little impact on DM)

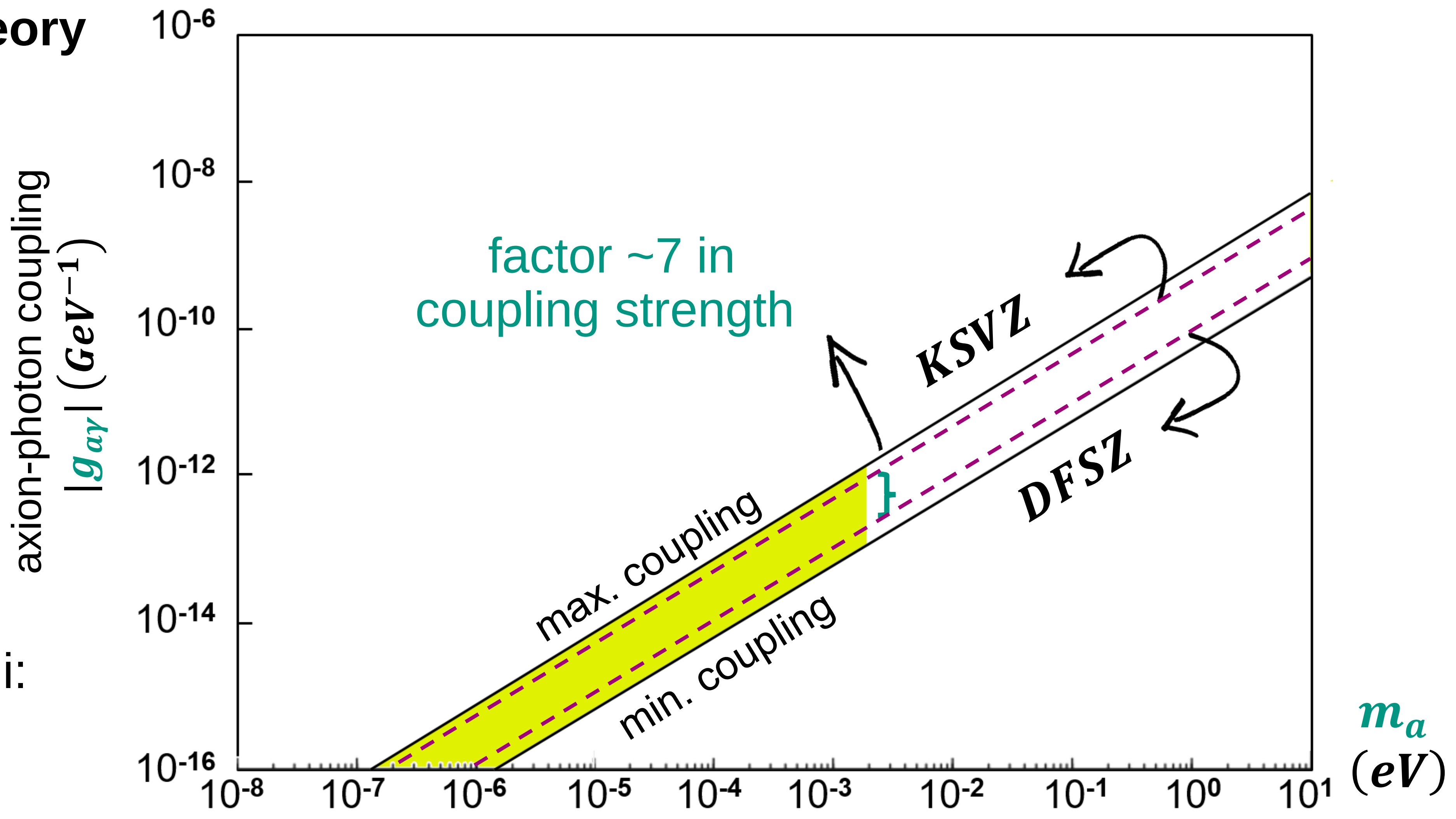


Axion plot: parameters for QCD – axions

- QCD – axion theory

- $KSVZ$
  Kim-***S***hifman-***V***ainstein-***Z***akharov: **stronger** axion coupling

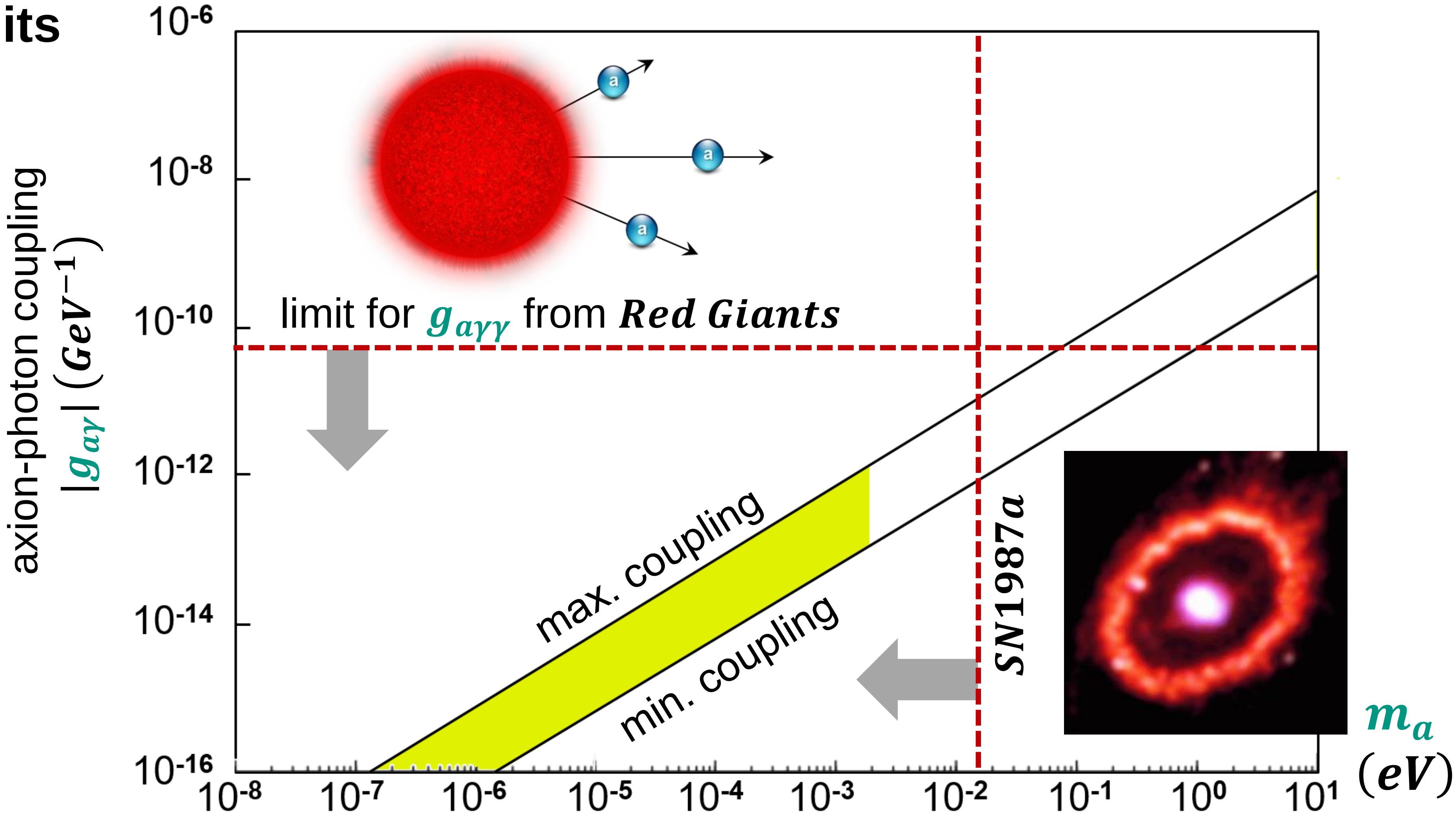
- $DFSZ$
  Dine-***F***ischler-***S***rednicki-***Z***hitnitskii: **weaker** axion coupling



Axion plot: limits from astrophysics

- QCD – axion limits

- limits due to observed time constants of cooling processs of stars:
  Red Giants
  Supernovae
  White Dwarfs
  star clusters
  ...



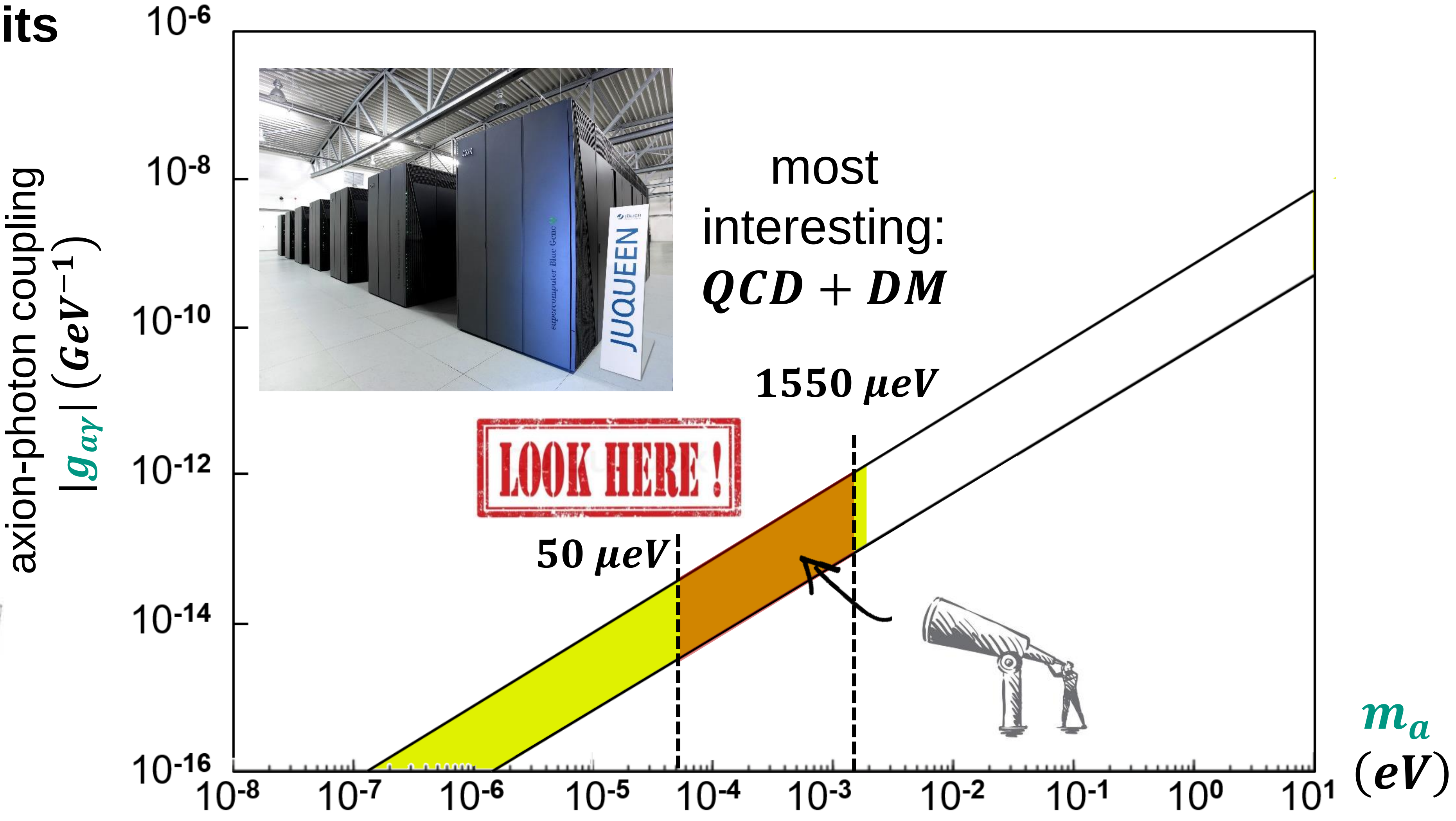
Axion plot: preferred values from lattice−QCD

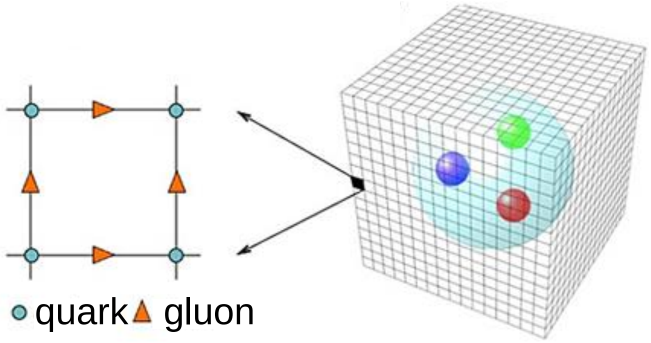
- QCD – axion limits

- limits from modern lattice QCD-calculations

- 2022 update:

$m_a =$ $40 \ldots 180\ \mu eV$





Axion experiments

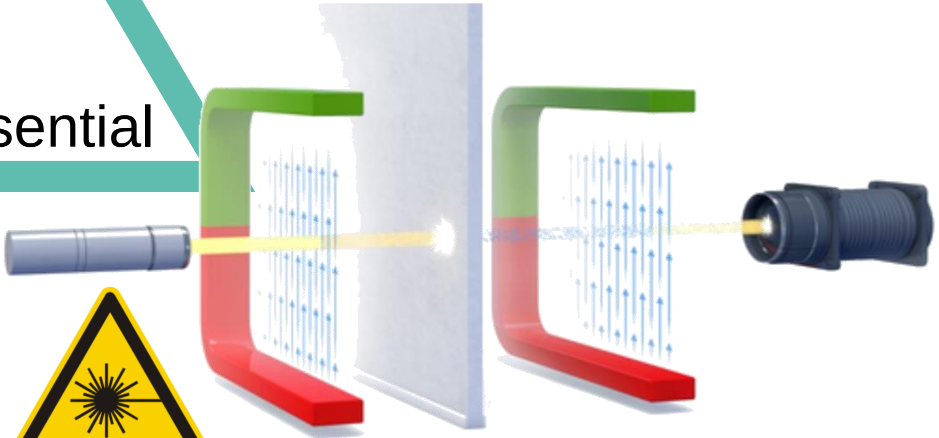
- **Detecting axions from**
  - dark matter halo, sun
  - indirectly

axion- (helio-) telescopes:
$CAST, IAXO$

Microwave-cavities (haloscopes):
$ADMX, HAYSTACK, \ldots$

$\boldsymbol{B}$ – fields are essential

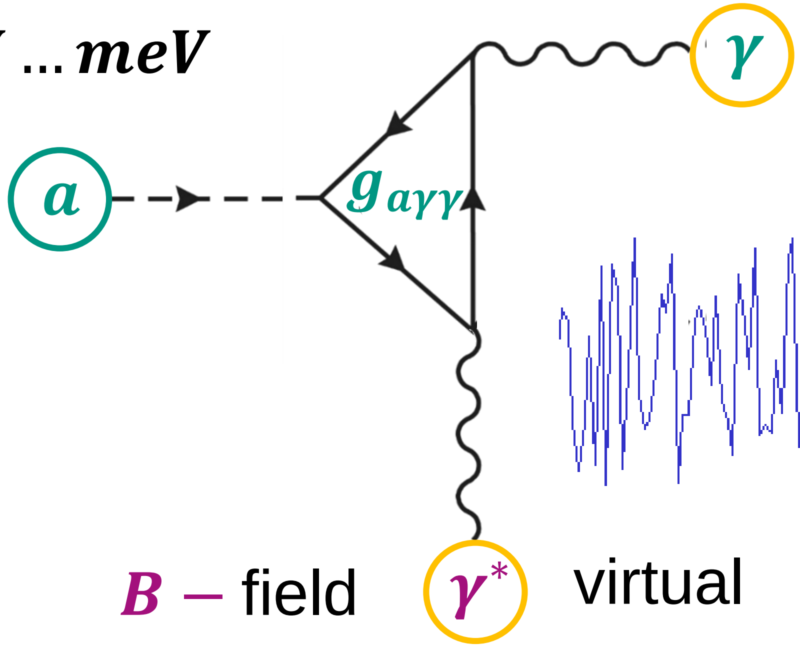
Light-***S***hining-through-***W***all (***LSW***):
$ALPS\ I, II\ \ JURA$



Axion experiments – haloscopes for galactic DM

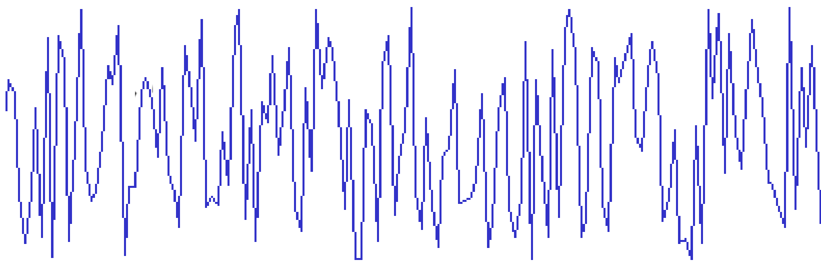
- **Listening for low-mass axions from the galactic DM – halo**

- sensitive mass range: $m_a = \mu eV \dots meV$



real

microwave band



B – field

virtual

Microwave-cavities (haloscopes):
$ADMX, HAYSTACK, \dots$

Axion experiments – haloscopes for galactic DM

- **Listening for low-mass axions from the galactic DM – halo**

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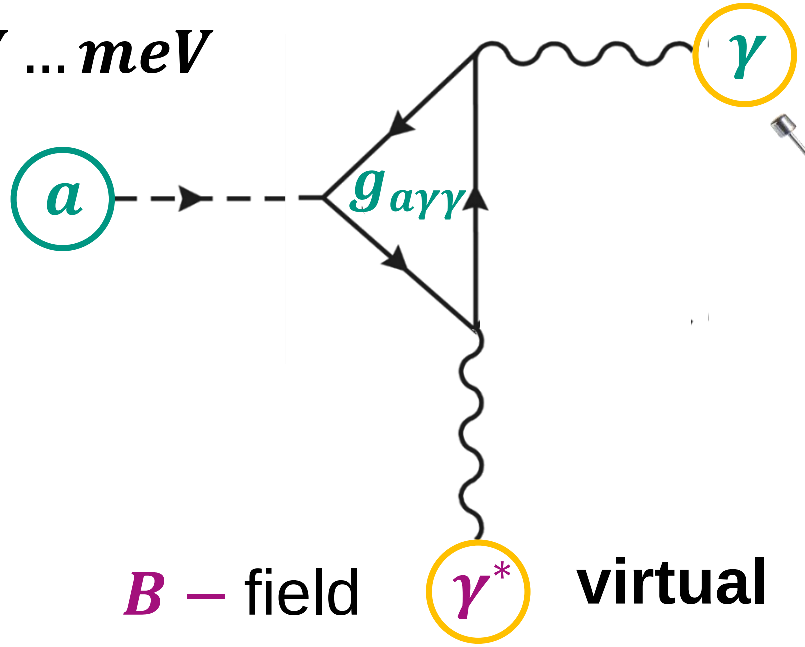
Microwave-cavities (haloscopes):
$ADMX, HAYSTACK, \ldots$



real
microwave band

B – field
virtual

- on which **frequency f** can I tune into the galactic ´DM –radio´?

Axion experiments – haloscopes for galactic DM

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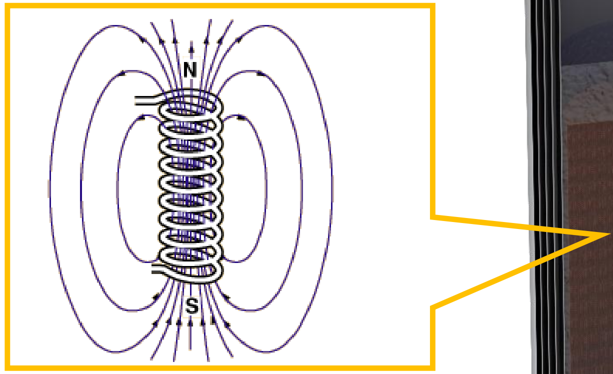
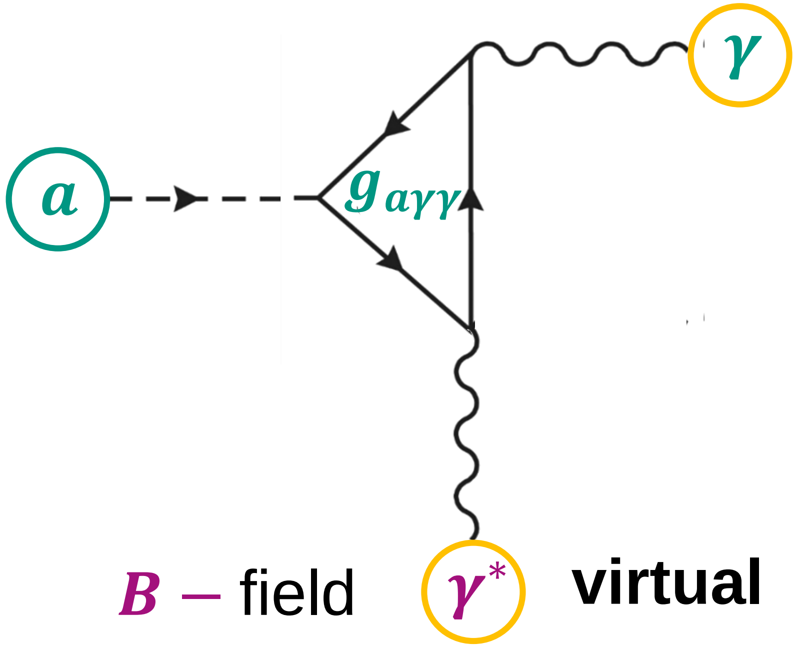
- **Superconducting solenoid with $B = 6 \dots 9\ T$ & a large bore**

- axion conversion rate (signal power) is a **coherent process**

$$P_{sig} \sim B^2$$





real

microwave band

B – field

virtual

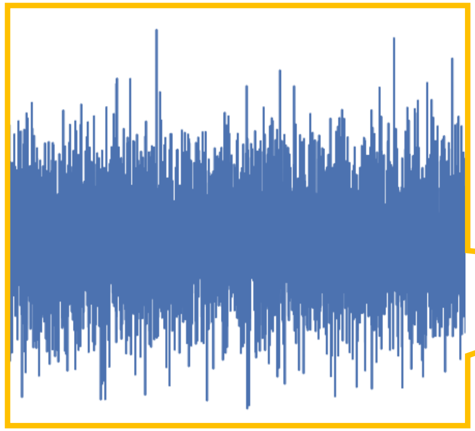
superconducting solenoid

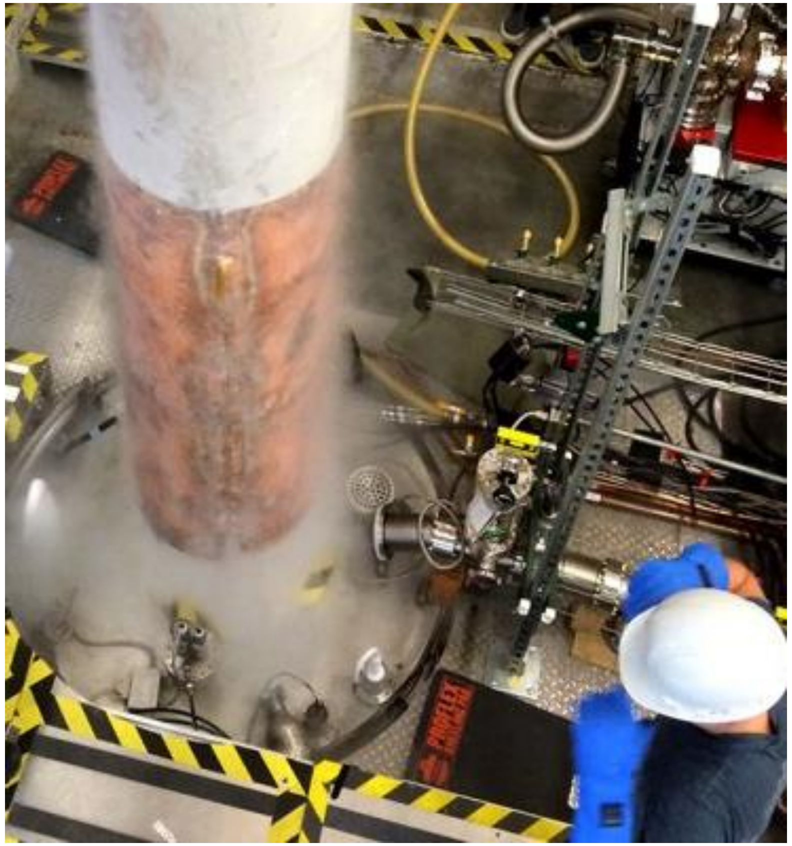
Axion experiments – haloscopes for DM –axions

- **Superconducting solenoid with $B = 6 \ldots 9\ T$ & a large bore at cryogenic T**

- axion conversion rate (signal power) vs. **thermal noise**

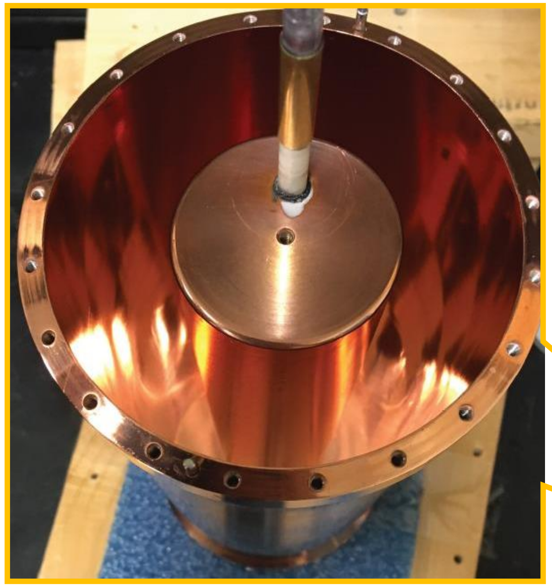
$$P_{noise} \sim T^4$$



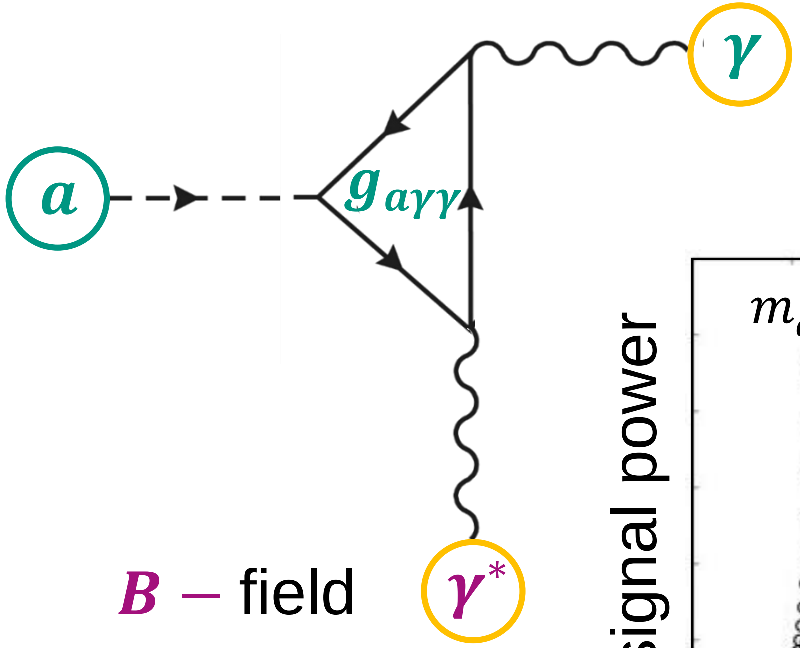


Axion experiments – haloscopes for DM –axions

- A Cu-based cylindrical resonance cavity: low thermal noise at cryogenic T

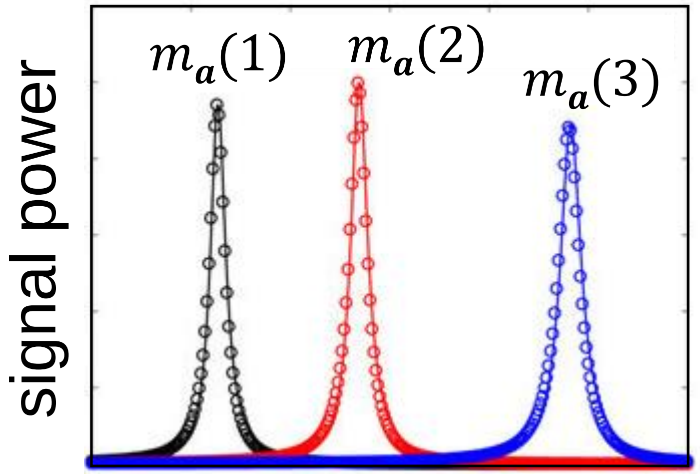


Cu – cavity & tuning rods for resonant amplification



$MHz \ldots GHz$ band

$100 \ldots 250\ mK$



resonance frequency of the Cu – cavity

Haloscopes for DM –axions: where is f_{res}?

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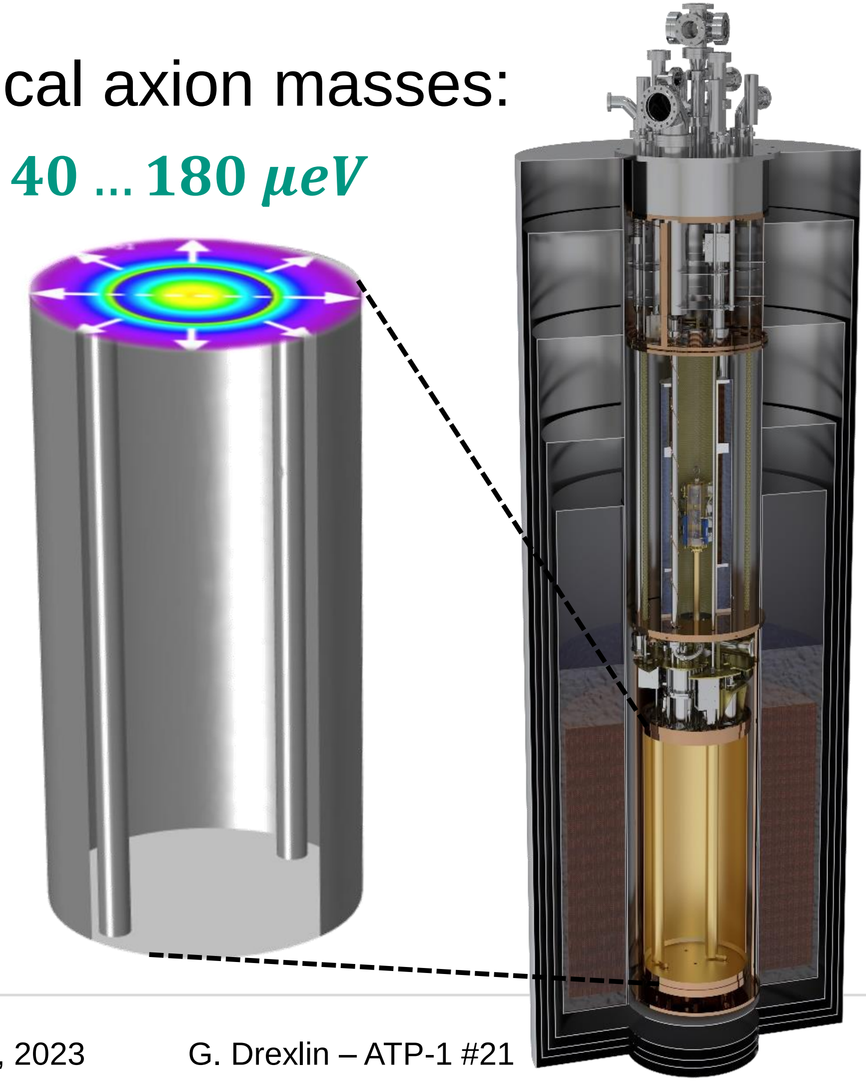
- **A Cu-based cylindrical resonance cavity: modify frequencies over broad f_{res}**

- theoretical axion masses:

$$m_a = 40 \ldots 180\ \mu eV$$



- experiment relies on **resonance** condition

axion energy $E_a = m_a \cdot c^2 + E_{kin}$

photon energy $E_\gamma = h \cdot f_{res}$

- examples

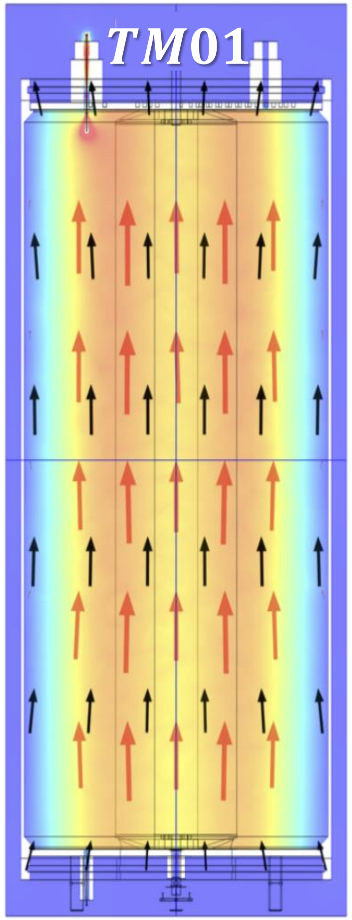
$$m_a = 10\ \mu eV \Leftrightarrow f_{res} = 2.4\ GHz$$

$$m_a = 100\ \mu eV \Leftrightarrow f_{res} = 24\ GHz$$

HF – mode

Haloscopes for DM – axions: use $TM01$ – mode

- **A Cu-based cylindrical resonance cavity with $TM01$ – mode**

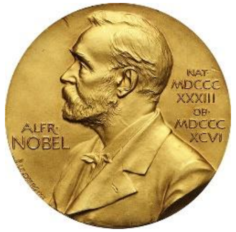


- excitation of the basic $\boldsymbol{TM01}$ – mode

- $\boldsymbol{TM01}$ – mode:
  magnetic flux is transversal to propagtion

- $\boldsymbol{TM01}$ – mode:
  $\boldsymbol{Cu}$ – cavity acts as wave-guide

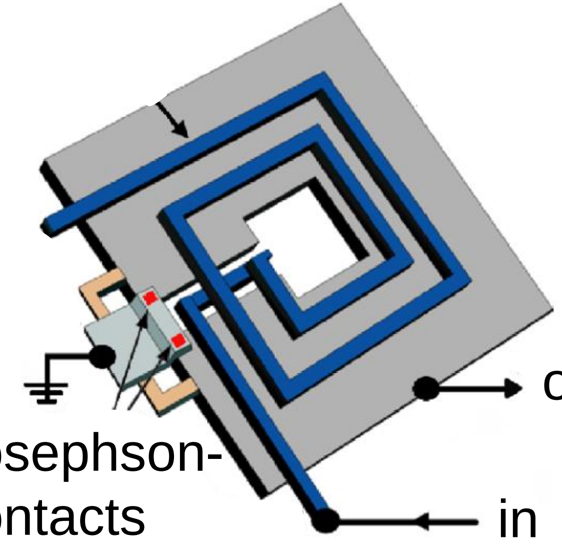
1981

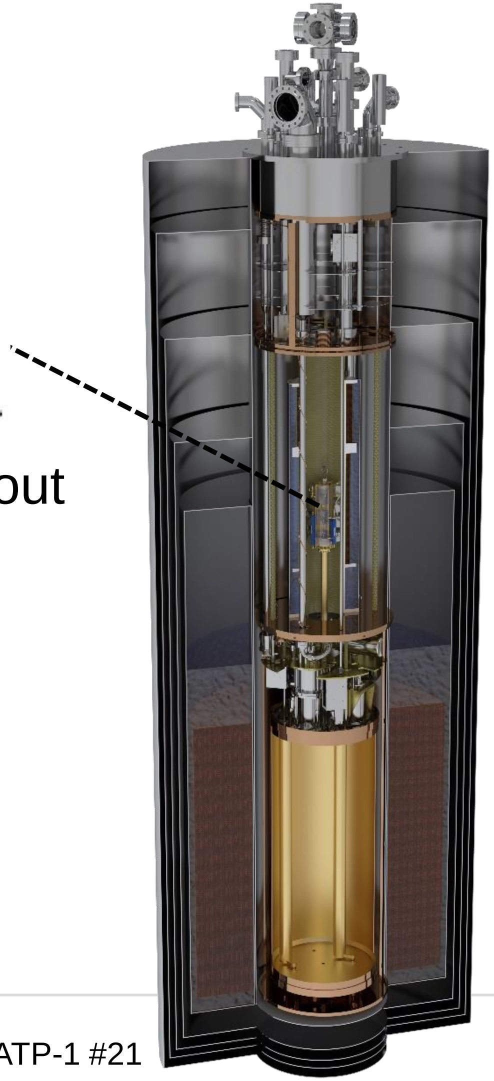


Arthur Schawlow:
„Never measure anything but frequency“

Haloscopes for $DM-$axions: signal & noise

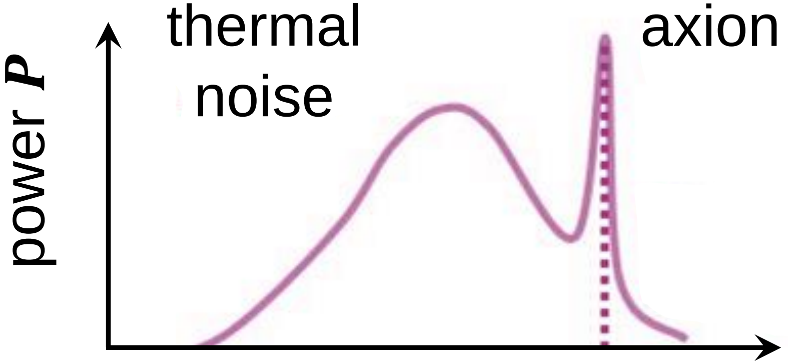
- **Read-out of haloscopes via a $SQUID-$unit***





- expected signal of a haloscope:

$$m_a \cdot c^2 + E_{kin} = h \cdot f$$



- experimental resolution:

$$\Delta f / f \sim 10^{-11}$$

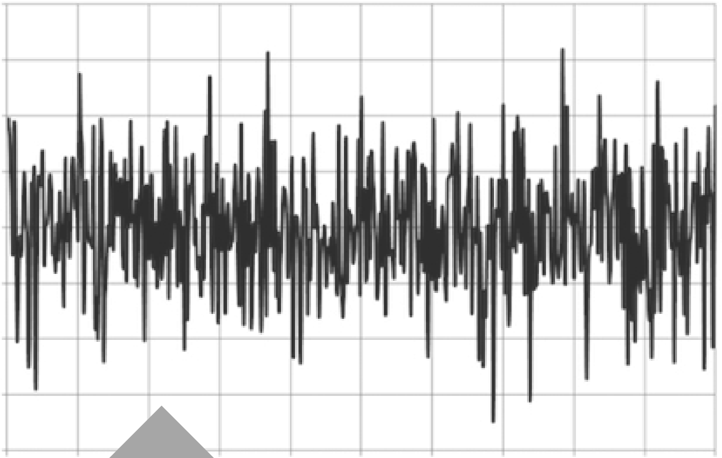
*s. lecture #19 p. 23-24

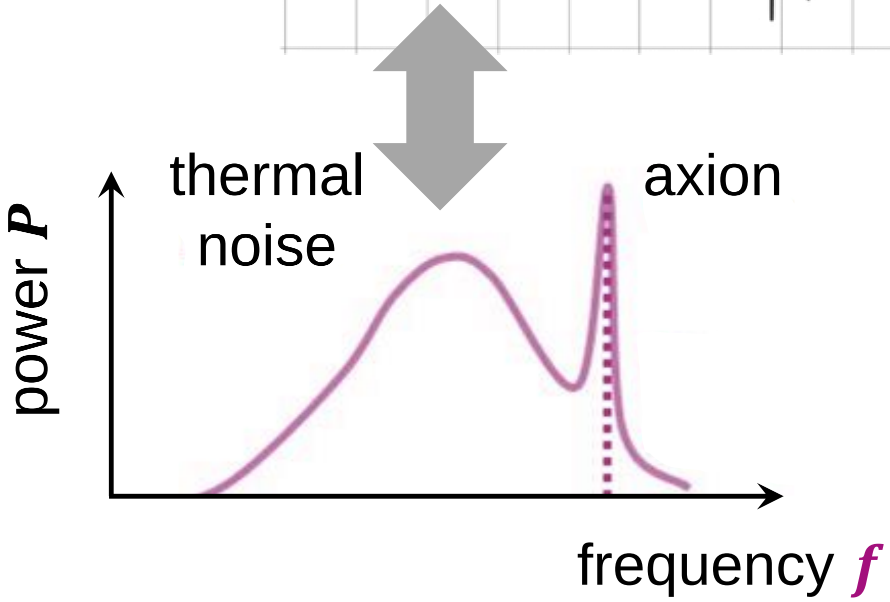
Haloscopes for DM – axions: signal & noise

- **haloscopes: cooling of microwave cavity is essential to limit the overall noise**

- thermal microwave photons are the dominant source of noise: ⇨ **cooling**

$$P_{noise} \sim T^4$$



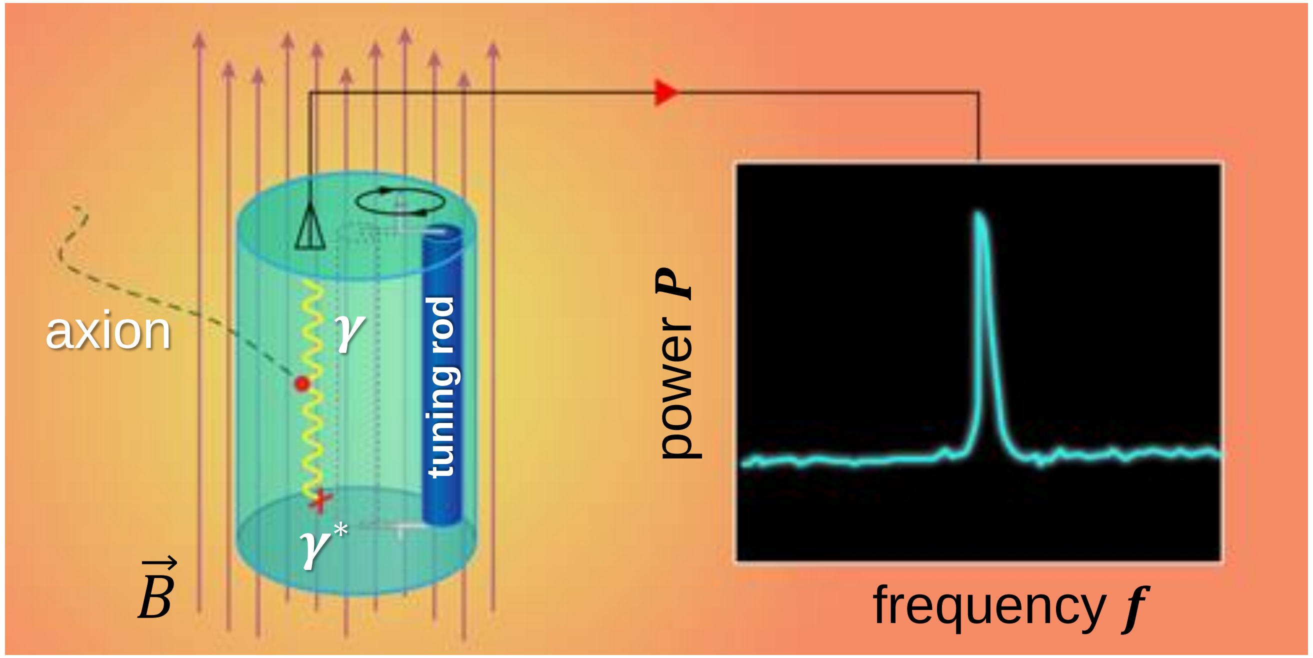


Haloscopes for DM – axions: signal & noise

- **haloscopes: detection via advanced sensors ($SQUID$) & FFT & strong B & cooling (T)**

what are the most important parameters?

signal power $P_{sig} \sim 10^{-22}\ W$



Haloscopes for DM – axions: figure–of–merit

- haloscopes: tiny (!!) expected axion signal power $P_{sig} \sim 10^{-22}\ W$

- *figure-of-merit*:

strong B – field

$B \approx 7.16\ T$

large volume V

$V \approx 0.15\ m^3$

high quality factor Q

$Q \approx 10^5$

local DM – density

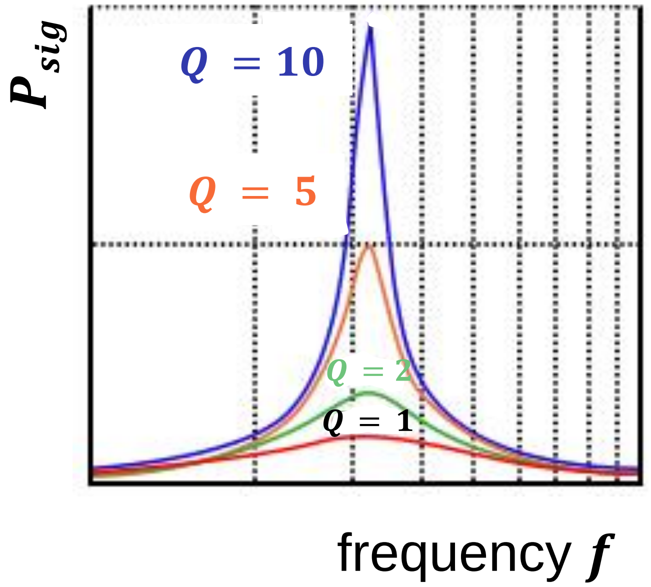
experimental parameters

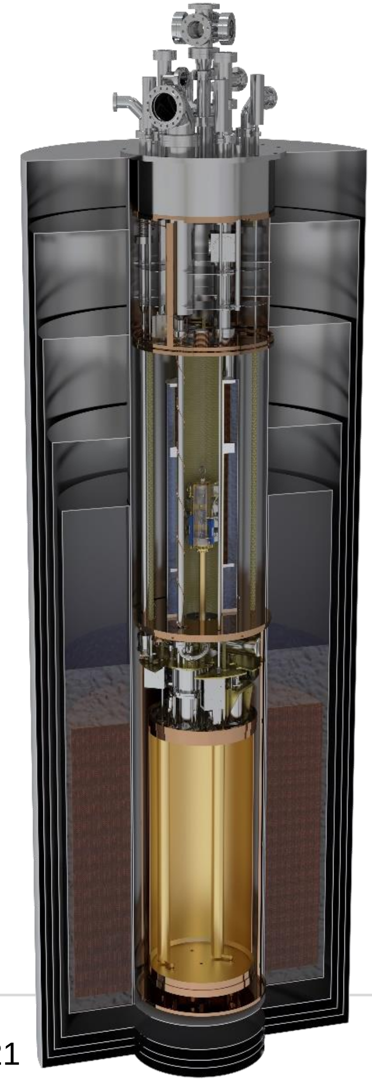
$$P_{sig} \sim g_{a\gamma\gamma}^2 \cdot \frac{\rho_{a,lokal}}{m_a} \cdot B^2 \cdot V \cdot Q$$

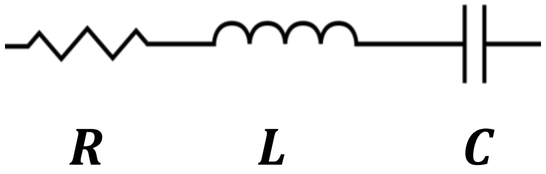
axion parameters

Haloscopes for DM – axions: figure–of–merit

- haloscopes: a high Q – value implies a very narrow bandwidth Δf







local DM – density

experimental parameter: Q

$$P_{sig} \sim g_{a\gamma\gamma}^2 \cdot \frac{\rho_{a,lokal}}{m_a} \cdot B^2 \cdot V \cdot Q$$

axion parameters

$$\frac{1}{Q} = \frac{\Delta f}{f_{res}}$$

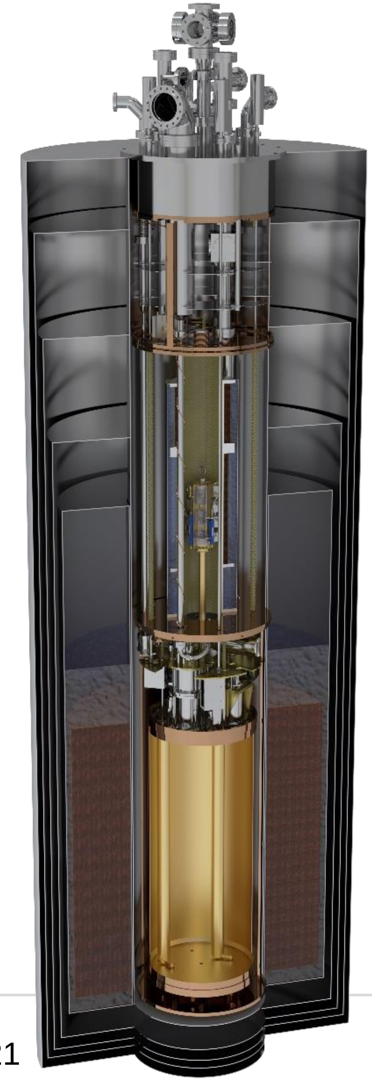
*A*xion *D*ark *M*atter E*X*periment - *ADMX*

- **A haloscope now based at *UW* Seattle: measurements since 1995**

- 1994-2004:
  measurements
  with conventional
  radio amplifiers

- 2007-…:
  measurements
  with ***SQUID***s
  exclusion limits
  for axion masses

$$m_a = (1.9 \ldots 3.65)\ \mu eV$$



$ADMX$: exclusion limits for axions

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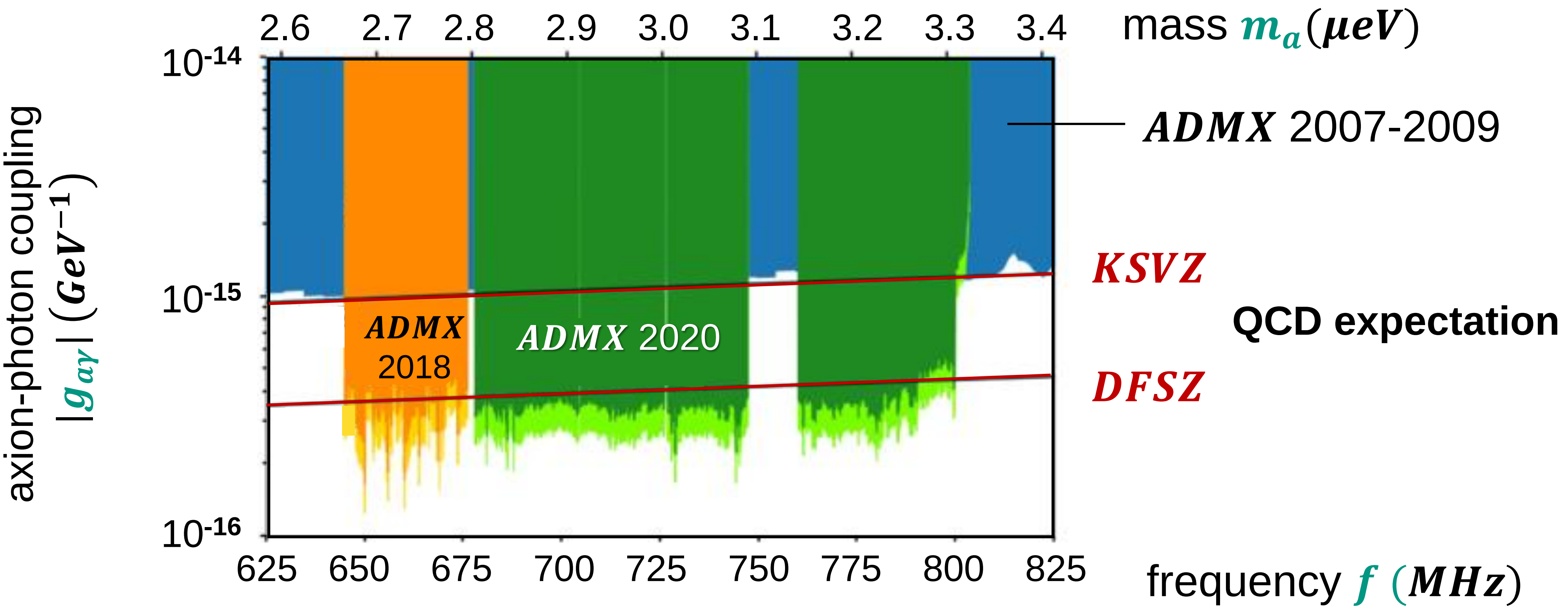
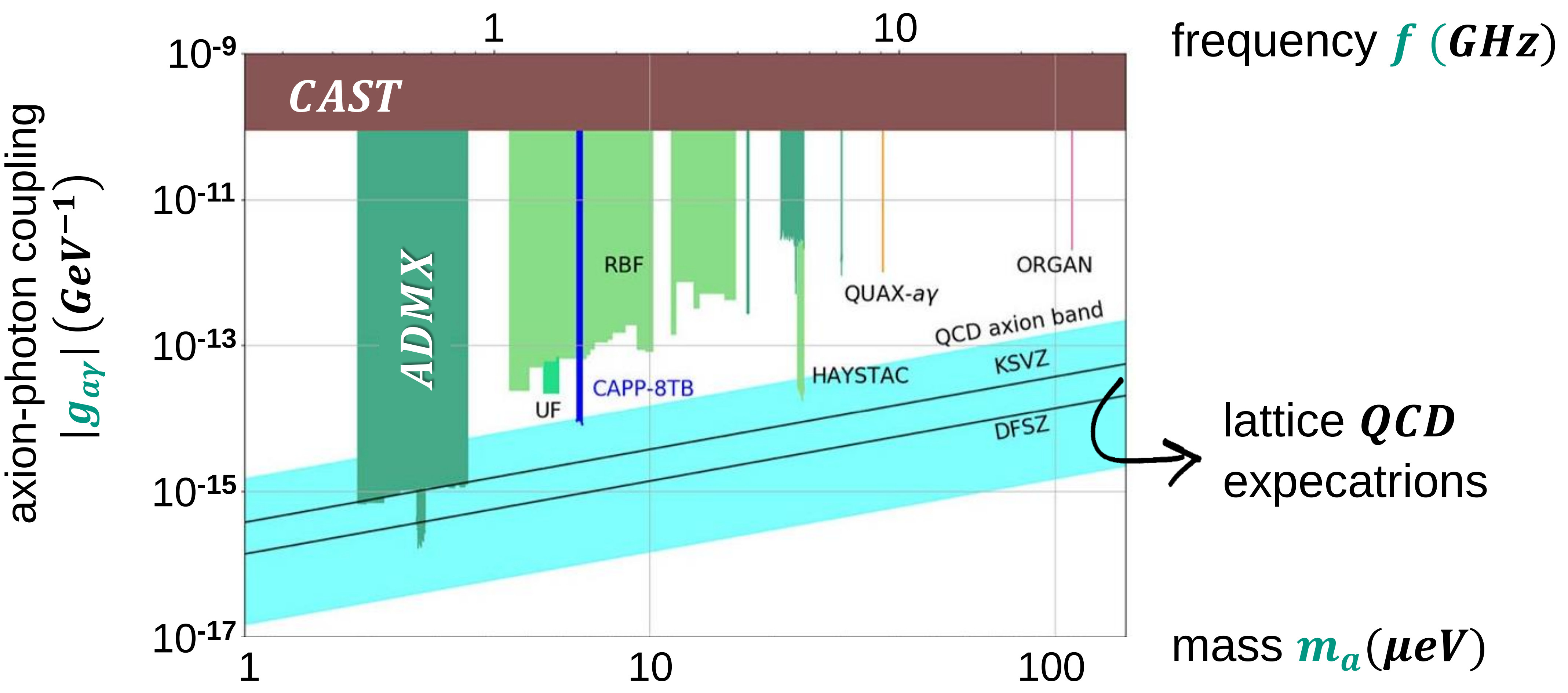
- **Overview of different axion campaigns over the years**



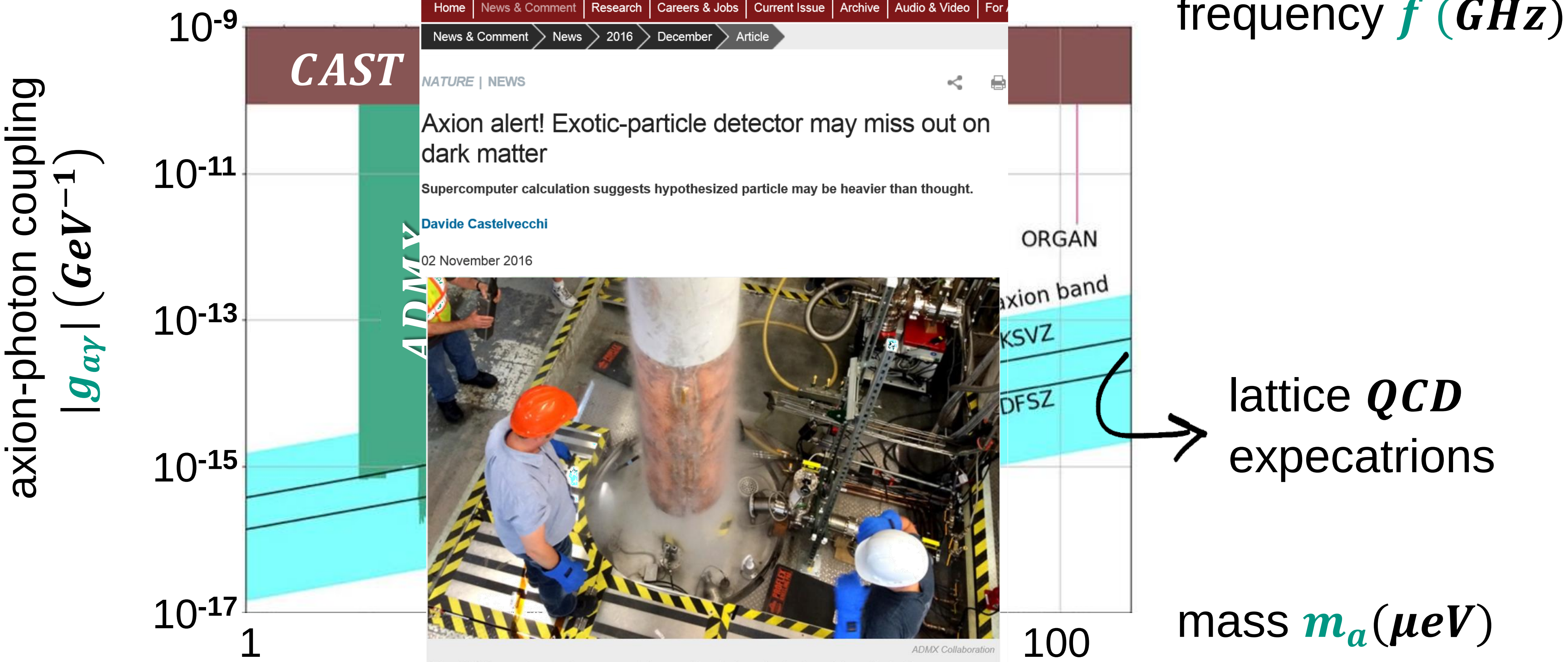
$ADMX$ & $HAYSTACK$: future campaigns

- **Overview of different axion campaigns: a lot more parameter space to cover**



$ADMX$ & $HAYSTACK$: axion alert

■ **Overview of different axion campaigns: a lot more parameter space to cover**



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NATURE | NEWS

Axion alert! Exotic-particle detector may miss out on dark matter

Supercomputer calculation suggests hypothesized particle may be heavier than thought.

Davide Castelvecchi

02 November 2016

ADMX Collaboration

The AMDX experiment, a large magnet, is searching for hypothesized particles called axions.

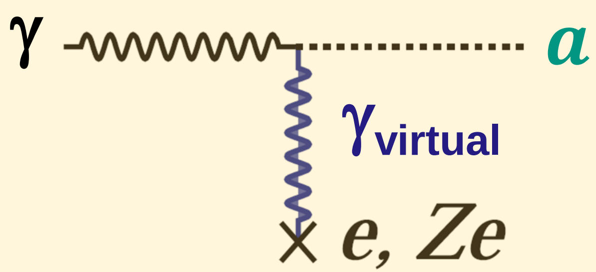
An ambitious supercomputer calculation has brought good and bad news for physicists hunting the 'axion' — a hypothetical particle that is considered a leading candidate for dark matter.

Axion experiments: helioscopes

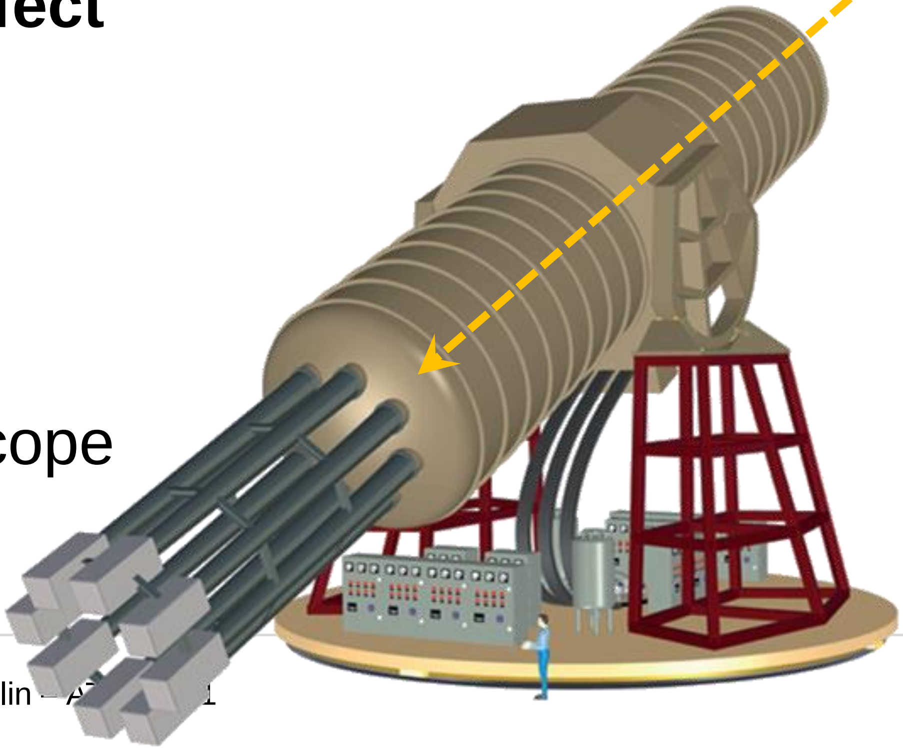
- **Detecting** **solar axions** **from the magnetized plasma on** $E_a \approx keV - scale$

  - **high mass** axions (eV) could be produced in the solar interior via the **incoherent Primakoff effect**

solar plasma with electrons & ions:

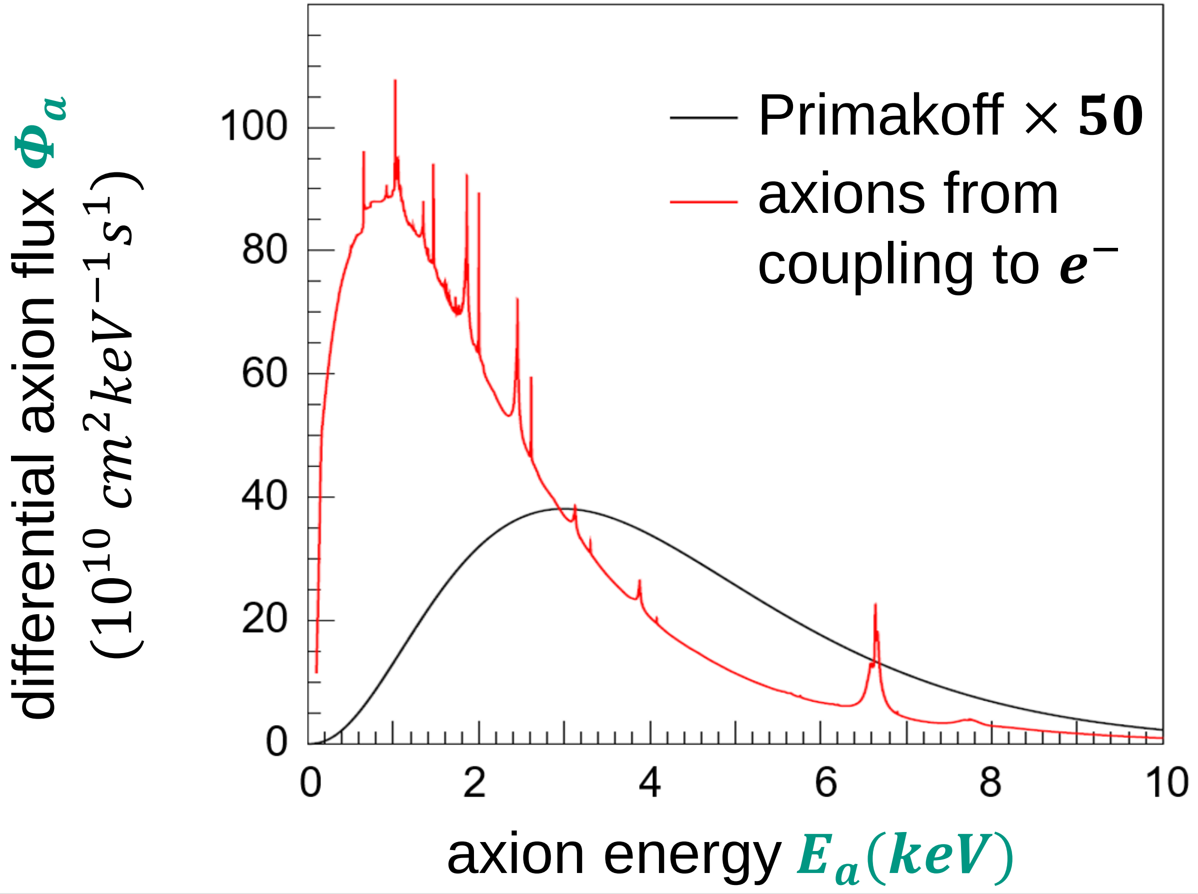


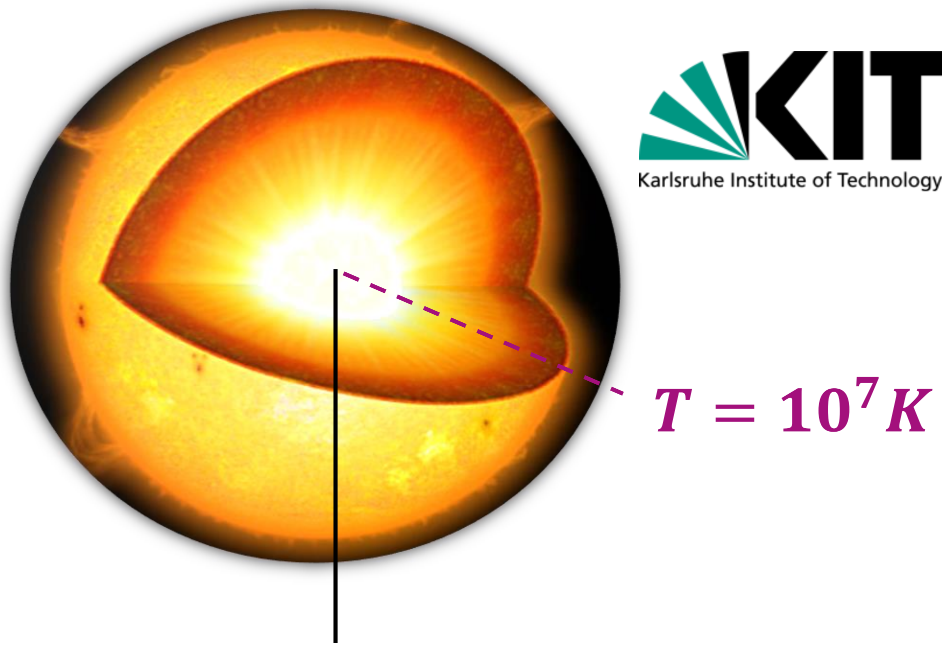
pointing a helioscope towards to sun



Axion experiments: helioscopes

- **Detecting** **solar axions** **from the magnetized plasma on** $E_a \approx keV - scale$





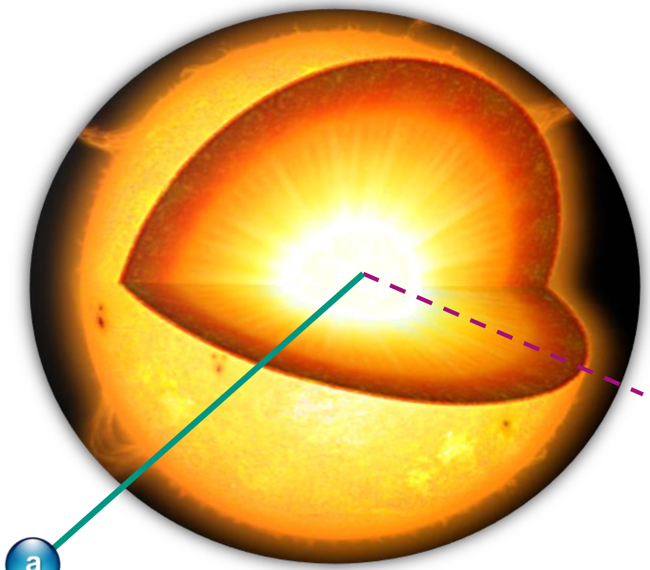
- dominant (***incoherent***) process:
  axions generated in **electric field** of magnetized plasma (ions, e^-)

flux $$\Phi_a = \left(\frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}}\right)^2$$

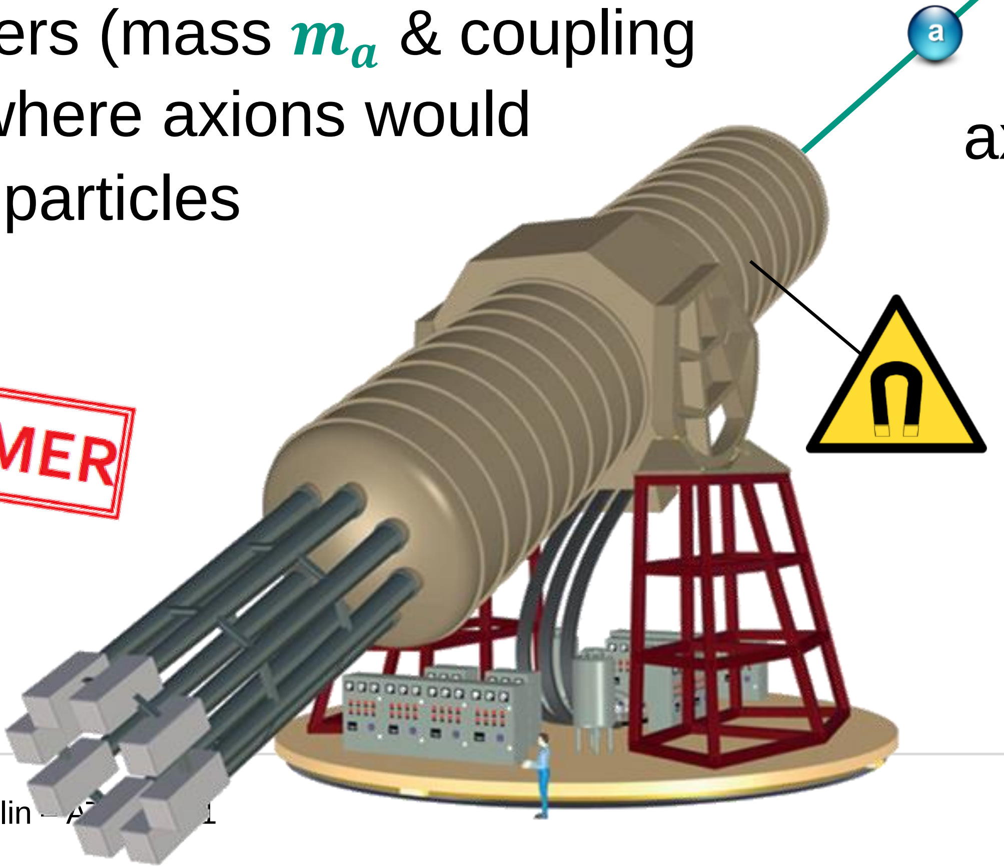
Axion experiments: helioscopes

- **Detecting** **solar axions** **from the magnetized plasma on** $E_a \approx keV - scale$

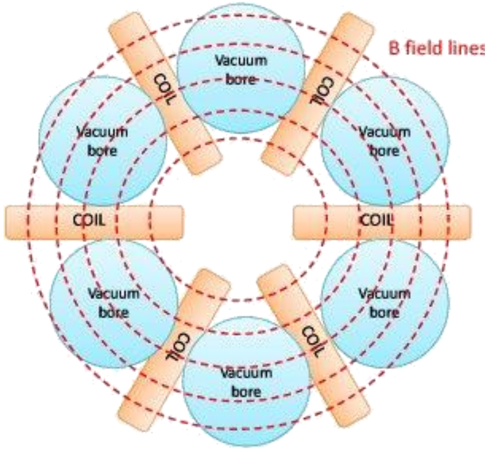
- helioscopes are only sensitive to axion parameters (mass m_a & coupling regime $g_{a\gamma\gamma}$) where axions would <u>*not*</u> be $\boldsymbol{CDM}$ – particles



$T = 10^7 K$



axion- conversion into $\boldsymbol{X}$ –rays in a strong dipole $\boldsymbol{B}$ – field

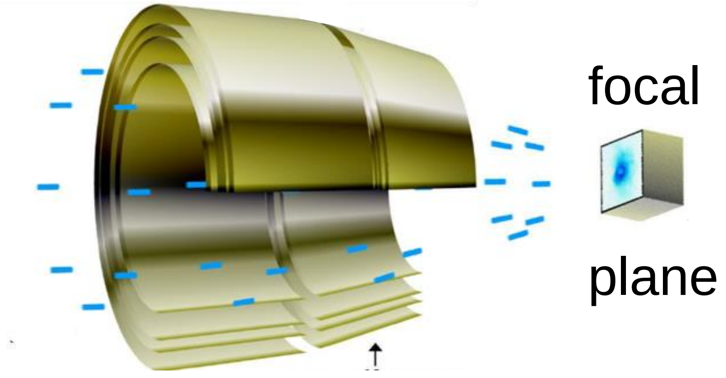


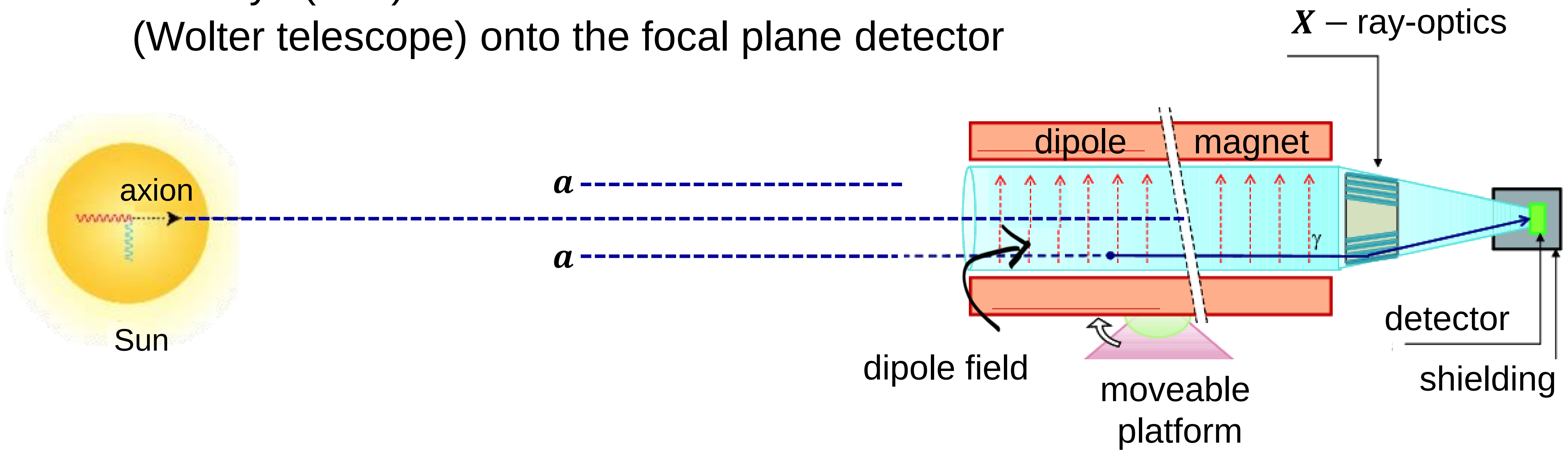
Schematic set-up of a helioscope

- **Reconverting solar axions into X – ray photons**

  - inverted Primakoff-effect is used to convert the high-mass axions back into energetic X – rays (keV)

  - X – rays (keV) have to be focused via ´mirrors´ (Wolter telescope) onto the focal plane detector

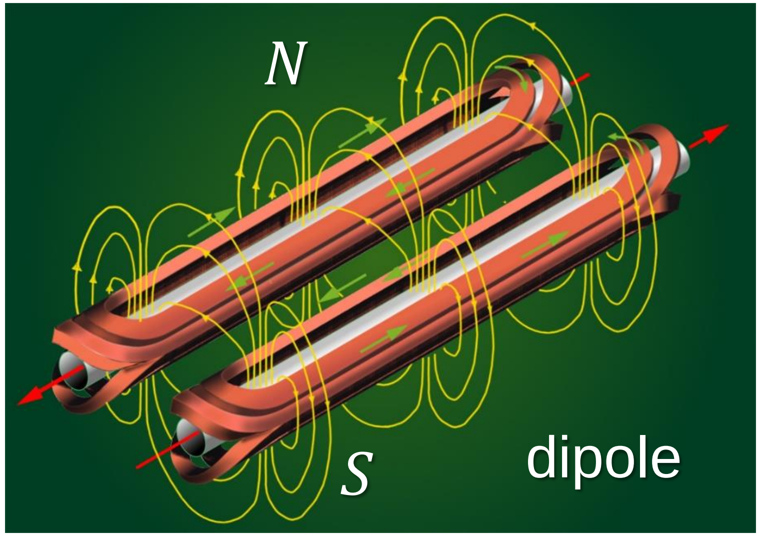


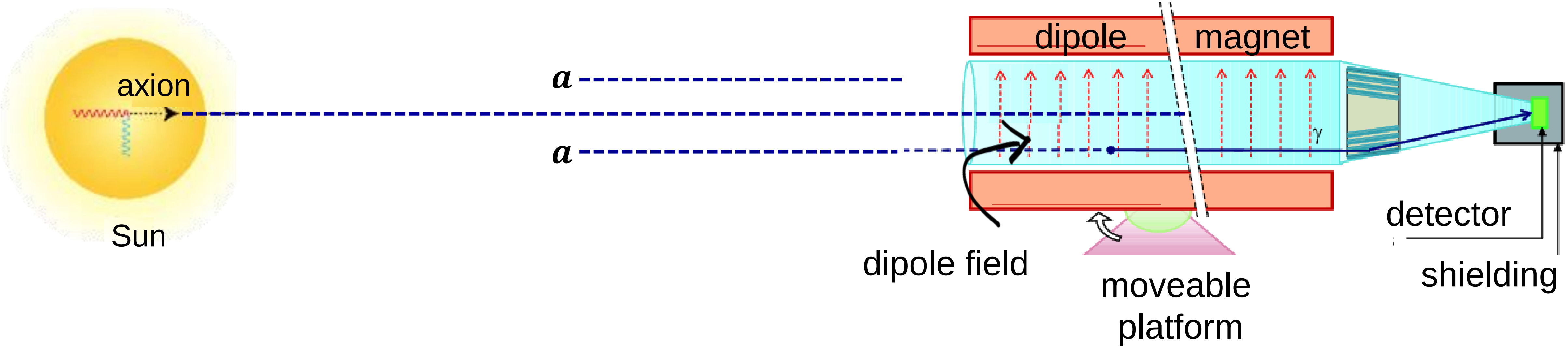


Schematic set-up of a helioscope

- **We can make use of unused LHC dipoles**

  - we again need a **magnetic dipole field**
  ⇨ only $\boldsymbol{\gamma}$´$\boldsymbol{s}$ with polarisation parallel to the $\boldsymbol{B}$ – field mix with axions
  ⇨ photon propagation transversal to $\boldsymbol{B}$ – field



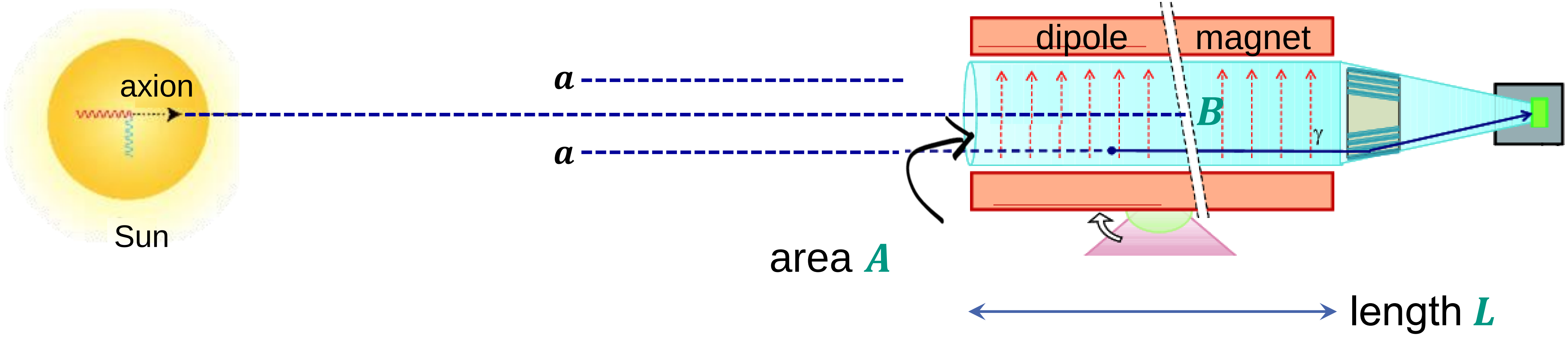


Schematic set-up of a helioscope

- **Conversion probability $P_{a\gamma}$ to transform an axion into an X – ray photon**

$$P_{a\gamma} = 2.6\times 10^{-17}\cdot\left(\frac{B}{10T}\right)^2\cdot\left(\frac{L}{10m}\right)^2\cdot\left(g_{a\gamma\gamma}\times 10^{10}\,\text{GeV}\right)^2\cdot F$$

- experimental „*figure-of-merit*“ ~ $B^2\cdot L^2\cdot A$ (magnetic field B, length L, cross section A)

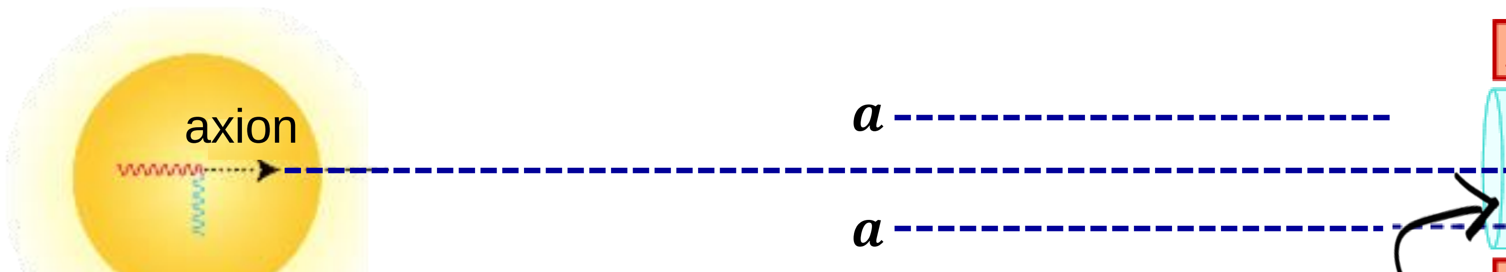


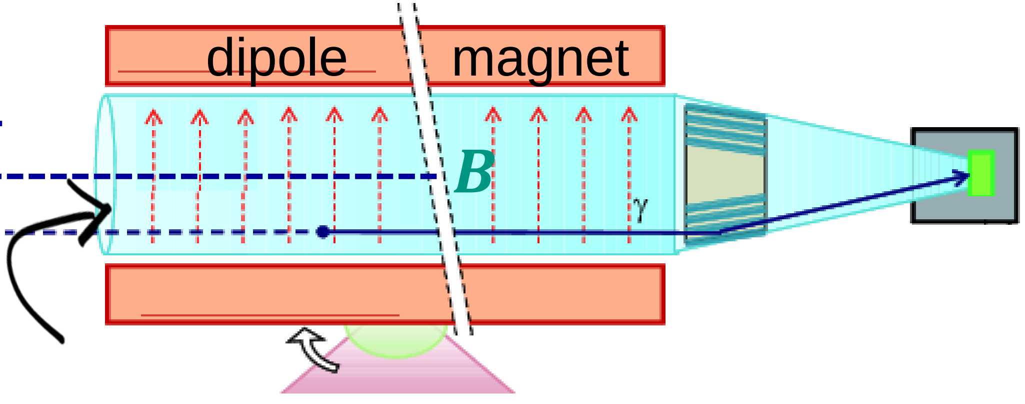
Schematic set-up of a helioscope

- **Conversion probability $P_{a\gamma}$: the importance of coherence – factor F**

$$P_{a\gamma} = 2.6\times10^{-17}\cdot\left(\frac{B}{10T}\right)^2\cdot\left(\frac{L}{10m}\right)^2\cdot\left(g_{a\gamma\gamma}\times10^{10}\,\mathrm{GeV}\right)^2\cdot F$$

- conversion is **coherent** over entire length L if the **phase** of the massive axion and the massive photon remain the same!





goal: *coherent* process over entire length L (only then: $P_{a\gamma} \sim L^2$)

length L

Maintaining coherence in a helioscope

Karlsruhe Institute of Technology

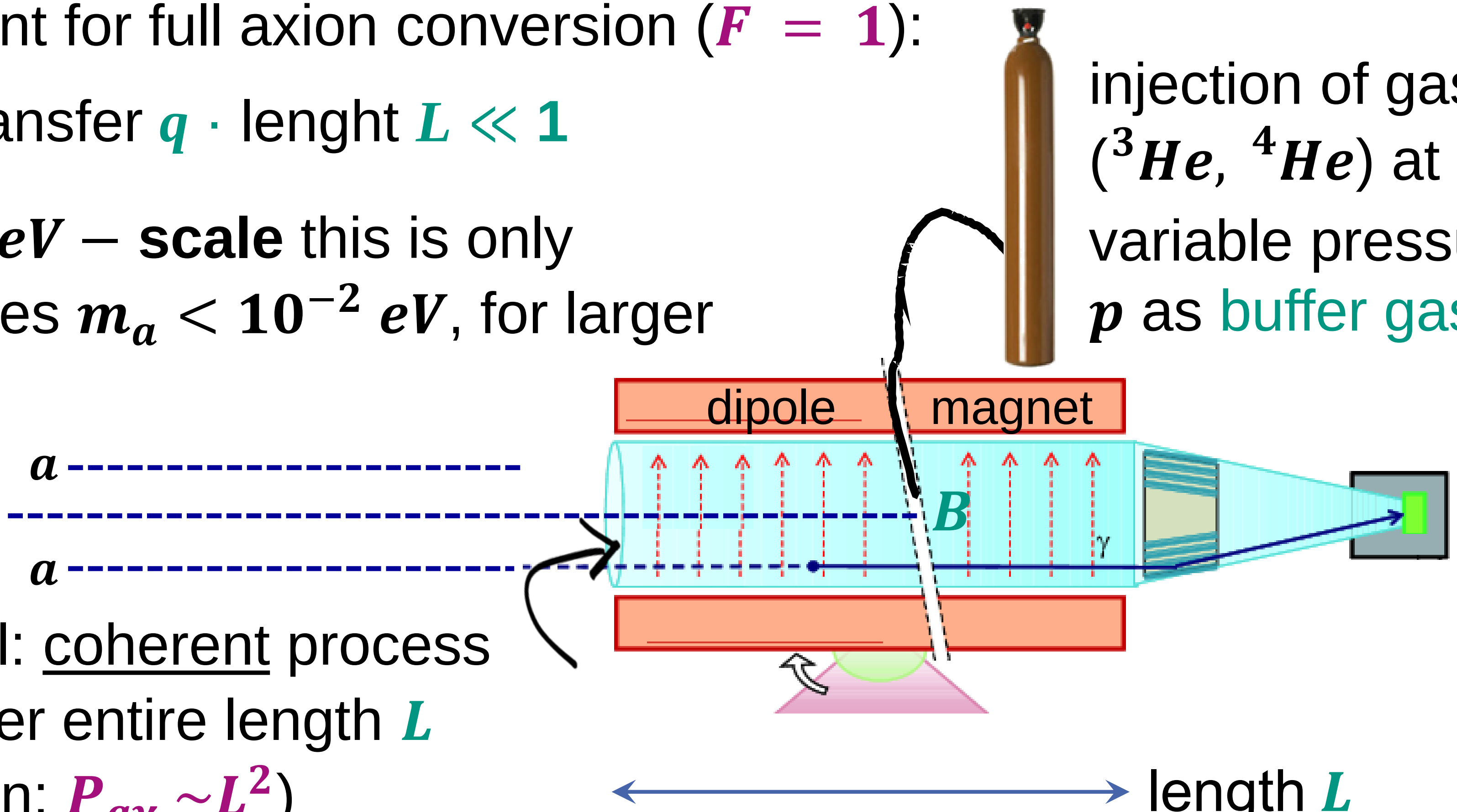
- **Enhancing the coherence – factor F via the injection of buffer gas**

- **coherence** requirement for full axion conversion ($F = 1$):

  momentum transfer $q \cdot$ lenght $L \ll 1$

- for axions with $E_a \approx keV -$ **scale** this is only fulfilled for small masses $m_a < 10^{-2}\ eV$, for larger masses we need to add a buffer gas to adjust the **effective mass** of X –ray photons!

injection of gas (^3He, ^4He) at variable pressure p as buffer gas

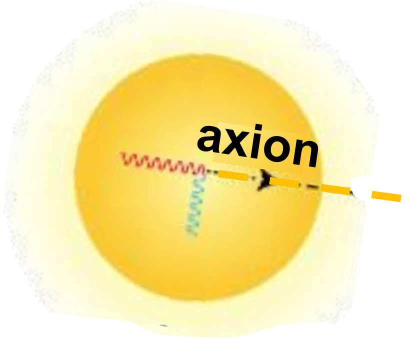


goal: coherent process over entire length L (then: $P_{a\gamma} \sim L^2$)

Helioscopes: $CAST$* experiment at $CERN$

Karlsruhe Institute of Technology

- Making use of a spare $L = 9.3\ m$ long dipole magnet ($B = 9.5\ T$) of the LHC



- magnet axis follows path of the Sun over several hours per day

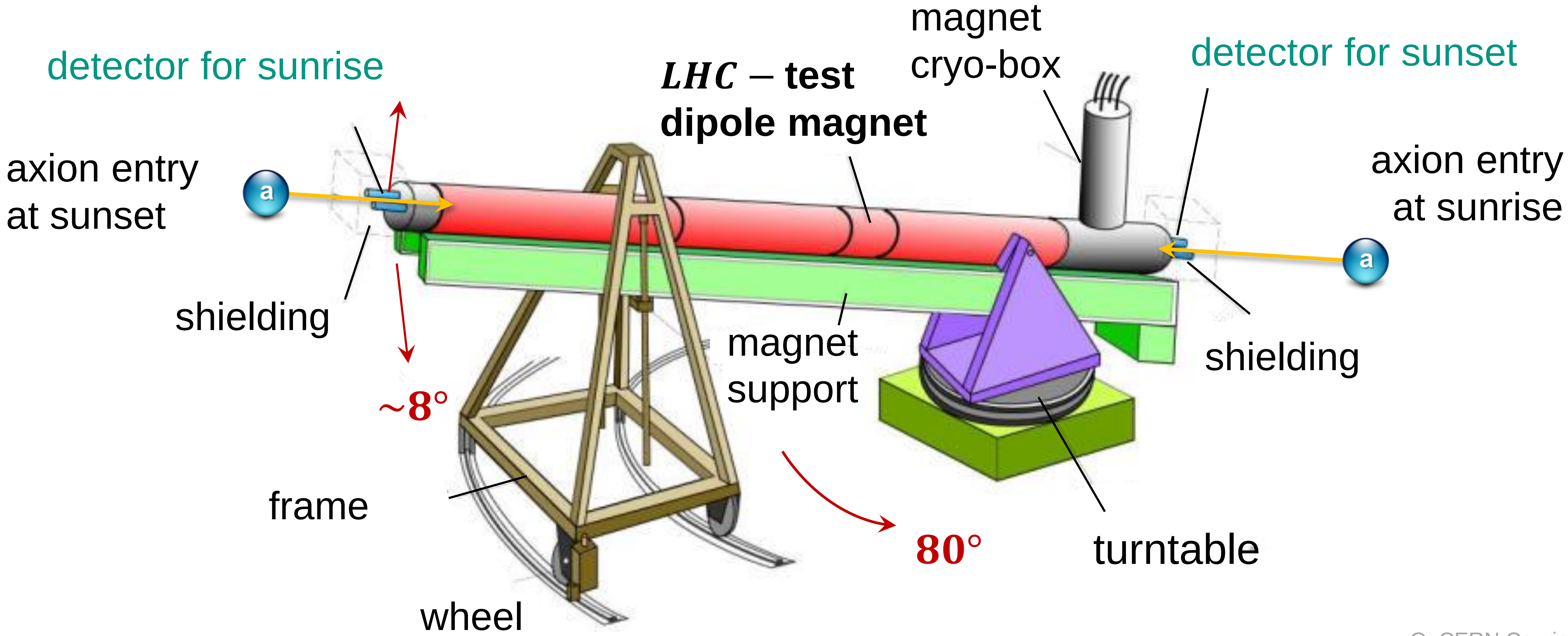
- both magnet entries (side of the setting / rising sun) are fully instrumented with modern X – ray detector systems

Q: CERN Courier

*CERN Axion Solar Telescope

Helioscopes: $CAST$ experiment at $CERN$

- **A moveable dipole magnet that can also be tilted to follow the Sun**



Q: CERN Courier

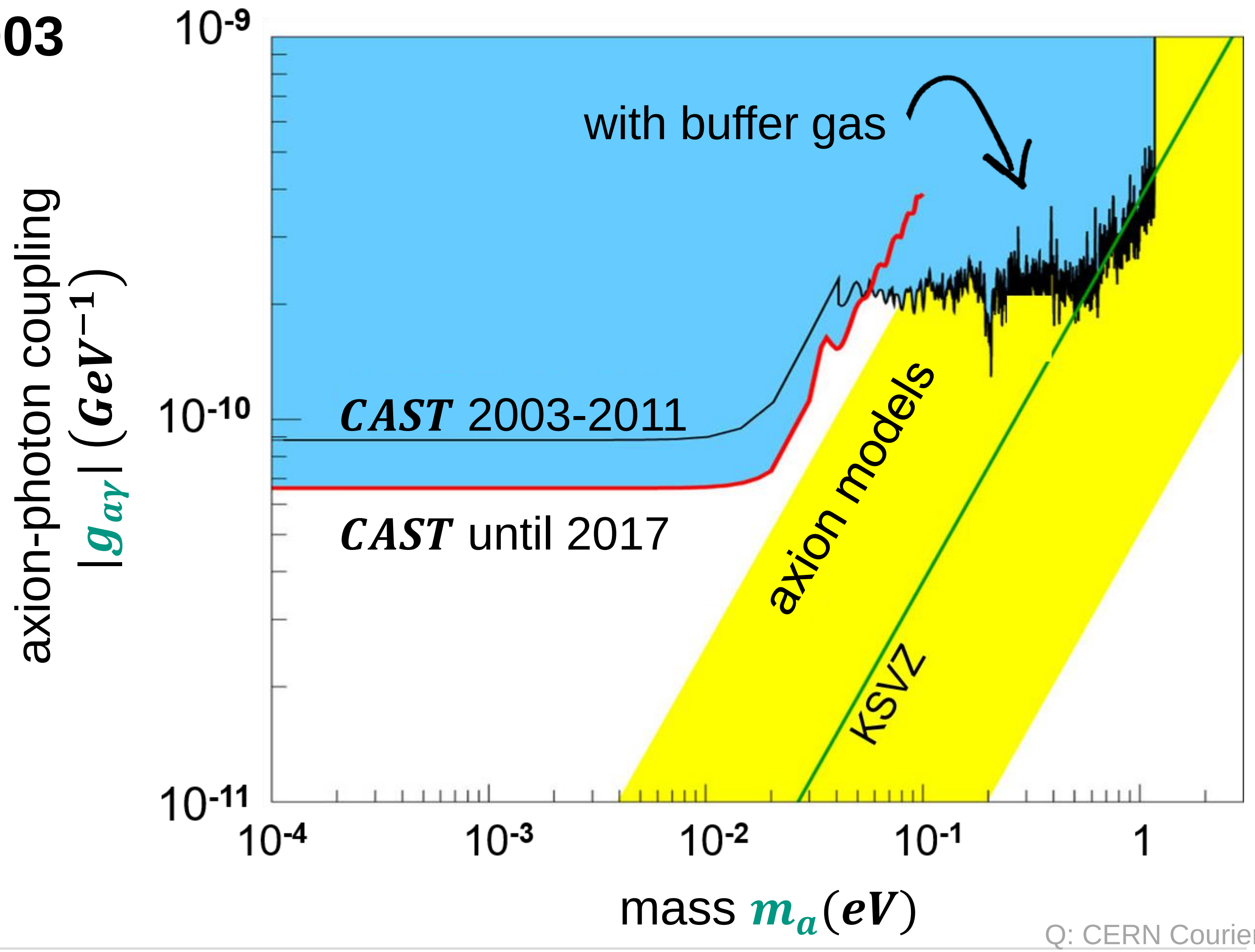
Helioscopes: $CAST$ results – use of buffer gas

- **Axion measurements since 2003**

2005-2006:
measurements with ^4He

2008-2011:
measurements with ^3He
first push forward into the region of QCD – axions

since 2012:
improved measurements with ^4He & in vacuum



Q: CERN Courier

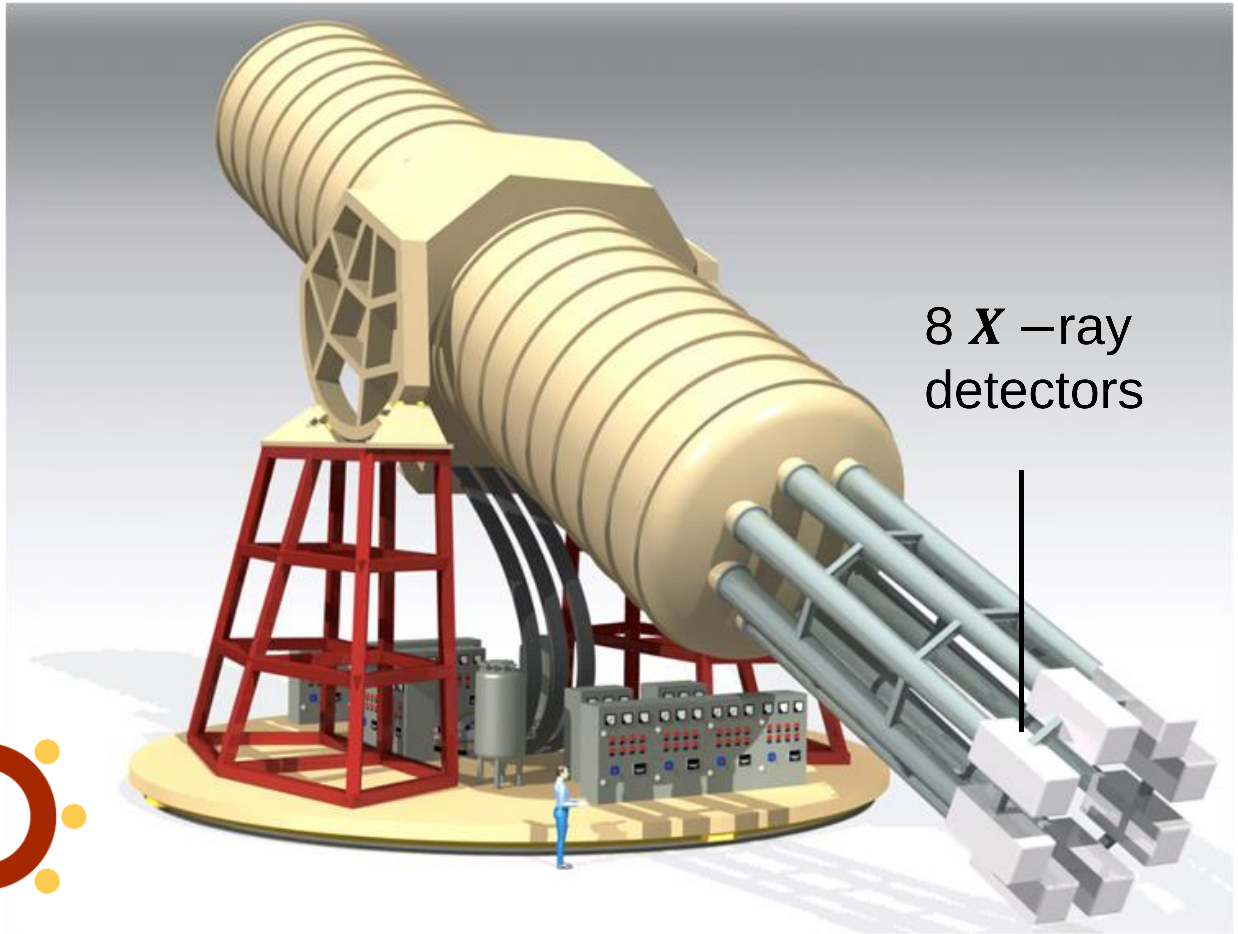
Helioscopes: $IAXO$* – an outlook

- **Future search for solar axions with a large toroidal magnet system**

- setup: $\boldsymbol{L = 20\,m}$ long **toroidal magnet** with $\boldsymbol{\varnothing = 5.2\,m}$

- toroidal magnet system formed by 8 coils ($\varnothing = 0.6\,m$) with $\boldsymbol{B = 2.5\,T}$

- **factor 20** improved sensitivity relative to $\boldsymbol{CAST}$



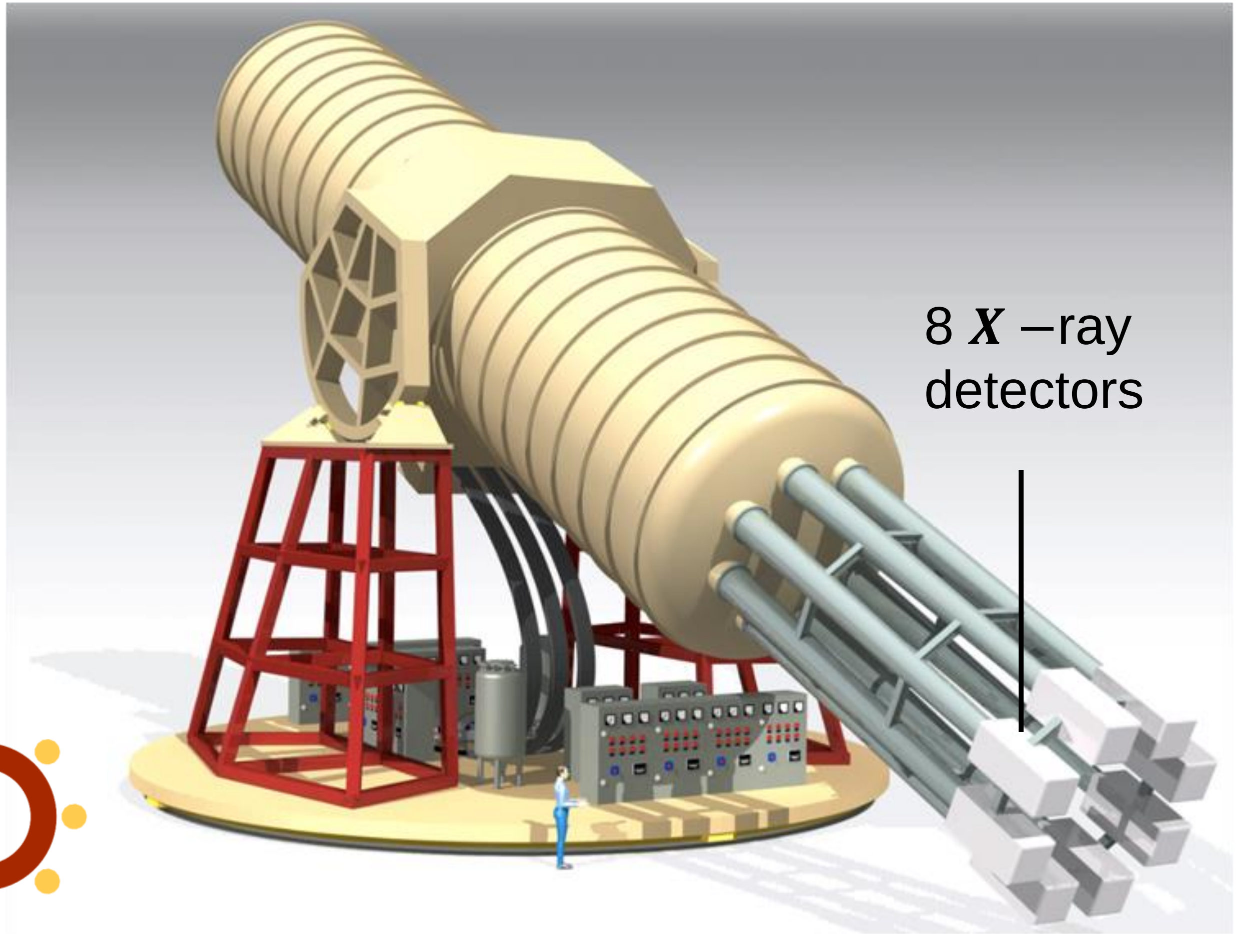
Helioscopes: $IAXO$ – an outlook

- **Future search for solar axions with a large toroidal magnet system**

- figure-of-merit: ~ $B^2 \cdot L^2 \cdot A$

  - $\boldsymbol{CAST}$: $21\ T^2\ m^4$
  - $\boldsymbol{IAXO}$: $\sim 6000\ T^2\ m^4$

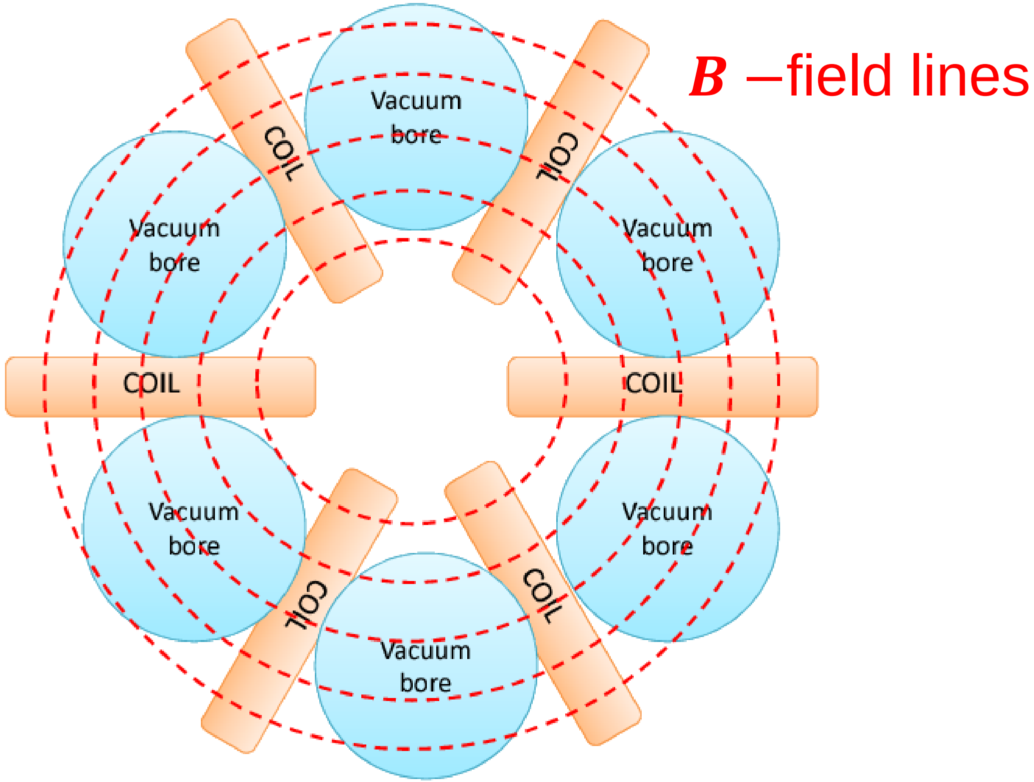
- **factor 20** improved sensitivity relative to $\boldsymbol{CAST}$

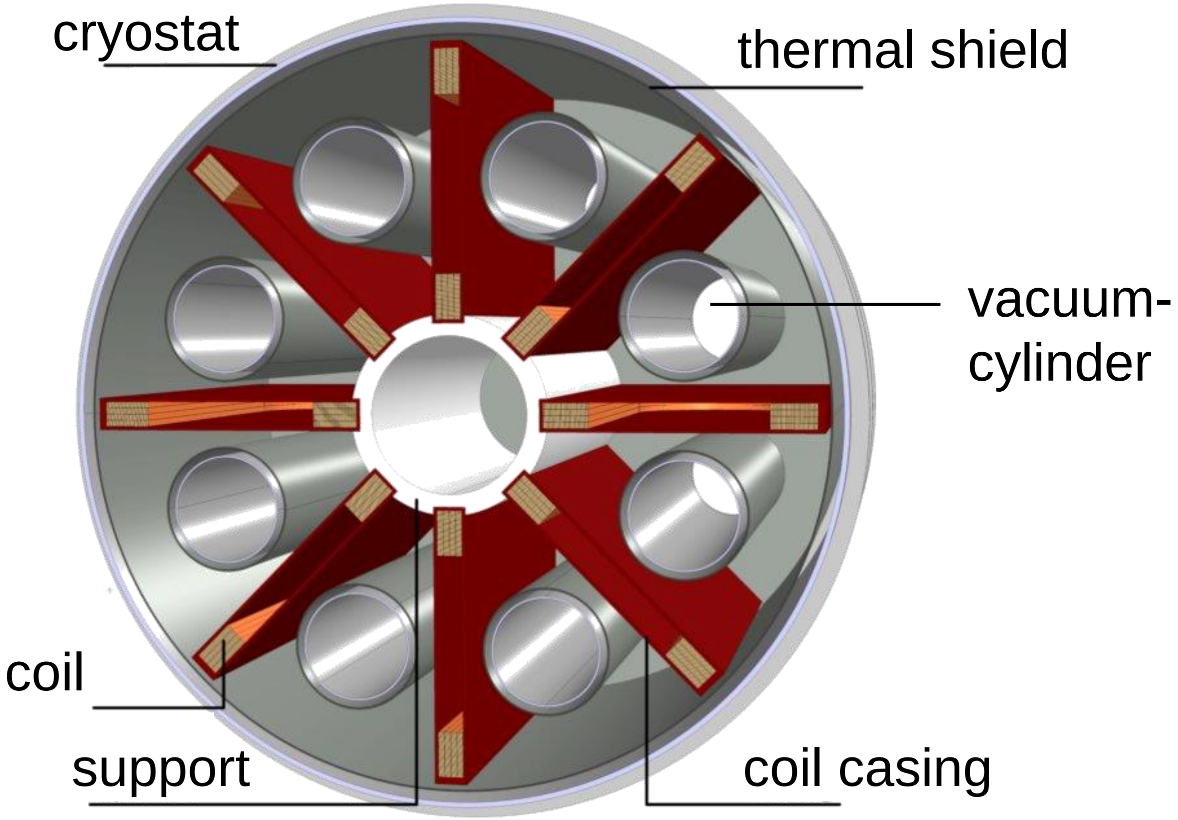


Helioscopes: $IAXO$ – an outlook

- **Future search for solar axions with a large toroidal magnet system**

  - 8 (6) vacuum cylinders interspersed with 8 (6) coils in a toroidal set-up





Helioscopes: $IAXO$ – an outlook

- **Future search for solar axions**

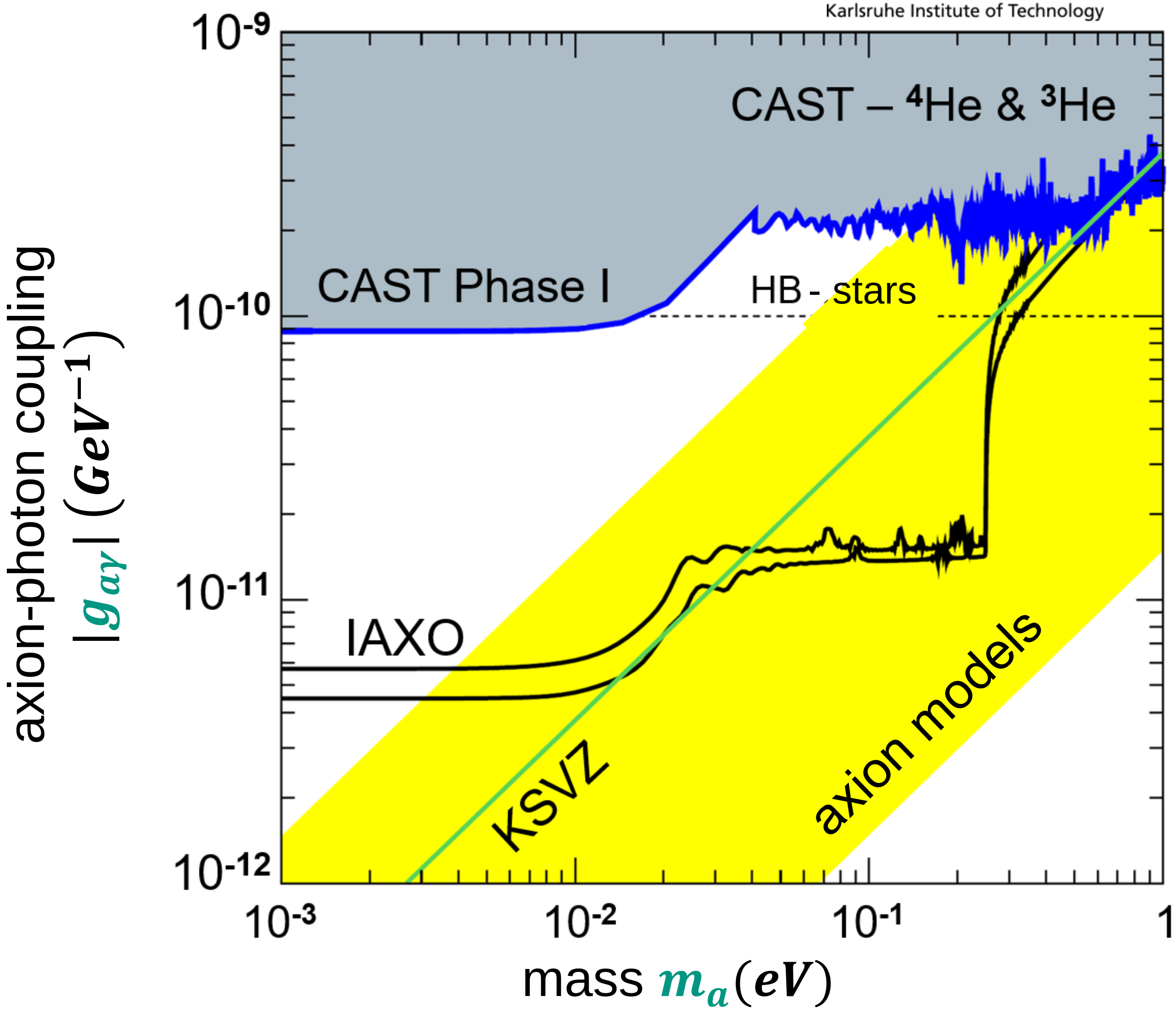
CAST

- results after ~20 year long data taking (vacuum / buffer gas)

IAXO

- expected for 3 years data taking (vacuum / buffer gas)

- test of realistic QCD – axion parameter regions



Helioscopes: first step - Baby$IAXO$

- **Search for solar axions with a smaller toroidal magnet at $DESY$**

- figure-of-merit: ~ $B^2 \cdot L^2 \cdot A$

  - $CAST$: $21\ T^2\ m^4$
  - $BabyIAXO$: $\sim 230\ T^2\ m^4$

- follows path of Sun $t = 24\ h$ a day

- magnet design: uses expertise from the $ATLAS$ experiment ($CERN$)

- Wolter-Telescope (X-Ray): from ESA (for the XMM – Newton telescope)