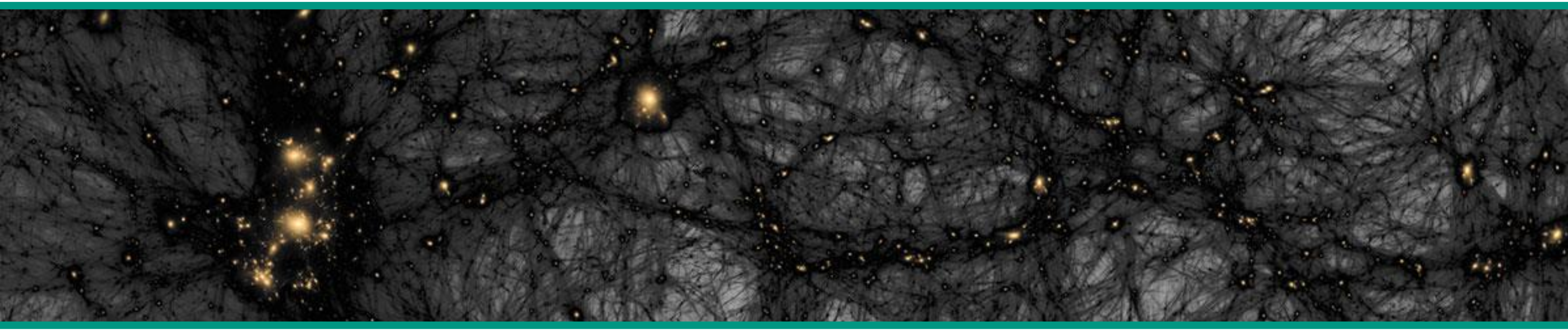
Astroparticle physics I – Dark Matter

Winter term 23/24 Lecture 21 Feb. 8, 2024



Recap of Lecture 20

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

  - $\boldsymbol{axions}$ 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: $\boldsymbol{m_a = 40 \ldots 180\ \mu eV}$)

  - $\boldsymbol{ALPs}$ = $\boldsymbol{A}$xion–$\boldsymbol{L}$ike–$\boldsymbol{P}$articles: no solution to the $\boldsymbol{QCD}$ – & $\boldsymbol{DM}$ – topics

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

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

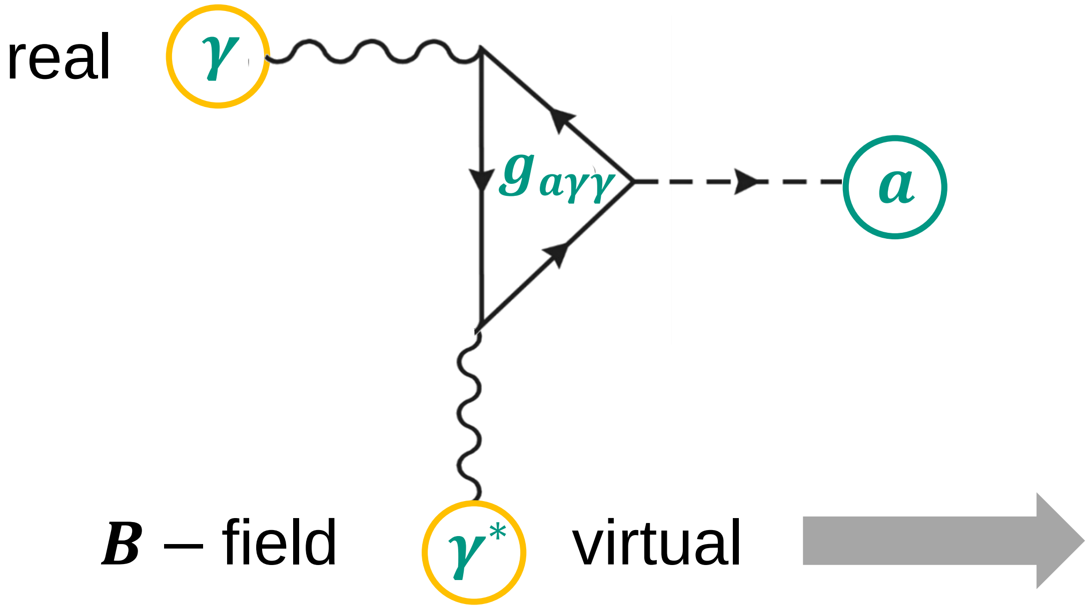
Generating *axions* via the *Primakoff* effect

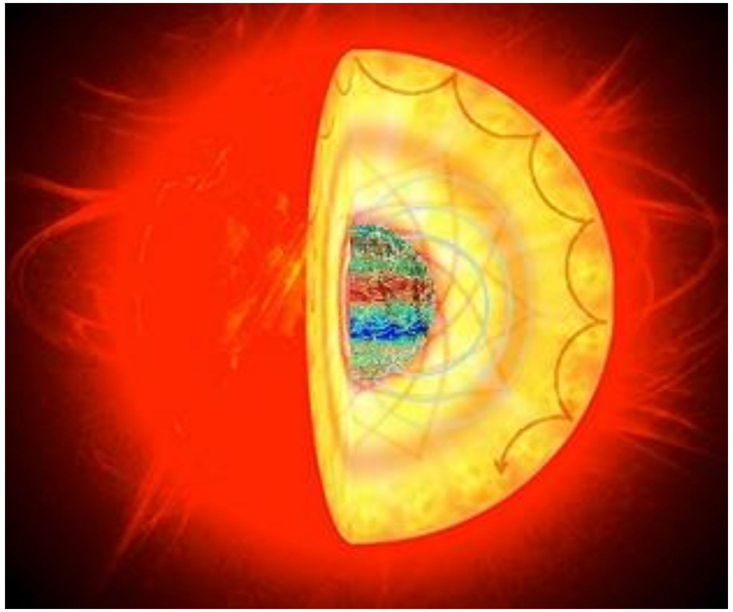
Karlsruhe Institute of Technology

- **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 γ´s** (from the plasma) into ***axions*** **via *Primakoff* effect**

  - ***axions*** will leave the **solar interior** without further interaction: ⇨ can be observed



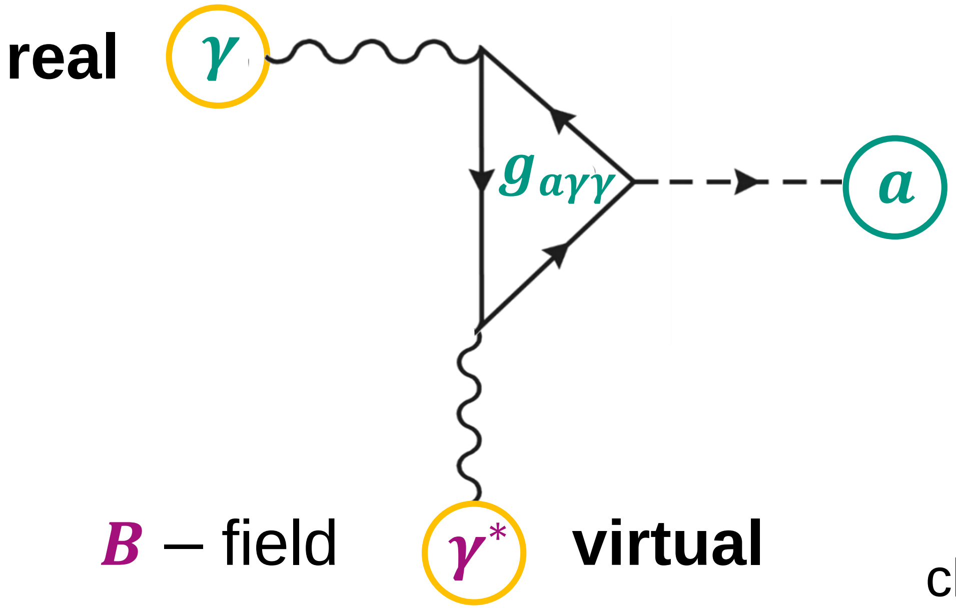


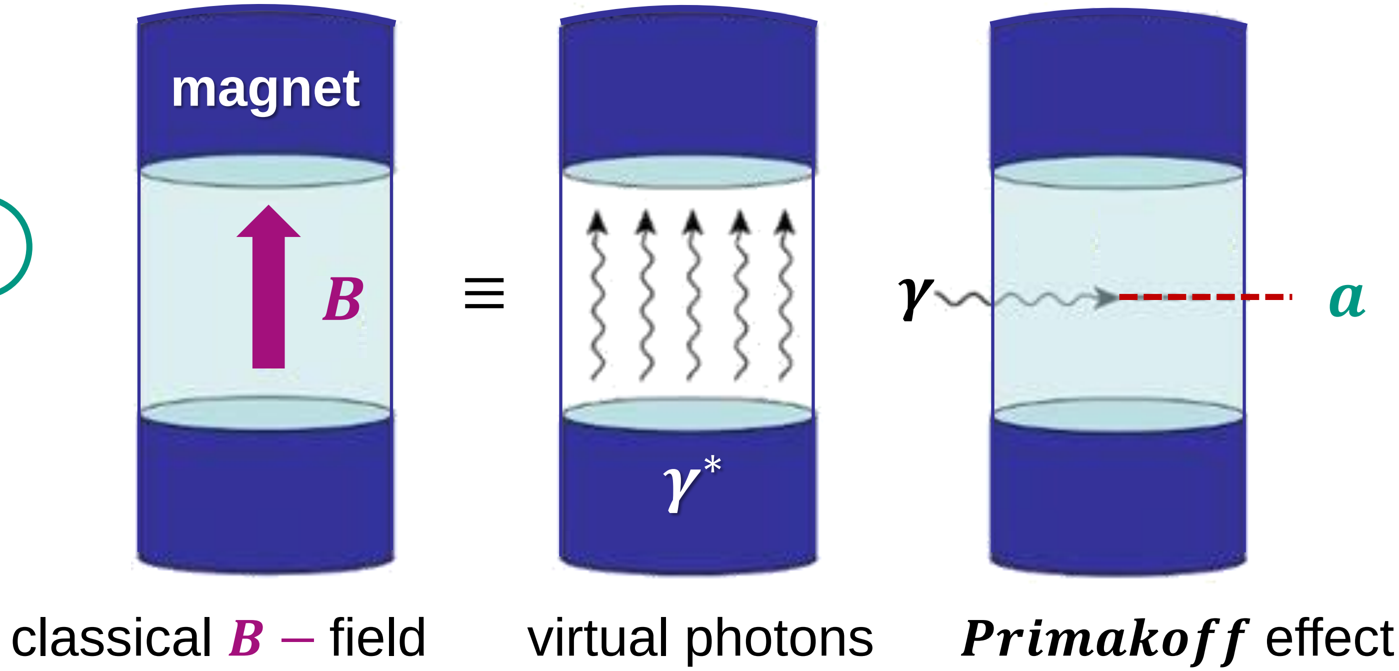
example: **magnetised plasma** in the solar interior

Generating $axions$ via the $Primakoff$ effect

- **A** **coherent** **process to generate $axions$: here – we use a $s.c.$ magnet**

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

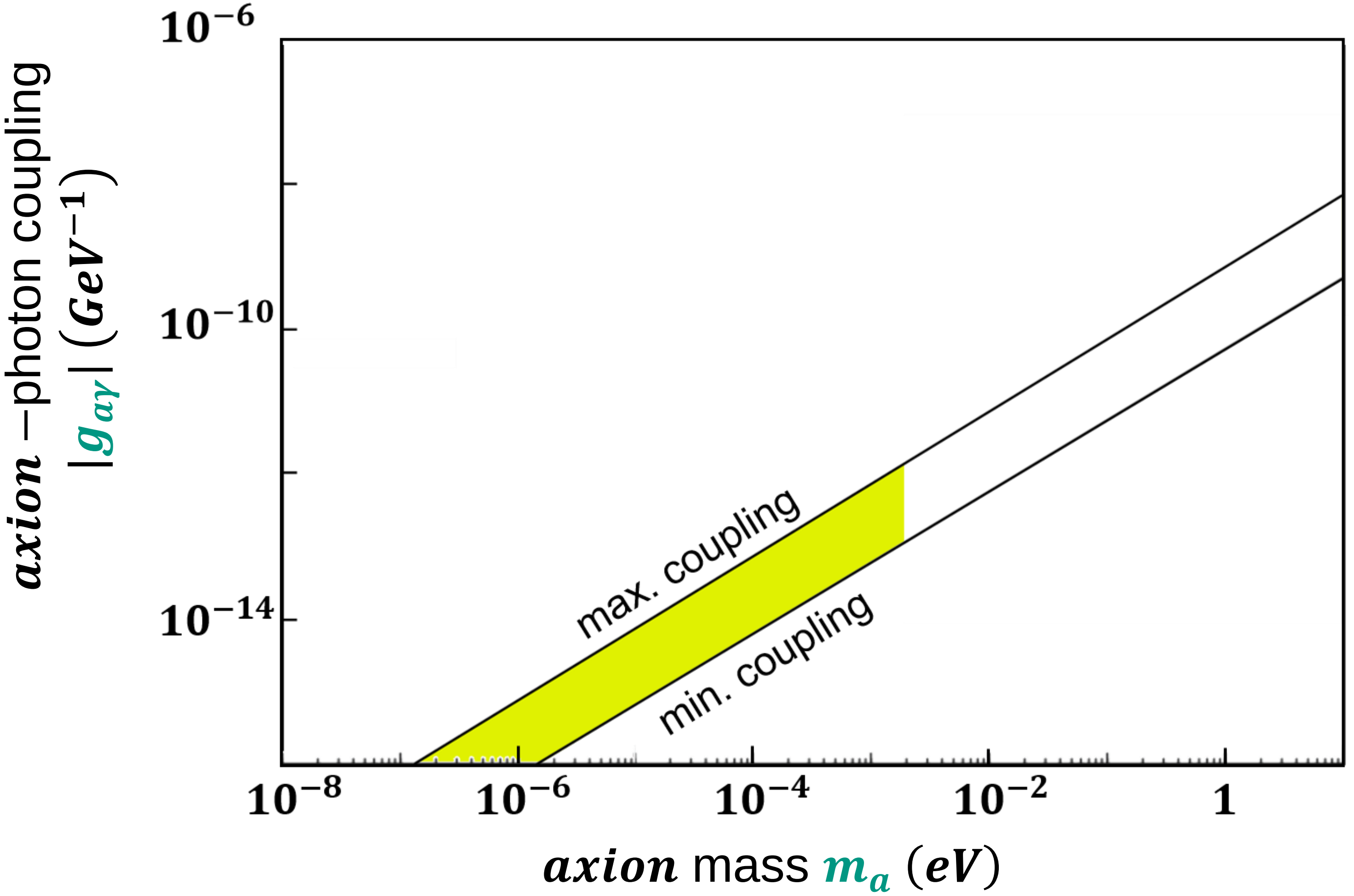




$Axion$ plot: mass m_a vs. coupling $g_{a\gamma\gamma}$

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

coupling



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

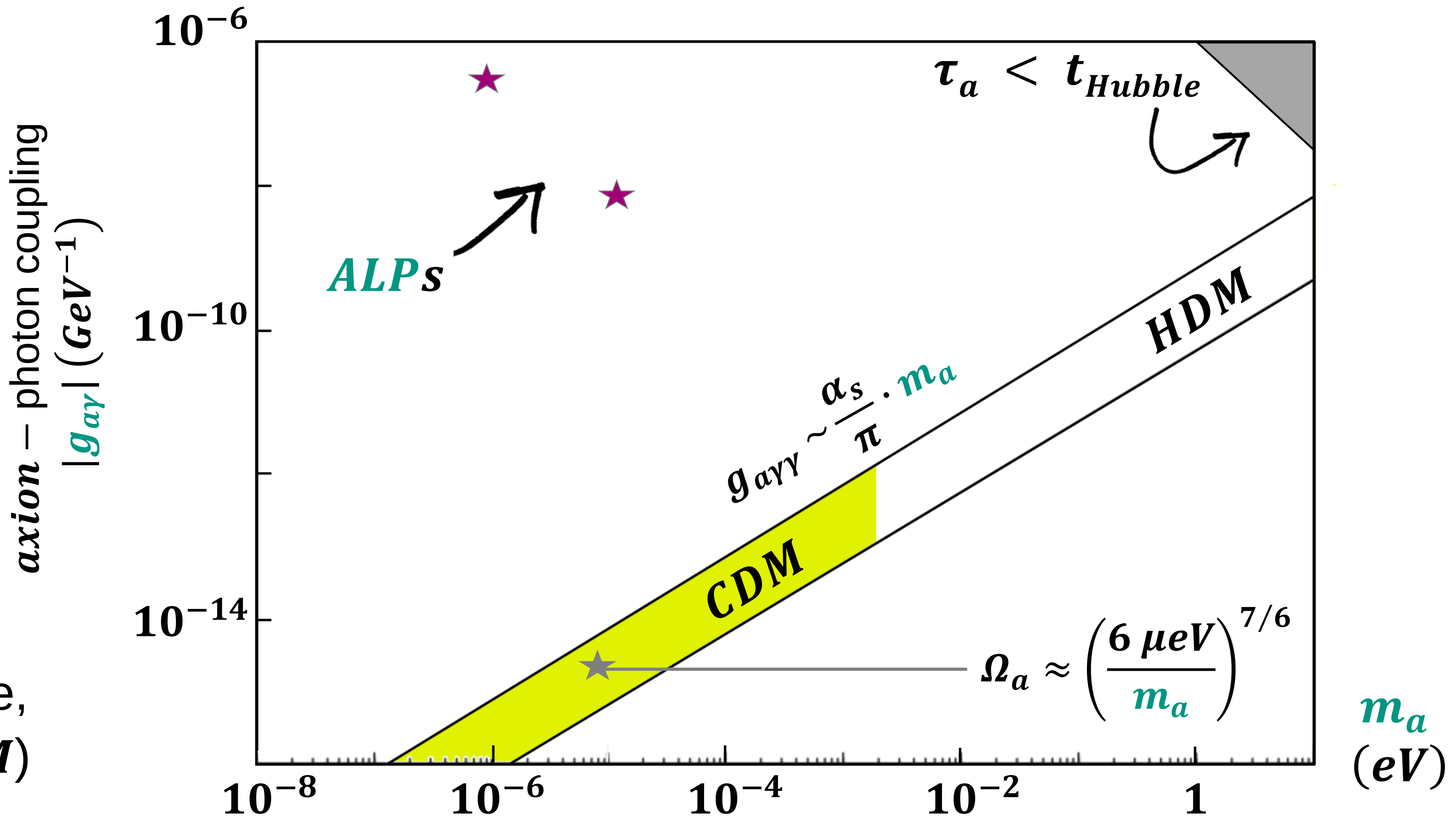
mass

$Axion$ plot: parameters for QCD – axions

- QCD – axions

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

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

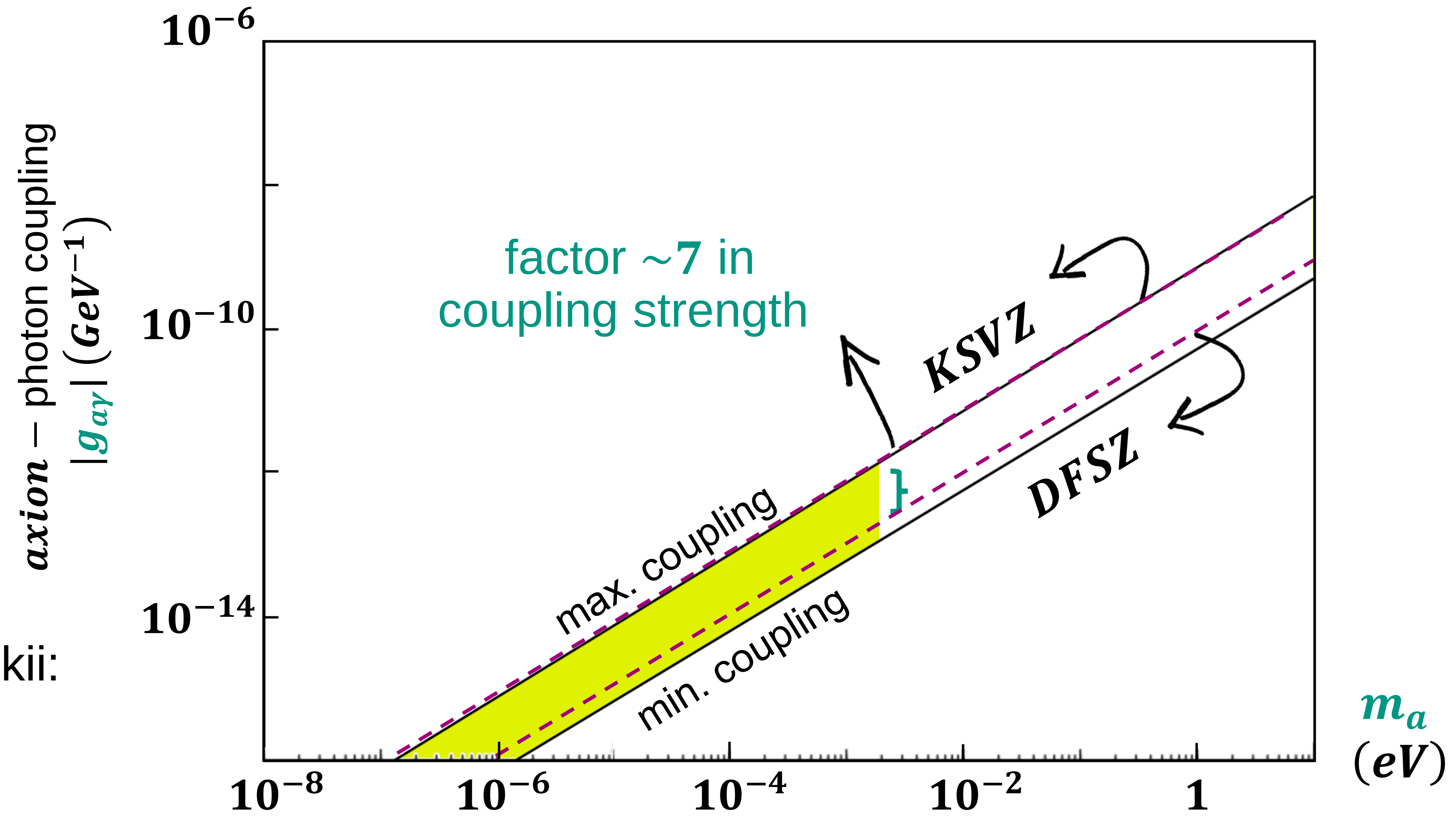


$Axion$ plot: parameters for QCD – axions

- **Two models:**

- $KSVZ$
  Kim–Shifman–Vainstein–Zakharov: **stronger** (´hadronic´)

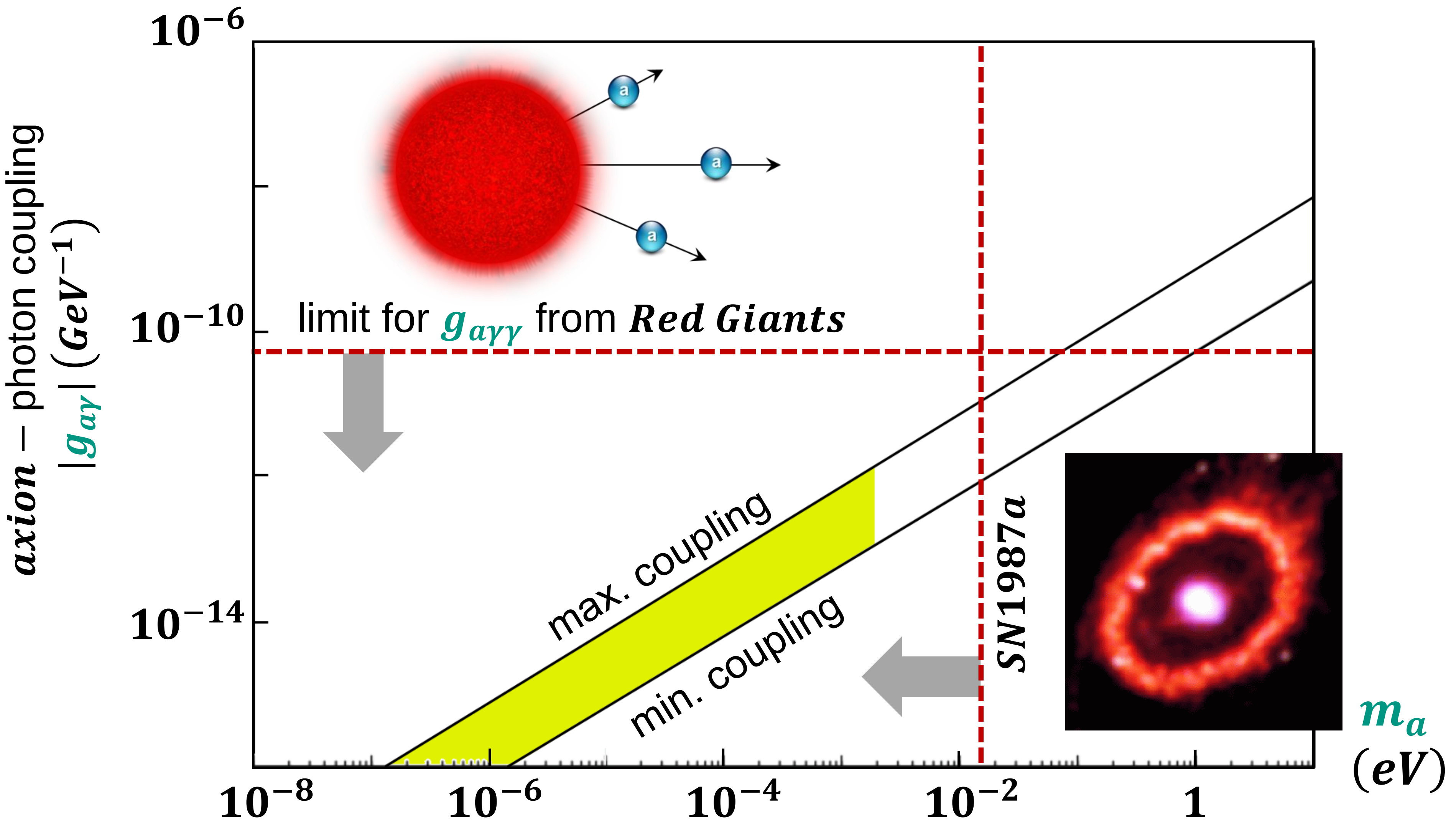
- $DFSZ$
  Dine–Fischler–Srednicki–Zhitnitskii: **weaker** (´leptonic´)



Axion plot: recent limits from astrophysics

- **limits**

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

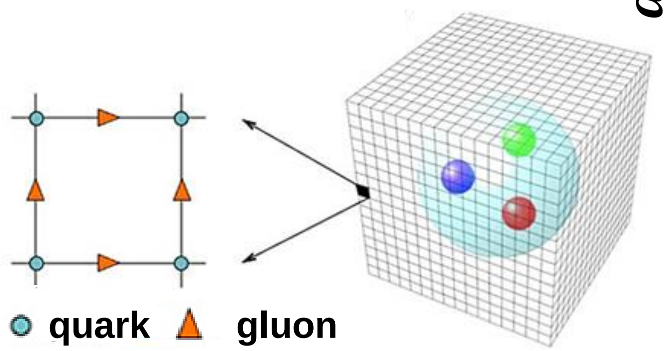


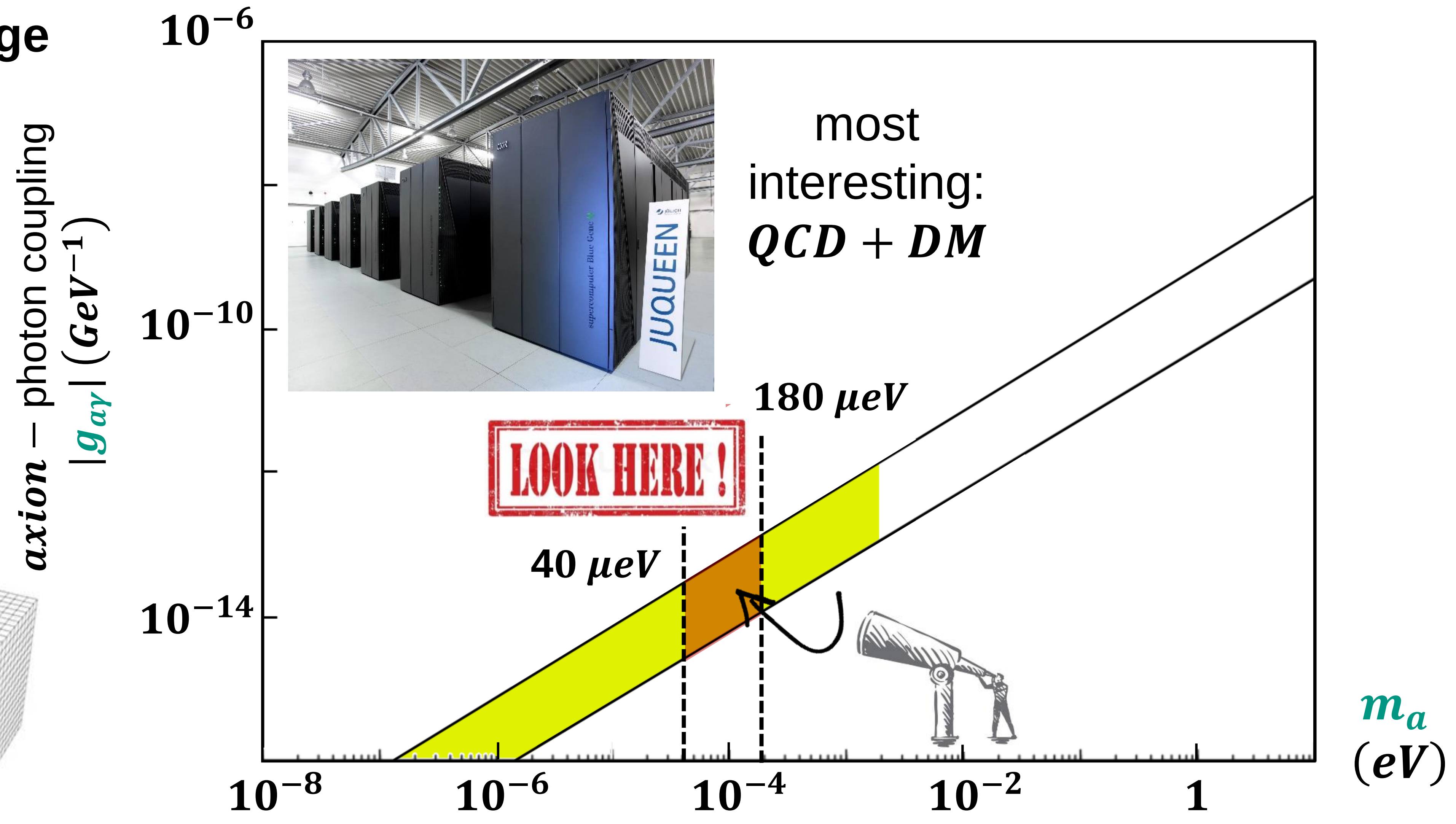
$Axion$ plot: preferred values from lattice$-QCD$

- **Parameter range**

- results from modern lattice QCD – calculations
- 2022 update:

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





Axion experiments

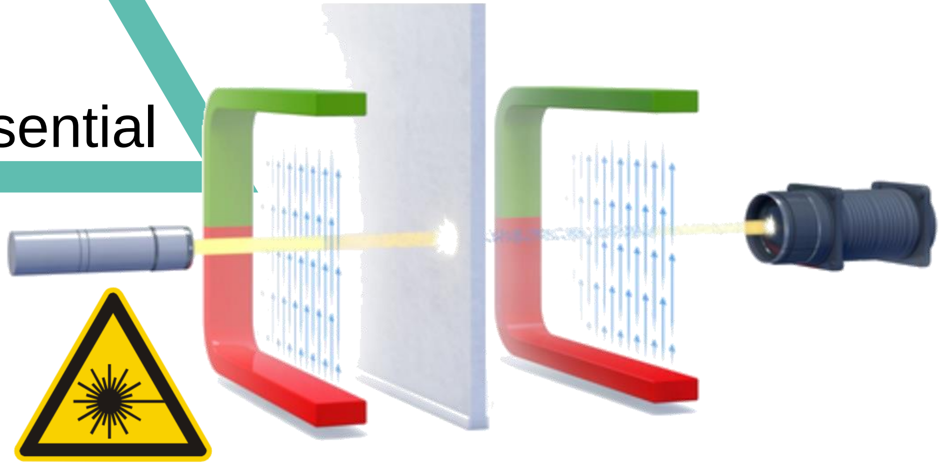
- **Detecting *axions* from**
  - dark matter halo, sun
  - indirectly

axion – (helio–) telescopes:
CAST*, *IAXO

microwave–cavities (haloscopes):
***ADMX*, *HAYSTACK*, ...**

$\boldsymbol{B}$ – fields are essential

*L*ight–*S*hining–through–*W*all (*LSW*):
ALPS I, II JURA



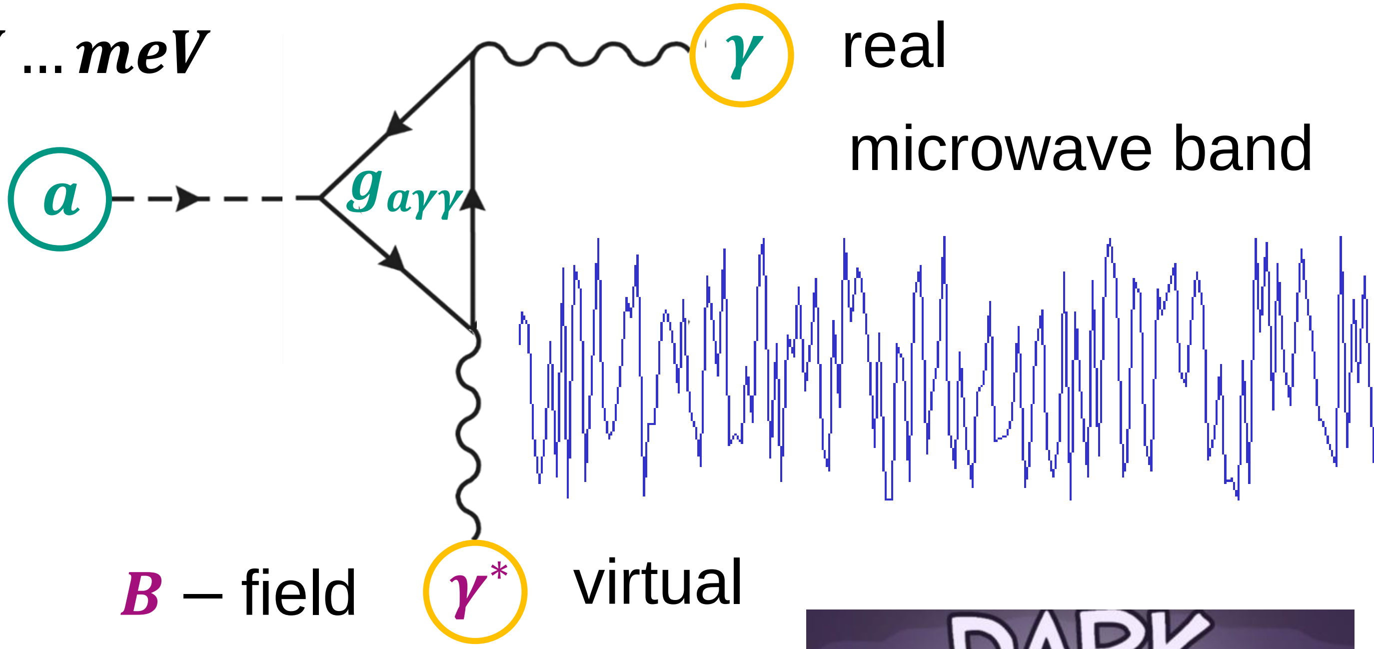
Axion experiments: haloscopes for galactic *DM*

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

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

microwave−cavities (haloscopes):

$ADMX, HAYSTACK, \ldots$



$Axion$ experiments: haloscopes for galactic DM

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

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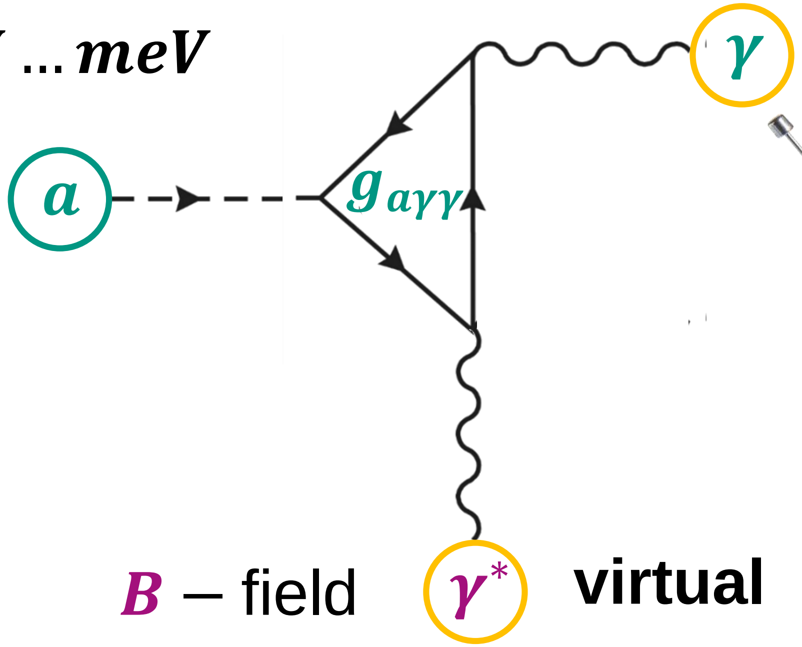
microwave–cavities (haloscopes):
$ADMX, HAYSTACK, \ldots$



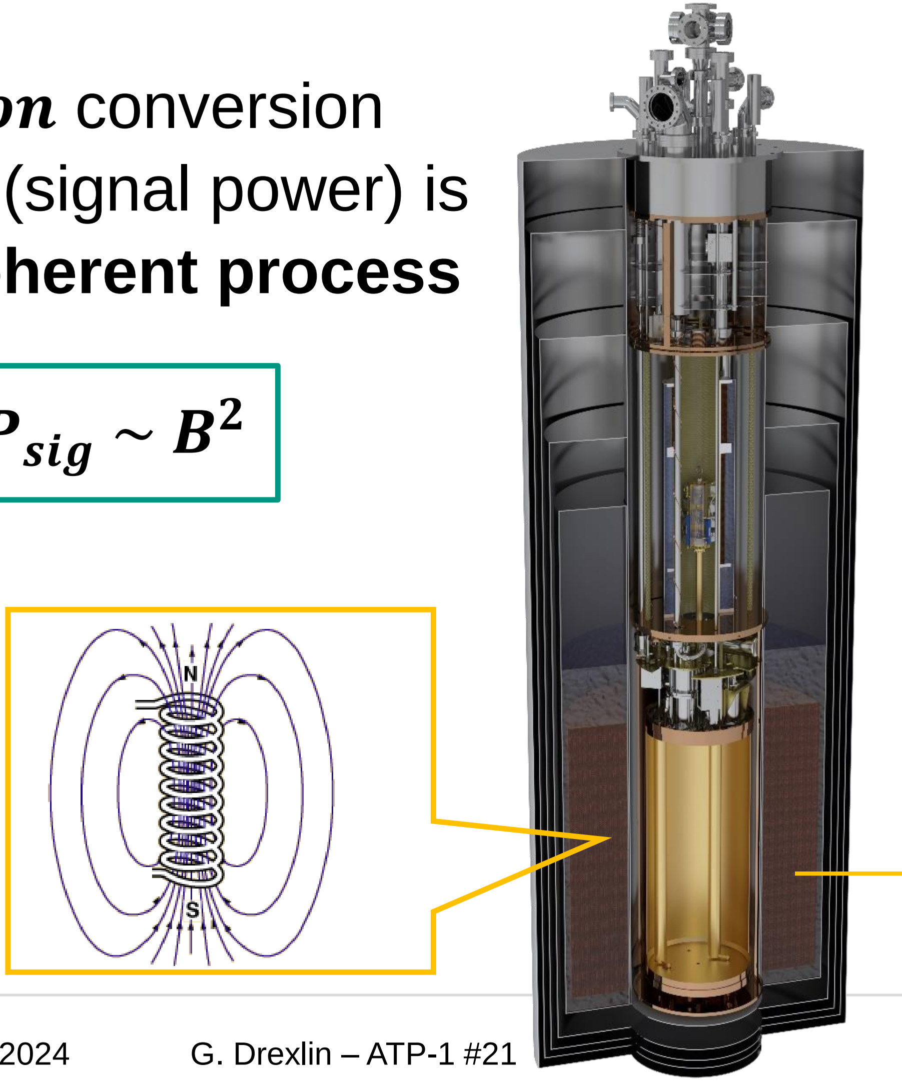
- at which **frequency f** can I **tune** into the galactic ´DM – radio´?

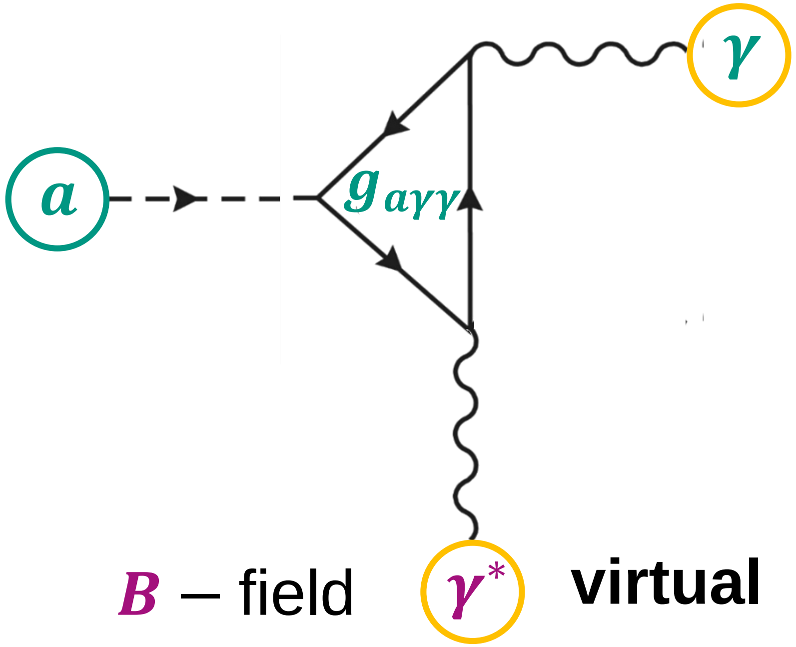
$Axion$ experiments: haloscopes for galactic DM

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

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

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



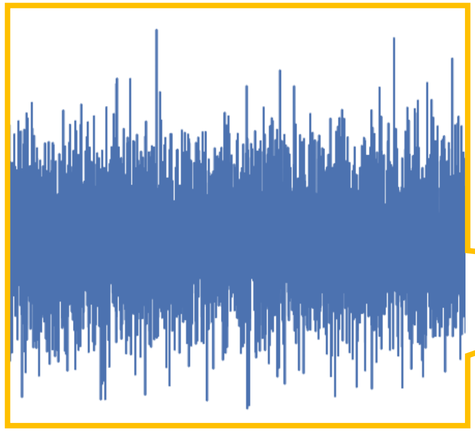


$Axion$ experiments: haloscopes for galactic DM

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

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

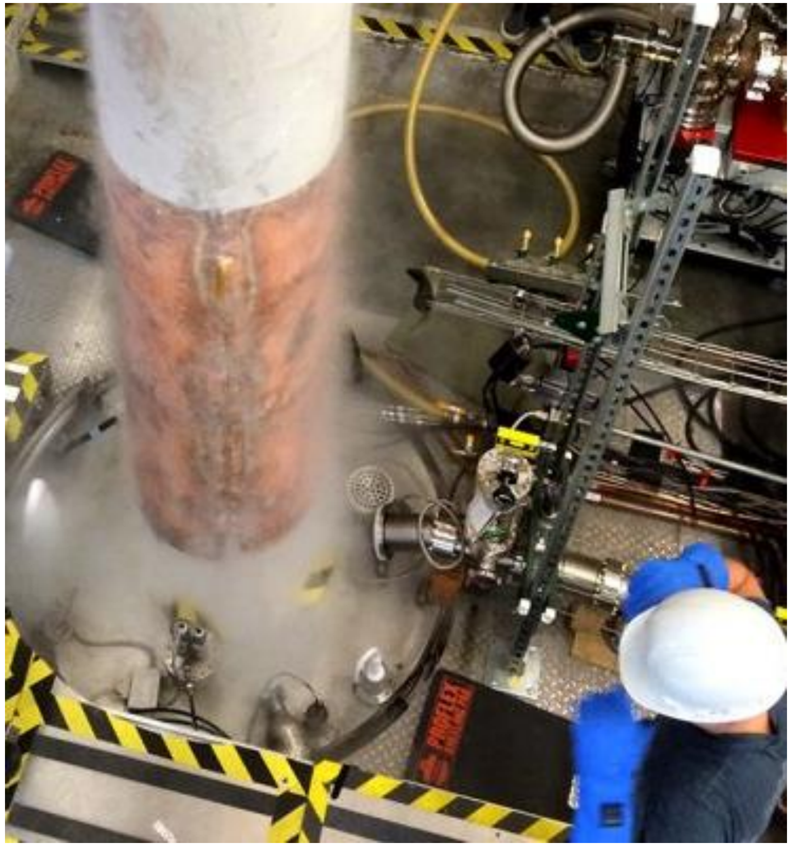
$$P_{noise} \sim T^4$$



$4\ K$

$1\ K$

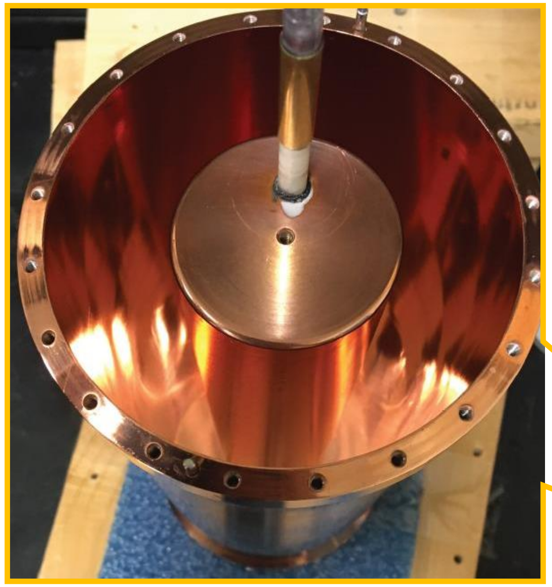
$100 \dots 250\ mK$



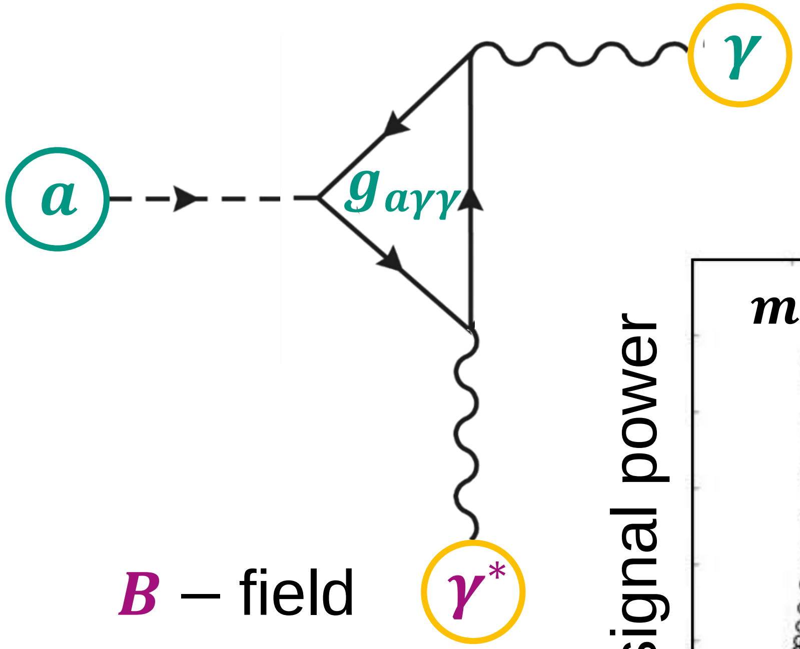
$Axion$ experiments: haloscopes for galactic DM

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

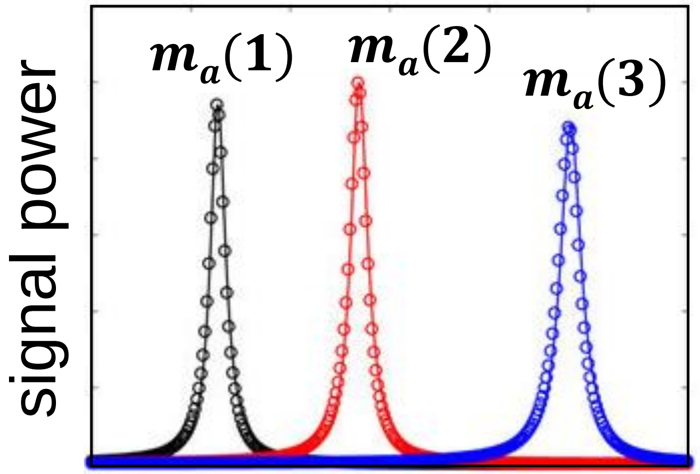
γ^*



Cu – cavity & **tuning** rods for **resonant** amplification



$100 \ldots$
$250\ mK$



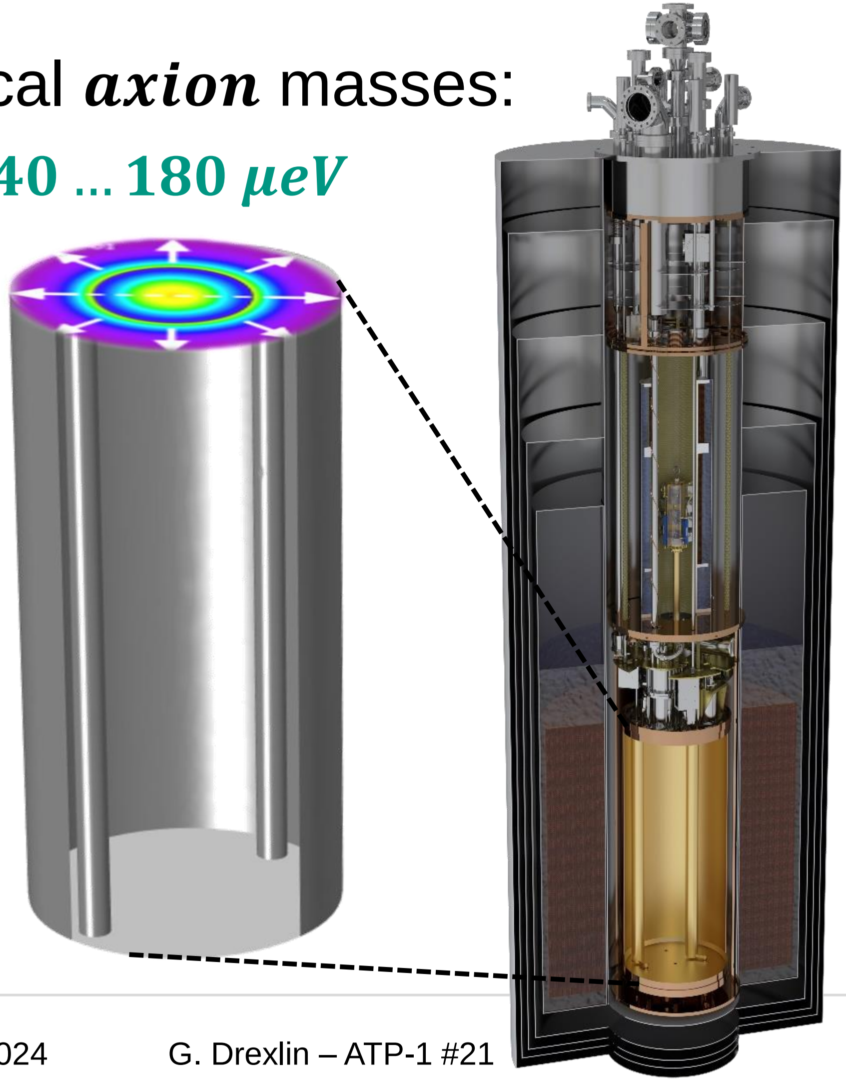
resonance frequency of the Cu – cavity

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

- **Resonance cavity: modify frequency over broad range so that $f_{res} = m_a$**

- 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

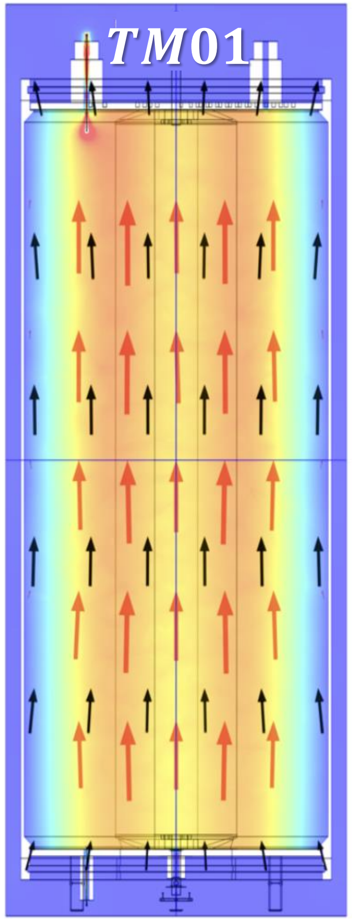
$m_a = 10\ \mu eV \Leftrightarrow f_{res} = 2.4\ GHz$

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

HF – mode

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

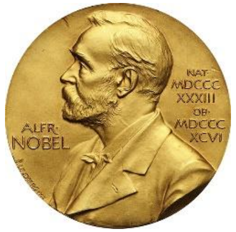
- Cylindrical resonance cavity: working with the basic $TM01 -$ mode



- excitation of $\boldsymbol{TM01} -$ mode

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

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

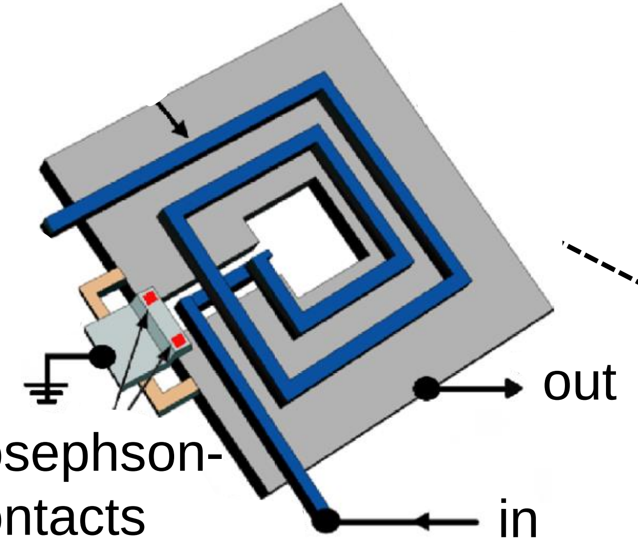


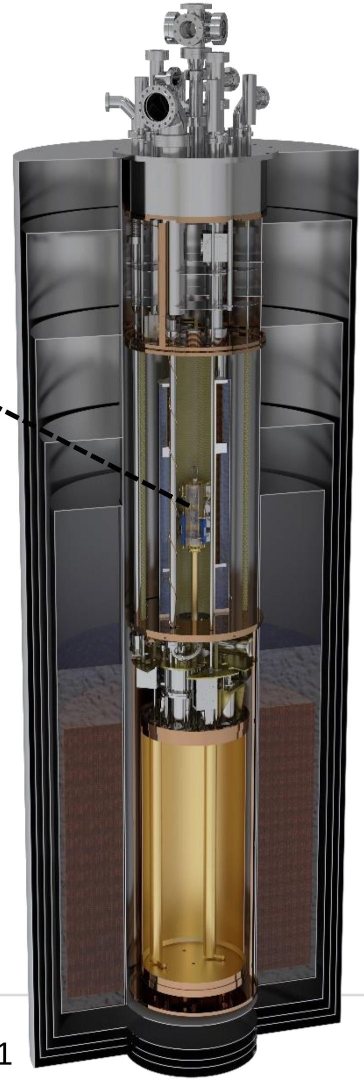
1981

Arthur Schawlow:
„Never measure anything but frequency"

Haloscopes for $DM - axions$: signal & noise

- **Read−out of haloscopes via quantum sensor: $SQUID$ − unit***



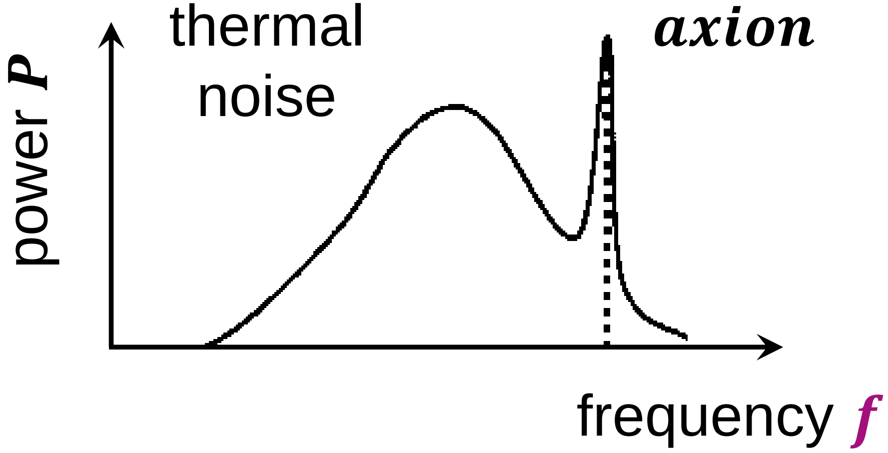


- experimental resolution:

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

- expected signal of a haloscope:

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



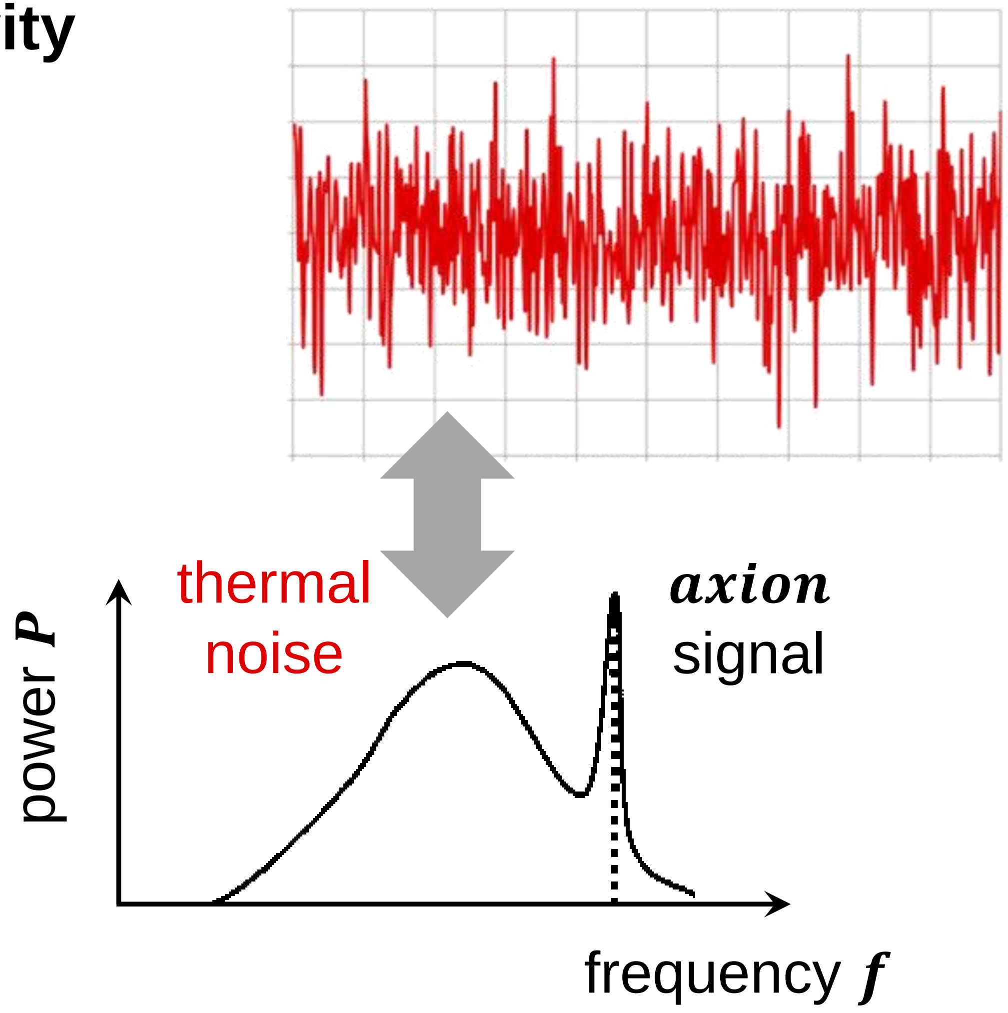
*s. lecture #19

Haloscopes for DM – axions: signal & noise

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

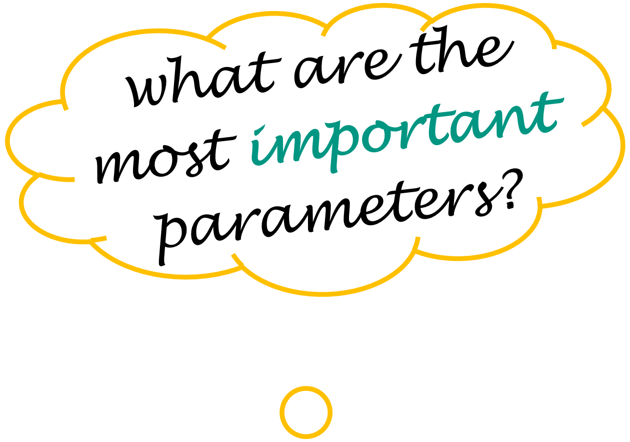
- thermal microwave photons are the dominant source of noise: ⇨ **cooling**

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

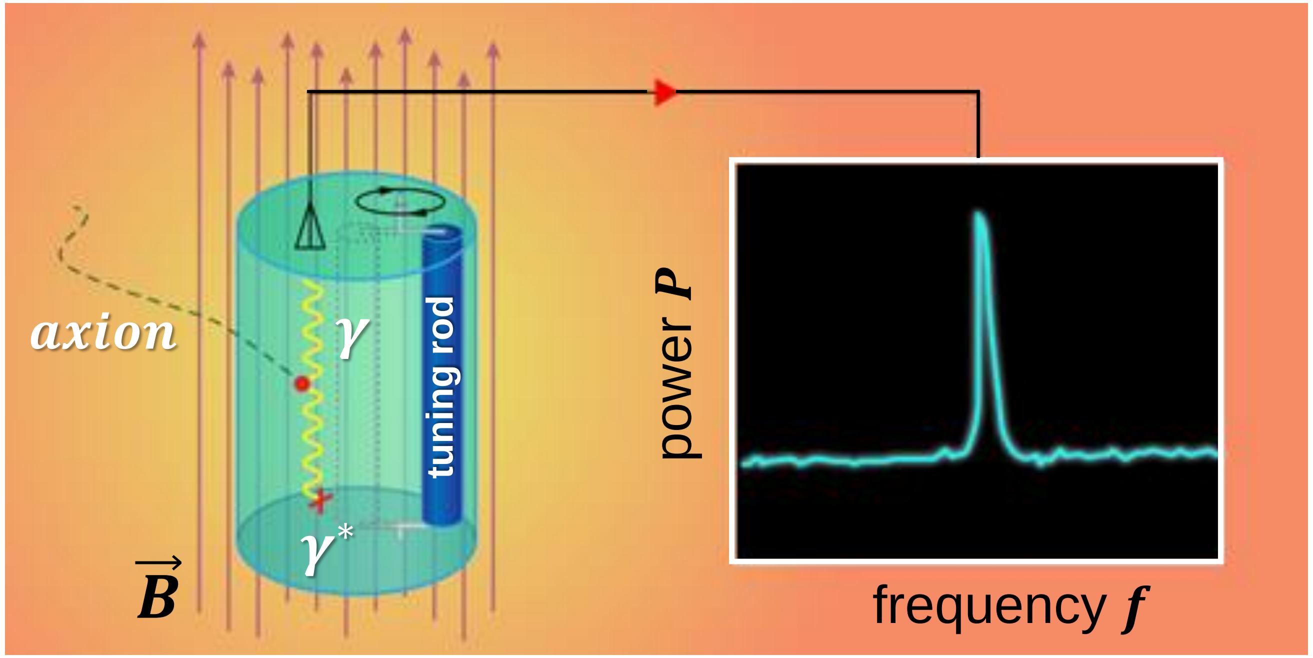


Haloscopes for $DM - axions$: signal & noise

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



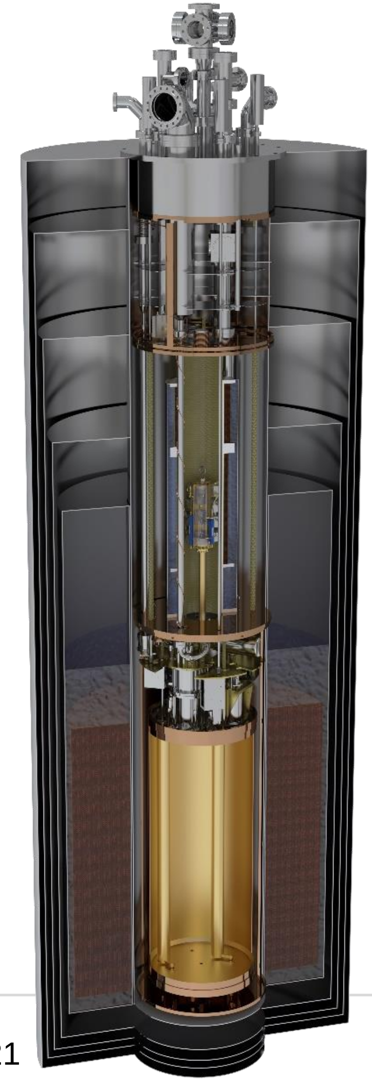
signal power $P_{sig} \sim 10^{-22}\ W$



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

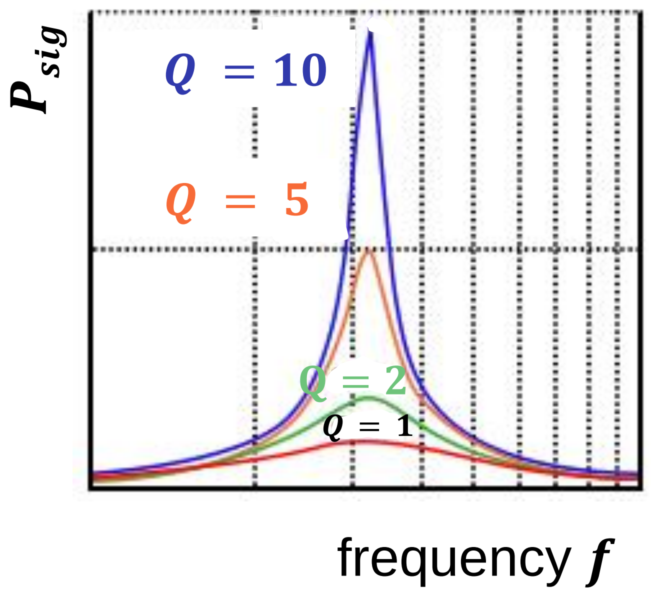
experimental parameters

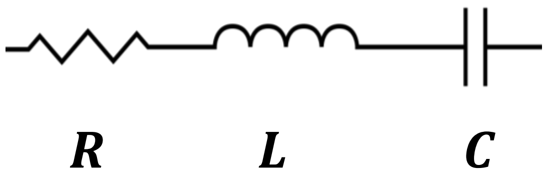
$$P_{sig} \sim g_{a\gamma\gamma}^2 \cdot \frac{\rho_{a,local}}{m_a} \cdot B^2 \cdot V \cdot Q$$

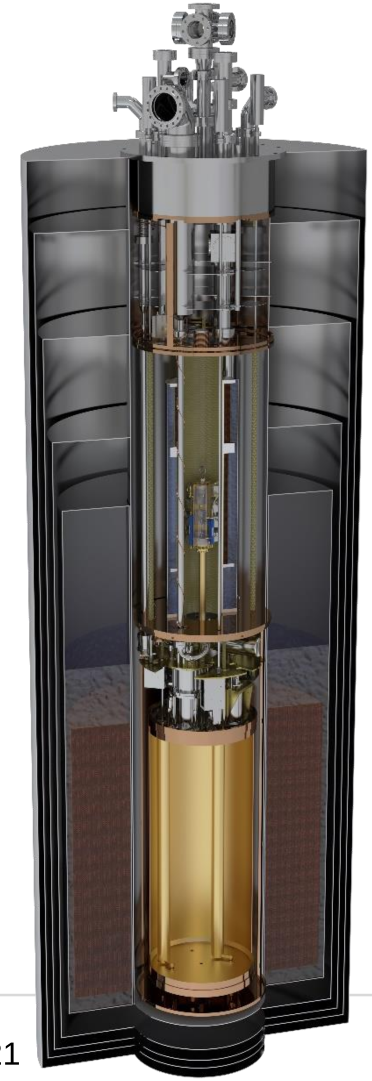
axion parameters

Haloscopes for $DM - axions$: figure–of–merit

- haloscopes: tradeoff – higher Q – value ⇔ more narrow bandwidth Δf







experimental parameters

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

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

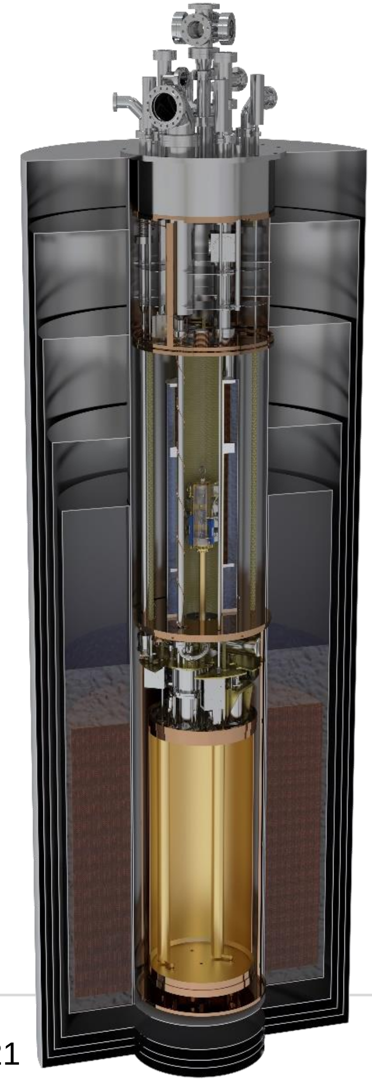
*A*xion *D*ark *M*atter e*X*periment – *ADMX*

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

- $\mathbf{1994 \ldots 2004}$
  measurements
  with **conventional**
  radio amplifiers

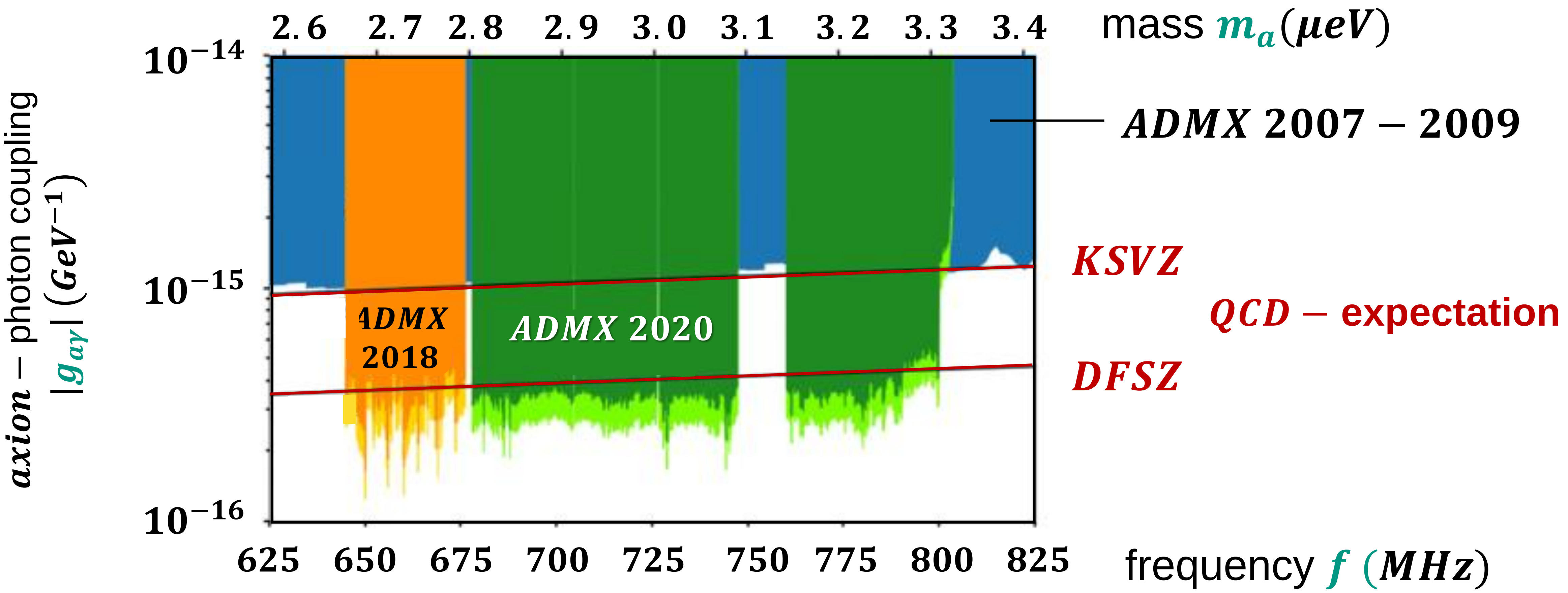
- $\mathbf{2007 \ldots}$
  measurements
  with $\boldsymbol{SQUID}$s
  exclusion limits
  for $\boldsymbol{axion}$ masses

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



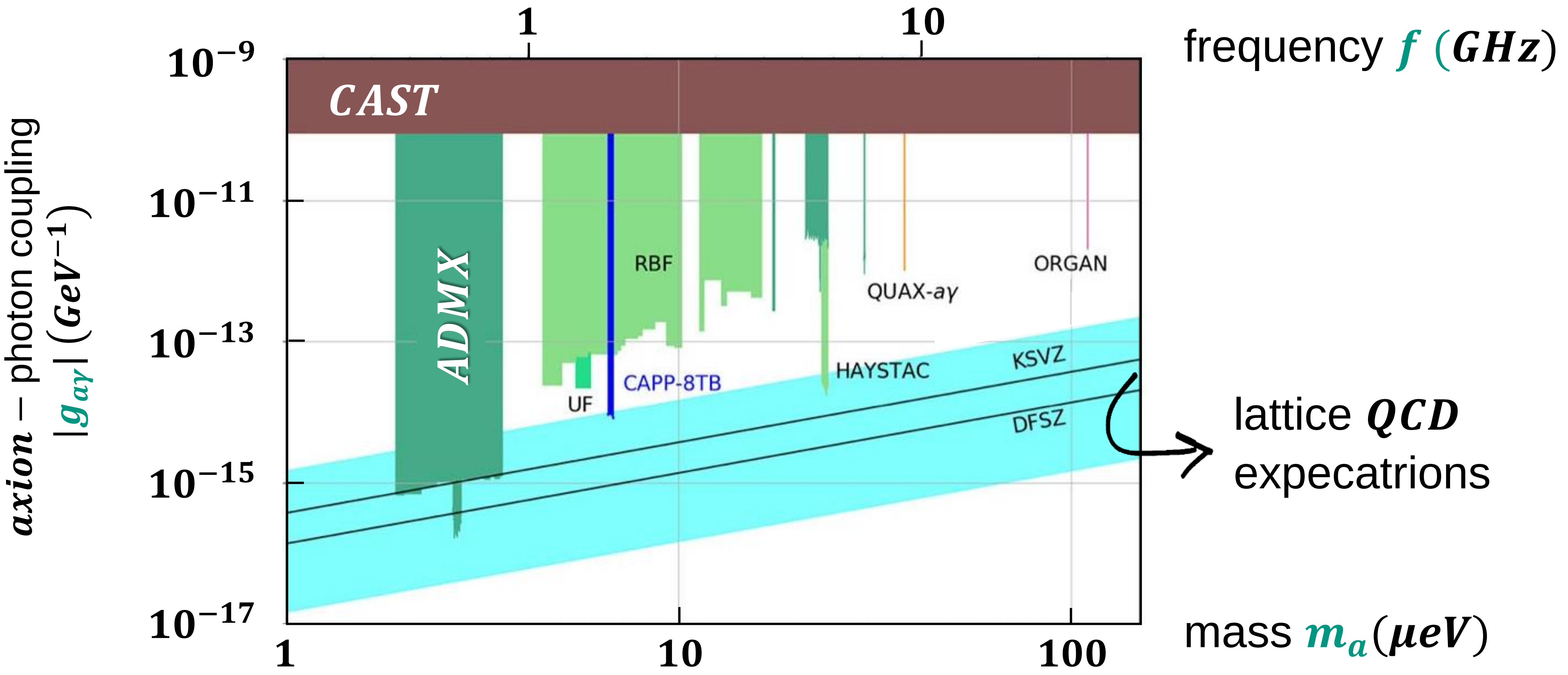
$ADMX$: exclusion limits for $axions$

- Overview of different $axion$ campaigns over the years



$ADMX$ & $HAYSTACK$: future campaigns

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



$ADMX$ & $HAYSTACK$: future campaigns

- **Overview of different ... re 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

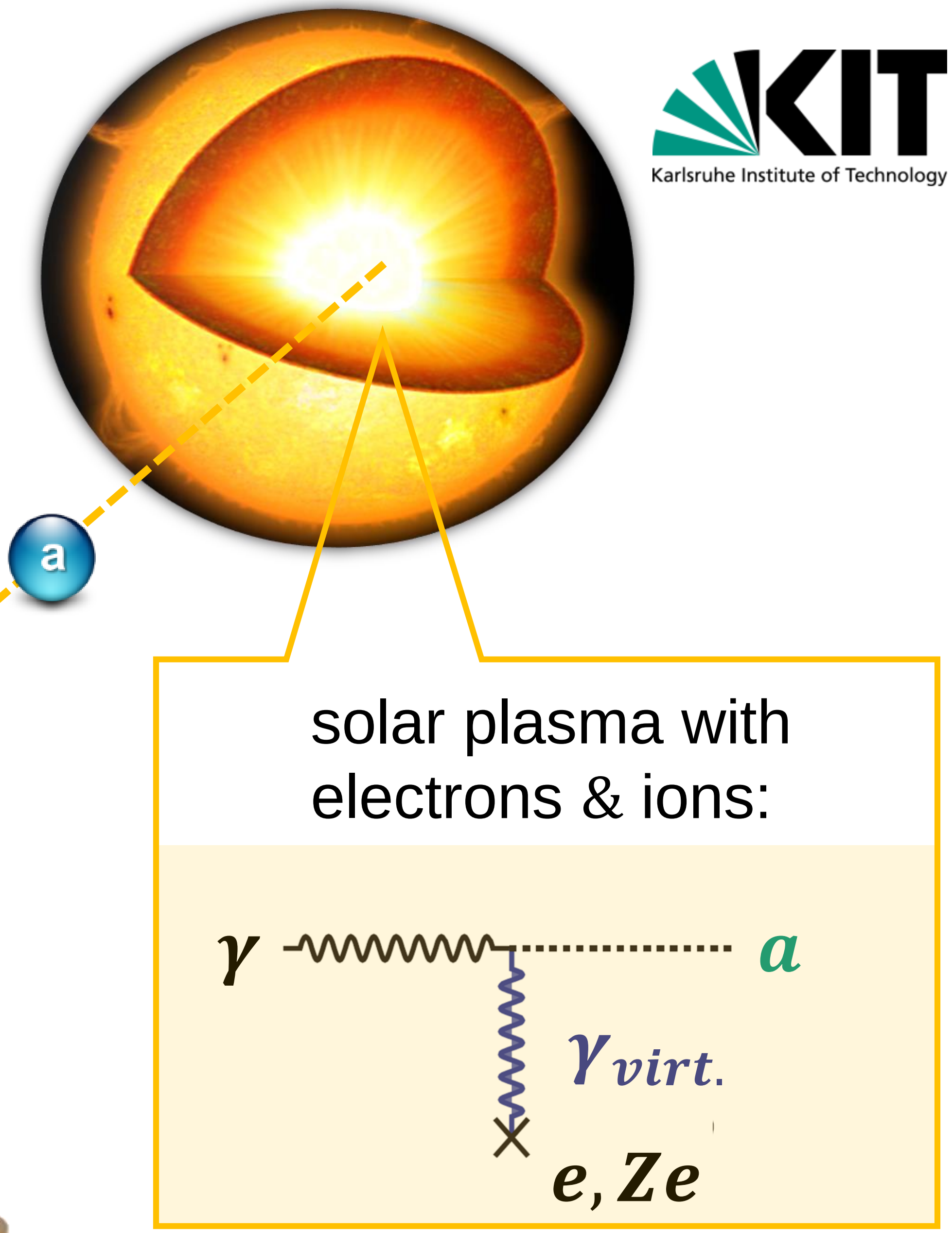
The AMDX experiment, a large magnet, is searching for hypothesized particles called axions.

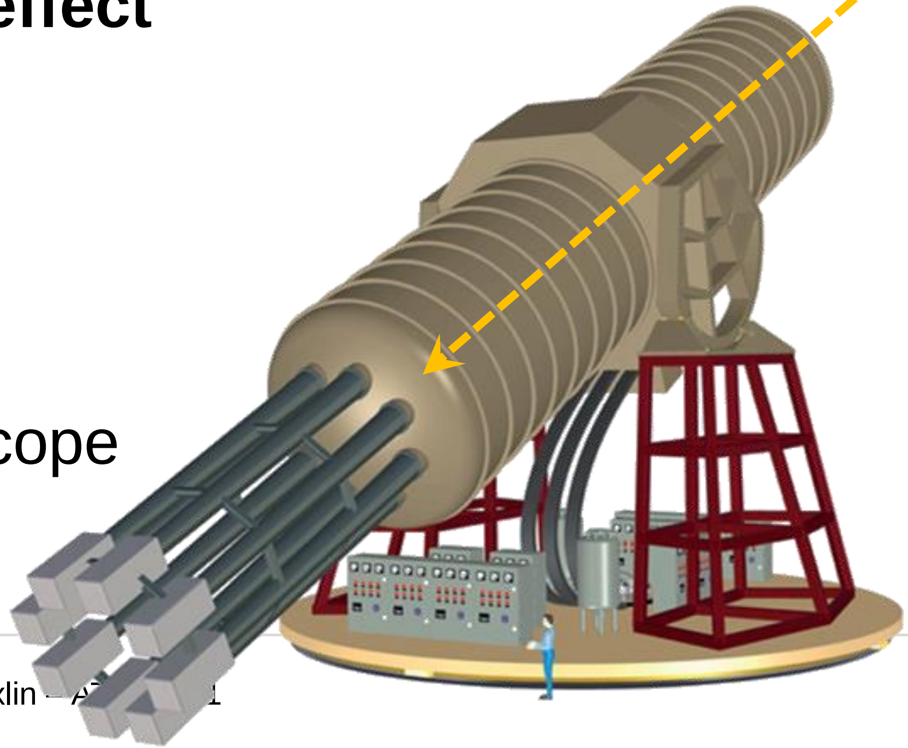
An ambitious supercomputer calculation has brought good and bad news for physicists hunting the 'axion' — a hypothetical particle that is considered a leading candidate for dark matter.

$Axion$ 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**

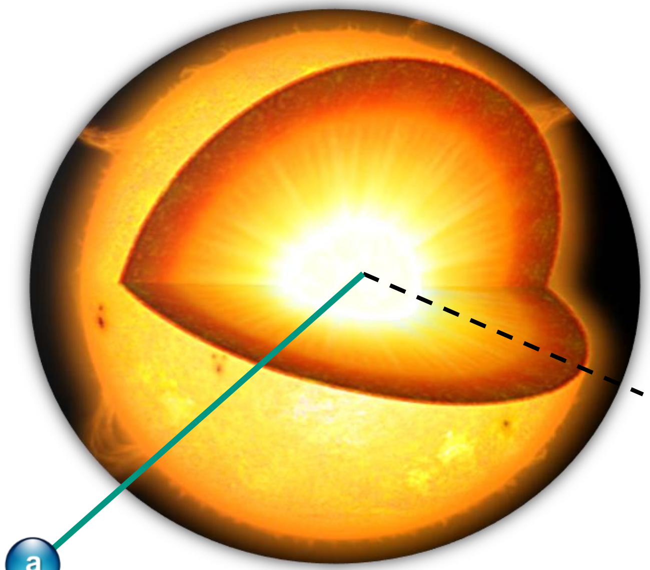




pointing a helioscope towards to sun

Axion experiments: helioscopes

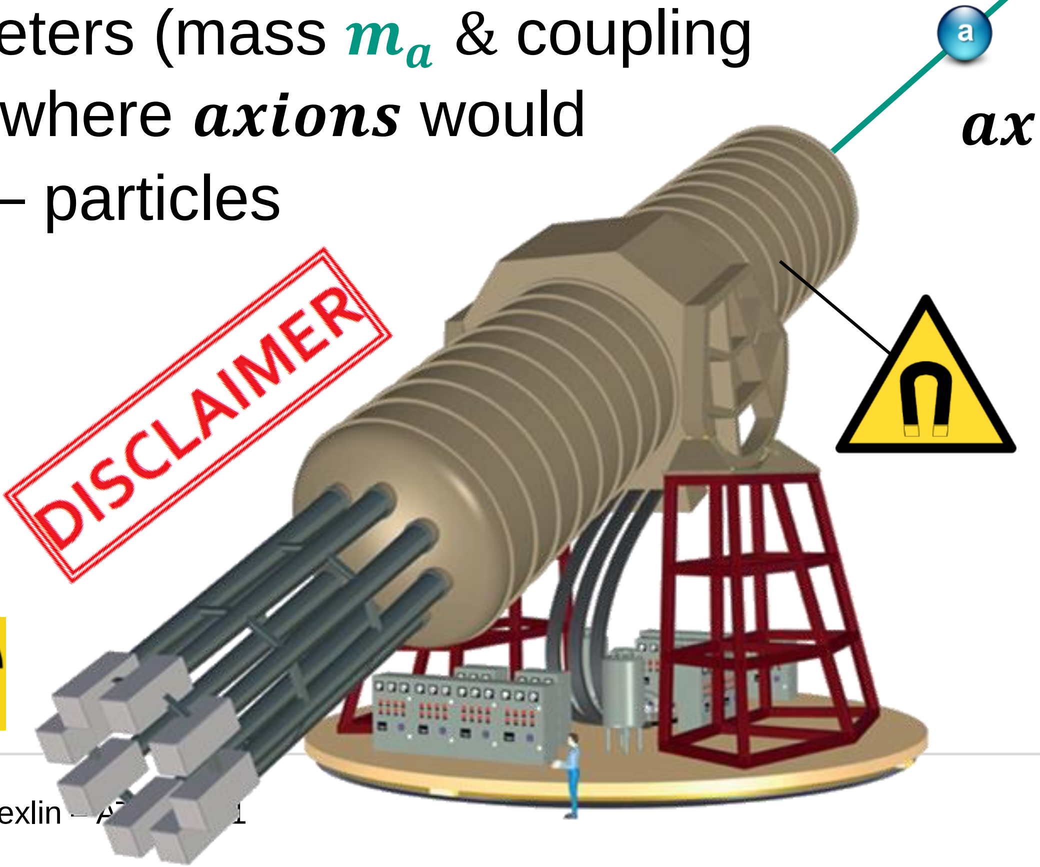
- **Detecting solar *axions* from the magnetized plasma on $E_a \approx keV - scale$**

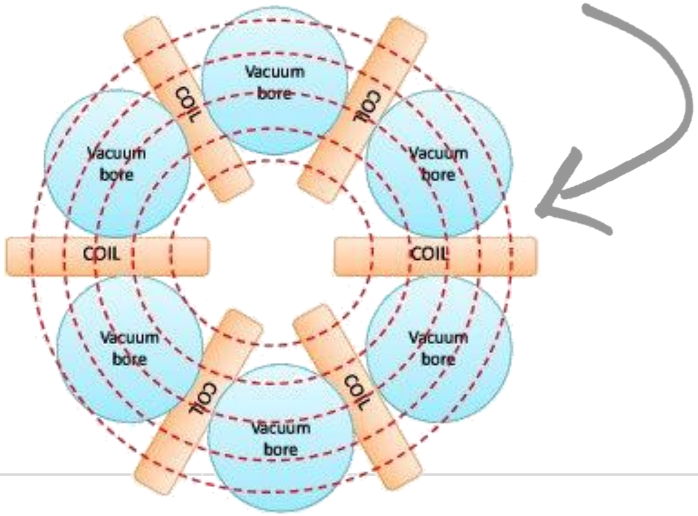


$T = 10^7 K$

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

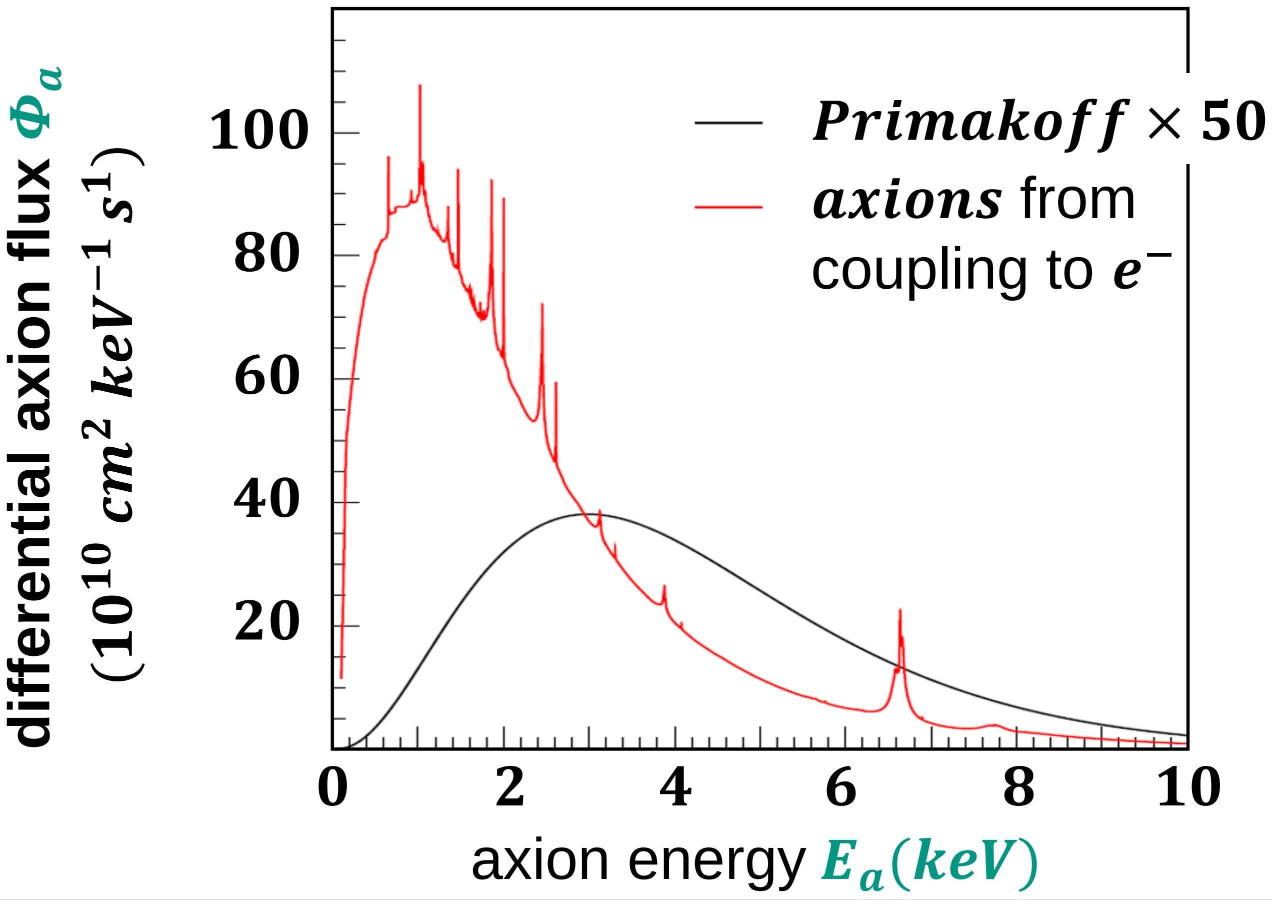
axion – conversion into X – rays in a strong **dipole B** – field

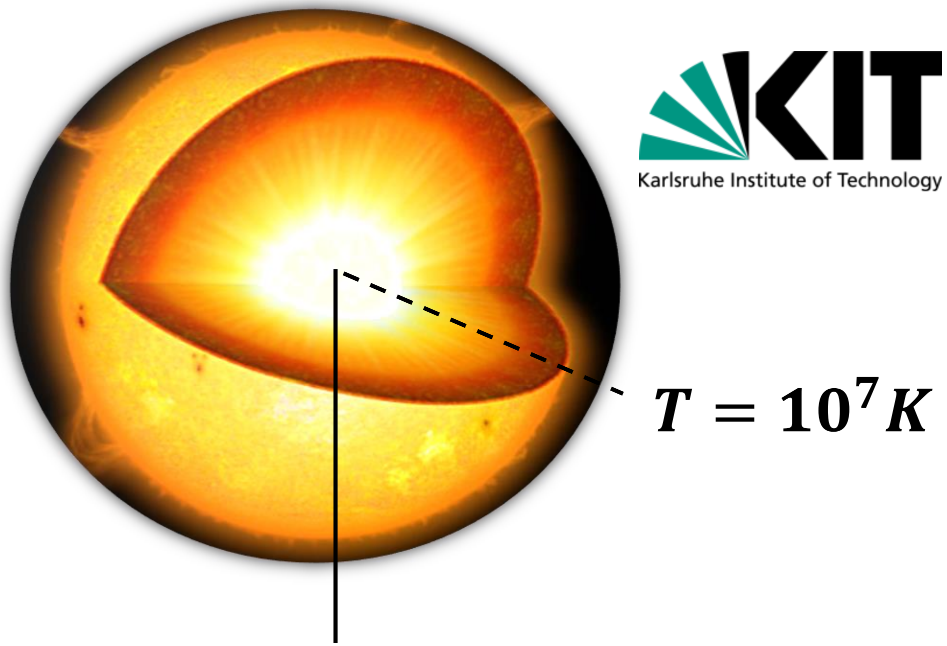




Axion experiments: helioscopes

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





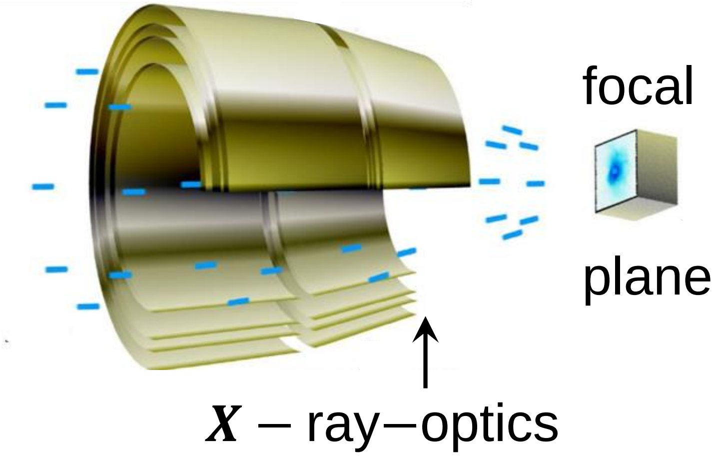
- dominant (***incoherent***) process: axions generated in **electric field** of magnetized plasma (**ions**, e^-)

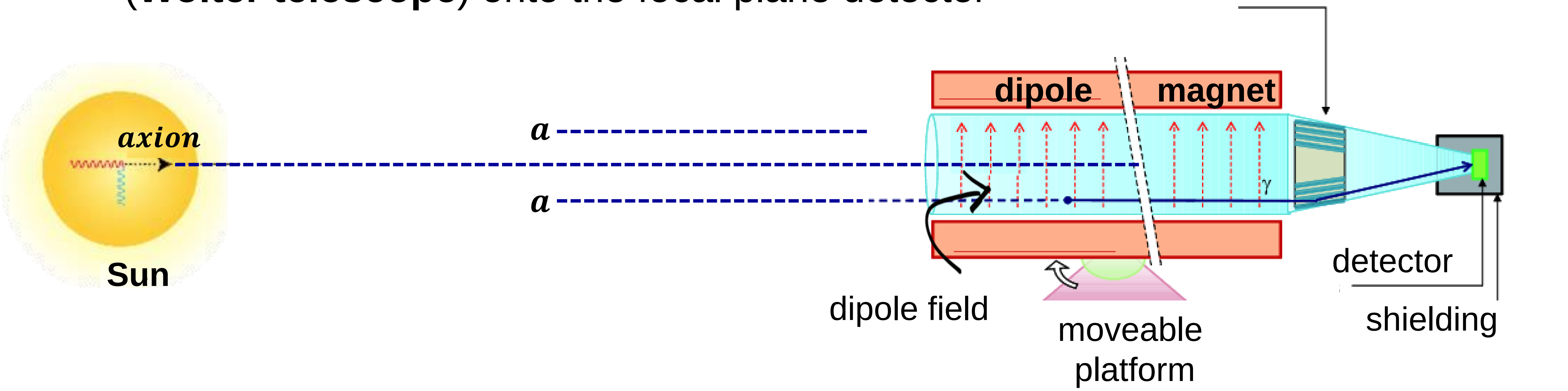
flux $$\Phi_a = \left(\frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}}\right)^2$$

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

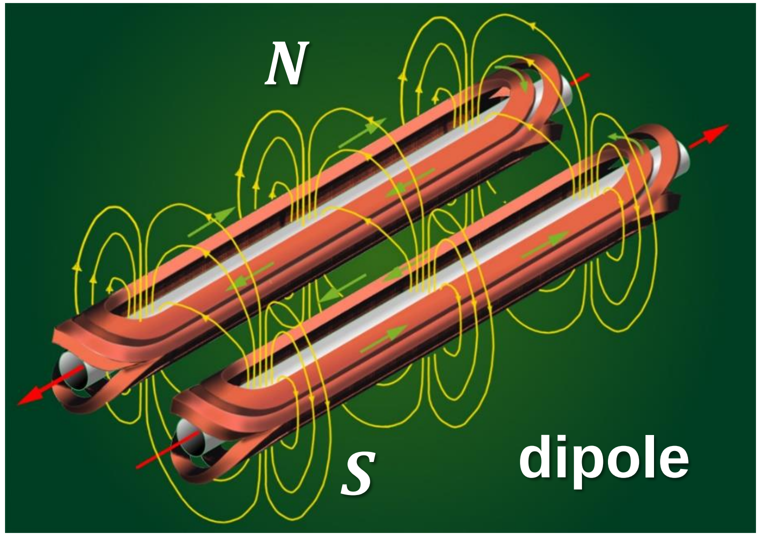


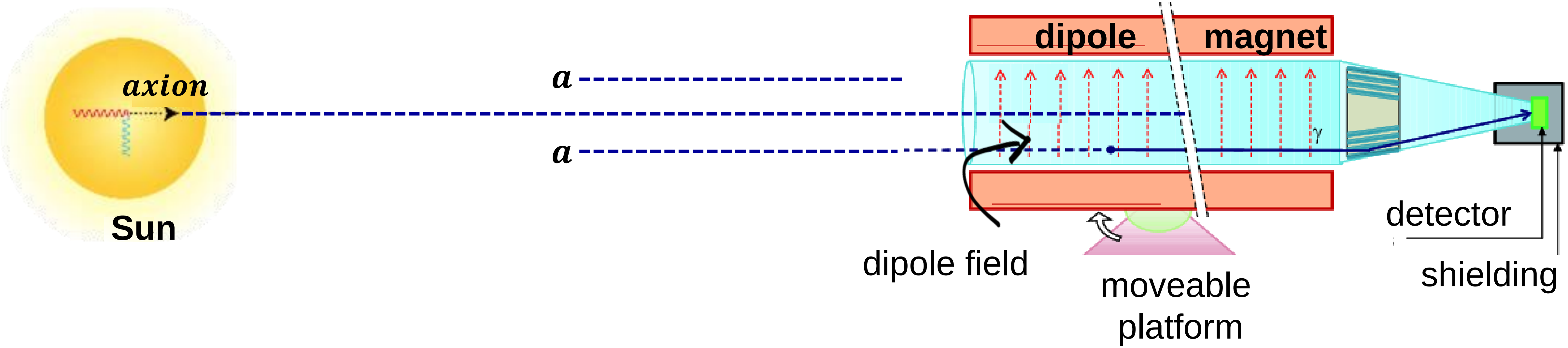


Schematic set–up of a helioscope

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

- we again need a **magnetic dipole field**
  ⇨ only γ´s with polarisation **parallel** to the B – field mix with axions
  ⇨ photon propagation transversal to B – field



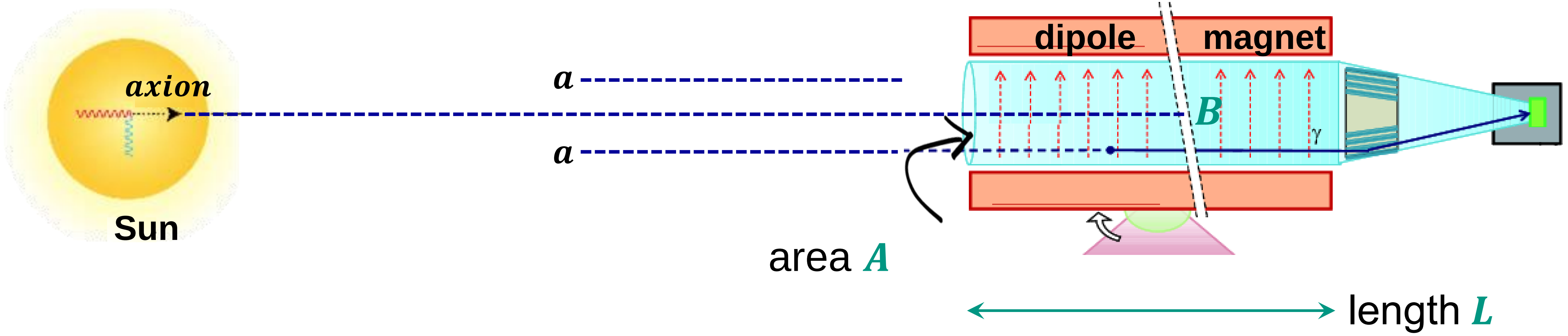


Schematic set–up of a helioscope

- Conversion probability P_{sig} to transform an $axion$ into an X – ray photon

$$P_{sig} \sim g_{a\gamma\gamma}^2 \cdot \left(\frac{B}{10\ T}\right)^2 \cdot \left(\frac{L}{10\ m}\right)^2 \cdot A$$

- exp. ´*figure–of–merit*´ ~ $B^2 \cdot L^2 \cdot A$ (magnetic field B, length L, cross section A)

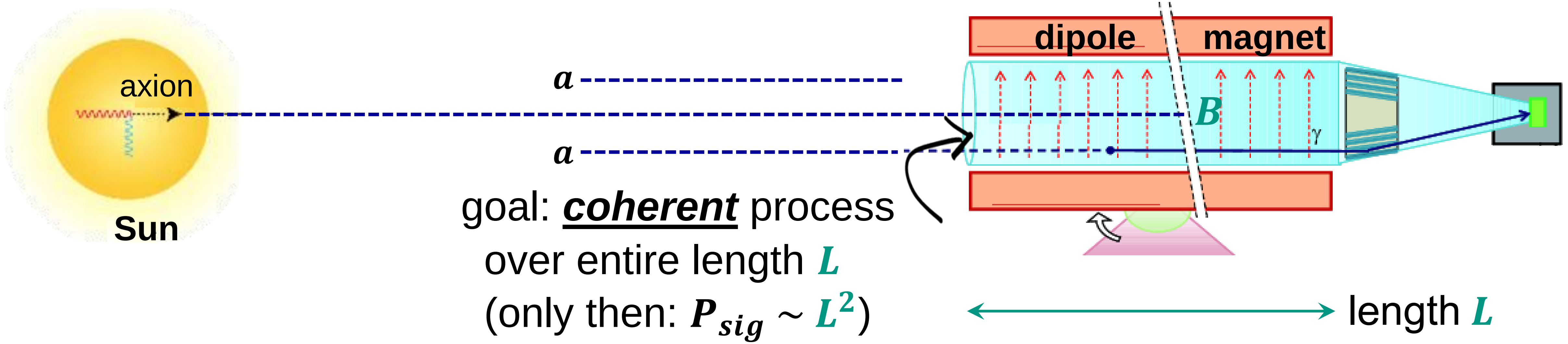


Schematic set–up of a helioscope

- **Optimising the signal strength: the importance of the coherence – factor F**

$$P_{sig} \sim B^2 \cdot L^2 \cdot A \cdot F$$

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



Maintaining coherence condition in a helioscope

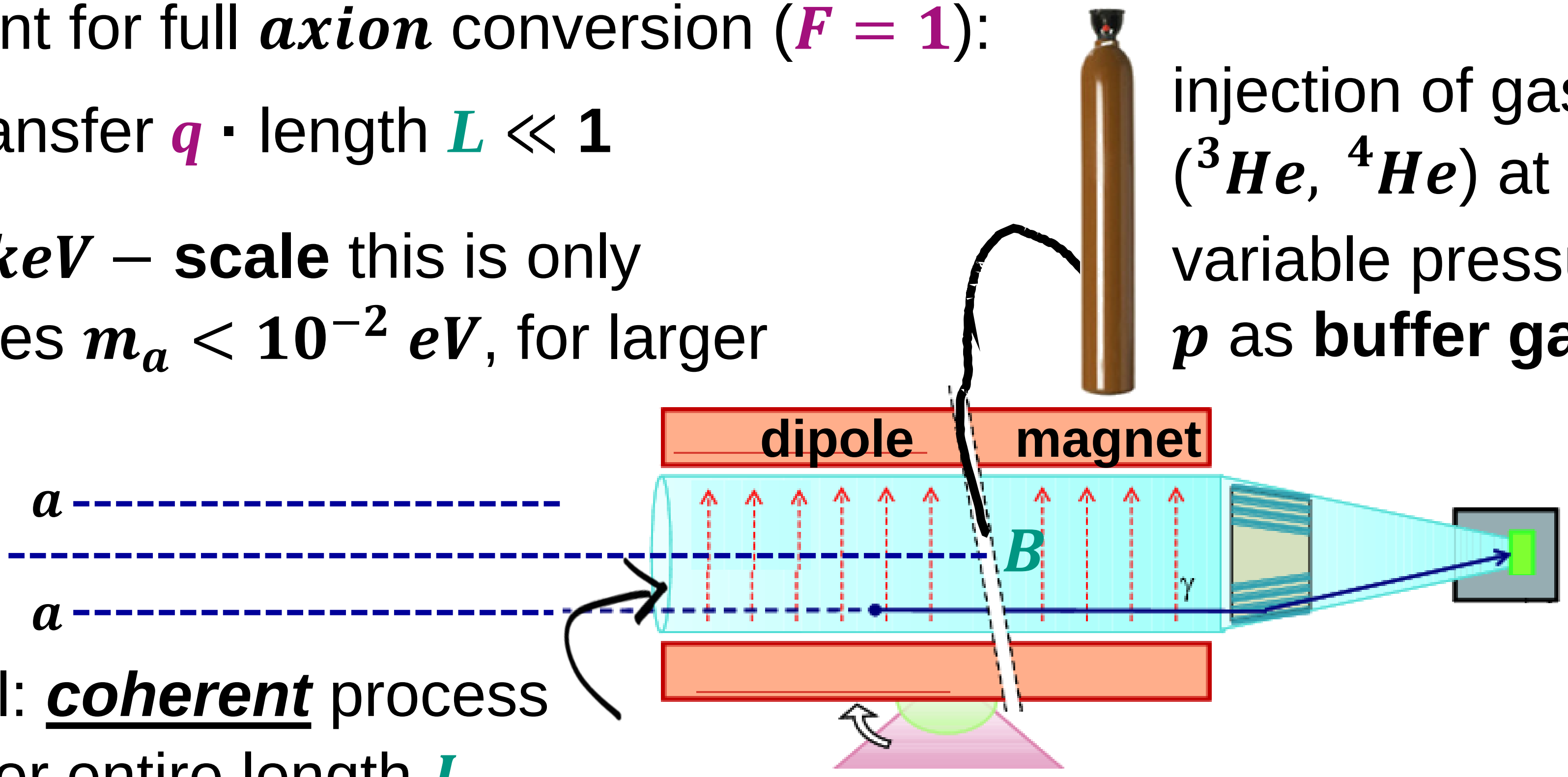
- **Enhancing the coherence – factor F : injection of buffer gas into bore**

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

momentum transfer q · length $L \ll 1$

- 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**

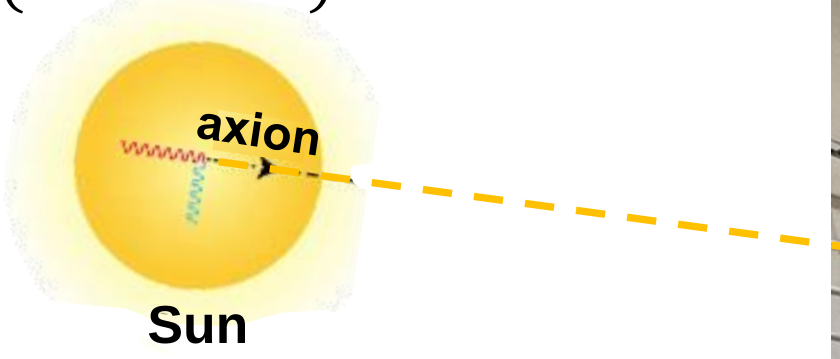


goal: ***coherent*** process over entire length L (only then: $P_{sig} \sim L^2$)

length L

Helioscopes: CAST* experiment at CERN

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



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

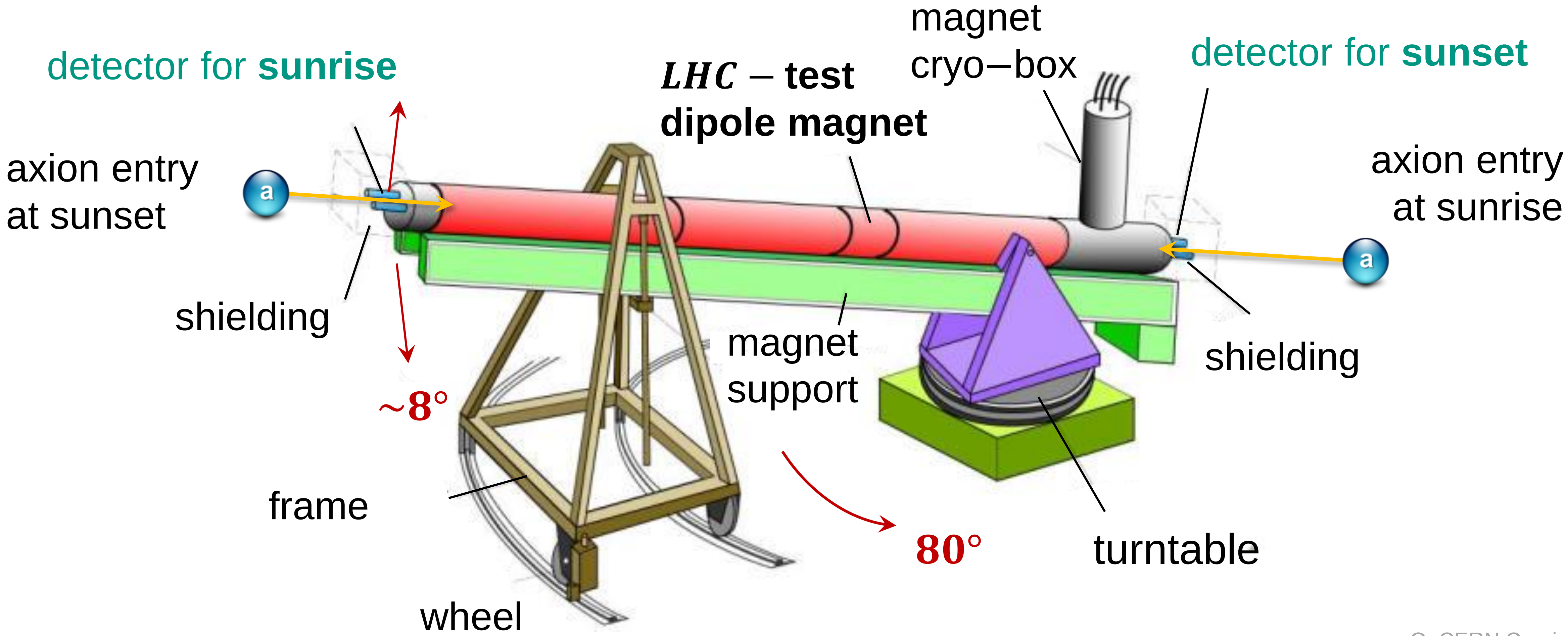
- both magnet entries (side of the setting / rising sun) are fully instrumented with modern $\boldsymbol{X}$ – **ray detector** systems

Q: CERN Courier

*CERN A*xion* Solar Telescope

Helioscopes: $CAST$ experiment at $CERN$

- A moveable dipole magnet: allows tilting to follow the Sun for a few $h\ /\ day$



Q: CERN Courier

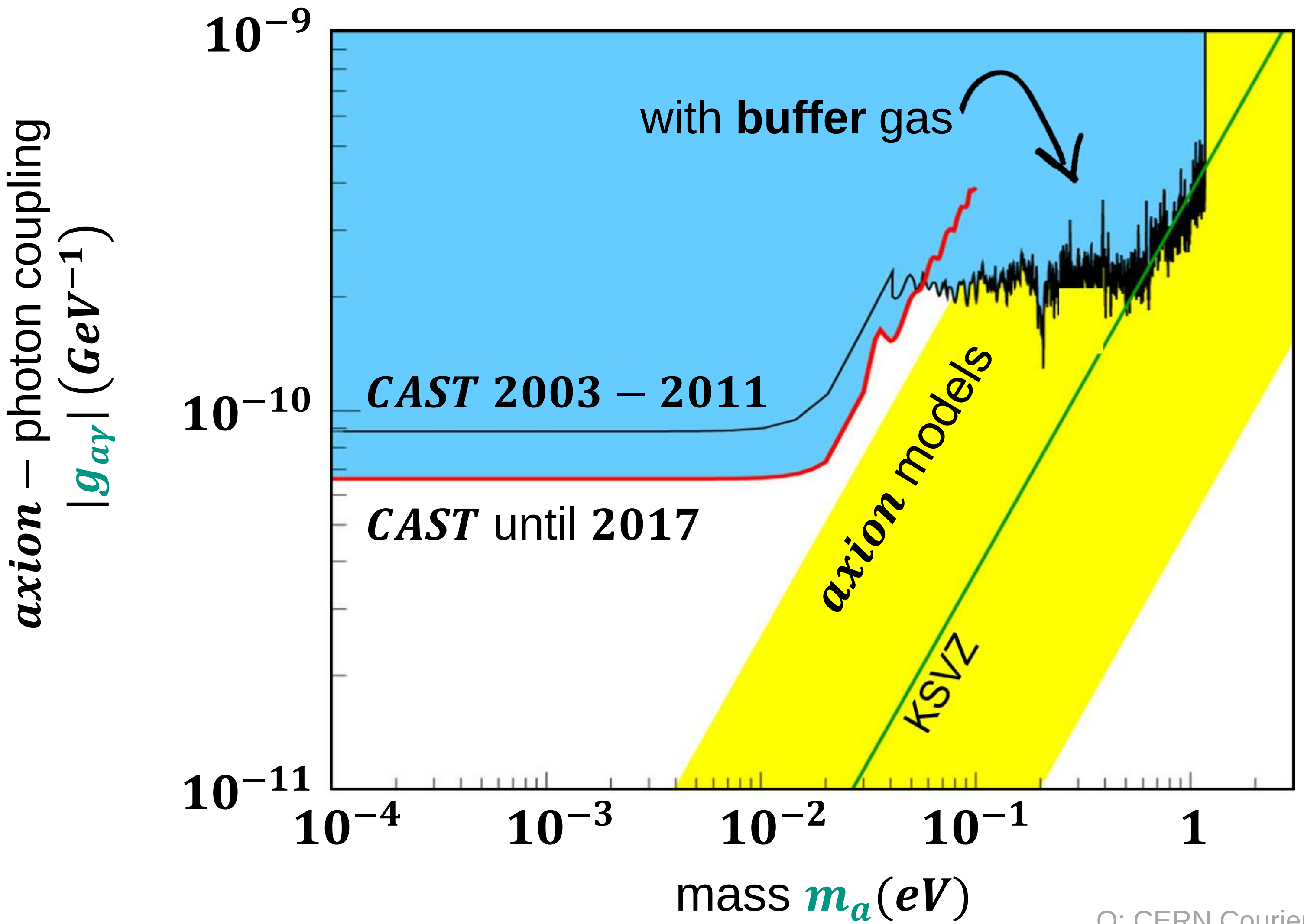
Helioscopes: *CAST* results – use of buffer gas

- ***Axion*** **runs since 2003**

2005 … 2006:
measurements with ^{4}He

2008 … 2011:
measurements with ^{3}He
first push forward into the region of ***QCD*** – axions

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



Q: CERN Courier

Helioscopes: $IAXO$* – an outlook

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

- setup: $L = 20\ m$ long **toroidal magnet system** with $\emptyset = 5.2\ m$

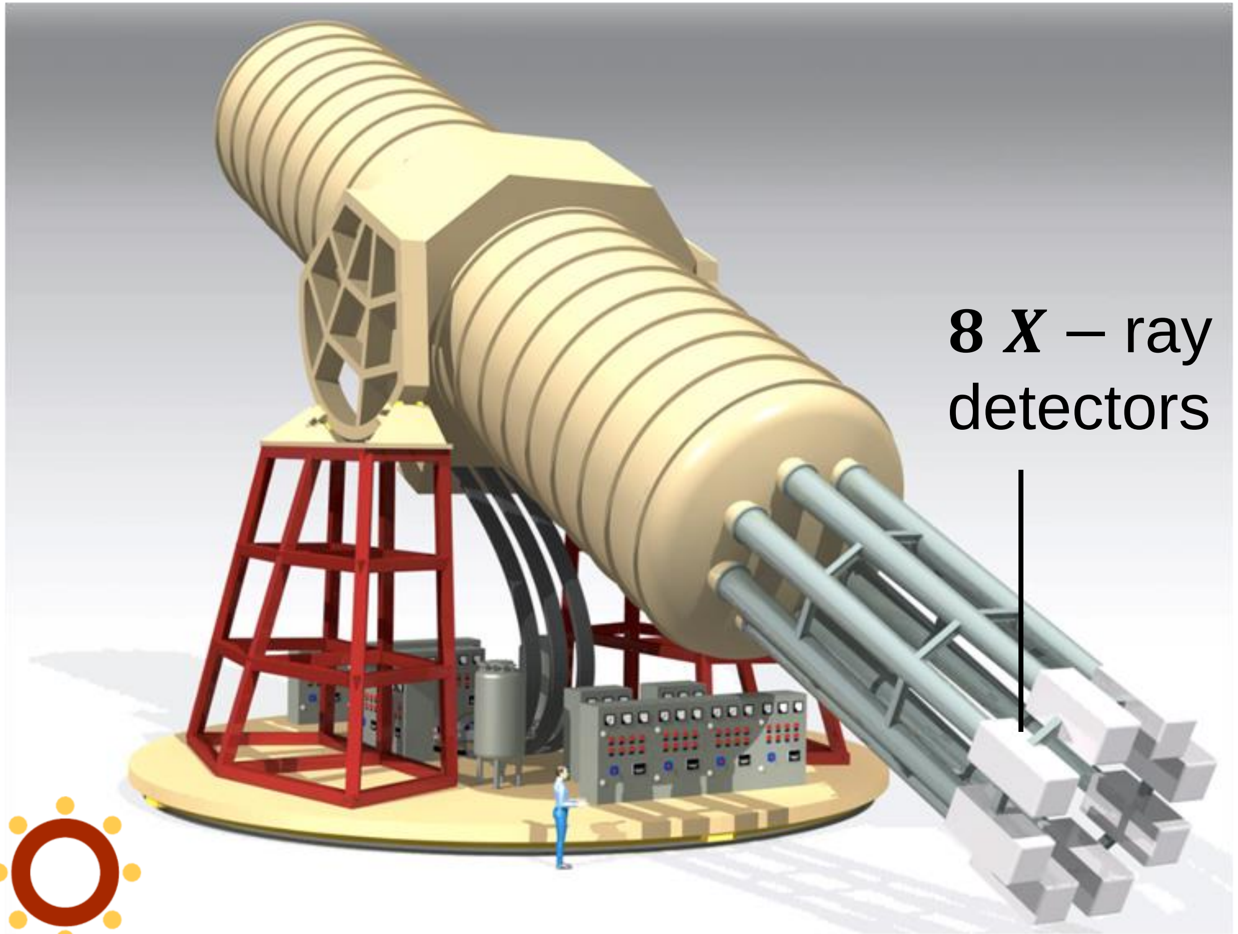
- toroidal system is being formed by **8 coils** ($\emptyset = 0.6\ m$) with $B = 2.5\ T$

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

$CAST$: $21\ T^2\ m^4$

$IAXO$: $\sim 6000\ T^2\ m^4$

- **factor 20** improved sensitivity relative to $CAST$

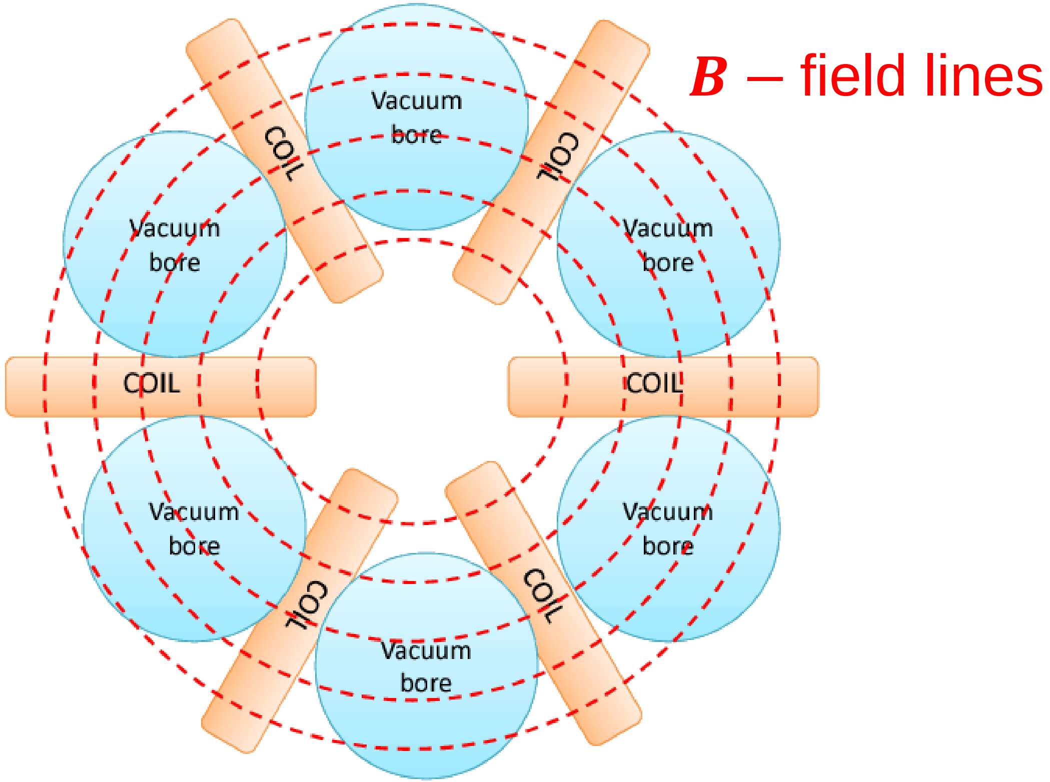


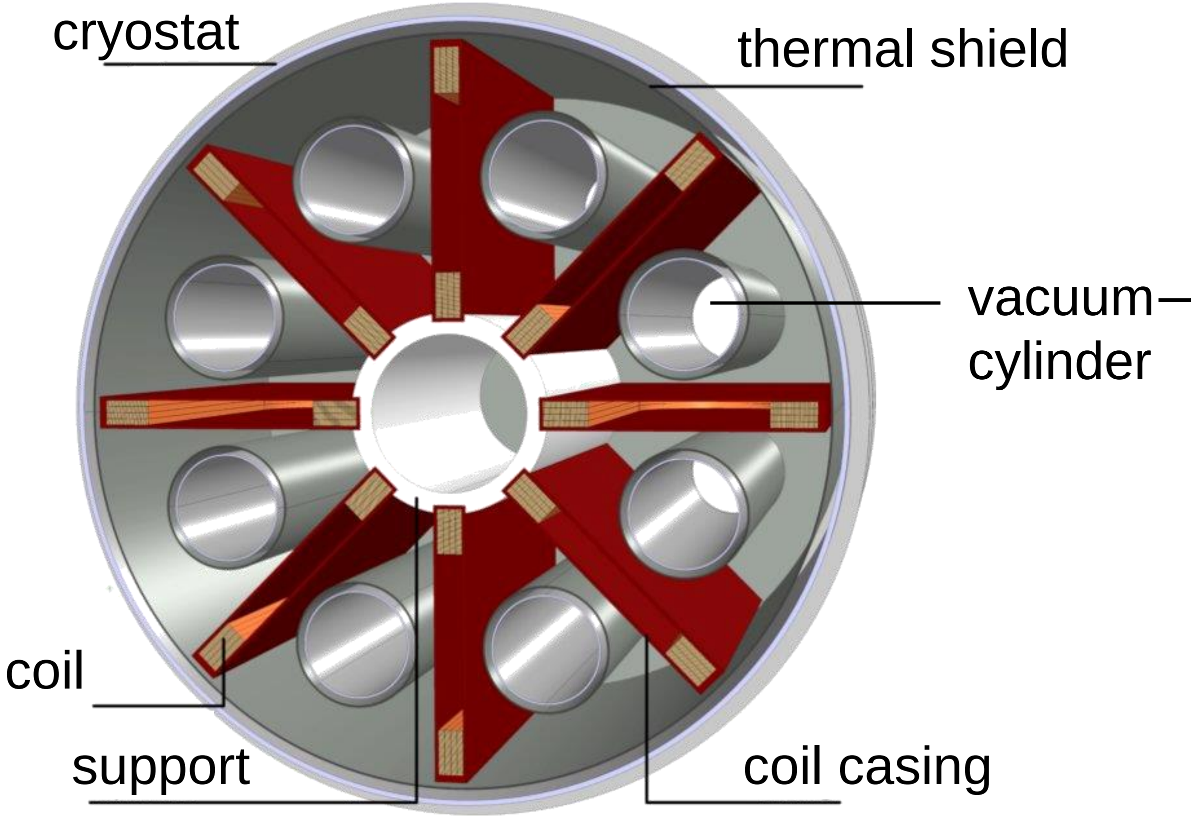
*$IAXO$ – International AXion Observatory

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 $axions$**

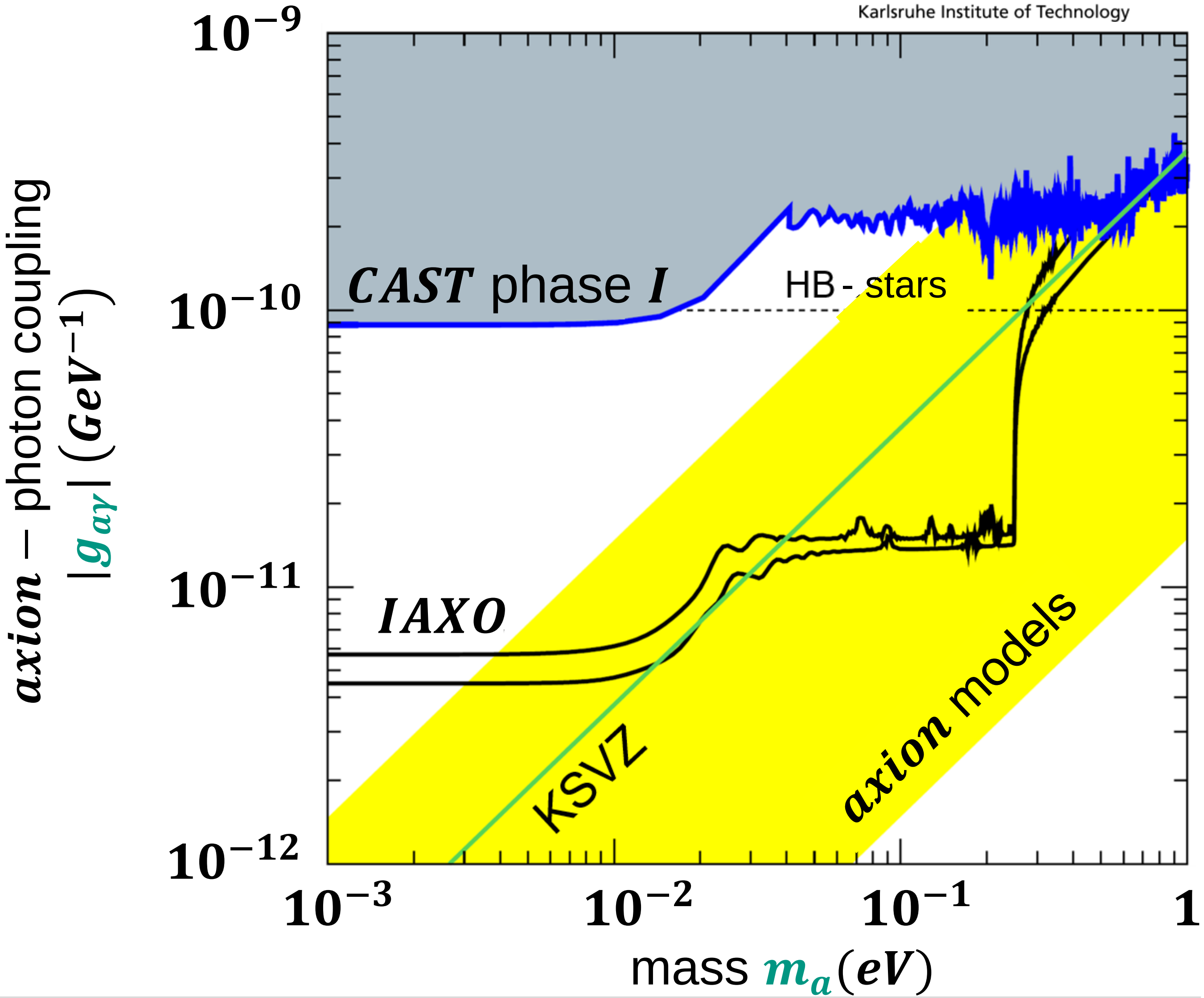
$CAST$

- results after $\sim\mathbf{20}$ year long data taking (vacuum / buffer gas)

$IAXO$

- expected for $\mathbf{3}$ years data taking (vacuum / buffer gas)

- test of ´realistic´ QCD – axion parameter regions (see limits)



Helioscopes: first step – $BabyIAXO$

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

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

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

- will follow path of Sun: $t = 24\, h\, /\, day$

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

- X – ray optics: uses expertise from $XMM -\ Newton$ telescope (ESA)