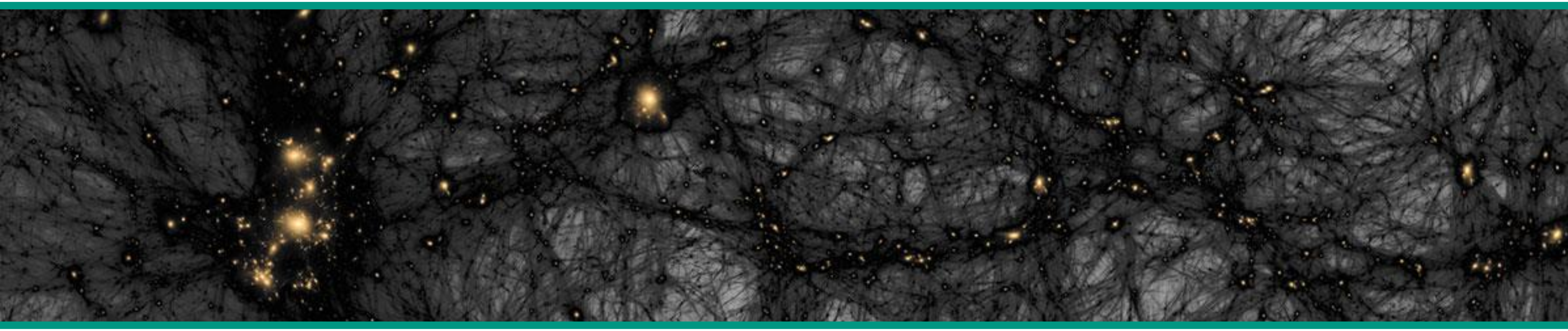
Astroparticle physics I – Dark Matter

WS22/23 Lecture 20 Feb. 9, 2023



Recap of Lecture 19

- **Hunting low-mass $WIMPs$ ($GeV-$ scale & below) with cryogenic bolometers**

  - read-out of **ballistic & thermal phonons** requires $mK-$ temperature regime

  - requirement to minimize specific heat C_V : low-mass bolometers $m = g-$ scale

  - **thermal** phonons: read-out via $NTD-$ thermistors (high impedance)

  - **ballistic** phonons: read-out via $TES-$ thermistors (low impedance) + $SQUIDs$

  - **P**article **ID**entification (PID): via quenching of charge signal / scintillation light

  - **no $WIMP-$ signals** found so far in $CRESST$, Edelweiss,…

4.6 Non-thermal DM – candidates

- **Generating DM: non-thermal means**

  - A truly broad mass scale:

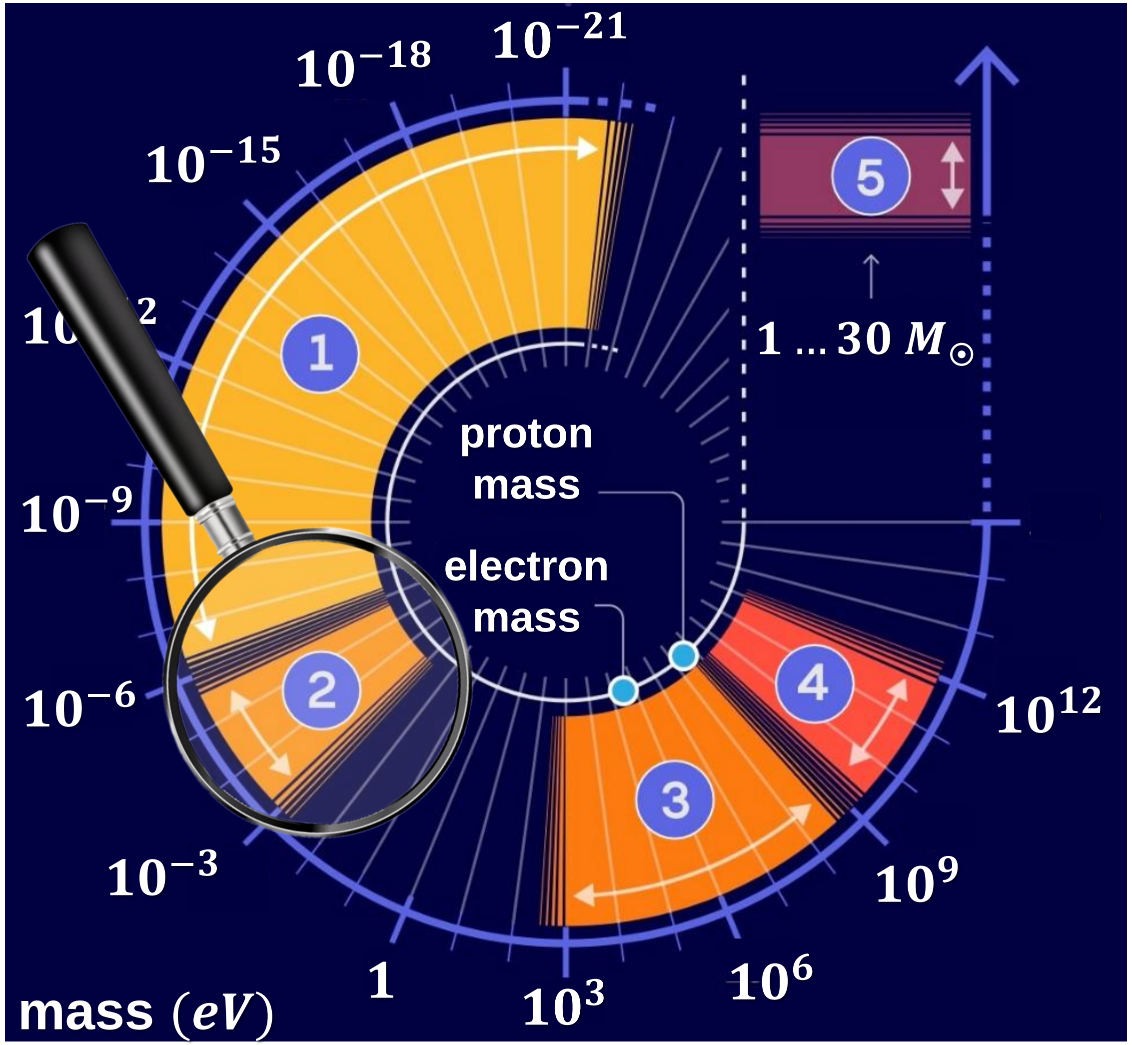
❶ ultra-light DM (**A**xion-**l**ike **P**articles, **ALP**s & axions)

❷ **axions** (⇨ strong CP –problem)

❸ DM on $sub-GeV$ scale ⇨ bolometers

❹ WIMPs: **neutralinos** ⇨ Xe/Ar TPCs

❺ primordial black holes (MACHOs*)



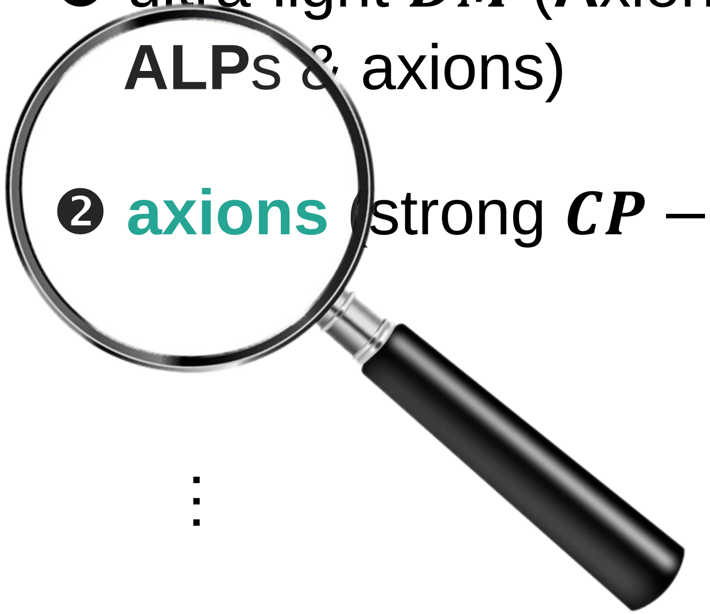
 *MAssive Compact Halo Objects

Non-thermal DM – candidates: axions

- **Generating Dark Matter in a non-thermal way by a new symmetry principle**

❶ ultra-light DM (**A**xion-**l**ike **P**articles, **ALP**s & axions)

❷ **axions** (strong CP –problem)

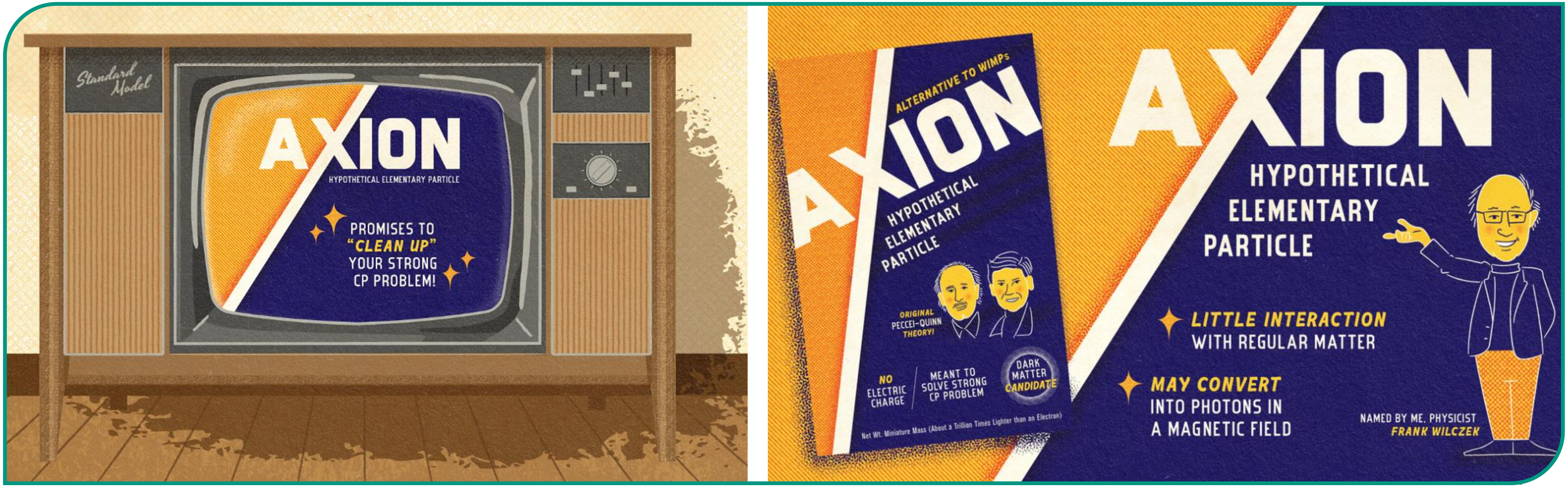


⋮

4.6.1 Axions

- **Properties of axions as Dark Matter in the universe**

  - central motivation for the axion: the **strong CP −problem**



Axions – a completely new DM – candidate

- **Basics of the surprising origin of the axion: ´who ordered that*?´**

  - massive neutral boson with $J^P = 0^-$ (pseudo-scalar)

    ⇨ extremely light: $m_a \sim (10^{-9} \ldots 1)\ eV$

    ⇨ extremely small interaction (coupling) with normal matter (´the ***invisible*** axion´)

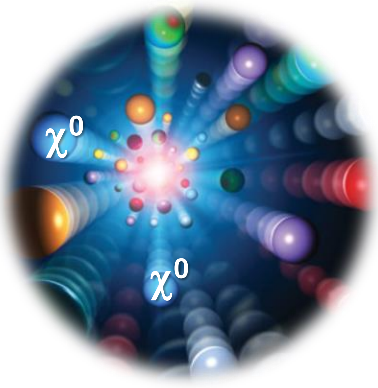
    ⇨ extremely long-lived $\tau_a > \tau_{Hubble}$ for $m_a < 20\ eV$

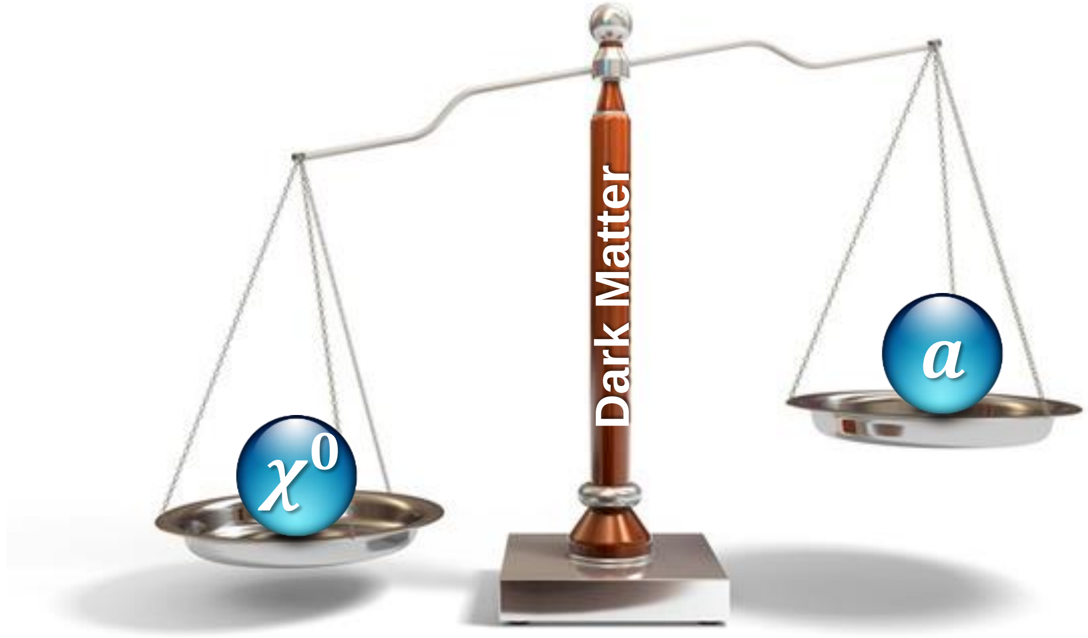
  - solves the ´**strong CP –problem**´

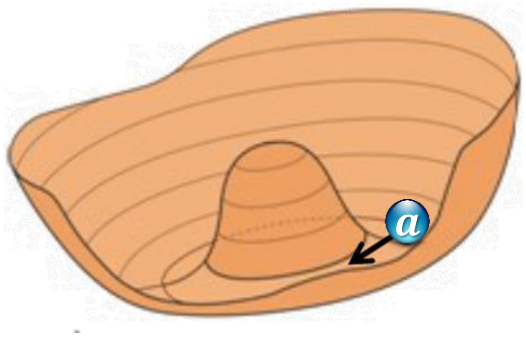
*I. *Rabi* (1936), after the discovery of the muon

Axions – a completely different DM – candidate

- **Comparing axions as $\boldsymbol{WISP}$s to our ´$good\ olde$´ massive $\boldsymbol{WIMP}$s**







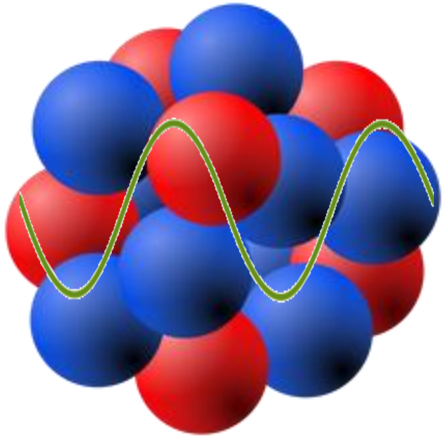
thermal production			non-thermal production
$\boldsymbol{WIMP}$			$\boldsymbol{WISP}$
$\boldsymbol{S = ½}$	mass: $\boldsymbol{GeV \dots TeV}$	mass: $\boldsymbol{\mu eV \dots meV}$	$\boldsymbol{S = 0}$
´thermal gas´			**´Bose condensate´**

$\boldsymbol{WISP}$ = **W**eakly **I**nteracting **S**lim **P**article

Axions – a completely different DM – candidate

- Comparing axions as $WISP$s to massive $WIMP$s: *de Broglie* wavelength λ

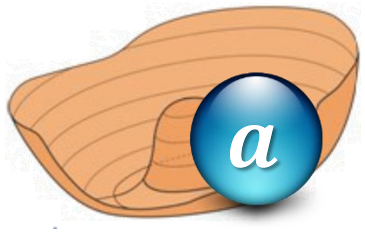
elementary particle



$\lambda \sim nm$

***de Broglie* wavelength**

$$\lambda = \frac{h}{p}$$



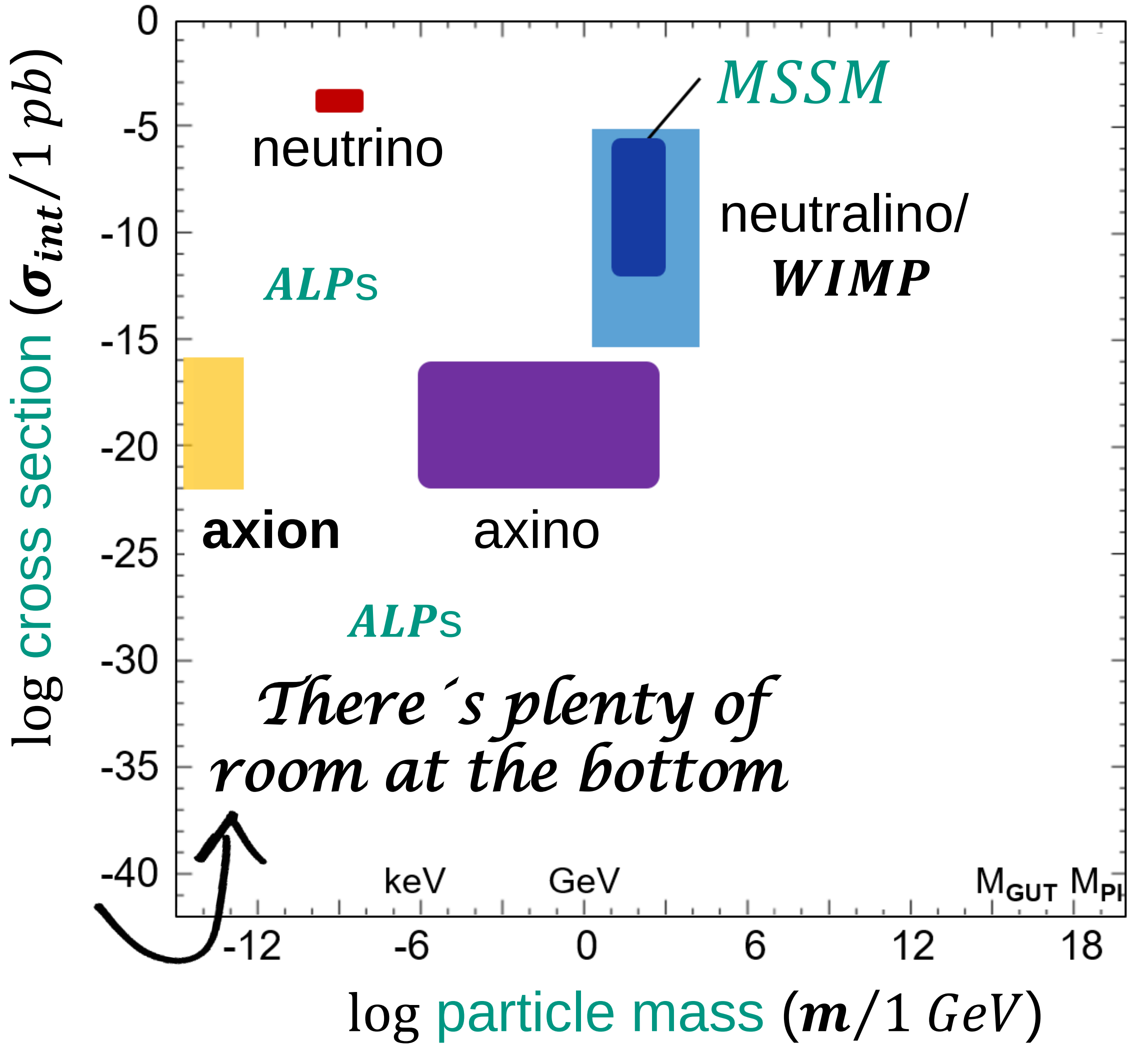
field-oscillation

$\lambda \sim m \dots km \dots pc$

RECAP: DM – candidates with mass m & xsec σ

Karlsruhe Institute of Technology

- **Axion a as $WISP$**
  - motivation: ´QCD – axion´ for conservation of CP in QCD
  - axion = prototpe of a $WISP$
  - axions could act as CDM in universe if their mass falls in the range: $m_a = (10^{-6} \dots 10^{-3})\ eV$
  - ALPs = Axion Like Particles



29.12.1959

Axions and the symmetry CP in QCD

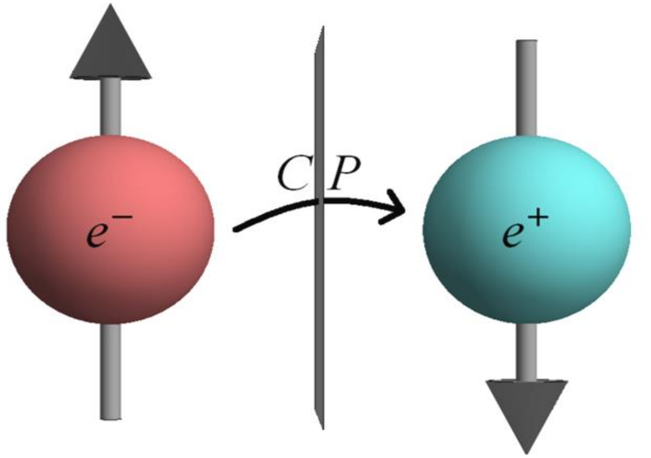
- **How to solve the ´strong CP – problem´**

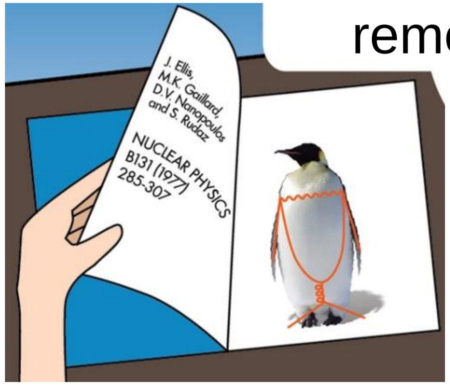
  - general statement: in case that
    CP **invariance** is violated:
    ⇨ violation of T **invariance** (& vice versa)

  - CP – violation so far only detected in the
    weak interaction!

  - CP – violation has never been detected in the
    strong interaction!

spin up electron **spin down positron**





remember those penguin diagrams ?

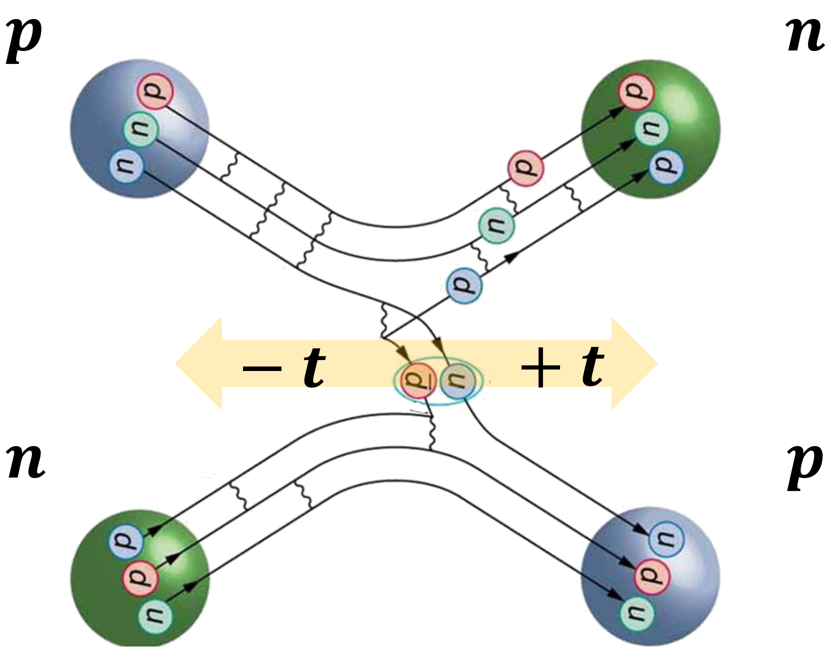
Axions and the symmetry CP in QCD

- **Implictions of ´strong CP – problem´**

  - general statement: in case that **CP invariance** is violated:
    ⇨ violation of T **invariance** (& vice versa)

  - CP – violation so far only detected in the weak interaction!

  - CP – violation has never been detected in the strong interaction!



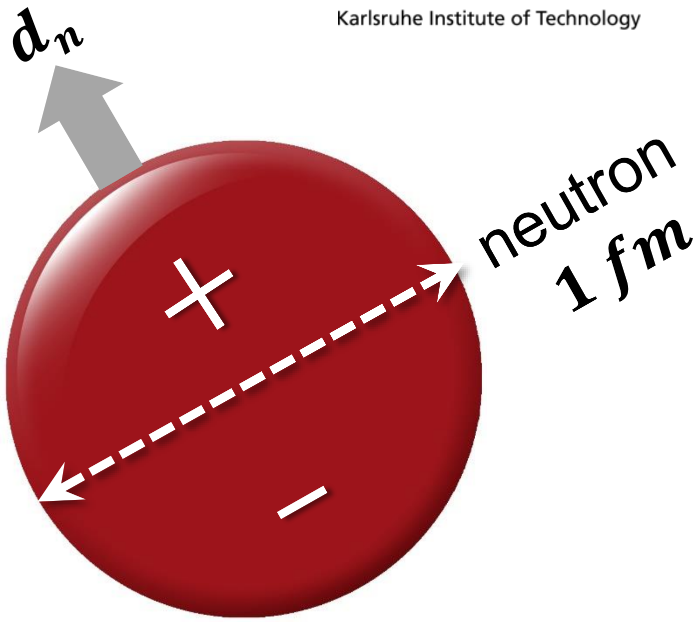
QCD: do we have CP – and T – symmetry ?

Axions and the symmetry CP in QCD

- **A key observable of the ´strong CP – problem´: the $n - EDM$**

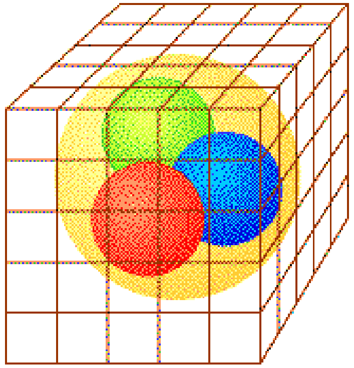
  - QCD – **Lagrangian** contains CP – violating terms:
    ⇨ how can we detect them experimentally?

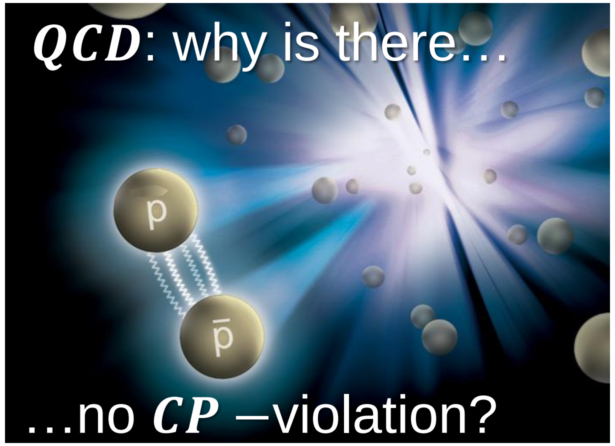
  - we then expect a non-zero value of the **Electric Dipole Moment** (EDM) of the neutron: $d_n \neq 0$



theoretically allowed value (QCD):

$$d_{n,theo} \sim 3.6 \cdot 10^{-16}\ e \cdot cm$$





Axions and the symmetry CP in QCD

- **A key observable of the´strong $CP-$ problem´: the $n-EDM$ in a ´back of the envelope´ ansatz**

  - we estimate a maximum value for EDM of the neutron

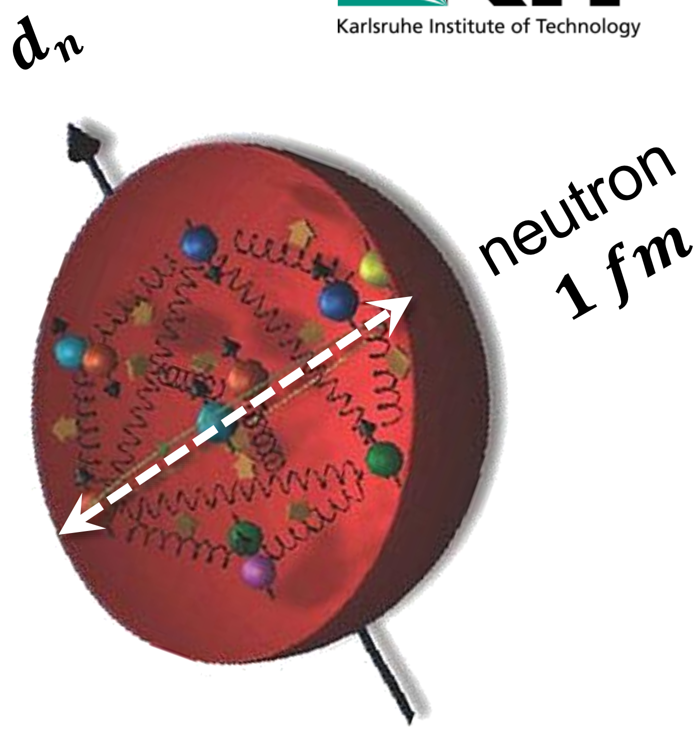
  - ´naive´ model: one quark ($q = 1/3$) over neutron size

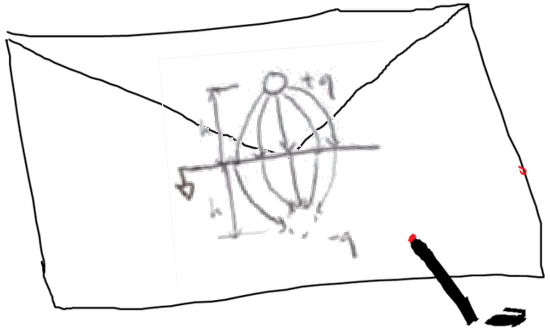
$$d_{n,naive} \sim 1/3 \ e \cdot 1 \cdot 10^{-13} \ cm$$

$$d_{n,naive} \sim 3 \cdot 10^{-14} \ e \cdot cm$$

theoretically allowed value (QCD):

$$d_{n,theo} \sim 3.6 \cdot 10^{-16} \ e \cdot cm$$

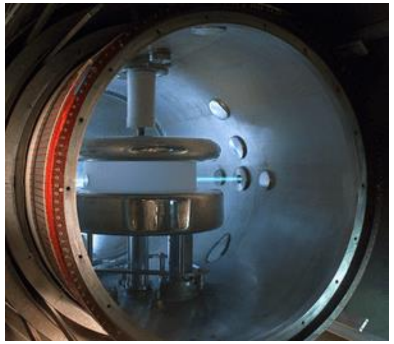




´back of the envelope´ calculation

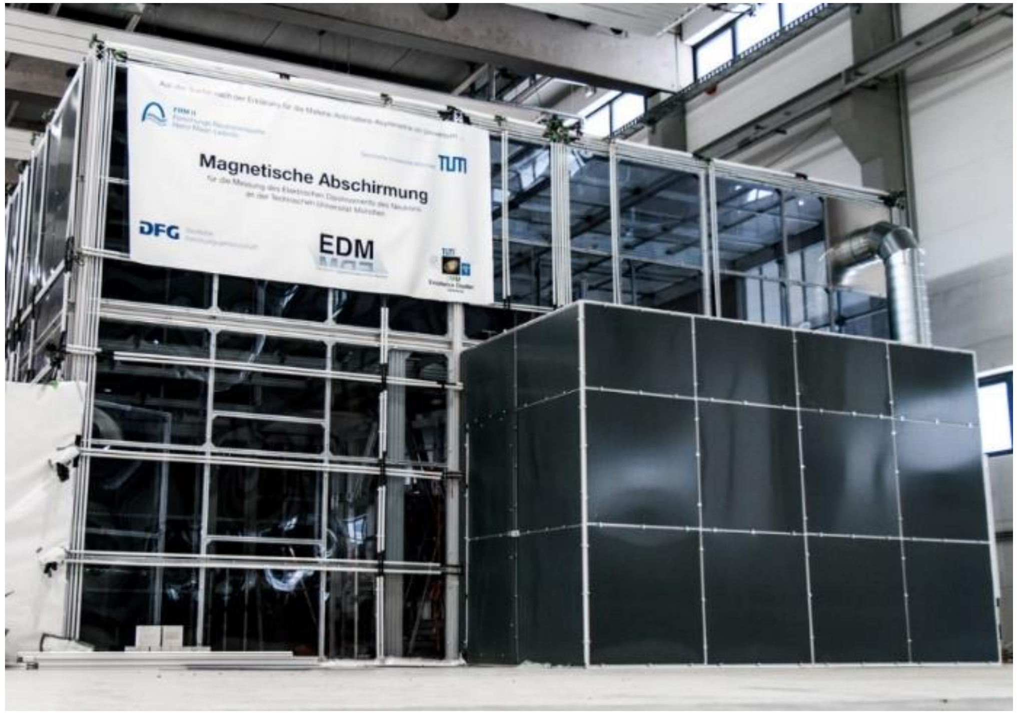
Axions and the symmetry CP in QCD

- **A key observable of the´strong CP – problem´: the $n - EDM$ in experimental searches**



- many experiments looking for EDM of the neutron

- only upper limits published so far:
  latest (2020) limit at *Paul Scherrer Institute*



$$d_{n,exp} < 1.8 \cdot 10^{-26}\, e \cdot cm \;(90\%\, CL)$$

theoretically allowed value (QCD):

$$d_{n,theo} \sim 3.6 \cdot 10^{-16}\, e \cdot cm$$

Axions and the symmetry CP in QCD

- **A key observable of the´strong CP – problem´:**
  the $n - EDM$ in our theory understanding today

- introduction of an **angle θ_{QCD}**, which parameterizes the amount of
  CP – violating effects in QCD (or strong interactions)

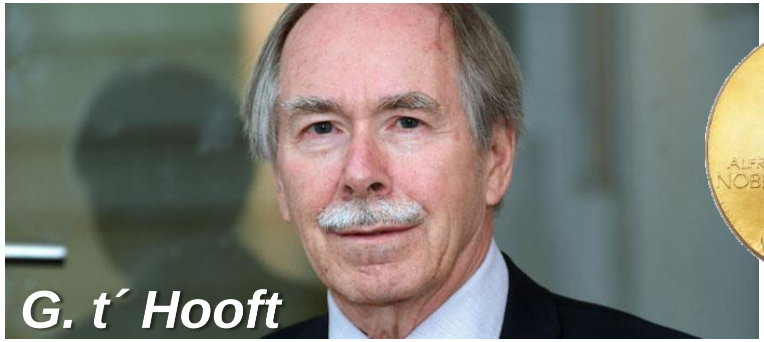
- vacuum state of QCD is CP –conserving with $|\theta_{QCD}| < 10^{-10}$

$$d_{n,exp} < 1.8 \cdot 10^{-26}\ e \cdot cm\ (90\%\ CL)$$

θ_{QCD}

theoretically allowed value (QCD):

$$d_{n,theo} \sim 3.6 \cdot 10^{-16}\ e \cdot cm\ \times \theta_{QCD}$$



Axions and the symmetry CP in QCD

- **A key observable of the´strong CP – problem´: the $n - EDM$ in our modern theoretical understanding today**

  - introduction of an **angle θ_{QCD}**, with a ´natural´ expecation value in the range of $\theta_{QCD} = [0 \ldots 2\pi]$

  - extreme fine tuning: why is $|\theta_{QCD}| < 10^{-10}$

θ_{QCD}

$$d_{n,exp} < 1.8 \cdot 10^{-26}\, e \cdot cm \; (90\%\ CL)$$

theoretically allowed value (QCD):

$$d_{n,theo} \sim 3.6 \cdot 10^{-16}\, e \cdot cm \times \theta_{QCD}$$

Peccei and Quinn: a new symmetry

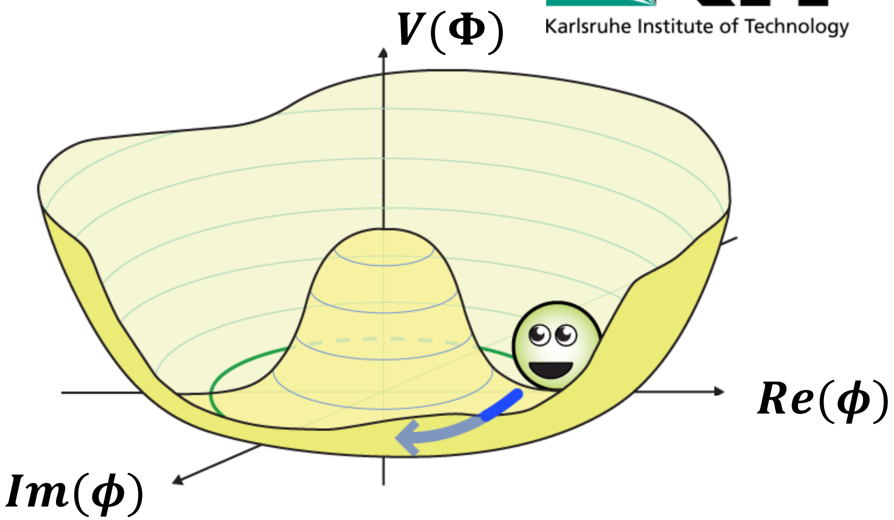
- **A new $U(1)$ – symmetry to solve the strong CP – problem**

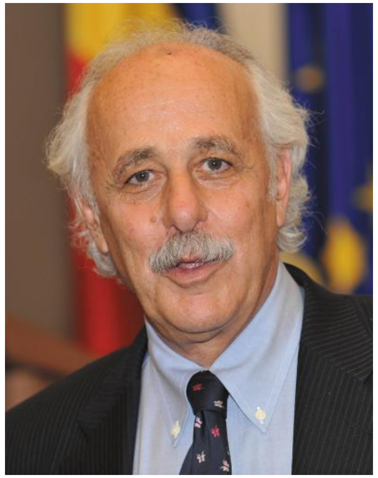
  - enter a new global (chiral) symmetry $U(1)_{PC}$

  - if unbroken, $U(1)_{PC}$ guarantees $\theta_{QCD} \rightarrow 0$

  - however, **spontaneous symmetry breaking** of $U(1)_{PC}$ may occur at an (unknown) very high energy scale $f_a = (10^6 \dots 10^{19})\ GeV$

  - **Goldstone-theorem**:
    ⇨ from this we get a strictly massless scalar gauge-(Goldstone-) boson





Roberto Peccei

Helen Quinn

Wilczek and Weinberg: explicit breaking of $U(1)_{PC}$

Karlsruhe Institute of Technology

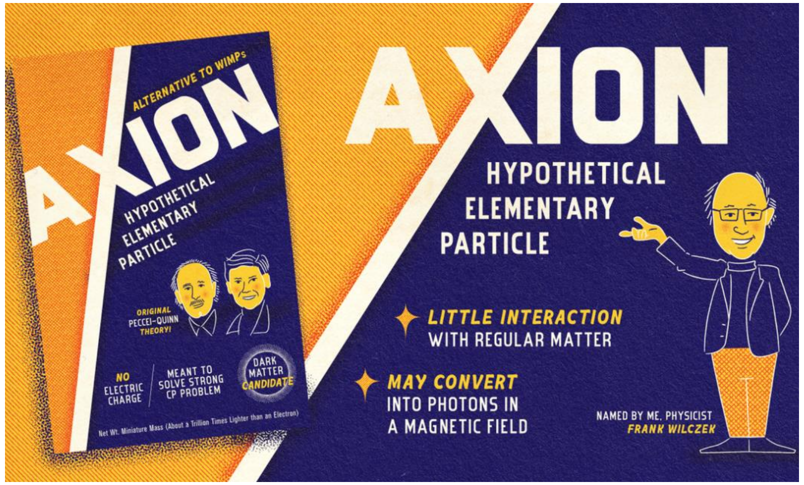
- **The axion emerges as a very light but massive particle (could it serve as our DM –particle?)**

  - the new global (chiral) symmetry $U(1)_{PC}$ is not only broken spontaneously, but ***explicitly*** at the **energy scale of QCD** (´axial anomaly´)

  - from this we get a **massive new gauge boson a**

  - the new particle, the **axion a**, with its vacuum-expectation-value (VEV) explicitly breaks the former symmetry $U(1)_{PC}$

resulting angle: $\theta_{QCD} = a/f_a \Rightarrow 0$



Frank Wilczek

Steven Weinberg

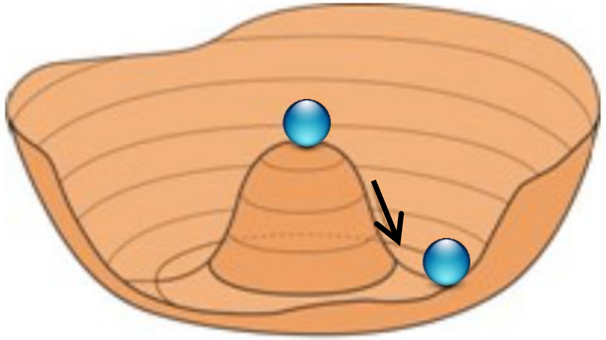
Axion as DM – candidate: history & a bit of theory

- **Axions arise from a broken symmetry: a non-thermal pathway to DM**

  - a close analogy to the very massive Higgs-boson

very early universe: $T \sim f_a$, $T = (10^6 \ldots 10^{19})\ GeV$

- $U(1)_{PC}$ symmetry is broken **spontanously**
- axion field a rolls down ´**Mexican Hat**´* potential
  ⇨ **massless axions** (Goldstone bosons)
- CP – violating phase θ is in interval $\theta = [0, 2\pi]$
  ⇨ CP – violating interactions occur



$\theta = [0, 2\pi]$

*analog to the Higgs-potential

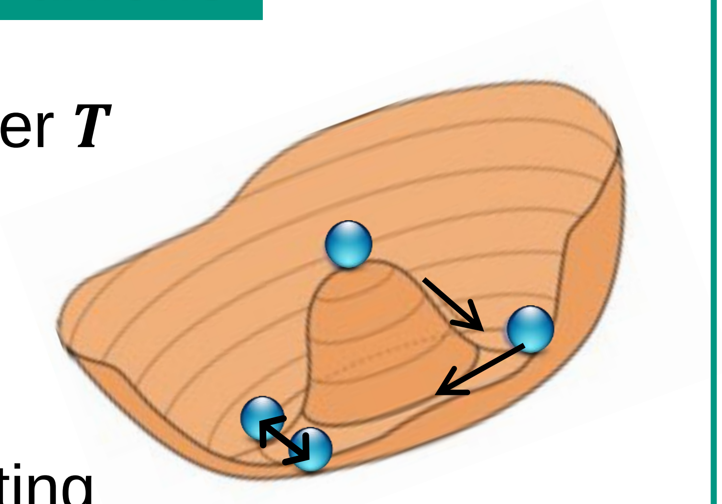
Axion as DM – candidate: history & a bit of theory

- **Axions arise from a broken symmetry: a non-thermal pathway to DM**

  - a close analogy to the very massive Higgs-boson

very early universe: $T \sim 1\ GeV$ we have massive DM axions

- $U(1)_{PC}$ symmetry is broken **explicitly** at much lower T
- this occurs due to QCD – vacuum effects (´instantons´): ´**Mexican Hat**´ potential is tilted
- CP – violating phase $\theta = a/f_a \Rightarrow 0$ ⇨ CP – violating interactions stop, **axions as field oscillations**



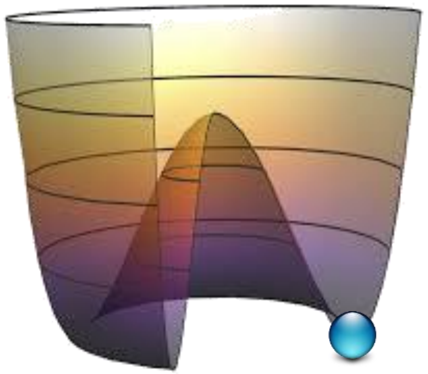
$\theta \rightarrow 0$

Axion as DM – candidate: history & a bit of theory

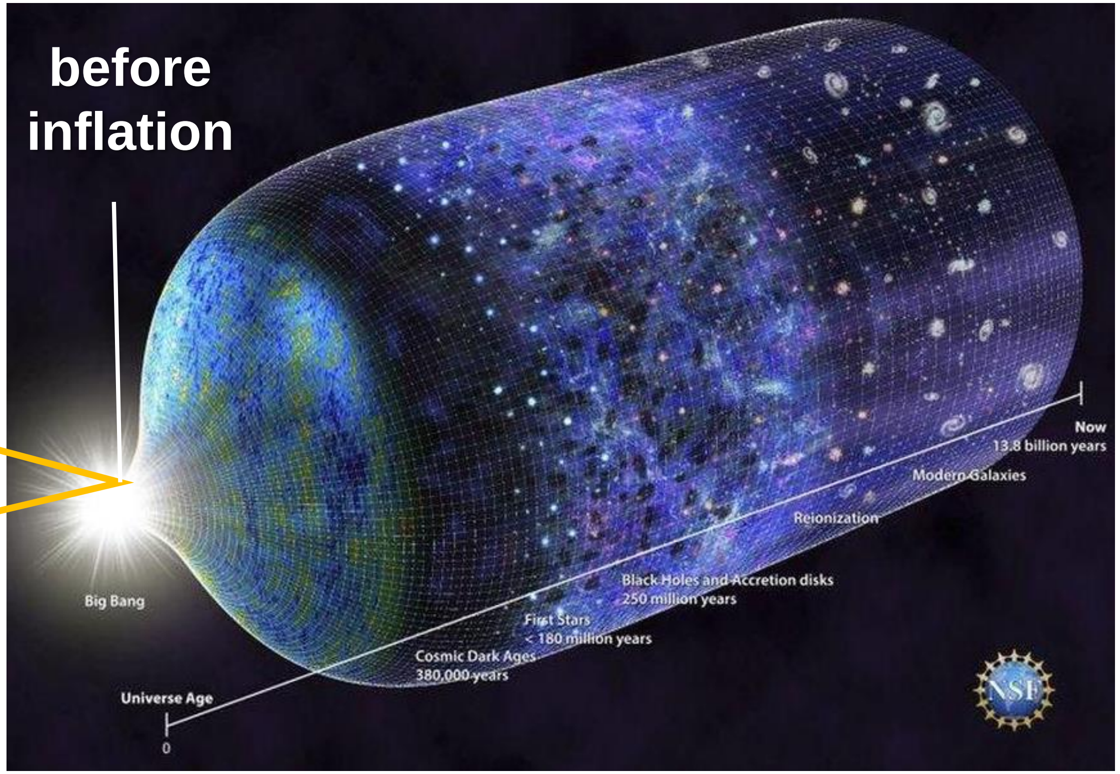
- **Spontaneous breaking of PC – symmetry: before or after inflationary phase?**

  - energy scale f_a is **larger** than GUT – scale relevant for inflation:

    only one PQ – phase* in the entire universe, thus: same axion physics everwhere



$\theta = [0, 2\pi]$



inflationary phase & the physics of axions

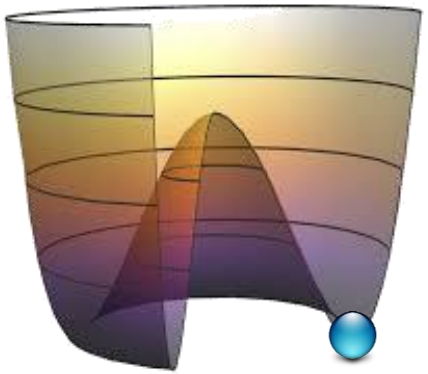
*Peccei-Quinn phase

Axion as DM – candidate: history & a bit of theory

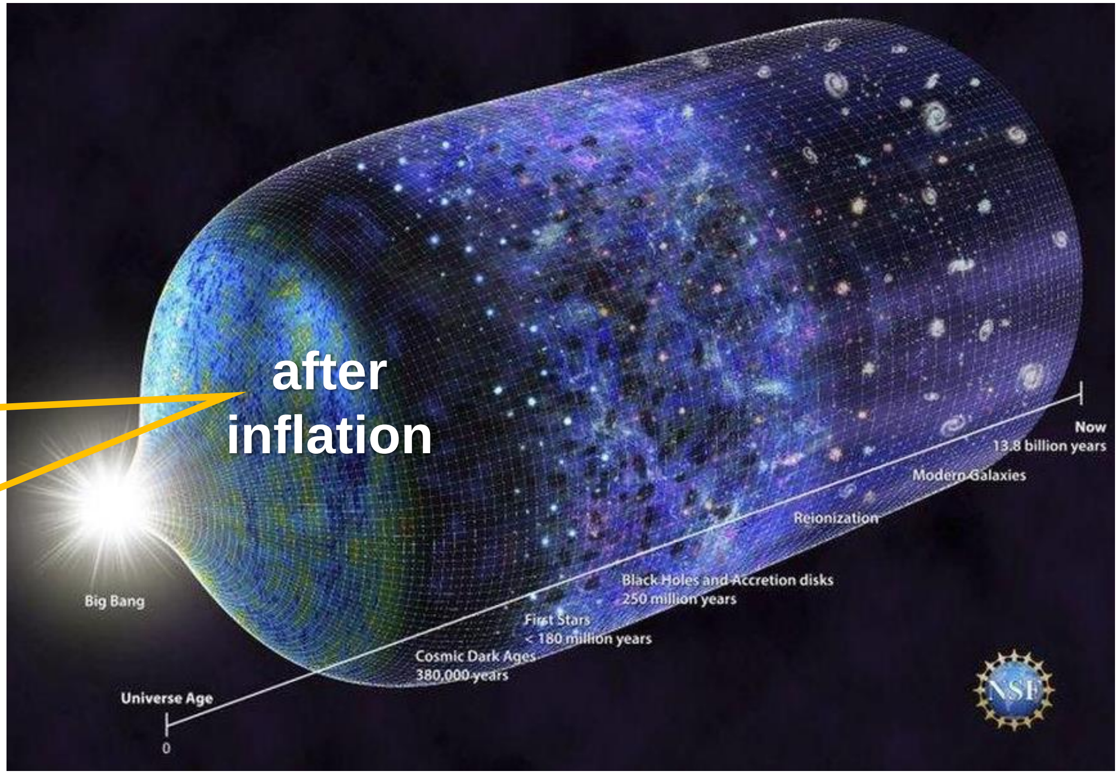
- **Spontaneous breaking of PC – symmetry: before or after inflationary phase?**

  - energy scale f_a is **smaller** than GUT – scale relevant for inflation

many PQ – phases in the entire universe, labelled ´**patches**´ in between: topological defects



$\theta = [0, 2\pi]$



inflationary phase & the physics of axions

Axion as DM – candidate: Wilczeks´ ´formula´

- **Explicitely breaking the Peccei-Quinn symmetry $U(1)_{PC}$**

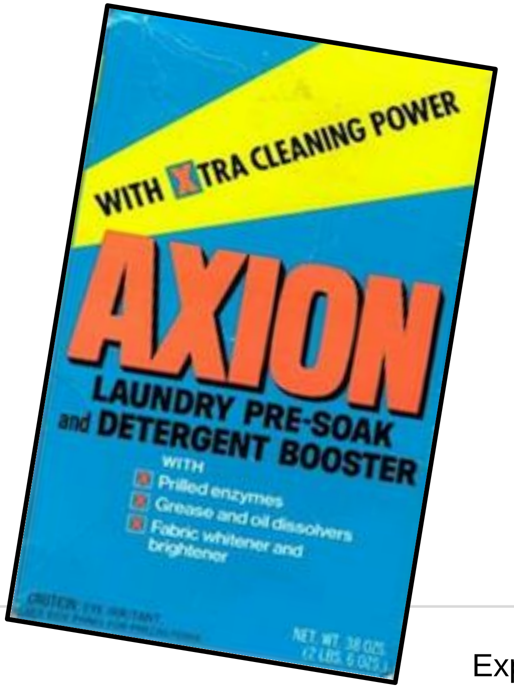
- what does this all mean for DM?

- we have one particle to solve two issues in physics:

a) we cure the ´strong CP – problem´

b) we have a ´well motivated´ DM – candidate

„*I named it axion, after the laundry detergent, since it removes a stain*“

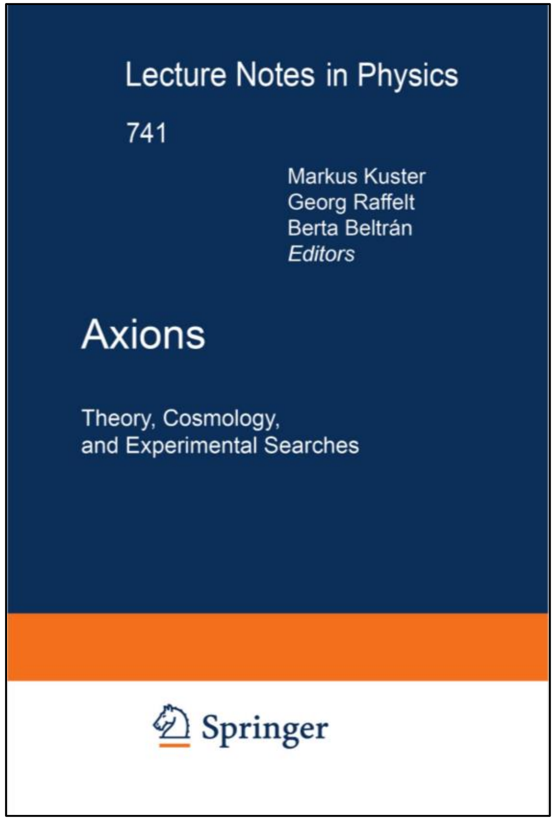


Frank Wilczek

Axion as DM – candidate: Wilczeks´ ´formula´

- **Explicitely breaking the Peccei-Quinn symmetry $U(1)_{PC}$**

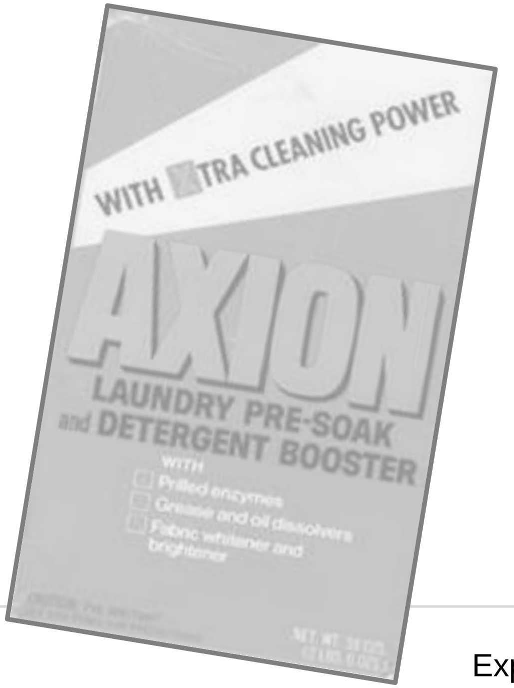
- looking at these axions from all sides…



[10.1007/978-3-540-73518-2.pdf (springer.com)](10.1007/978-3-540-73518-2.pdf)

…have a look, if you like…

„I named it axion, after the laundry detergent, since it removes a stain“



Frank Wilczek

Axion as DM – candidate: properties at a glance

Karlsruhe Institute of Technology

- **Axions in a nutshell: a light pseudo-scalar with $J^P = 0^-$**

  - properties of axions: determined by fundamental **very high energy scale f_a**

  - very light axion mass, as : $m_a \sim 1/f_a$
    $10^{-9}\ eV \ldots 1\ eV$

  - very small axion coupling strength*: $g_{a\gamma\gamma} \sim m_a$
    ´the lighter the more difficult to detect…,
    ´the invisible axion´

  - very long-lived axions, decay typically via $a \to \gamma\gamma$
    rate fixed by f_a ⇨ for $m_a < 20\ eV$: $\tau_a > t_{Hubble}$

*see p. 42 - 44

Axion as DM – candidate: comparison to $WIMPs$

- Axions in our local galactic DM – halo with $\rho_{DM,loc} = 0.3\ GeV/cm^3$

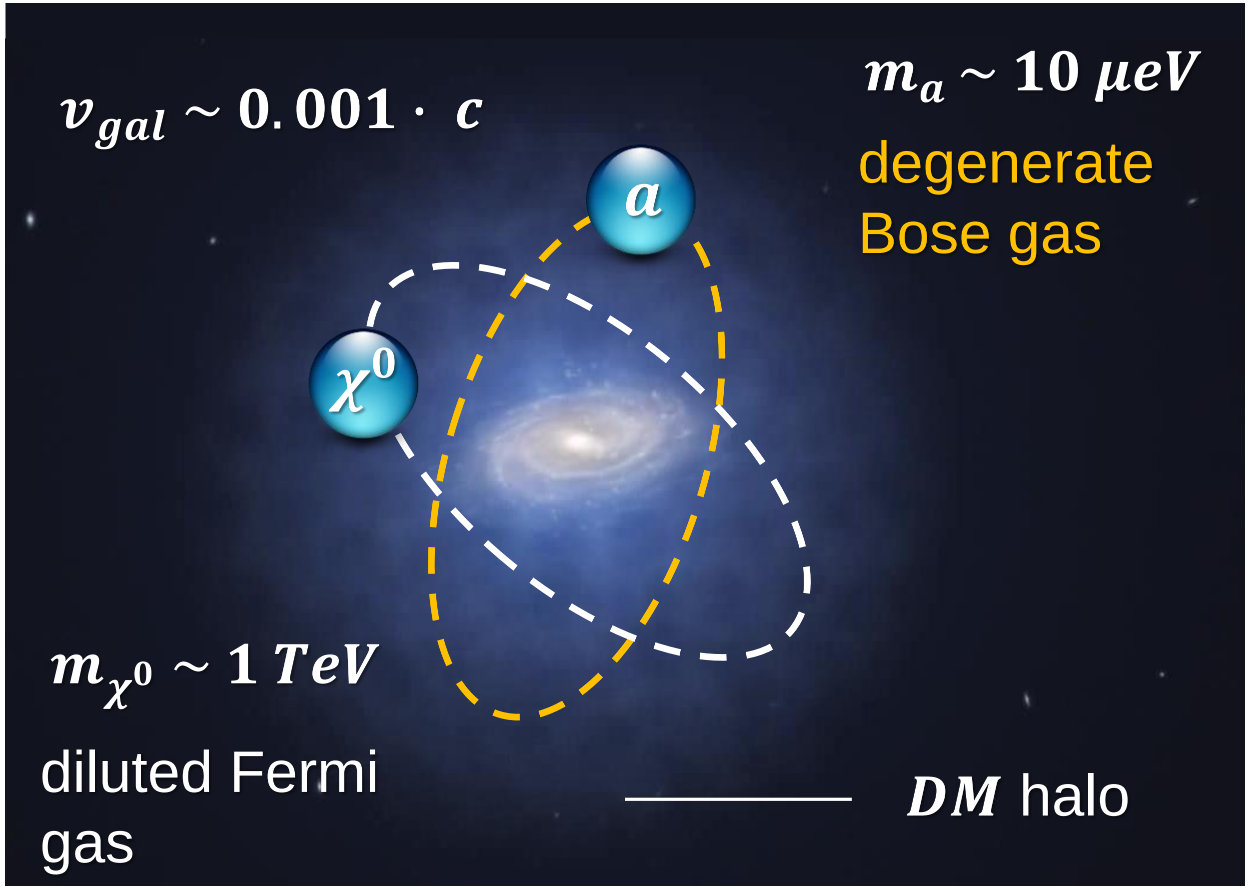
- local **axion** number density:

  $N = 3 \cdot 10^{13}/cm^3$ (for $m_a = 10\ \mu eV$)

- local $WIMP$ number density:

  $N = 3 \cdot 10^{-4}/cm^3$ (for $m_{\chi^0} = 1\ TeV$)

- comparable mean velocities in the DM – halo: $v_{gal} \sim 0.001 \cdot c$



local halo: comparing neutralinos to axions

Axion as DM – candidate: *de Broglie* wavelength

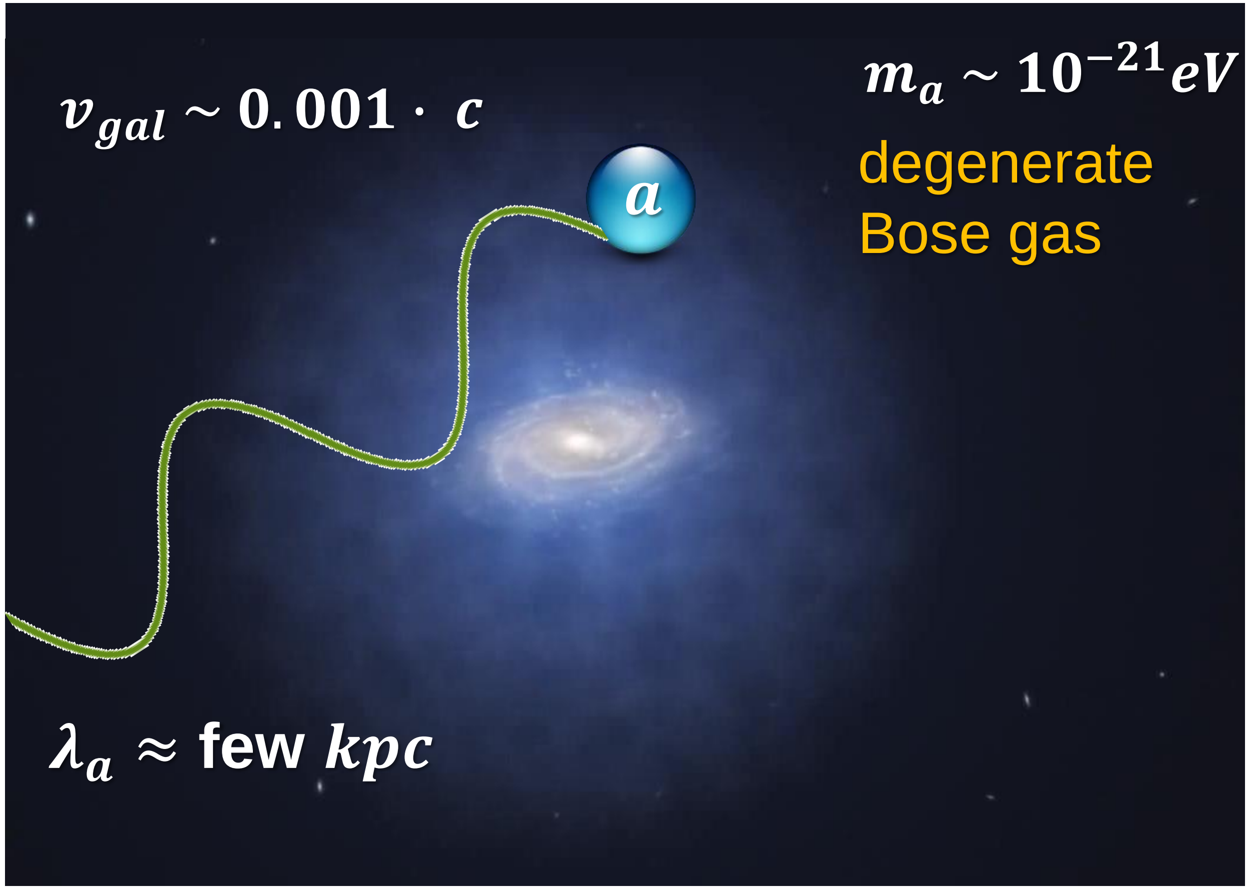
Karlsruhe Institute of Technology

- **Axions in DM – halos: do they fit in even in case of dwarf galaxies?**

- definition of ***de Broglie*** wavelength λ_a:

$$\lambda_a \approx \frac{2\pi}{m_a \cdot v_{gal}} = 100\ m \cdot \frac{10\ \mu eV}{m_a}$$

- for extremely tiny axion masses of $m_a \approx 10^{-21}\ eV$ we thus reach a value of $\lambda_a \approx$ **few** kpc , the size of a typical dwarf galaxy (≡ a ***lower*** bound on m_a)



local halo: axion de Broglie wavelength…

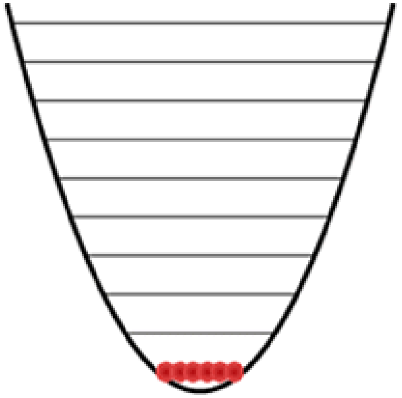
Axion as DM – candidate: a Bose condensate

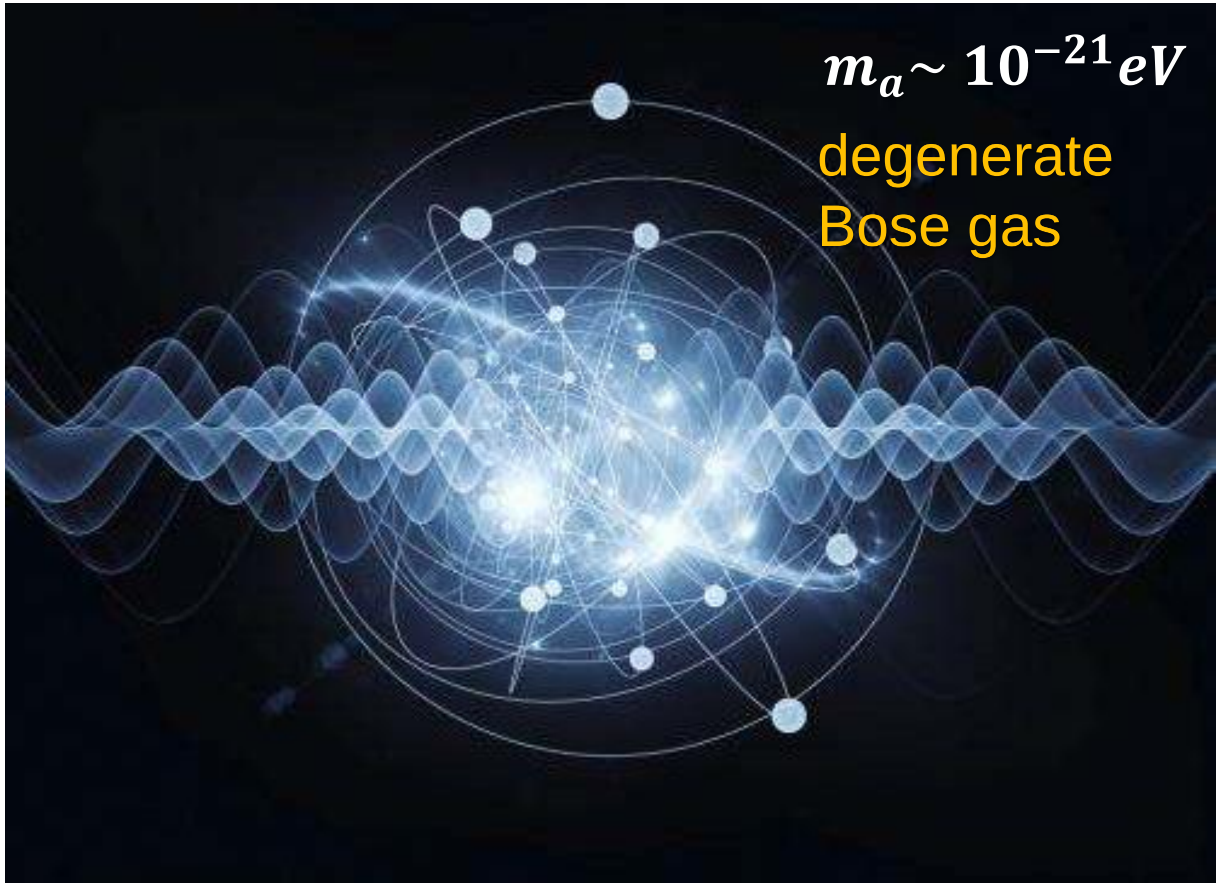
- **Axions in DM – halos: they can form a Bose-Einstein condensate**

- typical occupation numbers:

$$n_a \approx 10^{25} \cdot \left(\frac{10\ \mu eV}{m_a}\right)^4$$

- thermalised axions can form a **Bose-Einstein condensate** in the galactic halo





local halo: how to visualize a condensate?

Axion as DM: scale m_a

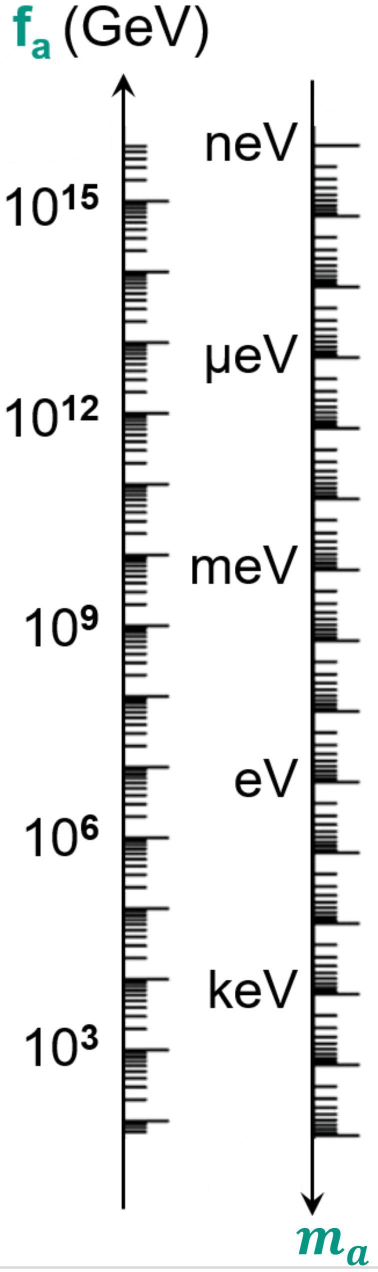
- **Comparing the energy scale f_a with the mass m_a of axions**

- axion mass scale m_a is given by the energy scale f_a where the Peccei-Quinn symmetry $U(1)_{PC}$ is broken

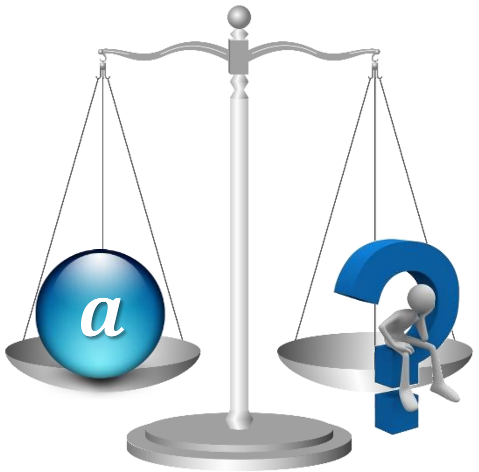
$$m_a \approx 6\ eV \cdot \frac{10^6\ GeV}{f_a}$$

small m_a ⇔ high scale f_a

large m_a ⇔ low scale f_a



GUT – scale



electroweak scale

Axion as DM: scale Ω_a

- **Comparing the mass scale m_a & the $DM -$ contribution Ω_a of axions**

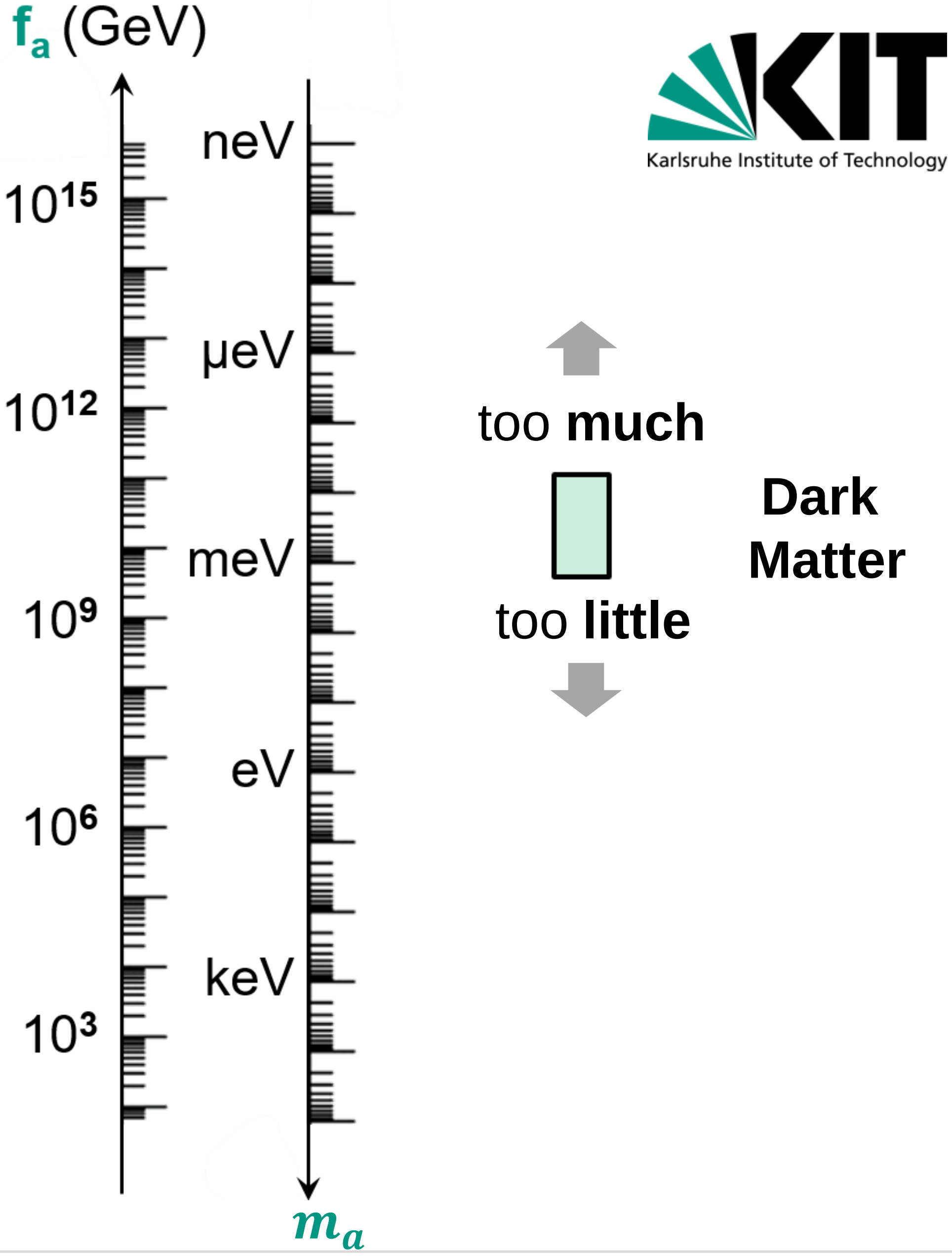
- axion mass scale m_a is strongly model-dependent, but there is a region where m_a ideally fits to obtain a value $\Omega_{DM} \approx 0.27$

$$\Omega_a \approx \left(\frac{6\ \mu eV}{m_a}\right)^{7/6}$$

(popular ´vacuum misalignment model´)

small m_a ⇔ (too?) high fraction of Ω_a

large m_a ⇔ (too?) small fraction of Ω_a



Axion as DM: QCD calculations

- **Calculating the mass scale m_a & the $DM -$ contribution Ω_a of axions**

- 2016: new **lattice-QCD results** seem to point to a very interesting m_a


WISSENSCHAFT EIN TEILCHEN NAMENS AXION

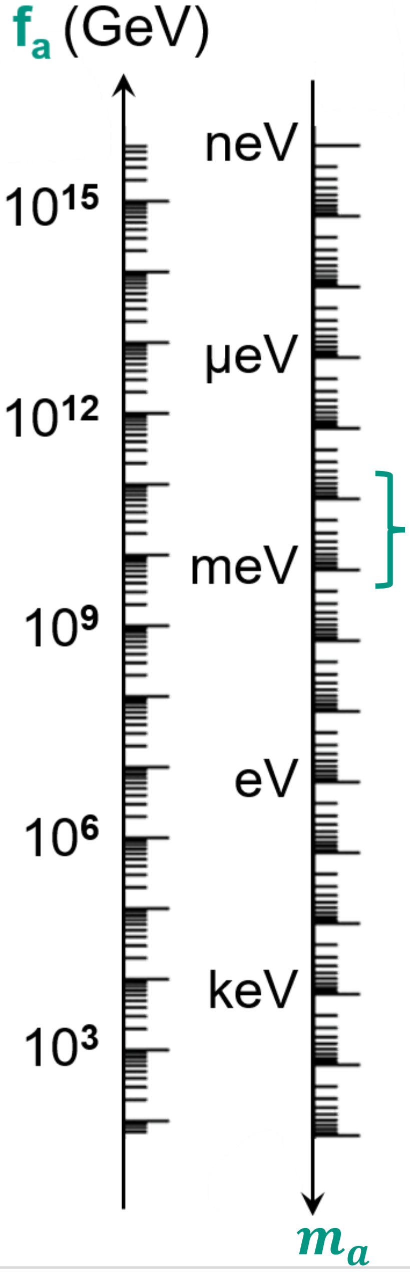
Forscher lüften Geheimnis der Dunklen Materie .. at the ´PC´?...

Von Norbert Lossau | Veröffentlicht am 02.11.2016

Spiralgalaxien werden durch unsichtbare, Dunkle Materie zusammengehalten

Quelle: Getty Images/Science Photo Library RF GEtty

Bislang war die Suche nach Teilchen der Dunklen Materie erfolglos. Nun zeigen Simulationen auf einem Supercomputer, wo genau die Forscher nach den bislang noch hypothetischen Axionen suchen müssen.



most probable QCD axion

$m_a = 50 \ldots 1500\ \mu eV$

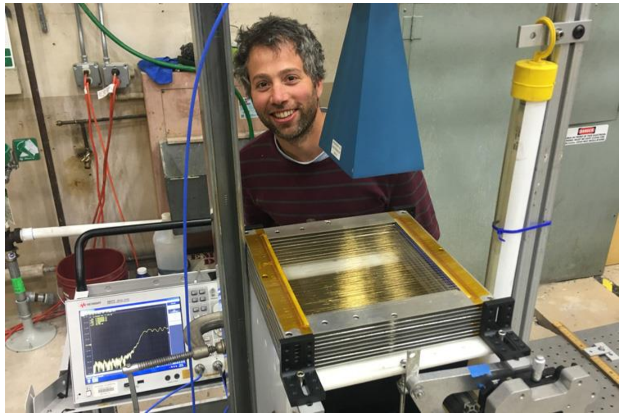
local axion density

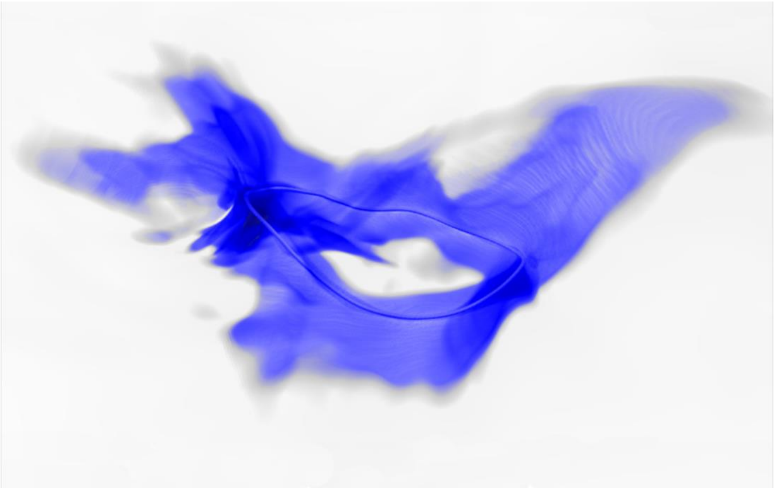
$N_a \approx 10^9 / cm^3$

Axion as DM: QCD calculations

- **Calculating the mass scale m_a & the $DM -$ contribution Ω_a of axions**

- 2022: new **lattice-QCD results** seem to point to an even more interesting $m_a \approx 65\ \mu eV$



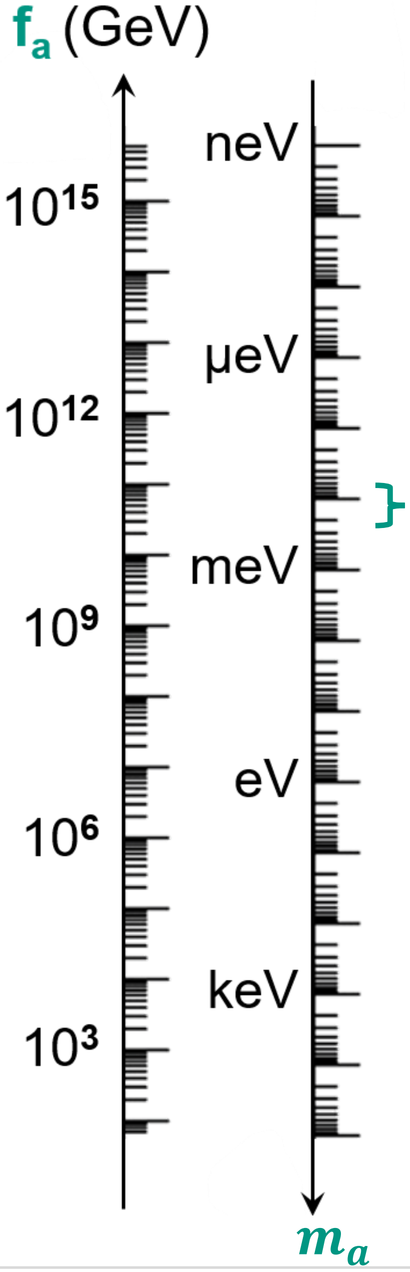


Berkeley News

RESEARCH, SCIENCE & ENVIRONMENT, TECHNOLOGY & ENGINEERING

New simulations refine axion mass, refocusing dark matter search

In a simulation of the early universe, shortly after the Big Bang, tornado-like strings (dark blue loop) throw off axion particles. These axions should still be around today, and could be the dark matter that astrophysicists have been searching for. (Credit: Malte Buschmann, Princeton University)

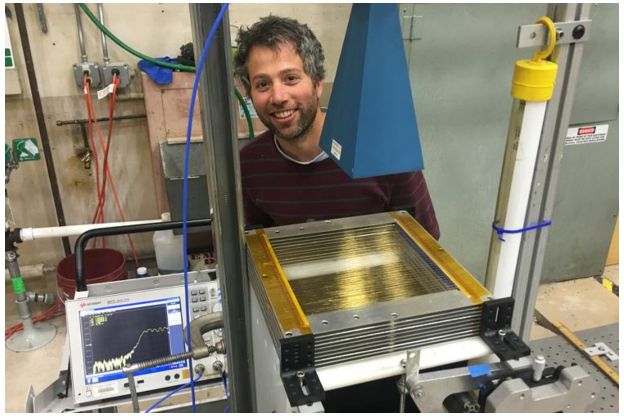


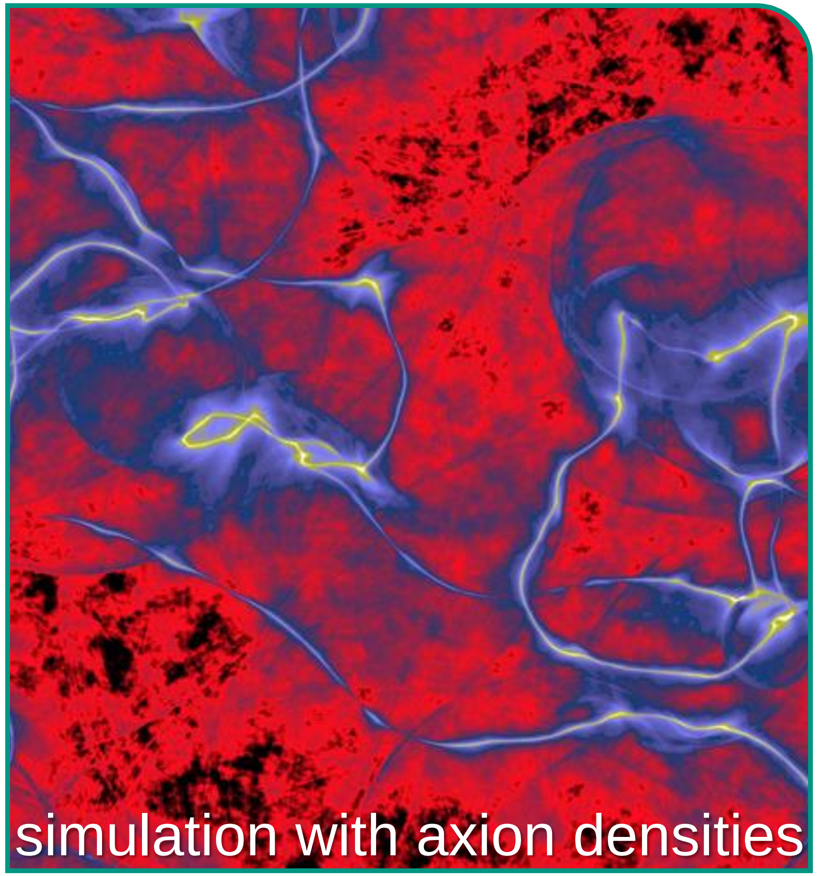
most probable QCD axion
$m_a = 40 \ldots 180\ \mu eV$

Axion as DM: QCD calculations

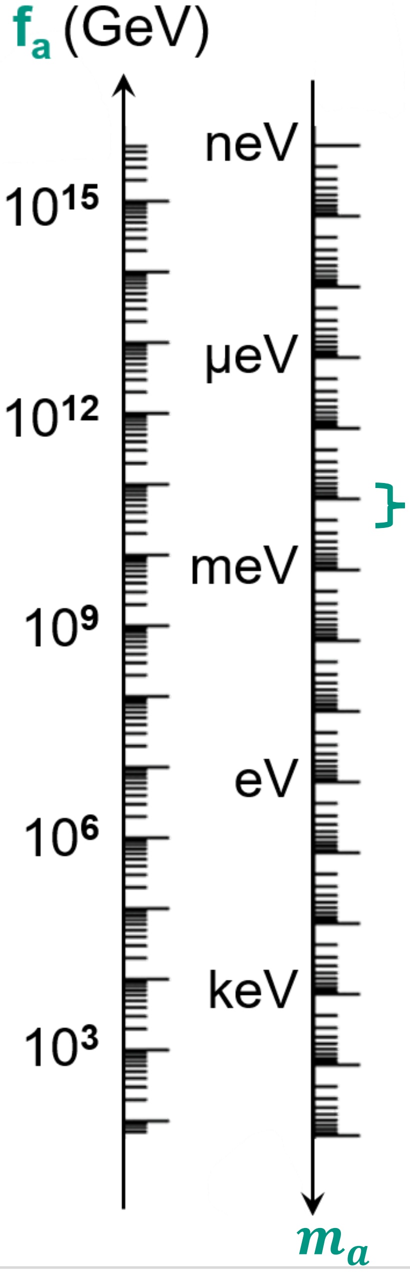
- **Calculating the mass scale m_a & the $DM-$ contribution Ω_a of axions**

- 2022: new **lattice-QCD results** seem to point to an even more interesting $m_a \approx 65\ \mu eV$





simulation with axion densities



most probable QCD axion
$m_a = 40 \ldots 180\ \mu eV$

Axion as DM: cosmological limits

- **Cosmology requests light axions on the $sub - eV$ scale**

 - axions have to act as **Cold Dark Matter**

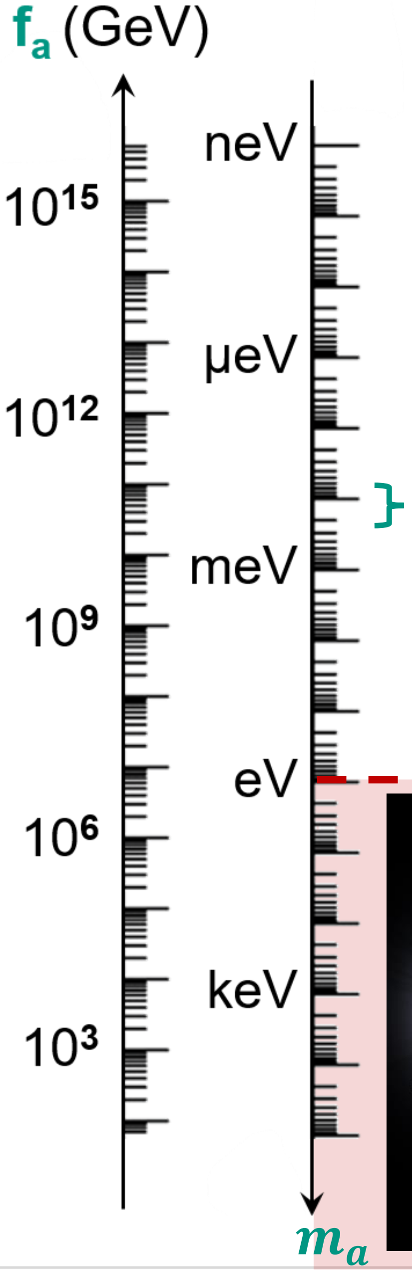
$$m_a < 1\ eV$$

for larger masses m_a : axions would be **Hot Dark Matter**, in contrast to the ΛCDM concordance model of cosmology

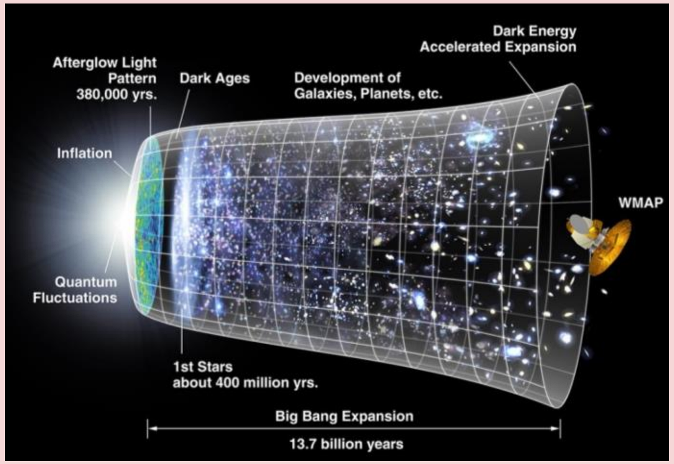
 - also: axion lifetime requirement: $\tau_a > t_H$

$$m_a < 20\ eV$$

no axion decays occur over Hubble time t_H



most probable QCD axion



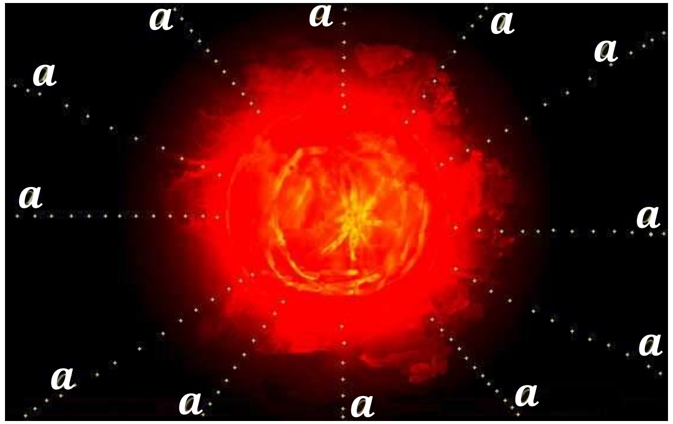
Axion as DM: astrophysical limits

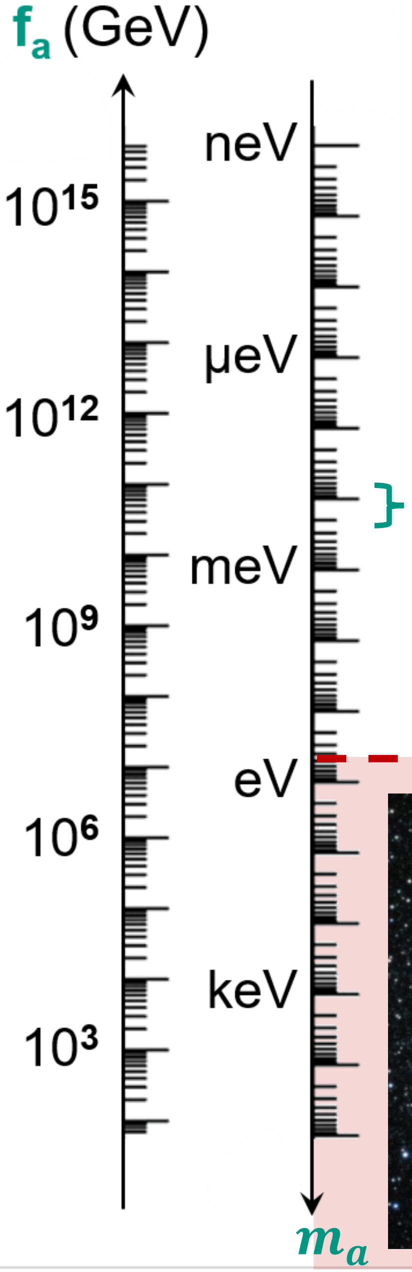
- **Astrophysics requests light axions on the $sub - eV$ scale**

- no axion emission from **stars**

$$m_a < 0.5\ eV$$

from the evolution of globular clusters & long stellar lifetimes (He – burning phase)





most probable QCD axion

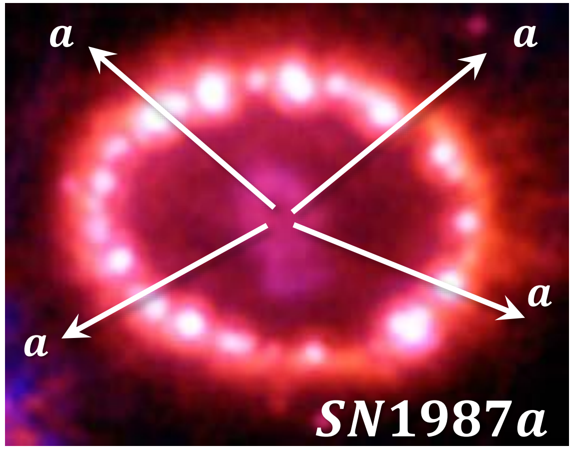
Axion as DM: astrophysical limits

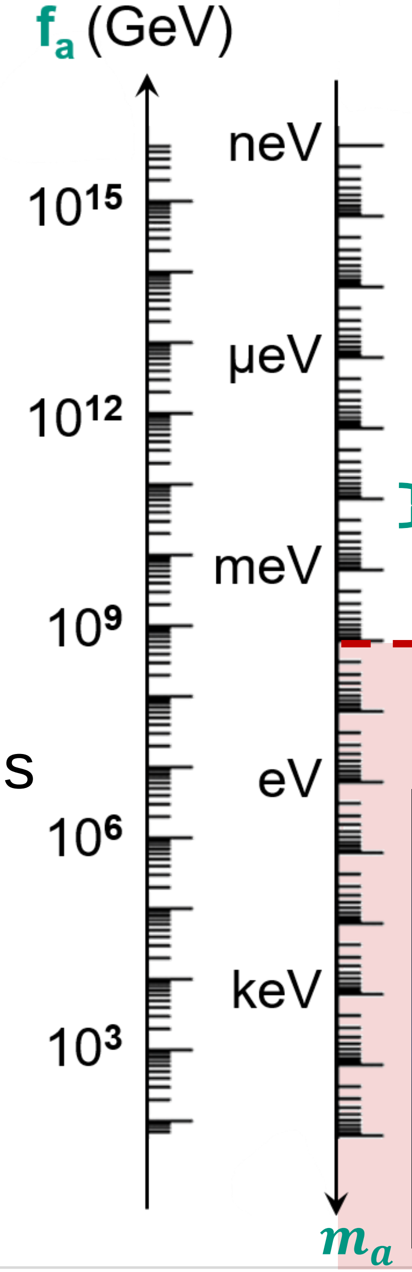
- **Astrophysics requests light axions on the $sub - eV$ scale**

- no axion emission from **supernovae, WDs***

$$m_a < 16\, meV$$

from the 1987 observation of a 10 s **ν-pulse** in $SN1987a$ & very long cooling times of WDs

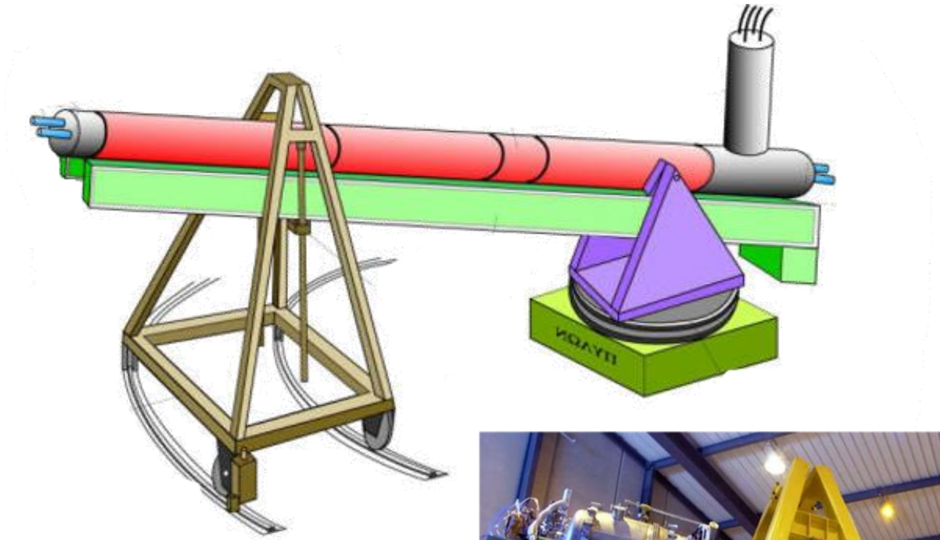




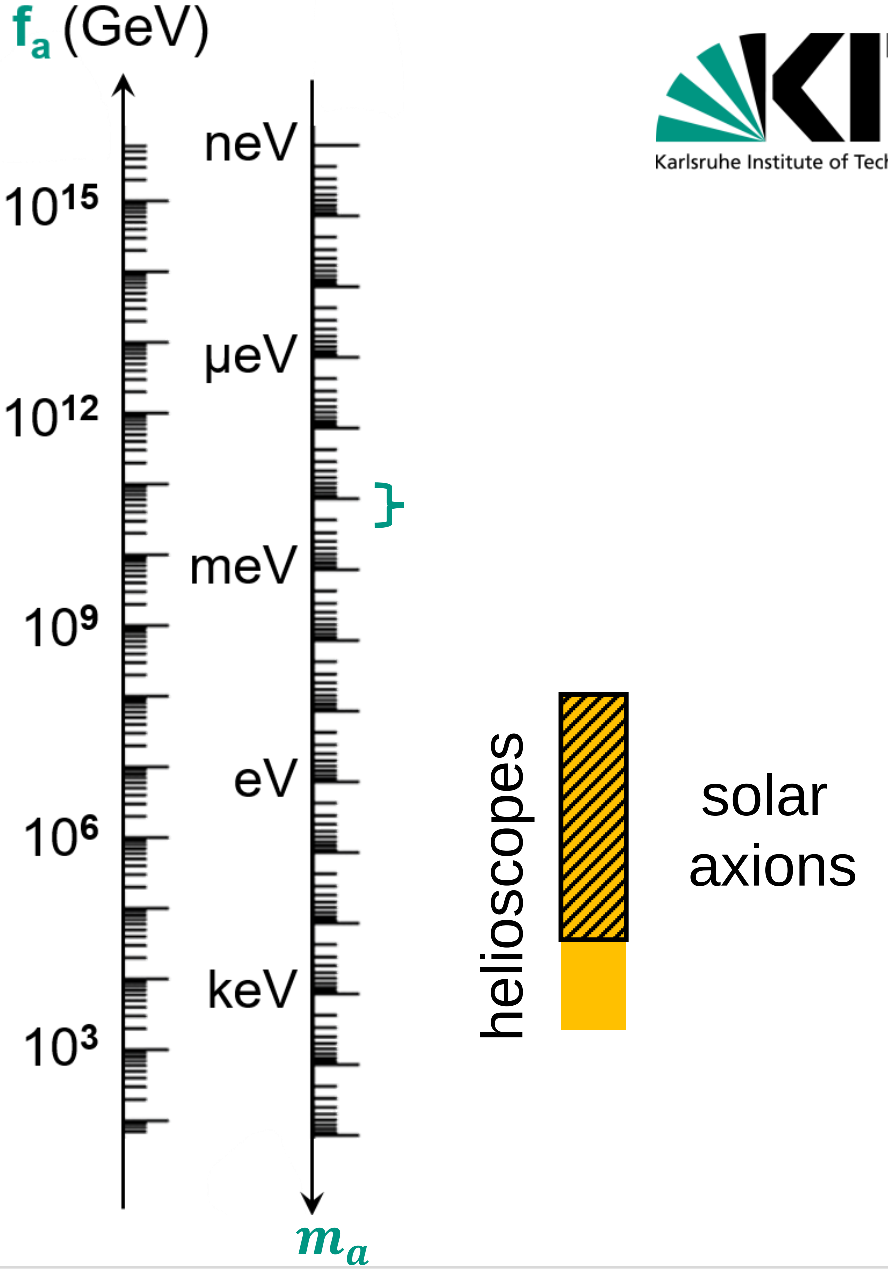
*White Dwarf, see ATP-II summer 2023

Axions: ´telescope´ searches

- **Helioscopes: axions from the Sun?**

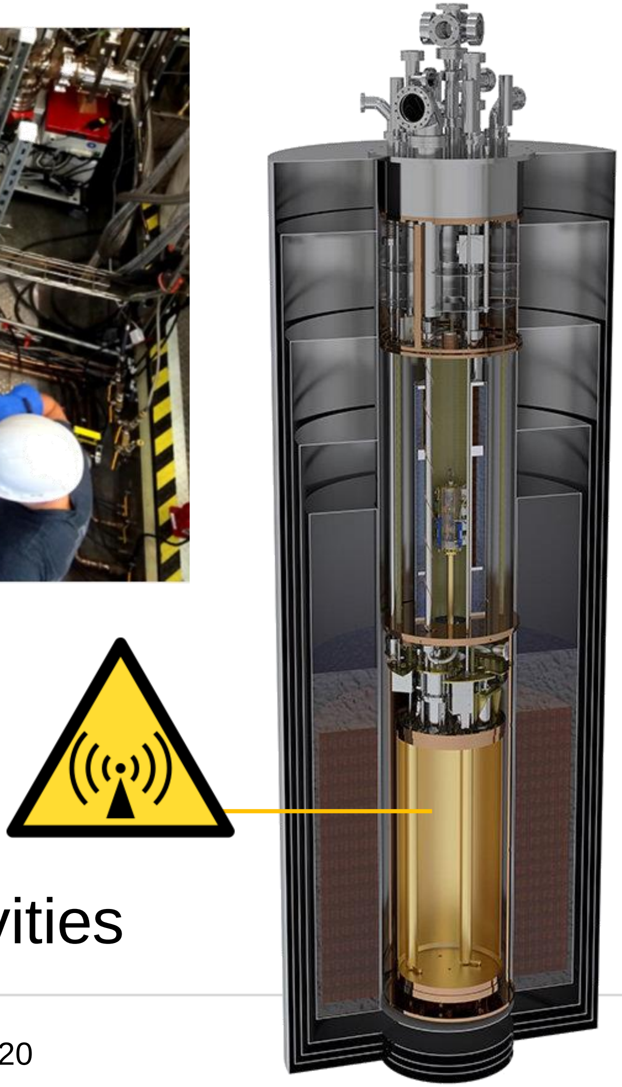


- let´s look into the heart of the Sun to see if axions are emitted there

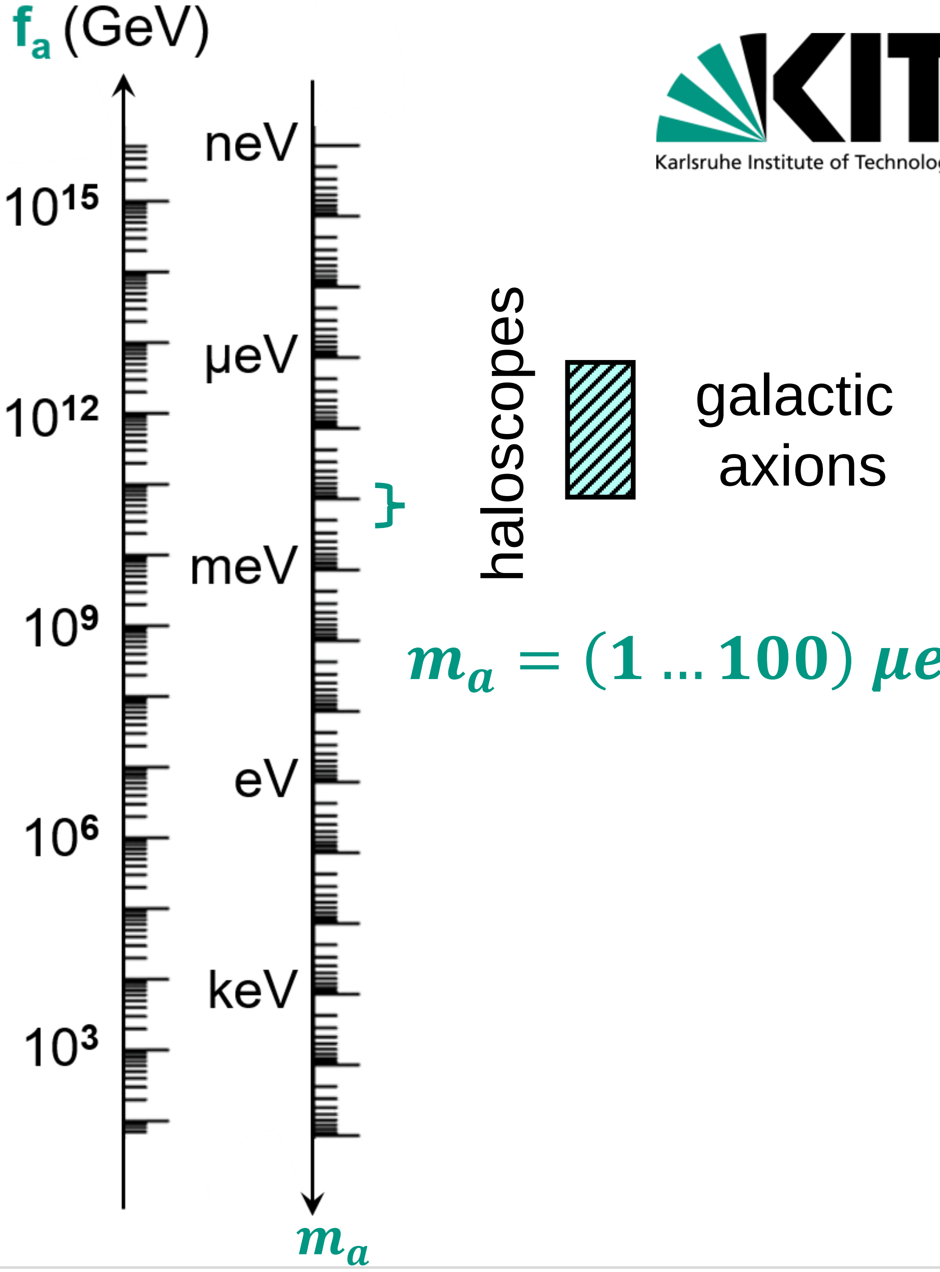


Axions: MW-cavity searches

- **Haloscopes: axions from the DM – halo?**



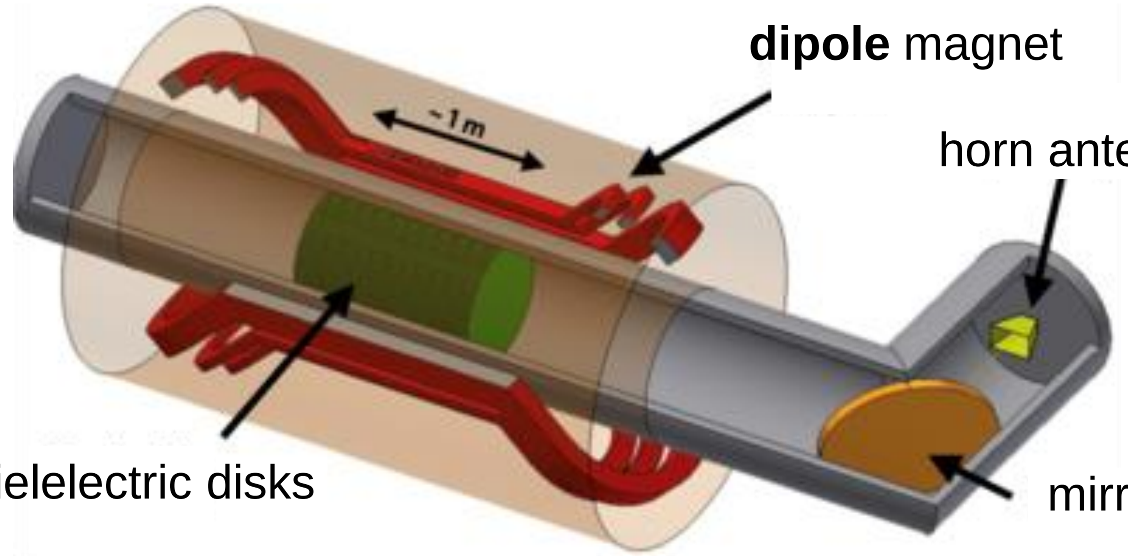
- let´s look whether we can convert the galactic $\boldsymbol{DM}$ –axions into $\boldsymbol{EM}$ radiation in cavities



$m_a = (1 \ldots 100)\ \mu eV$

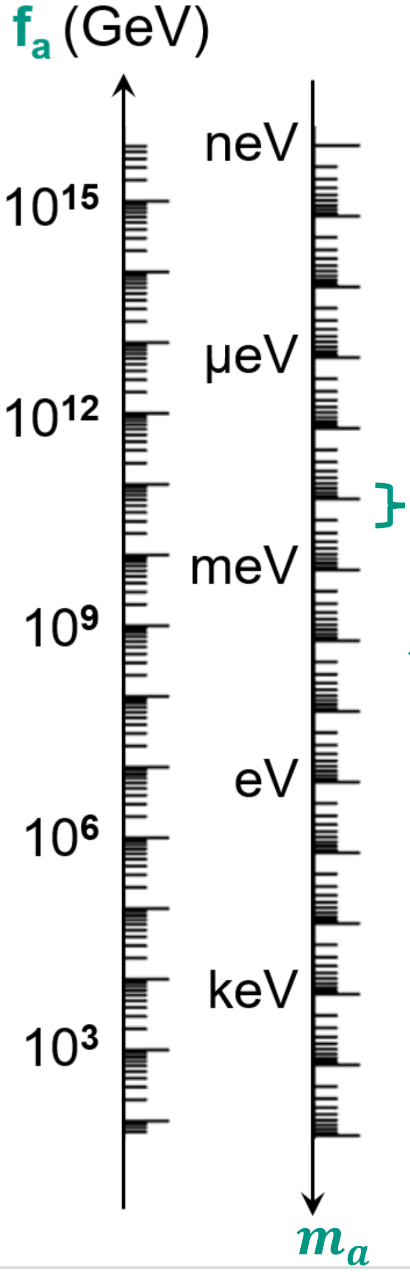
Axions: dielectric haloscopes

- **Haloscopes: axions from the DM – halo?**



- let´s look whether we can convert the galactic DM – axions via dielectric disks in a strong B – field

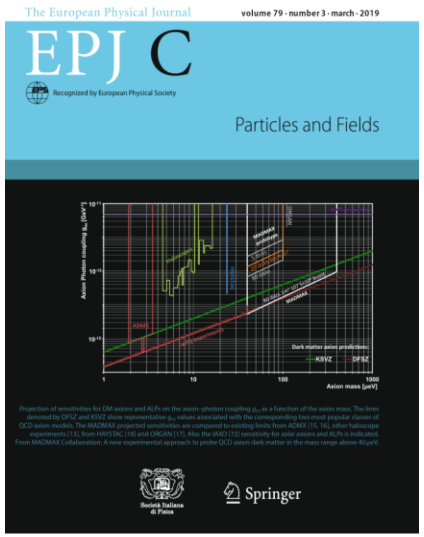
MADMAX



haloscopes

galactic axions

$$m_a = (40 \dots 400)\ \mu eV$$



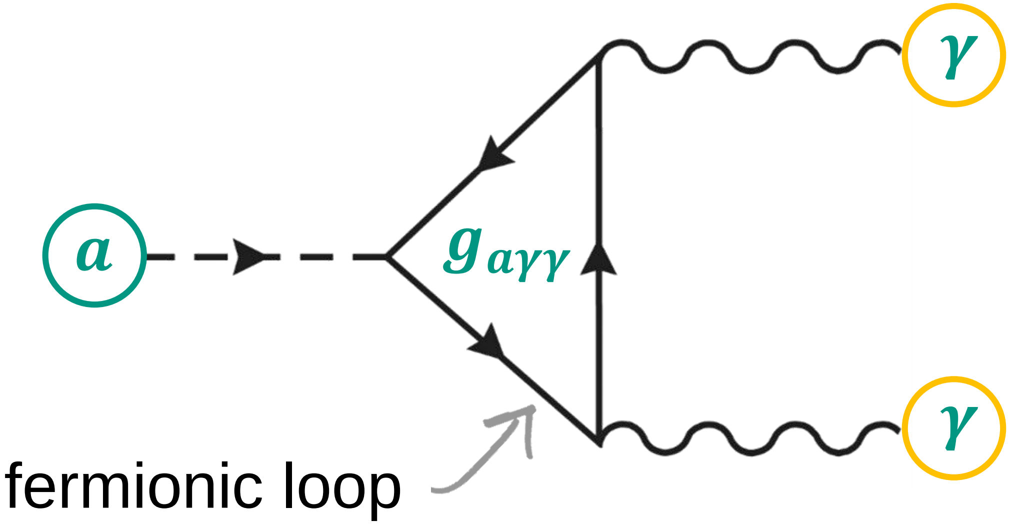
Axions & their interactions: the Primakoff process

Karlsruhe Institute of Technology

- **The fundamental Feynman loop diagram for interactions of axions**

  - axion a can couple to **two photons** via a **fermionic loop**: **Primakoff effect**

  - coupling strength can be parameterized via the (a priori unknown) **axion-photon coupling constant** $g_{a\gamma\gamma}$

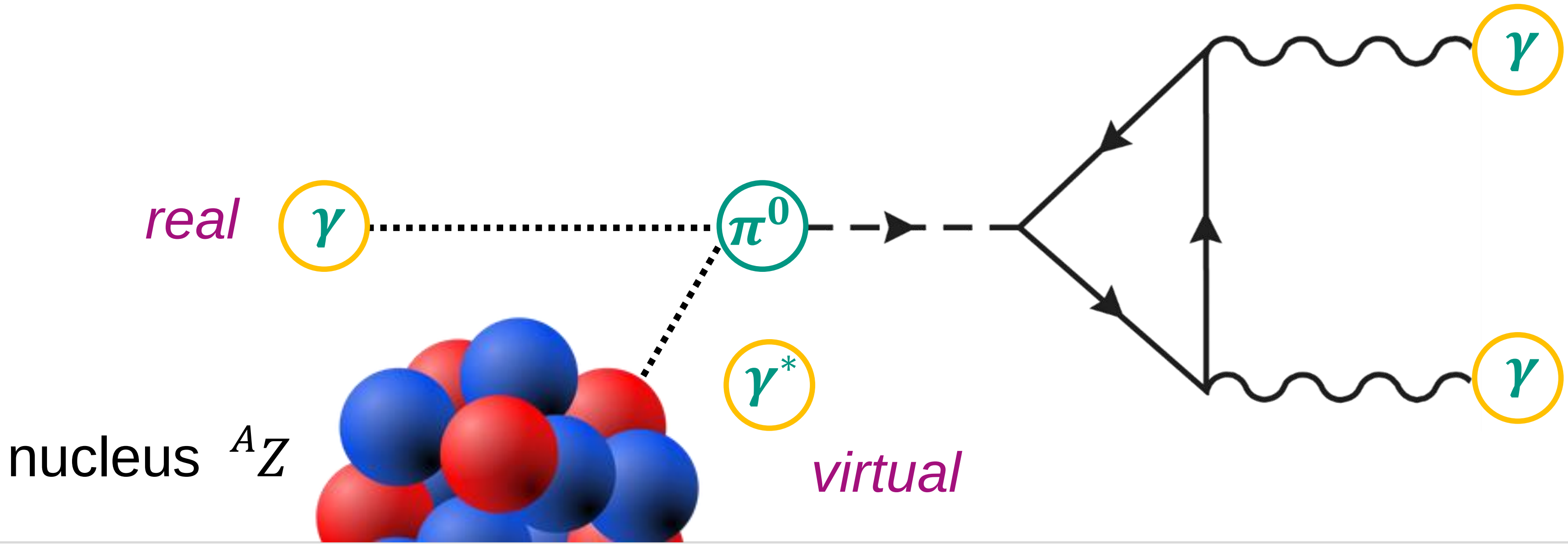


Axions & their interactions: the Primakoff process

- **The fundamental Feynman diagrann modelled analog to decay $\pi^0 \rightarrow \gamma\gamma$**

  - neutral pion π^0 generated & decay to **two photons**: (inverse) **Primakoff effect**

  - **nuclear physics**: generation of the photo-nuclear resonance π^0 in the field of a nucleus via energetic gammas & subsequent π^0 decay to two photons



Axions & their interactions: the coupling $g_{a\gamma\gamma}$

- **The axion coupling to matter is exceedingly weak – be warned!**

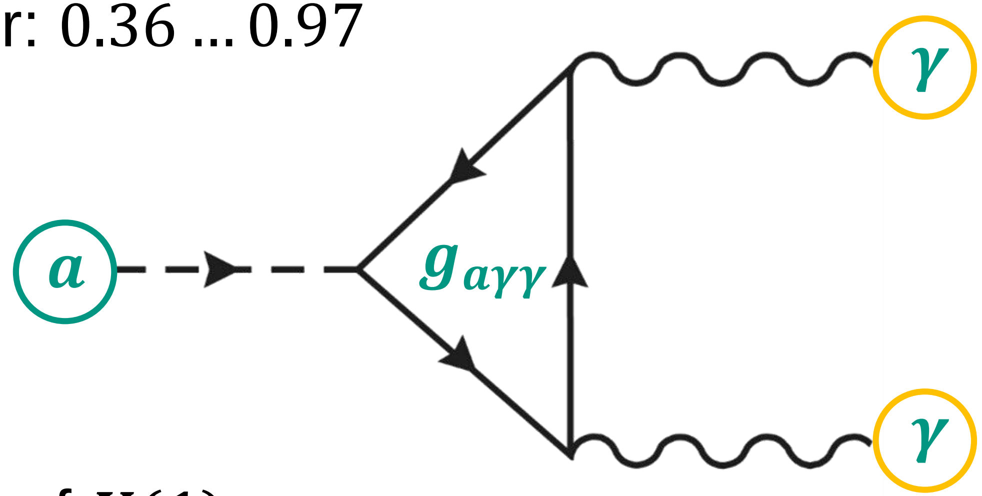
  - coupling constant $g_{a\gamma\gamma}$ is not known *a priori*, as it is related to the (unknown) very high energy scale f_a

α_s: coupling of strong interaction

g_γ: model-dependent QCD – parameter: $0.36 \ldots 0.97$

$$g_{a\gamma\gamma} \sim \frac{\alpha_s}{\pi} \cdot \frac{1}{f_a} \cdot g_\gamma$$

f_a: energy scale of breaking of $U(1)_{PC}$



Axions & their interactions: the coupling $g_{a\gamma\gamma}$

- **The axion coupling to matter is exceedingly weak – be warned!**

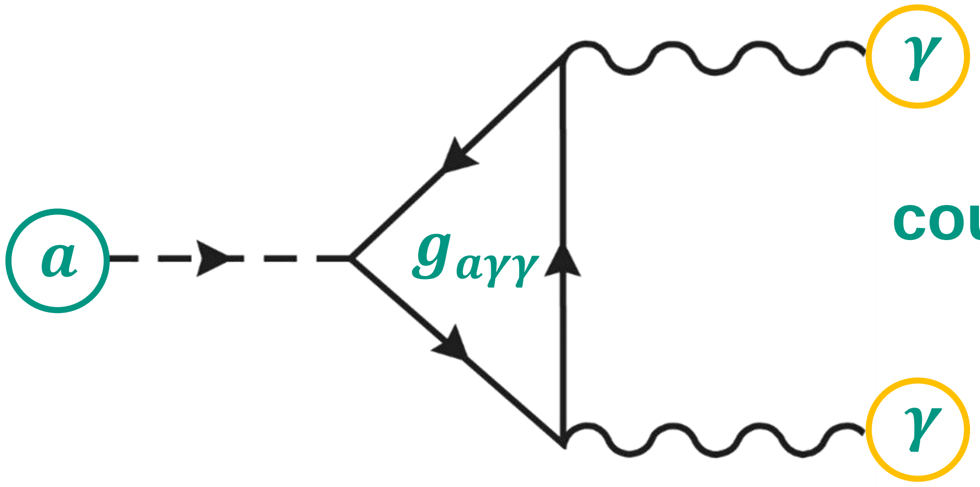
  - coupling constant $g_{a\gamma\gamma}$ is not known *a priori*, as it is related to the (unknown) mass scale m_a

the smaller the axion mass, the more difficult to detect it

α_s: coupling of strong interaction

$$g_{a\gamma\gamma} \sim \frac{\alpha_s}{\pi} \cdot m_a$$

m_a: mass scale of axions



coupling strength ~ axion mass

Axions & their interactions

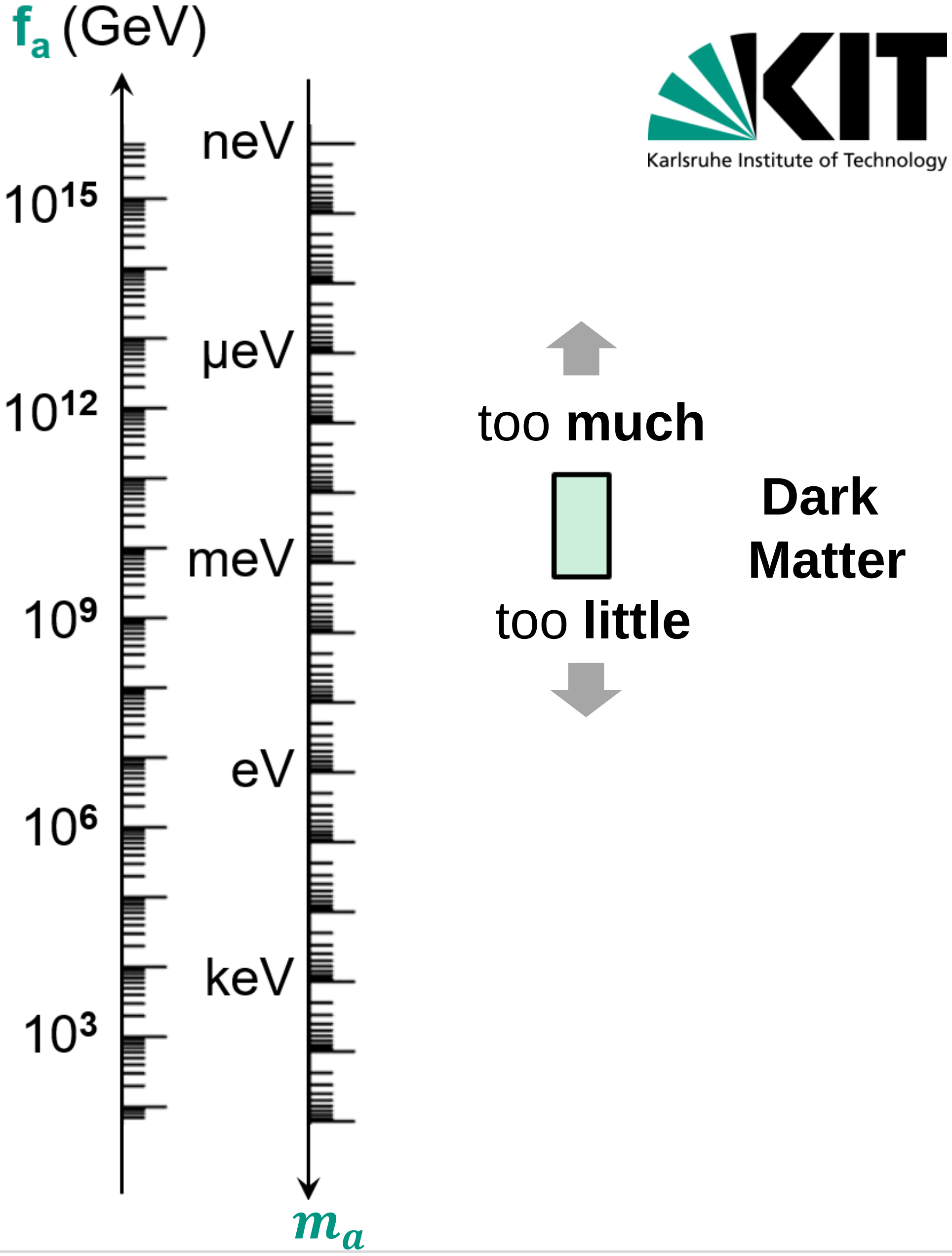
- **The axion coupling to matter**

  - coupling constant $g_{a\gamma\gamma}$ has all the ´desired´ properties of a DM – candidate

    when the axion mass m_a **gets smaller**, we have **more axions** in the universe, but (non-gravity) **interaction rates drop**

$$g_{a\gamma\gamma} \sim \frac{\alpha_s}{\pi} \cdot m_a$$

m_a: mass scale of axions



Axions & their interactions: *J.C. Maxwell*, wake up!

- **The axion coupling to $EM-$ fields: we have to modify the Maxwell equations!**

$$\nabla\cdot\mathbf{E} = \rho - g_{a\gamma\gamma}\mathbf{B}\cdot\nabla a$$

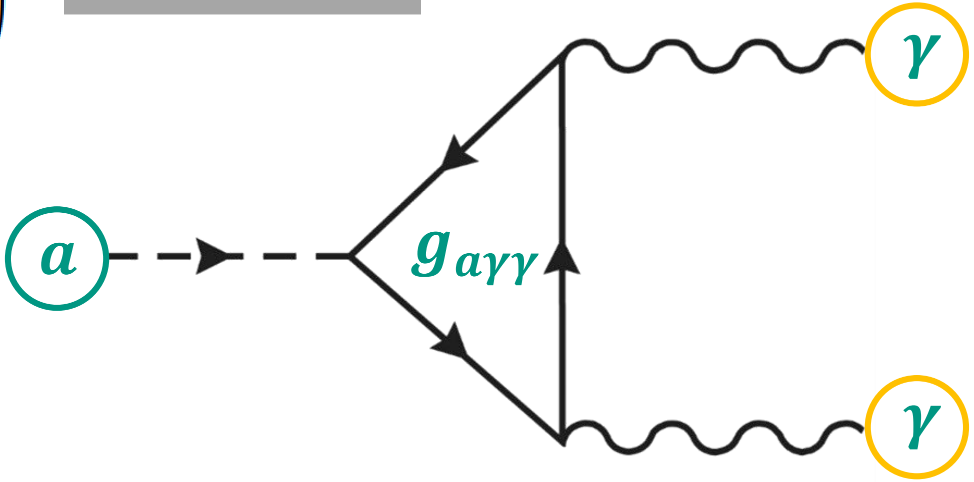
$$\nabla\cdot\mathbf{B} = 0$$

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$$

no changes here, great

$$\nabla\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} + \mathbf{J} - g_{a\gamma\gamma}\left(\mathbf{E}\times\nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right)$$

can be used to reveal the presence of axions

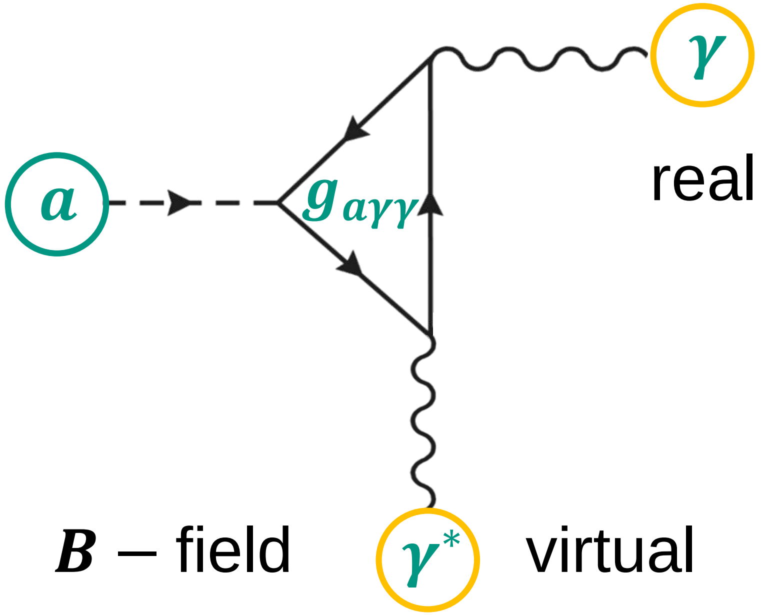


but … **my** equations…

Axion detection: making use of magnetic fields

- A **coherent*** **process (inverted Primakoff) to convert axions in a B – field**

  - a **very strong B – field** (in the lab: few T) is used to generate a **virtual photon γ^*** to initiate the conversion of an axion into a **real photon γ**



- there is a ´mismatch´ of the spins of the axion (pseudoscalar, $S = 0$) and of the photon (vector, $S = 1$):

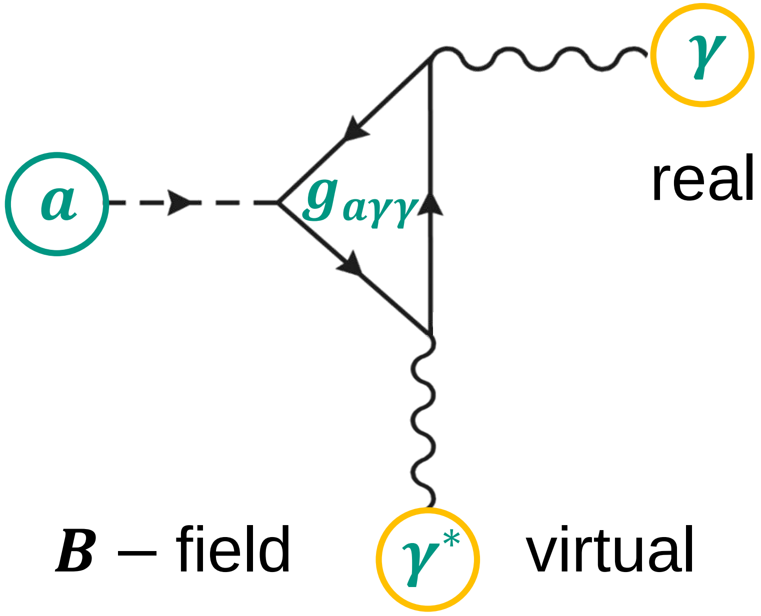
⇨ the external **B-**field has to be transversal, i.e. we need a typical magnetic **dipole** field

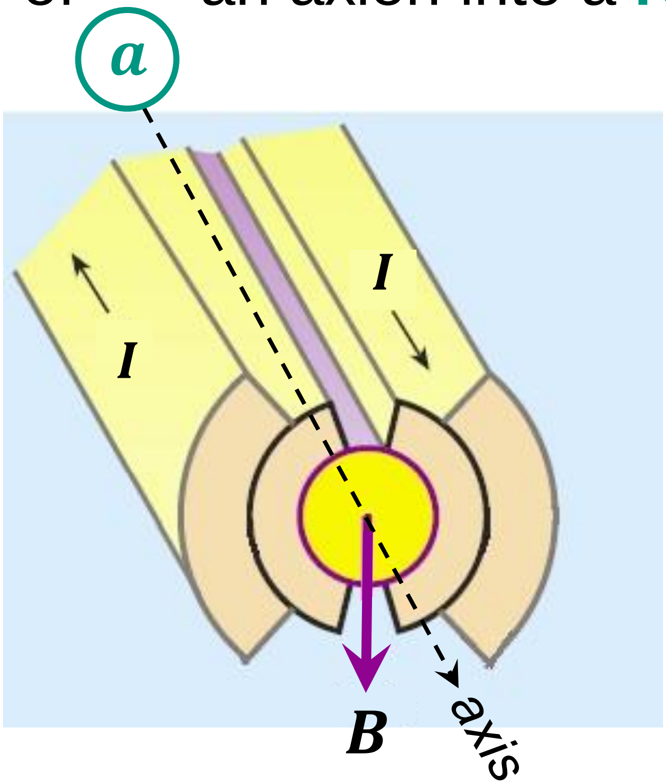
*experimentalists: always get *excited* if it´s coherent

Axion detection: making use of magnetic fields

- A coherent process (inverted Primakoff) to **convert axions in a B – field**

- a **very strong B – field** (in the lab*: few T) is used to generate a **virtual photon γ^*** to initiate the conversion of an axion into a **real photon γ**





dipole magnet

B is transversal to axion flight path which is travelling along magnet axis with its length L

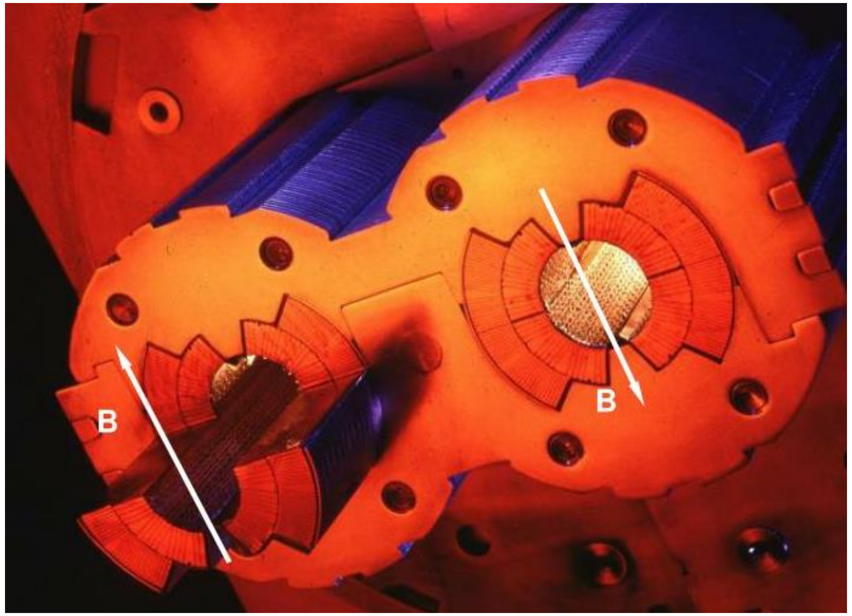
*experimentalists: we go to the limit before quench

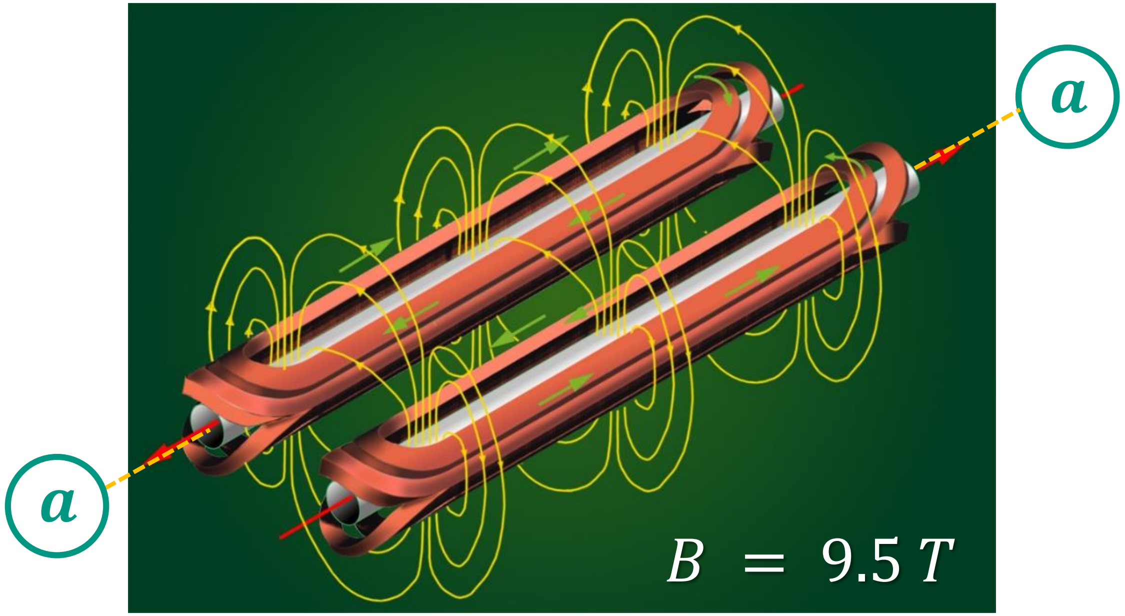
Axion detection: making use of magnetic fields

- A coherent process (inverted Primakoff) to **convert axions in a $B-$ field**

  - a **very strong $B-$ field** (in the lab*: few T) is used to generate a **virtual photon γ^*** to initiate the conversion of an axion into a **real photon γ**

dipole magnets at LHC





*experimentalists: we go to the LHC & its dipoles