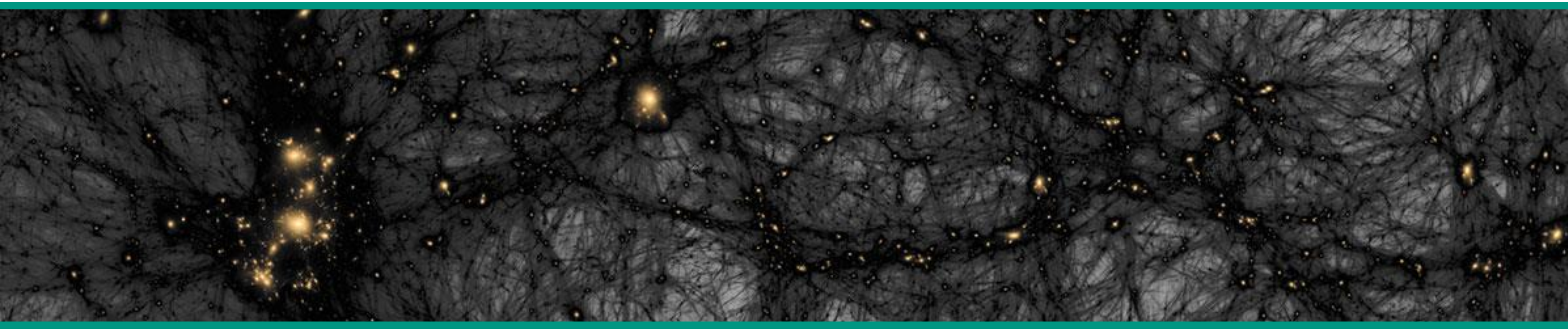
Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 20 Feb. 1, 2024



Recap of Lecture 19

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

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

  - requires 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) + $SQUID$s

  - Particle IDentification (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:

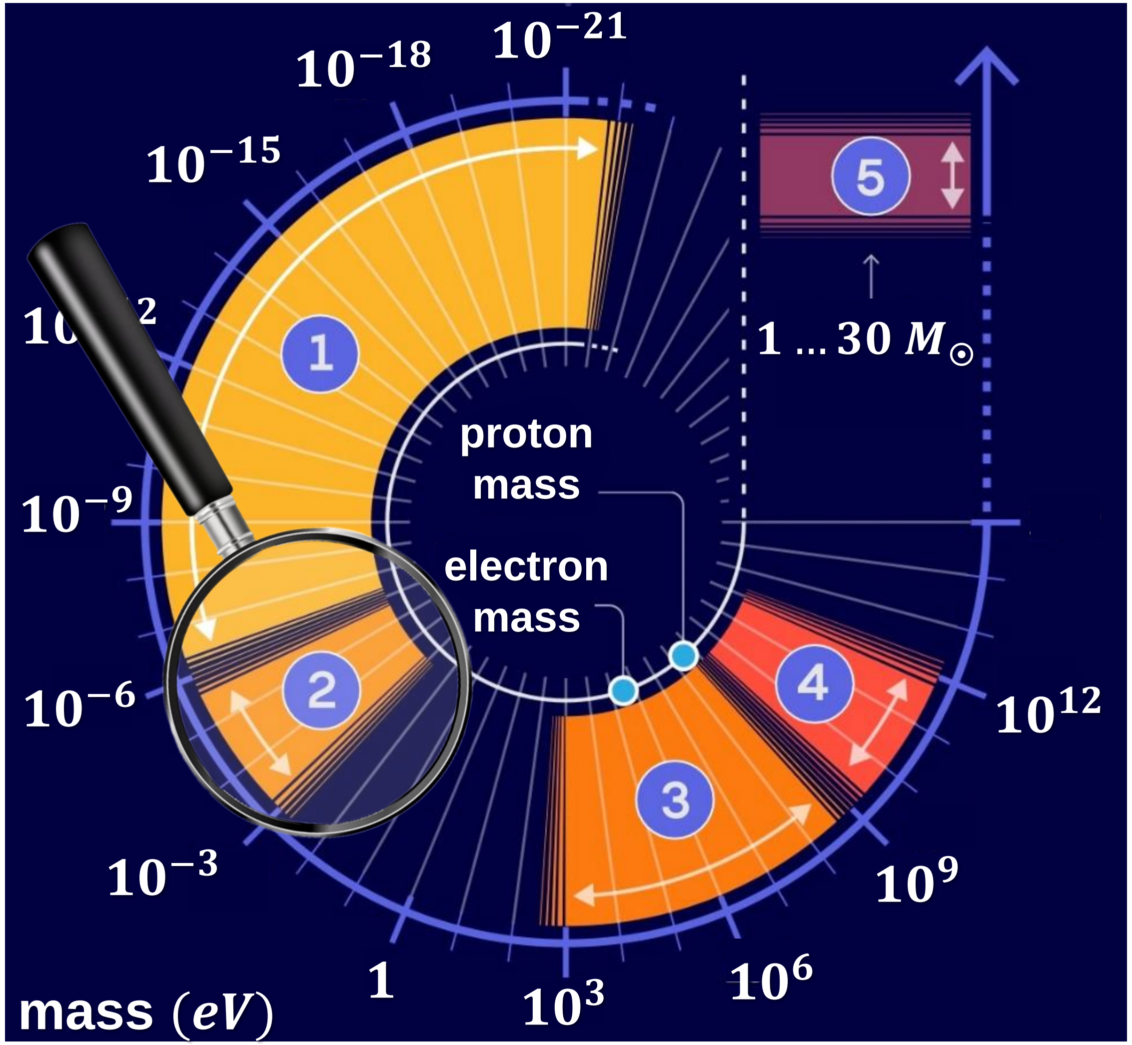
❶ ultra–light DM: Axion–Like Particles (ALPs)

❷ $axions$: ⇨ strong CP – problem

❸ DM on $sub-GeV$ scale: ⇨ bolometers

❹ $WIMPs$: neutralinos ⇨ $Xe/Ar\ TPCs$

❺ primordial black holes ($MACHOs$*)

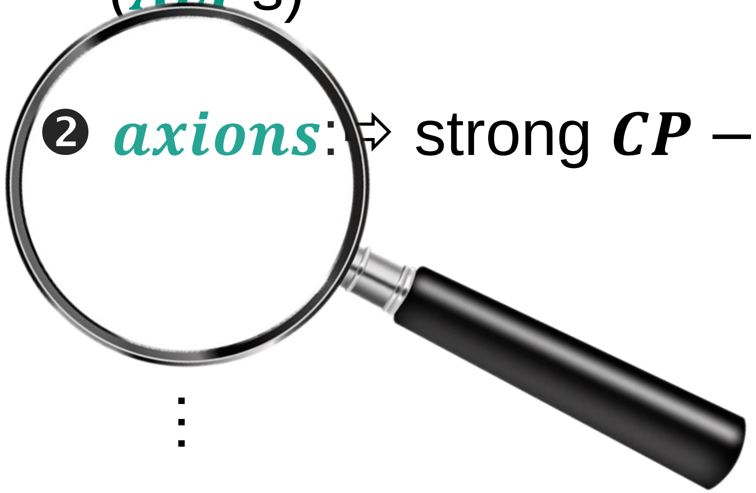


*MAssive Compact Halo Objects

Non−thermal DM − candidates: $axions$

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

❶ ultra−light DM: Axion−Like Particles (ALPs)



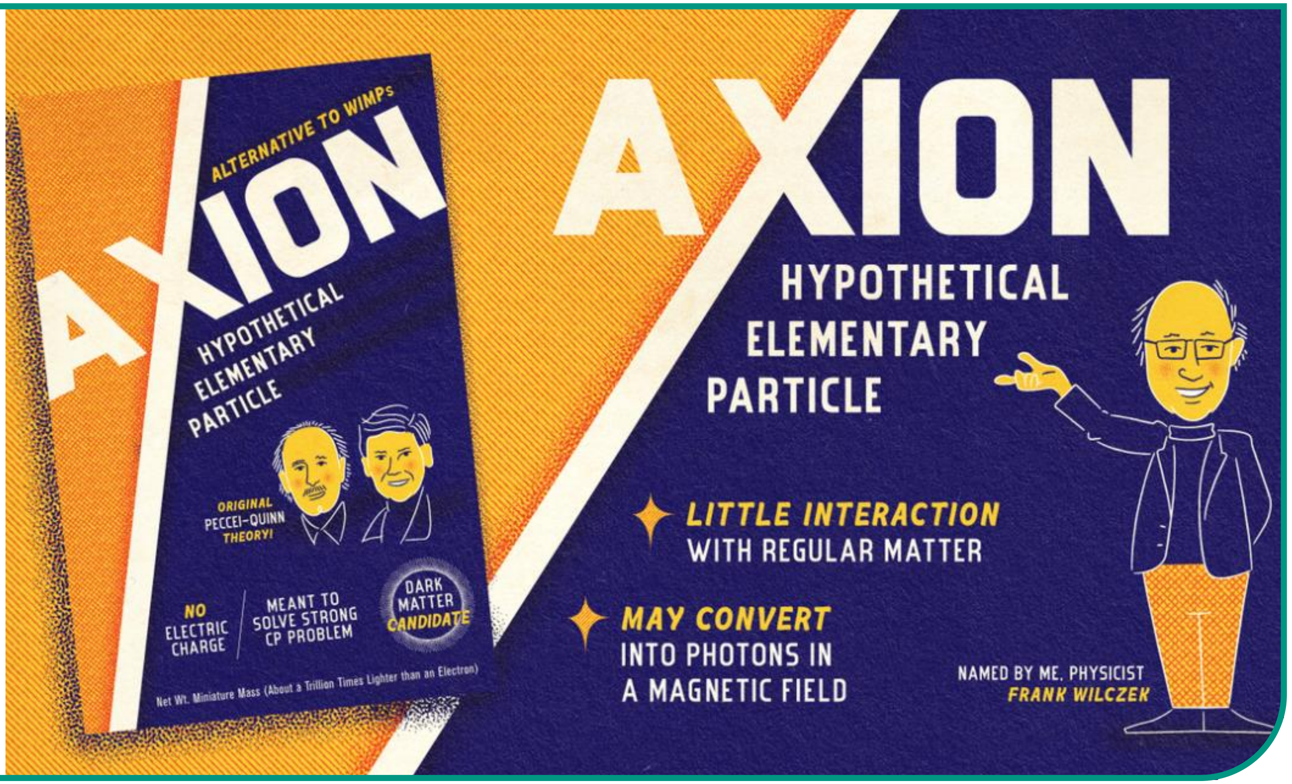
❷ $axions$: ⇨ strong CP − problem

⋮

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:** ´$\boldsymbol{who\ ordered\ that}$***** ?´

  - 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

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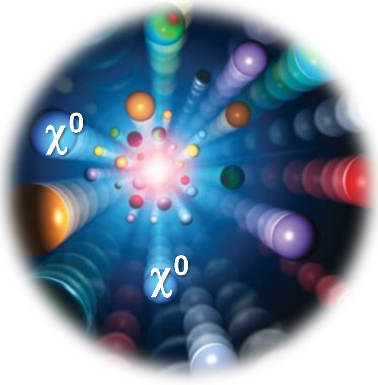
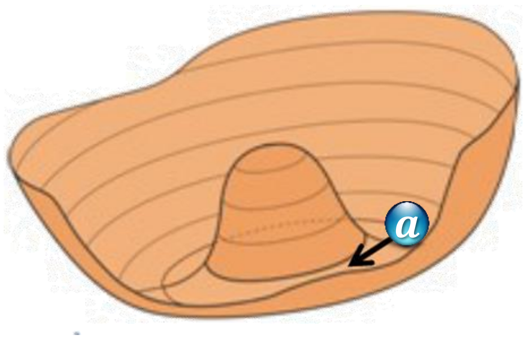
- Comparing $axions$ as $WISPs$ contrast our ´*good olde*´ massive $WIMPs$



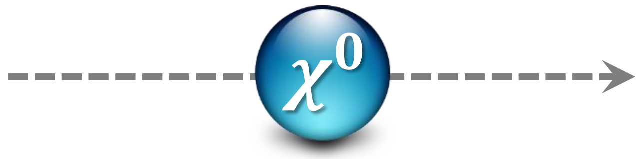


thermal production			non–thermal production
$WIMP$			$WISP$
$S = ½$	mass: $GeV \ldots TeV$	mass: $\mu eV \ldots meV$	$S = 0$
´thermal gas´			´Bose condensate´

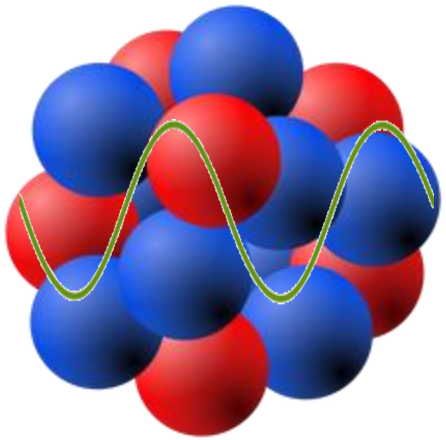
$WISP$ = Weakly Interacting Slim Particle

$Axions$ – a completely different $DM -$ candidate

- Comparing axions as $WISPs$ to massive $WIMPs$: *de Broglie* wavelength λ



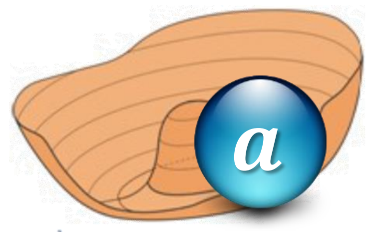
elementary particle



$$\lambda \sim nm$$

***de Broglie* wavelength**

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



field–oscillation

$$\lambda \sim m \ldots km \ldots pc$$

RECAP: DM – candidates with mass m & $xsec\ \sigma$

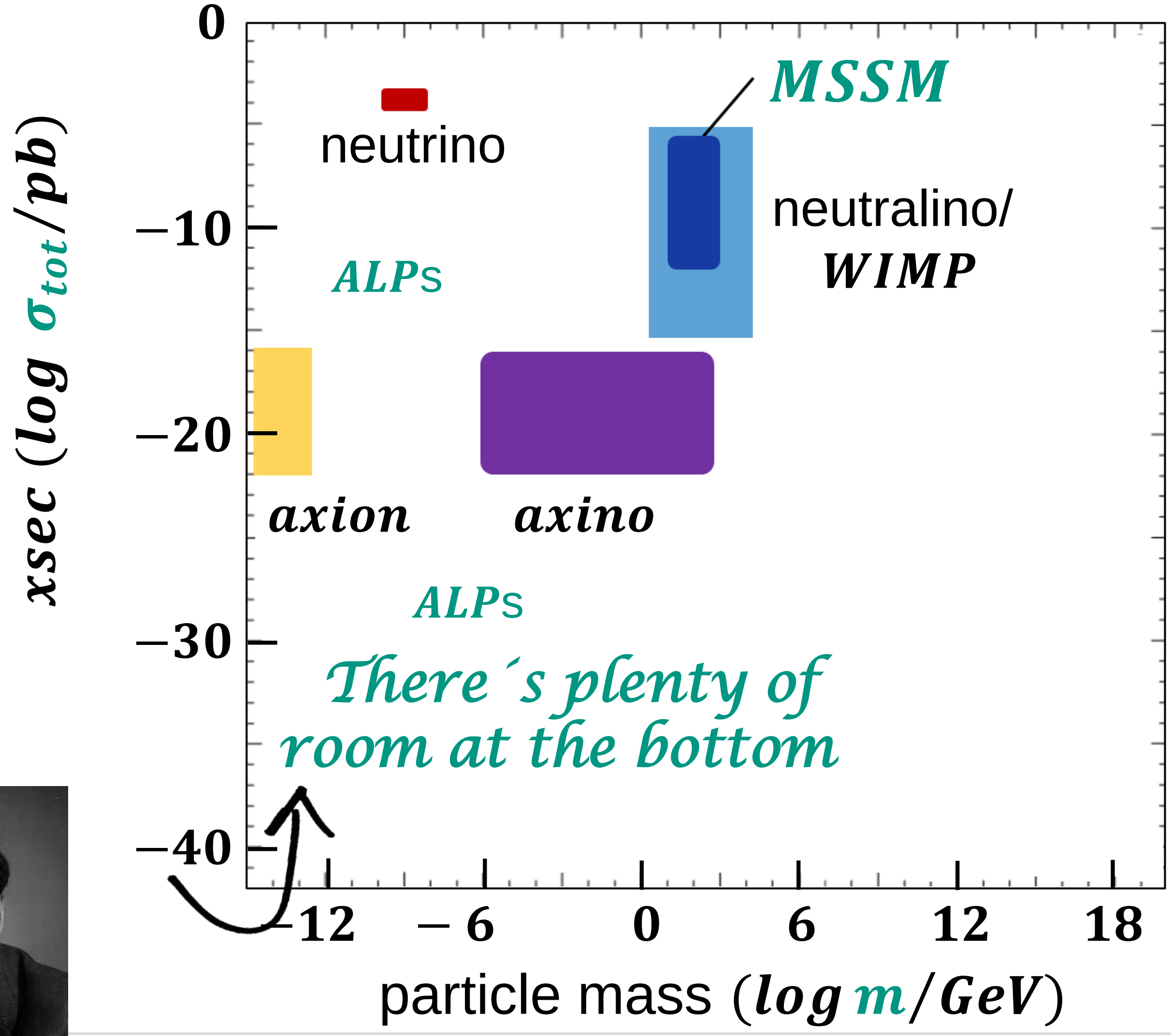
- ***Axion a*** **as** ***WISP***

  - motivation: ´QCD – axion´ for conservation of CP in QCD

  - $axion\ a$ = prototype of a $WISP$

  - $axions$ could act as CDM in the universe if their **mass** falls in the range:
    $m_a = (10^{-6} \ldots 10^{-3})\ eV$

  - $ALPs$ = Axion Like Particles



29.12.1959

Axions and the symmetry CP in QCD

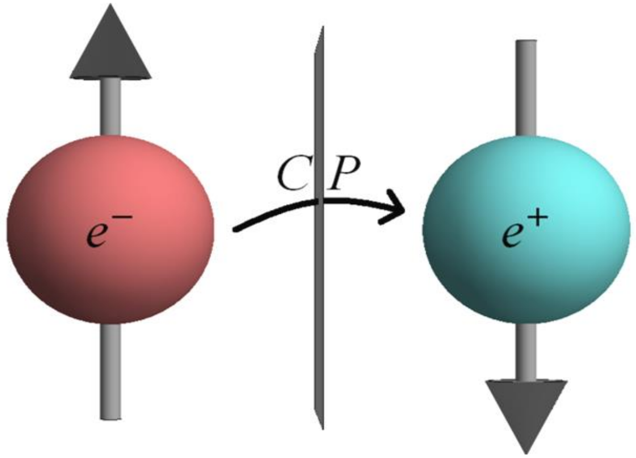
- **How to solve the ´strong CP – problem´**

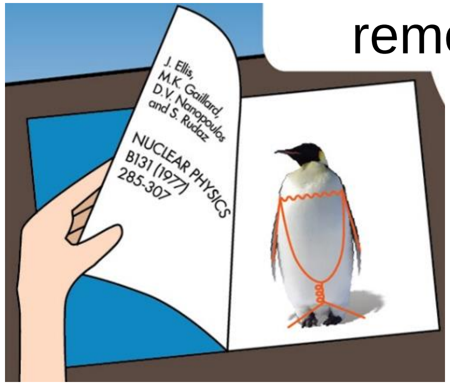
  - general statement: in case that
    CP invariance is violated:
    ⇨ violation of **T invariance** (& ***vice versa***)

  - CP – violation so far only detected in
    weak interactions!

  - CP – violation has **never** been detected in
    strong interactions!

spin ***up*** ***electron*** **spin** ***down*** ***positron***





remember those ***Penguin*** diagrams ?

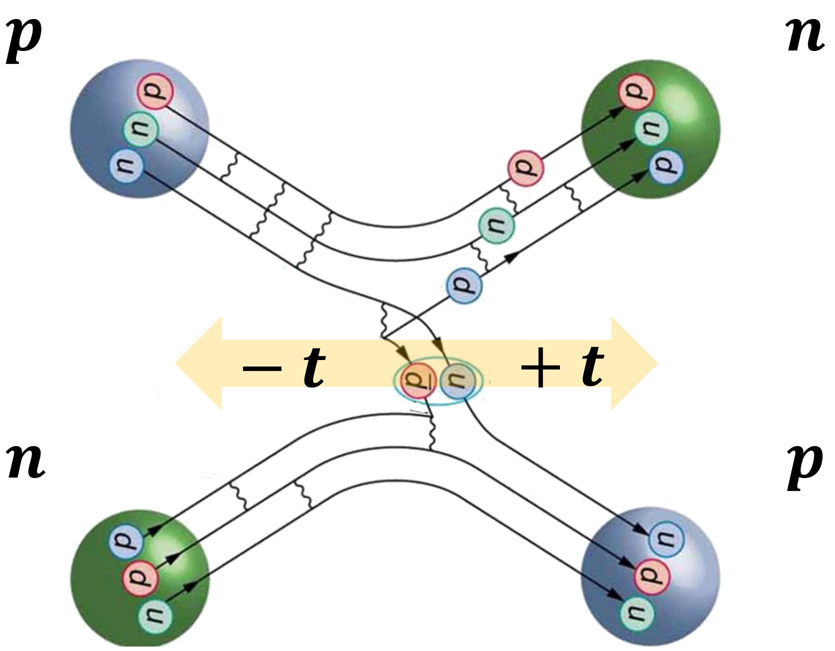
$Axions$ and the symmetry CP in QCD

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

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

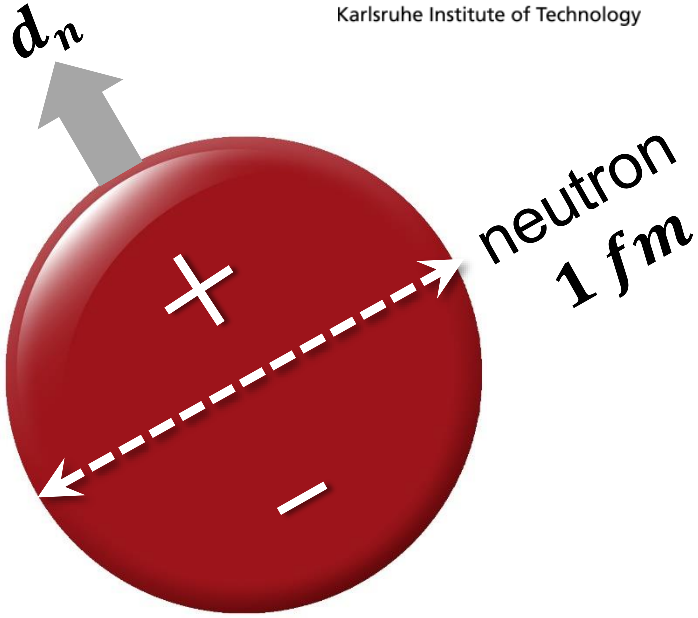
  - CP – violation so far only detected in
    weak interactions!

  - CP – violation has **never** been detected in
    strong interactions!



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

Axions and the symmetry CP in QCD



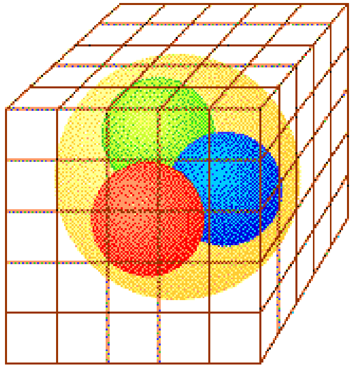
- **A key observable of the ´strong CP – problem´: the $n - EDM$**

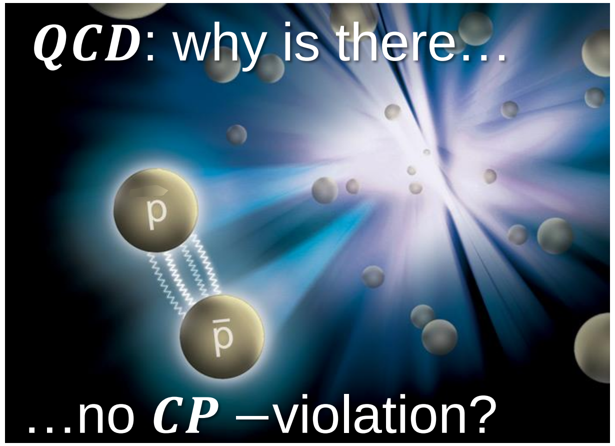
  - QCD – **Lagrangian** contains CP – violating terms:
    ⇨ how can we detect them experimentally?

  - 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

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- **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

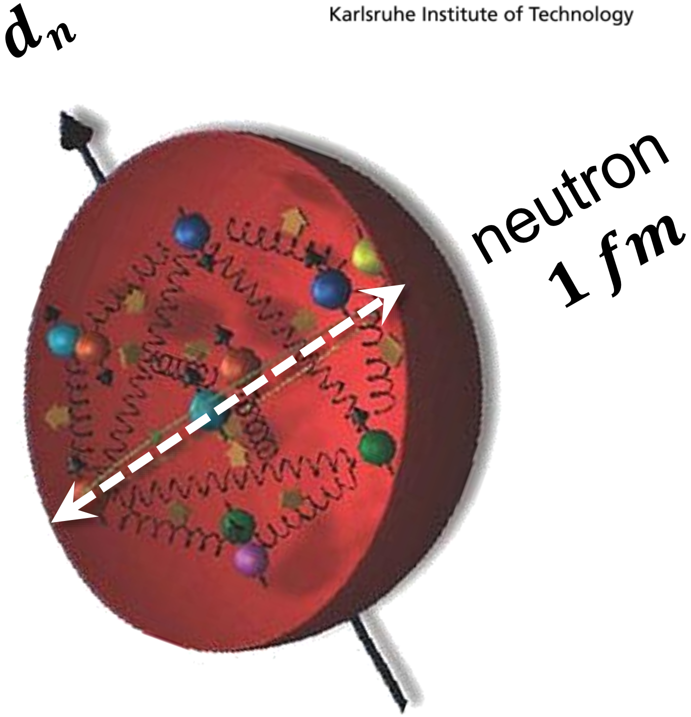
  - ´$naive$´ model: one quark ($q = 1/3$) over neutron size

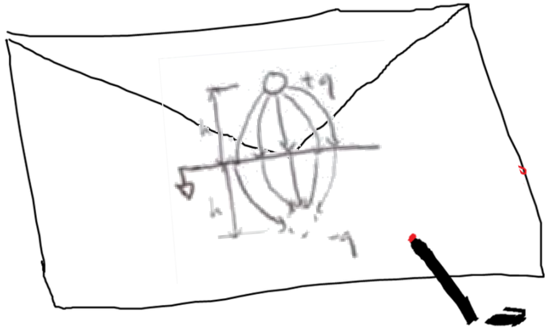
$$d_{n,naive} \sim 1/3 \; e \cdot 1 \cdot 10^{-13} \; cm$$

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

theoretically allowed value (QCD):

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

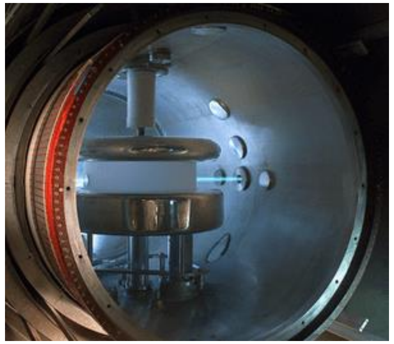




´back of the envelope´ calculation

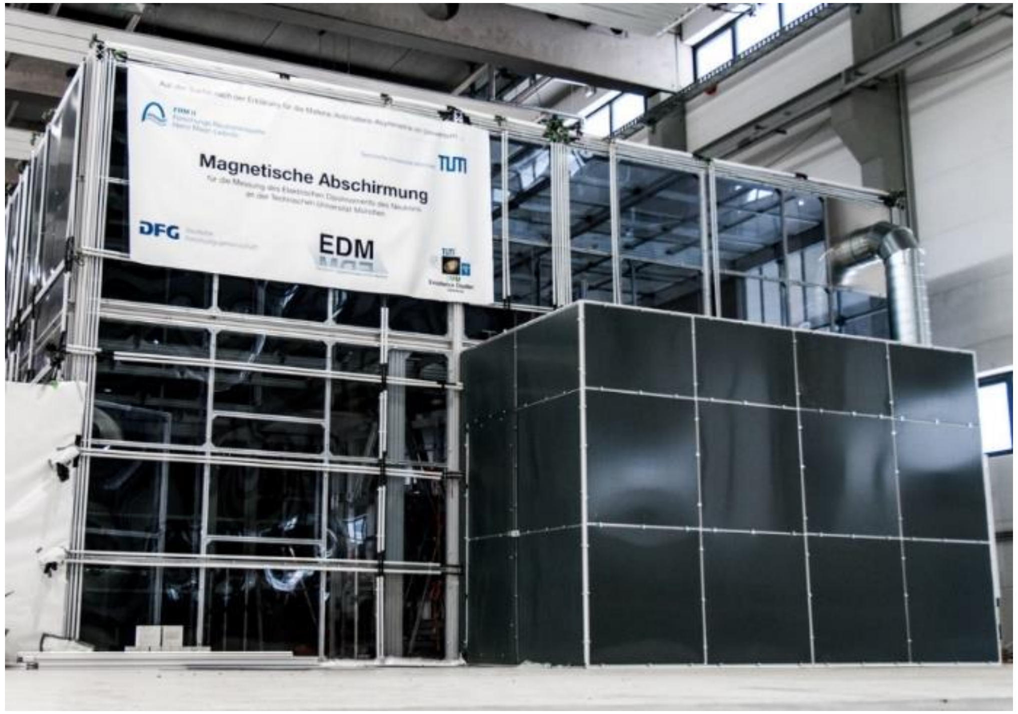
Axions and the symmetry CP in QCD

- **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):

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

* Phys. Rev. Lett. 124, 081803 (2020) - Measurement of the Permanent Electric Dipole Moment of the Neutron (aps.org)

Axions and the symmetry CP in QCD

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

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

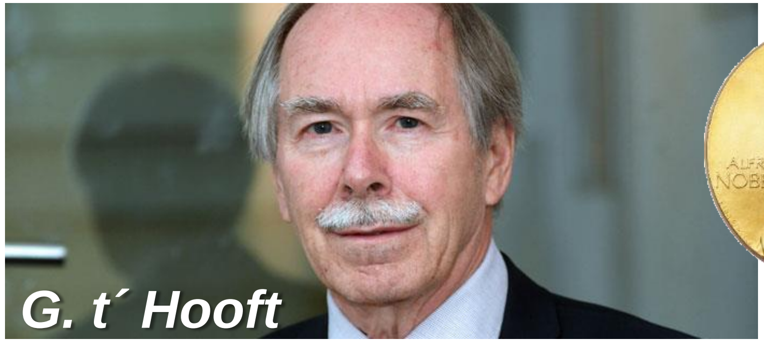
  - vacuum state of QCD is CP – conserving with $|\theta_{QCD}| < 10^{-10}$

θ_{QCD}

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

theoretically allowed value (QCD):

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



1999

Axions and the symmetry CP in QCD

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

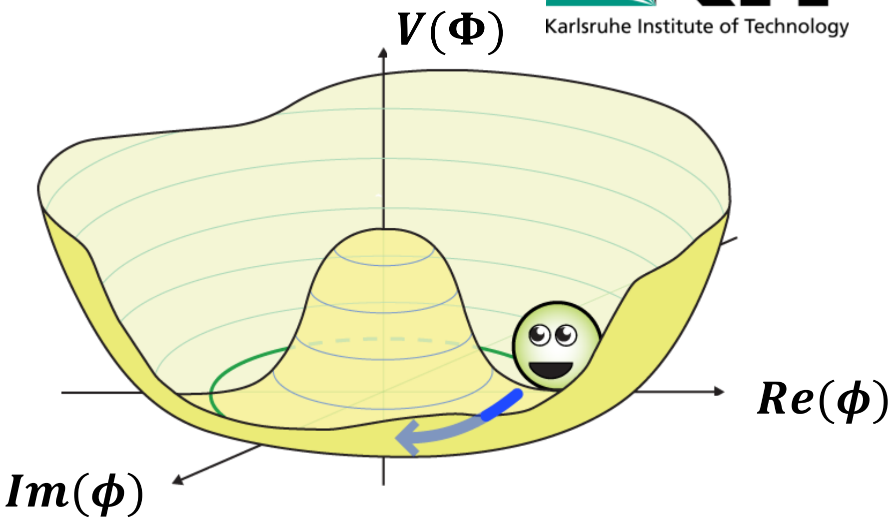
- **A new $U(1)-$ symmetry to solve the strong $CP-$ problem**

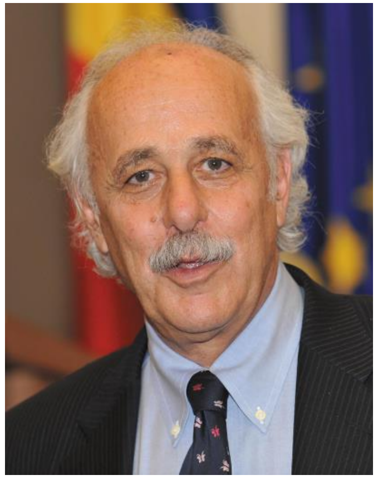
  - enter a new global ($\boldsymbol{chiral}$) symmetry $\boldsymbol{U(1)_{PQ}}$

  - if unbroken, $\boldsymbol{U(1)_{PQ}}$ guarantees $\boldsymbol{\theta_{QCD} \to 0}$

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

  - **Goldstone–theorem**:
    ⇨ from this we obtain a strictly $\underline{\boldsymbol{massless}}$ scalar gauge– (Goldstone–) $\boldsymbol{boson}$





Roberto $\boldsymbol{P}$eccei

Helen $\boldsymbol{Q}$uinn

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

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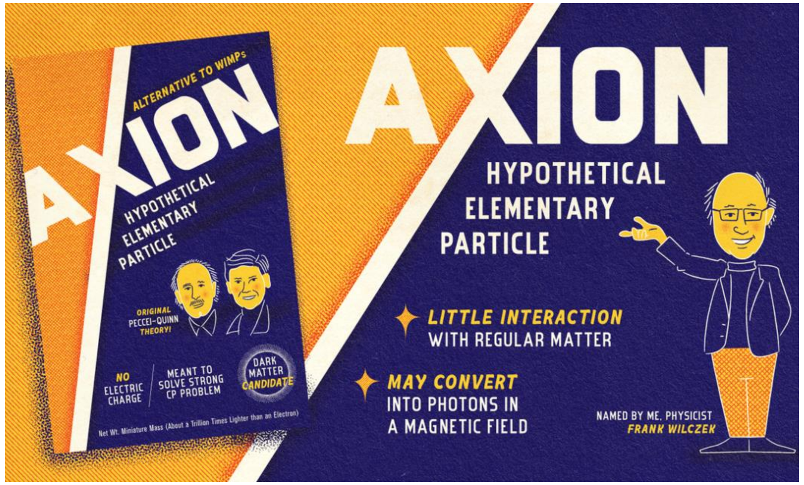
- **The *axion* emerges as a very light but massive particle (could it serve as our $DM-$ particle?)**

  - the new global (chiral) symmetry $U(1)_{PQ}$ 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 $\boldsymbol{axion\ a}$, with its $\boldsymbol{V}$acuum–$\boldsymbol{E}$xpectation–$\boldsymbol{V}$alue $(\boldsymbol{VEV})$ $\boldsymbol{explicitly}$ breaks the former symmetry $\boldsymbol{U(1)_{PQ}}$

    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**

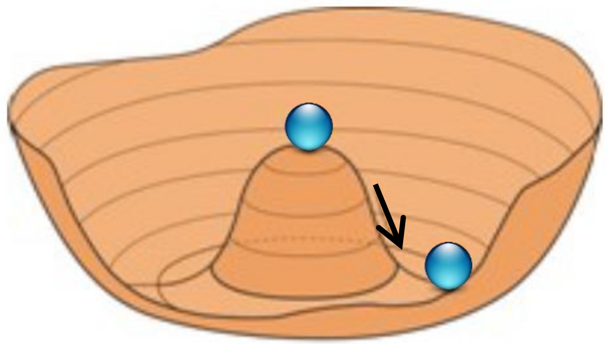
  - a close analogy to the very $massive\ Higgs - boson$

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

- $U(1)_{PQ}$ 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 will occur



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

*close analogy 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**

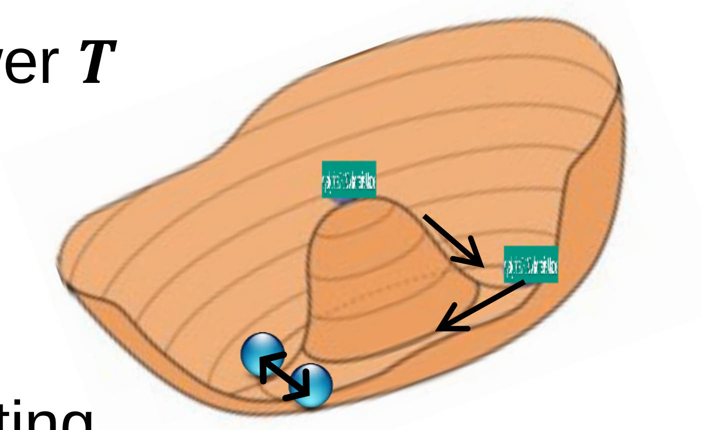
  - a close analogy to the very $massive\ Higgs - boson$

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

- $U(1)_{PQ}$ 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, $axions$ **emerge as field oscillations**



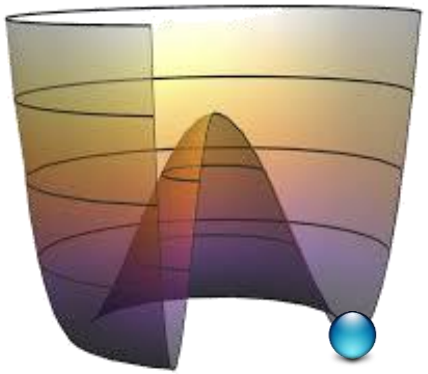
$\theta \rightarrow 0$

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

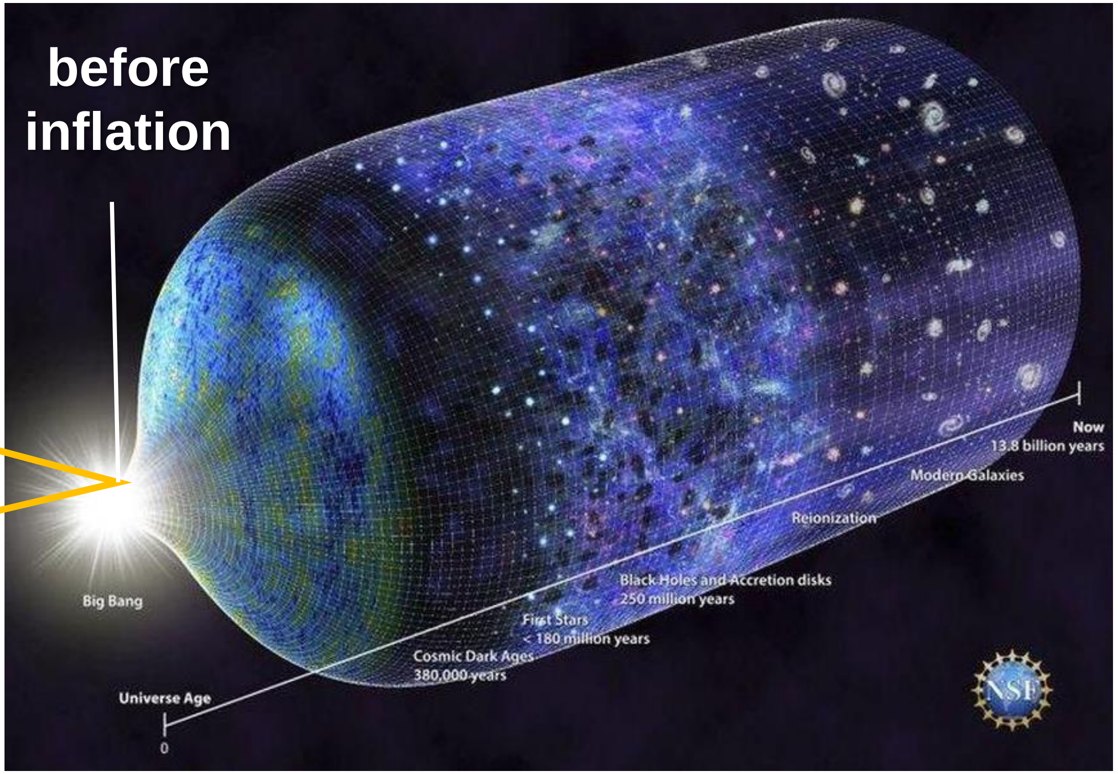
- **Spontaneous breaking of PQ – symmetry: before or after inflationary phase?**

  - 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

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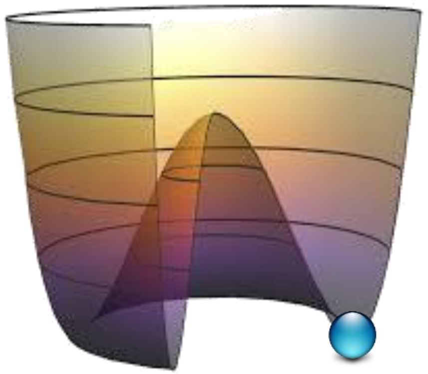
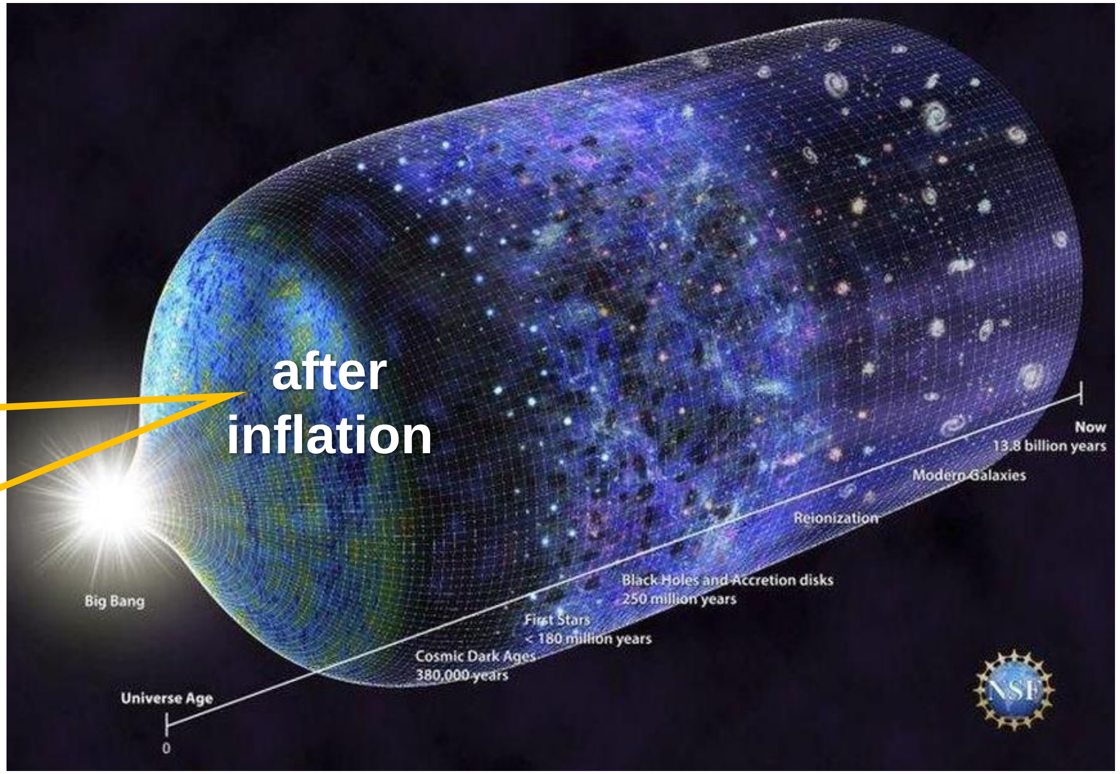
- **Spontaneous breaking of PQ – symmetry: before or after inflationary phase?**

  - 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 $U(1)_{PQ}$**

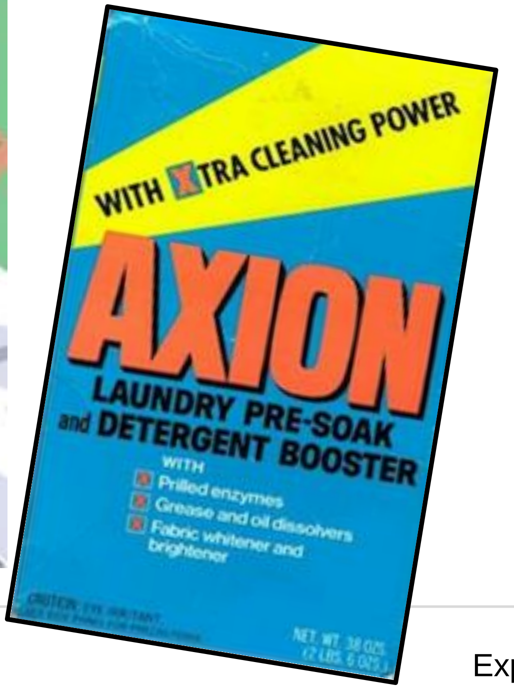
  - what does this all mean for DM?

  - 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"



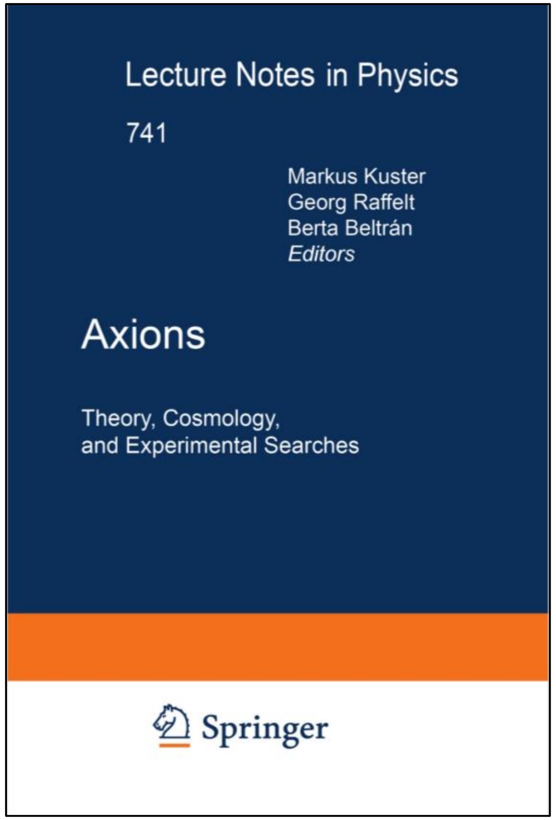
Frank Wilczek

$Axion$ as DM – candidate: Wilczeks´ ´$formula$´

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

  - looking at these $\boldsymbol{axions}$ from all sides…

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



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

…have a look, if you like…

Frank Wilczek

$Axion$ as DM – candidate: properties at a glance

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- $Axions$ **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 : $m_a \sim 1/f_a$
    $10^{-9}\ eV \dots 1\ eV$

  - 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 $a \rightarrow \gamma\gamma$
    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 $\rho_{DM,loc} = 0.3\ GeV/cm^3$

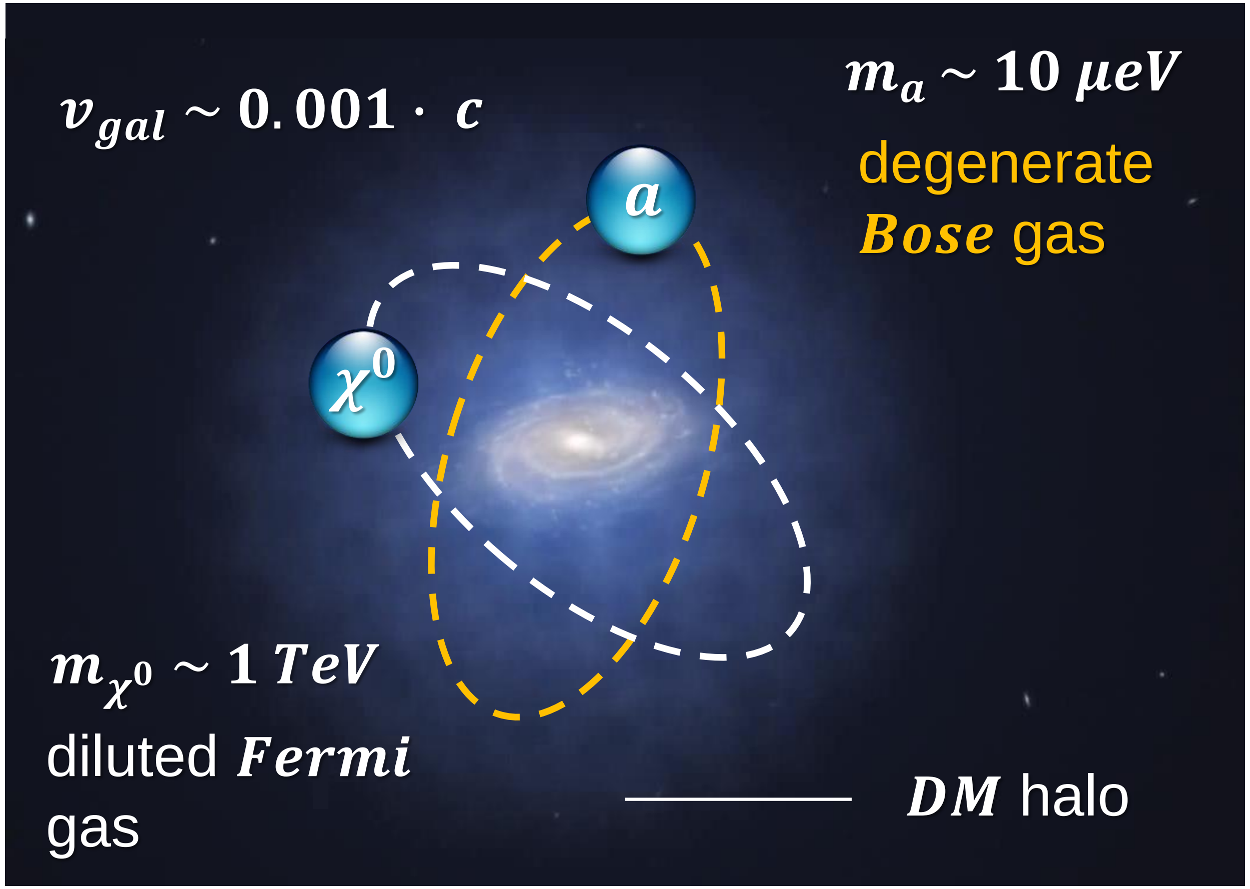
- local $axion$ number density:

  $N = 3 \cdot 10^{13}/cm^3$ (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

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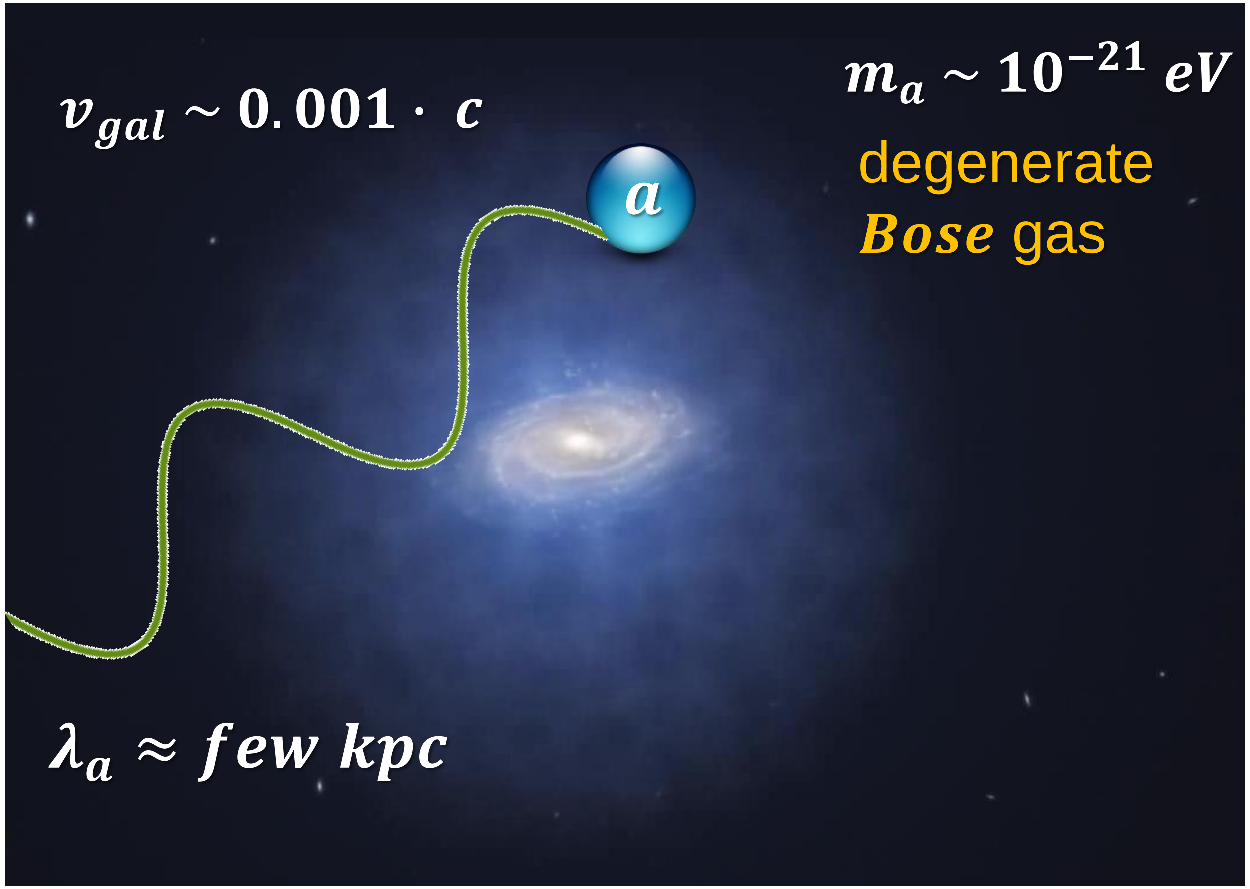
- $Axions$ in DM – halos: do they fit in even in case of dwarf galaxies?

- 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…

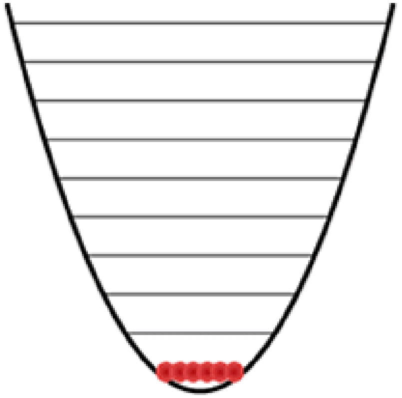
$Axion$ as DM – candidate: a Bose condensate

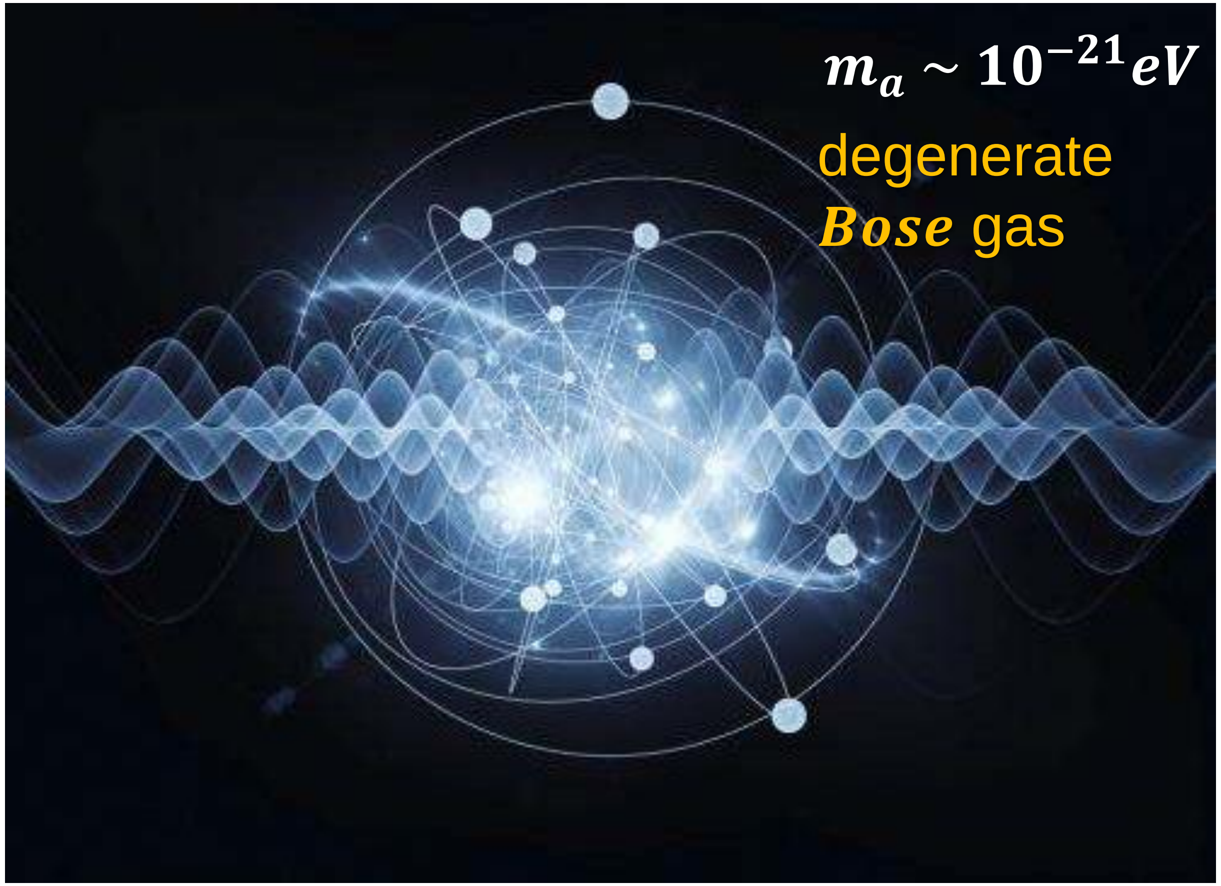
- $Axions$ in DM – halos: they can form a Bose–Einstein condensate

- typical **occupation numbers**:

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

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





local halo: how to visualize a condensate?

$Axion$ as DM: scale m_a

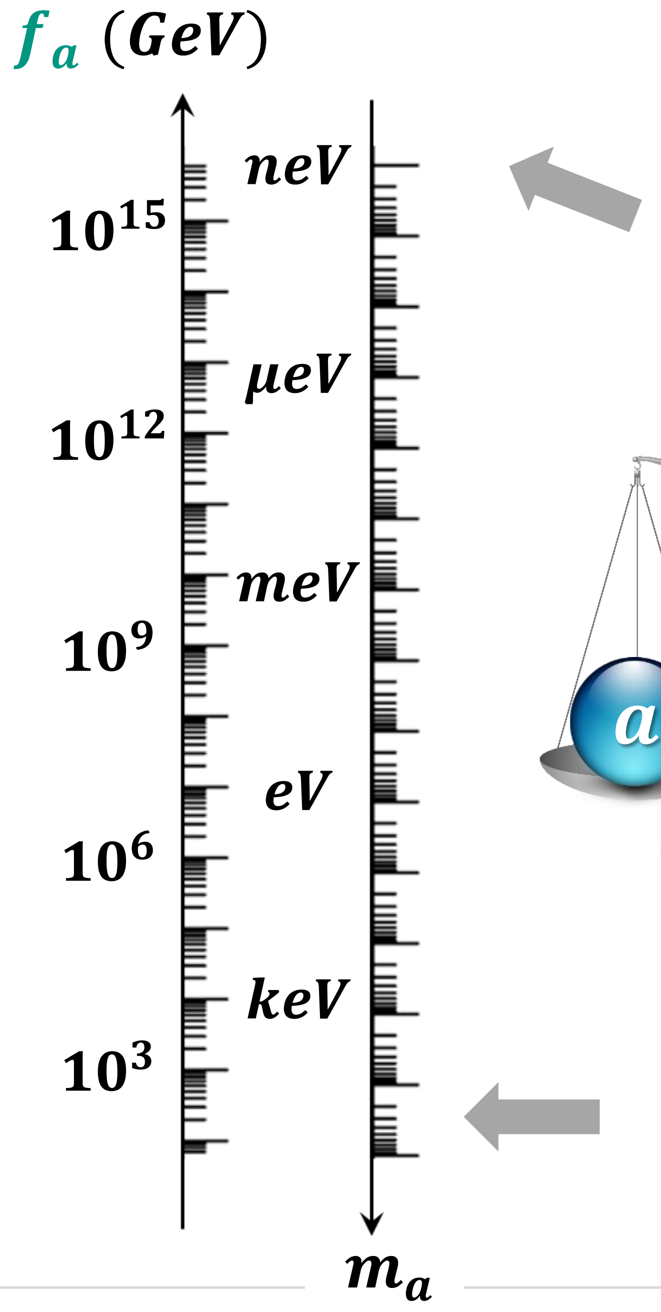
- **Comparing the energy scale f_a with the mass m_a of axions**

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

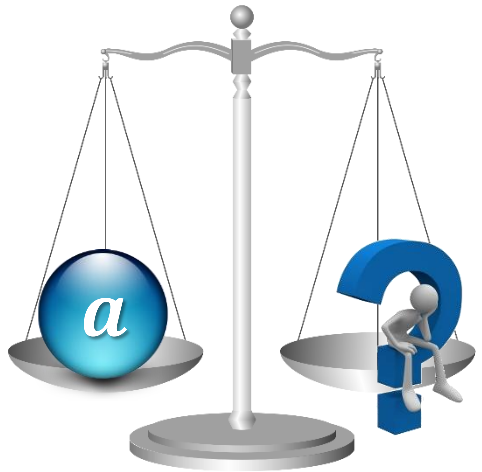
$$m_a \approx 6\ eV \cdot \frac{10^6\ GeV}{f_a}$$

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 $axions$**

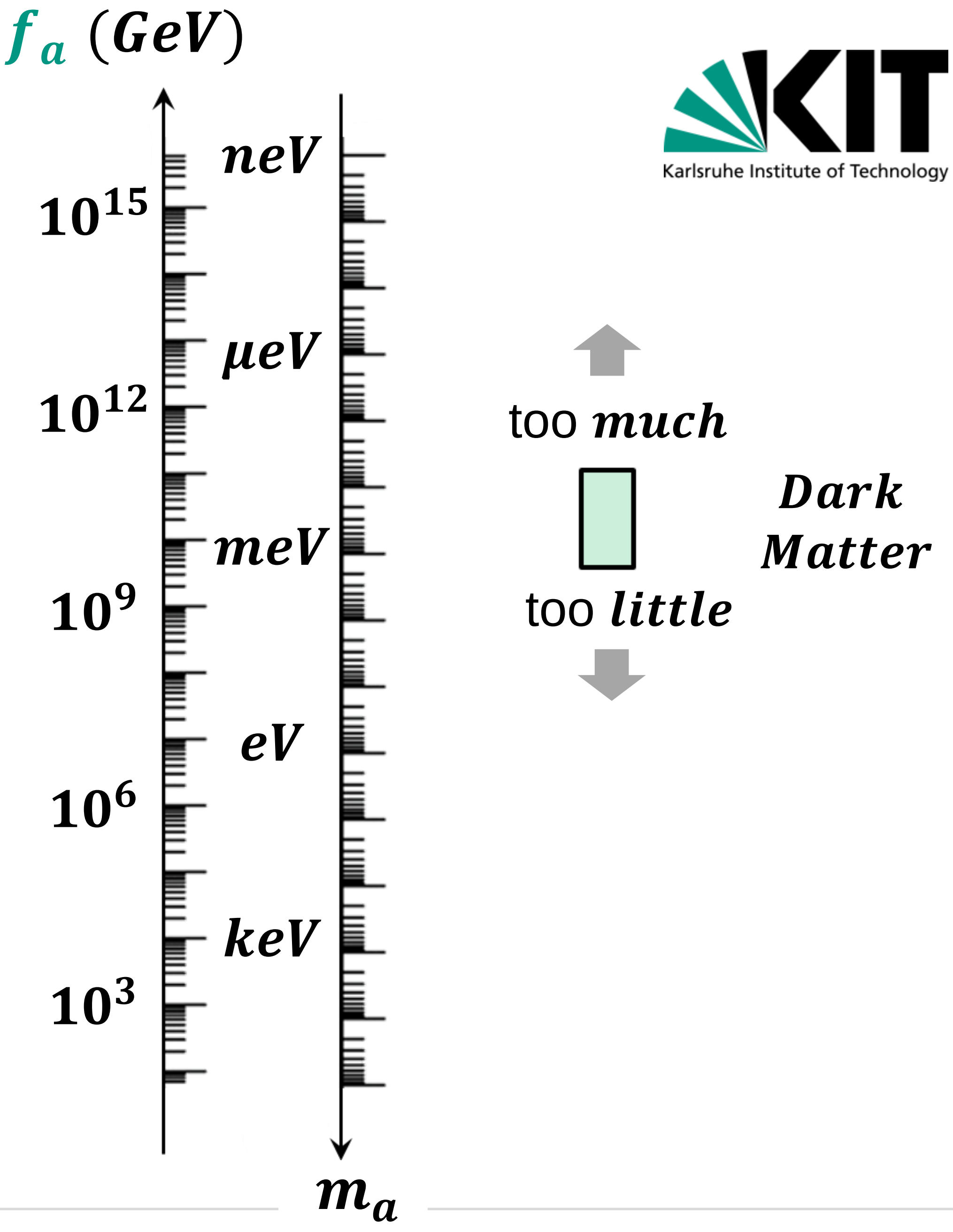
- $axion$ **mass scale m_a** is strongly model–dependent, but there is a region where m_a ideally fits to obtain a value $\Omega_{DM} \approx 0.27$

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

(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

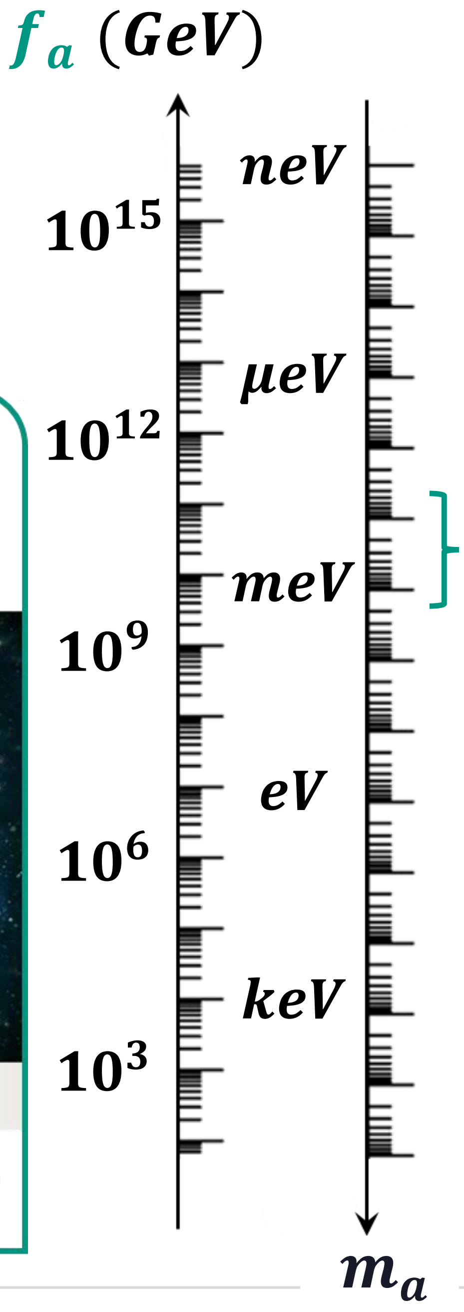
Forscher lüften Geheimnis der Dunklen Materie *

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

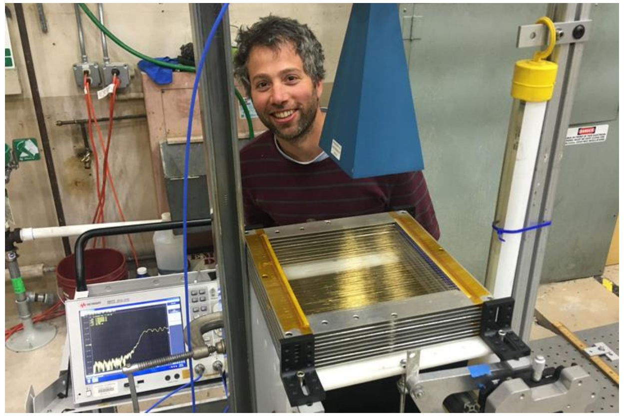
$N_a \approx 10^9/cm^3$

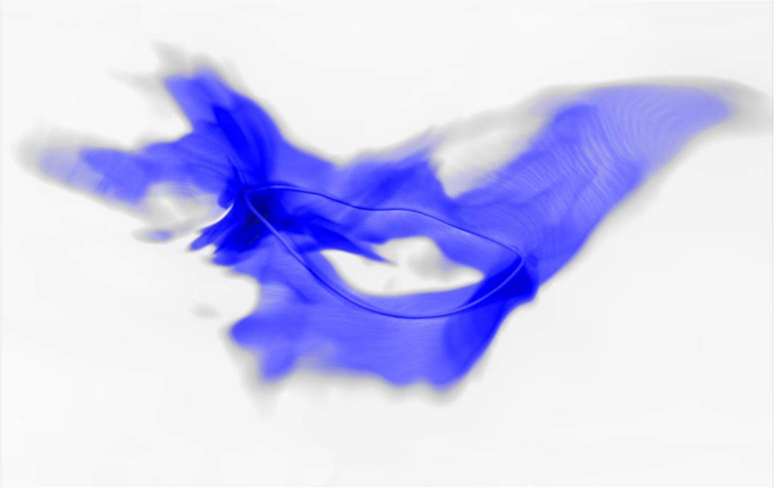
*researchers reveal the secret of Dark Matter (at the PC??....)

$Axion$ 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**
  $m_a \approx 65\ \mu eV$

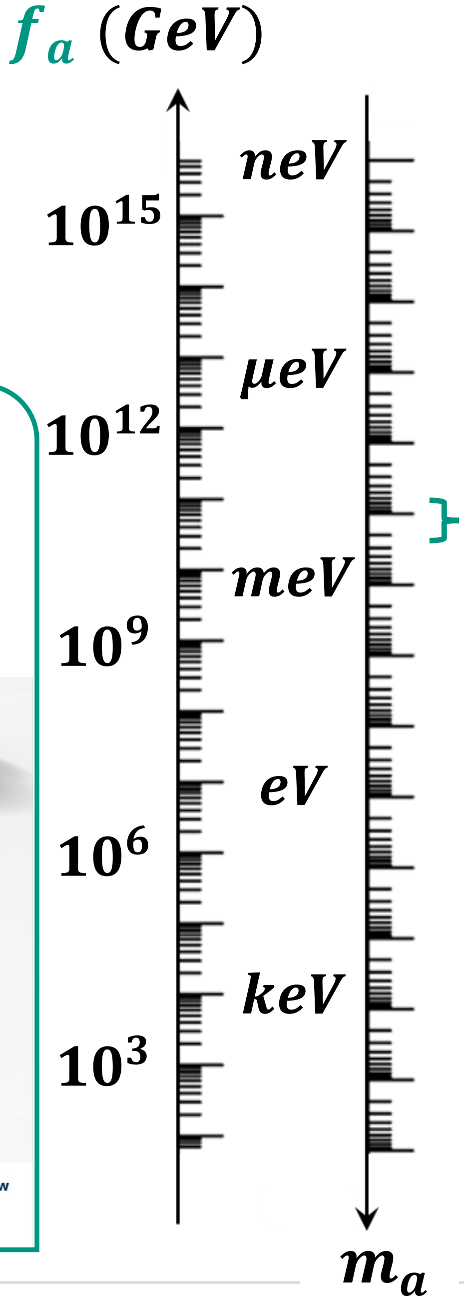



Berkeley News

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)

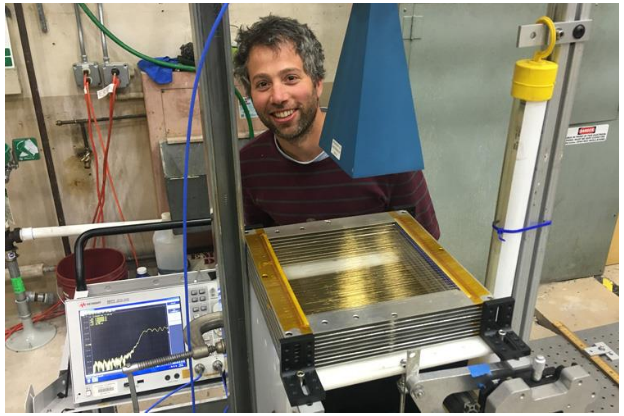


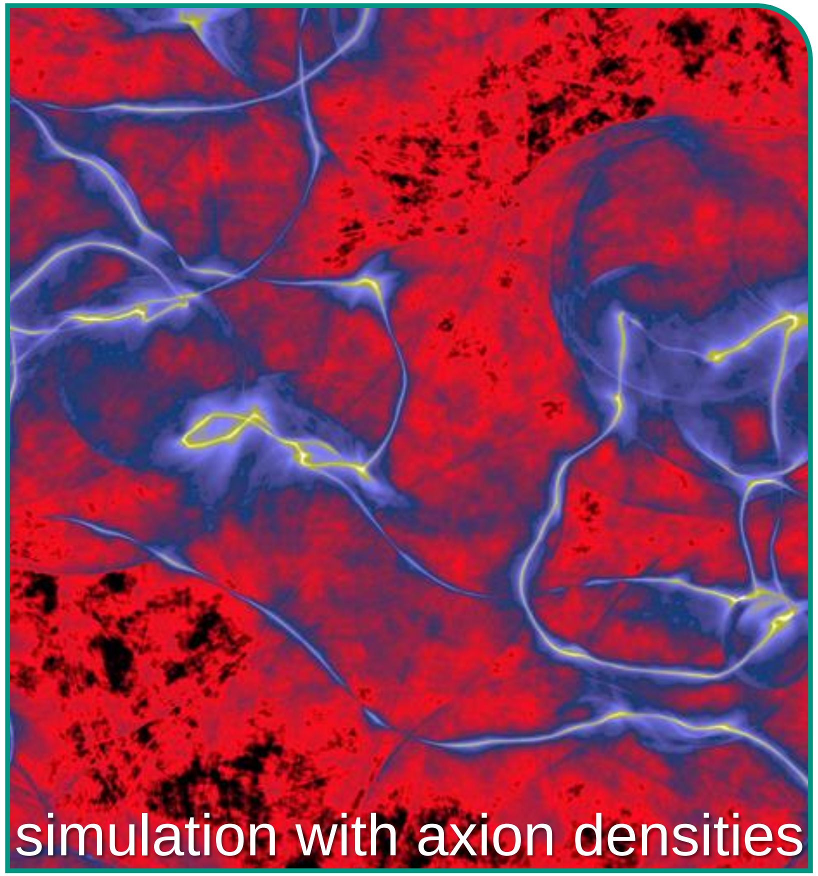
most probable
$QCD\ axion$
$m_a = 40 \dots 180\ \mu eV$

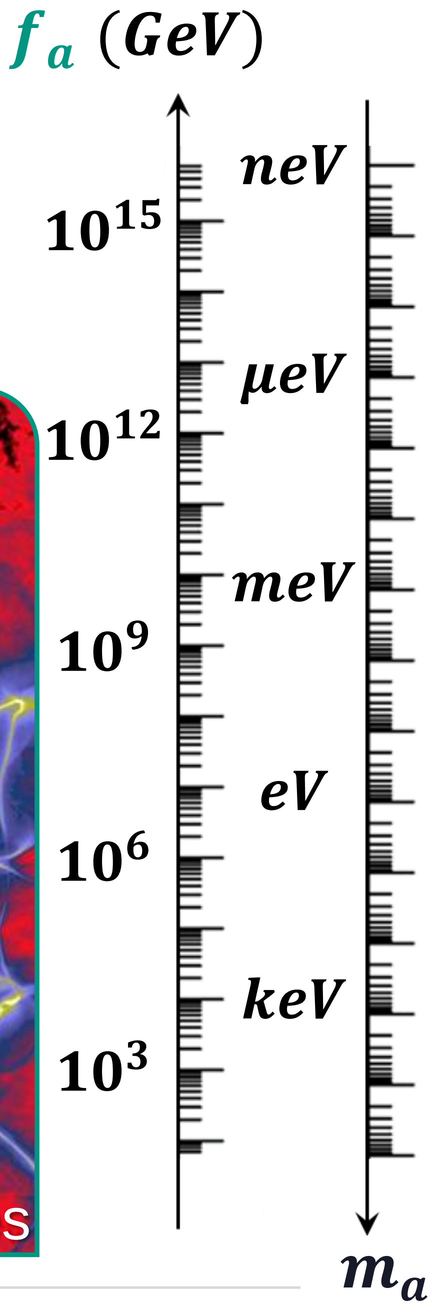
$Axion$ as DM: QCD calculations

- 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** $m_a \approx 65\ \mu eV$







$Axion$ as DM: cosmological limits

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

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

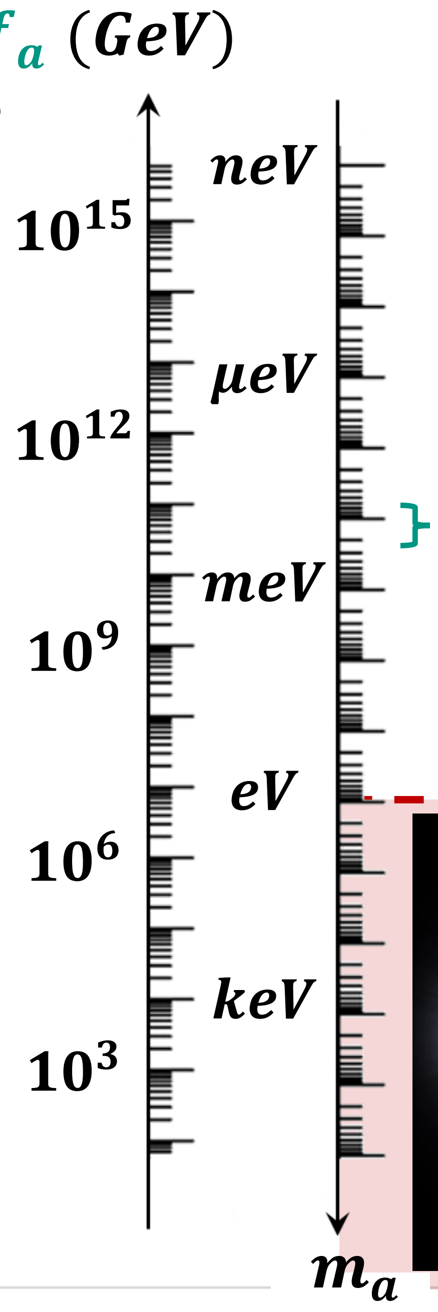
    $$m_a < 1\ eV$$

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

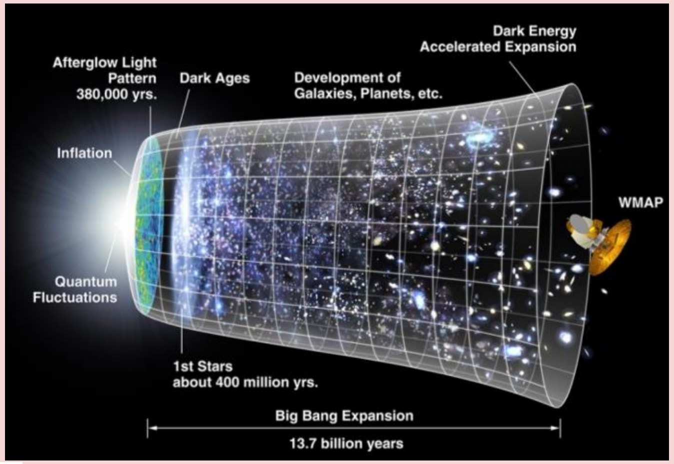
  - also: $axion$ lifetime requirement: $\tau_a > t_H$

    $$m_a < 20\ eV$$

    no $axion$ decays over Hubble time t_H



most probable $QCD\ axion$



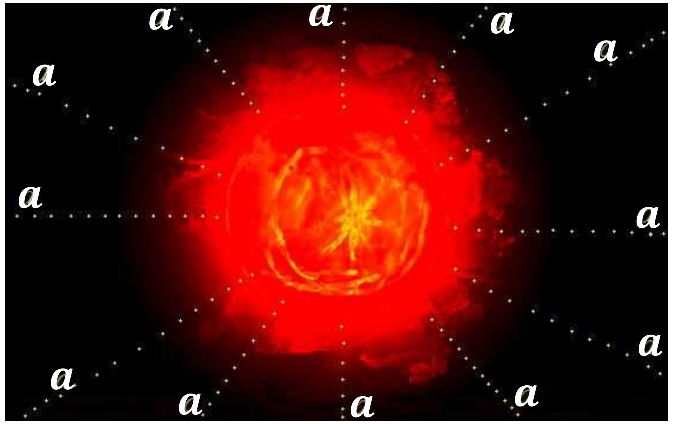
Axion as *DM*: astrophysical limits

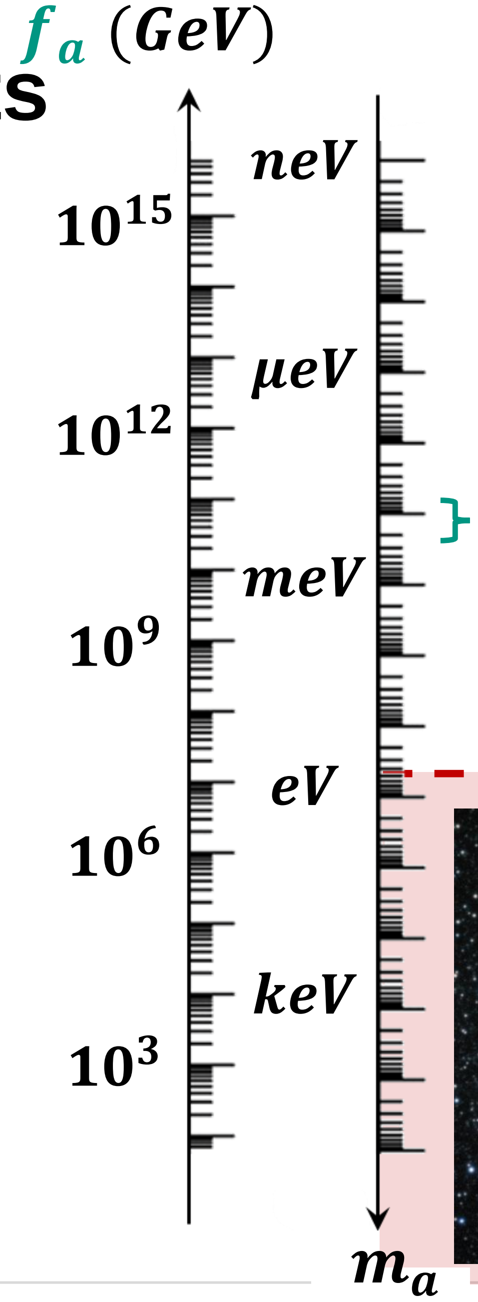
- **Astrophysics requests light *axions* on the *sub – eV* scale**

- need: 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

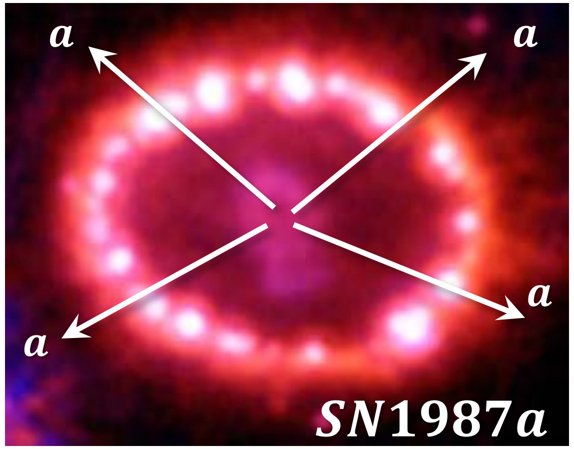
Axion as *DM*: astrophysical limits

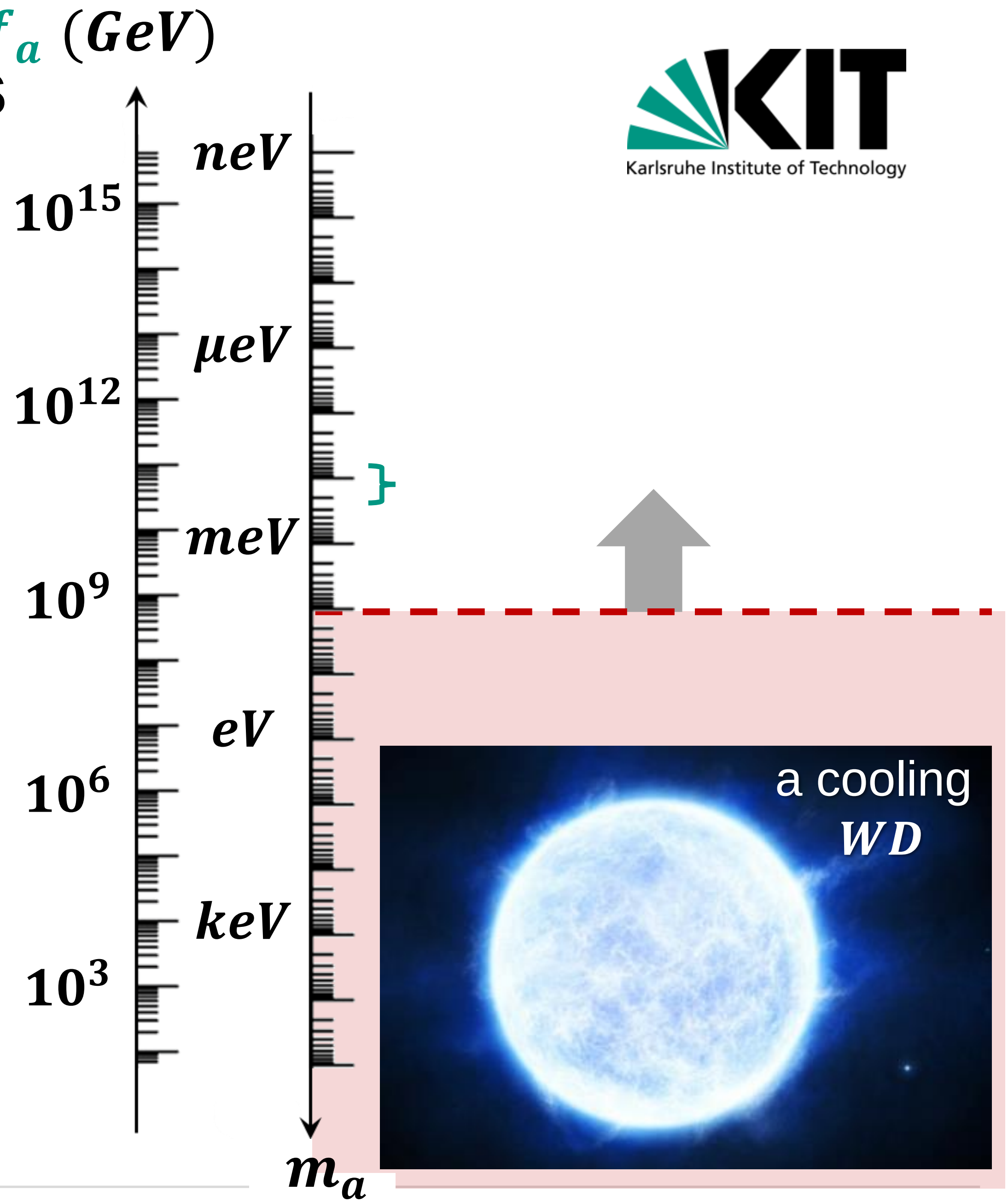
- **Astrophysics requests light *axions* on the *sub − eV* scale**

- no ***axion*** emission from ***SNae, WD****

$m_a < 16\ meV$

from the **1987** observation of a **10 *s ν*** – pulse (***SN1987a***) & long ***WD*** – cooling time



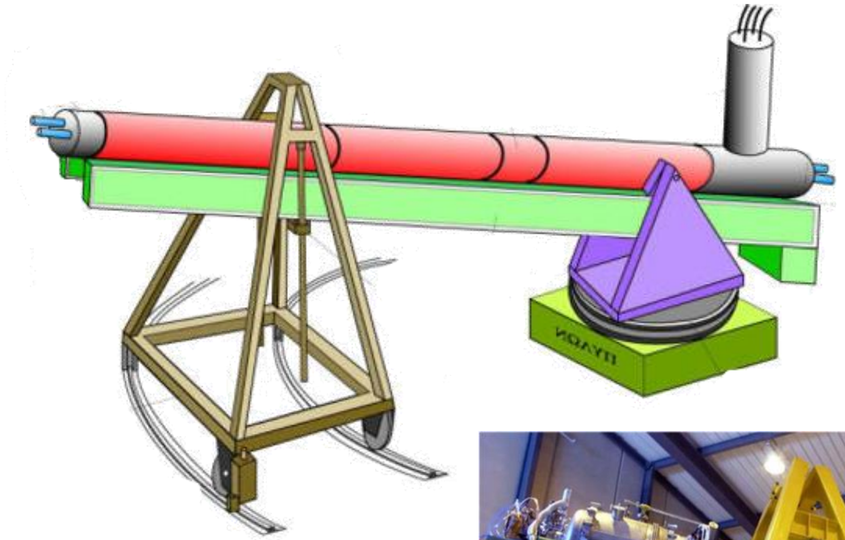


*White Dwarf, see ***ATP – II*** summer **2024**

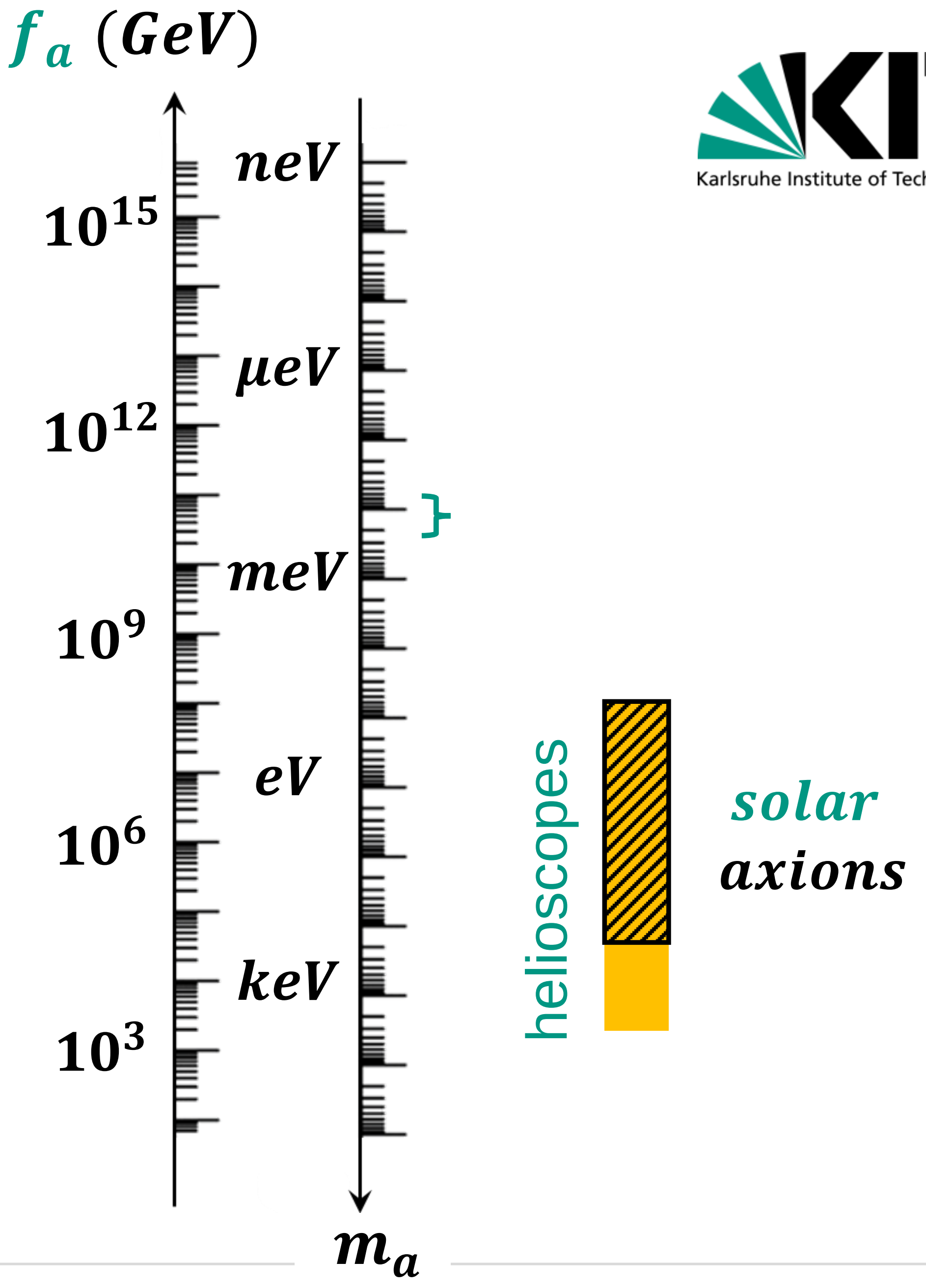
Axions: ´telescope´ searches

Karlsruhe Institute of Technology

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



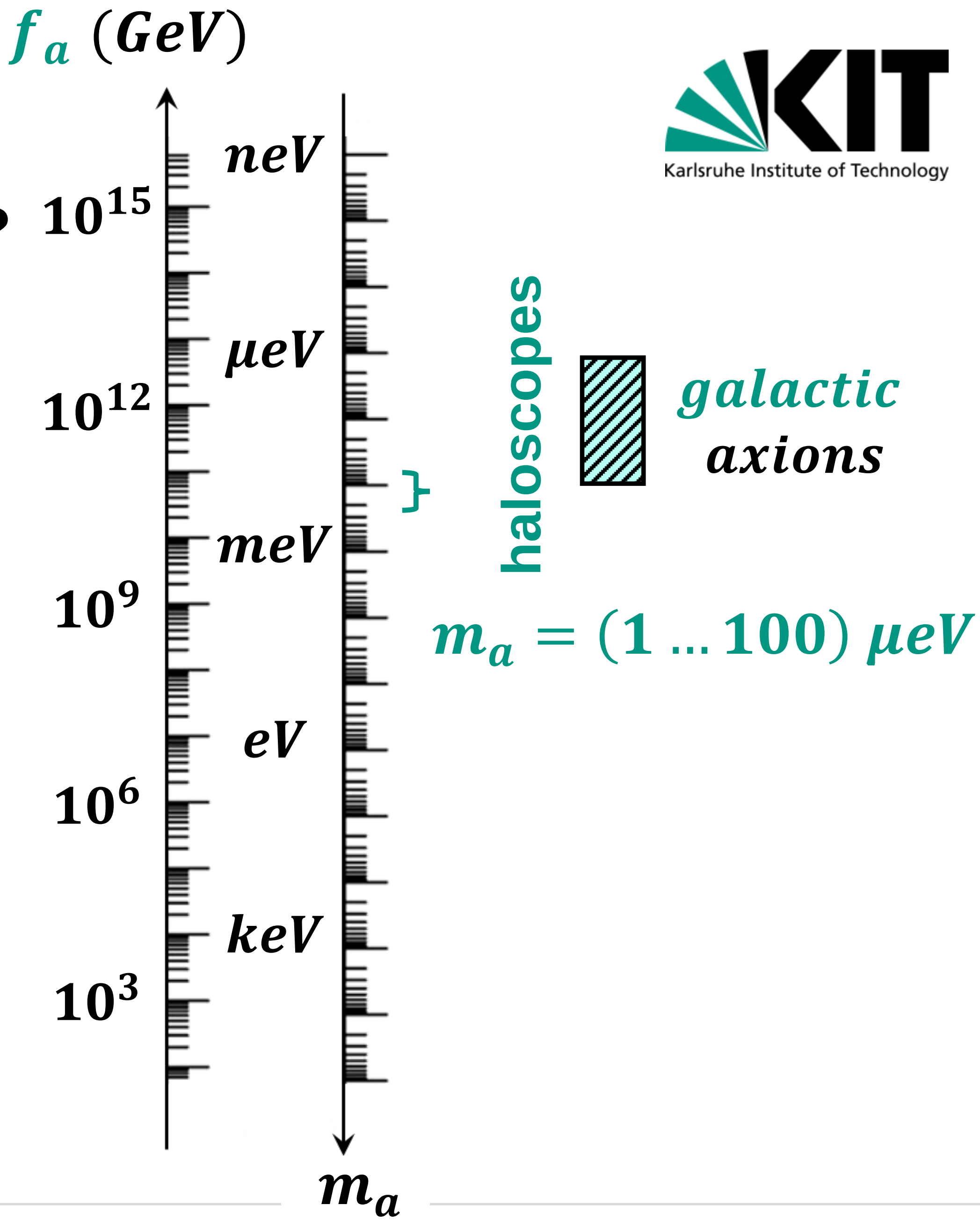
- let´s look into the **heart of the Sun** to see if ***axions*** are emitted there



Axions: *MW* – cavity searches

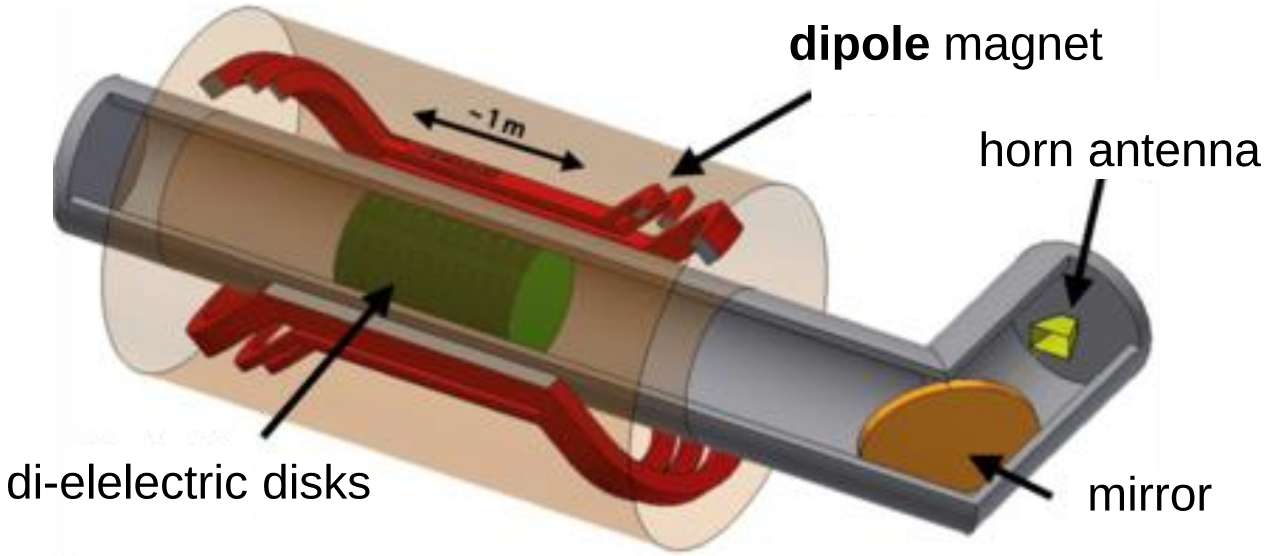
- **Haloscopes**: ***axions*** **from the *DM* – halo?**

- let´s look whether we can convert the galactic ***DM* – *axions*** into ***EM*** radiation in cavities



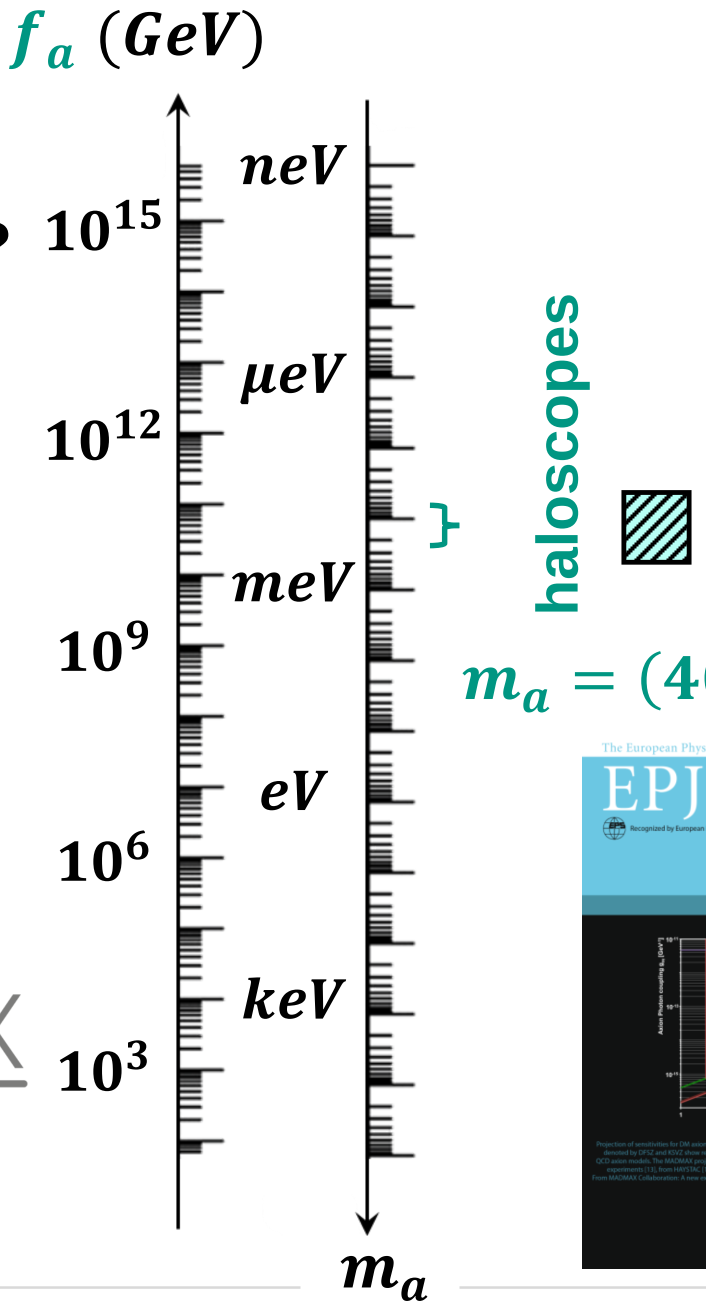
$Axions$: dielectric haloscopes

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



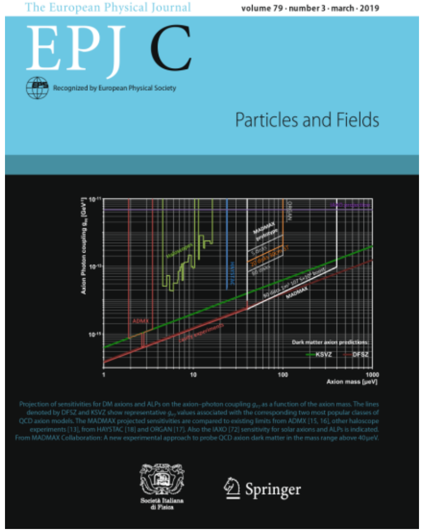
- let´s look whether we can convert the galactic $DM - axions$ via dielectric disks in a strong $B -$ field

MADMAX



$galactic$
$axions$

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

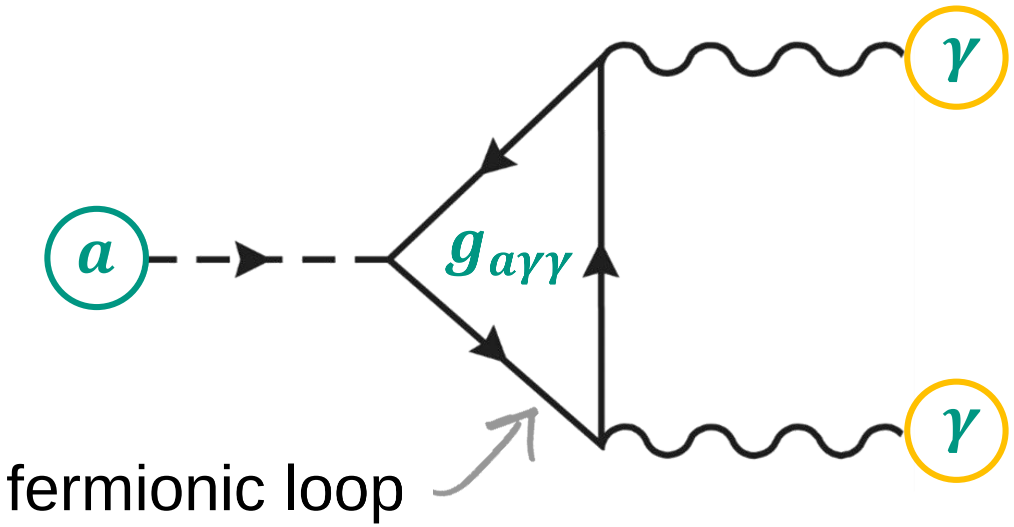


$Axions$ & their interactions: $Primakoff$ process

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

  - $axion\ a$ can couple to **2 photons** via a **fermionic loop**: $Primakoff$ **effect**

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



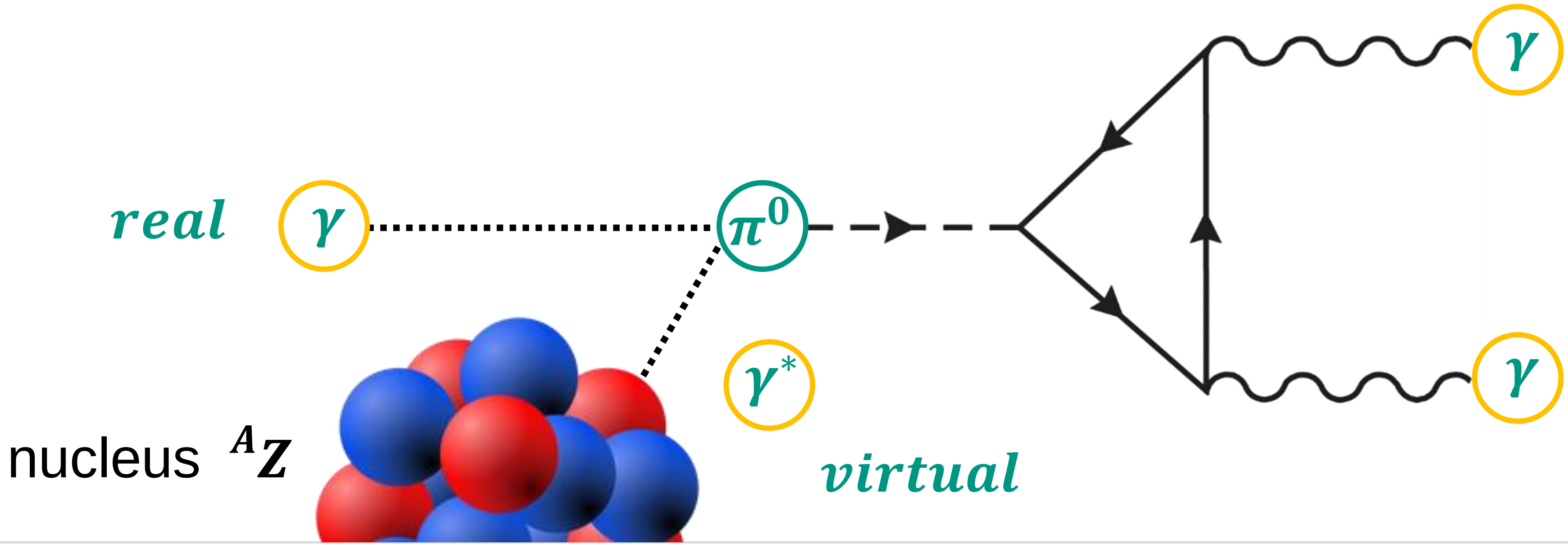
$Axions$ & their interactions: $Primakoff$ process

Karlsruhe Institute of Technology

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

  - neutral pion π^0 generated & decays to **2 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 **2 photons**



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

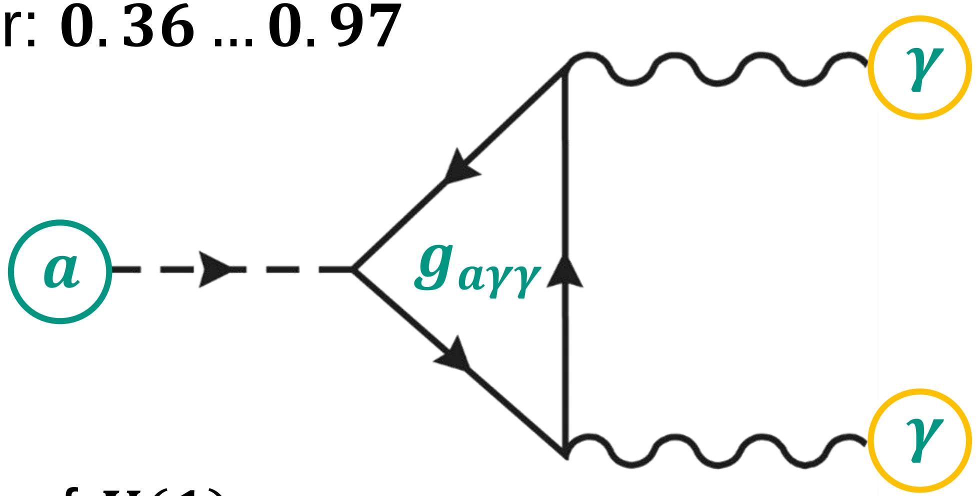
- **The $axion$ coupling to matter is exceedingly weak – be warned!**

  - **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: $\mathbf{0.36 \ldots 0.97}$

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



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

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

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

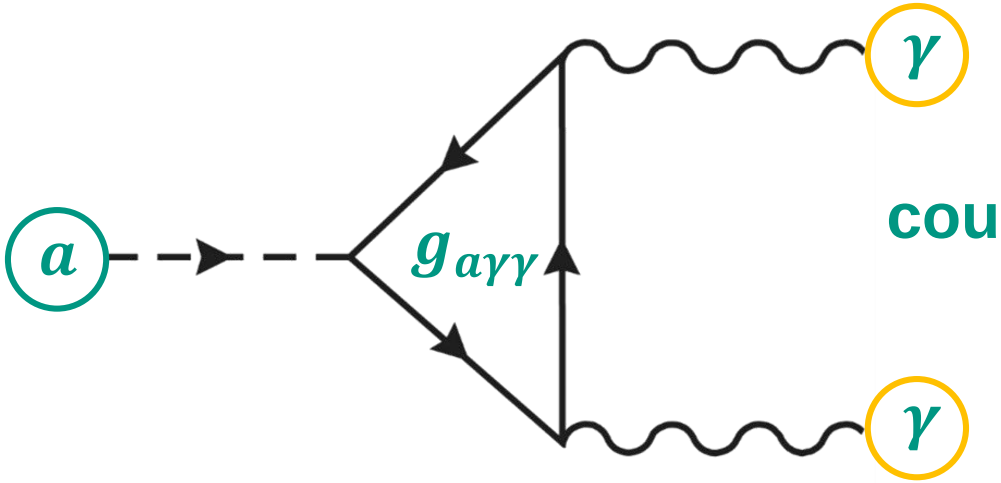
  - **coupling constant** $g_{a\gamma\gamma}$ is not known $a\ priori$, as it is related to the **(unknown) mass scale** m_a

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

Karlsruhe Institute of Technology

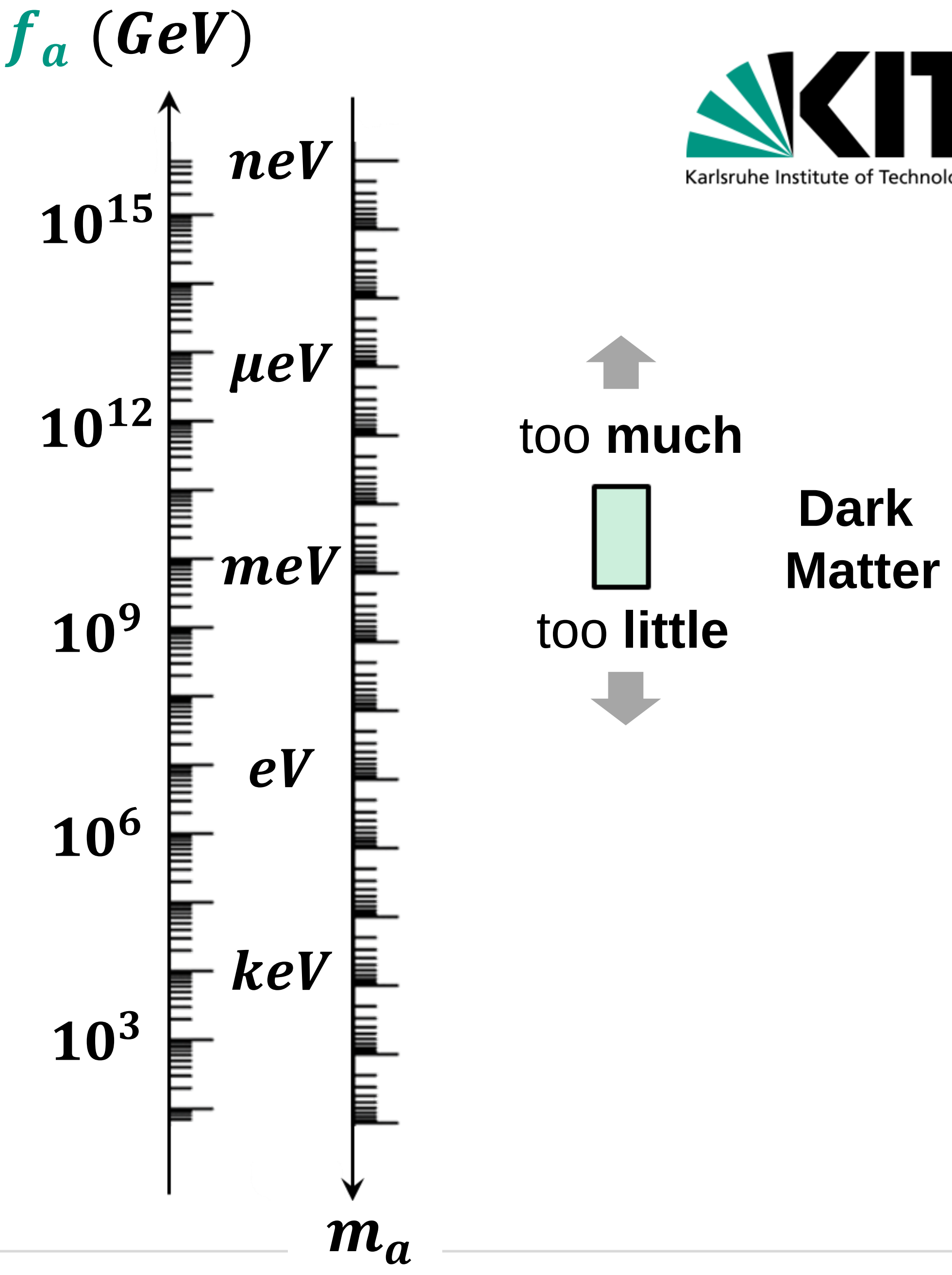
- **The *axion* coupling to matter**

  - 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!

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

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

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

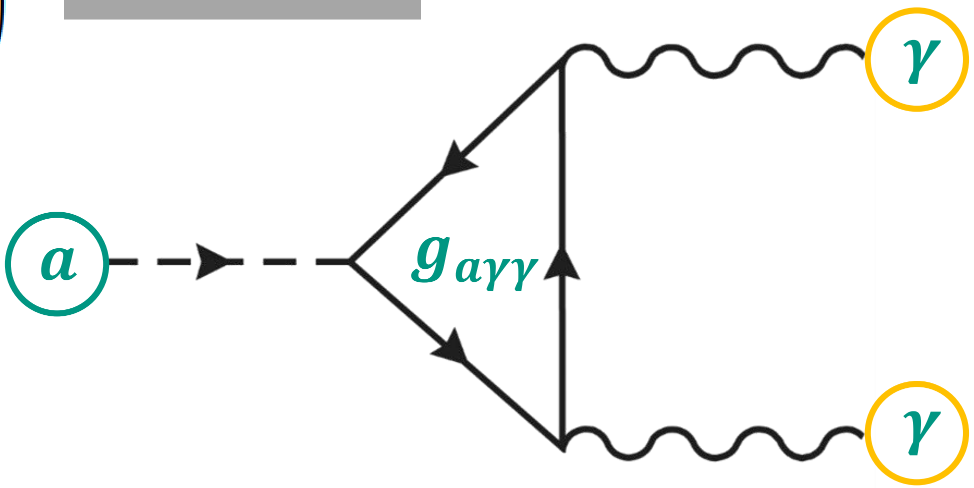
$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$$

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***

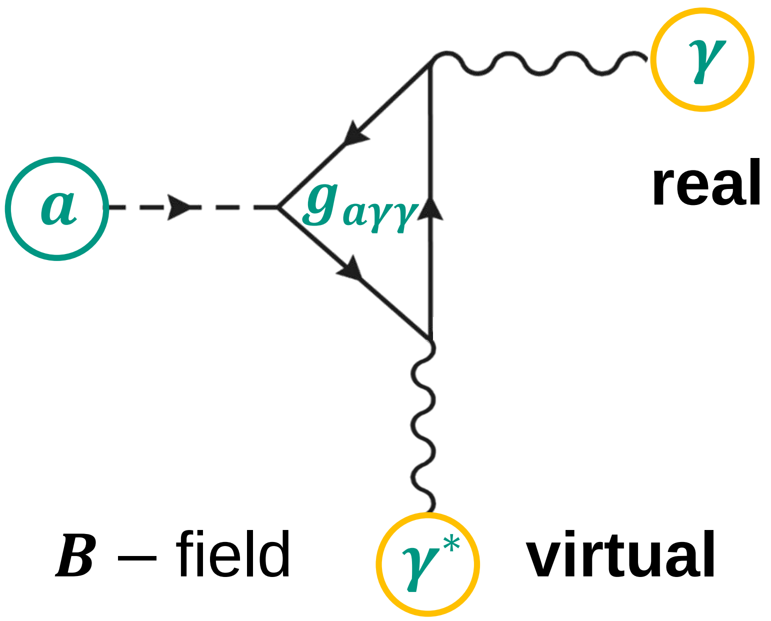
but ... ***my*** equations ...



$Axion$ 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** $photon\ \gamma^*$ to initiate the **conversion** of an $axion$ into a **real** $photon\ \gamma$



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

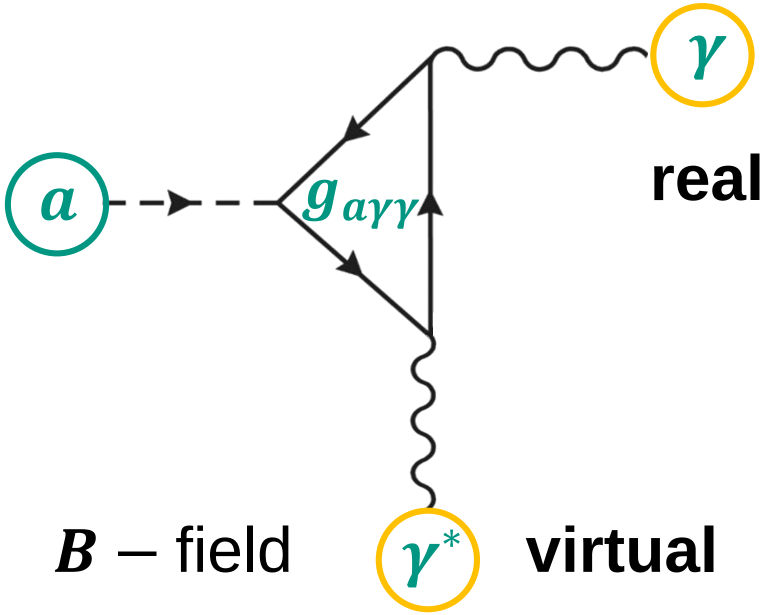
⇨ the external B –field has to be **transversal**, i.e. we need a typical magnetic **dipole** field

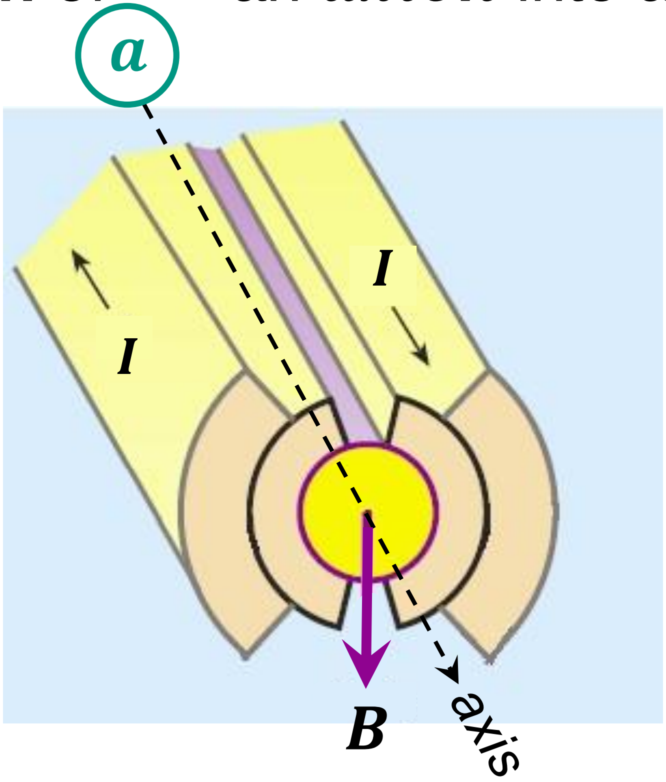
*experimentalists: always be *excited* if it´s coherent

$Axion$ 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

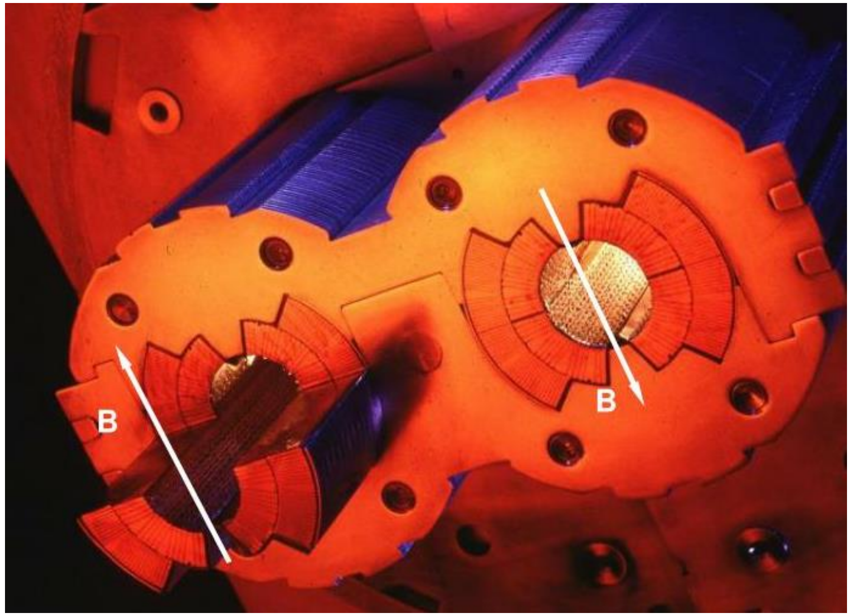
*experimentalists: we go to the limit before quench

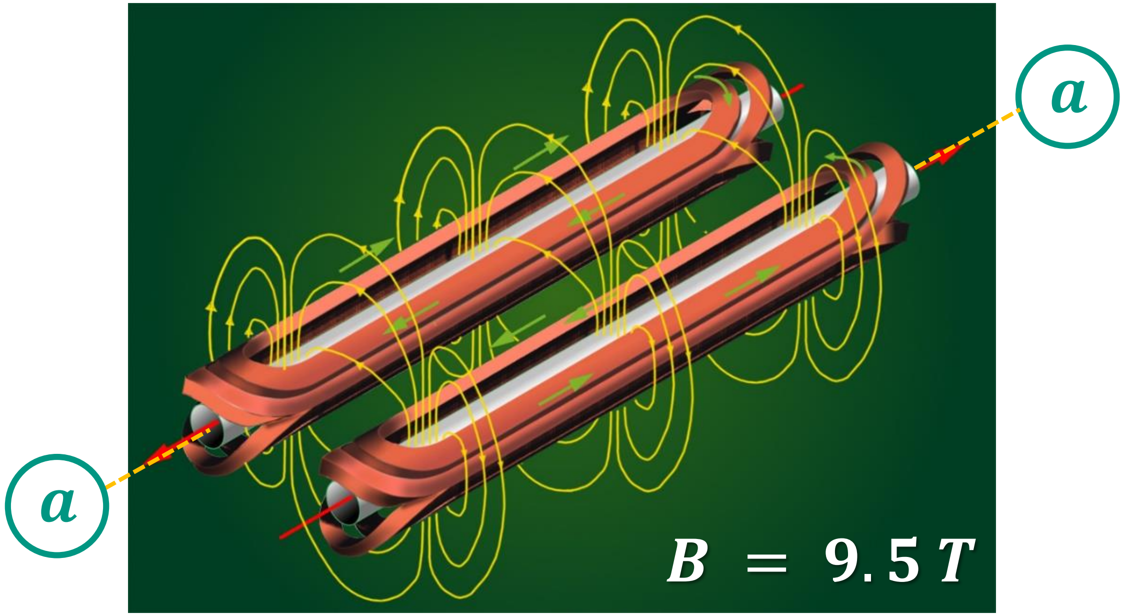
$Axion$ detection: making use of magnetic fields

- **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