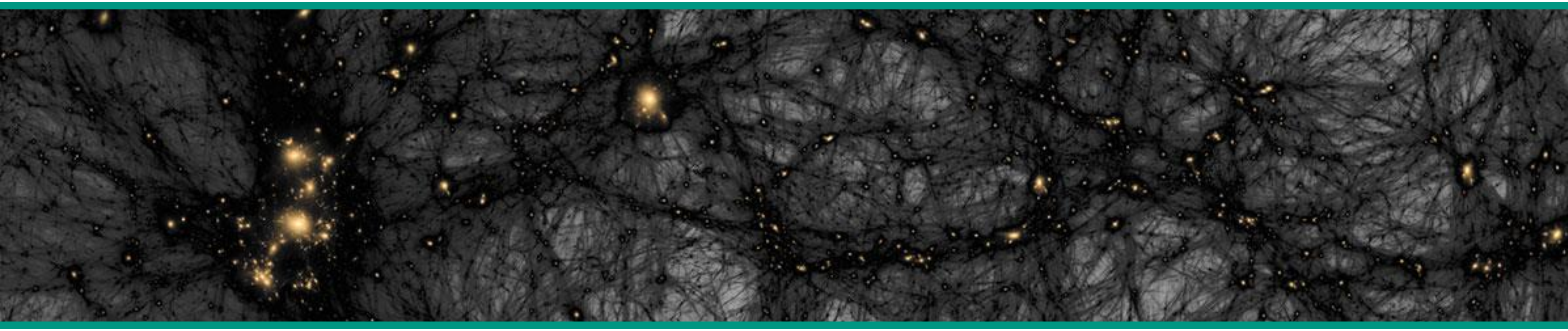
# Astroparticle physics I – Dark Matter

WS22/23 Lecture 22 Feb. 16, 2023



# Recap of Lecture 21

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- **Axion detection in haloscopes & helioscopes**

  - **detection**: based on **Primakoff effect** using virtual photons in strong $\boldsymbol{B}$ – field

  - **axion plot**: limits & expectations for **axion mass $\boldsymbol{m_a}$** & **coupling $\boldsymbol{g_{a\gamma\gamma}}$**

  - **$\boldsymbol{QCD}$ – axions**: allowed band ($KSVZ$ & $DFSZ$) & astrophysical limits

  - **axion searches**: 3 methods – haloscopes – helioscopes & $LSW$ experiments

  - **haloscopes**: $\boldsymbol{DM}$-´radio´ in resonance cavity surrounded by $\boldsymbol{B}$ –field ($\boldsymbol{ADMX}$)

  - **helioscopes**: convert $\boldsymbol{keV}$ –scale solar axions to $\boldsymbol{X}$ –rays in dipole ($\boldsymbol{CAST}$,…)

# Axion experiments: *L*ight-*S*hining-through-*W*alls*

■ **Converting a photon to an axion & back again**

- applying the **Primakoff effect** twice
  to transmit light through a wall

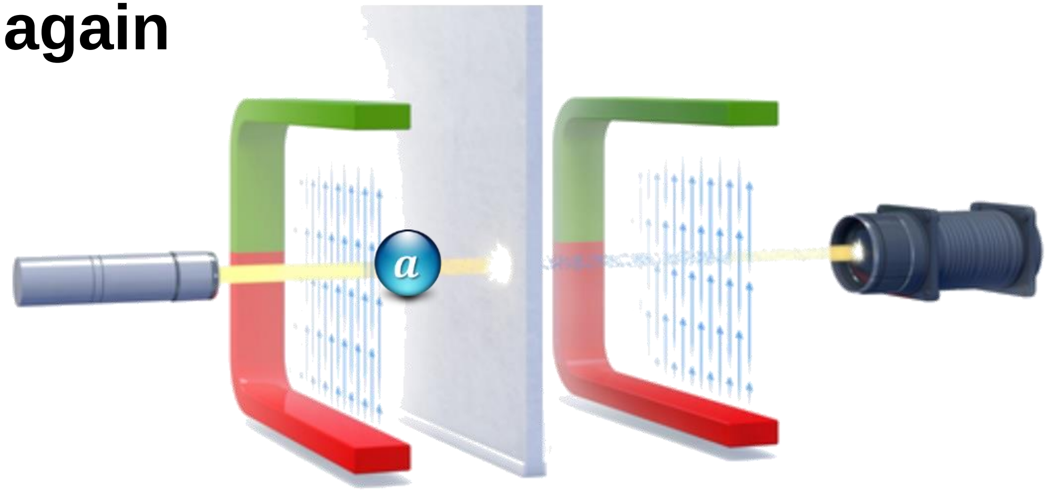
  laser light passes transversal $\boldsymbol{B}$ – field

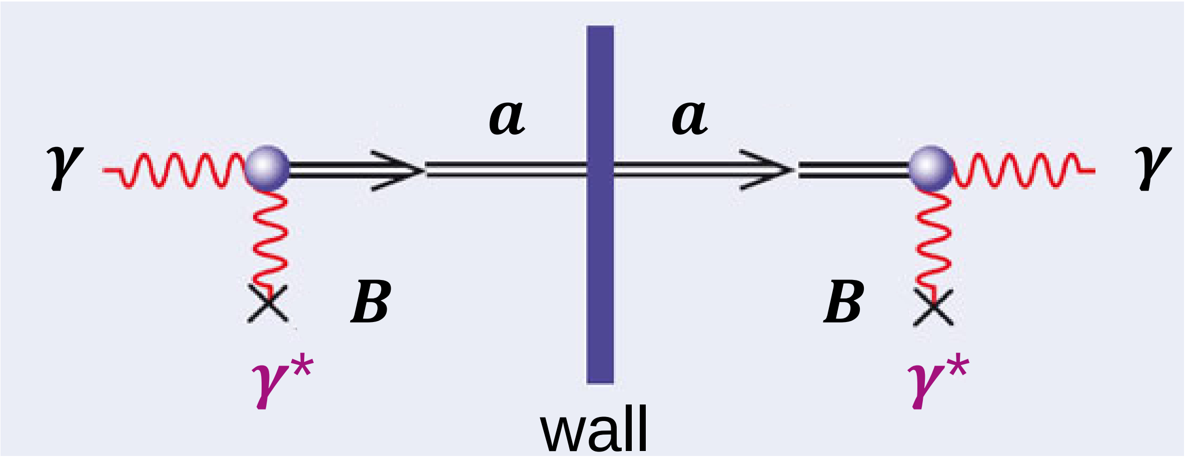
  conversion into $\boldsymbol{ALP}$s / axions

  $\boldsymbol{ALP}$s / axions pass the wall

  identical $\boldsymbol{B}$ –field: back-conversion

- disadvantage: second order weak effect



# RECAP: Light Shining through the Universe

- **Surprisingly large range of $TeV-$ gammas: conversion to axions/$ALPs$?**

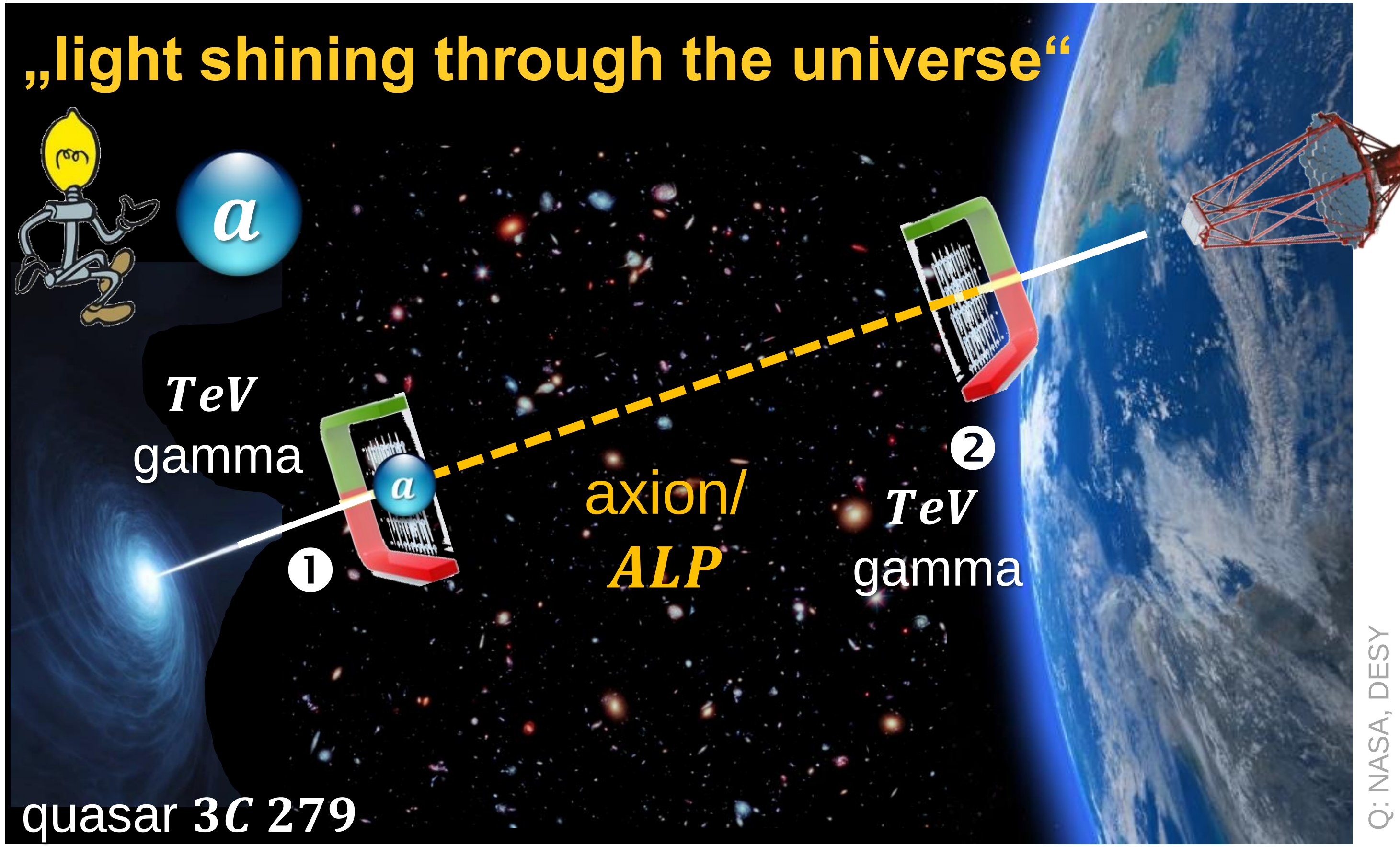
- key observation* of $TeV-$ gamma astronomy:

- we detect $TeV-\gamma$´s from great distances $d$ despite limited range of $\gamma$´s due to $IR$ –light

- hypothesis:

❶ $TeV-\gamma$ converts close to its source to an axion / $ALP$

❷ galactic $B$ –field: axion / $ALP$ converts back to $TeV-\gamma$




Q: NASA, DESY

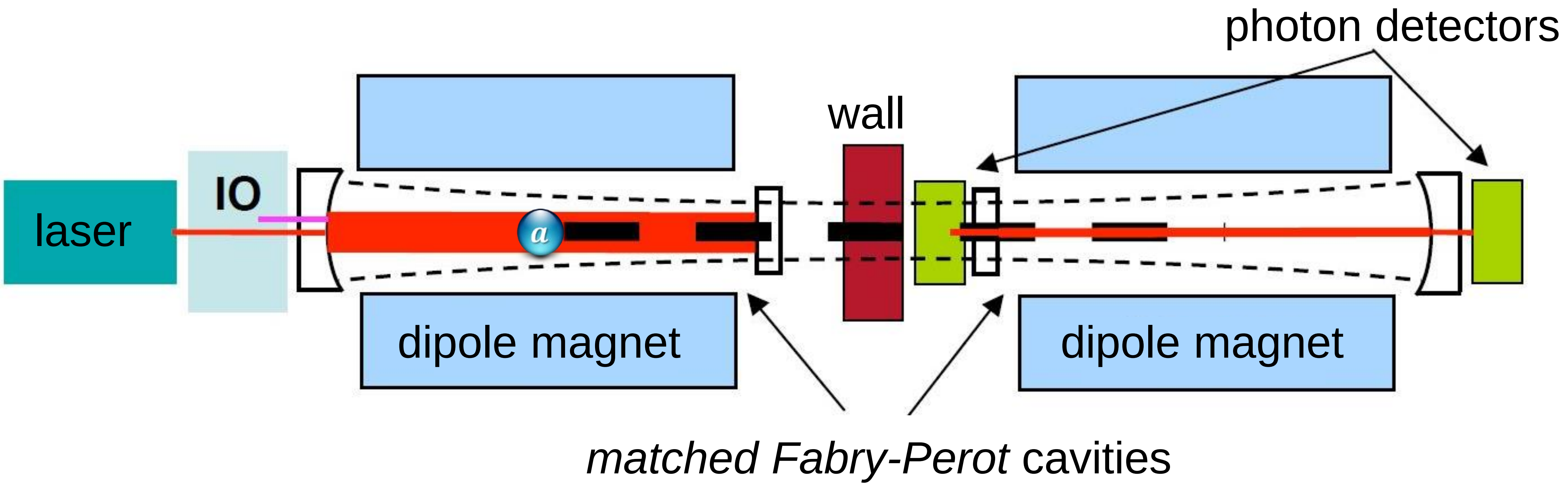
*see lecture #2 p. 38-41

# Axion experiments: *Light-Shining-through-Walls*

- **Converting a photon to an axion & back again: Primakoff effect $2^{nd}$ order**

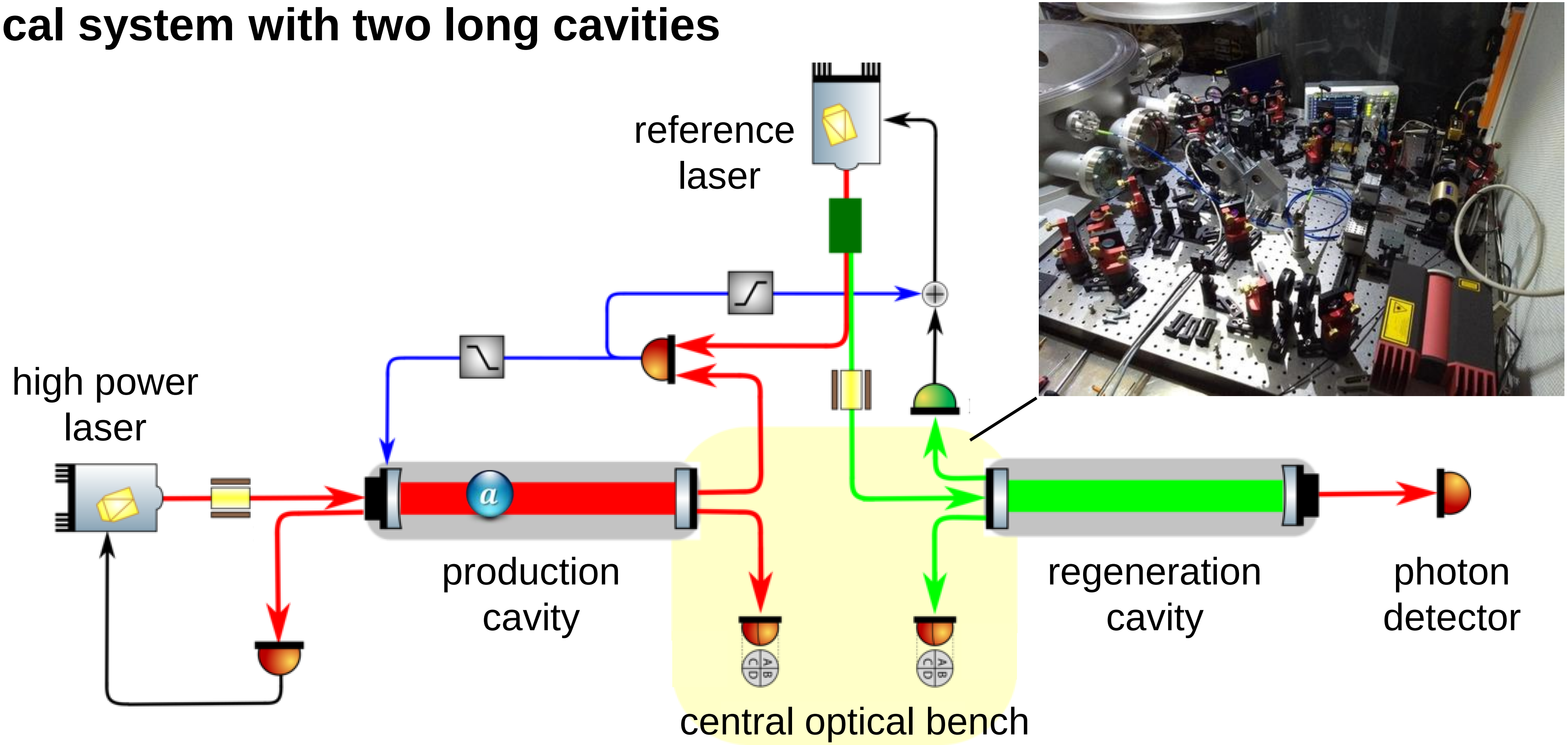
  - optical cavities (***Fabry-Perot***) enhance light intensity by huge factor

  - cavities surrounded by dipole magnets: **laser light** → axion /*ALP* → **photon**



# $LSW$ experiments: $ALPS-II$

- **Optical system with two long cavities**



# $LSW$ experiments: $ALPS-II$

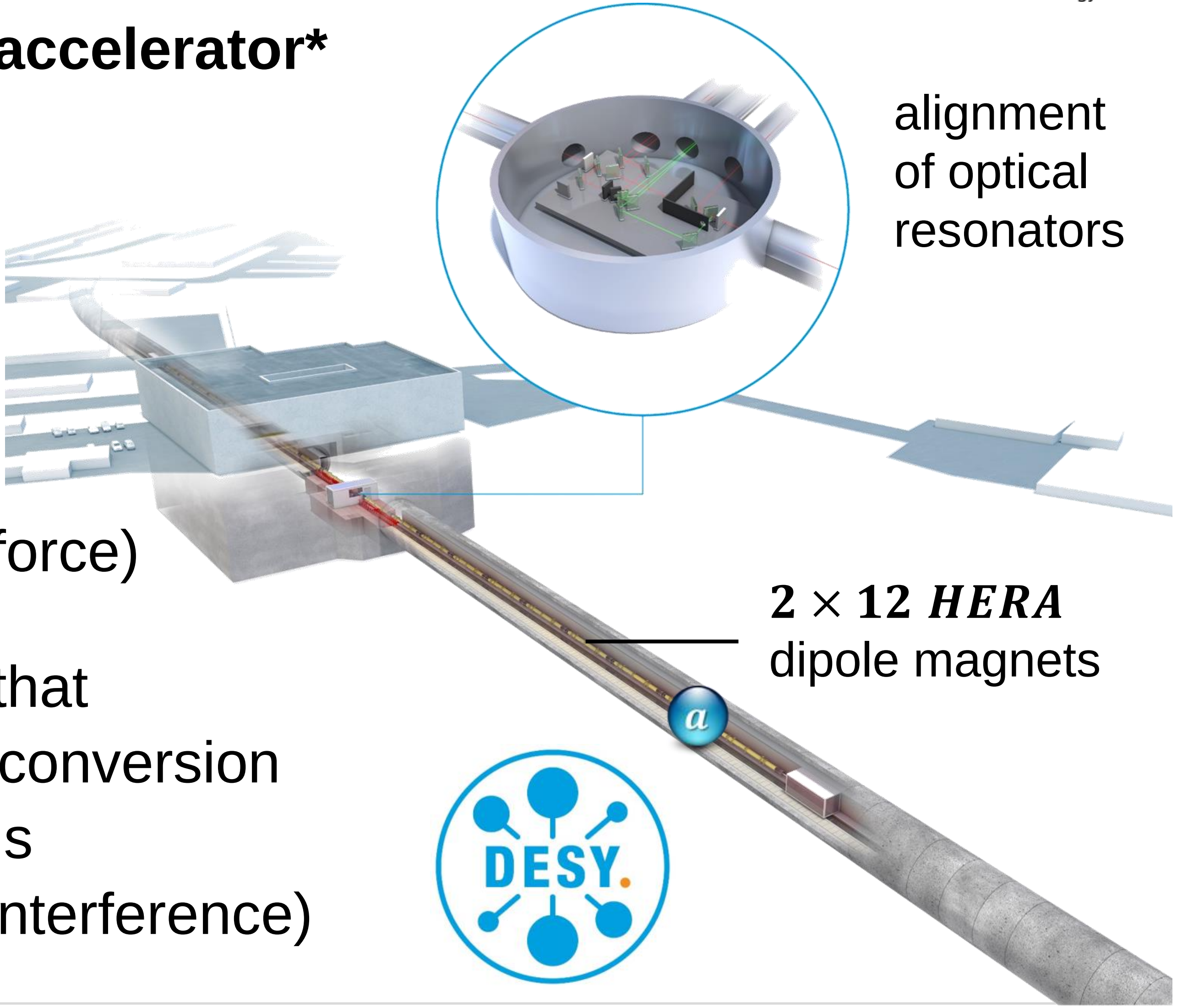
- **Using existing dipoles from $HERA$ accelerator***

  - laser ($\lambda = 1064\ nm$) power in *FP*-cavity: $P = 150\ kW$

  - length of optical cavity: $2 \times 124\ m$

  - magnets: $2 \times 12$ dipoles ($2 \times 106\ m$) with $B\ =$ with $5.3\ T$ (straigthened by force)

  - detect very small number of photons that have coupled into other cavity due to conversion & back-conversion via special $SQUID$s (Fabry-Perot operated at destructive interference)




*$H$adron $E$lektron $R$ing $A$nlage

# $LSW$ experiments: $ALPS - II$

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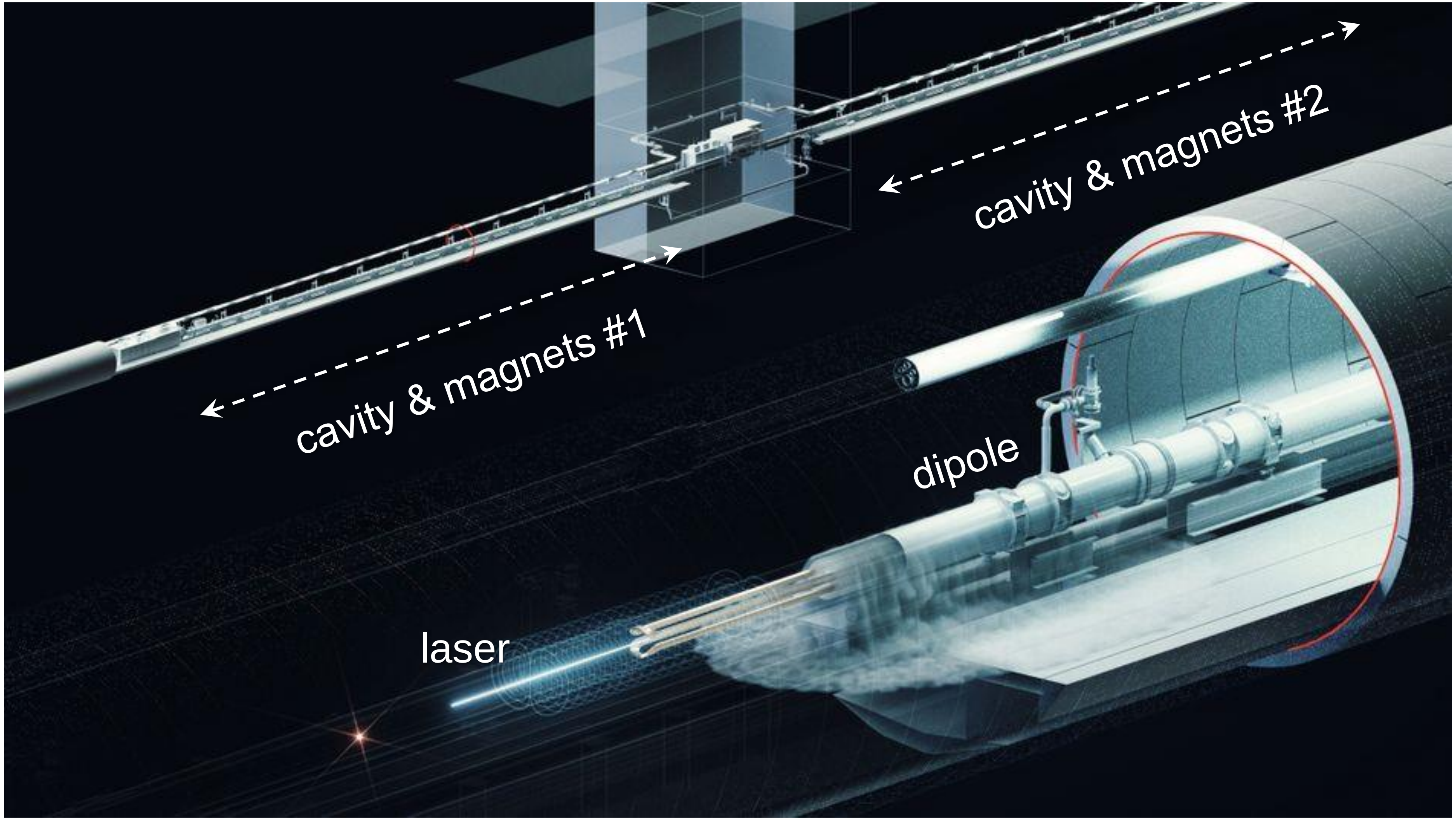
- **Status @ $DESY$**

- magnets are all powered up

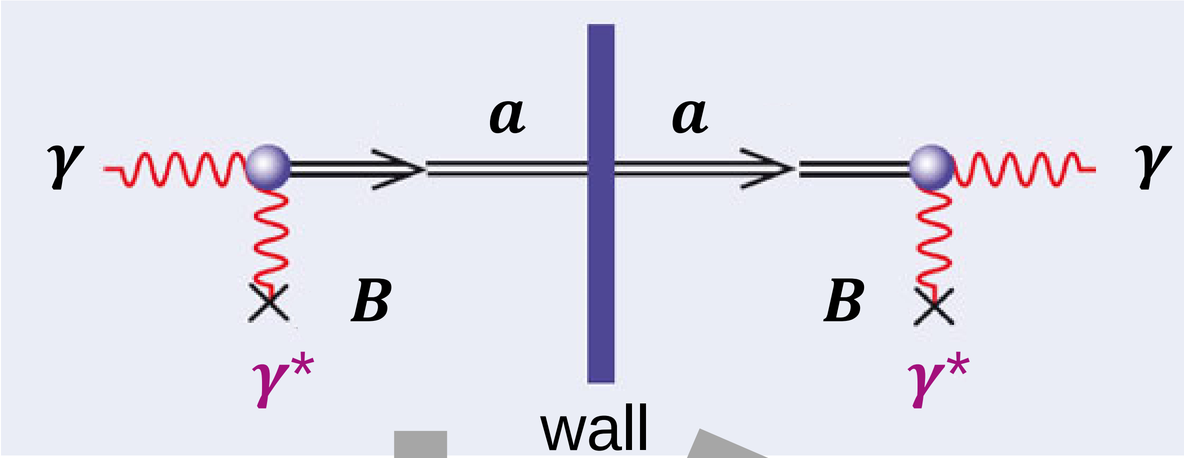
- optical cavities store laser light for $t = 6.75\, ms$ (world-record!)

ALPS



# $LSW$ experiments: $ALPS - II$

- **Impressions during installation phase**



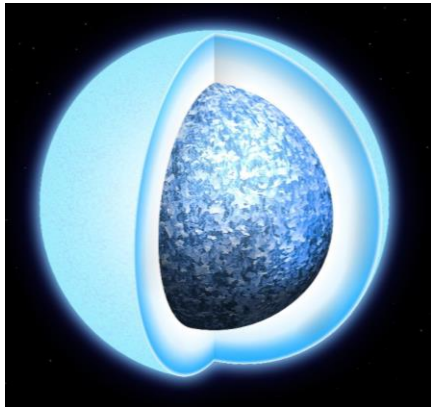

# $LSW$ experiments: $ALPS - II$

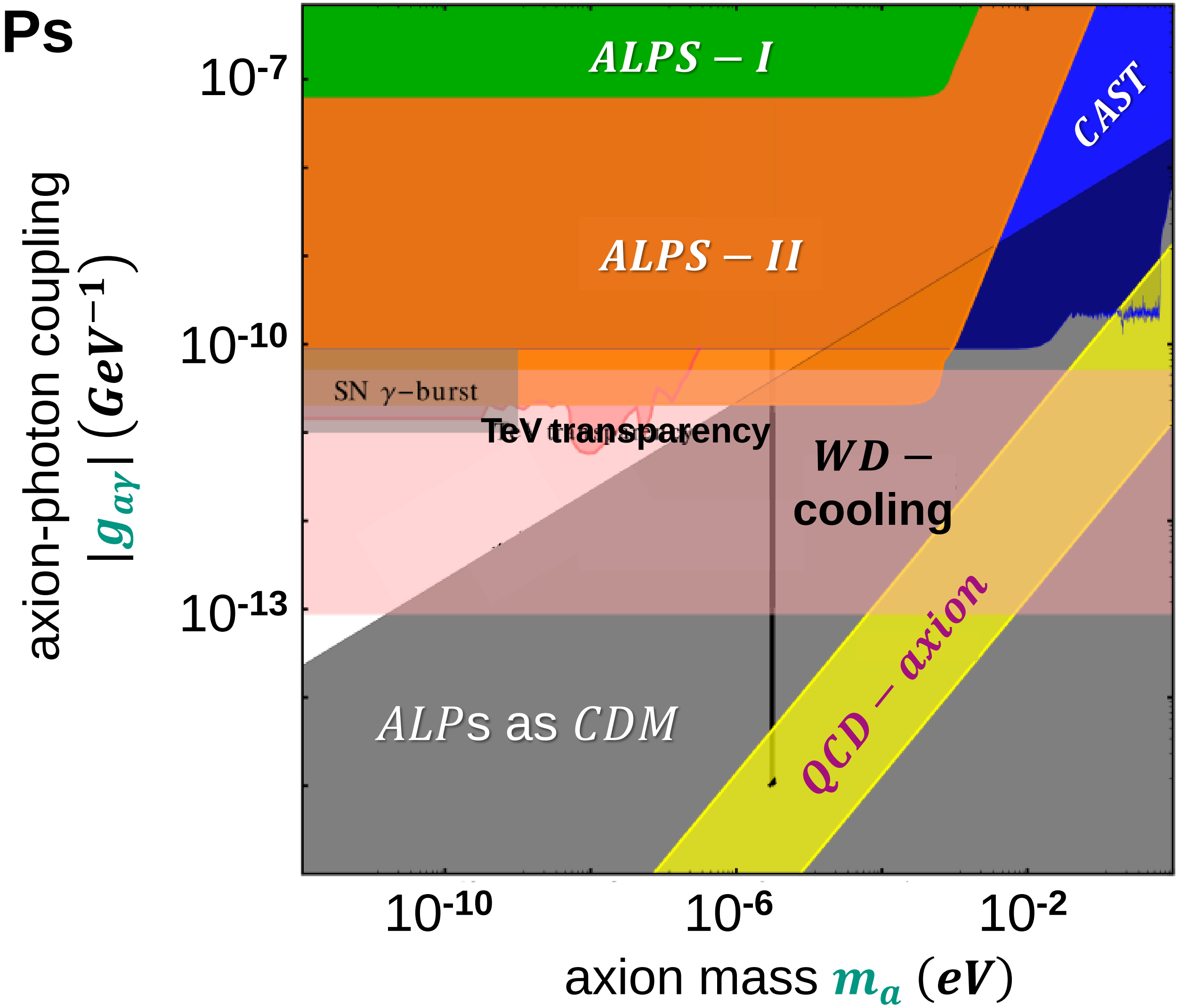
- **Expected sensitivity for axions / ALPs**

  - only sensitive to $ALP$s with mass $m_a < meV$ – scale & large coupling $g_{a\gamma\gamma}$

  - not sensitive to parameter region of $QCD$ – axions

  - **astrophysical limits** from cooling times of White Dwarfs

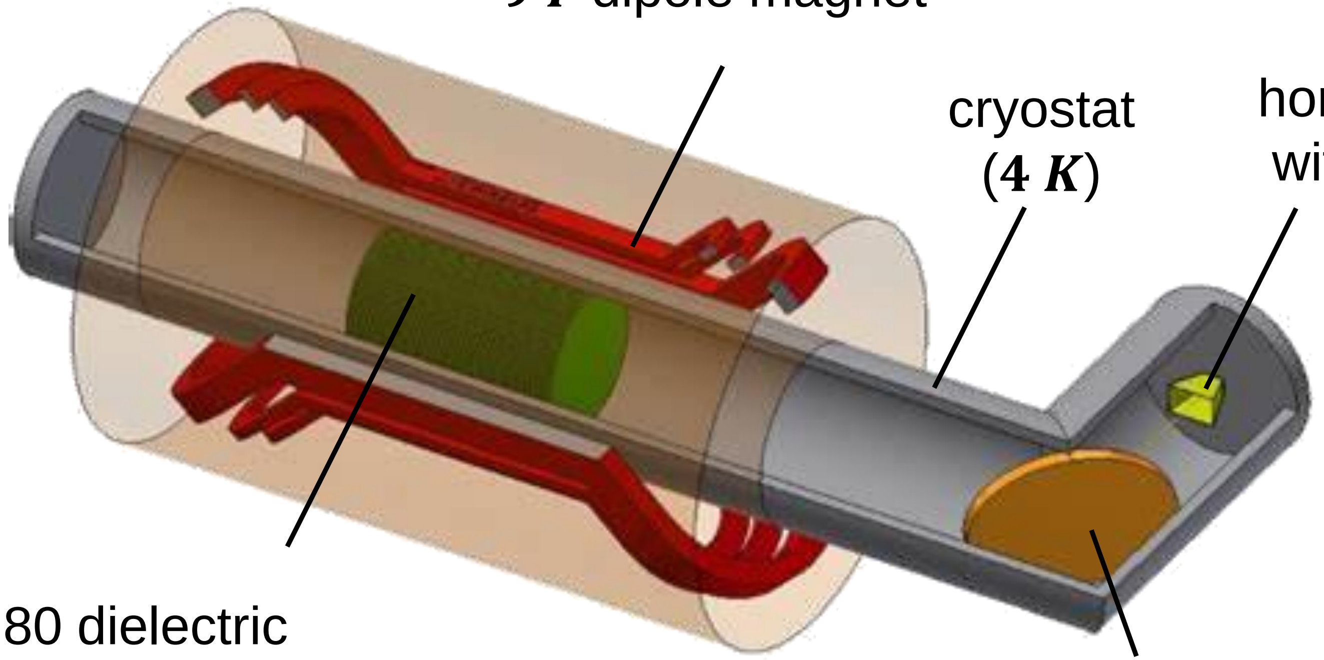




# Dielectric haloscopes: enter $\boldsymbol{MADMAX}$*

- **Central element: large dielectric plates in $\boldsymbol{B}$ – field**

  - searching for $\boldsymbol{CDM}$ – axions with mass $\boldsymbol{m_a \approx 100\ \mu eV}$







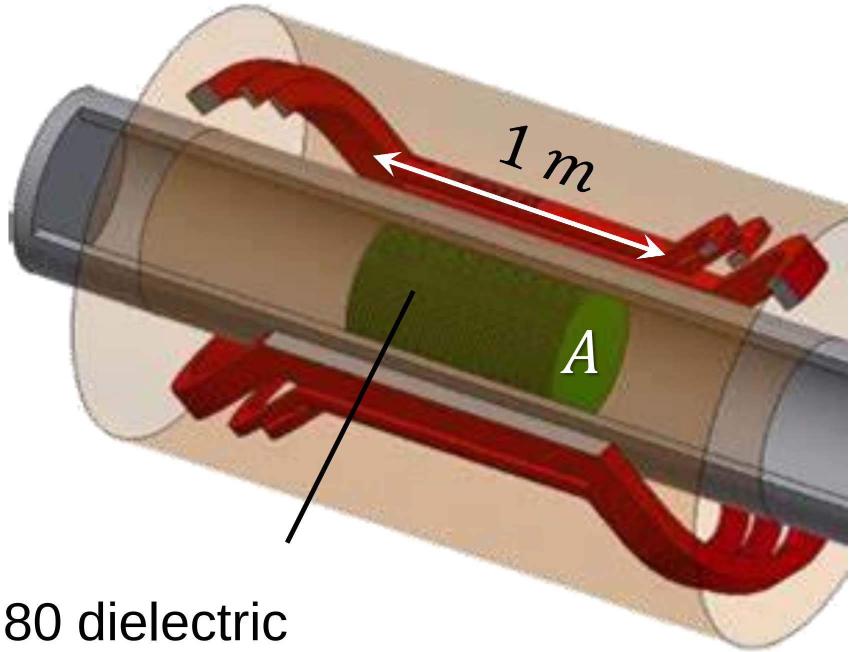
*$\boldsymbol{MA}$gnetized $\boldsymbol{D}$isc and $\boldsymbol{M}$irror $\boldsymbol{A}$xion E$\boldsymbol{X}$periment

# Dielectric haloscopes: disks of $MADMAX$

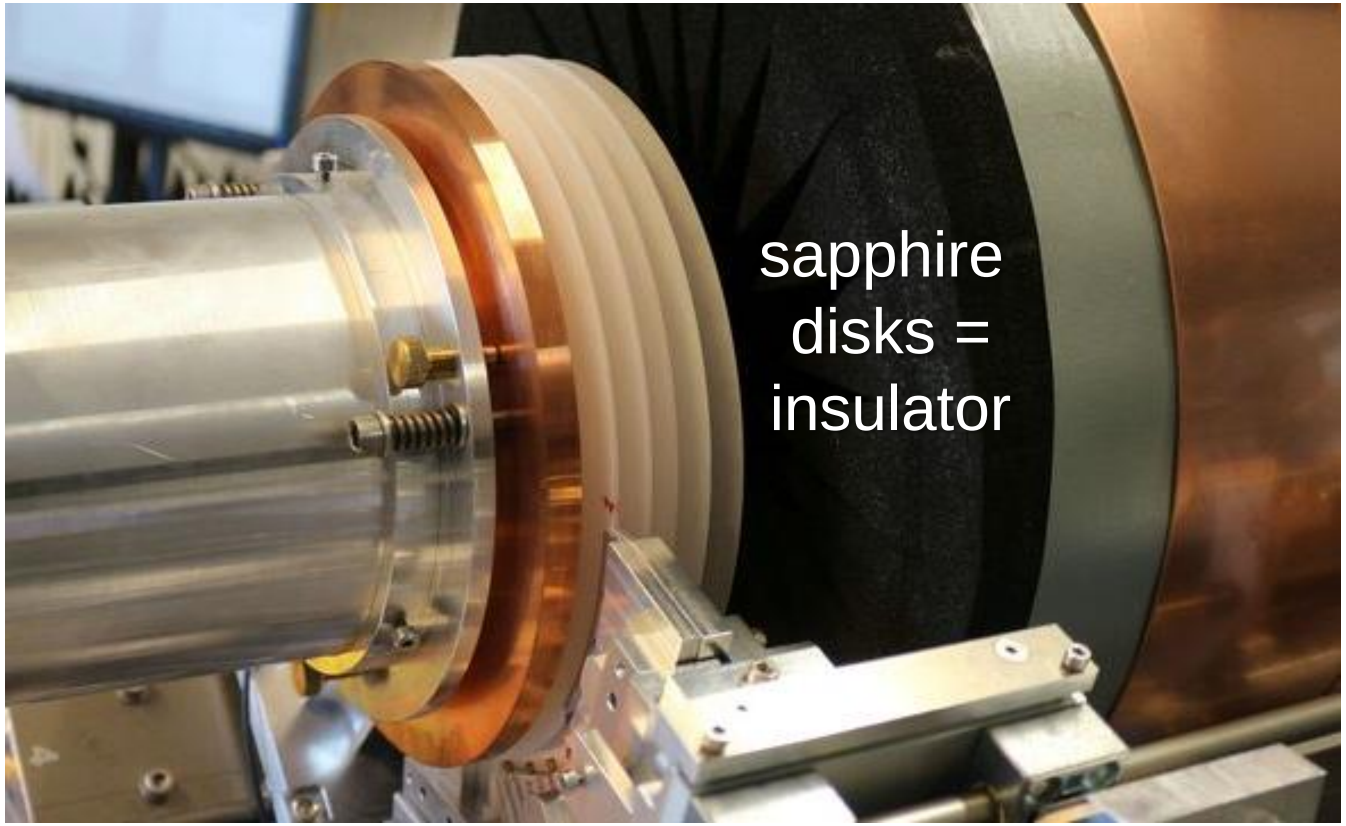
- **Central element: large dielectric sapphire disks in $B$ – field**

  - axion sensitivity scales as $\sim B^2 \cdot A$ + coherence boost from many disks

  goal: $B^2 \cdot A = 100\ T^2 m^2$




80 dielectric
plates ($\varnothing = 1.25\ m$)



# Dielectric haloscopes: principle of *MADMAX*

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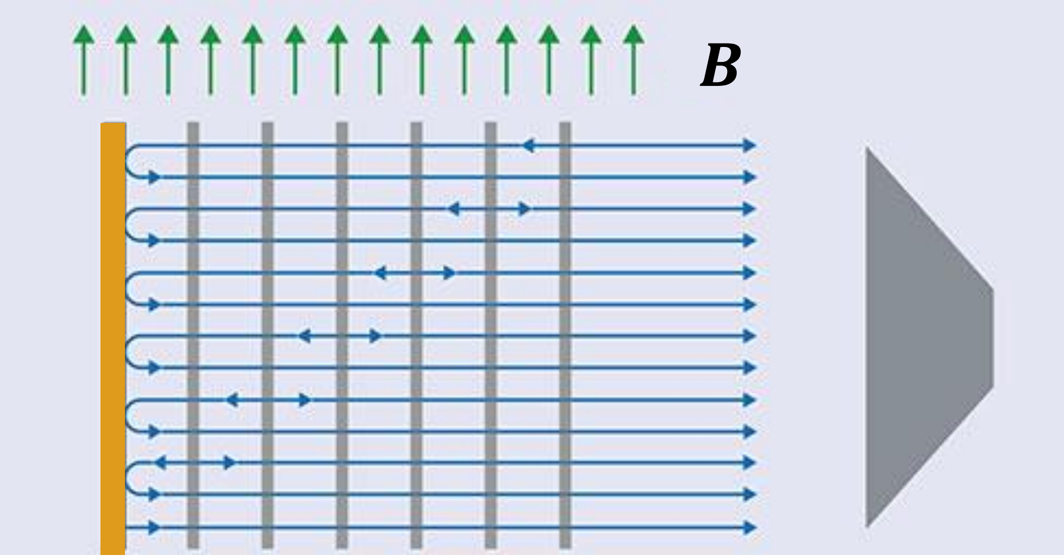
- **Axion field induces electromagnetic field at surfaces of dielectric plates**

  - **surface of one dielectric plate**: discontinuity of axion-induced electromagnetic oscillations (⇨ emission of radio waves)

  - many dielectric plates: ⇨ **coherent emission** (constructive interference)




mirror dielectric plates receiver

- expected axion signal power:
  1 plate with $\boldsymbol{A = 1\,m^2}$ in $\boldsymbol{B = 10\,T}$
  ⇨ $\boldsymbol{P = 10^{-27}\,W}$ (too small…)

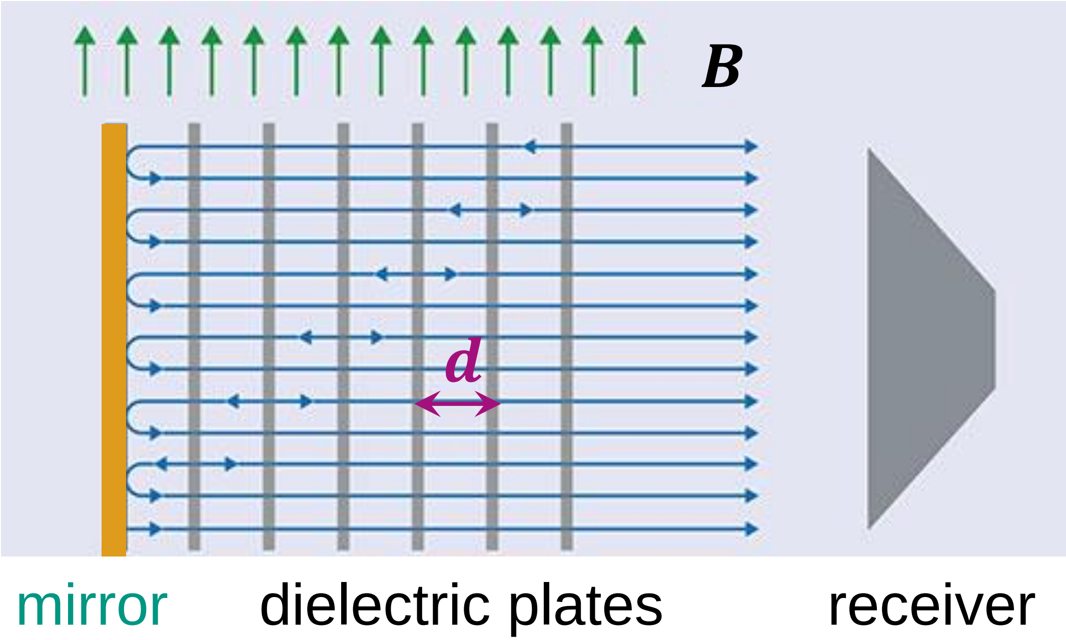
- solution:
  large number of dielectrics & 1 mirror
  ⇨ **coherence boosts signal by** $> \mathbf{10^4}$

# Dielectric haloscopes: principle of $MADMAX$

- **Axion field induces electromagnetic field at surfaces of dielectric plates**

  - constructive interference of emitted radio waves: requires **extremely precise positioning** (**$\mu m$ – scale!**) of large, heavy dielectric plates in strong $B$ – field!

  - variation of **distance $d$** between plates allows to scan **axion mass range $m_a$**



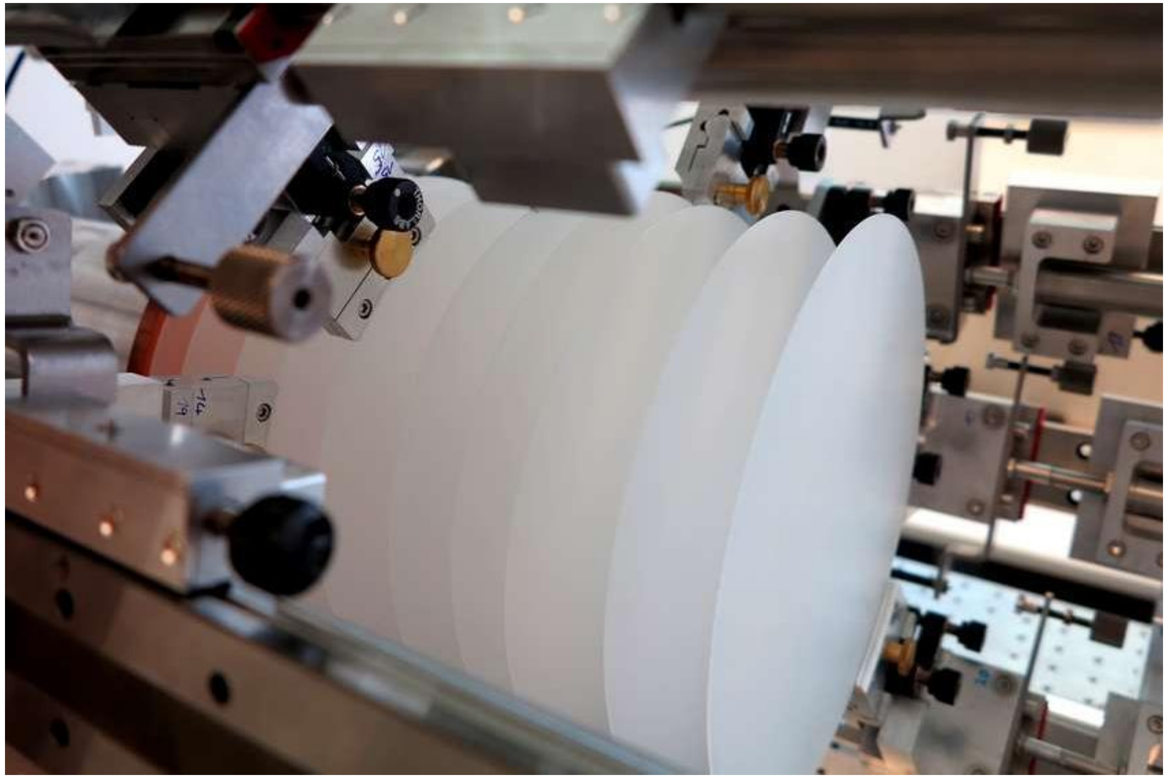

- dielectric plates made of lanthanum aluminate $LaAlO_3$ with $\epsilon_r = 24$
  ⇨ generation of **radio waves**

- boosting of signal power: many resonant transitions of $\epsilon_r$ at surfaces
  ⇨ reasonable band-width in axion scans

# Dielectric haloscopes: testing of $MADMAX$

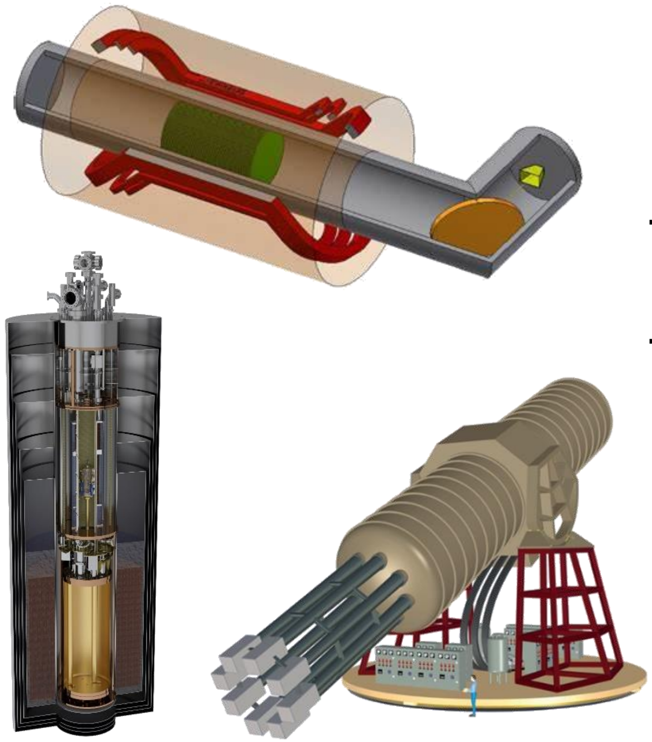
- **2022: testing the positioning accuracy in a strong magnetic field**

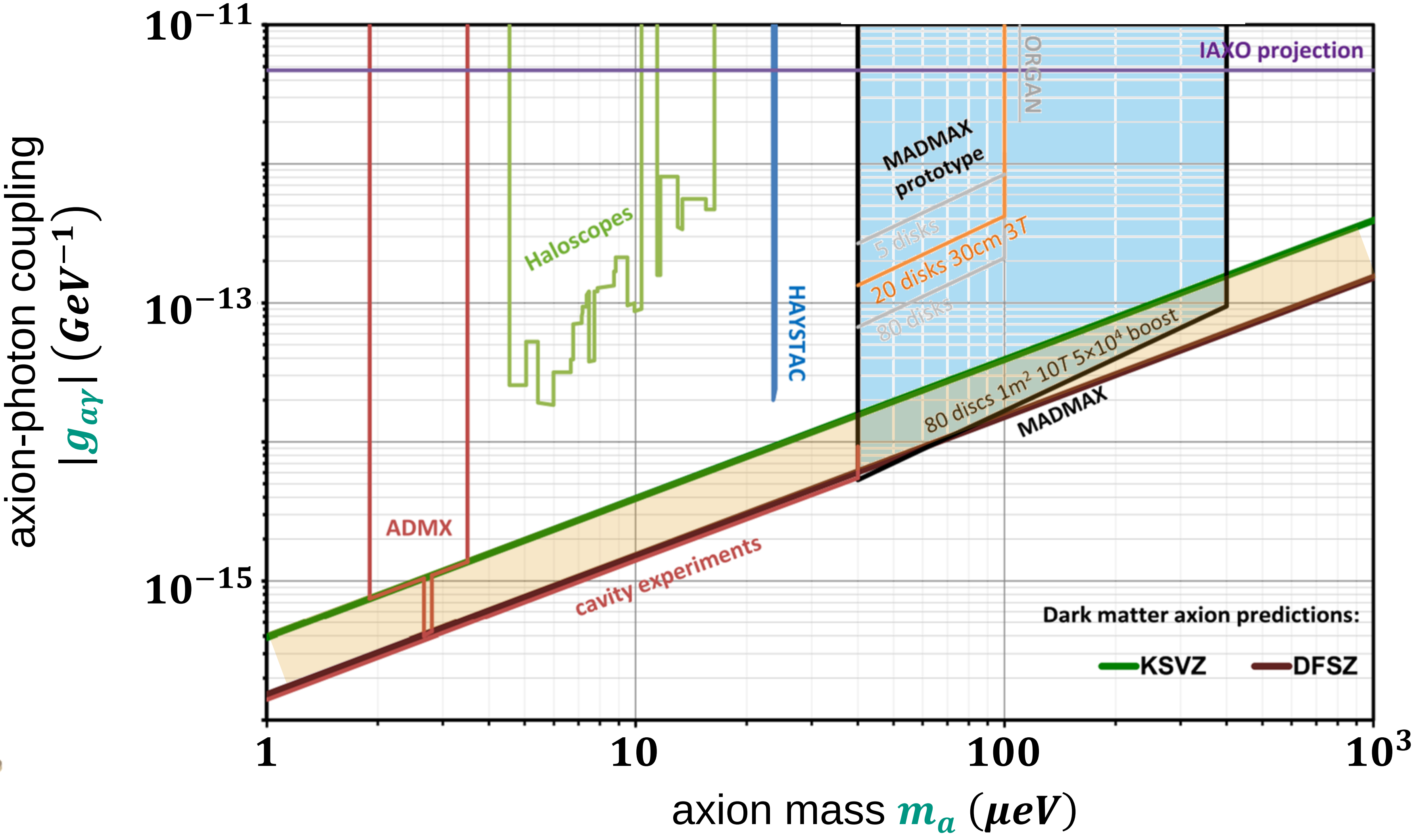
  - set-up tested at the $\mathbf{40}\ \boldsymbol{yr}$ – old ´Morpurgo´ magnet ($\boldsymbol{B} = \mathbf{1.6}\ \boldsymbol{T}$) at $\boldsymbol{CERN}$



# Dielectric haloscopes: sensitivity of $MADMAX$

- Dielectric haloscopes & others





# 4.6.2 $keV$ – neutrinos

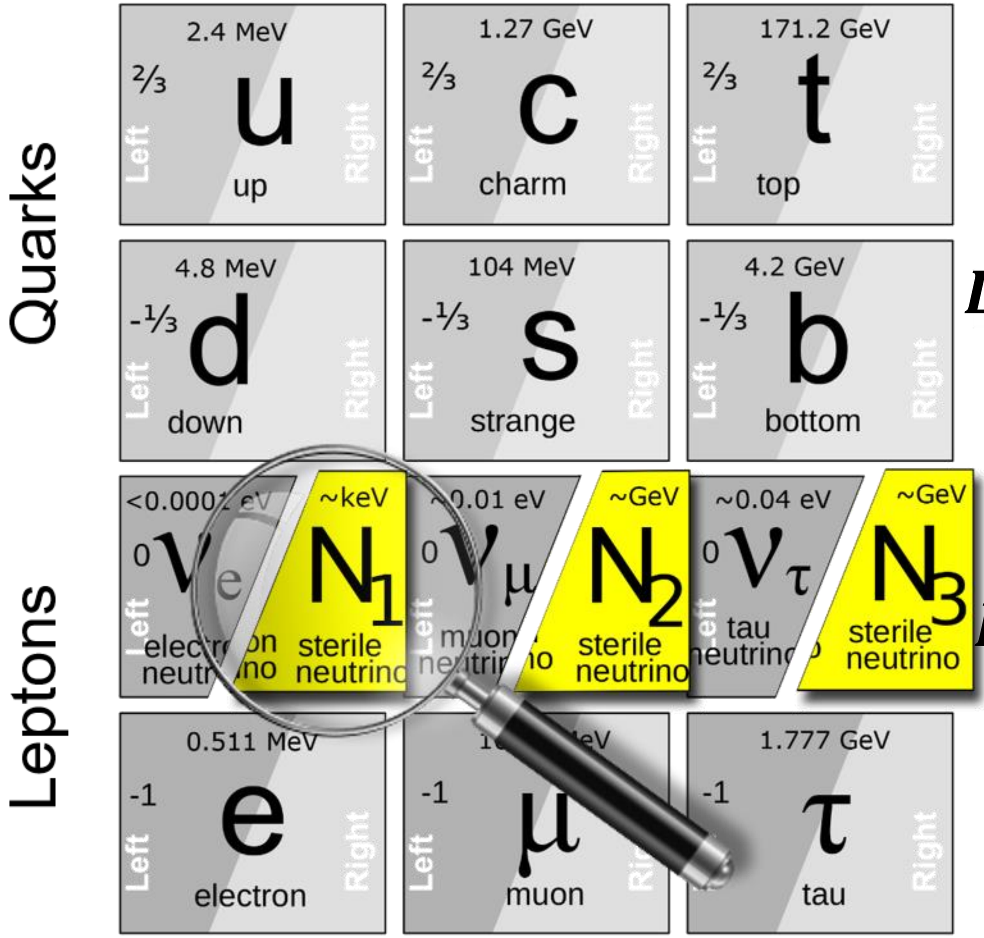
- **Sterile neutrinos as $WDM$**

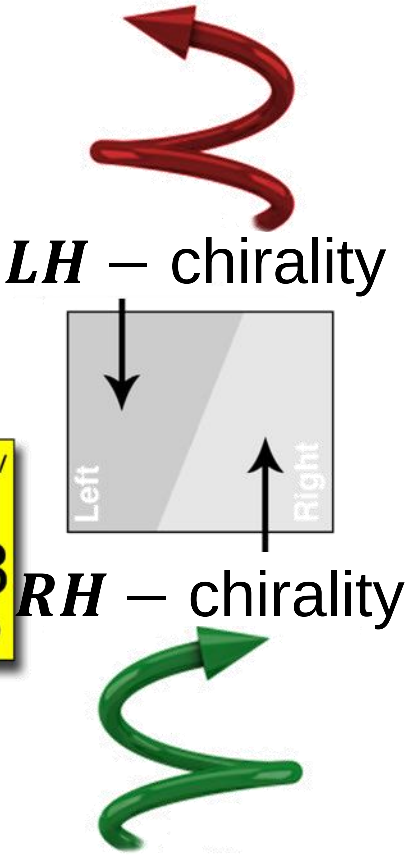
  - minimum extension of the Standard Model: $\nu MSM$

  - only added: sterile neutrinos as $RH$ – counterparts of active neutrinos
    ⇨ 3 new neutral fermions

  - 1 light state: $N_1 \sim keV$ – scale
    2 quasi-degenerate heavy states $N_{2,3} \sim GeV$ – scale

nuMSM - model



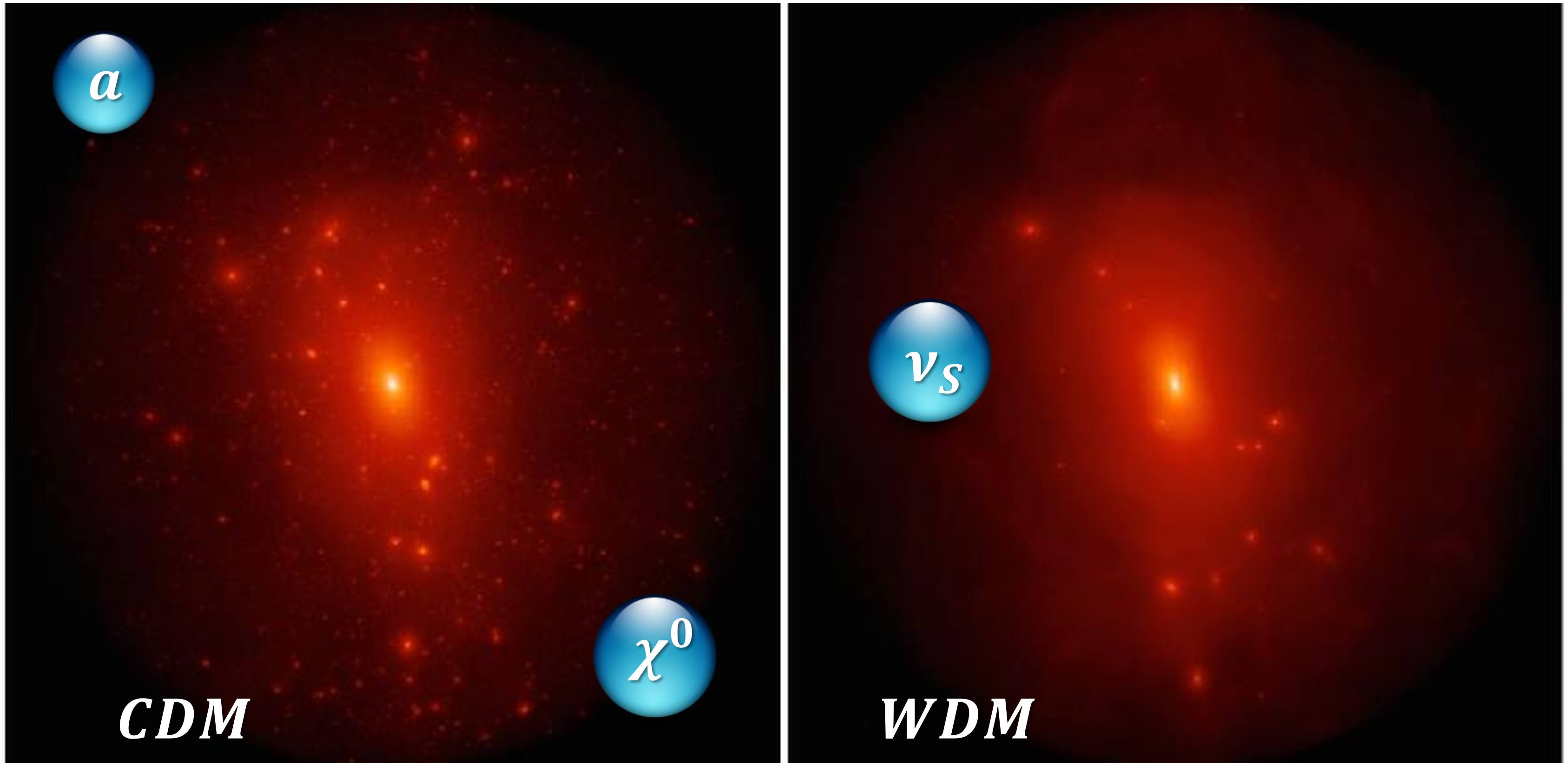
# $keV$ – steriles act as $W$arm $D$ark $M$atter ($WDM$)

- **$keV$ – steriles as $WDM$ could solve the problem of missing dwarf galaxies**

- a persistent problem in cosmology: we see **less dwarf galaxies than predicted**

- sterile neutrinos act as $WDM$ **–** neither $HDM$ nor $CDM$

**-** $WDM$ solves many issues related to dwarf galaxies, both locally (Milky Way, Andromeda) & beyond



# $keV$ – steriles: a signal observed in $X$ – rays?

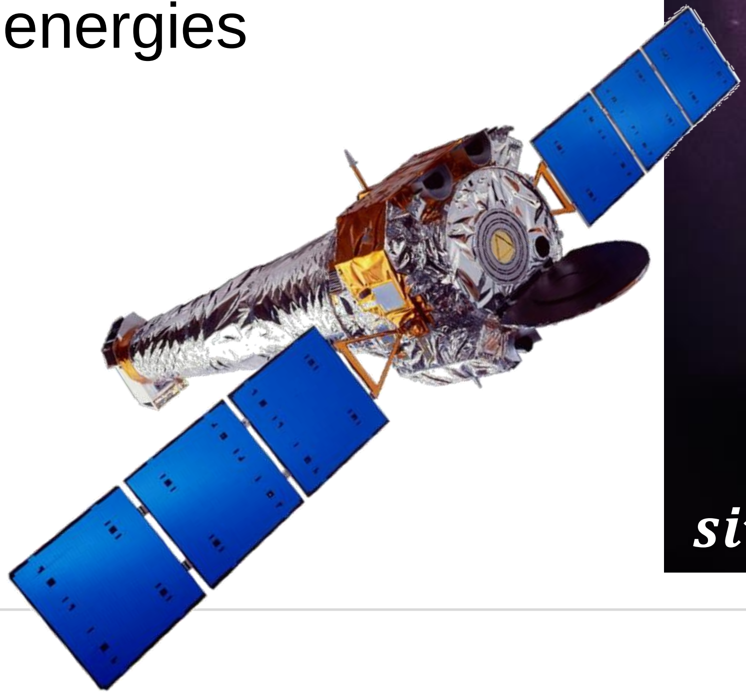
- **Observation of a weak $X$ – ray line in clusters at $E = 3.55\ keV$: from $\nu_s$?**

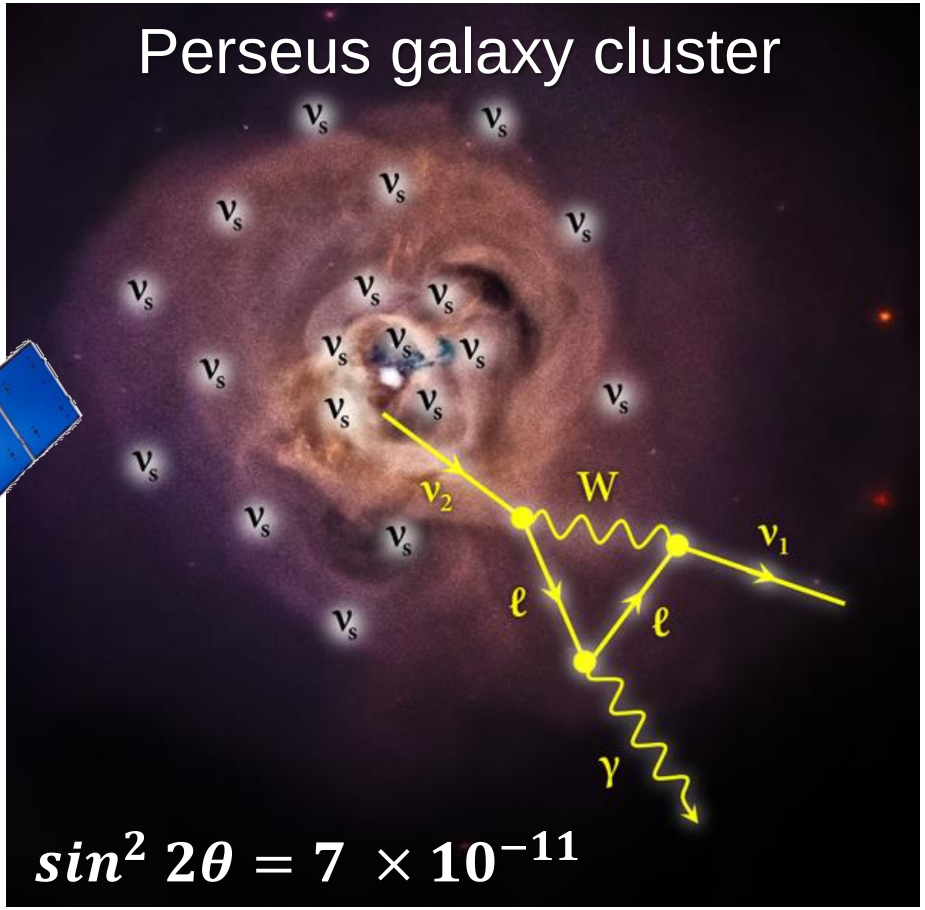
- results of leading $X$ – ray observatories (Chandra, XMM-Newton):

  ⇨ data point to the existence of a **weak emission line** at $X$ – ray energies

$$E_\gamma = 3.55\ keV$$

- observed in many (not all) galaxy clusters





# $keV$ – steriles: a signal observed in $X$ – rays?

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- **Observation of a weak $X$ – ray line in clusters at $E = 3.55\ keV$: from $\nu_s$?**

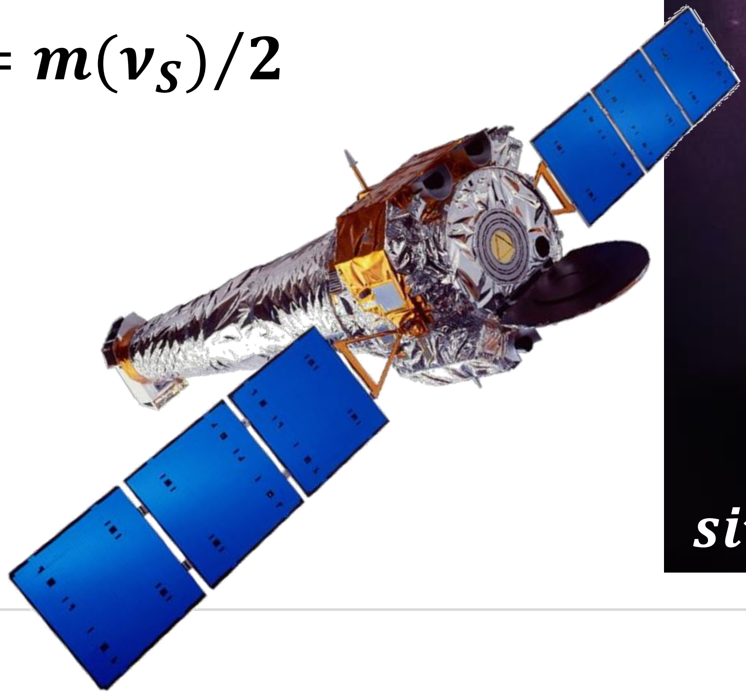
- is this the signature of a decaying sterile neutrino $\nu_s$?

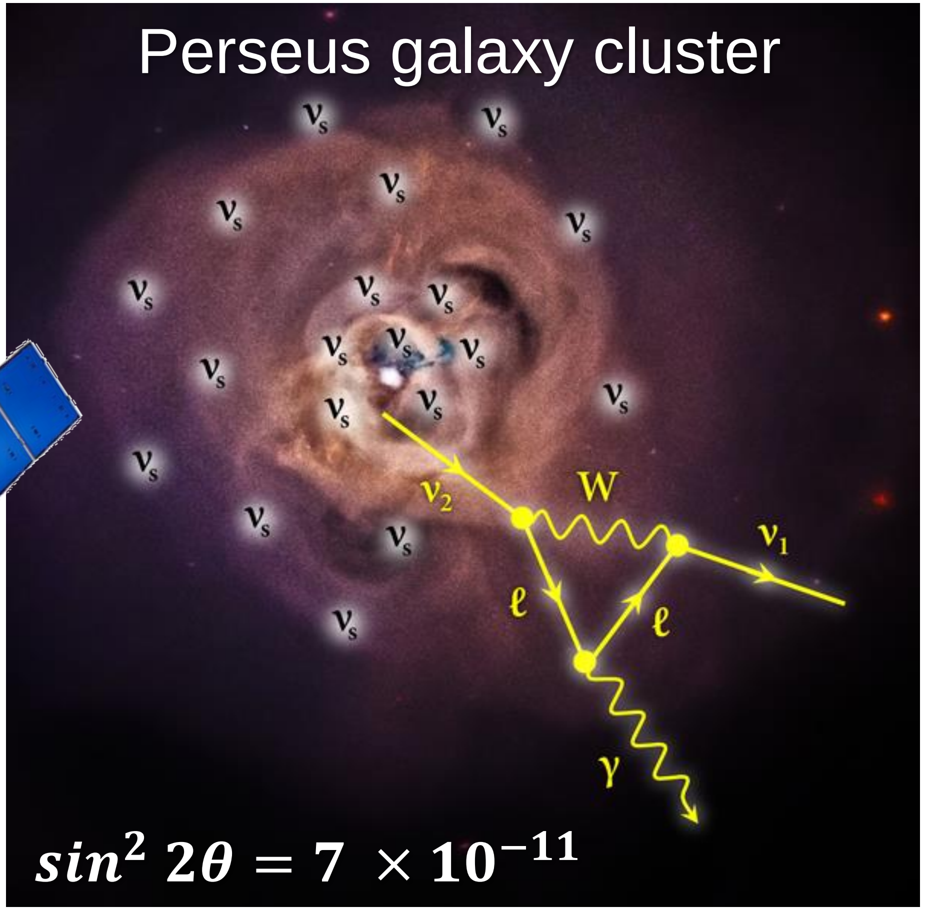
⇨ mass: $m(\nu_S) = 7.1\ keV$

decay: $X$ – ray line at $E_\gamma = m(\nu_S)/2$

$$E_\gamma = 3.55\ keV$$

- sterile neutrino would act as ´Warm Dark Matter´





# $keV$ – steriles: a signal observed in $X$ – rays?

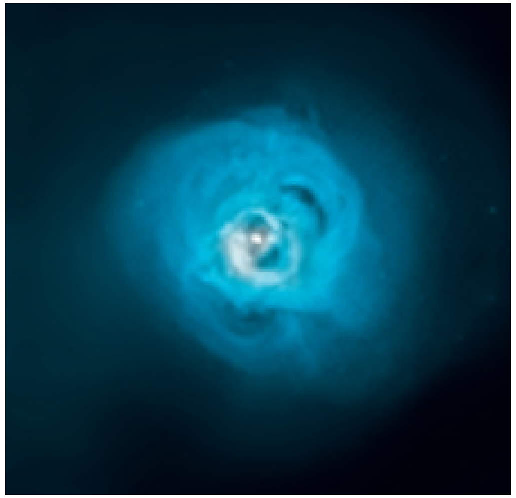
- Observation of a **weak $X$ – ray line** in clusters at $E = 3.55\ keV$


CERN COURIER

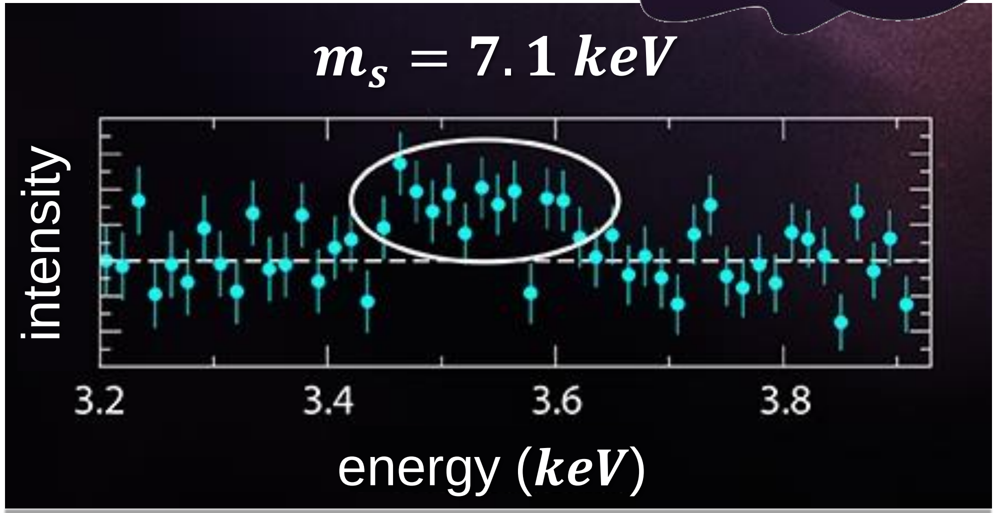
Jul 23, 2014

**Do X-rays reveal a sterile neutrino?**

A detailed study of galaxy clusters using NASA's Chandra X-ray Observatory and ESA's XMM-Newton has found a mysterious X-ray signal. One intriguing possibility is that the X-rays are produced by the decay of sterile neutrinos - a candidate particle for dark matter -



Perseus galaxy cluster



# $keV$ – steriles: signature in $KATRIN$

- **Search for a ´kink´ in the $\beta$ – spectrum**

- tritium $\boldsymbol{\beta}$ – spectrum allows to investigate sterile neutrinos with masses

$$m(\nu_s) < 18.6\ keV$$

- energy spectrum of decay electrons:

$$\frac{dN}{dE} = \cos^2\theta_s \cdot \frac{dN}{dE}(m_{active}) + \sin^2\theta_s \cdot \frac{dN}{dE}(m_{sterile})$$

mixing angle $\theta_s$


TURNING THE SCREW ON RIGHT-HANDED NEUTRINOS

Extending the elementary-particle inventory with heavy neutral leptons could solve the key observational shortcomings of the Standard Model, explain Alexey Boyarsky and Mikhail Shaposhnikov, with some models placing the new particles in reach of current and proposed experiments.

# $keV$ – steriles: signature in $KATRIN$

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## Search for a ´kink´ in the $\beta$ – spectrum

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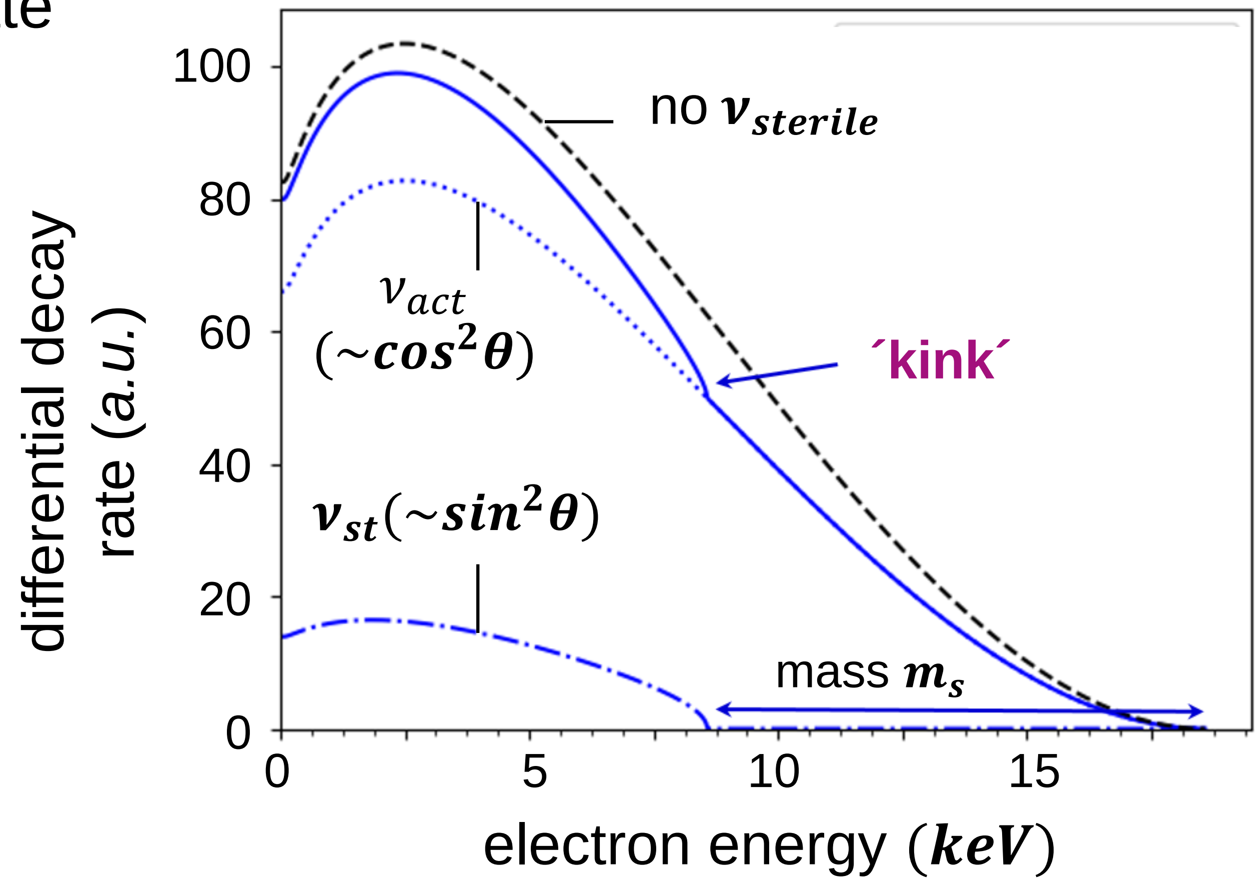
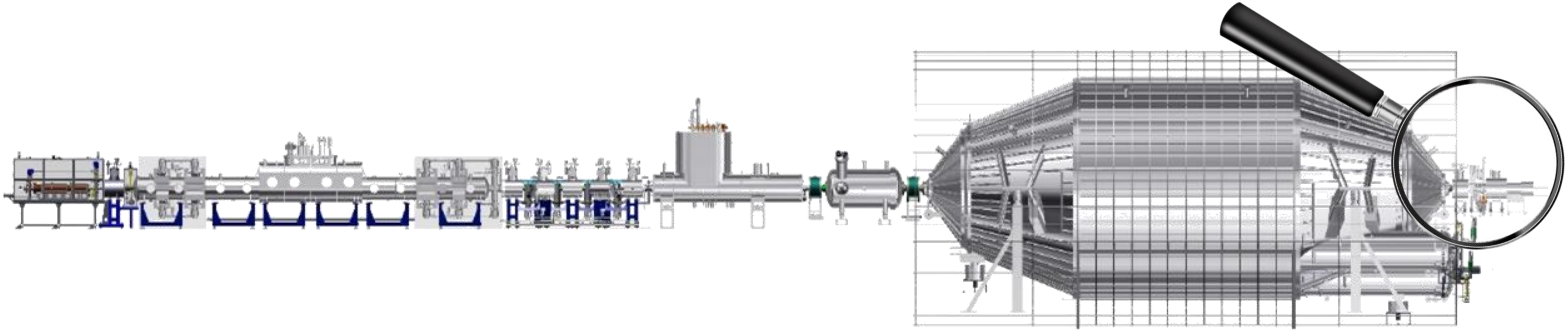


# $keV-$ steriles: a new detector for $KATRIN$

- **TRISTAN detector: TR**itium **I**nvestigation on **ST**erile (**A**) **N**eutrinos

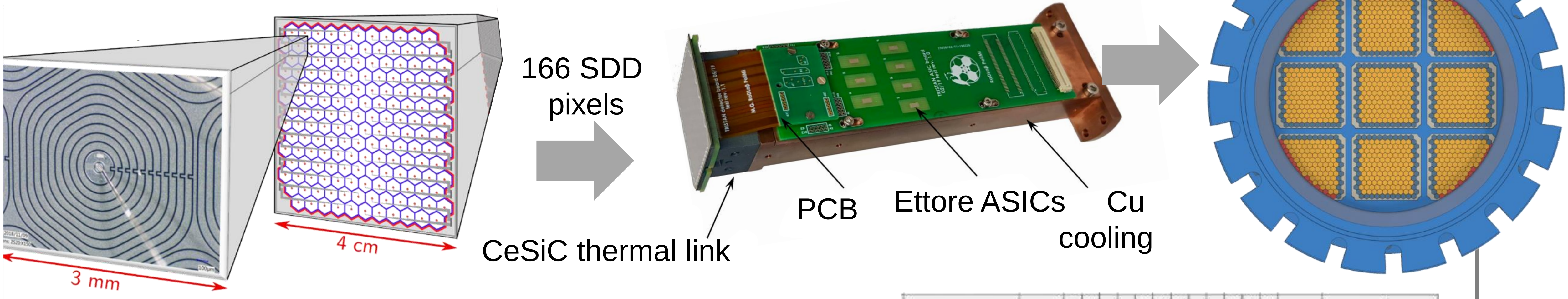
  - excellent energy resolution: ability to detect the expected **kink-like signature** i.e. $\boldsymbol{\Delta E \approx 200 \ldots 300\ eV}$ over entire energy interval from $\boldsymbol{0 \ldots 18.6\ keV}$

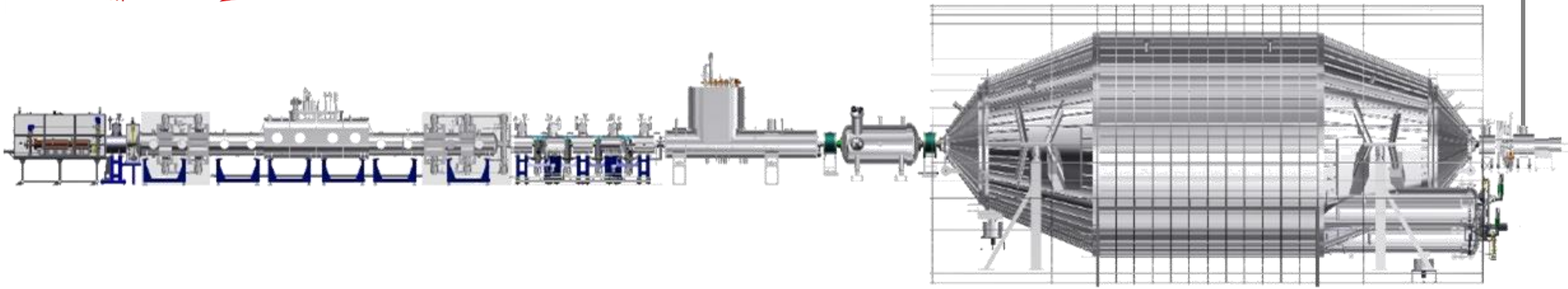
  - able to handle huge rate of $\beta -$ decay electrons when operating the source at ~1% of nominal column density



# $keV-$ steriles: a new $SDD$ detector for $KATRIN$

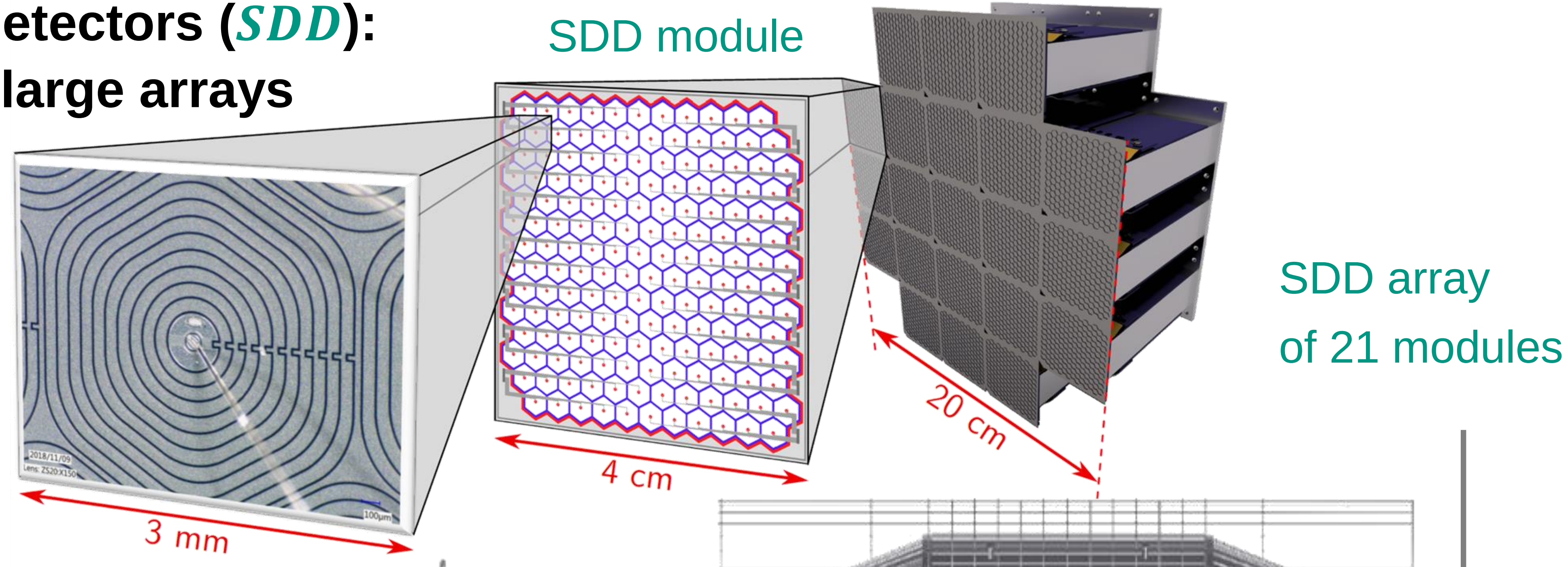
- **Silicon Drift Detectors ($SDD$): a novel detector technology**

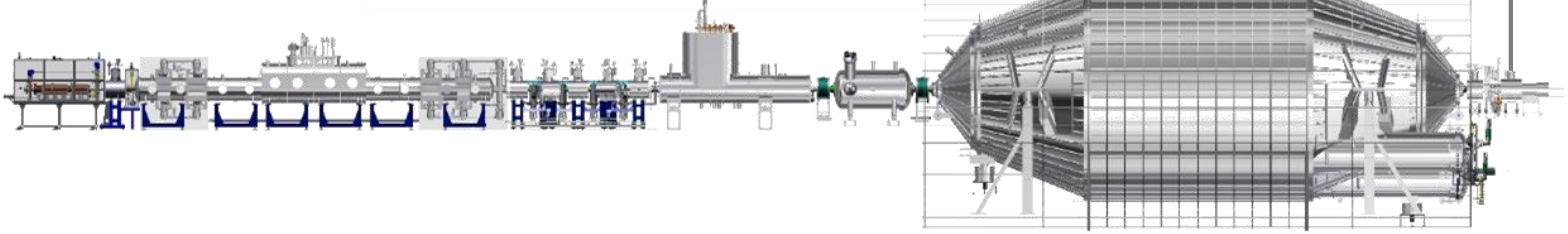


# $keV-$ steriles: a new $SDD$ detector for $KATRIN$

- ***S***ilicon ***D***rift ***D***etectors (***SDD***): towards very large arrays



# $keV -$ steriles: sensitivity of $KATRIN$

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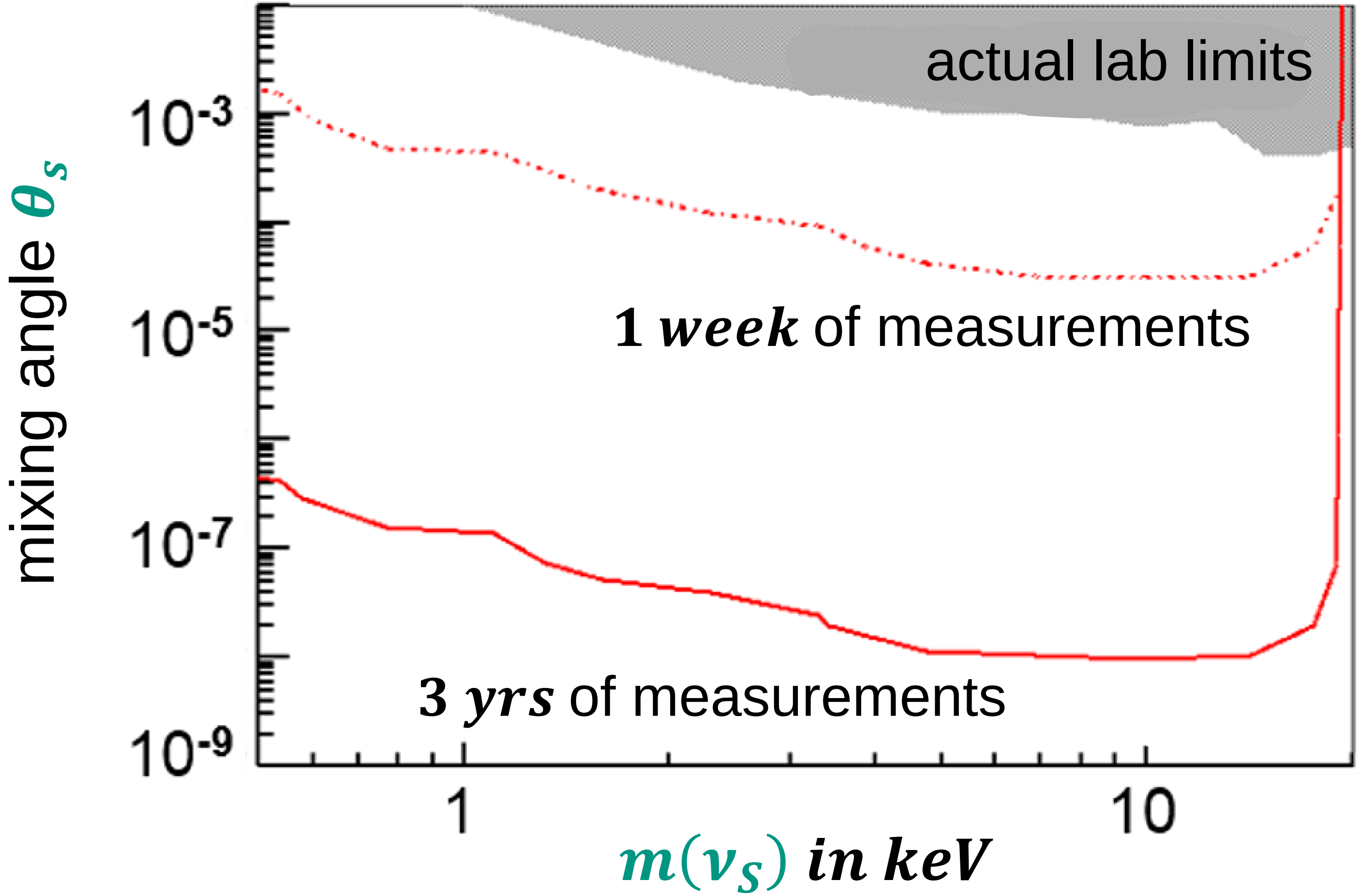
- **Calculated experimental sensitivity of $KATRIN$ with $TRISTAN -\ SDD$ array**

- significant improvement of the present experimental sensitivities after 1 week!

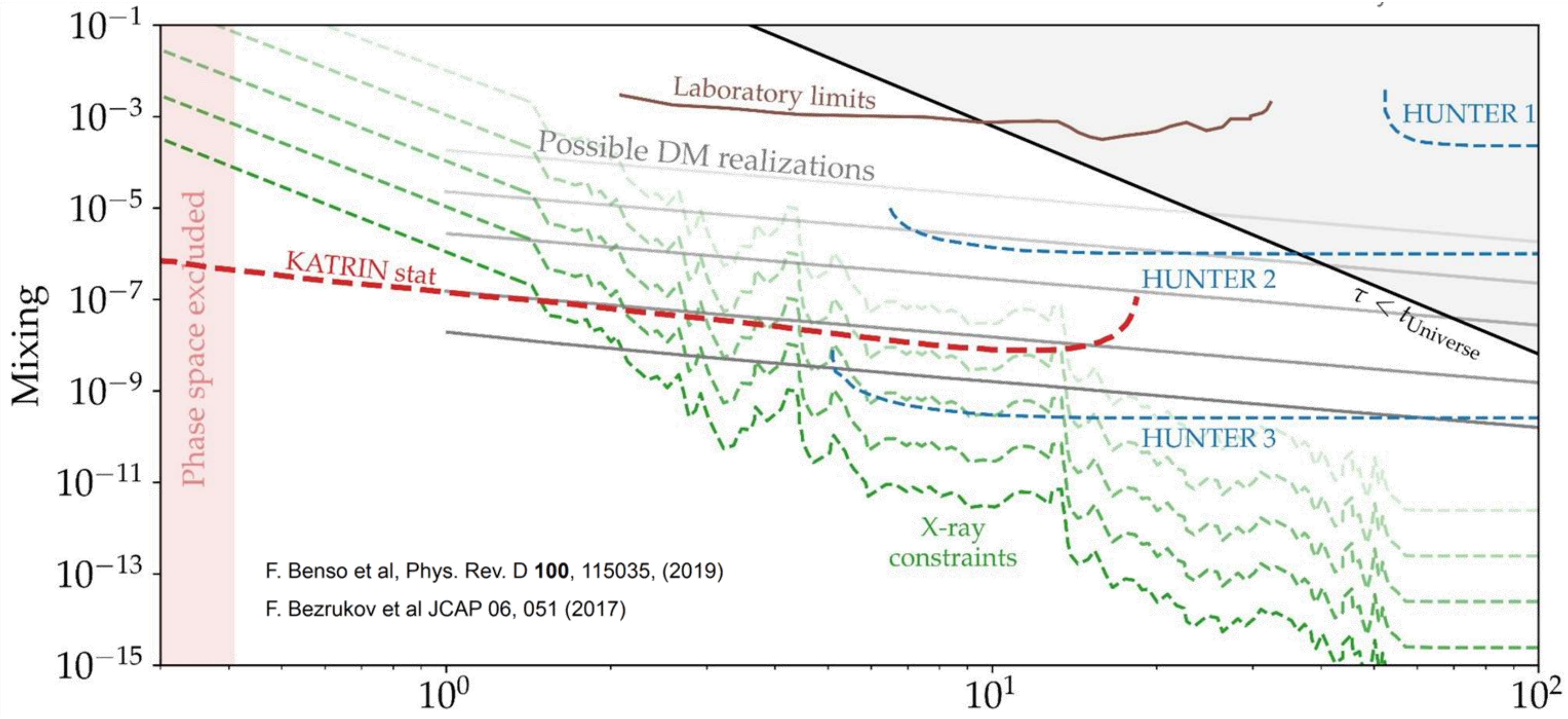
- add-on: search for new particles and **new physics / interactions** in $\beta -$ decay

- broad & rich physics programme



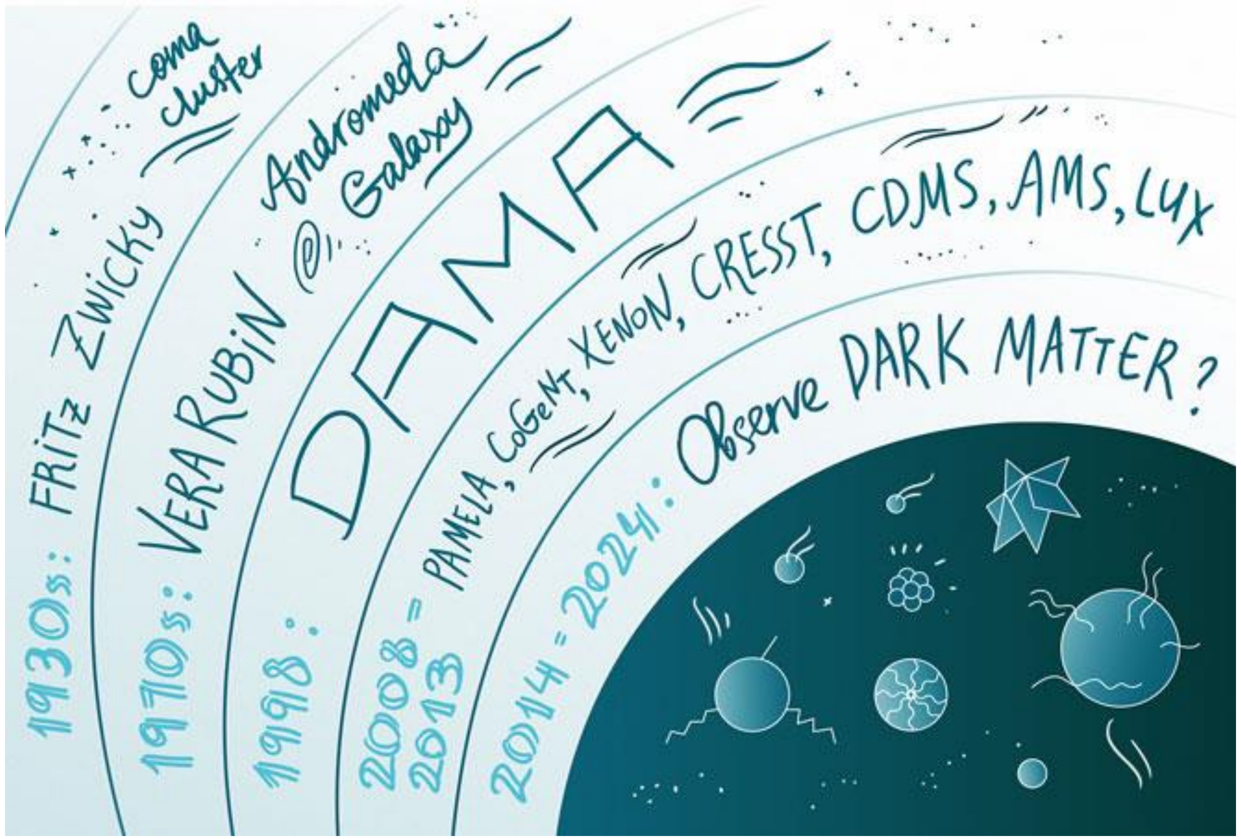
# $keV -$ steriles: sensitivity of $KATRIN$ & others

- KATRIN will advance the experimental sensitivty by many orders



# Dark Matter: neutralinos, axions & neutrinos

- **Coming decade will be decisive in our quest to unravel the nature of $DM$**



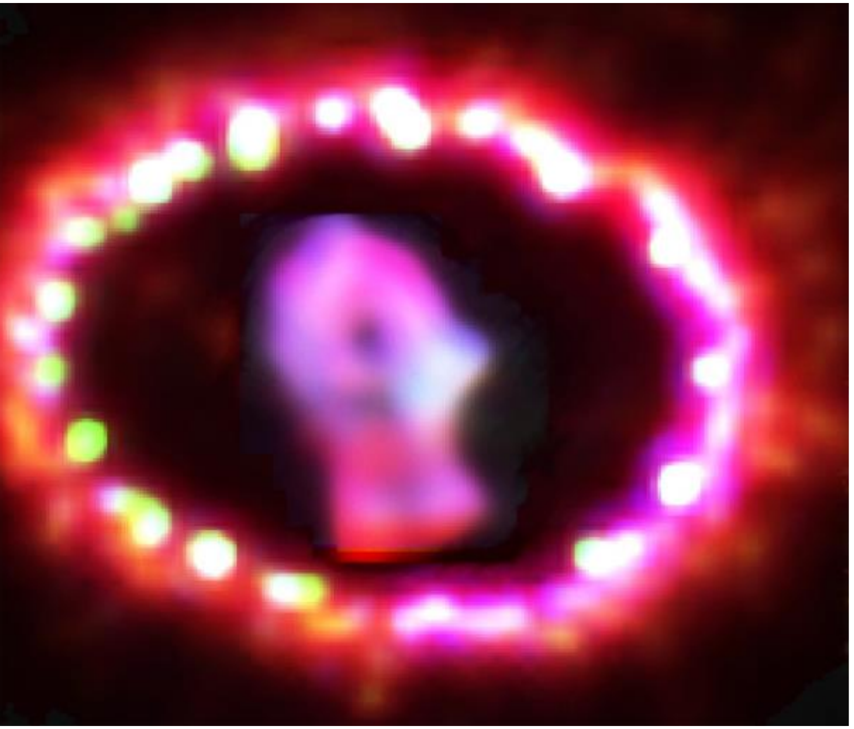

search for exceedingly rare processes

# ATP-II: Topics in the summer term 2023

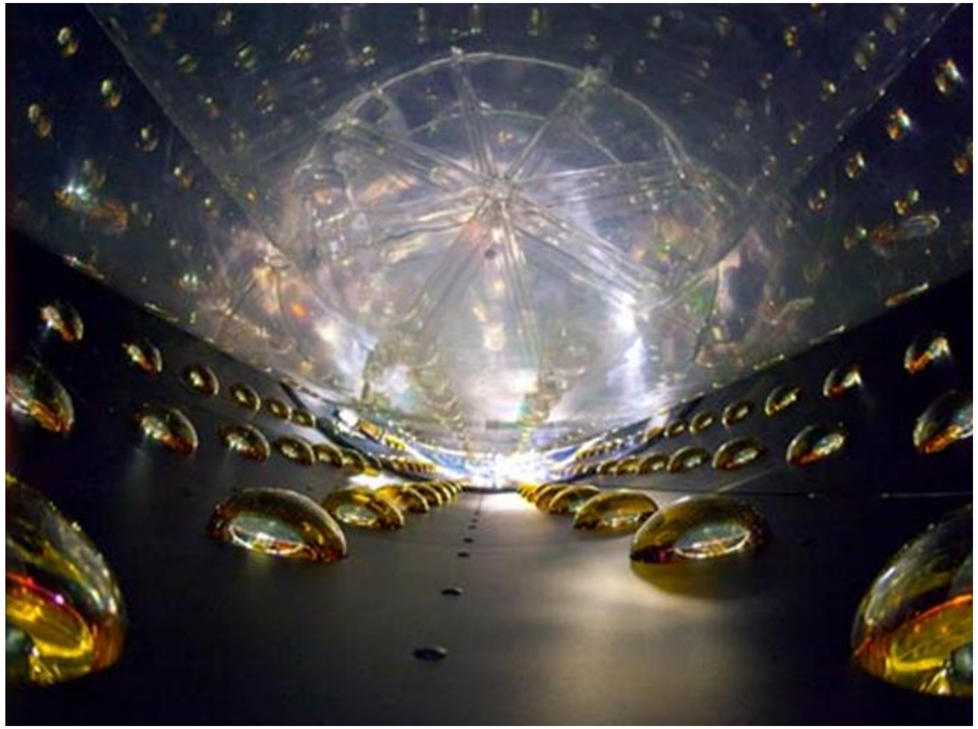
- **Stay tuned…**

**Astroparticle physics – II**

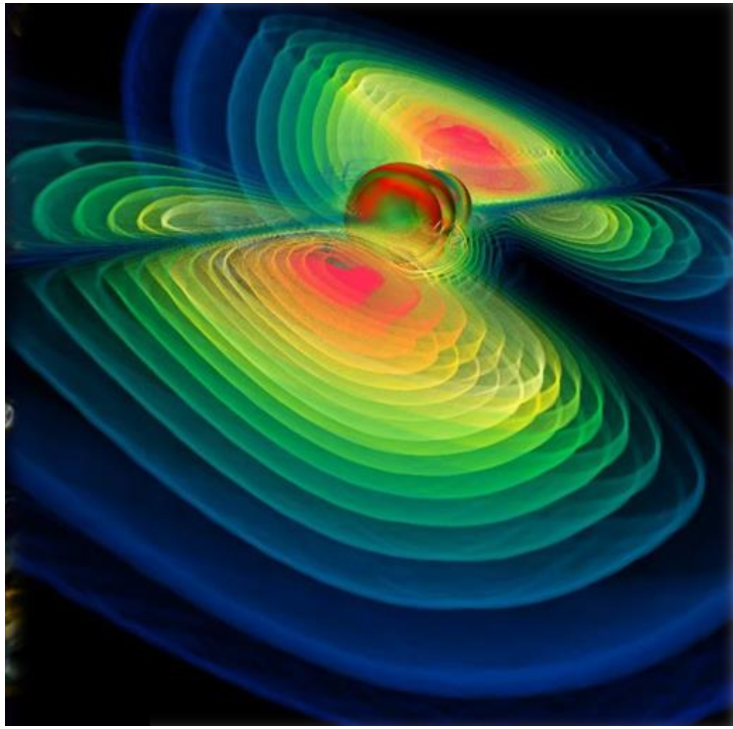
particles & stars



**supernovae**



**neutrinos**



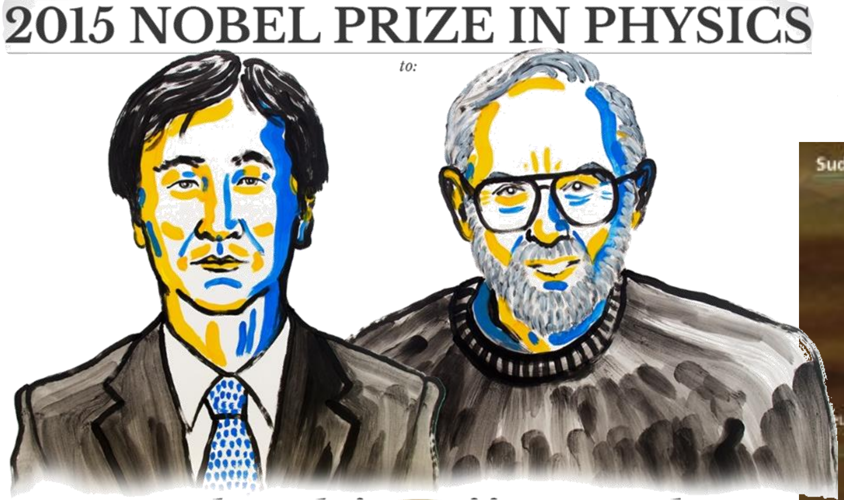
**gravitational waves**

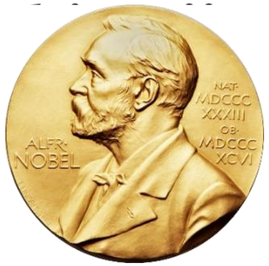
# ATP-II: Topics in the summer term 2023

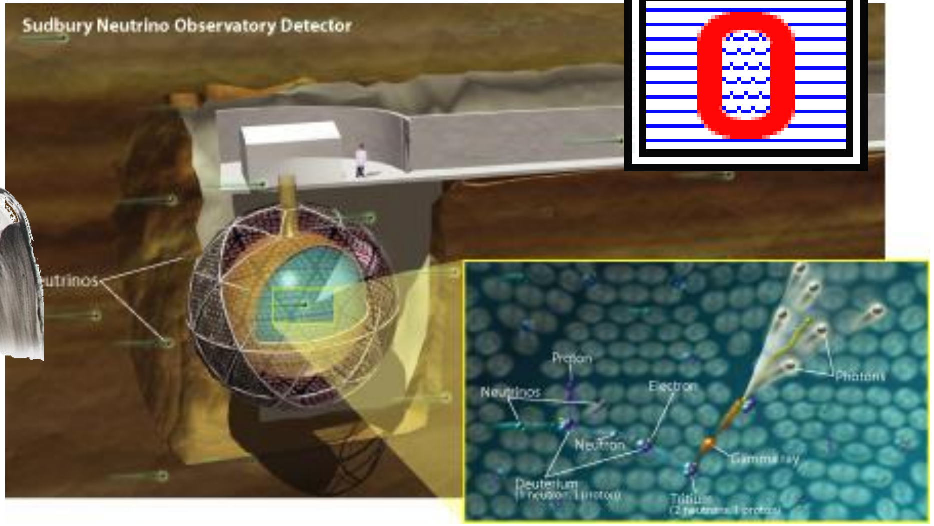
- **Stay tuned…**

**Astroparticle physics – II**

particles & stars: **neutrinos**



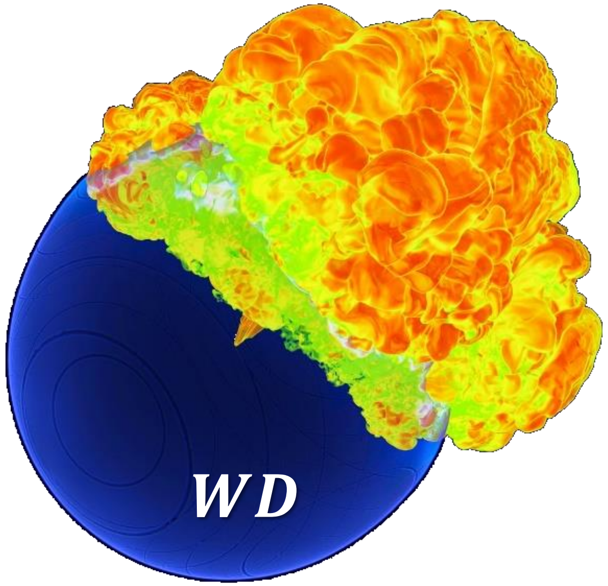



# ATP-II: Topics in the summer term 2023

- **Stay tuned…**

## Astroparticle physics – II

particles & stars: **exploding stars**


Supernova!!

# ATP-II: Topics in the summer term 2023

- **Stay tuned…**

## Astroparticle physics – II

particles & stars: **gravitational waves**


$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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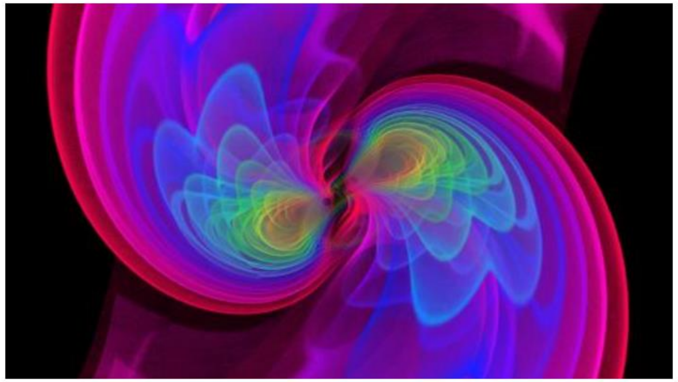
**+++ EILMELDUNG +++**

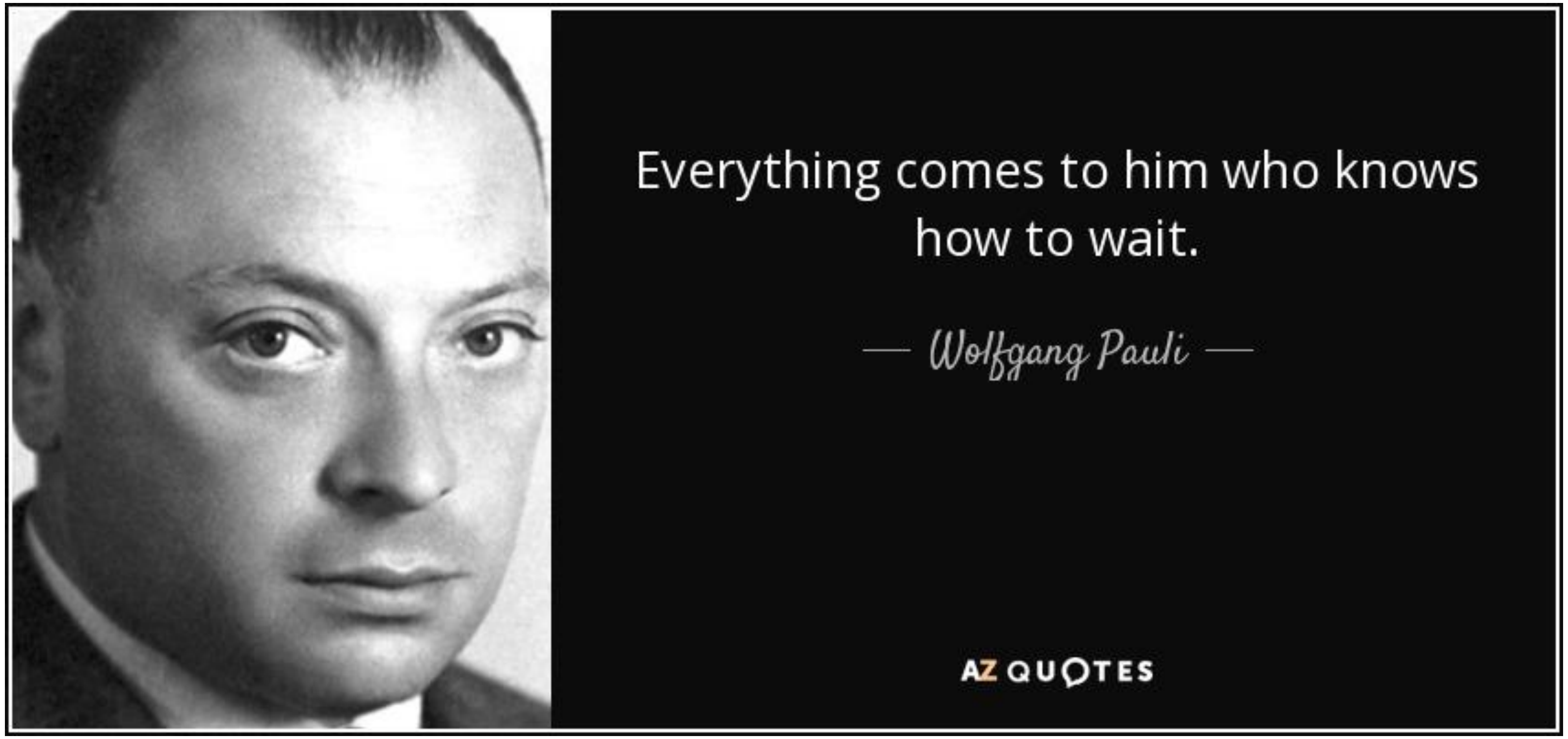
**Physik-Nobelpreis geht an Gravitationswellen-Forscher**



Albert Einstein sagte Gravitationswellen vor hundert Jahren voraus, für den Nachweis bekommen nun drei Forscher den Physik-Nobelpreis. Die Auszeichnung geht an die US-Wissenschaftler Rainer Weiss, Kip Thorne, Barry Barish. mehr...

# ASTROPARTICLE PHYSICS … ON THE MOVE!

- **Axions, neutrinos, neutralinos: a lot to explore in the coming years…**




**THANK YOU**