III. Physikalisches Institut A

RWTH AACHEN UNIVERSITY

Experimental Techniques in Particle Physics (WS 2020/2021)

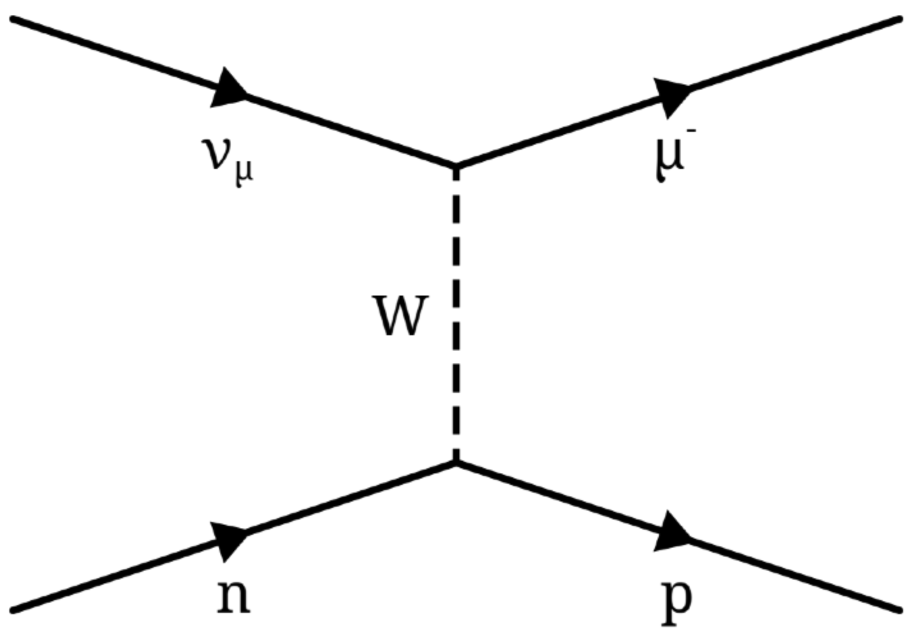
Some selected applications, and other detection techniques

Prof. Alexander Schmidt

09.02.2021

neutrino detectors

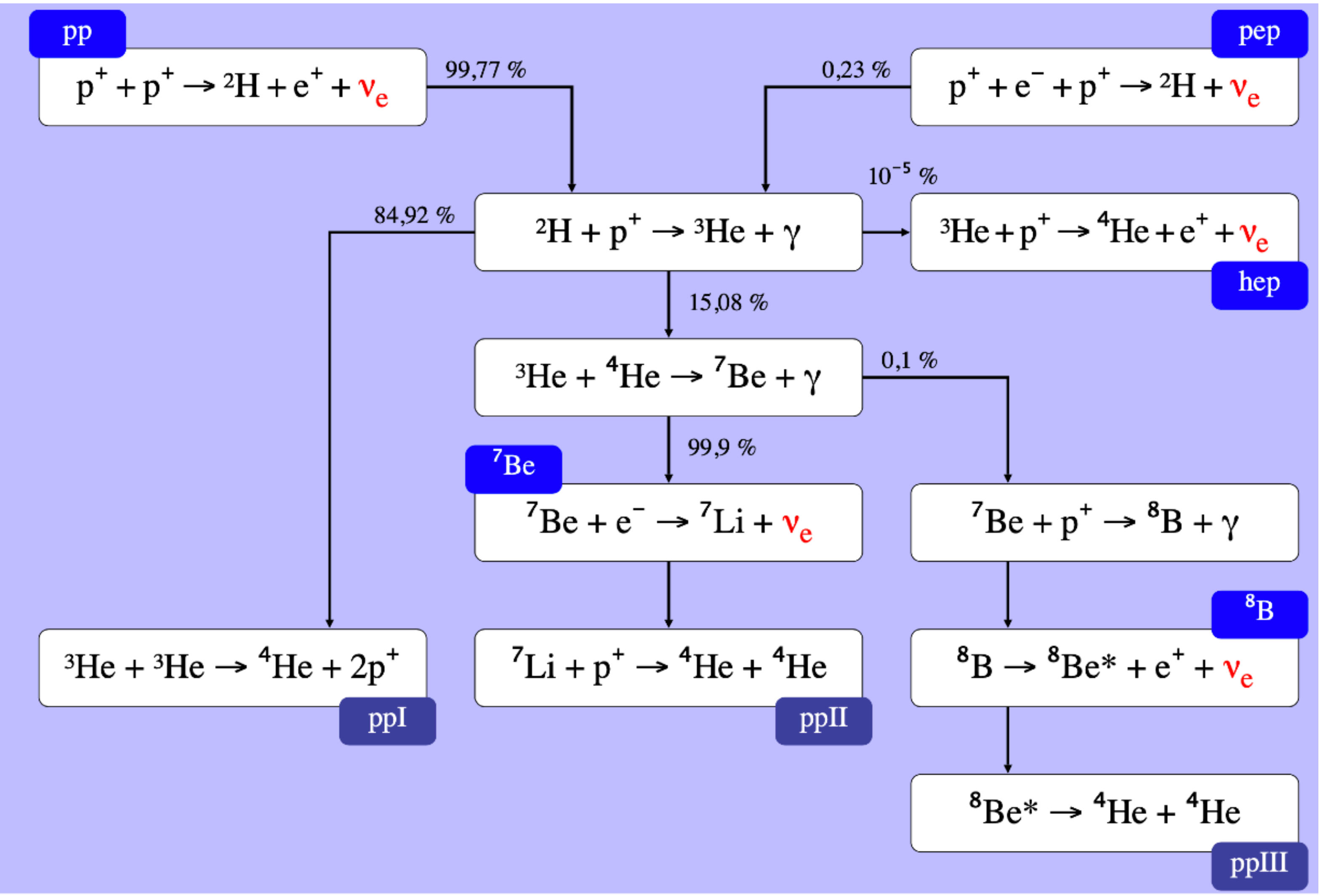
- neutrinos can be detected through weak interactions only
- example of neutrino-neutron scattering:

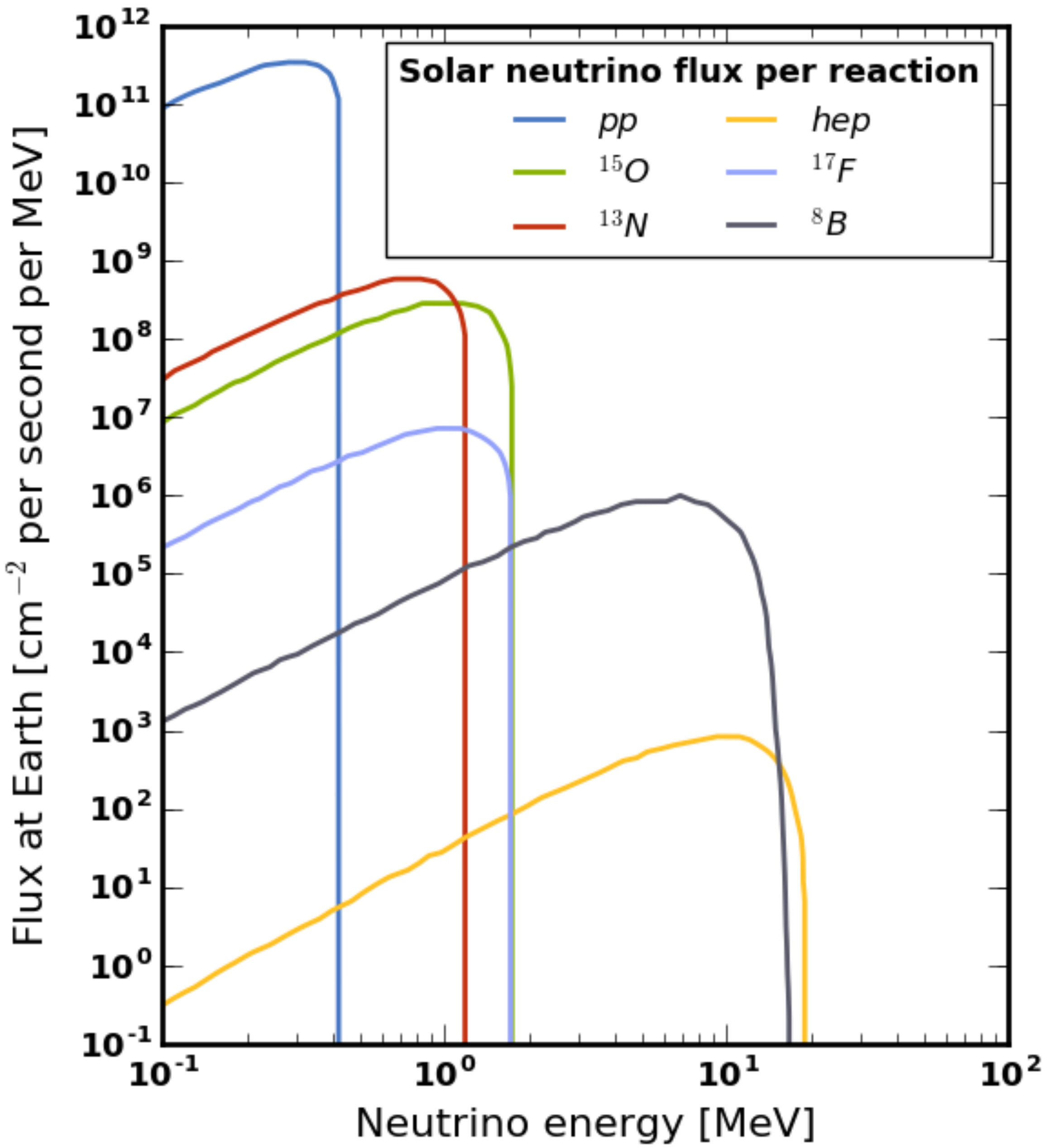


- also directional information can be extracted this way
- neutrino sources:
  - sun (electron-neutrinos)
  - nuclear reactors
  - cosmic (extragalactic origin)
  - …

solar neutrinos

- standard solar model:





Homestake neutrino experiment

380 m³ underground tank containing perchlorethylene

neutrinos are captured in chlorine nucleus:

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + \mathrm{e}^-$$

^{37}Ar has a half-life of 35 days
→ extract Ar by bubbling the tank with Helium

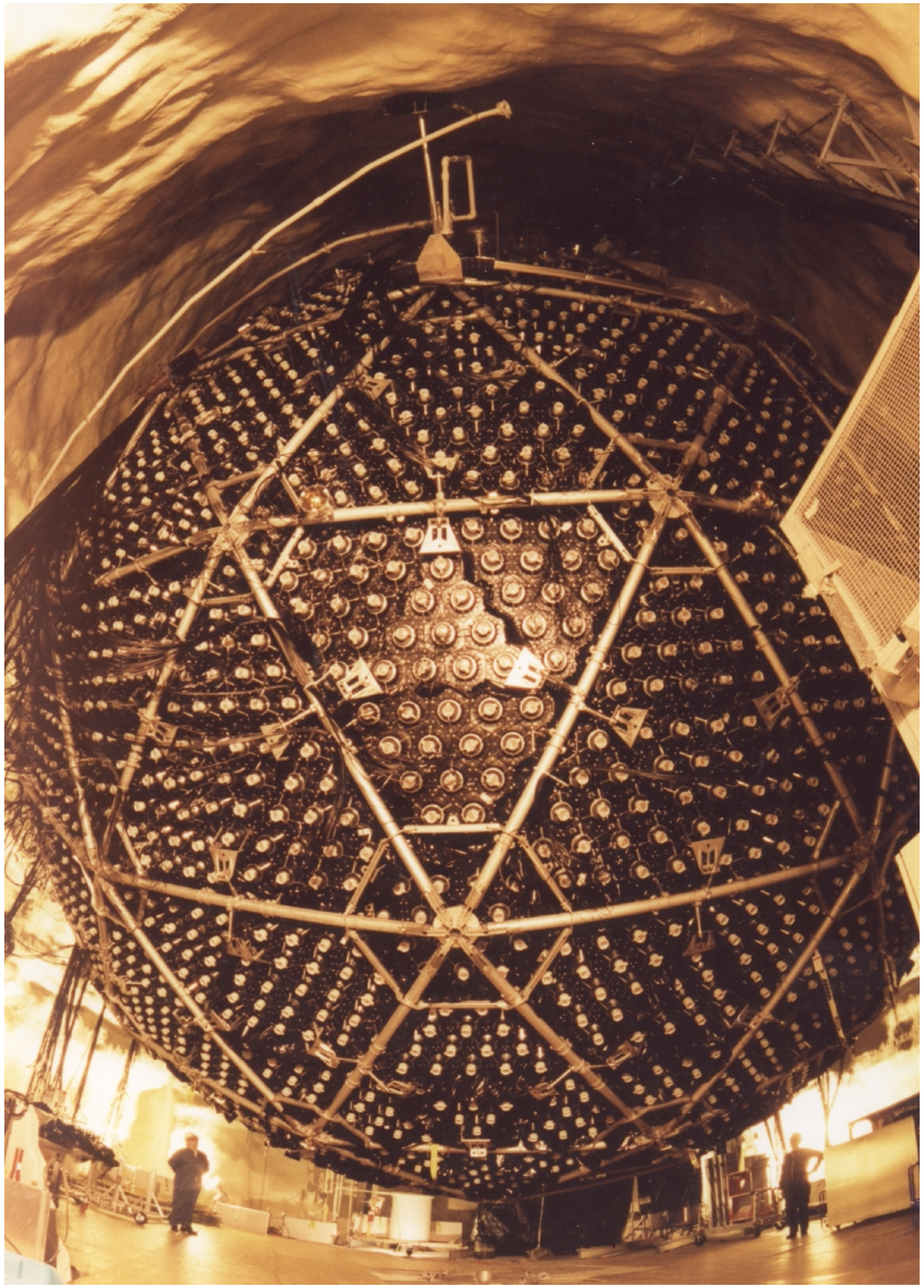
only a couple of Ar atoms will be produced and extracted this way

radioactive decay of these few extracted Ar atoms are counted

- neutrino flux from the sun can be measured this way
- observe only 2/3 of the expected electron-neutrino flux
- explanation found later: neutrino oscillations (Nobel prize)

➡"chemical" particle detector

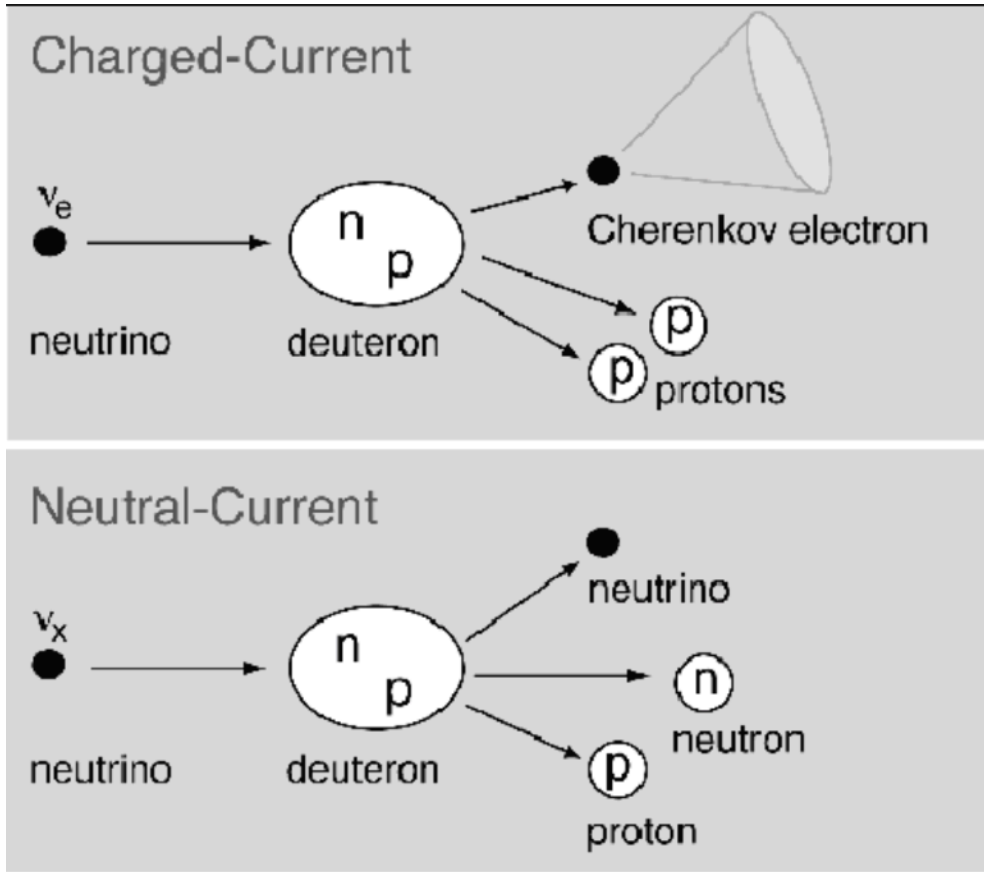
Sudbury neutrino experiment



1000 tons of heavy water observed by photo multipliers

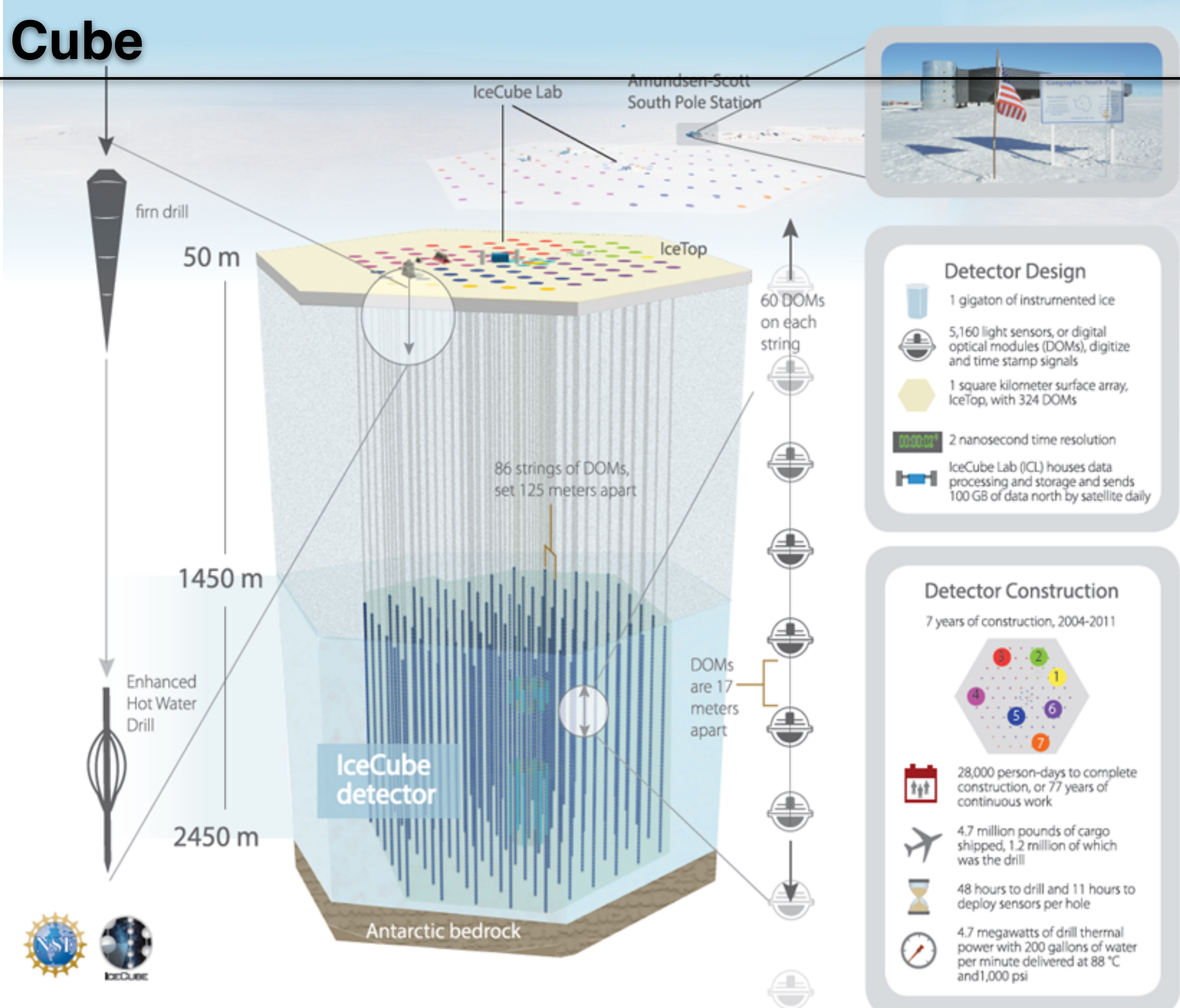
can detect charged current interactions (see previous slides) for electron neutrinos

can also detect neutral currents for all neutrino flavours, and therefore detect solar neutrino oscillations



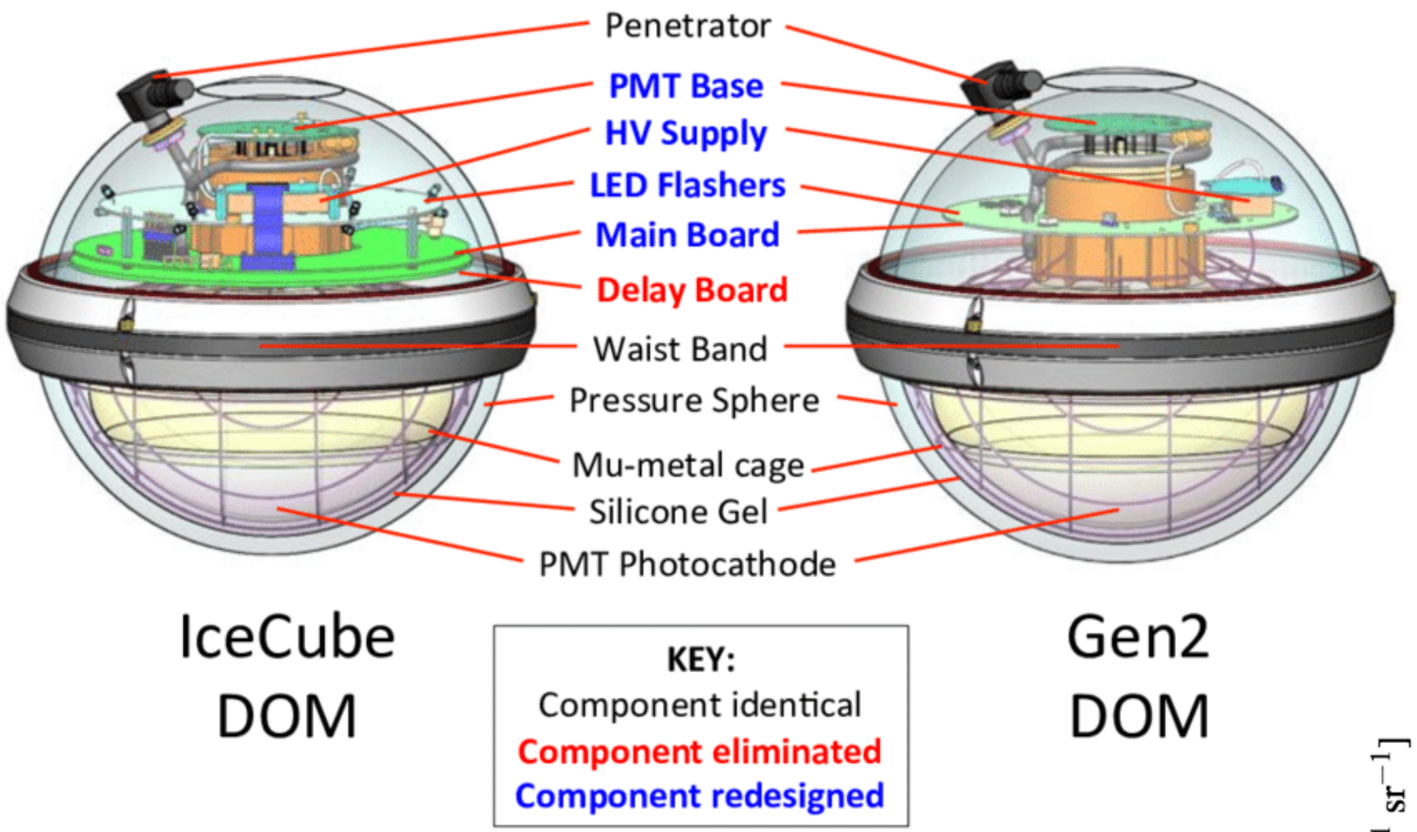
neutrino oscillations confirmed in 2002

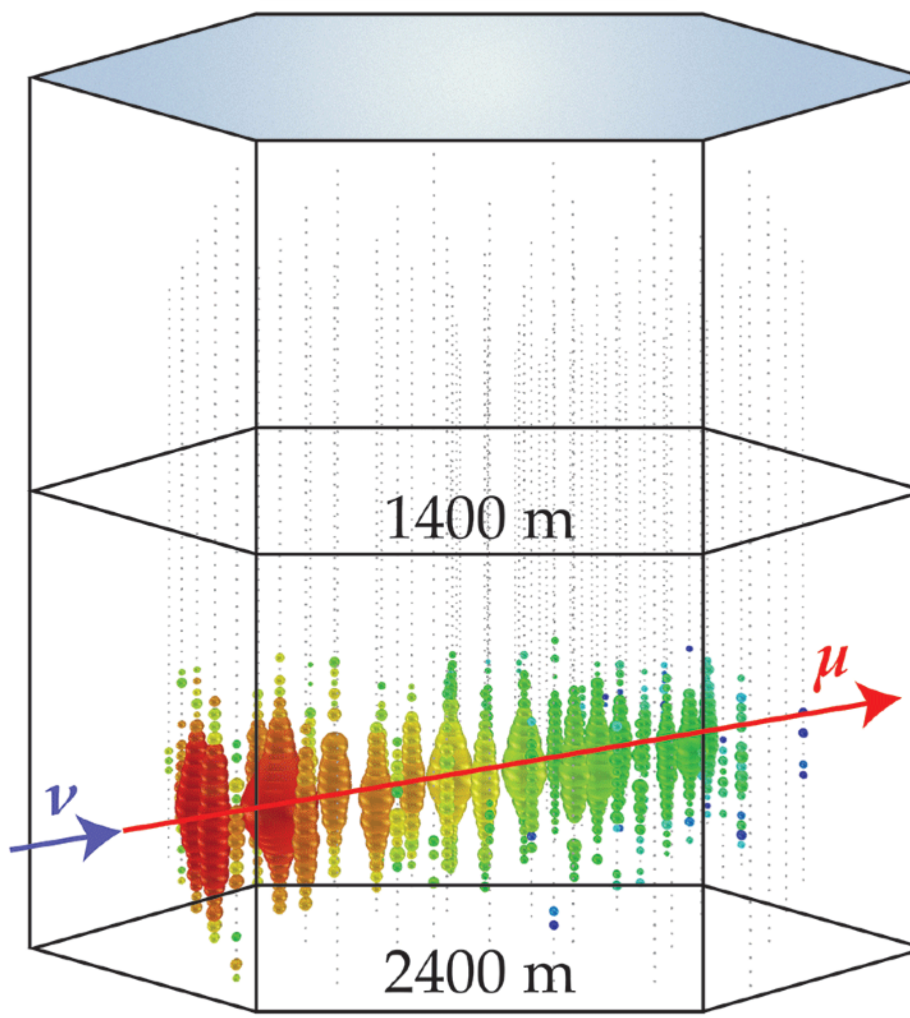
Ice Cube



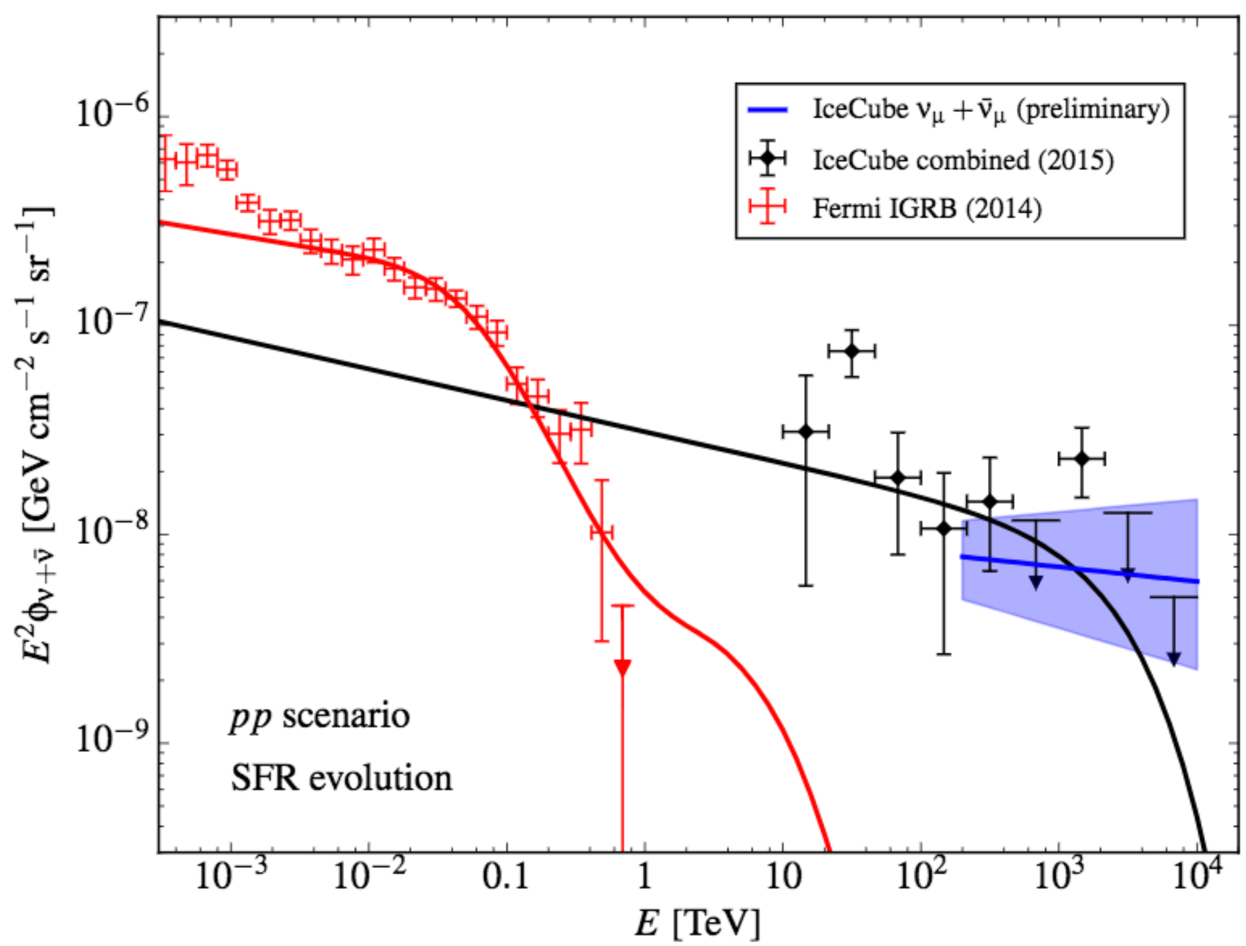
IceCube Lab
Amundsen-Scott
South Pole Station
firn drill
50 m
IceTop
60 DOMs
on each
string
86 strings of DOMs,
set 125 meters apart
1450 m
Enhanced
Hot Water
Drill
DOMs
are 17
meters
apart
IceCube
detector
2450 m
Antarctic bedrock
Detector Design
1 gigaton of instrumented ice
5,160 light sensors, or digital optical modules (DOMs), digitize and time stamp signals
1 square kilometer surface array, IceTop, with 324 DOMs
2 nanosecond time resolution
IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily
Detector Construction
7 years of construction, 2004-2011
28,000 person-days to complete construction, or 77 years of continuous work
4.7 million pounds of cargo shipped, 1.2 million of which was the drill
48 hours to drill and 11 hours to deploy sensors per hole
4.7 megawatts of drill thermal power with 200 gallons of water per minute delivered at 88 °C and1,000 psi

Ice Cube

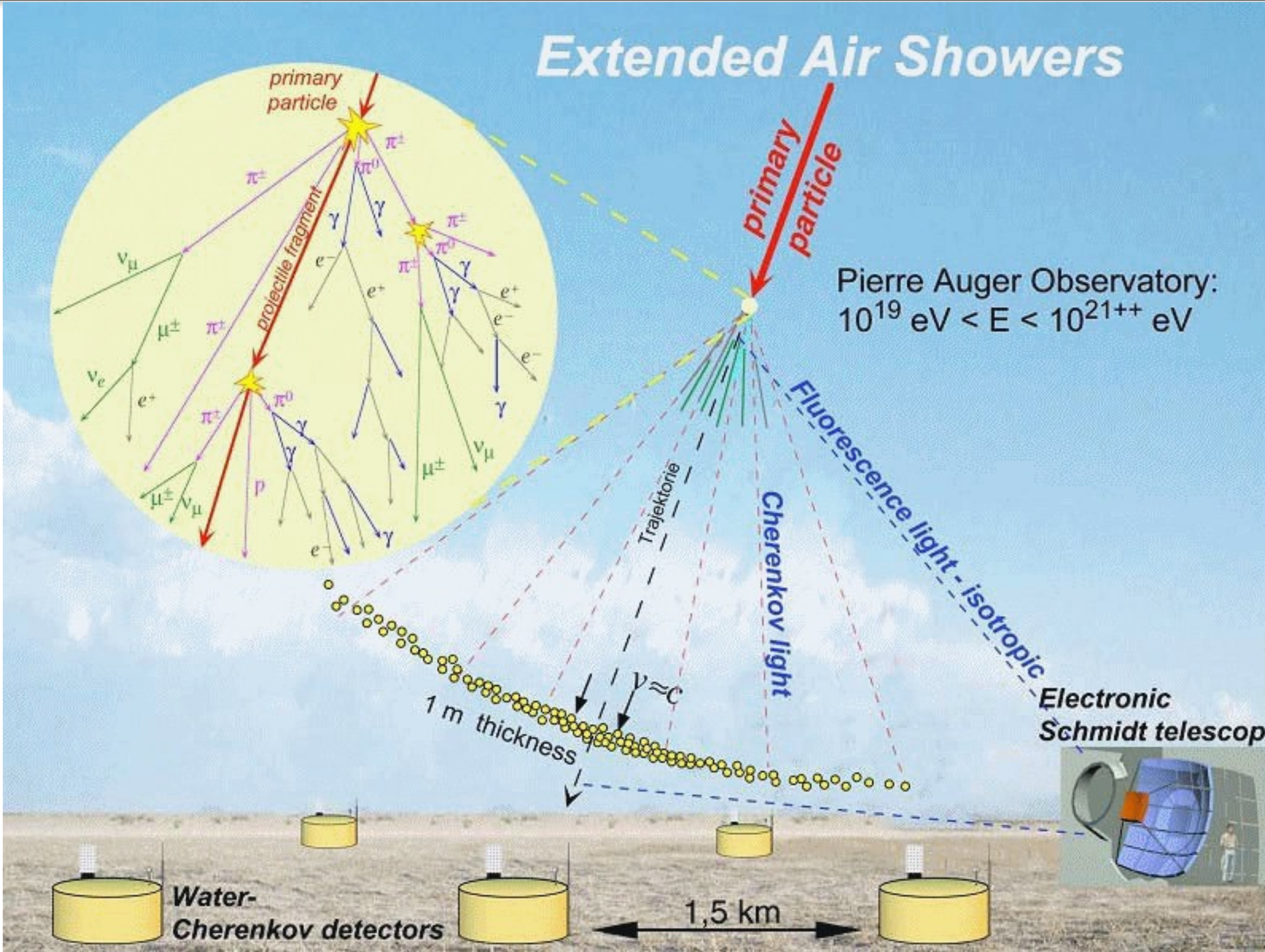




astrophysical neutrino flux



Pierre Auger Observatory



Pierre Auger Observatory

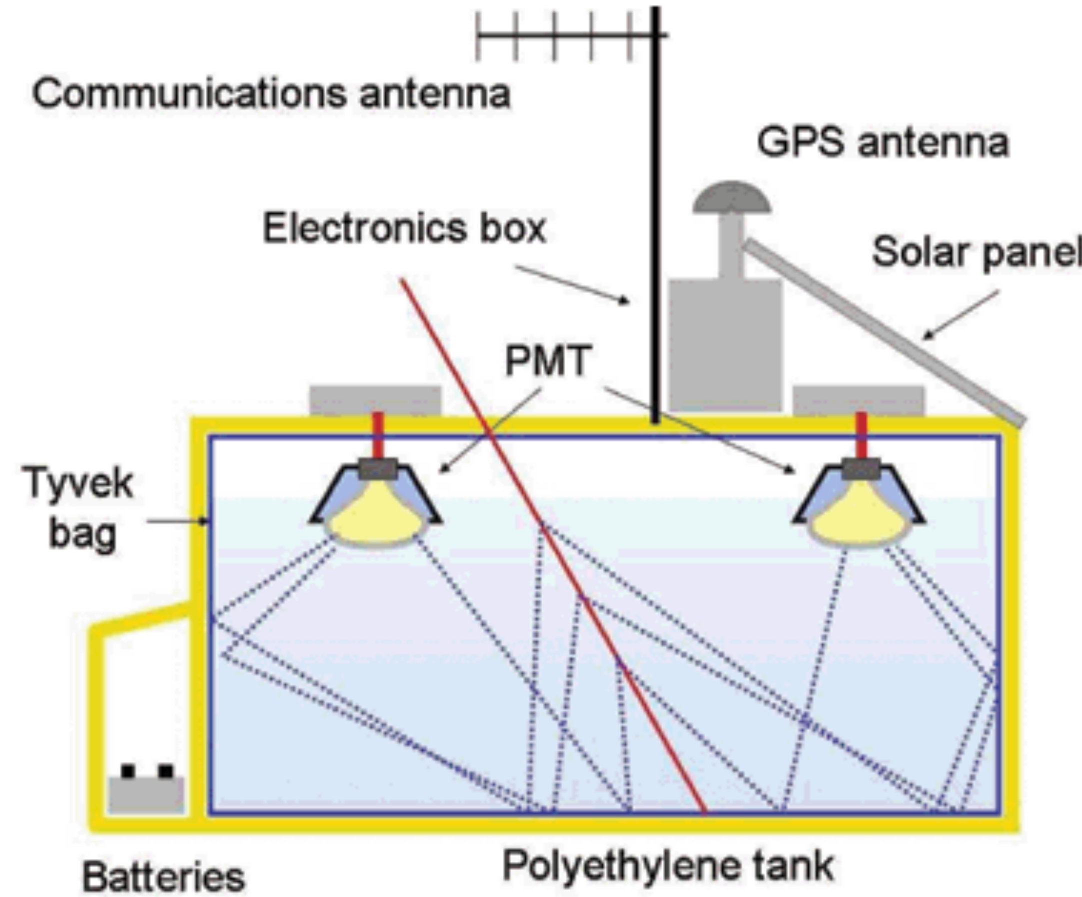
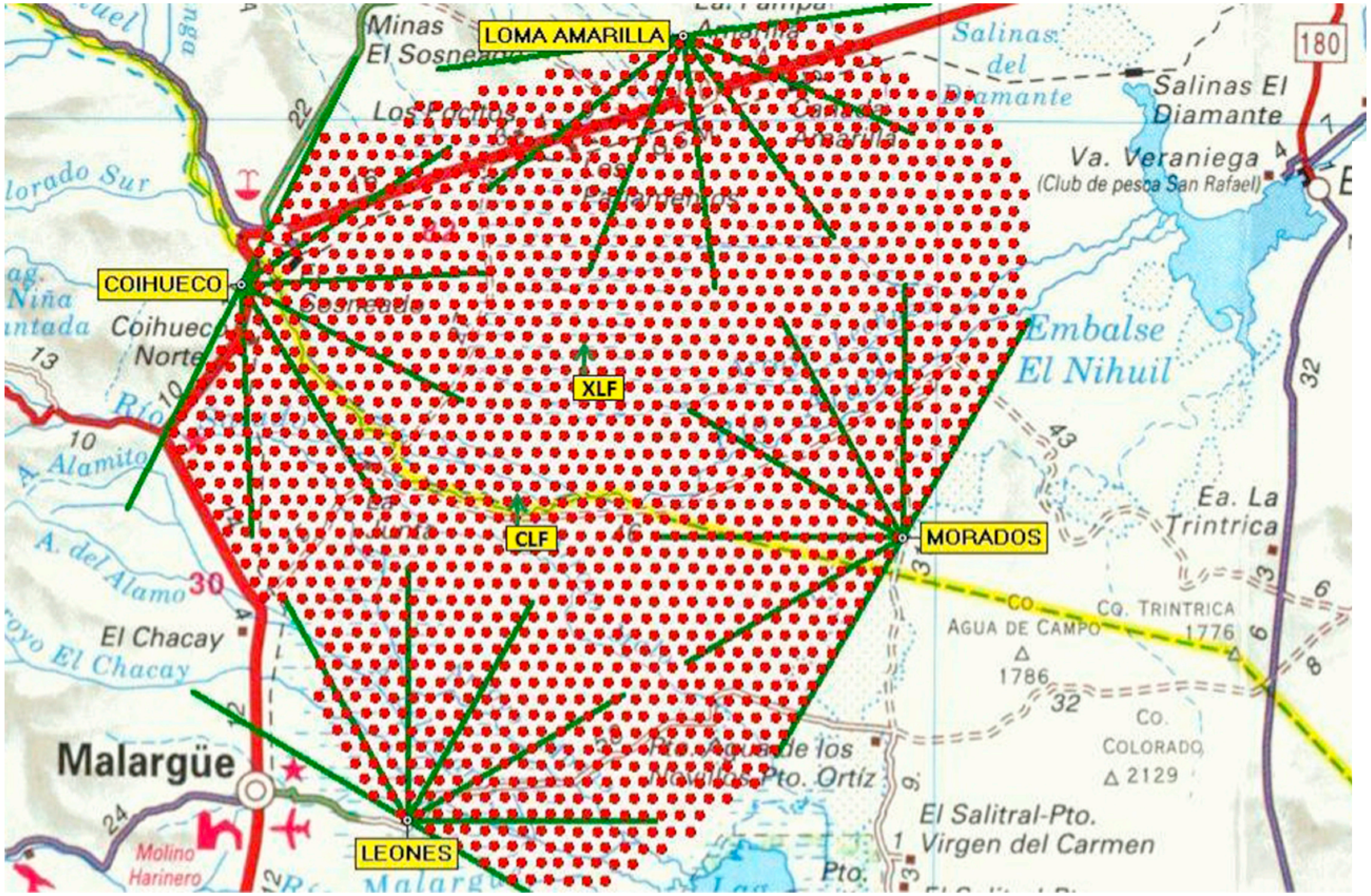


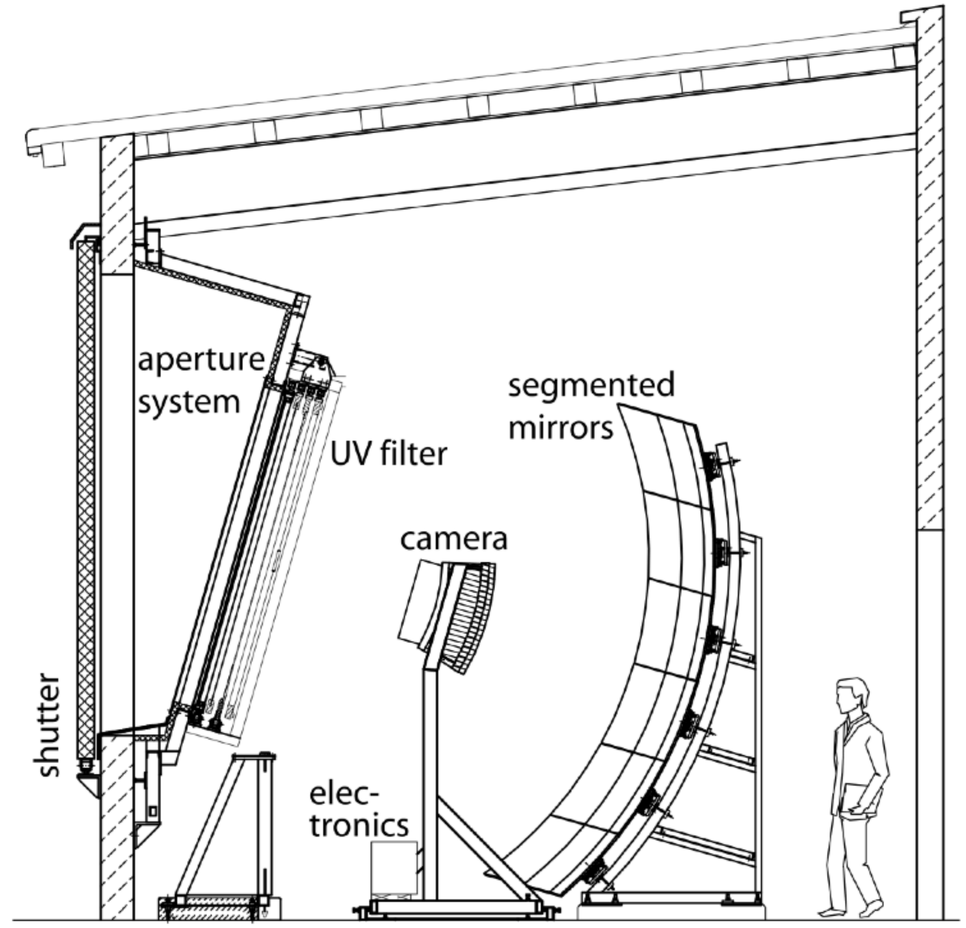
FIG. 2: A schematic view of the Cherenkov water tanks, with the components indicated in the figure.

- array of >1600 water cherenkov surface detectors (SD) covering 3000 km2
- sensitive to charged particles as well as high energy photons converting into e^+e^- in the volume

Pierre Auger Observatory



- four sites with fluorescence detectors

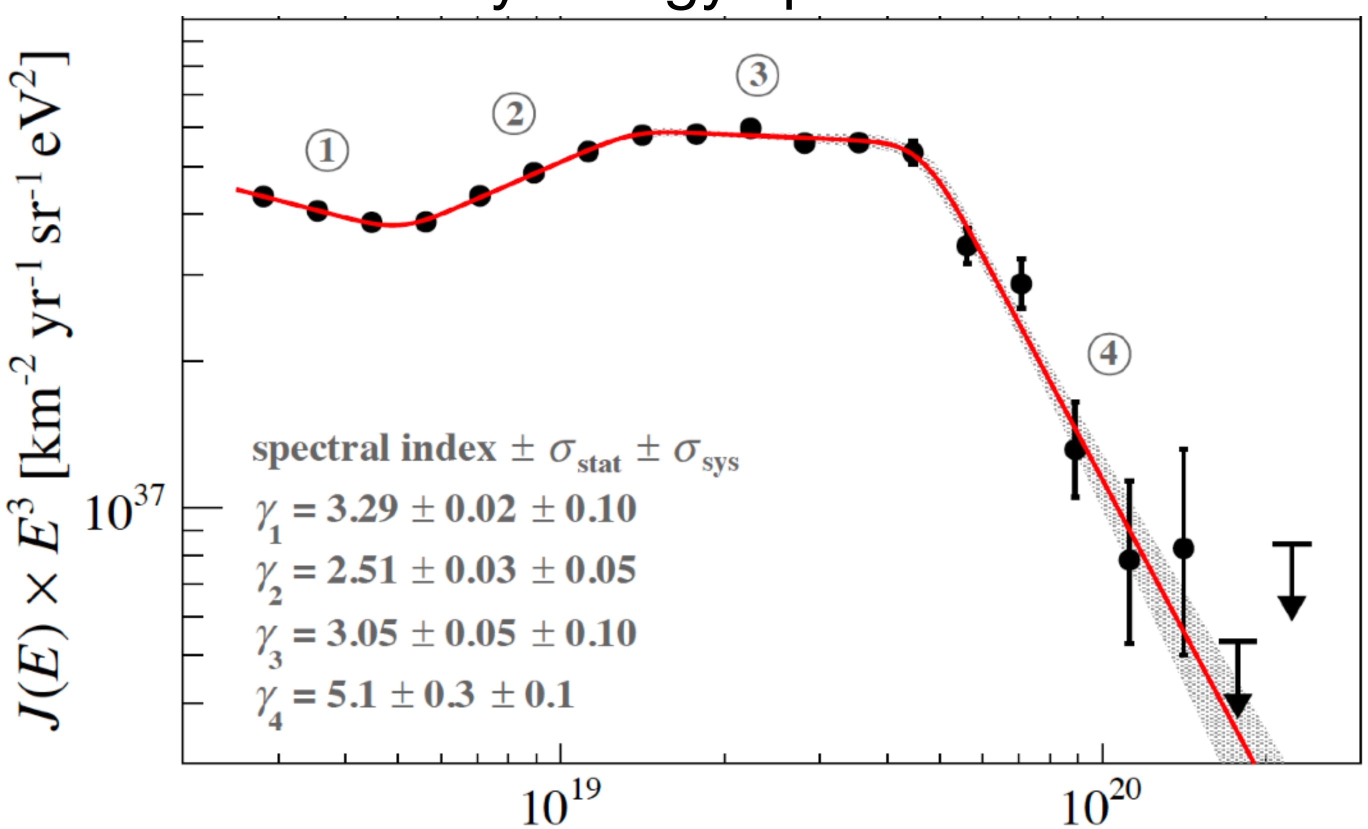


upgrades for the observatory:

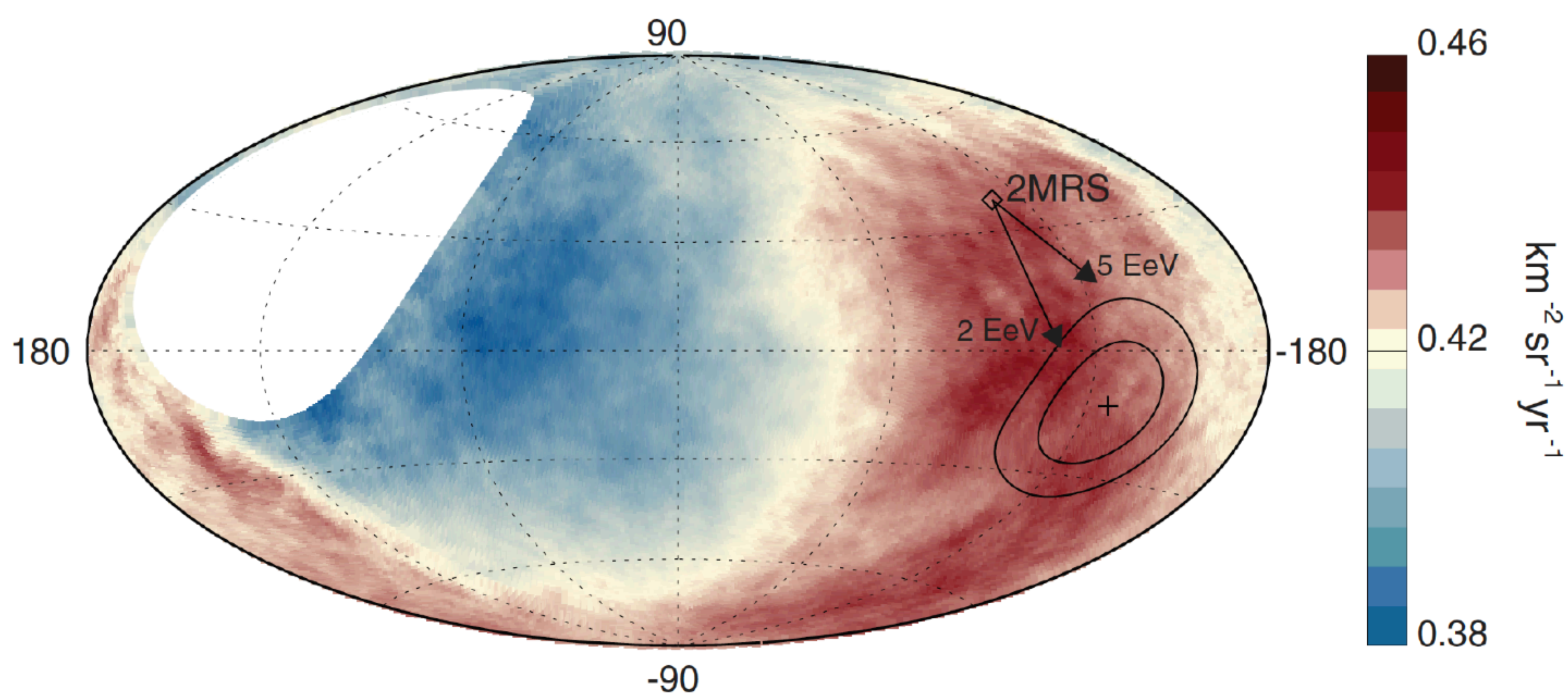
- the surface detectors enhanced by scintillation detectors and radio antennas
- two higher-density nested arrays of surface detectors combined with underground muon counters (AMIGA)
- radiotelescope array (AERA) for detecting radioemission from the shower cascade, in the frequency range 30–80 MHz

Pierre Auger Observatory

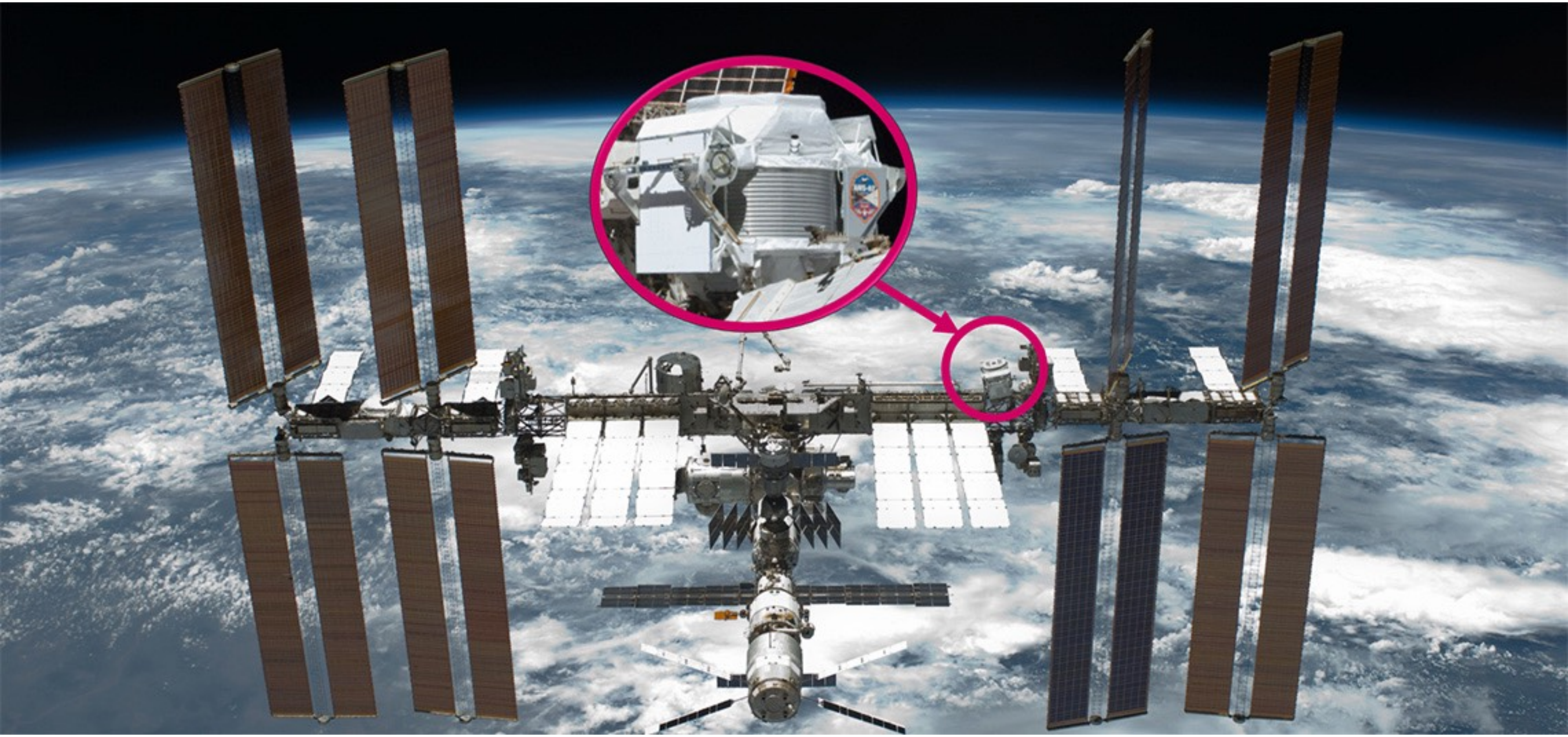
cosmic ray energy spectrum:



- most precise measurement of highest energy cosmic ray spectrum
- observation of large scale anisotropy in arrival direction of cosmic rays in a specific energy regime
- extra galactic origin of UHECR

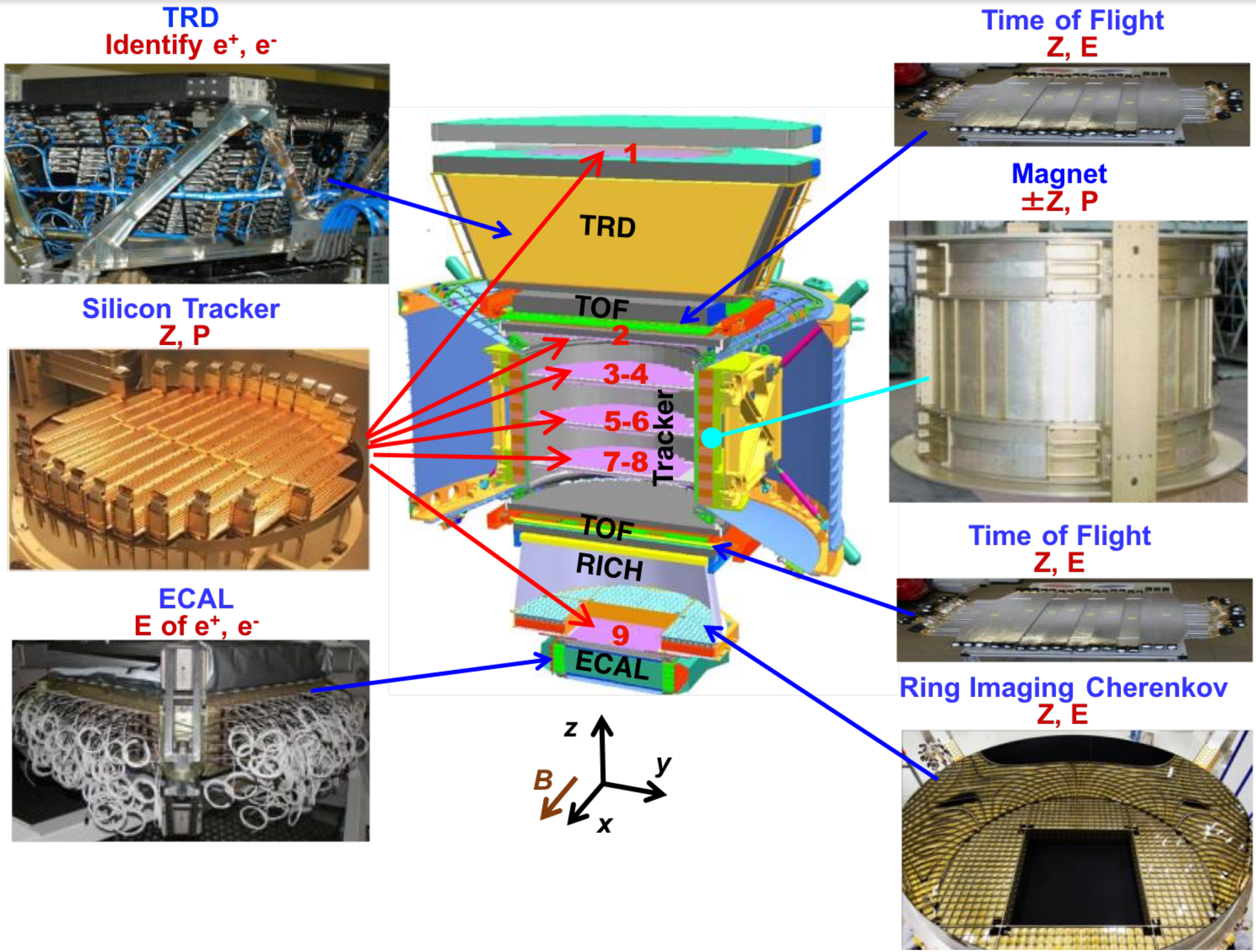


AMS experiment on the international space station

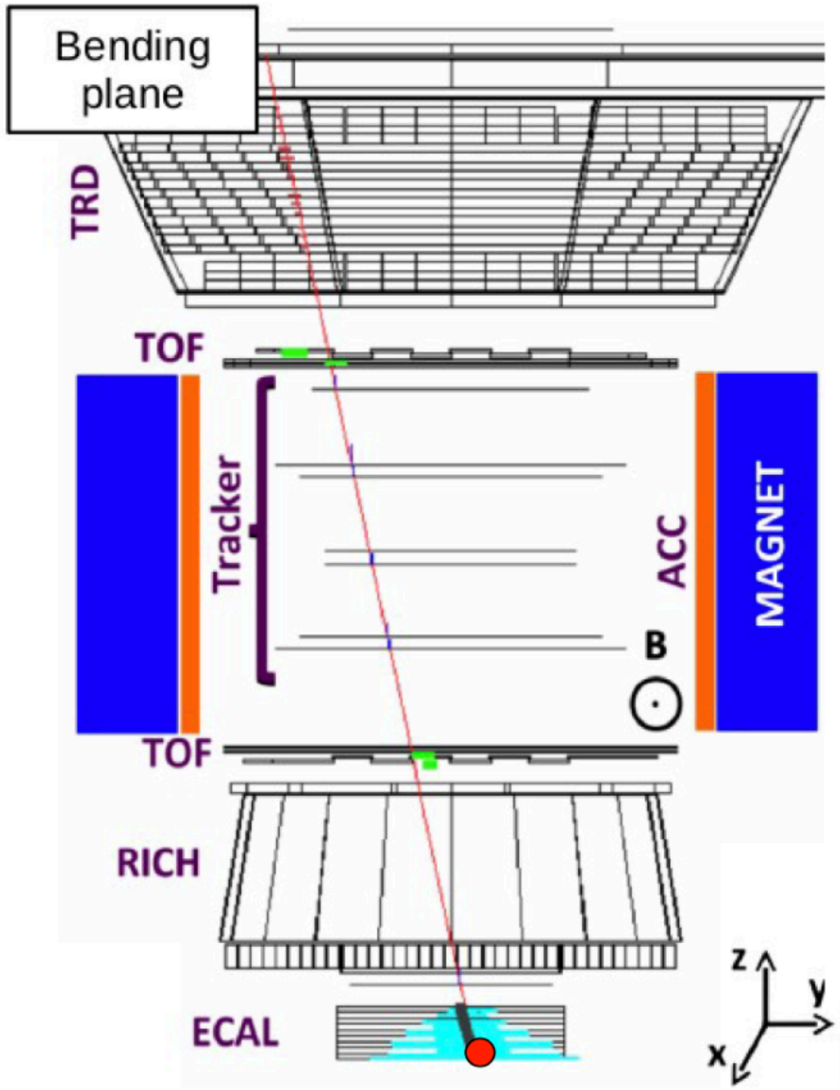


- measures cosmic rays in space without absorption through earth's atmosphere

AMS experiment



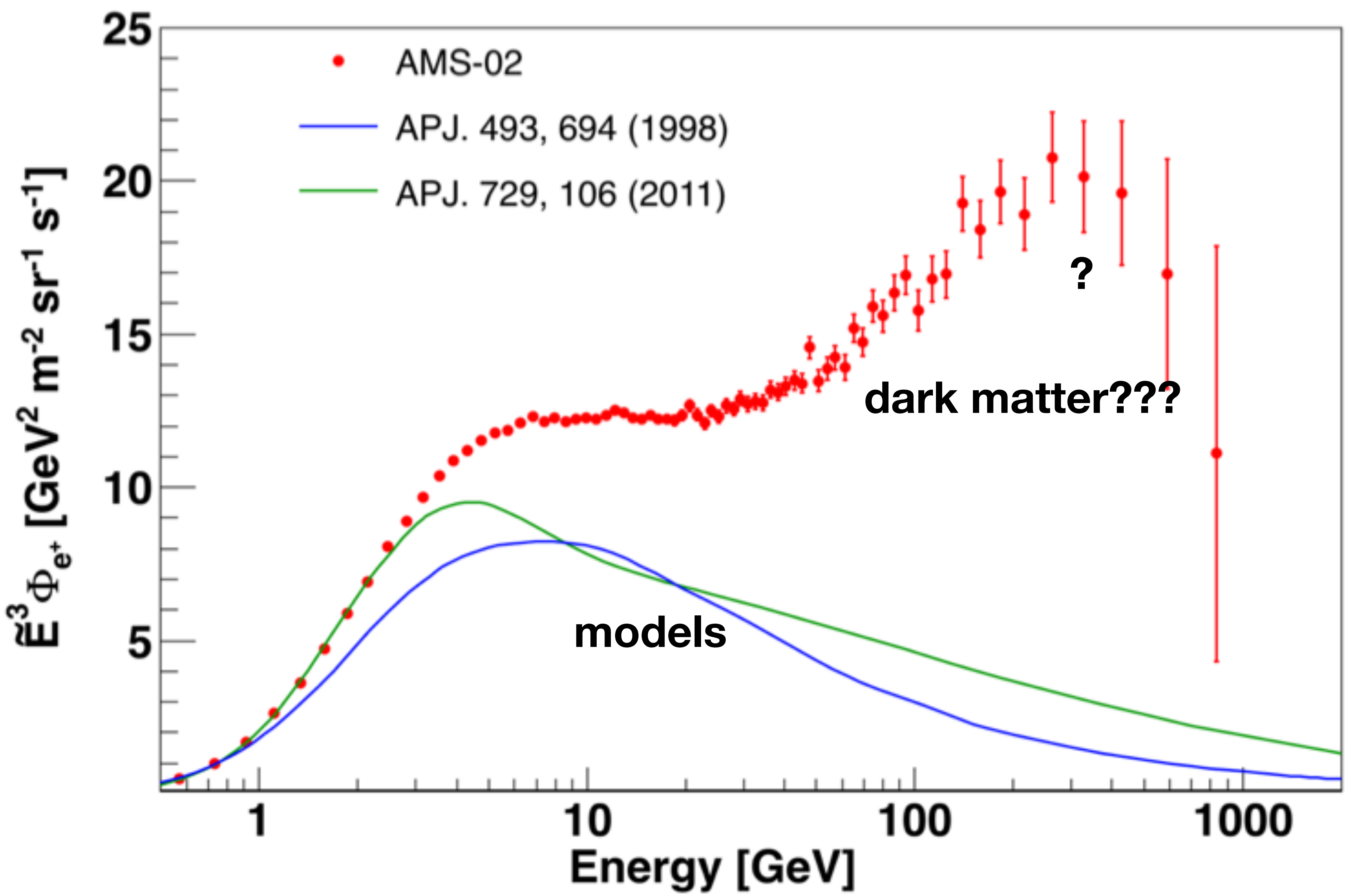
AMS experiment



	e⁻	p	He	
TRD 20 layers				e/p separation charge (|Z|)
TOF 4 layers				trigger velocity (β) charge (|Z|)
TRK 9 layers				momentum (p) sign (±Q) charge (|Z|)
RICH				velocity (β) charge (|Z|)
ECAL 20 layers				$e^{\pm}$ energy e/h separation γ trigger

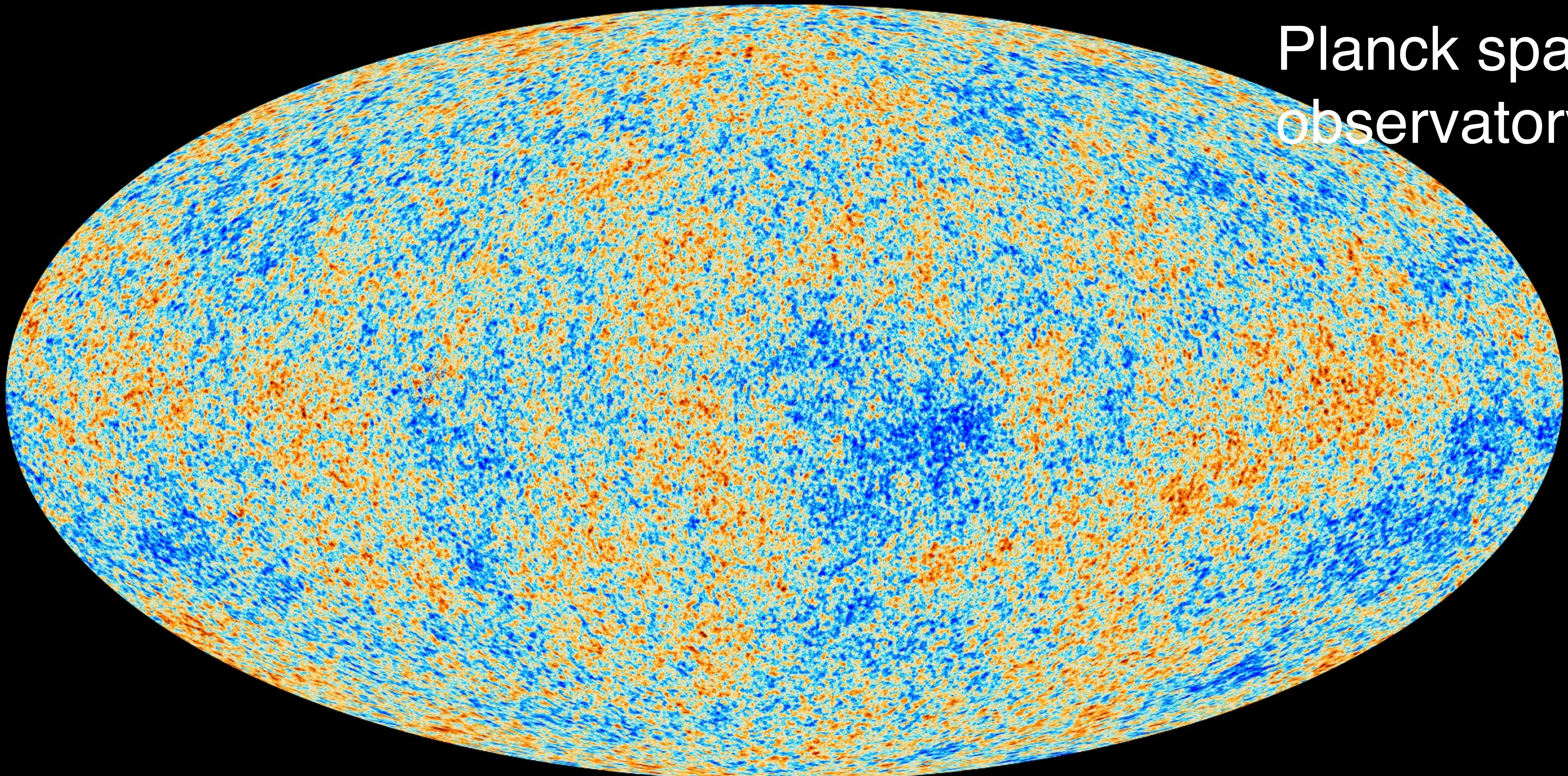
AMS experiment

- one of the highlights: positron spectrum



- countless other results, measurements still ongoing

cosmic microwave background

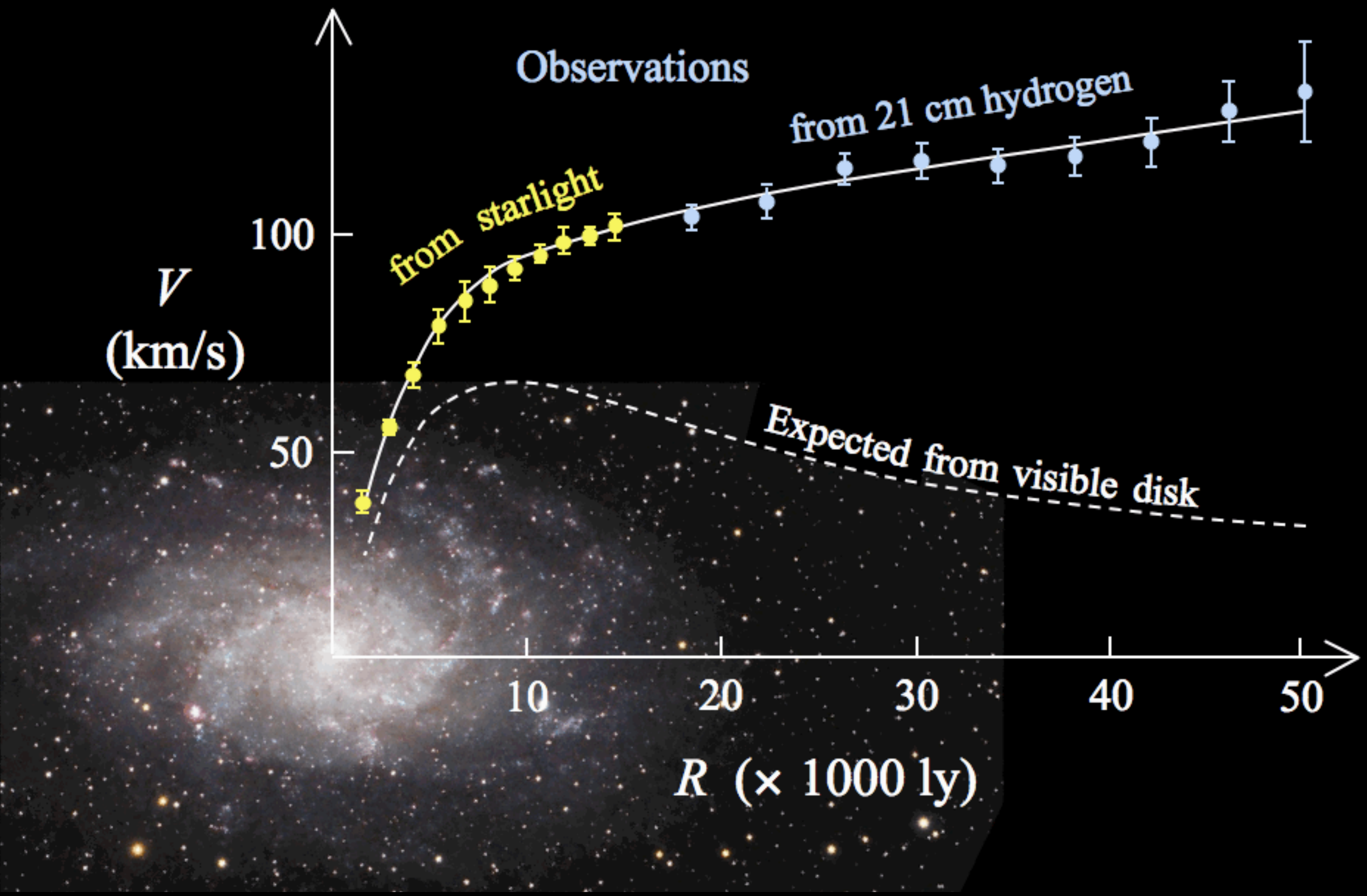


Planck space observatory

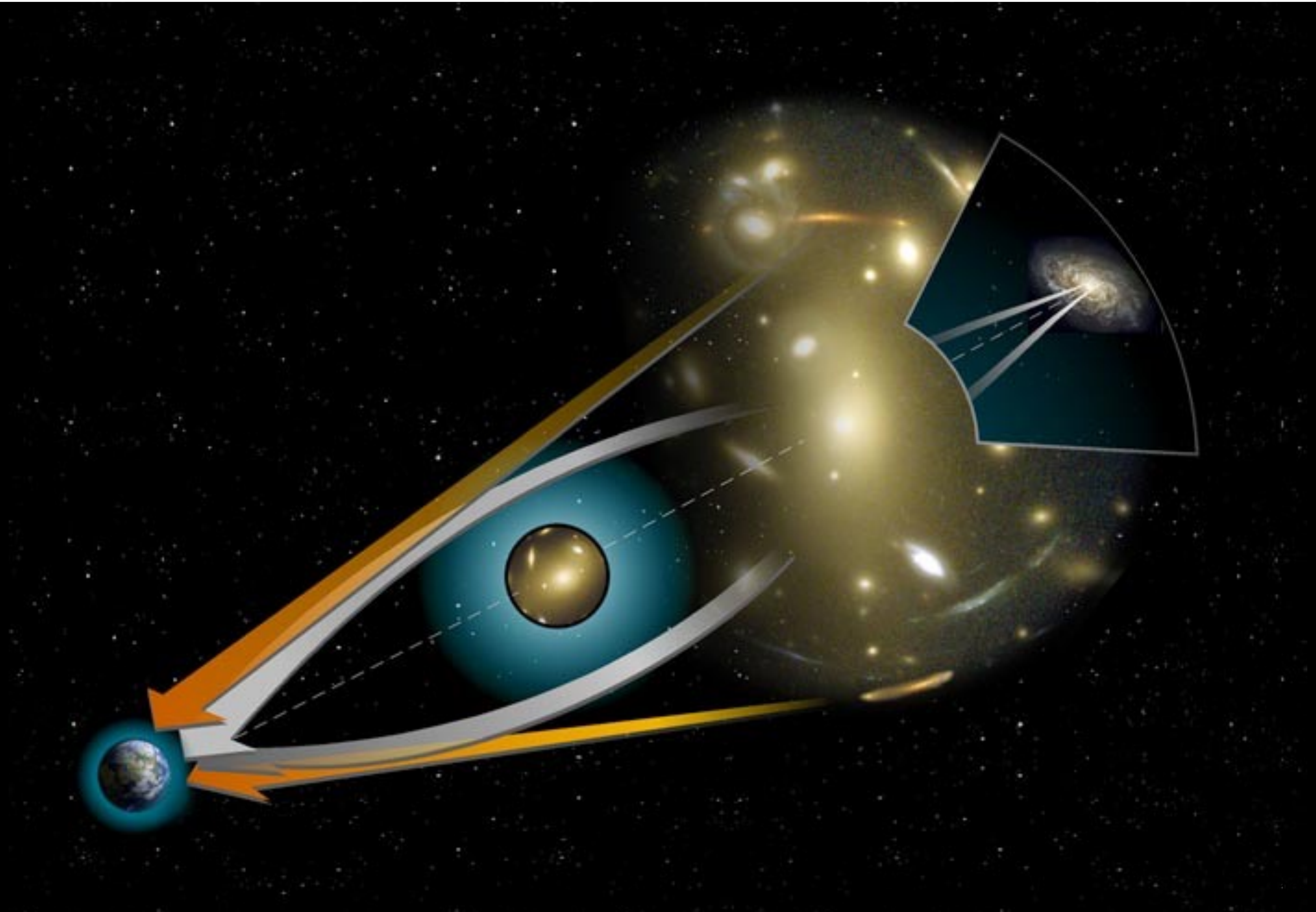
anisotropy distribution constrains cosmological models:

- expansion of the universe
- dark matter
- structure formation

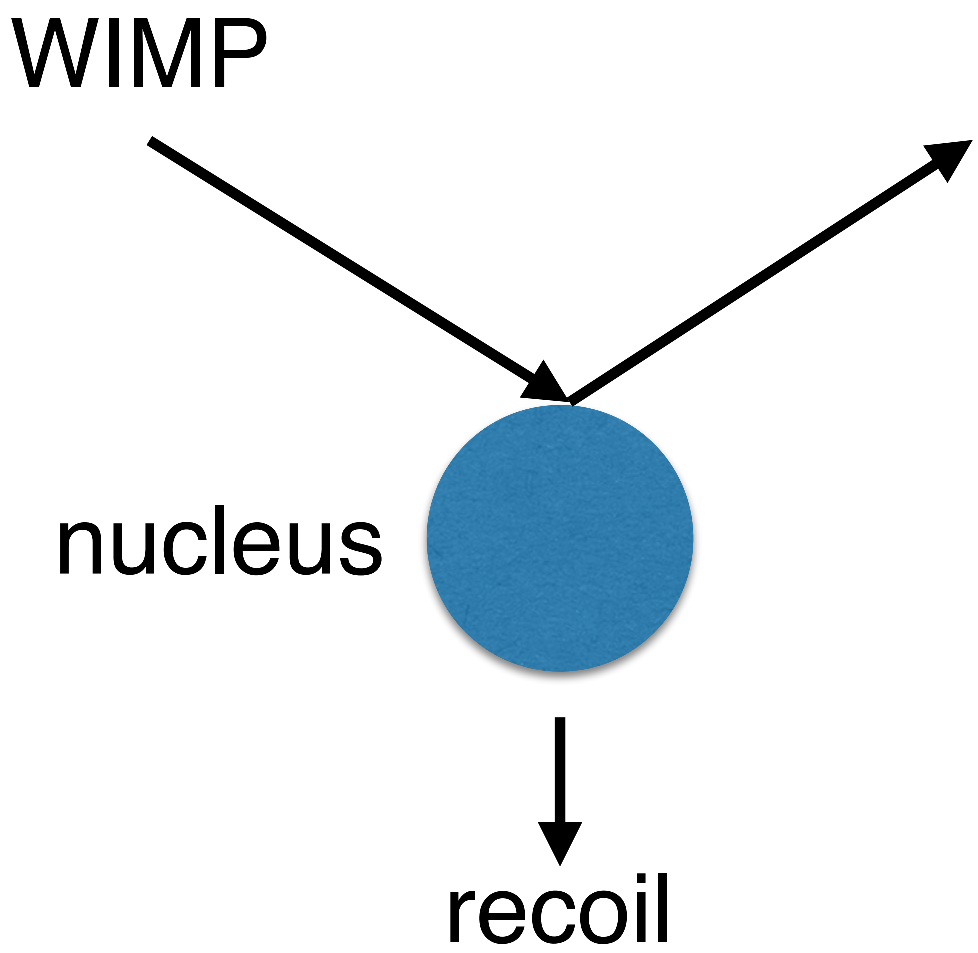
indications for dark matter

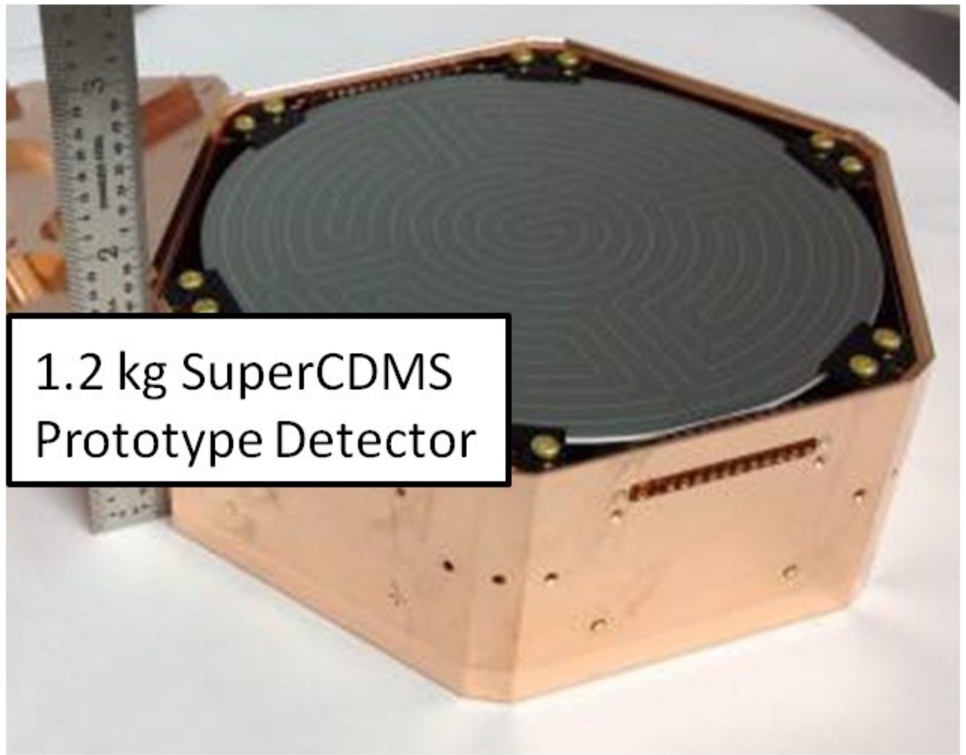


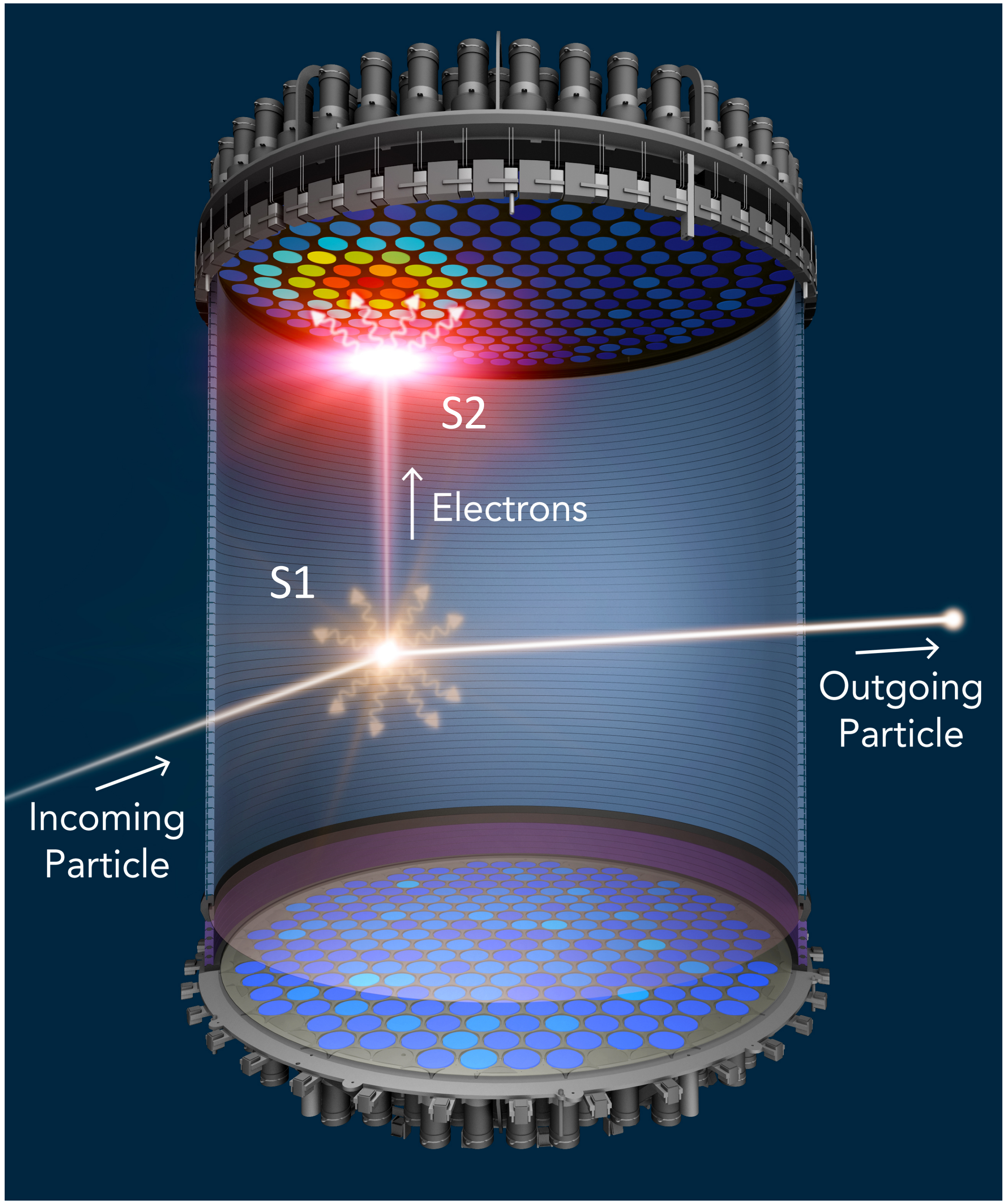
indications for dark matter



direct search for WIMPs





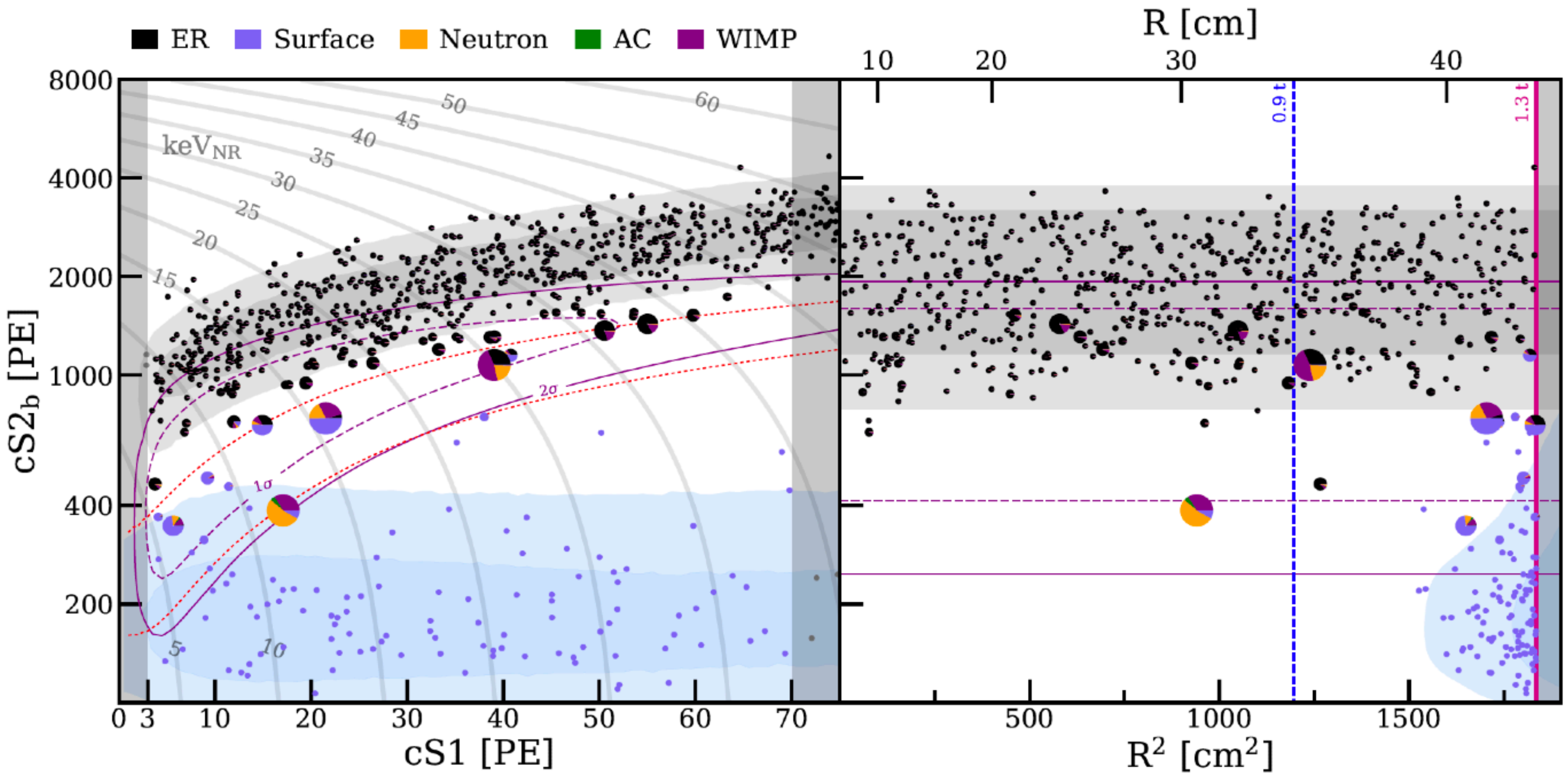


XENON experiment

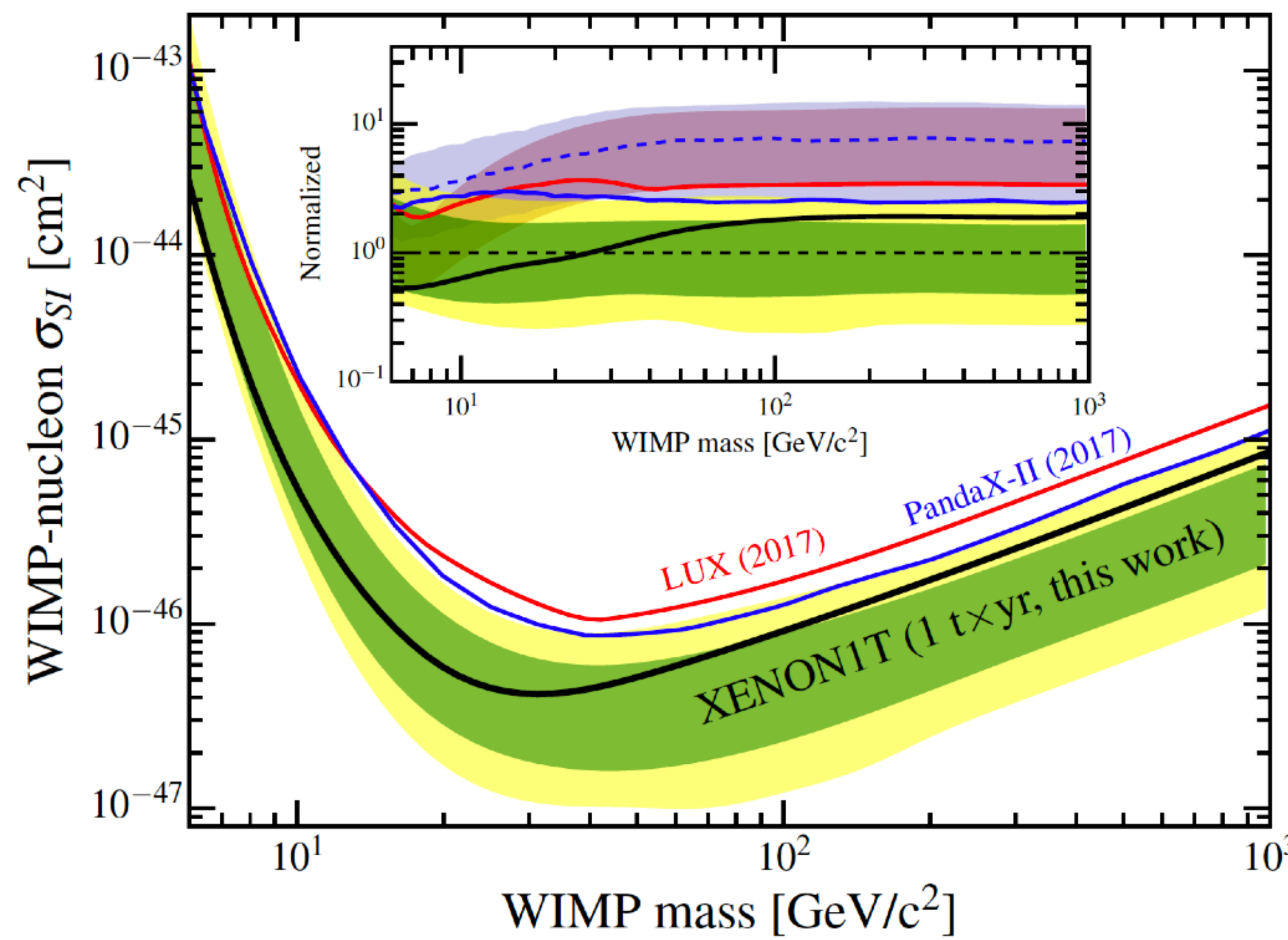
- incoming dark matter WIMP recoils on Xenon, which emits 178 nm photons (S1 signal)
- even single photons can be detected with the photo multiplier array
- in addition: ionisation drifts slowly in the electric field through the liquid phase.
- once the charge arrives at the surface (gaseous Xenon phase) a proportional gas amplification happens and the ionisation signal is read out (S2 signal)
- the S1/S2 signal ratio is used to suppress background and noise

XENON experiment

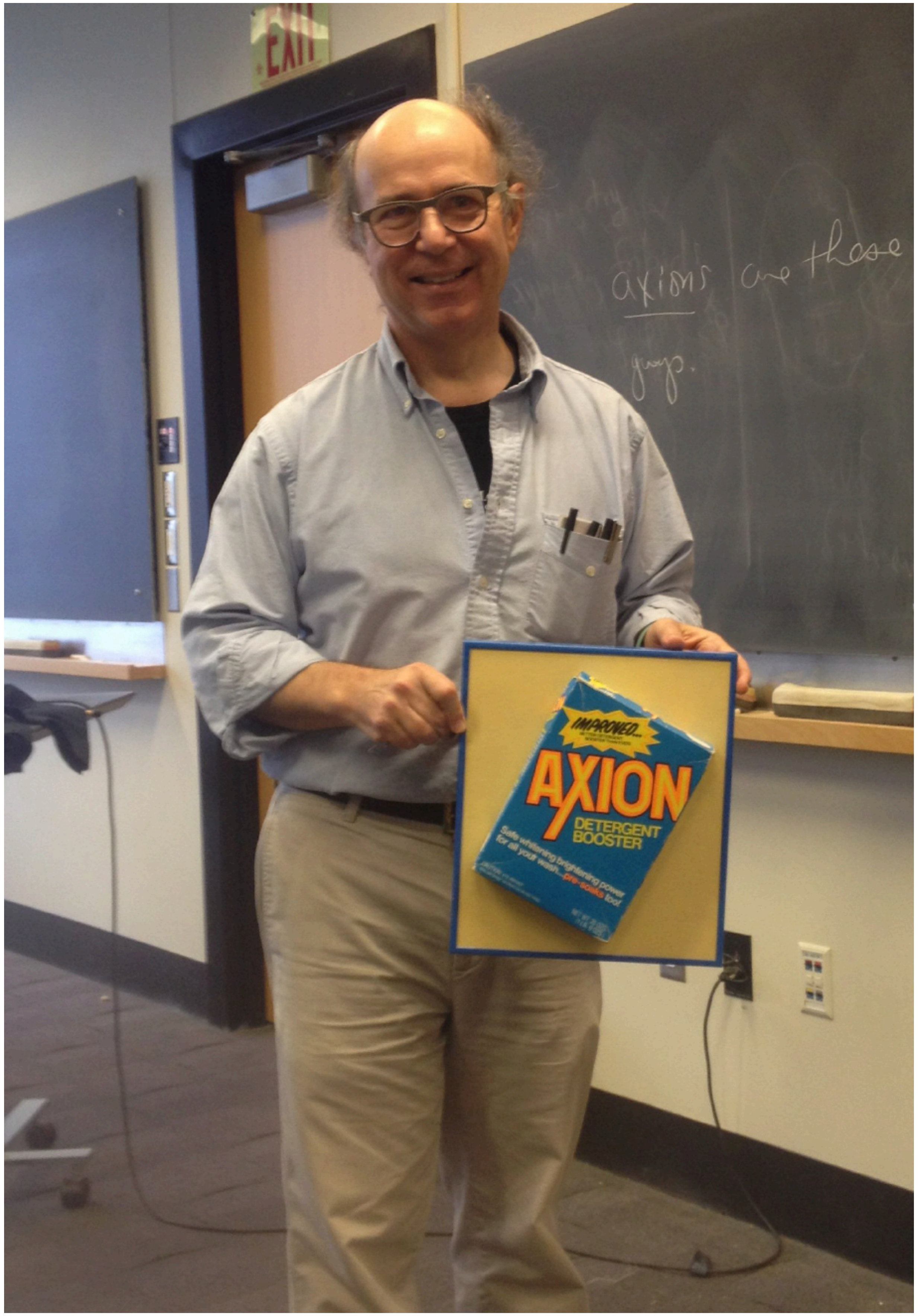
- black markers are background
- large coloured markers indicate the probability for a WIMP



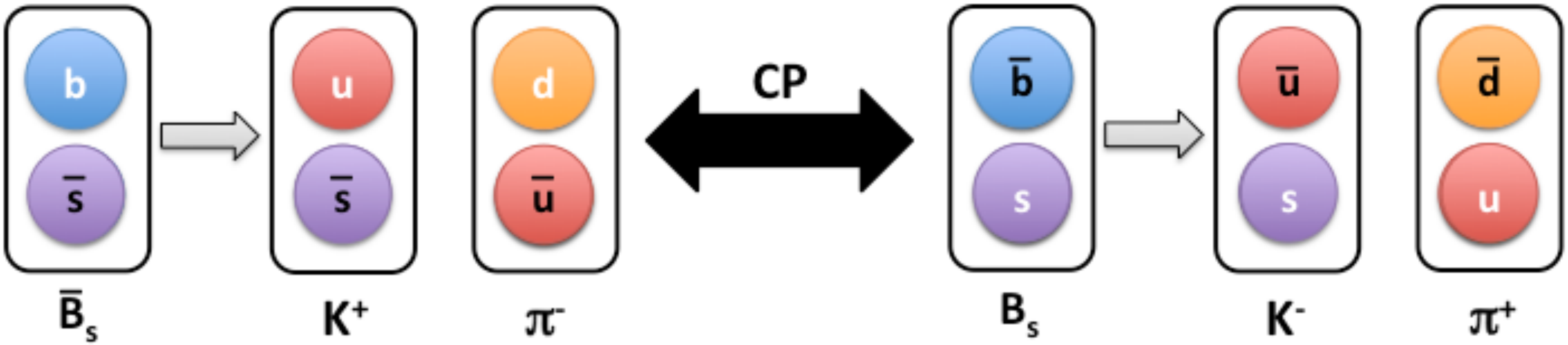
- no DM observed but slight excess
- more data taking necessary



Axion physics



CP violation



- decay rates **differ** at percent level
- CP symmetry is violated
- well established in EWK theory
- CPT is the **true symmetry**

strong CP problem

- CP violation
  - **not** established in strong interaction

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} \tilde{G}^{a\mu\nu} G^a_{\mu\nu}$$

- CP violating term
- θ is arbitrary angle

- gluon field

- why is $\theta == 0$?

- possible solution:
  - θ is a new scalar field
  - QCD potential dynamically sets $\theta == 0$

axion electrodynamics

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^{\mu}A_{\mu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2a^2 - \frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a,$$

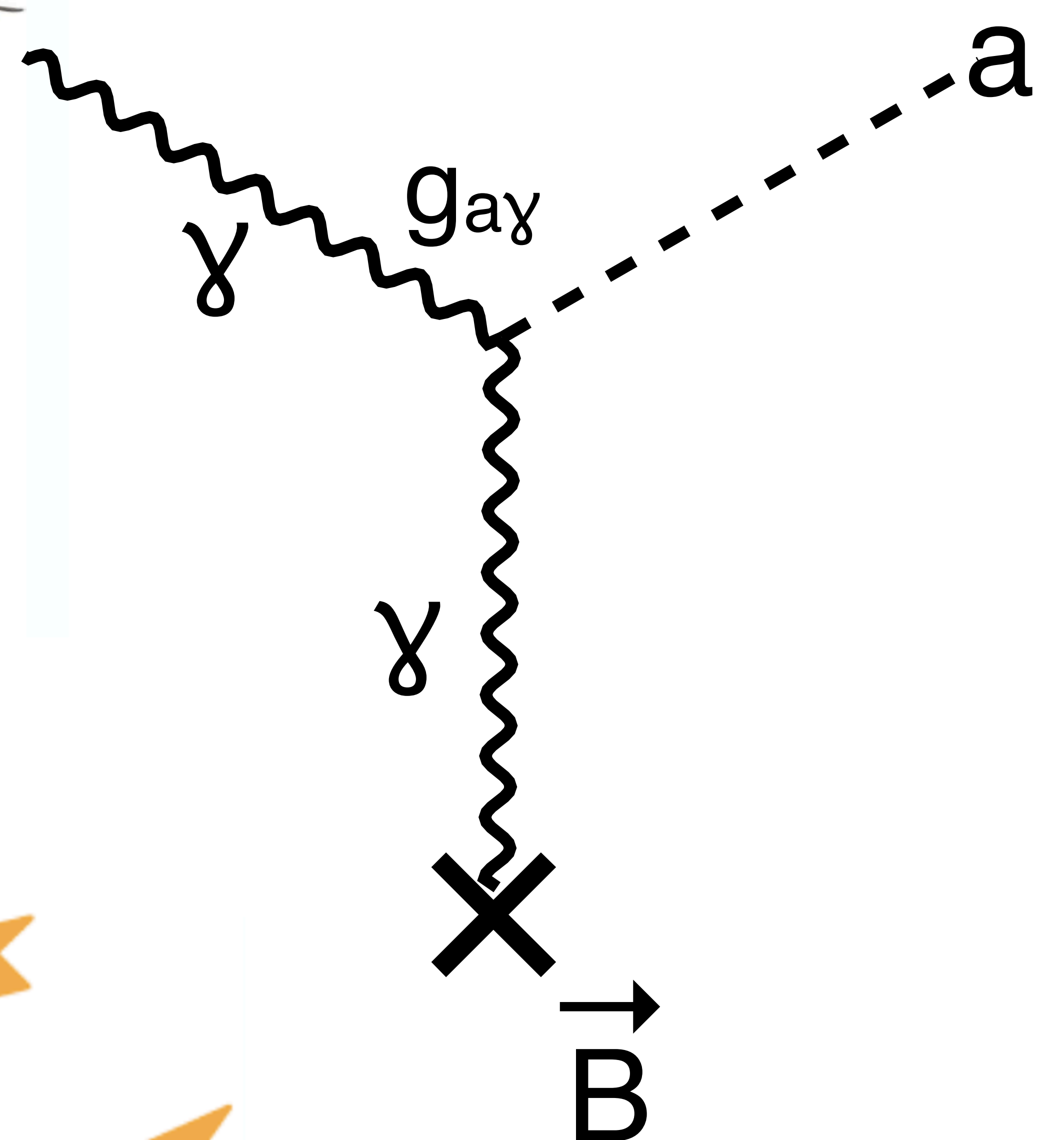
axion DM modifies maxwell equations:

- new equations:

$$\begin{aligned}
\boldsymbol{\nabla}\cdot\mathbf{E} &= \rho - g_{a\gamma}\mathbf{B}\cdot\boldsymbol{\nabla}a\,,\\
\boldsymbol{\nabla}\times\mathbf{B} - \dot{\mathbf{E}} &= \mathbf{J} + g_{a\gamma}\left(\mathbf{B}\,\dot{a} - \mathbf{E}\times\boldsymbol{\nabla}a\right)\\
\boldsymbol{\nabla}\cdot\mathbf{B} &= 0\,,\\
\boldsymbol{\nabla}\times\mathbf{E} + \dot{\mathbf{B}} &= 0\,,\\
\ddot{a} - \boldsymbol{\nabla}^2a + m_a^2a &= g_{a\gamma}\mathbf{E}\cdot\mathbf{B}\,.
\end{aligned}$$

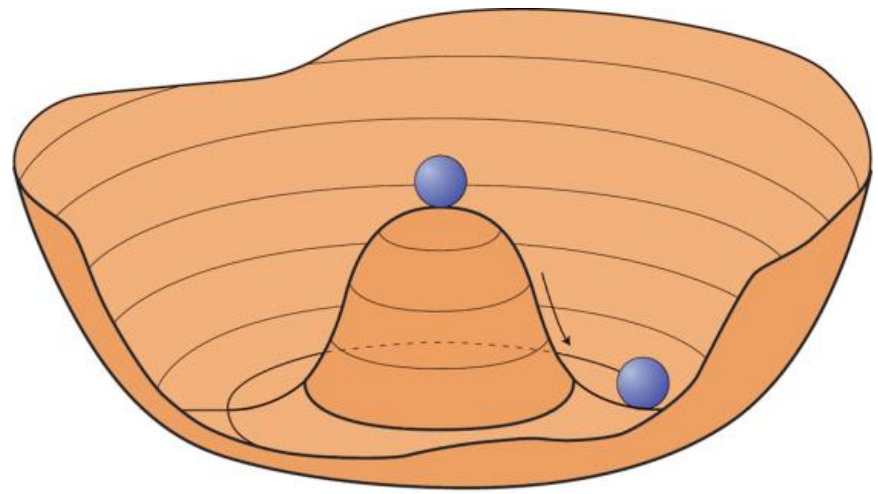
Axion Photon Kopplung

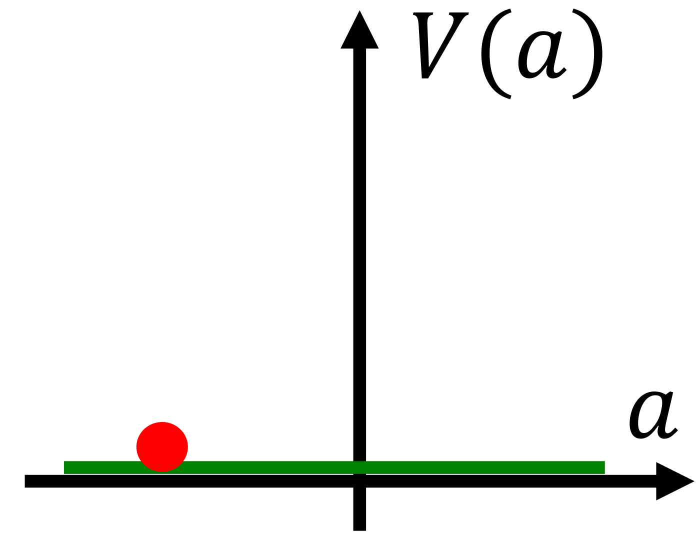
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^{\mu}A_{\mu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2a^2 - \boxed{\frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a,}$$



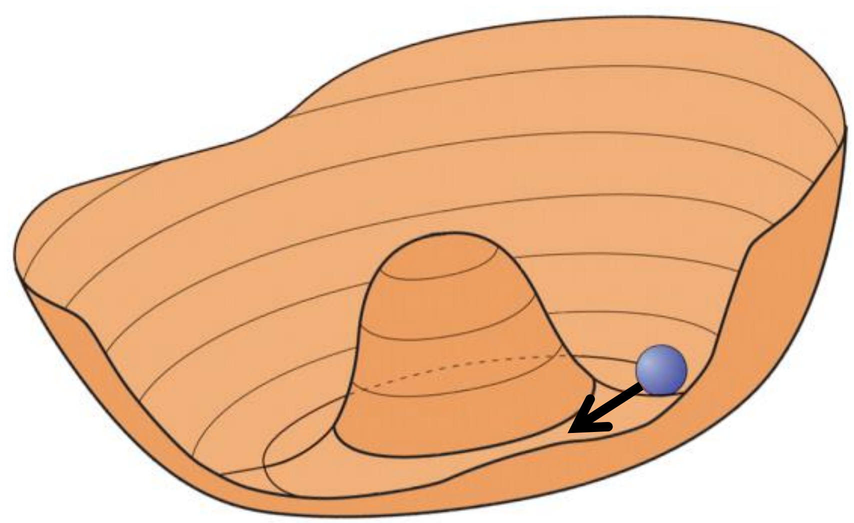
the axion in the early universe

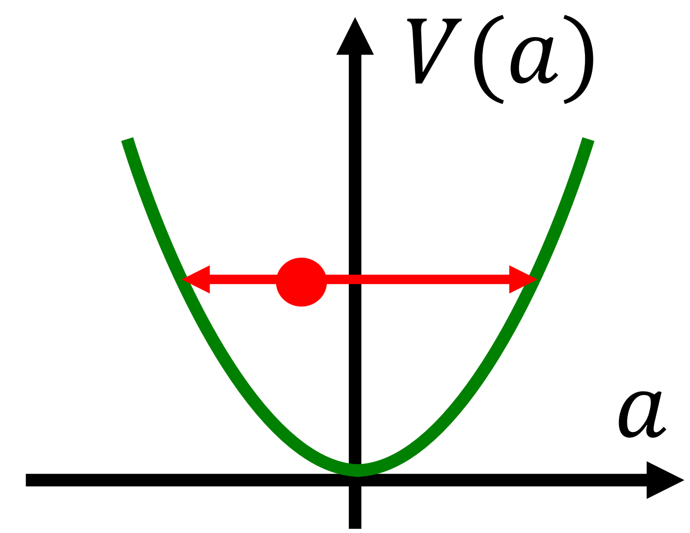
- new $U(1)_{PQ}$ symmetry breaks at high scale f_a





- potential changes shape when universe cools down (T~1GeV)
- axion acquires mass
- field starts oscillating
- expected density compatible with DM





$\bar{\Theta} = 0$

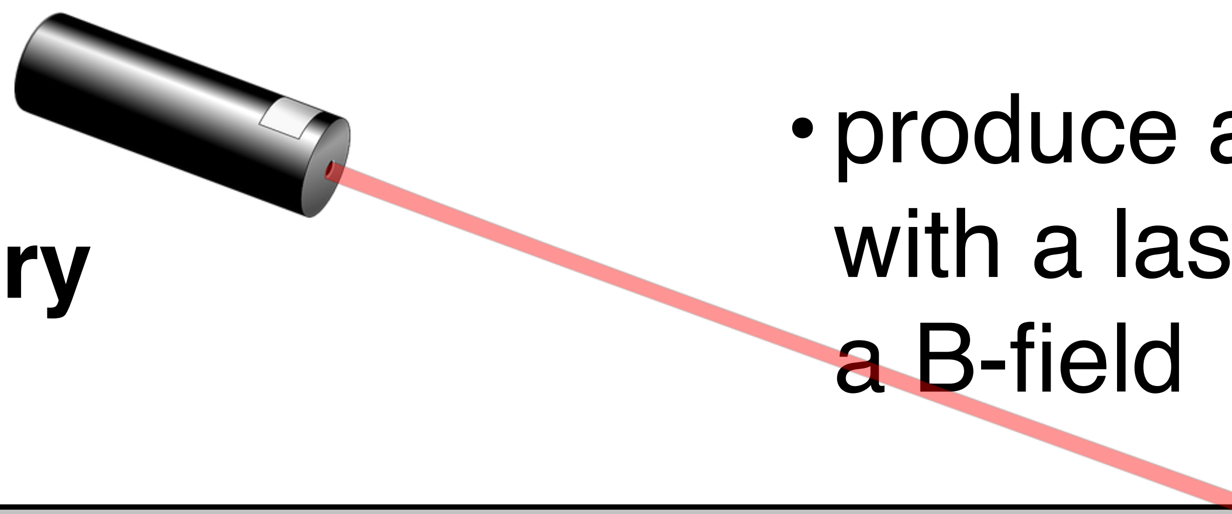
axions born from vacuum realignment

how to search for axions

- **helioscope**

- search for axions emitted by the sun

- **laboratory**

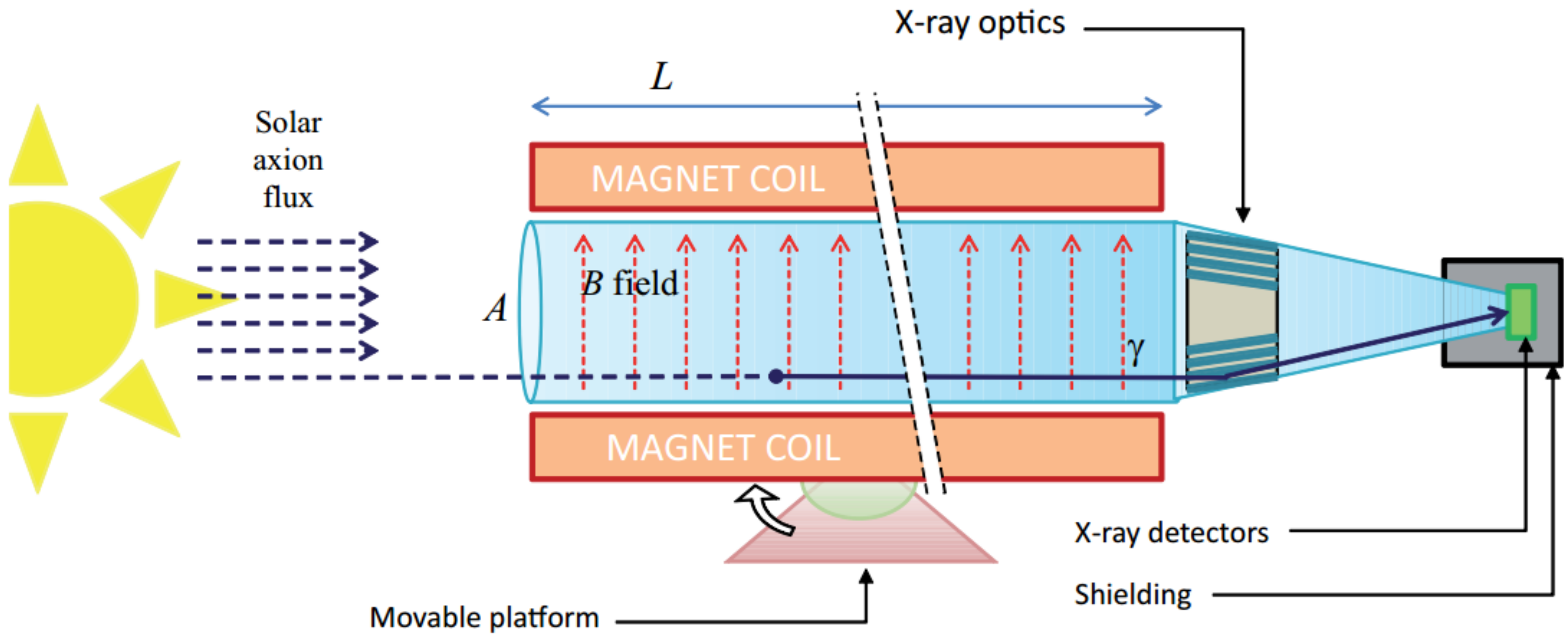


- produce axions with a laser and a B-field

- **haloscope**

- find axions in the galactic DM halo

helioscope: “CAST”

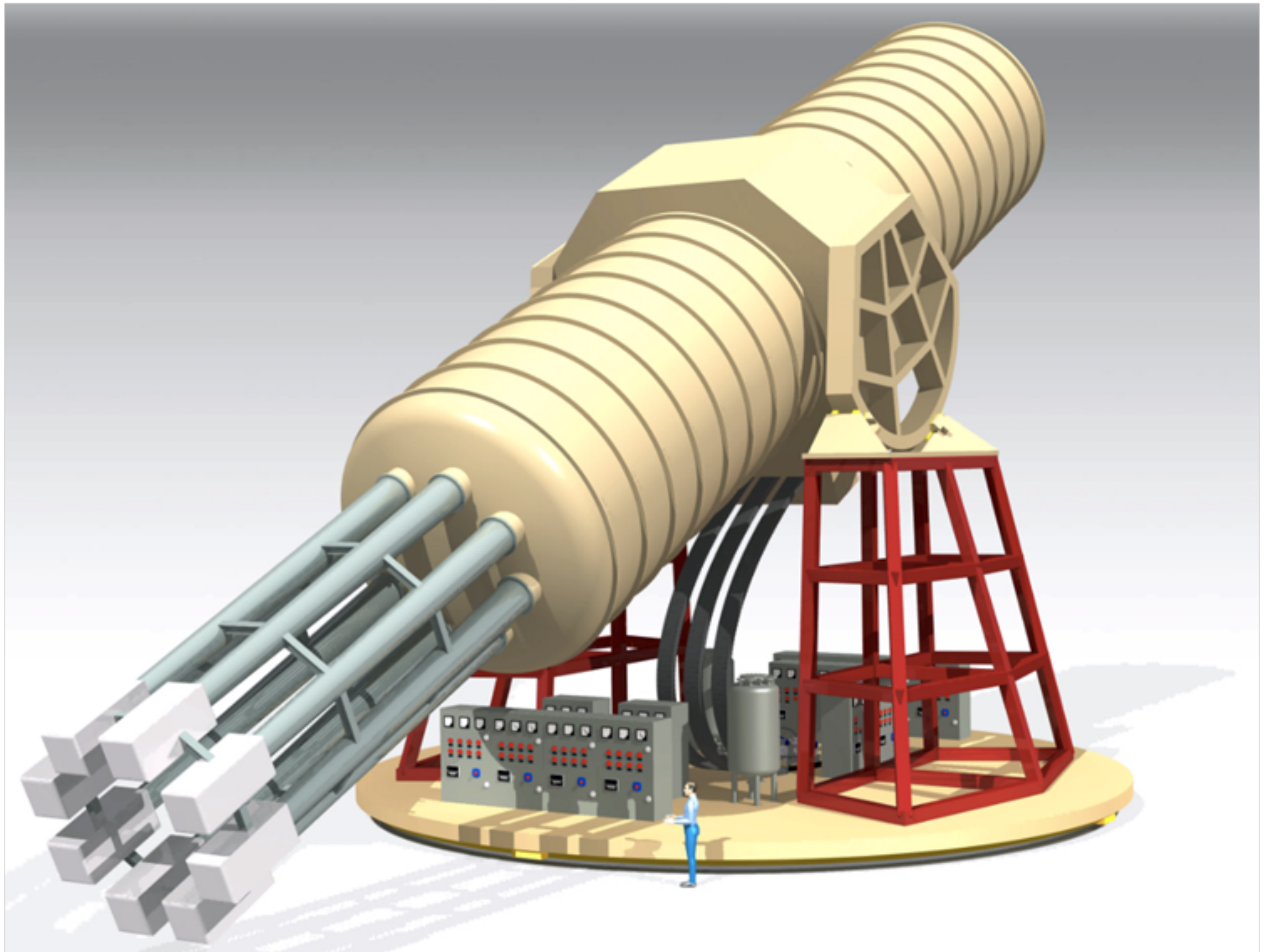


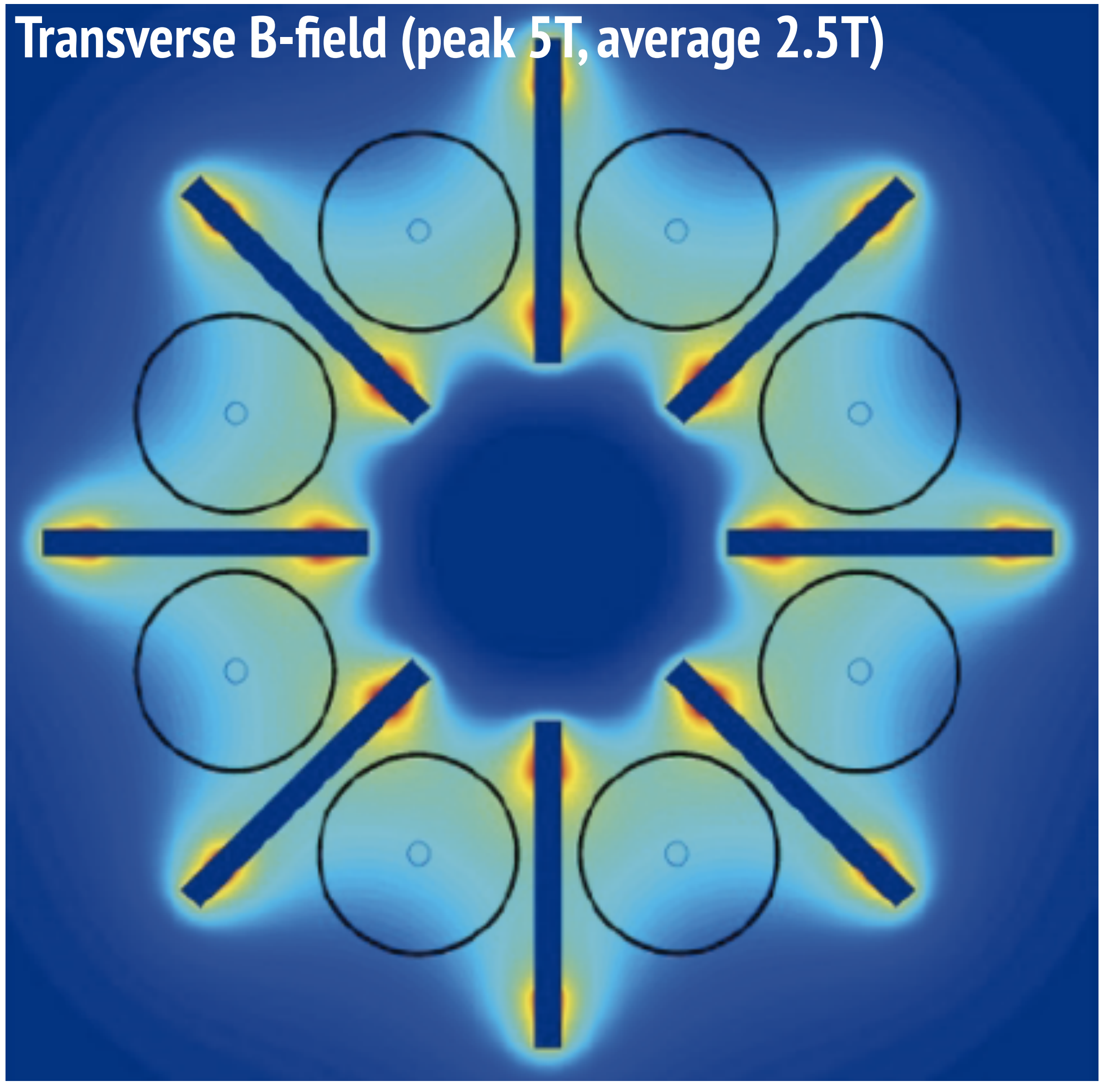
- in operation since 2003

future experiments

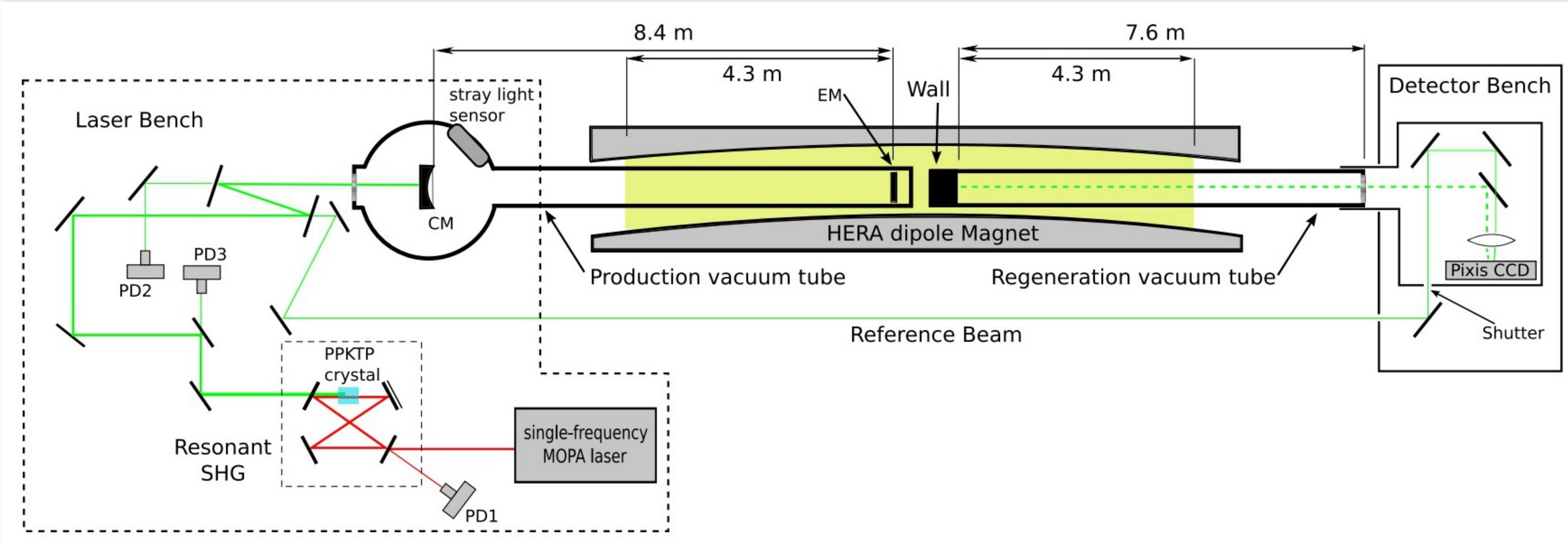
- IAXO: next generation helioscope
  - larger, stronger magnet
- when and how not yet clear

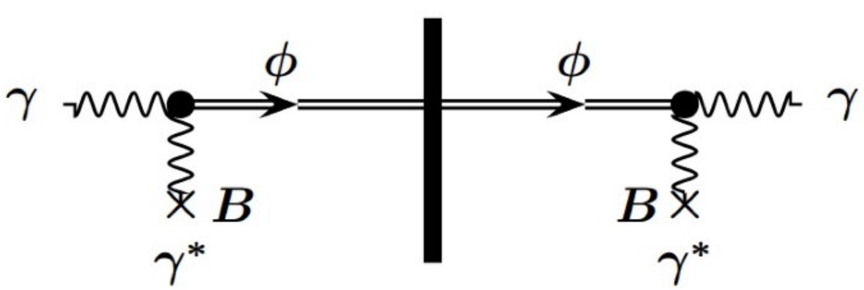
- more than one order of magnitude improvement over CAST





laboratory: "ALPS"

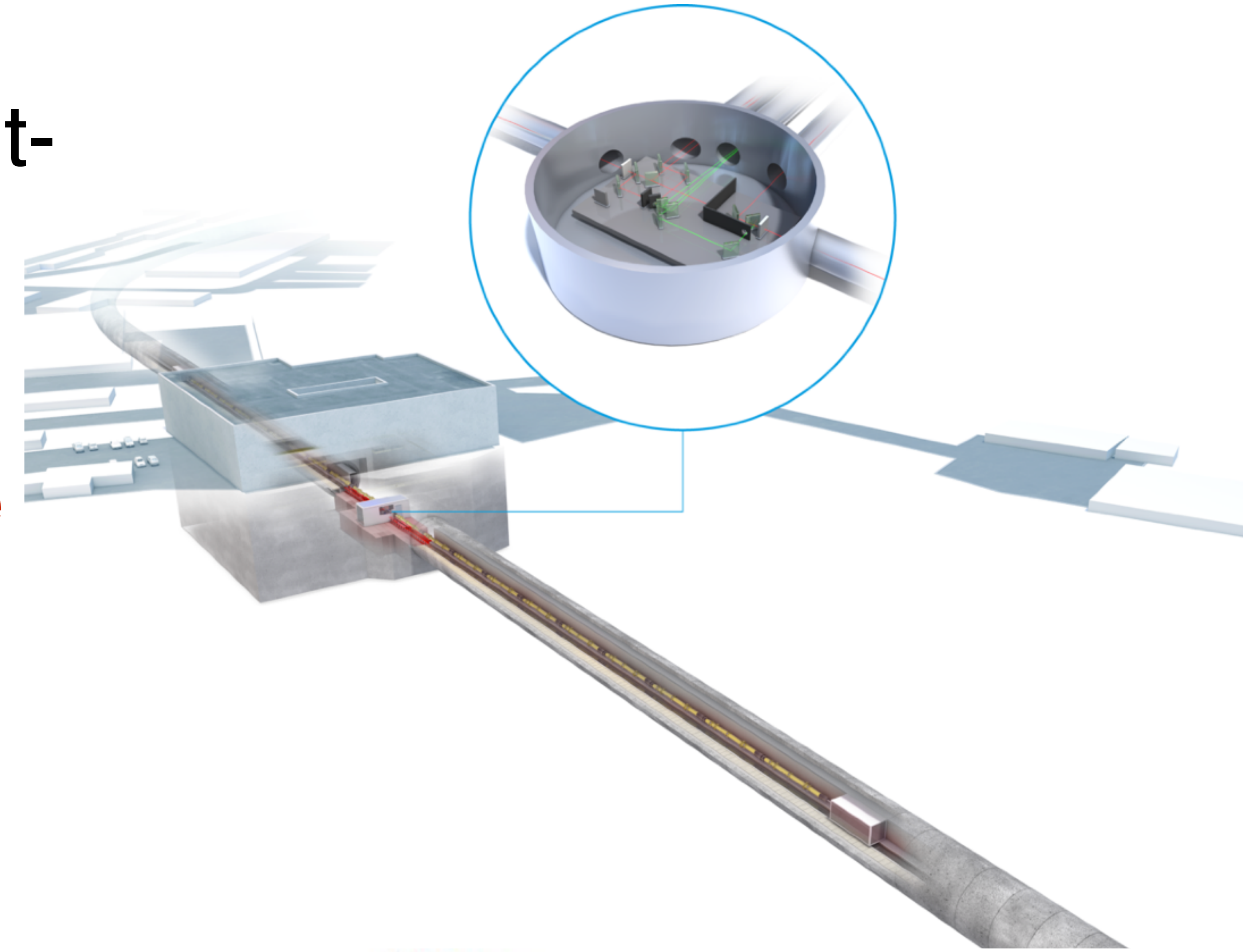


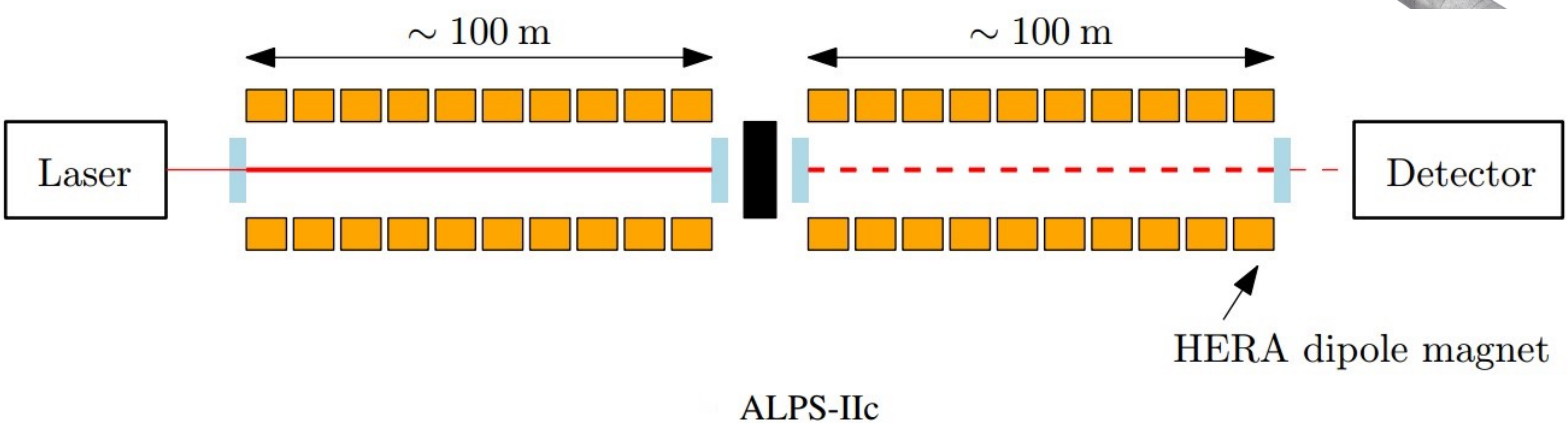


future experiments

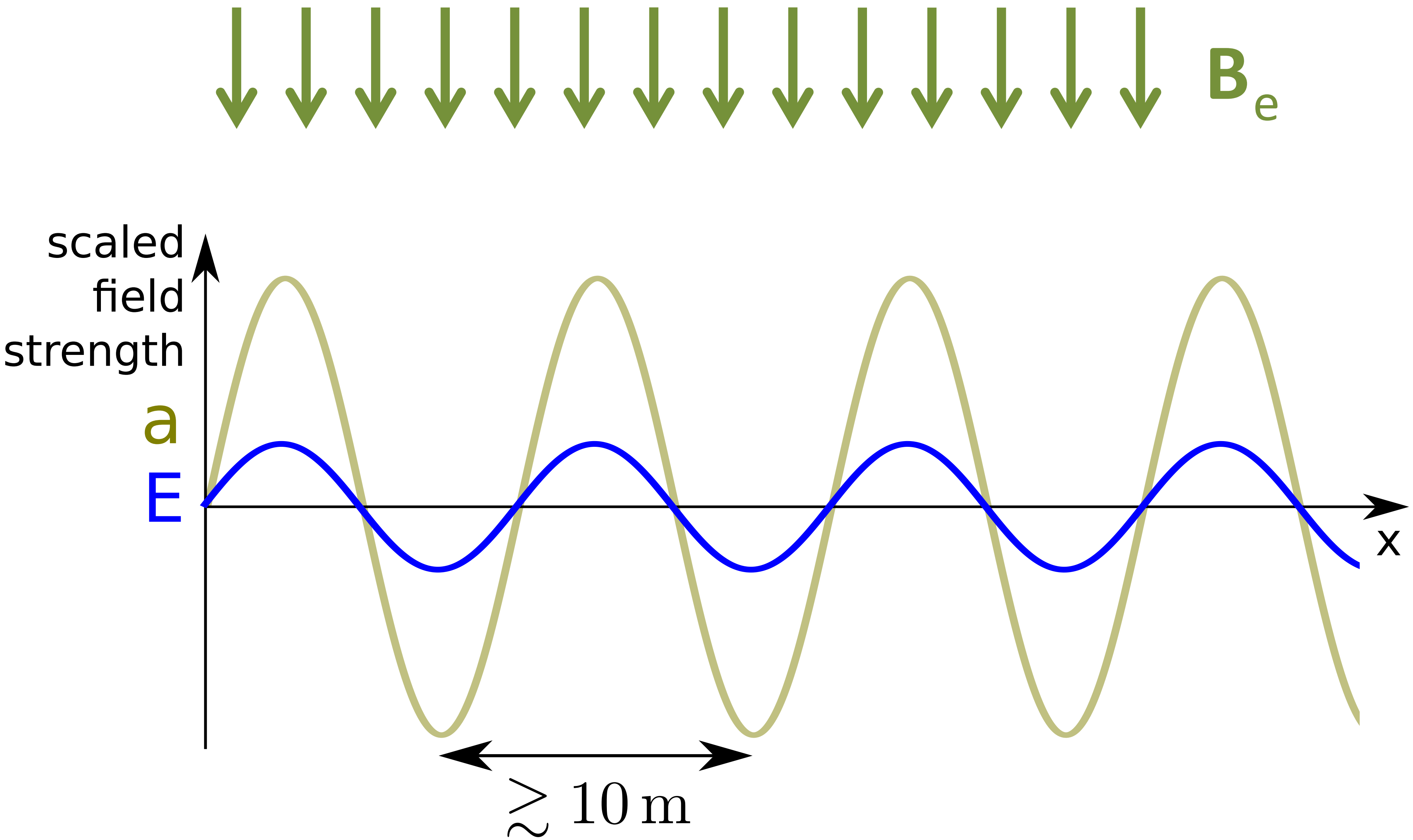
arXiv:1302.5647

- ALPS-II: next generation light-shining-through-the-wall
  - more magnets, better laser, better detector
  - resonator in regeneration volume



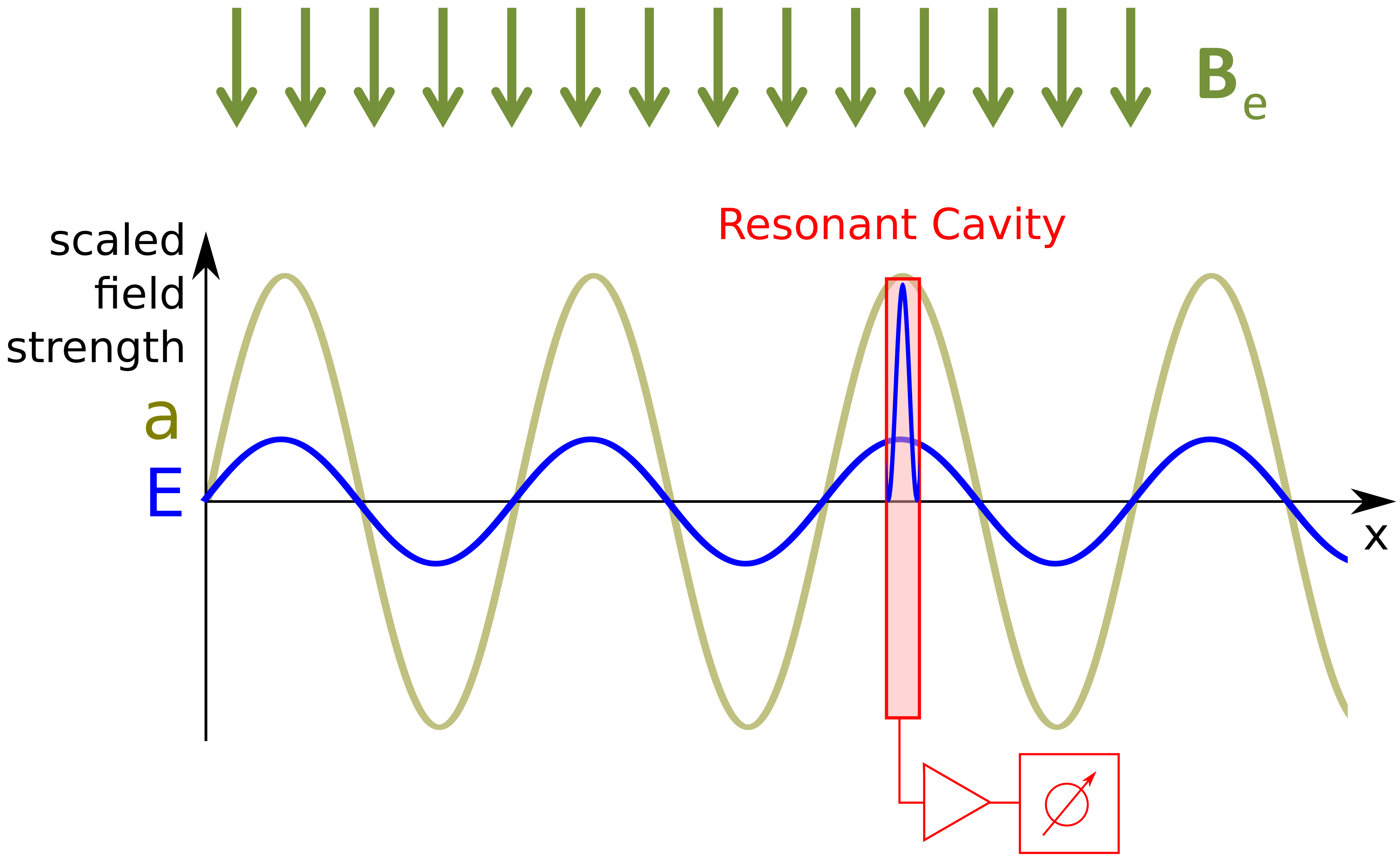


axion electrodynamics



$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$$

axion electrodynamics



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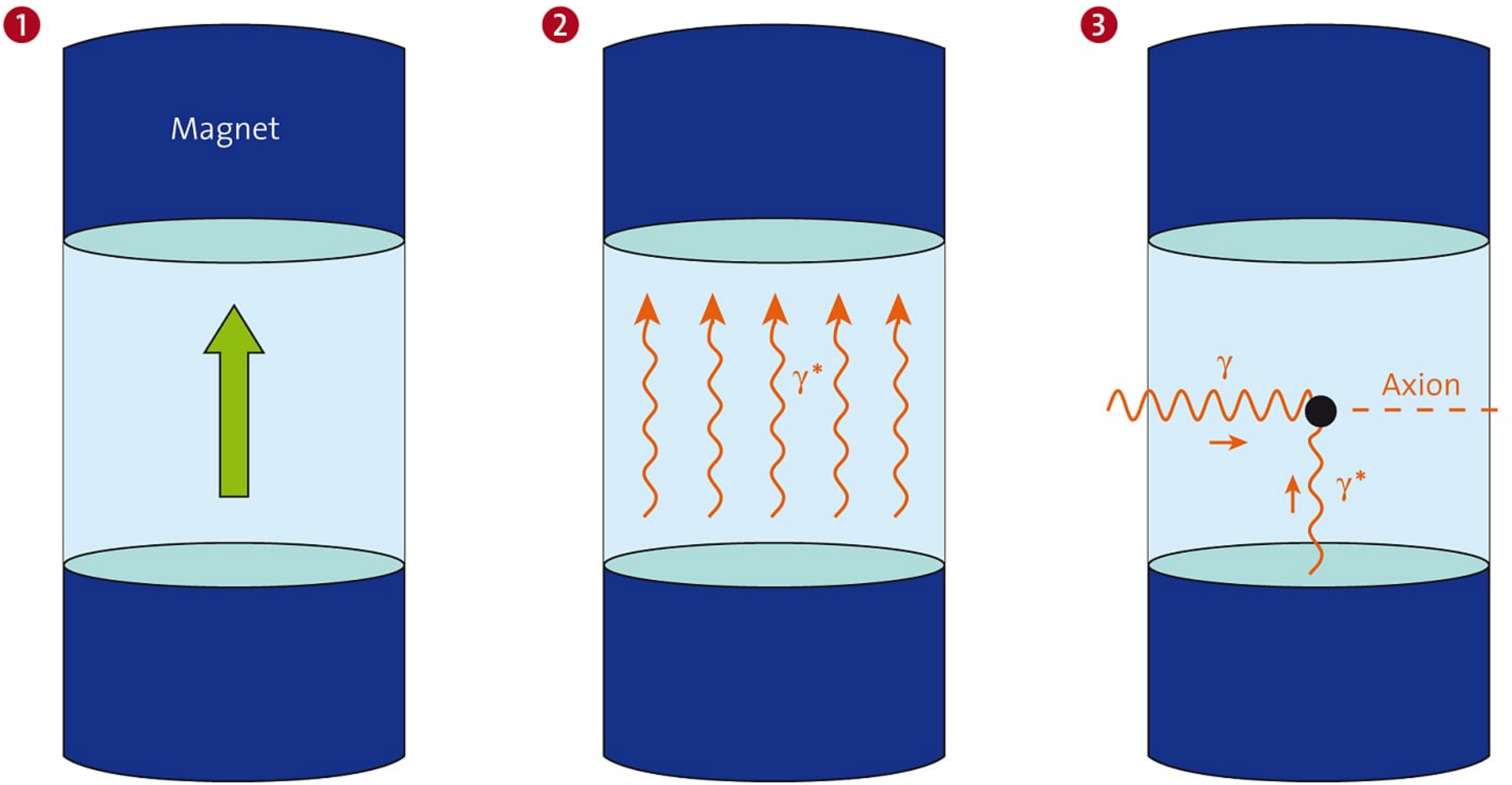
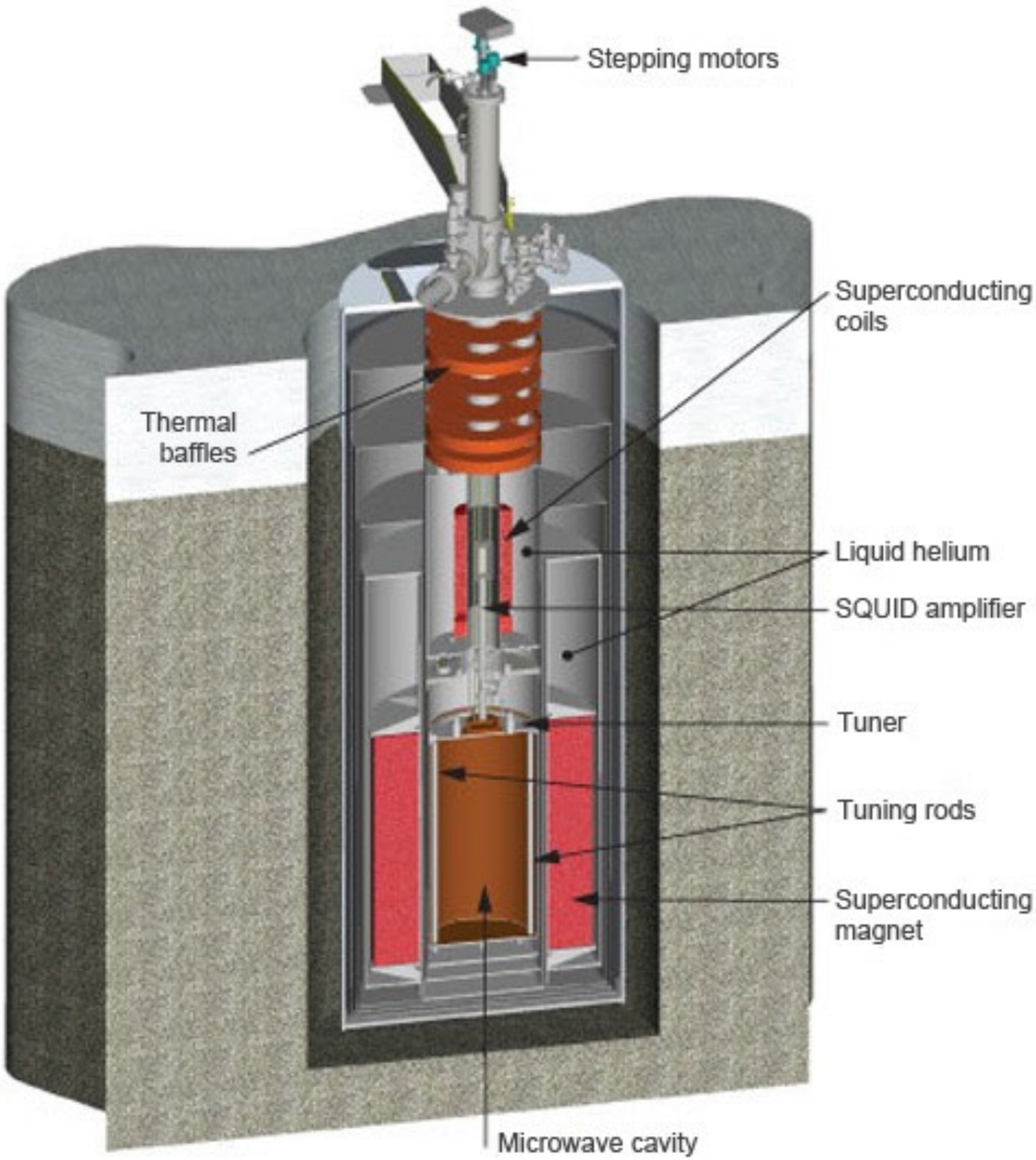


Magnetfeld

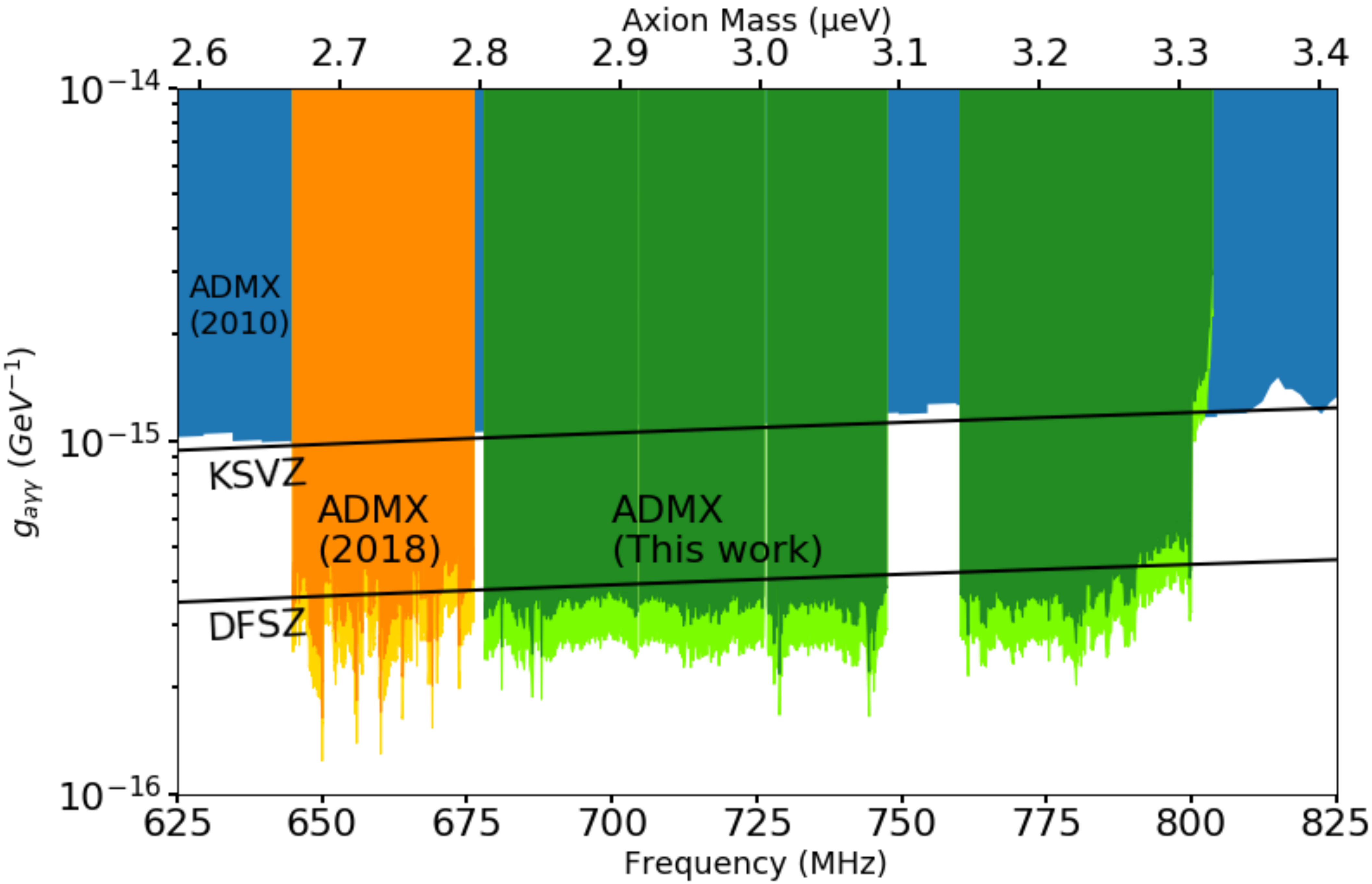
Magnetfeld, dargestellt als »See« virtueller Photonen

Umwandlung von Photonen in ein Axion

haloscope: "ADMX"



ADMX results



no axion found, but limits are set (ruled out in the colored regions of the parameter space)

challenges for ADMX-like experiments

emitted power from cavity

arXiv:1804.05750

$$P_{\text{axion}} = 1.9 \times 10^{-22}\text{W} \left(\frac{V}{136\ l}\right) \left(\frac{B}{6.8\ \text{T}}\right)^2 \left(\frac{C}{0.4}\right) \left(\frac{g_\gamma}{0.97}\right)^2 \left(\frac{\rho_{\text{a}}}{0.45\ \text{GeV cm}^{-3}}\right) \left(\frac{f}{650\ \text{MHz}}\right) \left(\frac{Q}{50,000}\right)$$

needs to scale with f^{-3}

is expensive

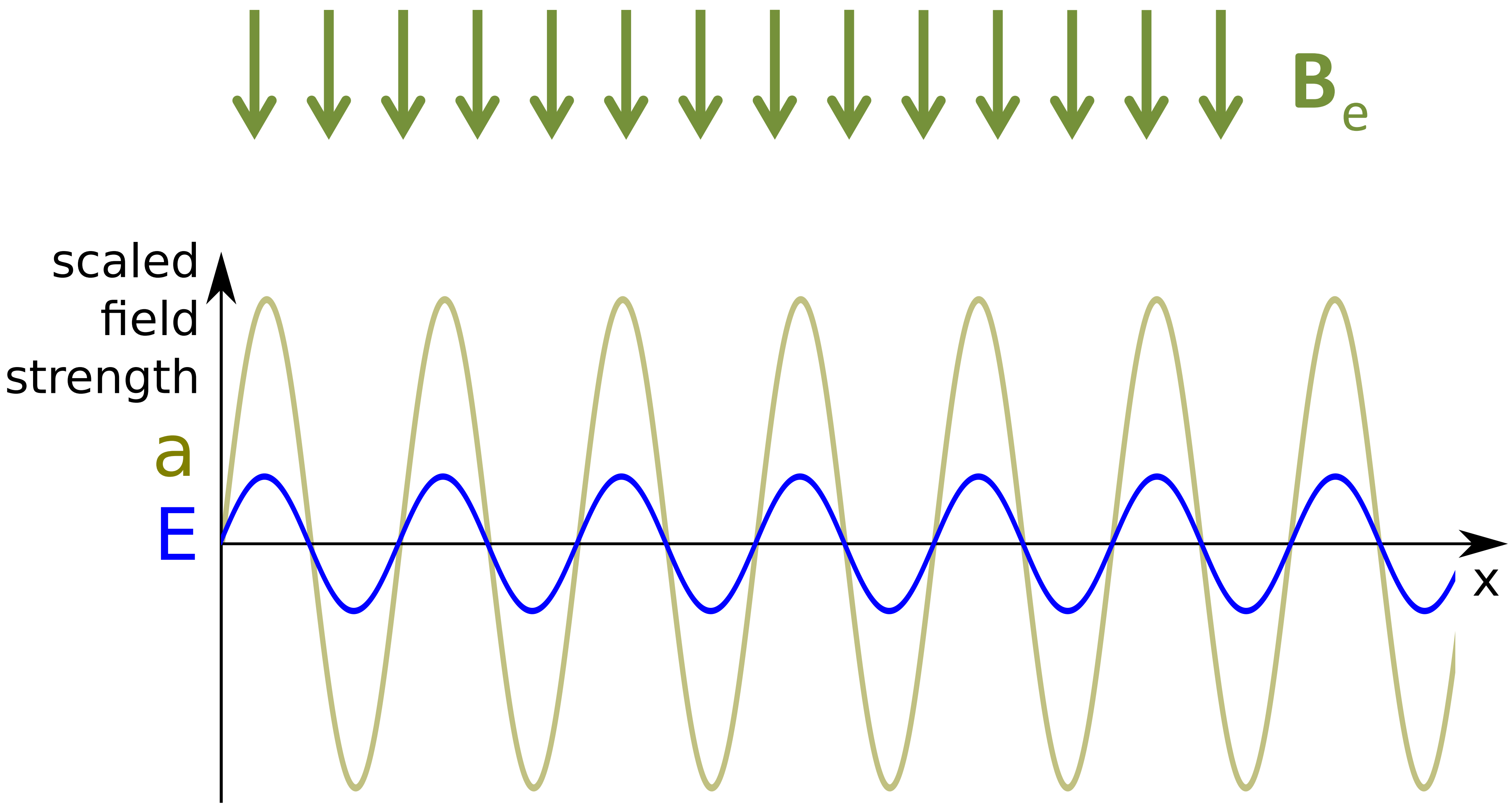
given by nature

scan this

technical limitations, decreases with larger f

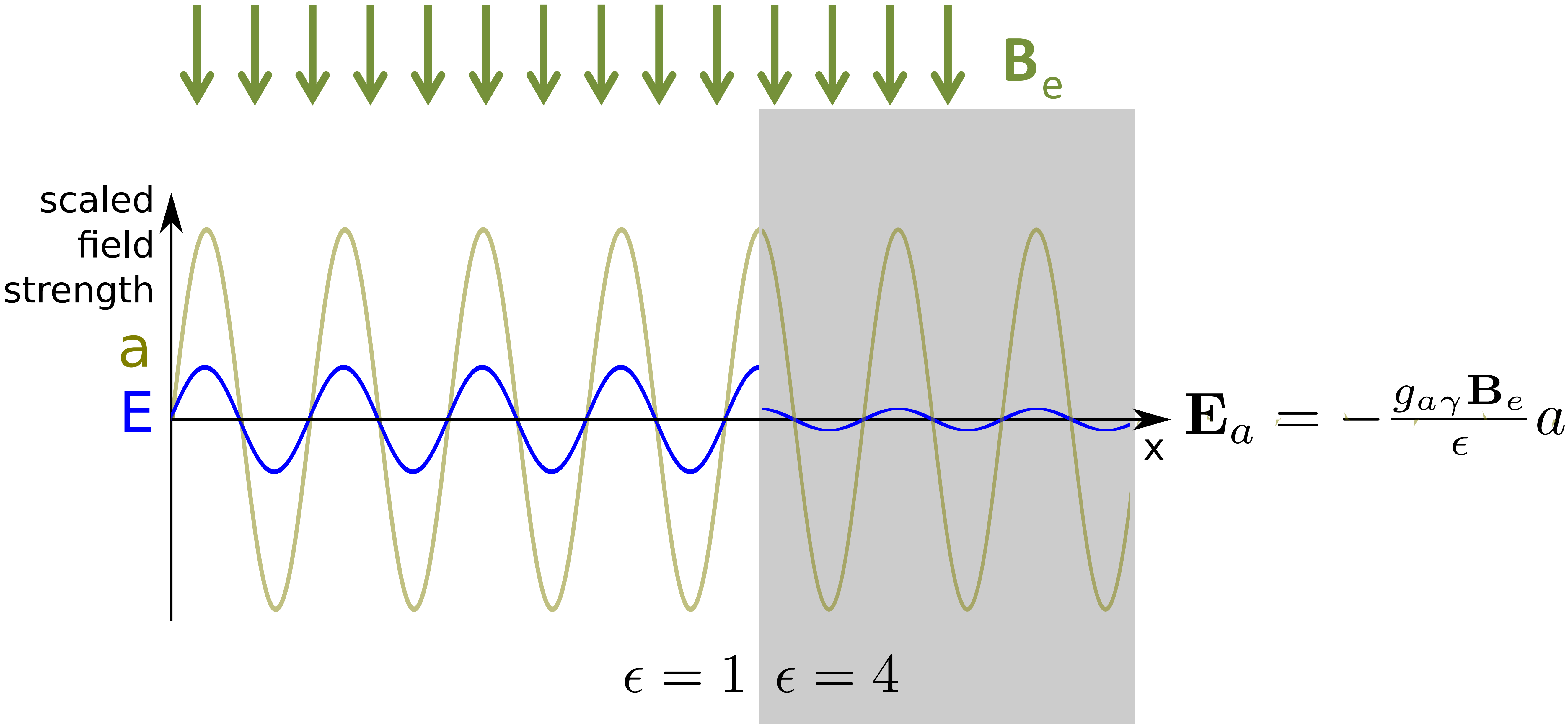
reach of cavity haloscope limited for higher frequency (mass)
solution: dielectric haloscope

axion electrodynamics

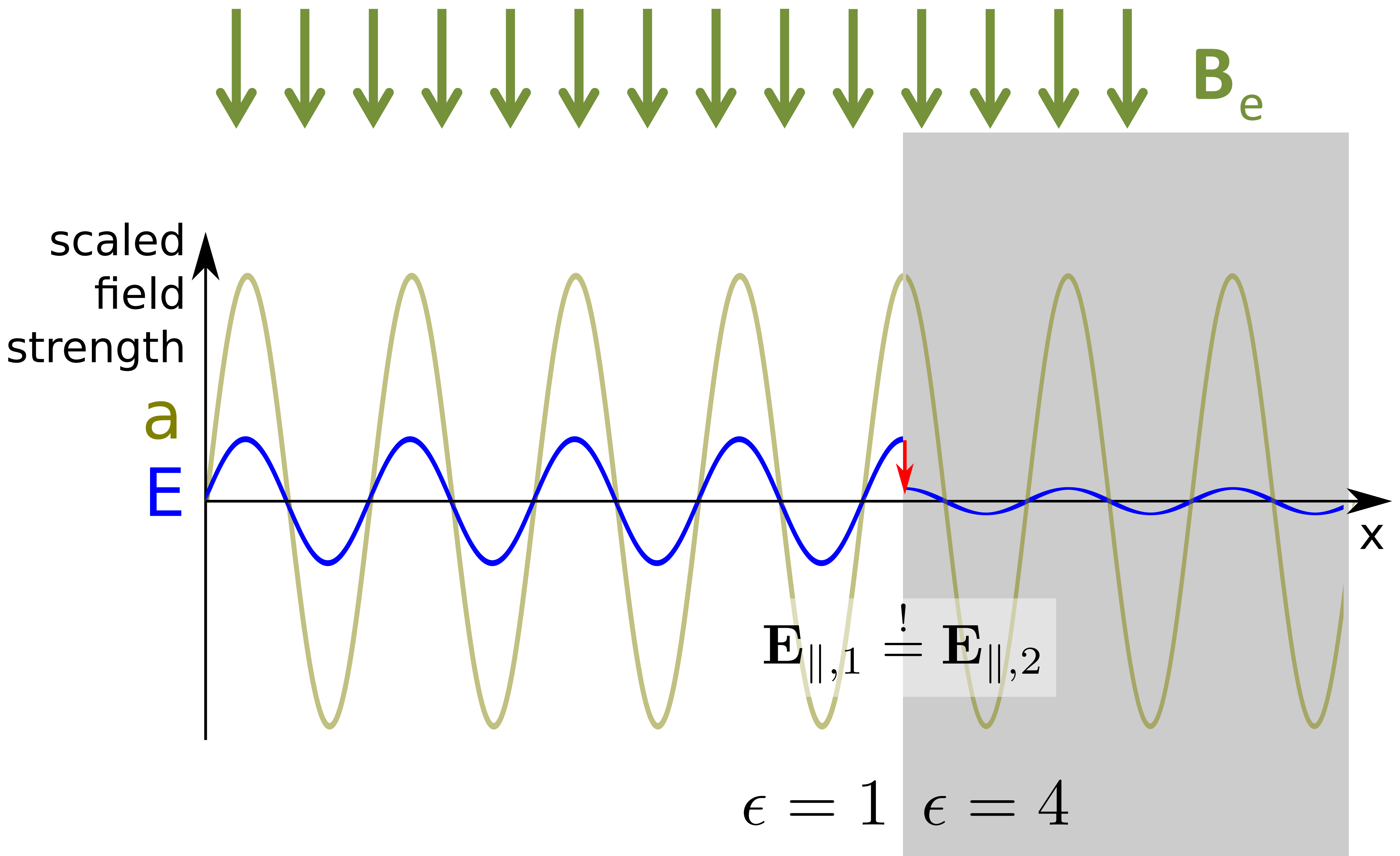


$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$$

axion electrodynamics



axion electrodynamics



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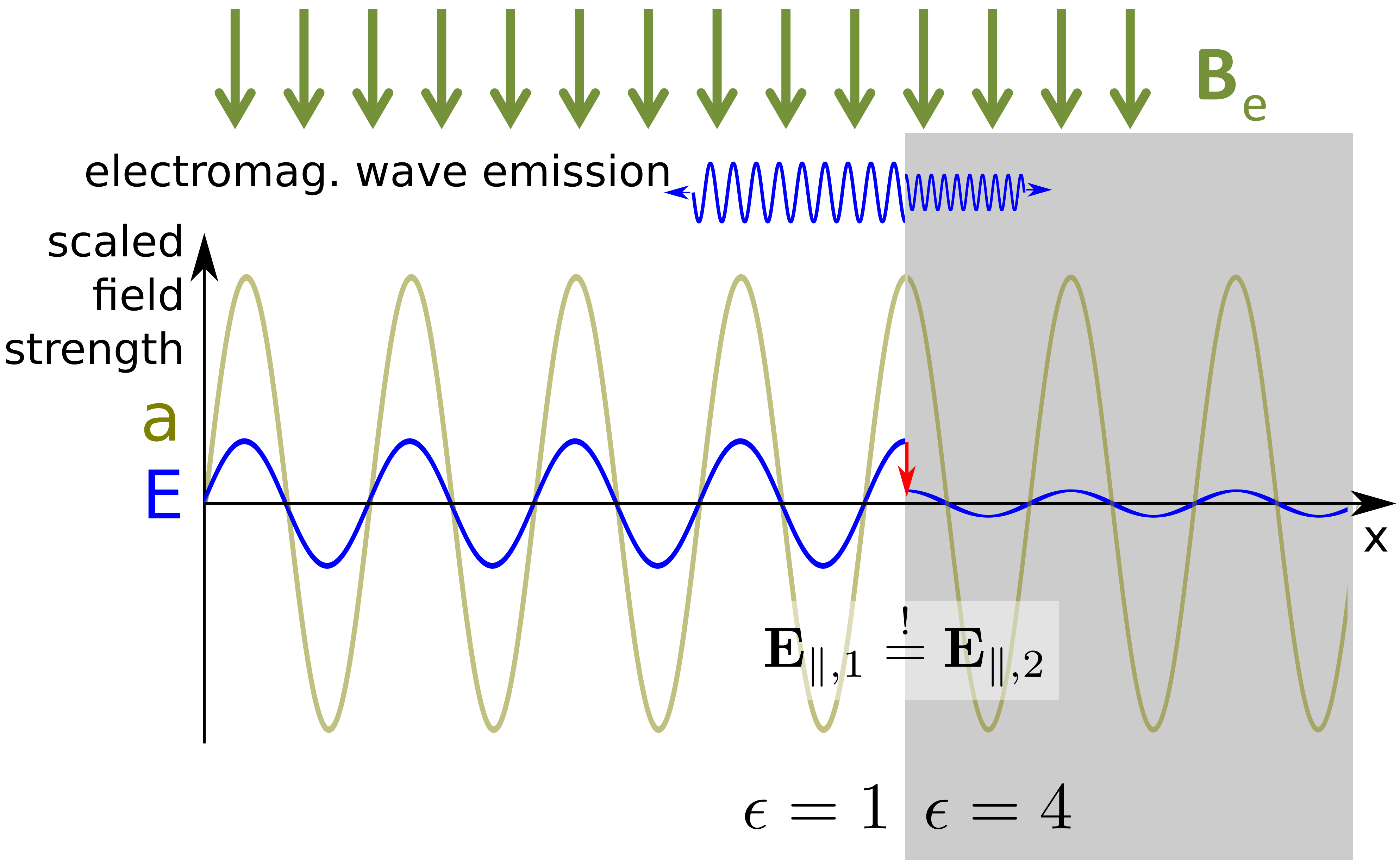
axion electrodynamics



$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$$

dielectric haloscope

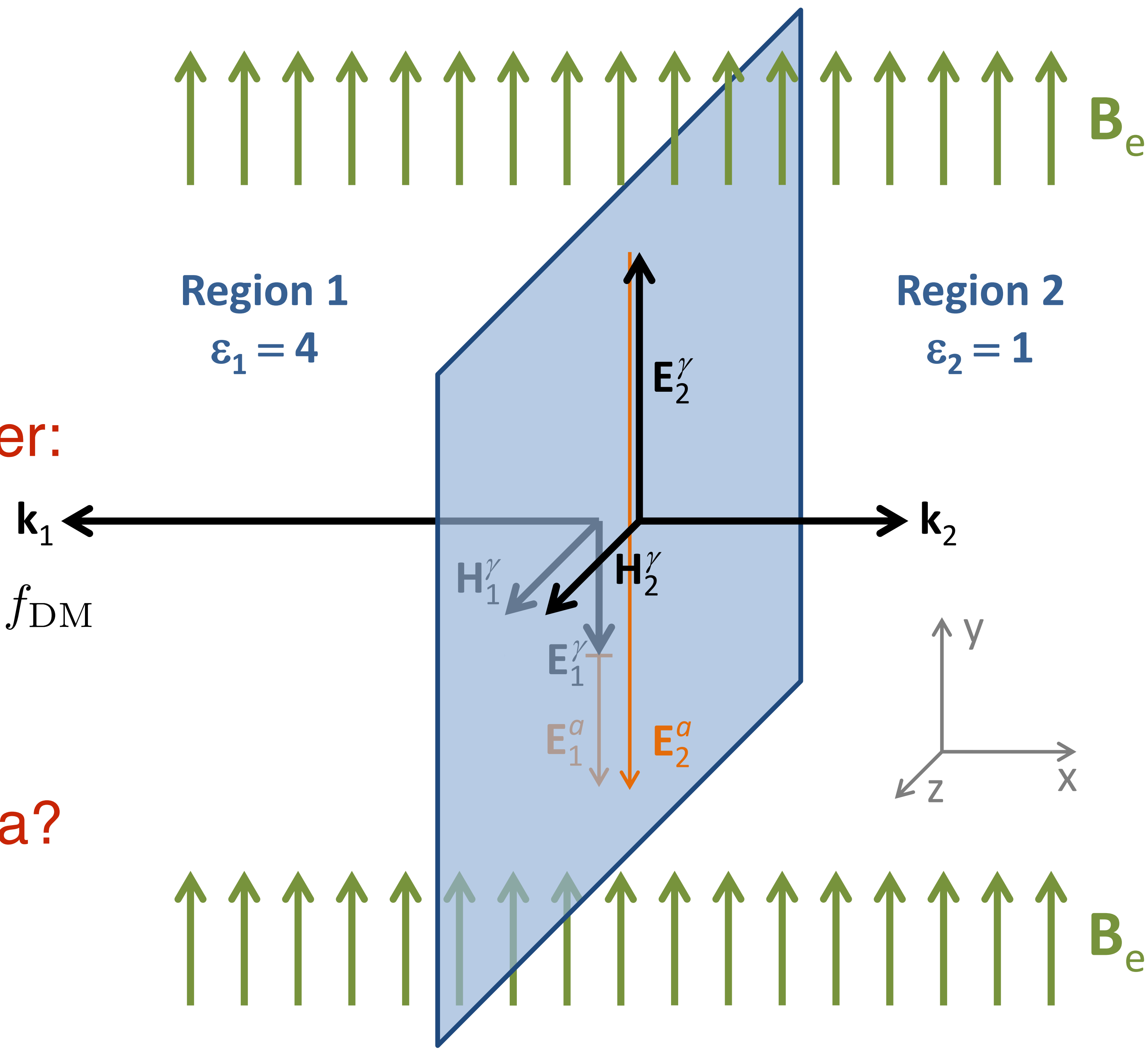
arXiv:1612.07057

- EM radiation emitted at dielectric transition region
- power emission by one layer:

$$\frac{P}{A} = 2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_e}{10\mathrm{T}}\right)^2 C_{a\gamma}^2 f_{\mathrm{DM}}$$

- too small to detect?
- stronger B field? larger area?

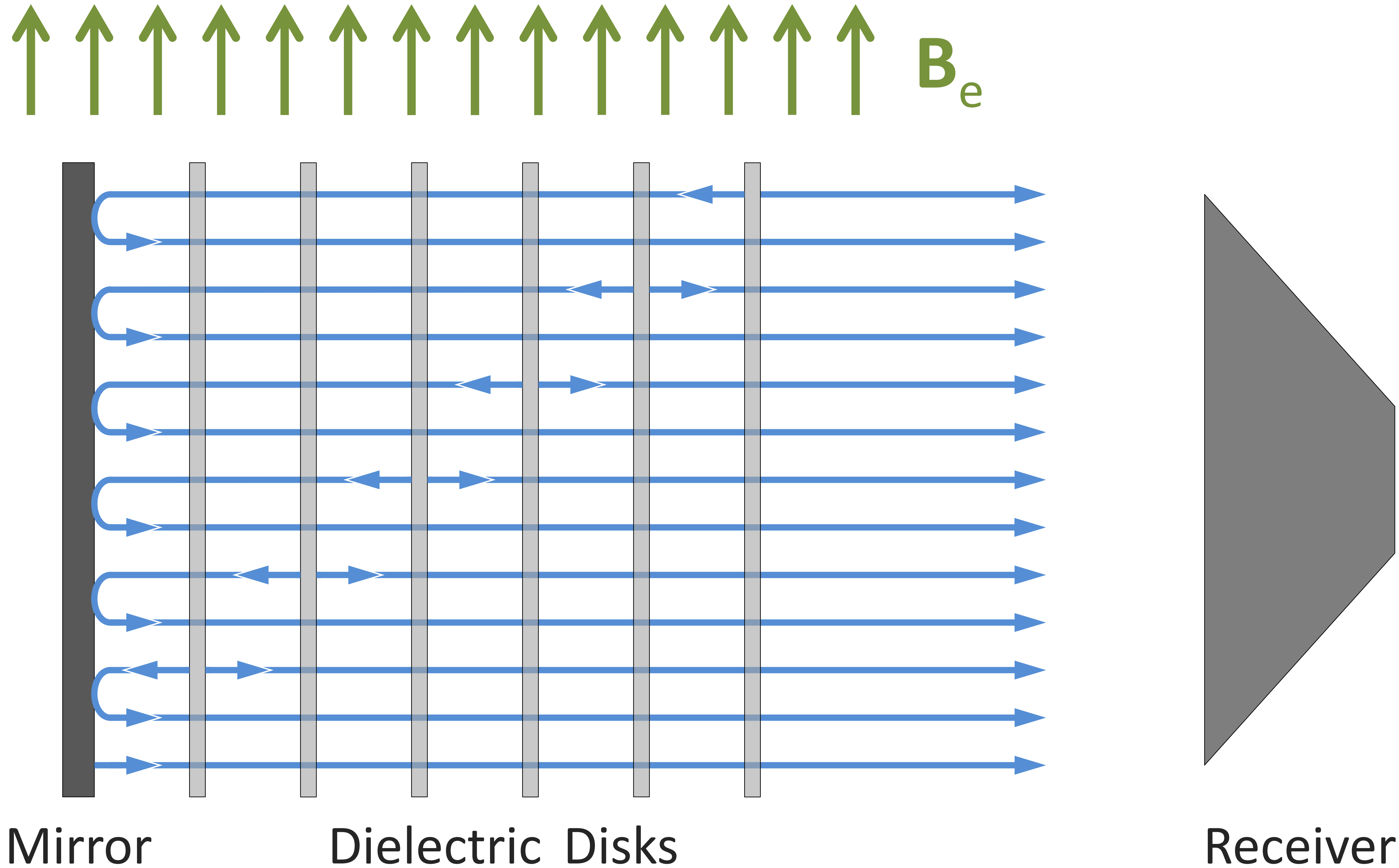
➡resonator



dielectric haloscope

arXiv:1612.07057

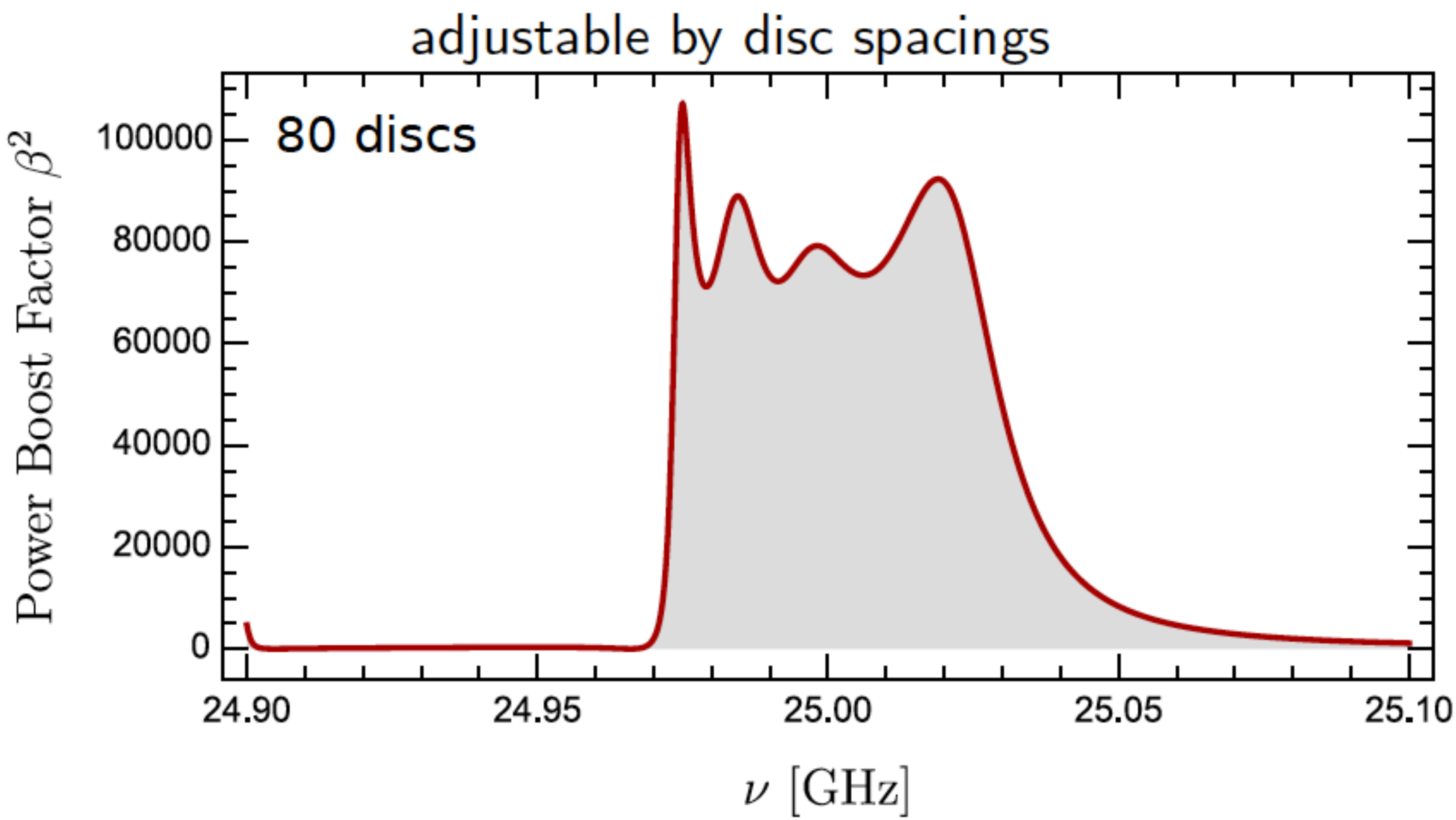
- resonator: multiple layers



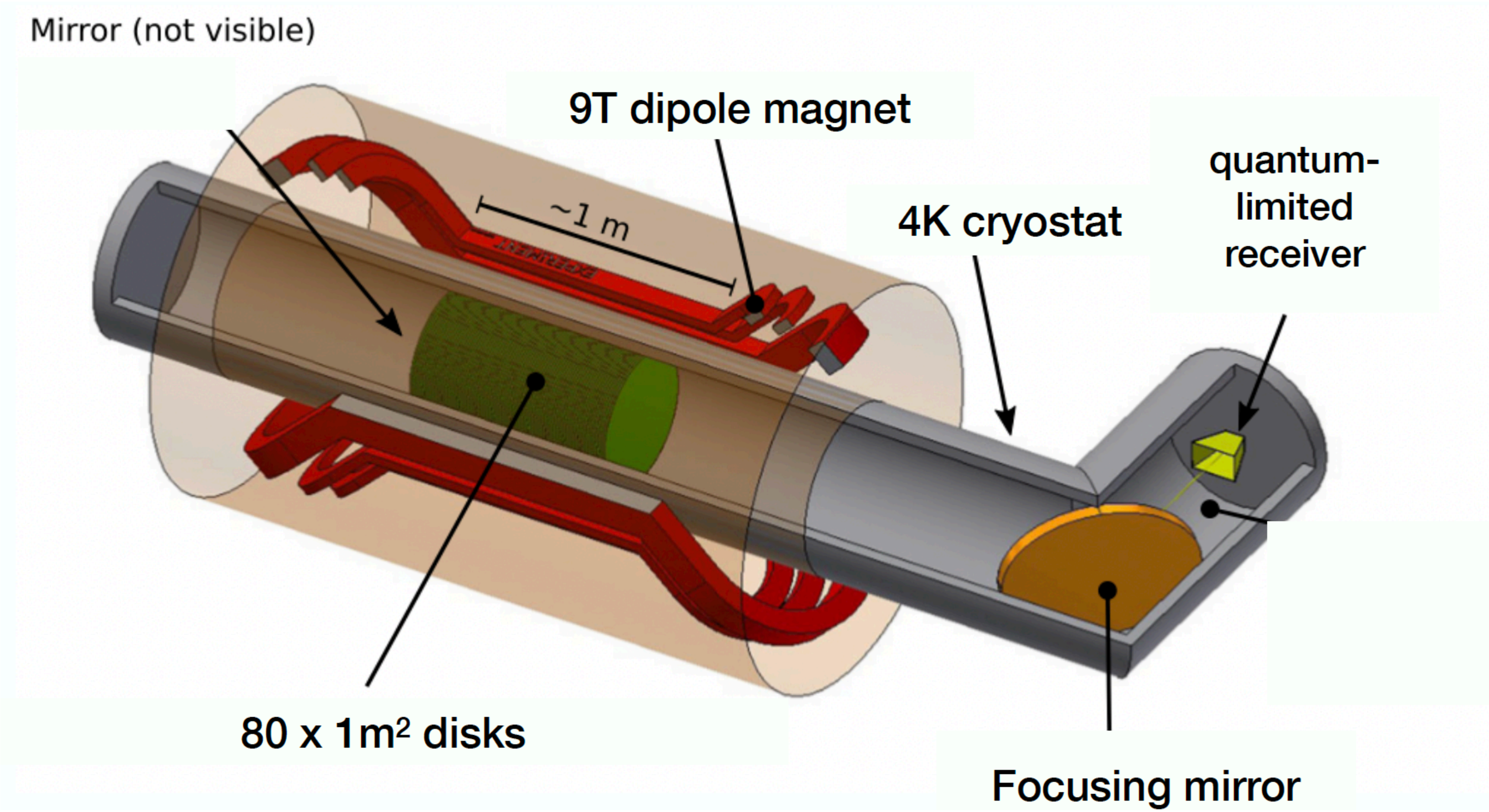
boost factor

- boosted power emission by 80 layers:

$$\frac{P}{A} = 2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_e}{10\mathrm{T}}\right)^2 C_{a\gamma}^2 f_{\mathrm{DM}} \bullet \beta^2$$

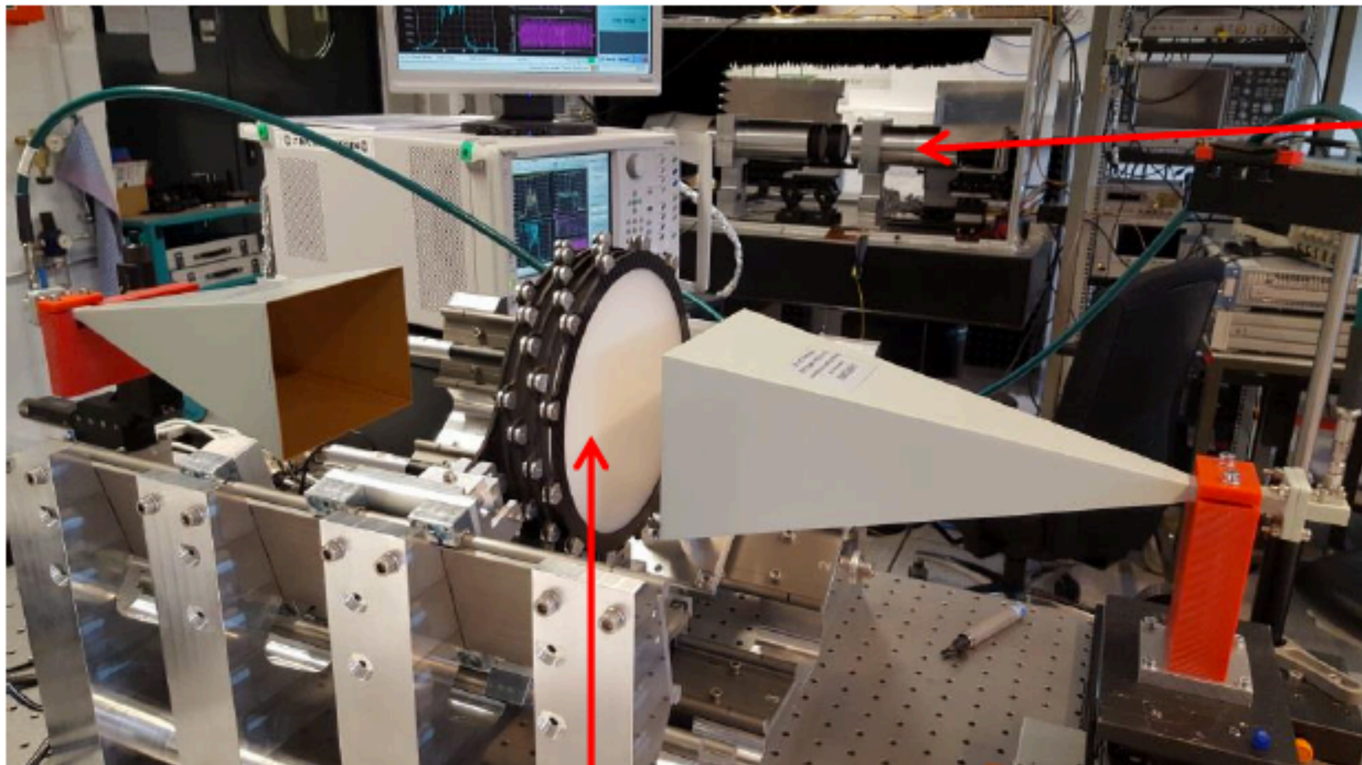


sketch of the MADMAX experiment



test setup in Munich

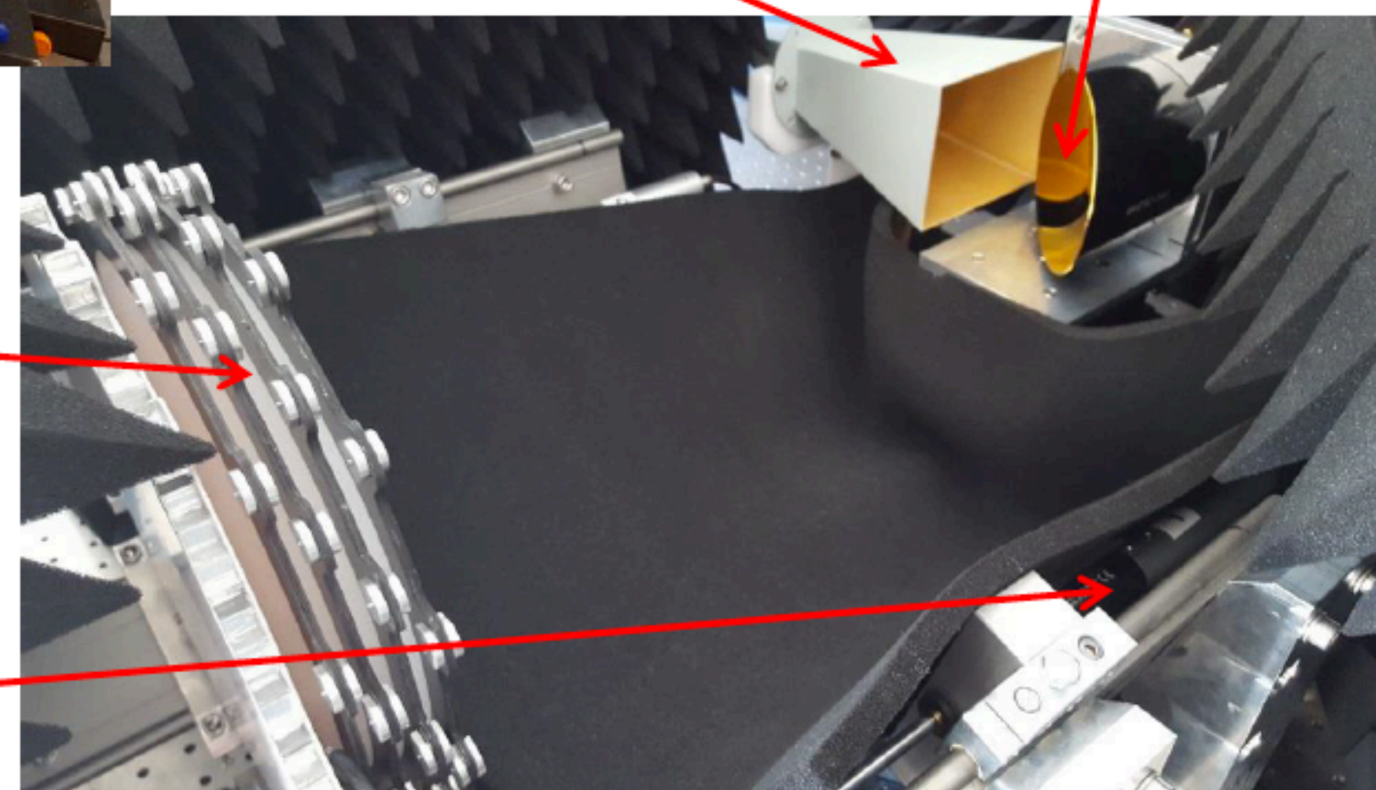
- The real device (200mm sapphire disks):



Waveguide system
(for background reduction)

Parabolic
mirror

Receiver horn

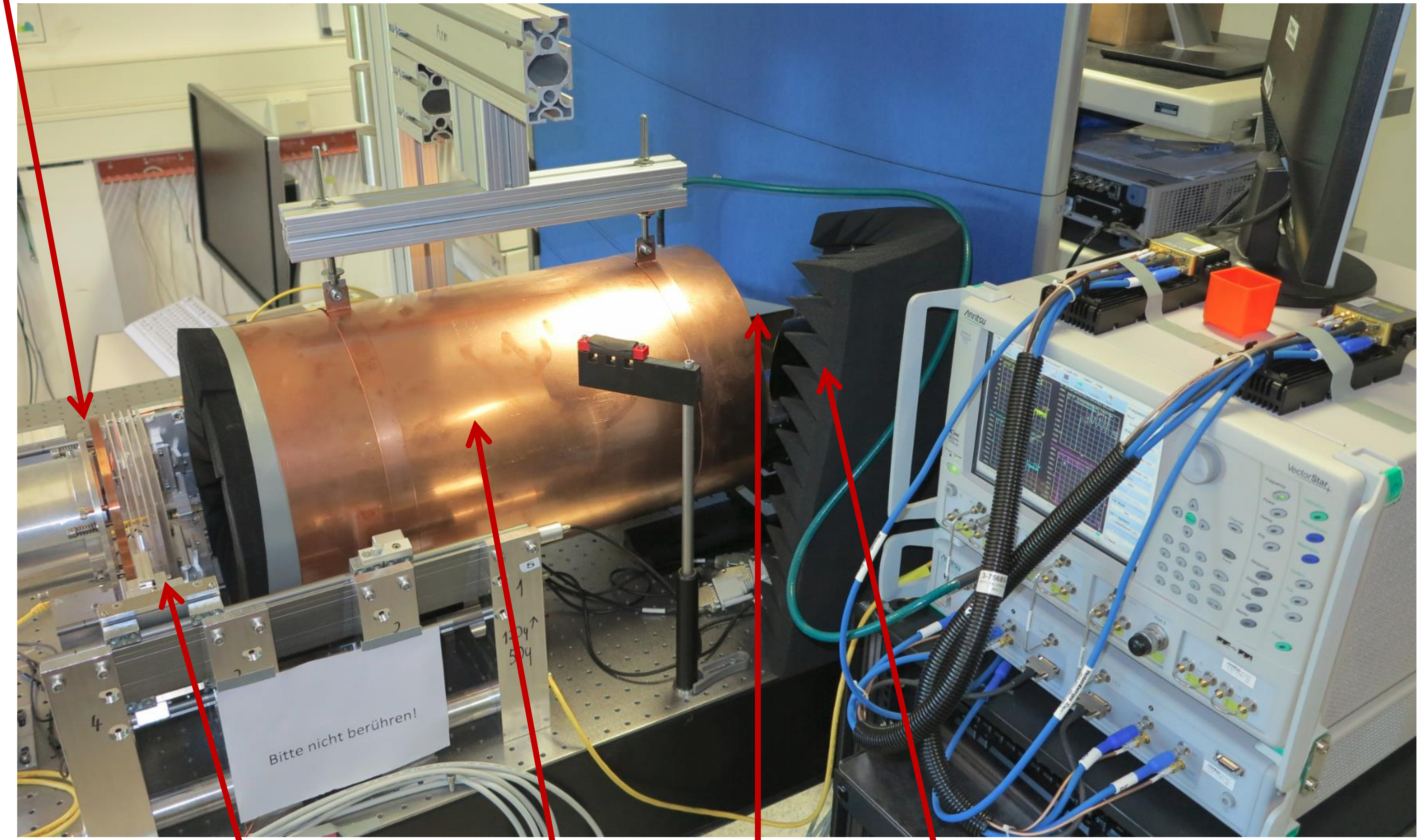


Resonator (adjustable)
5(4) disks, sapphire

Drive motor
(100nm accuracy)

test setup in Munich

Removable copper mirror



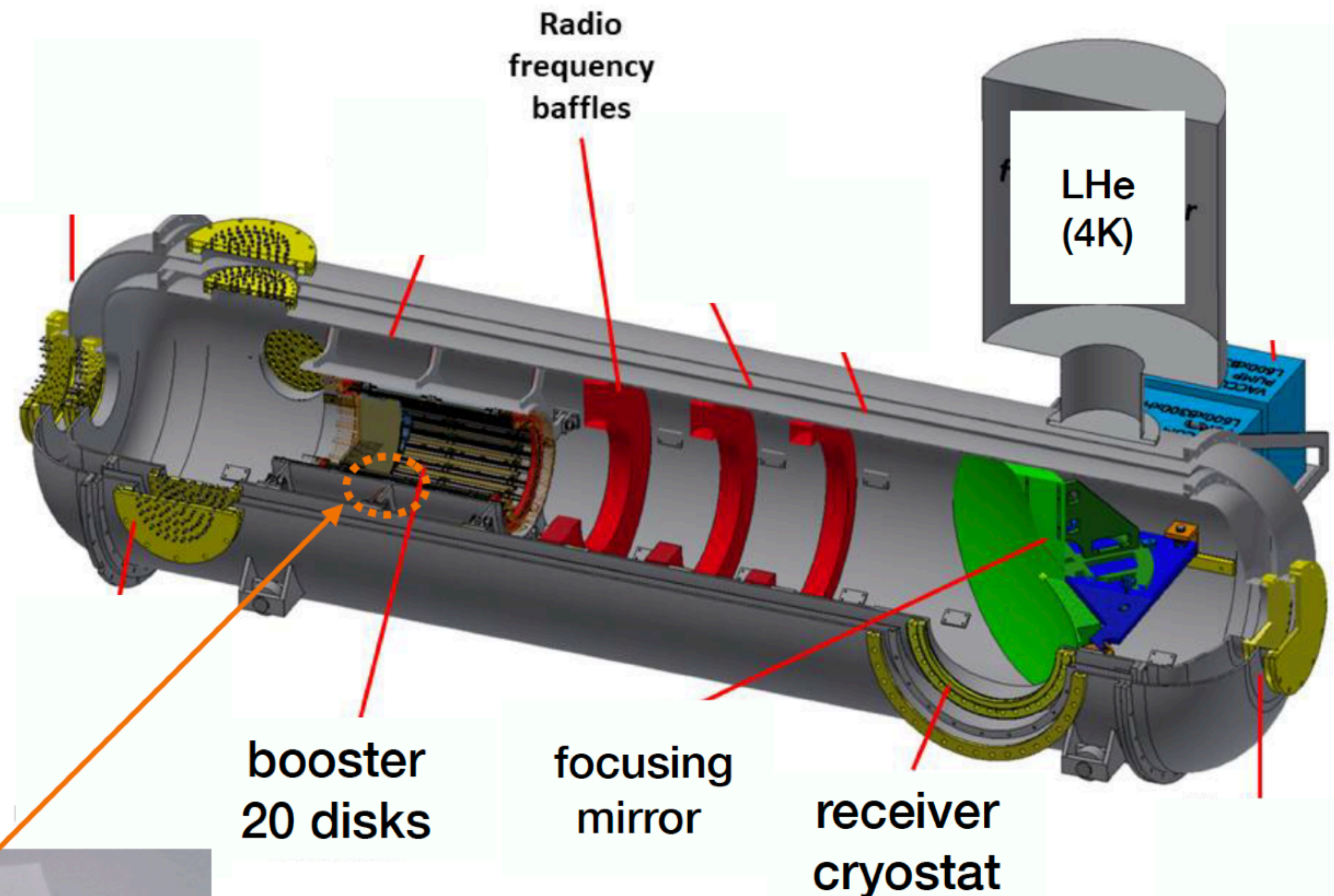
Dielectric discs (Saphire)

„Wave guide“

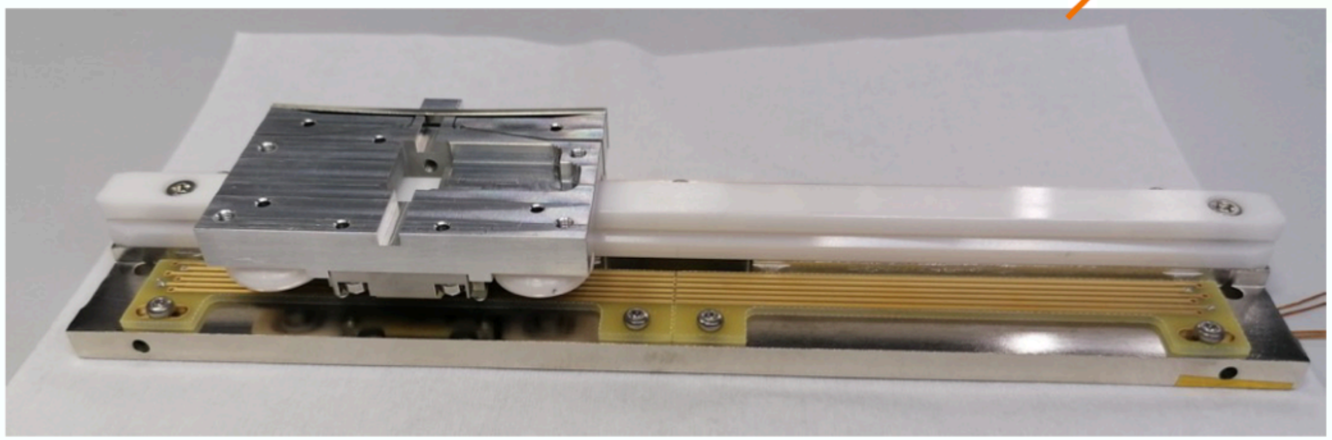
Horn antenna

Mirror

planned MADMAX prototype



- R&D platform
- Cryostat design fixed
- ALPs / HP search



Cryogenic piezo positioner x laser interferometer assembly

possibilities for Master thesis projects at RWTH

summary

- this was a very small subset of selected experiments making use of standard and non-standard detection techniques
- they all want to answer the remaining unsolved questions of particle physics (e.g. dark matter)
- they all use simulation, fast electronics and most are exploiting the fundamental principles of interaction between radiation and matter
- some of them represented by groups in Aachen with many possibilities for **you** to participate in ongoing research
- the next big scientific break-through could come from one of these experiments