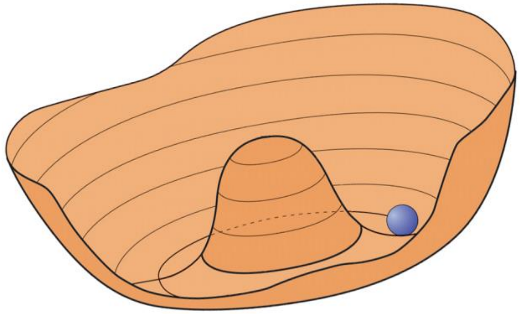
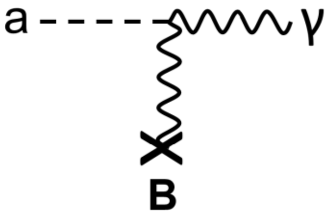
Results and Progress of Axion Haloscope Experiments

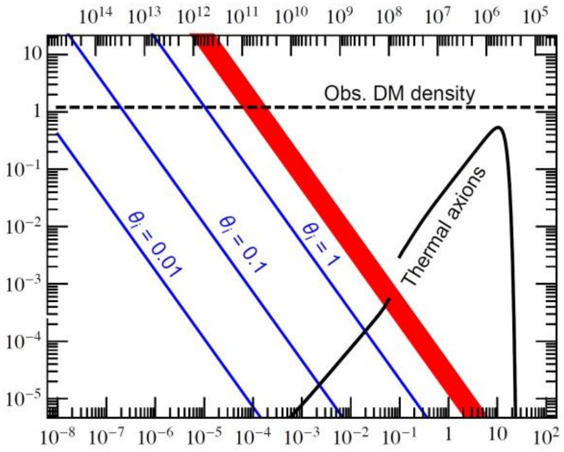
Béla Majorovits

MAX-PLANCK-INSTITUT FÜR PHYSIK

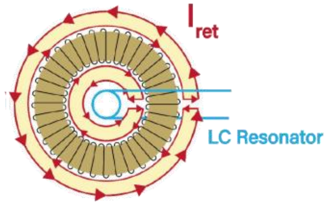
19.09.2023

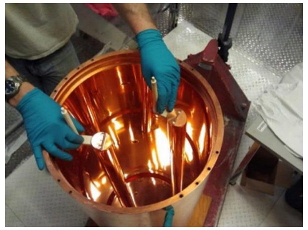






- Setting the stage: axions as dark matter
- How to search for axions?
- Some experimental efforts:



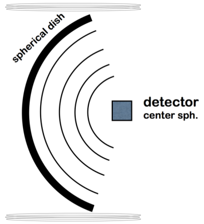


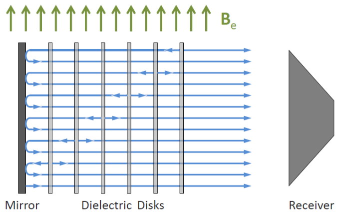
LC - cricuits: DM radio

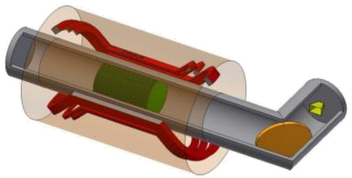
Cavities: ADMX & CAPP

Dish antenna: BREAD & BRASS

Dielectric Haloscope: MADMAX







Setting the stage: axions as dark matter

CP violating term in QCD SM Lagrangian: $\bar{\Theta}\,\frac{\alpha_s}{8\pi}G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$

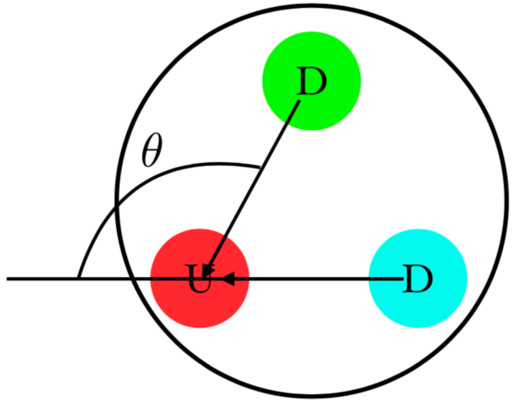
$$\bar{\Theta} = \Theta - \arg\det M_q$$

Random phase from Θ-vacuum

phases from Yukawa coupling: CKM matrix

Two sources for CP violation → Phase difference!

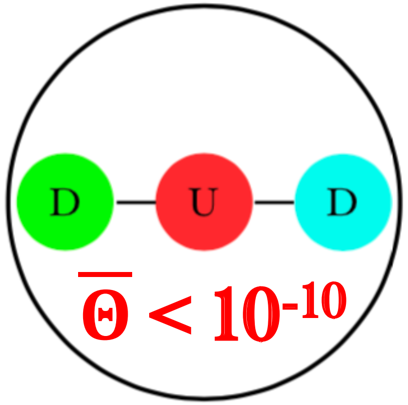
Physically observable CP violation expected: non vanishing neutron EDM



$d_n \sim \bar{\Theta} \cdot 10^{-16}$ e cm

Limit on EDM of neutron:

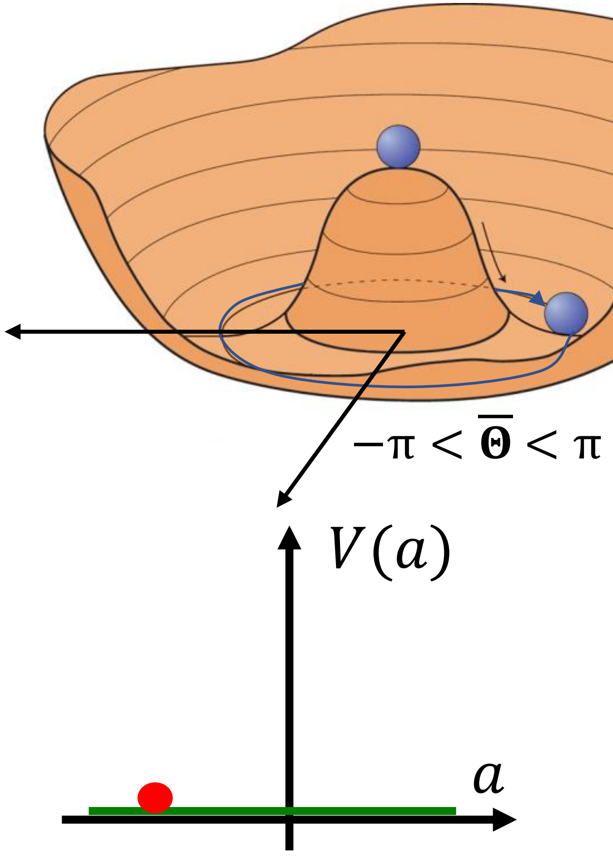
$d_n < 2 \cdot 10^{-26}$ Abel et al., Phys. Rev. Lett. 124, 081803 (2020)



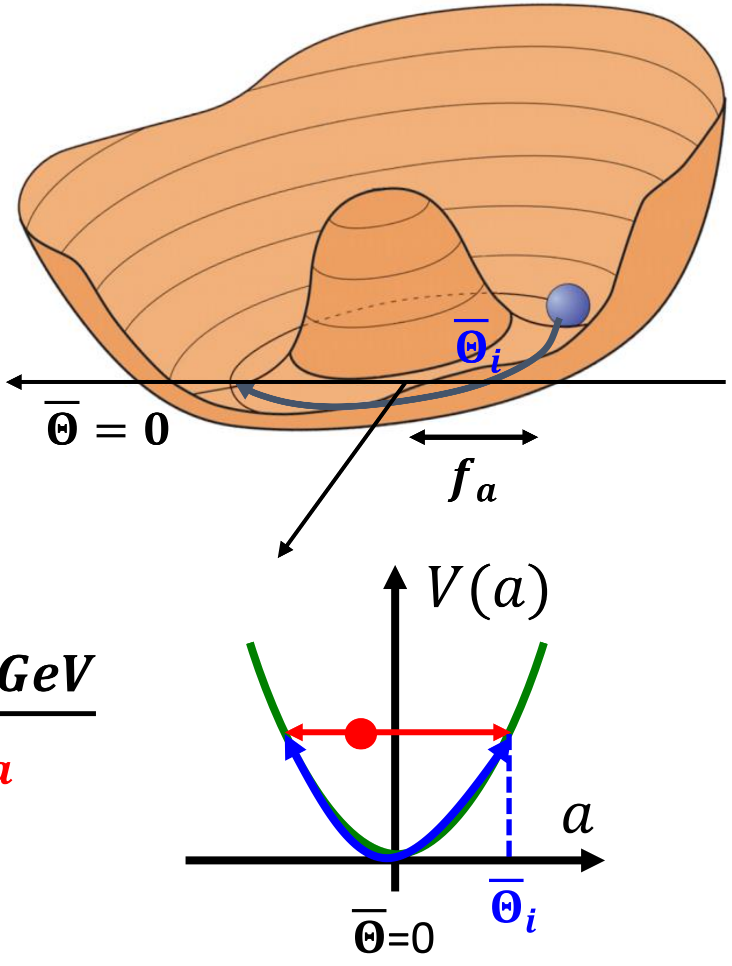
→ Strong CP problem

Setting the stage: axions solving strong CP problem

Make $\overline{\Theta}$ dynamical → U(1) with spontaneous Peccei Quinn symmetry breaking



QCD: explicit symmetry breaking



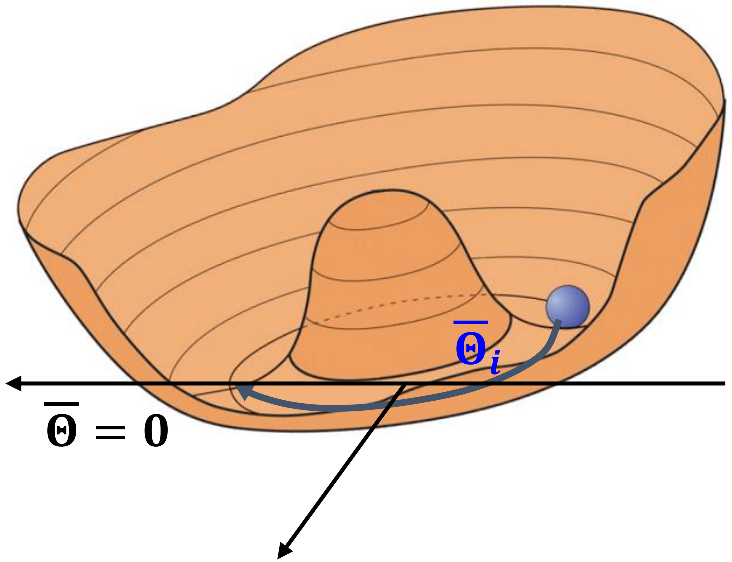
$$m_a \sim 5.7 \mu eV \frac{10^{12} GeV}{f_a}$$

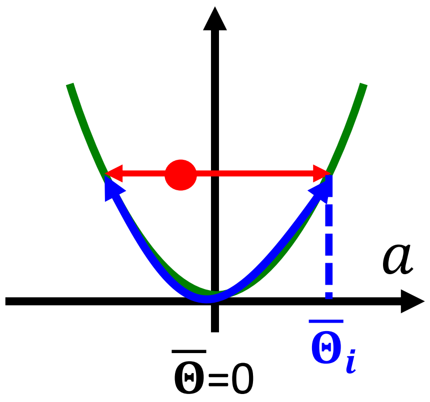
Setting the stage: axions as dark matter

If axion exists:

→ Contribution to Dark Matter:

as relic oscillations of $\overline{\Theta}$ around minimum

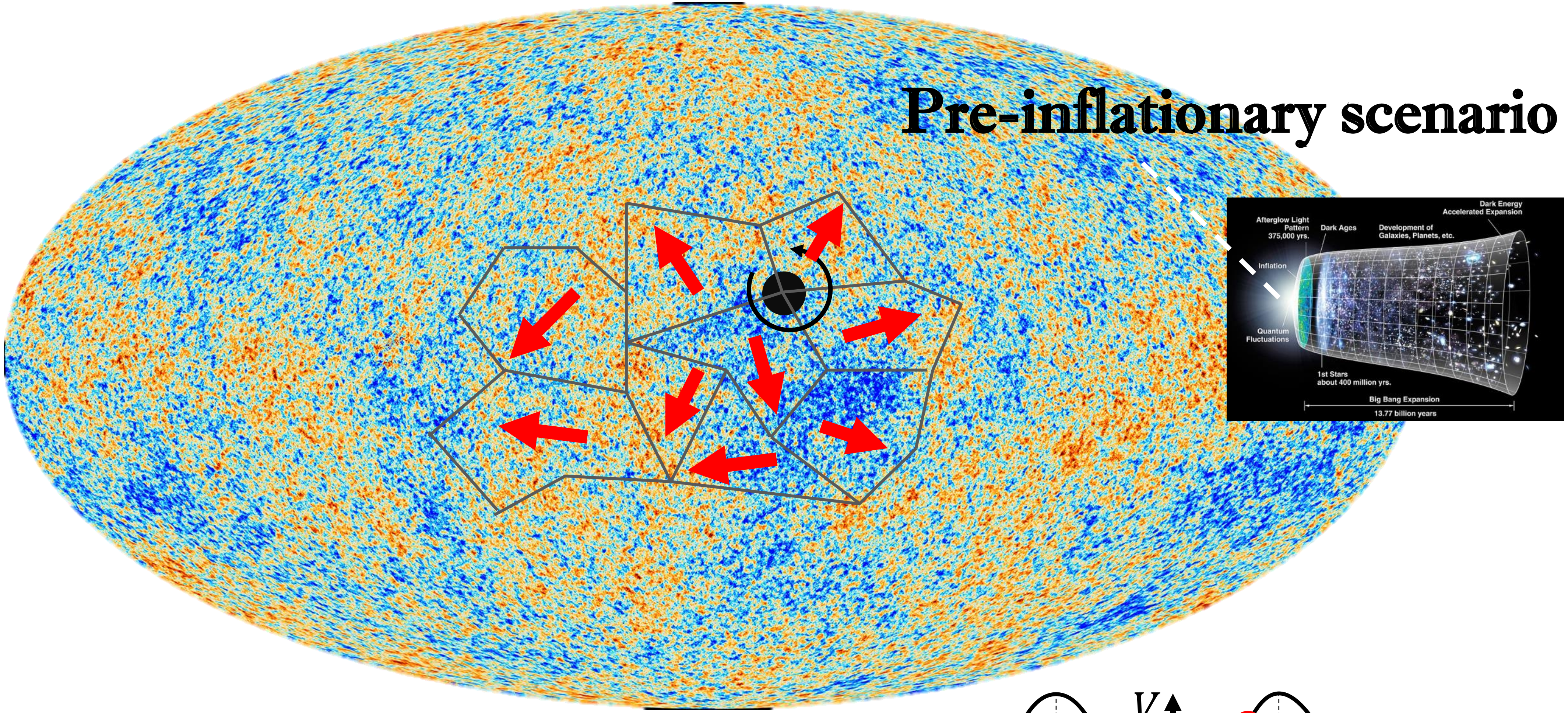




Oscillations amplitude: „particle density“
damped by expansion of universe H(t)
Damping depends on ratio
oscillation frequency (m_a) to H(t)

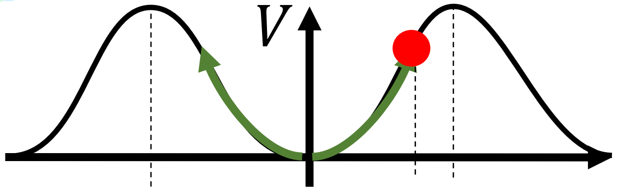
Setting the stage: axions as dark matter

Pre-inflationary scenario

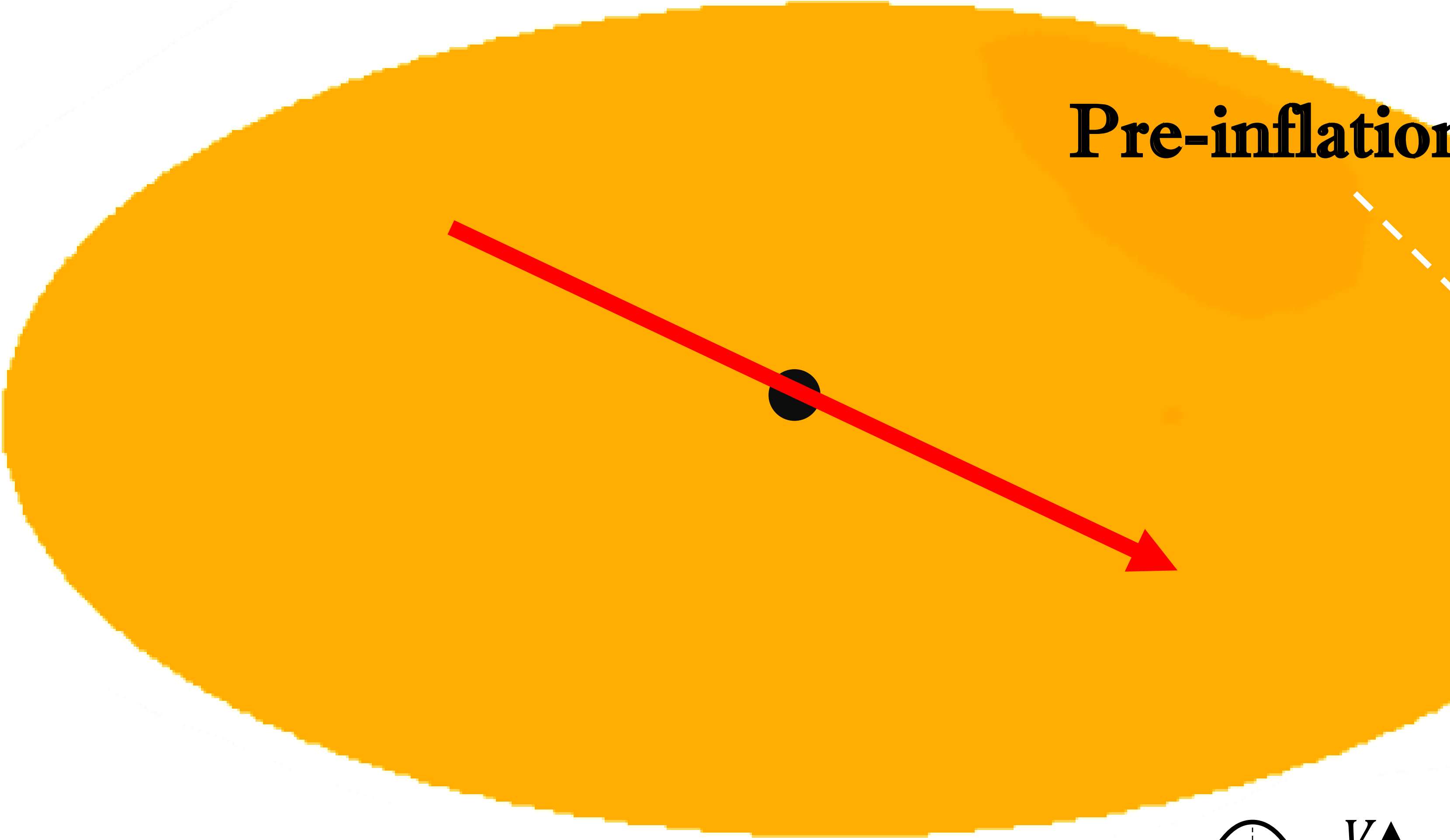


One value of $\bar{\Theta}_i$ in entire visible universe

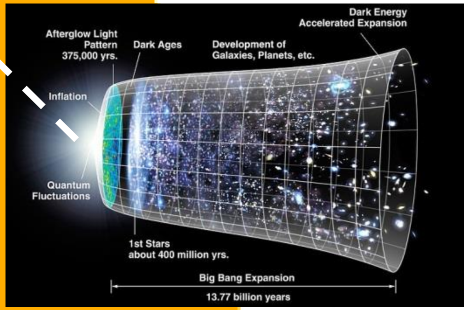
$$0 < |\bar{\Theta}_i| < \pi$$



Setting the stage: axions as dark matter

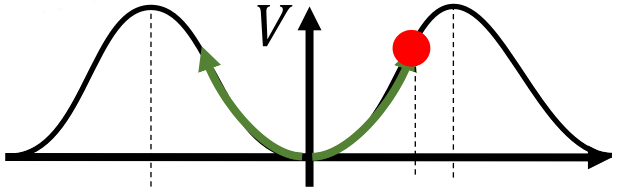


Pre-inflationary scenario



One value of $\overline{\Theta}_i$ in entire visible universe

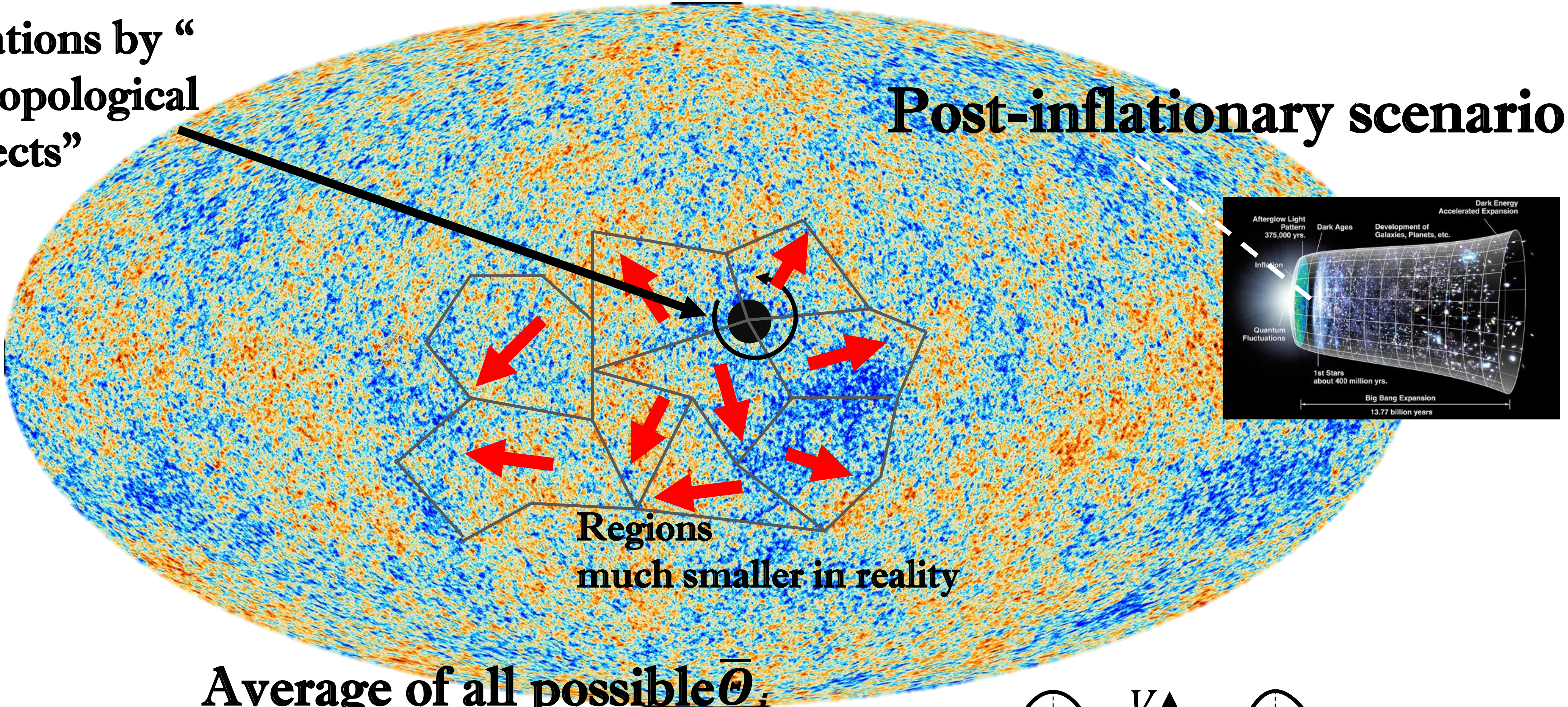
$$0 < |\overline{\Theta}_i| < \pi$$



Setting the stage: axions as dark matter

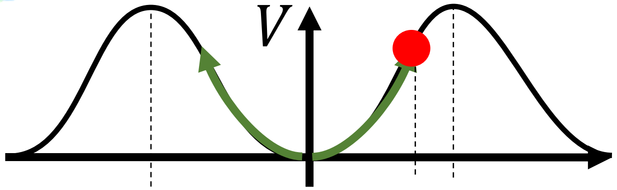
Complications by "decay of topological defects"

Post-inflationary scenario

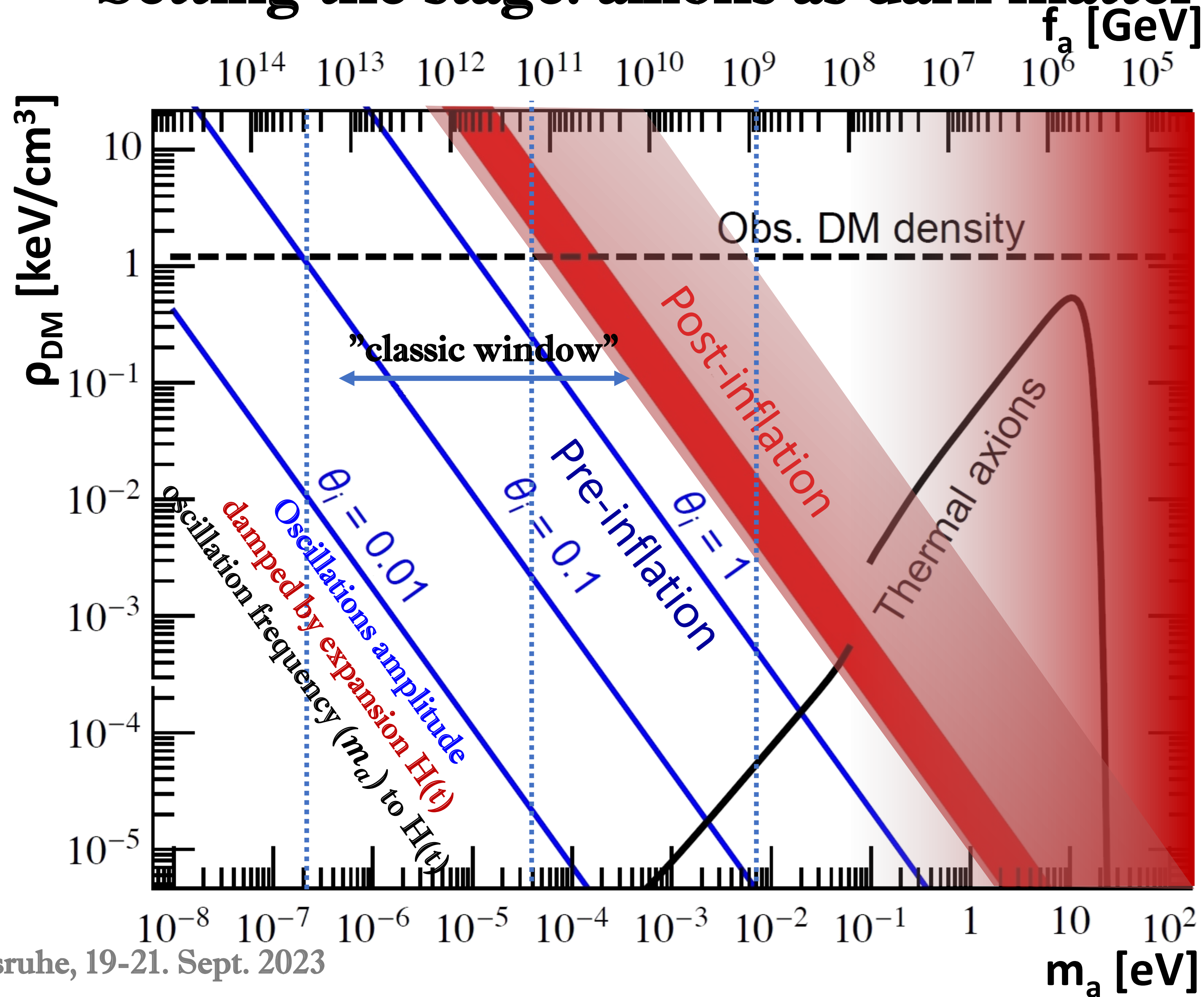


Average of all possible $\overline{\theta}_i$

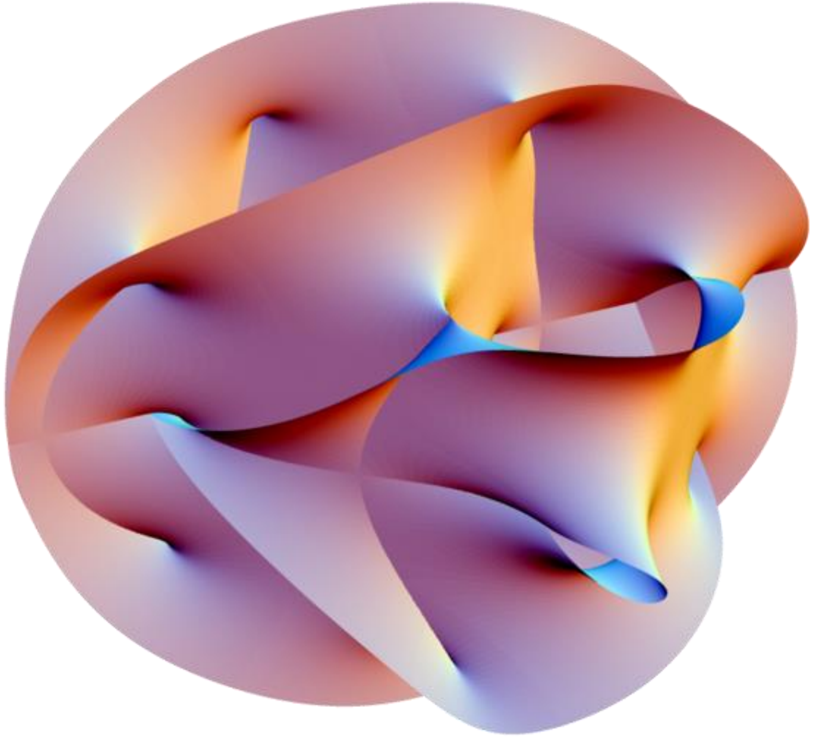
→ Prediction for overall density



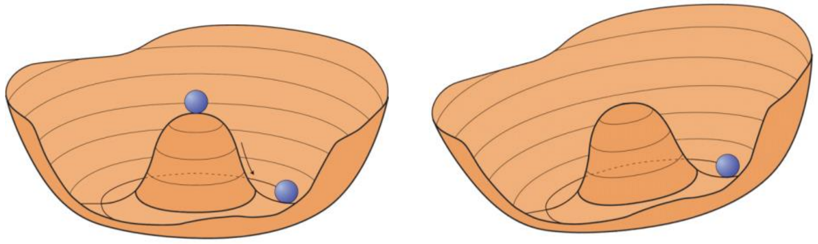
Setting the stage: axions as dark matter



Setting the stage: ALPs as dark matter



ALPs emerging from string compactification: the Axiverse



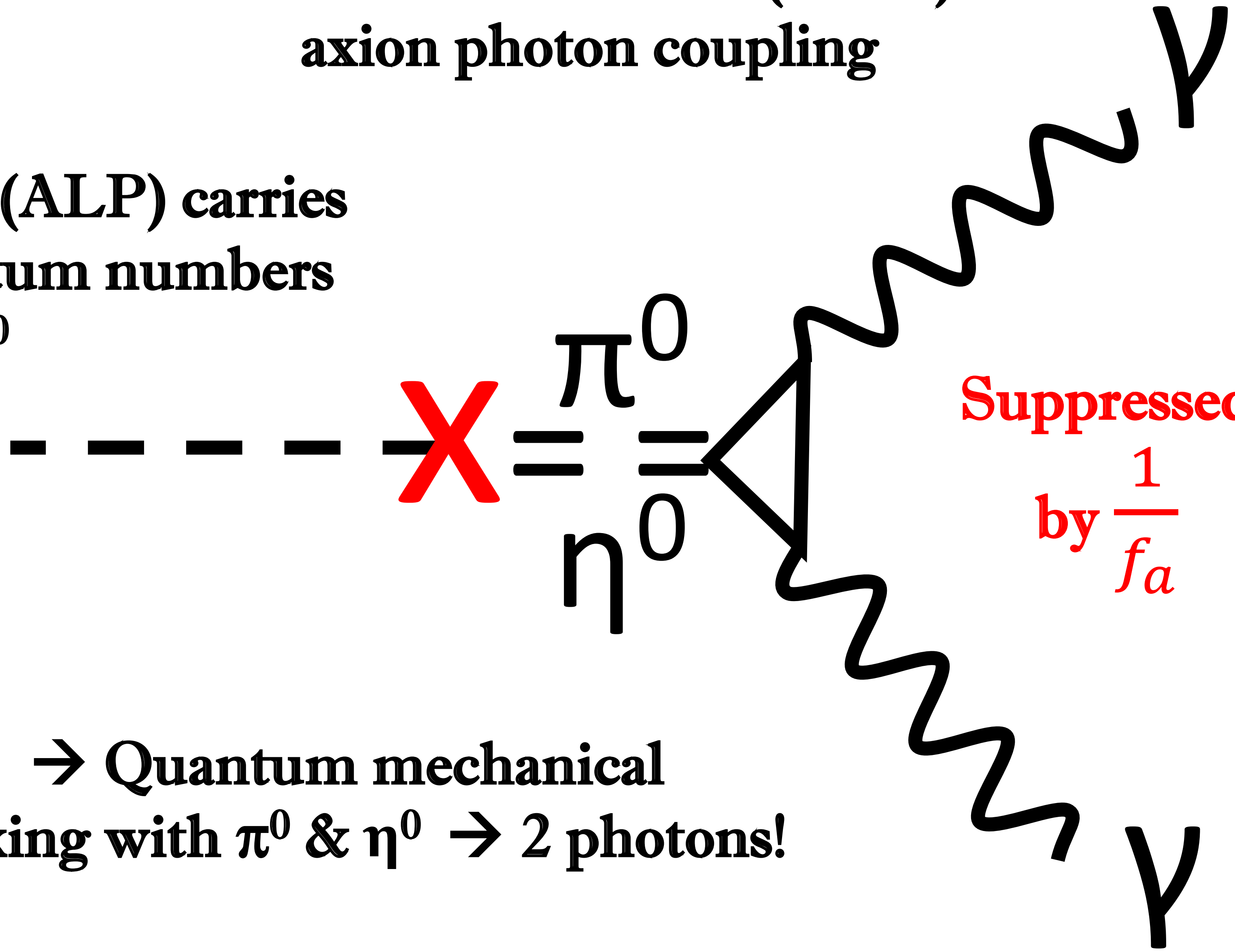
No directe relation btw. m_{ALP} and f_{ALP}

Some astrophysical inconsistencies:
- Transparency hint
- Cooling anomalies

Could be explained by ALPs

How to detect axions (ALPs): axion photon coupling

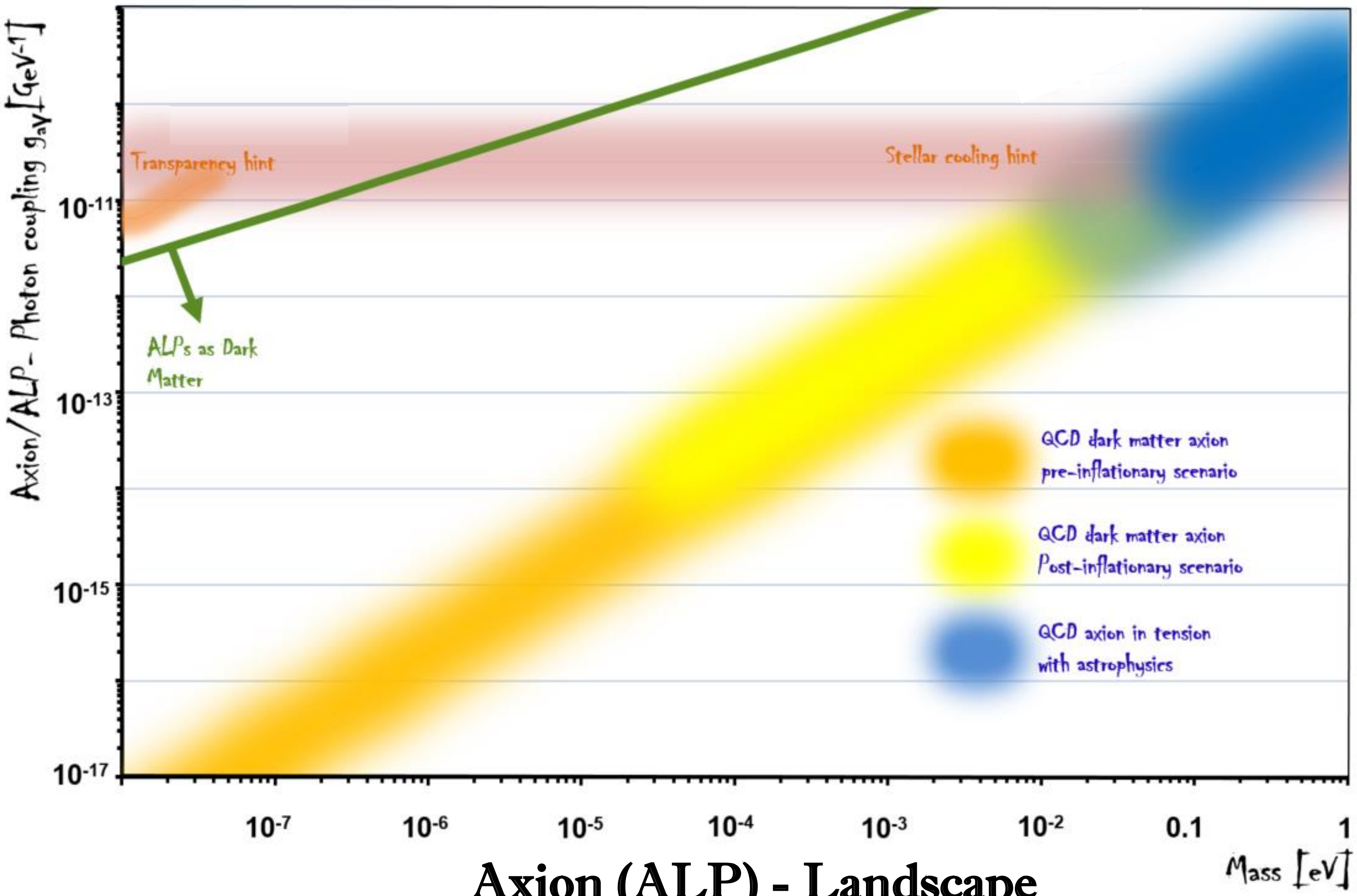
The Axion (ALP) carries same quantum numbers as η^0 and π^0



Suppressed by $\frac{1}{f_a}$

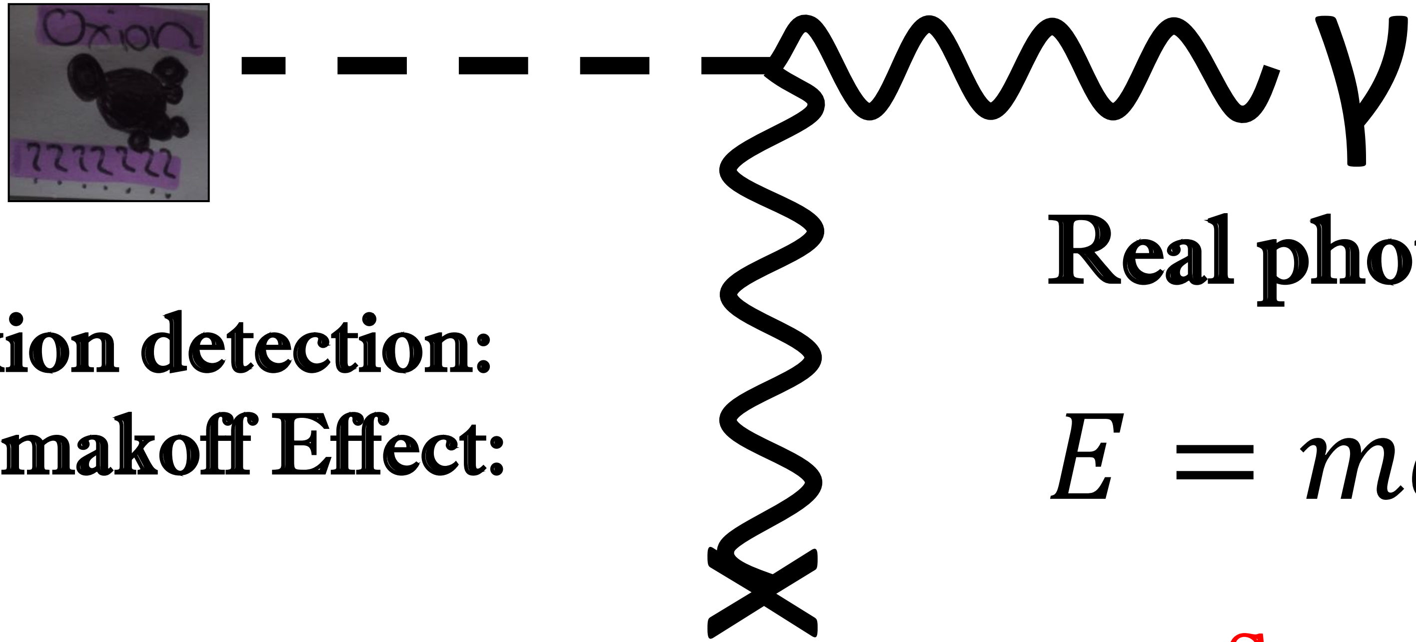
→ Quantum mechanical mixing with π^0 & η^0 → 2 photons!

Setting the stage: axions as dark matter



Axion (ALP) - Landscape

How to detect axions (ALPs)



Real photon

Axion detection:
Primakoff Effect:

$$E = mc^2 = h\nu$$

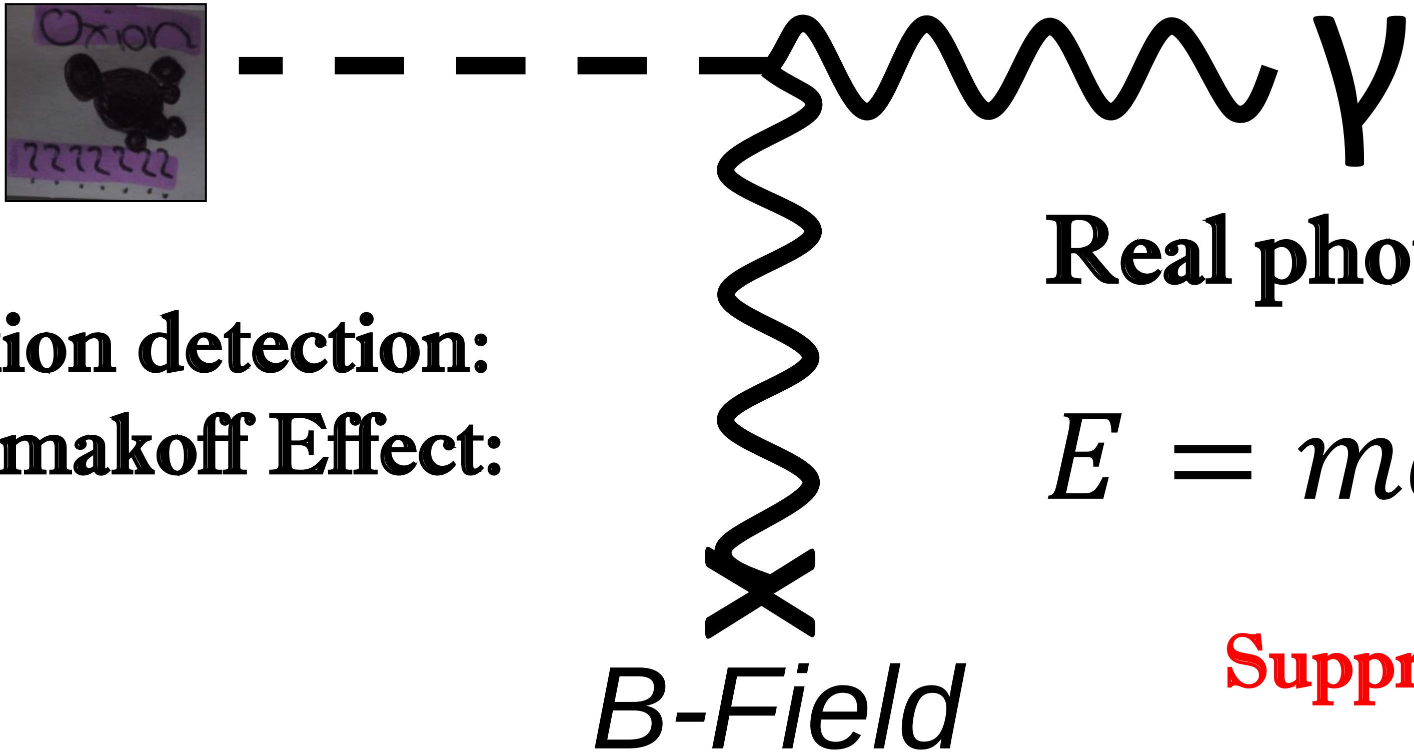
B-Field

Suppressed by $\frac{1}{f_a}$

$$\mathcal{L}_{a\gamma} = \frac{\alpha}{2\pi} C_{a\gamma} \frac{a(t)}{f_a} \boldsymbol{E} \cdot \boldsymbol{B}$$

How to detect axions (ALPs)

Axion detection:
Primakoff Effect:

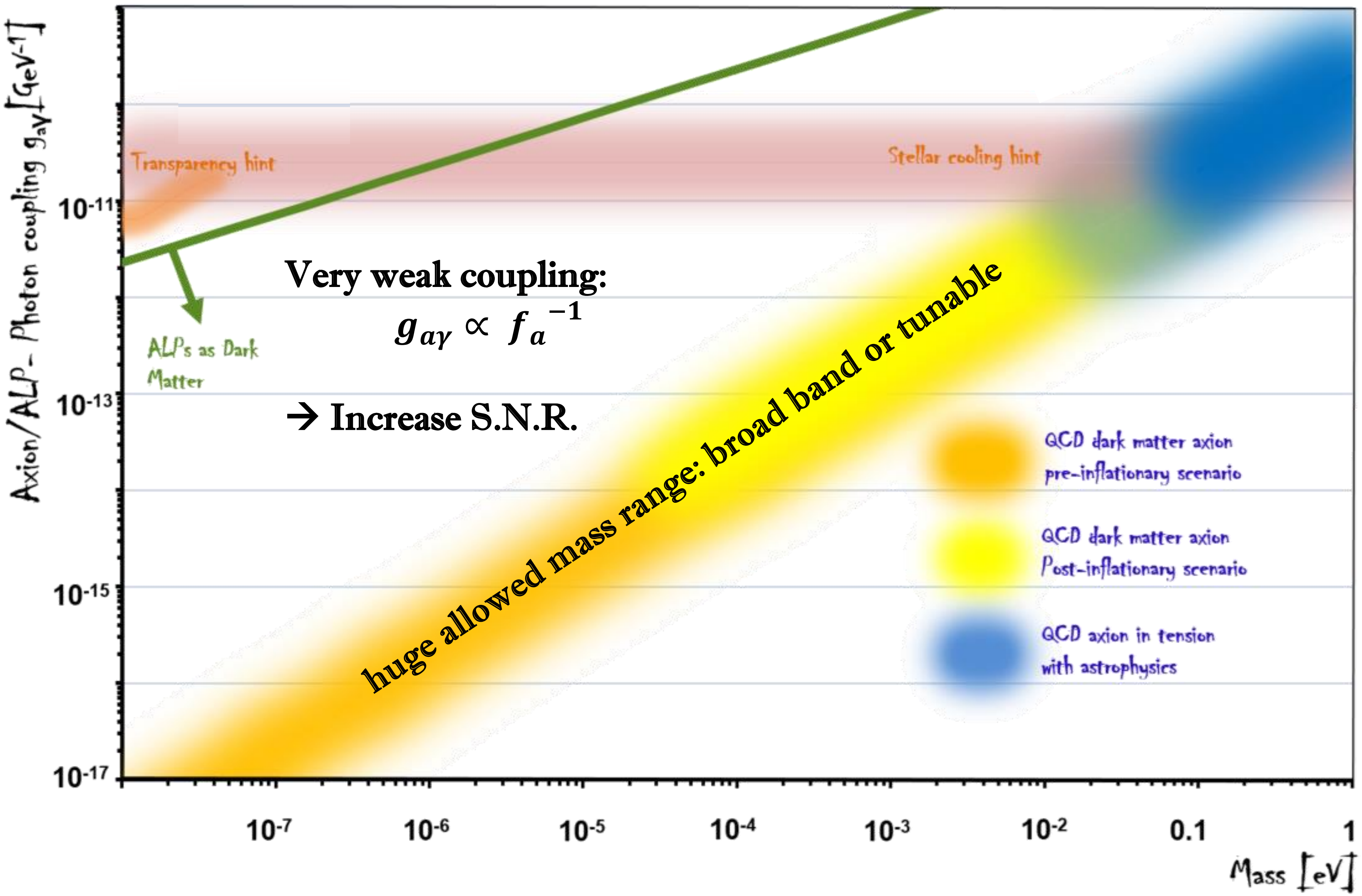


$$E = mc^2 = h\nu$$

Suppressed by $\frac{1}{f_a}$

Additional axion source term in Maxwell equations
→ Axion in B-field induces E-field oscillations!

How to detect axions (ALPs)



Haloscopes share common challenges

Scan mass range:

- Broadband DAQ
- Tunable or broadband resonator

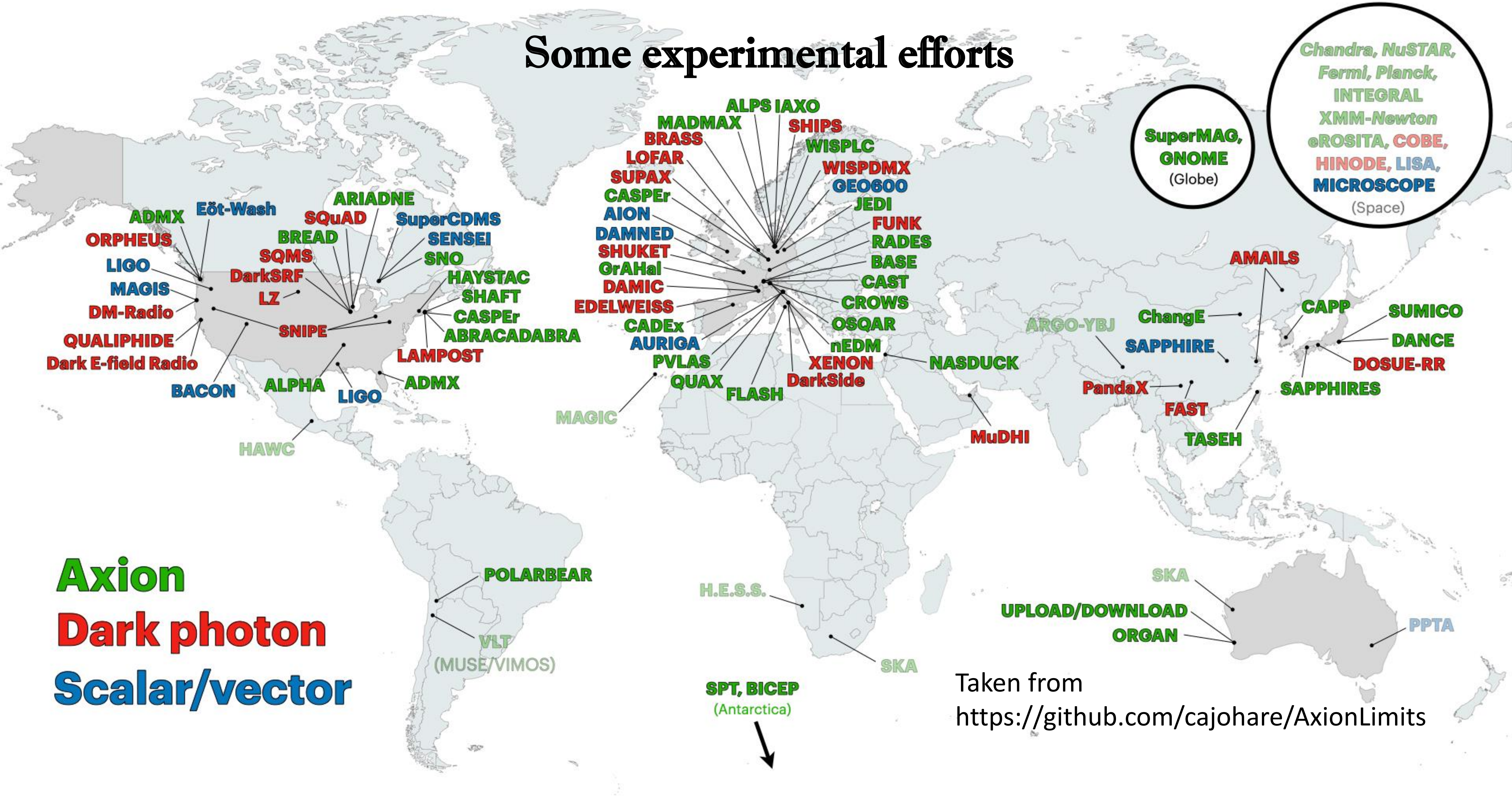
Signal increase:

- Exploit resonance
- Increase B-field

Reduce background:

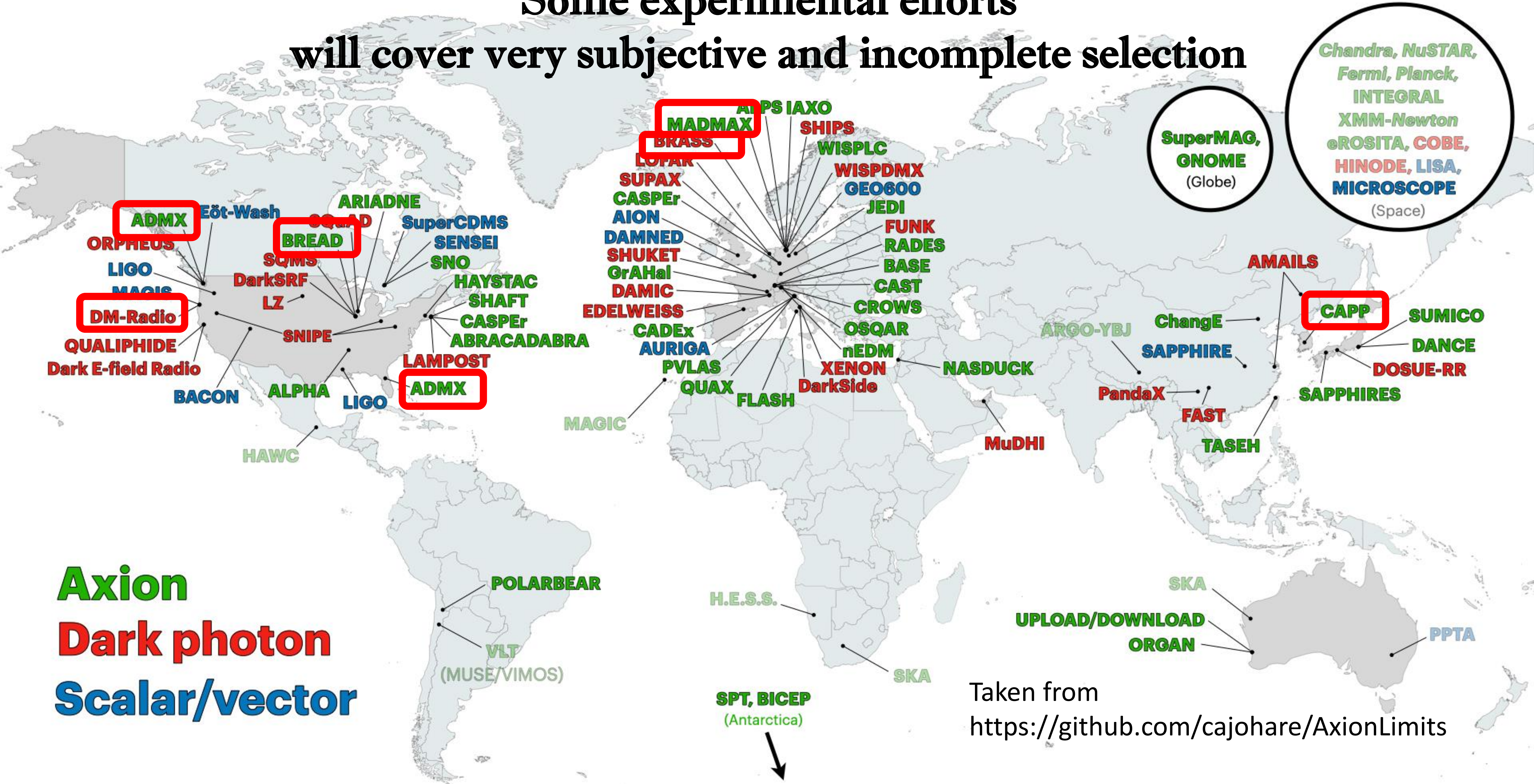
- cryogenic temperatures
- Use quantum technology

Some experimental efforts



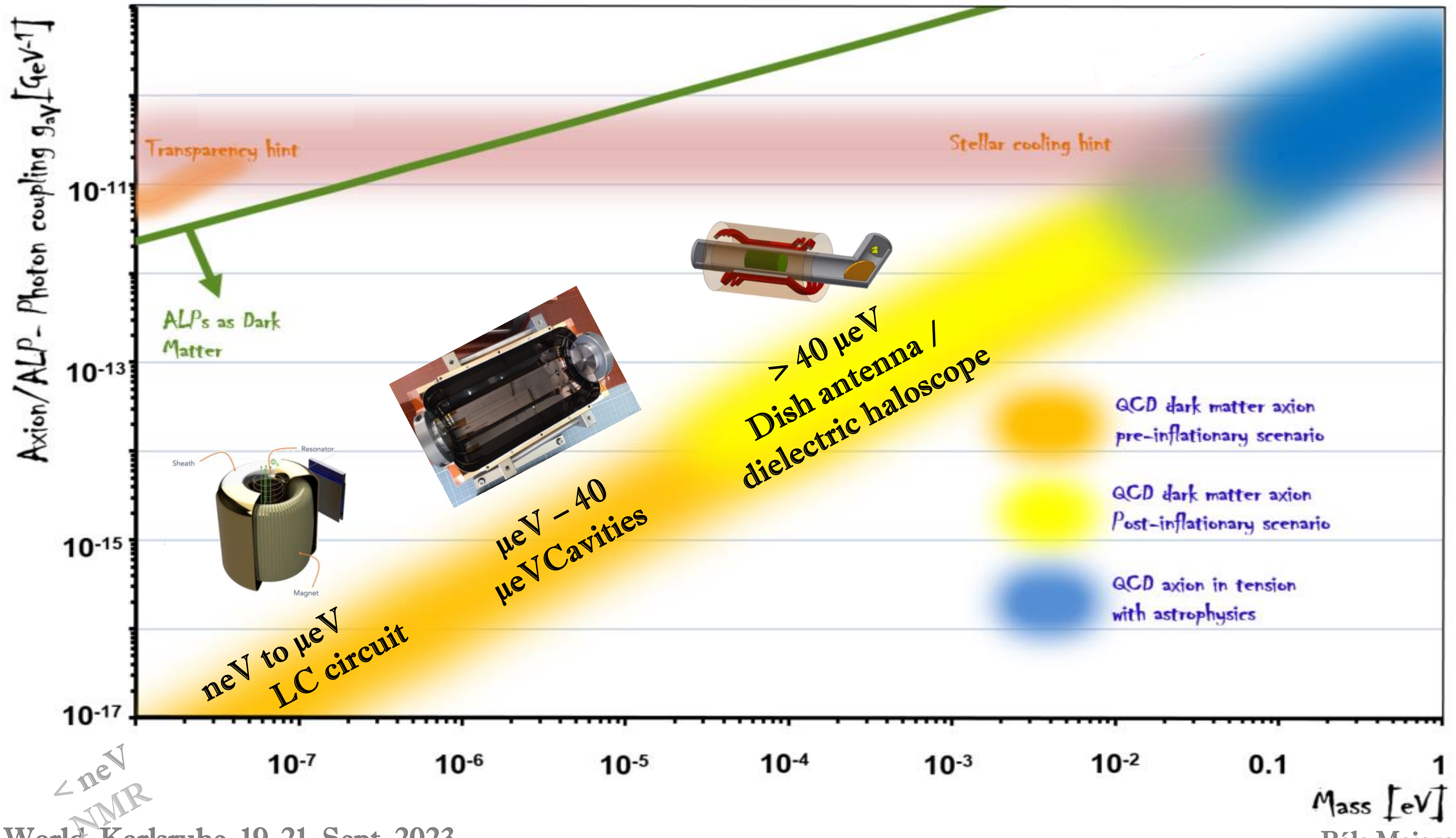
Taken from
https://github.com/cajohare/AxionLimits

Some experimental efforts
will cover very subjective and incomplete selection



Taken from
https://github.com/cajohare/AxionLimits

Some experimental haloscope efforts



Some experimental efforts: LC circuits

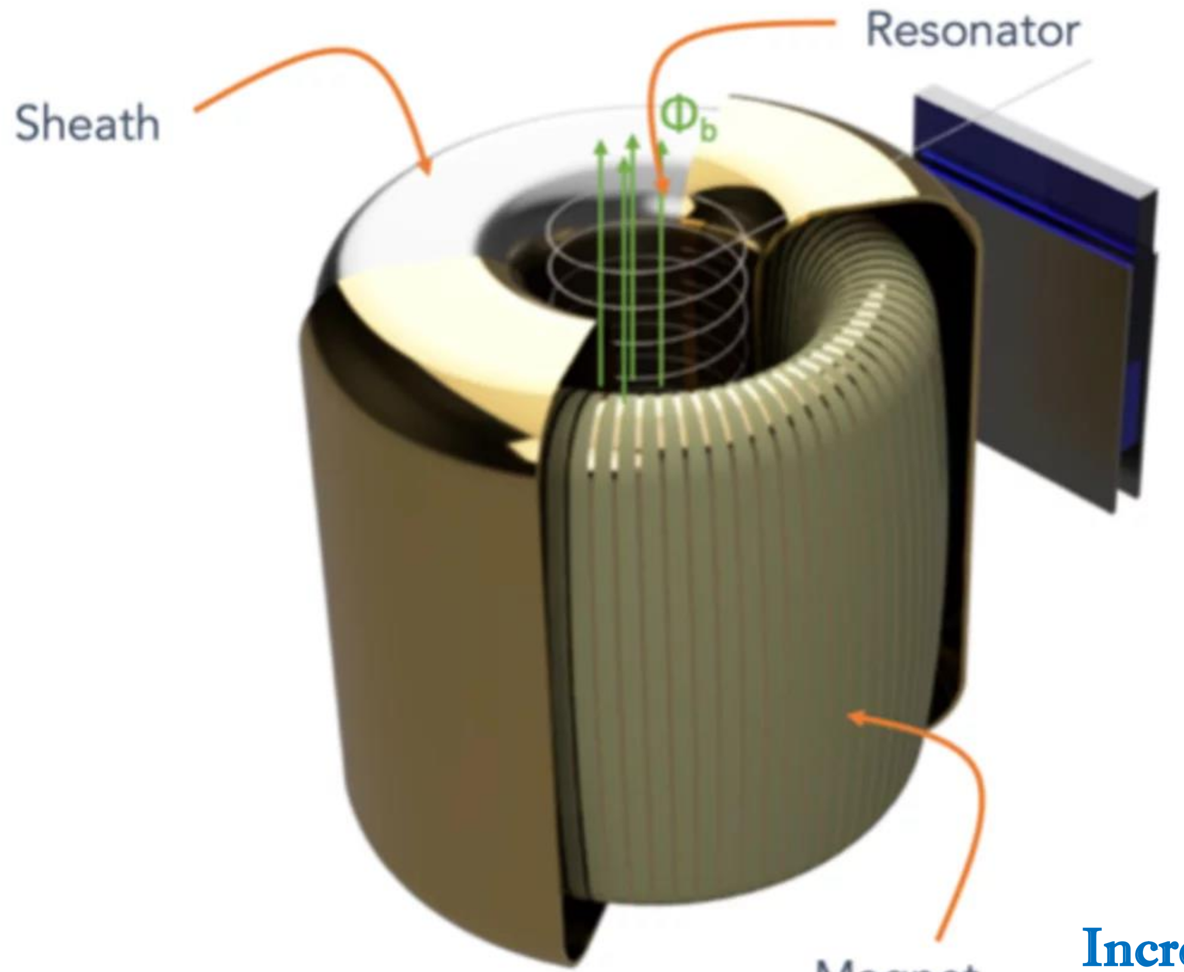
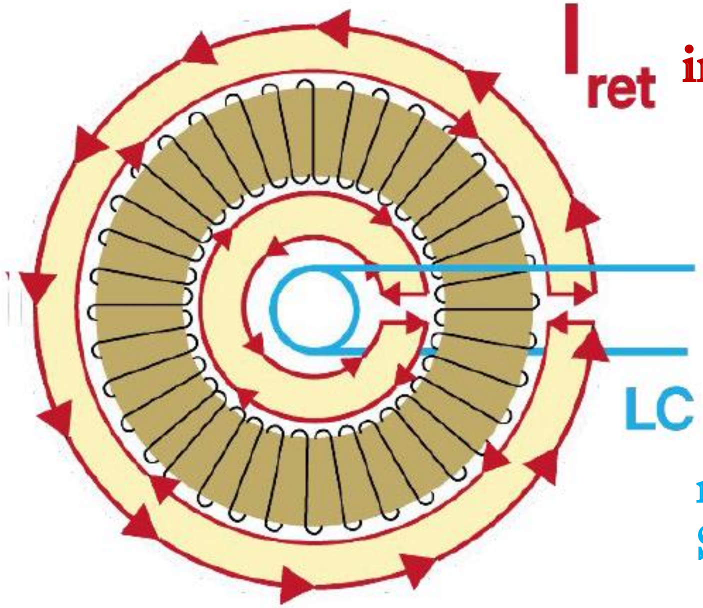


Figure taken from
https://irwinlab.stanford.edu/dark-matter-radio-dm-radio

B_a-field oscillations in center of toroidal magnet
→ Pick up with LC resonator using SQUIDs



induced by B_a

read out using
SQUID amplifier

Increase sensitivity:
→ Increase of Volume, B-field, resonator Q-factor
→ Decrease Temperature, LC Pickup Impedance

Taken from M Simanovskaia Patrs 2023 conference

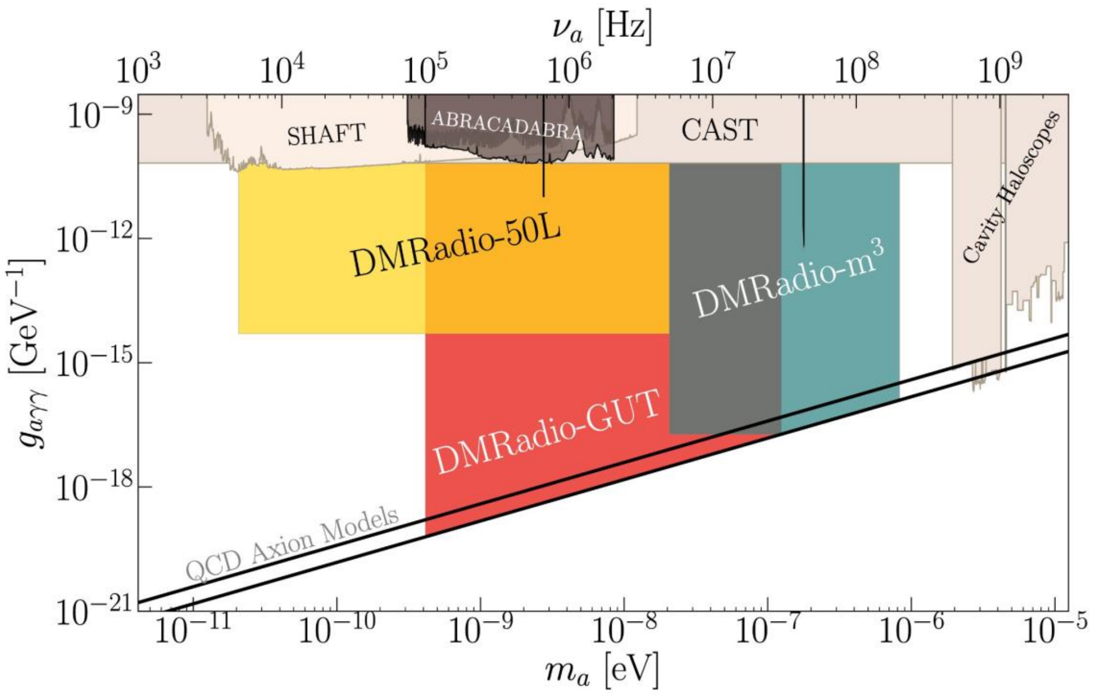
Some experimental efforts: LC circuits
DM Radio

DMRadio Science Goals

DMRadio-50L
- 5 kHz - 5 MHz
- Quantum sensor testbed

DMRadio-m³ (arXiv:2204.13781)
- Primary goal:
  - DFSZ 30 MHz - 200 MHz
- Secondary goals:
  - KSVZ down to 10 MHz
  - QCD axion band to 5 MHz
- Funding: DOE DMNI

DMRadio-GUT (arXiv:2203.11246)
- DFSZ 100 kHz - 30 MHz
- Next-generation detector



Taken from Dale Li Patrs 2023 conference

DMRadio-50L
- Commissioning in early 2024!
- Quantum Sensing in 2025

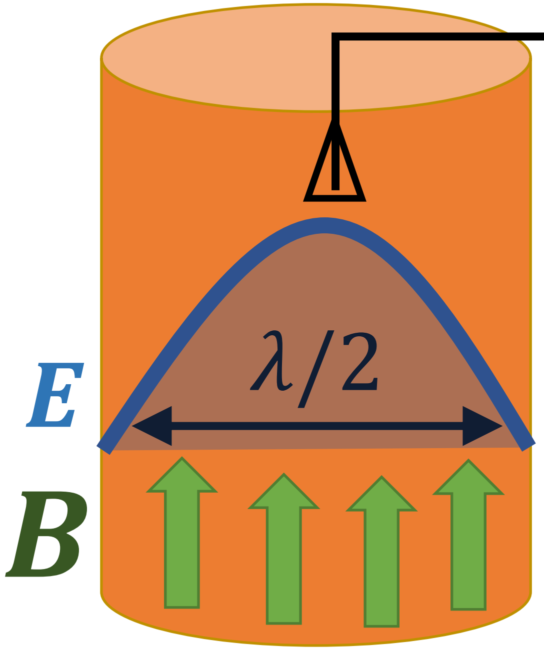
DMRadio-m³
- Engineering Complete Spring 2024
- Construction Ready 2025

DMRadio-GUT (arXiv:2203.11246)
- DFSZ 100 kHz - 30 MHz
- Technological improvements in
  - Magnets 16 Tesla
  - Quantum sensing (from 50L)
  - Active Feedback

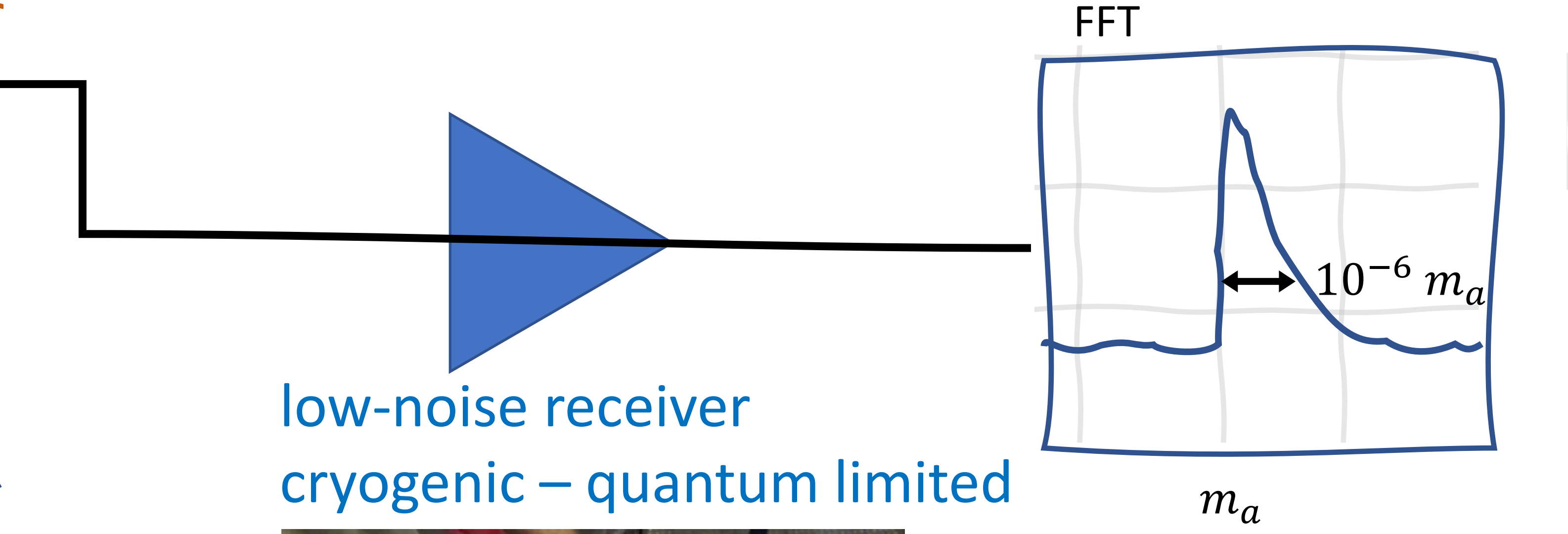
Some experimental efforts: Cavities

→ Use resonator to "pump cavity"
Adjusting resonance frequency: "Tuning Rod"

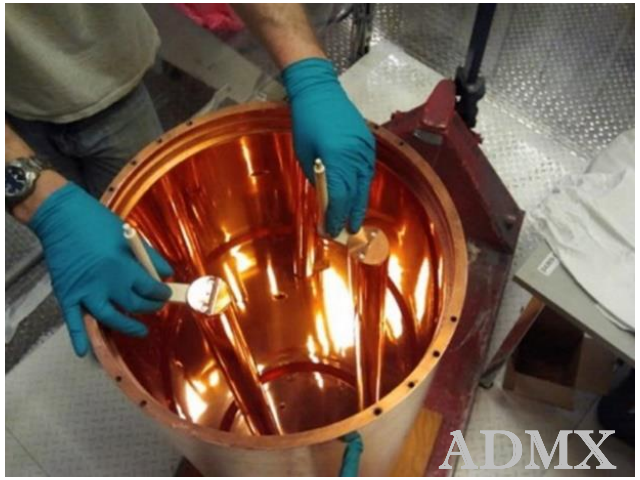
high-Q resonator



high B-field



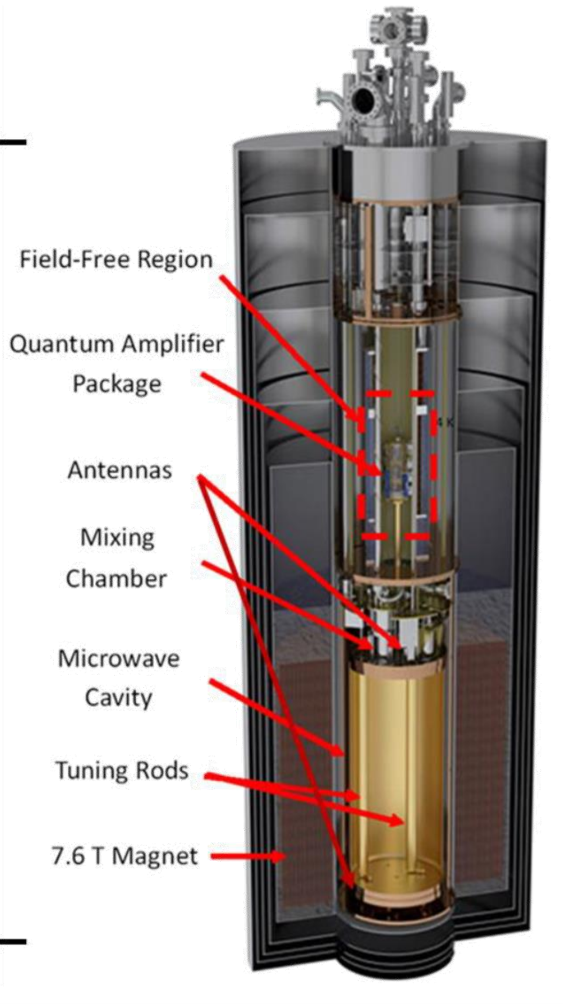
low-noise receiver
cryogenic – quantum limited

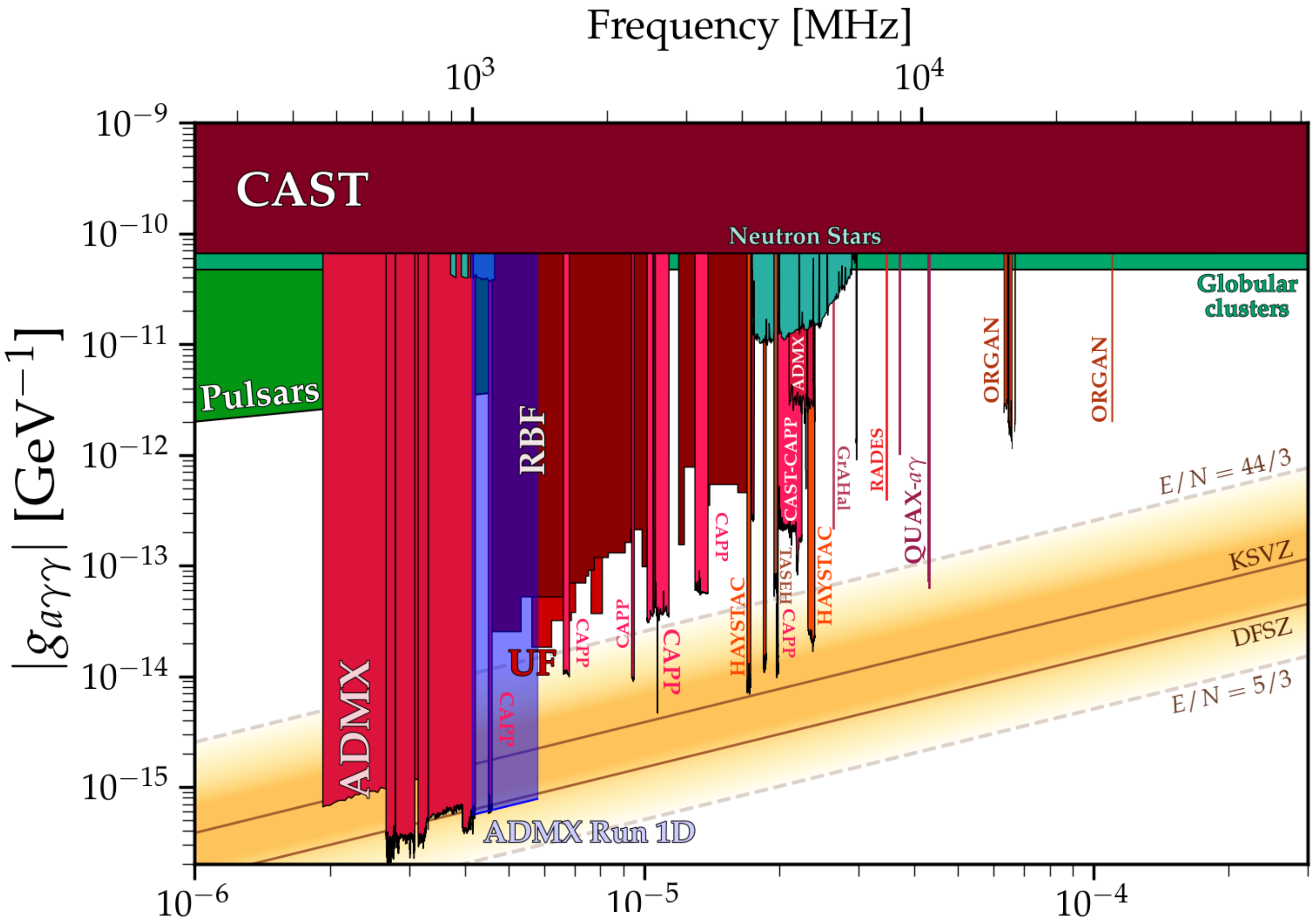


Tuning rods for changing resonant frequency

Taken from Stefan Knirck Patras 2023 conference

Some experimental efforts: ADMX



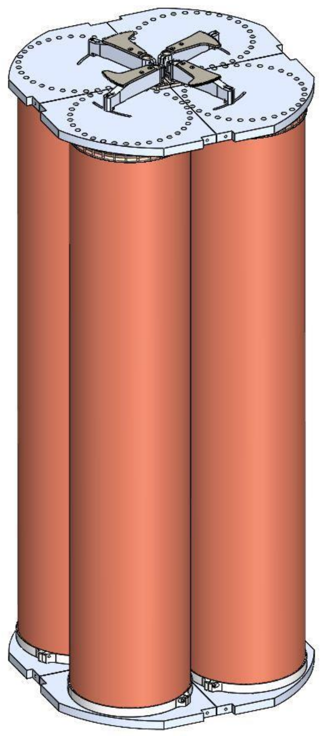


Taken from:
N. Du, PATRAS 2023

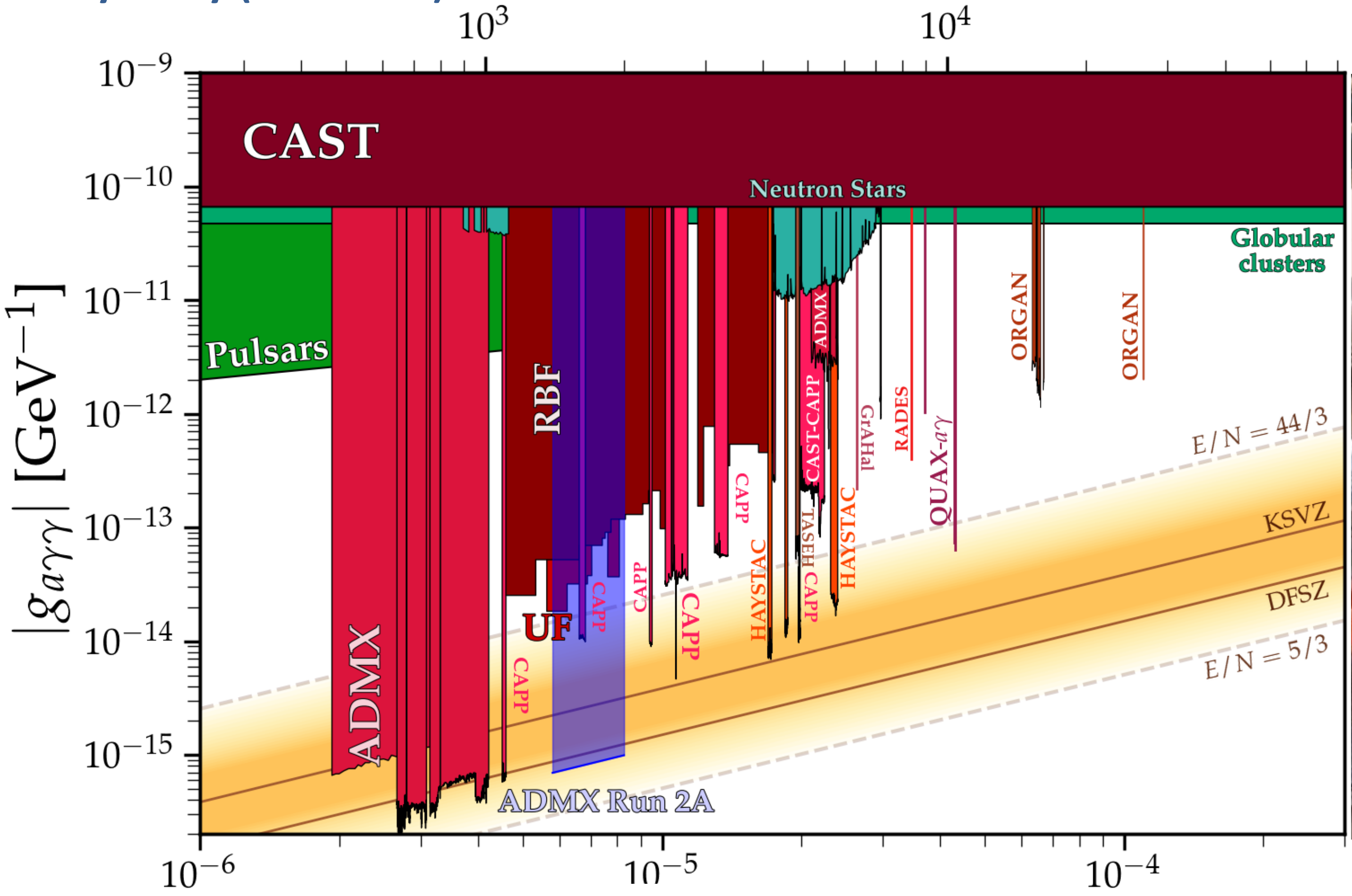
Ultra low temperatures
Quantum detectors
High Q cavity
→ Running at DFSZ sensitivity

Some experimental efforts: ADMX

ADMX Run 2A: 4-Cavity Array (1.4-2 GHz)



4 individual cavities tuned by rotors

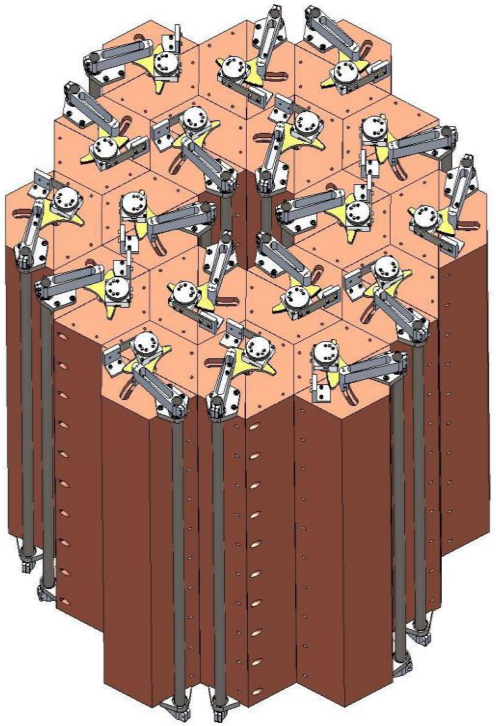


Increasing frequency range:
→ Multi cavity

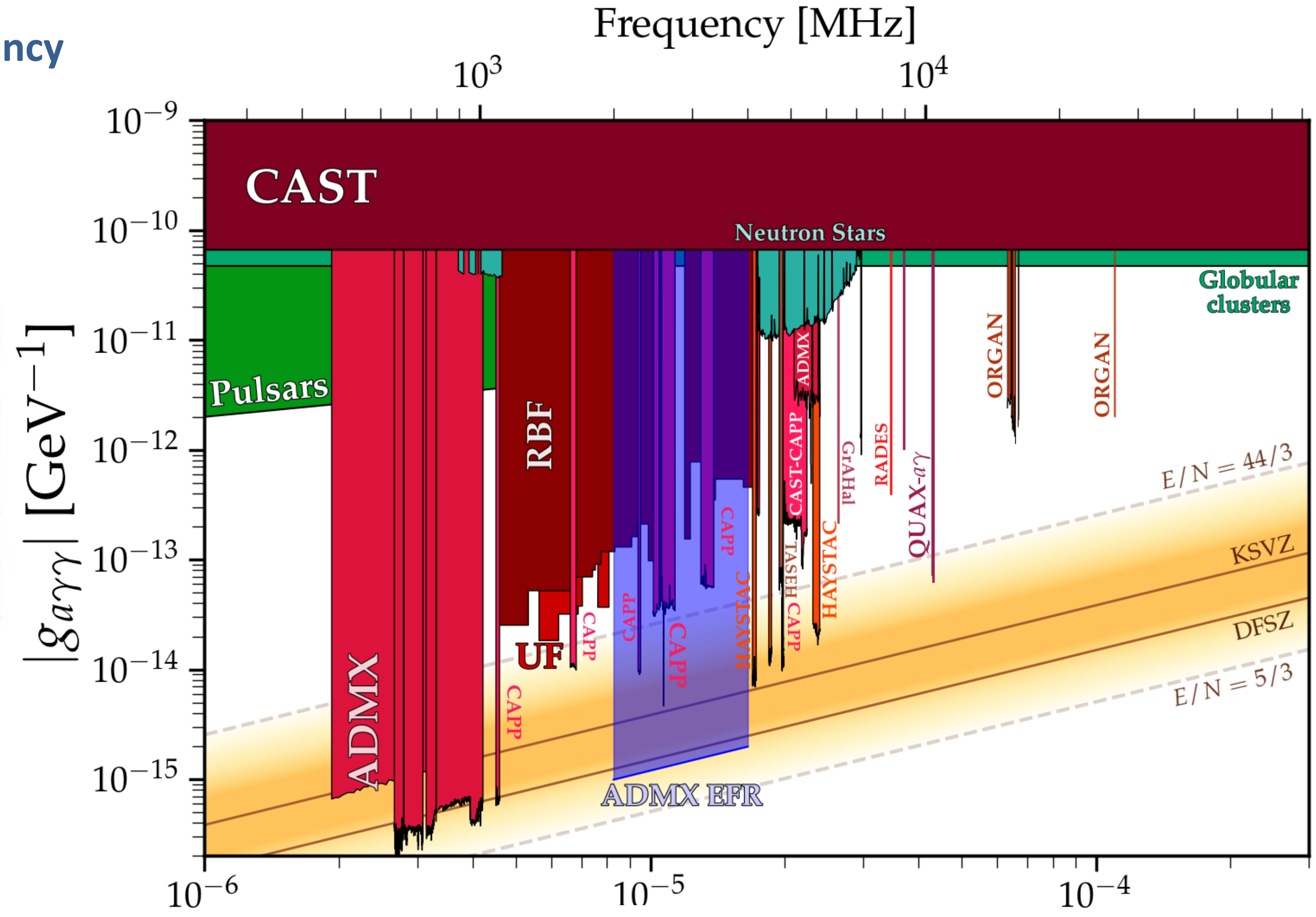
Taken from:
N. Du, PATRAS 2023

Some experimental efforts: ADMX

ADMX Extended Frequency Range (EFR): 2-4 GHz



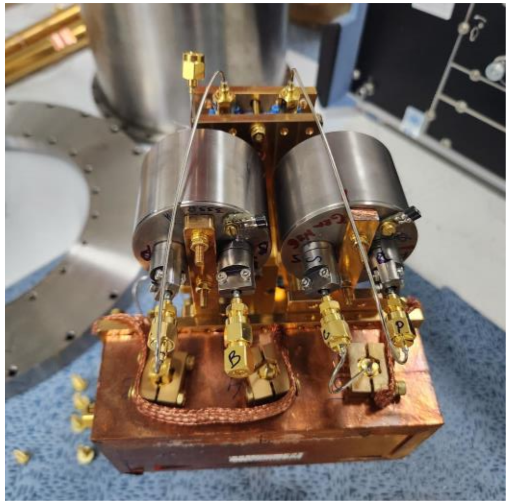
Taken from:
N. Du, PATRAS 2023



Increase number of cavities
New magnet (MRI)
to scan up to 4 GHz

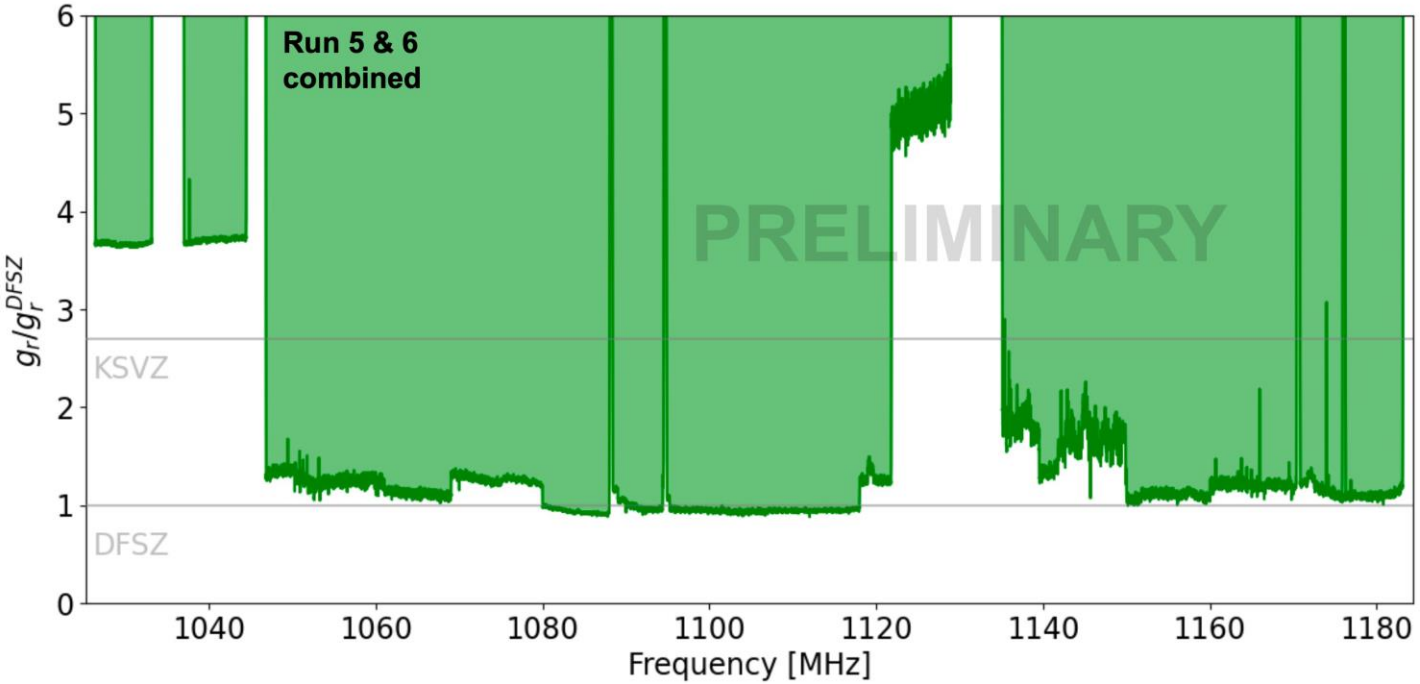
Magnet picture taken from:
N. Oblath, TAUP2023

Some experimental efforts: CAPP



Taken from: S. Ahn, PATRAS 2023

Sensitivity (preliminary)

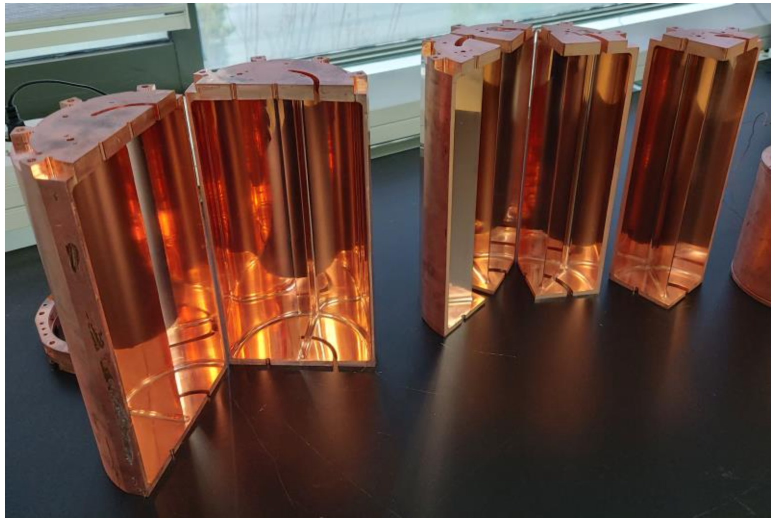


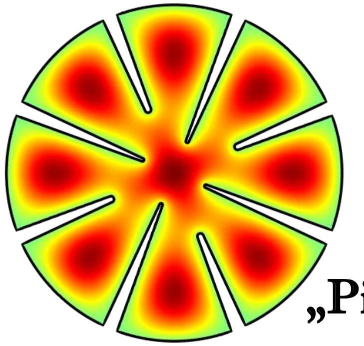
Ultra low temperatures
Quantum detectors - JPAs
High Q cavity - HTSuperconductor
→ **Running at DFSZ sensitivity**

Some experimental efforts: CAPP novel designs

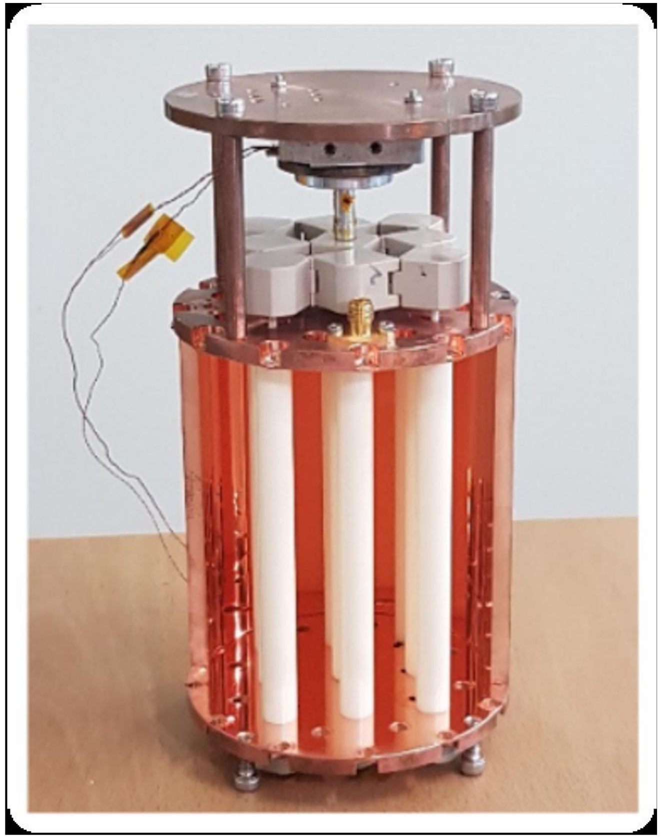
Taken from: W. Chung, PATRAS 2023

Coupled smaller cavities → higher frequencies





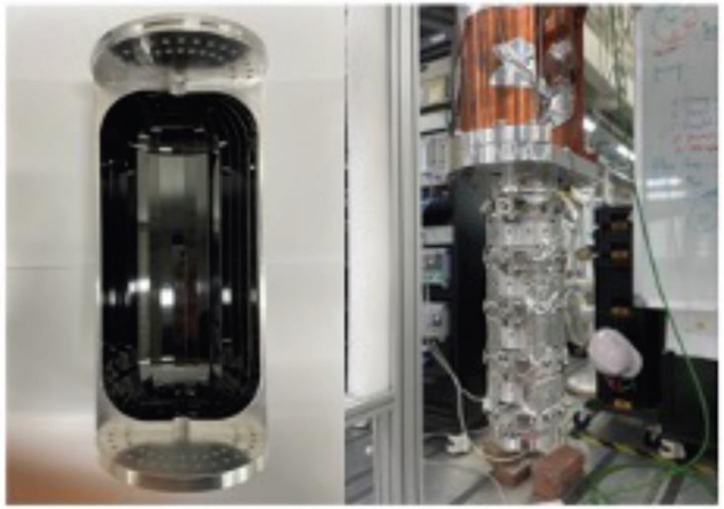
„Pizza cavity“

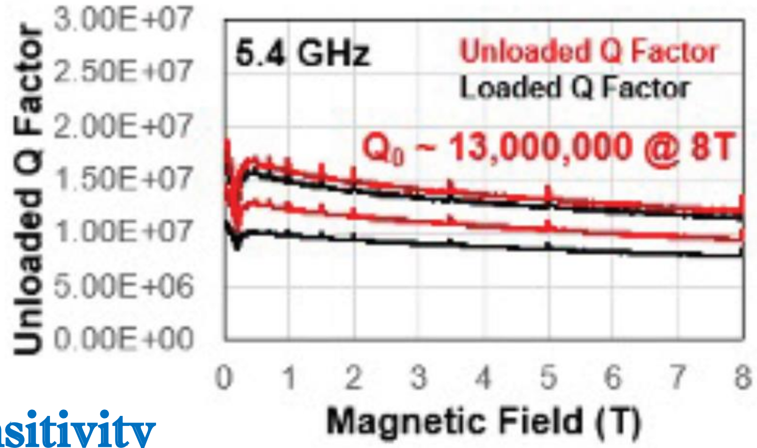


„Tunable photonic crystal“

Superconducting cavity at 8T (RebCo)

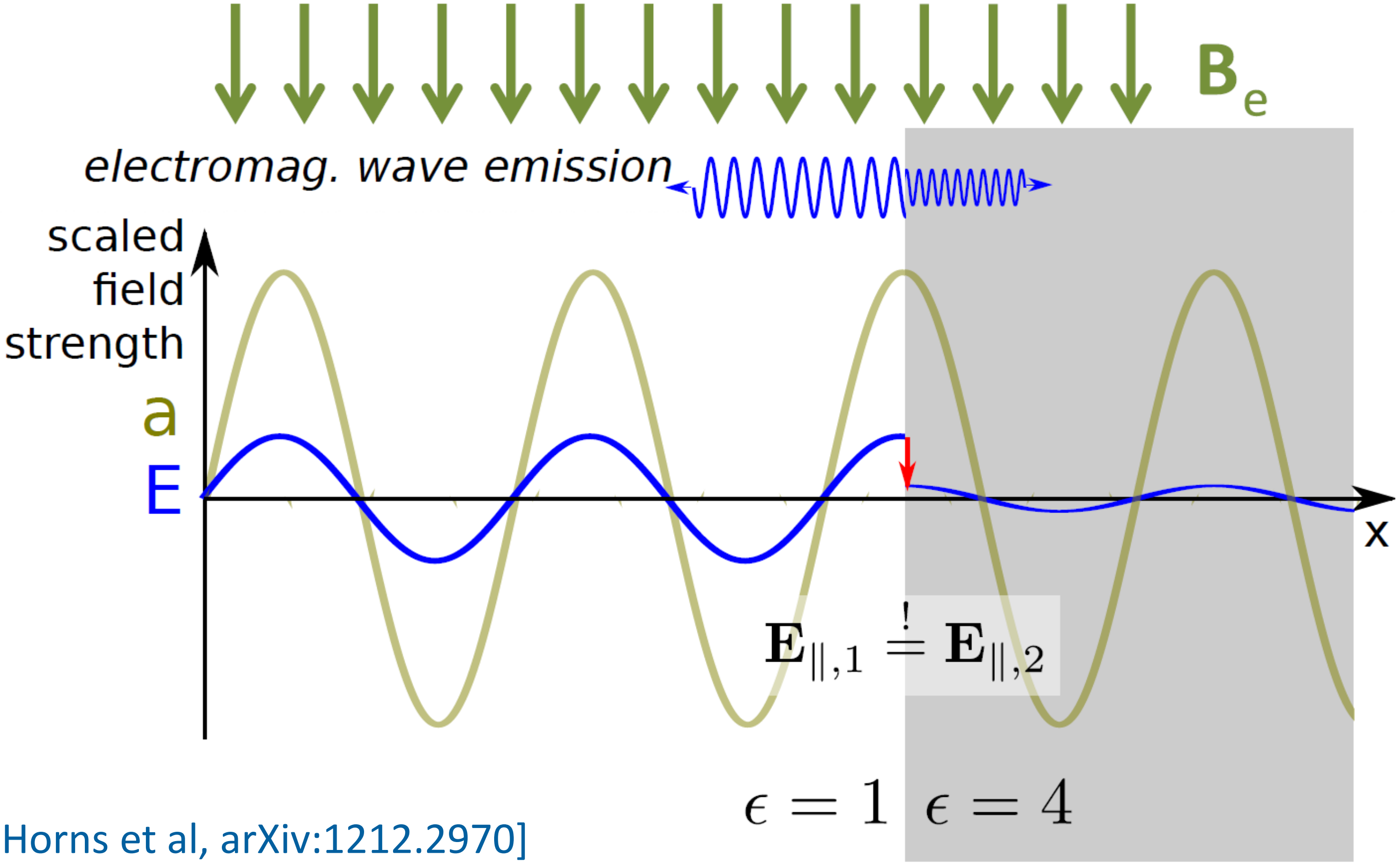
Third Gen. (2.2 GHz & 5.4 GHz)

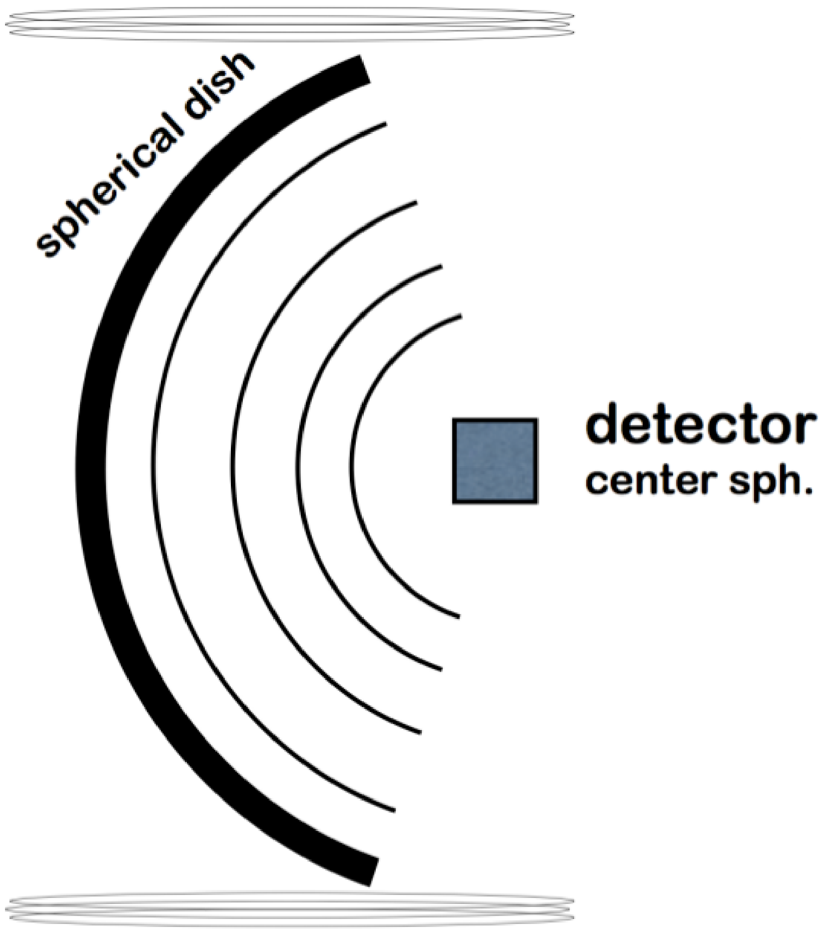




Soon to be sensitive in 1-8 Ghz range at KSVZ sensitivity

Dish Antenna:





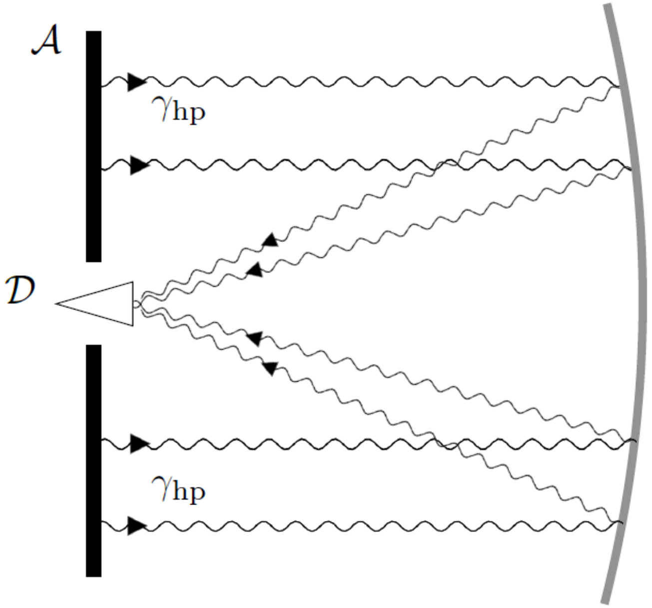
[Horns et al, arXiv:1212.2970]

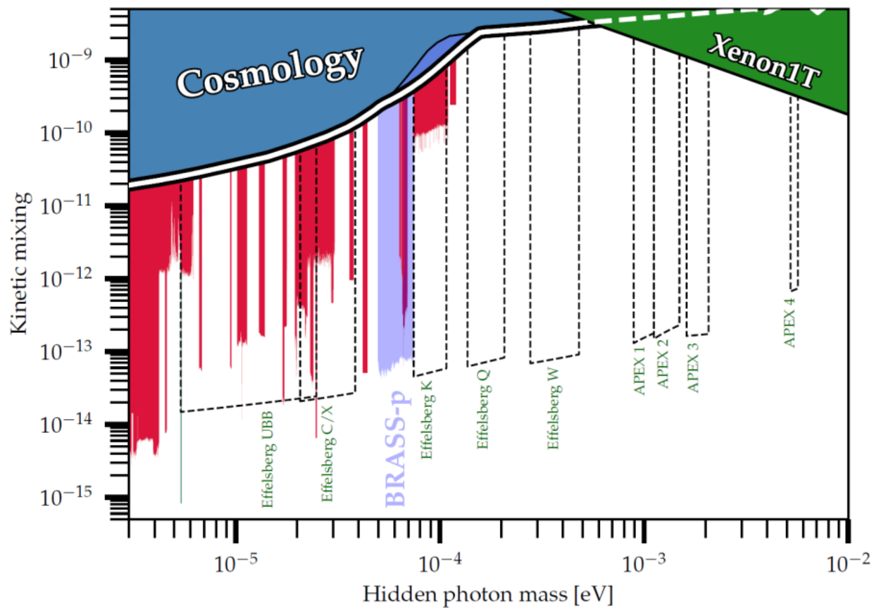
$$\left(\frac{P}{A}\right)_{mirror} \sim 2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_{||}}{10\ T}\right)^2 (g_{a\gamma\gamma} m_a)^2$$

Hidden photon measurements (no-B field): BRASS, Tokyo, SHUKET, FUNK,…

Dish Antenna: BRASS
Hidden Photon search

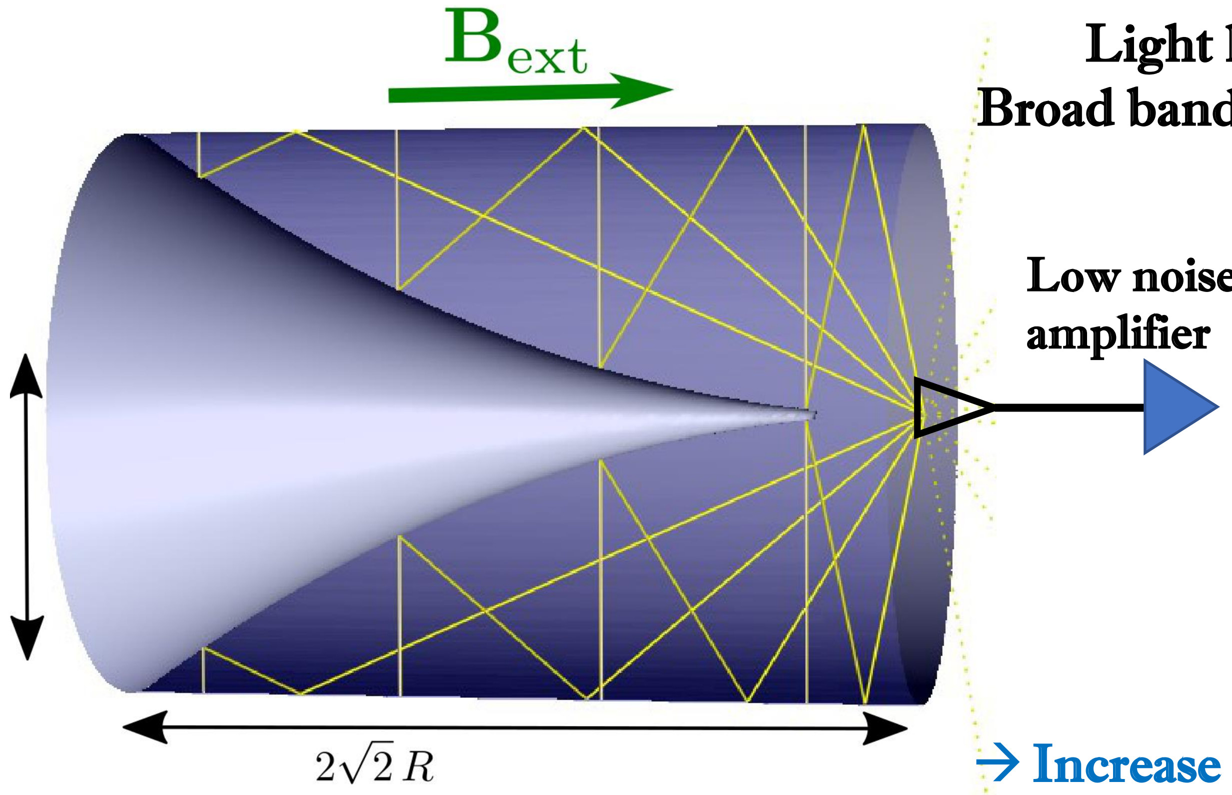
arXiv:2306.05934





Development of NdFeB magnet with ~3 T^2m^3 → ALP measurements

Dish Antenna:
Broadband Reflector Experiment for Axion Detection



Taken from: S. Knirck, PATRAS 2023

Light house reflector design
Broad band disch antenna in solenoid

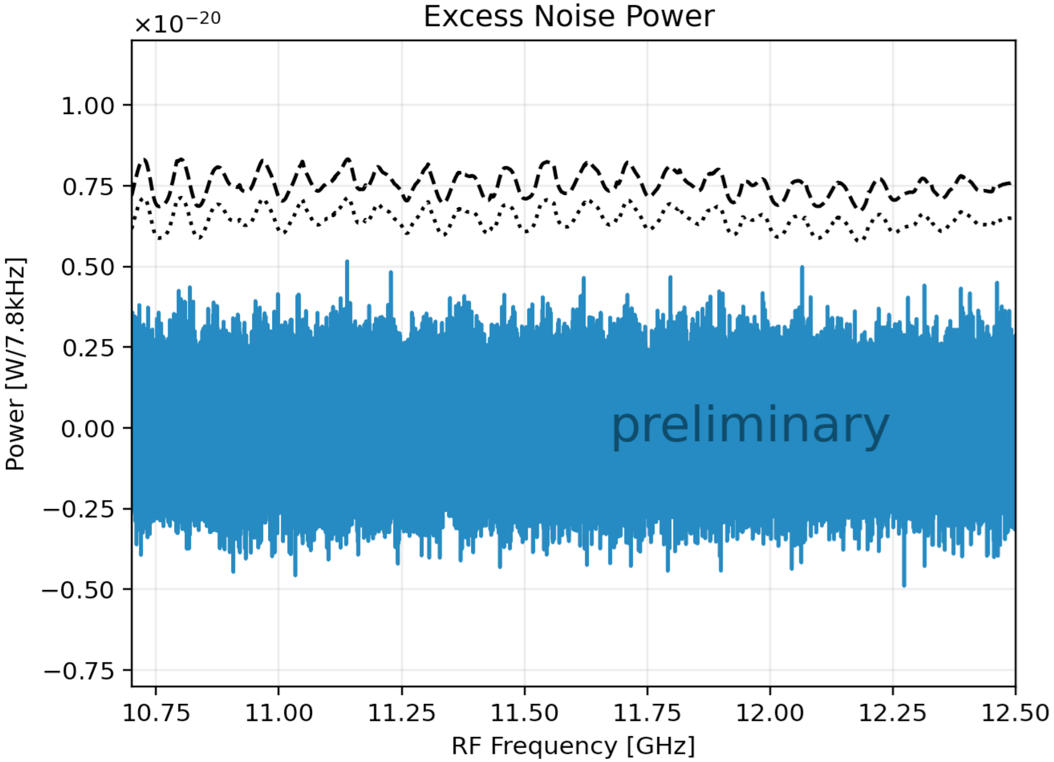
→ Increase area
→ Cryogenic temperatures
→ Quantum limited amplifier
Single photon detection
→ Brood band read out
→ Solenoid magnet

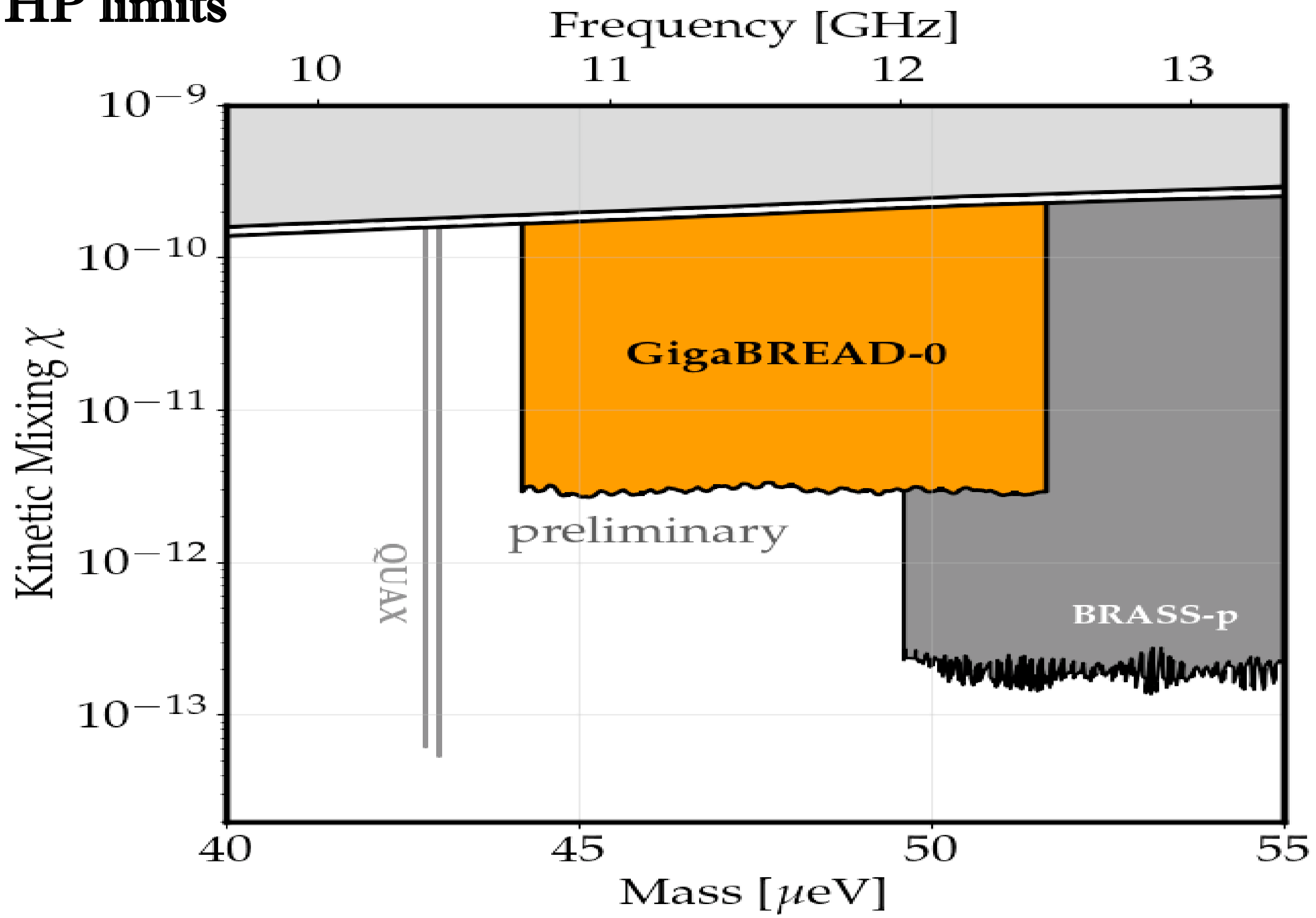
MAX-PLANCK-INSTITUT FÜR PHYSIK

BREAD COLLABORATION

Dish Antenna: Broadband Reflector Experiment for Axion Detection

First data with proof of principle without cryostat, no B-field → HP limits





Taken from: S. Knirck, PATRAS 2023

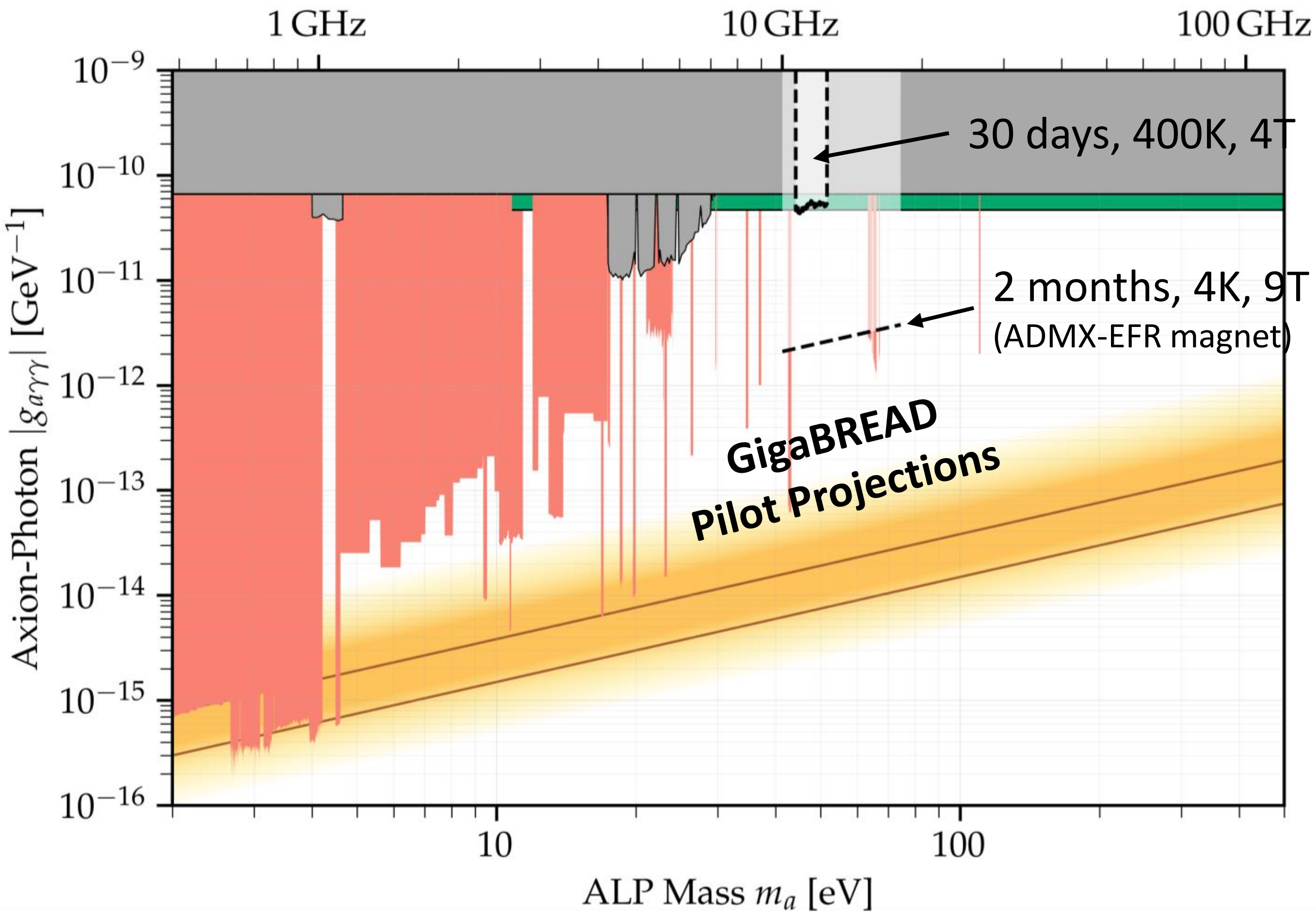
MAX-PLANCK-INSTITUT FÜR PHYSIK

BREAD COLLABORATION

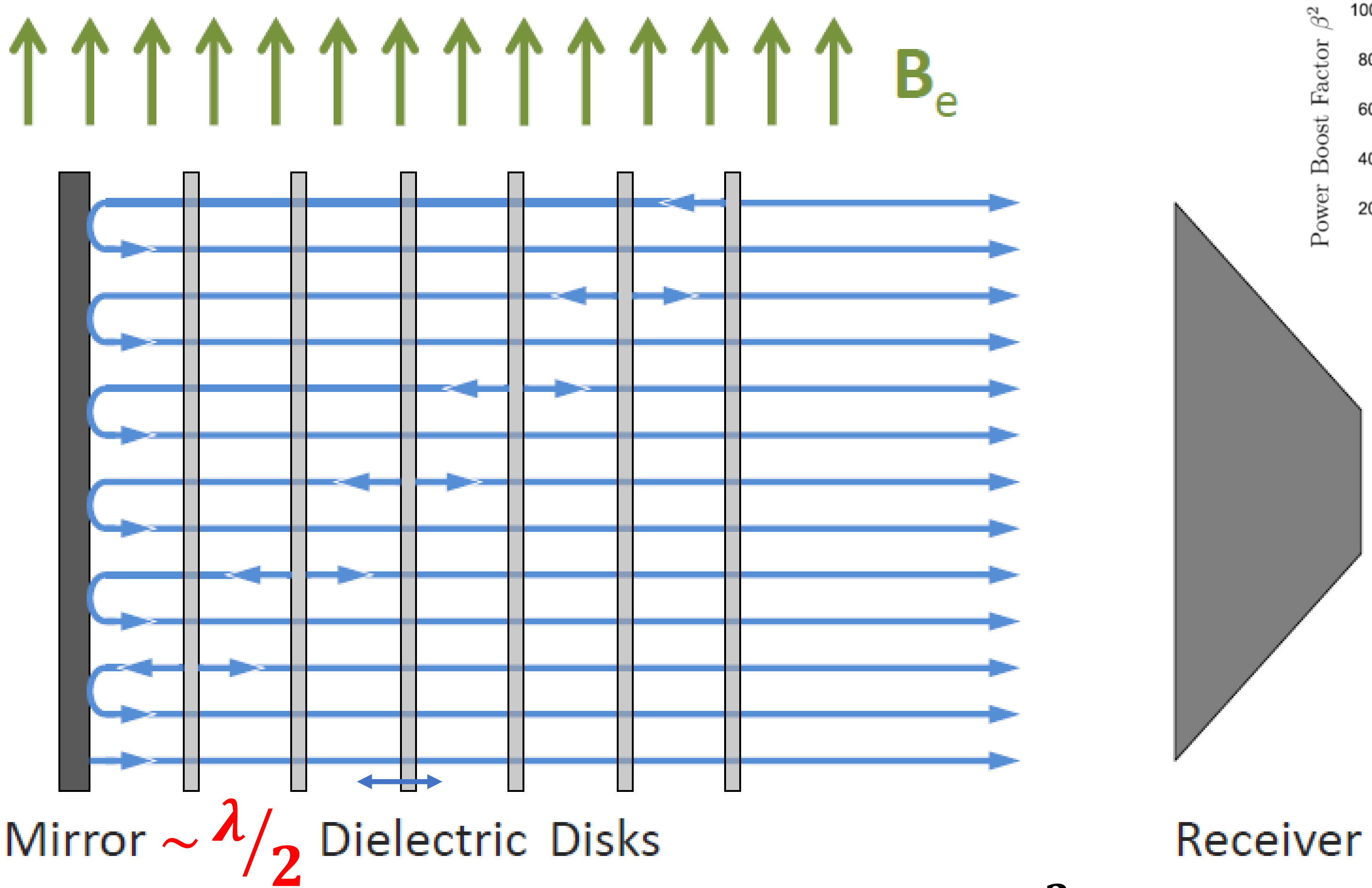
Dish Antenna: Broadband Reflector Experiment for Axion Detection

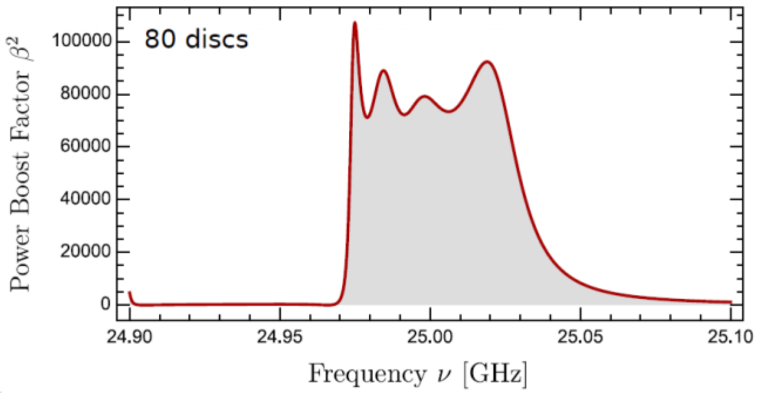
Upgrade soon: cryostat + 4T magnet → ALP senstivity

Taken from: S. Knirck, PATRAS 2023



Dielectric Haloscope





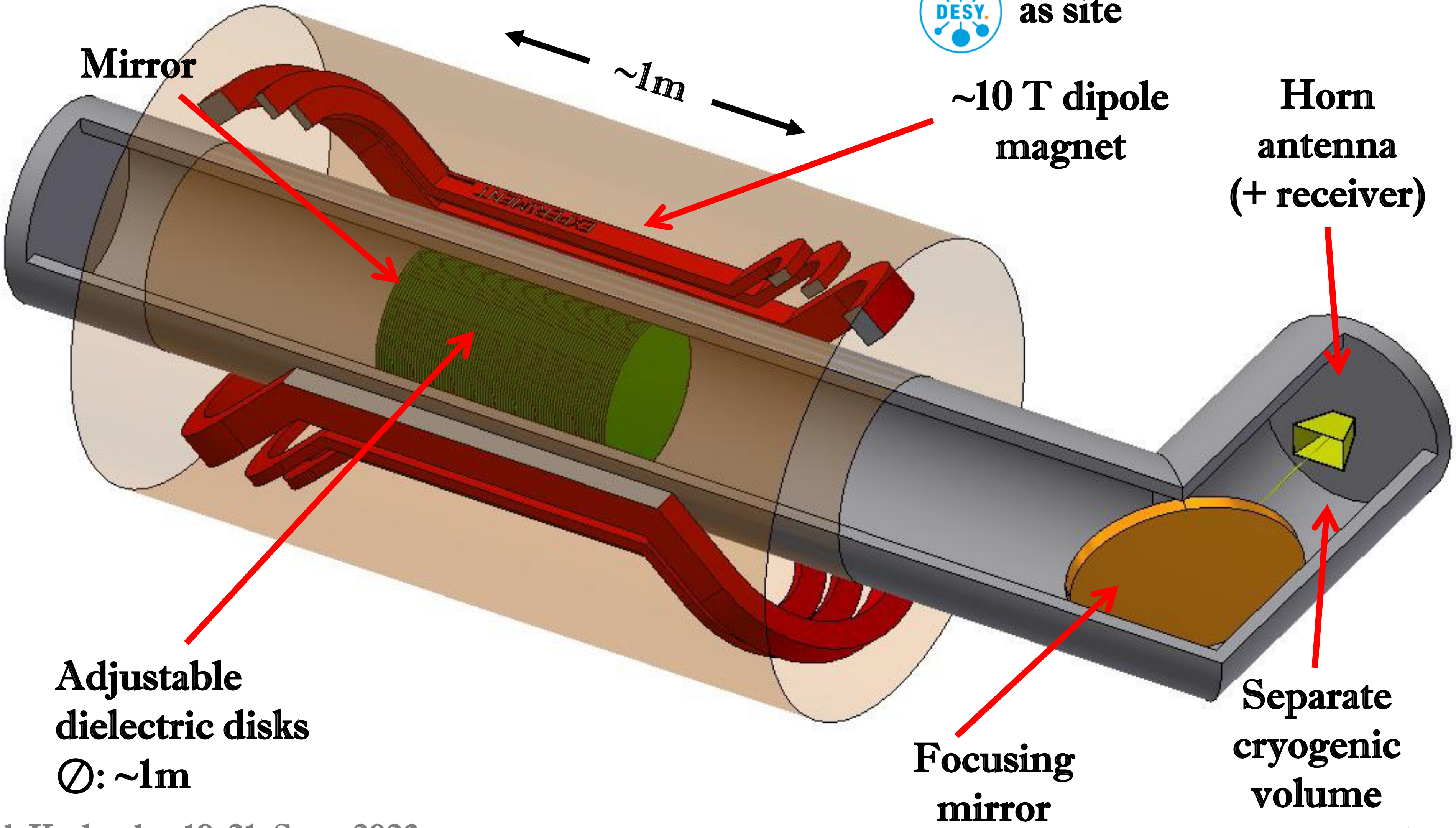
$$\beta^2 = \frac{P_{cavity}}{P_{mirror}}$$

$$\left(\frac{P}{A}\right)_{cavity} \sim 2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_{||}}{10\,T}\right)^2 (g_{a\gamma\gamma} m_a)^2 \beta^2$$

Dielectric Haloscope MADMAX

MAgnetized disk and Mirror Axion eXperiment

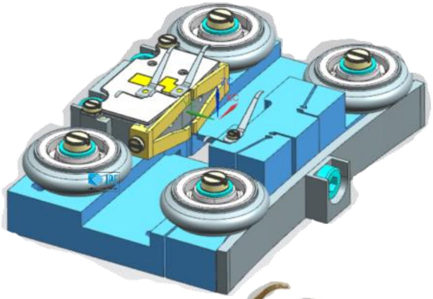
DESY. as site



MAX-PLANCK-INSTITUT FÜR PHYSIK

The MADMAX mechanics

JPE
Driven by innovation



Feasibility of disc motors at 4K in strong B-field

✓ Developed Piezo motor drive unit

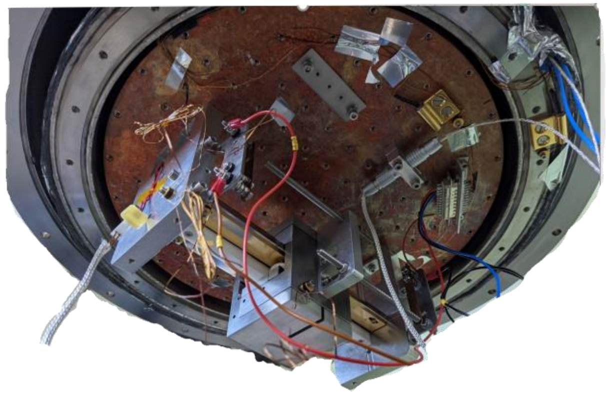
Repeatability < 1μm

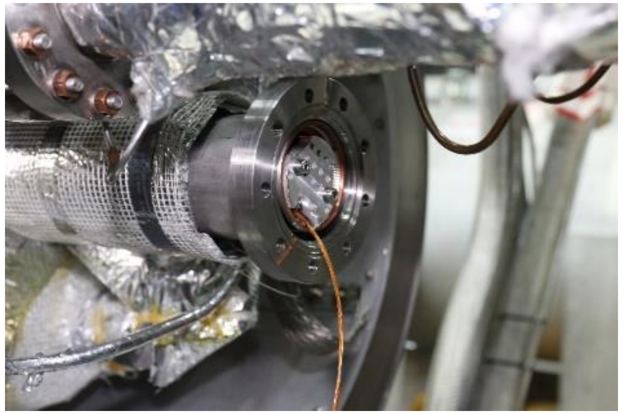
✓ Characterized at 4.2 K ambient temperature

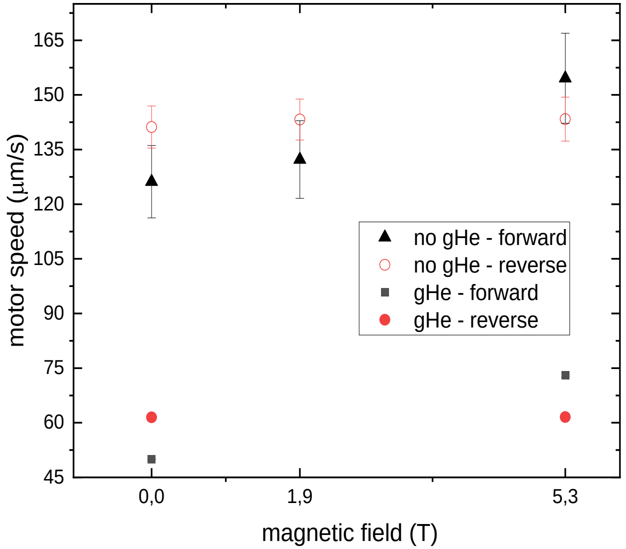
Speed > 0.1mm/sec

✓ Tested at 5 K in 5.3T magnet at DESY:

Moves reliably



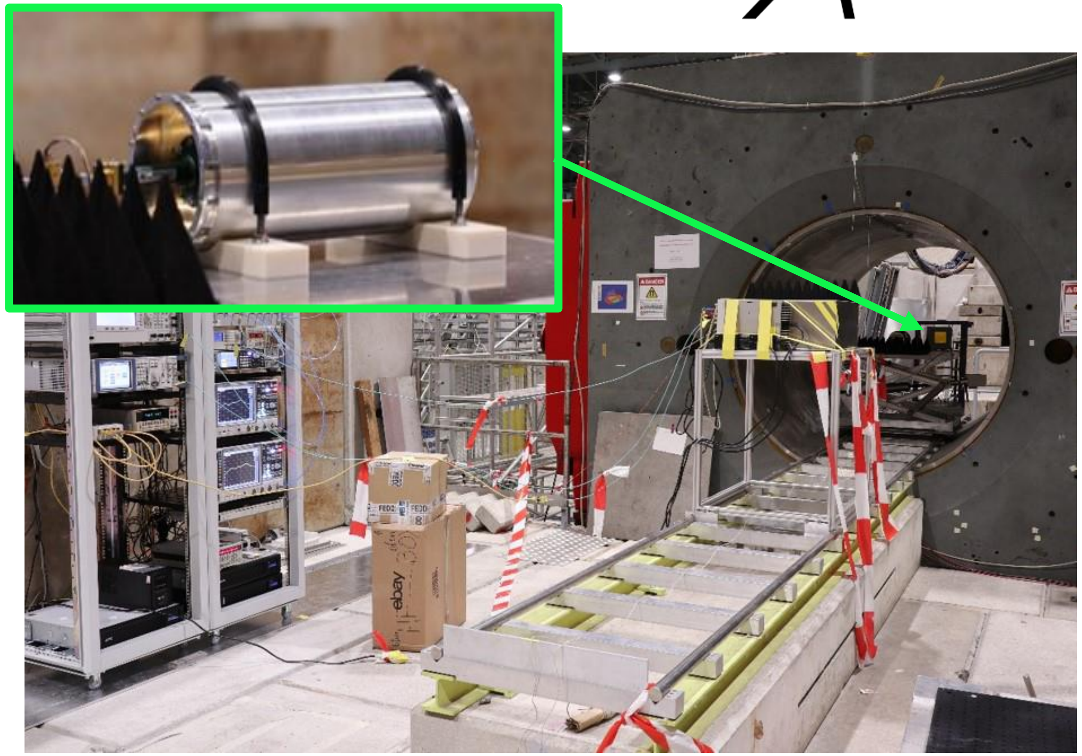


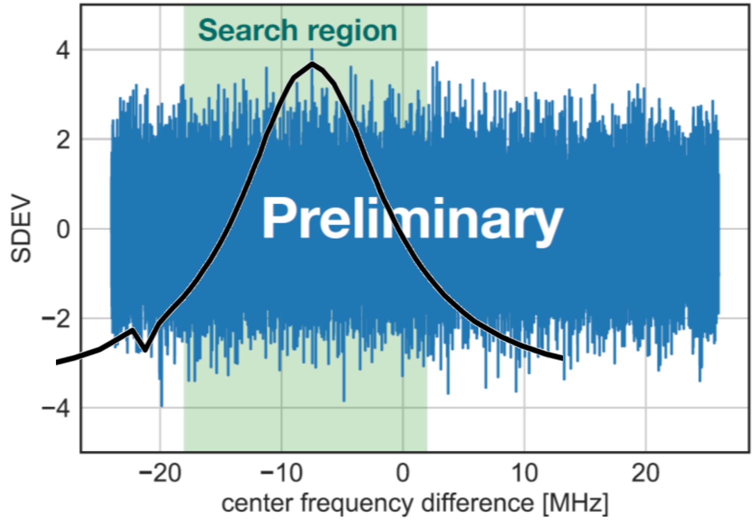


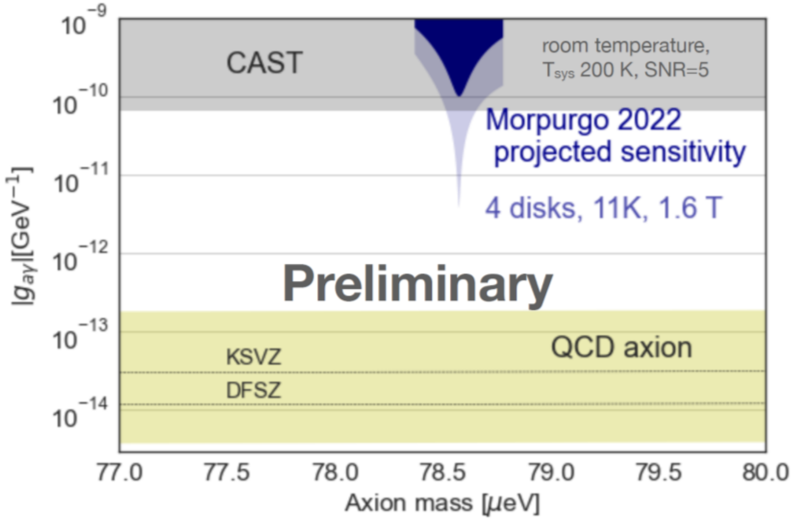
First MADMAX ALP measurement

B = 1.6 T, t = 10.5 hours

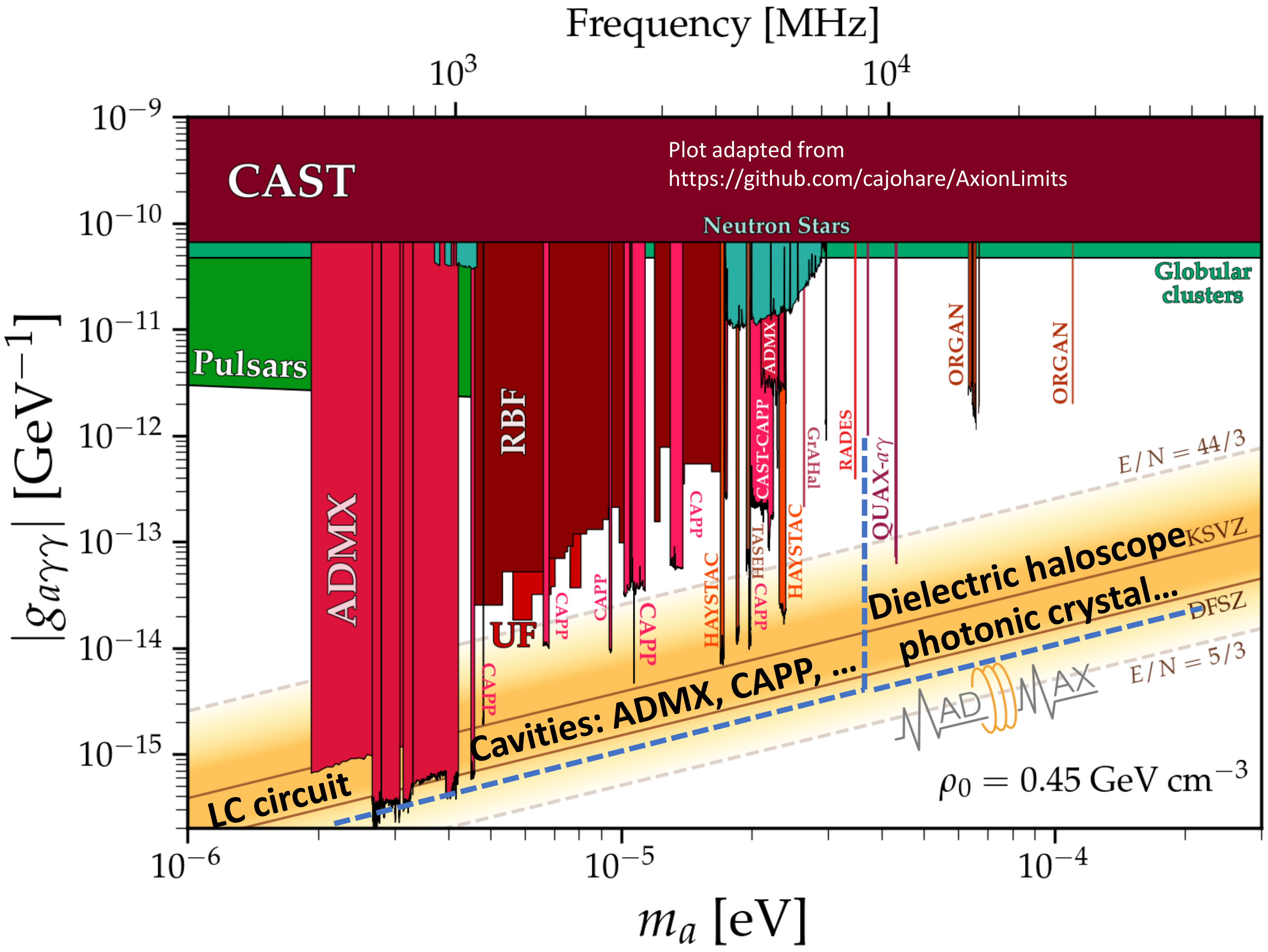
MORPURGO magnet at CERN







Experimental haloscope efforts: Summary



- **First cavity experiments with DM sensitivity taking data!**
- **Last decade has seen many new ideas / efforts emerging**
- **Huge mass range will be scanned with complementary technologies: NMR – LC circuit – cavities – dielectric haloscopes – …**
- **Major R&D efforts ongoing: Magnets – quantum sensors – HTS – dielectrics**