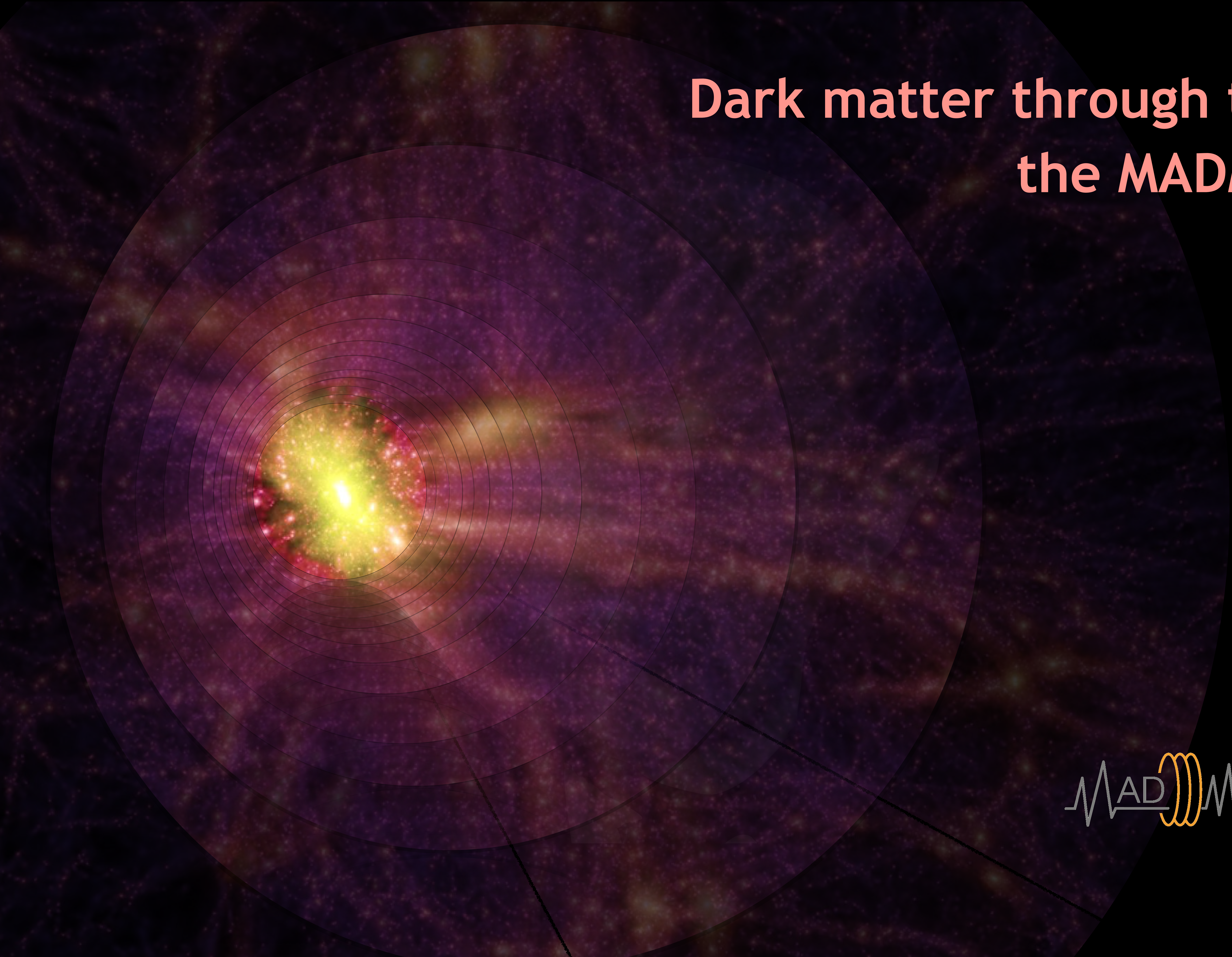

Dark matter through the looking glass the MADMAX experiment

Javier Redondo
DESY colloquium 2/4/2019

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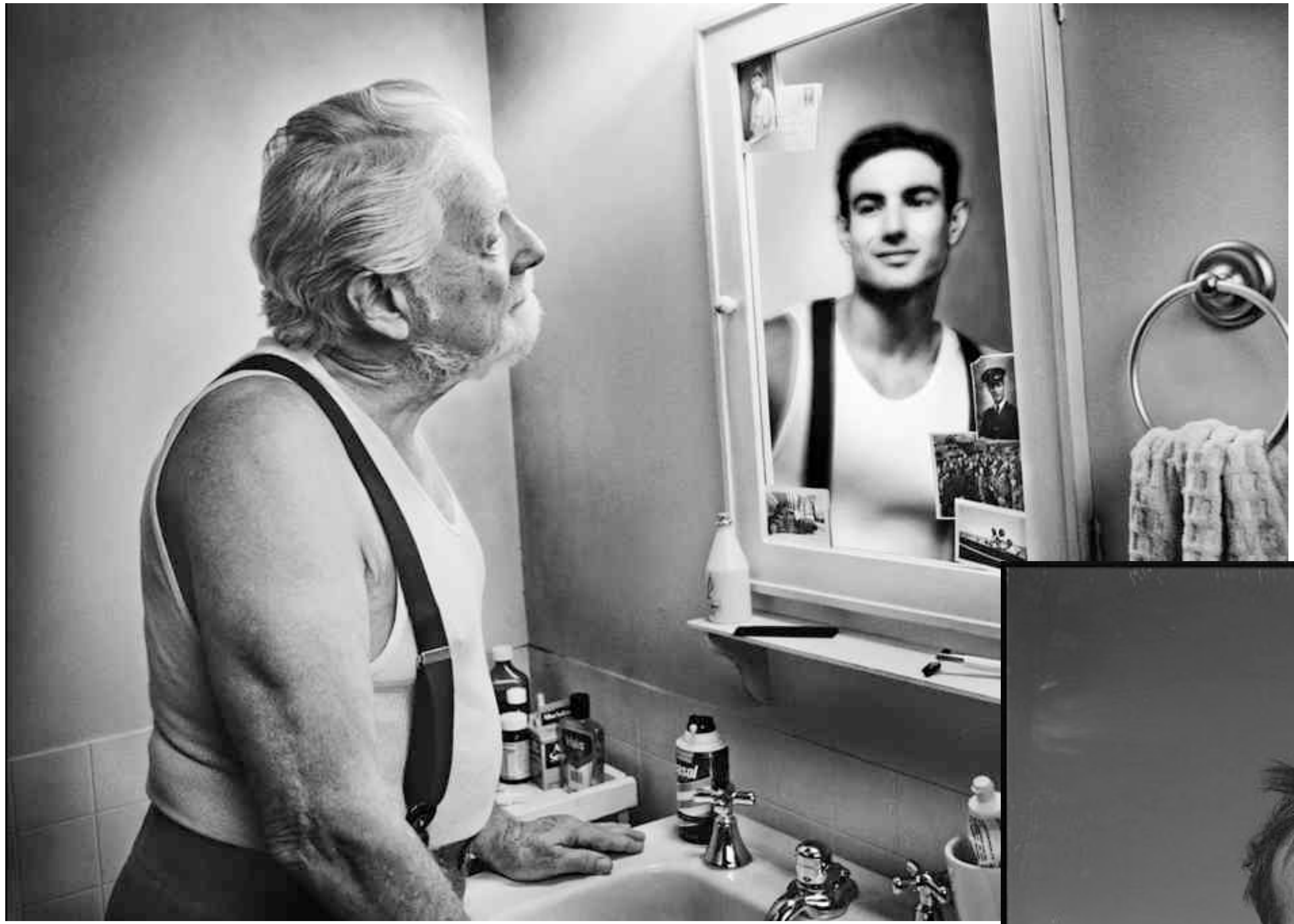
MPP Munich

Outline

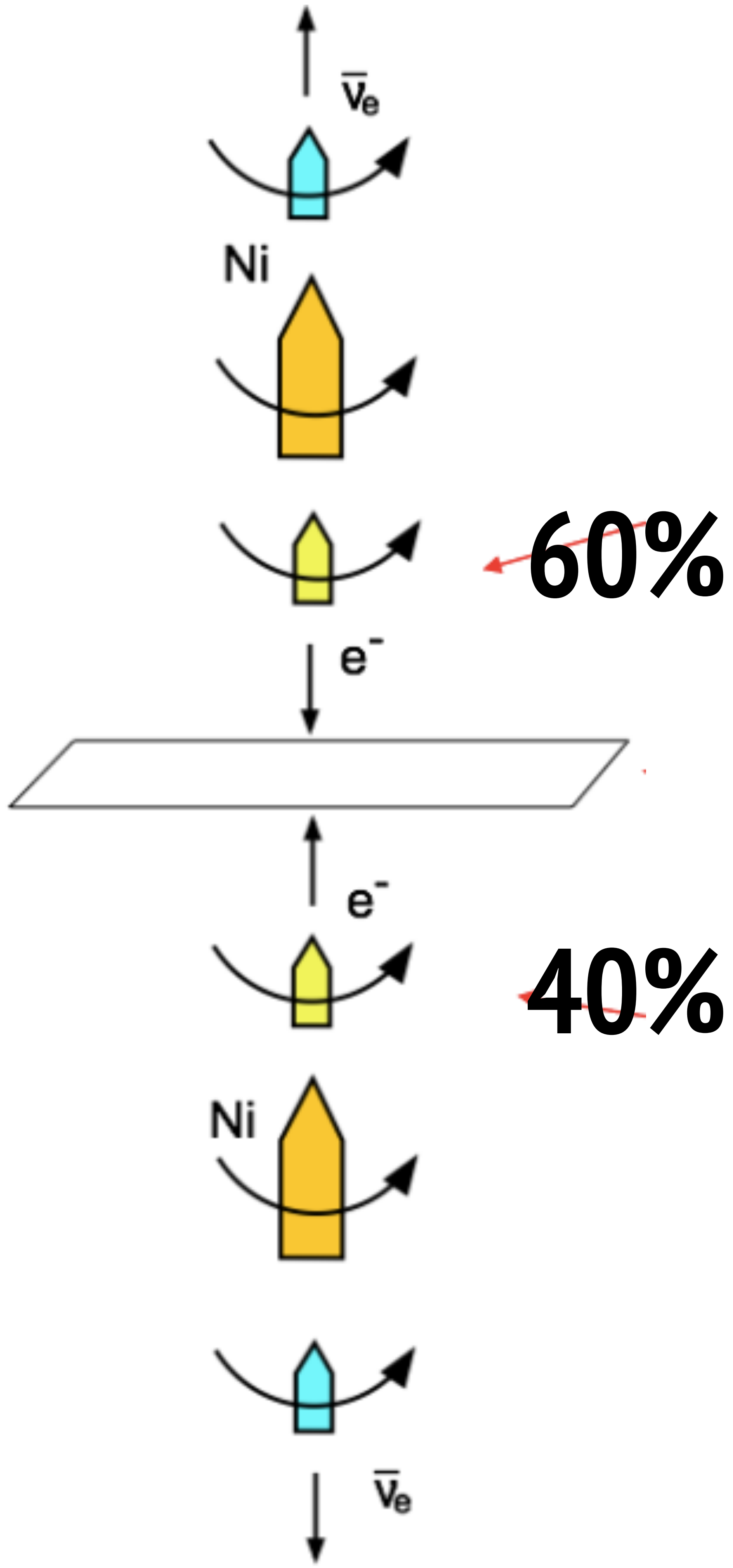
- Strong CP problem and axions
- Axion Dark matter
- The axion from hell
- MADMAX

Parity and Time reversal



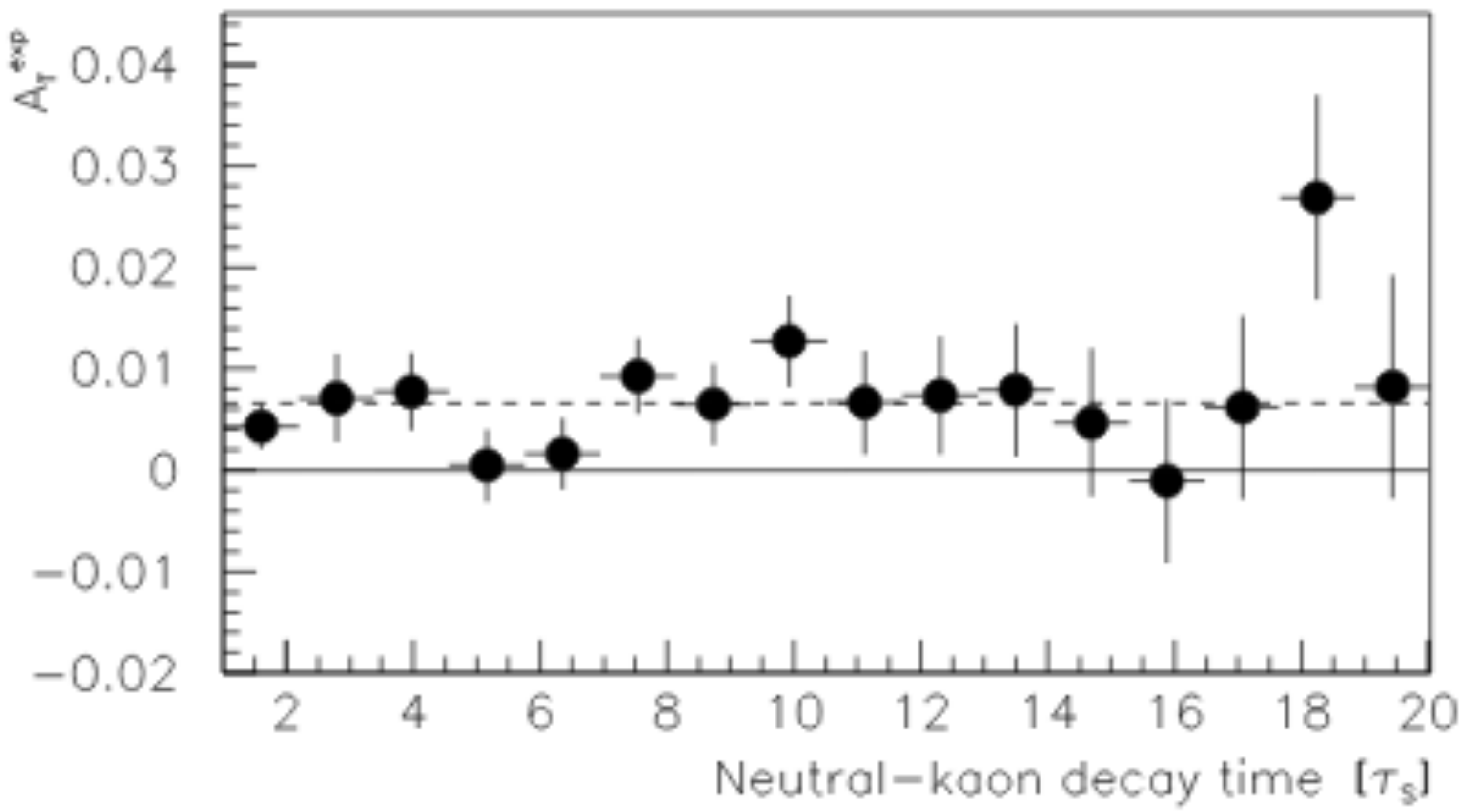
P and T are violated by electroweak interactions

P-violation (Wu 56)



T-violation (CPLEAR 90's)

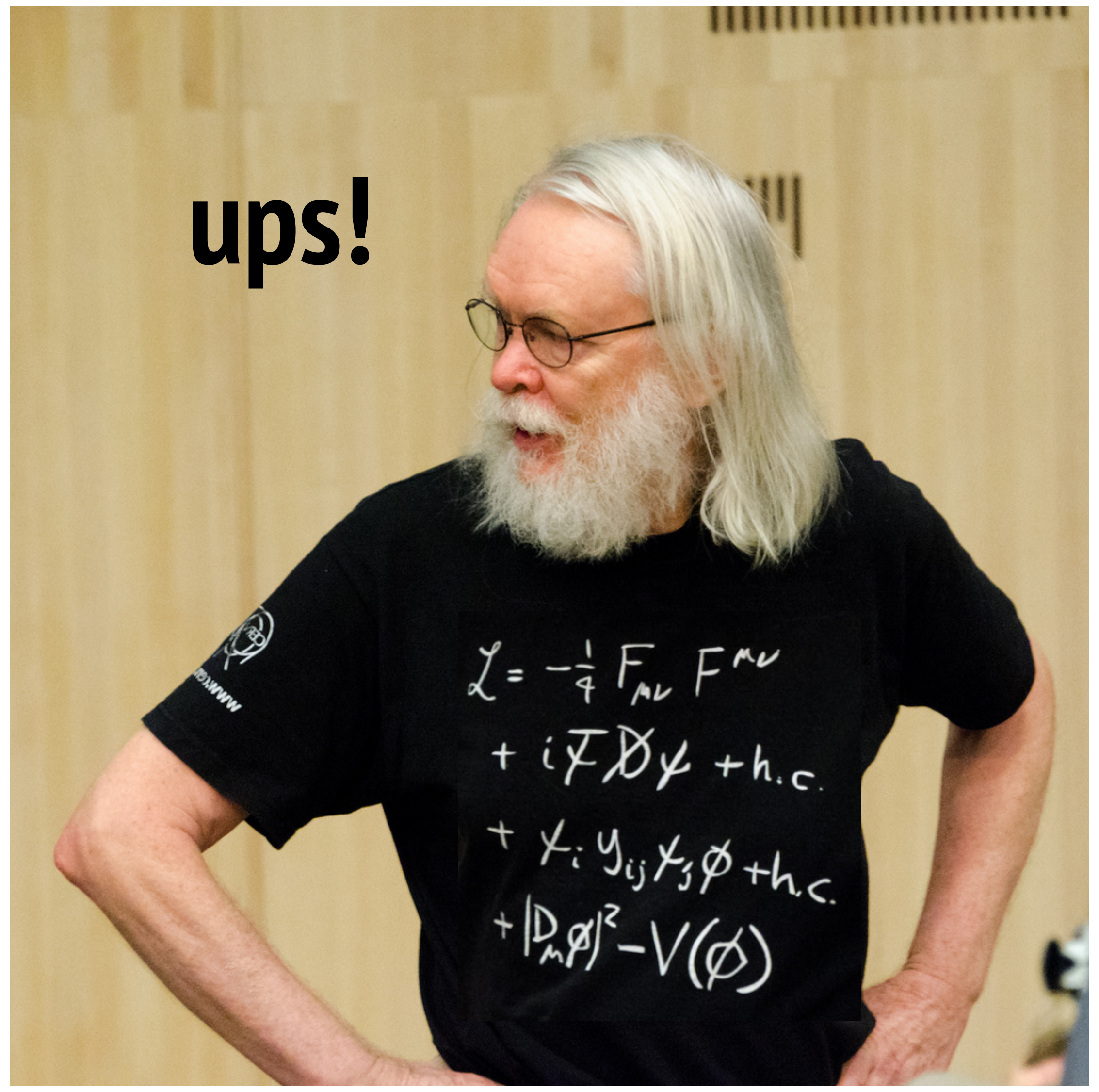
$$\frac{R(\bar{K}^0 \to K^0) - R(K^0 \to \bar{K}^0)}{R(\bar{K}^0 \to K^0) + R(K^0 \to \bar{K}^0)}$$



… but not in the strong interactions

which is shocking! QCDs are P, T violating

$$\mathcal{L}_{\rm QCD} = \underbrace{-\frac{1}{4}G_{\mu\nu a}G_a^{\mu\nu} + \sum_q i\bar{q}\gamma^\mu D_\mu q - \bar{q}mq}_{\text{P,T conserving}} + \underbrace{\frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}}_{\text{P,T violating}}$$



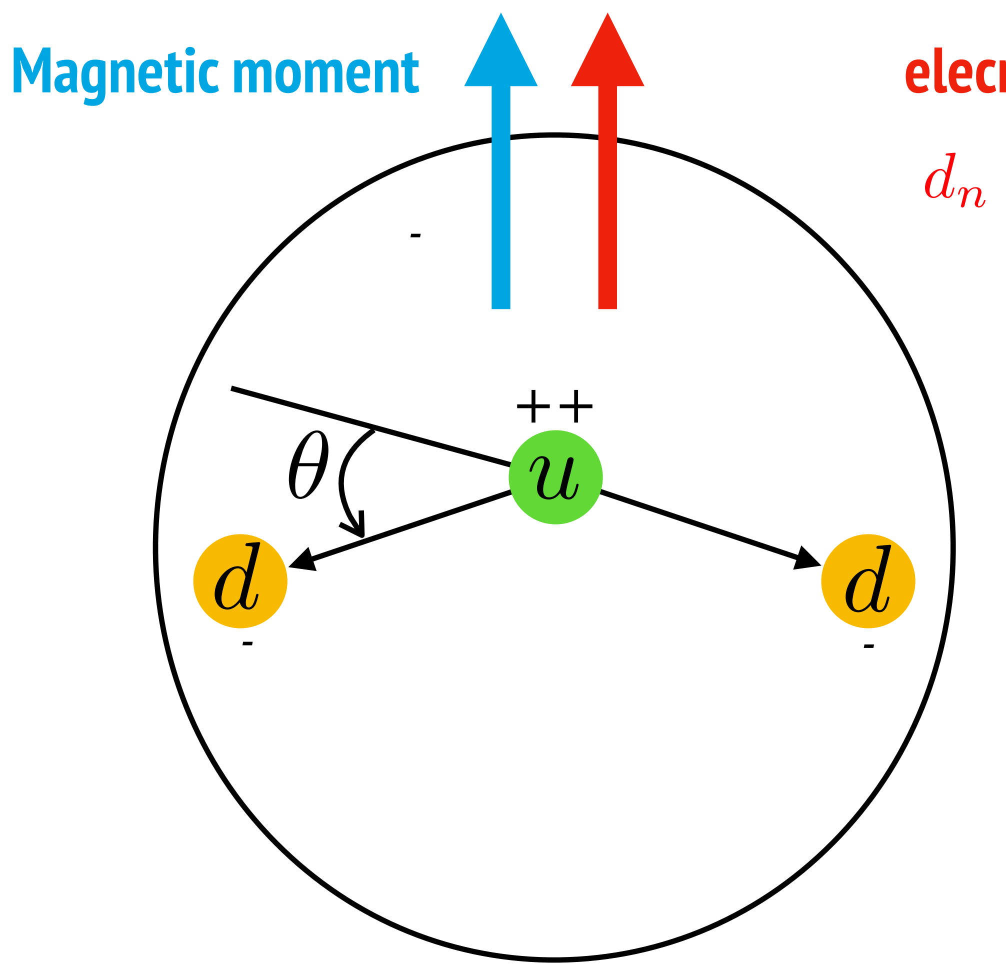
we tend to forget this

In SM, quark phases contribute to θ through the anomaly $\theta = \theta_{\rm QCD} + \arg{\rm Det}\{M_q\}$

$\frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}$ **induces P and T (CP) violation** $\propto \theta$

Electric Dipole Moment of the neutron?

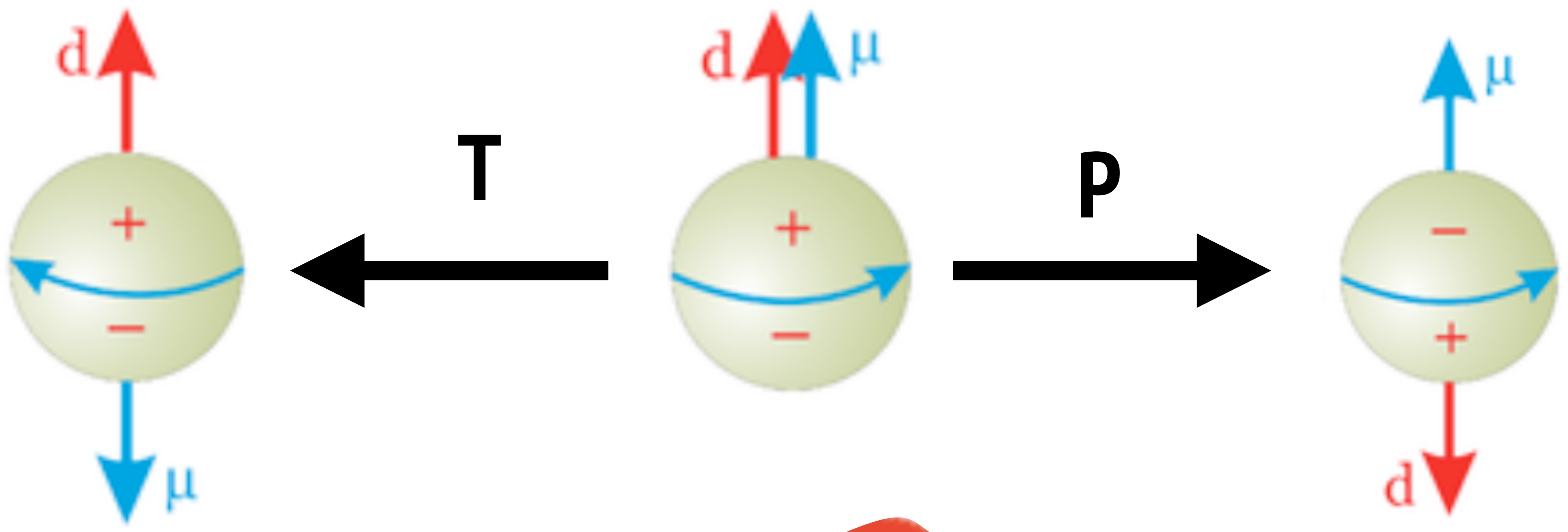
A classical pic of a neutron (~ 2 fm)



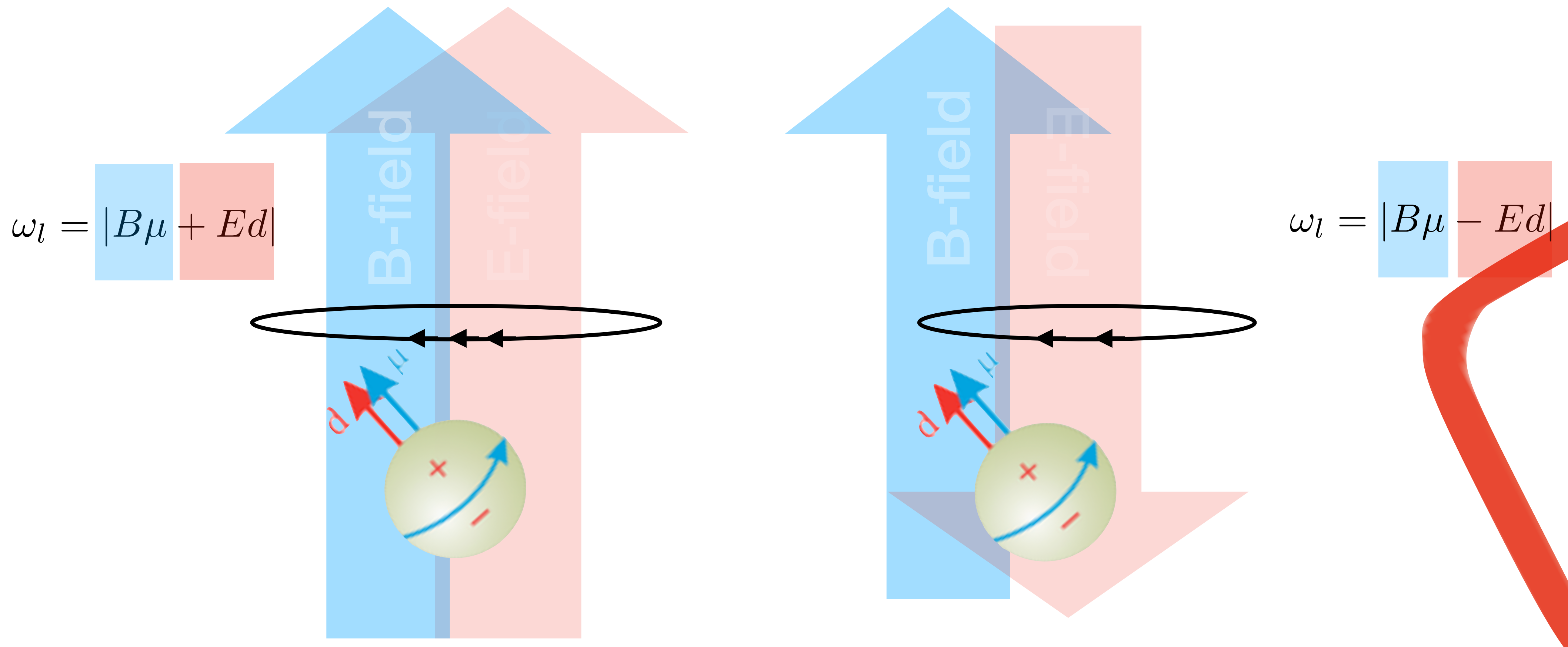
$d_n = (2.4 \pm 1.0)\theta \times 10^{-3} \mathrm{e\,fm}$

Pospelov 09

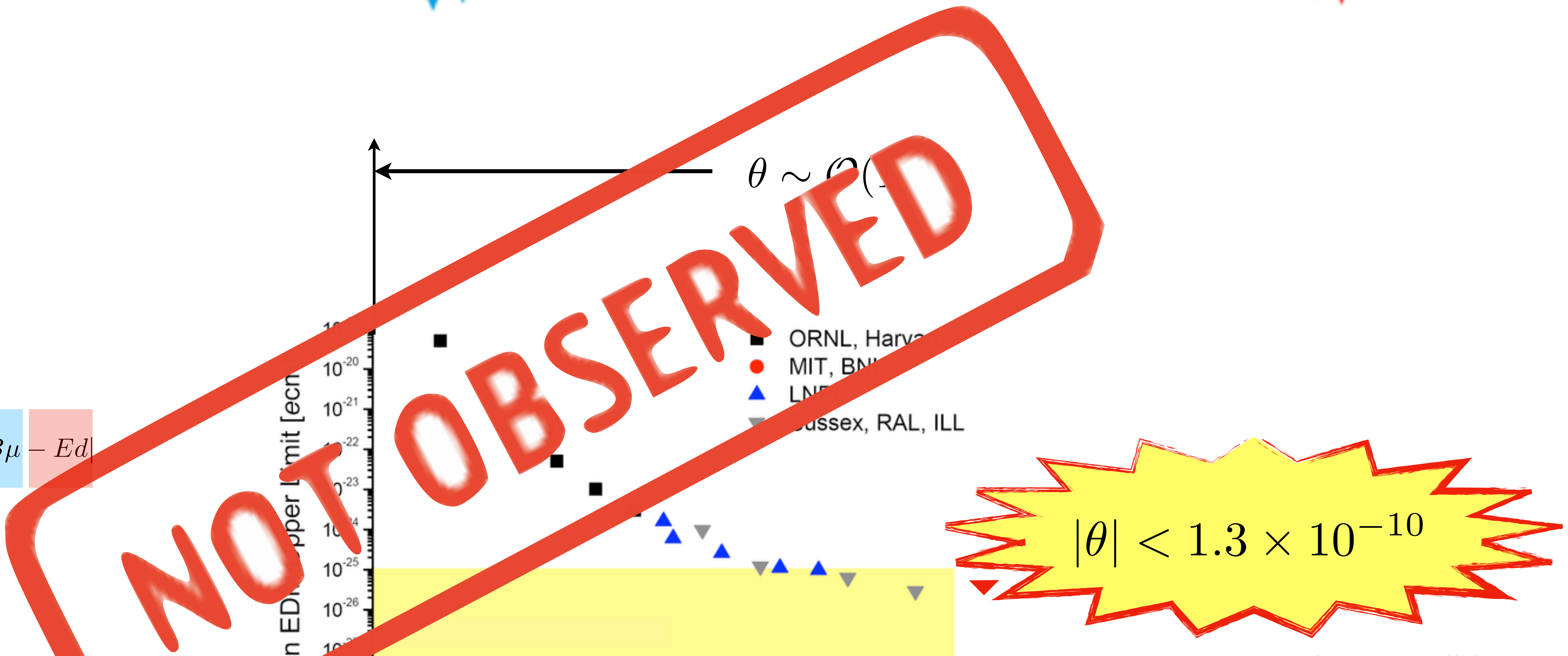
Neutron EDM breaks P, T



Experimental search ...



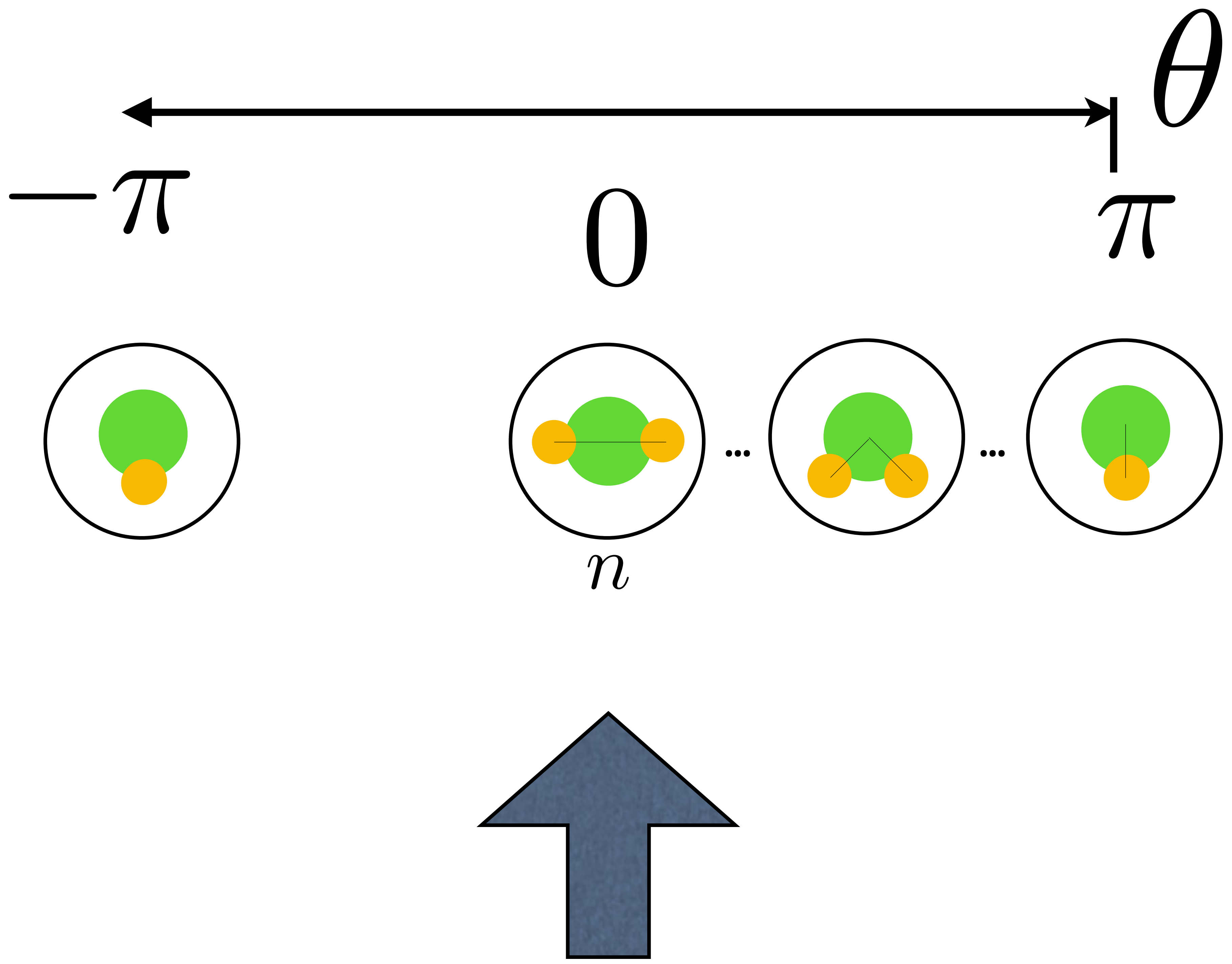
Mesurable larmor precession difference?



Baker '13 Pendlebury '15

The theta angle of the strong interactions

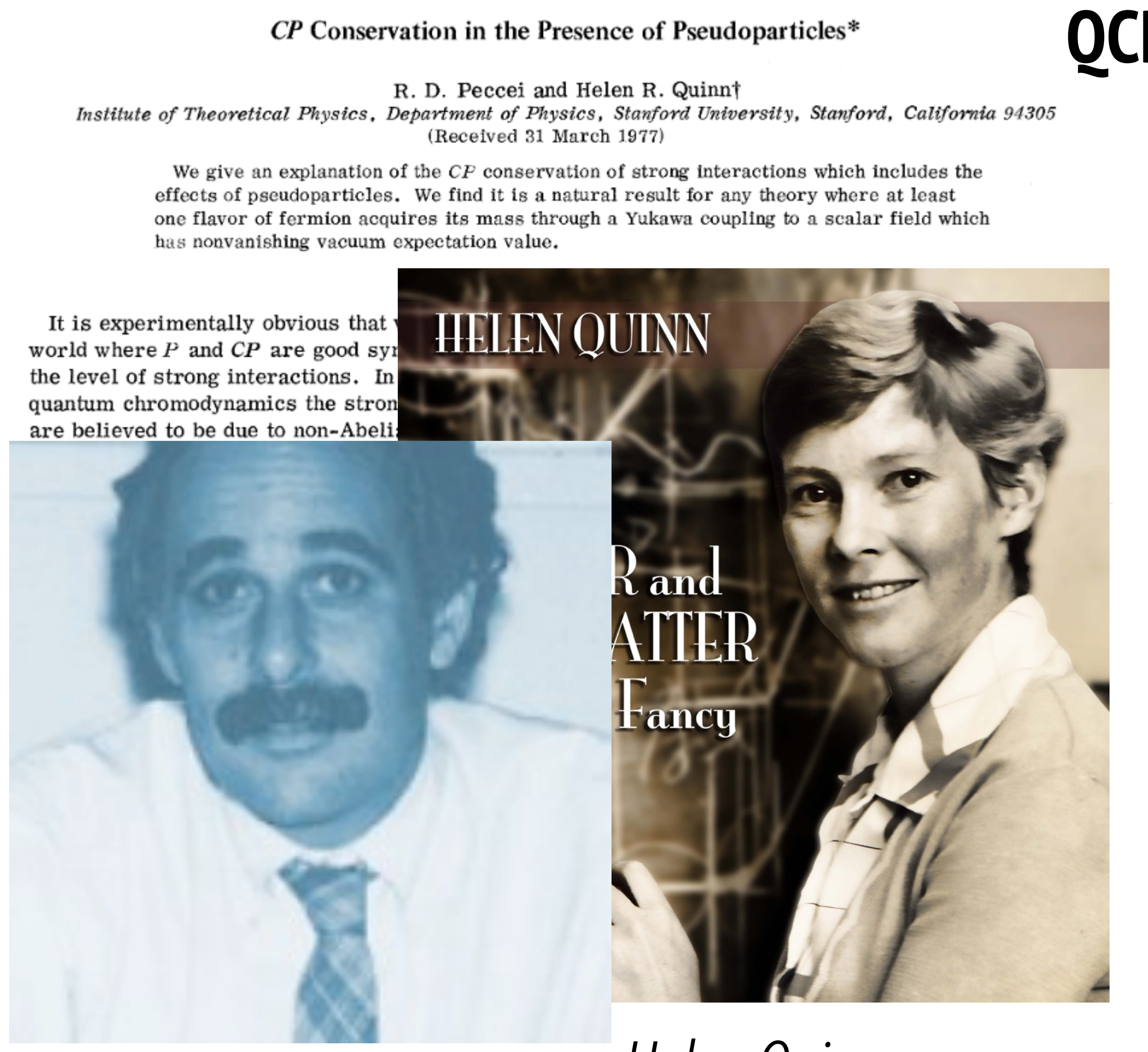
- The value of θ controls neutral P,T violation in the QCD, SM



Measured today $|\theta| < 10^{-10}$ **(strong CP problem: why???)**

QCD vacuum energy minimised at theta = 0 !!

1 - ... if $\theta(t, \mathrm{x})$ is a dynamical field, QCD will relax it to its minimum ... strong CP explained! *Peccei & Quinn 77*


CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†

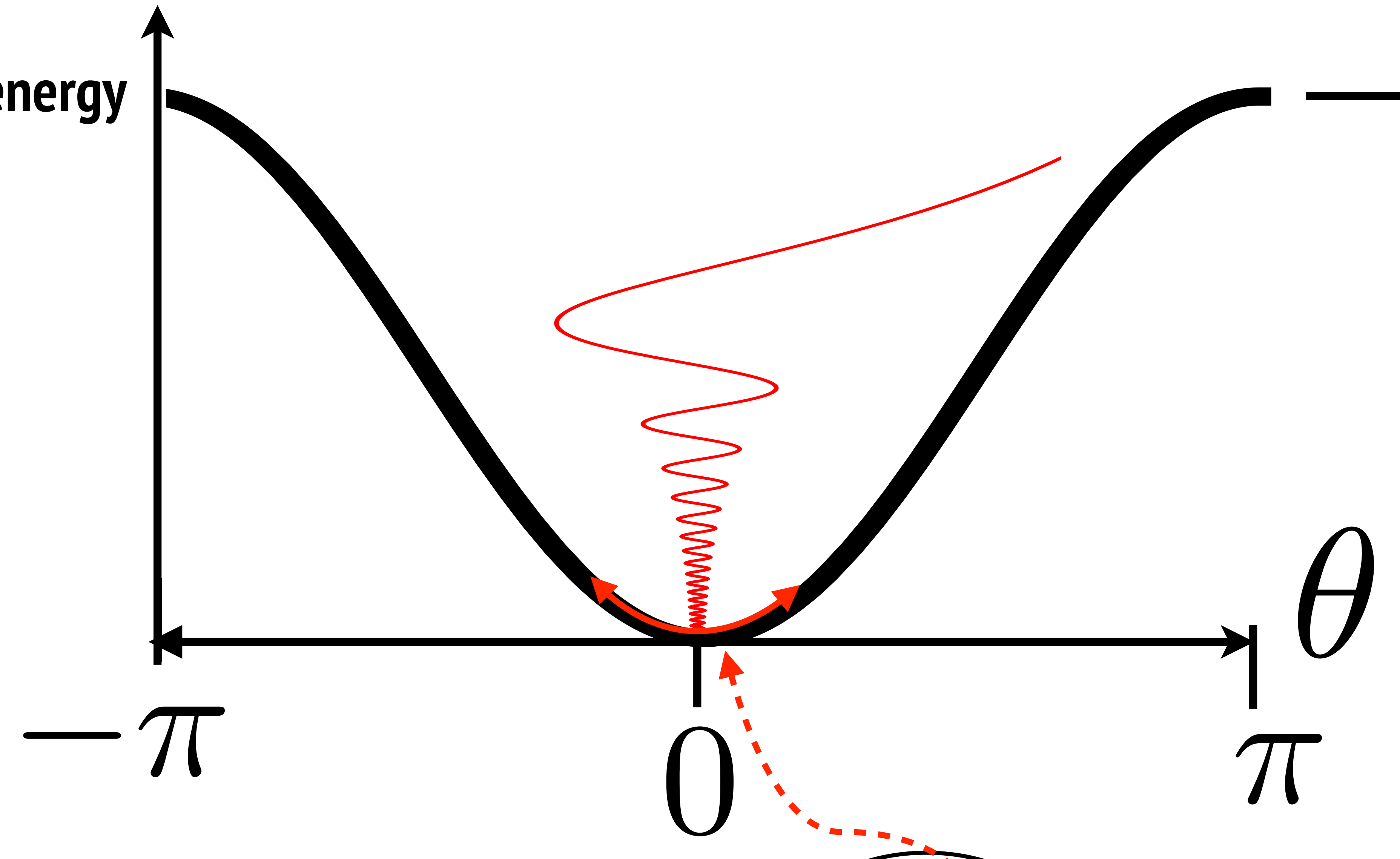
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

It is experimentally obvious that ... world where *P* and *CP* are good sy... the level of strong interactions. In ... quantum chromodynamics the stron... are believed to be due to non-Abeli...

Roberto Peccei

Helen Quinn



2 - PQ Mechanism: Global U(1) axial sym spontaneously broken-> Goldstone boson

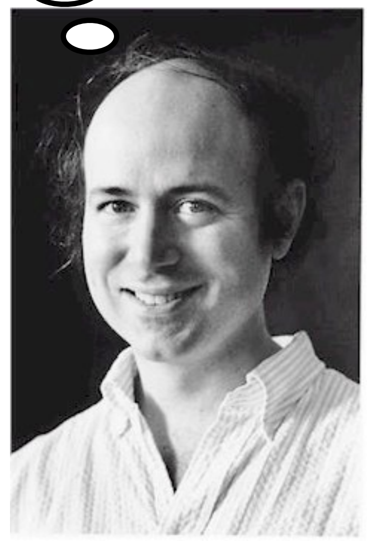
$$\mathcal{L}_\theta = \frac{1}{2}(\partial_\mu\theta)(\partial^\mu\theta)f_a^2 - \frac{\alpha_s}{8\pi}G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}\theta$$

Canonically normalised θ-field is the QCD AXION! $a(x) = \theta(x) f_a$

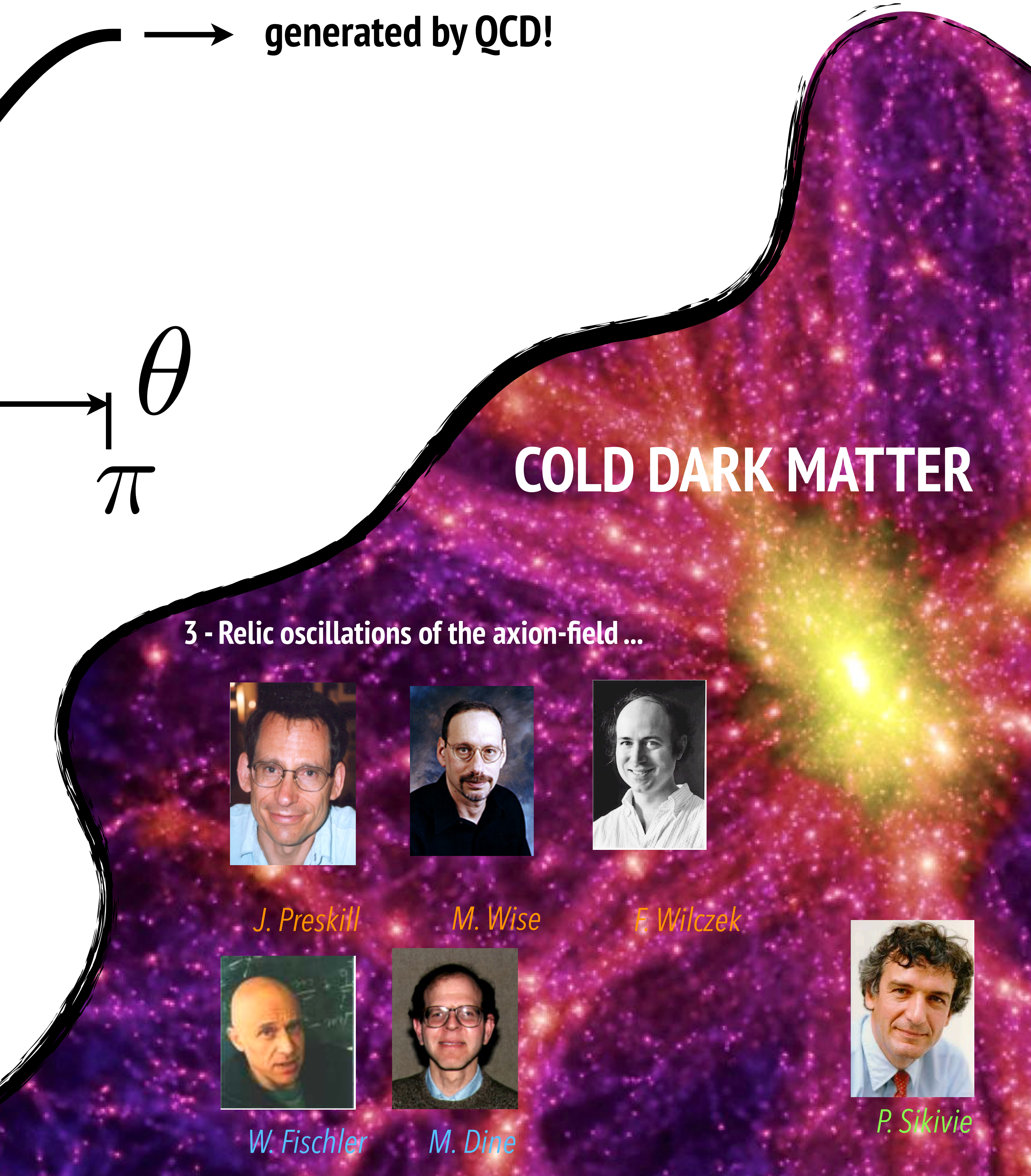
New Spontaneous symmetry breaking [energy] scale f_a

New scale f_a can relate to fundamental scales (string, flavor)

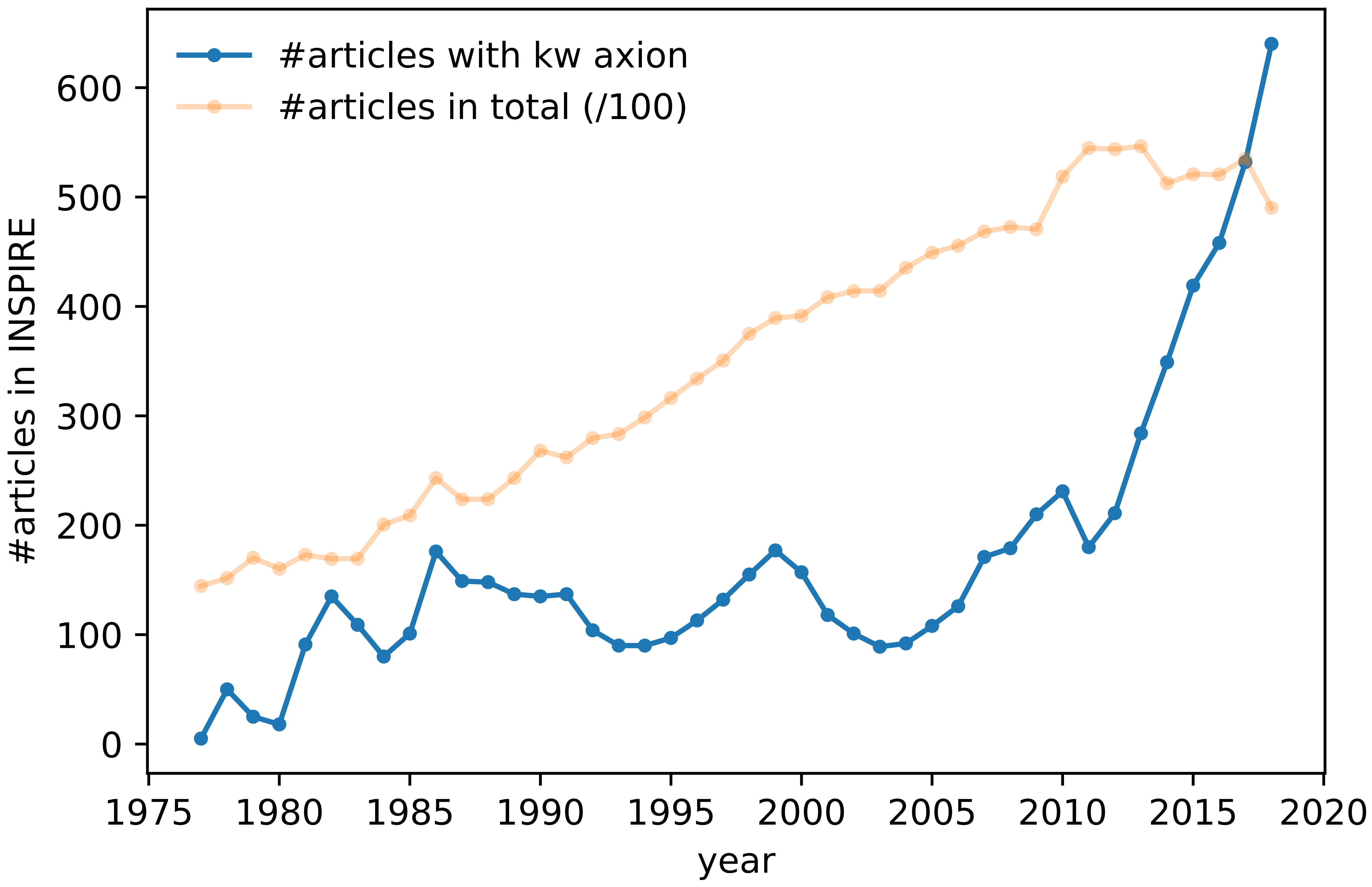
S. Weinberg



F. Wilczek



The axion "field" is NOT relaxing...

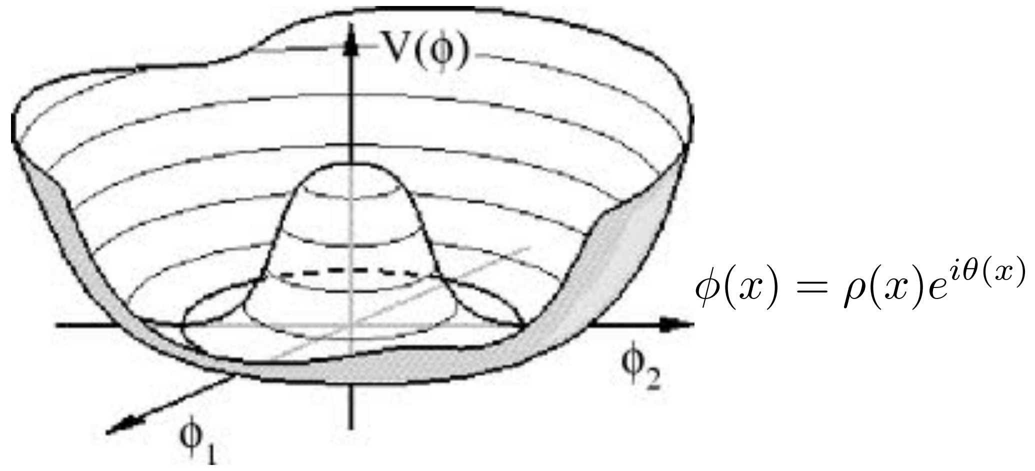


Motivations (hep-th): axions and axion-like particles beyond the SM

- Axions and "axion-like" particles are generic in BSM + compatible with SUSY, GUTs and String Theories

pseudo Goldstone Bosons

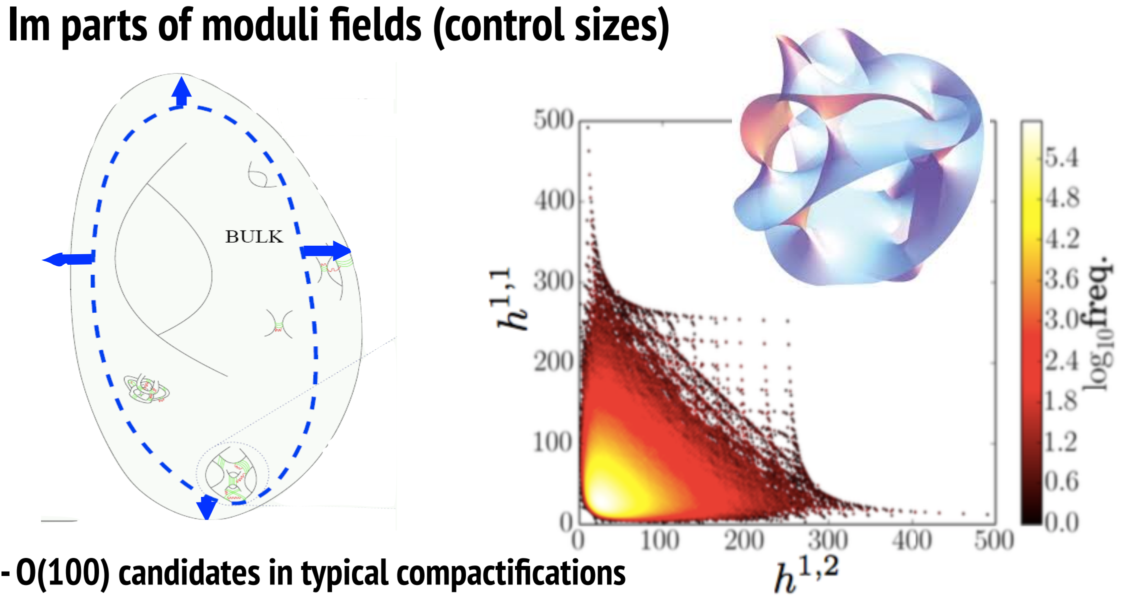
- Global symmetry spontaneously broken



Examples: QCD mesons,..., QCD axion, Majoron, R-axion, Familon ...

stringy axions

- Im parts of moduli fields (control sizes)



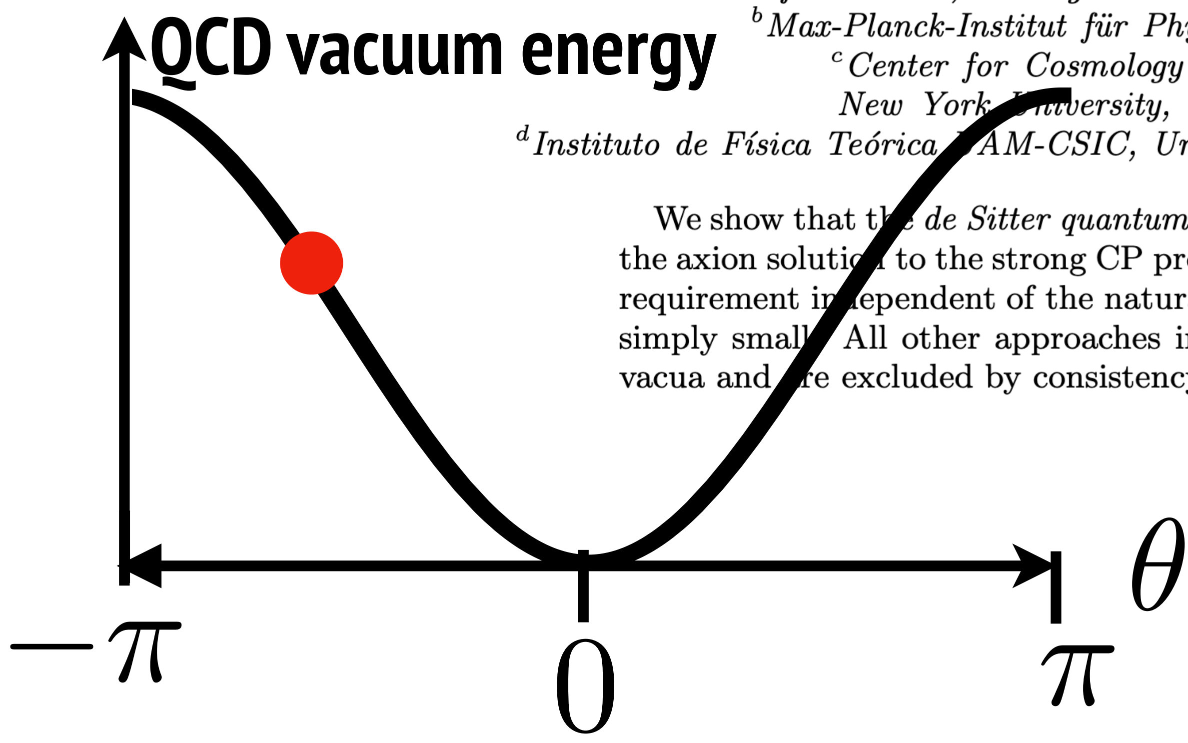
- O(100) candidates in typical compactifications
- masses from non-perturbative effects

- The QCD axion might be a requirement of quantum gravity

A Proof of the Axion?

Gia Dvali[a,b,c], Cesar Gomez[d] and Sebastian Zell[a,b]
[a] Arnold Sommerfeld Center, Ludwig-Maximilians-Universität, Theresienstraße 37, 80333 München, Germany
[b] Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
[c] Center for Cosmology and Particle Physics, Department of Physics, New York University, 726 Broadway, New York, NY 10003, USA
[d] Instituto de Física Teórica UAM-CSIC, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain

We show that the *de Sitter quantum breaking bound* when applied to QCD exposes the necessity of the axion solution to the strong CP problem. The Peccei-Quinn mechanism emerges as a *consistency* requirement independent of the naturalness questions. The ϑ-angle must be unphysical rather than simply small. All other approaches including a fine-tuning of ϑ lead to the existence of de Sitter vacua and are excluded by consistency.



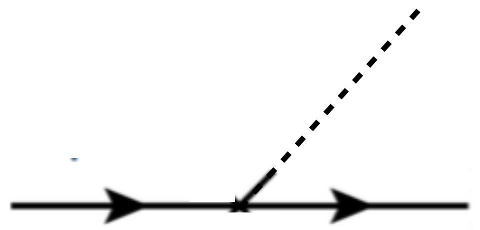
- Axion couplings with SM particles are also generic (shift-symmetry determines leading interactions)

photon coupling

$$-\frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a$$

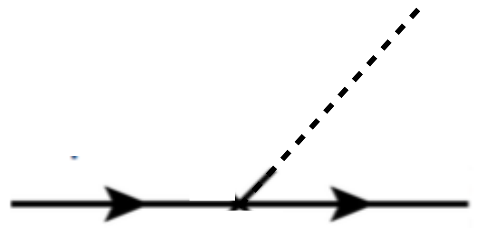
electron coupling

$$g_{ef}[\bar{e}\gamma_5 e]a$$



nucleon coupling

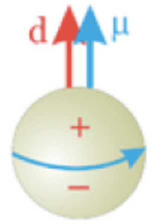
$$g_{Nf}[\bar{N}\gamma_5 N]a$$



~~CP~~ Neutron electric dipole

$$\propto \frac{1}{m_n}[F_{\mu\nu}\bar{n}\sigma^{\mu\nu}\gamma_5 n]\frac{A}{f_A}$$

X

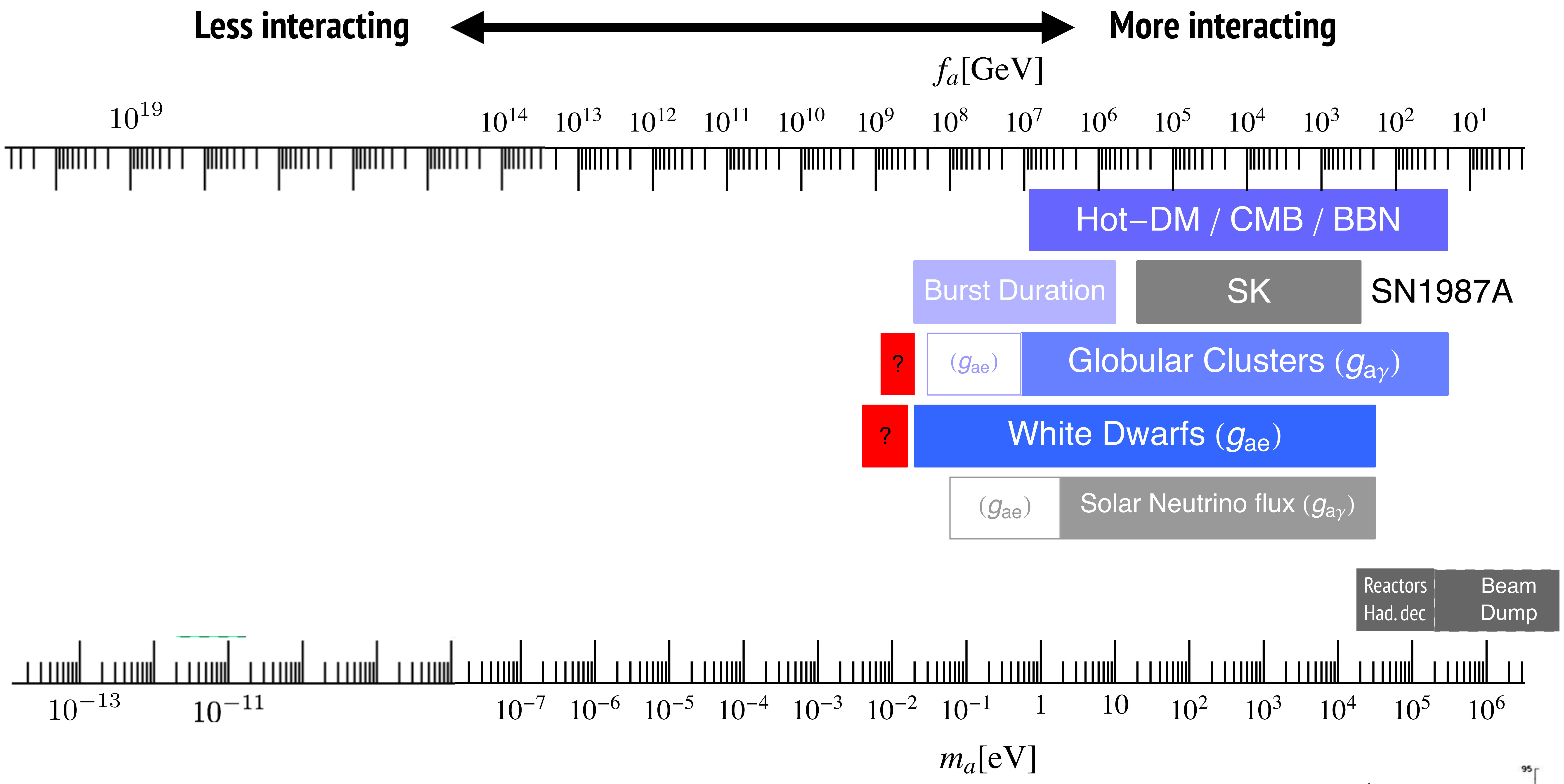


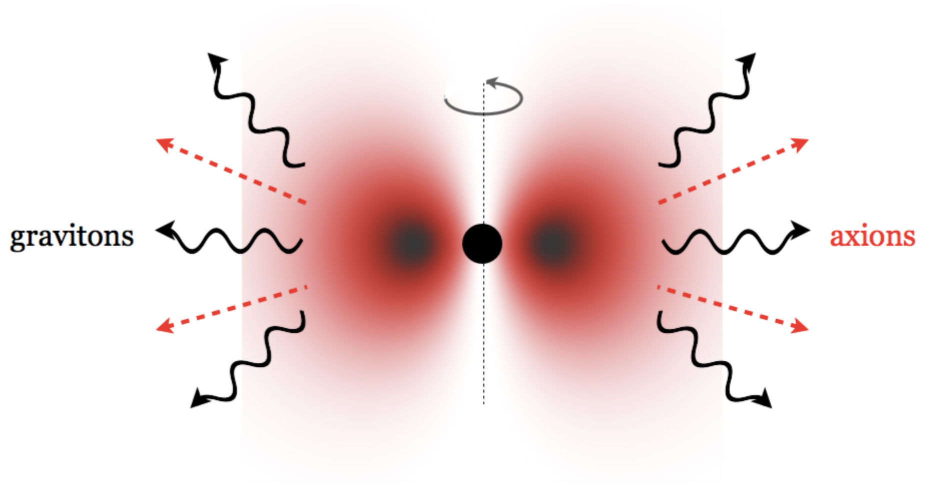
$$\mathcal{L}_{a\gamma} = -C_{a\gamma}\frac{\alpha}{2\pi}\frac{F^{\mu\nu}\widetilde{F}^{\mu\nu}}{4} = -g_{a\gamma}\frac{F^{\mu\nu}\widetilde{F}^{\mu\nu}}{4}a = -g_{a\gamma}\vec{E}\cdot\vec{B}a$$

Model	N_{DW}	High-E couplings: E/N	C_{Au}	C_{Ad}	C_{Ae}	Low-E couplings: $C_{A\gamma}$	C_{Ap}	C_{An}	C_{Ae}
PQWW	3	$8/3$	$c_\beta^2/3$	$s_\beta^2/3$	$s_\beta^2/3$	0.75	...	...	...
DFSZ I	6,3	$8/3$	$c_\beta^2/3$	$s_\beta^2/3$	$s_\beta^2/3$	0.75	(-0.2,-0.6)	(-0.16,0.26)	(0.024,⅓)
DFSZ II	6,3	$2/3$	$c_\beta^2/3$	$s_\beta^2/3$	$-c_\beta^2/3$	-1.25	(-0.2,-0.6)	(-0.16,0.26)	(-⅓,0)
KSVZ	1	0	g-loop	g-loop	0	-1.92	-0.47	-0.02(3)	$\sim 2\times10^{-4}$
Hadronic 1$\mathcal{Q}$ [83]	1...20	$1/6 \ldots 44/3$	g-loop	g-loop	γ-loop	-0.25 ... 12.7†	-0.47	-0.02(3)	(0.05 ... 5) $\times10^{-3}$
SMASH [16]	1	$8/3, 2/3$	g-loop	g-loop	ν-loop	0.75,-1.25	-0.47	-0.02(3)	$(-0.16, 0.16)$
MFVA [91]	9	$2/3, 8/3$	0	$1/3$	$1/3$	$0.75, -1.25$	~ -0.6	~ -0.26	$\sim 1/3$
Flaxion/Axi-flavon [11, 12]	-	$8/3$	$\sim 10^{-5}$	$\sim 10^{-5}$	$\sim 10^{-6}$	(0.5,1.1)	-	-	-
Astrophobic M1,2 [93]	1,2	$2/3, 8/3$	$\sim 2/3$	$\sim 1/3$	~ 0	-1.25,0.75	$\sim 10^{-2}$	$\sim 10^{-2}$	~ 0
Astrophobic M3,4 [93]	1,2	$-4/3, 14/3$	$\sim 2/3$	$\sim 1/3$	~ 0	-3.3,2.7	$\sim 10^{-2}$	$\sim 10^{-2}$	~ 0

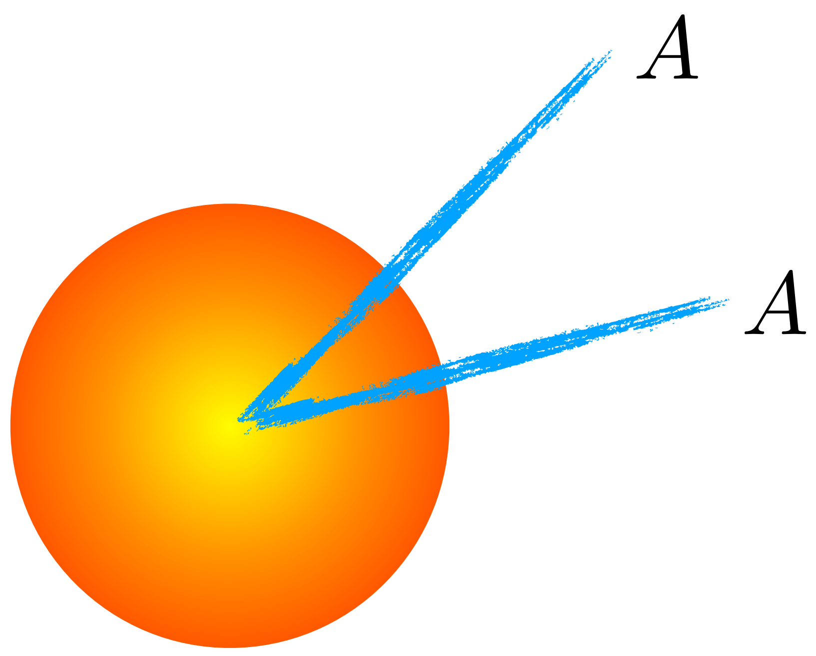
Some Popular PP Axion models

what do we know about f_A??

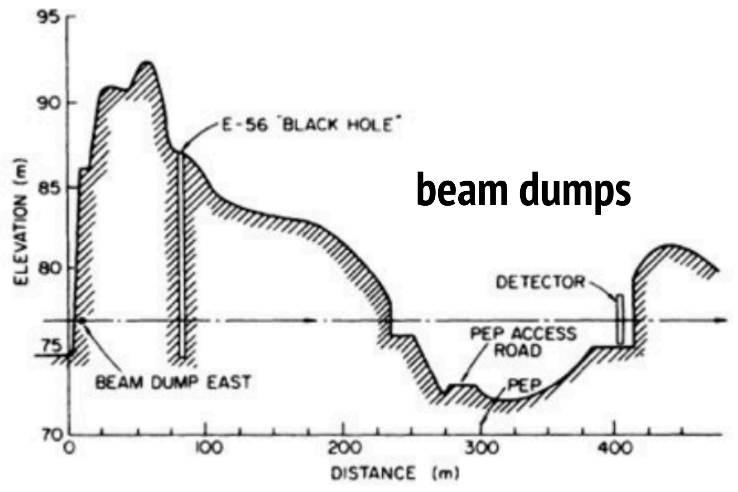




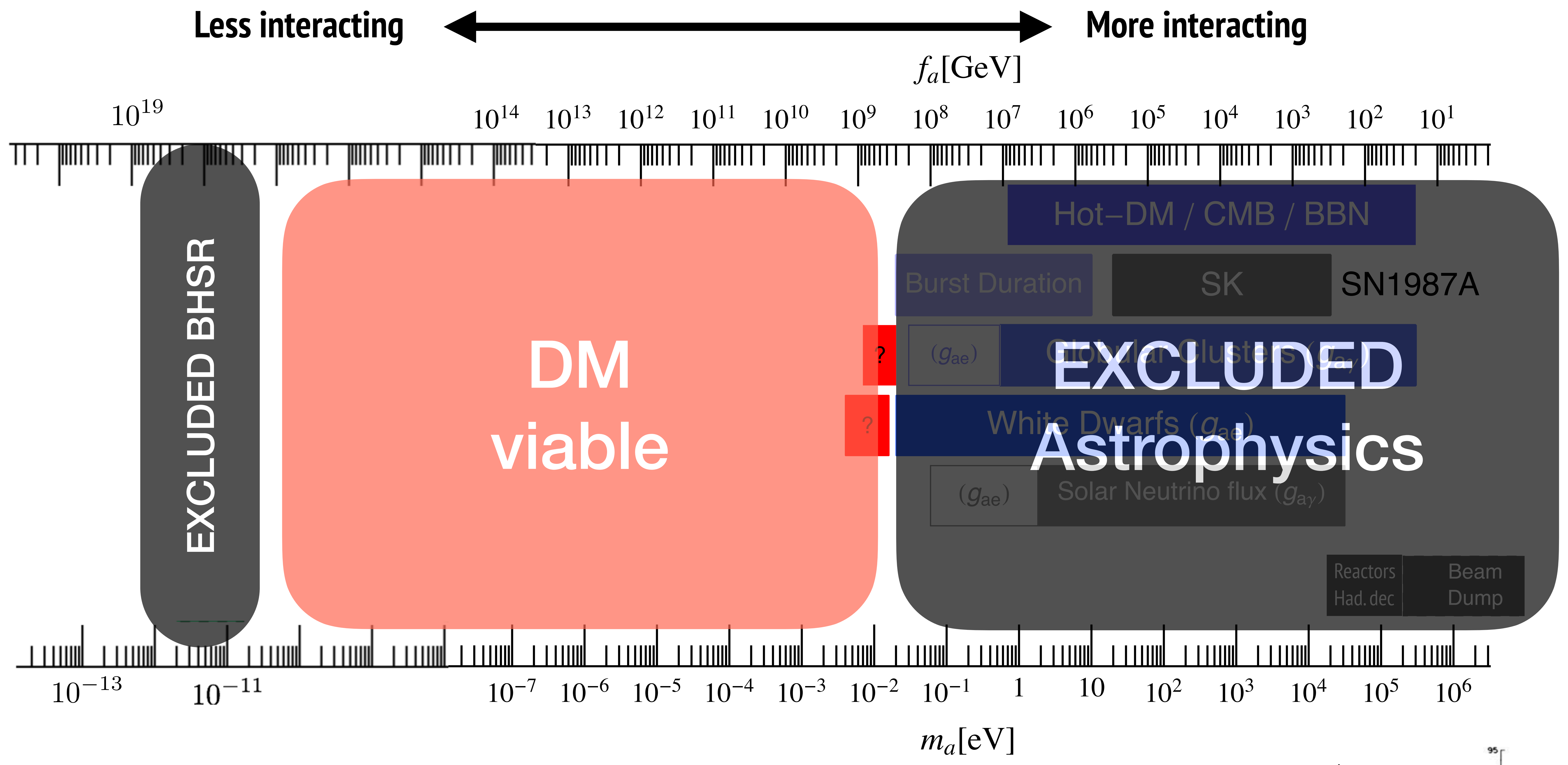
Black hole spin radiated

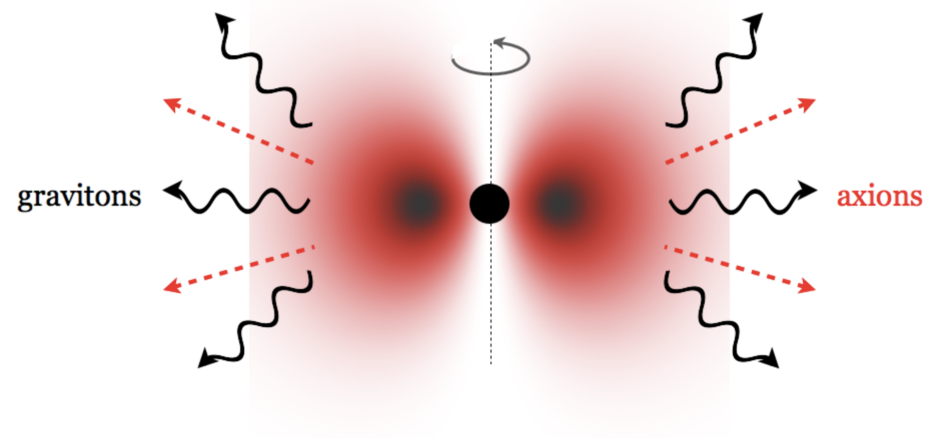


Stellar evolution accelerated*

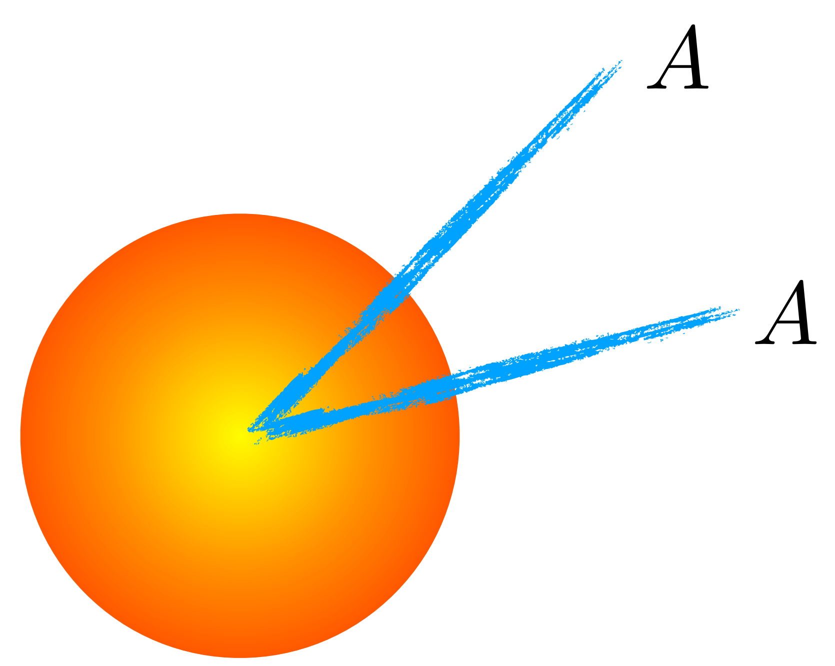


what do we know about f_A??

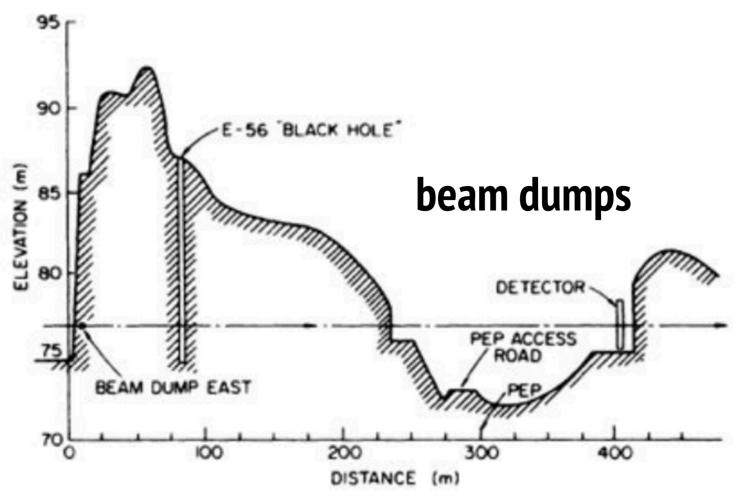




Black hole spin radiated

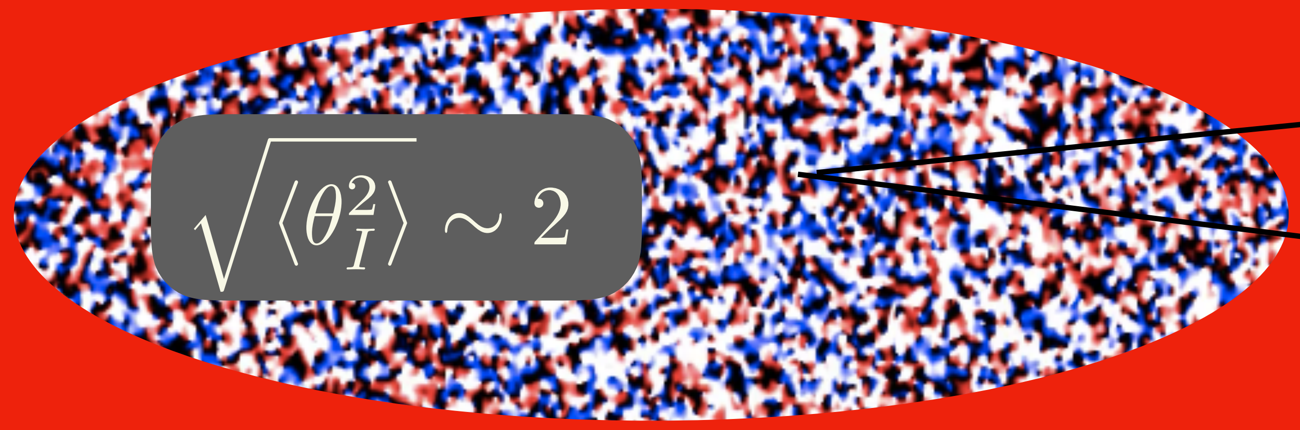


Stellar evolution accelerated*



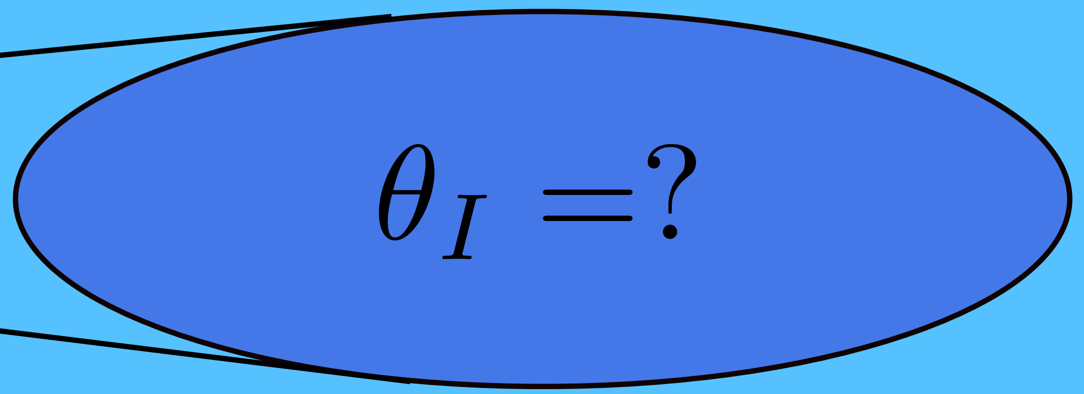
Axion dark matter in a nutshell

5: Scenario B : Initial conditions after inflation



dark matter inhomogeneous at scales below ~ pc

6: Scenario A : Inflation AFTER initial conditions



dark matter homogeneous

4: Axion dark matter abundance depends:
- Axion mass
- Initial angle

$$\Omega_c h^2 \sim 0.12\theta_I^2 \left(\frac{10\mu\mathrm{eV}}{m_A}\right)^{1.17}$$

3: Axions field rolls down potential at

$t_{\rm osc} \sim 1/m_A$

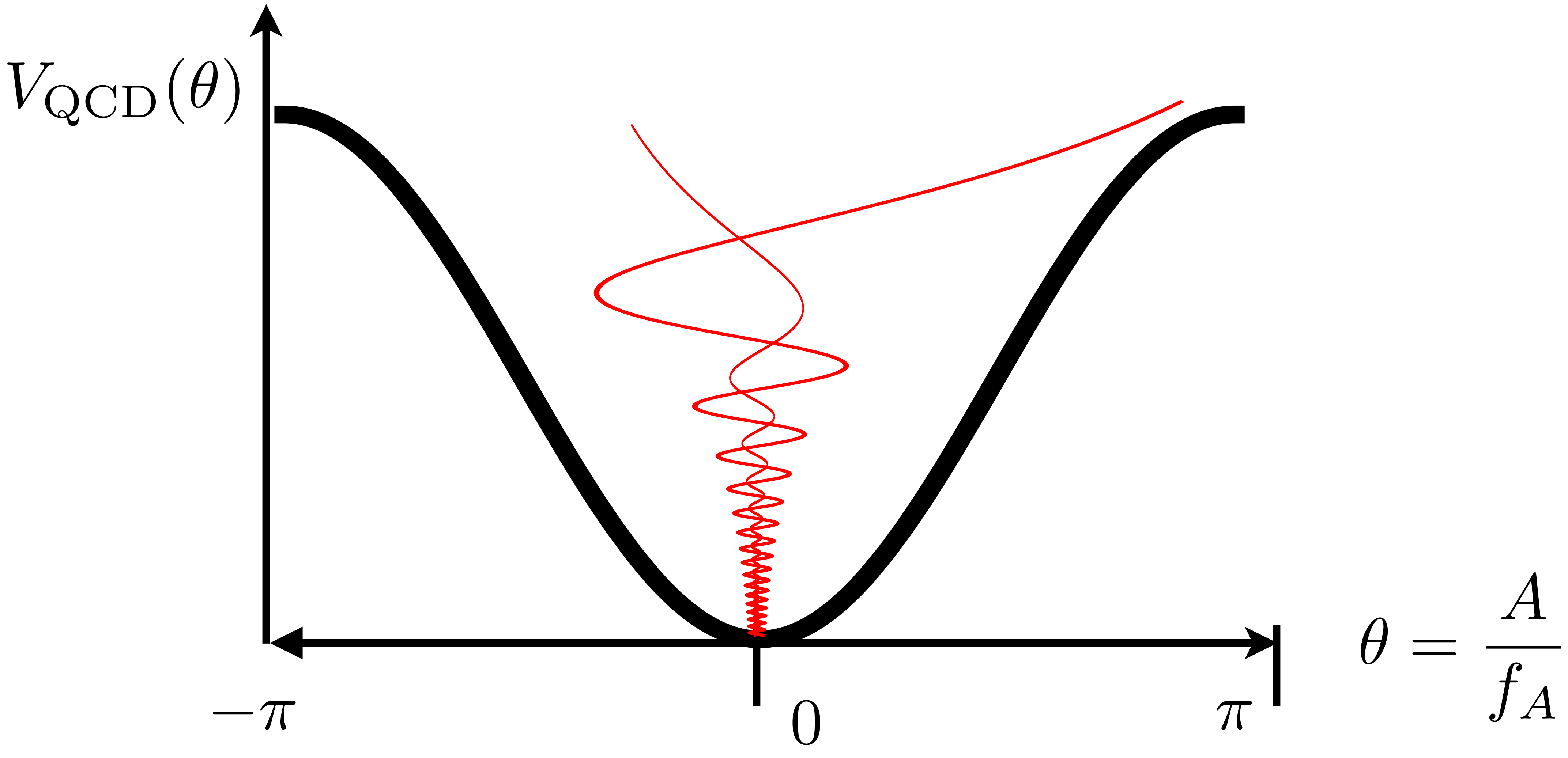
and becomes dark matter (like inflaton)

2: The QCD vacuum energy depends on θ

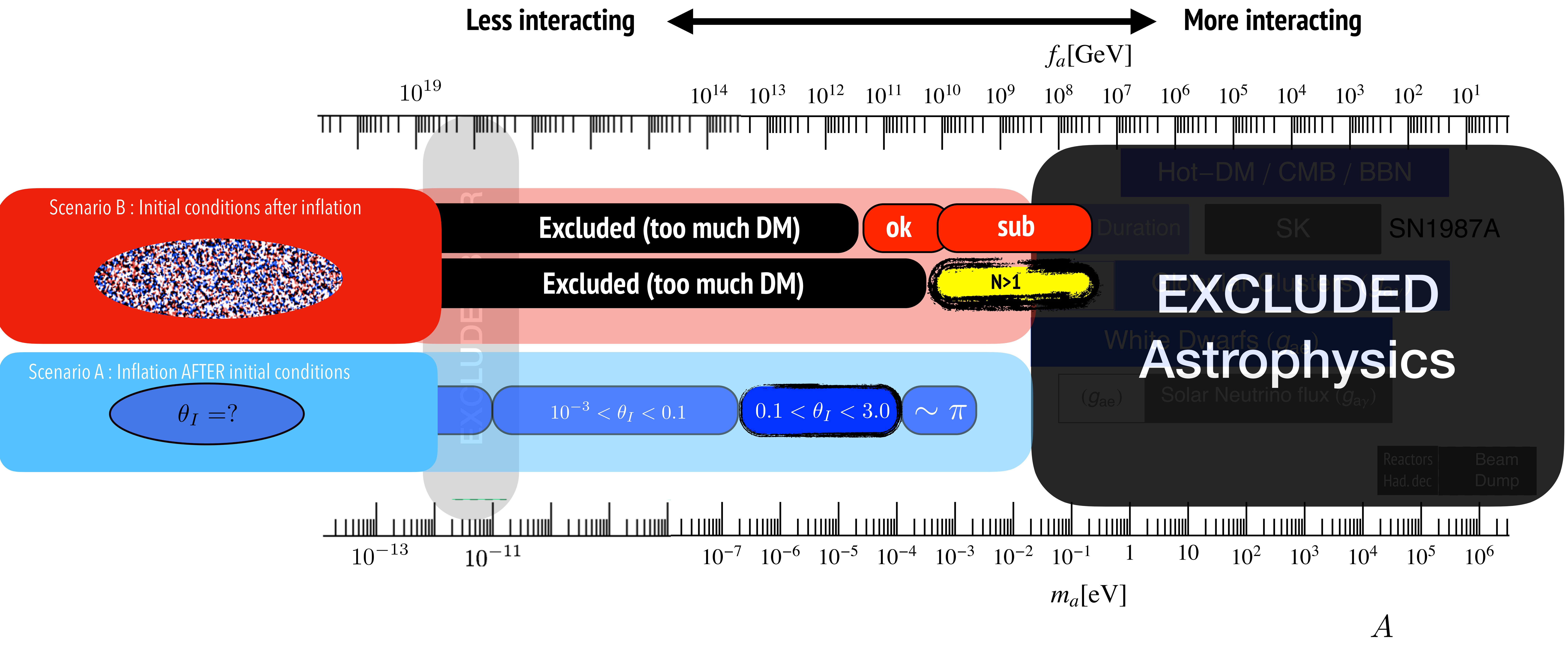
it has a minimum at $\theta = 0$!!!!

1: The axion field (A) is the dynamical version of the theta angle of QCD

We observe $\theta \simeq 0$

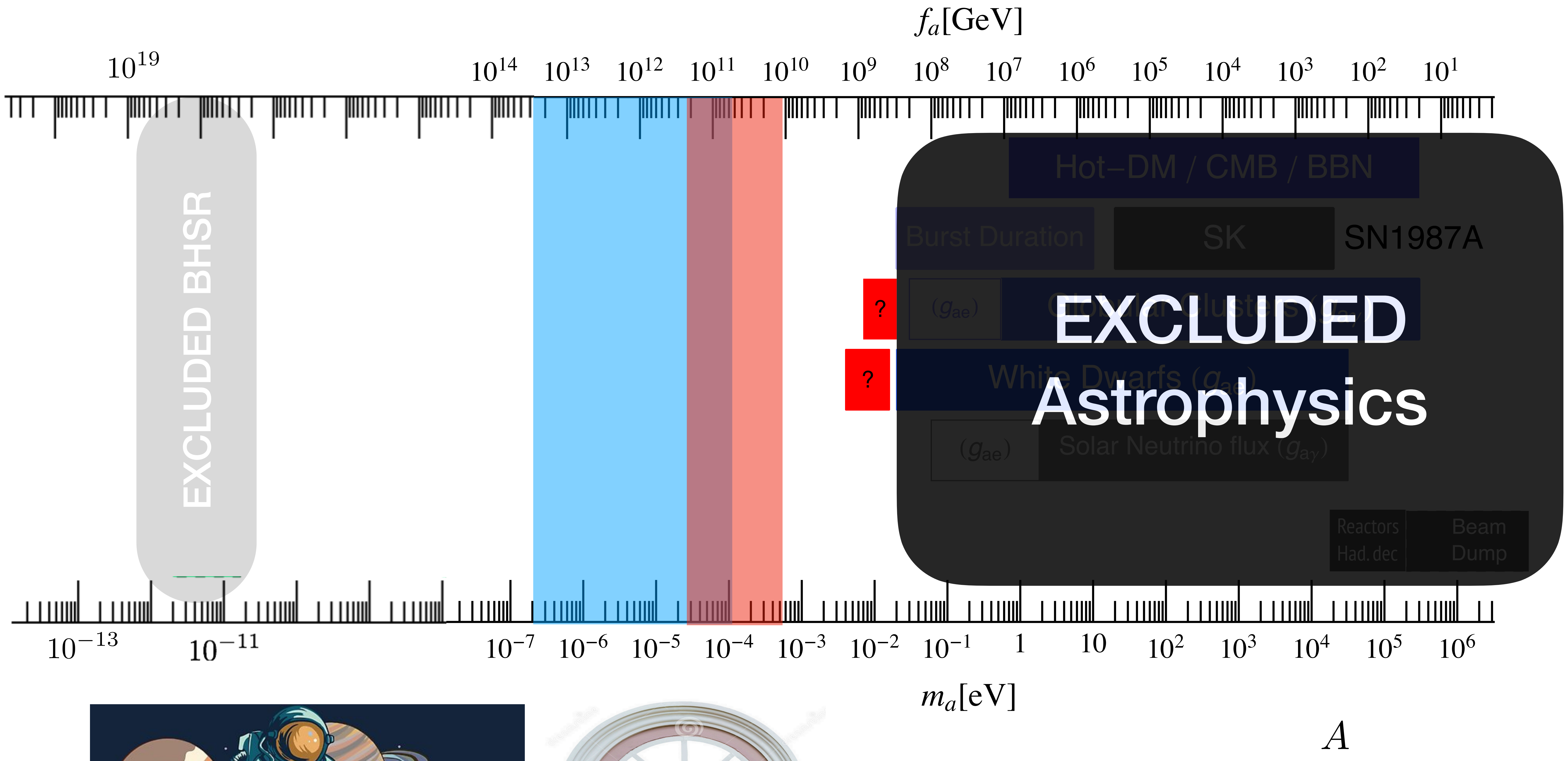


The axion DM mass?

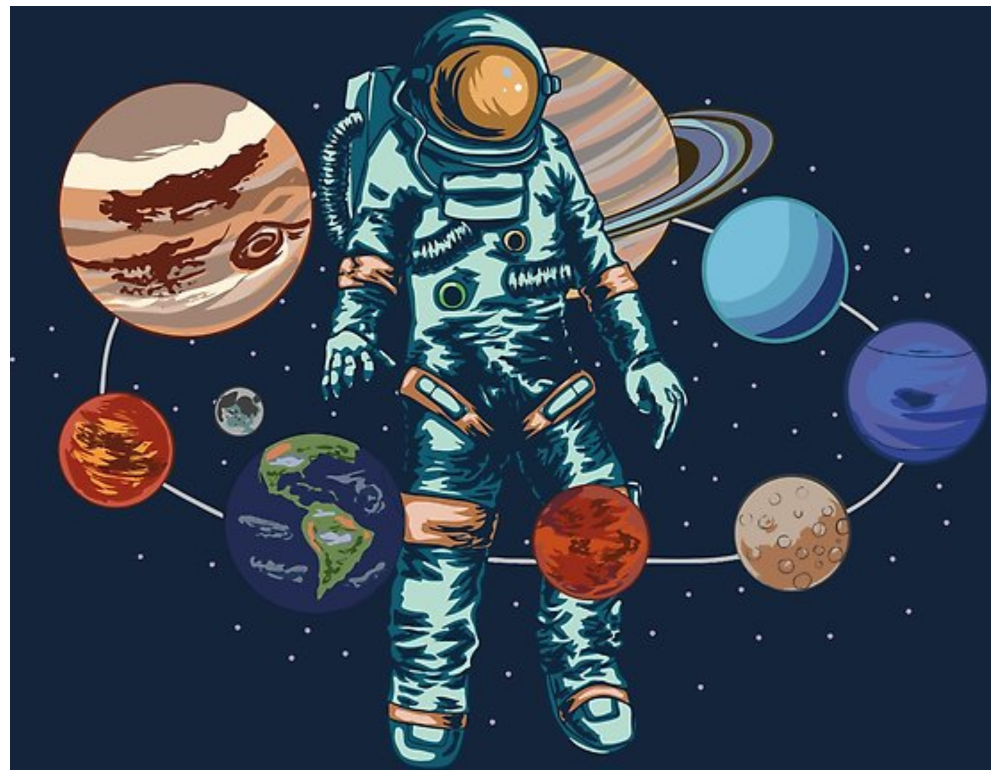


The axion DM mass?

Less interacting ⟷ More interacting

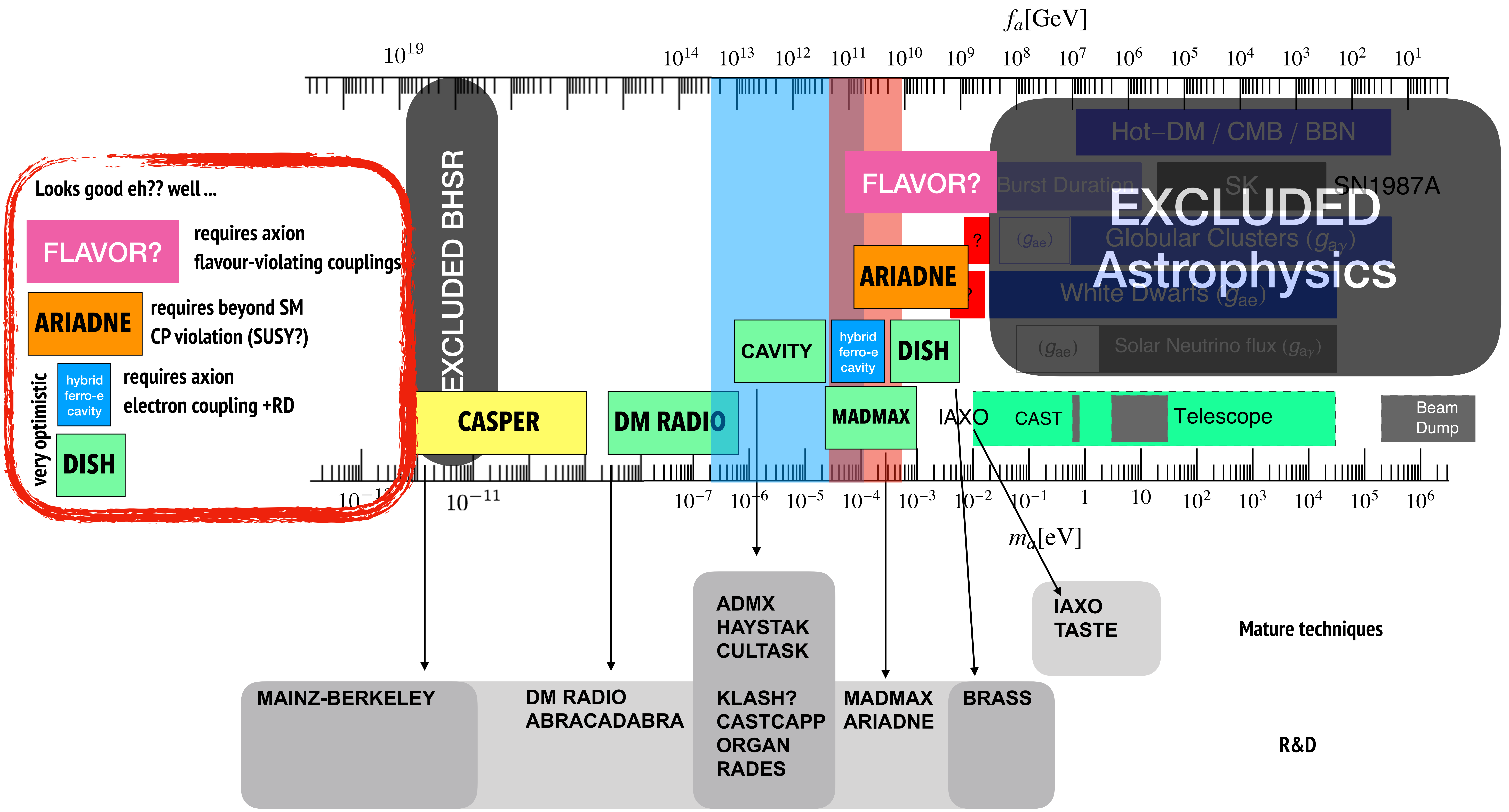


Anthropic axion window
(seemingly tuned ICs)



Classical axion window
(natural initial conditions)

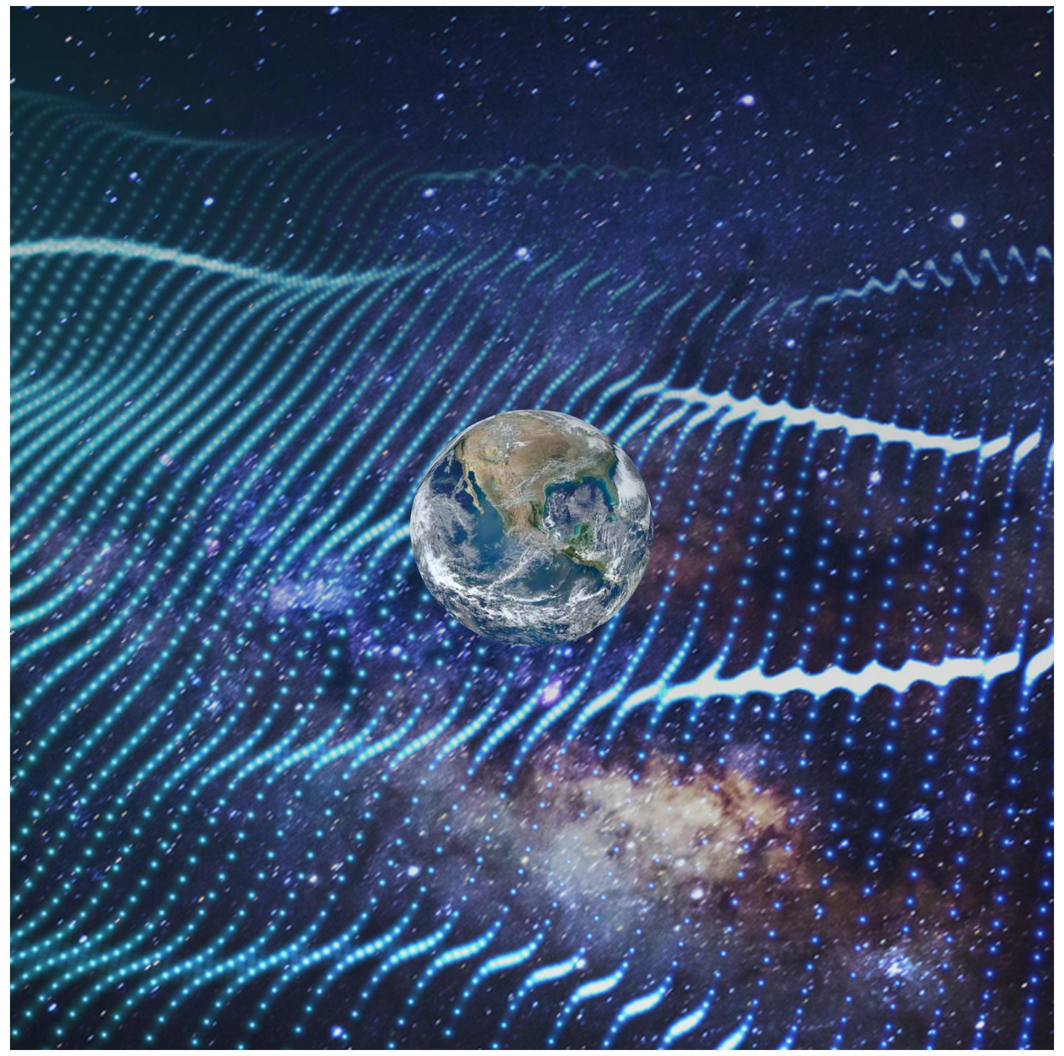
On the search for the axion: 2019



Detecting axion DM

Detecting axion DM

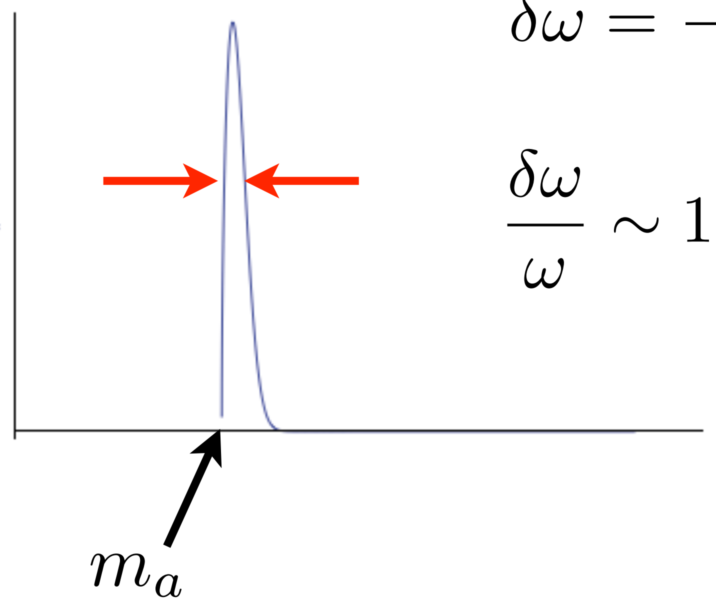
$$\theta = \sum_k \theta_k \cos(\omega t - \vec{k}\cdot\vec{x})$$



$$v_g = \frac{k}{\omega} \sim v_{\rm vir} \sim 200{\rm km/s} < v_{\rm esc}$$

- Axion spectrum is not exactly monochromatic, non-zero velocity of DM in the galaxy -> finite width

frequency $\omega \simeq m_a(1 + v^2/2 + \ldots)$



$$\delta\omega = \frac{m_a v^2}{2}$$

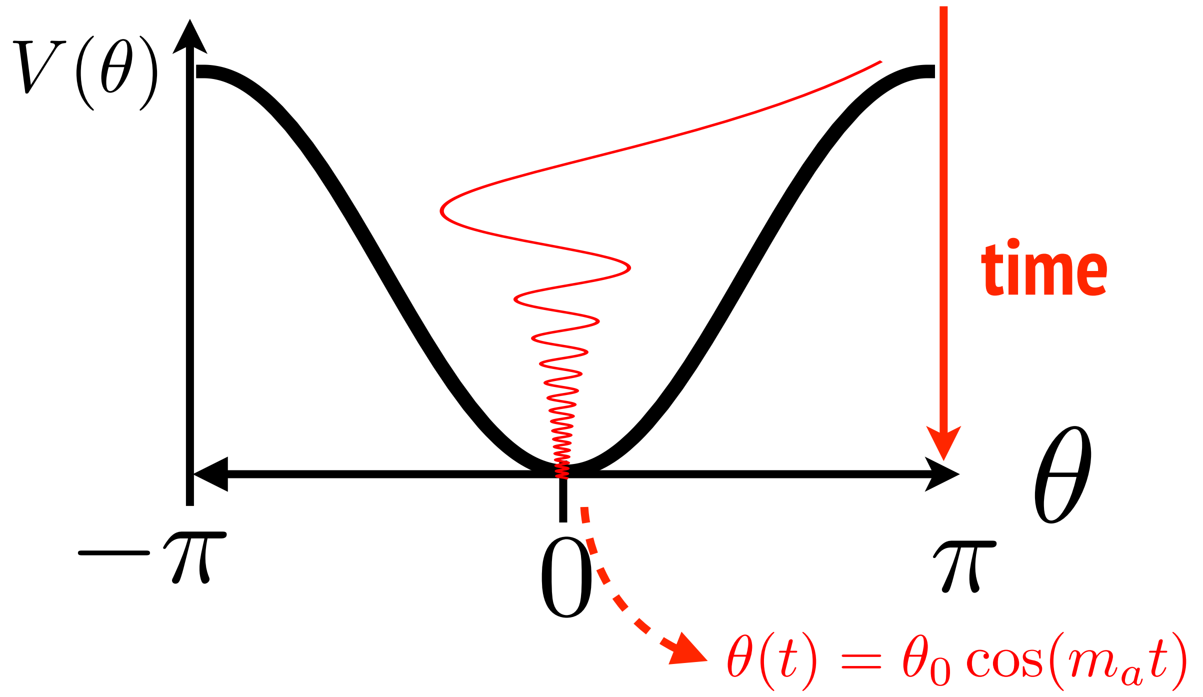
$$\frac{\delta\omega}{\omega} \sim 10^{-6}$$

coherence time

$$\delta t \sim \frac{1}{\delta\omega} \sim 0.13{\rm ms}\left(\frac{10^{-5}{\rm eV}}{m_a}\right)$$

coherence length

$$\delta L \sim \frac{1}{\delta p} \sim 20{\rm m}\left(\frac{10^{-5}{\rm eV}}{m_a}\right)$$



Local Dark Matter density*

$$\rho_{c,0} \simeq \frac{1}{2}\dot{a}^2 + \frac{1}{2}m_a^2 a^2 = 0.4\frac{\rm GeV}{\rm cm^3}$$

$$\theta_0 = 3.6 \times 10^{-19}$$

Axion DM and the cavity concept

- Axion DM, $\theta = \theta_0 \cos(m_a t)$ +B, source in Maxwell'

$$\begin{aligned} \nabla \cdot \mathbf{D} &= \rho_f \\ \nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} &= \mathbf{J}_f - C_{a\gamma}\frac{\alpha}{2\pi}\mathbf{B}\frac{\partial \theta}{\partial t} \\ \nabla \cdot \mathbf{B} &= 0 \\ \frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} &= 0 \end{aligned}$$

In a magnetised medium

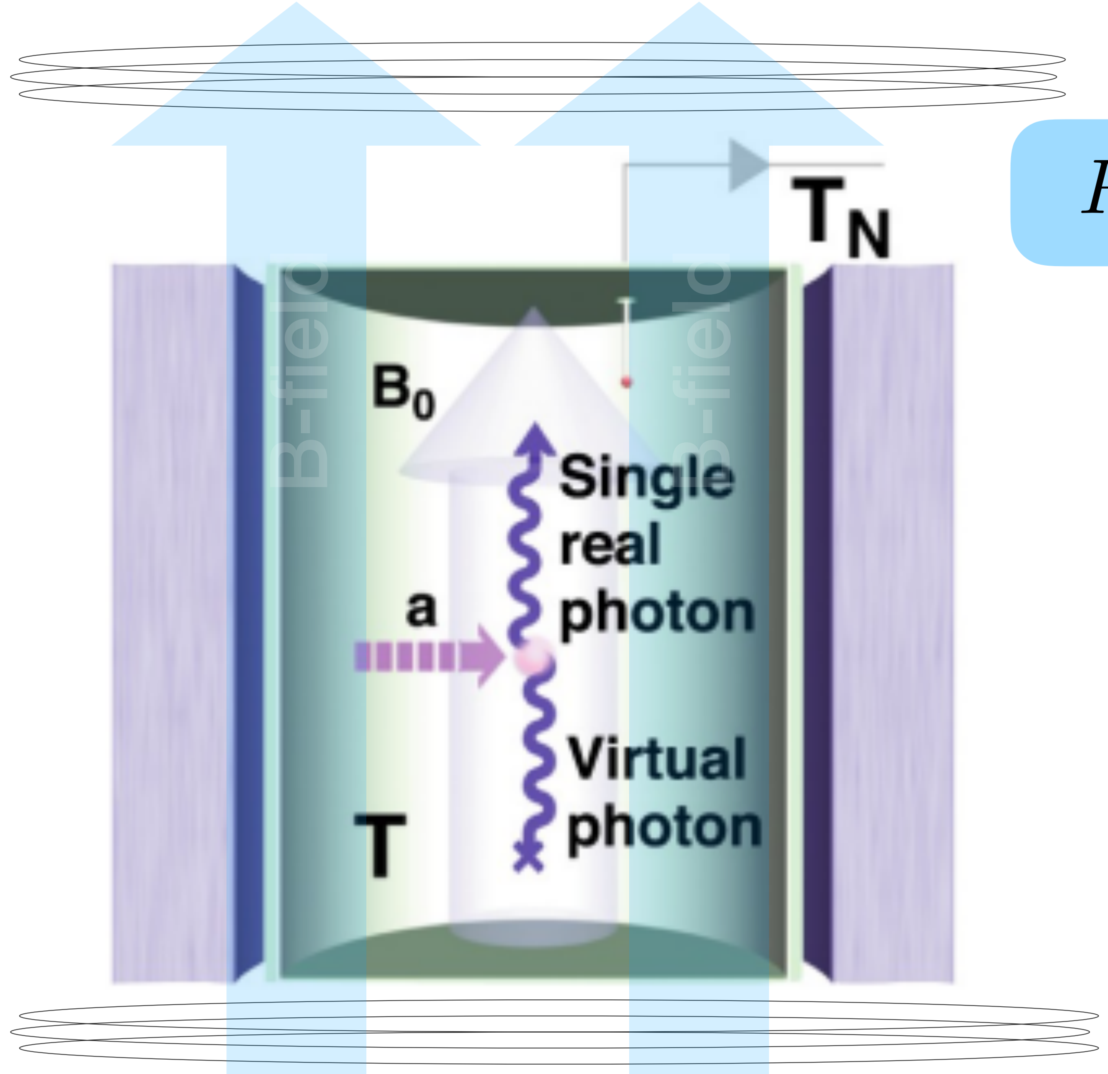
$$\mathbf{E}(t) = \frac{C_{a\gamma}\alpha\theta_0 \mathbf{B}}{2\pi\epsilon}\cos(m_a t)$$

$$|\mathbf{E}| \simeq 10^{-12}\frac{V}{m}\frac{C_{a\gamma}}{2}\frac{|\mathbf{B}|}{10\mathrm{T}}$$

- Haloscope (Sikivie 83)

"Amplify resonantly the EM field in a resonant cavity"

P. Sikivie

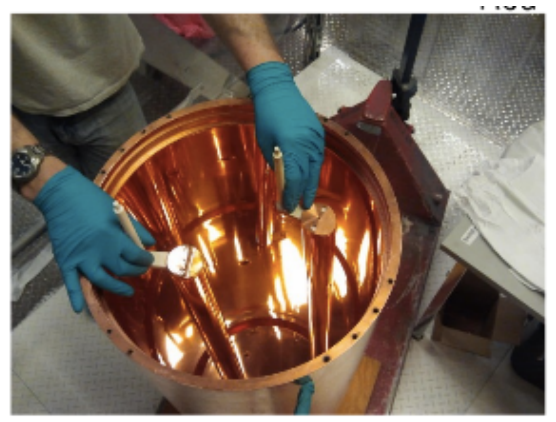


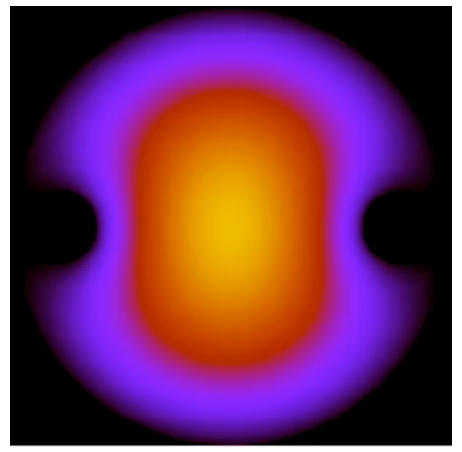
$P_{\rm out} \sim Q|\mathbf{E}_a|^2 V m_a$ (on resonance)

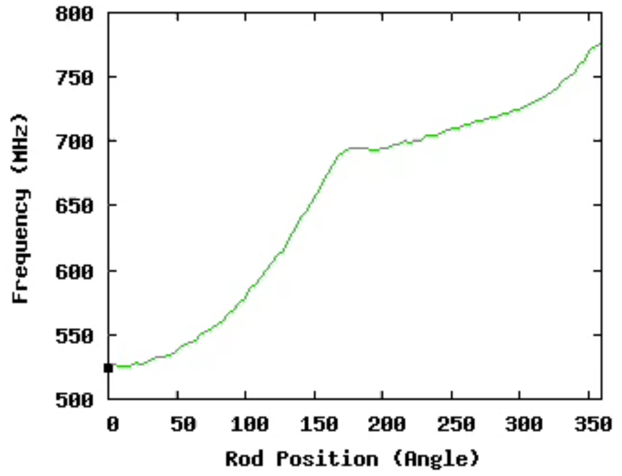
- Cavity quality factor $Q \sim 10^5$
- B-fields $B \sim 10\mathrm{T}$
- Volume $\sim 1/m_a^3$ (typically a few liters)

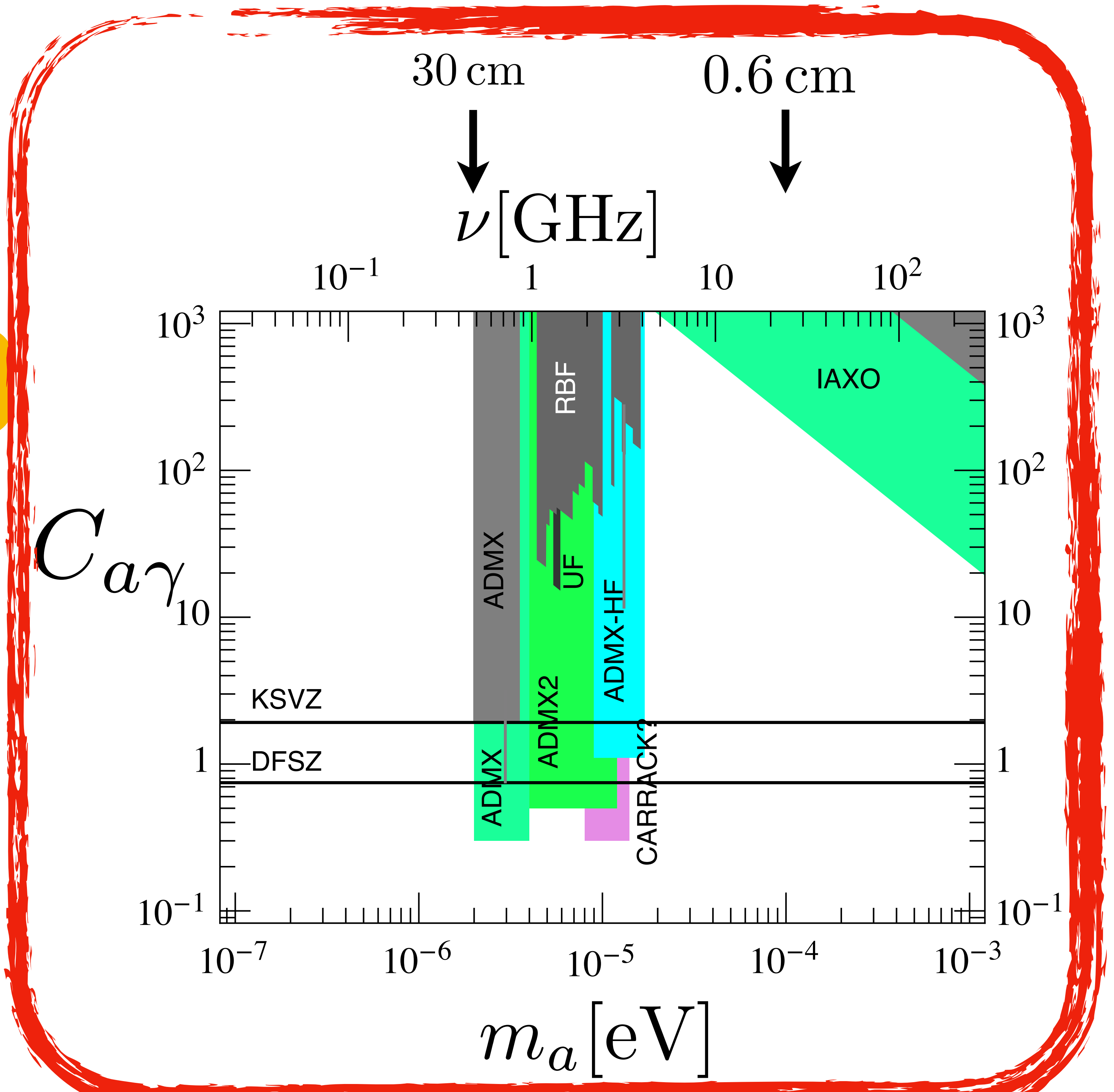
$P_{\rm noise} = T_{\rm sys}\Delta\nu_a \sim T_{\rm sys}10^{-6}m_a$

- Temperature $T \sim 0.2 - 4\,\mathrm{K}$
- System T ~ Quantum limited (SQUID, JPA



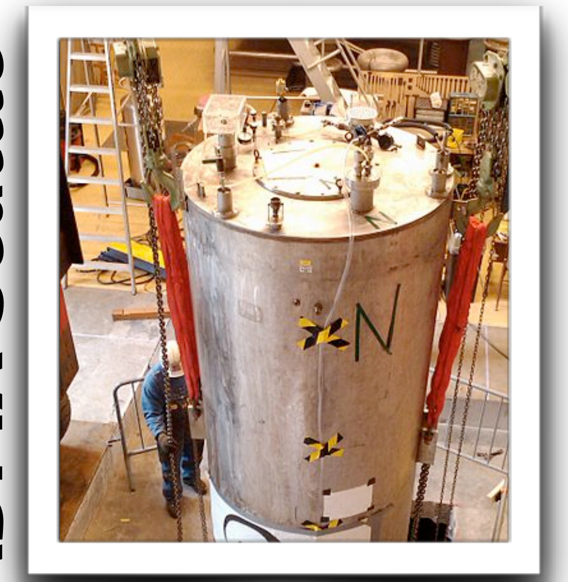






Cavities at high-mass?

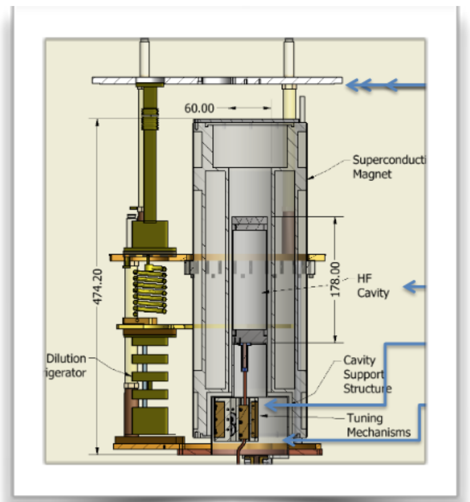
ADMX-Seattle



HAYSTAC-Yale

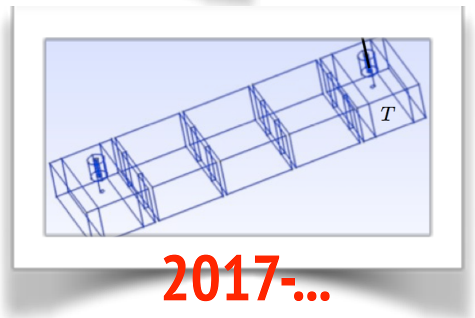
KLASH?

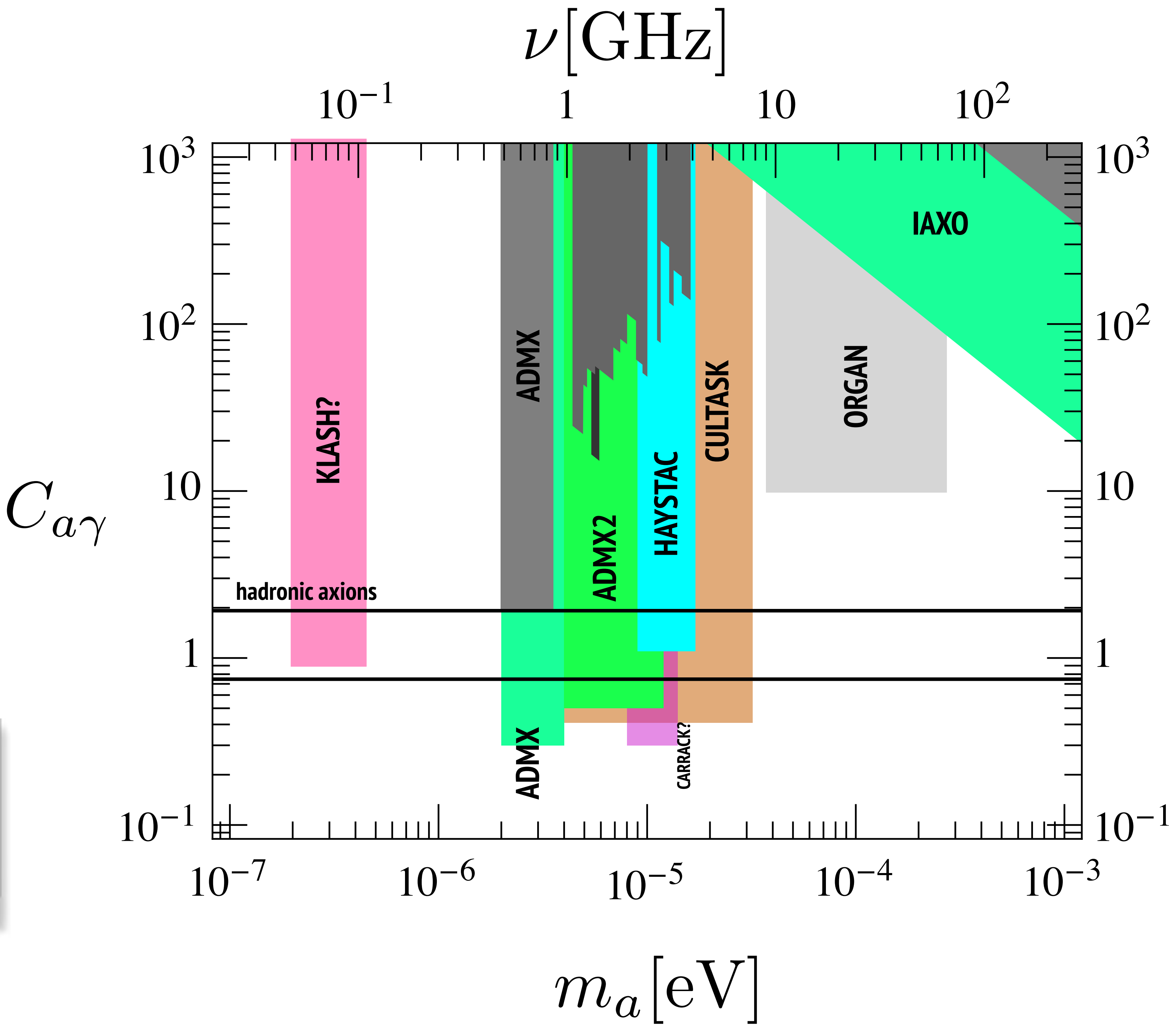
CULTASK - CAPP -Korea



CAST-CAPP

RADES





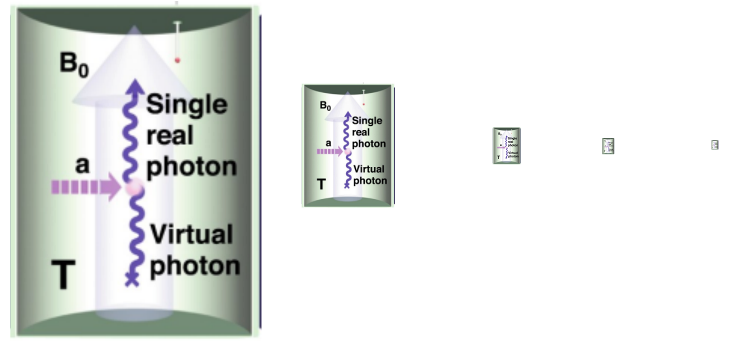
ORGAN-UWA Perth

$P_{\text{out}} \sim Q|\mathbf{E}_a|^2 V m_a$ **(on resonance)**

$Q \downarrow \qquad V m_a \sim \frac{1}{m_a^2}$

$P_{\text{noise}} = T_{\text{sys}} \Delta\nu_a \sim T_{\text{sys}} 10^{-6} m_a$

$T \gtrsim T_Q = \omega = m_a \qquad \Delta\nu_a \propto m_a$



$$\frac{P_s}{P_n} \propto \frac{1}{m_a^4}$$

Ideas:

- Less V, More B!
- Couple + cavities ~ x4 per octave
- QL amplifiers
- Squeezed light detection
- Quantum non demolition meas.

Radiation from a dielectric interface ...

$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$

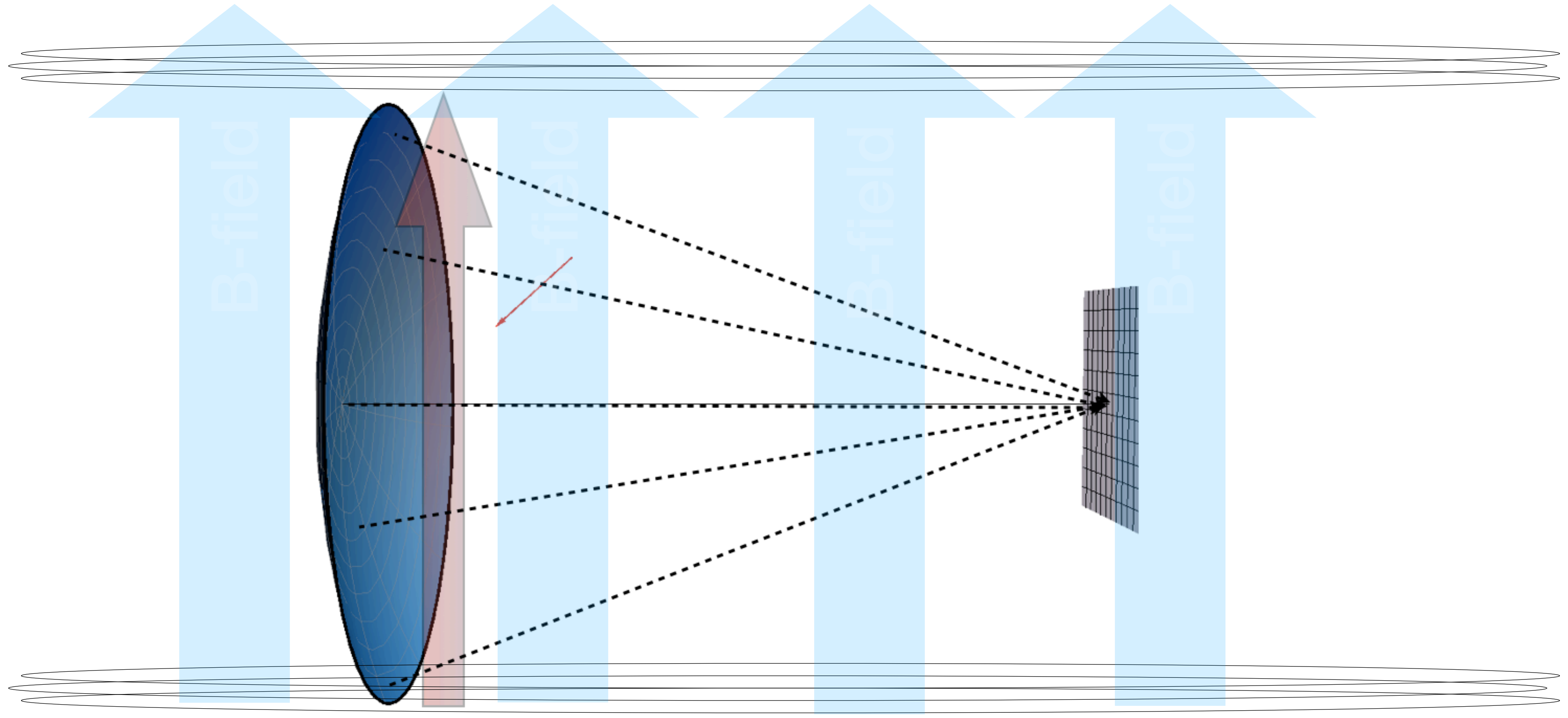
$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi} \cos(m_a t)$$

$$\mathbf{E}_{||1} = \mathbf{E}_{||2}$$

Dish antenna

Horns 2013

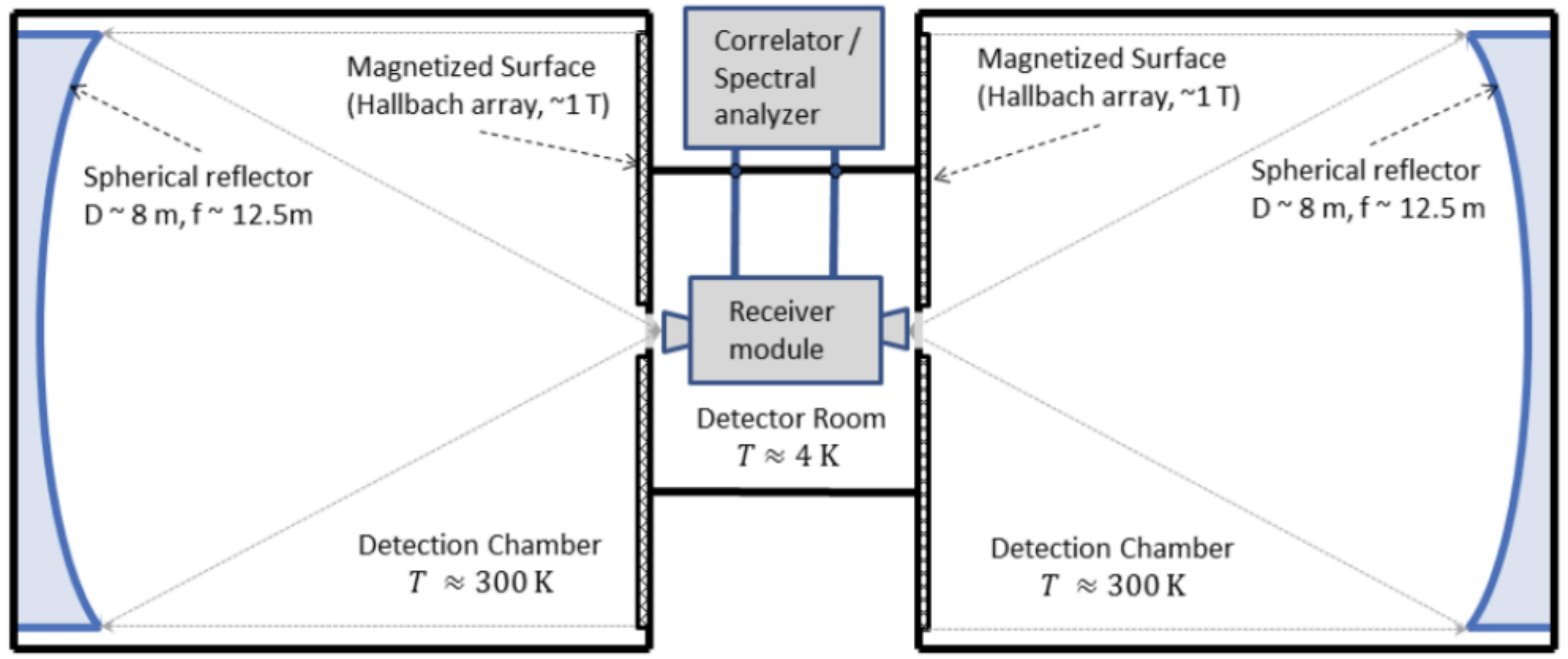
- Detect radiated power from a huge ($Am_a^2 \gg 10^6$) magnetised dish
  - Broadband, no resonance enhancement; Only detector needs to be at T~mK (high reflectivity dish)
  - Maximise Volume even if you loose Q



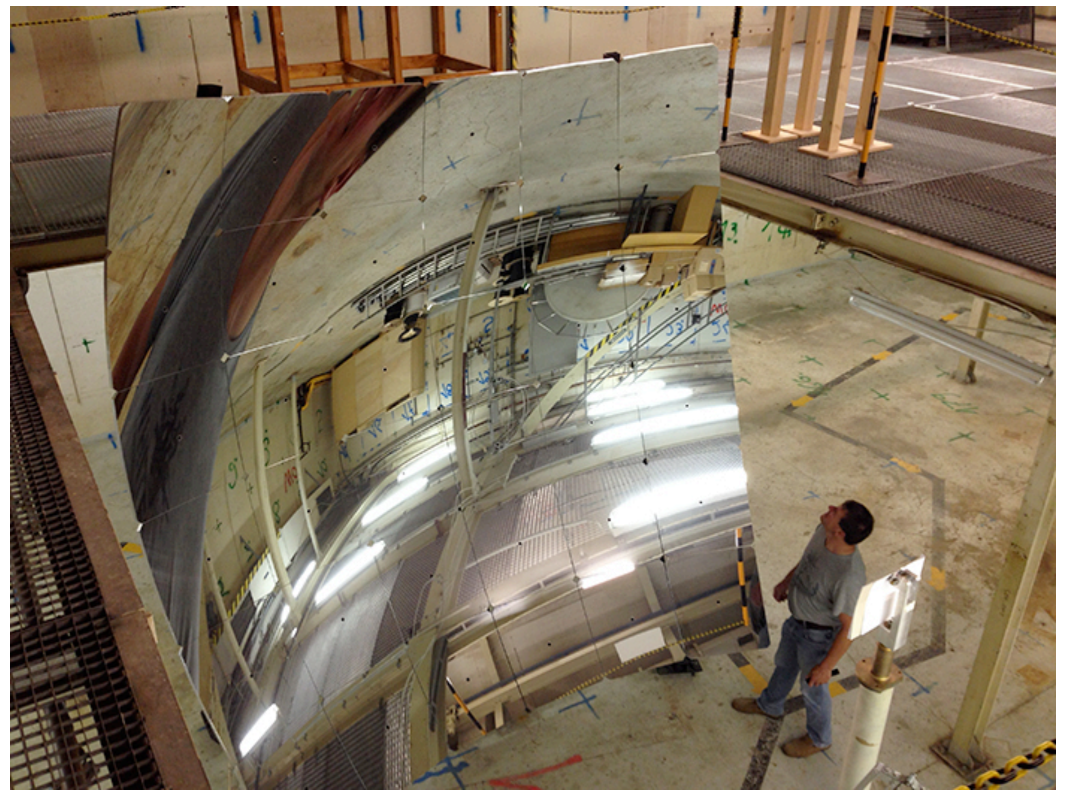
$$P_s \sim |\mathbf{E}_a|^2 \times \text{Area} \sim 2 \times 10^{-27} \left(\frac{\text{B}}{10\text{T}} \frac{C_{a\gamma}}{1} \right)^2 \text{Watt} \times \frac{\text{Area}}{1\,\text{m}^2}$$

$$\frac{P_{\text{dish}}}{P_{\text{cavity}}} \sim \frac{|\text{E}_a|^2 A}{Q|\text{E}_a|^2 V m_a} \sim \frac{Am_a^2}{Q}$$

Plus:
- No tuning!
- Absolute simplicity
- Backgrounds (only detector)
- Eventually better than cavities, but for $m_a \sim \text{meV}$ (where both are not good)



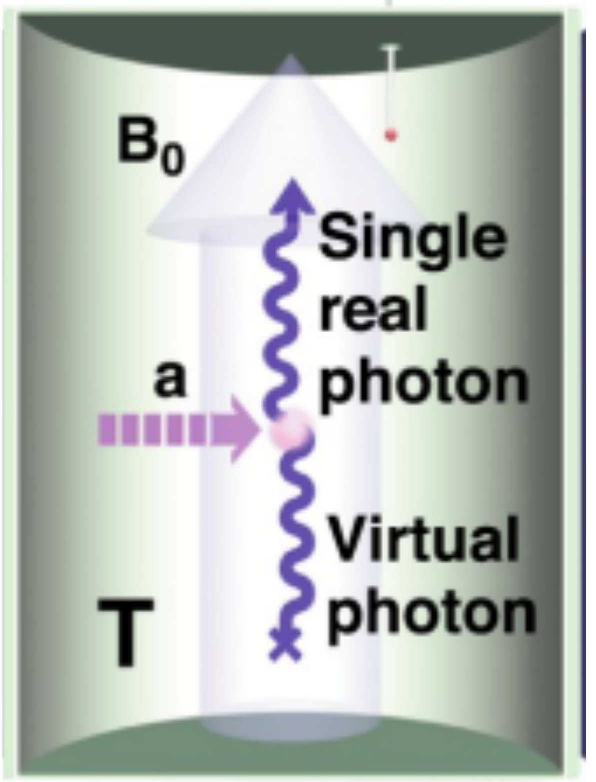
BRASS @ Hamburg



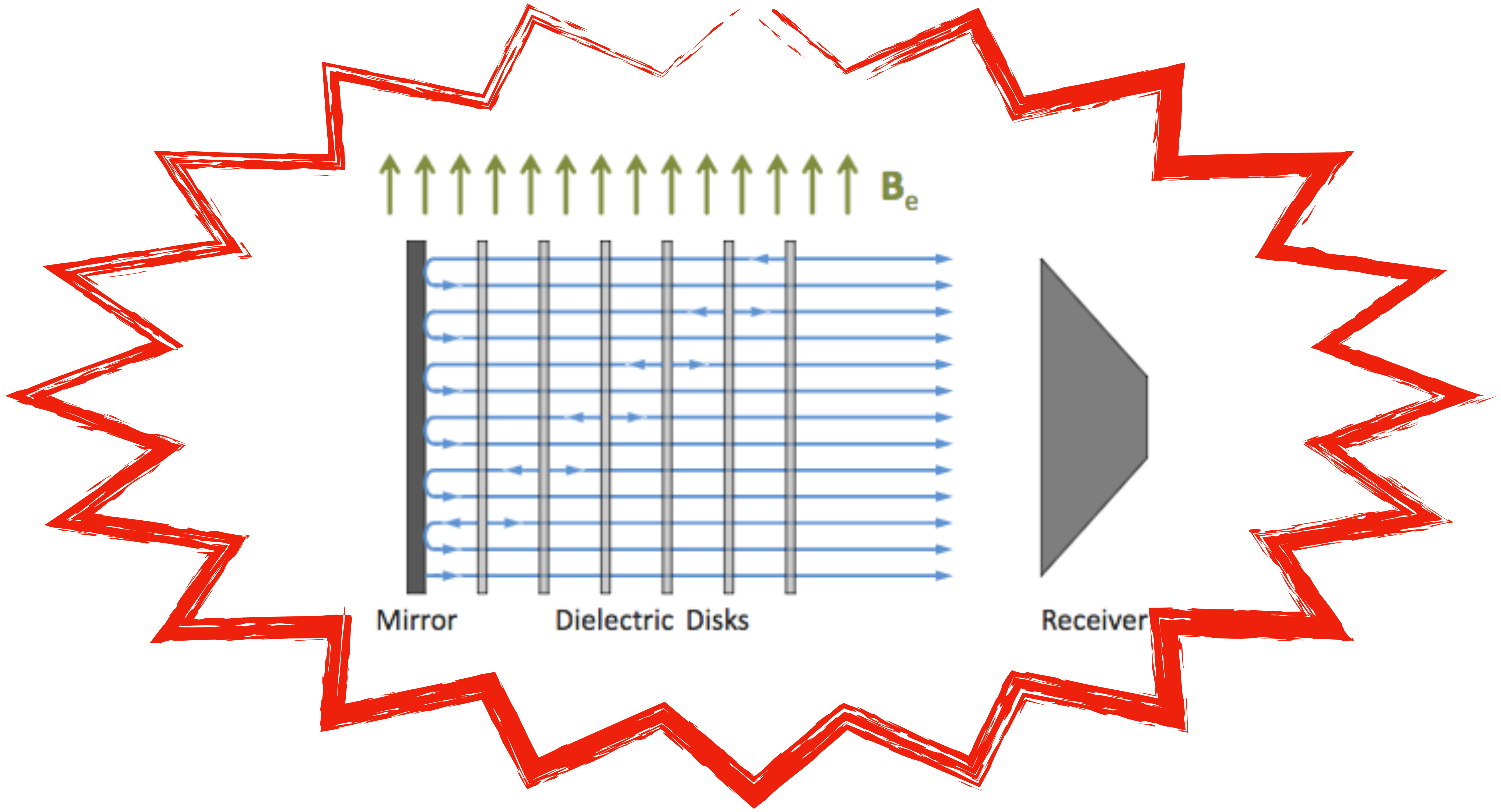
FUNK experiment (KIT)

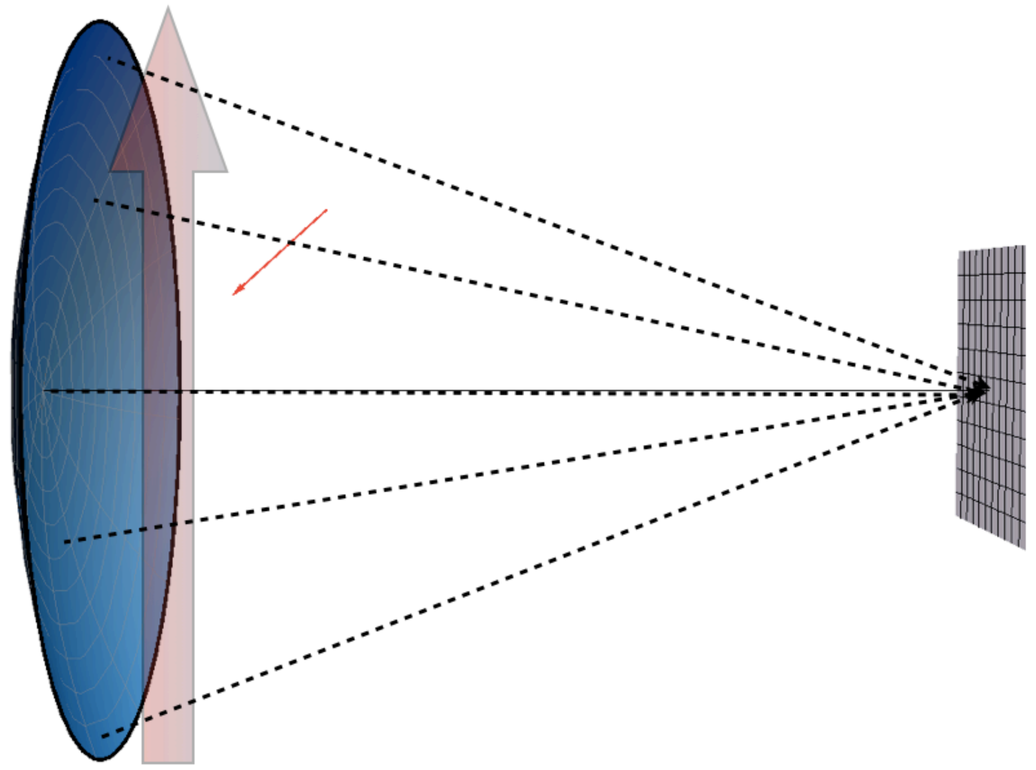
is there something in between ?

Dielecrtic Haloscopes Millar 2017



$P_s \propto Q V m_a$

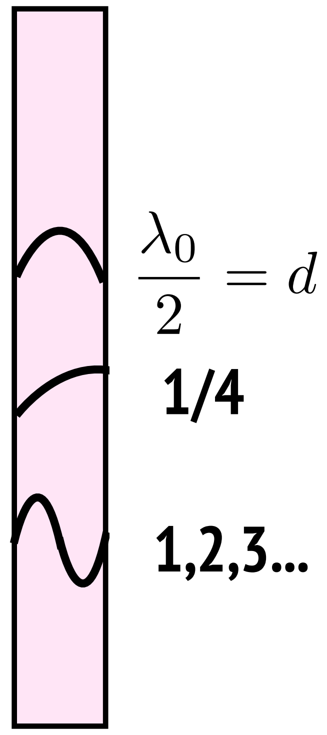




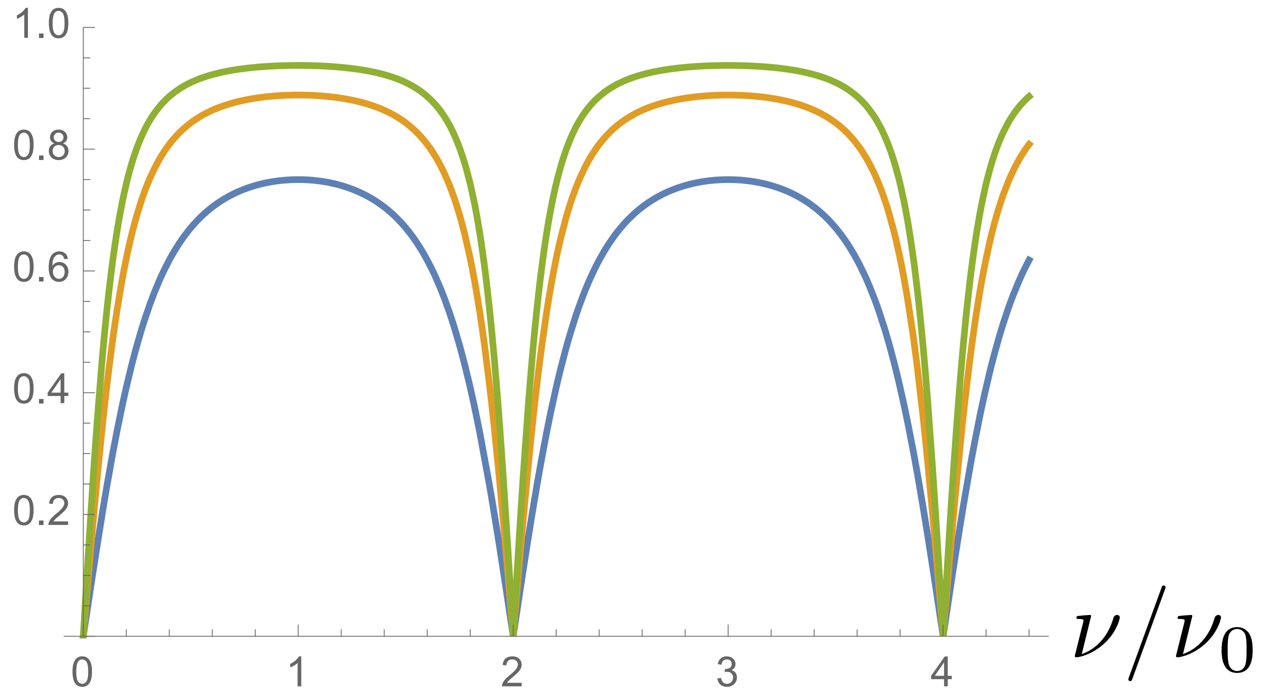
$P_s \propto A$

- Emission from a STACK of dielectrics ... add coherently! $P_s = |\mathbf{E}_a|^2 \mathrm{A} \times \beta^2(\nu)$

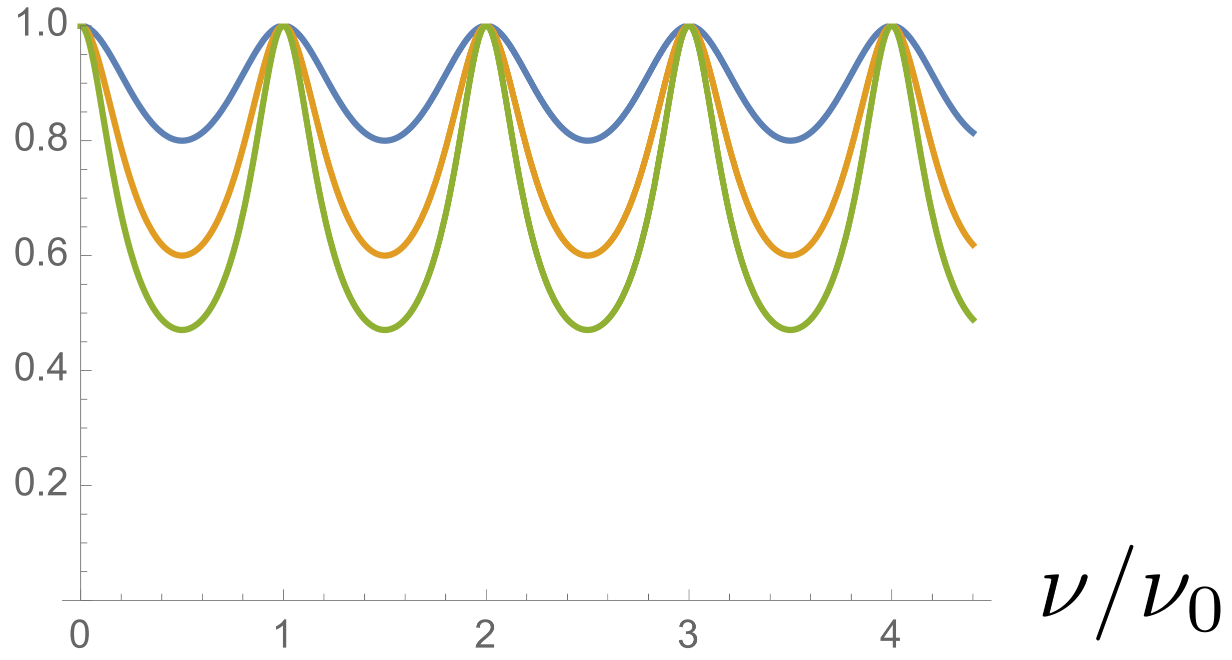
- transparent mode $P_s \propto \mathrm{A} \times N^2 ...$
- maximum reflection... cavity effect
- no emission!



Axion emission (boost factor) (n=2,3,4)

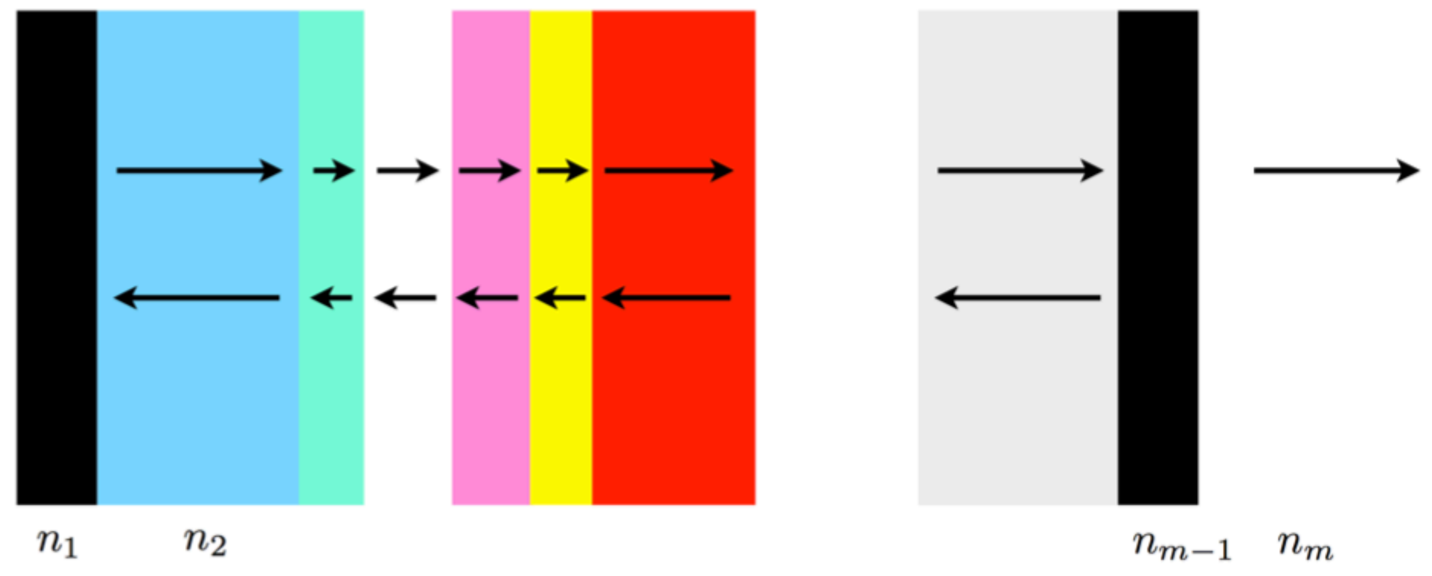


transmission coefficient



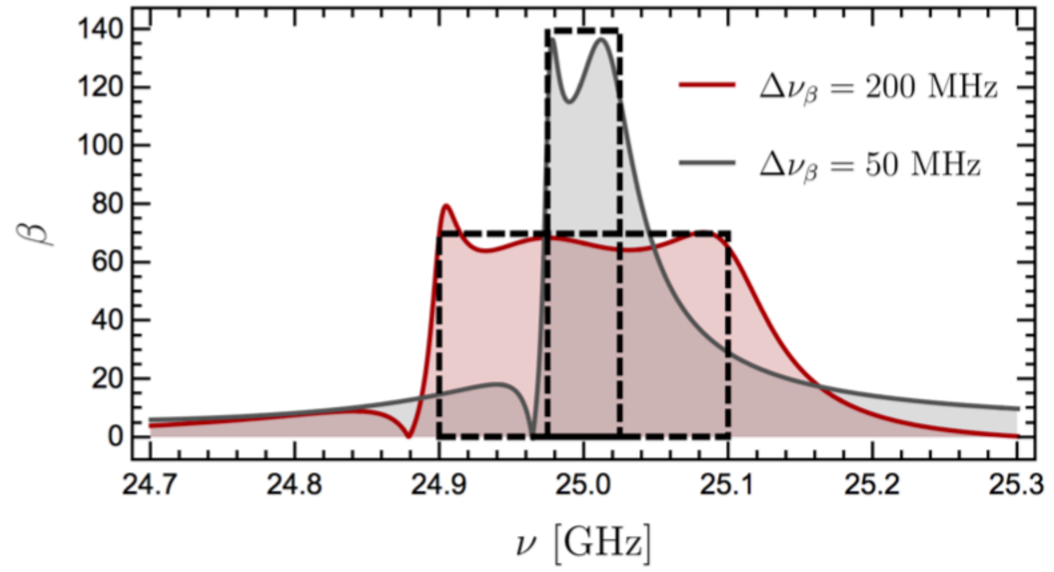
Dielectric haloscopes to search for axion DM

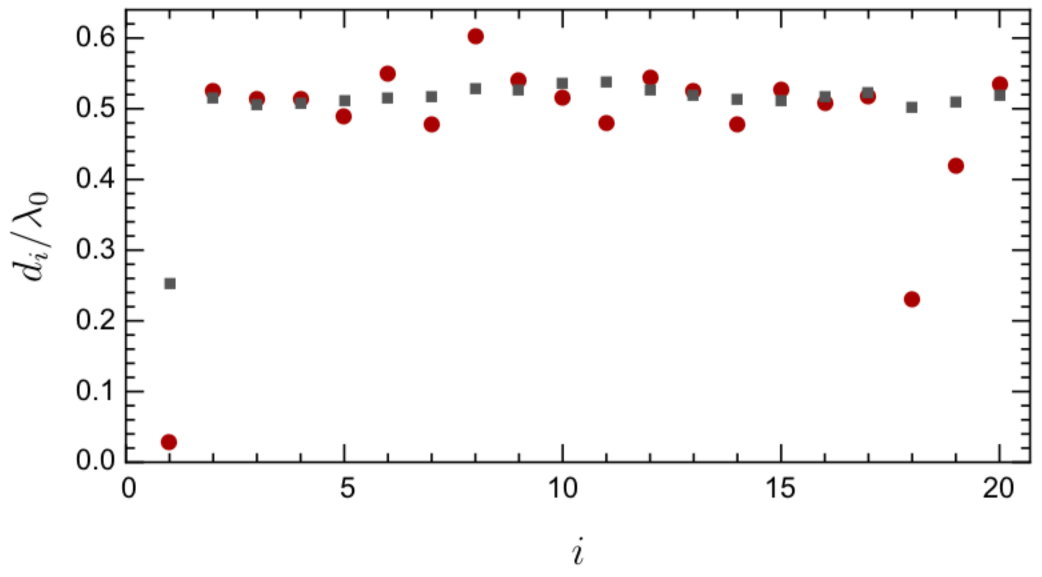
- 1D Transfer matrix formalism + axion emission from each interface



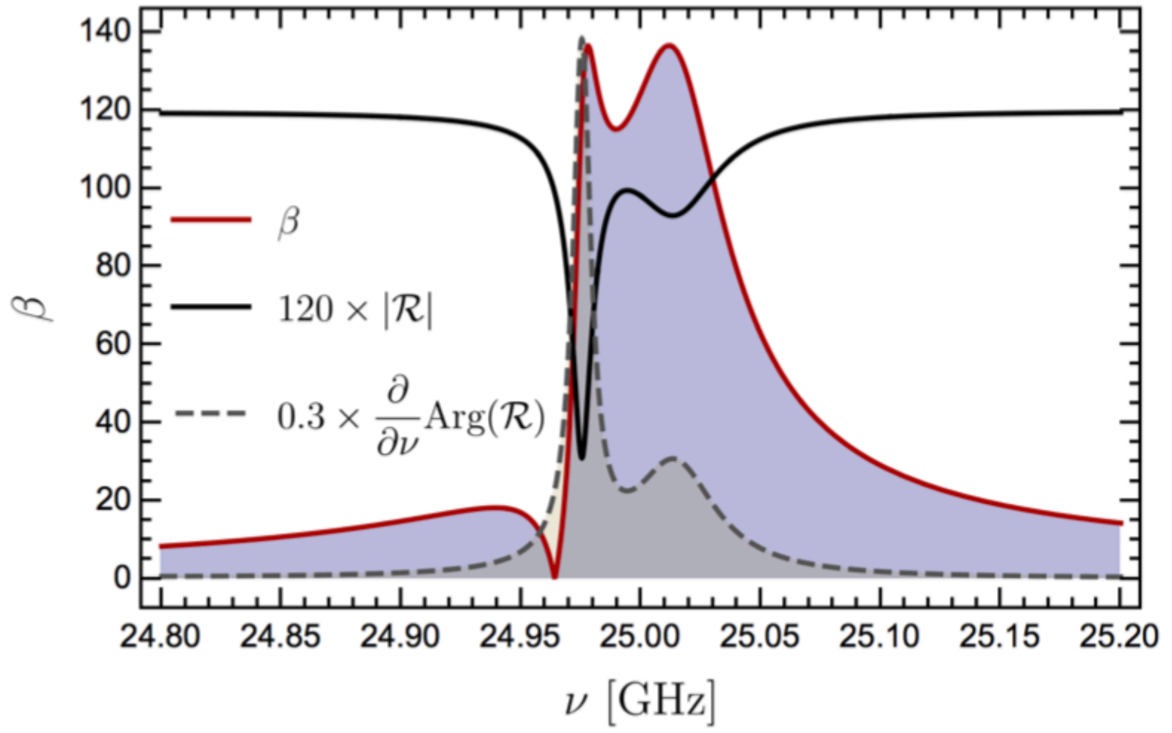
- Optimise setups $\beta^2 \sim \text{const in } \Delta\omega$ by adjusting distances

- optimal bandwidth = max (time to read

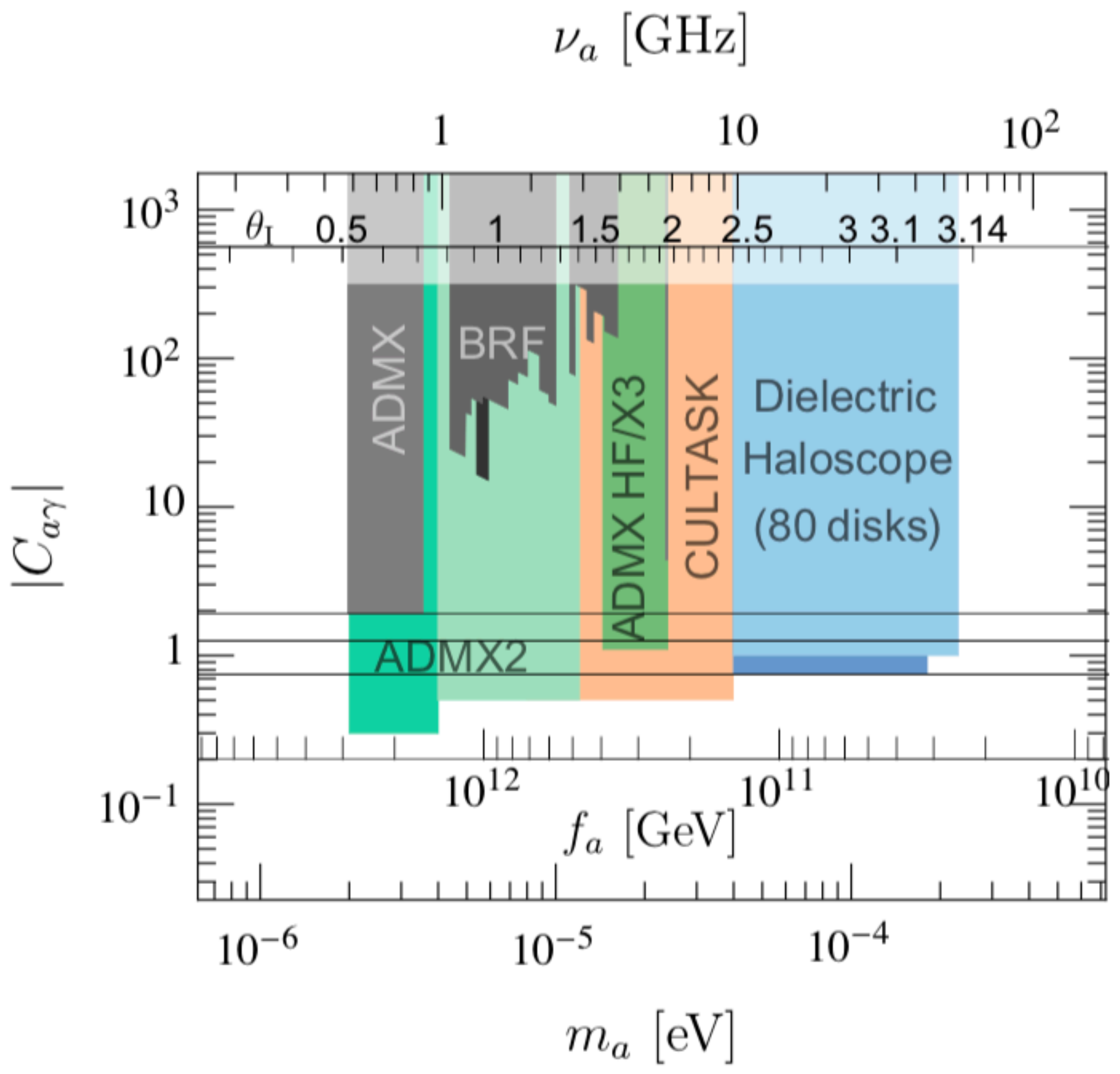




- Correlate boost factor with reflectivity and phase delay



- make sure that you are boosting in the correct range!



B = 10 T
A = 1 m^2

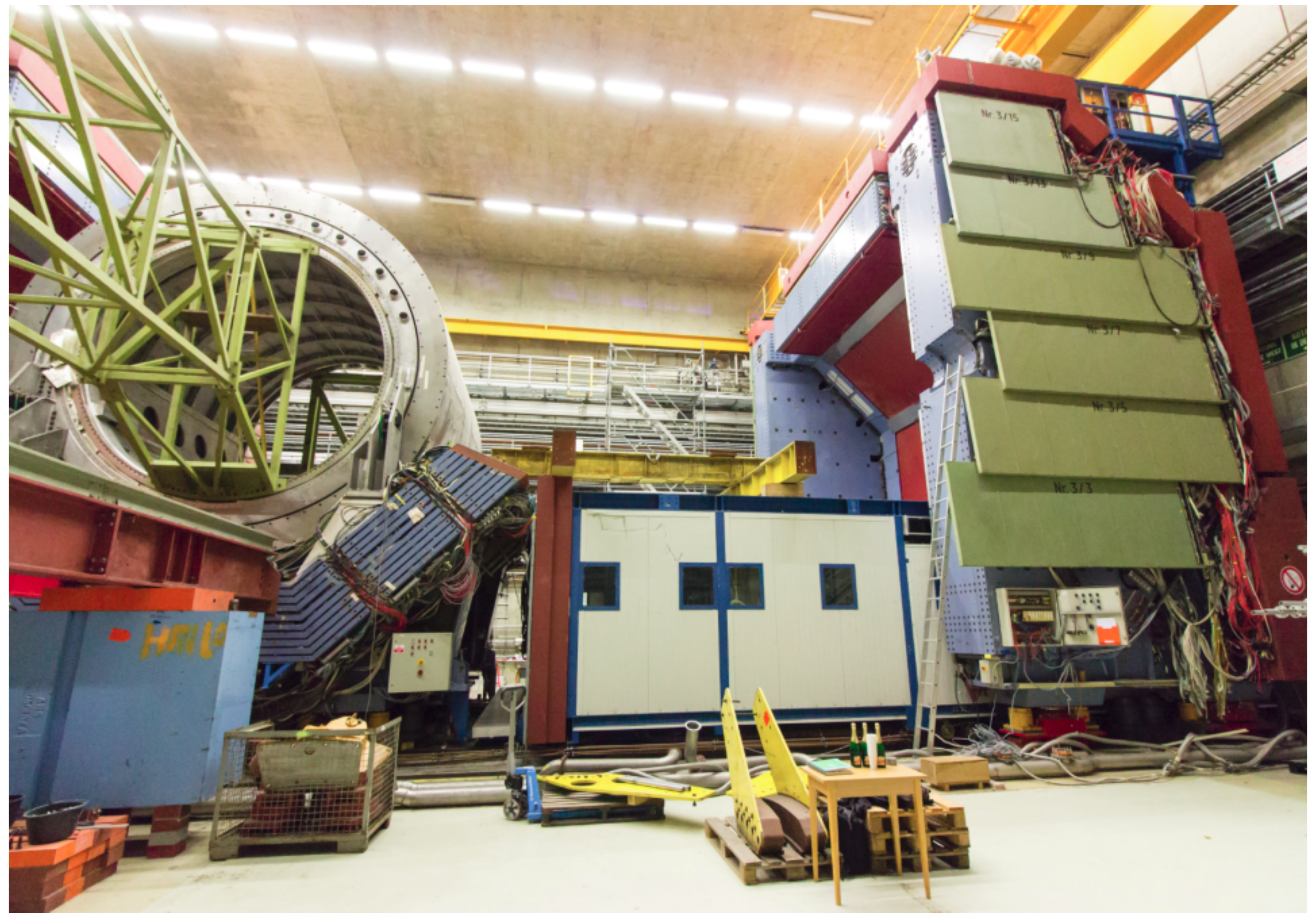
80 disks
LaAlO3 (n~5)

QL detection
3 year

Magnetized Disc-and-Mirror Axion Experiment: MADMAX

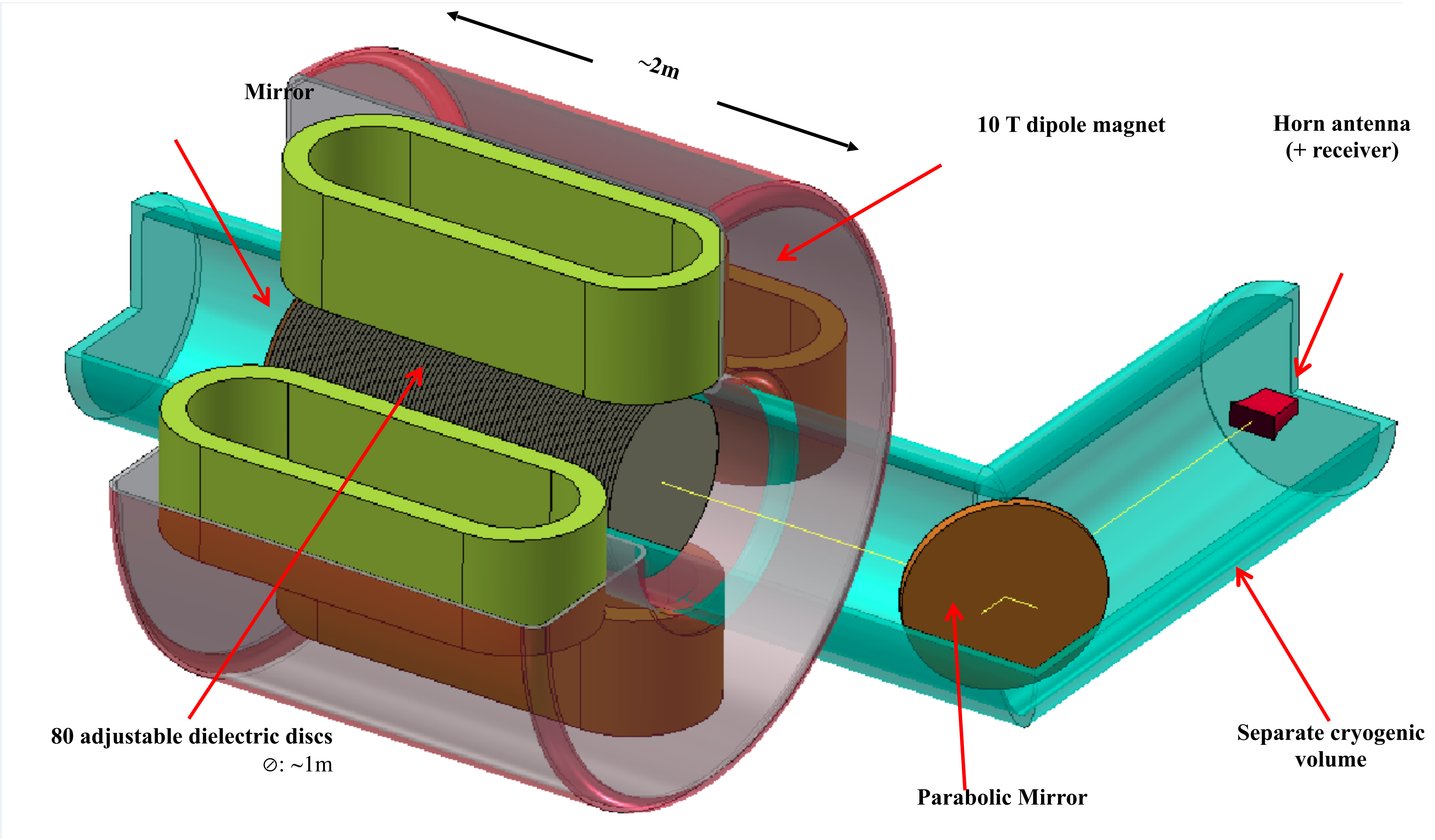
Collaboration forming on 18th Oct. 2017

Site: DESY Hamburg, hall north



- CEA-IRFU, Saclay, France
- DESY Hamburg
- MPI for Physics, Munich
- MPI for Radio Astronomy, Bonn
- RWTH Aachen
- University of Hamburg
- University of Tübingen
- University of Zaragoza, Spain

Dielectric haloscope : MADMAX



Disks

Dielectric disc, chose material:

- High dielectric constant (for large boost & conversion)
- Low loss → low tan δ (reduce photon losses)
- Stable
- Cheap

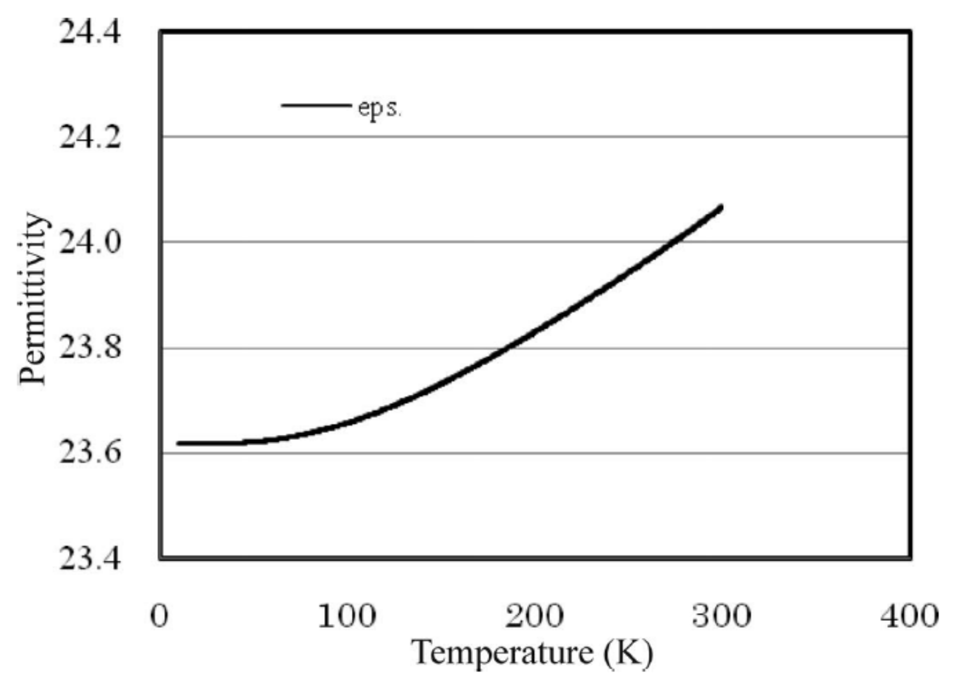
→ **Sapphire (Al_2O_3) @ 300K, 10 GHz:**

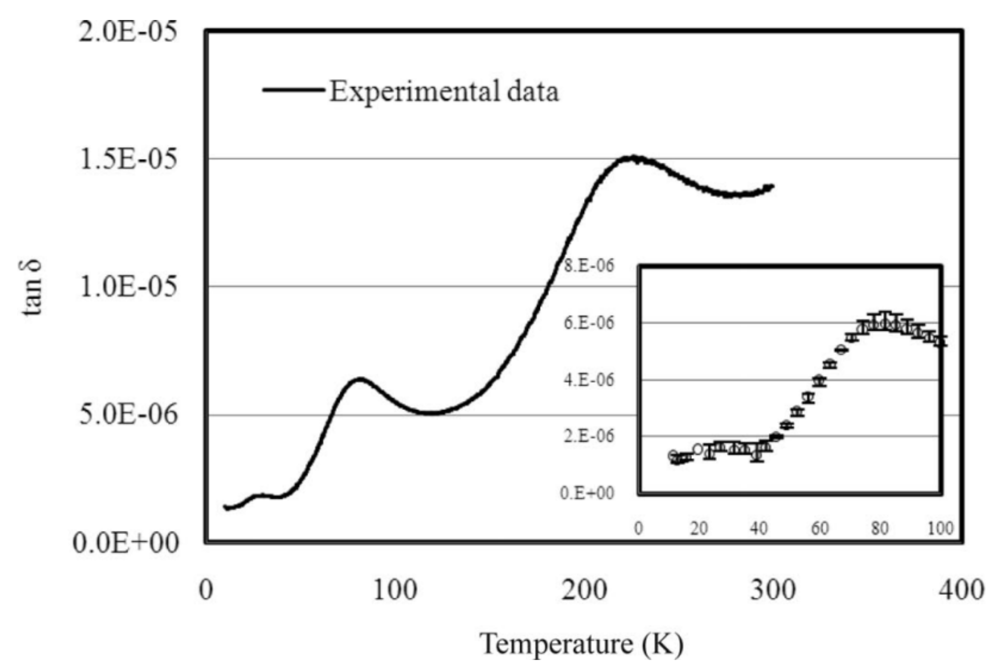
→ **Lanthanide Aluminate ($LaAlO_3$) @ 77K**

→ **Titanium dioxide – Rutil (TiO_2) @10 K, 8 GHz**

10^{-6}

IEEE Trans. Ultrasonics, Ferroelectrics, and Freq. Control, vol. 57, no. 10, October 2010





J. Appl. Phys. 78 (11), 1 December 1995

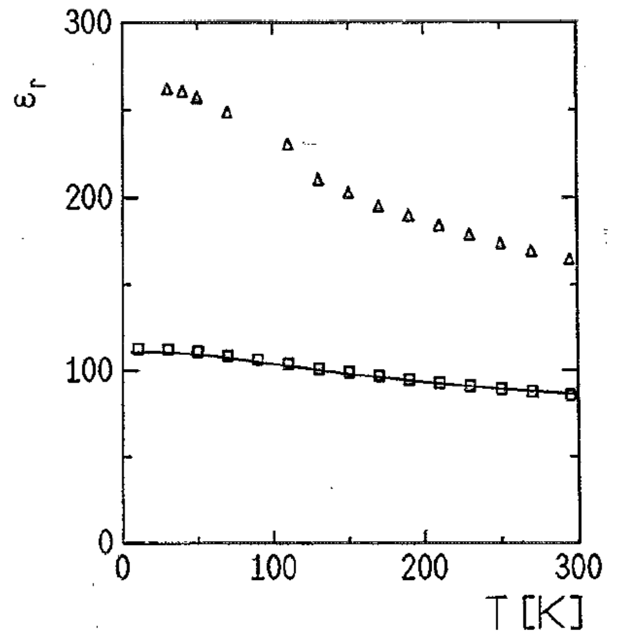


FIG. 2. Permittivity of rutile: $\epsilon_{a,b}(T)$ at 200 GHz (squares) and between 7.5 GHz (4 K) and 8.3 GHz (300 K) (solid line), ϵ_c at 200 GHz (triangles).

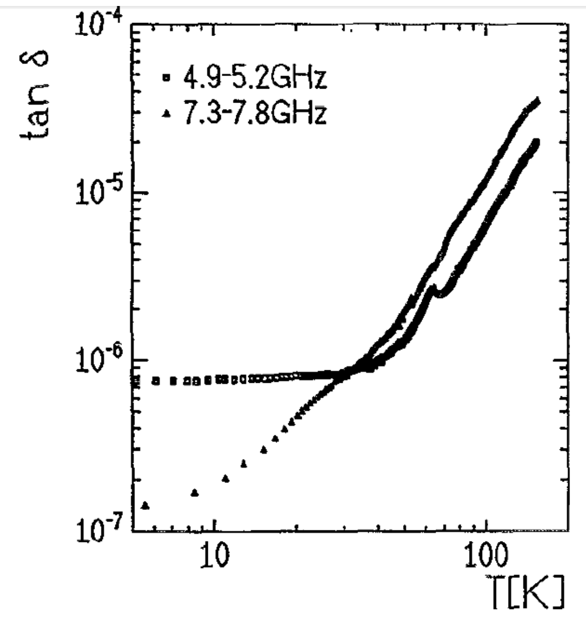
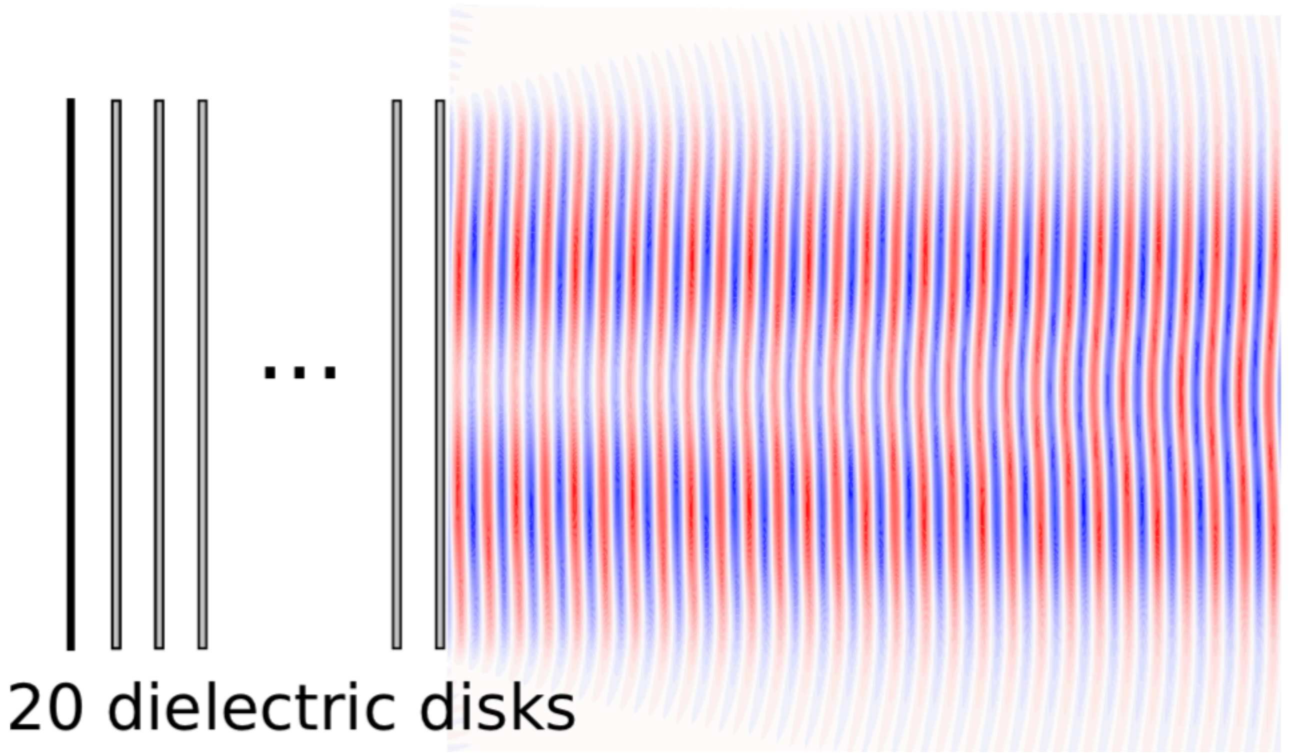


FIG. 4. Loss tangent tanδ of rutile measured with the 4 mm diameter (f =7.3–7.8 GHz from T=4 to 150 K) and with the 6 mm diameter rutile cylinder (f=4.9–5.2 GHz from T=4 to 150 K) from subsequent Q_0 measurements (Fig. 3) in the niobium and copper shielding cavities [Fig. 1(a)].

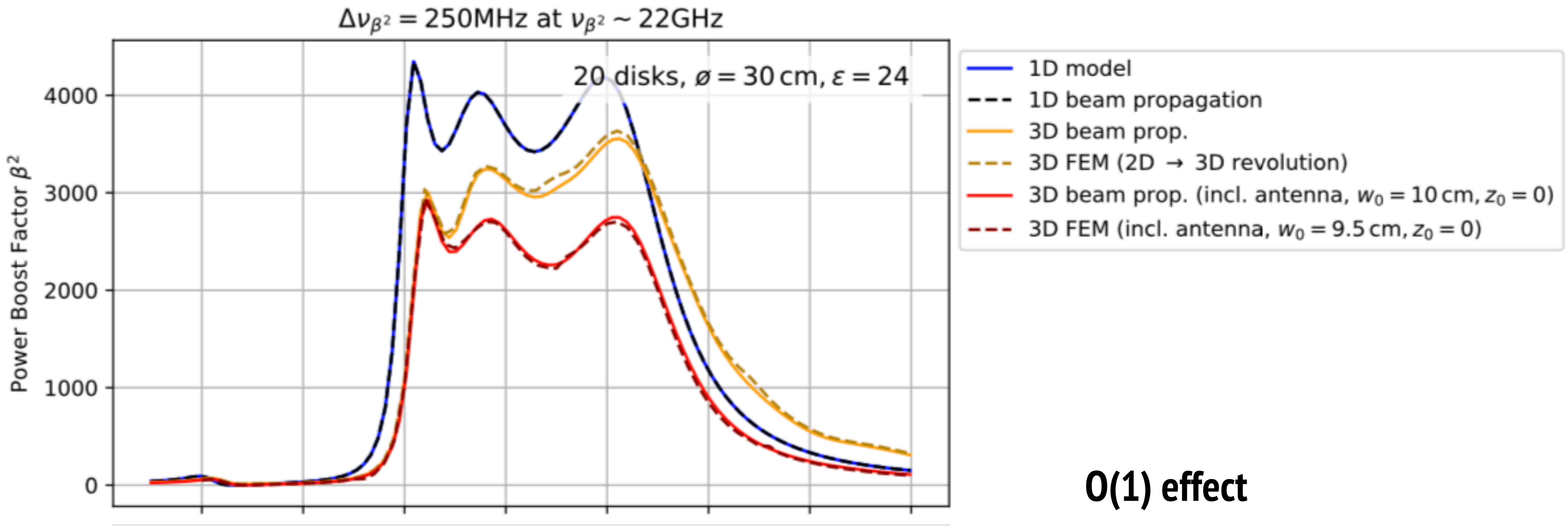
1D to 3D ... difraction!

- Suite of 1D, LEC, 2D cilindrical, 3D simulations

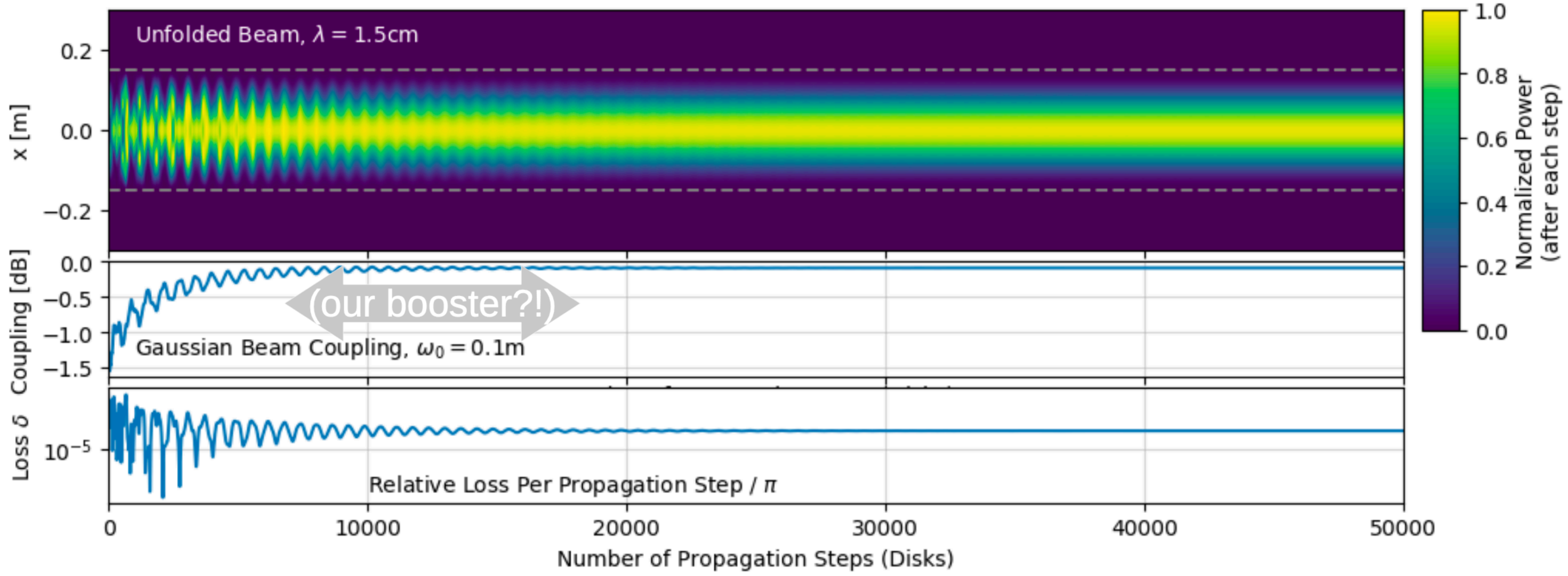


diffraction angle

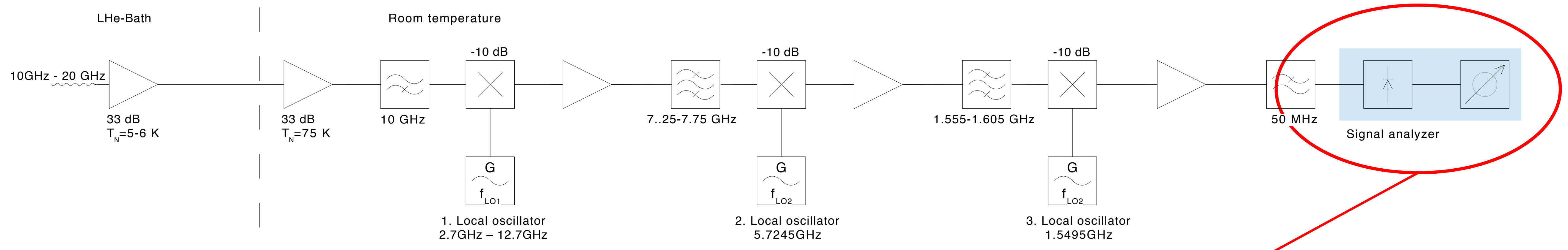
$$\gamma \sim \frac{k_{||}}{k_{\perp}} \sim \frac{1}{m_a D}$$

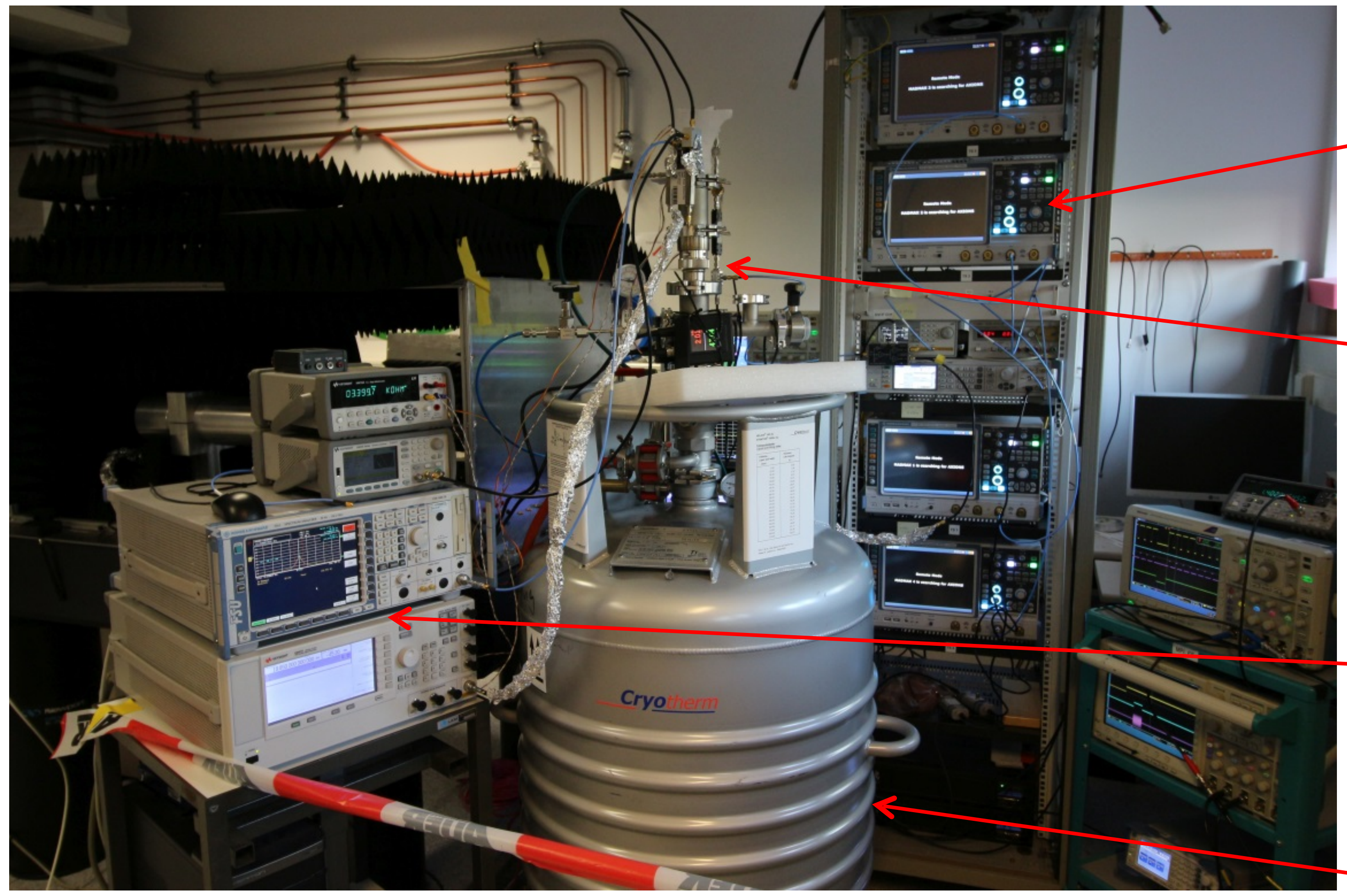


O(1) effect



Receiver





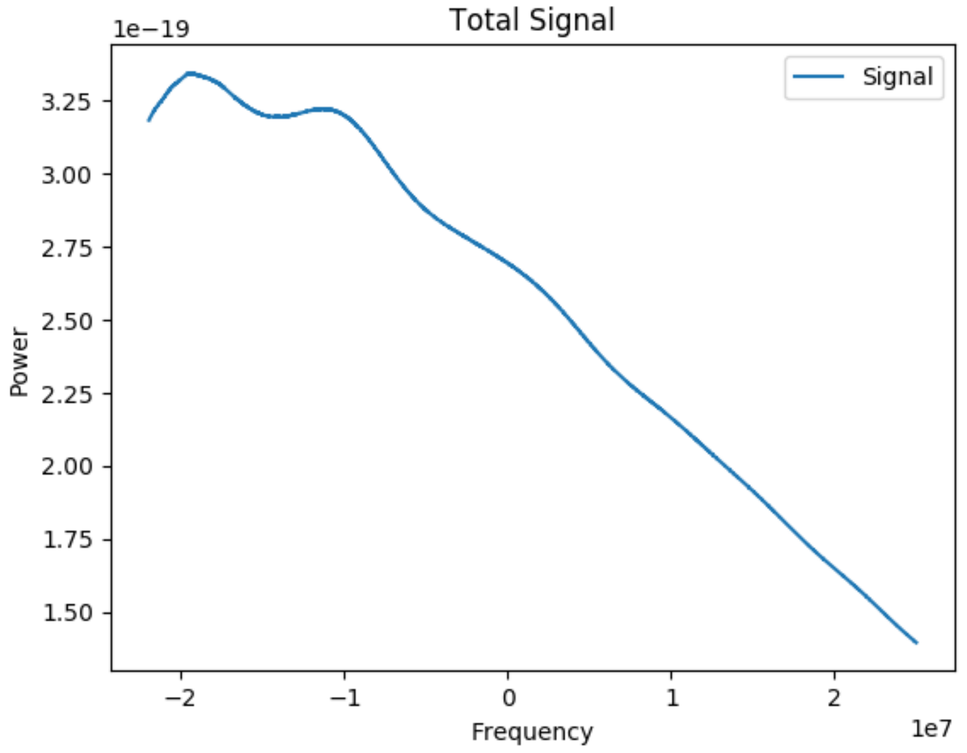
Signal analyzer
(4 samplers, 1.4% dead time)

Front end mixers and amps

Fake axion

LHe bath
→ 4K T_{He} + 5.5K T_{Amp}
= 9.5K T_{Sys}

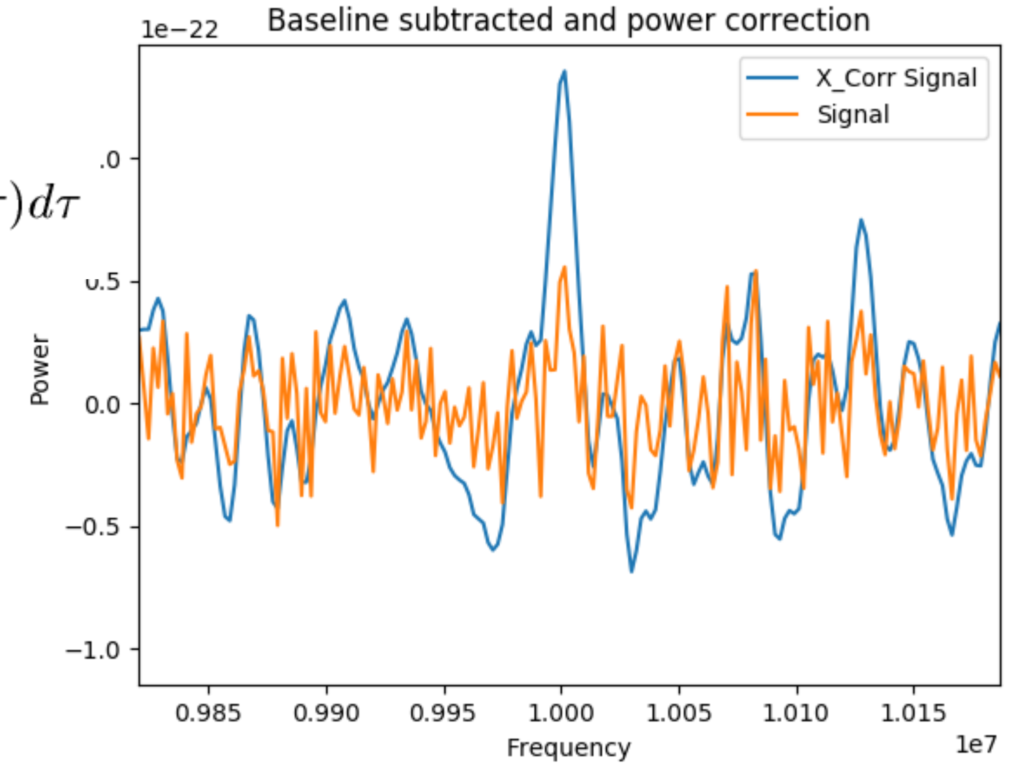
Low Noise preamp, HEMT



$$X(\tau) = \int s(t)\,T(t+\tau)d\tau$$

→

s: Signal
T: Testfunction
(Lorentz, Gauss, …)



- **Inject fake 18GHz axion signal with 10^{-22} W power**
- **Measurement for 28 hours (integrate signal): Receiver at LHe temp.**

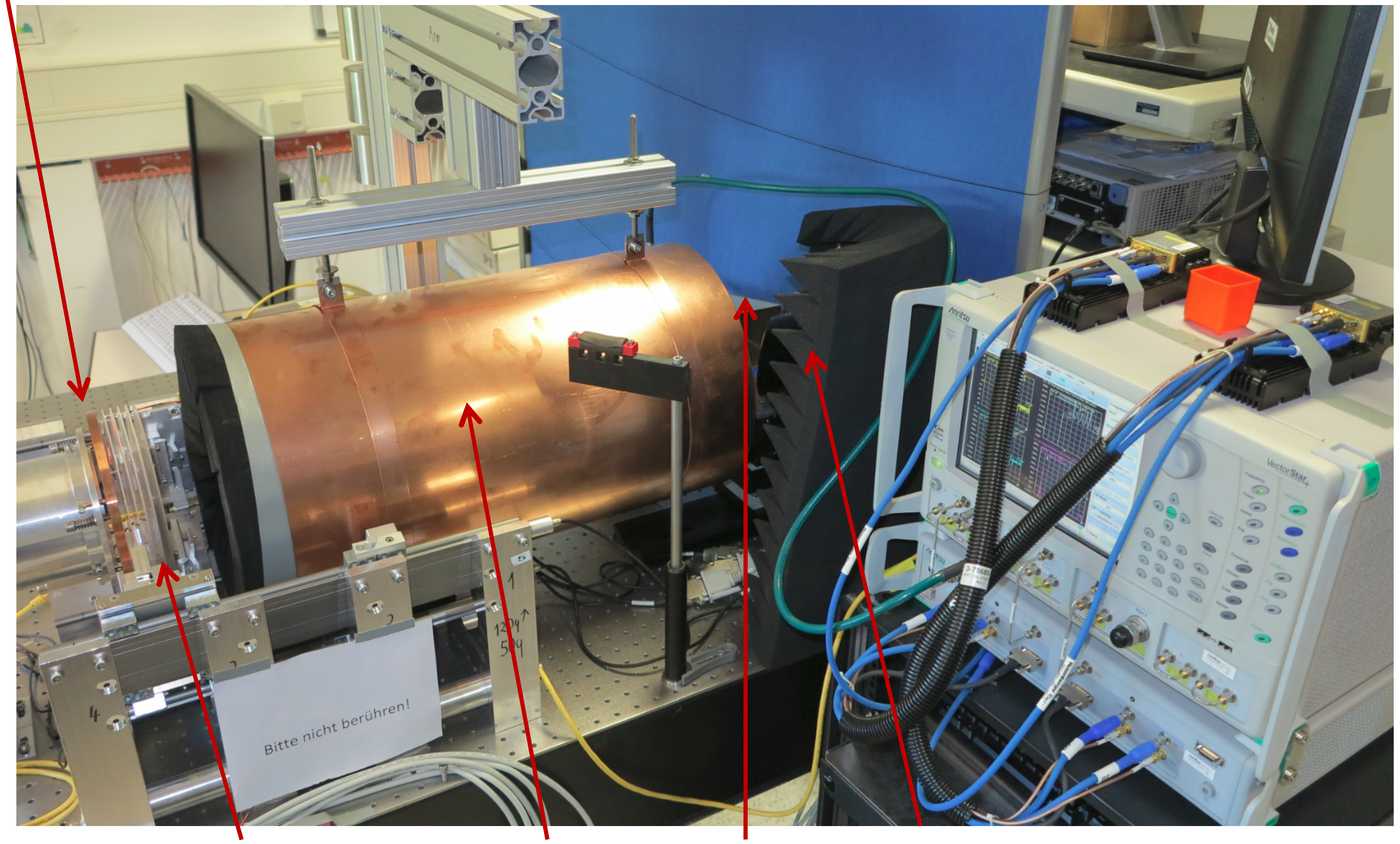
→ **Cross correlation analysis (8kHz Lorentz shaped)**
→ **found ~5σ signal succesfully**

→ **For 1 week measurement:**
Sensitivity at the level of ~ few 10^{-23} W

Seed setup!

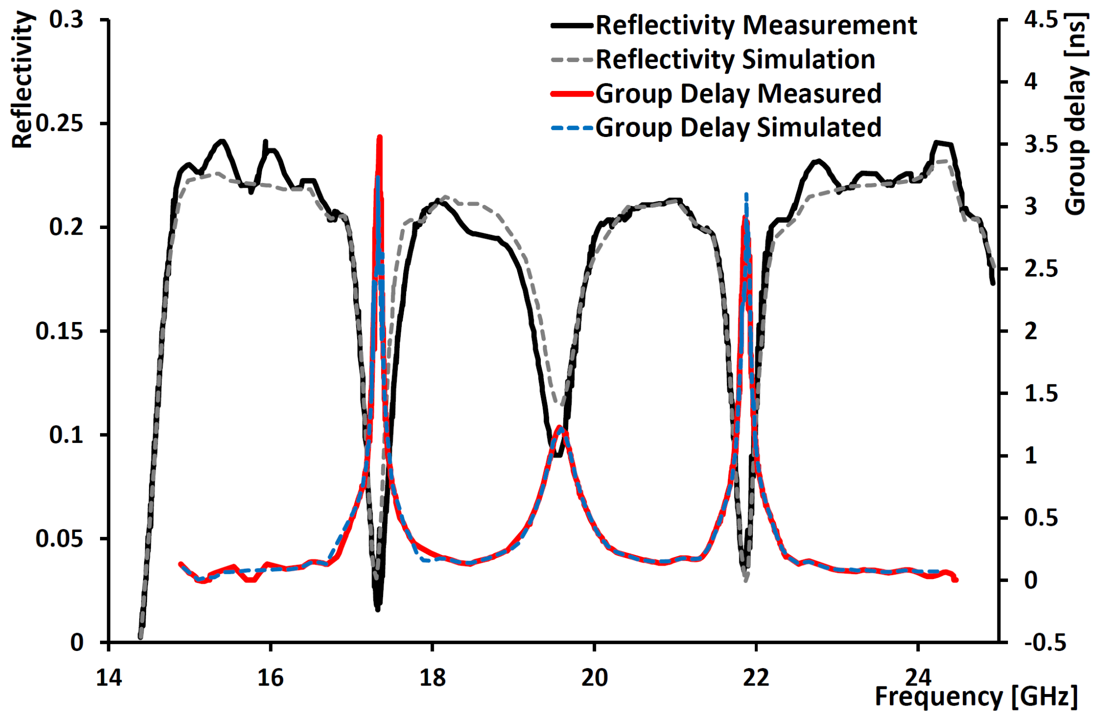
Removable copper mirror

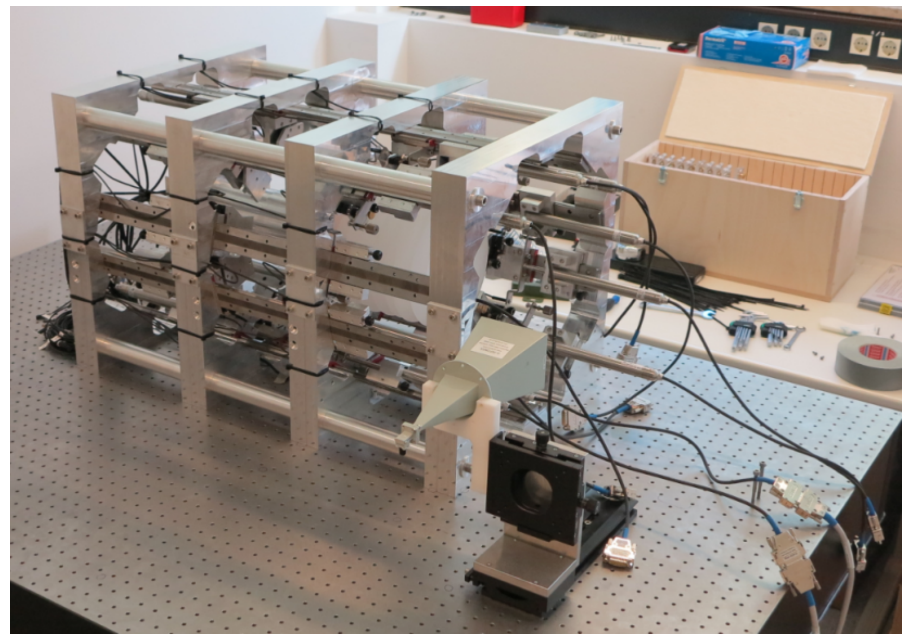
Booster response, Reflectivity



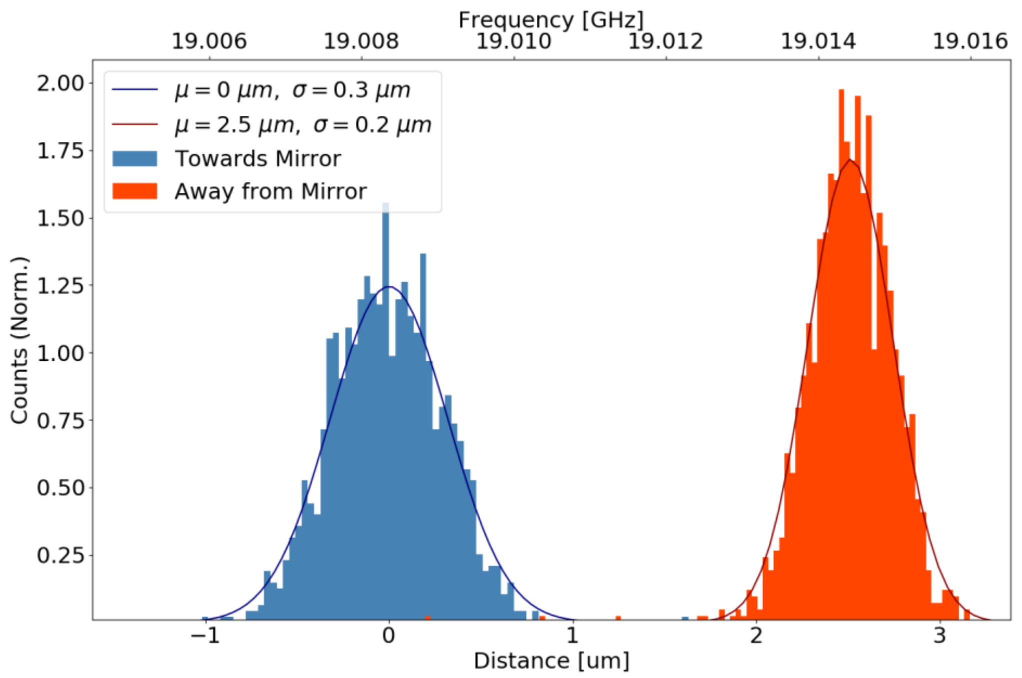
Dielectric discs (Saphire) **„Ab-sorber“** **Horn antenna** **Mirror**

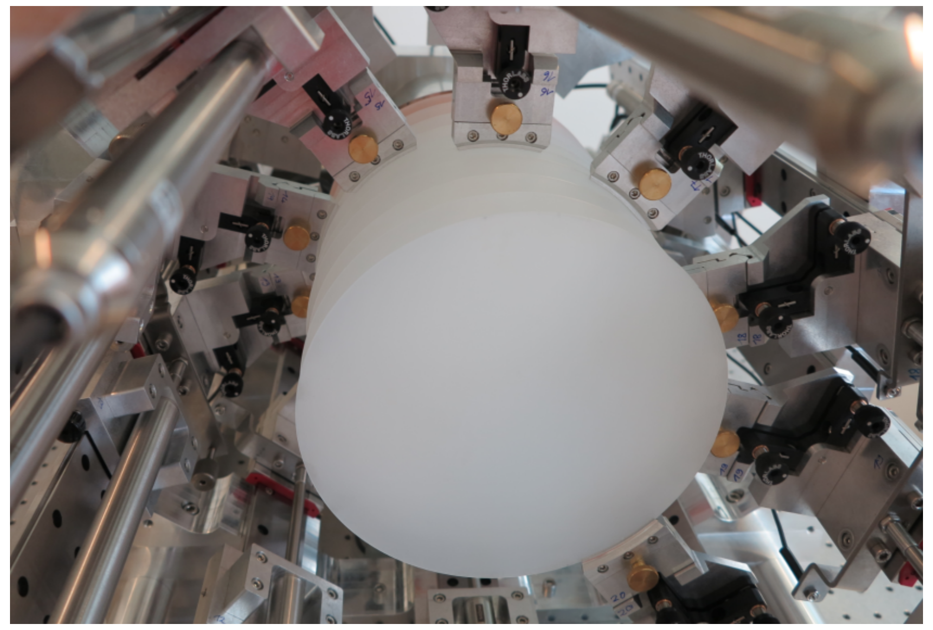
Excellence Cluster Universe

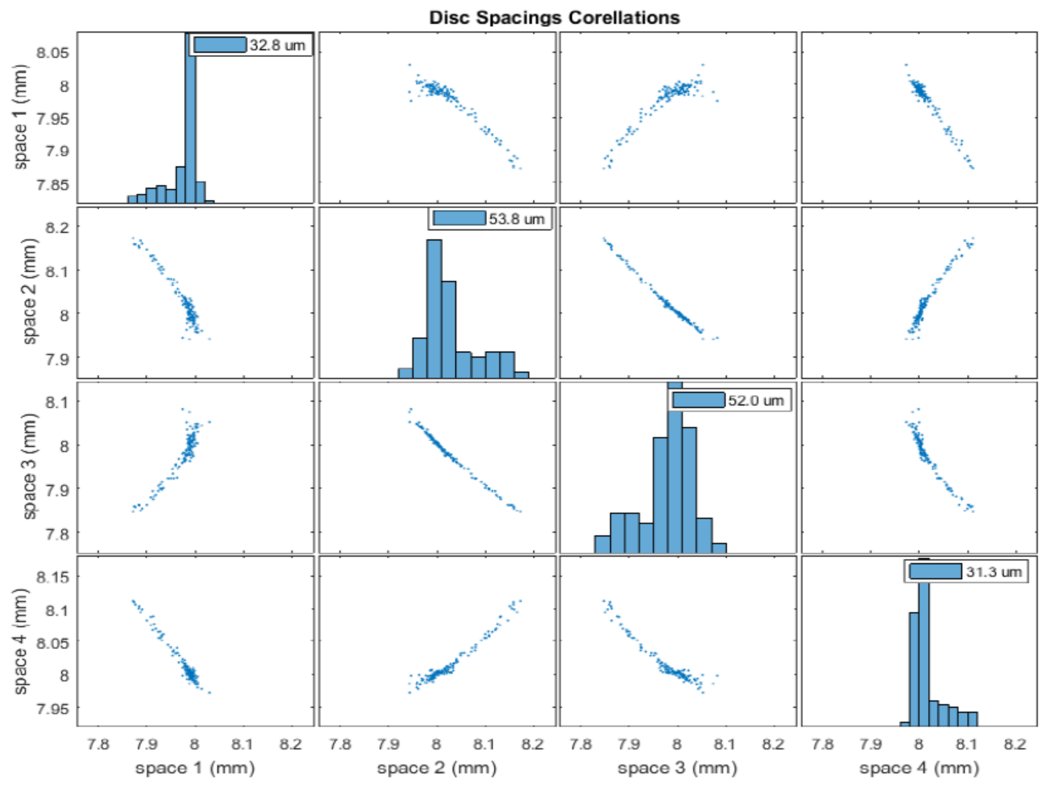




Now available:
Reflectivity measurements with up to 20 discs
First results:
Reproducibility of positioning without algorithm: ~ µm







MADMAX Magnet …

| Sitemap | Legal notice | Cooki

European Commission

INNOVATION UNION
A Europe 2020 Initiative

European Commission > Innovation Union > European Innovation Partnerships

Home | About IU | What we do | Prizes | Events | Documents | Press | Funding

European Innovation Partnerships

European Innovation Partnerships (EIPs) are a new approach to EU research and innovation.

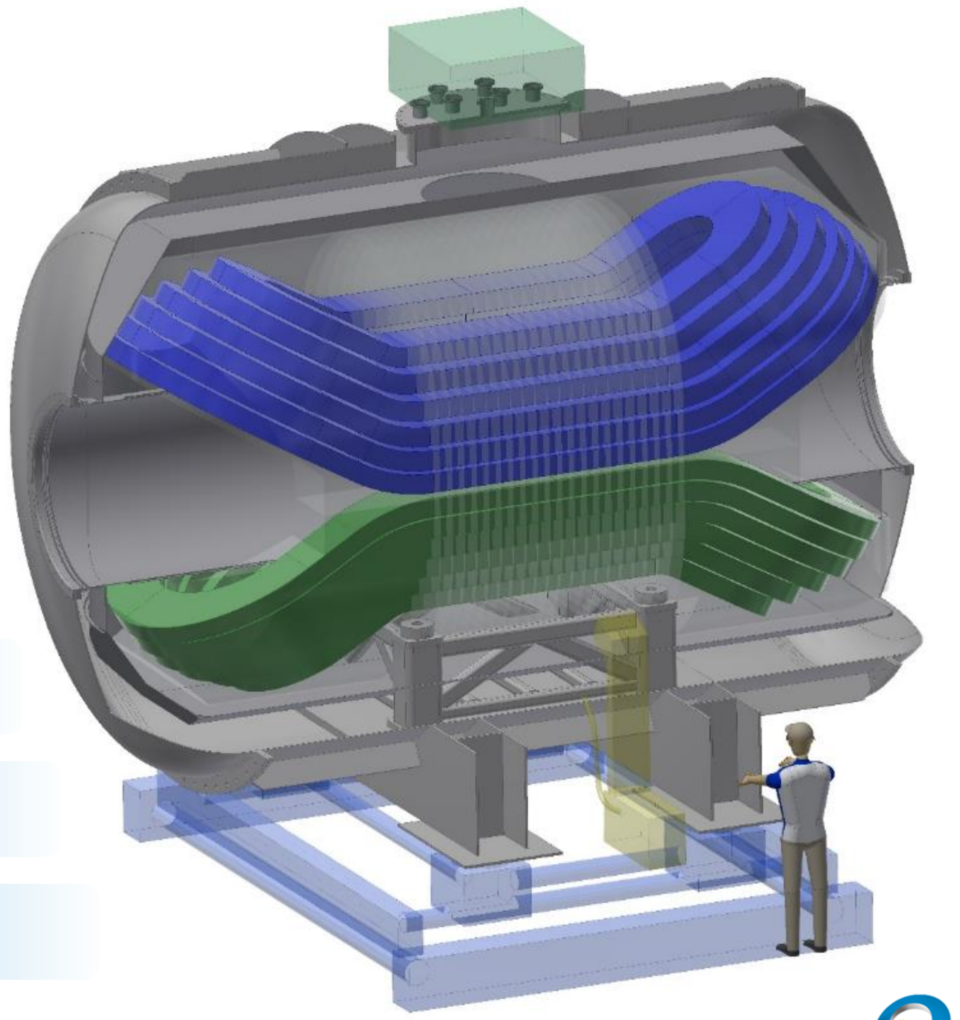
EIPs are challenge-driven, focusing on societal benefits and a rapid modernisation of the associated sectors and markets.

100 T²m² dipole magnet:
Never ever done before
- → **Design Study**
- → **Prototype**
- → **Full scale magnet**

Innovation partnership: First in MPG
- → **Tedious 16 months EU tendering process: Aug. 2016 – Dec 2017**
- → **Two innovation partners:**
  CEA-IRFU Saclay, France
  Bilfinger Noell, Würzburg

One tender for whole magnet project!

- Weight: < 200.000 Kg
- Length: 6900 mm
- Diameter: 4400 mm
- Warm bore: 1350* mm
- Superconducting cable: 35.000 m
- Superconducting wire: > 700.000 m NbTi
- Operating temperature: ~2 K

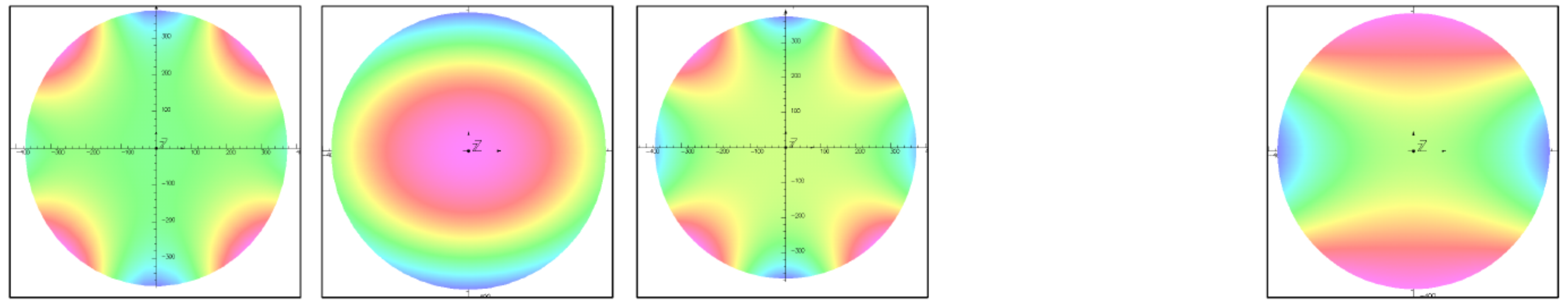


So far no show stoppers, the show goes on!

BILFINGER

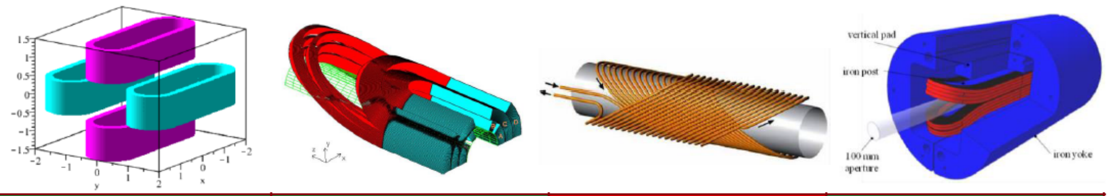
Comparison
Preparing for the next step

BILFINGER



Cosine Theta	CCT	Block design	Racetrack	Helmholtz pair
Traditional design Extensive exp. Good homogeneity Small cross section	Easy to optimize High potential Easy to produce Good homogeneity	Easier to manufacture than cos theta Flat or cc cable Harder to optimize		Short setup solution Lots of space Low homogeneity

cea First evaluations summary (previous meeting)



Field specification	+ +	+ +	- -	+ +
Peak field	-	++	+	++
Stress analysis	+	- -	- -	+
Conductor design	+	- -	- -	+
Mechanical layout	+ +	- -	+ +	- -
Superconductor	-	+ +	+	+ +
Stray field	+ +	- -	- -	- -
Compatibility H1 yoke	- -	+ +	-	+ +
Magnet volume	+	+ +	- -	+ +
First order conclusions that will be confirmed by further detailed studies	Encouraging solution that has to be optimized if shielding is required	Seems not feasible due to technological limits (conductor , layers, …)	Seems not feasible due to design, techno and cost limits (field, cond, vol)	Encouraging solution if the H1 yoke fits with the stray field requirements

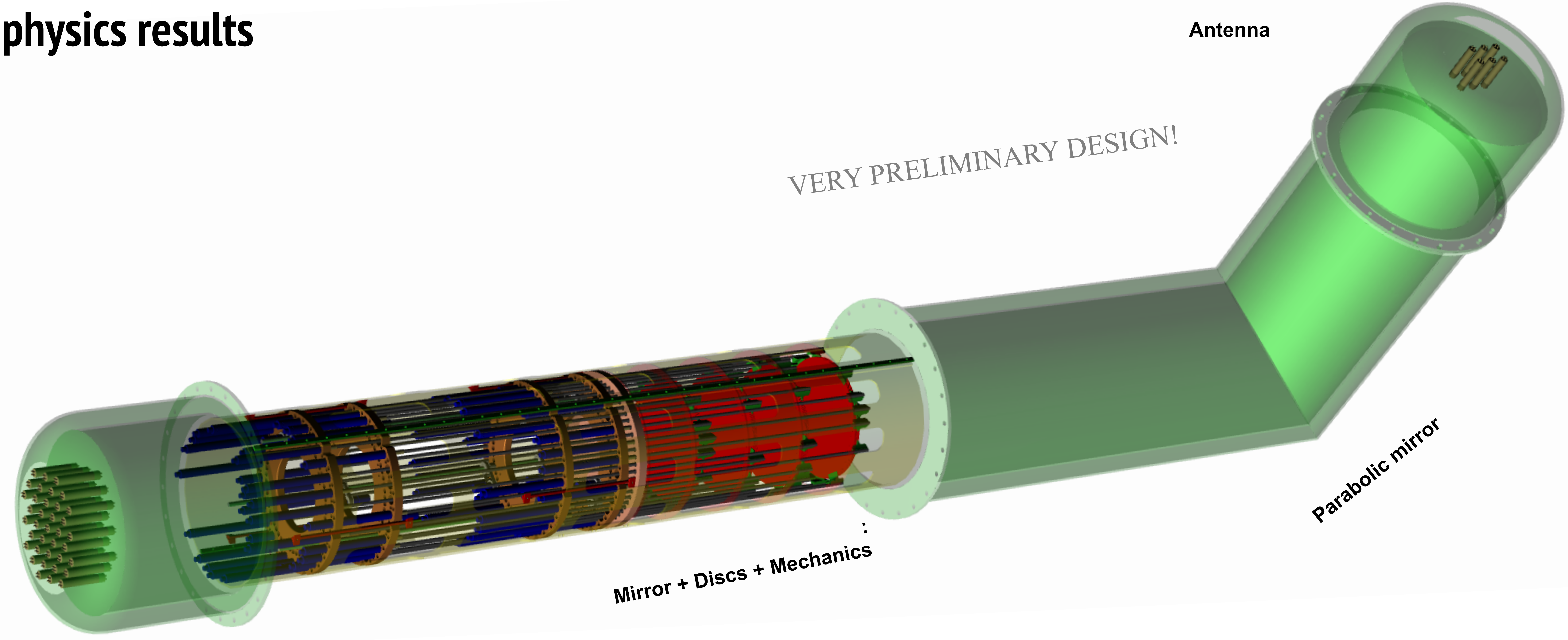
Prototype booster

Build prototype with 20 discs, 30cm diameter

Use inside prototype (few T) magnet:

→Test feasibility of $1m^2$ booster

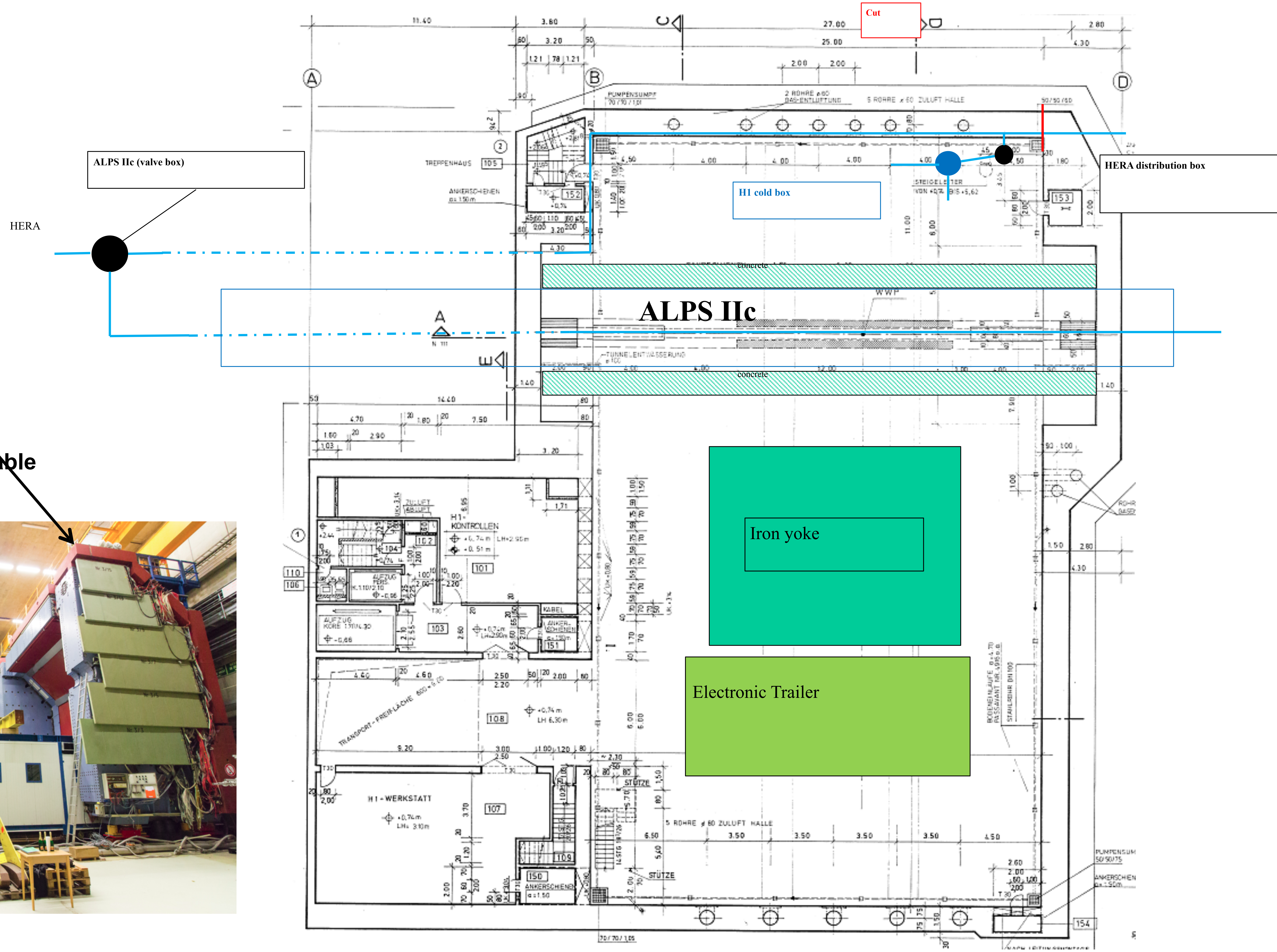
→First physics results



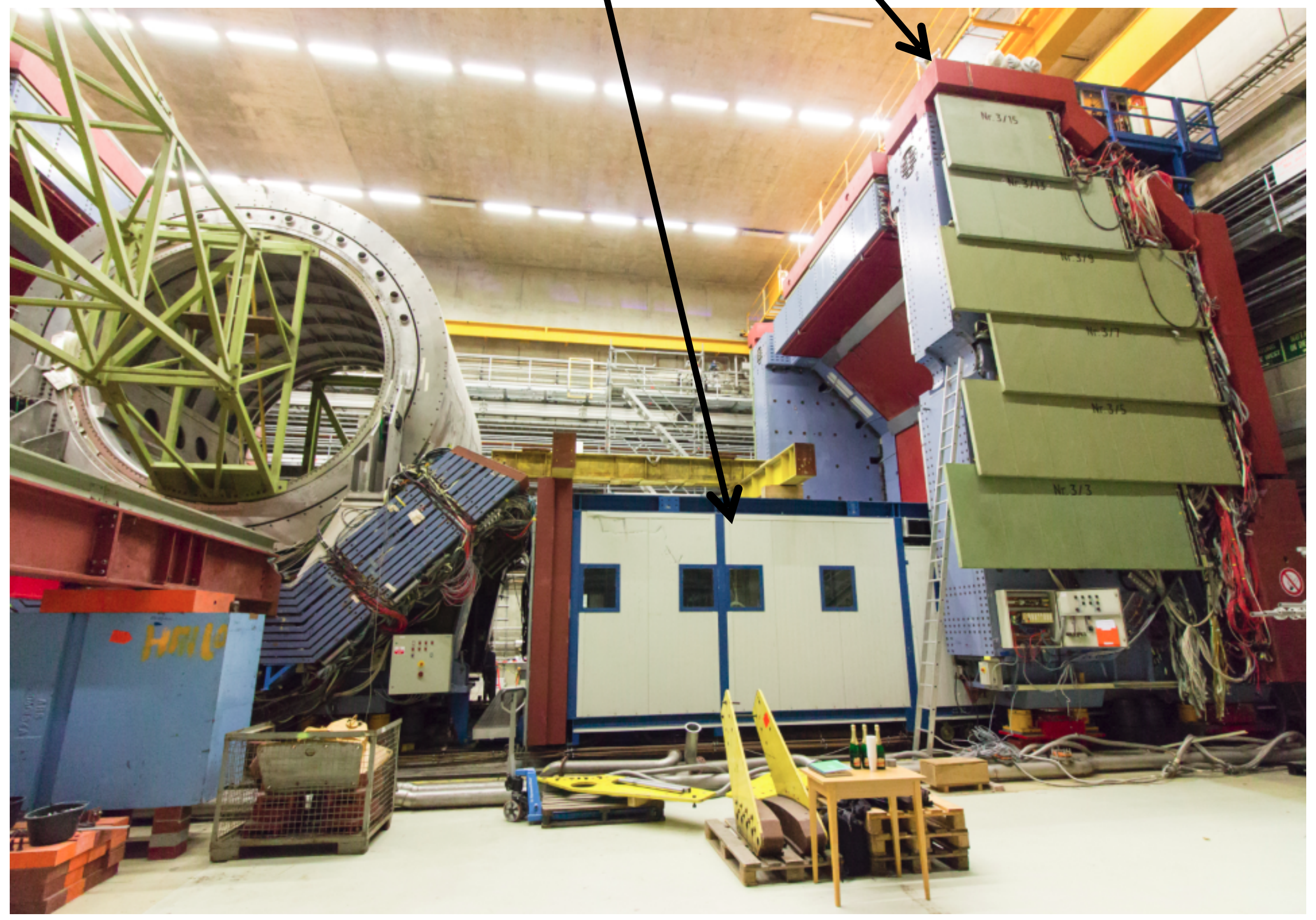
MADMAX Discovery site @DESY

DESY becoming an internation reference in axion searches:
- **ALPS II,**
- **IAXO (baby IAXO) > solar axions ...**
- **MADMAX !!**

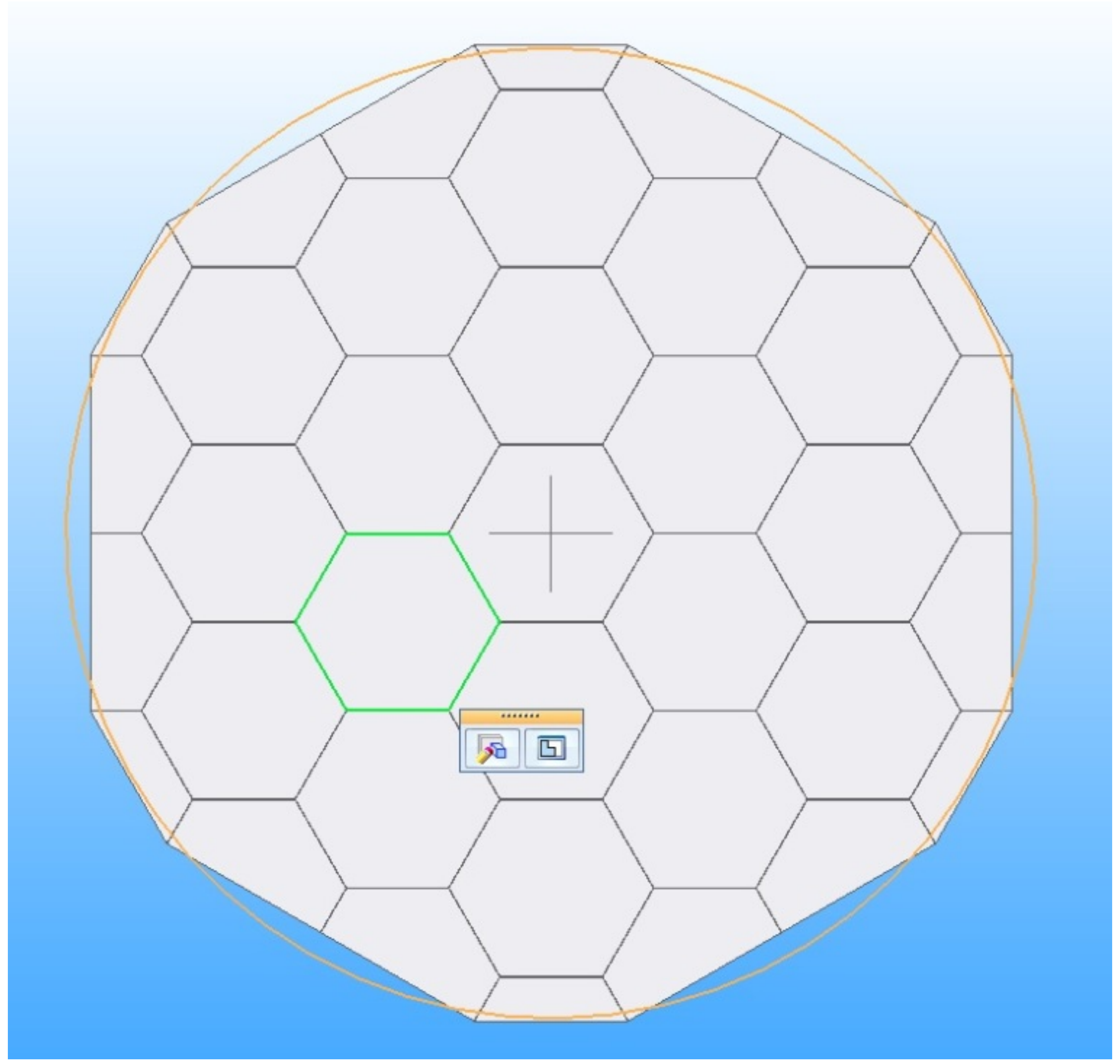
@ DESY HERA hall north

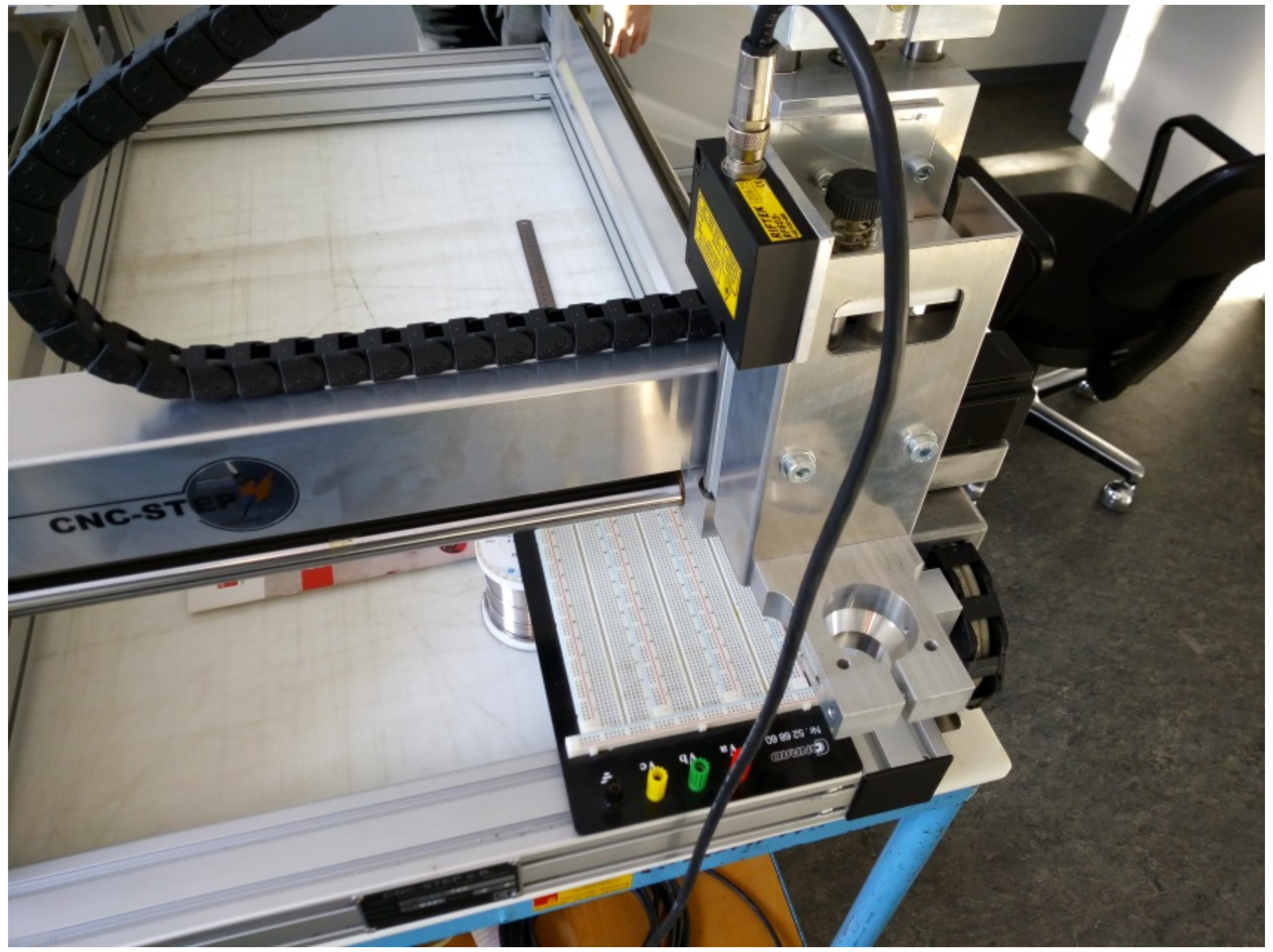


HERA yoke and control room available



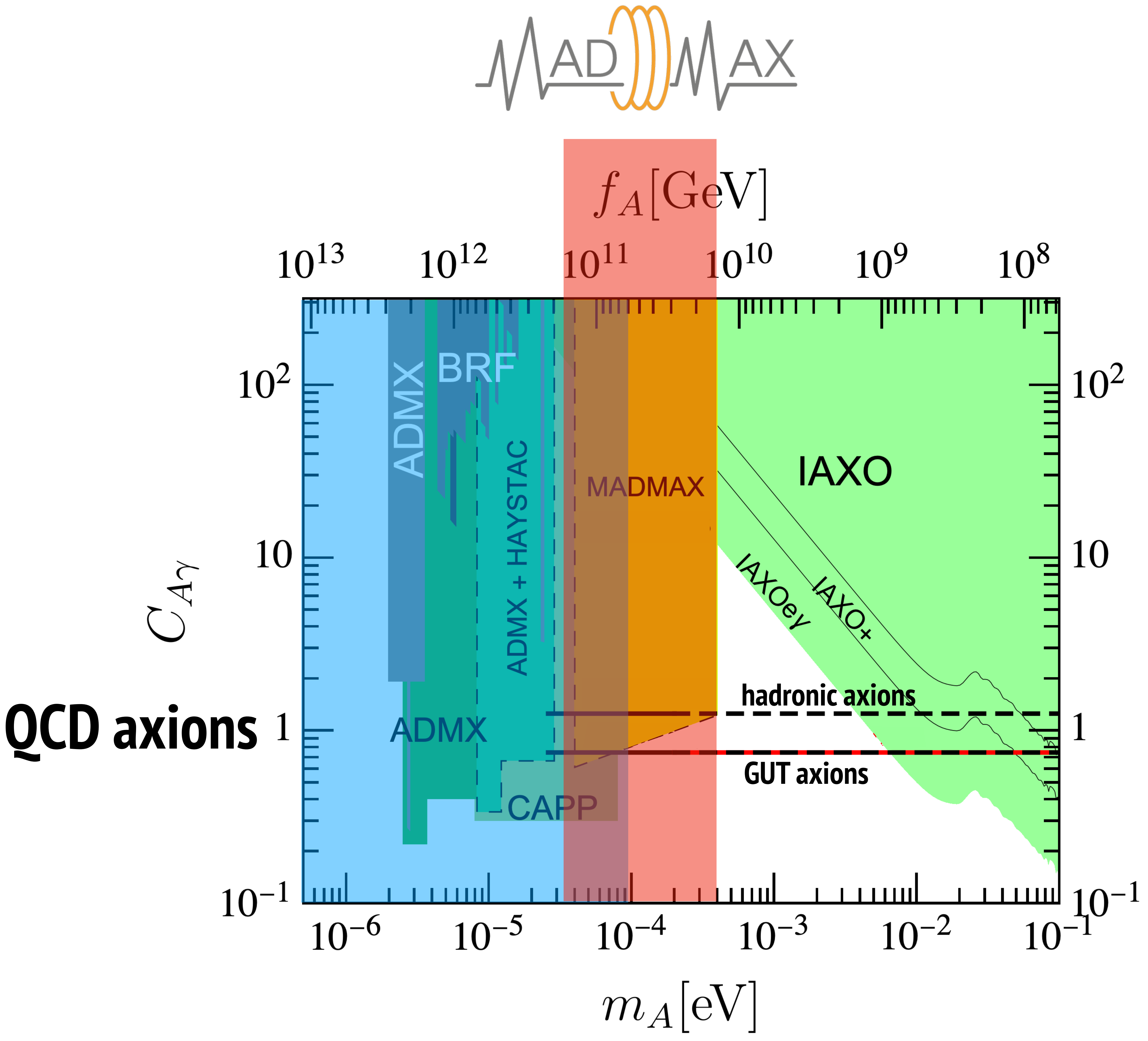
Discs with 1m² surface **→Tiling needed**
→Glueing
→Properties of glue?

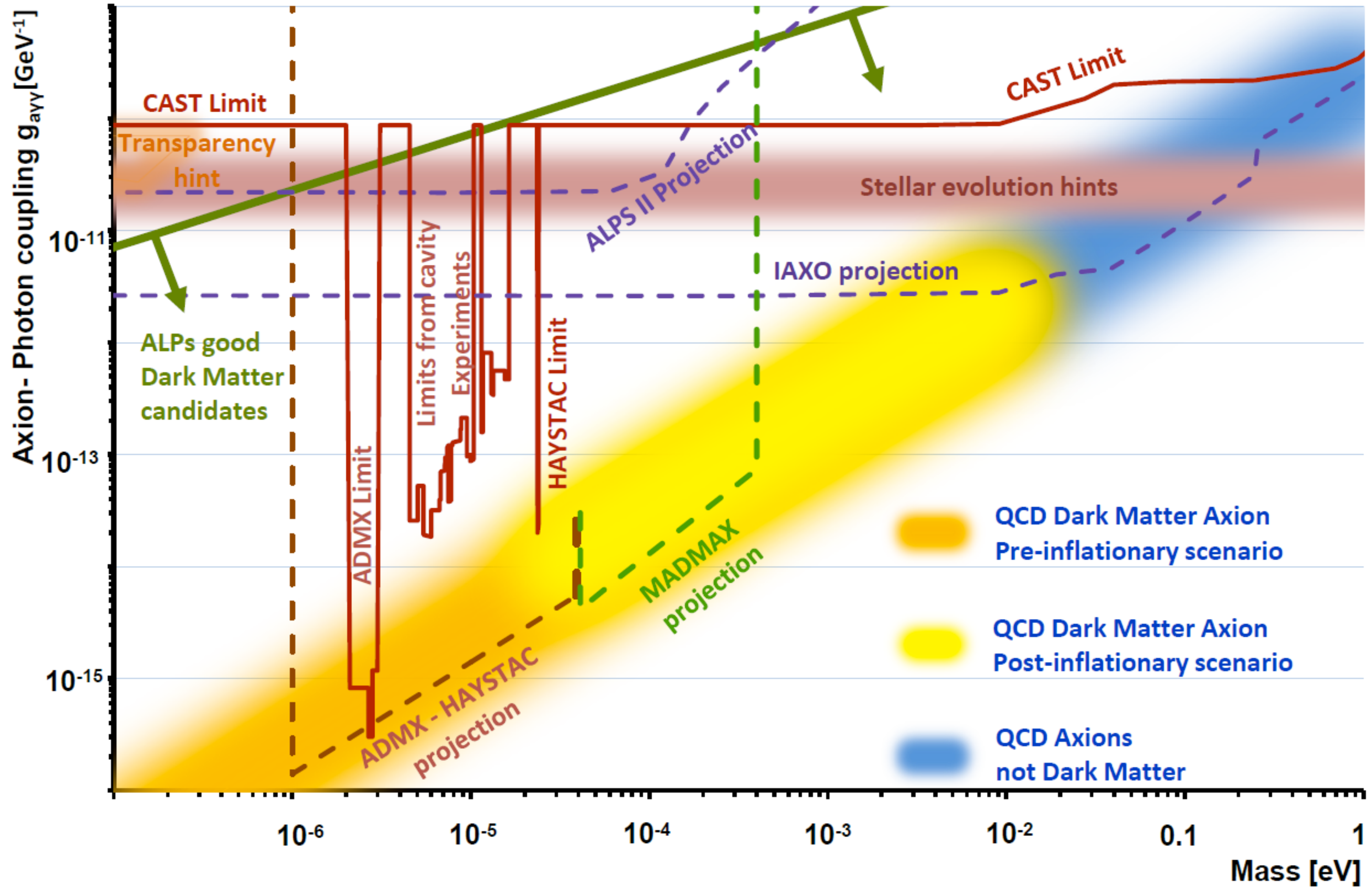




Bigger tiles are better!

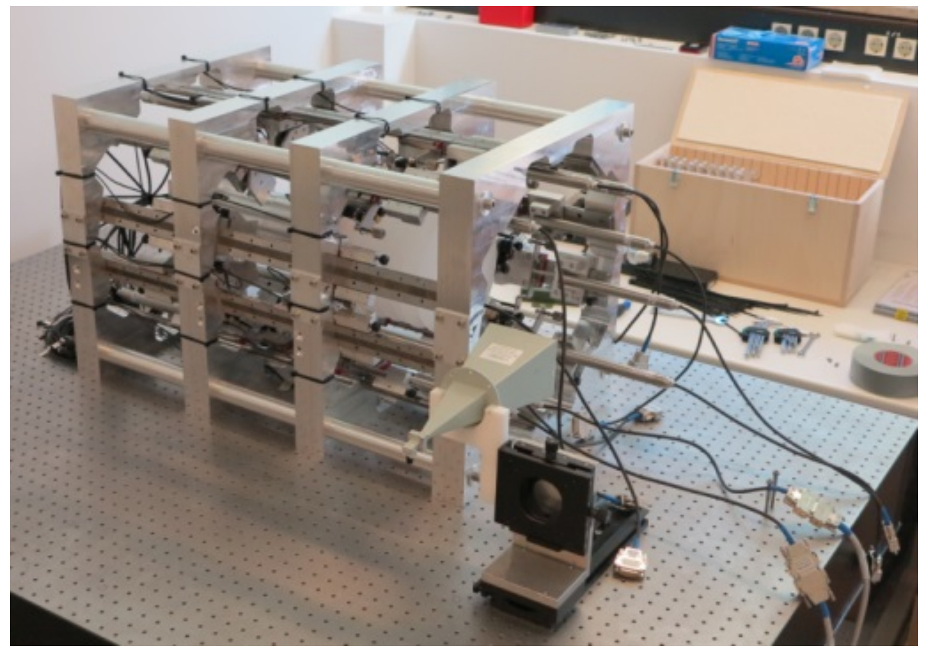
Sensitivity proyection



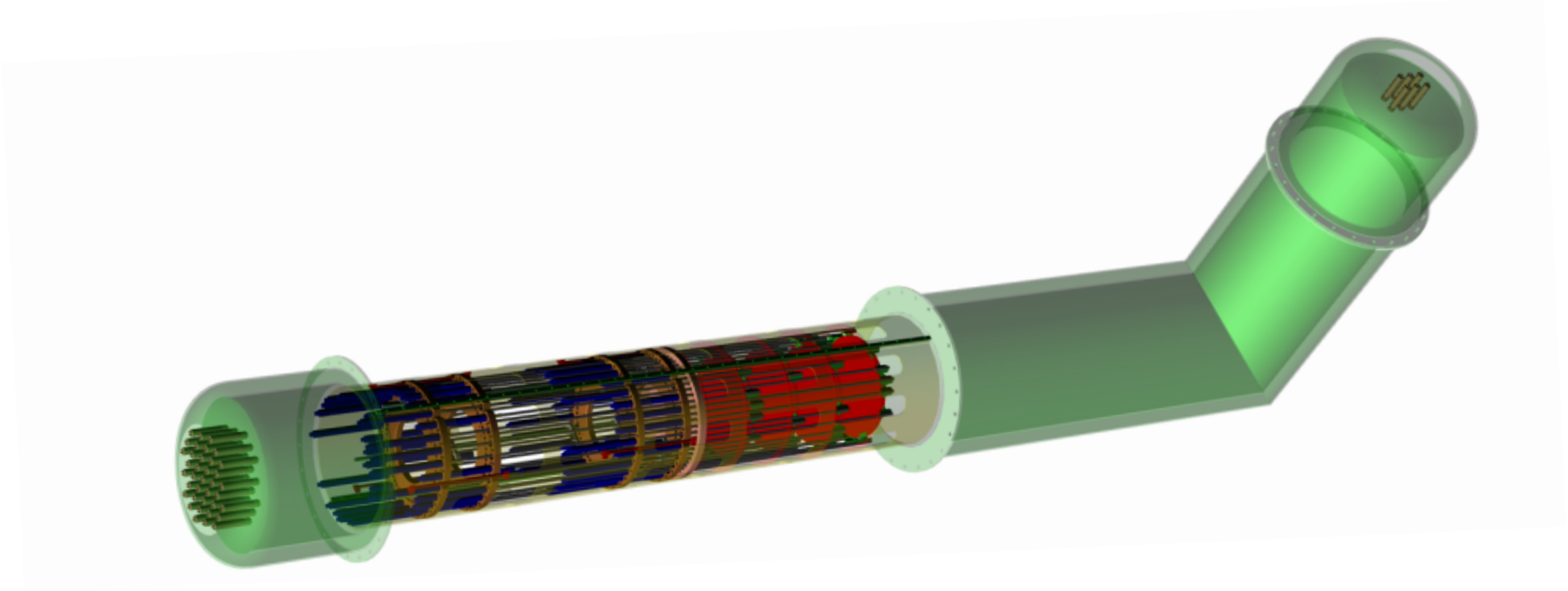


Aheads

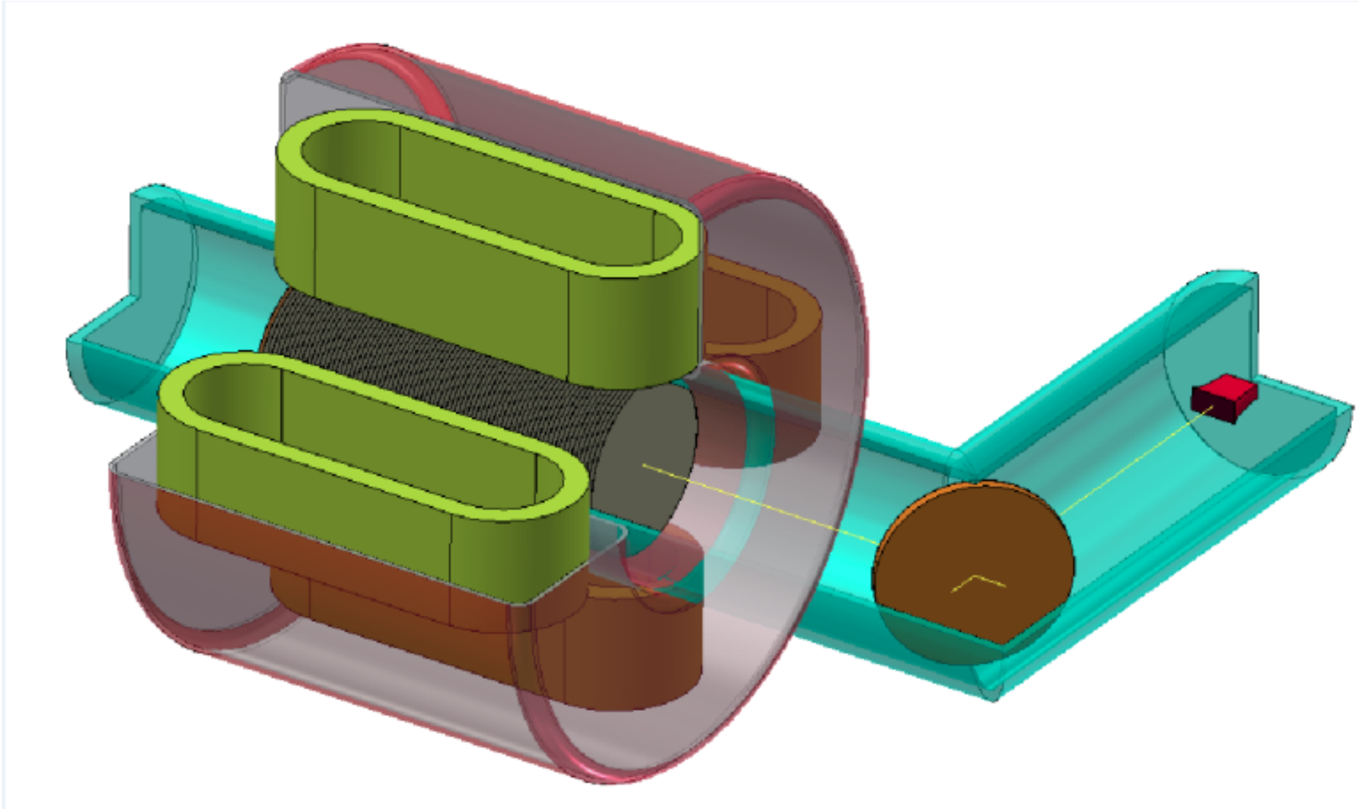
2018-2020
Finish Proof of principle phase, full understanding of 3D effects



2018-2022
Prototype magnet & booster Integration, first physics runs, search for ALPs and hidden photons



Afterwards:
Build final magnet
Build final booster
→ Start scanning 10-30GHz (40-120 μeV) range



Conclusion

- QCD axion hinted by Strong CP problem
- Axions and Axion-like particles fit very well BSM
- They are perfect cold-dark matter candidates

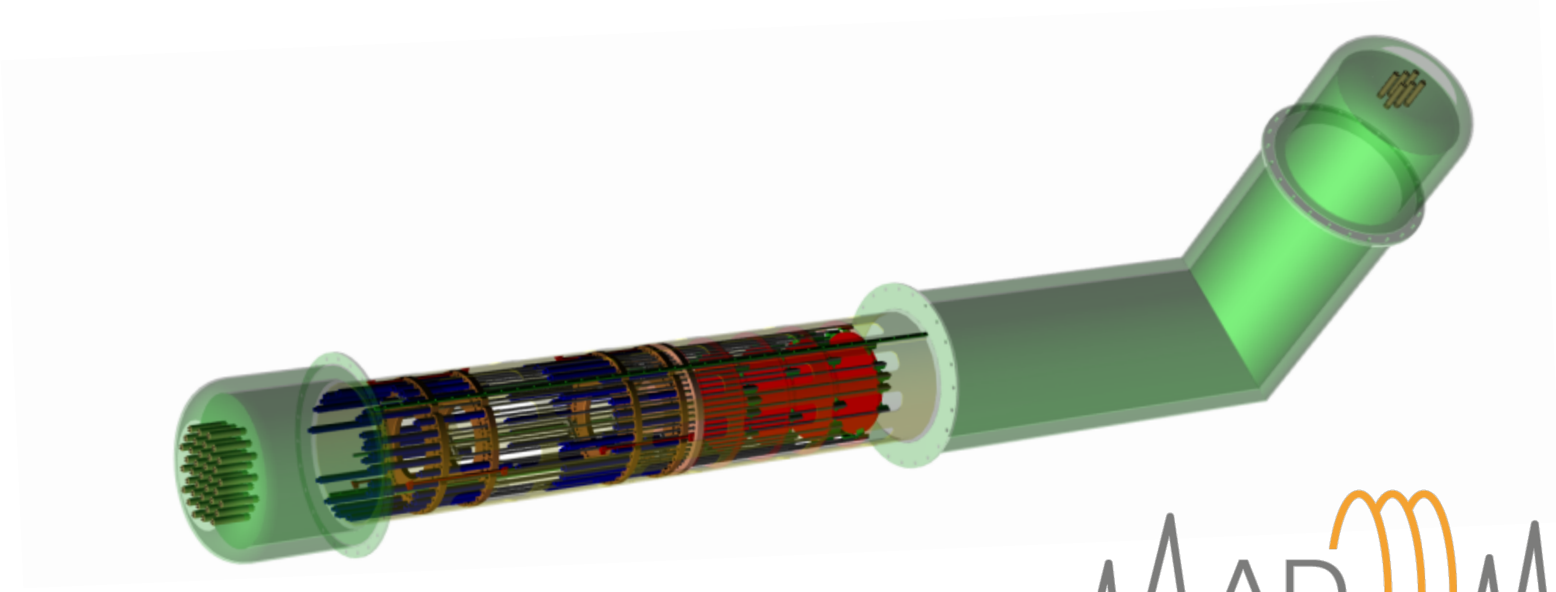
- postinflation scenario > predictive ~ 100 microeV
- preinflation scenario ... who knows!

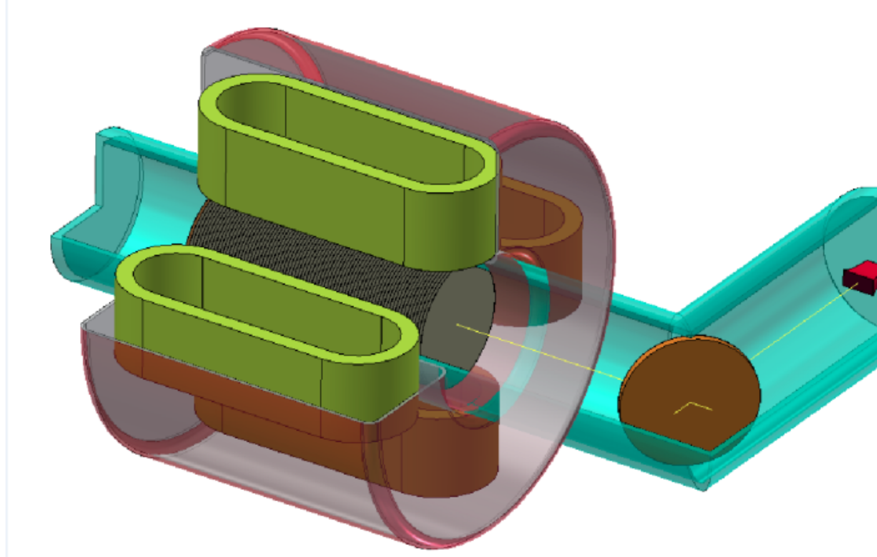
- Current cavity experiments optimal ~ microeV
- very hard at 100 times that frequency!

- MADMAX experiment: only experiment feasible and actively targeting that region

- Challenges:
  - Magnet never done before!
  - 1m^2 dielectric disks never done before!
  - tuning ~10 um 80 disks never done before!
  - Operating a QL

  - but no showstopper so far!





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