CERN

# Dark Matter and Axion Searches

Babette Döbrich

European Research Council
Established by the European Commission

## Disclaimer

- impossible to do justice to the title of the talk within 30 min when going at reasonable pace (provided clickable references)
- *biased selection mandatory* $\rightarrow$ choice of 'hot topics' along the 'low' DM mass scale from the sub-eV to MeV scale
- even presenting a selection only, not all I talk about is my expertise, tried to talk to experts as much as possible

(acknowledgements & thanks given after conclusions)

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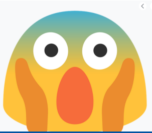
- impossible to prepare talk adapted to everyone's familiarity with the topic; compromise: try to assume little previous knowledge, but allow myself to not go into high-energy physics but dwell on topics *possibly* outside its comfort zone



not all quite 'HEP' (energy scales <eV etc)

## selection of DM landscape across mass scales (direct & indirect)

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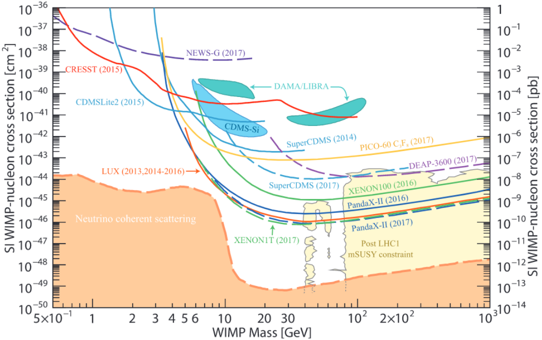
- **keV-MeV**: recent fast progress even at rather small exposures with electronic recoils and parasitic (or dedicated) detectors at (for example) fixed targets/beam dumps (advent of the hidden sector using high intensities)
- $<$**eV**: domain of (among else!) axions: research goes back many decades (notably ADMX) but currently many new contenders joining the field (loss of 'fear' of 'classical' particle physicists embarking on associated technologies, increase in funding possibilities (buzzword quantum....)), both haloscopes & searches by production/from sun

# “Lighter” Dark Matter (showing outdated plot on purpose)

Archeology: PDG plot in Chapter ‘Dark Matter’ 2018



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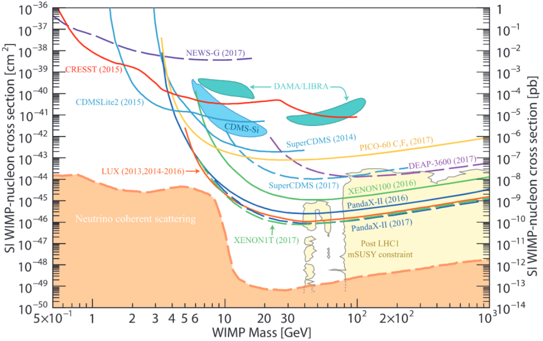


← low masses *poorly constrained* so far (but motivated, see e.g. link)

1) DD: energy below recoiling nucleus below energy threshold

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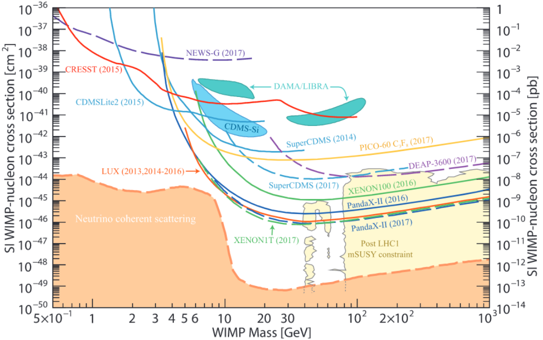


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1) DD: energy below recoiling nucleus below energy threshold

2) ultra-low masses: non-thermal DM: axions & dark photons

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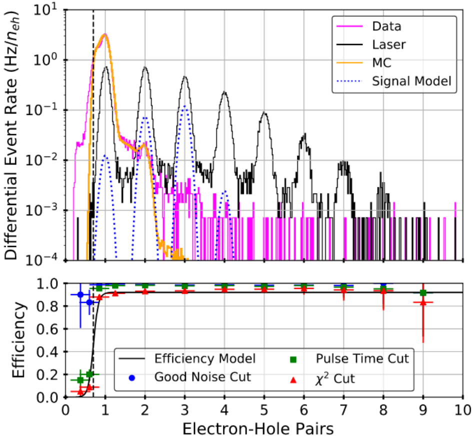
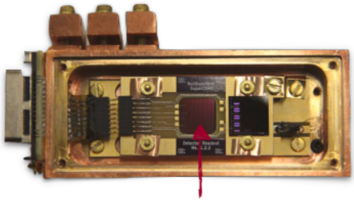
- for simplicity pick one example: (cryogenic) Silicon

# Si detector SuperCDMS HVeV

comments:
individual electron-hole pairs ('peaks') visible




Cabrera et al., Appl. Phys. Lett. 112, 043501 (2018)



Si chip (1cm² x 4mm, 0.93 g)
with phonon sensors

PRL 121,051301 (2018): 0.49 gram-days (newer result 2020 of 1.2 gram-days also available)

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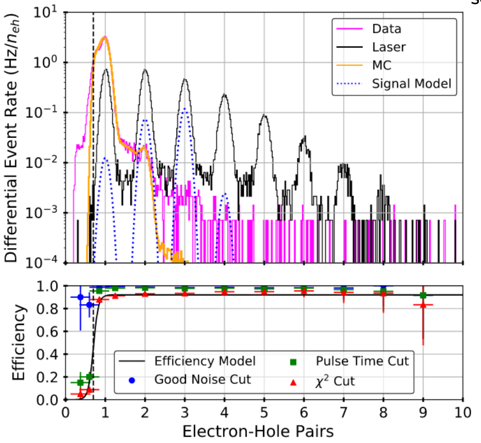


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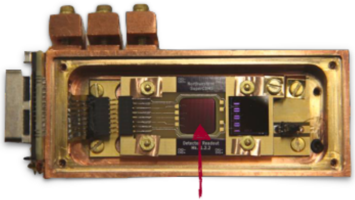

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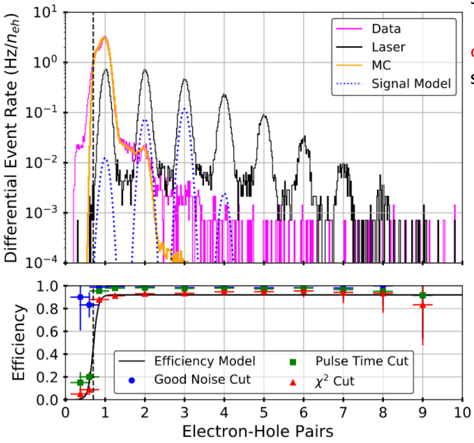


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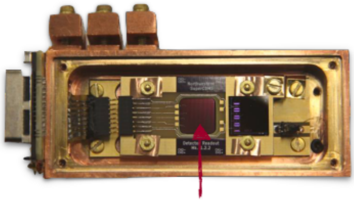
challenge: understanding background
see e.g. Barak et al (2021), Du et al (2021)
+ Excess workshop June 2021

Cabrera et al., Appl. Phys. Lett. 112, 043501 (2018)



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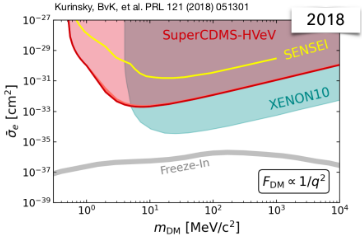
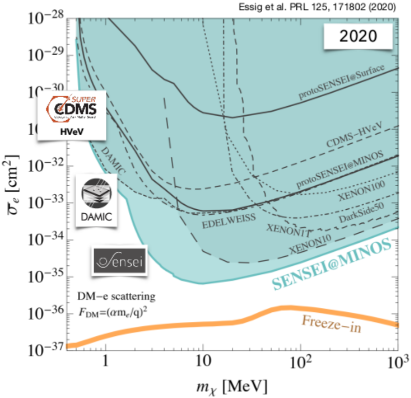
# A fast-developing field (background reduction and exposure as lever-arm)




1st SuperCDMS-HVeV Results
with ~ 0.5 g/day data



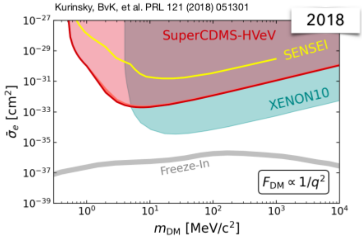

Belina von Krosigk Heraeus seminar, June 2021

# A fast-developing field (background reduction and exposure as lever-arm)

Take away message:

one couple of days of data-taking can gain orders of magnitude in sensitivity

see for example: Sensei 2018 (0.2 g-days) vs Sensei 2020 (48 g-days)

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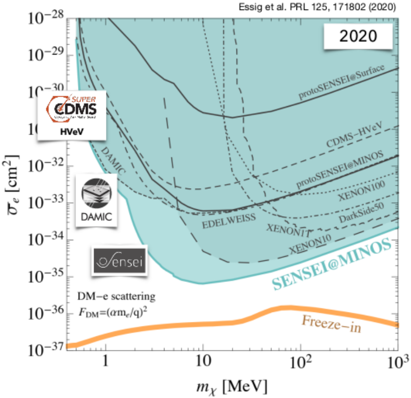


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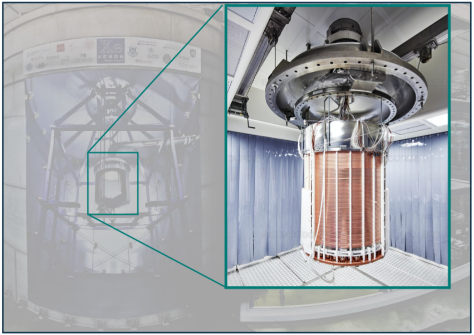
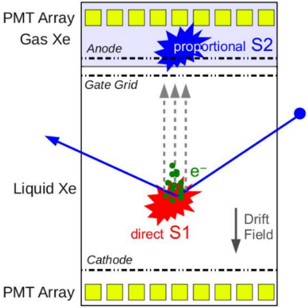
# Intermezzo: Do we have seen already a BSM $e^-$ recoil signal?


*Laboratori Nazionali del Gran Sasso*



search directly for GeV scale DM via nuclear recoil
in a Xenon TPC: XENON1T

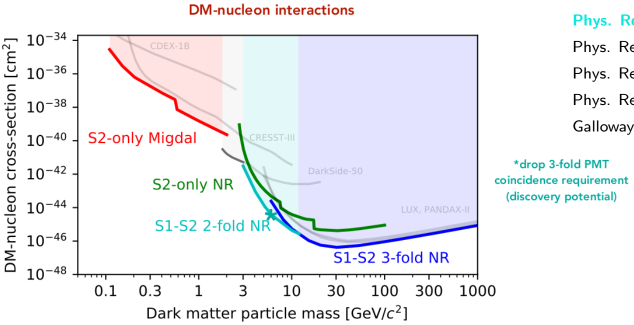
# Simplified working principle XENON1T




*taken from here*

*combining S1 (prompt light signal) & S2 (secondary light from drifted charges): information → position & energy*

# Status: XENON1T full reach DM-nucleon cross-section




**Phys. Rev. Lett. 126, 091301 (2021)**

Phys. Rev. Lett. 123, 241803 (2019)

Phys. Rev. Lett. 123, 251801 (2019)

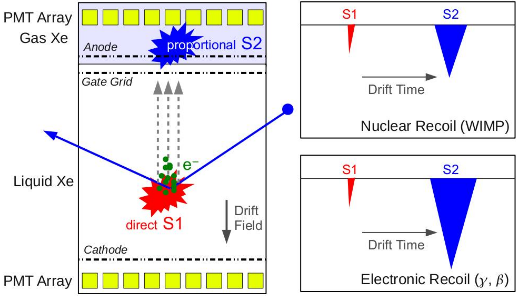
Phys. Rev. Lett. 121, 111302 (2018)

Galloway @Heraeus 2021

to realize: ratio S1/S2 different for electronic and nuclear recoils

**study of nuclear recoil is not the only option!**

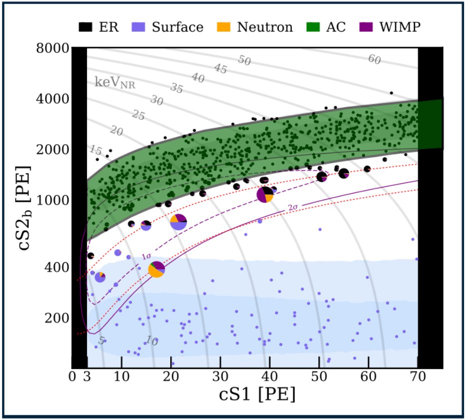
# Electronic & nuclear recoil in XENON1T




*taken from here*

*ratio S1/S2 completely different for electronic and nuclear recoils*

# S1/S2 events cf Phys. Rev. Lett. 121, 111302



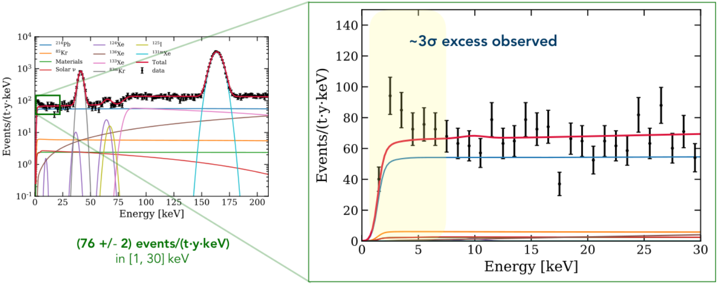

*ER band 'busier' than NR band but still amazingly little occupancy!*

**Electronic Recoils (ER)**

(gammas, betas, light DM)

**< 100 events/(t/yr/keV$_{ee}$)**

# The plot that kept phenomenologists busy in home office in 2020




**Excess between 1-7 keV**
**285** events observed
vs.
**232** events expected (from best-fit)

*excess reported first June 2020: Phys. Rev. D 102, 072004, published in Oct 2020*

*(Updates added on Ar37 discussion, tritium estimation, solar axion energy spectrum)*

## So what is causing the excess?

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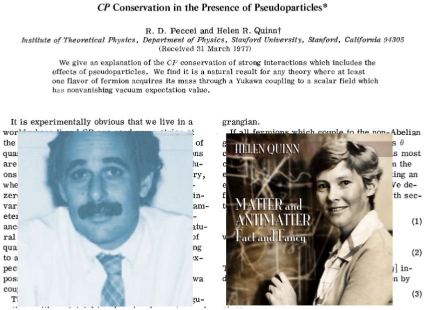
- in the meanwhile: let's talk about axions!

# The Axion was not invented to be the Dark Matter!



*CP* Conservation in the Presence of Pseudoparticles*

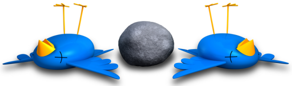
R. D. Peccei and Helen R. Quinn†
*Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305*
(Received 31 March 1977)

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 we live in a ...

grangian.
If all fermions which couple to the non-Abelian ...

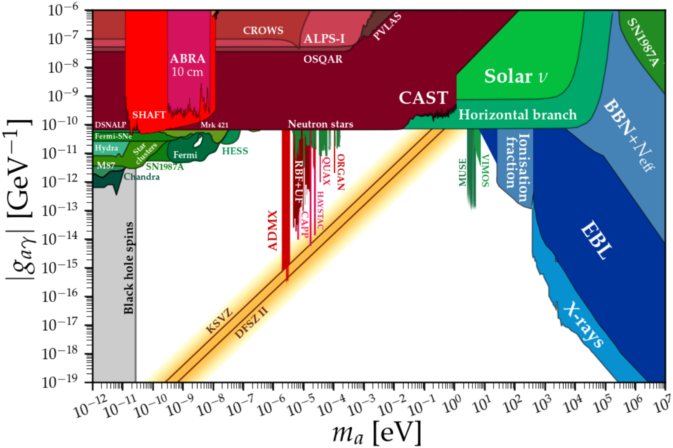




but Axions (or more generally axion-like particles (ALPs)) which must be extremely weakly interacting can be the Dark Matter or a portal to it!

# Present and future hide-outs of (low-mass) axions

limit compilation by C O'Hare `https://github.com/cajohare/AxionLimits`




QCD axion lives on yellow line
an ALP almost anywhere.

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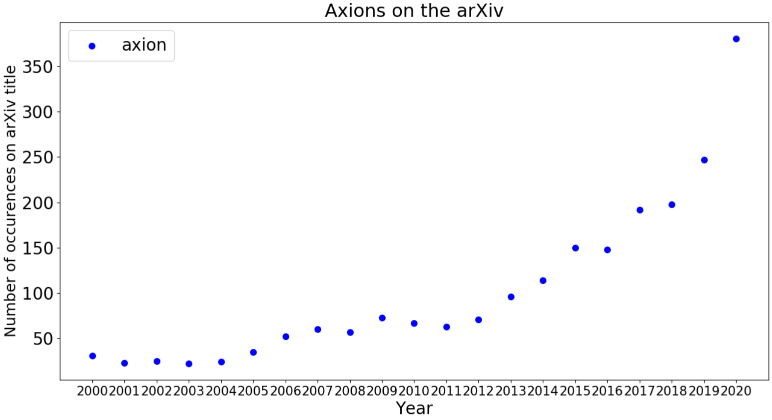

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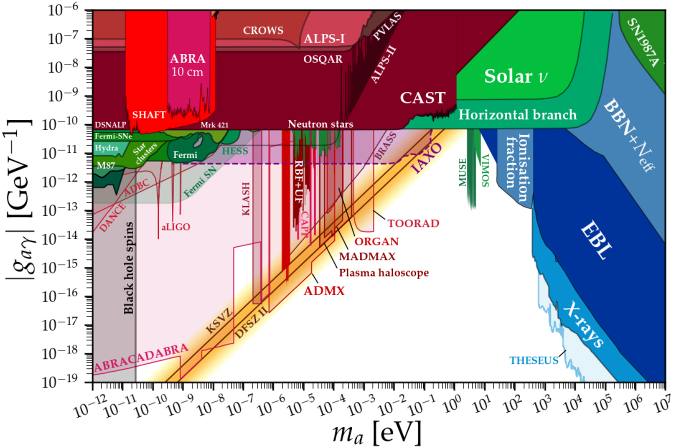


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Projections!!! with

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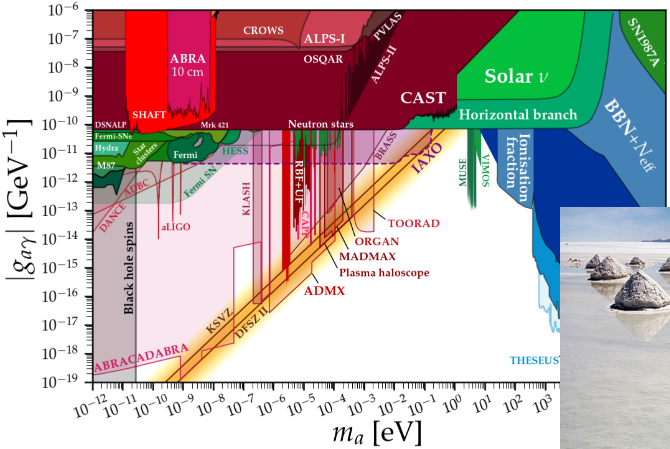


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Projections!!! with
more than a grain of salt

Luca Galuzzi via Wikimedia Commons

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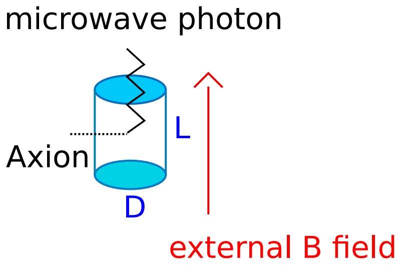
types typically different in ability to probe vast mass-/coupling- scales:

$\rightarrow$ direct cavity Dark Matter search: typically 'needle-like' relies on resonant conversion in a narrow resonance

## A poor (wo-)man's axion haloscope




- figure of merit: $F \sim g^4 m^2 B^4 V^2 T_{\mathrm{sys}}^{-2} \mathcal{G}^4 Q$
- typically high-field solenoids, several Tesla
- typically few-/sub- Kelvin
- scanning: tune in steps $\sim$ size of axion width
- resonance quality $Q$ worth to push up to $\sim 10^6$
- design requirement $\mathcal{G}$: cavity modes: right direction/ well spaced/ correctly coupled

# Pioneers & 'old hands' - ADMX

2020 Bartram et al: Axion Dark Matter eXperiment: Run 1B Analysis

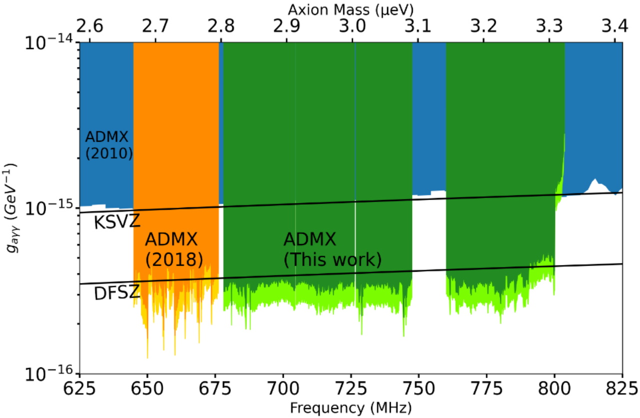



FIG. 17. Exclusion plot for Run 1B, shown in green. Dark green represents the region excluded using a standard Maxwell-Boltzmann filter, whereas light green represents the region excluded by an N-body filter [42].

# Pioneers & ‘old hands’ - ADMX

2021 June preliminary: T.Nitta@Patras workshop and here at EPS

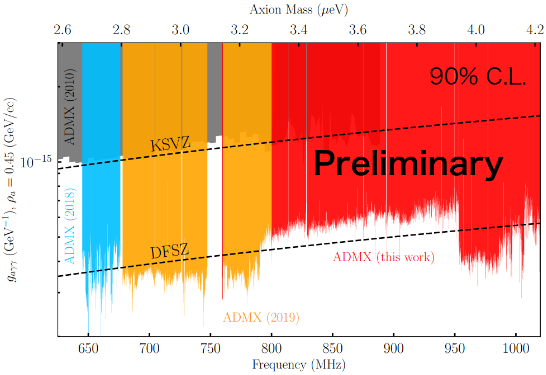
Sensitivity:

**KSVZ axions**

800 – 1020 MHz

**DFSZ axions**

~ 970 MHz



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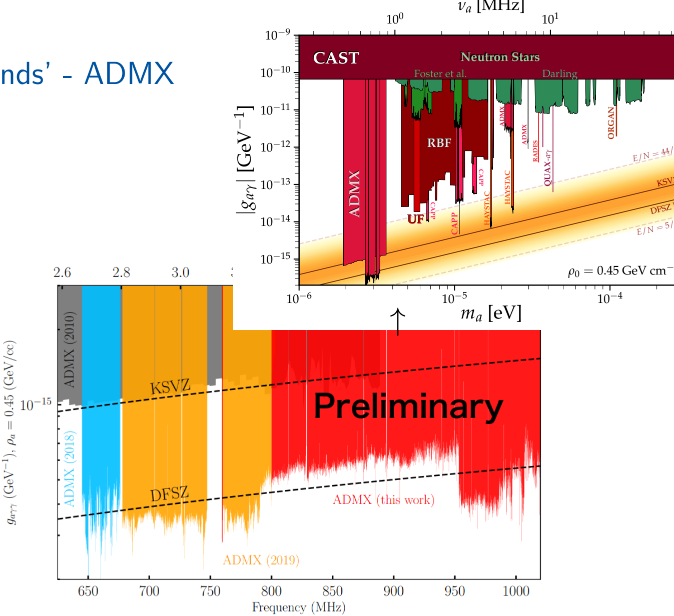
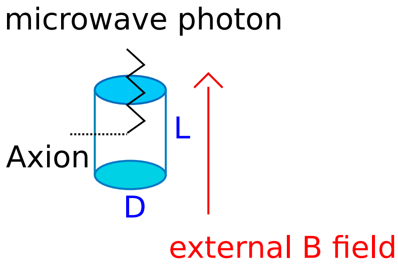
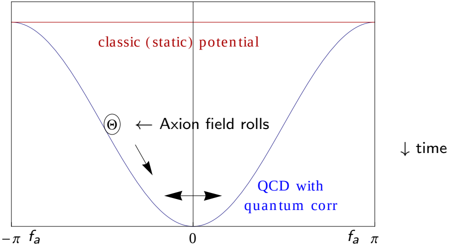


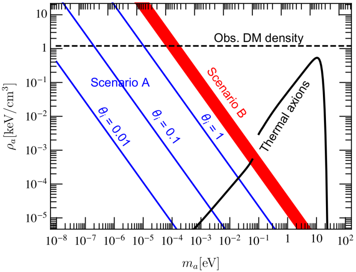
## Interlude: Why large masses are harder to test



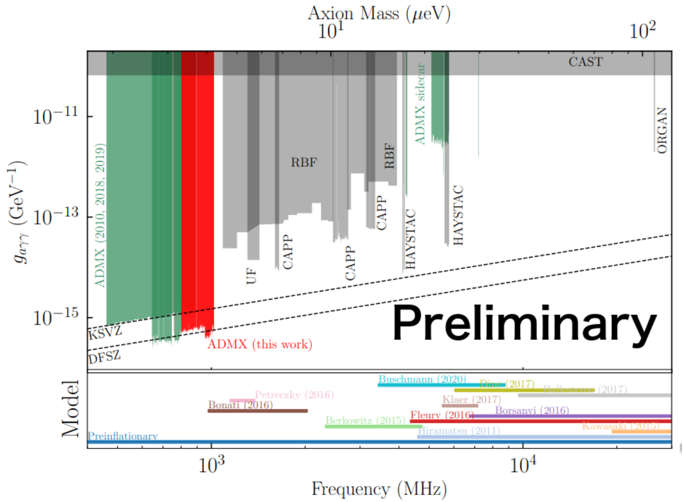

- figure of merit: $F \sim g^4 m^2 B^4 V^2 T_{\mathrm{sys}}^{-2} \mathcal{G}^4 Q$
- naively: large $m \rightarrow$ higher resonance $f \rightarrow$ lower dimension
- $Q \sim \frac{V}{\delta S}$ Volume to surface ratio: gets bad at low Volumes

# Interlude: Why large masses are interesting to test




- axion mass depends on initial misalignment angle & inversely proportional to symmetry breaking scale
- **"large"** axion masses test the 'post-inflationary' axion, in which the axion mass can be more "easily" predicted (average of possible initial conditions, whereas otherwise one unknown initial condition stretched by inflation)
- scenario B: *m* prediction somewhat possible




T.Nitta@Patras workshop

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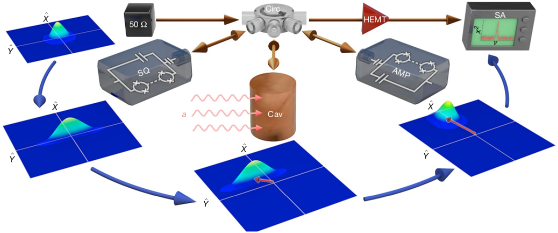
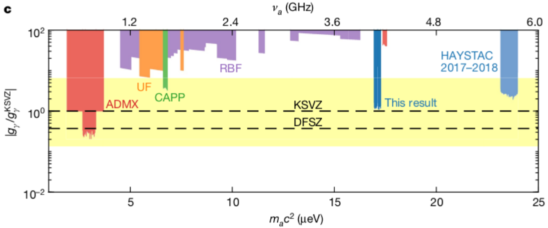
# Progress at large m: going ‘beyond’ quantum uncertainty



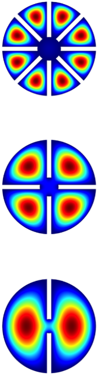

Bakes et al. Nature volume 590, pages 238–242(2021)

# That's not all...

large $m$: **segmented**/sc cav. (CAPP, RADES), higher $B$ (CAPP), ultralow $T$ (LNF, CAPP)...


← RADES

JHEP sub 2021



CAPP, Phys.Rev.Lett. 125 (2020)

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large $m$: **segmented**/sc cav. (CAPP, RADES), higher $B$ (CAPP), ultralow $T$ (LNF, CAPP)...
see also talk by C. Gatti on QUAX this morning

## Summary

- provided you with a biased selection of ‘hot’ cold Dark Matter topics: electron recoil and axion searches
- coming year should give clarity on XENON1T $e^-$ recoil excess through statistics
- axion searches become much more widespread $\rightarrow$ fast-pace can be expected

# Summary

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- thank you for your attention. feel free to get in touch with me for further discussions/feedback: cern.ch/bdobrich

# Acknowledgements

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- **Felix Kahlhoefer, Tien-Tien Yu** (Pheno)
- **Marc Schumann** (XENON)
- **Belina von Krosigk** (SuperCDMS)

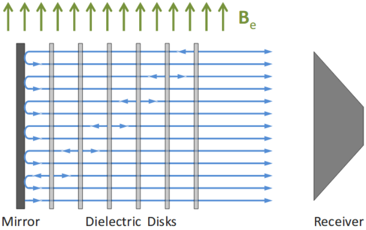
other resources:

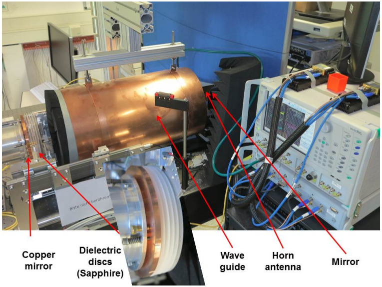
- 2104.07634: Direct Detection of Dark Matter – APPEC Committee Report
- talks presented at Heraeus Light Dark matter Seminar, June 2021
- talks presented at Patras workshop June 2021

# Backup

## The biggest european contender - MADMAX

- constructively combine axion emission at dielectric surface by choice of plate separation → allows to probe 'large' axion DM mass
- amongst challenges: 9T dipole with 1.35m bore



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