Direct searches for Dark Matter with DarkSide and MadMax experiments

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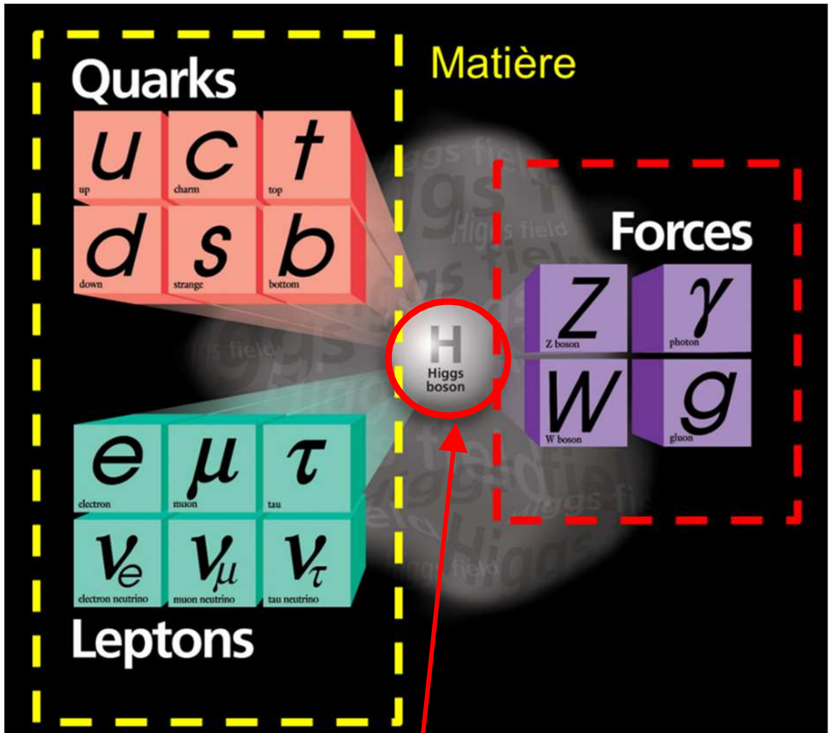
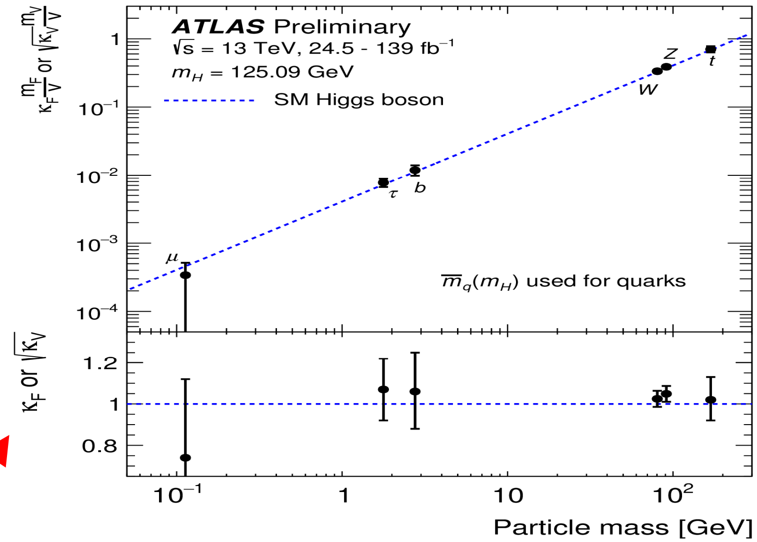
1- Scientific context
2- Scientific opportunities for WIMP and axion searches
3- Technical opportunities and first achievements at CPPM
4- Conclusions and perspectives

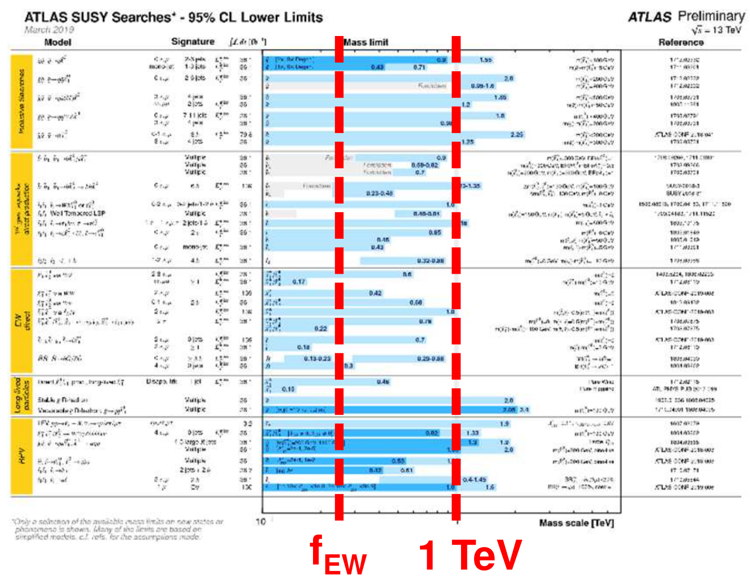
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

Introduction (1/6)

❑ After LHC runs 1 and 2, Standard Model is stronger than ever…



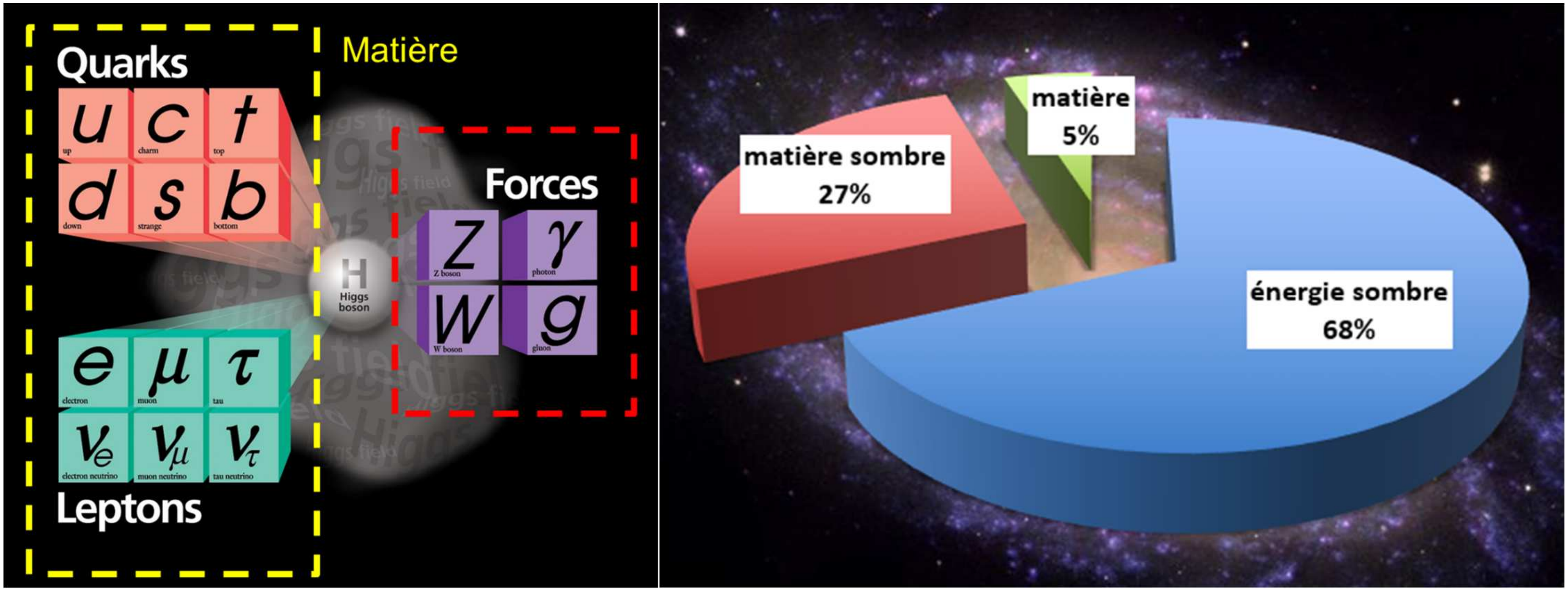




- ➢ Higgs discovery
- ➢ Precision measurements in all sectors
- ➢ Direct searches → no sign of New Physics so far up to TeV scale

Introduction (2/6)

❑ … but only describes ~5% of the Universe content



➔ Dark Matter = puzzle of fundamental physics … that calls for new physics

[together with Dark Energy nature, matter-antimatter asymmetry, …]

Introduction (3/6)

❑ **In XX^th^ century, lots of problems solved by postulating a new particle**

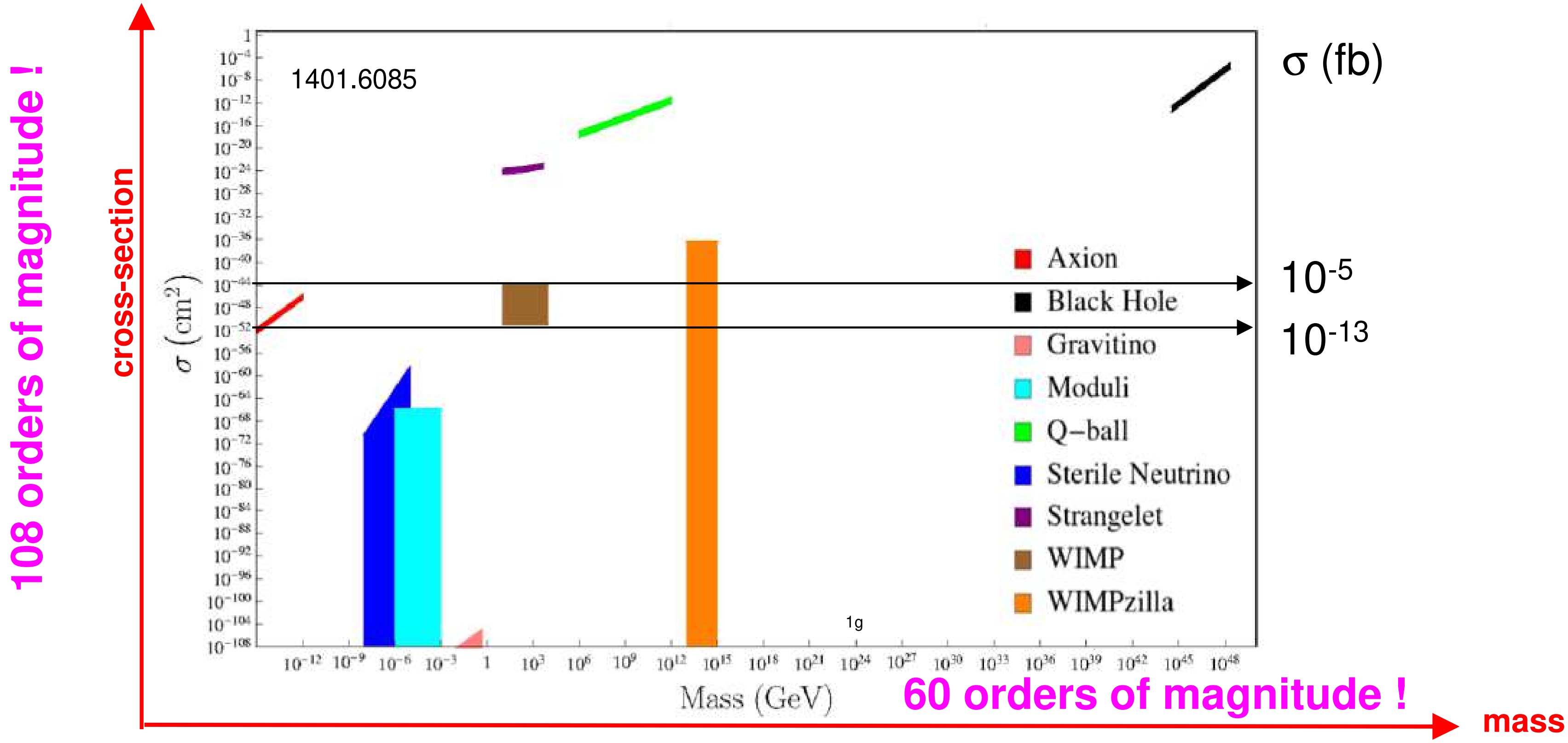
– QM and Special Relativity:	Antimatter
– Nuclear spectra:	Neutron
– Continuous spectrum in β decay:	Neutrino
– Nucleon-nucleon interactions:	Pion
– Absence of lepton number violation:	Second neutrino
– Flavour SU(3):	Ω^-
– Flavour SU(3):	Quarks
– FCNC:	Charm
– CP violation:	Third generation
– Strong dynamics:	Gluons
– Weak interactions:	$W^\pm$, Z^0
– Renormalizability:	H

Courtesy of J. Ellis

Introduction (4/6)

❑ In XXIth century, many dark matter candidates in a gigantic phase space

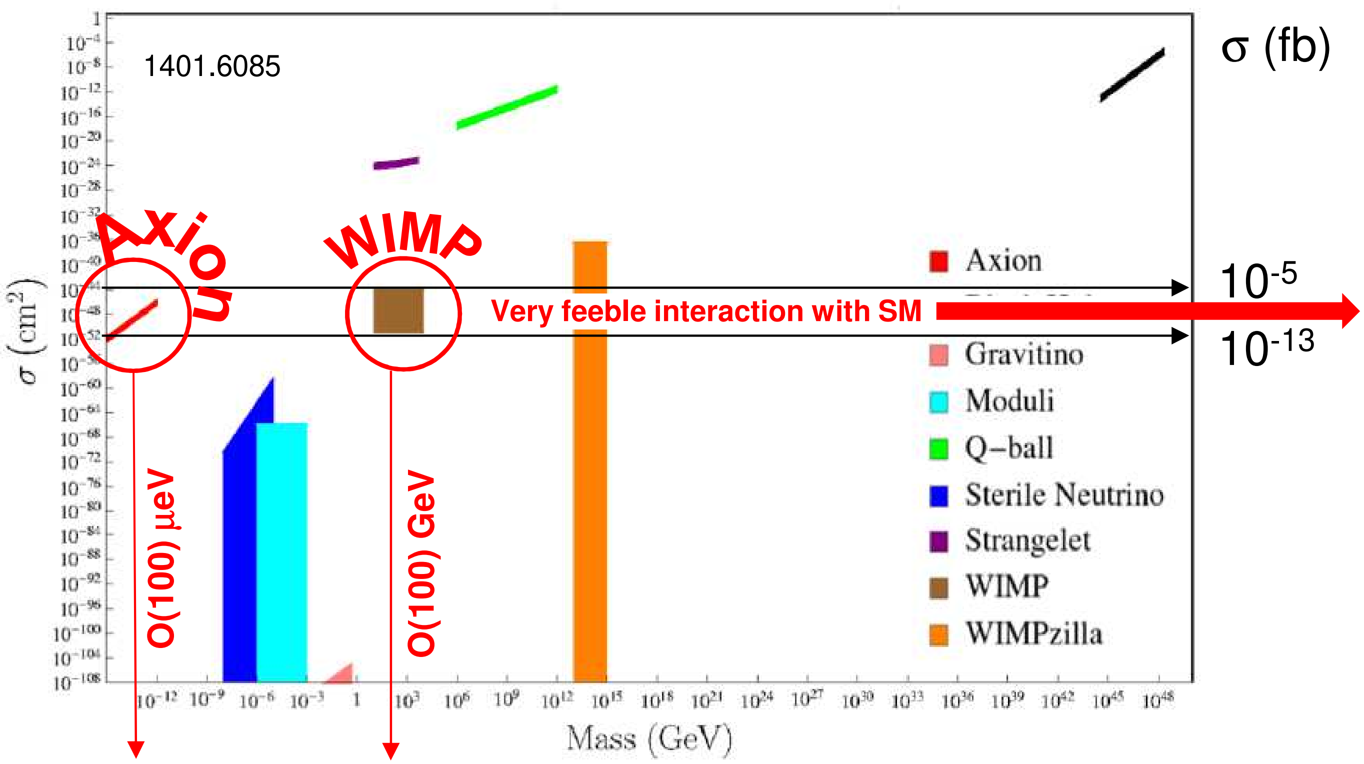
- No known particle within the SM of particle physics has the required properties to be DM
  → all candidates (new **stable** particle) come from Beyond SM theories…[except primordial black holes]



- …but only a few of them are **also strongly motivated by particle physics**, i.e. solving current theoretical SM problems → **WIMP** *(hierarchy pb)*, **Axion** *(~no CP violation in strong interaction)*
  [lightest sterile N (neutrino masses and mixing), but only indirect search through X-ray emission line N→νγ, $E_\gamma = m_N/2$]

Introduction (5/6)

❑ Many dark matter candidates in a gigantic phase space



… balanced by abundance of DM particles* stream from our galaxy halo → O(0.1) GeV/cm^3 moving at v=10^{-3}c wrt earth

*produced in very early Universe

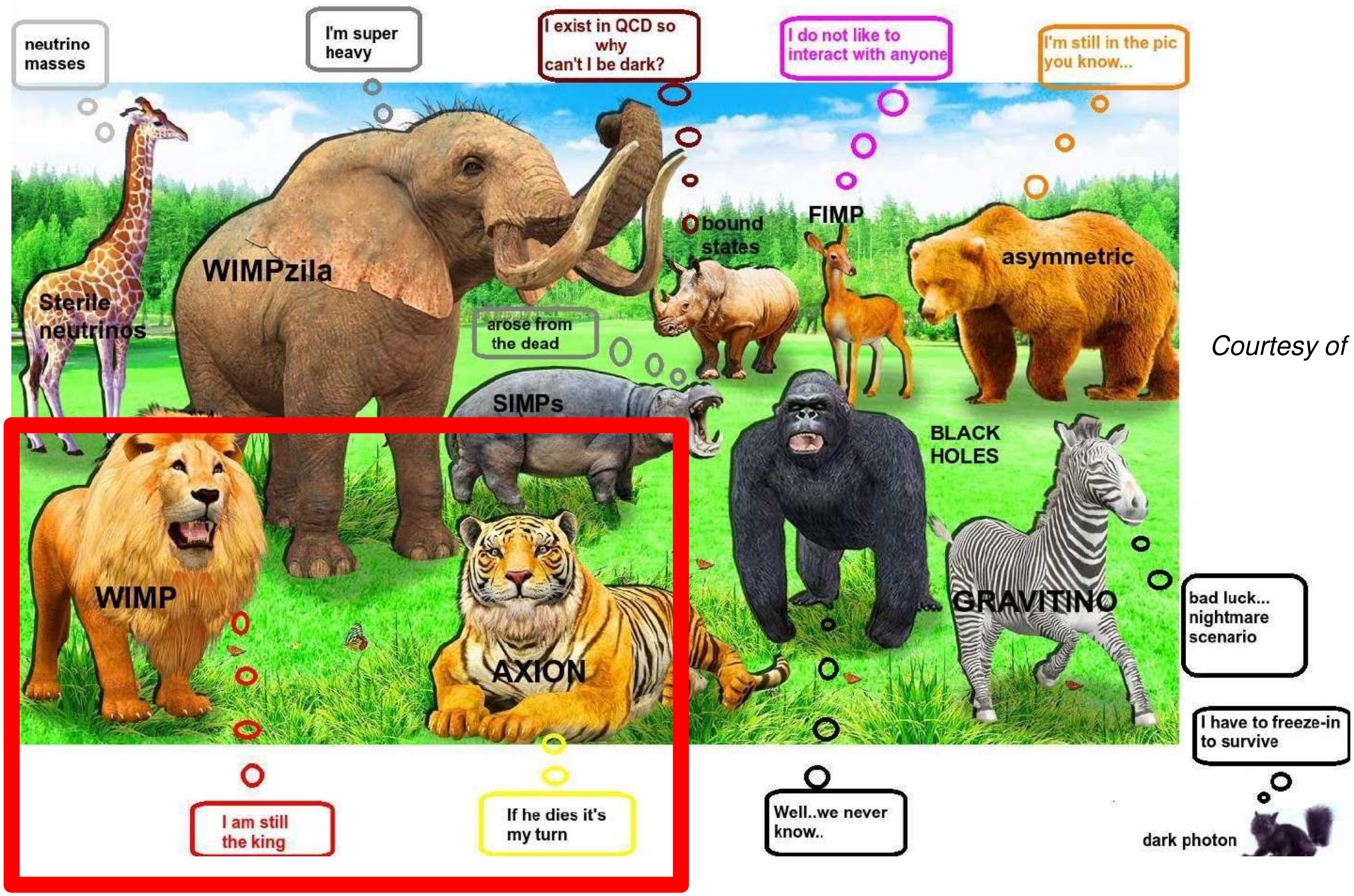
- O(10^{12})/cm^3 ~ gaz → High occupancy
- Tiny mass & interaction → **Very feeble signal**

Challenge: Boost the signal

- O(10^{-3})/cm^3 → **Low occupancy**
- High mass → visible signal

Challenge: High detection volume (low background)

Introduction (6/6)



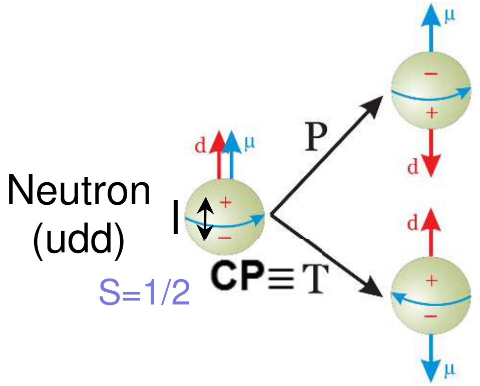
Courtesy of F. Queiroz

Status/prospects of **direct searches** for best motivated candidates (**WIMP** and **axion)**

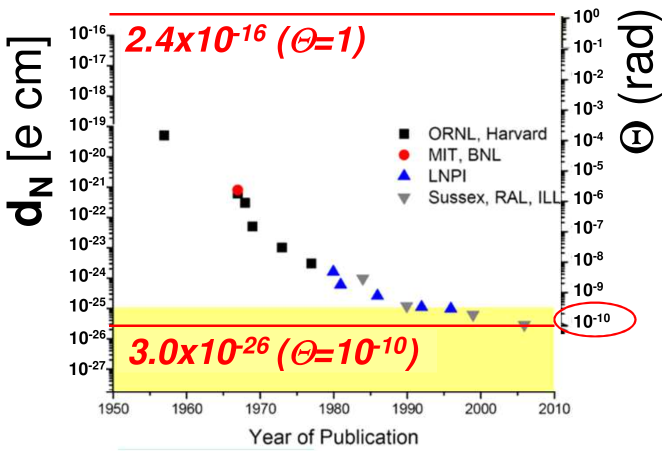
Axion (1/5)

❑ (Short) Theoretical motivations

- Studies of C, P, T symmetries in particle physics : major subject since >60 years
- CP violation in weak interaction: observed in 1964 in the kaon system
  - ✓ CP violation appears via complex phases in fermion mass matrices
  - ➔ δ_{13} ~ **1.2 rad in CKM**. To be measured in PMNS (DUNE, T2K)
- CP violation in strong interaction ?
  - ✓ CP-violating term in QCD Lagrangian (controlled by Θ) **is allowed and should exist**
  - ✓ … but Θ **< 10^{-10}** from neutron electric dipole moment



- Electric dipole moment: $d_N = e \cdot l$
- If strong CP : $d_N \sim \Theta \times 10^{-16}$ e·cm
- Experimental results today:
  → $d_N < 3 \times 10^{-26}$ e·cm → $\Theta < 10^{-10}$



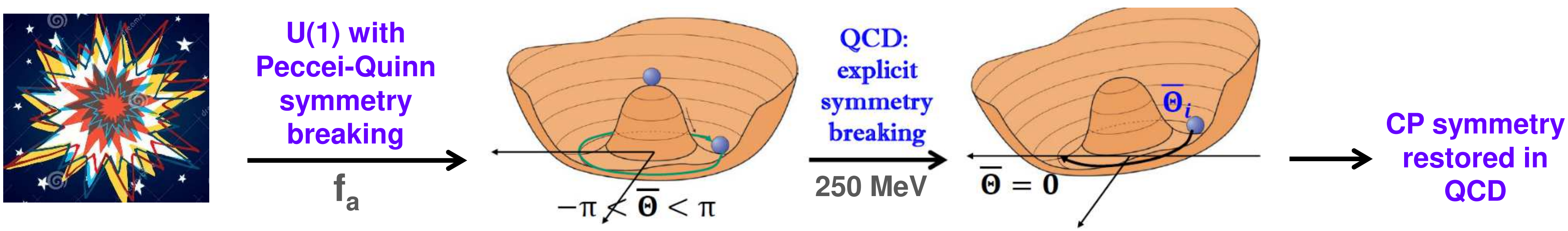
➔ Strong CP Problem = naturalness problem. Why is Θ so small ?

Axion (2/5)

❑ Solution to Strong CP problem

- Mechanism: new global U(1) symmetry *(Peccei-Quinn, 1977)* spont. broken at scale $f_a >> f_{EW}$
  - ➔ Makes Θ a dynamical field ($\Theta = a/f_a$) with a = pseudo-goldstone boson= axion *(Weinberg-Wilczek, 1978)*
  - ➔ Cancels CP-violating term in the Lagrangian ($\Theta_{eff} \rightarrow \Theta - a/f_a$) : explains absence of CP strong

- Cosmology: Non-thermal axion production at $T \sim f_a$ *(can occur before or after inflation)*



- Axion = pseudo-scalar boson with very small mass (i.e. ~stable)
  - ➔ Properties are all known given the scale of symmetry breaking f_a [mass $\mathbf{m_a} \approx m_\pi f_\pi / \mathbf{f_a}$ << eV]
  - ➔ Couplings to SM particles suppressed by f_a : very weak interaction with SM

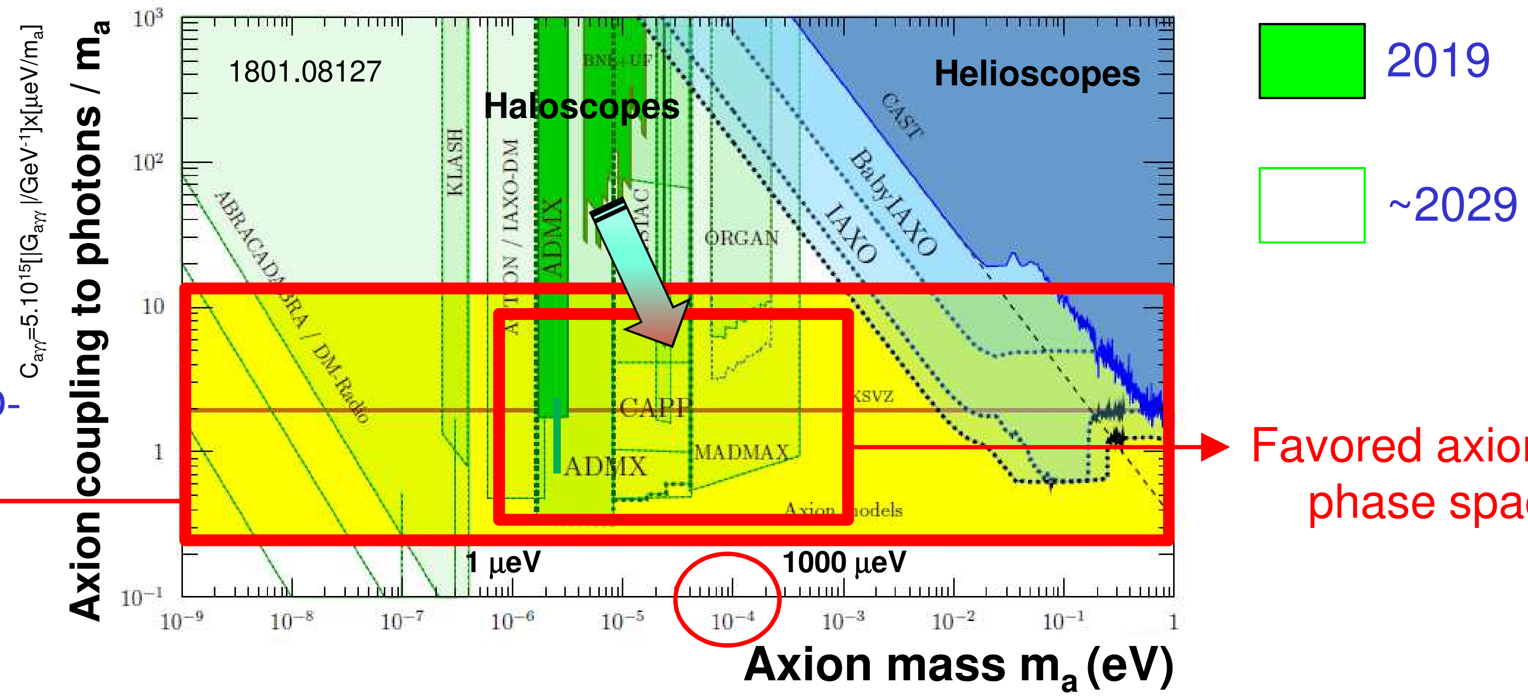
➔ Axion = natural candidate for DM for m_a=1-10^3 μeV *(i.e. $f_a = 10^{12}$ - 10^9 GeV >> f_{EW})*

Axion (3/5)

❑ Status and prospects for direct searches

- Extremely challenging because of extraordinary weak coupling of axions [muucchh lower than neutrinos]

Yellow band: QCD-axion, i.e. **solving strong CP** pb



Favored axion DM phase space

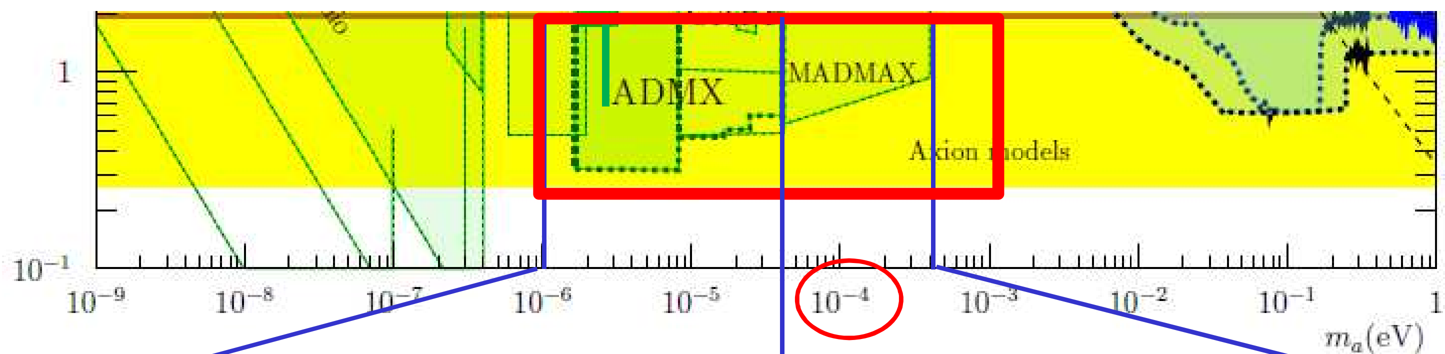
- Only 1 experiment (ADMX) currently probe a (very small) part of the interesting phase space
- Vast R&D program to improve signal sensitivity and expand range of axion mass search

➔ Next decade will be decisive, probing axion most favorable region

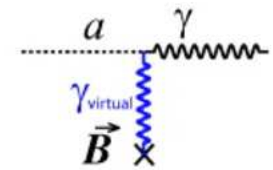
Axion (4/5)

❑ Main challenges for direct searches

- Convert axions into photons *[E field of O(10^{-12}. $\frac{B}{10\,T}$) V/m]* ➔ high magnetic field >> 1T
- Boost photon field *[up to P~10^{-22} W]* ➔ resonant cavities or emission at dielectric interfaces
- Scan over range of axion mass ➔ need tunable set-up



Primakoff effect aγ^*→γ



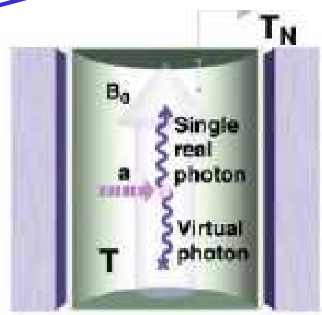
1 μeV

40 μeV [10 GHz]

400 μeV [100 GHz]

[$\nu_a = \nu_\gamma$]

Cavities



ADMX, HAYSTACK, CAPP, GrAHal

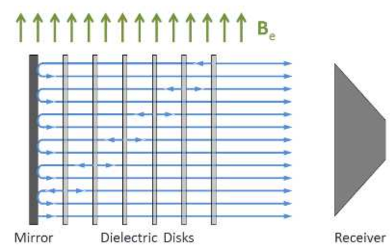
Multicavities

RADES, ADMX-SideCar

Very High B

CAPP, GrAHal

Cavity size too small + high noise



MadMax

Dielectric haloscopes

[novel concept 2013]

Phys.Rev. D88 (2013) 115002

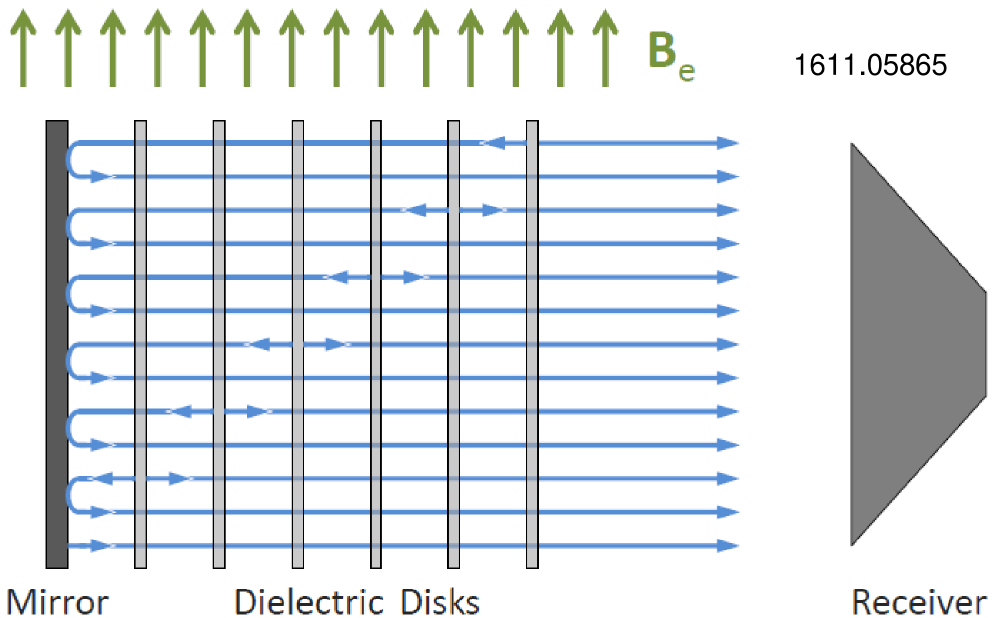
➔ New ideas of last decade coming to maturity to scan preferred mass range

Axion (5/5)

❑ Dielectric haloscope → MadMax experiment

- New experimental concept to alleviate cavity limitation at high m_a ($V \sim 1/m_a^3$)
- Stack of dielectric disks with mirror on one side, inside B field ➔ wave emission at interfaces
- Adjustable distance between disks ➔ constructive interferences ➔ tune to scan over m_a

[spacing 15 mm for 40 μeV and 1.5 mm for 400 μeV]



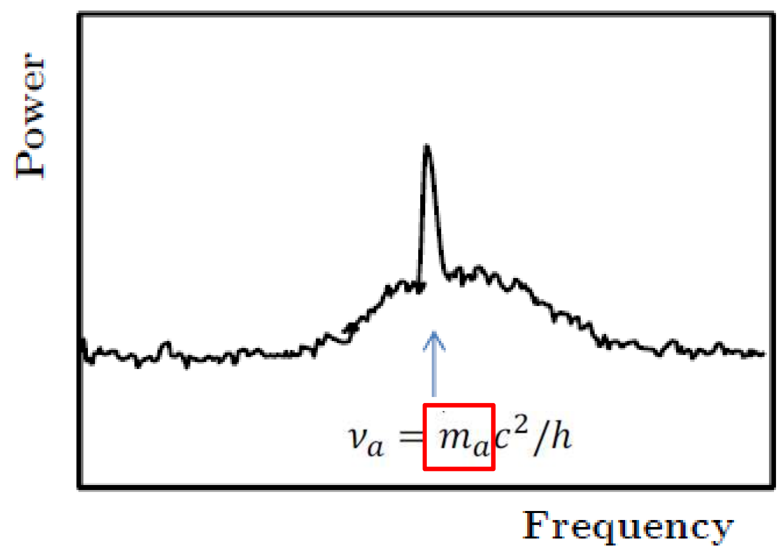
Lanthanide Aluminate ($LaAlO_3$)

Sensitive to $P \sim 10^{-22}$ W in GHz regime (very low noise)

Power / Area

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

Signal boost x10^5



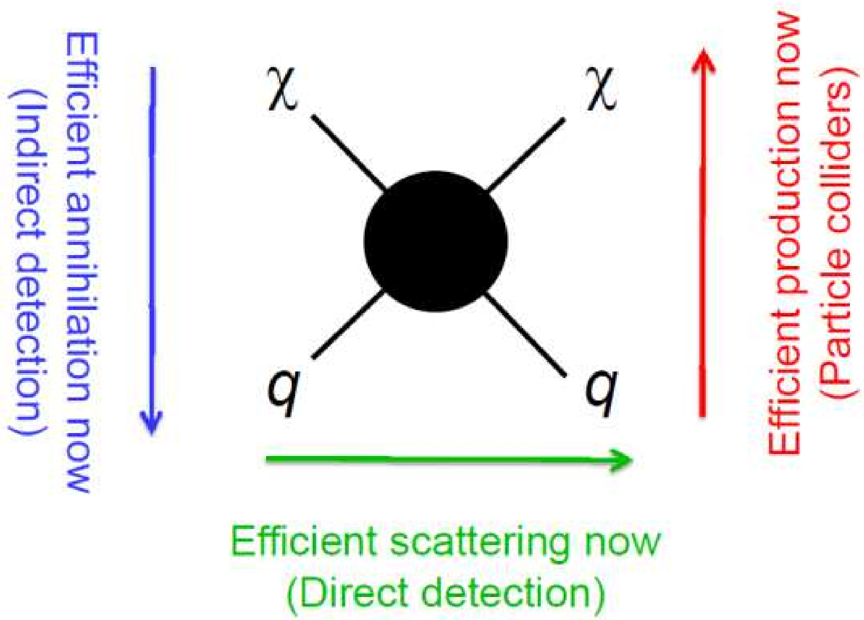
➔ **MadMax only capable to explore m_a=40-400 μeV** *(favored by post-inflation theory)*

WIMP (1/6)

❑ Short reminder on Dark Matter WIMPs

- **WIMP "miracle" (80's)** : A 10-10000 GeV weakly interactive particle can solve the hierarchy problem and explain dark matter (thermally produced in the early Universe)
- Can be experimentally accessed in **3 ways**:

in astrophysical objects, e.g. with KM3NeT, CTA



pp → Higgs → invisible, E_T^{miss}+X *(and other SUSY searches)*

with galaxy halo WIMPs on SM particles

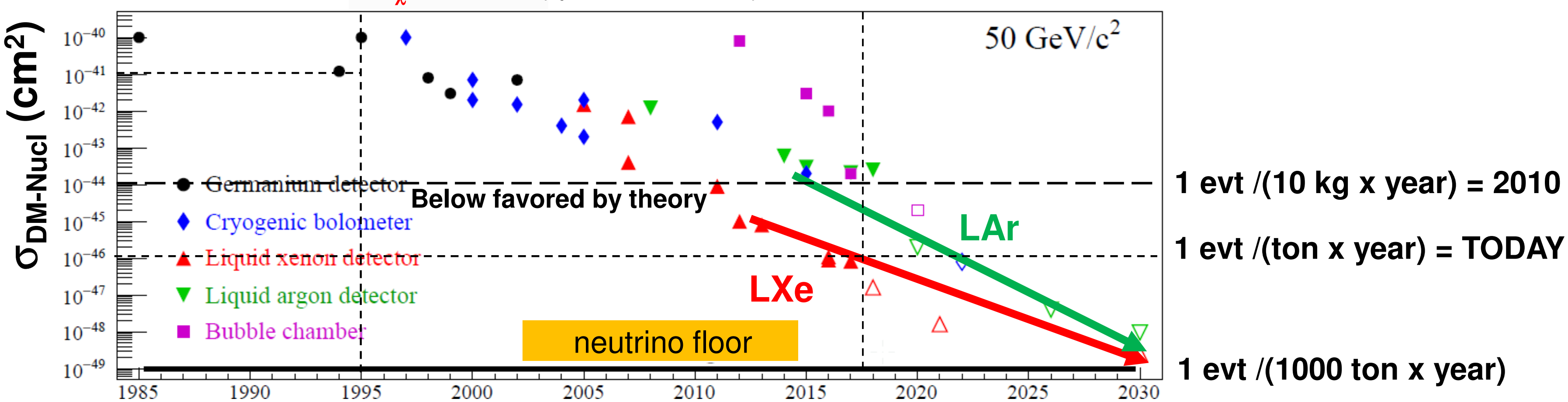
➔ Contrarily to axions, complementary approaches to discover WIMPs

WIMP (2/6)

❑ Direct detection of Dark Matter WIMPs

- Scattering of galaxy halo WIMPs on SM particles (direct search)
  - ✓ Very large volume ➔ need **scalable** technologies
  - ✓ Very low background ➔ low **noise** electronics + detector under control

1509.08767 m_χ=50 GeV (quite low for Ar)



Leading techno: Ge Bolo LXe LXe+LAr **Year**

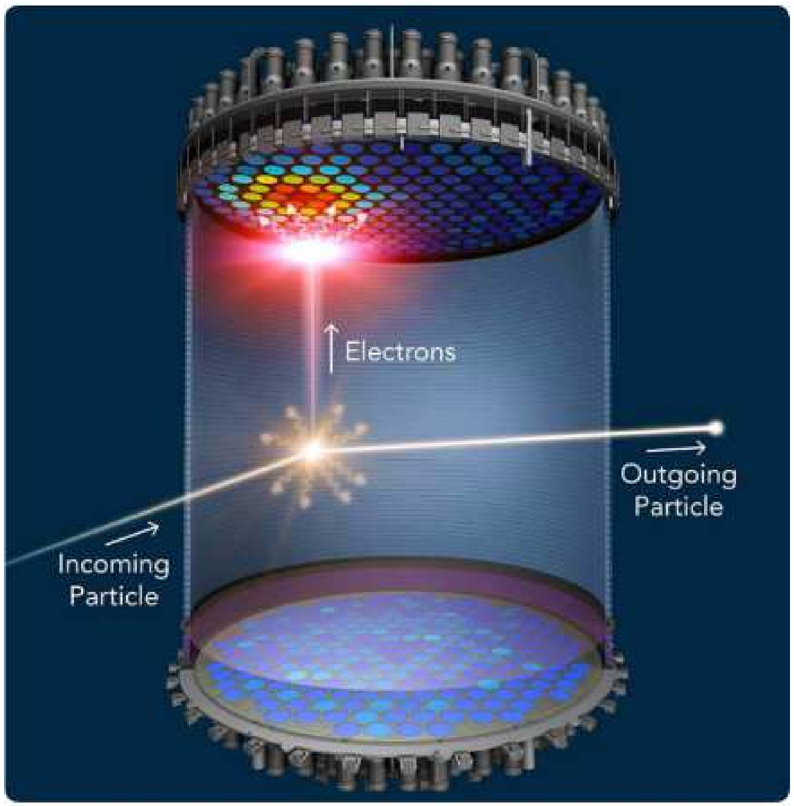
- Gained 5 orders of magnitude in sensitivity in last 20 years
- By end of next decade : should reach neutrino floor

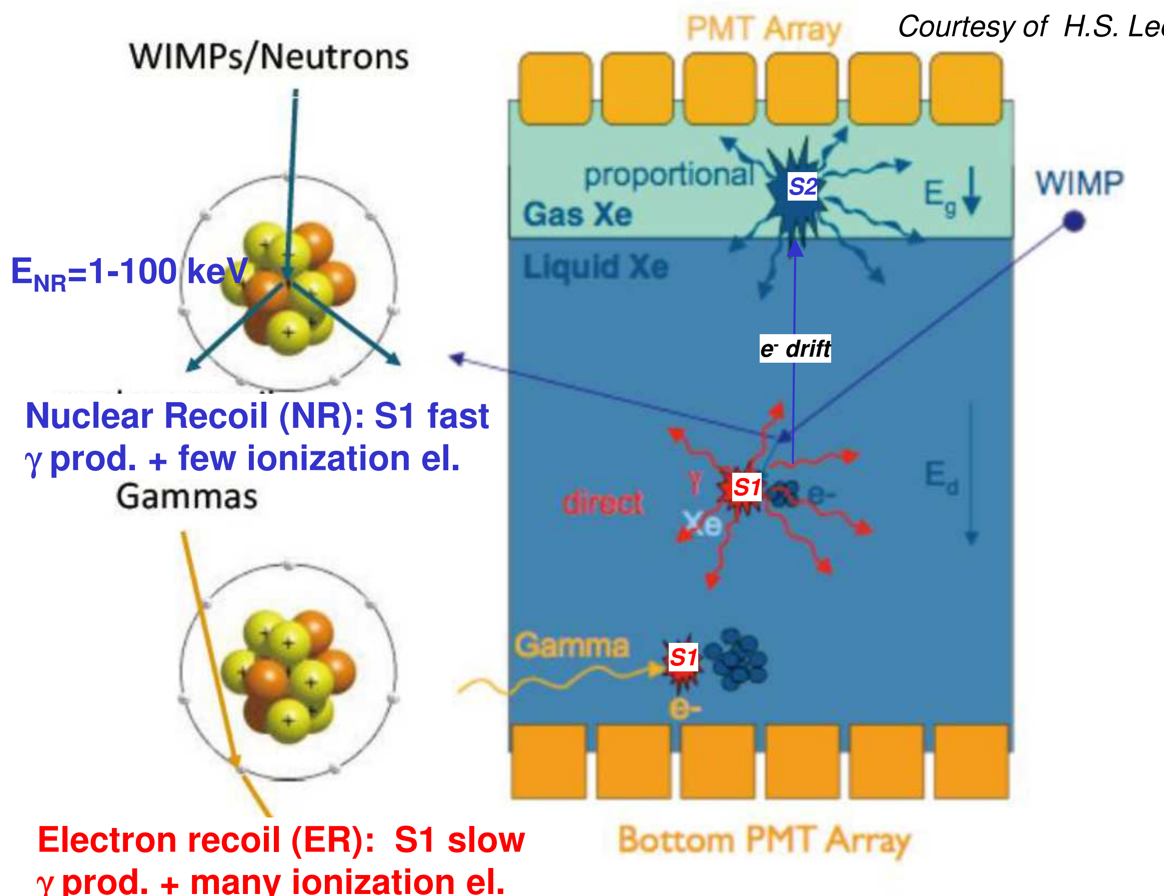
➔ LXe / LAr dual phase TPC are now leading the race [m_χ >O(1 GeV)]

WIMP (3/6)

❑ Principles of noble liquid/gas TPC experiments

- Cryostat hosting a Time Projection Chamber (TPC) equipped with photo-multipliers
- Dual phase TPC → scintillation signal (S1,~40 γ/keV*) followed by ionization one (S2,~15 e^-/keV*)





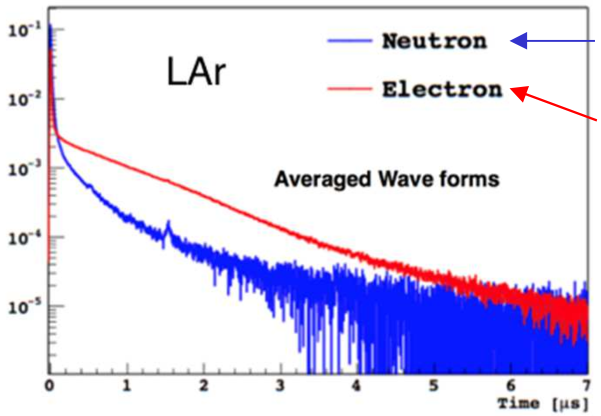
$S2/S1_{ER} >> S2/S1_{NR}$

*in DarkSide-50 @ 200 V/cm → S1= 7 pe

WIMP (4/6)

❑ LAr technology starts to be mature …

- **High removal of Electron Recoils** → **Background free at high WIMP mass**
  - ✓ S1 pulse shape discrimination : additional rejection depending on nuclear properties



Nuclear Recoil : mainly fast scintillation → peaked

Electron Recoil : mainly slow scintillation → more scattered

  - ➢ In Xenon, slow scintillation is actually quite fast (27 ns instead of 6 ns for fast scint.)
  - ➢ In Argon, large difference between slow (1000 ns) and fast (6 ns) scintillations

→ Discrimination with rejection $>10^8$ (~none with LXe) thanks to intrinsic properties of Argon

✓ TPC filled with Underground Argon (less ^{39}Ar) + Further purification (^{39}Ar, ^{85}Kr, O, H_2O)

- **Merging of all world-wide LAr experiments in 2017** *(DEAP3600, DarkSide-50, miniCLEAN, ArDM → DarkSide-20k)* : most advanced technology from each experiments

WIMP (5/6)

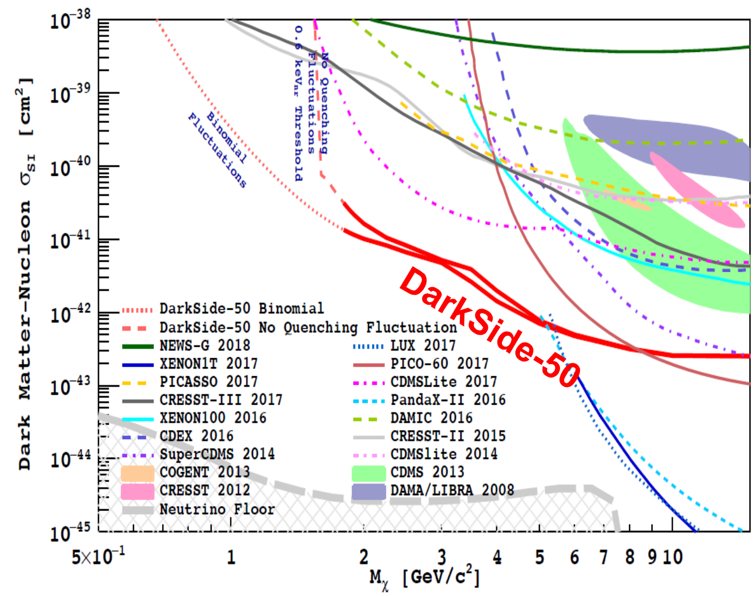
❑ … demonstrating high level performance with 50 kg LAr *(DarkSide-50)*

- **Best observed exclusion limits @ O(GeV) mass** from DarkSide-50 with pioneering S2-only analysis

IN2P3 news (26/02/2018)

Une contribution fondamentale à ce résultat vient de l'expérience ARIS (*Argon Response Ionization and Scintillation*) qui a permis la caractérisation détaillée de la réponse de l'argon liquide. L'expérience ARIS, qui utilise un faisceau de neutrons, a été réalisée au laboratoire ALTO (Orsay) sous la direction des équipes françaises de l'APC et du LPNHE en collaboration avec l'IPNO. La modélisation précise de la réponse du détecteur et du bruit de fond a été le fruit du développement de plusieurs années d'une simulation Monte Carlo détaillée des détecteurs de la famille *DarkSide*, mise au point par les équipes de l'APC et du LPNHE.

1802.06994



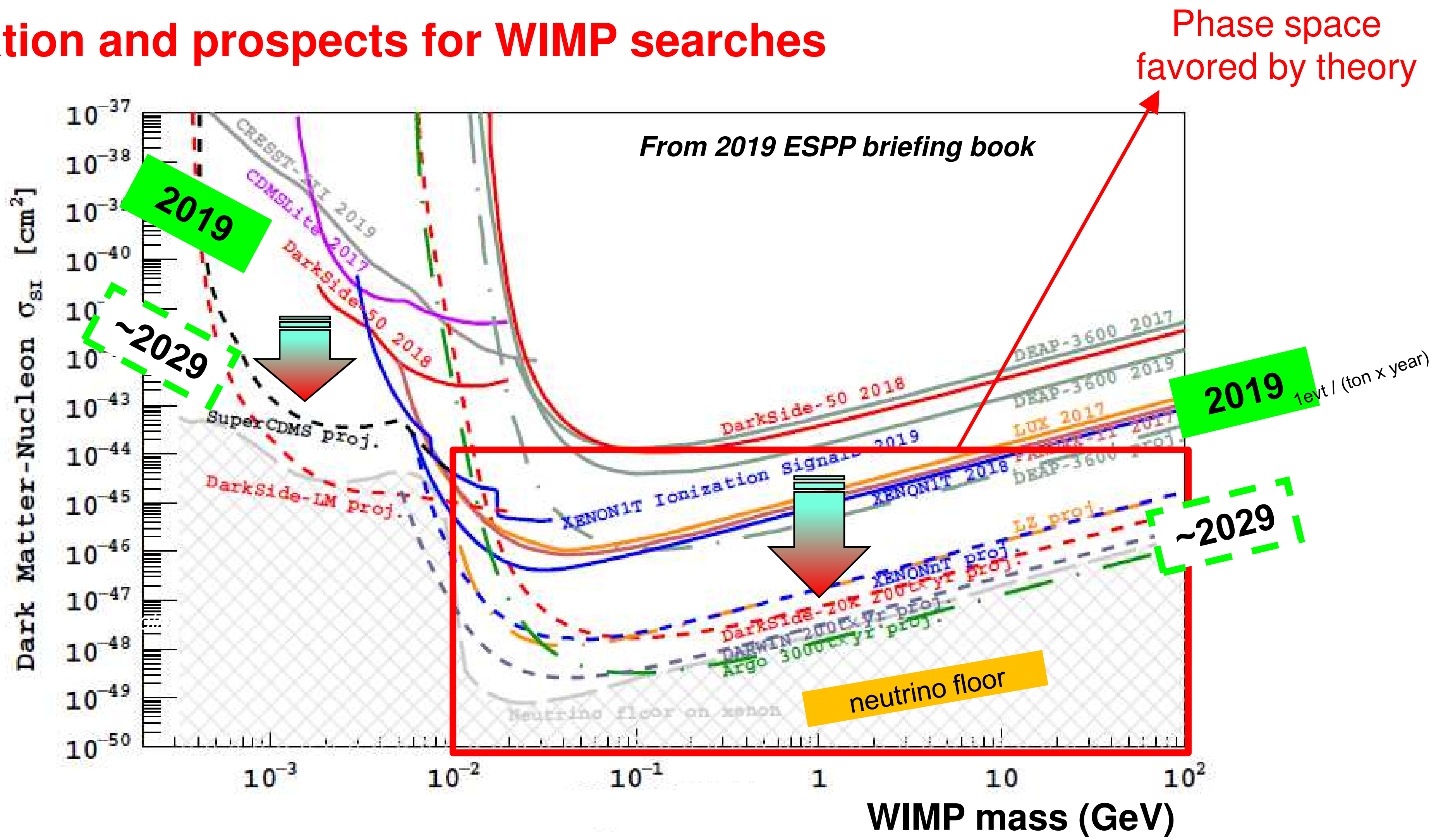
❑… and expect more in the next 10 years with 20 t LAr *(DarkSide-20k)* :

- **Strong discovery potential for high mass** (>30 GeV) in an almost background free mode (~0.1 background event expected in 5 years [100 t.yr]) 1707.08145
- Very complementary in case of discovery by LXe (currently leading the race)

➔ Liquid Argon technology promising and complementary with LXe

WIMP (6/6)

❑ Situation and prospects for WIMP searches



➔ **Next decade will be decisive, probing WIMP most favorable region**

Scientific Opportunities (1/2)

❑ **Two DM candidates motivated by particle physics since 40 years …**

- Axion : very low mass (m_a=1-10^3 μeV) → Conversion to photon field
- WIMP: high mass (m_χ=10-10000 GeV) → Elastic scattering on nucleon

❑ **… can be discovered / excluded in the next O(10) years**

- Recently, sensitivity in the theory-favored region in 2010 (WIMP) and 2018 (axion)
- Will now be extended to most of the range with new very promising experiments
  - ✓ **Axion → MadMax** : only capable to explore phase space favored by theory
  - ✓ **WIMP → DarkSide** : leader at O(GeV) + background-free at high mass
- DarkSide and MadMax are preparing their prototype now ➔ physics in early 2020's

	2019	2020	2021	2022	2023	2024	2025	≥2026
MadMax	Preparation Proto	Construction Proto		Exploitation proto		Construction final detector		Exploitation final detector
DarkSide	Construction Proto	Exploitation Proto		Construction Final detector		Exploitation final detector		

Scientific Opportunities (2/2)

❑ Scientific council IN2P3 (28-Oct 2018)

http://old.in2p3.fr/actions/conseils_scientifiques/media/2018_octobre/Rapport-2018-10-final.pdf

- **DarkSide:** CS-IN2P3 very positive

> Aujourd'hui, parmi les projets de détection directe de matière noire présentés, seuls XENON et DarkSide-50 sont opérationnels et au niveau de la rude concurrence internationale, dans des domaines de masse différents. La participation à ces projets est à soutenir et à renforcer en développant les équipes actuelles. [APC+LPNHE in DarkSide]

Avis et recommandations

Le programme DarkSide présenté par ces groupes est ambitieux et vise une participation à toutes les étapes du projet, de DS-50 à GADMC. Le conseil recommande que le groupe se focalise sur quelques points clés de manière à maximiser son impact dans la collaboration. Le conseil recommande de trouver des forces humaines supplémentaires pour s'engager plus avant dans un projet de cette envergure.

⇨ ***CPPM : strengthen french activity with technical contributions (calibration)***

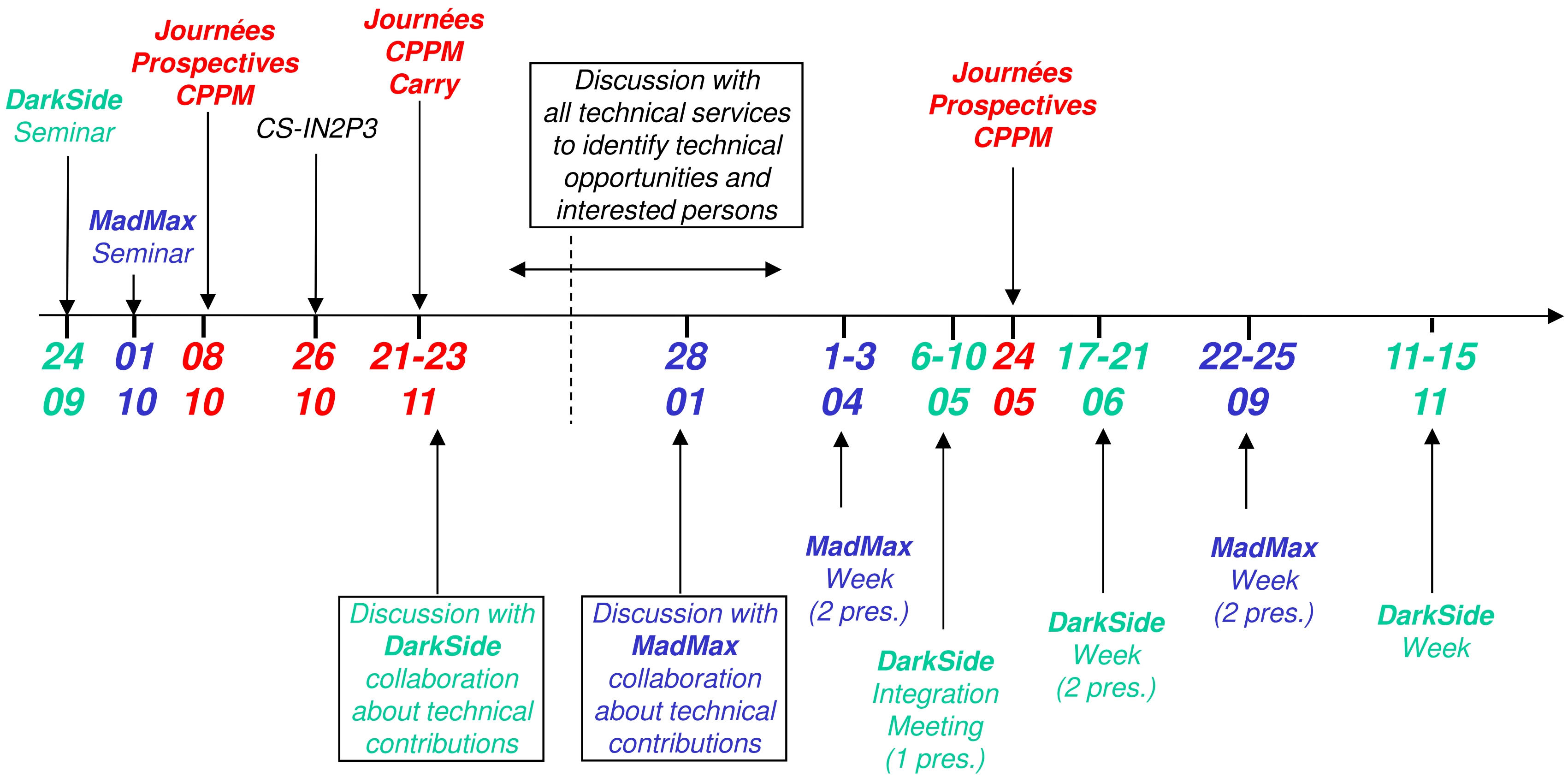
- **Axions:** no participation from IN2P3

Il faut noter que les axions sont un candidat générique à la matière noire, également physiquement motivé, et ce depuis plusieurs dizaines d'années. L'un des piliers des WIMPs étant mis à mal par l'absence de signe de nouvelle physique dans les résultats du LHC, cette alternative doit être gardée à l'esprit, en parallèle à l'élargissement du domaine de paramètres du candidat de type WIMP.

⇨ ***CPPM : open this thematic with technical contributions (innovative R&D)***

Technical Opportunities

- ❑ Started as prospects in our lab in 2018 …
- ❑ … and get involved (MadMax and DarkSide) since beginning of 2019



➔ Identified technical opportunities + first achievements in last 9 months

Opportunities in MadMax (1/4)

White Paper (1901.07401)

- ❑ **~40 collaborators** e.g. from MPI-Münich, U-Hamburg, DESY, CEA/IRFU, I. Néel + CPPM

Associate members since 2019

	2019	2020	2021	2022	2023	2024	2025	≥2026
MadMax	Preparation prototype	Construction prototype		Exploitation prototype		Construction final detector		Exploitation final detector

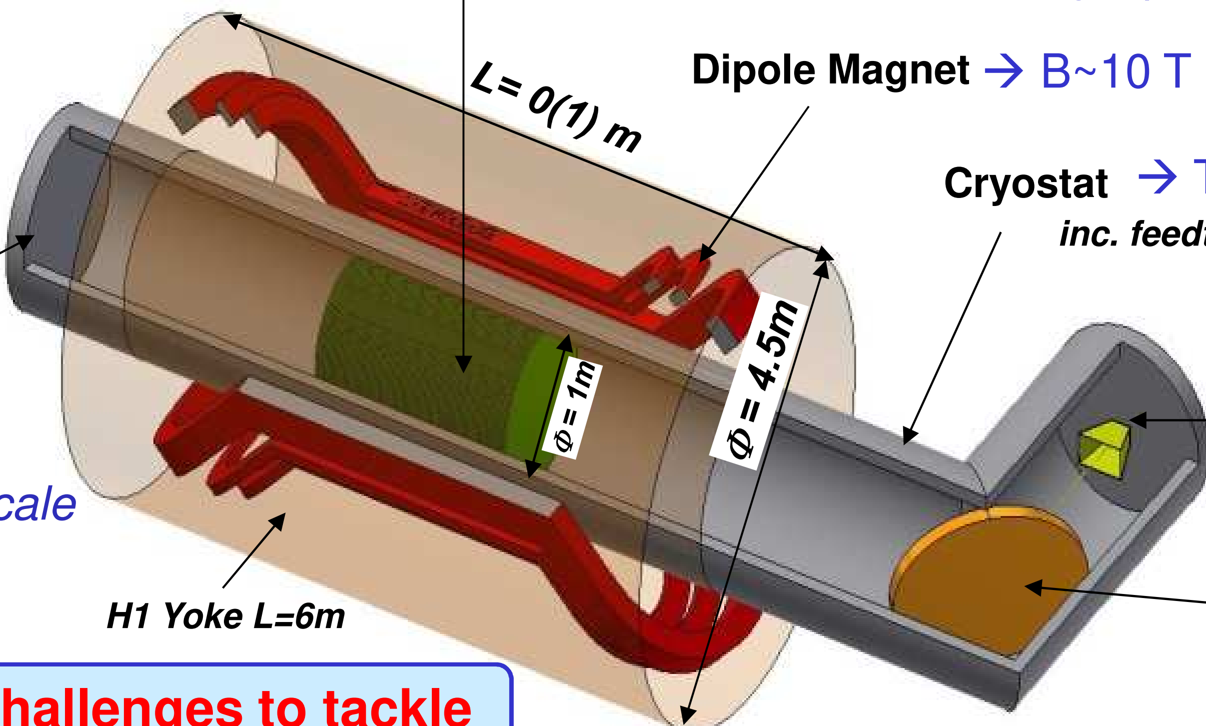
@DESY axion hub
(IAXO, ALPS, MadMax)

Cover page of EPJC in March' 19

Booster → 80 dielectric disks (lanthanum aluminate ε~24) of ∅=1m (thickness 1 mm), few kgs, positioned at O(10 µm)

Dipole Magnet → B~10 T → $B^2.A$ ~ 100 $T^2.m^2$

Cryostat → T~4 K
inc. feedthrough

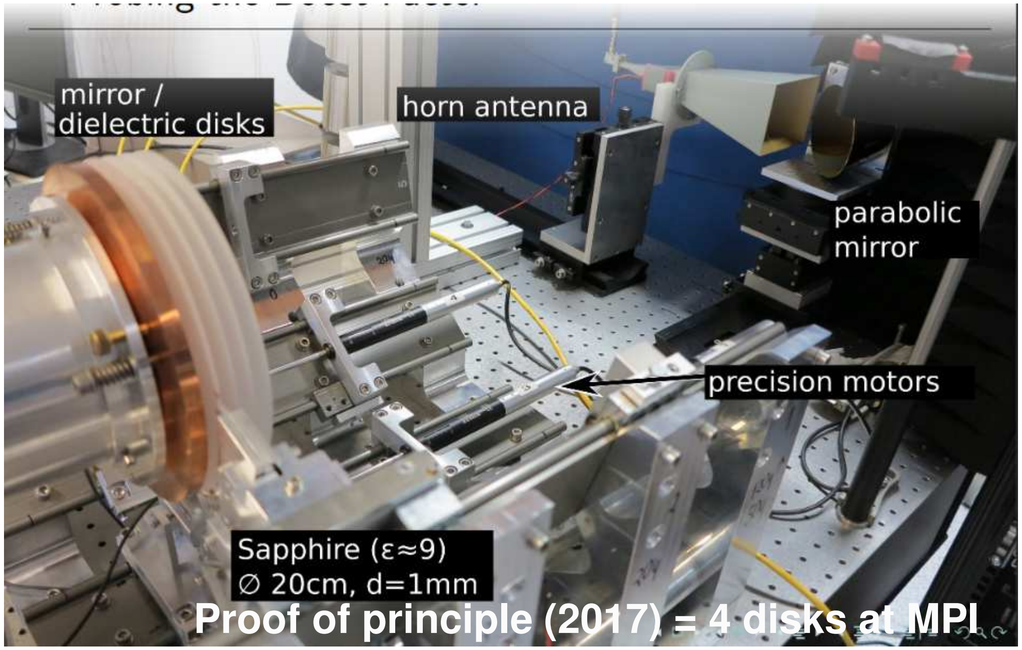


Picture not to scale

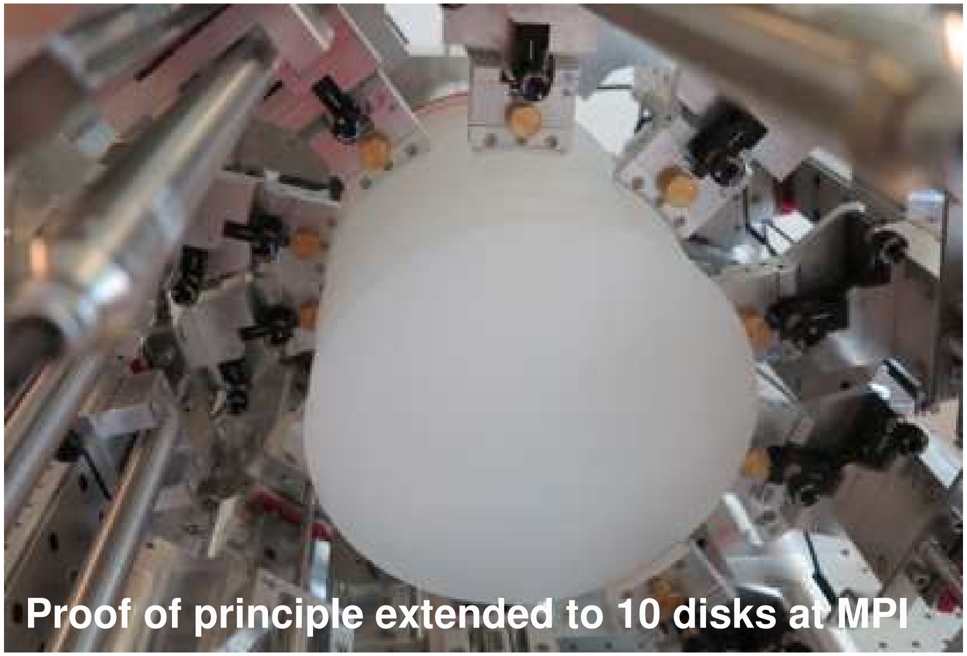
→ Many challenges to tackle

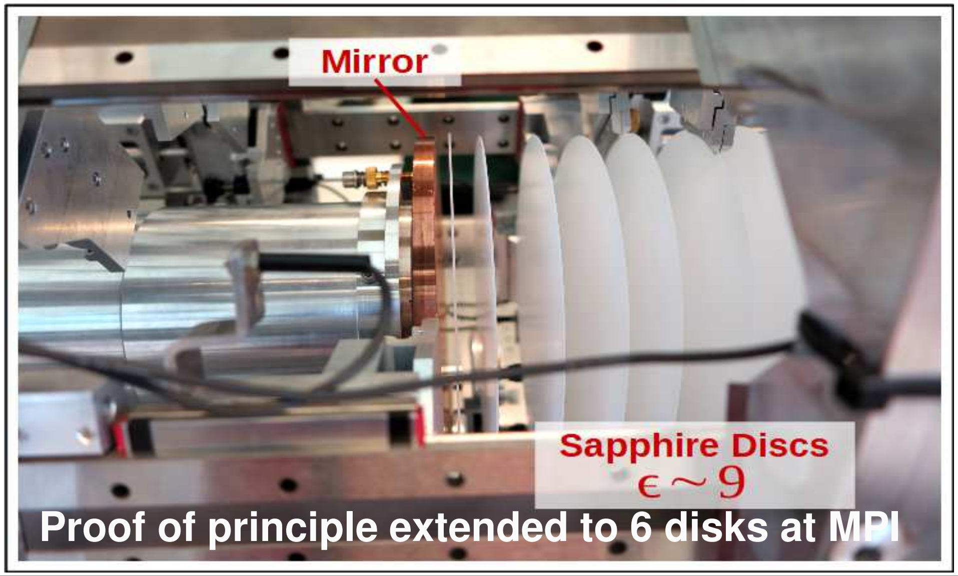
Opportunities in MadMax (1/4)

White Paper (1901.07401)



Proof of principle (2017) = 4 disks at MPI


Proof of principle extended to 10 disks at MPI



Proof of principle extended to 6 disks at MPI

collaboration formed in Oct. 2017

Opportunities in MadMax (2/4)

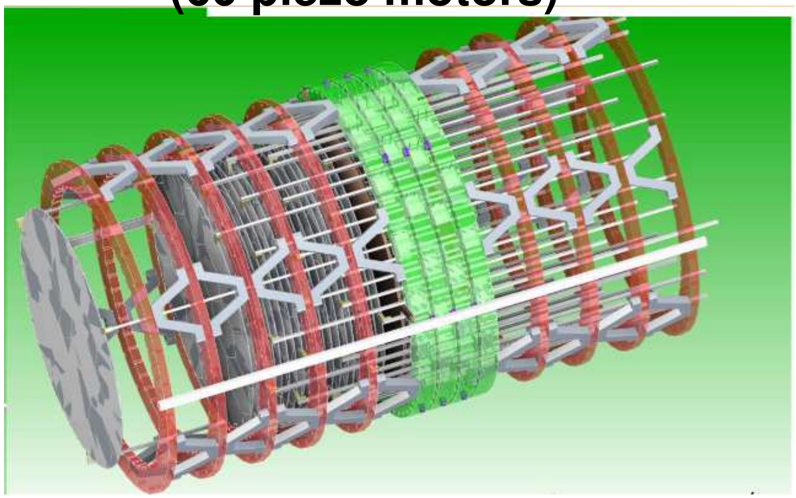
❑ Best match for CPPM: mechanics of the prototype booster

- Prototype booster composed of **20** disks of **30 cm** diameter
- Need to control precisely disk thickness **1 mm +/10 μm**
- Need to position precisely disks (**10 μm**) with piezo motors

→ The whole set-up is embedded in a cryostat **T~4K and B~2T**

Sapphire disks at MPI

Mechanics of the prototype booster (60 piezo motors)

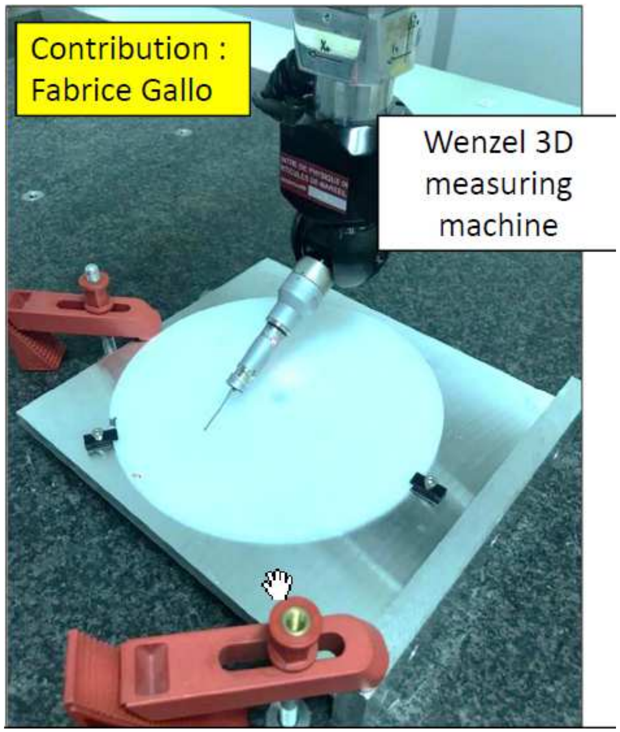


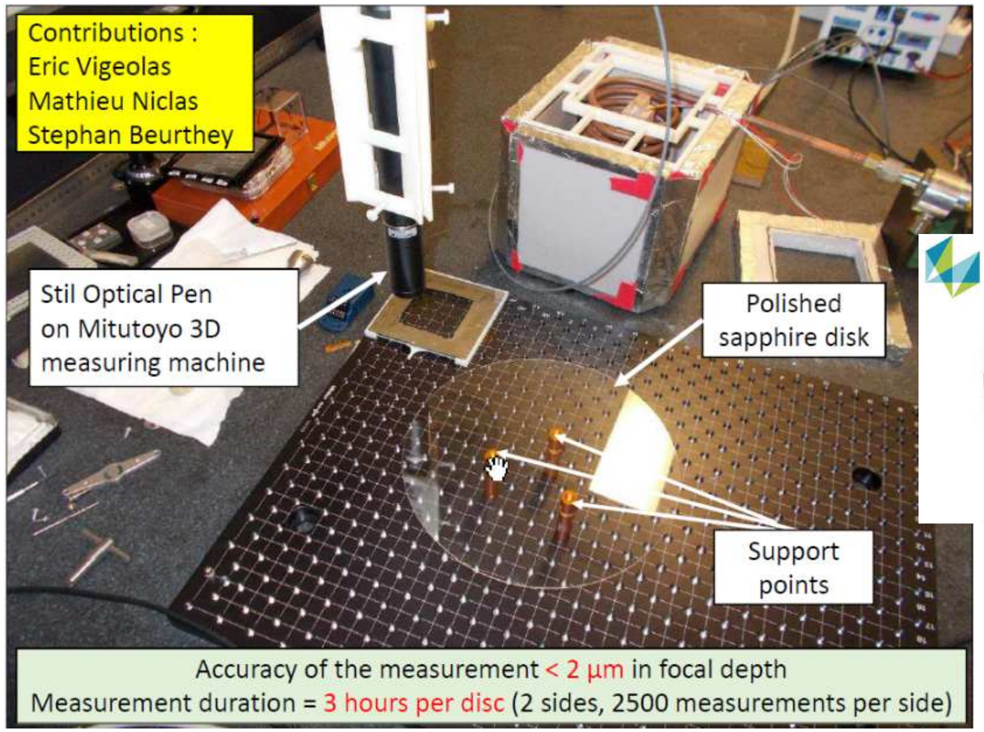
Very challenging R&D ongoing → many technical opportunities

Opportunities in MadMax (3/4)

❑ First CPPM contributions on mechanics

- Profit from the precision measurement infrastructure of the lab to control disk planarity and thickness with 3 different set-up, with precision <10 µm





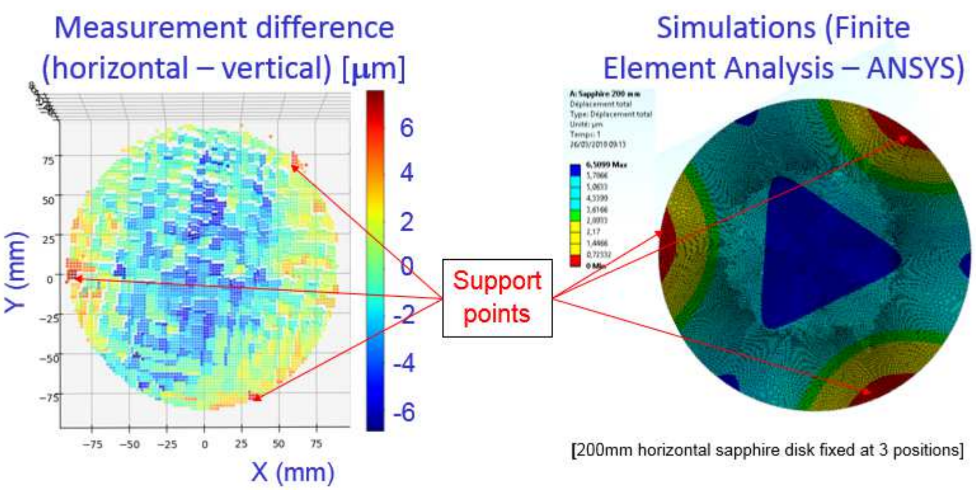
Results presented at MadMax meetings in 2019

Opportunities in MadMax (3/4)

❑ First CPPM contributions on mechanics

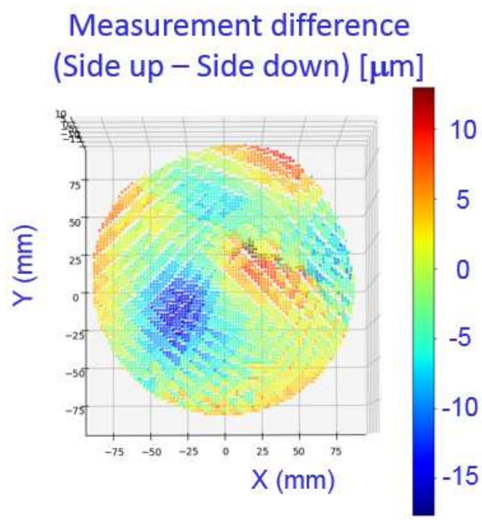
- Profit from the precision measurement infrastructure of the lab to control disk planarity and thickness with 3 different set-up, with precision <10 μm

Disc #1 - 200 mm unpolished surface - Difference Horizontal-Vertical



➔ Good qualitative agreement between measurements and simulations

Disc #2 - 200mm polished surface - Difference Side #2 – Side #1



RMS= 4 μm → lower than RMS of each side (10-11 μm)

➔ Correlation between both sides

➔ Disk thickness uniformity better than surface non-planarity

➢ **We included the measurements in the MadMax simulation code → increased realism**

➔ Entry point in MadMax identified and work started with reduced manpower

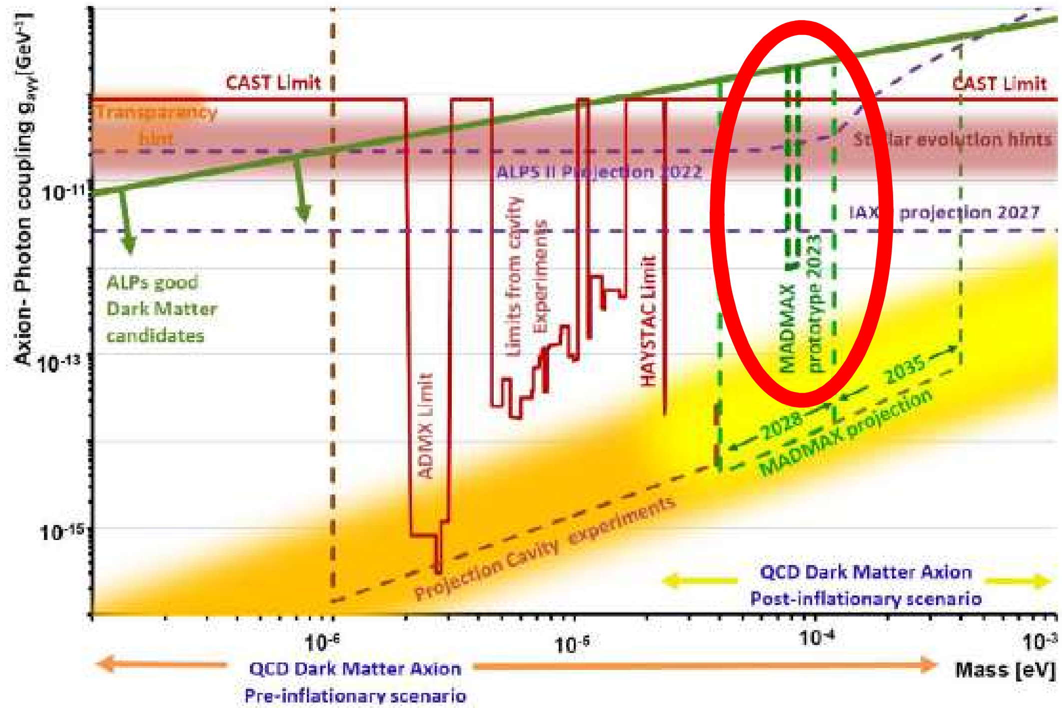
Opportunities in MadMax (4/4)

- **We proposed the prototype to be operated at CERN**
  - Identified ATLAS testbeam magnet → can be used during LHC shutdowns (2021/22 + 22/23)

Cooling system

Iron Yoke

Coil (2 face-to-face saddle shaped coils)



- ➢ LoI submitted to SPSC in June
- ➢ Can already probe unexplored region of phase space (ALPs) with the prototype

→ Can do physics at short term at CERN

Opportunities in DarkSide (1/4)

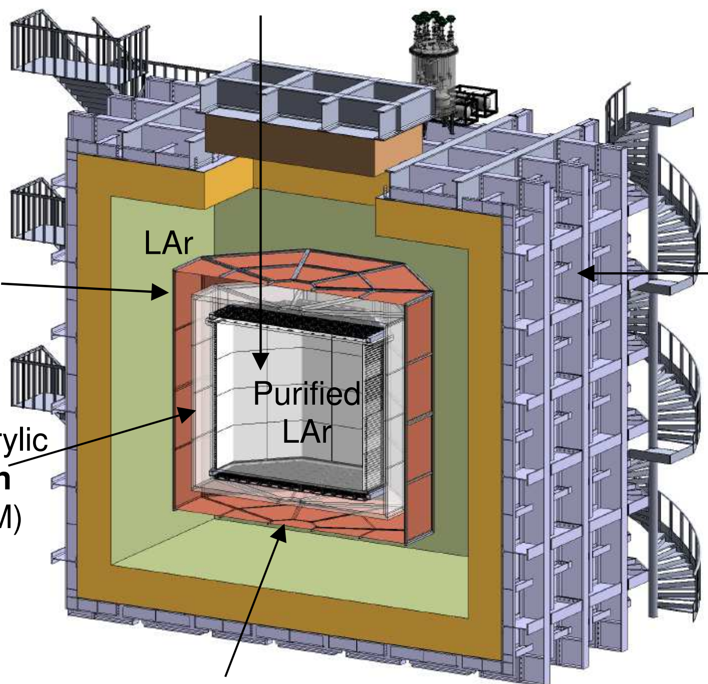
White Paper (1707.08145)

- **~300 collaborators.** Main contacts: APC, LPNHE, INFN, LNGS, Princeton, Triumf

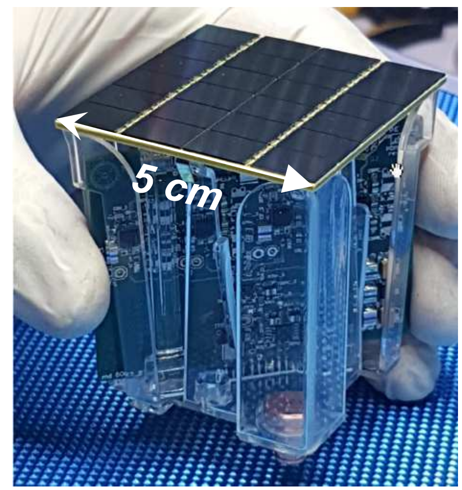
	2019	2020	2021	2022	2023	2024	2025	≥2026
DarkSide	Construction prototype	Exploitation prototype		Construction Final detector		Exploitation final detector		

@ GranSasso
+ CERN recognized experiment (RE 37)

Acrylic TPC (3.5x3.5x3.5 m^3, 50t purified LAr)
read by 8300 PDMs (~200k SiPM)



1 PDM = 24 SiPM



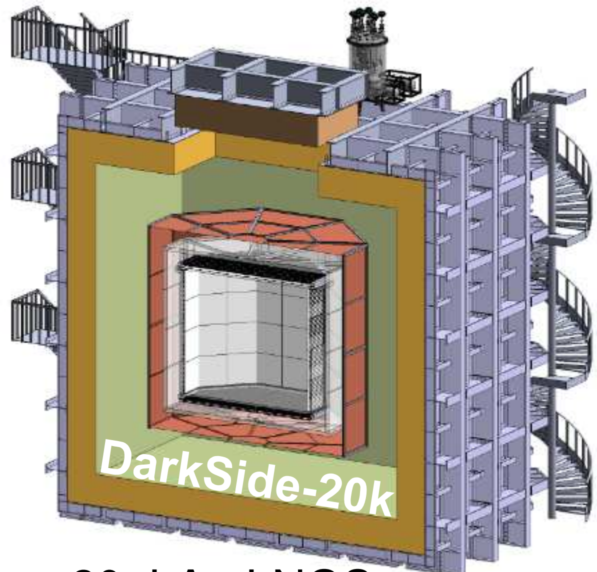
Developed by FBK (Fondazione Bruno Kessler company) in Trento and then produced by LFoundry

Opportunities in DarkSide (1/4)

❑ Liquid Argon (LAr) Dark Matter experiments

10kg LAr, LNGS

50kg LAr, LNGS

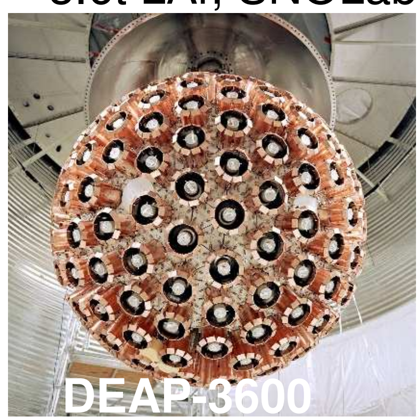


20t LAr, LNGS

2010 2020 2030

1t LAr, Canfranc

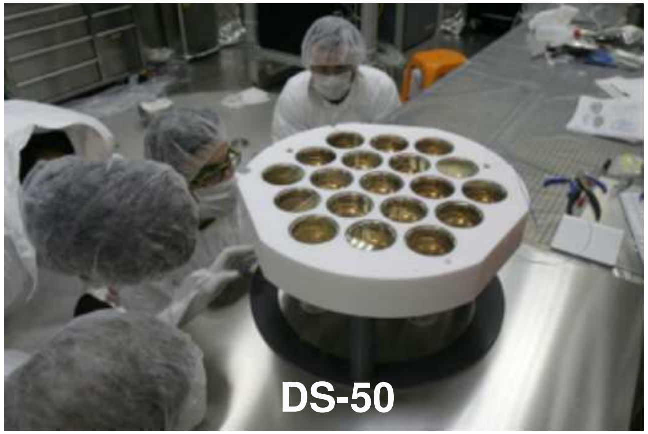
3.6t LAr, SNOLab

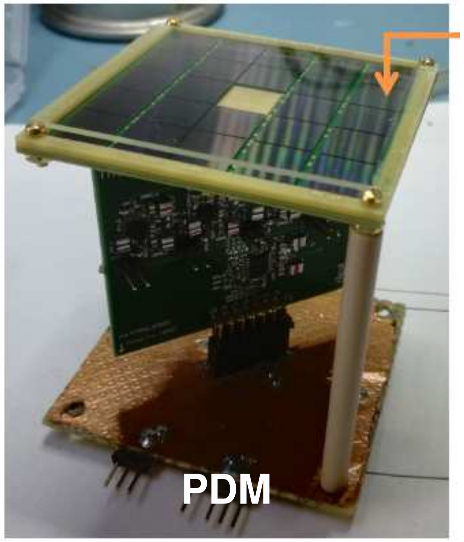


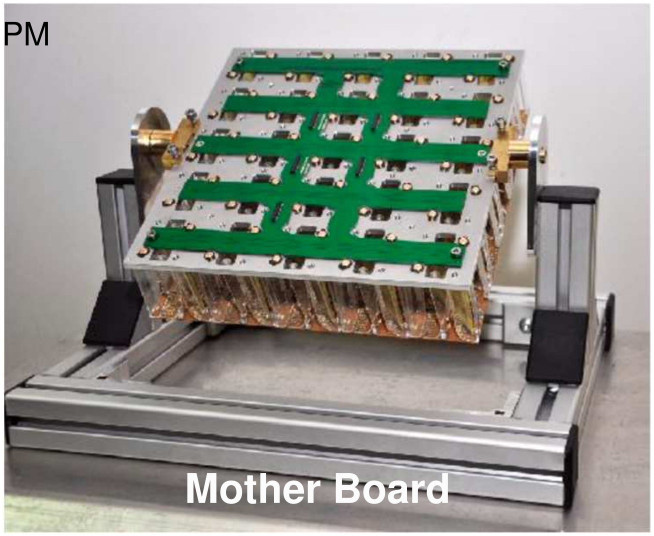
ARGO
400t LAr, Snolab

Opportunities in DarkSide (1/4)

White Paper (1707.08145)



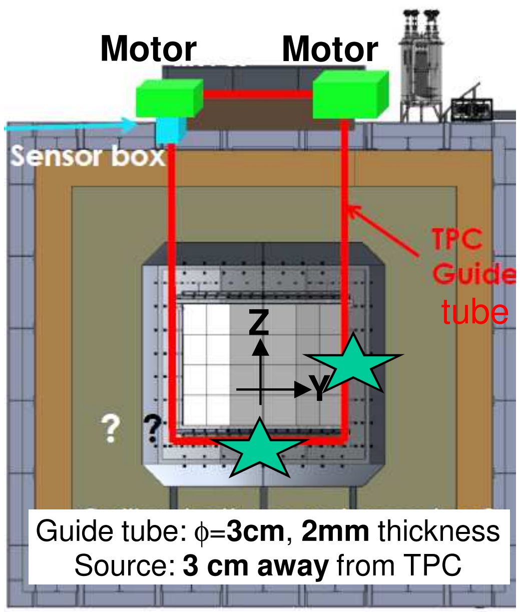




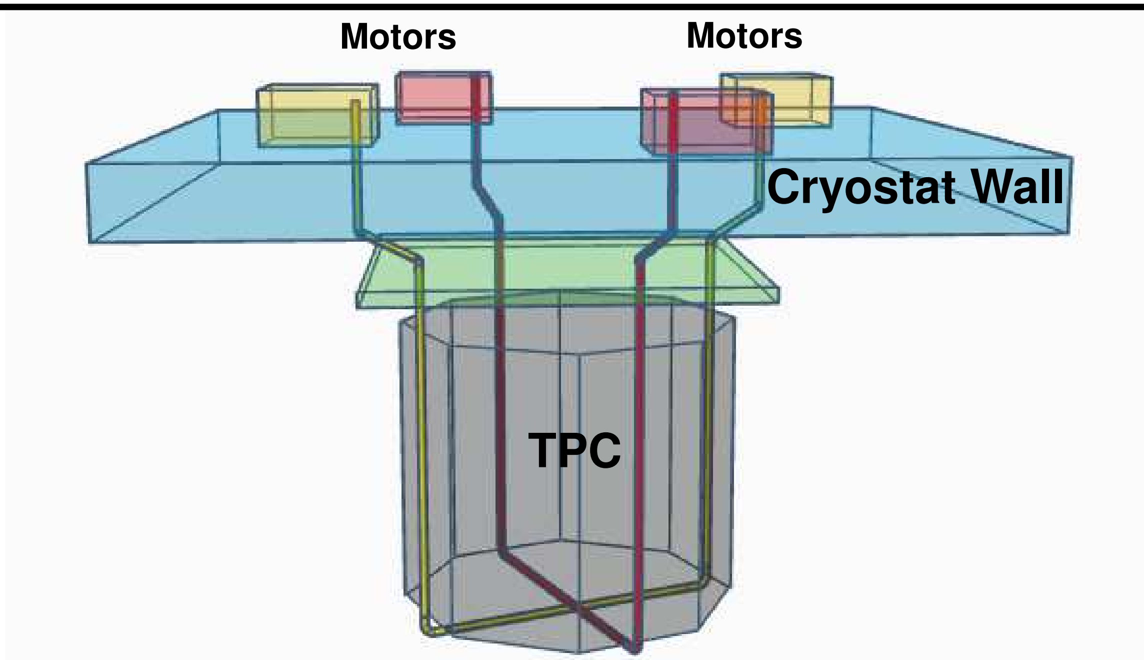
Opportunities in DarkSide (2/4)

❑ Best match for CPPM: detector calibration

- Central and rich program, in line with CS-IN2P3 of Oct. 2018
- Benefit from expertise of APC and LPNHE + add technical contributions ➔ IN2P3 dynamics
- **Guide tube system** that will circulate neutron and gamma sources in the final detector



Guide tube: ϕ=**3cm**, **2mm** thickness
Source: **3 cm away** from TPC

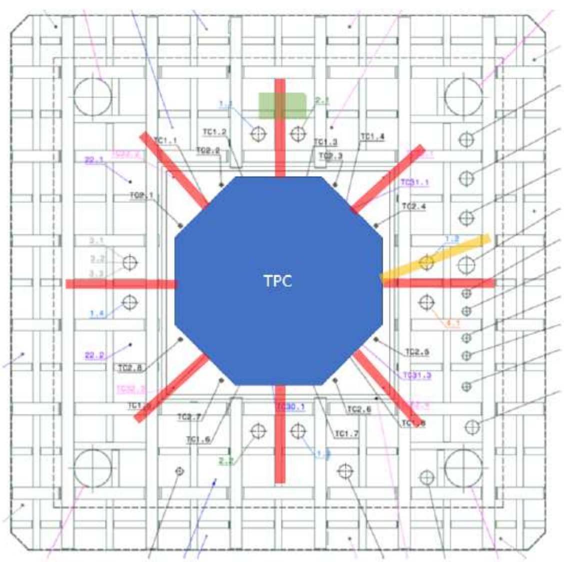


Opportunities in DarkSide (3/4)

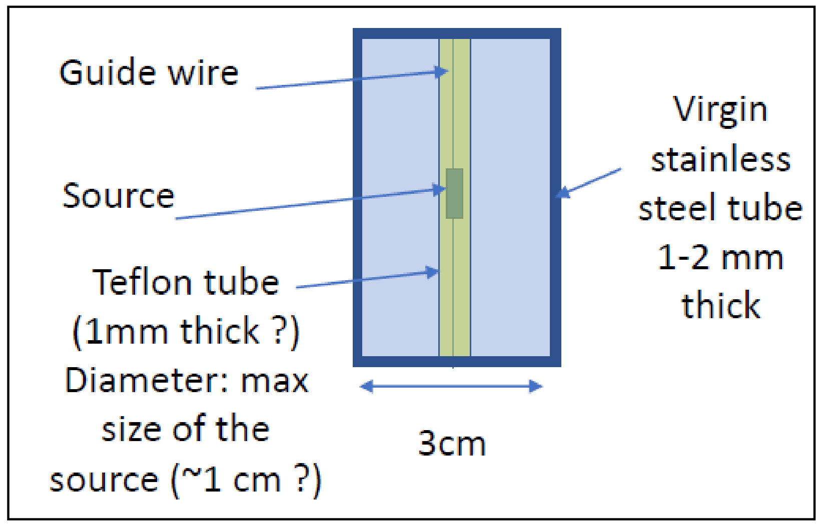
❑ First CPPM contributions on detector calibration

- Central and rich program, in line with CS-IN2P3 of Oct. 2018
- Benefit from expertise of APC and LPNHE + add technical contributions → IN2P3 dynamics
- In 2019, **conceptual design** of guide tube system that will circulate neutron and gamma sources in the final detector → used for energy and position calibration + MC tuning

Motor position on cryostat roof



Guide tube size and material



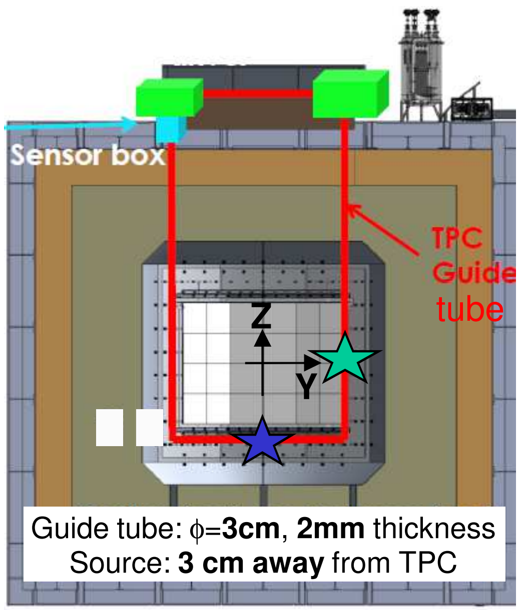
Results presented at DarkSide meetings in 2019

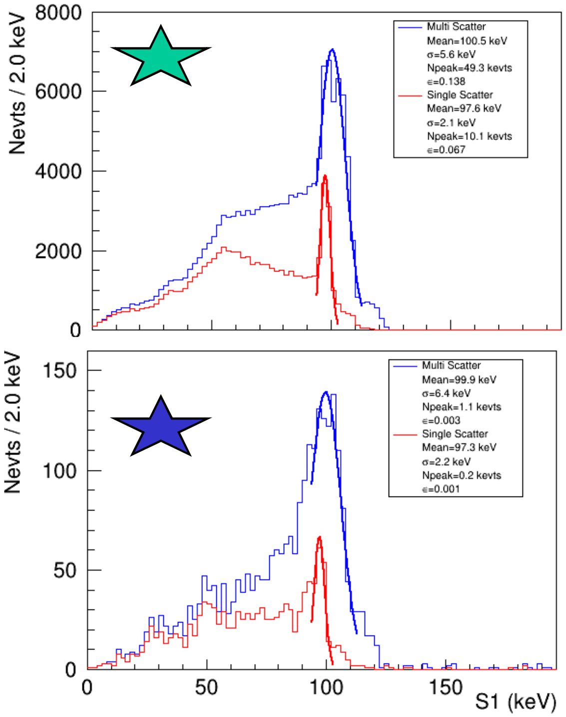
Opportunities in DarkSide (3/4)

❑ First CPPM contributions on detector calibration

- Central and rich program, in line with CS-IN2P3 of Oct. 2018 ➔ IN2P3 dynamics
- Conceptual design of the guide tube system
- Currently working on optimization of the guide tube system using simulations *(example below for ^{57}Co)* → Propose a **complete calibration strategy**

^{57}Co source *(122 keV γ)* **in guide tube**





➔ Entry point in DarkSide identified and work started with reduced manpower

Opportunities in DarkSide (4/4)

❑ Participation to data analysis of prototype at CERN

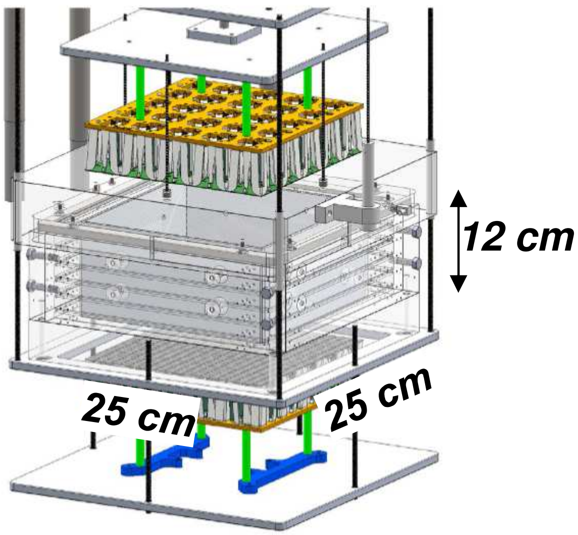
- Two prototypes will be built at CERN and tested with calibration sources
- Supervised one CERN summer student (shared with proto-DUNE project)

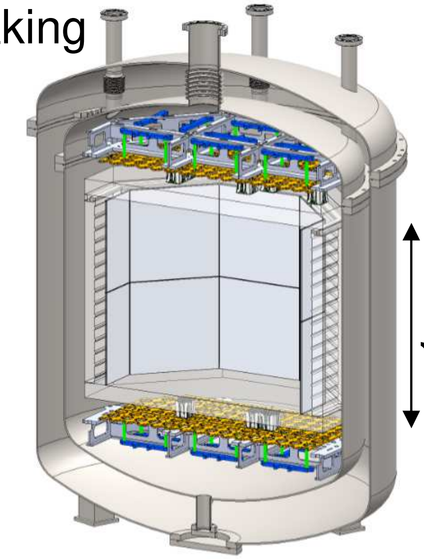
proto-0 (2kg LAr, 1.2k SiPM)

➔ First validation of SiPM
➔ Run scheduled in Nov. 2019

proto-1 ton (1 ton LAr, 9k SiPM)

➔ Full scaled-down version of final detector
➔ Operational in Summer 2020
➔ Might then send this proto to LNGS for physics data-taking





➔ Can do physics at short term at CERN

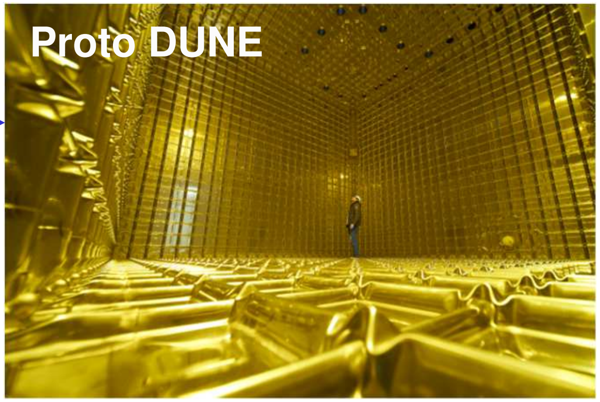
Synergies

❑ Dark matter experiments at the technological frontier

- **DarkSide**: Medical Imaging PET10ps, SiPM FCC LAr, …
- **MadMax**: Receiver (Josephson Parametric Amplifier at Institut Néel), dipole magnet conceived at CEA, Nb-Ti cable on Cu conductor developed at LNMCI-Grenoble, …

❑ Some natural connections

- **Theoreticians** and experimental indirect searches
- **DUNE** via ν platform @ CERN:
  - ✓ Same external cryostat (to be installed in Gran Sasso) →
  - ✓ LAr TPC with some common problematics
  - ✓ Galatic Supernovae → ν mass hierarchy
- **CERN** infrastructure



Conclusions

❑ Dark Matter direct searches : dynamic research field in next decade

- WIMP and axion searches entering the phase space favored by theory
- Identified one promising experiment for each candidate, with large discovery potential in the next 10 years ➔ consistency and complementarity

❑ Strong associated opportunities & Rising activities at CPPM

- Technical entry points in both collaborations identified :
  - ✓ **MadMax**: challenging R&D in disk booster mechanics → *new @ IN2P3 !*
  - ✓ **DarkSide**: calibration → *reinforce IN2P3 activity as recommended by CS-IN2P3*
- Early physics (beg. 2020's) with prototypes operated at CERN
- \+ Interesting synergies identified

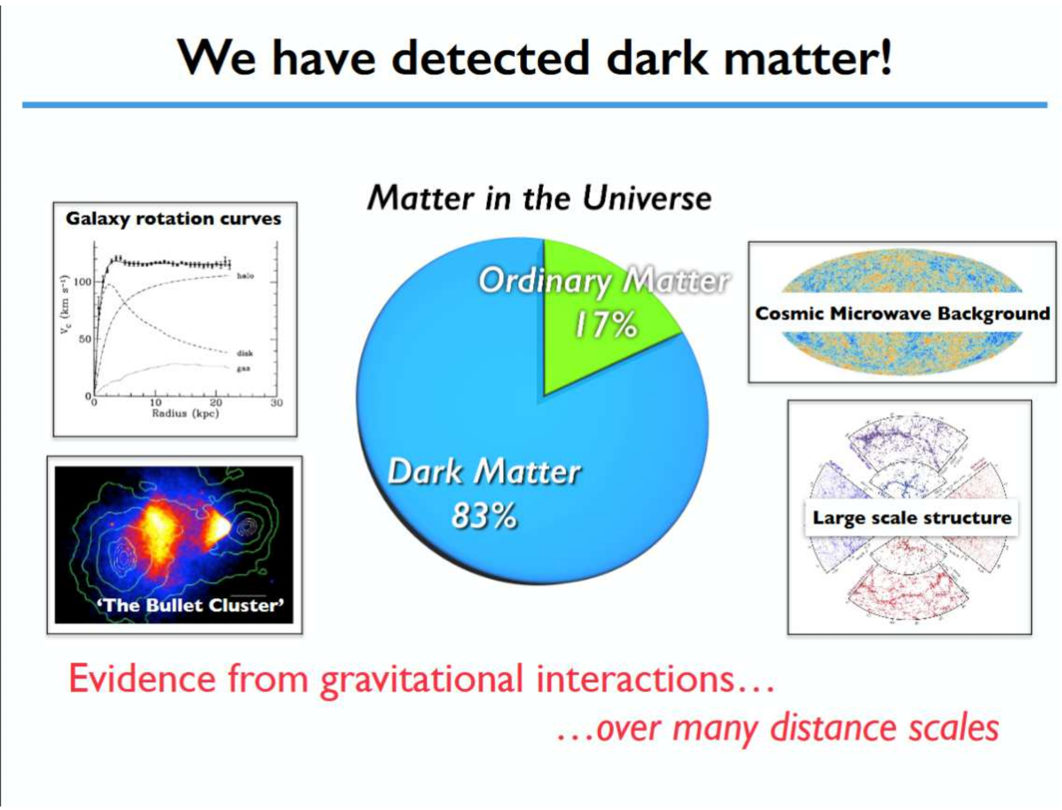
Short term Opportunities (**scientific & technical**) on a **fundamental question** of particle physics with a **strong discovery potential**

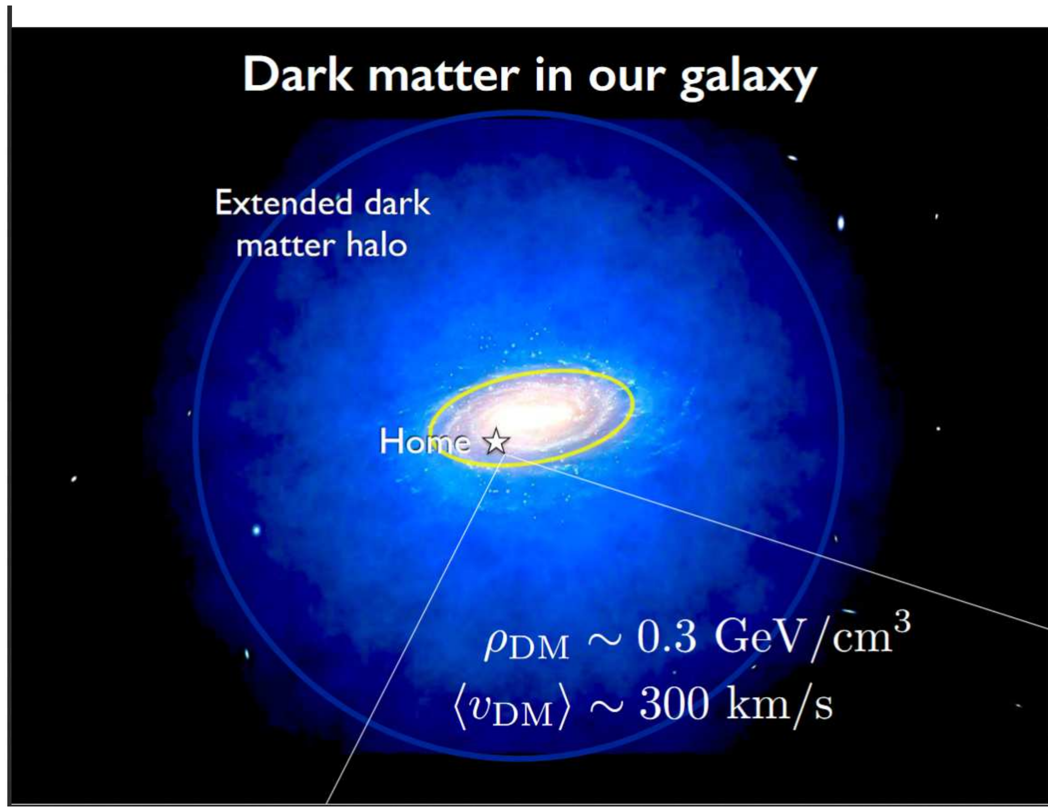
➢ More details in contributions submitted to IN2P3 prospectives :

https://indico.in2p3.fr/event/19776/contributions/75430/
https://indico.in2p3.fr/event/19776/contributions/75431/

SPARE

Dark Matter Generalities





Scientific Opportunities

EU APPEC Strategy (2017→2026), **US** Cosmic vision (2017), **ESPP** European Strategy (2019)

❑ World-wide community (2017-2019)

- http://www.appec.org/wp-content/uploads/Documents/Current-docs/APPEC-Strategy-Book-Proof-19-Feb-2018.pdf
- https://arxiv.org/abs/1707.04591
- http://cds.cern.ch/record/2691414

▪ Dark Matter

✓ "Elucidating the nature of Dark Matter is a key priority at the **leading tip of astroparticle physics**" **(EU)**

✓ "Deciphering the **fundamental nature of dark matter** ... is one of the **foremost open questions in fundamental science** today with tremendous potential to deepen our understanding of the laws of Nature." **(US)**

▪ DM candidate WIMP / Axion, Experiment

✓ "Among the plethora of subatomic particles proposed to explain the Dark Matter content of our Universe, **one category stands out: the Weakly Interacting Massive Particle (WIMP)**." **(EU)**

✓ "Encourage the continuation of a **diverse and vibrant programme** (including experiments as well as detector R&D) searching for **WIMPs** and **non-WIMP Dark Matter**" **(EU)**

✓ "**Complete exploration of this parameter space** remains the **highest priority** of the dark matter community" **(US)**

✓ "The flagships of the US Dark Matter search program are the G2 experiments ADMX, LZ, and SuperCDMS, which will **cover well-motivated axion and WIMP dark matter** over a range of masses." **(US)**

✓ "The search for ultralight Dark Matter like the axion has gained significant momentum" **(ESPP)**

✓ "The search for the axion is a central task in particle physics" **(ESPP)**

▪ Technology for WIMP and Axion discovery

✓ "Converge around 2019 on a strategy aimed at realizing **worldwide** at least one **'ultimate' Dark Matter detector based on xenon** (~50 tons) **and one based on argon** (~300 tons), as advocated respectively by DARWIN and Argo." **(EU)**

✓ "SiPM will likely be on of the key enabling technologiee for Lar and Lxe based detectors" **(ESPP)**

✓ ''Confirmation by multiple experiments with independent detection searches and target is essential for a **convincing (WIMP) discovery**''' **(ESPP)**

✓ '' CERN support for selected dark matter programmes that can take critical advantage of technology developed at CERN can deliver a decisive boost of their sensitivy'' **(ESPP)**

More on Axion (1)

- CP-violating terms in QCD Lagrangian are allowed and should exist:

$$\mathcal{L}_{QCD} = -\frac{1}{2}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) + \Theta\frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{\mu\nu a} + \overline{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

Gluon Dynamics — from QDC vacuum; CP violating — kinetic Quark terms — Quark Masses

- This is a CP (or T)-violating term associated to QCD (the weak one exists and understood by Kobayashi/Maskawa)
- Yet, it is ~0 ($\Theta<10^{-10}$), as measured from neutron electric dipole moments ($<3\times10^{-26}$ e cm)
  → strong CP-problem (=naturalness pb). Why is Θ so small?? [$d_n \sim 2.4\times10^{-15}\,\Theta$ e cm]

  [every possible interaction in the SM has been measured to occur, with this only exception!]

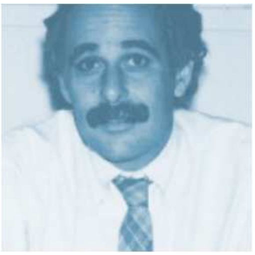
- Only viable solution: New global symmetry $U(1)_{PQ}$ (Peccei-Quinn, 1977), spontaneously broken at some large E scale → make Θ a dynamical variable ($\Theta=a/f_a$) [where a is the axion field, and f_a the new mass scale]
  - now, the QCD Lagrangian reads:

$$\mathcal{L}_{QCD} = -\frac{1}{2}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) + \overline{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi + \left(\Theta - \frac{a}{f_a}\right)\frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{\mu\nu a} + \frac{1}{2}\partial_\mu a\partial^\mu a$$

  - non-perturbative effects induce a potential for *a* with the minimum

$$a = \Theta f_a$$

  This cancels the Θ terms and restores *CP* symmetry



[nice analogy with a pooltable in hep-ph/9506229]

More on Axion (2)

- Axion → classical homogeneous field oscillating with frequency $\nu_a = m_a/(2\pi)$ [$\omega_a = m_a$]

As DM is highly non-relativistic ($v_a \sim 10^{-3}$), the associated De Broglie wavelength is large, i.e. larger than the detector

$$\lambda_{\rm dB} = \frac{2\pi}{m_a v_a} = 12.4\ \mathrm{m} \left(\frac{100\ \mu\mathrm{eV}}{m_a}\right)\left(\frac{10^{-3}}{v_a}\right)$$

→ the field is not propagating in space, i.e. the oscillations are coherent over the experiment

This comes from the relic oscillations around the minimum axion-field potential

$\nu_a \sim 10$ GHz for $m_a = 40\ \mu$eV

$\nu_a \sim 100$ GHz for $m_a = 400\ \mu$eV

→ $a(t) = a_0 \cos(m_a t)$

[a_0 drives the axion density $\rho_a = m_a^2 |a_0|^2/2 = \rho_{DM}$ → $|a_0| = \sqrt{(2\rho_{DM})}/m_a$]

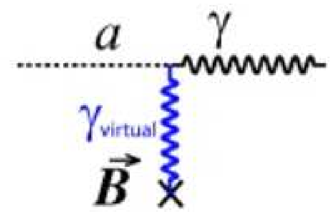
~300 MeV/cm^3

[Axion DM is highly degenerate Bose gas and can locally be thought of as classical field oscillating with frequency $m_a/2\pi$, i.e. in the microwave regime]

More on Axion (3)

- Axion field induces an homogeneous electric field in presence of a B field [Primakoff effect $a\gamma^* \rightarrow \gamma$]

Photon-photon-axion coupling: $\mathcal{L}_{a\gamma} = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}\, a$



$$g_{a\gamma} = -\frac{\alpha}{2\pi f_a} C_{a\gamma} = -2.04(3) \times 10^{-16}\ \mathrm{GeV}^{-1} \left(\frac{m_a}{1\,\mu\mathrm{eV}}\right) C_{a\gamma} \qquad C_{a\gamma} = \frac{\mathcal{E}}{\mathcal{N}} - 1.92(4)$$

0 for KSVZ and 8/3 for DFSZ

➔ $E_a(t) = -g_{a\gamma}/\varepsilon\, B_e\, a(t) = -E_0/\varepsilon \cos(m_a t)$ with $E_0 = g_{a\gamma} \cdot B_e \cdot a_0$ and ε the permittivity of the medium

- This electric field is oscillating with the same frequency as the axion field: $\omega = m_a$
- The amplitude E_0 is independent on m_a, as $|a_0| \propto \rho_a^{1/2}/m_a$ whereas $g_{a\gamma} \propto m_a$

  For $\rho_a = \rho_{DM}$ =300 MeV/cm³, E_0 can be rewritten as $E_0 = 1.3 \times 10^{-12}\ \mathrm{V/m}\, \frac{B_e}{10\ \mathrm{T}} |C_{a\gamma}|$.

- The associated energy density is $\frac{1}{2} E_a^2 = \frac{1}{2} E_0^2/|\epsilon|^2$ In vaccum (ε=1): $2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 C_{a\gamma}^2$

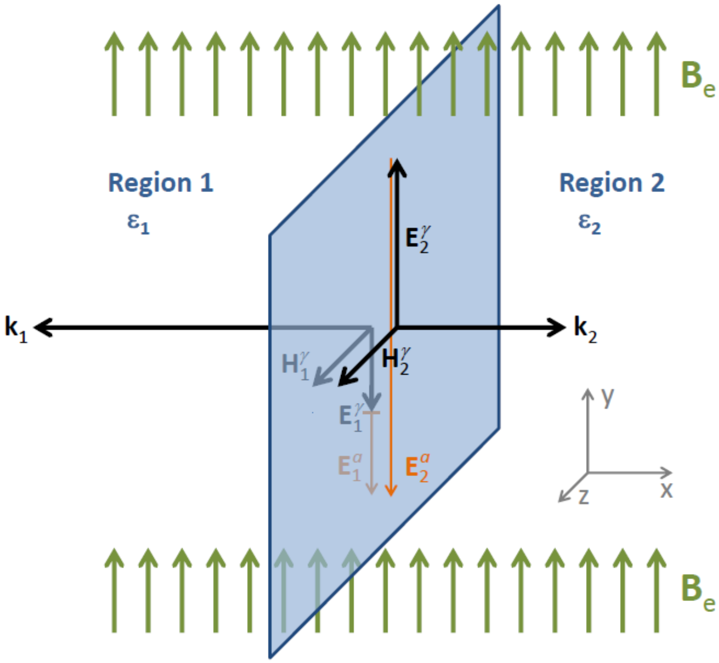
➔ extremelly tiny→ has to be enhanced to be measurable

Resonant cavity tuned to outgoing frequency $\nu_a = m_a/(2\pi)$

Dielectric interface to generate microwave photons propagating in both perpendicular directions
→ using multiple interfaces will boost the signal

More on Axion (4)

- The axion-induced electric field implies the emission of EM waves at dielectric interfaces, which are propagating in space



→ Jump of dielectric constant → field discontinuity $E^a_{1,2}\,e^{-i\omega t}$

[E_1^a prop to $1/\varepsilon_1$ and E_2^a prop to $1/\varepsilon_2$]

→ To restore continuity and match boundary conditions, EM waves emitted $E^\gamma_{1,2}\,e^{-i(\omega t - k_{1,2}x)}$

→ EM waves propagating away from the interface on either side in perpendicular directions [$k_1=-n_1\omega$ (wave moving in the negative x-direction), $k_2=n_2\omega$ (wave moving in the positive x-direction)]

$$E_1^\gamma = +\left(E_2^a - E_1^a\right)\frac{\epsilon_2 n_1}{\epsilon_1 n_2 + \epsilon_2 n_1},$$

$$E_2^\gamma = -\left(E_2^a - E_1^a\right)\frac{\epsilon_1 n_2}{\epsilon_1 n_2 + \epsilon_2 n_1},$$

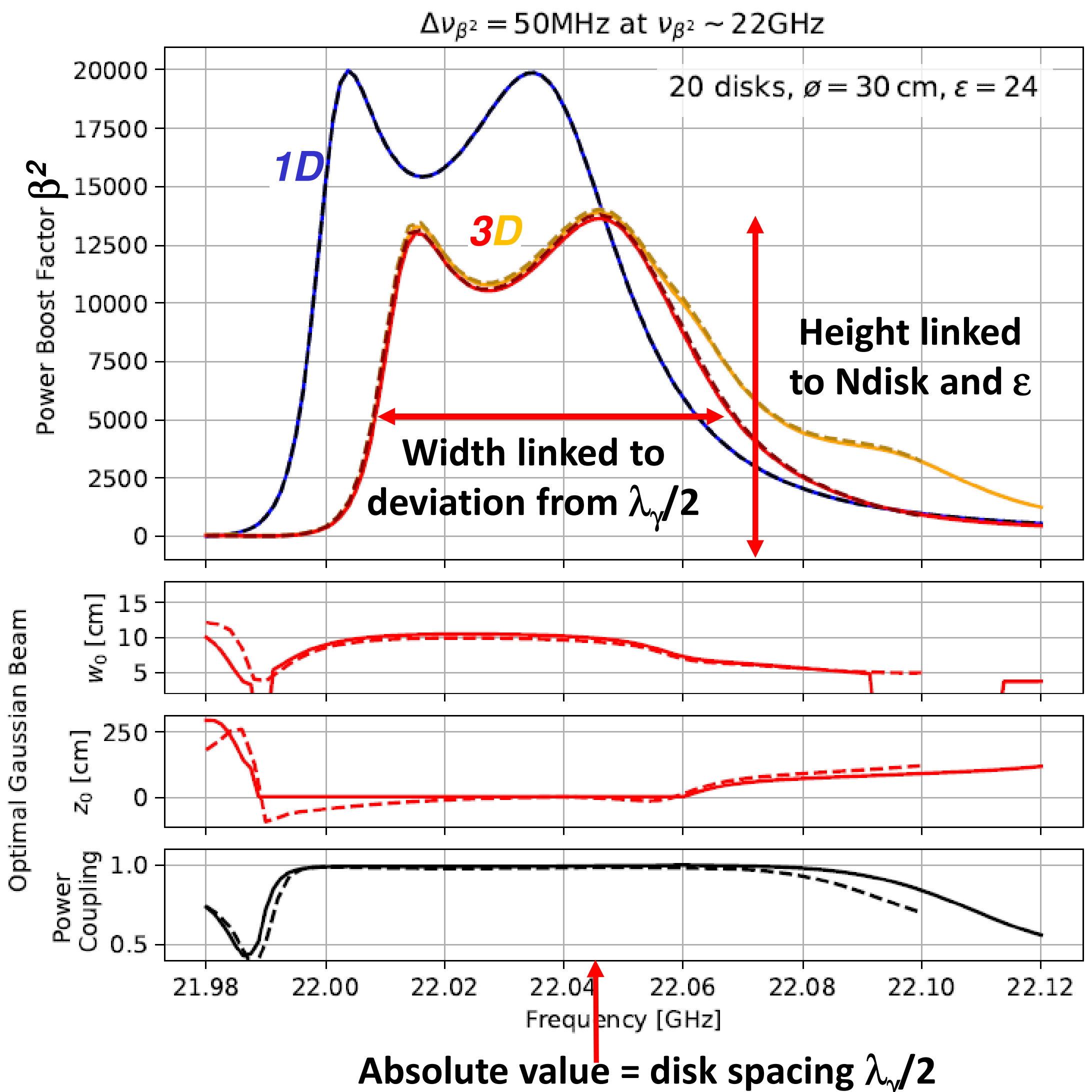
n=√ε

➔ $E_1^\gamma = -\frac{E_0}{n_1}\left(\frac{1}{n_2}-\frac{1}{n_1}\right)$ and $E_2^\gamma = +\frac{E_0}{n_2}\left(\frac{1}{n_2}-\frac{1}{n_1}\right)$

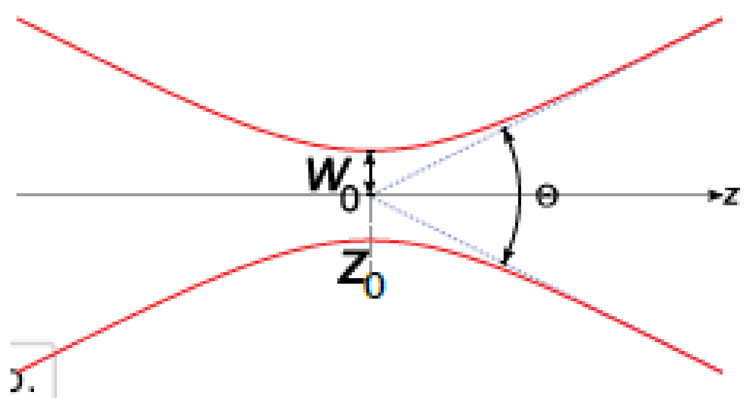
Remark: in the far receiver (outside of the B-field), the only EM fields will be those of these propagating waves (i.e. no E_a)

More on Axion (5)

- More elements on Boost factor (exemple for the prototype)



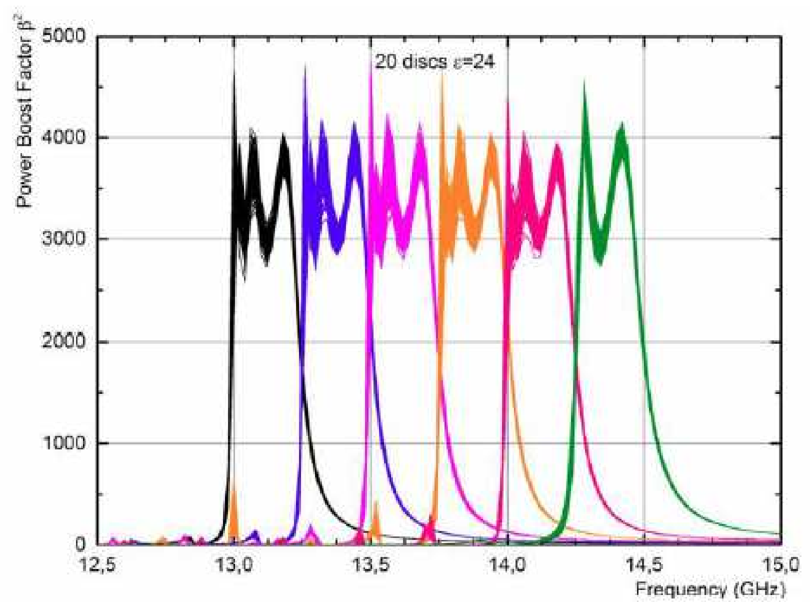
$$\frac{P}{A} = \beta^2 \frac{P_0}{A} = 2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \beta^2 \left(\frac{B_\mathrm{e}}{10\ \mathrm{T}}\right)^2 C_{a\gamma}^2$$



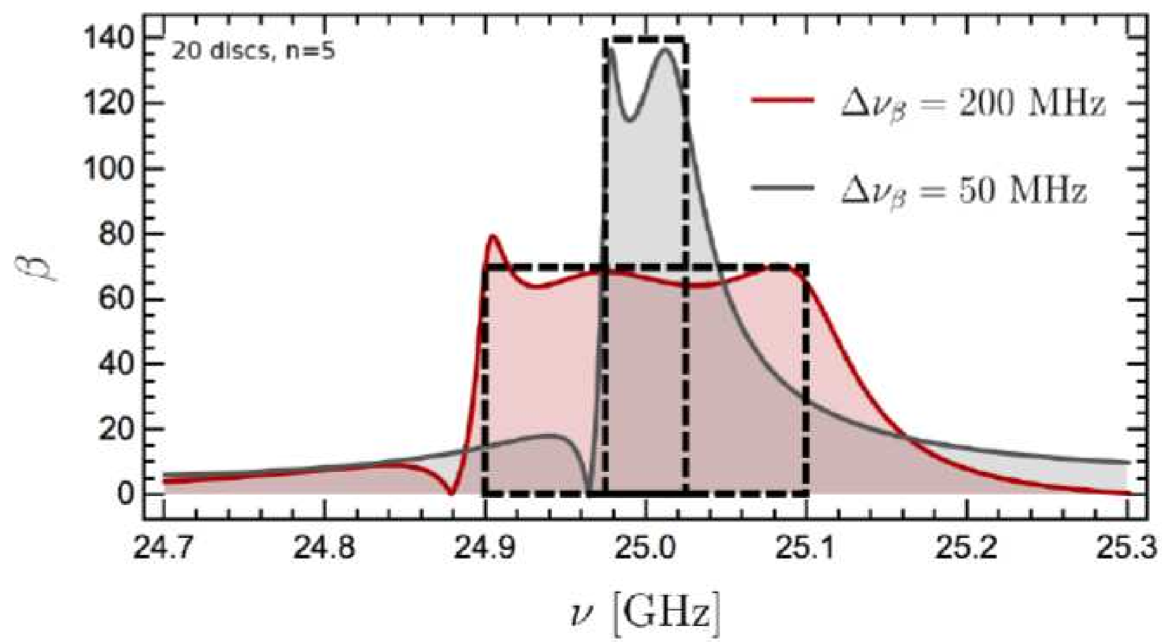
More on Axion (6)

- More elements on Boost factor

Tuning of sensitive frequency range by adjusting disc spacing



Area law: $\beta^2 \Delta\upsilon_\beta$ ~ const.
→ broad-band scan for search
→ narrow-band to confirm possible signals



More on Axion (7)

- Signal to Noise ratio (SNR) → Dicke radiometer equation

$$\mathrm{SNR} = \frac{P_{sig}}{k_B T_{sys}} \sqrt{\frac{t_{scan}}{\Delta\nu}}$$

t_{scan} = integration time at a given frequency

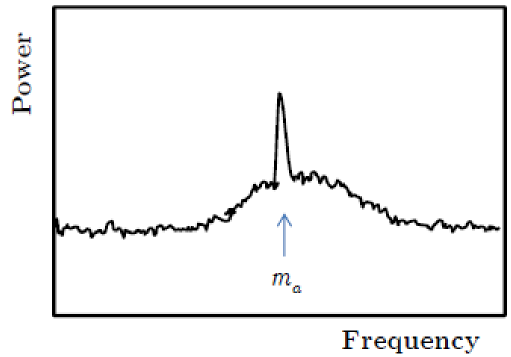
$\Delta\nu = 10^{-6}\nu_a$ given but the axion line width

$T_{sys} = T_{receiver} + T_{booster}$

	System	Receiver *	Booster
Prototype	9 K	5K*	4K
Final detector	4K	<100 mK **	4K

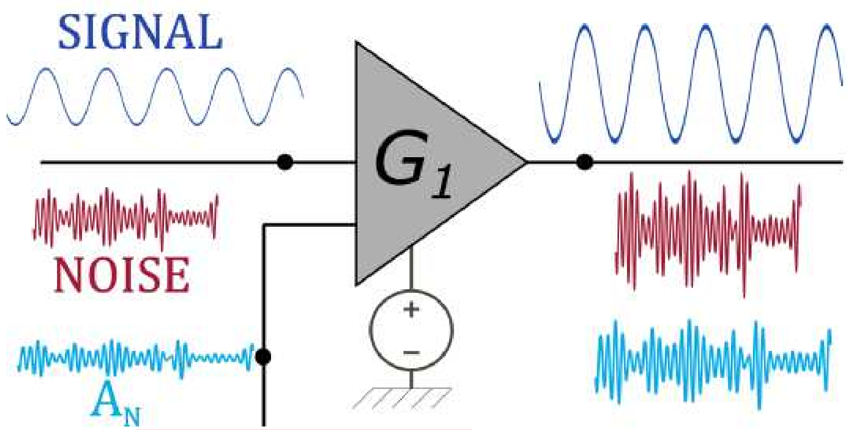
* High Electron Mobility Transistor (HEMT). Already used for the proof-of-principle set-up

** HEMT + Josephson Parametric Amplifier (JPA) in development



JPA

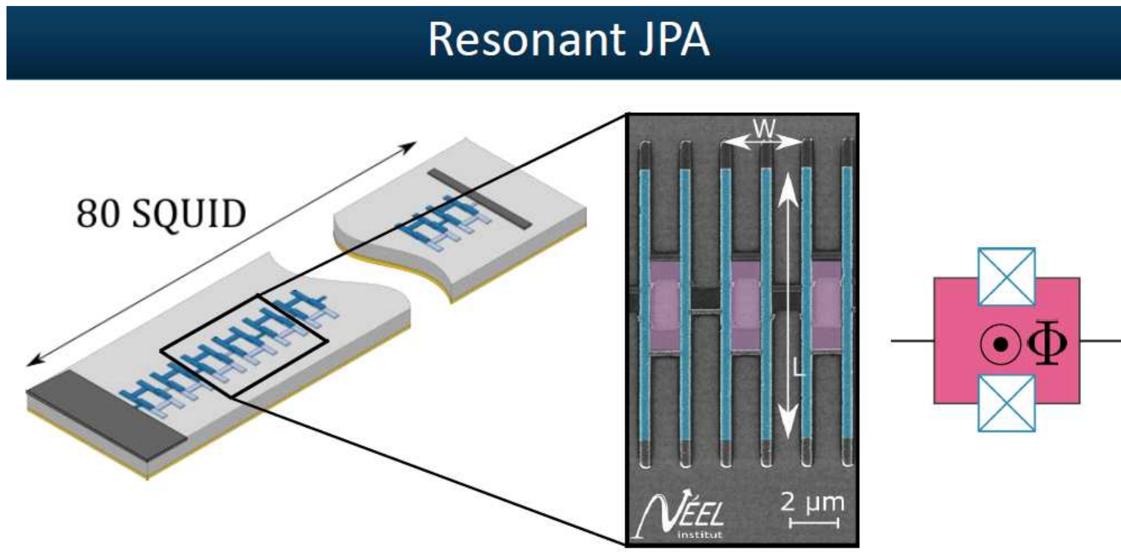
L. Planat (Néel institute)

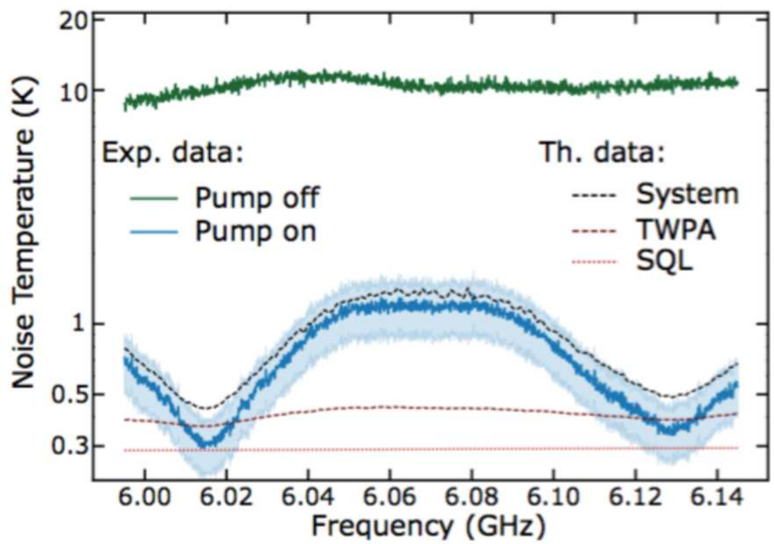


$$A_N \geq \frac{1}{2}|1 - G_1^{-1}|$$

Added noise

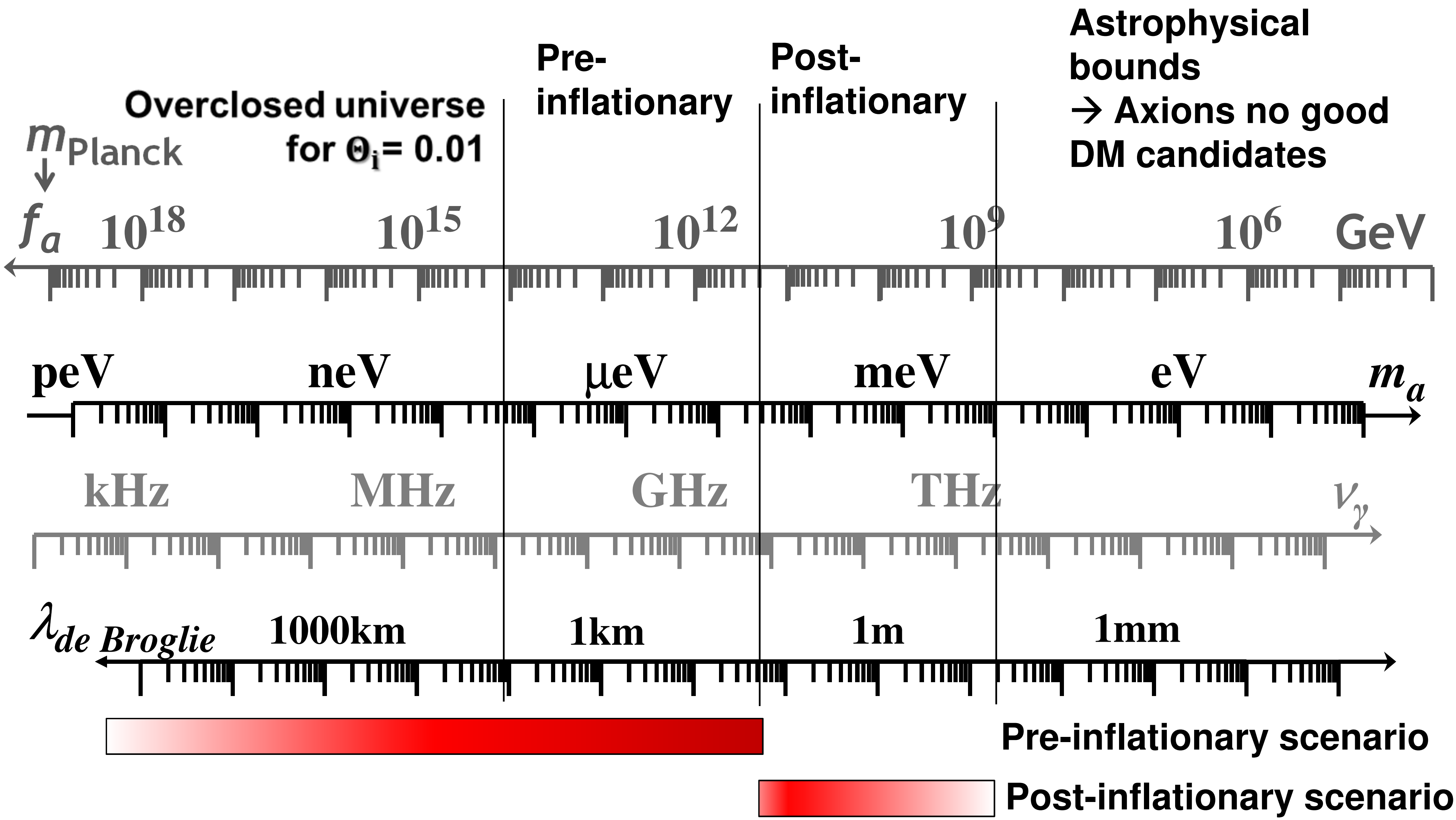
Quantum noise limit



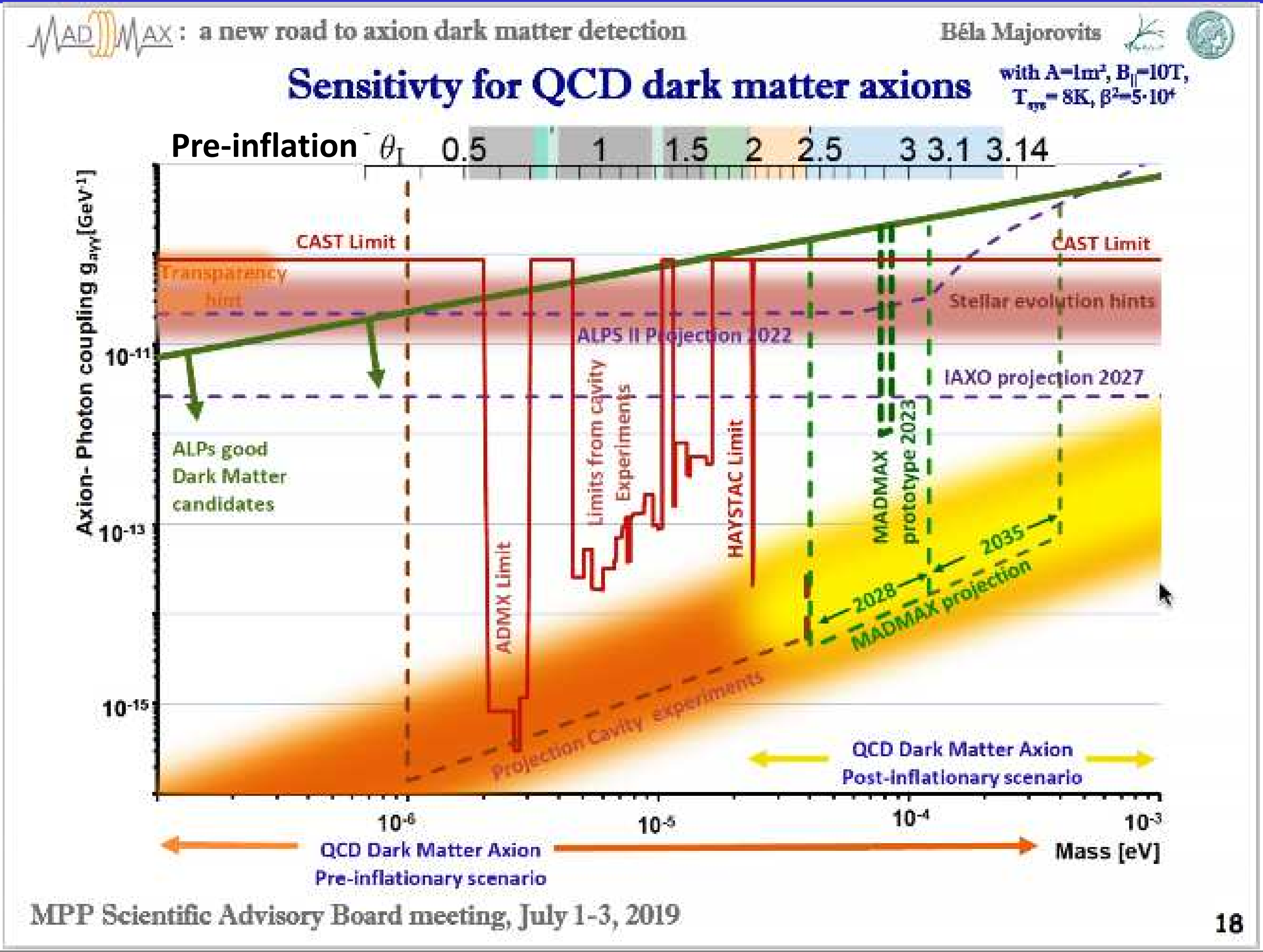


→ **Low noise and broadband**

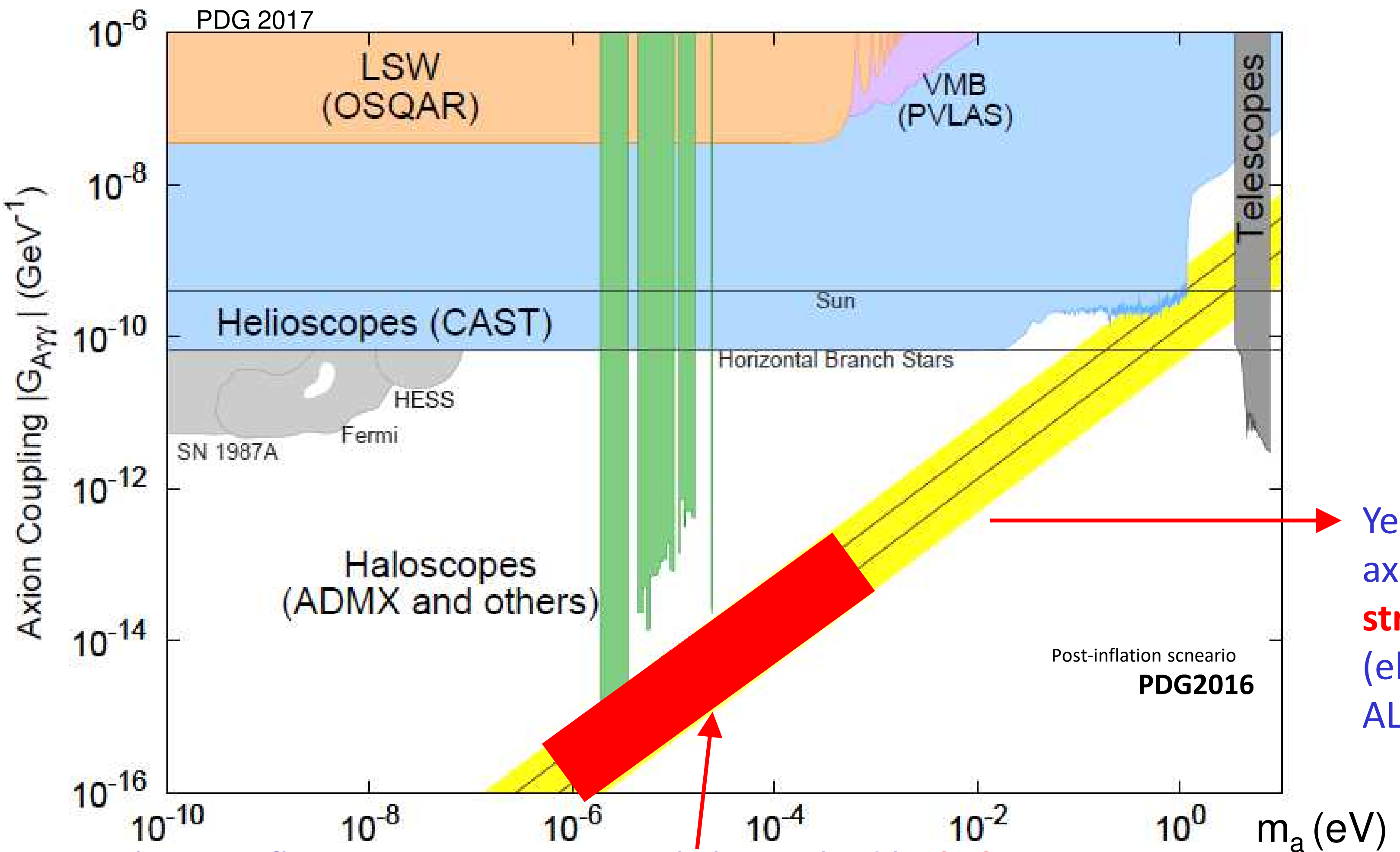
More on Axion (8)



More on Axion (9)



More on Axion (10)



Yellow band: QCD-axion, i.e. **solving strong CP** problem (elsewhere: ALP=axion-like part.)

Natural post-inflation QCD-axion can only be probed by **haloscopes**

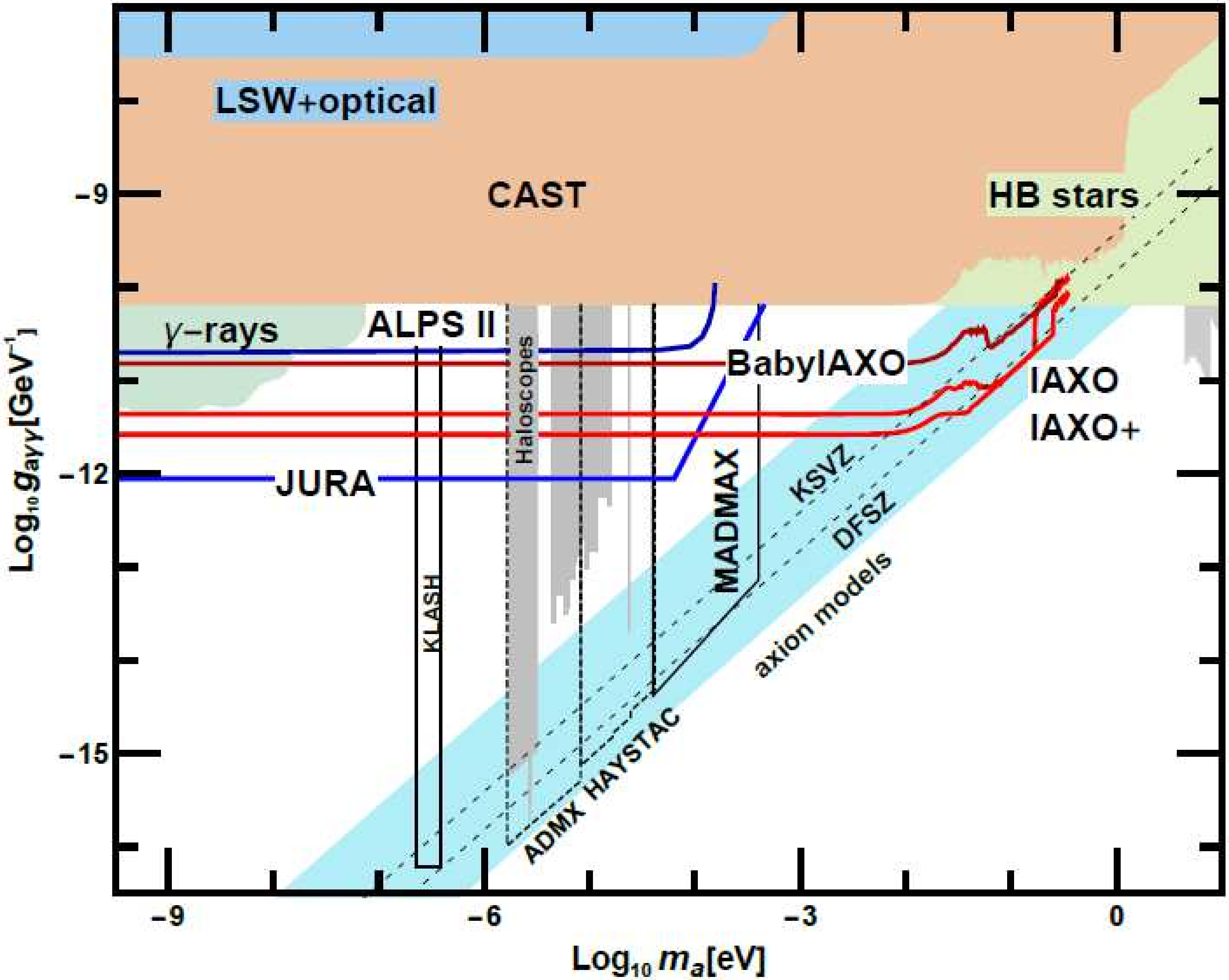
(assumed axions only present as Dark Matter wind from QCD realignement)

[(muucchh lower than neutrinos]

Extremely challenging because of extraordinary weak coupling of axions

More on Axion (11)

Projections from 2019 ESPP briefing book



More on Axion (12)

Axion phenomenology

- Some phenomenology depends on the **"axion model"**, e.g.
  - KSVZ axions are "hadronic axions" (no coupling with leptons at tree level)
  - DFSZ axions couple to electrons

Gluon coupling	Mass	Photon coupling	Fermion couplings
$\frac{\alpha_s}{8\pi f_a} aG\tilde{G}$	$m_A = 5.70(7)\mu\text{eV} \times \left(\frac{10^{12}\text{GeV}}{f_A}\right)$	$g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a$ $g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	Electron coupling Nucleon coupling ...
generic	*generic*	*generic but value model dependent*	*Model dependent*

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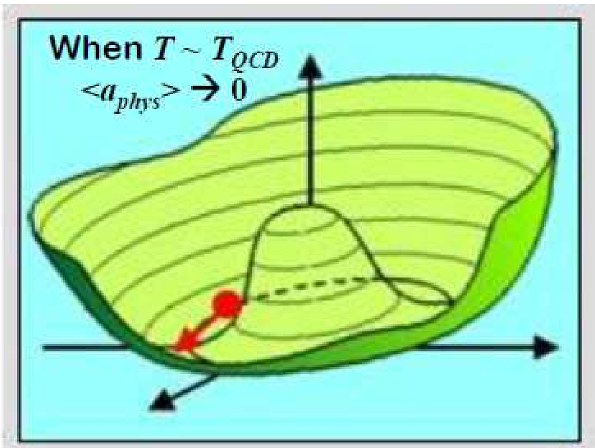
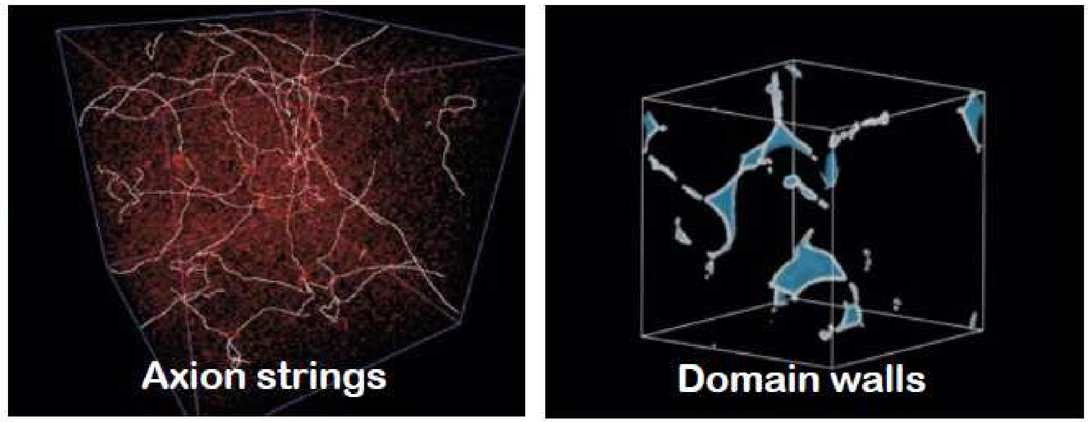
More on Axion (13)

Cosmological axions





Axion realignment

(initial misalignment angle?)

But also… topological defects

(inflation can wipe them out if it happens afterwards)

Note: thermal production of axions (as neutrinos) gives hot DM (upper limit ma~1 eV)

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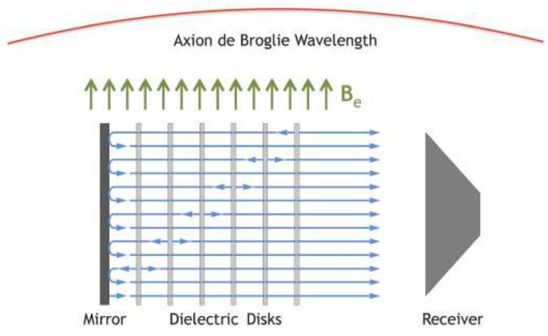
Directionality with MADMAX

1707.04266
1806.05927

- « Search / Discovery » mode = MADMAX with 80 disks



As DM is highly non-relativistic (v_a~10^{-3}), the associated De Broglie wavelength is large, i.e. larger than the detector with 80 disks

$$\lambda_{\rm dB} = \frac{2\pi}{m_a v_a} = 12.4\ \text{m} \left(\frac{100\ \mu\text{eV}}{m_a}\right)\left(\frac{10^{-3}}{v_a}\right)$$

- ➢ Velocity effects only important for haloscopes with a size >~20% of de Broglie wavelength
- ➢ Can be safely neglected for setup with 80 disks → Good (no model dependence of boost factor)
- ➢ Annual modulations could be detected for sufficiently long measurements

- « Axion telescope » mode → directionally sensitive to axion velocity

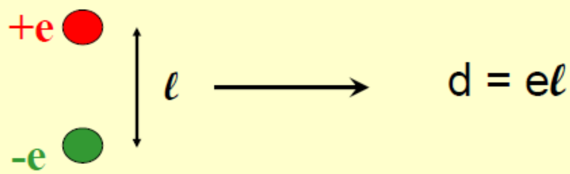
➔ Effects come from axion velocity in direction perpendicular to the disks (→ change in phase over the haloscope)

➔ need increased length of the device: O(1) effect if haloscope length similar to De Broglie wavelength

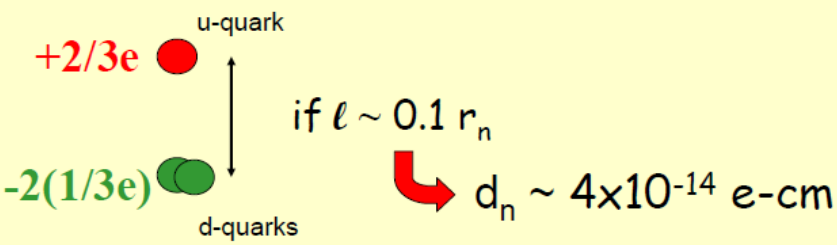
→ Use the same disks but increase separation between disks: from λ/2 → 3λ/2, 5λ/2
→ Increase the number of disks

Electric Dipole Moment

What is an EDM?



How big is the neutron EDM?

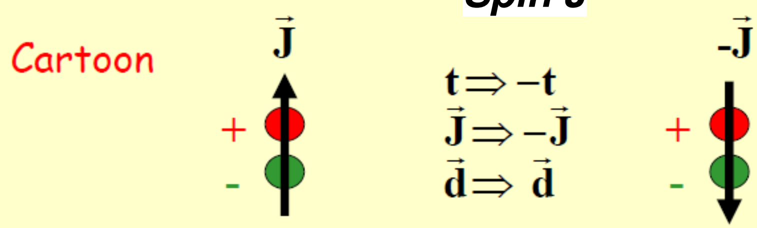


Experiment says $d_n < 3x10^{-26}$ e-cm

Why Look for EDMs?

- Existence of EDM implies violation of Time Reversal Invariance

Spin J

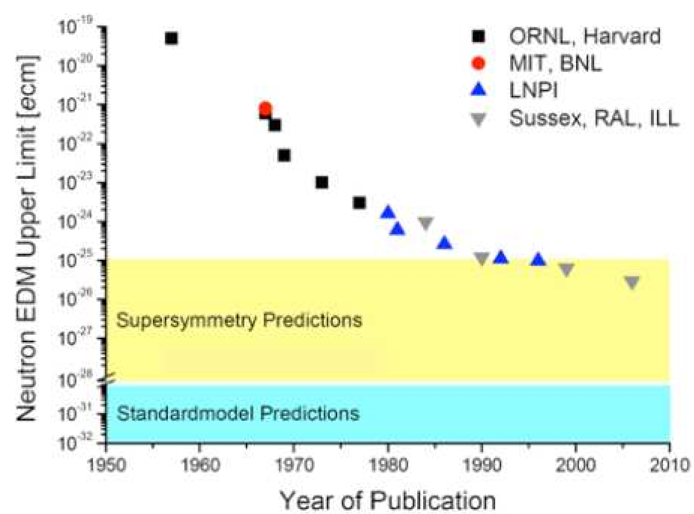


- Time Reversal Violation seen in K^0-$\overline{K}^0$ system
- May also be seen in early Universe
  - Matter-Antimatter asymmetry

but the Standard Model effect is too small !

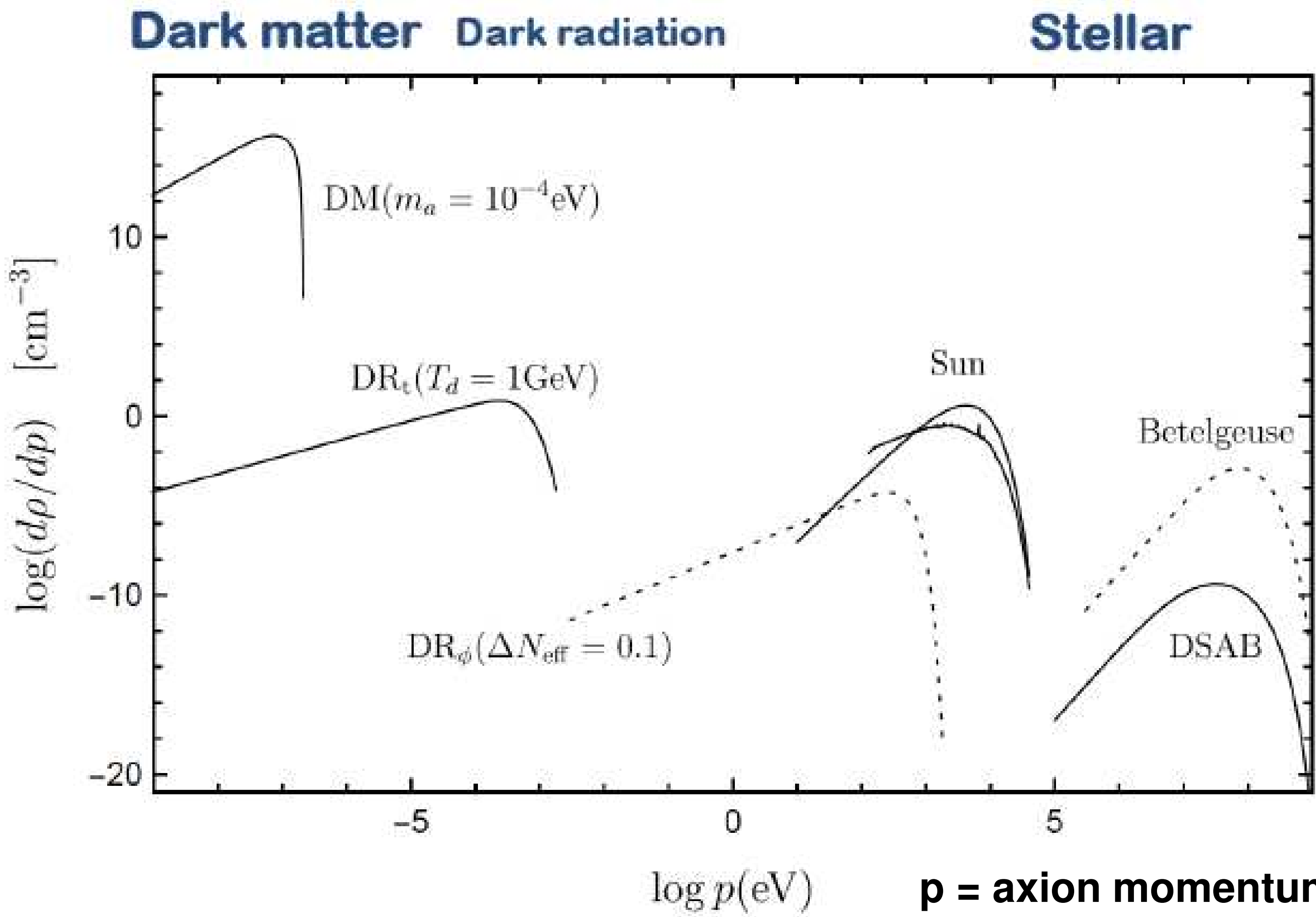
Non-zero d violates T and CP
(Field Theories generally preserve CPT)

NOTE: neutron magnetic dipole moment measured since the 40's



Axion experiments (1)

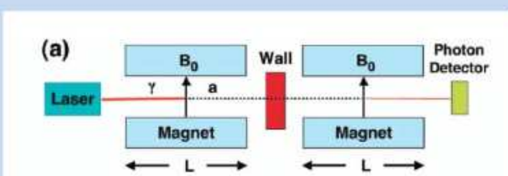
- Sources axions

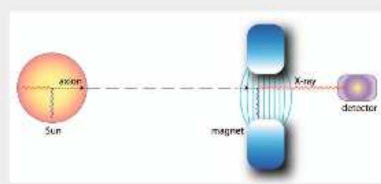


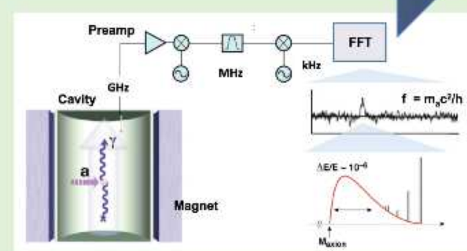
p = axion momentum

Axion experiments (2)

Lab Experiments	Helioscopes	Haloscopes
Axion Like Particle	ALPS & QCD Axion	ALPS & **QCD Axion**
Wide band experiment	Wide band experiment	Resonance experiment
Optical photons	X rays photons	Microwave photons
Model independent	Model dependent	Strong model dependency
Low axion flux	Medium axion flux	High axion flux
Low sensitivity to alps coupling	Good sensitivity to alps coupling	Reaches axion models

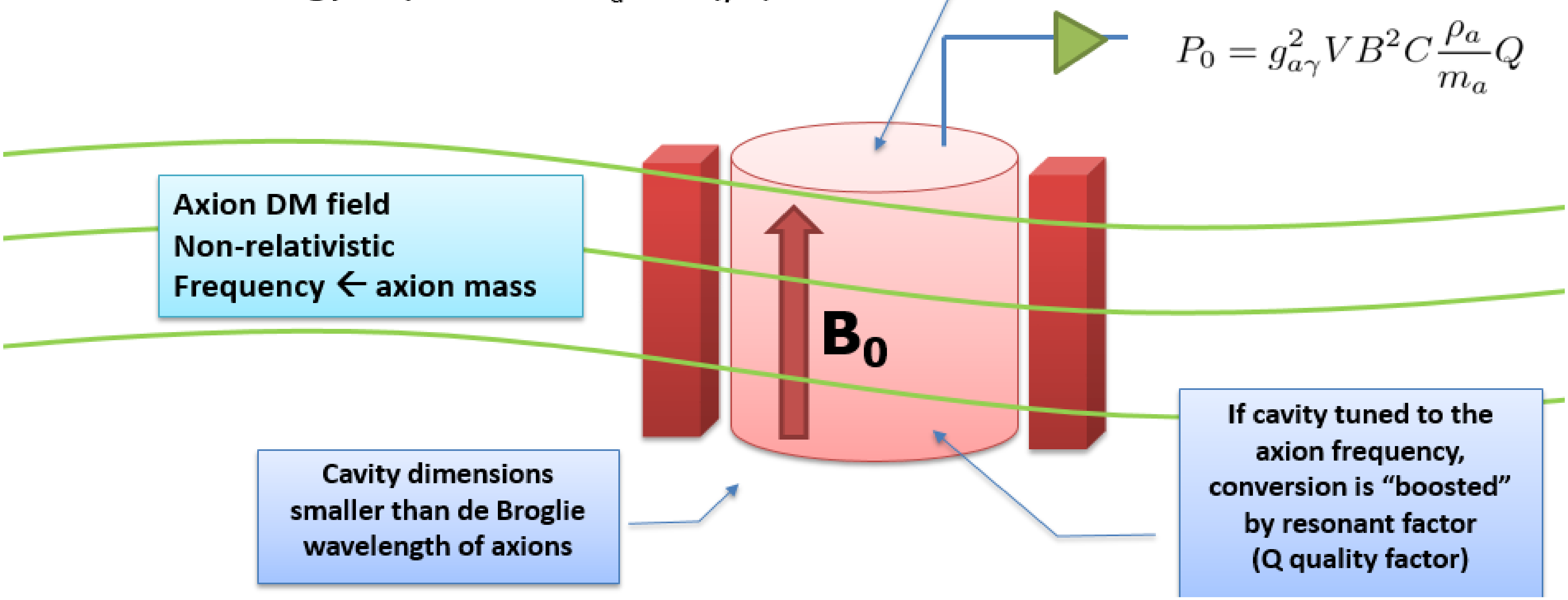






Axion experiments (3)

- Resonant cavities (Sikivie,1983)
  - Primakoff conversion inside a "tunable" resonant cavity
  - Energy of photon = $m_a c^2 + O(\beta^2)$



$$P_0 = g_{a\gamma}^2 V B^2 C \frac{\rho_a}{m_a} Q$$

Courtesy of I. G. Irastorza

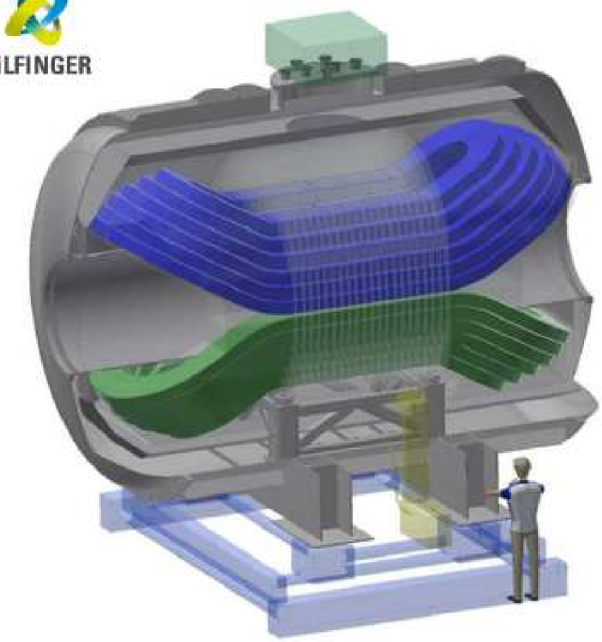
MADMAX (1)

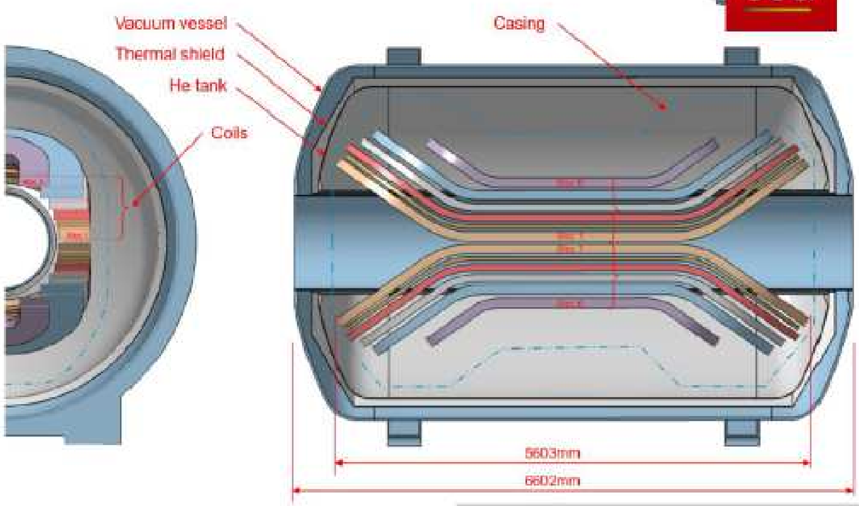
Magnetized Disc and Mirror Axion eXperiment

The MADMAX collaboration

associate members

MADMAX (2)





Block design with NbTi as superdconductor

- Magnet design and construction drives the time scale of the project
- **Peak field 9 T**, homogeneity < 20%
- Length ~ 1 m, **Ø ~ 1.5 m**

First ever!

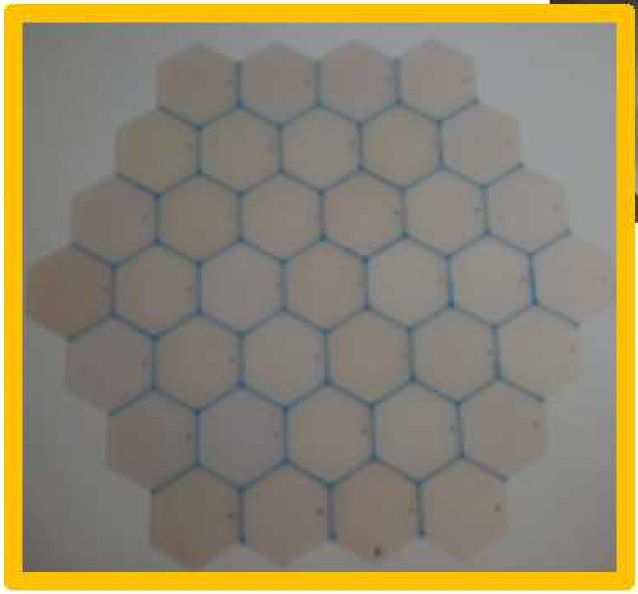
FoM = B^2 m^2 = 100 T^2 m^2

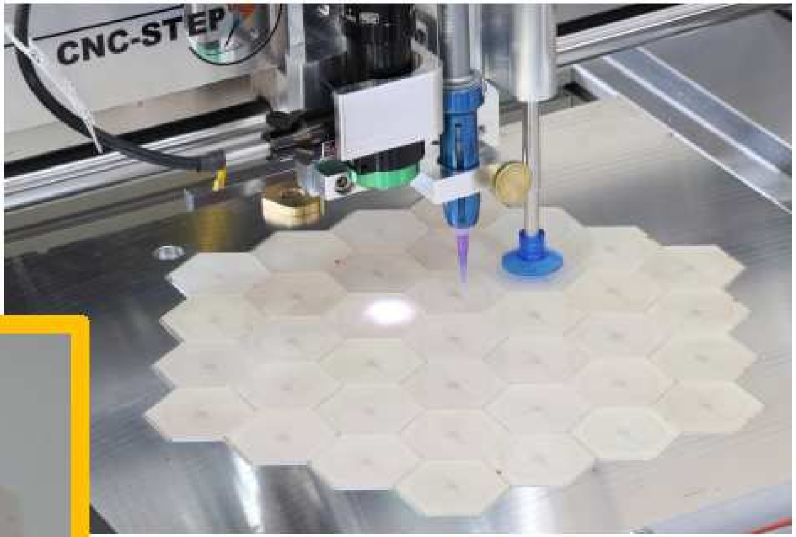
MADMAX (3)

- Discs with **Ø = 1.25 m** needed for **FoM = $B^2 m^2$ = 100 $T^2 m^2$**
- Candidate materials:
  - **$LaAlO_3$ (ϵ ≈ 24, *tanδ* ≈ a few 10^{-5})**
  - Sapphire (ϵ ≈ 9, *tanδ* ≈ 10^{-5})
- $LaAlO_3$ grown in 3" wafers max
- Tiling necessary

- Hexagonal tiles cut by laser cutter
- Glued with Stycast-blue

- Characterisation of dielectric properties @ 4 K, f = 10 - 15 GHz ongoing





First tiled $LaAlO_3$ disc:
Ø = 30 cm
d = 1 mm
Single wafer size 2"
Procedure scalable to Ø = 1.25 m

MADMAX (4)

Dielectric disc, chose material:

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

→ Sapphire (Al_2O_3) @ 300K, 10 GHz:

$$\varepsilon \sim 10; \qquad \tan\delta \sim few \cdot 10^{-5}$$

→ Lanthanide Aluminate ($LaAlO_3$) @ 77K

$$\varepsilon \sim 24; \qquad \tan\delta \sim 3 \cdot 10^{-5}$$

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

$$\varepsilon \sim 100; \qquad \tan\delta \sim 10^{-6}$$

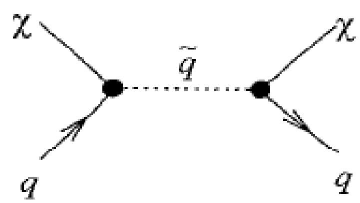
More on WIMPs

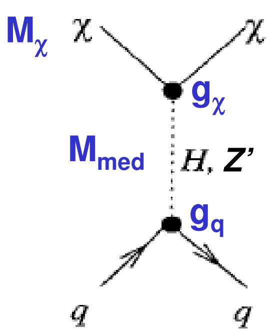
❑ (Short) Theoretical motivations

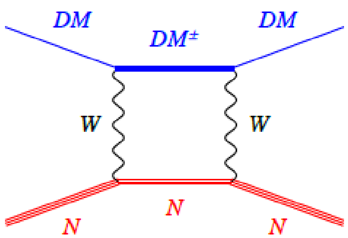
- **Cosmology (80s):**
  - ✓ WIMP produced "thermally"* in the very early Universe (after inflation)
  - ✓ Universe cools down + expands and WIMP co-annihilation stops → a very small fraction survives → correct relic density if **m=O(100) GeV and weakly interacting ➔ WIMP**

- **Particle physics (70s-80s):**
  - ✓ Need to protect the Higgs vacuum from quantum fluctuations
    ➔ SUSY particles + R-Parity** → **Majorana fermion** lightest SUSY particle (LSP) stable
  - ✓ LSP matches the WIMP Properties: **WIMP miracle**

- Elastic scattering on nucleon via unknown **Mediator** :





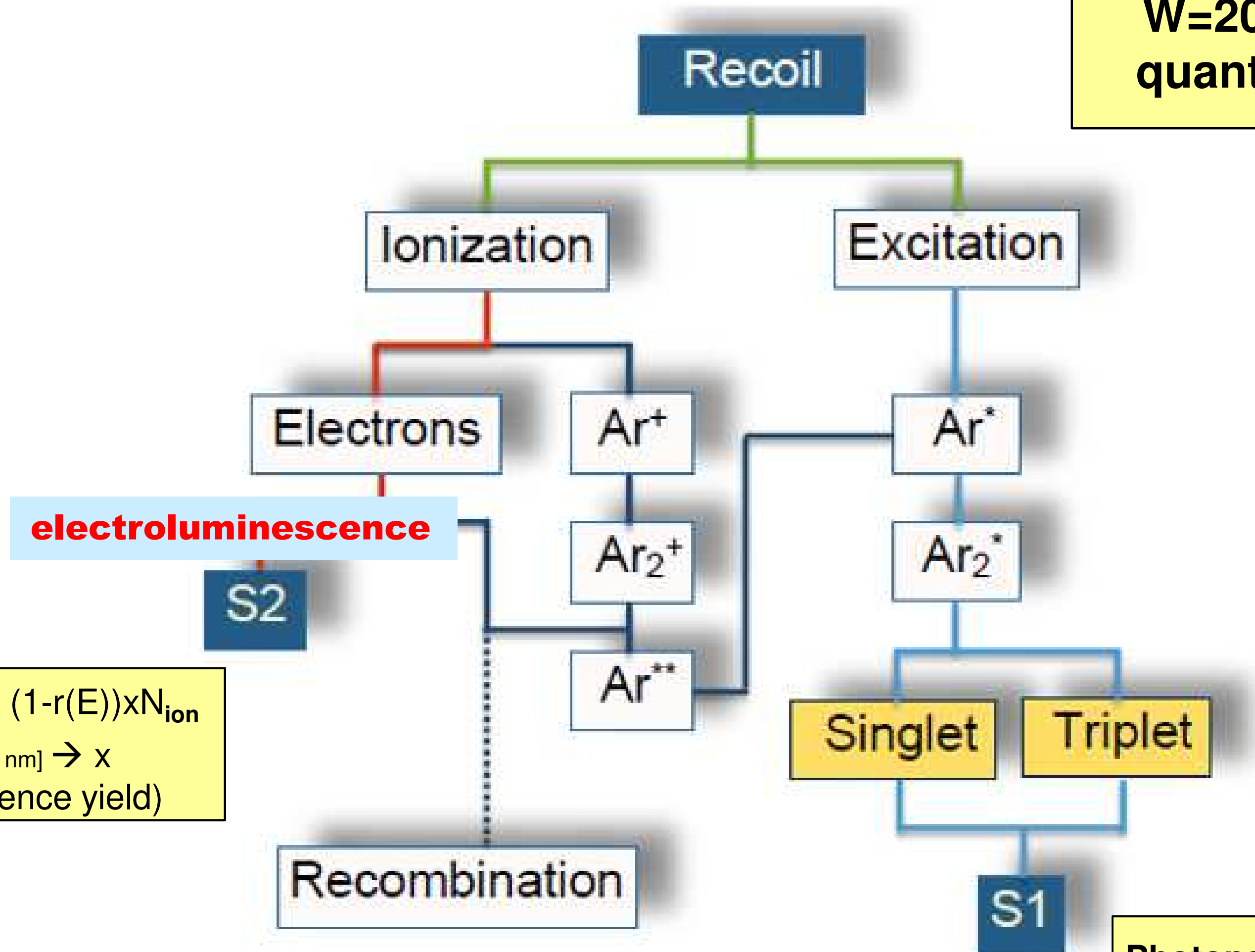


➔ "Natural" DM WIMP window: m_χ=10-10000 GeV

* In thermal equilibrium with SM particles ("freeze-out")   ** Other BSM theories work with similar principles (but not necessary Majorana type)

Lar scintillation and ionization

W=20 eV to produce 1 quantum (e or photon)



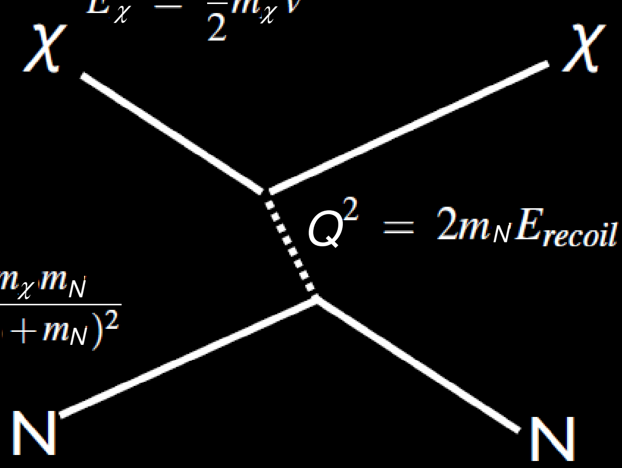
Electrons S2 = (1-r(E))xN_{ion}
(photons [128 nm] → x electroluminescence yield)

Photons (128 nm) **S1**
=N_{ex}+r(E)xN_{ion}

Xenon vs Argon (1)

❑ Elastic scattering of WIMP on Nucleon

$$E_\chi = \frac{1}{2} m_\chi v^2$$



$$Q^2 = 2 m_N E_{recoil}$$

$$r = \frac{4 m_\chi m_N}{(m_\chi + m_N)^2}$$

$$E_{recoil} = E_\chi \, r \frac{(1 - \cos\theta)}{2}$$

Spin Independent: **Ar (A=40), Xe (A=131)**

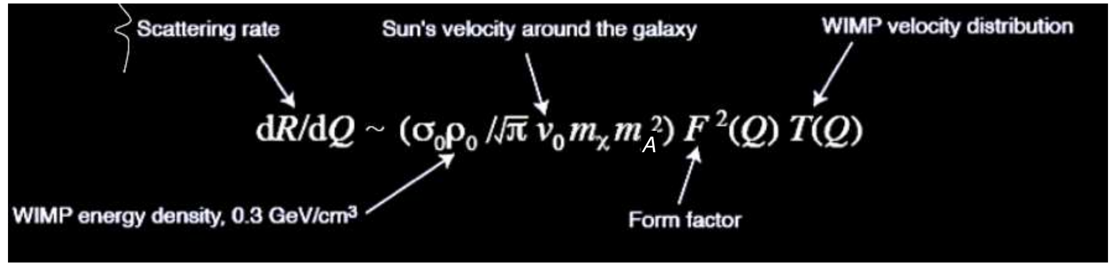
χ scatters coherently off of the entire nucleus A: $\sigma \sim A^2$

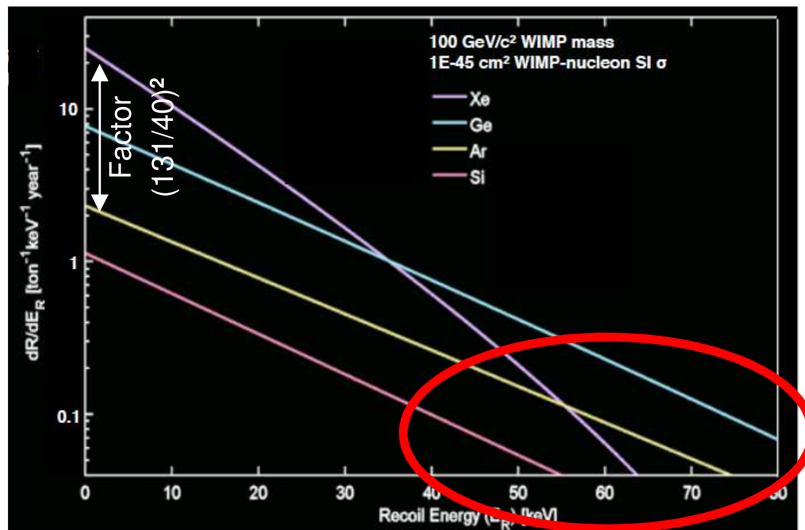
D. Z. Freedman, PRD 9, 1389 (1974)

Spin Dependent: **Xe (Ar is spinless)**

mainly unpaired nucleons contribute to scattering amplitude: $\sigma \sim J(J+1)$

❑ Expected rate (R) in the experiment





Convoluted with E reco. in the expt.

R~1 evt/(ton.yr) for $\sigma = 10^{-47}$ cm^2

- ***Nuclear Recoil:*** *10-100 keV*
- ***LAr wrt Lxe event rate:***
  - SI cross-section ~10 times lower ($\sigma \sim A^2$)
  + But energy transfer ~3 more efficient since radius smaller → higher form factor F ($F^2 \sim A^{-5/6}$)
  + Higher energy recoil → more "golden events" but lower sensitivity for m_χ=10-100 GeV

Xenon vs Argon (2)

❑ Detection of elastic WIMP scattering driven by noble atom properties …

	Ar	Xe	Consequence for DM search
Spin J	0 (^{40}Ar)	3/2 (^{131}Xe)	σ_{SD} ~ J(J+1) → **SD only possible for LXe**
Atomic Mass (u)	40	~132	σ_{SI} ~ A^2 → σ_{Xe} = **10**xσ_{Ar}, E^{rec}_{Xe} << E^{rec}_{Ar} → **More events for LXe** → **More golden events for LAr**
Radius (pm)	71	108	Form factor F : F_{Ar} ~ **3**xF_{Xe} → **Better energy transfer for LAr**
Fast / Slow Scintillation (ns)	6/1000	6/27	**Background free mode for LAr @ high mass** (remove all ER with pulse shape discrimination)

❑ … naturally leads to a complementarity btw Xenon-nT vs DarkSide-20k

1 — 10 — 100 — 10000 M (GeV)

LAr >> LXe

- Small signal better for Ar (m_{Ar} < m_{Xe})
- NR energy ~3 times less quenched for LAr
- S2only: Background under control for LAr

LXe >> LAr

- Medium signal better for Xe (σ_{Xe} = 10xσ_{Ar})
- Minimum of the sensitivity proport. to 1/A
  → better for Xe

LXe ~ LAr

- High signal better for Xe (σ_{Xe} = 10xσ_{Ar})
- LAr larger volume, form factor & golden events
- Background free mode for LAr (LHood for LXe)
- Having 2 expt. central to cross-check discovery

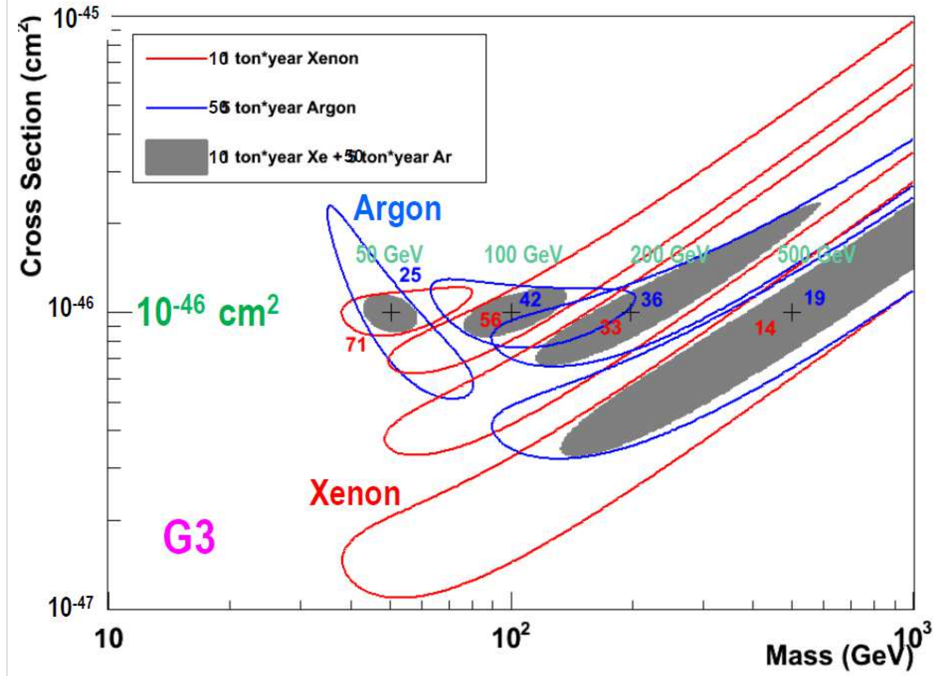
→ LAr and LXe complementary to cover 1-10000 GeV range !

Xenon vs Argon (3)

Properties of Noble Liqud

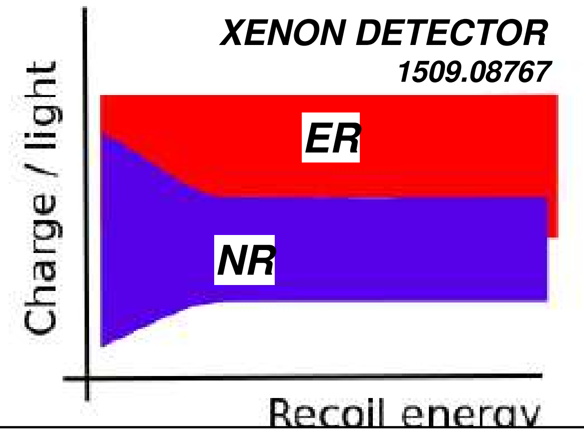
	Unit	Neon	Argon	Xenon
Z		10	18	54
A		20	40	~132
Liquid Density	*g/cc*	1.21	1.4	3.06
Energy Loss (dE/dX)	*MeV/cm*	1.4	2.1	3.8
Radiation Length	*cm*	24	14	2.8
Collision Length	*cm*	80	80	34
Boiling Temperature	*°K*	27.1	87.3	165
Scintillation Wavelength	*nm*	85	125	178
Scintillation	*photon/keV*	30	40	46
Ionization	*e-/keV*	46	42	64
Decay time (Fast Component)	*nsec*	19	7	4
Decay time (Slow Component)	*nsec*	1500	1600	26
Isotope		No	^{39}Ar (1 Bq/kg)	^{136}Xe
Price	*$ /ton*	$90k	~$2k	~$1M
Single Phase Experiments		CLEAN	DEAP/CLEAN	XMASS
Double Phase Experiments			WARP, ArDM, DarkSide, MAX	ZEPLIN, XENON, MAX LUX, LZD

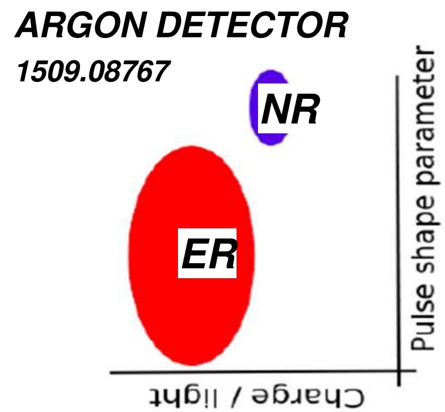
6/1/2011 *Katsushi Arisaka, UCLA* *8*



Astro. Phys. 36 (2012) 93, 1107.1295

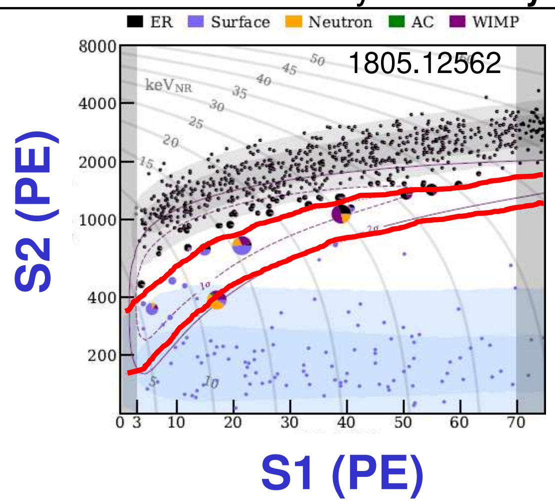
Xenon vs Argon (4)

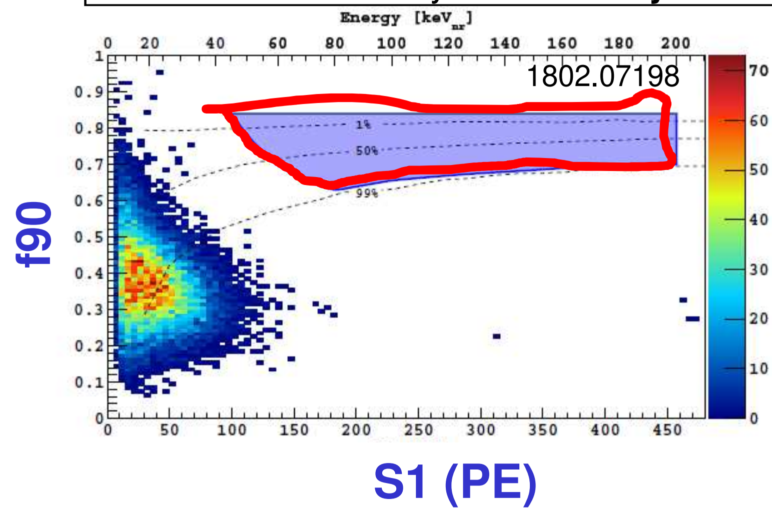




XENON-1T 2018 result: in SR, nB=7.36+/-0.61
1.3 t x 280 days → **1 t x yr**

DS-50 2018 result: in SR, nB=0.09+/-0.04
0.04 t x 532 days → **0.05 t x yr**

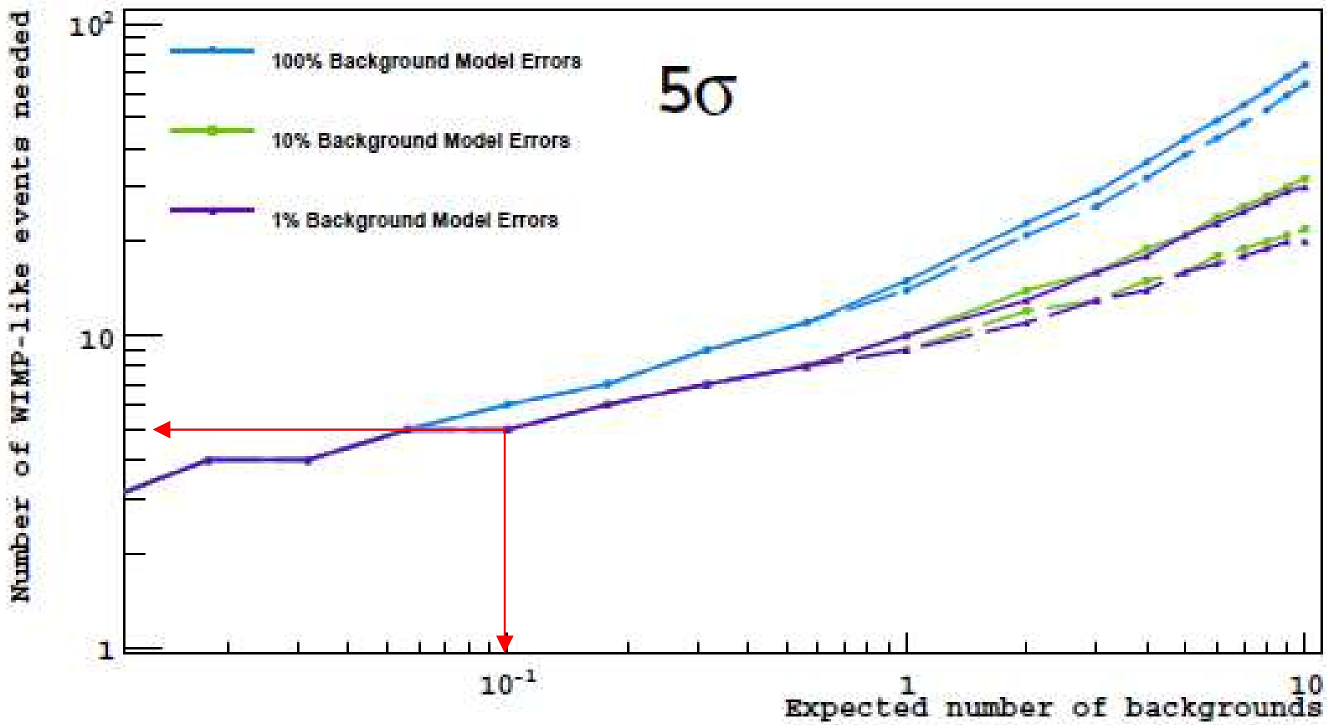




→ Argon detectors are background free → better for discovery

Xenon vs Argon (5)

- **Sensitivity discovery is driven by nB**
  - With nB = 0.1+(and <100% error) need only 5 evts !

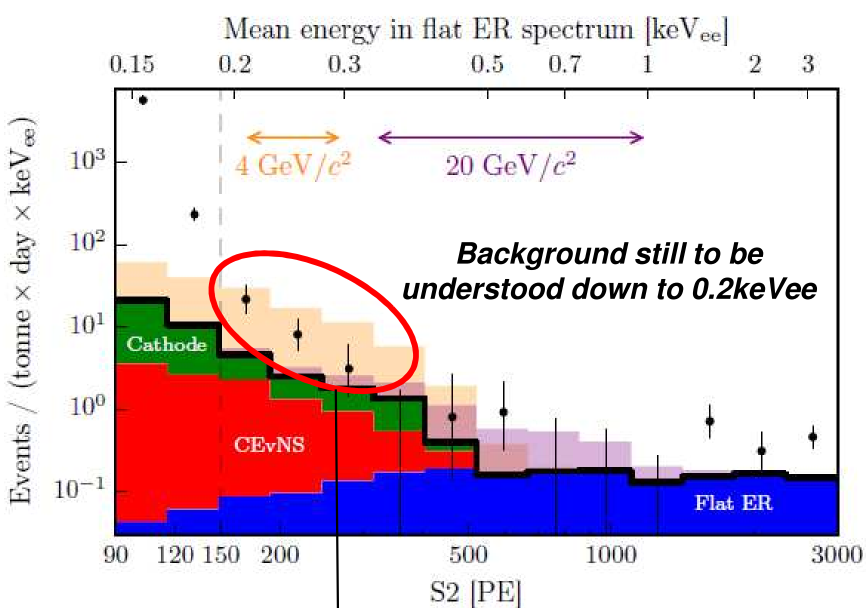


➔ Argon detectors are background free → better for discovery

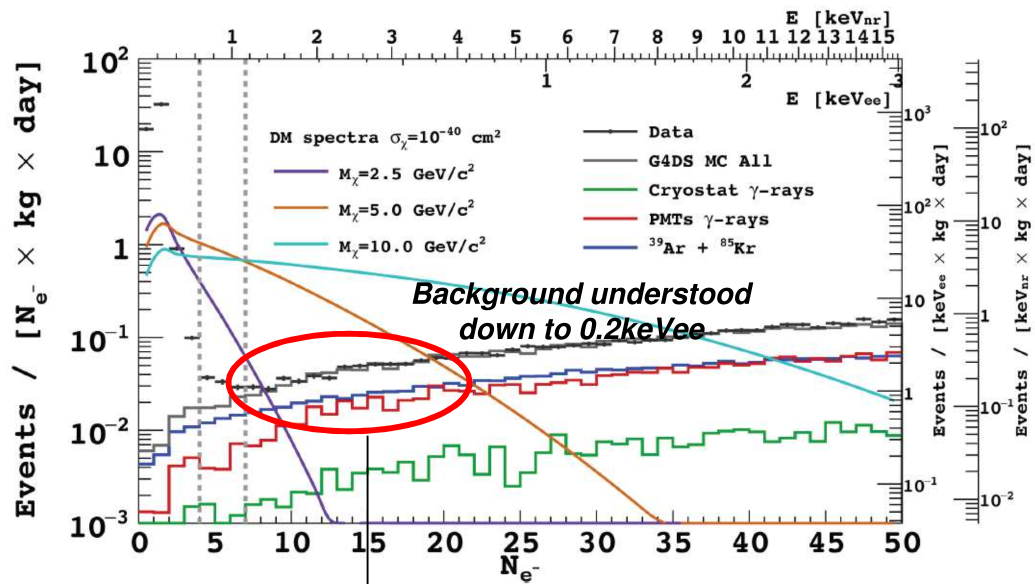
Xenon vs Argon (6)

❑ S2 Spectrum for low-mass analysis

Xenon-1T	***DarkSide-50***
1907.11485	***1802.06994,*** PRL **121** (2018) 081307



While a complete model of backgrounds in the S2-only channel is unavailable,

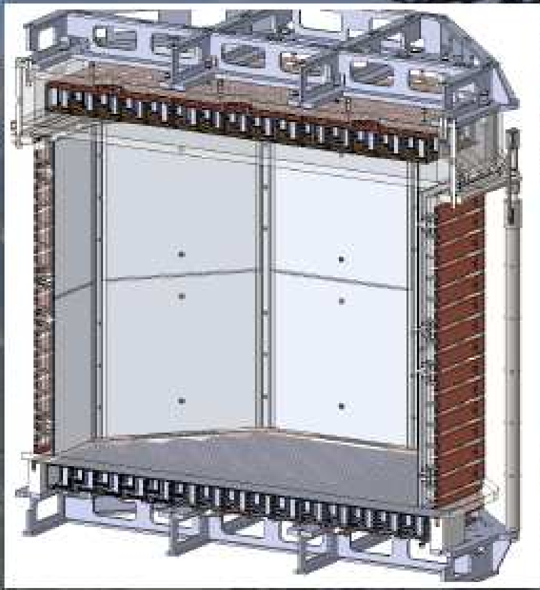


where the background is described within uncertainties by the G4DS simulation.

The DarkSide program at LNGS

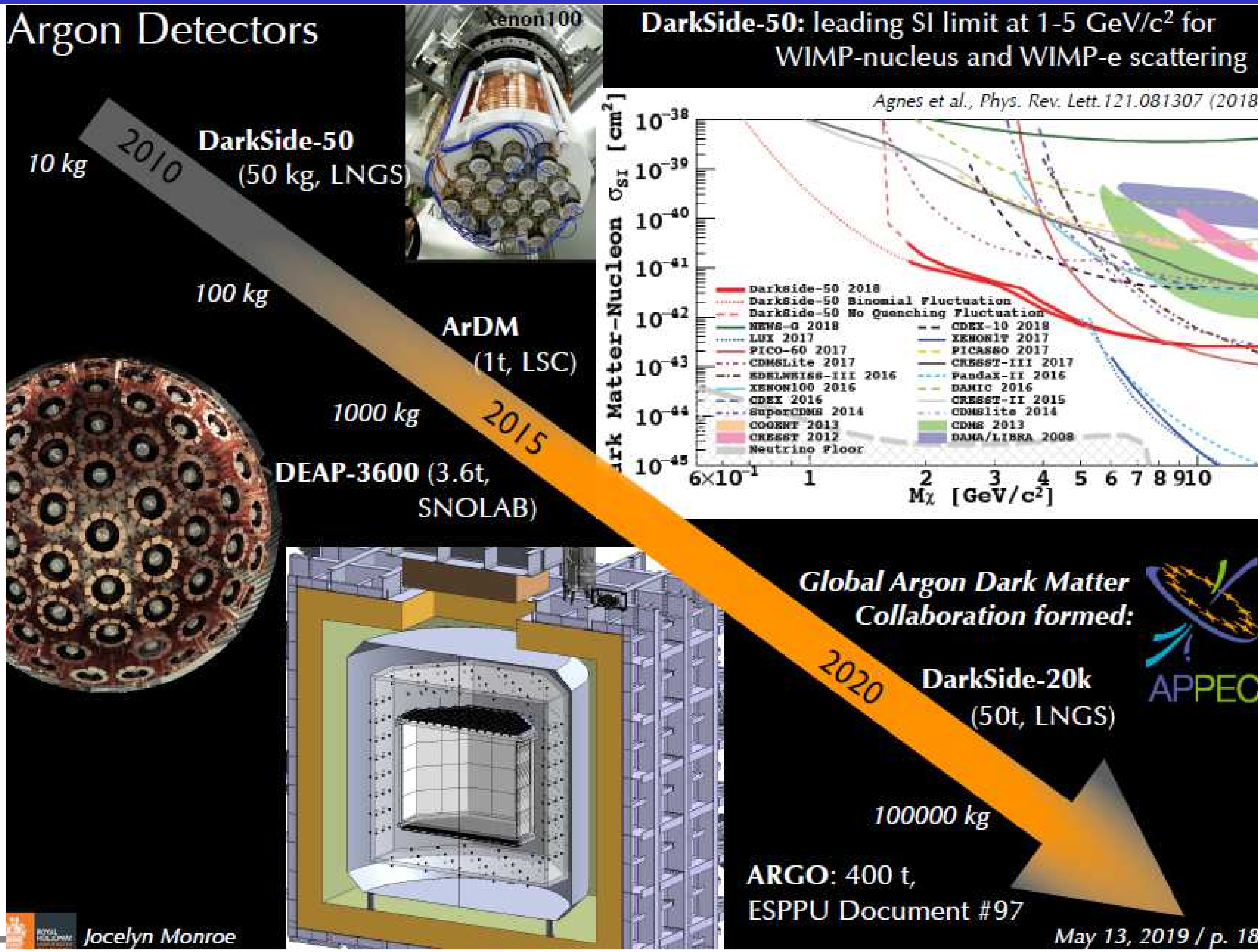
A scalable technology for direct WIMP search:

2-phase low background Argon TPC

DarkSide-10	DarkSide-50	DarkSide-20k
		
technical prototype no DM goal	sensitivity 10^{-44} cm^2	sensitivity 10^{-48} cm^2

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022

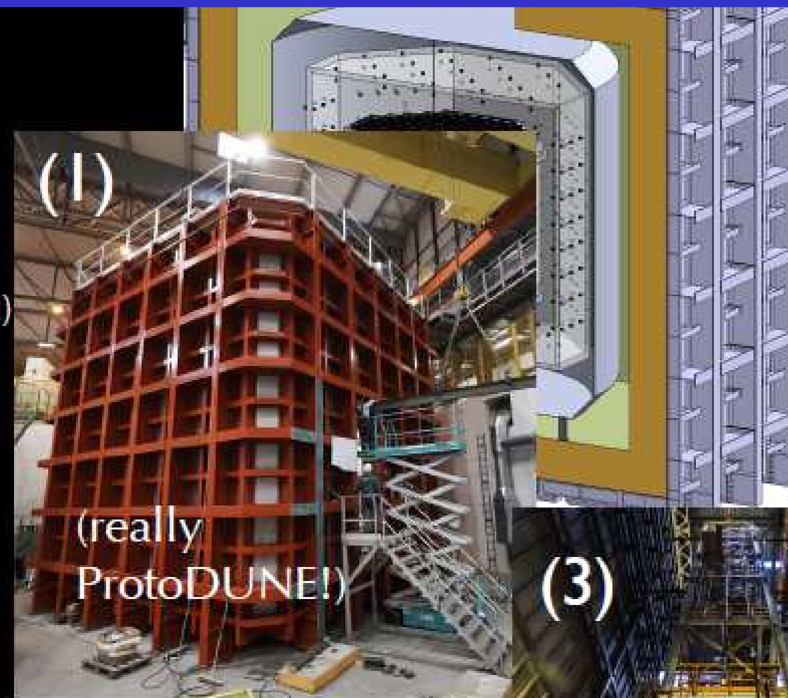
DarkSide (1)

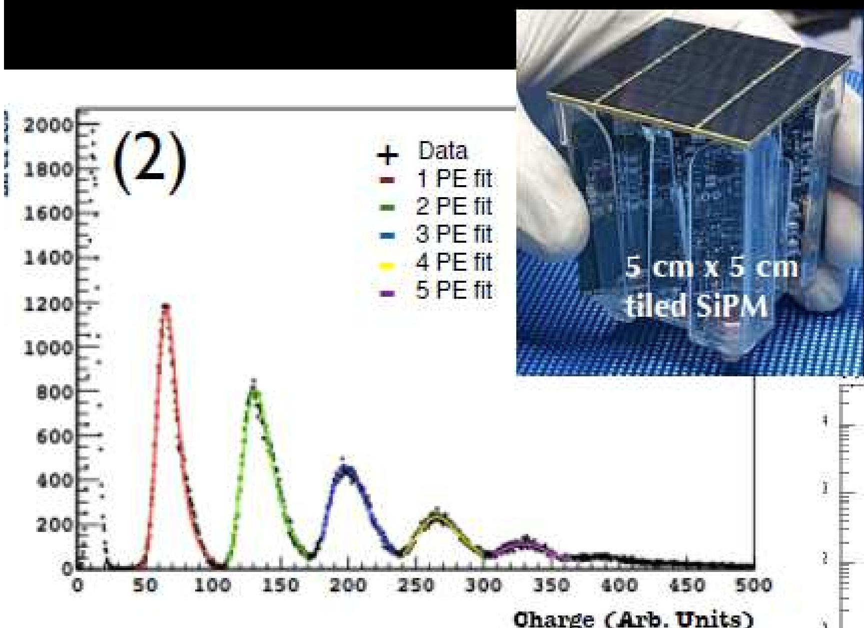

Argon Detectors
Xenon100
DarkSide-50: leading SI limit at 1-5 GeV/c² for WIMP-nucleus and WIMP-e scattering
Agnes et al., Phys. Rev. Lett.121.081307 (2018)
10 kg
2010
DarkSide-50 (50 kg, LNGS)
100 kg
ArDM (1t, LSC)
1000 kg
2015
DEAP-3600 (3.6t, SNOLAB)
DarkSide-50 2018
DarkSide-50 Binomial Fluctuation
DarkSide-50 No Quenching Fluctuation
NEWS-G 2018
LUX 2017
PICO-60 2017
CDMSLite 2017
EDELWEISS-III 2016
XENON100 2016
CDEX 2016
SuperCDMS 2014
COGENT 2013
CRESST 2012
Neutrino Floor
CDEX-10 2018
XENON1T 2017
PICASSO 2017
CRESST-III 2017
PandaX-II 2016
DAMIC 2016
CRESST-II 2015
CDMSlite 2014
CDMS 2013
DAMA/LIBRA 2008
Mχ [GeV/c²]
Global Argon Dark Matter Collaboration formed:
APPEC
2020
DarkSide-20k (50t, LNGS)
100000 kg
ARGO: 400 t, ESPPU Document #97
Jocelyn Monroe
May 13, 2019 / p. 18

DarkSide (2)

Technology Synergies

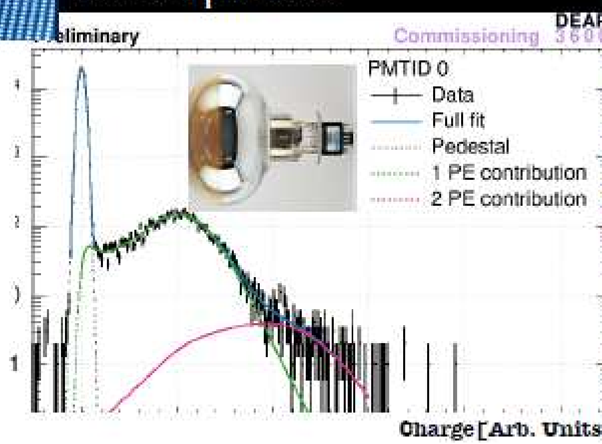
1. Cryostat technologies: DarkSide-20k cryostat uses technology developed for ProtoDUNEs
2. Photon sensors: low noise, high efficiency, cryo Si sensors developed by DarkSide-20k with FBK (LHC Si)
3. Isotopic enhancement: ARIA facility for depletion of Ar-39 in UAr, CERN Vacuum Group collaboration





Aalseth, et al. JINST 12 (2017) no.09, P09030

for comparison:



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DarkSide (3)

LOW RADIOACTIVITY ARGON – PROCUREMENT AND PURIFICATION

Urania plant

– extraction plant in Cortez, Colorado

– 250 kg/day UAr production (compare to 153 kg/6 years for DS-50)

Aria plant

– Distillation plant in Seruci, Sardinia

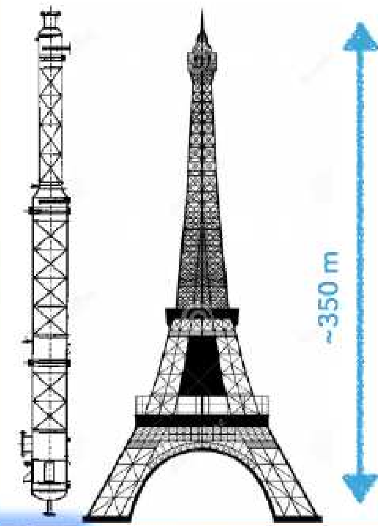
– production of depleted argon DAr with 0.01 content of ^{39}Ar compared to UAr

– removal of impuritis such as Kr

– isotopic cryogenic distillation: utilizes tiny difference in the volatility of ^{39}Ar and ^{40}Ar

– two 350 m tall distillation columns under construction in Sardinia: Seruci I (30 cm diameter column) and Seruci II (1.5 m diameter column) with 10 depletion factor

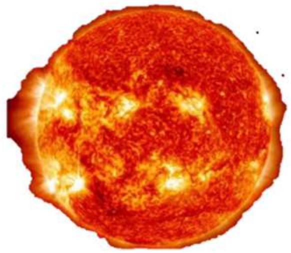
18



Seruci 0
- prototype column

DarkSide (4)

❑ Potential synergies within IN2P3

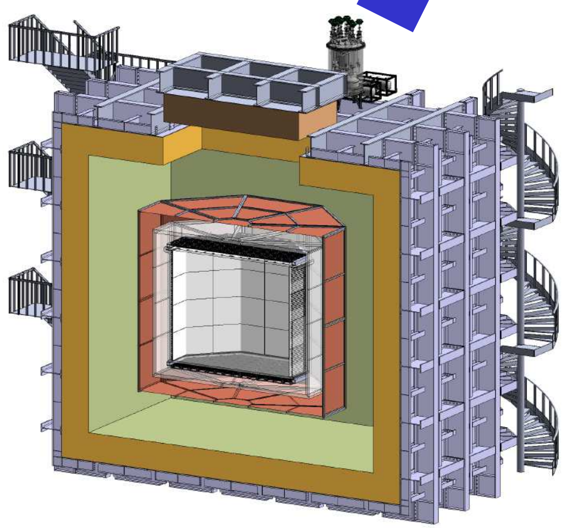


Solar neutrino (νe → νe)

Excellent energy resolution allowing to detect CNO neutrinos with Argo with O(1-10)% on rates

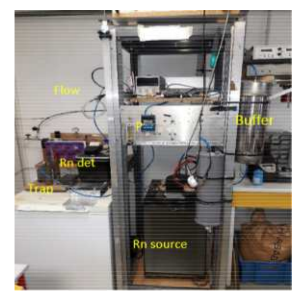
PET 10 ps challenge (1.5 mm reso.)

State of the art =200 ps with inorganic scint. Can benefit from fast light yield of LAr (LXe) + SiPM (Cerenkov radiation)



DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

- *Same outside cryostat*
- *LAr TPC with some common pb*
- ***Galatic SNovae → ν Mass hierarchy*** *(DUNE=CC, DarkSide=Coh. Scat.)*

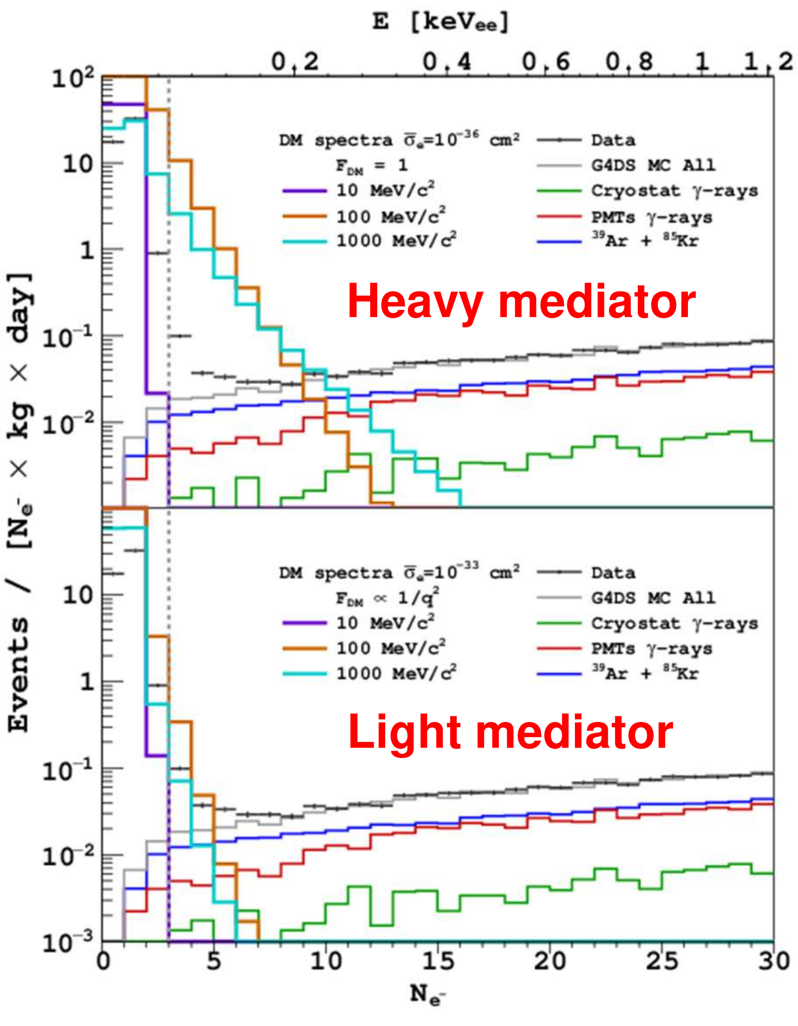


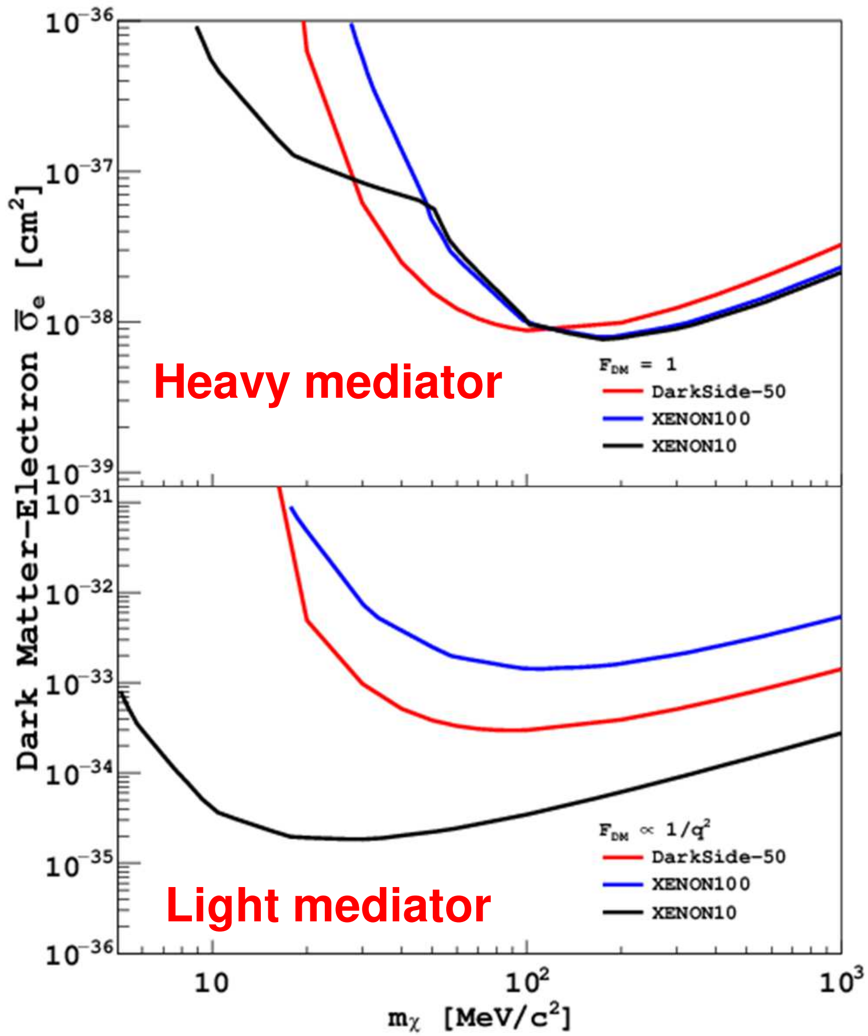
Radon mitigation

Not a major pb in DarkSide, but should be studied with care (use SuperNemo CPPM infrastructure)

DarkSide (4)

Sensitivity to WIMP-electron scatering (1802.06998)



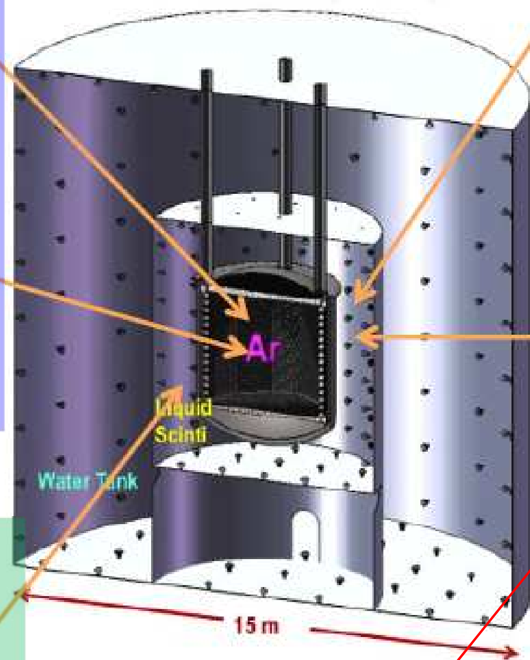


Calibration strategy

Natural internal source
(^{39}Ar)
Uniformly distributed
Limited number of sources

Injected gaseous source
(^{83m}Kr)
Direct measurement
Limited number of sources
Electron Recoil only

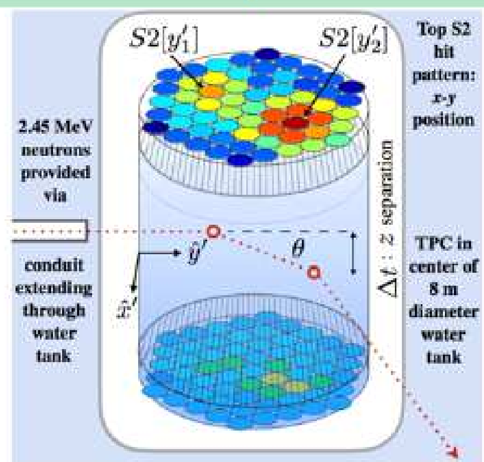
Courtesy D. Franco



External neutron source
(AmBe, AmC)
Direct measurement in nuclear recoil mode
Non-monochromatic

D-D gun in the veto
Monochromatic neutrons*
Recoil energy reconstruction

* With no photon

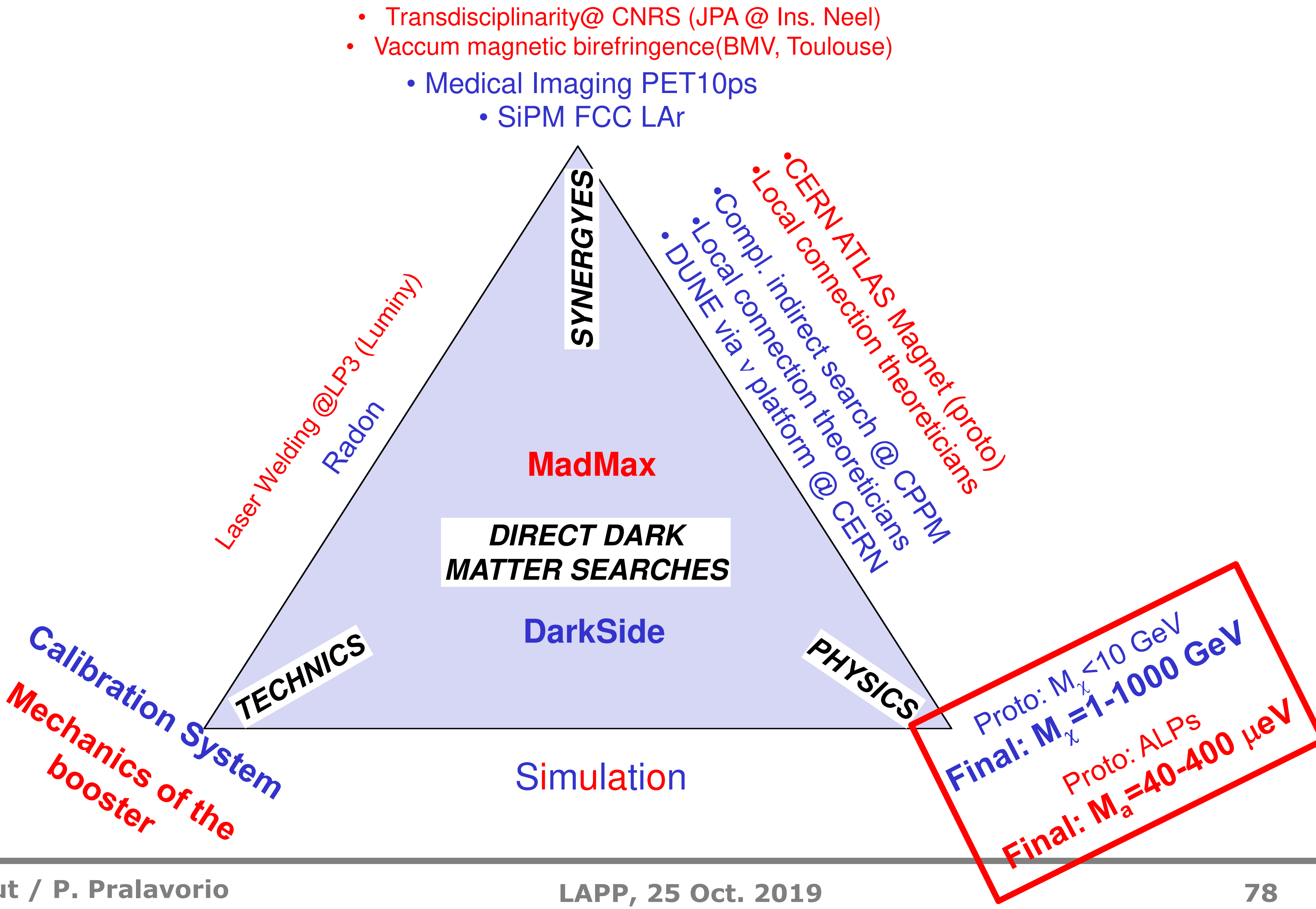


External gamma source
(^{241}Am, ^{133}Ba)
Known energy
Events close to the borders

+ external calibrations

to be inserted through dedicated system

Synergies


• Transdisciplinarity@ CNRS (JPA @ Ins. Neel)
• Vaccum magnetic birefringence(BMV, Toulouse)
• Medical Imaging PET10ps
• SiPM FCC LAr
SYNERGYES
•CERN ATLAS Magnet (proto)
•Local connection theoreticians
•Compl. indirect search @ CPPM
•Local connection theoreticians
• DUNE via ν platform @ CERN
Laser Welding @LP3 (Luminy)
Radon
MadMax
DIRECT DARK MATTER SEARCHES
DarkSide
TECHNICS
PHYSICS
Calibration System
Mechanics of the booster
Simulation
Proto: Mχ<10 GeV
Final: Mχ=1-1000 GeV
Proto: ALPs
Final: Ma=40-400 µeV