# 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
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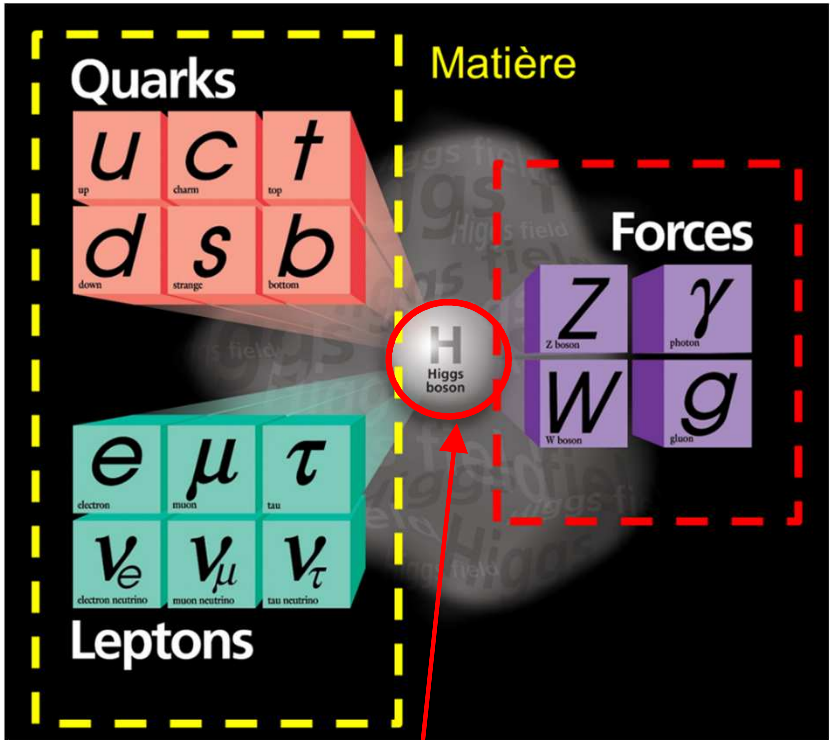
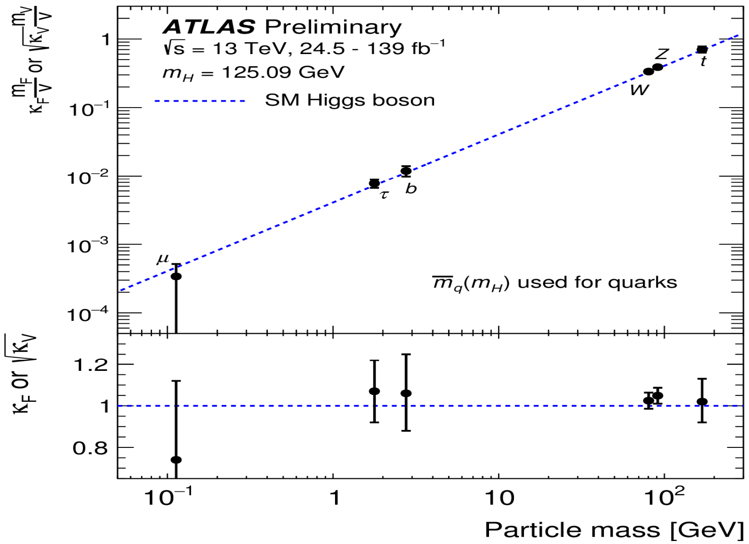
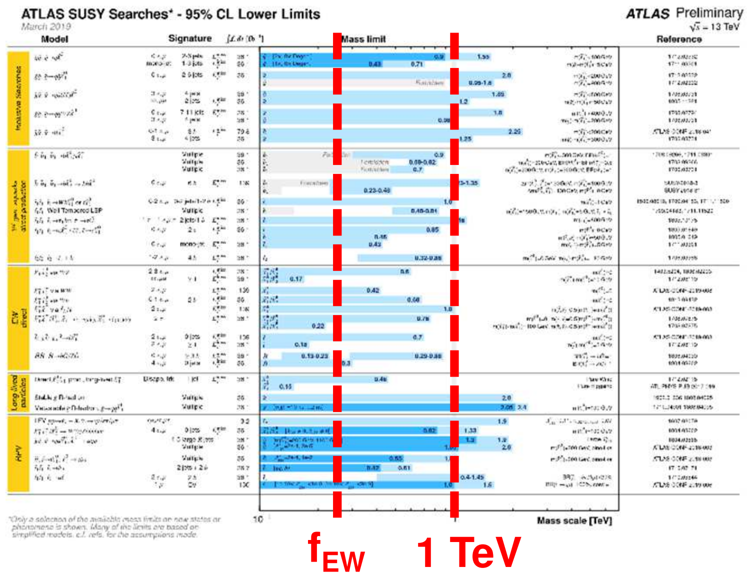
# Introduction (1/5)

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



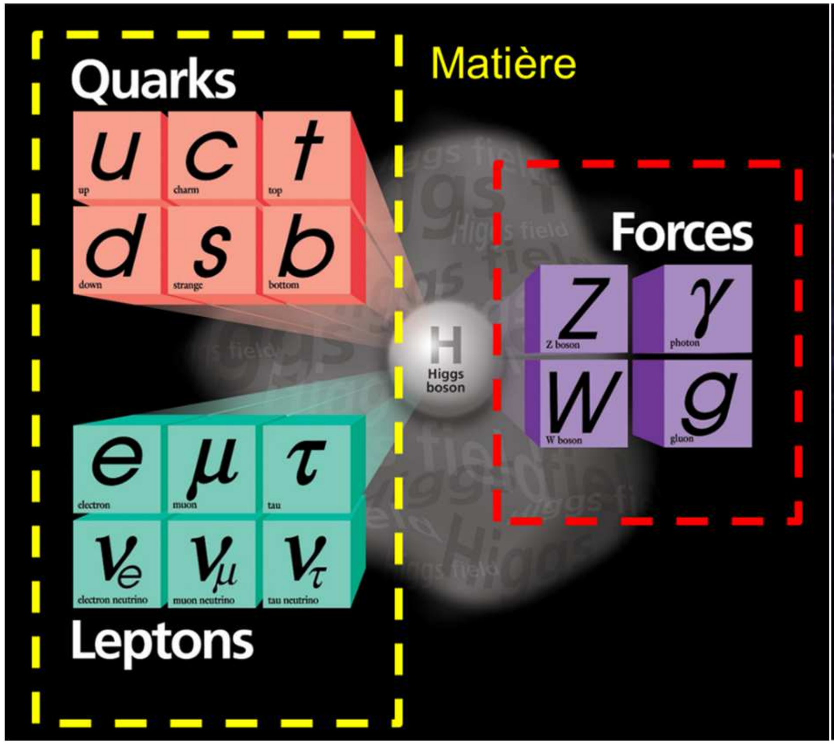



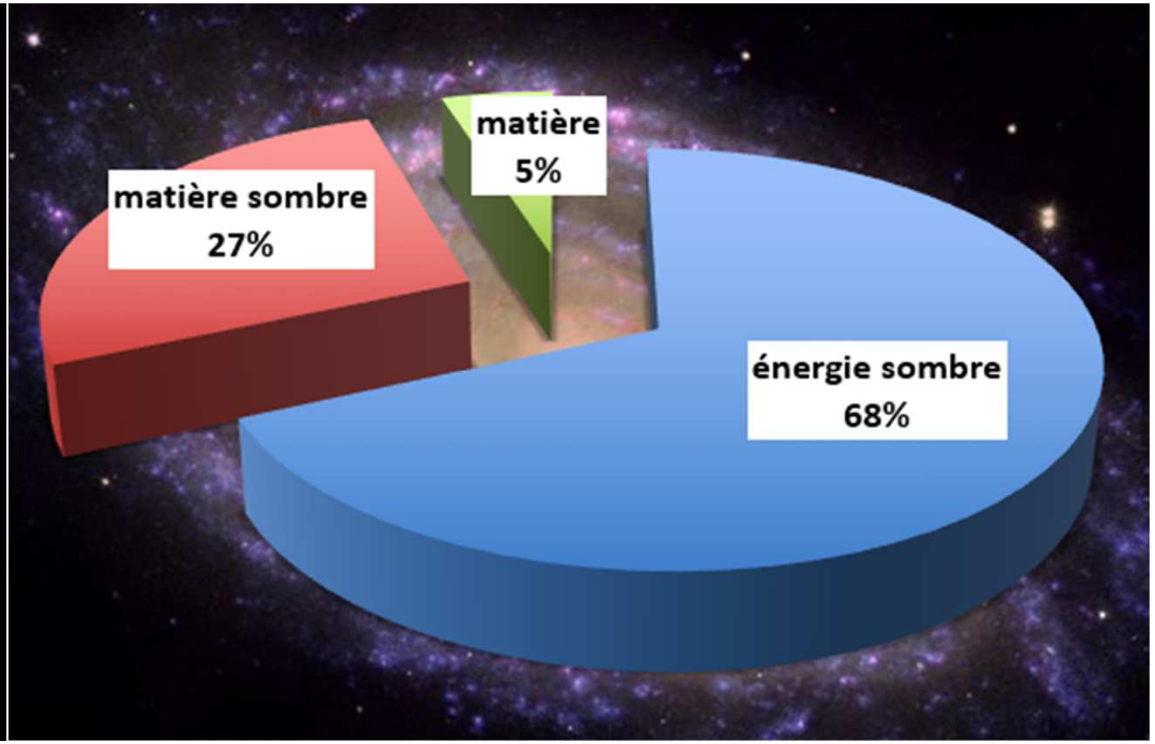




- ➢ Higgs discovery
- ➢ Precision measurements in all sectors
- ➢ Direct searches → no sign of New Physics so far up to TeV scale

# Introduction (2/5)

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



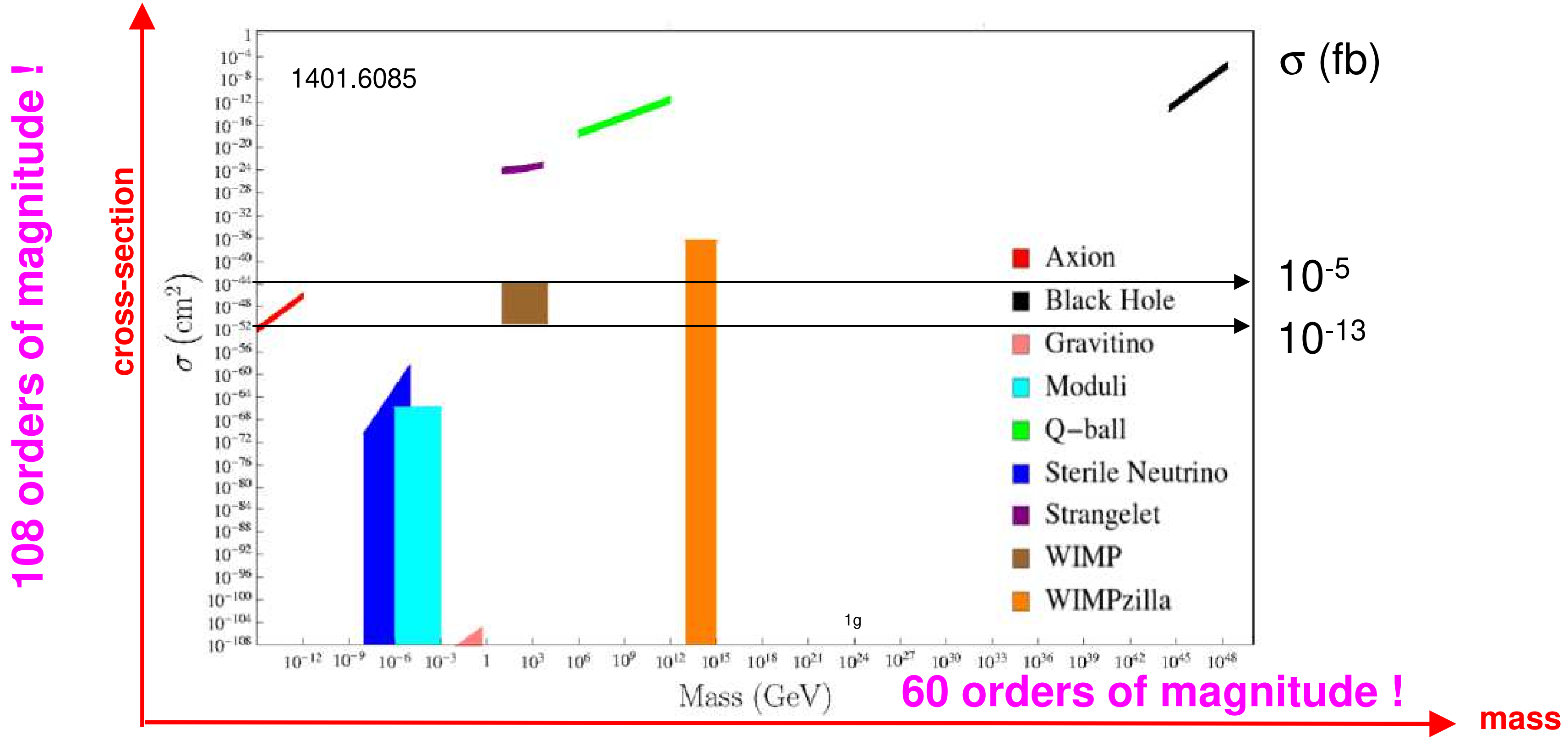

**➔ Dark Matter is one of the main puzzles of today's fundamental physics**

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

# Introduction (3/5)

## ❑ 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]

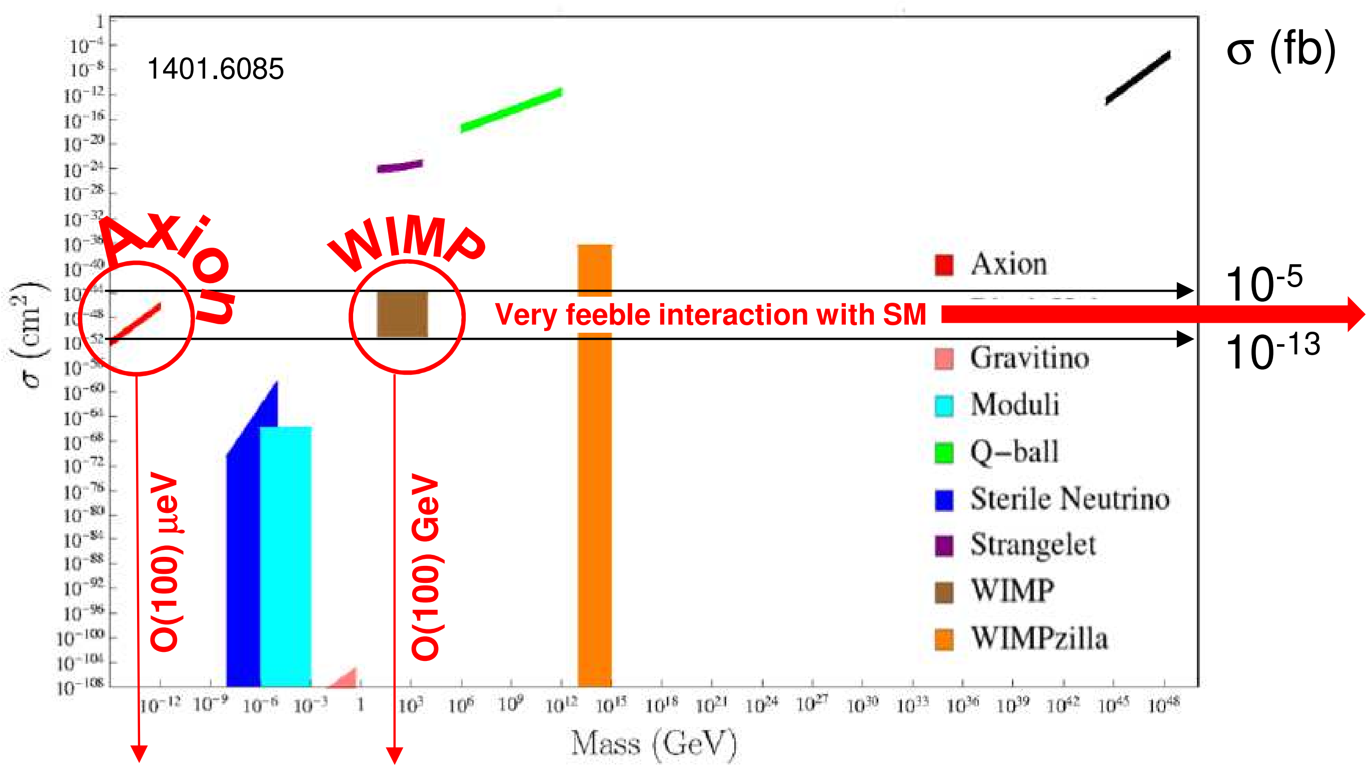



- …but only a few of them are **also strongly motivated by particle physics**, i.e. solving current theoretical SM problems → **WIMP** *(hierarchy pb)*, **Axion** *(~no CP violation in strong interaction)*

  [lightest sterile N (neutrino masses and mixing), but only indirect search through X-ray emission line $N \rightarrow \nu\gamma$, $E_\gamma = m_N/2$]

# Introduction (4/5)

## ❑ 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

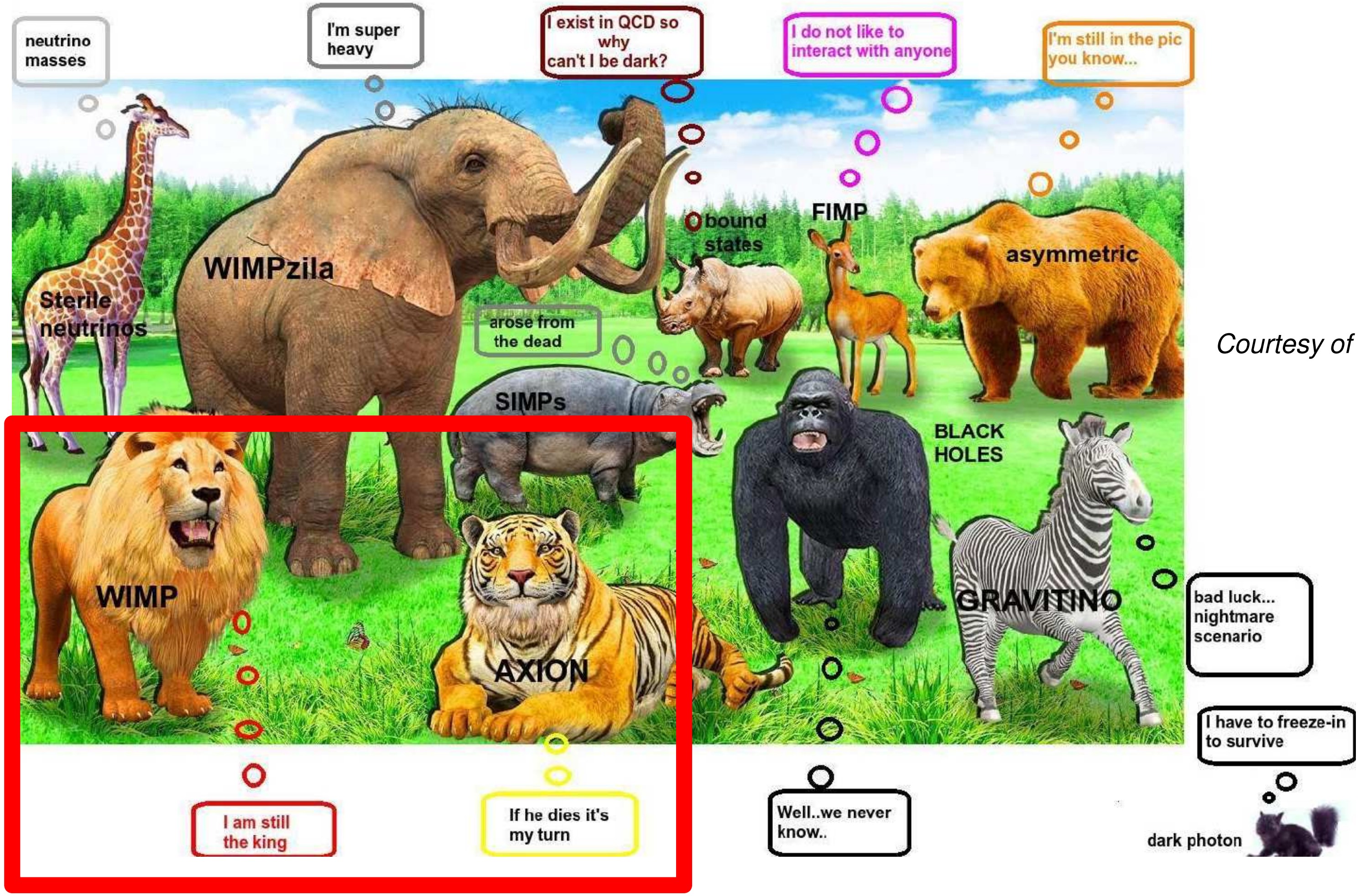
- O(10$^{12}$)/cm$^3$ ~ gaz → High occupancy
- Tiny mass & interaction → **Very feeble signal**

**Challenge: Boost the signal**

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

**Challenge: High detection volume (low background)**

# Introduction (5/5)



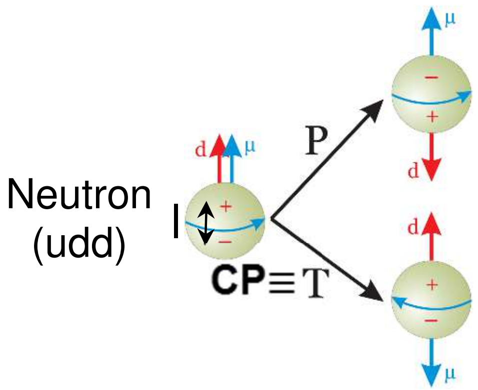

*Courtesy of F. Queiroz*

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

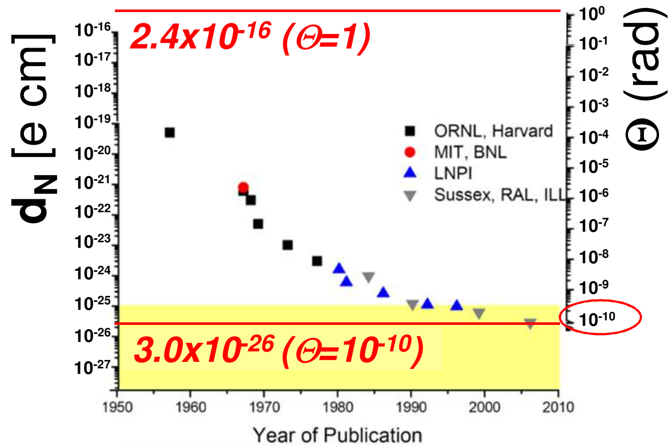
# Axion (1/5)


## ❑ (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
  - ➔ $\delta_{13}$ ~ **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 → $\Theta < 10^{-10}$

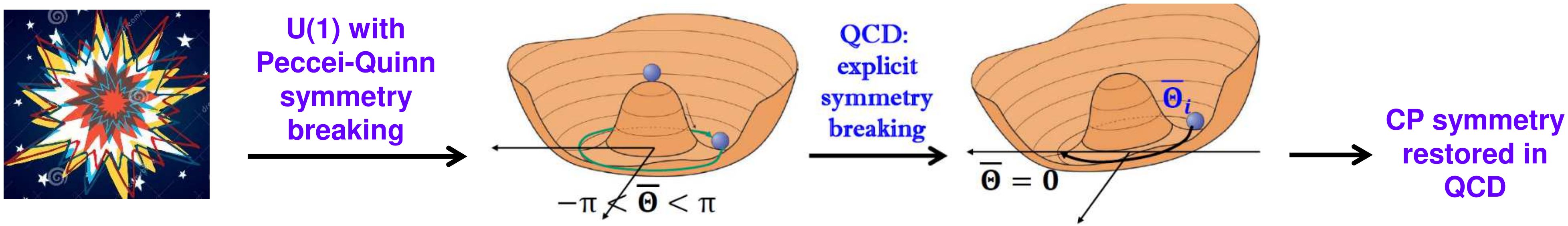



**➔ Strong CP Problem = naturalness problem. Why is Θ so small ?**

# 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 $\Theta$ a dynamical field ($\Theta = a/f_a$), with a = pseudo-scalar boson
  - ➔ Cancels CP-violating term in the Lagrangian ($\Theta_{eff} \rightarrow \Theta - a/f_a$) : explains absence of CP strong
- Consequence: Goldstone boson of the new theory = axion *(Weinberg-Wilczek, 1978)*
  - ➔ 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
- Cosmology: Non-thermal axion production at $T \sim f_a$ *(can occur before or after inflation)*



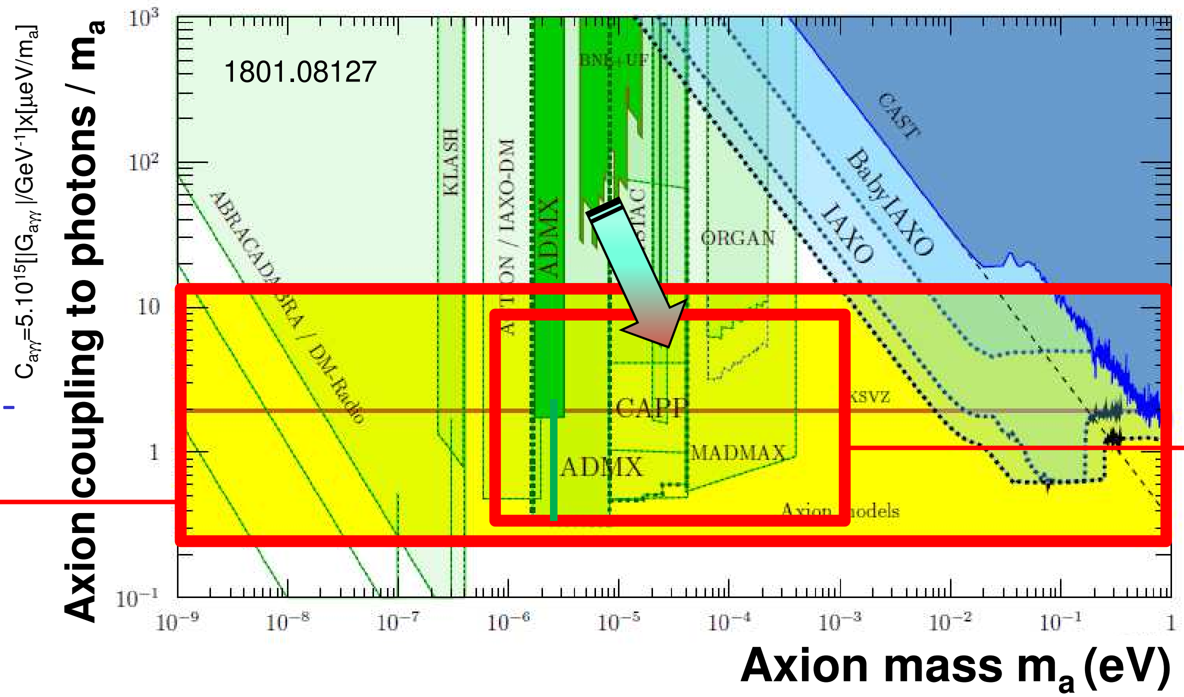

**➔ Axion = natural candidate for DM for $m_a$=1-$10^3$ μeV** ***(i.e. $f_a = 10^{12} - 10^9$ GeV >> $f_{EW}$)***

# 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




2019

~2029

Favored DM axion phase space

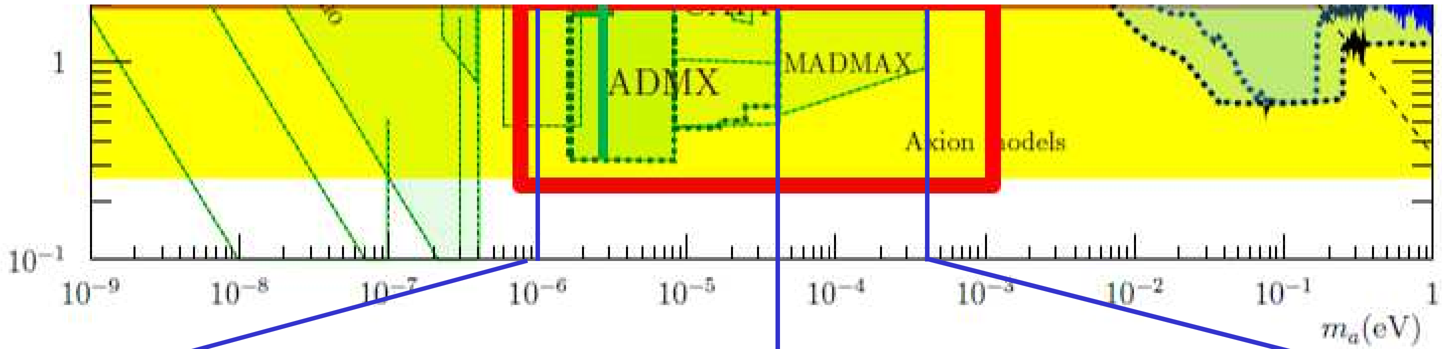
- Only 1 experiment (ADMX) currently probe a (very small) part of the interesting phase space
- Vast R&D program to improve signal sensitivity and expand range of axion mass search

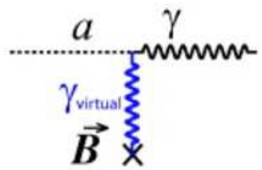
**➔ Next decade will be decisive, probing axion most favorable region**

# Axion (4/5)

## ❑ Main challenges for direct searches

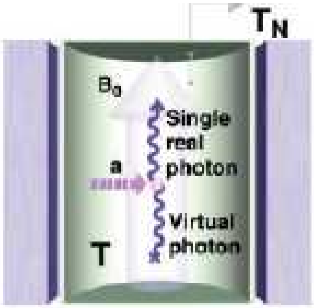
- Convert axions into photons *[E field of O($10^{-12}$. $\frac{B}{10\ T}$) V/m]* ➔ high magnetic field >> 1T
- Boost photon field *[up to P~$10^{-22}$ W]* ➔ resonant cavities or emission at dielectric interfaces
- Scan over range of axion mass ➔ need tunable set-up




**1 µeV** **40 µeV** [10 GHz] **400 µeV** [100 GHz] [$\nu_a$=$\nu_\gamma$]

**Cavities**

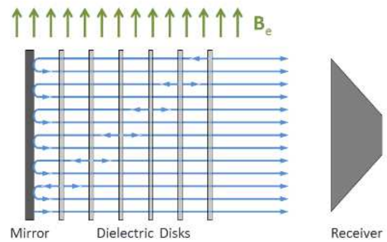



*ADMX, HAYSTACK, CAPP, Organ*

**Multicavities**
*RADES, ADMX-SideCar*

***Very High B***
*CAPP*

***Cavity size too small + high noise***




*MadMax*

**Dielectric haloscopes**

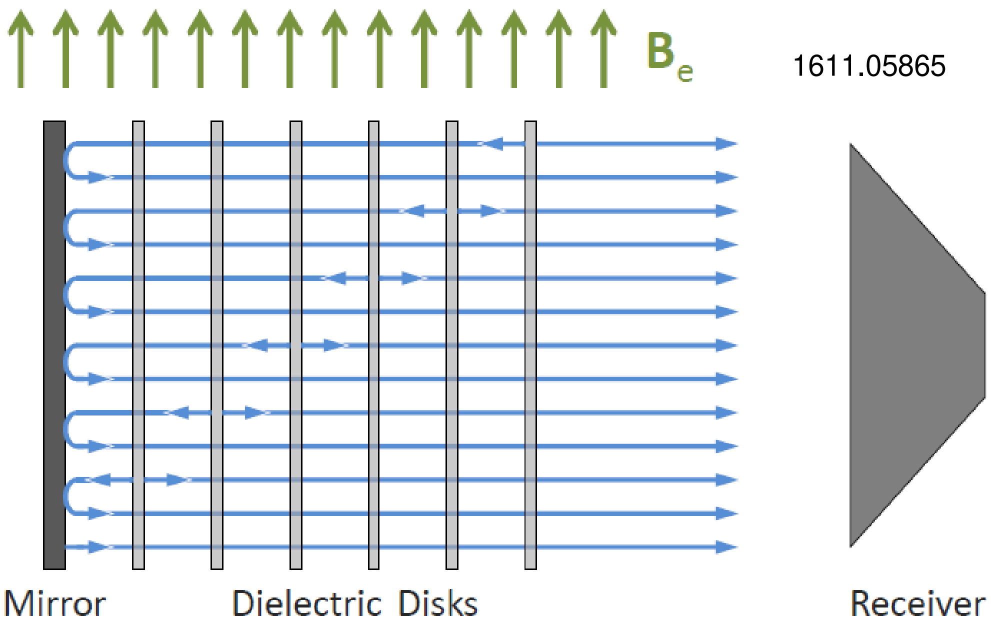
**➔ New ideas of last decade coming to maturity to scan preferred mass range**

# 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 20 mm for 40 μeV and 2 mm for 400 μeV]



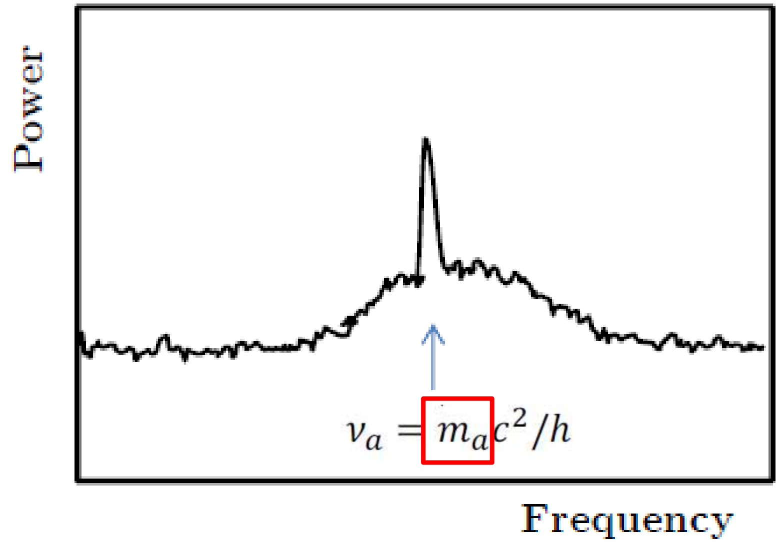

Lanthanide Aluminate ($LaAlO_3$)

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 x$10^5$



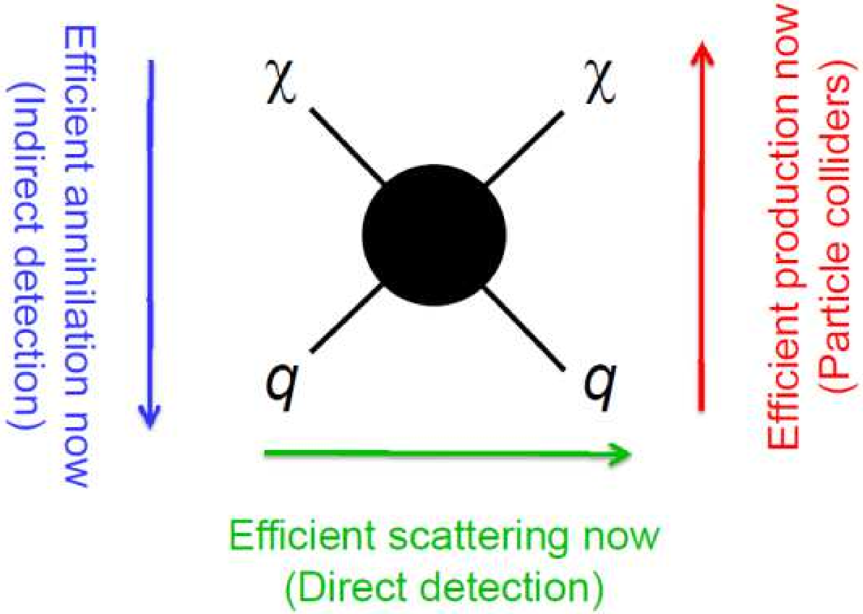

**➔ MadMax only capable to explore $m_a$=40-400 μeV** *(favored by post-inflation theory)*

# 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

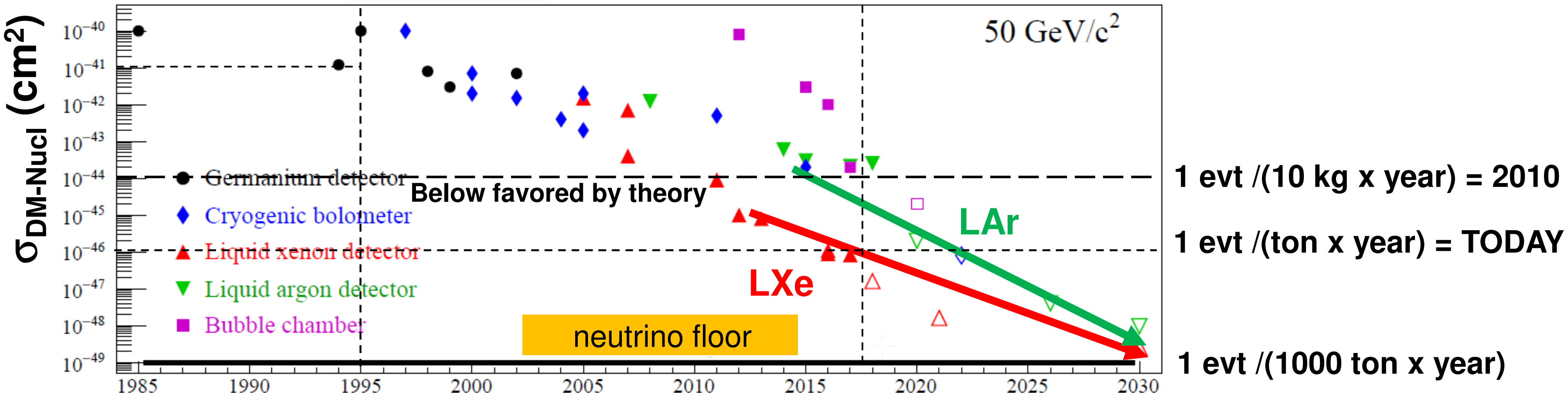
**➔ Contrarily to axions, complementary approaches to discover WIMPs**

# 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* $m_\chi$=50 GeV (quite low for Ar)



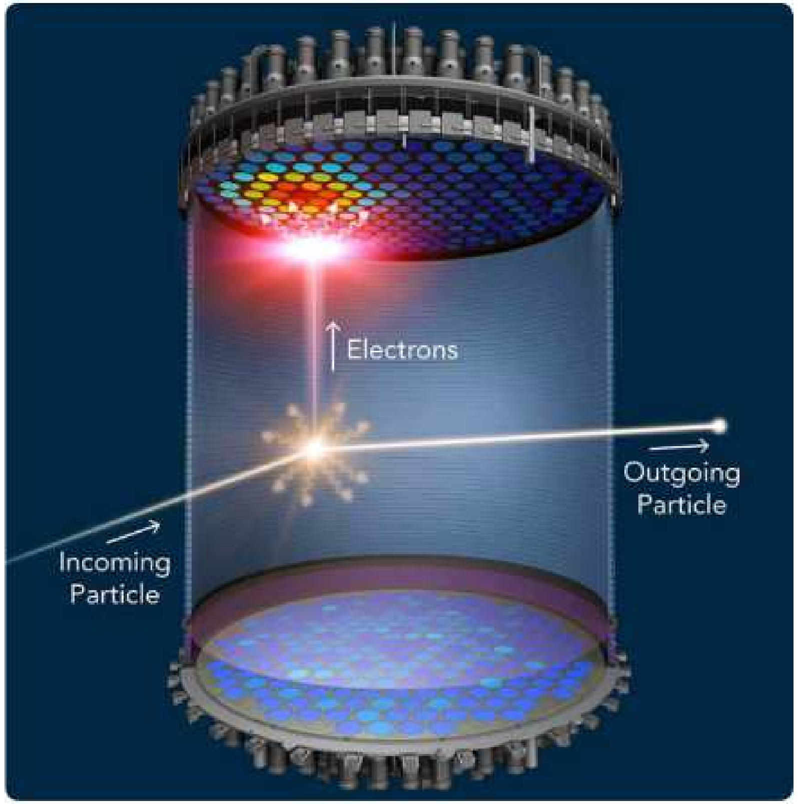

Leading techno: Ge Bolo LXe LXe+LAr **Year**

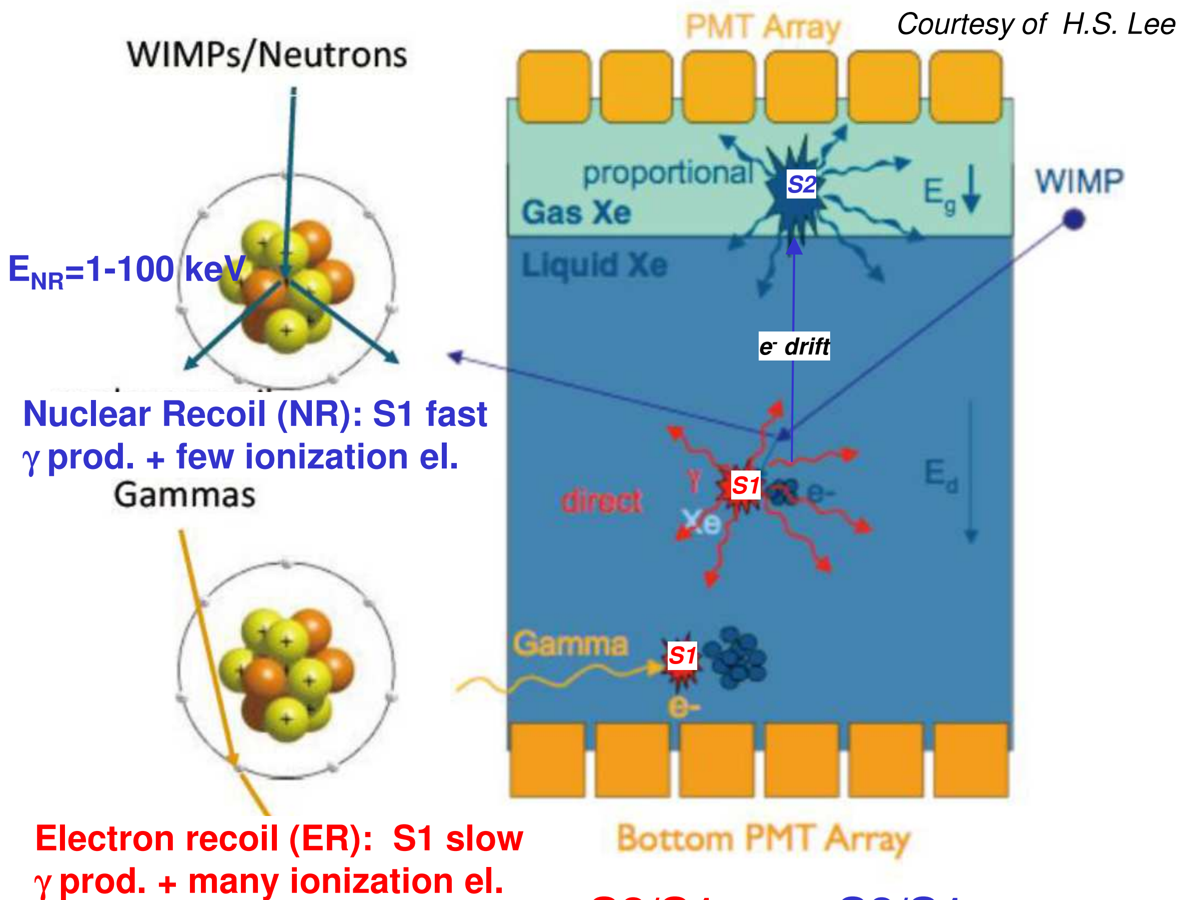
- Gained 5 orders of magnitude in sensitivity in last 20 years
- By end of next decade : should reach neutrino floor

**➔ LXe / LAr dual phase TPC are now leading the race [$m_\chi$ >O(1 GeV)]**

# 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,~50 e⁻/keV*)



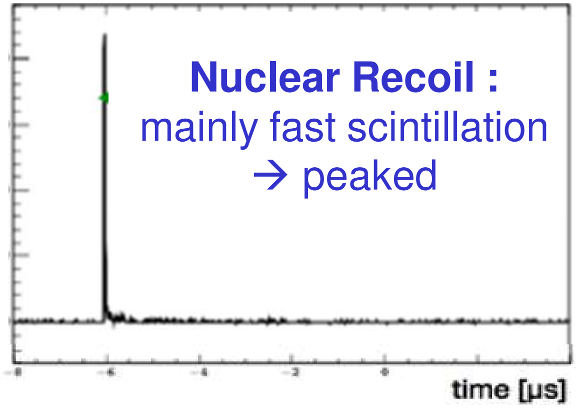

$S2/S1_{ER} >> S2/S1_{NR}$

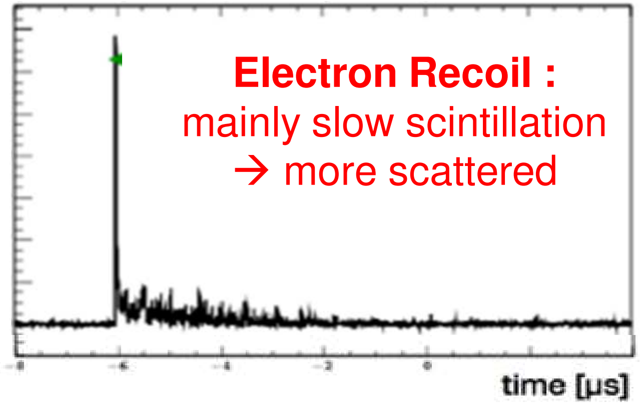
*for electron recoils

# 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




  - ➢ 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)

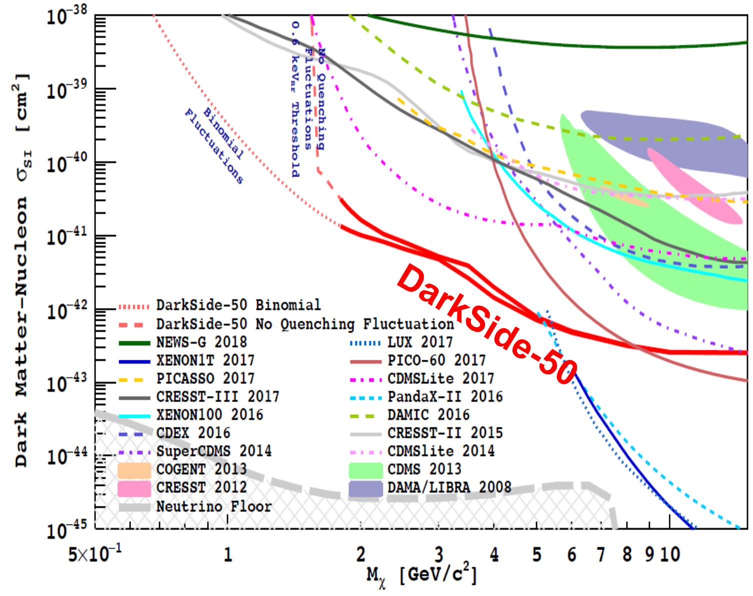
## … demonstrating high level performance with 50 kg LAr *(DarkSide-50)*

- **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



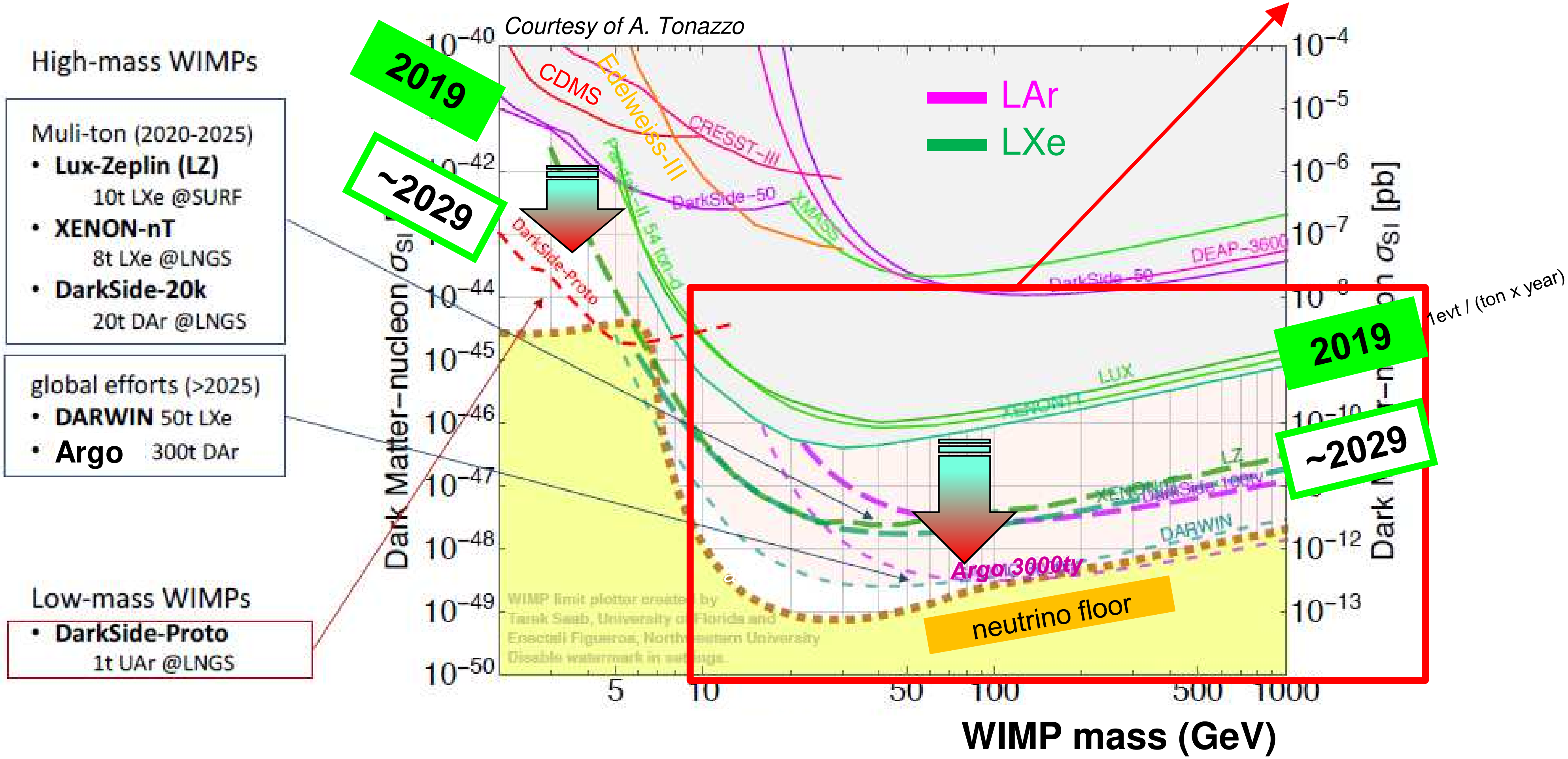

## … and expect more in the next 10 years with 20 t LAr *(DarkSide-20k)* :

- **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 ($m_\chi$=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 experiments
  - ✓ **Axion → MadMax** very promising: only capable to explore phase space favored by theory
  - ✓ **WIMP → DarkSide** very promising: 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]

*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)***

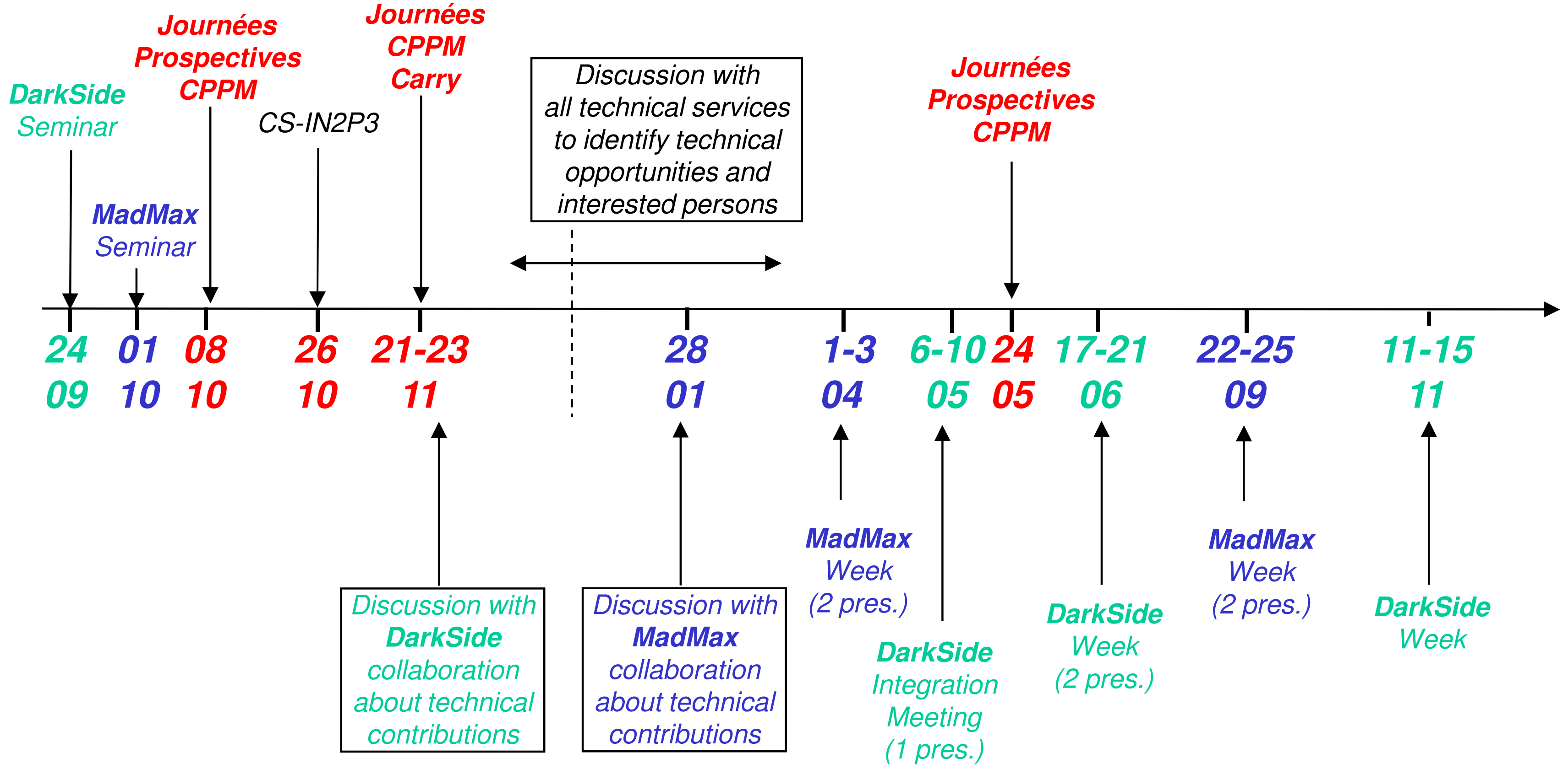
- **Axions:** no participation from IN2P3

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)

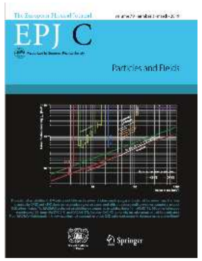
White Paper (1901.07401)

- **~30 collaborators.** Main contacts: MPI-Münich, U-Hamburg, DESY, CEA

| | 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)*

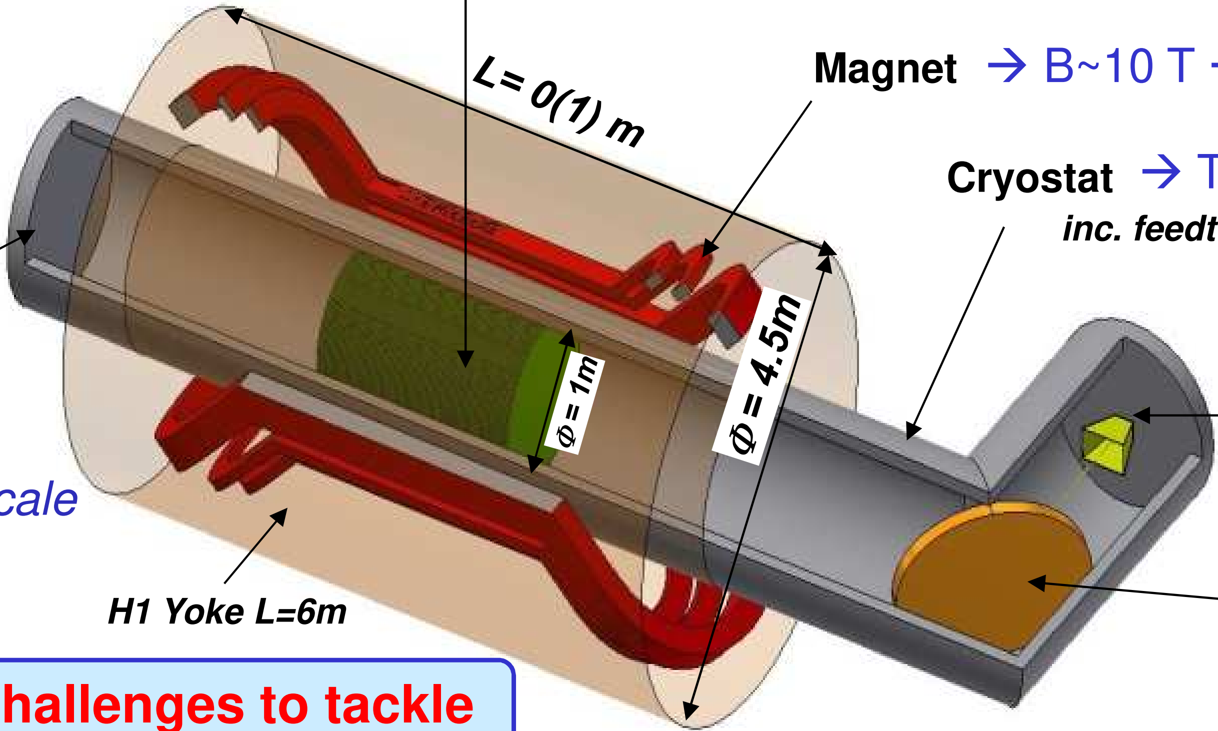
***Cover page of EPJC in March' 19***




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

**Magnet** → B~10 T → $B^2.A \sim 100\ T^2.m^2$

**Cryostat** → T~4 K
***inc. feedthrough***

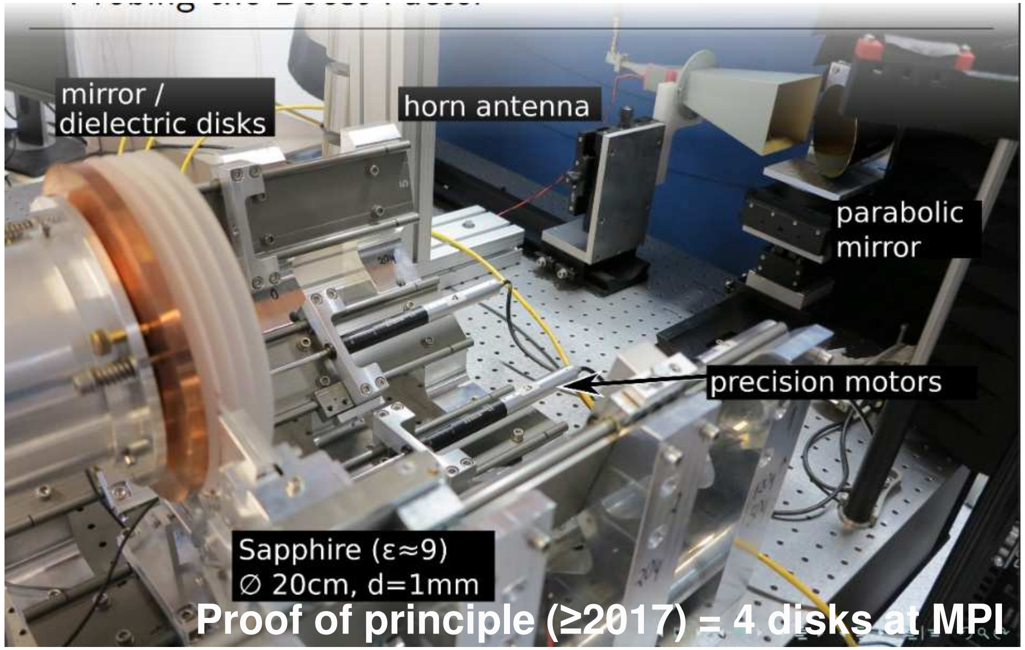



*Picture not to scale*

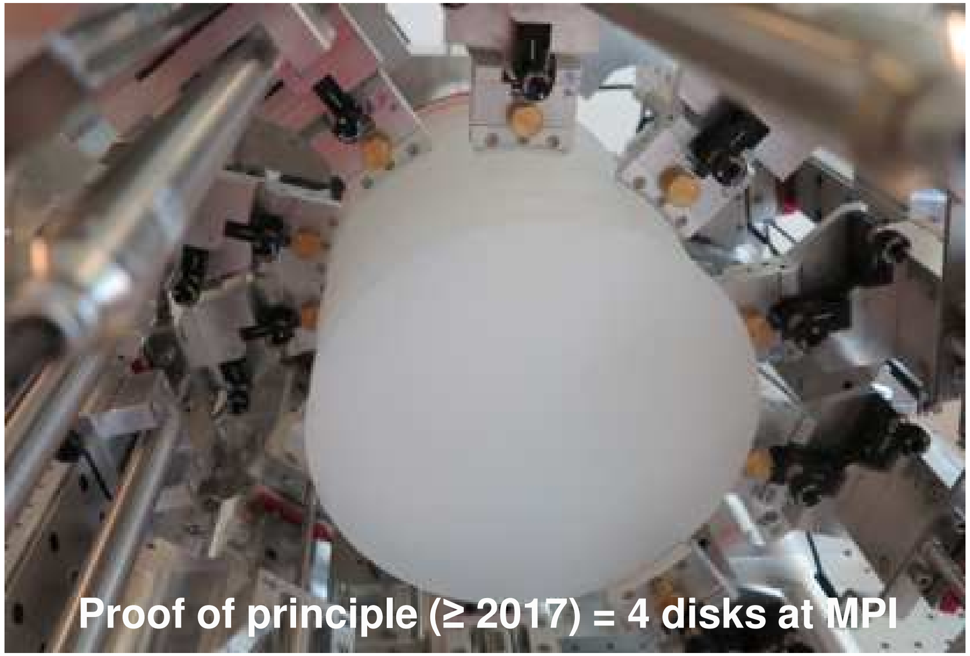
➔ **Many challenges to tackle**

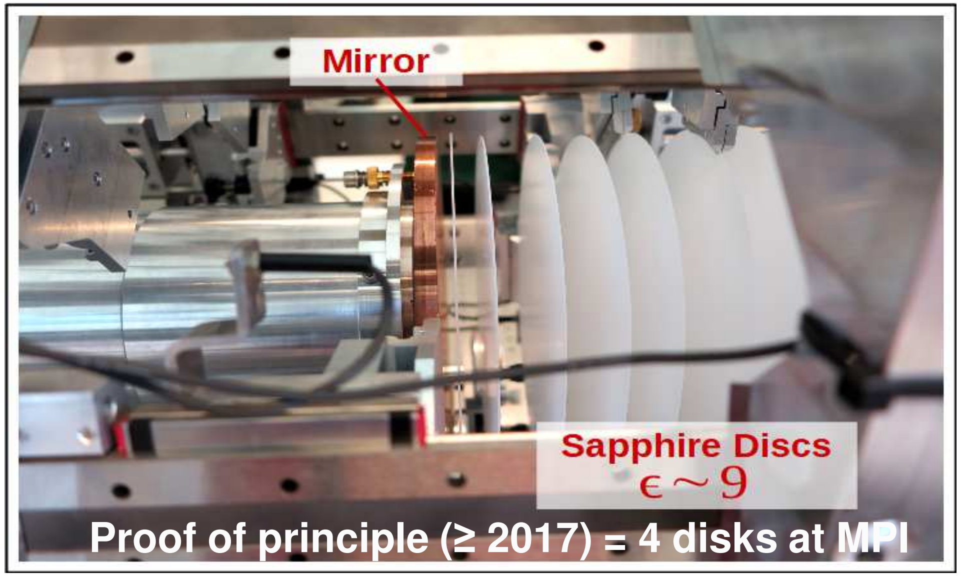
# Opportunities in MadMax (1/4)

White Paper (1901.07401)



Proof of principle (≥2017) = 4 disks at MPI


Proof of principle (≥ 2017) = 4 disks at MPI



Proof of principle (≥ 2017) = 4 disks at MPI


collaboration formed in Oct. 2017

# Opportunities in MadMax (2/4)

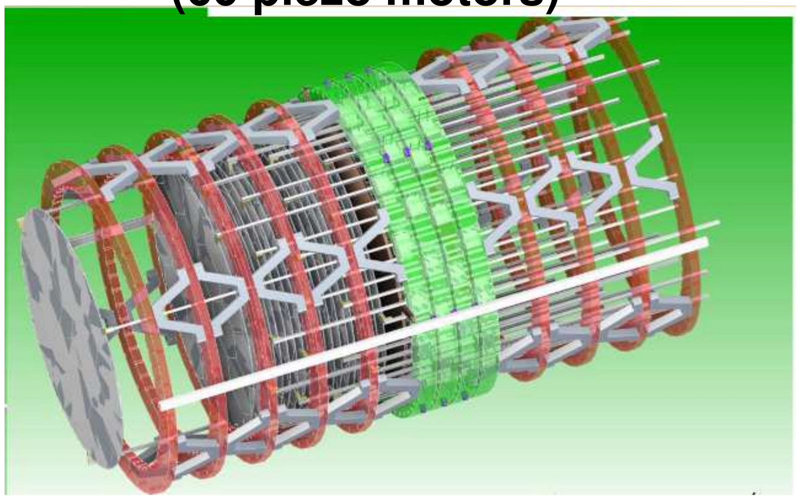
## ❑ Best match for CPPM: mechanics of the prototype booster

- 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)**

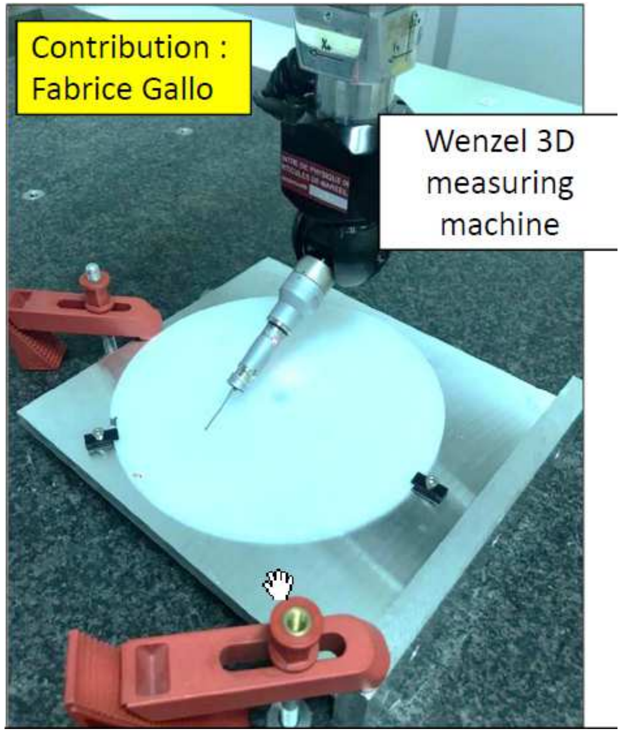


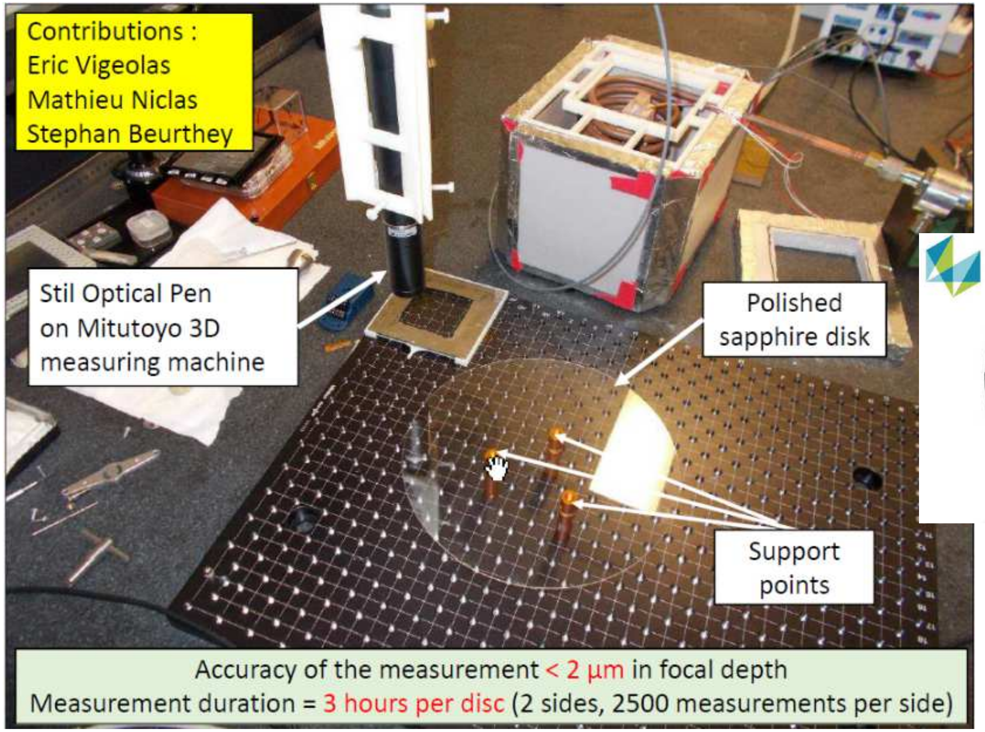
**Very challenging R&D ongoing ➔ many technical opportunities**

# 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)

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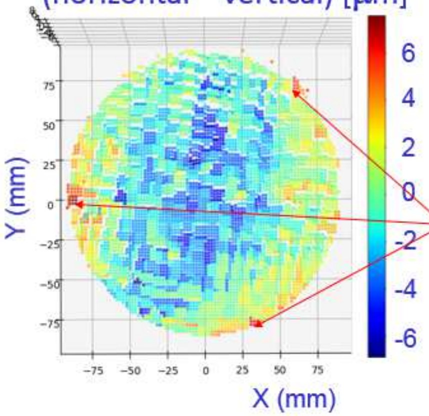
- Profit from the precision measurement infrastructure of the lab to control disk planarity and thickness with 3 different set-up, with precision <10 μm

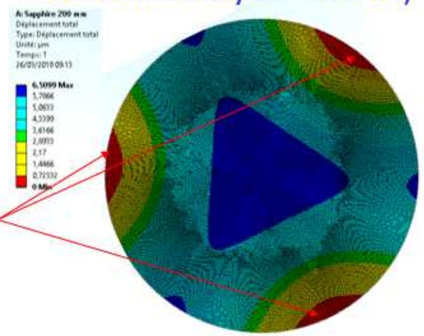
**Disc #1 - 200 mm unpolished surface Difference Horizontal-Vertical**

Measurement difference (horizontal – vertical) [μm]




Support points

Simulations (Finite Element Analysis – ANSYS)

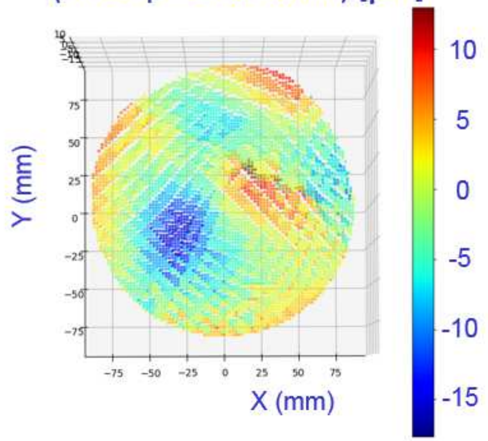


[200mm horizontal sapphire disk fixed at 3 positions]

➔ Good qualitative agreement between measurements and simulations

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

Measurement difference (Side up – Side down) [μm]




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

➔ Correlation between both sides

➔ Disk thickness uniformity better than surface non-planarity

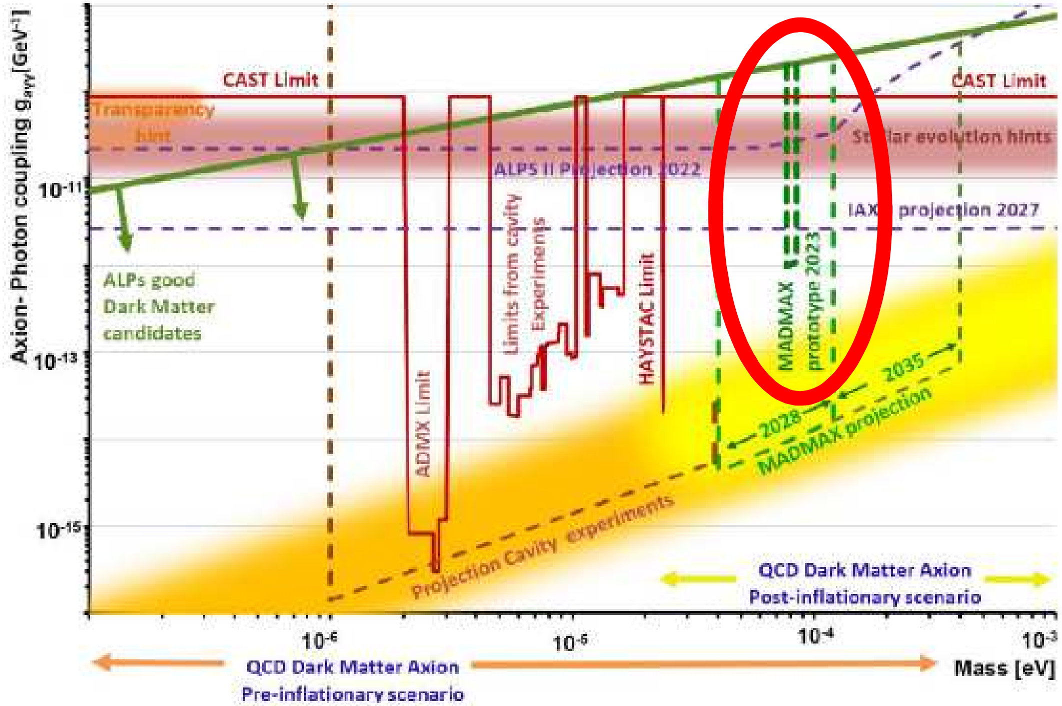
➢ **We included the measurements in the MadMax simulation code → increased realism**

**➔ 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)


- ➢ 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)

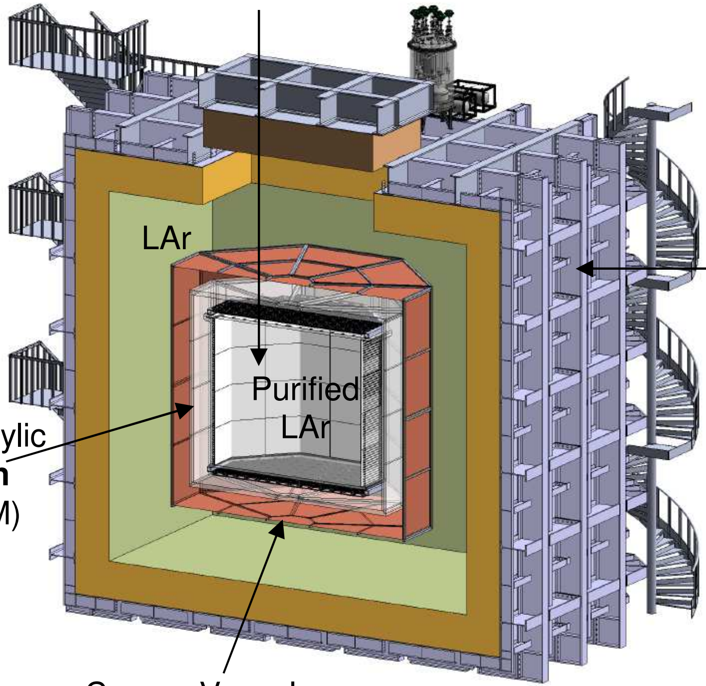
White Paper (1707.08145)

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

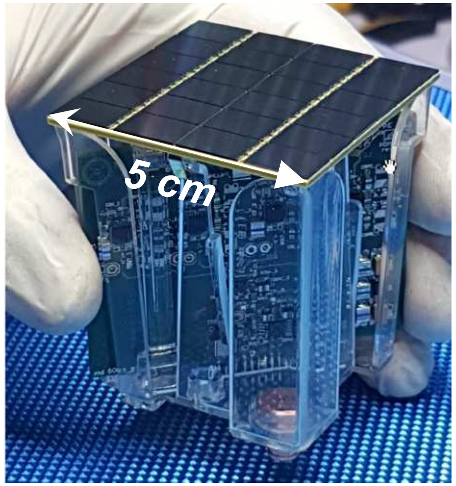
| | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | ≥2026 |
|---|---|---|---|---|---|---|---|---|
| **DarkSide** | Construction prototype | Exploitation prototype | | Construction Final detector | | Exploitation final detector | | |

@ **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

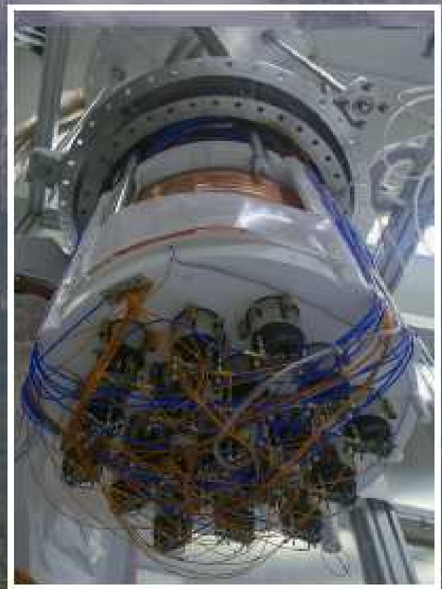
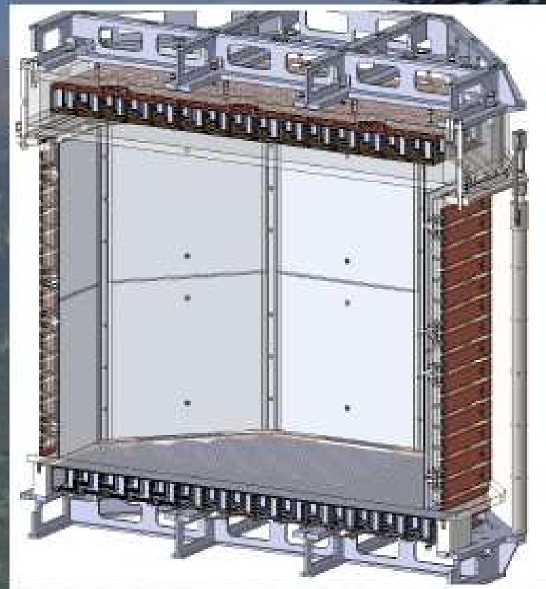



Developed by FBK (Fondazione Bruno Kessler company) in Trento and then produced by LFoundry

# The DarkSide program at LNGS

A scalable technology for direct WIMP search:

2-phase low background Argon TPC

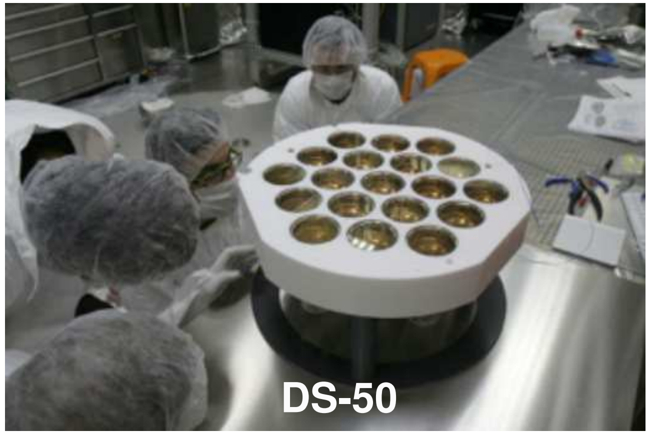
| DarkSide-10 | DarkSide-50 | DarkSide-20k |
| --- | --- | --- |
|  |  |  |
| technical prototype<br>no DM goal | sensitivity<br>$10^{-44}$ cm$^2$ | sensitivity<br>$10^{-48}$ cm$^2$ |

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

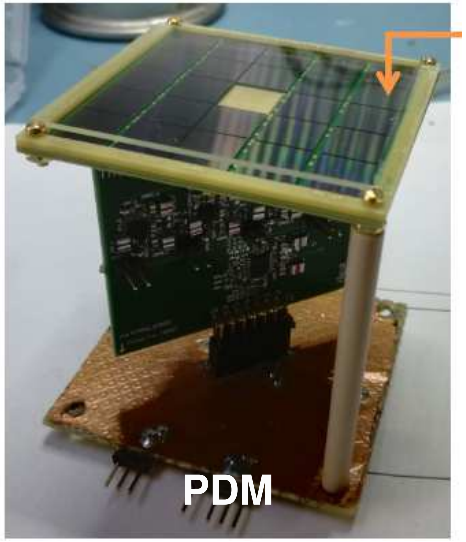
# Opportunities in DarkSide (1/4)

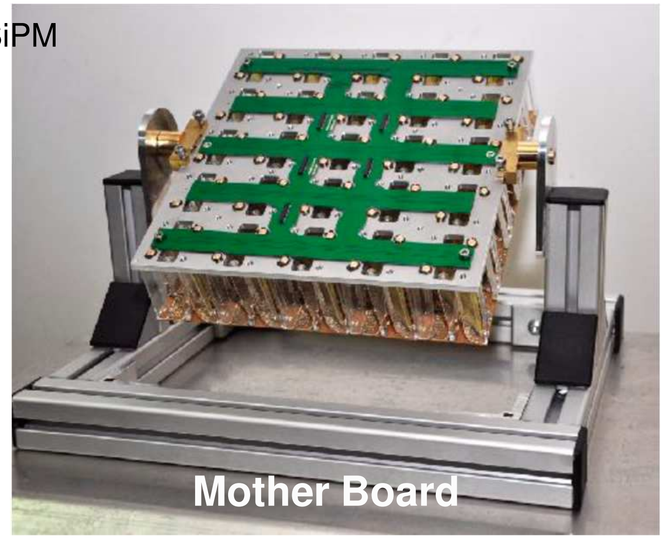
White Paper (1707.08145)



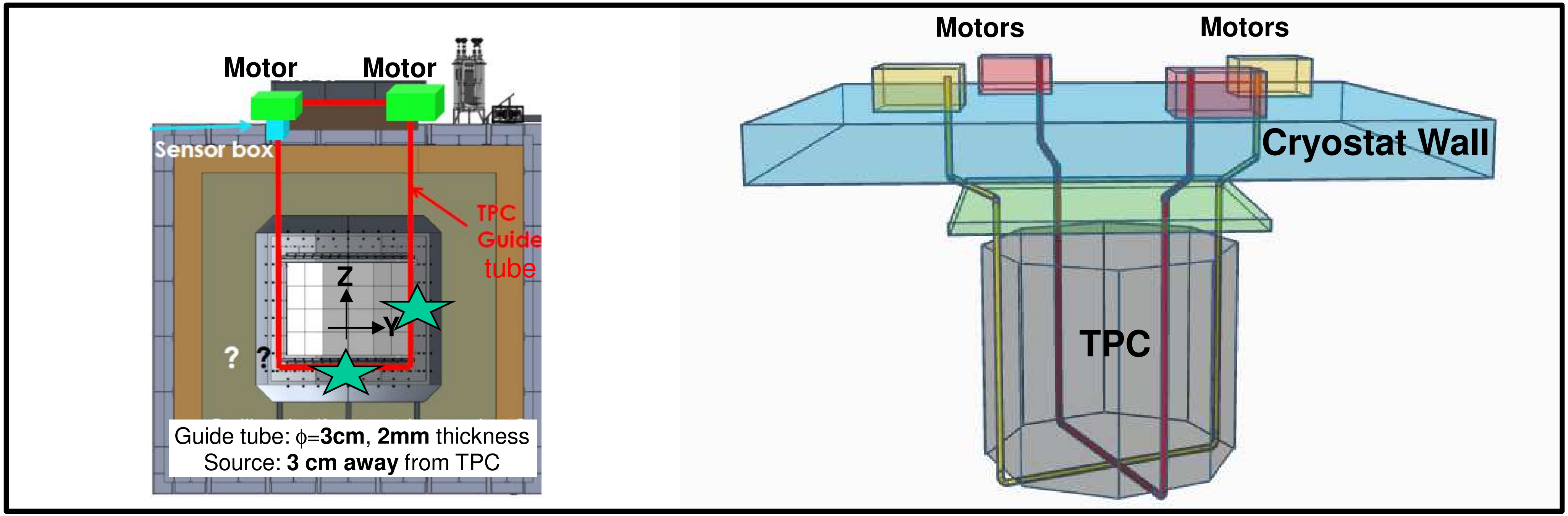




# Opportunities in DarkSide (2/4)

- **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

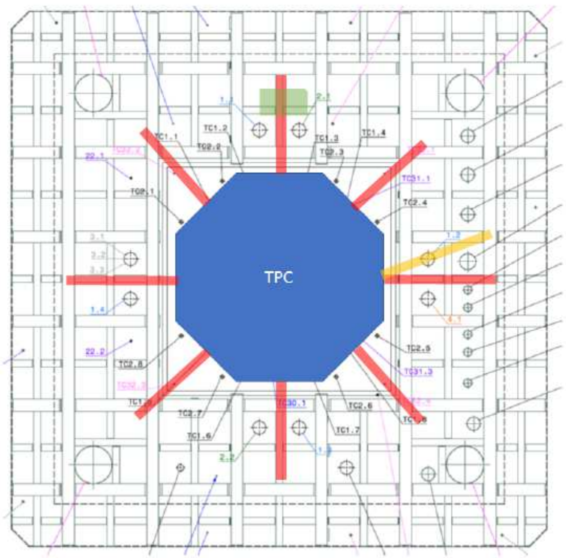


# Opportunities in DarkSide (3/4)

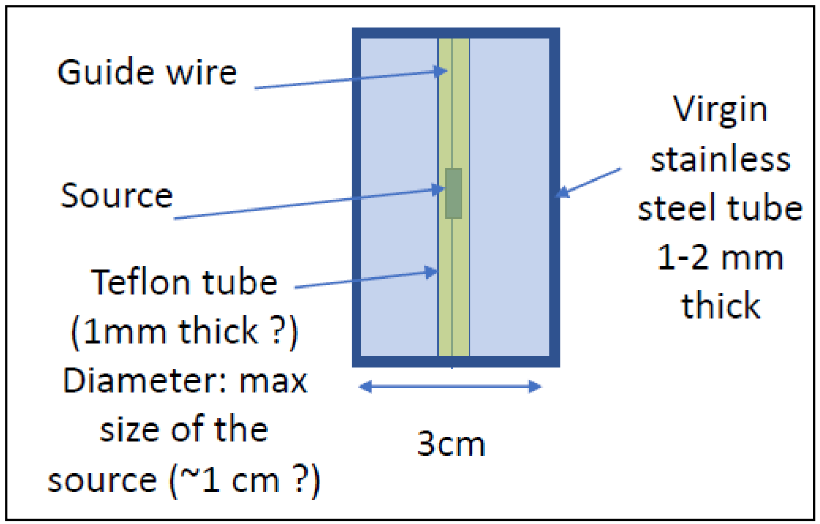
## ❑ First CPPM contributions on detector calibration

- 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**



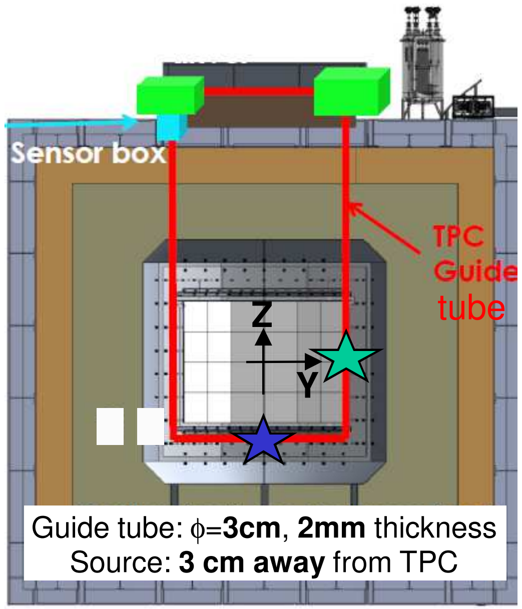

**Results presented at DarkSide meetings in 2019**

# Opportunities in DarkSide (3/4)

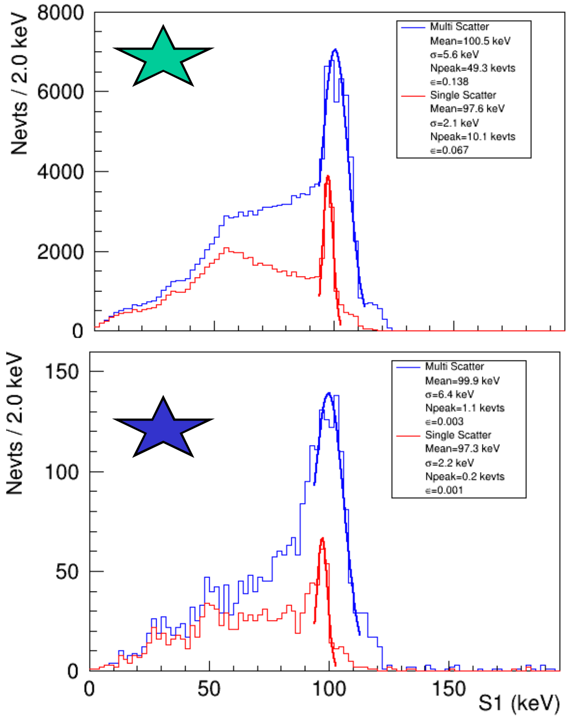
## ❑ First CPPM contributions on detector calibration

- 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 $\gamma$)* **in guide tube**




Guide tube: $\phi$=**3cm**, **2mm** thickness
Source: **3 cm away** from TPC




**➔ 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

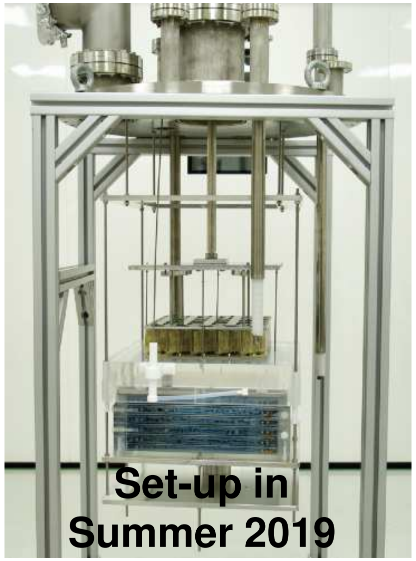
➔ Run scheduled in Nov. 2019

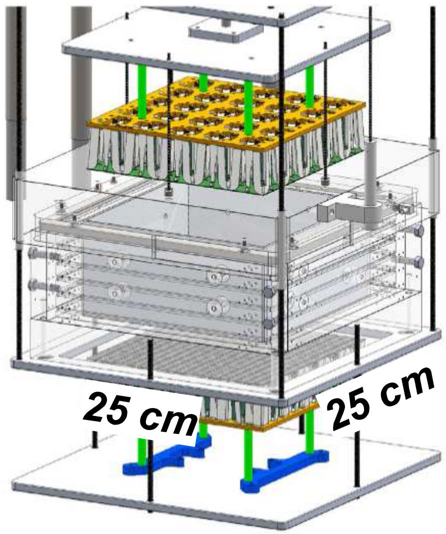
**proto-1 ton (1 ton LAr, 9k SiPM)**

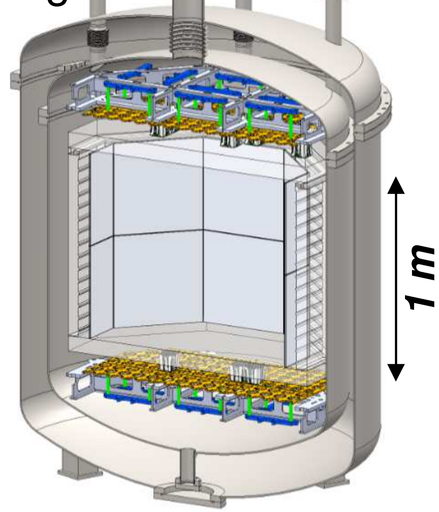
➔ Full scaled-down version of final detector

➔ 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), High magnetic fields, …

  - Institut Néel Grenoble: associate member of MadMax collaboration [N. Roch, L. Planat]
  - LNCMI (Grenoble + Toulouse): magnet expert for MadMax [P. Pugnat] + vacuum magnetic birefringence measurement (pulsed magnetic fields)

## ❑ Some other natural connections

- Theoreticians and experimental indirect searches, DUNE via ν platform @ CERN, 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
  - ✓ **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://www.cppm.in2p3.fr/~hubaut/ProspectivesIN2P3/Prosp_IN2P3_MADMAX.pdf, https://www.cppm.in2p3.fr/~hubaut/ProspectivesIN2P3/Prosp_IN2P3_DarkSide.pdf