Ricerche dirette di materia oscura (WIMPs, assioni, altro)

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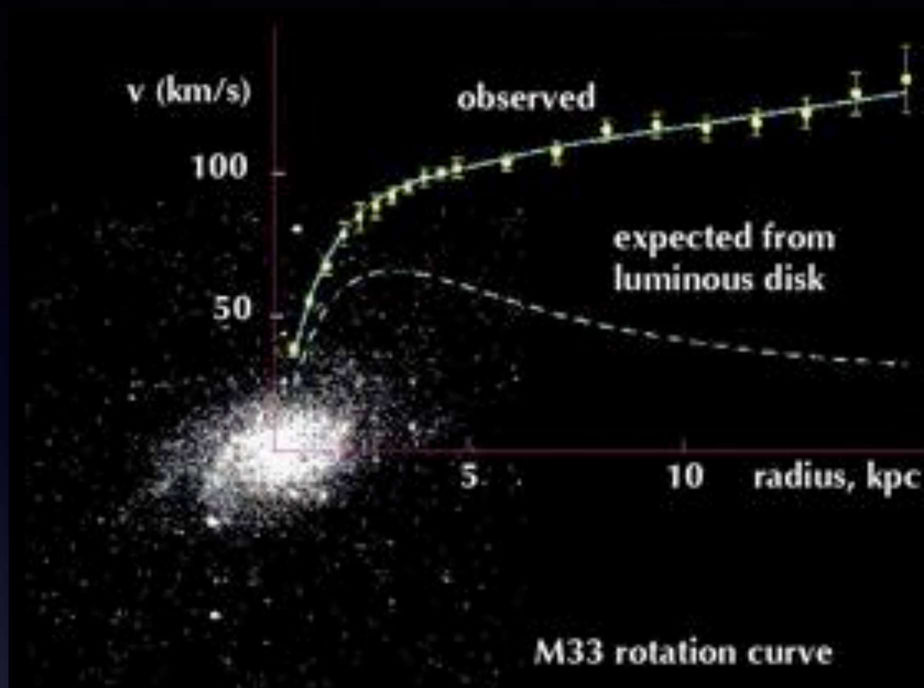
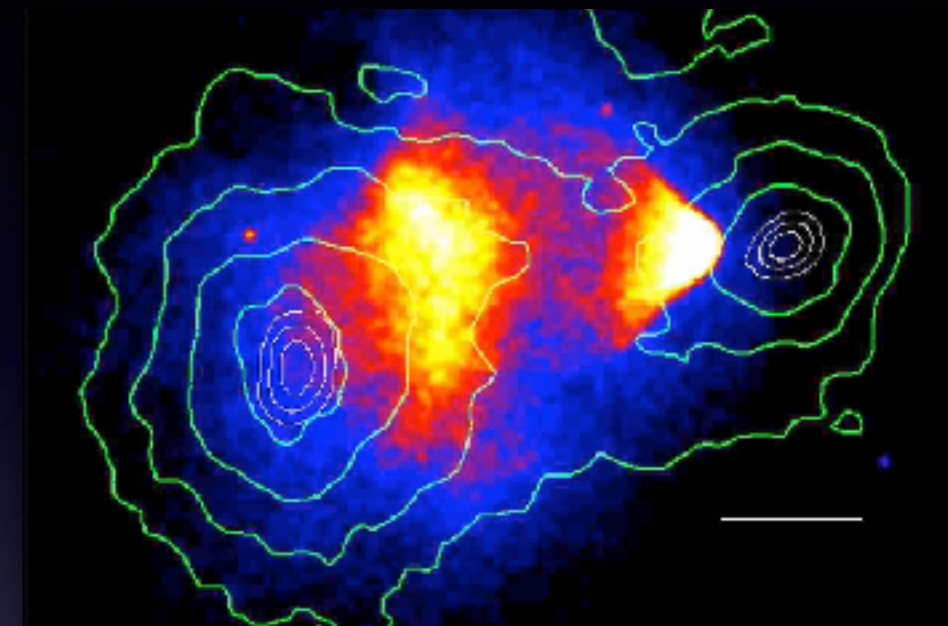
Fisica delle Particelle, verso la nuova Strategia Europea
Roma 7 settembre 2018

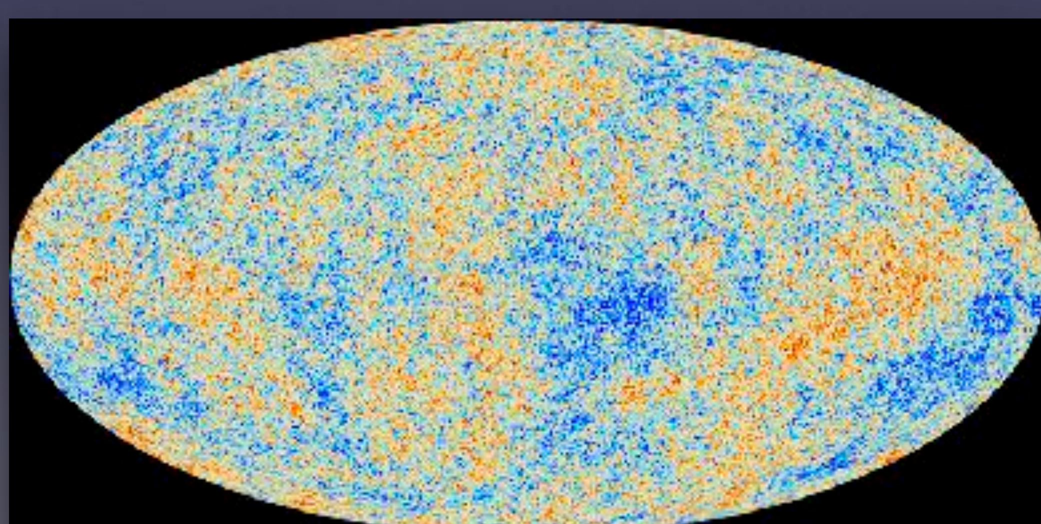
Observational evidence for DM at all scales



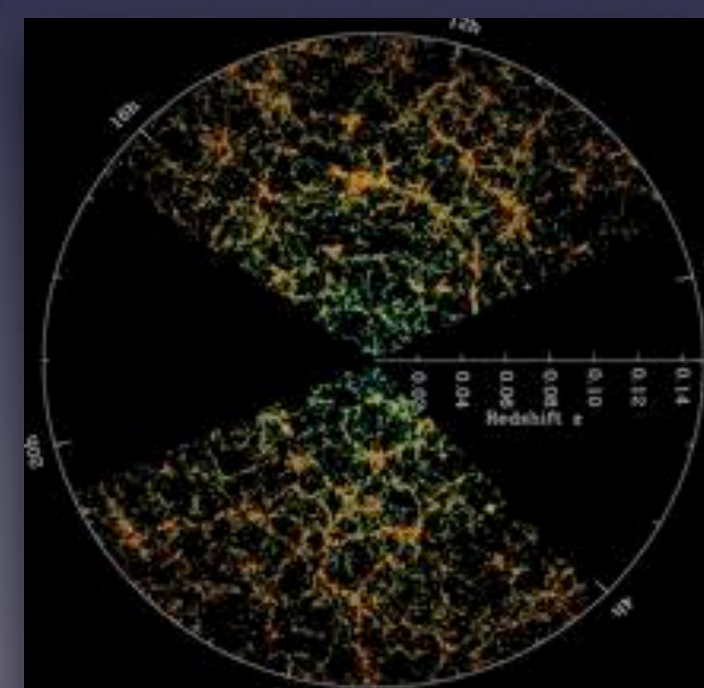
Galaxies



Galactic Clusters



CMB



Structure

What do we know of Dark Matter?

Mostly “negative” information:

- No colour charge
- No electric charge
- No strong self-interaction

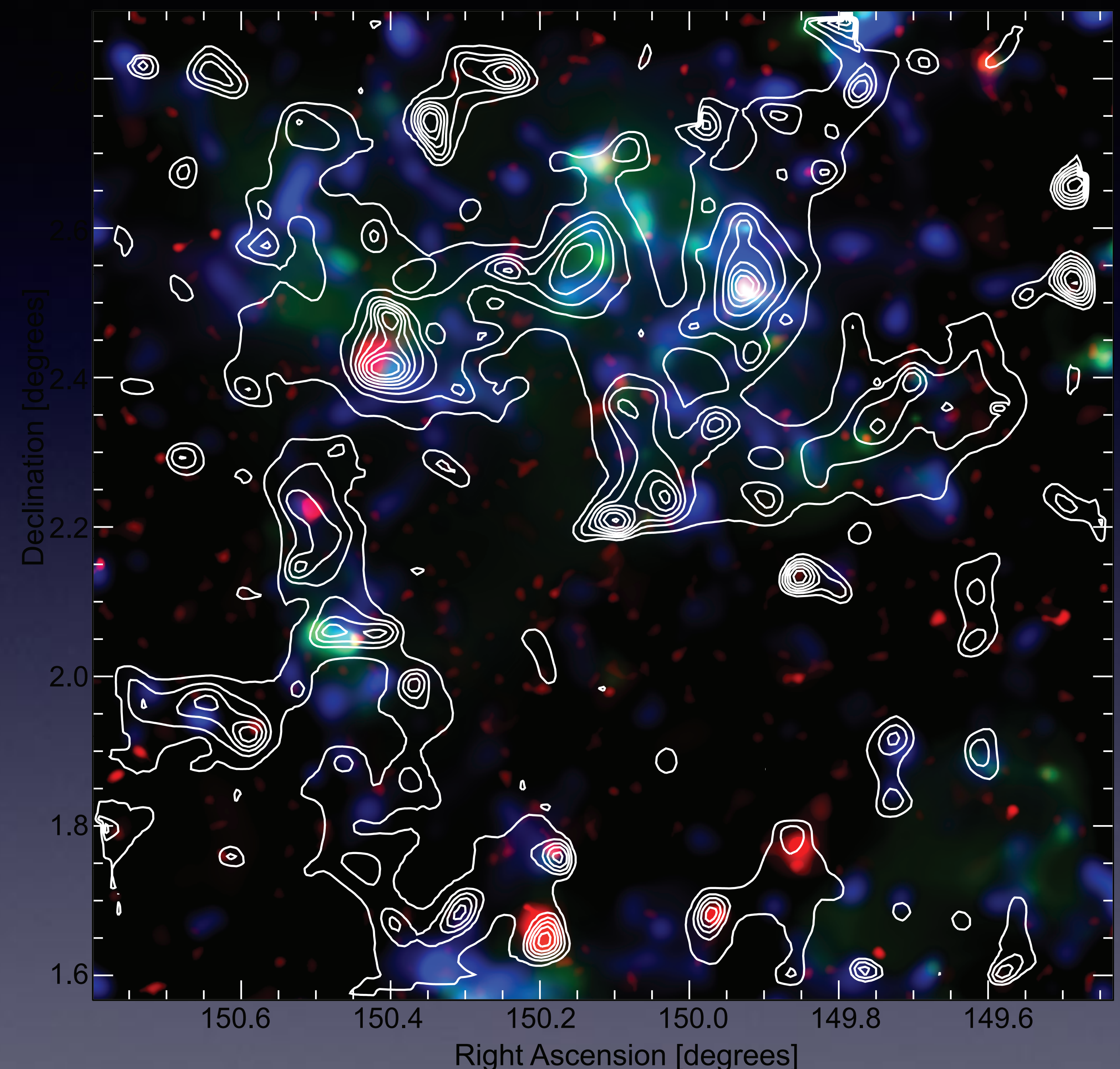
Stable, or very long-lived

Cold

CMB evidence that it is non-baryonic
PLANCK: $\Omega_c \approx 5\ \Omega_b$

DM accounts for almost 85% of total matter in Universe

Nature 445, 286 (2007)

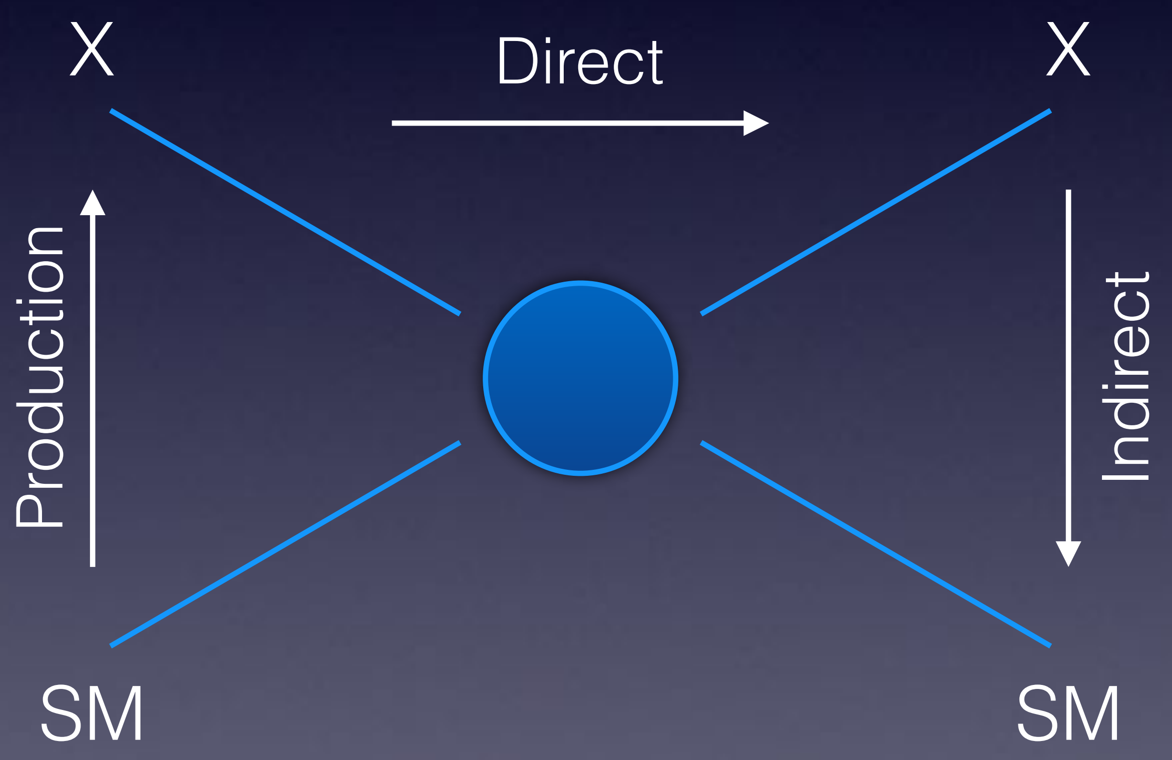


dark matter forms a loose network of filaments, growing over time, which intersect in massive structures at the locations of clusters of galaxies

WIMPs

Weakly Interacting Massive Particles

- Non-baryonic, cold thermal relics from the early Universe
- To account for the missing matter masses should be order of 1-1000 GeV and cross-sections at the electroweak scale
- Three ways to search for WIMP DM
  - **Direct detection** of scattering on matter
  - **Indirect detection** of signals from annihilation (or decay) with CR detectors in space or on ground
  - **Production** in high energy collisions (LHC)
    - need confirmation from DD or ID to establish it is DM



WIMP direct detection

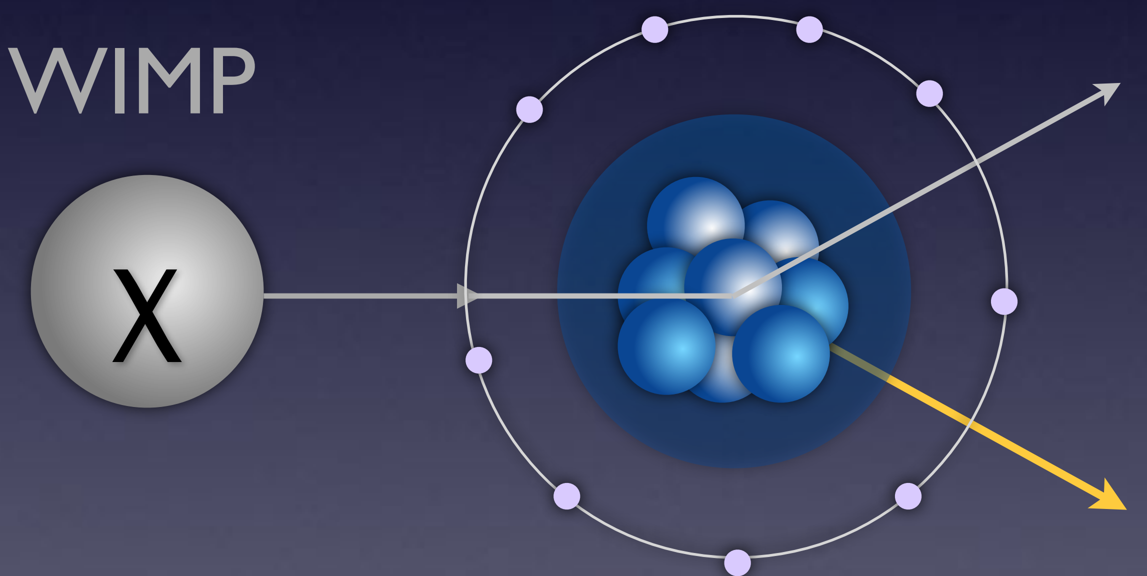
- Goodman & Witten (1985): "Detectability of certain dark matter candidates"

$\chi N \rightarrow \chi N$

elastic scattering off nuclei

coherent scattering off nuclei

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \times \int d\mathrm{v}\, f(\mathrm{v})\, \mathrm{v} \frac{d\sigma_\chi}{dE_R}$$

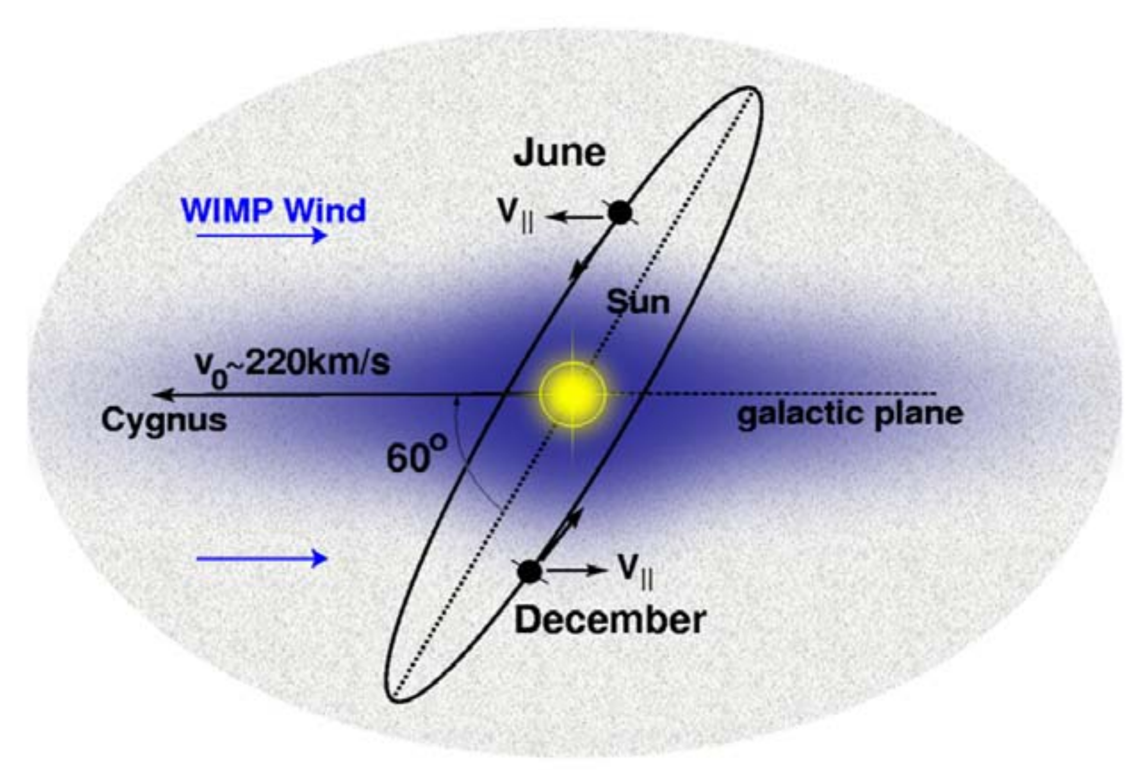


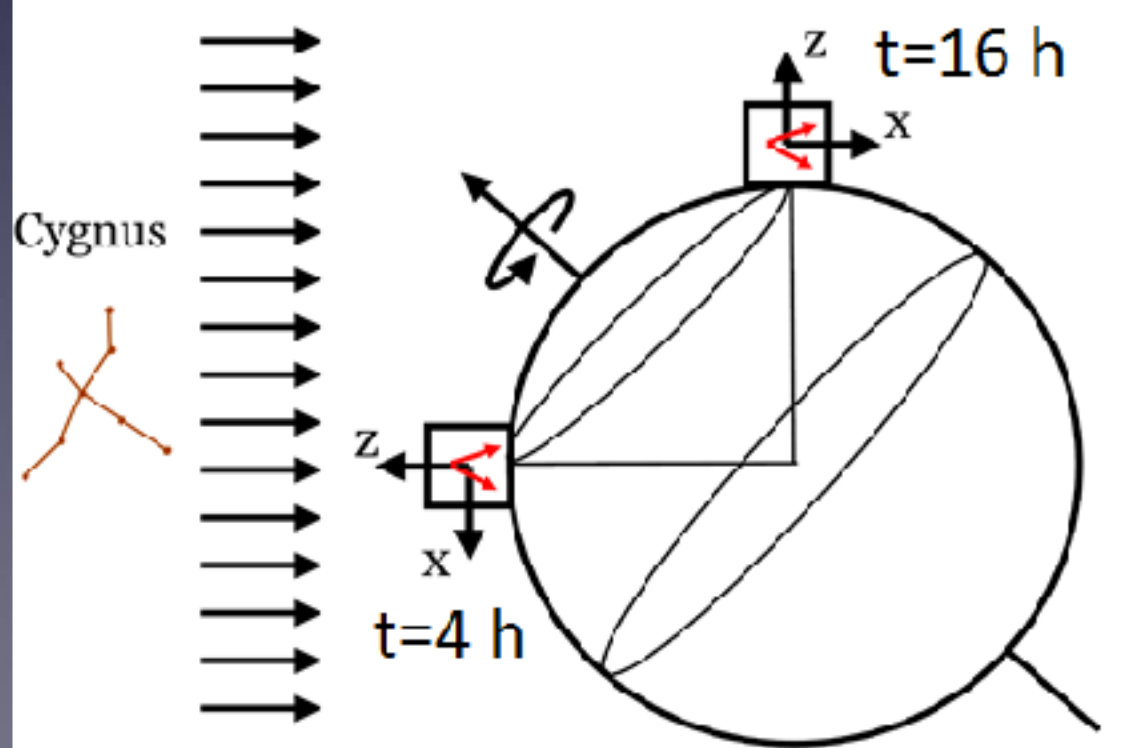
- Large detector mass, long exposure
- Low energy threshold
- Ultra-low radioactive bg
- Good bg discrimination

Nuclear recoil energy $\approx$ 1÷100 keV

WIMP signatures

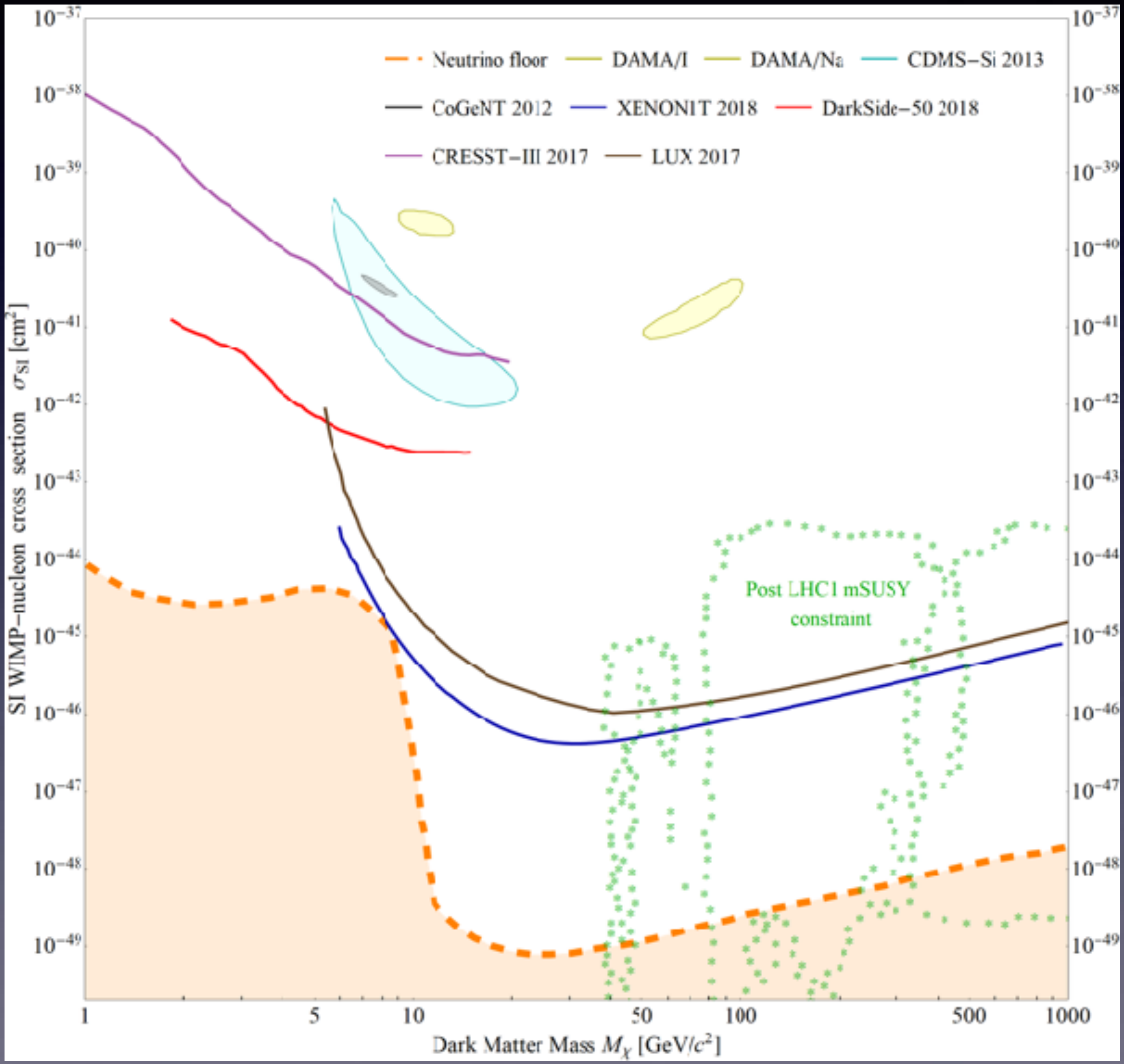
- WIMP halo → WIMP wind
  - Solar system orbit around the galactic center (~220 km/s)
- Annual rate modulation
  - Earth orbit (±30 km/s, few % effect)
  - Model independent, but background could in principle be similarly modulated!
- Sidereal direction modulation
  - Measure angle between WIMP apparent direction and Earth bound detector
  - Directional signature (unique to WIMPs)
  - O(10) rate variation between parallel and perpendicular directions (large effect)





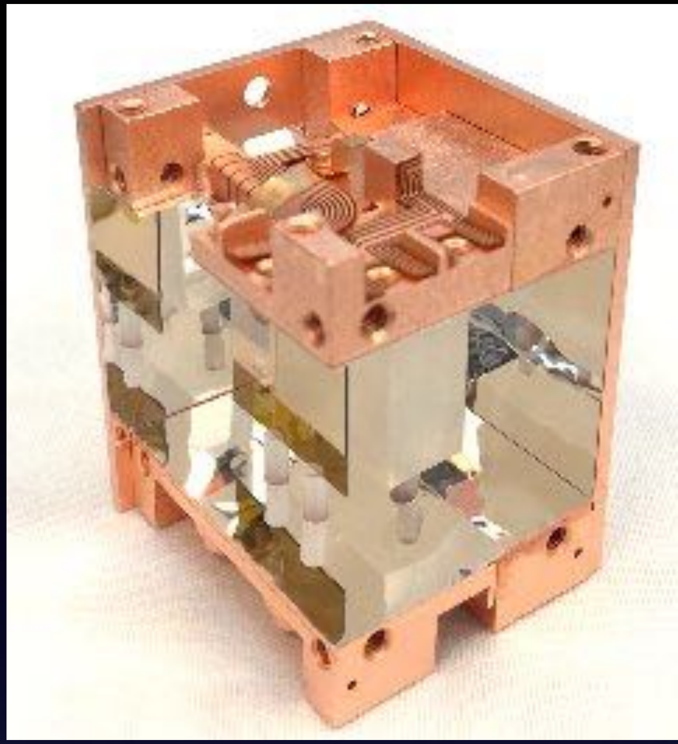
WIMP direct searches current status

- DAMA signal
  - 2.46 ton × yr exposure
  - annual modulation signature observed over 20 annual cycles (12.9 σ)
  - ANAIS, COSINE-100 and SABRE set to replicate the experiment
- Other techniques
  - no observations so far
  - hard to reconcile results under standard WIMP scenarios

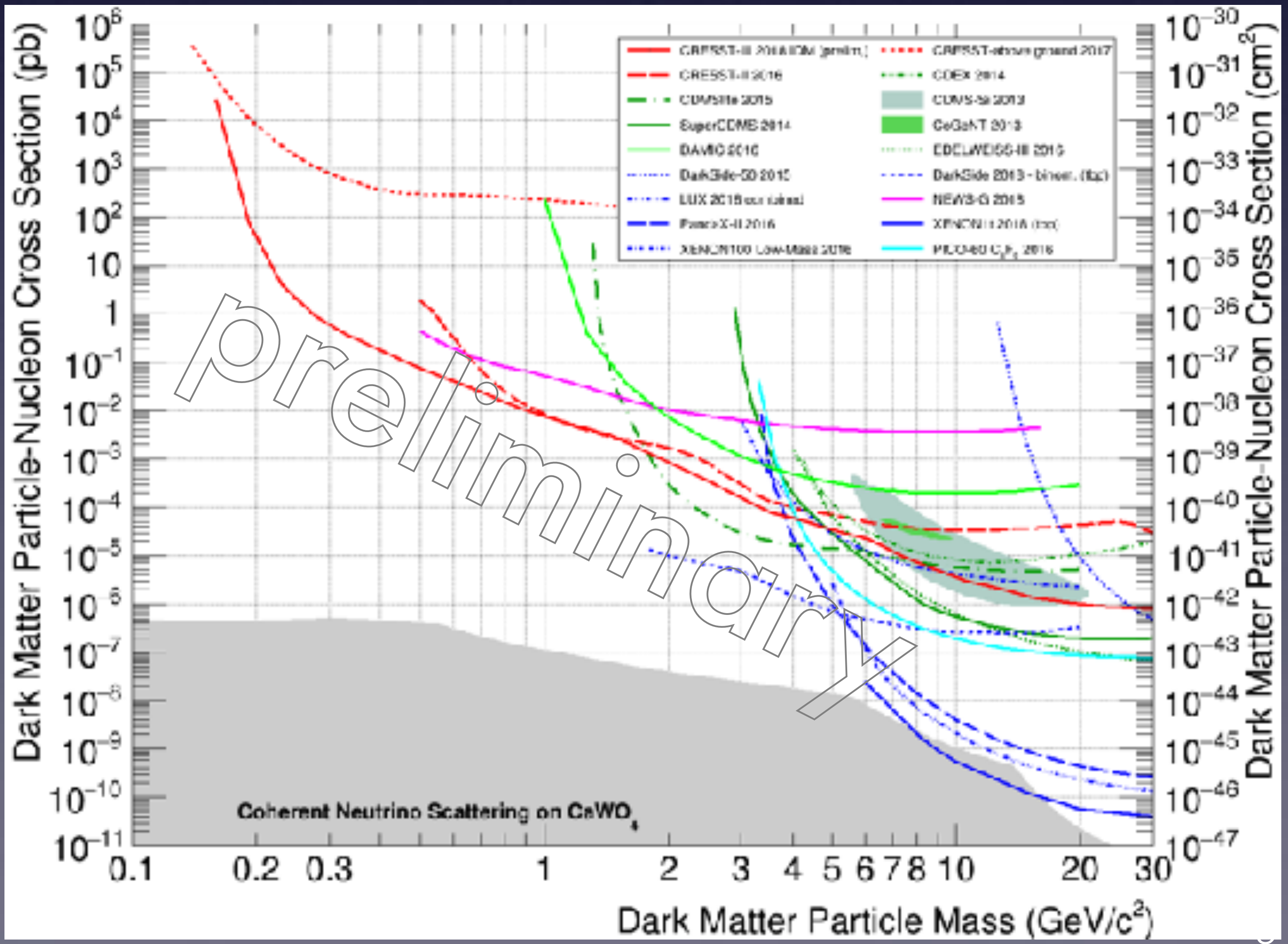


Adapted from **NATURE PHYSICS** DOI: 10.1038/NPHYS4039

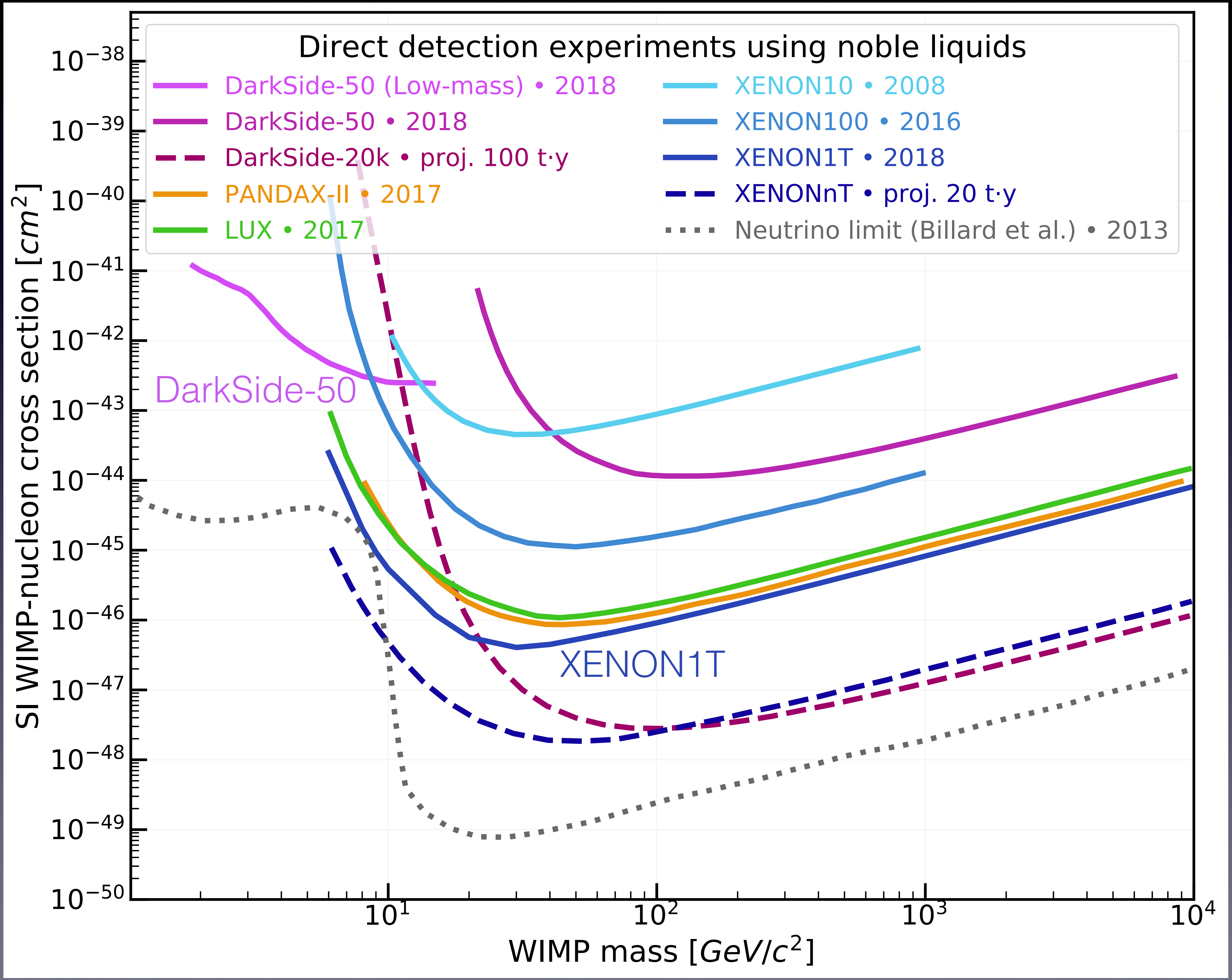
Low mass: CRESST



- First CRESST-III run 07/2016 - 02/2018
- Unprecedented low nuclear recoil thresholds of 30 eV
- Leading sensitivity over one order of magnitude:
  - 160 MeV/c² → 1.8 GeV/c²
- CRESST-III phase 2 will push further the threshold (10 eV), exposure (1tonne*day with 1000 CRESST modules) and background (improving a factor of ~100) to approach the neutrino floor.



Noble liquids spearheading WIMP searches



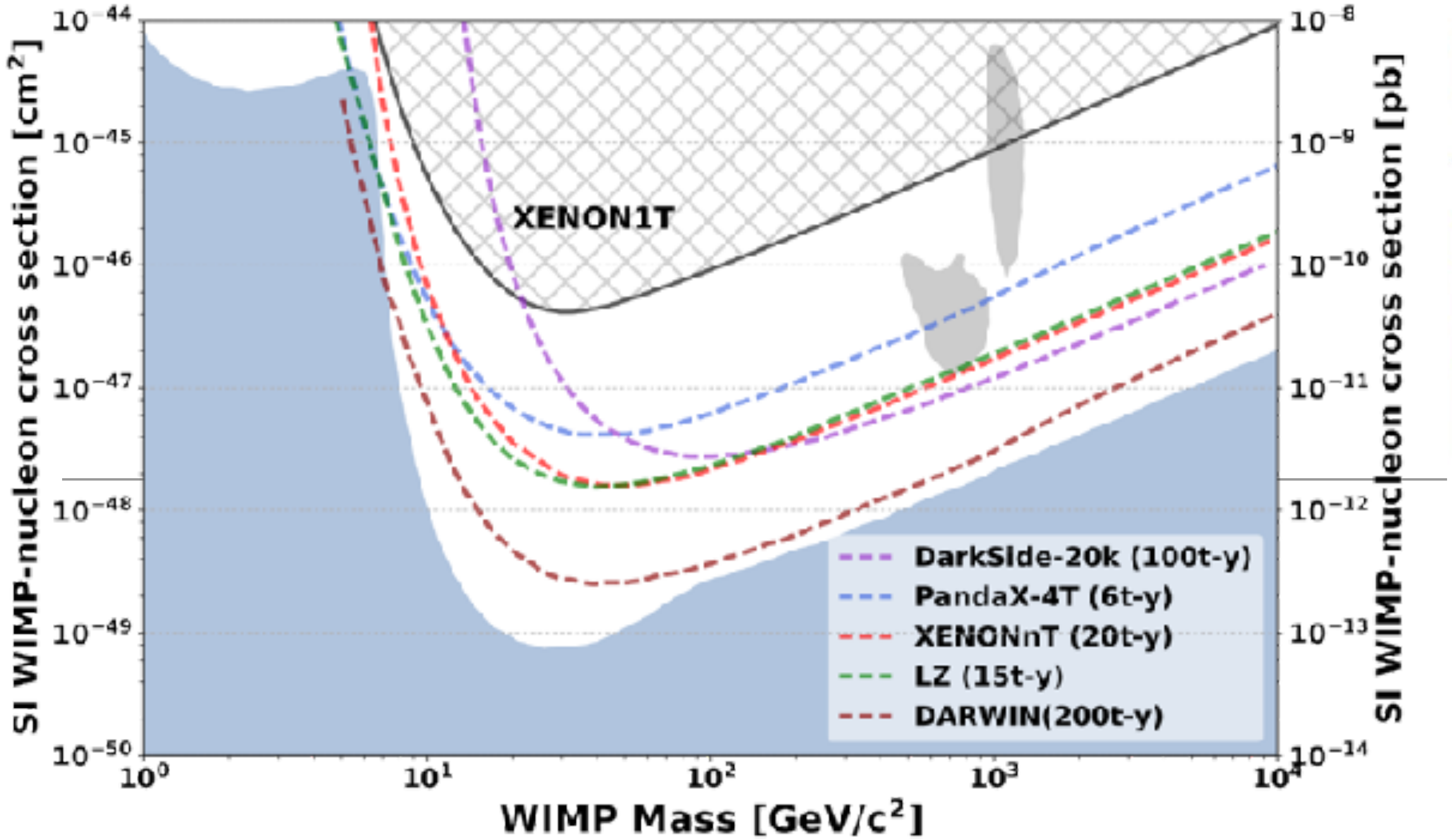
M. Selvi

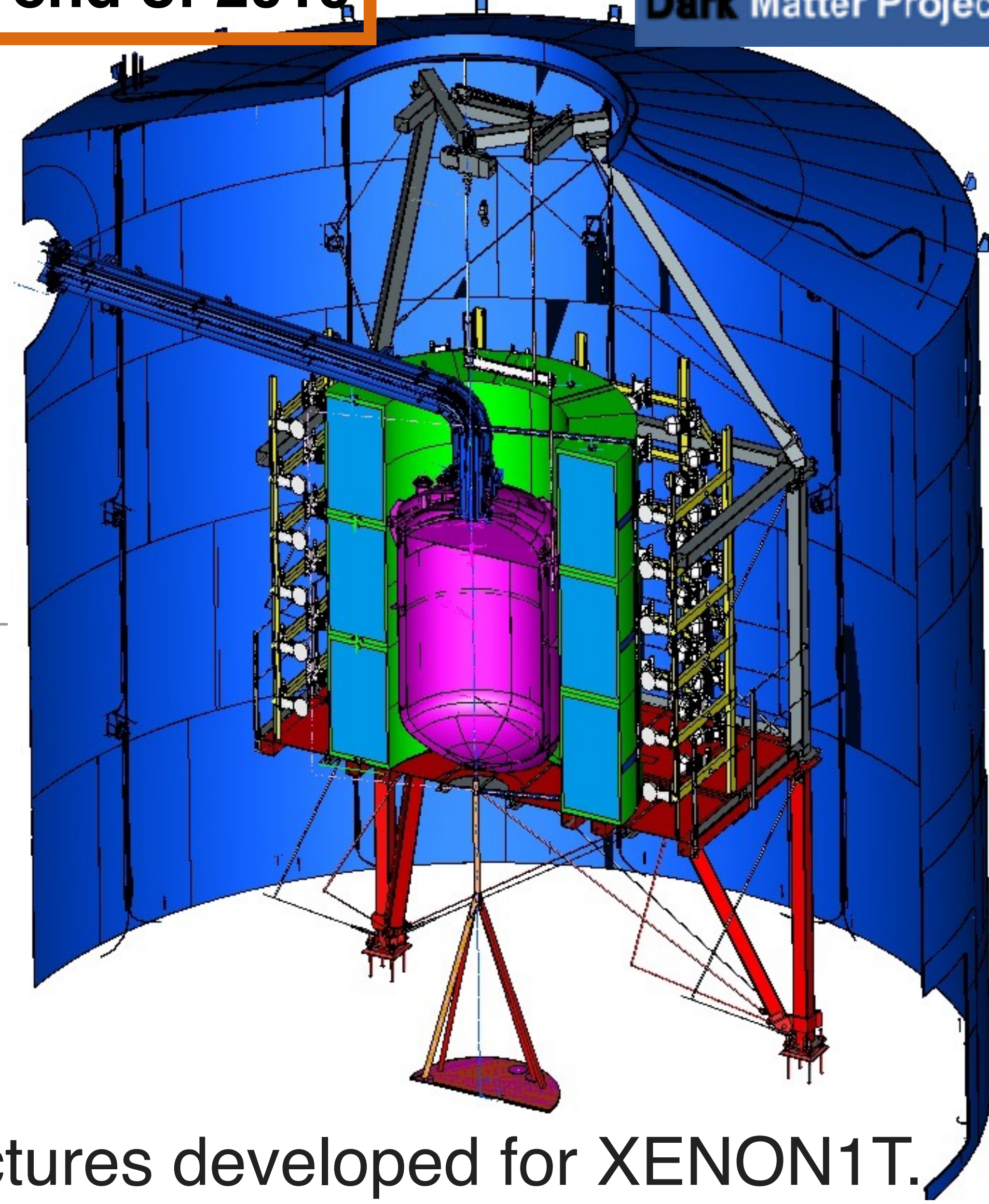
Istituto Nazionale di Fisica Nucleare

XENONnT

XENON Dark Matter Project

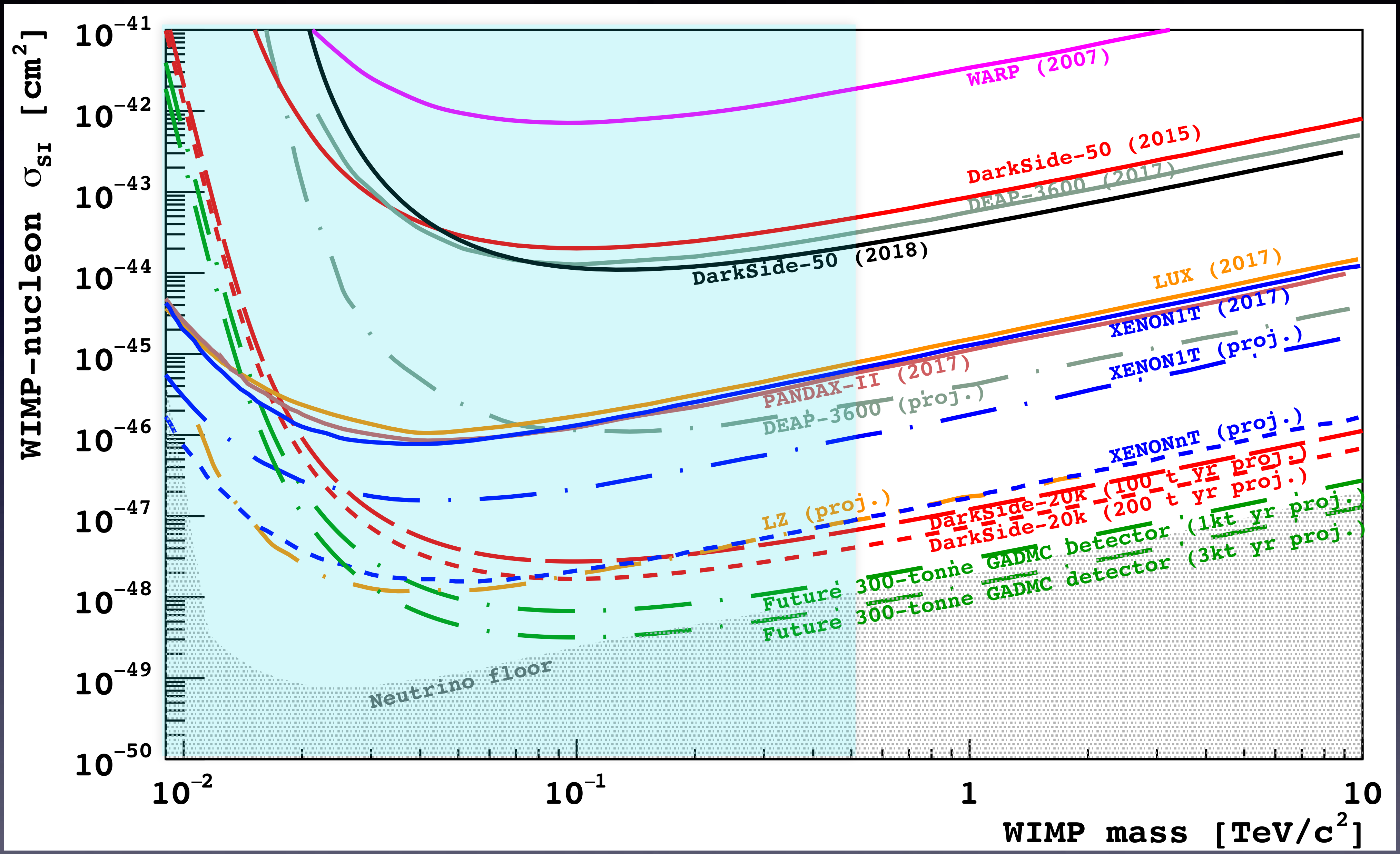
Commissioning will start by the end of 2019





- Increased LXe mass in the TPC: 2t → 6t.
- Reused most of the existing systems and infrastructures developed for XENON1T.
- Background from Rn reduced by factor 10, thanks to cryogenic distillation.
- Neutron background reduced with an active neutron veto around the cryostat.
- Expected sensitivity on WIMP-nucleon SI cross-section will improve by a factor 10 with 20 tonne x year data (about 5 years of live time).

The Global Argon Dark Matter Collaboration



- Currently taking data:
  - ArDM at LSC
  - DarkSide-50 at LNGS
  - DEAP-3600 at SNOLAB

- Next step: **DarkSide-20k** at LNGS (2022-)
- Last step: 300 tonnes detector, location t.b.d (2027-)
- A collaboration supported by the three Underground Labs

CERN as a technological hub for DarkSide

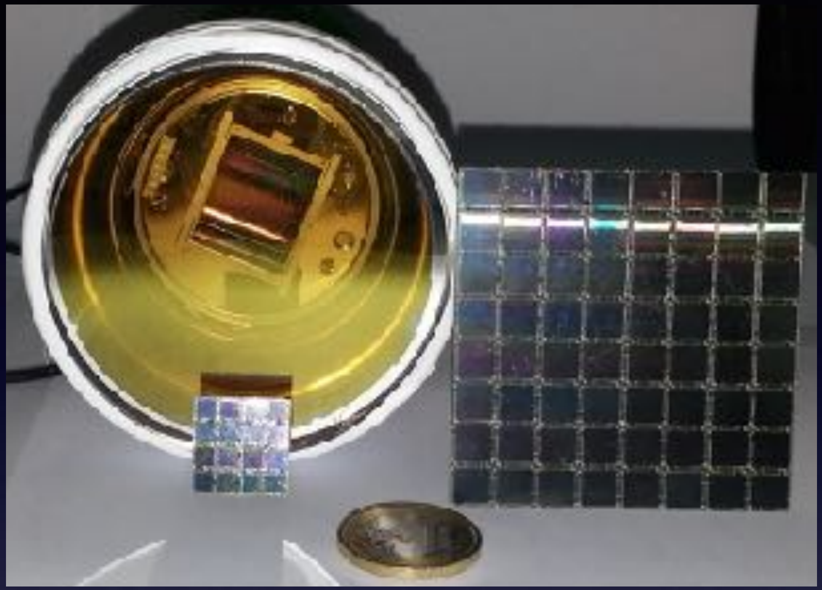
- Key technologies enabling DarkSide-20k and future liquid argon program
- Low radioactivity argon
  - **ARIA** cryogenic distillation column leak tests and technical review
- Cryogenic Photosensors
  - **NOA** large area Photon Detector Modules integration tests
- Cryogenics for liquid argon detectors
  - **Proto-DUNE** cryostats

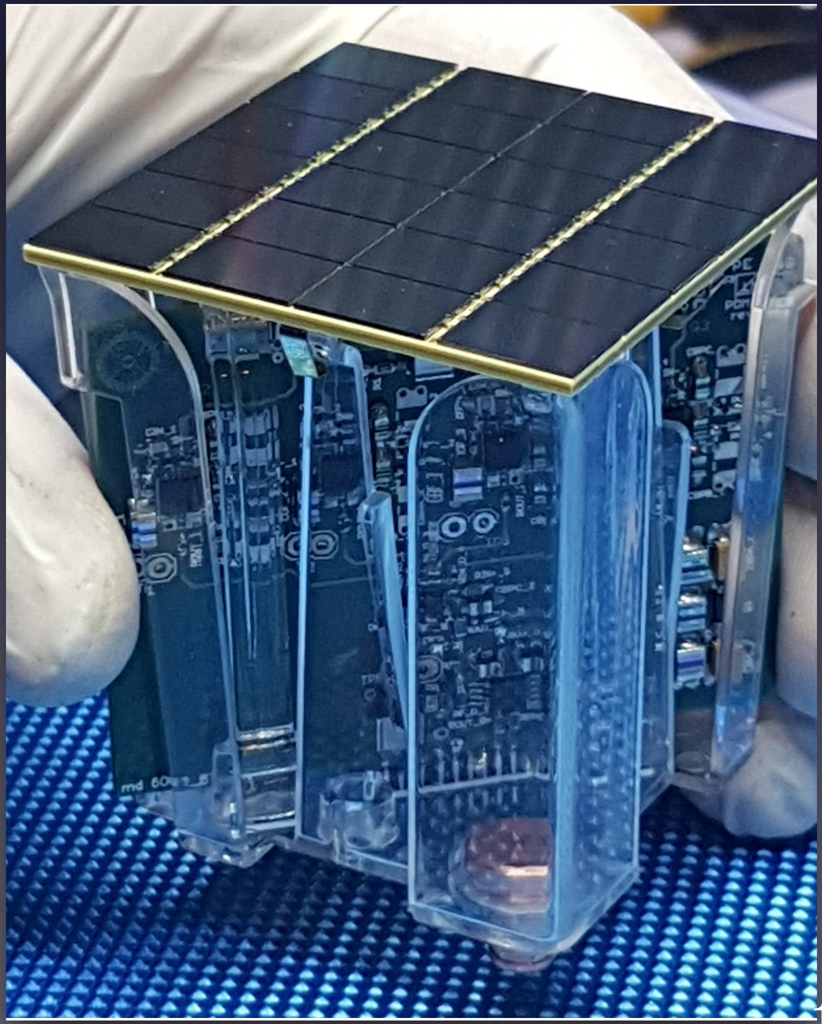
SERUCI-0 @ CERN

January 2018

SiPM to enhance LAr technology

- Advantages w/r to cryogenic PMTs
  - Very compact, much lower radioactivity
  - Light yield increase by 50%
  - Greater stability
  - Ten-fold reduction of costs per unit area
  - SiPMs love to run at LAr temperature!
- A full chain (development-production-packaging-testing) strategy largely funded by Regione Abruzzo
  - Custom SiPM development for cryogenic temperature (FBK)
  - Industrial cooperation for large-scale production (LFoundry)
  - Radiopure packaging of the tiles and of the cryogenic FE readout board (Nuova Officina Assergi - NOA)

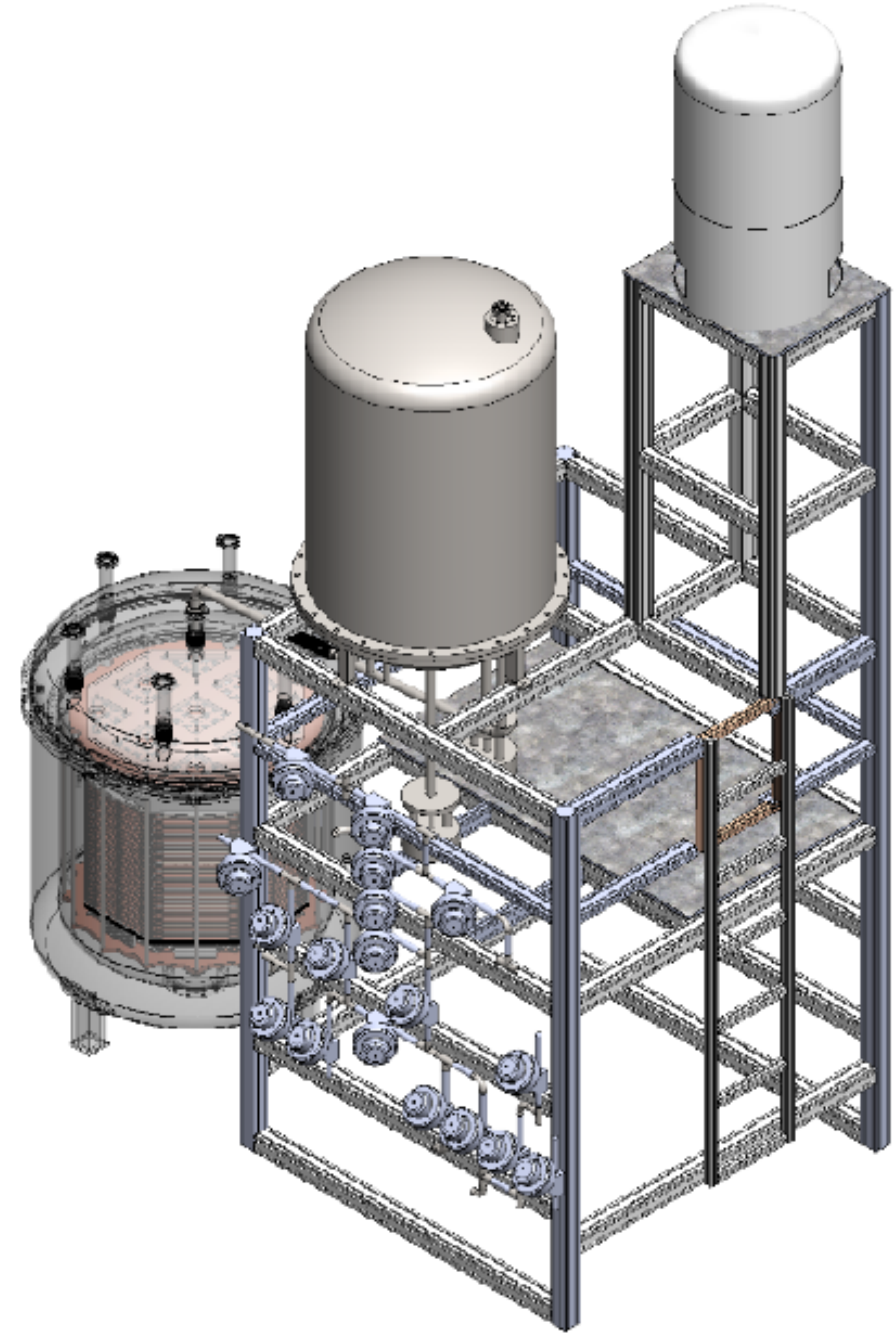




DarkSide-Proto @ CERN

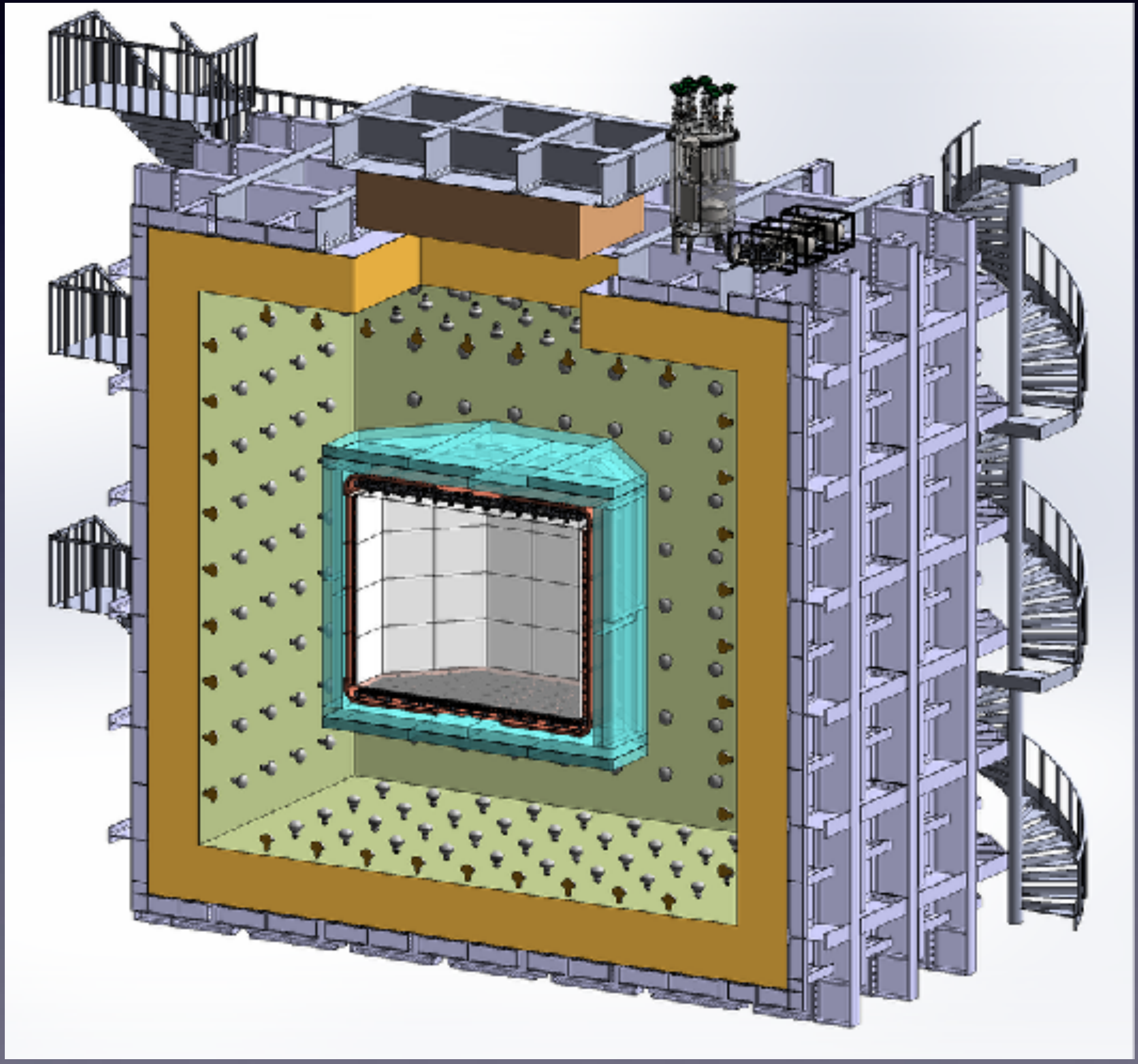
1-ton TPC prototype of DS-20k detector will allow:

- validation of the design of mechanics and cryogenics of the TPC
- integration tests of the custom SIPM-Photosensors and of the full read-out electronics and data acquisition chain

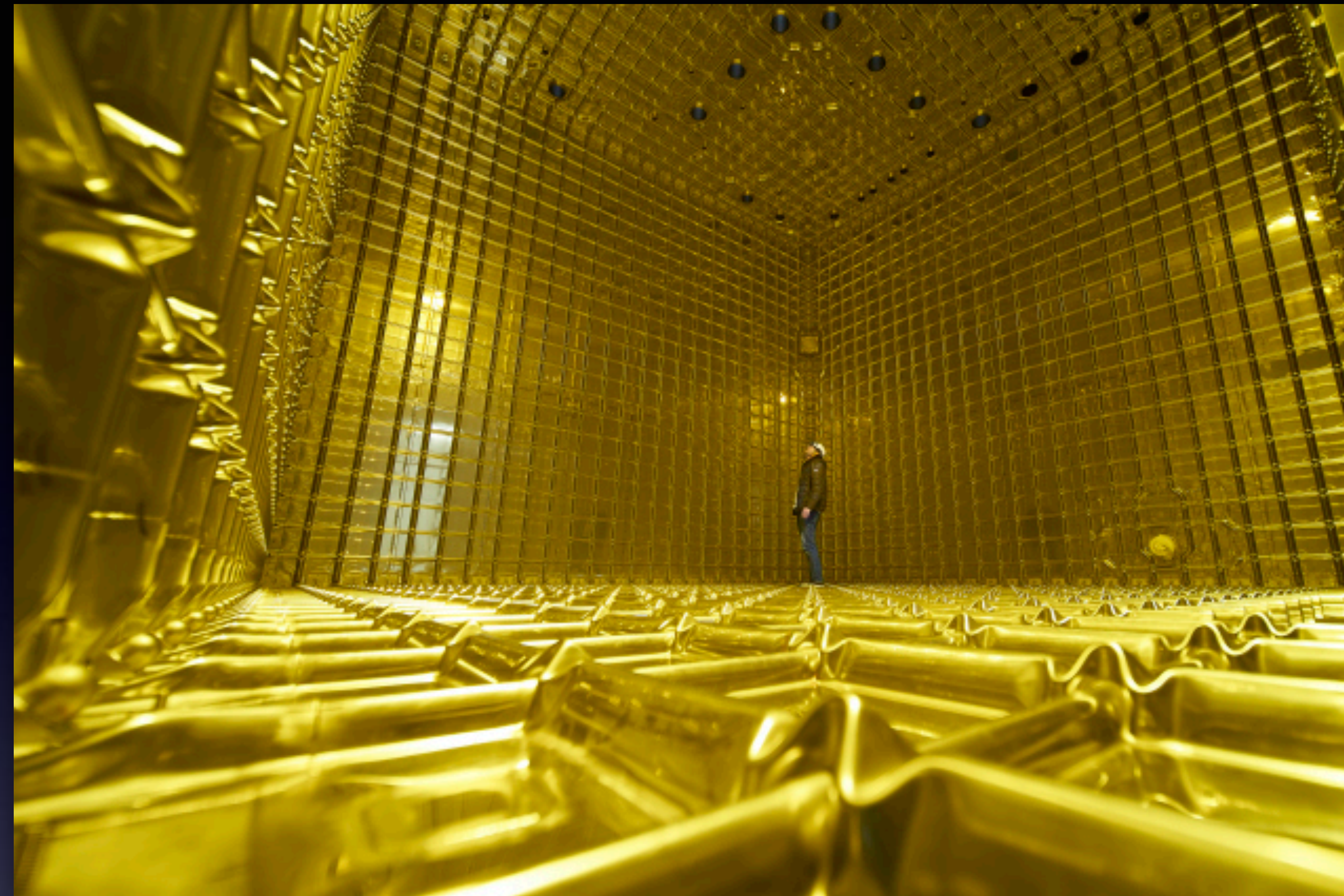


Scalability: a LAr shield for DarkSide-20k

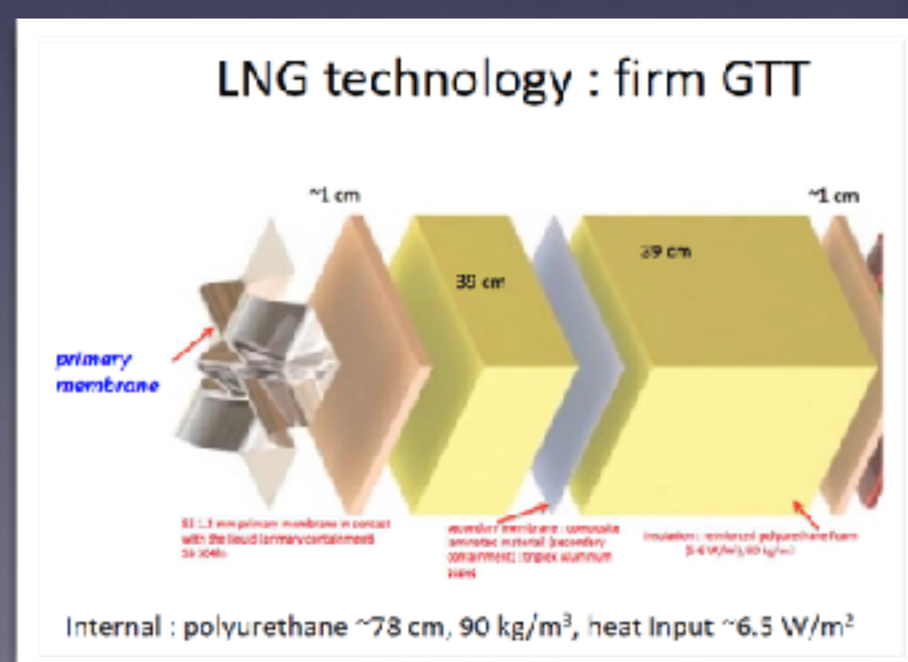
- AAr in ProtoDune style large cryostat to provide shielding and active VETO
- Would benefit from an important technological contribution from CERN allowing to eliminate Liquid Scintillator Veto and Water tank
- Significantly simplify the overall system complexity and operation
- Fully scalable design for future larger size detector (300 ton)



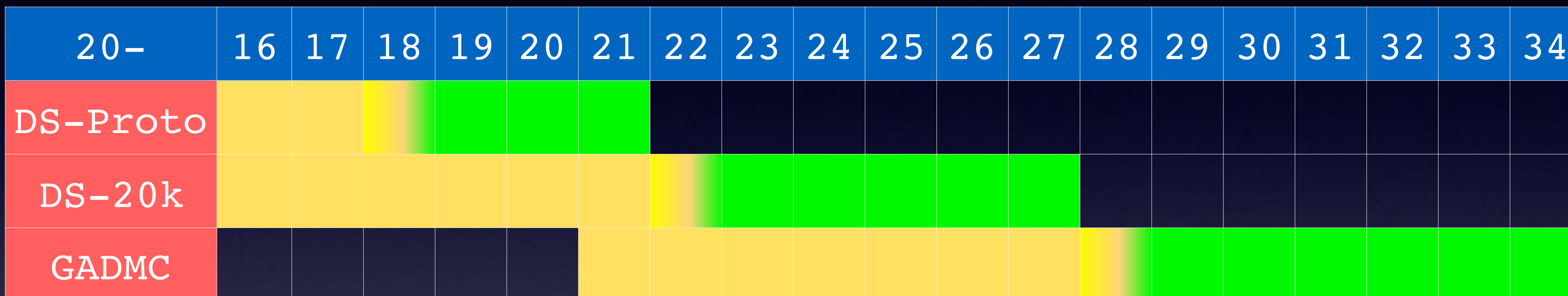
CERN Neutrino Platform:



- Two almost identical cryostats built for NP02 and NP04 experiments
- About 8x8x8 m^3 inner volume, 750 t of LAr in each one
- Cryostat technology and expertise taken from LNG industry
- Construction time: 55 weeks (NP04), 37 weeks (NP02)
- Thought since the beginning to be installable underground



DarkSide future program



DarkSide-20k

a 20-tonnes fiducial argon detector

100 tonne×year background-free search for dark matter

GADMC detector

a 300-tonnes depleted argon detector

1,000 tonne×year background-free search for dark matter

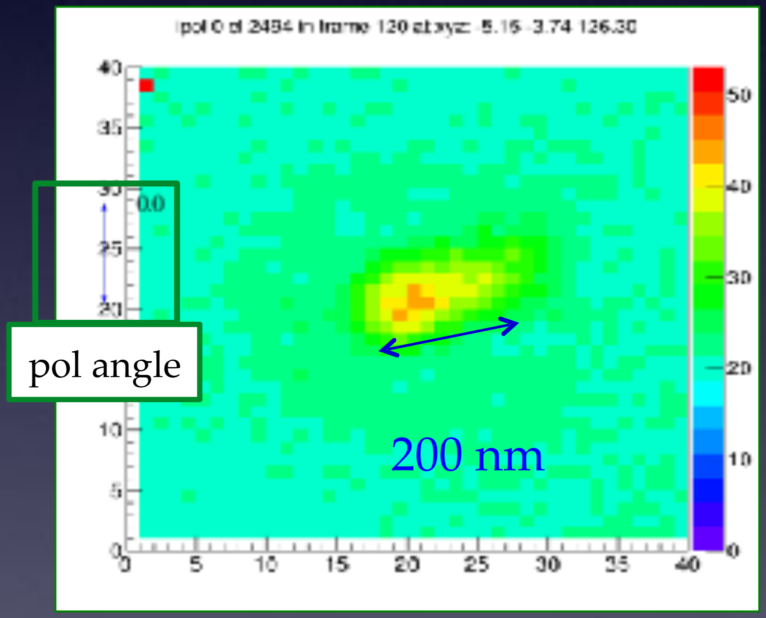
European Astroparticle Physics Strategy 2017-2026

5. Dark Matter

APPEC encourages the continuation of a diverse and vibrant programme (including experiments as well as detector R&D) searching for WIMPs and non-WIMP Dark Matter. With its global partners, APPEC aims to converge around 2019 on a strategy aimed at realising worldwide at least one 'ultimate' Dark Matter detector based on xenon (in the order of 50 tons) and one based on argon (in the order of 300 tons), as advocated respectively by DARWIN and Argo.

Directional detection: beyond the neutrino floor

- Mature technology: gaseous TPC (DRIFT, MIMAC, DMTPC, NEWAGE, D3, CYGNO)
- R&D on several other techniques:



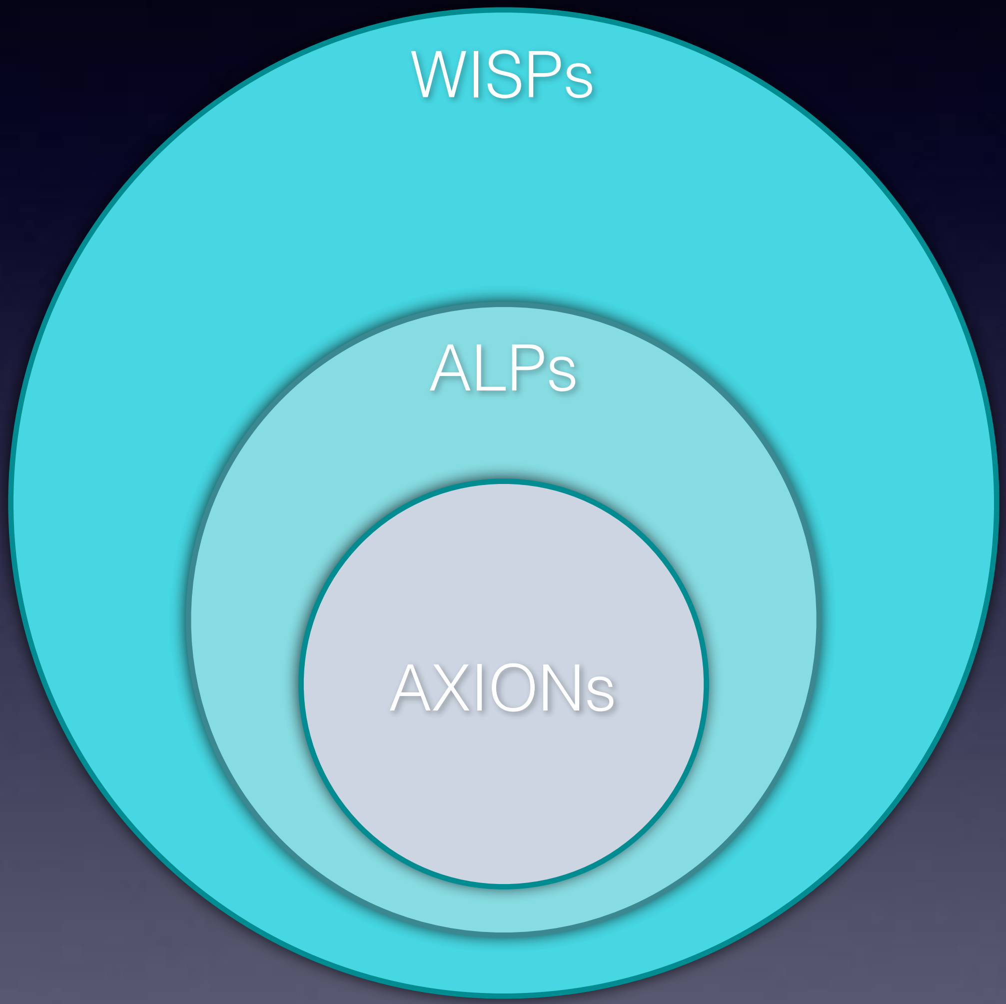
Barycenter shift (100keV C ion)

- NEWS
  - Nanometric track direction measurement in nuclear emulsions
  - Exploit resonant light scattering using polarised light
  - Measurement of track slope and length beyond the optical resolution
  - Unprecedented accuracy of 6 nm achieved on both coordinates

- RED
  - Columnar Recombination in liquid argon TPC
- PTOLEMY
  - Graphene target (nanoribbon or nanotubes)

Axions, ALPs, WISPs

- Origins in particle physics (extensions to Standard Model, strong CP problem)
- sub-eV **Dark Matter** candidates
- Low energy scale dictates experimental approach
- WISP searches are complementary to WIMP searches



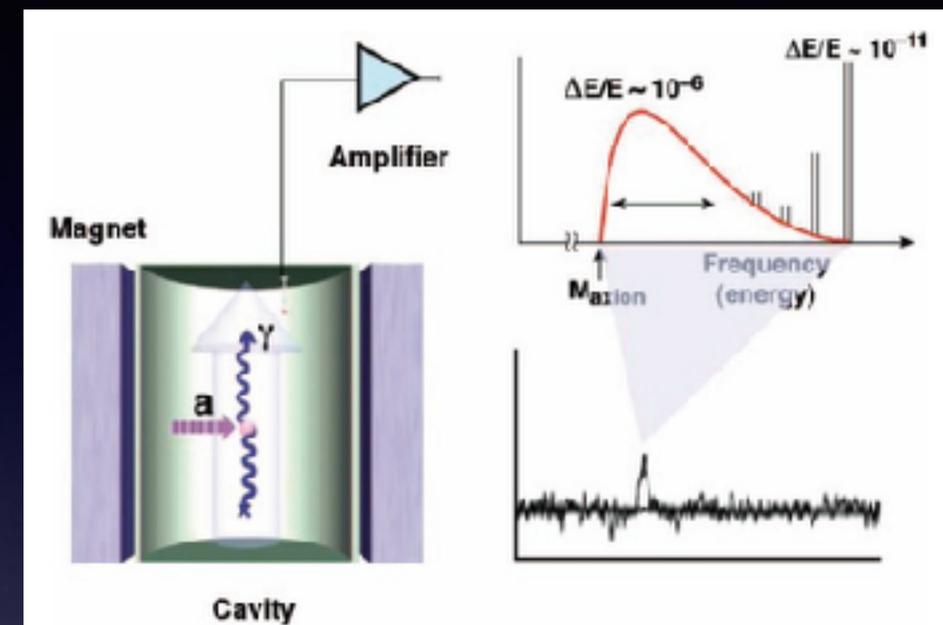
WISP = Weakly Interacting Slim Particles

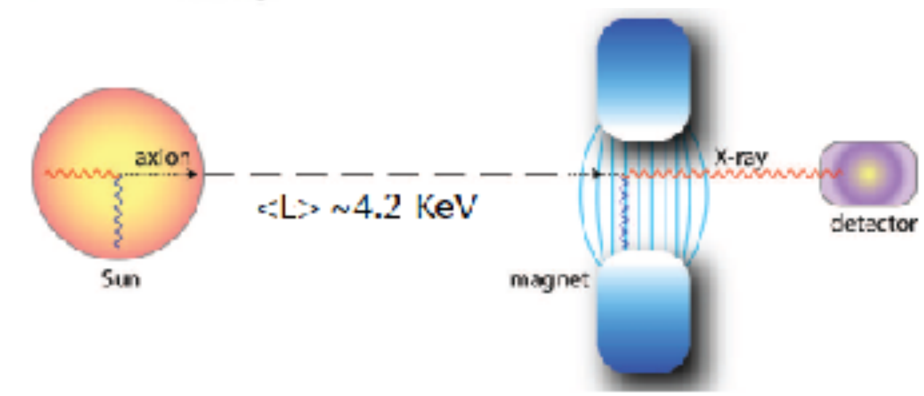
Slim = sub-eV

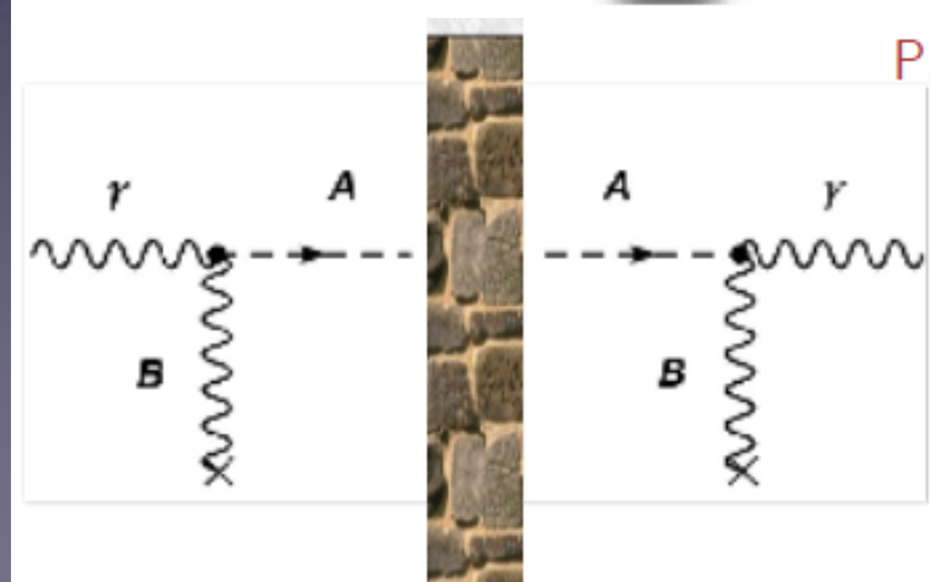
ALP = Axion Like Particles

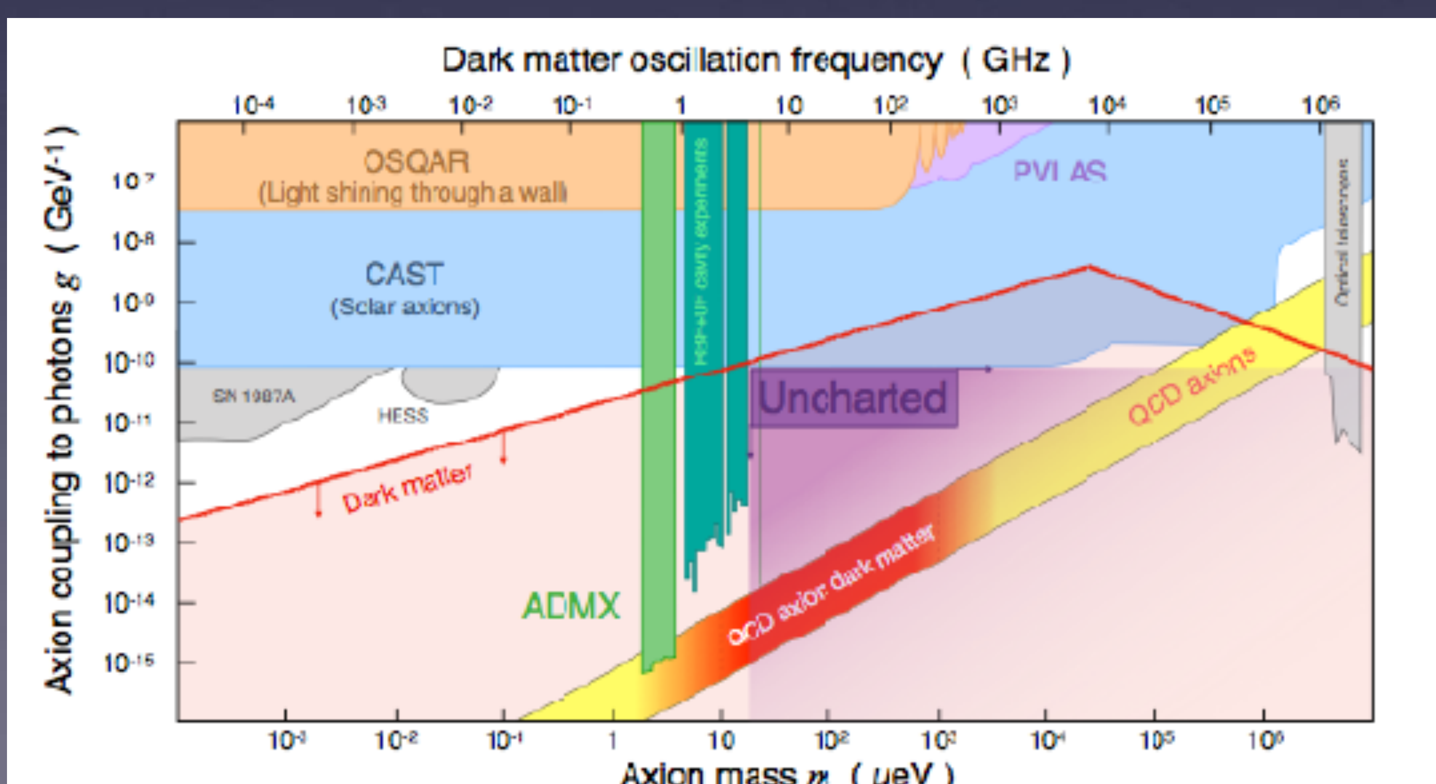
WISP detection

- Pierre Sikivie (1983): “Experimental Tests of the invisible Axion”, based on the conversion of axions to photons:
    - in a static magnetic field, the axion can “borrow” a virtual photon from the field and turn into a real photon
- Three main approaches being pursued:
    - **Haloscopes** (look directly for dark-matter WISPs in the galactic halo of MW)
    - **Helioscopes** (search for ALPs or axions emitted by the Sun)
    - **Laboratory experiments** (generate and detect ALPs in a single setup)





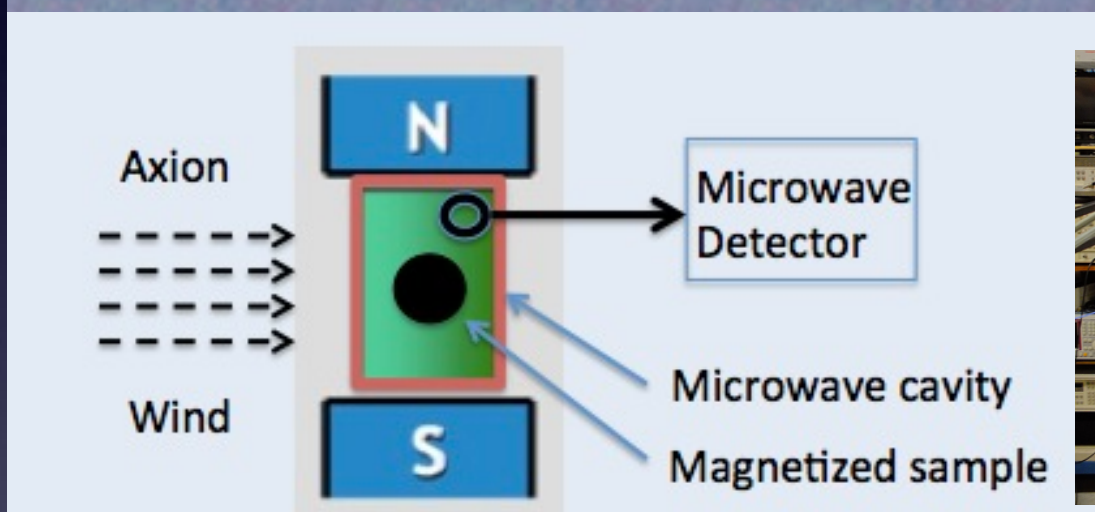


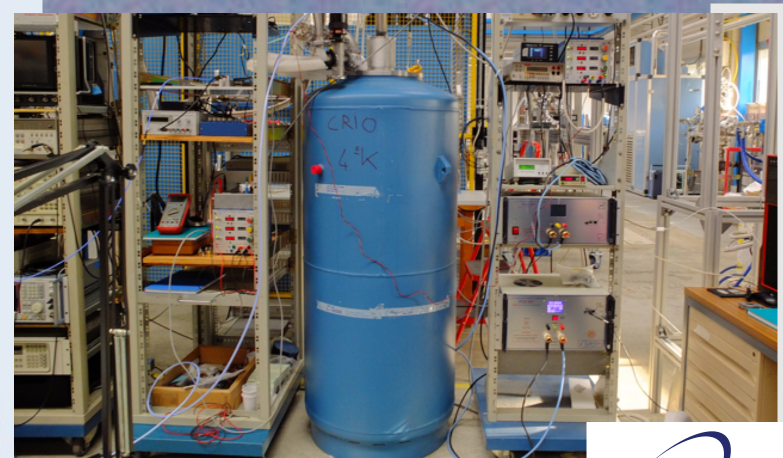


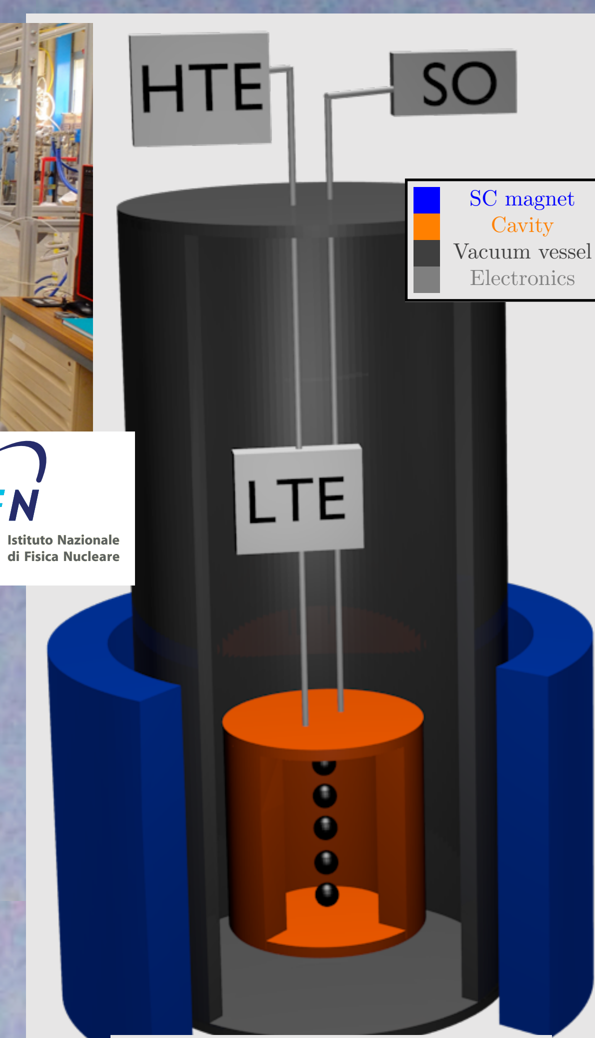
Haloscopes

The QUAX approach: axion-electron coupling

- **Due to the motion of the solar system** in the galaxy, the axion DM cloud acts as an **effective RF magnetic field on electron spin**
- RF field excites **magnetic transition in a** **magnetized sample** (Larmor frequency) with a static magnetic field $\mathbf{B_0}$ and can produces a detectable signal
- **The interaction with axion field produces a variation of magnetization which is in principle measurable**



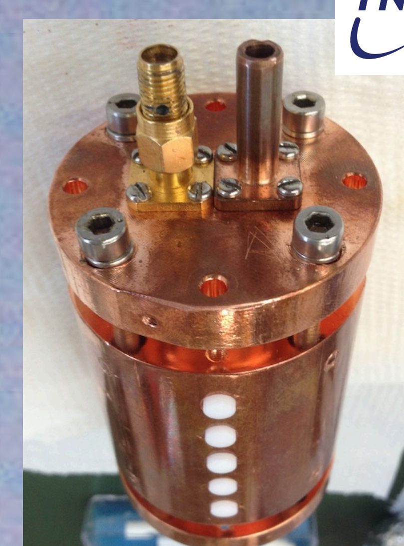




HTE – high temp electronics
LTE – low temp electronics
SO – source generator

Extremely challenging!

$$P_{\rm out} = \frac{P_{\rm in}}{2} = \mathbf{3.8 \times 10^{-26}} \left(\frac{m_a}{200\,\mu\rm eV}\right)^3 \left(\frac{V_s}{100\ \rm cm^3}\right) \left(\frac{n_S}{2 \cdot 10^{28}/\rm m^3}\right) \left(\frac{\tau_{\rm min}}{2\,\mu s}\right)\ \rm W$$



Microwave cavity loaded with magnetic samples

Looking for a different coupling will be crucial to identify the particle in case of discovery

G. Carugno

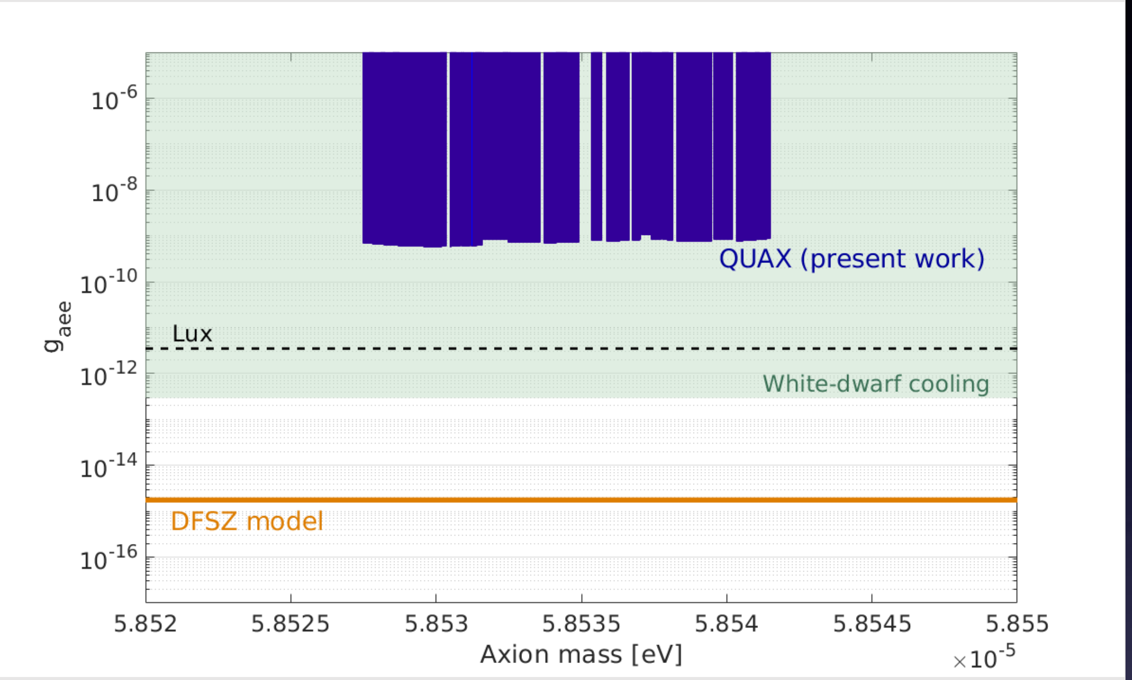
Haloscopes

QUAX: latest results / perspectives

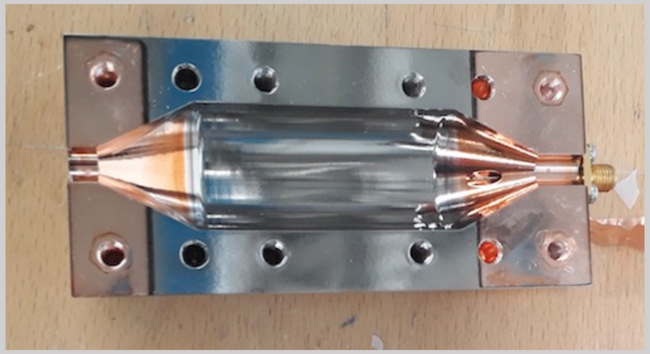
First limits of axion electron coupling from a dark matter haloscope

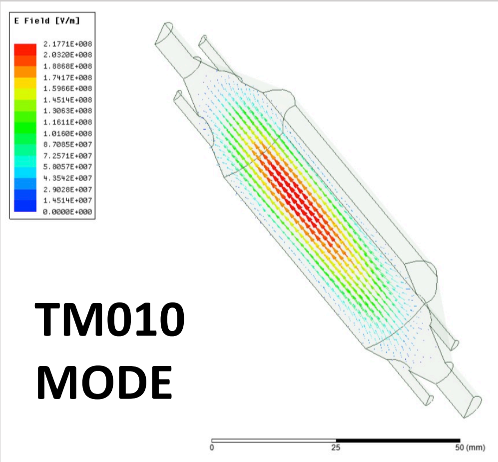
$$g_{aee} > \frac{e}{\pi m_a v_a}\sqrt{\frac{2\sigma_P'}{\mu_B \gamma n_a n_s V_s \tau_+}},$$

R & D in progress to define a complete apparatus

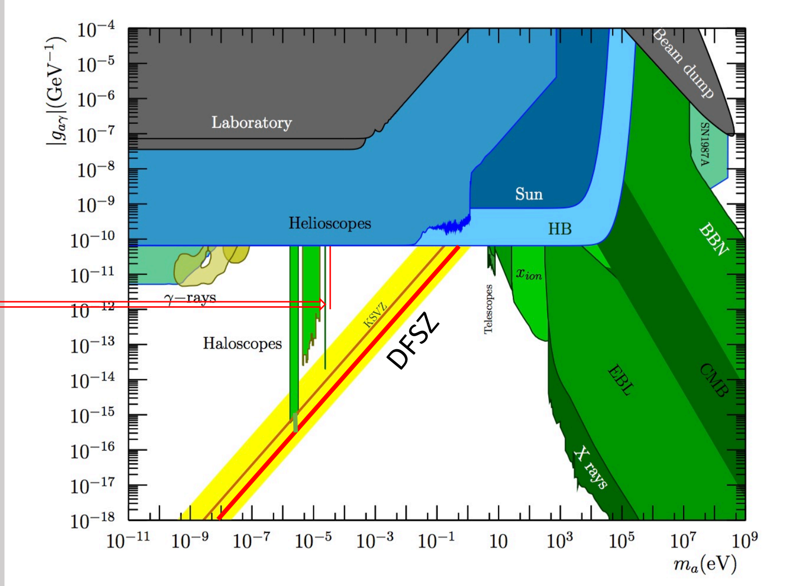


QUAX can operate in Primakoff mode too!
Use a different resonant mode.





Preliminary point



In the next 2-3 years possibility to reach cosmological sensitivity in the 30 μeV mass range for QUAX

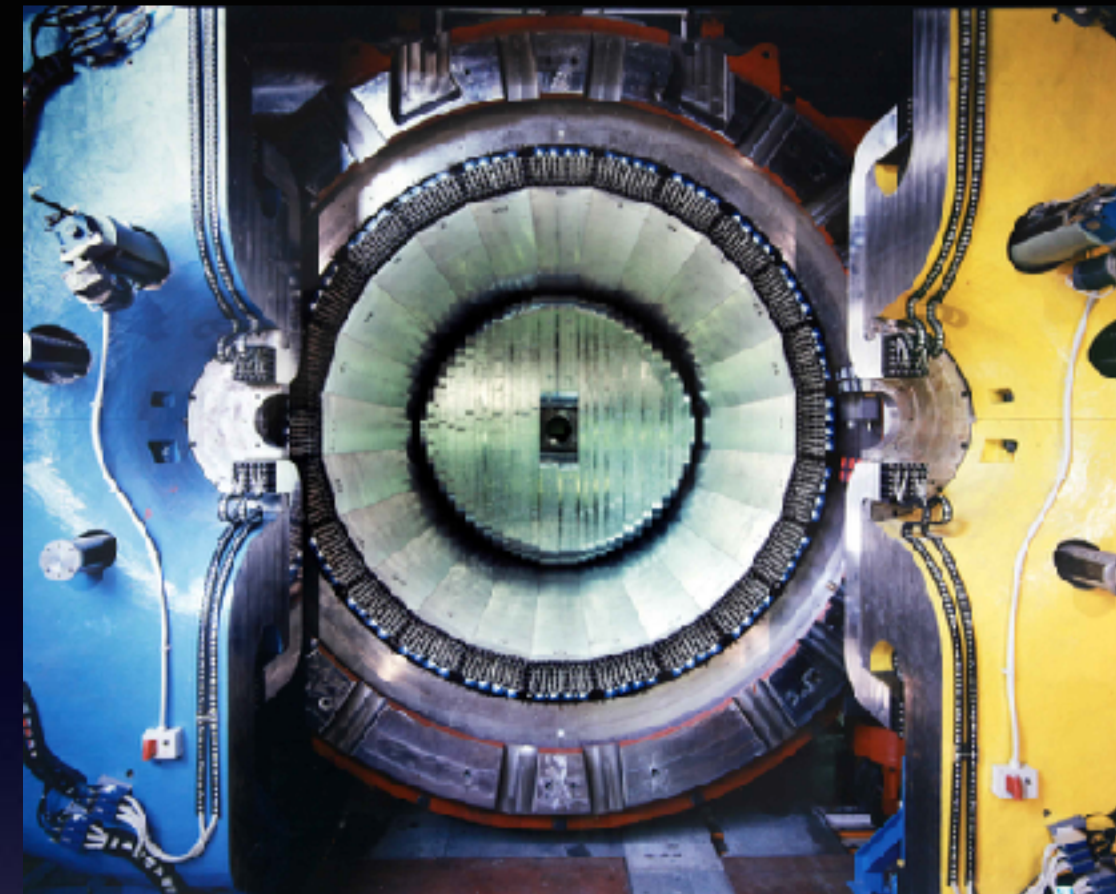
Another proposal called KLASH is exploring the possibility of studying the 0.2 μeV range

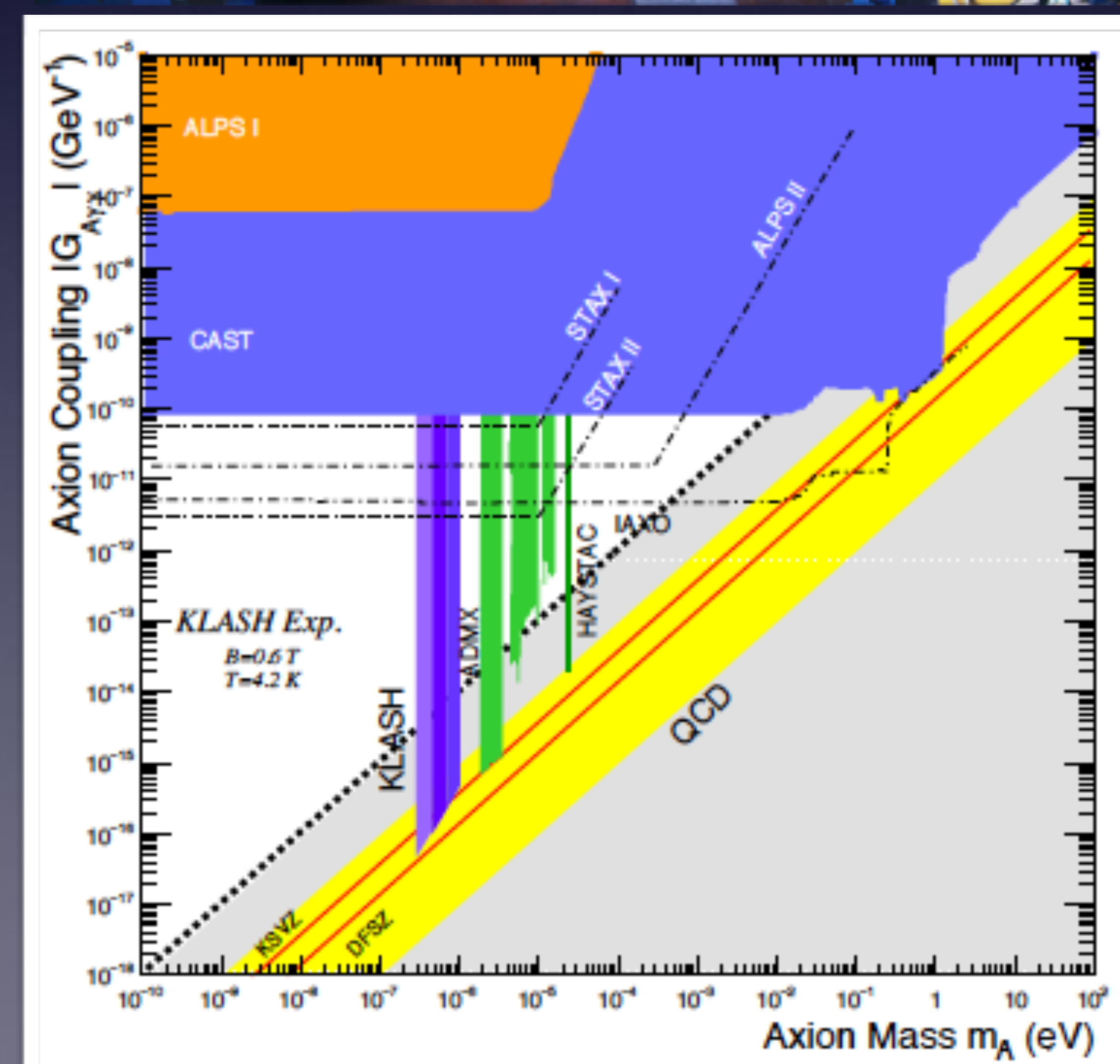
THE KLASH

AXION CALLING

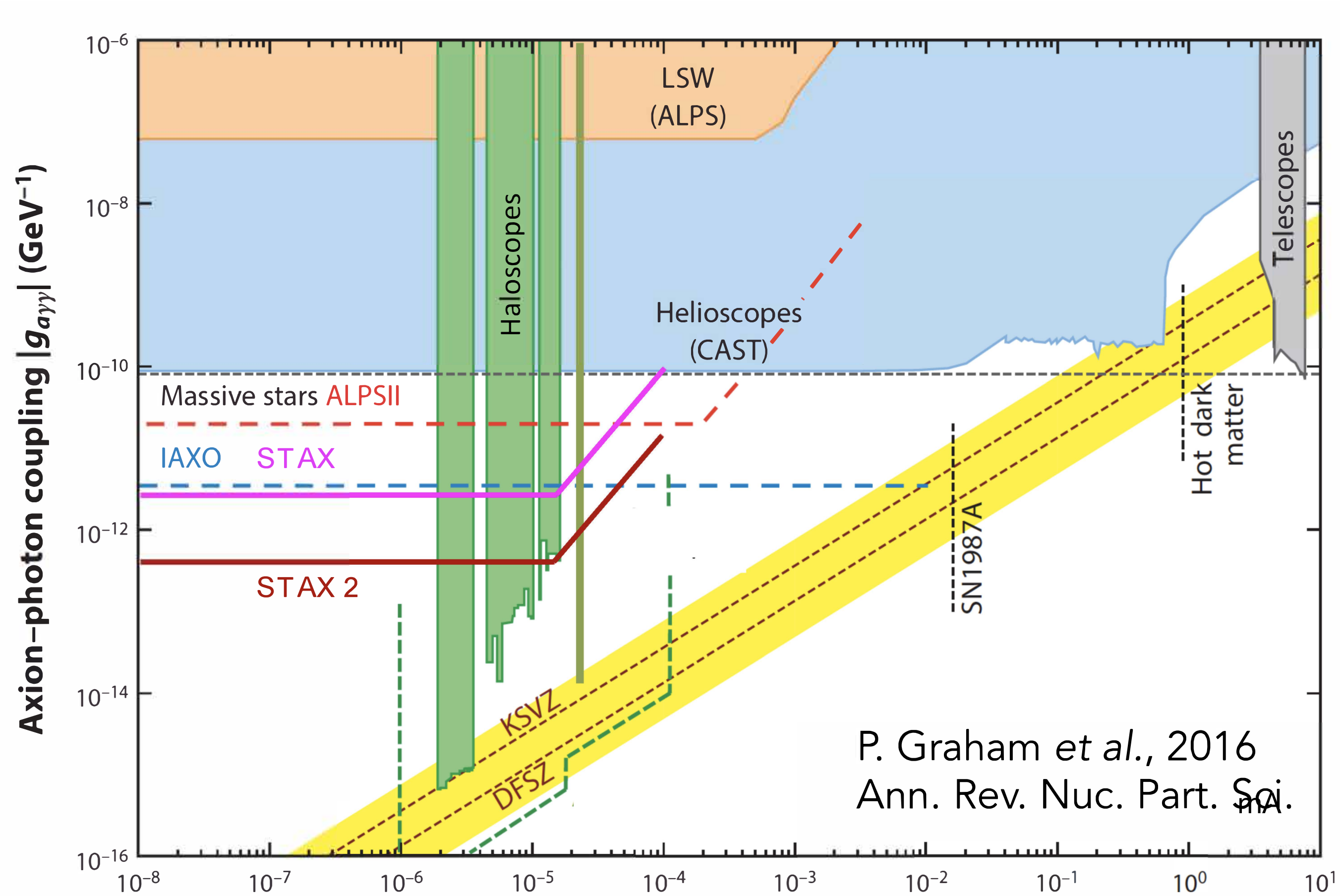
(… and I live by the river)

- KLoe magnet for Axions SearcH
  - arXiv:1707.06010 (Alesini, Babusci, Di Gioacchino, Gatti, Lamanna, Ligi)
  - Draft LOI submitted to CSN2
- **Proposal of a large Haloscope @ LNF**
- Search of galactic axions in the mass range 0.3-1 µeV
- Large volume RF Cavity (35 m³)
- Moderate magnetic field (0.6 T)
- Copper rf cavity Q~600,000
- T 4.2 K

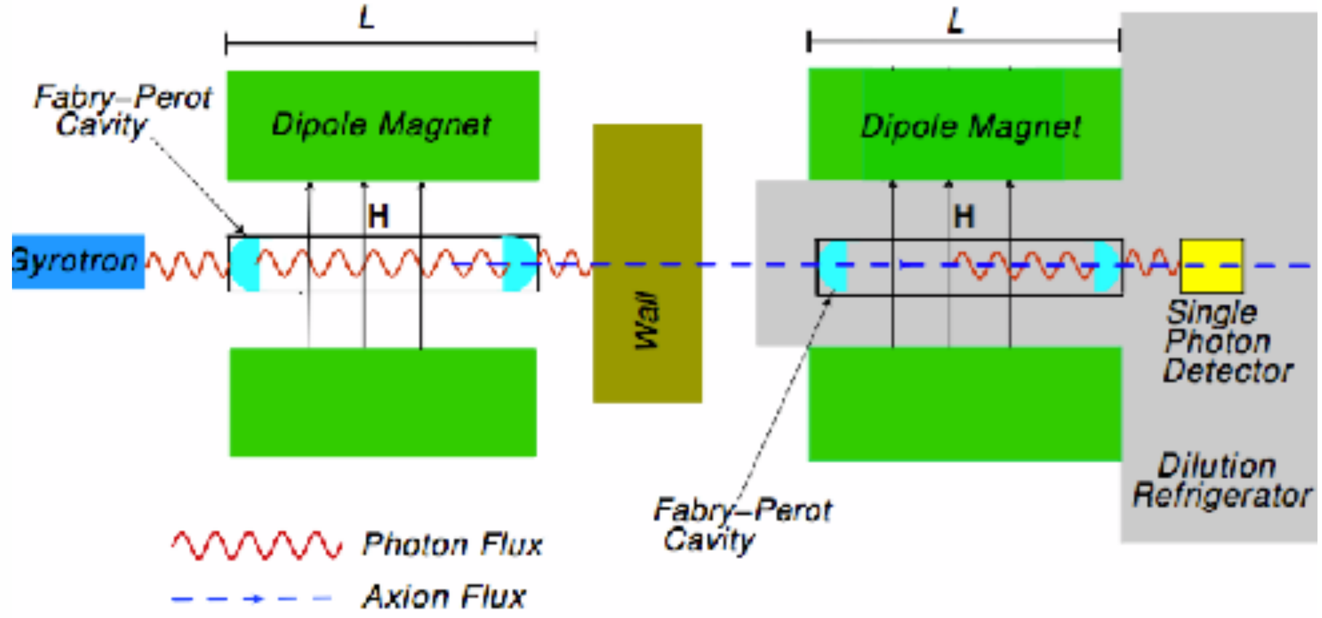




Light shining through a wall

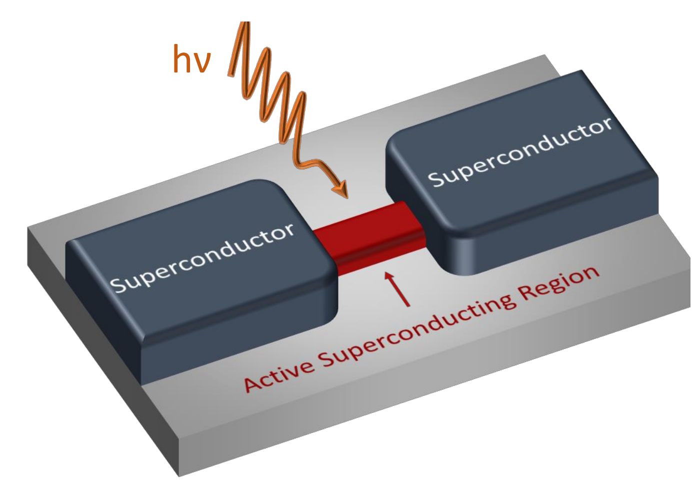


STAX proposal: optimisation of the LSW experiments for Axion Search



$$\dot{N}_{\text{evts}} \propto \dot{N}_\gamma \, P_{\gamma\to a} \times P_{a\to\gamma} \sim \dot{N}_\gamma \, G^4 H^4 L^4$$

- Magnetic field: H = 11T, L = 1.5 m
- Source: gyrotron; $P \approx$ 100 kW, $\Phi_\gamma = 10^{27}$ s^{-1}, ε_γ = 120 μeV ($\nu \approx$ 30 GHz)
- Fabry-Perot cavity: finesse $Q \approx 10^4$
- Sub-THz single-photon detection based on TES technology, $\eta \approx 1$
- Possible second FP cavity behind the wall to enhance axion-photon conversion rate



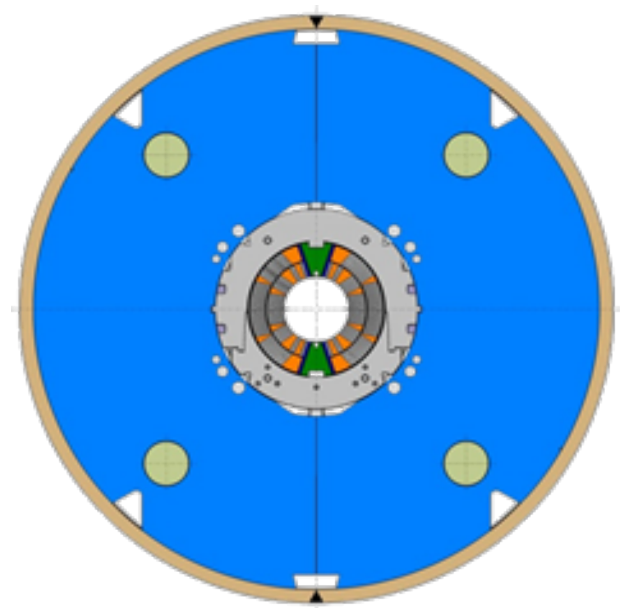
P. Sikivie, D.B. Tanner and K. Van Bibber, Phys. Rev. Lett. 98, 172002 (2007)

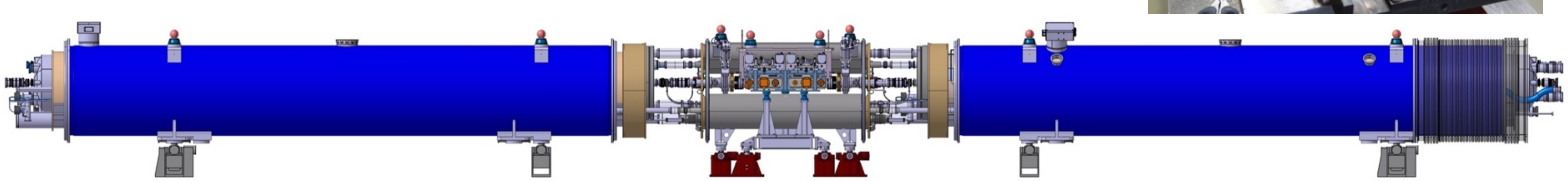
Light shining through a wall

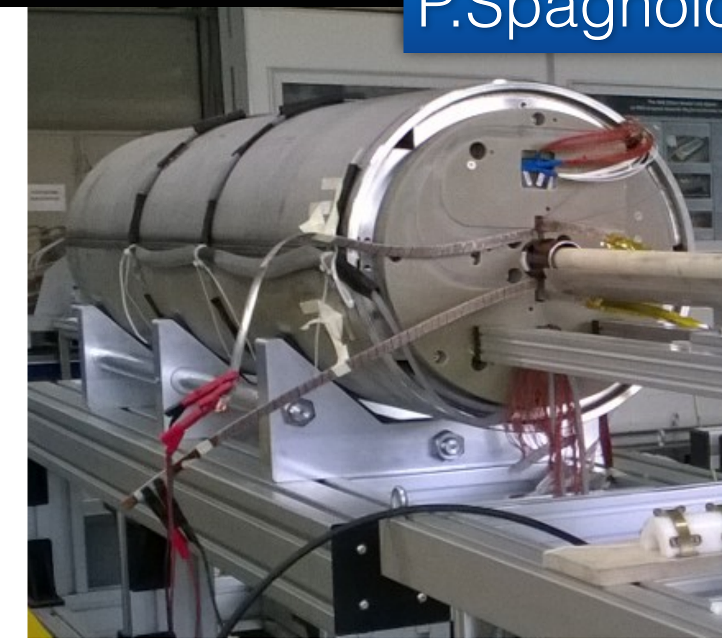
P.Spagnolo

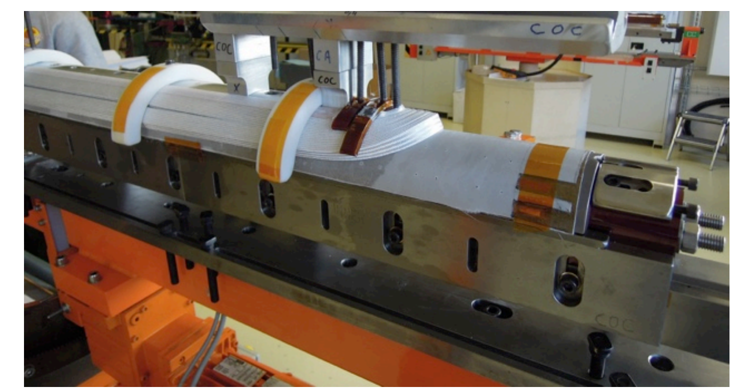
11T dipole magnet

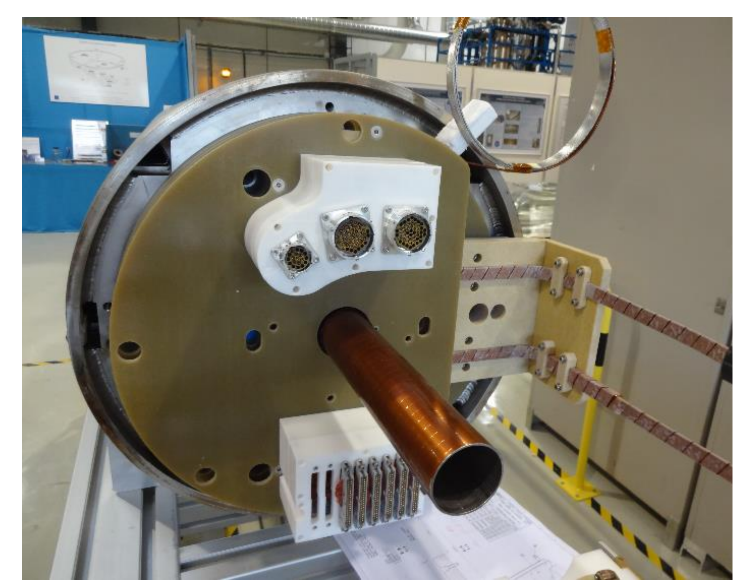
- The **HL-LHC Project** implies beams of larger intensity
  - Additional collimators are needed
- Two collimators to be installed on either side of interaction point 7
  - Replace a standard Main Dipole by a pair of shorter **11 T Dipoles**
- 5 single aperture **short models** fabricated and tested by CERN TE-MSC team
  - Bore field ranging from **10 to 12 T**
  - **60 mm** coil aperture
  - **~1.5 m** magnetic length









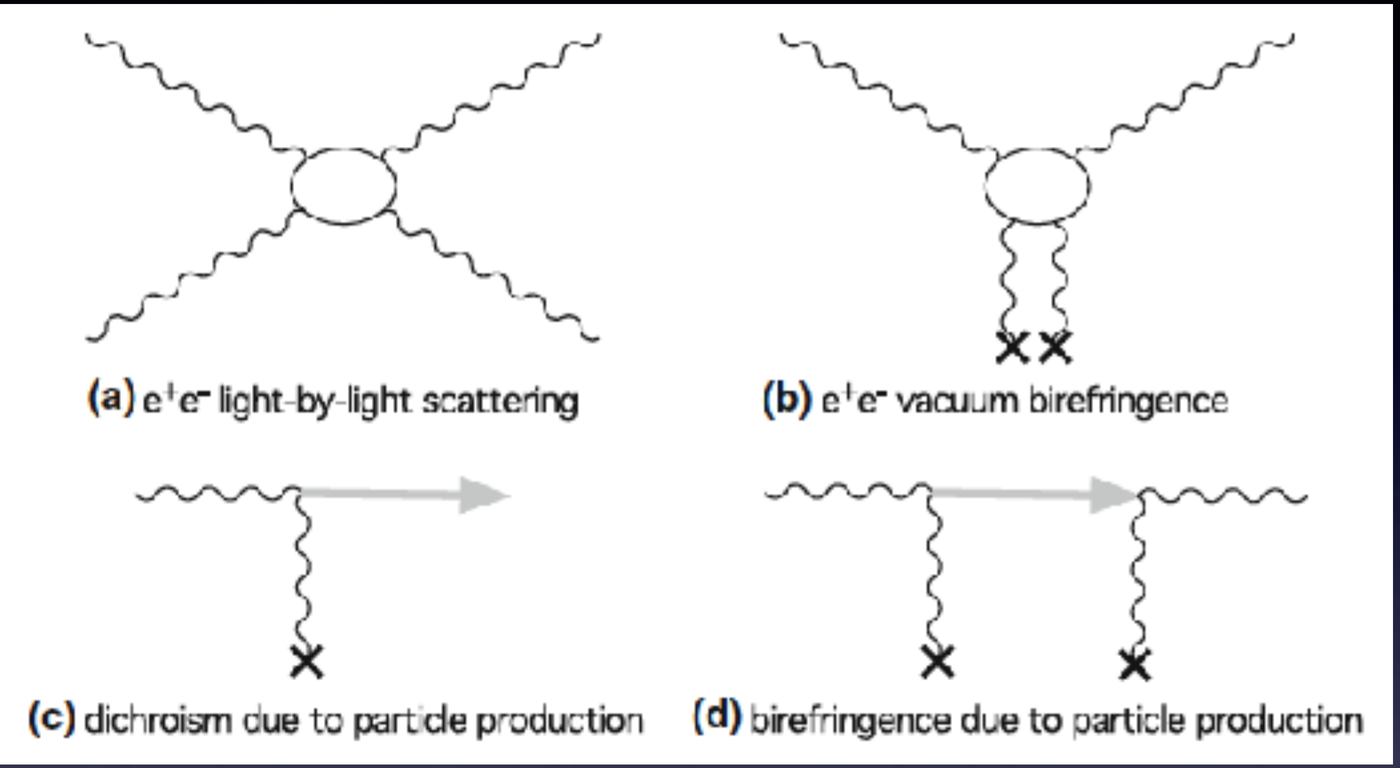


STAX project presented within the CERN Physics Beyond Collider document for the EU Strategy

Detector developed in collaboration with the CNR-nano and NEST Scuola Normale Pisa

Vacuum magnetic birefringence (VMB) and Vacuum magnetic dichroism (VMD)

- The existence of ALPs is expected to generate both VMB and VMD.
- Light-by-light scattering predicted by QED will also generate VMB but not VMD.
- These effects could in principle be detected by very sensitive polarimeters.



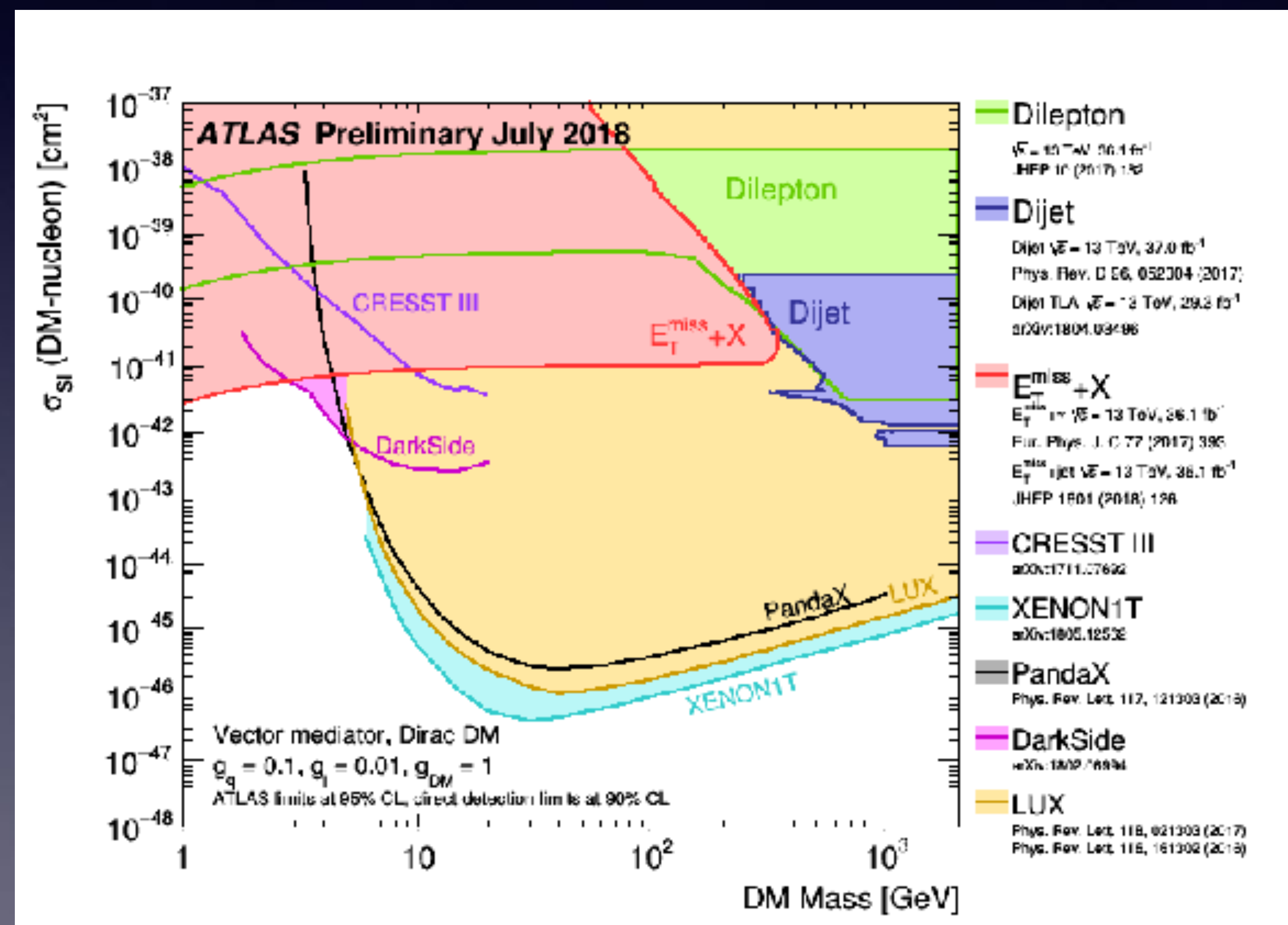
- **PVLAS** has reached a noise floor in VMB a factor 7 above the expected QED value. The same experiment has also set laboratory limits on the existence of ALPs.
- A new optical scheme has been proposed which would allow the use of superconducting dipole magnets such as those developed at CERN for LHC. This possibility would greatly enhance the physics potential [EPJC (2016) 76:294].
- The **OSQAR** collaboration has already used LHC magnets to set limits on the existence of axion-like-particles at lower masses with respect to the PVLAS limits using regeneration.

Food for thought

Understanding the nature of Dark Matter

Complementarity

- LHC experiments probe the sub-TeV range for WIMPs. But, if WIMPs are discovered by the LHC, an astrophysical detection will be necessary to connect the produced particles with the cosmic dark matter.
- For WIMP masses at multi-TeV, only direct and indirect detection methods have significant discovery potential.



➡ **Common strategic planning of future research**

- maximize the combined DM search potential

Food for thought

Beyond detector R&D: CERN as a technological Hub

Technology

- Magnets, Superconductors, Cryostats
- Vacuum & Cryogenics
- LAr detectors
- SiPM + electronics
- R&D + applications

Food for thought

Global collaboration and coordination

Underground laboratories

- Historically, in competition to gain scientific leadership in different fields of research
- However, increasing size of experiments needs larger investment of human, technological and financial resources

➡ Birth of a global strategy for international collaboration:

- specialization of laboratories → "network" by pooling resources and expertise
- ambition to create supranational structures, on the **CERN model**, possibly "spread" on different experimental sites.

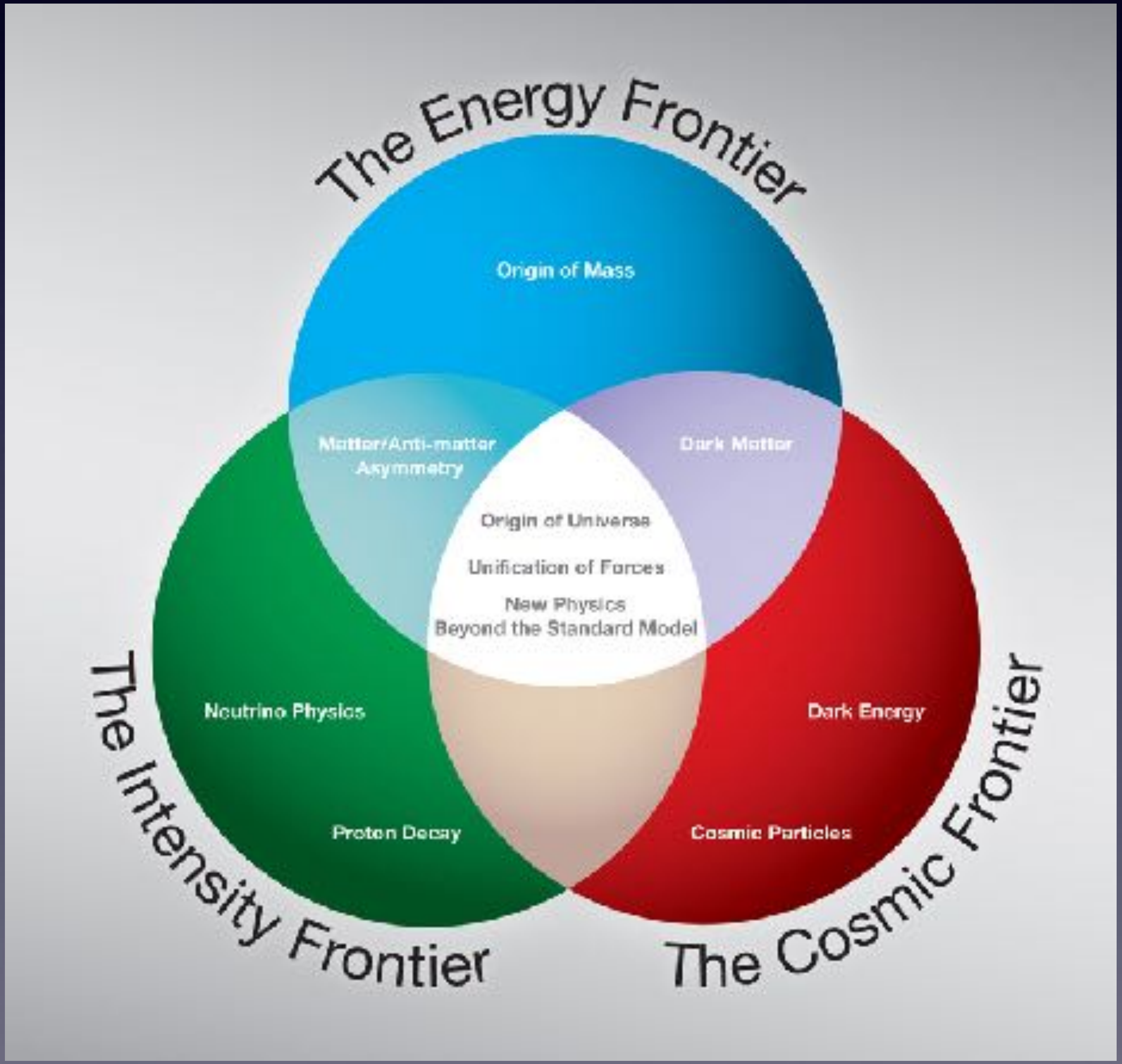
Food for thought

Overlapping areas of research

- See for instance US Particle Physics Project Prioritization Panel (P5):
    - Cosmic, Energy and Intensity Frontiers, on equal grounds within the larger field of particle physics

Diversification strategy

- An example: CERN/Fermilab joint LAr programme for neutrino physics
    - Technology + physics reach



Convention for the Establishment of a European Organization for Nuclear Research (1953)

ARTICLE II : Purposes

2. The Organization shall, … *(omissis)* …, confine its activities to the following:
   a. the construction and operation of one **or more** international laboratories (hereinafter referred to as "the Laboratories") for research on high-energy particles, **including work in the field of cosmic rays**; each Laboratory shall include:
      i. one or more particle accelerators;
      ii. the necessary ancillary apparatus for use in the research programmes carried out by means of the machines referred to in (i) above;
      iii. the necessary buildings to contain the equipment referred to in (i) and (ii) above and for the administration of the Organization and the fulfilment of its other functions;

   b. the organization and sponsoring of international co-operation in nuclear research, **including co-operation outside the Laboratories**; this co-operation may include in particular:
      a. work in the field of theoretical nuclear physics;
      b. the promotion of contacts between, and the interchange of, scientists, the dissemination of information, and the provision of advanced training for research workers;
      c. collaborating with and advising other research institutions;
      d. work in the field of cosmic rays.