CYGNUS 2019 - WORKSHOP ON DIRECTIONAL DARK MATTER DETECTION
ROME, JULY 10-12 2019

STRATEGY FOR DIRECT DM SEARCH

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WHAT IS DARK MATTER?

The Minimal WIMP Model Basic Assumptions:

- Single particle that does not interact with itself
- Interacts weakly with Standard Model
- 2→2 annihilations primarily in s-wave
- Annihilations set thermal abundance today

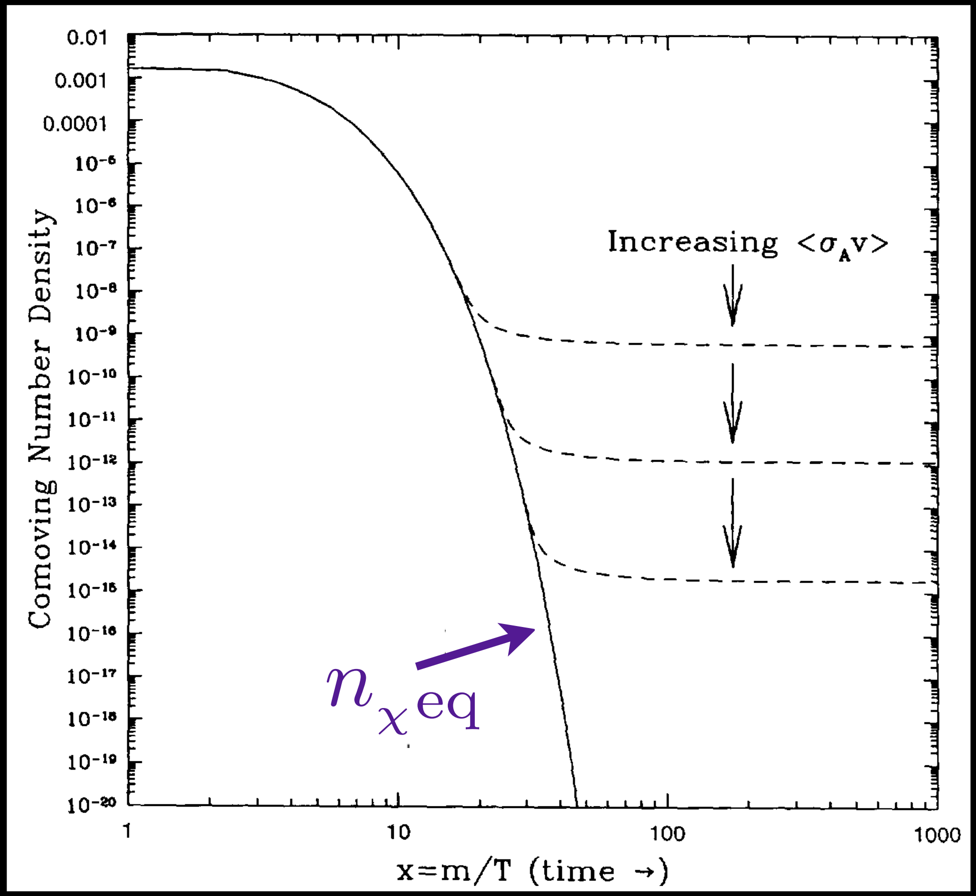
THE WIMP MIRACLE

WIMP number density in the early universe:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle (n_\chi^2 - n_{\chi eq}^2)$$

$$\langle \sigma v \rangle : \chi\chi \rightarrow \text{SM SM (thermal average)}$$

“Freeze-out” when annihilation rate falls behind expansion rate (→ $a^3 n_\chi \sim$ const.)



Relic density (today)

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \text{cm}^3/\text{s}}{\langle \sigma v \rangle}$$

for weak scale interaction

$$\simeq 0.1 \cdot \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m_\chi}{100 \text{ GeV}}\right)^2$$

Planck 2018 results

$$\Omega_\chi h^2 = 0.120 \pm 0.001$$

“weak” coupling
“weak” mass scale
→ correct abundance

PARTICLE DM: PARADIGM SHIFT DRIVING SOCIAL CHANGE

Murayama @ ESPP, Granada, 2019

We used to think

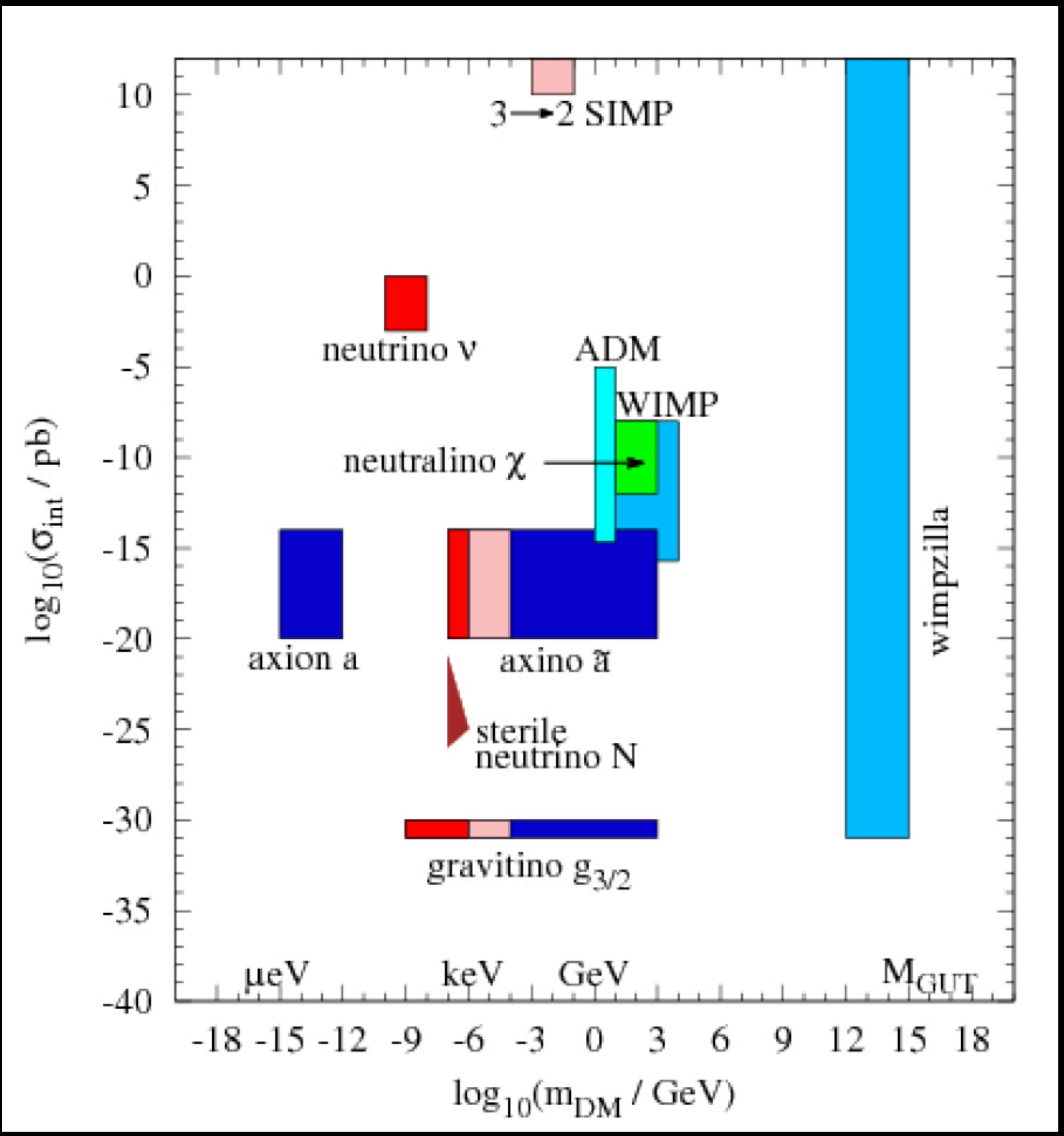
- need to solve problems with the SM of Particle Physics (hierarchy problem, strong CP, etc)
- great if new theory (supersymmetry, extra dim) also gives a DM candidate as a byproduct

$\Downarrow$

Now we think

- need to explain DM on its own
- great if the DM solution also helps to elucidate important issues with the SM
- WIMP should be explored at least down to the neutrino floor
  - heavier? e.g., wino @ 3TeV
  - or rather lighter and weaker coupling? e.g., ALPs

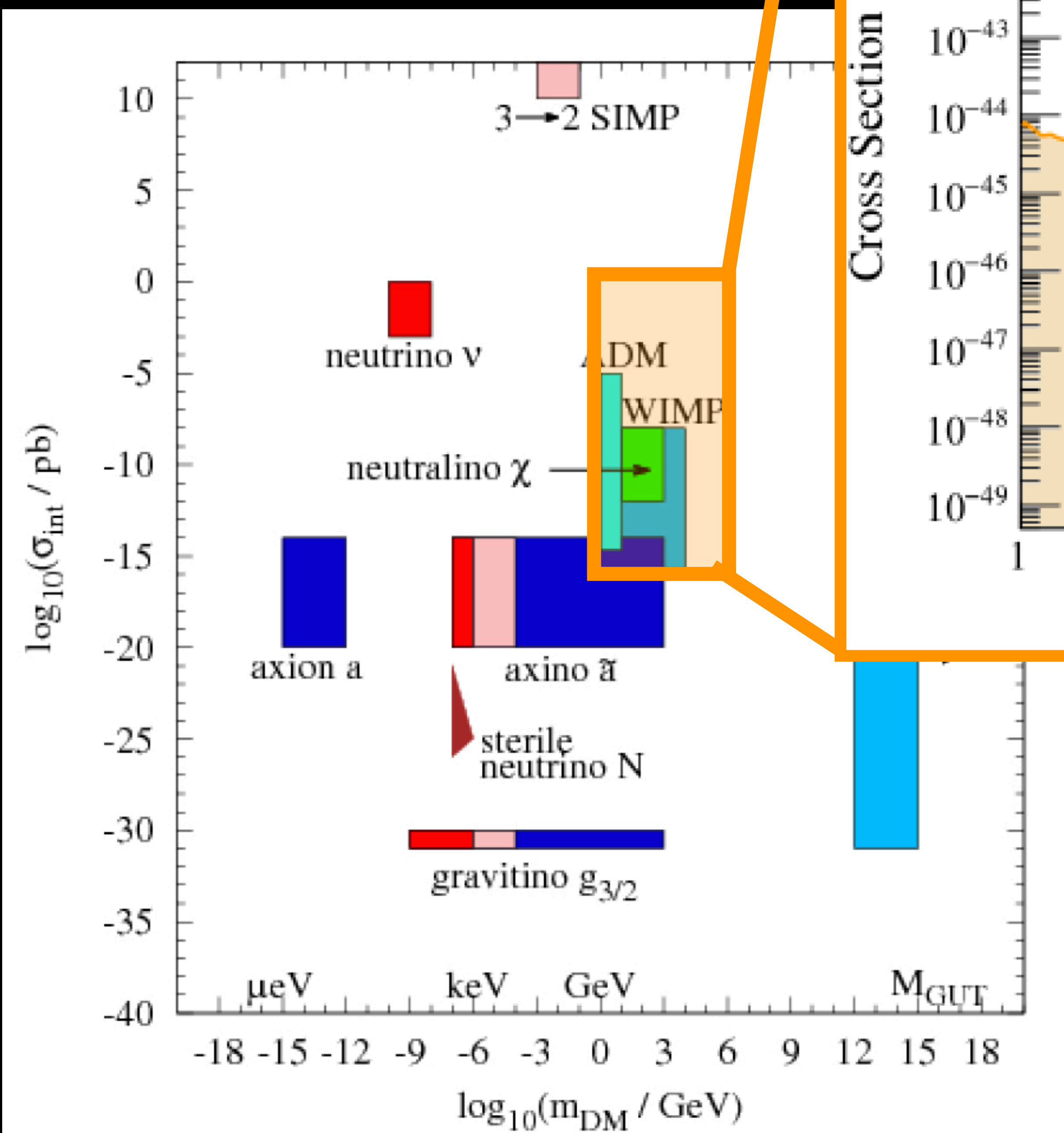
DARK MATTER CANDIDATES



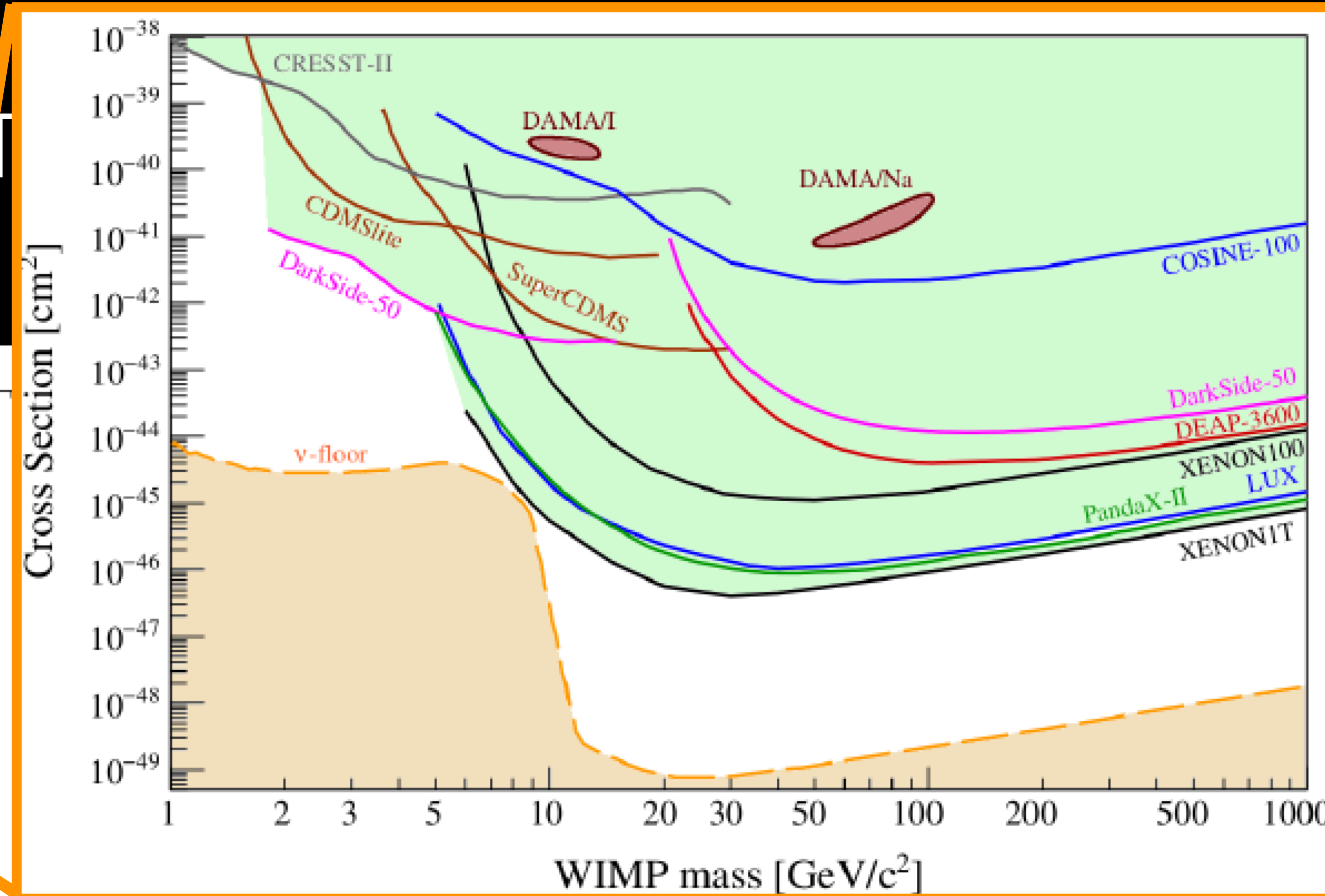
Baer et al., arXiv:1407.0017

- Thermal relics:
  - WIMP: generic weakly interacting massive particle
  - ADM: asymmetric dark matter
  - SIMP: strongly interacting massive particle
  - …
- Non- thermal relics
  - Axion: very light mass (10^{-5} eV), CDM because produced at rest in the early Universe. Its interaction strength is strongly suppressed relative to the weak strength by a factor $(m_W/f_a)^2$, where $f_a \sim 10^{11}$ GeV is the PQ breaking scale
  - … and many more

DARK MATT



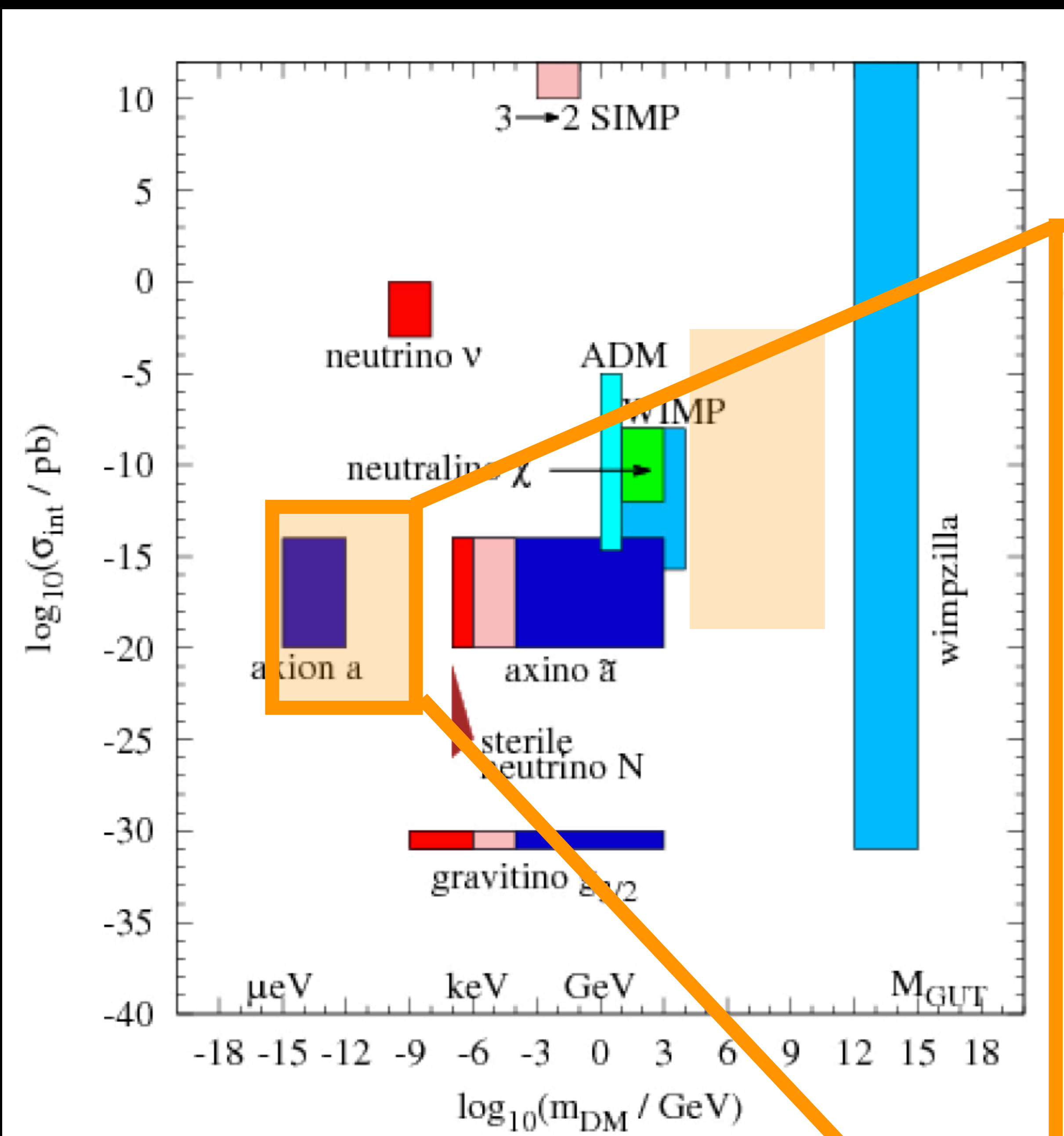
Baer et al., arXiv:1407.0017



Schumann, arXiv:1903.03026

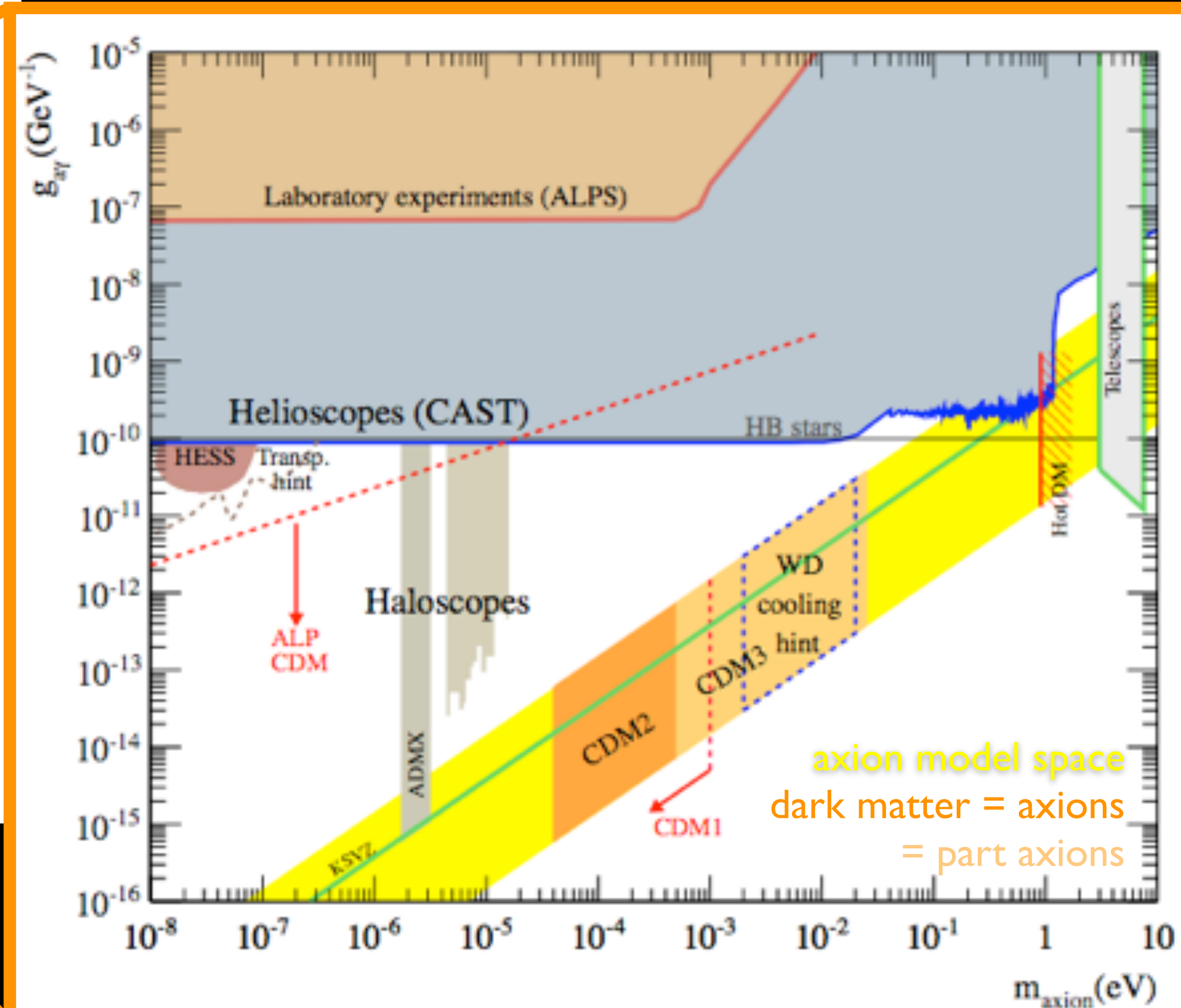
Direct searches generally optimised for WIMP sensitivity...

DARK MATTER CANDIDATES



Baer et al., arXiv:1407.0017

… starting to look for axions/ALPs too!



WIMP DIRECT DETECTION

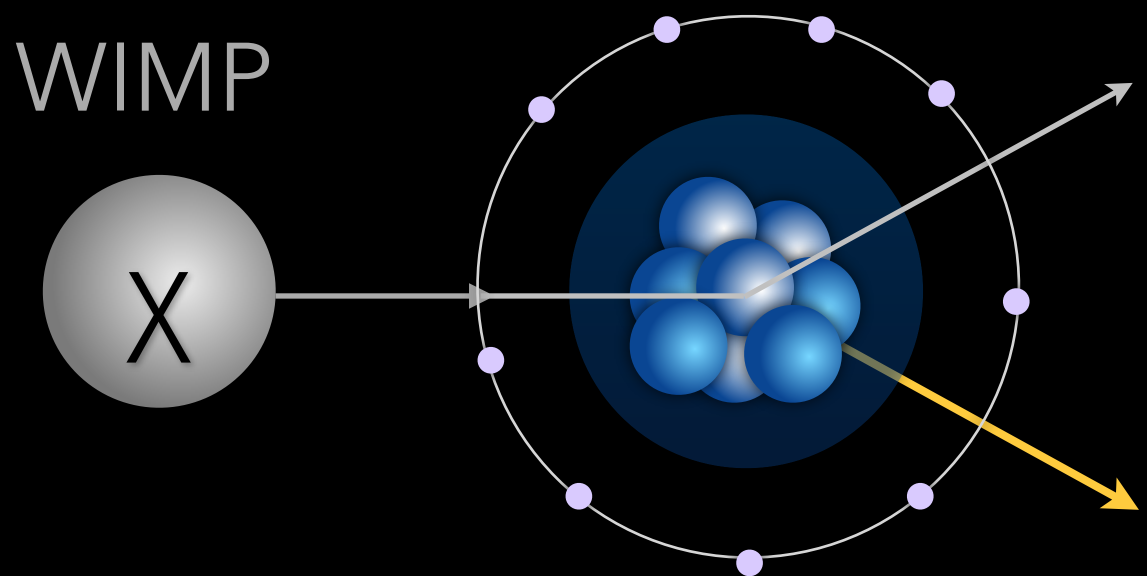
- Goodman & Witten (1985): "Detectability of certain dark matter candidates"

  coherent scattering off nuclei

$\chi N \rightarrow \chi N$

elastic scattering off nuclei

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



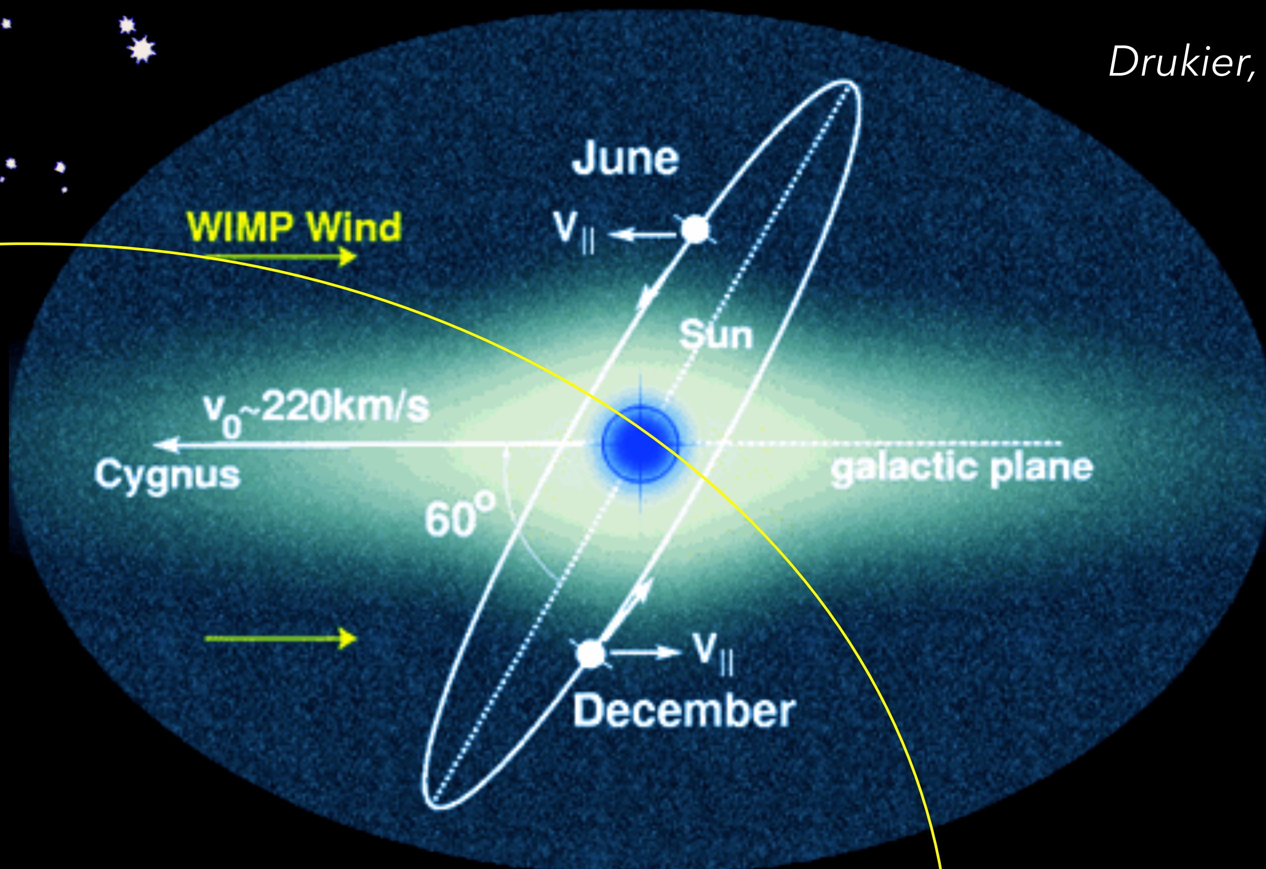
- Large detector mass, long exposure
- Low energy threshold
- Ultra-low radioactive bg
- Good bg discrimination

Nuclear recoil energy $\approx 1 \div 100$ keV

MODULATION SIGNATURES

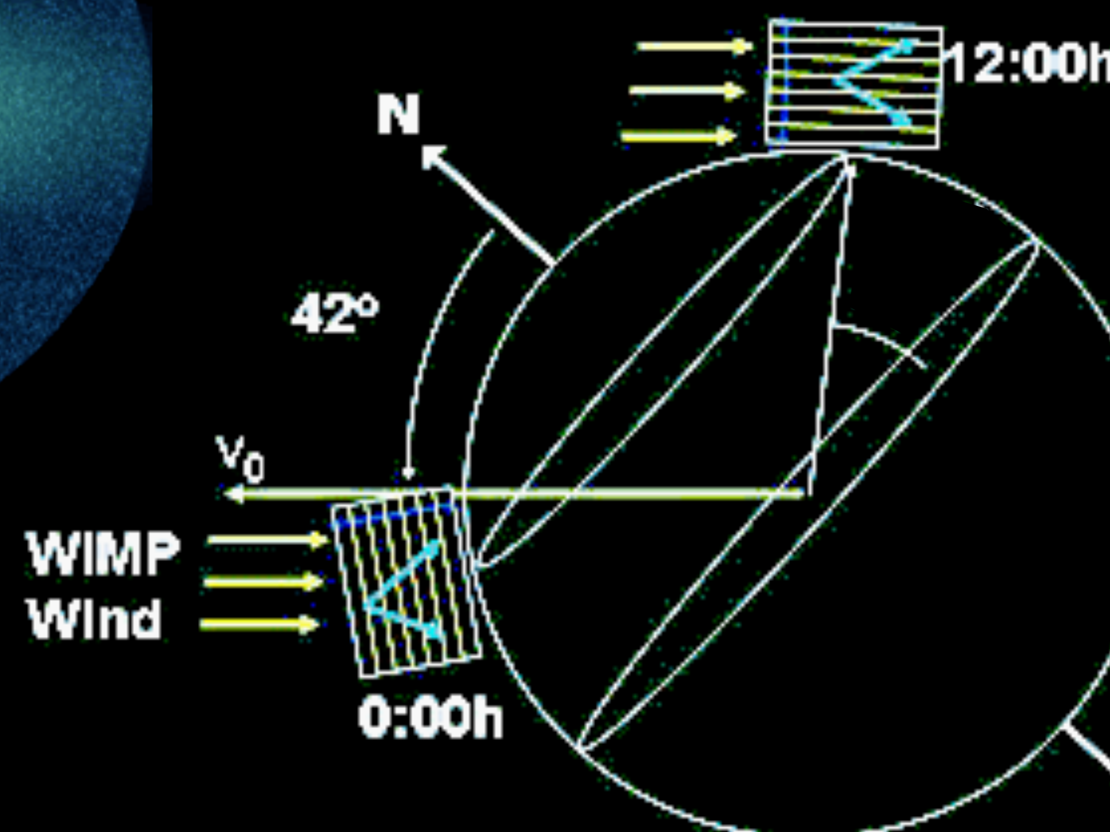
Annual event rate modulation:
June-December asymmetry ~2-10%

Drukier, Freese, Spergel, Phys. Rev. D33:3495 (1986)



Sidereal direction modulation:
asymmetry ~ 20-100% in
forward-backward event rate

Spergel, Phys. Rev. D36:1353 (1988)



×3 rate variation of parallel vs
perpendicular directions

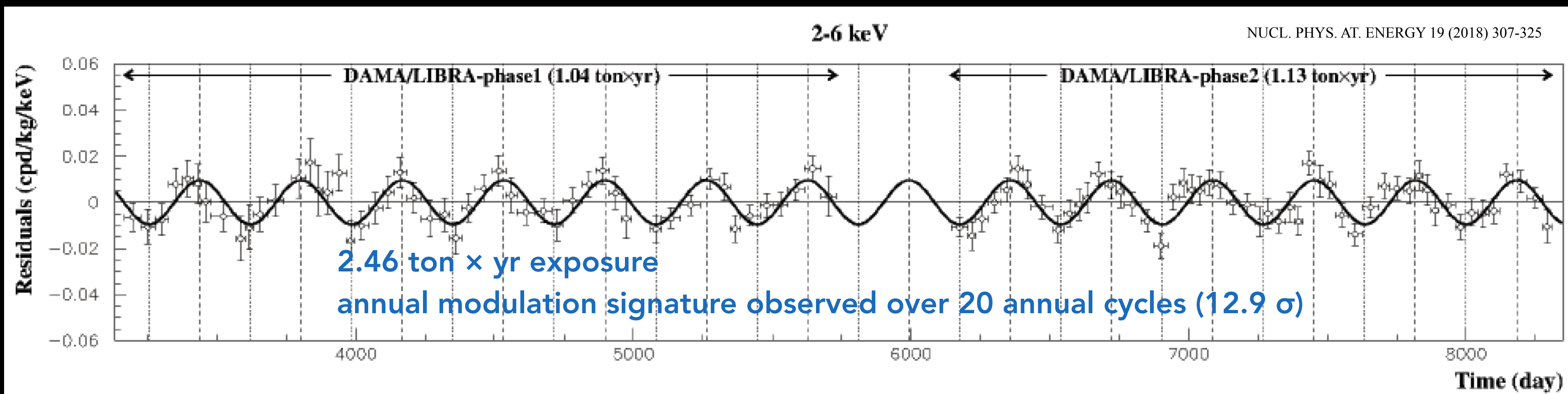
Credits Jocelyn Monroe

MODULATION RECENT RESULTS

Standard Halo Model predicted modulation A~0.02-0.1, t_0=152.5 days

DAMA/NaI + DAMA/LIBRA-phase1 + phase2:

A= (0.0103 ± 0.0008) cpd/kg/keV, t_0 = (145±5) d in 2.46 t-yr (2 - 6 keV)



many other searches, on Ge, CsI, Xe, etc. observe no evidence of modulation

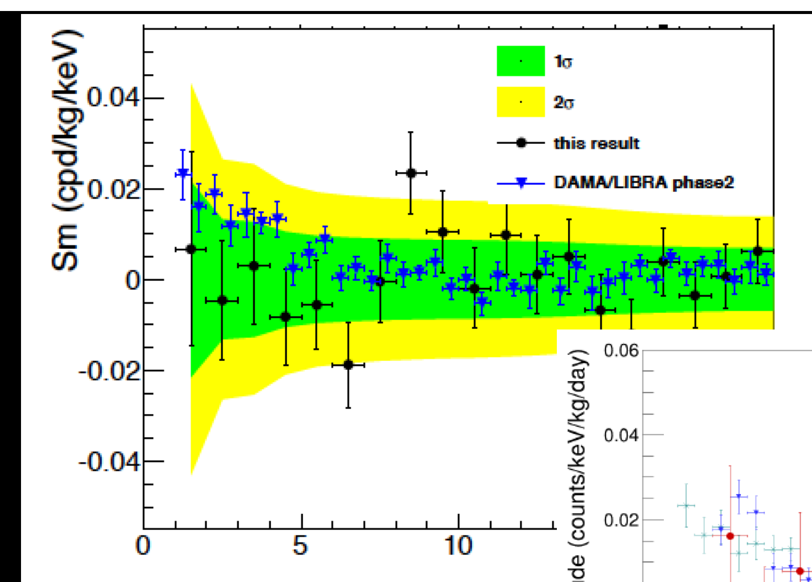
In the same underground laboratory:

XENON100: Xe, 5.7σ exclusion of DAMA, dark matter electron interactions via axial vector coupling *PRL118,101101 (2017)*

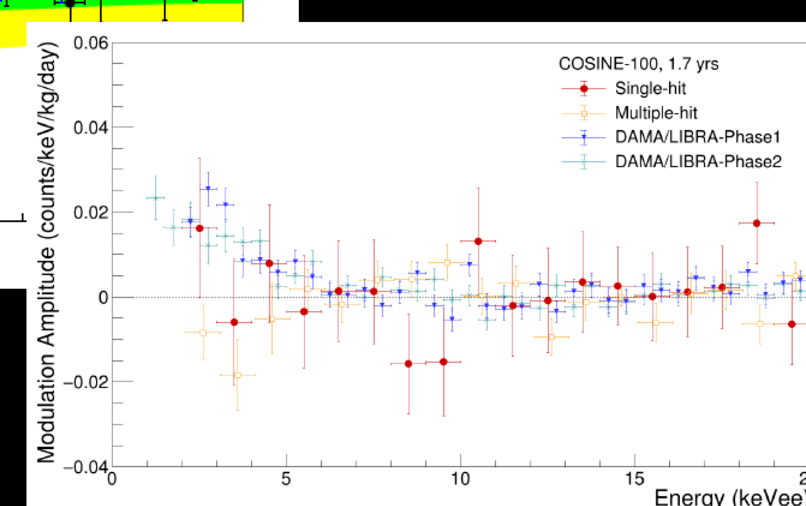
Using the same target (NaI):

ANAIS (LSC), **COSINE-100** (Y2L)

~consistent at 1σ, project 3σ test in 5 years



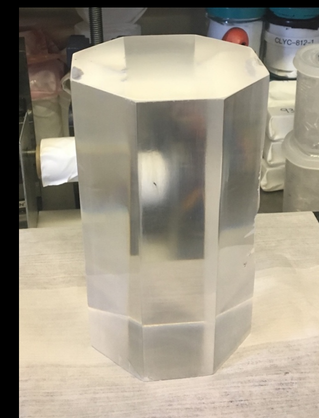
ANAIS, arXiv: 1903.03973

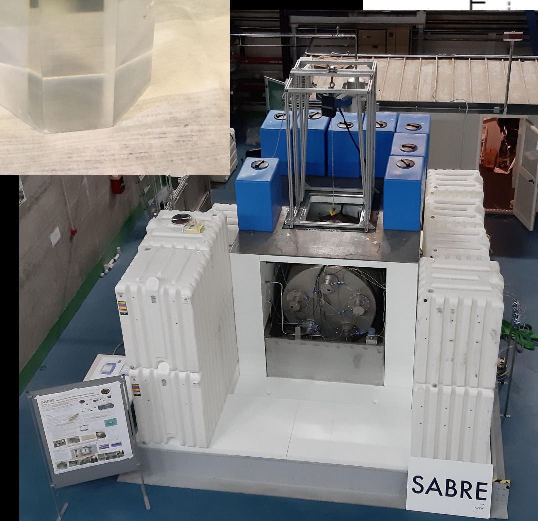


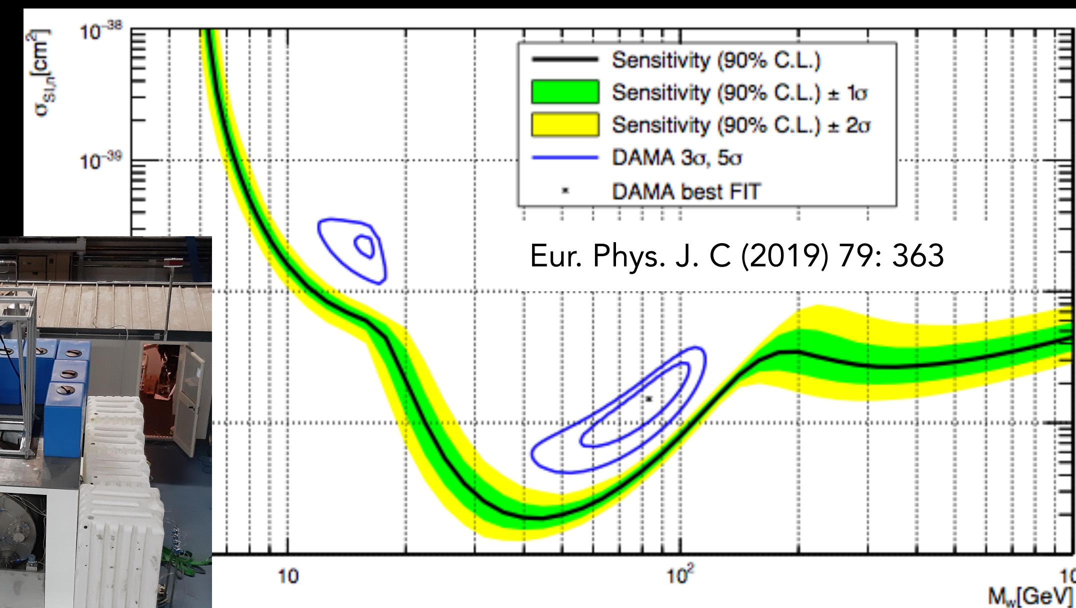
COSINE-100, arXiv: 1903.10098

MODULATION PERSPECTIVE

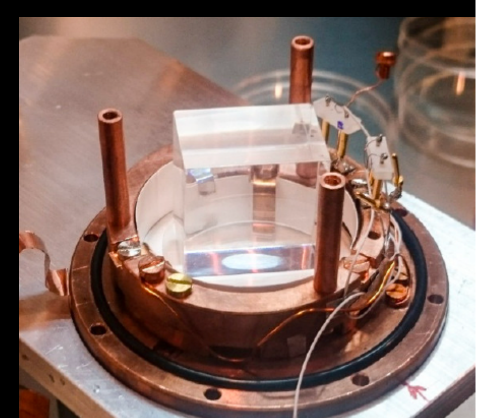
- **SABRE**
  - Development of ultra-high purity NaI(Tl) crystals
  - Passive shielding + active veto
  - Two sites: LNGS in Northern and SUPL in Southern hemisphere
  - PoP ready to start
- **COSINUS**
  - NaI detectors operated as cryogenic calorimeters
  - dual readout of heat and scintillation light
  - R&D phase, several prototypes, mass 50g → 300g

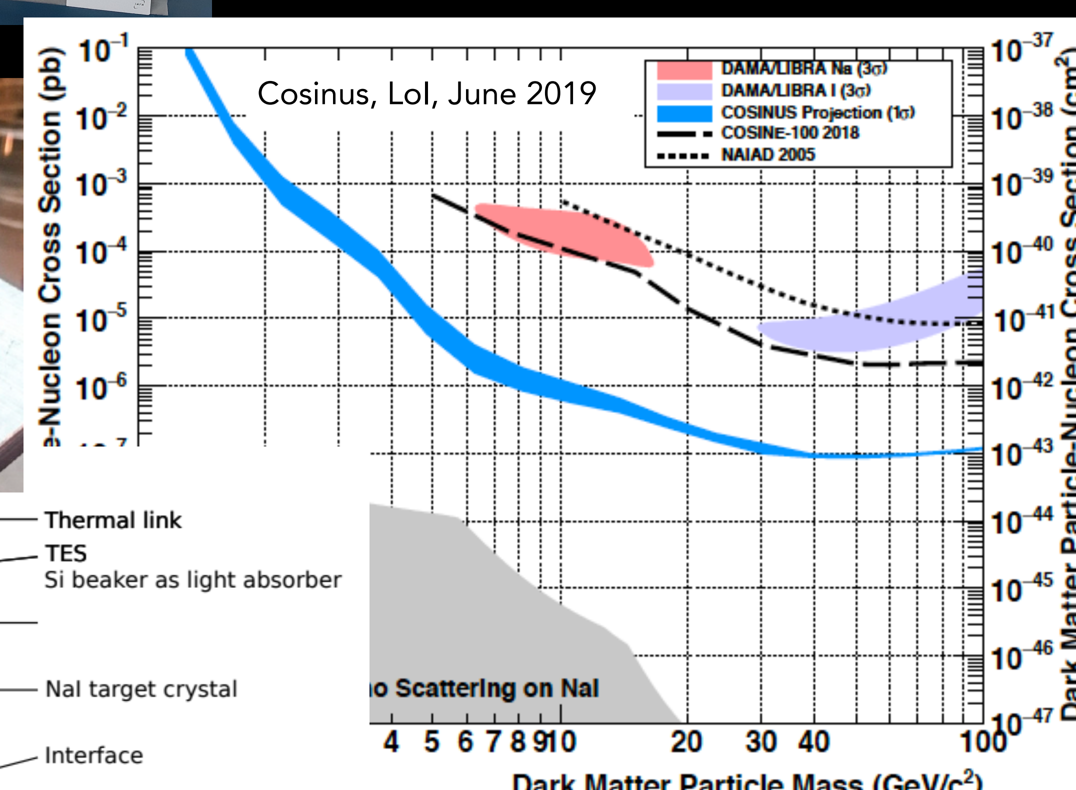


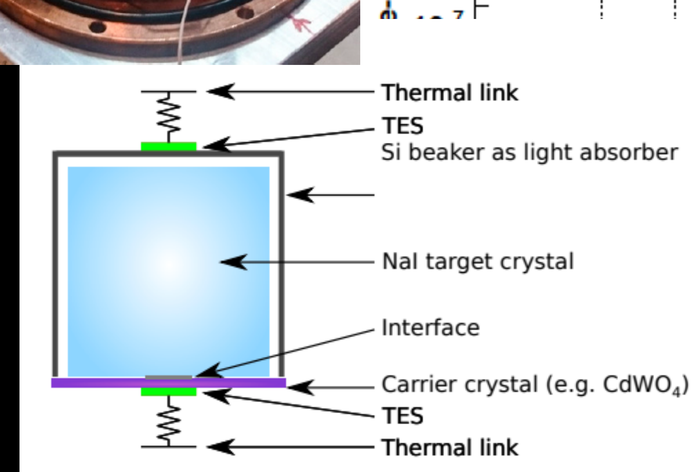




exposure of 150 kg yrs

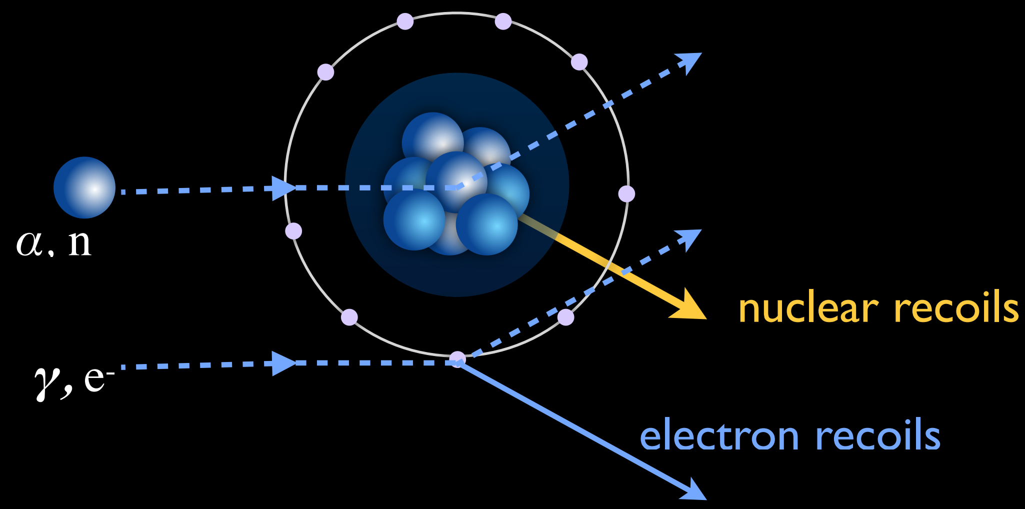






exposure of 100 kg days

DISCRIMINATING BACKGROUNDS



from natural radioactivity:

γ e⁻ → γ e⁻

nN → nN

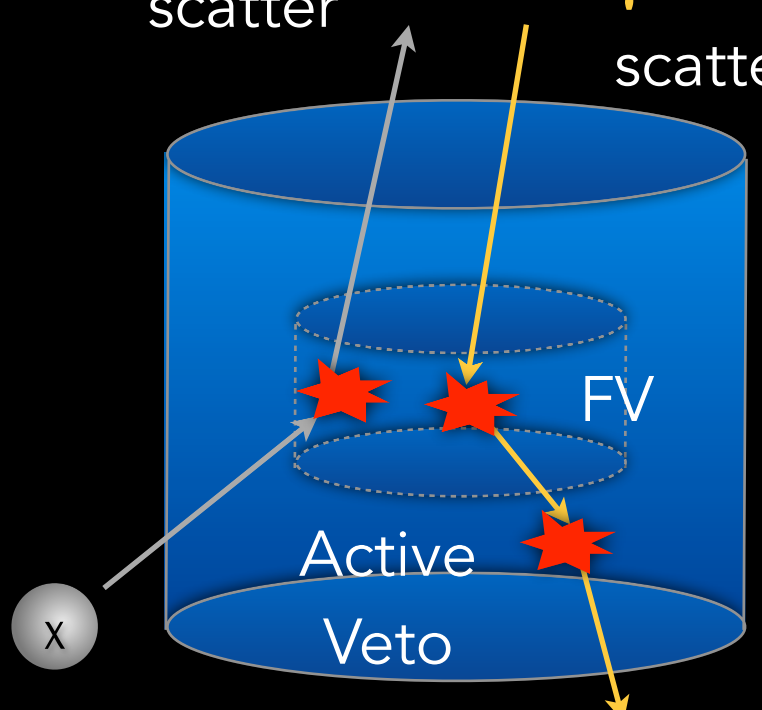
N → N′ + α, β

Active veto shield and fiducialization
→ identification of neutron recoils

Signal split in two components which respond differently to NR/ER
→ separation of S and B

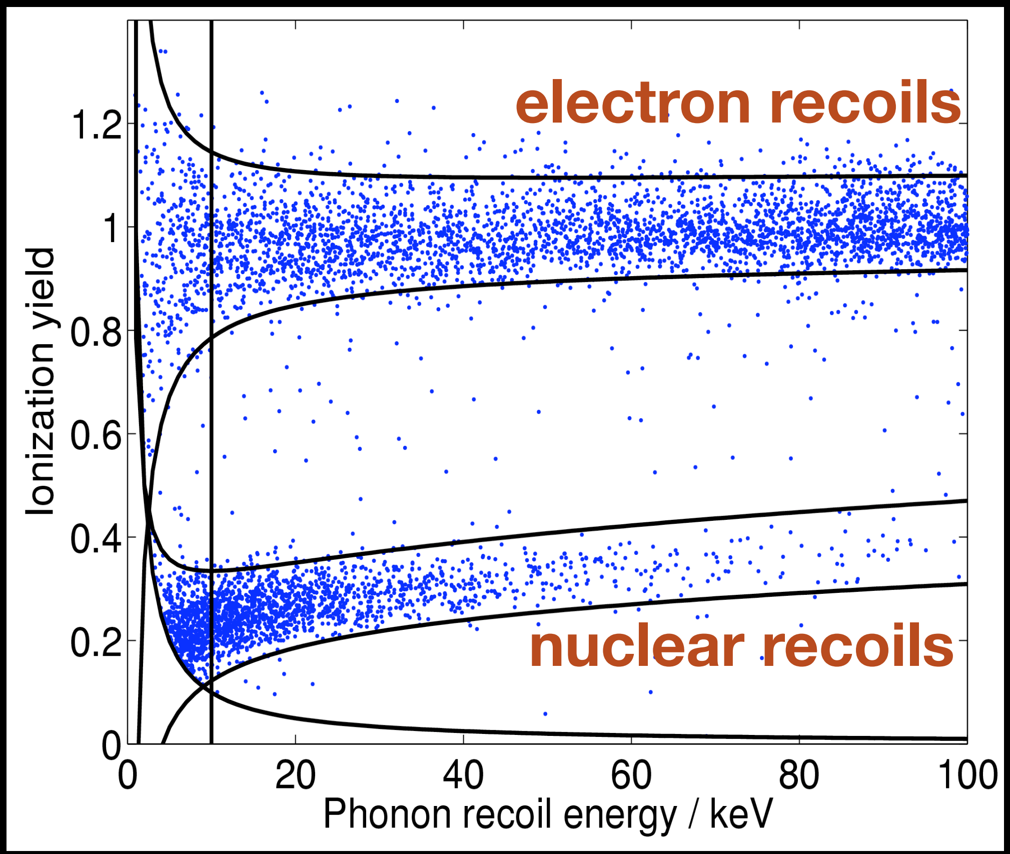
WIMP single scatter

n/γ double scatter



Background region

Expected signal region



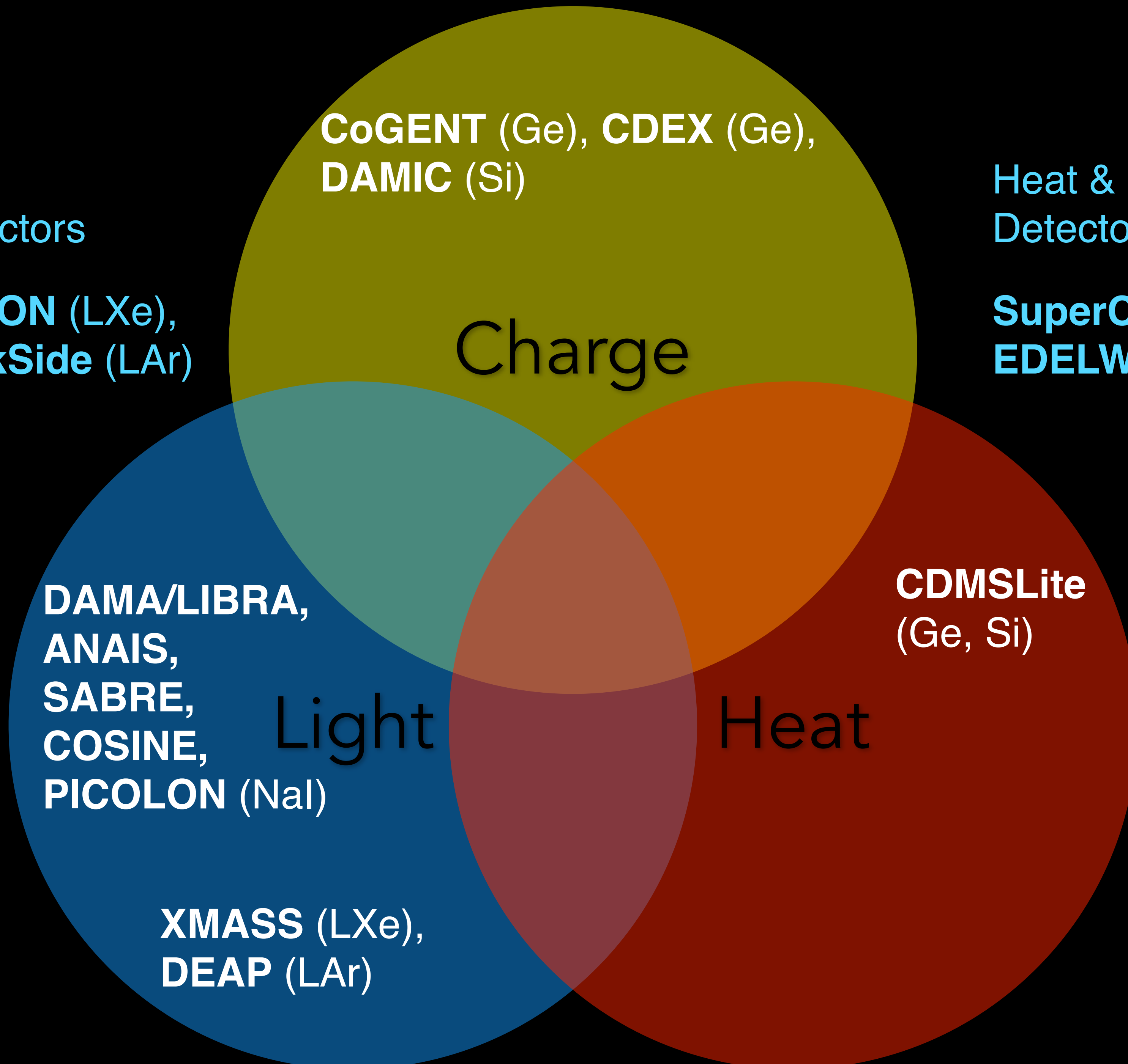
DETECTOR TECHNOLOGIES

Light & Charge Detectors

PandaX (LXe), **XENON** (LXe), **LUX/LZ** (LXe), **DarkSide** (LAr)

Heat & Charge Cryogenic Detectors

SuperCDMS (Ge, Si), **EDELWEISS** (Ge)



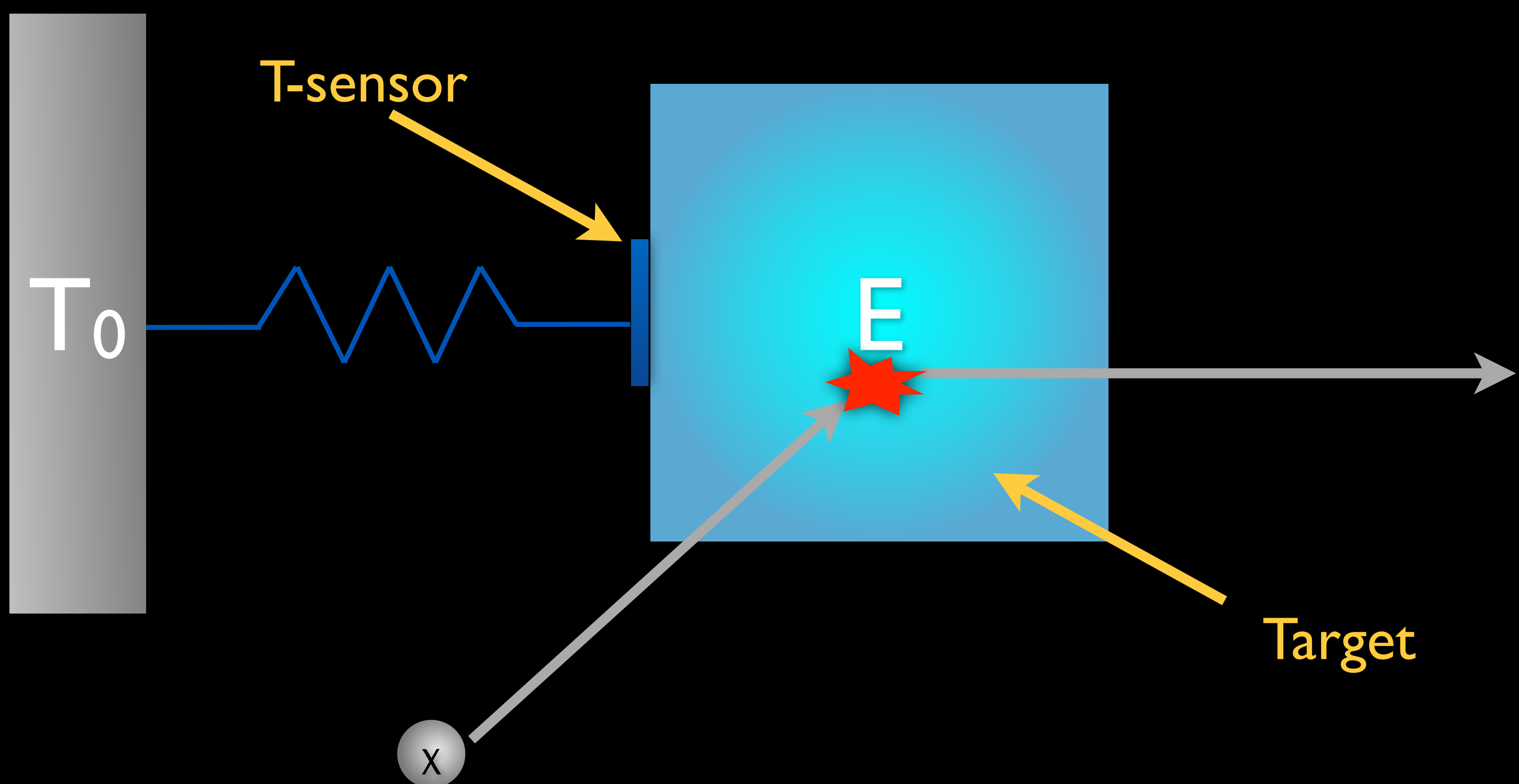
PICO (C_3F_8, CF_3I)

Light & Heat Cryogenic Detectors

CRESST ($CaWO_4$), **COSINUS** (NaI)

Too many experiments: only a selection here

CRYOGENIC CRYSTALS

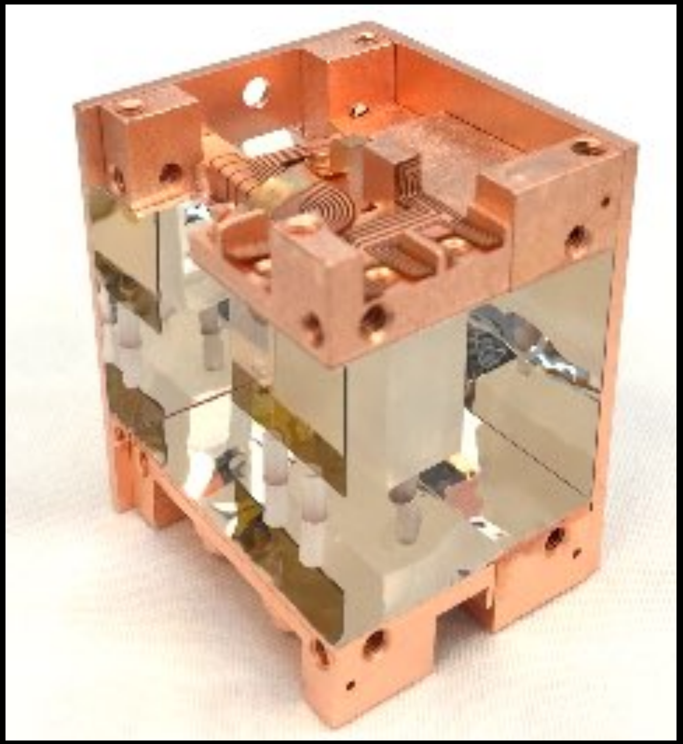


CHARGE & PHONONS:	SUPERCDMS
	CDMSLITE
	EDELWEISS
LIGHT & PHONONS:	CRESST

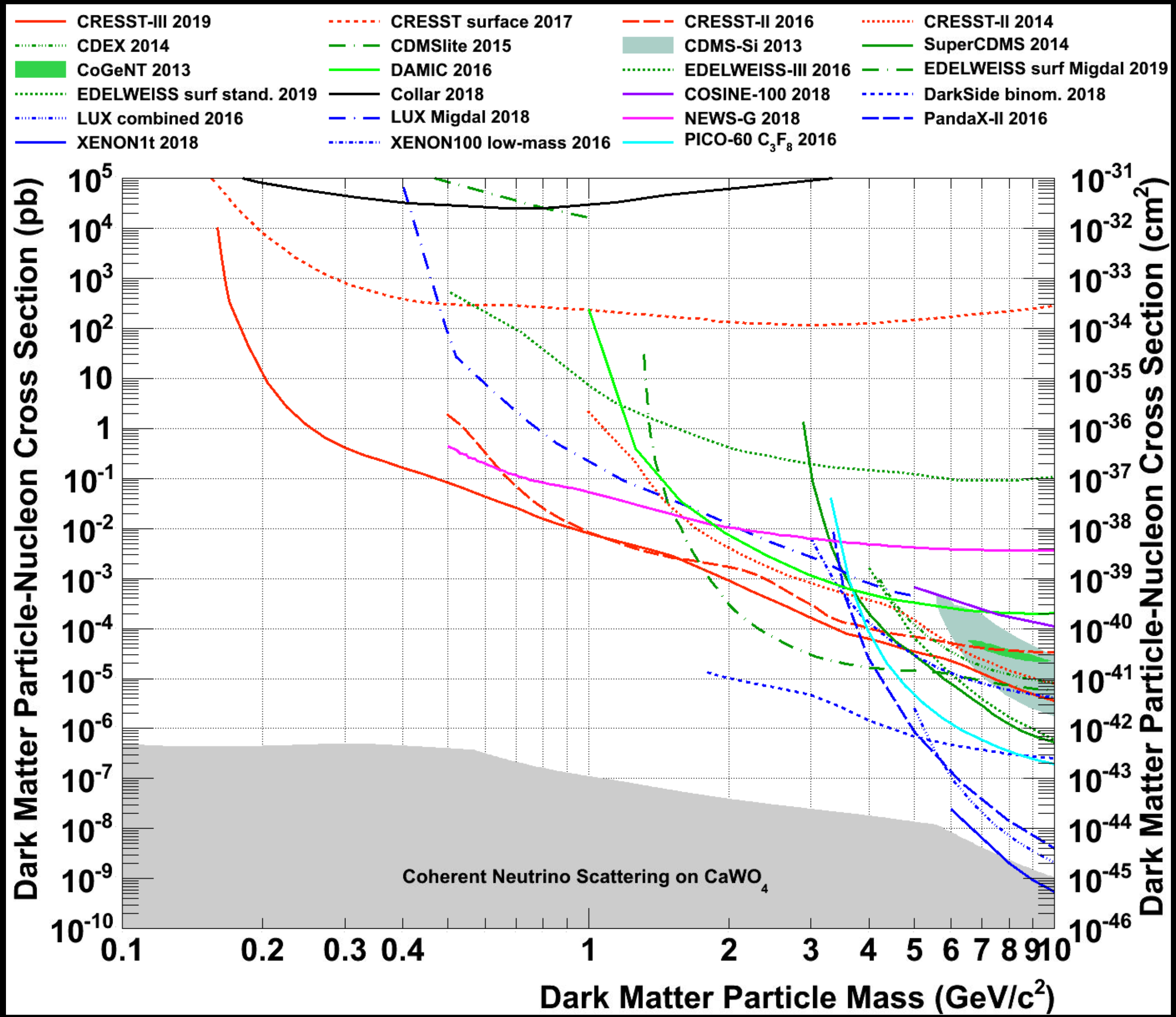
E deposition → temperature rise $\Delta T \sim \mu K$ → requires detectors at mK

- Crystals: Ge, Si, $CaWO_4$, NaI
- T-sensors:
  - superconductor thermistors (highly doped superconductor): NTD Ge → **EDELWEISS**
  - superconducting transition sensors (thin films of SC biased near middle of normal/SC transition): TES → **CDMS, CRESST**

LOW THRESHOLD: CRESST



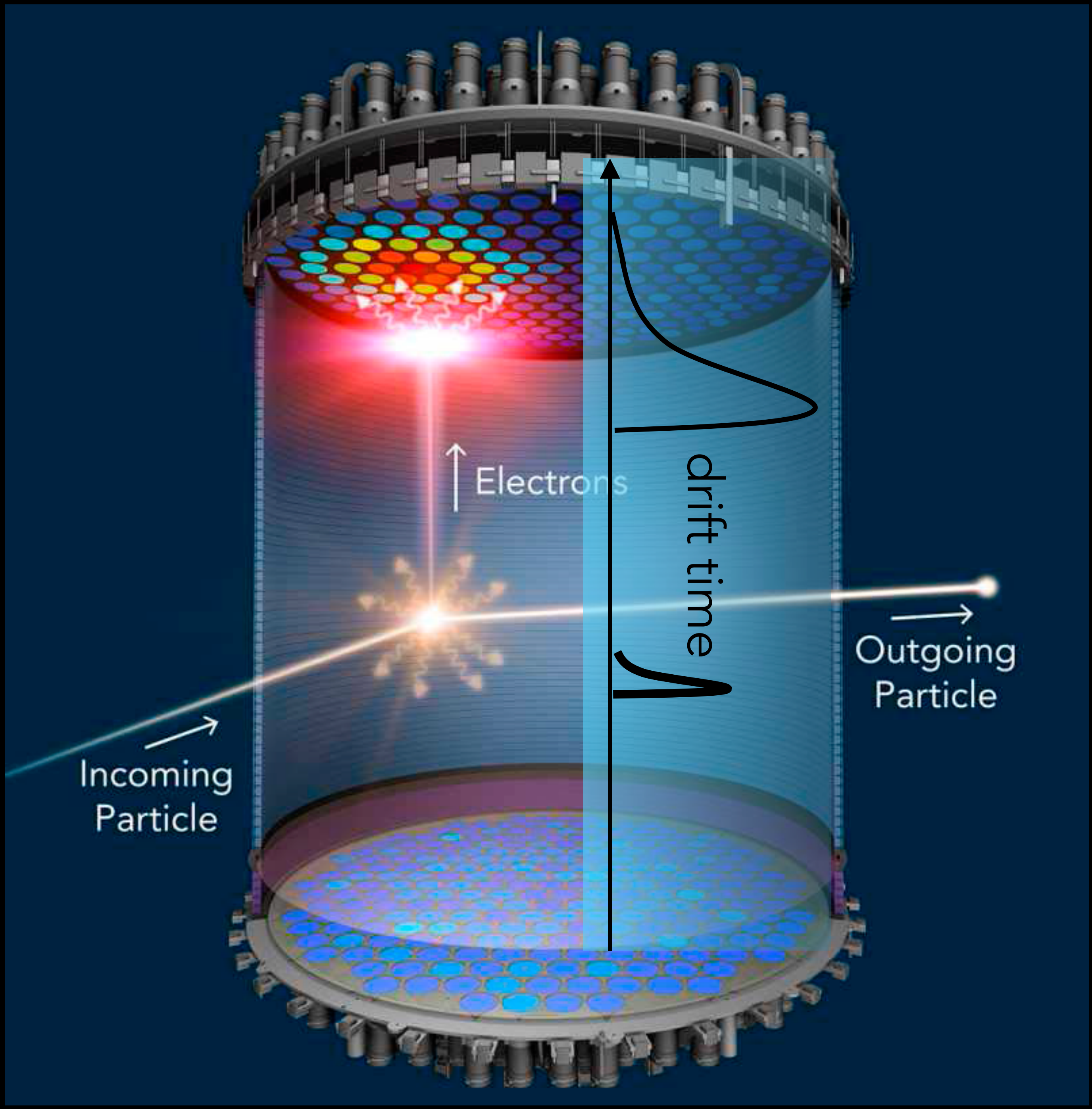
- First **CRESST-III** run 07/2016 - 02/2018
- Unprecedented low nuclear recoil thresholds of 30 eV
- Leading sensitivity over one order of magnitude:
  - 160 MeV/c² →1.8 GeV/c²
- **CRESST-III** phase 2 will push further the threshold (10 eV), exposure (1tonne*day with 1000 CRESST modules) and background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



arXiv:1904.00498v1

LARGE MASS: NOBLE LIQUIDS

- dual-phase Time Projection Chambers with multi-tonne liquid Xe, Ar targets
- read out primary scintillation: "S1" + proportional gas scintillation from drifted electrons: "S2"
- 3D position reconstruction:
  - time difference between S1 and S2 gives Z position (few mm resolution)
  - pattern of S2 light gives XY position (~1cm resolution)
- background identification + passive suppression
- zeptobarn (10^{-45} cm^2) to yoctobarn (10^{-48} cm^2) sensitivity to dark matter



XENON DETECTORS

10 kg

XENON 10 (LNGS)

ZEPLIN II (Boulby)

ZEPLIN III (Boulby)

2010

XENON 100 (LNGS)

100 kg

LUX (250 kg, SURF),

PANDA-X (500 kg, CJPL)

XMASS (0.8t, Kamioka)

2015

1000 kg

XENON 1T (1t, LNGS)

PandaX-4:(4t, CJPL)

XENONnT: (6t, LNGS)

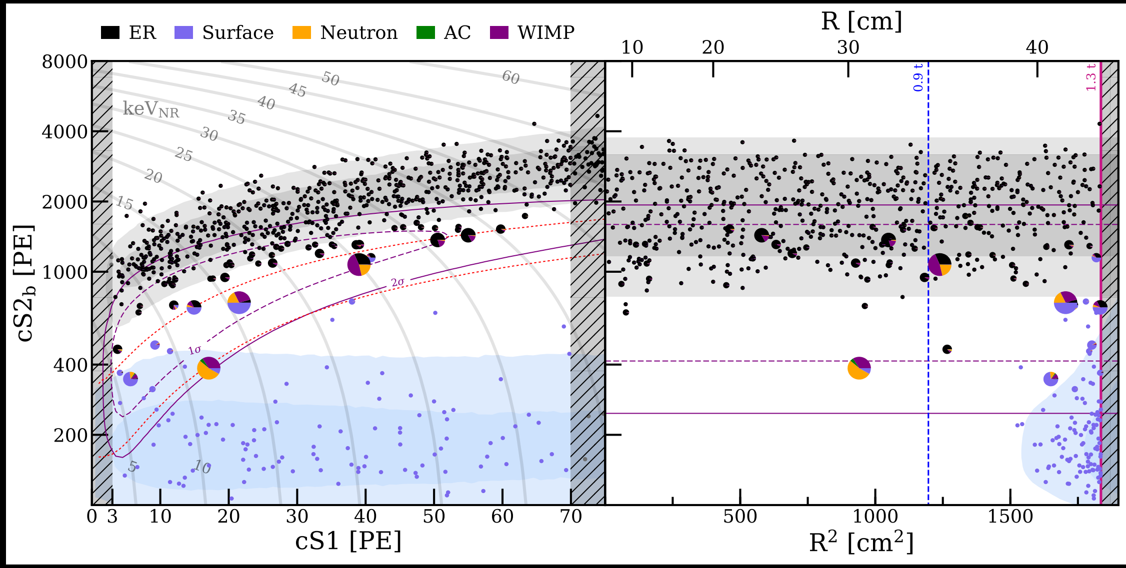
LZ: (7t, SURF)

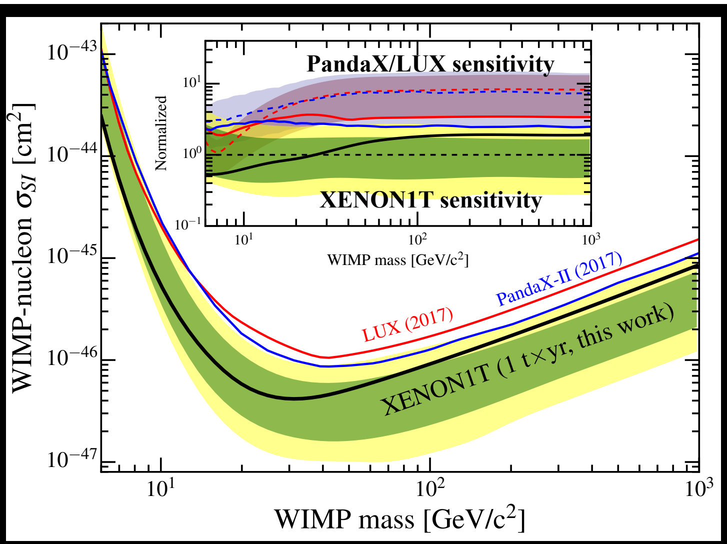
2020

10000 kg

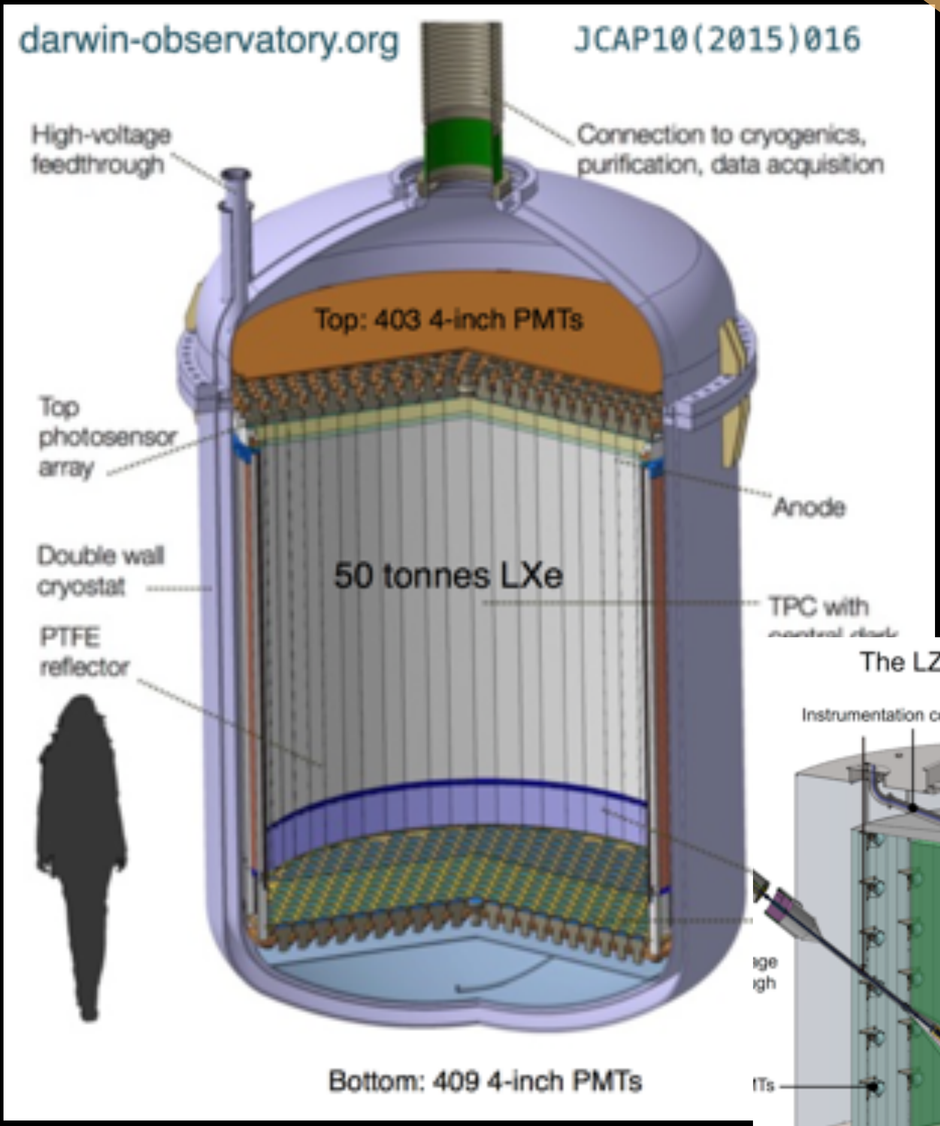
DARWIN: 50 t, ESPPU Document #62

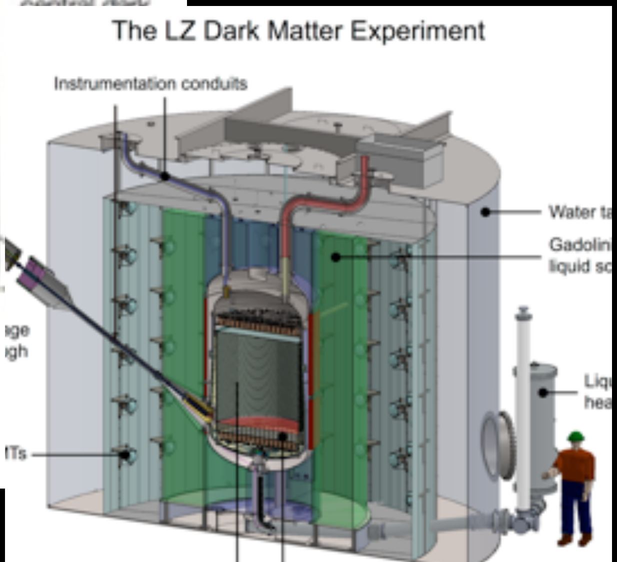
XENON1T: best limit for high WIMP masses





Aprile et al, Phys. Rev. Lett. 121, 111302 (2018)





Jocelyn Monroe, ESPP, Granada 2019

ARGON DETECTORS

2010

10 kg

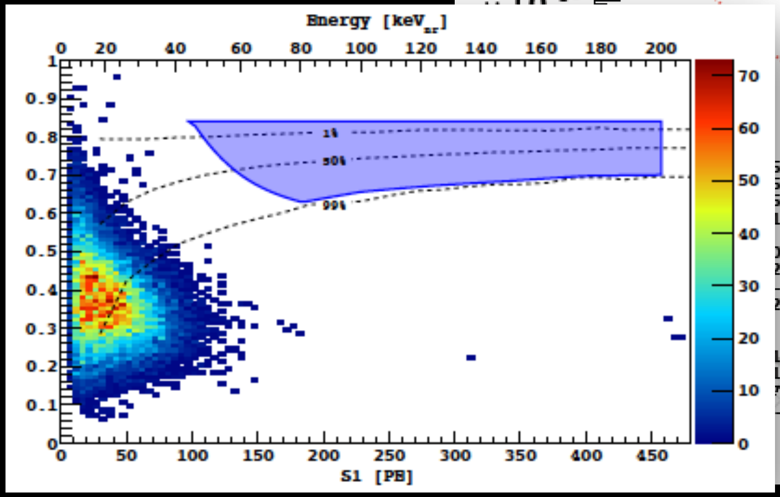
DarkSide-50
(50 kg, LNGS)

DS50 low mass: leading SI limit at 1-5 GeV/c²

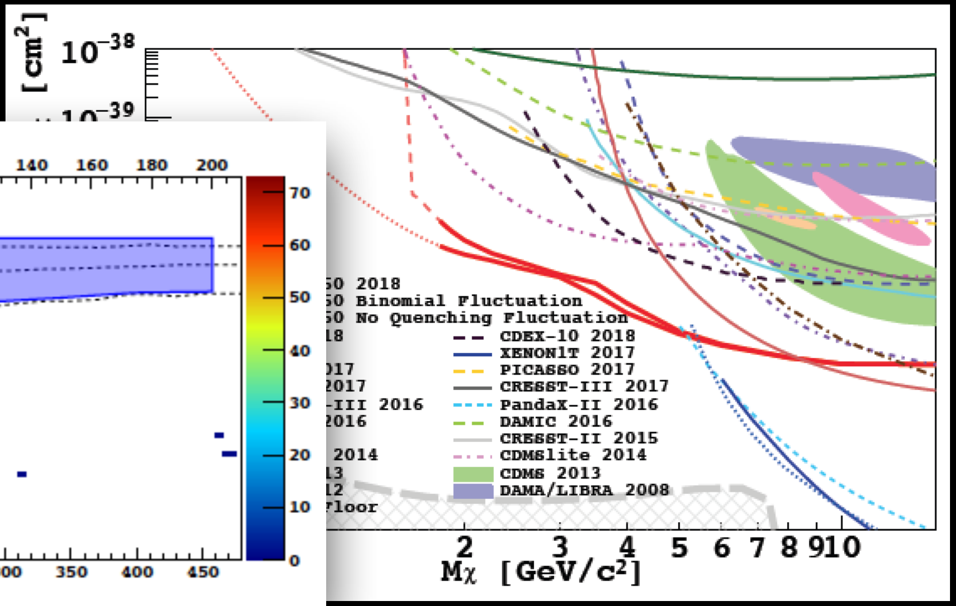
DS50 high mass:
background discrimination

ArDM
(1t, LSC)

100 kg



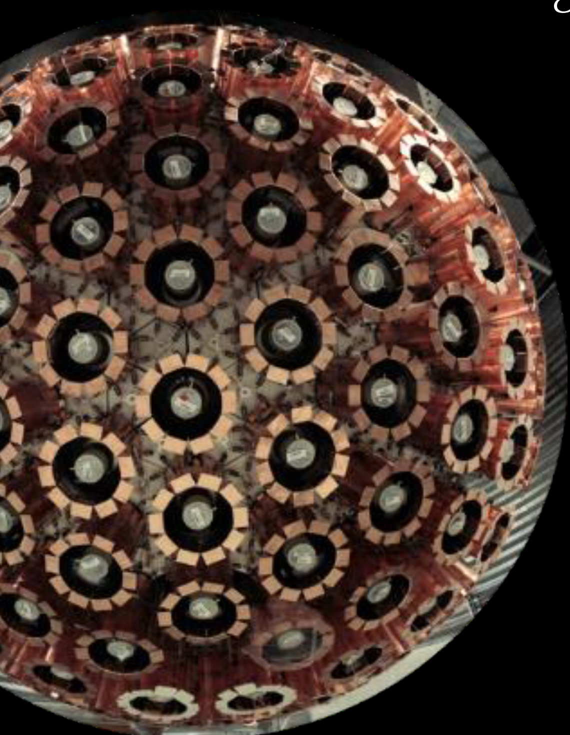
Phys. Rev. D 98, 102006 (2018)



Phys. Rev. Lett.121.081307 (2018)

1000 kg

2015



DEAP-3600 (3.6t, SNOLAB)

10000 kg

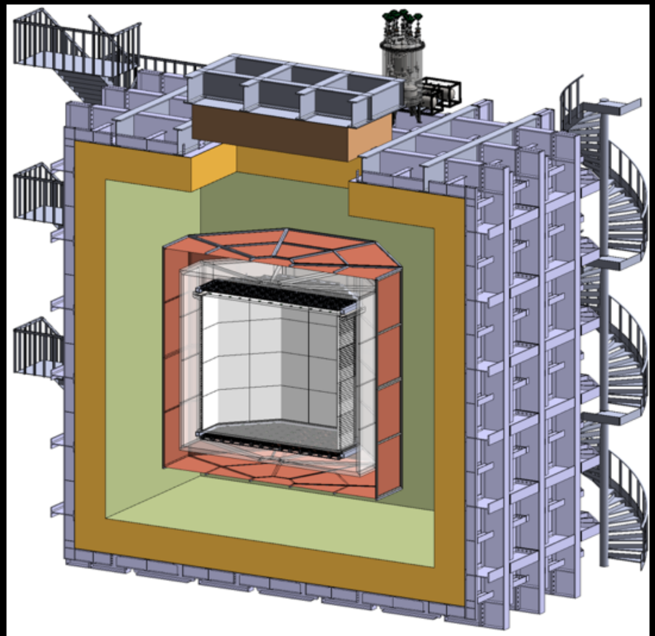
Global Argon Dark Matter Collaboration formed:

2020

DarkSide-20k
(50t, LNGS)

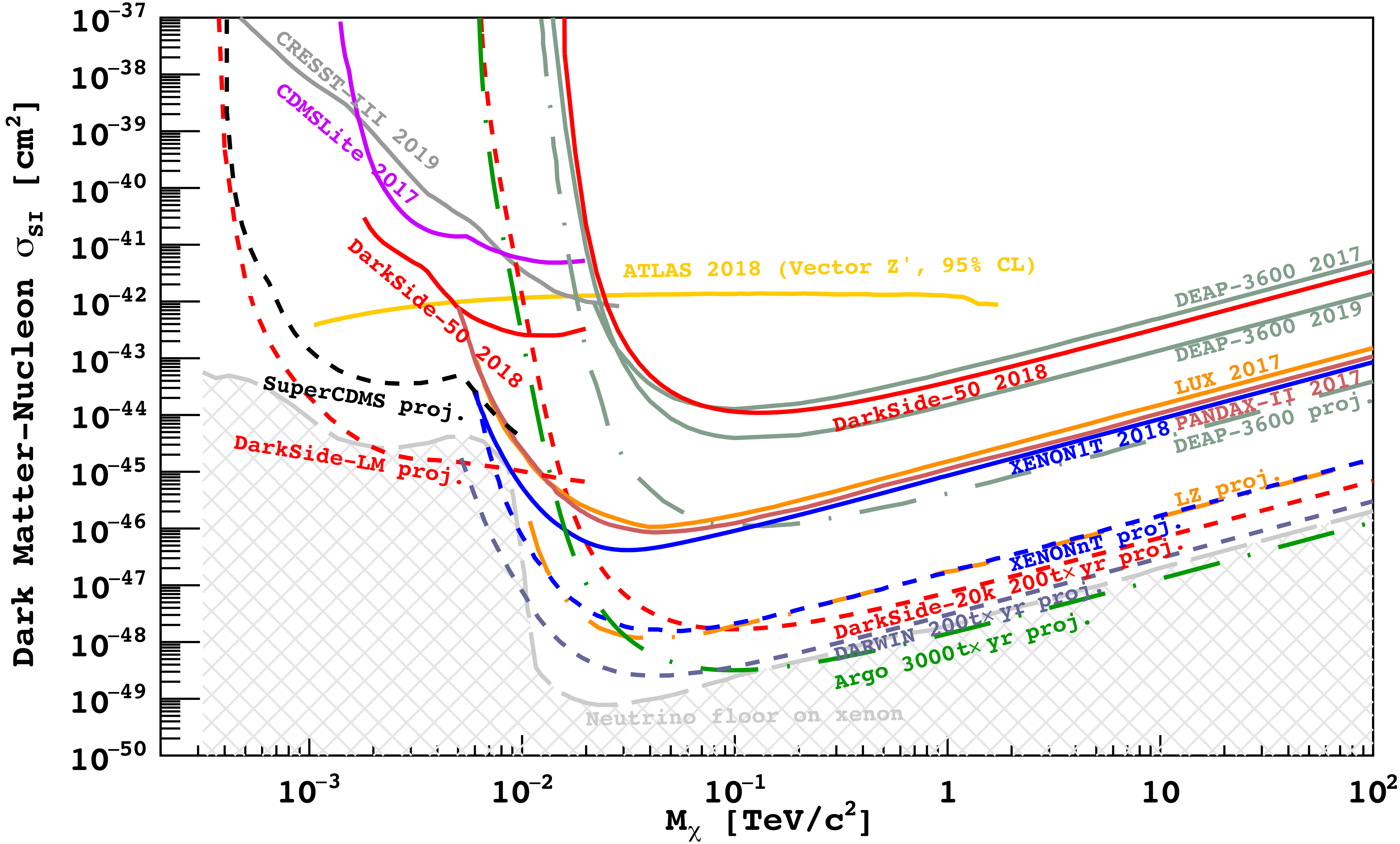
100000 kg

ARGO: 400 t,
ESPPU Document #97



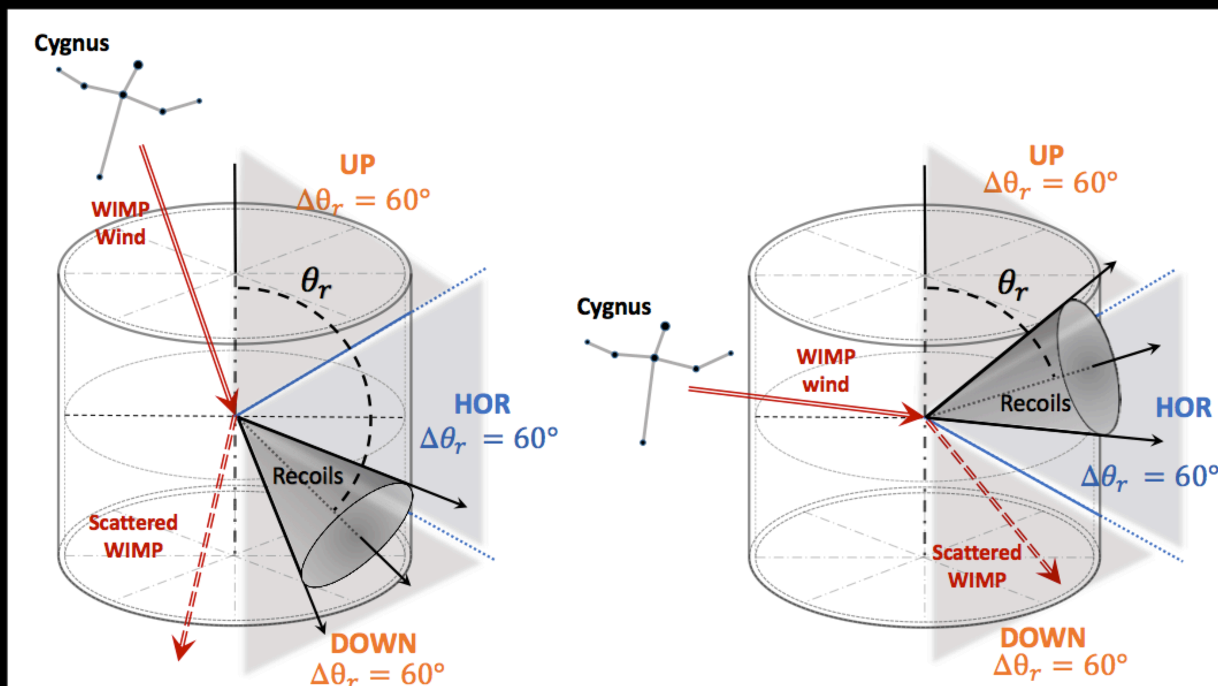
Jocelyn Monroe, ESPP, Granada 2019

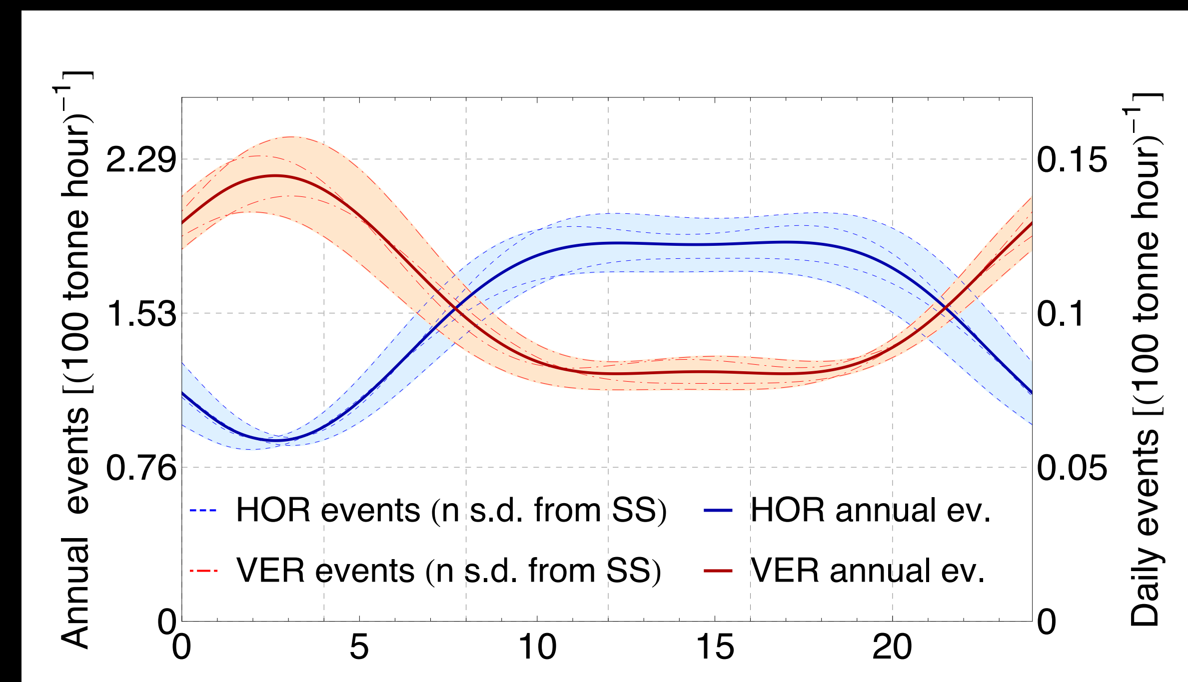
WIMP DIRECT DETECTION STATUS AND PROSPECTS



BEYOND THE NEUTRINO FLOOR: LAR DIRECTIONAL DETECTOR SENSITIVITY

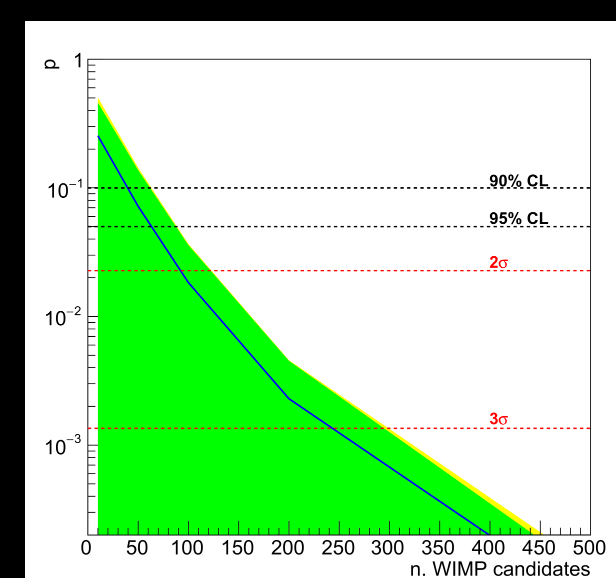
JCAP 01 (2019) 014





Worst case scenario
Horizontal/Vertical 2 class only event subdivision

- 2D info with no head-tail discrimination
- Still retain relevant information with even modest angular resolution
- Sensitivity to reject flat background hypothesis with O(100) events
  - Corresponding to σ_{SI} 10^{-47} cm^2 for 200 GeV Wimps and Darkside-20k full exposure



Assuming 400 mrad resolution

EUROPEAN ASTROPARTICLE PHYSICS STRATEGY 2017-2026

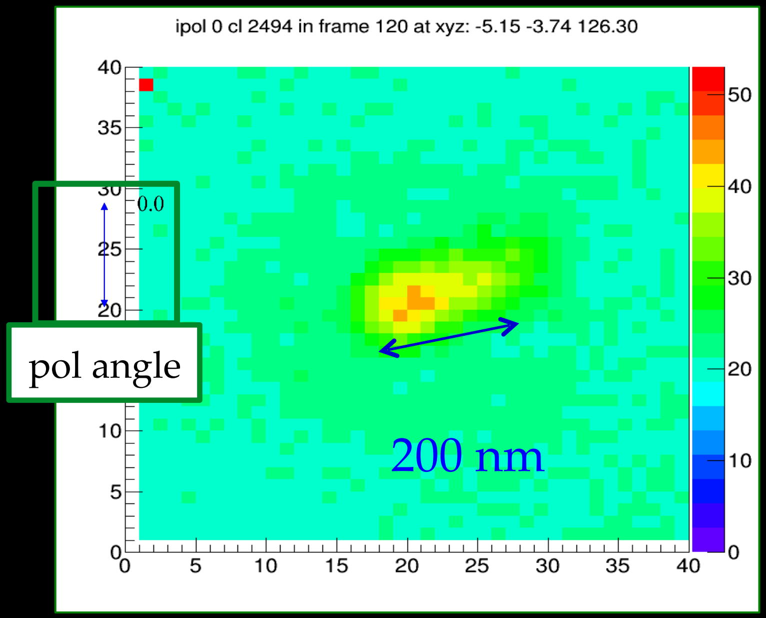
5. Dark Matter

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****.*

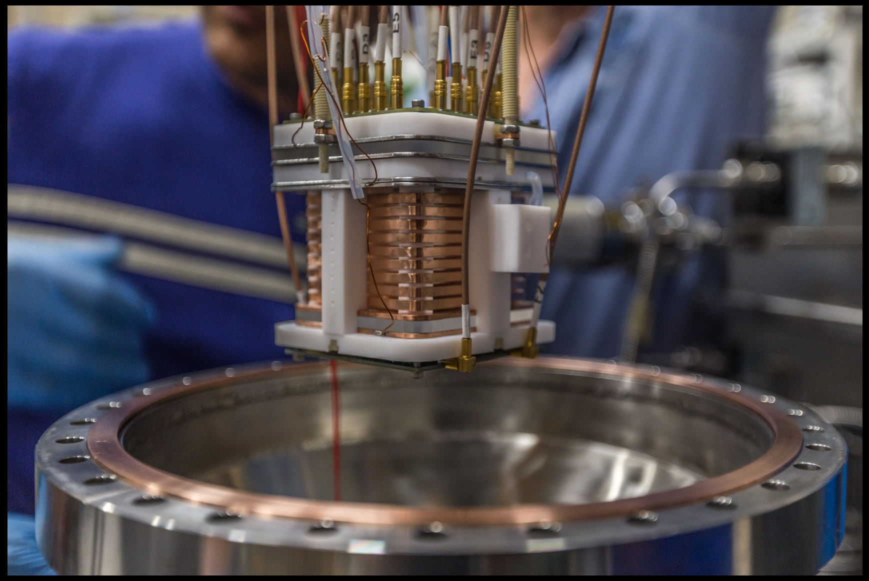
DIRECTIONAL DETECTION: BEYOND THE NEUTRINO FLOOR

- 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)

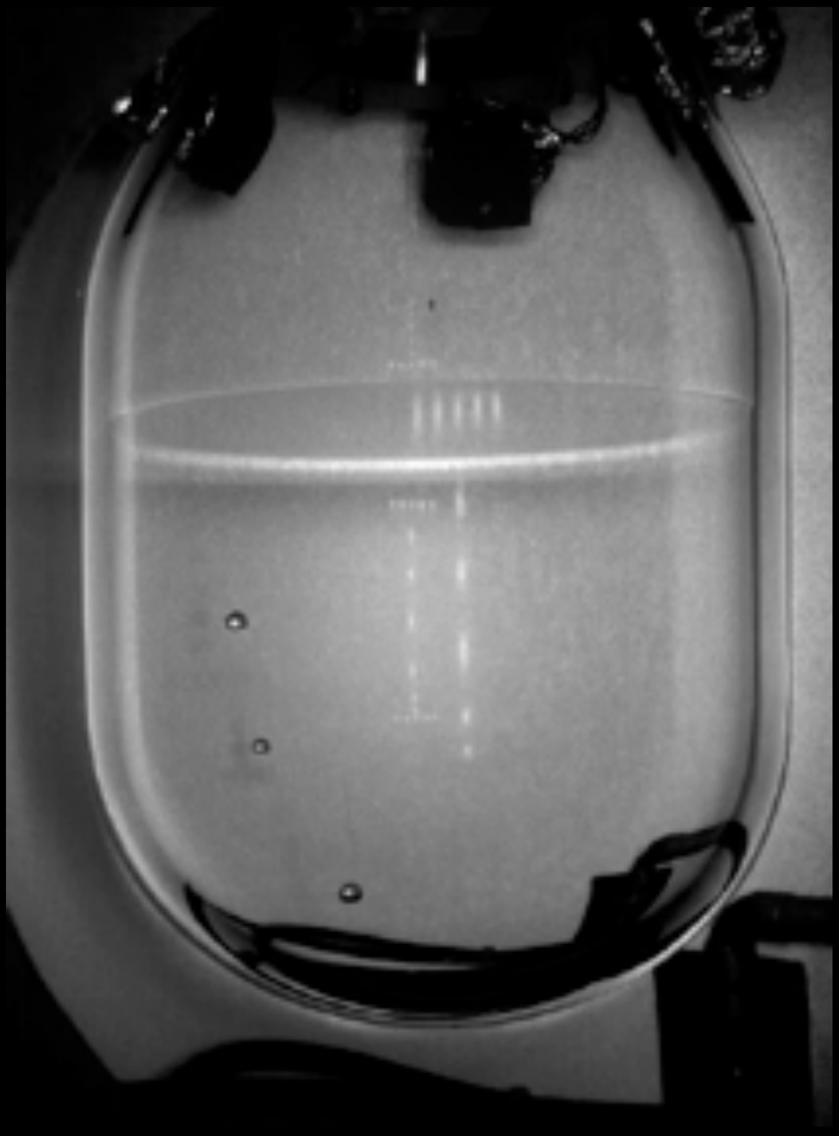


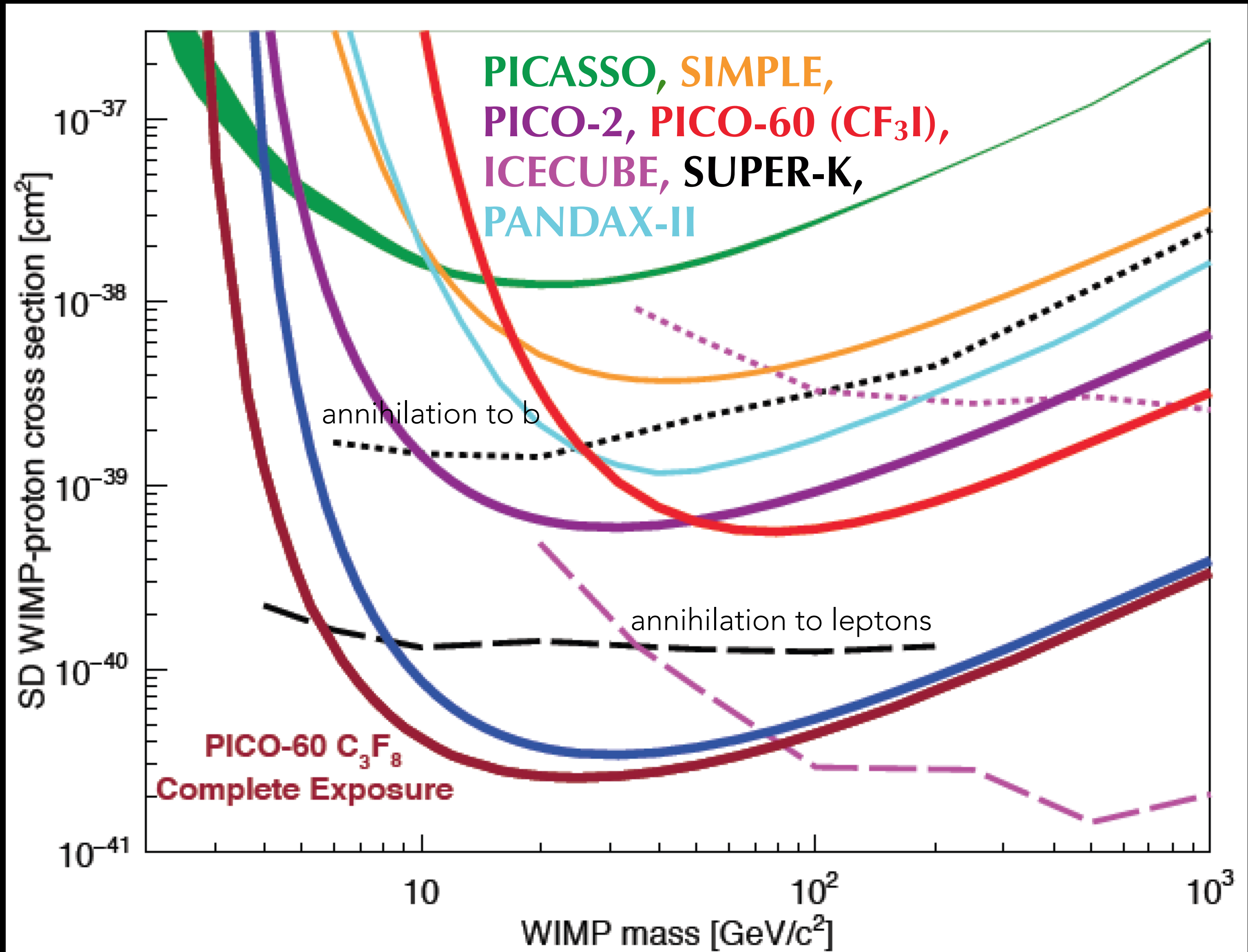
SPIN-DEPENDENT INTERACTIONS

superheated target (C_NF_M), camera + acoustic readout, background rejection based on topology O(10^{-2}), measure counts above threshold when dE/dx > nucleation,
SIMPLE (GESA), **PICASSO+COUPP** = **PICO** (SNOLAB)

PICO-60: leading WIMP-p limit, C_4F_8 target (60 kg), 500 kg planned
competitive limits from neutrino telescopes (IceCube, Antares, SuperK)
leading WIMP-n limits from Xe 2-phase TPCs

arXiv:1902.04031v1



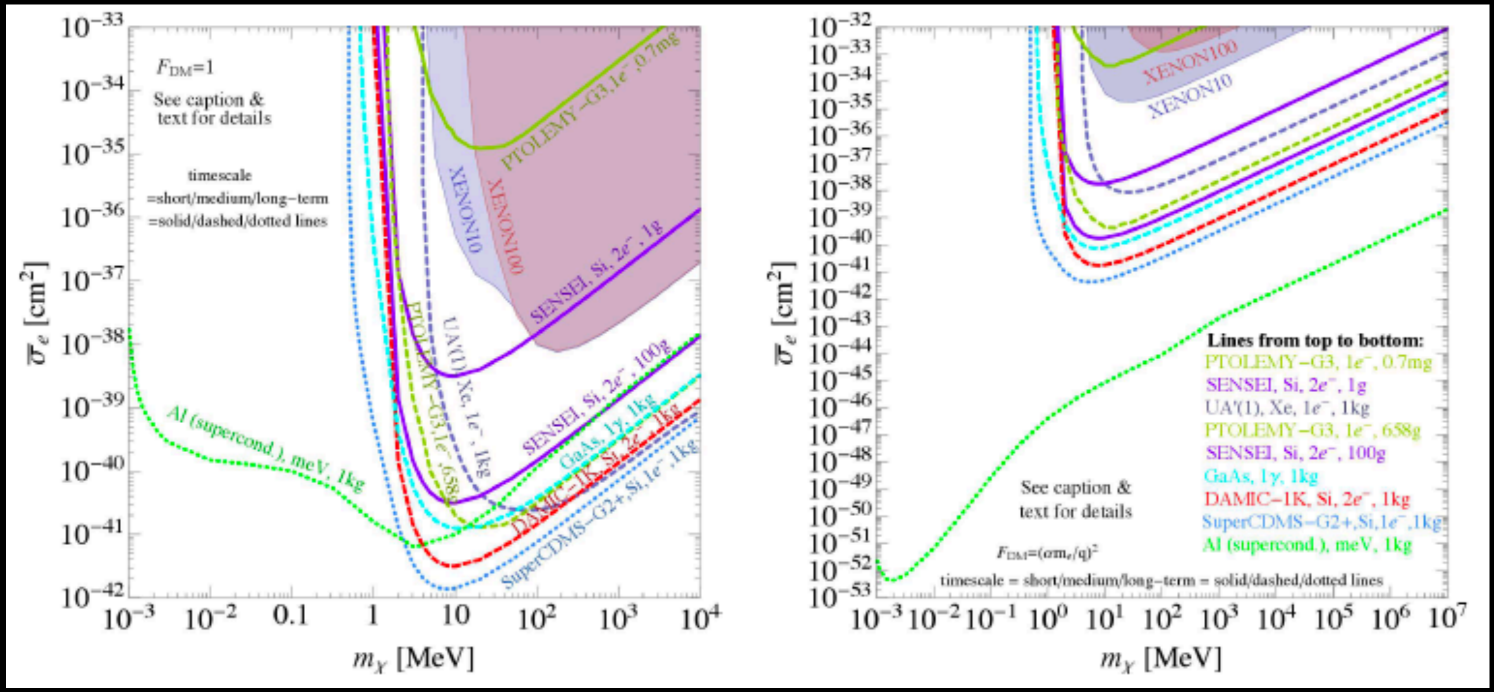


LIGHT DARK MATTER (SUB-GEV)

- Scattering on electrons (keV - GeV)
- Absorption on electrons (meV - keV)
- Increasing number of dedicated experimental efforts
  - **DAMIC**
  - **SENSEI**
  - **PTOLEMY-G³**
  - Noble liquid 2-phase TPC (e.g. **UA'(1)**, **DarkSide-LM**)
  - Drift chambers
  - Superconductors
  - …

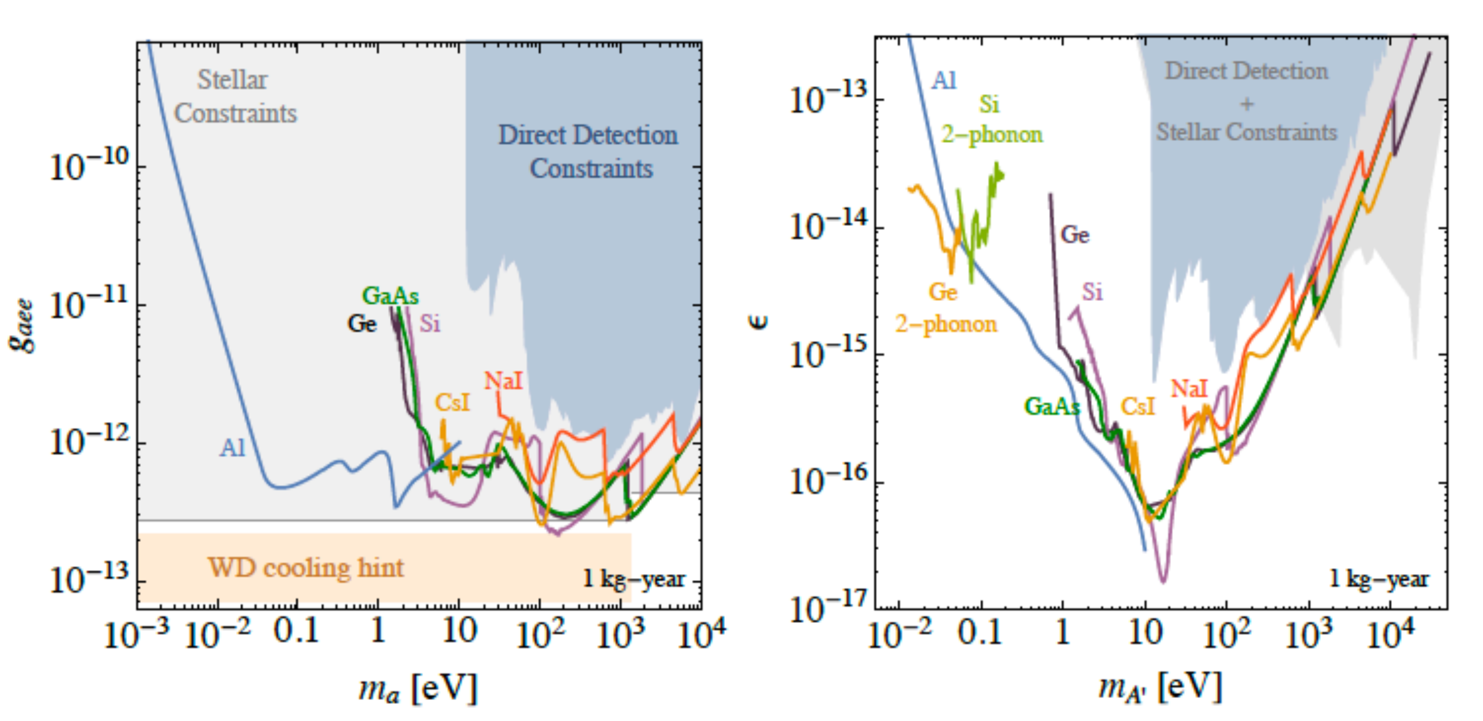
DM-electron scattering

momentum-independent inter. momentum-dependent inter.



Absorption on electrons

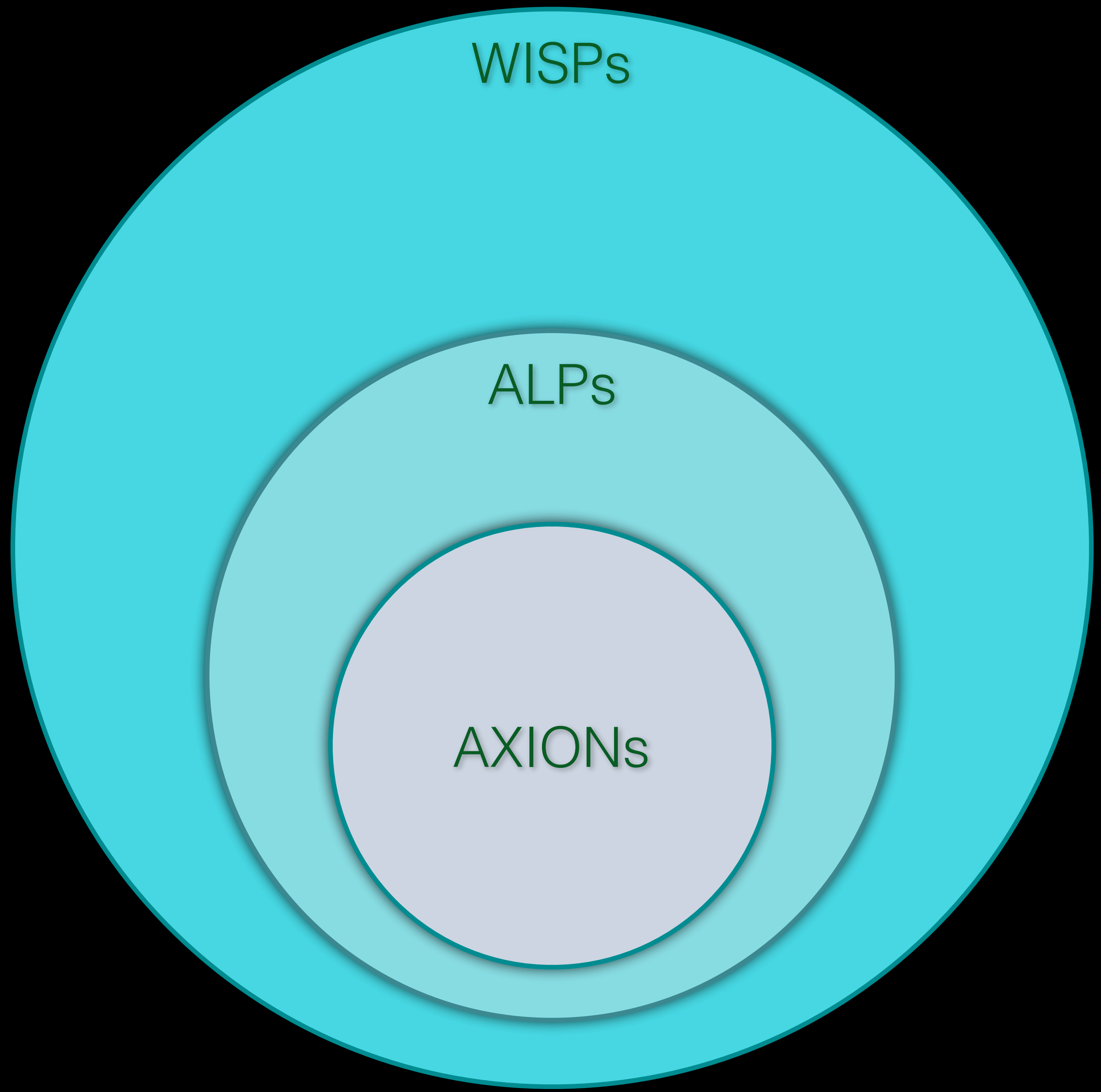
axion-like particle (ALP) dark-photon (A')



arXiv:1707.04591v1

ULTRA LIGHT DM: 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



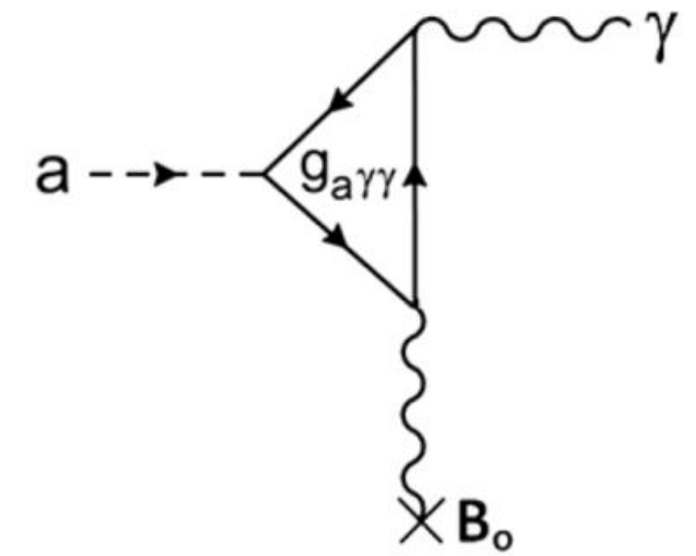
WISP = Weakly Interacting Slim Particles
Slim = sub-eV
ALP = Axion Like Particles

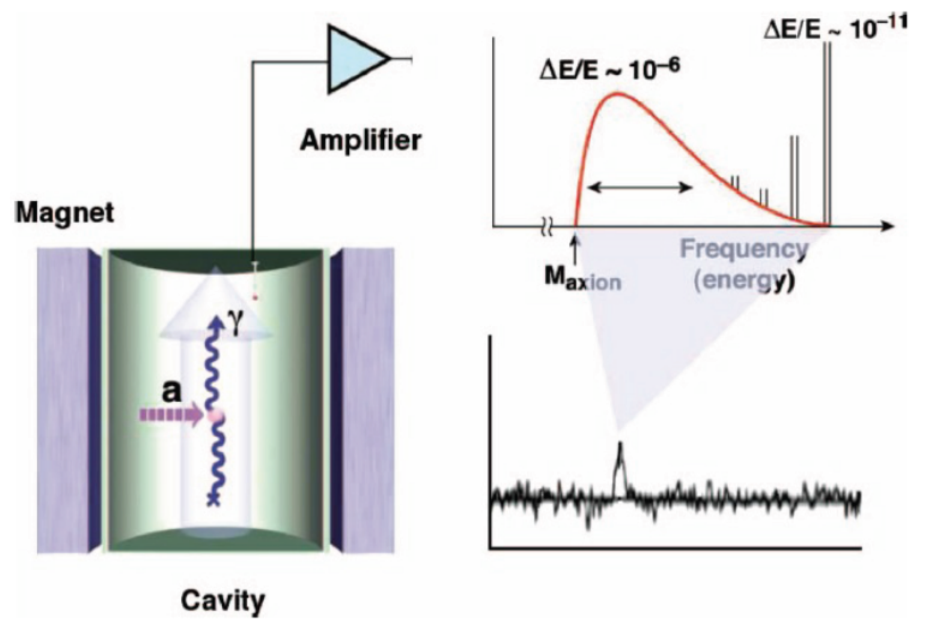
WISP DETECTION

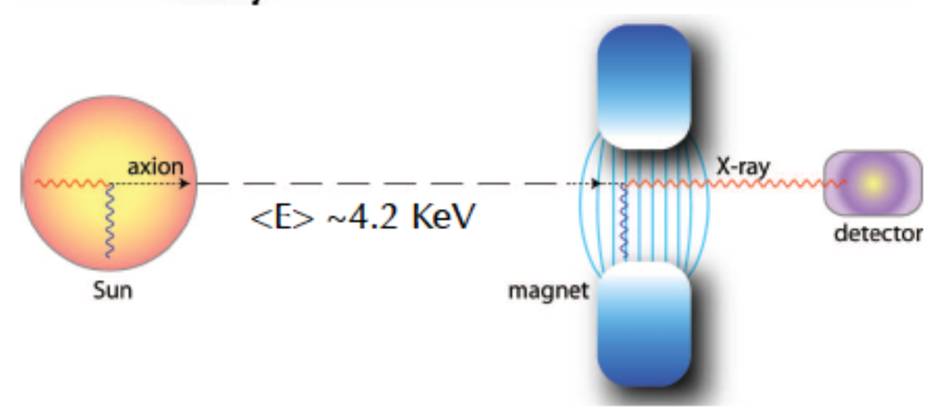
- Pierre Sikivie (1983): "Experimental Tests of the invisible Axion", based on the conversion of axions to photons:
  in a static magnetic field, the axion can "borrow" a virtual photon from the field and turn into a real photon

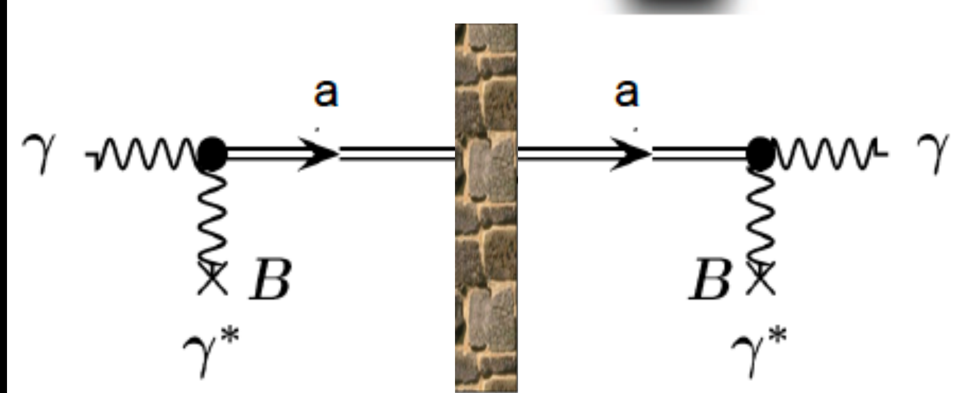
Three main approaches being pursued:

- **Haloscopes** (look directly for dark-matter WISPs in the galactic halo of MW)
- **Helioscopes** (search for ALPs or axions emitted by the Sun)
- **Light Shining trough a Wall** (generate and detect ALPs in a single setup)



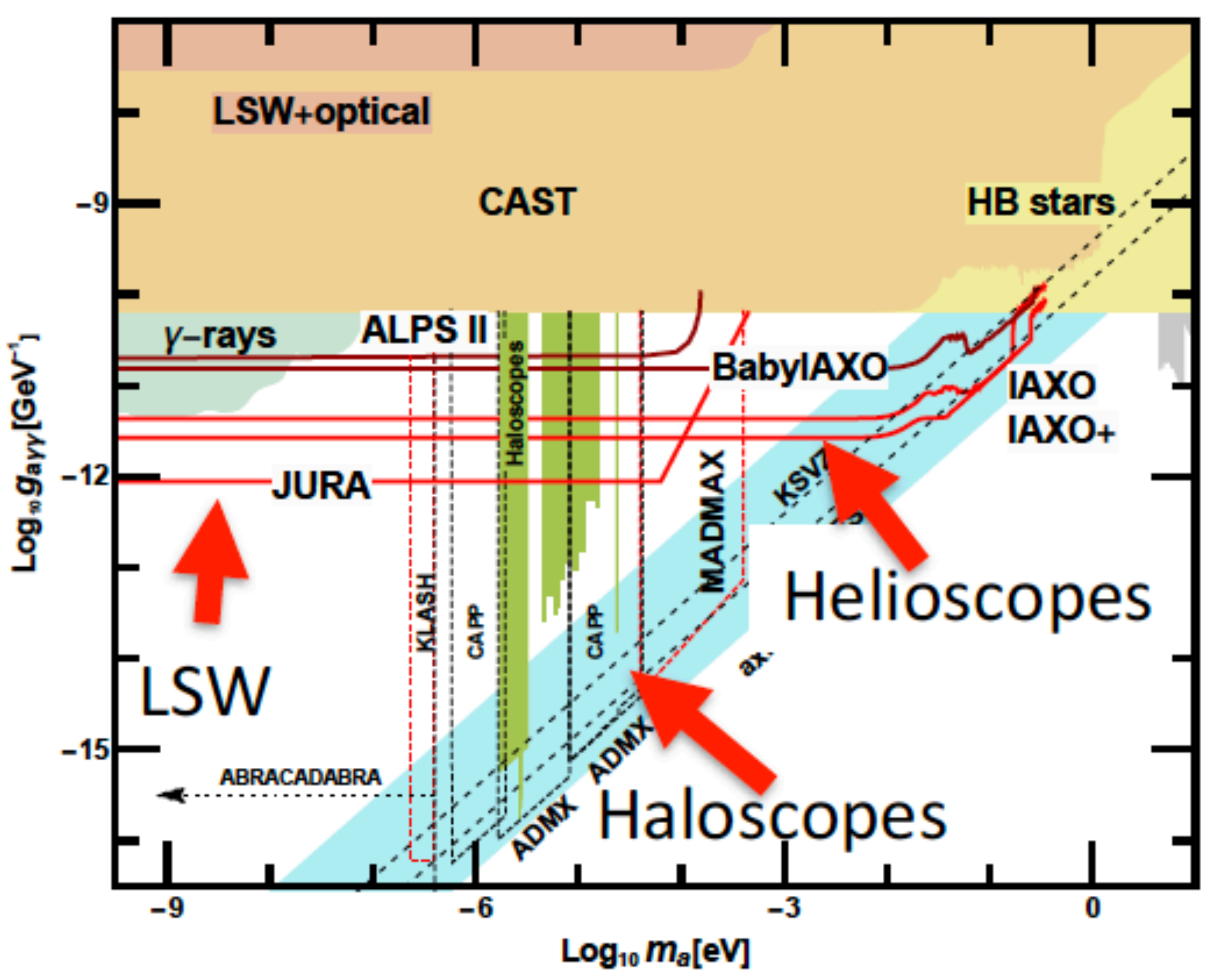






AXION/ALPS SEARCHES

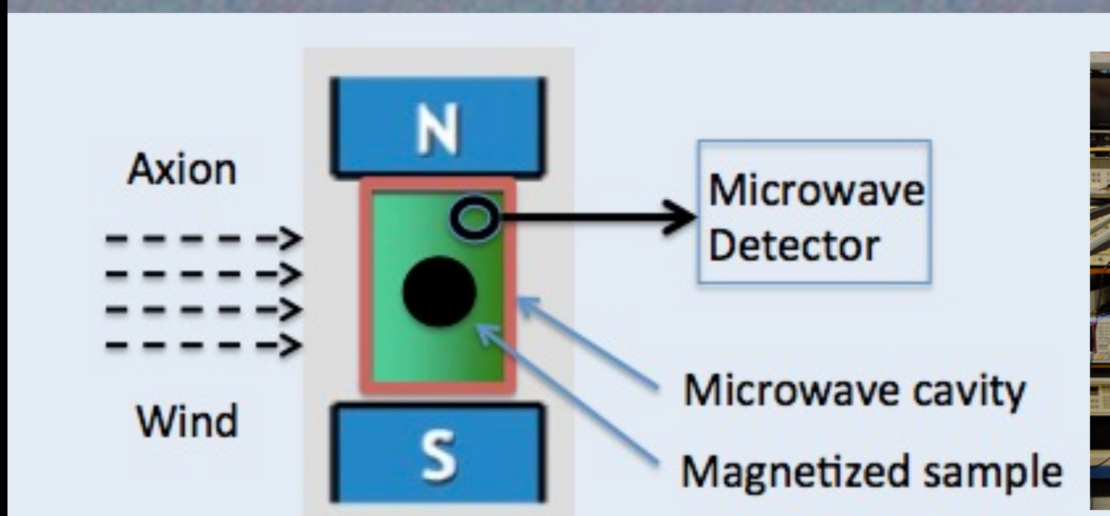
- **Haloscopes**
  - **ADMX** (US) is leading the field
  - In Europe, **MadMax** is new key player
  - Smaller efforts developing new techniques
- **Helioscopes**
  - Build on success of **CAST** hosted by CERN
  - Proposed **BabyIAXO**, leads to **IAXO**, with large discovery potential
- **Light Shining through a Wall (LSW)**
  - **ALPS II** is well underway
  - **STAX** is a new idea RF based
  - **JURA** is long term plan

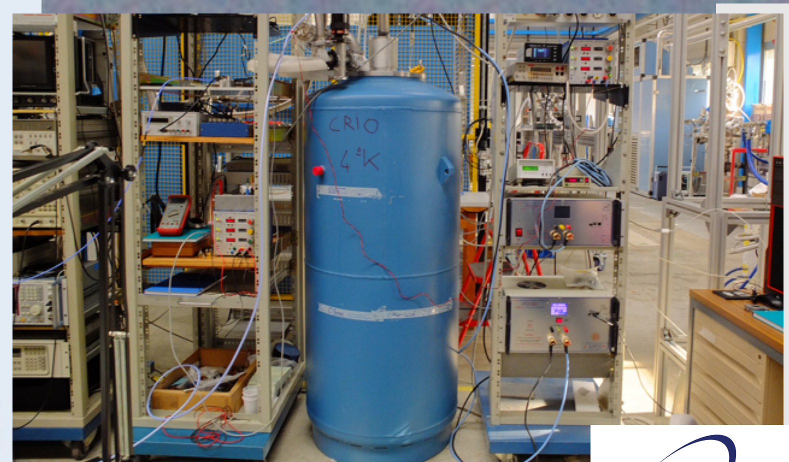


Marcela Carena @ ESPP, Granada, 2019

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 **B_0** and can produces a detectable signal
- **The interaction with axion field produces a variation of magnetization which is in principle measurable**



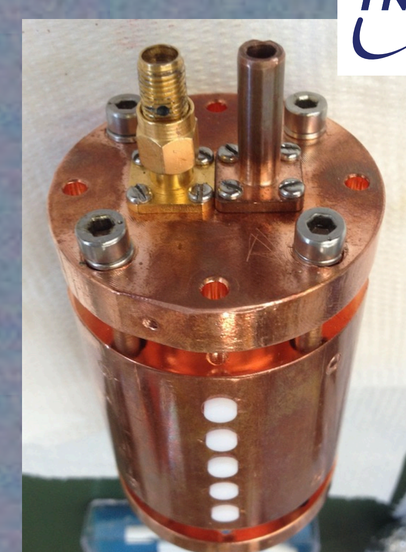


Extremely challenging!

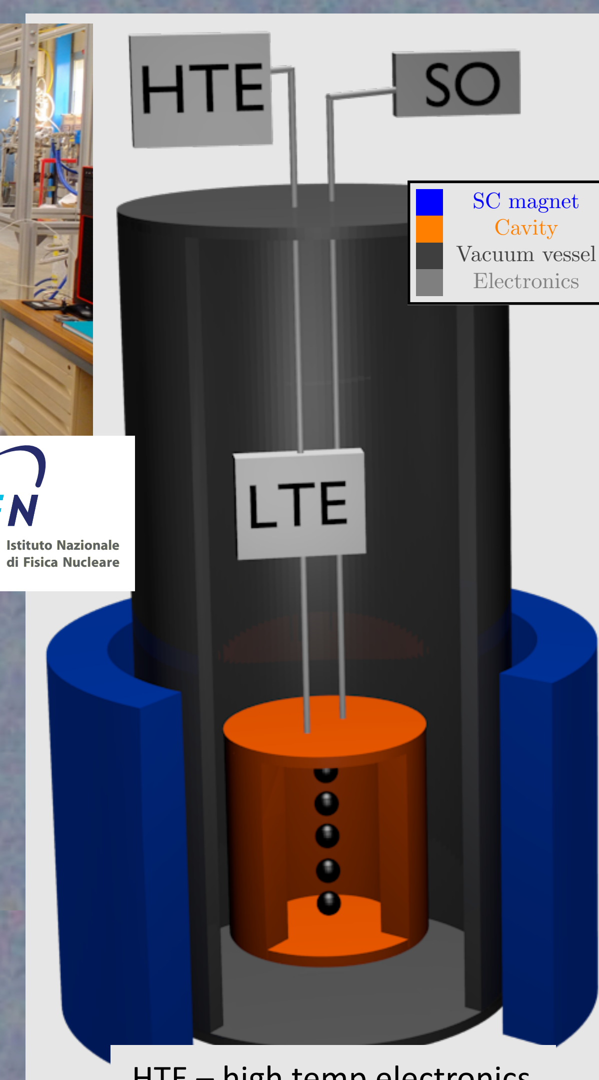
$$P_{\rm out} = \frac{P_{\rm in}}{2} = \mathbf{3.8 \times 10^{-26}} \left(\frac{m_a}{200\ \mu\text{eV}}\right)^3 \left(\frac{V_s}{100\ \text{cm}^3}\right) \left(\frac{n_S}{2 \cdot 10^{28}/\text{m}^3}\right) \left(\frac{\tau_{\rm min}}{2\ \mu\text{s}}\right)\ \text{W}$$

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

INFN Istituto Nazionale di Fisica Nucleare



Microwave cavity loaded with magnetic samples



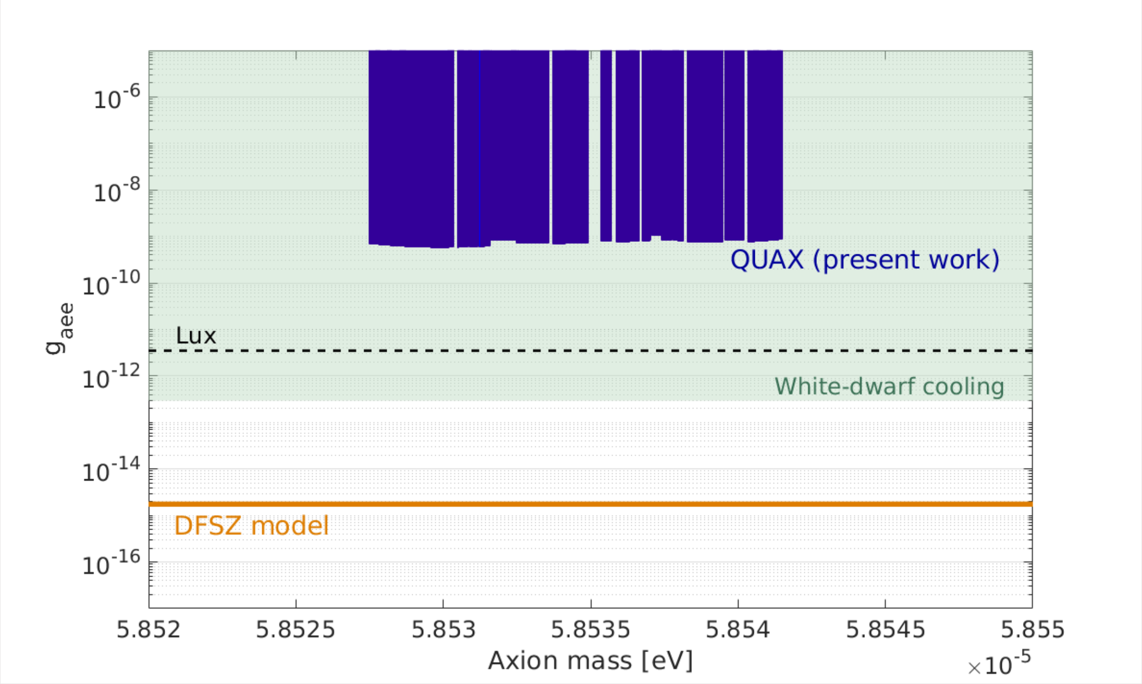
HTE – high temp electronics
LTE – low temp electronics
SO – source generator

QUAX: latest results / perspectives

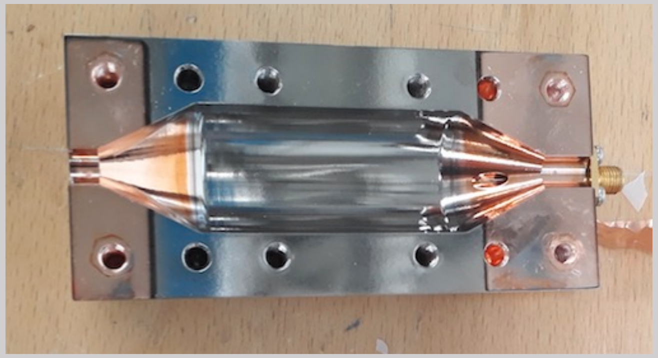
First limits of axion electron coupling from a dark matter haloscope

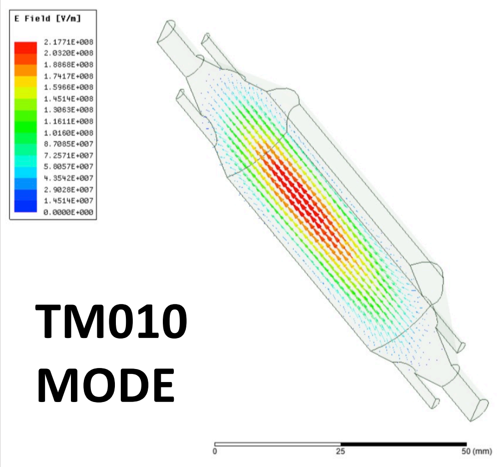
$$g_{aee} > \frac{e}{\pi m_a v_a}\sqrt{\frac{2\sigma'_P}{\mu_B \gamma n_a n_s V_s \tau_+}},$$

R & D in progress to define a complete apparatus

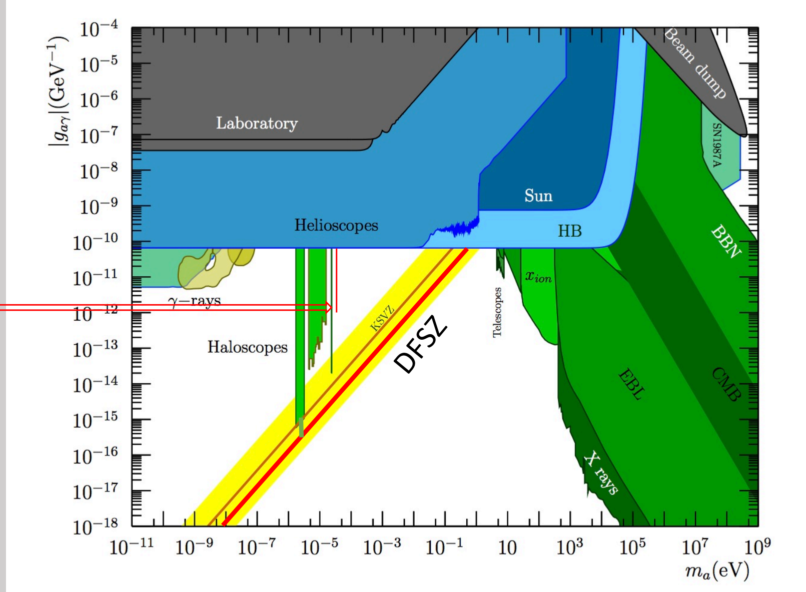


QUAX can operate in Primakoff mode too!
Use a different resonant mode.





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

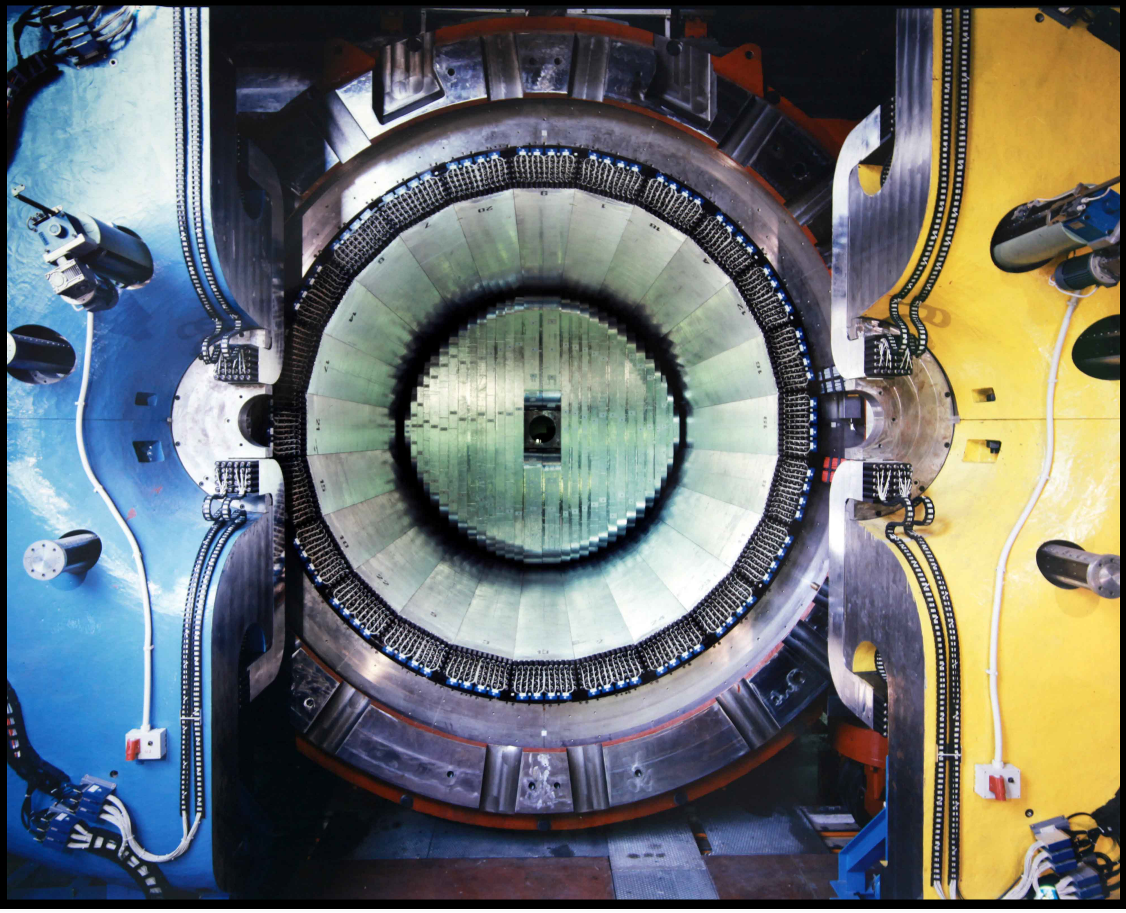
HALOSCOPES

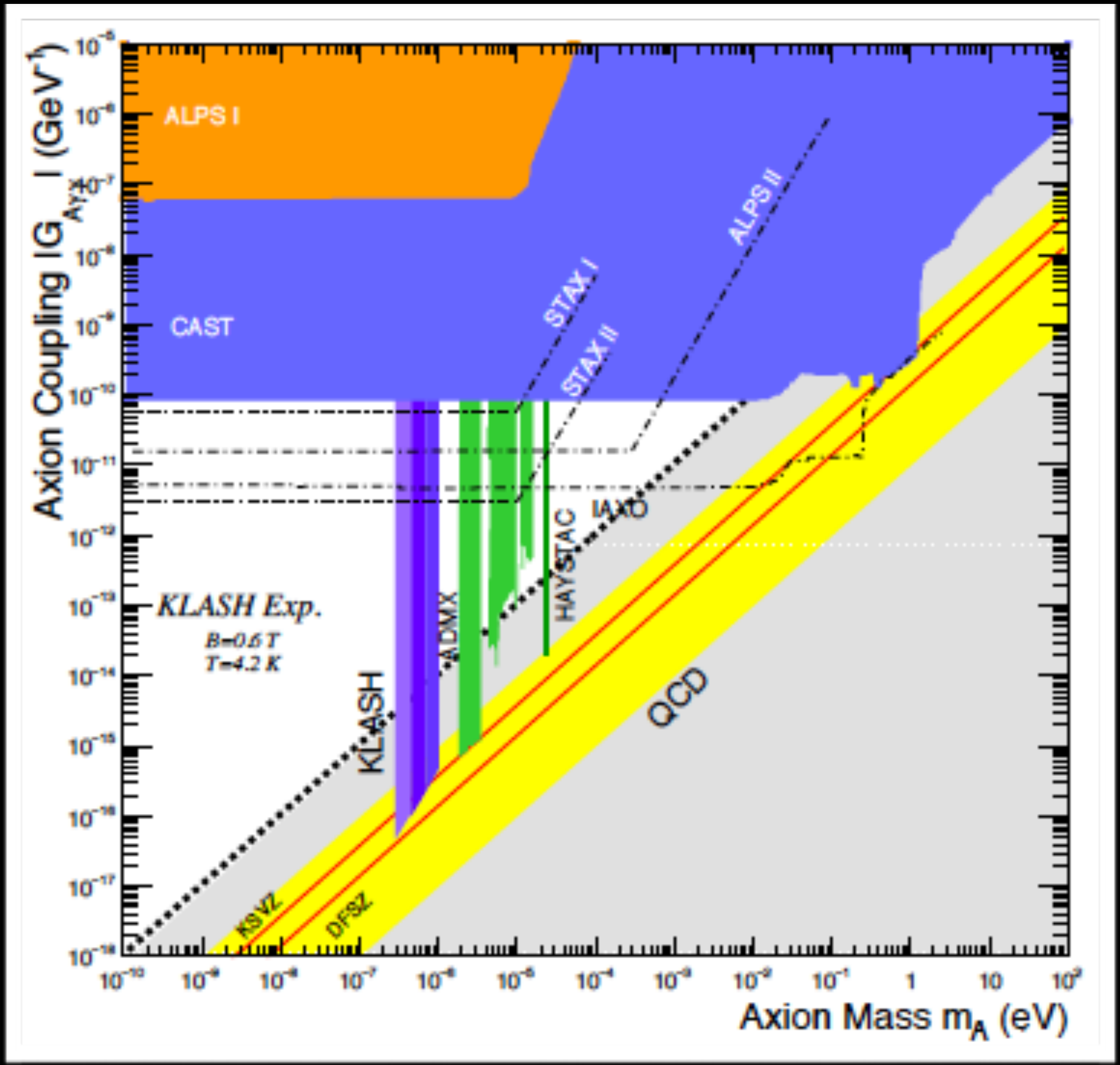
THE KLASH

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 m^3)
- Moderate magnetic field (0.6 T)
- Copper rf cavity Q~600,000
- T 4.2 K

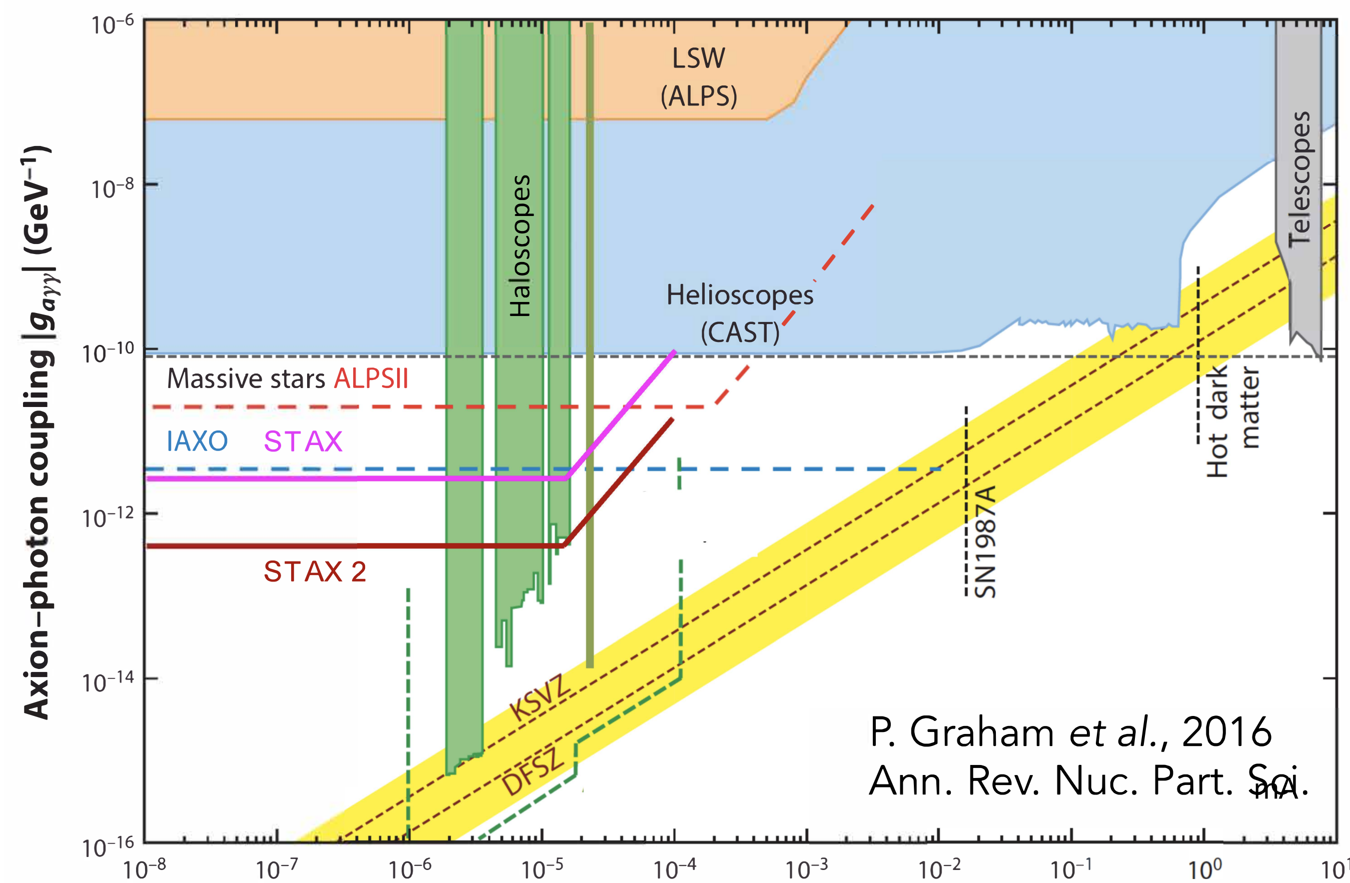
If KLOE magnet used for DUNE Near Detector:
→FLASH: Finuda magnet for Light Axion SearcH



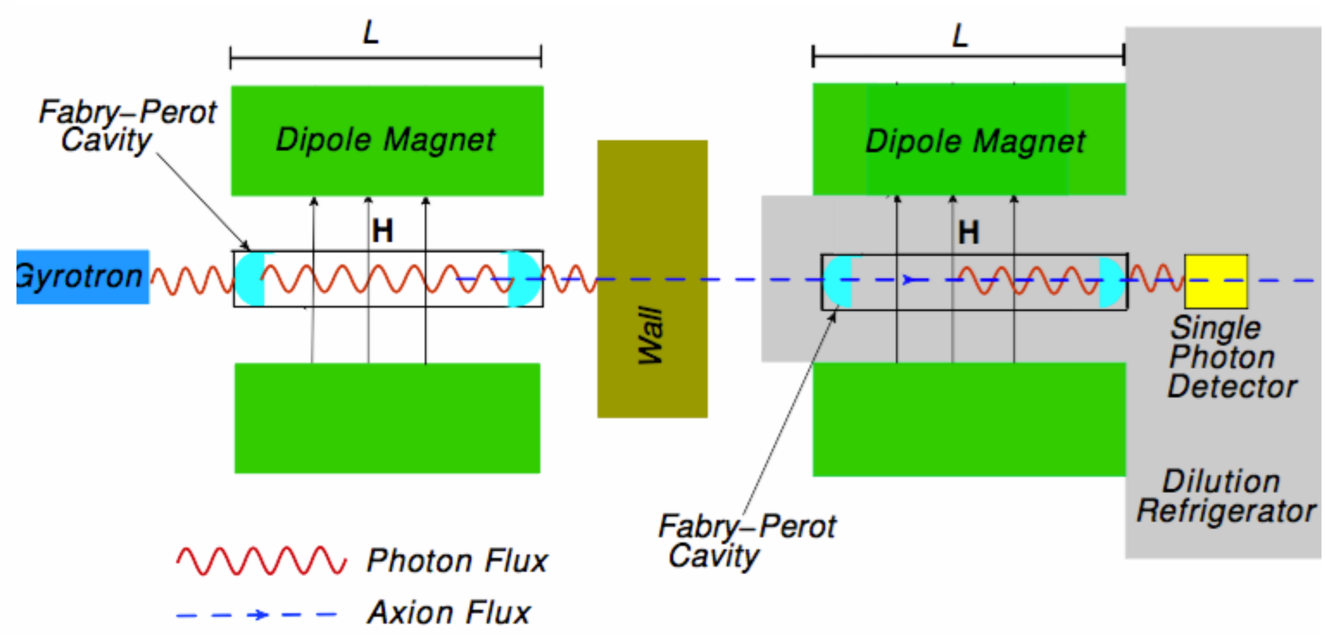


C. GATTI

LIGHT SHINING THROUGH A WALL

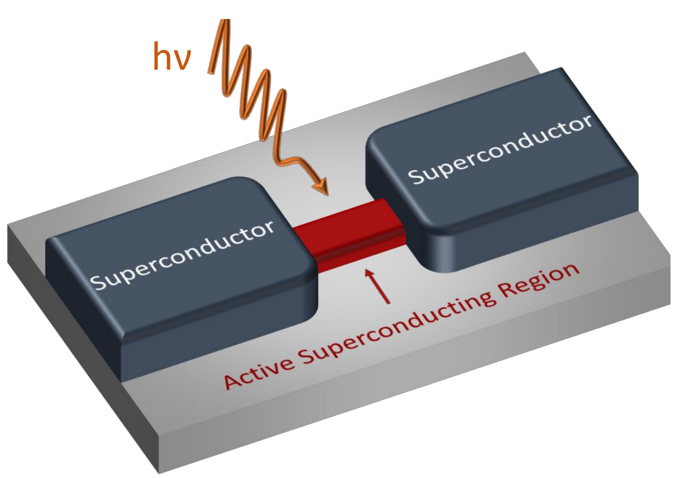


STAX proposal: optimisation of the LSW experiments for Axion Search



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

- Magnetic field: H = 11T, L = 1.5 m
- Source: gyrotron; $P \approx 100$ kW, $\Phi_\gamma = 10^{27}$ s^{-1}, $\varepsilon_\gamma = 120$ 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)

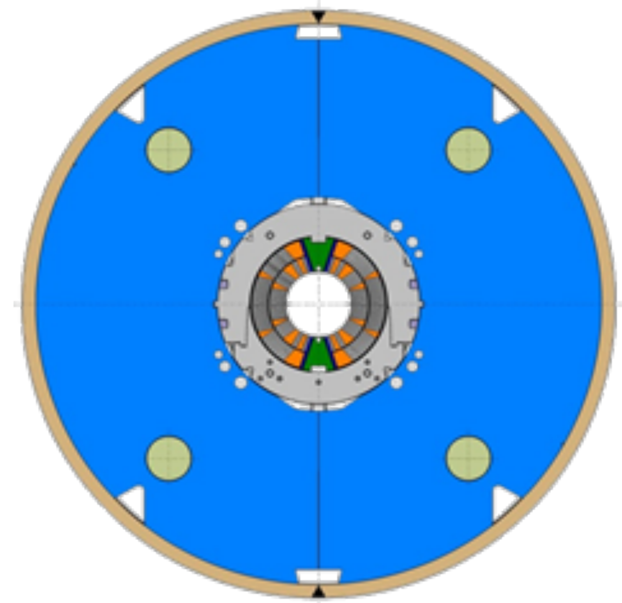
P.SPAGNOLO

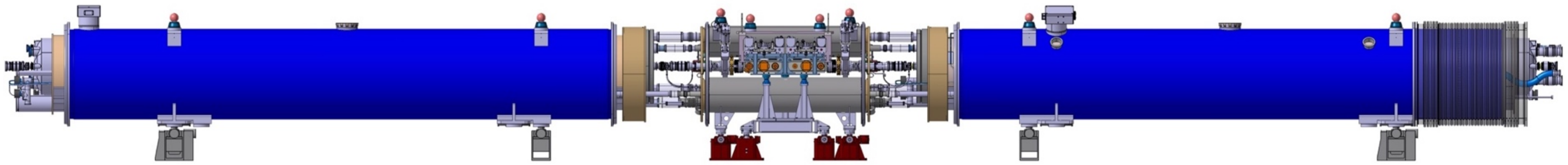
LIGHT SHINING THROUGH A WALL

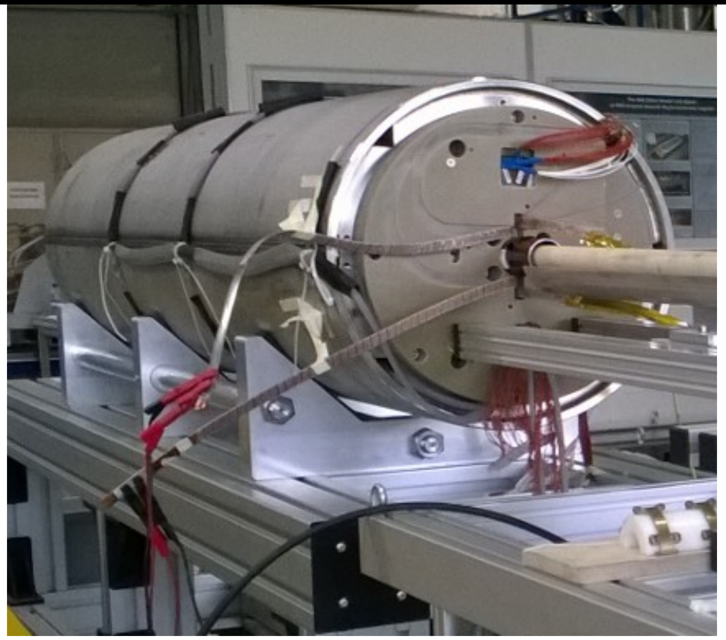
P.SPAGNOLO

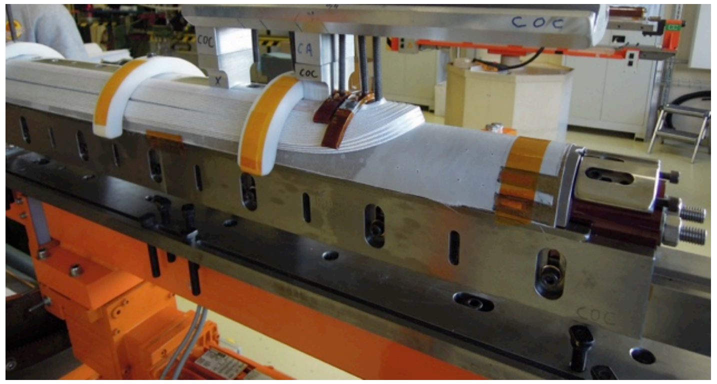
11T dipole magnet

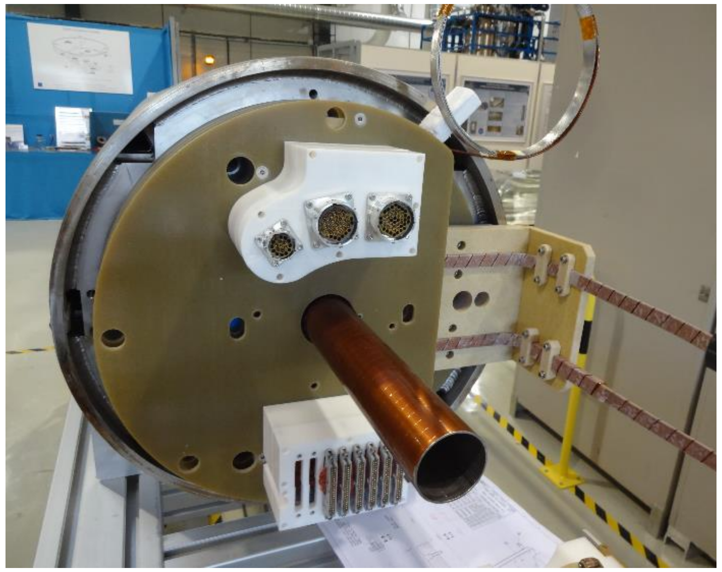
- The **HL-LHC Project** implies beams of larger intensity
  - Additional collimators are needed
- Two collimators to be installed on either side of interaction point 7
  - Replace a standard Main Dipole by a pair of shorter **11 T Dipoles**
- 5 single aperture **short models** fabricated and tested 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

FOOD FOR THOUGHT

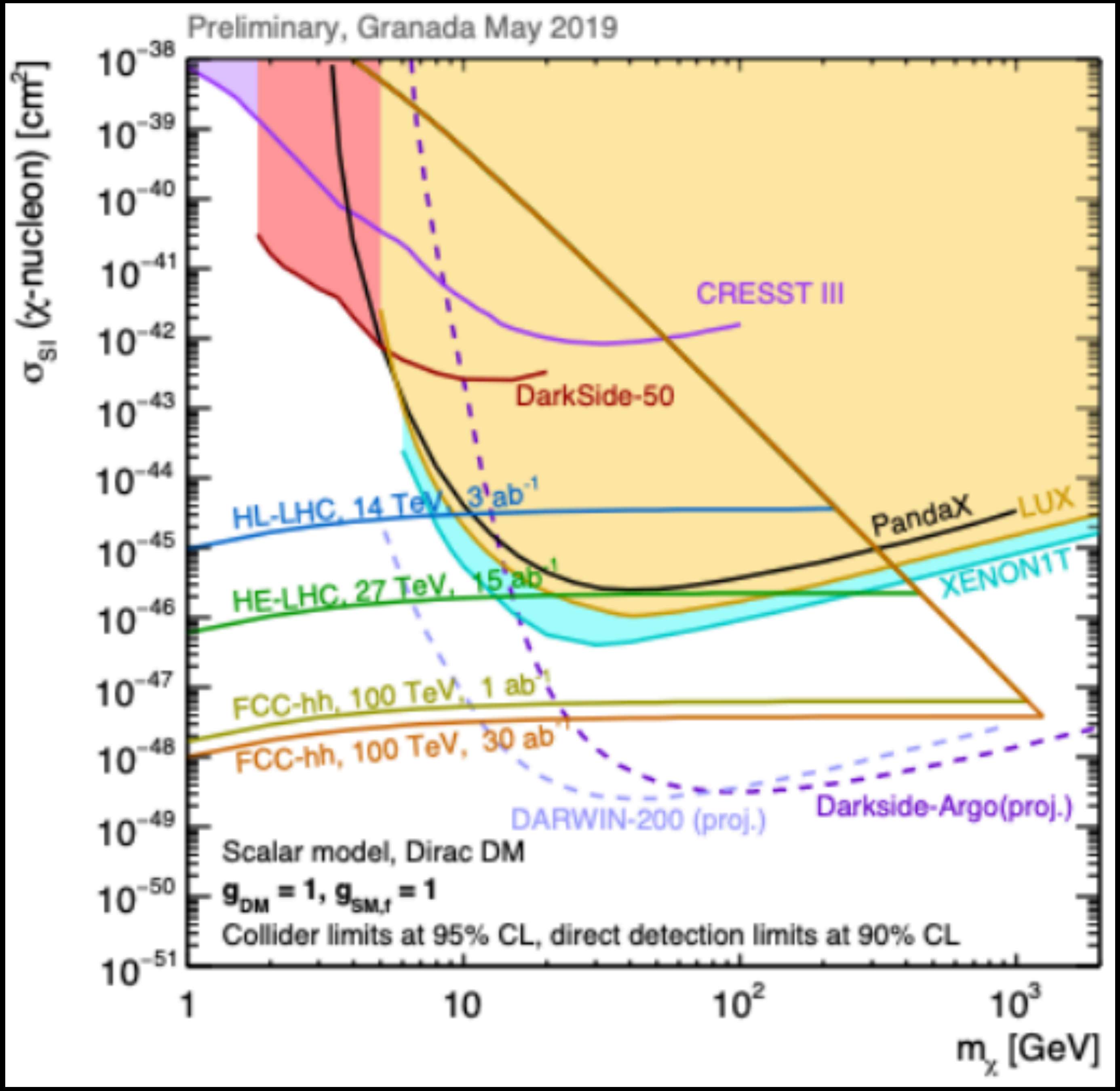
UNDERSTANDING THE NATURE OF DARK MATTER

Complementarity

- Collider 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

Overlapping areas of research

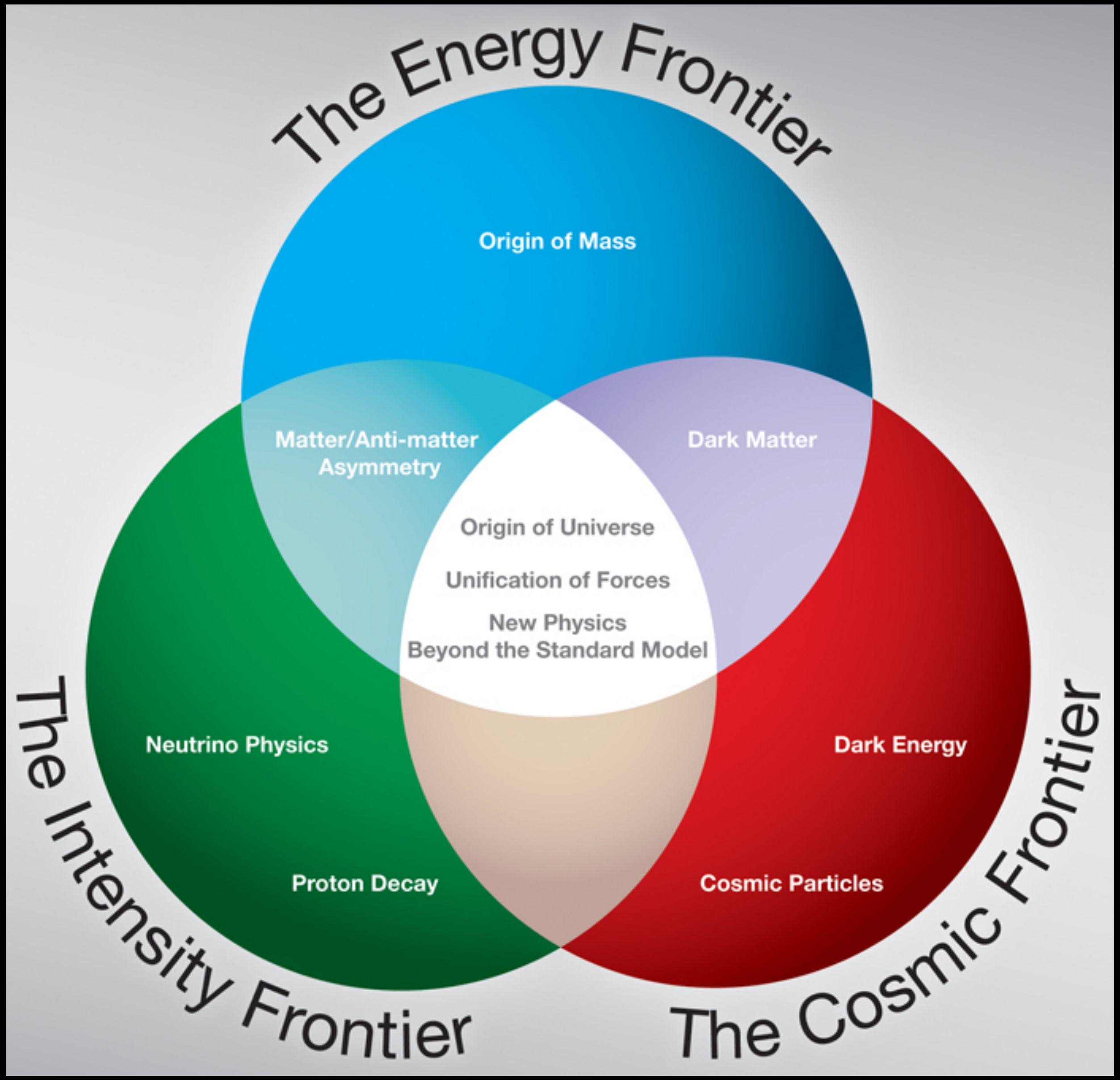
- Need a coordinate effort within Particle Physics community
- See for instance US Particle Physics Project Prioritization Panel (P5):
  - Cosmic, Energy and Intensity Frontiers, on equal grounds within the larger field of particle physics

Technology

- Magnets, Superconductors, Radiofrequency cavities techniques
- Vacuum & Cryogenics
- LAr detectors
- SiPM + electronics

Diversification strategy

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



SUMMARY & CONCLUSIONS

- A new era in the search for dark matter: need to explore DM everywhere
- WIMP still main paradigm → reach ν floor
- Light DM probed via scattering to 1 MeV (and via absorption to ~eV), and possibly much lower
- *Ultra Light DM: a wealth of dedicated initiatives search for WISP dark matter covering > 10 orders of magnitude in mass*