Dark Matter and Neutrino Experiments

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Reunión Anual (RADPyC), CINVESTAV-IPN
CDMX, México; Junio 19, 2026

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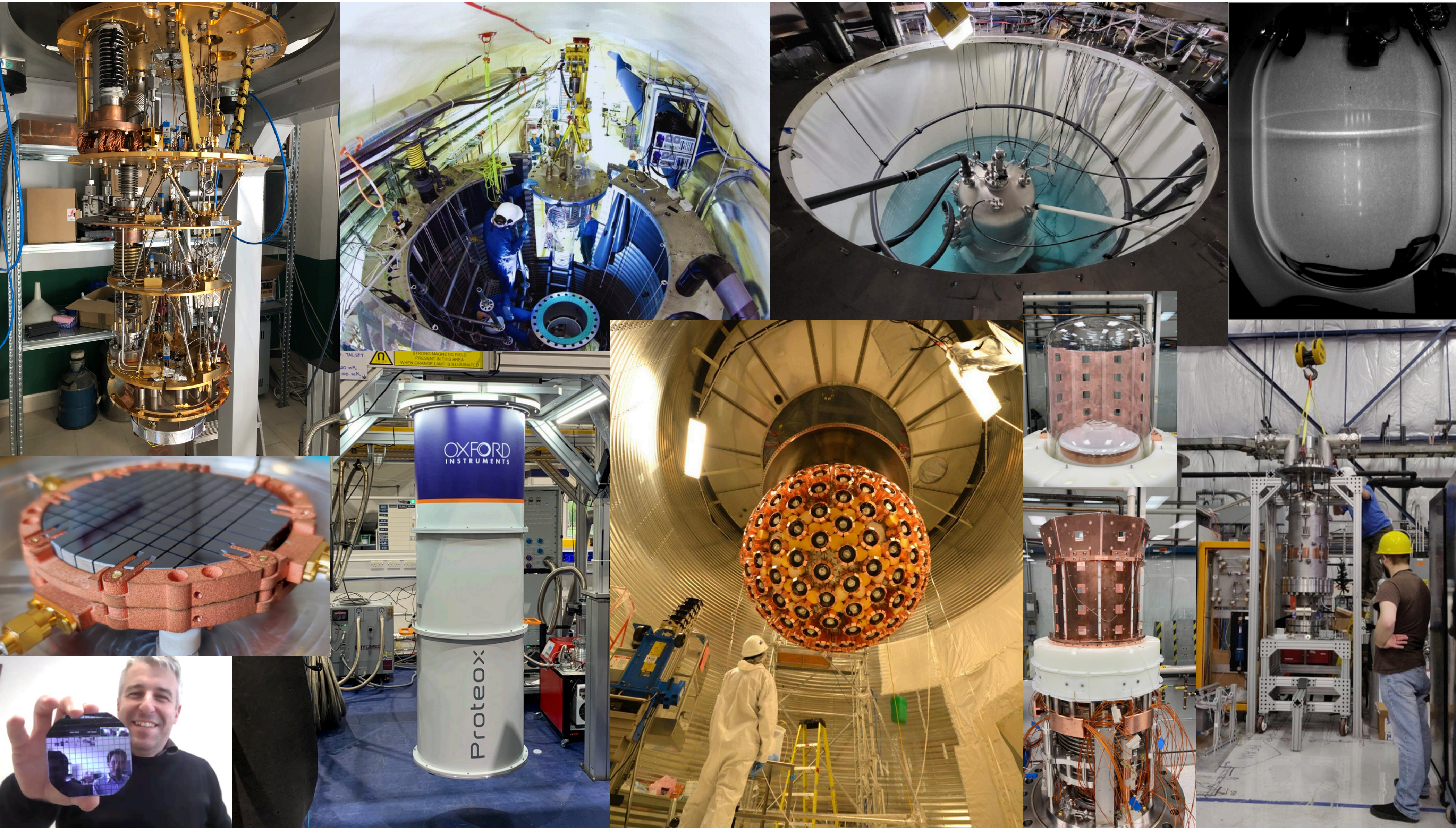
Outline

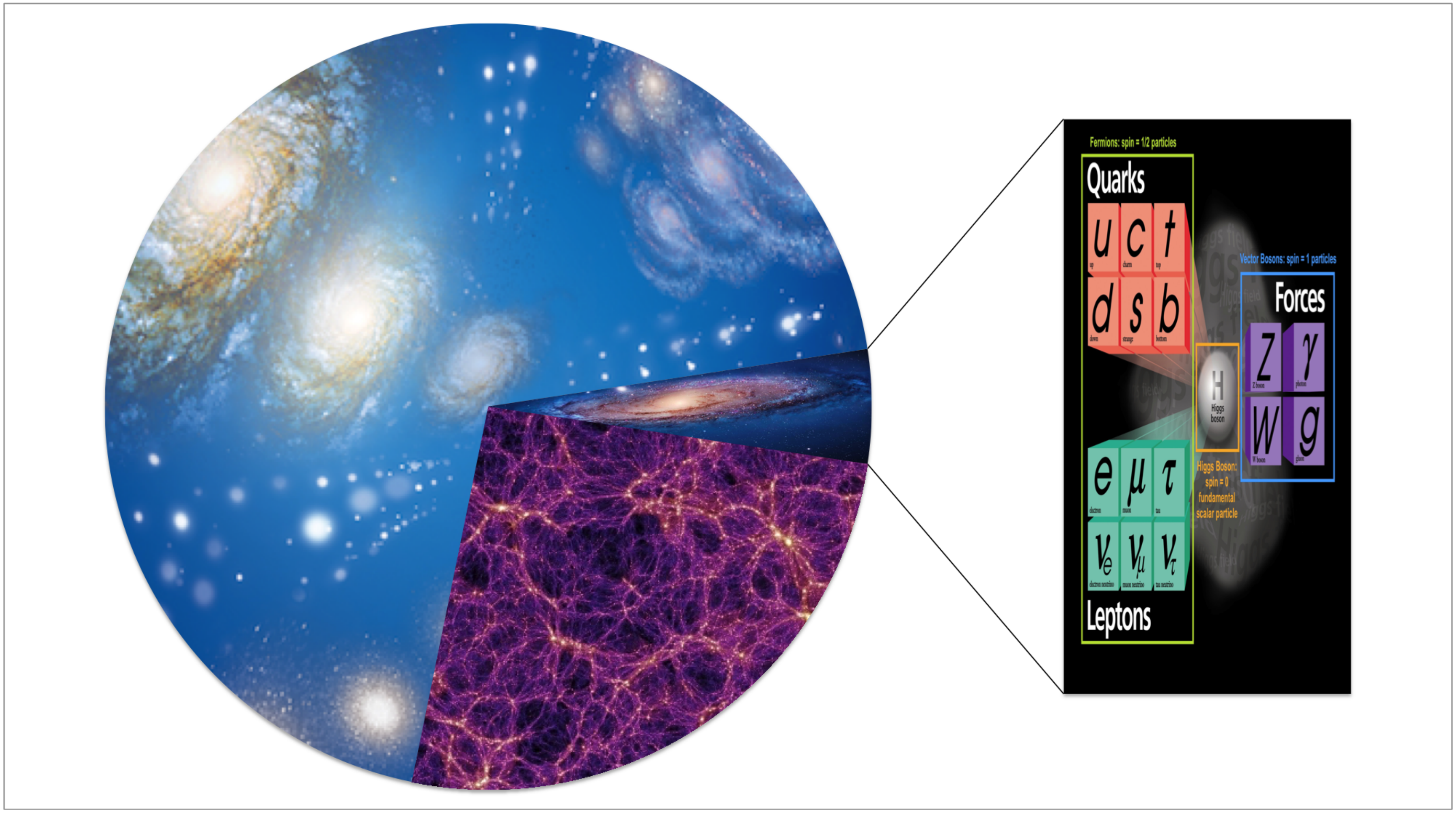
- **Dark Matter: a (very) brief introduction**
- **Neutrino Physics: CEνNS in reactors (even briefer intro)**
- **Dark matter search using Fluorine with PICO**
- **BULLKID: Kinetic Inductance Detectors for dark matter**
- **Searching for dark matter with Argon in DEAP-3600**
- **SBC: A Scintillating Bubble Chamber with Argon for CEνNS and DM**
- **Final remarks**


STRONG MAGNETIC FIELD PRESENT IN THIS AREA WHEN ORANGE LAMP IS ILLUMINATED
OXFORD INSTRUMENTS
Proteox

Dark Matter Direct Detection and Reactor Neutrinos

Pie chart of the Universe

What is the dark matter that makes up about one quarter of the contents of the universe? (85% of the matter in the Universe)

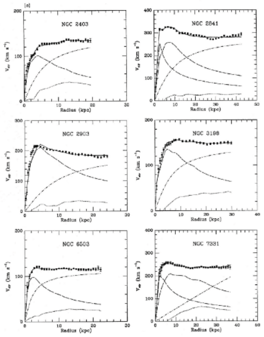


Our Universe today: ΛCDM
from an impressive number of observations

An impressive and overwhelming number of observations on all scales!

Rotation curves of galaxies

Scale $\sim 10^{21-22}$m

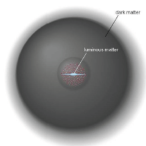


From Newtonian dynamics:

$$F = \frac{mv^2}{r} = G\frac{mM}{r^2}$$
$$v(r) \propto r^{-1/2}$$

For constant v:

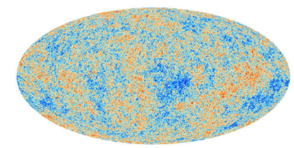
$$M(r) \propto r$$
$$\rho(r) \propto r^{-2}$$



Fritz Zwicky (1933)

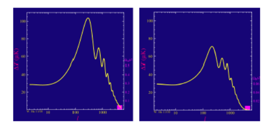
Cosmic Microwave Background

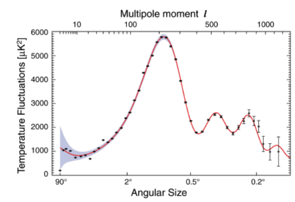
CMB angular power spectrum depends on several parameters, including Ω_b, Ω_c, Ω_Λ



$\Omega_{tot} = 1.080^{+0.093}_{-0.071}$

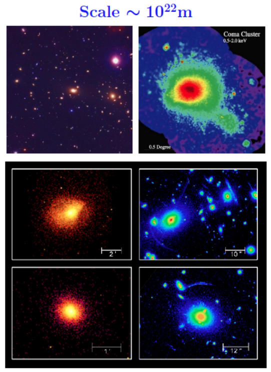
- $\Omega_b = 0.0449 \pm 0.0028$ (0.049)
- $\Omega_c = 0.222 \pm 0.026$ (0.268)
- $\Omega_\Lambda = 0.734 \pm 0.029$ (0.683)





Galaxy clusters: x rays

Scale $\sim 10^{22}$m



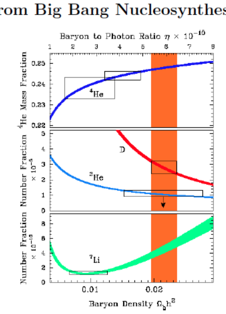
X rays radiated by the intracluster medium (hot gas)

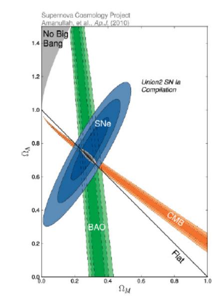
temperature and distribution of gas
↓
average speed of gas molecules
↓
mass

Cluster masses obtained by x-ray measurements agree well with the galactic velocity method

Precision cosmology

Abundance of primordial elements combined with predictions from Big Bang Nucleosynthesis





Λ_{CDM} (Lambda Cold Dark Matter) Standard model of cosmology

Galaxy clusters: gravitational lensing

Scale $\sim 10^{22}$m

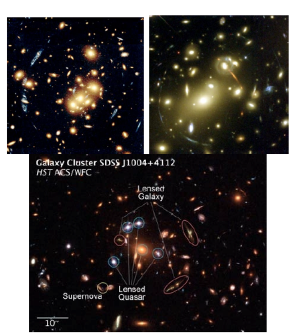
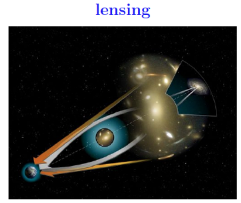


Image distortion by gravitational potential

strong/weak

sensitive to total mass

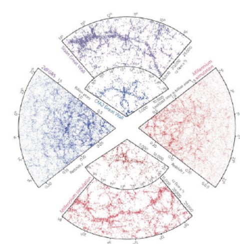
Rotational curves and x-ray measurements agree with gravitational lensing



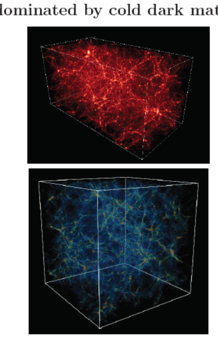
Structure formation

Simulations of structure formation

Structure growth depends on the amount and type of dark matter



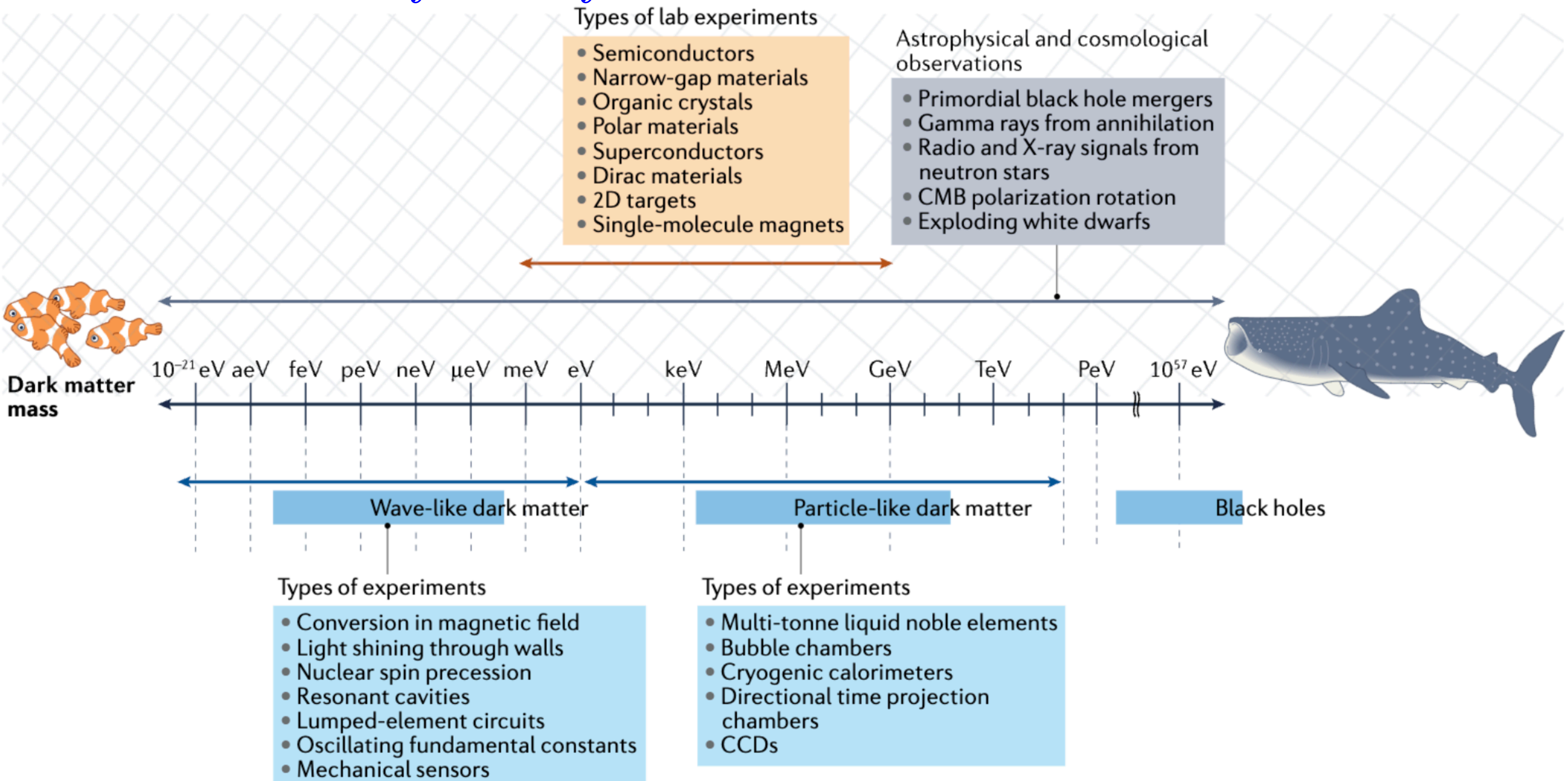
All viable models are dominated by cold dark matter



What do we know about dark matter?

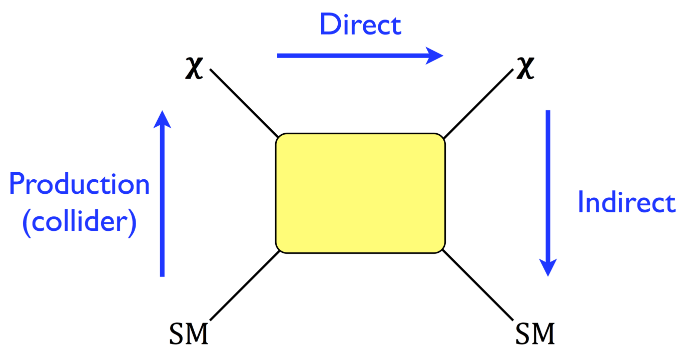
- Gravitationally interacting — Stable or long-lived
- Cold or warm, not hot (relativistic) — Non-baryonic
- Electrically neutral — No Color — Feebly interacting

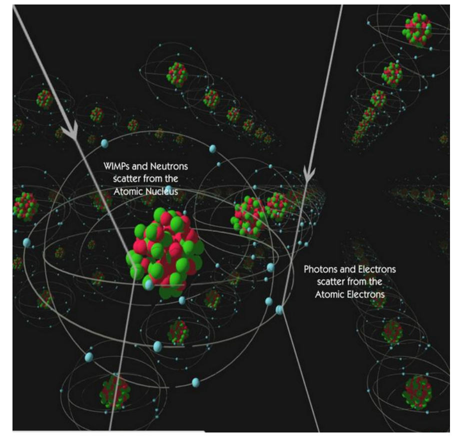
Physics beyond the Standard Model



Direct detection

WIMPs can scatter elastically with nuclei and the recoil can be detected





- **Calculate rate based on assumptions about the dark matter distribution and interaction**
- **Historically two interactions are considered (by DM experimentalists)**
  - **Spin independent (SI) - couples to all nucleons (enhancement for large nuclei)**
  - **Spin dependent (SD) - couples to the spin of the nucleus (unpaired spin of one nucleon)**

Spin-independent   Spin-dependent

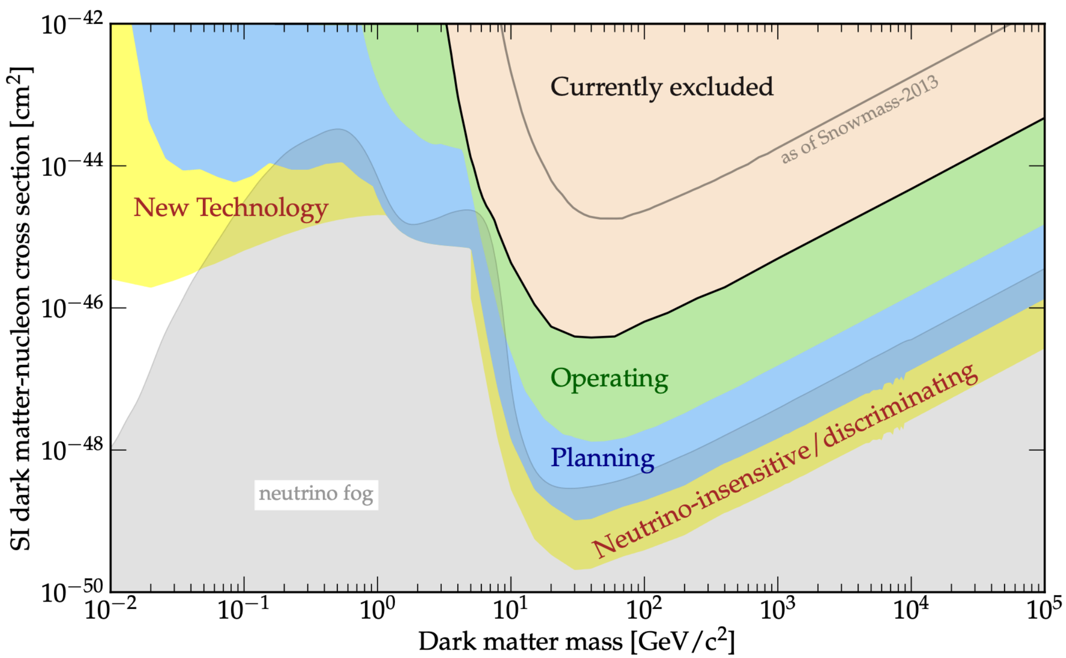
$$\sigma_0 = \frac{4\mu^2}{\pi}\left[f_p N_p + f_n N_n\right]^2 + \frac{32 G_F^2 \mu^2}{\pi}\frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

Rate calculation

The differential cross section (evts/kg/keV mass per unit recoil energy):

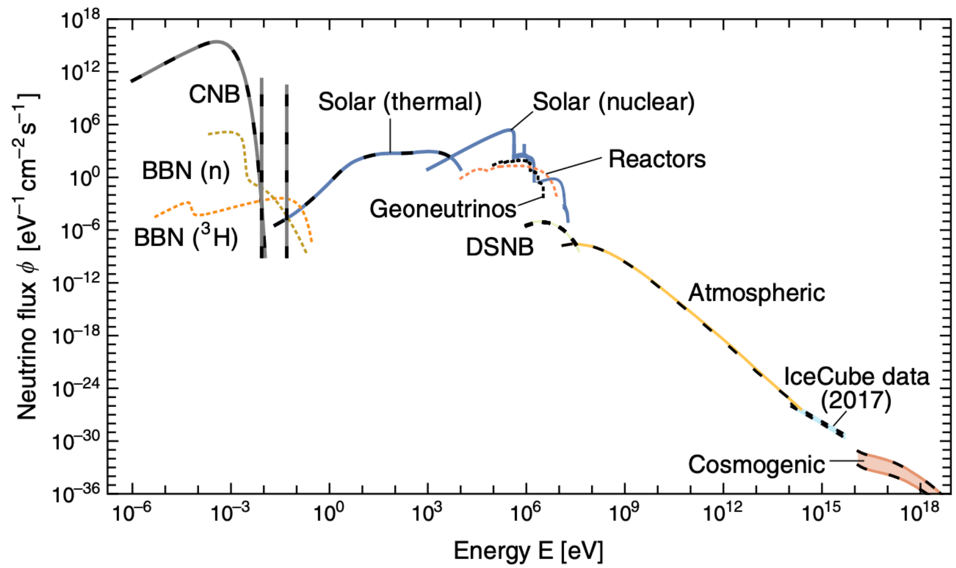
$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv$$

- **Dark matter density component**
- **The unknown particle physics component**
- **The nuclear part**
- **The velocity distribution of dark matter in the galaxy**

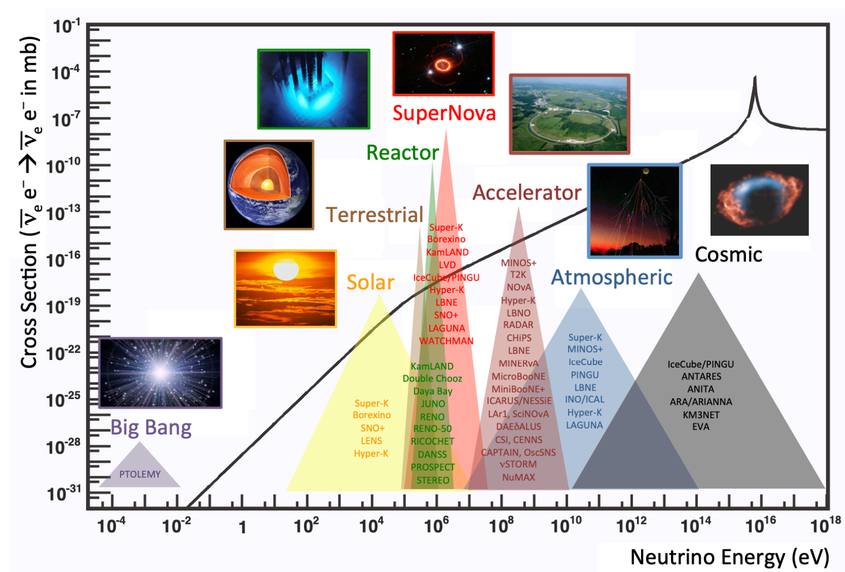


Neutrinos: they are everywhere

Within each person:
Roughly 30 million Big Bang neutrinos
We emit neutrinos:
4000/second from potassium
4000/second from carbon



Passing through each person on earth every second:
One hundred trillion neutrinos from the sun:100,000,000,000,000
The earth receives more than:
40 billions neutrinos / sec $\cdot$ cm^2



What we know and don't know about Neutrinos

What we know:

-Neutrinos have mass

-Squared mass differences

What we don't know:

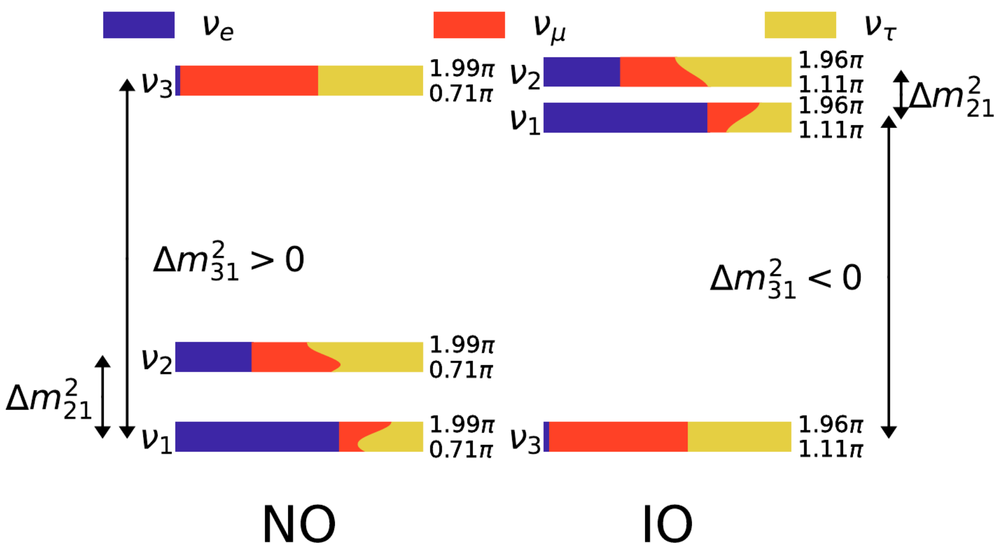
-Absolute mass scale

-Mass hierarchy

-Dirac vs Majorana

-New Physics?

- **Dirac neutrino**
  (ΔL=0, $\nu \neq$ anti ν)
- **Majorana neutrino**
  (ΔL=2, $\nu =$ anti ν)

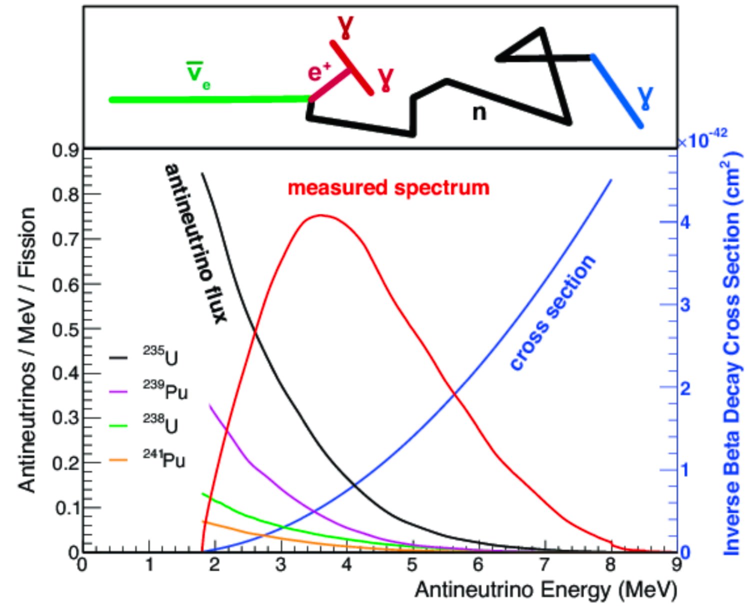


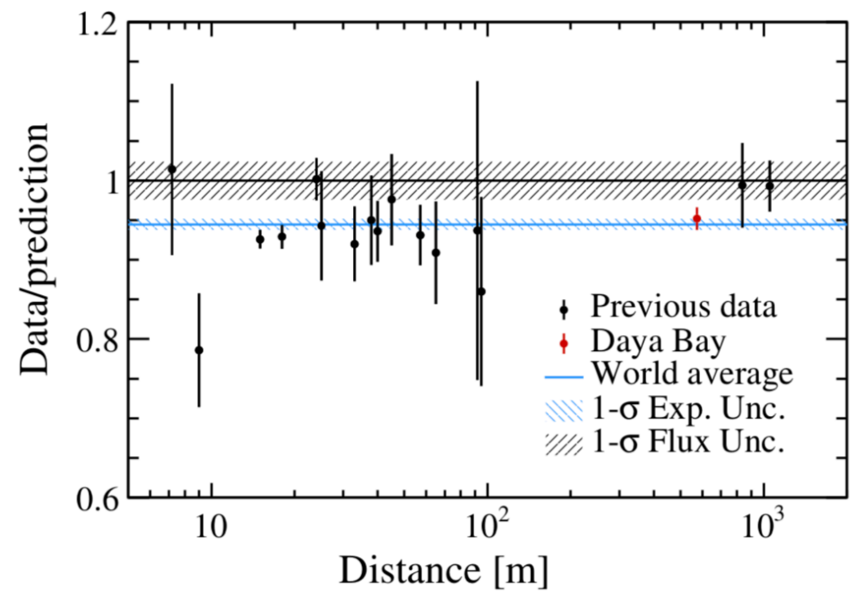
Neutrinos from nuclear reactors

- Beta decays of fission daughters
- Low energy: < 10 MeV
- 6 anti-neutrinos / fission
- 2×10^{20} s^{-1} per GW

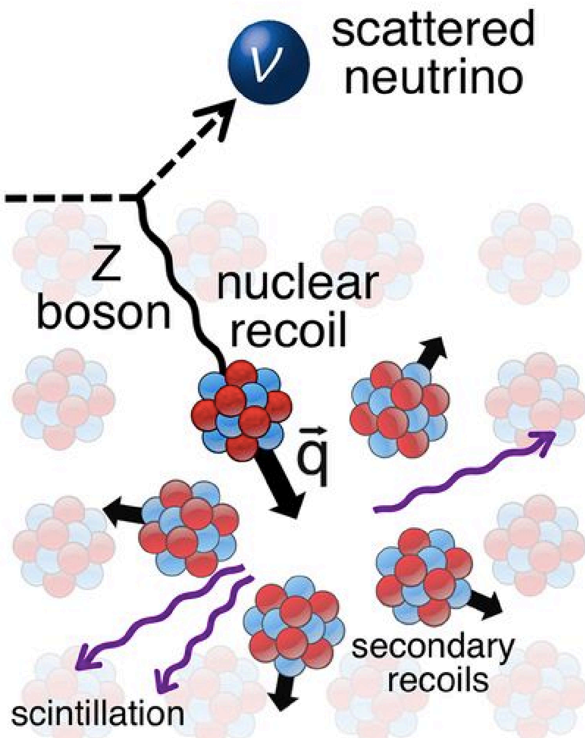
free for physicists

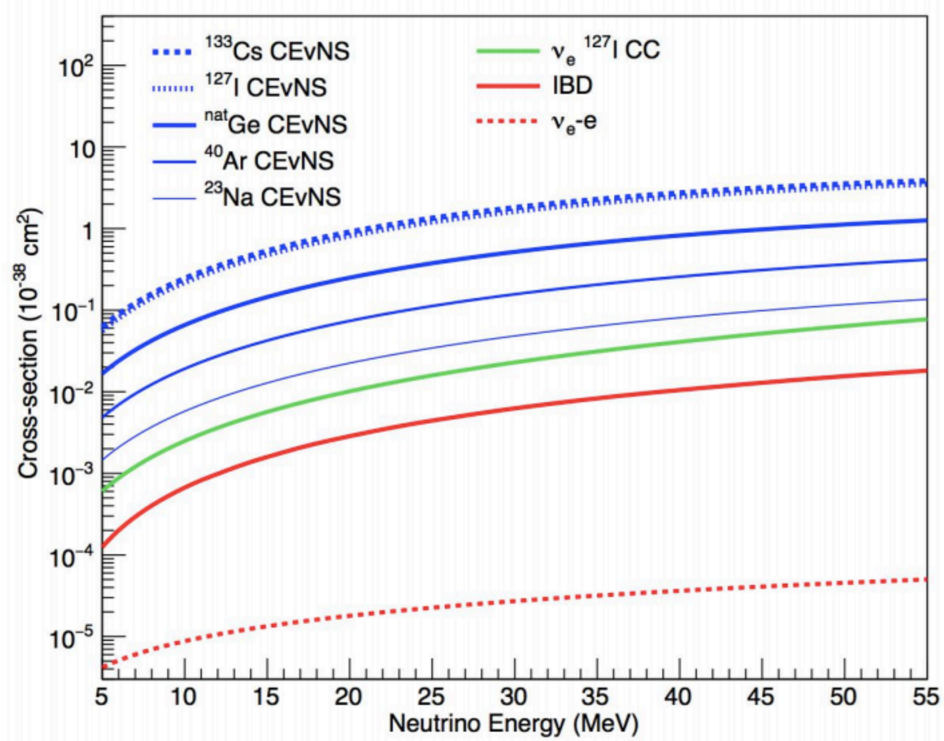
- Commercial reactors (Nuclear Power plants) low-enriched uranium (LEU)
  - Mixture of fissions: 235U (55%), 239Pu (30%), 238U (10%), 241Pu (5%)
  - Large power: 3 GW$_{th}$
- Research reactors highly-enriched uranium (HEU)
  - 235U fission fraction 99%
  - Lower power, few tens of MW$_{th}$
  - compact size





Spallation Neutron Source in Oak Ridge

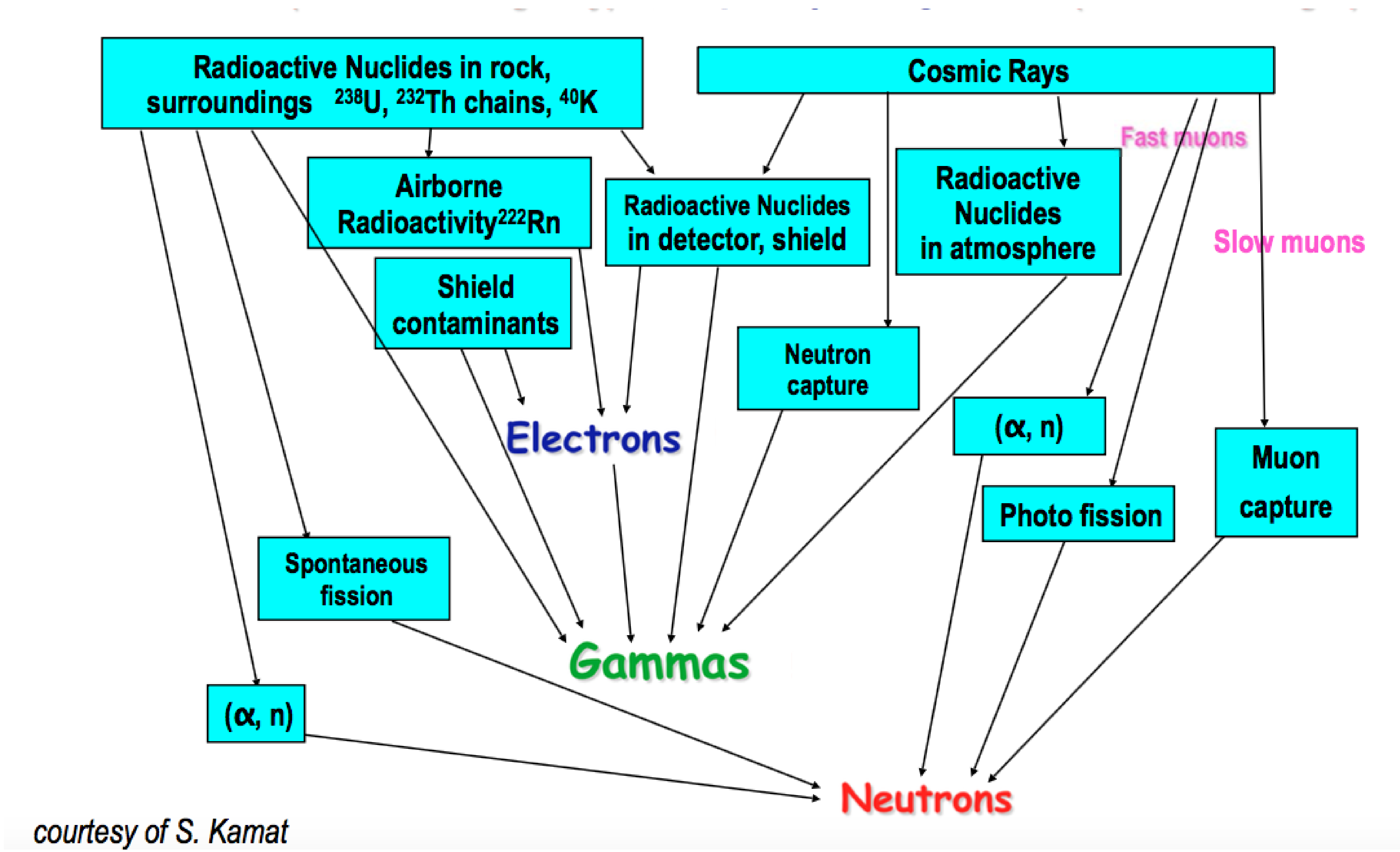




First observation
π-decay-at-rest neutrino source
Science, Sep 15, 2017
DOI: 10.1126/science.aao0990

Backgrounds, Backgrounds and Backgrounds

Cosmic rays and natural radioactivity



Backgrounds in our detectors

- **How much radioactivity (in Bq) is in your body? where from?**
  4000 Bq from 14C, 4000 Bq from 40K (including about 8000 neutrinos)

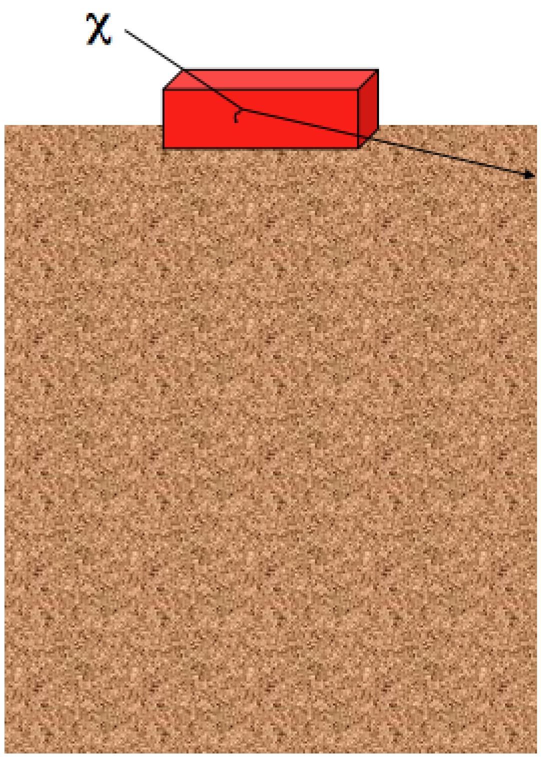
- **What is the most radioactive food we eat?**
  Bananas and coffee (1000 Bq)

- **How many radon atoms escape per m^2 of ground, per second?**
  7000 atoms/m^2/s

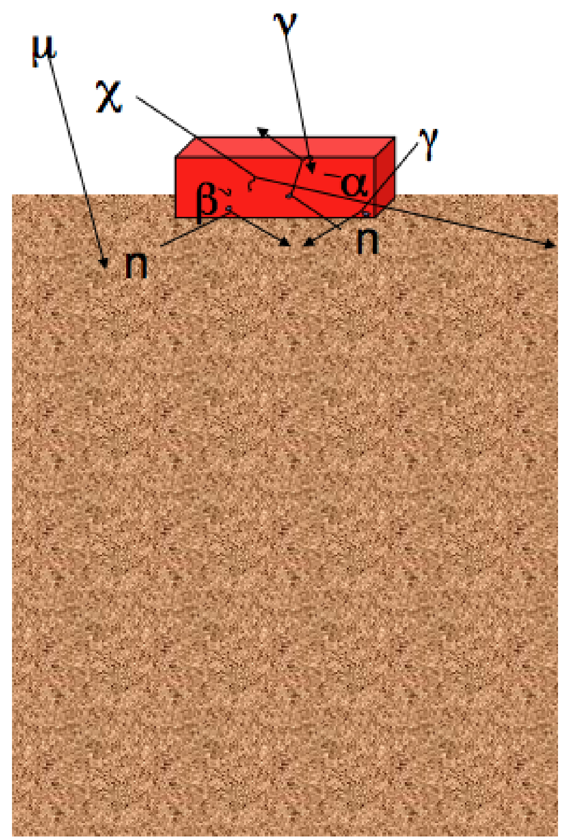
Backgrounds: $> 10^{11-12}$ events/ton/year

How to catch a WIMP

- We live in a Dark Matter halo!
- Look for coherent elastic scattering off nuclei

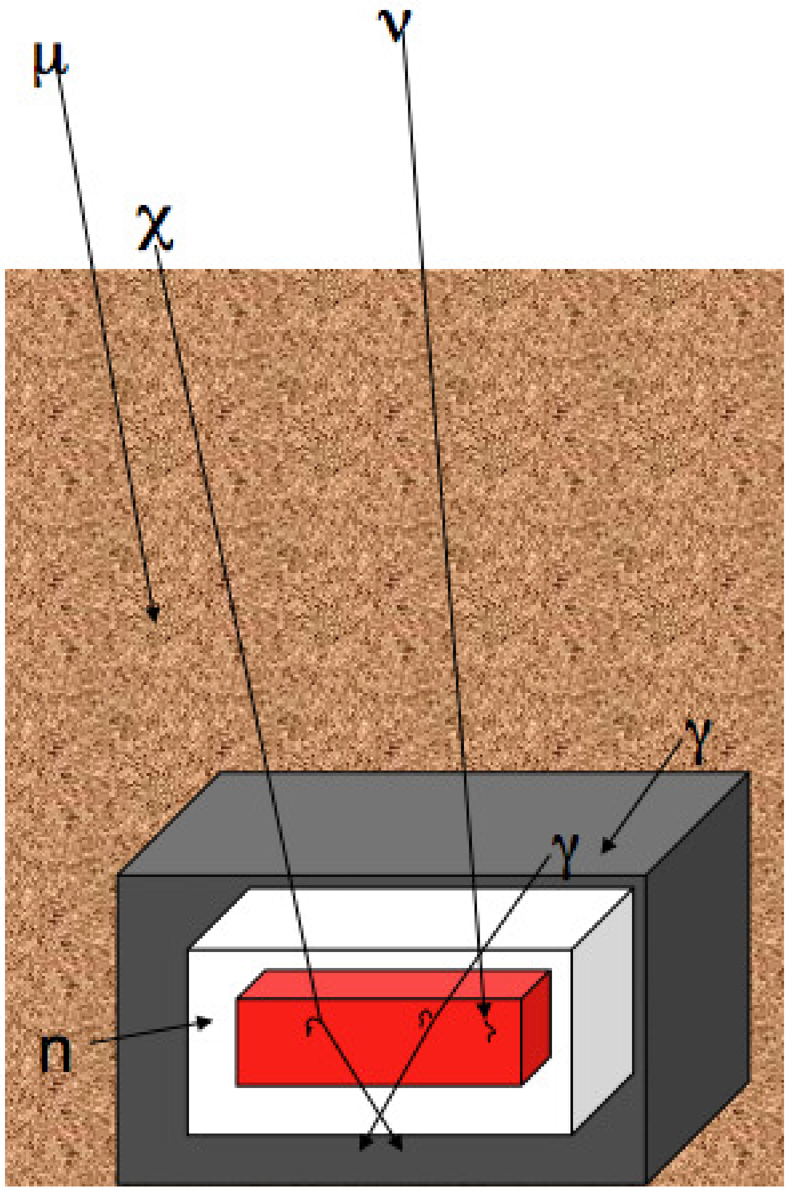


- Neutrons
- Muons
- Gammas, beta decays
- alpha decays
- Neutrinos



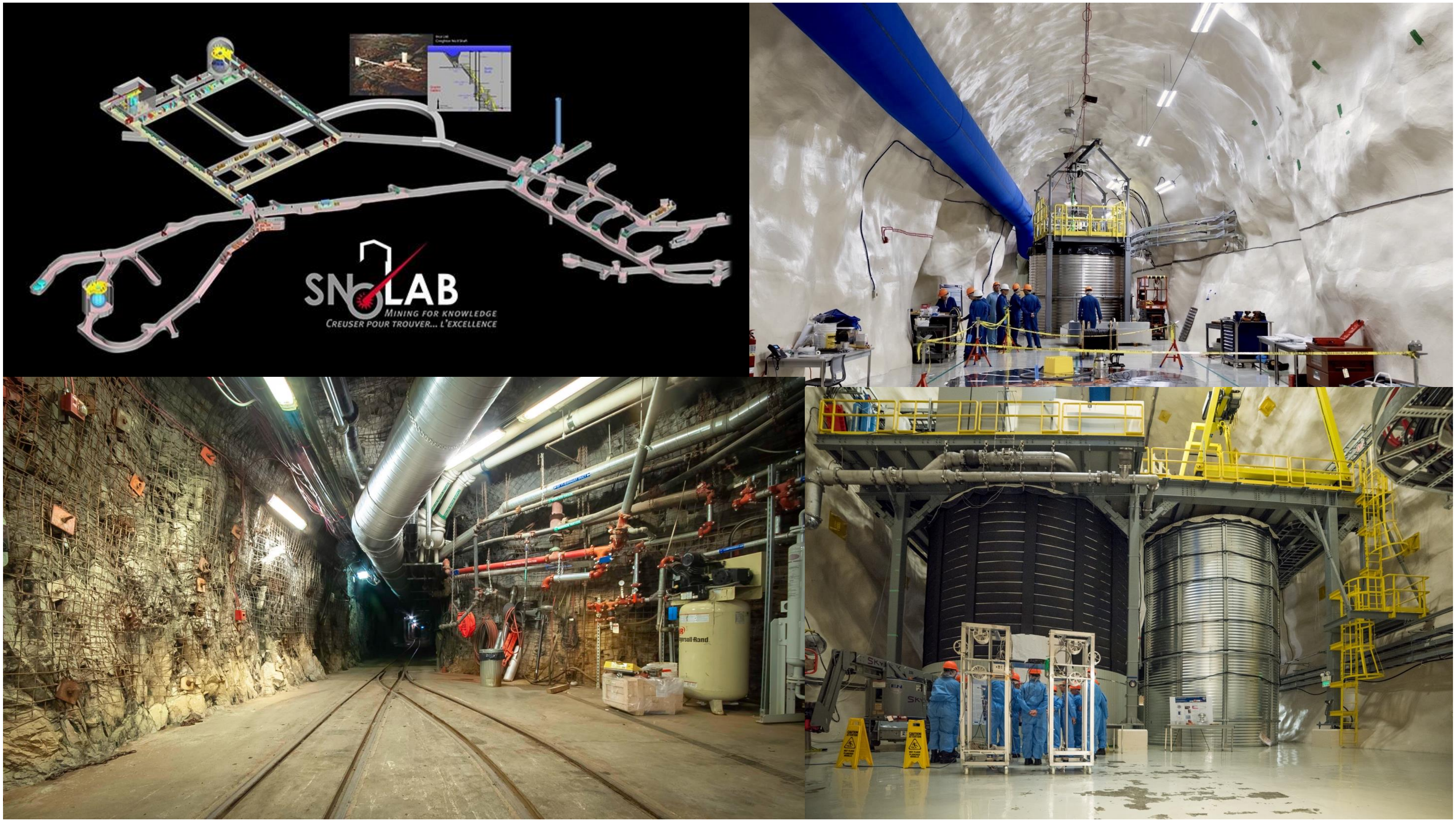
How to catch a WIMP

- **Go underground**
- **Shielding**
- **Material selection**



WIMP scatters:
(<1 event/ton/year)

SNOLAB (Sudbury Neutrino Observatory Laboratory): Canada



Gran Sasso (Laboratorio Nazionale del Gran Sasso): Italia

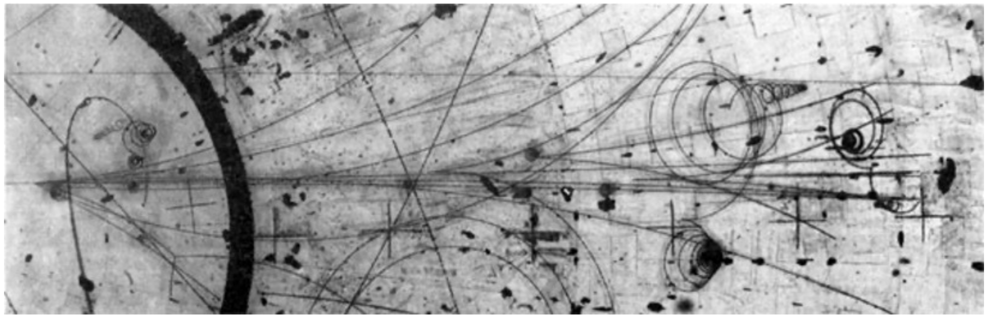
PICO: dark matter searches using bubble chambers

PICO Collaboration

Physics with bubble chambers

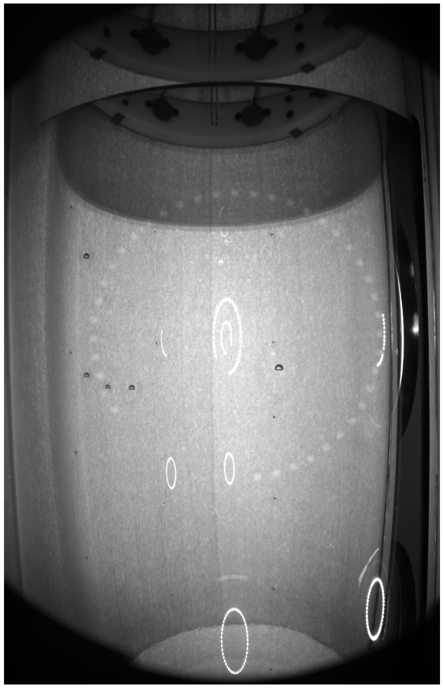
1970s: Neutrino Beam Physics

- Sensitive to MIPs
- Particle tracks visible
- Threshold << 1 keV
- Multi-ton chambers, multiple fluids



2000-today: Nuclear Recoil Detectors

- Dark matter searches with fluorocarbon bubble chambers
- Electron recoil blind
- Nuclear recoil threshold $\sim$ 3keV
- Scalable at modest cost



PICO bubble chambers

- Target material: superheated CF_3I, C_3F_8, C_4F_{10} spin-dependent/independent

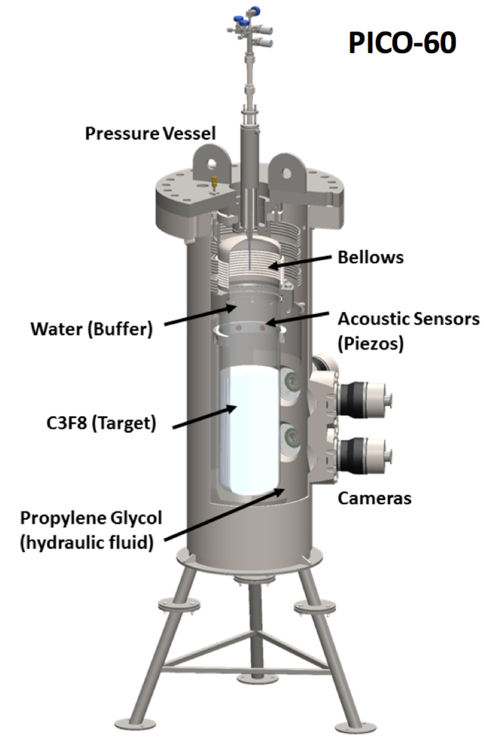
  Could make a dark matter bubble chamber with any liquid!

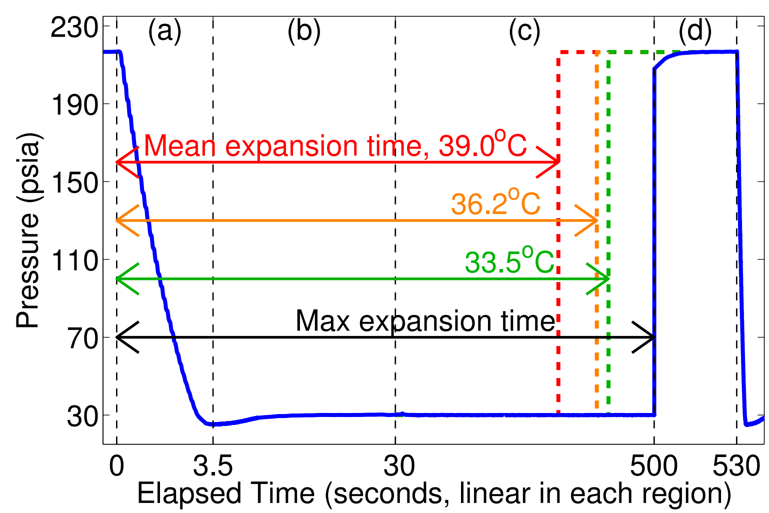
- Particles interacting evaporate a small amount of material: bubble nucleation

- Four Cameras record bubbles

- Eight piezo-electric acoustic sensors detect sound

- Recompression after each event



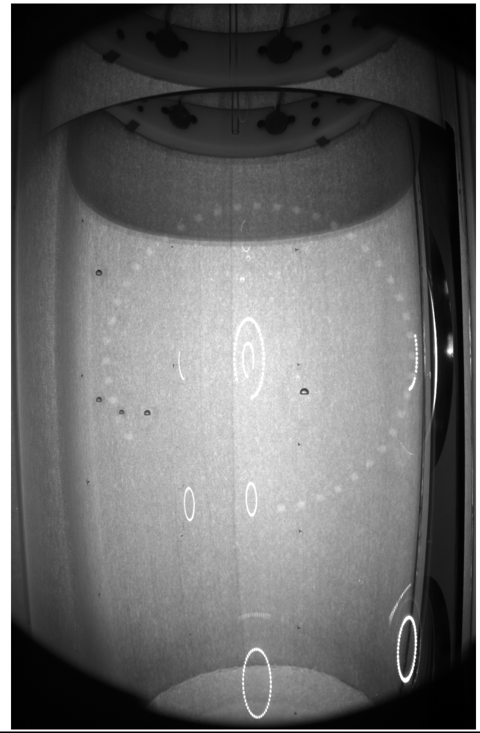


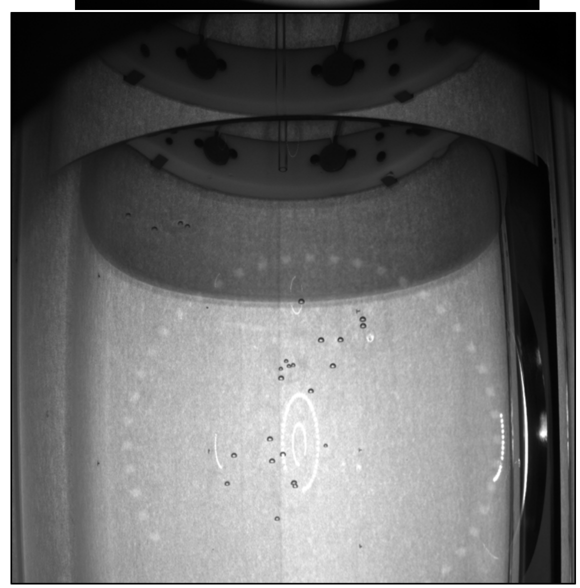
Bubble chambers: signal

- **Alpha decays:**
  Nuclear recoil and
  40 μm alpha track
  1 bubble

- **Neutrons:**
  Nuclear recoils
  mean free path ∼20 cm
  3:1 multiple-single ratio
  in PICO-60

- **Neutrinos or WIMPs:**
  Nuclear recoil
  mean free path $> 10^{10}$ cm
  1 bubble



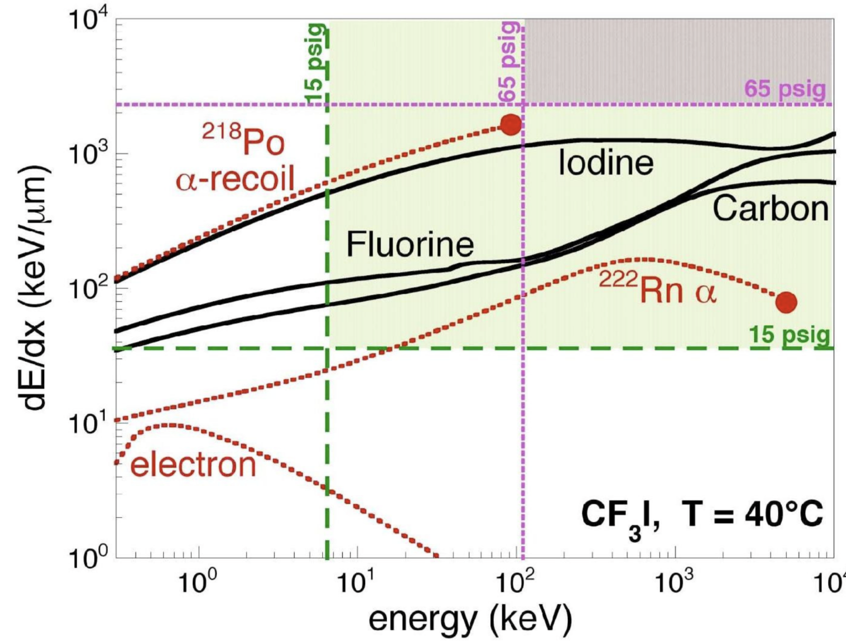


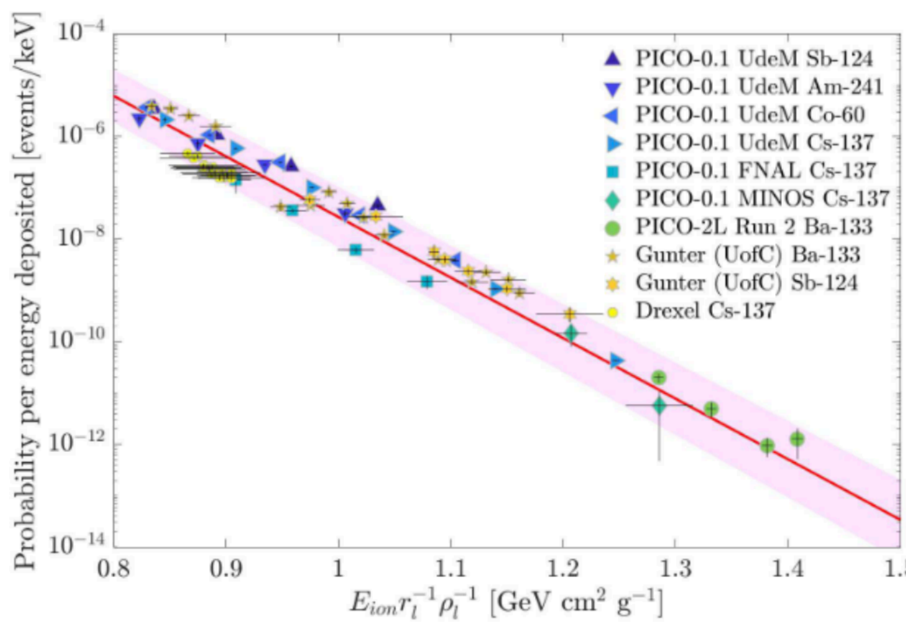
Bubble nucleation

Dependence of bubble nucleation on the total deposited energy and dE/dx

- Region of bubble nucleation at 15 psig
- Backgrounds: electrons, ^{218}Po, ^{222}Rn
- Signal processes of Iodine, Fluorine and Carbon nuclear recoils

insensitive to electrons and gammas



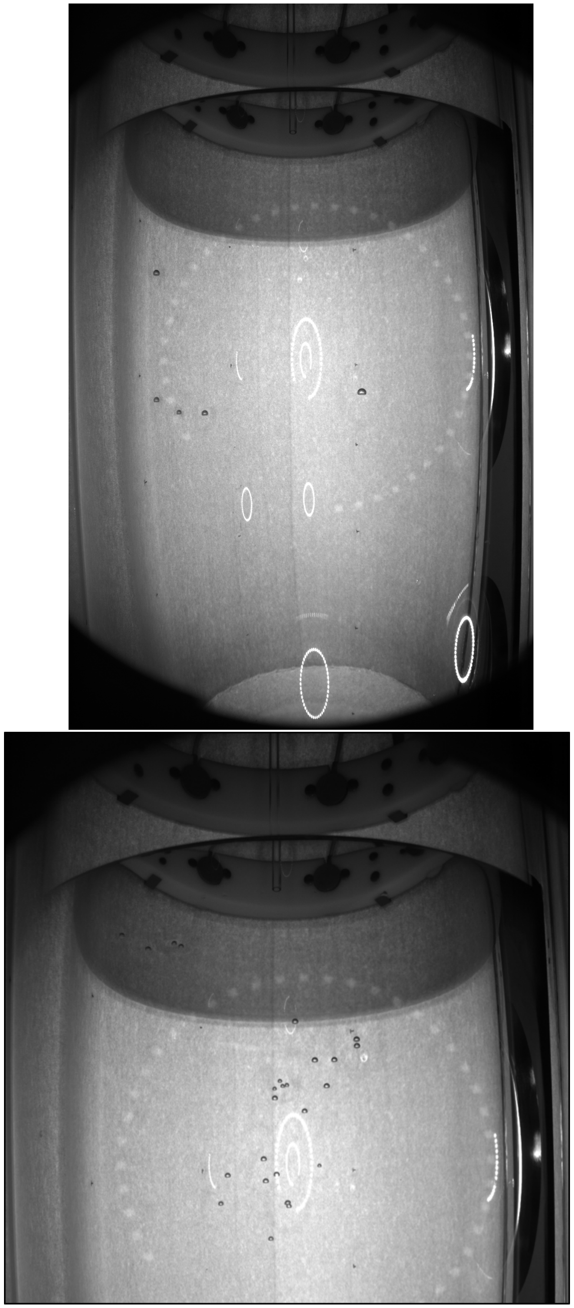


Bubble chambers: signal

- **Alpha decays:**
  Nuclear recoil and
  40 μm alpha track
  1 bubble

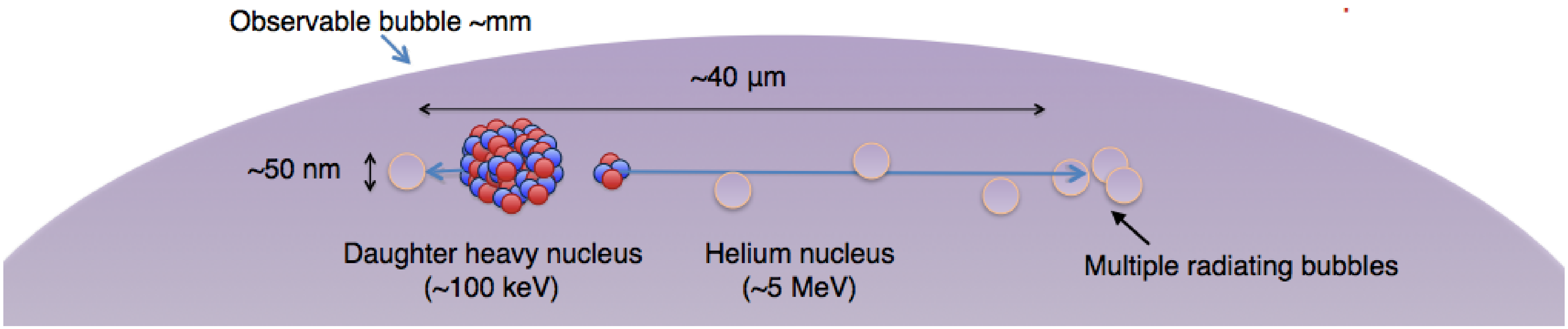
- **Neutrons:**
  Nuclear recoils
  mean free path $\sim$20 cm
  3:1 multiple-single ratio
  in PICO-60

- **Neutrinos or WIMPs:**
  Nuclear recoil
  mean free path $> 10^{10}$ cm
  1 bubble

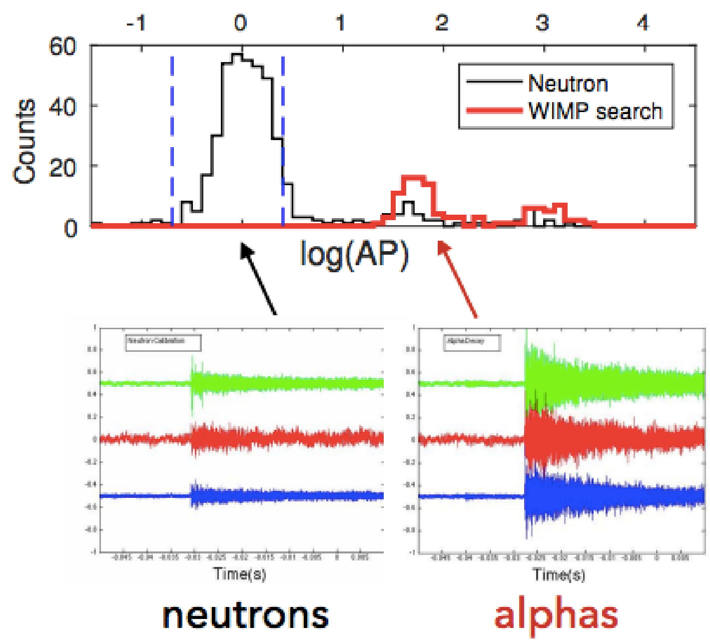


Bubble chambers: Acoustics

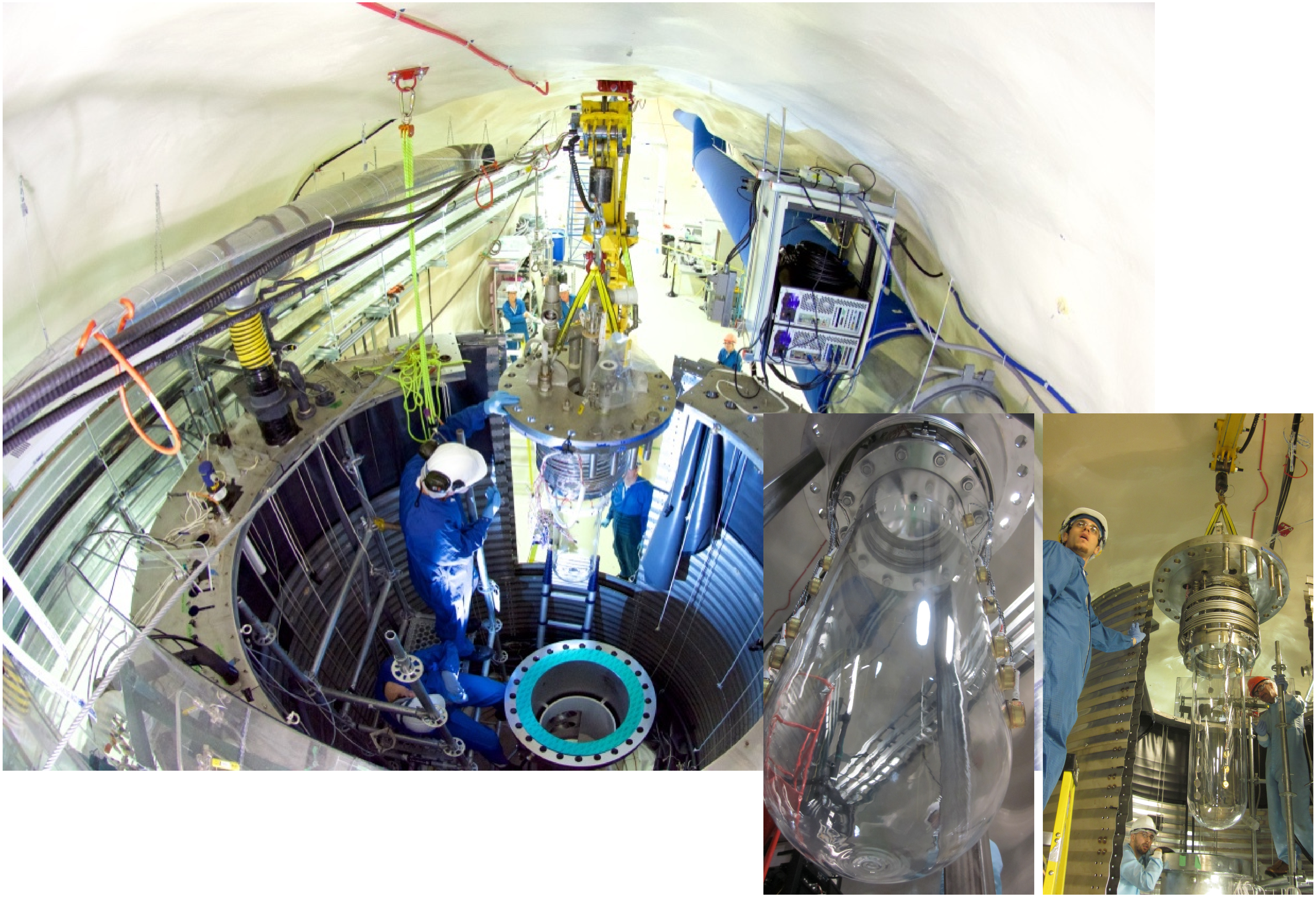
- Alphas are ~ 4 times louder than nuclear recoil bubbles



- $> 99.4\%$ discrimination against alpha events demonstrated
- Discovered by the PICASSO collaboration



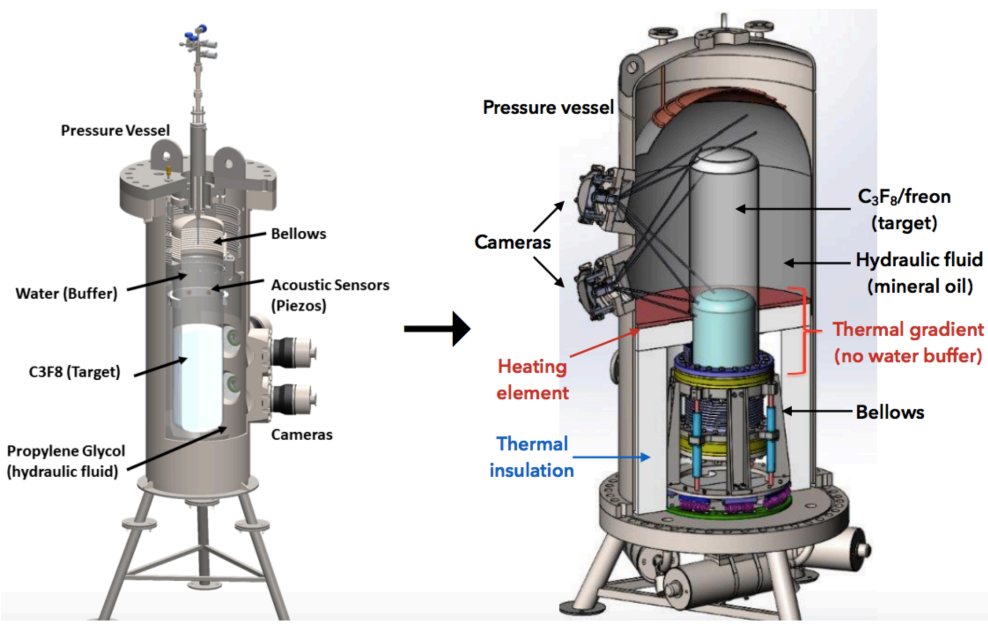
COUPP60 and PICO-60

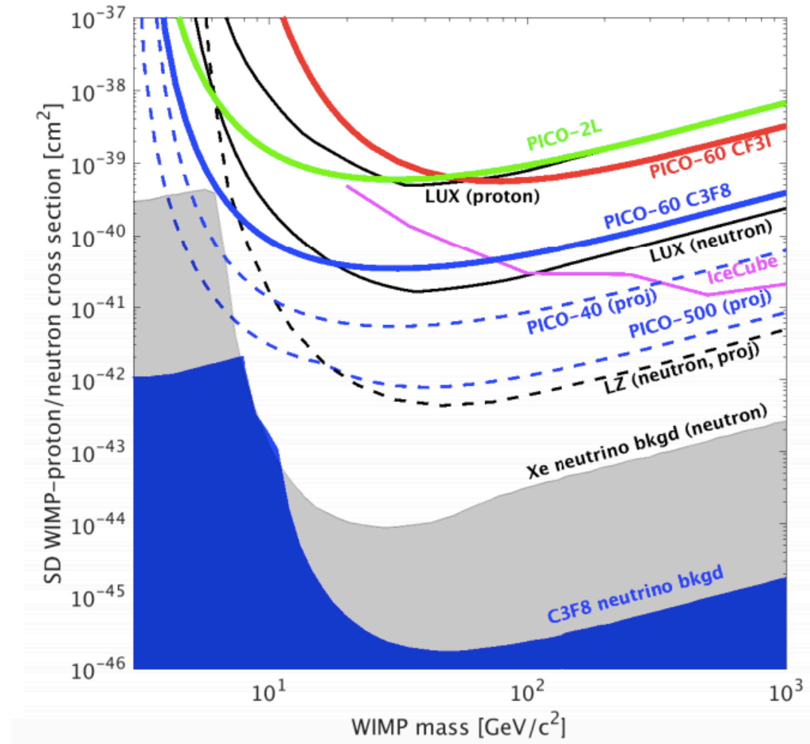


COUPP60 and PICO-60

PICO-40L:"Right side up" (RSU)

- Engineering:
  demonstrate background reduction and technology improvements for PICO-500
  - Focus on (neutron) background reduction
  - Confirm "RSU" design used in prototype chambers

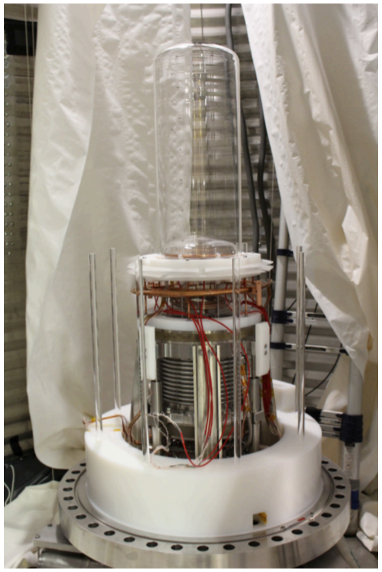


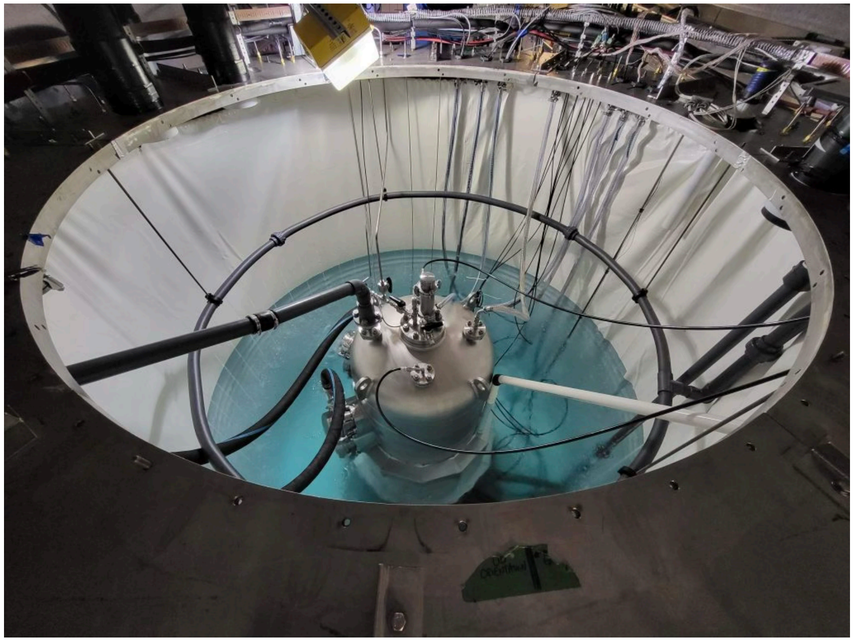


- Science:
  acquire one-year background-free exposure
  - Order of magnitude improvement on PICO-60 limits

PICO-40L and PICO-500

Commissioning and data taking





PICO-500 coming soon

NREFT approach in PICO

- In the NREFT, the differential cross section is presented as the product of the WIMP response function and the Nuclear response function.

- In NREFT, the nucleus is not treated as a point particle, but its composite nature is reflected

$$\frac{d\sigma_T(v, E_r)}{dE_r} = \frac{2m_T}{4\pi v^2}\left[\frac{1}{(2j_\chi+1)}\frac{1}{(2J+1)}|\mathcal{M}_T|^2\right]$$

probability of dispersion

$$\frac{1}{(2j_\chi+1)}\frac{1}{(2J+1)}\sum_{spins}|\mathcal{M}_T|^2 \equiv \sum_k \sum_{\tau=0,1}\sum_{\tau'=0,1} R_k\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}, \{c_i^\tau c_j^{\tau'}\}\right) W_k^{\tau\tau'}(\vec{q}^2 b^2)$$

$$k = M, \Sigma'', \Sigma', \Phi'', \Phi''M, \Delta, \Delta\Sigma'$$

- With this theory, 6 new nuclear response functions have been identified in addition to the classical SI/SD

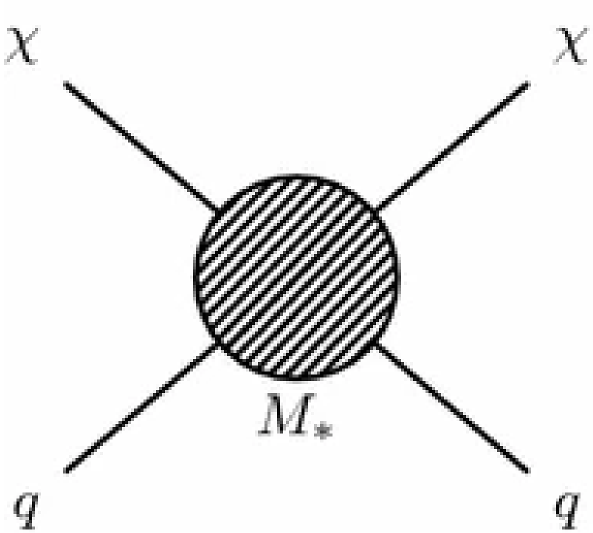
Particle physics: WIMP response functions

Nuclear physics: Nuclear response functions

- In this theory we have 11 operatos

$$\mathcal{L}_{\rm int} = \sum_{N=n,p}\sum_i c_i^{(N)}\mathcal{O}_i\chi^+\chi^-N^+N^-$$

NREFT operators



$$i\vec{q}, \qquad \vec{v}^{\perp} \equiv \vec{v} + \frac{\vec{q}}{2\mu_N}, \qquad \vec{S}_{\chi}, \qquad \vec{S}_N,$$

$\mathcal{O}_1 = \mathbb{1}_X \mathbb{1}_N$	$\mathcal{O}_{11} = i\boldsymbol{S}_X \cdot \frac{\boldsymbol{q}}{m_N} \mathbb{1}_N$
$\mathcal{O}_3 = i\boldsymbol{S}_N \cdot \left(\frac{\boldsymbol{q}}{m_N} \times \boldsymbol{v}^{\perp}\right) \mathbb{1}_X$	$\mathcal{O}_{12} = \boldsymbol{S}_X \cdot \left(\boldsymbol{S}_N \times \boldsymbol{v}^{\perp}\right)$
$\mathcal{O}_4 = \boldsymbol{S}_X \cdot \boldsymbol{S}_N$	$\mathcal{O}_{13} = i\left(\boldsymbol{S}_X \cdot \boldsymbol{v}^{\perp}\right)\left(\boldsymbol{S}_N \cdot \frac{\boldsymbol{q}}{m_N}\right)$
$\mathcal{O}_5 = i\boldsymbol{S}_X \cdot \left(\frac{\boldsymbol{q}}{m_N} \times \boldsymbol{v}^{\perp}\right) \mathbb{1}_N$	$\mathcal{O}_{14} = i\left(\boldsymbol{S}_X \cdot \frac{\boldsymbol{q}}{m_N}\right)\left(\boldsymbol{S}_N \cdot \boldsymbol{v}^{\perp}\right)$
$\mathcal{O}_6 = \left(\boldsymbol{S}_X \cdot \frac{\boldsymbol{q}}{m_N}\right)\left(\boldsymbol{S}_N \cdot \frac{\boldsymbol{q}}{m_N}\right)$	$\mathcal{O}_{15} = -\left(\boldsymbol{S}_X \cdot \frac{\boldsymbol{q}}{m_N}\right)\left[\left(\boldsymbol{S}_N \times \boldsymbol{v}^{\perp}\right) \cdot \frac{\boldsymbol{q}}{m_N}\right]$
$\mathcal{O}_7 = \boldsymbol{S}_N \cdot \boldsymbol{v}^{\perp} \mathbb{1}_X$	$\mathcal{O}_{17} = i\frac{\boldsymbol{q}}{m_N} \cdot \boldsymbol{\mathcal{S}} \cdot \boldsymbol{v}^{\perp} \mathbb{1}_N$
$\mathcal{O}_8 = \boldsymbol{S}_X \cdot \boldsymbol{v}^{\perp} \mathbb{1}_N$	$\mathcal{O}_{18} = i\frac{\boldsymbol{q}}{m_N} \cdot \boldsymbol{\mathcal{S}} \cdot \boldsymbol{S}_N$
$\mathcal{O}_9 = i\boldsymbol{S}_X \cdot \left(\boldsymbol{S}_N \times \frac{\boldsymbol{q}}{m_N}\right)$	$\mathcal{O}_{19} = \frac{\boldsymbol{q}}{m_N} \cdot \boldsymbol{\mathcal{S}} \cdot \frac{\boldsymbol{q}}{m_N}$
$\mathcal{O}_{10} = i\boldsymbol{S}_N \cdot \frac{\boldsymbol{q}}{m_N} \mathbb{1}_X$	$\mathcal{O}_{20} = \left(\boldsymbol{S}_N \times \frac{\boldsymbol{q}}{m_N}\right) \cdot \boldsymbol{\mathcal{S}} \cdot \frac{\boldsymbol{q}}{m_N}$

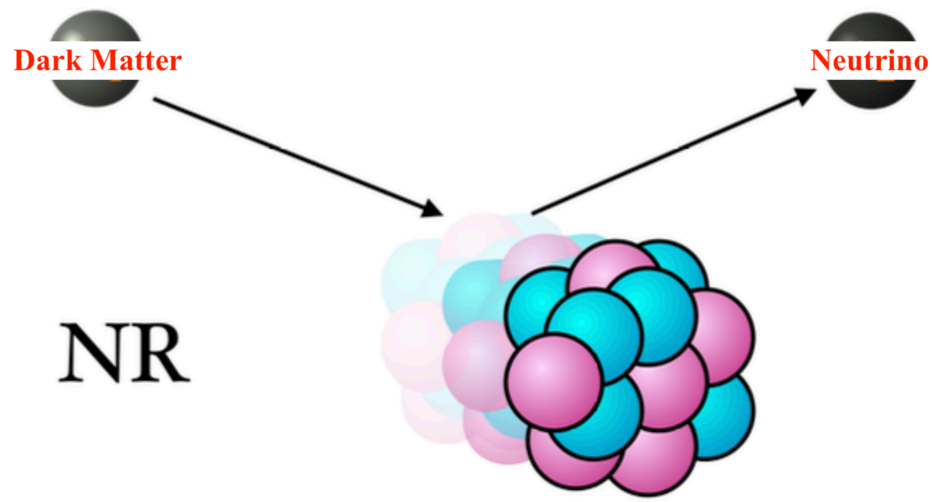
Absorption of fermionic dark matter

Study of fermionic dark matter absorption via $\chi + \mathrm{N} \rightarrow \nu + \mathrm{N}$ (neutral current interactions).

$$q = \frac{m_N m_\chi + \frac{m_\chi^2}{2}}{m_N + m_\chi},$$

- **Absorption converts fermionic DM into a relativistic neutrino-like, mediated by neutral currents leaving a nuclear recoil.**

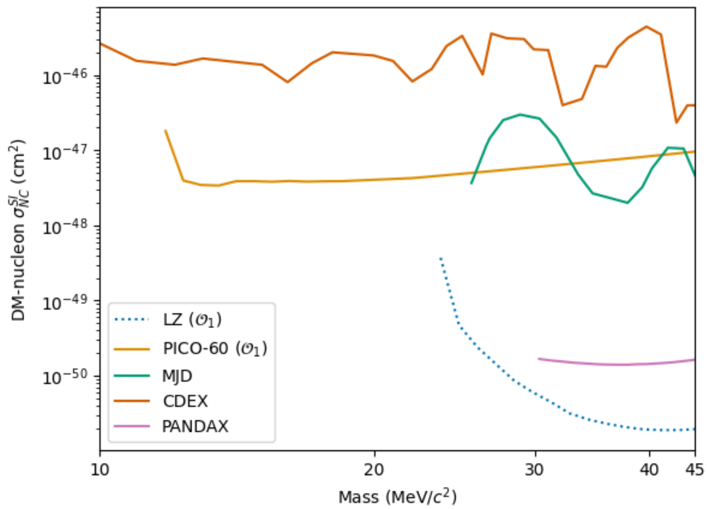
- **Low-mass DM (∼MeV) producing nuclear recoils with fixed energy.**

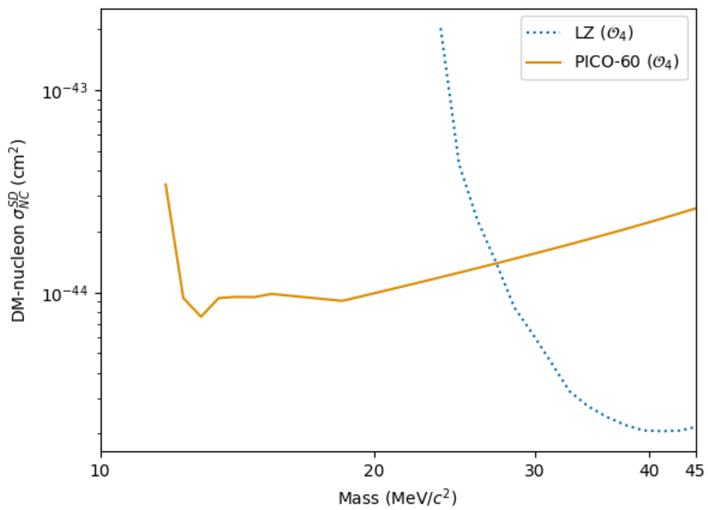


$$\mathcal{L}_{\text{int}} \propto \frac{1}{\Lambda^2} (\overline{\chi}\, \Gamma_i\, \nu)(\overline{N}\, \Gamma_j\, N)\,,$$

(https://doi.org/10.1103/PhysRevLett.124.181301)

Absorption of fermionic DM in PICO



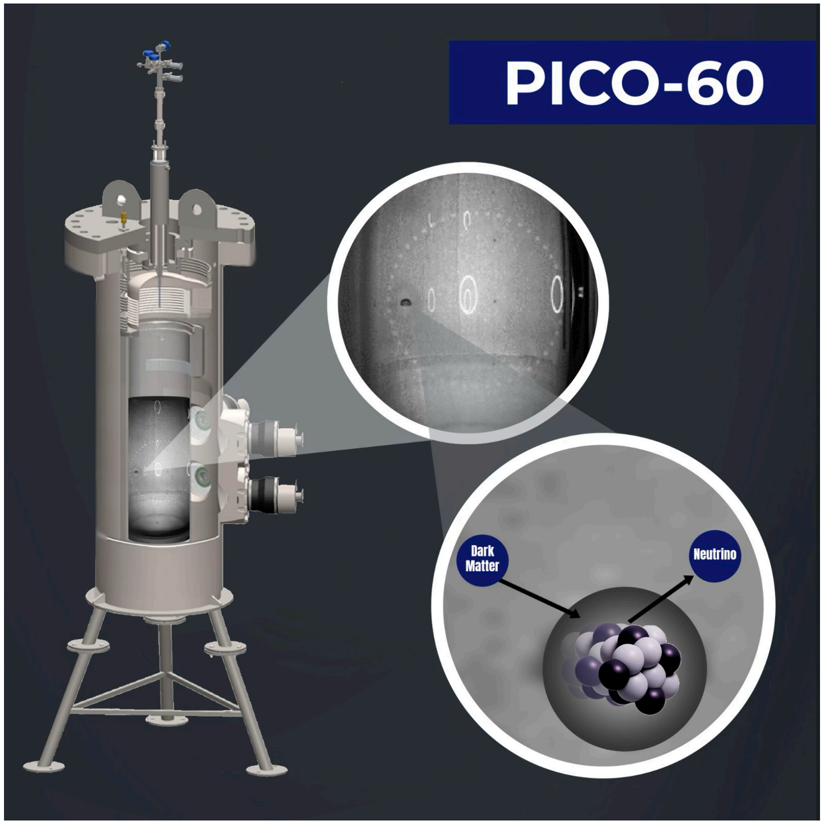


Leading constraints on absorption for DM masses below 23 MeV/c^2

Absorption of Fermionic Dark Matter in the PICO-60 C_3F_8 Bubble Chamber

Phys. Rev. Lett. 135, 011001 (2025)

Editor's suggestion



Anapole moment

- The anapole moment is the lowest electromagnetic moment allowed for a Majorana particle

$$\mathcal{L}_{\mathcal{A}} = c_{\mathcal{A}} \bar{\chi} \gamma^{\mu} \chi \partial^{\nu} F_{\mu\nu} \qquad \mathcal{O}_{\mathcal{A}} \to c_{\mathcal{A}} \sum_{N=n,p} (Q_N \mathcal{O}_8 + g_N \mathcal{O}_9)$$

$c_{\mathcal{A}}$: anapole coupling constant $[GeV^{-2}]$

Q_N: is the nucleon charge ($Q_p = 1,\ Q_n = 0$)

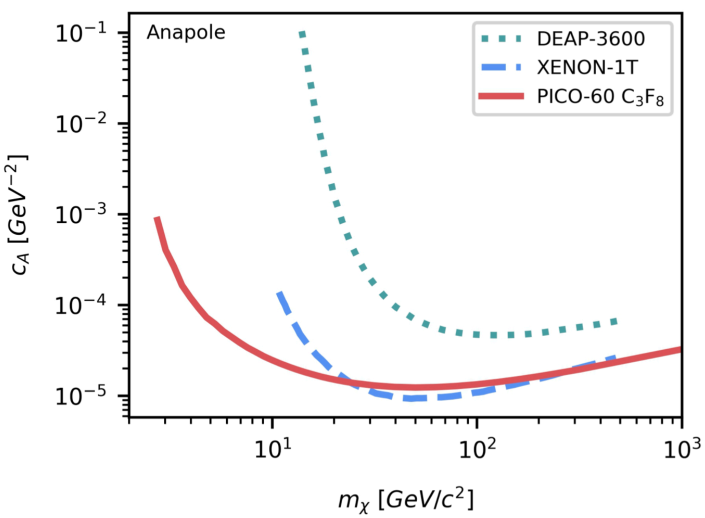
g_N: is the nucleon g-factor ($g_p = 5.59,\ g_n =- 3.83$)

$\mathcal{O}_8 = \vec{S}_{\chi} \bullet \vec{v}^{\perp}$ momentum independent

$\mathcal{O}_9 = i\vec{S}_{\chi} \bullet (\vec{S}_N \times \frac{\vec{q}}{m_N})$ momentum dependent

$$\sigma_{\mathcal{A}} = \frac{c^2{}_{\mathcal{A}} \mu^2{}_N}{\pi}$$

The only possible electromagnetic moment for a Majorana fermion is the anapole moment since the magnetic and electric dipole moments vanish



limits using the PICO-60 data were studied

Electric and magnetic moments

- Long-range interactions ($|\vec{q}| \gg m_\phi$), where m_ϕ is the mass of the mediator, are enhanced at small momentum transfer
- Examples of long-range interactions are DM with magnetic/electric dipole moments and millicharged DM

$$\mathcal{L}_{\mathcal{MD}} = \frac{\mu_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} \qquad \mathcal{O}_{\mathcal{MD}} = 2e\mu_\chi \sum_{N=n,p}\left[Q_N m_N \mathcal{O}_1 + 4Q_N \frac{m_\chi m_N}{q^2}\mathcal{O}_5 + 2g_N m_\chi \left(\mathcal{O}_4 - \frac{1}{q^2}\mathcal{O}_6\right)\right]$$

$$\mathcal{L}_{\mathcal{ED}} = \frac{d_\chi}{2} i\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu} \qquad \mathcal{O}_{\mathcal{ED}} = 2ed_\chi \frac{1}{q^2}\mathcal{O}_{11}$$

μ_χ: is the magnetic moment coupling in units of μ_B

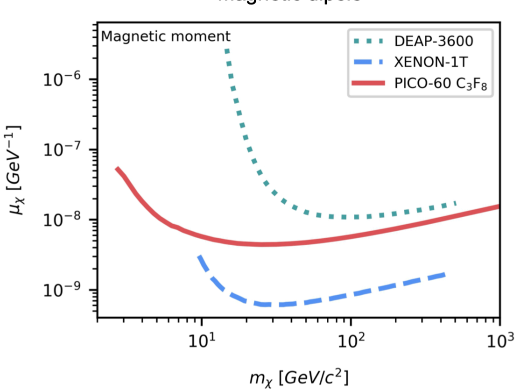
$$\sigma_{\mathcal{MD}(\mathcal{ED})} = \frac{\mu^2{}_\chi}{\pi}$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N \qquad \mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$

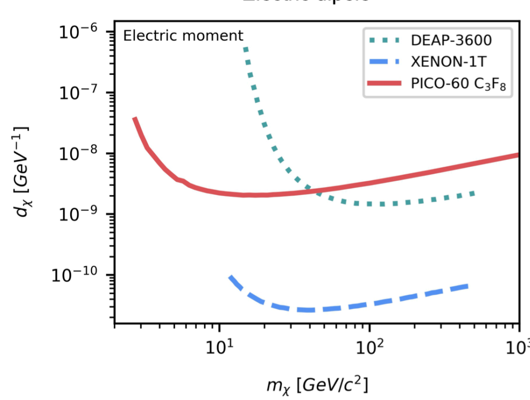
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \qquad \mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

Assuming DM is a fermion with electromagnetic moments, the lowest order electromagnetic interaction is through the magnetic or electric dipole moments

Magnetic dipole



Electric dipole



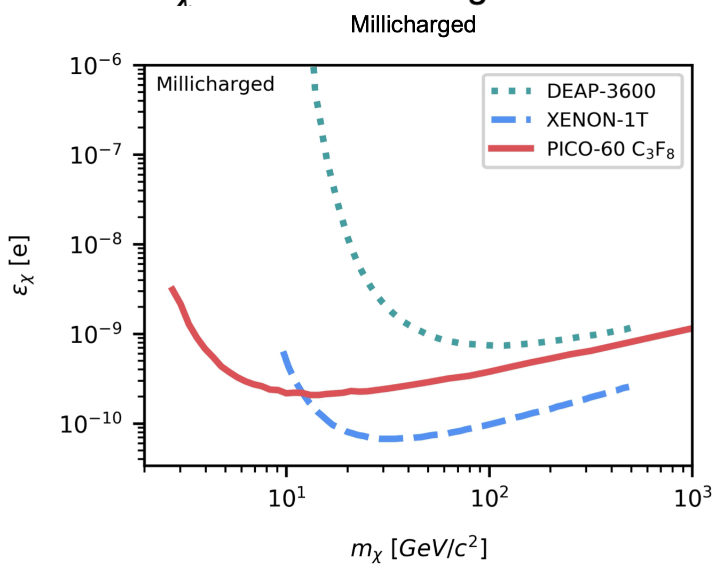
Millicharged DM

- Millicharged particles have attracted interest since they represent elegant extensions to the SM

$$\mathcal{L}_{\mathcal{M}} = e\epsilon_{\chi} A_{\mu} \bar{\chi} \gamma^{\mu} \chi \qquad \mathcal{O}_{\mathcal{M}} = e^2 \epsilon_{\chi} \frac{1}{q^2} \mathcal{O}_1$$

ϵ_{χ}: is the millicharge fraction of the electron charge

$$\mathcal{O}_1 = 1_{\chi} 1_N$$



$$\sigma_{\mathcal{M}} = \frac{\epsilon^2{}_{\chi}}{\mu^2{}_N \pi}$$

eps = ϵ_{χ}

Results on photon-mediated dark-matter–nucleus interactions from the PICO-60 C3F8 bubble chamber
Phys. Rev. D 106, 042004 (2022)

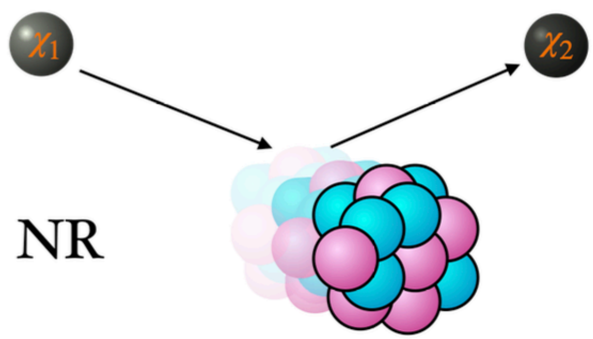
Inelastic dark matter

If dark matter can't scatter elastically, kinematical effects distinguish experiments

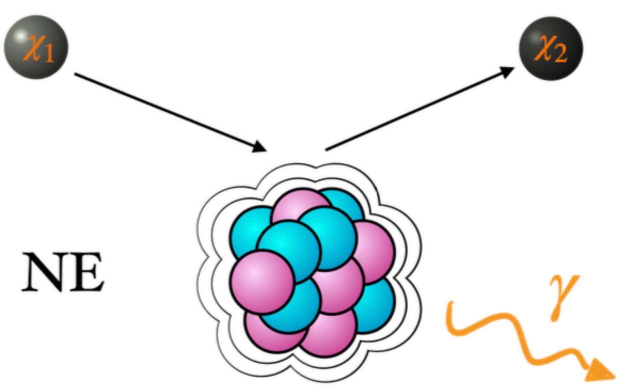
$$\delta_{\max} = \frac{1}{2}\mu_{\chi N}(v_e + v_{esc})^2$$

$$v_{\min}(E_R) = \frac{1}{\sqrt{2M_N E_R}}\left(\frac{M_N}{\mu_{\chi N}}E_R + \Delta\right)$$

- Expected in varied dark matter models
- Possible explanation for 511 keV γ-ray excess in galactic center and DAMA-LIBRA annual modulation

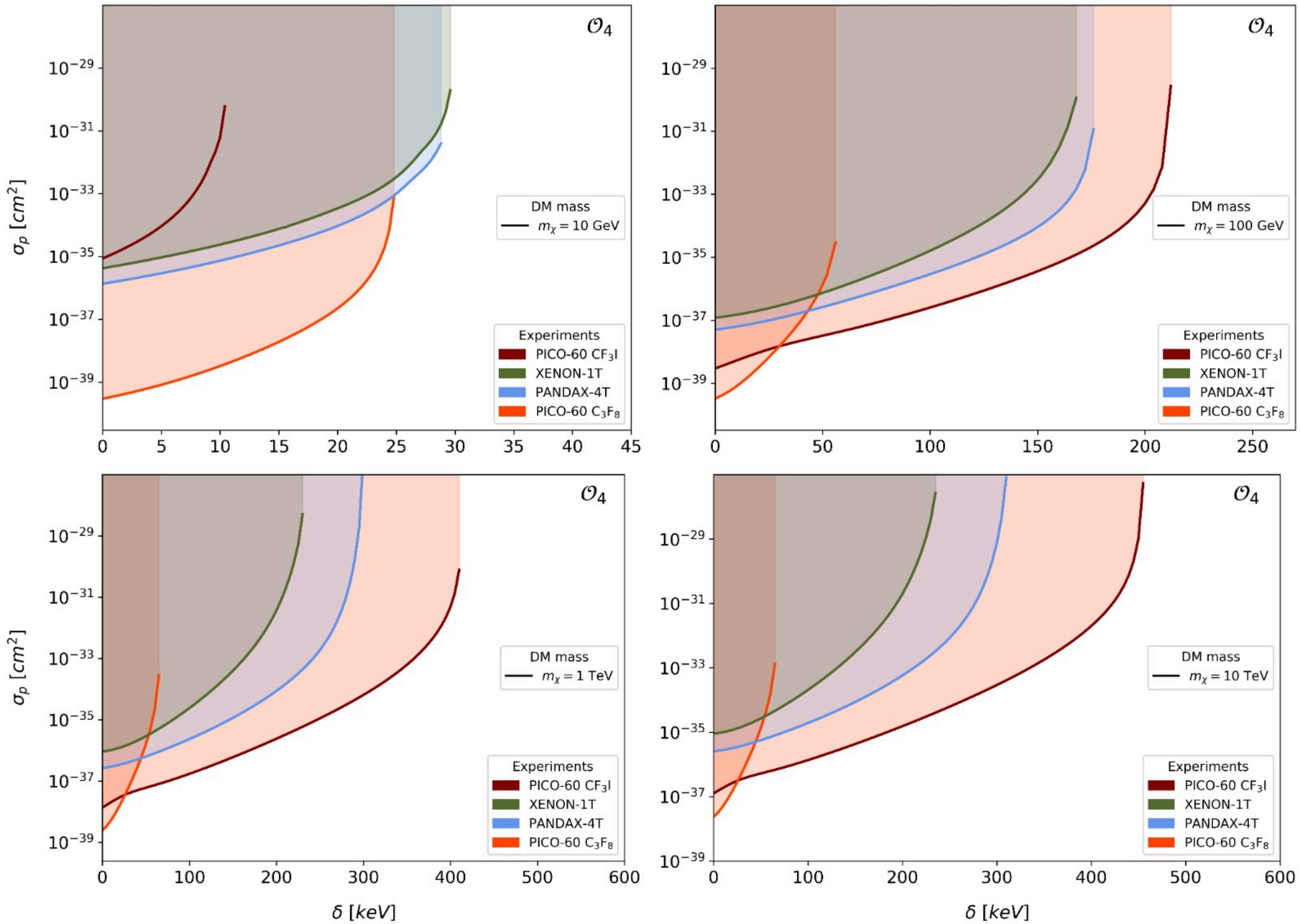


- kinetic energy must overcome mass splitting
- only scatter with heavier nuclei



(https://doi.org/10.1103/PhysRevD.104.103032)

Inelastic DM in PICO



Search for inelastic dark matter-nucleus scattering with the PICO-60 CF3I and C3F8 bubble chambers

Phys. Rev. D 108, 062003 (2023)

BULLKID: BULky and Low-threshold Kinetic Inductance Detectors

BULLKID Collaboration

INFN
Istituto Nazionale di Fisica Nucleare

25 people
6 institutions
4 countries

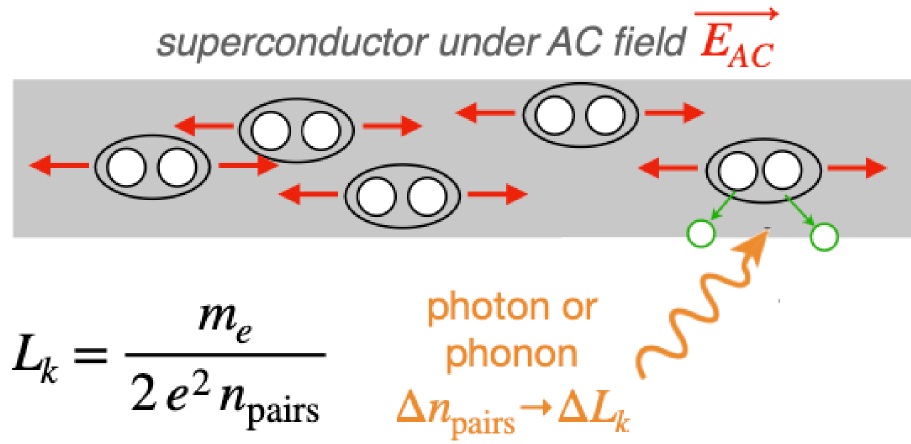
KIT
Karlsruher Institut für Technologie

NÉEL institut

Physics with kinetic inductance detectors

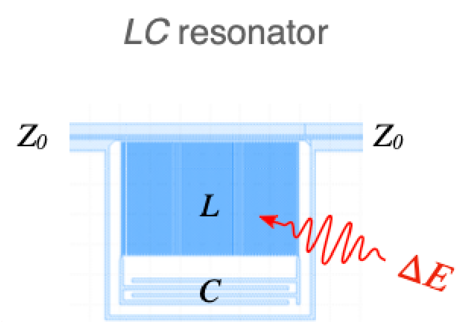
AC superconductivity

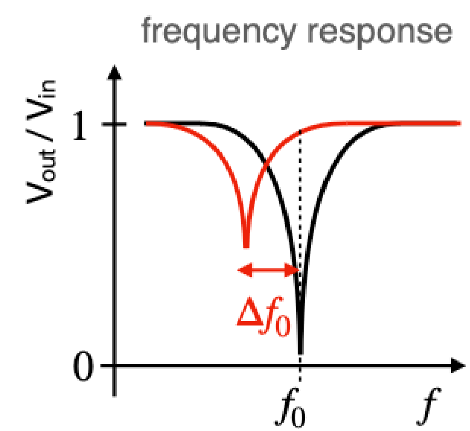
- Electrons bound into Cooper pairs
- Kinetic inductance from physical inertia of mass pairs dependent on Cooper pair density
- High quality factors ($Q \sim 10^4 - 10^6$)



Kinetic Inductance Detectors

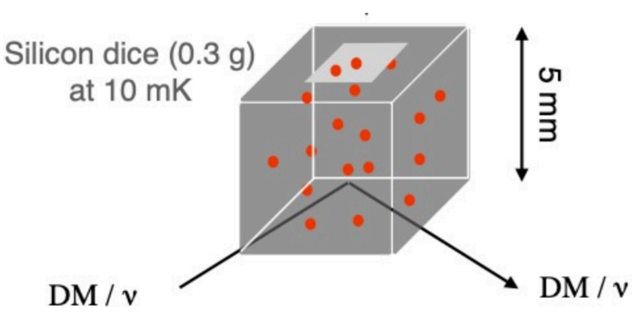
- Superconductor at T < 200 mK (Aluminium)
- Resonant circuit
- Energy deposition breaks Cooper pairs

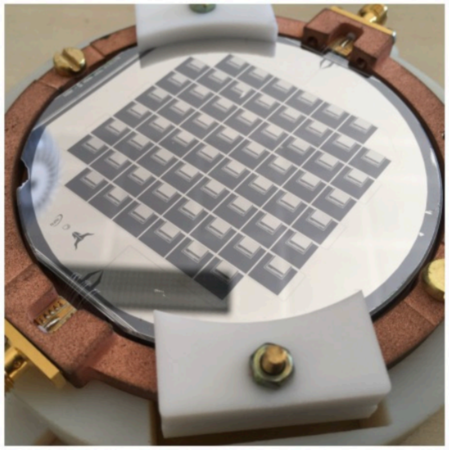


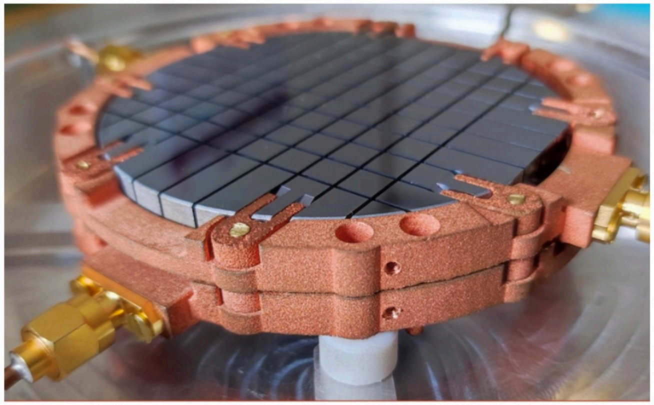


A scalable detector for rare event searches

- Detection of phonons created by nuclear recoils in a silicon dice (0.3 g)
- Multiplexed readout: several KIDs coupled to the same feedline at different frequencies
- KID: $\sim 2 \times 2$ mm$^2 \times 50$ nm, 0.5 μg
- Dices carved in a thick silicon wafer: 60 detectors in 1
- Calibration using optical photons of known energy

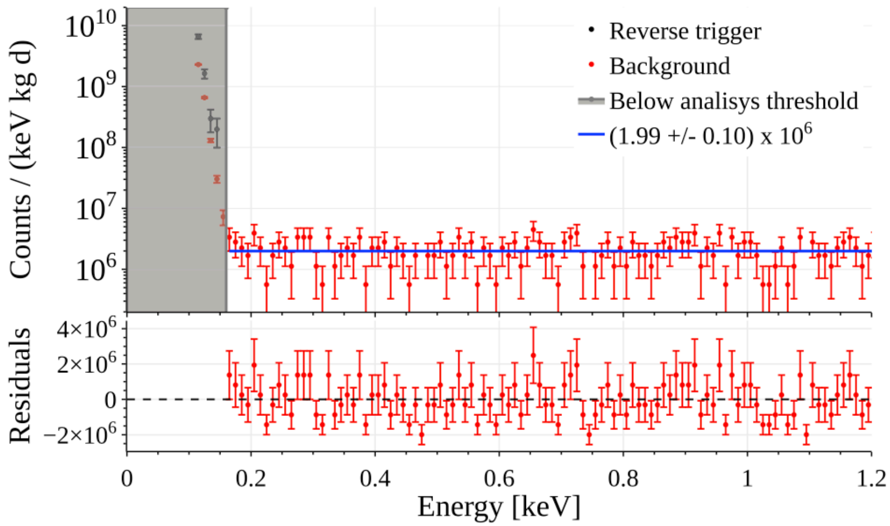






First demonstration of BULLKID-DM

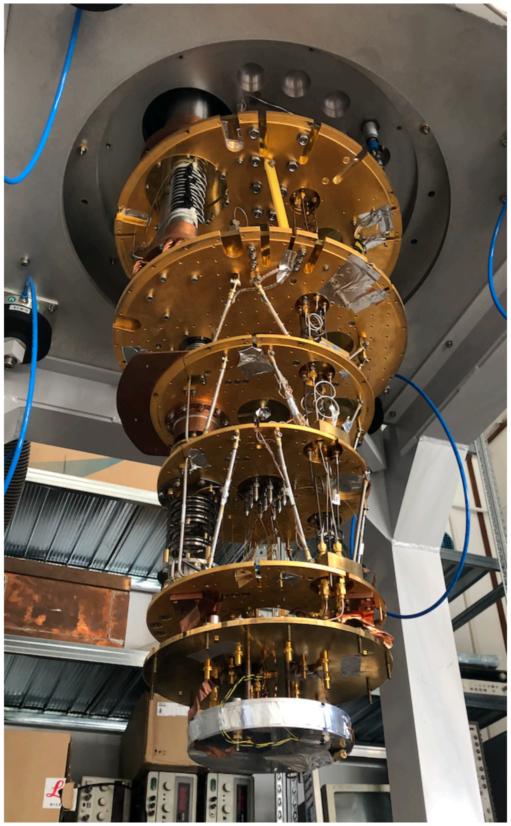
Eur. Phys. J. C (2024) 84:353



- Exposure of 39 hrs. (environmental backgrounds)
- Flat spectrum observed: $(2.0 \pm 0.1 \text{ stat.} \pm 0.2 \text{ syst.}) \times 10^6$ counts/keV kg days
- Energy threshold of 160 ± 13 eV
- Energy resolution: 27 ± 2 eV

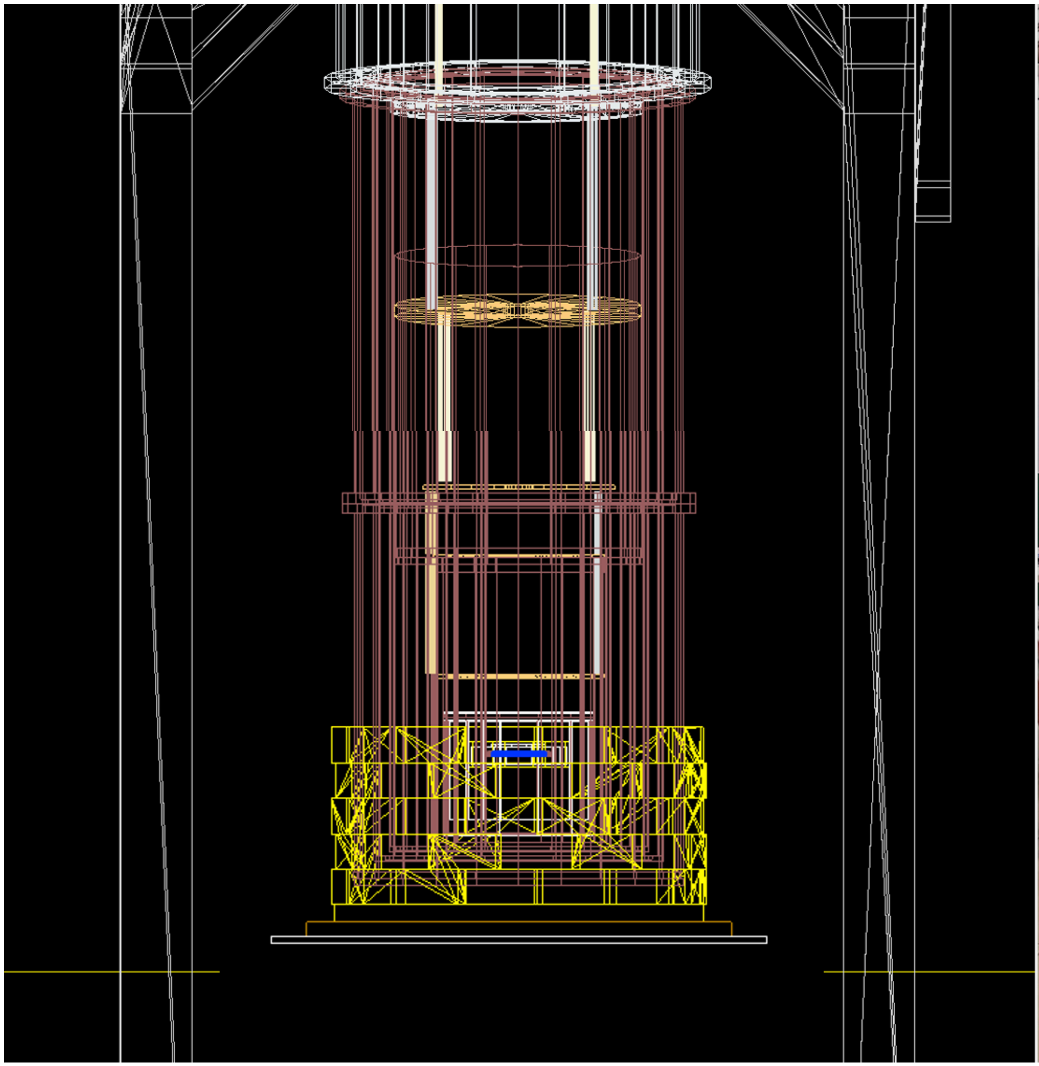
Experiment at Sapienza:

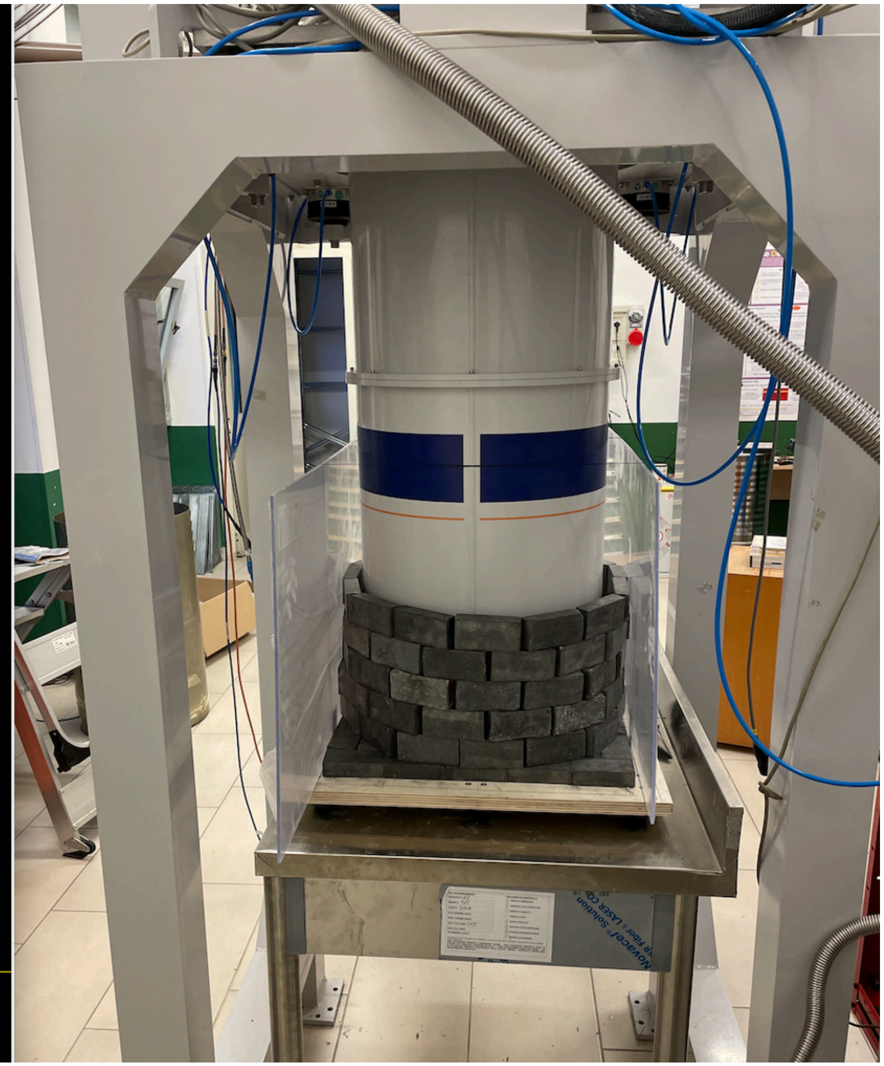
- Array of 60 cubic silicon particle absorbers (0.3 g each)
- Analysis on one of the central elements of the array using surrounding elements as veto



Shielding on surface

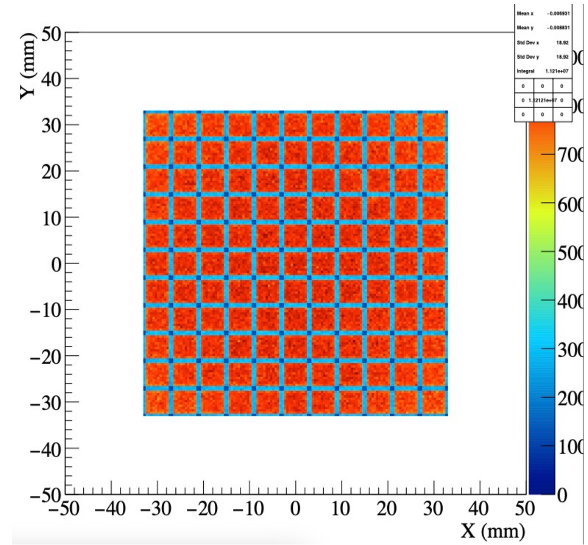
- Moderate γ-rays with Pb to reduce backgrounds by at least a factor of two
- Continue validating the GEANT4 model on surface





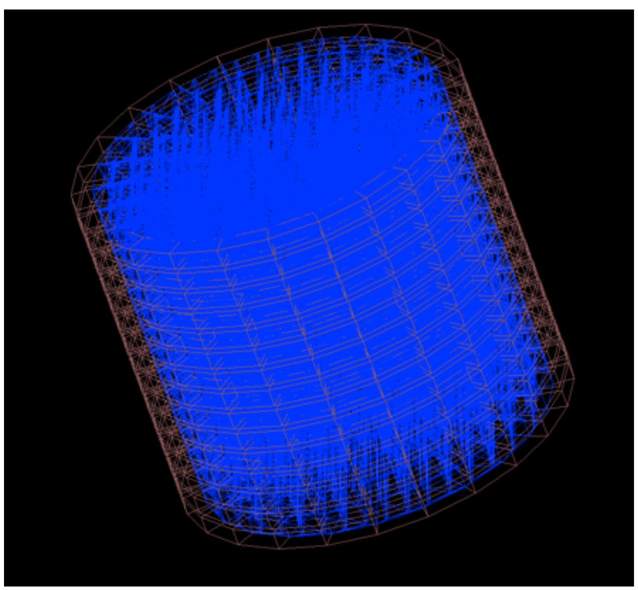
Underground experiment at Gran Sasso

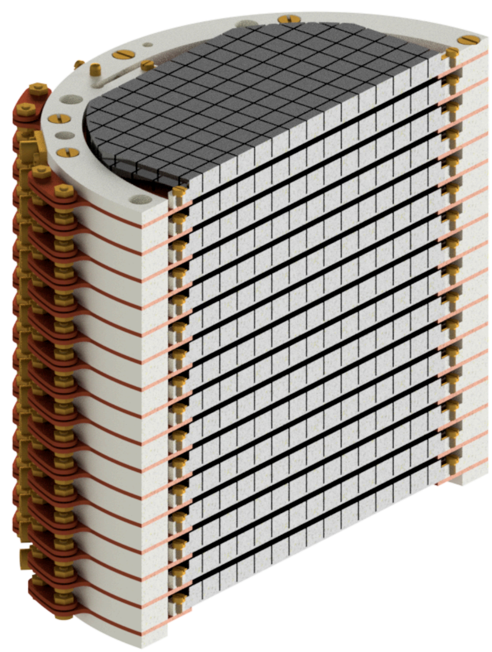
- Active silicon target: $\sim$ 600 gr.
- 16 waffers each 5 cm radius and 5 mm thick



Initial simulation of most relevant backgrounds underground to define shielding configuration:

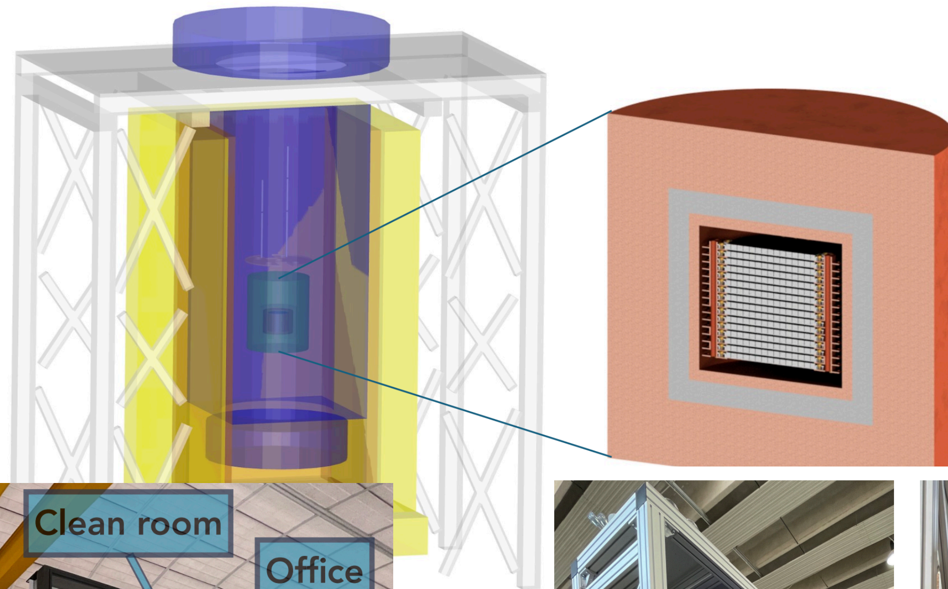
- Gamma-rays: 0.729 $\gamma/\mathrm{cm}^2/\mathrm{sec}$
- Neutrons in several energy ranges: thermal, radiogenic, cosmogenic
- Muon flux: $3.2 \times 10^{-8}\ \mu/\mathrm{cm}^2/\mathrm{sec}$

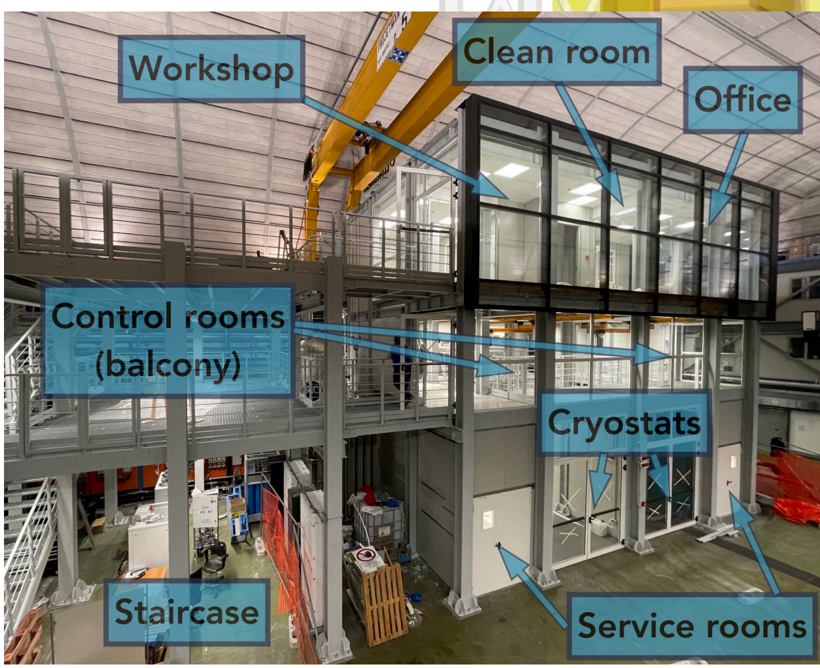




Model for underground experiment

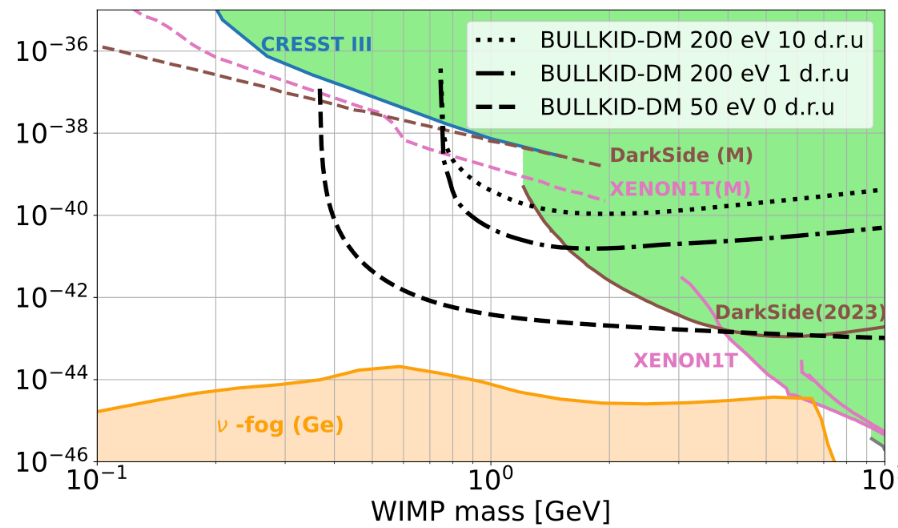
- Installation planned in the cryo facility at Gran Sasso (Hall B) in 2026
- Large volume available inside cryostat for additional shielding and veto



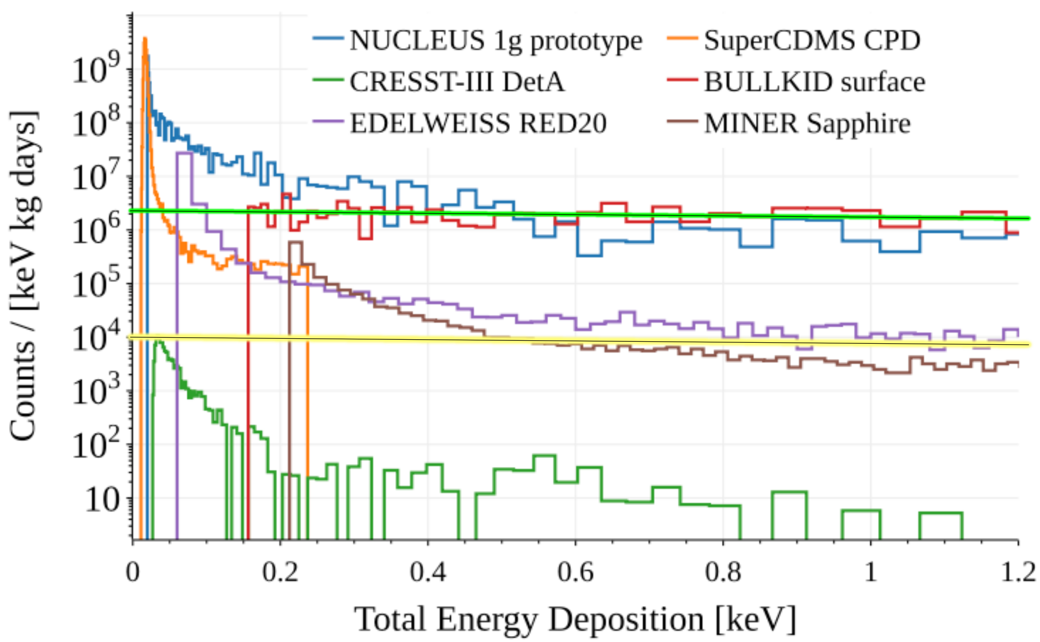


BULLKID

- **BULLKID-DM proved as a promising technology for low-mass dark matter searches**
- **Possible to reduce backgrounds on surface by two orders of magnitude to explore background excess in phonon experiments**
- **Underground detector has the potential to be a leading experiment**



- **Monte Carlo simulations are in good shape with excellent agreement and validation**

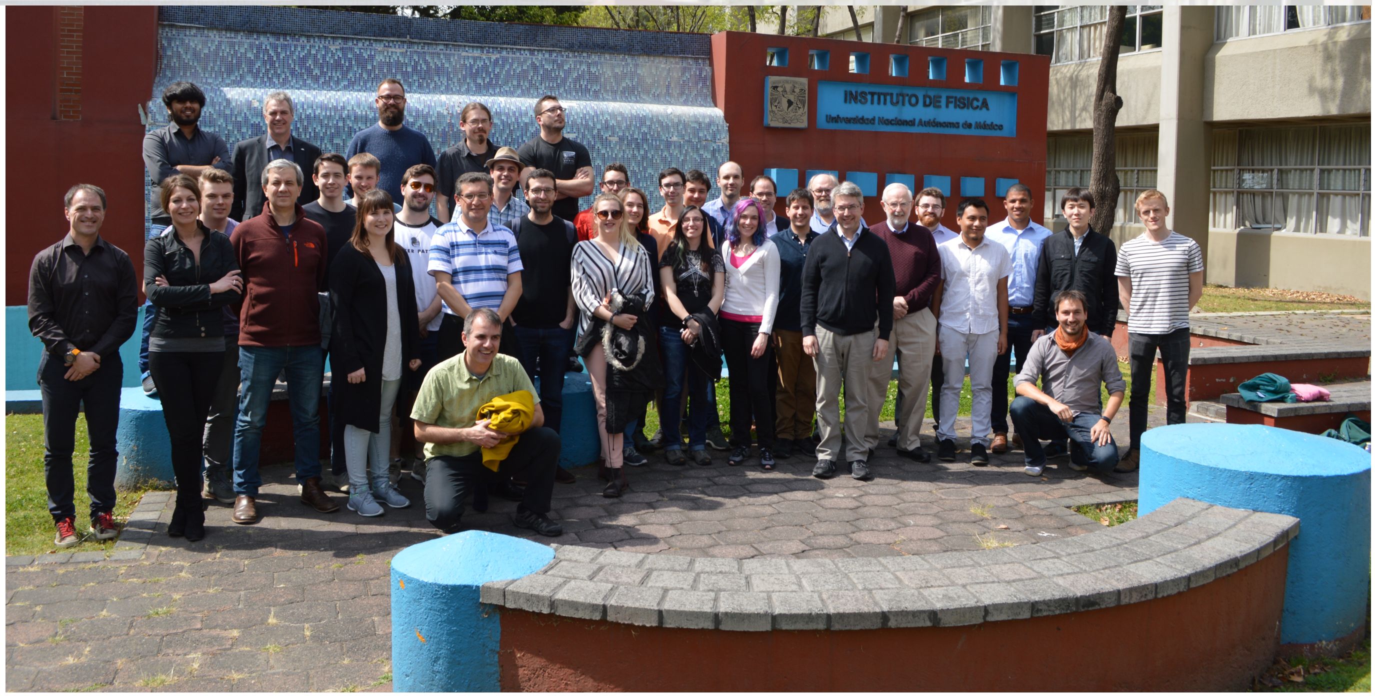


DEAP-3600: a single phase LAr detector

DEAP Collaboration

University of Alberta
Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens
Carleton University
Ciemat
INFN Istituto Nazionale di Fisica Nucleare
National Research Center "Kurchatov Institute"
Laurentian University / Université Laurentienne
UMass Amherst
iF Instituto de Física
Princeton University
Queen's University
Royal Holloway University of London
Particle Physics Rutherford Appleton Laboratory
SNOLAB
US University of Sussex
Technical University of Munich
TUM
TRIUMF

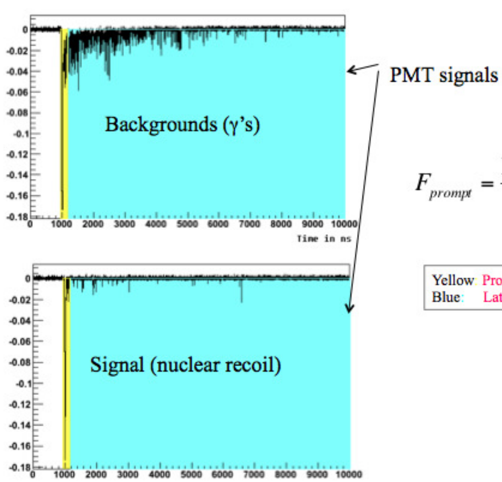
80+ researchers in Canada, Germany, Italy, México, Russia, Spain, UK and USA



DEAP

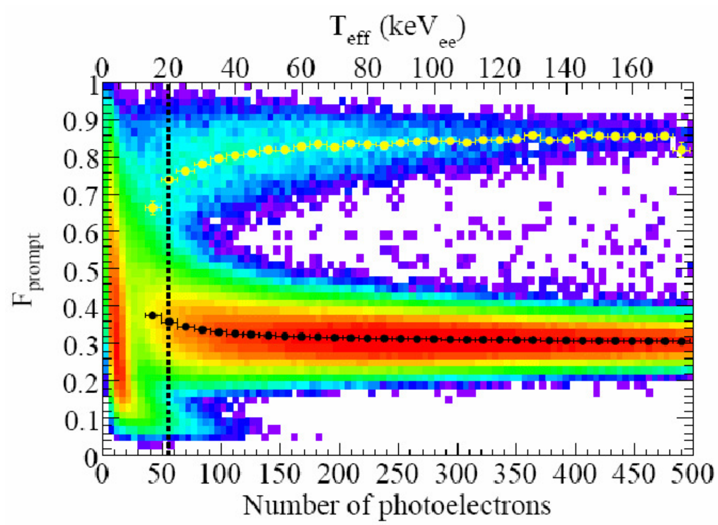
Dark Matter Experiment with Argon and Pulse-shape Discrimination:

- **scattered nucleus detected via scintillation**
- **pulse shape discrimination for suppression of β/γ events (Ar singlet and triplet states have different lifetimes, 7ns vs 1.6μs)**
- **LAr advantages:**
  - **is easily purified and high light yield, well understood, has an easily accessible temperature ($85K$), allows a very large detector mass with uniform response**
- **Detectors:**
  - **DEAP-1: prototype, 7 kg LAr, 2 PMTs**
  - **DEAP-3600: 3600 kg LAr, 255 8” PMTs**



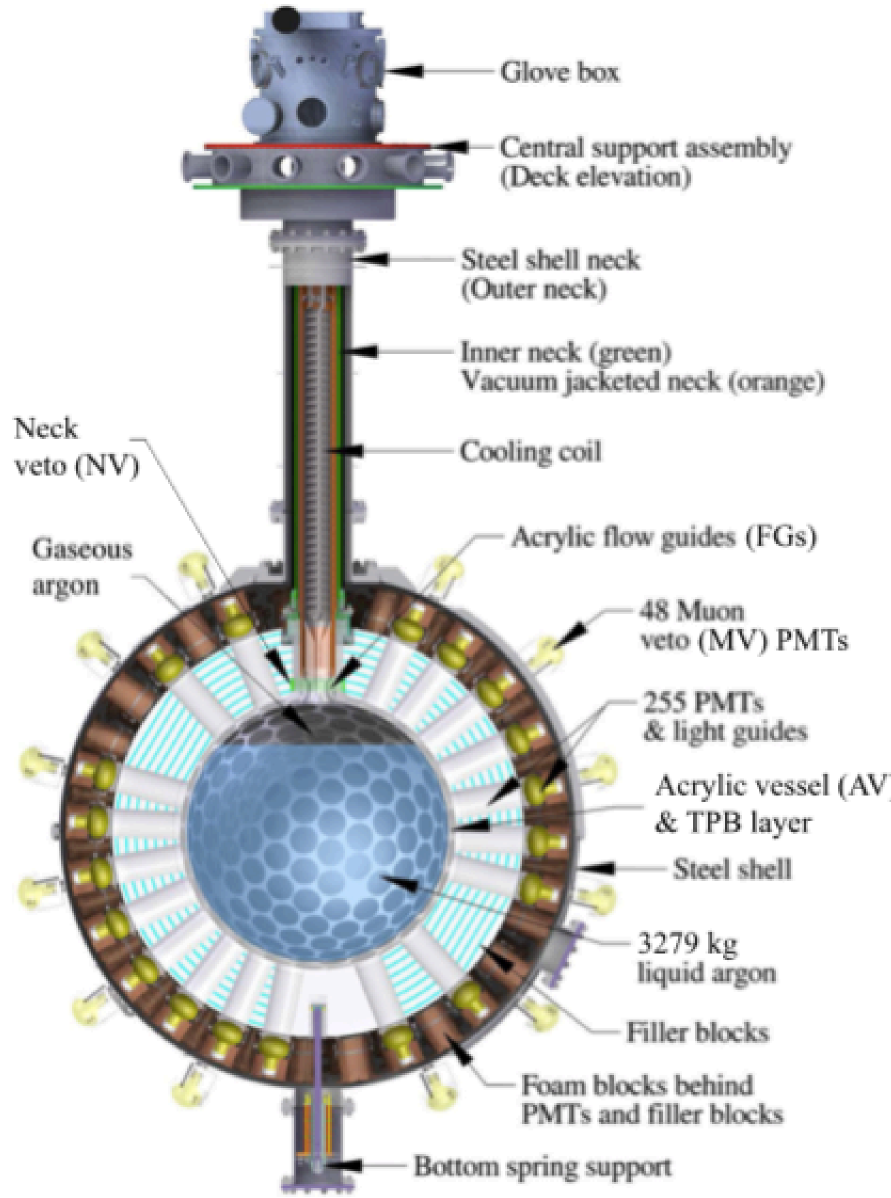
$$F_{prompt} = \frac{\text{PromptPE }(150ns)}{\text{TotalPE }(9\mu s)}$$

Yellow: Prompt light region
Blue: Late light region



DEAP-3600

- Single phase liquid argon: simple, scalable, inexpensive
- Capacity of up to 3600 kg argon (1000 kg fiducial) in ultra-clean AV
- Vessel is "resurfaced" in-situ to remove Rn daughters
- TPB wavelength shifter deposition: in-situ vacuum evaporation
- 255 Hamamatsu R5912 HQE 8" PMTs (32% QE, 75% coverage)
- 50 cm light guides and PE shielding for neutron moderation
- Detector immersed in 8 m water shield tank in Cube Hall



DEAP-3600: NatGeo

Current Issue
February 2015
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A First Glimpse of the Hidden Cosmos

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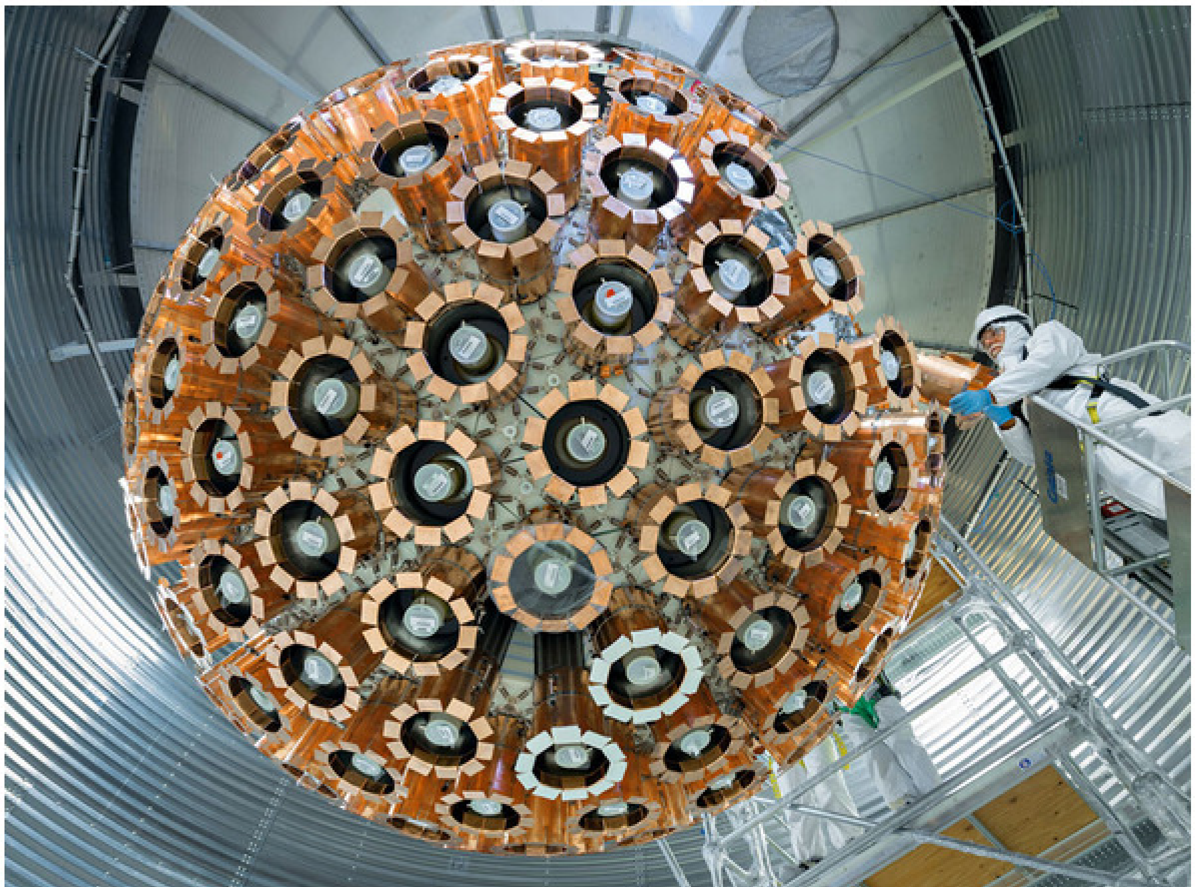
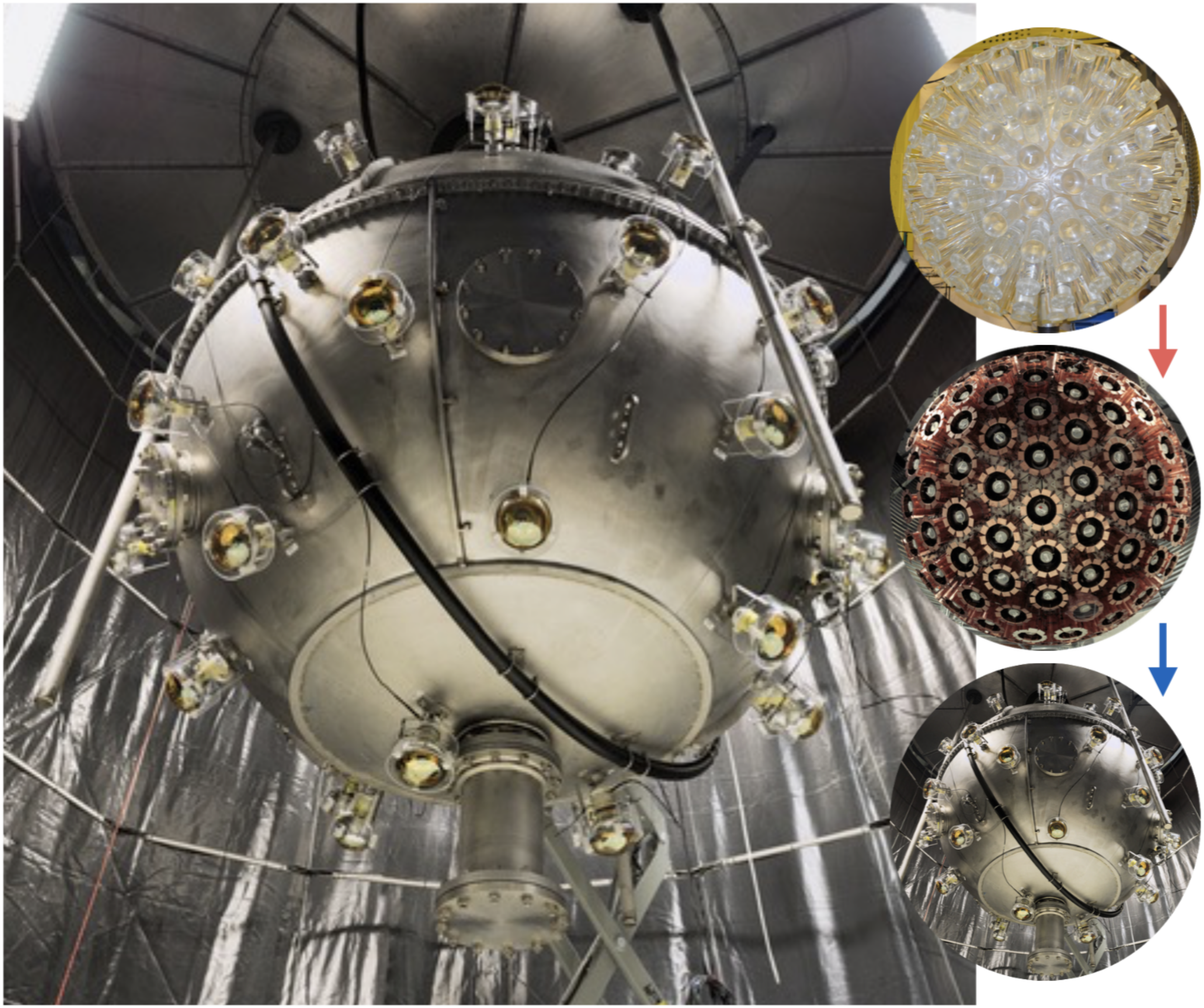
As scientists map the universe, what they can't see—dark energy and dark matter—is key.



PHOTOGRAPH BY ROBERT CLARK

FIRST TO CAPTURE DARK MATTER ON EARTH? DEAP-3600, maybe the most sensitive dark matter detector yet, was installed last year more than a mile underground in a nickel mine in Ontario. Its spherical array of light sensors points inward, toward a core full of liquid argon. The hope is that dark matter particles striking argon atoms will trigger tiny flashes of light.

DEAP-3600



DEAP and EFT

Effective operators for ^{40}Ar

$$\mathcal{O}_1 = 1_\chi 1_N,$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right),$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right),$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}_\perp,$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N},$$

$$\mathcal{O}_{12} = \vec{v}_\perp \cdot (\vec{S}_\chi \times \vec{S}_N),$$

$$\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left[(\vec{S}_N \times \vec{v}_\perp) \cdot \frac{\vec{q}}{m_N}\right].$$

Sub-dominant

Building block:
$\mathbf{S_\chi}$: DM spin, $\mathbf{S_N}$: nucleon spin, **q** : momentum transfer and $\mathbf{v}^\perp$: component of the velocity perpendicular to q.

Non-Relativistic Effective Field Theory (NREFT): provides a general formulation for possible dark matter-nucleus interactions and a better description of the nuclear response.

JCAP 11 (2010) 042, JCAP 02 (2013) 004, Phys. Rev. C 89, 065501 (2014)

Interaction Lagrangian (L_{int}): a sum over i effective operators, where c_i is the coupling constant associated with the O_i operator.

$$\mathcal{L}_{\text{int}} = \sum_i c_i \mathcal{O}_i$$

Photon-mediated interactions can also be parametrized as linear combination of NREFT operators:

Anapole

$$\mathcal{O}_\mathcal{A} = c_\mathcal{A} \sum_{N=n,p} (Q_N \mathcal{O}_8 + g_N \mathcal{O}_9)$$

Millicharge

$$\mathcal{O}_\mathcal{M} = e^2 \epsilon_\chi \frac{\mathcal{O}_1}{q^2}$$

Electric dipole

$$\mathcal{O}_\mathcal{ED} = 2\, e\, d_\chi \frac{\mathcal{O}_{11}}{q^2}$$

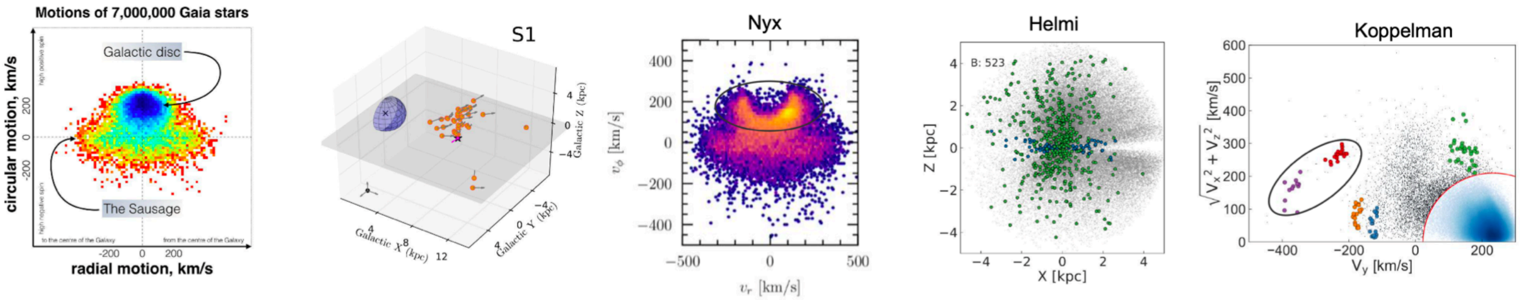
Magnetic dipole

$$\mathcal{O}_\mathcal{MD} = 2\, e\, \mu_\chi \sum_{N=n,p} \left[Q_N\, m_N \mathcal{O}_1 + 4\, Q_N \frac{m_\chi m_N}{q^2} \mathcal{O}_5 + 2\, g_N\, m_\chi \left(\mathcal{O}_4 - \frac{1}{q^2}\mathcal{O}_6\right)\right]$$

Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the DEAP-3600 detector

Phys. Rev. D 102, 082001 (2020)

DEAP and Halo Substructures



MNRAS 478:1(2018), p.611–619	Phys. Rev. D 98, 103006 (2018)	Nat. Astron. Vol. 4, p.1078-1083 (2020)	Astrophys. 625, A5 (2019)	Astrophys. J. 860, L11 (2018)

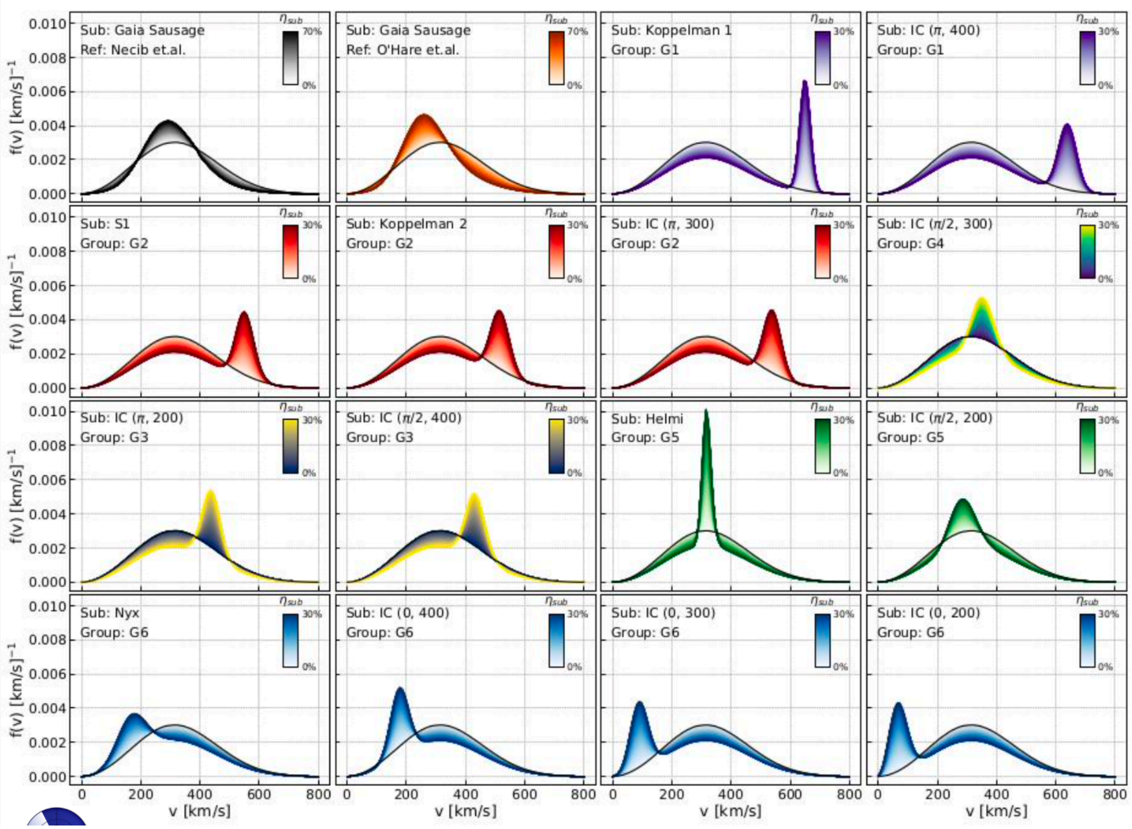
Gaia Sausage: Debris flow with high radial velocity, likely caused by a merger event with a dwarf galaxy.

S1: Retrograde stellar stream; member stars impact almost head-on the Solar System (v ∼ 500 km/s). a.k.a. DM hurricane.

Nyx: Prograde stellar stream; evidence suggests stream intersects solar neighbourhood

Helmi: stellar stream in the solar neighbourhood in several galactic surveys; could indicate similar substructure in the local DM halo

Koppelman 1 & 2: pair of stellar streams in solar neighbourhood; appear to be recently accreted



The color gradient indicates the relative DM density in each substructure, varying from 0 % (light) to 30 % (dark), with the exception of the two Gaia Sausage models, which go up to 70 %.

The solid black line corresponds to the SHM.

The distributions are normalized to 1 and boosted to the Earth reference frame.

(G1, G2, G3) - Fast
(G4, G5) - Medium speed
(G6) - Slow

DEAP, EFT and Halo Substructures

$$\frac{\mathrm{d}R(t)}{\mathrm{d}E_r} = N_T \frac{\rho_0}{m_\chi} \int_{v>v_{\min}} v\, f(\mathbf{v} + \mathbf{v}_\mathrm{E}(t)) \frac{d\sigma_T(v, E_r)}{dE_r} \mathrm{d}^3 v$$

Velocity Distribution Function
(astrophysics model)

Maxwell-Boltzmann distribution

$$f(\mathbf{v}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{|\mathbf{v}|^2}{2\sigma^2}\right)$$

DM velocity distribution with the substructure

$$f_\mathrm{DM}(\vec{v}) = (1-\eta_\chi)\, f_\mathrm{R}(\vec{v}) + \eta_\chi\, f_\mathrm{Sub}(\vec{v})$$

$\mathbf{f_R}$: velocity distribution of a nearly round dark halo - SHM (Maxwell-Boltzmann distribution).

$\mathbf{f_{Sub}}$: velocity distribution of the substructure (3D Gaussian distribution).

$\boldsymbol{\eta_\chi}$: relative DM density in substructure (0-30% for streams and ICs, 0-70% for Gaia Sausage).

Differential cross-section
(particle/nuclear physics model)

Spin-independent cross-section

$$\frac{d\sigma_T(v, E_r)}{dE_r} = \frac{m_N A^2 \sigma_p^{\mathrm{SI}}}{2\mu_p^2\, v^2} F^2(E_r)$$

NREFT cross-section

$$\frac{d\sigma_T(v, E_r)}{dE_r} = \frac{4\pi}{2J+1} \sum_k \sum_{\tau=0,1} \sum_{\tau'=0,1} R_k^{\tau\tau'} \left[v_T^{\perp 2}, \frac{q^2}{m_N^2}, \left(c_i^\tau\, c_j^{\tau'}\right) \right] W_k^{\tau\tau'}(y).$$

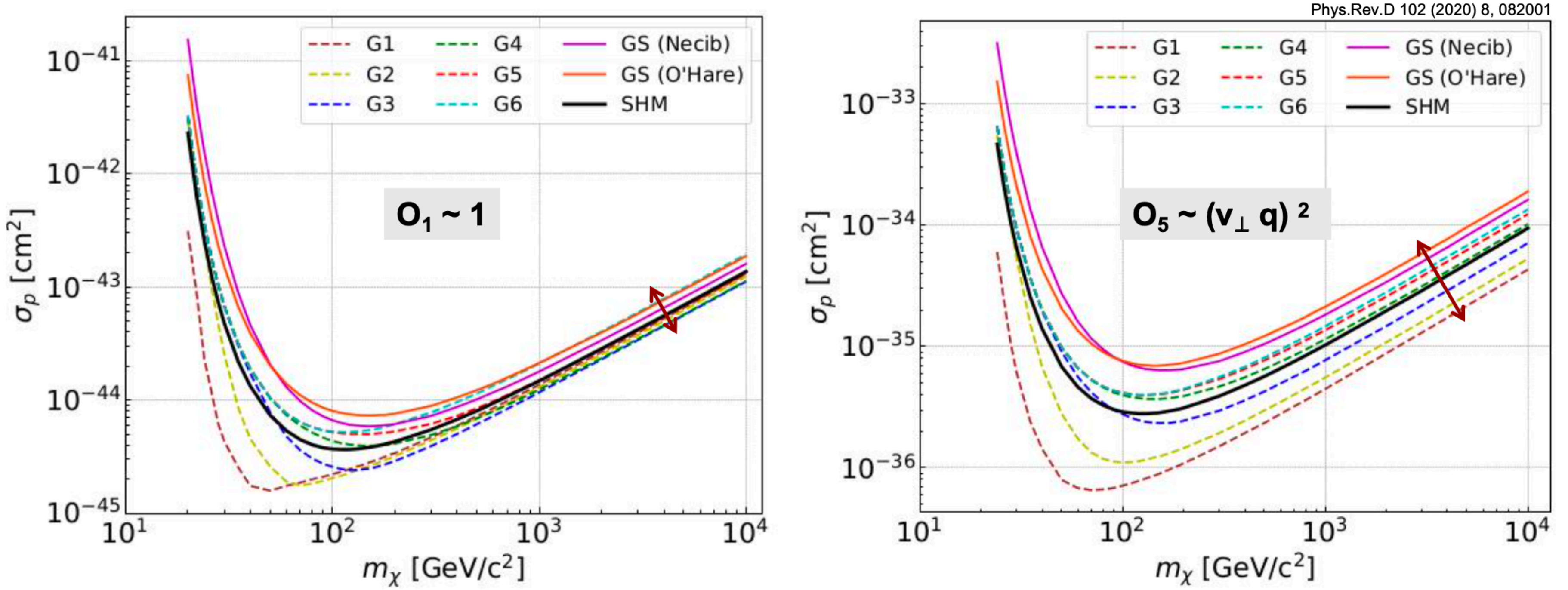
R: DM response function (contains the couplings strength)
W: nuclear response function (depends on the target used)
k-index: represents 6 interactions (M, Φ”, Φ”M are the non-zero for ^{40}Ar).

- ✓ M = describes the nucleon density inside the nucleus.
- ✓ Φ” = related to the angular momentum and spin of nuclei. It favors heavier elements with large, not fully occupied, orbitals.
- ✓ Φ”M = interference term, product of Φ” and M.

DEAP: impact on operators and substructures

- Strongest effects at lower m_χ where the experiment probe the high-velocity tail of the distributions.
- Limits behave quite different at high-masses for O_5 due to its dependence with $v_\perp$ (enhancement/reduction in sensitivity). Non-linear effect not reported before, a result of merging the astrophysical and particle physics uncertainties.

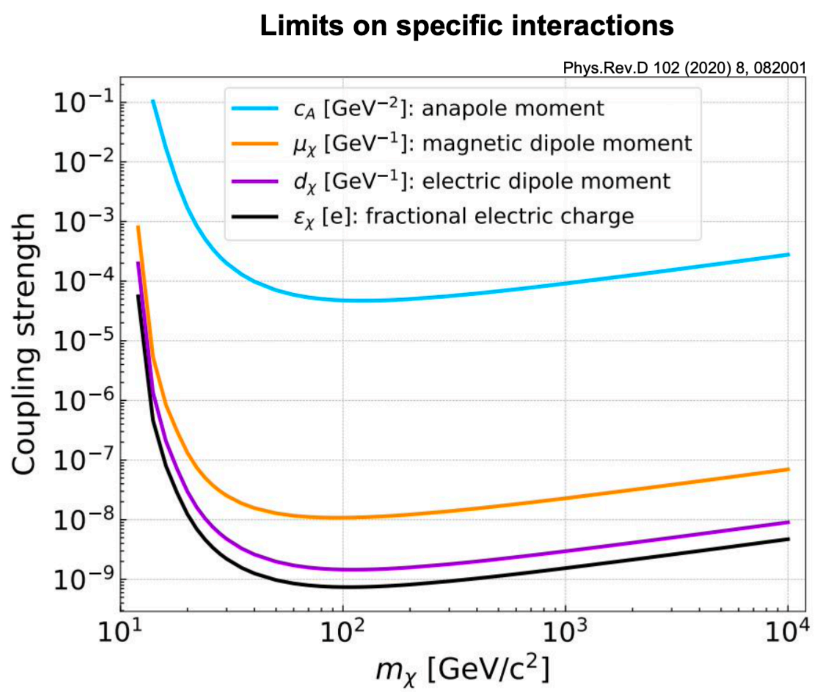
Phys.Rev.D 102 (2020) 8, 082001

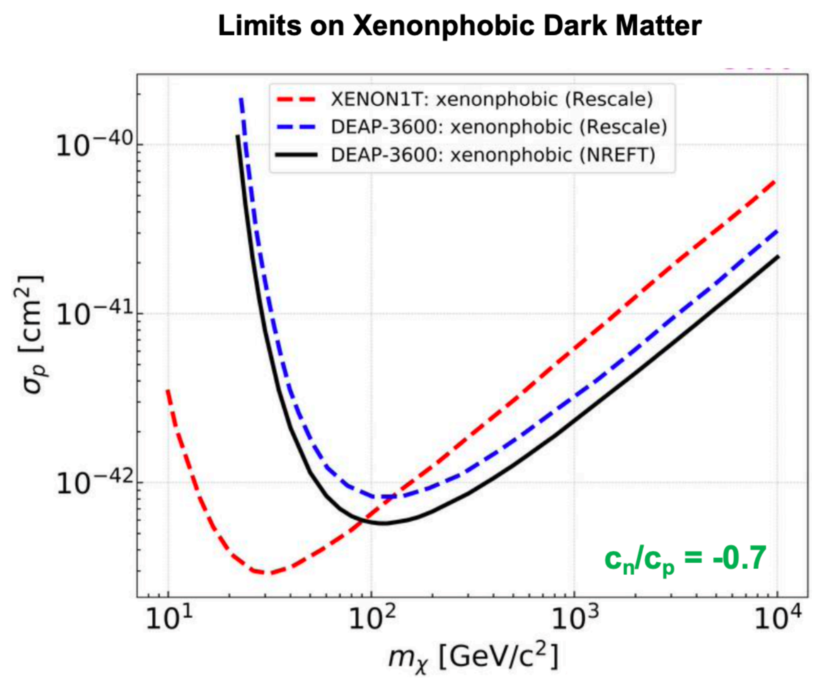


(a) $\mathcal{O}_1$ interactions

(b) $\mathcal{O}_5$ interactions

DEAP: specific interactions

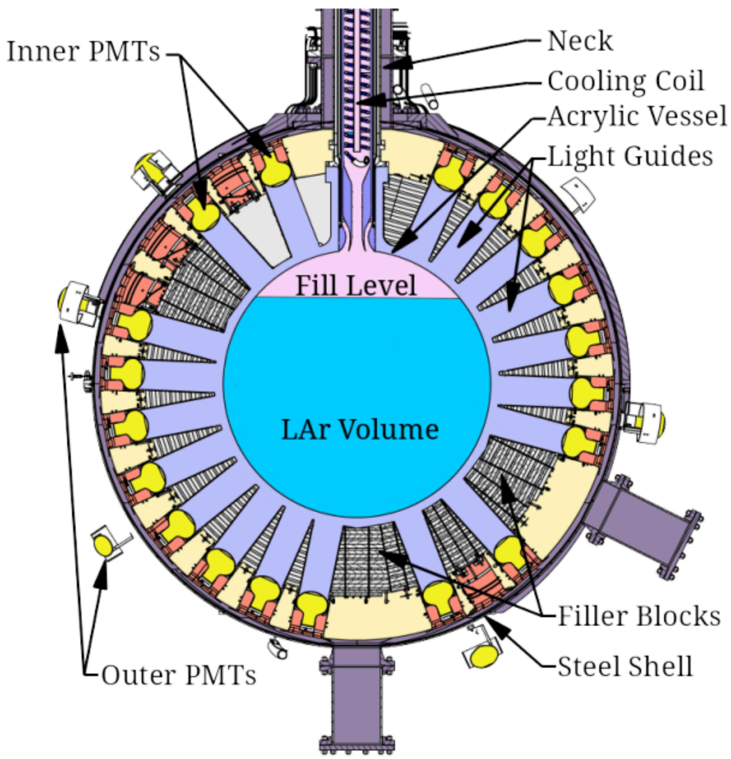


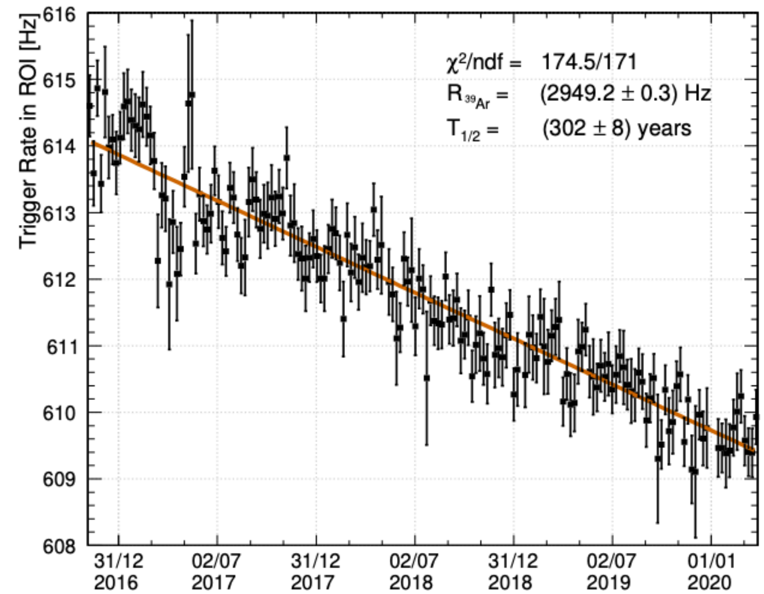


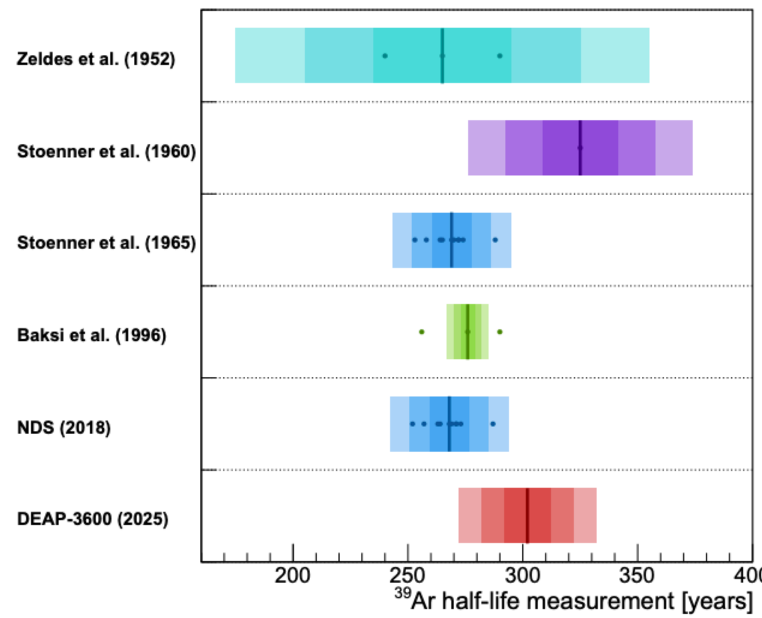
Full set of exclusion curves for all model combinations available online: Zenodo: (DOI: 10.5281/zenodo.3998892) https://zenodo.org/record/3998892

Update from DEAP-3600: Ar39 half-life

- 39Ar Half-life
- arXiv:2501.13196 submitted to Eur. Phys. J. C in Jan. 2025
- In tension with Nuclear Data Sheets (NDS) value at the 2.5σ level

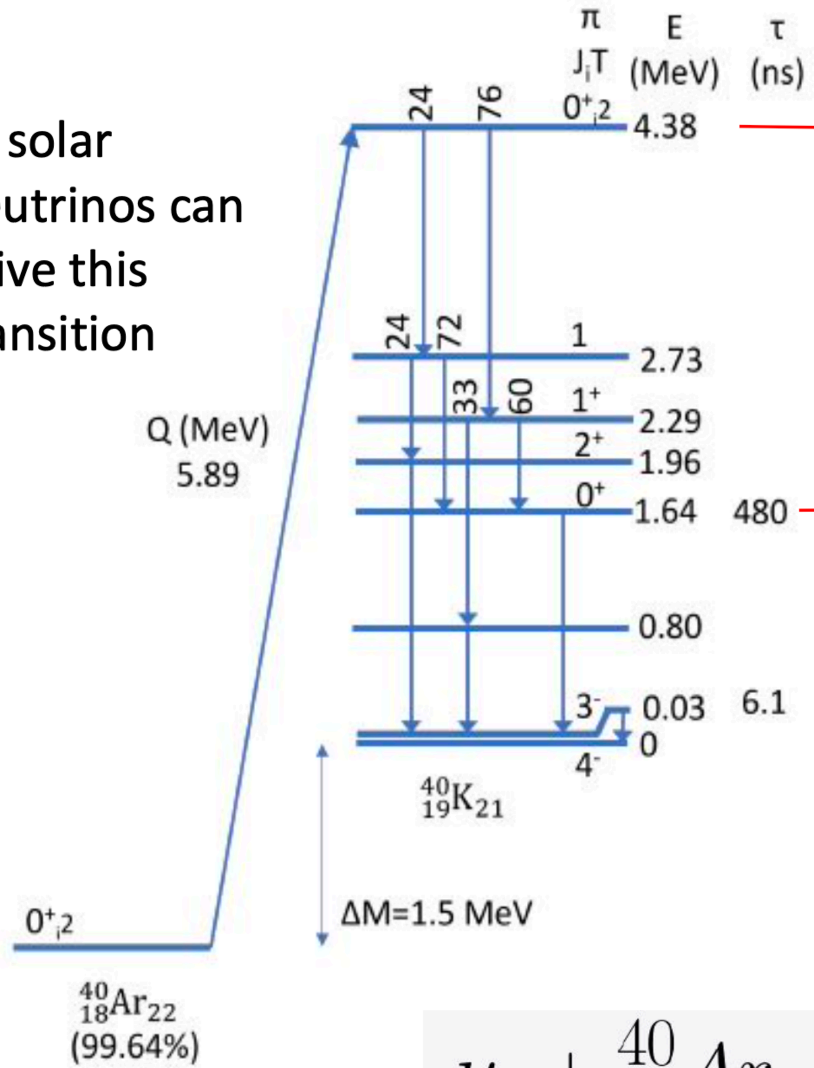






Results from DEAP-3600: neutrino absorption search

^{8}B solar neutrinos can drive this transition



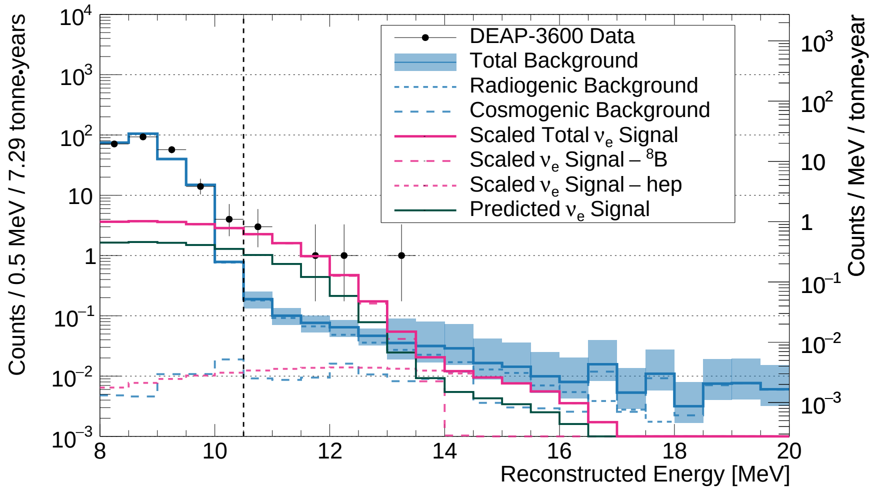
cascade of prompt γs

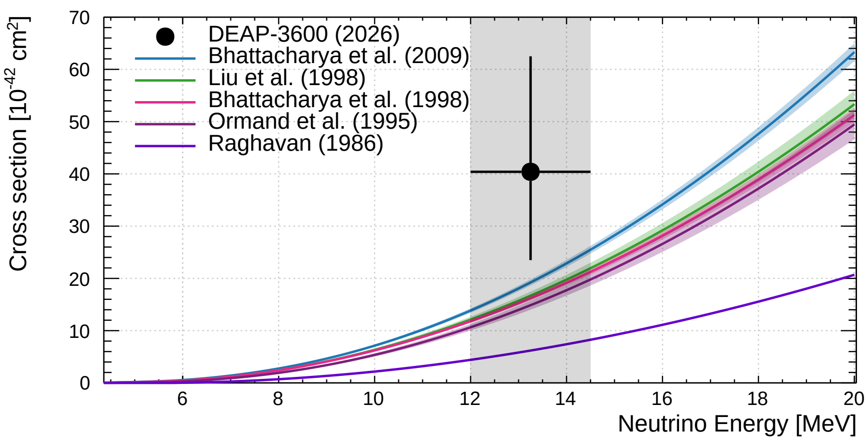
65% of de-excitations through this metastable state (2.74 MeV of prompt γs followed by 1.64 MeV of delayed γs)

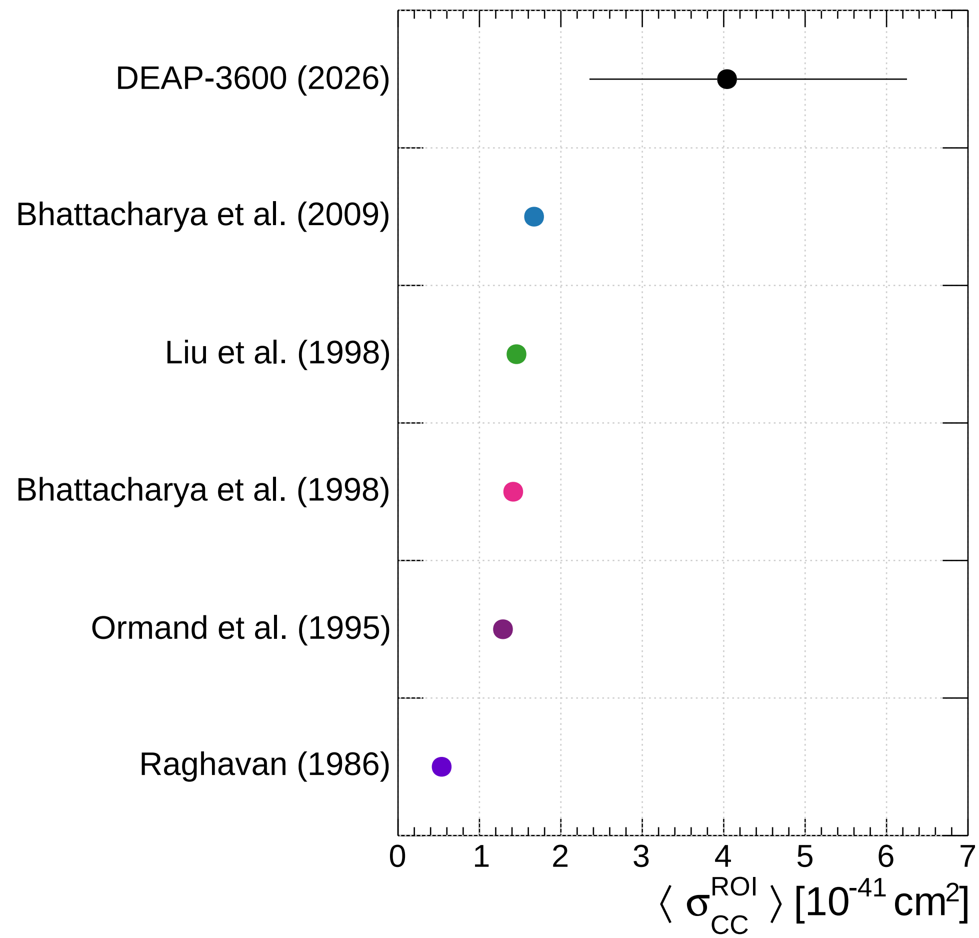
$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

Results from DEAP-3600: neutrino absorption search

Evidence for electron neutrino charged-current interactions (neutrino absorption, CC ν_e) from 8B solar neutrinos on 40Ar







(https://arxiv.org/pdf/2605.12769)

Results from DEAP-3600

Profile-Likelihood WIMP Search

- **Updated background model inclusive of:**
  - **data-driven surface alpha model**
  - **degraded-energy alphas from dust**
  - **shadowed alphas from neck region**
  - **radiogenic neutrons**
  - **cosmogenic neutrons**
  - **Cherenkovs**
  - **39Ar**
- **813 days of detector exposure**
- **Extended fiducial volume and relaxed cuts for increased WIMP acceptance**
- **Detector cool down in process for third fill**

SBC: a 10 kg LAr bubble chamber for dark matter and CEνNS

SBC Collaboration

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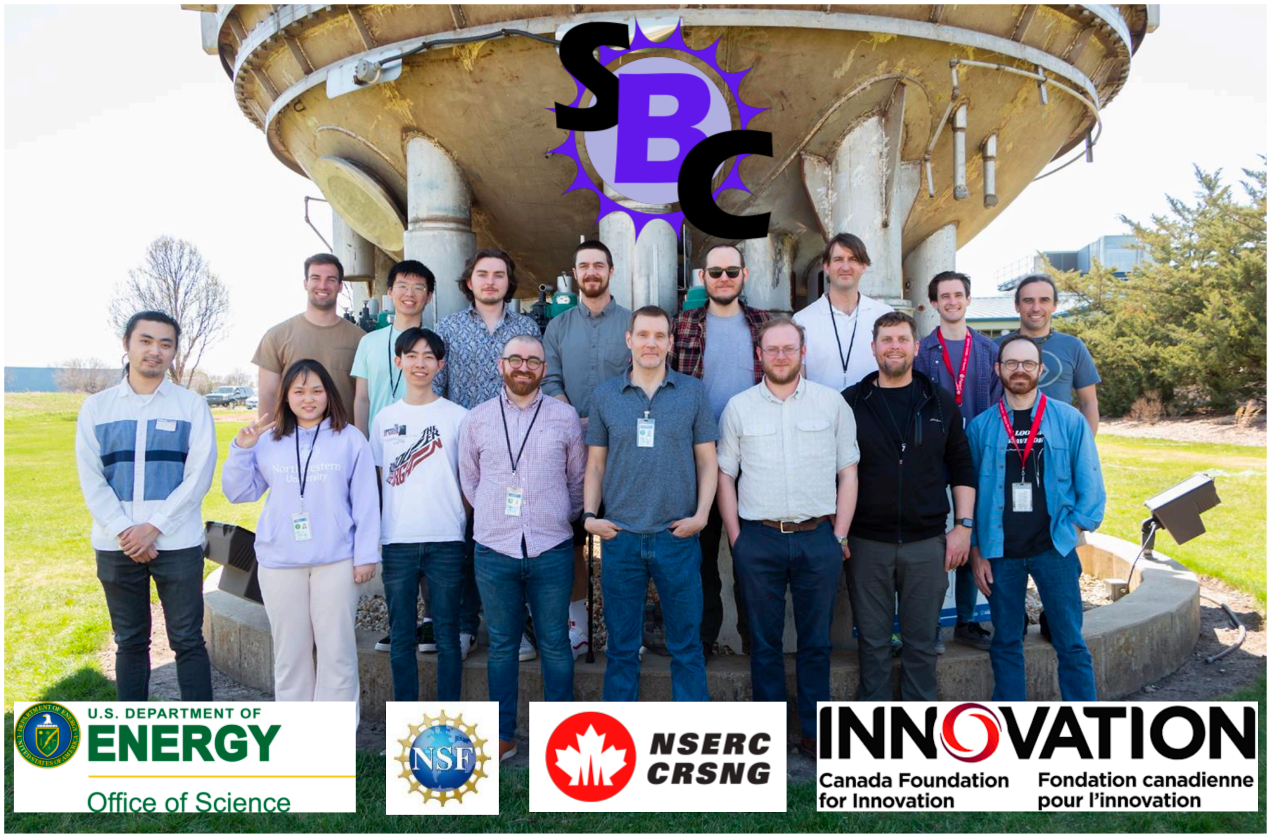

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Northeastern Illinois University

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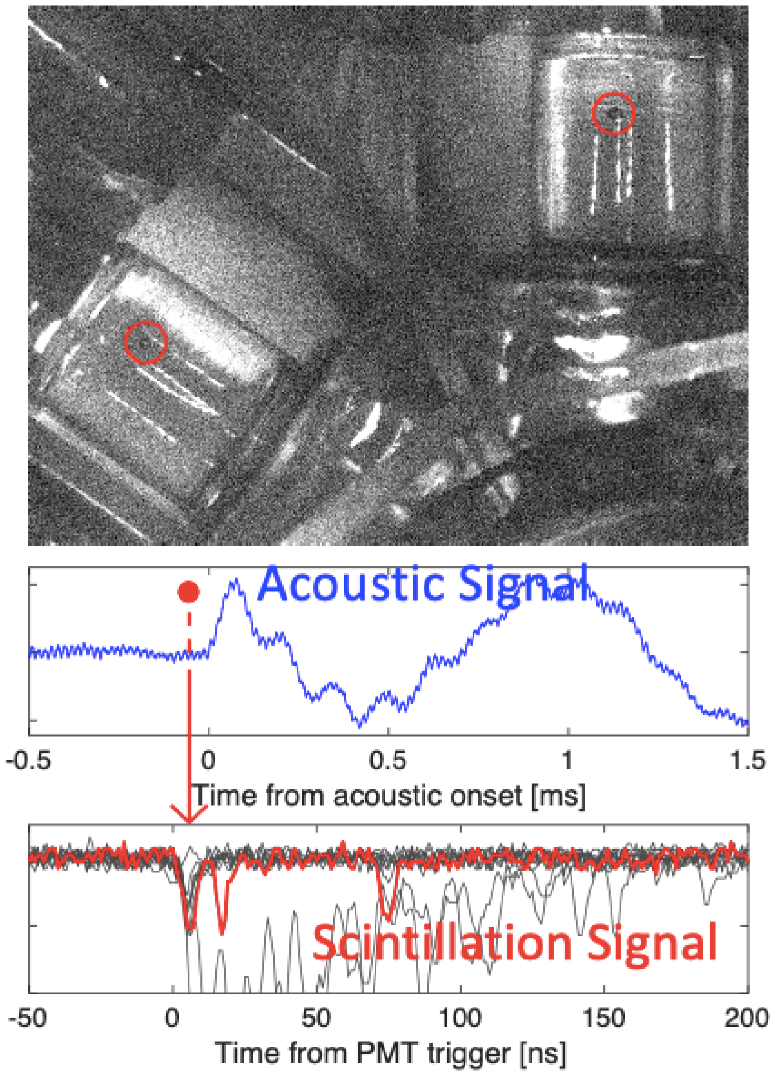
UC Riverside

Shawn Westerdale

First demonstration of SBC

Phys Rev Lett 118, 231301

A nuclear recoil:



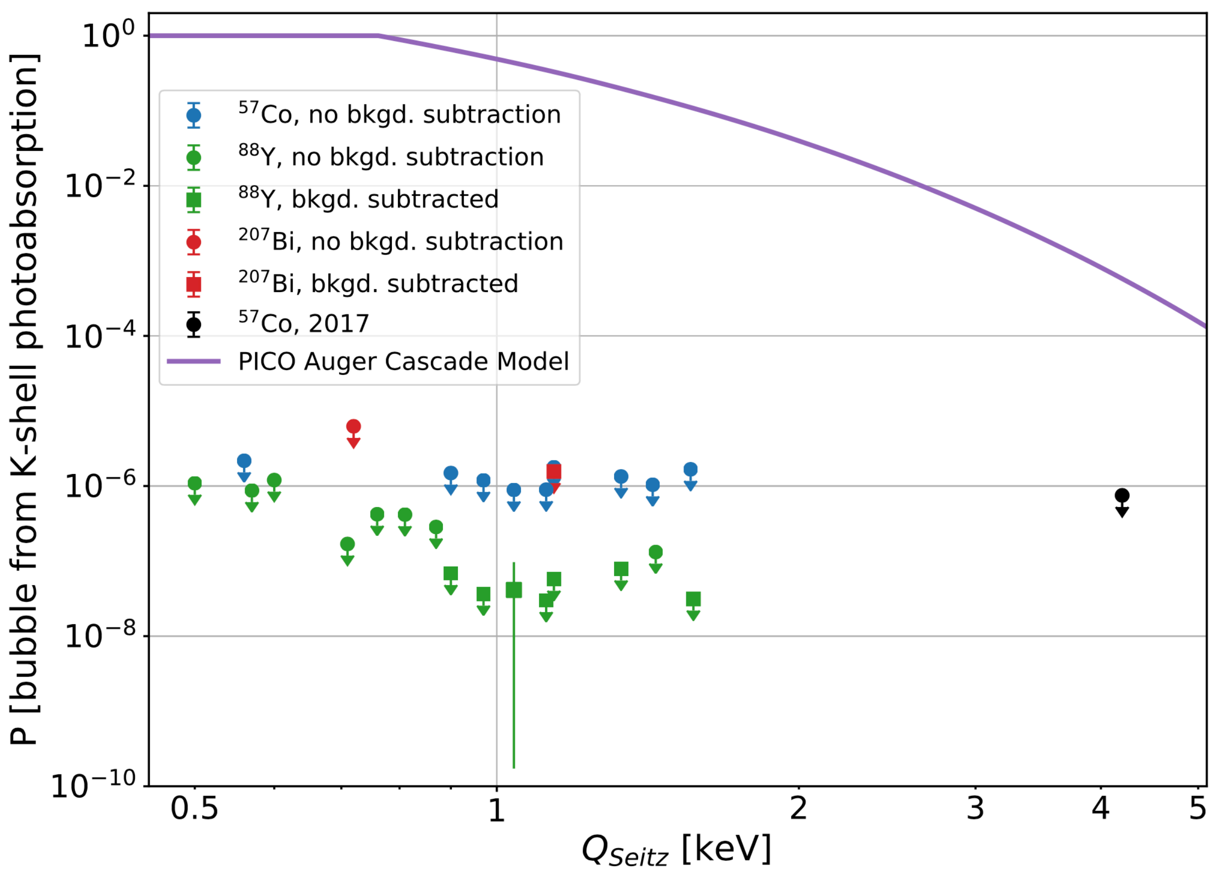
- Demonstrated (NU):
  - Xenon at 500 eV threshold
  - 30-gram target
  - 0.3% photon-detection efficiency

- Argon down to 40 eV threshold (1 bubble/ton-year from thermal fluctuations)
  - 10-kg target
  - 5% photon-detection efficiency (1 phd @ 2 keVr)

  Events with zero photons are signal

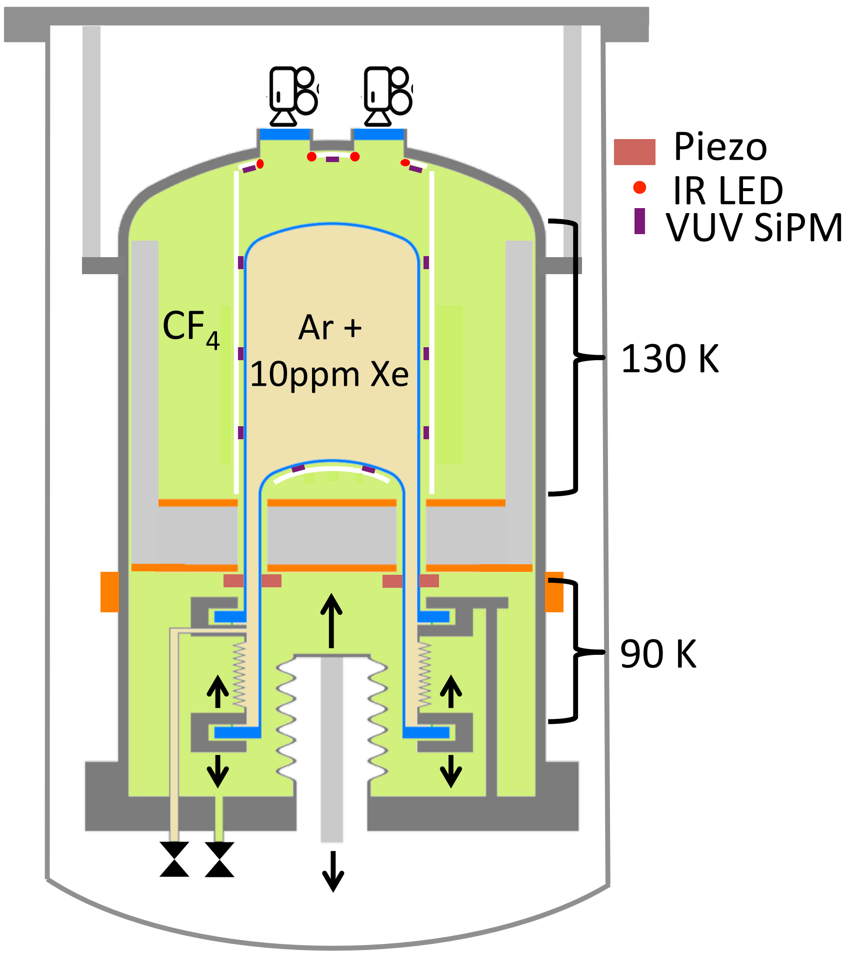
Xenon bubble chamber

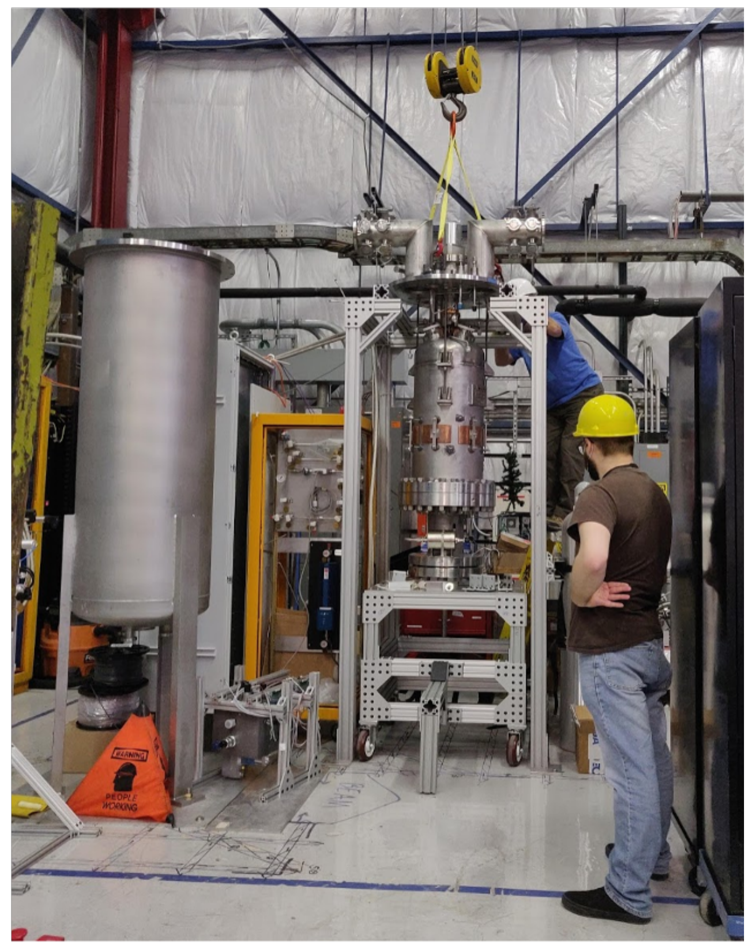
- Xenon measured to have outstanding ER discrimination
- Thresholds explored down to 500 eV
- No gamma induced ER observed
- Xe bubble chambers don't work for tracks (J.L. Brown, D.A. Glaser and M.L. Perl, Phys Rev 102, 1956), "solved" by adding 2% ethylene.



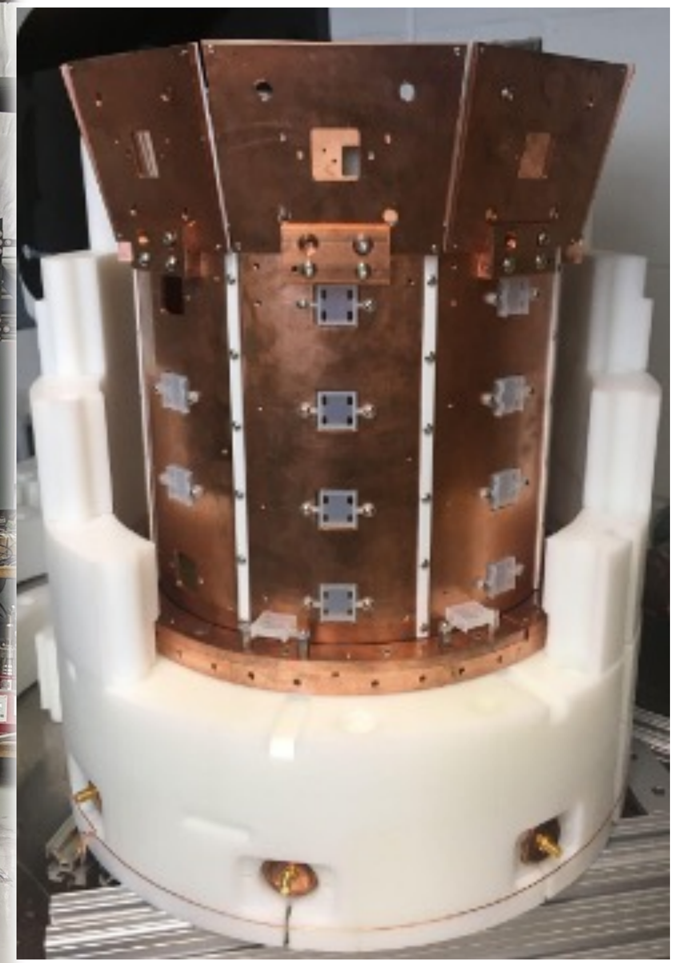
10 kg liquid Argon bubble chamber: 100 eV threshold

- **Ar + 10-100 ppm Xe target, 178 nm scintillation**
- **SiPMs immersed in hydraulic fluid (CF4 at 130K)**
- **20-360 psia (∼1-25 bar) cycles**
- **Single-fluid, "right-side-up" geometry used by PICO-40L**



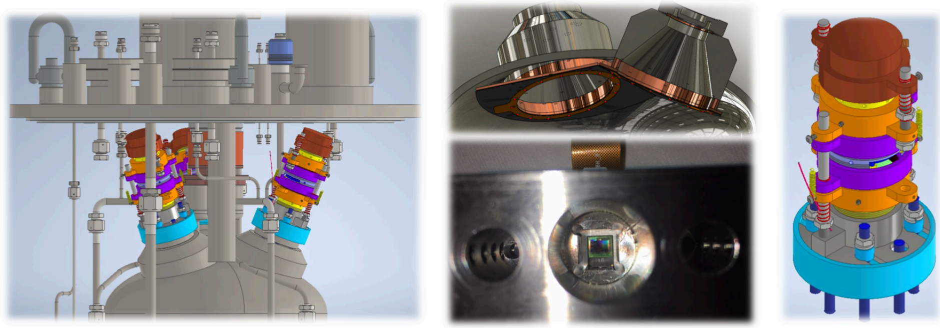


10 kg liquid Argon bubble chamber

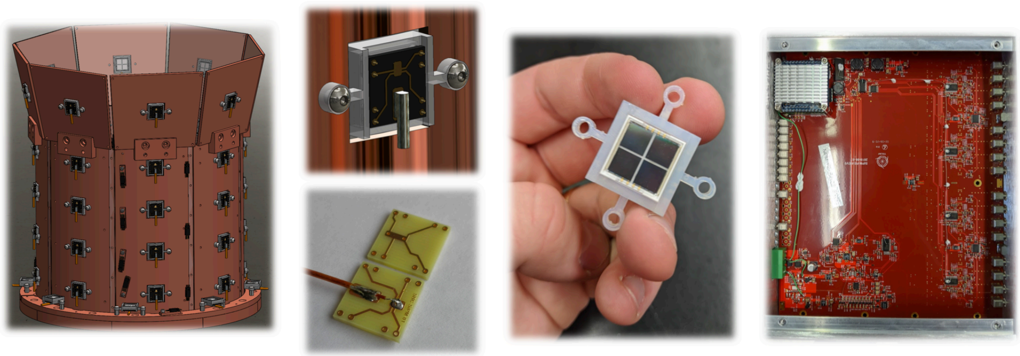


SBC-10kg: Readout systems

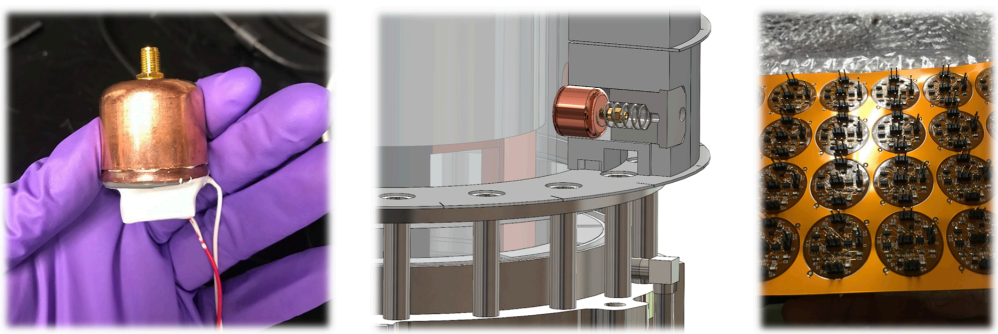
- **3 Raspberry-Pi controlled cameras and LED rings for illumination:**



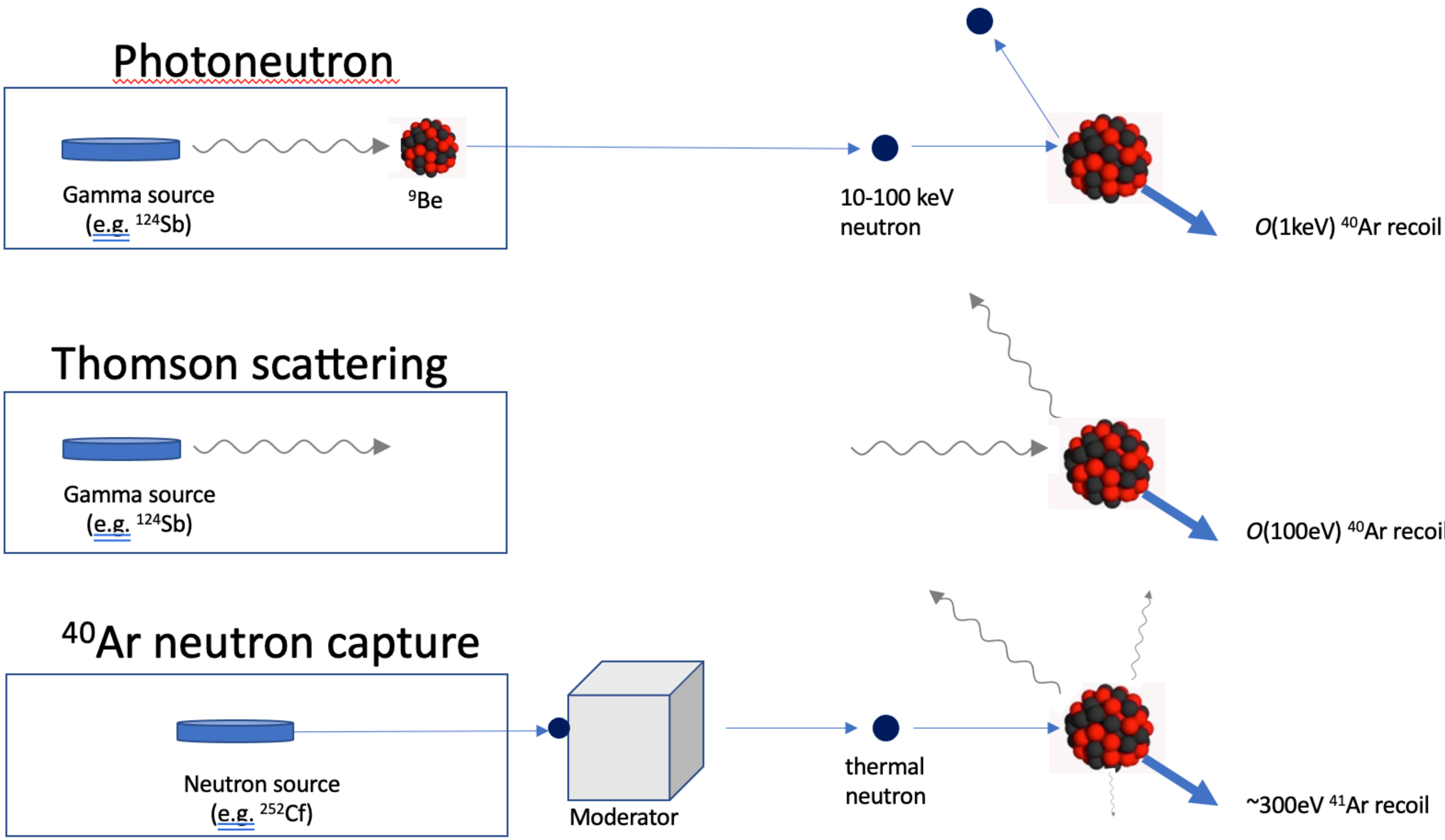
- **32 Hamamatsu VUV4 Quads to measure scintillation light:**



- **8 piezo acoustic sensors to monitor the nucleation process:**



- Different nuclear recoil calibration techniques



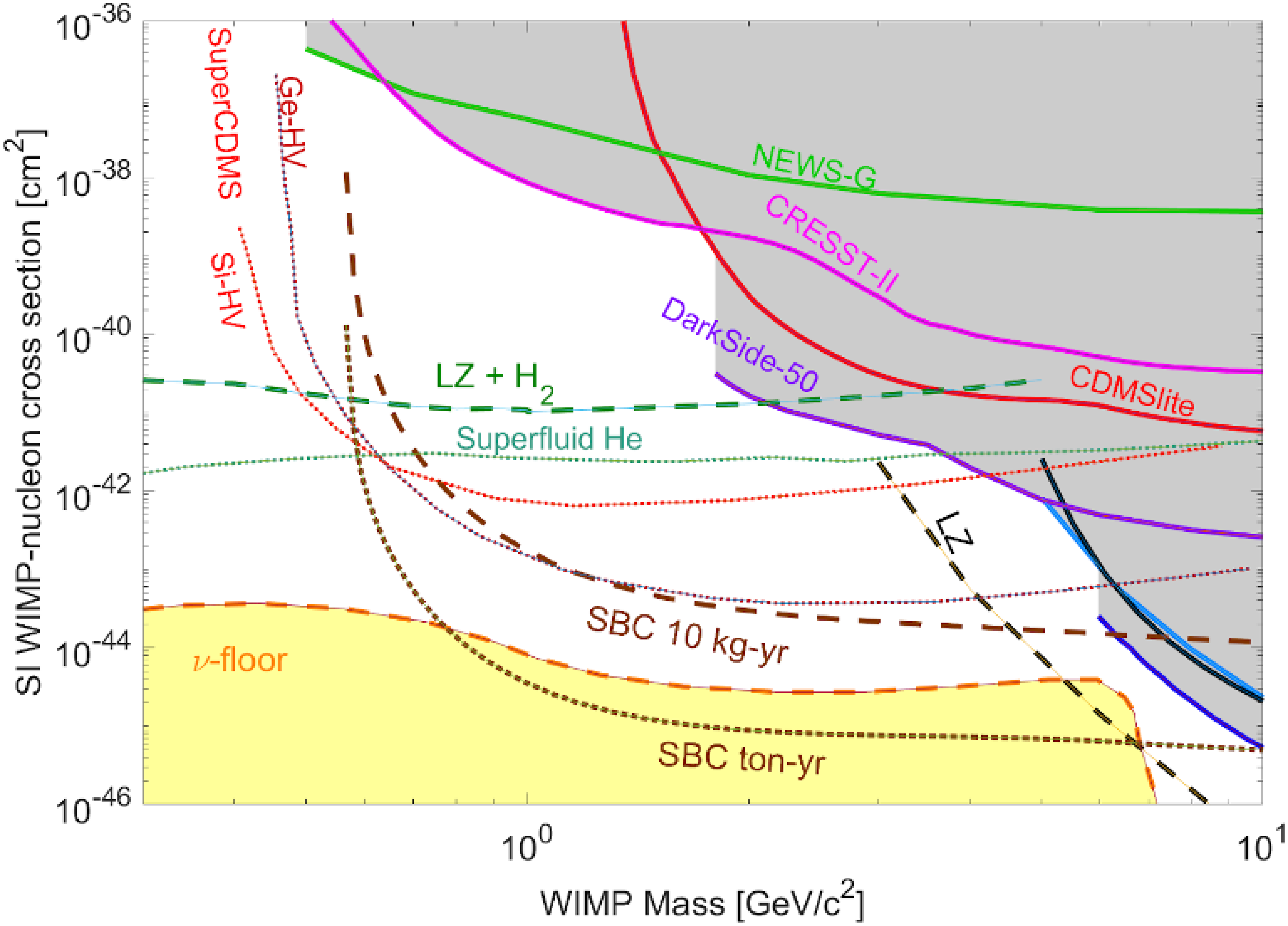
SBC: possible strategy

- **SBC-Fermilab:**
  Build and commission detector
  Calibrate NR and ER

- **SBC-SNOLAB:**
  Build and install 2nd detector
  Low mass dark matter searches

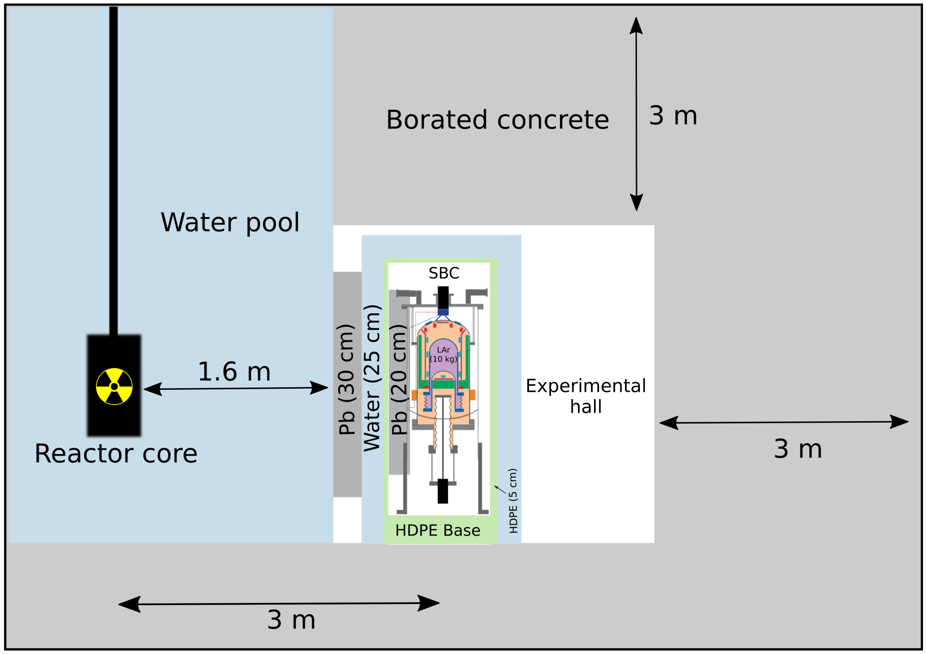
- **SBC-CEνNS:**
  Upgrade SBC-Fermilab detector
  Install at a reactor site for CEνNS

SBC underground at SNOLAB: dark matter

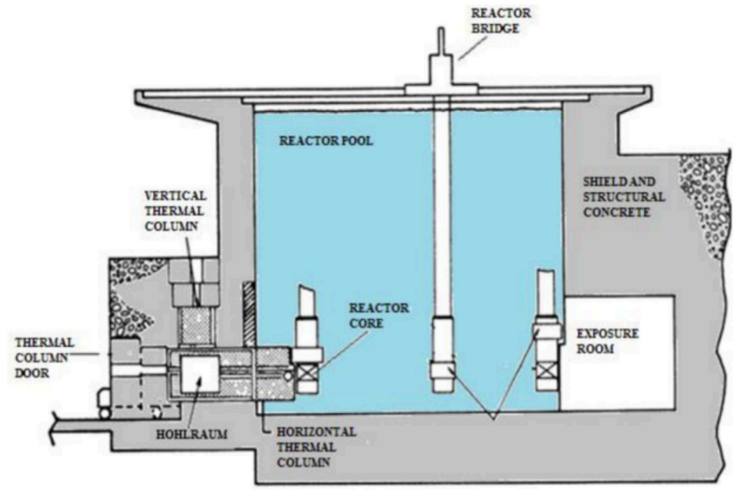


Projected sensitivity to WIMP-like Dark Matter with an energy threshold set at 100 eV, and a background budget target of 1 event/year

SBC CEνNS: physics reach



ININ 1MW Triga Mark-III reactor in Mexico

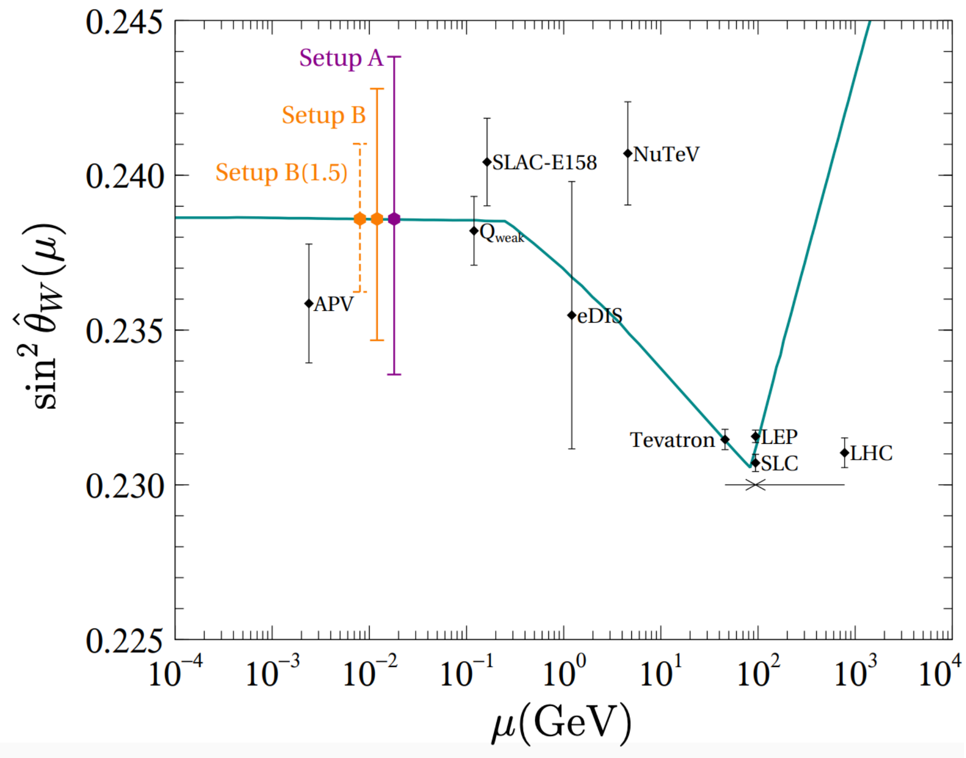


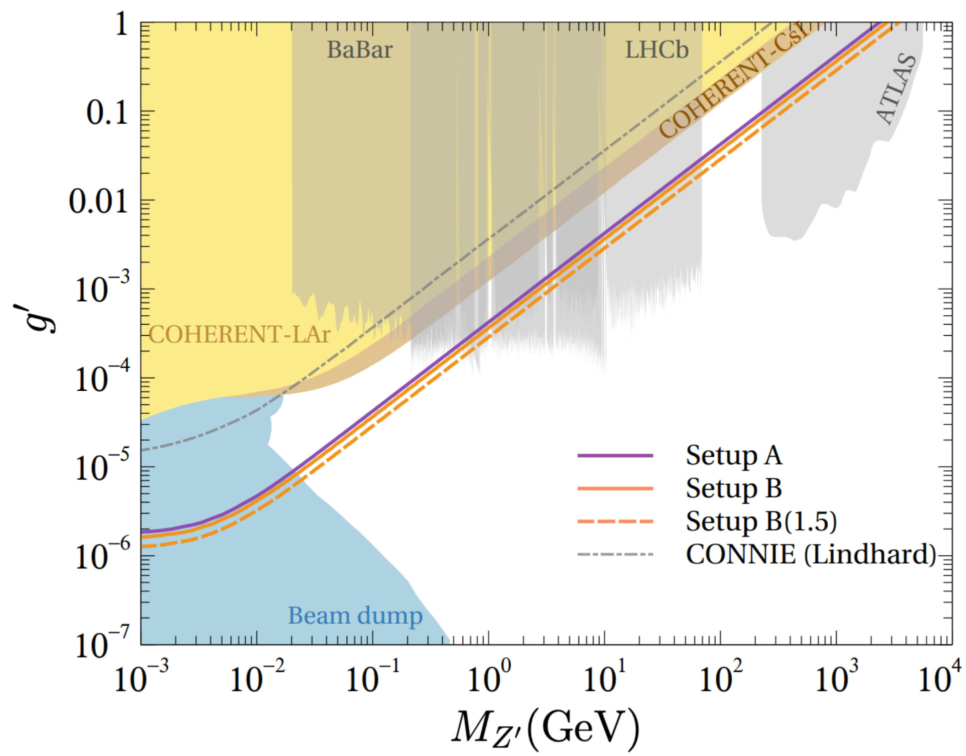
ININ exposure room

- **Two sites explored: ININ and Laguna Verde**

Setup	LAr mass (kg)	Power (MW_{th})	Distance (m)	Anti-ν flux uncertainty (%)	Threshold uncertainty (%)
A	10	1	3	2.4	5
B	100	2000	30	2.4	5
B(1.5)	100	2000	30	1.5	2

SBC CEνNS Physics: weak mixing angle and Z' boson





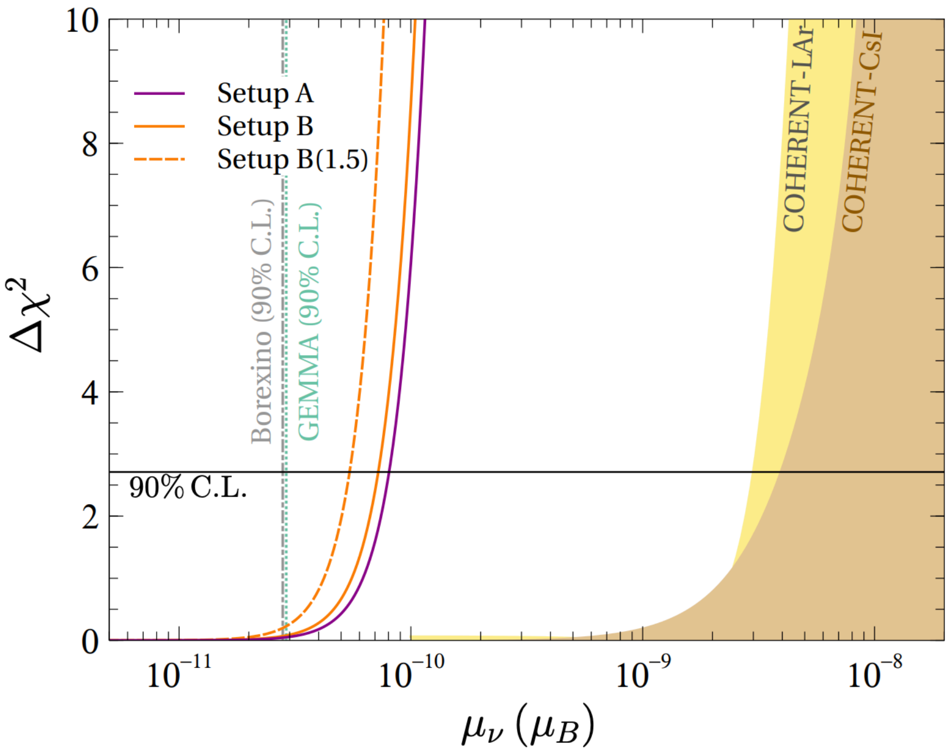
- **Precision as good as 1% in the weak mixing angle, similar to APV.**

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left(2 - \frac{M_N T}{E_\nu^2}\right) F^2(q^2)$$

- **Most stringent bounds for new gauge vector bosons (0.02 - 1 GeV and 70 - 230 GeV).**

$$\mathcal{L}_{\rm eff} = -\frac{g'^2 Q_l Q_q}{q^2 + M_{Z'}^2}\left[\sum_\alpha \bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha\right]\left[\sum_q \bar{q}\,\gamma_\mu q\right]$$

SBC CEνNS Physics: ν magnetic moment

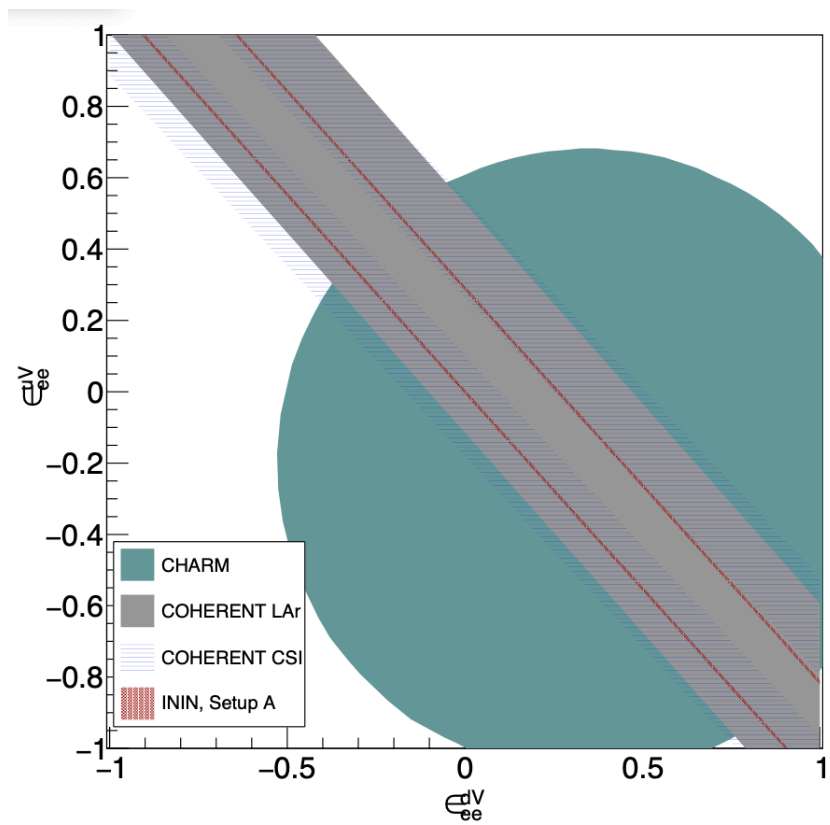


- $\mu_\nu = 5.4 \times 10^{-11} \mu_B$ **(90% C.L.), similar to GEMMA and Borexino.**

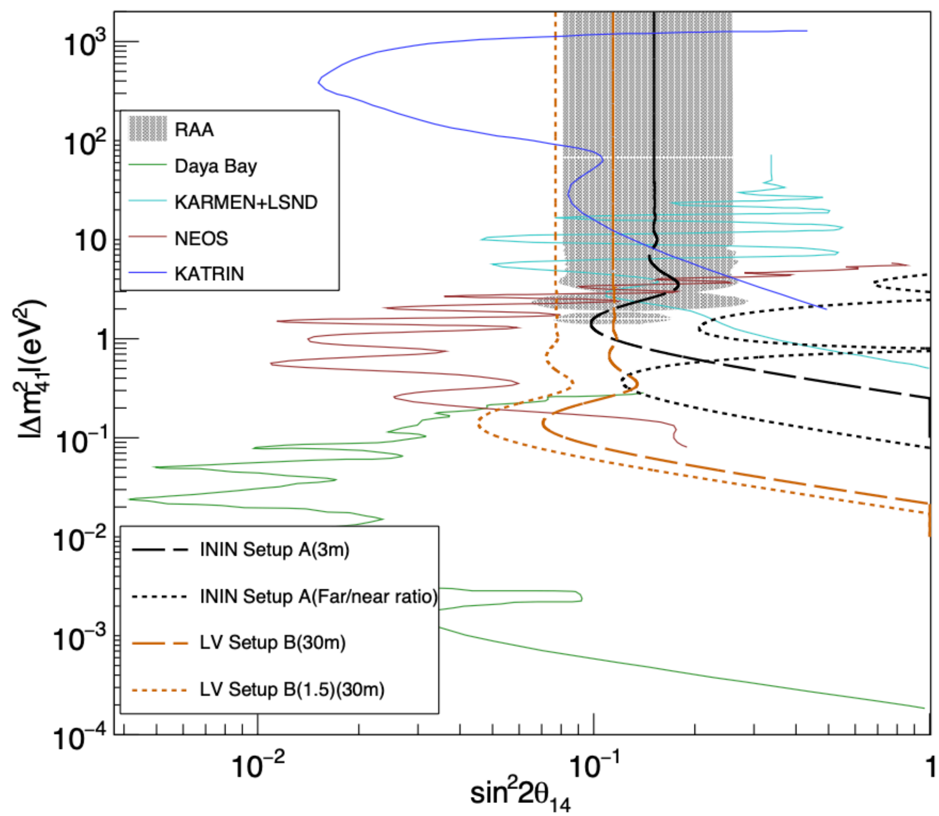
$$\frac{d\sigma}{dT} = \pi \frac{\alpha_{\rm EM}^2 Z^2 \mu_\nu^2}{m_e^2} \left(\frac{1}{T} - \frac{1}{E_\nu} + \frac{T}{4E_\nu^2} \right) F^2(q^2)$$

Physics reach of a low threshold scintillating argon bubble chamber in coherent elastic neutrino-nucleus scattering reactor experiments
Phys. Rev. D 103, L091301 (2021)

SBC CEνNS: New Physics



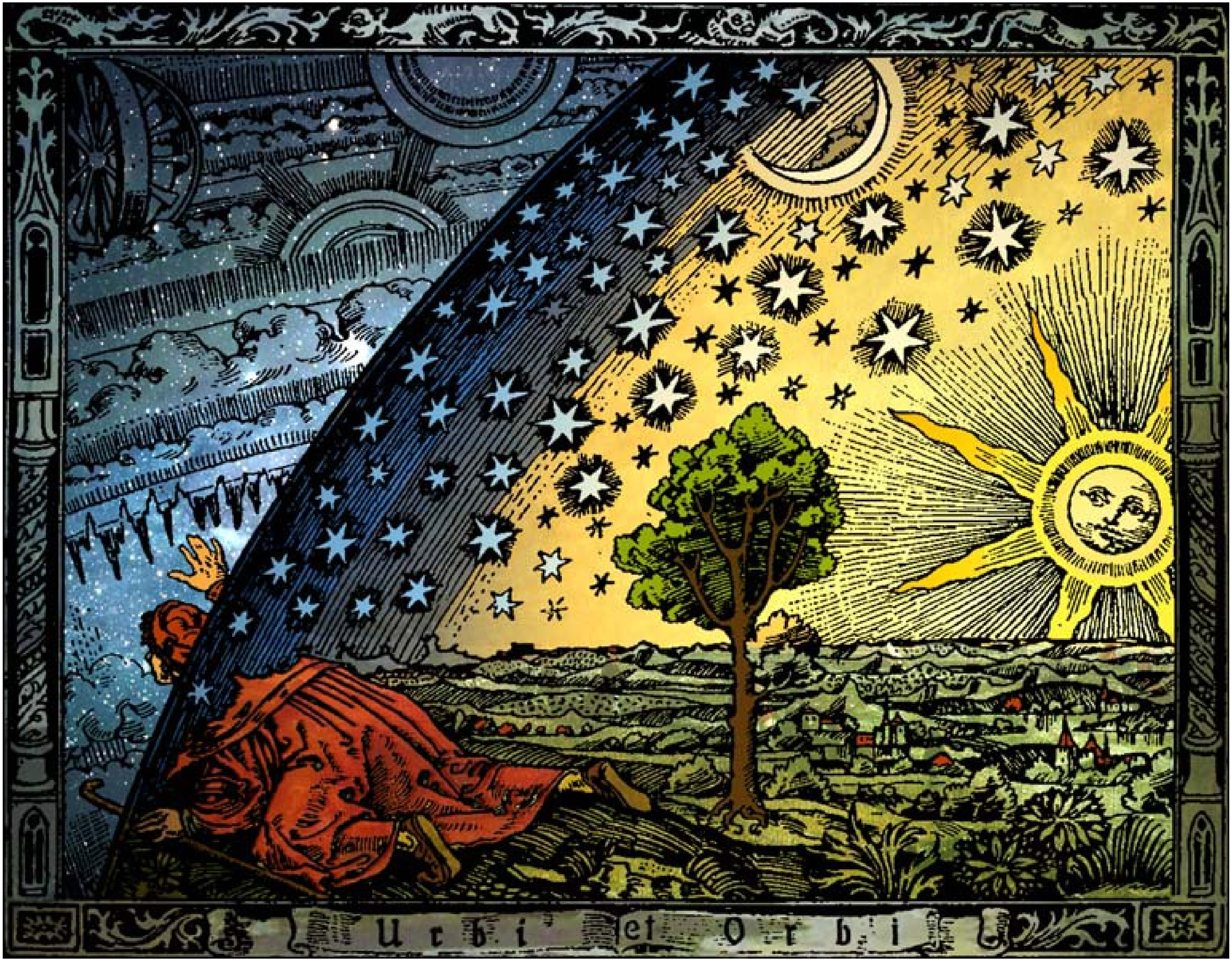
Non-standard interactions

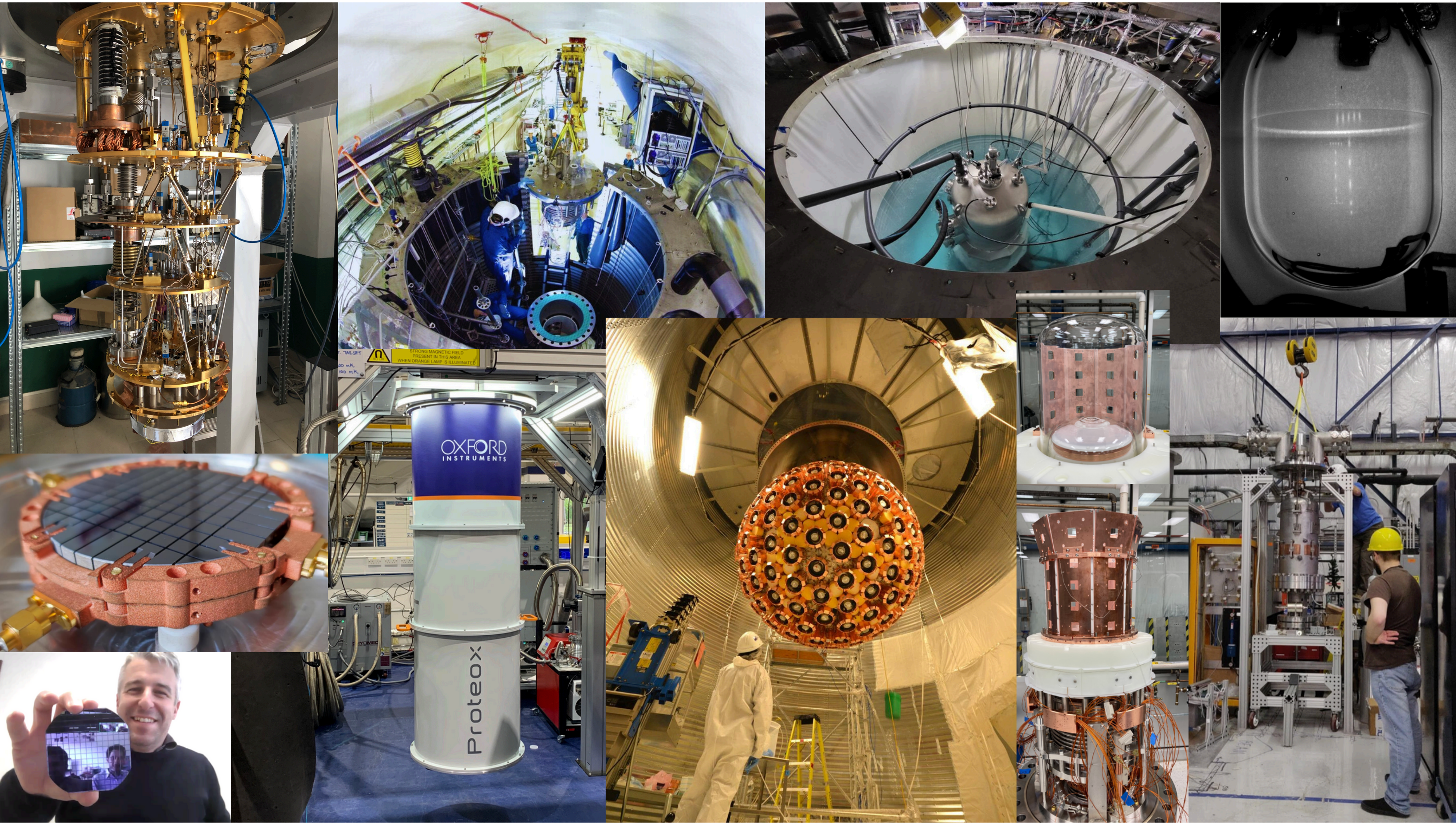


Sterile neutrinos

New Physics searches in a low threshold scintillating argon bubble chamber measuring coherent elastic neutrino-nucleus scattering in reactors

Phys. Rev. D 105, 113005 (2022)


Urbi et Orbi


STRONG MAGNETIC FIELD
PRESENT IN THIS AREA
WHEN ORANGE LAMP IS ILLUMINATED
OXFORD
INSTRUMENTS
Proteox