Dark Matter Searches: Direct Detection

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IFUNAM

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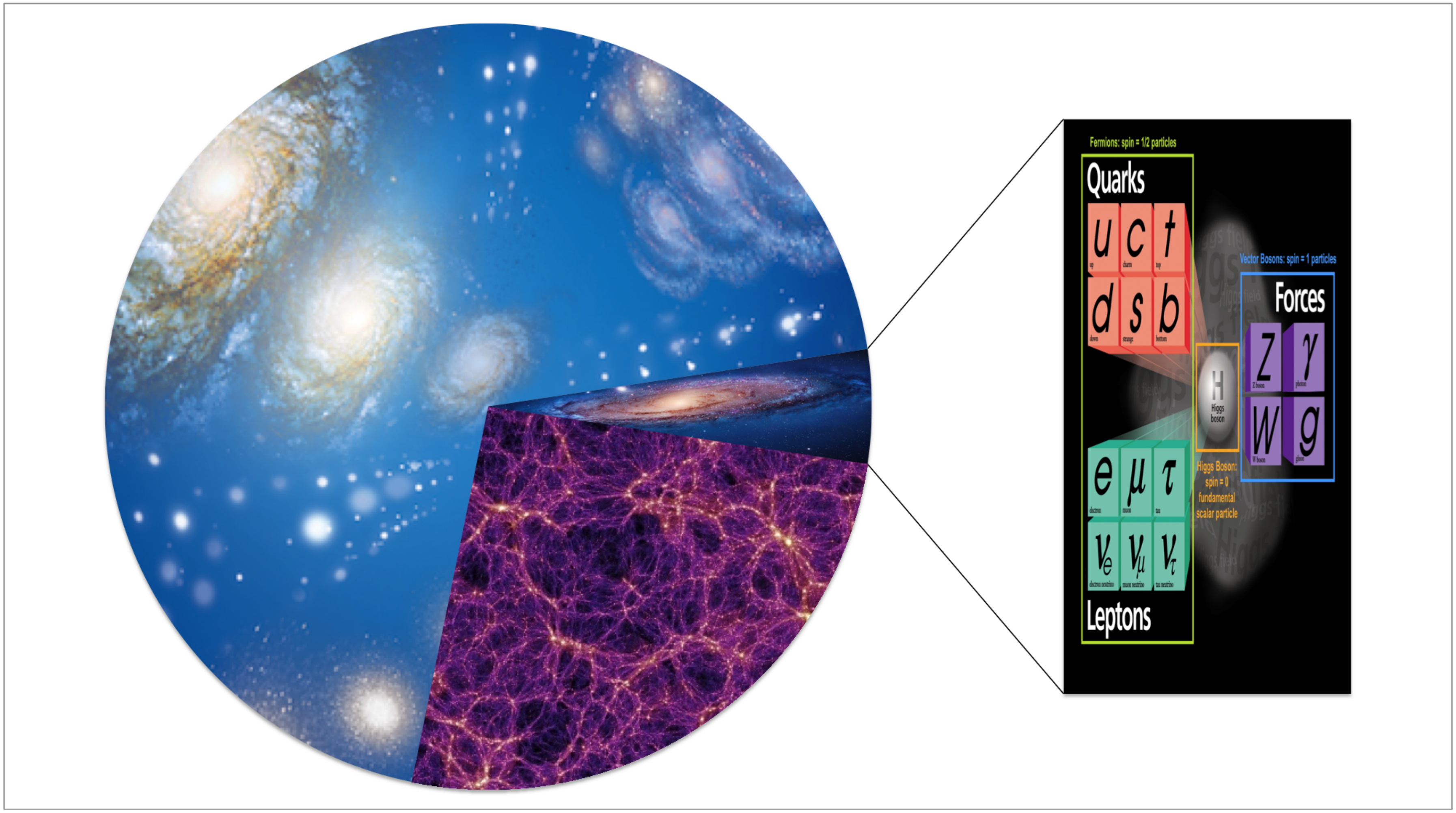
Outline

- **Direct detection of dark matter**
- **Noble fluids**
- **Crystals**
- **Threshold detectors**
- **New techniques**
- **Final remarks**

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)

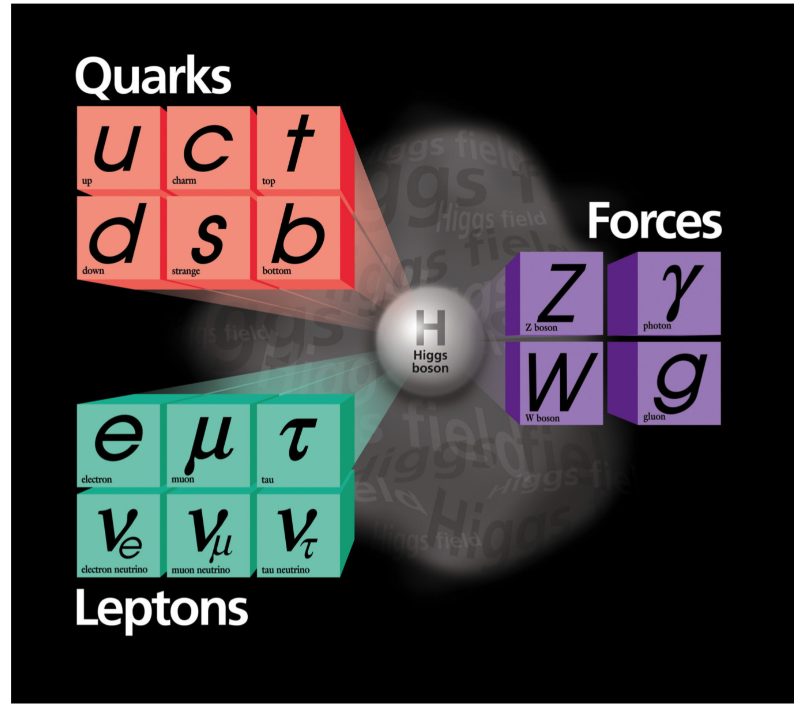


Our Universe today: ΛCDM
from an impressive number of observations

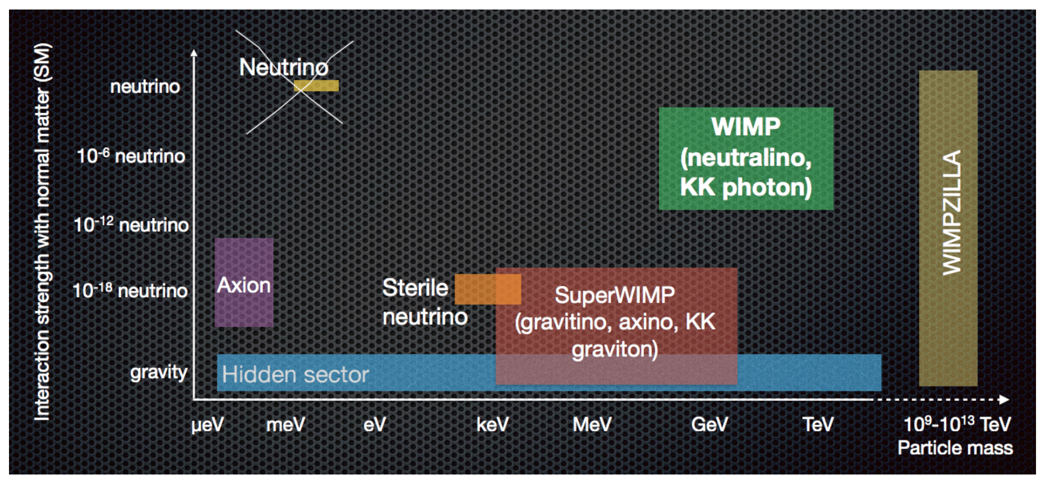
What do we know about dark matter?

- 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



Mass and cross section range
span many orders of magnitude



Candidates to dark matter

Two main candidates attract most of the present activity in the field

WIMPs

(Weakly Interacting Massive Particles)

a neutral heavy fermion like the LSP in SUSY

Supersymmetry produces a theoretical candidate, but others exist (e.g. Kaluza-Klein particles, ...)

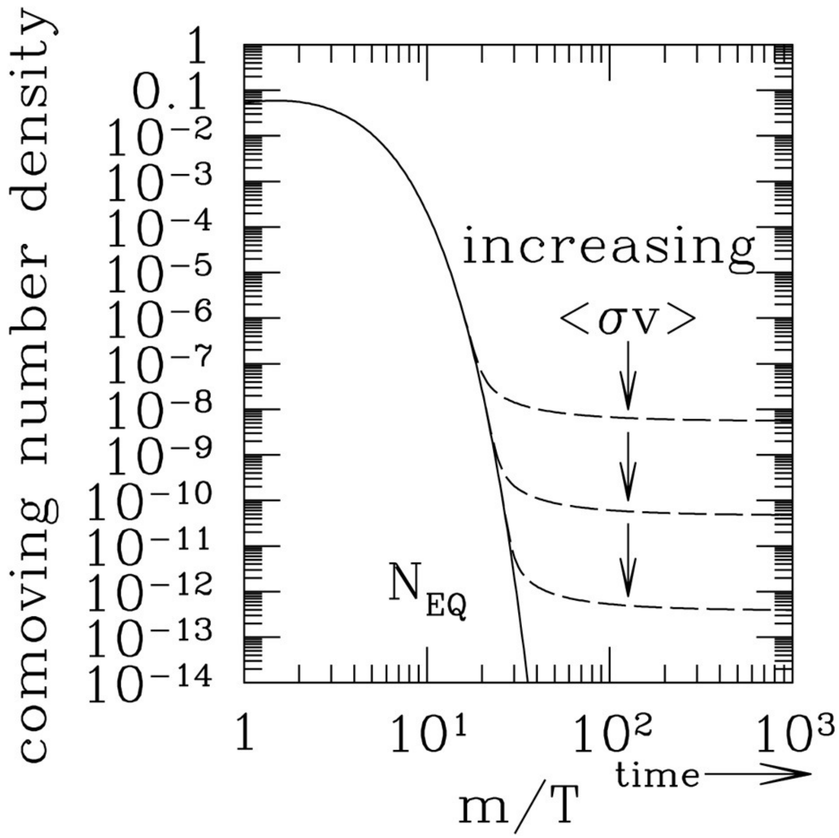
Introduced by Peccei & Quinn as a solution to the strong CP problem

Axion-like particles to refer to fundamental very light (pseudo) scalar of similar properties without referring to a specific theory model

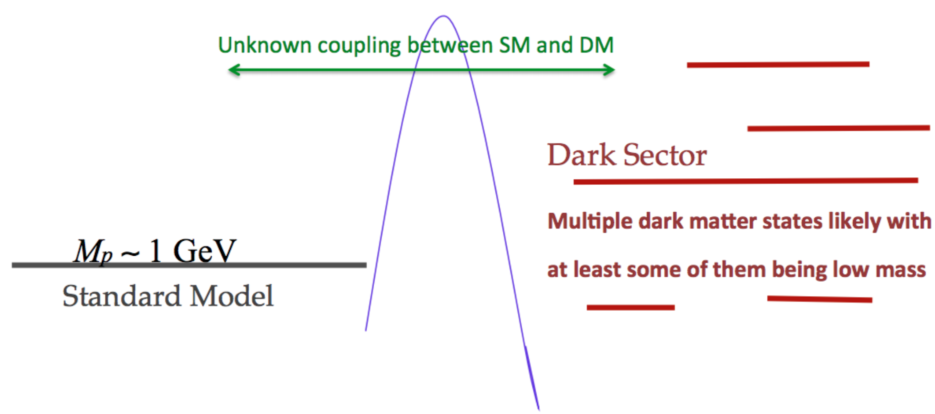
Axions

WIMP

- Most discussed candidate:
  Weakly Interacting
  Massive Particle
- Produced during Big Bang, in thermal equilibrium in the early Universe
- Decouples from ordinary matter as the Universe expands and cools
- Still around today with densities of about a few per liter

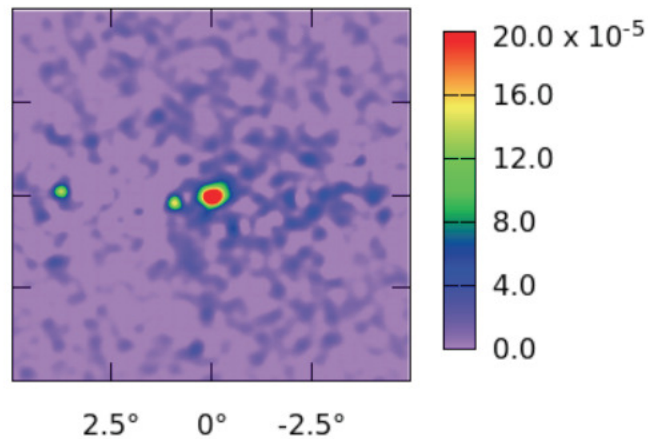


Dark sector could be
as complicated as the SM
Searches not limited by
expectations from SUSY models

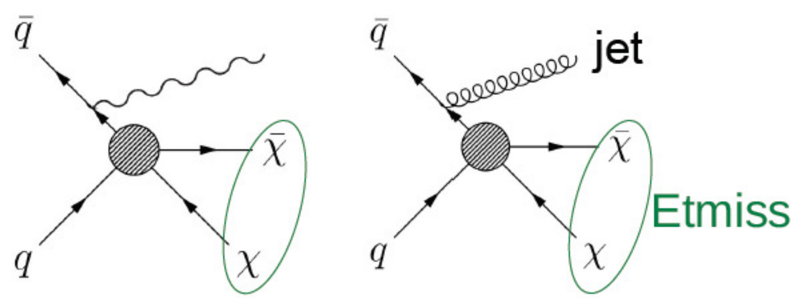


Detection methods

- **Astrophysics / Cosmology:**
  measurement of gravitational effects
- **Indirect detection:**
  from annihilation or decay (AMS, HAWC)



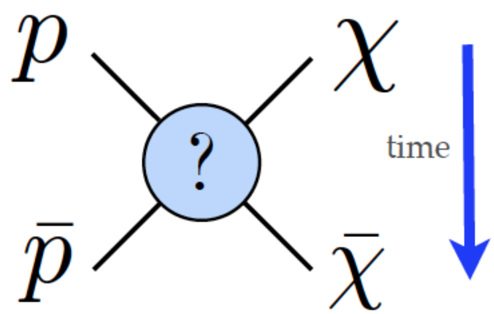
- **Accelerator-based creation and measurement (LHC)**



- **Direct detection: WIMP scattering**

Direct detection

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



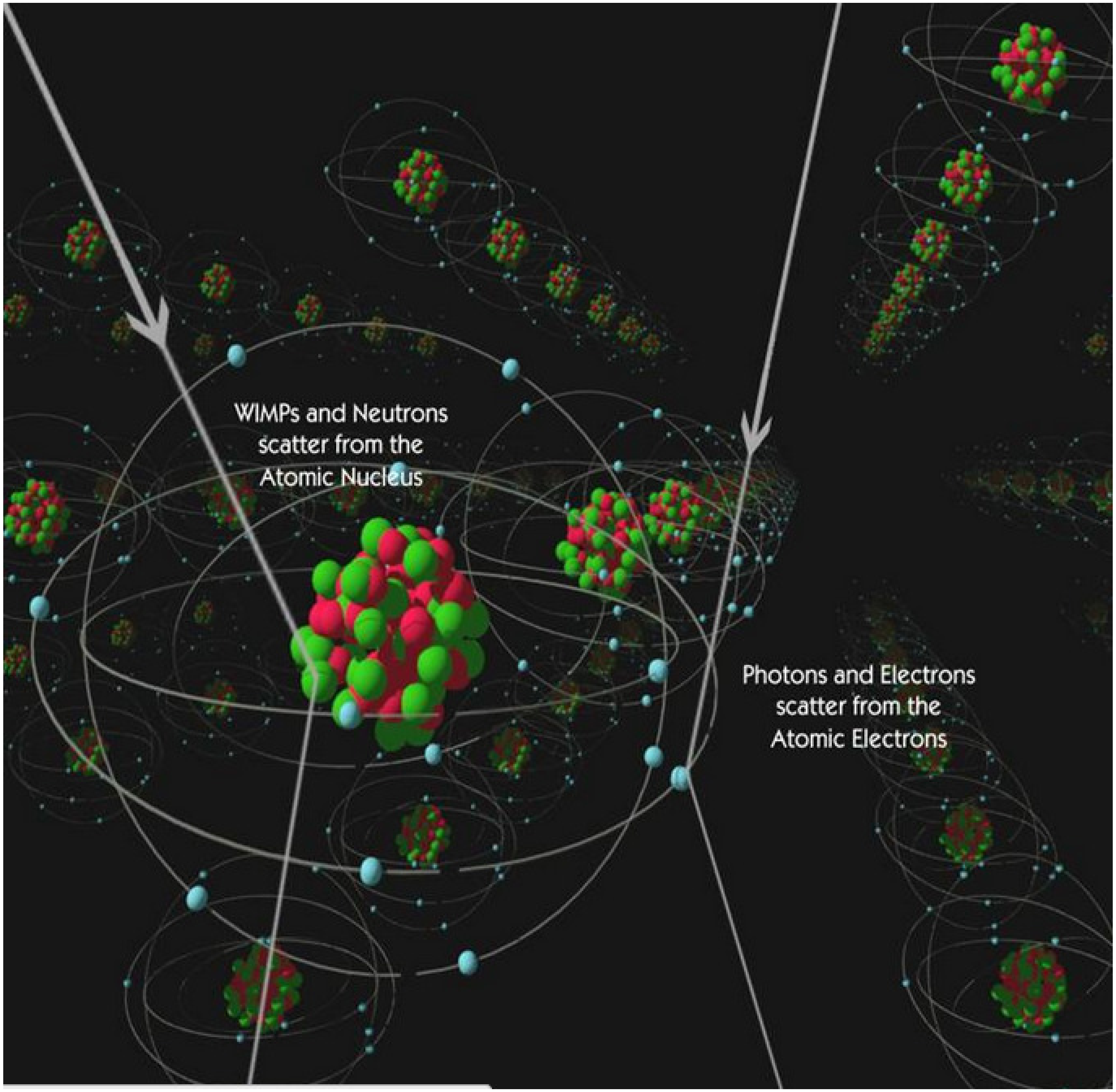
- **Calculate rate based on assumptions about the dark matter distribution and interaction**
- **Historically two interactions are considered (by DM experimentalists)**
  - **Spin independent (SI) - couples to all nucleons (enhancement for large nuclei)**
  - **Spin dependent (SD) - couples to the spin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

Spin-independent

Spin-dependent

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

Direct detection



Rate calculation

The differential cross section (for spin-independent interactions) in events/kg/keV mass per unit recoil energy is:

$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv \qquad (1)$$

- Dark matter density component, from local and galactic observations with historically a factor of 2 uncertainty
- The unknown particle physics component σ_0 (where μ_p is the reduced mass of the proton)
- The nuclear part, approximately given by $F^2(Q) = e^{-Q/Q_0}$ (where $Q_0 = \frac{80}{A^{5/3}}$ MeV)
- The velocity distribution of dark matter in the galaxy of order 30% uncertainty (not-statistical) and $v_m = \sqrt{Q m_N / 2 m_r^2}$

Backgrounds in dark matter detectors

- **Radioactivity of surroundings**
- **Radioactivity of detector and shield materials**
- **Cosmic rays and secondary reactions**

Some comparisons:

- **How much radioactivity (in Bq) is in your body? where from?**
- **What is the most radioactive food we eat?**
- **How many radon atoms escape per m^2 of ground, per second?**

Backgrounds in dark matter detectors

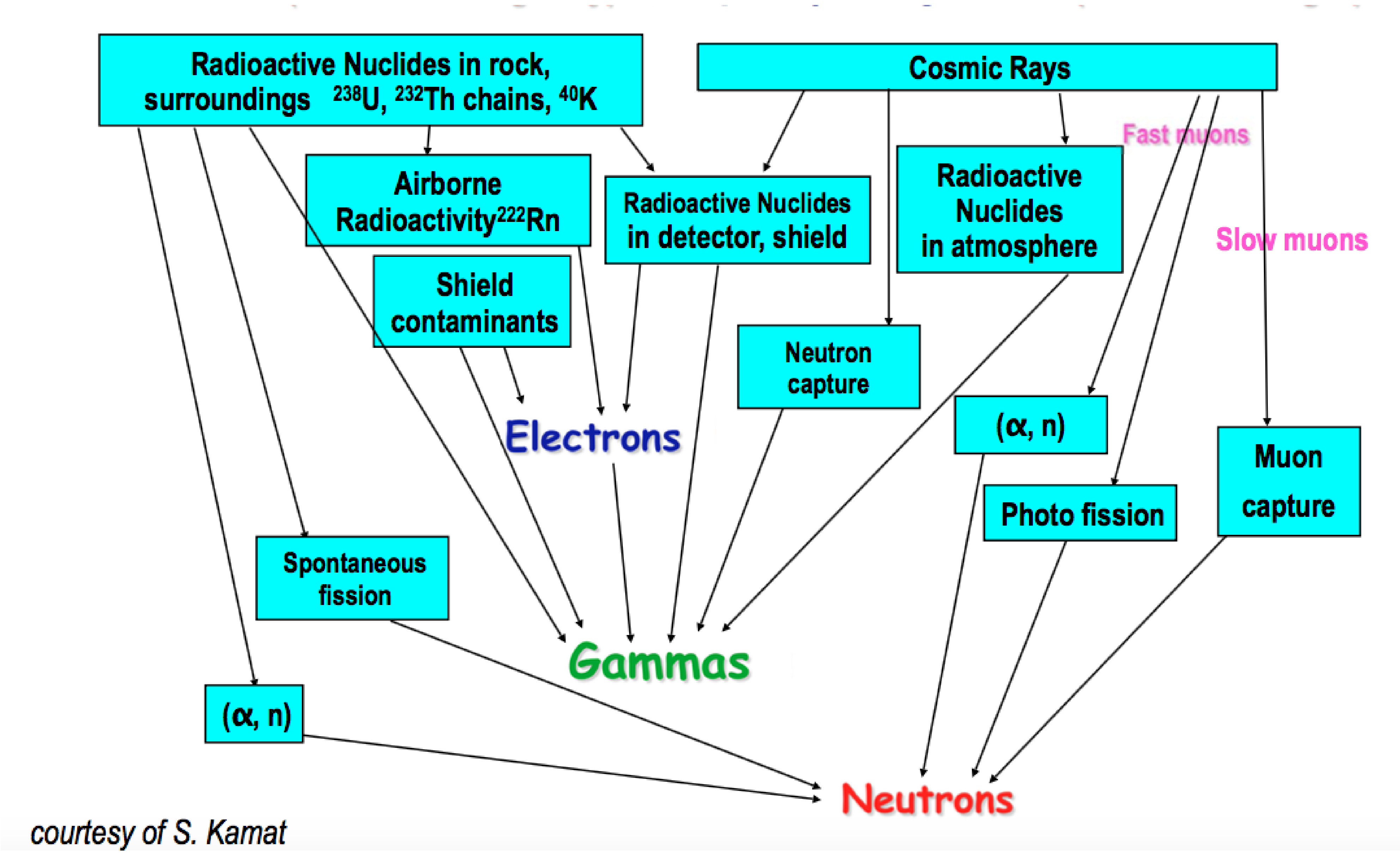
- **Radioactivity of surroundings**
- **Radioactivity of detector and shield materials**
- **Cosmic rays and secondary reactions**

Some comparisons:

- **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

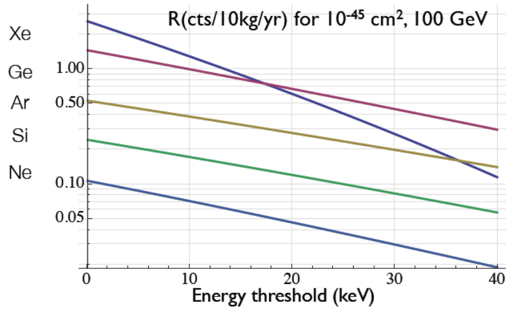
WIMP scatters (<1 event/ton/year) swamped by backgrounds
($> 10^{11-12}$ events/ton/year)

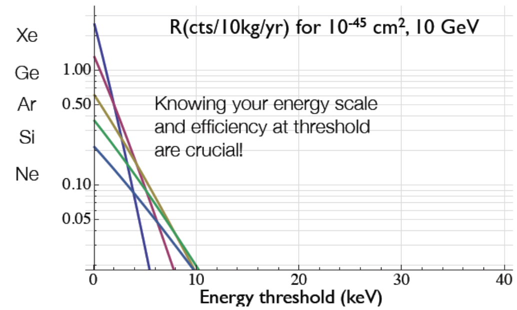
Cosmic rays and natural radioactivity



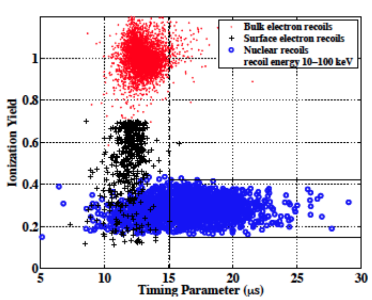
The recipe for direct detection of dark matter

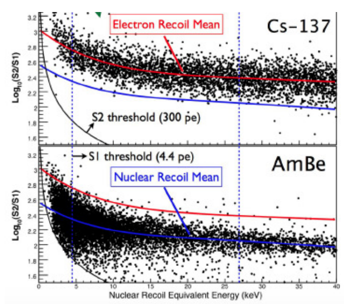
- **Detect tiny energy deposits, energy of recoils is tens of keV**
  $\frac{1}{2}m_N v_N^2 = \frac{1}{2}(100GeV)(10^{-6}) = 50keV$

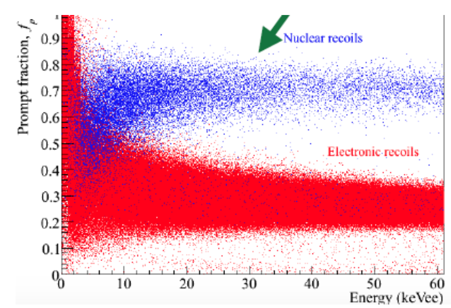




- **Background suppression:**
  - Deep sites to reduce cosmic ray flux
  - Passive/active shielding
  - Careful choice and preparation of material
- **Background discrimination (electronic recoils vs nuclear recoils)**



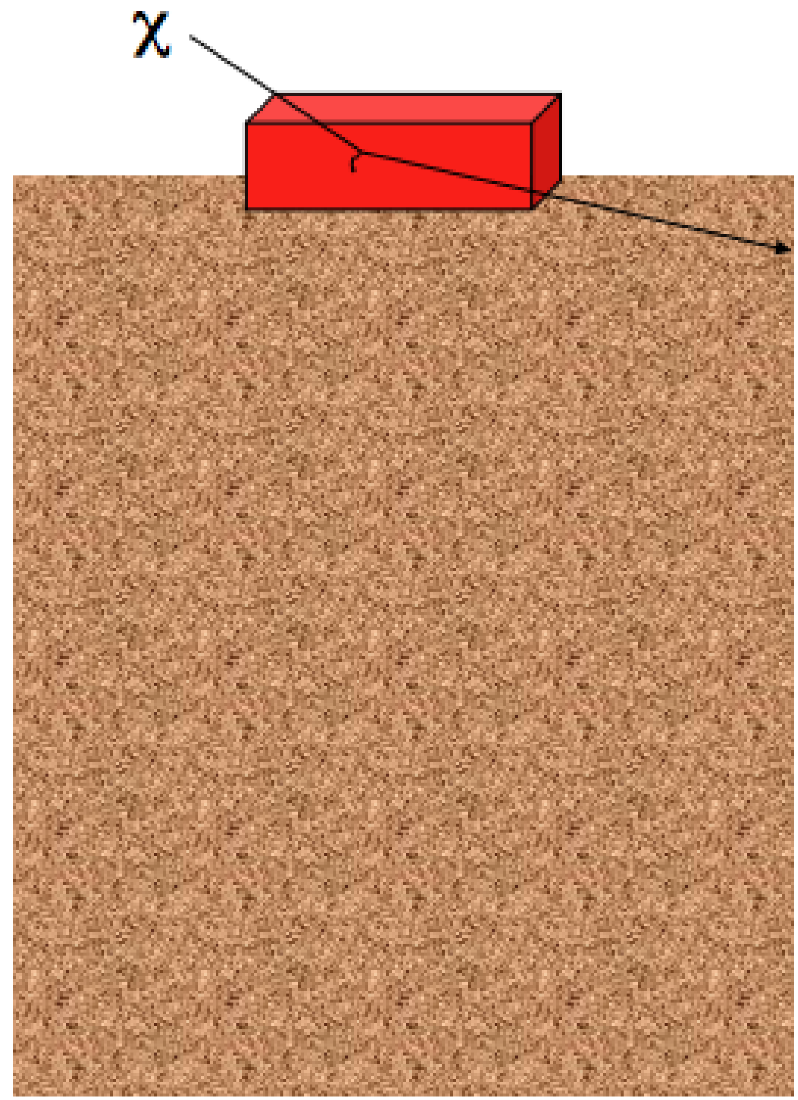




- **Large target mass, scalability to ton-scale targets**

How to catch a WIMP

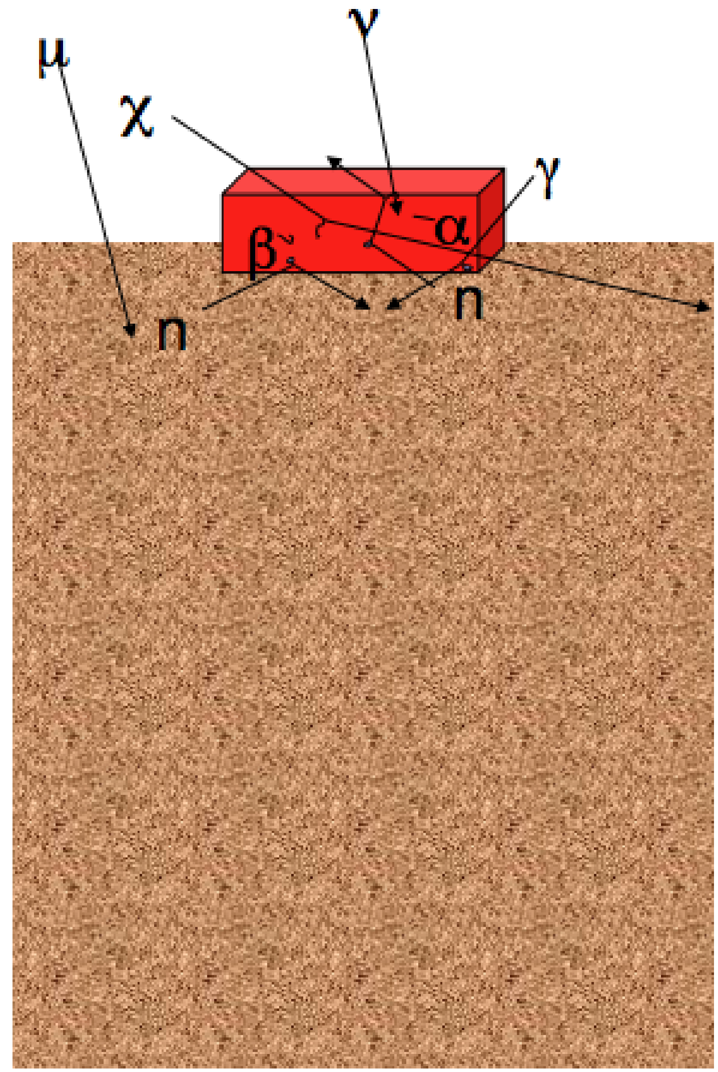
- **We live in a Dark Matter halo!**
  - **Local density ~ 0.4 GeV/cm^3**
  - **rms velocity 230 km/s**
- **Look for coherent elastic scattering off nuclei**
- **Two generic interactions**
  - **spin-independent: scalar coupling, coherent scattering ($\sigma \propto A^2$)**
  - **spin-dependent: vector coupling, couples to odd-nucleon**



How to catch a WIMP

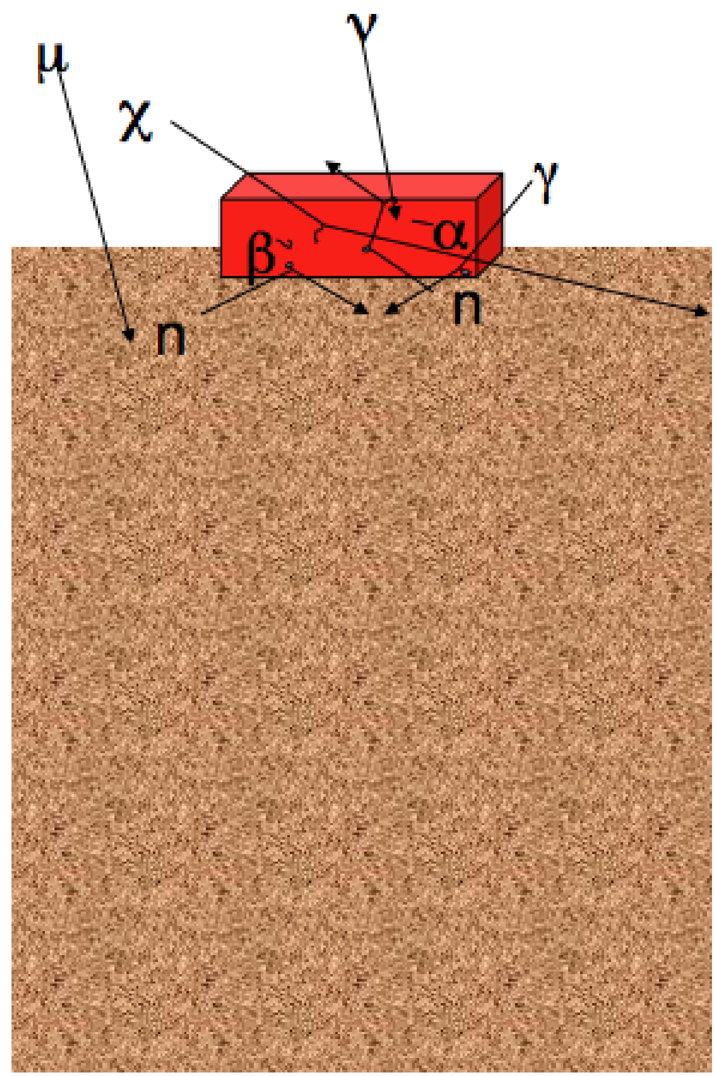
- **We live in a Dark Matter halo!**
  - **Local density ~ 0.4 GeV/cm^3**
  - **rms velocity 230 km/s**

- **Look for coherent elastic scattering off nuclei**
  - **Recoil energies $O(10)$ keV**
  - **Rates $\leq O(1)$ event/kg-year**
  - **Many backgrounds from natural radioactivity**

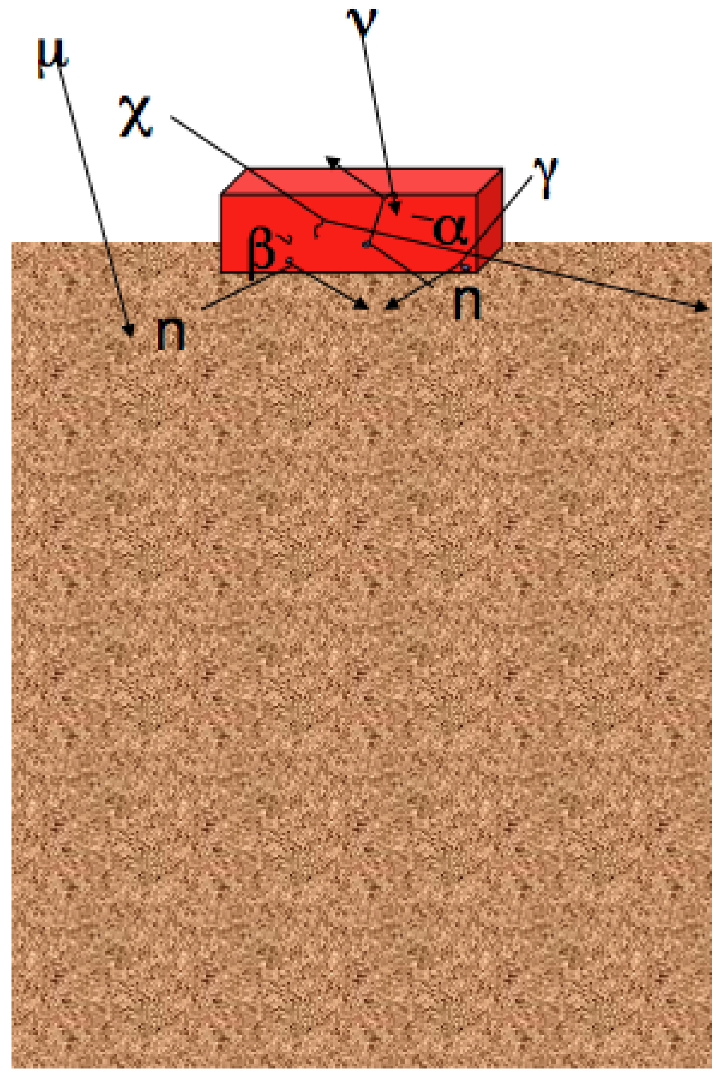


Internal backgrounds

- **β decays**
  - **screen and purify detector materials**
  - **discriminate between electron tracks and nuclear recoils**
- **α decays**
  - **screen and purify detector materials**
  - **discriminate between $O(10)$ keV WIMP events and 5 MeV α-decays**

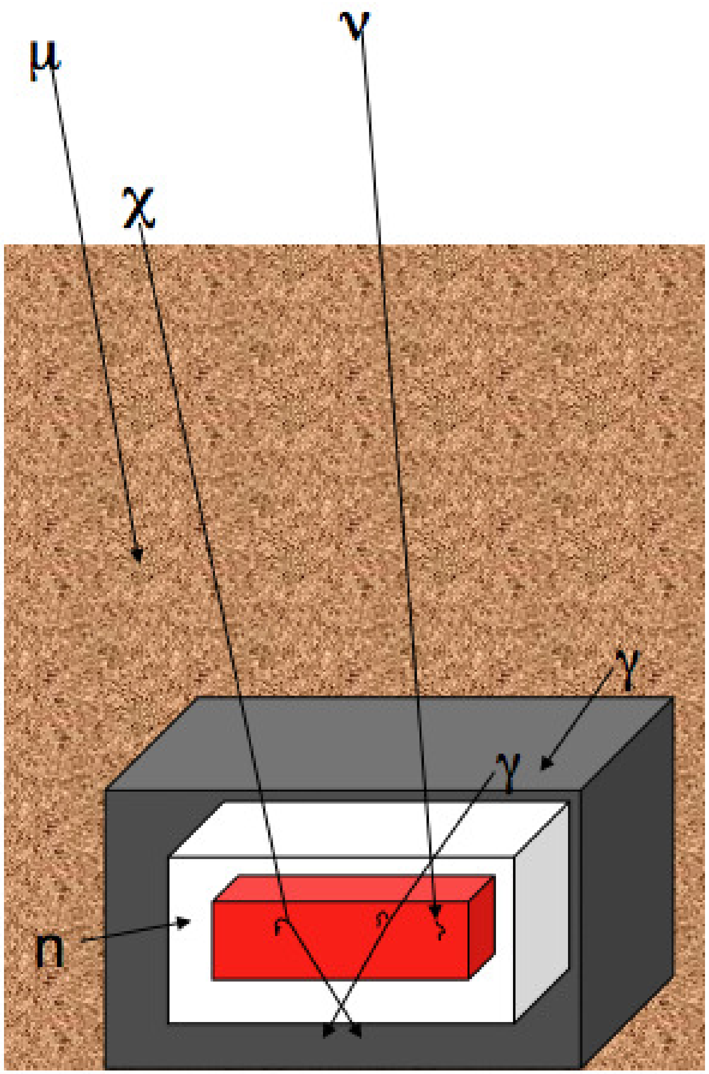


- **neutrons**
  - **Produced by fission, (α,n) reactions, cosmic rays**
  - **Give elastic scatters off nuclei, same as WIMP signal**
  - **Shield detector with low-Z moderator, screen materials, go underground**
  - **Reject multiple-scatters**



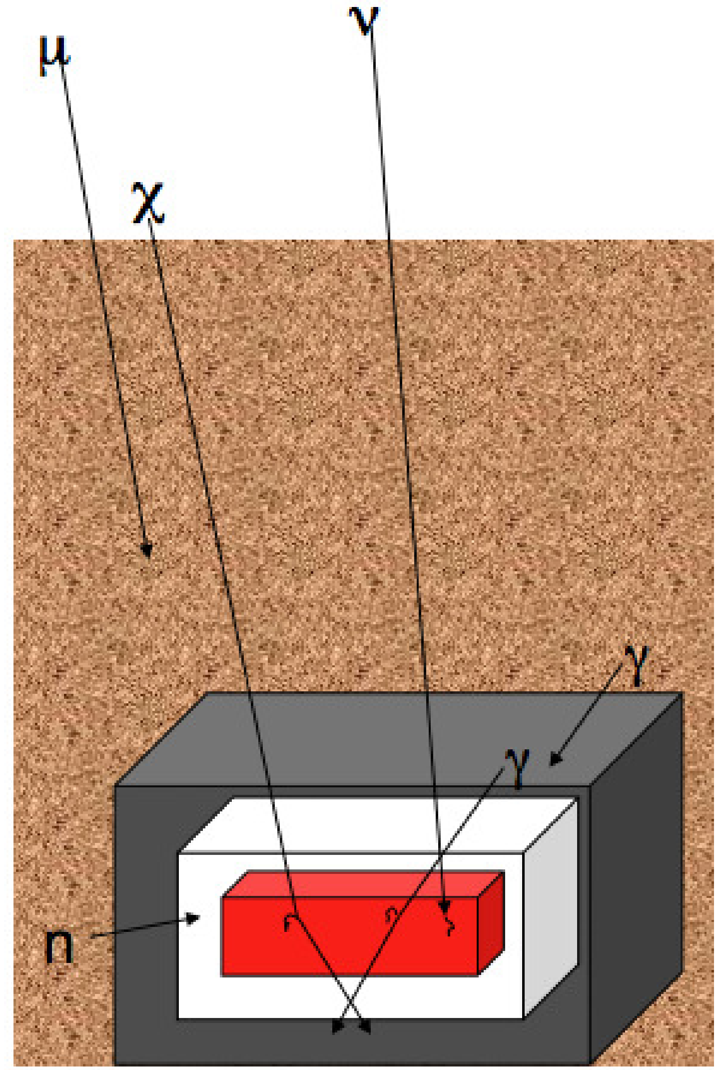
External backgrounds

- **neutrons**
  - **Produced by fission, (α,n) reactions, cosmic rays**
  - **Give elastic scatters off nuclei, same as WIMP signal**
  - **Shield detector with low-Z moderator, screen materials, go underground**
  - **Reject multiple-scatters**



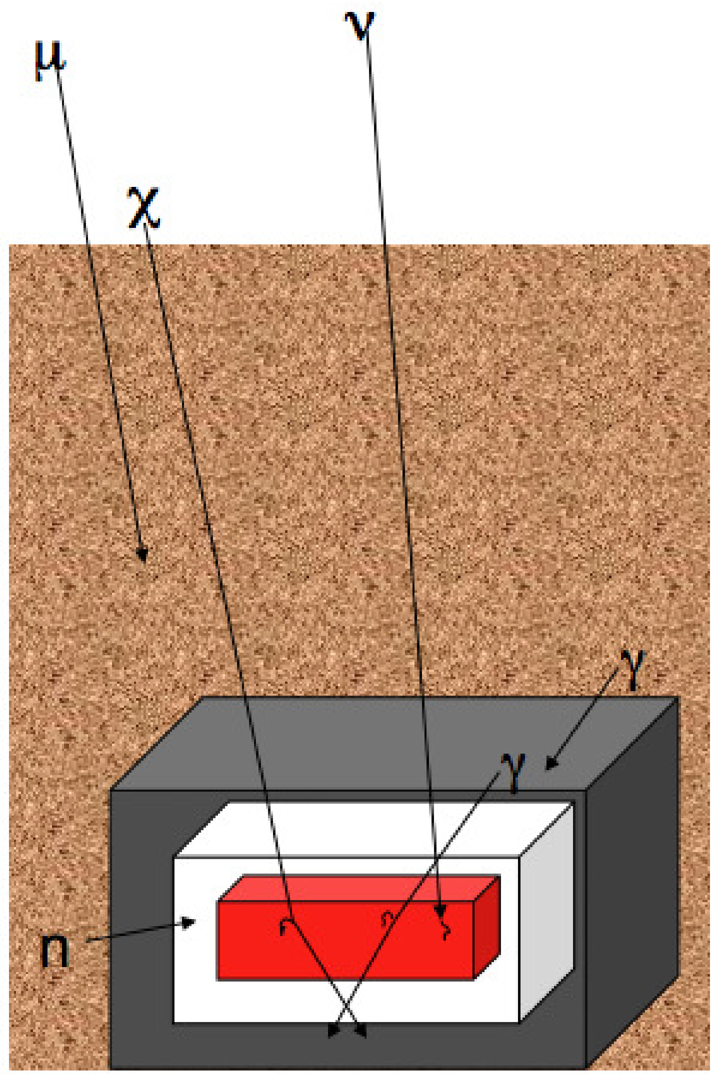
External backgrounds

- gammas
  - Compton scatter in detector
  - discriminate between electron tracks and nuclear recoils
  - Shield detector with low-Z moderator, screen materials, go underground
  - Reject multiple-scatters



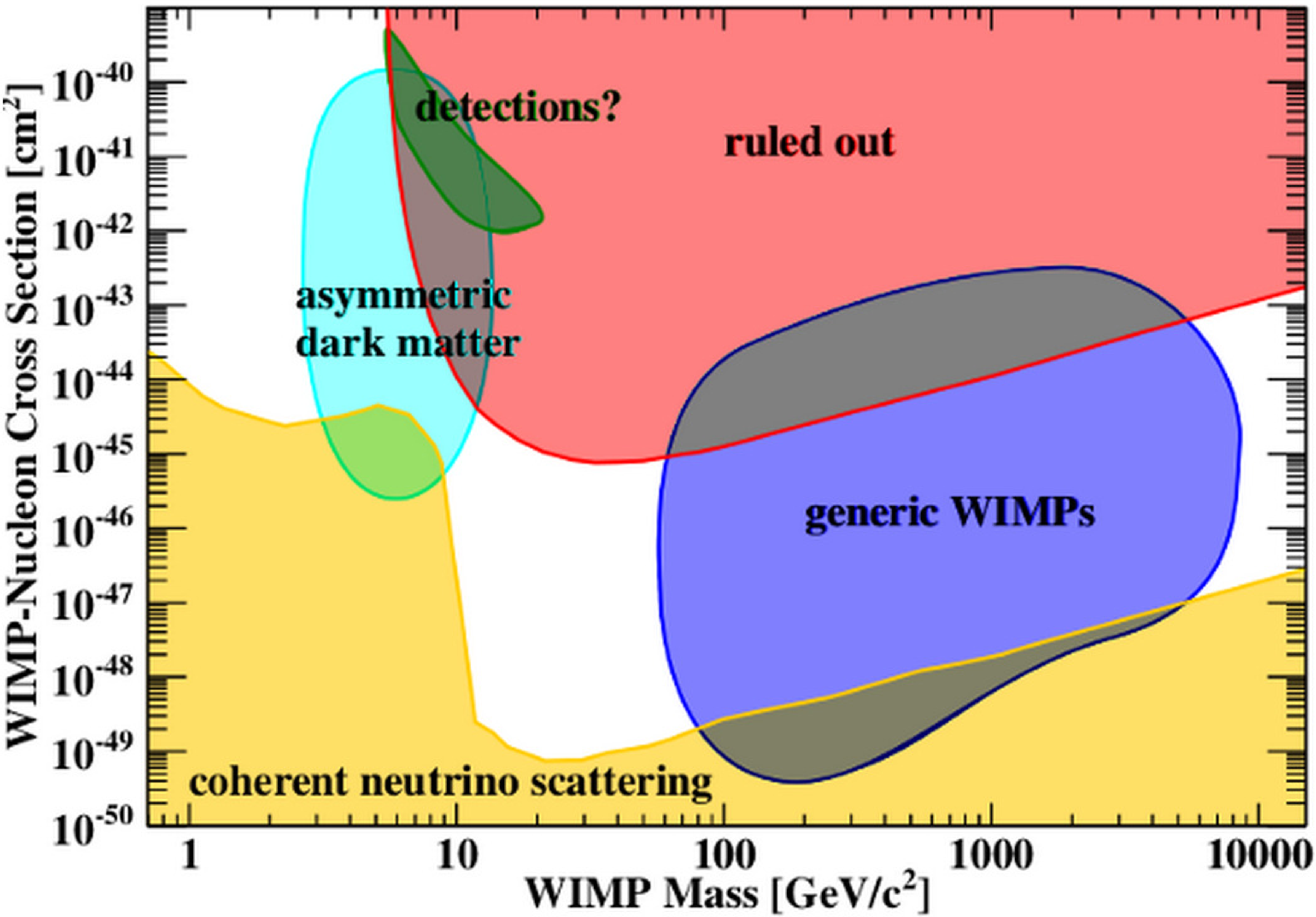
External backgrounds

- neutrinos
  - discriminate against charged-current interactions
  - No defense against high-energy neutrino neutral-current elastic scatters off nuclei

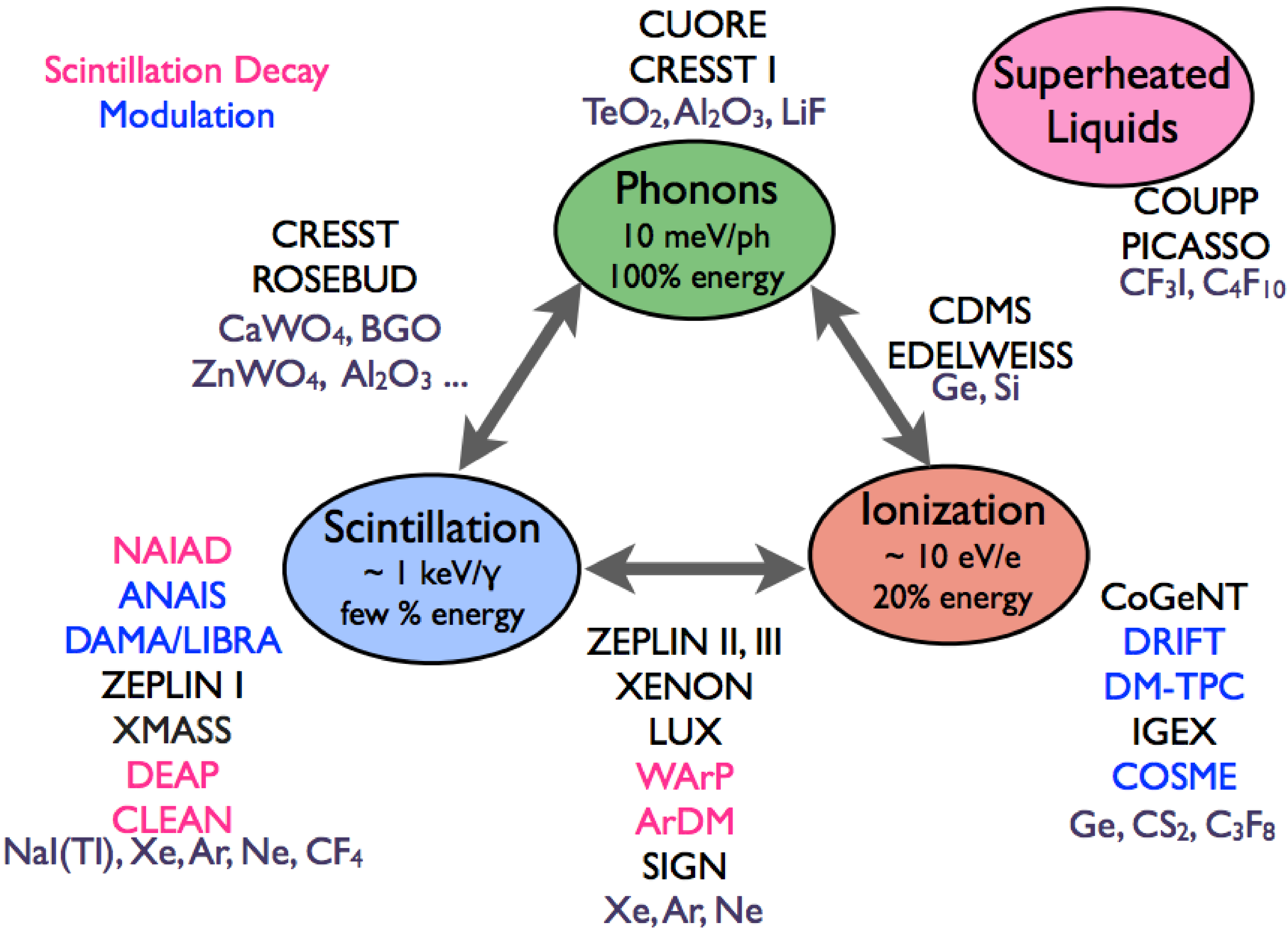


Irreducible neutrino background at $O(1)$ event/10 ton-years

Where are the WIMPs?: the canonical picture



Experimental programme

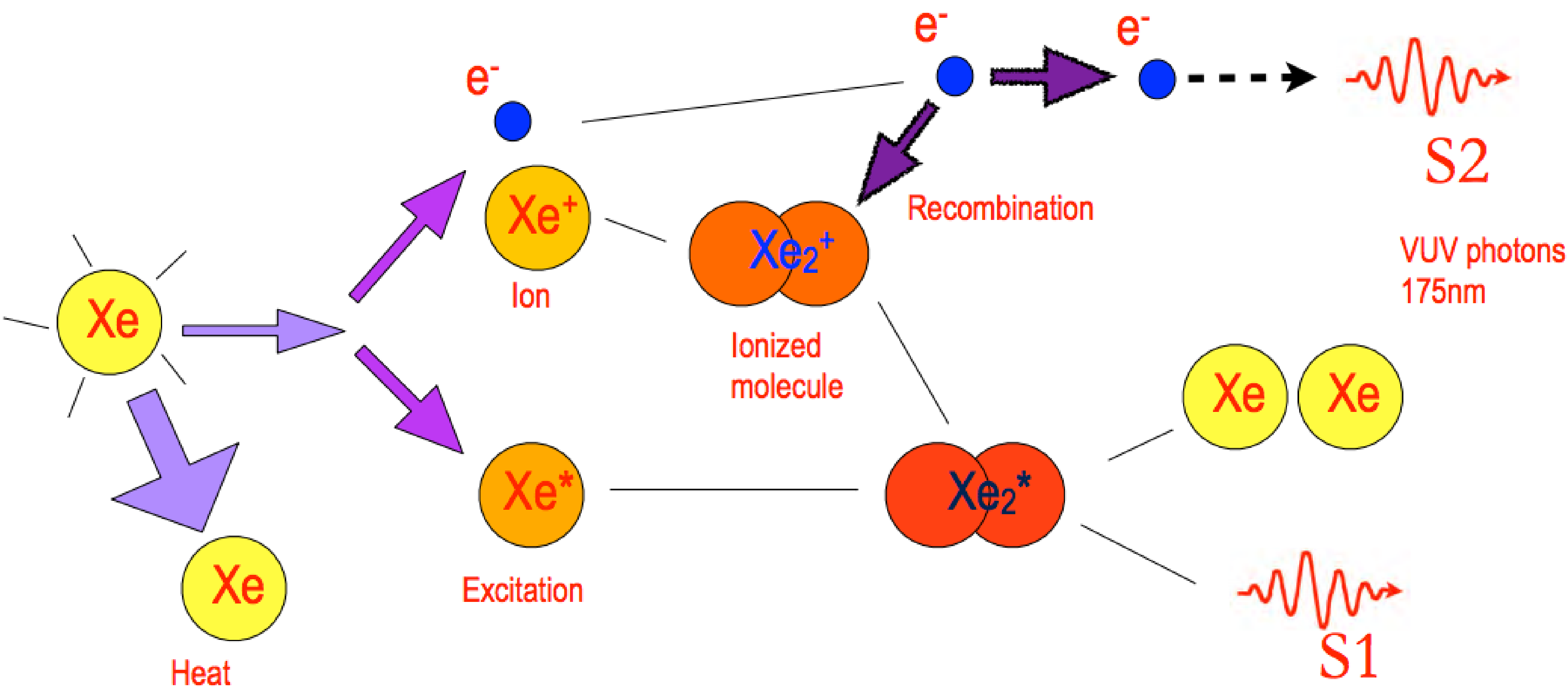


Noble fluids

Some properties of liquid noble detectors

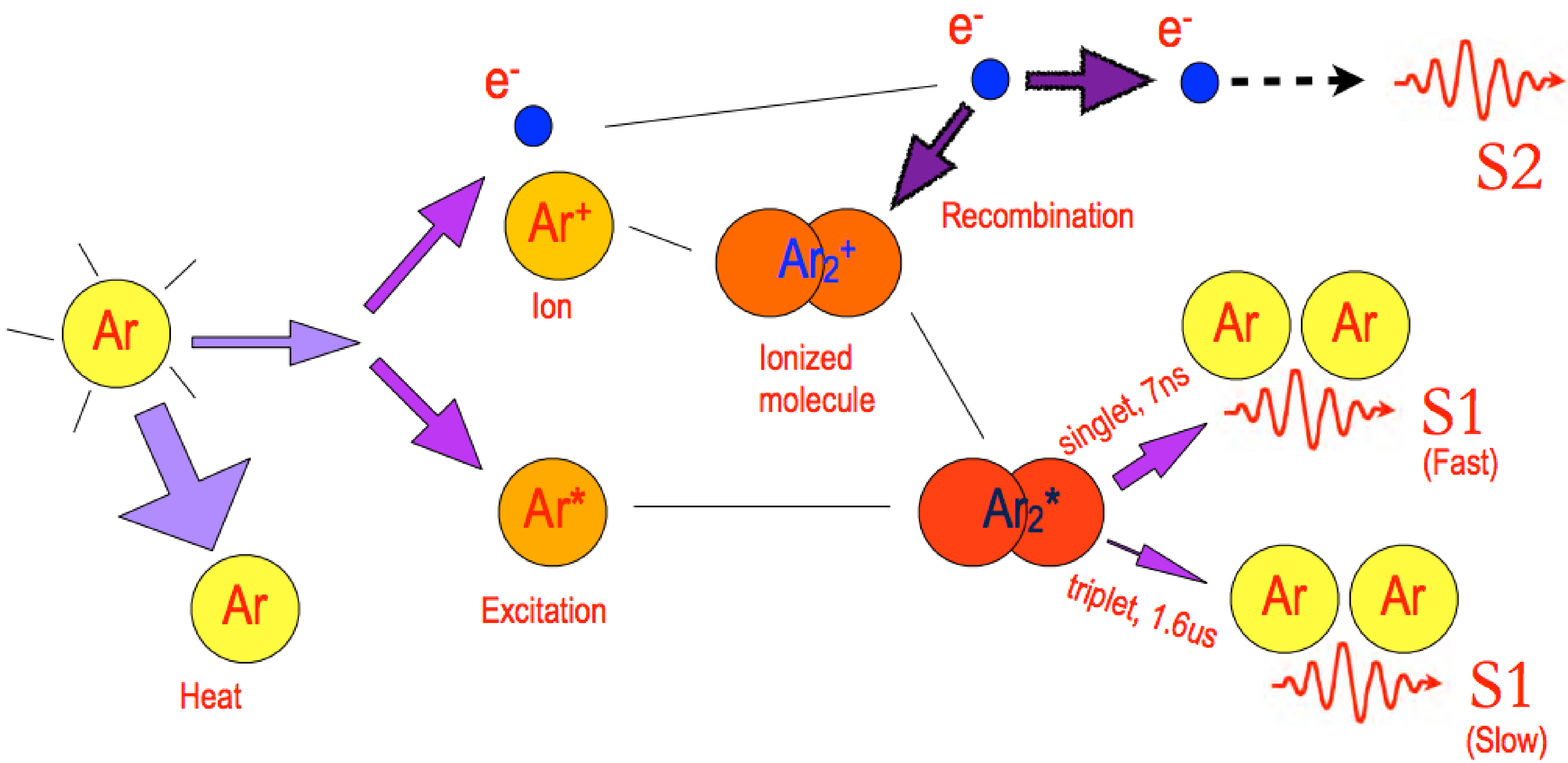
- **VUV to EUV**
  challenging but not impossible for PMTs
- **Long attenuation length**
  nominally transparent; depends on impurities
- **Long charge drift length**
  but requires significant engineering for purification and high voltage
- **Good dielectric / cryo environment**
  "nice" for PMTS
- **Low-background PMTs**
  steadily improved by Hamammatsu
- **Differential response for ER vs NR**
  Pulse Shape Discrimination (PSD) and S2/S1

Signal in Xe



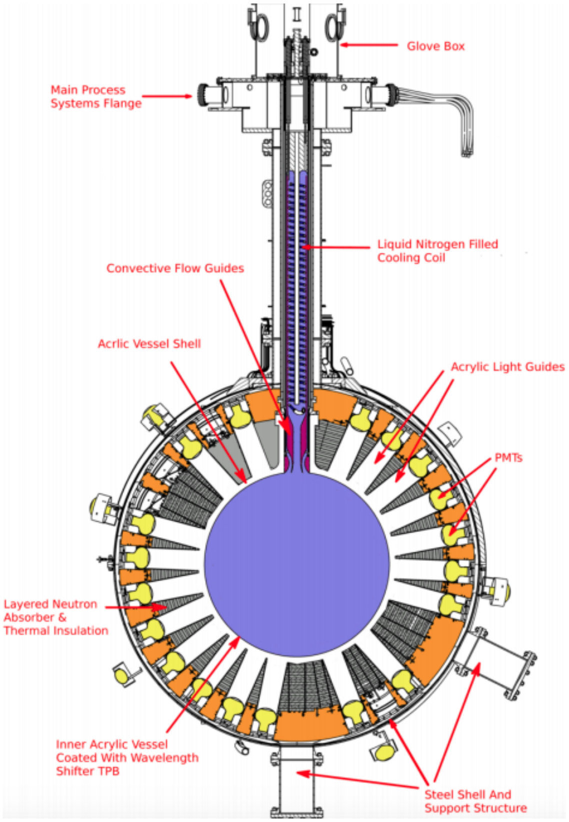
e-
e-
e-
S2
Xe+
Ion
Xe2+
Recombination
VUV photons
175nm
Ionized
molecule
Xe
Xe
Xe
Xe*
Xe2*
Xe
Excitation
S1
Heat

Signal in Ar



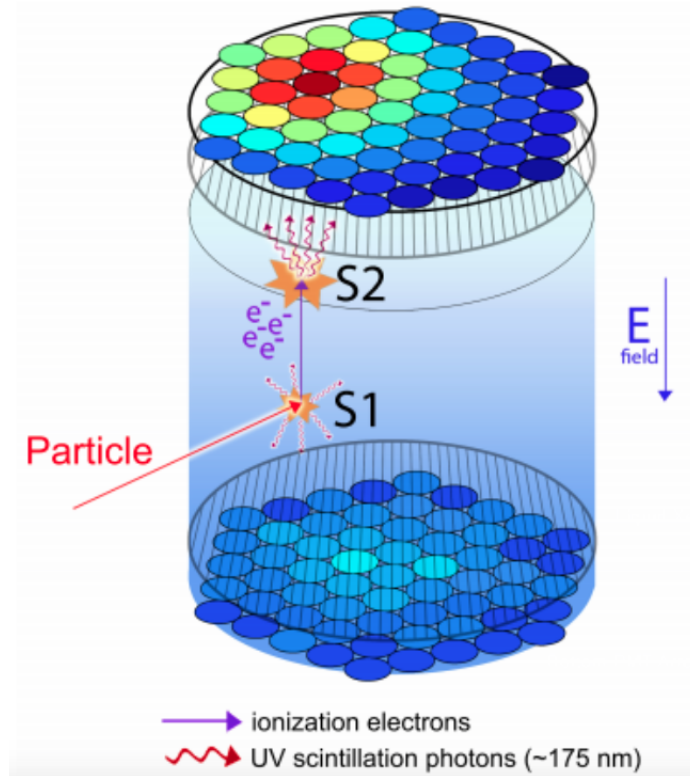
e-
e-
e-
S2
Ar+
Ion
Ar_2^+
Recombination
Ionized molecule
Ar
Ar
Ar
singlet, 7ns
S1
(Fast)
Ar*
Ar_2^*
Ar
Ar
triplet, 1.6us
Excitation
S1
(Slow)
Ar
Heat

Scintillation (4π):



- **Xenon: XMASS**
- **Argon: DEAP, miniCLEAN**

Time projection chamber:



- **Xenon: LUX/LZ, XENON-100/1T/nT, PANDA-X**
- **Argon: DarkSide, ArDM**

Noble liquid experiments: some examples

Dark Matter Experiment with Argon and Pulse-shape Discrimination:

- **scattered nucleus detected via scintillation**
- **pulse shape discrimination for suppression of β/γ events**
- **LAr advantages:**
  - **is easily purified and high light yield**
  - **is 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**

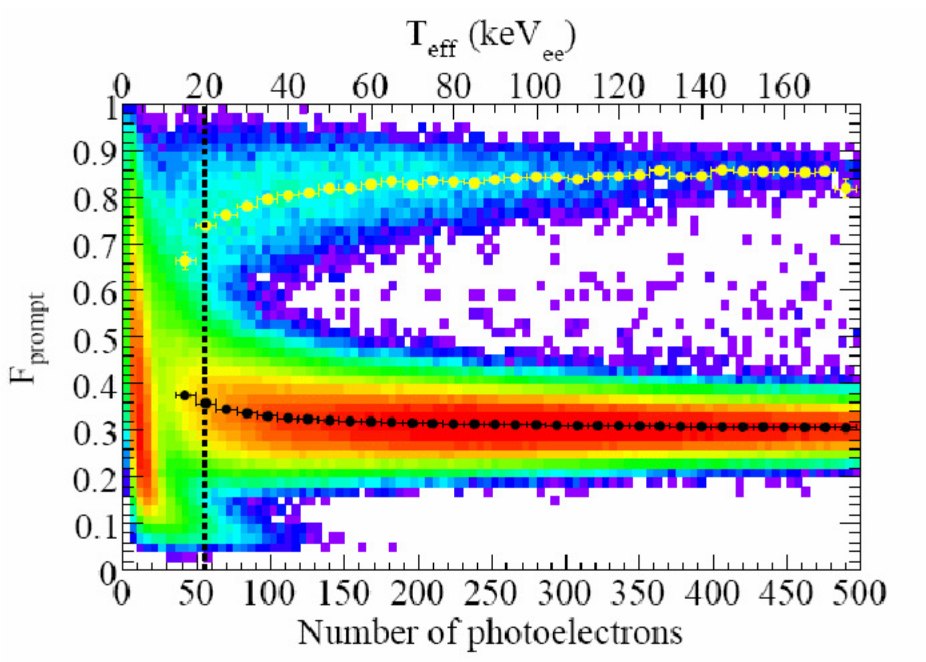
Backgrounds in liquid argon dark matter detector:

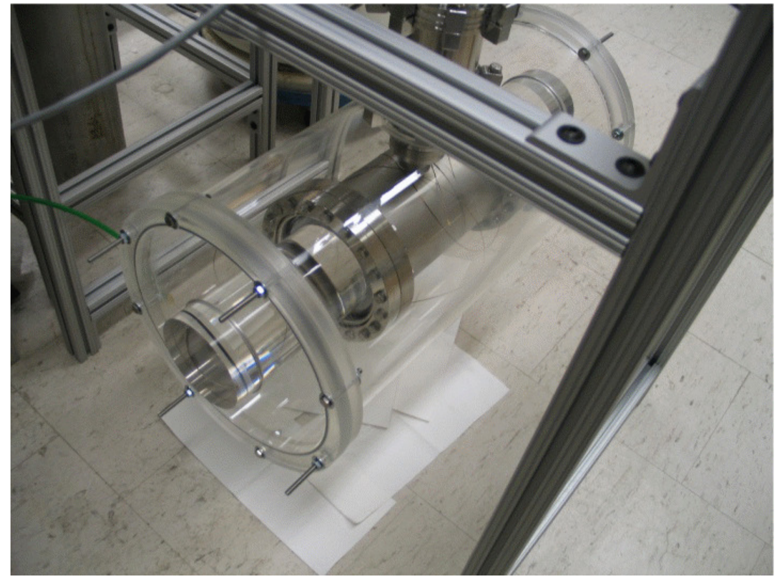
- **β/γ events:**
  dominated by ^{39}Ar, 1 Bq/kg
  PSD to distinguish from recoils, use depleted argon

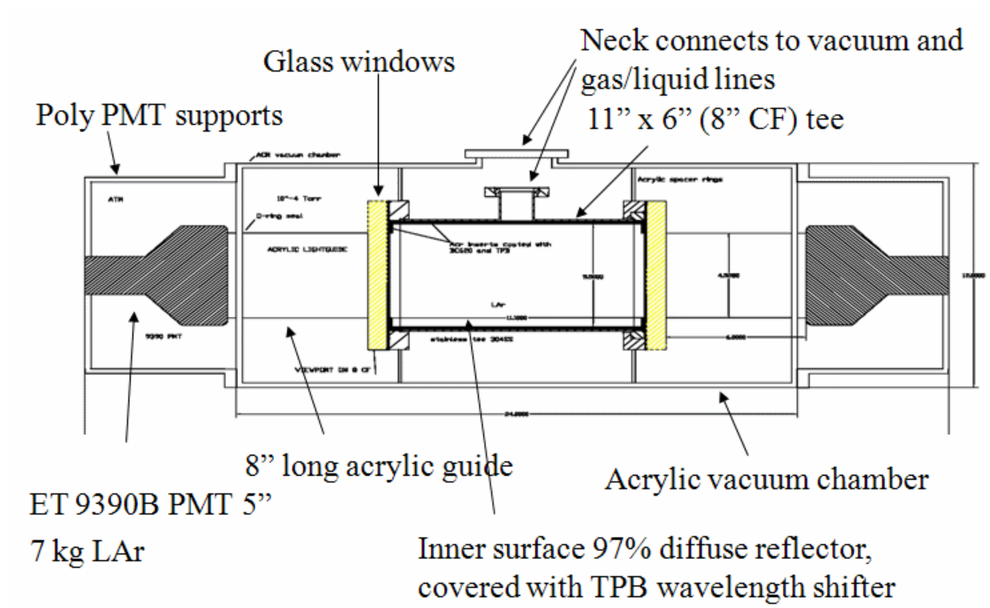
- **nuclear recoils:**
  (α,n), fission, μ induced
  clean detector materials, shielding

- **surface events:**
  Rn daughters and other impurities
  clean surfaces in-situ, position reconstruction

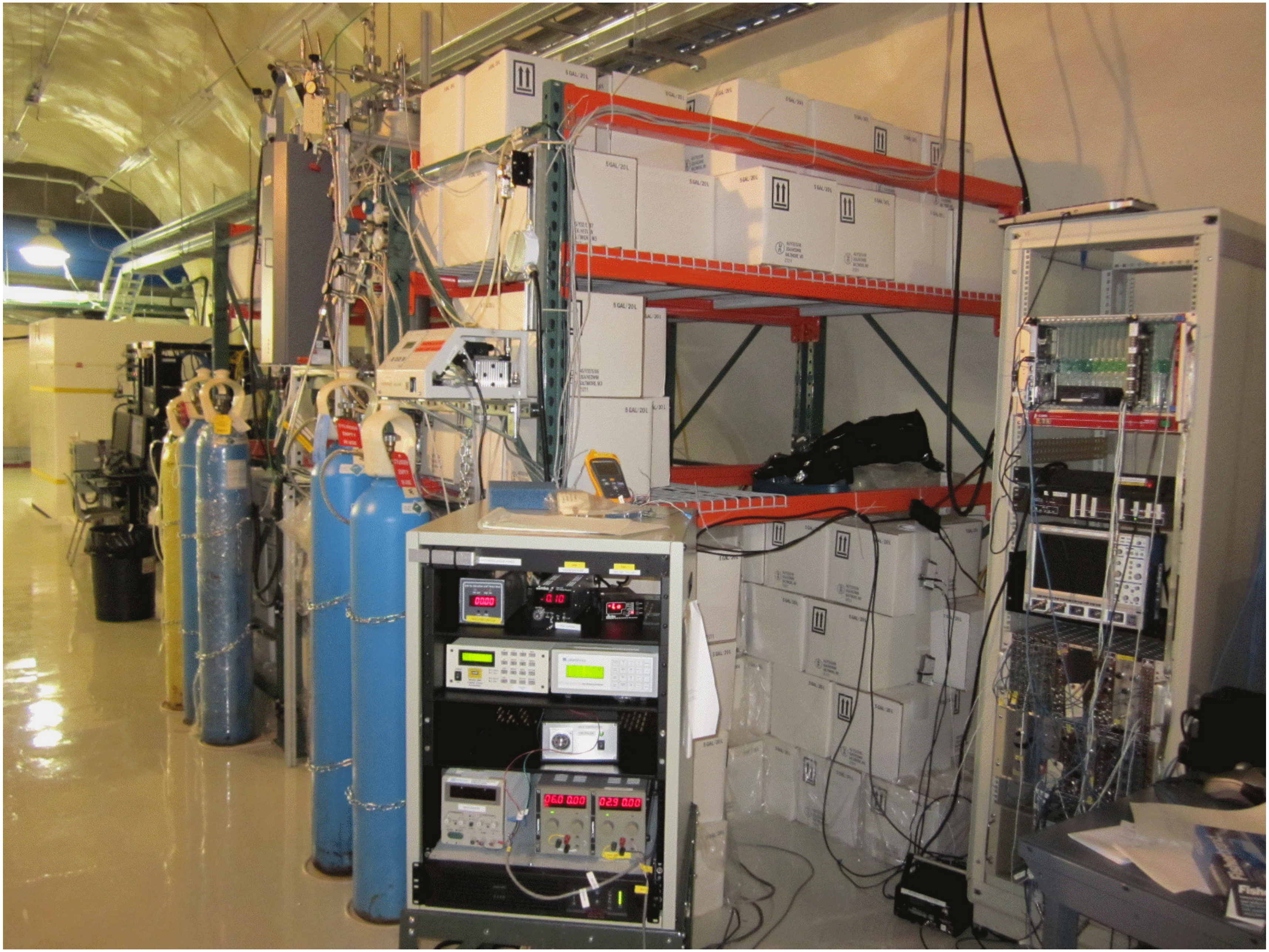
Demonstrate discrimination between electromagnetic events and nuclear recoils γ suppression better than: 3×10^{-8}, 120-240 PE, using tagged γ source





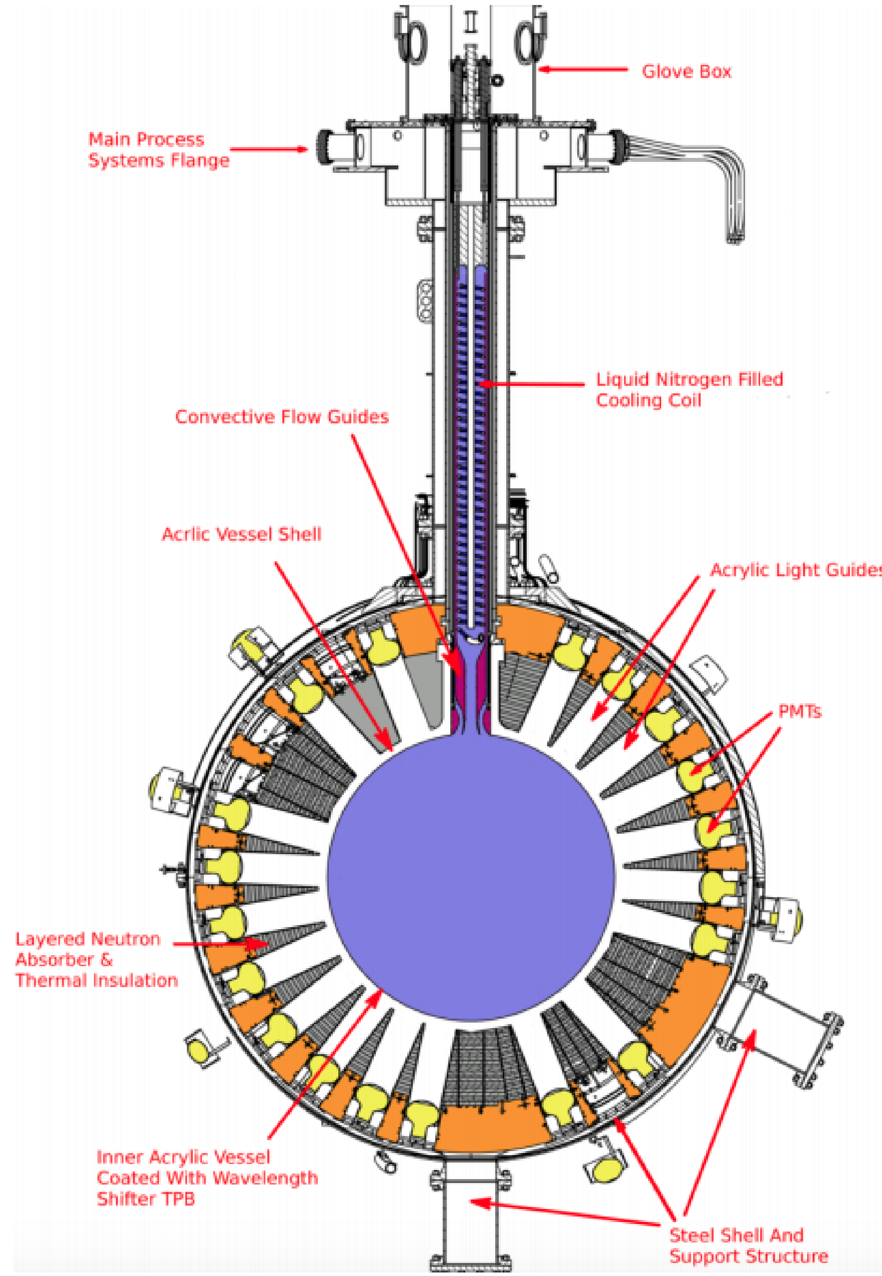


DEAP-1



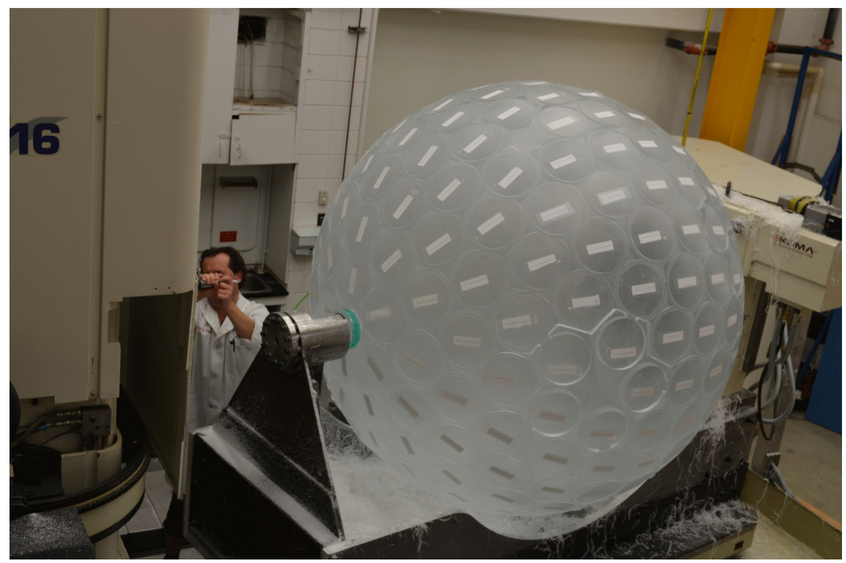
DEAP-3600

- **3600 kg argon (1000 kg fiducial) in ultra-clean AV**
- **Vessel is "resurfaced" in-situ to remove Rn daughters**
- **TPB wavelength shifter deposition**
- **255 Hamamatsu R5912 HQE 8" PMTs (75% coverage)**
- **50 cm light guides PE shielding for neutron moderation**
- **8 m water shield in Cube Hall**



DEAP-3600

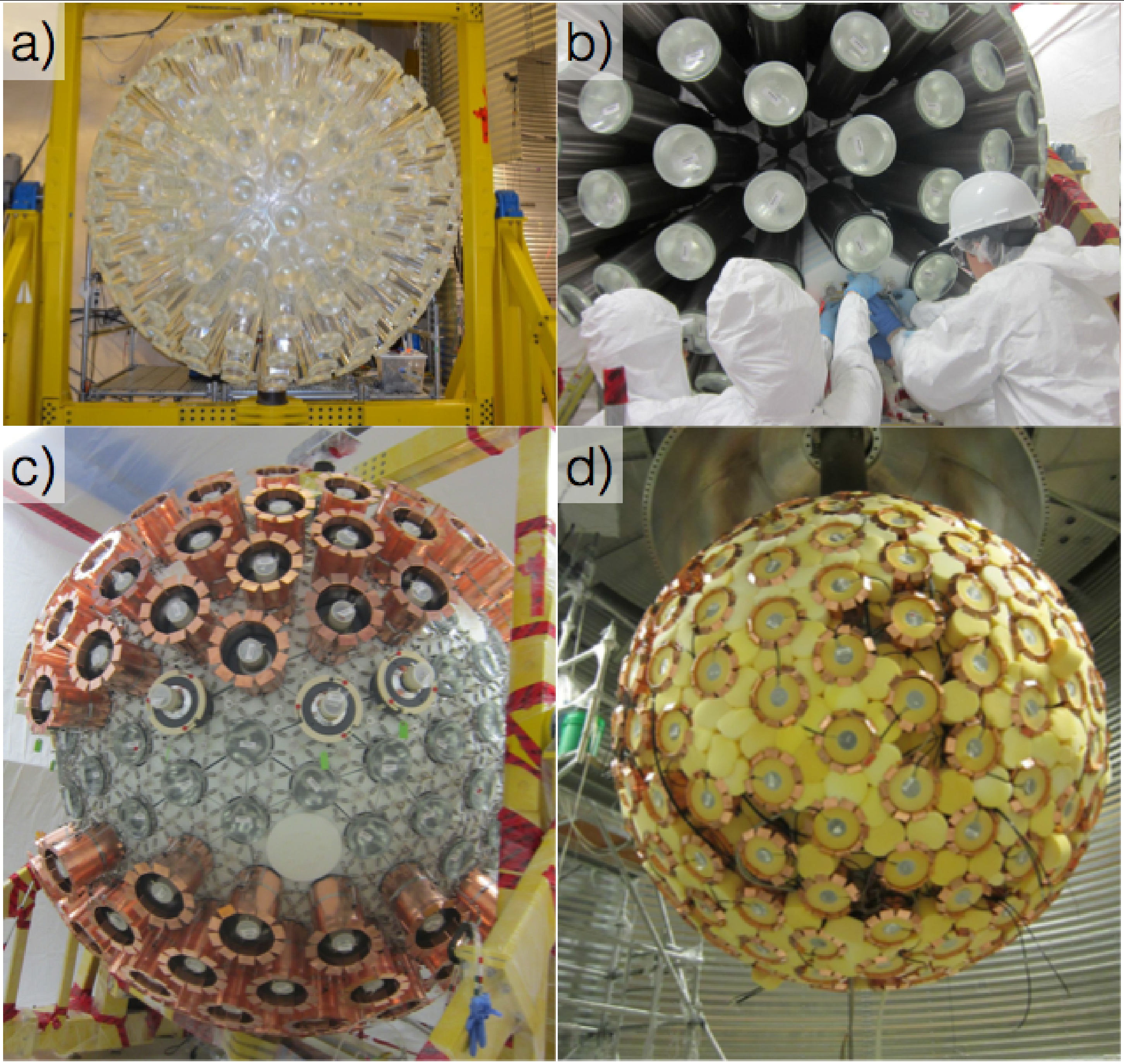
DEAP-3600



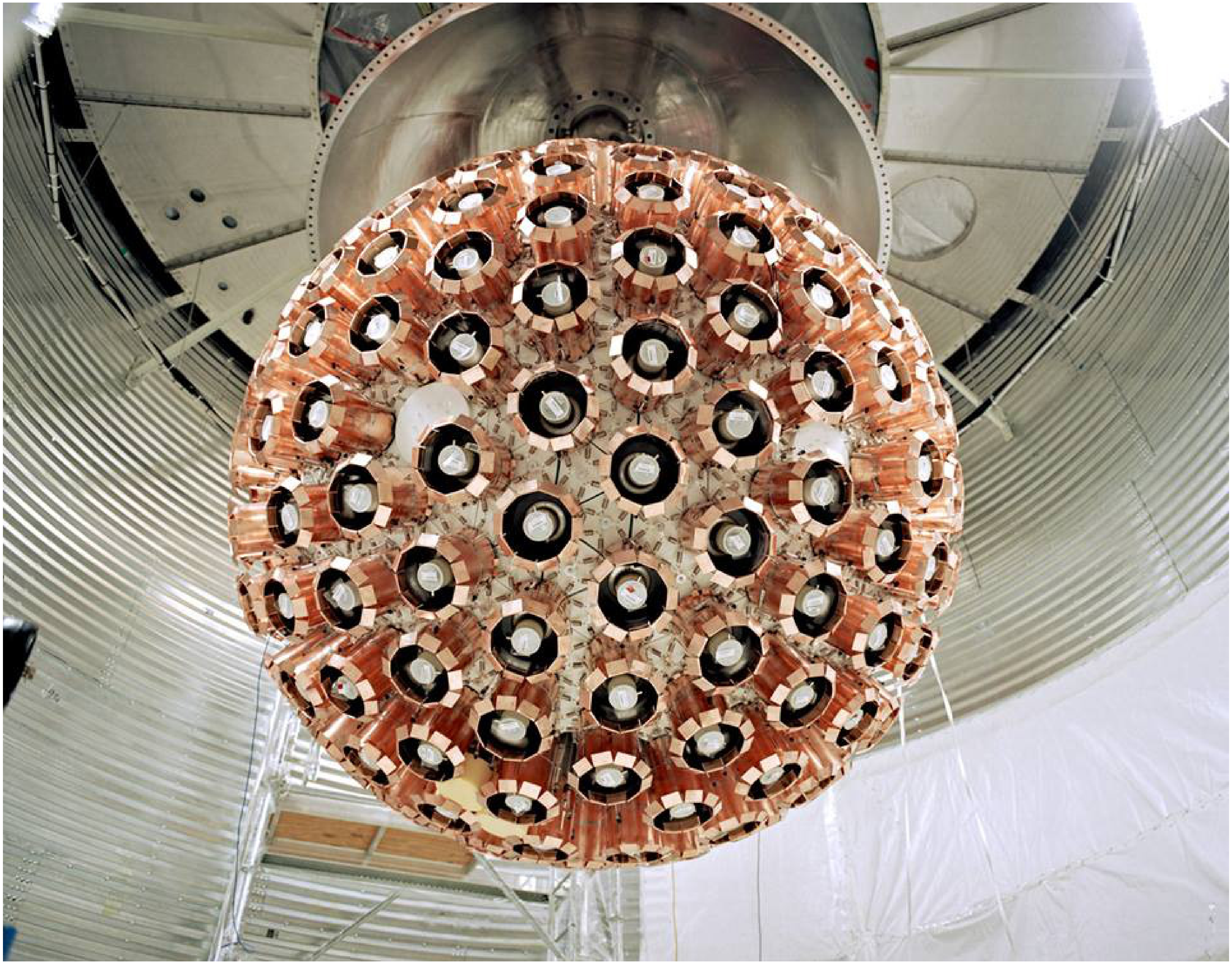
DEAP-3600

Light guide bonding

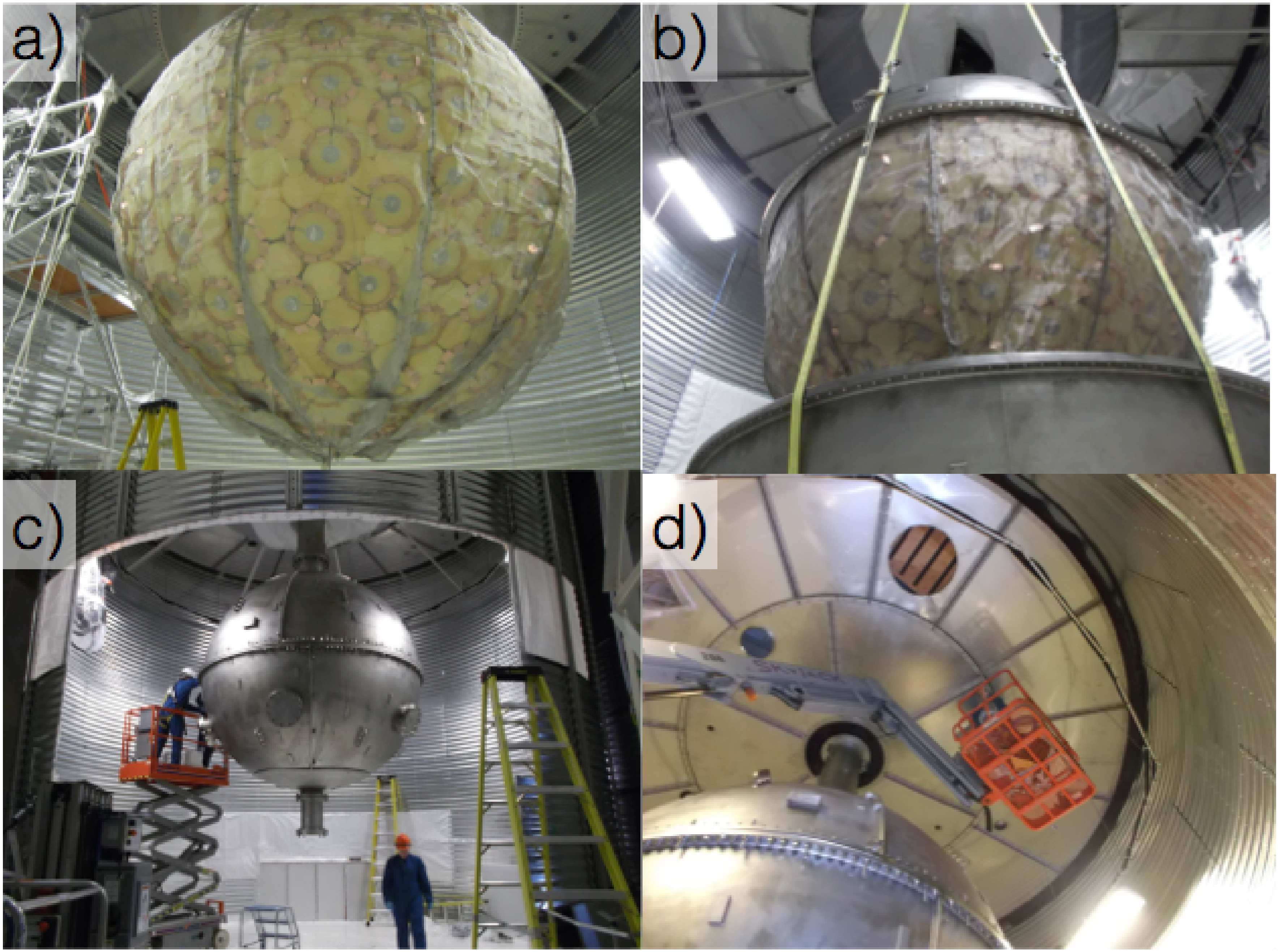
DEAP progress



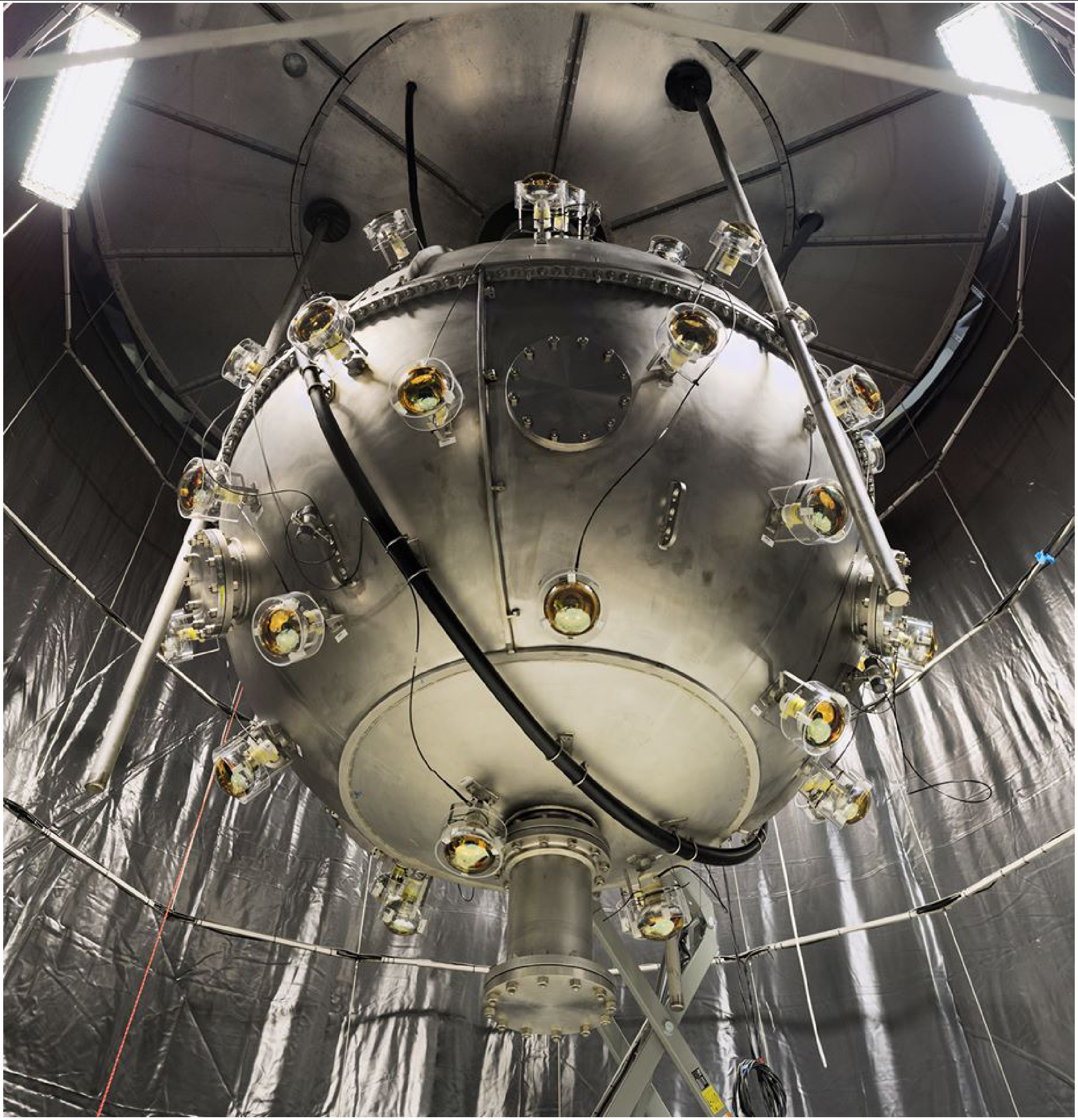
DEAP-3600 almost ready!



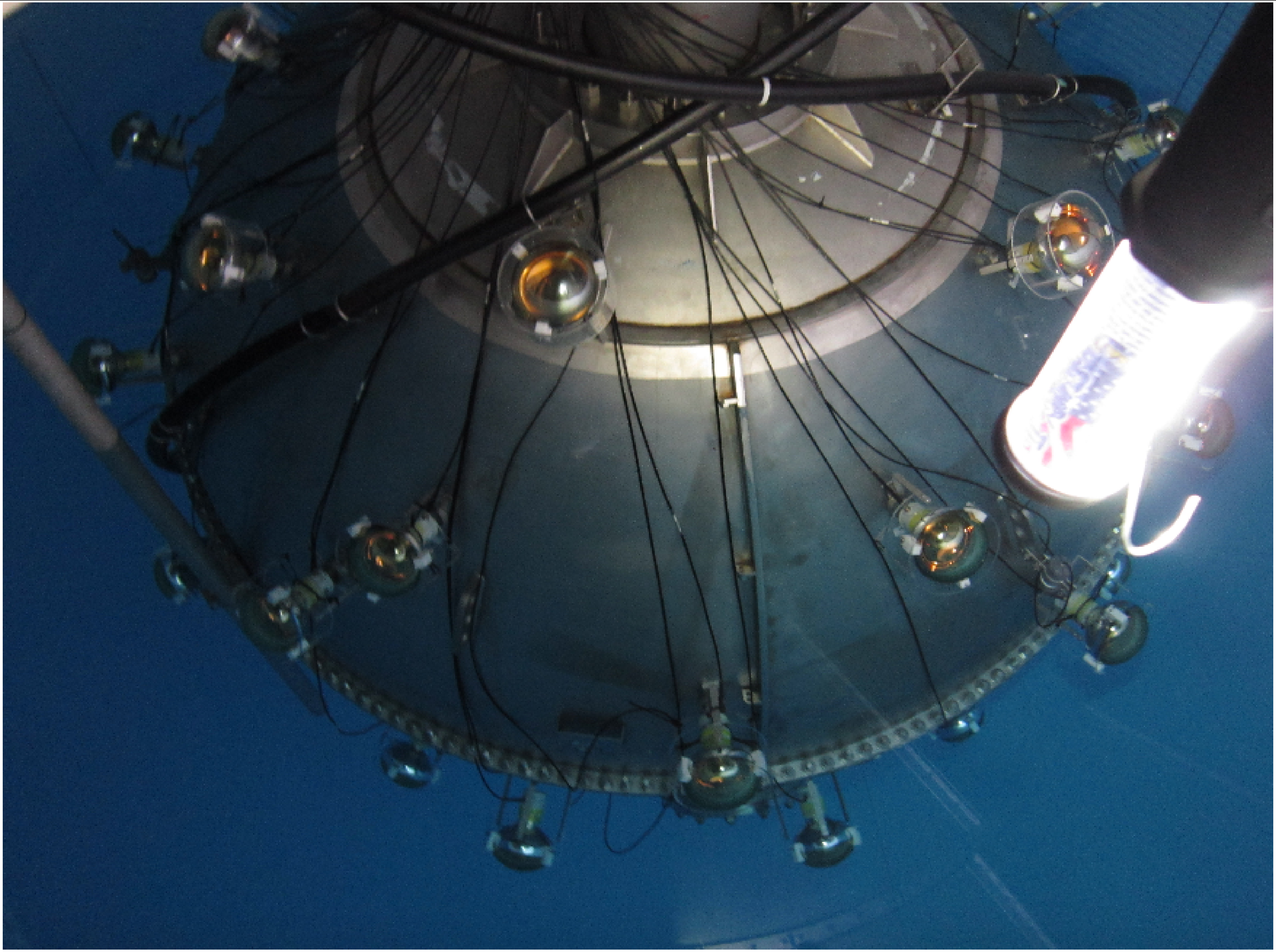
DEAP progress



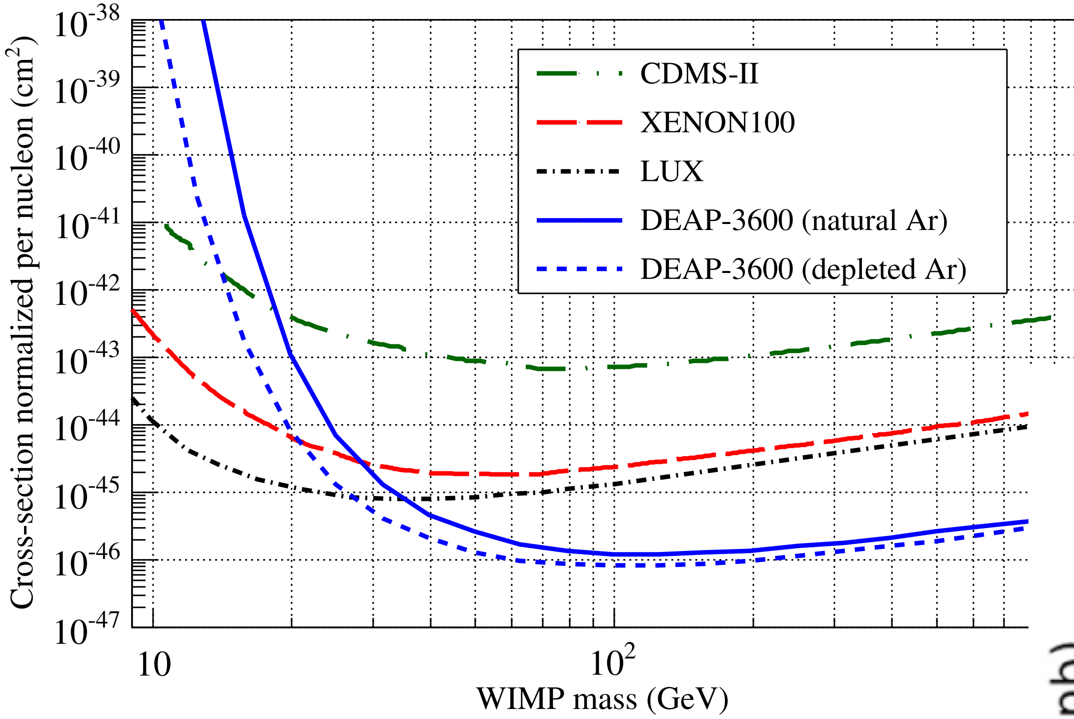
DEAP almost ready

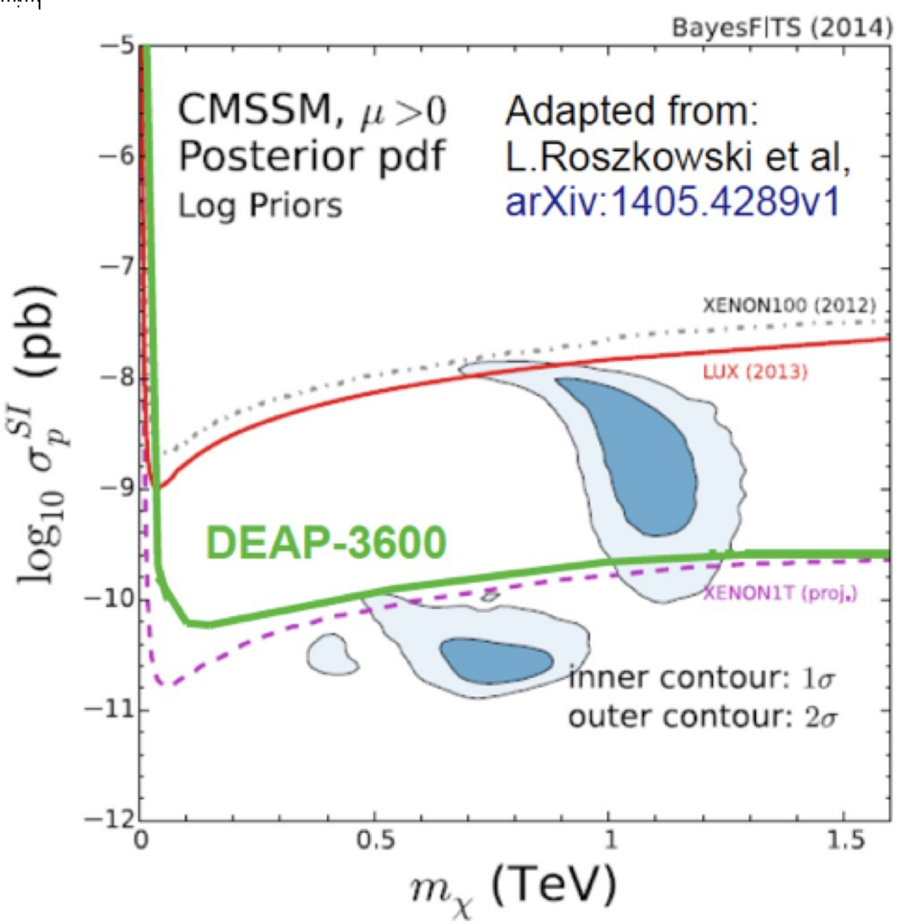


DEAP almost ready



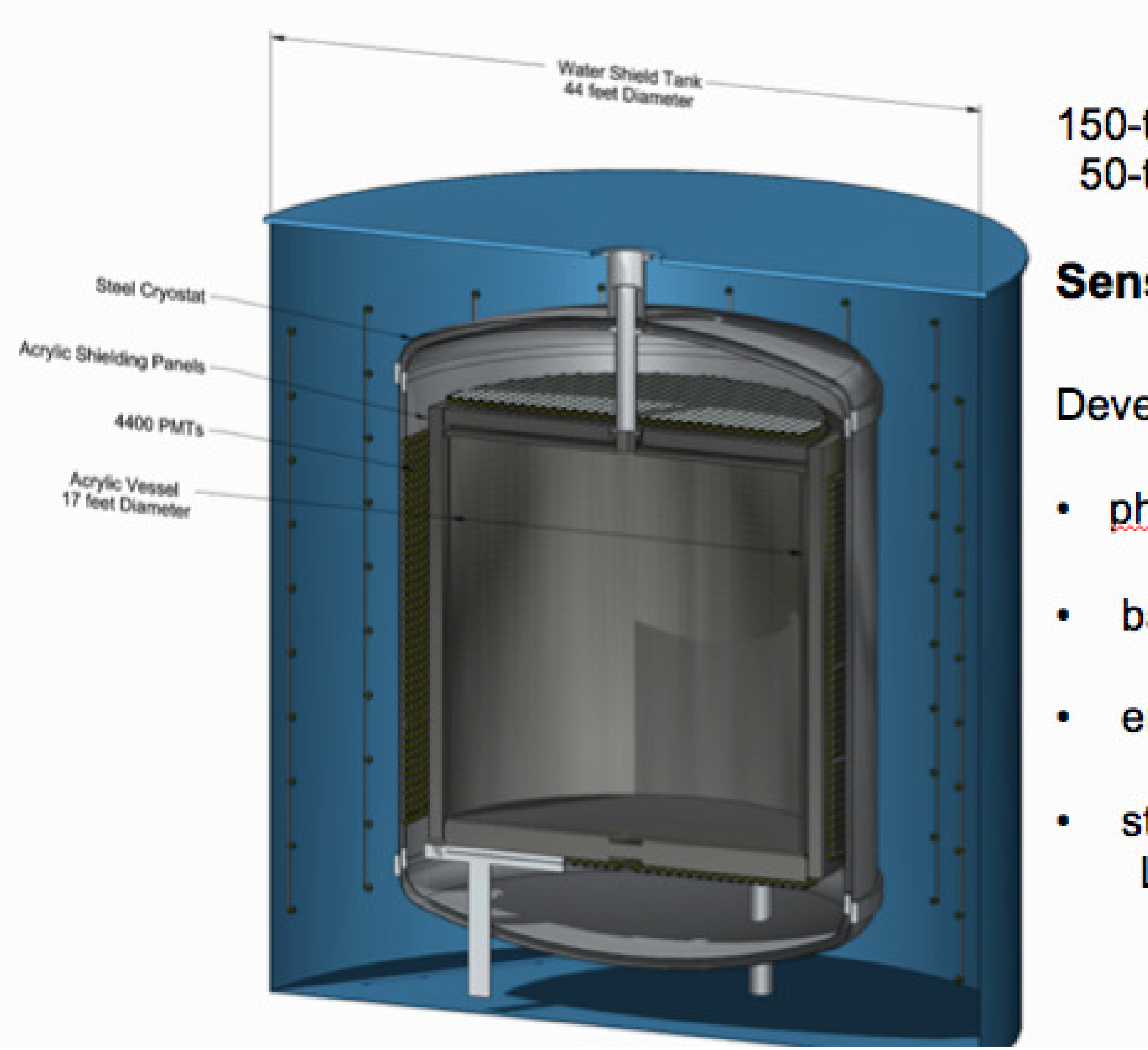
DEAP-3600 sensitivity





Future: DEAP-50T

DEAP-50T: 50-tonnes (fiducial) of liquid argon



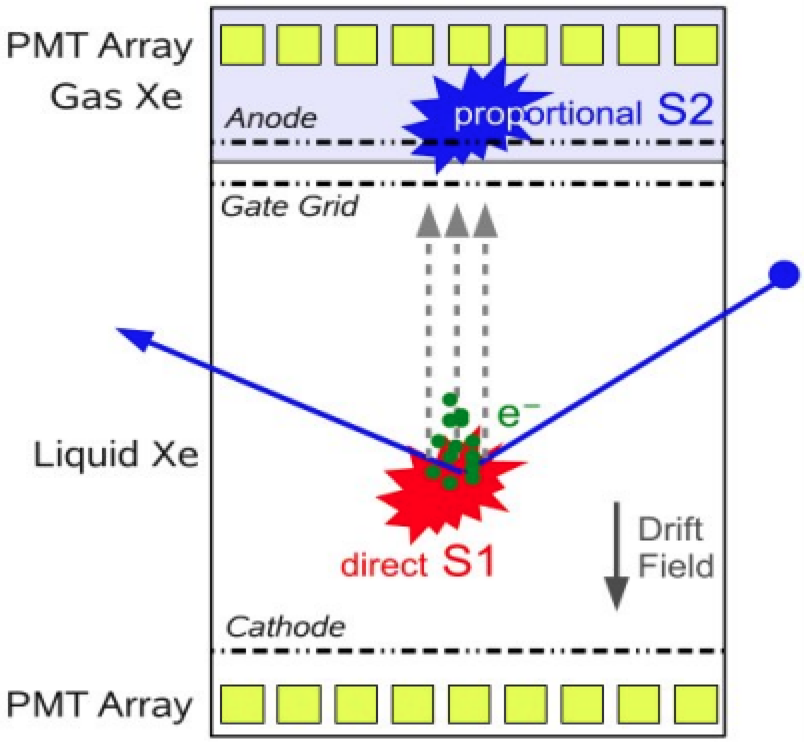
150-tonnes DAr in AV
50-tonne fiducial

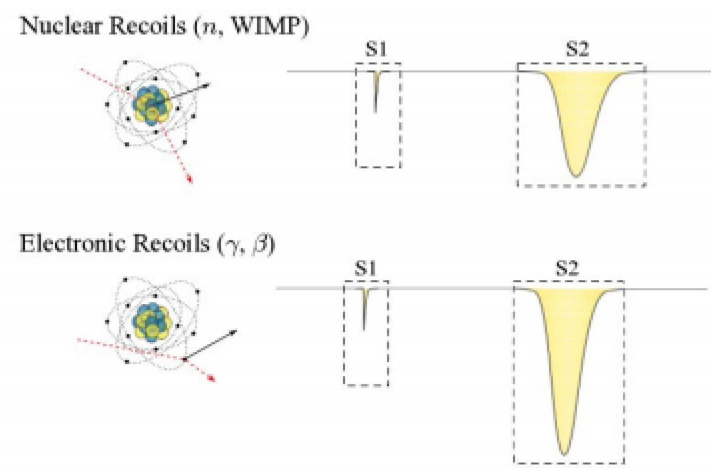
Sensitivity 10^{-48} cm^2

Development Proposal:

- photodetector characterization
- background reduction
- engineering design and safety
- storage and screening of Low-Radioactivity Argon

Dual Phase TPC Principle



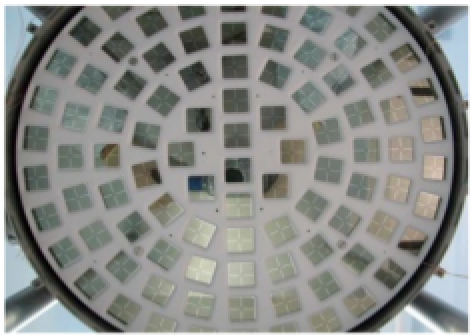


- Bottom PMT array detects scintillation signal (S1)
- Top PMTs detect the proportional signal (S2)
- Distribution of the S2 $\rightarrow xy$ coordinate
- Drift time $\rightarrow z$ coordinate

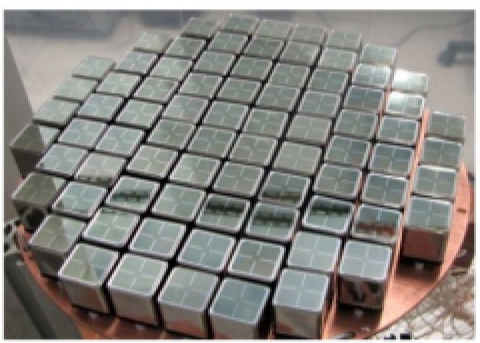
- S2/S1 allows for discrimination between electron recoils and nuclear recoils

The XENON100 TPC

Top array: 98 PMTs

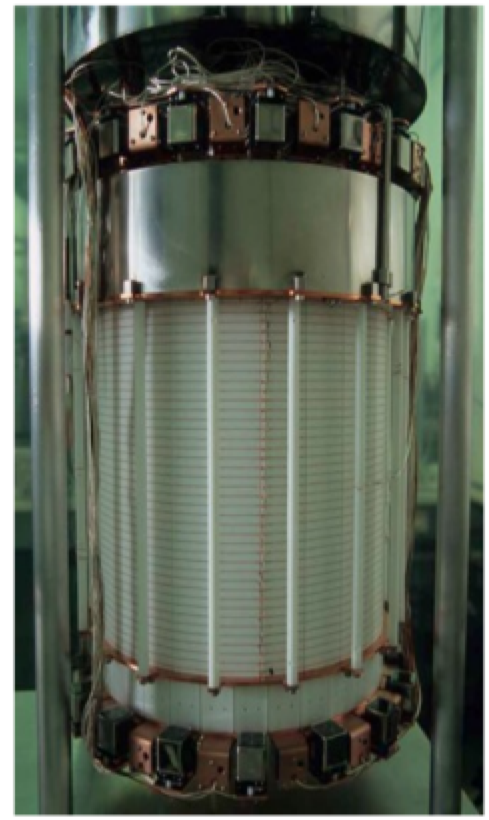


low-activity Hamamatsu R8520-06-Al 1"



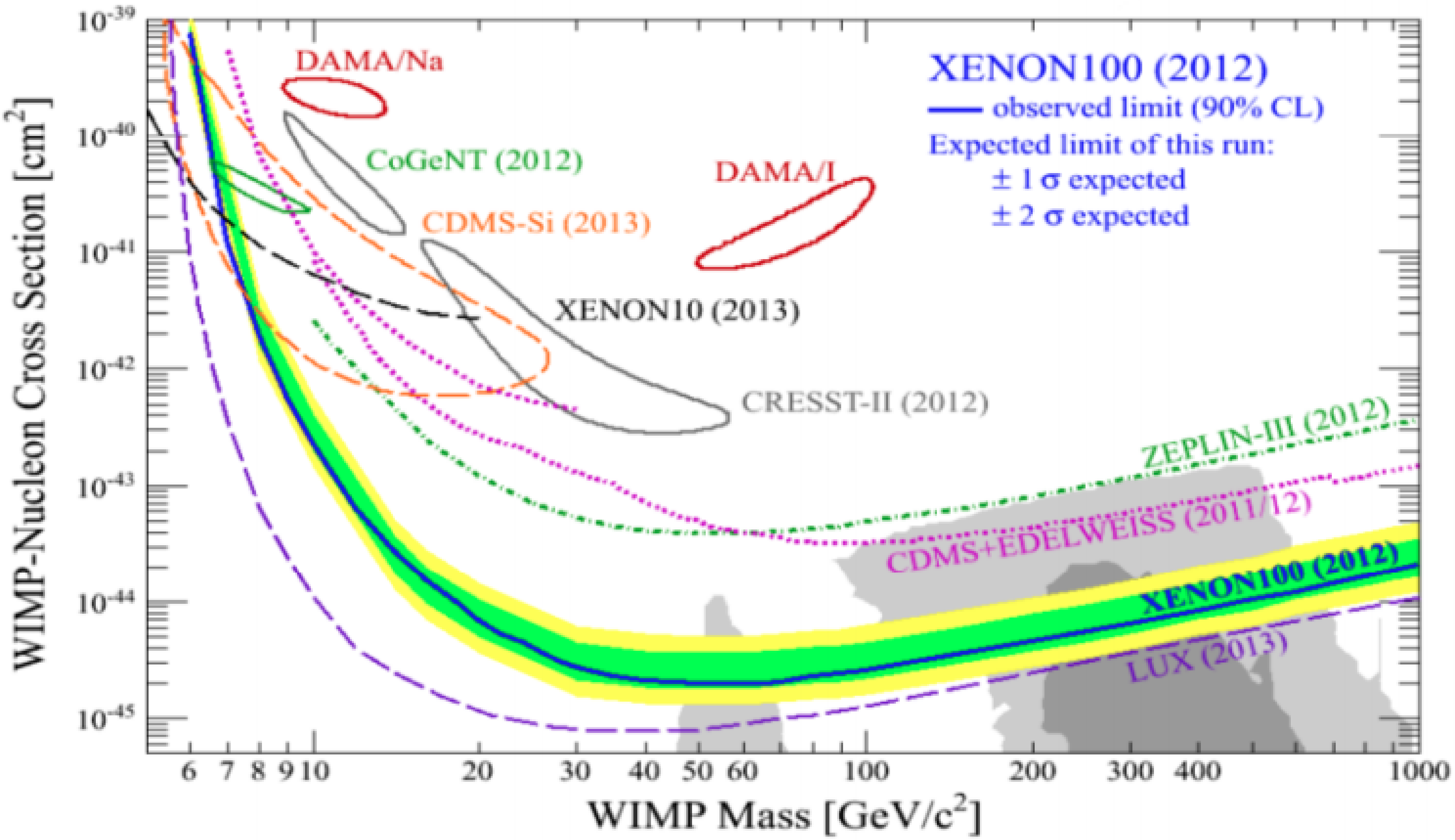
Bottom array: 80 PMTs

- 161 kg Xe, 62 kg target
- 15 cm radius, 30 cm drift length
- 0.53 kV/cm drift field
- $\sim$ 12 kV/cm proportional scintillation region field
- radiopurity
  - material screening
  - ^{85}Kr distillation column
- LXe veto
- Passive shielding: water, lead, polyethylene, copper



WIMP Search 225 Live-Days: Spin Independent

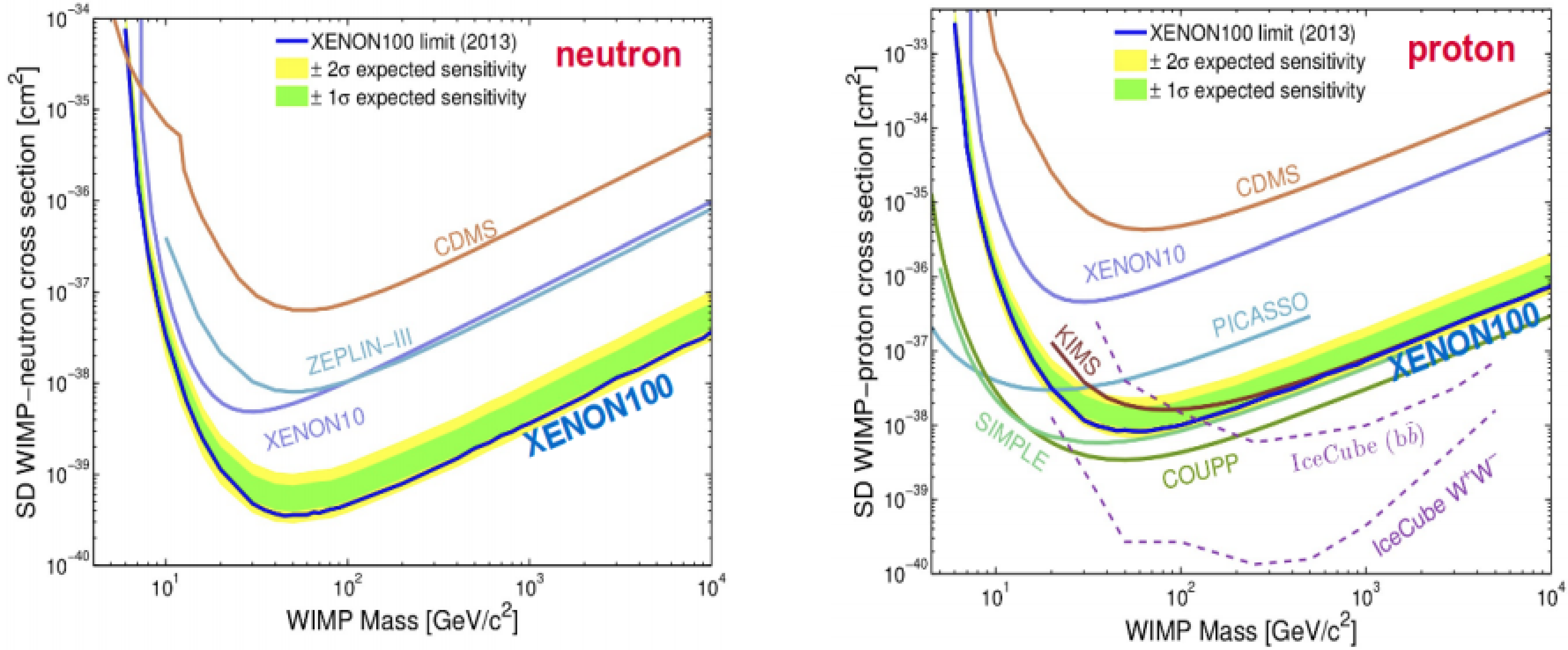
Limit 2012: $\sigma_{SI} < 2.0 \times 10^{-45}$ cm^2 @ 50GeV/c^2 (90% CL)



E. Aprile et al, Phys. Rev. Lett. 109, 181301 (2012)

WIMP Search 225 Live-Days: Spin Dependent

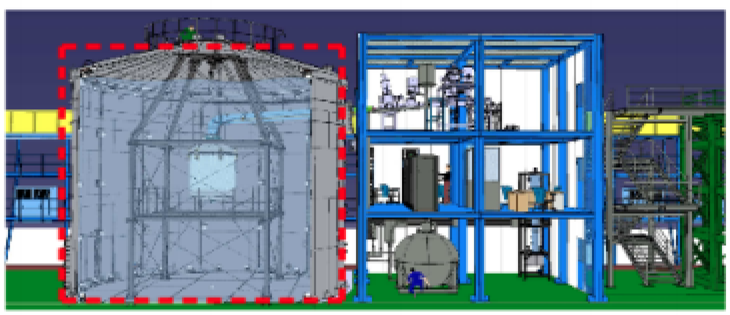
World-best limit for neutron coupling: $\sigma_n < 3.0 \times 10^{-40}$ cm^2 @ 45GeV/c^2 (90 % CL).

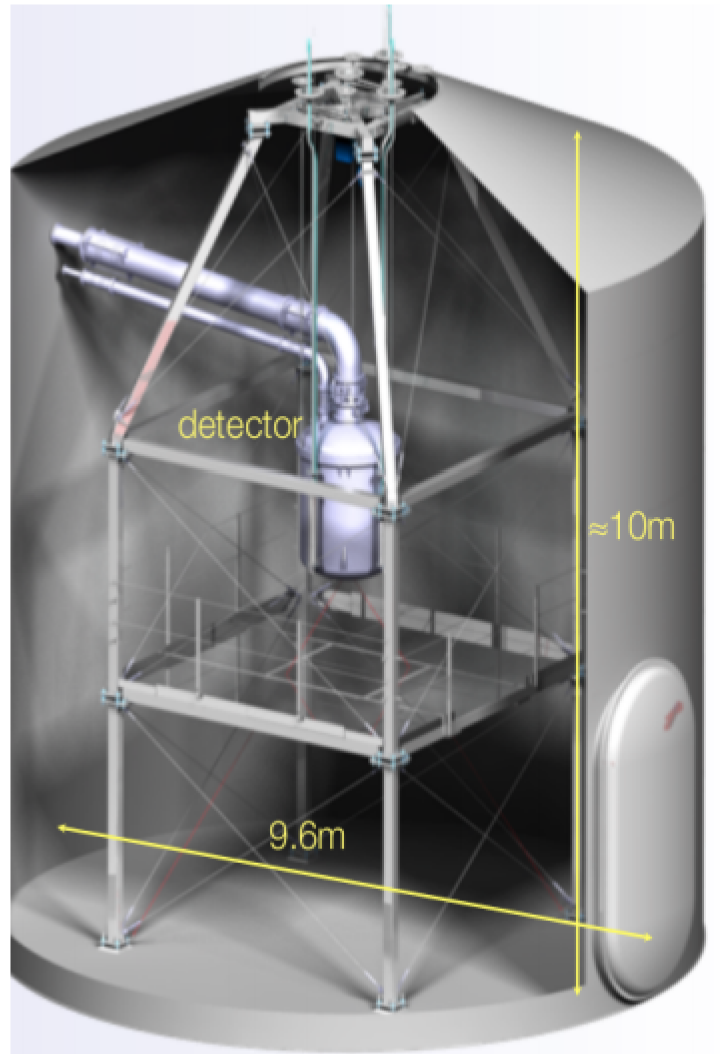


E. Aprile et al, Phys. Rev. Lett. 111, 021301 (2013)

XENON1T Design

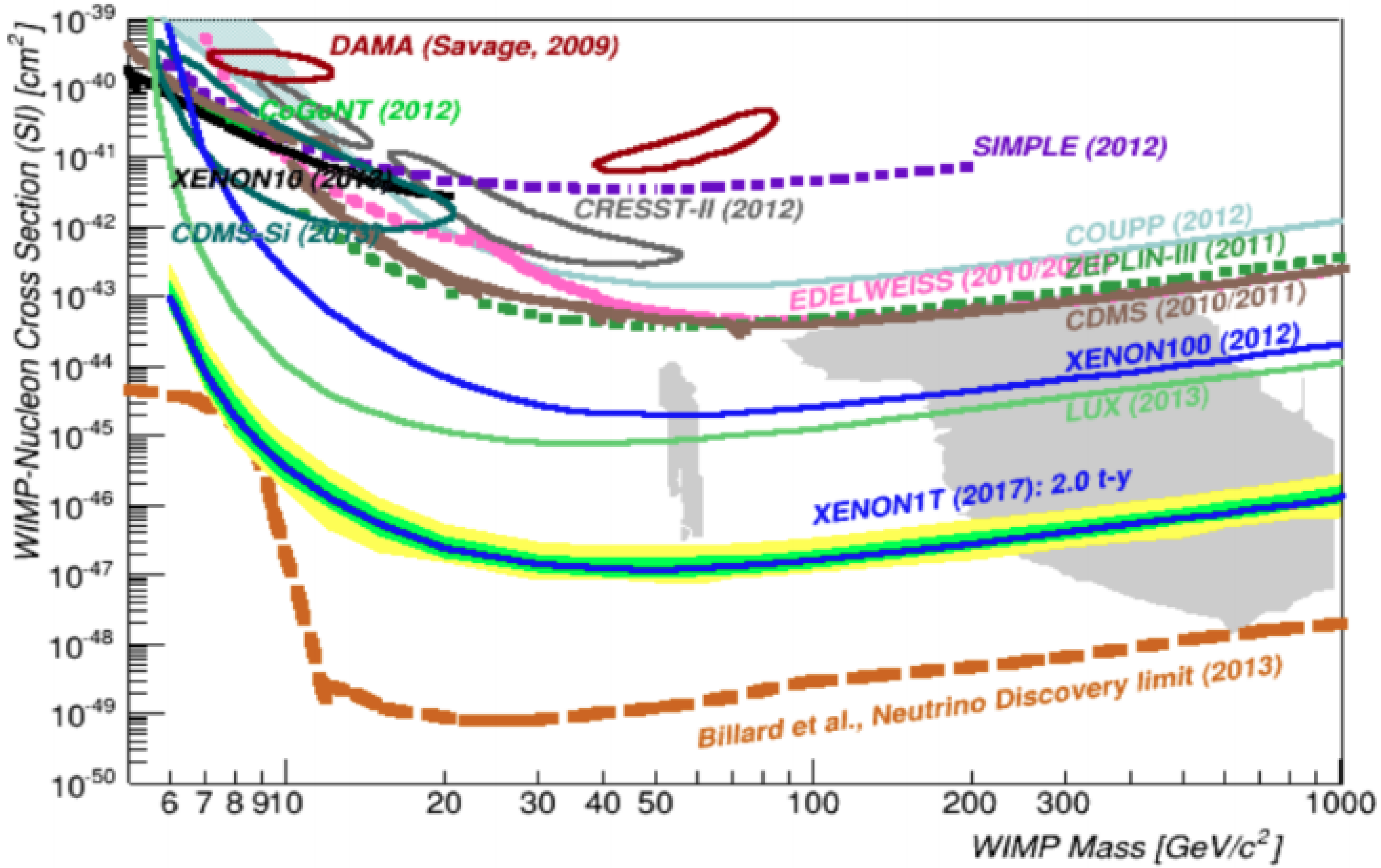
- Dark matter detector inside cryostat
- Surrounded by 10m diameter Cherenkov active shield
- Infraestructure outside of the water tank
  - DAQ + HV + Slow Control
  - Cryogenic system
  - Xenon purification and handling



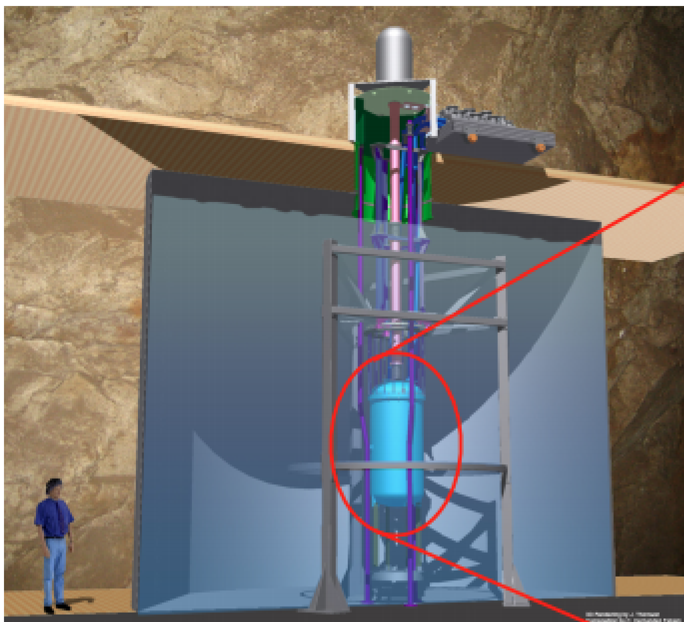


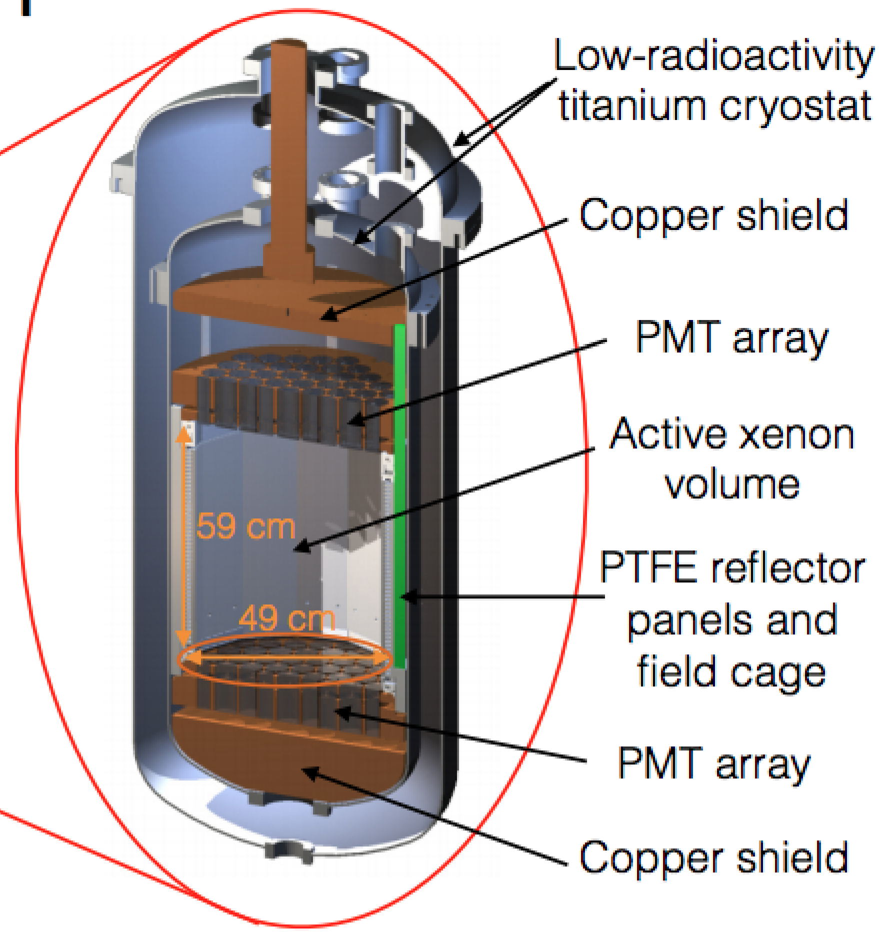
From XENON100 to XENON1T: Sensitivity

Spin independent sensitivity



The Large Underground Xenon Experiment

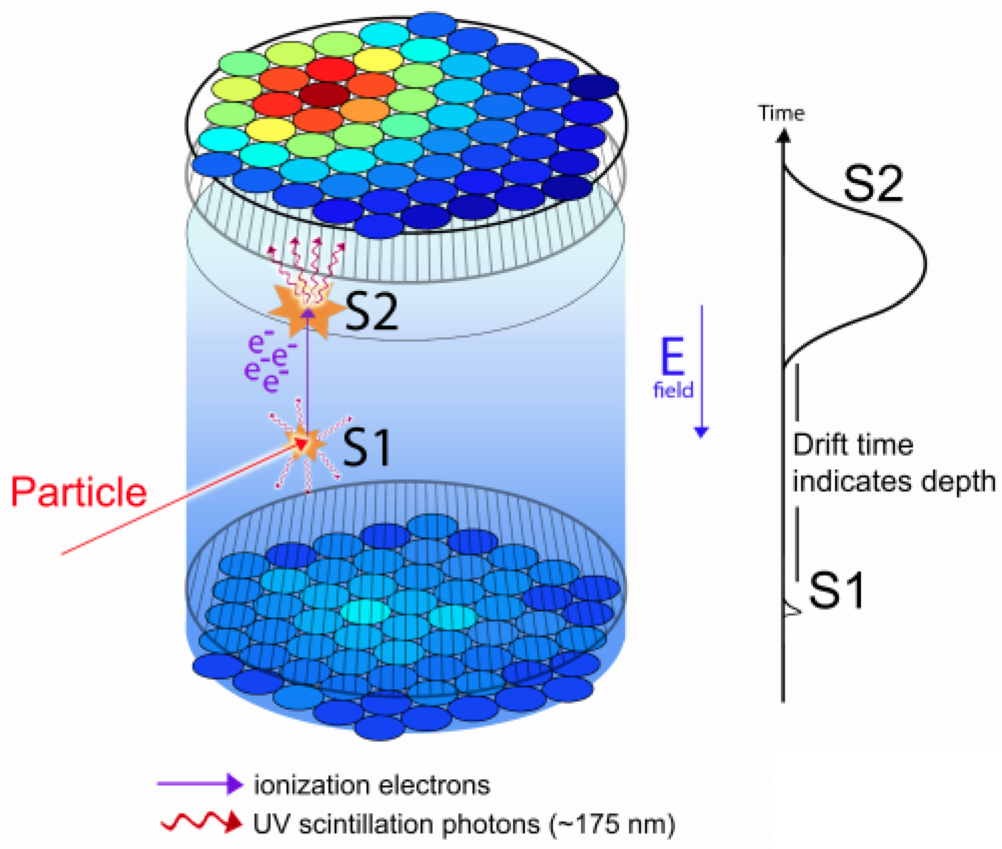




370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass

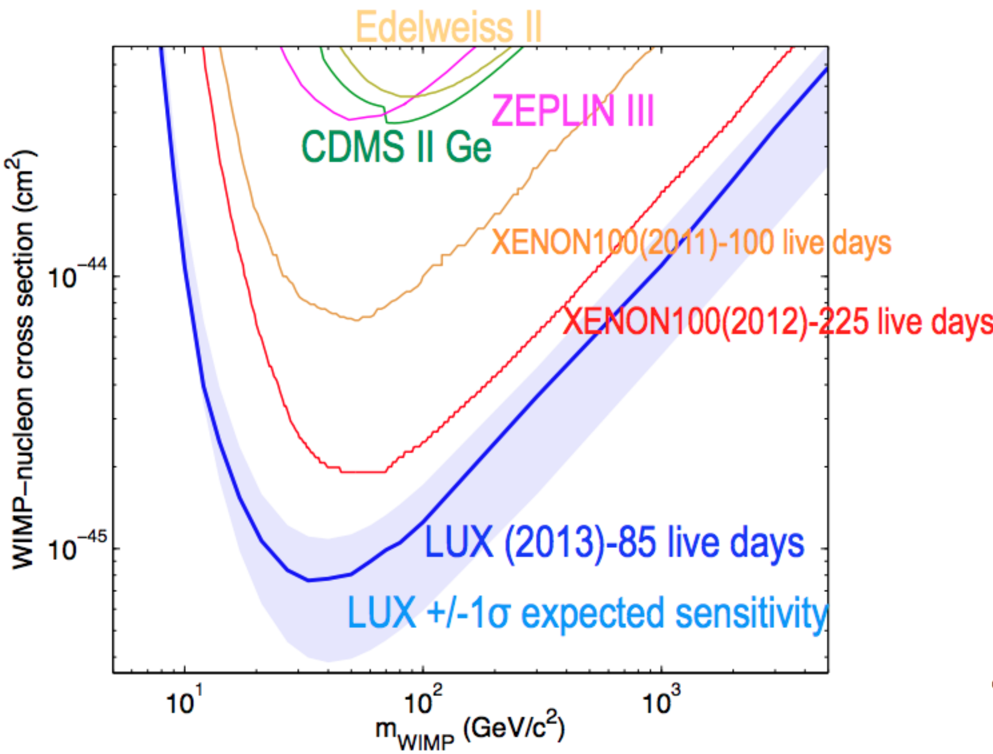
2

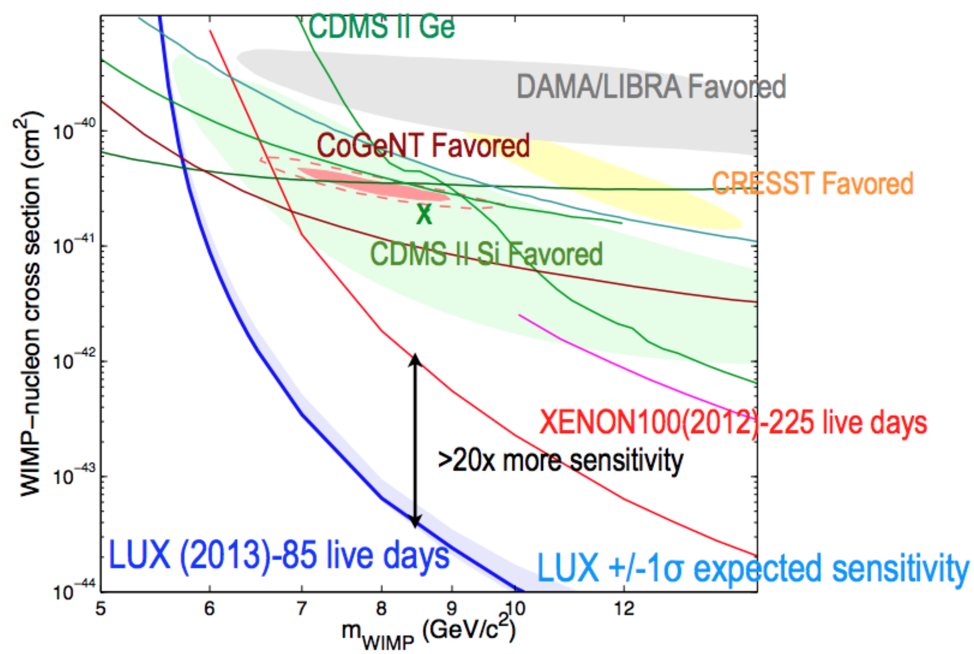
How the LUX Detector Works



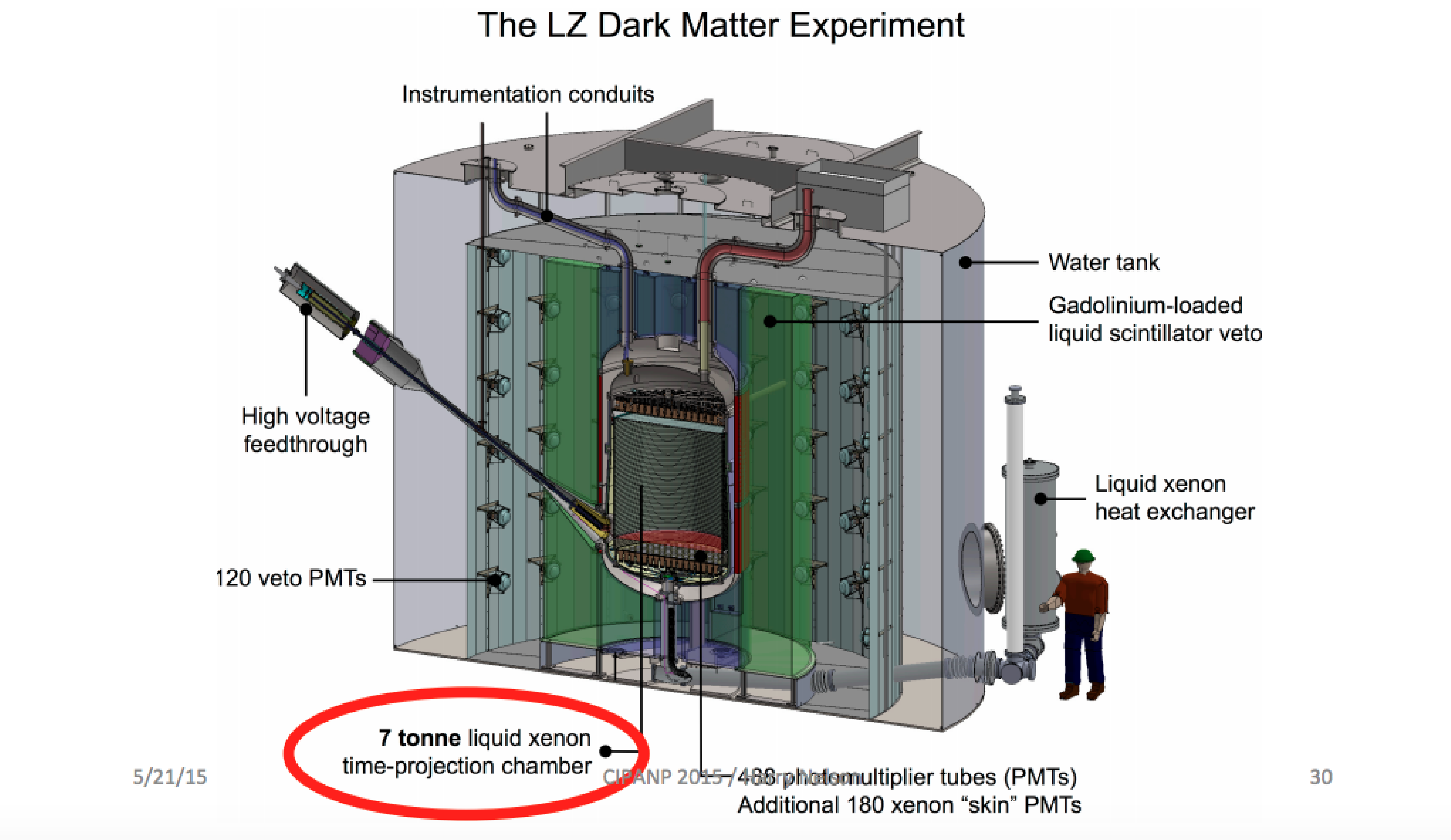
3

LUX sensitivity





LZ Design Overview



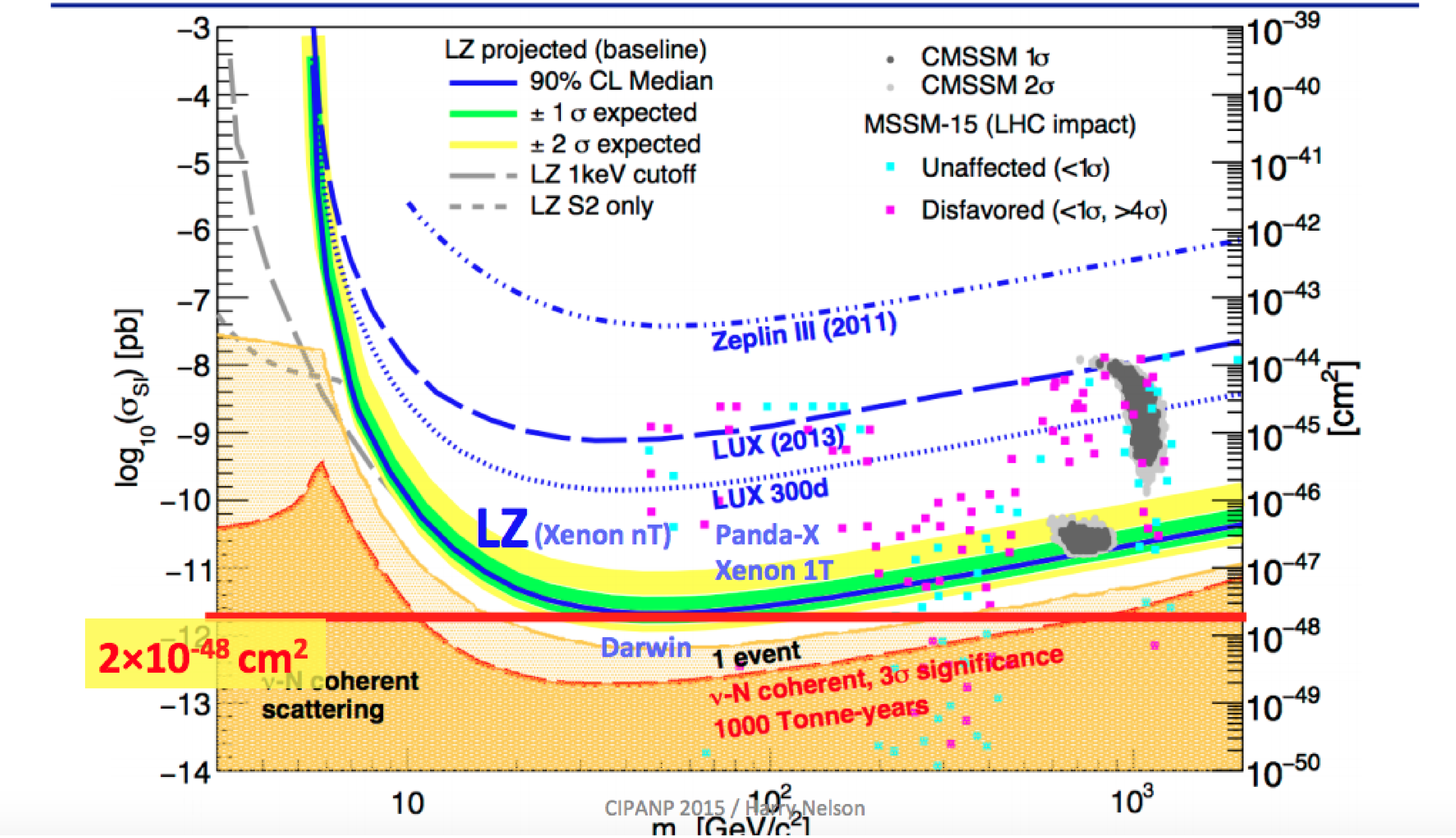
Xenon Future

- XENON1T- 2t active Xe; LZ – 7t active Xe **(G2)**

From Laura Baudis

5/21/15 CIPANP 2015 / Harry Nelson

Expected LZ Sensitivity
(1000 live days)



Crystals

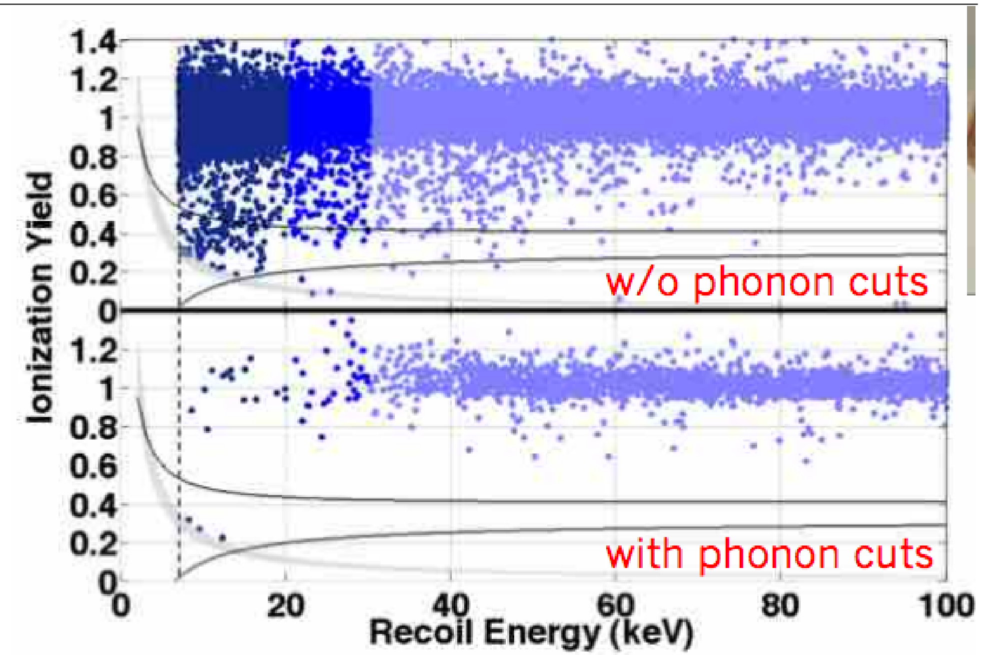
Some properties of crystals

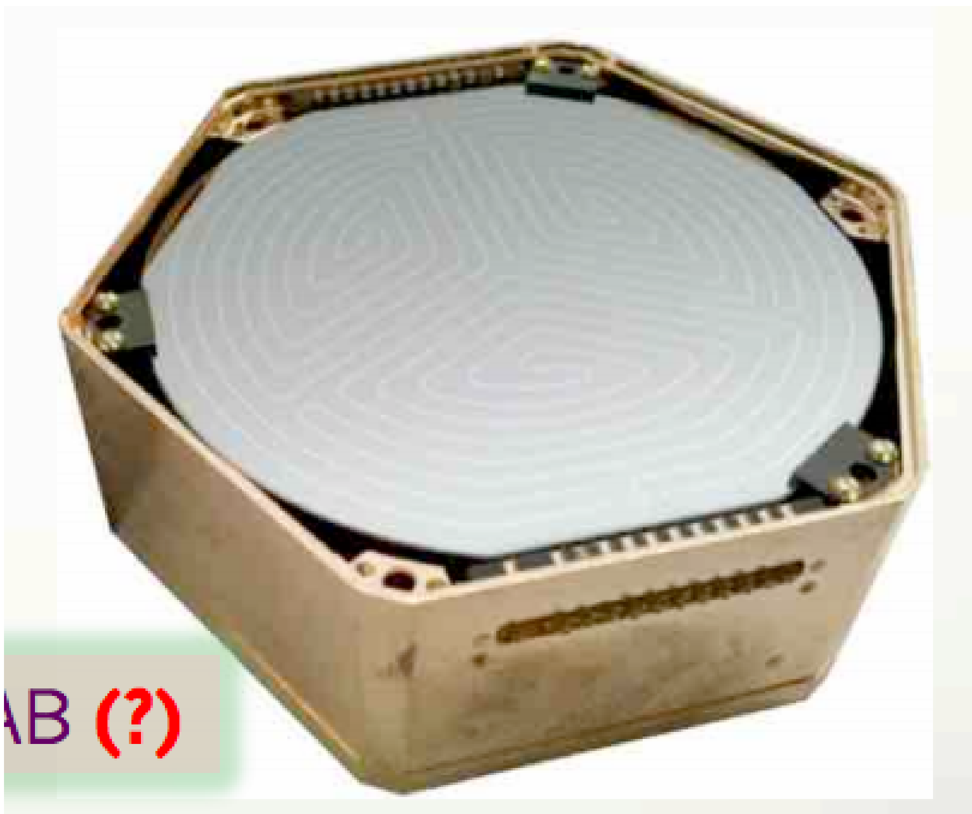
- **Many cuts on the data**
- **Low duty cycle**
  (selected exposure) / (data taking time x mass) about 10%
- **The systematics can be variable along the data taking period**
- **Phonon timing cut**
  time and energy response vary across the detector
- **Poor detector performances**
  many detectors excluded in the analysis
- **Critical stability of the performances**
- **Non-uniform response of detector**
  intrinsic limit
- **Surface electrons: PSD**
  needed with related uncertainty

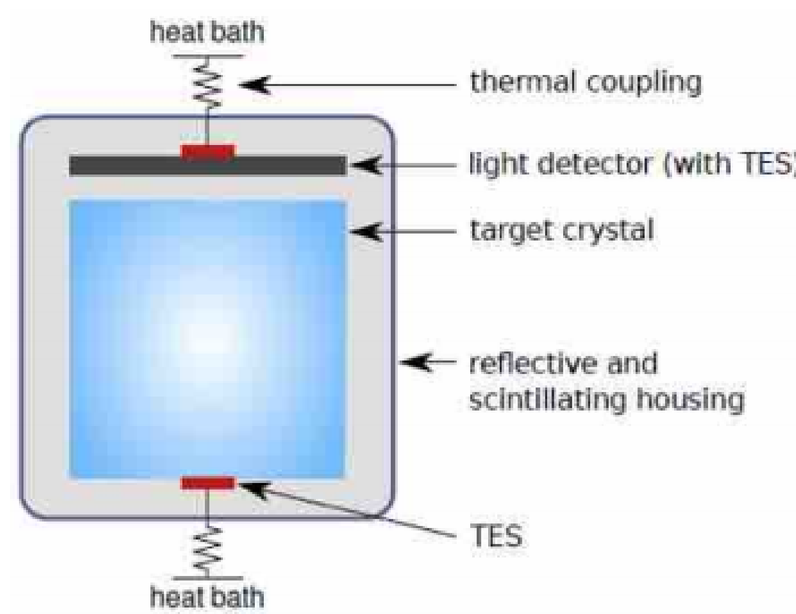
Double read-out bolometric technique

ionization/scintillation vs heat

- CDMS-Ge/Si, Edelweiss, CRESST, Eureka CoGeNT, DAMA-LIBRA ANAIS, DM-ICE, KIMS SABRE, DAMIC



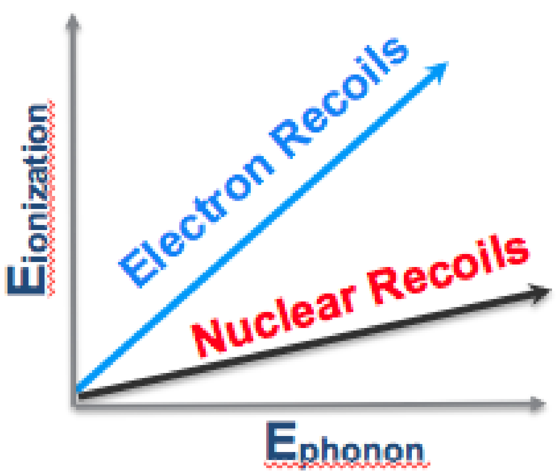




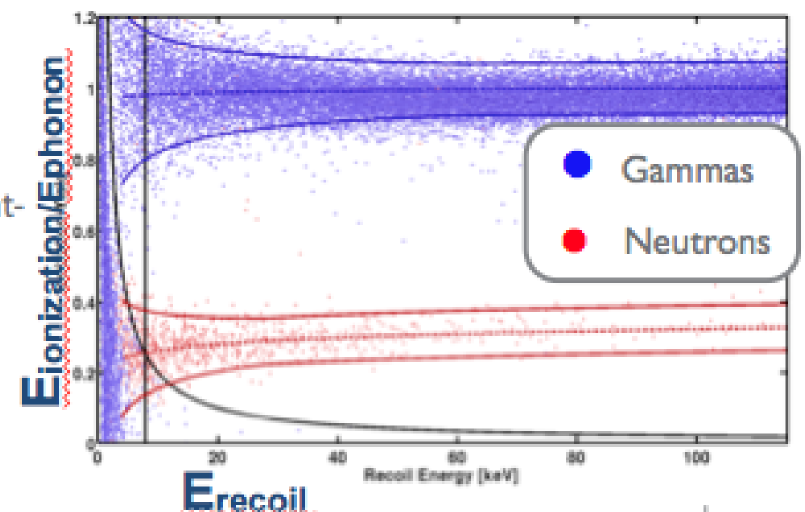
The Cryogenic Dark Matter Search

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- The CDMS Collaboration has developed and deployed cryogenic semi-conductor detectors for rare event searches
- Recent interesting results include (from CDMS-II)
  - Lightly Ionizing Particles, arXiv:1409.3270; PRL 114, 111302 [2015]
  - Maximum Likelihood Analysis, arXiv:1410.1003; PRD 91, 052021 [2015]
  - Reanalysis of CDMS-II, arXiv:1504.05871
- SuperCDMS consists of two experiments with substantial detector improvements
  - SuperCDMS-Soudan, an operating 9 kg germanium array
  - SuperCDMS-SNOLAB, a Generation-2 60 kg array of germanium and silicon



CDMS measures both the heat deposition and the ionization from particle scattering. This allows event-by-event identification the interaction as a nuclear or electron recoil to energies well below 10 keVr.



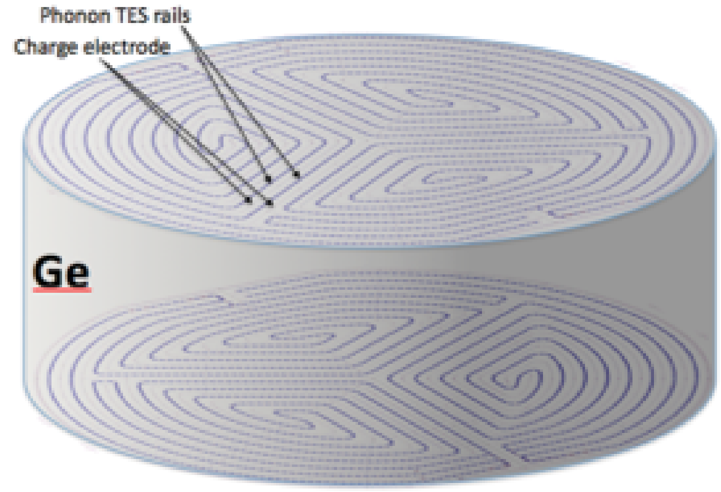
SuperCDMS - Jeter Hall - CIPANP 2015 May 22, 2015 | 2

SuperCDMS Technology – iZIPs

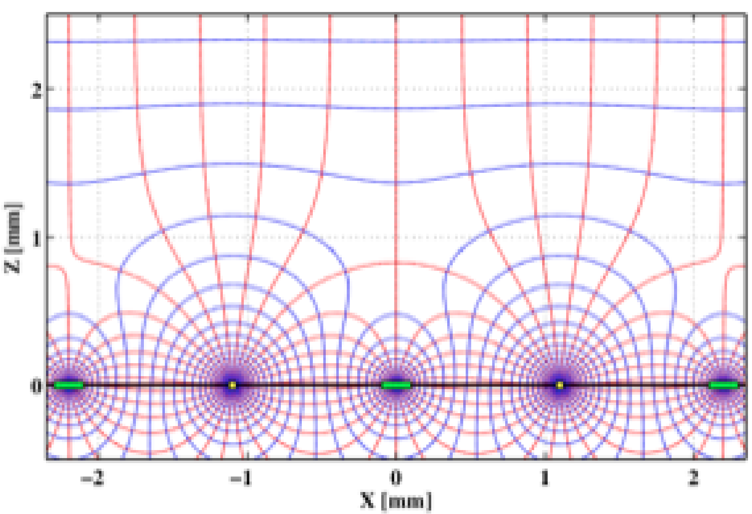
Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

- Search with germanium iZIP detectors
- Operating at ~50 mK
  - Enables phonon and charge readout
  - Charge to phonon ratio separates nuclear and electron scatters
- interleaved Z-sensitive ionization and phonon sensors (iZIP) on both faces
  - Surface event identification
  - Outer phonon guard ring

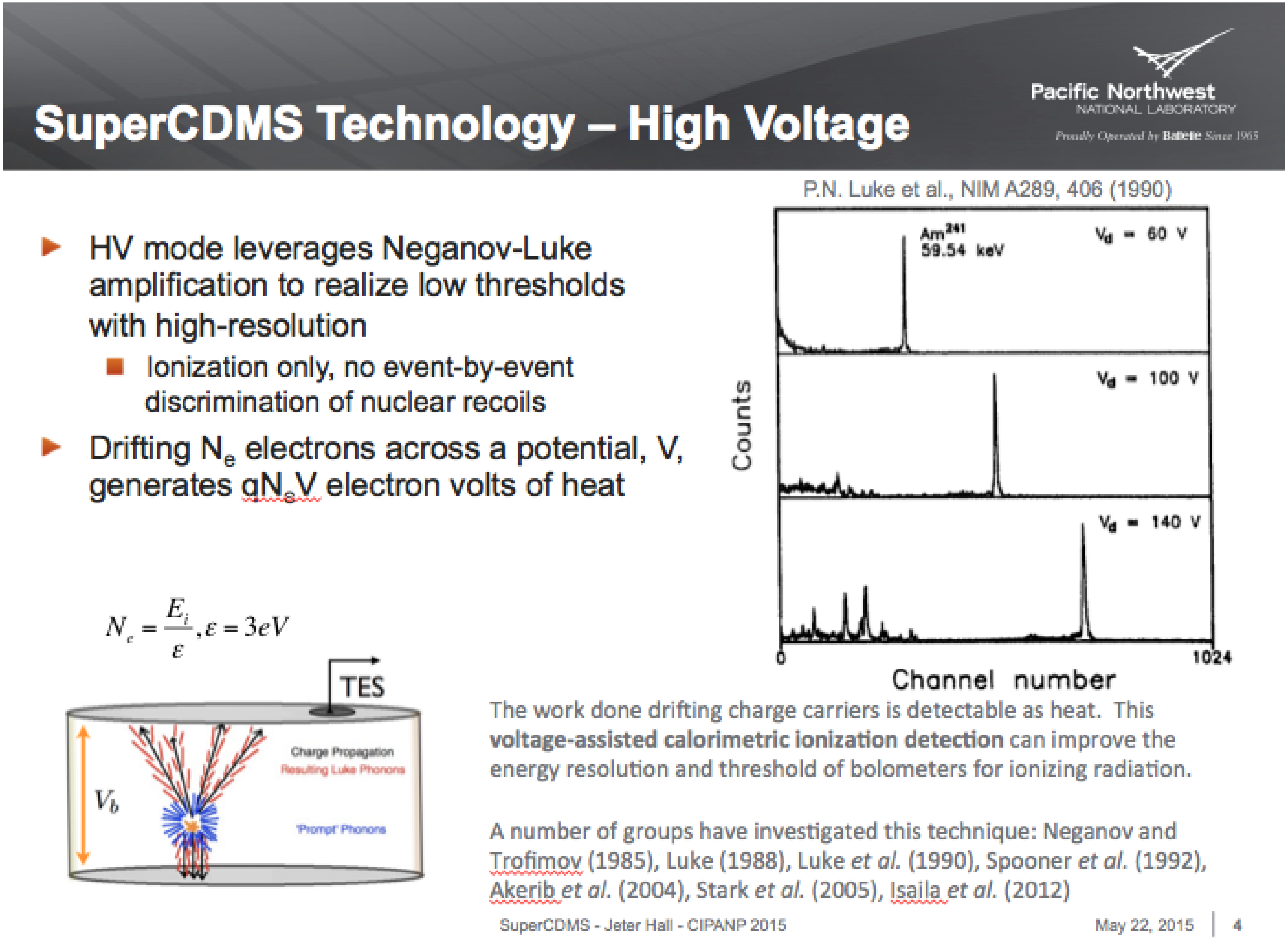


SuperCDMS iZIP detectors have phonon and ionization instrumentation on both faces allowing superior z-sensitivity.
J. Low Temp. Phys. 176, 194 (2014)



By holding a potential between ionization and phonon electrodes, a more complex electric field is created. Charge near the surface of the detector is collected on only one side. Charge in the bulk of the detector is collected on both faces.

SuperCDMS - Jeter Hall - CIPANP 2015 May 22, 2015 | 3


SuperCDMS Technology – High Voltage
Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965
P.N. Luke et al., NIM A289, 406 (1990)
HV mode leverages Neganov-Luke amplification to realize low thresholds with high-resolution
Ionization only, no event-by-event discrimination of nuclear recoils
Drifting N_e electrons across a potential, V, generates qN_eV electron volts of heat
$N_e = \frac{E_i}{\varepsilon}, \varepsilon = 3eV$
TES
V_b
Charge Propagation
Resulting Luke Phonons
'Prompt' Phonons
Am241 59.54 keV
Vd = 60 V
Vd = 100 V
Vd = 140 V
Counts
0
1024
Channel number
The work done drifting charge carriers is detectable as heat. This **voltage-assisted calorimetric ionization detection** can improve the energy resolution and threshold of bolometers for ionizing radiation.
A number of groups have investigated this technique: Neganov and Trofimov (1985), Luke (1988), Luke *et al.* (1990), Spooner *et al.* (1992), Akerib *et al.* (2004), Stark *et al.* (2005), Isaila *et al.* (2012)
SuperCDMS - Jeter Hall - CIPANP 2015
May 22, 2015
4

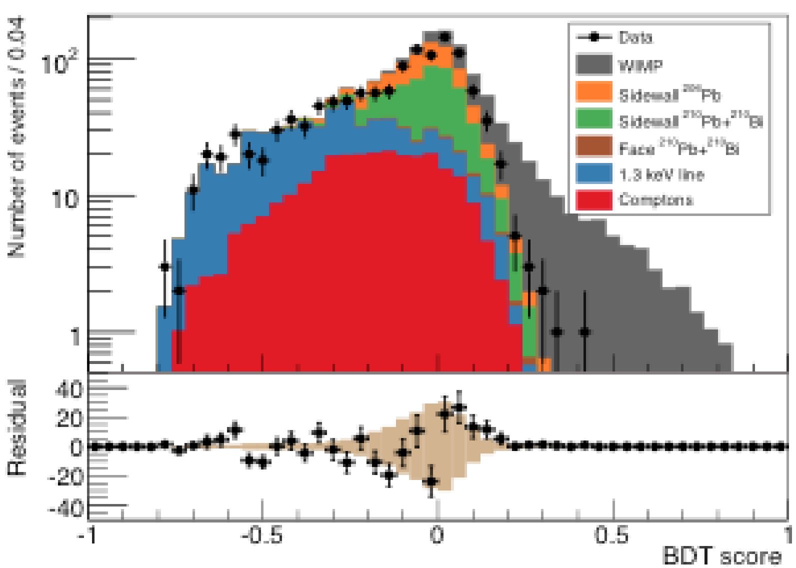
SuperCDMS-Soudan
Search for Low-Mass WIMPs

arXiv:1402.7137; Phys. Rev. Lett. 112, 241302 (2014)

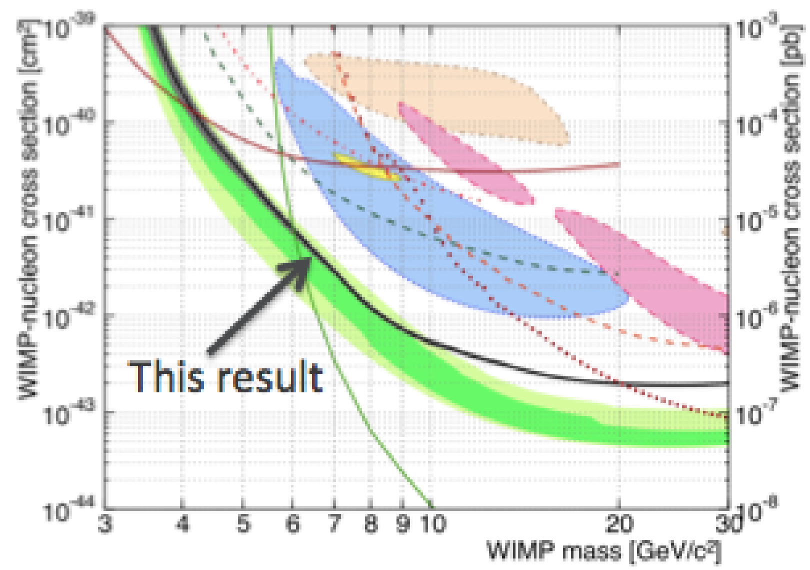
Pacific Northwest NATIONAL LABORATORY

Proudly Operated by **Battelle** *Since 1965*

- Boosted decision tree analysis demonstrates background model
  - Discrepancy for 1 damaged detector
- Tension with CDMS-II silicon results
- Also see Effective Field Theory interpretation (arXiv:1503.03379; accepted in Phys. Rev. D)



The most significant sources in the background model were ^{210}Pb, ^{68,71}Ge 1.3 keV L-capture, and gamma rays from K, U, Th contamination in the detector construction



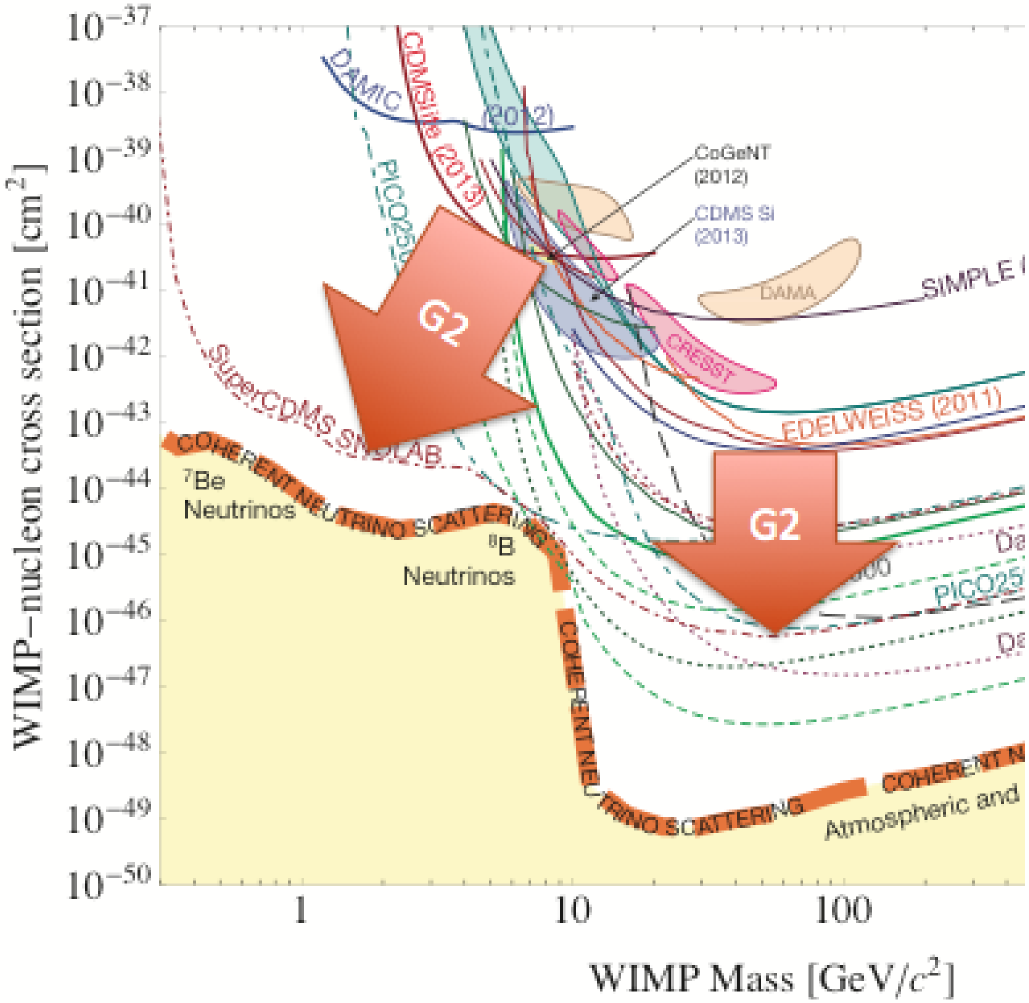
The resulting dark matter limits show excellent agreement across most of the analysis range. The discrepancy at 20-30 GeV may be due to a damaged detector.

SuperCDMS - Jeter Hall - CIPANP 2015 May 22, 2015 | 8

SuperCDMS-SNOLAB
Generation 2 Low Mass Dark Matter Search

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

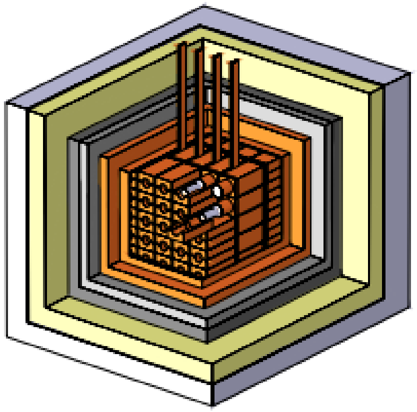
- The goal of Generation 2 SuperCDMS-SNOLAB is a dramatic increase in sensitivity, especially for WIMPs with mass<10 GeV
- Two main technology advances make this possible
  - X10 better energy resolution
    - Better electronics
    - Lower temperatures
  - X200 lower backgrounds
    - Material selection
    - Better cleaning/handling
    - Minimize cosmic-ray exposure



SuperCDMS - Jeter Hall - CIPANP 2015   May 22, 2015 | 9

DAMA Modulation Signal

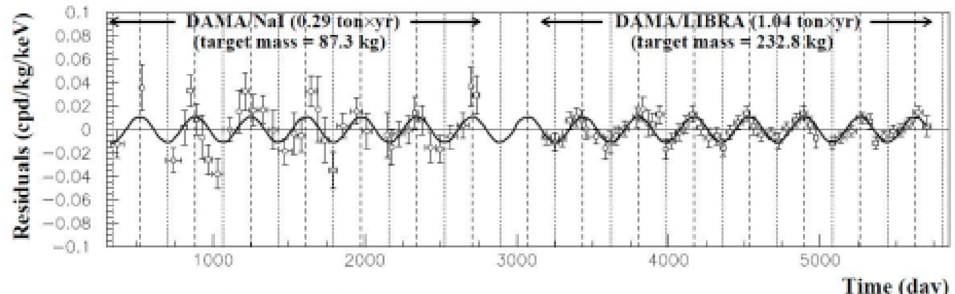
Performed search for dark matter annual modulation with NaI(Tl) crystal array



Bernabei *et al.*, NIM A, (2008)

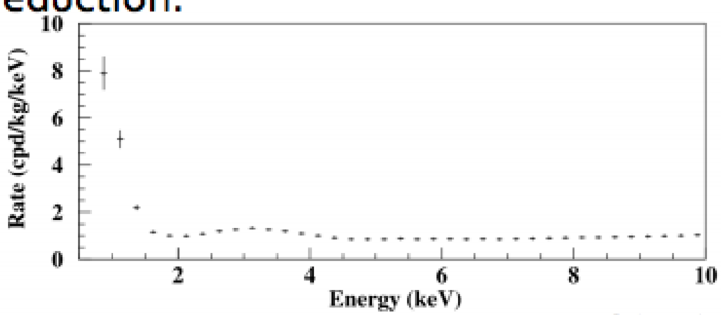
Observe non-zero amplitude at ***9.3-sigma***

- Consistent signal spanning 15 cycles



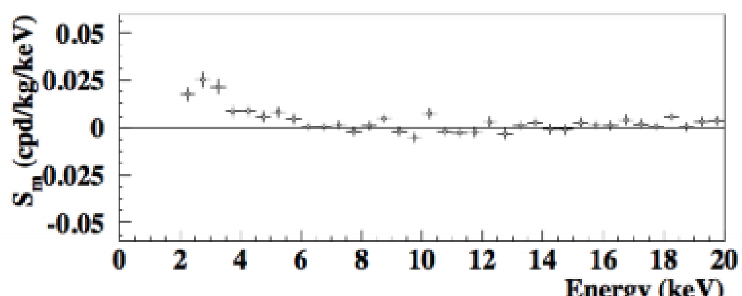
Bernabei *et al*, arXiv:1412.6524

Demonstrated excellent background reduction:



Bernabei *et al*, Eur Phys J C (2008)

Modulation only observed at low-energy:



Bernabei *et al*, Eur Phys J C (2013)

No background or environmental effect has been shown to replicate the DAMA signal

Walter C. Pettus CIPANP: May 2015 2

Threshold detectors

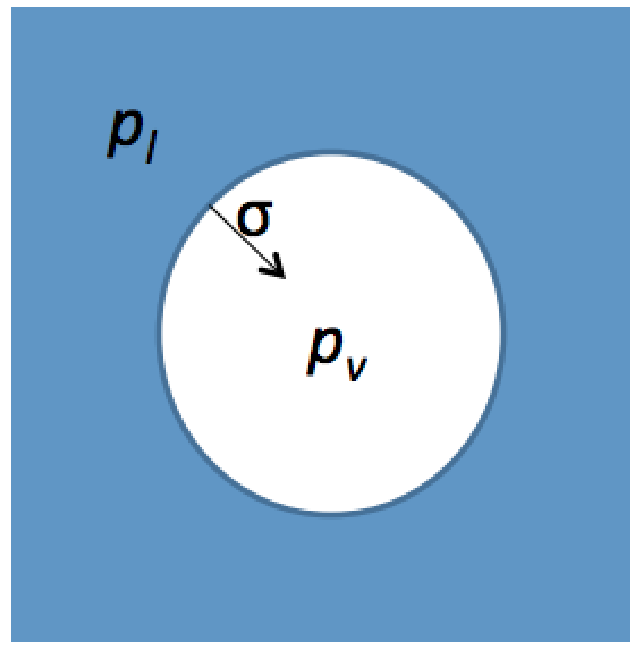
Some properties of threshold detectors

- **Threshold detector**
- **Fluid in a metastable state**
- **Can be quenched by energy depositions of particles**
- **Tiny energy deposition**
  macroscopic phase transition
- **Gammas can't or almost nucleate bubbles**
- **In principle, any liquid works**

- **In a superheated fluid, energy deposition greater than E_{th} in a radius less than r_c will result in a bubble large enough to overcome surface tension (Seitz "Hot-Spike" Model)**
- **Low E or dE/dx result in smaller bubbles that immediately collapse**
- **Classical Thermodynamics:**

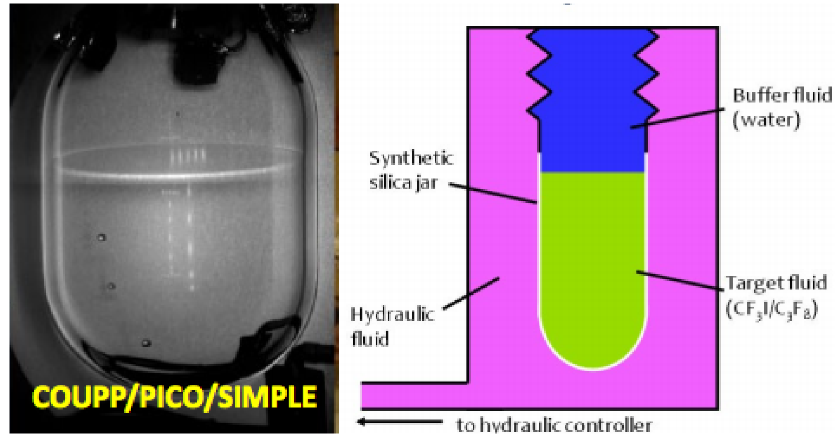
$$p_v - p_l = \frac{2\sigma}{r_c}$$

$$E_{th} = \underbrace{4\pi r_c^2 \left(\sigma - T\frac{\partial\sigma}{\partial T}\right)}_{\text{Surface energy}} + \underbrace{\frac{4}{3}\pi r_c^3 \rho_v h}_{\text{Latent heat}}$$

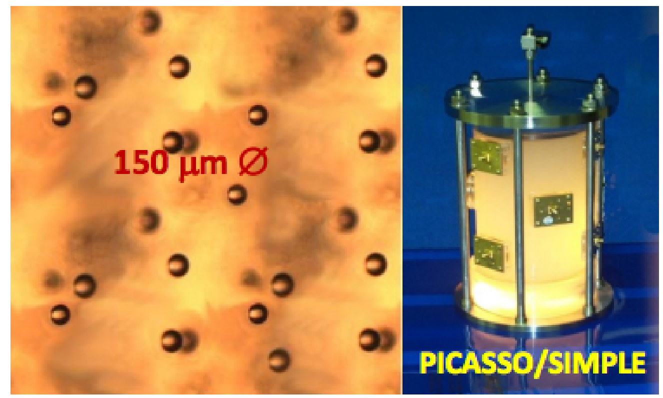


Bubble chambers/droplet/geyser

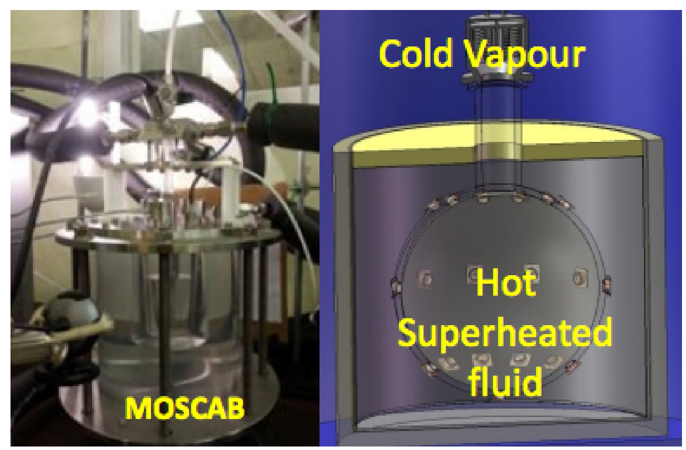
- Bubble chambers: COUPP, PICO
  Acoustic and optical readout



- Droplet detectors:
  PICASSO, SIMPLE
  Optical readout

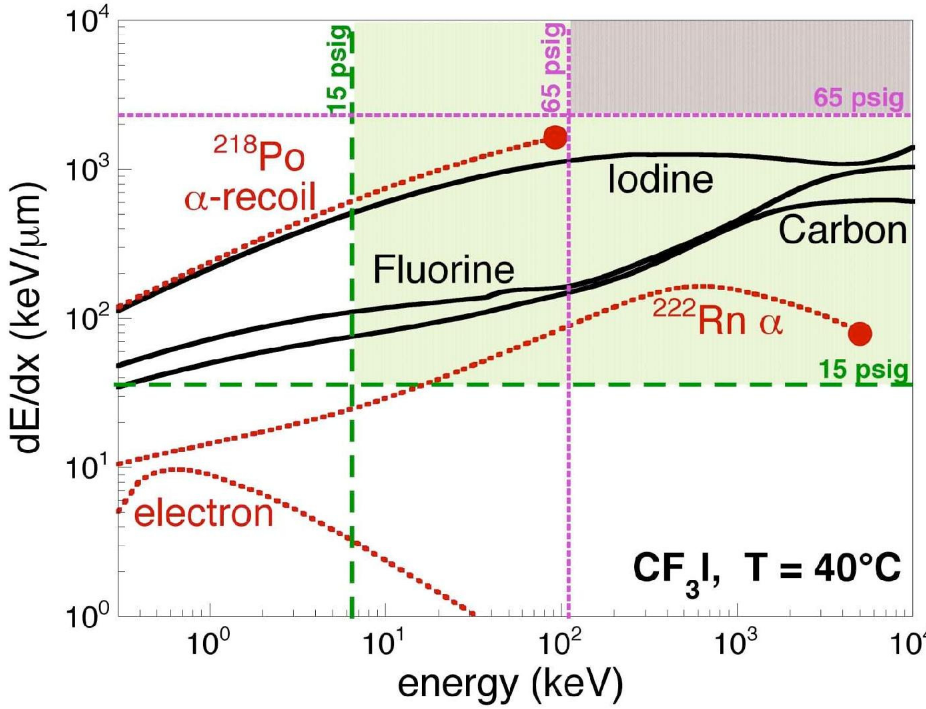


- Condensation chambers (Geyser):
  MOSCAB
  Acoustic and optical readout



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



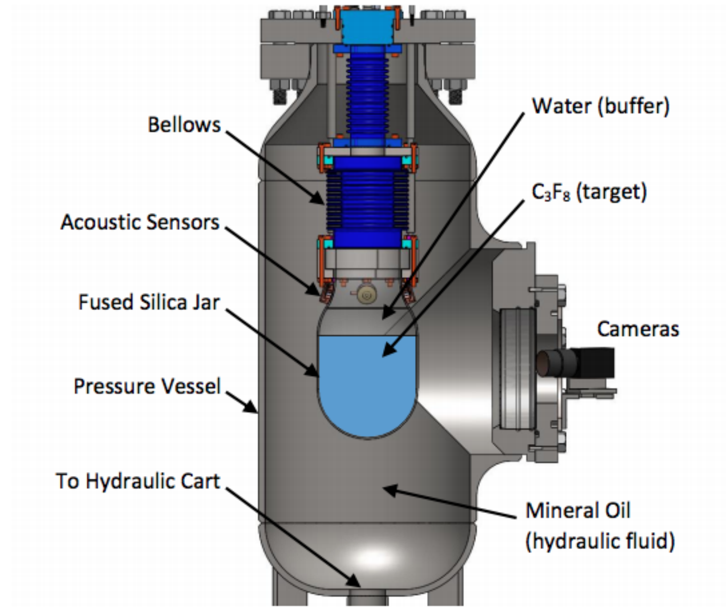
insensitive to electrons and gammas

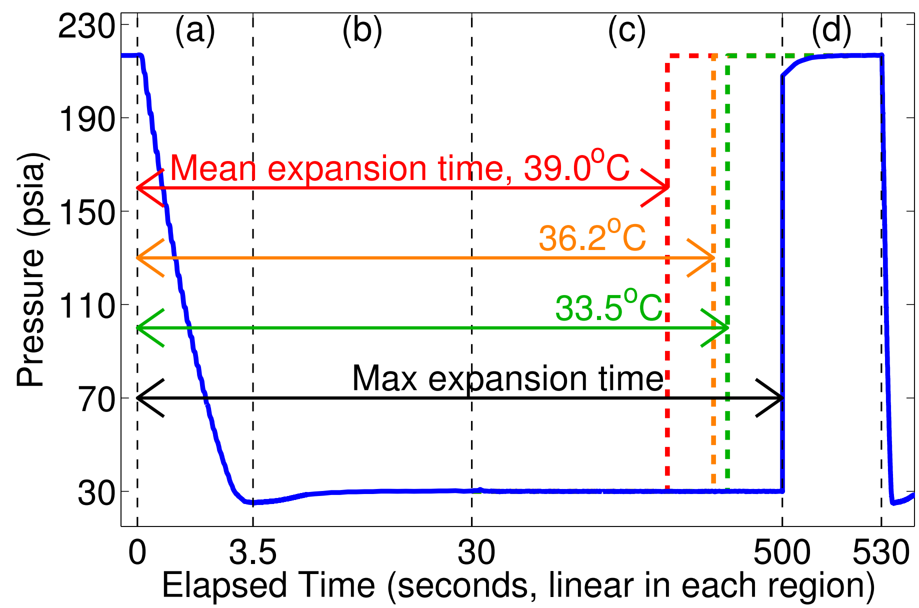
PICO bubble chambers

- Target material: superheated CF_3I, C_3F_8, C_4F_10 spin-dependent/independent

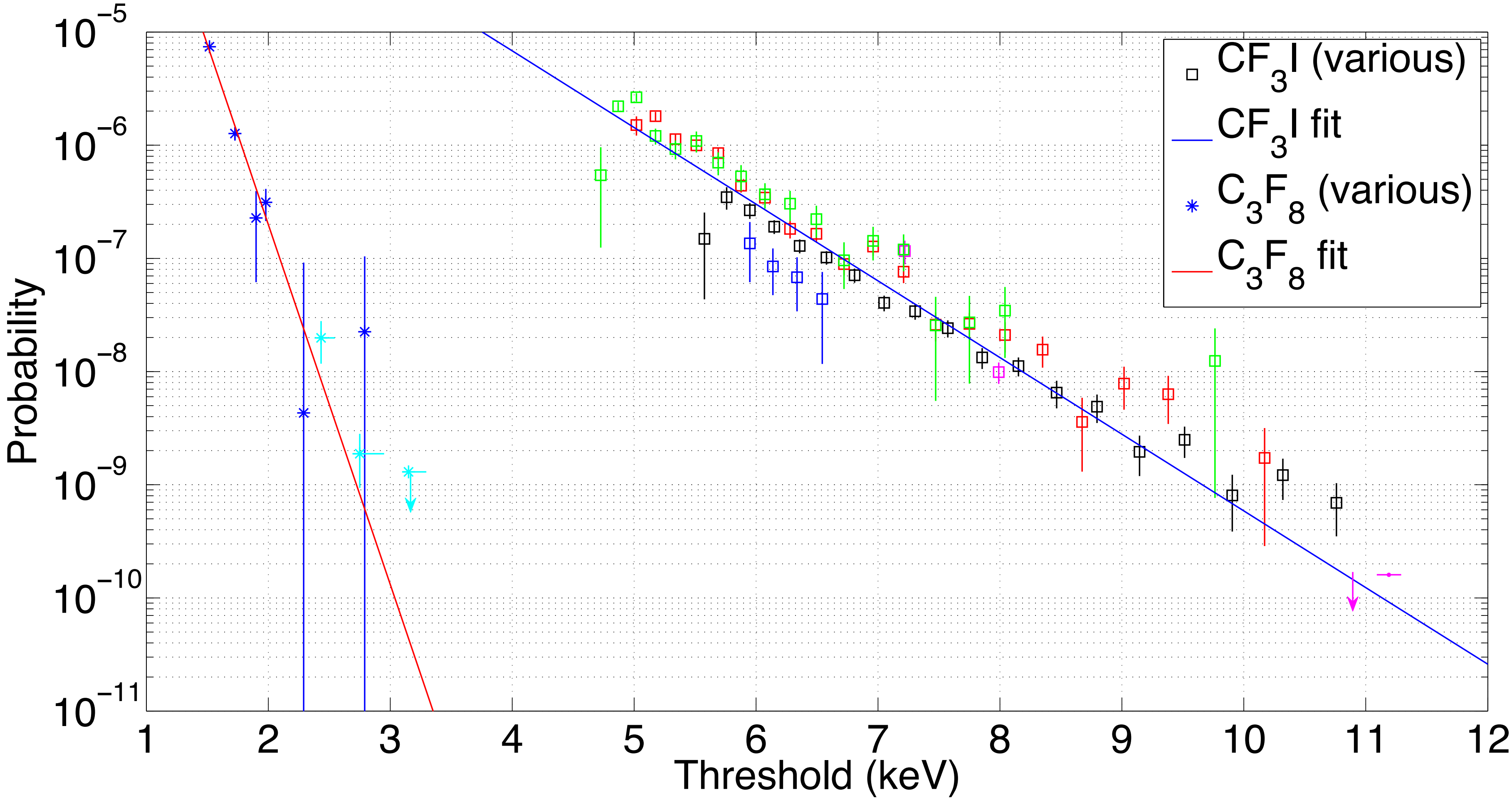
  Could make a dark matter bubble chamber with any liquid!

- Particles interacting evaporate a small amount of material: bubble nucleation
- Cameras record bubbles
- Piezo sensors detect sound
- Recompression after each event





Backgrounds in PICO: γ rejection



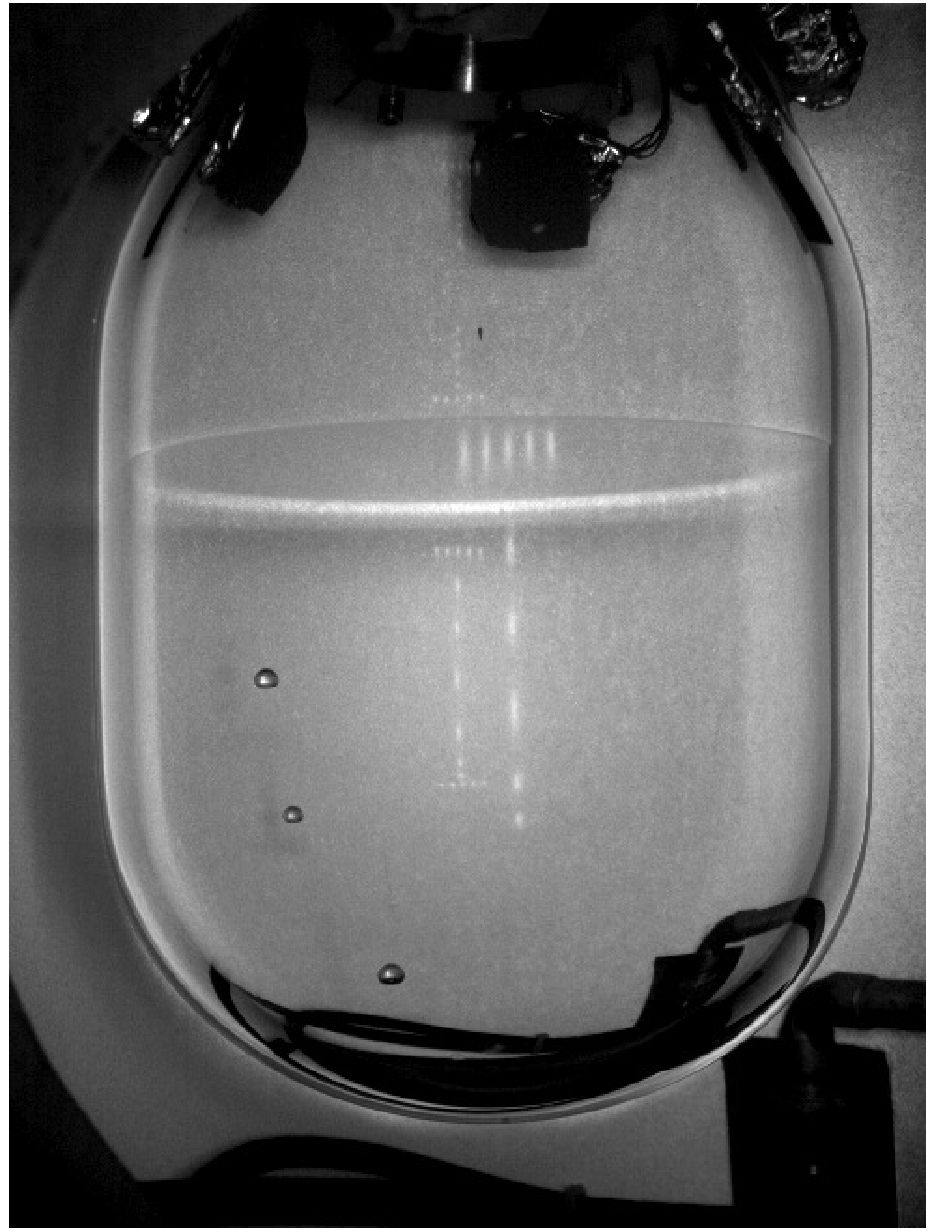
Bubble nucleation probability from gamma interactions in C_3F_8 and CF_3I

PICO bubble chambers

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

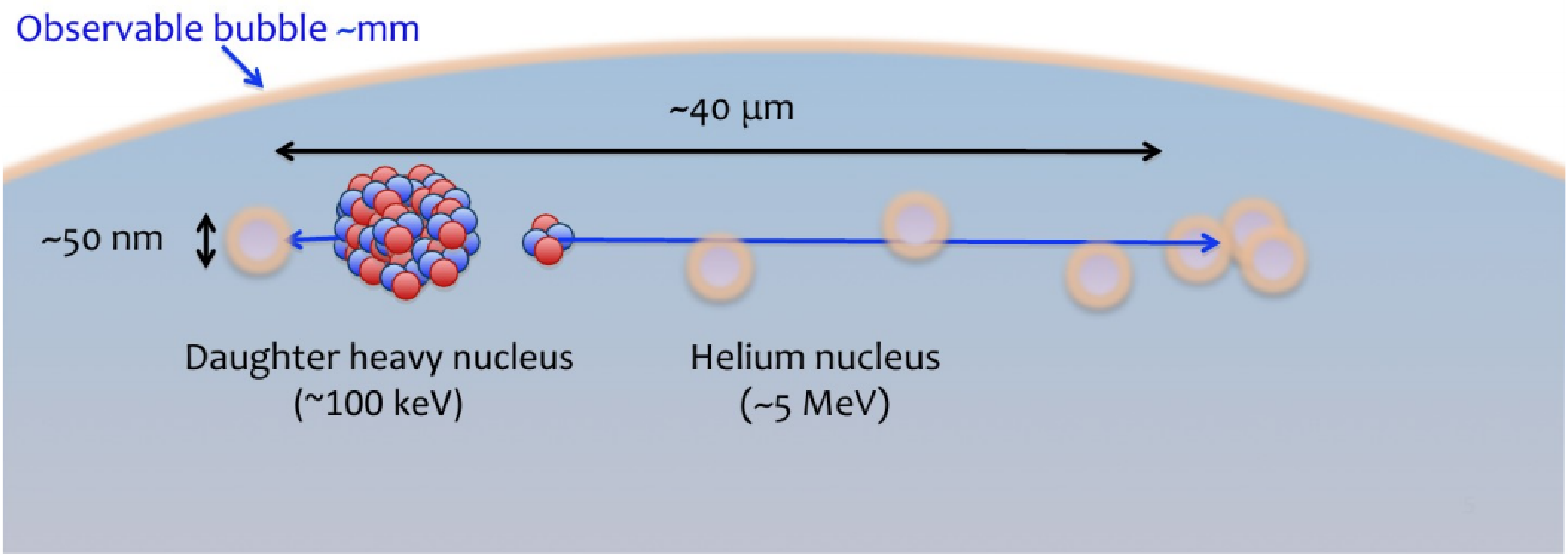
- **Neutrons:**
  Nuclear recoils
  mean free path ∼20 cm
  3:1 single-multiple ratio
  in COUPP4

- **WIMPs:**
  Nuclear recoil
  mean free path $> 10^{12}$ cm
  1 bubble



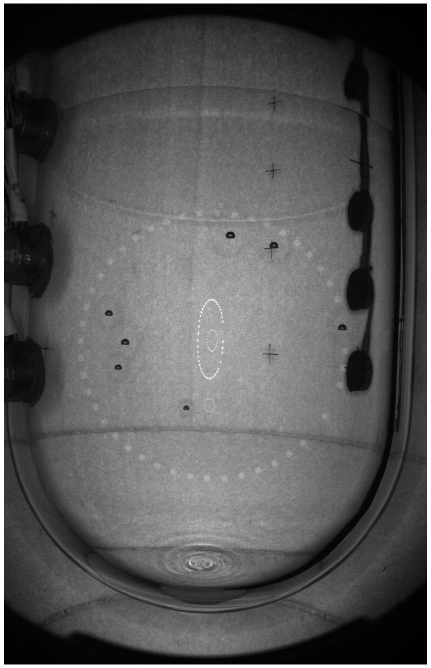
PICO bubble chambers

- Alphas deposit energy over tens of microns,
  nuclear recoils deposit theirs in tens of nanometers
- Alphas are $\sim$ 4 times louder than nuclear recoil bubbles
- $>$ 99.4% discrimination against alpha events demonstrated
- Discovered by the PICASSO collaboration



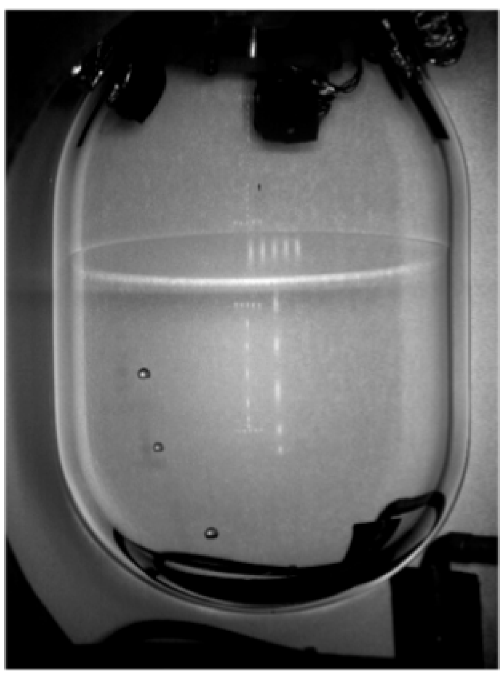
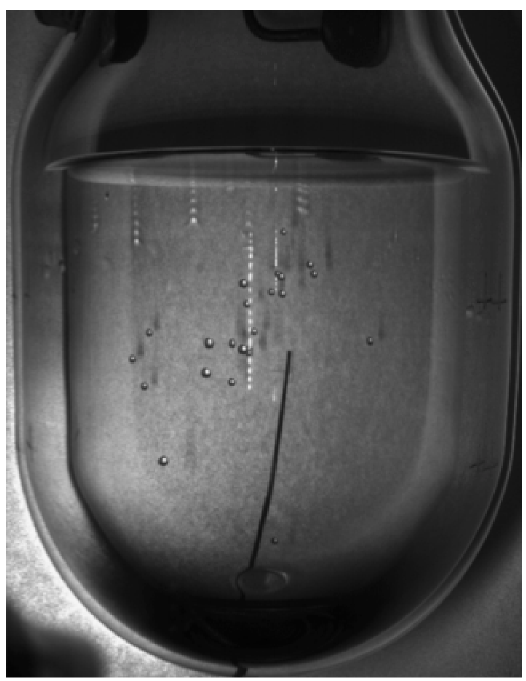
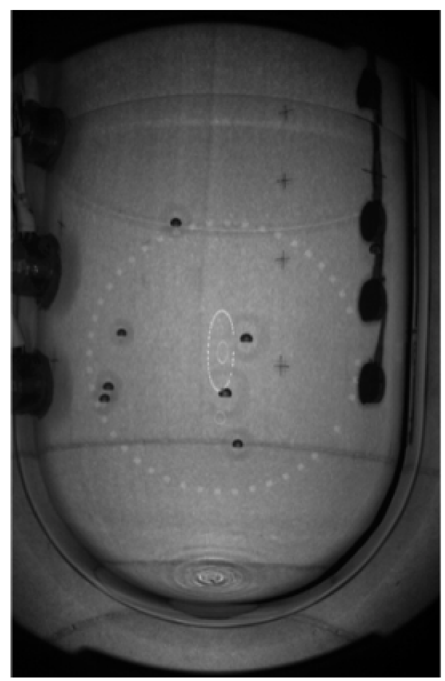
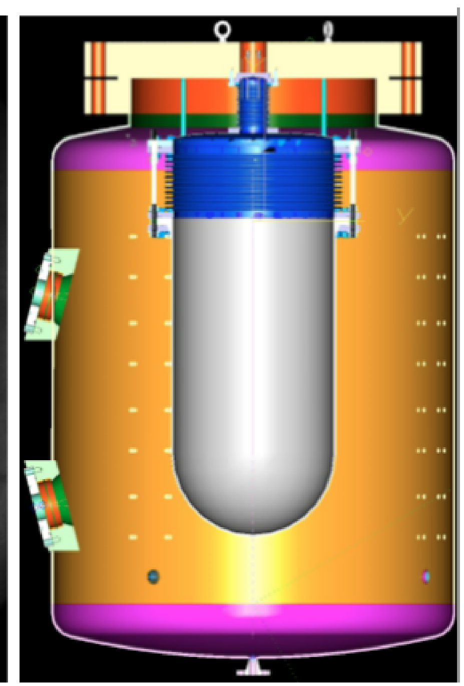
PICO detectors features

- **Energy: threshold detector**
- **Background suppression:**
  - **UG at SNOLAB**
  - **Water shielding**
  - **Clean materials**
- **Background discrimination:**
  - **Neutrons:**
    multiples bubbles
    Nuclear recoil, $l \sim 20$ cm
  - **α: acoustic parameter**
    Nuclear recoil, 40 μm track
- **Large target mass:**
  COUPP4 to COUPP60
  PICO-2L to PICO-60

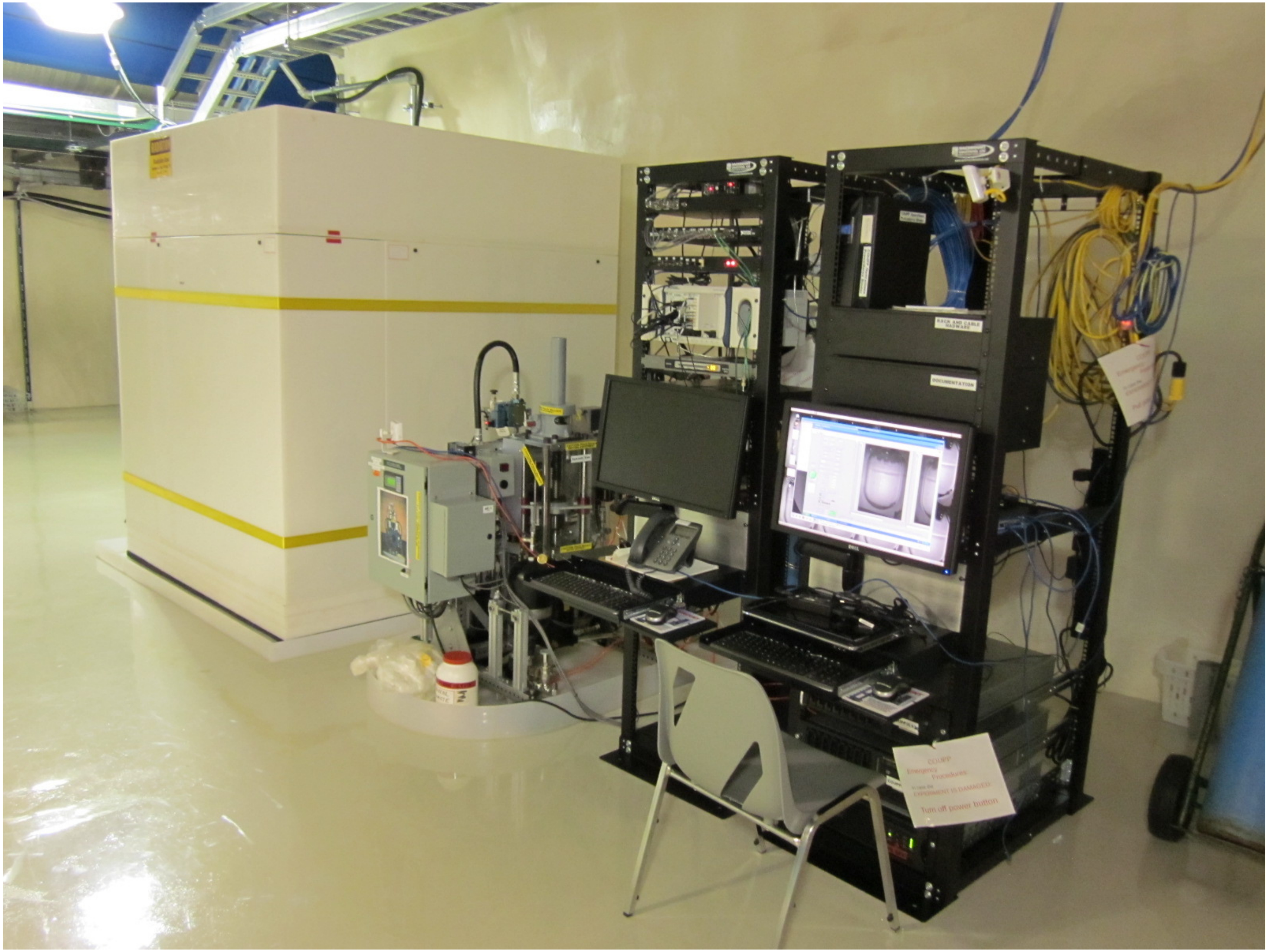


PICO bubble chambers

- COUPP4: a 2-liter CF3I chamber run at SNOLAB in 2010 and 2012
- COUPP60: up to 40 liter CF3I chamber run at SNOLAB 2013-2014
- PICO-2L: a 2-liter C3F8 chamber run at SNOLAB 2013-2014 and 2015
- PICO-250L: future ton-scale experiment

COUPP4

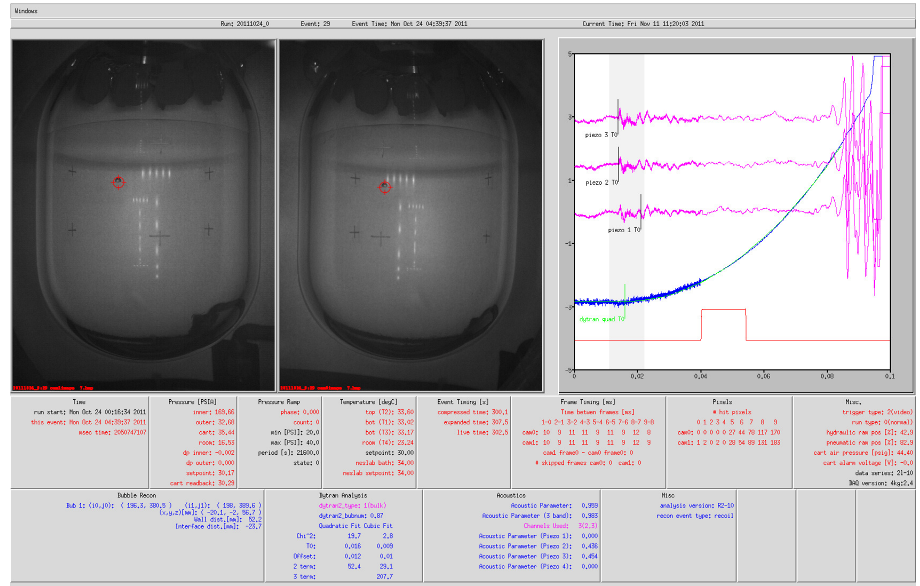


PICO: data analysis

- Examination of images: algorithm searching for clusters among pixels that changed between consecutive frames

- Examination of pressure rise: fit to the rate of pressure rise by a quadratic time dependence for bubbles in the bulk

- Examination of the acoustic signal



hand-scanned to resolve disagreement

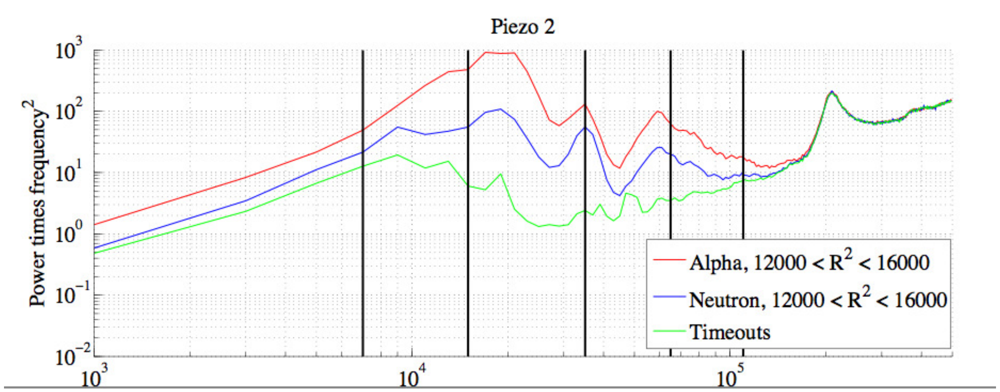
overall efficiency for all data quality and fiducial volume cuts is $\sim 80\%$

COUPP4 at SNOLAB

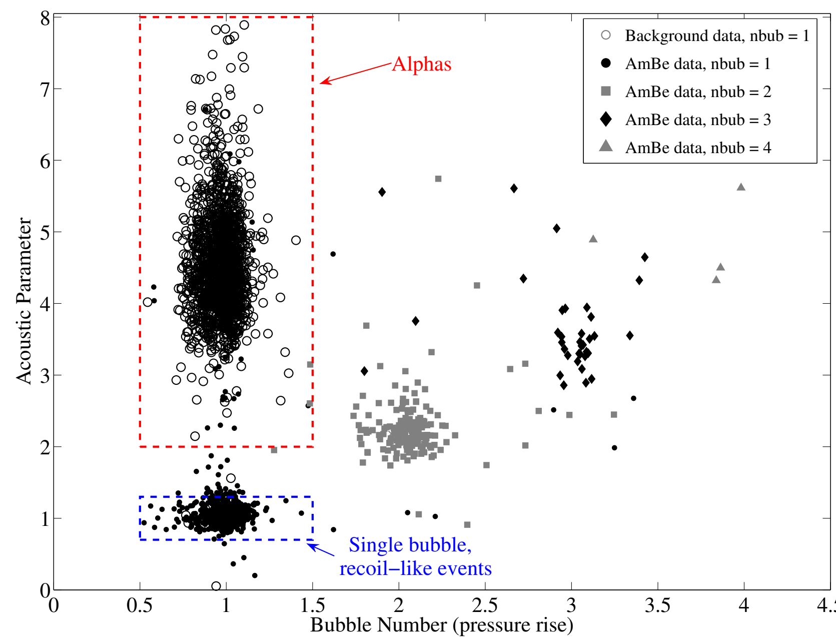
Acoustic transducer signals digitized with a 2.5 MHz sampling rate and recorded for 40 ms for each event

3 ways of counting:

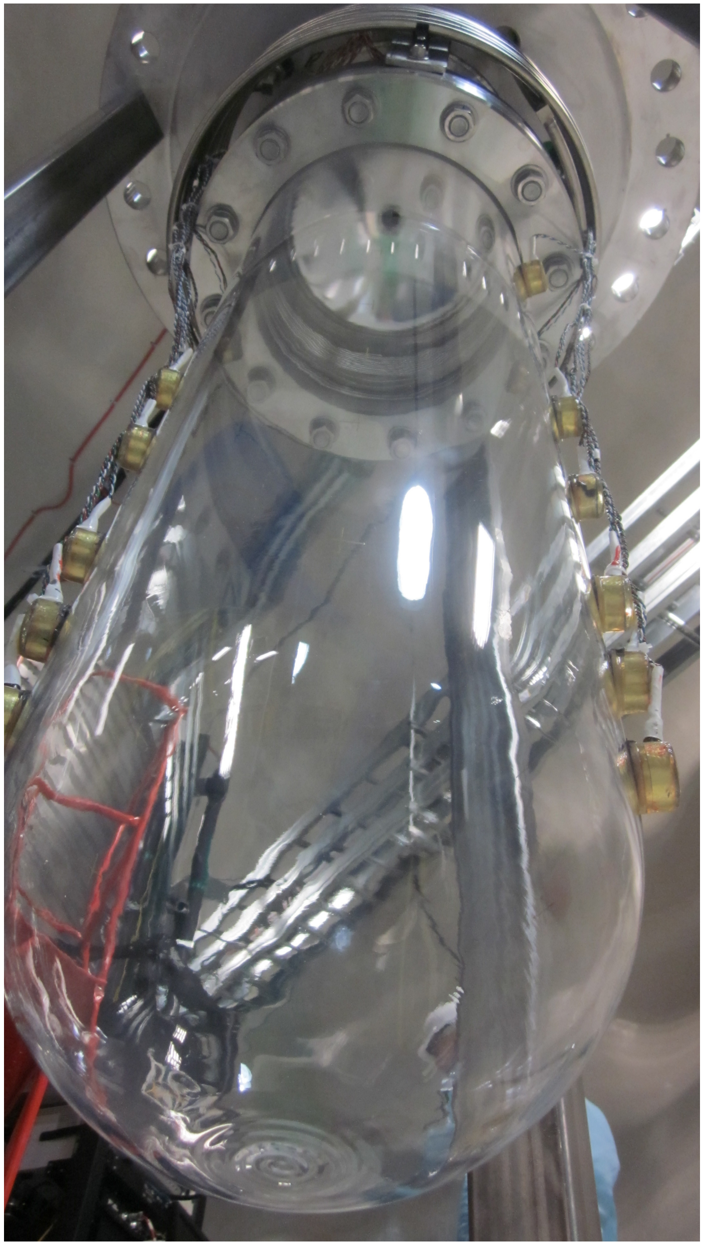
- Images: cameras
- Pressure rise: transducer
- Acoustic parameter: piezos



The nuclear recoil acceptance of the AP cut is ∼ 95%

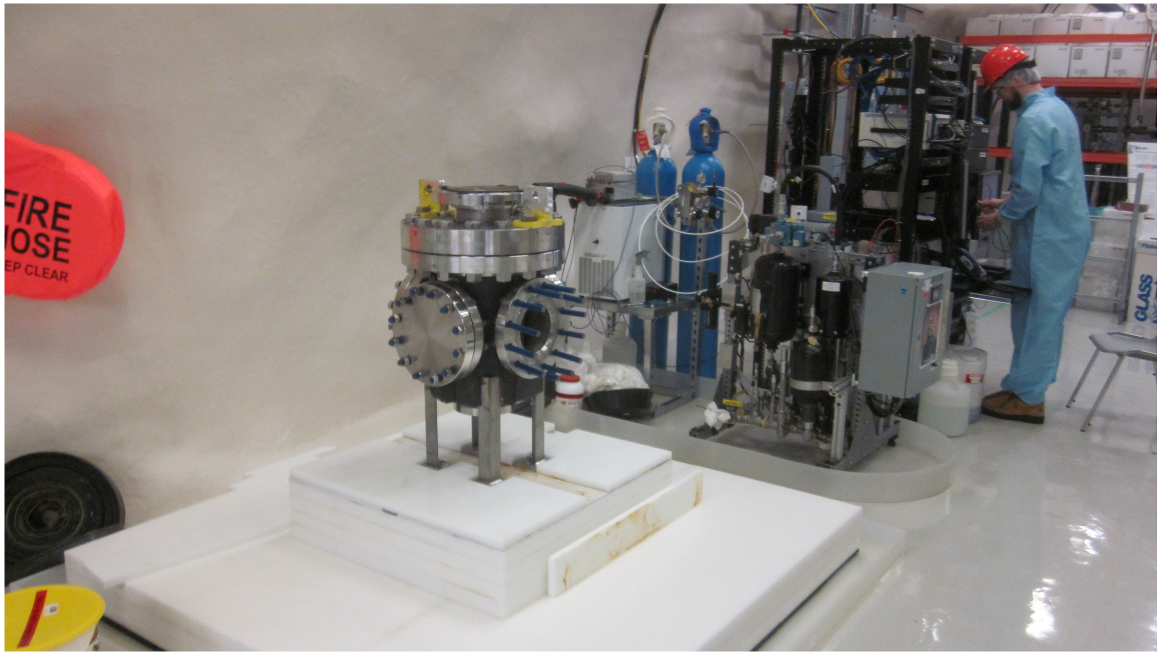


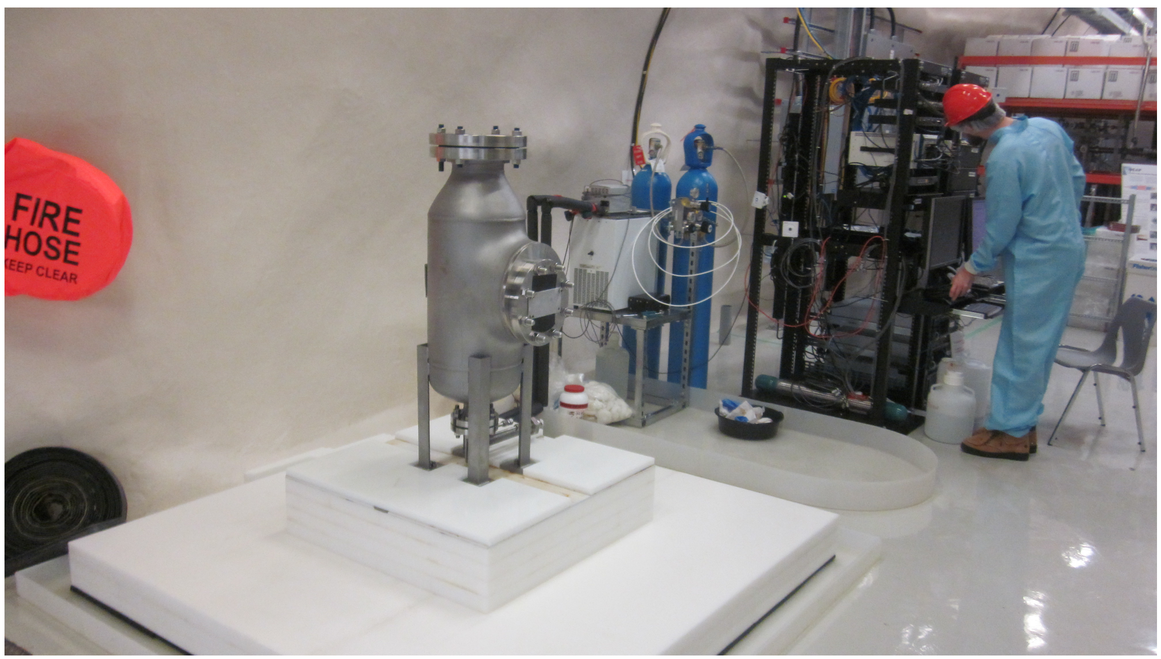
COUPP60



COUPP60

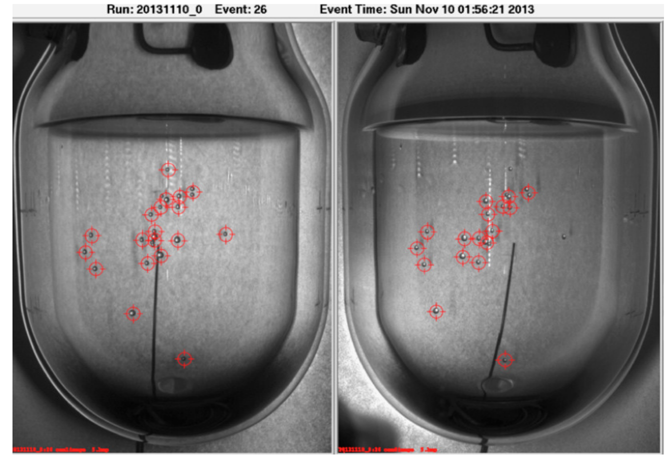
From COUPP4 to PICO-2L

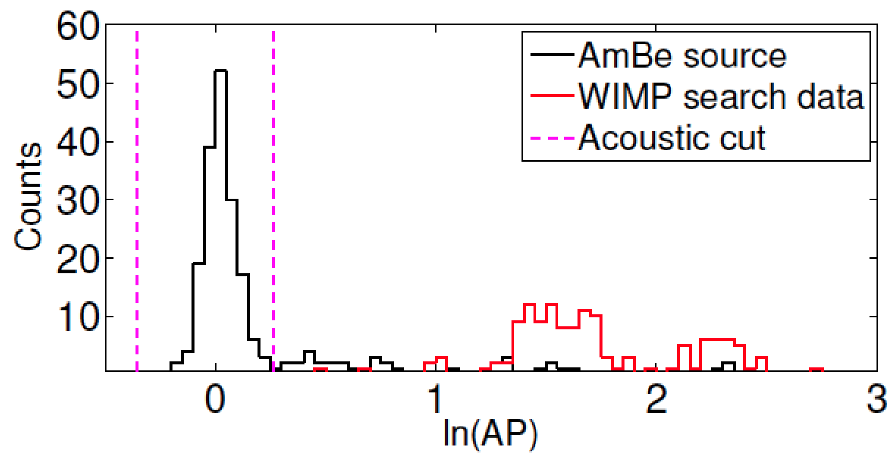


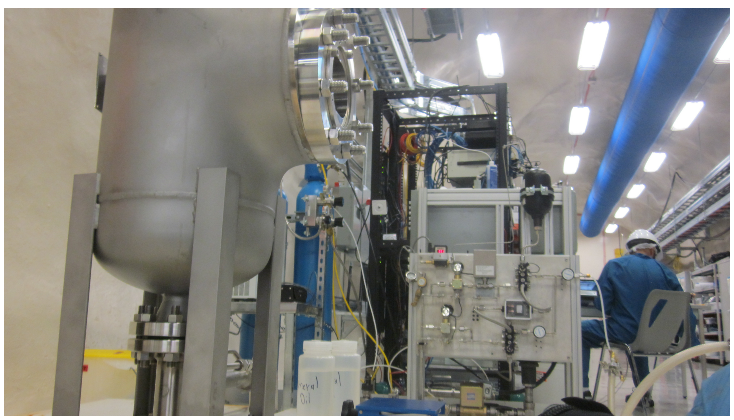


PICO-2L

- C_3F_8 as target material
- spin-dependent sensitivity: world leading limit
- Low energy threshold, as low as 3 keV
- Test recent claims of evidence for light WIMPs







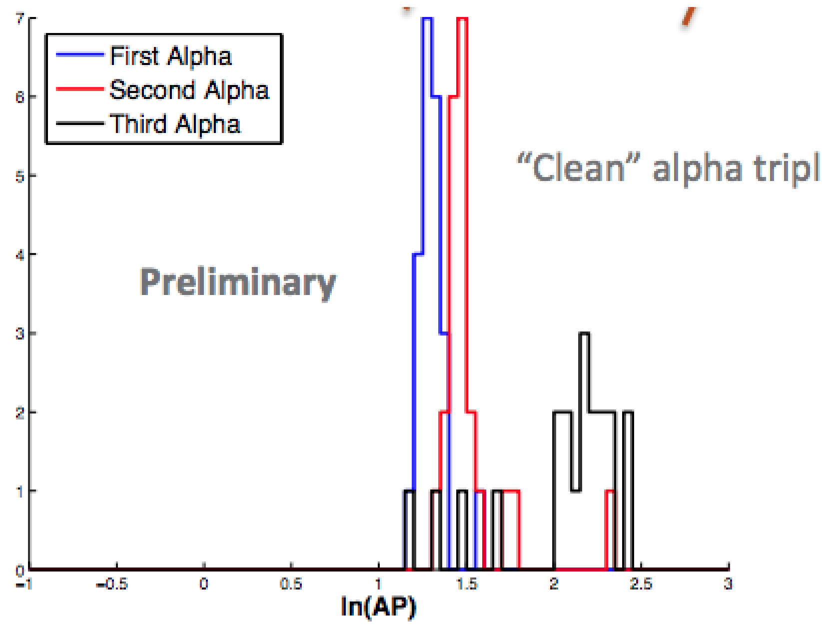
(alpha calorimetry observed for the first time)

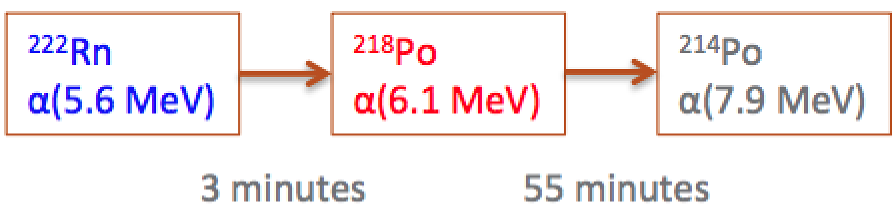
Results from run I published on June!

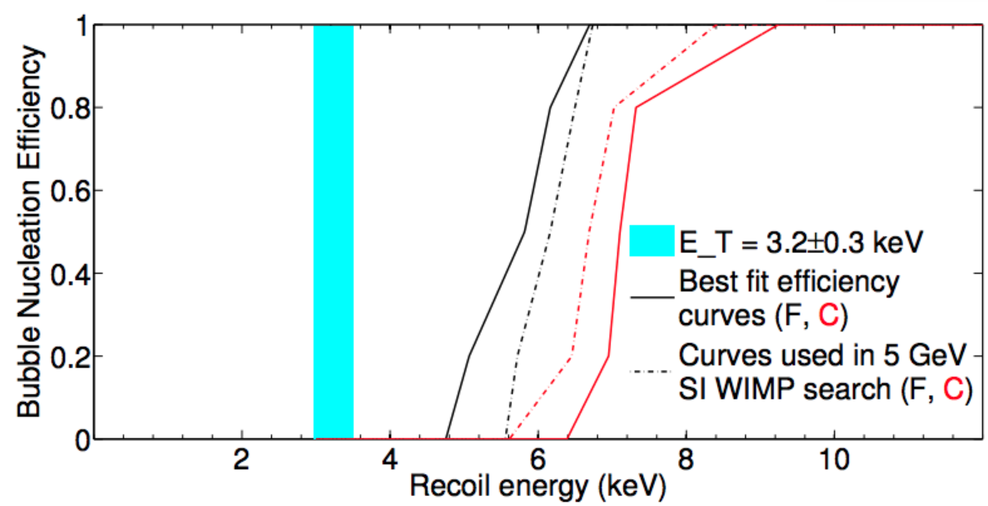
PRL 114(2015), 231302

PICO-2L

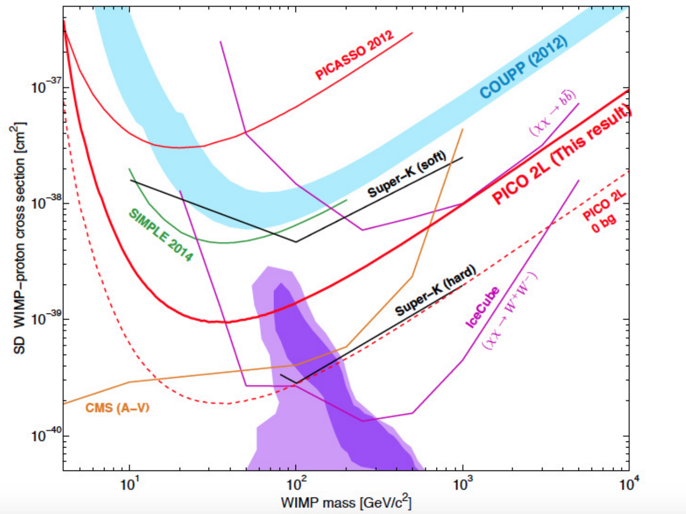
- No multiple bubble events in the low background data
- Two distinct alpha peaks, clearly separated from nuclear recoils
- Timing of events in high AP peaks consistent with radon chain alphas, and indicate that the higher energy 214Po alphas are significantly louder (a new effect not seen in CF3I)

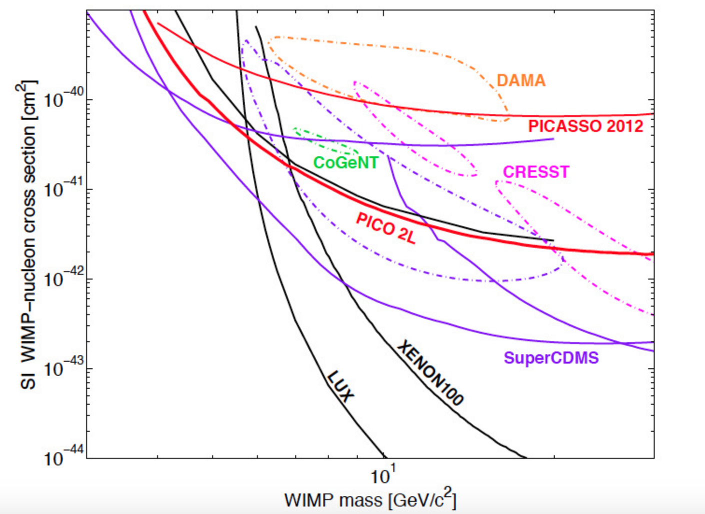




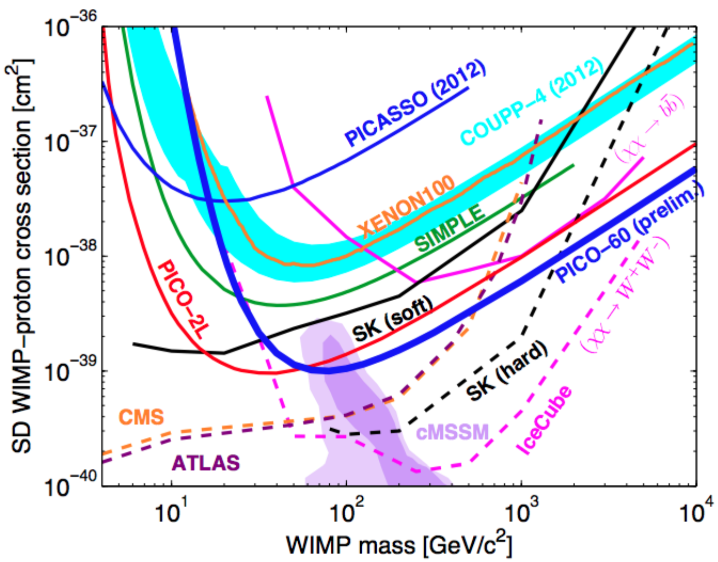


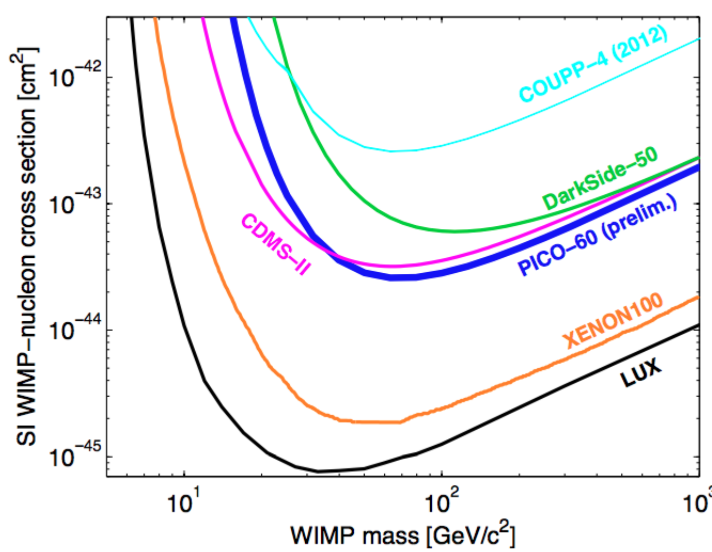
Results and preliminary results





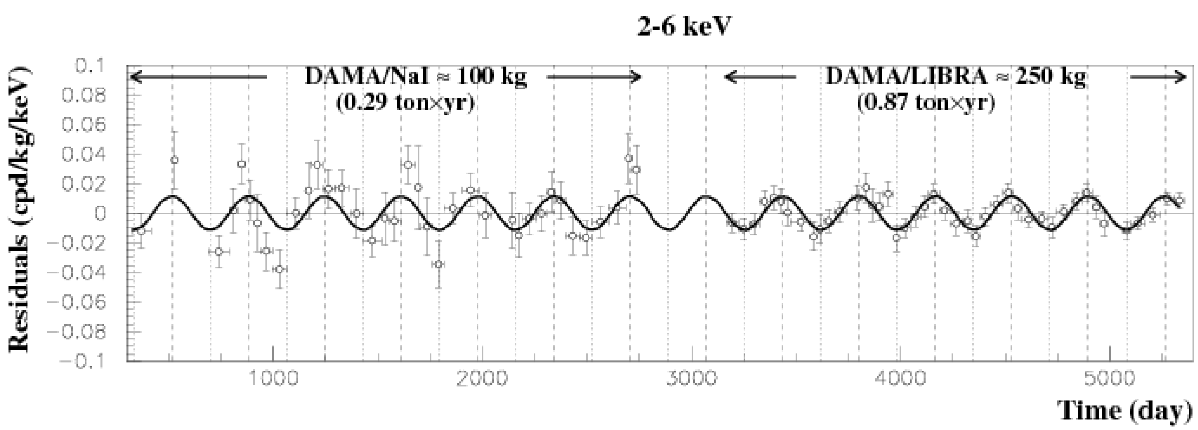
PICO-2L is world leading experiment for SD WIMP-proton scattering, first time supersymmetric parameter space has been probed by direct detection in the SD-proton channel

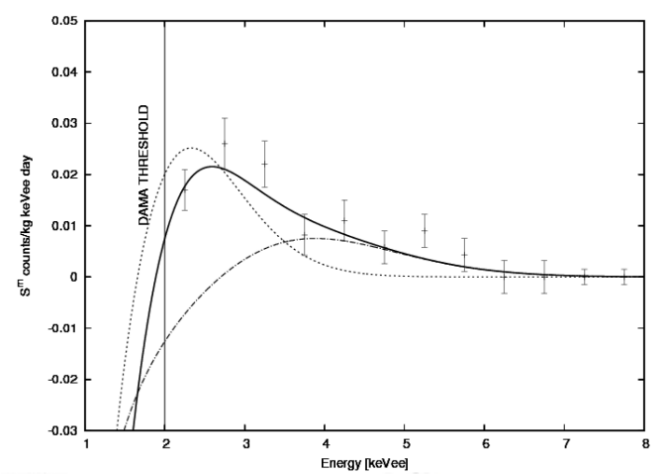




Implications to DAMA-LIBRA signal

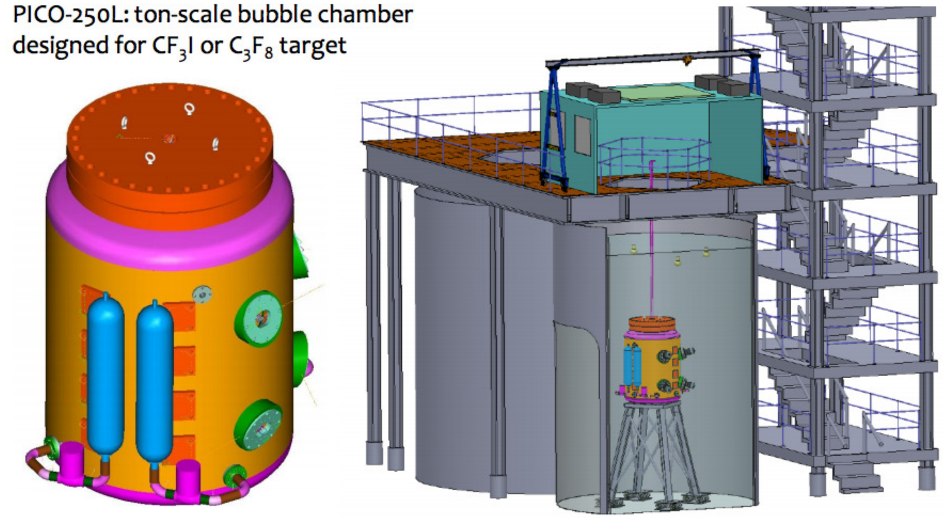
- Using DAMA spectrum between 2 and 6 keV
- Applying DAMA iodine quenching factor (0.09) results in expectation of 49 recoils above 22 keV
- PICO-60 observes <4.1 events at 90% C.L.
- Background estimate:
  singles $= 4.27 \pm 1.06$ per yr, multiples $= 3.85 \pm 0.94$ per yr

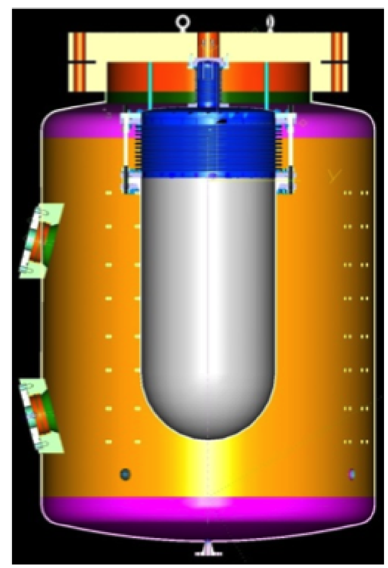




PICO-250L

- $> 10^{10}$ γ/β insensitivity
- $> 99.3\%$ acoustic α discrimination
- Multi-target capability
  SD- and SI-coupling
  High- and low-mass WIMPs
- Easily scalable,
  inexpensive to replicate





Data taking by 2017-2018

**Working to deploy new detector:
Right Side Up chamber**

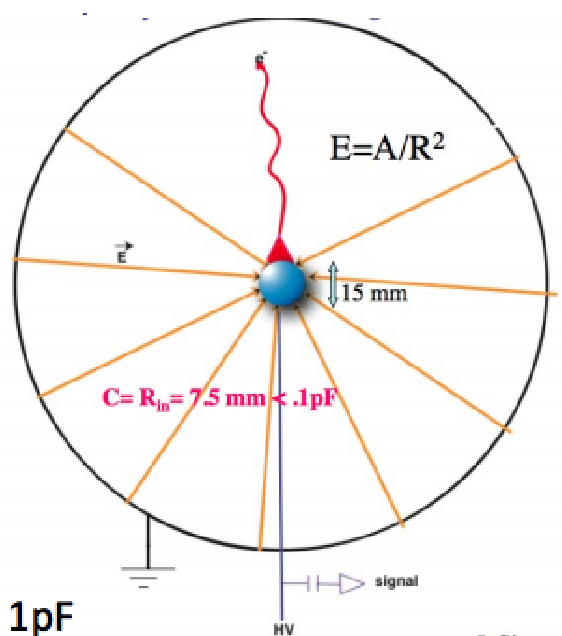
Solve background issues

New techniques

New Experiments With Spheres

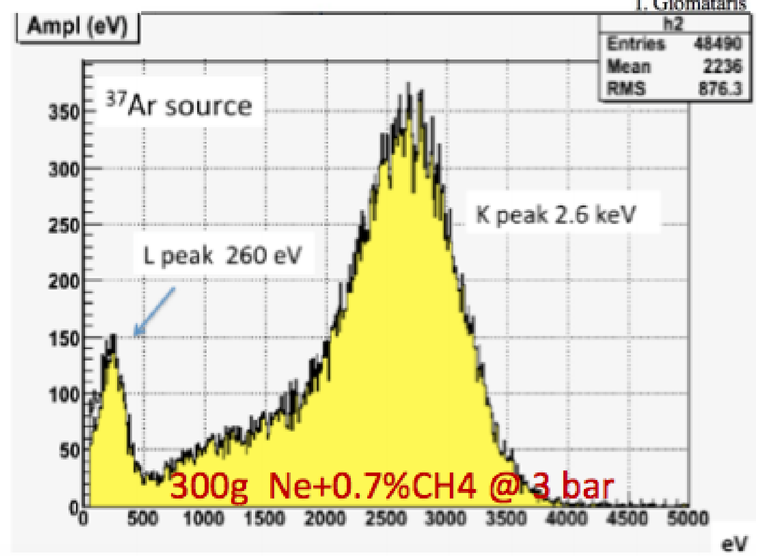
Queen's, SNOLAB, Saclay, LSM, Tessaloniki, Grenoble, Munich

- Spherical cavity + sensor
- Proportional counter mode
- Target: Ar, Ne, He, H (CH4)
- Large volume/mass (30g)
- Single channel R/O
- Low threshold – low cap. < 1pF



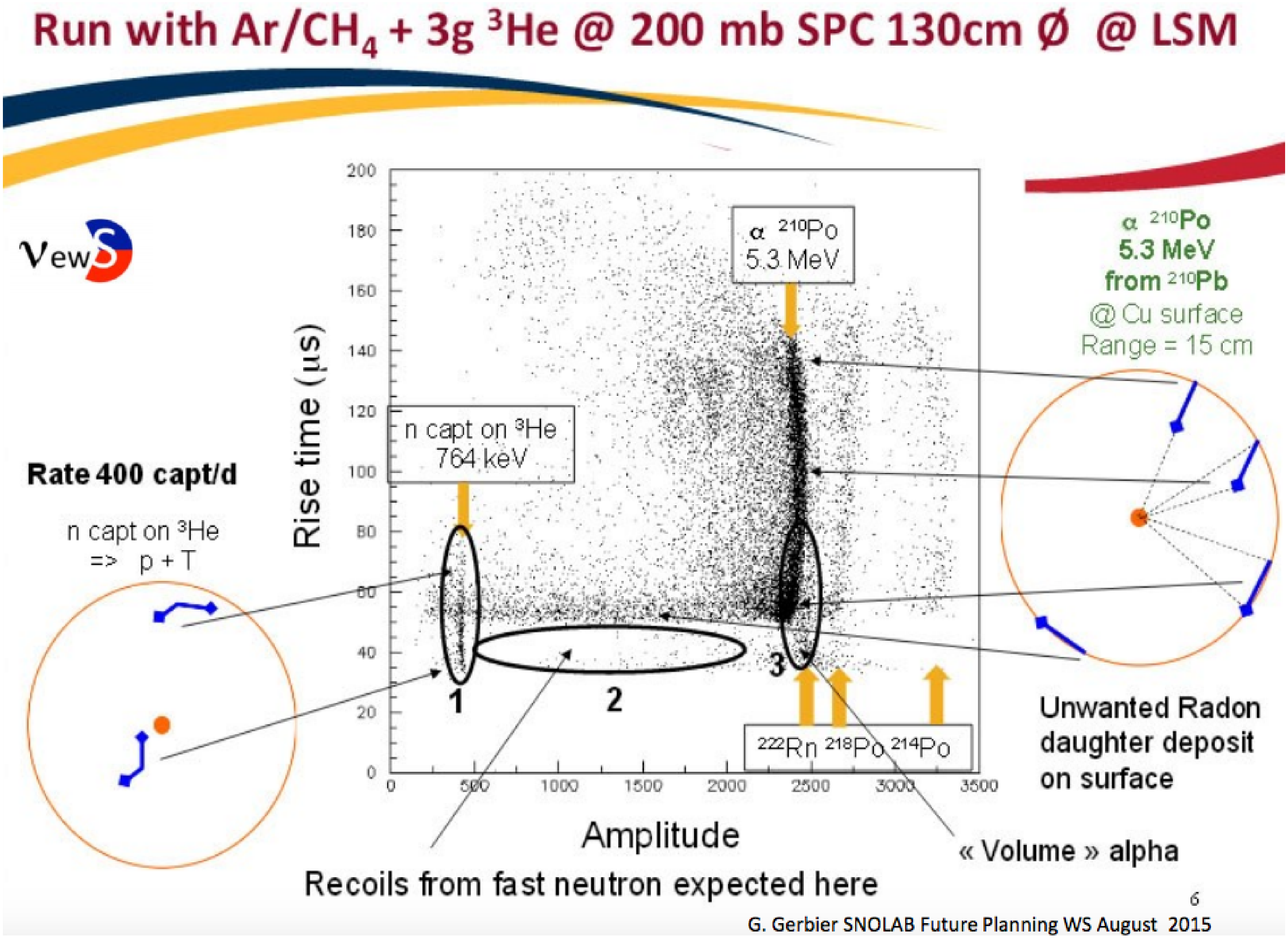
I. Giomataris

- E_{thr} = 120 eV demonstrated in Ne @3b
- Localisation by rise time
- 2 LEP cavities with 130 cm ∅ tested
- SEDINE @LSM: low activity 60 cm Ø module

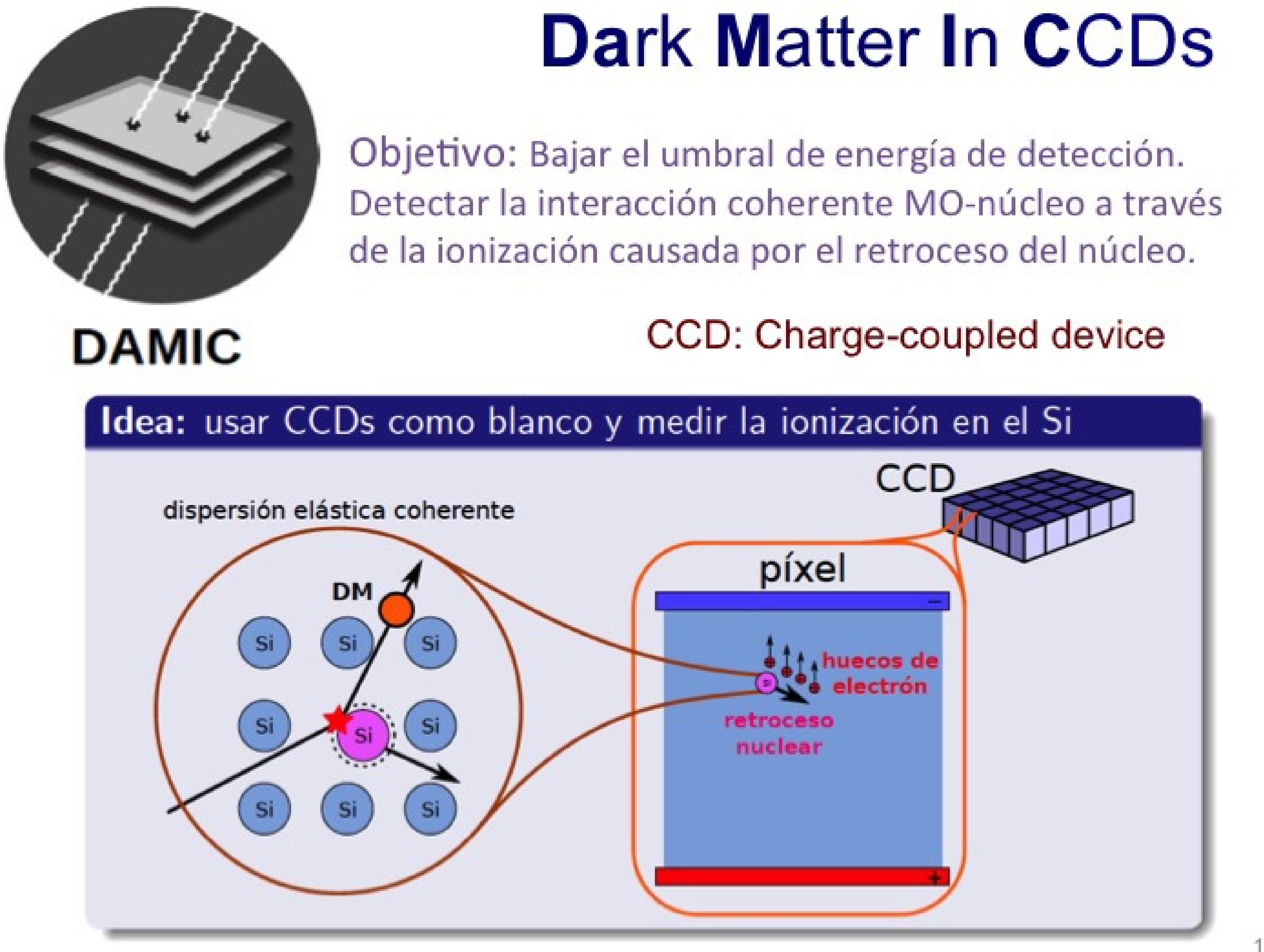


G. Gerbier SNOLAB Future Planning WS August 2015

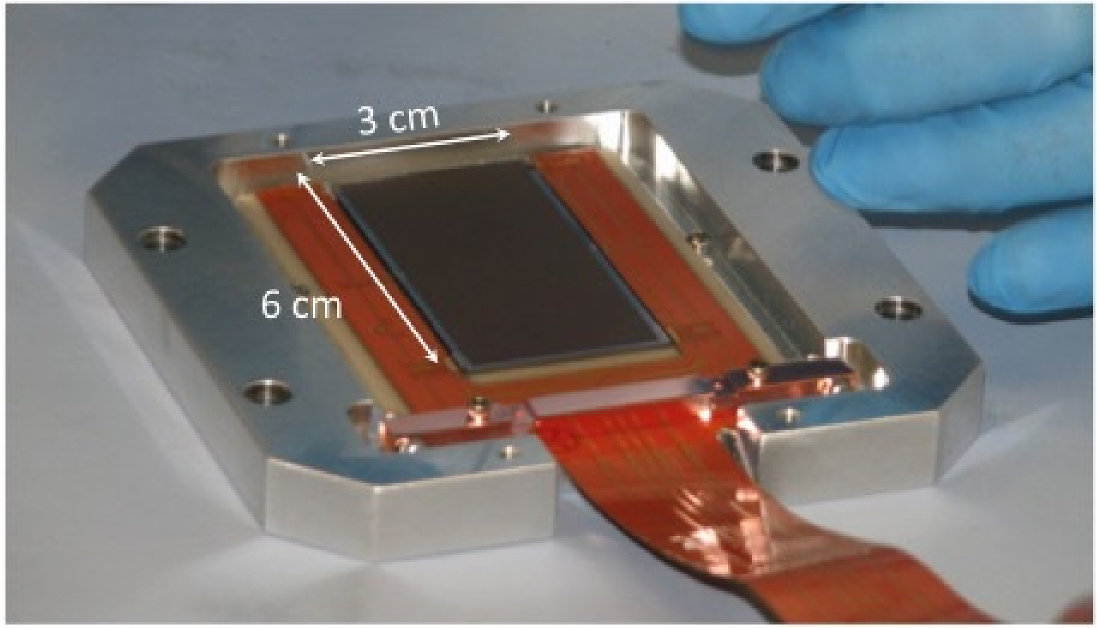
Low WIMP masses: NEWS



Low WIMPS masses: DAMIC



TECNOLOGÍA: CCD de uso científico



Tamaño de los pixeles: 15 mm x 15 mm

No. of pixels: 16 millones

Espesor: 675 mm

Masa: 5.2 gramos

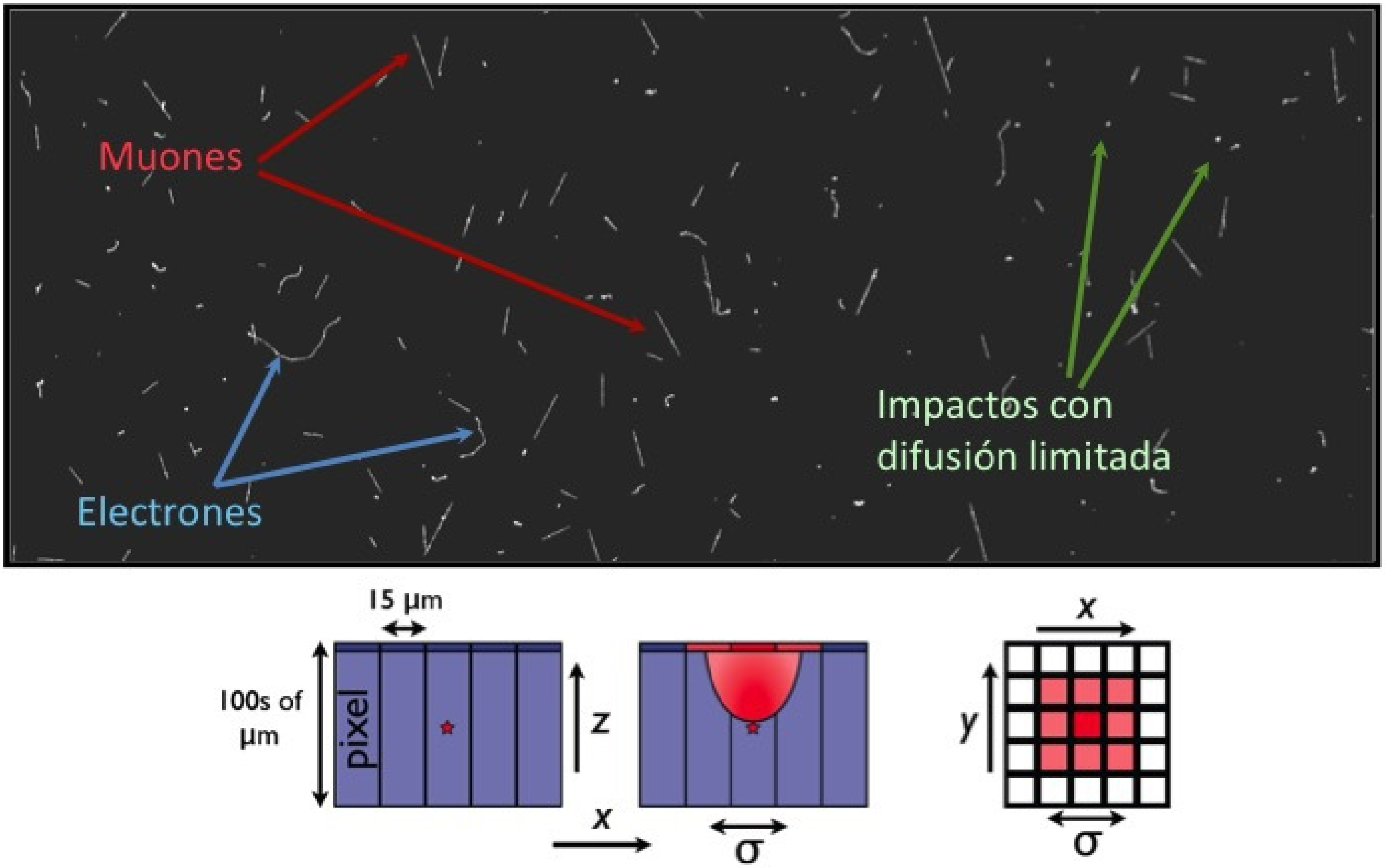
Temp de operación: -140 C

Desarrolladas en LBLN

Bajo ruido electrónico.
Umbral de detección de
< 50 eV

2

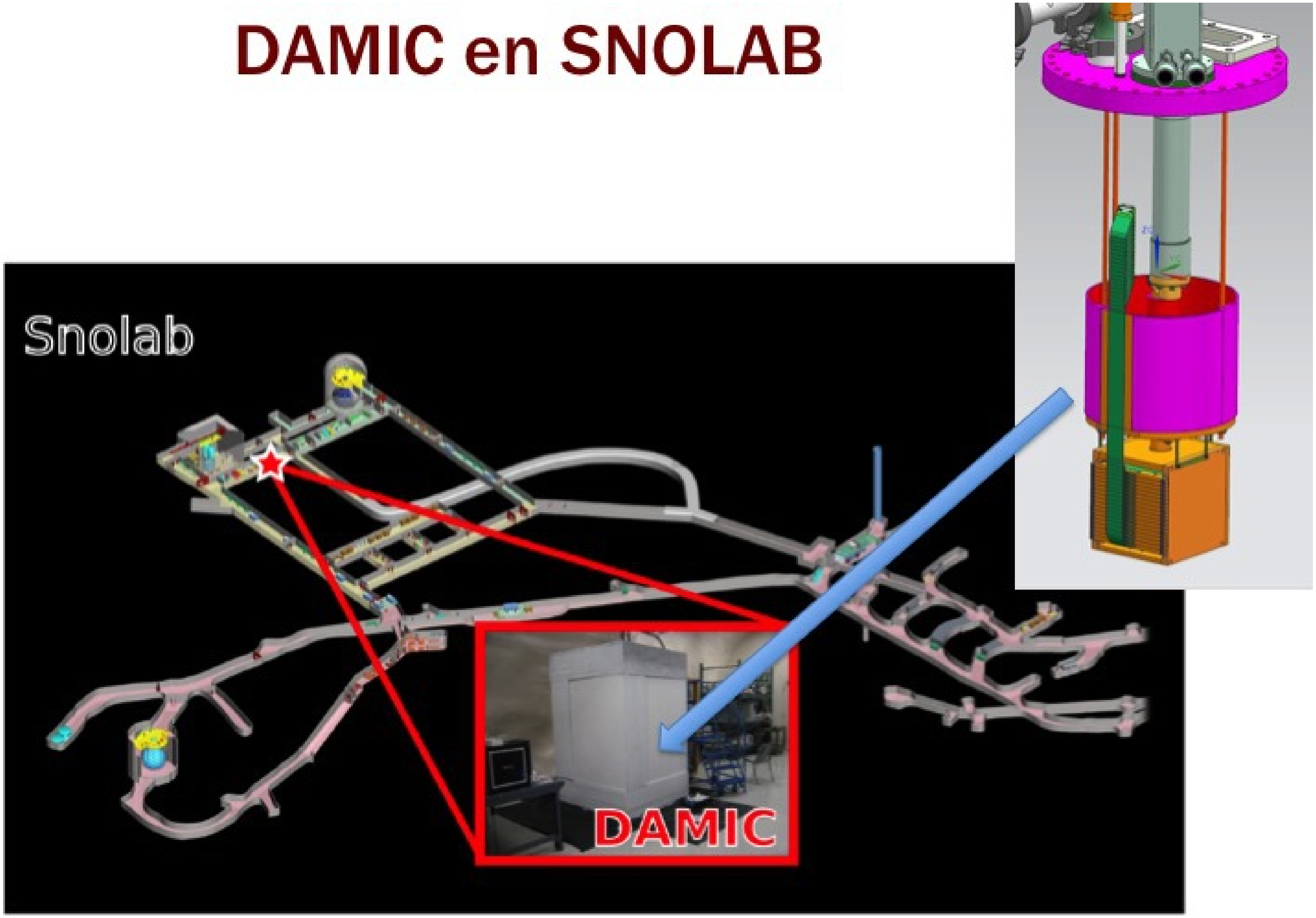
DAMIC



Los retrocesos nucleares producen impactos de difusión limitada.
Se espera que las partículas de MO generen estos impactos

3

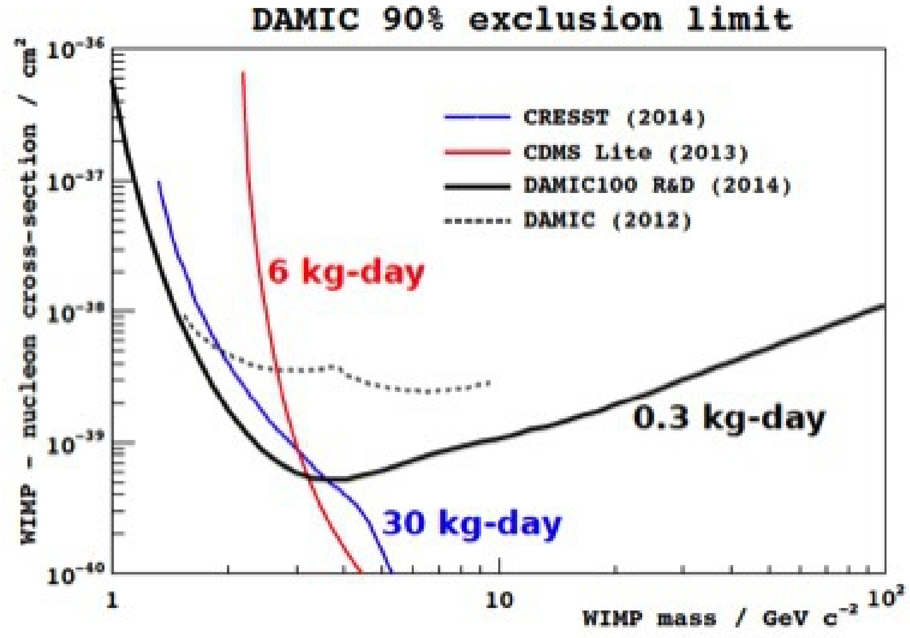
DAMIC en SNOLAB

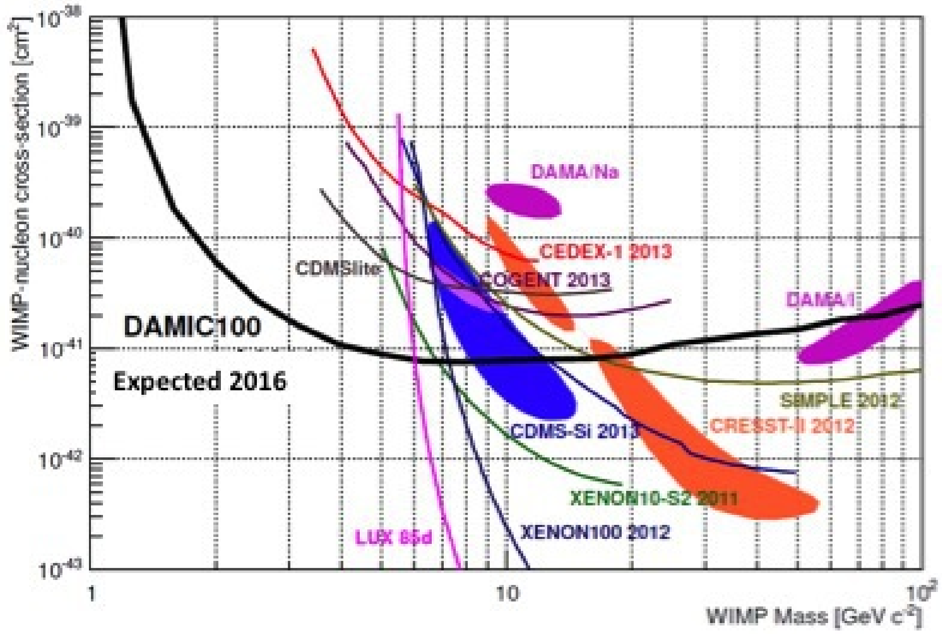


Arreglo de ingeniería instalado en diciembre de 2012

4

DAMIC

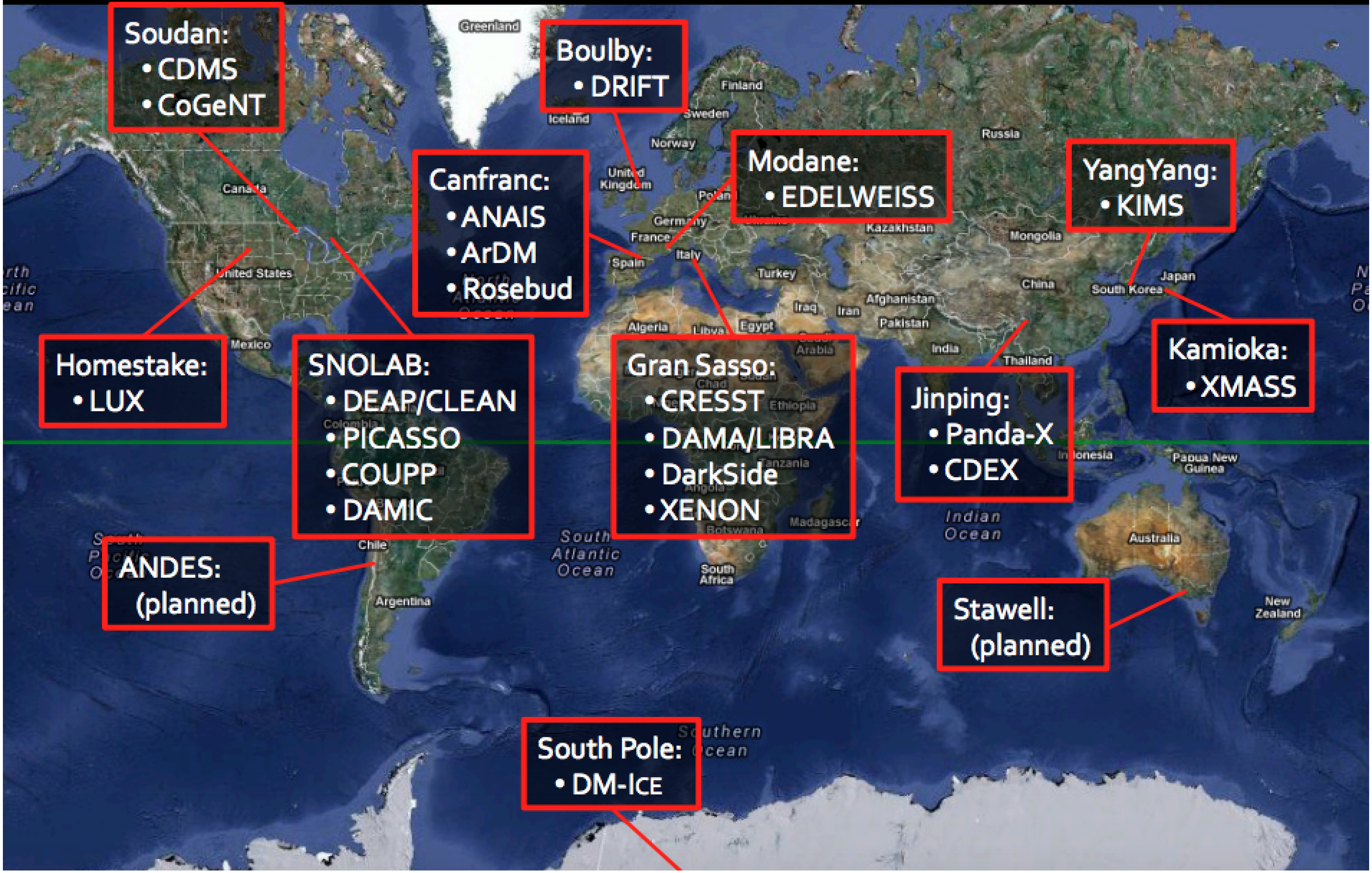

DAMIC 90% exclusion limit
WIMP - nucleon cross-section / cm^2
WIMP mass / GeV c^{-2}
CRESST (2014)
CDMS Lite (2013)
DAMIC100 R&D (2014)
DAMIC (2012)
6 kg-day
0.3 kg-day
30 kg-day


WIMP-nucleon cross-section [cm^2]
WIMP Mass [GeV c^{-2}]
DAMIC100
Expected 2016
DAMA/Na
CEDEX-1 2013
CDMSlite
COGENT 2013
DAMA/I
SIMPLE 2012
CDMS-Si 2013
CRESST-II 2012
XENON10-S2 2011
LUX 85d
XENON100 2012

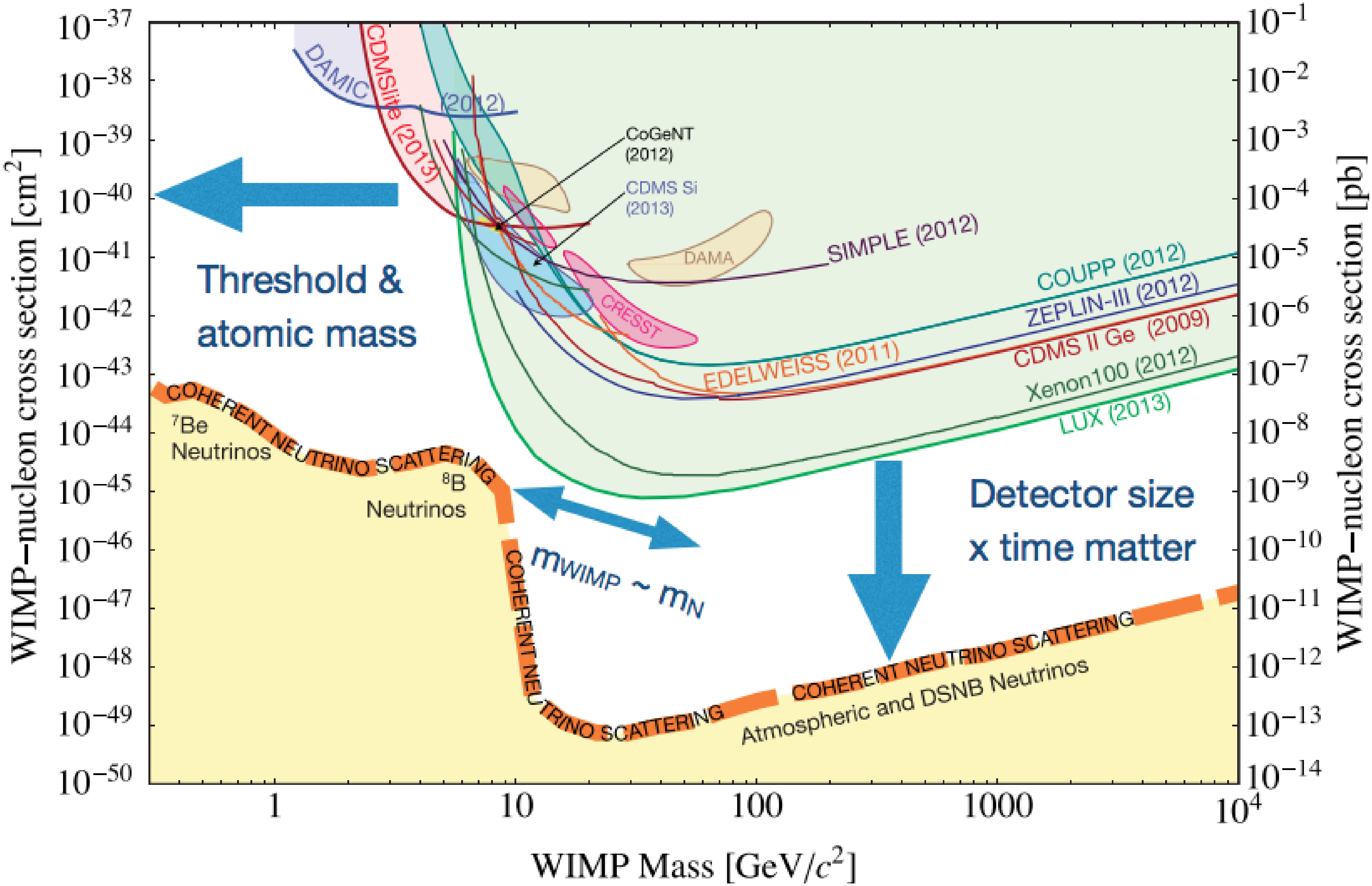
More on new techniques

- **Scintillating bubble chambers**
- **Exploit directionality: DRIFT, DM-TPC**
- **DNA detectors: directionality**
- **Moving beyond the standard WIMP: MeV**
- **Anisotropic scintillators**
- **New ideas...**

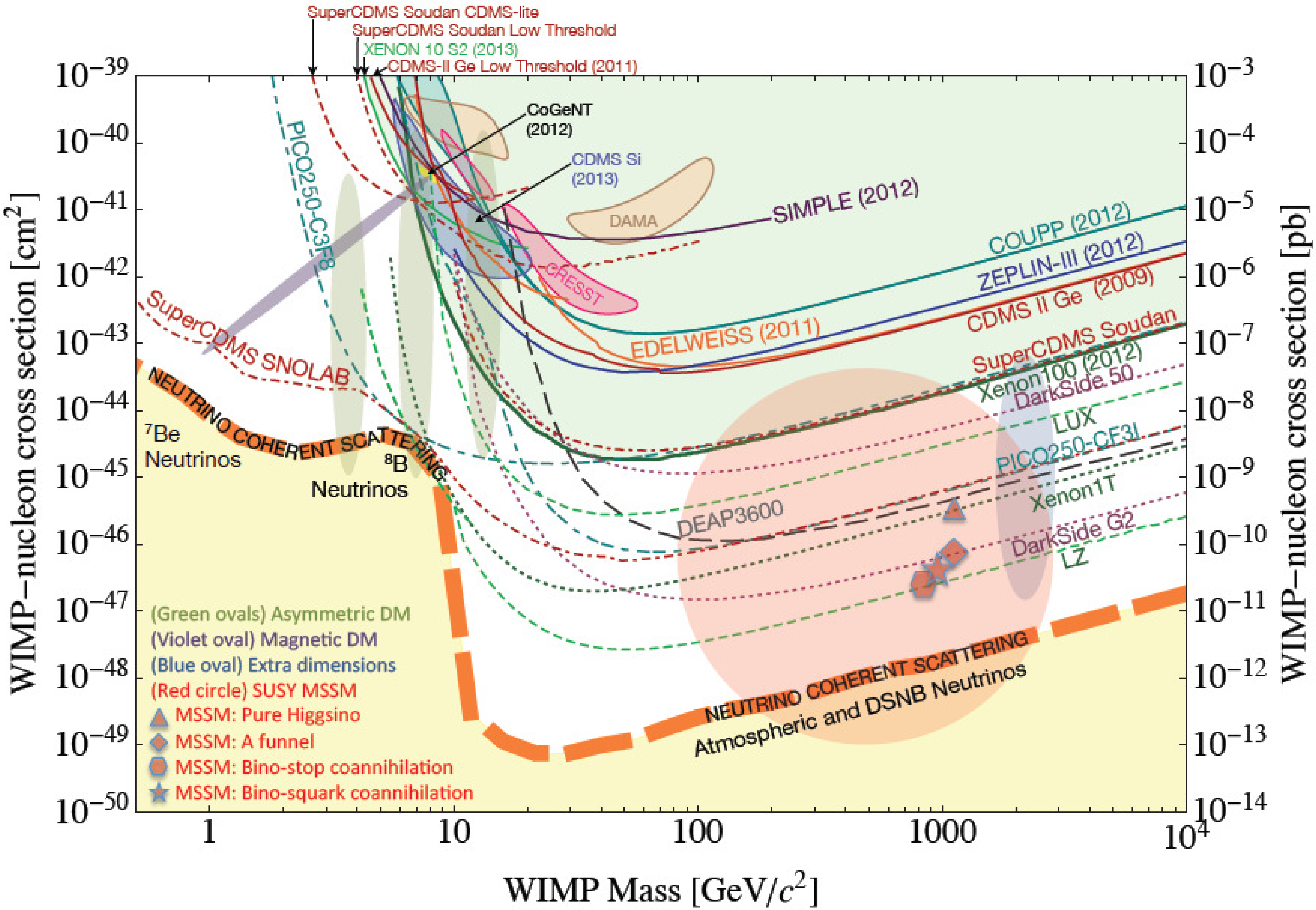
A World of Dark Matter Searches



The complete picture



The future



SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c2]

Final remarks

- **Cold dark matter is still a viable paradigm explaining cosmological & astrophysical observations**
- **It could be made of axions, and/or WIMPs (+ many other options, some less predictive and/or more difficult to test in the laboratory)**
- **So far, no convincing detection of a dark matter particle**
- **Optimistic: multiple discoveries (direct detection, the LHC, indirect detection) & constraints of the dark matter properties**
- **Clearly, multiple detectors / multiple techniques will be required to build a robust case**
- **Need to understand 3 things in detectors: backgrounds, backgrounds and backgrounds**
- **Calibration strategies that can provide abundant statistics, and have low systematic uncertainties are critically important**
- **If no discovery: "ultimate" detectors might at least be able to disprove the axion & WIMP hypotheses (still valuable information)**
- **However, we should be open for new theoretical ideas & of course new experiments**