Direct Detection of Dark Matter

Amy Cottle

Fermilab 50th Anniversary Users Meeting

The Case for Dark Matter

50 Years Ago…

- 1967 – Vera Rubin begins survey of spiral galaxies
- Finds orbital velocities of stars same near outer radius

  -> Spherical halo of dark matter – gravitationally interacting

- Gravitational lensing – the Bullet Cluster
- CMB power spectrum -> ΛCDM model -> $\Omega_{DM} = 0.26$
- Large scale structure -> ΛCDM N-body simulations
- Big bang nucleosynthesis -> constraint on baryon density

-> Overwhelming indirect evidence!

Majority of dark matter is stable, non-baryonic, non-relativistic.

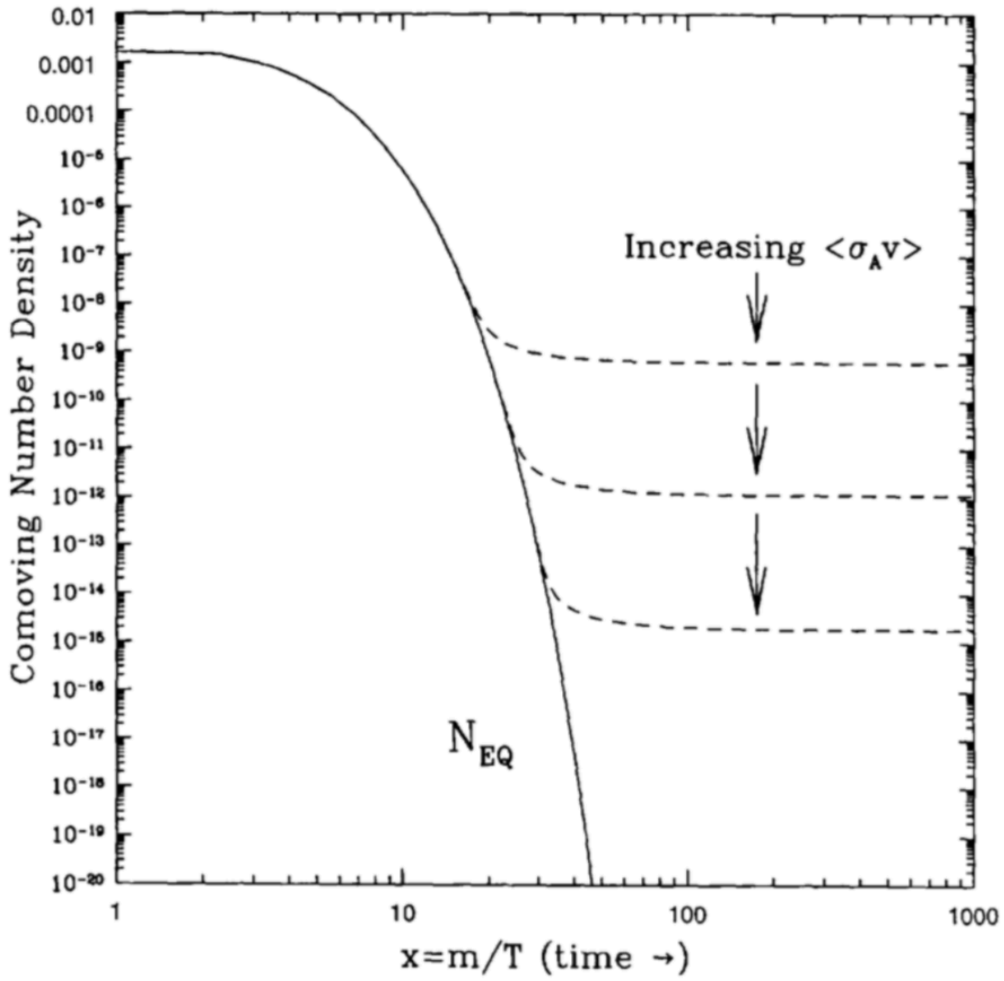
The Case for WIMPs

- Dark matter a thermal relic of Big Bang
- Universe expansion -> freeze-out

'WIMP Miracle'

Annihilation cross-section for weak interaction → ~ observed CDM density

- EW symmetry breaking -> hierarchy problem -> new physics -> new particles
- WIMP candidate - lightest supersymmetric particle
- Mass range of ~GeV-TeV



WIMP Event Rate

- Elastic scattering off nuclei -> nuclear recoils

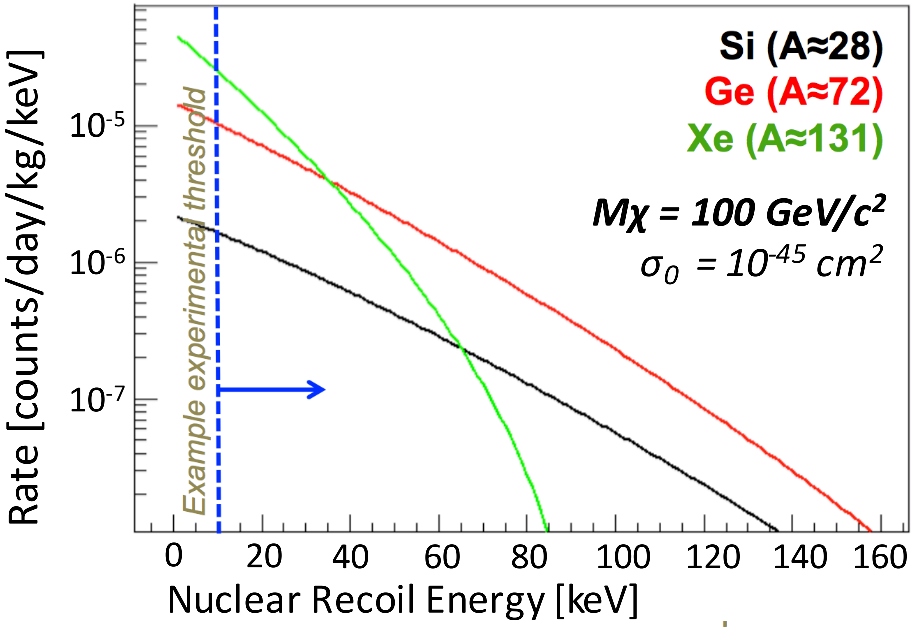
$$\frac{dR}{dE_R} = \frac{\sigma_0 A^2}{2\mu^2} F^2(q) \frac{\rho_\chi}{m_\chi} \int_{v_{min}}^{v_{esc}} \frac{f(v)}{v} dv$$

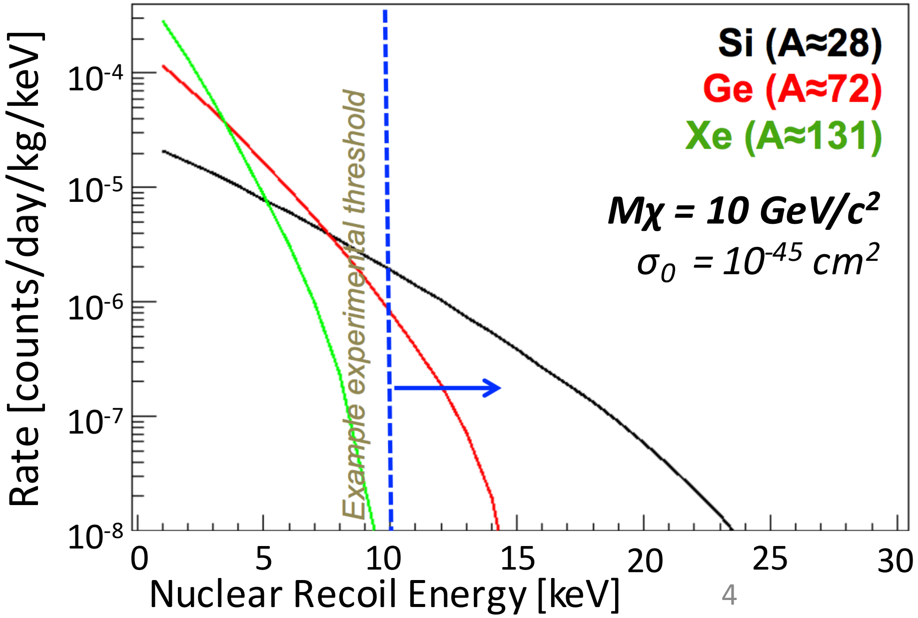
<u>WIMP-nucleon Cross-section</u>

- Spin-independent – A^2 enhancement -> heavy targets
- Spin-dependent – no coherent effect -> odd spin
- SI form factor -> coherence loss with ↑E_R, countering A^2

<u>Milky Way dark matter halo</u>

- Local DM mass density - ρ_χ = 0.3 GeV/cm^3
- Maxwell-Boltzmann velocity distribution
  - v_c = 220 km/s , v_{esc} = 544 km/s





Detection Methods

WIMP signatures

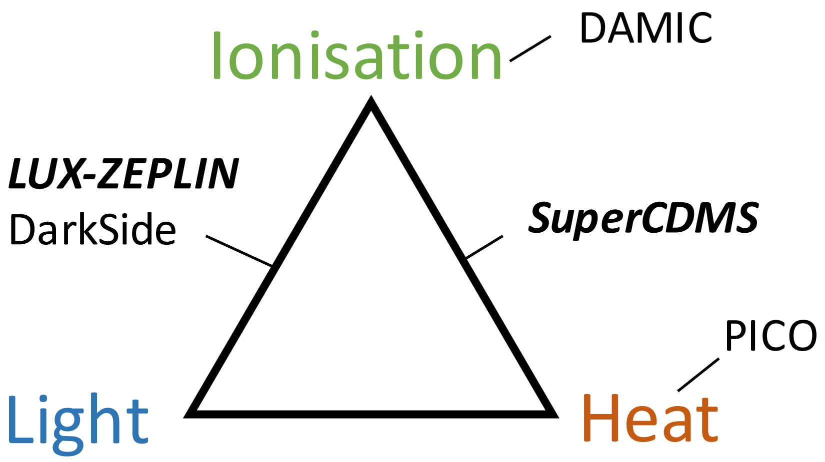
- Low interaction rate -> scatters once
- Annual modulation -> larger signal in summer
- Directionality -> increased flux into WIMP wind

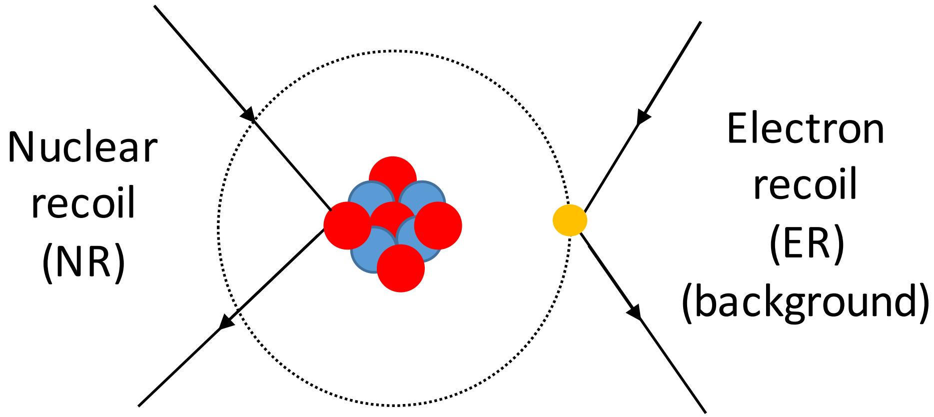
Background Mitigation

- γs & βs -> ERs; αs, ***neutrons*** -> NRs
- Material screening - reduce trace radioactivity
- Locate underground -> ↓ cosmogenic background
- Passive and active vetoes – attenuate or tag
- Multiple detection channels -> discrimination

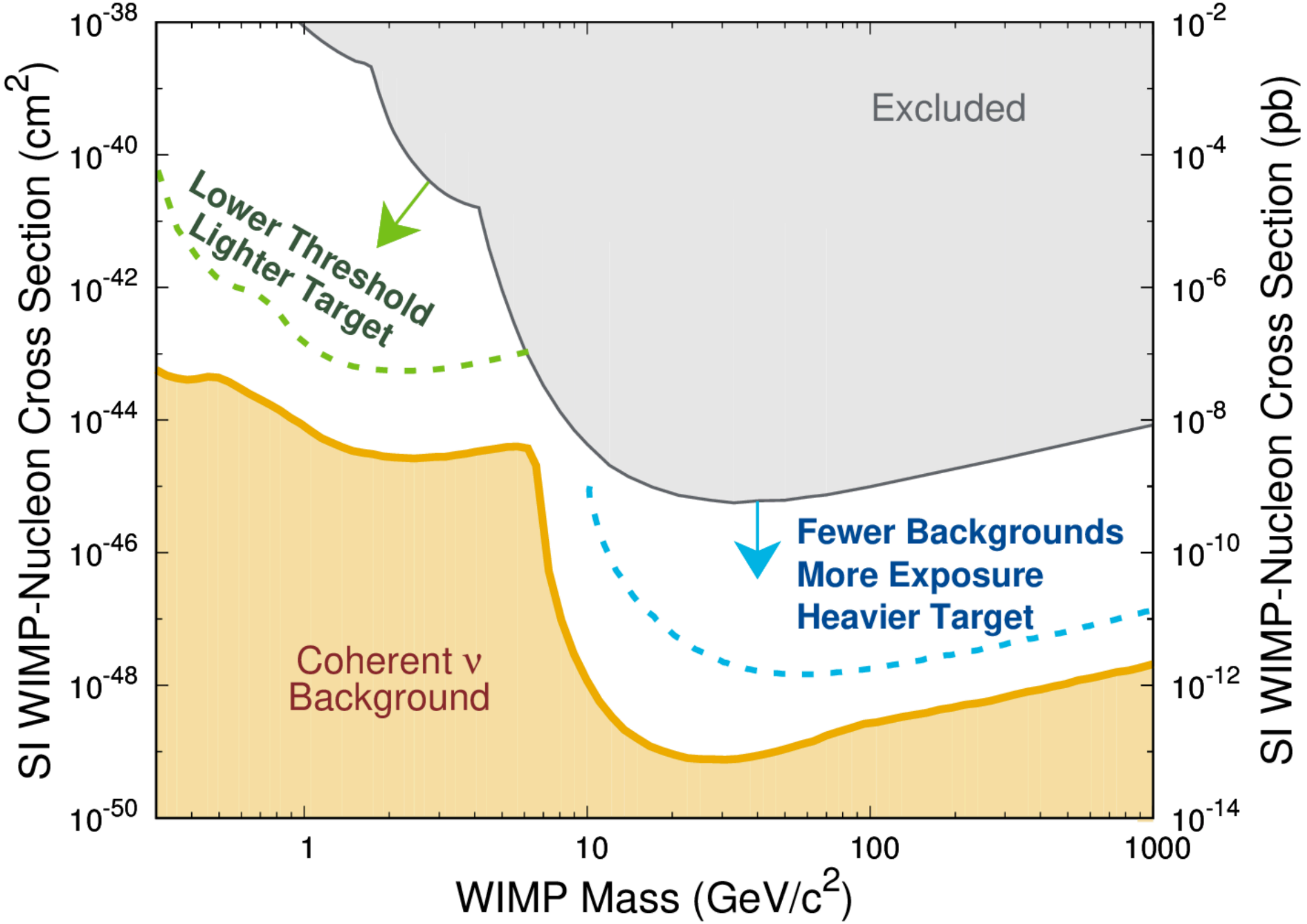
Complementary approaches to detection

(DOE Generation 2 (G2) in bold)





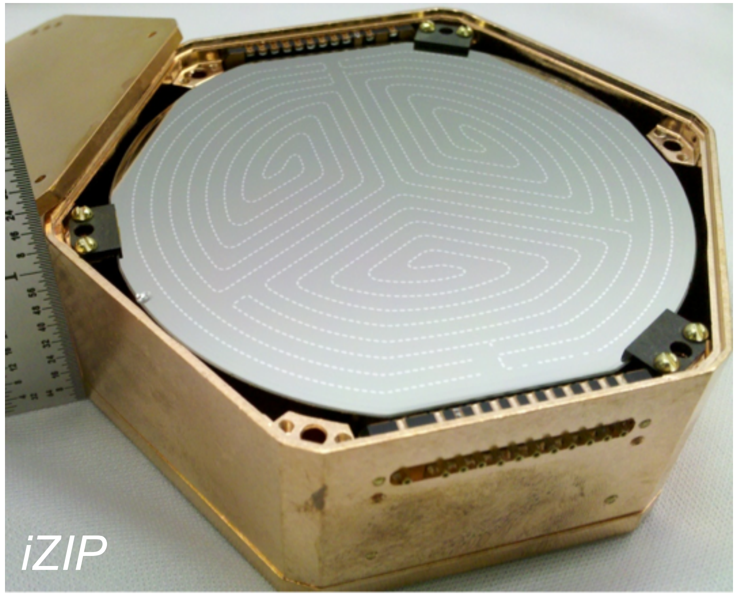
WIMP Sensitivity



SuperCDMS

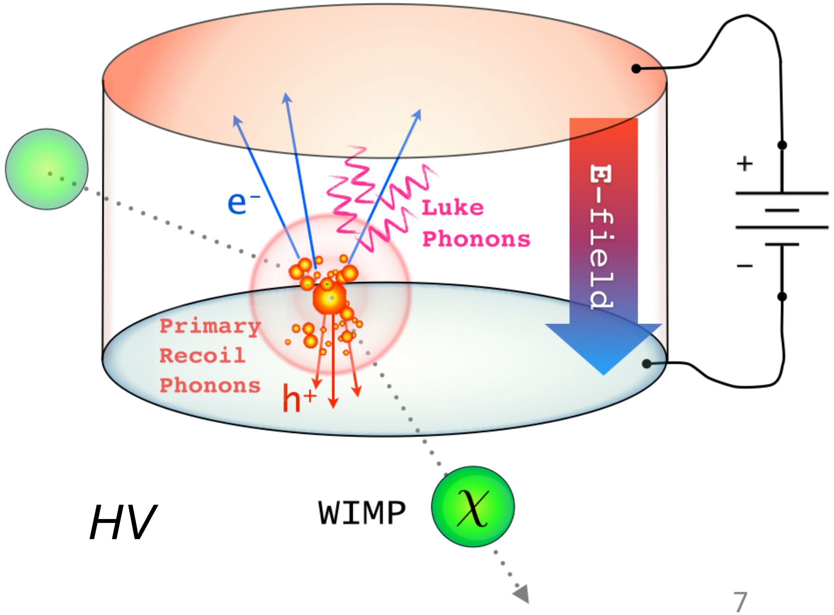
- Soudan -> SNOLAB – focus on low mass WIMPs
- 24 detectors with Ge and Si targets

  -> Improve sensitivity with complementarity



<u>iZIP Detectors</u>

- >1:10^6 separation NR vs ER in bulk above 10 keV
- Asymmetric ionisation signal -> surface rejection



<u>HV Detectors</u>

- Luke-Neganov effect -> amplify phonon signal
- No direct ionisation sensitivity -> no discrimination
- Lower thresholds -> probe low WIMP masses

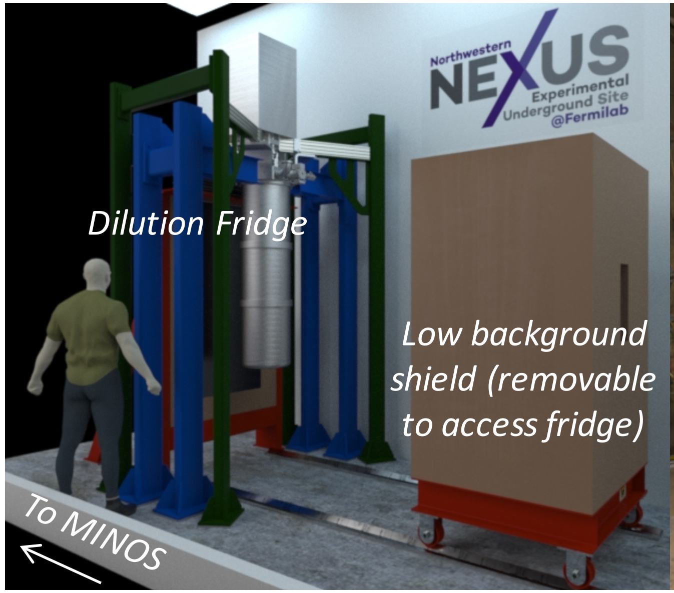
SuperCDMS @ Fermilab

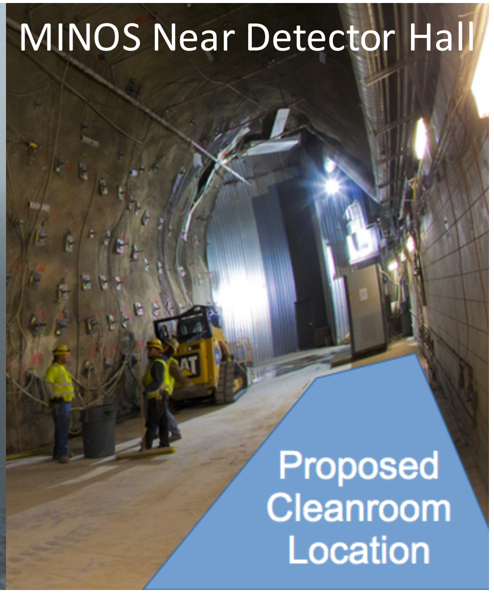
5 years of operation, 80 % livetime ->

Projected WIMP-nucleon SI cross-section limit:

~ 10^{-43} cm^2 for WIMP mass ~ 1 GeV/c^2

- Strong Fermilab involvement for G2
  - Newly renovated Lab G
    - Cryogenic & calibration systems
  - R&D with NEXUS
    - Low background test of G2+ detectors
    - Expect facility turn-on early 2018
    - Joint collaboration with Northwestern

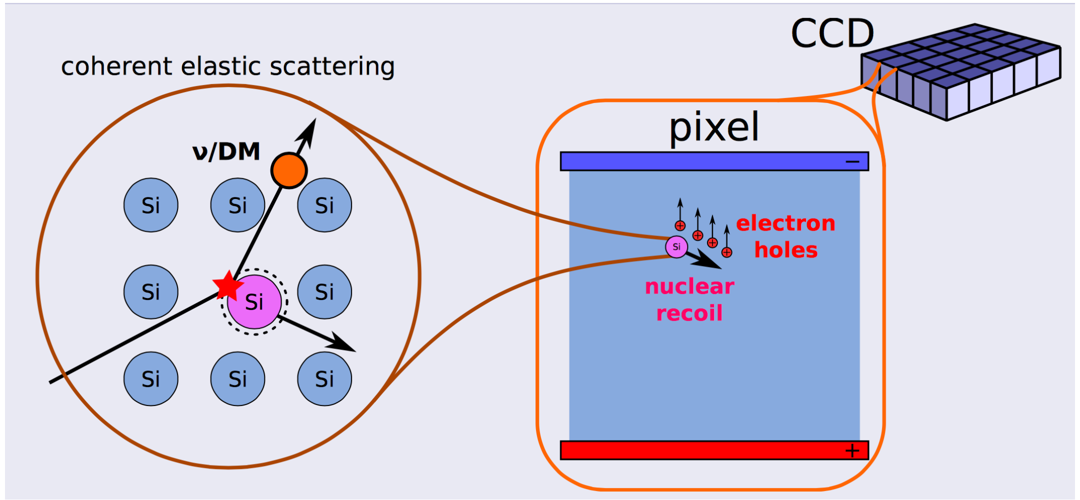


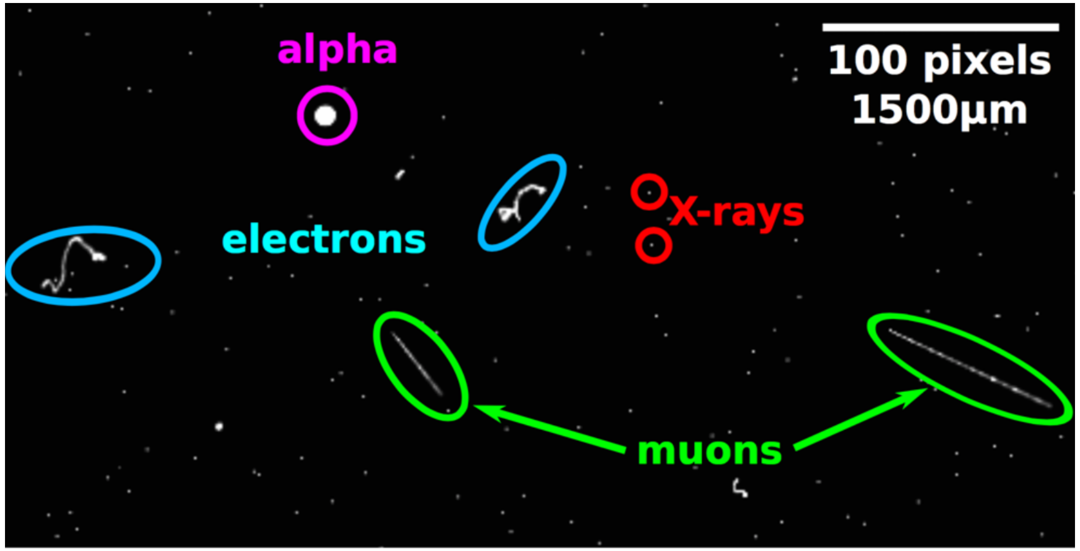



SuperCDMS Clean Room in Lab G

DAMIC

- Proof-of-concept – DECAM CCDs at Fermilab
- 675 µm thick silicon CCDs
- 40 V bias -> drift ionisation charge carriers
  - Record amplitude and position
- Low inefficiency of charge transfer ($<10^{-6}$)
- **Low readout noise (RMS 2 e^-/pix)**
  - CCD dark current negligible
- Long exposures (~8 hours) minimise readouts
- **Low detection threshold (0.5 keV_{nr})**
  - 1-20 GeV/c^2 target mass range
- Calibrations to characterise response

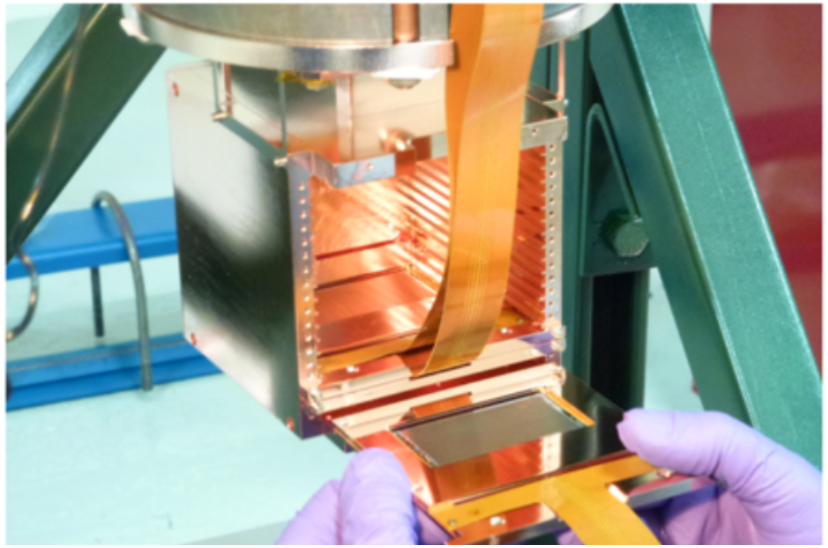


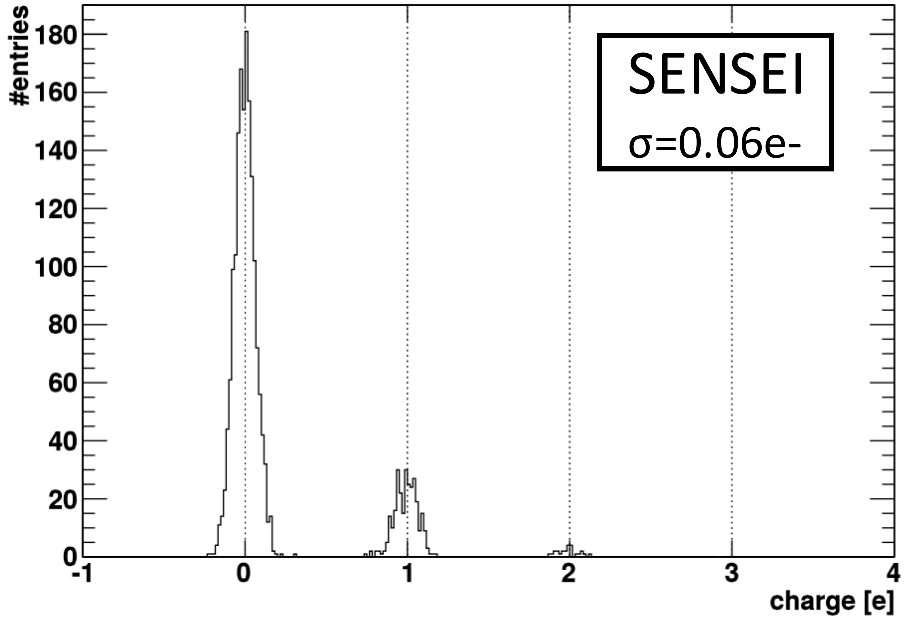


DAMIC

0.6 kg·days -> WIMP-nucleon SI cross-section limit:
$<10^{-39}$ cm^2 for WIMP masses >3 GeV/c^2

- Full deployment of DAMIC-100
  - Expect 13 kg·days exposure (2017) -> $<10^{-40}$ cm^2
- Hidden photons from search in 1.2–30 eV/c^2 range
  - First sensitivity to DM ionisation <12 eV
  - Most stringent direct detection constraints for 3–12 eV/c^2 mass in galactic halo
- SENSEI LDRD project
  - Skipper CCD -> multiple readout technique
  - Sub-electron noise (RMS 0.06 e$^-$/pix)
  - 1 g SENSEI detector installed at MINOS in May





Noble Liquid Detectors

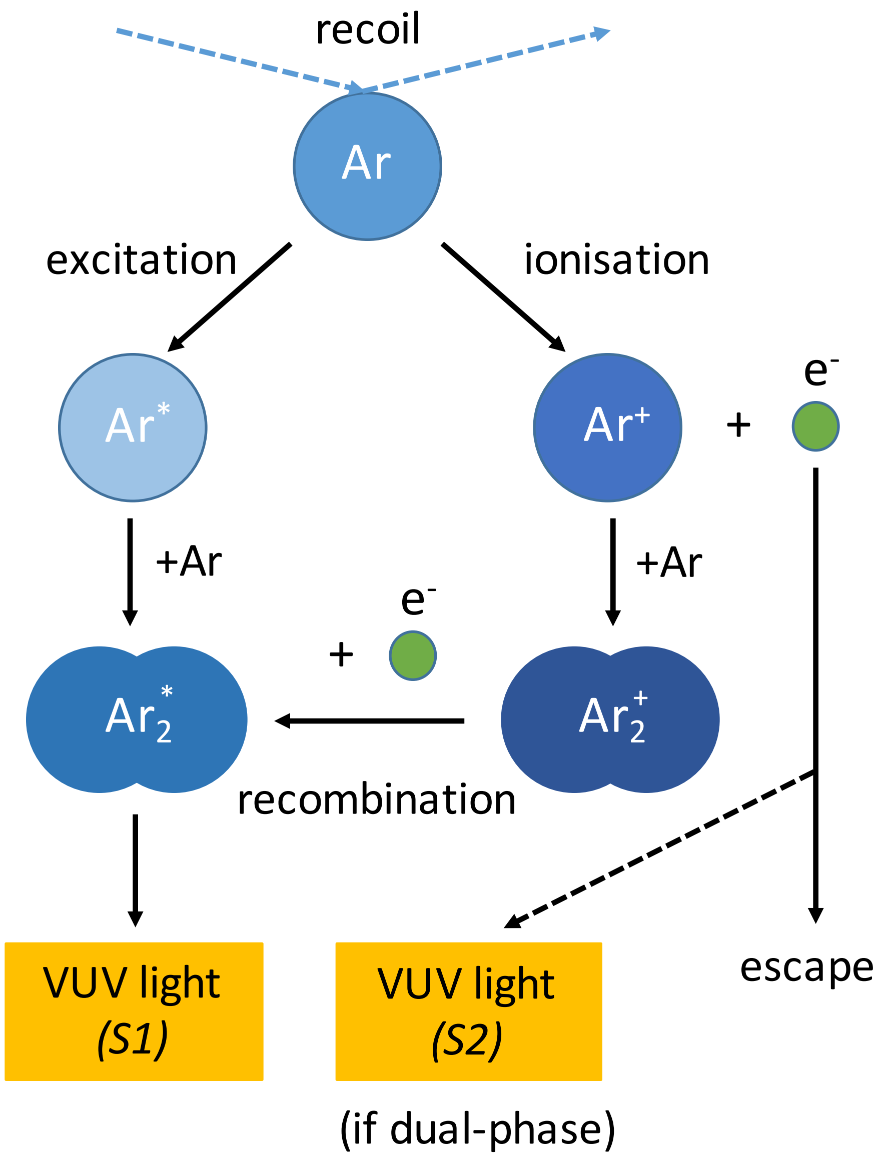
- Recoils dissipate energy as excitation, ionisation and heat
- Excitation & recombination -> excited dimers -> UV light

ER/NR Discrimination

- Ratio of excitation/ionisation -> dual channel
- Ratio of dimers in singlet/triplet states -> pulse shape

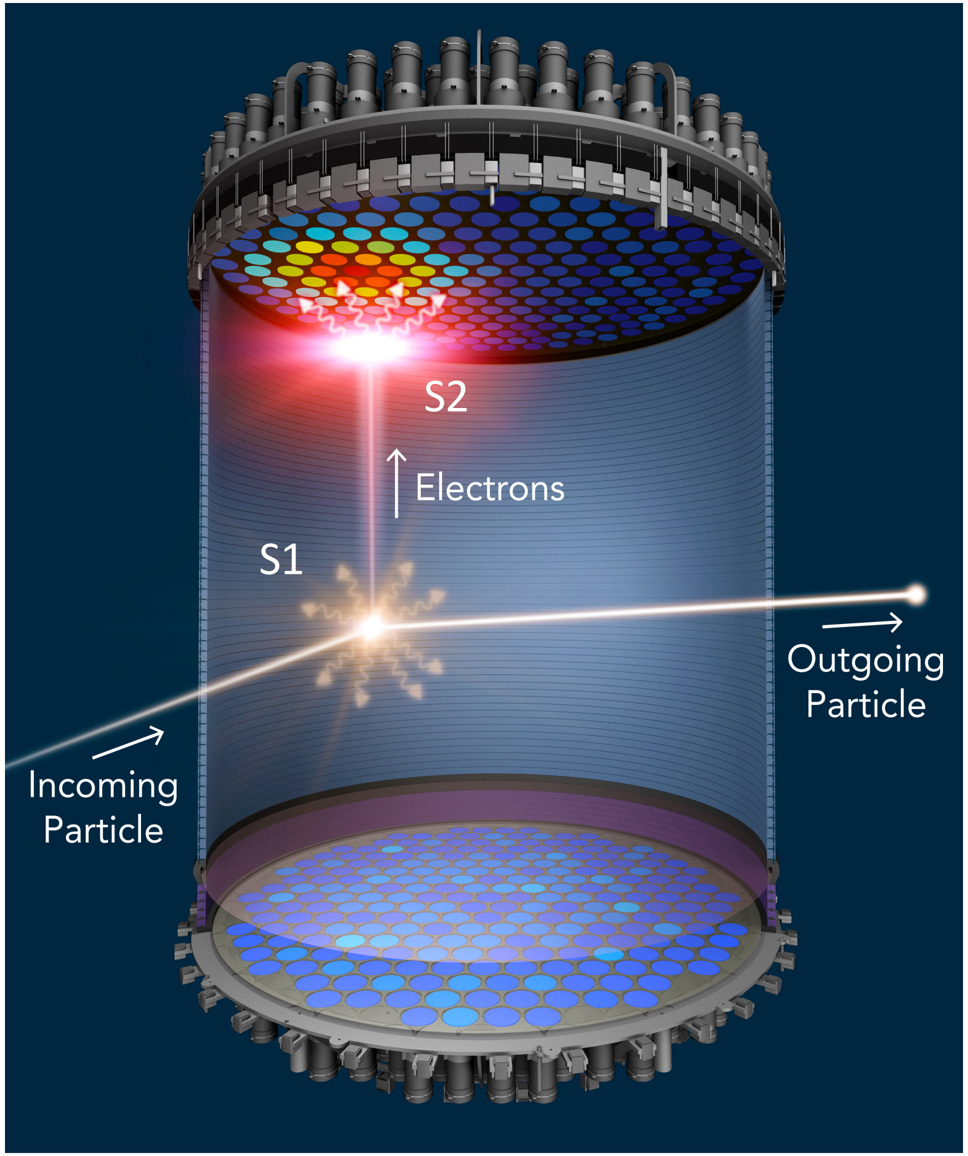
Beneficial Properties

- High density -> self-shielding -> fiducialisation
- Purification -> suppress internal backgrounds
- High scintillation yield -> low thresholds
- High ionisation yield at low recoil energies
- Scalability -> multi-tonne detectors



Dual-Phase Noble TPC

- Measure ionisation as well as scintillation
- ~1 kV/cm drift field -> ionisation electrons to gas layer
- ~10 kV/cm extraction field -> proportional scintillation
- Prompt (S1) signal followed by charge (S2) signal
  - Z position reconstruction from drift
  - X-Y from S2 hit pattern
  - Ratio gives NR/ER discrimination

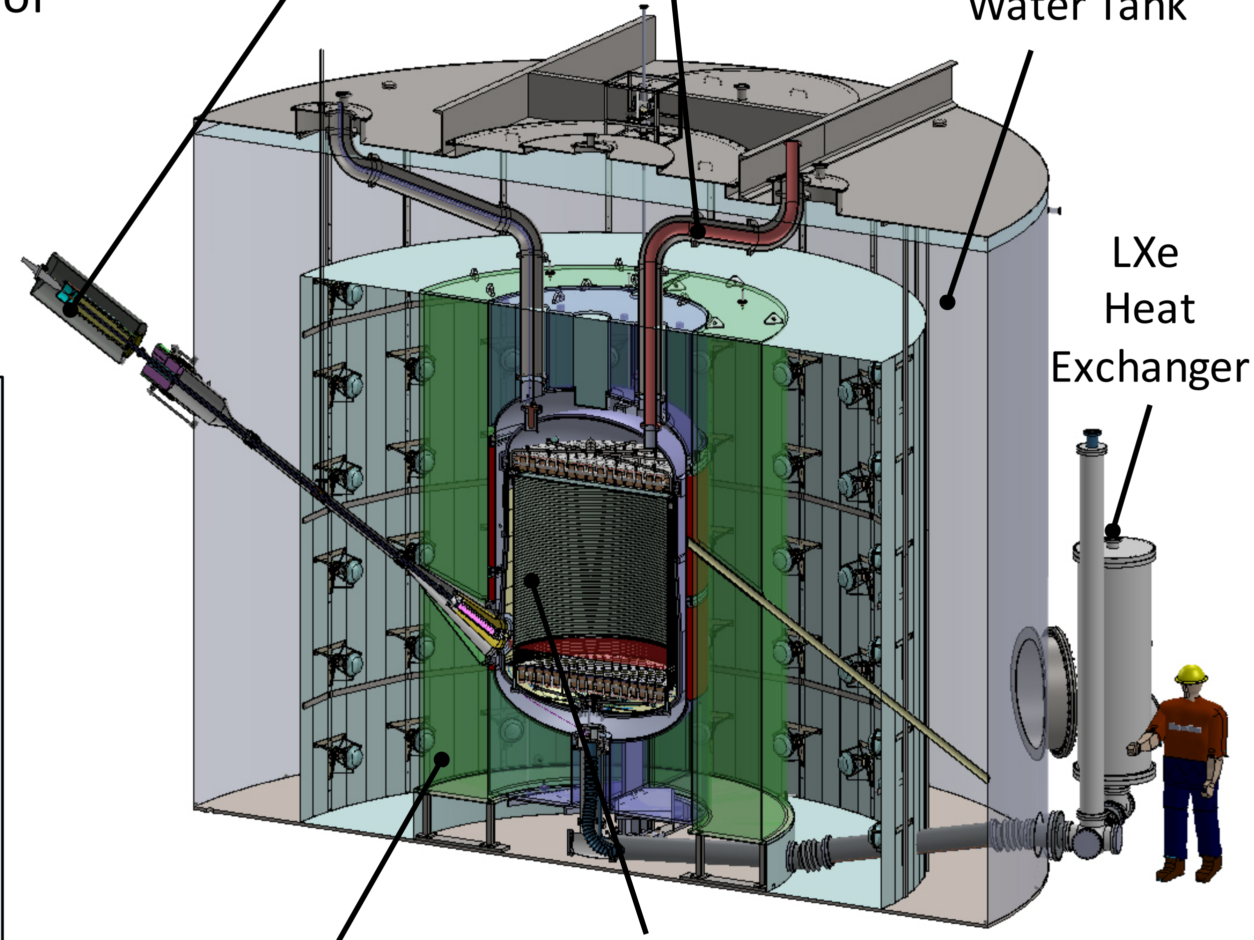


Challenges

- Lower light collection -> higher energy threshold
- High purity -> electron collection efficiency
- High drift field (slow drift –> event pile-up in LAr)

LUX-ZEPLIN

- G2 experiment -> 7-tonne, xenon dual-phase TPC
- Fermilab: purification system, process control
- Current activities:
  - Extensive detector prototyping
  - Background assays & simulations

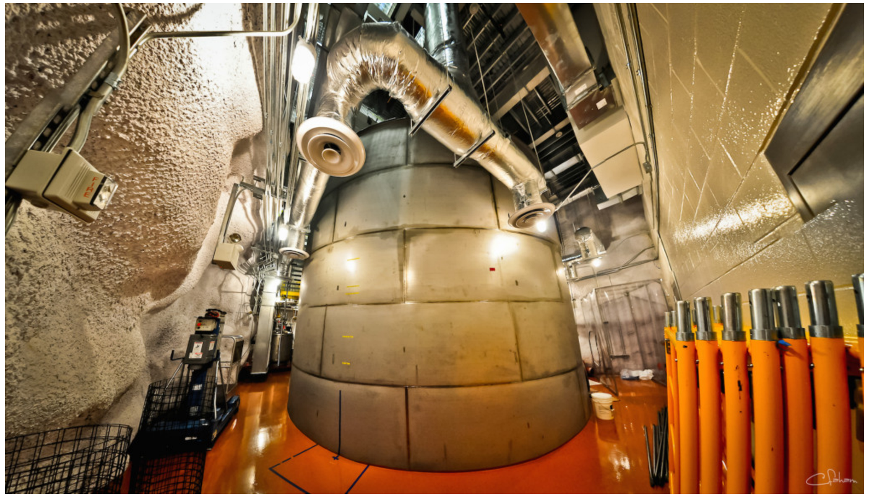


<u>Backgrounds Control</u>

- 'Skin' & liquid scintillator veto detectors
  - -> Fiducial mass of 5.6 tonnes
- Internal backgrounds
  - Kr <15 ppq to limit ^{85}Kr events
  - ^{222}Rn < 0.67 mBq in active target

LUX-ZEPLIN

- Accelerated schedule
  - Early 2017 – LUX decommissioned
  - Early-Mid 2019 – initial commissioning

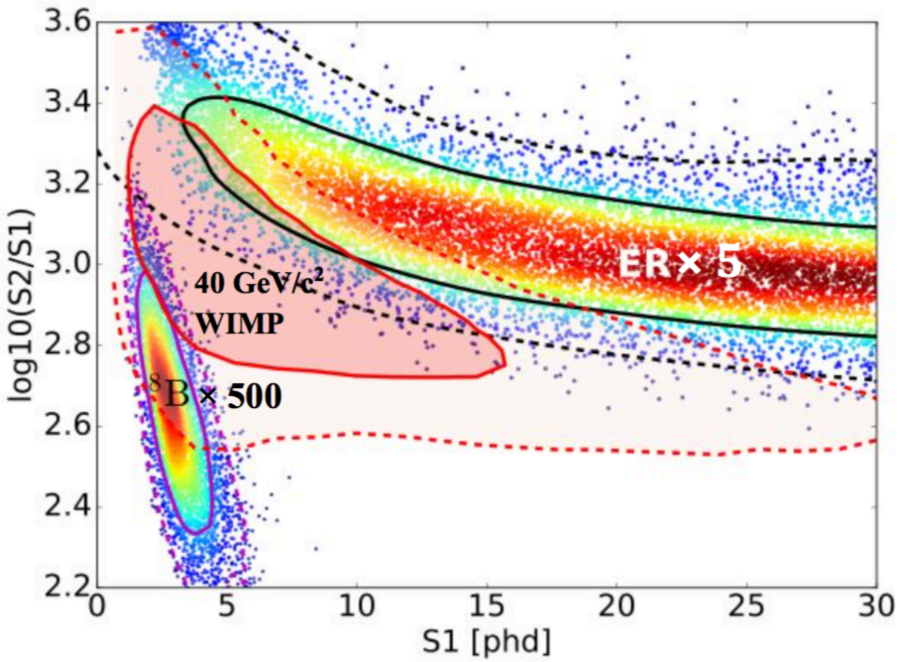


Performance Drivers

Detector Parameter	Baseline Requirement
Light Collection Efficiency	7.5 %
Electron Lifetime (μs)	850
Drift Field (V/cm)	310
Extraction Efficiency	95 %

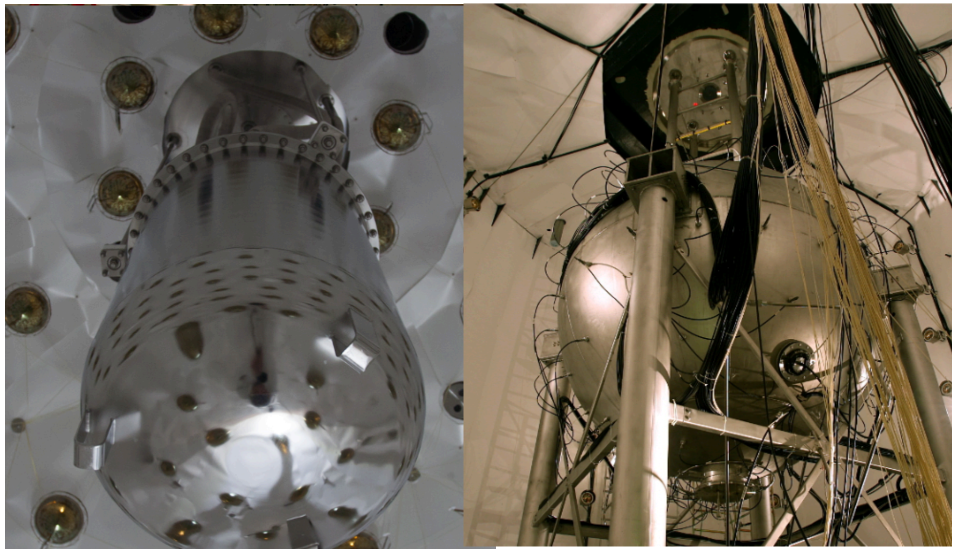
1000 live days

Predicted limit on WIMP-nucleon SI cross-section:
2.3×10^{-48} cm^2 for a 40 GeV/c^2 WIMP mass



DarkSide-50

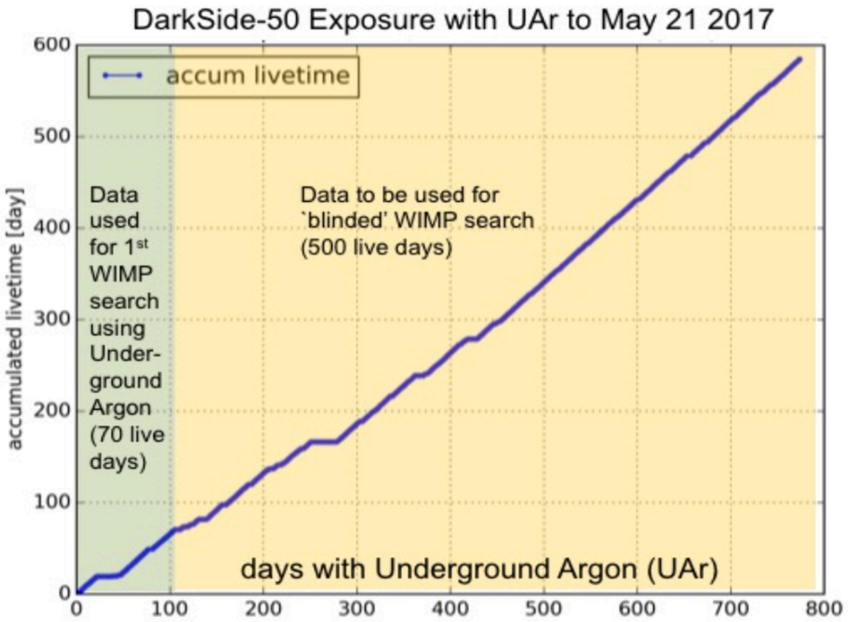
- Dual-phase argon detector with 45 kg fiducial mass
- Active vetoes for muons and neutrons
- $\tau_{singlet}$ ~7 ns & $\tau_{triplet}$ ~1.6 μs -> NRs vs ERs pulse shape
- Taking data since Nov 2013 – UAr since Apr 2015
  - ^{39}Ar reduced by ~1400 -> not dominant background
  - Distillation at Fermilab -> ARIA project, Sardinia



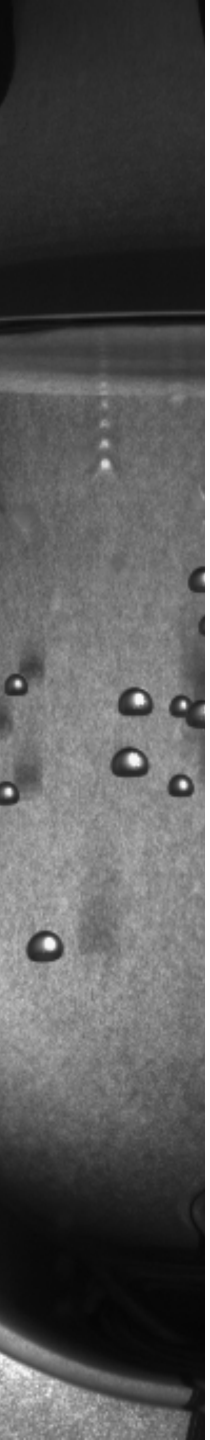
Limit on WIMP-nucleon SI cross-section:

2.0×10^{-44} cm^2 for 100 GeV/c^2 WIMP mass

-> ~ 2×10^{-45} cm^2 by campaign end



- DS-20k (20 t fiducial mass) in 2020; Argo (200 t FM)
  - Push to 10^{-47} cm^2 and 10^{-48} cm^2 respectively

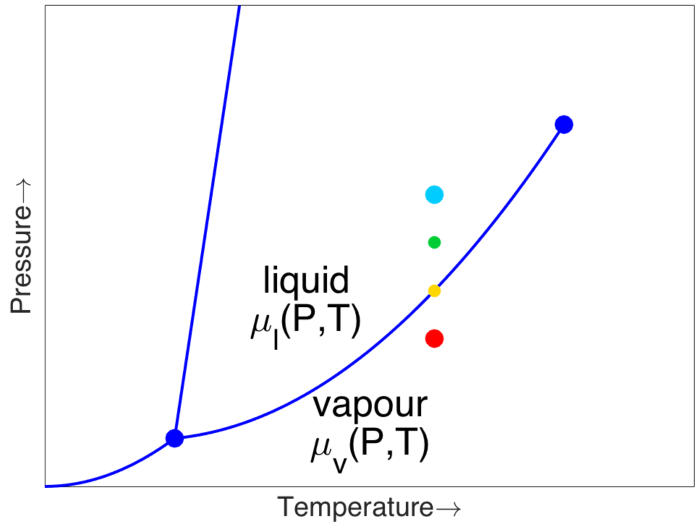


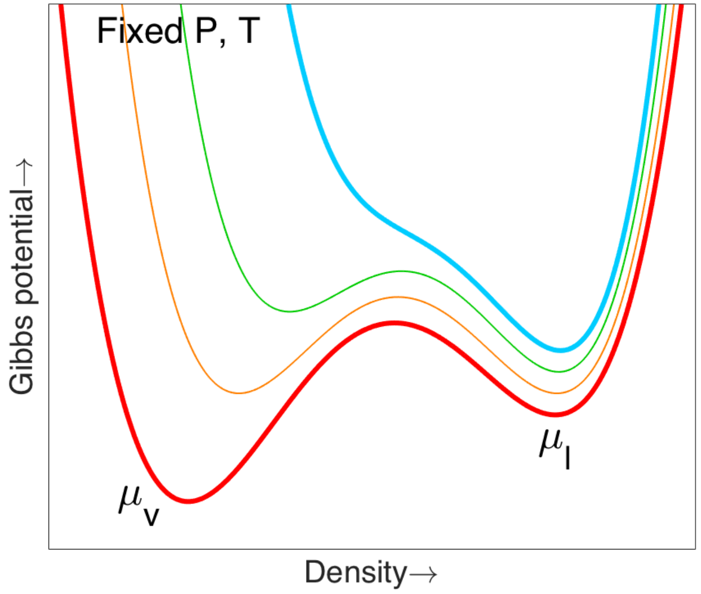
Bubble Chambers

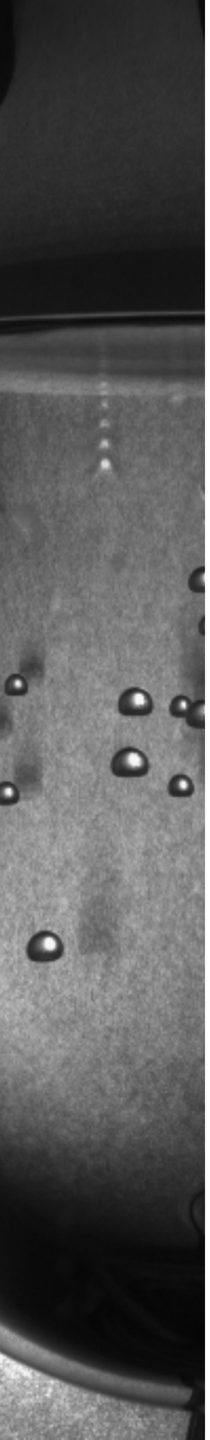
- Superheated liquid -> metastable state
- Energy deposition -> phase transition -> bubble nucleation
- Threshold detector
  - Does not allow determination of interaction energy

Background Discrimination

- Tune P & T -> **insensitive to ER backgrounds**
  - Smaller dE/dx for ER -> no bubble formation
- Separate NR backgrounds by acoustic power
  - α depositions -> louder
- Multiple bubble rejection
- Fiducialisation







PICO-60

- Build on knowledge from COUPP and PICO-2L
- Strong Fermilab involvement
- 52 kg C_3F_8 target -> fluorine -> SD proton-coupling
- Blind analysis -> acoustic cuts from non-WIMP search

1167 kg day exposure at 3.3 keV threshold

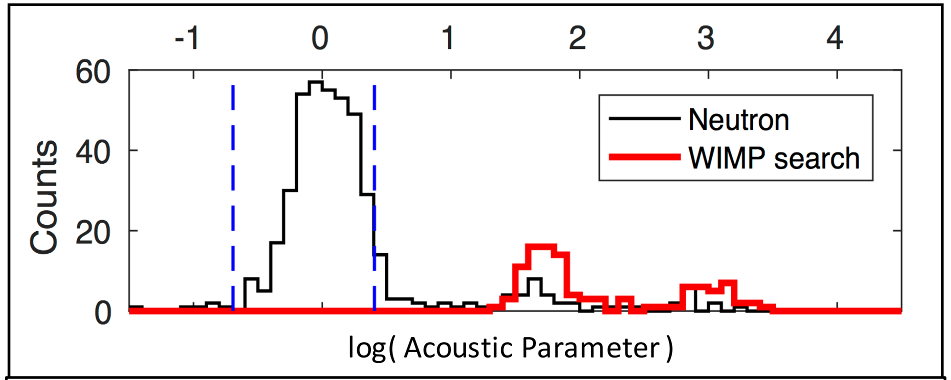
↓

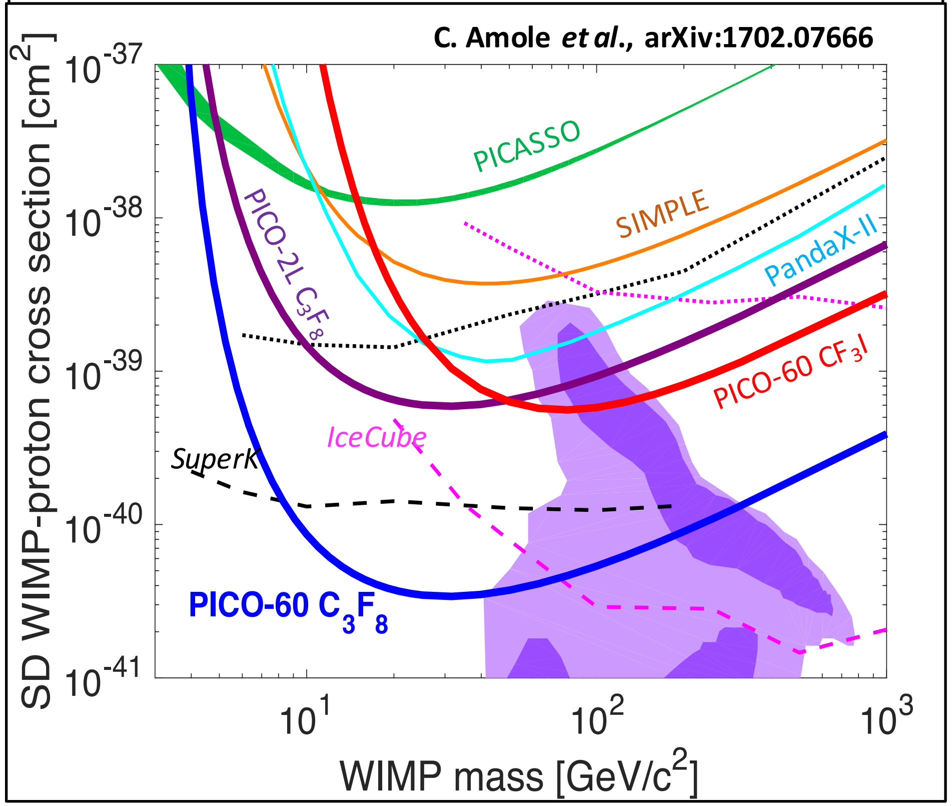
Zero single bubble events consistent with neutron-induced NR (and hence WIMPs)

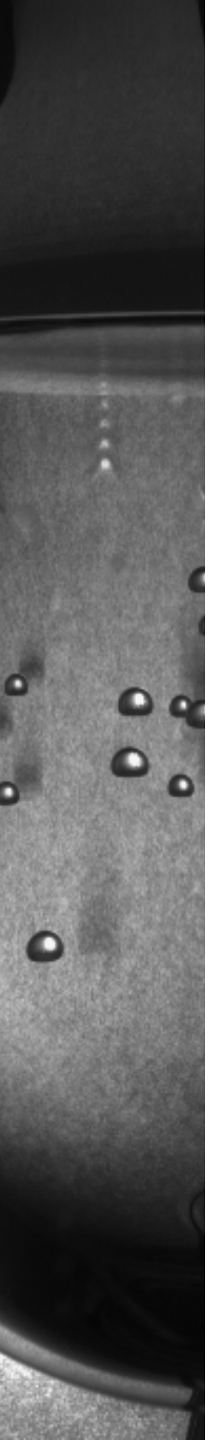
↓

New limit on WIMP-proton SD cross-section:

3.4 x 10^{-41} cm^2 for 30 GeV/c^2 WIMP mass







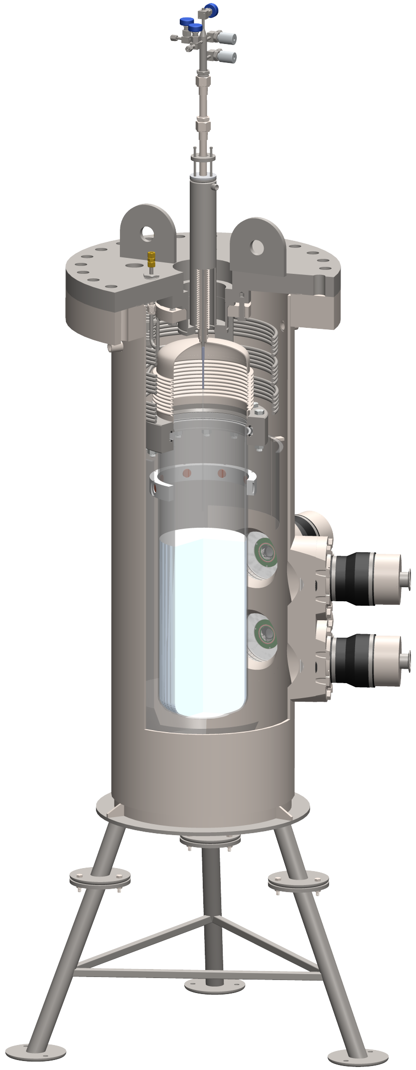
PICO

PICO-40L

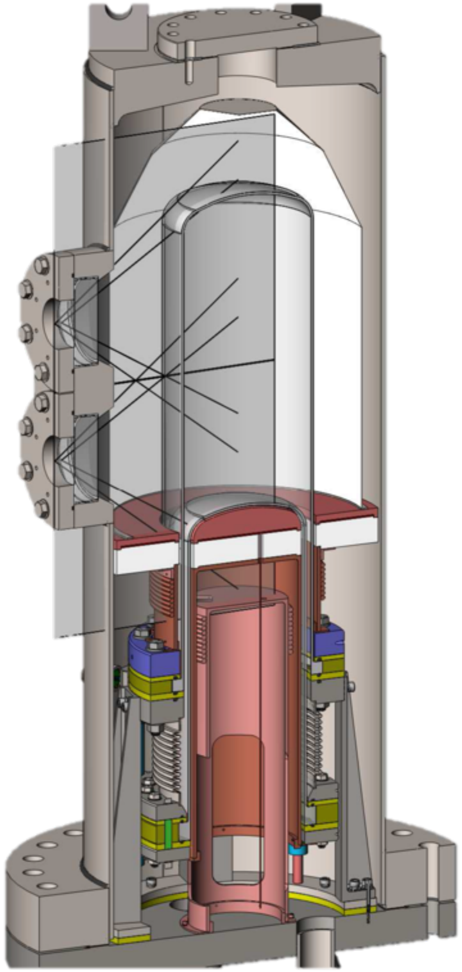
- Proof-of-principle experiment
- Buffer fluid -> thermal gradient
  - Remove potential source of contamination
  - In-situ purification
- Planned data-taking in 2018

PICO-500

- $3M CAD proposal submitted, decision pending
  - Would be online 2020
- SD WIMP-nucleon cross-section limit ~10^{-42} cm^2
  - Similar to upcoming LXe detectors

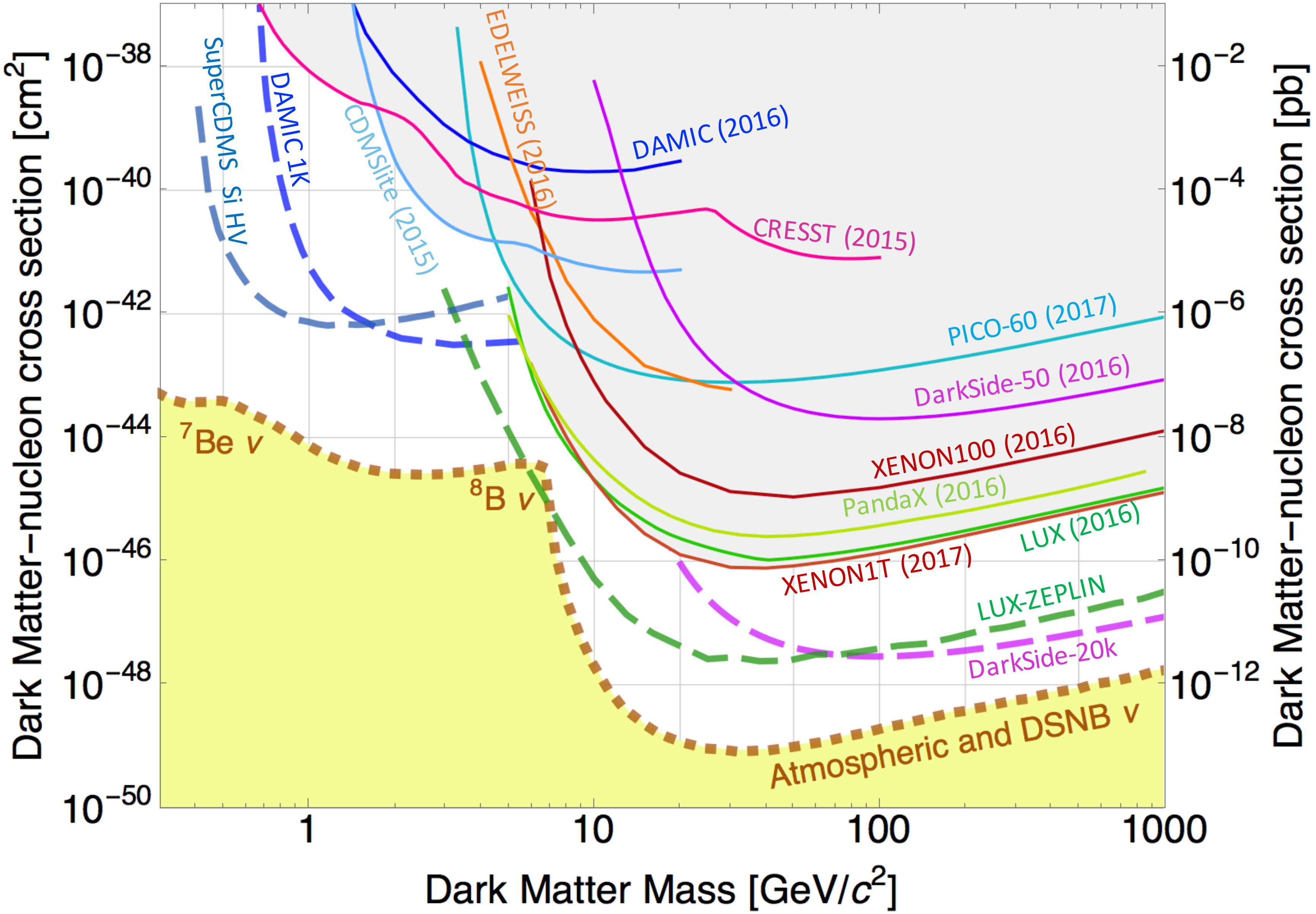


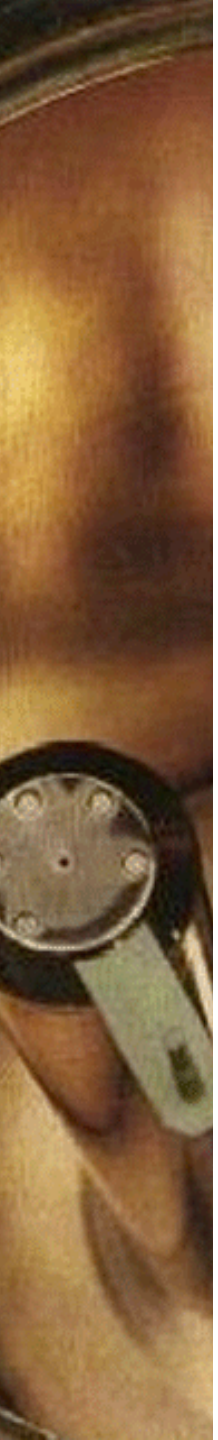
PICO-60



PICO-40L

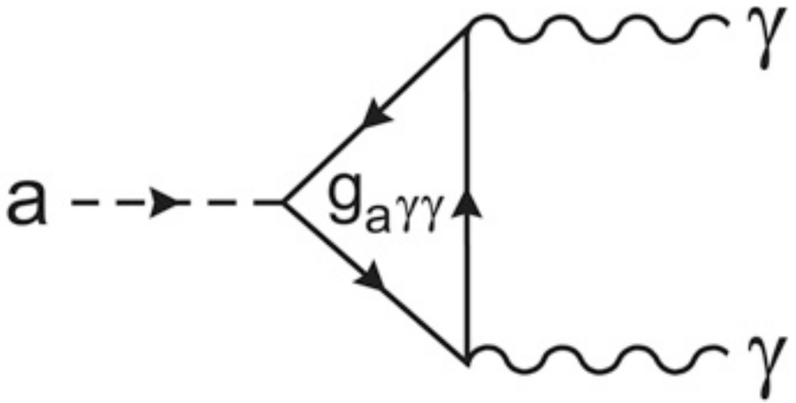
The WIMP SI Landscape

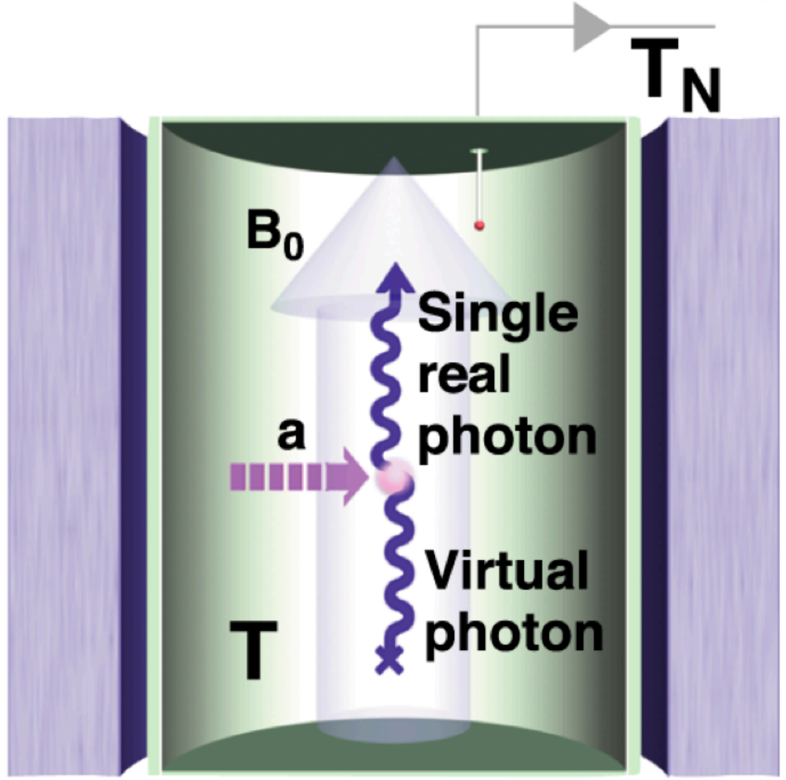


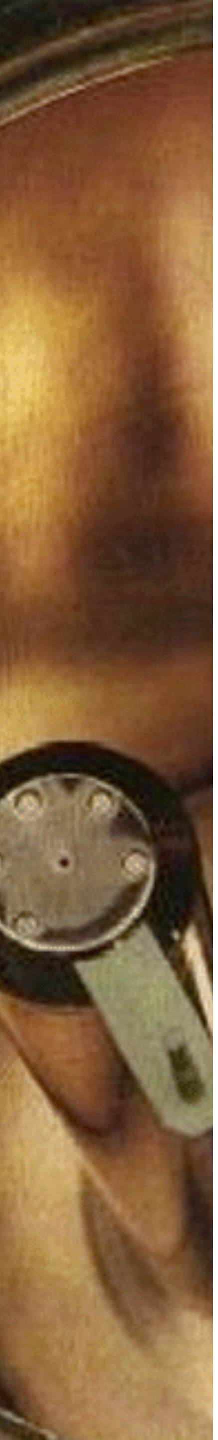


The Case for Axions

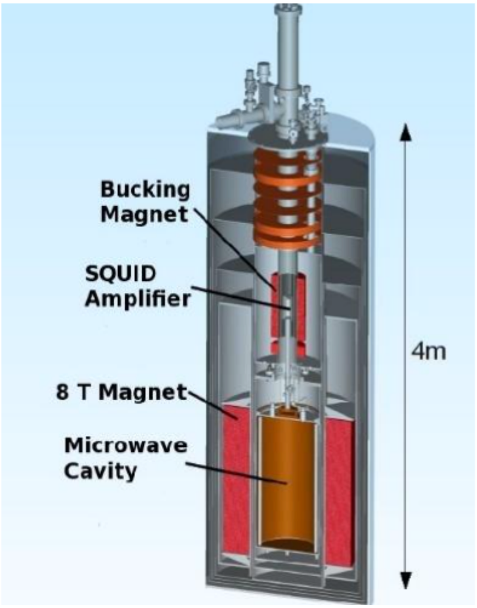
- Solution of strong CP-problem
  - Fine-tuning of CP-odd QCD parameter, $\bar{\theta} < 10^{-10}$
  - Peccei-Quinn symmetry -> axion = Goldstone boson
- Axion as a cold dark matter candidate
  - $m_a \approx 6\ \mu eV \left(\frac{10^{12}\ GeV}{f_a} \right)$ (f_a = axion decay constant)
  - Astrophysical constraints -> $10^{-6} < m_a < 10^{-2}\ eV/c^2$
    - -> Density can account for large part of DM density
- Electromagnetic interaction, $\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$
  - Axion-photon coupling $g_{a\gamma\gamma} \propto 1/f_a$
  - KSVZ & DFSZ models provide range for $g_{a\gamma\gamma}$
  - Probe with inverse Primakoff effect…

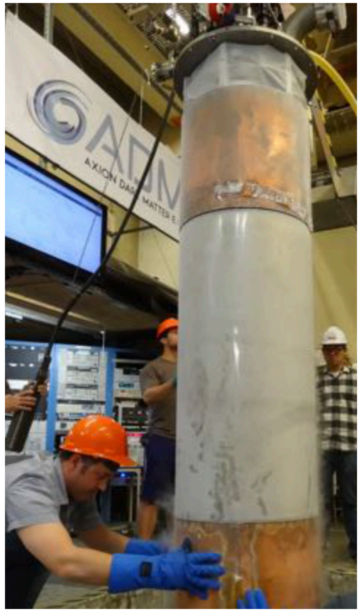






ADMX





Axion Haloscope

- Sikivie -> axion decay accelerated in strong B field
- Tune microwave cavity in steps

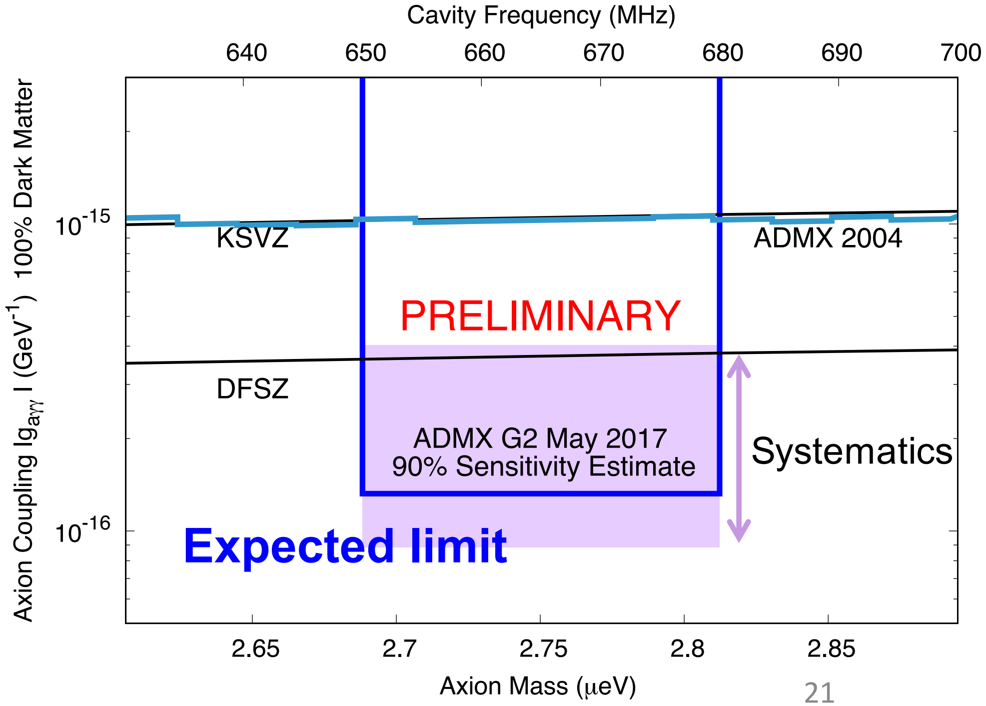
  -> Expected signal ~ 10^{-23} W
- World's lowest noise resonant radio receiver

ADMX Current Limit

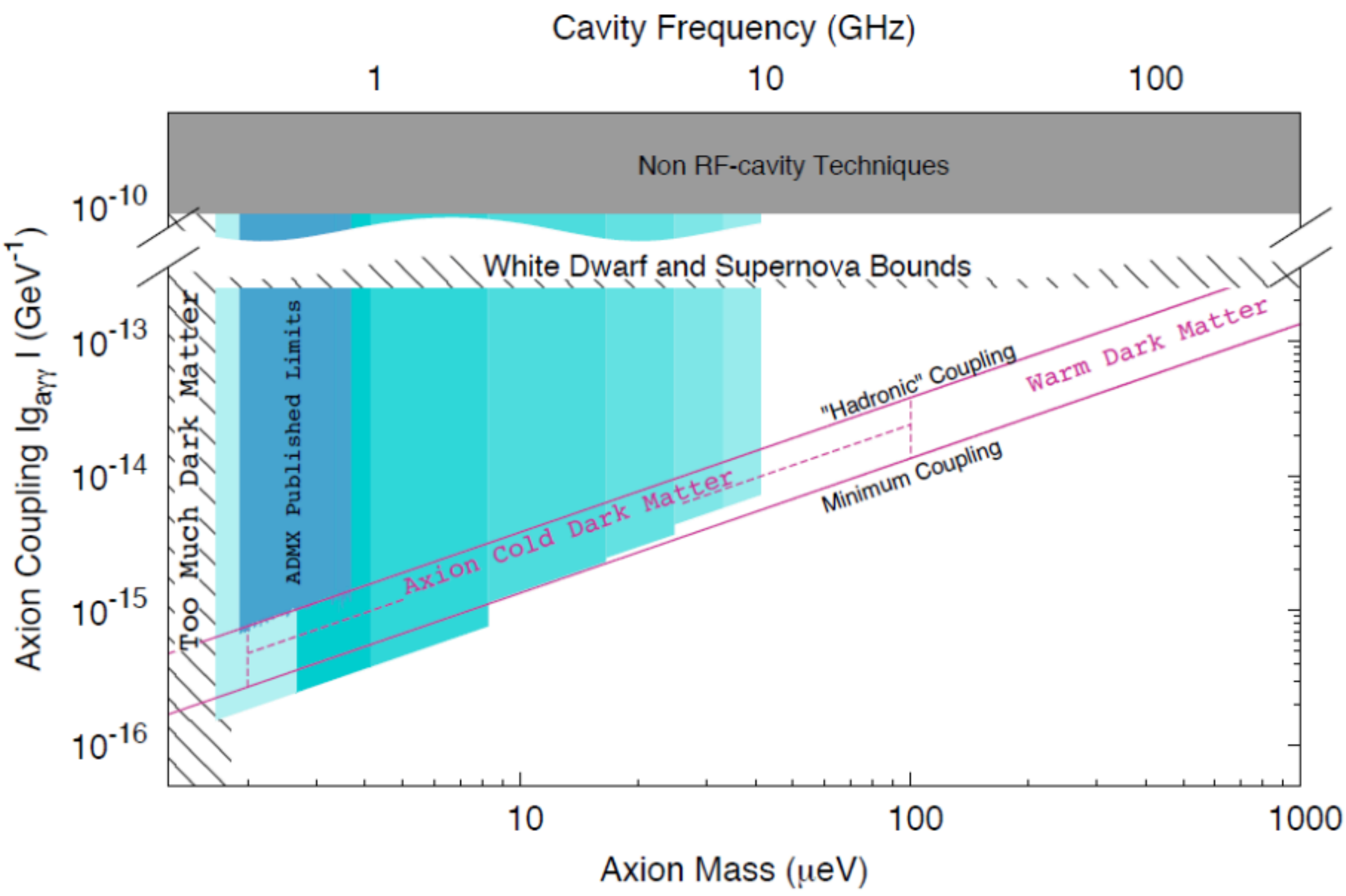
Exclude $g_{a\gamma\gamma}$ to KSVZ limit for 1.9-3.7 μeV/c²

- Run 1 post-G2 upgrades (since January)

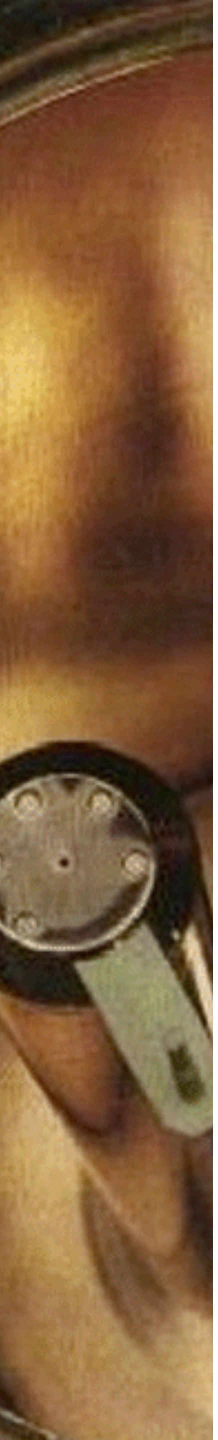
  - Major milestone -> first time to conclusively test axion DM model

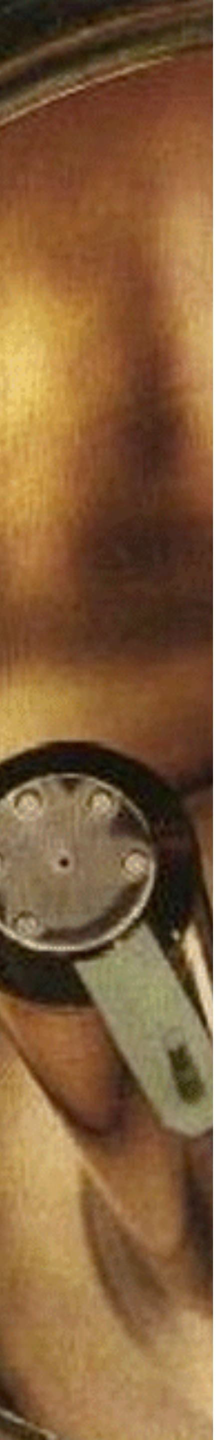


ADMX



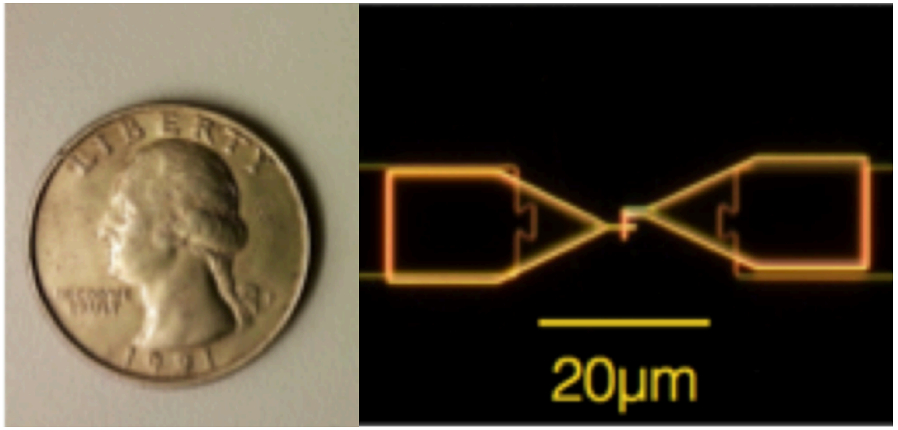
Tiered frequency method -> 2-40 μeV/c^2 (0.5-10 GHz) to DFSZ coupling

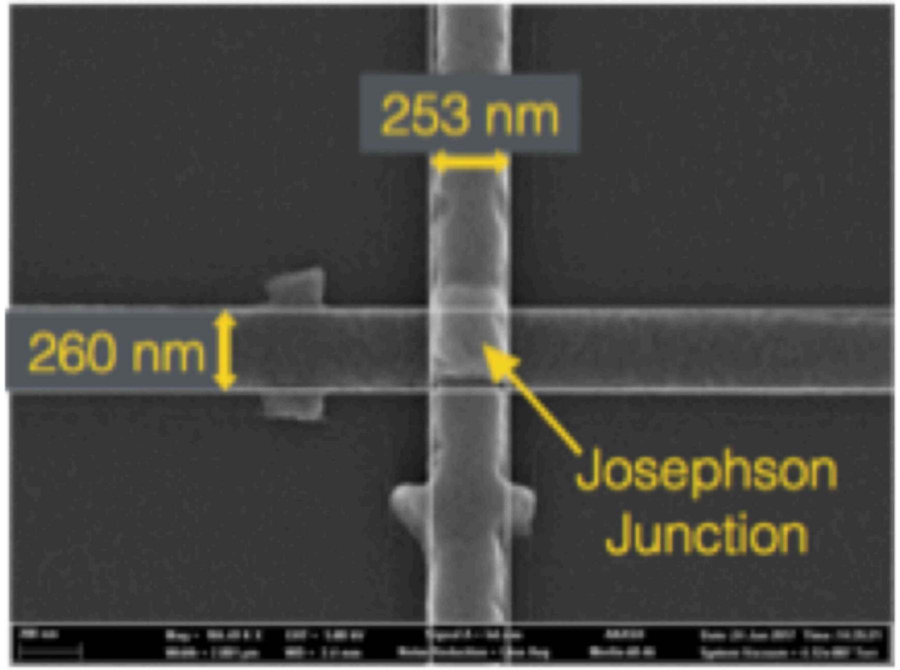




ADMX @ Fermilab

- Now DOE lead lab for ADMX-G2
- Ongoing R&D to achieve G2 goals by 2022
- Pioneering interdisciplinary LDRD projects
  - Dielectrics for tunable microwave cavities





<u>Quantum Sensor R&D for G3</u>

- ADMX-G2 uses superconducting amplifiers that are quantum-limited
- Implement quantum non-demolition measurements to squeeze the detection noise
- Develop ultra-low threshold microcalorimeters capable of resolving single far infra-red photons

Conclusions and Future Prospects

- Extensive Fermilab involvement in dark matter program
  - 6 DM experiments, all 3 G2 projects
  - R&D - 3 LDRDs; plans for test facilities
- Complementary methods for wide range of WIMP masses
- New avenues for direct detection
  - Even bigger scale -> beyond ν floor with directionality
  - New targets for low mass WIMPs (light gases, superfluid ^{4}He)
  - New candidates -> sub-GeV light dark matter