Dark Matter Direct Detection Experiments
II. Specific Experiments and Axions

Ranny Budnik

Department of Particle Physics and Astrophysics
Weizmann Institute of Science

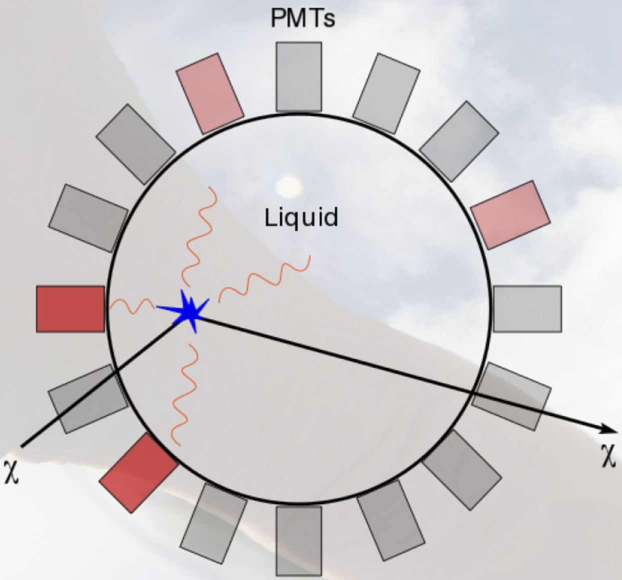
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Contents II

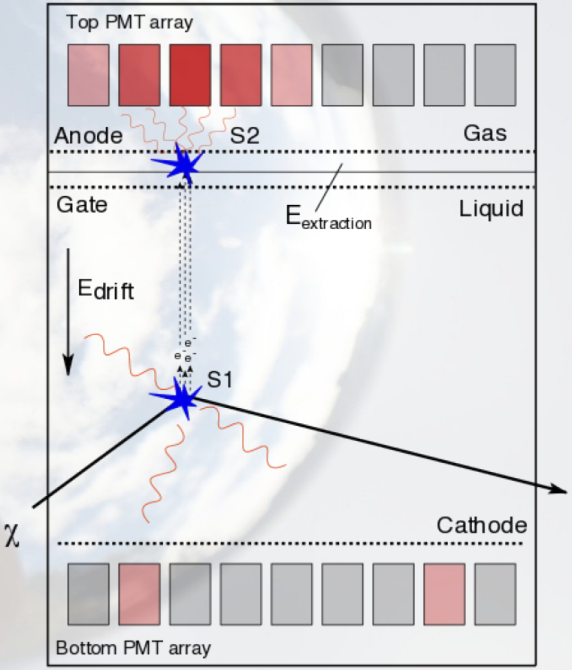
- Liquid Noble Elements
- Bubble Chamber
- Crystal detectors
- Electron Scattering
- Axion Detection
  - In DD experiments
  - Axion Haloscope

Liquid Noble Gas detectors

- Currently and in the foreseeable future leading the field for classical WIMPs, >10GeV

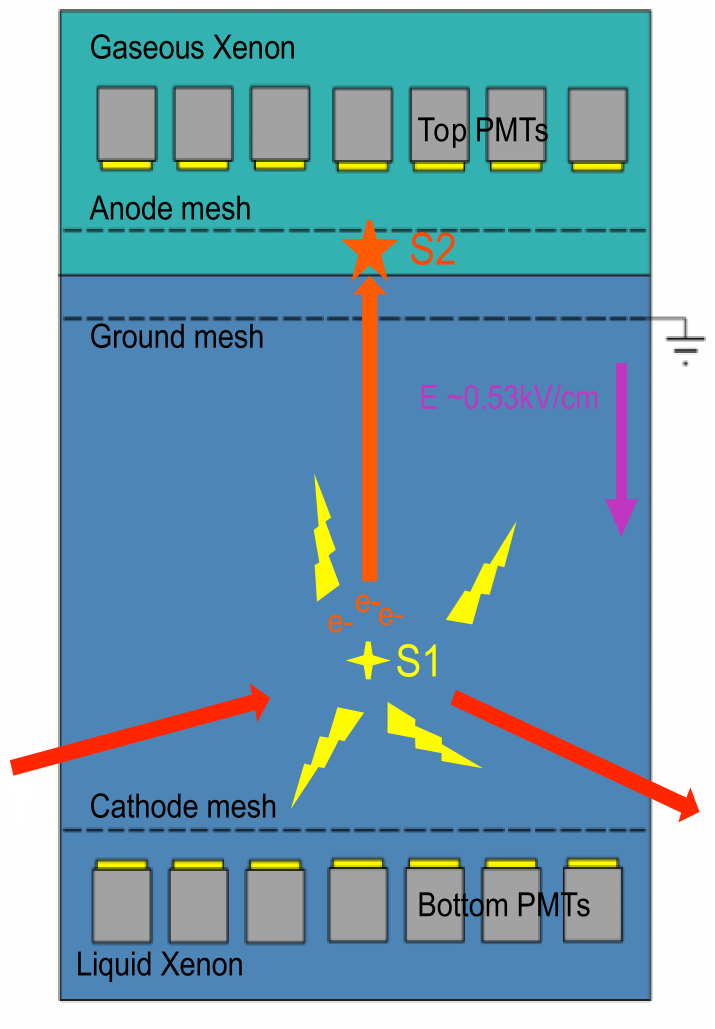


Single phase



Dual phase

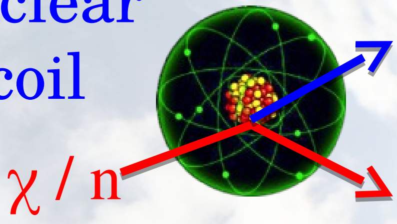
Dual Phase Xenon TPC – AGAIN...



S1: Prompt scintillation

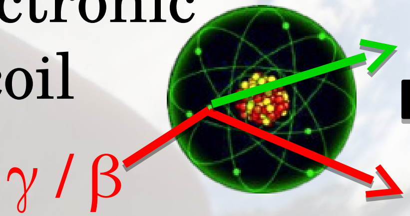
S2: Proportional scintillation after *e-* drift and extraction into gas

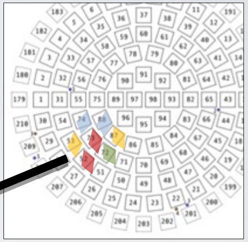
Nuclear Recoil



Discrimination by S2/S1

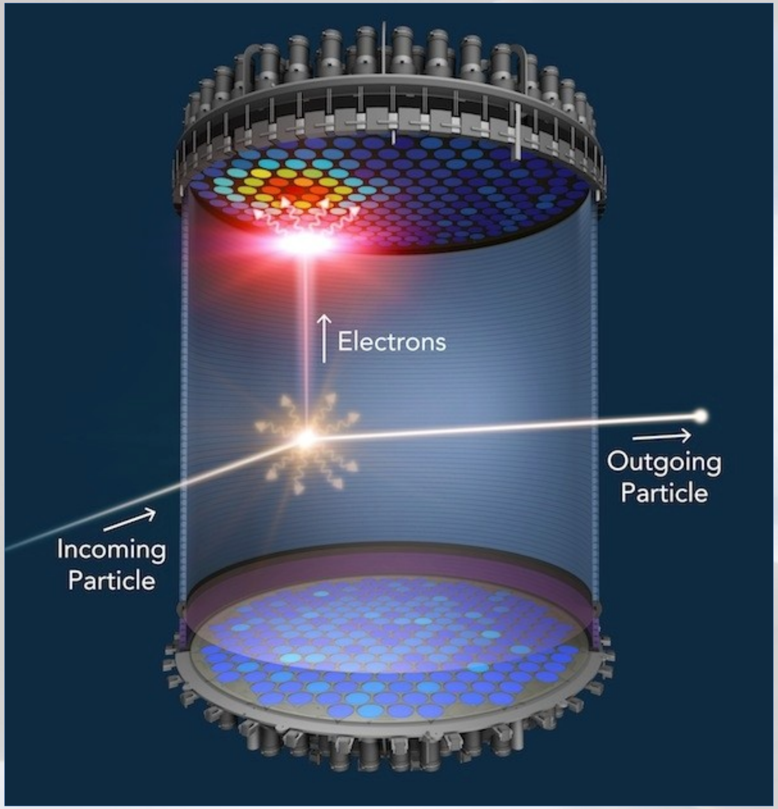
Electronic Recoil

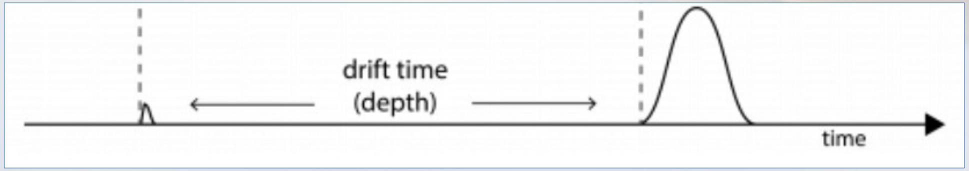




<u>Interaction vertex reconstruction:</u>
- Horizontal from top PMT array
- Vertical from drift time

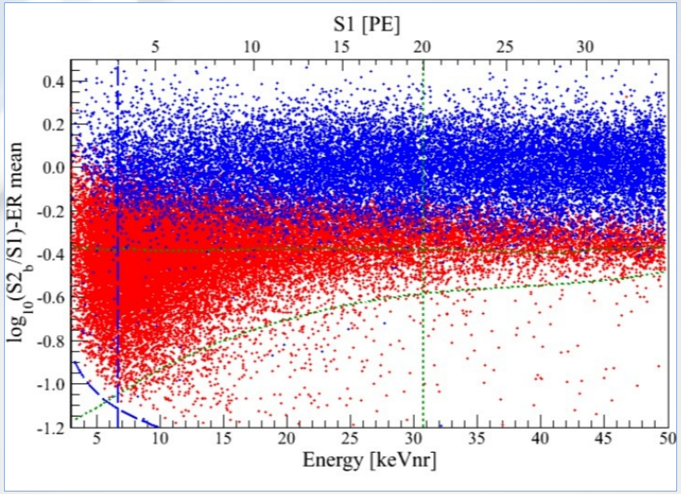
Dual Phase TPC Distributions





- Prompt scintillation photons give first signal (S1)
- Ionized e[-] drift up to the anode and amplified, giving S2
- Time difference gives Z position
- S2 Hit pattern on top gives XY position
- Ratio S2/S1 indicates type of interaction

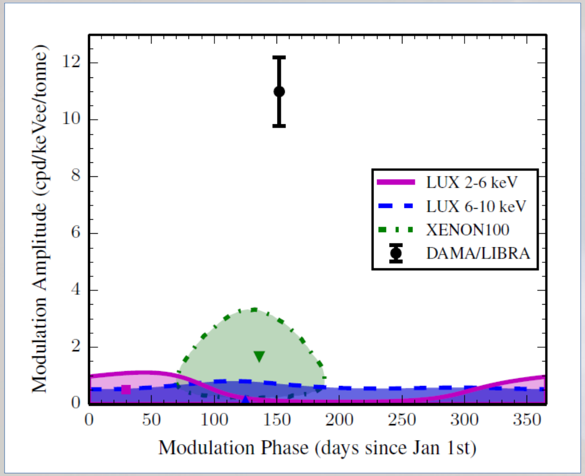
NR

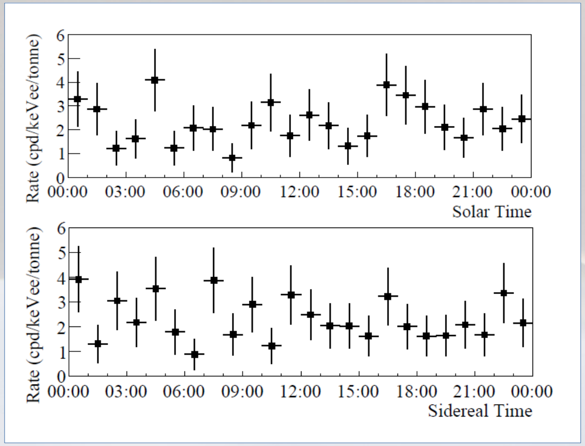


ER

R. Budnik, ISAPP 2019

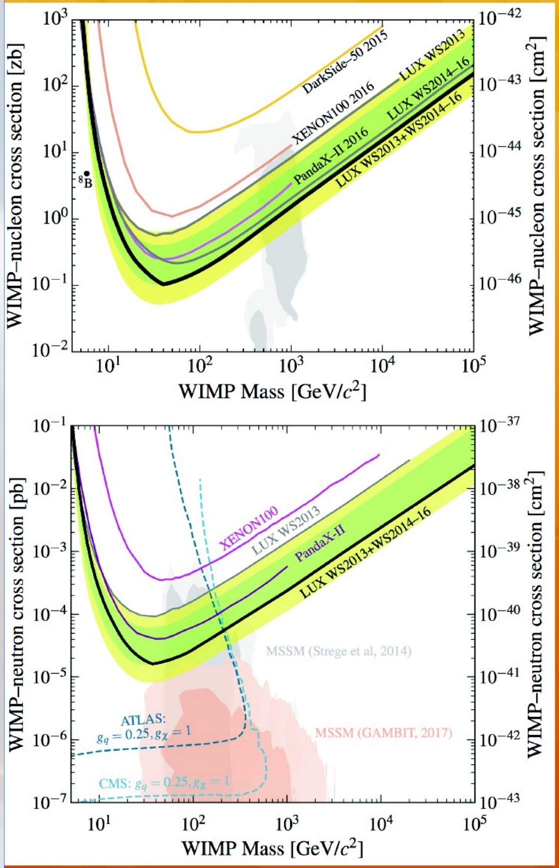
LUX – Forerunner Summer 2016





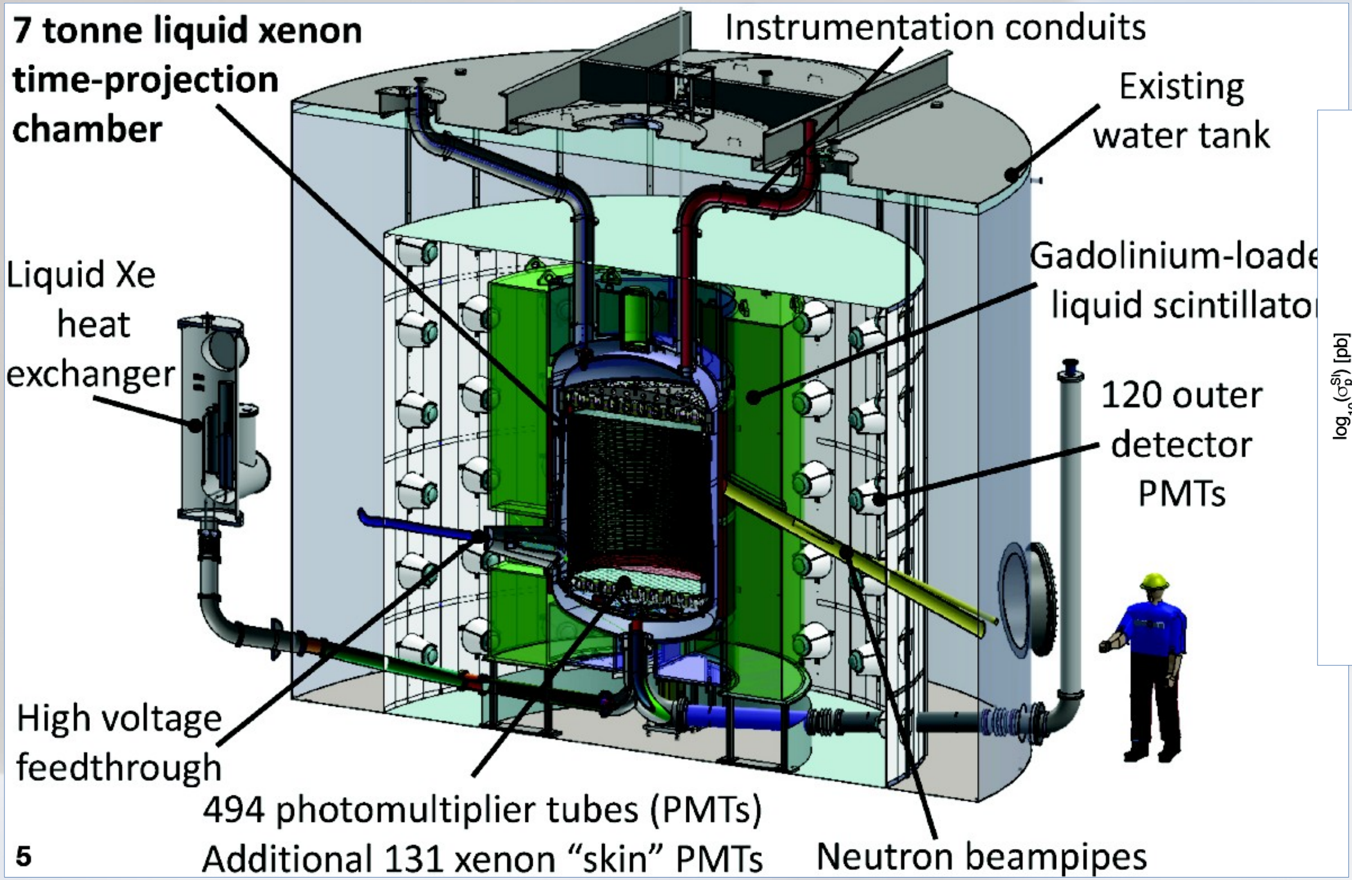
1807.07113

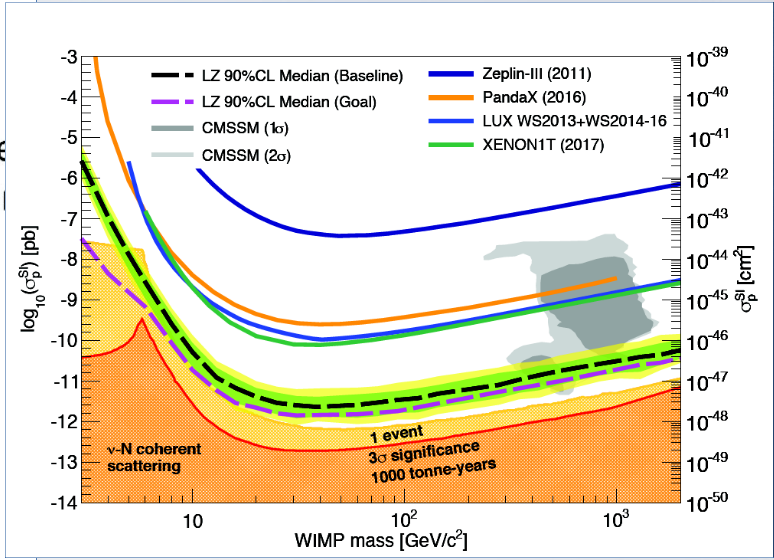
LUX Impact 2013/17



- LUX First Science Run in 2013
  Second Science Run 2014-2016
  Full exposure: 47.5 tonne.days
  (427 live-days)
- Improved Spin-Indep. WIMP Sensitivity by Factor 20x since state prior to 2013.
  Also Neutron Spin-Dep. Sensitivity.
- Axion/ALP Search
- Full self-consistent models for all backgrounds events and detector response
- In parallel: Major program improving LXe ER and NR calibration over wide energy range (including sub keV) with high statistics and low systematics.
  Allowed significant improvement in accuracy of Xe response models.
  Also clearly establishes sensitivity to 8B coh. scattering.
- LZ: Kim Palladino Tues 15:30
  LZ: Christine Ignarra, Tues 15:45
  LUX: Rick Gaitskell Wed 14:00

LZ- LUX+Zeplin

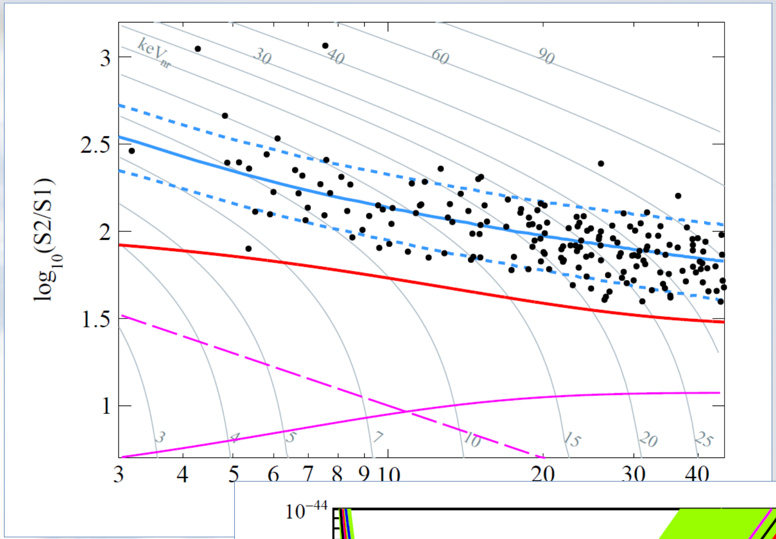


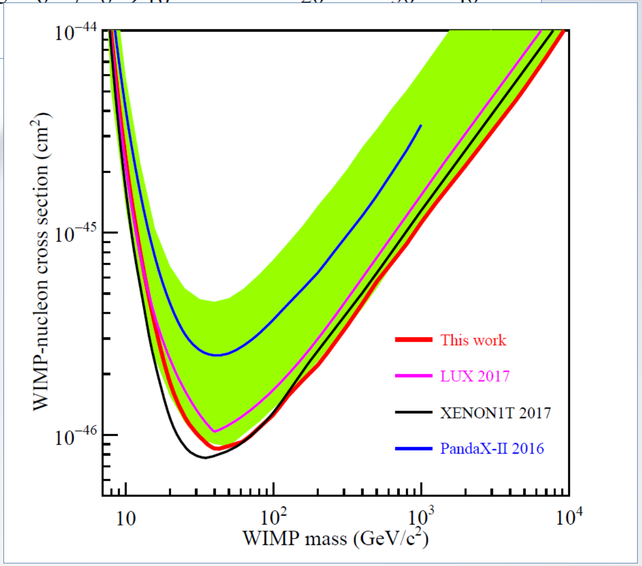


- To start 2020 @SURF
- Use of n-veto, 7-ton TPC, 5 year run

PandaX-II – Just behind

- Combining all runs, 54 ton X day
- Reduced Kr background, plus under-fluctuation
- Future plans for PandaX-4T and PandaX-III ($2\nu0\beta$)

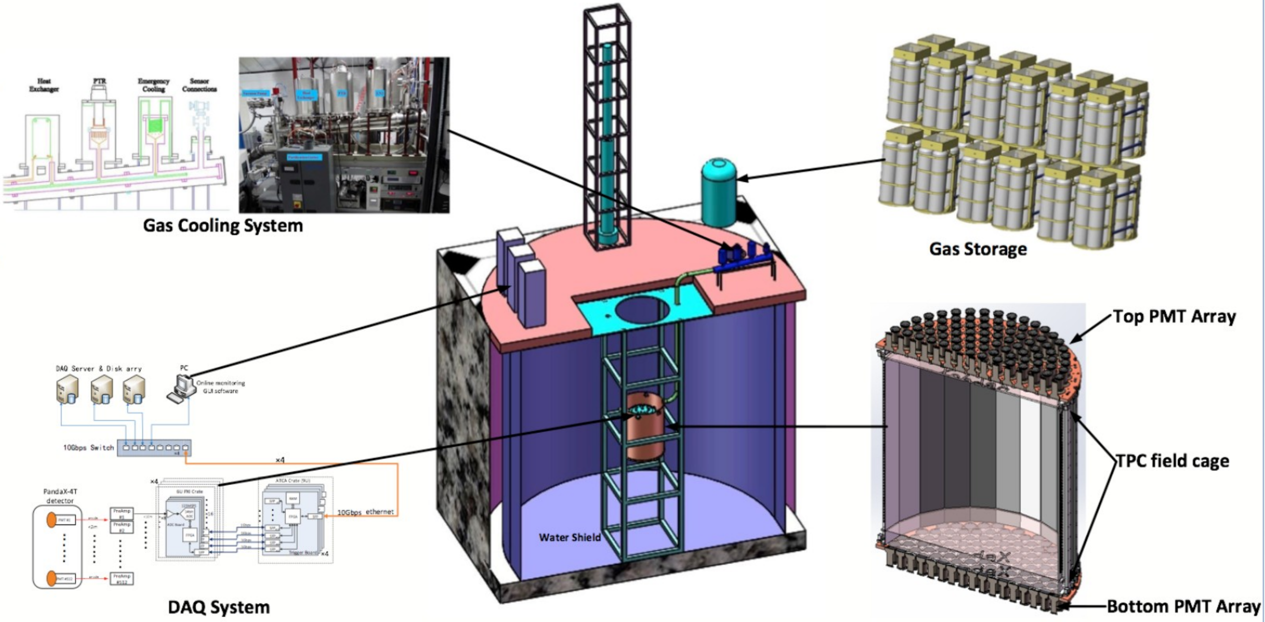




1708.06917

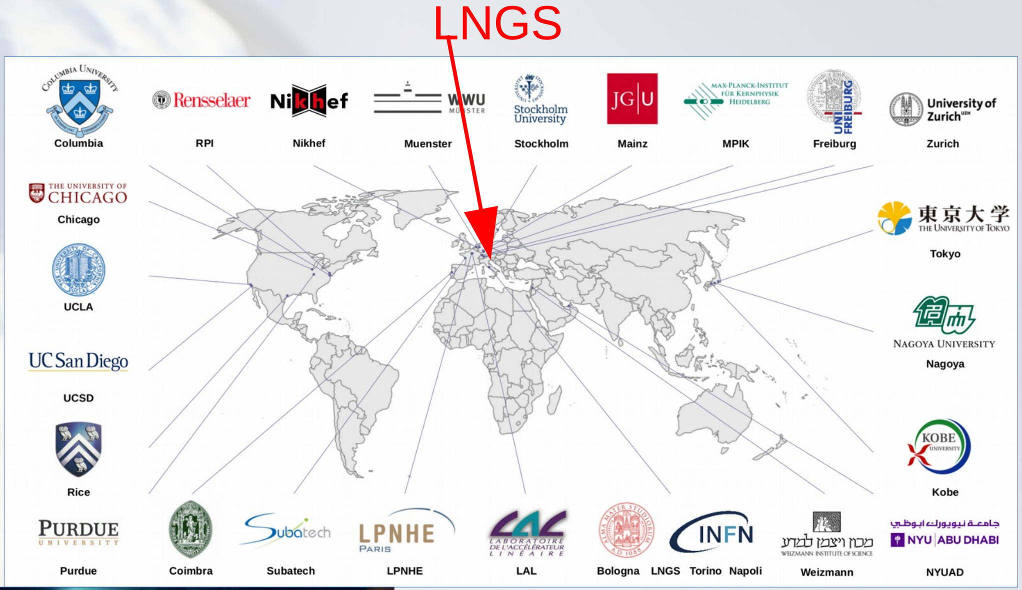
PandaX-4T: Not wasting time

PandaX – 4t
to be installed at CJPL-II; scale-up by factor 8
4t LXe target
with 6×10^{-48} cm^2 sensitivity to SI interactions @ 40 GeV/c^2
assembly and commissioning: 2019-2020



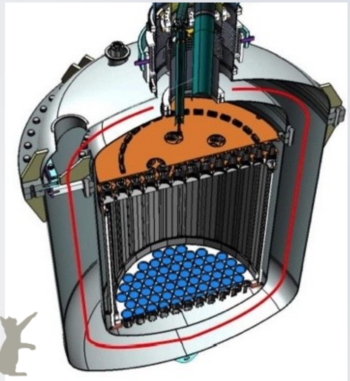
1806.02229

The XENON Collaboration at LNGS



R. Budnik, ISAPP 2019

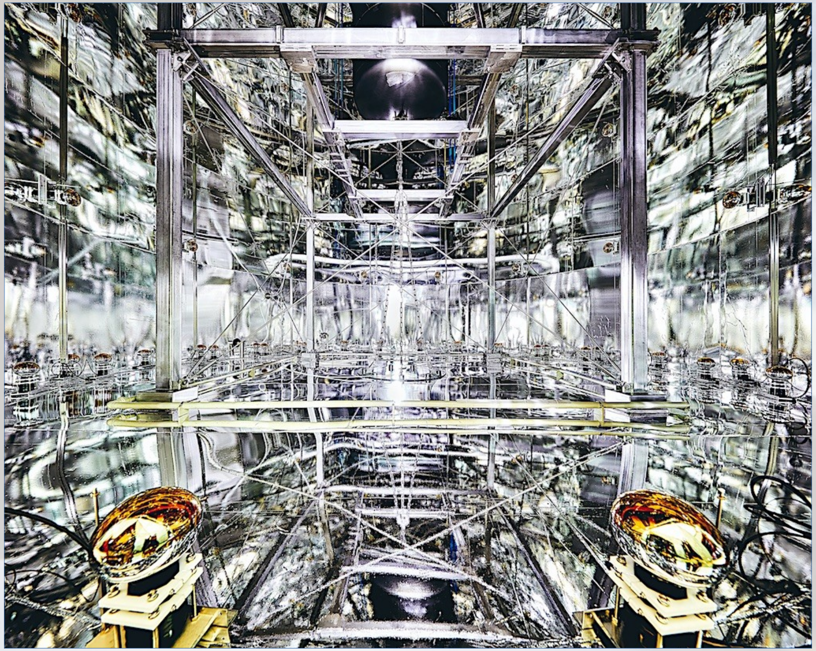
Timeline of the Xenon Program

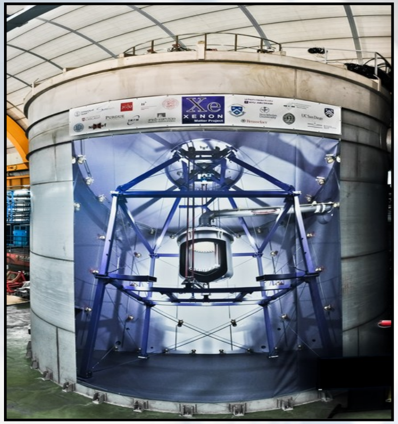


	XENON10	XENON100	XENON1T	XENONnT
Era	2005-2007	2008-2016	2012-2018	2019-2023
Mass	25 kg	161 kg	3200 kg	~8000 kg
Drift	15 cm	30 cm	100 cm	144 cm
Status	Achieved (2007)	Achieved (2016)	Projected (2018)	Projected (2023)
σ_{SI} Limit (@50 GeV/c^2)	8.8×10^{-44} cm^2	1.1×10^{-45} cm^2	1.6×10^{-47} cm^2	1.6×10^{-48} cm^2

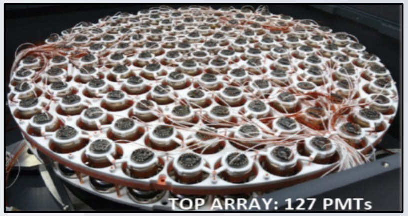
Keeping XENON1T alive and well

Water Cerenkov Muon Veto



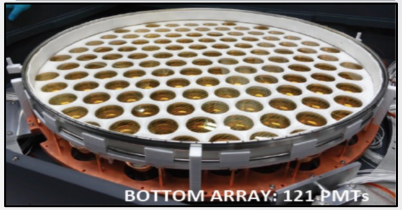


PMTs
Top

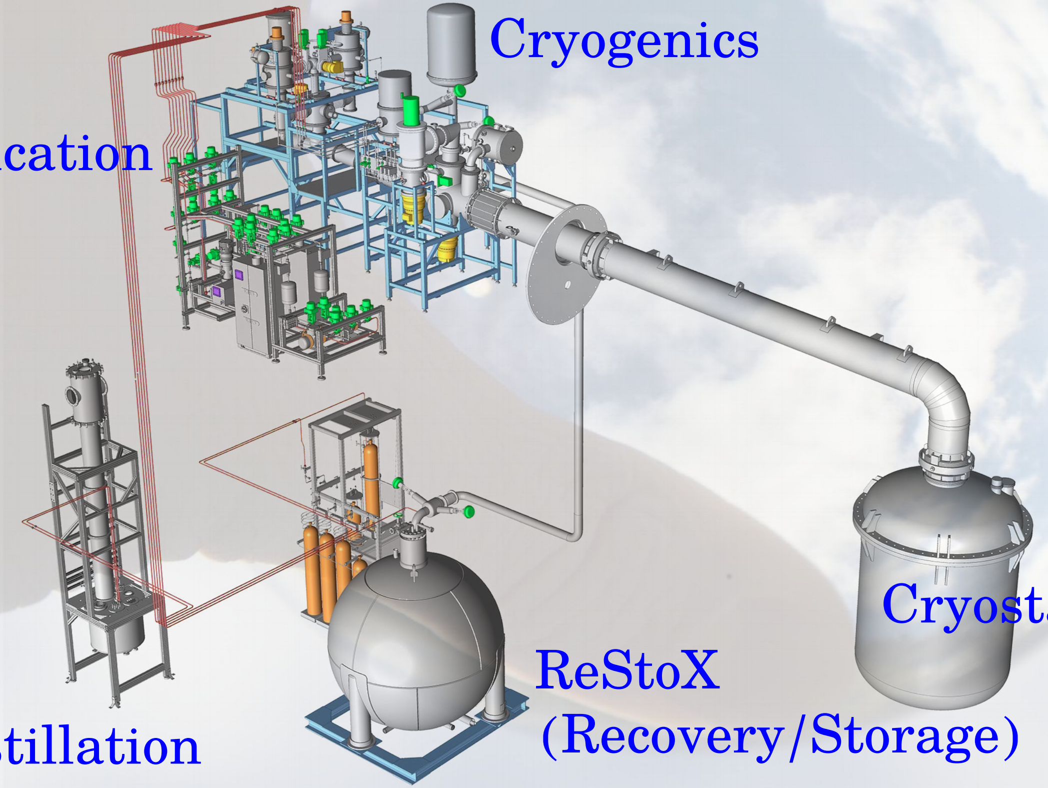


TPC

PMTs
Bottom

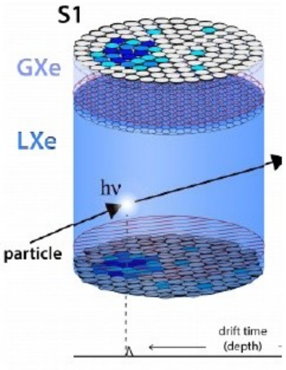


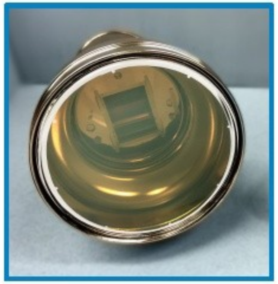
Keeping XENON1T alive and well



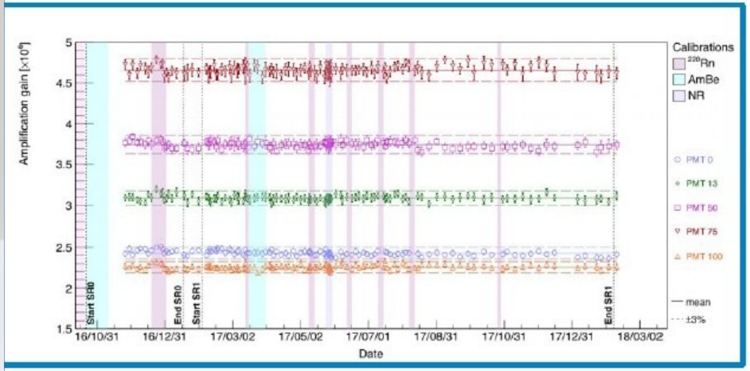
DAQ, HV, Control

Light collection: S1



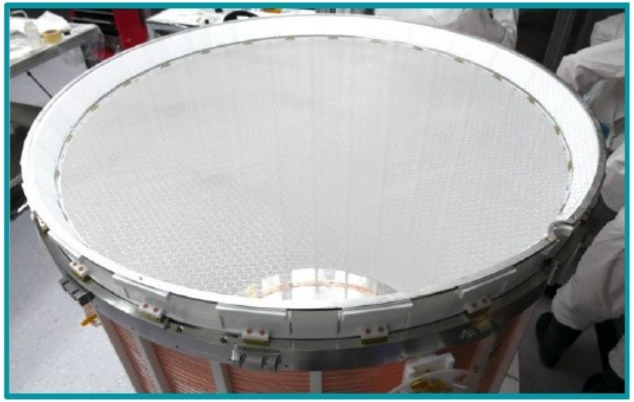


PTFE Lining
- High reflectivity
- Low radioactive background
- Covers entire inner volume



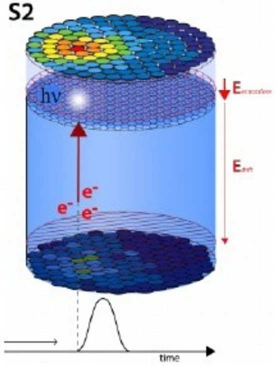
Highly sensitive light detection
- 248 Hamamatsu R11410-21 PMTs
- Quantum efficiency: 35% @178nm
- Operating gain 5×10^6 @ 1.5kV
- Single photoelectron acceptances ~94%
- Gains stable within 1-2%
- Low background design

JINST 12 (2017) no.01, P01024 2017-01-30)

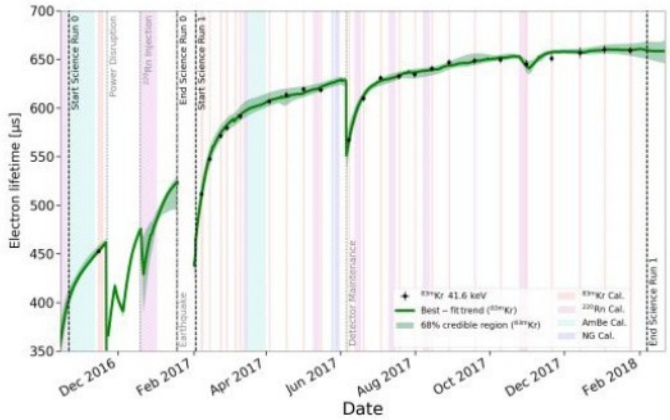


Near-transparent field grids
- Transparencies >90%

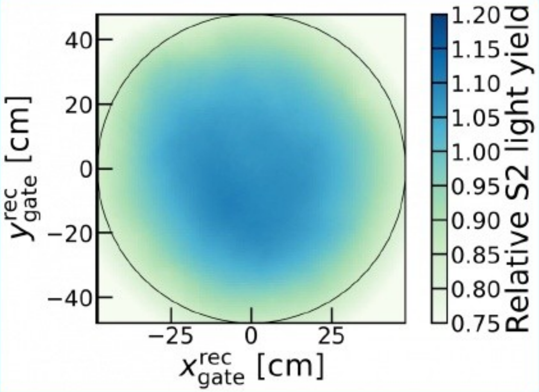
Charge – S2 Energy estimate



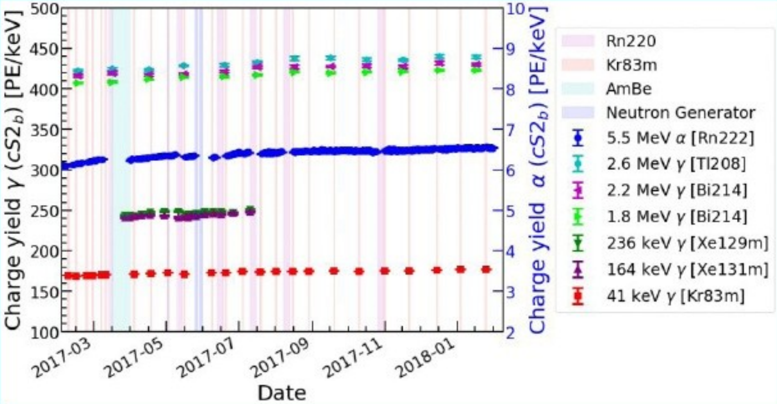
Electron Lifetime
- Ionization e- absorbed by impurities
- Exponential loss w.r.t. drift time
- Monitoring with ^{222}Rn alpha decays and ^{83m}Kr calibrations



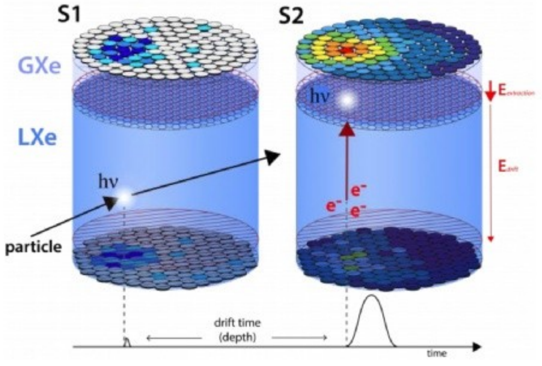
Amplification correction
- x-y dependent amplification correction
- Driven by anode 'sagging' w.r.t. gate



Charge yield
- Monitored with ^{222}Rn progeny, activated Xe, ^{83m}Kr
- Stable within a few percent
- Slight rise during science run probably driven by improving purity



S1+S2 Energy reconstruction

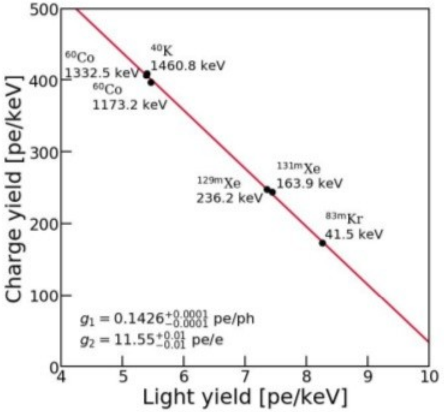


Energy loss to *either* light or charge channel
→ S1/S2 anticorrelation

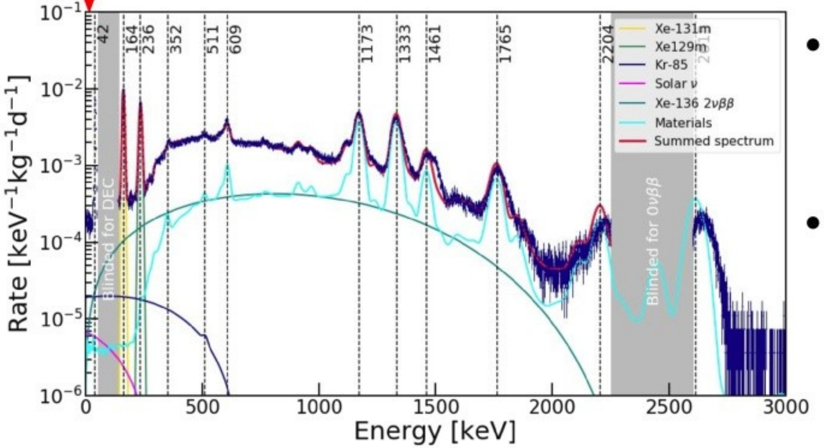
$$\frac{S1}{E} = \frac{n_\gamma}{n_e + n_\gamma} \times \frac{g1}{W}$$

$$\frac{S2}{E} = \frac{n_e}{n_e + n_\gamma} \times \frac{g2}{W}$$

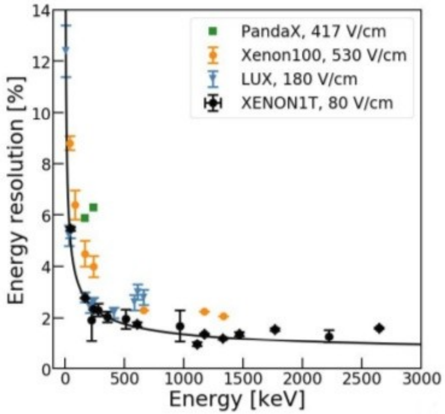
"Doke plot" → linear fit to calibration isotopes



ROI for WIMP search up to ~30 keV

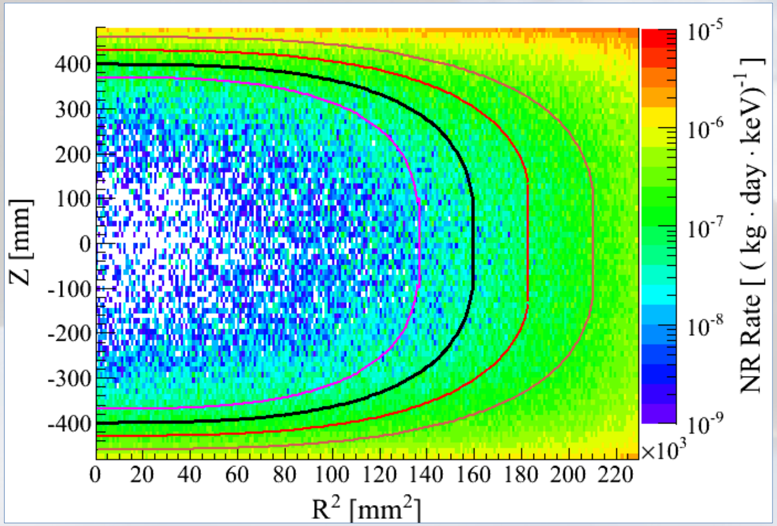


- Solve the above for E for combined energy reconstruction
- Excellent resolution across a broad energy range



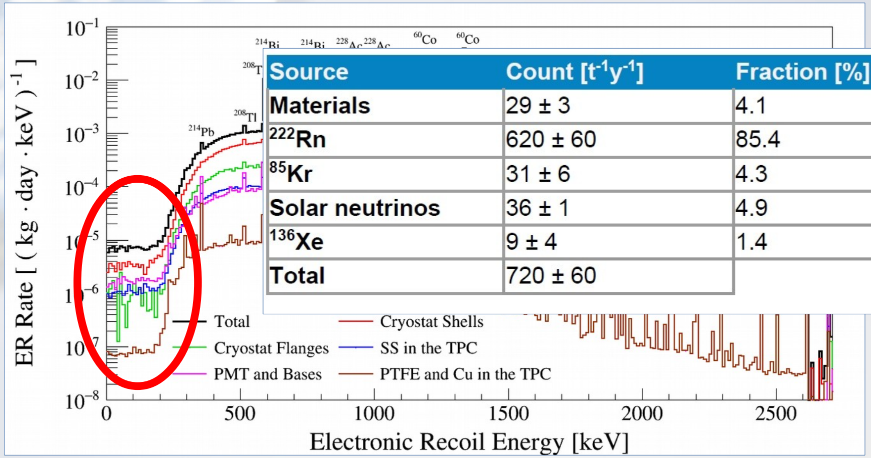
Backgrounds

- Nuclear Recoils
  - From U, Th (radiogenic)
  - From cosmic radiation
  - Total <1 for full exposure



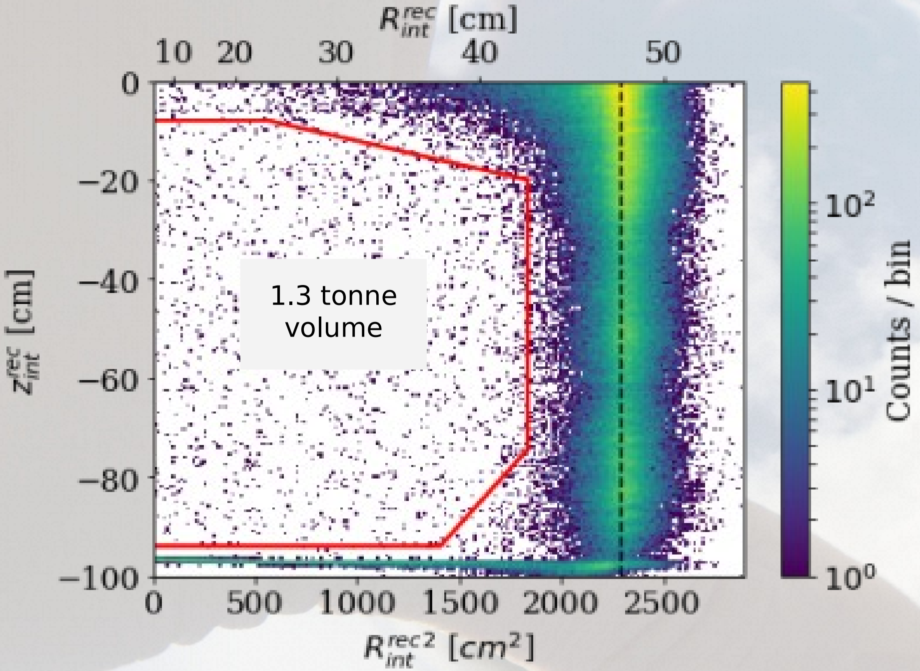
JCAP04(2016)027

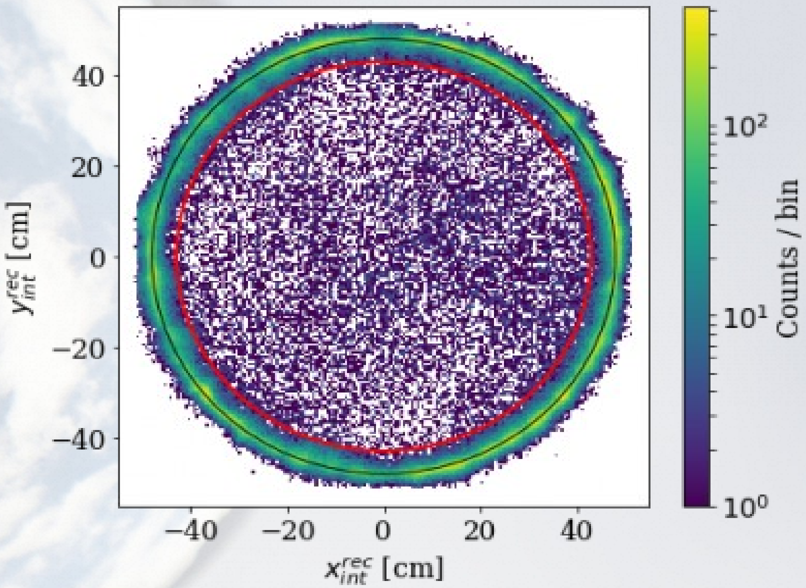
- Electron Recoil
  - From internal sources (mostly Rn, Kr)
  - From radioactivity of materials
  - With discrimination o(1) for full exposure



Source	Count [$t^{-1}y^{-1}$]	Fraction [%]
Materials	29 ± 3	4.1
^{222}Rn	620 ± 60	85.4
^{85}Kr	31 ± 6	4.3
Solar neutrinos	36 ± 1	4.9
^{136}Xe	9 ± 4	1.4
Total	720 ± 60	

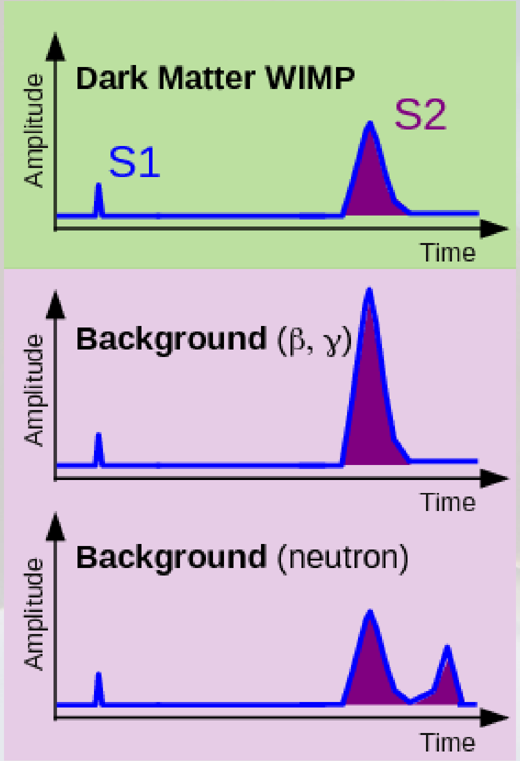
Fiducialization

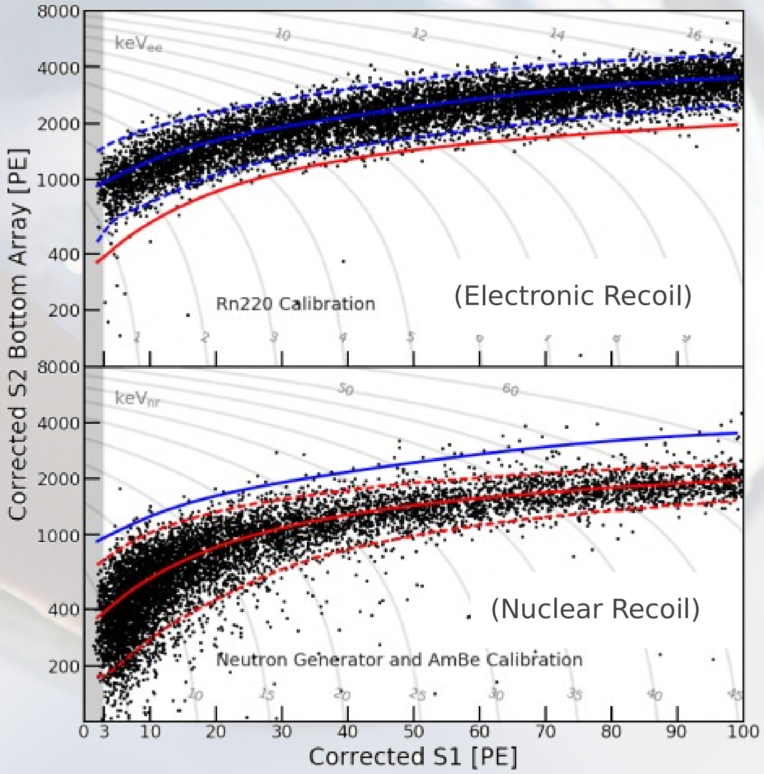




Removes high rate of events from detector materials

Particle Discrimination





Electronic recoils (ER) and nuclear recoils (NR) give different amounts of scintillation and ionization

Scintillation/Ionization ratio gives particle discrimination

Calibrations to determine ER and NR bands

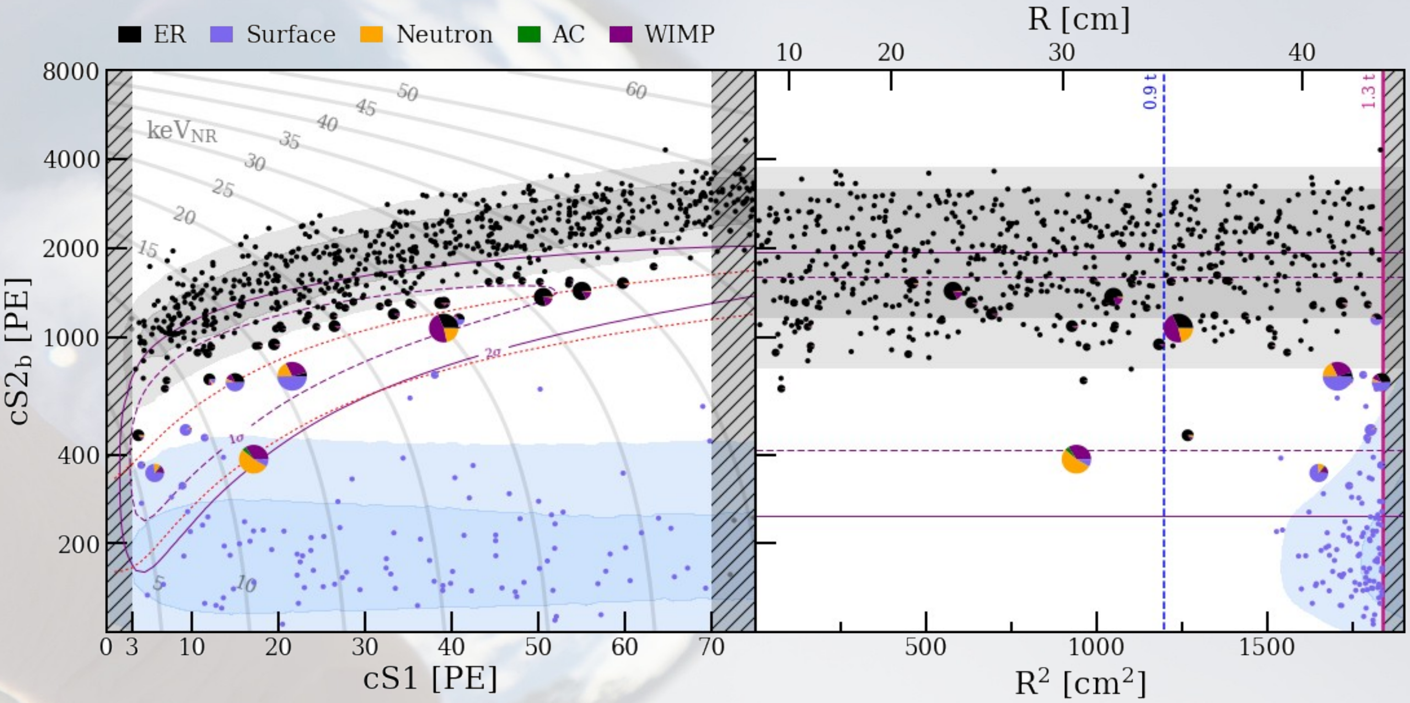
R. Budnik, ISAPP 2019

Spin-independent WIMP search results

278 day live time, 1.3 tonne volume: 1 tonne yr exposure

Background and WIMP distributions are fed into a 4D profile-likelihood fit

Small points show background-like events, larger points show larger WIMP likelihood



Pie chart color shows the likelihood that each event comes from each source distribution

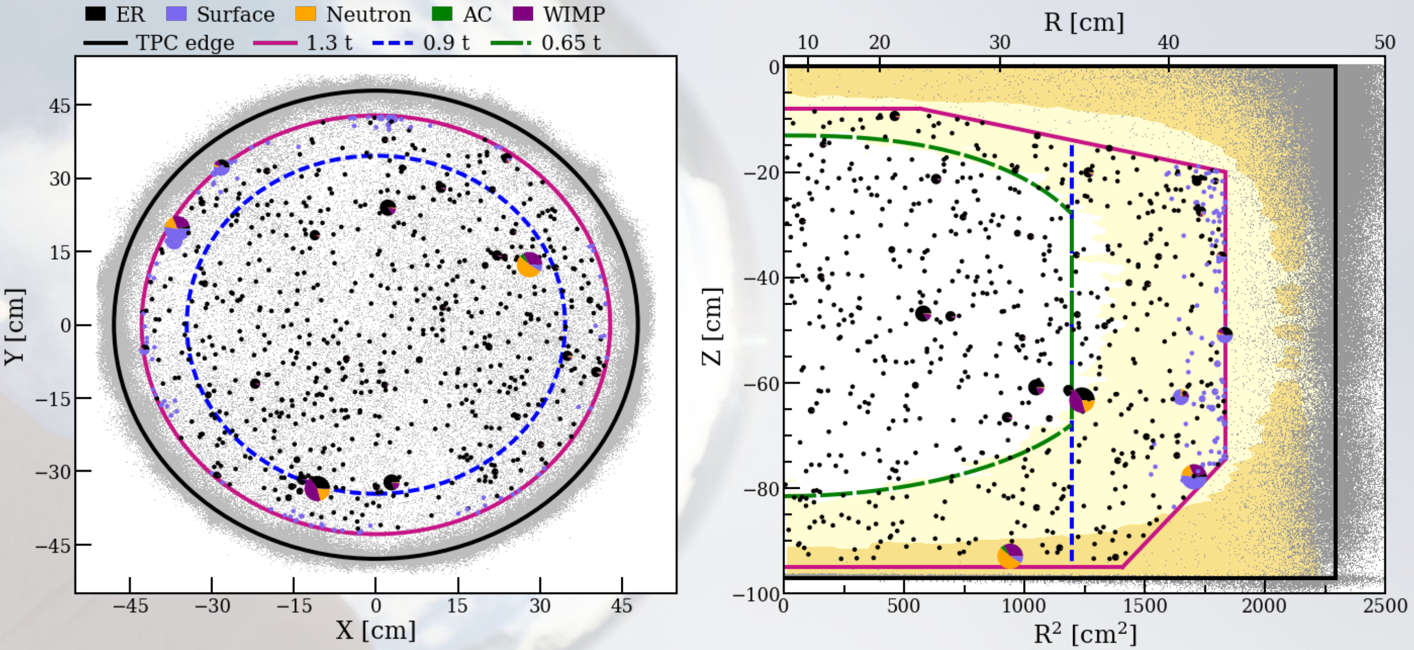
R. Budnik, ISAPP 2019

Spin-independent WIMP search results

Mass	1.3 t	0.65 t
$(cS1, cS2_b)$	Full	Reference
ER	627±18	0.60±0.13
neutron	1.43±0.66	0.14±0.07
CEνNS	0.05±0.01	0.01
AC	$0.47^{+0.27}_{-0.00}$	$0.04^{+0.02}_{-0.00}$
Surface	106±8	0.01
Total BG	735±20	0.80±0.14
$\mathrm{WIMP}_{\text{best-fit}}$	3.56	0.83
Data	739	2

Full likelihood analysis shows no excess over expected background

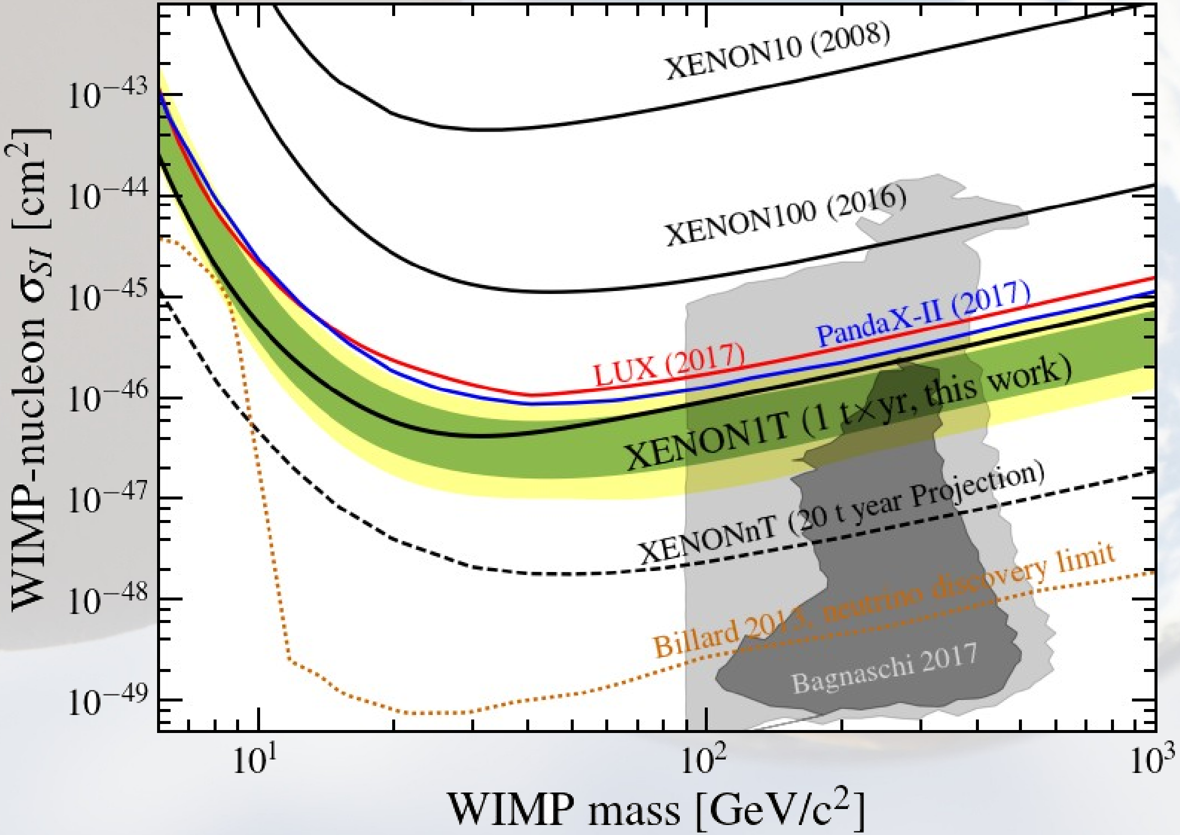
Events near the surface can be removed using a more stringent fiducial cut



Pie chart color shows the likelihood that each event comes from each source distribution

R. Budnik, ISAPP 2019

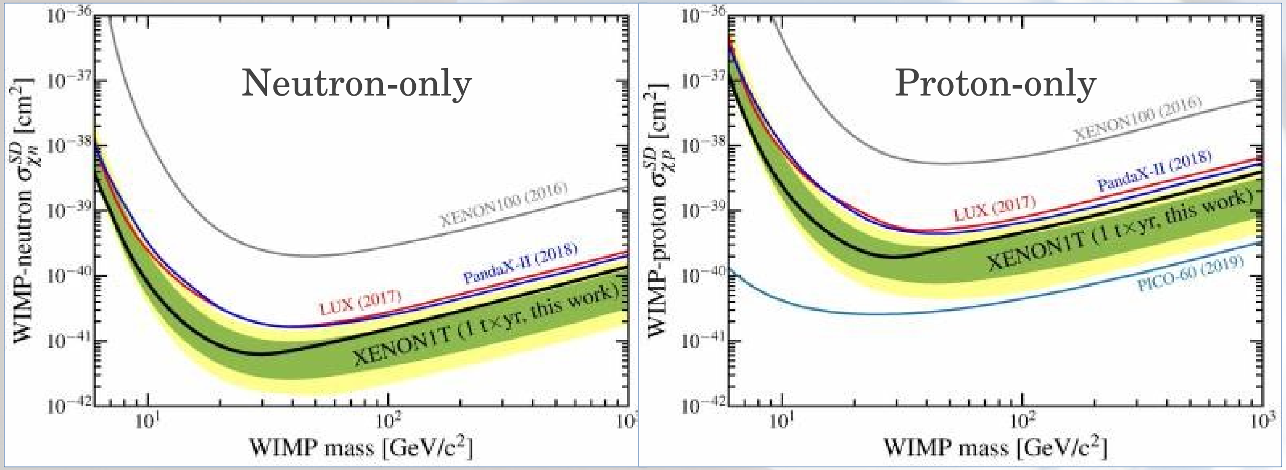
Spin-independent WIMP Search results



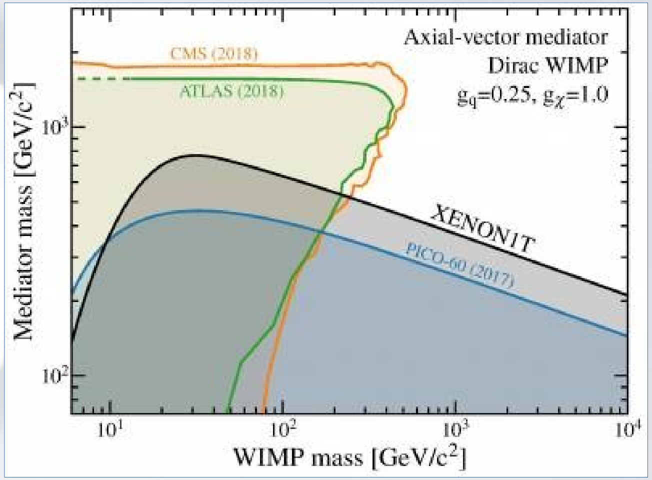
Most stringent limit on WIMP-Nucleon cross-section at all masses above 6 GeV

No excess greater than 2σ over full mass range

Spin-dependent WIMP Search



Comparison with LHC limits



Limits on WIMP interactions with ^{129}Xe and ^{131}Xe

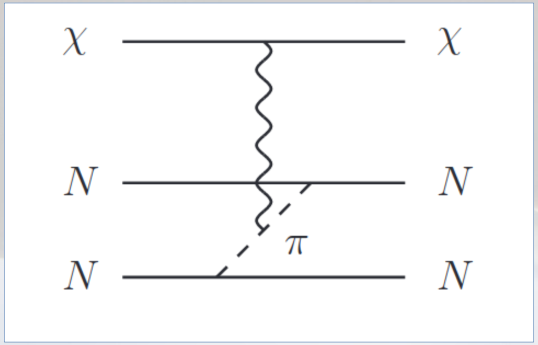
Event selection same as SI WIMP search

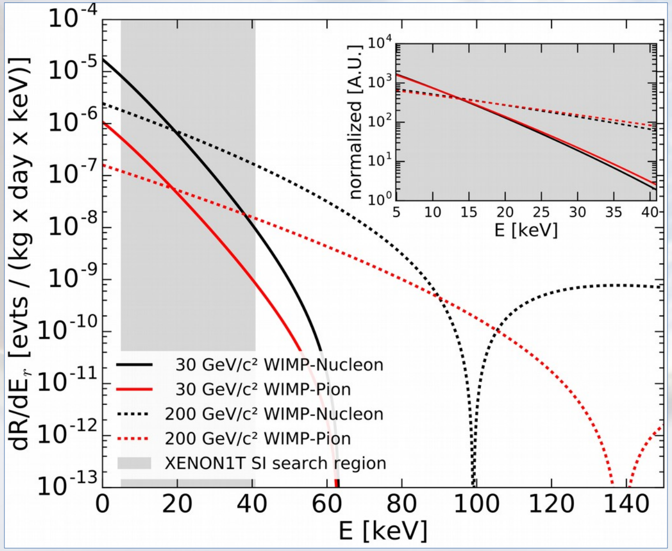
Constrain new region in WIMP mass-mediator mass space using a restricted model for comparison with LHC results

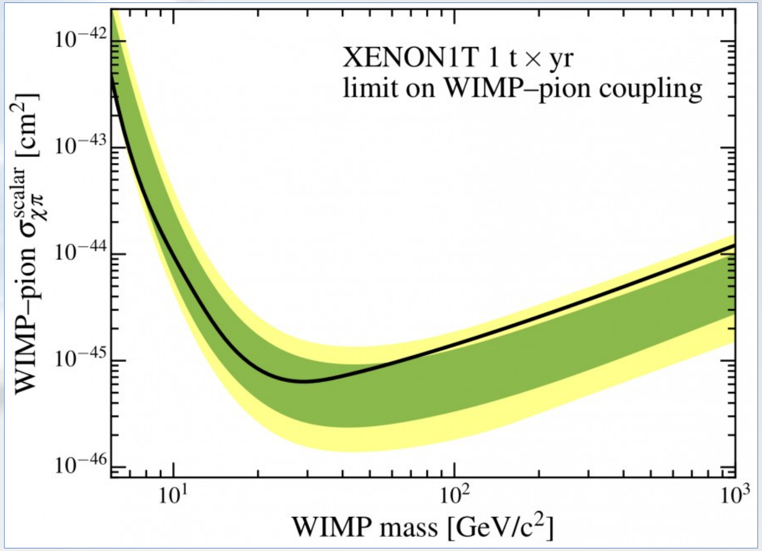
WIMP-pion cross-section limits

WIMPs could also interact with pions exchanged in the nucleus

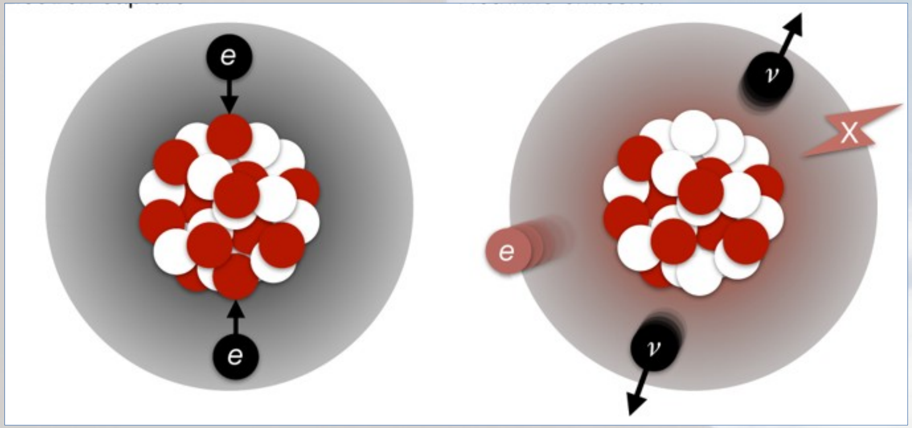
In the case that WIMP-nucleon cross-section is suppressed, can set limit on WIMP-pion interactions



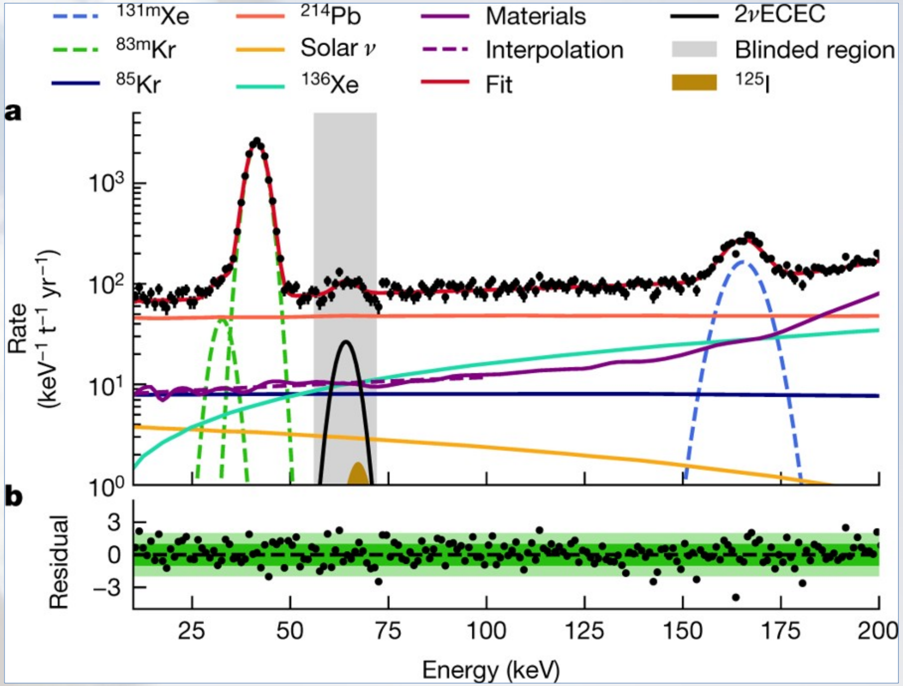




Double Electron Capture in ^{124}Xe



^{124}Xe ^{124}Te

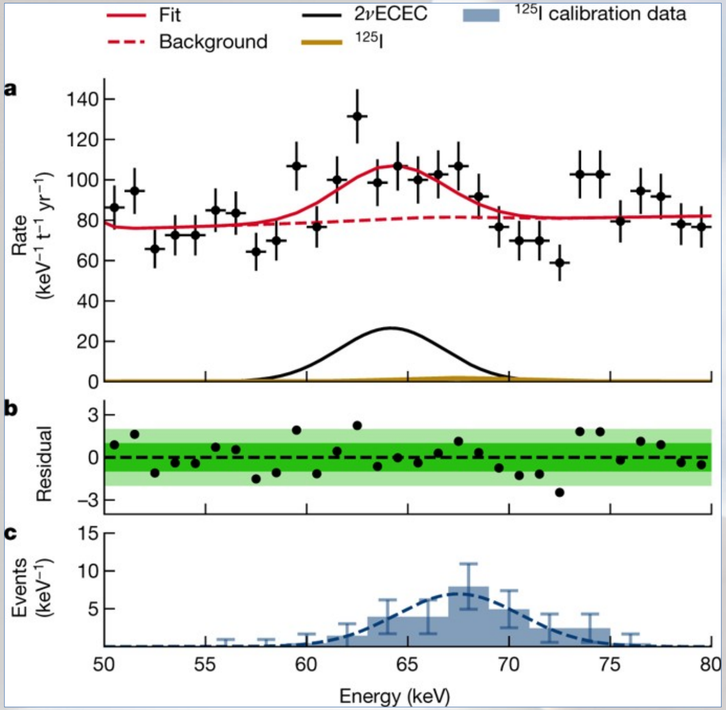


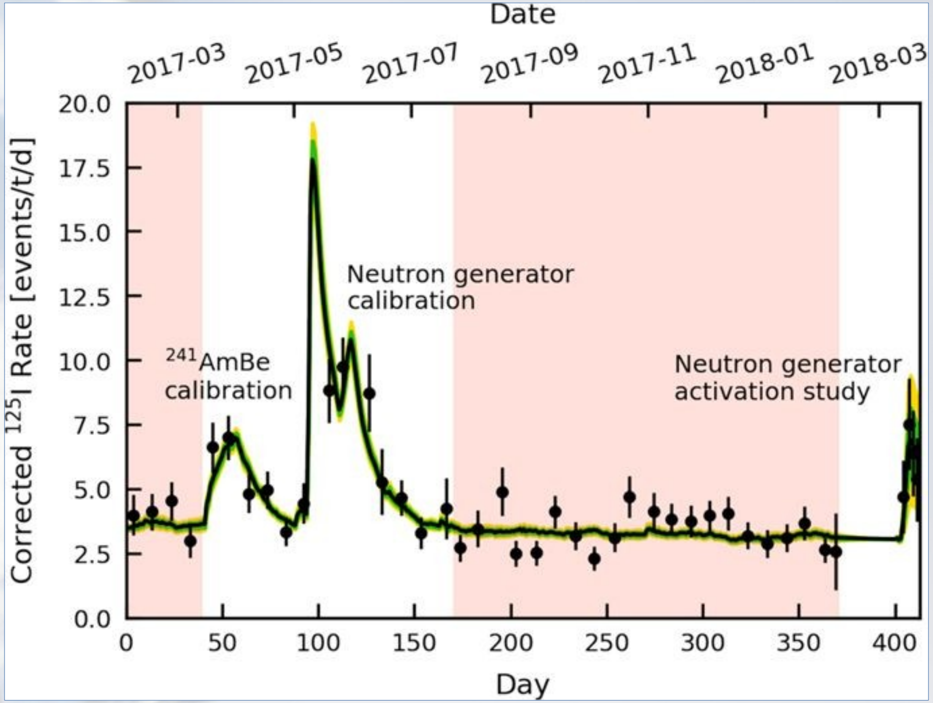
1 kg ^{124}Xe per tonne of liquid Xe

Never-before measured process

XENON, (2019)

Double Electron Capture in ^{124}Xe

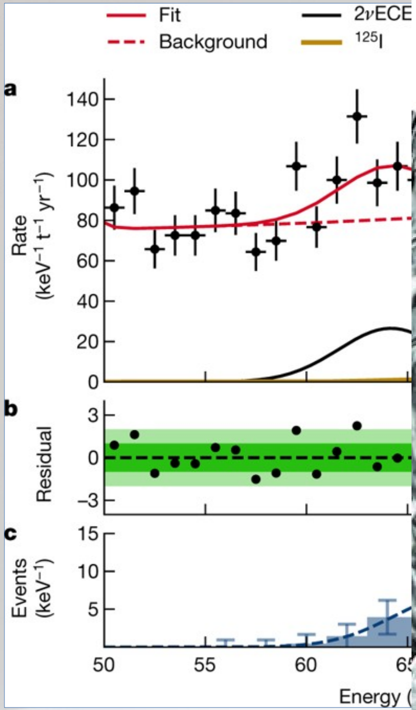


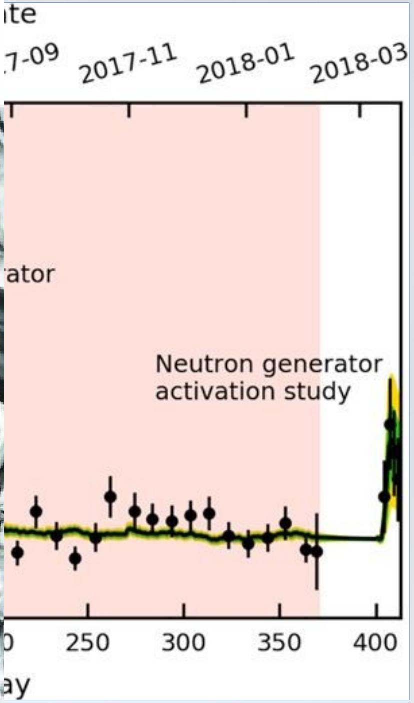


Half-life of (1.8 ± 0.6) x 10^{22} years, longest directly measured half-life to date

Modeled nearby background ^{125}I from activation from neutron calibration

Double Elec





Half-life of (1.8 ± 0.6) x

Modeled nearby backgro

XENONnT – Swift upgrade

MINIMAL UPGRADE

XENON1T infrastructure and sub-systems originally designed for a larger LXe TPC

FIDUCIAL XE TARGET

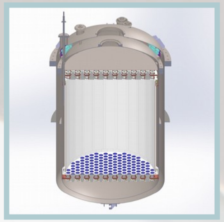
Fiducial mass: ~4 t
Target LXe mass: 5.9 t
Total LXe mass: 8 t

BACKGROUND

Identified strategies to reduce ^{222}Rn backgorund by a factor ~10

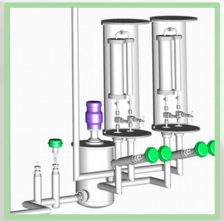
FAST TURNAROUND

Installation starts in 2018
Commissioning in 2019



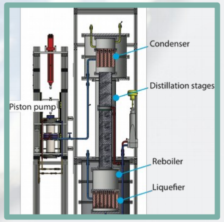
NEW TPC

Larger inner cryostat
476 PMTs



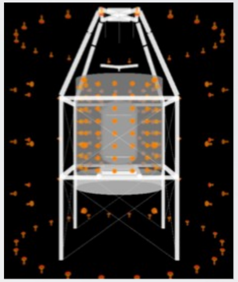
LXe PURIFICATION

Faster cleaning of large LXe volume (5000 SLPM)



Rn DISTILLATION

Online removal of ^{222}Rn emanated inside the detector

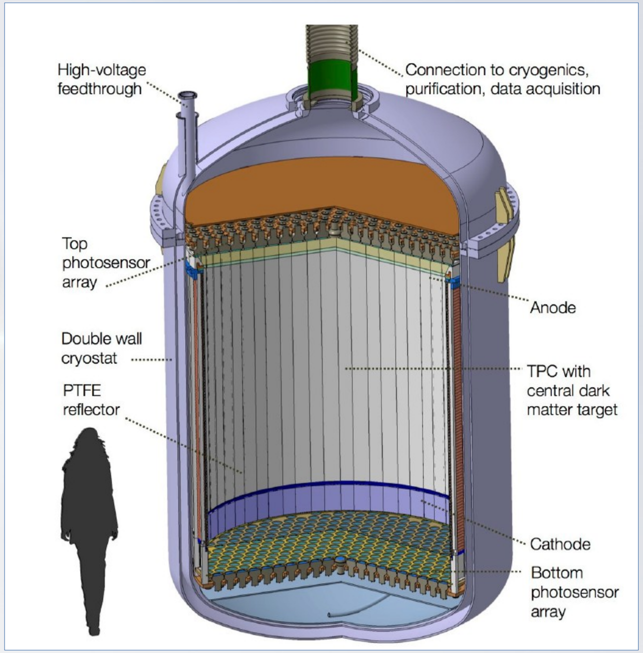


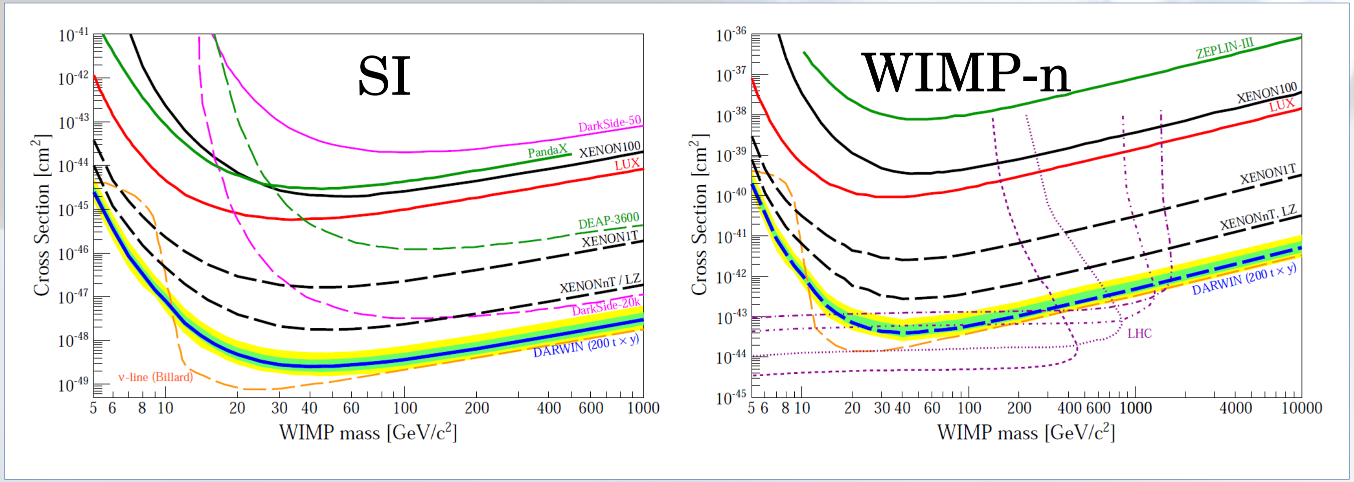
NEUTRON VETO

Tagging and in-situ measurement of neutron-induced background – Gd Sulphate in water

DARWIN – The ultimate LXe exp?

- Can we reach the ν floor?
  - Would require O(50t) Xe
  - **Backgrounds** at unprecedented levels
  - Technology stretching to the end: HV, purity, calibration, stability…
  - Probably means cooperation between long-time competitors
  - PandaX might surprise (again)!





1606:07001

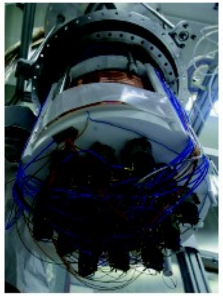
R. Budnik, ISAPP 2019

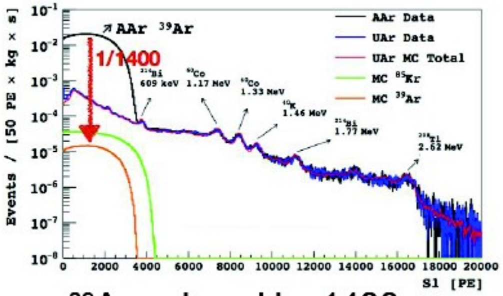
DarkSide50 and 20k: Argon!

- High light yield: LAr Pulse Shape Discrimination $>10^7$
- Underground Argon: low ^{39}Ar
- TPC 3D event reconstruction
- High-efficiency neutron vetoing

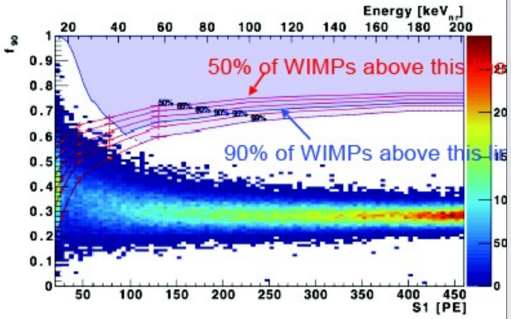
DarkSide-50

150/50/30 kg
total/active/fiducial
Sensitivity $<10^{-44}$ cm^2
Data: 2013-present





^{39}Ar reduced by 1400

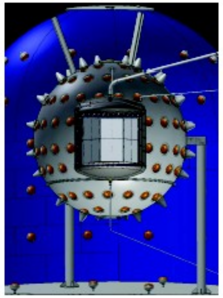


70-d of Underground Ar

Blind analysis of 500-d underway

DarkSide-20k

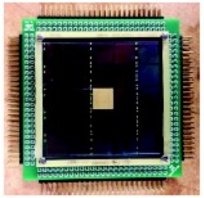
30/23/20 T
tot/act/fiducial
Sensitivity $<10^{-47}$ cm^2
Data: ~2021



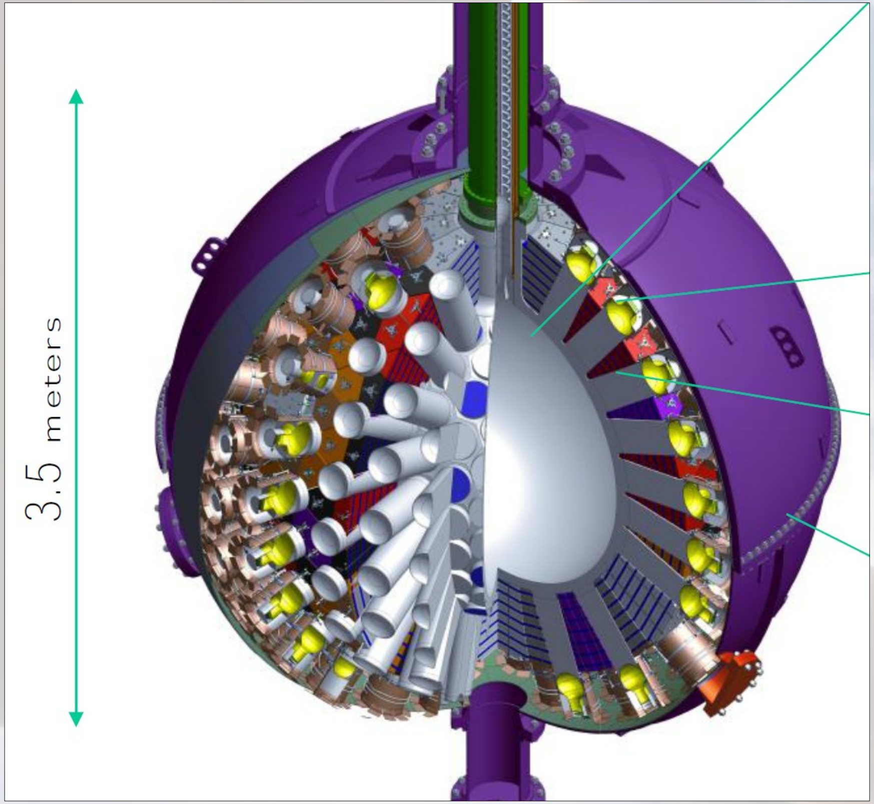
New Argon Collaboration
DarkSide
DEAP
MiniCLEAN
ArDM
} DS-20k⟶ Multi-100 ton

← Massive effort to extract and purify UAr

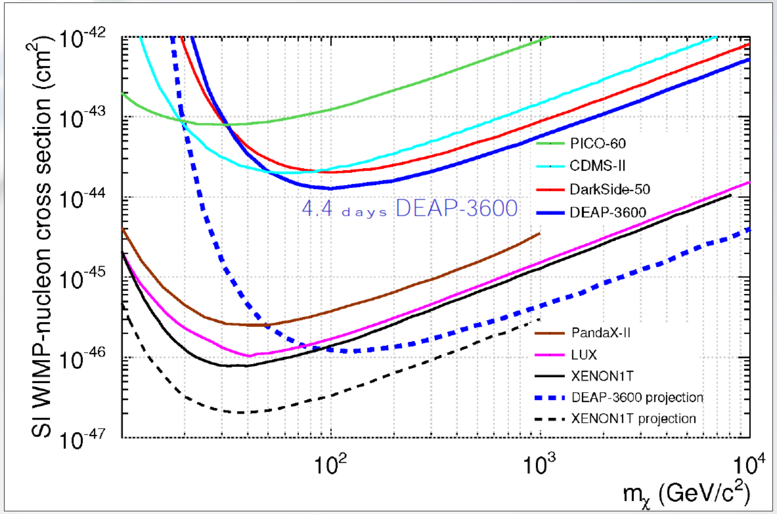
SiPMs replace → PMTs



Single phase - DEAP3600

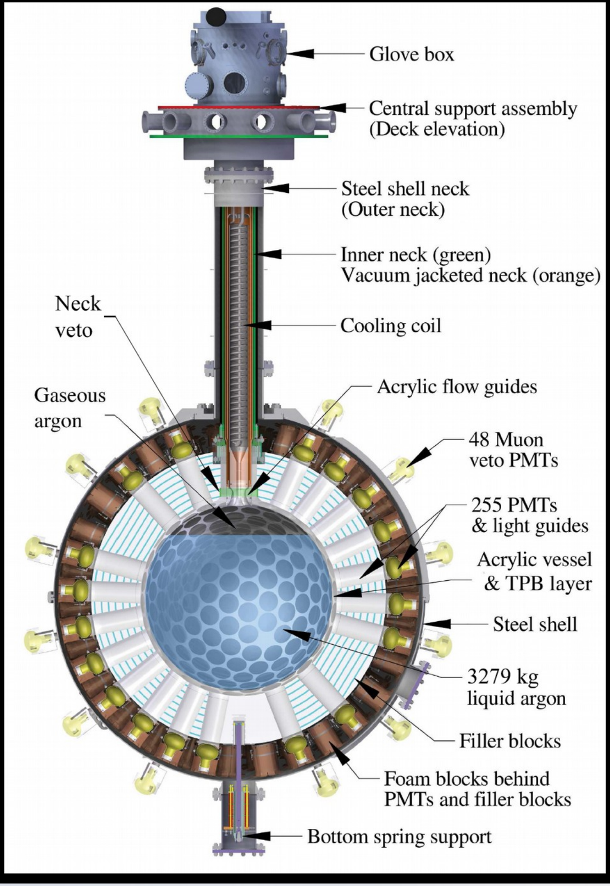


- 3.6t of LAr
- Low radioactivity underground Ar
- Great discrimination, LY, purity
- Has great potential at high masses
- Future prospects for **>100t** global experiment (with DS, ArDM, CLEAN)



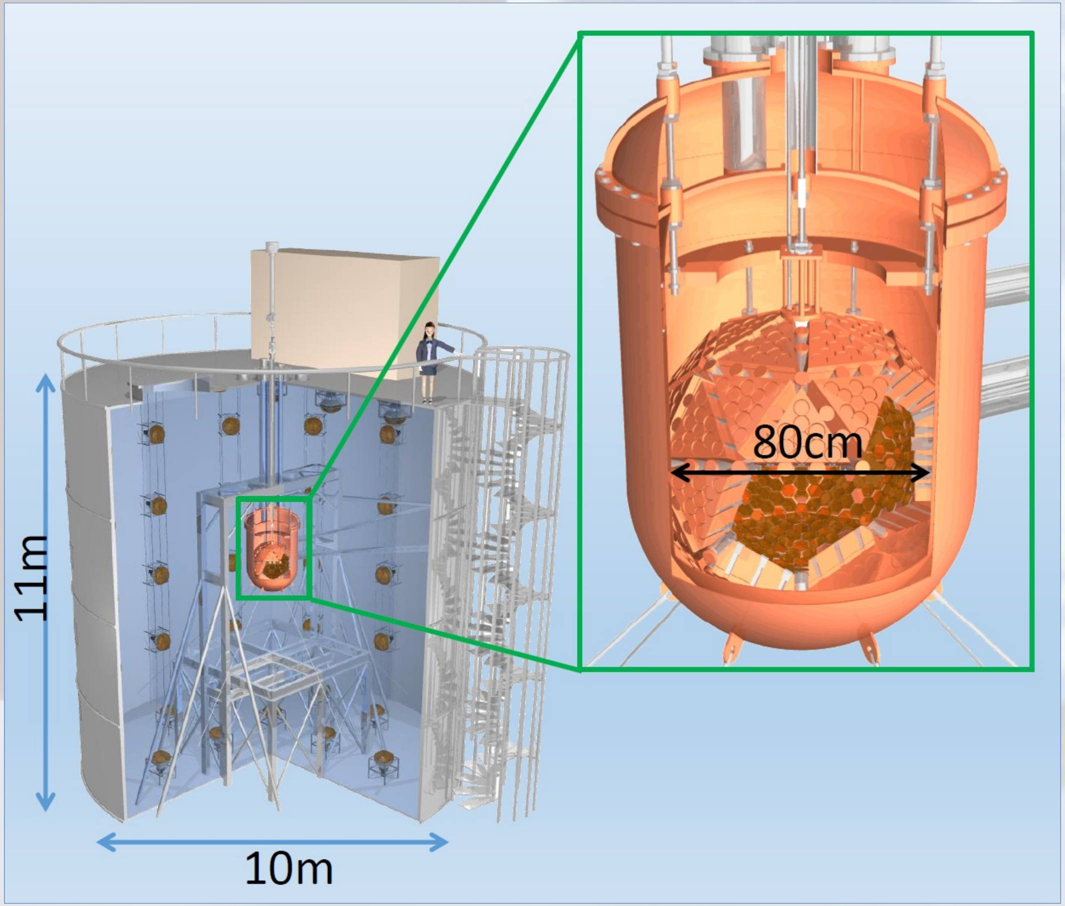
DEAP new results

- 3300 kg single phase LAr in SNOLAB in Canada
- Single acrylic vessel viewed by 255 PMTs
- Filled in 2016, running since then
- Recent result in 1902.04048
    - Largest exposure of dark matter experiment to date
    - Power of PSD
    - Good light collection
    - Low external backgrounds



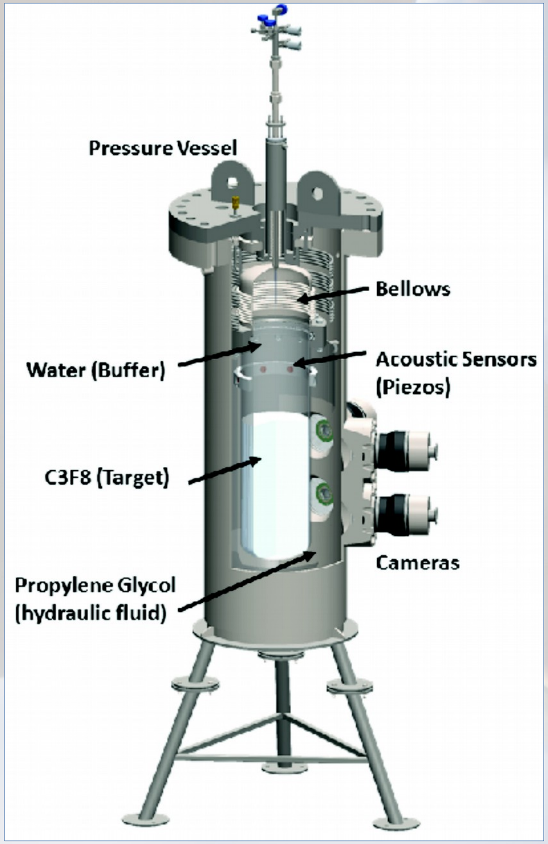
- Unexpected background of 210Po in the “neck” caused reduced acceptance
- Eventual limits not world leading
- Largest exposure ≠ Highest sensitivity!

XMASS in a nutshell

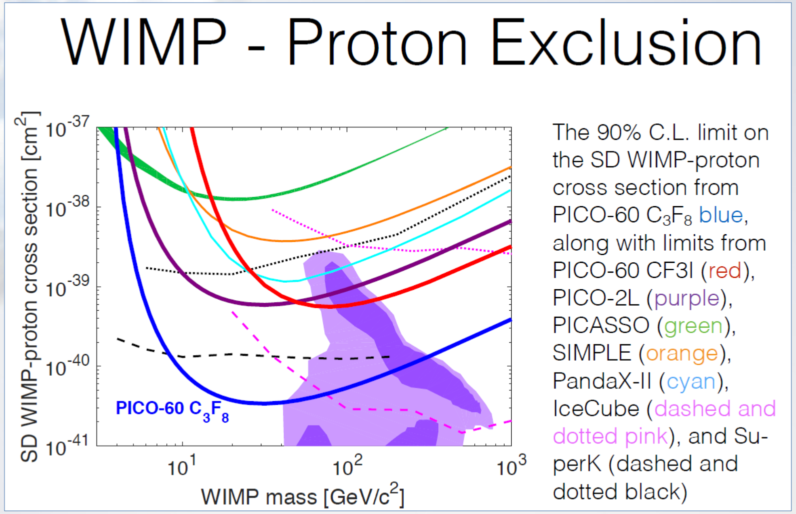


- Single phase Xe detector
- Precise and beautiful technology
- However, without the PSD of Ar proved to be "slower" than competing technologies
- Decommissioned

PICO – Bubble chambers back in the biz

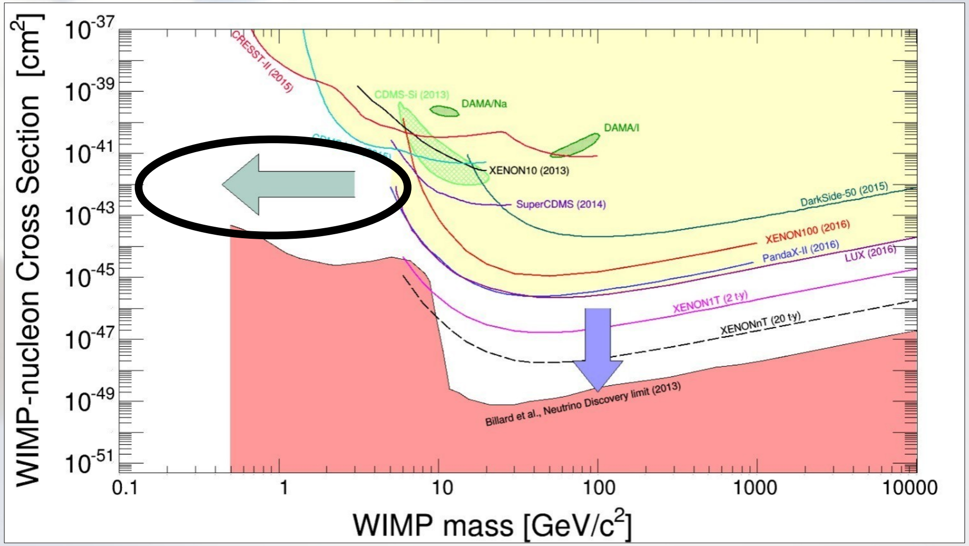


- Using bubble nucleation plus acoustic (to reject α's)
- PICO60 best in **SD proton cross section**
- PICO500 under construction
- Fight with n-background, water background



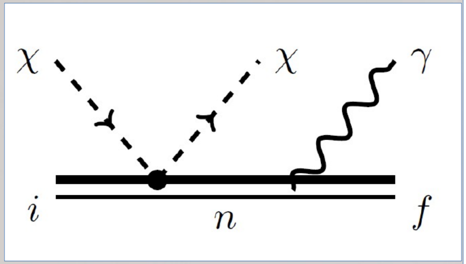
The "Low Mass Frontier"

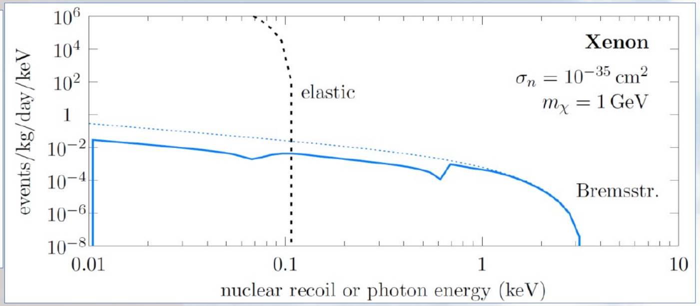
- Name of the game – Lower threshold, control backgrounds
- Main competitors: Crystals with all channels
  - BUT – maybe LXe has a say with Migdal or Bremmstrahlung?
- Ongoing R&D efforts for low noise, low T, low background, low threshold

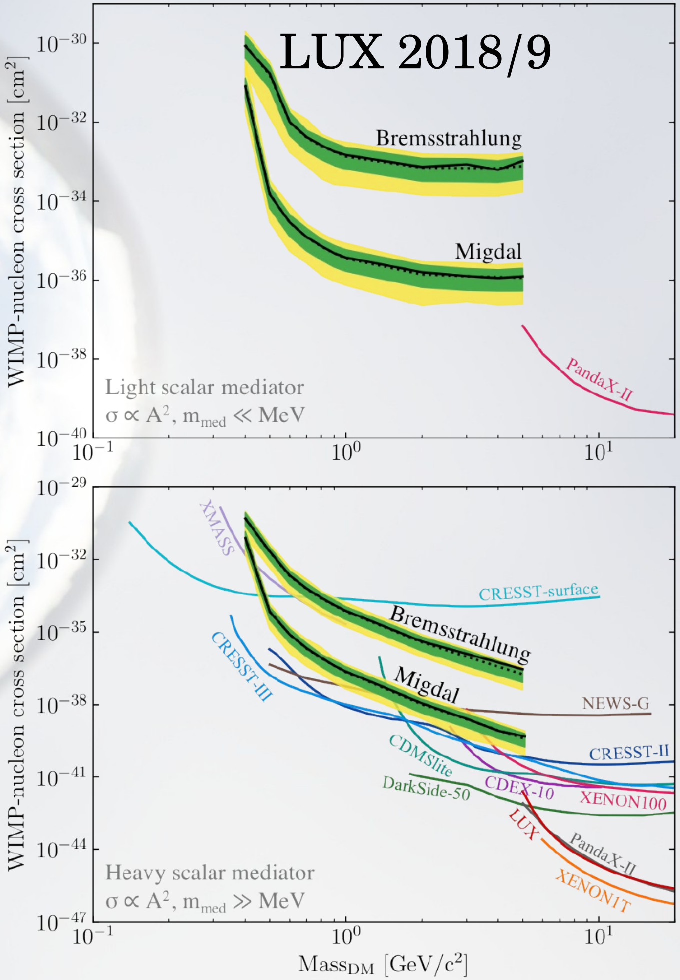


BUT – new ideas for interpretation may bring LXe here as well!

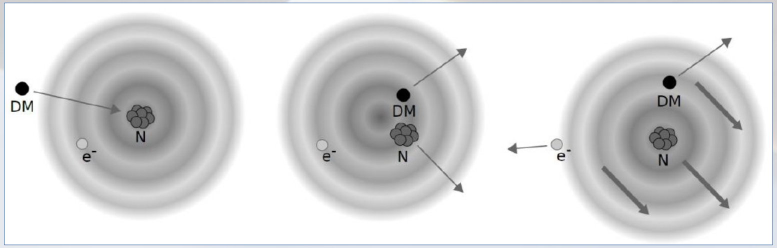
- Bremmstrahlung PRL 118, 031803 (2017)







- Migdal effect JHEP03(2018)194



And… Giving up on S1 for low threshold

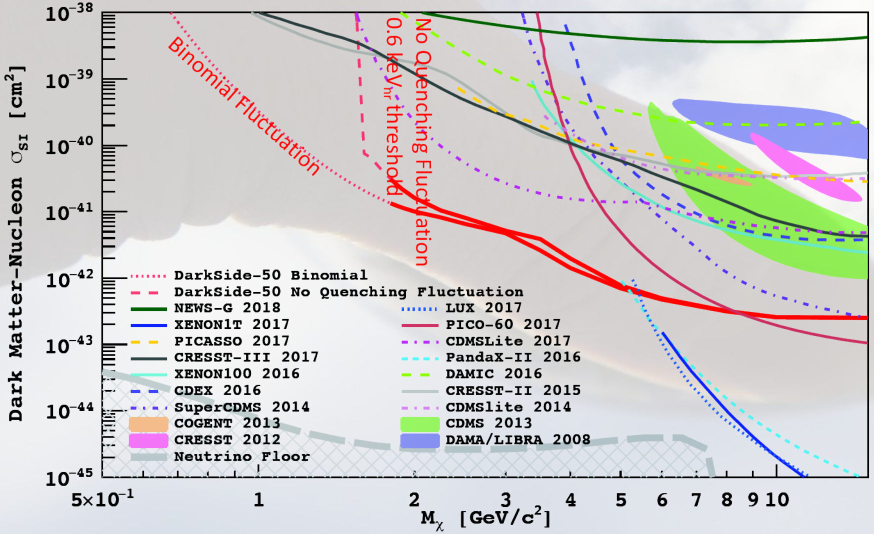
Ionization signal (S2): threshold < 0.1 keV_{ee} / 0.4 keV_{nr}

Sensitive to low mass WIMPs

Use Ionization (S2) Only.

- PMTs have almost zero dark rate at 88K
- Amplified in the gas region (~23 PE/e^-)
- Sensitive to a single extracted electron
- Radioactivity rate in the detector is remarkably low
- No need of PSD
- The electron yield for nuclear recoils increases at low energy

DS-50 can detect down to **single electron**.



Phys. Rev. Lett. 121 081307 (2018)

- Both Xe and Ar TPCs can go "S2-Only"
- Much lower threshold, both NR and ER
- Larger backgrounds – reduced fiducialization, no discrimination
- Can (mostly) only set limits and not discover
- Here, DS-50 as the latest example

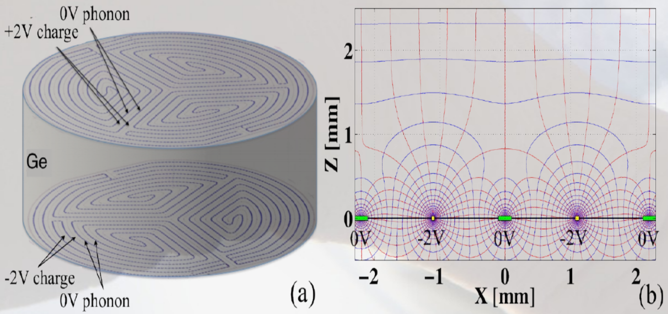
Semiconductor Calorimeters

Phonon + Ionization

EDELWEISS, CDMS

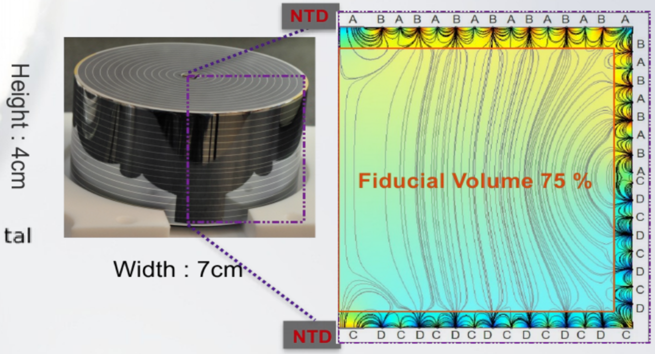
CDMS interleaved Z-sensitive Ionization Phonon (iZIP) detector

- 15 x 600g detectors
- 2 charge + 2 charge
- 4 + 4 TES – fast phonon channel



EDELWEISS FID800

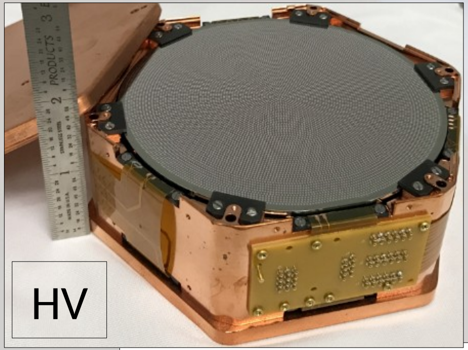
- 36 x 800 g detectors
- 2 charge + 2 charge
- 2 NTD – simple phonon channel

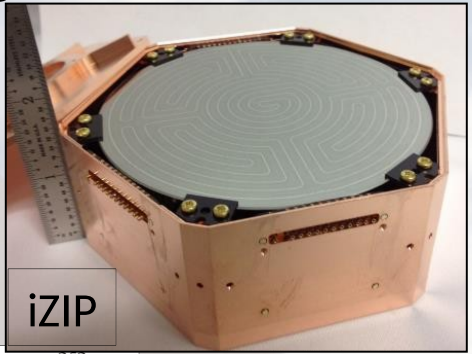


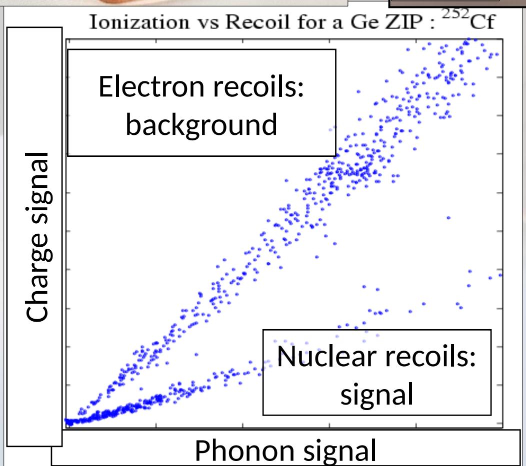
- Cryogenic temperatures (20-50mK)
- Discrimination of e/γ- events via ionization yield
- Low threshold (sub keV)
- Surface events identified thanks to ID electrodes

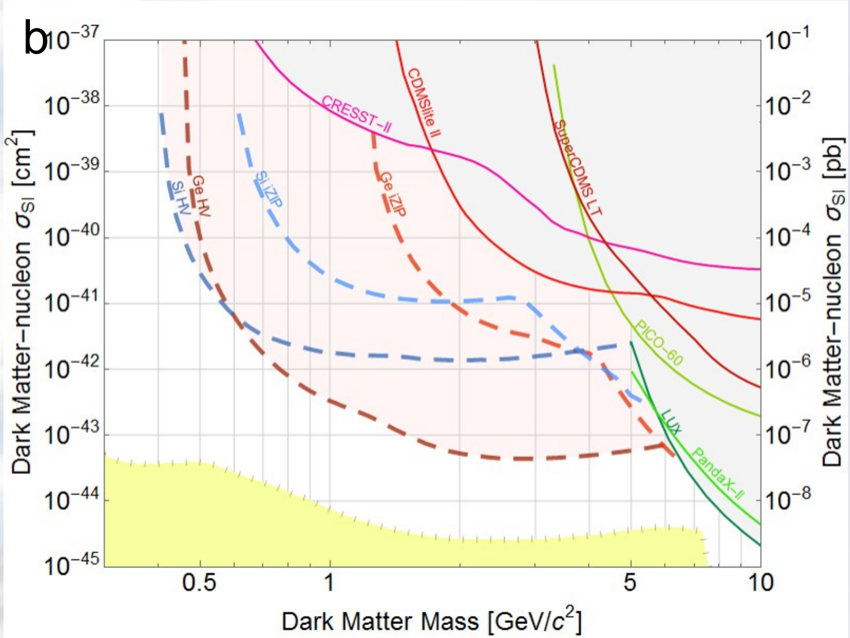
SuperCDMS

- Ge and Si crystals at 10s of mK – using TES for phonons, plus ionization
- The old-time leader, re-invented to lead in the low mass range
- Will start data taking 2020 @SNOLAB







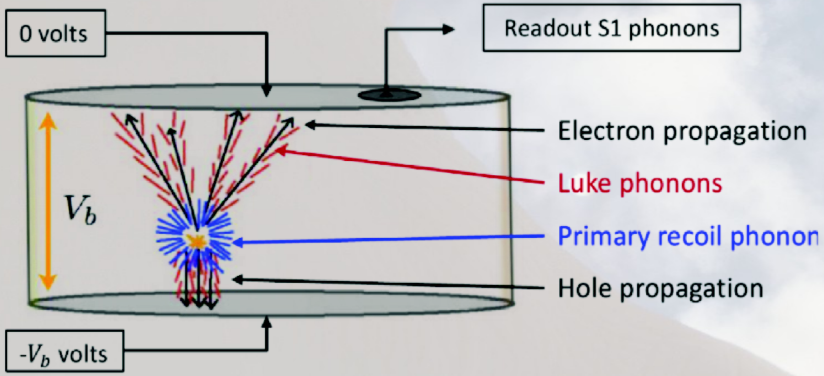


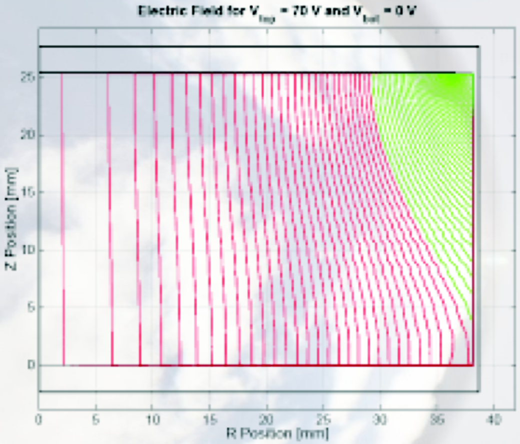
R. Budnik, ISAPP 2019

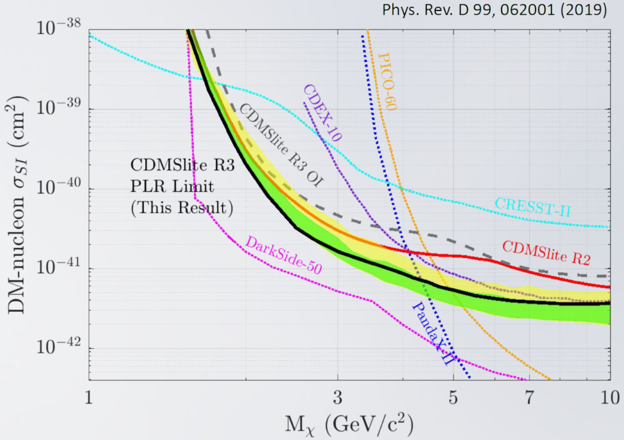
CDMSLite – Aggressively lowering the threshold

Lite/HV-mode

Charge mediated phonon amplification (Neganov-Trofimov-Luke Effect)





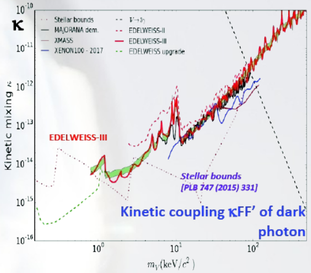


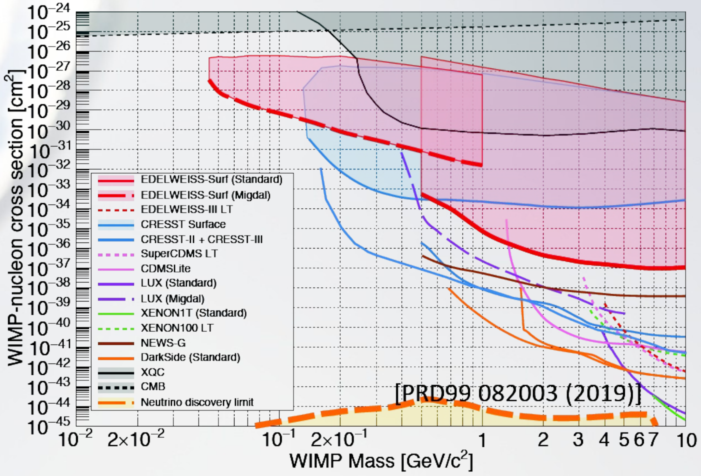
- Drifting charges produce large phonon signal proportional to ionization
- Electron recoils much more amplified than nuclear recoils
  - gain in threshold AND dilute background from electron recoil events

NTL effect mixes charge and phonon signal reducing discrimination Requires Lindhard Model to convert to nuclear recoil equivalent energy

EDELWEISS STATUS AND PLANS

- **EDELWEISS-III: operation of largest mass of cryogenic Ge (30 kg) for DM searches**
  - Cumulated exposure (2014-2015): 8 kg.y
  - Excellent ID of nuclear recoils and surface events [JINST12 P08010 (2017)]
  - DM searches involving nuclear recoils [EPJC 76 (2016) 548] or electron recoils [PRD 98 082004 (2018)]
- **Prospects in the sub-GeV-WIMP range:**
  - Limited potential of 860g units in this domain. [PRD 97 022003 (2018)].
  - Sub-GeV goal: keep rejection capabilities → 33g units, resolutions 10 eV phonon, 20 eV_{ee} charge
- **2018 surface run with a 33g prototype:**
  - 30x improvement in phonon resolution achieved: 18 eV phonon resolution + 60 eV recoil threshold
  - *Best surface limit for WIMPs above 0.6 GeV/c^2*
  - *Best surface neutron spin-dependent limits between 0.5 and 1.3 GeV/c^2*
  - *Limits using Migdal effect: best for 45-150 MeV/c^2*

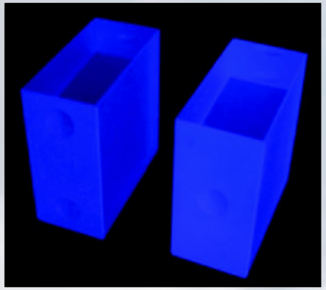


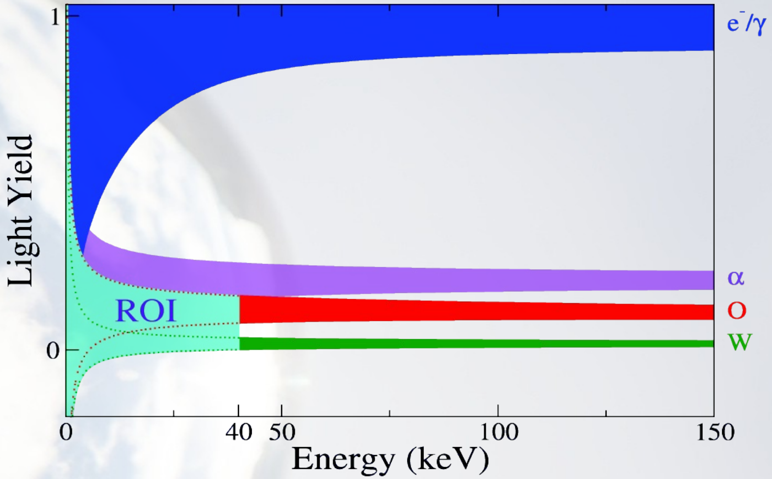


CRESST III – Scintillating Calorimeter

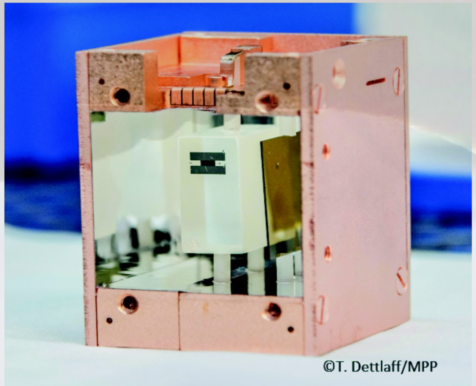
Phonon + Light

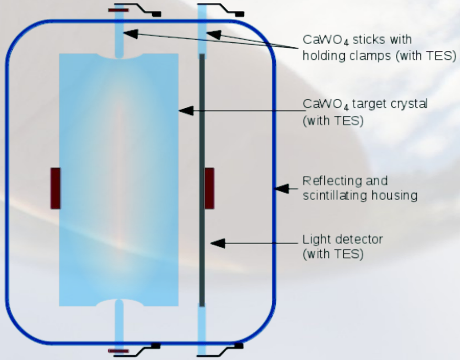
CRESST: Scintillating $CaWO_4$ crystals as target





- Target crystals operated as **cryogenic calorimeters** (~15mK)
- Separate **cryogenic light detector** to detect the scintillation light signal

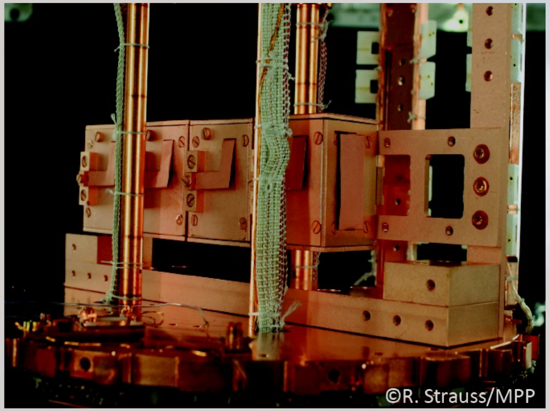


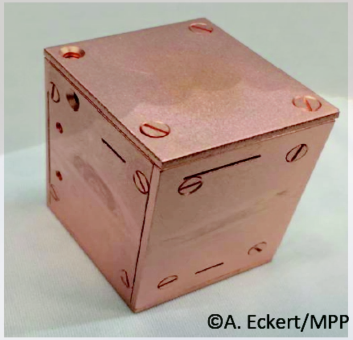


CRESST-III detector layout optimized for low-mass dark matter

CRESST III demonstrating record thresholds

First CRESST-III data taking from
May 2016 to February 2018

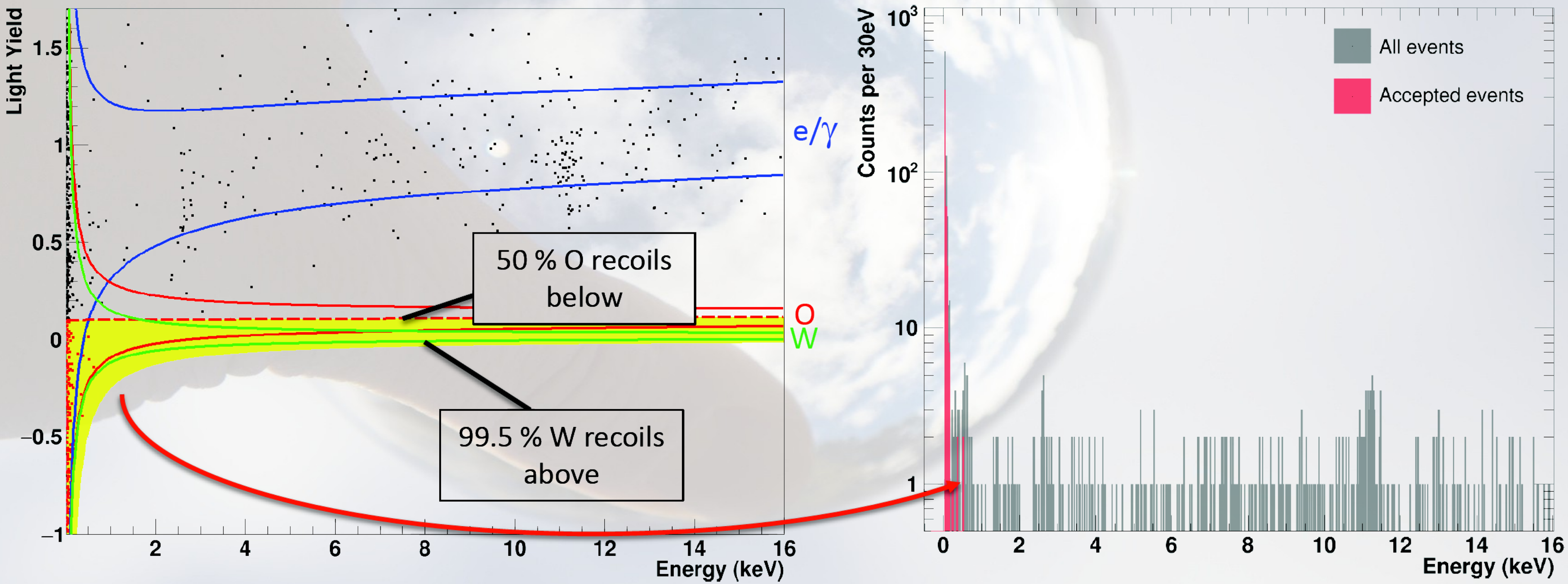




arXiv:1904.00498
One crystal of 23.6g
Nuclear recoil threshold of 30.1 eV
Resolution at zero energy σ = 4.5eV

CRESST III demonstrating record thresholds

Analysis optimized for very low energies: 30eV → 16keV

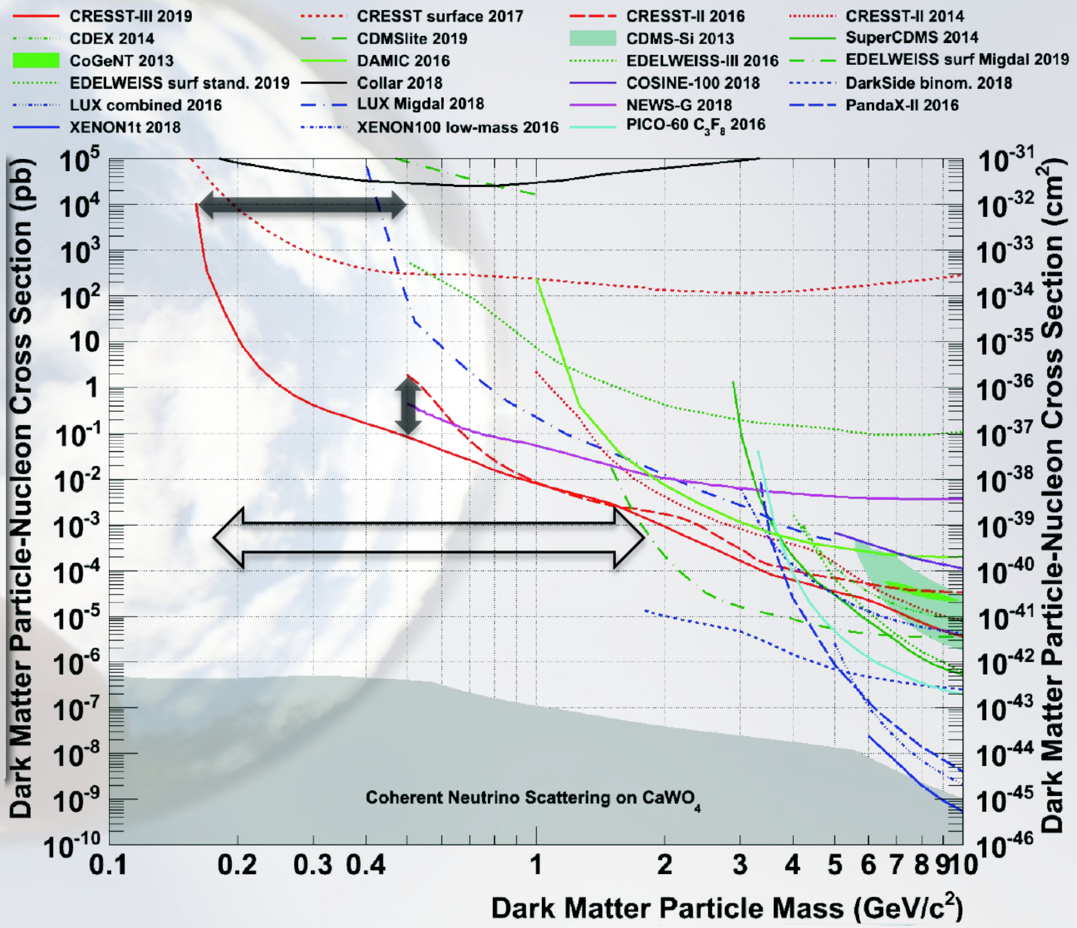


R. Budnik, ISAPP 2019

CRESST III results

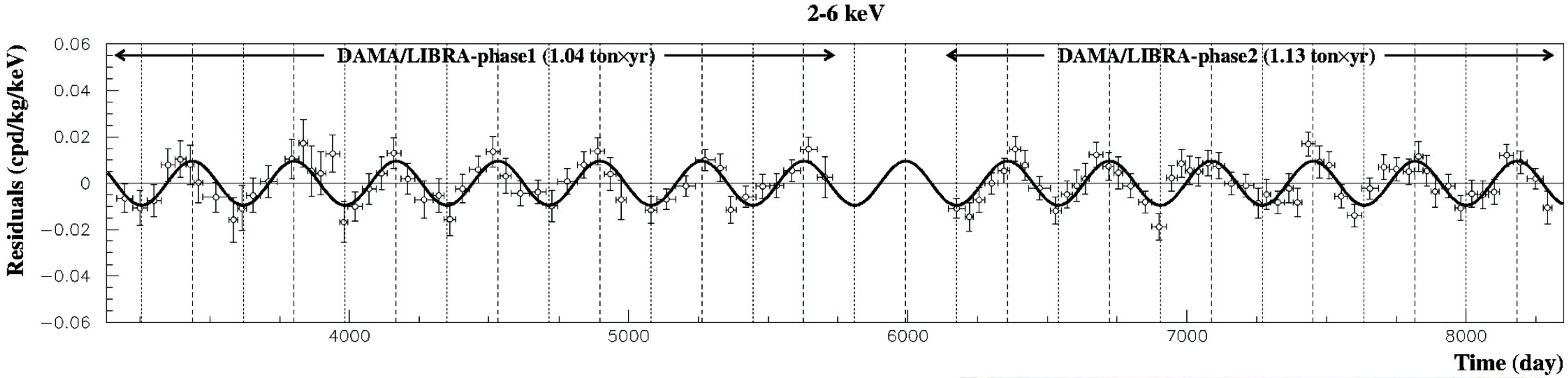
- Unexpected rise of event rate < 200eV
- Unprecedented low nuclear recoil threshold of 30.1eV
- More than one order of magnitude improvement at 0.5 GeV/c²
- Extended reach from 0.5GeV/c² to 0.16GeV/c²
- Leading sensitivity over one order of magnitude: 160MeV/c² → 1.8GeV/c²

+Upgrade for 2020!



DAMA/LIBRA – Still unanswered?

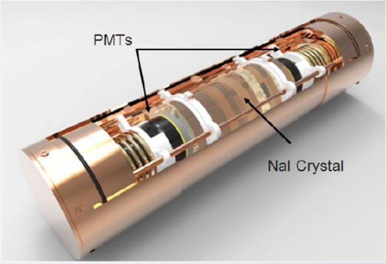
Experimental residuals of the single-hit scintillation events rate vs. time and energy

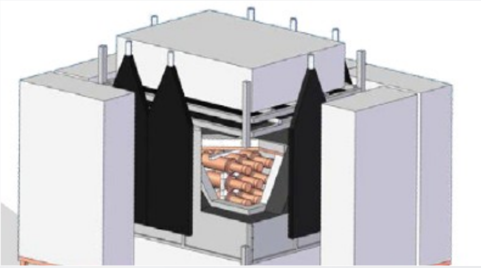


- 250kg of NaI(Ti) with PMTs (scintillation light)
- DAMA/LIBRA Phase 1 + 2 : 2.17 tonne years
- Statistical significance: 11.9σ
- Model independent
- Modulation evident in the lowest energy bins
- Excluded by other DM searches

Can someone finally solve the DAMA/LIBRA conundrum?

- Can we resolve a two decade old puzzle of disagreement with so many experiments?
  - SABRE
  - ANAIS
  - DM-ICE
  - PICOLON
  - COSINE-100
  - COSINUS





- Efforts should yield an answer is a few years…

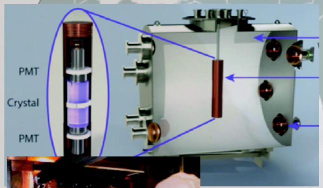
DAMA/LIBRA Yay or Nay around the world

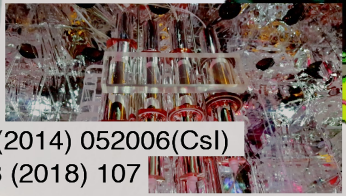
DAMA

SABRE

COSINUS

★ Gran Sasso + Australia



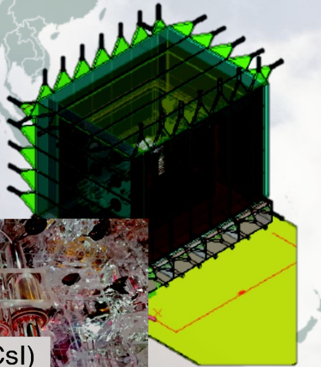


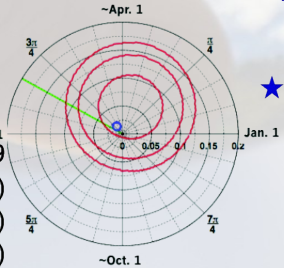
Phys.Rev. D **90** (2014) 052006(CsI)
Eur.Phys.J. C **78** (2018) 107
Eur.Phys.J. C **78** (2018) 490
Nature **564**, 83 (2018)

KIMS (+ DM-Ice)

COSINE-100

★ Yangyang ★ Kamioka



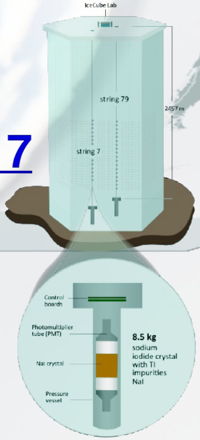


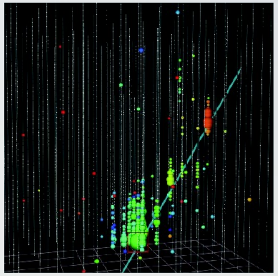
Astropart. Phys. **35** (2012) 749
Phys. Rev. D **90** 092005 (2014)
Phys. Rev. D **93** 042001 (2016)
Phys. Rev. D **95** 032006 (2017)

PICOLON

DM-Ice17

★ South Pole

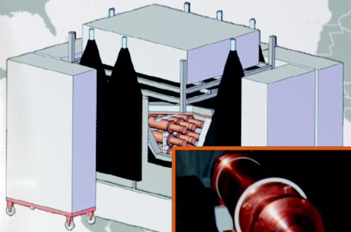




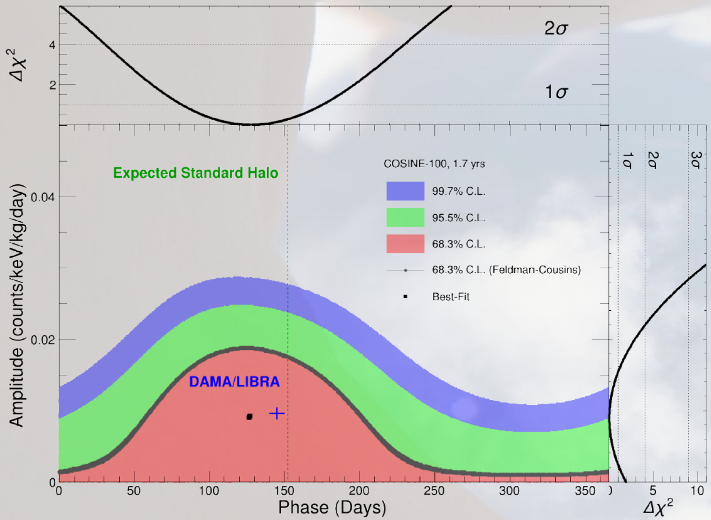
ANAIS

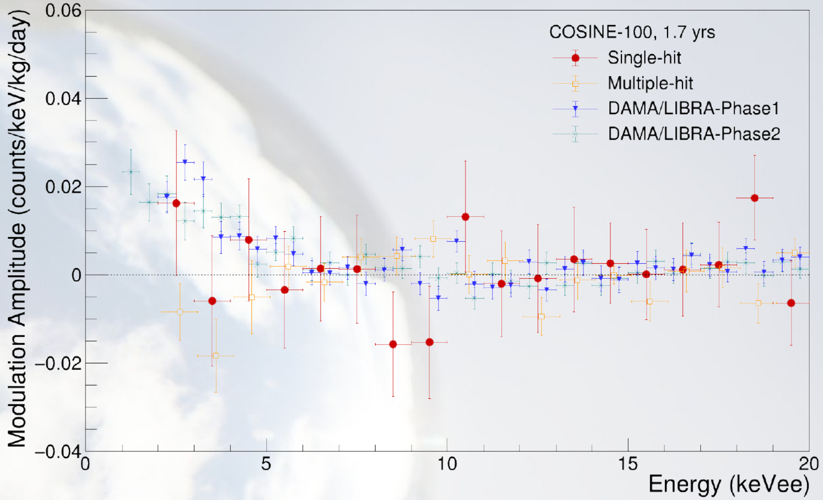
★ Boulby

★ Canfranc



COSINE-100 First results – caution!





Configuration	χ^2	*d.o.f.*	p-value	Amplitude (counts/keV/kg/day)	Phase (Days)
COSINE-100	175.3	174	0.457	0.0092±0.0067	127.2±45.9
DAMA/LIBRA (Phase1+Phase2)	–	–	–	0.0096±0.0008	145±5
COSINE-100	175.6	175	0.473	0.0083±0.0068	152.5 (fixed)
COSINE-100 (Without LS)	194.7	175	0.143	0.0024±0.0071	152.5 (fixed)
ANAIS-112	48.0	53	0.67	-0.0044±0.0058	152.5 (fixed)
DAMA/LIBRA (Phase1+Phase2)	71.8	101	0.988	0.0095±0.0008	152.5 (fixed)

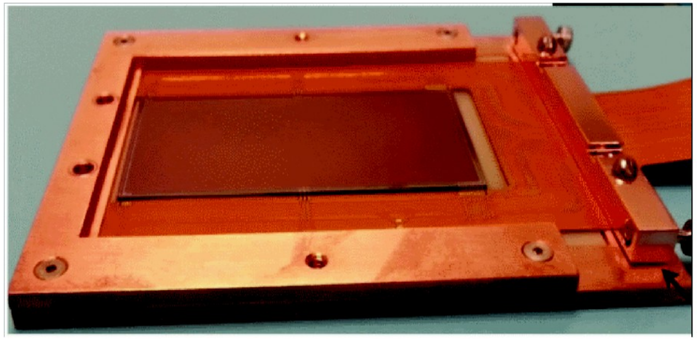
Best fit amplitude and phase for 2–6 keV:

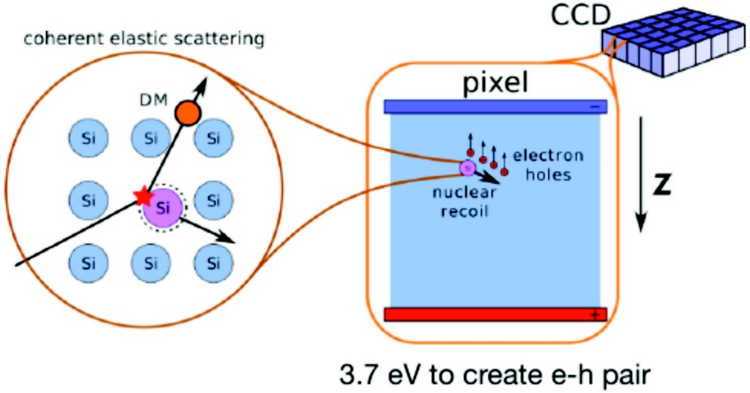
- 0.0092 ± 0.0067 cpd/kg/keV
- 127.2 ± 45.9 days

Result is consistent with both the null hypothesis and DAMA/LIBRA's best fit value.

DAMIC

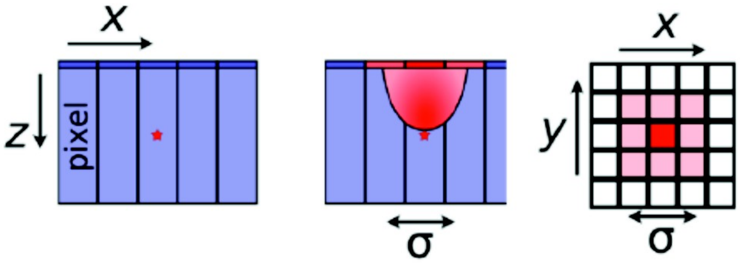
- Silicon ionization device with pixel arrays, much like off the shelf cameras (16 Mpx CCDs)
- 40 g detector commissioned in 2017



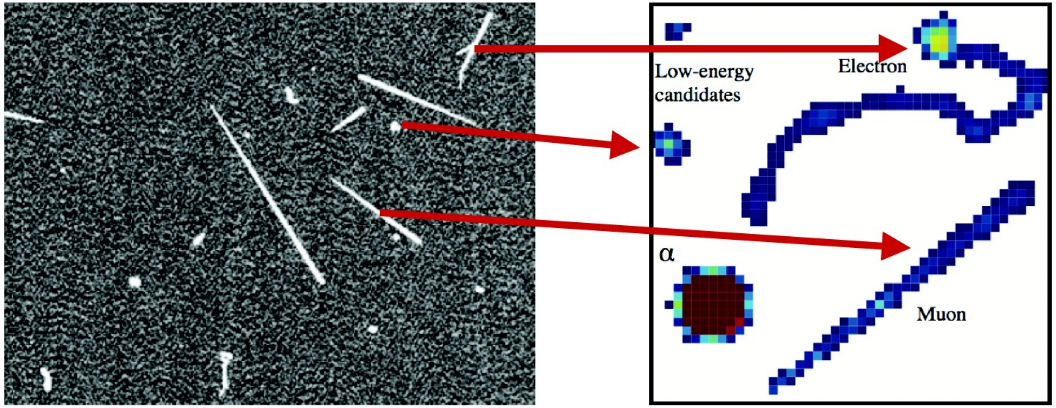


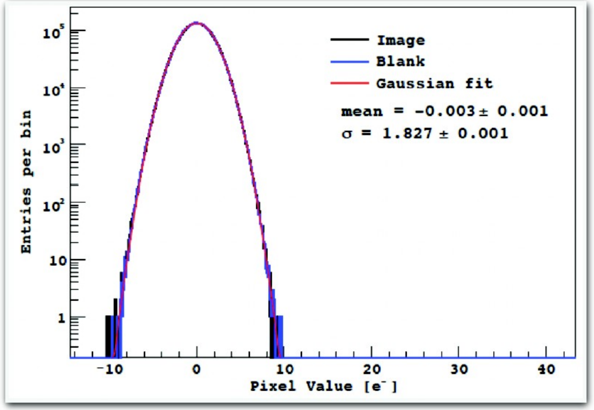
- Detection of point-like energy deposits induced by particle interactions in bulk of detector

- 3D reconstruction (x,y,z) and unique spatial resolution.



DAMIC





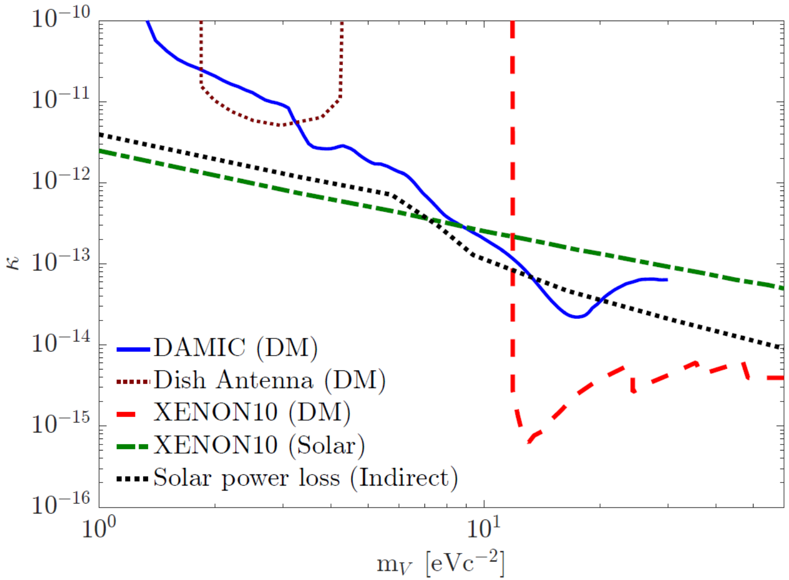
- Powerful ability to "image" particles and discriminate interactions
- Lowest ever measured dark current (~thermal excitations) in a Si detector:
  - <0.001 e-/pix/day (@ 140 K)
  - very low read out noise of ~1.6 e-

} allow a very low detection threshold of ~50 eVee

- Excellent sensitivity to light dark matter candidates!

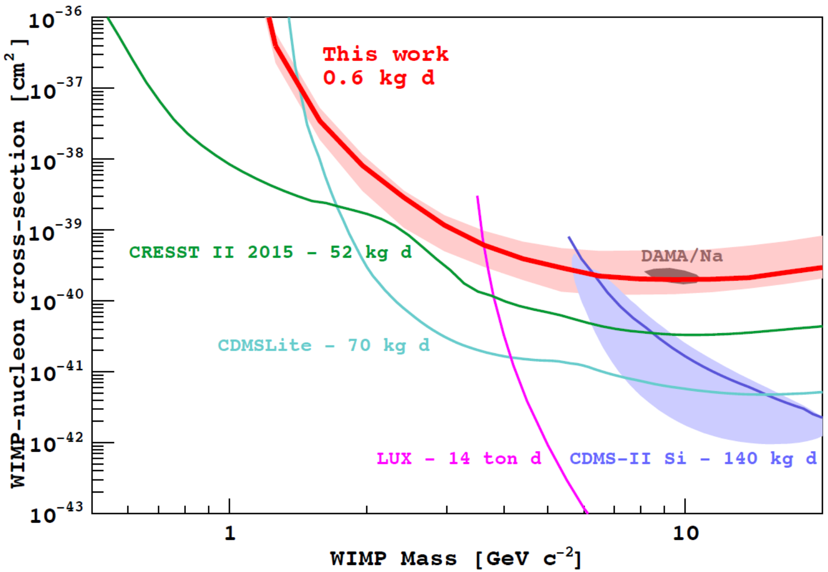
DAMIC results

Hidden Photons



Phys. Rev. Lett. 118, 141803 (2017)

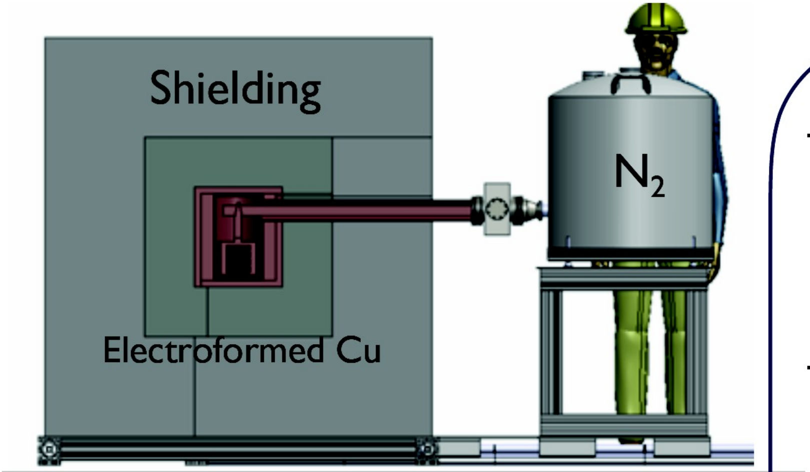
WIMP Dark Matter

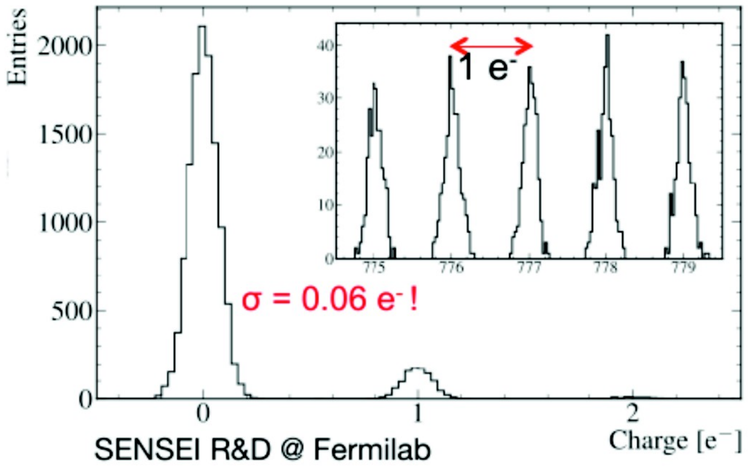


Phys. Rev. D 94, 082006 (2016)

- (90% C.L.) for the hidden-photon kinetic mixing $\varkappa$ as a function of hidden photon mass m_V.
- (90% C.L.) for WIMP dark matter using a likelihood analysis.

DAMIC-M @ Modane – the future





- A kg sized detector at LSM (Laboratorie Souterrain de Modane)
- Largest CCDs ever constructed
  - 36 M pixels, 20 g each
  - 50 CCDs
- Single e- counting (sub-electron noise resolution)
- Commissioning in 2023

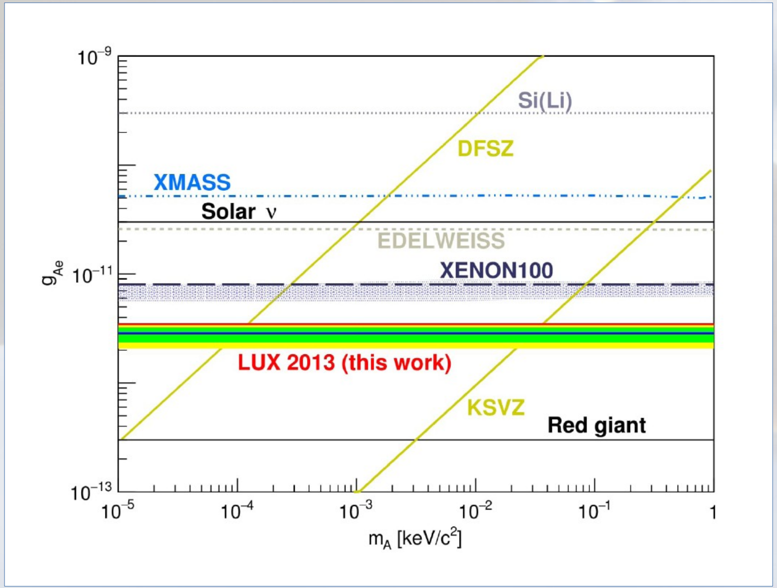
Things we did not cover

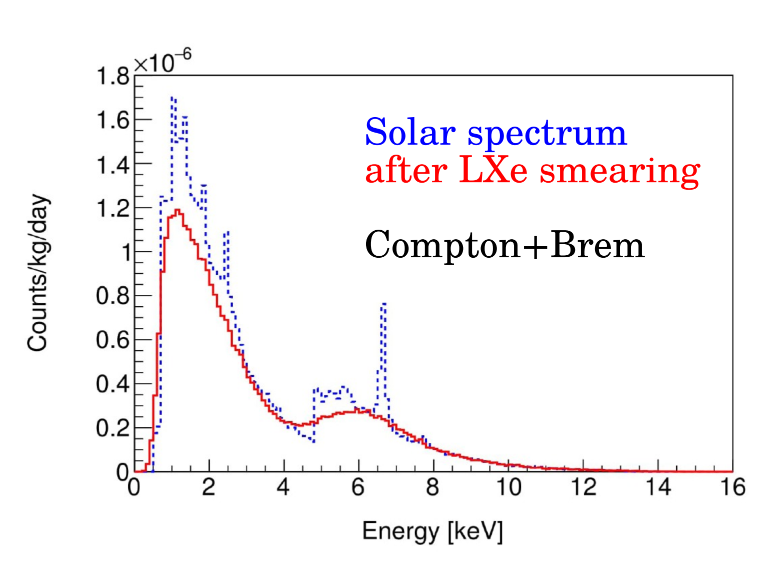
- Effective Field Theories (EFT) interpretation
- "Paleo" detectors
- Single channel Ge, Si detectors
- R&D for future LDM experiments
- Up-scattering of LDM in the Sun/halo/Crs
- Indirect searches through neutrinos
- "double scatter" DM
- And more…

Axions – Solar/ALPs with DD

- Axion or Galactic Axion-Like-Particles (ALPs) can be searched for in the ER data of DM experiments
- The search is for absorption through the "axio-electric" effect
- Limited range, coping with keV scale signals

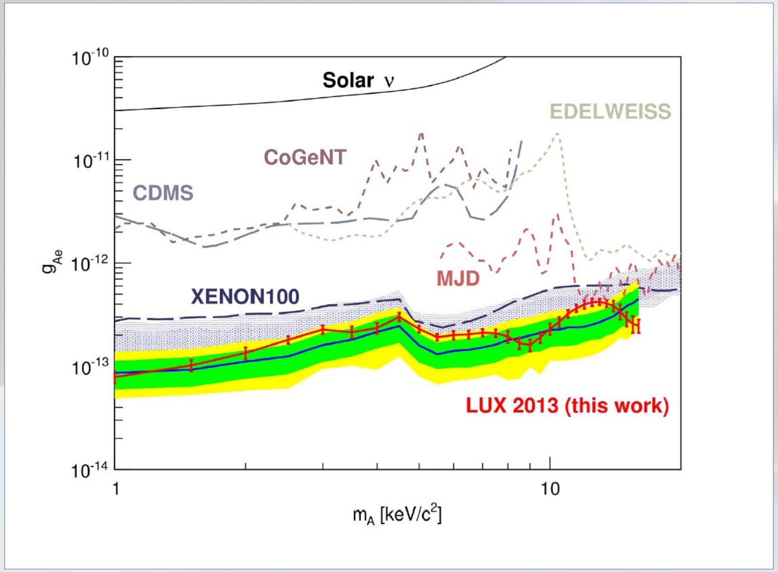
$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1-\frac{\beta_A^{2/3}}{3}\right)$$





ALP search with DD experiments

- ALPs move non-relativistically, hence the energy comes from the absorption of the rest mass – searches are for keV range of masses
- Cross sections change significantly, following the photoeletric effect



$$\frac{dN}{dE} = \sigma_{Ae} \cdot \frac{d\Phi}{dE}$$

Axion makes the whole of dark matter (ρ = 0.3 GeV/cm^3) => $\Phi = \rho\, v_A/M_A = 9 \times 10^{15}\, \beta_A$

$$\frac{evt}{kg \cdot day \cdot E} = \sigma_{Ae} \cdot (\frac{1.29 \times 10^{19}}{A}) \cdot g_{Ae}^2 \cdot M_A$$

$$g_{Ae} \sim (\frac{dN}{Exposure})^{1/4}$$

Axions as cold dark matter

Density

$$\Omega_a \sim \left(\frac{10^{-5}\ \mathrm{eV}}{m_a}\right)^{\frac{7}{6}} \alpha(t_1)^2$$

Velocity dispersion

$$\delta v_a(t_0) \sim 3 \cdot 10^{-17} c \left(\frac{10^{-5}\ \mathrm{eV}}{m_a}\right)^{\frac{5}{6}}$$

Effective temperature

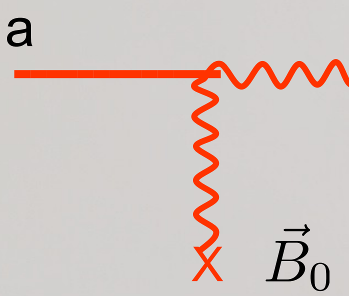
$$T_{a,\mathrm{eff}}(t_0) \sim 10^{-34}\ \mathrm{K} \left(\frac{10^{-5}\ \mathrm{eV}}{m_a}\right)^{\frac{2}{3}}$$

Axion Search Techniques

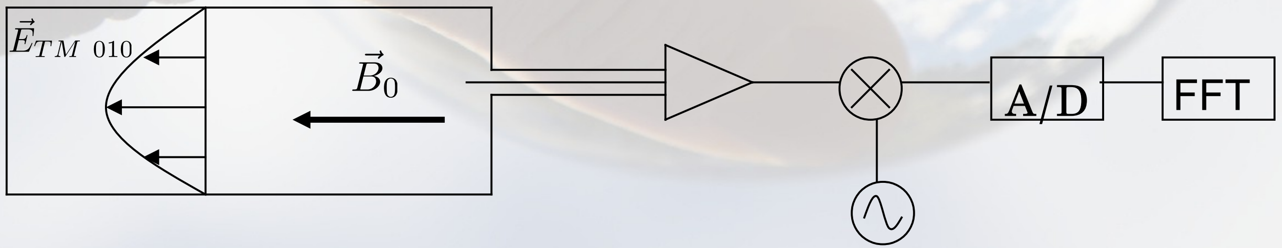
- the cavity haloscope
- the axion helioscope
- shining light through wall
- axion mediated long-range forces
- NMR methods
- LC circuit
- atomic transitions

(Taken from Sikivie, Daw)

Axion dark matter is detectable



$$\mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{a}{f_a} \vec{E} \cdot \vec{B}$$



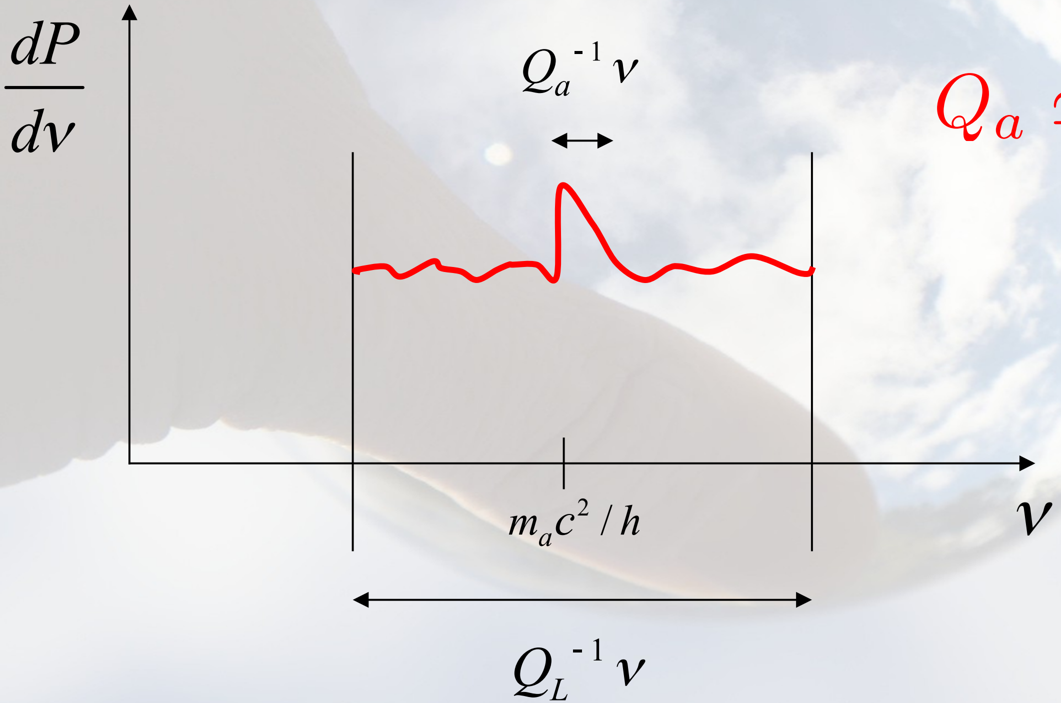
Sikivie '83

$$h\nu = m_a c^2 (1 + \frac{1}{2}\beta^2)$$

$$\beta = \frac{v}{c} \simeq 10^{-3}$$

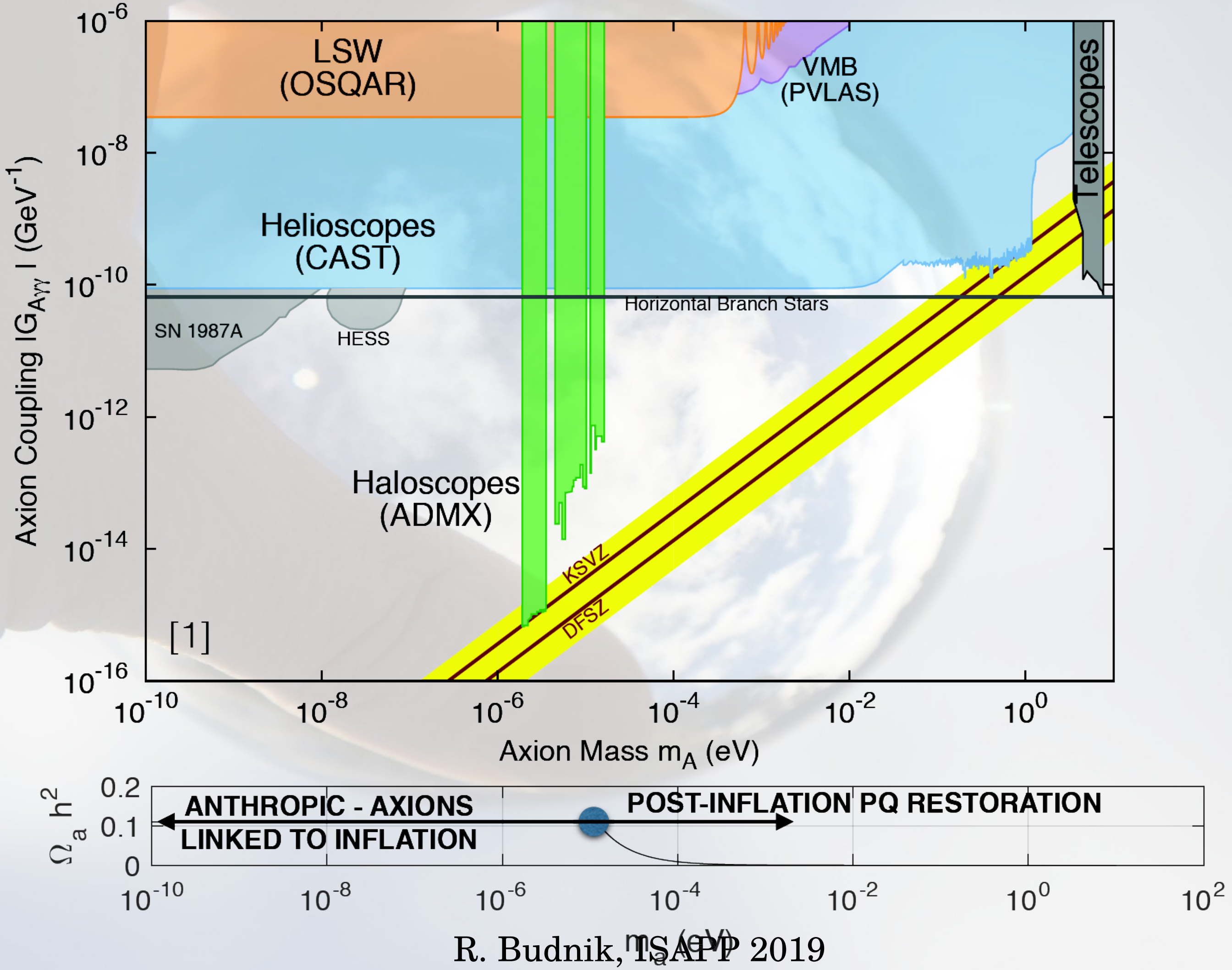
$$Q_a \simeq 10^6$$

Dispersion of axion energies



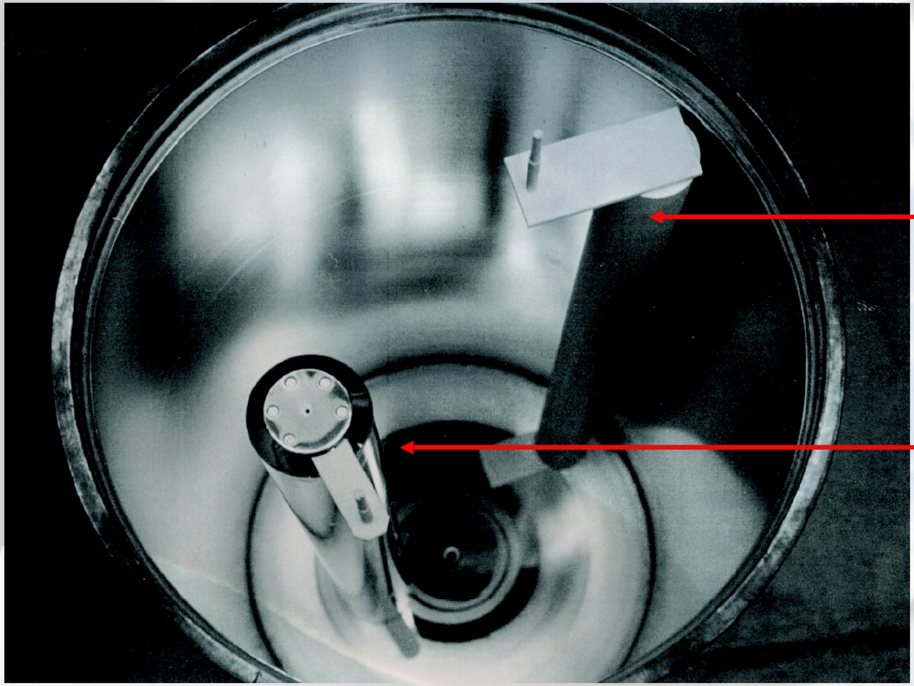
Cavity quality

$g_{a\gamma\gamma}$ vs. m_a parameter space



R. Budnik, TSAPP 2019

Resonant Cavity Detectors



50cm

alumina tuning rod

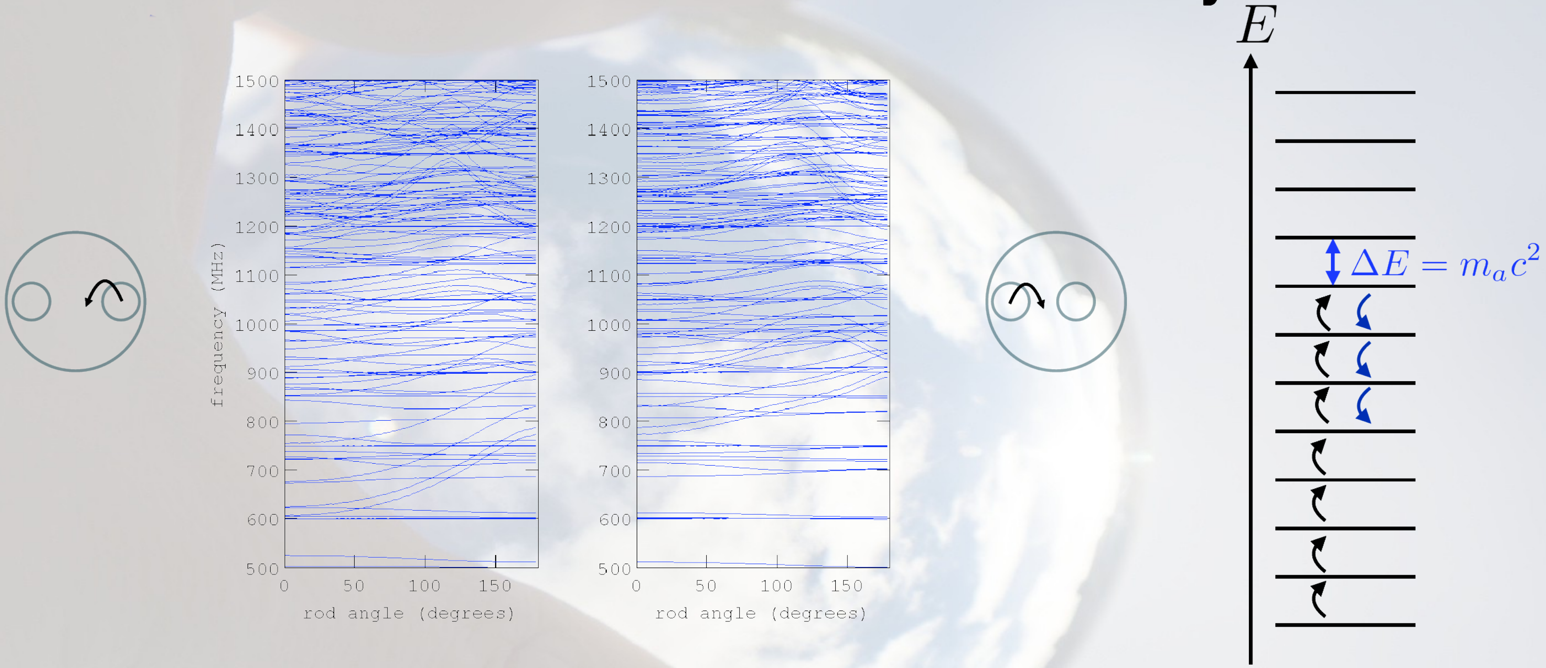
(a dielectric)

copper coated
stainless steel

(a metal)

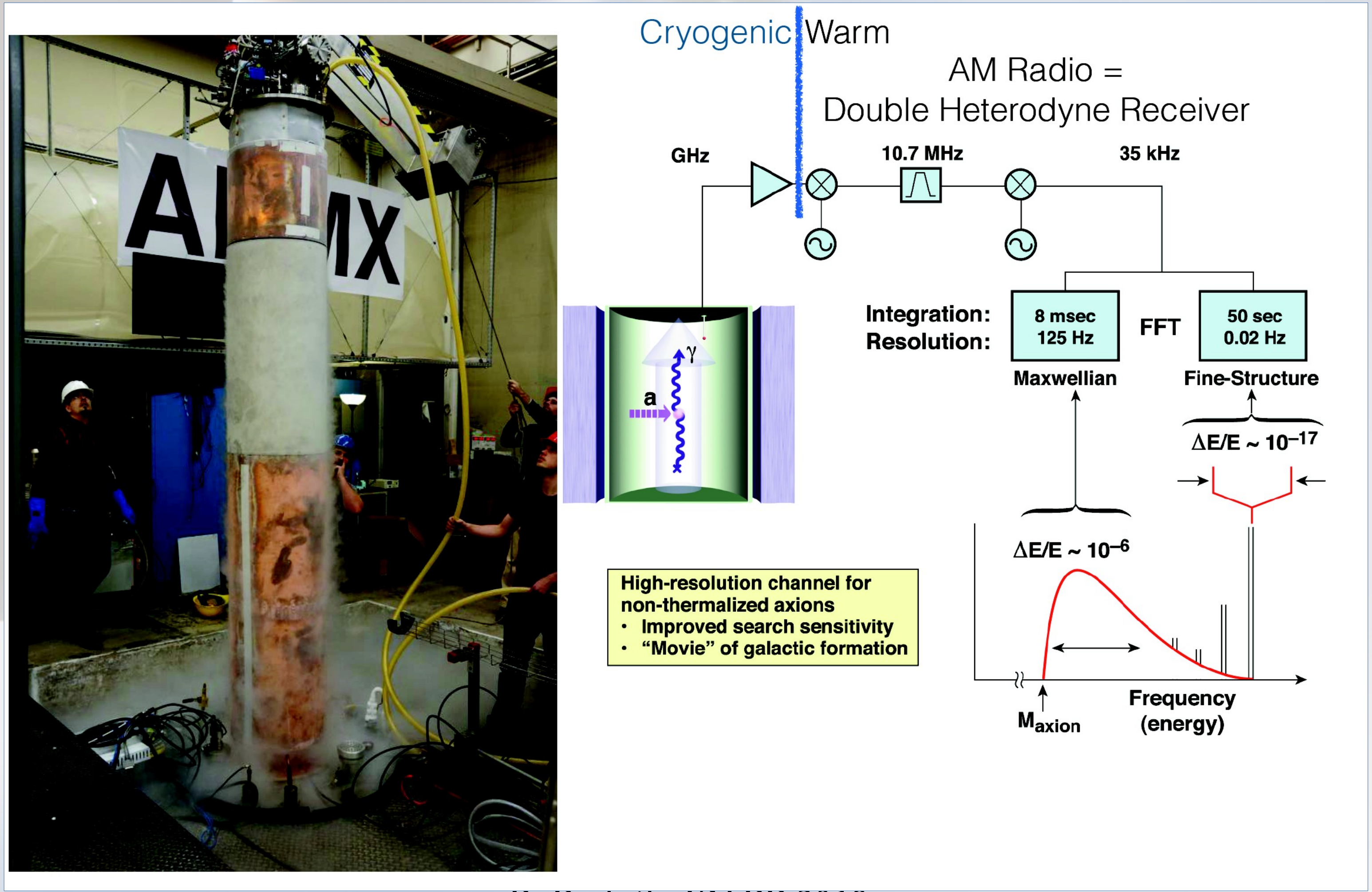
from above with lid removed.
Depth is 1m.

Modes of a Resonant Cavity

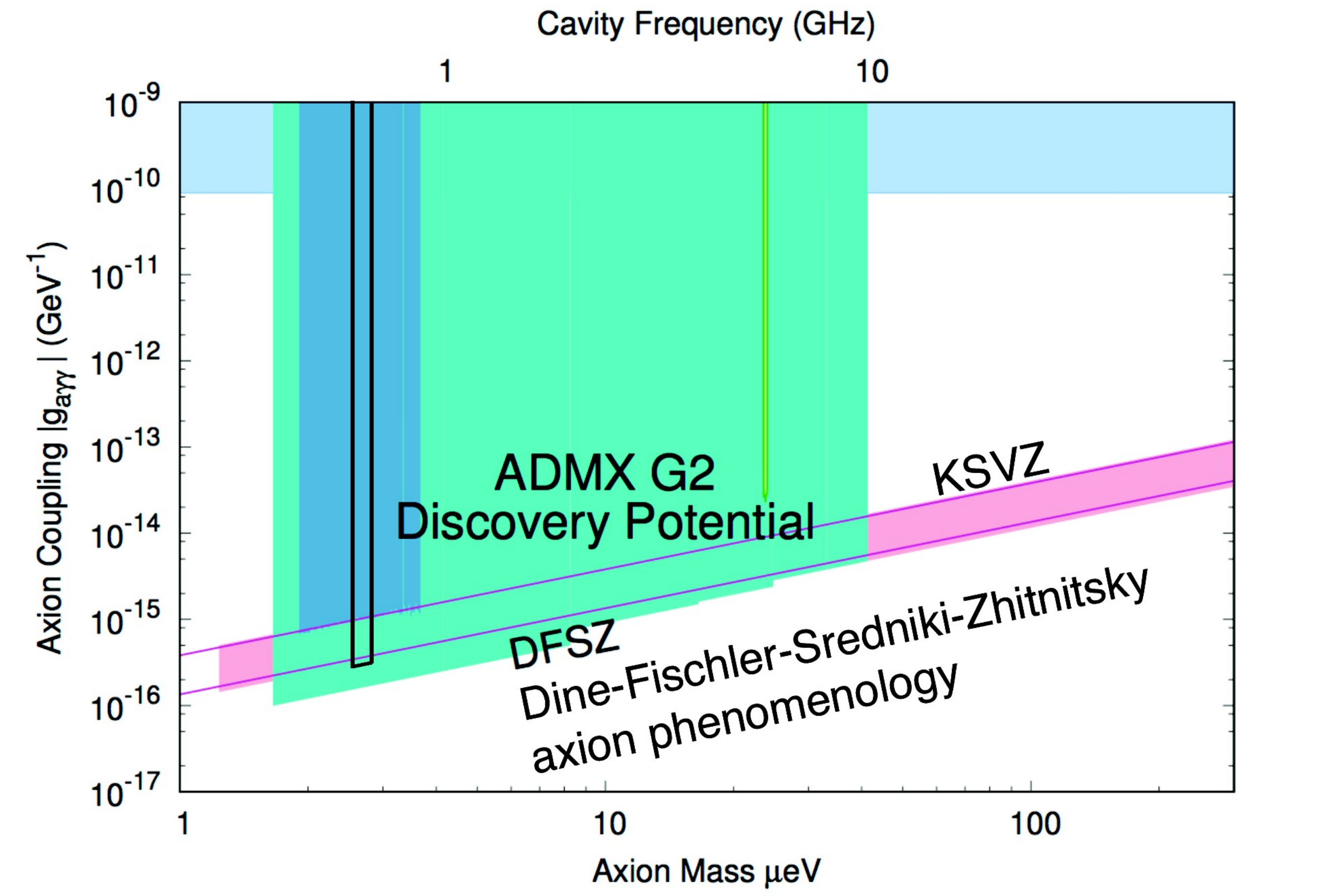


Incoming axions convert into quanta of excitation of TM modes of the cavity. Equilibrium between axion-stimulated excitation of the mode and spontaneous de-excitation due to thermal relaxation. Equilibrium population controlled by axion conversion rate, cavity Q

The ADMX experiment



ADMX G2 projected ensitivity



First Probe of sub-DFSZ coupling halo axions!

Better Amplifiers
Lower Noise
…

Quick Recap

- We went over concepts of DD for DM
- We have seen a pretty large list of projects, hopefully not confusing to a blurry level
- We even gave a few minutes to Axion Dark Matter Haloscopes
- Take home message:
  - **Dark Matter is out there, but out where?**