Direct Detection with Liquid Scintillation

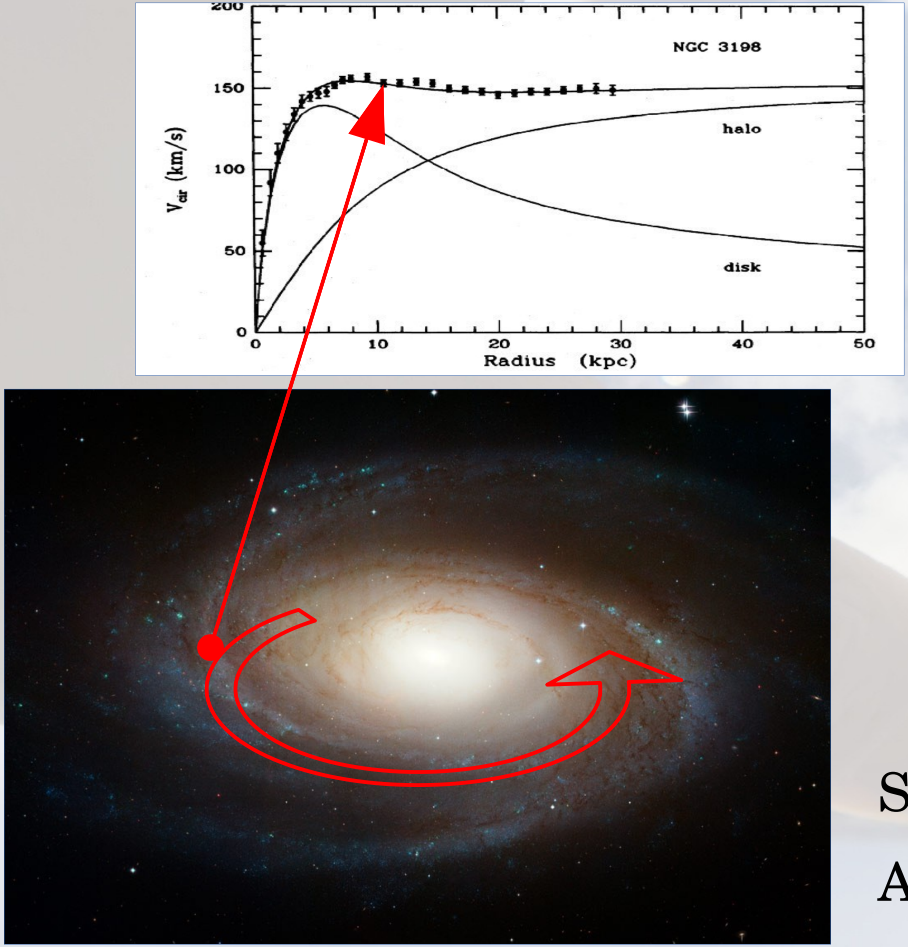
ISAPP 2021 - Vienna

Ranny Budnik

Department of Particle Physics and Astrophysics
Weizmann Institute of Science

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Direct Detection of Galactic DM



- Our Galaxy is rotating at ~200 km/s at the Sun's orbit
- DM is "standing still"
- Hence, there is a "constant" flux of DM through Earth
- Velocities are non-relativistic, $\beta \sim 10^{-3}$
- $\langle v^2_{DM} \rangle \approx v^2_{SUN}$ (or close to it)

Search for an interaction with the **nucleus**!

Almost all backgrounds interact with **electrons**

Principles of Direct Detection

- Movement with respect to the galactic frame implies DM flux,

$$\Phi \simeq 7.5 \times 10^4 \text{ particles/cm}^2\text{/sec}$$ (for ~100 GeV particle)

- DM recoils off a target material, leaving some energy in the form of:
  - Ionized electrons.
  - Scintillation light.
  - Heat/phonons.

Signal is collected and the recoil energy is extracted, in the **KeV range**.

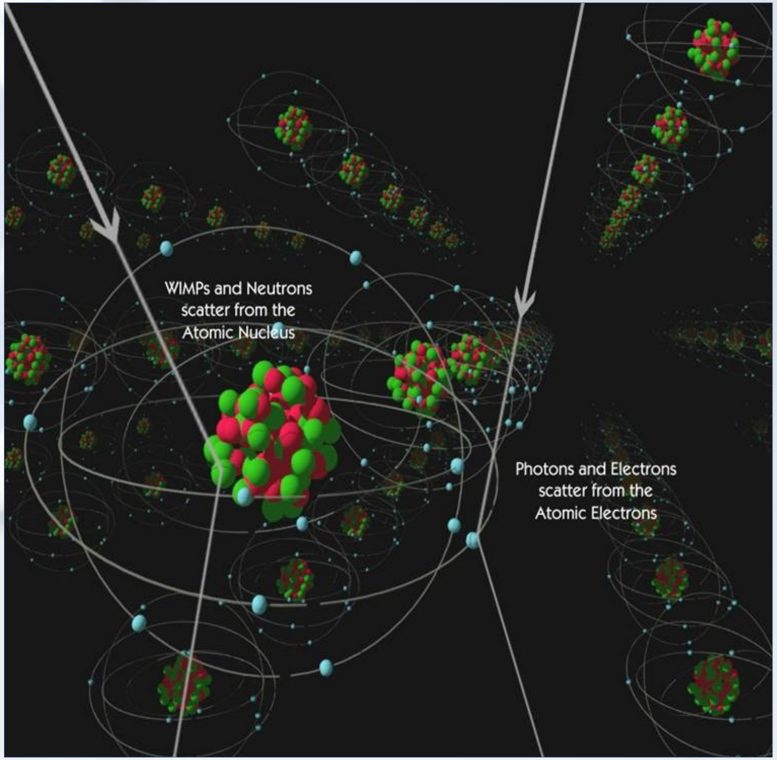
- A^2 enhancement for the simplest (SI) models

REVIEW D VOLUME 31, NUMBER 12

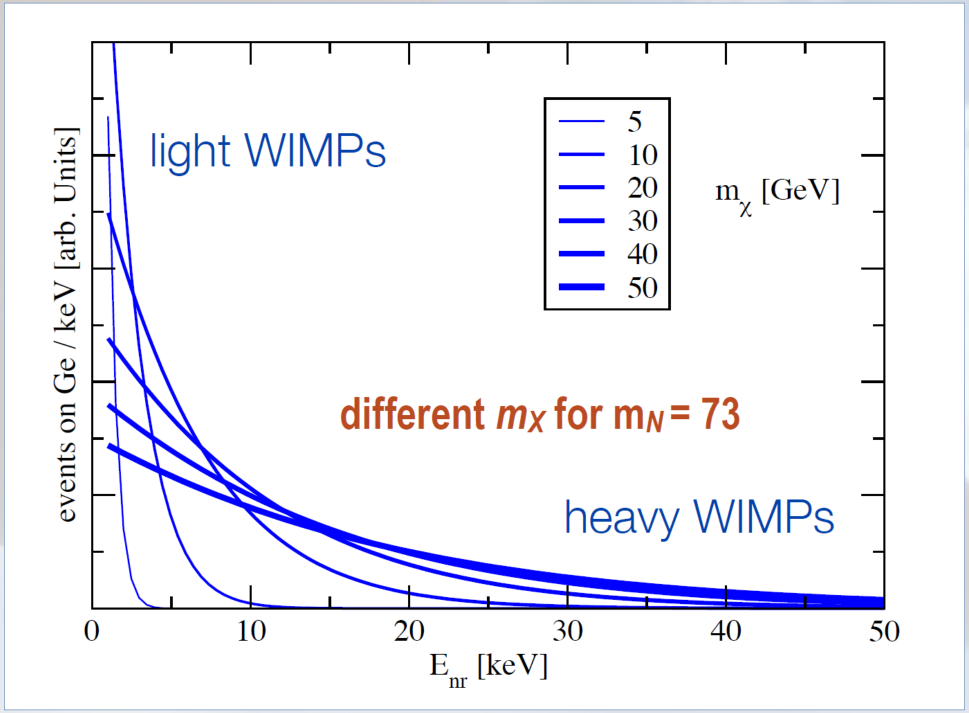
Detectability of certain dark-matter candidates

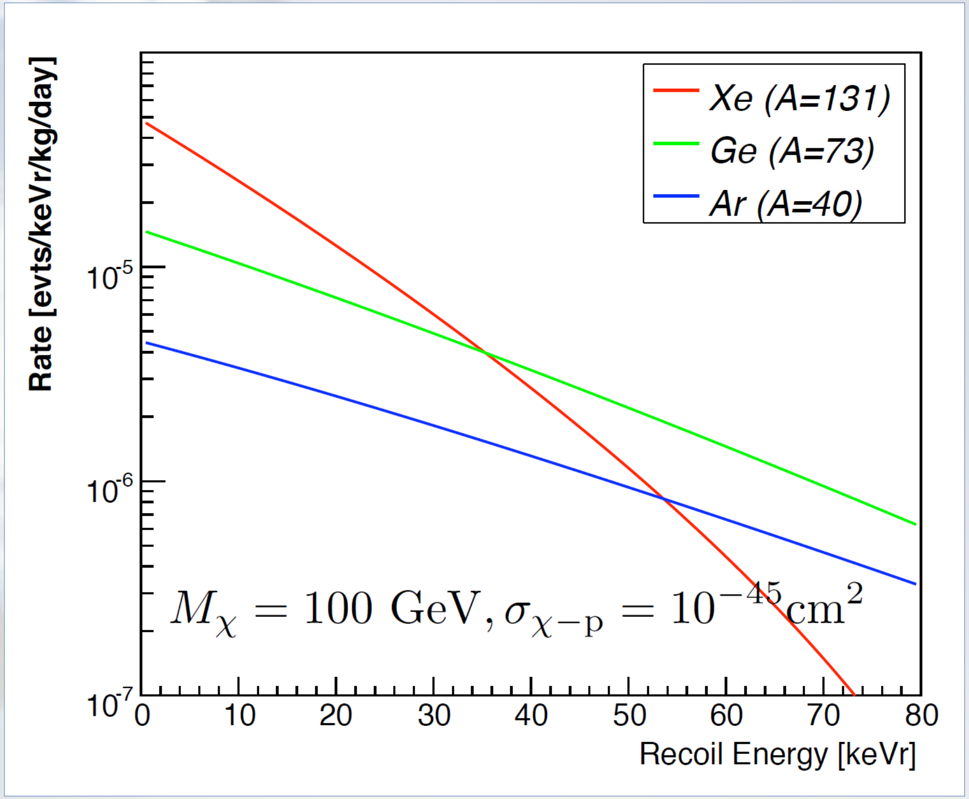
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.



Recoil Spectrum



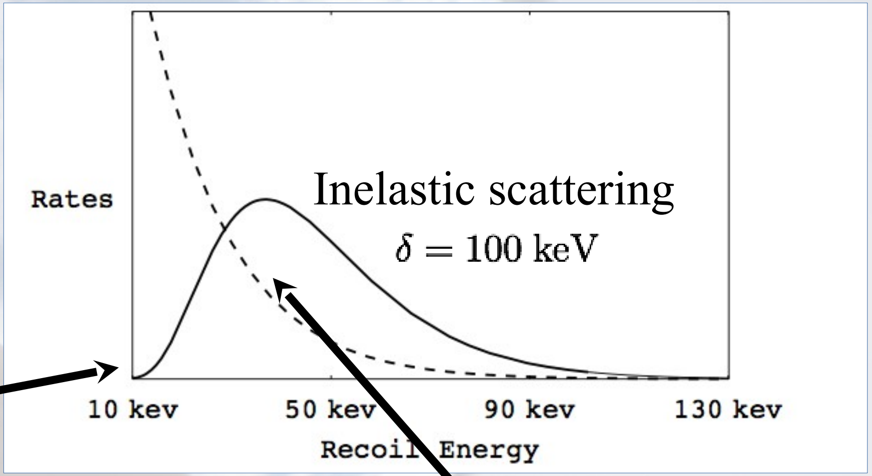


Recoil Energy Spectrum – beyond vanilla

- Exponentially falling for simple scenarios, however there are complications

Elastic scattering

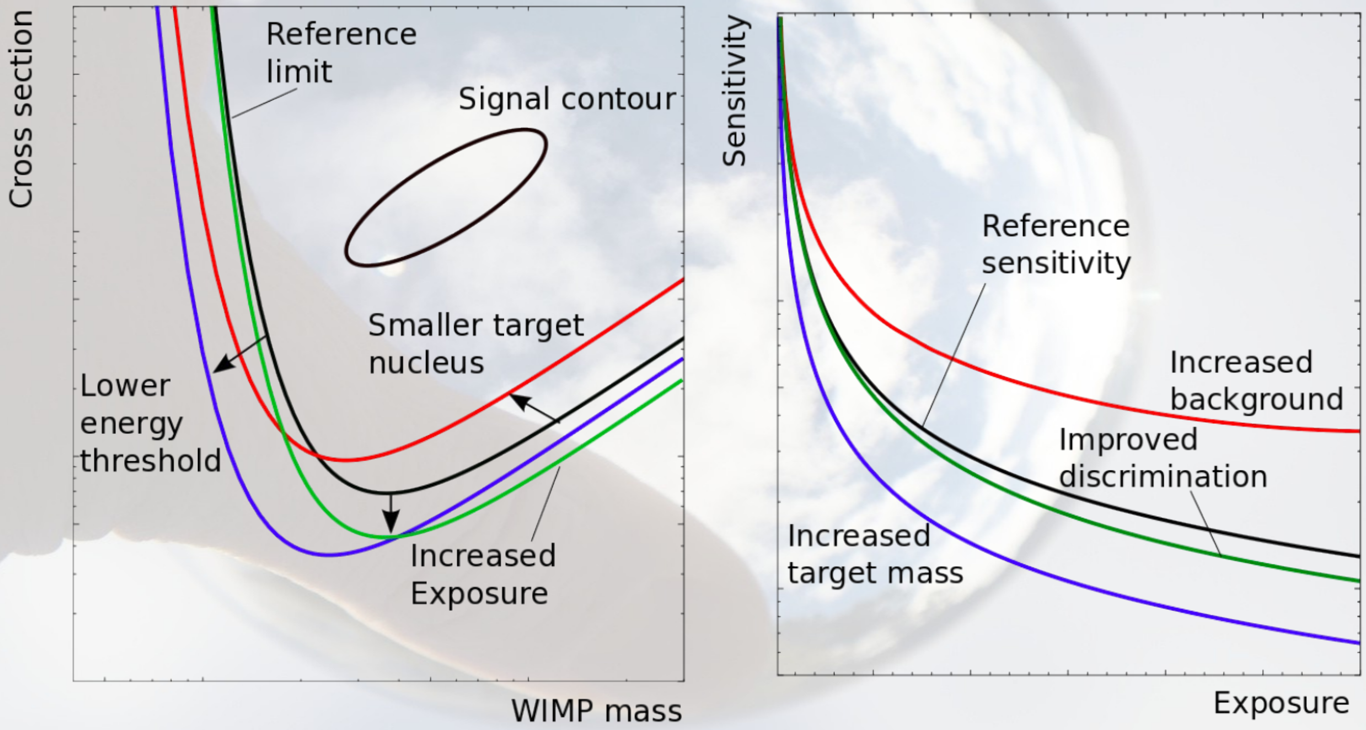
$$v_{\min} = \frac{1}{\sqrt{2 m_N E_R}} \left| \frac{m_N E_R}{\mu} + \delta \right| .$$



Drop at low energy for inelastic scattering

Exponential fall due to nucleus form-factor and velocity distribution

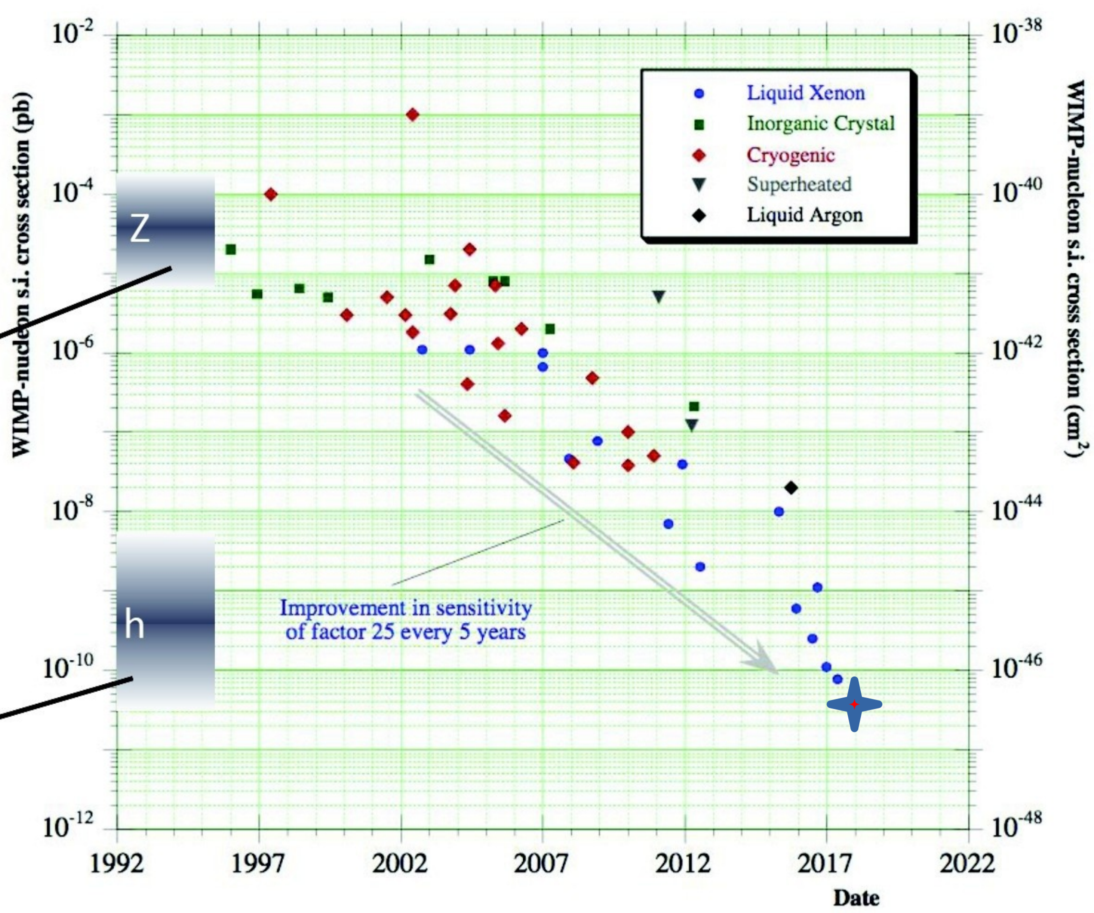
Exclusion/Discovery plots



J. Phys. G43 (2016) 1, 013001, 1509.08767

Fast progress over ~2 decades

- Direct detection sensitivities improving factor 25 every 5 years
- Already (1990's) excluded Z-mediated exchanges (e.g. heavy neutrinos)
- Now into higgs-mediated cross sections



After Gaitskell

Backgrounds in Dark Matter Detectors

- **Most problematic: muons and muon induced neutrons. MeV neutrons can mimic WIMPs**
- **Cosmic rays and secondary/tertiary particles: deep underground** laboratories
- **Hadronic component (n, p)**: reduced by few meter water equivalent (m.w.e.)

hadrons

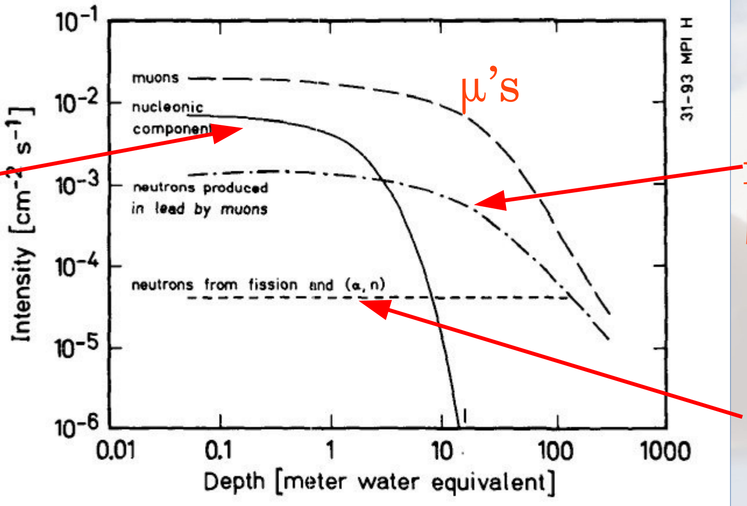


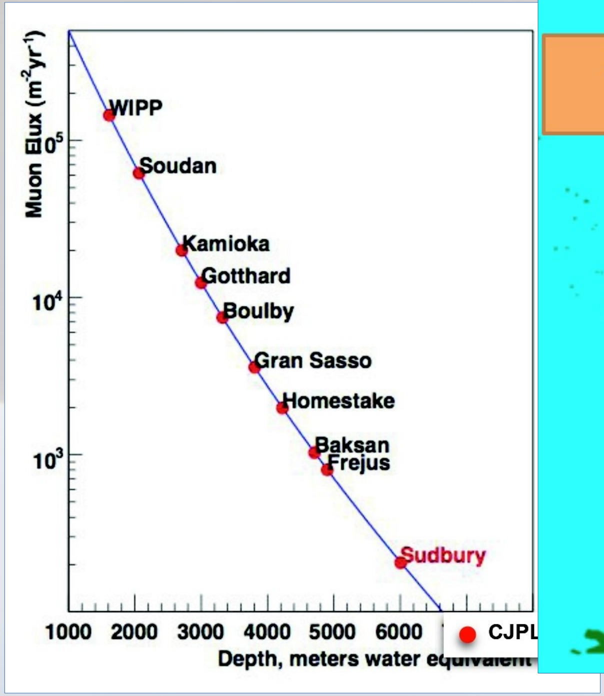
Figure 2 Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth. Neutron flux from natural fission and (α, n) reactions is also shown. The nucleonic component is more than 97% neutrons.

n produced by μ's

n produced by fission and (α,n)

Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth. Heusser, 1995

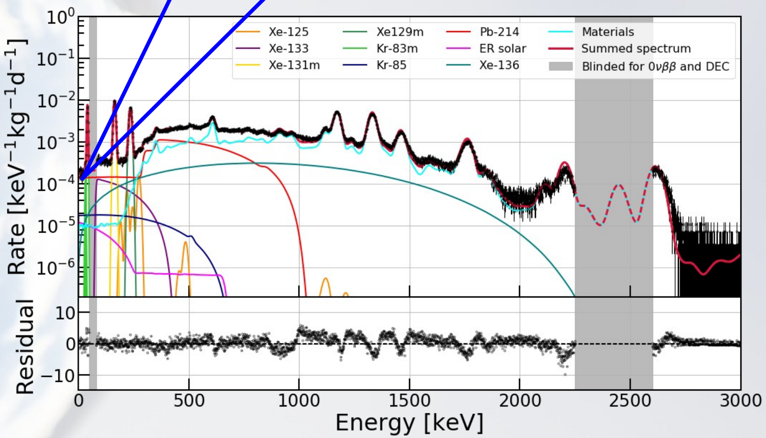
Underground facilities: A must



Fighting backgrounds - UG

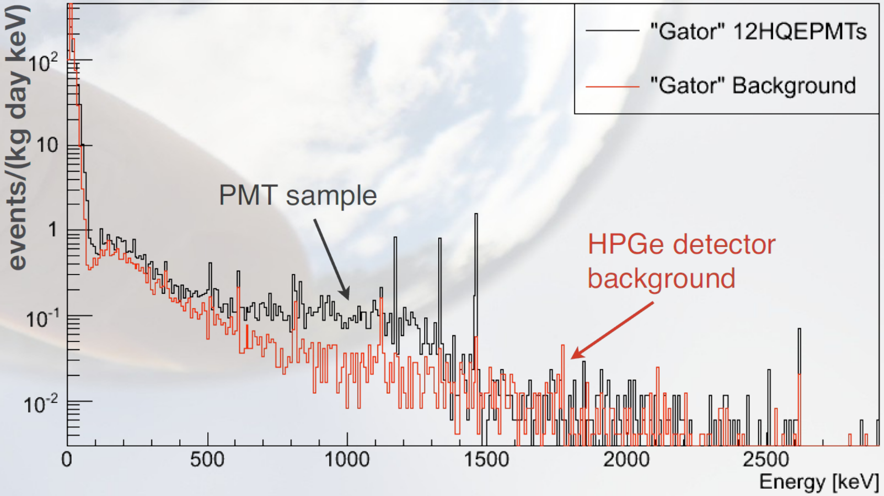
- External γ
  - Shielding and self shielding
  - Multiple scattering
  - Discrimination ER/NR
- Internal α, β
  - Cleaning, discrimination
- Neutrons: Fission, μ-generated, α-n
  - Multiple scattering, moderators, n-veto
- ν's: Solar and Atmospheric
- Plus, each detector carries extra unique backgrounds (instrumental, unknown source)

The least radioactive place in the known universe



Backgrounds – Internal EM

- Detector materials contain trace amounts of radioactive elements
- Usual suspects: ^{238}U, ^{232}Th, ^{40}K, ^{137}Cs, ^{60}Co, ^{39}Ar, ^{85}Kr, ^{222}Rn … decays in the detector materials, target medium and shields
- Ultra-pure Ge spectrometers (as well as other methods) are used to screen the materials before using them in a detector, down to parts-per-billion (ppb) (or lower) levels

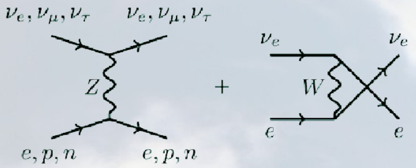


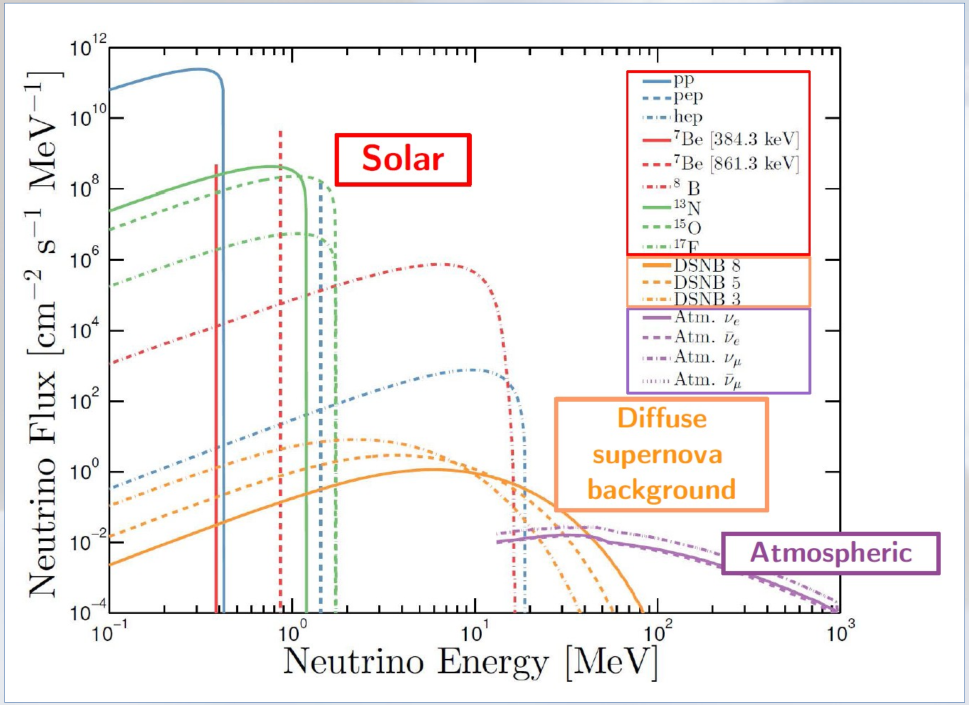
Backgrounds – Neutrons

- MeV+ neutrons mimic DM elastic scattering!
- Sources:
  - Cosmogenic – μ induced shower, high E neutrons
  - Radiogenic:
    - U, Th spontaneous fission
    - (α,n) from plate out of actinides on walls
- Solutions:
  - Shielding
  - Size (for multiple scattering)
  - Active neutron veto

Backgrounds – Neutrinos e⁻ recoil

$e^- + \nu \rightarrow e^- + \nu$



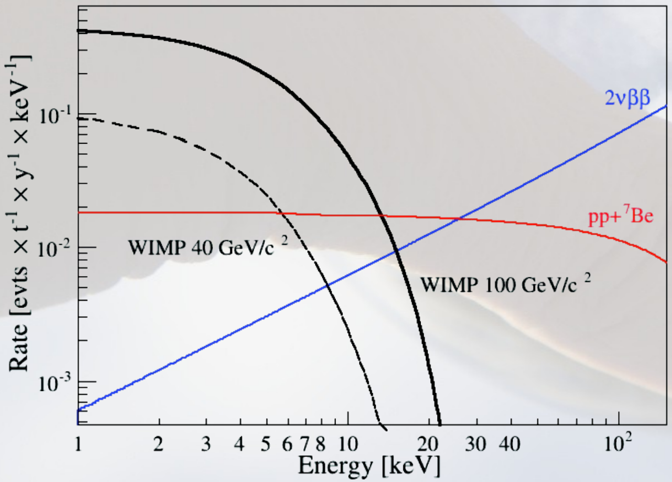


- Practically all neutrinos have enough energy to be relevant
- pp dominate in most scenarios
- “Irreducible” background – single scatter, homogeneous

Backgrounds – Neutrinos e⁻ recoil

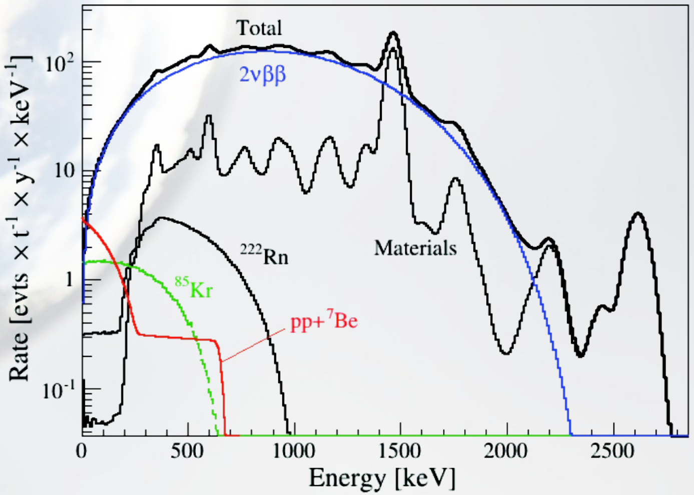
- Electron will recoil, producing a broad spectrum, uniform in the detector
- Some will pass the discrimination and look like signal!
- Taking LXe as an example

After discrimination (99.5%)



$$\nu + e^- \rightarrow \nu + e^-$$

Before discrimination

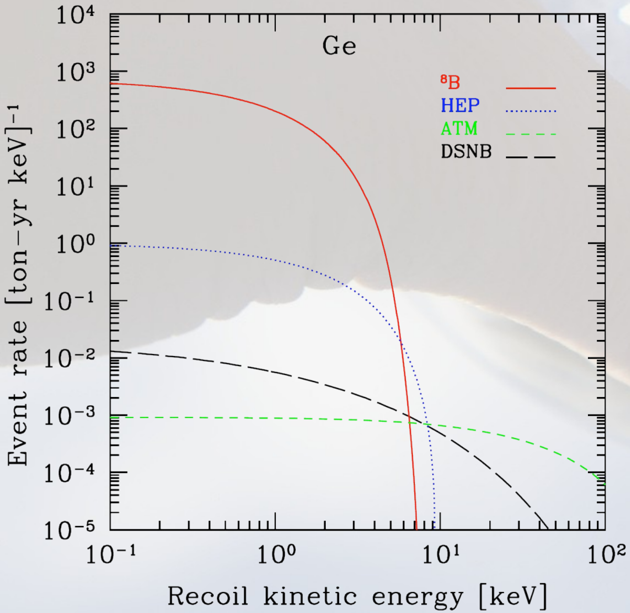


Baudis et. al., JCAP01 (2014) 044

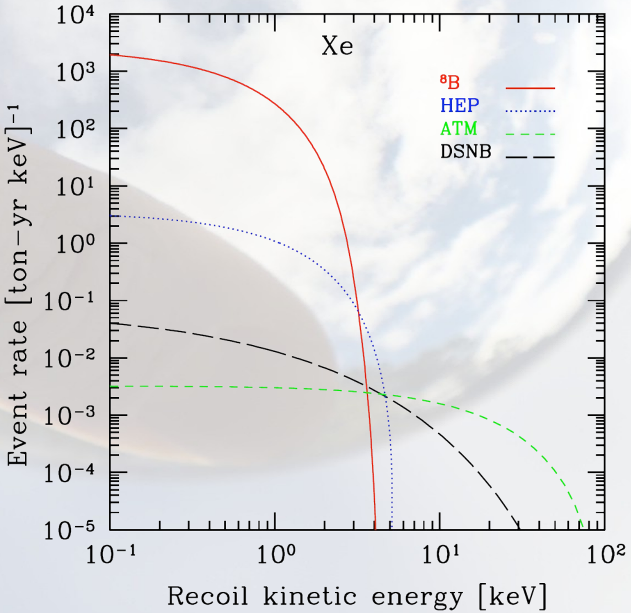
Backgrounds – Neutrino-Nucleus recoil

- ^{8}B dominate νs at low energy/low mass (<4 keV heavy targets, somewhat higher for light targets)
- DSNB and Atmospheric νs dominate at higher E, but still out of reach of current experiments

Germanium



Xenon



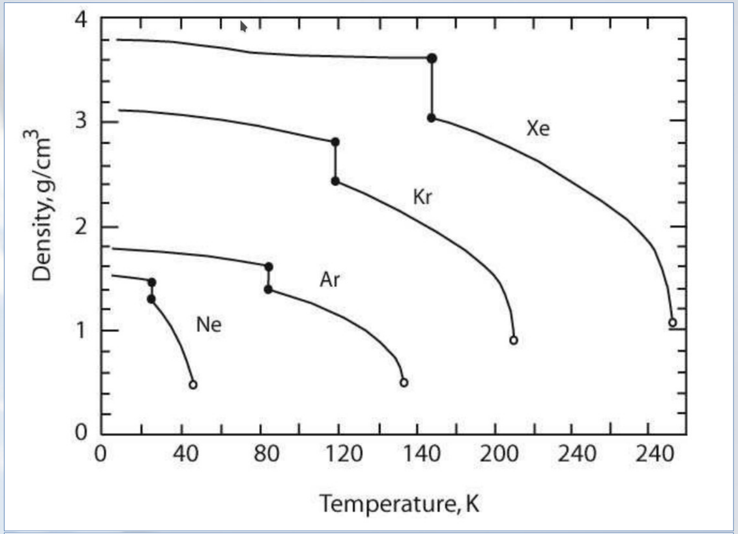
$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_\omega^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F_{SI}^2(E_r)$$

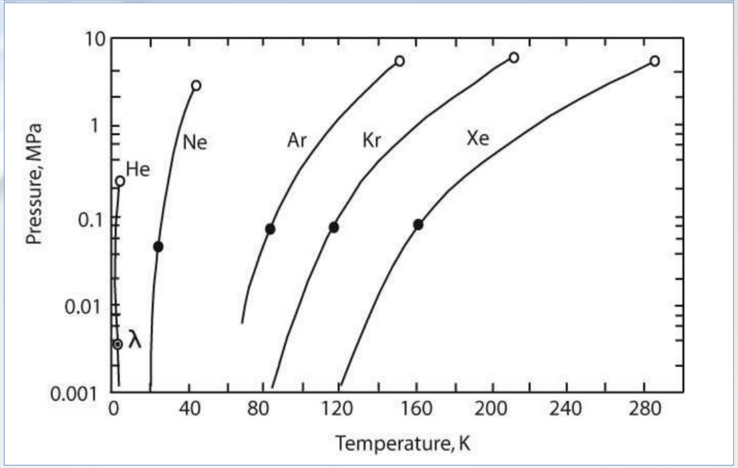
$$Q_\omega = N - (1 - 4\sin^2\theta_\omega)Z$$

Stigari, New J. Phys. 11 (2009) 105011

Crash course on noble element detectors

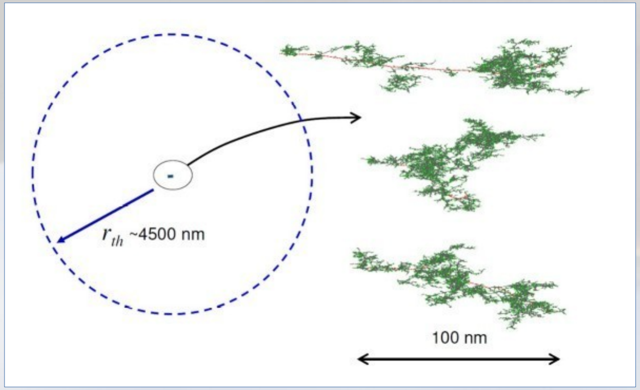
- Cryogenics:
  - Allows working in liquid phase
  - Ups:
    - High density
    - Shapes into a container
    - Allows scaling
    - Dielectric: can support E-fields
- Chemistry:
  - (almost) No chemical interactions – can be cleaned externally

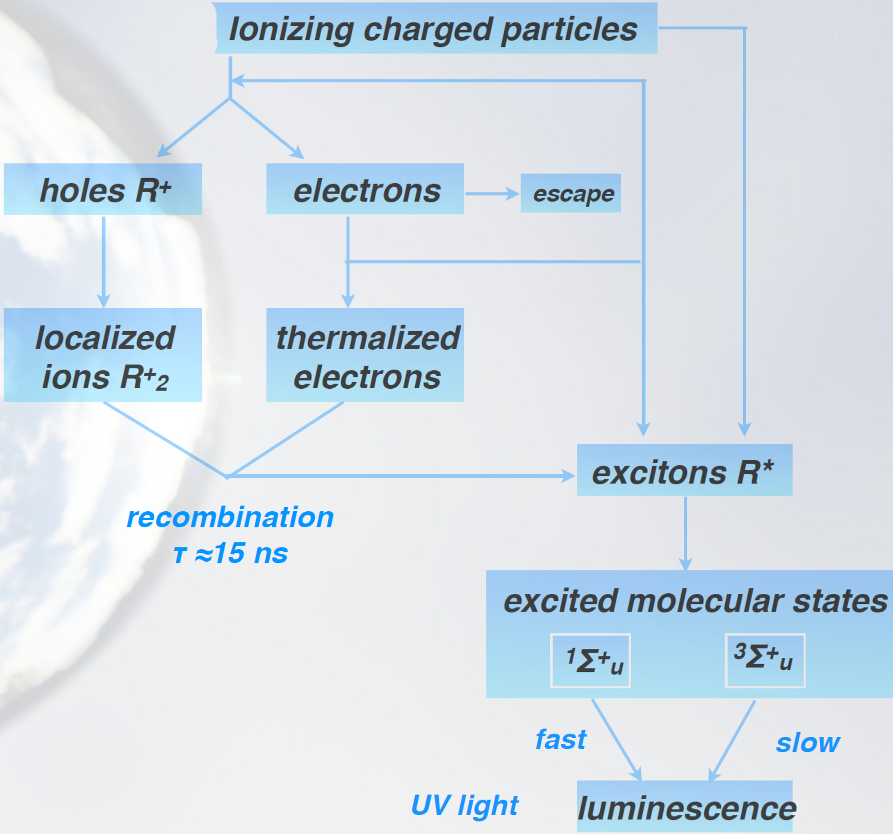




Scintillation in noble elements

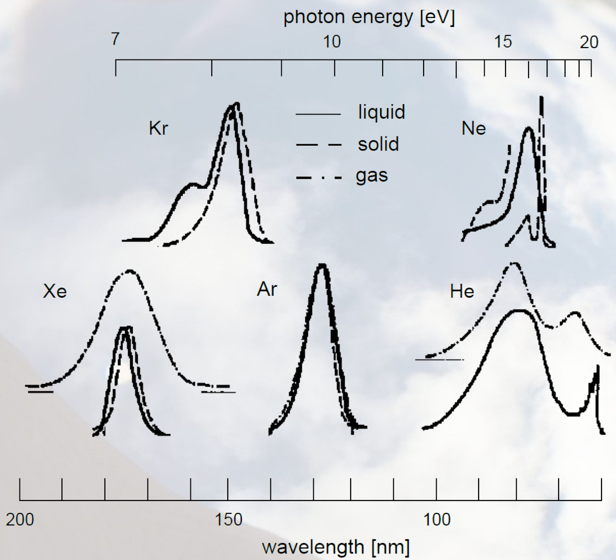
- An ionizing particle creates a cascade of ionized/excited states
- Via several channels, meta-stable molecules A_2* are formed - excimers
- After "a while" They decay, emitting UV photons

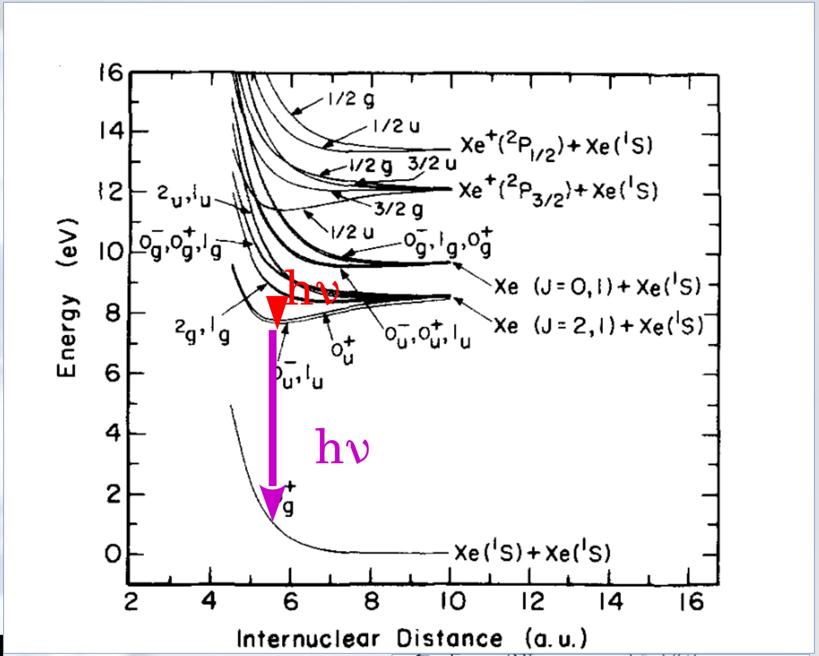


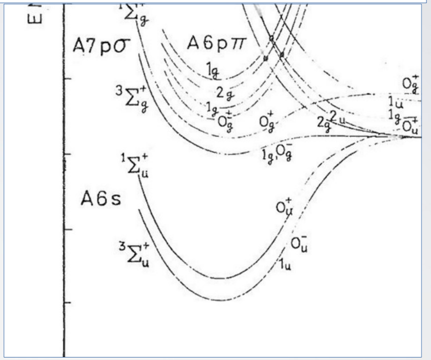


Scintillation in noble elements

- IR emission while going to excimer ground state
- Different broadening mechanisms gas/liquid
- Time scales singlet/ triplet
- Wavelengths in the deep UV



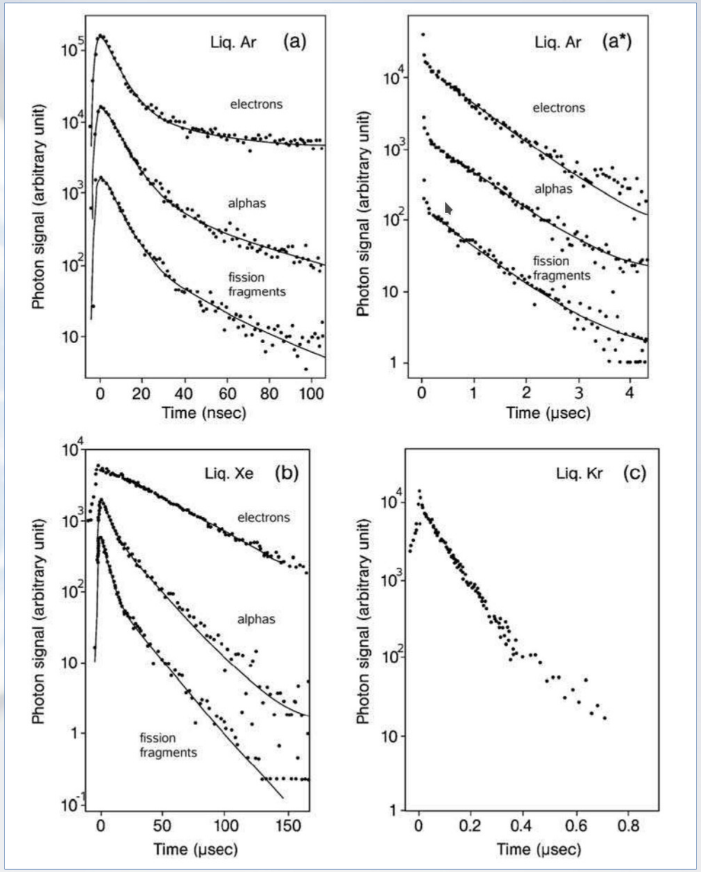




Element	Xe	Ar
Singlet	4-5 ns	7 ns
Triplet	22-25 ns	1500 ns
Cost per quanta	~~9.4~~ ~13 eV	~~12.2~~ ~19 eV

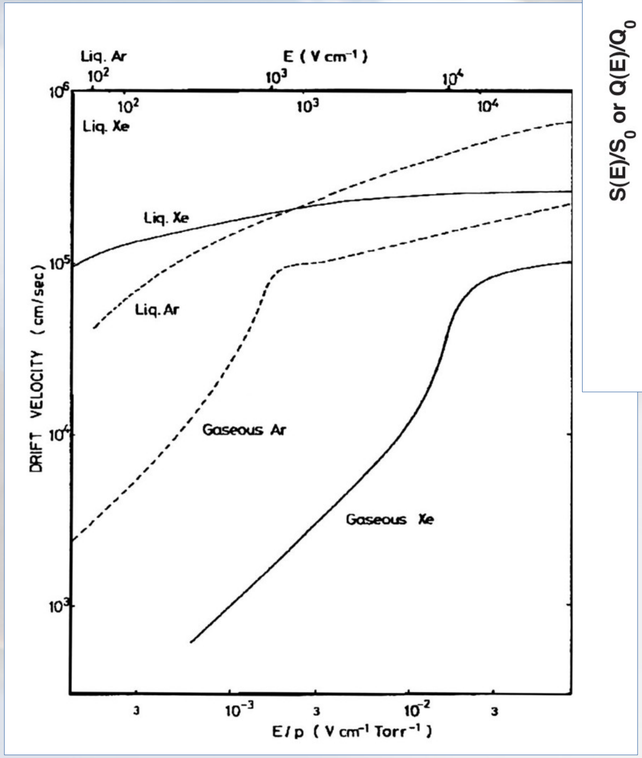
Time structure of scintillation

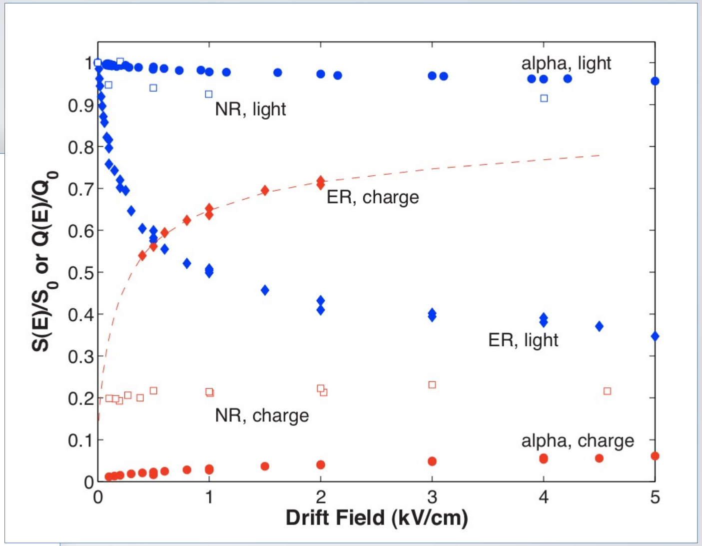
- Singlets and triplets differ in decay times
- Different processes (recombination, excitation) differ in S/T ratios, and depend on ionization density
- Discrimination between particle types is sometimes possible
- Dependence on: E-field, phase, T, density, quenchers



Ionization in noble elements

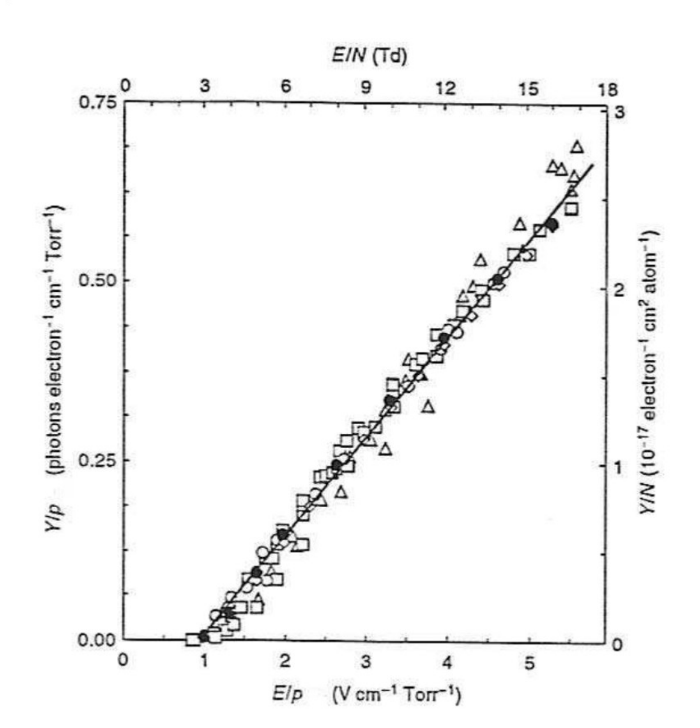
- Liberated electrons can be drifted away by an electric field ($\gtrsim$100 V/cm)
- There is a trade off between electrons and scintillation photons
- Fraction of removed electrons depends on the ionization density
- The same field can drift electrons far away

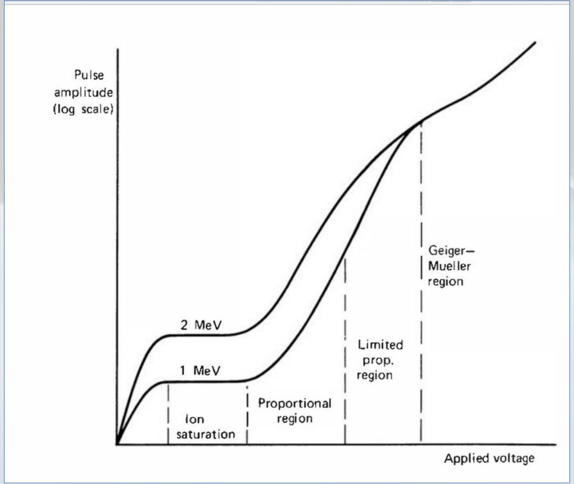




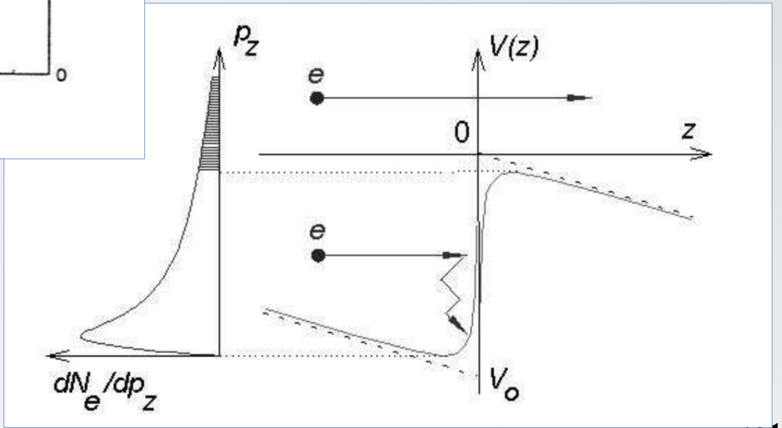
Proportional scintillation

- At high enough reduced electric field electrons can accelerate and create an ionization trail
- In the proportional range, the resulting scintillation light is proportional to the charge



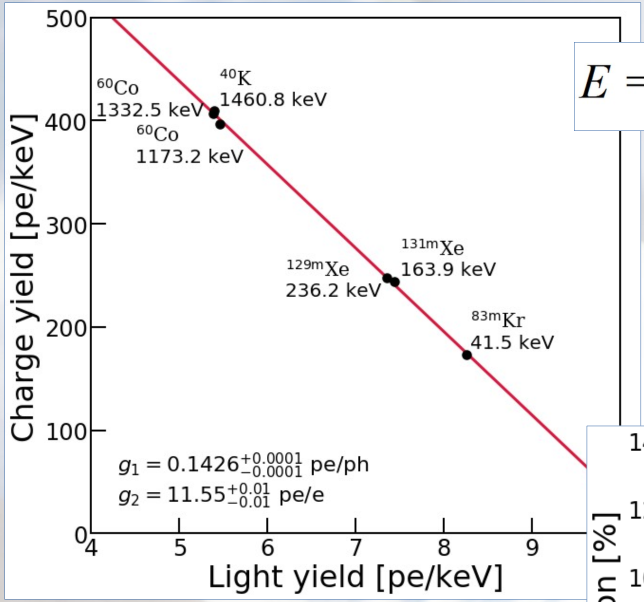


If electrons should cross from liquid to gas, they must go above a potential gap, using ≫kV/cm

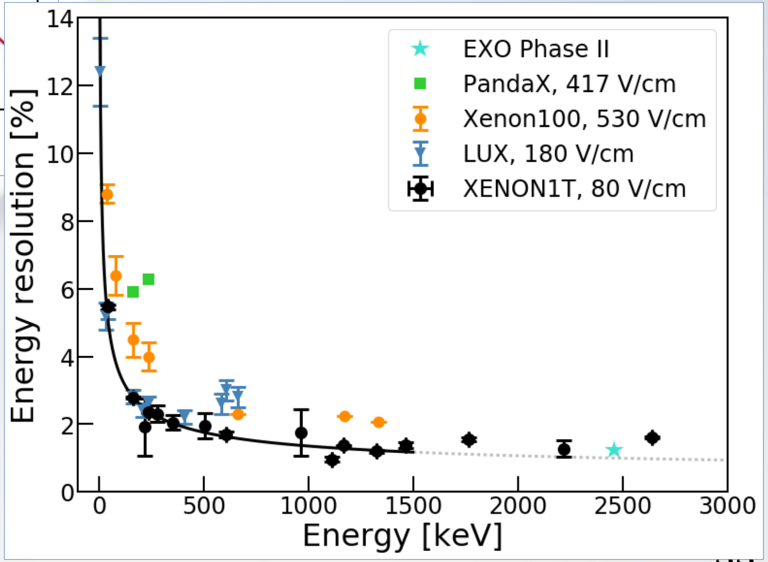


Combined Energy Scale

- Anti-correlation between photons and electrons can be used to get a better estimate of energy
- The resolution depends on many parameters, physics (# of quantas) and detector (efficiency of measuring quantas)



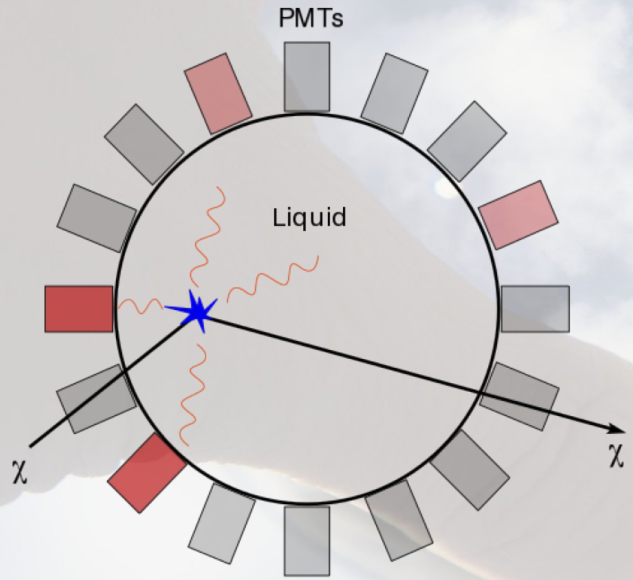
$$E = (n_{ph} + n_e) \cdot W = (\frac{S1}{g1} + \frac{S2}{g2}) \cdot W$$



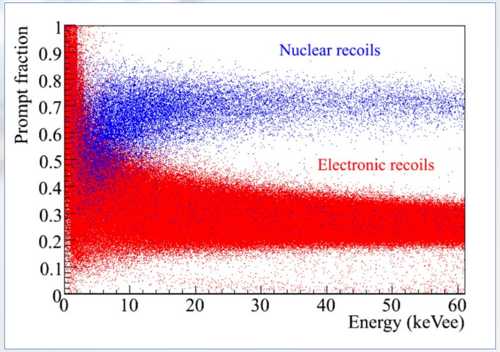
Quick comparison of Xe, Ar for DM

- Xe pro
  - High light yield
  - Low background
  - High A, Z
  - Odd isotopes
- Xe con
  - Expensive
  - "Poor" discrimination
  - Hard cryogenics, purification
- Ar pro
  - "Cheap"
  - Amazing discrimination
  - "Easy" handling
- Ar con
  - High intrinsic background ^{39}Ar
  - High threshold
  - Low, single, even A

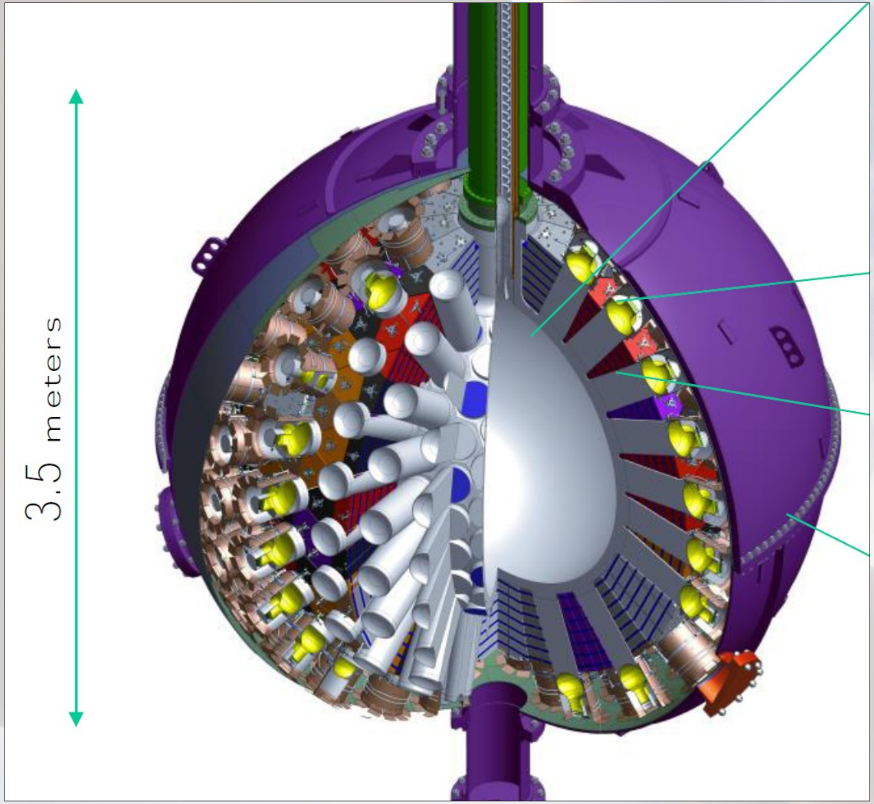
Single Phase Liquid Noble Element



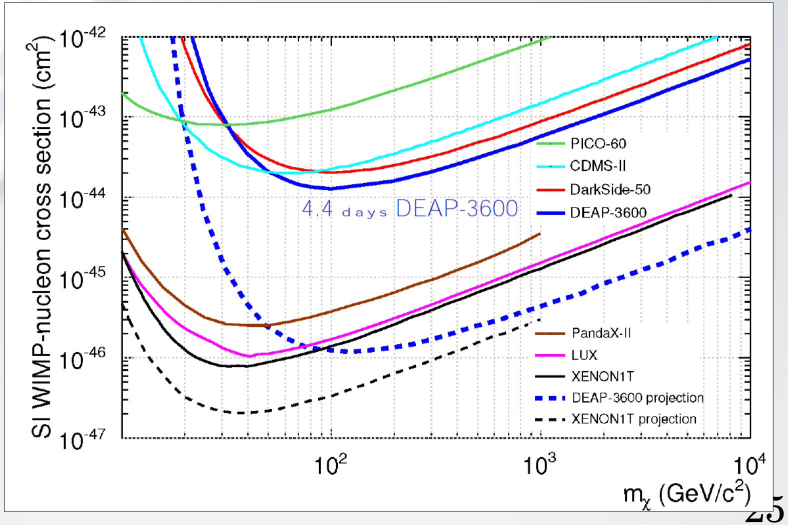
- Uses positioning from hit pattern, allows fiducialization
- Possible discrimination through Pulse Shape
- Keep in "Simple"



Single phase - DEAP3600

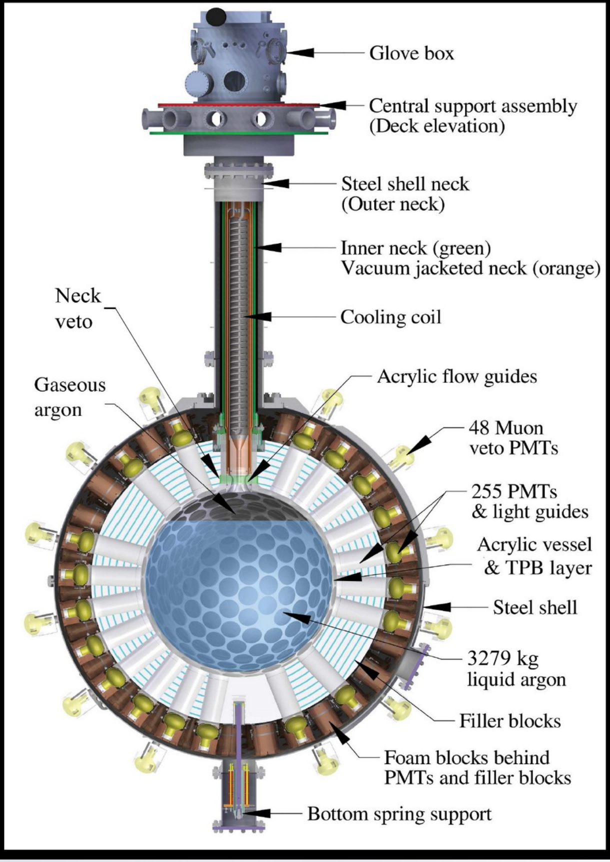


- 3.6t of LAr
- Low radioactivity underground Ar
- Great discrimination, LY, purity
- Has great potential at high masses
- Future prospects for **>100t** global experiment (with DS, ArDM, CLEAN)



DEAP new results

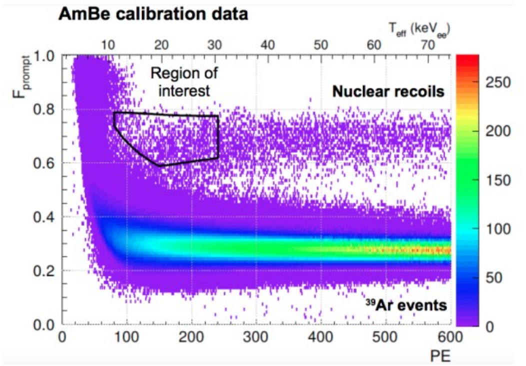
- 3300 kg single phase LAr in SNOLAB in Canada
- Single acrylic vessel viewed by 255 PMTs
- Filled in 2016, running since then
- Recent result in 1902.04048
    - Largest exposure of dark matter experiment to date
    - Power of PSD
    - Good light collection
    - Low external backgrounds



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

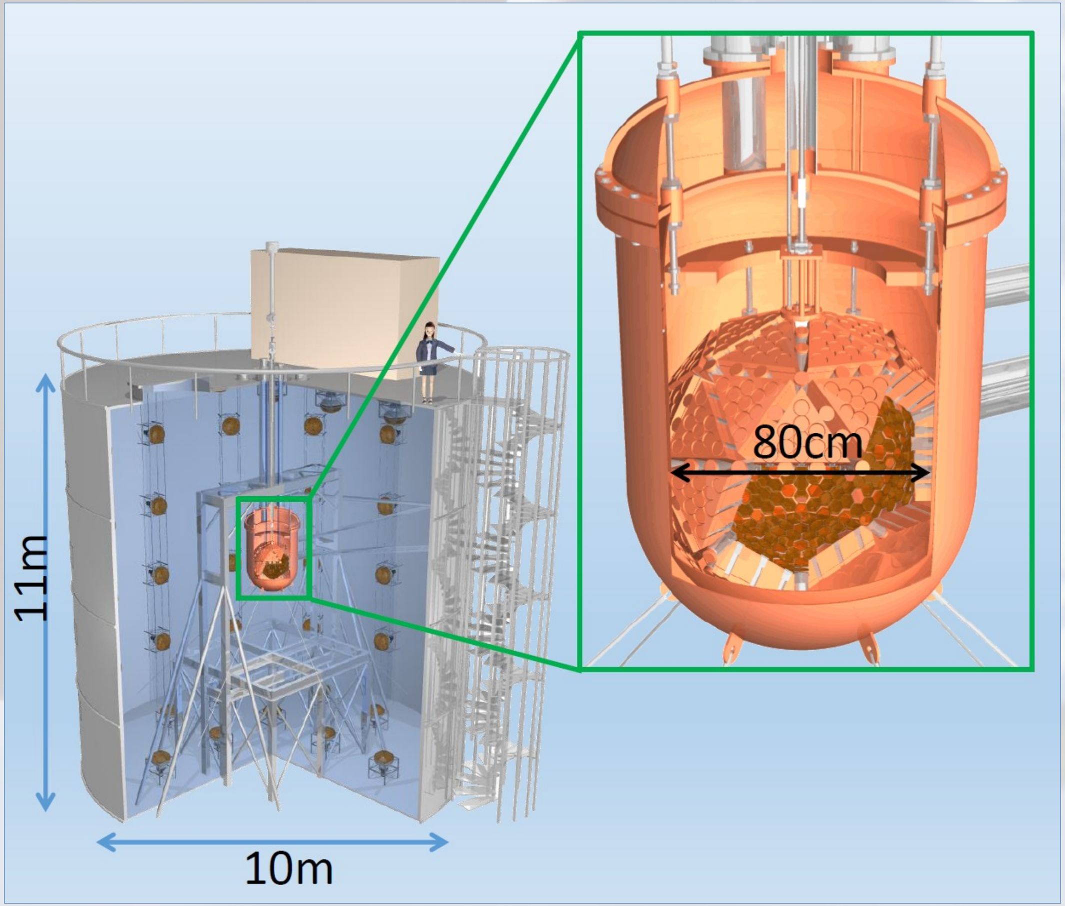
DEAP 3600 - performance

- Discrimination worked well
- Added advanced tagging of α's
- Most dominant ^{39}Ar β background handled well



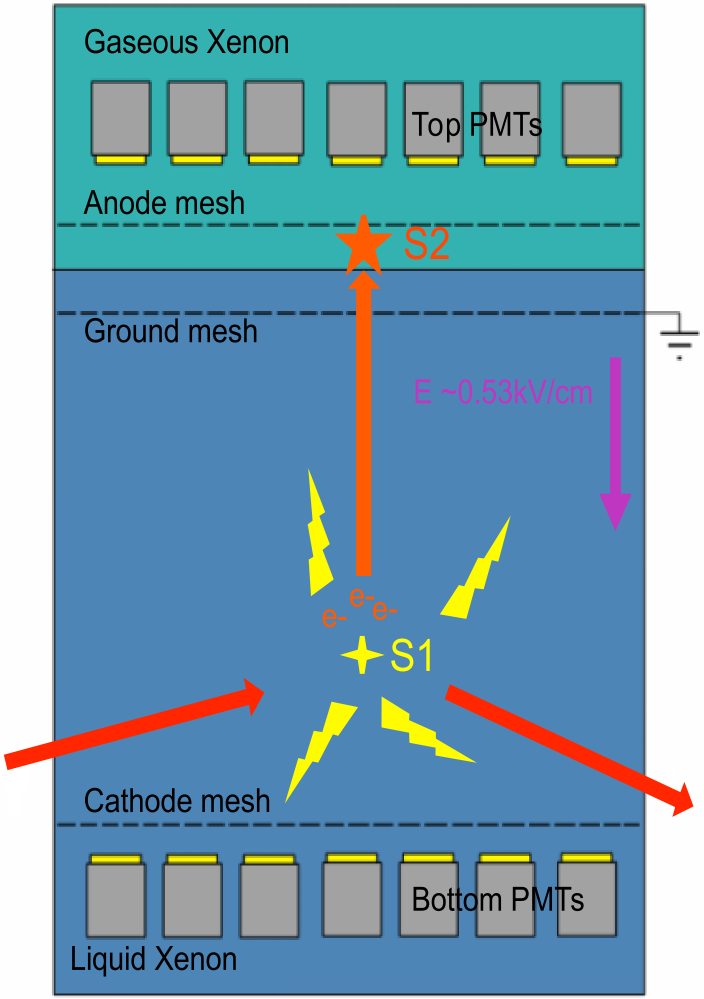
$$F_{prompt} = \frac{\text{Prompt Light}}{\text{Total Light}} = \frac{\int_0^{150\,ns} Q(t)dt}{\int_0^{13{,}500\,ns} Q(t)dt}$$

XMASS in a nutshell



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

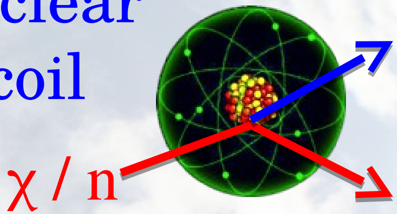
The leading tech: Dual Phase TPC



S1: Prompt scintillation

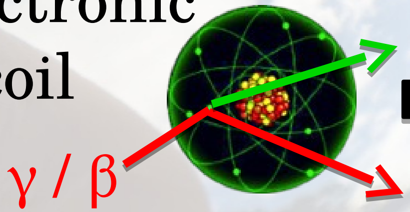
S2: Proportional scintillation after *e-* drift and extraction into gas

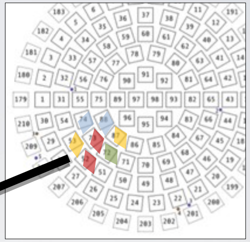
Nuclear Recoil



Discrimination by S2/S1

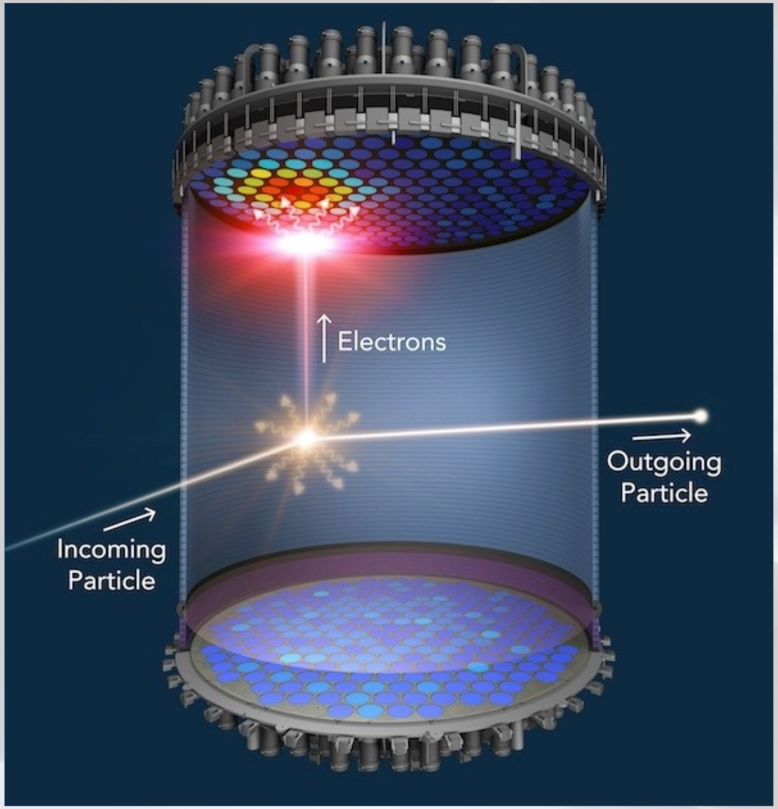
Electronic Recoil

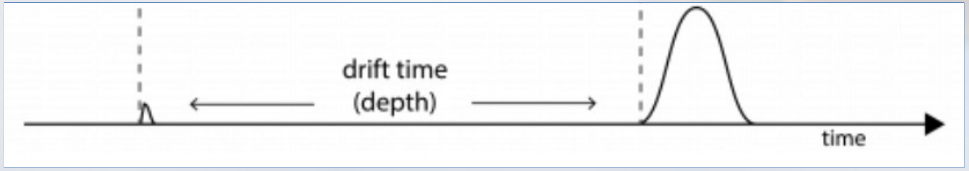




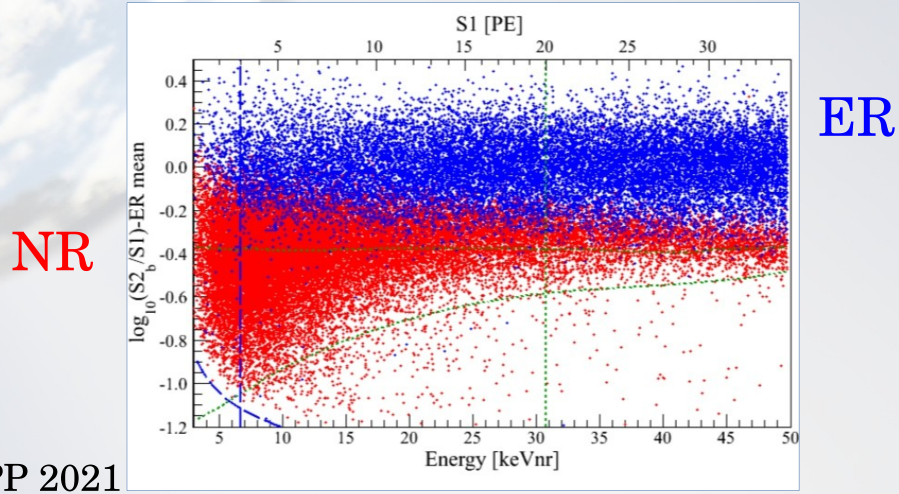
<u>Interaction vertex reconstruction:</u>
- Horizontal from top PMT array
- Vertical from drift time

Dual Phase TPC Distributions

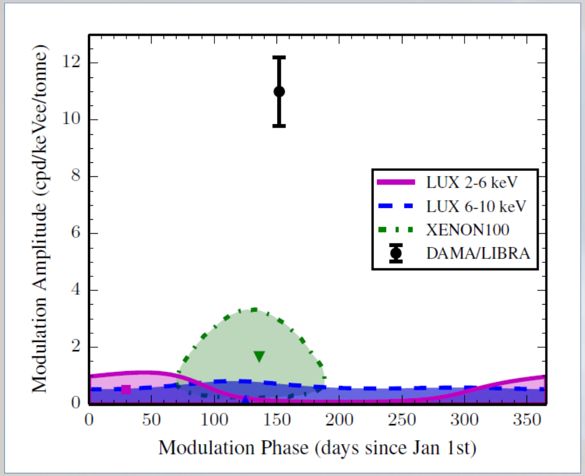


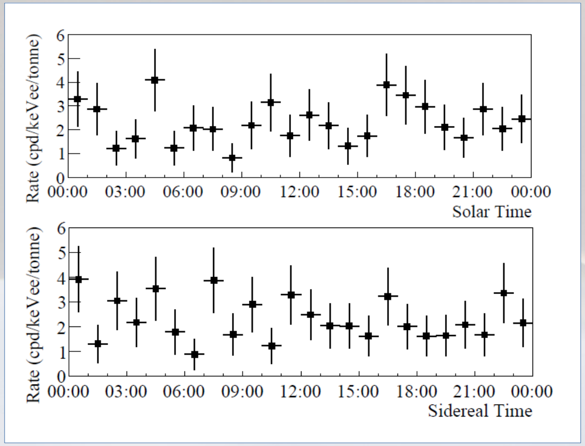


- Prompt scintillation photons give first signal (S1)
- Ionized e⁻ drift up to the anode and amplified, giving S2
- Time difference gives Z position
- S2 Hit pattern on top gives XY position
- Ratio S2/S1 indicates type of interaction



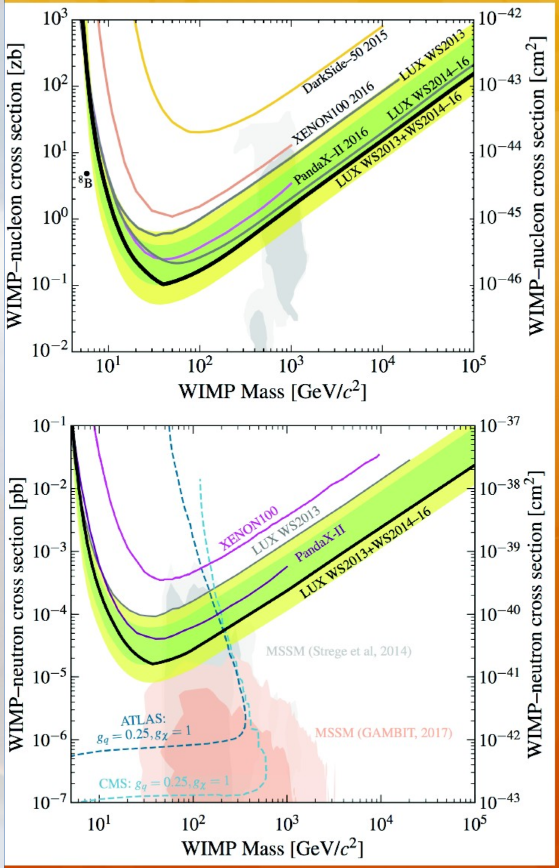
LUX – Forerunner Summer 2016





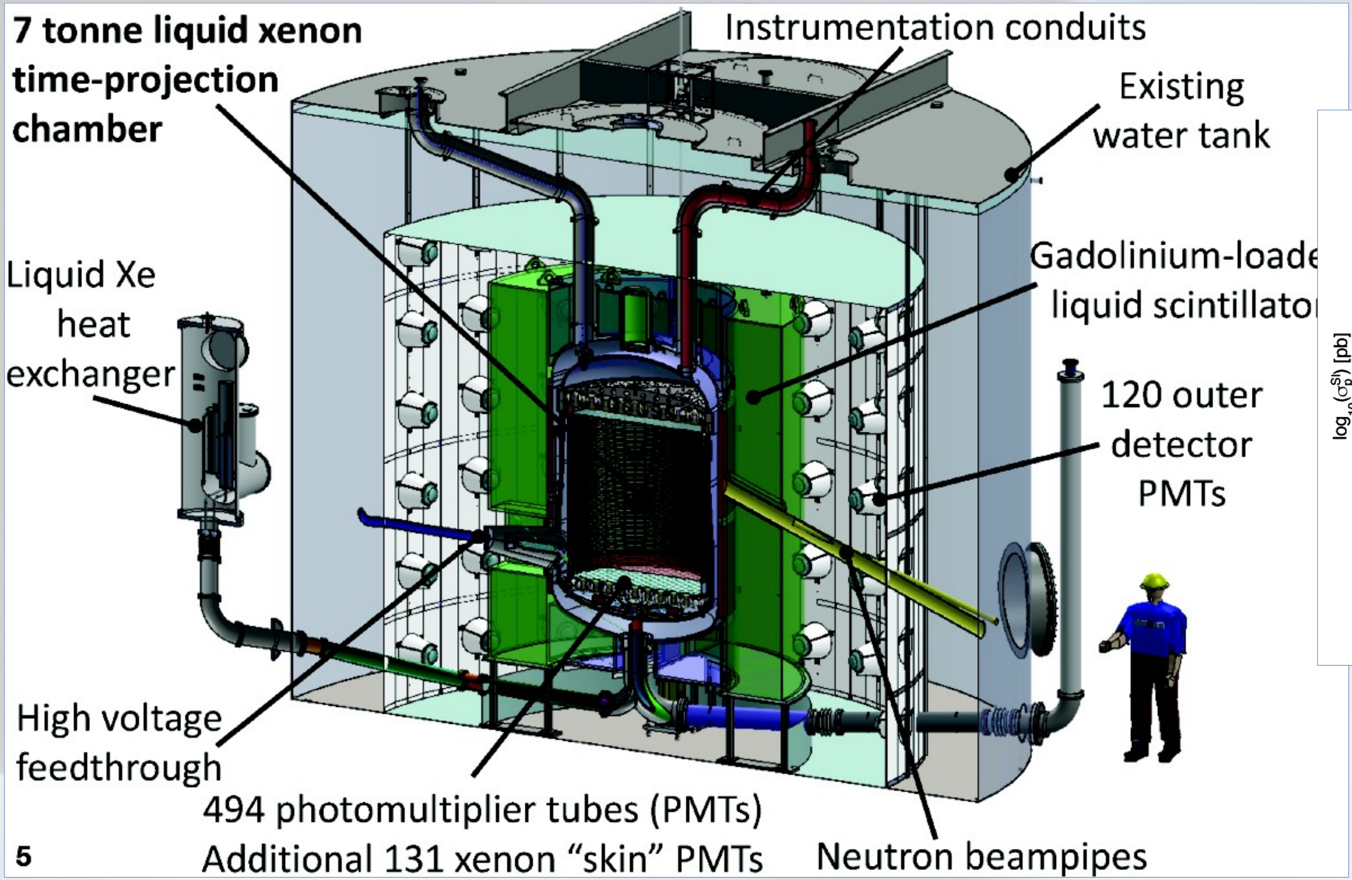
1807.07113

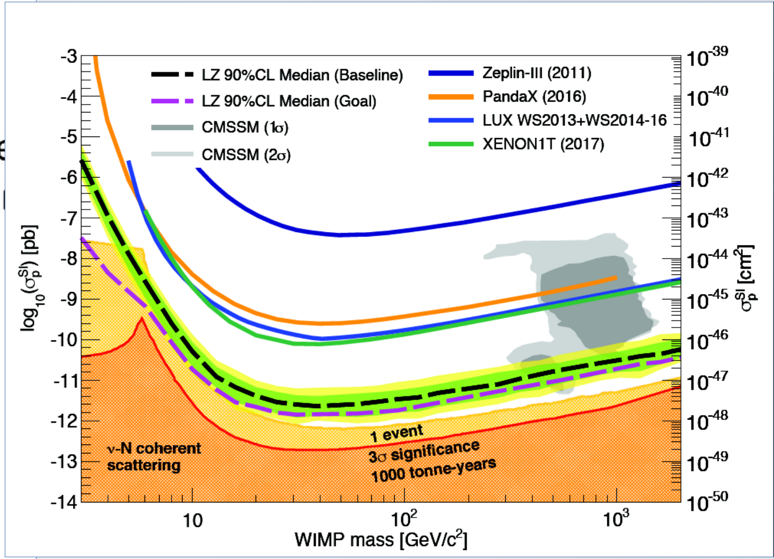
LUX Impact 2013/17



- 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

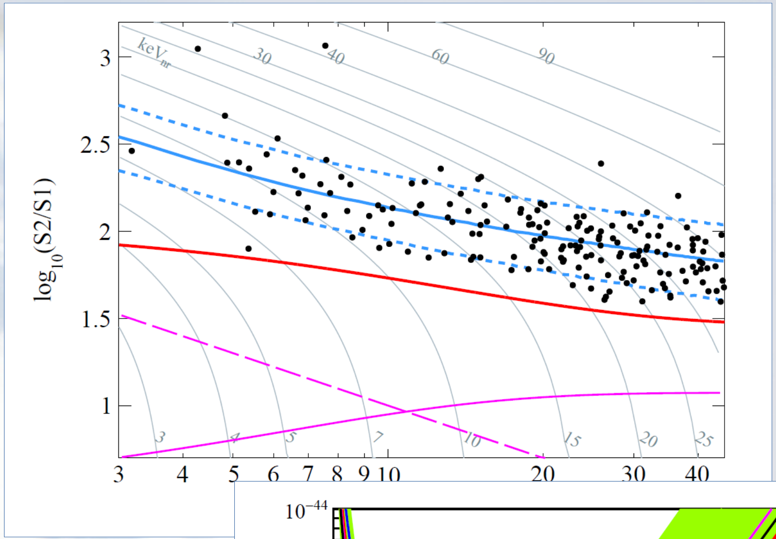




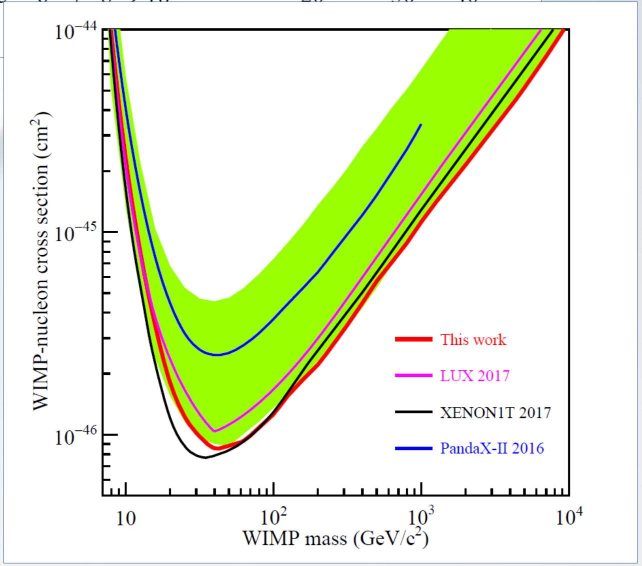
- To start 2021 @SURF
- Use of n-veto, 7-ton TPC, 5 year run

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 ($2\nu0\beta$)

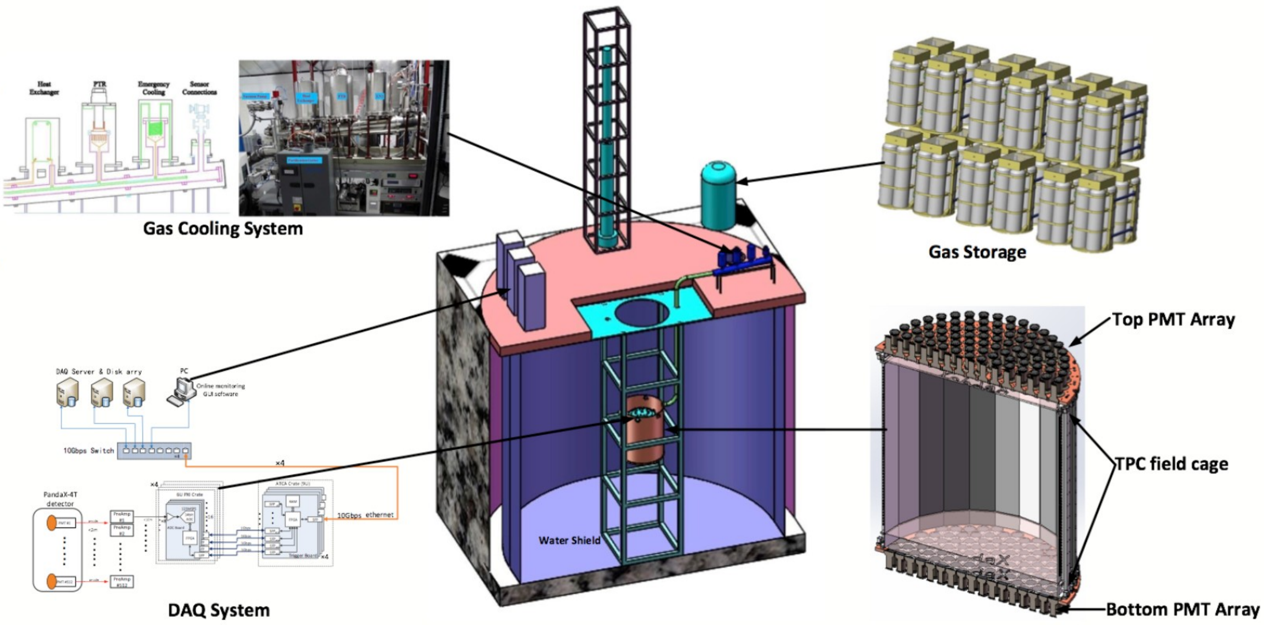


1708.06917



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

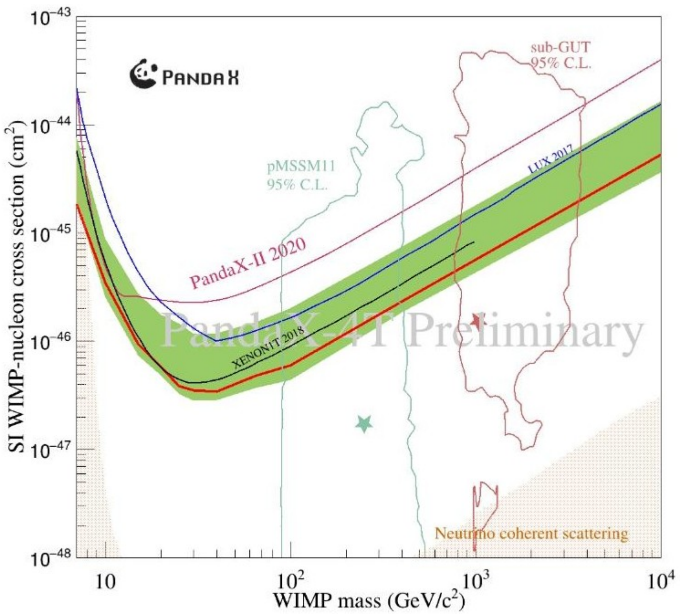


1806.02229

Indeed, PANDAX-4T did not waste time!

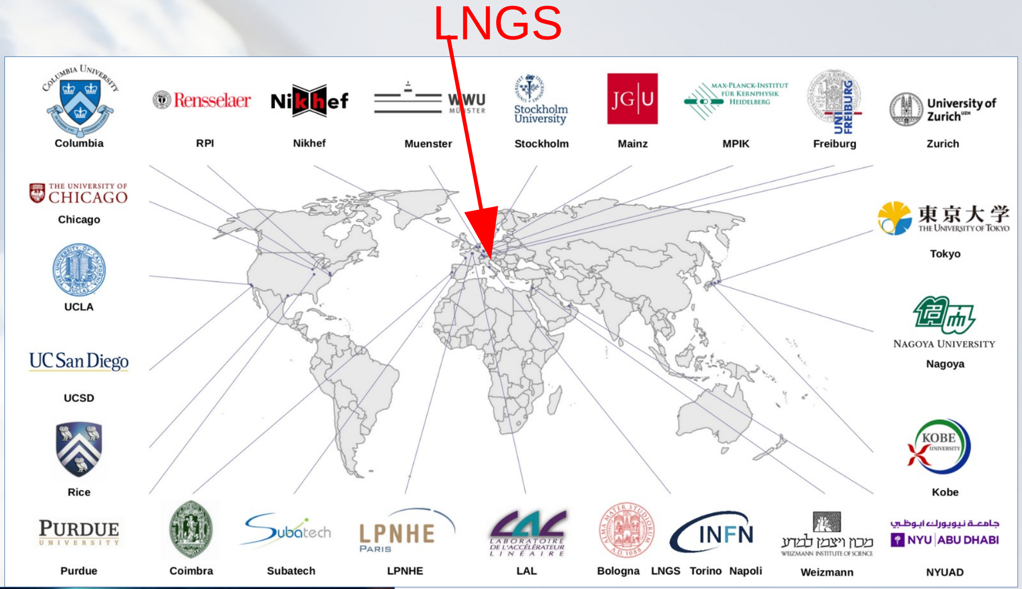
- Preliminary (yesterday!)
- Relatively high background expectations, but claim world best limit
- Anxiously waiting for the paper!

PandaX二期实验结束后的一次刻度注入。在95天的运行中，PandaX-4T探测器记录了约13.7亿次的事件，其中仅有1058个事例通过筛选进入了最终的暗物质分析数据集。这些事例中有6个事例落在了信号区域内，通过分析，它们和本底预期吻合，未出现暗物质事例超出的迹象。由于出众的灵敏度，PandaX-4T的这批数据覆盖了之前未被探测过的暗物质与普通物质作用的参数空间，取得了对暗物质最好的搜寻结果。



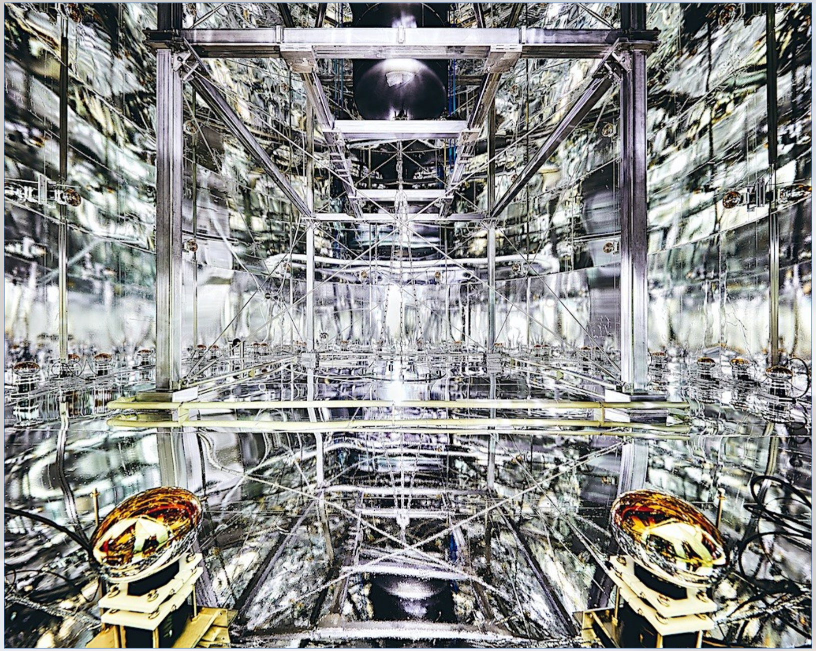
此次试运行结束后，PandaX实验组将加快开展对探测器中氚本底的提纯工作，预期将探测器的本底降低一倍以上，以更高的灵敏度搜寻暗物质。

The XENON Collaboration at LNGS

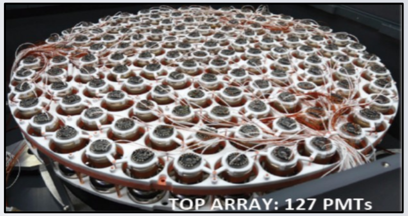


Keeping XENON1T alive and well

Water Cerenkov Muon Veto

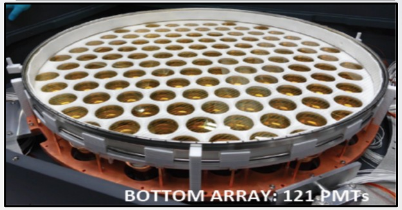


PMTs
Top

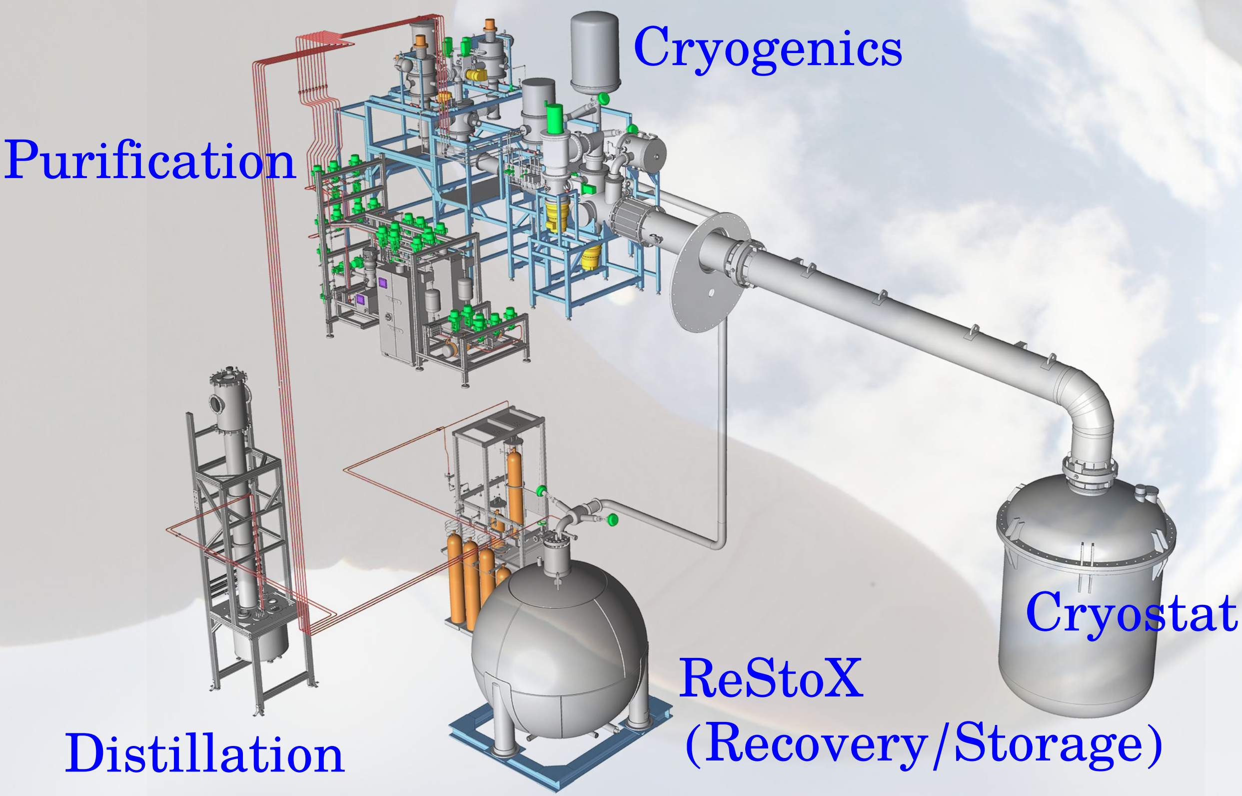


TPC

PMTs
Bottom



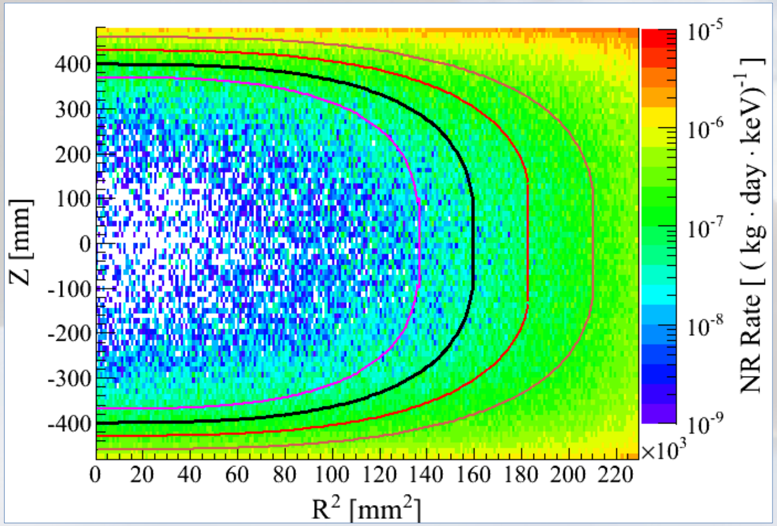
Keeping XENON1T alive and well



DAQ, HV, Control

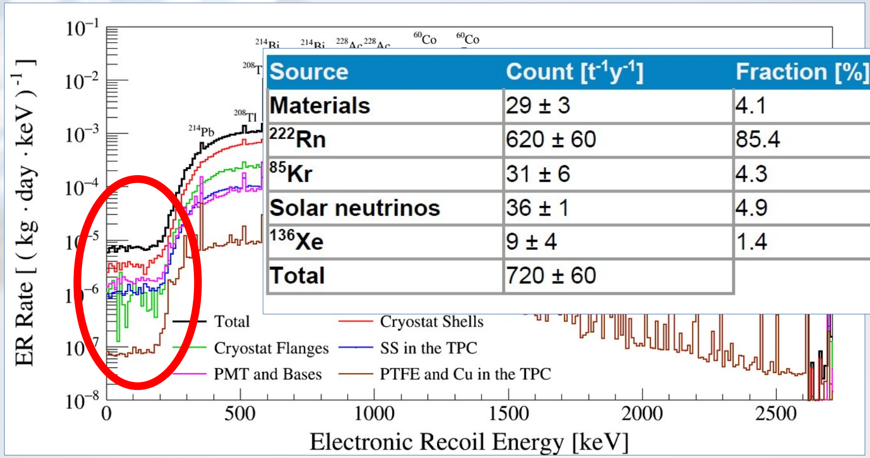
Backgrounds

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



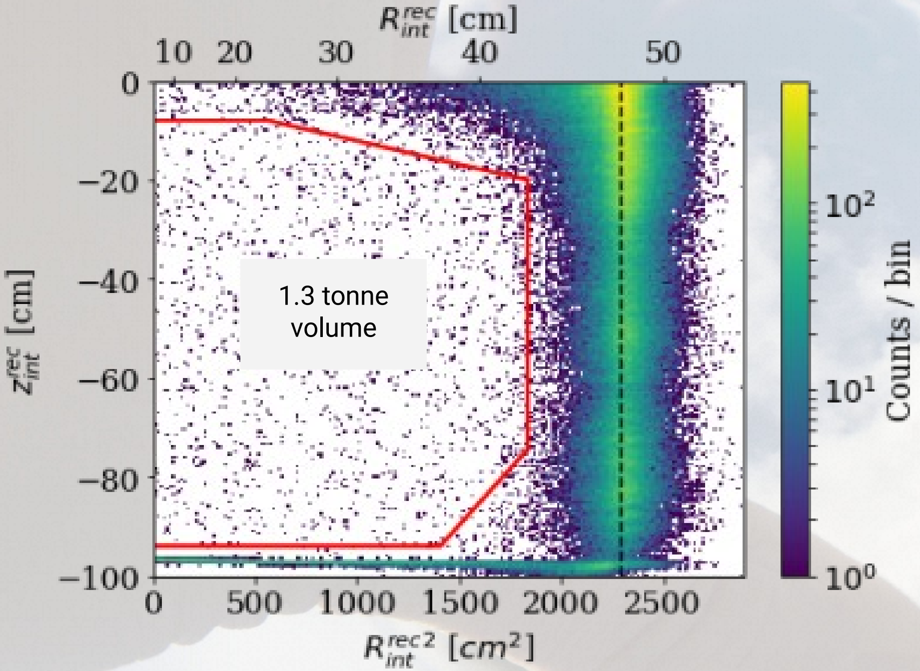
JCAP04(2016)027

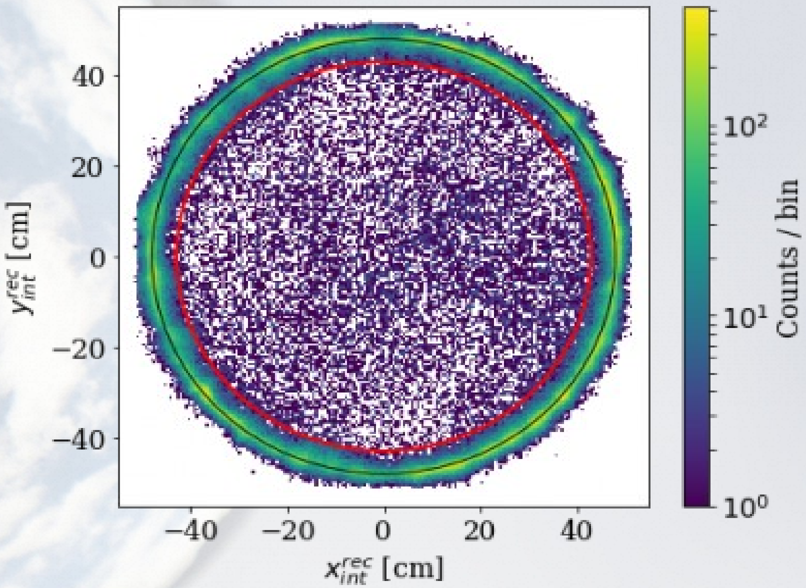
- Electron Recoil
  - From internal sources (mostly Rn, Kr)
  - From radioactivity of materials
  - With discrimination o(1) for full exposure



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	

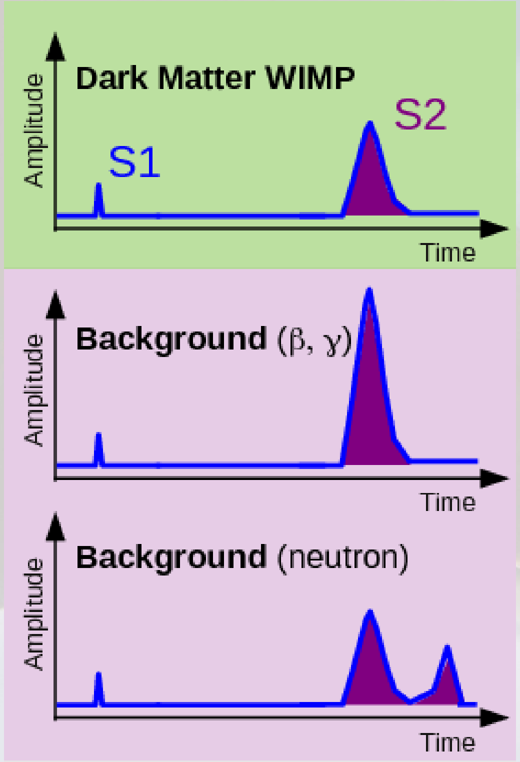
Fiducialization

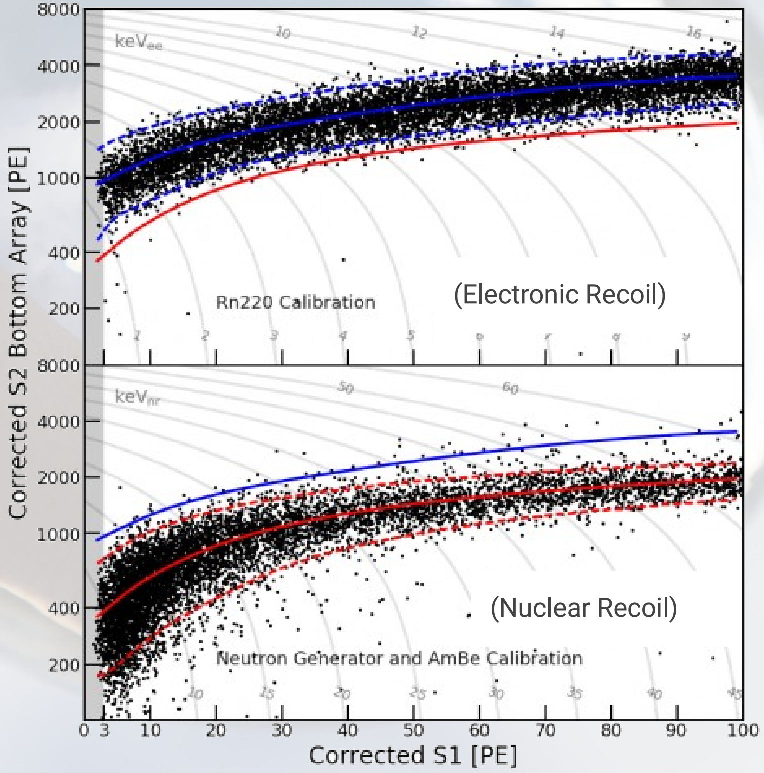




Removes high rate of events from detector materials

Particle Discrimination





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

Scintillation/Ionization ratio gives particle discrimination

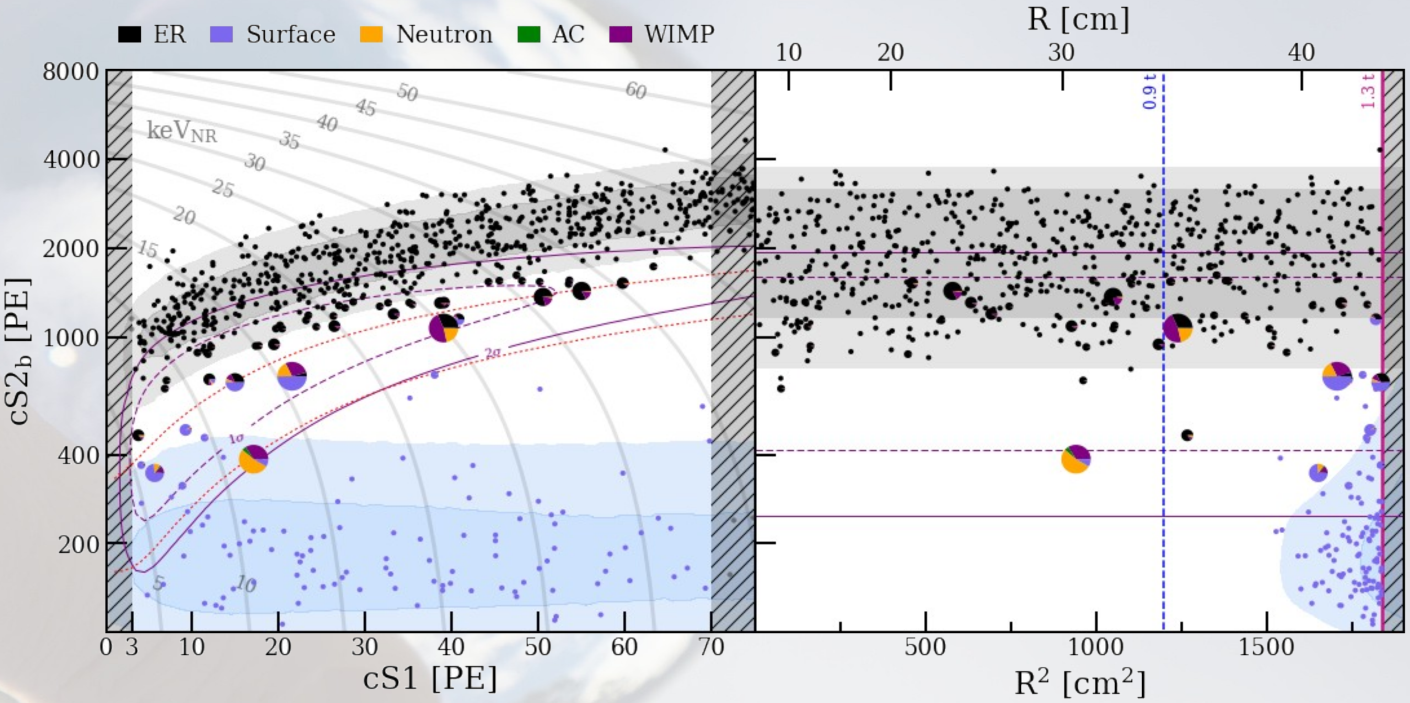
Calibrations to determine ER and NR bands

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



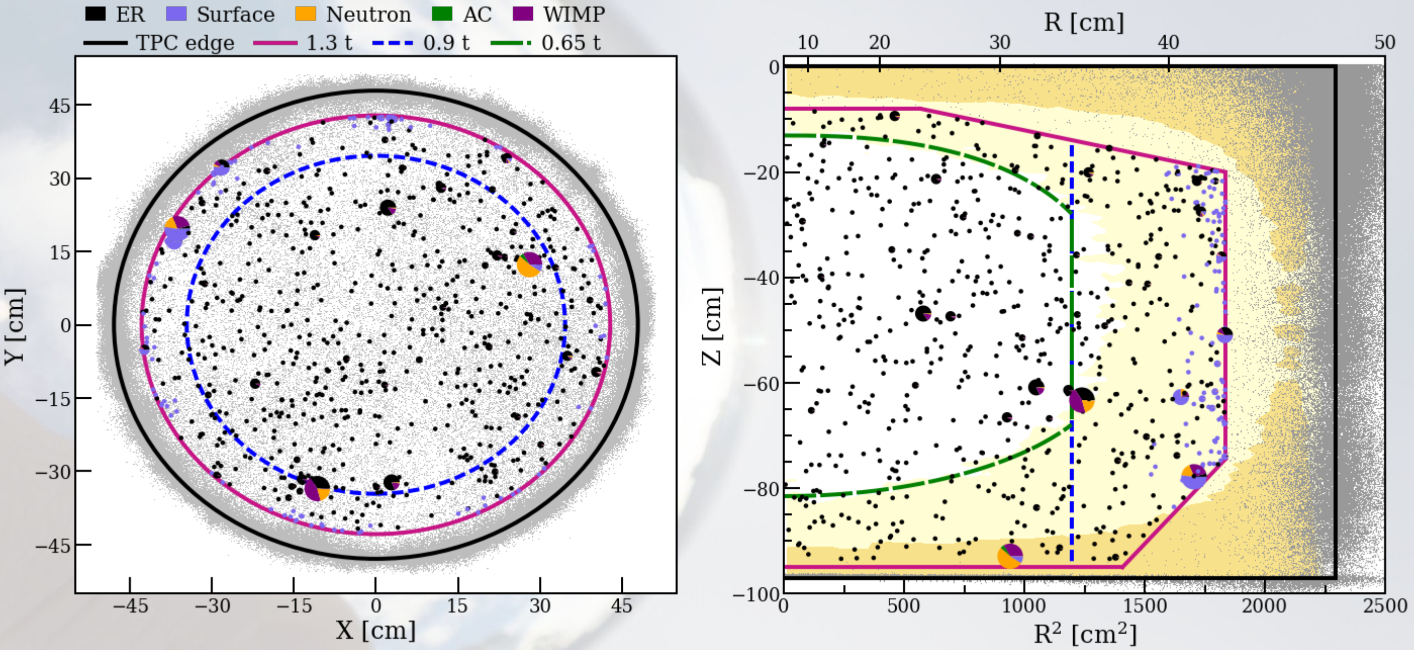
Pie chart color shows the likelihood that each event comes from each source distribution

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
$WIMP_{best-fit}$	3.56	0.83
Data	739	2

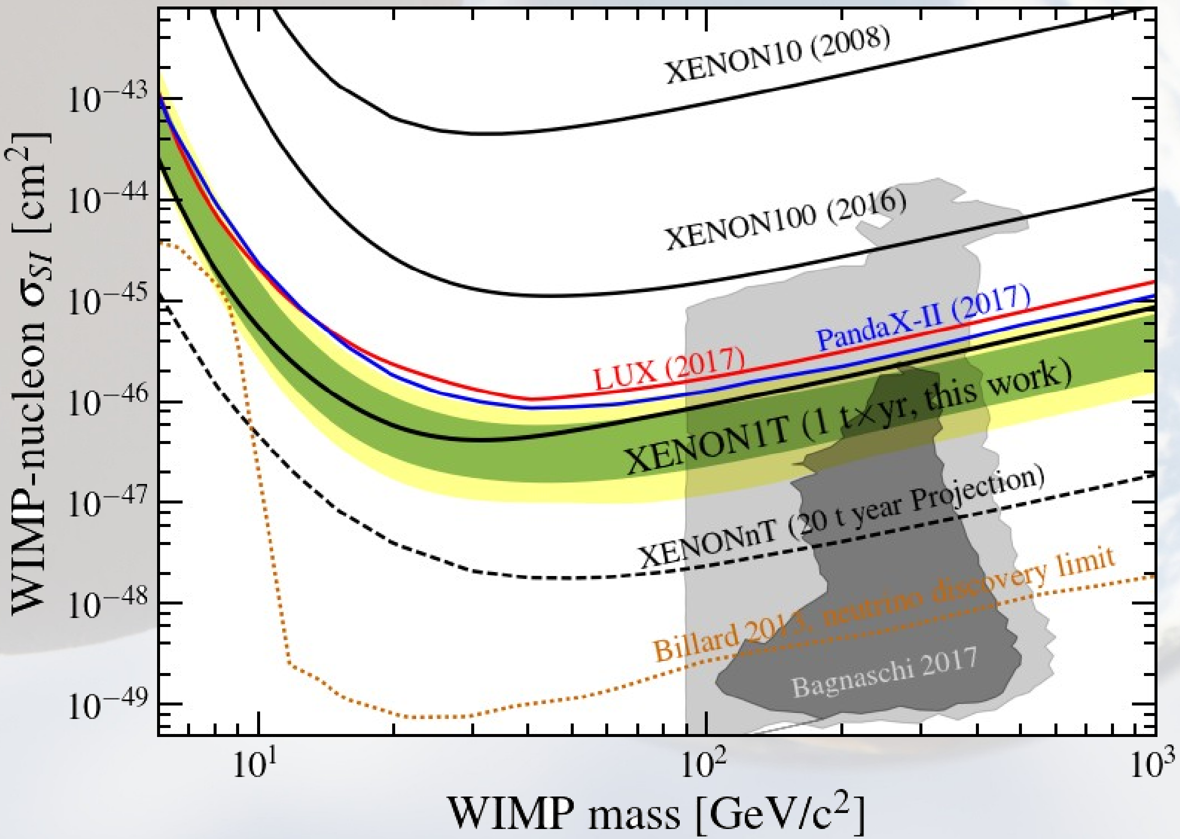
Full likelihood analysis shows no excess over expected background

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

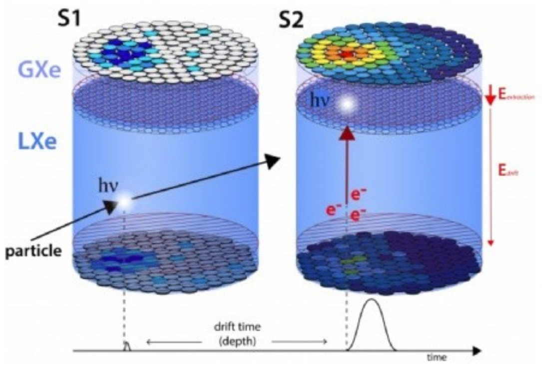
Spin-independent WIMP Search results



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

No excess greater than 2σ over full mass range

S1+S2 Energy reconstruction for ER

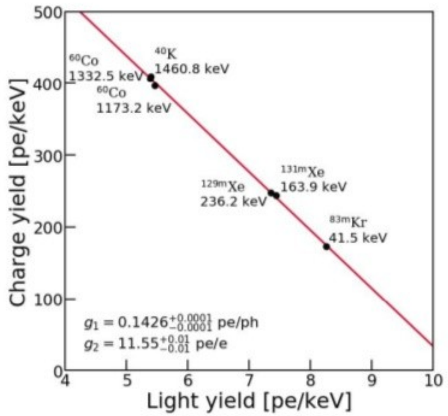


Energy loss to *either* light or charge channel
→ S1/S2 anticorrelation

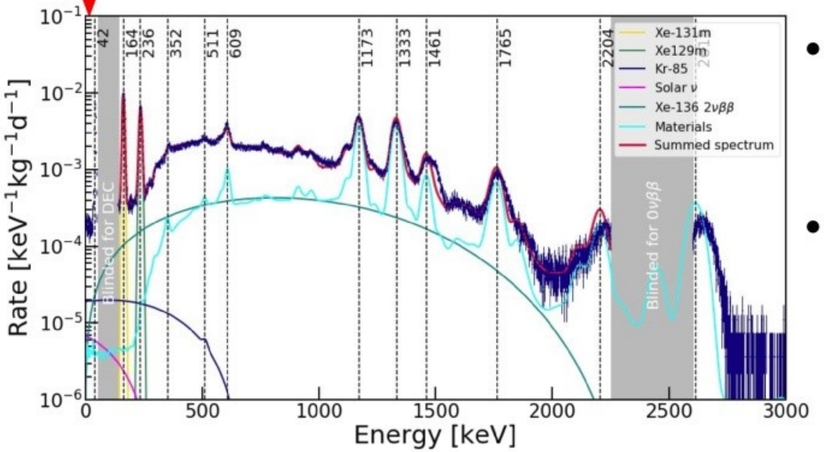
$$\frac{S1}{E} = \frac{n_\gamma}{n_e + n_\gamma} \times \frac{g1}{W}$$

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

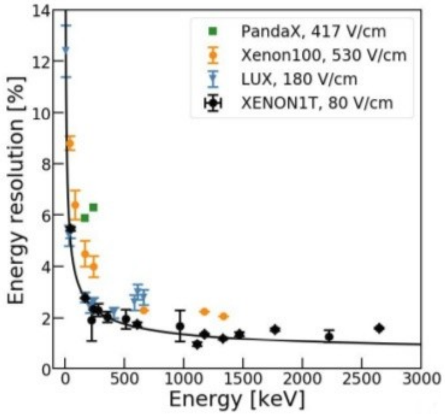
"Doke plot" → linear fit to calibration isotopes



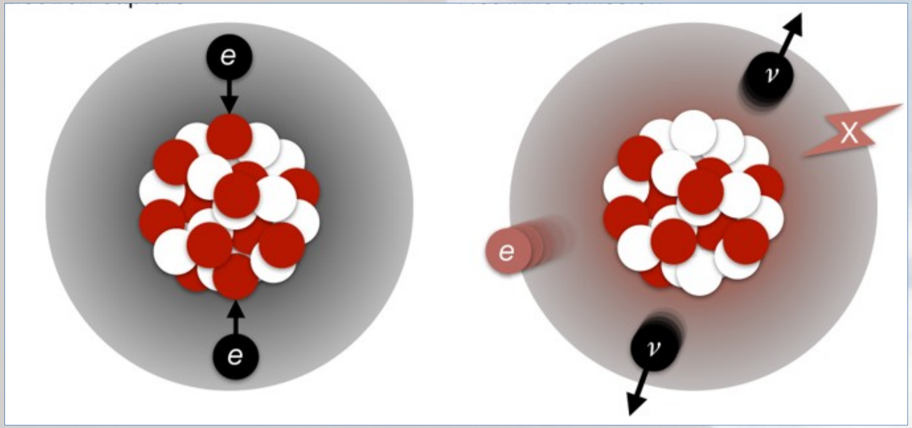
ROI for WIMP search up to ~30 keV



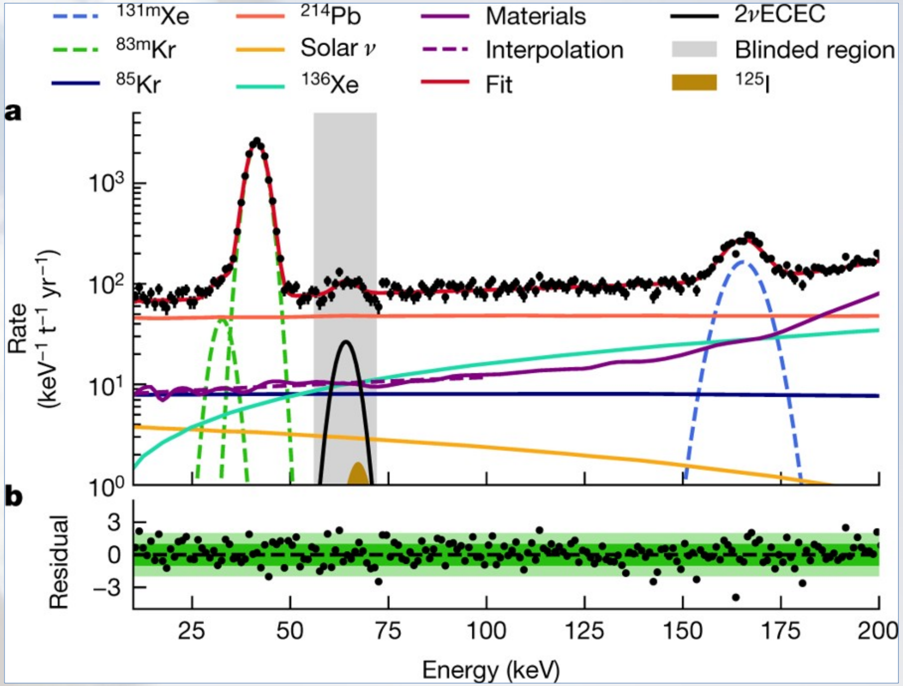
- Solve the above for E for combined energy reconstruction
- Excellent resolution across a broad energy range



Double Electron Capture in ^{124}Xe



^{124}Xe ^{124}Te

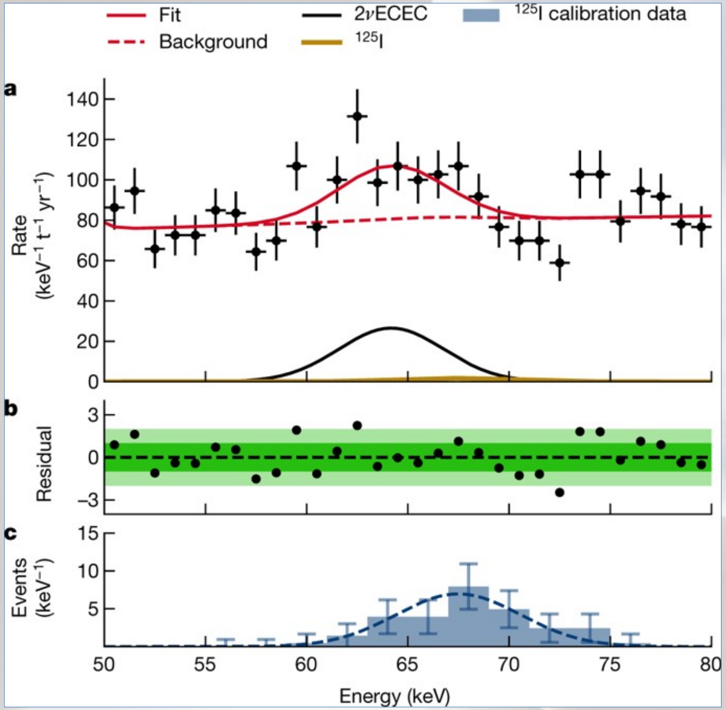


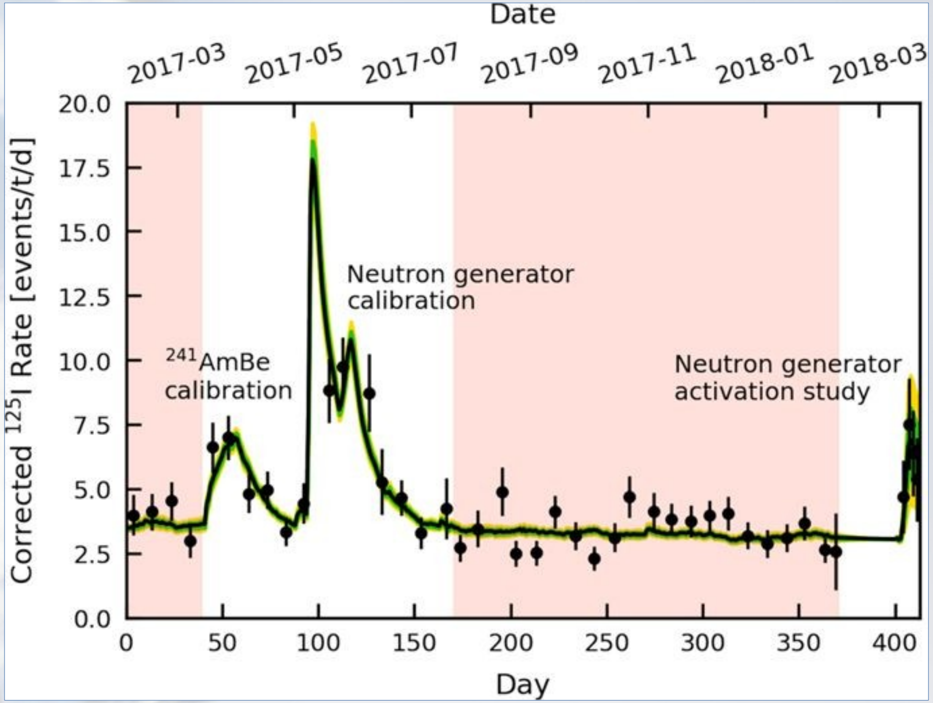
1 kg ^{124}Xe per tonne of liquid Xe

Never-before measured process

XENON, (2019)

Double Electron Capture in ^{124}Xe

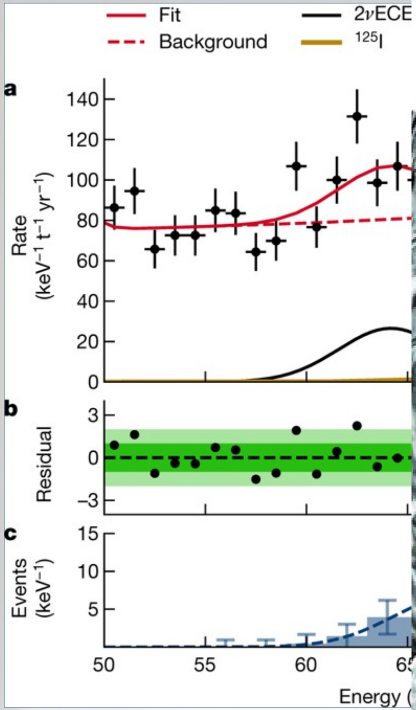


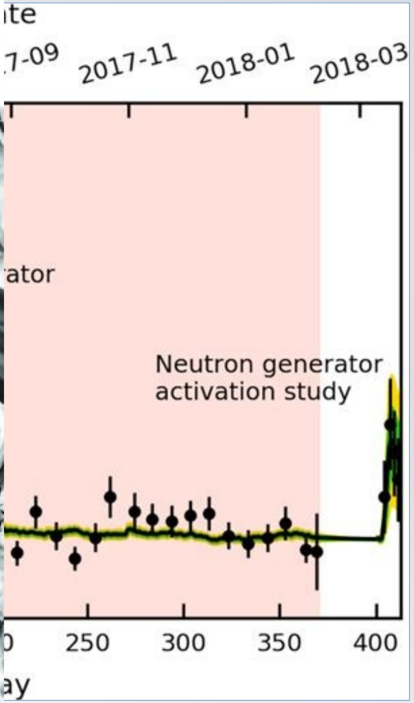


Half-life of (1.8 ± 0.6) x 10^{22} years, longest directly measured half-life to date

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

Double Elec



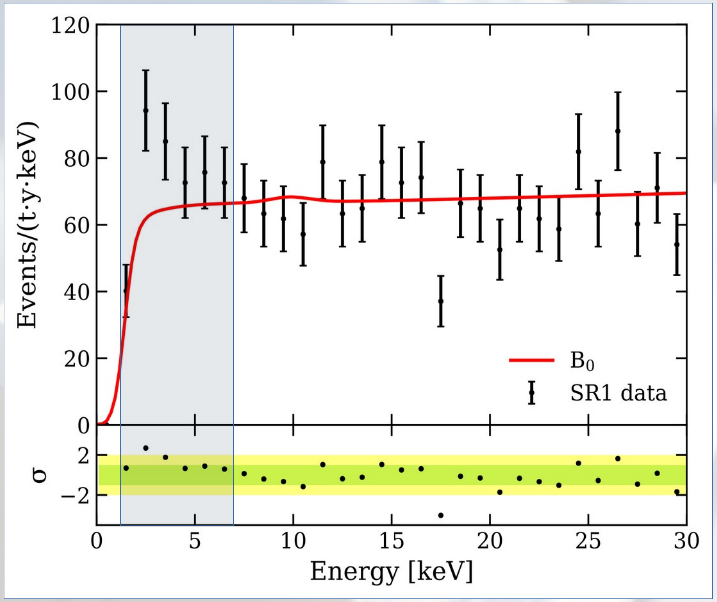


Half-life of (1.8 ± 0.6) x

Modeled nearby backgro

An unexpected excess in the ER “background”

- Might be…
  - New background (T? Ar?)
  - Solar axions – peaked around 1-2 keV, set by the Sun’s core T
  - Anomalous ν magnetic moment – a rising spectrum towards low E
  - Bosonic DM absorption – a monoenergetic peak

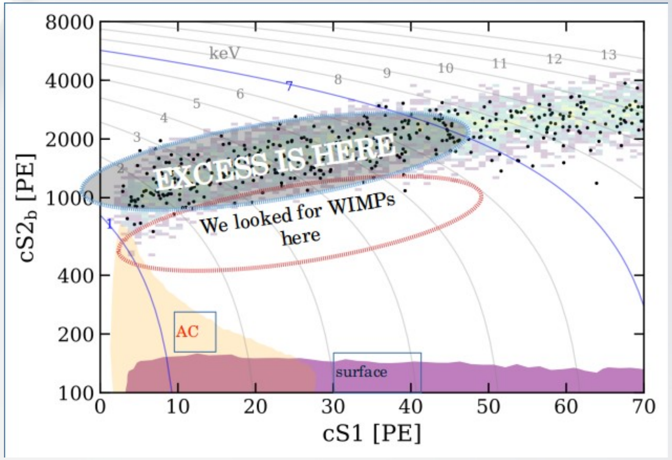


Phys.Rev.D 102 (2020) 7, 072004 (2006.09721)

3 - 3.5 σ excess in electronic recoils

Naive estimate:

285 events observed
vs.
232 (+/- 15) events expected (from best fit)
Would be a 3.5σ fluctuation



XENONnT – Swift upgrade

MINIMAL UPGRADE

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

FIDUCIAL XE TARGET

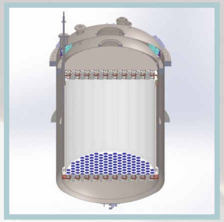
Fiducial mass: ~4 t
Target LXe mass: 5.9 t
Total LXe mass: 8 t

BACKGROUND

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

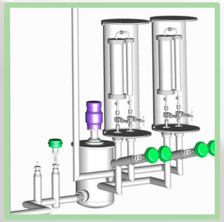
FAST TURNAROUND

Installation sterted in 2018
Commissioning in 2020



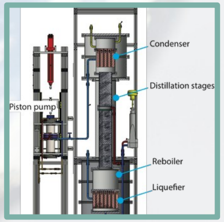
NEW TPC

Larger inner cryostat
476 PMTs



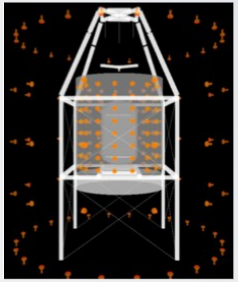
LXe PURIFICATION

Faster cleaning of large LXe volume (5000 SLPM)



Rn DISTILLATION

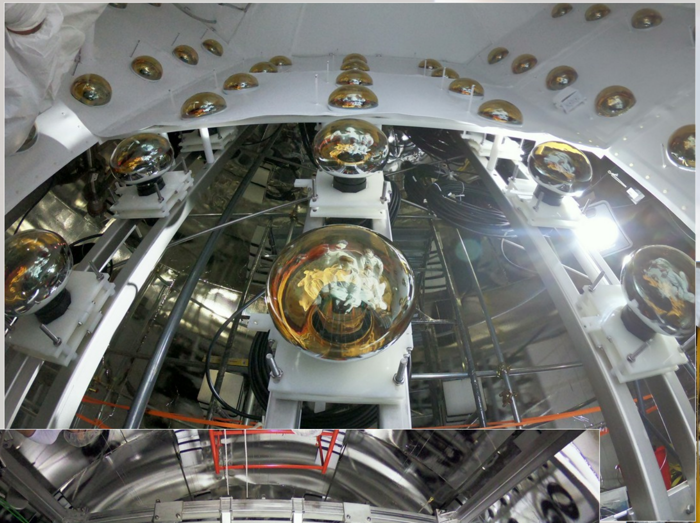
Online removal of ^{222}Rn emanated inside the detector

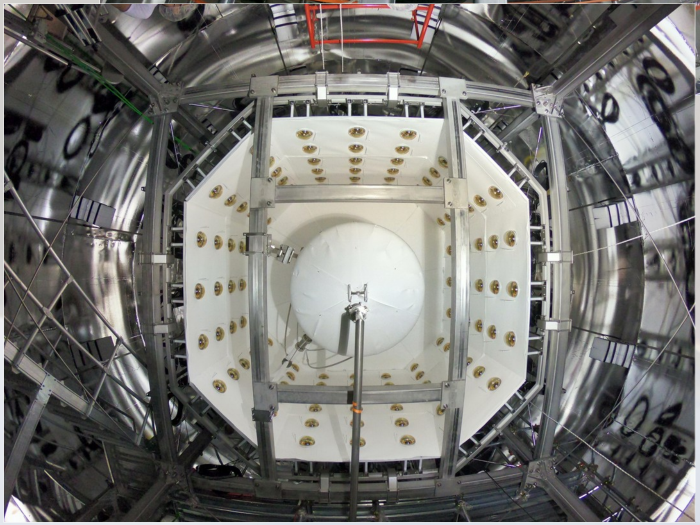


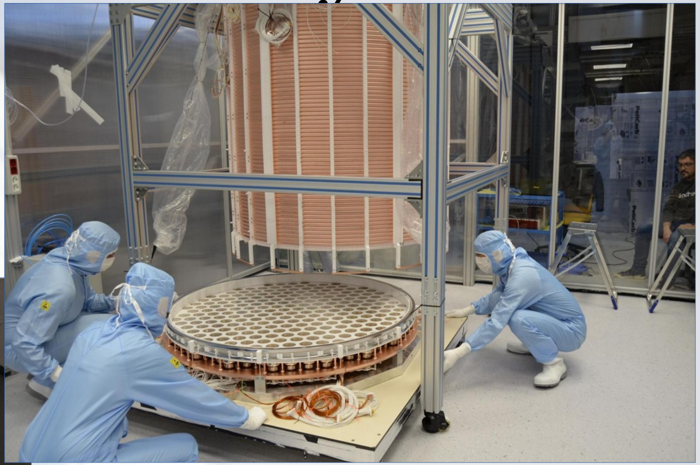
NEUTRON VETO

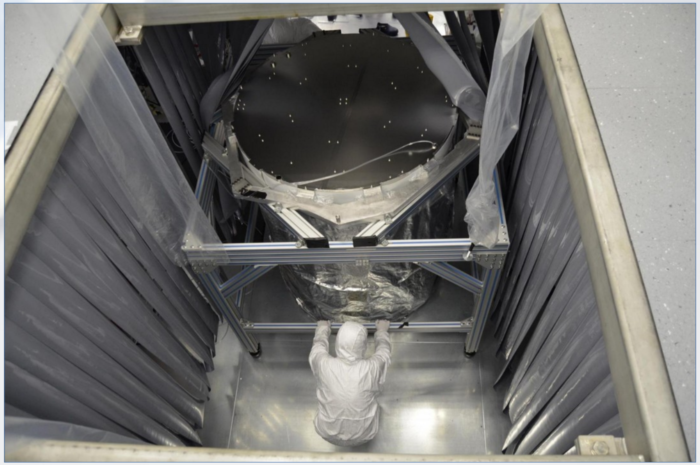
Tagging and in-situ measurement of neutron-induced background – Gd Sulphate in water

XENONnT on the runway



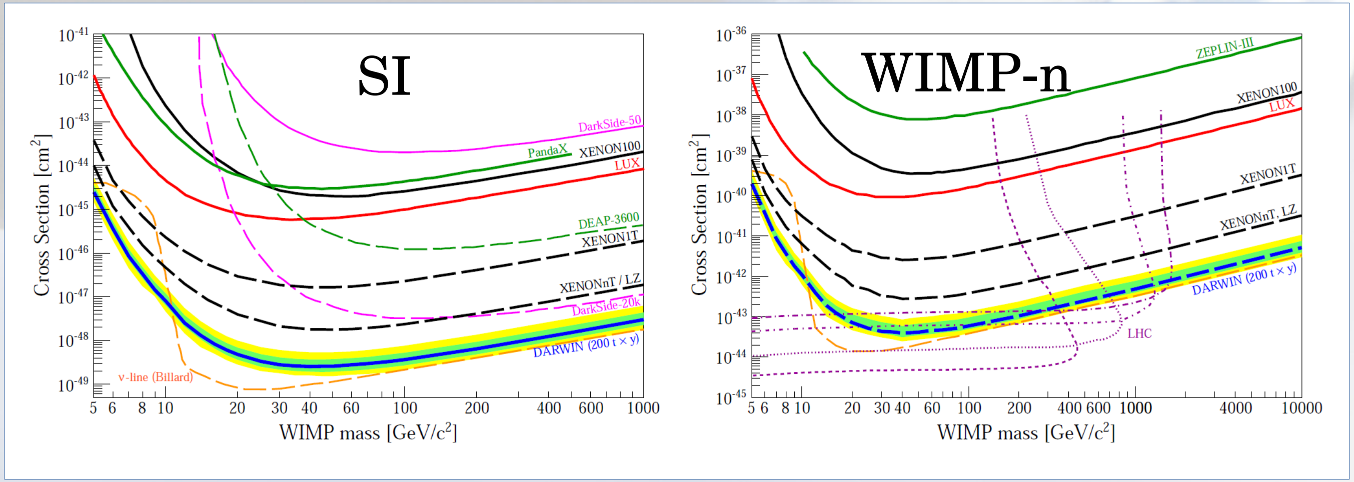


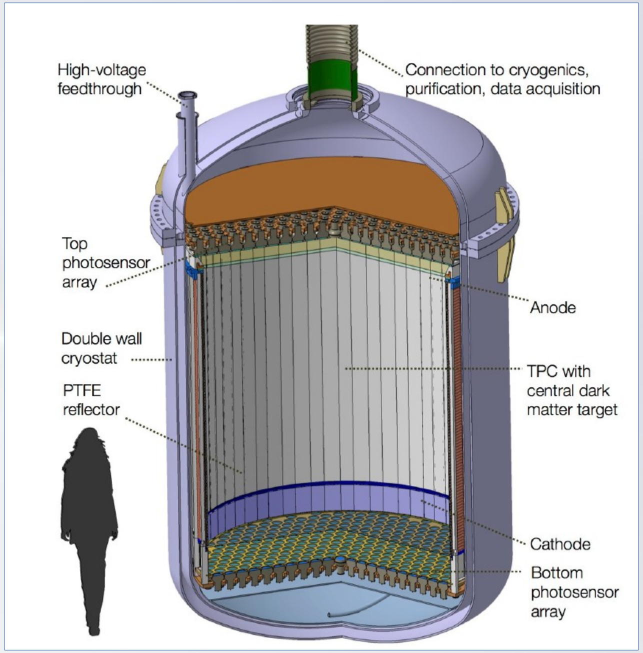




DARWIN – The ultimate LXe exp?

- 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)!

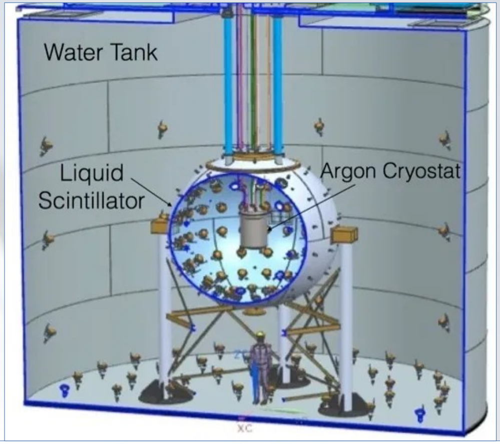


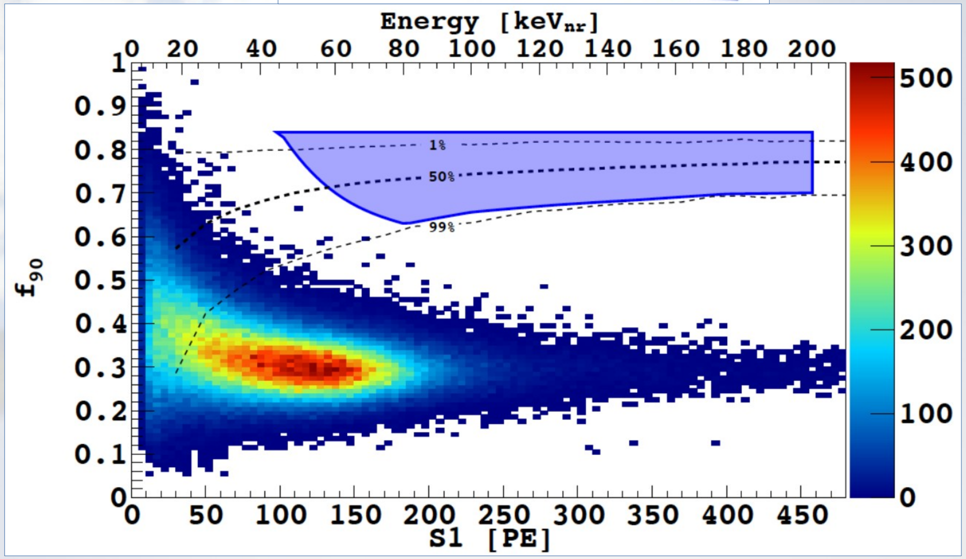


1606:07001

DarkSide50: Argon TPC!

- At LNGS (Italy)
- TPC with PSD discrimination
- Demonstrated excellent performance
- Not yet competitive due to size

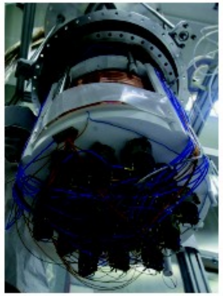


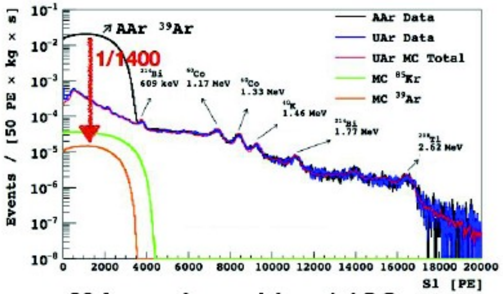


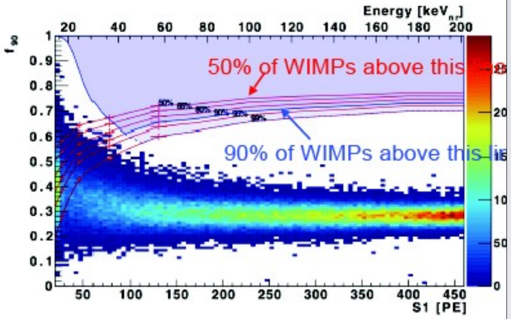
DarkSide50 and 20k: Argon!

- 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

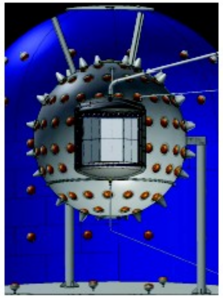






^{39}Ar reduced by 1400 70-d of Underground Ar
Blind analysis of 500-d underway

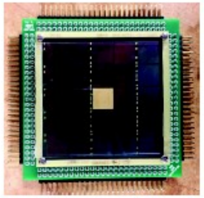
DarkSide-20k
30/23/20 T
tot/act/fiducial
Sensitivity<10^{-47} cm^2
Data: ~2021



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

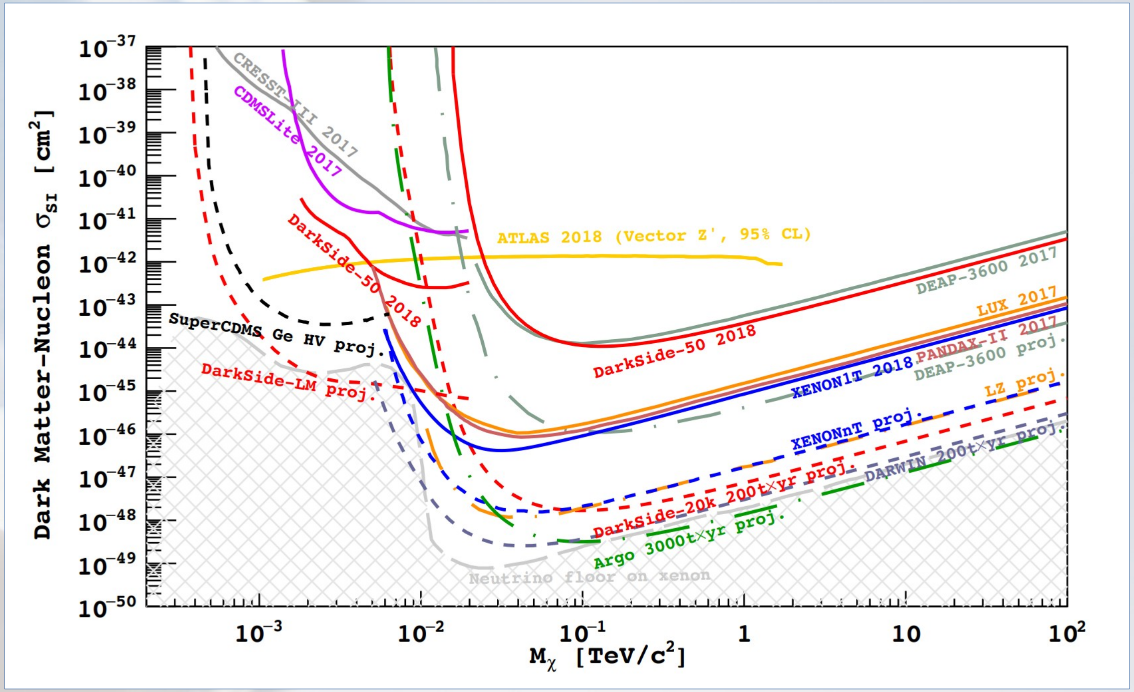
← Massive effort to extract and purify UAr

SiPMs replace → PMTs



ARGO

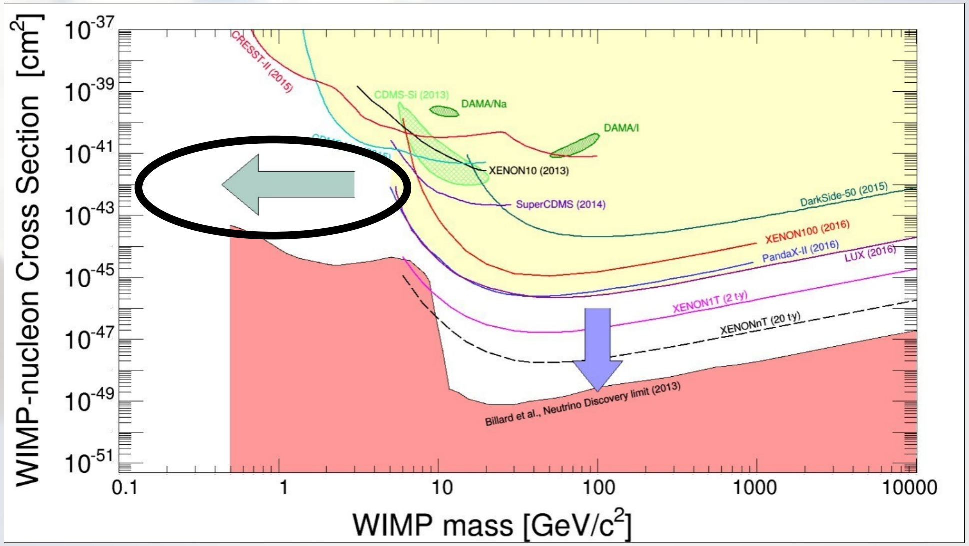
- Global collaboration – to reach 3000 t×yr!
- Massive efforts to harvest depleted Ar
- Demonstrated >3 orders of magnitude depletion for ^{39}Ar
- Choices of technology, location TBD
- Aims for the ν floor



DarkSide DEAP ArDM MiniCLEAN

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



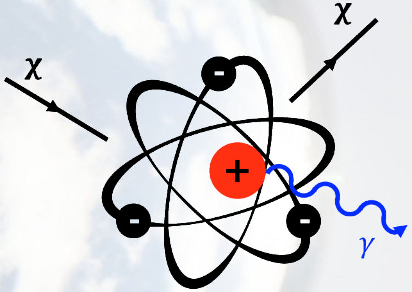
Low mass DM

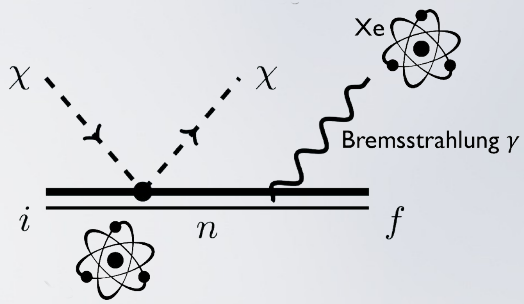
- For masses below a few GeV, the "classical" NR and discrimination fails, owing to the small energy deposit
- Lowering the threshold is key
- Some novel ideas may open the gate for "high threshold" experiments as well (but at a cost):
  - Bremmstrahlung
  - Migdal effect

Bremsstrahlung and Migdal:
Lowering the threshold for NRs

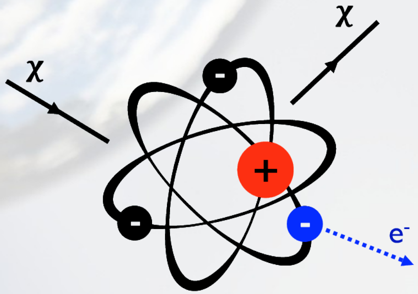
- Two proposed processes can "translate" a NR into a low energy ER through inelasticity of the interaction

Bremsstrahlung: Kouvaris & Pradler (2017), McCabe (2017)





Migdal effect: Ibe et. al. (2018), Dolan et. al. (2017)

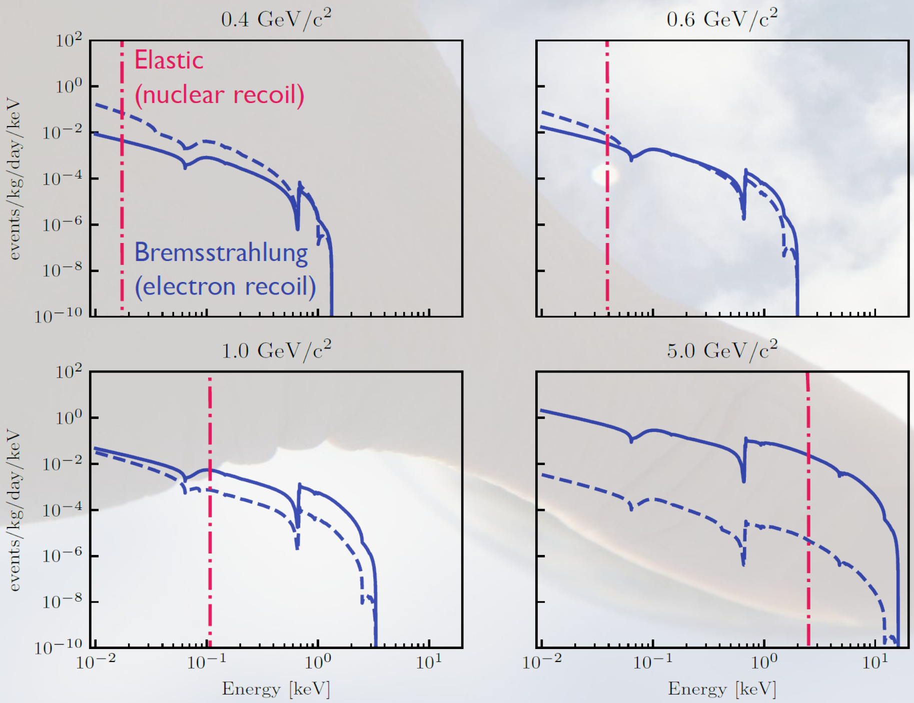


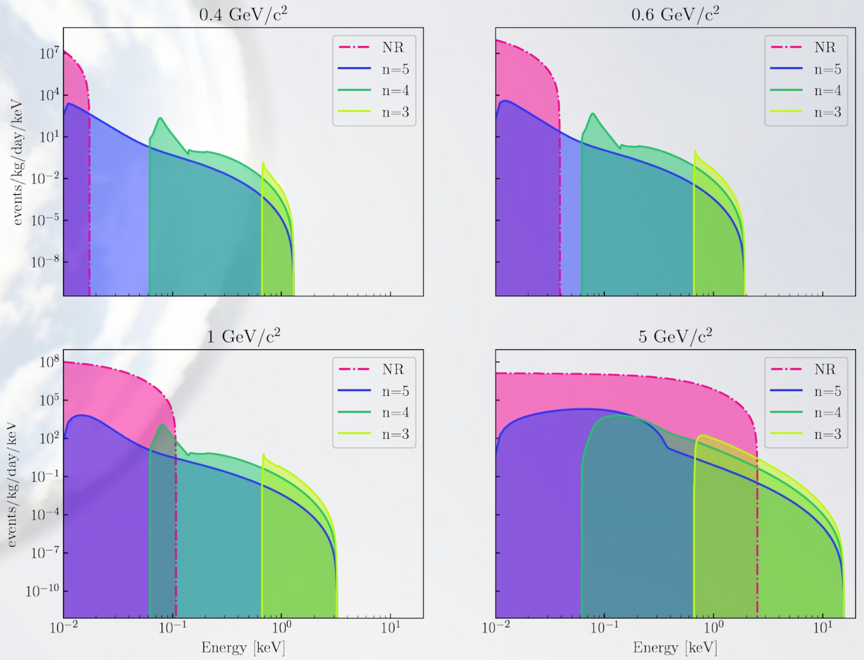
$$|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle$$

$$\mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$$

Brem & Migdal observables

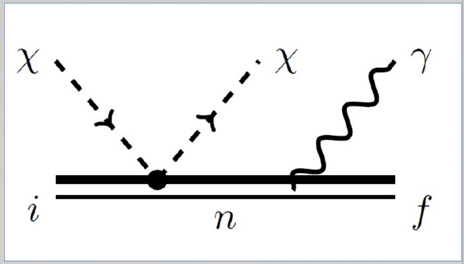
- Brem (left) and Migdal (right) @ $\sigma=10^{-35}$ cm^2

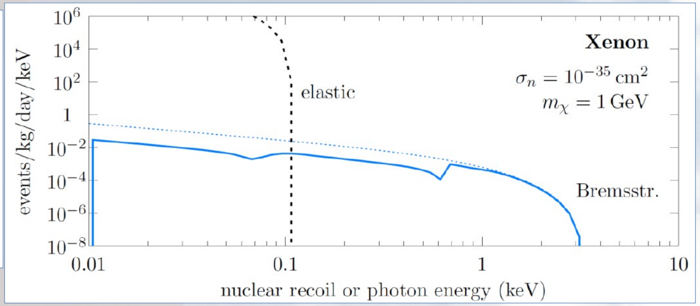




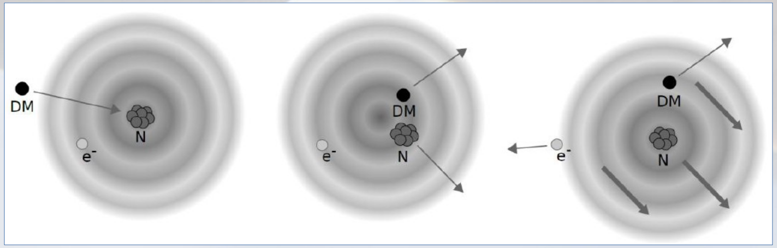
BUT – new ideas for interpretation may bring LXe here as well!

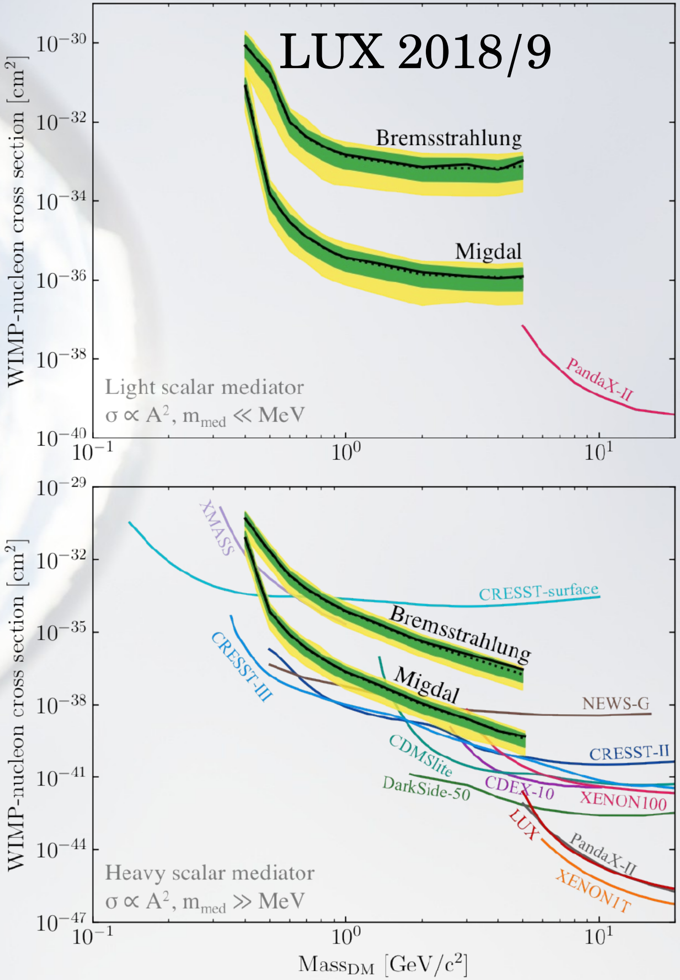
- Bremmstrahlung PRL 118, 031803 (2017)





- Migdal effect JHEP03(2018)194





And… Giving up on S1 for low threshold

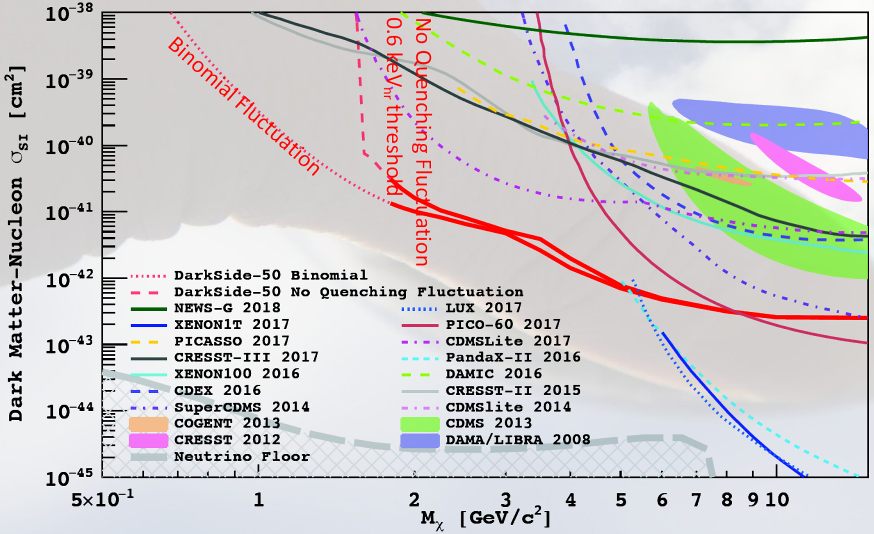
Ionization signal (S2): threshold < 0.1 keV_{ee} / 0.4 keV_{nr}

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**.

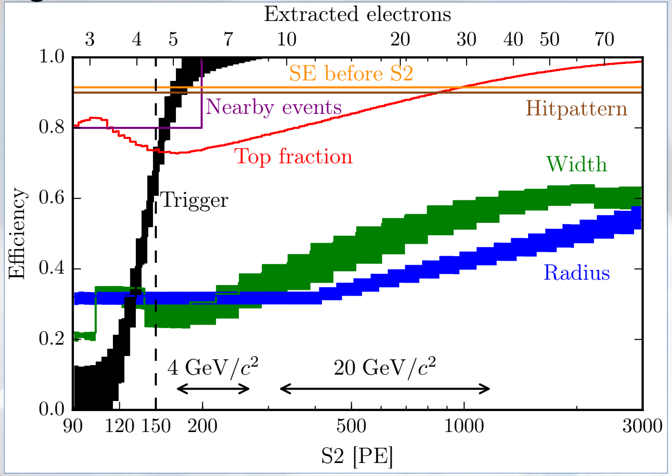


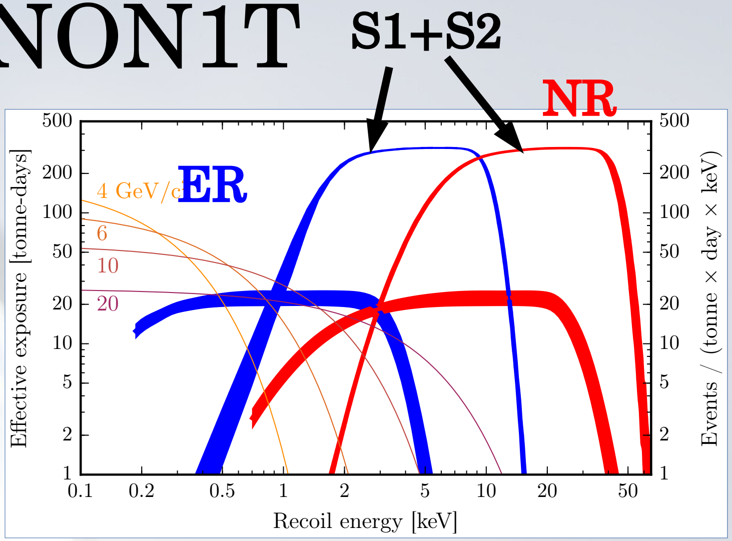
Phys. Rev. Lett. 121 081307 (2018)

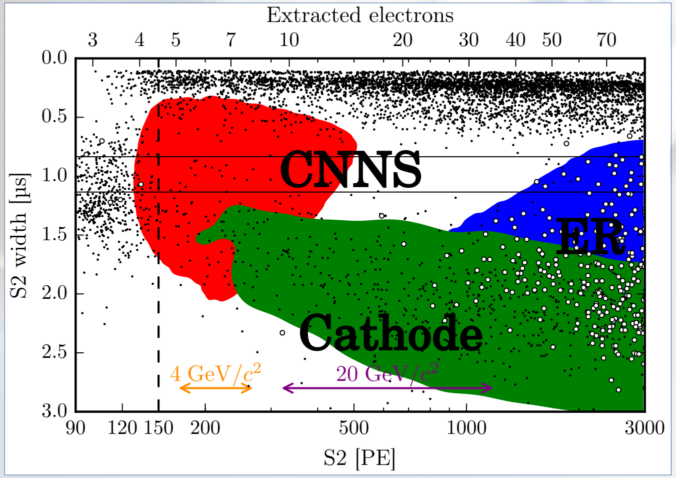
- Both Xe and Ar TPCs can go "S2-Only"
- Much lower threshold, both NR and ER
- Larger backgrounds – reduced fiducialization, no discrimination
- Can (mostly) only set limits and not discover
- Here, DS-50 as an example

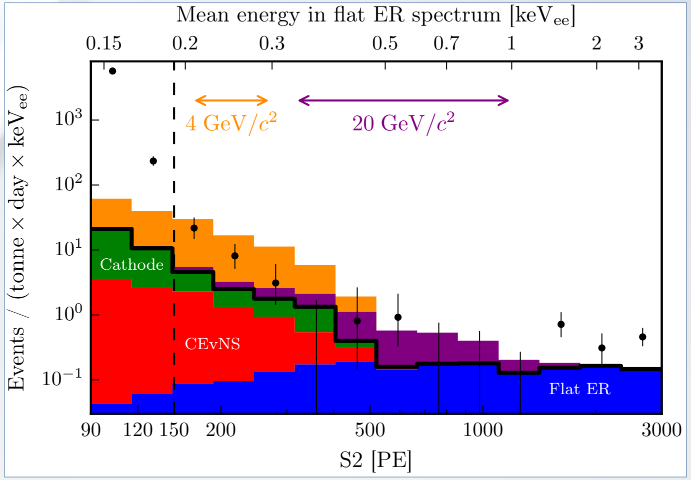
S2-only searches - XENON1T

- If we give up S1 the threshold can be lowered significantly
- Downsides:
  - Much higher background
  - No underlying background model
  - Instrumental effects dominate





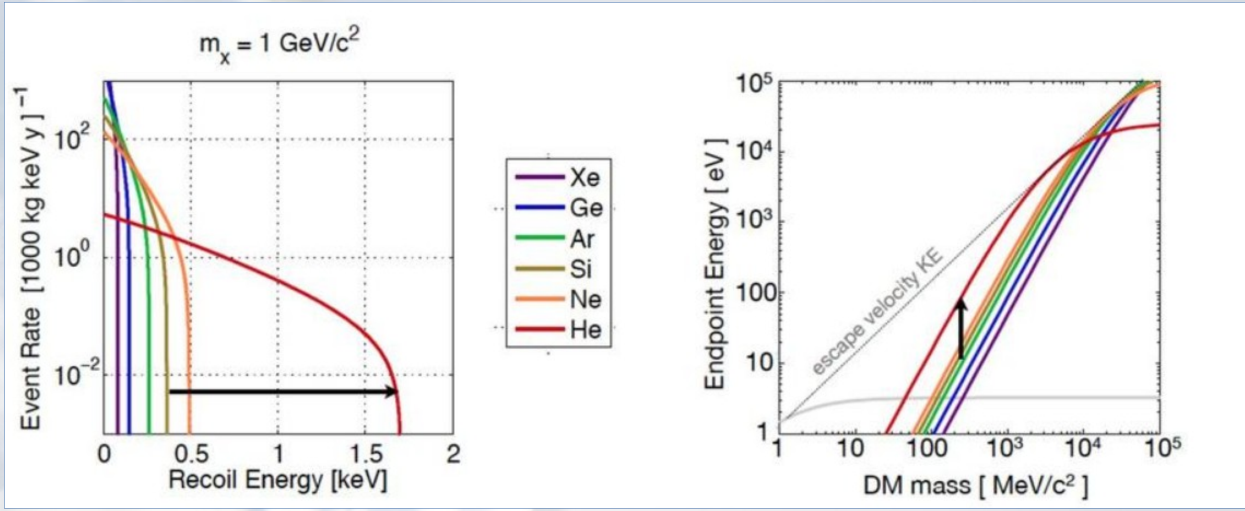




1907.11485, PRL (2019)

He – The lightest target?

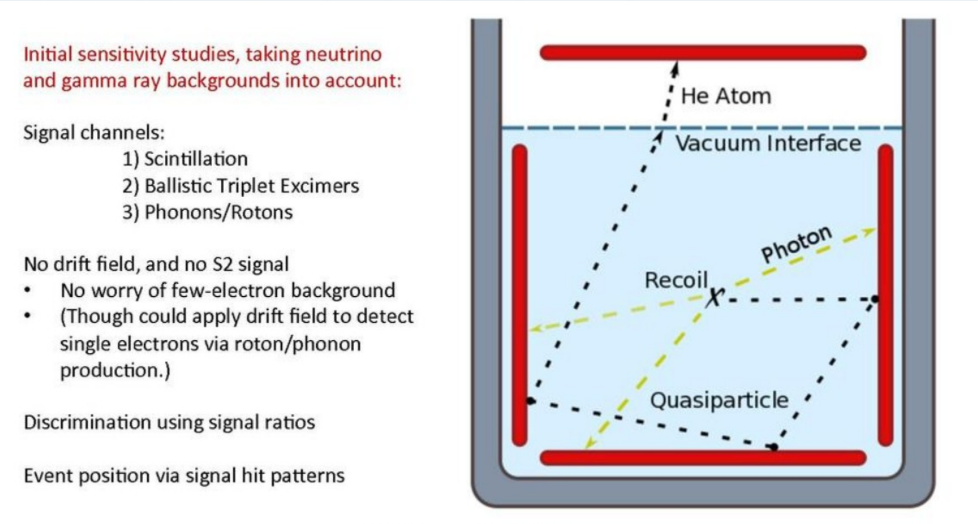
- Kinematic sensitivity to low mass DM
- Scintillation pulse shape discrimination much stronger than Ar
- Can detect also: charge, phonons, rotons
- No realization as DM detector yet

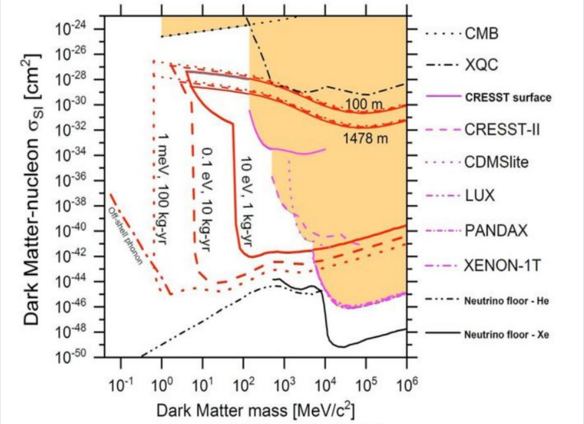


PRD 87, 115001 (2013)

Superfluid He detector?

- Breaking SF He requires a very low energy deposit (~meV)
- Extremely low mass sensitivities, natural discrimination
- Studies ongoing (McKinsey, Hertel)





Things we did not cover

- Alternative interpretations of DM (EFT, pions, double scatter, tracks…)
- Bubble chambers
- Dedicated low threshold R&D
- Ne targets (was a thing once)

Summary

- Noble elements are awesome!
  - They Scintillate!
  - They amplify electrons!
  - They can be accumulated!
  - They can find Dark Matter (maybe)!
- Experiments with noble liquids will dominate “high” mass range for the foreseeable future
  - Size can not be matched
  - Backgrounds are (seemingly) under control, with many approches (Xe and Ar) for handling
- “Low” mass DM – also a target! (not to mention He…)

The End