Title: Direct Search for Dark Matter with XENON

Date: Jun 13, 2009 09:40 AM

URL: http://pirsa.org/09060057

Abstract: The XENON project pursues the goal of directly detecting nuclear recoils resulting from scattering interactions with Weakly Interacting Massive Particles (WIMPs), using a phased approach of increasingly more sensitive experiments. The detector consists of a dual-phase liquid/gas xenon time projection chamber, which can measure down to ~2 keV(ee) energy threshold and discriminates against background using both the primary scintillation light and the charge signal resulting from interactions in the noble liquid. The current exeriment XENON100 is the successor of the highly successful XENON10 detector, featuring 10 times greater sensitive mass and 100 times lower background. Its sensitivity with an ultimate exposure of 6000 kg days will be 2 times 10^{-45} cm^2 for spin-independent interactions at 100 GeV/c^2. XENON100 has been installed and is operating. I will report on the present status and discuss its physics reach along with future prospects of detectors at the ton scale.

Direct Search for WIMP Dark Matter with XENON

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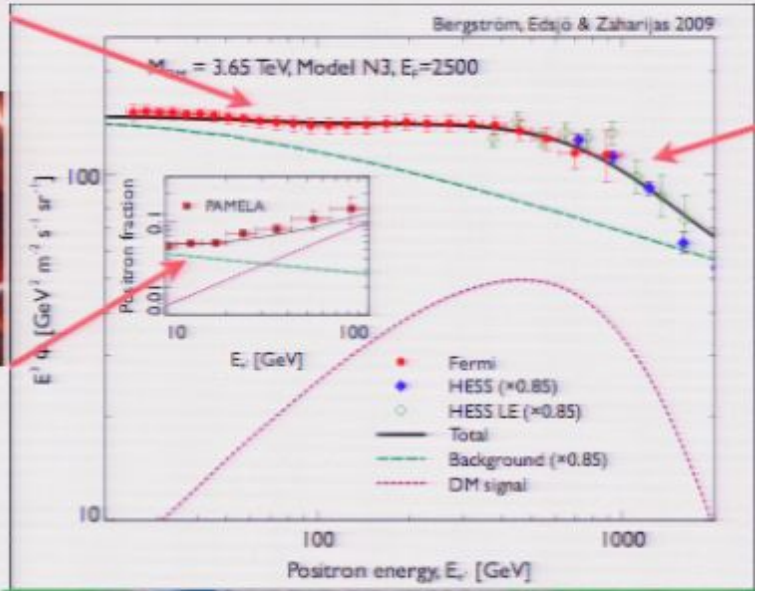
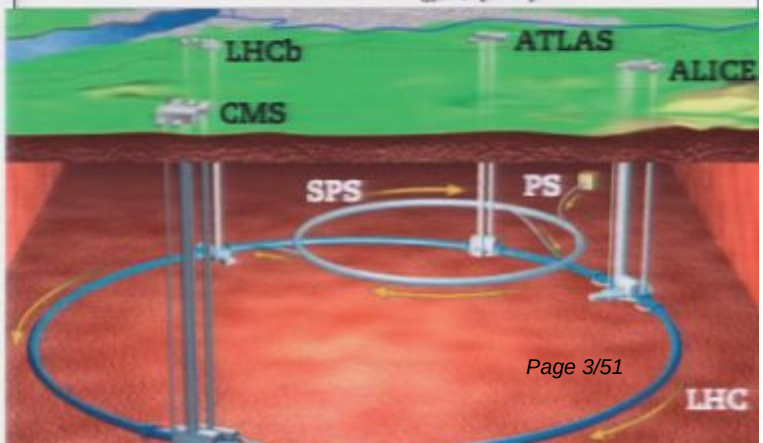
New Lights on Dark Matters
Waterloo, June 13, 2009

Dark Matter Detection Methods

- Astrophysics / Cosmology:
  Measurement of Gravitational Effects.
  - Rotation curves of spiral galaxies
  - Orbital velocities of galaxies in clusters (Zwicky 1933)
  - Colliding clusters (Bullet cluster)
  - Large scale structure, lensing

- **Direct Detection:**
  - WIMP scattering
  - Axion searches
- Indirect Detection: from annihilation or decay
  - Cosmic rays
    (PAMELA positron excess? Fermi electron spectrum?)
  - Neutrinos
  - Gamma-rays
- Accelerator-based Creation and Measurement:
  - Missing energy / momentum
  - Search for related particles (SUSY, extra dimensions) even if not the DM particle itself



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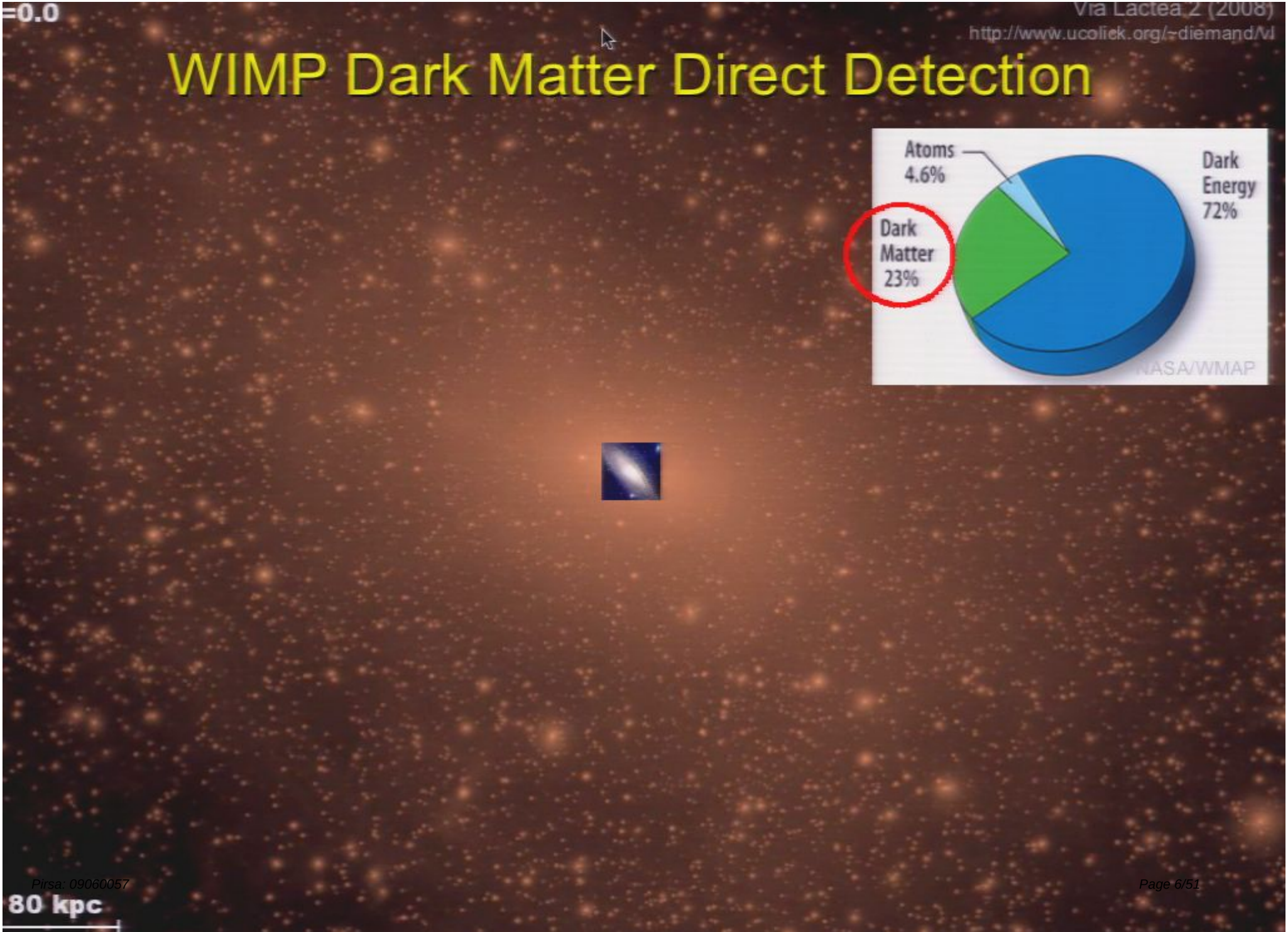
Via Lactea 2 (2008)
http://www.ucolick.org/~diemand/vl
80 kpc

WIMP Dark Matter Direct Detection

WIMP Dark Matter Direct Detection



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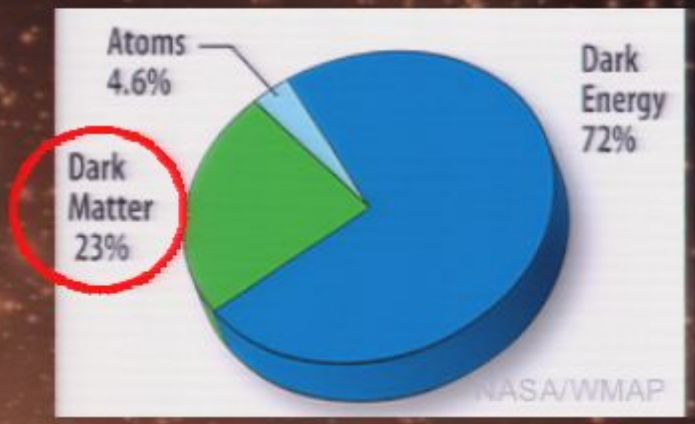
WIMP Dark Matter Direct Detection

- Dark Matter is non-bayonic, (rather) cold, ...
  if a thermal relic from the Big Bang ...
  ↪ Weakly Interacting Massive Particles: WIMPs



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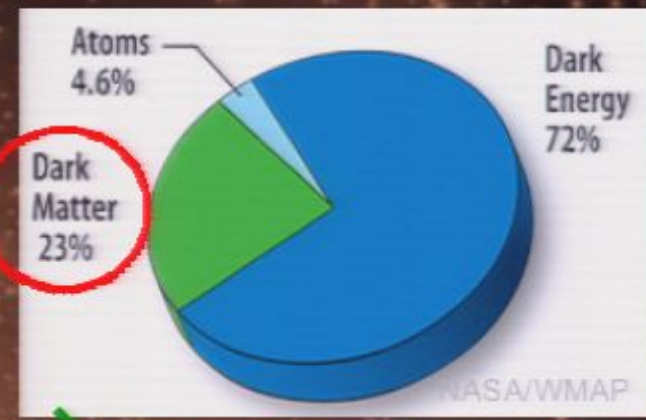
- Scattering of WIMPs χ off of nuclei A.
  - → elastic or inelastic?
  - → spin-independent ($\sim A^2$) or spin-dependent?



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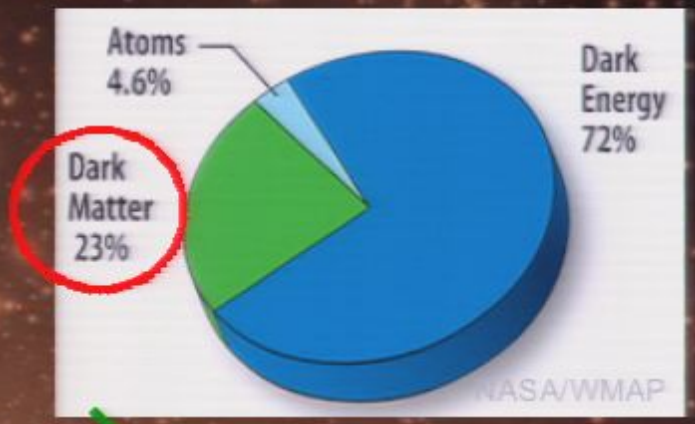
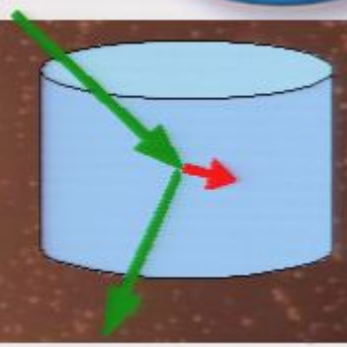
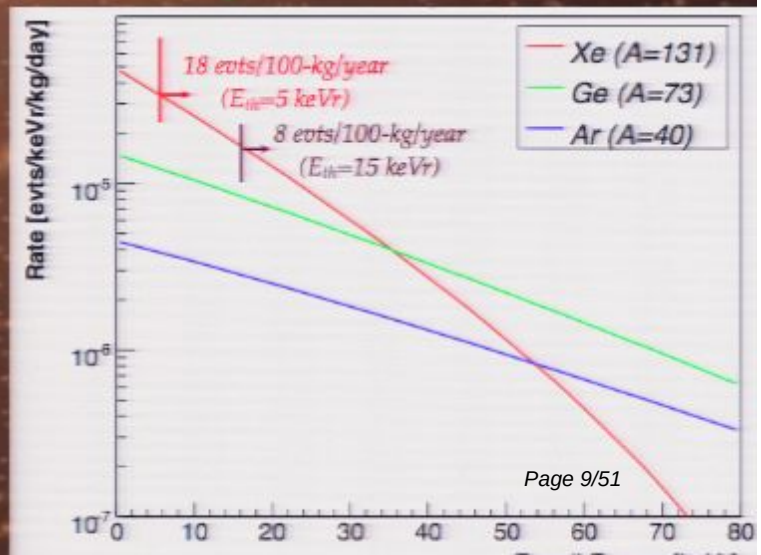
- Energy spectrum depends on WIMP velocity v_χ and mass m_χ.
  - → $m_\chi \gtrsim 30$ GeV/c^2 (?)
  - → $v_\chi \sim 230$ km/s
  - → "Standard" spherical halo:
    Featureless recoil spectrum <E> ~ O(10 keV)



XENON100





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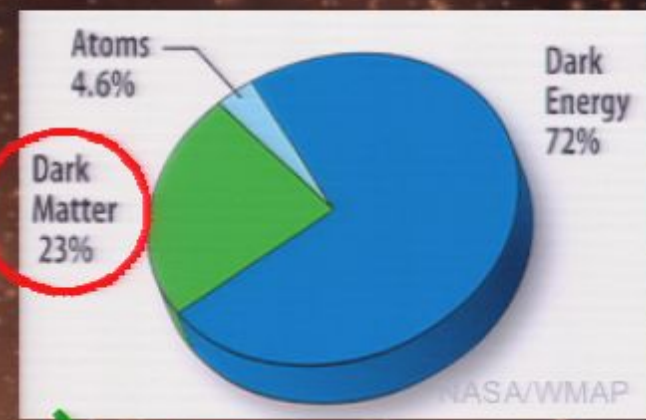
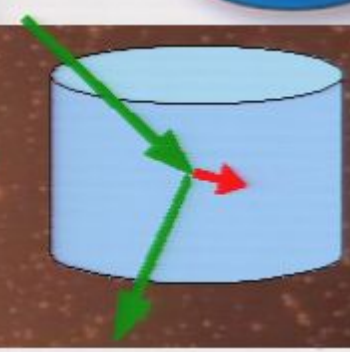
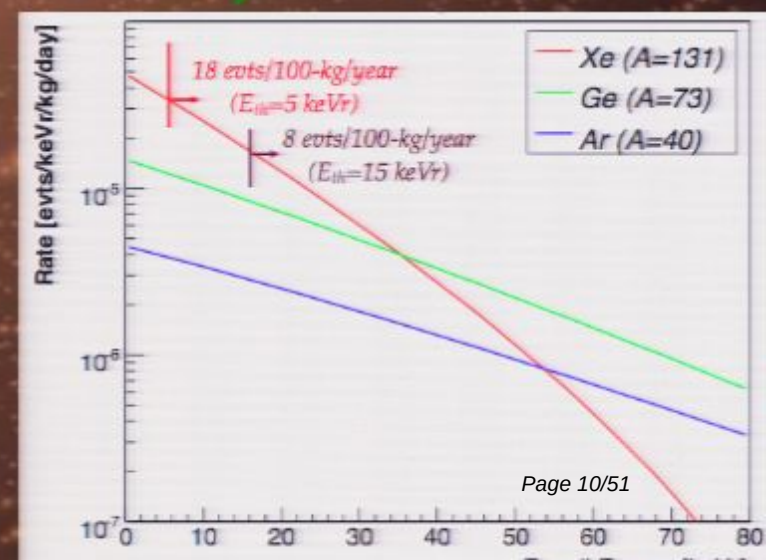
    Featureless recoil spectrum <E> ~ O(10 keV)
- Scattering rate ~ $N\,(\rho_\chi/m_\chi)\,\langle v_\chi\,\sigma_{scat}\rangle$
  - → N: number of target nuclei in the detector
  - → ρ_χ/m_χ: local number density of WIMPs
    $\rho_\chi \sim 0.3$ GeV/c^2/cm^3, $(\rho_\chi/m_\chi) \lesssim 10$ / L
  - → σ_{scat} cross section per nucleus.
    $< 10^{-2}$ events / kg / day





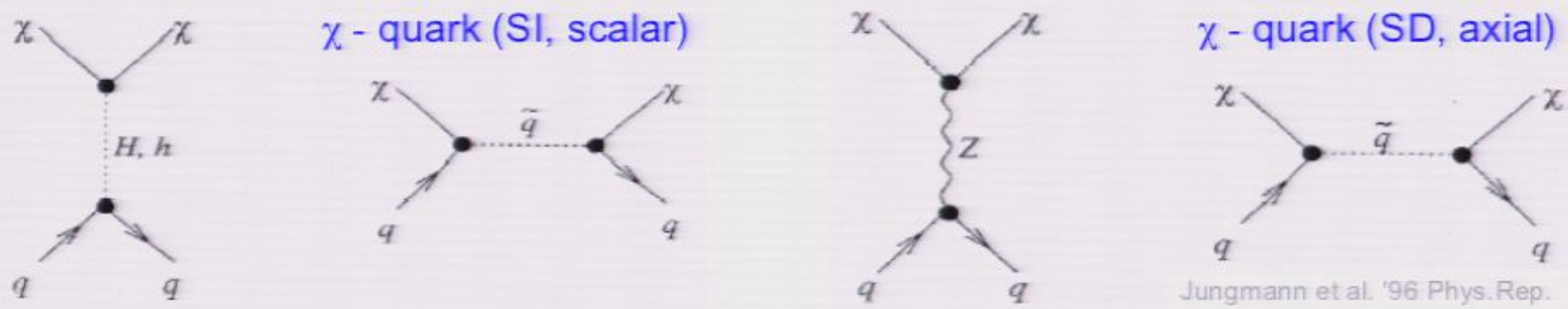


80 kpc

WIMP Scattering Cross Sections

Example: SUSY (but direct searches are sensitive to many other models as well)

- Compute cross sections χ – quark and χ – gluon with various SUSY models. Large parameter space, constrained by accelerator and direct search experiments, and cosmology.
  - **spin-independent**: coupling to mass of nucleus. Coherence $\Rightarrow \sigma \propto A^2$
  - **spin-dependent**: coupling of spins of nucleus and neutralino interaction with paired nucleons in the same energy state cancel => no A^2 enhancement



Jungmann et al. '96 Phys.Rep.

- Distribution of nucleons within nucleus: nuclear form factor.
  - SI: Large nuclei gain ~A^2 at small momentum transfer, but lose at higher momentum transfer due to coherence loss.

Backgrounds in Direct DM Search

Cross-sections are *very* small: $<10^{-43}$ cm^2 or 10^{-7} pb (spin-independent)

Without background, sensitivity $\propto$ (mass × exposure time)$^{-1}$

With background subtraction $\propto$ (M t)$^{-1/2}$ until limited by systematics.

Backgrounds:

Gamma-rays & beta decays:

- ~100 events/kg/day
- Need very good β and γ background discrimination.
- Shielding: low-activity lead, water, noble liquids (active), liquid N_2, ...

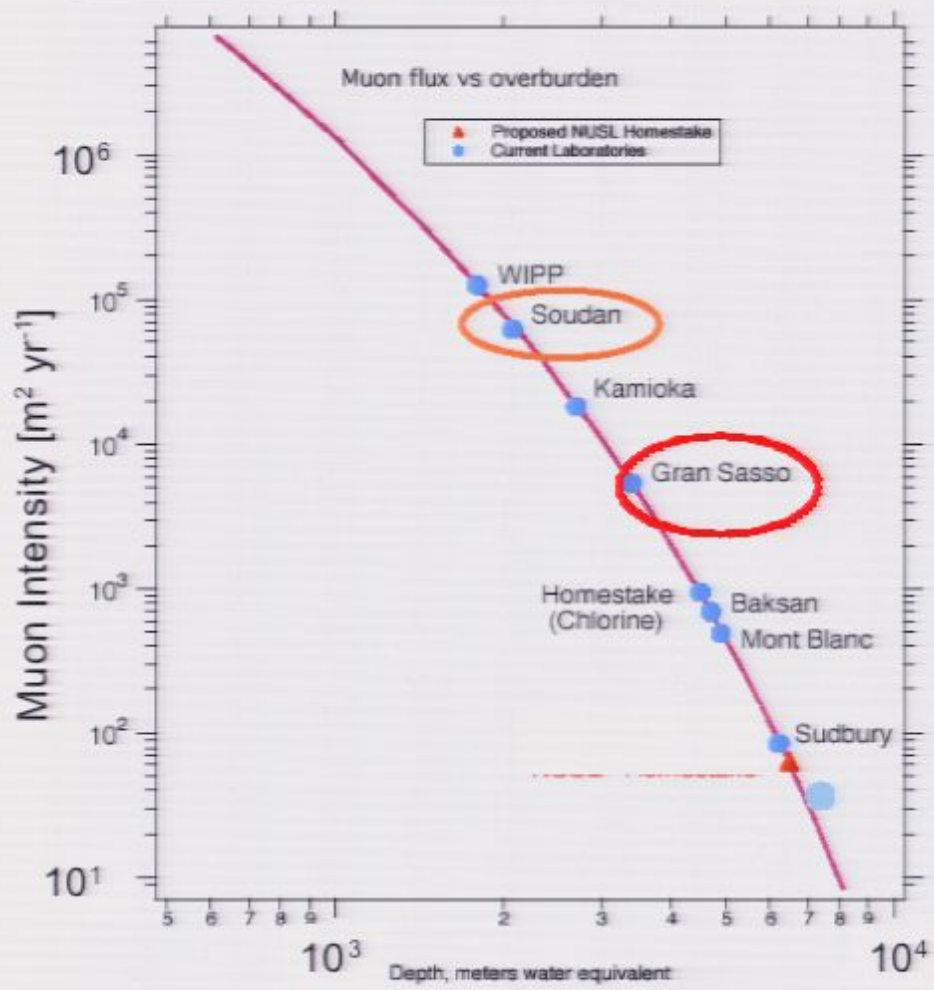
Neutrons from (α, n) and spontaneous fission (concrete, rock, etc.):

- ~ 1 event/kg/day (LNGS)
- Neutron moderator (polyethylene, paraffin, ...)

Neutrons from CR muons:

- Rate depending on depth.
- μ-veto, n-veto, shielding

α decays from Rn daughters, ...



Depth [meters water equivalent]

The XENON Program

GOAL: Explore WIMP Dark Matter with a sensitivity of $\sigma_S \sim 10^{-47}$ cm^2.

- Requires ton-scale fiducial volume with extremely low background.

CONCEPT:

- Target LXe: excellent for DM WIMPs scattering.
  - Sensitive to both axial and scalar coupling.
- Detector: two-phase XeTPC: 3D position sensitive, self-shielding.
- Background discrimination: simultaneous charge & light detection (>99.5%).
- PMT readout with >3 pe/keV. Low energy threshold for nuclear recoils (~5 keV).

PHASES:

R&D	XENON10	**XENON100**	XENON100+	XENON1T
Start: 2002	2005-2007	2007-2010	2009-2012	2011-2014 ?
	Proof of concept. Total mass: 14 kg 15 cm drift. Best limit in '07: $\sigma_{SI} \sim 10^{-43}$ cm^2	Under commissioning Total mass: 170 kg 30 cm drift. Goal: $\sigma_{SI} \sim 2 \times 10^{-45}$ cm^2	Approved by NSF. Total mass: 350 kg 60 cm drift. Goal: $\sigma_{SI} \sim 2 \times 10^{-46}$ cm^2	Under study. Total mass: 3 ton 100 cm drift. Goal: $\sigma_{SI} \sim 10^{-47}$ cm^2

The XENON100 Collaboration

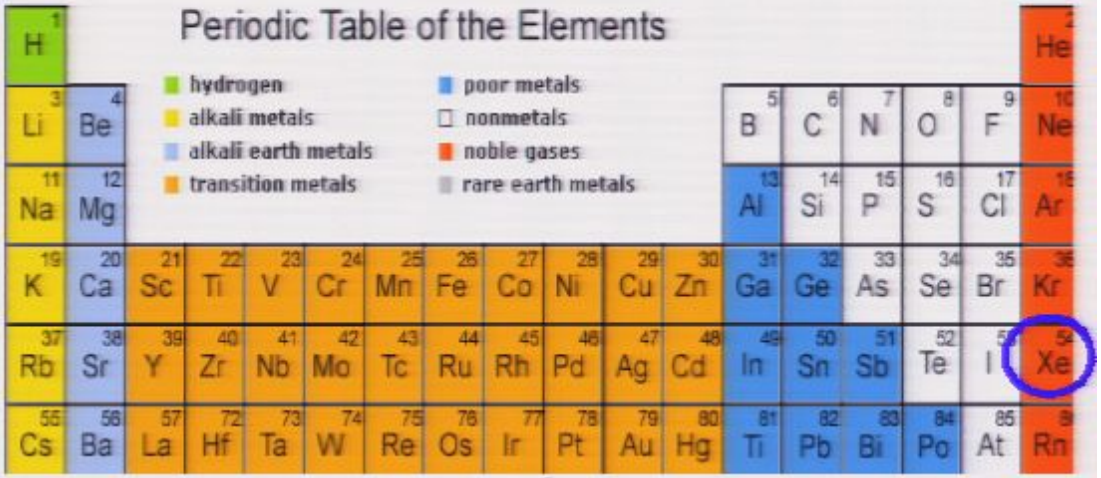
Elena Aprile	Uwe Oberlack	K. Arisaka, H. Wang	Laura Baudis	Jose M. Lopes	Francesco Arneodo
Columbia Univ.	Rice University	UCLA	Univ. of Zurich	Univ. of Coimbra	LNGS

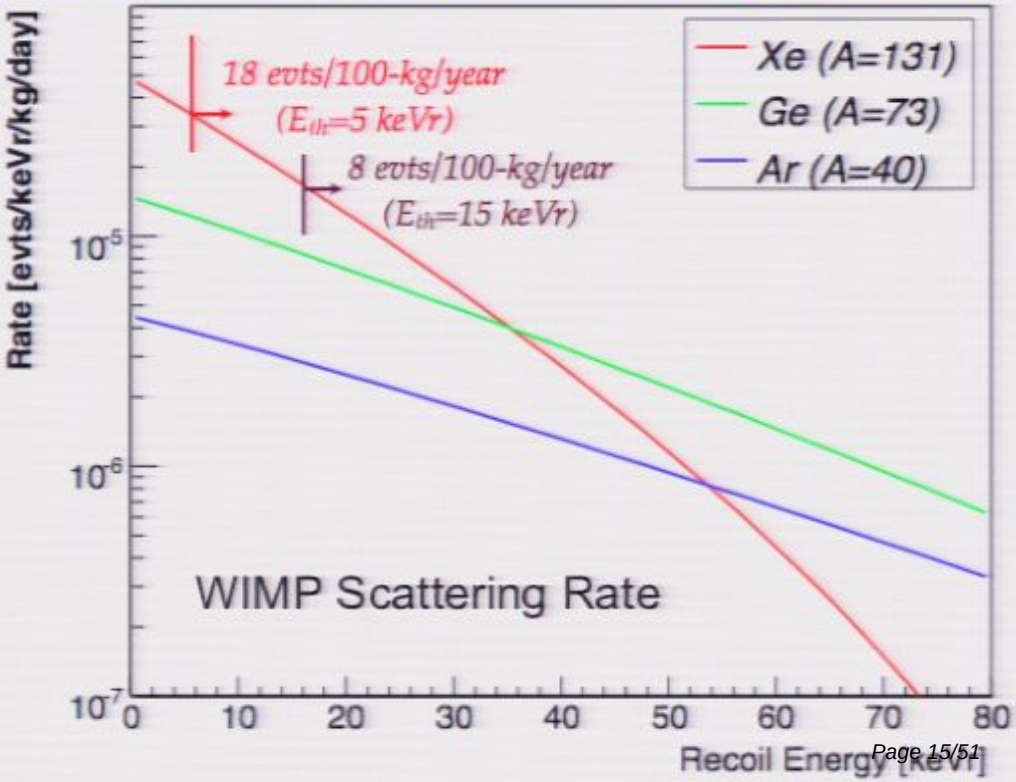
+ New groups: C. Weinheimer, Univ. of Münster (Germany)
D. Thers, Subatech (France)
N. Hasebe, Waseda Univ. (Japan)

+ K. Ni starting at
Shanghai Jiao Tong Univ. (China)

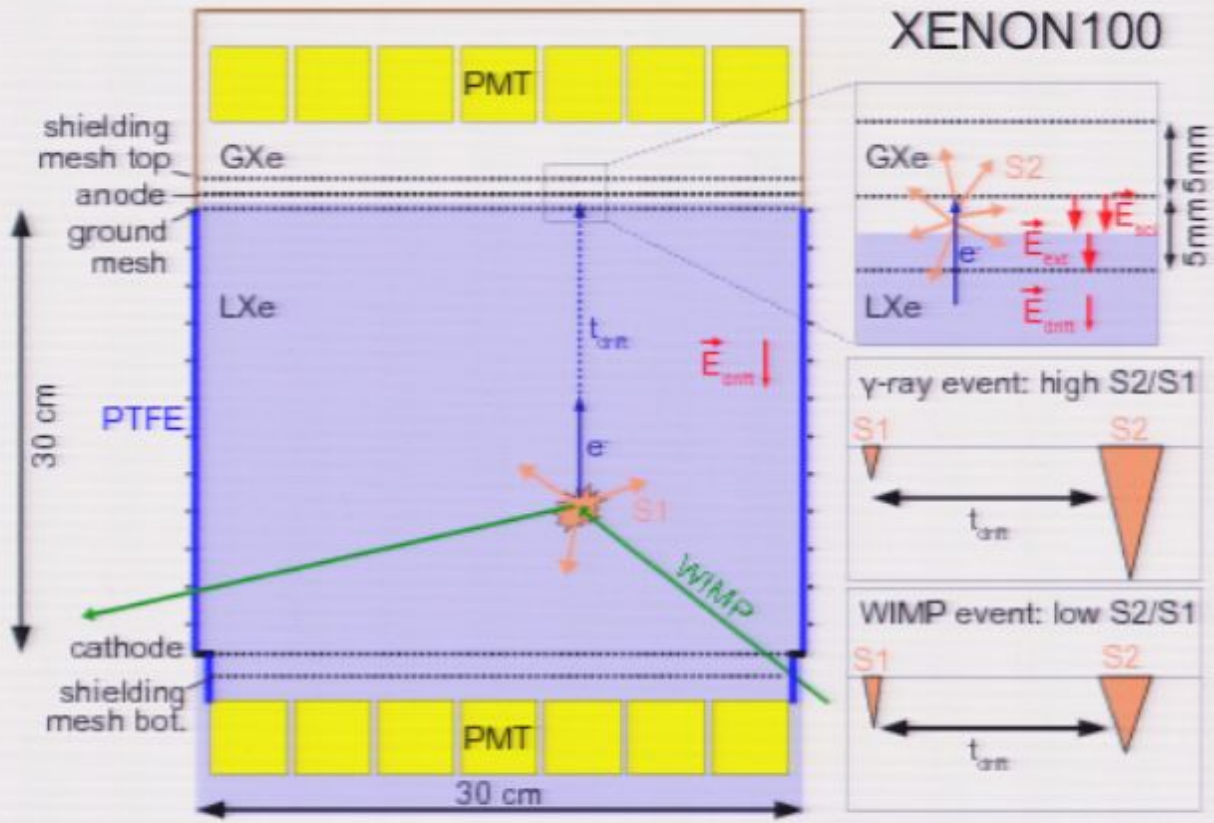
Liquid Xenon for Dark Matter Search

- Large atomic number A~131 best for SI interactions ($\sigma \sim A^2$).
  Need low threshold.
- ~50% odd isotopes: SD interactions
  If DM detected: probe physics with the same detector using isotopically enriched media.
- No long-lived isotopes.
  Proven Kr-85 reduction to ppt level.
- High Z (54) and density:
  compact & self-shielding
- Scalability to large mass for $\sigma \sim 10^{-47}$ cm^2 ~ 1 evt/ton/yr.
- "Easy" cryogenics (-100°C).
- Efficient and fast scintillator.
- Background discrimination in TPC.
  - Ionization/Scintillation
  - 3D imaging of TPC



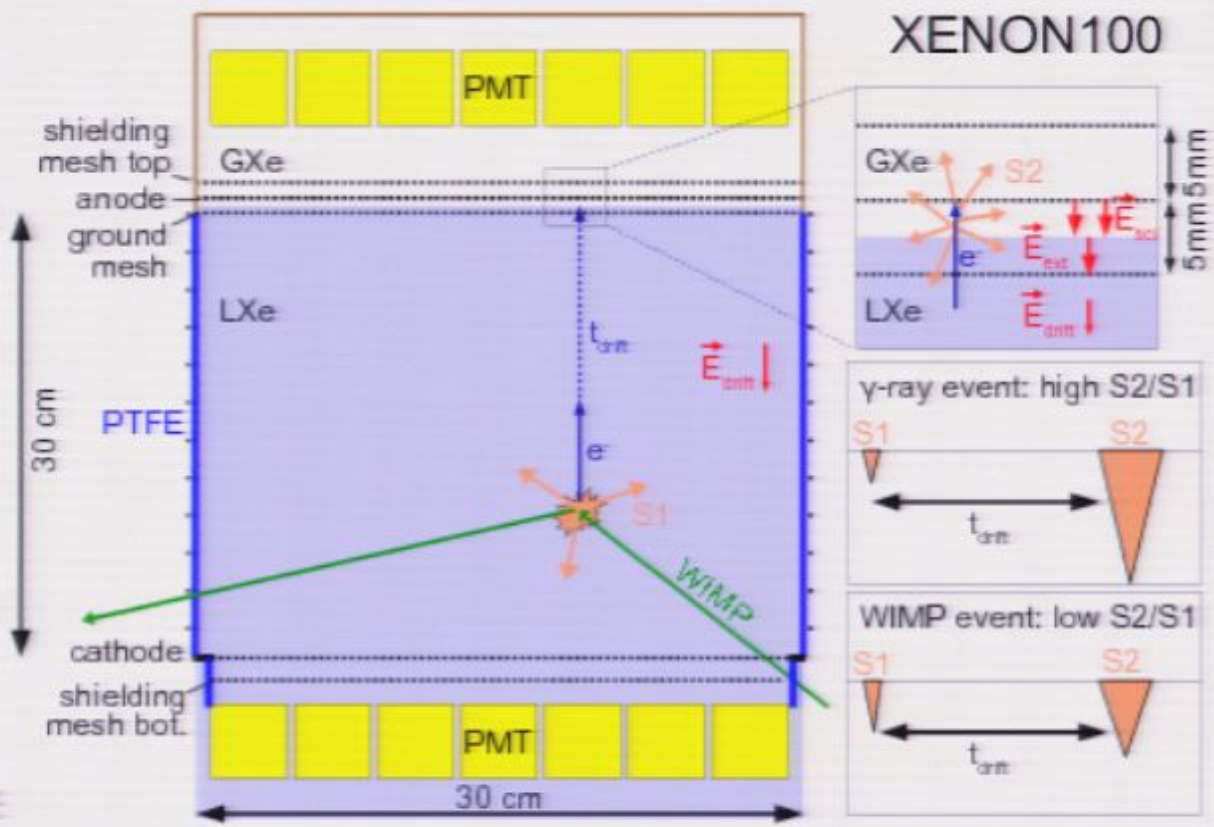


The Liquid Xenon Dual Phase TPC



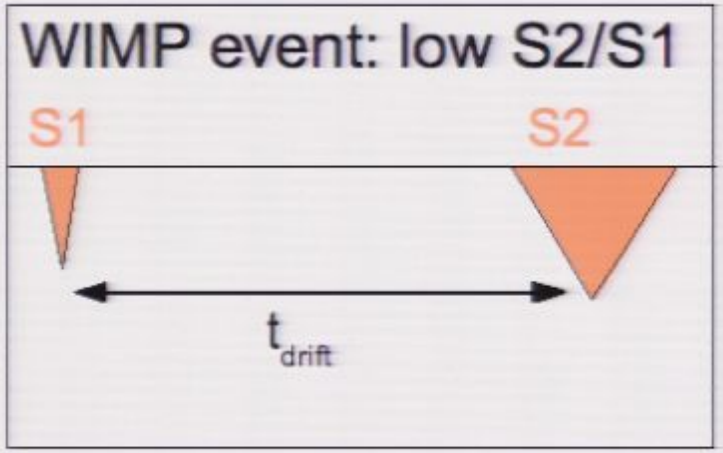
The Liquid Xenon Dual Phase TPC

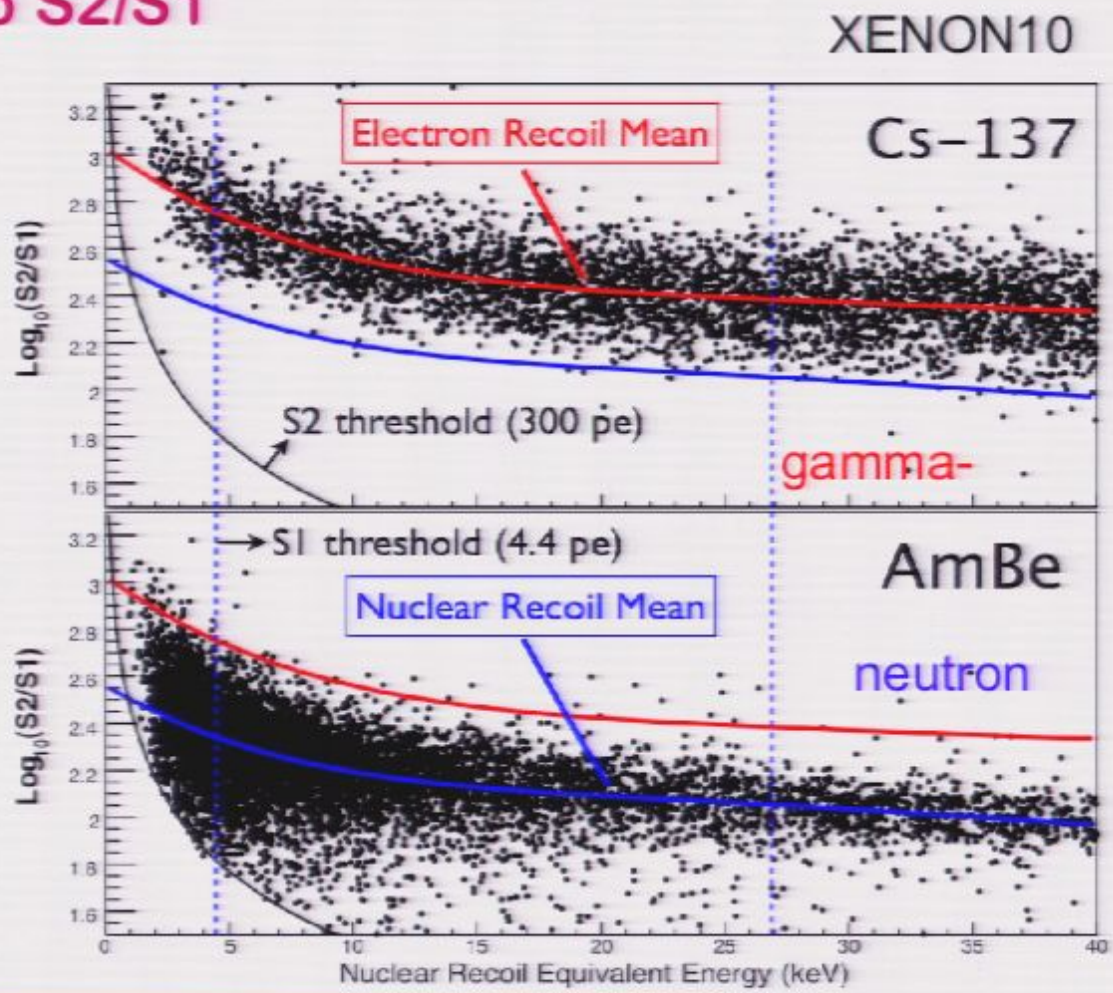
- Wimp recoil on Xe nucleus in dense liquid (2.9 g/cm^3)
  → Ionization + UV Scintillation
- Detection of primary scintillation light (S1) with PMTs.
- Charge drift towards liquid/gas interface.
- Charge extraction liquid/gas at high field (5 kV/cm) between ground mesh (liquid) and anode (gas)
- Charge produces proportional scintillation signal (S2) in the gas phase (10 kV/cm)



Background Discrimination in Dual Phase Liquid Xenon TPC's

Ionization/Scintillation Ratio S2/S1

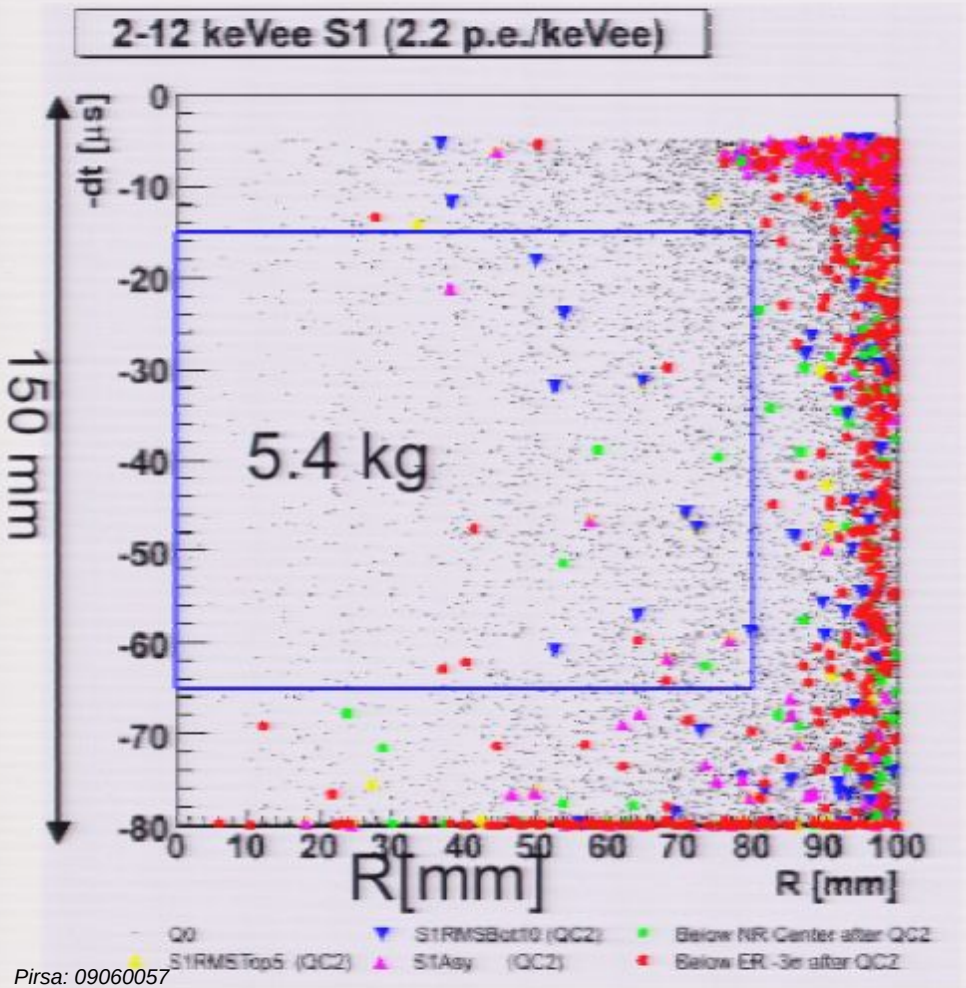


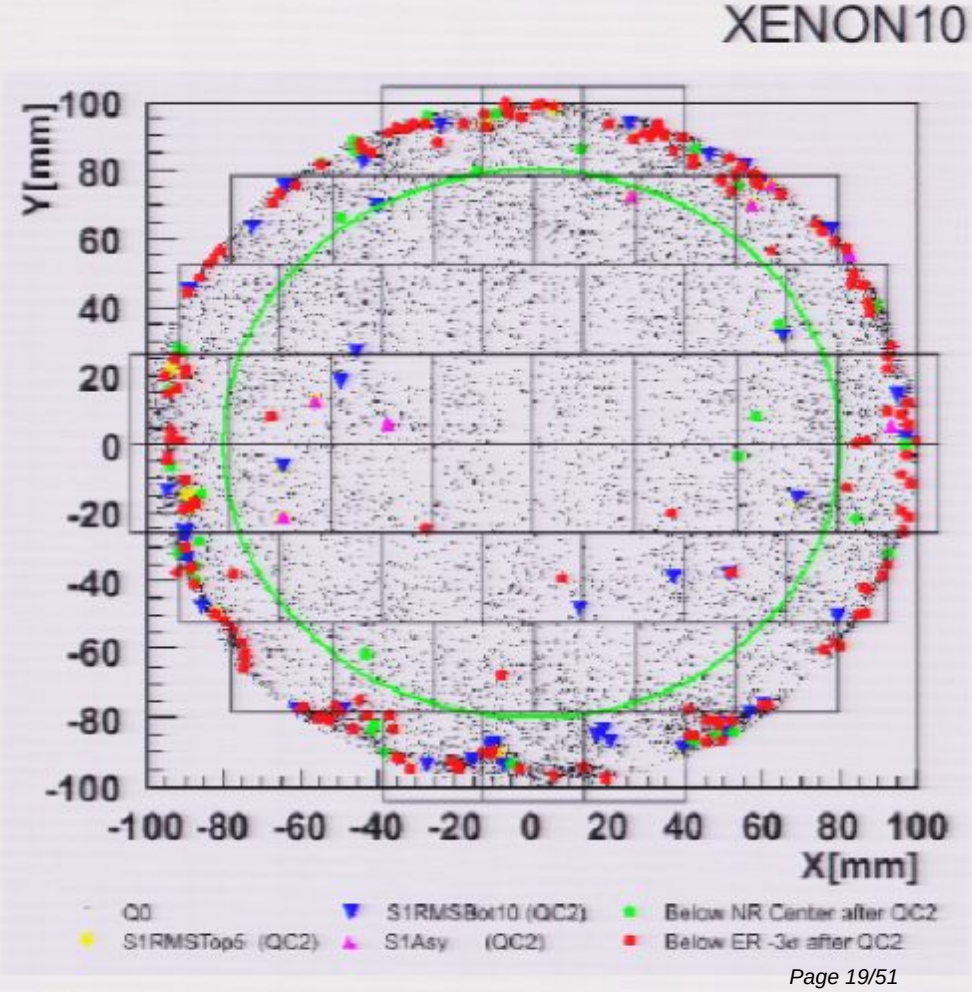


Factor 200-1000 background rejection at 50% acceptance in

Background Discrimination in Dual Phase Liquid Xenon TPC's

3D Position Resolution: fiducial cut, singles/multiples





Background Discrimination in Dual Phase Liquid Xenon TPC's

Comments on testing the DAMA/LIBRA annual modulation

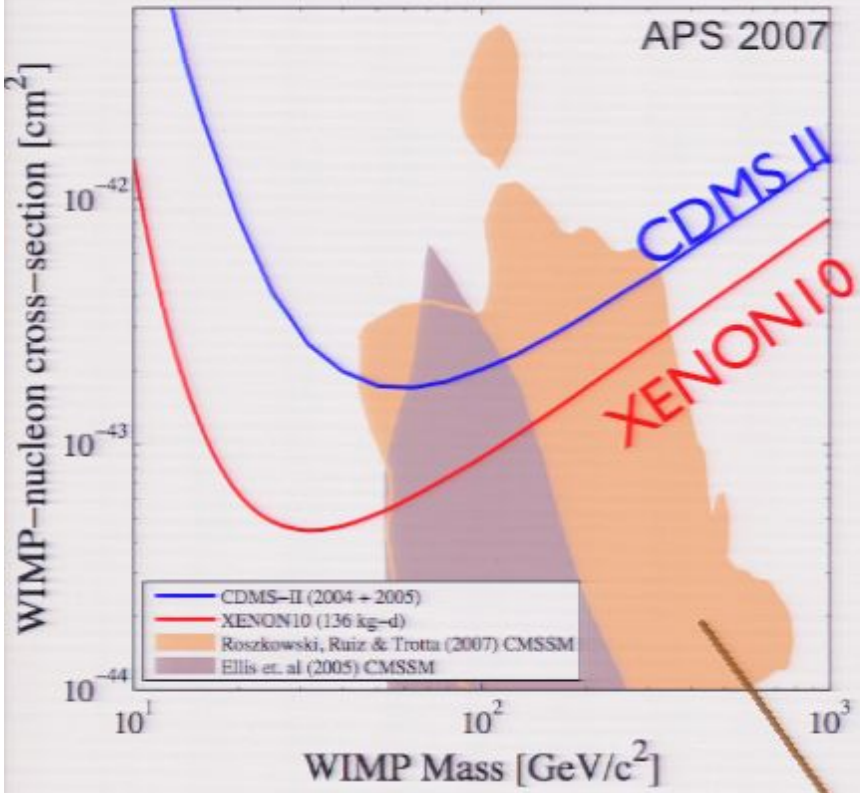
- Xe is an excellent scintillator, similar to NaI. Energy threshold are similar.
- Xe and I are next neighbours in the periodic table.
- Liquid Xe is homogeneous, and extremely radiopure.
- XENON100 (and XENON10) records all triggered events, making data selections only in software.
  - We can look at both nuclear recoils **and** interactions with electrons, and we know what we are looking at.
- Contrary to DAMA/LIBRA, we have background reduction even without nuclear recoil suppression, based on 3D position reconstruction and the excellent self-shielding of liquid Xe.
- Therefore, we can chose a fiducial volume of exquisitely low background (*), where we can look for rare events with a background rate two orders of magnitude lower than DAMA/LIBRA.
  - Annual modulation signal DAMA/LIBRA 2-4 keV: ~0.02 events / d / kg / keV
  - Background in DAMA/LIBRA: ~ 1 events / d / kg / keV , signal/bgd ~ 0.02
  - Background in XENON100: ~0.01 events / d / kg / keV , signal/bgd ~ 2 expected
    XENON100 with 6000 kg d exposure will be more sensitive than DAMA/LIBRA to annual modulation (if Xe is similar to NaI in response to DM articles)

$$\text{sensitivity} \propto \sqrt{\frac{M\,t}{b}}$$

The Previous Generation: XENON10
(2005-2007)
World Leading Upper Limits

Spin-independent

Phys. Rev. Lett. ***100***, *021303 (2008)*



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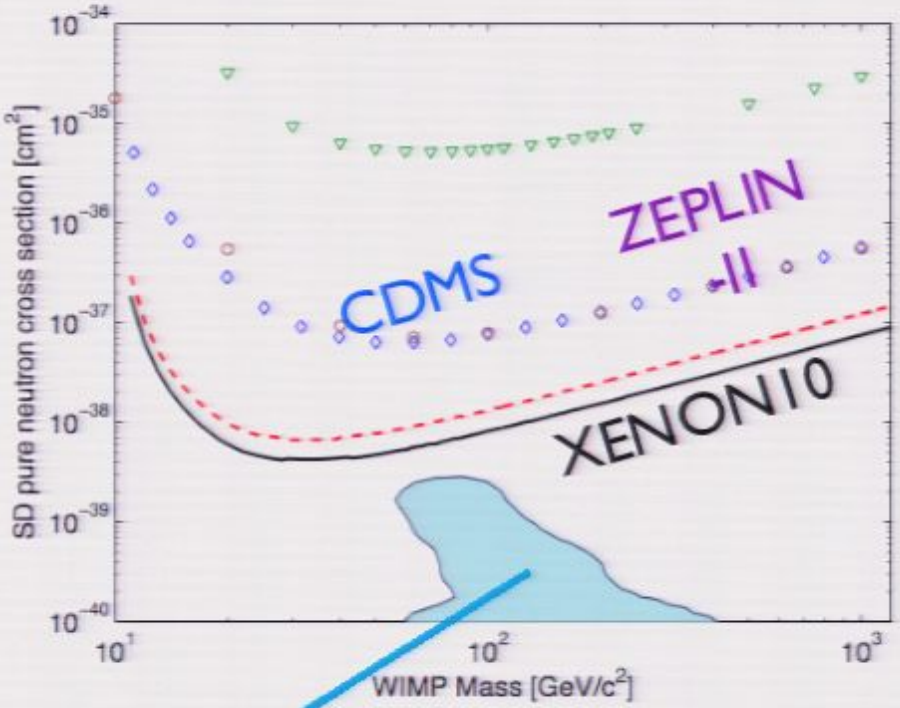
Phys. Rev. Lett. ***101***, *091301 (2008)*



8.8×10^{-44} cm^2 at 100 GeV
4.5×10^{-44} cm^2 at 30 GeV
(no background subtraction)

Constrained Minimal Supersymmetric Model

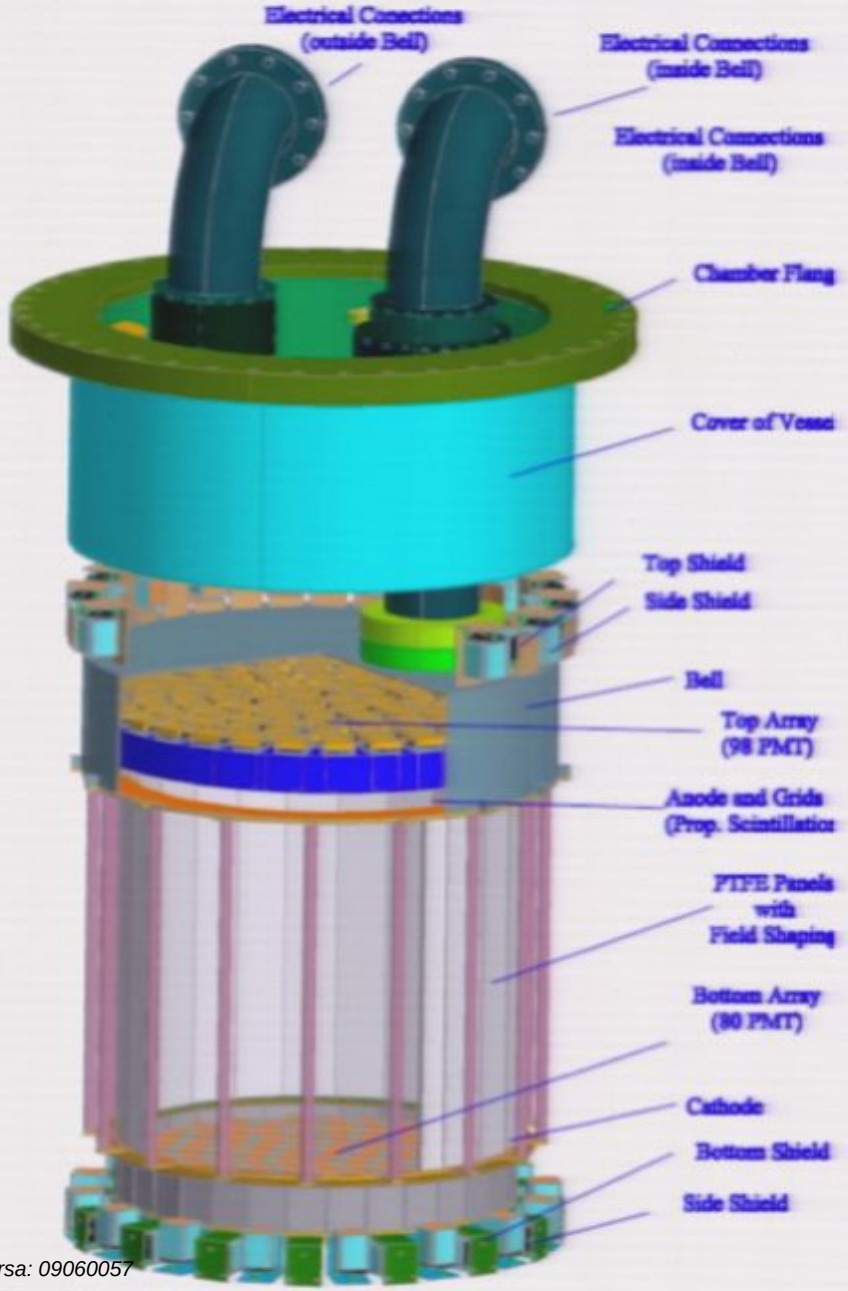
6×10^{-39} cm^2 at 30 GeV
(no background subtraction)

The Current Generation: XENON100 (2007-2010)

- 100 times lower background
  - Material screening
  - Active LXe Veto
  - Addition of inner Cu layer to XENON10 shield
  - Cryocooler/Feedthroughs outside shield
  - Low activity stainless steel
  - LXe self-shielding
- 10 times larger target mass
  - 70 kg in target volume, 170 kg total LXe
- New PMTs with low activity and high QE
- Improved electronics, grids, ...
- DM search to start in 2009

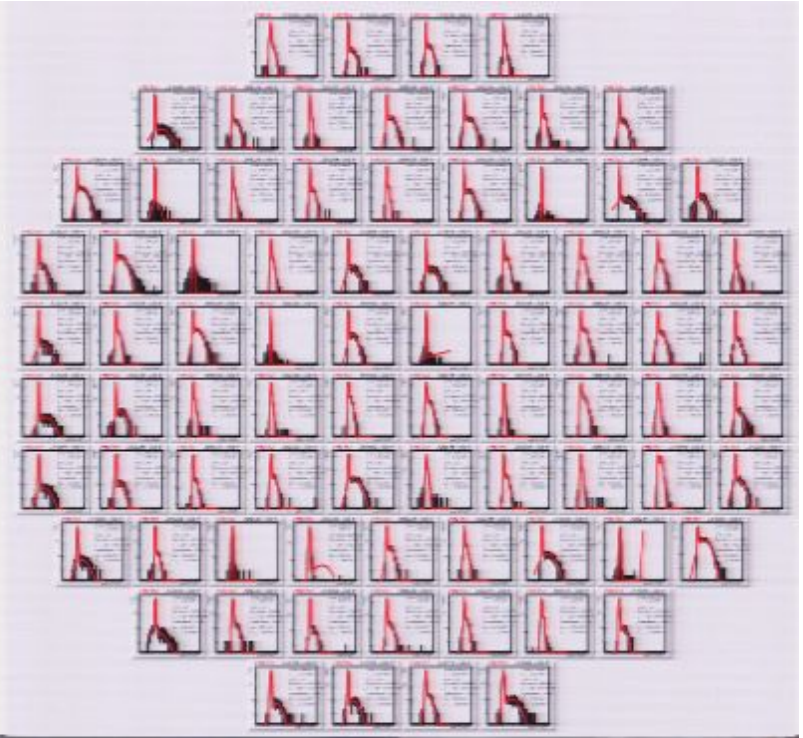
XENON100 before addition of Cu layer

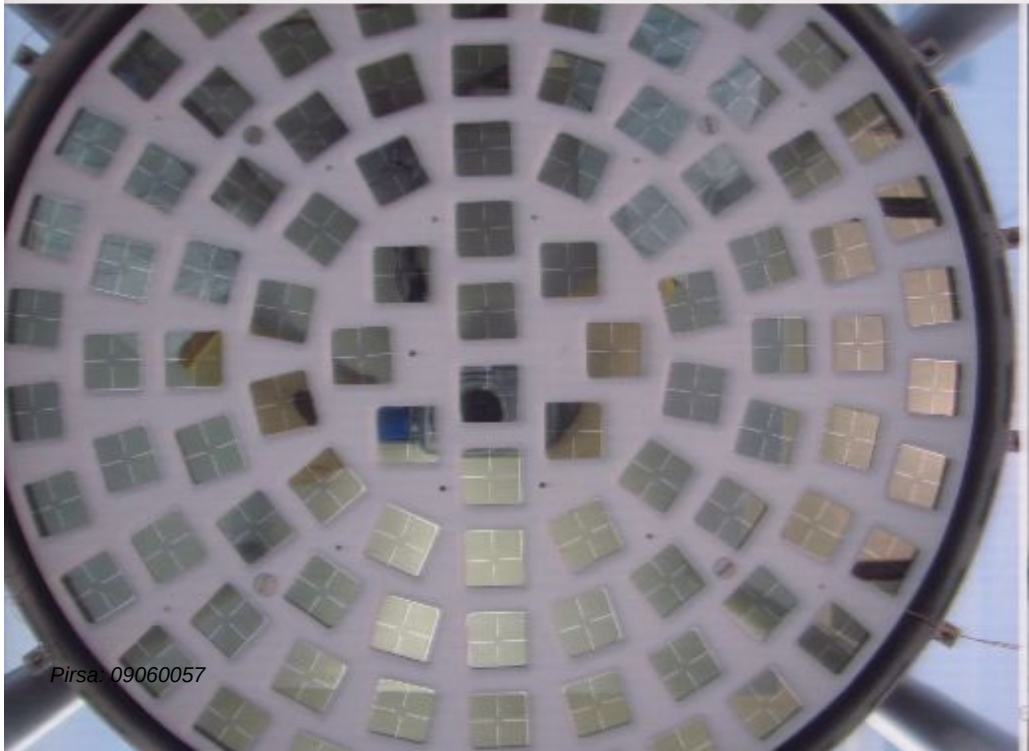
XENON100 TPC



XENON100 PMTs

- Photomultipliers: 1” square Hamamatsu R8520
- 98 on top - 80 on bottom - 64 in active LXe shield
- QE~23% for top array; QE~33% for bottom array
- XENON10 PMTs for LXe shield
- Calibrated with external LED's & quartz fibers
- S1 source calibrations with gamma sources

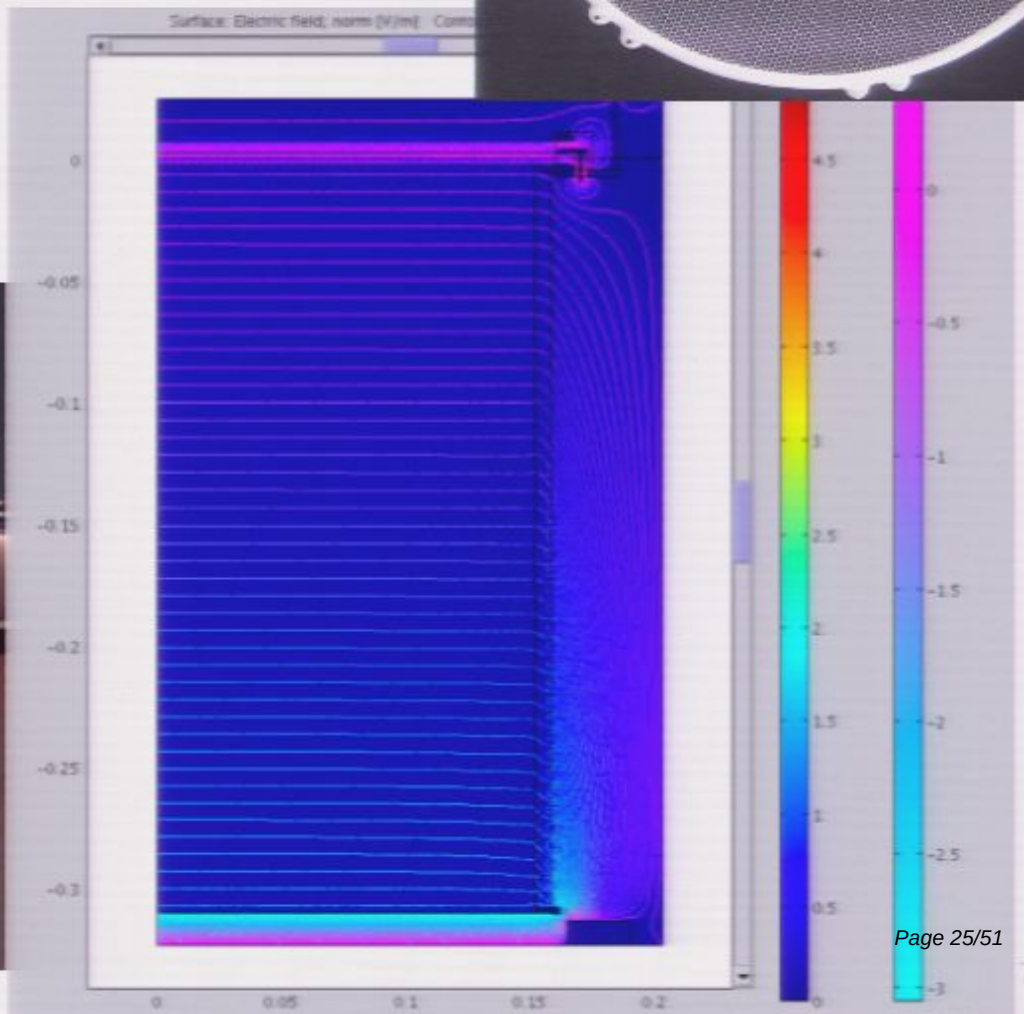


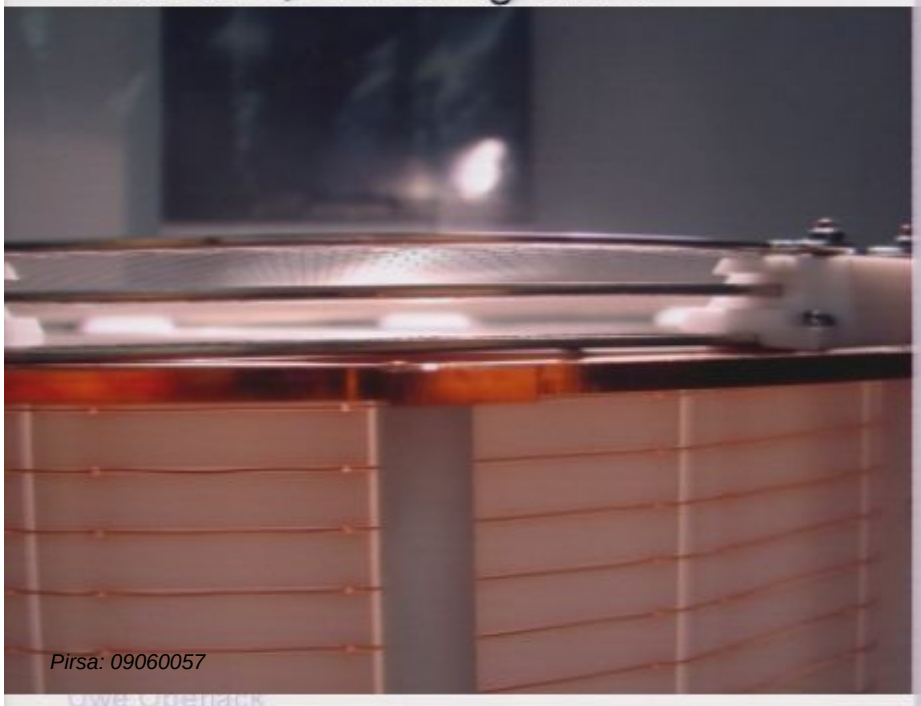


TPC Electric Field and Meshes

- Field cage optimized for uniformity with simulations: 40 double field shaping wires.
- 3 Mesh structure on top optimized
  - optical transparency
  - S2 energy broadening 4%
- Top mesh: ~5 mm pitch
- Anode, lower mesh: ~2.5 mm pitch
- Cathode, shielding mesh

P. Shagin, Y. Mei @ Rice





XENON100 DAQ & Trigger

- 248 PMTs into commercial fast x10 amplifiers
- FADC boards sampling @ 100 MHz
- Onboard zero suppression in FPGA, developed for XENON100.
- Analog sum output for trigger
- General purpose trigger module
  ⇒ trigger, veto

Marc Schumann @ Rice
Guillaume Plante @ Columbia
Uwe Oberlack

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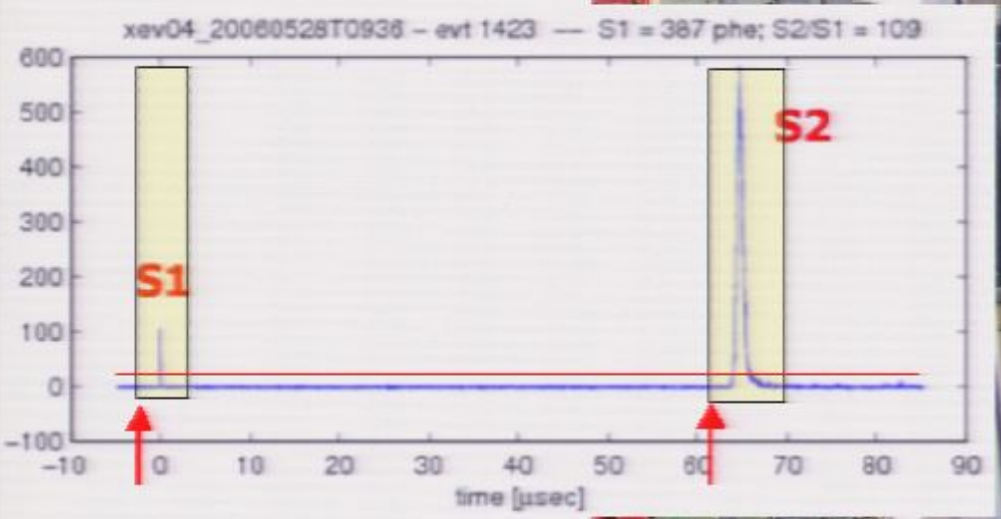
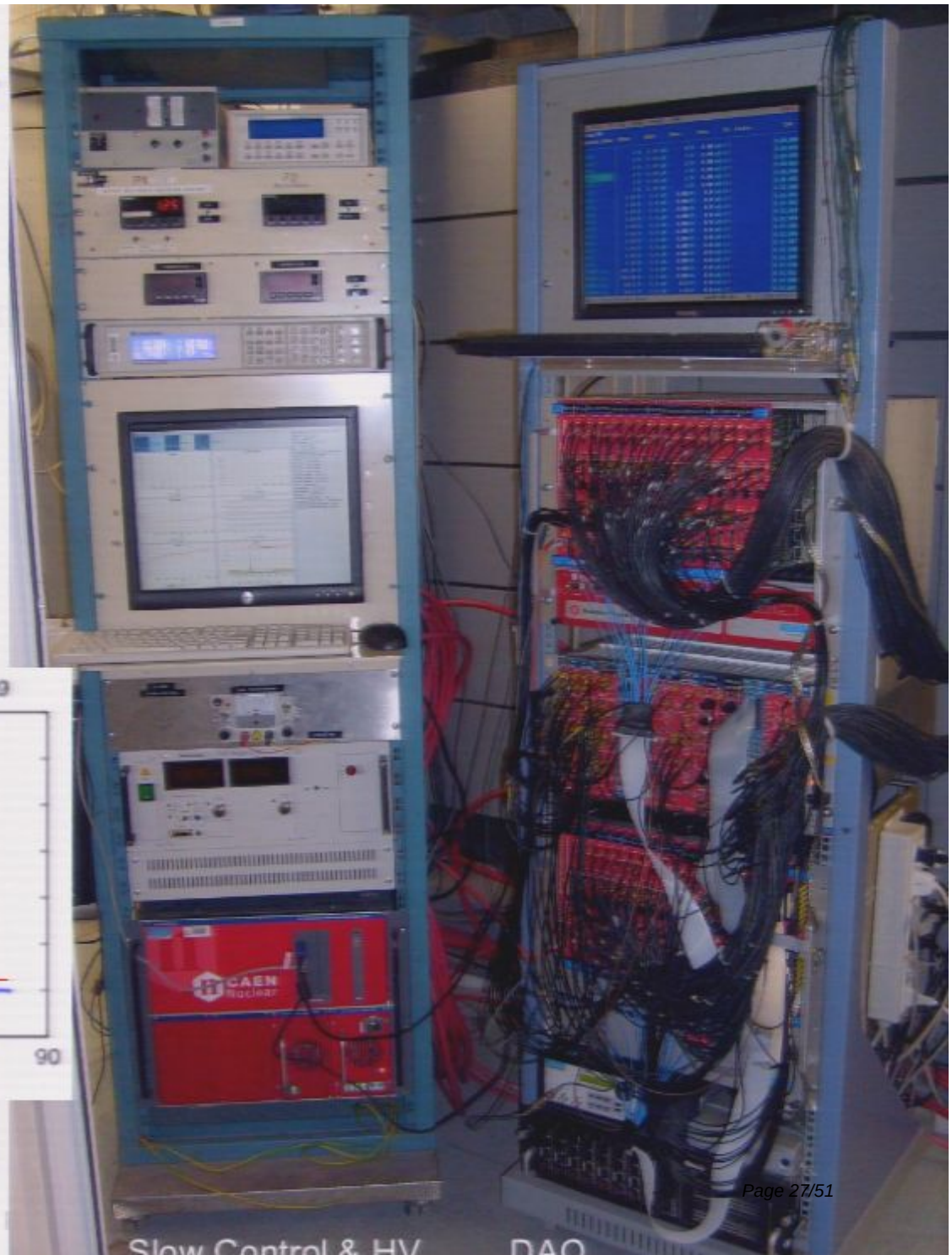


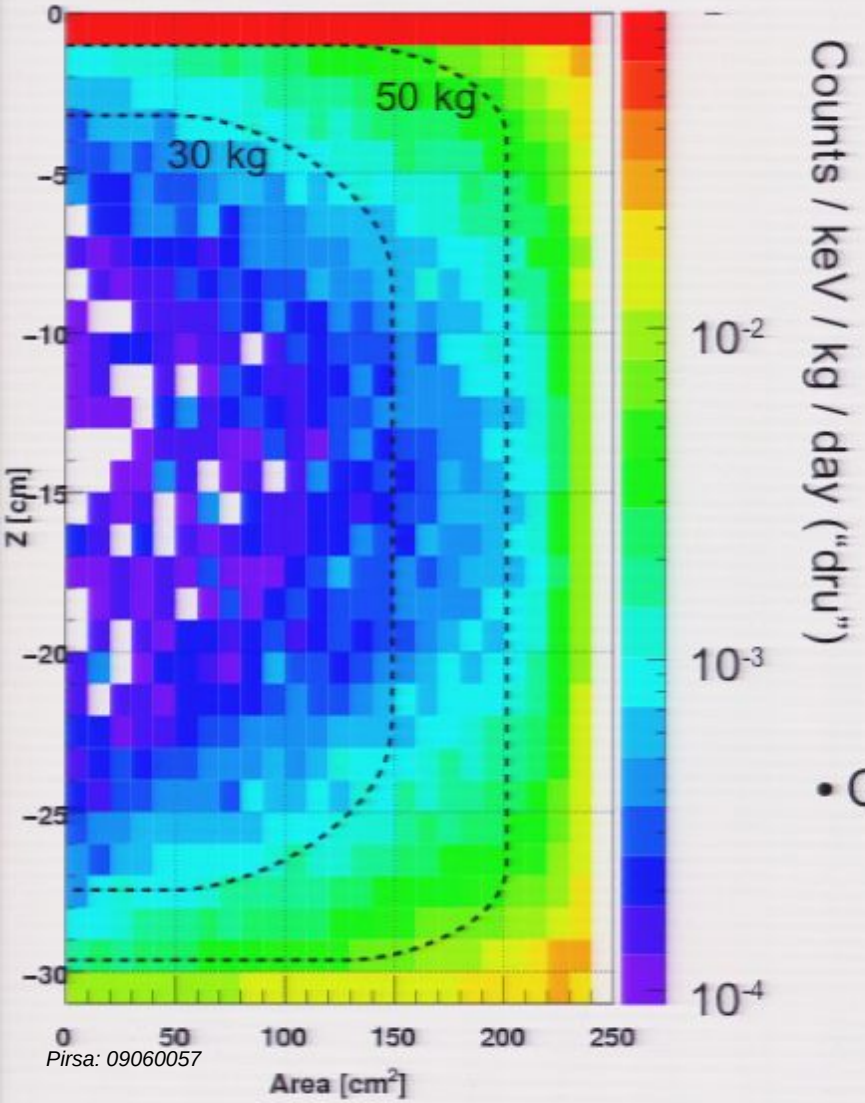


Marc Schumann @ Rice
Guillaume Plante @ Columbia
Uwe Oberlack

Slow Control & HV DAQ

Expected Background in DM Search Region

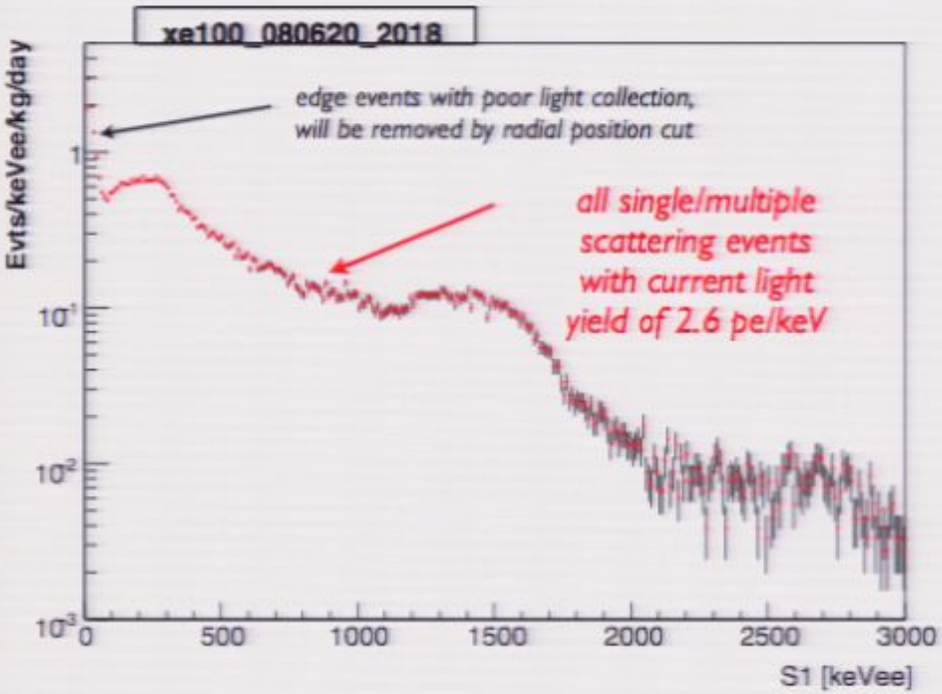
Gamma-Rays
before S2/S1 discrimination

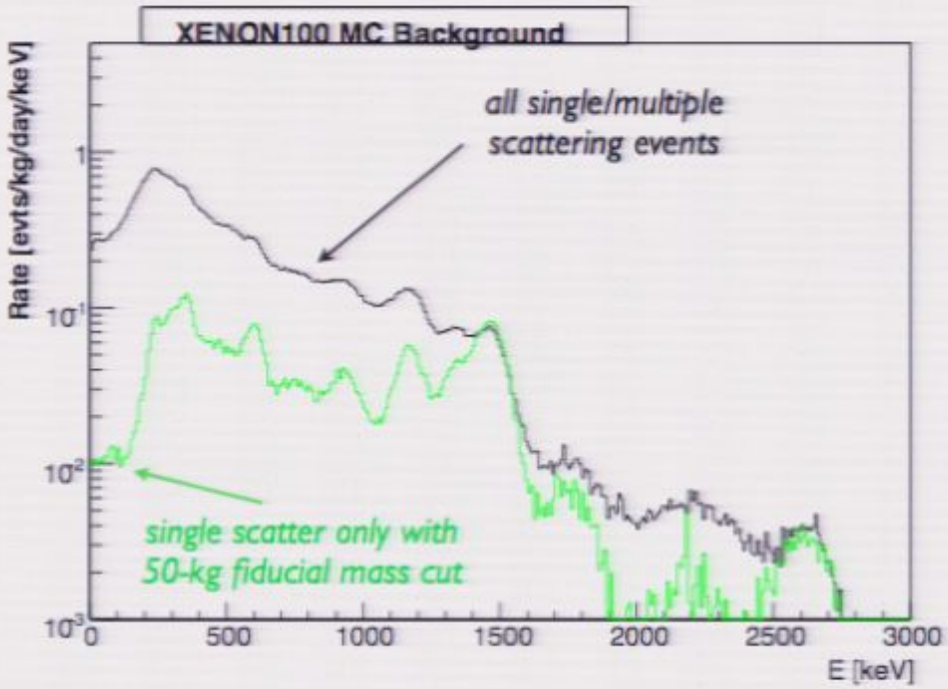


	Current XENON100			
Fiducial Mass	50 kg		30 kg	
Background	ER	NR	ER	NR
Units [a]	$[10^{-3} dru_{ee}]$	$[10^{-7} dru_{nr}]$	$[10^{-3} dru_{ee}]$	$[10^{-7} dru_{nr}]$
PMTs and bases	4.91		<1.4	
QUPIDs	–		–	
Stainless steel	<2.01		<0.35	
PTFE	<0.18		<0.03	
Copper Cryostat	–		–	
Polyethylene	<2.50		<1.2	
^{85}Kr/U/Th [b]	<0.2		<0.2	
Concrete/Rocks[c]	–		–	
μ-induced n in shield	–		–	
μ-induced n in rock	–		–	
Total Bkg	<9.8		<3.2	
Run Time	40 days		200 days	
Raw Exposure	2000 kg-day		6000 kg-day	
Total Bkg events	<1.0		<1.2	
# of WIMP events[e]	3.9		11.8	
SI $\sigma_{\chi-p}$ reach	6×10^{-45} cm^2		2×10^{-45} cm^2	

- Compare to XENON10: gamma bgd ~0.6 dru

Measured XENON100 – Background





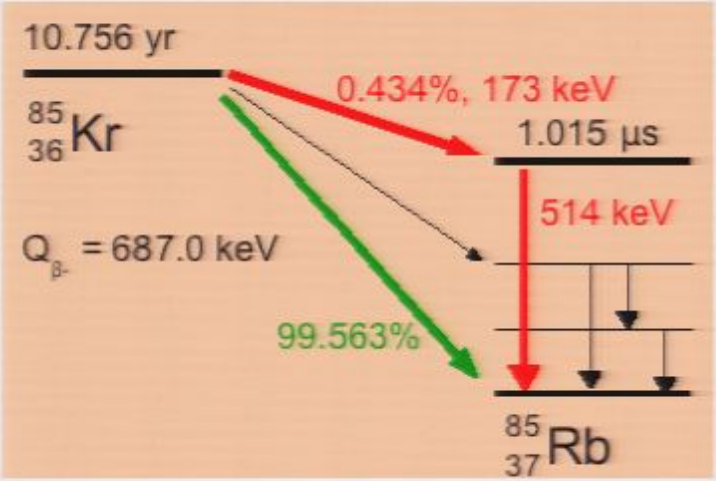
- First measured background spectrum (S1) in good agreement with MC prediction.

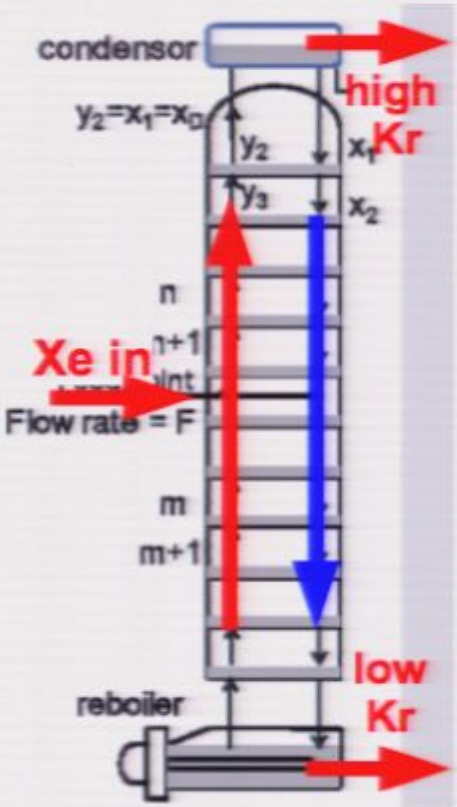
Removal of Krypton-85

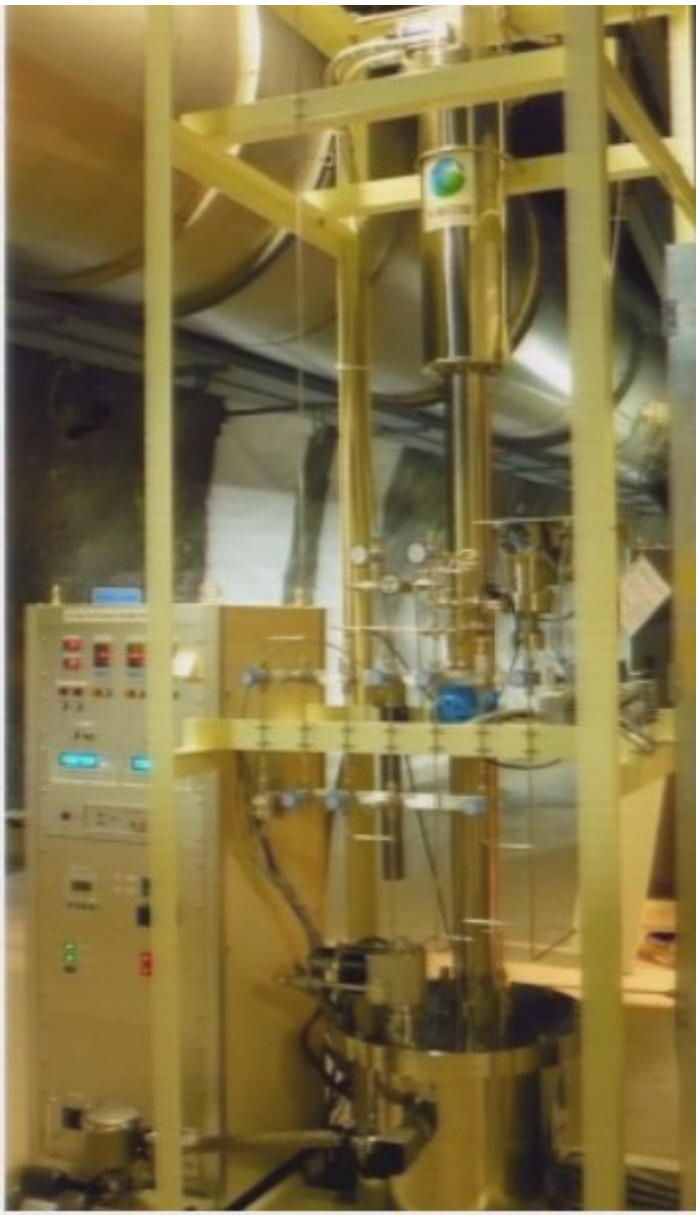
XENON100 science goal requires Kr (nat) contamination <~ 50 ppt (~ 1 leakage event per year in 50 kg fiducial mass)

Cryogenic distillation to separate Kr from Xe:

- Distilled by Spectra Gases to < 10 ppb Kr level
  - verified with XENON100 data by delayed coincidence analysis
  - Measured Kr contamination: 7±2 ppb



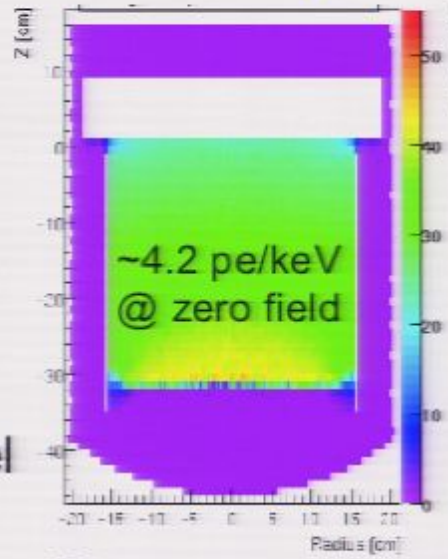


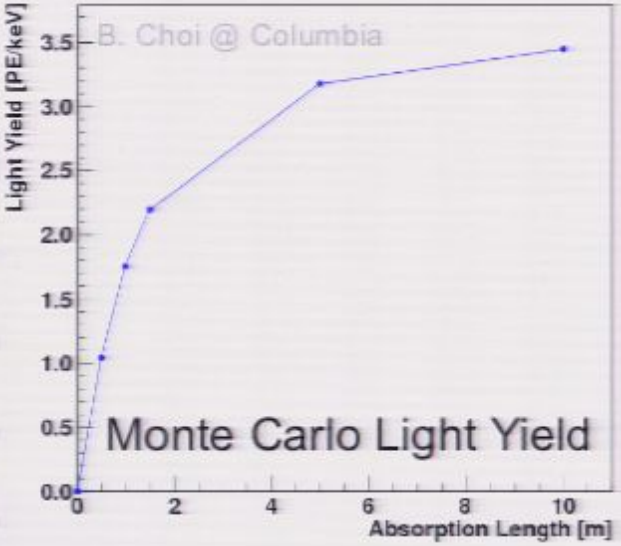


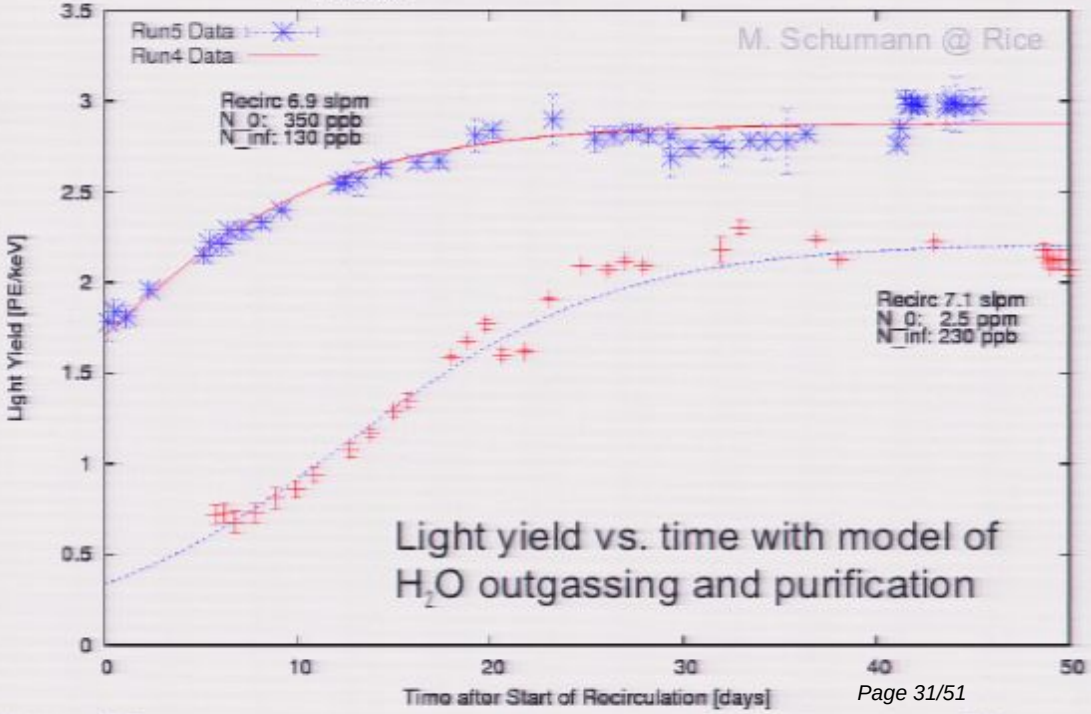
- Distilled on site by a dedicated cyyogenic distillation tower
  - designed to reduce Kr by factor 10^3 at a rate of 0.6 kg/hr

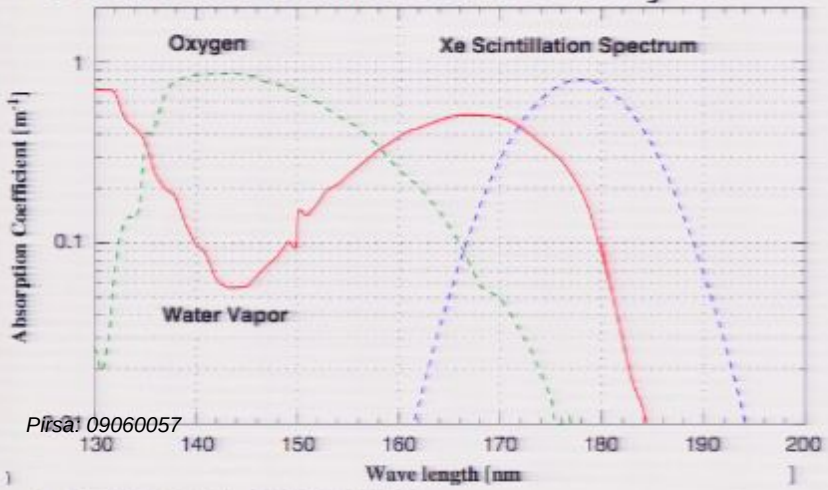
Light Yield Evolution and Purity

- Ongoing work on detector cleaning.
- Improvements in detector setup and outgassing.
  → Improved light absorption length.
- Saturation below expected level.
- Installation of a new monitoring tool capable of measuring H_2O to ppb level in Xe gas.
- After latest measures, H_2O level @ room temperature a factor 10 below level during last run.
- Detector refilled since May 9.





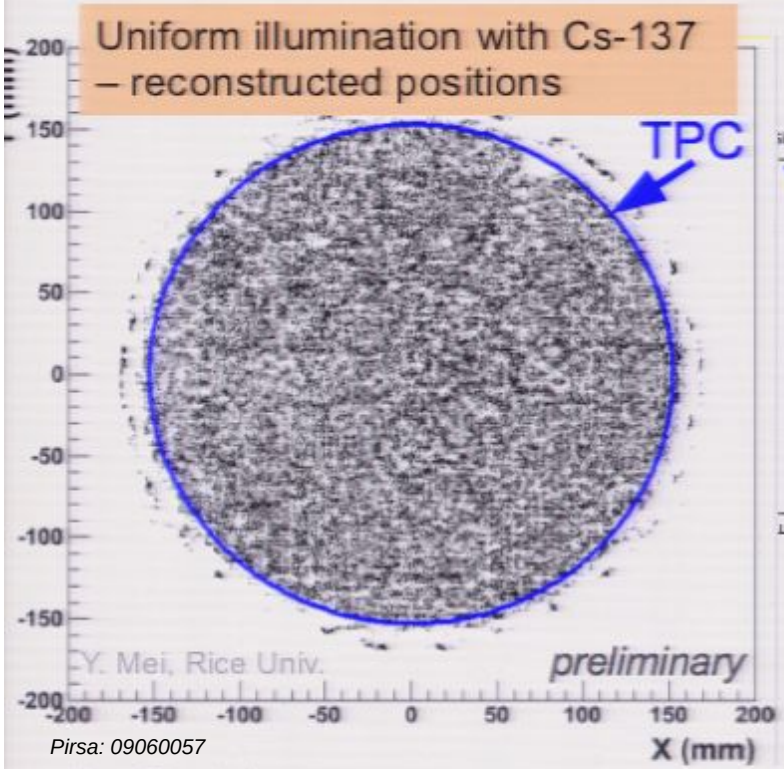


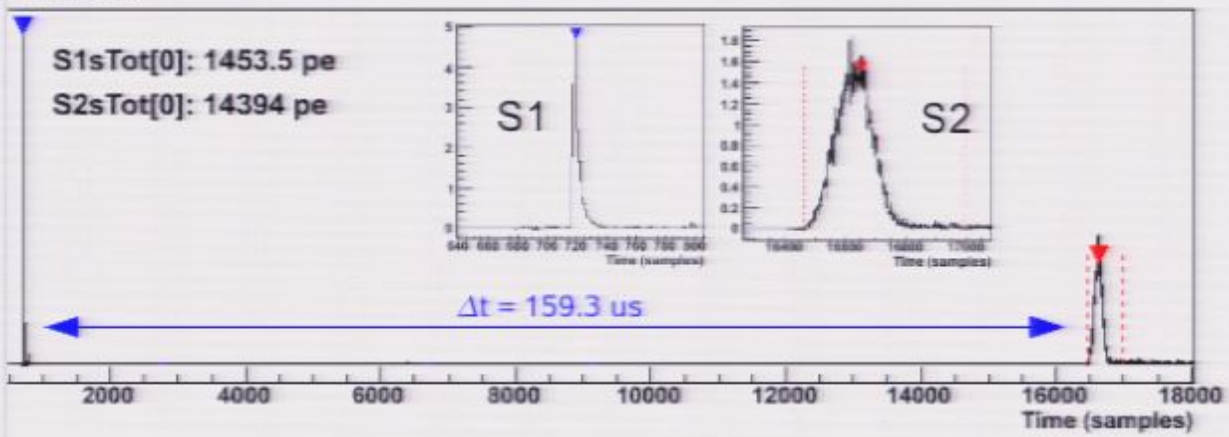


A. Baldini et al., 2005, NIMA

Charge Drift across 30 cm in XENON100

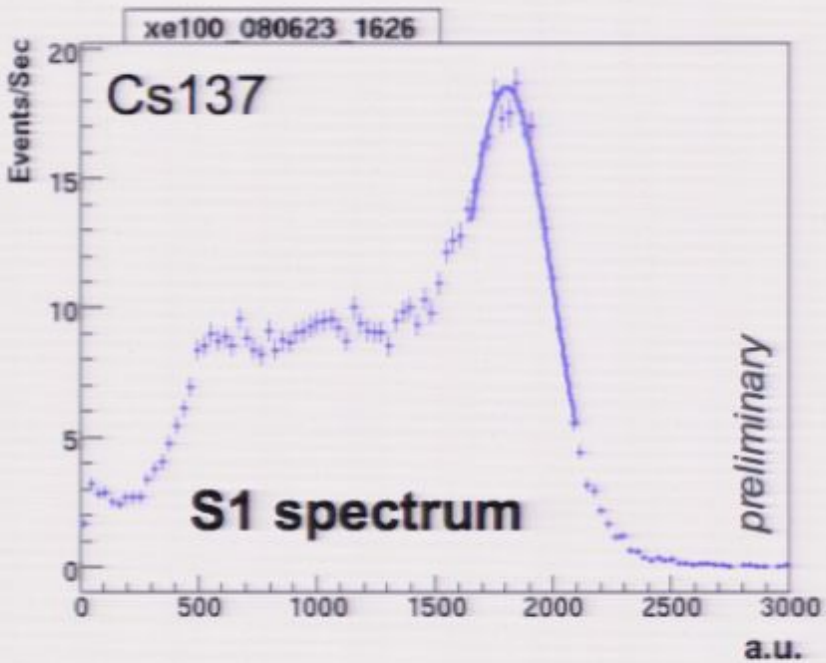
- Recent milestone: drifting electrons across the full drift length (30 cm).
- Purity improving daily.
- Expecting physics runs to start later in the summer.

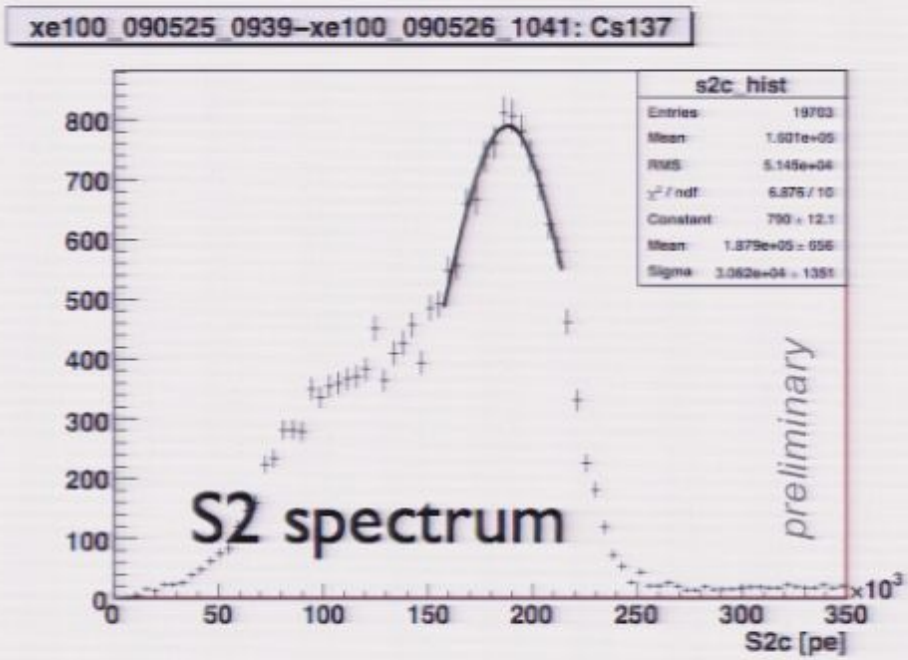




Drift length = 1.84 mm/μs × 159.3 μs = 293 mm

XENON100 Calibration: Light and Charge

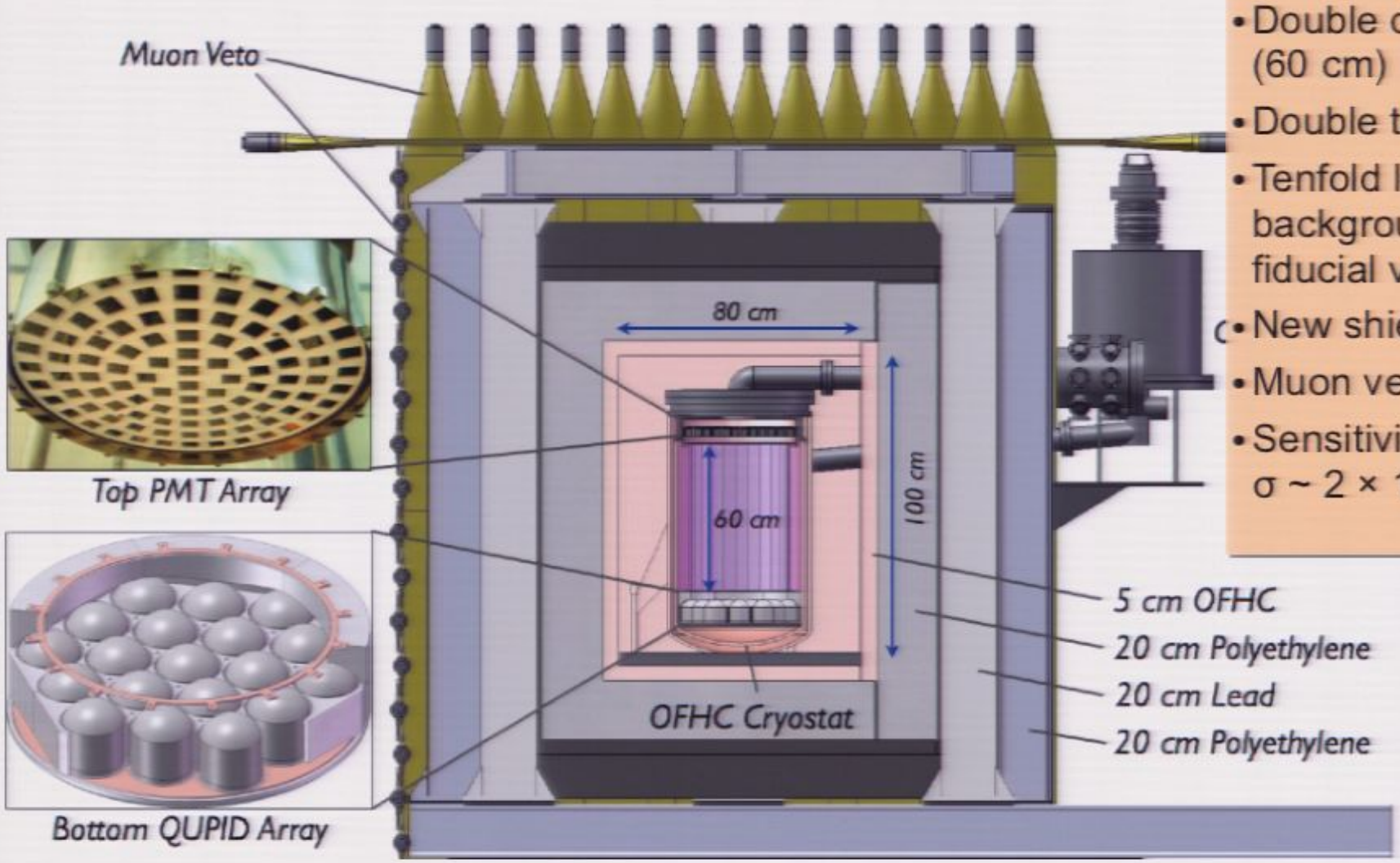




Approved Upgrade for XENON100
(2010-2012)

Test technologies for the ton-scale:

- Low-activity photosensor QUPID
- Double drift length (60 cm)
- Double target mass
- Tenfold lower background in fiducial volume
- New shield
- Muon veto
- Sensitivity goal $\sigma \sim 2 \times 10^{-46}$ cm^2



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(2011-2014 ?)

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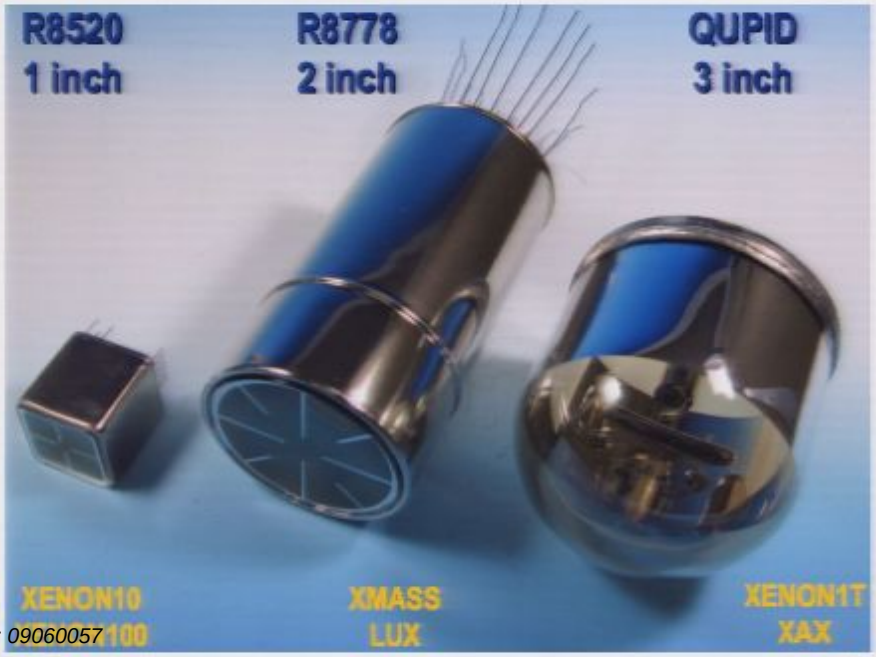
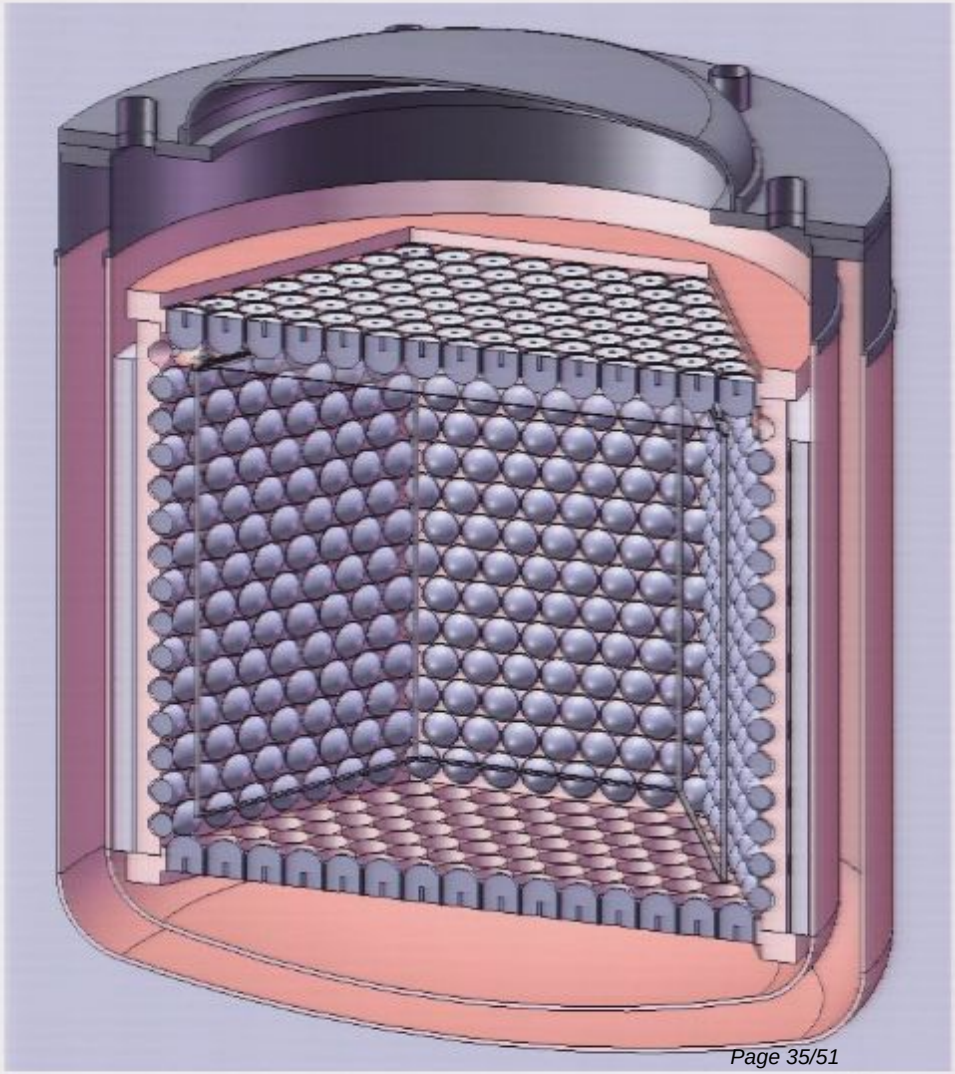
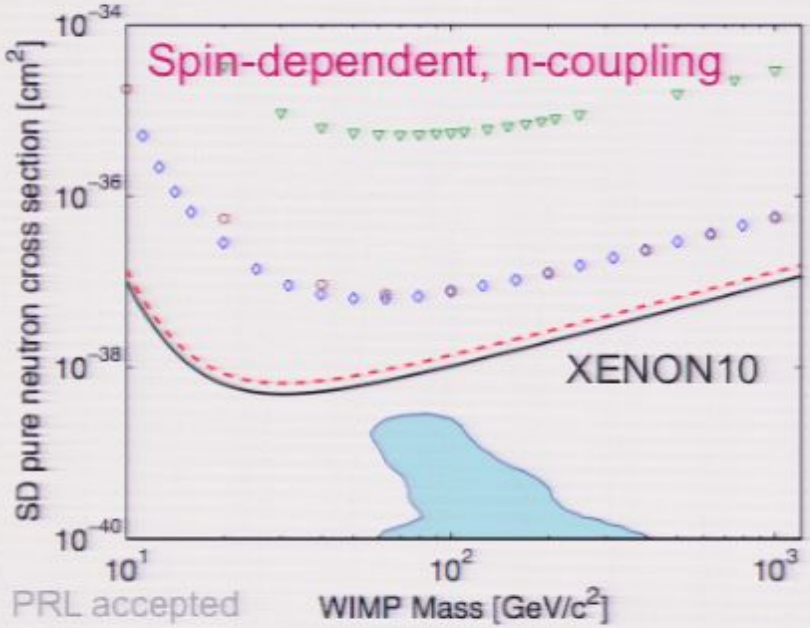




Current Status in WIMP DM Sensitivities



PRL accepted

- J. Angle et al., 2008 PRL 101 091301 (XENON10 SD)
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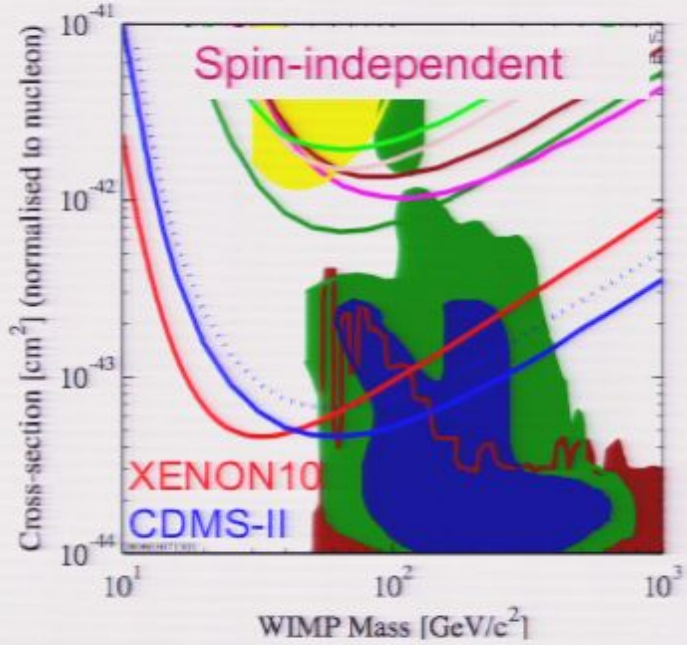
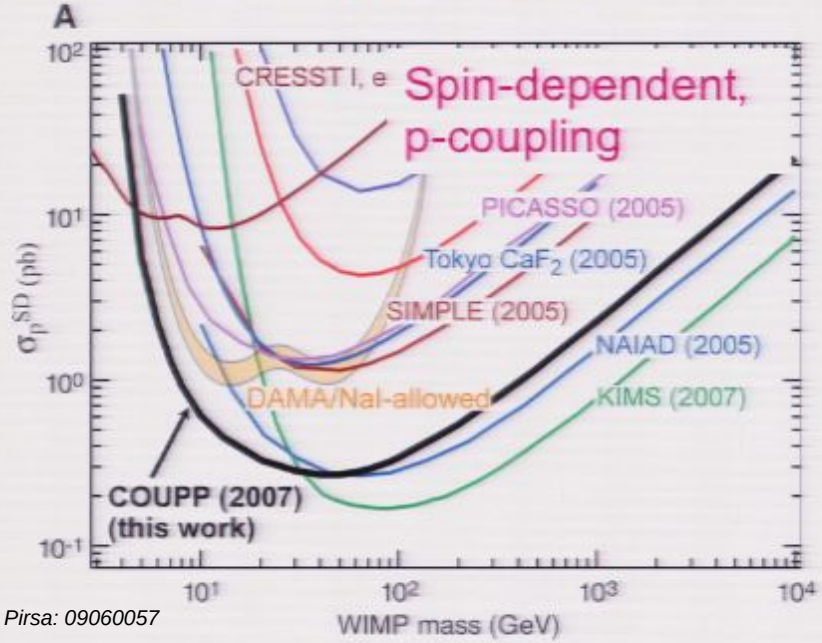
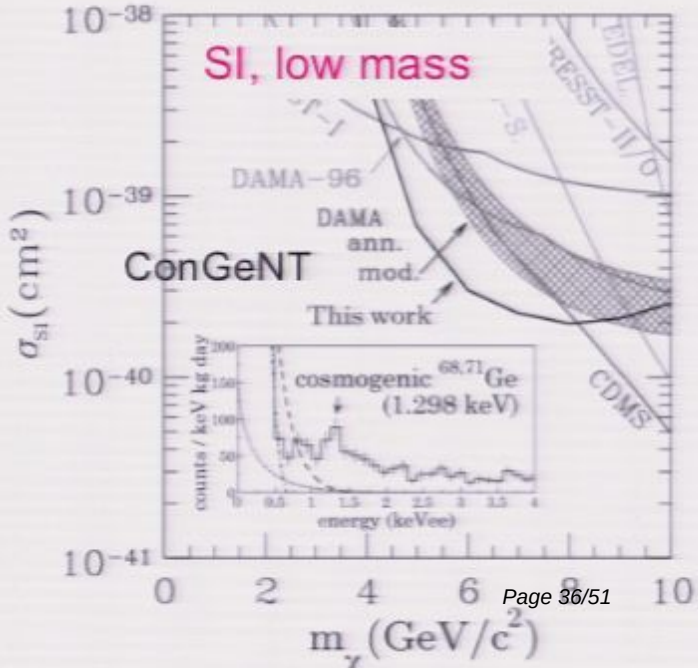
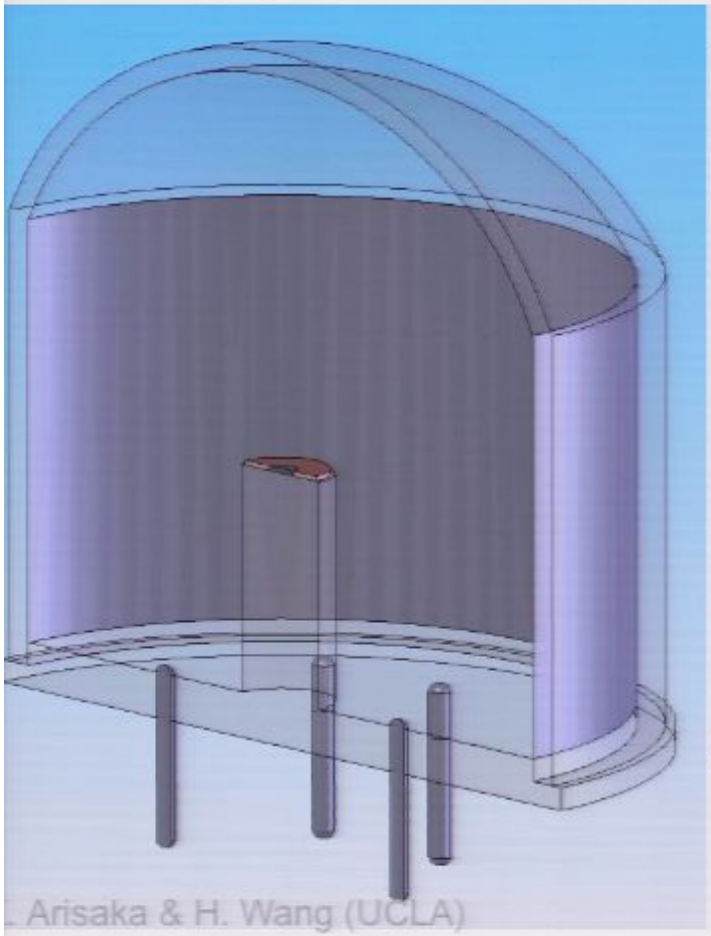
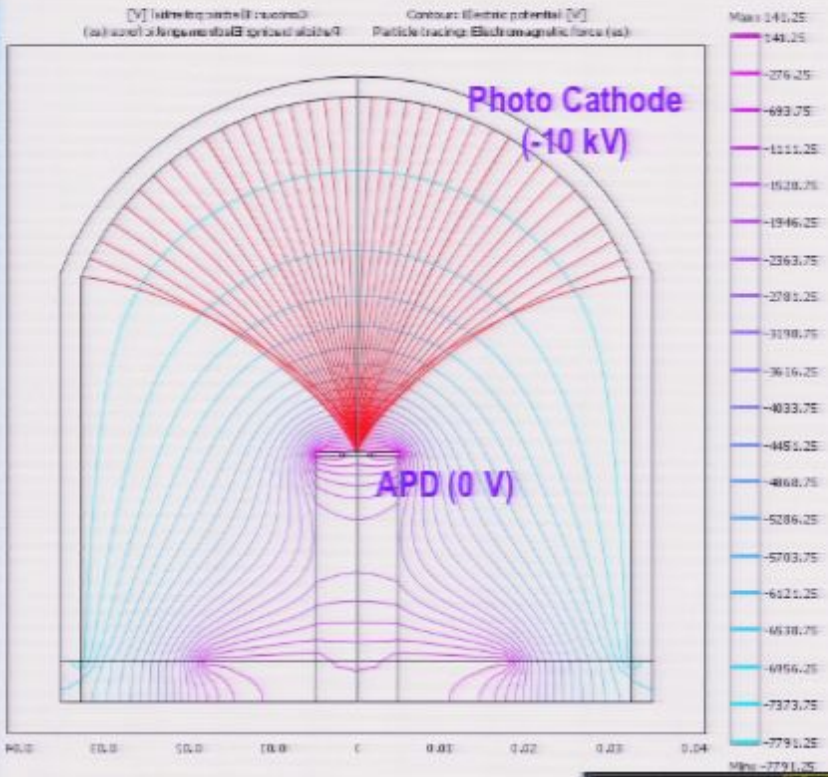


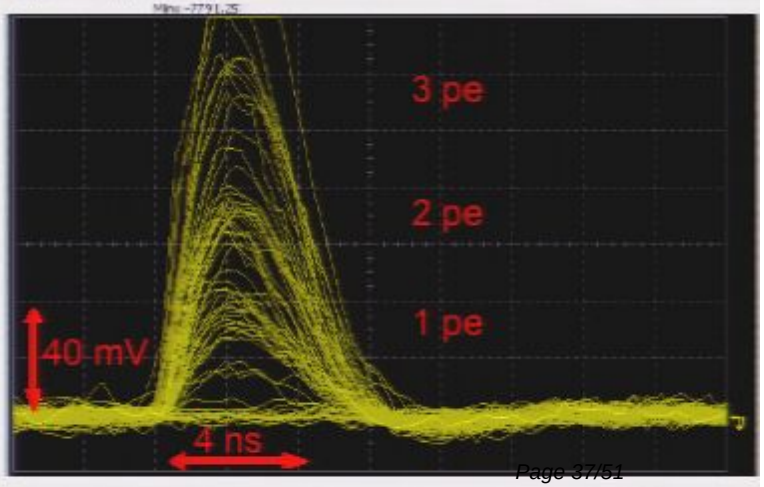




New Photosensor under Study: 3” QUPID







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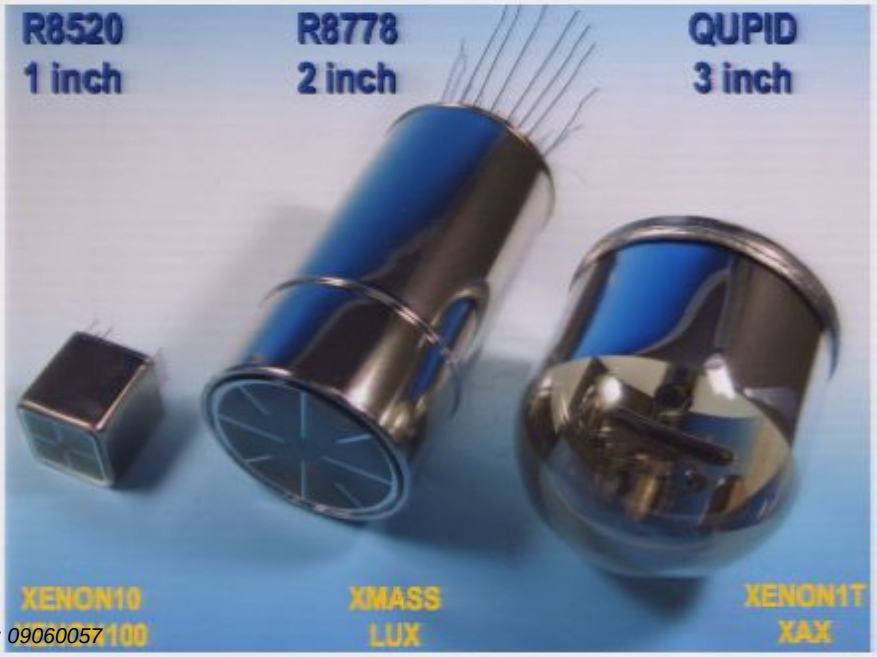

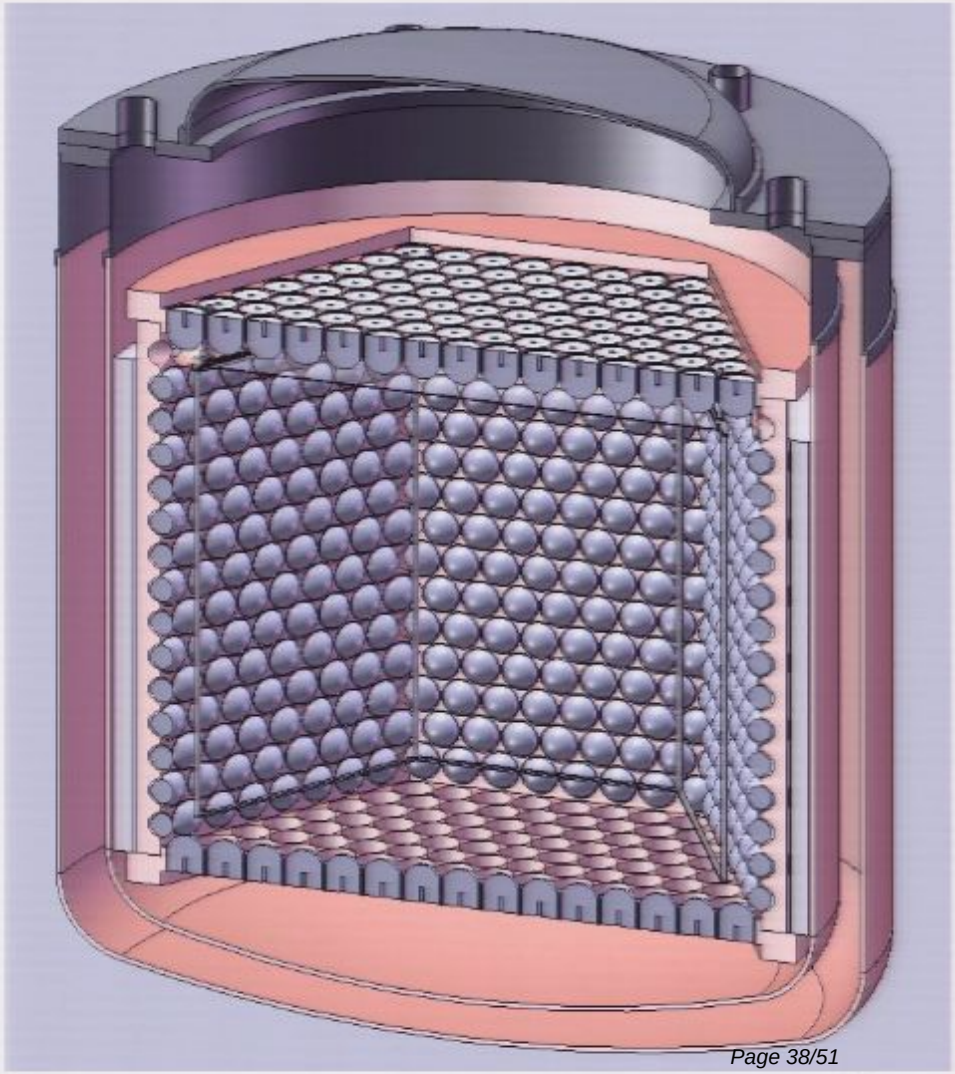

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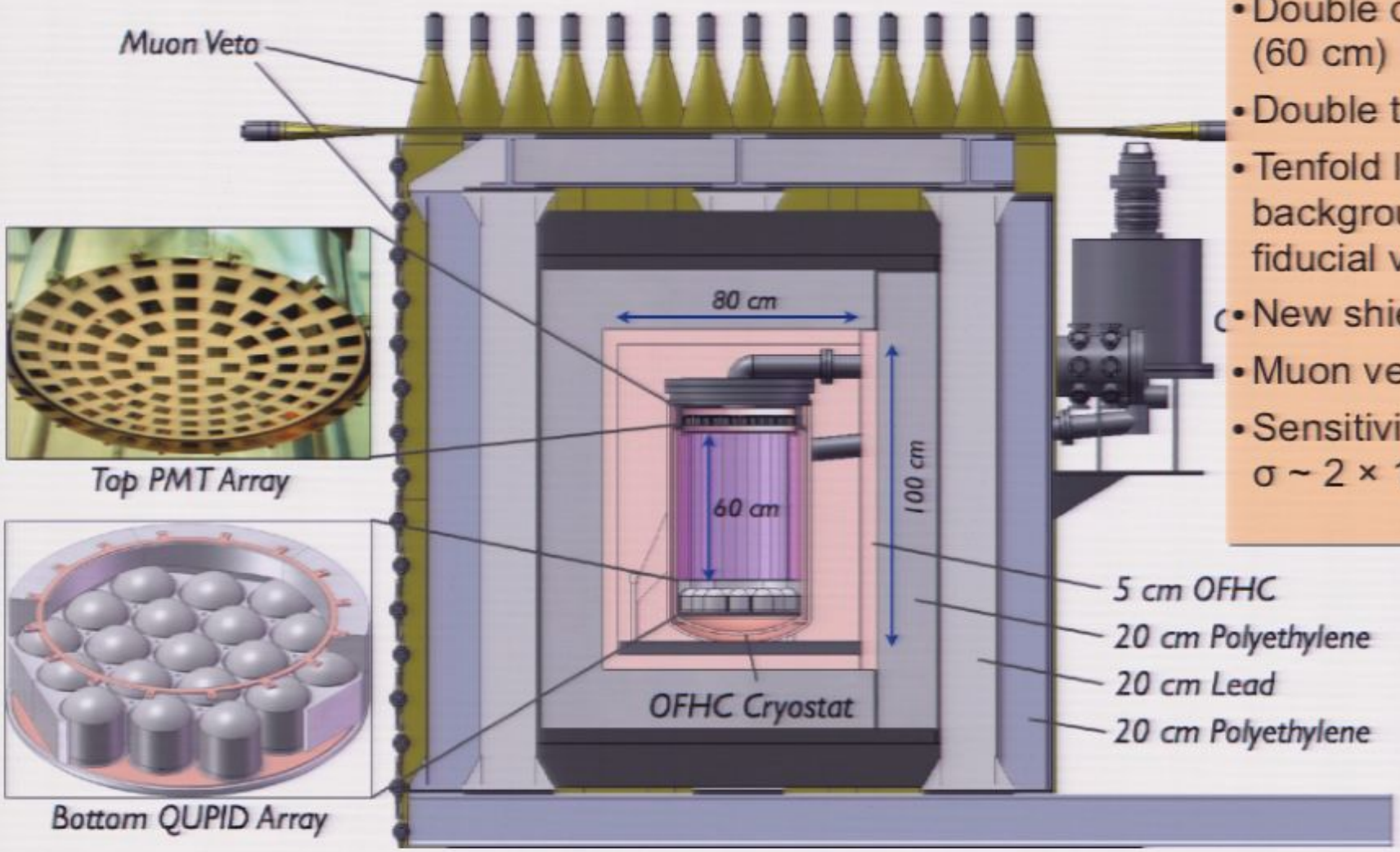

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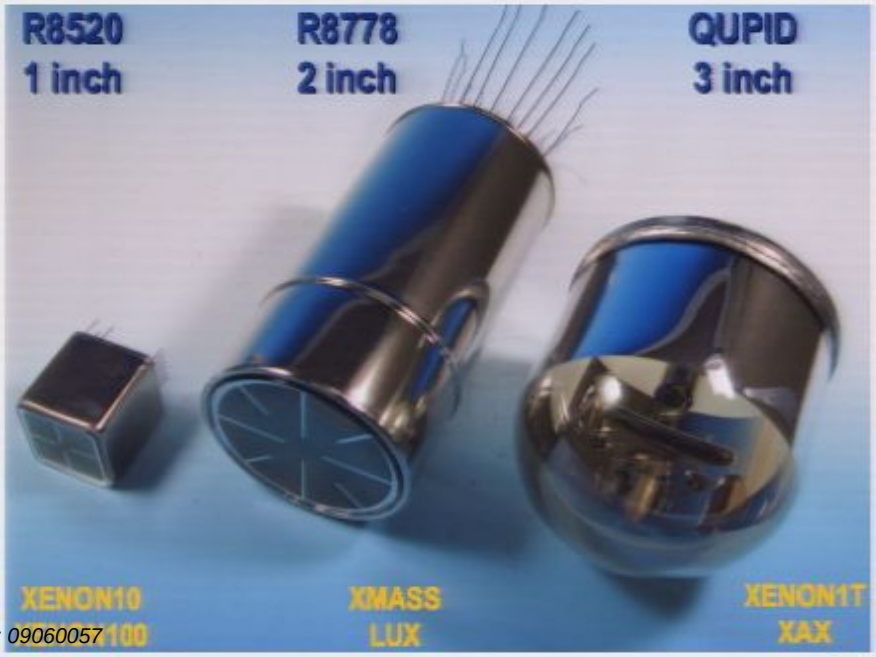

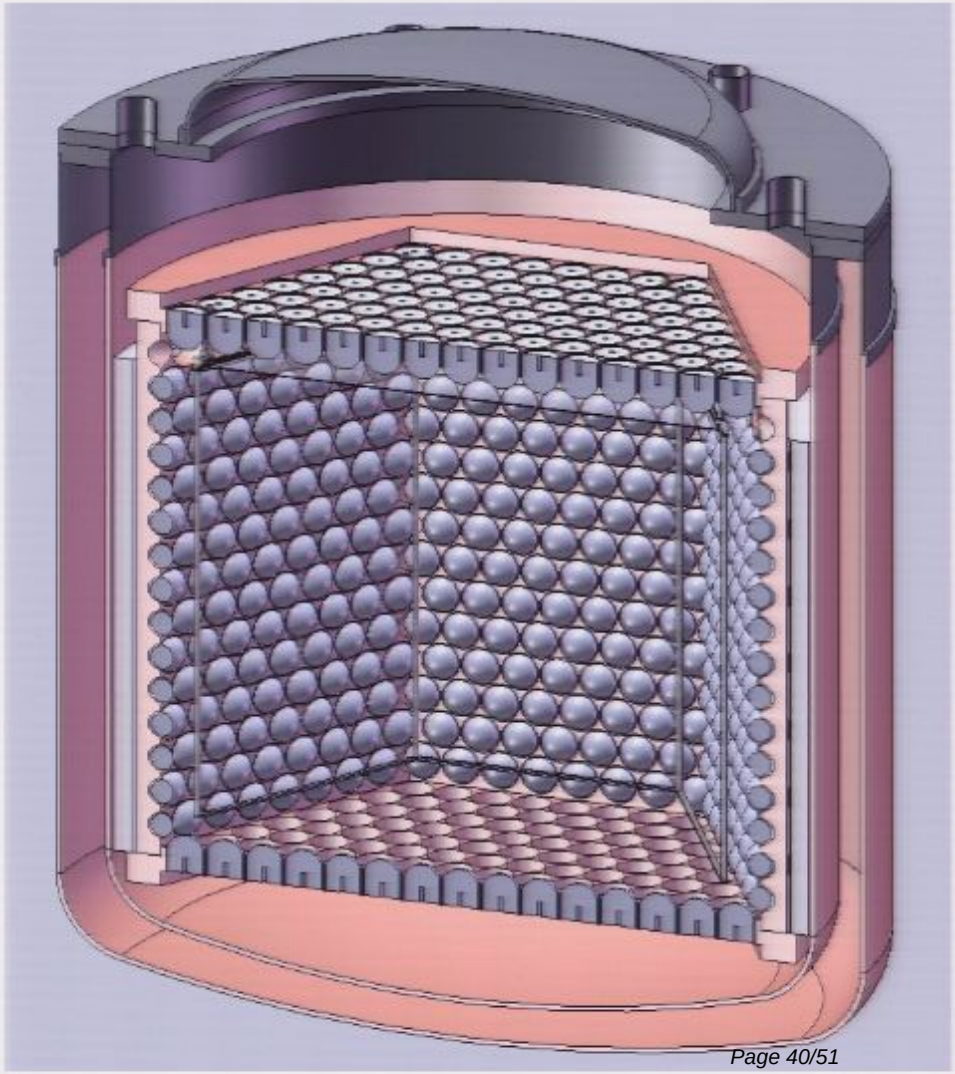

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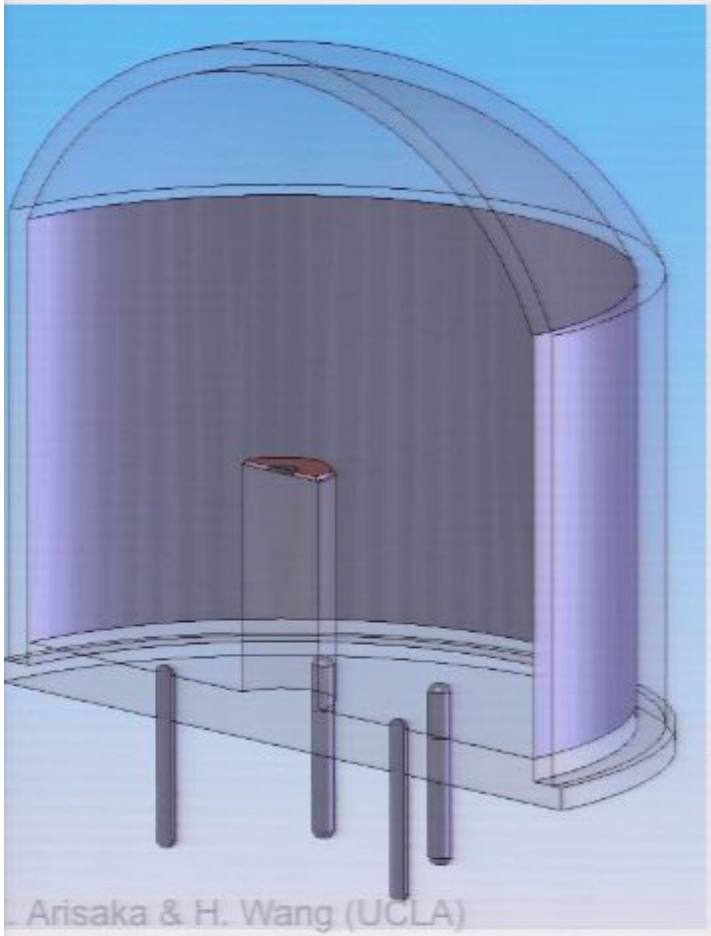

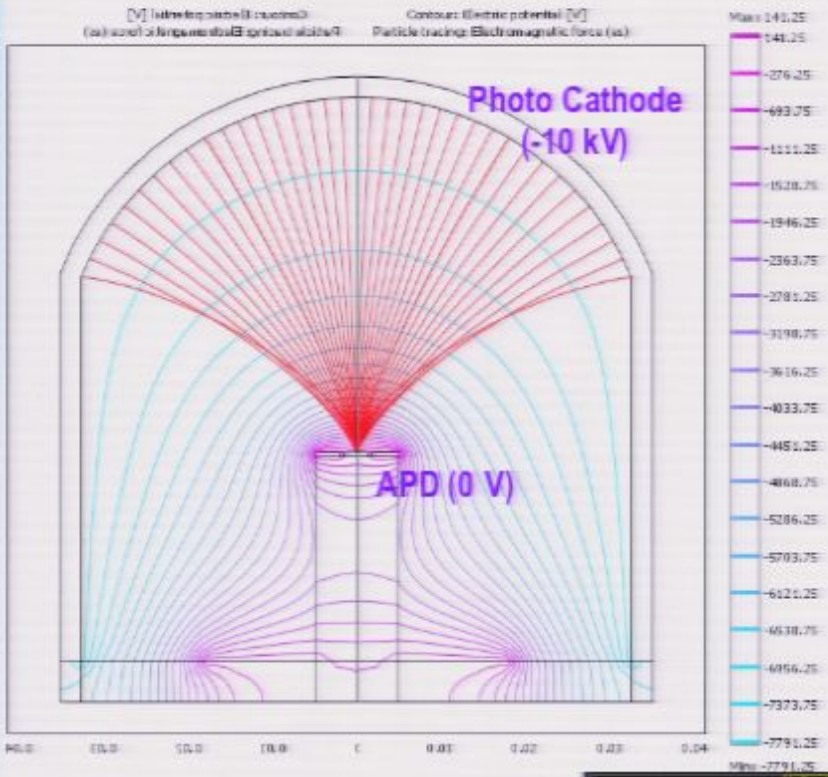

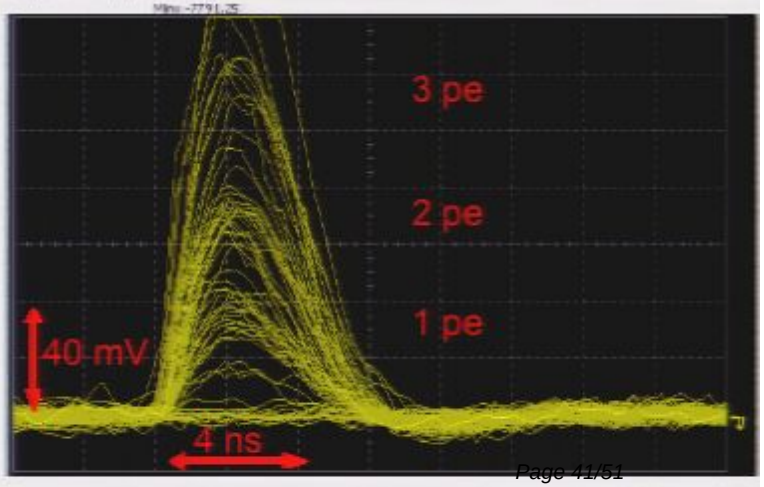

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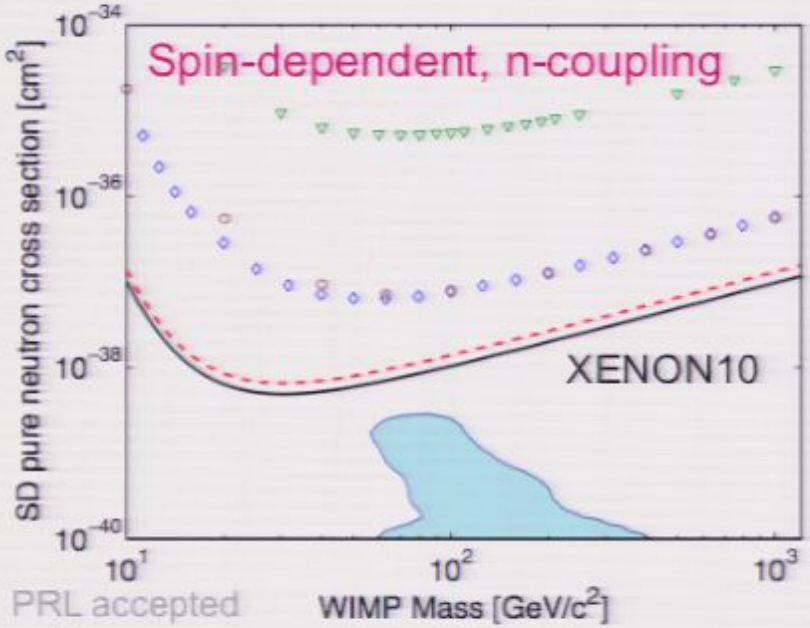

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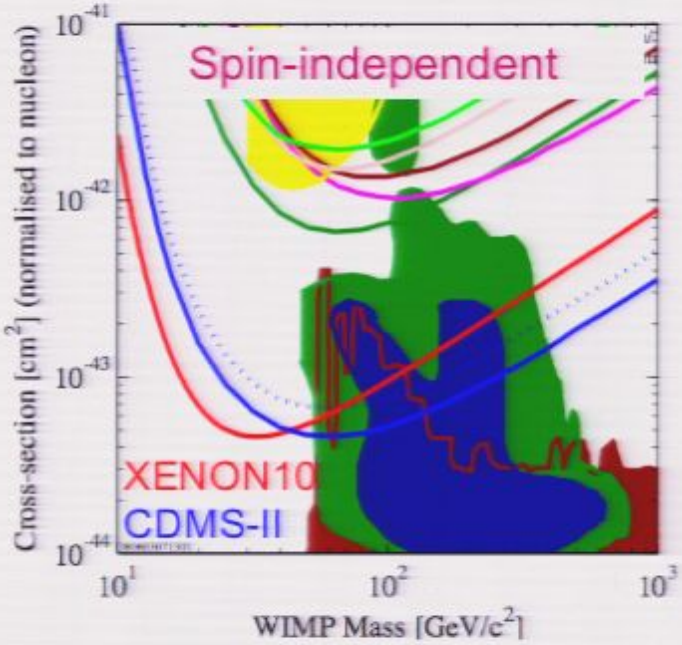

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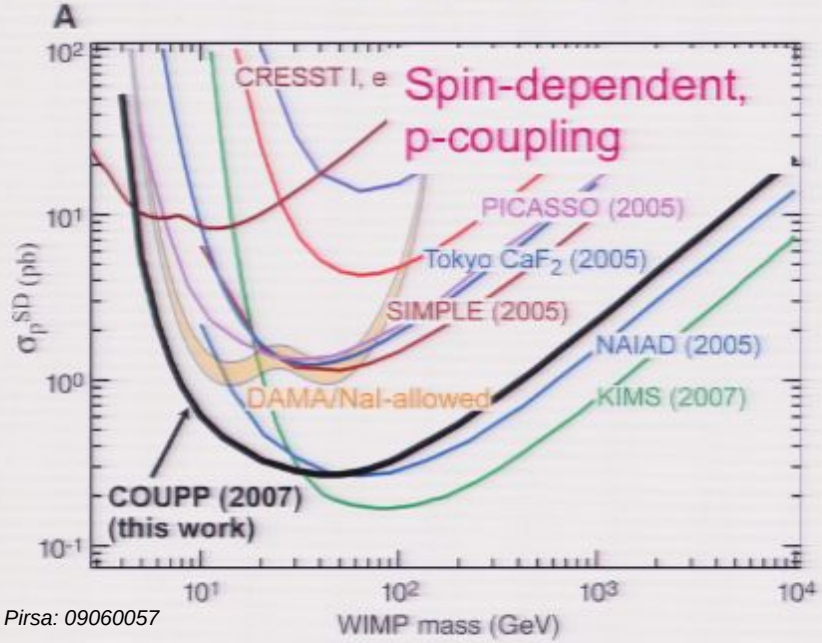
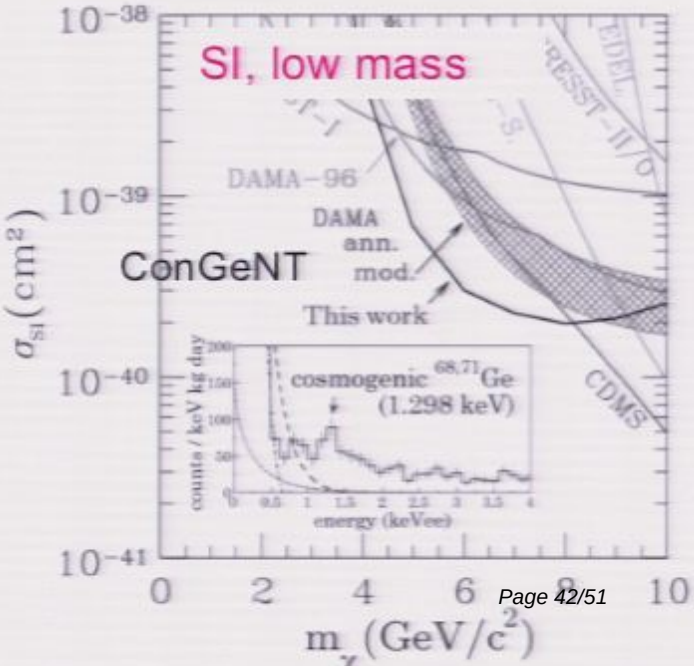
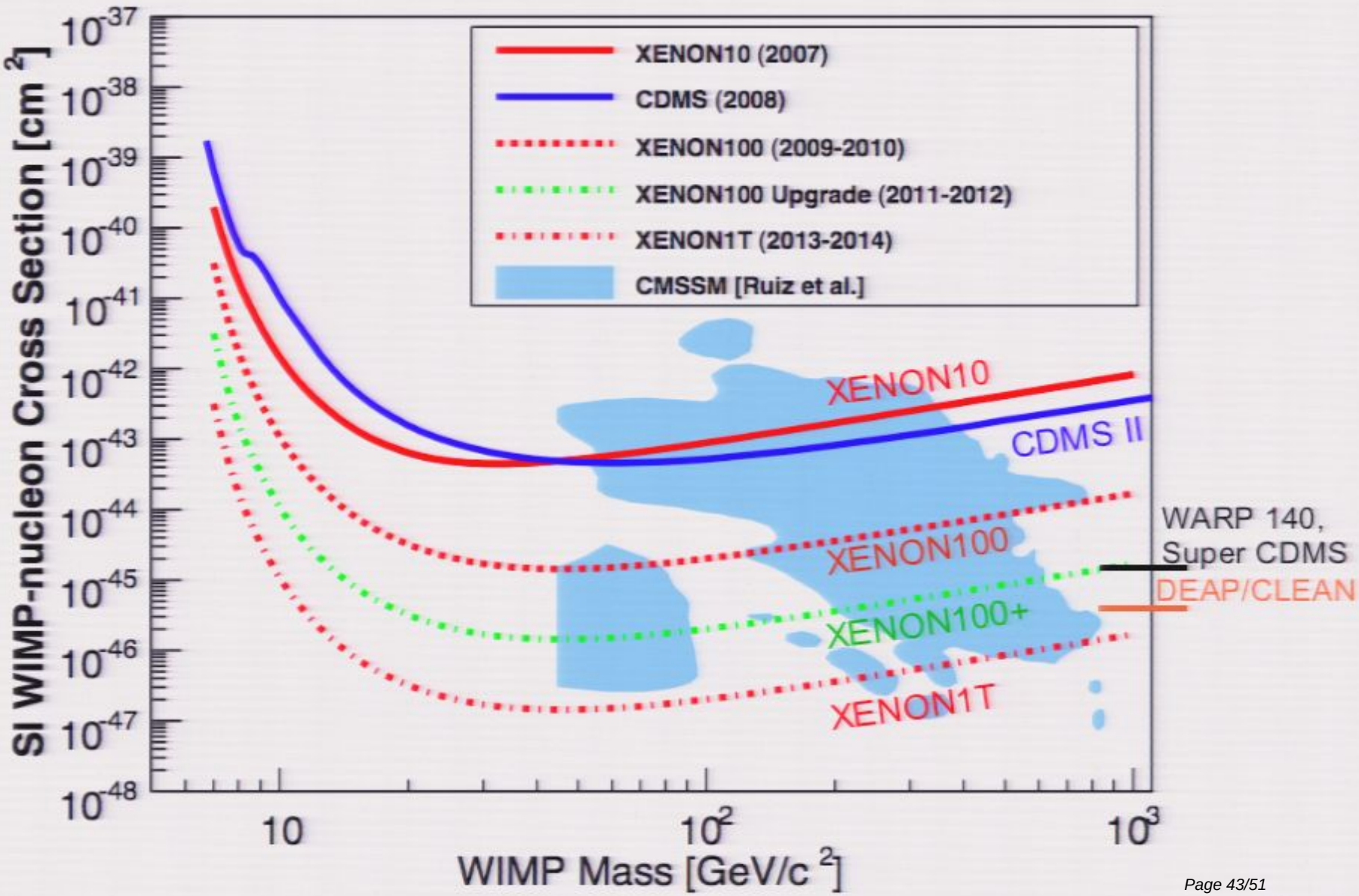
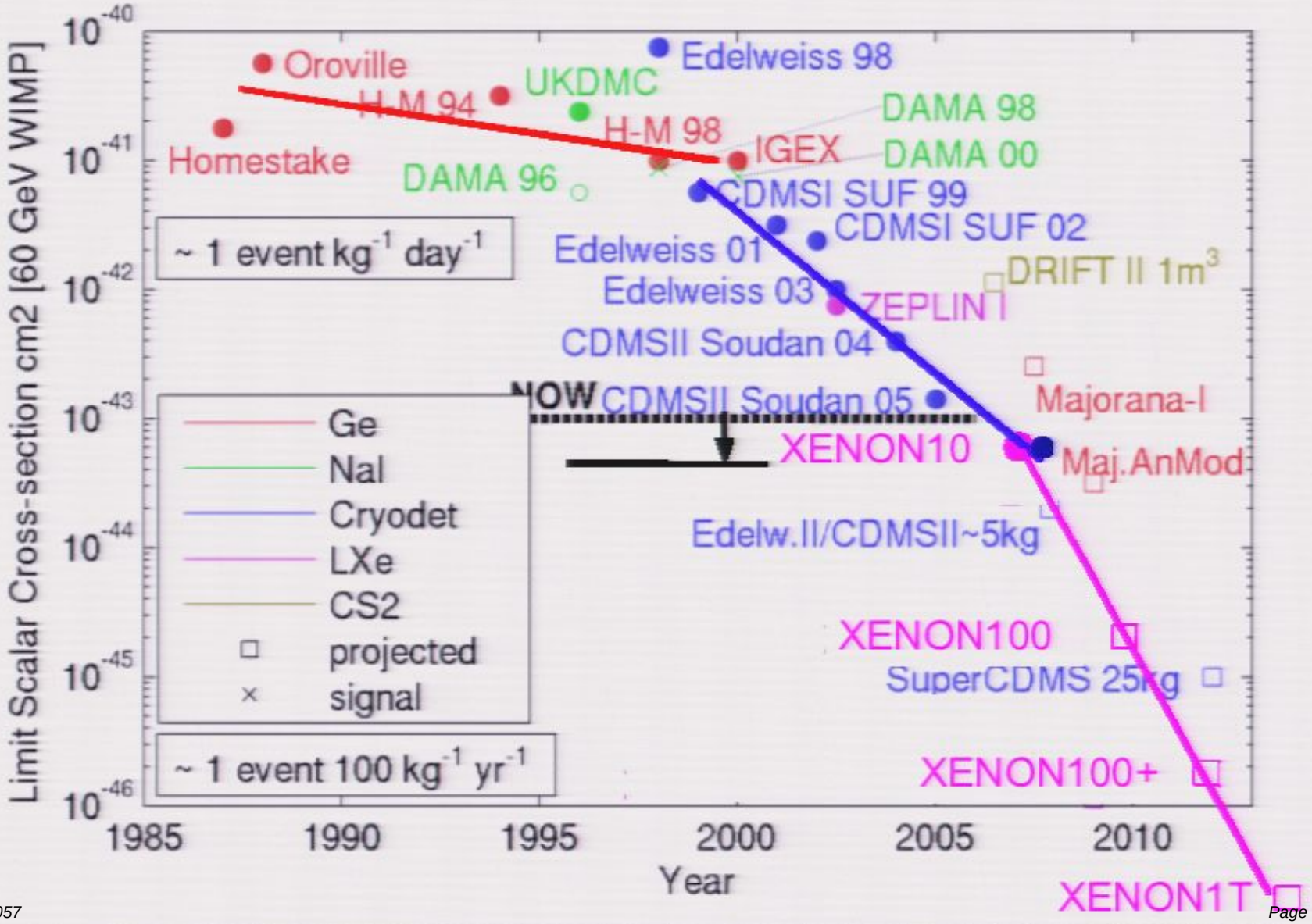




The Future of WIMP Searches with XENON



DM Direct Searches - Progress Over Time



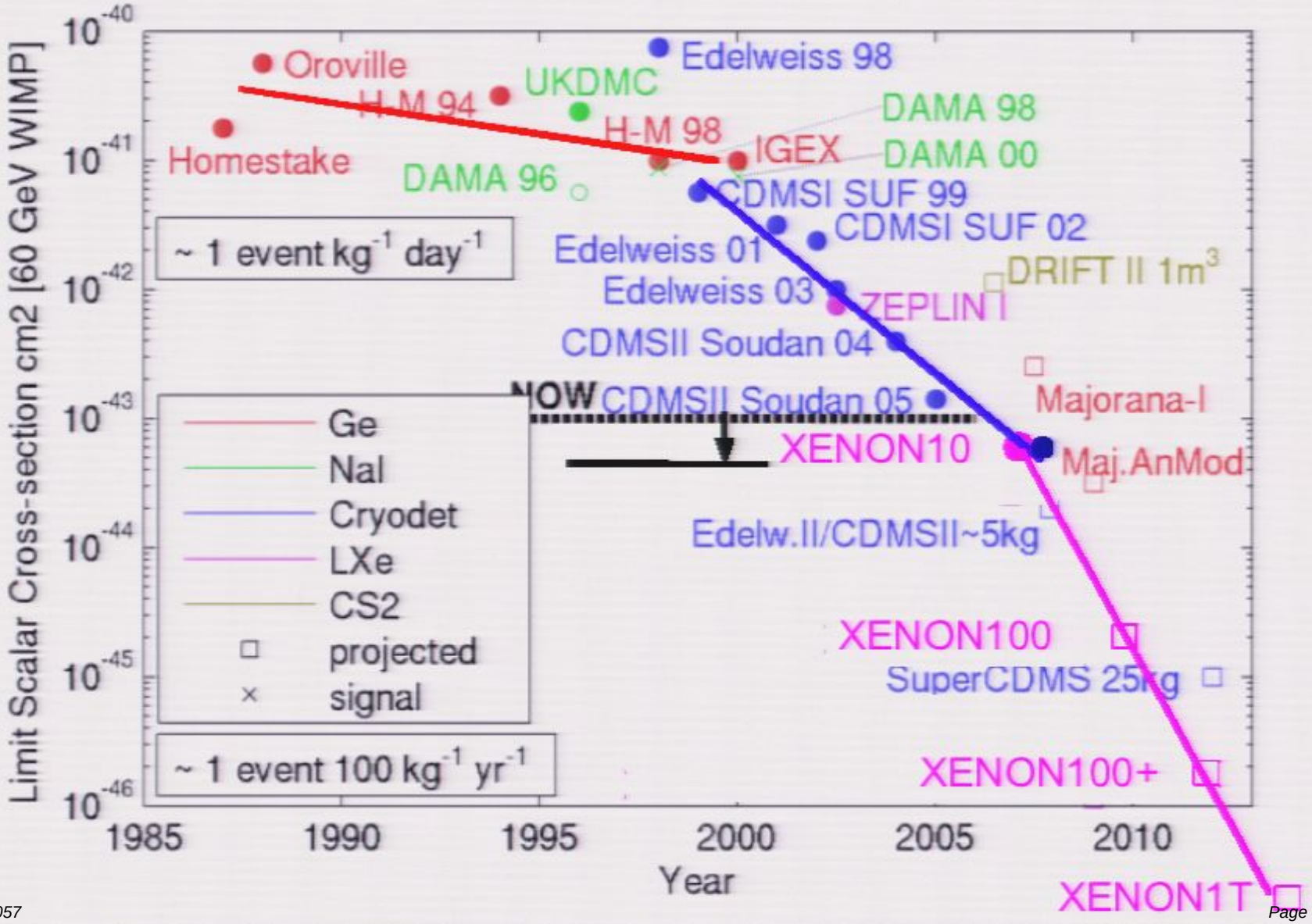
Plot updated from DM Review: R. Gaitskell, Ann. Rev. Nucl. and Part. Sci. 54 (2004) 315-359

Summary & Outlook

- The XENON Dark Matter program continues a phased approach towards a one ton fiducial mass detector (or beyond) with the realization of XENON100 and a next XENON100 Upgrade.
- XENON10 provided the best spin-independent DM limits in 2007.
  - Currently neck and neck with CDMS-II, Zeplin-III.
  - Best spin-dependent limits with unpaired neutrons.
- XENON100 is built and installed in an upgraded shield at LNGS.
- Gamma background is at the expected level.
- Achieved electron drift across 30 cm.
  - Purity continues to improve, and we have now improved tools in place that allow sensitive monitoring of impurities.
- Progress with analysis tools, simulations.
- Expecting to start full calibrations in the summer, DM search later this year.
- Timeline of XENON direct search experiments is compatible with LHC (2009) and indirect searches by Fermi (launched 2008).
- *It's an exciting time for Dark Matter searches!*

Thank you.

DM Direct Searches - Progress Over Time



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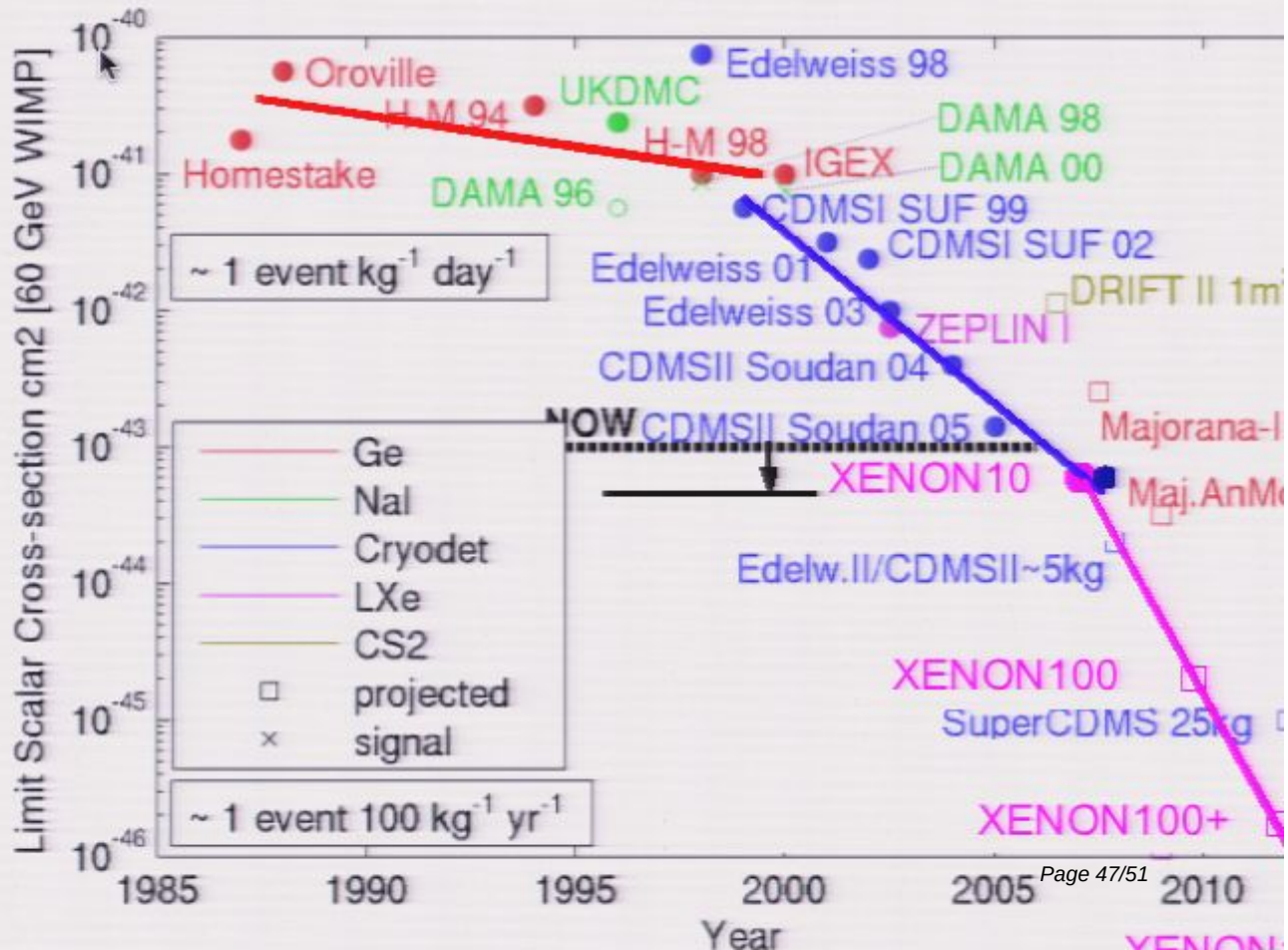
NewLights_XENON_DM.odp – NeoOffice Impress

Slides

Normal | Outline | Notes | Handout | Slide Sorter

DM Direct Searches - Progress Over Time



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NewLights_XENON_DM.odp – NeoOffice Impress

4 Slides

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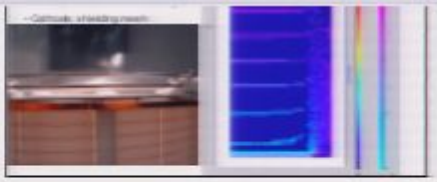

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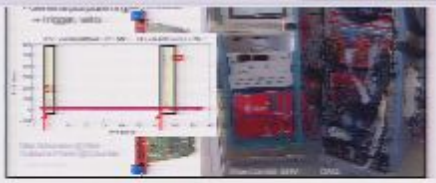

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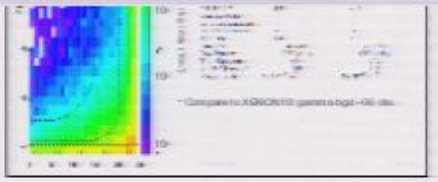

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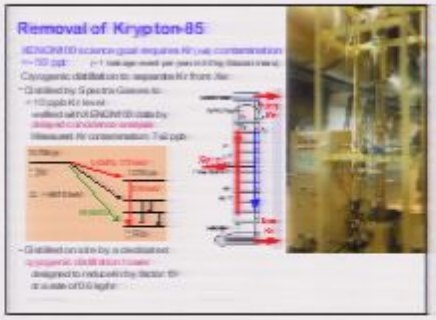

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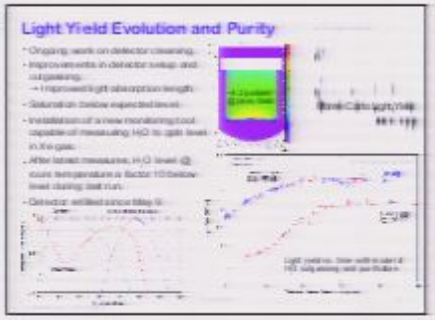

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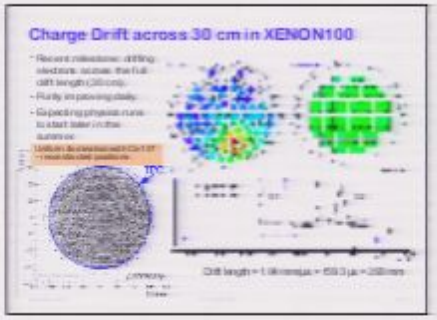

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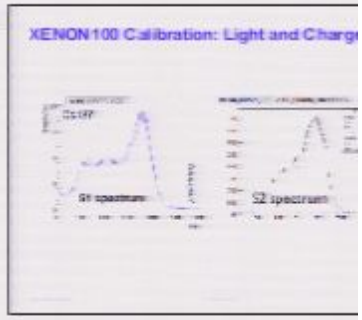

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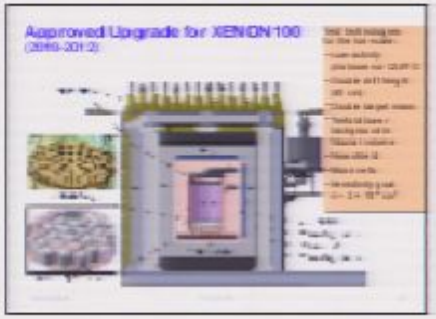

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Slide 26

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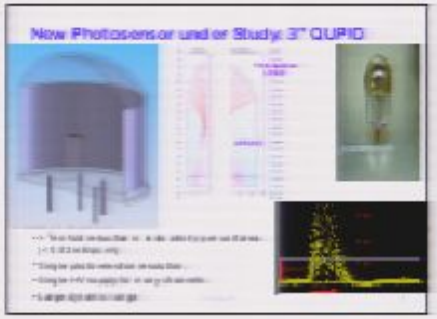

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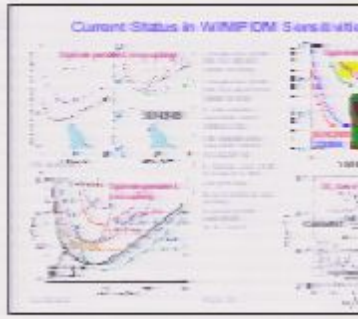

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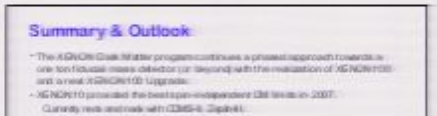
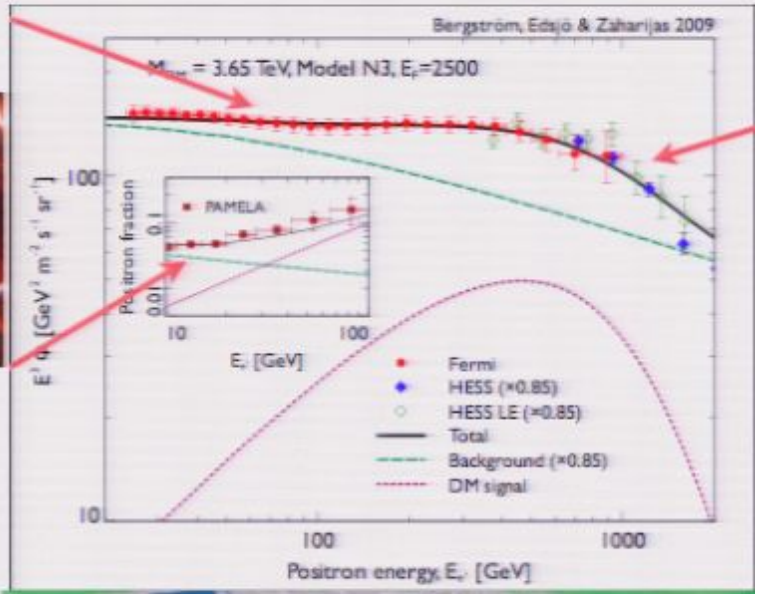
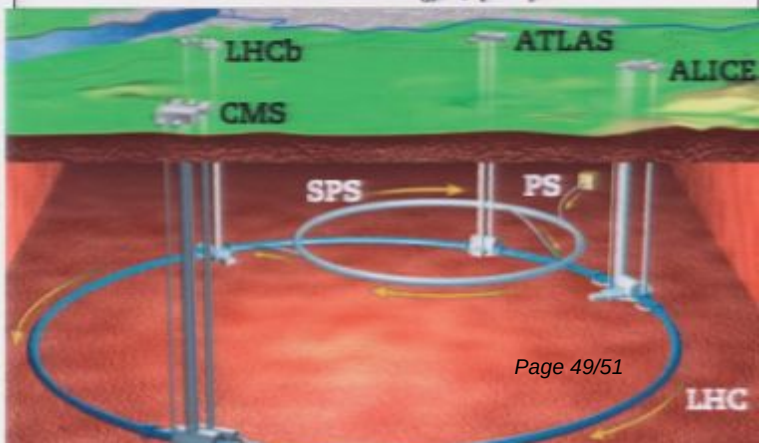


Dark Matter Detection Methods

- Astrophysics / Cosmology:
  Measurement of Gravitational Effects.
  - Rotation curves of spiral galaxies
  - Orbital velocities of galaxies in clusters (Zwicky 1933)
  - Colliding clusters (Bullet cluster)
  - Large scale structure, lensing

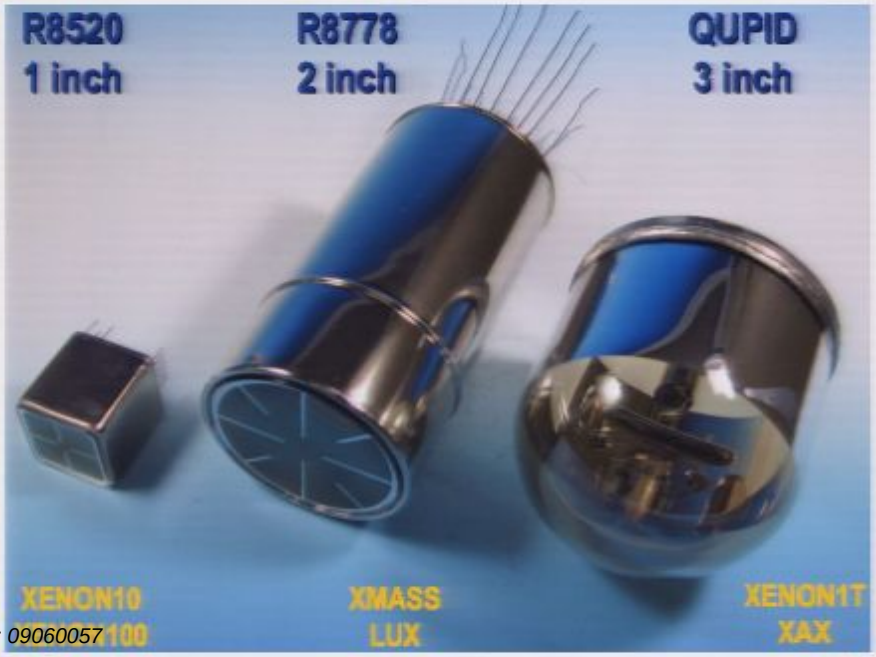
- **Direct Detection:**
  - WIMP scattering
  - Axion searches
- Indirect Detection: from annihilation or decay
  - Cosmic rays
    (PAMELA positron excess? Fermi electron spectrum?)
  - Neutrinos
  - Gamma-rays
- Accelerator-based Creation and Measurement:
  - Missing energy / momentum
  - Search for related particles (SUSY, extra dimensions) even if not the DM particle itself

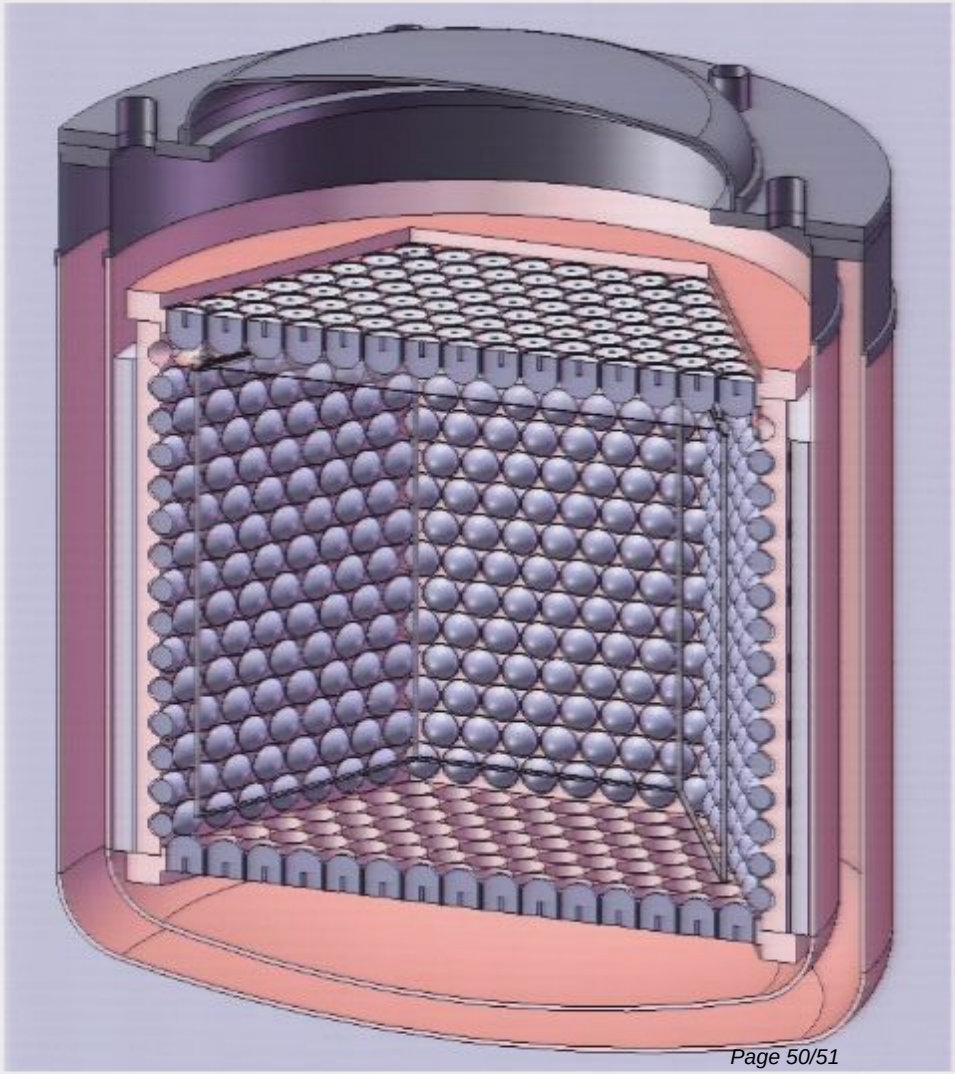




Further along: XENON-1T
(2011-2014 ?)

- Design studies proposed of 1T fiducial mass LXe detector to explore $\sigma \sim 10^{-47}$ cm^2
- DUSEL or European Laboratory
- R&D already being addressed in XENON100 Upgrade phase.
- Low-activity 3" photosensor: QUPID





XENON100 Calibration: Light and Charge