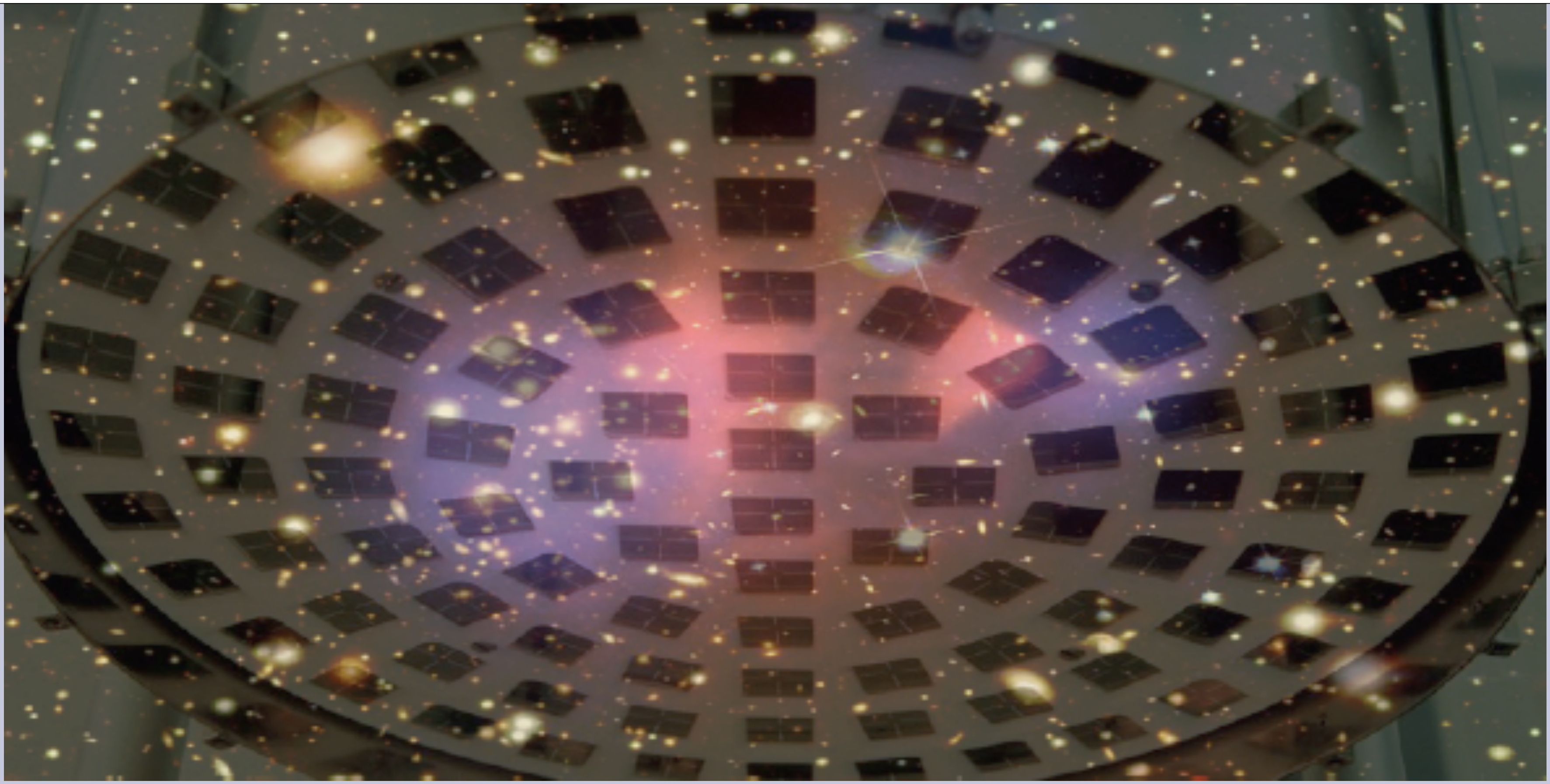
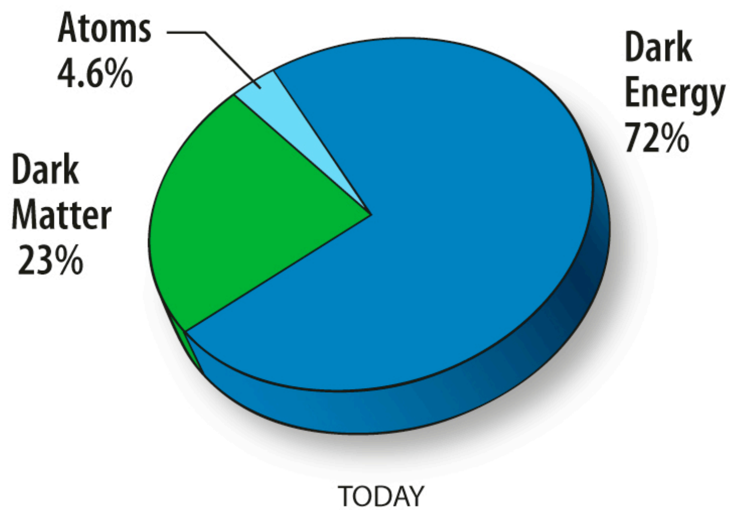


Direct Searches for Dark Matter

Elena Aprile
Columbia University

EPS - HEP, July 21 2009, Krakow, Poland

WHAT IS DARK MATTER?



- Evidence for Dark Matter convincing at all scales, BUT only from gravitational effects
- Relic Density known with precision: $\Omega_{DM} = 0.233 \pm 0.0013$
- Constraints on basic properties: non-baryonic, cold or warm, not strongly self-interacting
- Identity of DM impacts Cosmology and Fundamental Physics:
  - DM determines the physics of structure formation and impact evolution of Universe
  - DM is the leading empirical evidence for a new particle
- Favored scenario: DM is a thermal relic of the Big Bang, with only weak interaction
  - Weakly Interacting Massive Particle (WIMP)

Dark Matter and The WIMP Miracle

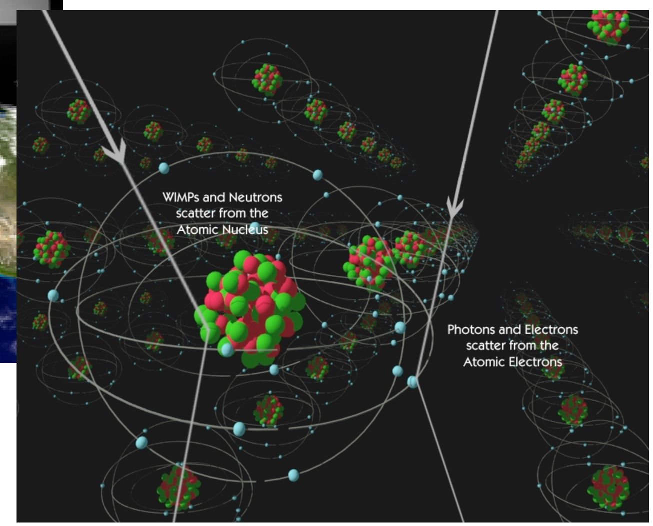
- Electroweak symmetry breaking requires new particles with mass ~100 GeV - TeV
- Particles at this mass scale with right relic abundance appear naturally in theories beyond SM
- Many candidates with a large difference in mass and cross-section
- Some favored WIMP candidates for Cold Dark Matter:
  - Lightest Neutralino of Supersymmetry with ~0.1 - 1 TeV and sub-weak interactions
  - Lightest Kaluza-Klein state of UED with mass ~0.4 - 1 TeV and sub-weak interactions
  - Axion, not a thermal relic, not easily testable, but search in progress

Strategies for WIMP Detection

PARTICLE COLLIDERS: Produce and Detect WIMPs

INDIRECT DETECTION: measure gamma rays, neutrinos , positrons, antiprotons, anti-deuterons, etc. from WIMP annihilation in GC, in Sun, in MW

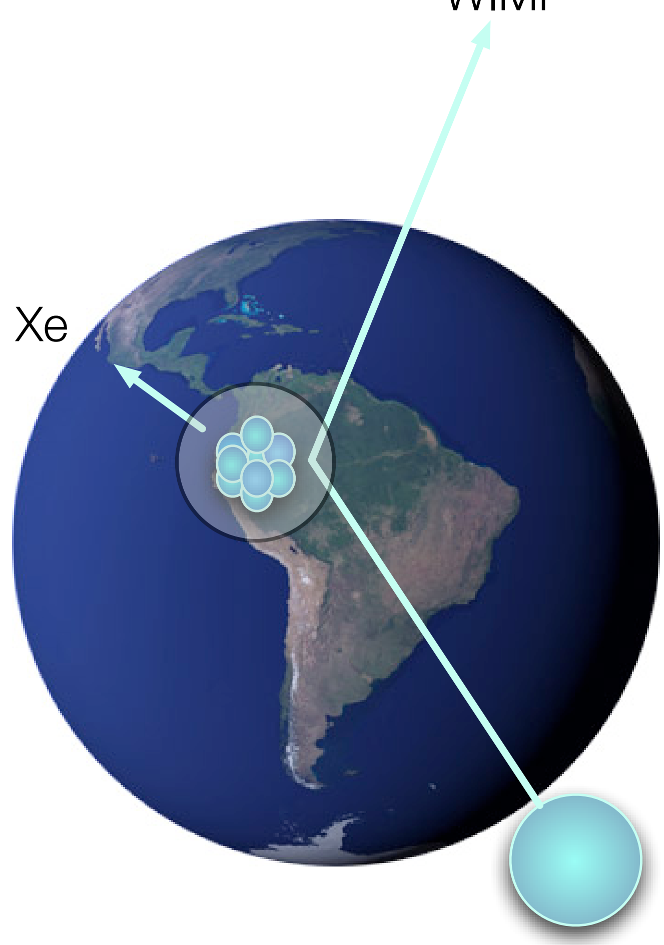
DIRECT DETECTION: measure WIMP scattering off targets in detectors on Earth



Potential for Breakthrough in coming decade: WIMP models will be stringently probed by one or more method

Principle of Direct Detection

Goodman and Witten: coherent scattering of WIMPs (1985)



- Elastic collisions with nuclei
- The recoil energy is:

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \leq 50\ keV$$

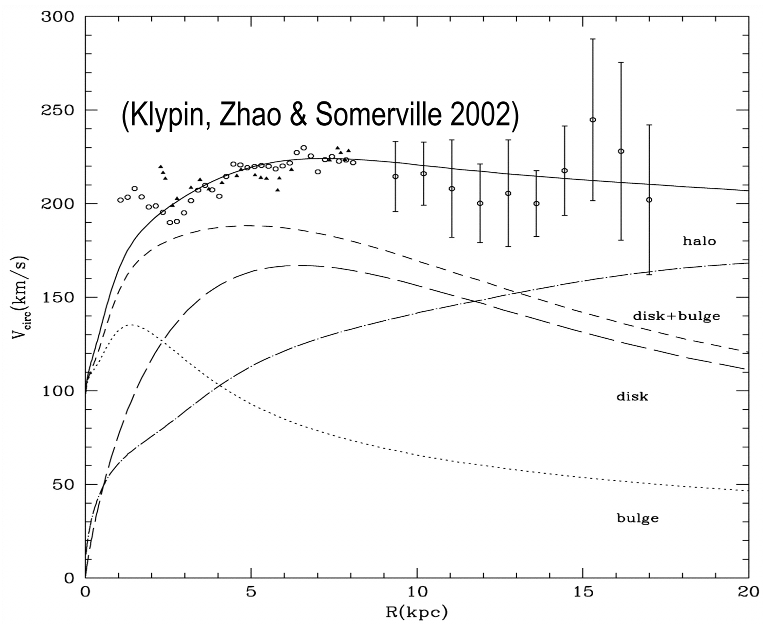
- and the expected rate:

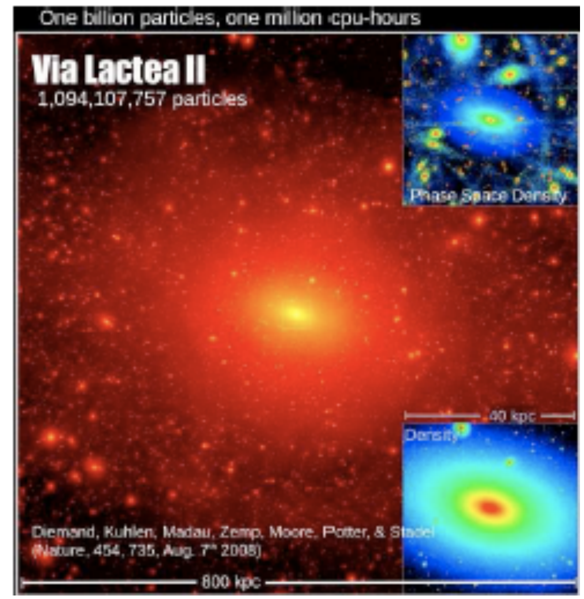
$$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi N} \rangle \qquad \mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

N = number of target nuclei in detector
ρ_χ = local WIMP density, m_χ = WIMP mass
$\langle \sigma_{\chi N} \rangle$ = scattering cross section

WIMP Density in the Halo

- **Measured galactic rotation curve + modeling of various components (disk, bulge, halo) -->** $\rho_0 \approx 0.3$ GeV cm^{-3}

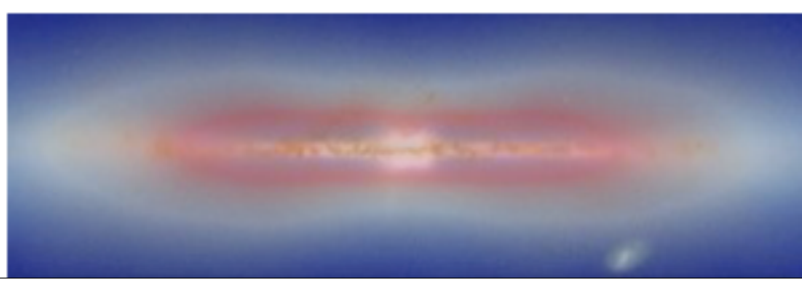




(J. Diemand et all, Nature 454, 2008, 735-738)

•Density and velocity could be very different if Earth is within a DM clump or stream or if there is a Dark Disk.

• Numerical simulations now include influence of baryons on DM..stars and gas significantly alter local DM density



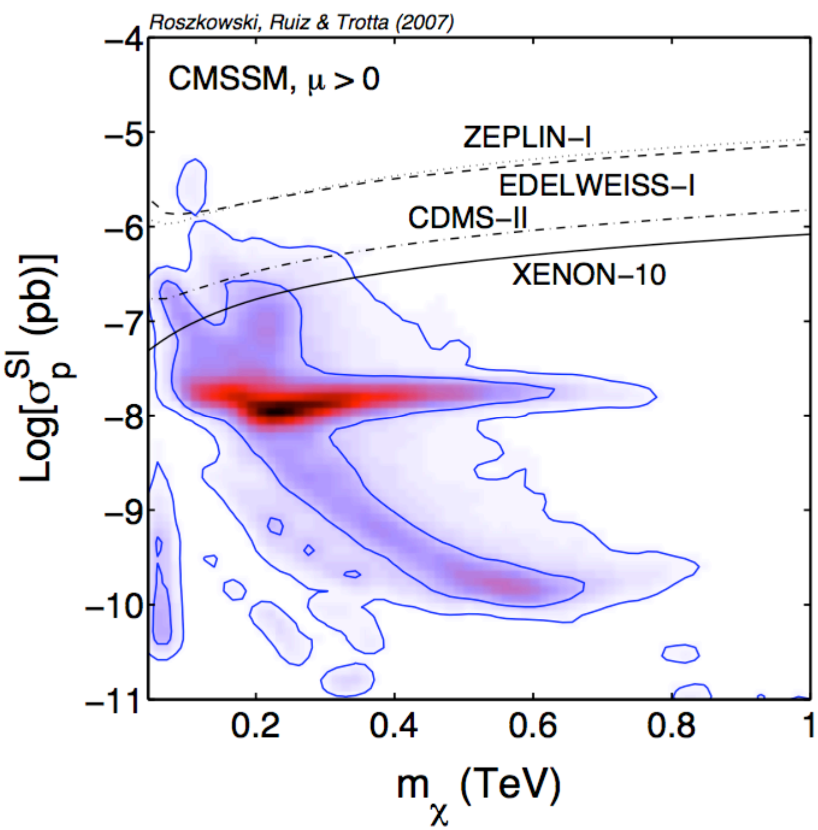
A DM Disk in the Milky Way

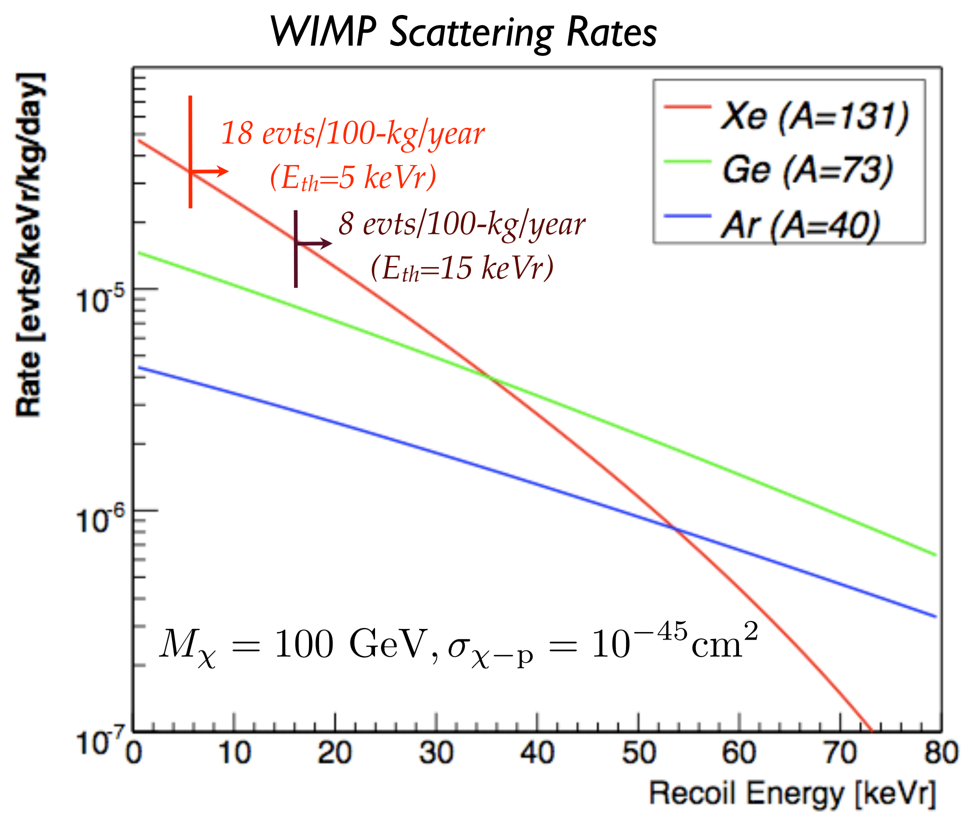
Read, Lake, Agertz, Debattista, MNRAS 389, 1041, 2008

Elena Aprile

Predicted Event Rates

- Constrained MSSM (mSUGRA) cross- section predictions: XENON10, CDMSII already below 10^{-7} pb!
- Rates: << 1 event/kg/month - Prospects good for some current and next generation searches

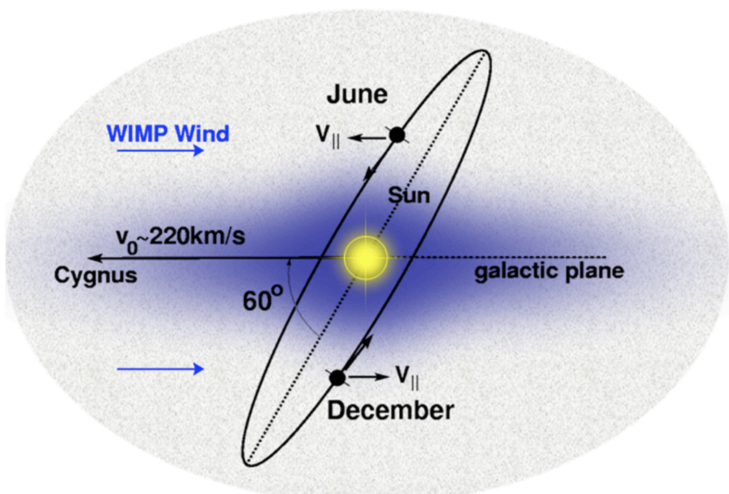


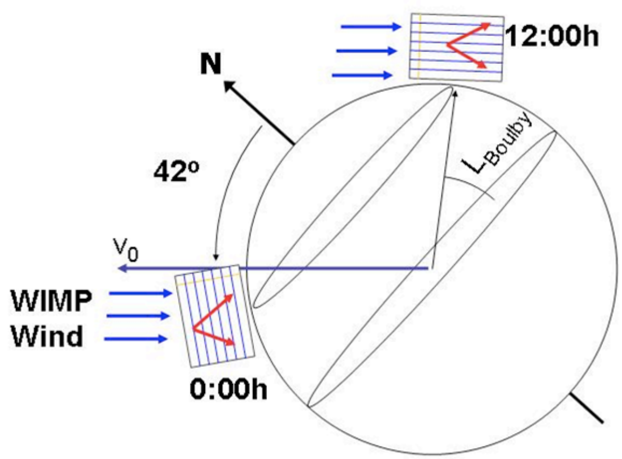


- Requirements for direct DM detectors: Large Mass + Low Background + Low Threshold

WIMP Signals

- *Nuclear recoils: single scatters with uniform distribution in target volume*
- *A^2 & F (Q) Dependence: test consistency of signal with different targets*
- *Annual Modulation: as a result of Earth motion relative to WIMP halo; rate modulation with a period of 1 year and phase ~2 June; large mass required (~2% effect)*
- *Diurnal Direction Modulation: Earth rotation about its axis, oriented at angle w/respect to WIMP "wind", change the signal direction by 90 degree every 12 hrs. ~30% effect.*





Backgrounds

- *Detector related:*
  - *intrinsic radioactivity (U, Th, K, Co, etc.) in materials: a source of gammas and neutrons background--> careful screening and selection*
  - *intrinsic radioactivity in target itself (U, Th, Rn, Kr85, Ar39, etc.) --> purification and careful handling*

- *Environment related:*
  - *radioactivity of environment materials (gammas and neutrons from (alpha,n) and muon-spallation): shielding (Pb, Cu, PE, H2O, etc.)*
  - *cosmic ray muons: go underground*
  - *fast neutrons induced by muons (ultimate background)*

- *Other physics processes related:*
  - *solar neutrinos, double beta decay --> start to be relevant for very sensitive DM searches and as threshold is lowered*

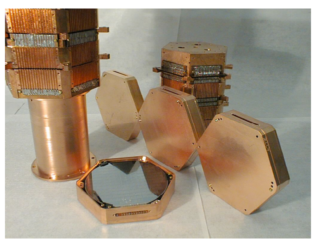
Direct Detection Experiments

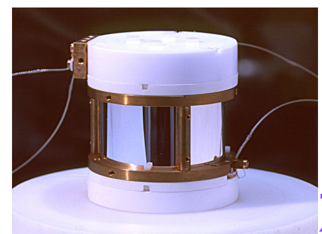
COUPP,
PICASSO

Phonons

CDMS
EDELWEISS

Ge, Si





CRESST
ROSEBUD

$CaWO_4$, BGO
$ZnWO_4$, Al_2O_3 ..

E_R

e-h, e-i

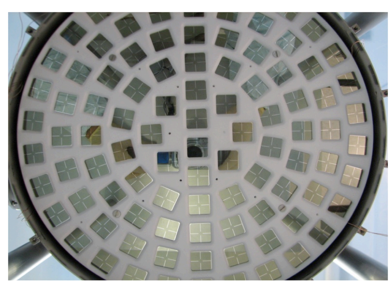
Photons

DAMA/LIBRA,
KIMS, ANAIS,
XMASS, CLEAN

NaI, CsI, Xe, Ar

DRIFT, DM-TPC,
COUPP
NEWAGE, MIMAC

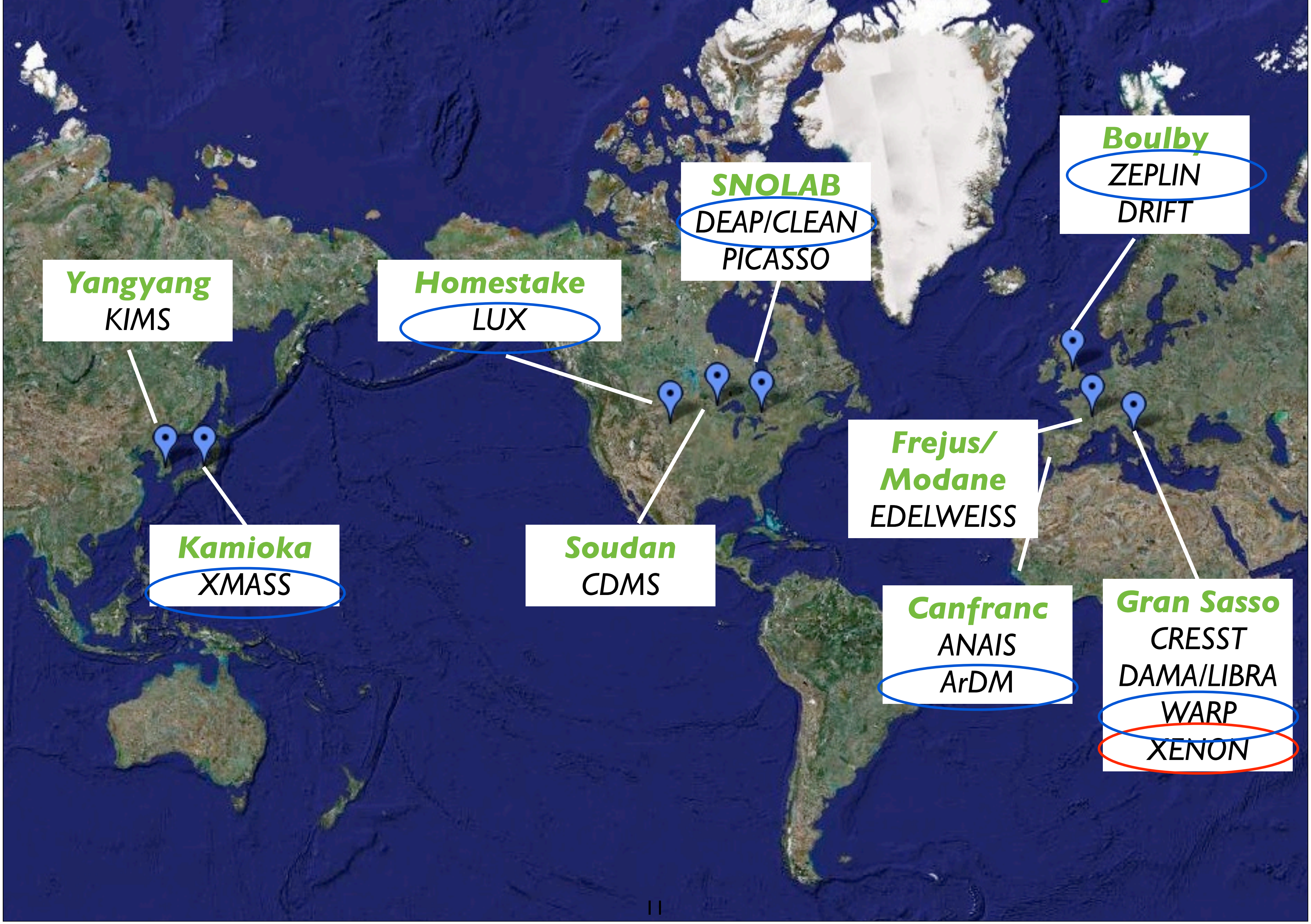
CS_2, CF_4, C_3F_8, ^3He



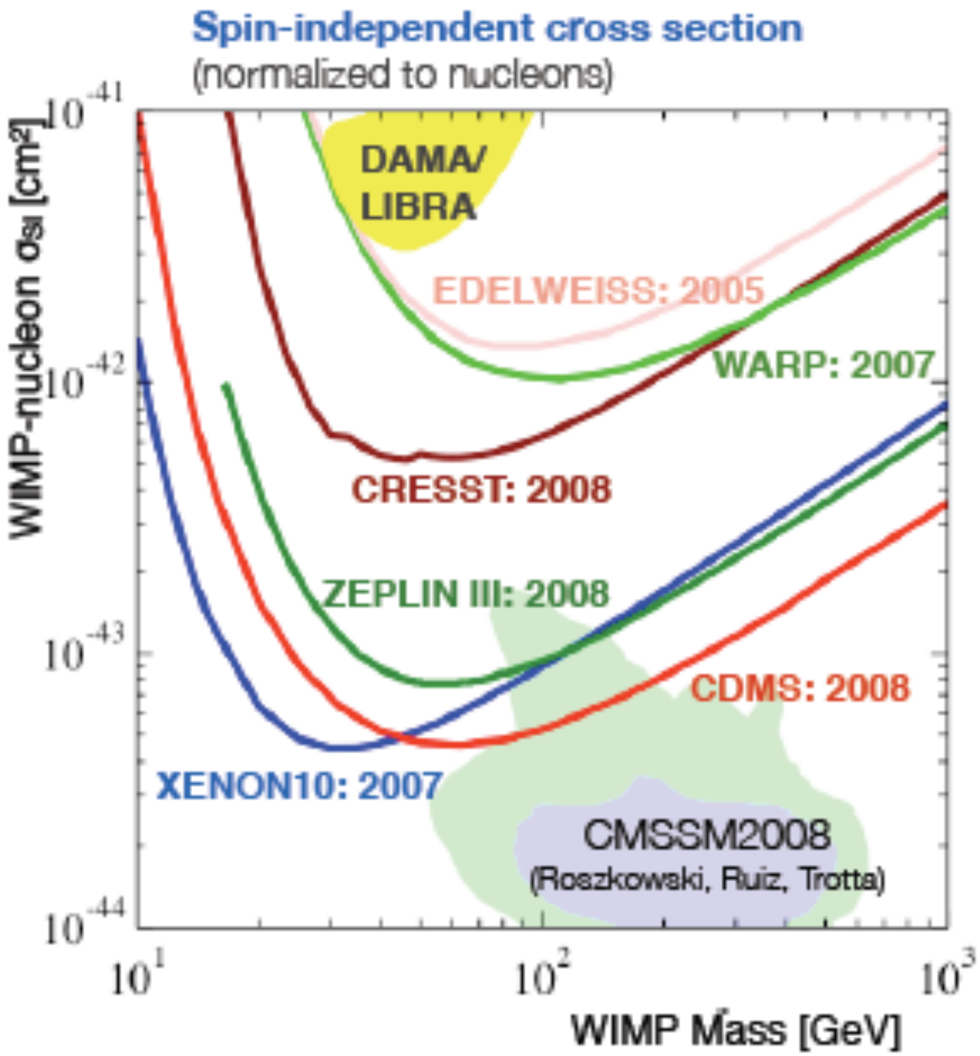
ZEPLIN, XENON,
WArP, ArDM

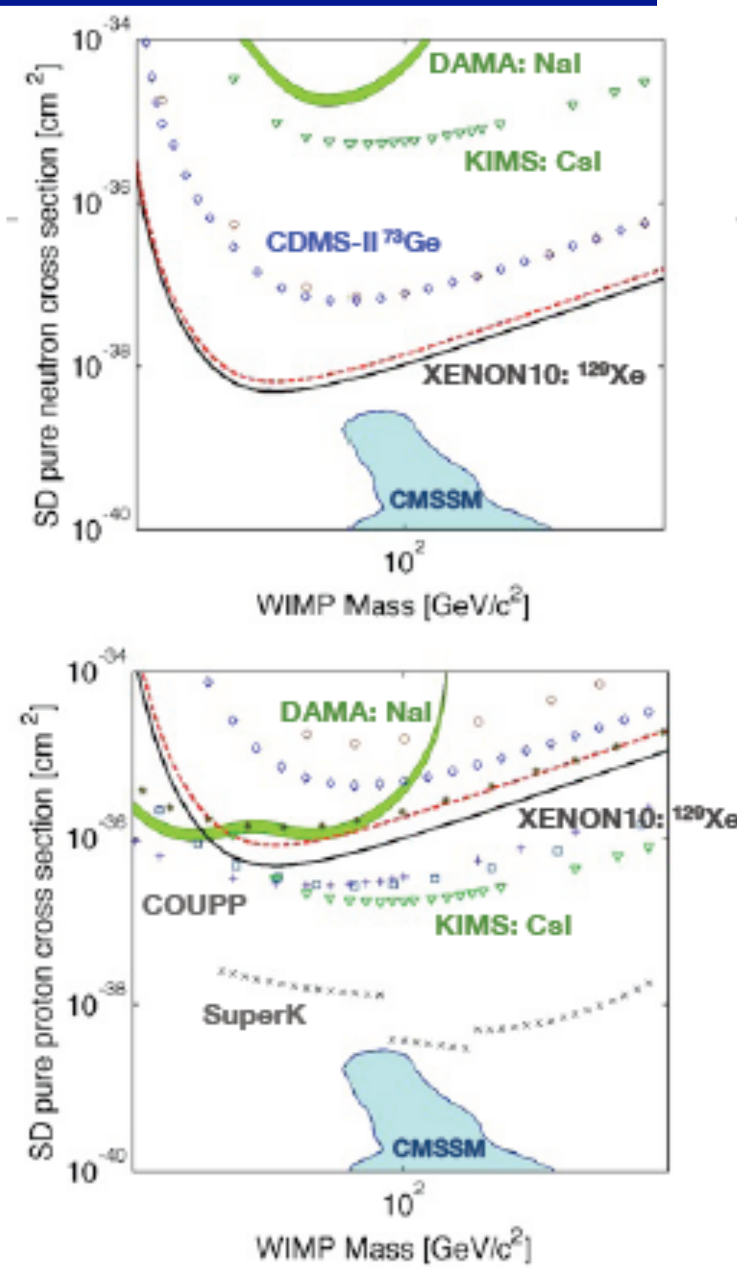
Xe, Ar

~50% of Dark Matter Searches use Noble Liquids



Experimental Results: July 2009

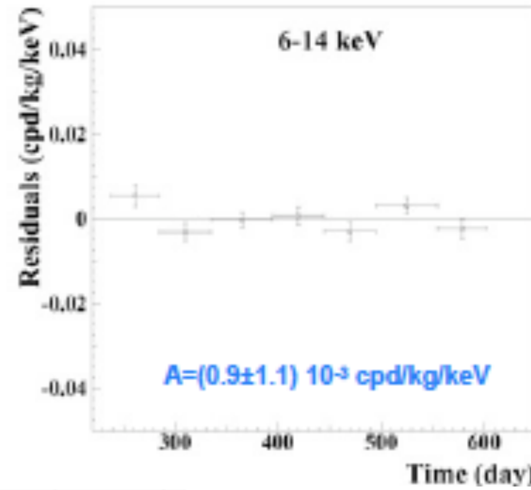


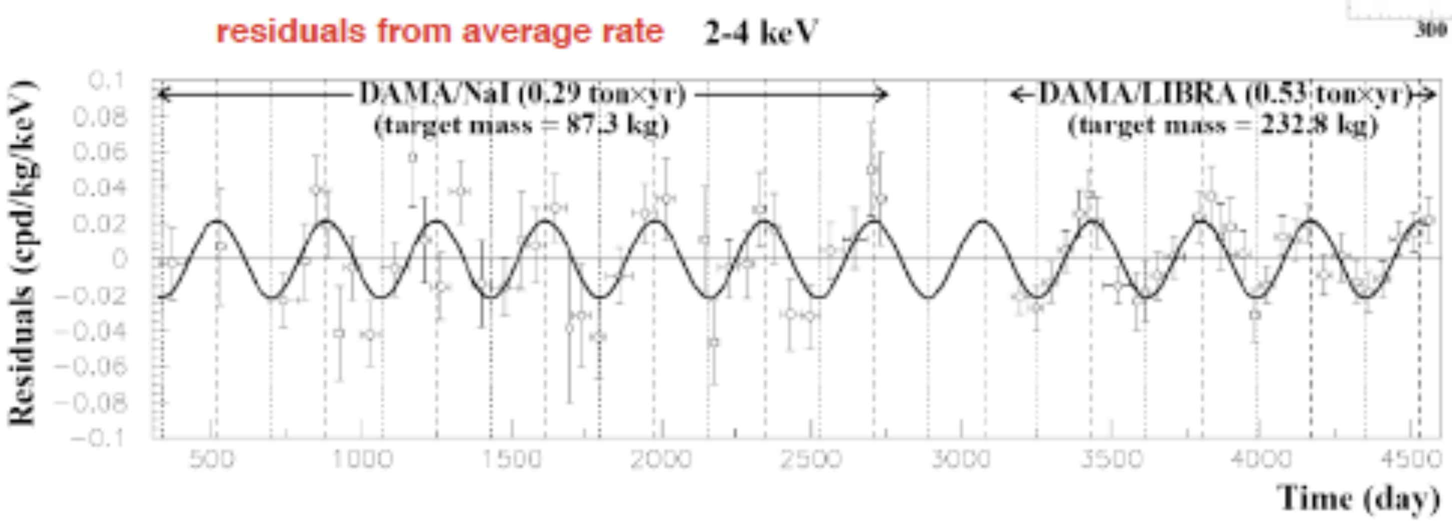


Spin-dependent

DAMA/LIBRA Results 2008

- 250 kg NaI detectors, each viewed by 2 PMTs.
- 4 years of data: Total exposure of 0.82 ton x year
- Event rate modulation confirmed in 2008 with a 8.3 σ CL
- No modulation above 6 keV
- WIMP hypothesis difficult to reconcile with other experiments





$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t - t_0)$$

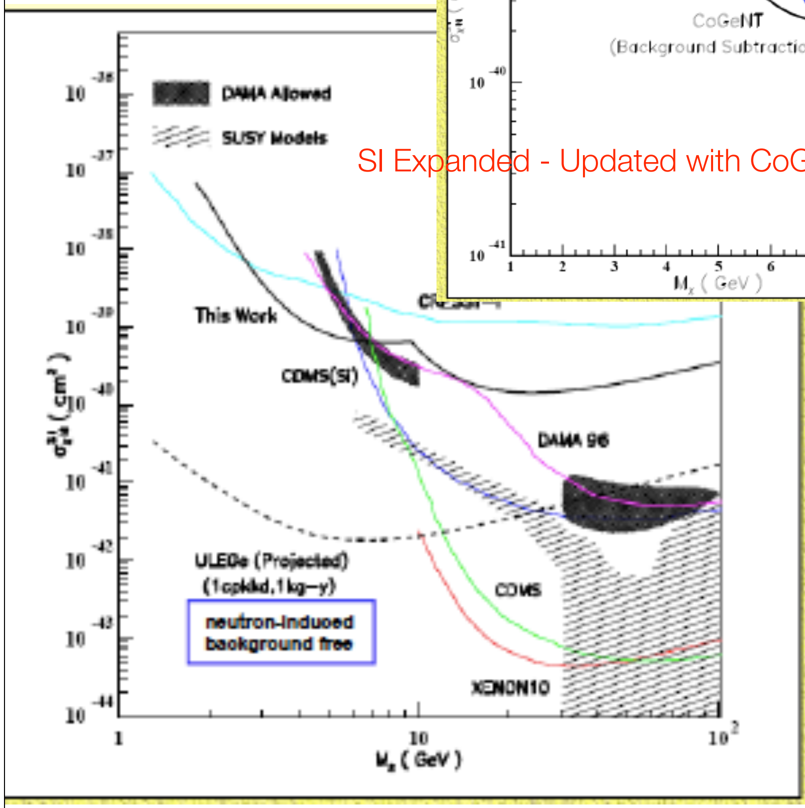
S_m = (0.0215 ± 0.0026) counts/(day kg keV)

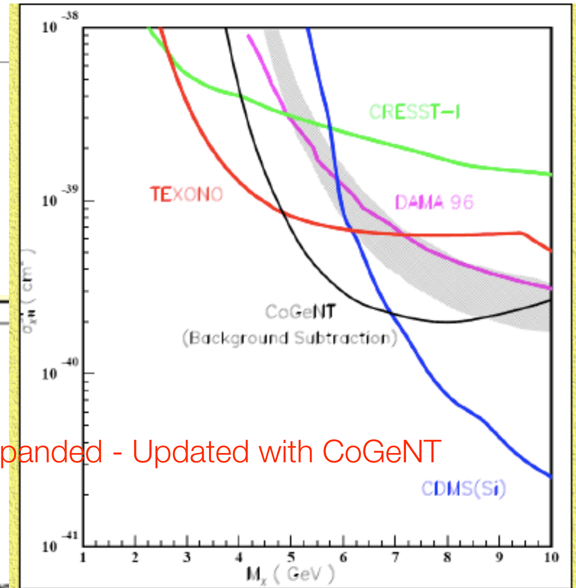
t_0 = 144 ± 8 days

T = 0.998±0.003 year

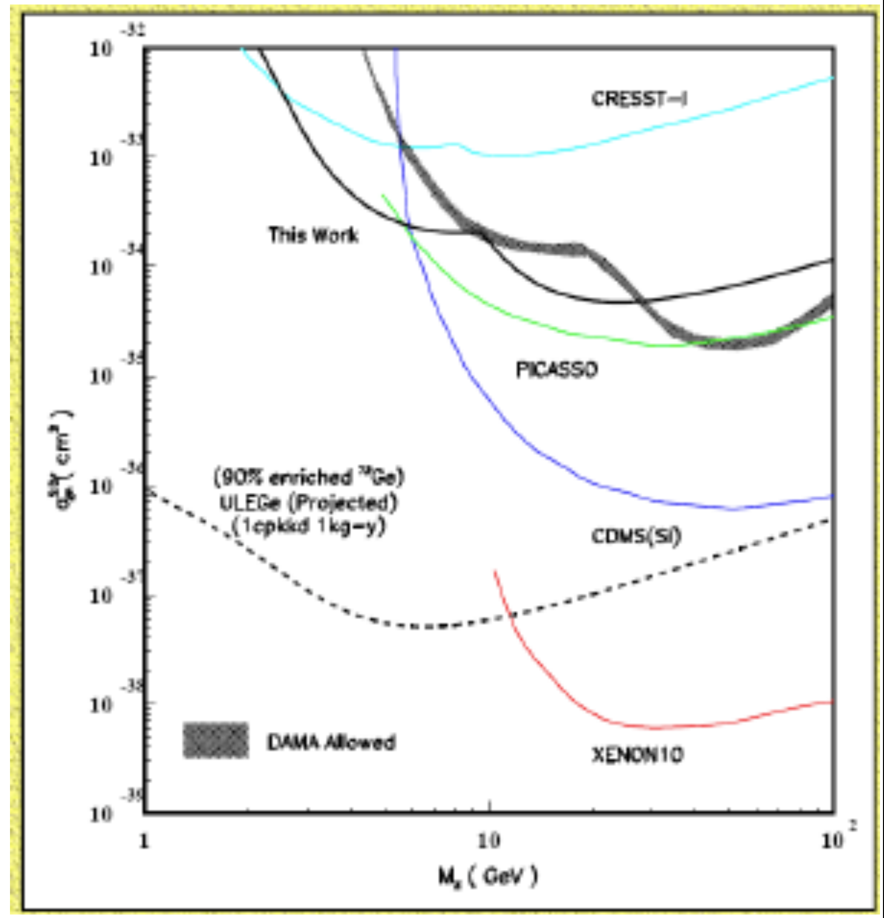
New Results at Low Mass WIMPs

TEXONO: 4 x 5g ULE Ge ; CoGeNT: 500 g PPC Ge





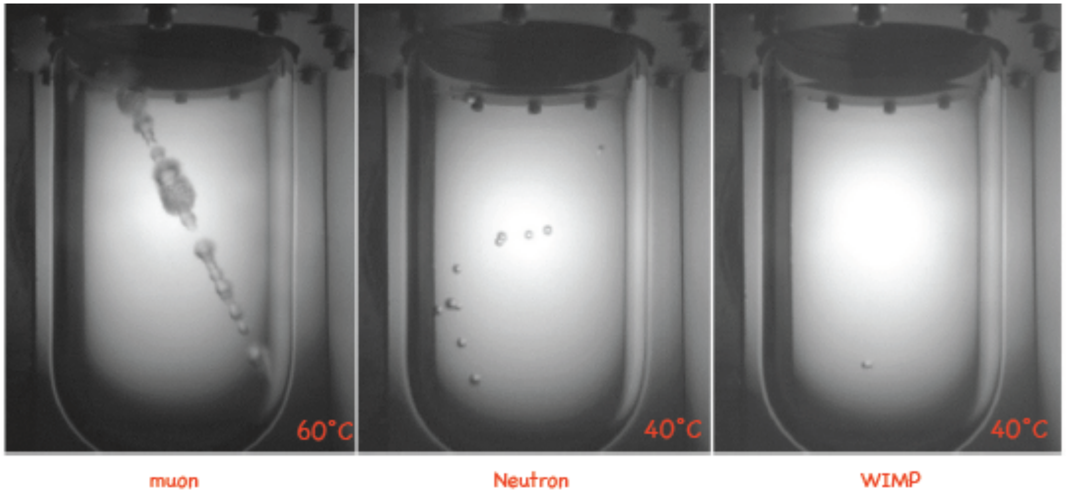
SI Expanded - Updated with CoGeNT

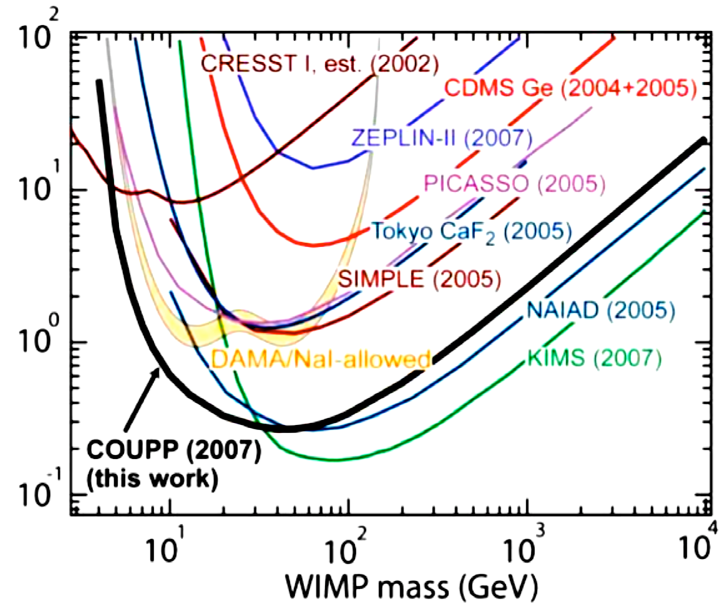


Spin Independent

Spin Dependent

The COUPP Bubble Chamber Experiment



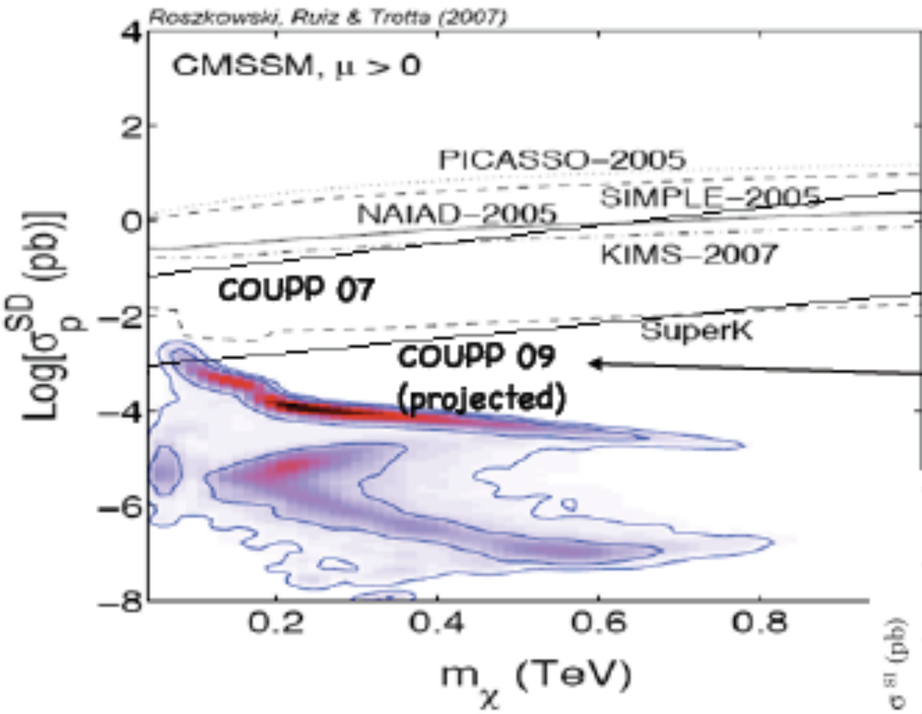


- COUPP approach to WIMP detection: detection of single bubbles induced by high dE/dx nuclear recoils in heavy liquid bubble chamber
- Insensitive to EM background. Large rejection factor for mips $>10^{10}$; High spatial granularity for additional n-rejection
- Scalability to large mass at low cost. Choice of three triggers:pressure, acoustic, motion (video)
- Excellent sensitivity to both SD and SI couplings; different target fluids
- With 2 kg chamber: most stringent limit on pure proton SD interactions for low mass WIMPs
- 2007 COUPP result excludes low mass region favored by a SD interpretation of DAMA signal

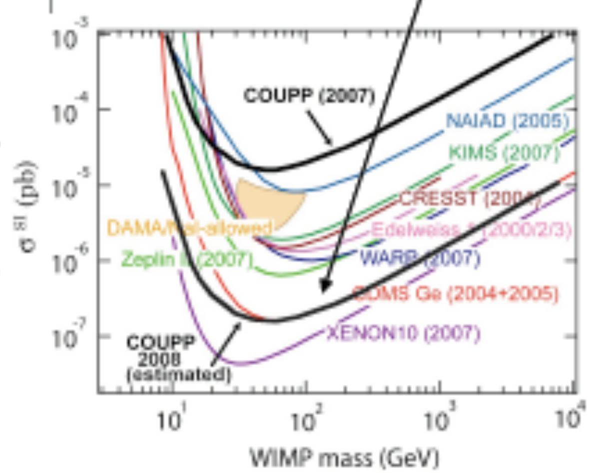
COUPP next step: 60 kg target mass

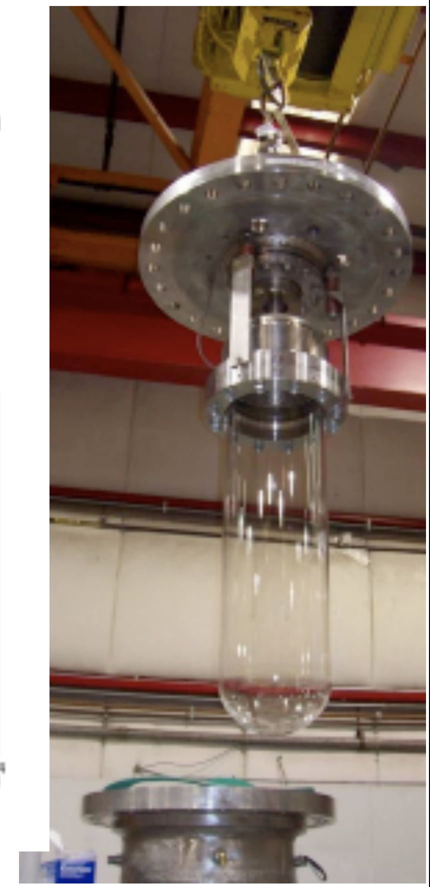
Physics Reach at Fermilab Site

Background goal for E-961: <1 event per kg per day

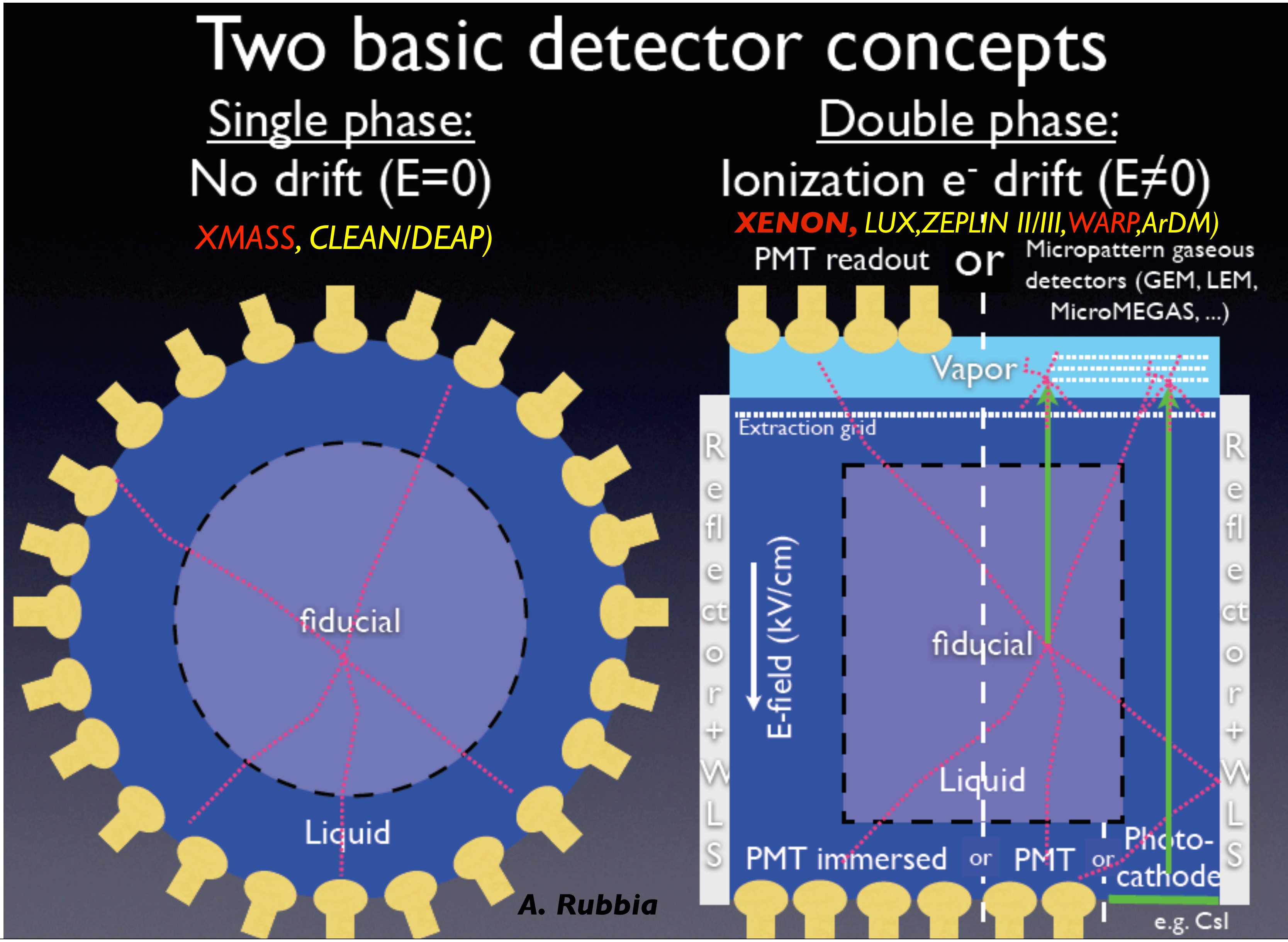


2009 goals: exploring SD favored region for the first time, and competitive SI limits.



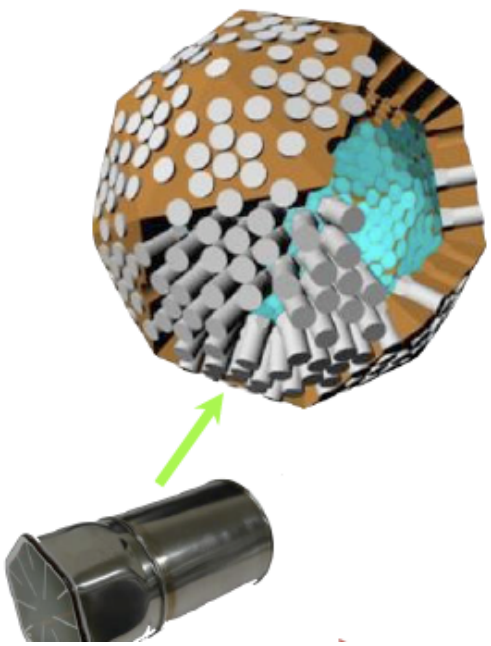


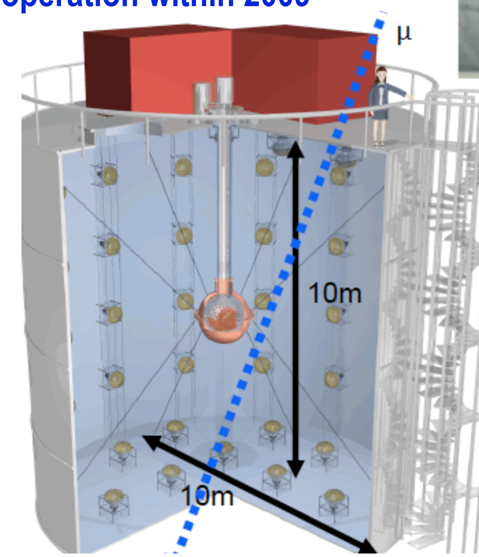
Noble Liquid Experiments for Dark Matter

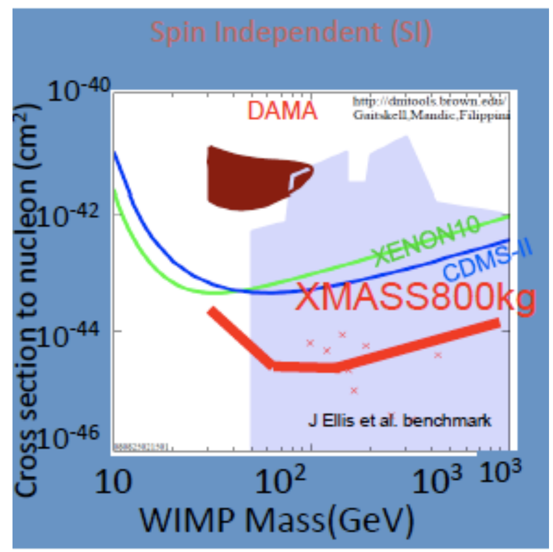


The XMASS Experiment @ Kamioka

- Exploit scintillation signal only, detected by PMTs in the liquid; event localization from light pattern reconstruction ~ a few cm
- low background inner core by self-shielding of LXe (Z=54; 3g/cc)
- active water shield for fast neutron background rejection
- 800 kg (100 kg FV) LXe detector with 642 low activity PMTs
- 5 keVee threshold; PMTs assembly has started; operation within 2009

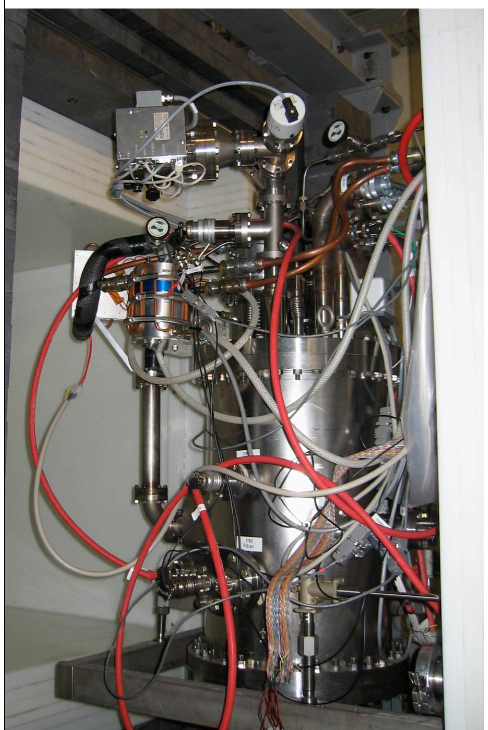
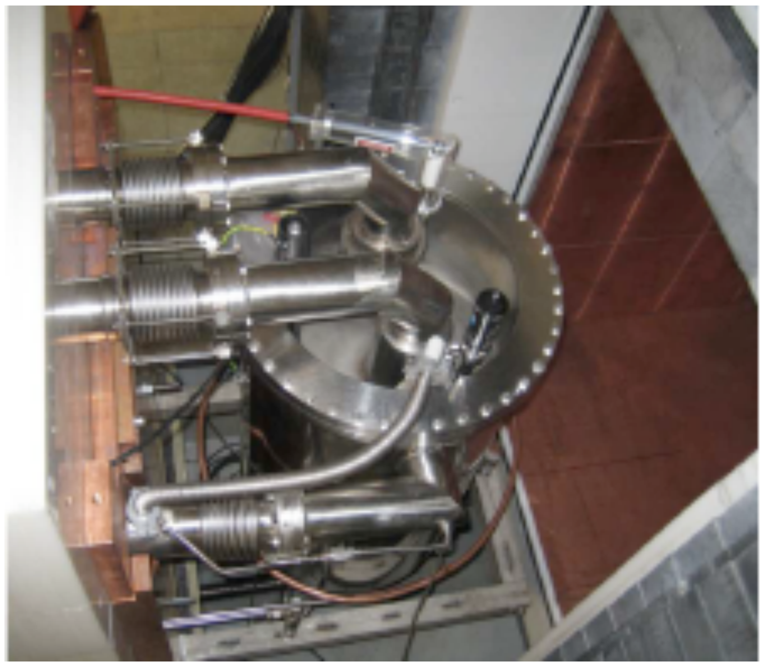
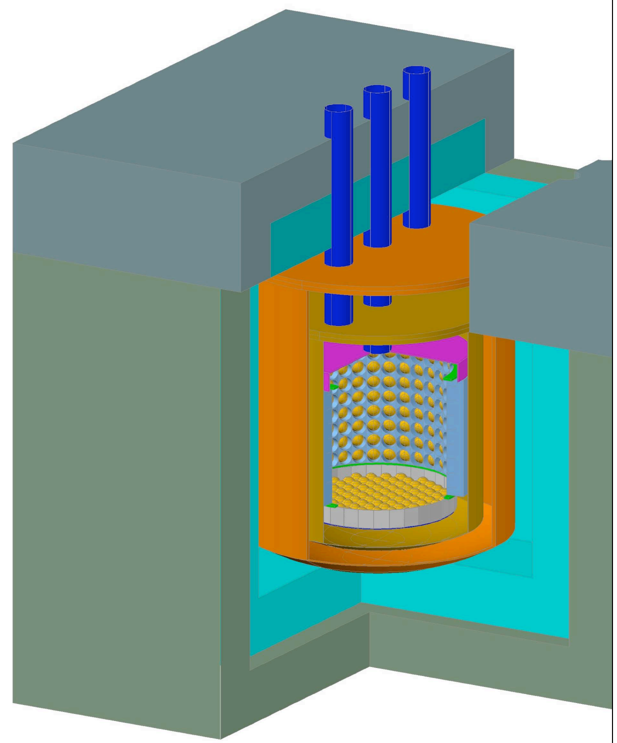






The XENON Dark Matter Phased Program

past (2005 - 2007)	*current* (2008-2012)	*future* (2013-2015)

XENON10

Achieved (2007) σ_{SI}=8.8 x10^{-44} cm^2

XENON100 & 100+

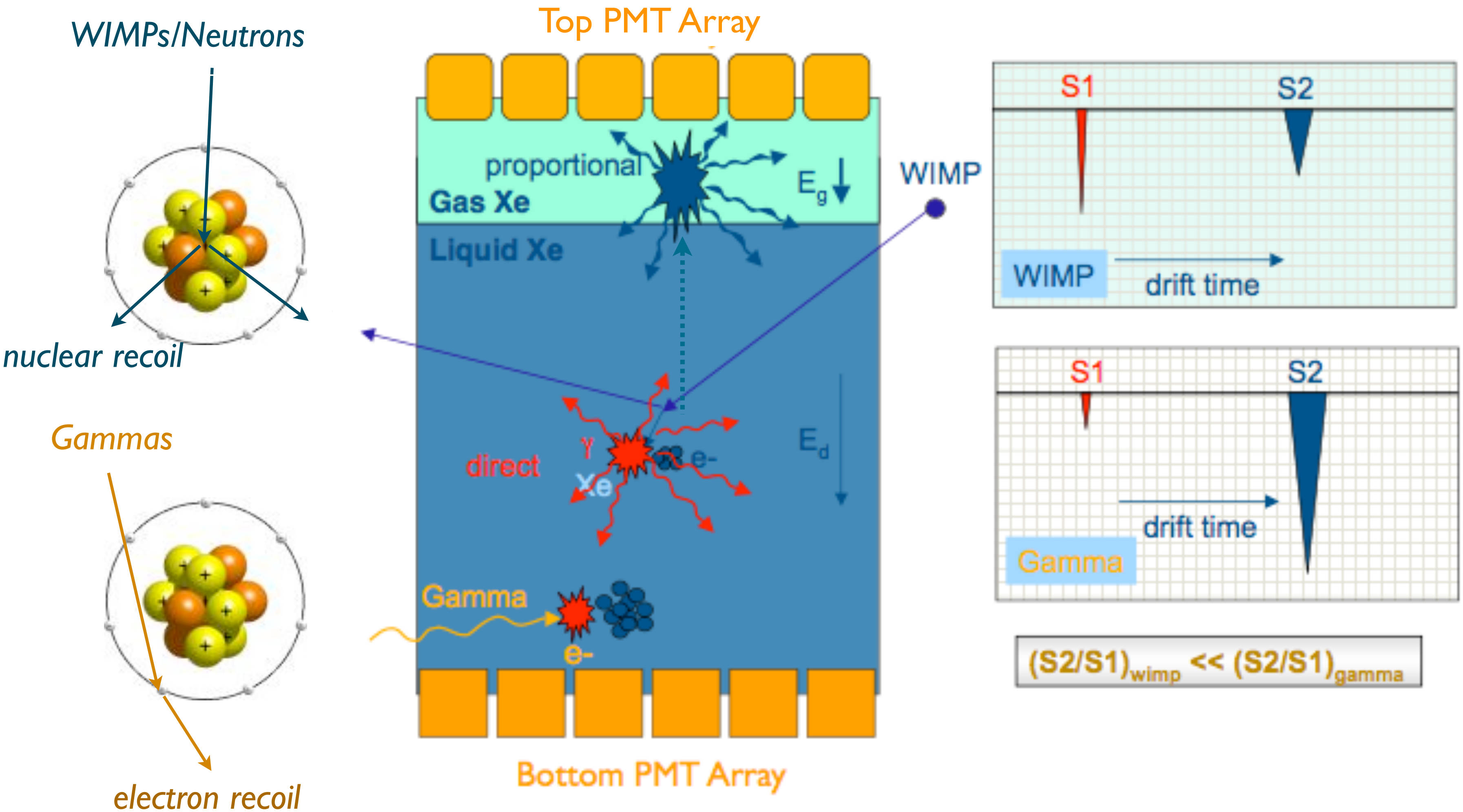
Projected (2010) σ_{SI}~2x10^{-45} cm^2

Projected (2012) σ_{SI}~2x10^{-46} cm^2

XENON1T

Projected (2015) σ_{SI} <10^{-47} cm^2

The XENON two-phase TPC

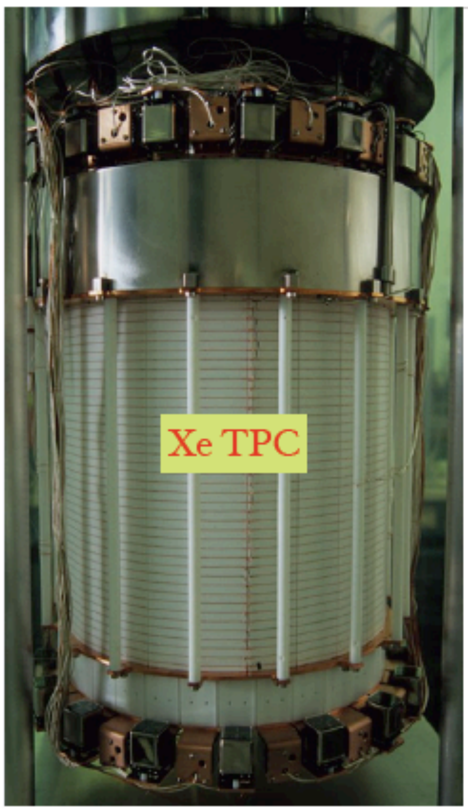


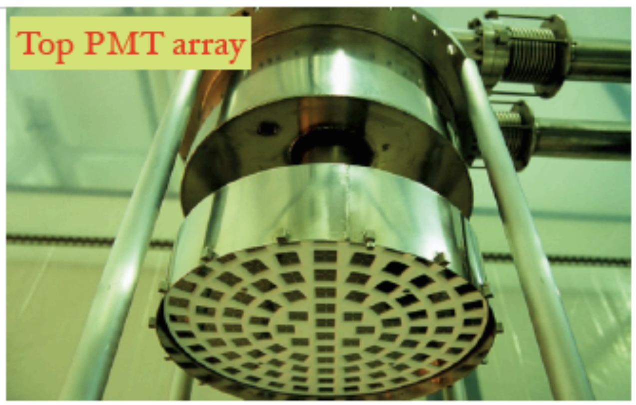
- Single electron and single photon measurement sensitivity
- > 99.5% ER rejection via Ionization/Scintillation ratio (S2/S1)
- 3D event-by-event imaging with millimeter spatial resolution

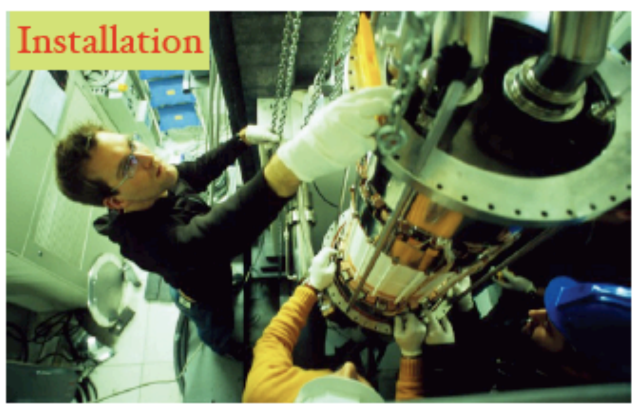
The XENON100 Experiment @ LNGS

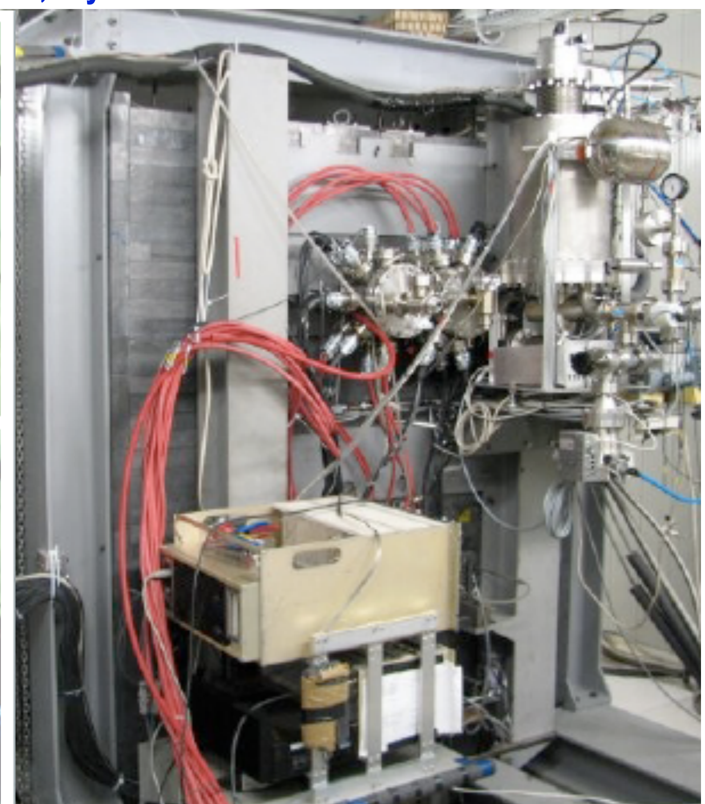
USA, Switzerland, Italy, Portugal, Germany, France, Japan, China

- 170 kg of ultra pure LXe: 70 kg as active target and 100 kg in a 4pi LXe scintillation veto
- 30 cm drift gap TPC (~1 kV/cm) with two PMT arrays to detect both charge and light signals
- 242 x 1 inch square PMTs with < 1mBq/PMT in U/Th) and high QE (25- 33 %) at 178 nm
- 3D event localization with a few millimeter resolution in X-Y and sub-millimeter in Z
- ~100 x less background than XENON10: low activity materials; crycooler outside shield and LXe veto



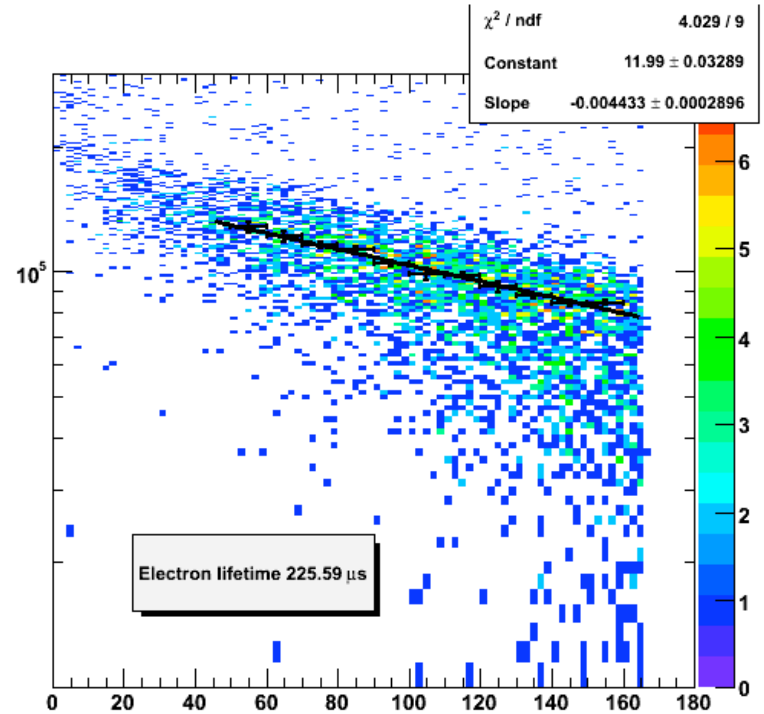


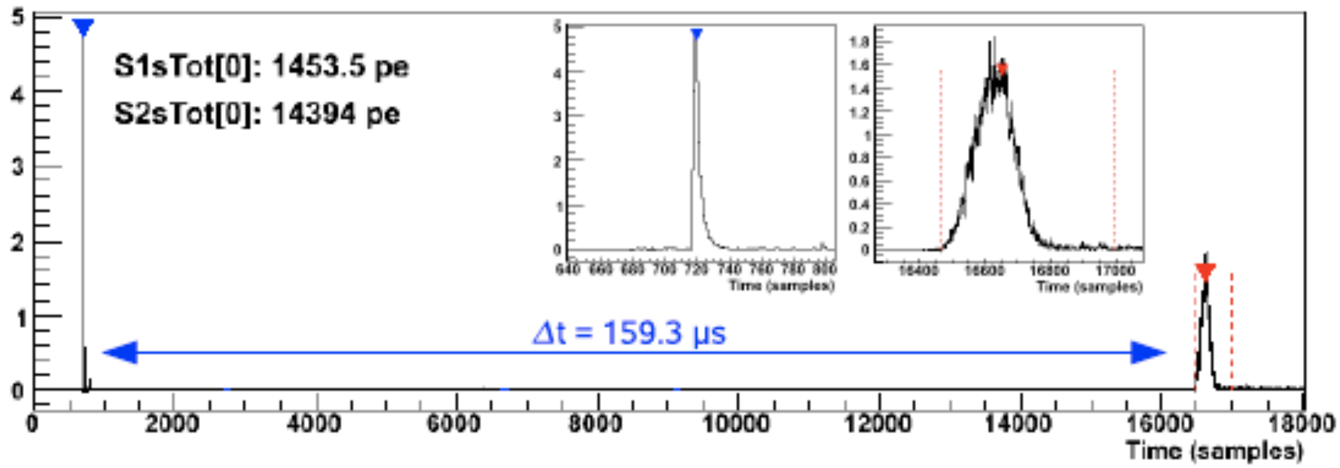


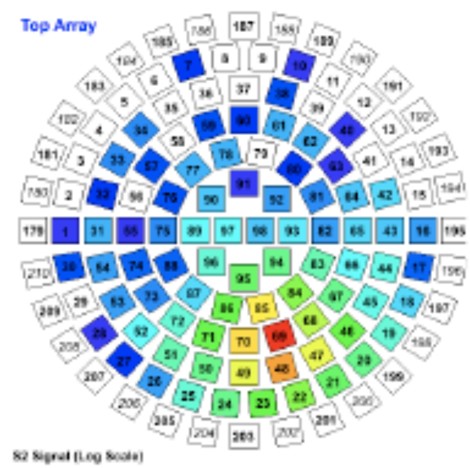


XENON100 Status and Schedule

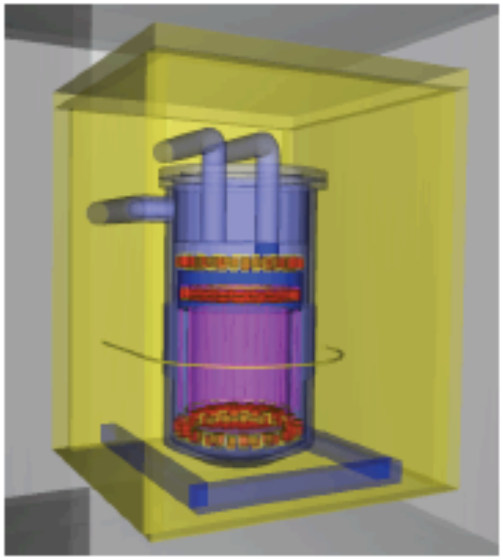
- Detector filled with low-Kr Xe and operational underground
- Taking gamma calibration data to optimize trigger level, energ threshold, overall S1 and S2 response
- Light Yield has reached a maximum value of ~4.5 pe/keVee
- The electron -lifetime increasing with continuous purification
- Initial background data show a level consistent with predicted
- Schedule: finalize Gamma and Neutron Calibration in Fall 09
- Start 1st DM search for ~ 1 month before end of 2009

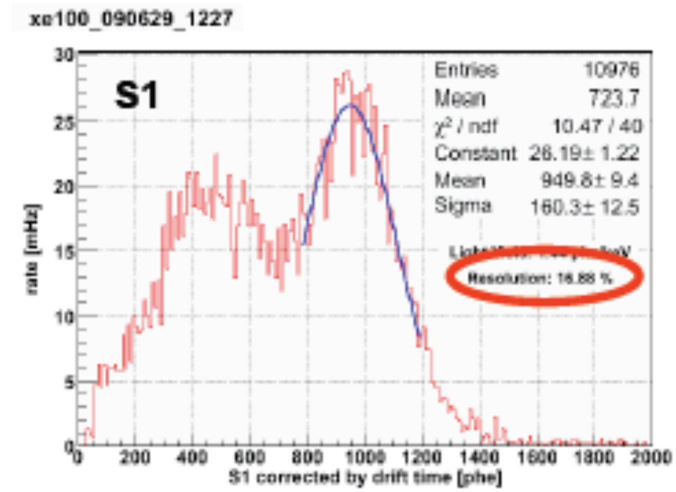




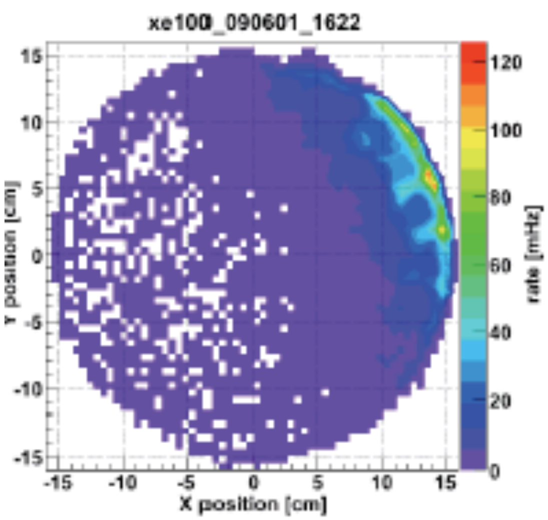


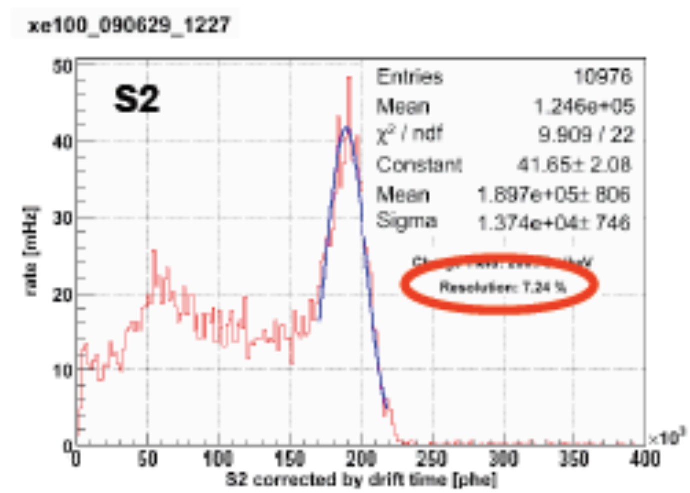
Initial Results from Cs-137 Gamma Calibration





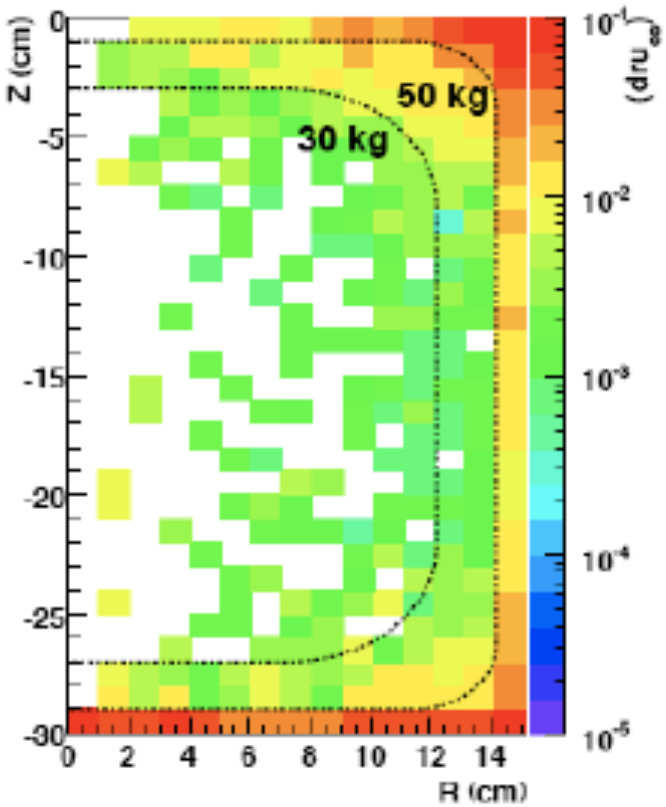
74kBq Cs-137 on the side





XENON100 Background: Monte Carlo & Data

Monte Carlo predicted rate

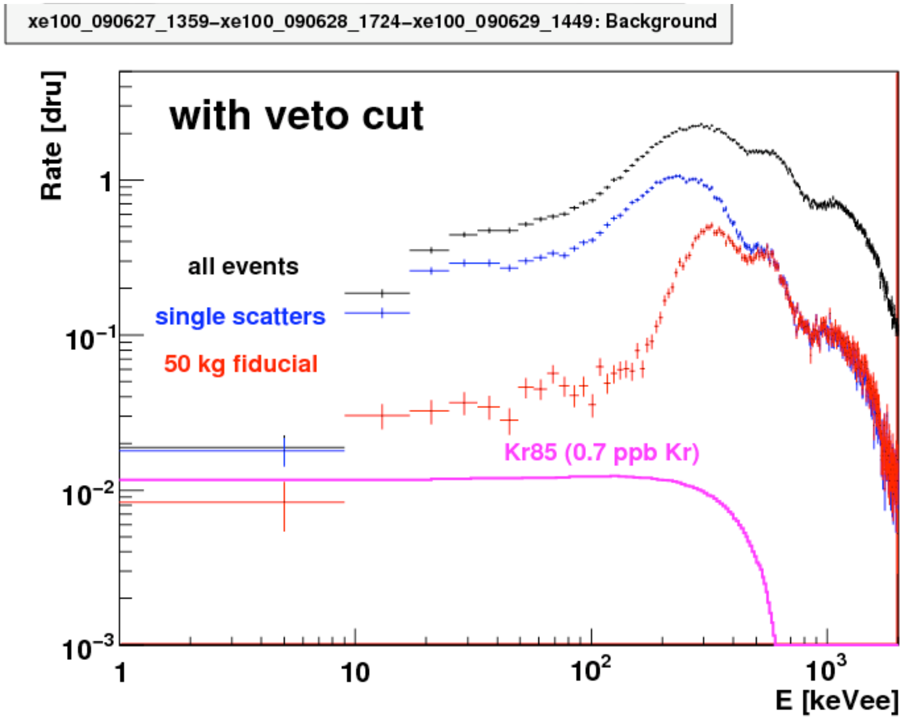


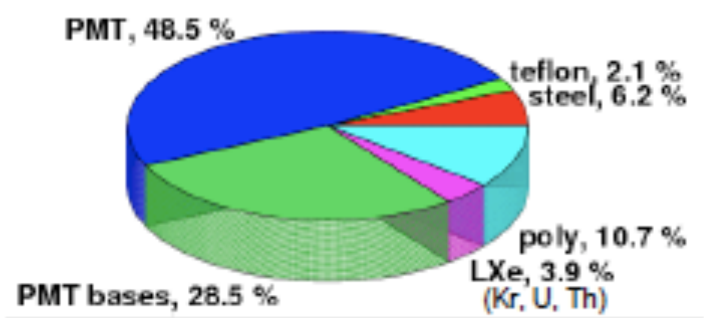
50 kg: <1x10^{-2} evts/kg/keV/day
(2000 kg-day, background free)

30kg: <3x10^{-3} evts/kg/keV/day
(6000 kg-day, background free)

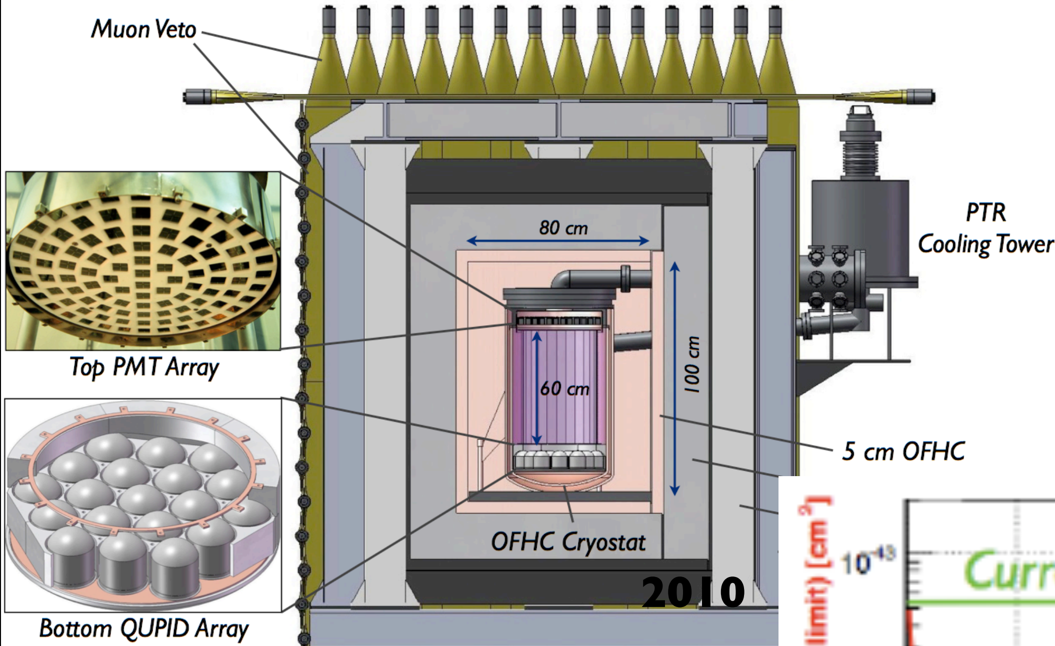
- rate before S2/S1 discrimination!

Preliminary Measured rate

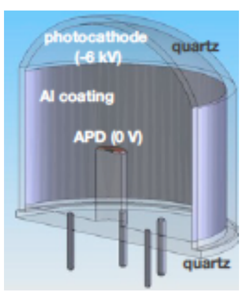


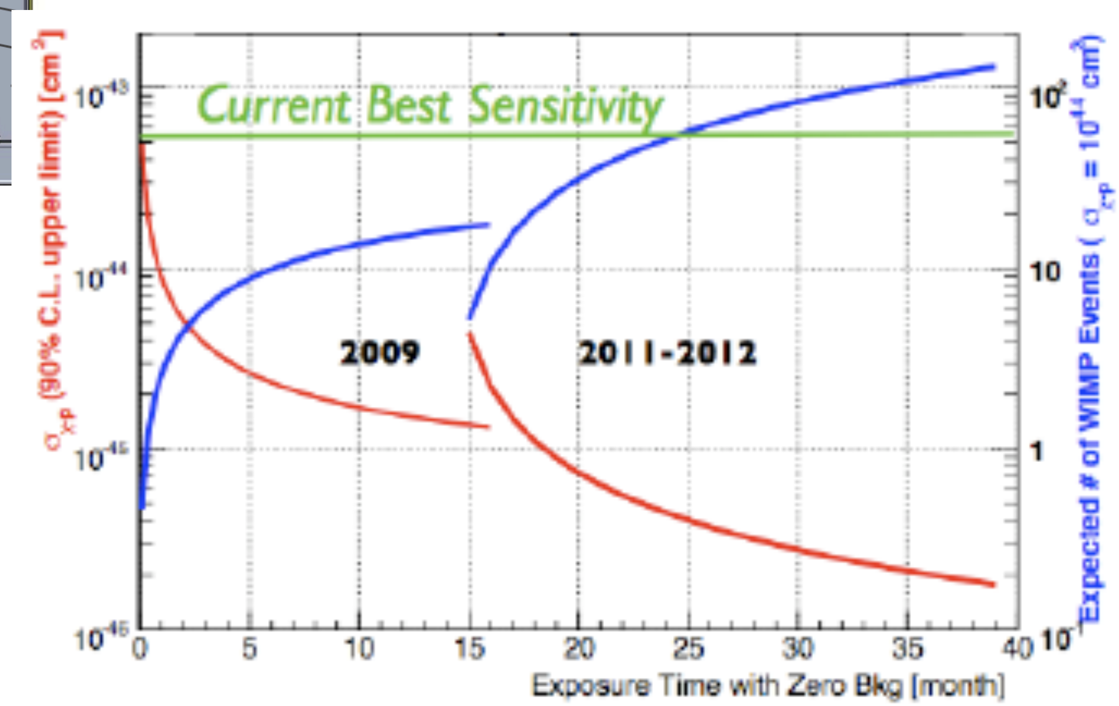


The Discovery Potential of the XENON100 Program



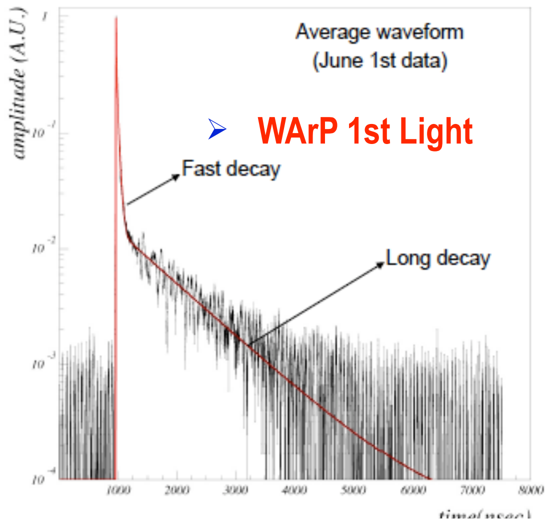
- reduce back from PMTs with QUPIDs
- XENON100+ funded by the NSF
- 300 kg (100kg fiducial) new TPC
- test key technologies for XENON1T





The WArP Experiment @ LNGS

- Exploit Ionization/Scintillation plus PSD for background reduction
- WArP @ LNGS: 140 kg active LAr volume (20 keVr threshold) surrounded by 8 ton LAr veto for beta/gamma and neutrons
- Detector filled since May 09; starting data taking; veto designed for 1 ton scale detector



waveform fit (two exp. components).

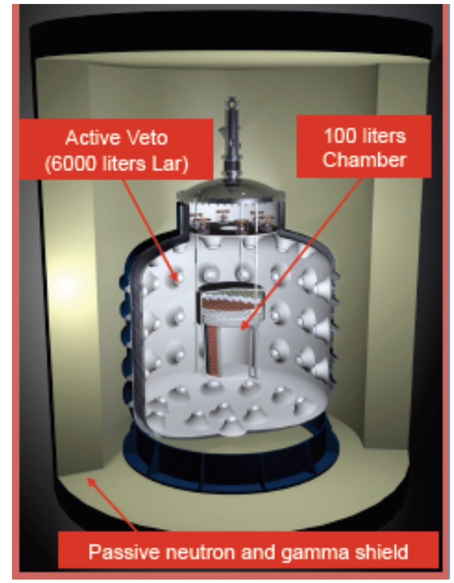
τ_{long} → indication of LAr purity:

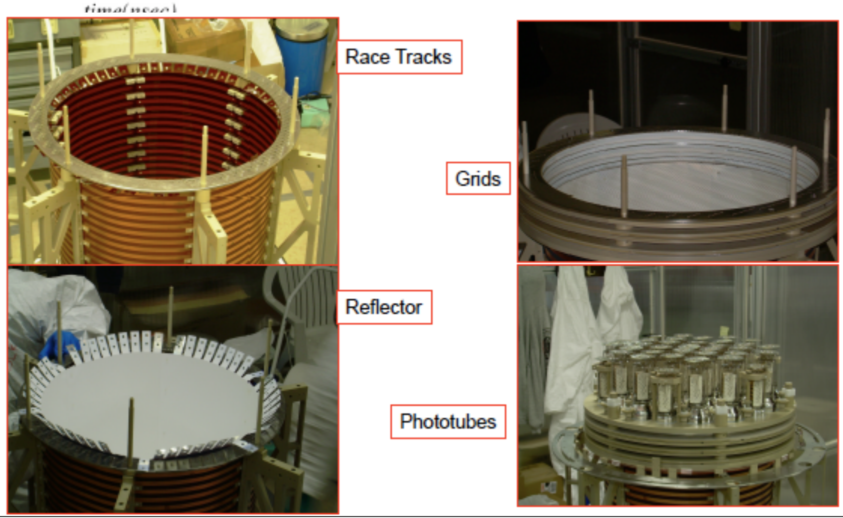
τ_{long}(fit) ≈ 1 μs (nominal 1.2 μs)

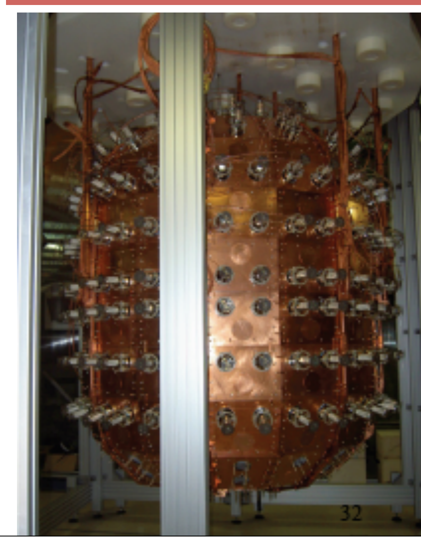
Text

⇓

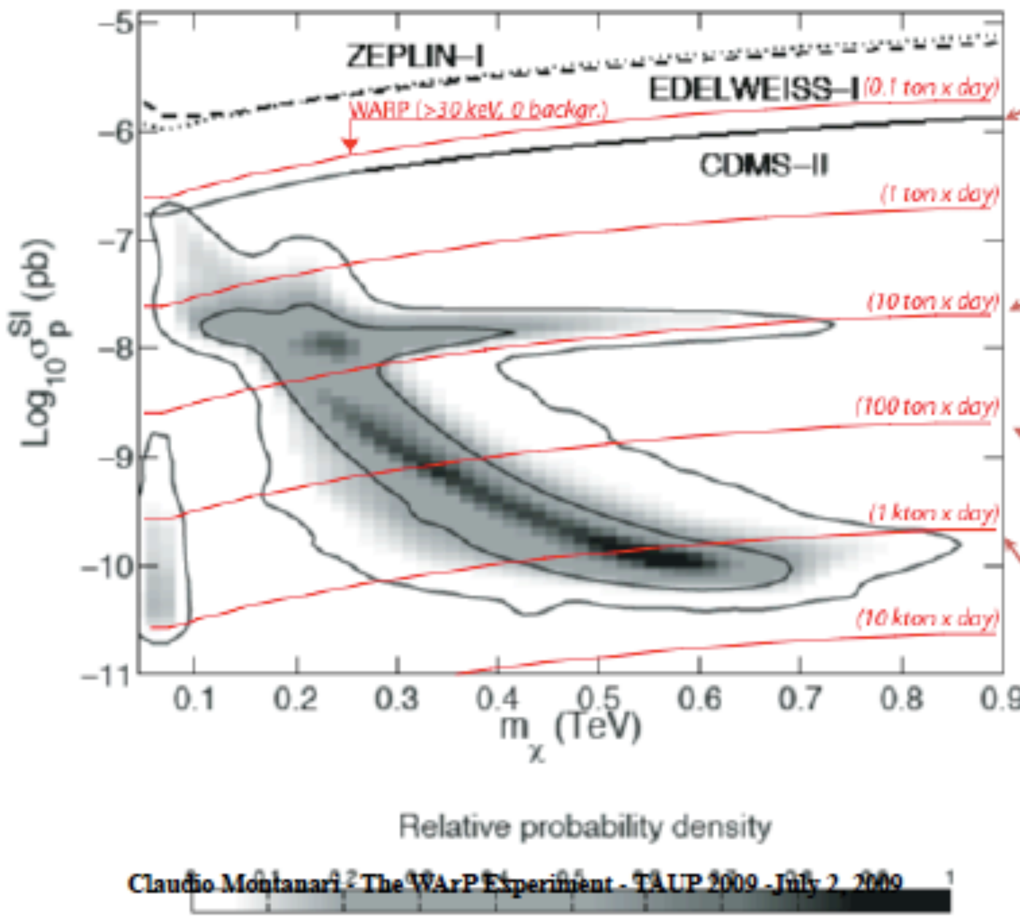
satisfactory LAr purity (after filling)







WArP Discovery Potentials



(2)-WArP 2.3 liters "clean" liquid, no background

(3)-WArP 100 liters 3 months no background (2009÷2010)

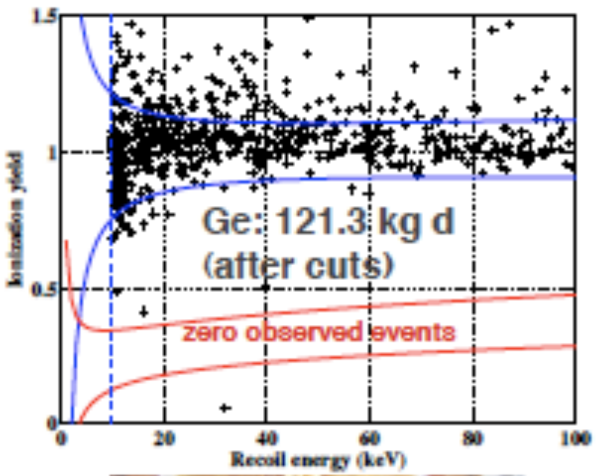
(4)-WArP 1 ton 3 months no background (2011÷2012)

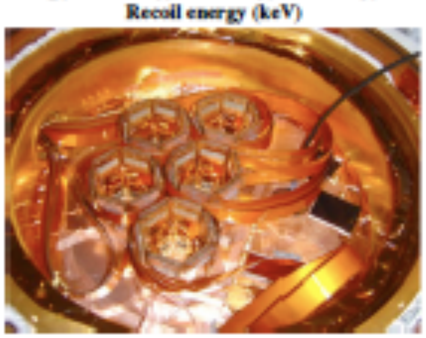
(5)-SuperWArP (10 ton) 3 months no background

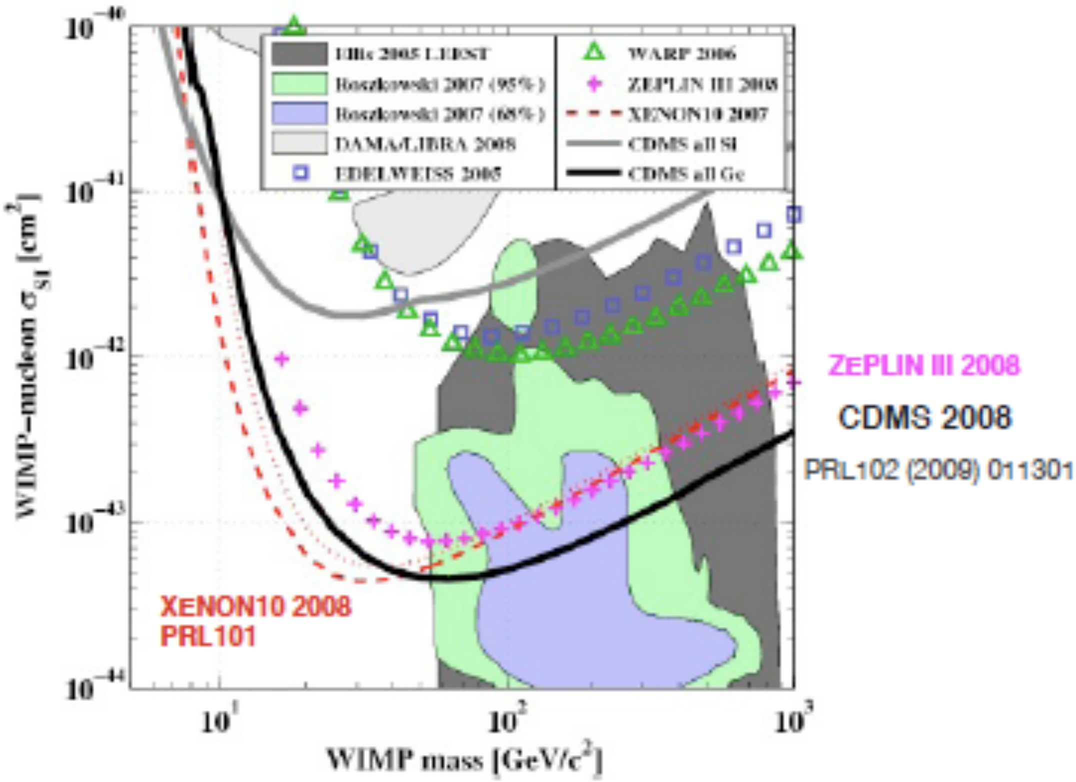
Claudio Montanari - The WArP Experiment - TAUP 2009 - July 2, 2009 44

The CDMS Experiment @ Soudan

- 30 Ge (4.75 kg) and Si (1.1 kg) detectors at ~ 20 mK in 5 towers
- **Run 123+124:** 163 live days, results published in PRL102 (2009) 011301
- **Run 125-128:** 270 live days under analysis, **first results in summer 09** (sensitivity reach ~ 1x10^{-44} cm^2)







Cryogenic mK Experiments: near future

CRESST at LNGS

10 kg array of 33 $CaWO_4$ detectors
new 66 SQUID channel array
- new limit from operating 2 detectors (48 kg d) published in 2008, arXiv:0809.1829v1
- new run in progress

EDELWEISS at LSM

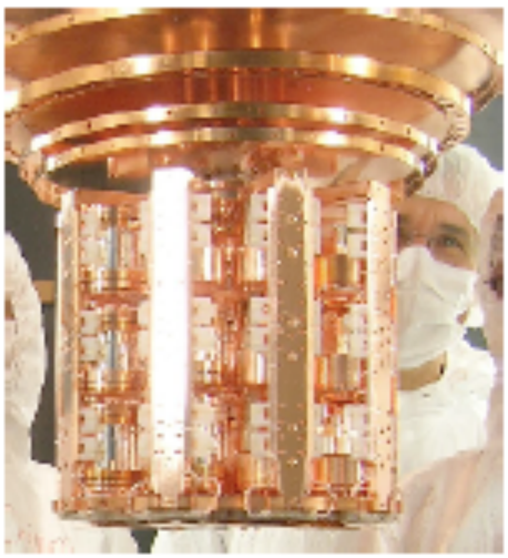
Goal: 10 kg (30 modules) of NTD and ID (new charge electrodes) Ge detectors in new cryostat
- data taking (with 19 detectors) in progress
- reach: 4×10^{-44} cm^2

CDMS/SuperCDMS at Soudan

SuperCDMS detectors (1" thick ZIPs, each 650 g of Ge) have been validated

First SuperTower installed at Soudan (3 kg of WIMP target)

Goal: 5×10^{-45} cm^2 with 16 kg Ge

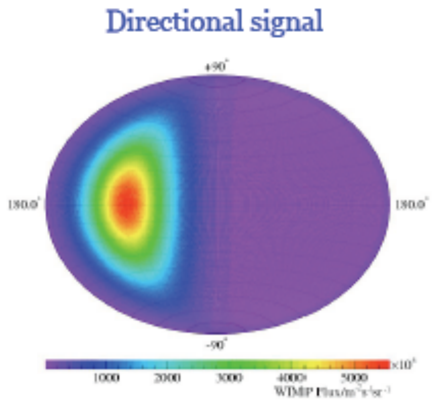


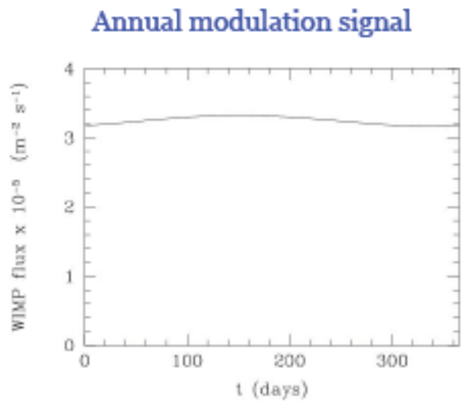
EURECA: joint effort for 100 kg-1t experiment in Europe

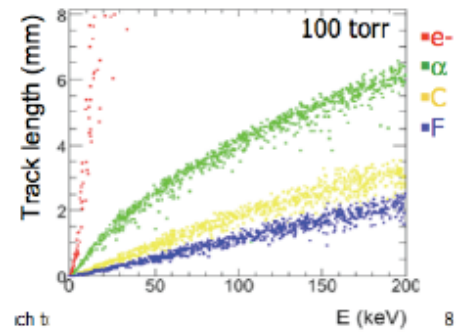
Goal: 7 SuperTowers at SNOLAB

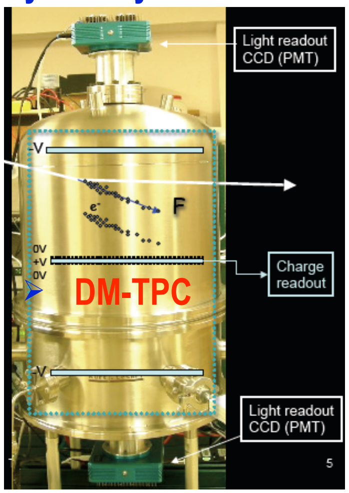
Directional Experiments

- WIMP events should globally come from Cygnus constellation direction. Strong forward/backward asymmetry
- Powerful signature: hard for background to mimic directional signal; order of 10 events sufficient

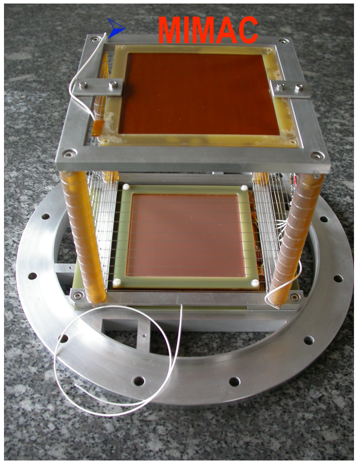








- Directional detectors with low pressure gas (large volume)
- Challenge is to measure 3D tracks of low energy recoils
- DRIFT-II @ Boulby mine: 1 m^3 MWPCs with 40 torr CS_2 (167 g)
- DM-TPC @ MIT: 2x 10^{-2} m^3 with 50 torr CF_4 (PMTs + CCD readout for 3D + E)
- NEWAGE @ Kamioka: 23 x 28 x 30 cm^3 TPC with 150 torr CF_4 and microwell readout
- MIMAC @ Saclay : ^3He & CF_4 TPC modules (3 x 3 cm Micromegas with pixellized anode)



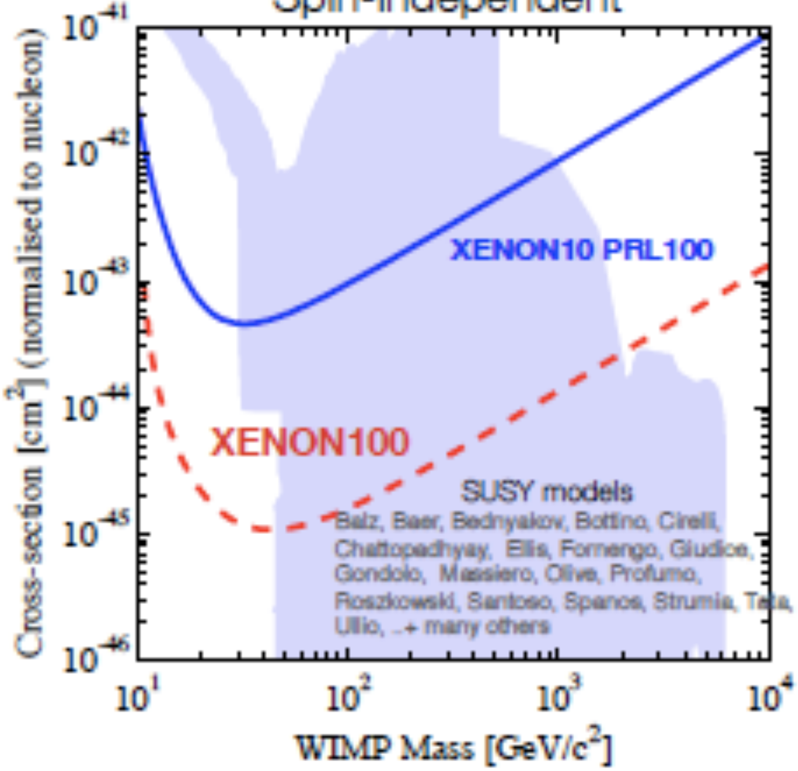
SUMMARY

- The identity of Dark Matter remains a mystery today but potential for breakthrough in the coming decade very likely
- Direct detection experiments have made significant progress in recent years, driven in part by an aggressive competition worldwide. Complementarity with indirect and collider searches has never felt stronger!
- Several 100 kg scale experiments in operation underground or under construction. For XENON100 the 2 x 10^{-9} pb SI sensitivity projection appears well within reach by 2010.
- On the other hand, if cross-section is at the 10^{-8} pb as in some favored SUSY models, we will start to see a handful of WIMP events and that is very exciting! Equally important is that for the first time a low background, massive target, other than NaI, can probe annual modulation
- Increasing mass while keep lowering backgrounds is the rule of the game and noble liquids continue to advance towards this goal. Ton scale experiments are technically feasible and will follow fast, if 100 kg phase is successful.
- A direct detection signal, from either or both SI and SD interactions, needs to be validated with more than one target and concept: current zoo of experiments vital for field. Directional experiments advancing at good pace. Will provide the ultimate “smoking gun” for DM signal

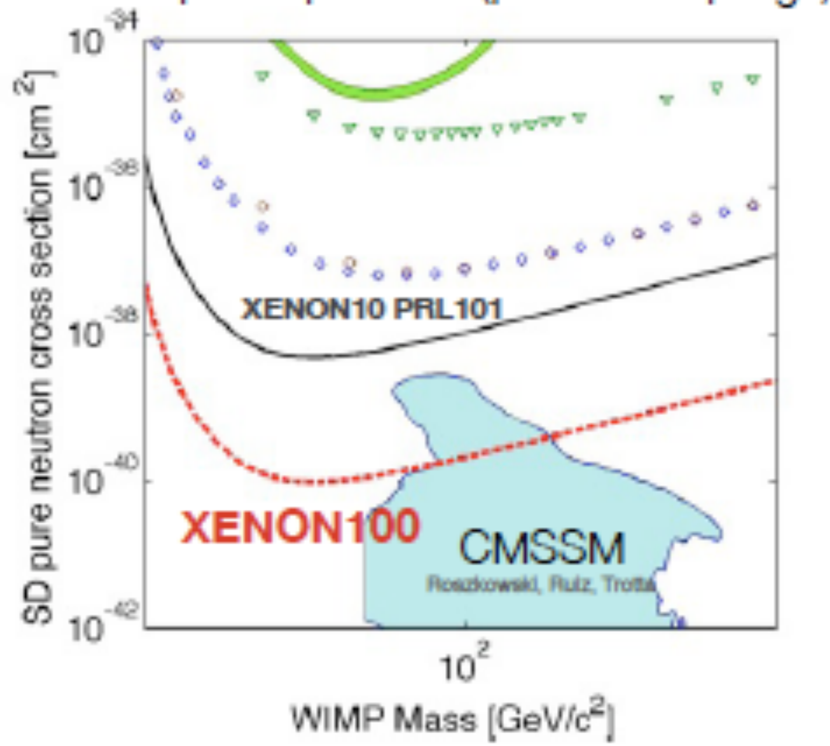
➢Back up Slides

XENON100 Sensitivity

Spin-independent



Spin-dependent (pure n-couplings)



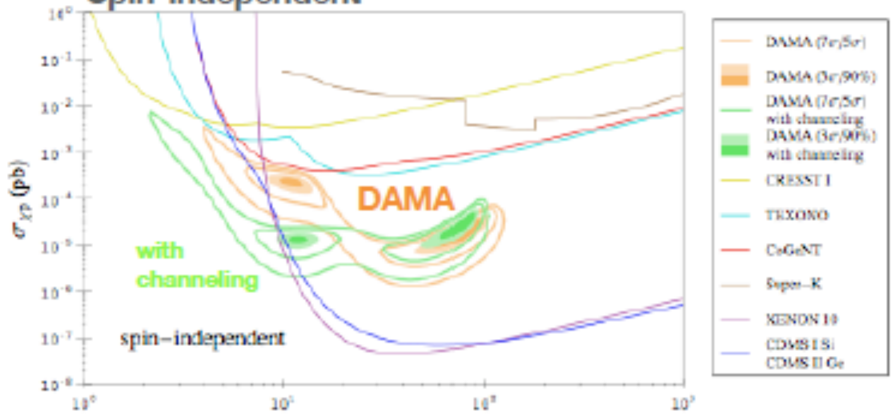
50 kg target, 40 days: $\sigma = 6 \times 10^{-45}$ cm^2 (at M_W =100 GeV)

30 kg target, 200 days: $\sigma = 2 \times 10^{-45}$ cm^2 (at M_W =100 GeV)

DAMA Signal and Existing Experimental Limits at Low WIMP Masses

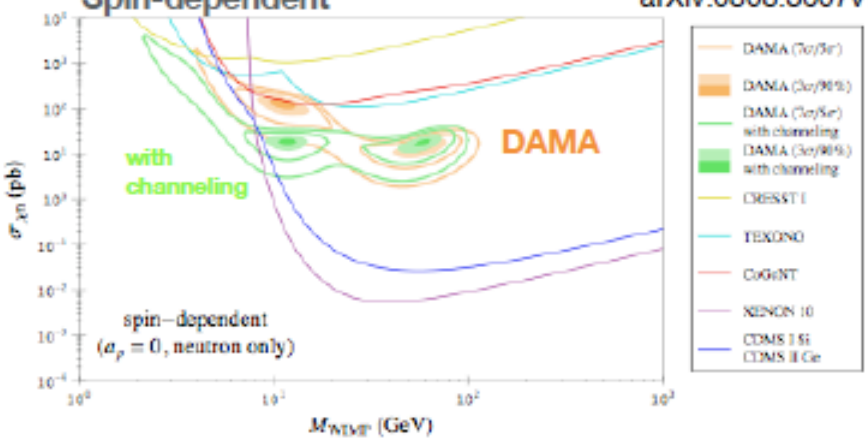
- WIMP hypothesis: severe tension with other experiments!

Spin-independent

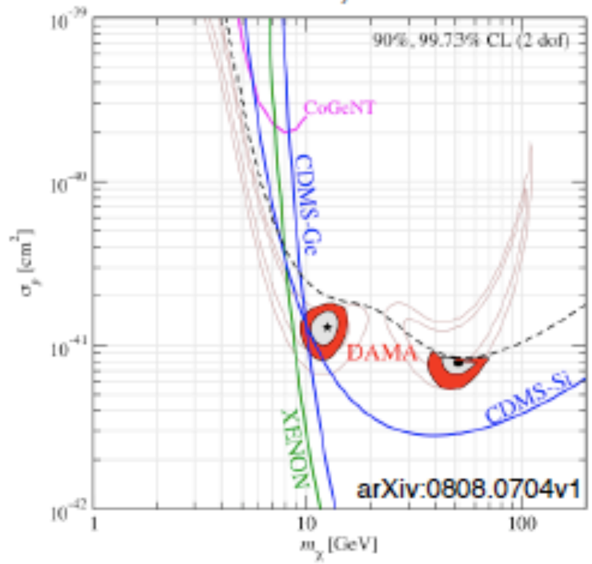


Savage, Gelmini, Gondolo, Freese
arXiv:0808.3607v1

Spin-dependent



M. Fairbairn, T. Schwetz



Ion channeling effect: scattered ion parallel to crystal axis will undergo small-angle scattering which will channel it along the gaps in the lattice; such an ion has lower dE/dx, yielding increased light , effectively reducing the energy threshold for low-energy nuclear recoils

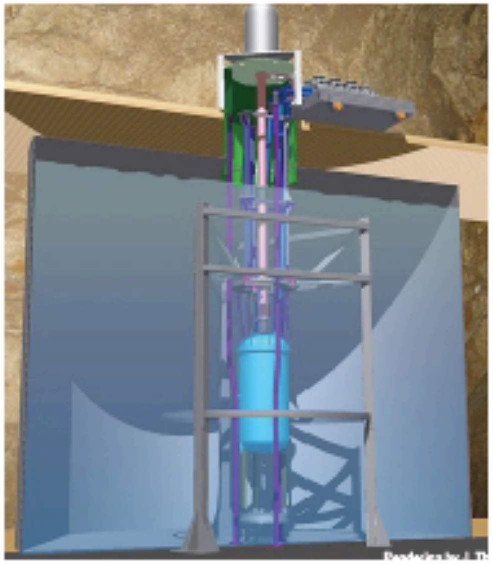
Channeling: has not yet been demonstrated for nuclear recoils starting from a lattice site, only for incident ion beams; should be tested in dedicated experiment

The LUX Experiment

- 350 kg dual phase LXe TPC (100 kg fiducial), with 122 PMTs in large water shield with muon veto
- LUX 0.1: 50 kg LXe prototype with 4 R8778 PMTs was assembled and tested at CWRU
- PMTs: 2” diameter, 175 nm > 30% QE; radioactivity: U/Th ~ 9/3 mBq/PMT
- LUX 1.0: full detector to be operated above ground at Homestake in fall 2009
- LUX 1.0: to be installed at Homestake Davis Cavern, 4850 ft in spring 2010 (in 8 m ⌀ water tank)
- Predicted WIMP sensitivity goal: 7×10^{-10} pb after 10 months

R8778 PMT

LUX 0.1

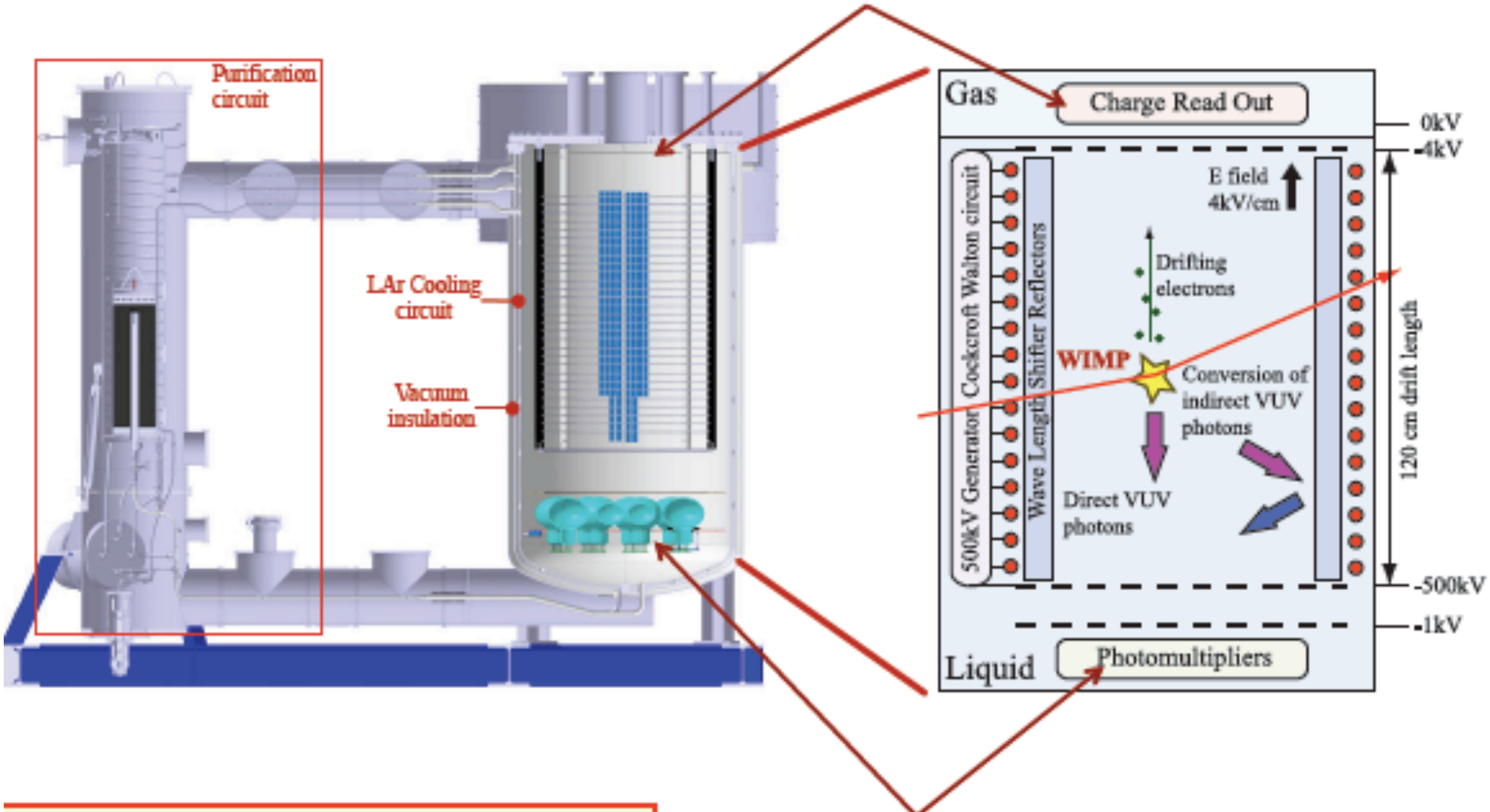


In water shield @ Homestake 4850 ft level

The ArDM Experiment

General Layout of the Experiment

Double stage LEM System

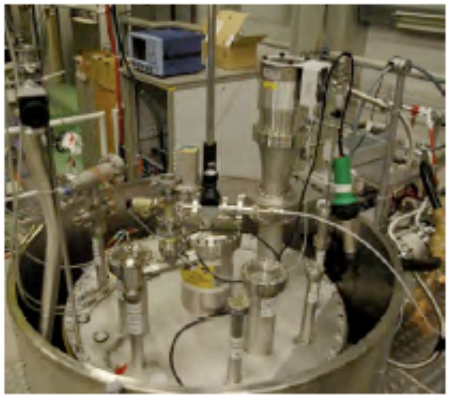


A. Rubbia, "ArDM: a Ton-scale liquid Argon experiment for direct detection of dark matter in the universe" J. Phys. Conf. Ser. 39 (2006)

14 Cryogenic PMTs to detect the scintillation light

ArDM Assembly Sept. 2007 - May 2008

Top flange



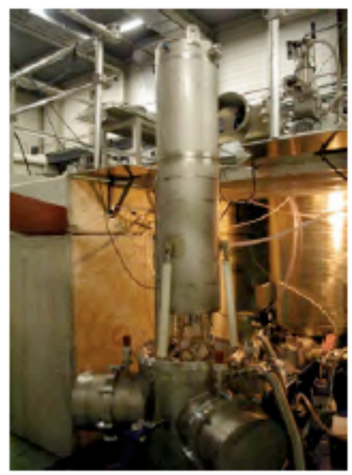
Exp. area at CERN

LAr bath

Detector insertion

PMT mechanics

CuO cartridge



Reflector foils