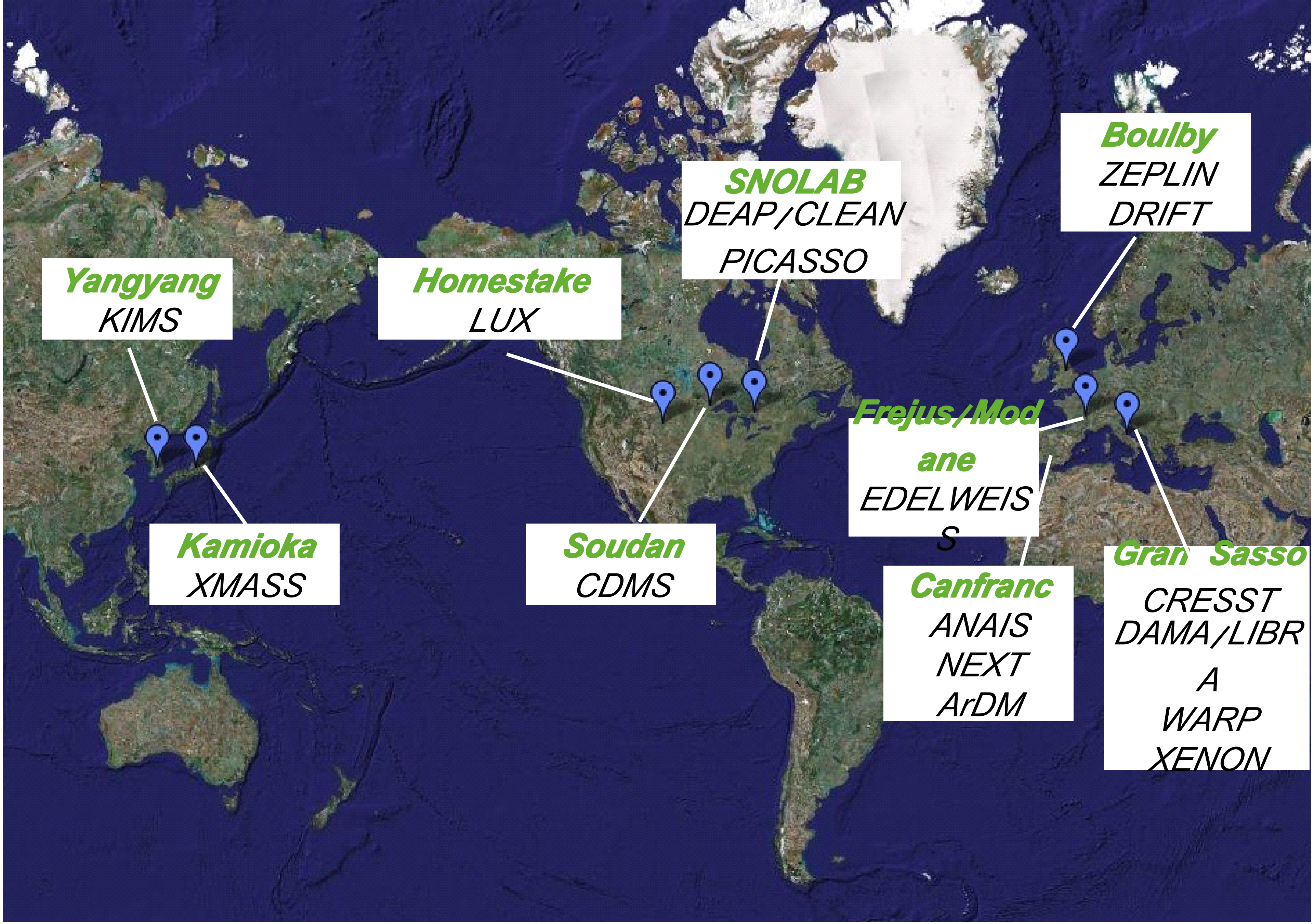
Status of the XENON Dark Matter Experiment

Karl-Ludwig Giboni
Columbia Astrophysics Laboratory

KEK Physics Seminar
February 10, 2009

World Wide Dark Matter Searches



XENON100 Collaboration

US – Swizerland – Germany – France – Italy – Portugal – Japan

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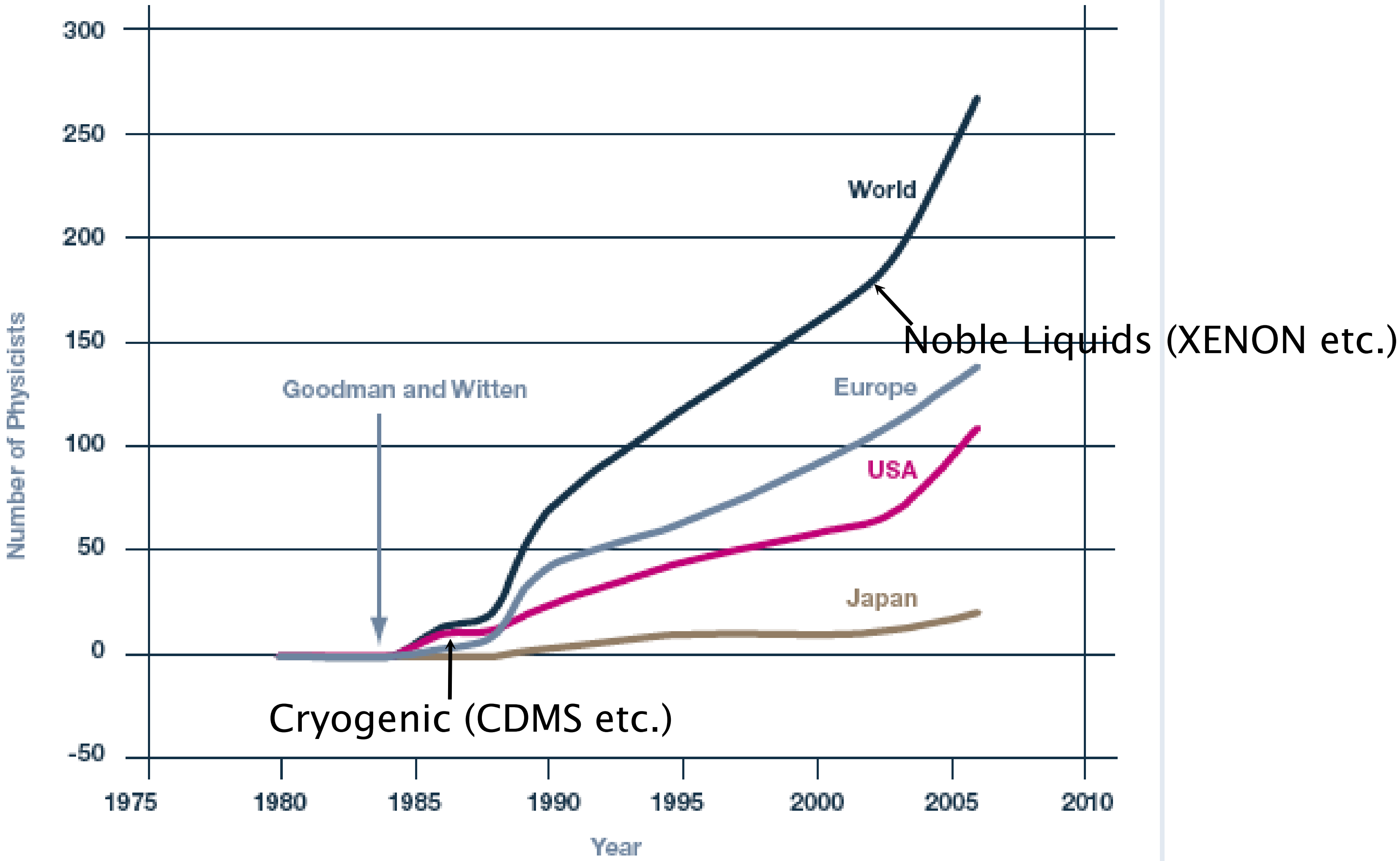
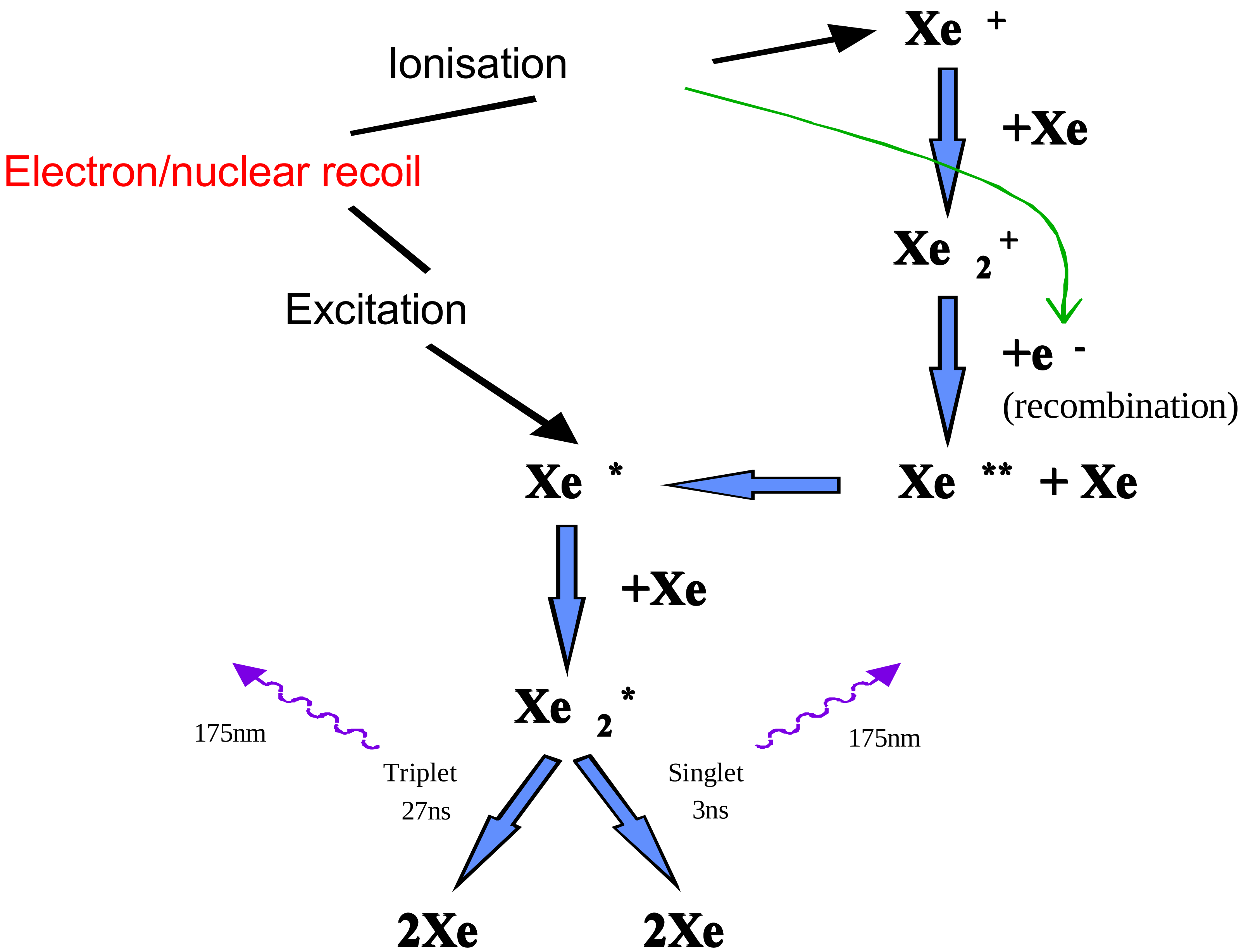
An international collaboration of 46 physicists from 9 institutions

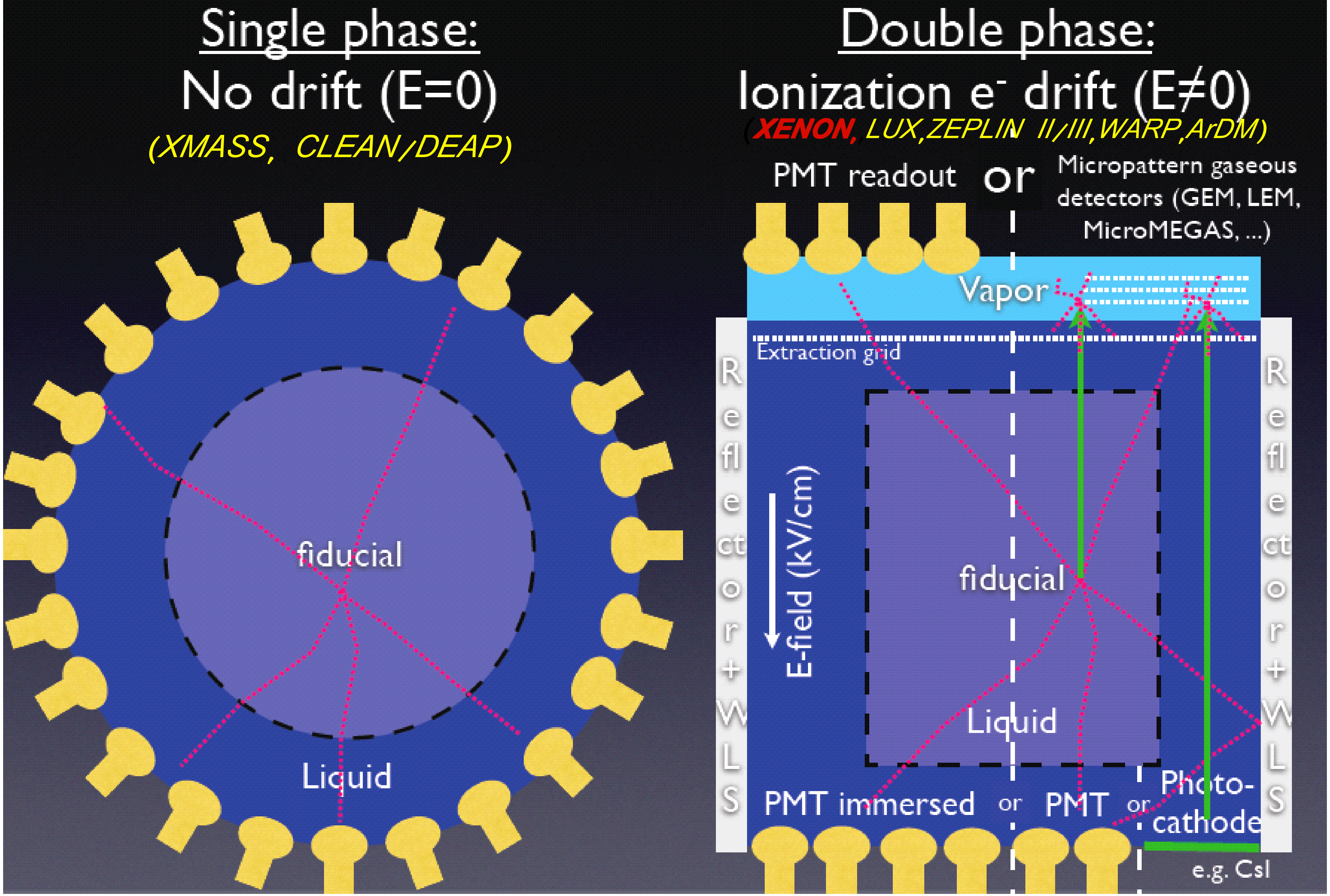
Dark Matter Physicists vs Time




Laboratori Nazionali del Gran Sasso, Italy
LNGS 1400 m Rock (3100 w.m.e)
XENON100
LVD
ICARUS
OPERA

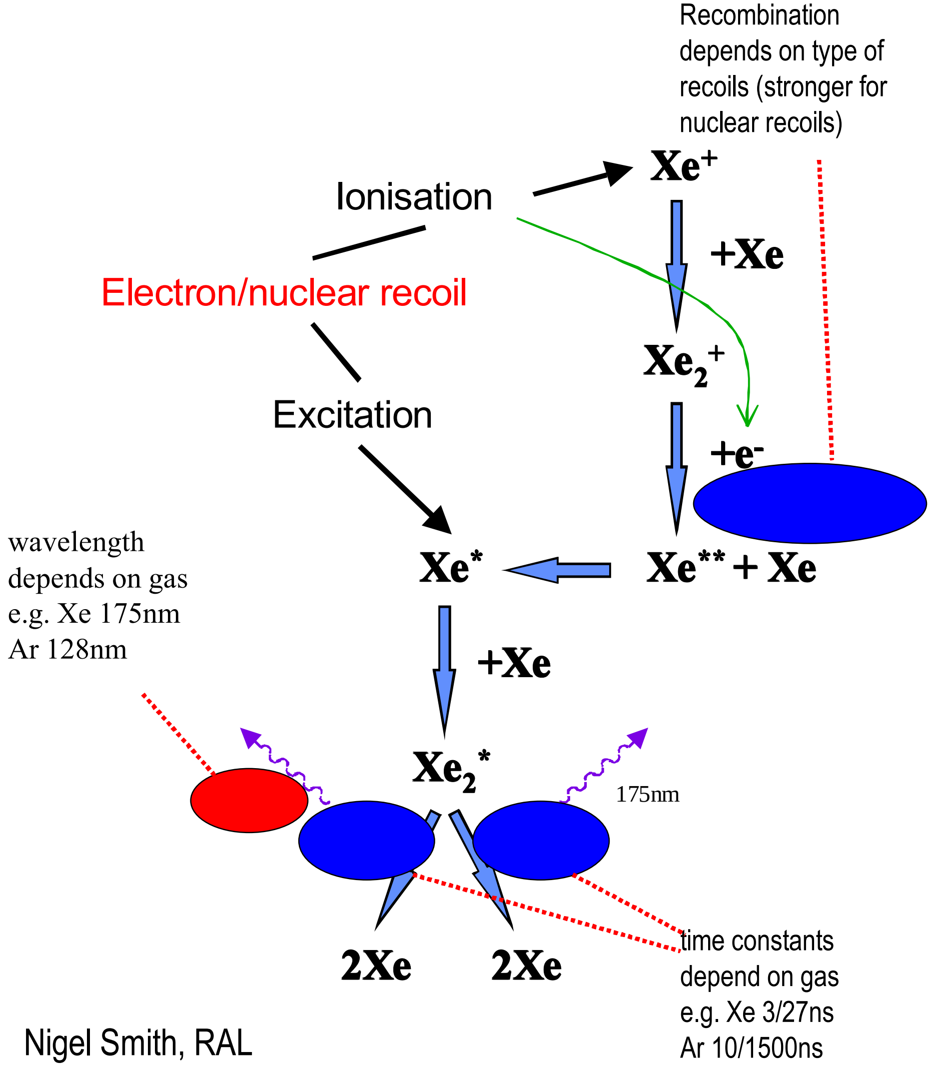

Ionisation
Electron/nuclear recoil
Excitation
Xe^+
+Xe
Xe_2^+
$+e^-$
(recombination)
Xe^{**} + Xe
Xe^*
+Xe
Xe_2^*
175nm
Triplet
27ns
Singlet
3ns
175nm
2Xe
2Xe

Two basic detector concepts



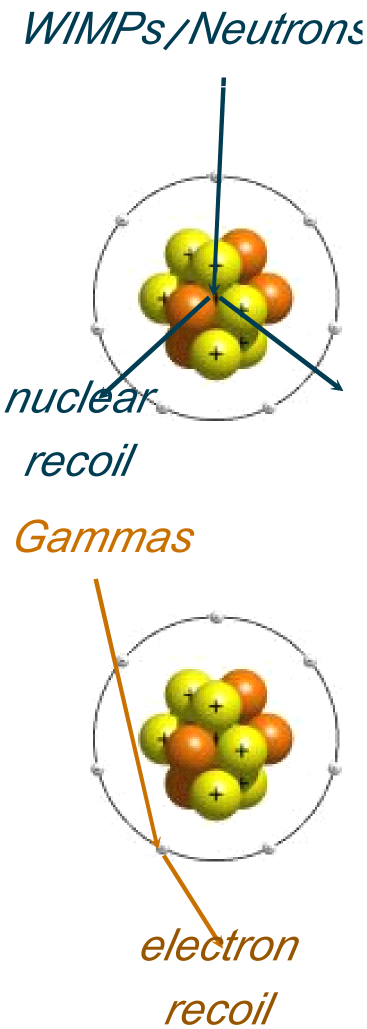
Why Noble Liquids for Dark Matter

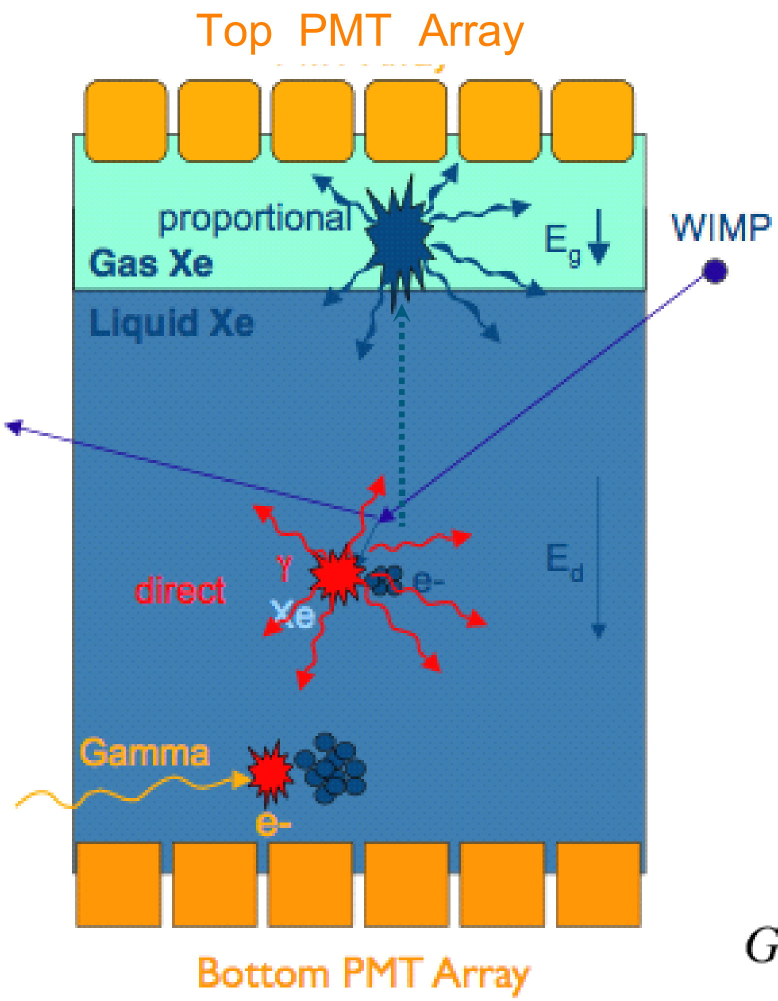
- *scalability : relatively inexpensive for large scale (multi-ton) detectors*
- *easy cryogenics : 170 K (LXe), 87 K (LAr)*
- *self-shielding : very effective for external background reduction*
- *low threshold : high scintillation yield (~50,000 photons/MeV)*
- *n-recoil discrimination: by charge-to-light ratio and PSD*

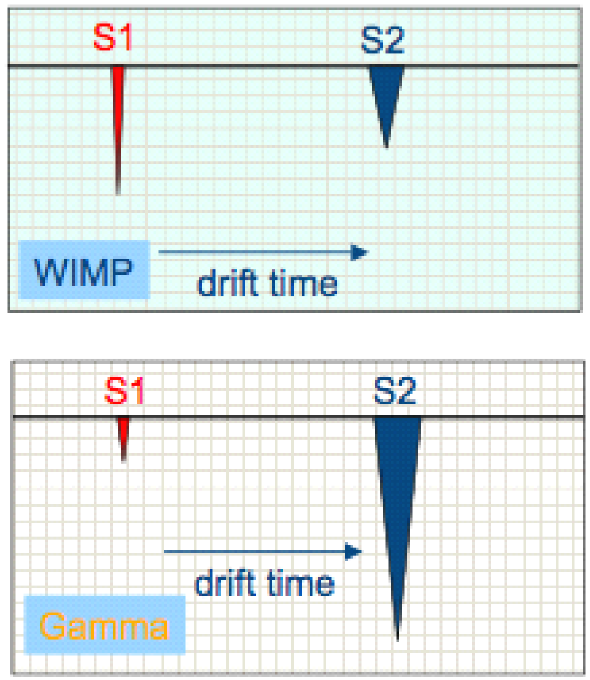


Nigel Smith, RAL

The XENON two-phase TPC concept





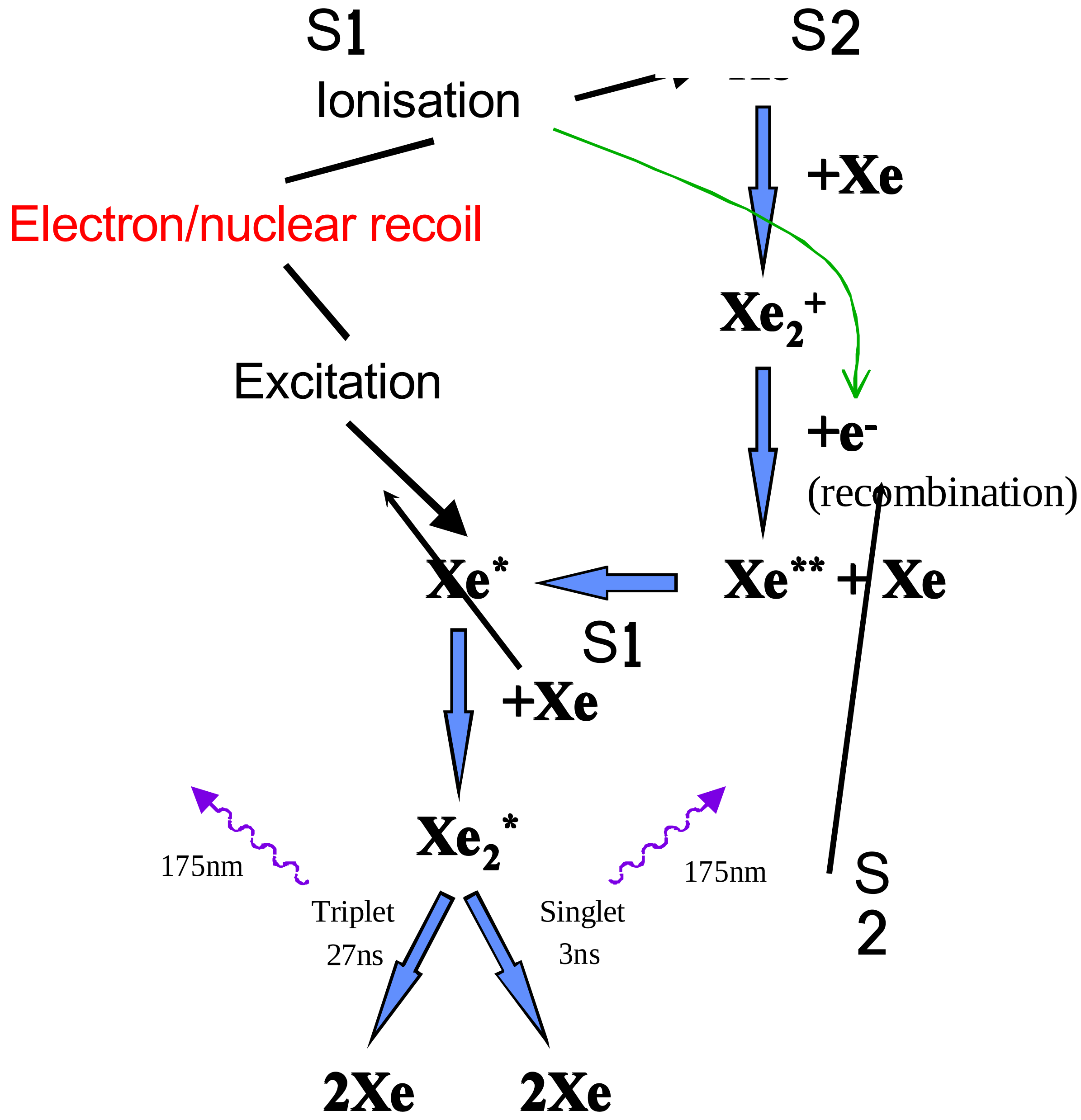


$(S2/S1)_{wimp} << (S2/S1)_{gamma}$

$$G_{\gamma} \approx \alpha\left(E/p - \varepsilon_{thresh}\right) \cdot x \cdot p$$

$$\alpha_{LXe} = 70\ \gamma/kV \qquad \varepsilon_{thresh}^{LXe} = 1.3kV/cm/atm$$

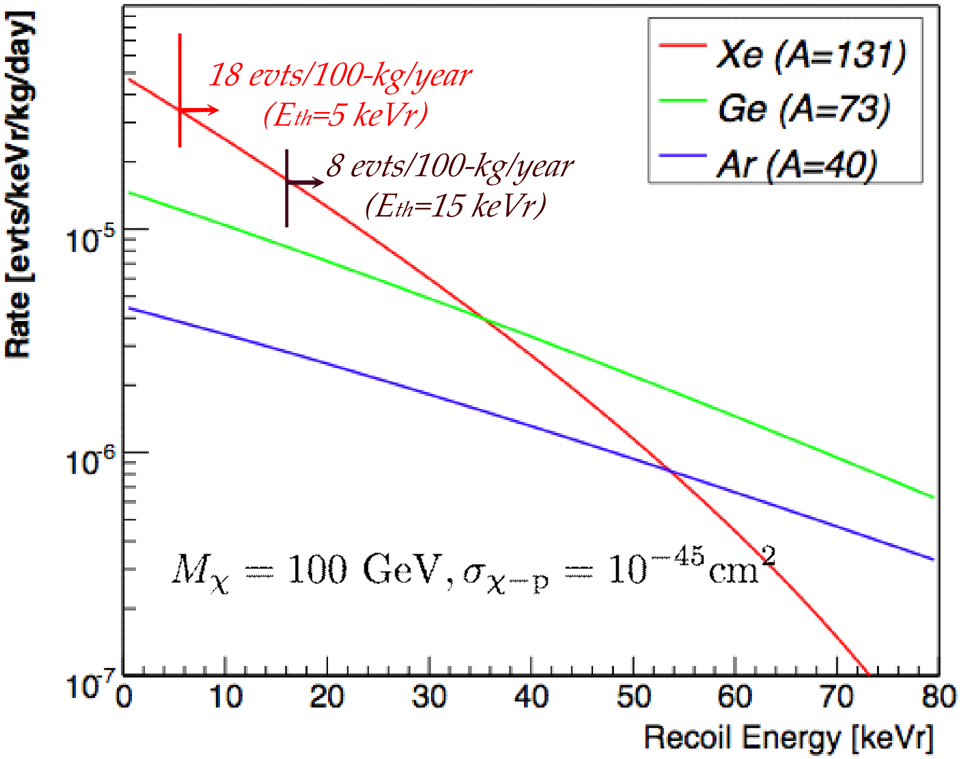
Signals from XENON10



Why Liquid Xenon for Dark Matter Detection

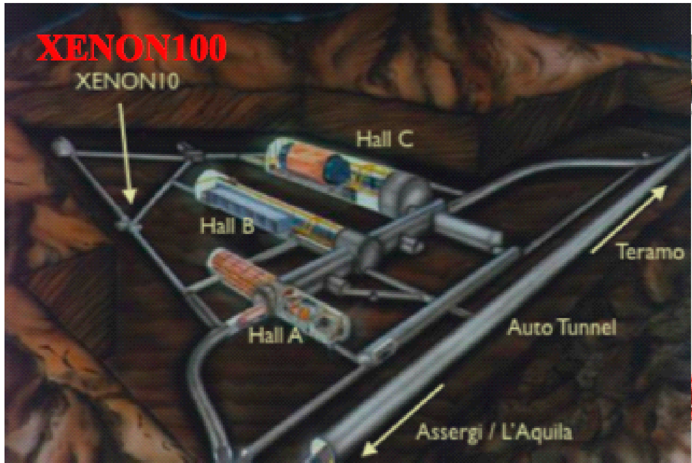
$$R \sim \frac{M_{det}}{M_\chi} \rho \sigma \langle v \rangle$$

WIMP Scattering Rates



- Large A (~ 131) good for SI σ~ A^2 if low E_{th}
- ^{129}Xe (26.4%) & ^{131}Xe (21.2%) good for SD σ
- No radioactive isotopes (Kr85 can be removed)
- High stopping power (Z=54, ρ=3 g/cc)
- Efficient and fast scintillator (~ 80% of NaI)
- Good ionization yield (W=15.6 eV)
- Modest quenching factor for NR (0.14 - 0.2)
- Background Rejection: Charge and Light detection (> 99.5%) plus 3D localization and self-shielding
- 'Easy' cryogenics at ~165K
- Inert, not flammable, very good dielectric
- Modest cost for large mass detector

XENON100 Underground at the Laboratori Nazionali del Gran Sasso



The XENON Phased Program

- XENON Concept: two-phase XeTPC, 3D position sensitive, self-shielded by an active LXe veto with simultaneous charge & light detection for event-by-event discrimination (>99.5%)
- XENON10: reached σ ~10^{-43} cm^2 sensitivity for 100 GeV WIMP in 2007

  ➡a very successful first demonstration of the approach

- XENON100: projected sensitivity reach σ ~2 x10^{-45} cm^2 for 100 GeV WIMP by 2009

  ➡currently under final commissioning at LNGS. Physics run starts Spring 2009. Supported by NSF, DoE and foreign contributions

- XENON100 Upgrade: projected sensitivity reach σ ~2 x10^{-46} cm^2 for 100 GeV WIMP by 2012

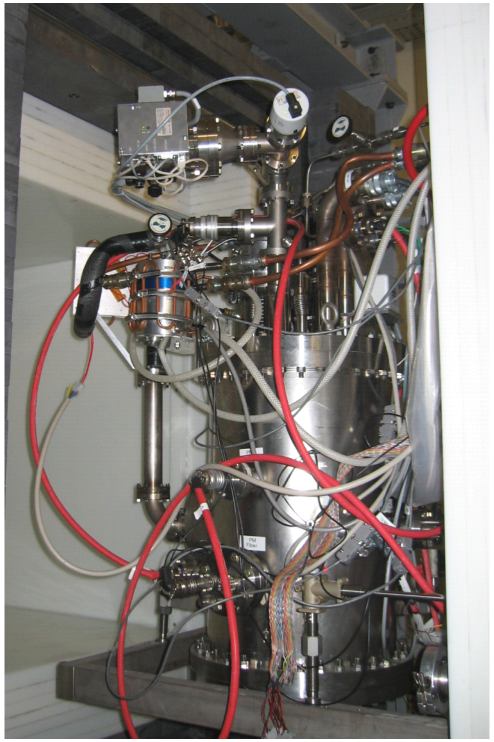
  ➡Proposed to NSF, DoE and foreign contributions

- XENON1T: projected sensitivity reach σ ~10^{-47} cm^2 for 100 GeV WIMP by 2014

  ➡Under study by larger collaboration in US, Europe, Japan. Started to test key technologie

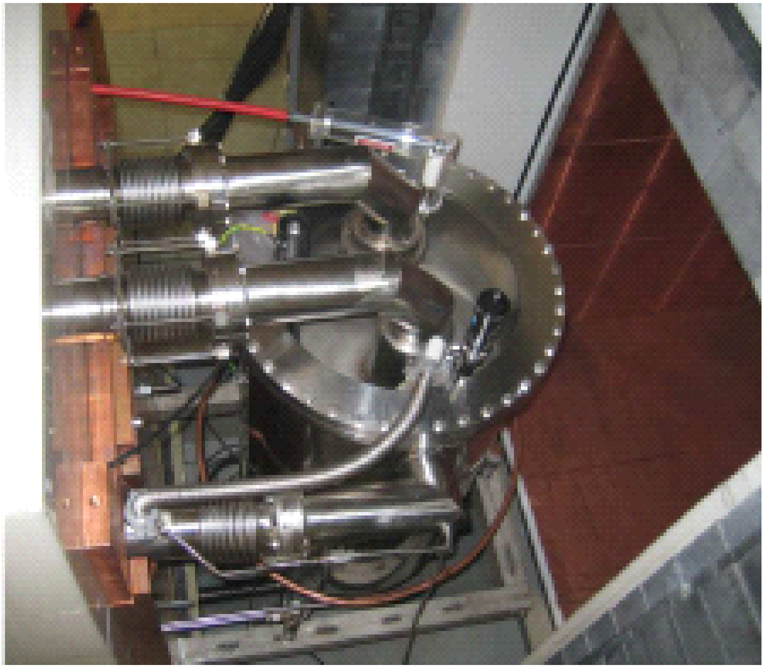
The XENON Dark Matter Search Phases

the past (2005 - 2007)	the current (2007-2010)	the future (2010-2014)



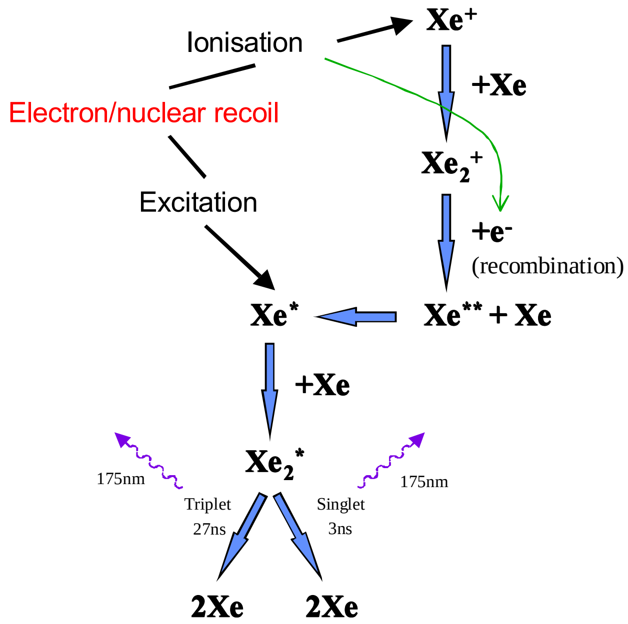
XENON10

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



XENON100

Projected (2009) σ_{SI}~2x10^{-45} cm^2



XENON1T

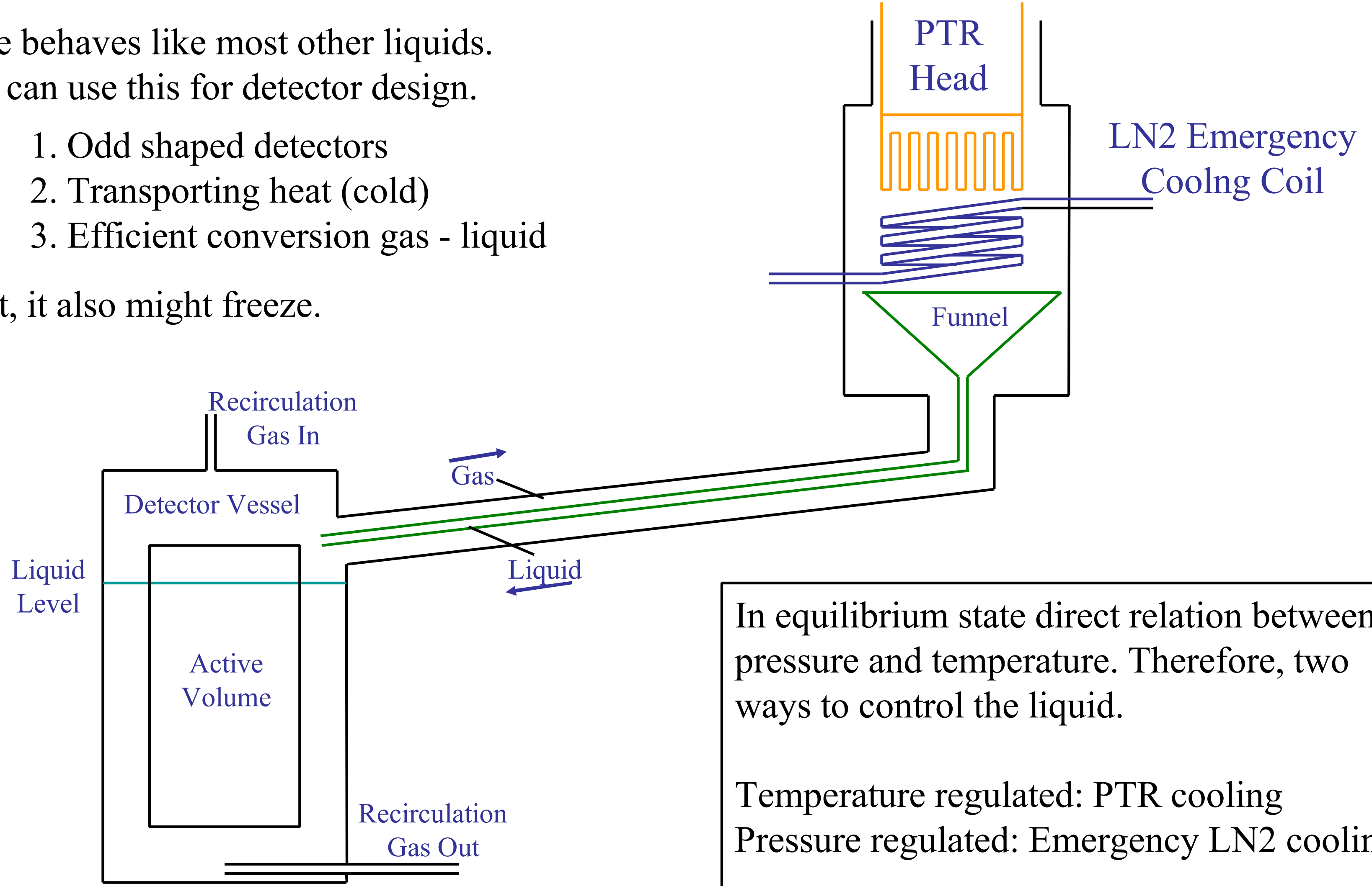
Projected (2014) σ_{SI}~10^{-47} cm^2

Liquid Detector Medium

LXe behaves like most other liquids.
We can use this for detector design.

1. Odd shaped detectors
2. Transporting heat (cold)
3. Efficient conversion gas - liquid

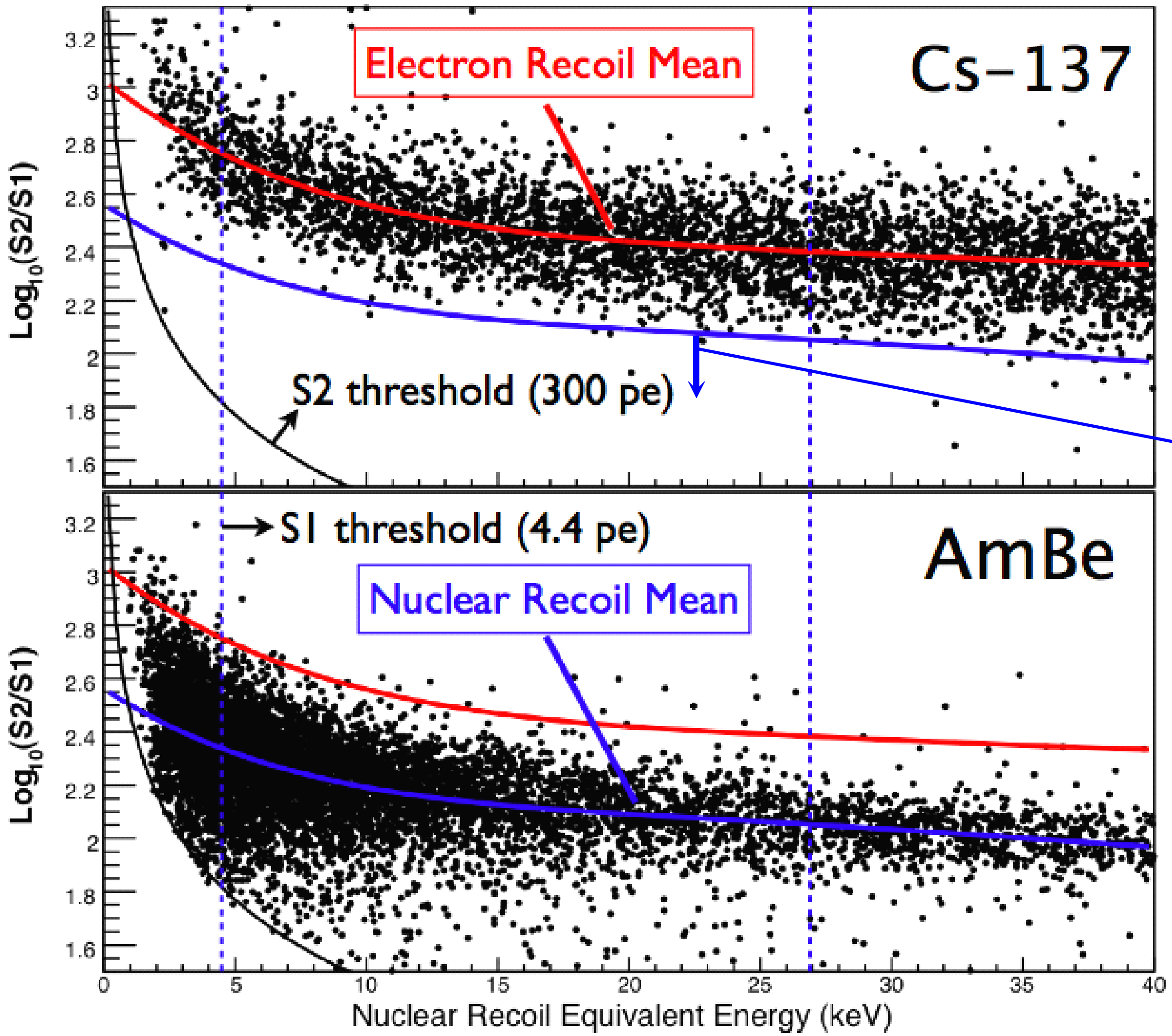
But, it also might freeze.



In equilibrium state direct relation between pressure and temperature. Therefore, two ways to control the liquid.

Temperature regulated: PTR cooling
Pressure regulated: Emergency LN2 cooling

XENON10 Gamma/Neutron calibration

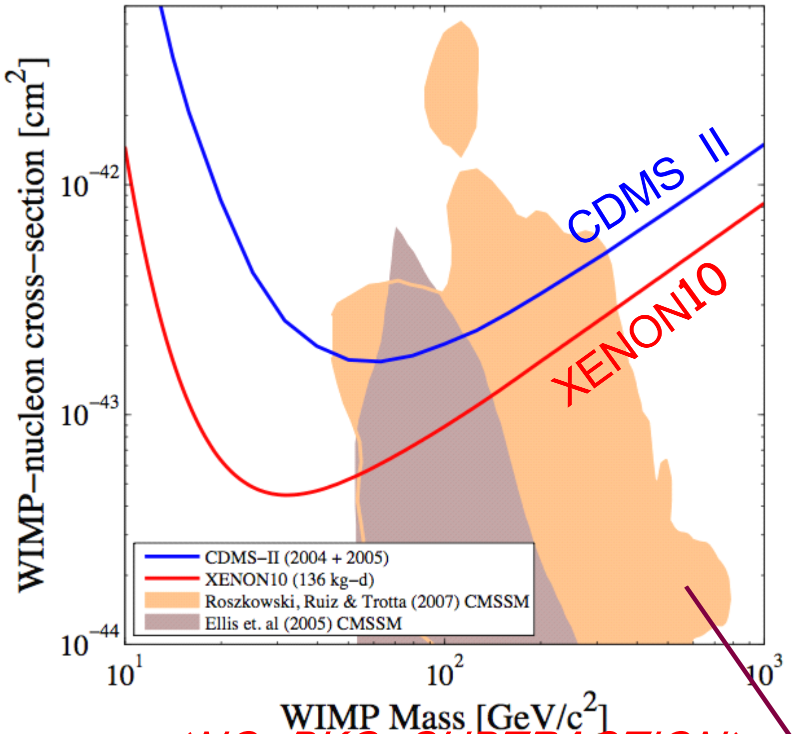


~ 99.5 % gamma events are rejected below the nuclear recoil mean

XENON10 WIMP-Nucleon Cross-Section Upper Limits

Spin-independent

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



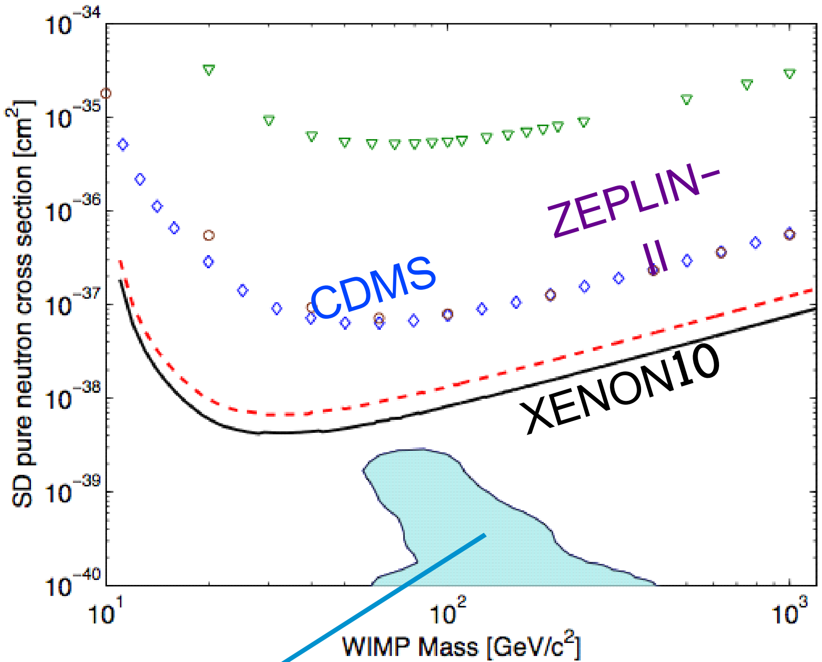
(NO BKG SUBTRACTION)

8.8×10^{-44} cm^2 at 100 GeV

4.5×10^{-44} cm^2 at 30 GeV

Spin-ependent

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

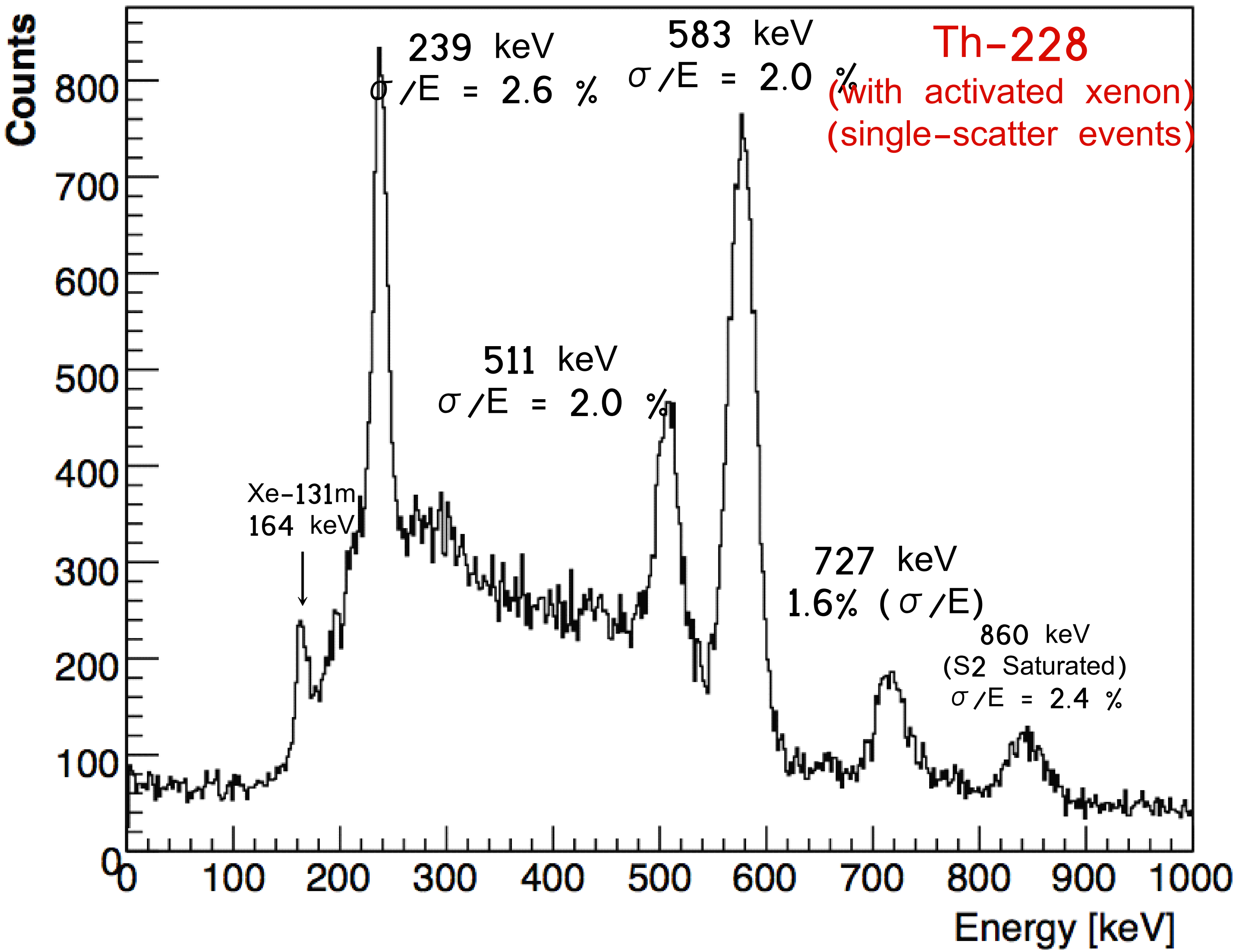


Constrained Minimal Supersymmetric Model

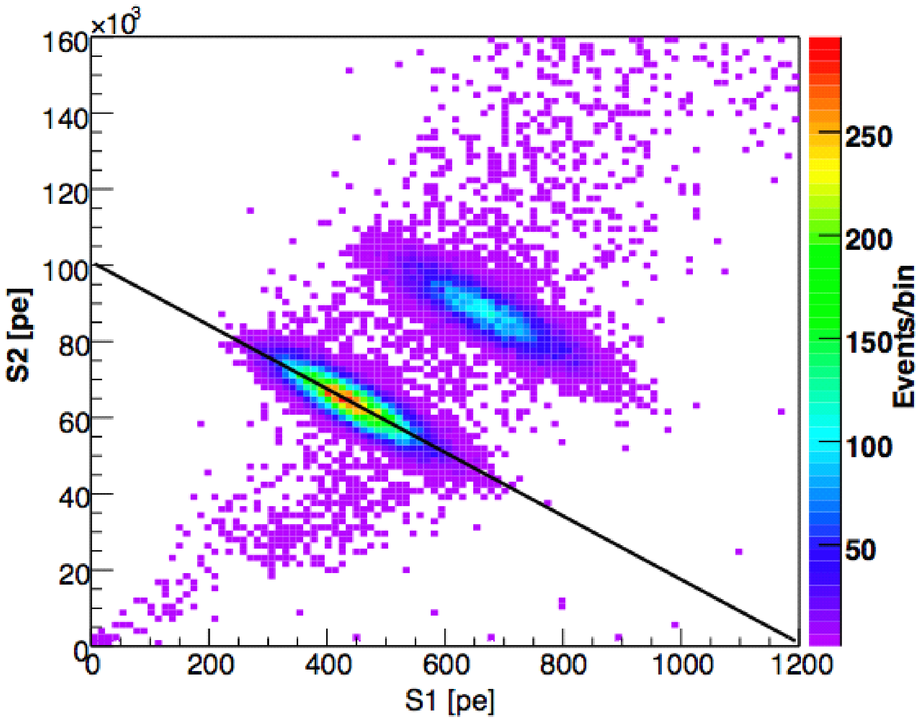
(NO BKG SUBTRACTION)

6×10^{-39} cm^2 at 30 GeV

The Energy Resolution of the XENON10 TPC

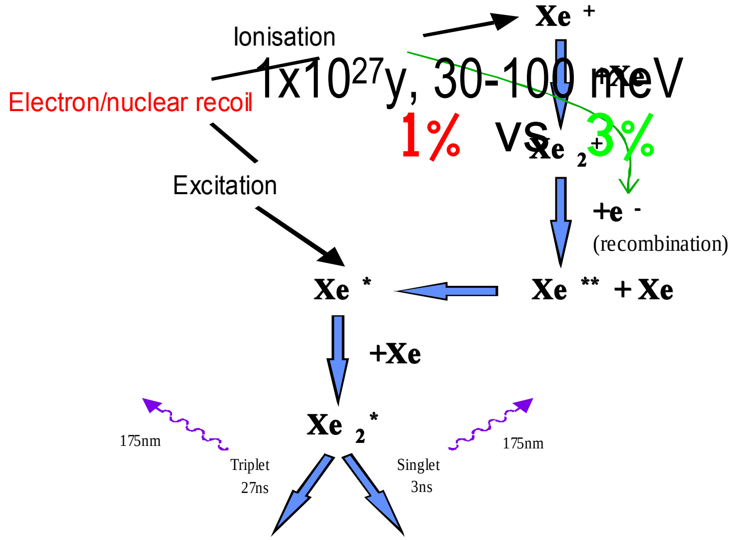


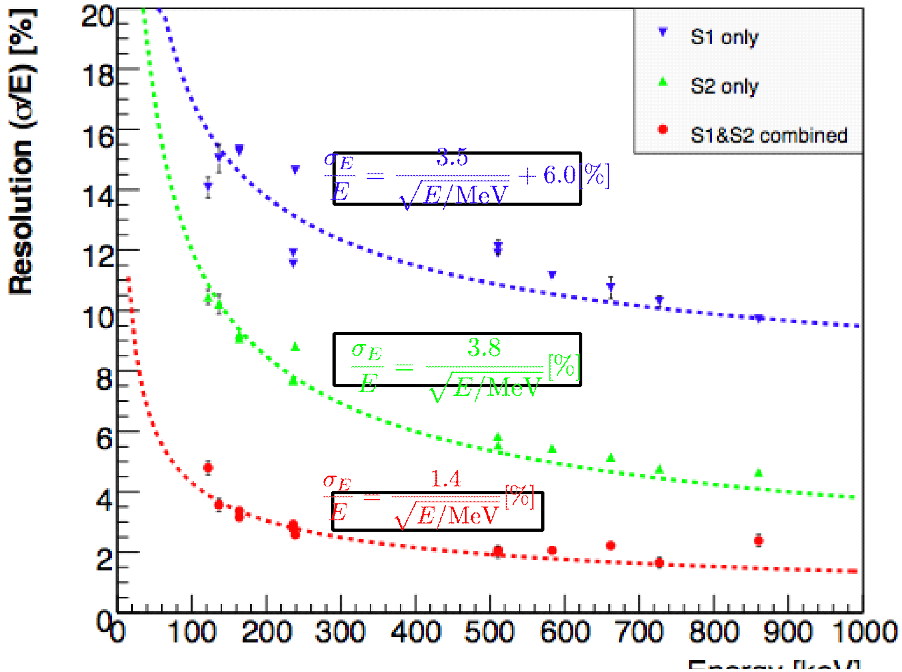
..quite good for neutrinoless double beta decay of Xe-136



1×10^{27}y, 30-100 meV

1% vs 3%

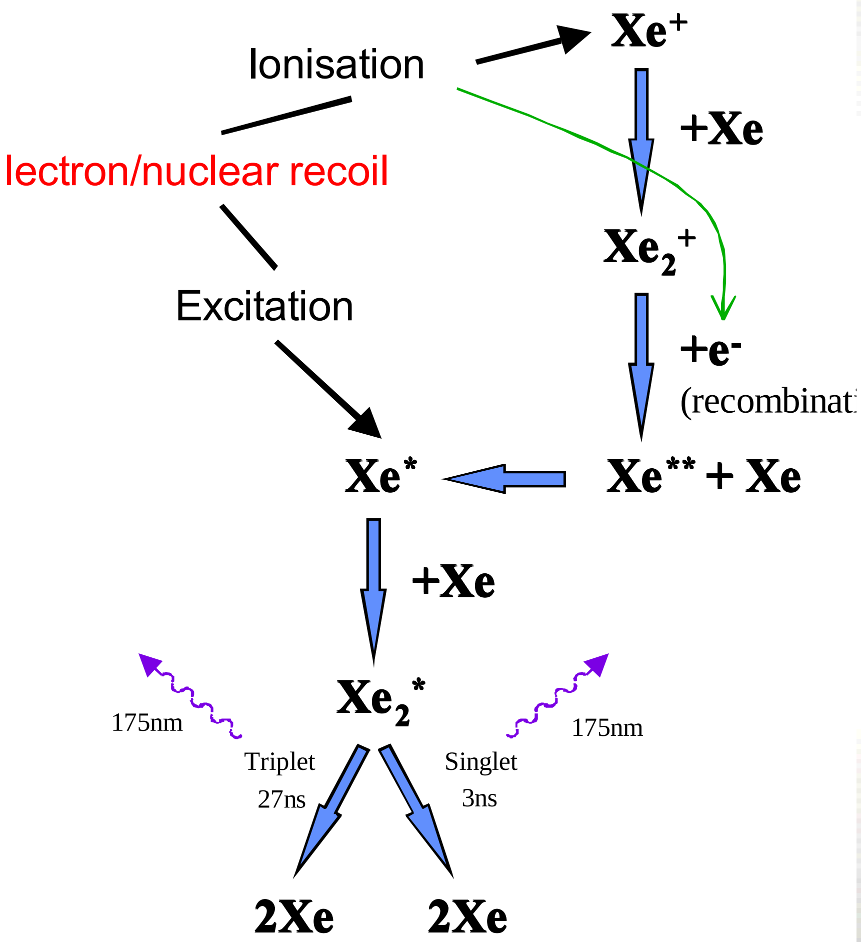


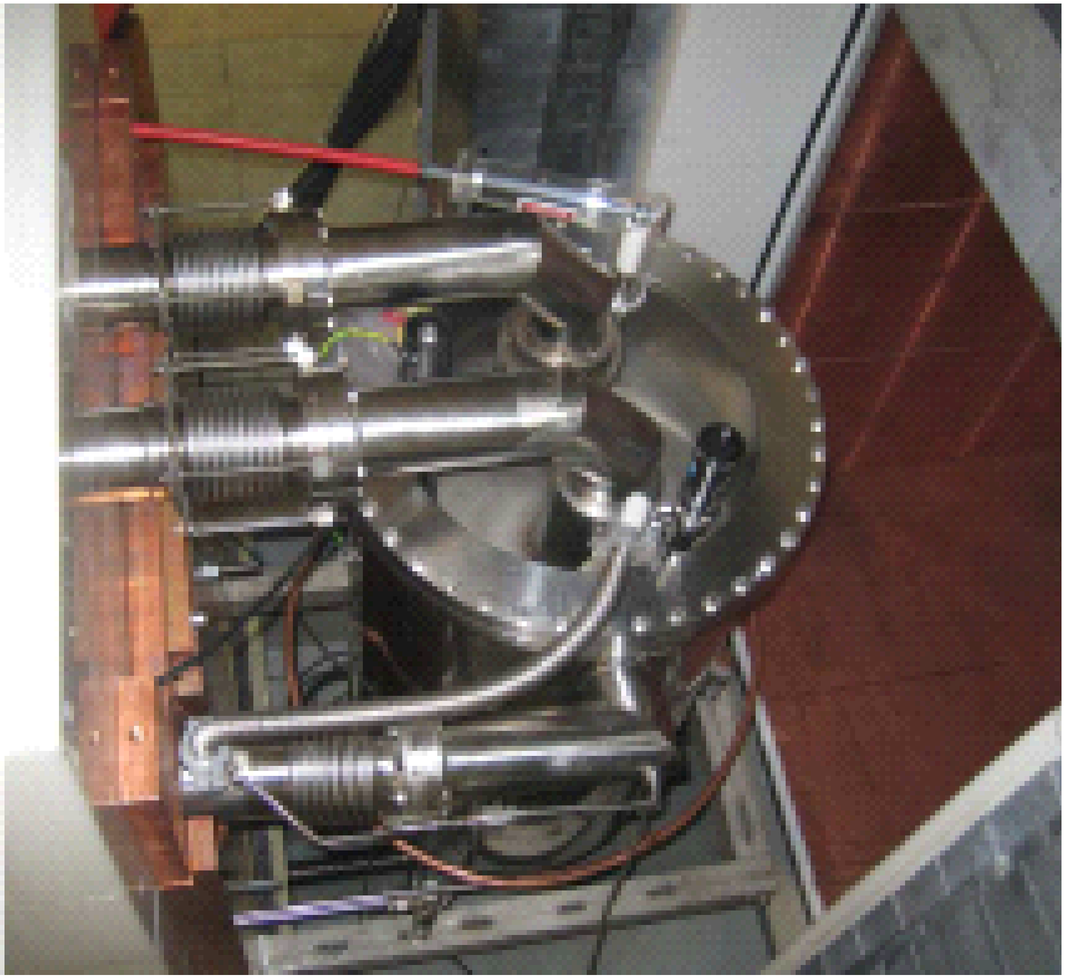


XENON100

A new low background TPC (100 x less than XENON10) in improved shield at LNGS

- *170 kg LXe (vs. 20 kg in XE10);*

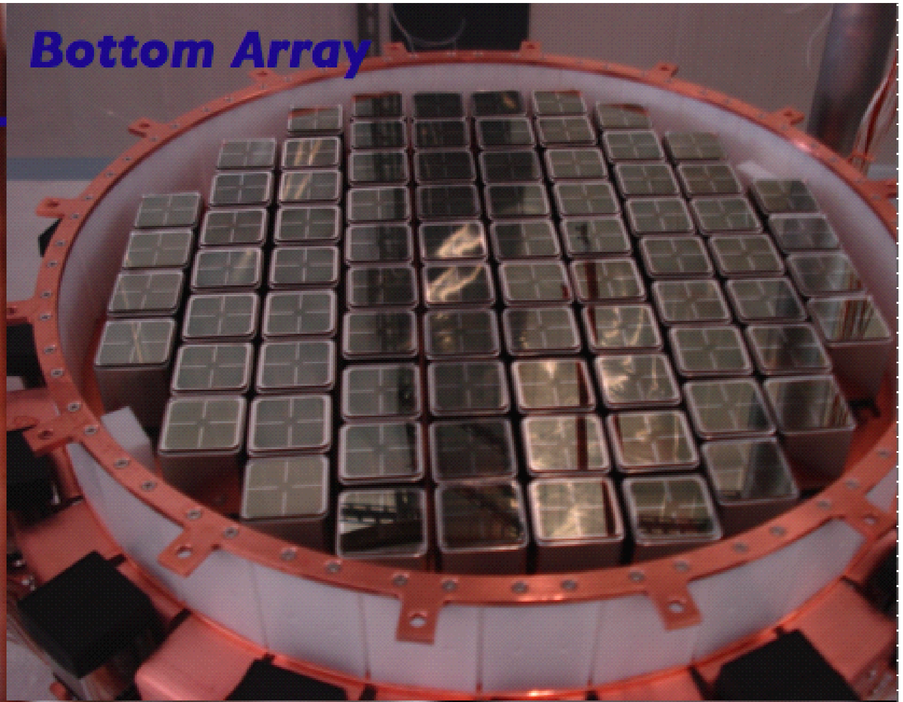


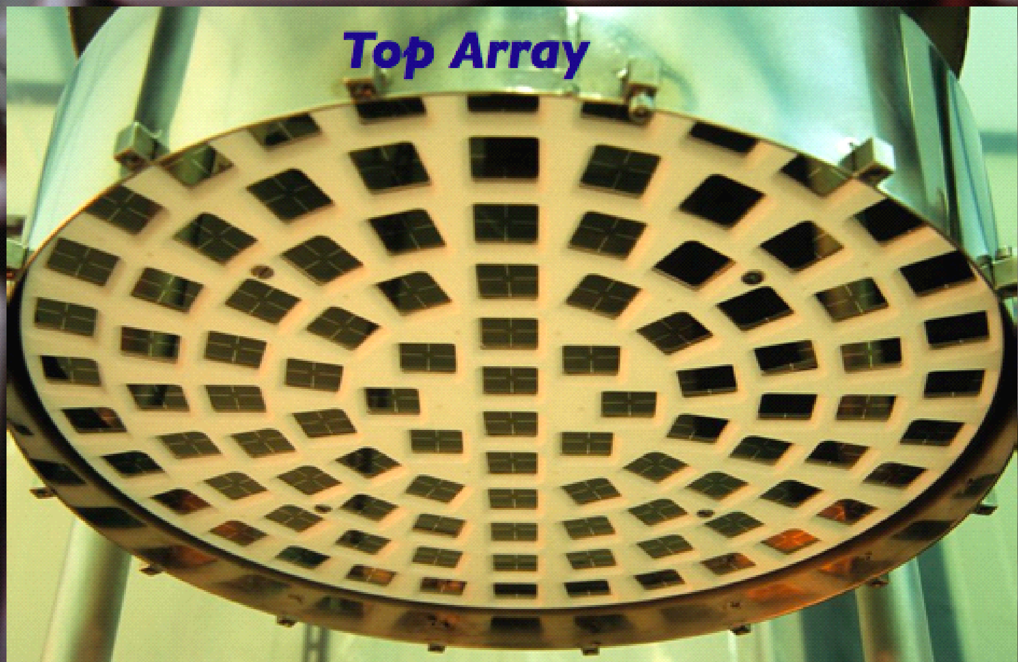


Status of XENON100: the TPC Assembly

XENON100: The PMTs

- 242 PMTs (Hamamatsu R8520-06-Al)
- 1 " square metal channel developed for XENON
- Low radioactivity (<1 mBq U/Th per PMT)
- 80 PMTs for bottom array (33% QE)
- 98 PMTs for top array (23% QE)
- 64 PMTs for top/bottom/side Veto (23% QE)



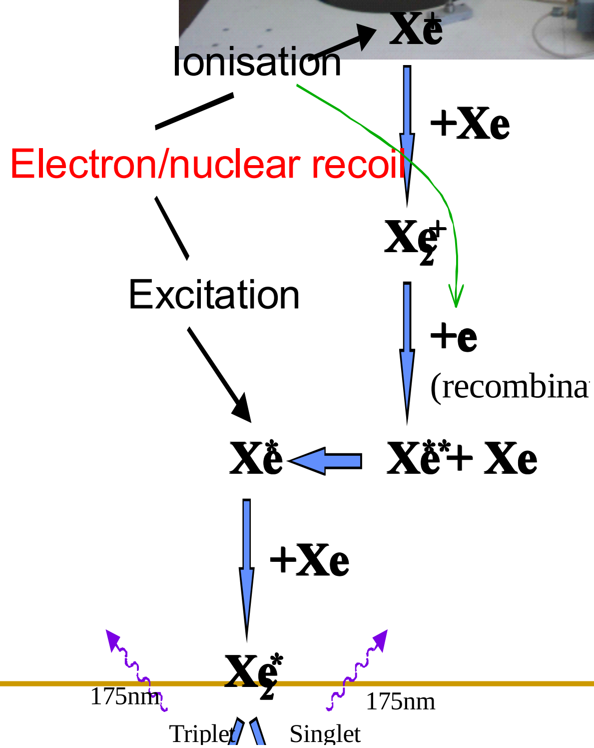


XENON100: Keeping it Cold! New Cryogenics System Design

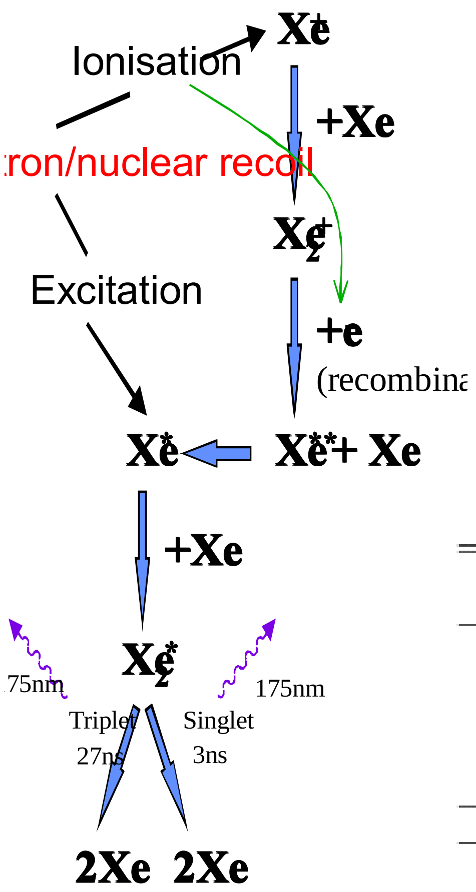
Pulse Tube Refrigerator (160 W)for Xe liquefaction and gas recirculation

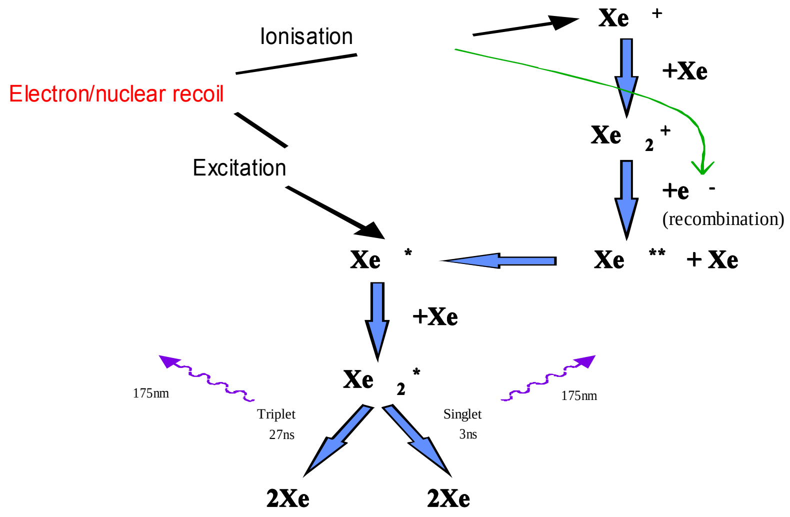
Cooling tower with PTR is an extension of the detector cryostat, mounted outside shield

Xe gas is liquefied in the tower and flows into the detector vessel via super-insulated pipe



XENON100 Materials Screening for low Radioactivity



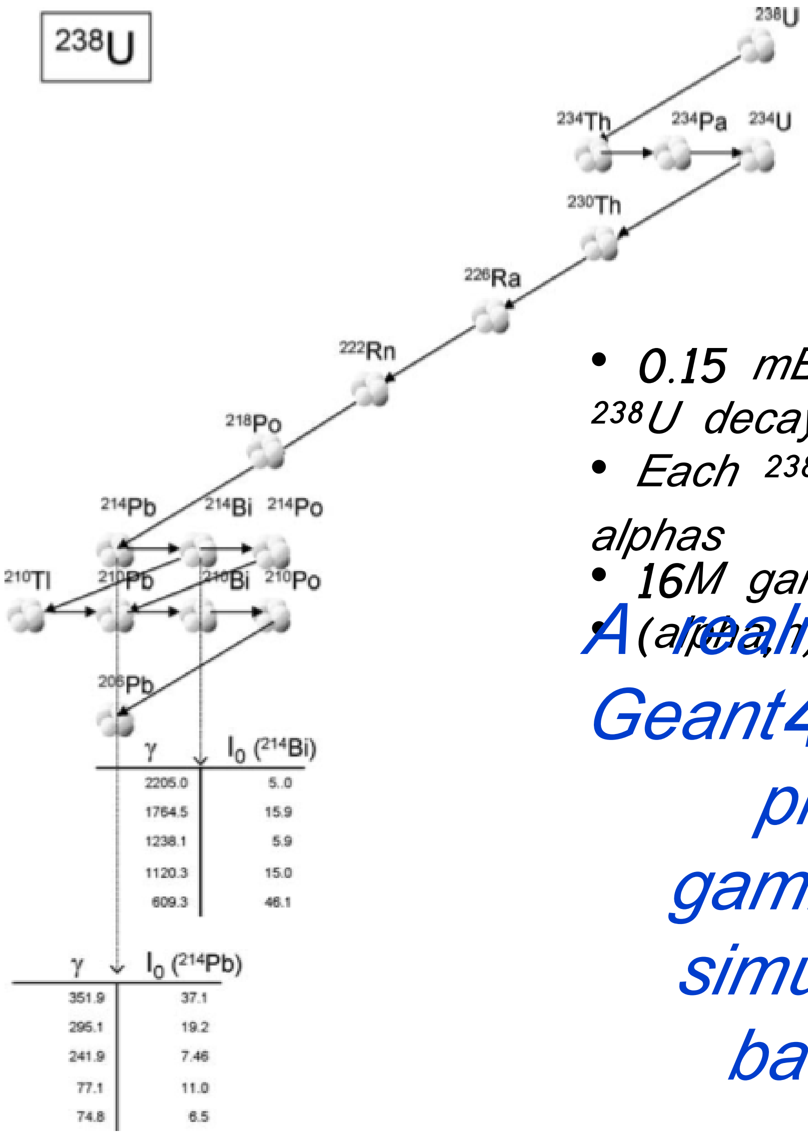


Radioactivity of all materials used in XENON100 measured with a dedicated HPGe counter at LNGS

TPC Material	Unit	Quantity used	^{238}U [mBq/unit]	^{232}Th [mBq/unit]	^{40}K [mBq/unit]	^{60}Co [mBq/unit]	^{210}Pb [Bq/unit]
R8520 PMTs	PMT	242	0.15 ± 0.02	0.17 ± 0.04	9.15 ± 1.18	1.00 ± 0.08	
PMT bases	base	242	0.16 ± 0.02	0.07 ± 0.02	< 0.16	< 0.01	
Stainless steel	kg	70	< 1.7	< 1.9	< 9.0	5.5 ± 0.6	
PTFE	kg	10	< 0.31	< 0.16	< 2.2	< 0.11	
QUPID	QUPID	-	<0.49	<0.40	<2.4	<0.21	
Shield Material							
Copper	kg	1600	< 0.07	< 0.03	<0.06	<0.0045	
Polyethylene	kg	1600	< 3.54	< 2.69	< 5.9	< 0.9	
Inner Pb (5 cm)	kg	6300	< 6.8	< 3.9	< 28	< 0.19	17 ± 5
Outer Pb (15 cm)	kg	27200	< 5.7	< 1.6	14 ± 6	< 1.1	516 ± 90

Table 1: Radioactivity of XENON100 materials: Average values are given if different activities were obtained for different material samples, such as different batches of PMTs and stainless steel. Upper limits are given if no activity above background was found. Radioactivity from other components, such as screws and cables, are negligible (at least a factor of 10 lower compared to those in the table).

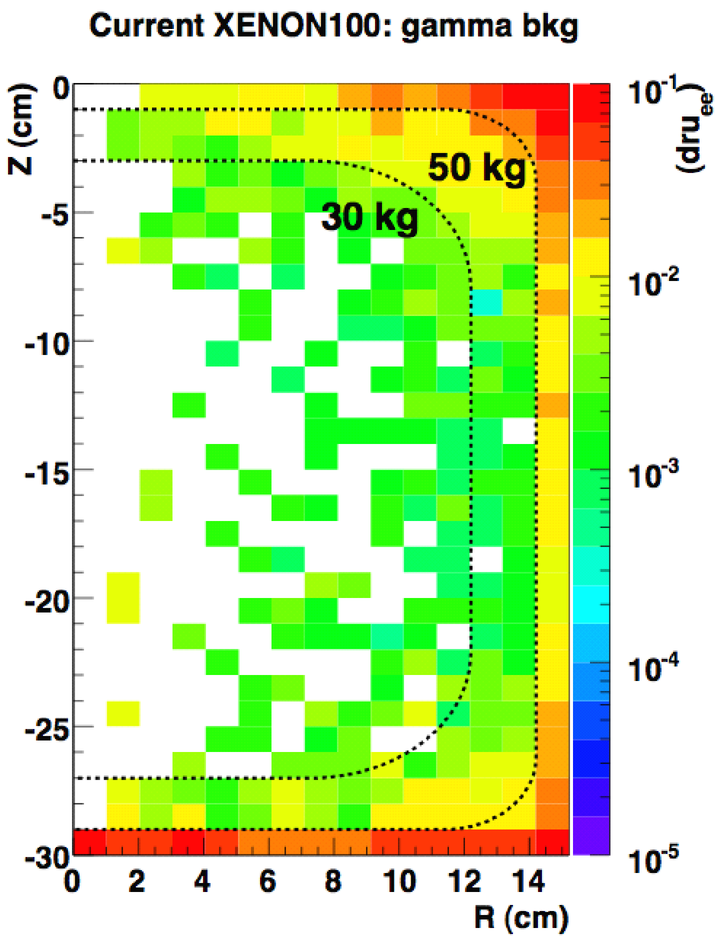
Background simulations



- *0.15 mBq/PMT x 242 PMTs gives 3000 ^{238}U decays/day*
- *Each ^{238}U decay produces 15 gammas and 9 alphas*
- *16M gamma/year*
- *(alpha,n) reaction results 7 neutron/year*

A realistic model based on Geant4 was constructed to propagate all the gammas/neutrons and simulate the expected background rate in XENON100.

Expected Background and Sensitivity Reach



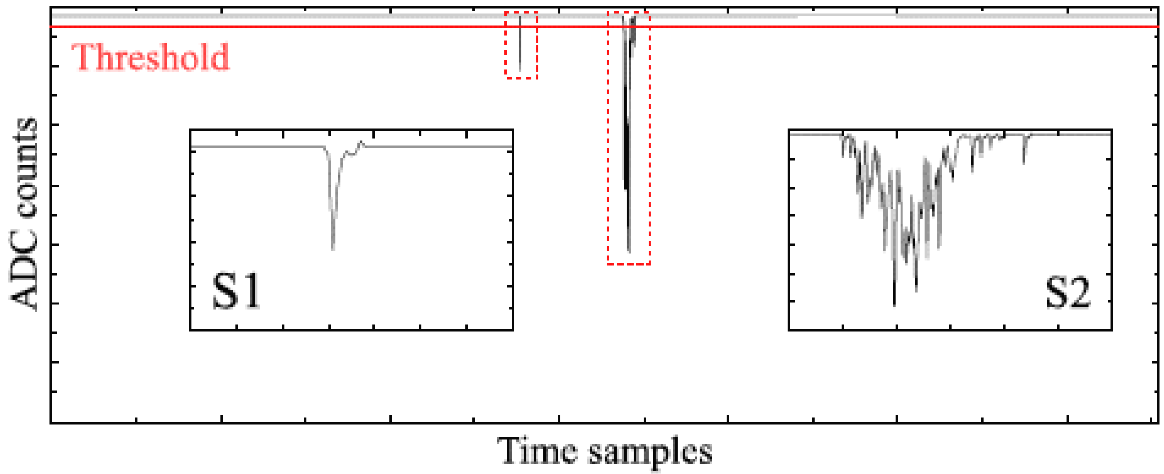
dru_{ee} = evts/keVee/kg/day

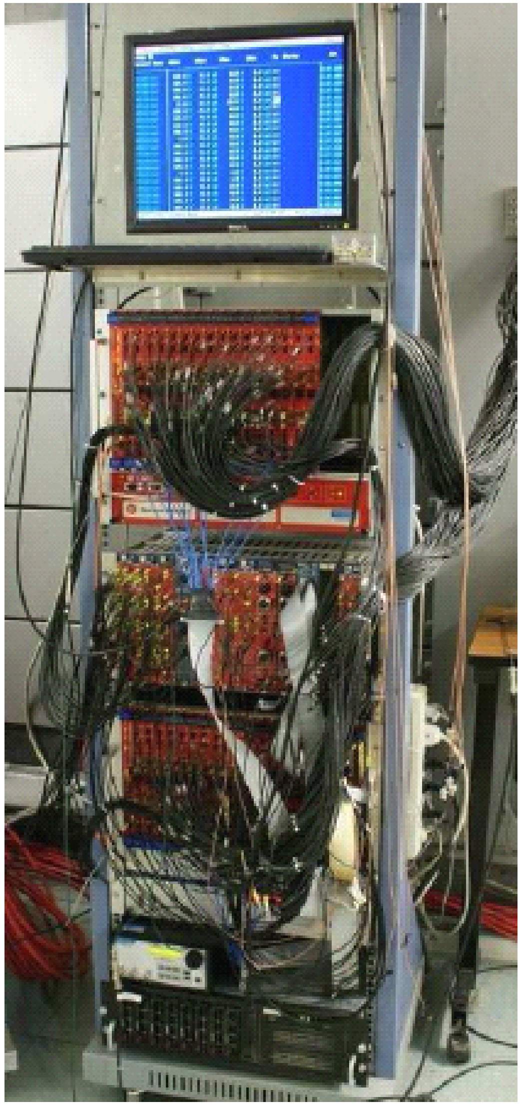
	Current XENON100			
Fiducial Mass	50 kg		30 kg	
Background	ER	NR	ER	NR
Units [a]	$[10^{-3} dru_{ee}]$	$[10^{-7} dru_{nr}]$	$[10^{-3} dru_{ee}]$	$[10^{-7} dru_{nr}]$
PMTs and bases	4.91	3.25	<1.4	2.87
QUPIDs	–	–	–	–
Stainless steel	<2.01	<2.01	<0.35	<1.66
PTFE	<0.18	<6.99	<0.03	<5.04
Copper Cryostat	–	–	–	–
Polyethylene	<2.50	<5.37	<1.2	<4.73
^{85}Kr/U/Th [b]	<0.2	–	<0.2	–
Concrete/Rocks[c]	–	1.34	–	1.11
μ-induced n in shield	–	33	–	33
μ-induced n in rock	–	< 3.7	–	< 3.7
Total Bkg	<9.8	<55.7	<3.2	<52.1
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 (early 2009)		2×10^{-45} cm^2 (end 2009)	

[e] assume cross section 10^{-44} cm^2

XENON100: Data Acqusition System

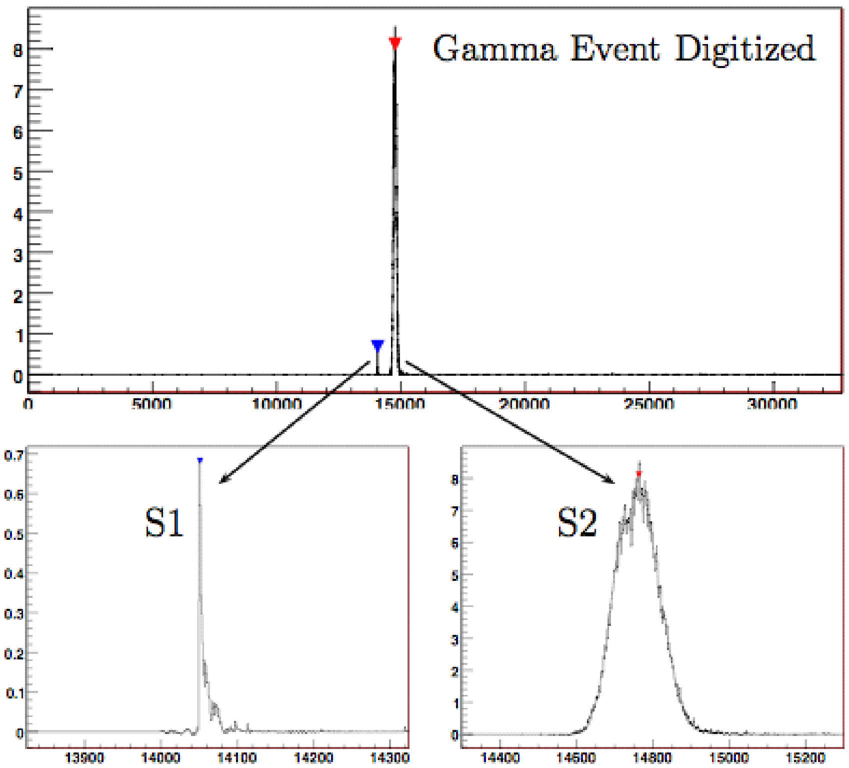
- Data acquisition system composed of 31 CAEN V1724 14 bit 100 MHz flash ADCs to digitize the 242 PMTs signals of 320 μs.
- Deadtime-less mode with data written to circular buffers and multiple event buffers for storage between VME read cycles.
- Digitized signals are "zero length encoded" by the V1724 FPGA, only the relevant signal portions are transfered from the ADCs to the DAQ computer. Allows fast event transfer rates (> 60 Hz).

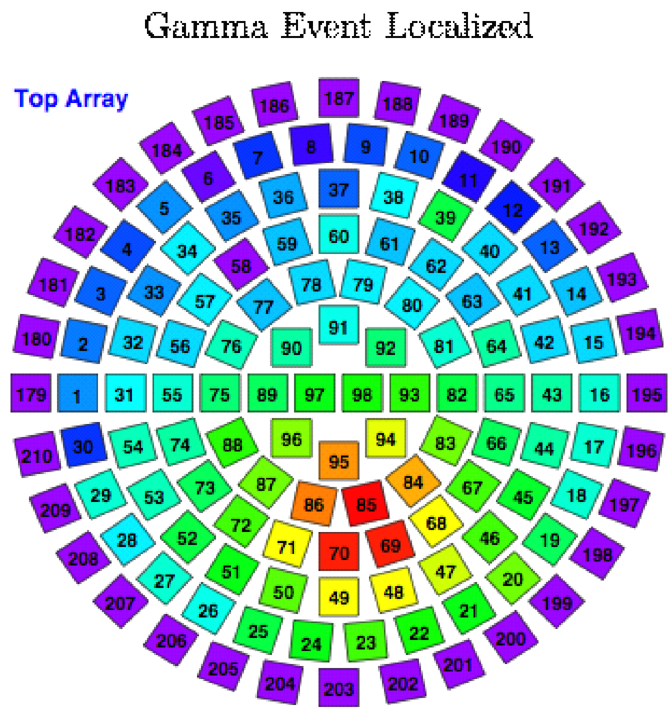




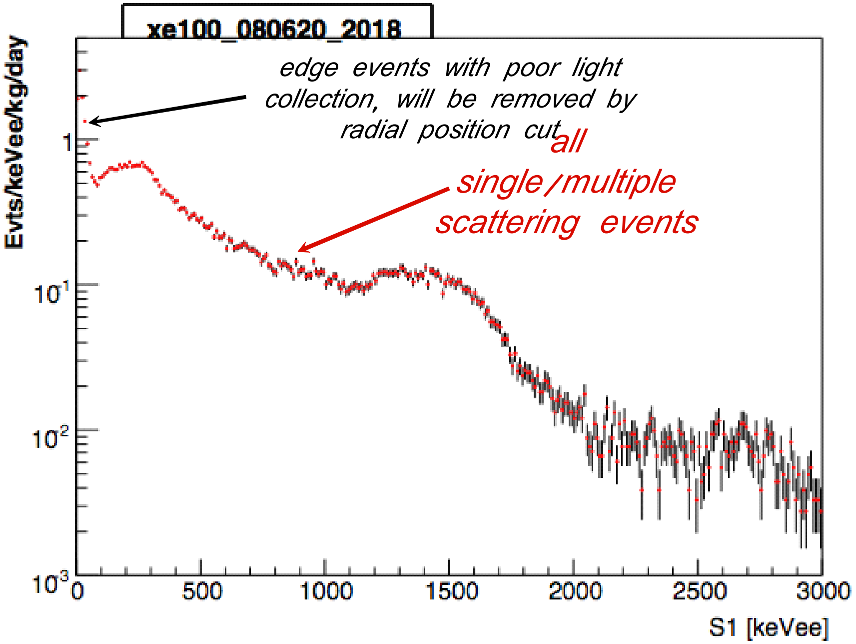
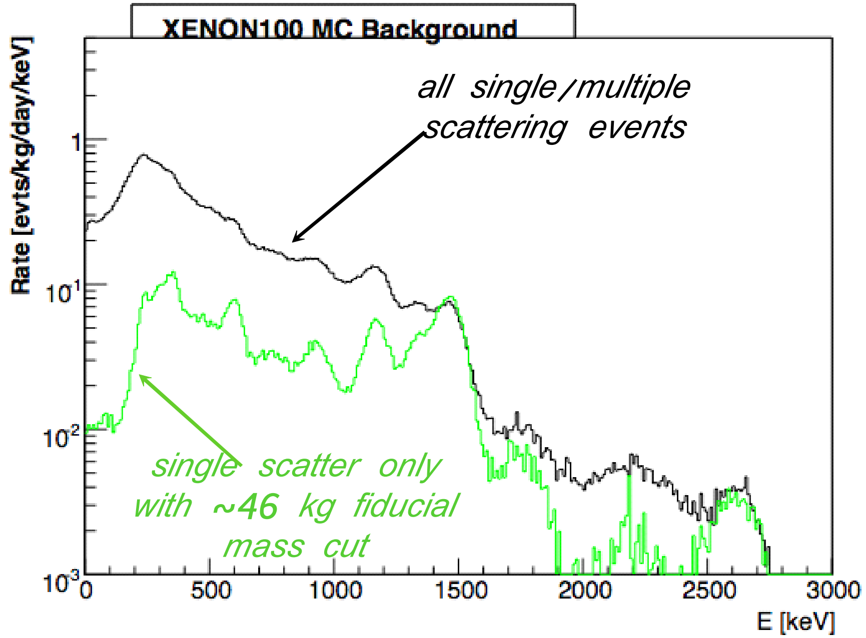
First signals from XENON100

- XENON100 is filled with 170 kg of Xe and running in stable conditions at LNGS
- Light and charge yields improving with continuous purification of the liquid by hot getter
- Currently 2.7 pe/keV; estimated light collection is 4-5 pe/keV





XENON100 background run

data	Simulation
	

Detector has been fully filled with liquid xenon.

First Measured background Spectrum in good agreement with MC prediction!

WIMP search run is planned to start in April 2009.

XENON100: Kr Removal

Kr85 (Beta, Emax = 687 keV, t = 10.8 y, br = 99.563%) -> Rb85

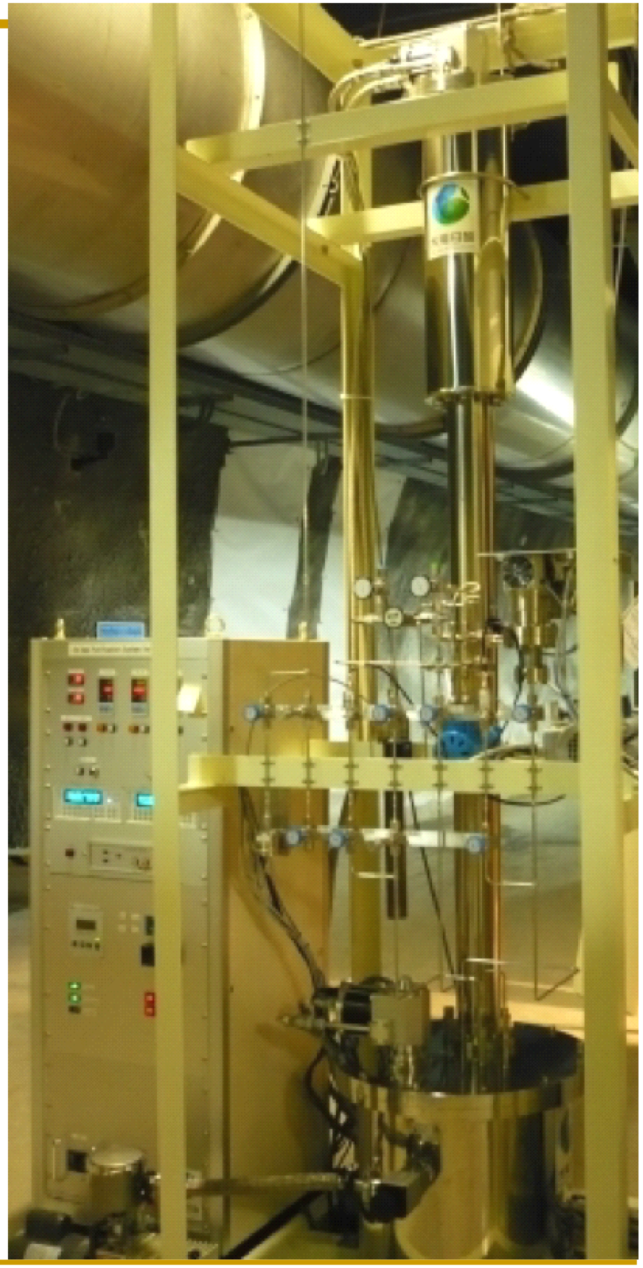
Kr85 (Beta, Emax = 173 keV, t = 10.8 y, br = 0.434%)
-> Rb85m (Gamma, E = 514 keV, t = 2.43 us) -> Rb85

XENON100 science goal requires Kr contamination ~ 50 ppt

We use cryogenic distillation to separate Kr from Xe:

1) distilled by Spectra Gases Industry to < 10 ppb Kr level
verified with XENON100 data by delayed coincidences analysis
Measured Kr contamination = 7+-2 ppb

2) distilled on site by dedicated Cryogenic Distillation Tower
designed to reduce Kr by factor 10^3 at a rate of 0.6 kg/hr



With continuous recirculation the purity improves with time.

Main impurities, but there are others:
Purity for light is determined by water.
Purity for charge is also determined by oxygen.

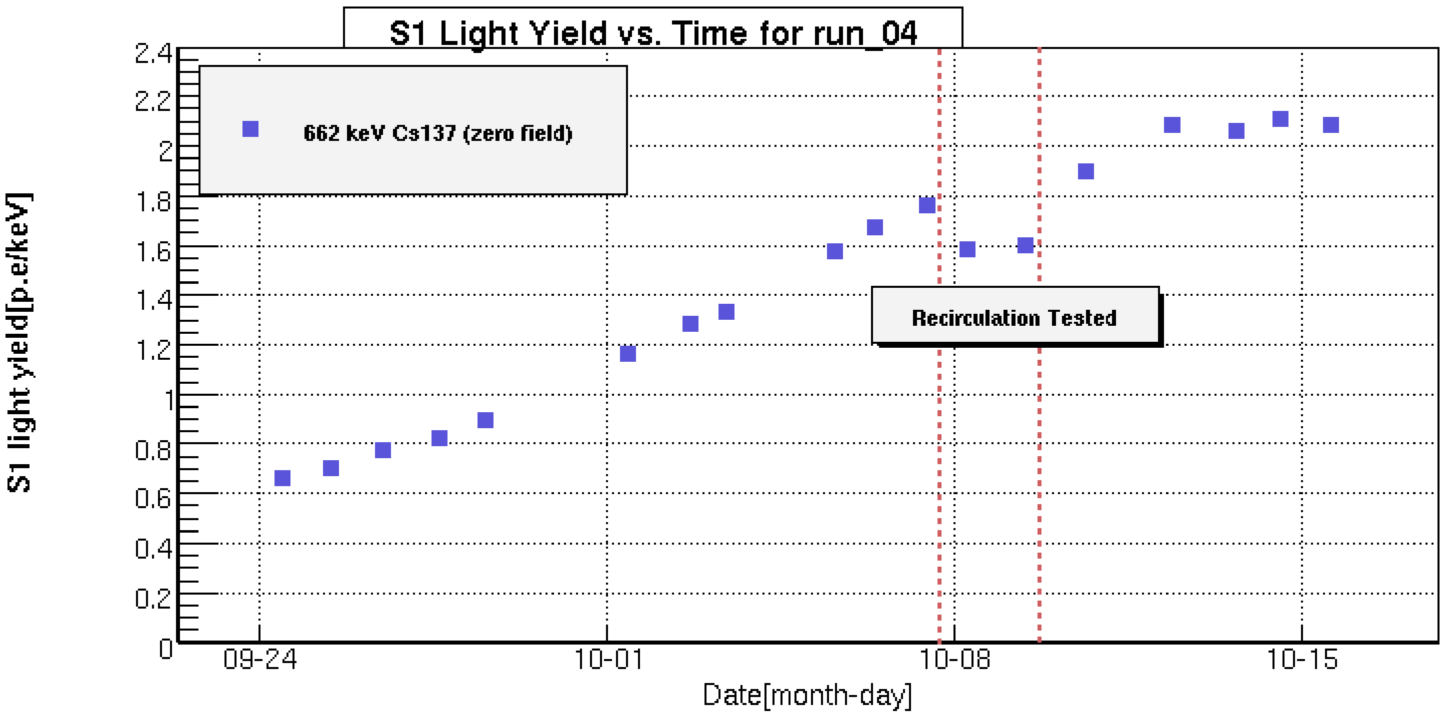
Purification of Gas. Recirculation speed about 10 SLPM

Cleaning time for XENON10: 2 months

We monitor:
Initially: light yield (S1)
Then: Charge yield vs. drift time (S2)

Cleaning of Detector takes time.

Time – “Driver” is out gassing rate, not recirculation speed.



New Photodetector for XENON:
Low Radioactivity – Single Photon Counting – high QE

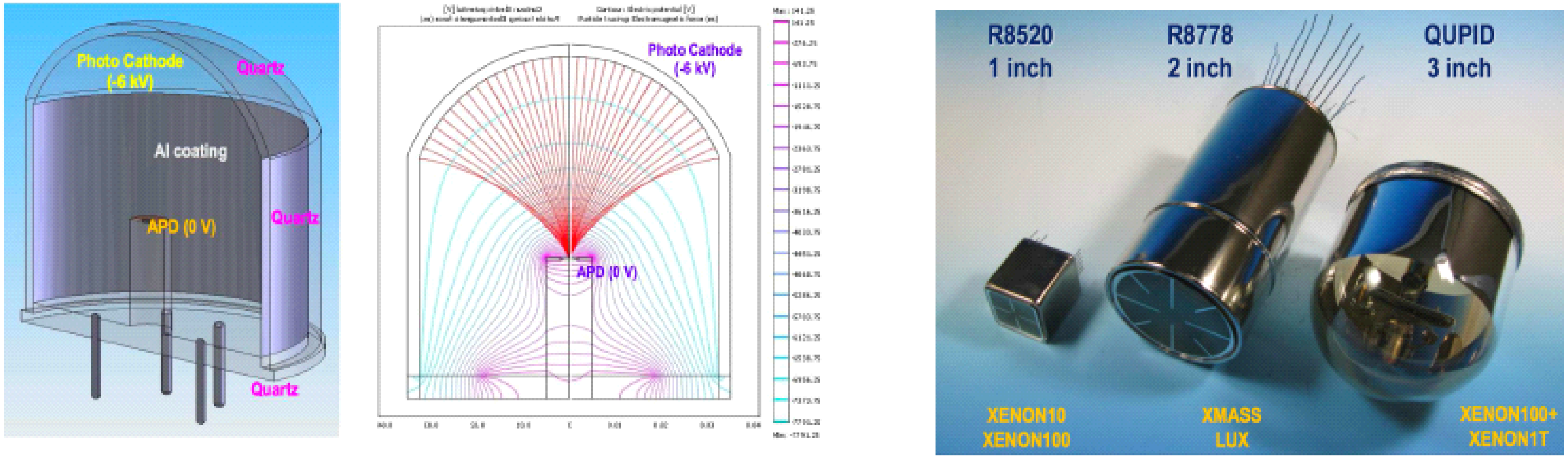


Figure 8: Left: Structure of a QUPID, made of pure Quartz with a 3 mm diameter APD at its center. Center: Simulation of electron trajectories, showing that all photoelectrons from the photocathode are well focused onto the APD. Right: Comparison of R8520 (used in XENON10/100), R8778 (used in LUX), and QUPID.

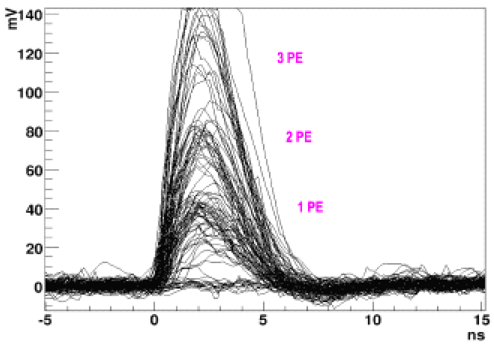
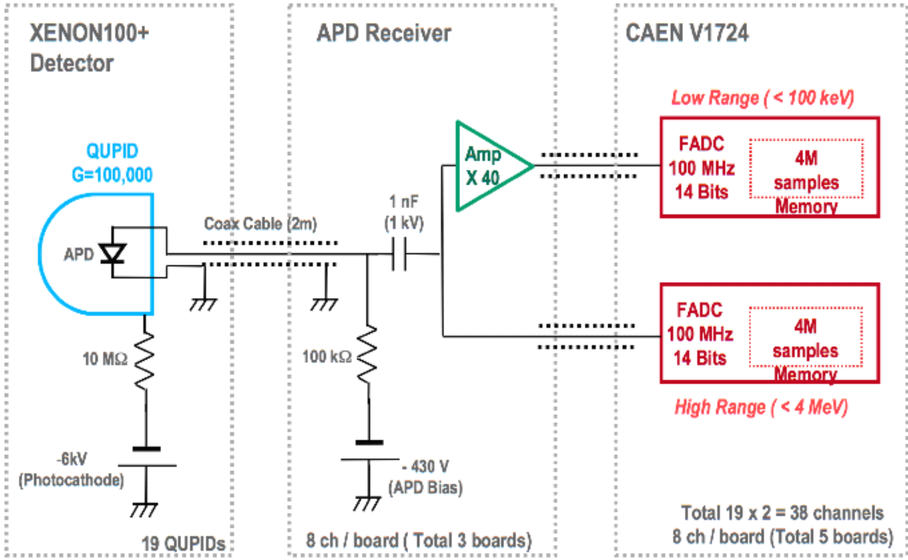
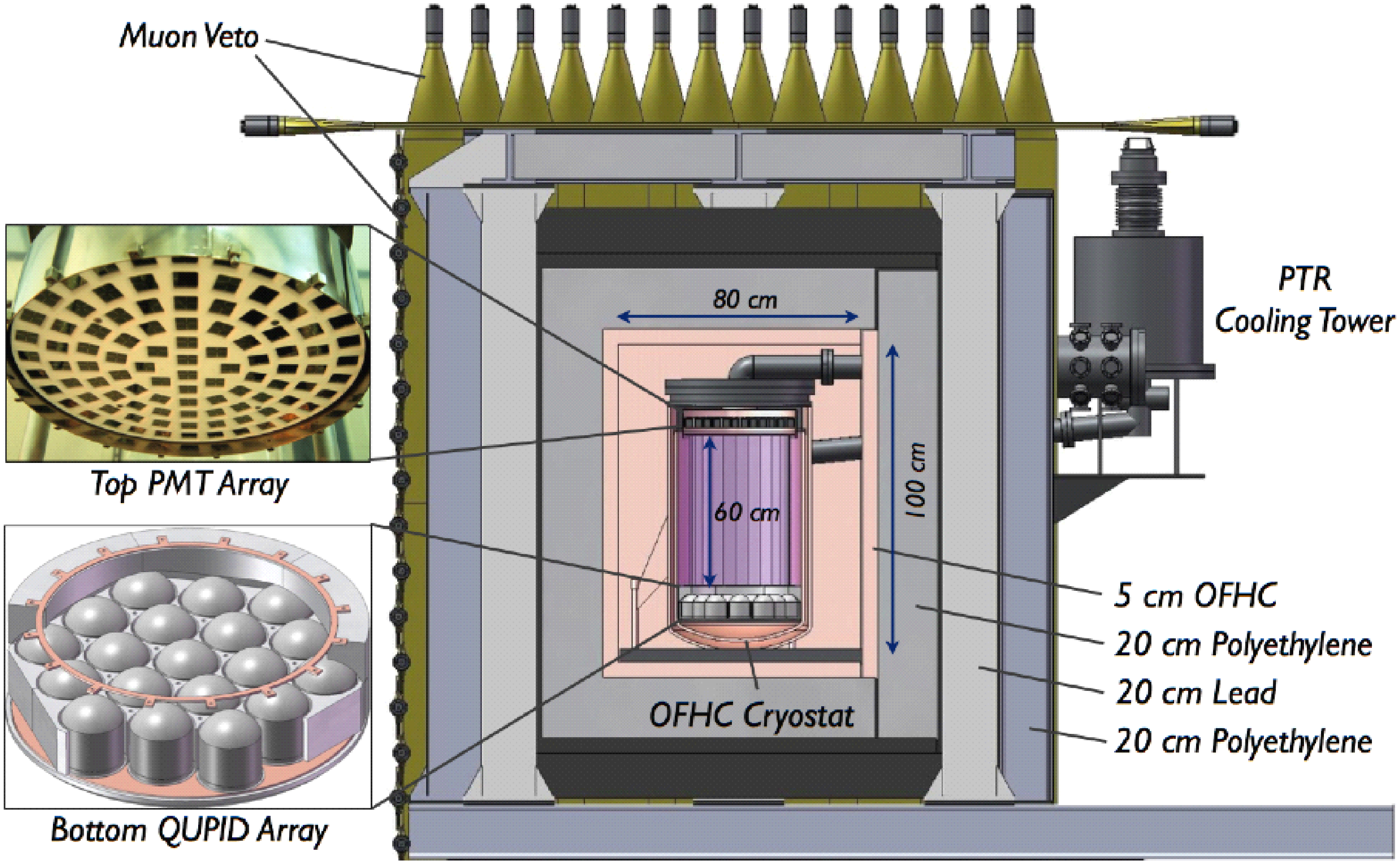


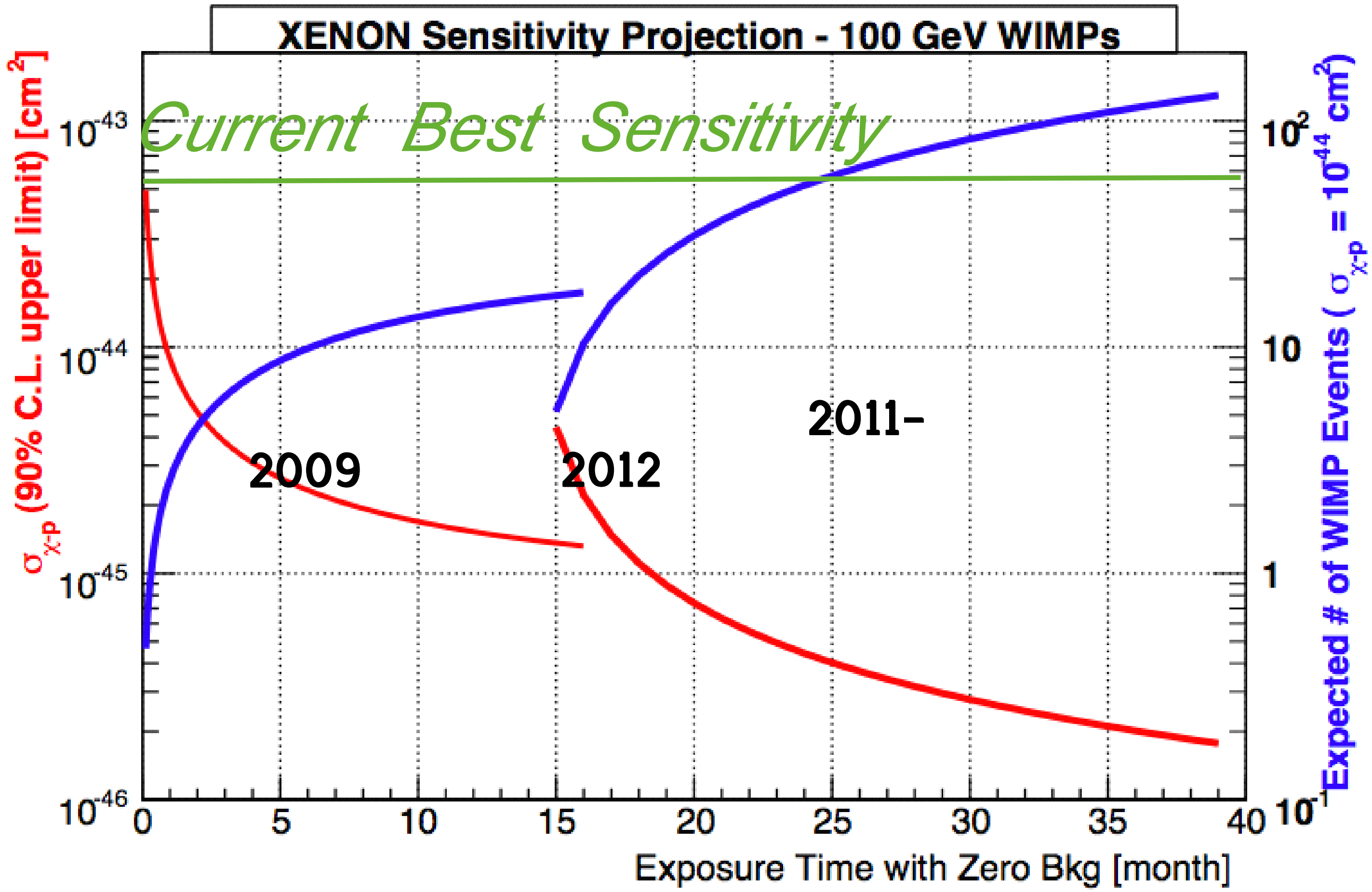
Figure 9: Typical waveforms taken with a QUPID. The three waveform bands at 40, 80, and 120 mV correspond to 1, 2 and, 3 photoelectrons.



Proposed upgrade for XENON100 (2009-2012)

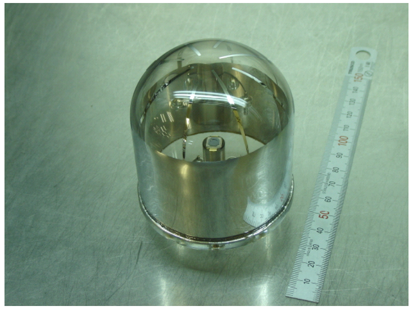


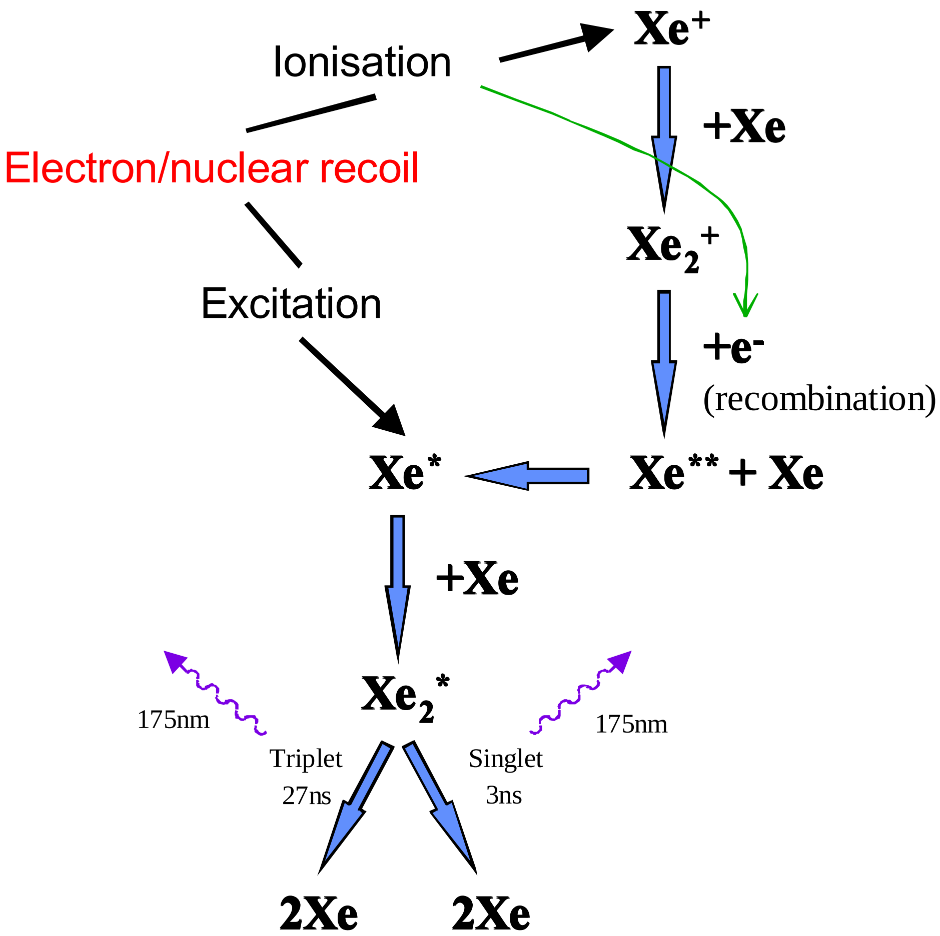
Sensitivity Reach of the XENON100 Program



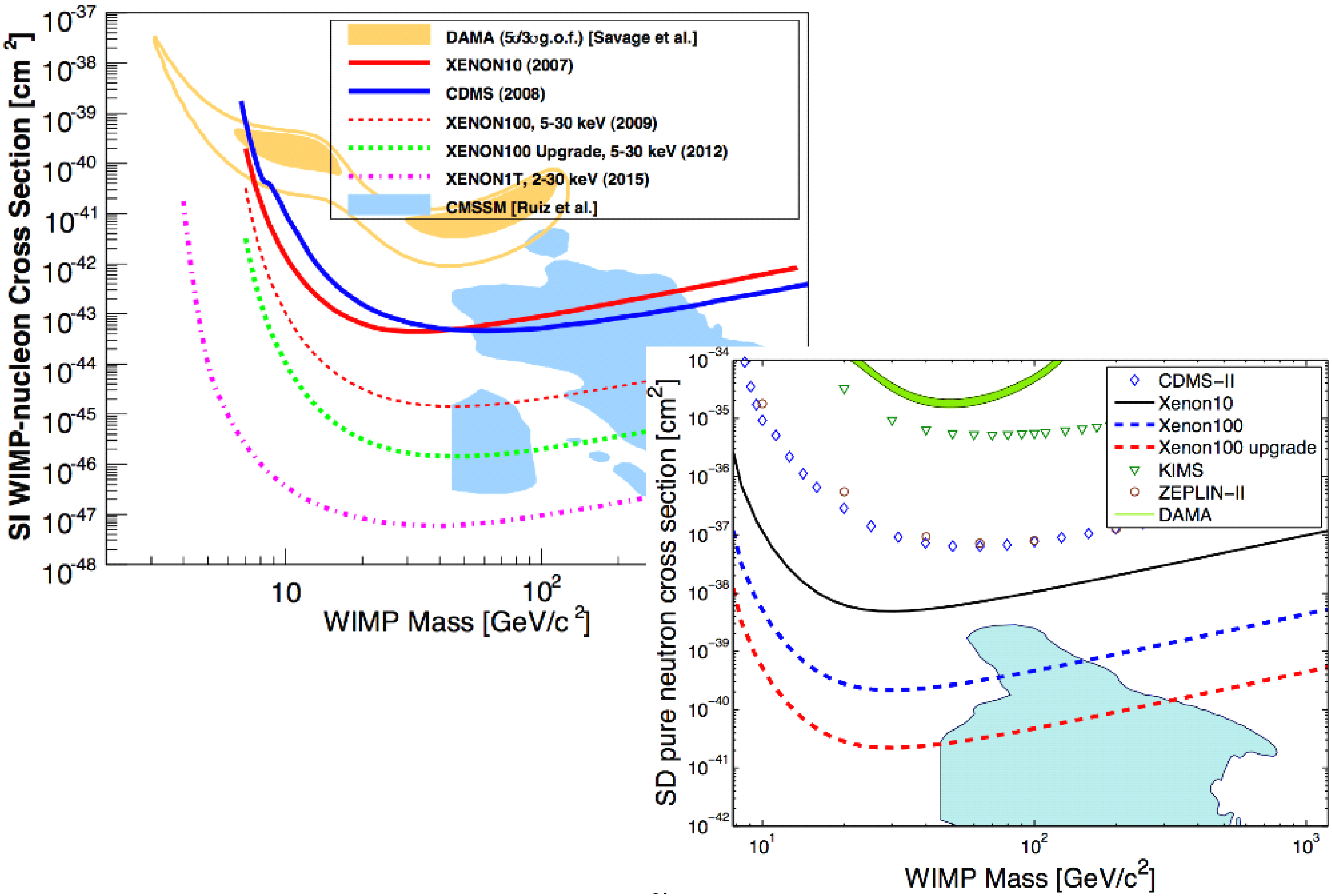
XENON1T Detector for pre-DUSEL era (before 2014)
Multi-ton XENON Detector for DUSEL (beyond 2014)

- *Explore most SUSY parameter space/accumulate WIMP statistics*
- *New design with full coverage of ultra-low background photodetectors and cryostat*
- *Larger International Collaboration*
- *Estimated project cost: $25M (XENON1T)*
- *Multi-ton scale for DM/neutrinoless double beta decay/pp solar neutrinos $50-100M*





XENON Sensitivity Goal



Summary

2008 an exciting year for direct DM detection : new SI and SD results (XENON10, CDMS, COUF

Annual modulation signal re-confirmed by DAMA/LIBRA

2008 also a very good year for indirect DM detection

2009 a crucial year for direct detection: expect new results from CDMS, XENON100, WARP, etc

XENON100 operational underground: currently the largest two-phase TPC at work

Presently: Filled with 170 kg of xenon, cleaning with continuous re-purification

Data taking for Dark Matter Search will start early 2009: $\sigma_{SI} \sim 2\times10^{-45}$ cm^2 after 7 months bkg fre

Proposed XENON100 upgrade: test key technologies for XENON1T and reach x 10 better sensitiv

	Current XENON100				Upgraded XENON100	
Fiducial Mass	50 kg		30 kg		100 kg	
Background	ER	NR	ER	NR	ER	NR
Units [a]	$[10^{-3} dru_{ee}]$	$[10^{-7} dru_{nr}]$	$[10^{-3} dru_{ee}]$	$[10^{-7} dru_{nr}]$	$[10^{-3} dru_{ee}]$	$[10^{-7} dru_{nr}]$
PMTs and bases	4.91	3.25	<1.4	2.87	0.098	0.23
QUPIDs	–	–	–	–	<0.027	<0.10
Stainless steel	<2.01	<2.01	<0.35	<1.66	<0.052	<0.14
PTFE	<0.18	<6.99	<0.03	<5.04	<0.017	<1.60
Copper Cryostat	–	–	–	–	<0.033	<0.02
Polyethylene	<2.50	<5.37	<1.2	<4.73	<0.105	<0.60
^{85}Kr/U/Th [b]	<0.2	–	<0.2	–	<0.02	–
Concrete/Rocks [c]	–	1.34	–	1.11	–	0.2
μ-induced n in shield	–	33	–	33	–	0.7 [d]
μ-induced n in rock	–	< 3.7	–	< 3.7	–	<3.7
Total Bkg	<9.8	<55.7	<3.2	<52.1	<0.35	<7.3
Run Time	40 days		200 days		600 days	
Raw Exposure	2000 kg-day		6000 kg-day		60000 kg-day	
Total Bkg events	<1.0		<1.2		<1.4	
# of WIMP events [e]	3.9		11.8		118	
SI $\sigma_{\chi-p}$ reach	6×10^{-45} cm^2 (early 2009)		2×10^{-45} cm^2 (end 2009)		2×10^{-46} cm^2 (2012)	

[a] dru_{ee} = evts/kg/keVee/day, dru_{nr} = evts/kg/keVnr/day

[b] with < 5 ppt Kr/Xe and U/Th in Xe below 10^{-13} g/g. XENON100 Upgrade requires another factor of ten reduction.

[c] with an additional layer of 20 cm polyethylene outside the current shield

[d] with a muon veto of 98% efficiency

[e] for 100 GeV/c^2 WIMPs with spin-independent $\sigma_{\chi-p} = 10^{-44}$ cm^2

Table 2: Predicted single scatter electron recoil (ER) and nuclear recoil (NR) background rates in the WIMP search region (2 – 12 keVee or 4.5 – 26.9 keVnr) in the central 50 kg (30 kg) target for the current XENON100 and in the central 100 kg target for the upgraded XENON100. To estimate the total background/WIMP events and the sensitivity reach, we assume 99.5% ER rejection, 50% NR acceptance and 90% software efficiency.