Dark Matter and the XENON100 Experiment

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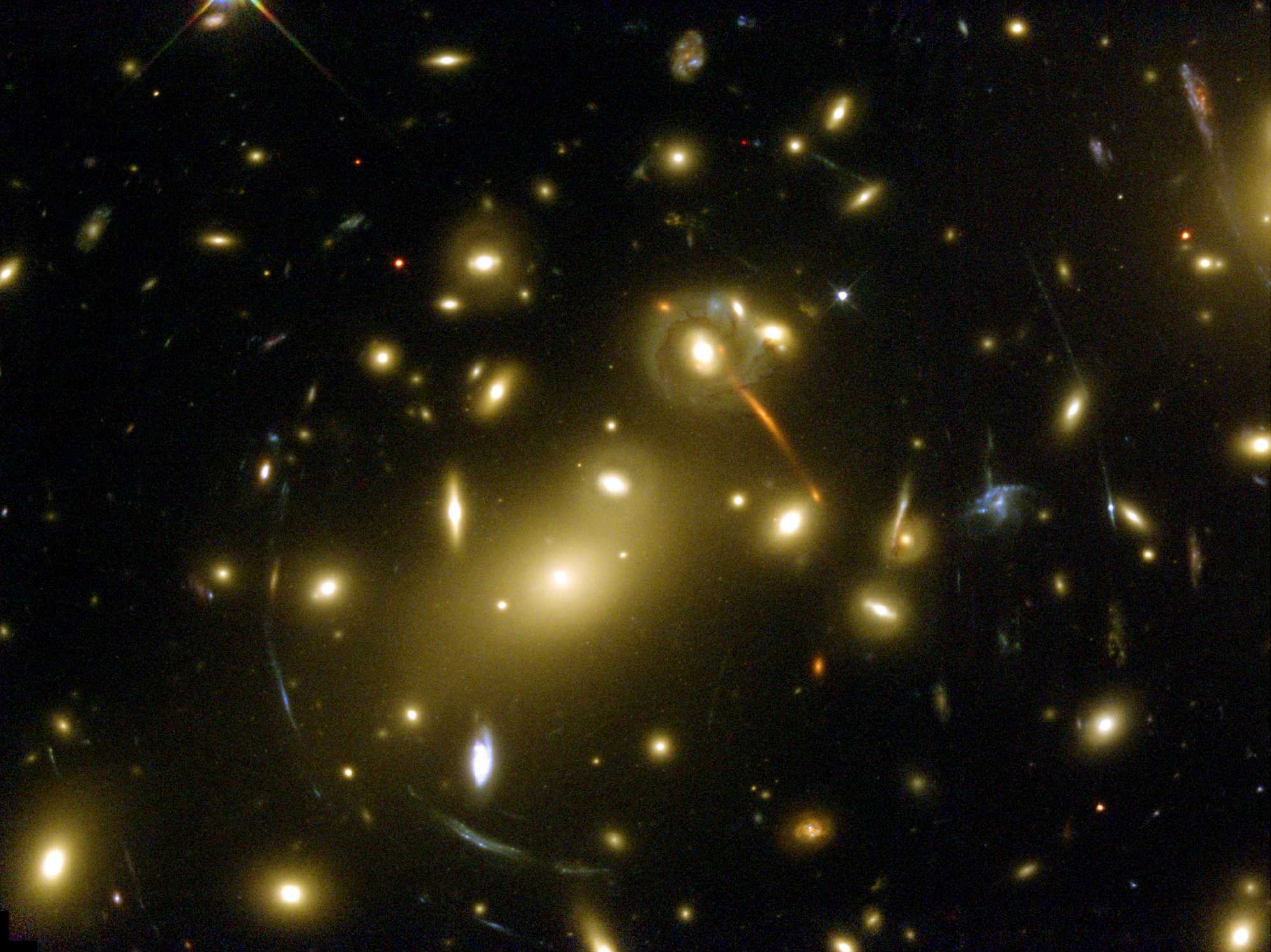
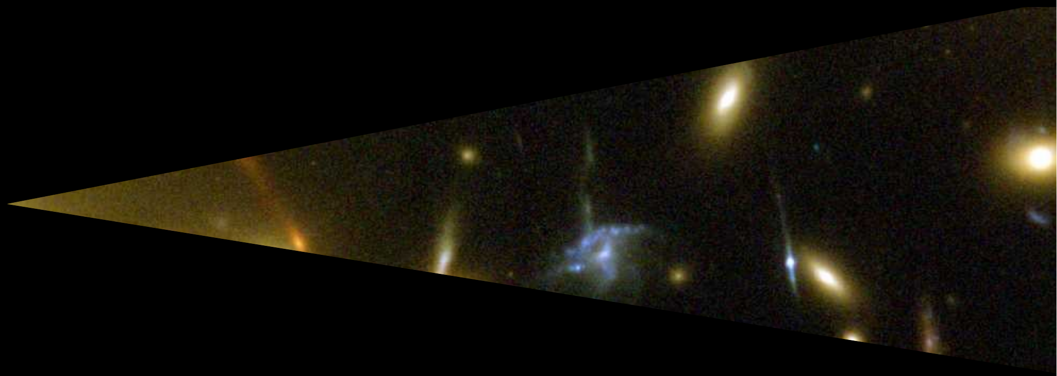
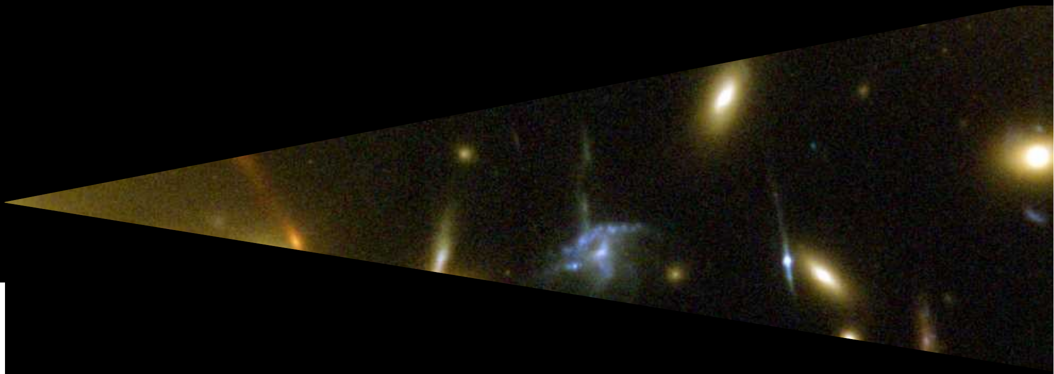
DPNC University of Geneva, April 14th, 2010

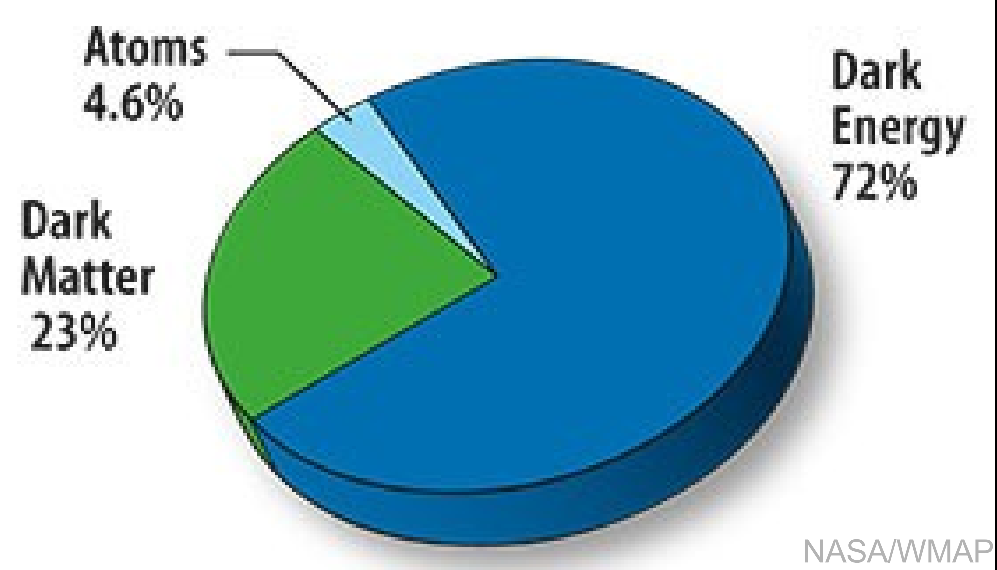
www.physik.uzh.ch/groups/groupbaudis/xenon/





95% of the Universe is DARK





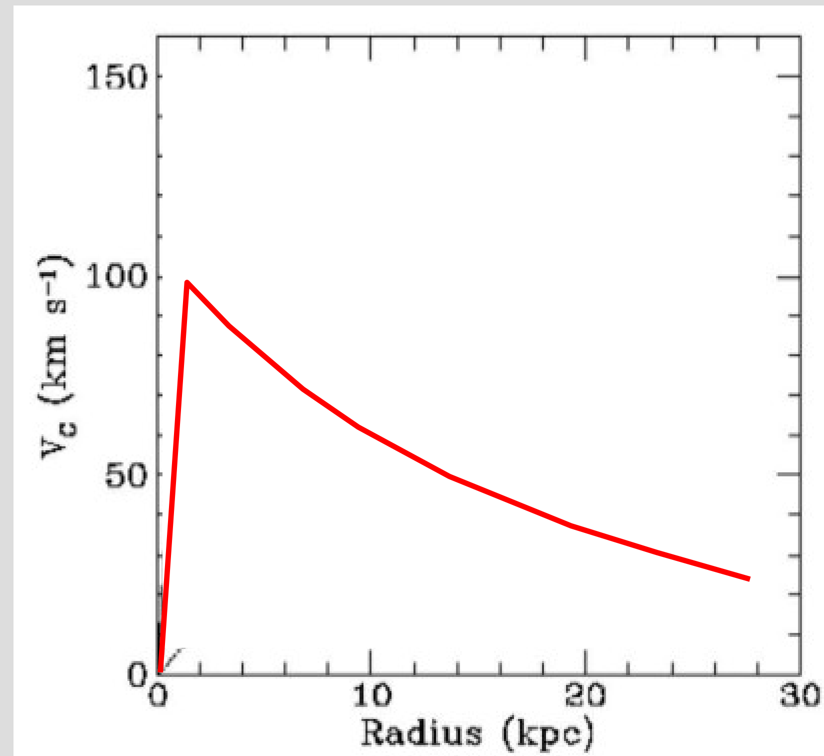
2 colliding galaxy clusters

separation of Dark and Light (baryonic) matter

→ **Dark Matter and not modified gravity**

Galactic Rotation Curves

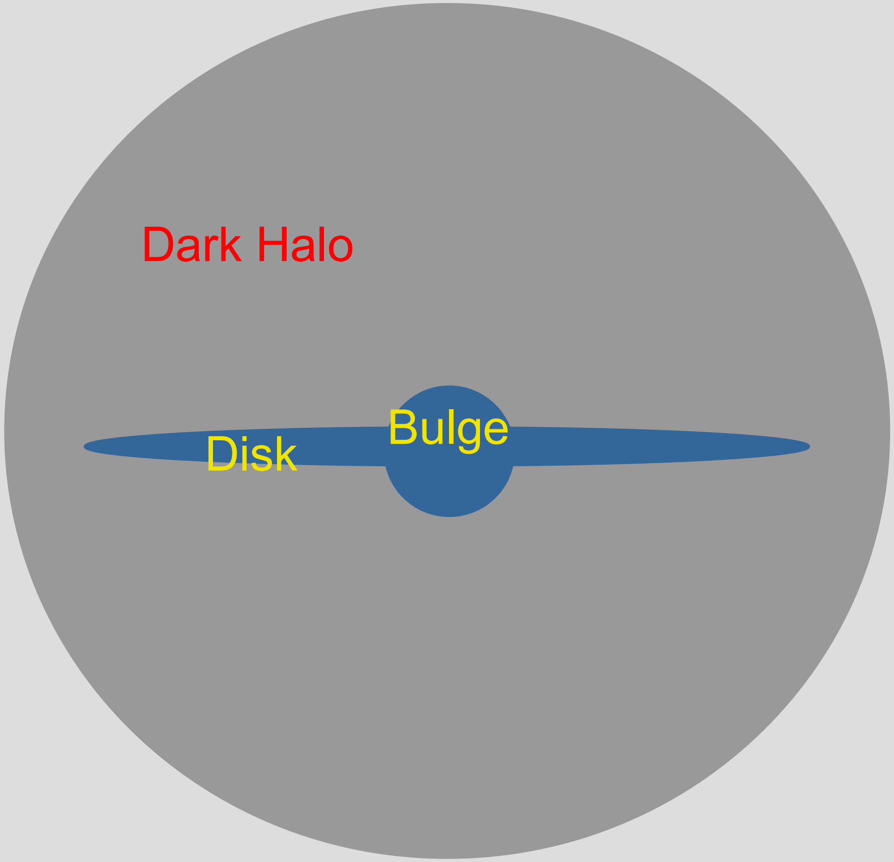
Expect: Kepler Rotation (as in the solar system)

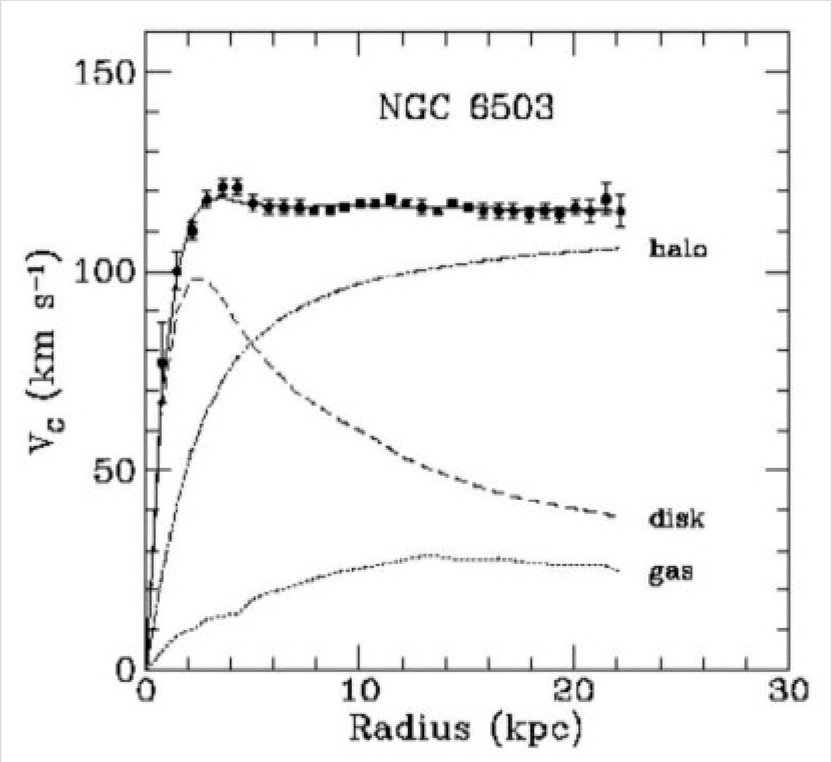


$$v^2 = \frac{G\ M(r)}{r}$$

Galactic Rotation Curves

Measurement: Flat Rotation Profile

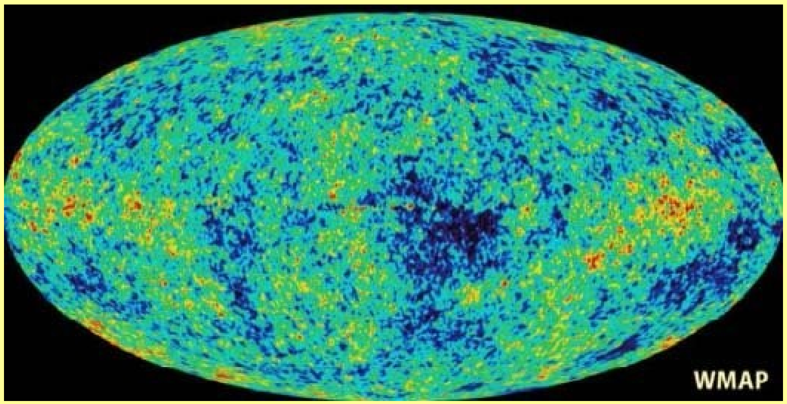




„ball of ideal gas at uniform temperature“

V. Rubin, K. Ford (1970)

Cosmic Microwave Background



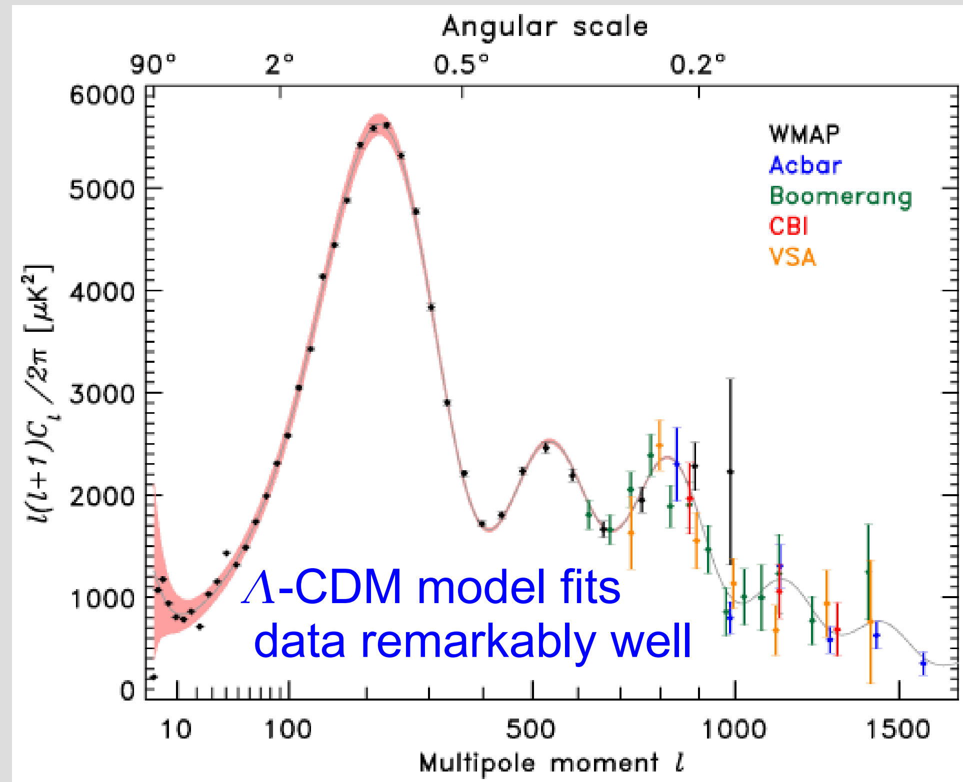
generated when radiation and matter decouple and photons can propagate freely

get information about structures in early universe

→ **Cold Dark Matter:**
- Invisible
- Cold ($v < 10^{-8}\ c$)
- Collisionless
- Stable
- from „new physics“

power spectrum of ΔT

„typical variation at typical distance“



$\Omega = \rho/\rho_{crit} = 1.02(2)$

H = 71(4) km/s/Mpc

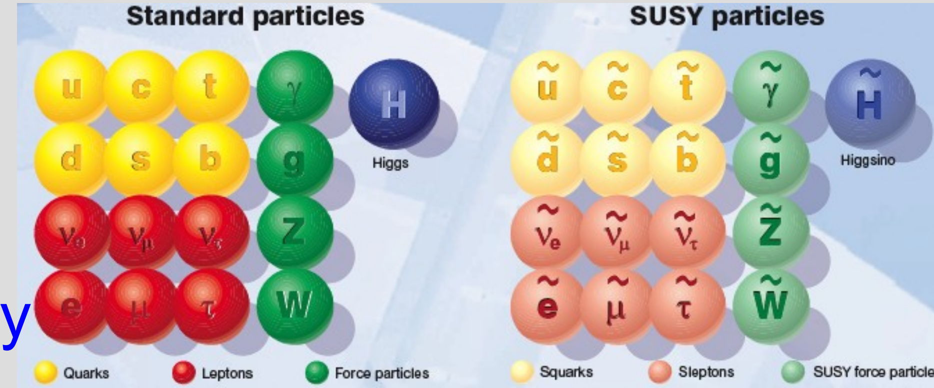
t_0 = 13.7(2) Gyr

$\Omega_\Lambda = 0.73(4)$

$\Omega_B = 0.044(4)$

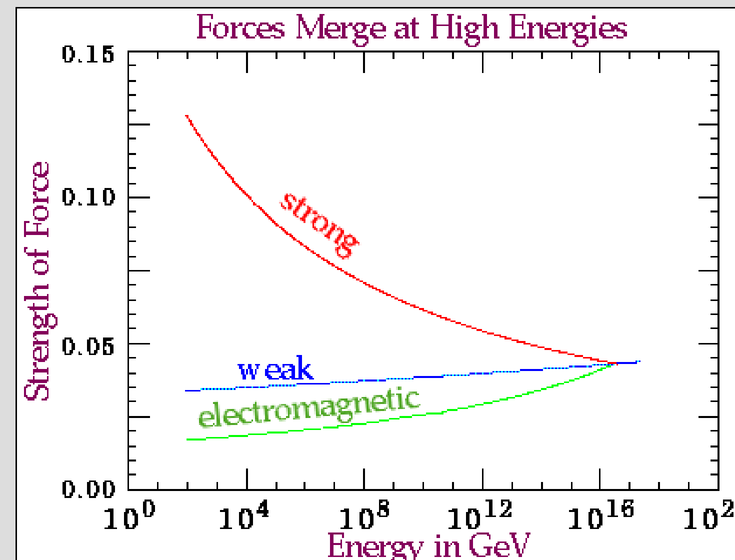
$\Omega_m = 0.27(4)$

SUSY and the WIMP



SUSY was introduced to solve Standard Model problems
(i.e. hierarchy problem, Higgs mass)

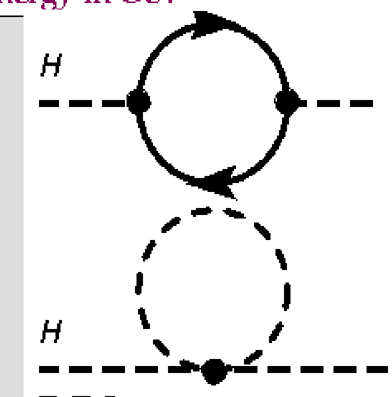
New fundamental space-time symmetry between fermions and bosons



R-parity avoids B/L number violation:

$$R = (-1)^{(3B+L+2S)}$$

→ lightest supersymmetric particle (LSP) is stable → cold DM candidate:
WIMP = weakly interacting massive particle



Neutralino: $\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_d^0 + N_{14}\tilde{H}_u^0$

SUSY WIMP production

In early Universe:

WIMPs in thermal equilibrium
creation ↔ annihilation

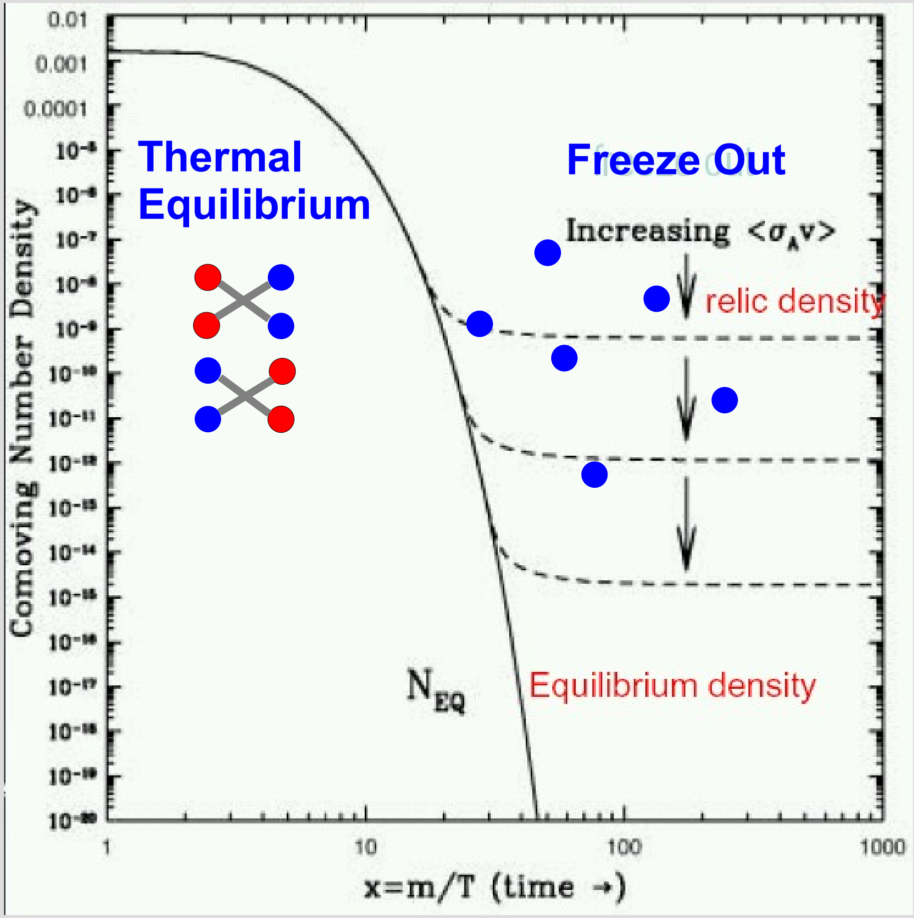
$$p(E) \propto \exp\left(-\frac{E}{k_B T}\right)$$

expanding Universe: „freeze out“

WIMPs fall out of equilibrium, cannot annihilate anymore

$$k_B T \sim \frac{m_\chi c^2}{20}$$

→ non relativistic when decoupling from thermal plasma
→ constant DM relic density
→ relic density depends on σ_A



WIMP relic density:

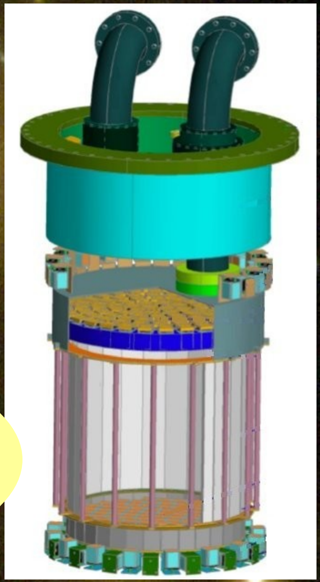
$$\Omega_\chi h^2 \approx \text{const.} \frac{T_0^3}{M_{Pl}^3 \langle \sigma_A v \rangle} \approx \frac{0.1\text{pb}}{\langle \sigma_A \; v/c \rangle}$$

O(1) when σ_A~10^{-9} GeV → weak scale

Outline

- Motivation: Dark Matter ✓
- Direct Dark Matter Detection
- Xenon as a Detector Medium
- XENON100
- The Future

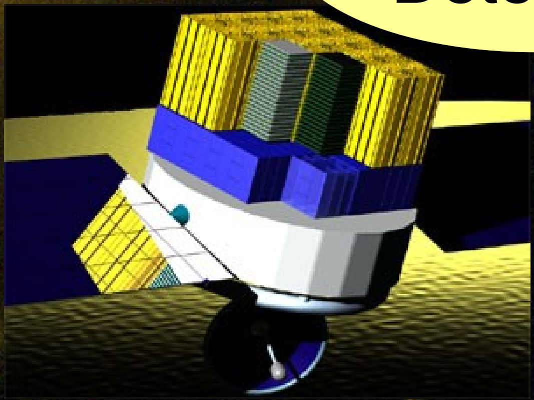
Dark Matter Search

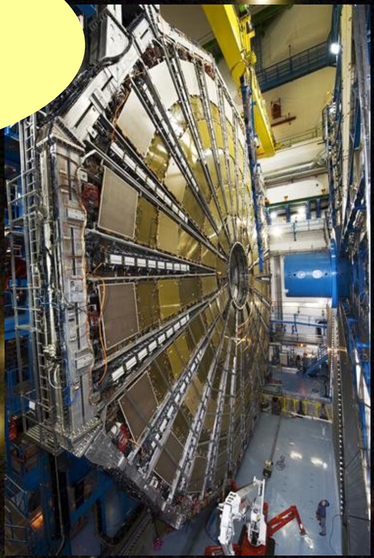


Direct Detection

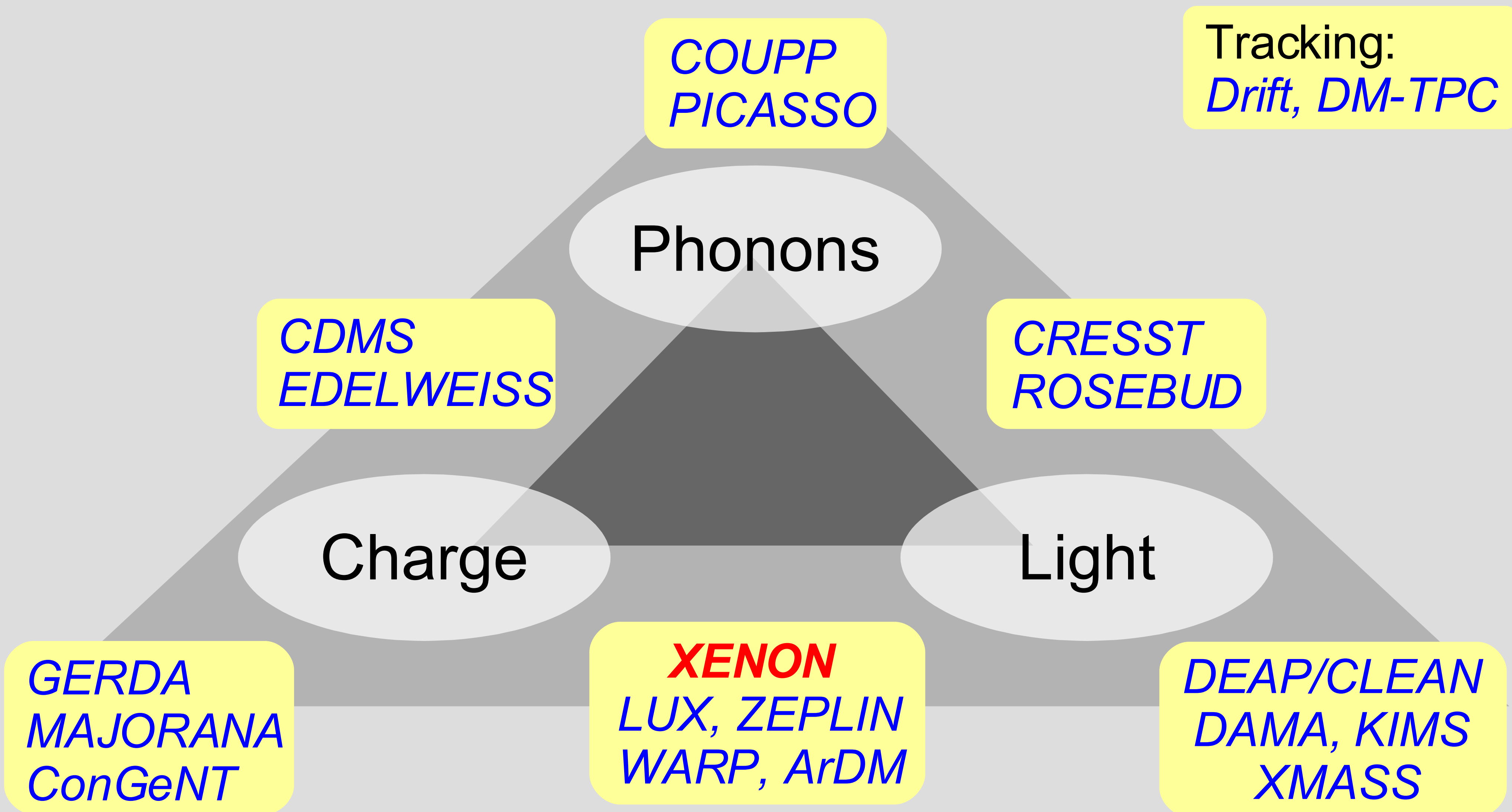
Indirect Detection

Production @Collider



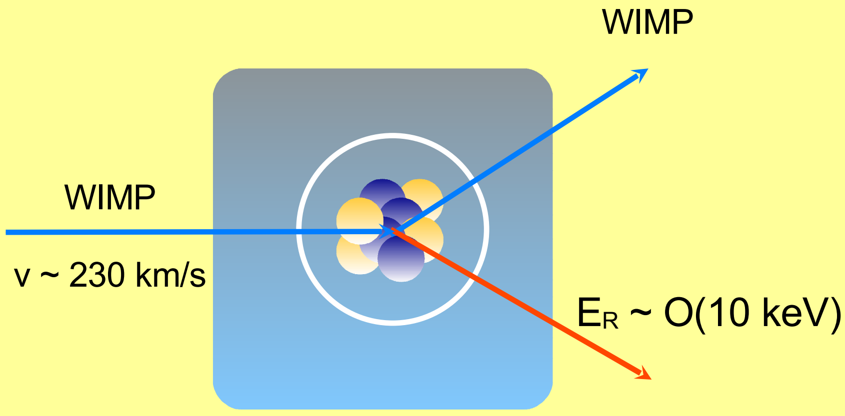


Direct WIMP Detection



Direct WIMP Search

Elastic Scattering of
WIMPs off target nuclei
→ nuclear recoil



Recoil Energy: $$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \sim \mathcal{O}(10\ \mathrm{keV})$$

Event Rate: $$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$$

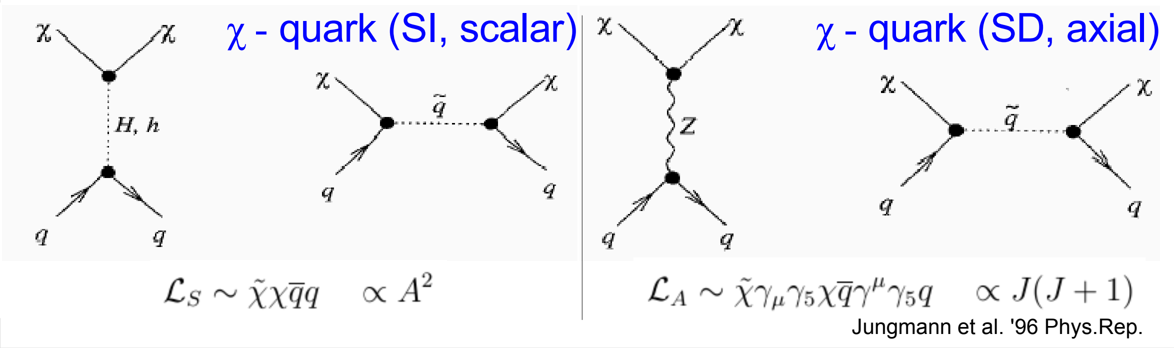
N	number of target nuclei
ρ_χ/m_χ	local WIMP density
$\langle\sigma\rangle$	velocity-averaged scatt. X-section

→ need information on halo and interaction to get rate

WIMP Interactions
Detector Requirements

Result: Tiny Rates

$R < 0.01$ evt/kg/day
$E_r < 100$ keV

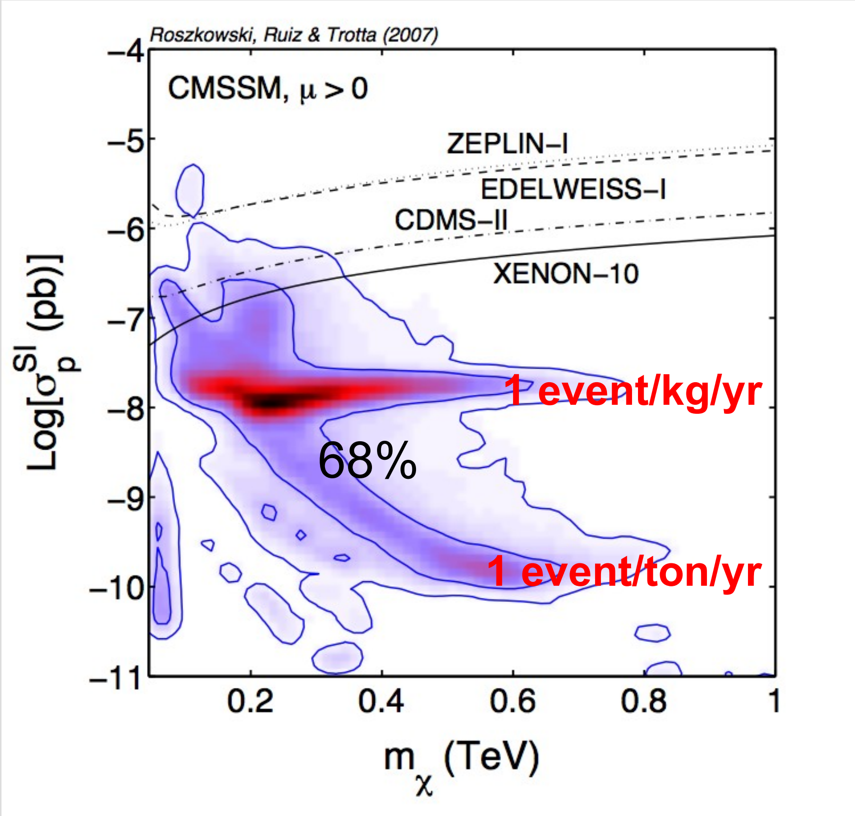


What do we look for?

- nuclear recoils, single scatters
- recoil spectrum falls with *E*
- dependence on *A*, spin?
- annual flux modulation?
- other possibilities? iDM, ...?

How to build a WIMP detector?

- large total mass, high *A*
- low energy threshold
- ultra low background
- good background discrimination



Backgrounds

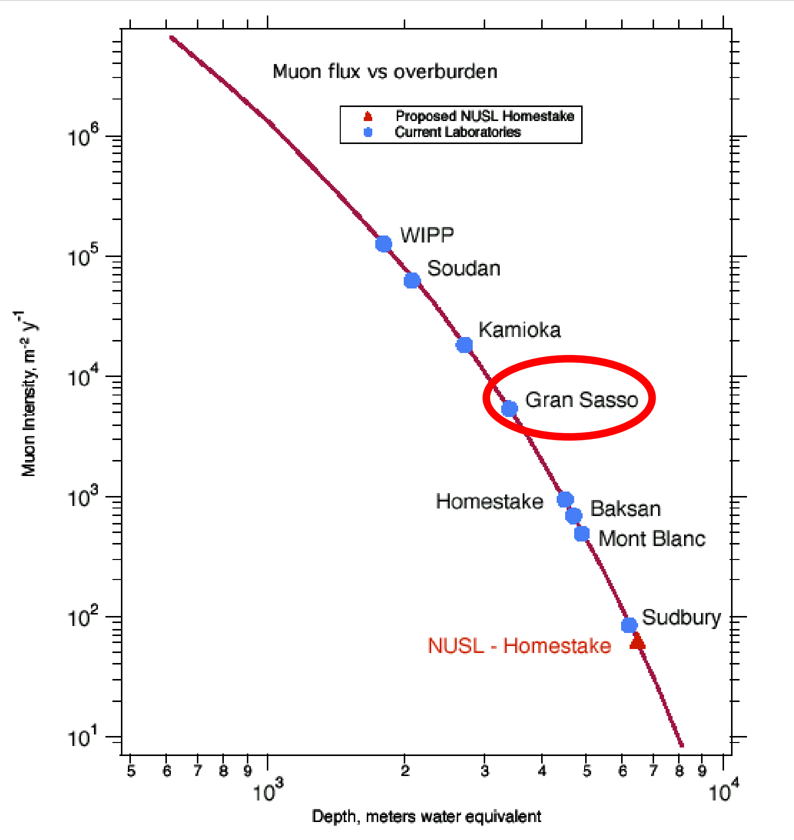
Experimental Sensitivity:
without background: $\propto (mt)^{-1}$
with background : $\propto (mt)^{-1/2}$

Background Sources:
environment: U, Th chains, K

$^{238}U \xrightarrow{\alpha} {}^{234}Th \xrightarrow{\beta} {}^{234m}Pa \xrightarrow{\beta} {}^{234}U \xrightarrow{\alpha} {}^{230}Th \xrightarrow{\alpha} {}^{226}Ra \xrightarrow{\alpha} {}^{222}Rn \xrightarrow{\alpha} {}^{218}Po \ldots$

$^{232}Th \xrightarrow{\alpha} {}^{228}Ra \xrightarrow{\beta} {}^{228m}Ac \xrightarrow{\beta} {}^{228}Th \xrightarrow{\alpha} {}^{224}Ra \xrightarrow{\alpha} {}^{220}Rn \xrightarrow{\alpha} {}^{216}Po \ldots$

- Gamma and Beta Decays (electron recoil)
  careful material selection, discrimination, shielding (Pb, Cu, Xe, Ar, water)
- Neutrons from (α,n) in rocks
  neutron moderators (paraffin, poly)
- Neutrons from cosmic ray muons
  go deep underground

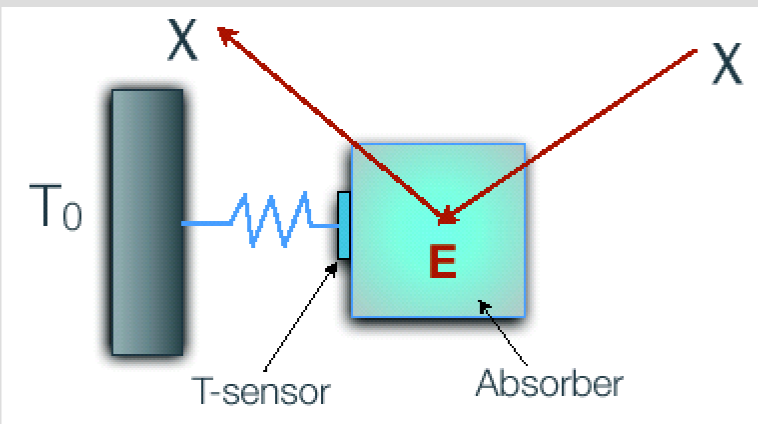


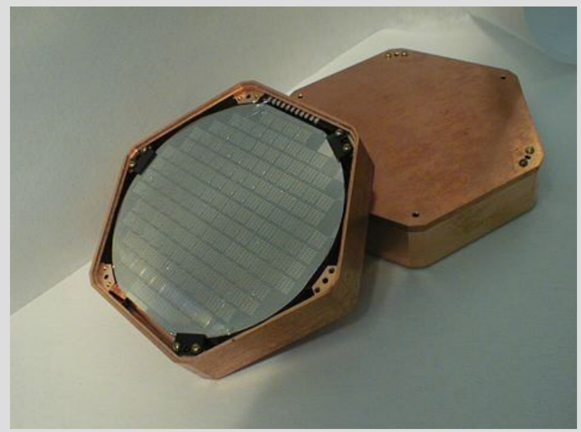
Neutrons are most dangerous background since they interact like WIMPS! (nuclear recoil)

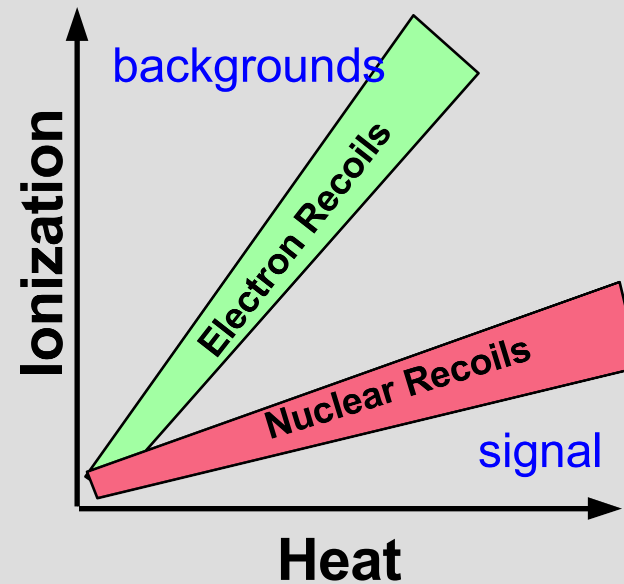
CDMS: Cryogenic Detectors

Located underground in Soudan Lab, Minnesota (USA)

Principle: measure charge and heat (phonons)
a deposited energy *E* produces temperature rise *ΔT*







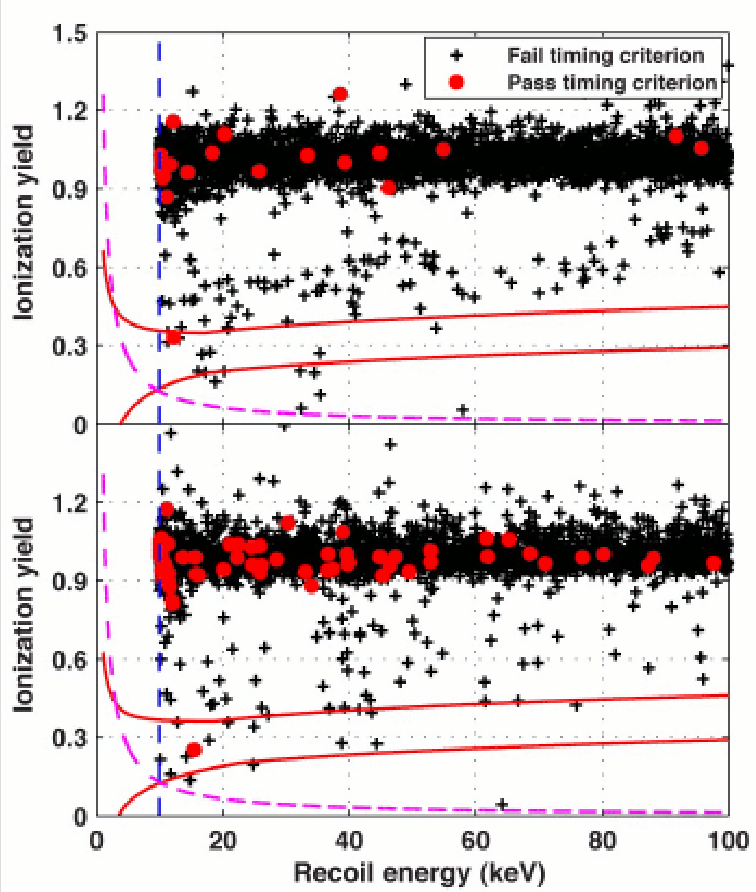
Crystals: Ge, Si cooled to few mK
➡ low heat capacity
➡ measurable µK temperature!

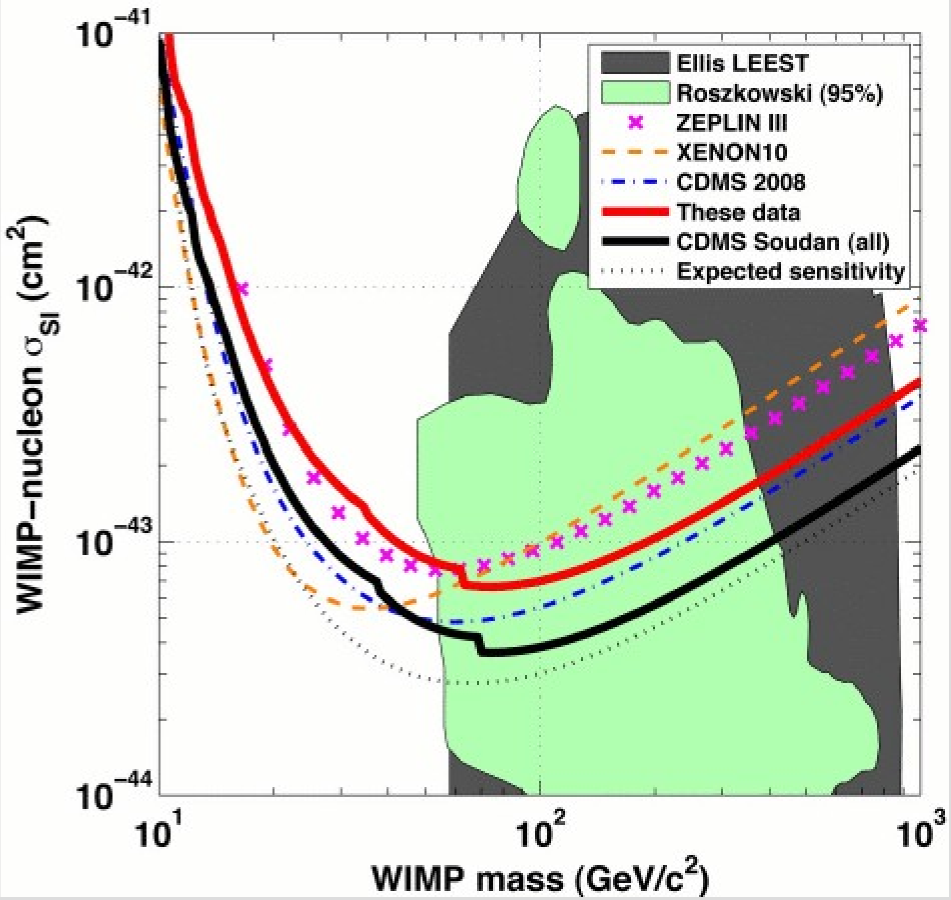
good discrimination
→ „backgound-free experiment“
→ BUT: reject surface events via PSA

similar: CRESST, EDELWEISS, Rosebud

The latest CDMS Result

Science 327, 1619 (2010)

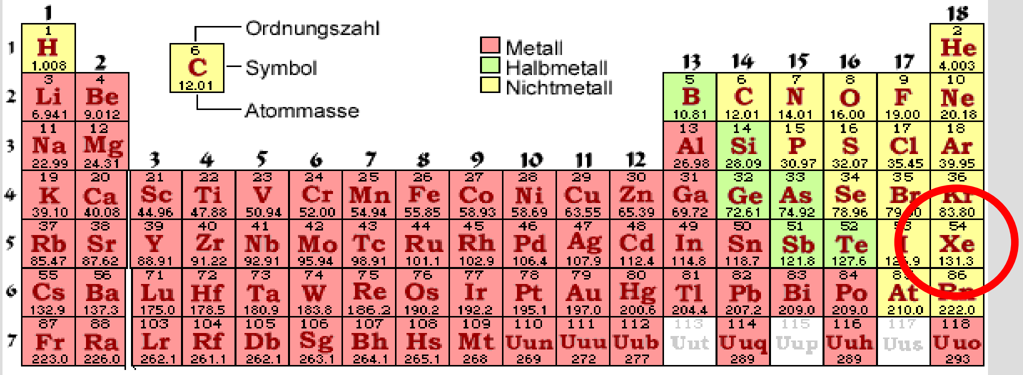


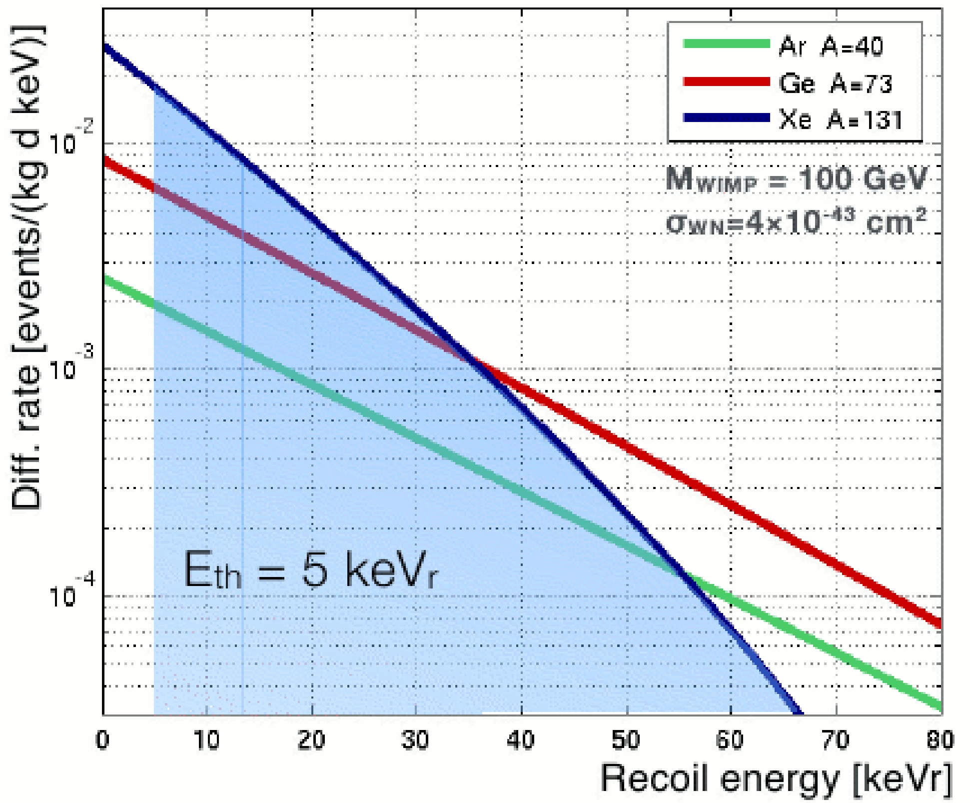


- 2 events remain after all cuts after un-blinding
- Background expection: 0.9 ± 0.2 events
- probability for 2 or more events: 23%

Why Xenon?

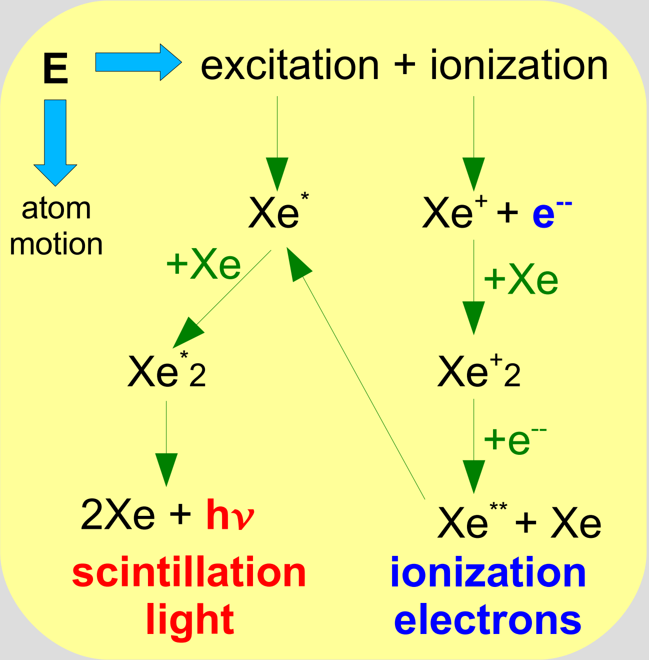
- efficient, fast scintillator (178nm)
- high mass number *A*~131:
  SI: high WIMP rate @ low theshold
- high atomic number *Z*=54,
  high density (~3kg/l):
  self shielding, compact detector
- SD: 50% odd isotopes
  allows further characterization after detection by testing only SI or SD
- no long lived Xe isotopes,
  Kr-85 can be removed to ppt
- "easy" cryogenics @ -100°C
- scalability to larger detectors
- in 2-phase TPC:
  good background discrimination

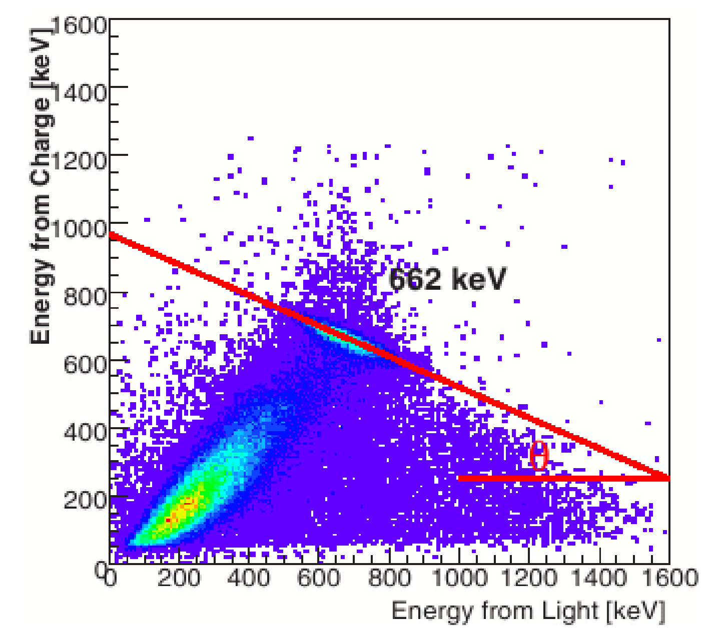


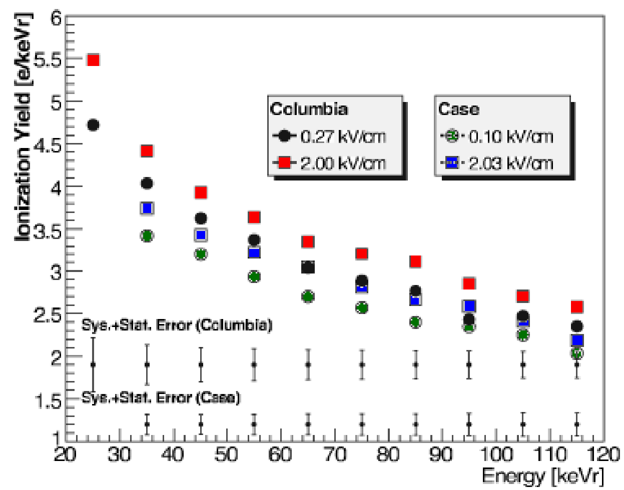


Xenon: Light and Charge

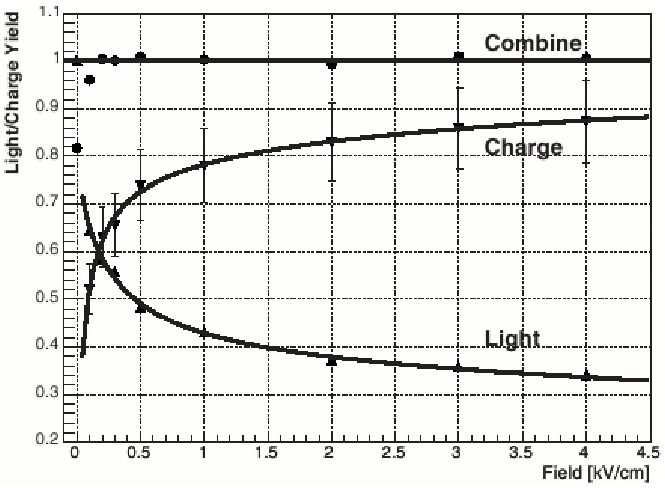
- energy deposited in LXe produces *electron-ion pairs* and *excited atom states*; both processes can lead to scintillation
- anti-correlation between charge and light
  ➡ improvement of energy resolution possible
- E-field dependence (field quenching)
- response also depends on particle energy







from: *Aprile et al., PRL 97, 081302 (2006)*



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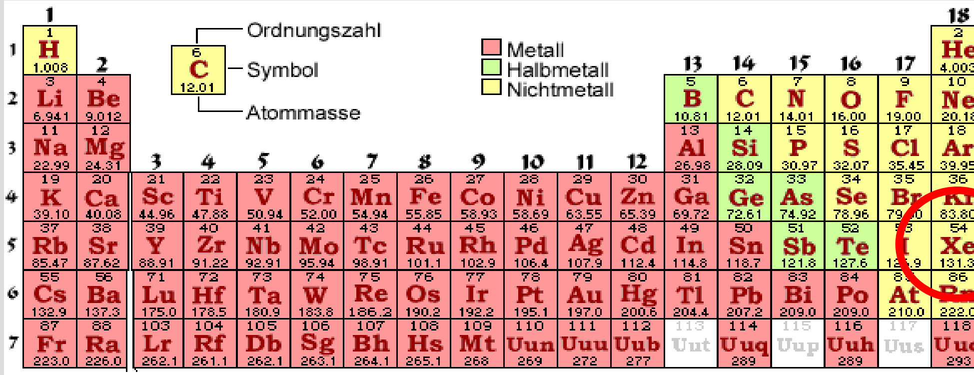
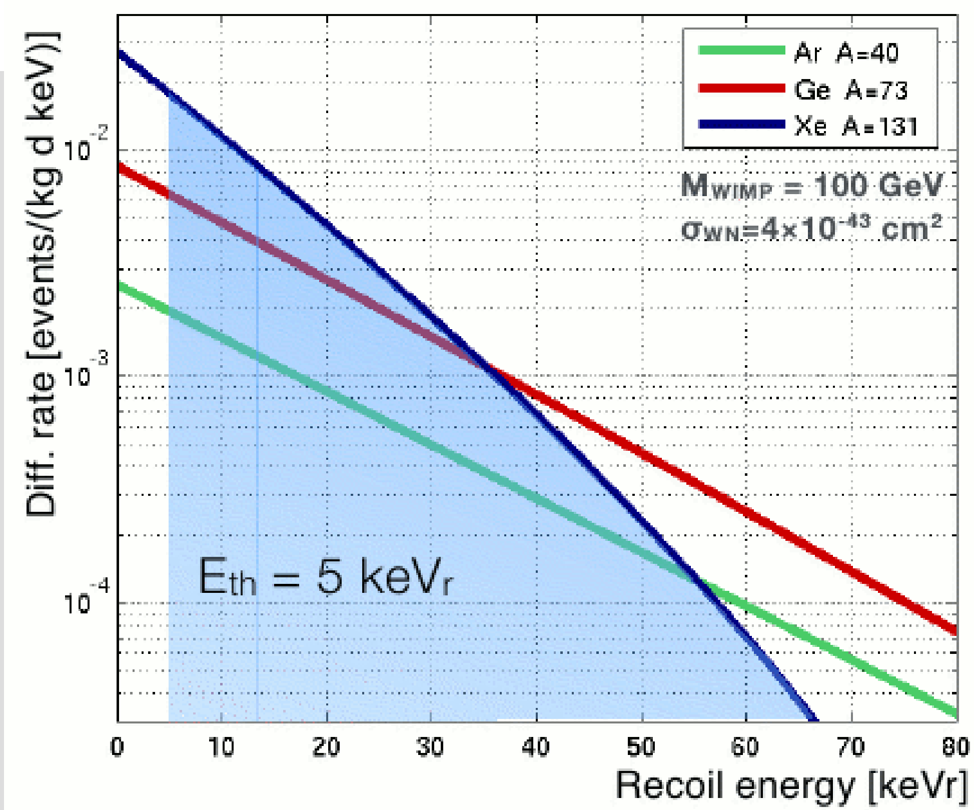
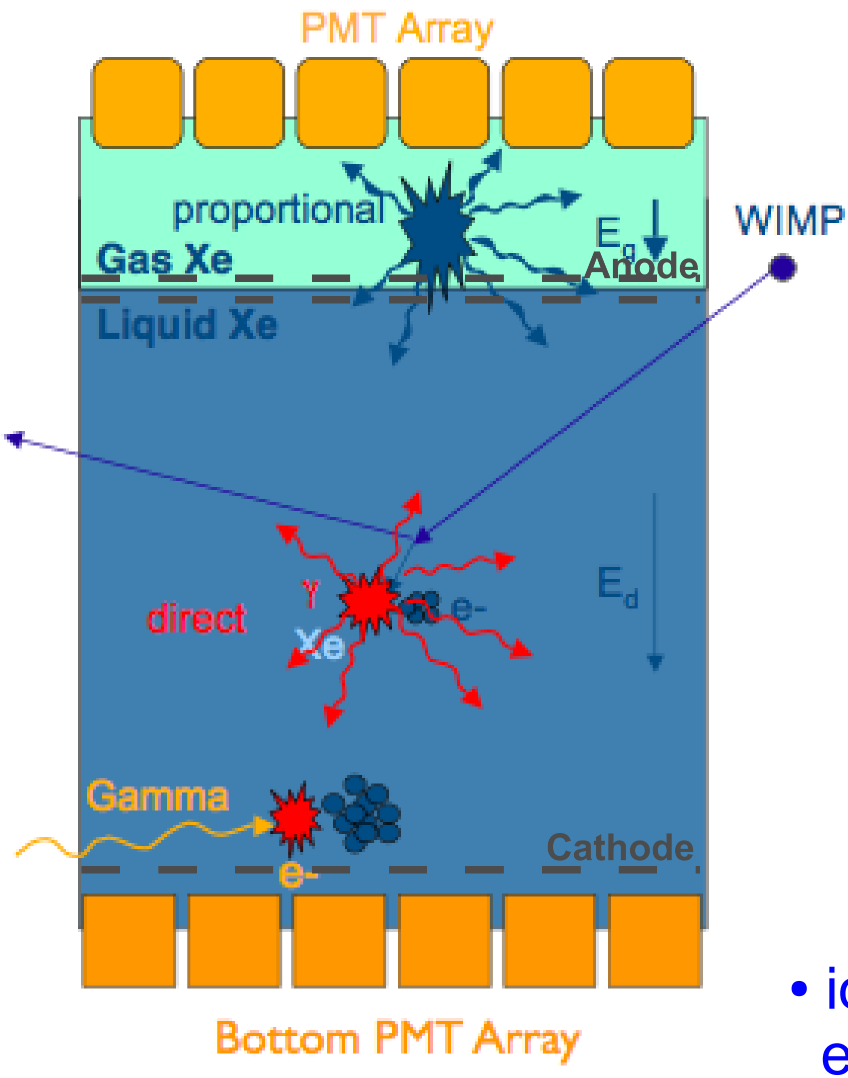
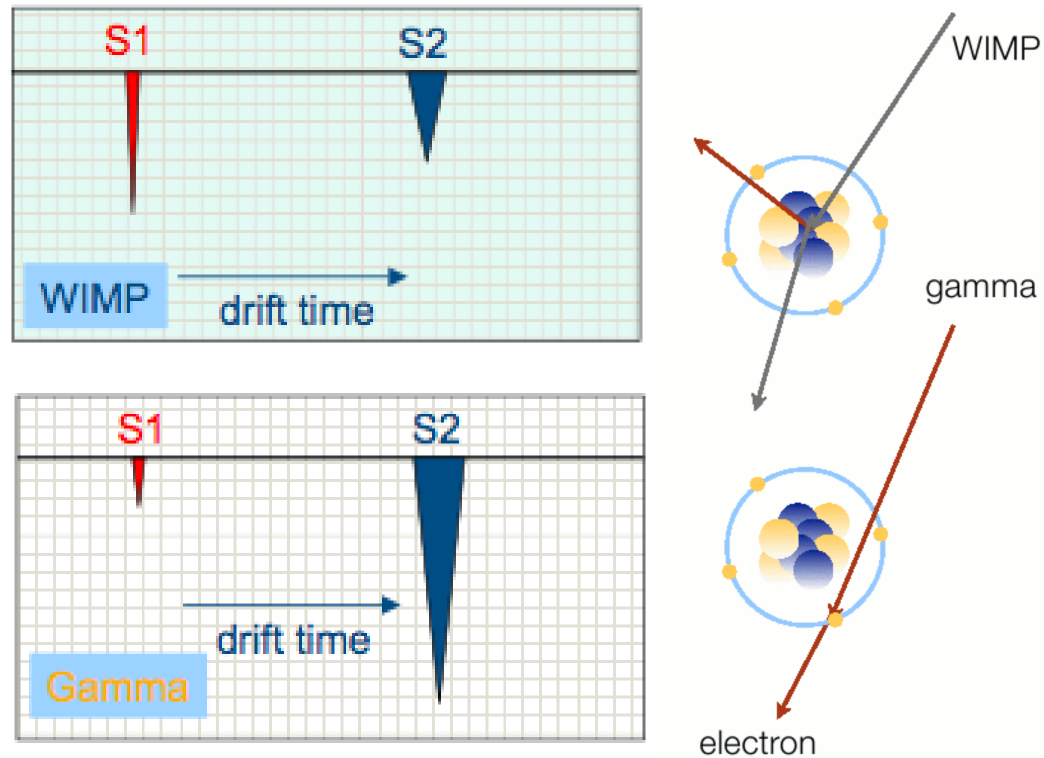




Dual Phase TPC

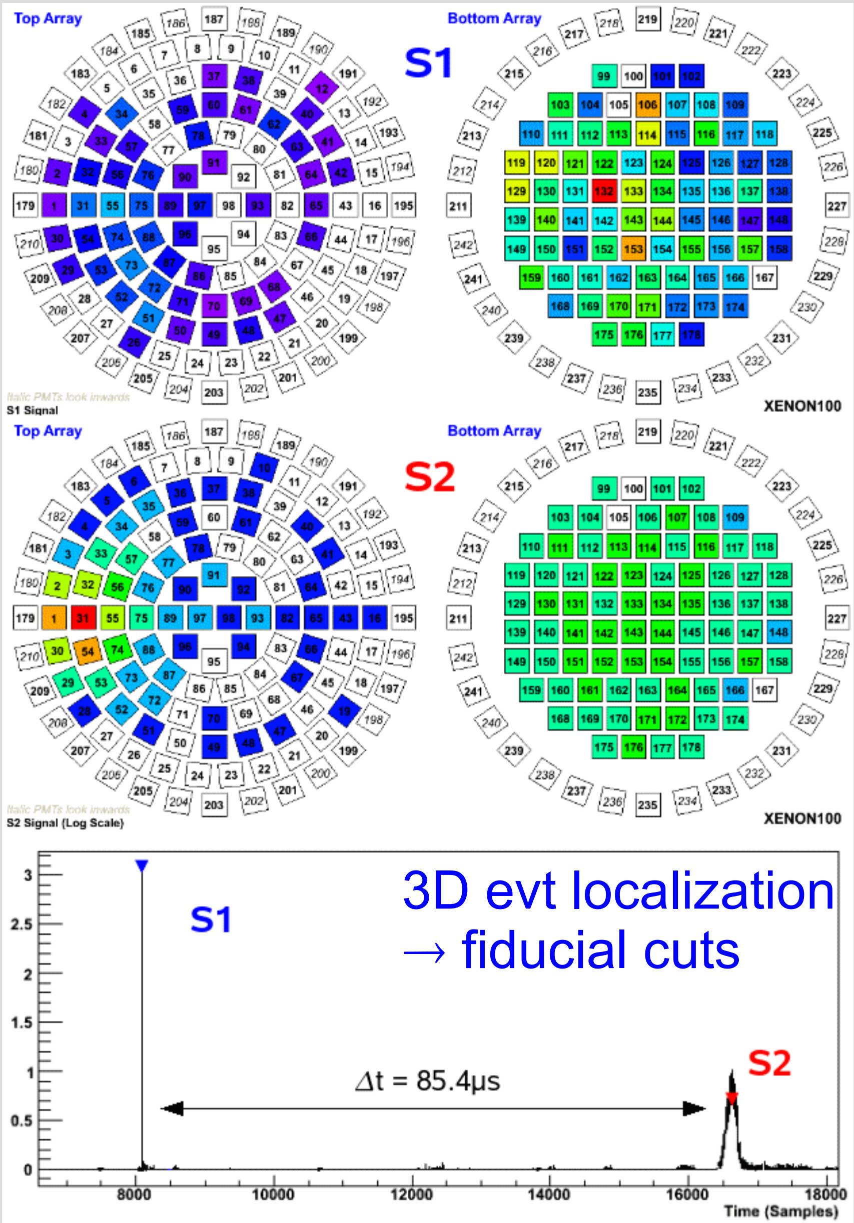




$(S2/S1)_{wimp} \ll (S2/S1)_{gamma}$

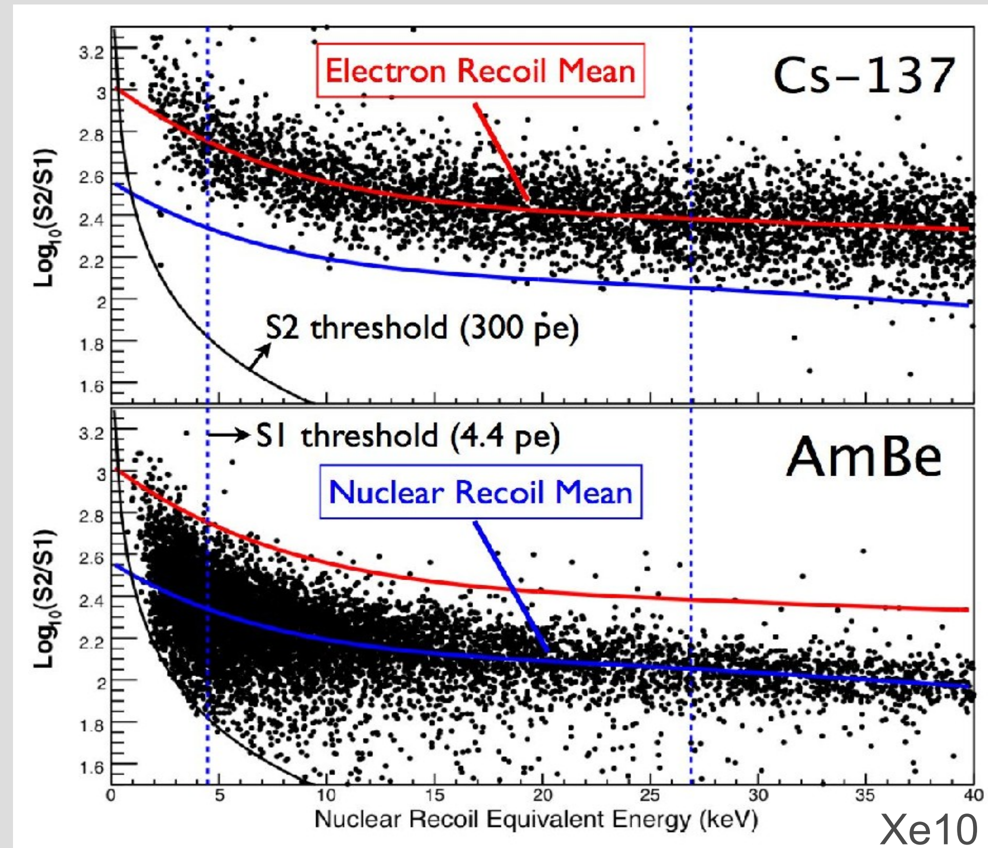
- ionization/scintillation ratio (S2/S1) allows electron recoil rejection to >99.5%
- 3d position reconstruction in TPC

Localization / Discrimination



3D evt localization
→ fiducial cuts

Discrimination:



99.5% bg rejection (99.9% at low *E*),
50% acceptance *(Xe10 performance)*
definition of *WIMP search region*

Outline

Motivation: Dark Matter ✓

Direct Dark Matter Detection ✓

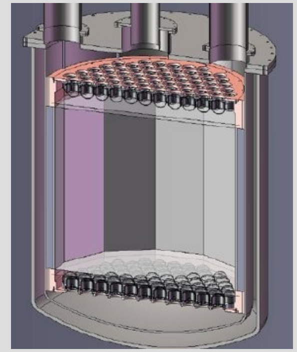
Xenon as a Detector Medium ✓

XENON100

The Future

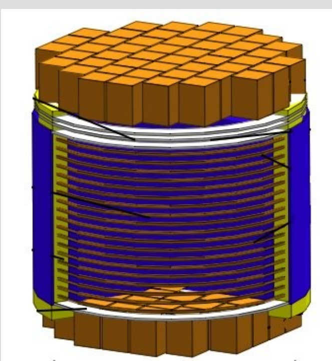
The XENON program

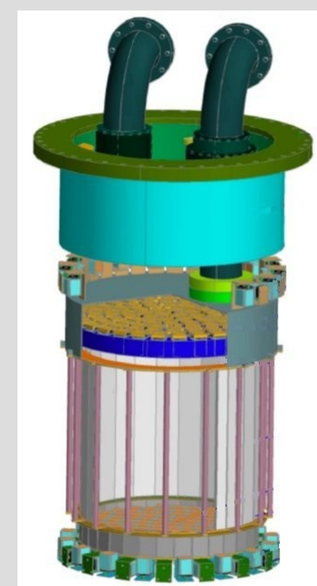
XENON:
A phased WIMP search program



2010-2015: XENON1T

2007-2010: XENON100





2005-2007: XENON10

XENON R&D

XENON100 Collaboration

Columbia · Rice · UCLA · U Zürich · Coimbra · LNGS

~45 people

+ new groups:

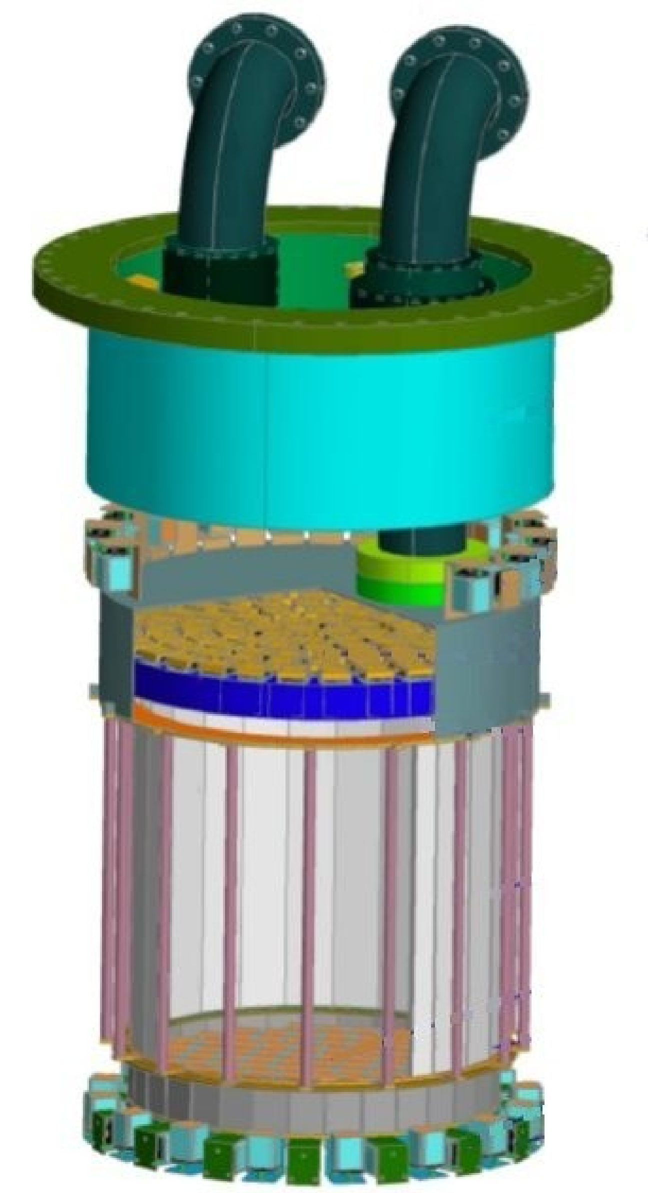
Münster · Subatech (F)
Bologna · Shanghai
NIKHEF · MPIK Heidelberg

XENON100

Goal:
- increase target × 10
- reduce gamma background 100 ×

→ material selection & screening
→ detector design

Quick Facts:
- 165 kg LXe TPC (mass: 10 × Xe10)
- ~50 kg in fiducial volume
- active LXe veto (≥4 cm)
- 242 PMTs
- improved Xe10 shield
  (Pb, Poly, Cu, H_2O, N_2 purge)



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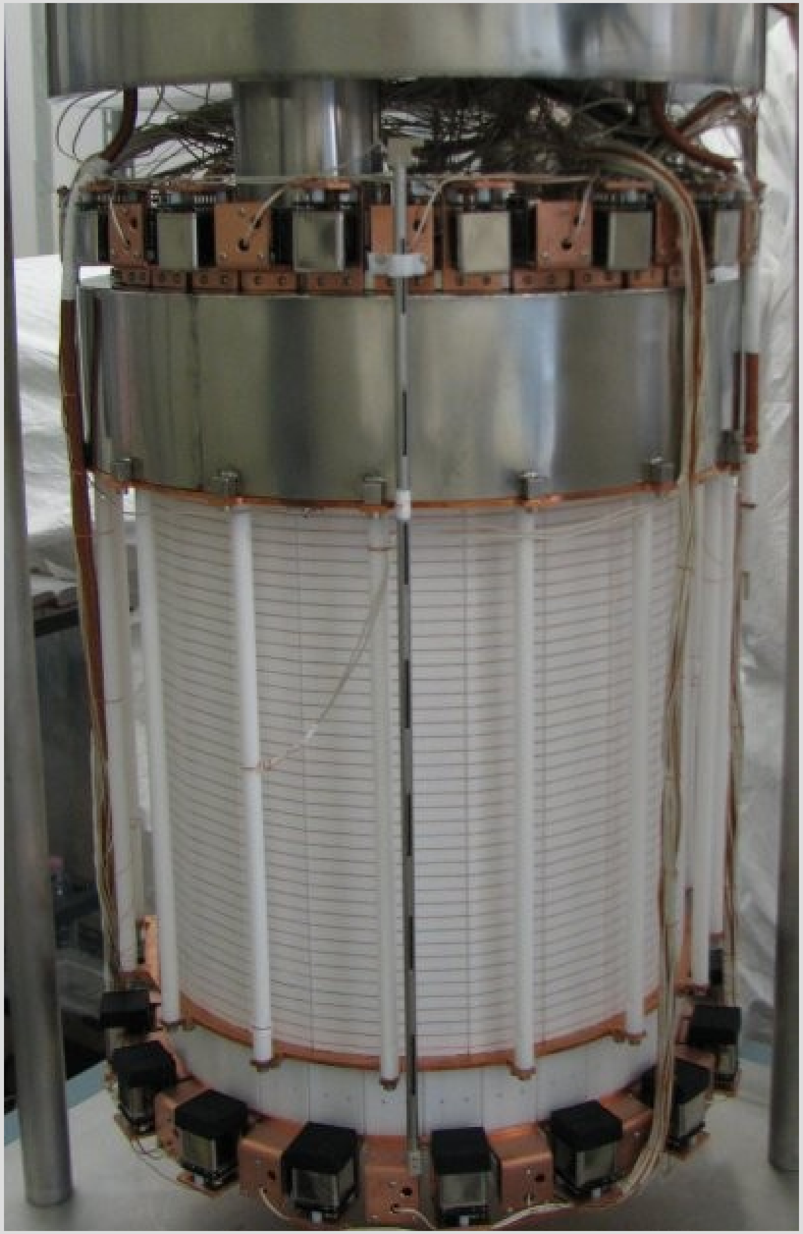

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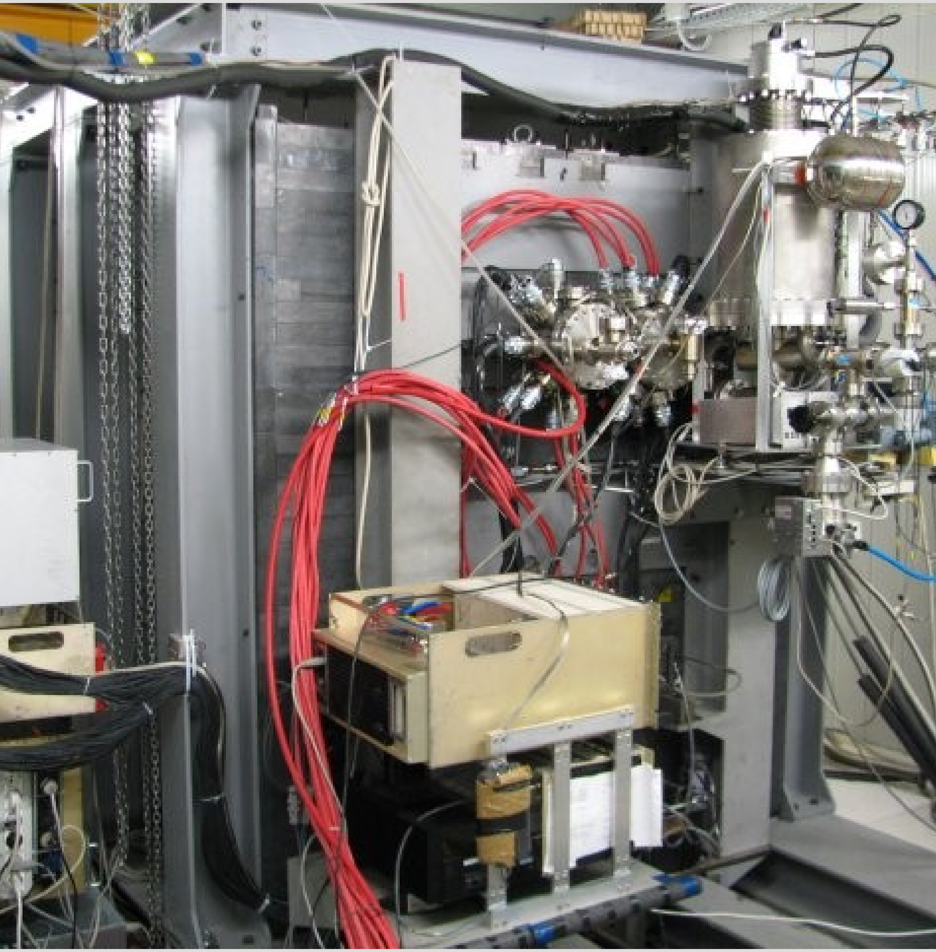
XENON100 @ LNGS



underground since end of February 08

first filled with Xe in mid May 08

detector fully operational, taking science data

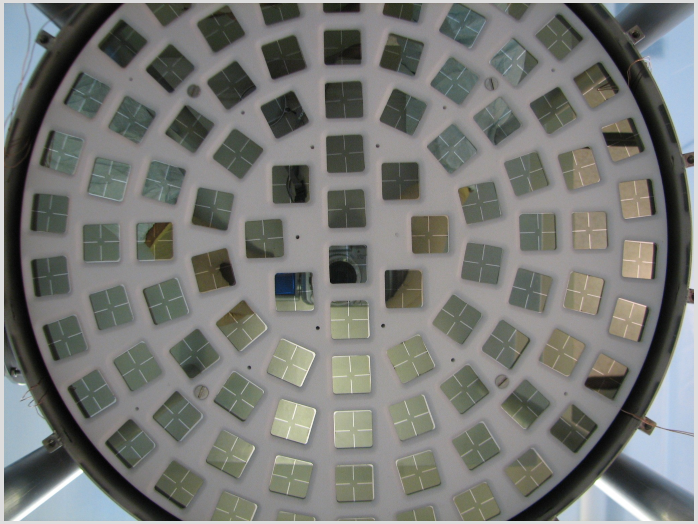
Site (Multiple levels given in ft) (from: R. Gaitskell)	Relative Muon Flux	Relative Neutron Flux T>10 MeV
WIPP (2130 ft) (1500 mwe)	x 65	x 45
Soudan (2070 mwe)	x 30	x 25
Kamioke	x 12	x 11
Boulby	x 4	x 4
Gran Sasso (3700 mwe) Frejus (4000 mwe), Homestake (4860 ft)	x 1	x 1
Mont Blanc	x 6^{-1}	x 6^{-1}
Sudbury	x 25^{-1}	x 25^{-1}
Homestake (8200 ft)	x 50^{-1}	x 50^{-1}

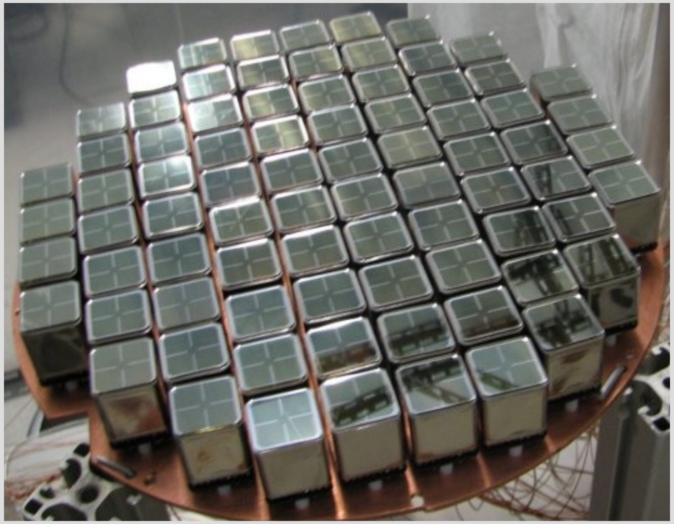
Photosensors

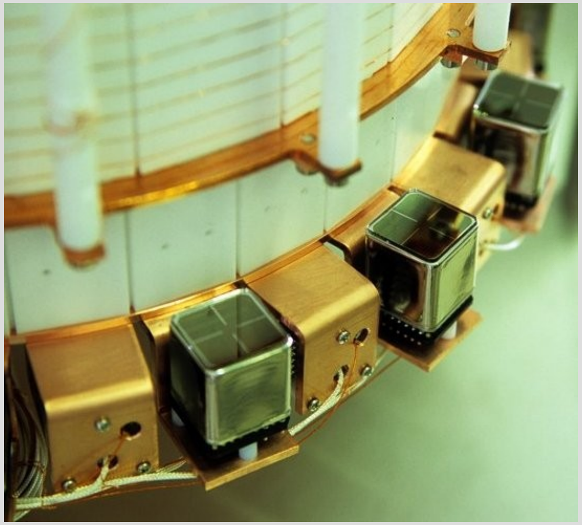
242 Hamamatsu R8520 PMTs

1"x1", optimized for response @ Xe scintillation wavelength
low radioactivity (>10 mBq/PMT)
80 with high QE ~35%

98 in top array:	arranged for good fiducial cut efficiency
80 in bottom array:	optimized for S1 collection → low threshold
64 in active veto:	gain factor 3-4 compared to passive shield

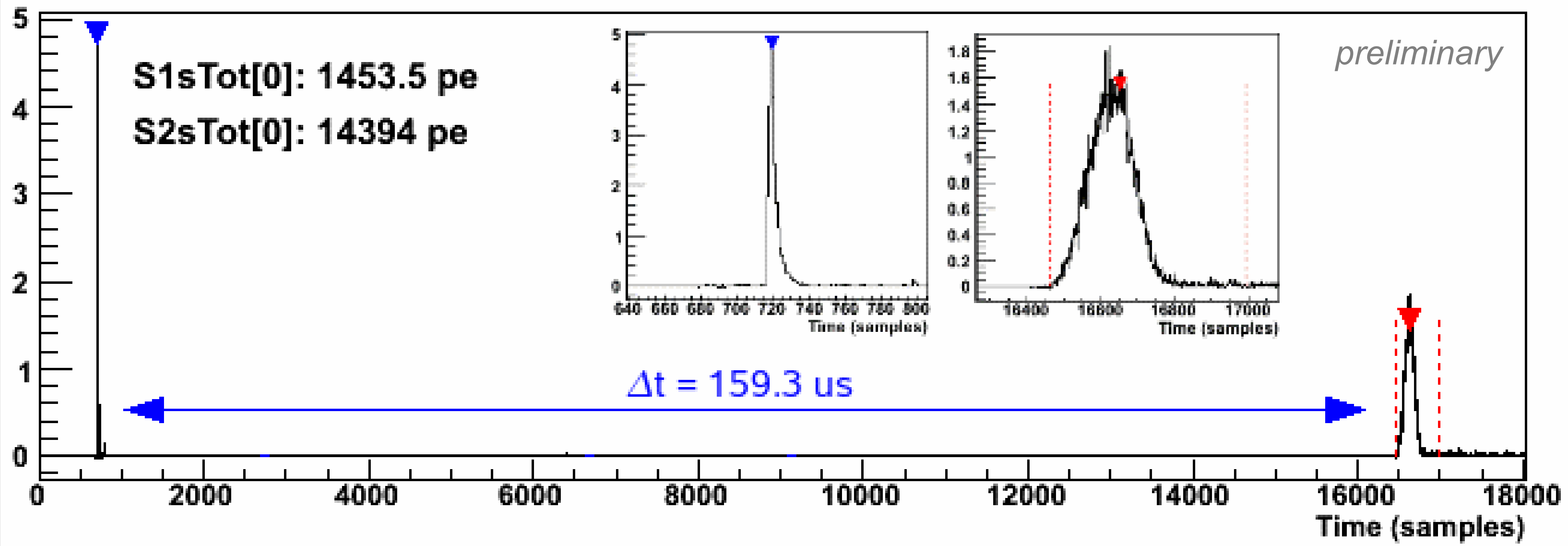




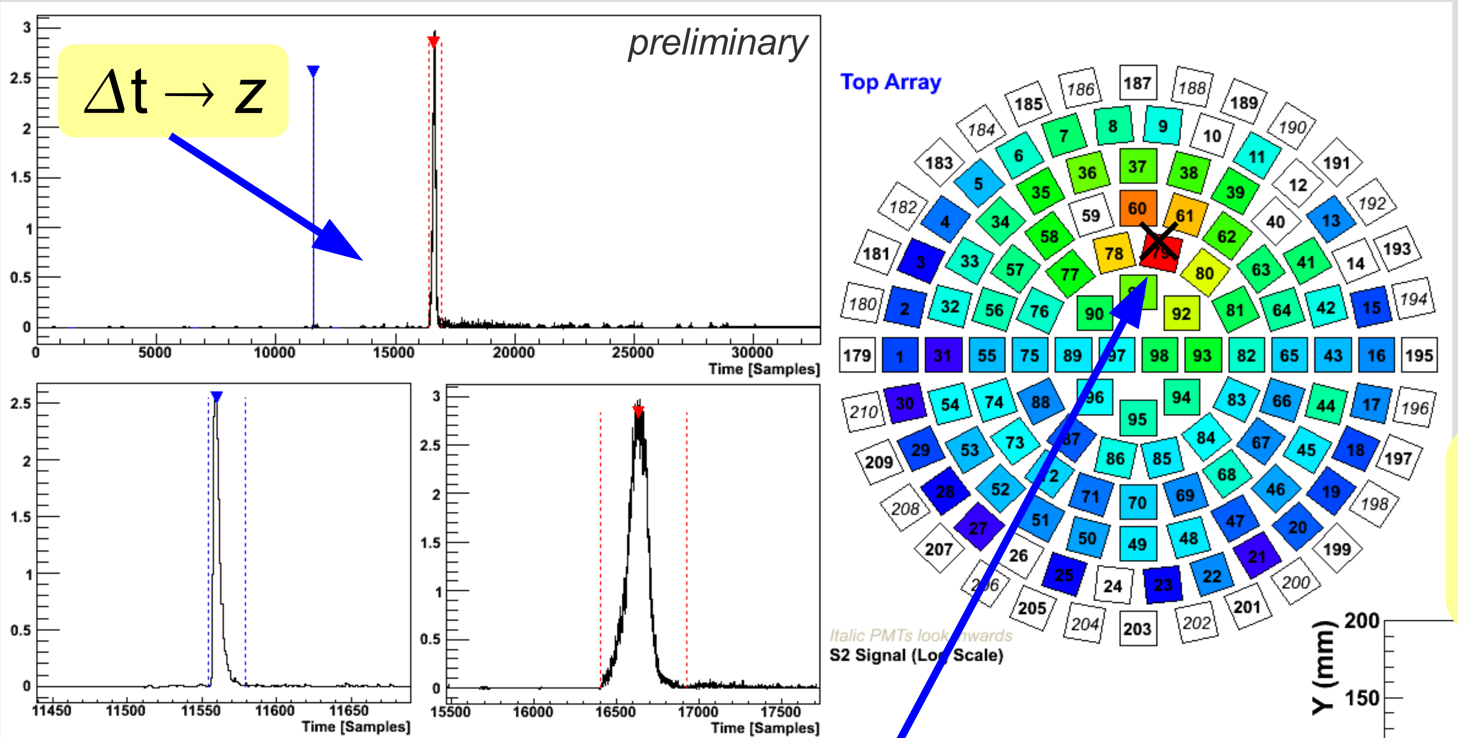


TPC is transparent...

we can see events from all parts of the TPC...



3D-Vertex Reconstruction

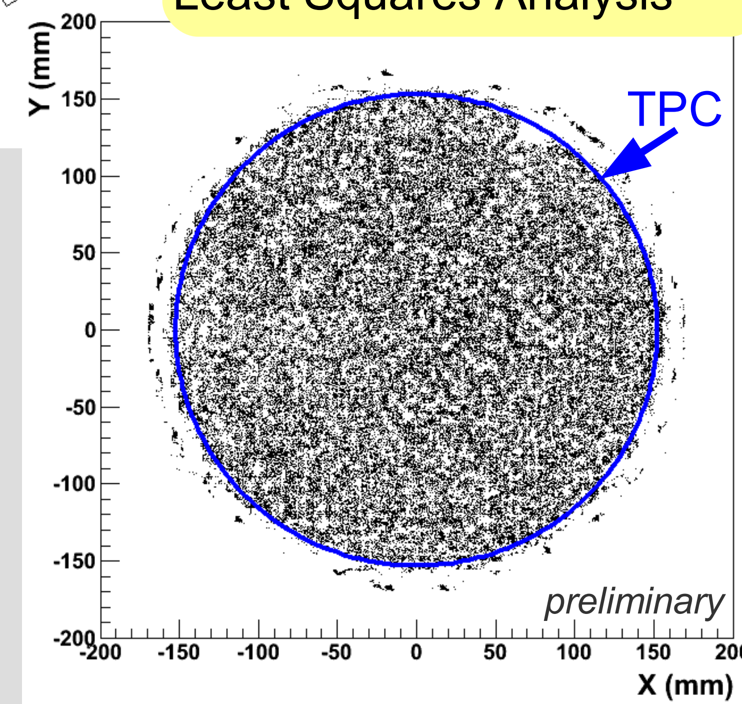


$\Delta t \rightarrow z$

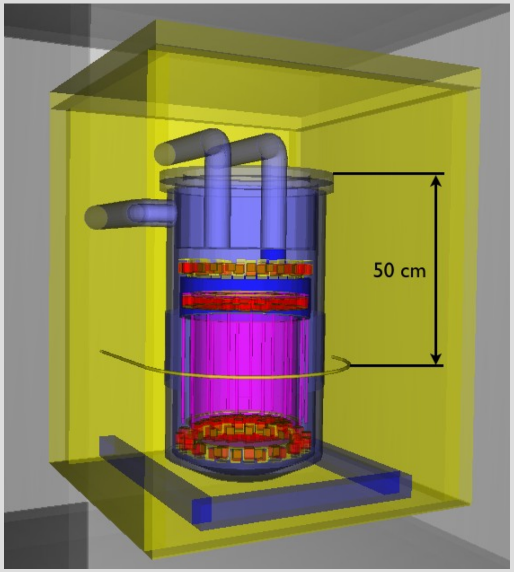
S2 *xy*-Position Reconstruction:
- Least Squares Minimization
- Neural Network
- Support Vector Machine

Resolution O(mm)
(measured and from MC)

Positions of real S2s
uniform Cs137 illumination
Least Squares Analysis



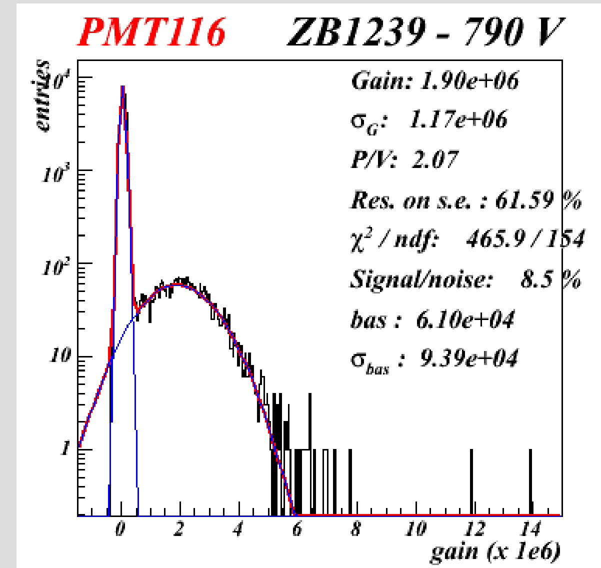
Calibration

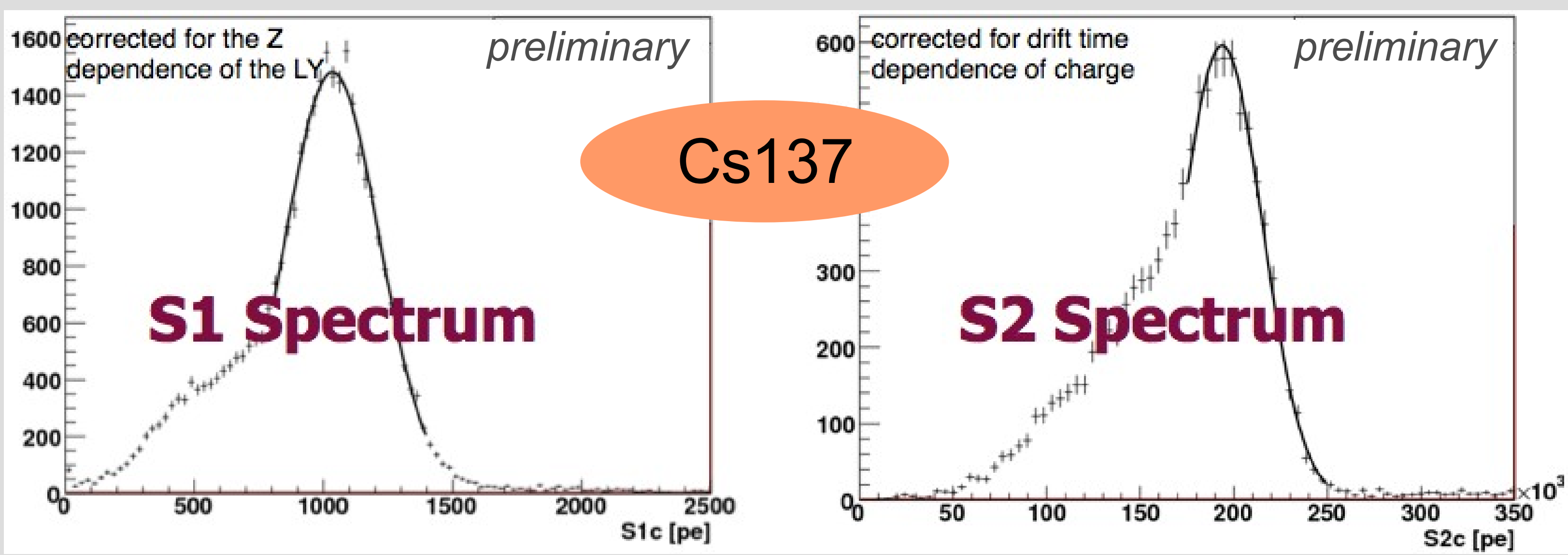


Gain calibration:
blue LED (+optical fibers)

γ-sources (ER band):
Co-57, Co-60, Cs-137, Th-228, Xe*, Kr-83m

Neutrons (NR band):
AmBe





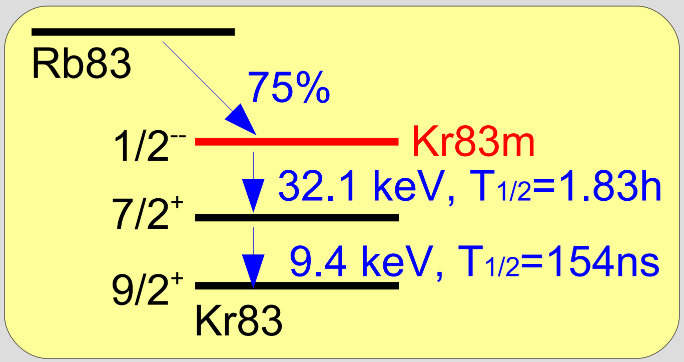
Calibration at low Energy

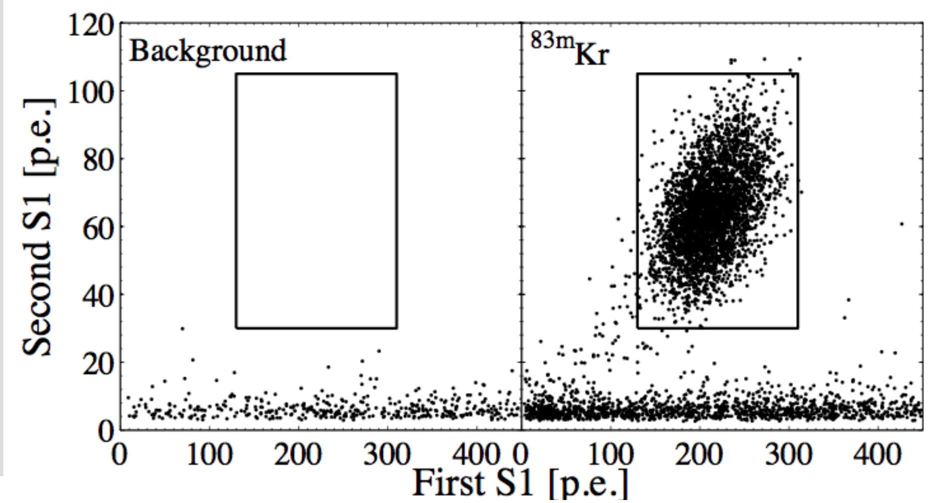
expect signal <40 keV (calibration from outside not possible)

⇨ n-activated Xe131, Xe129m

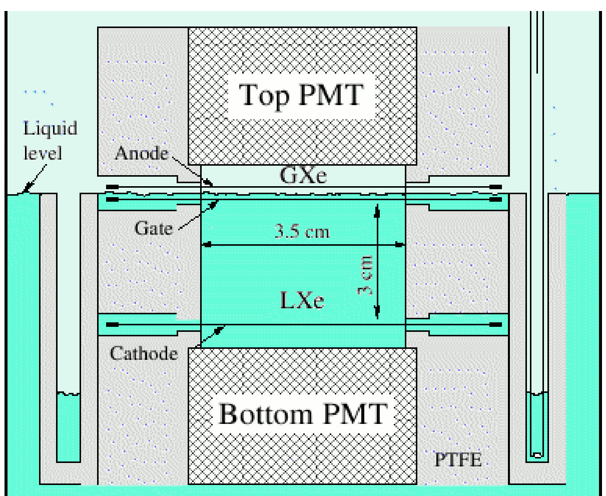
was used for Xe10, τ~O(10d)

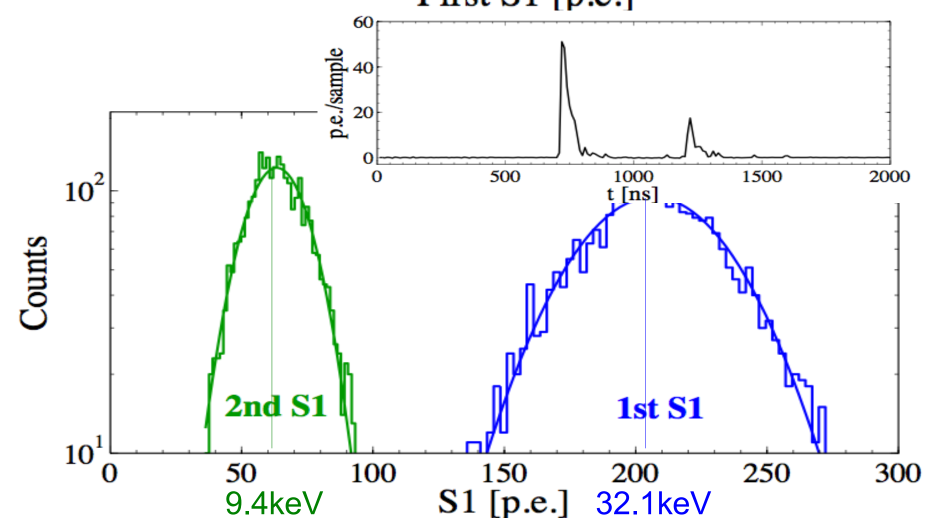
⇨ Kr83m





R&D in Zürich:





Manalaysay et al., arXiv:0908.0616

Calibration at low Energy

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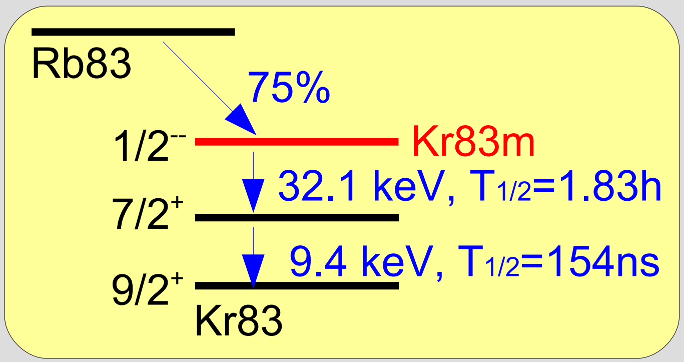
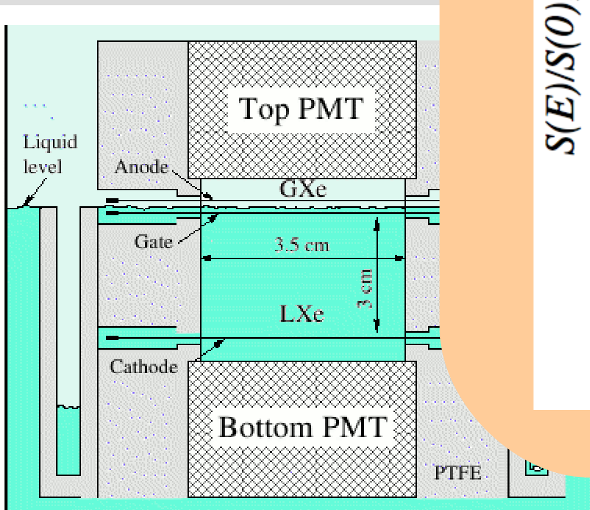
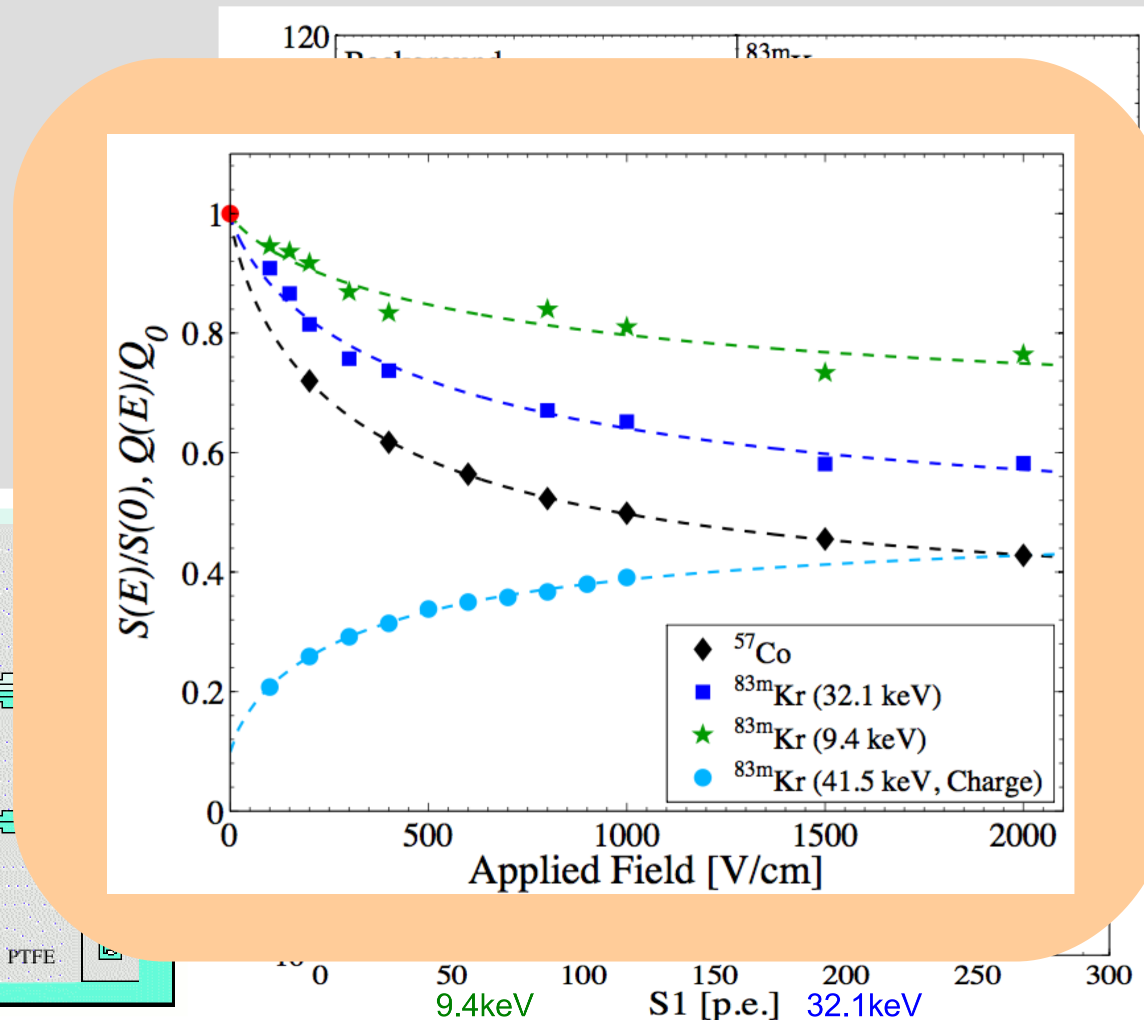


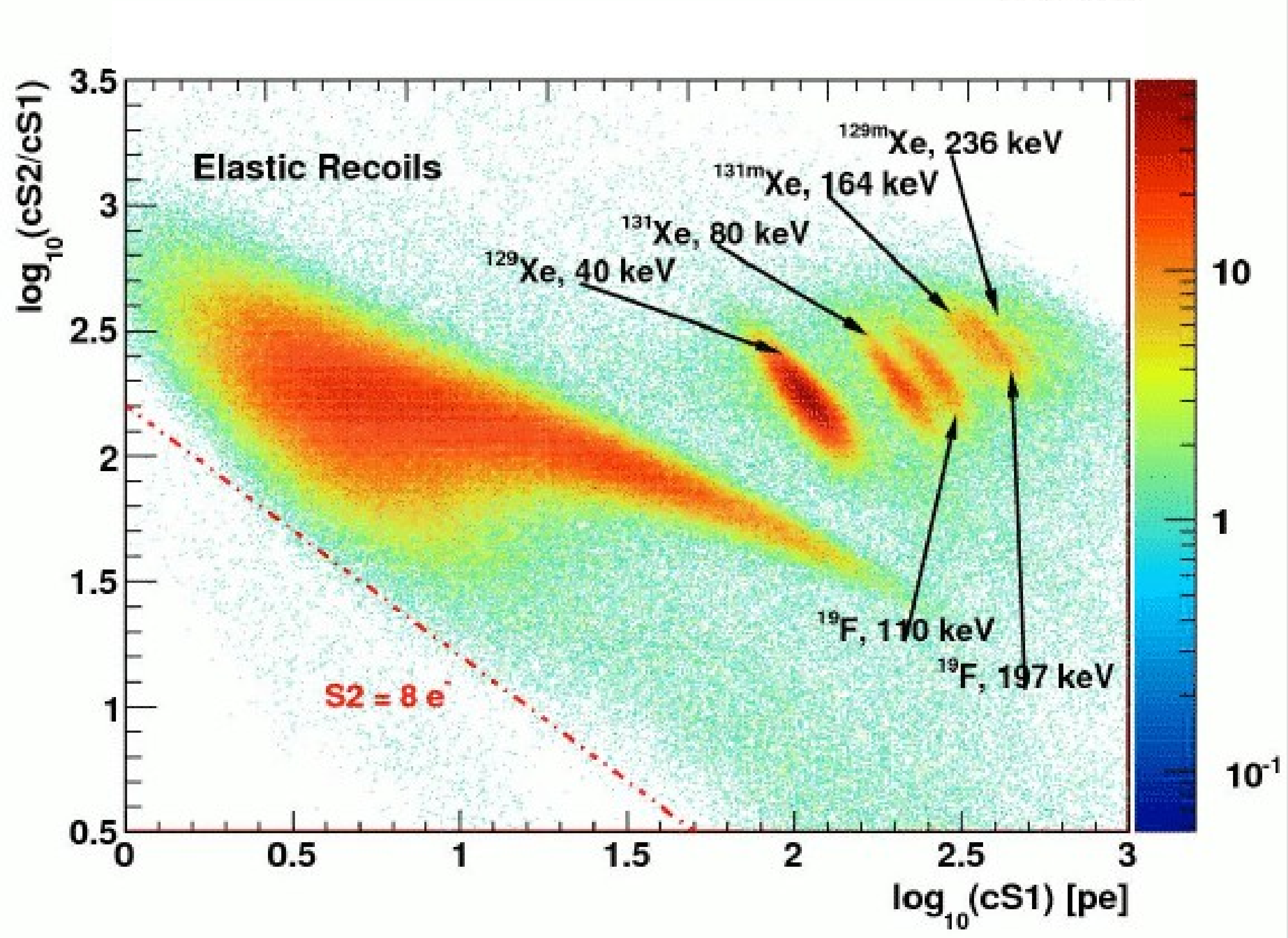
R&D in Zürich:



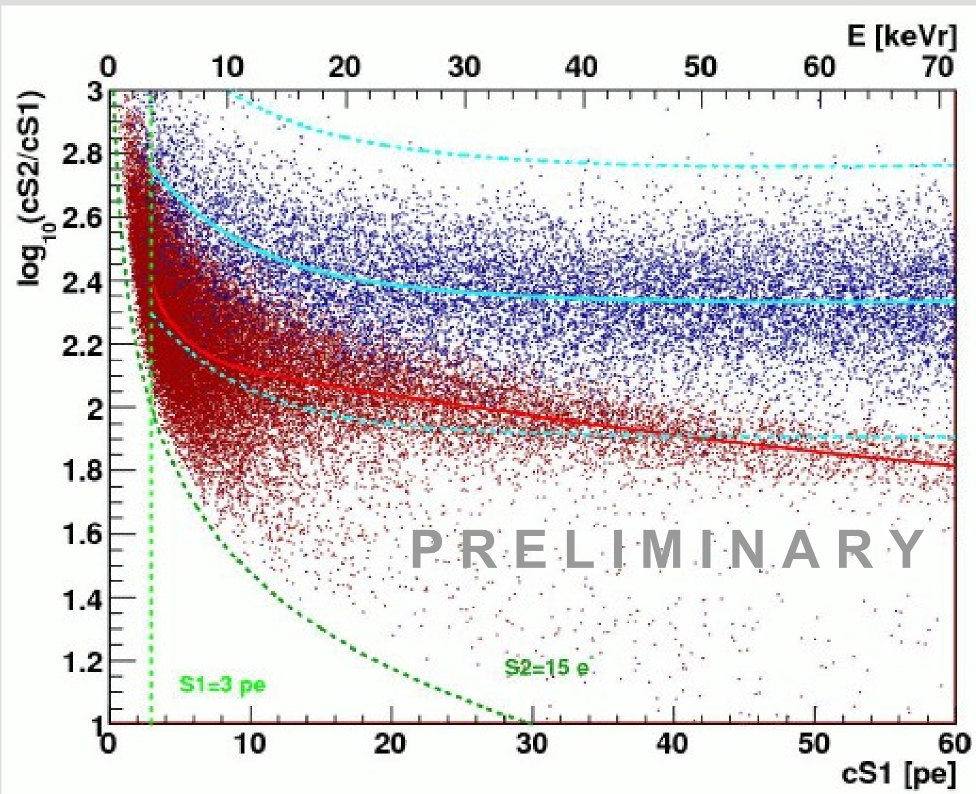


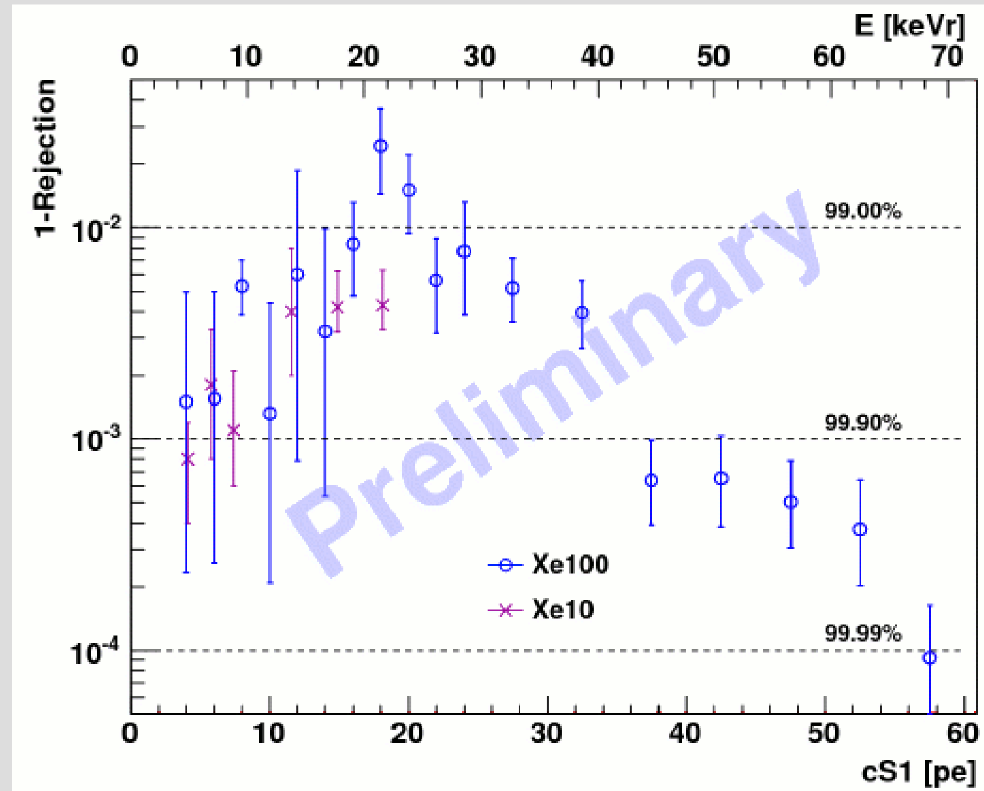
Manalaysay et al., arXiv:0908.0616

Calibration of the NR Band



ER/NR Discrimination

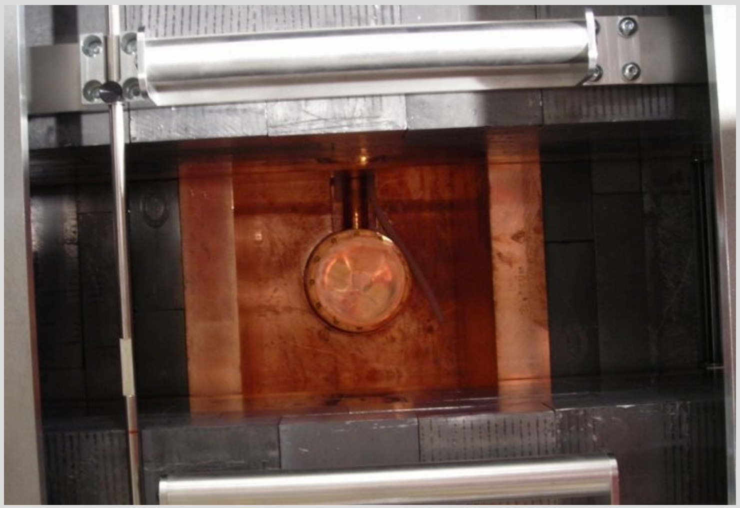


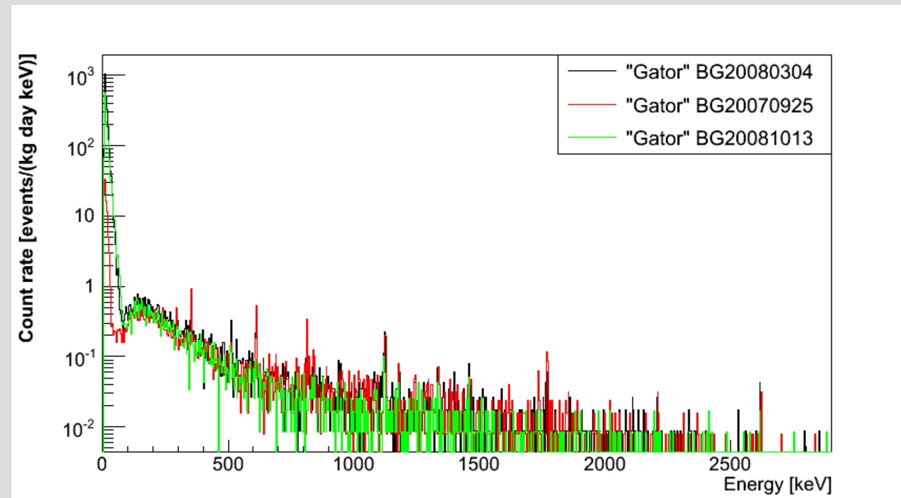


- ER/NR discrimination via S2/S1 ratio
- Dicrimination efficiency similar to XENON10 (>99%)

Material Screening

GATOR: 2.2kg high purity Ge detector
operated by UZH in low bg environment @ 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

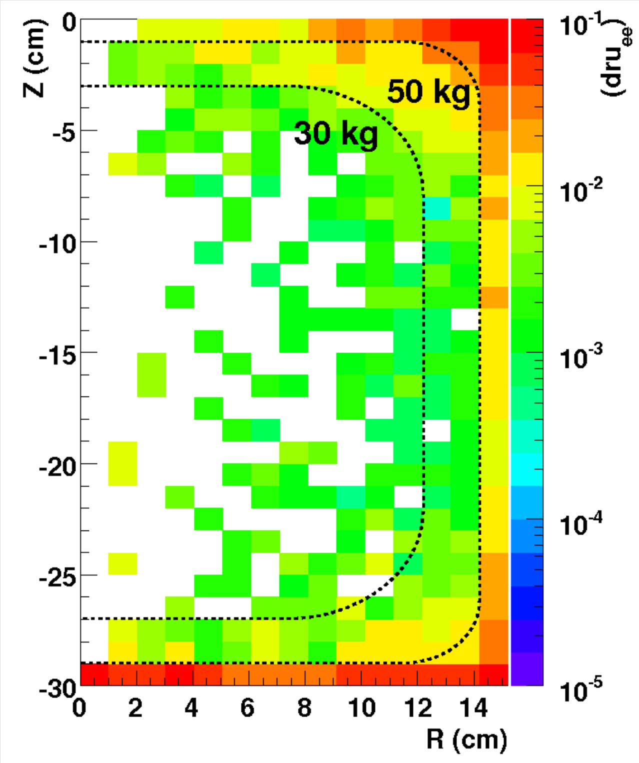
use results for Monte Carlo Simulations

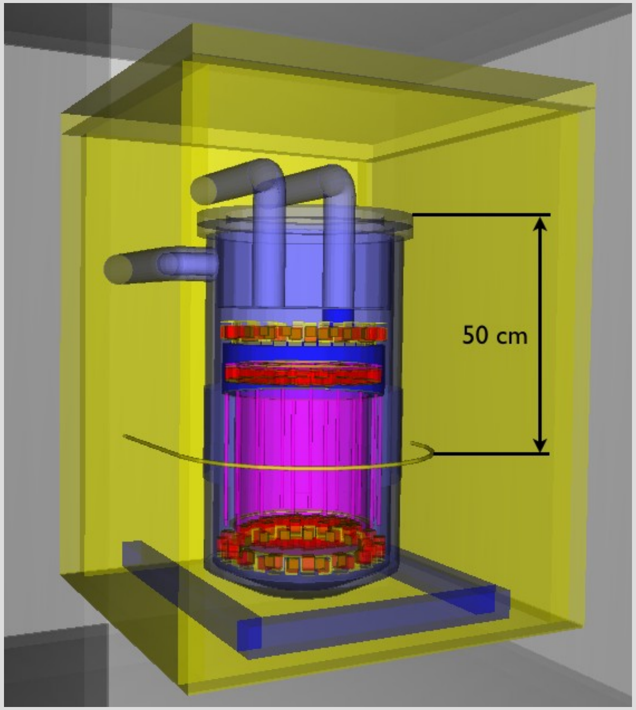
Monte Carlo Simulations

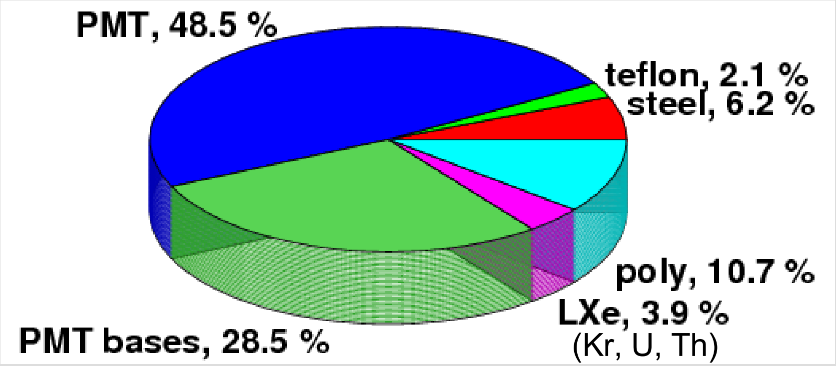
GEANT4 simulations of full experiment
(detector+shield+surrounding)

Gamma Background:

in DM search region, after cuts
50 kg: < 9.8×10^{-3} events/kg/keV/day
30 kg: < 3.2×10^{-3} events/kg/keV/day
before S1/S2 discrimination cut!





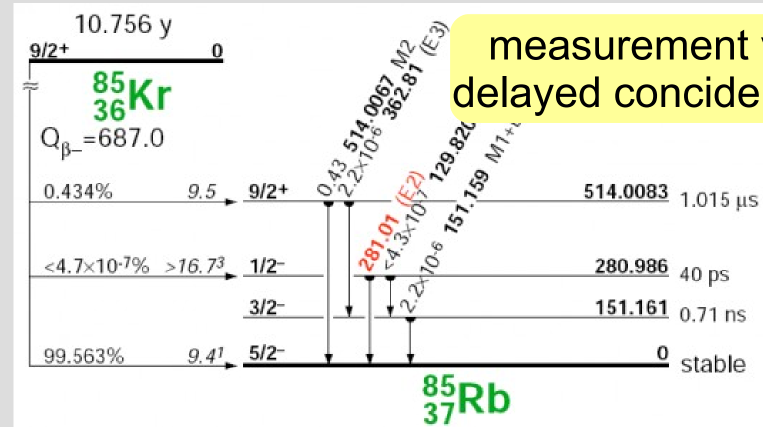


Kr-85-Removal

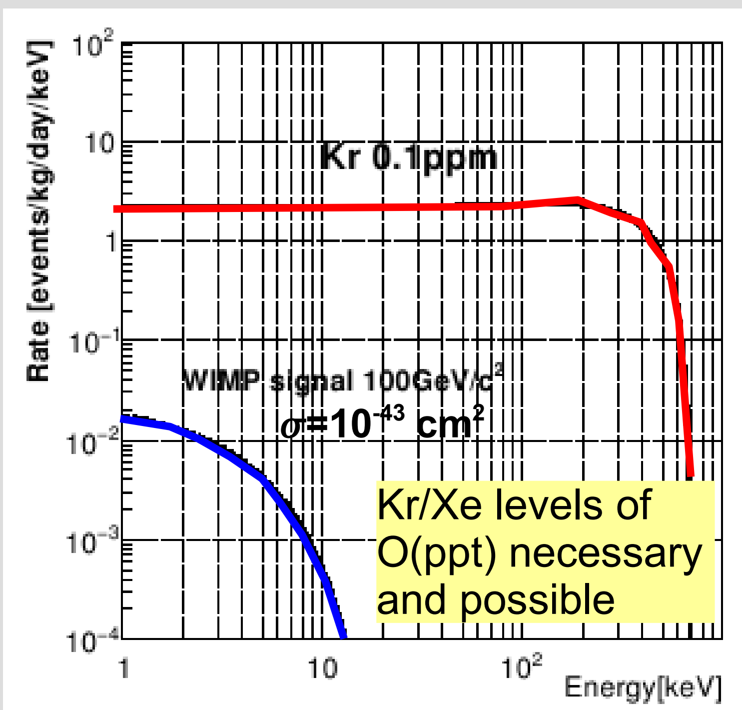
- Xe has no long lived radioactive isotope
- BUT: Xe contains Kr-85

in air:	Kr/Xe ~ 10
in Xe gas (commercial)	Kr/Xe ~ ppm-ppb
necessary (Xe100)	Kr/Xe ~ 100 ppt (<1 evt in 0.5 yr)

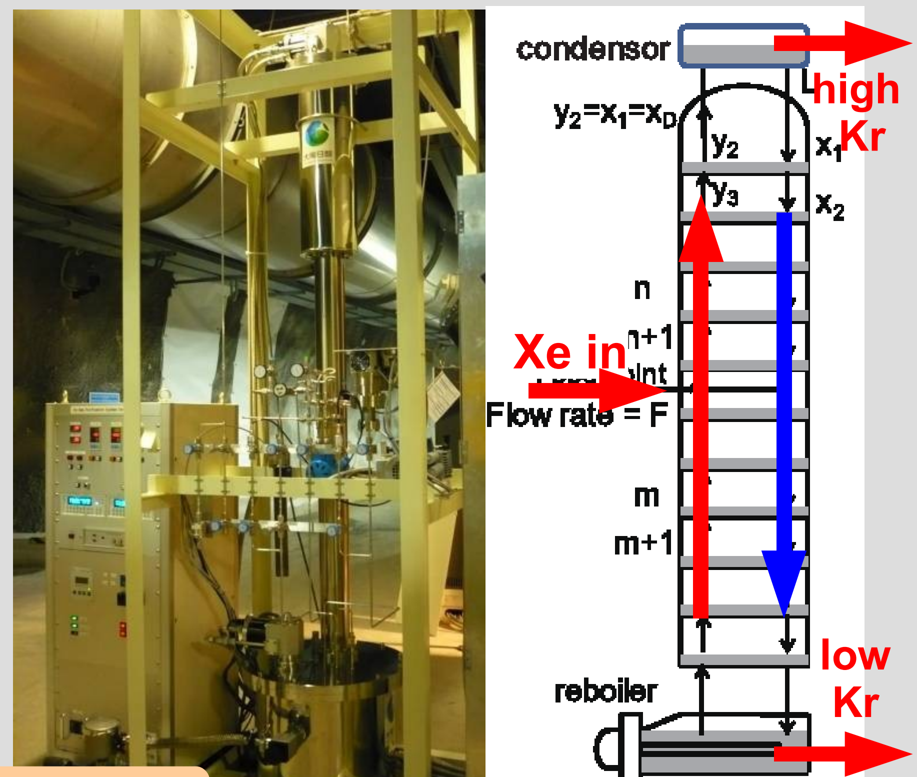
⇒ dedicated Kr-85 removal to ppt level



measurement via delayed concidences



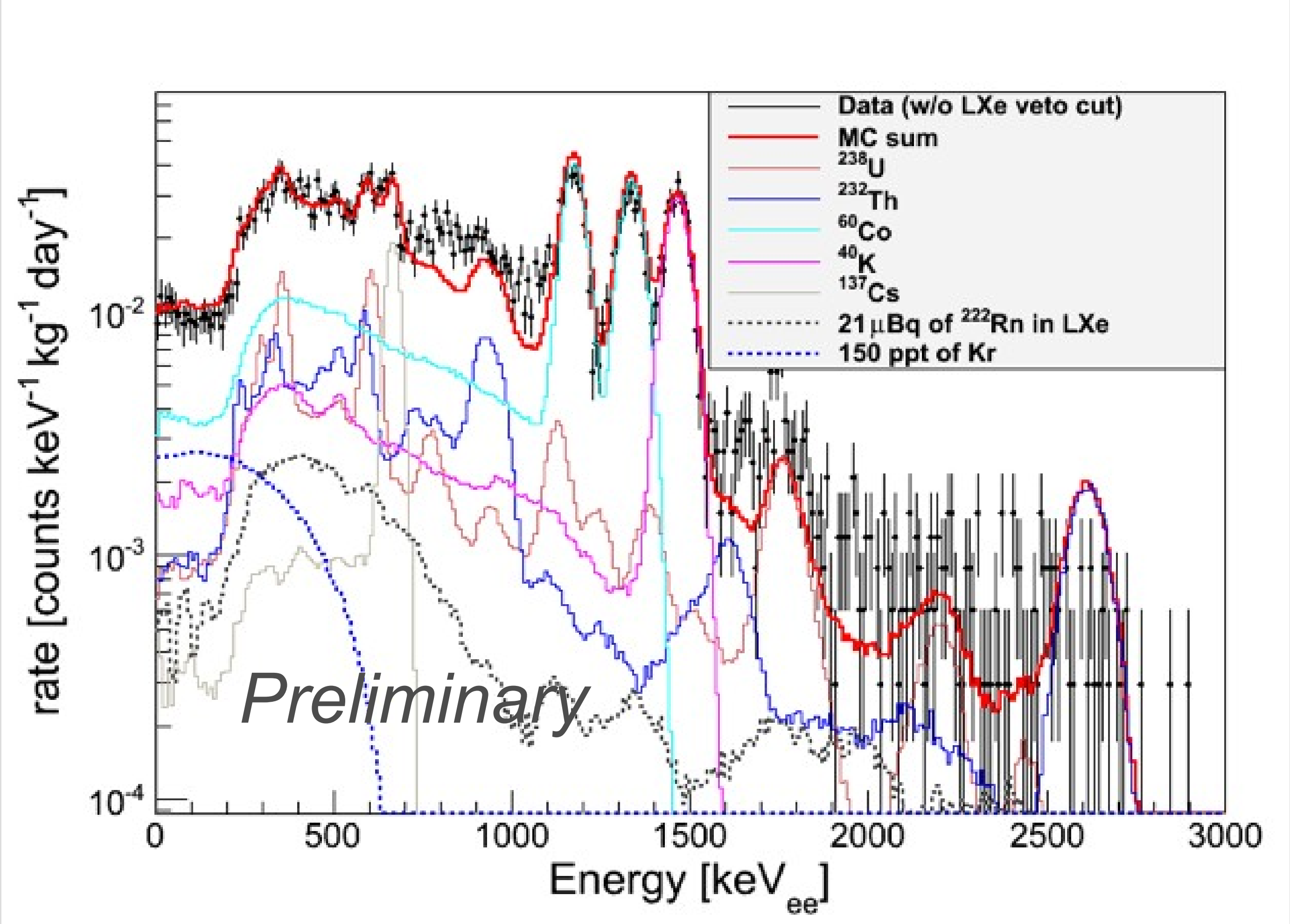
Kr/Xe levels of O(ppt) necessary and possible



used successfully

XMASS, arXiv:0809.4413 (2008)

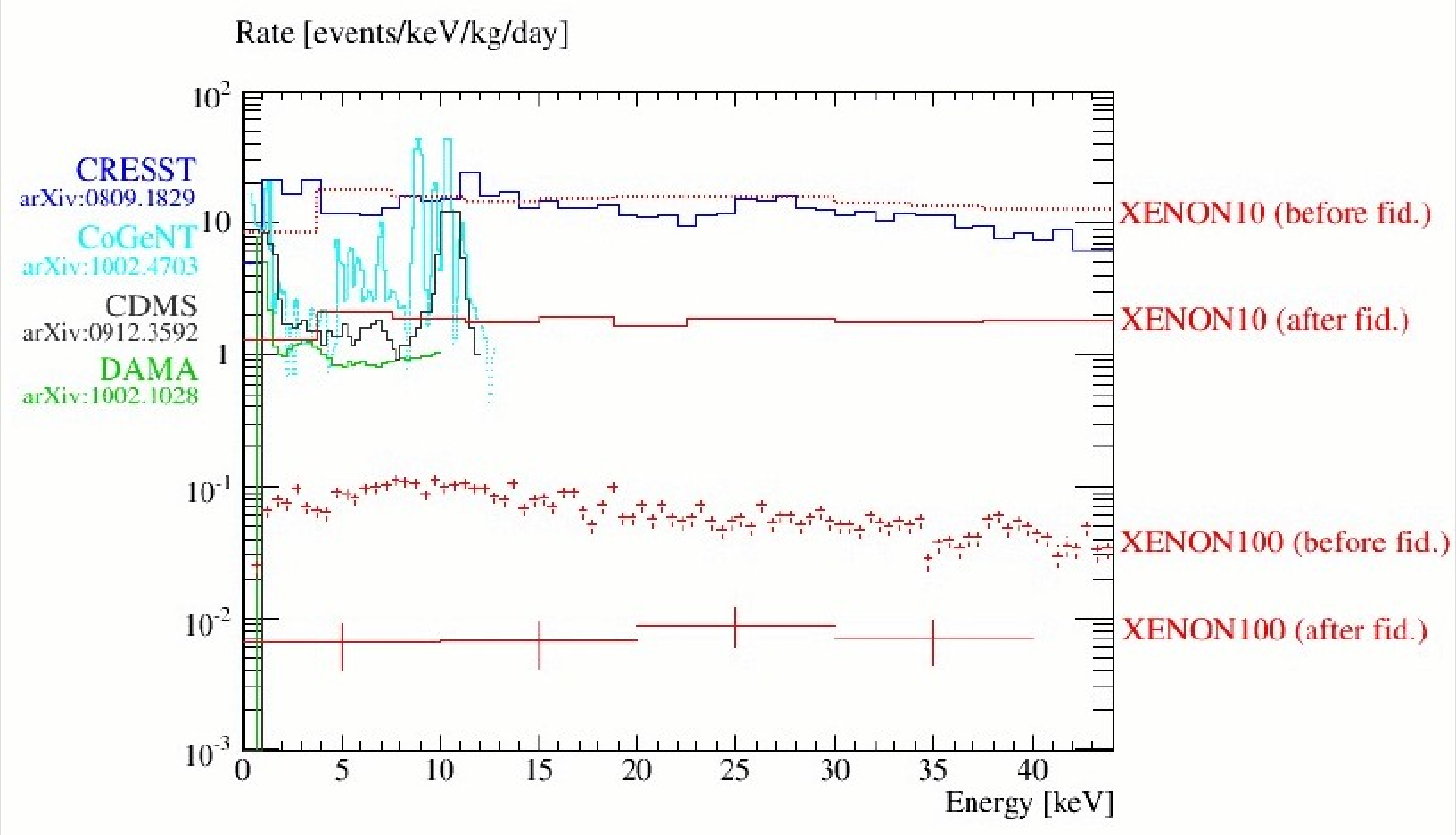
XENON100 Background



- 30 kg fiducial mass
- active LXe veto not used

Measured Background in good agreement with Monte Carlo prediction.

Background Comparison



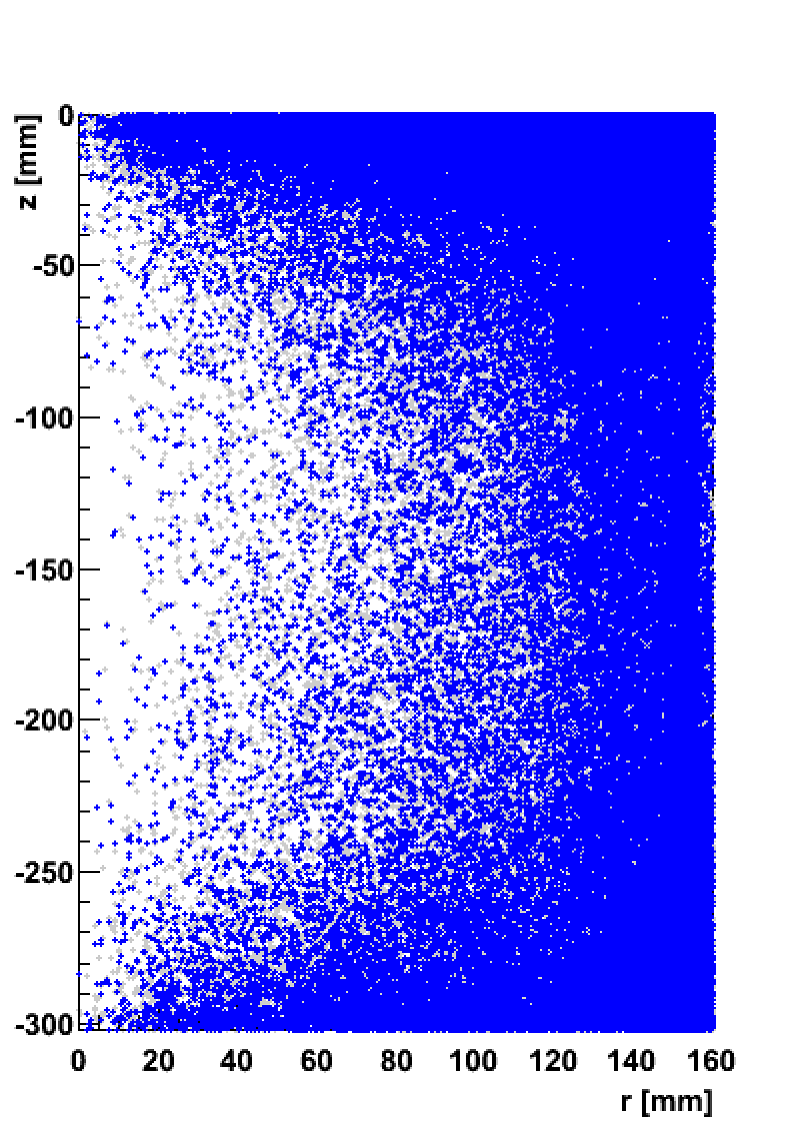
This is the lowest Background ever achieved in a Dark Matter Experiment!

A first glimpse at XENON100 data...

- Background data taken in stable conditions October-November 2009
- 11.2 life days
- Data analyzed non-blinded
- Cuts developed and optimized on calibration data, mostly AmBe and Co60

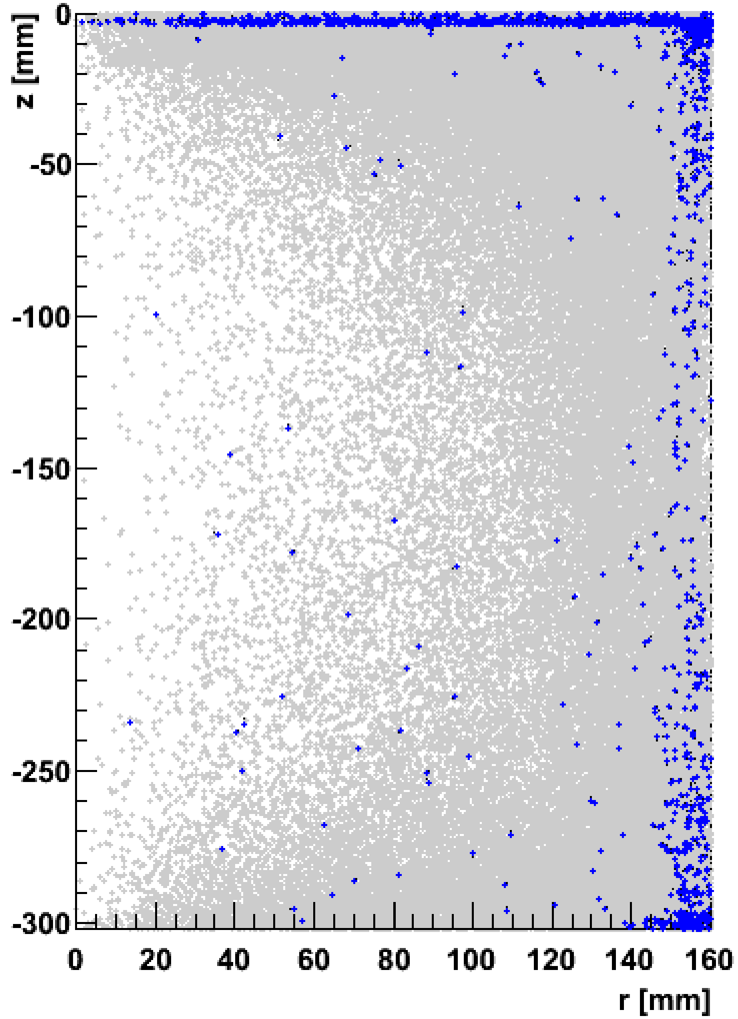
Let's have a look...

Basic Event Selection



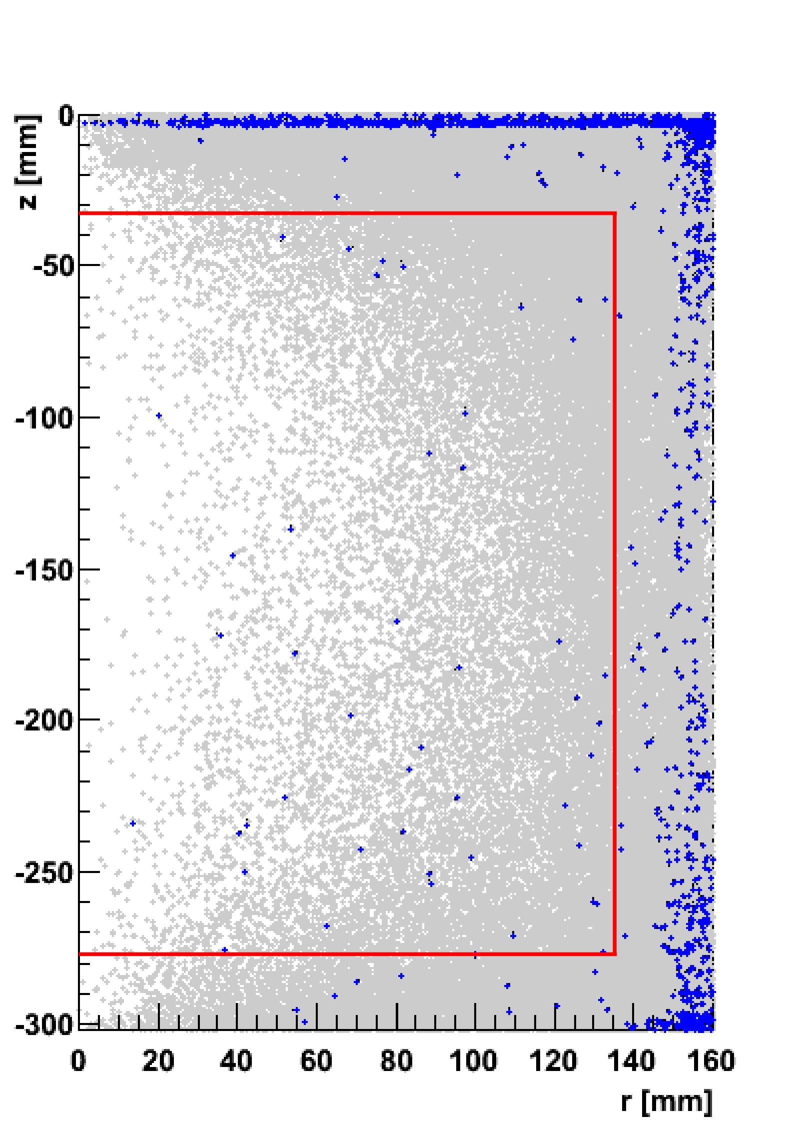
- select events with acceptable signal/noise ratio
  (very sensitive detector: SPE & single electron S2 sensitivity)
- select single S1 peak
  (remove accidentals)
- select single scatters
  (single S2 peak)
- remove gas events
- apply active veto cut

Energy Cut



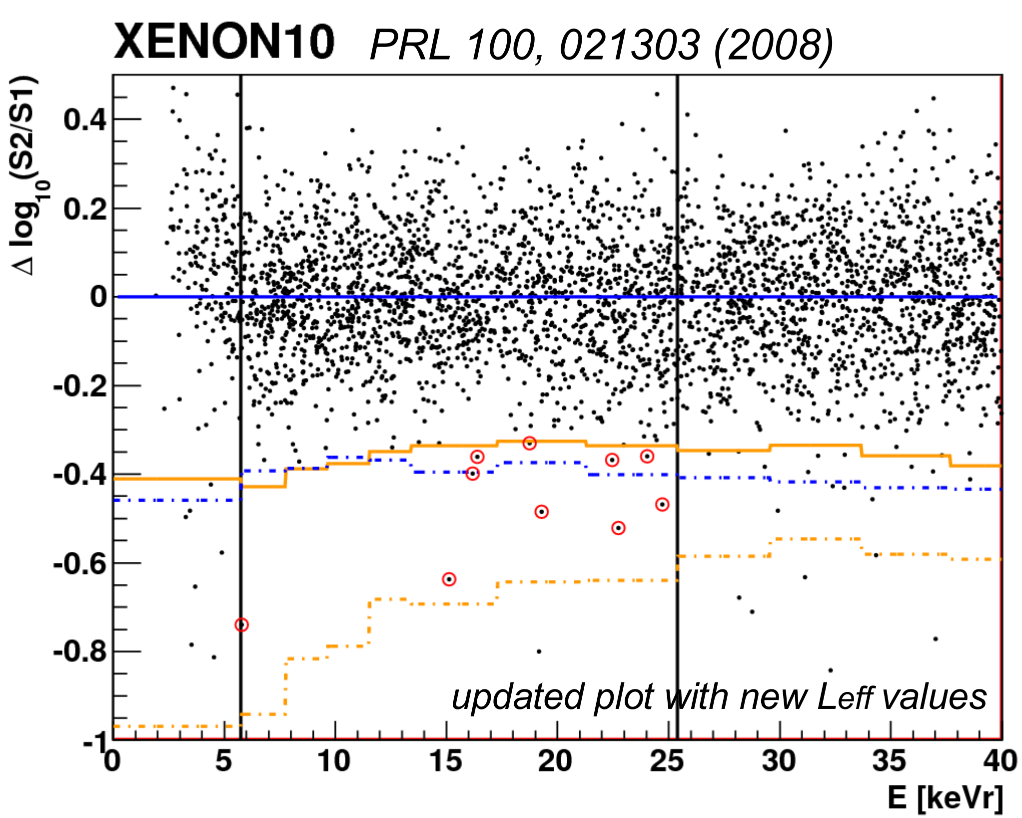
- select events with an S1 energy of < 28 keVnr
- this is the upper border of the XENON10 WIMP search region
- most remaining events are located at the edges

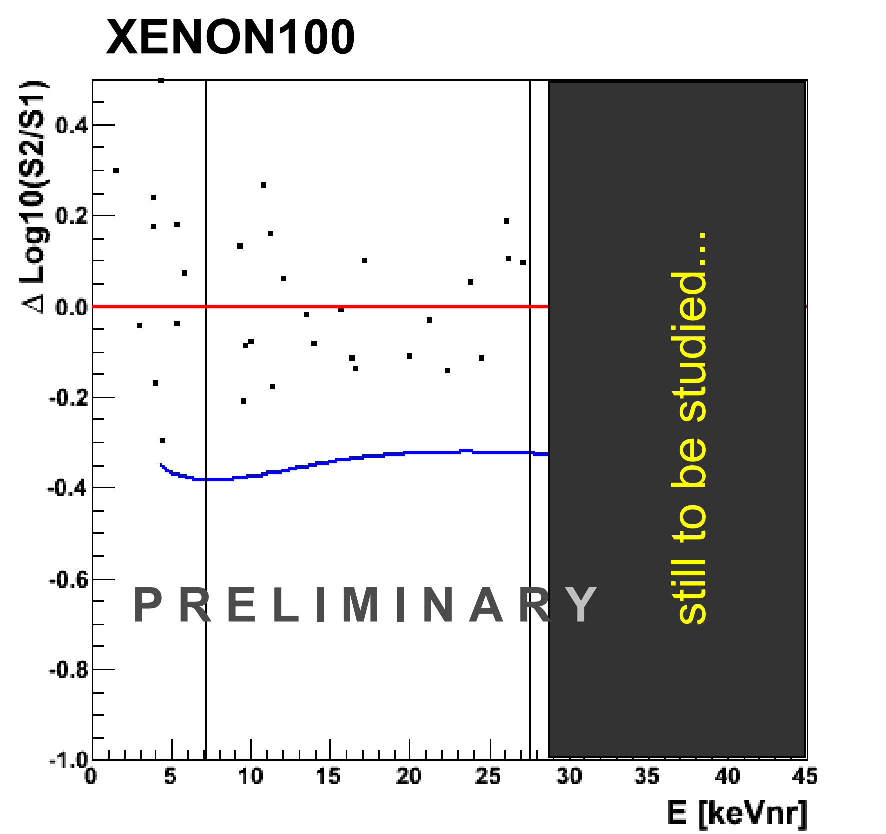
40kg Fiducial Mass



- make use of excellent self-shielding capability of liquid xenon
- cylindrical fiducial volume with 40 kg mass
- shape of volume will be further optimized

A Look at the Bands

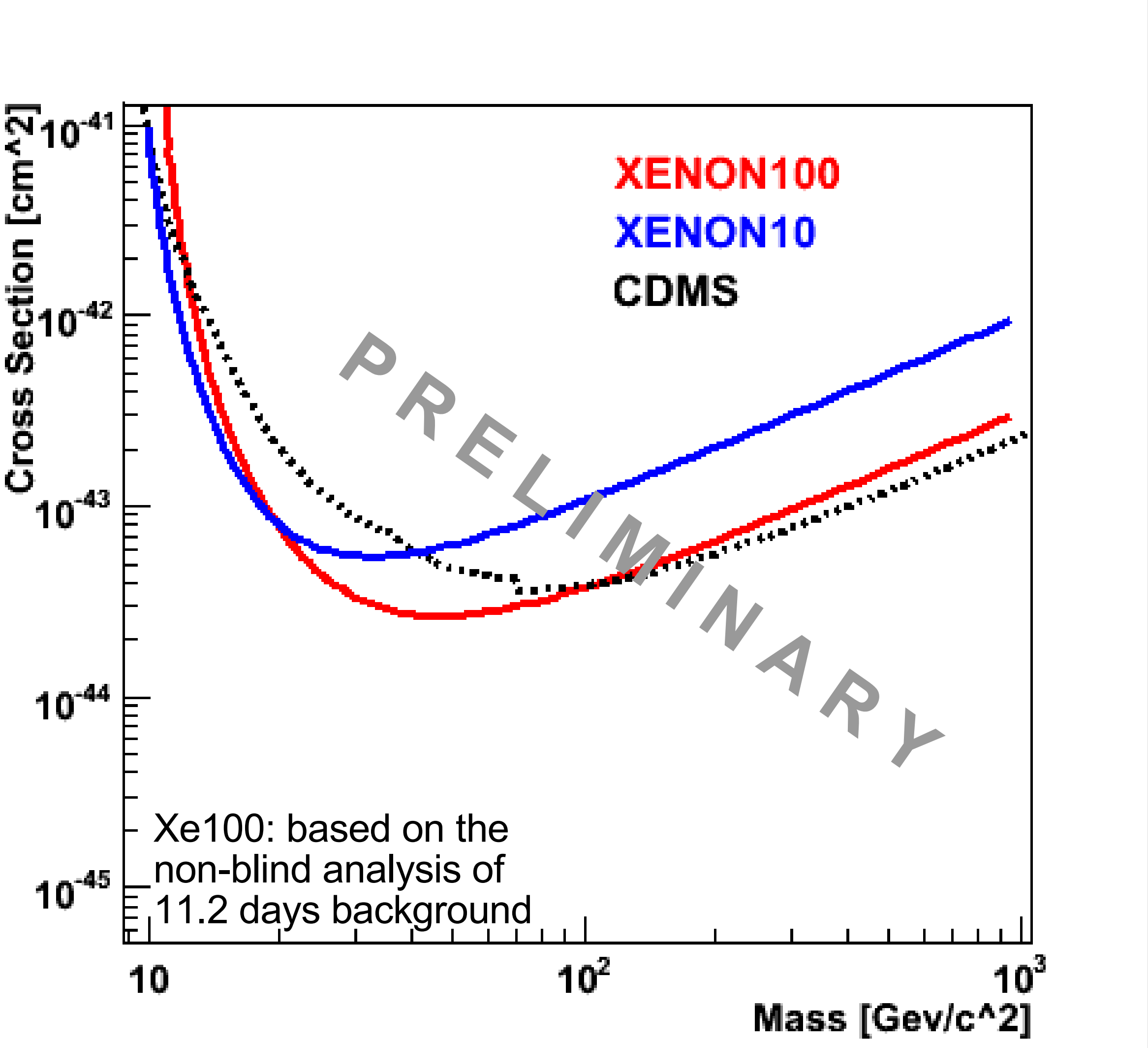




- „Background free“ in 11.2 days after S2/S1 discimination
- Both plots show similar exposure

NR acceptance ~ 50%
cut efficiency ~ 85%
(conservative)

A first Limit from XENON100

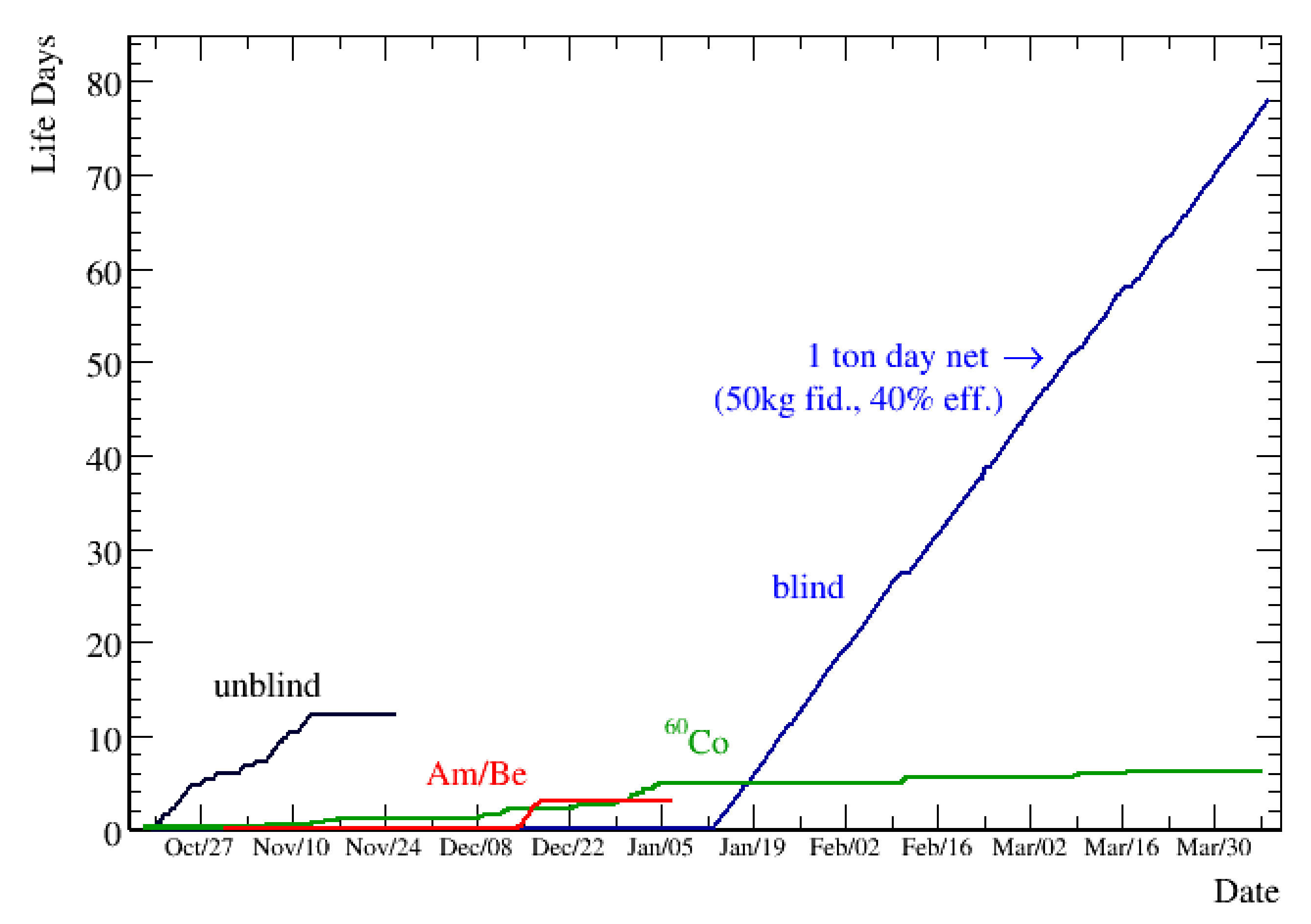


XENON100 is working extremely well and is back at the sensitivity frontier.

This is just a first glimpse! We have much more (blinded) data waiting to be analyzed.

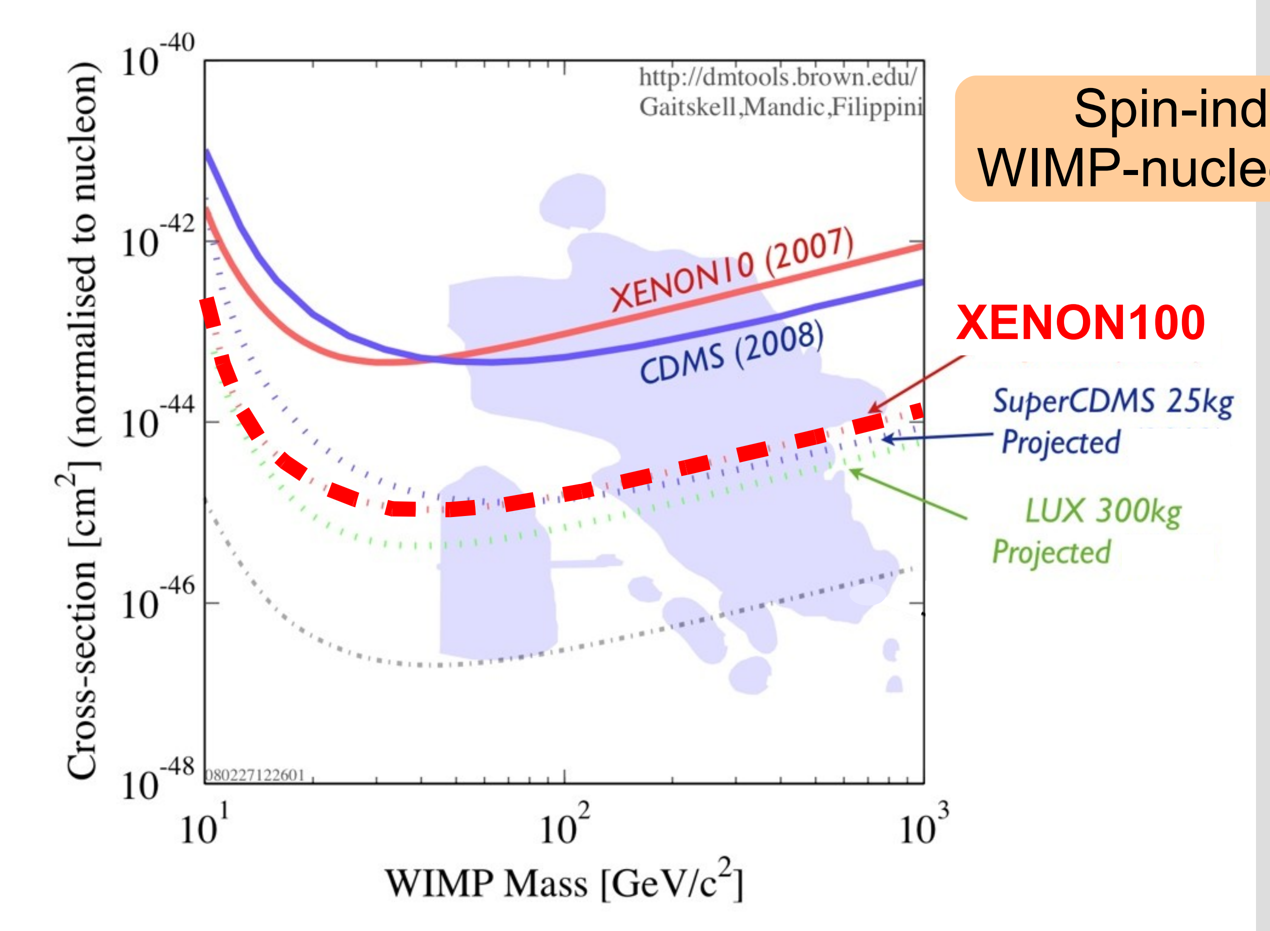
Results to be published soon

Ongoing Data Taking



XENON100 is taking science data since mid Jan 2010

XENON100: Sensitivity

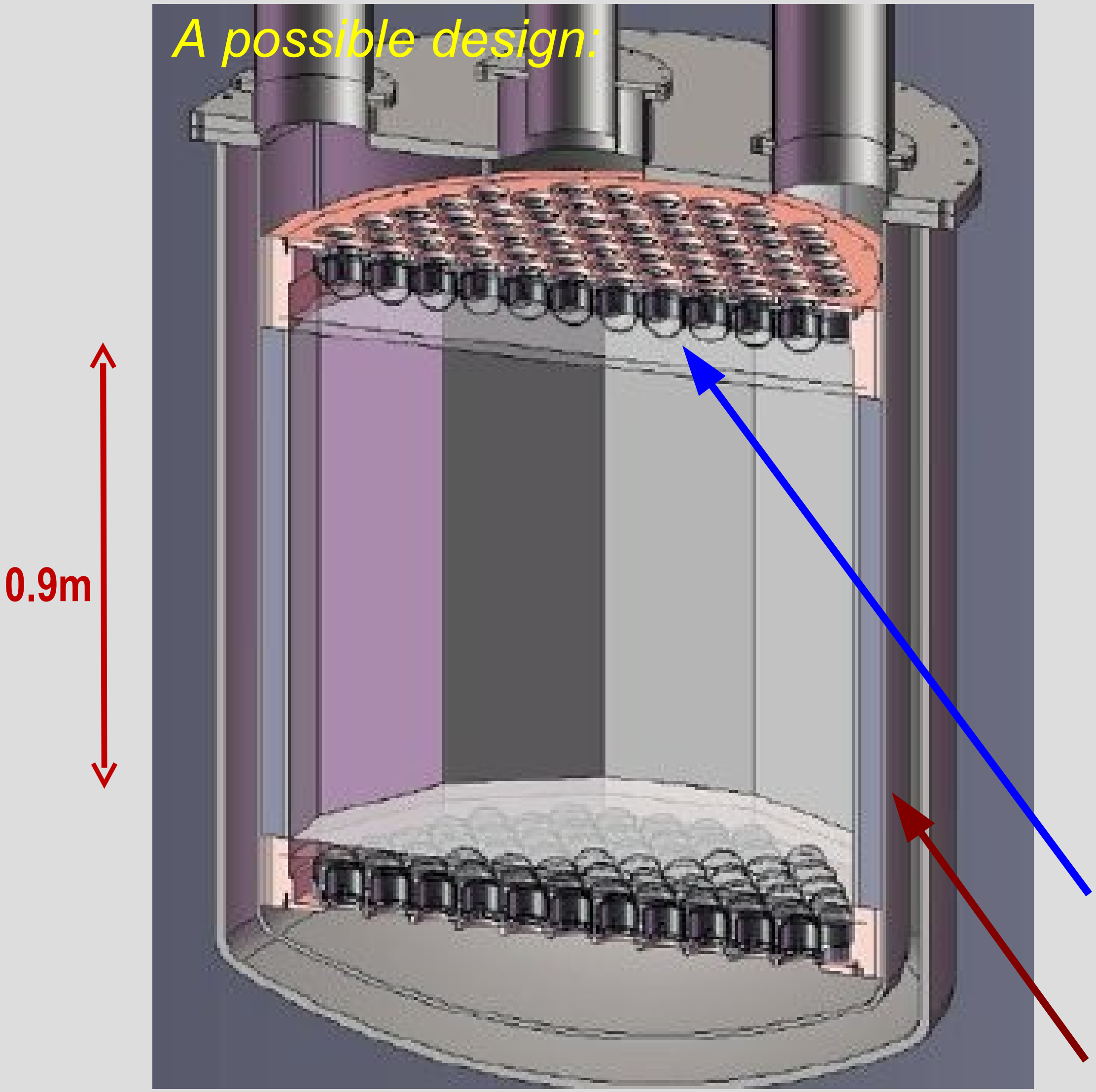


Spin-independent WIMP-nucleon interaction

50 kg Target: 40 days $\sigma = 6\times10^{-45}$ cm² (@ 100 GeV)

30 kg Target: 200 days $\sigma = 2\times10^{-45}$ cm² (@ 100 GeV)

The next step: XENON1T



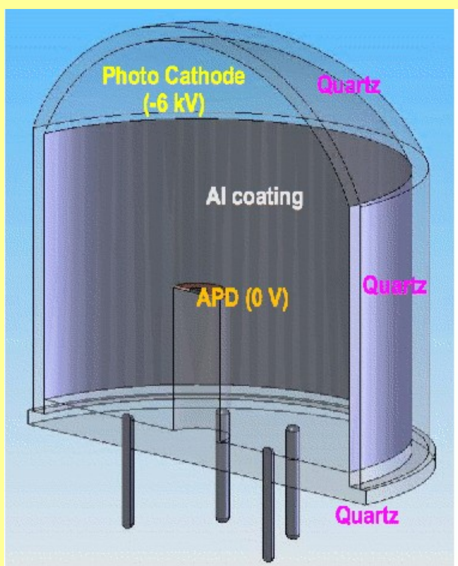
- 2.2t LXe ("1m³ detector")
  1t fiducial mass
- 100x lower background
  (10 cm self shielding, QUPID)
- MC studies, design studies already started 2009
- bigger collaboration
- currently: working on the details; secure funding
- Timeline: 2010 – 2015 ???

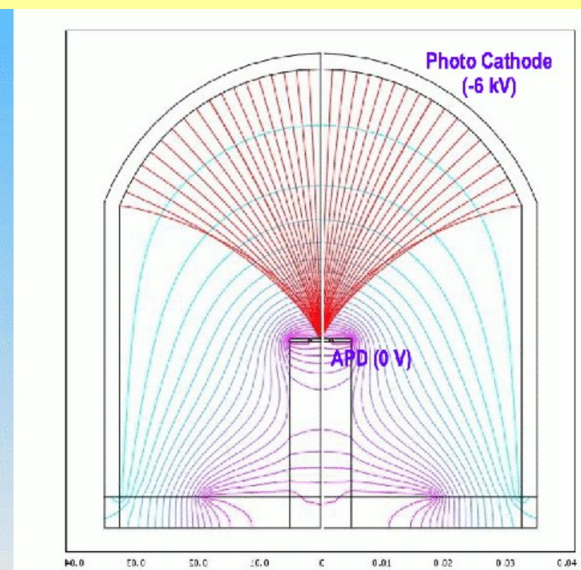
The QUPID

- invented and developed by UCLA group (Arisaka/Wang)
- very low radioactive photosensor to replace PMTs
  APD, quartz, only a few pins, no voltage divider
- QUPIDs are „invisible“ in GATOR screening facility
- first units were build by HAMAMATSU,
  ongoing tests and R&D at UCLA (later also UZH)

QUPID
Quartz
Photon
Intensifying
Detector

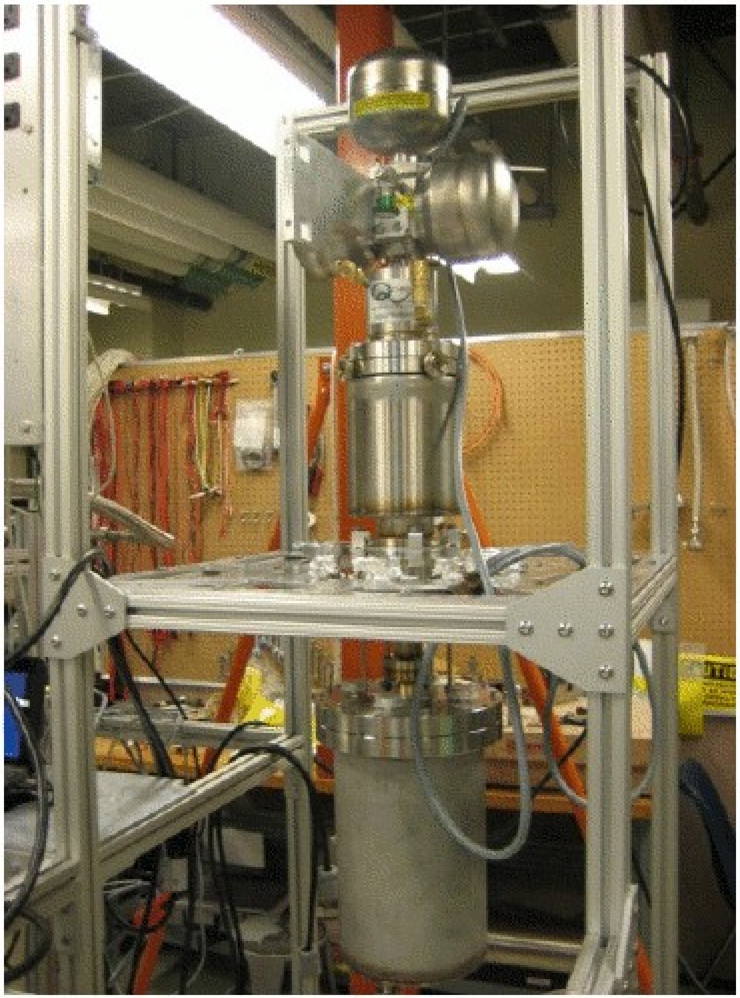
arXiv:0808.3968



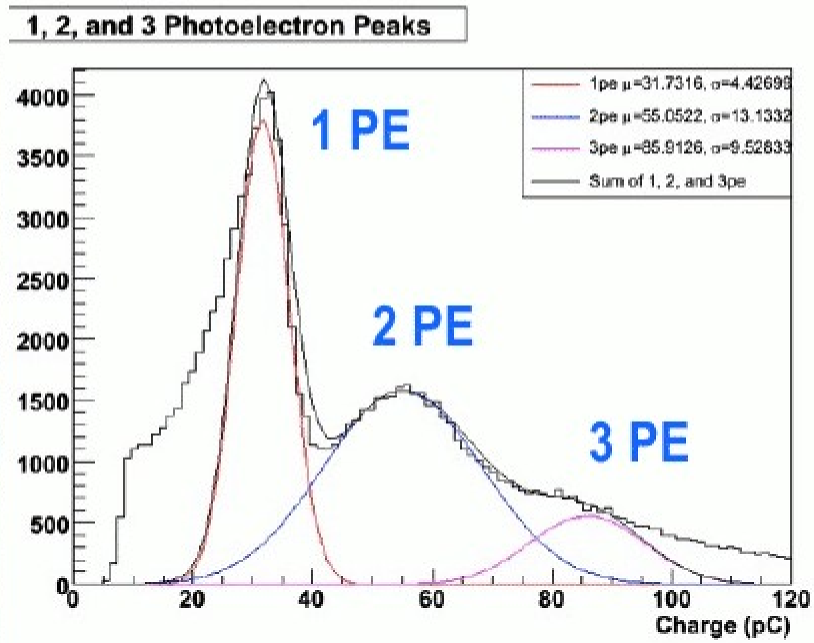


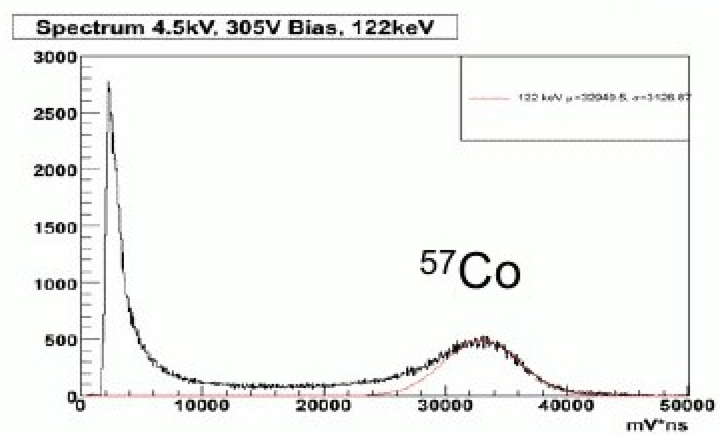
It is actually working...

Work done at UCLA (Arisaka/Wang):

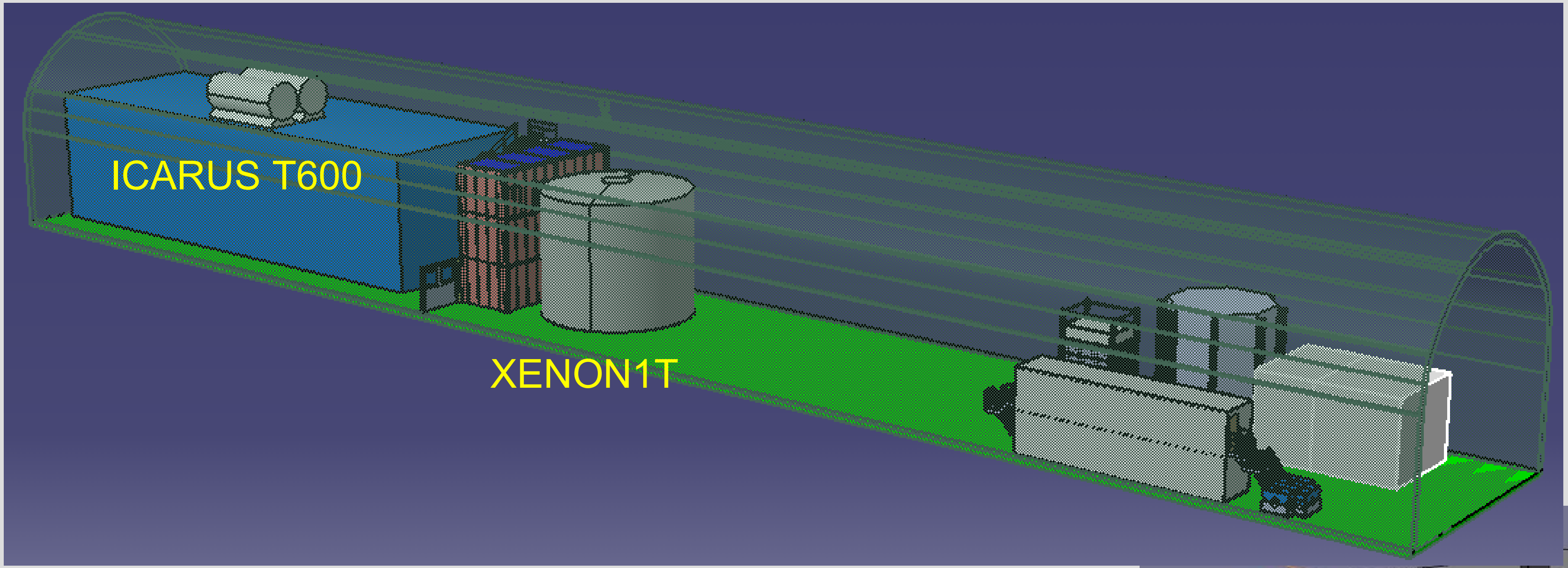


QUPID Test in Liquid Xenon



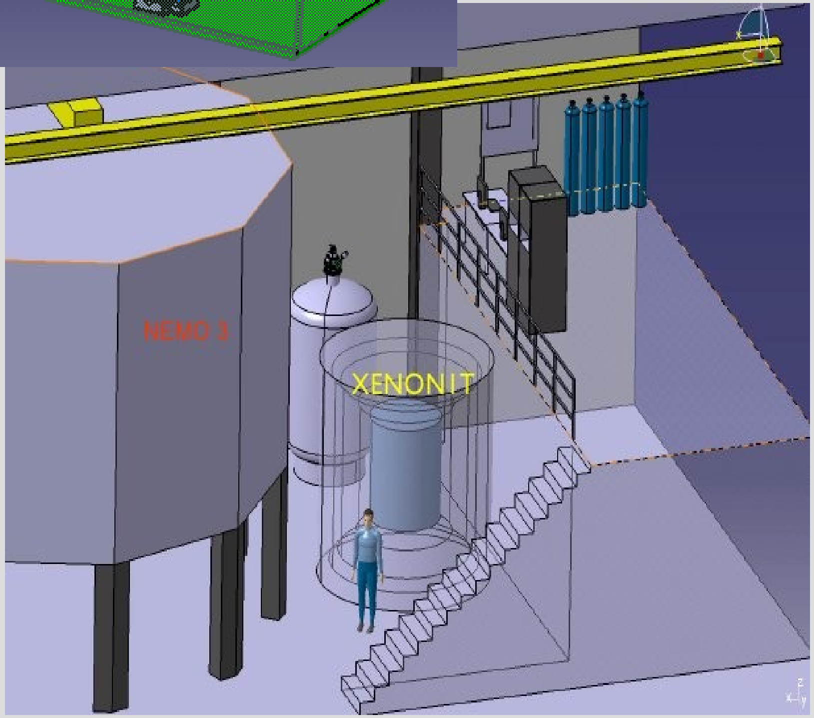


XENON1T: Location?

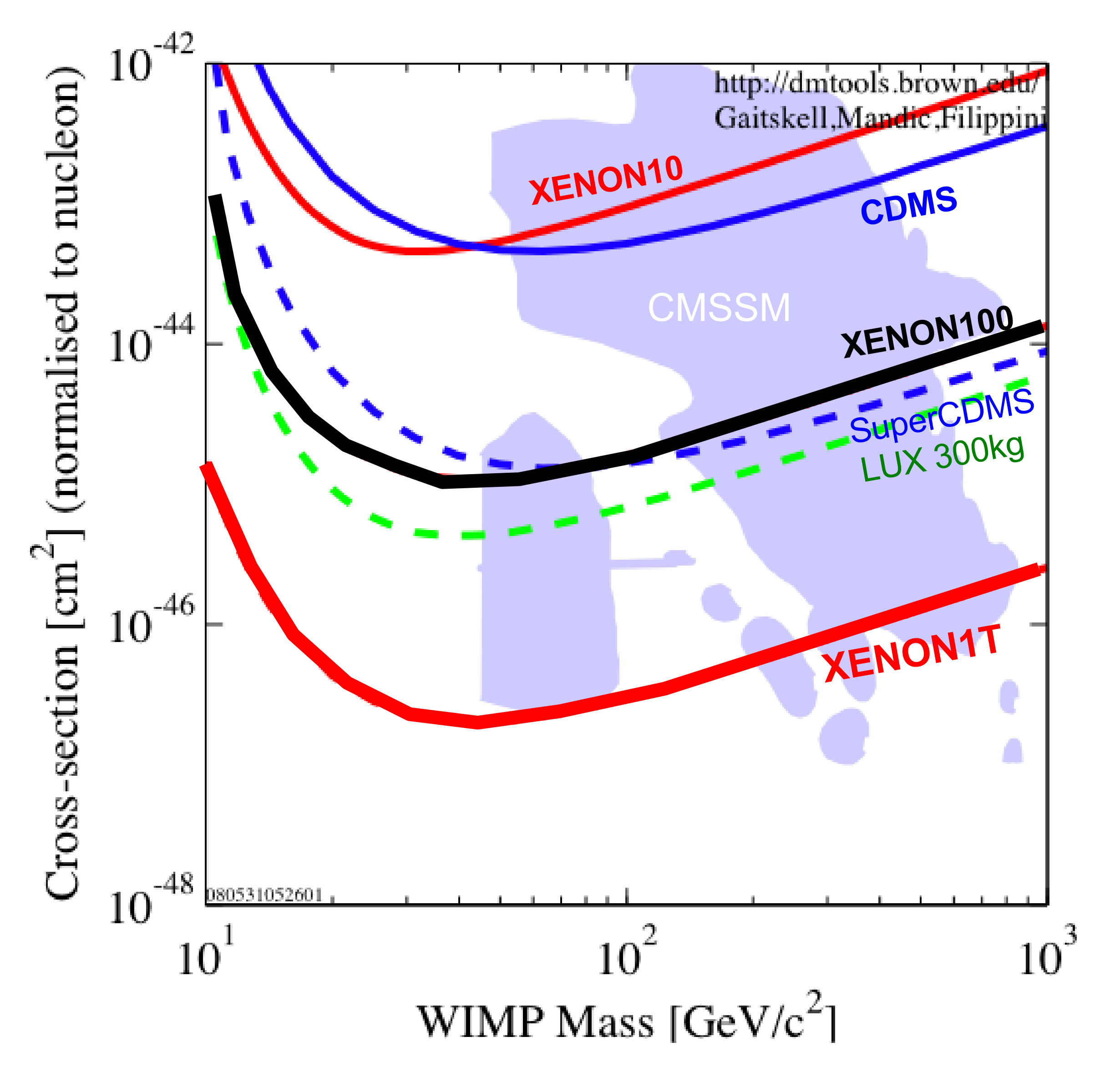


XENON1T @ LNGS (Hall B)
➞ 4 m water shield

XENON1T @ LSM
➞ solid shield (55cm poly, 20cm Pb, 15cm poly, 2cm ancient Pb, >99% muon veto)



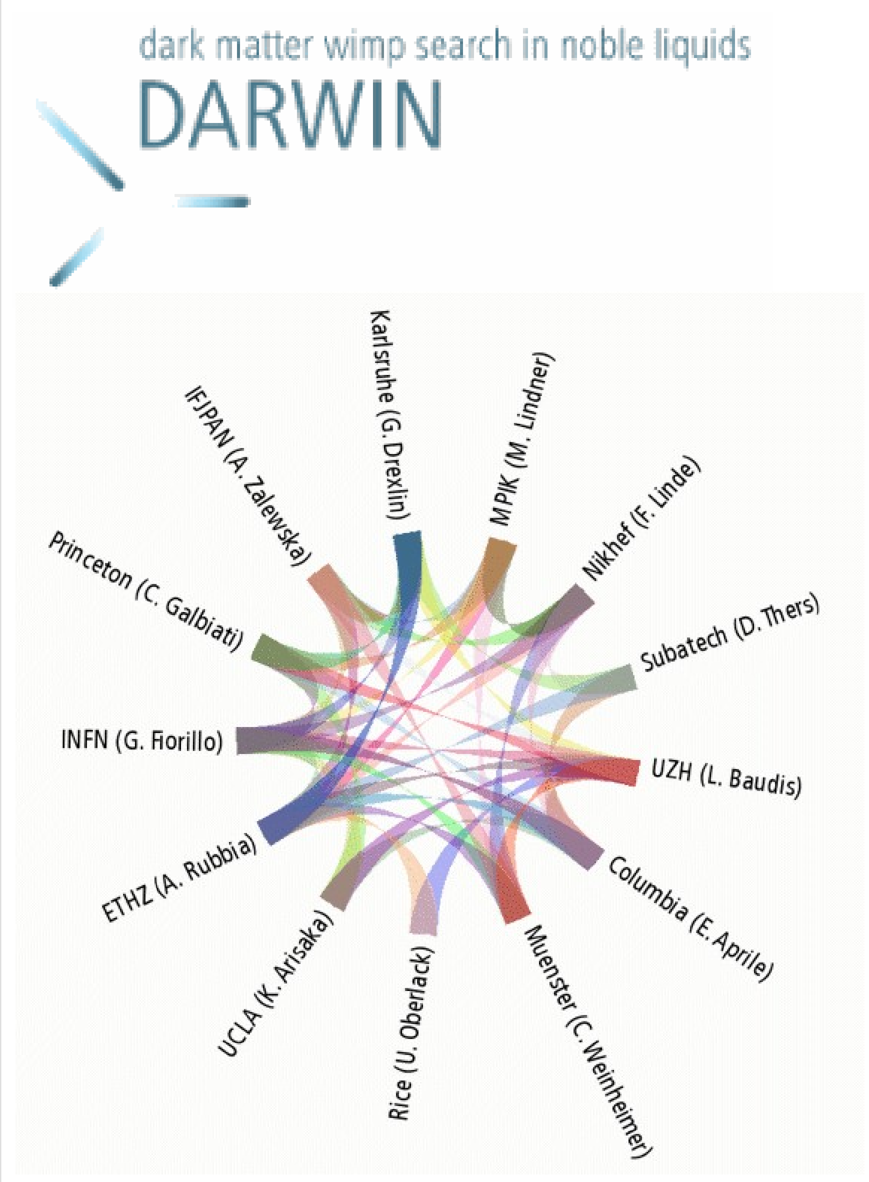
Projected Sensitivities



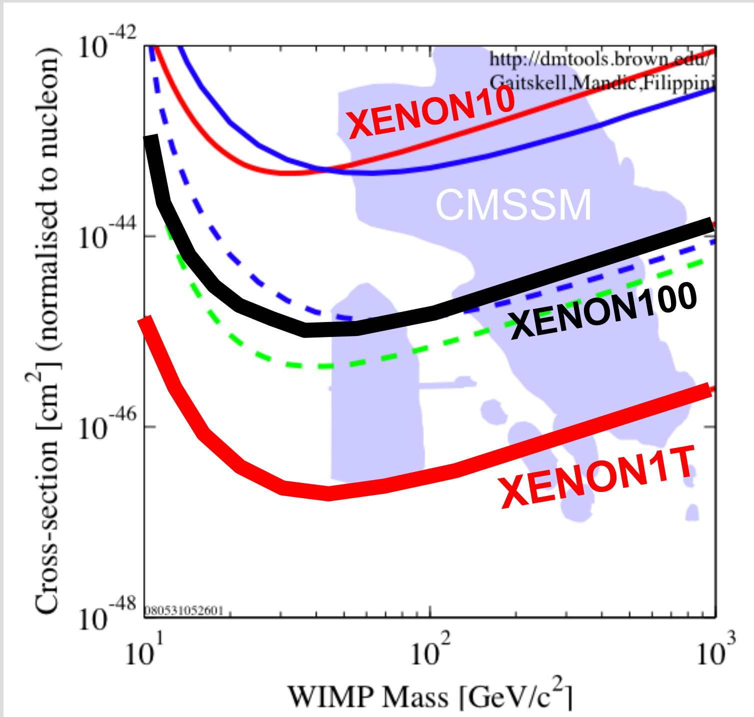
DARWIN

- the future of liquid noble gas Dark Matter detectors (Xe/Ar) in Europe
- DARWIN = design study towards the realisation of future astroparticle infrastructure in Europe as identified in the ASPERA Roadmap
- the DARWIN consortium was founded in 2009; approved by ASPERA
- DARWIN brings together several European and American groups working in the existing XENON, WARP and ArDM collaborations.

  It unites expertise on liquid noble gas detectors, low-background techniques, cryogenic infrastructure, shielding and astroparticle physics phenomenology.
- `http://darwin.physik.uzh.ch`



Summary



- Dark Matter: One of the big unsolved puzzles
- **XENON100**
  65 kg dual-phase TPC
- underground @ LNGS
- extremely low background
- first results from 11.2d data
- in science data mode now: stay tuned...

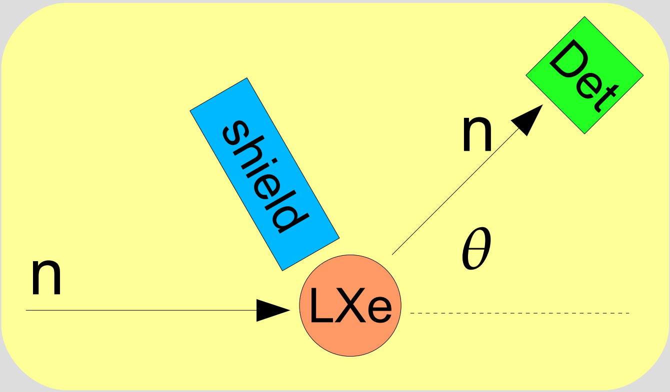
Backup

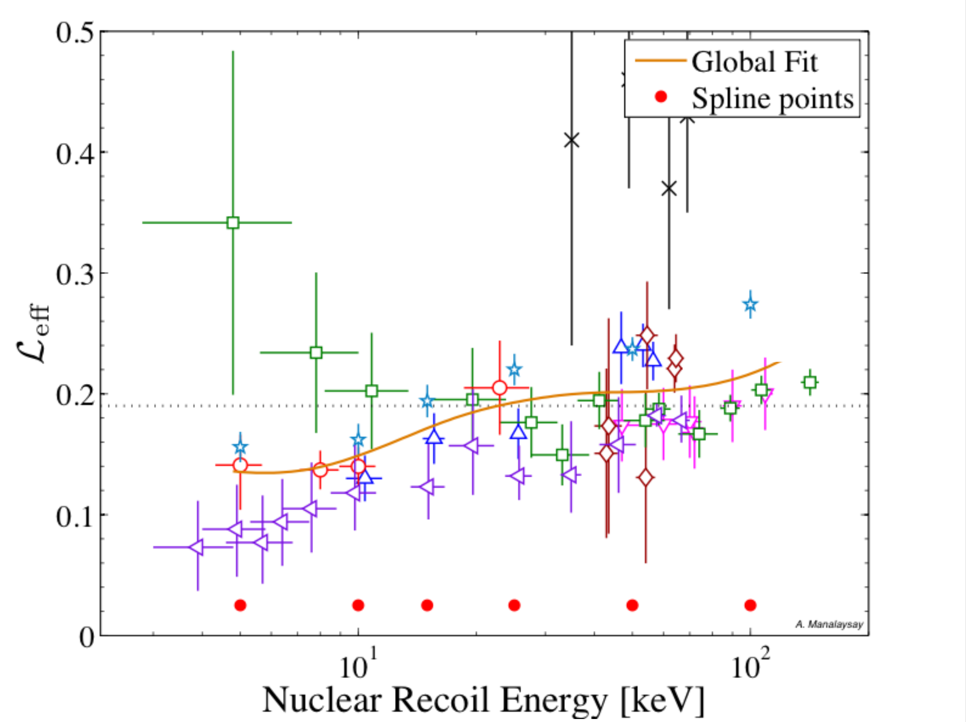
Determination of L_{eff}

- WIMPs interact with Xe nucleus
  ➞ nuclear recoil (*nr*) scintillation
- absolute measurement of *nr* scintillation yield is difficult
  ➞ measure relative to Co57 (122keV)
- relative scintillation efficiency L_{eff}:

$$\mathcal{L}_{\mathrm{eff}} = \frac{E_{\mathrm{ee}}}{E_{\mathrm{nr}}}$$

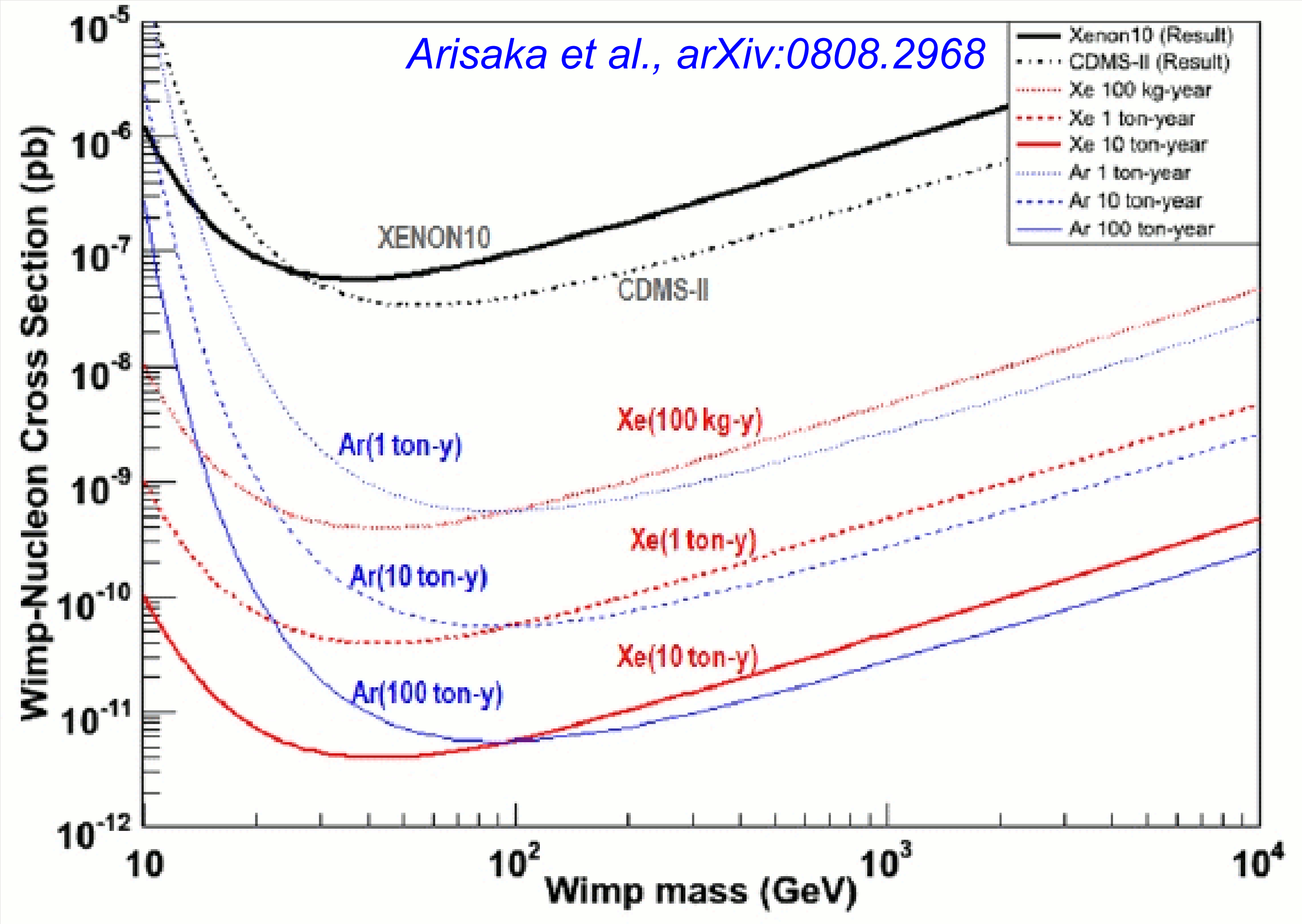
measurement principle:





most recent measurements:
○ *Aprile et al., PRC 79, 045807 (2009)*
◁ *Manzur et al., arXiv:0909.1063 (2009)*

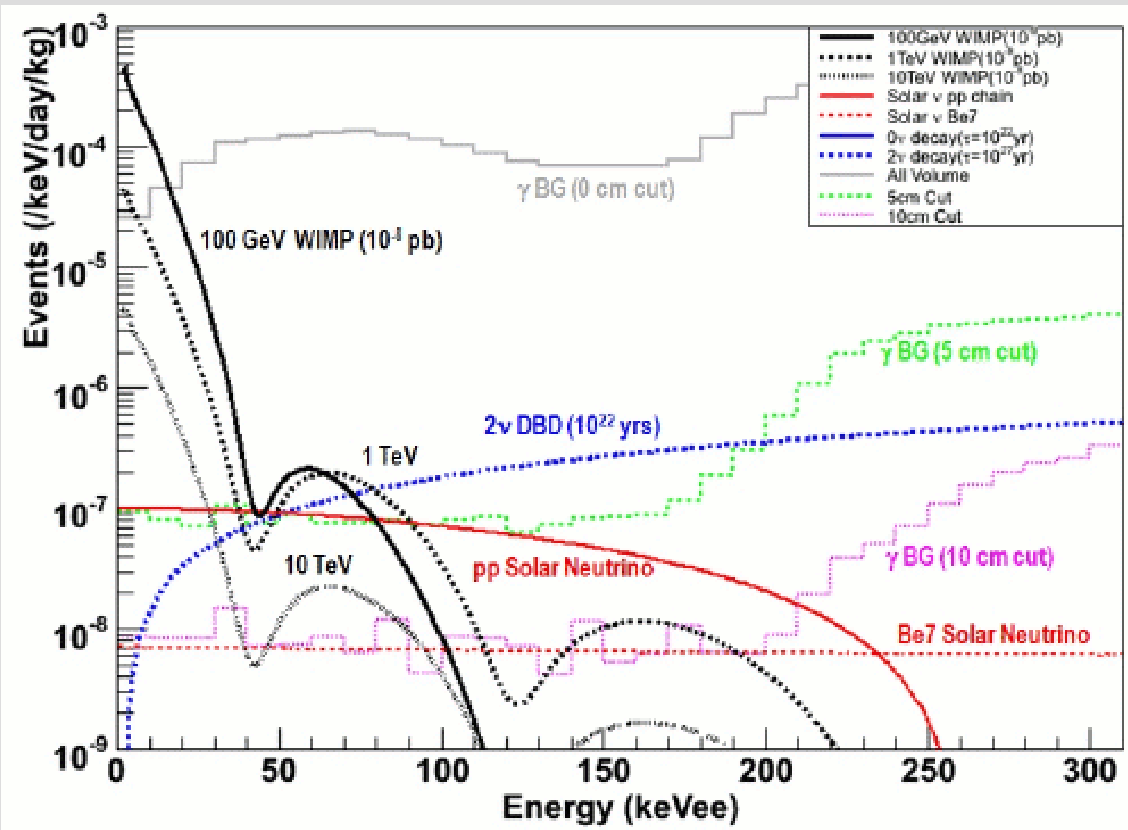
Scaling I



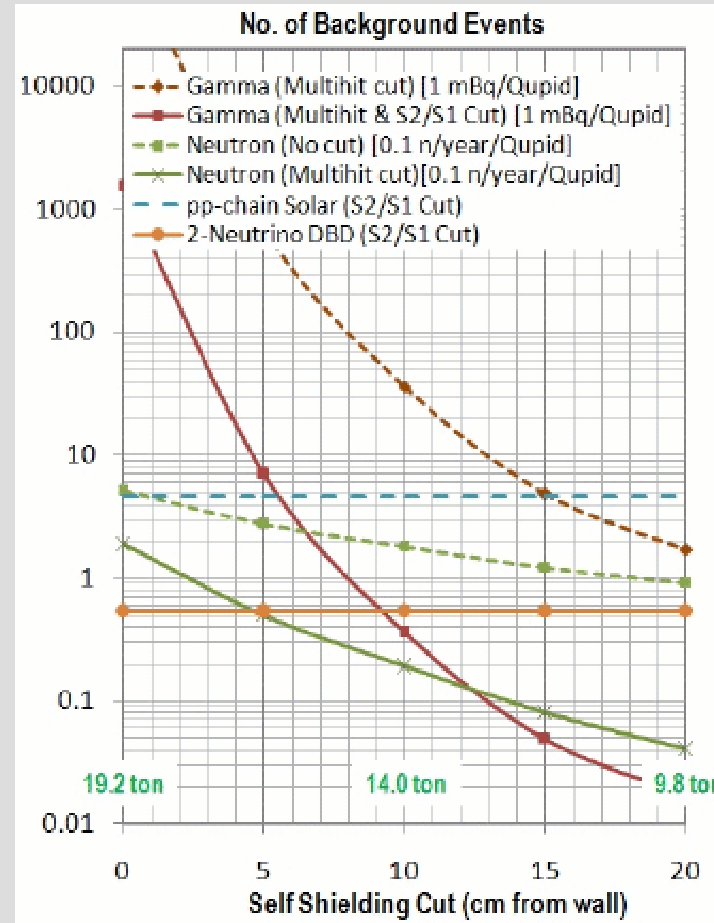
90% CF limits for one year of data taking

Scaling II

Arisaka et al., arXiv:0808.2968



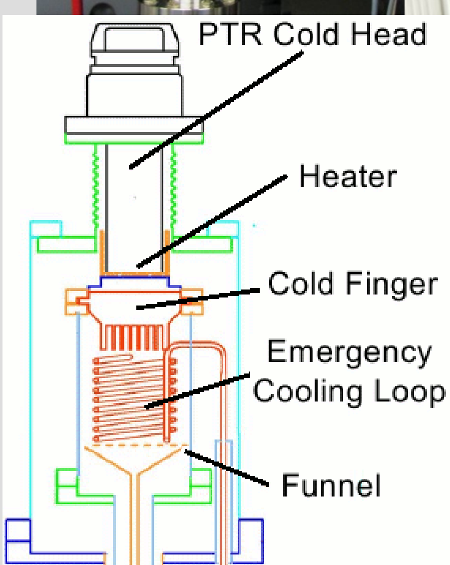
Expected energy spectrum of WIMP interactions, solar neutrinos, double beta decays, and gamma ray backgrounds (from QUPIDs) as a function of self shielding cuts.



Expected number of bg events in WIMP signal region (3-15 keVee) as function of active shielding cut for 10 ton-years of data taking.

Cryogenics & Recirculation

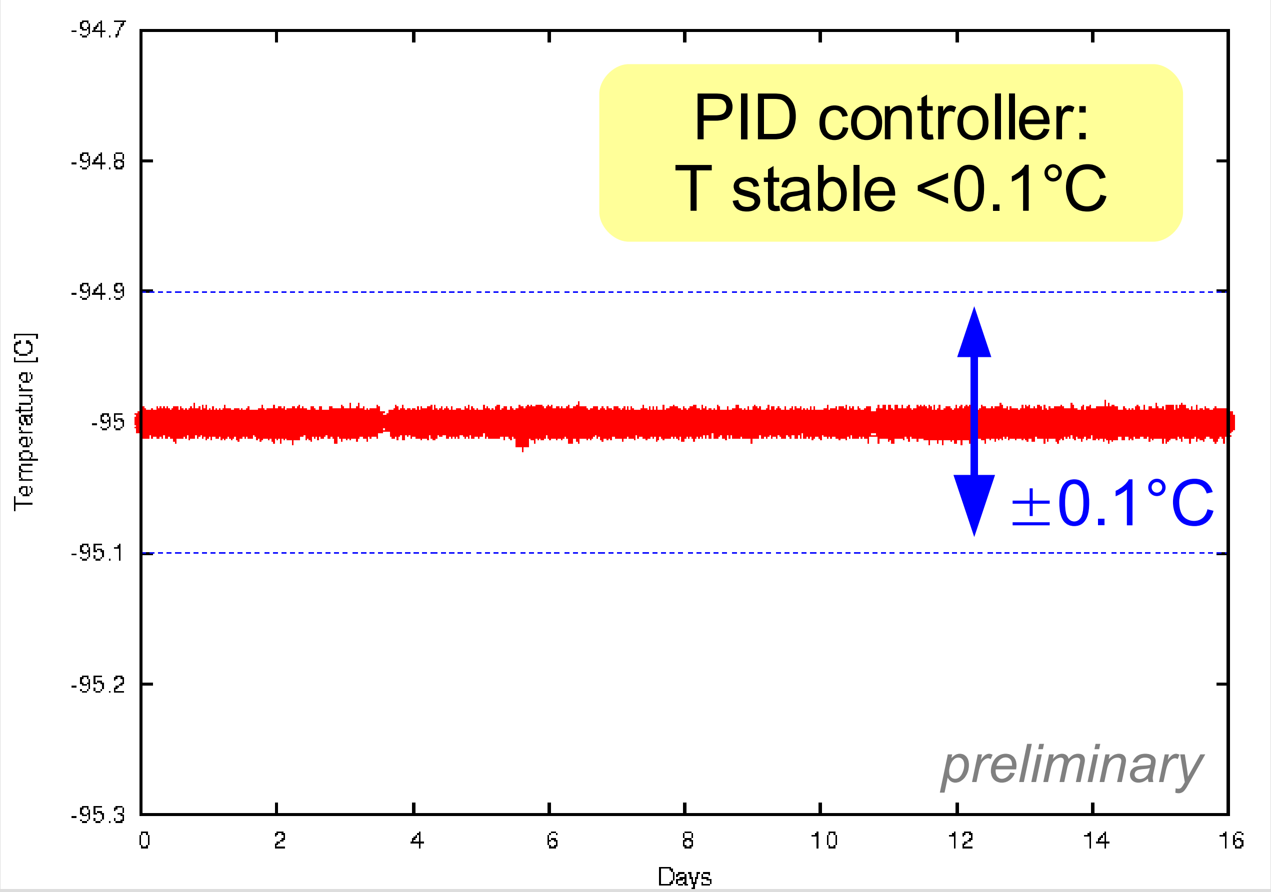
200 W PTR cryocooler
gas gets liquefied outside the shield



double wall SS cryostat
(low radioactivity steel, GERDA type)

continuous Xe purification
(high T Getter)

Detector Stability

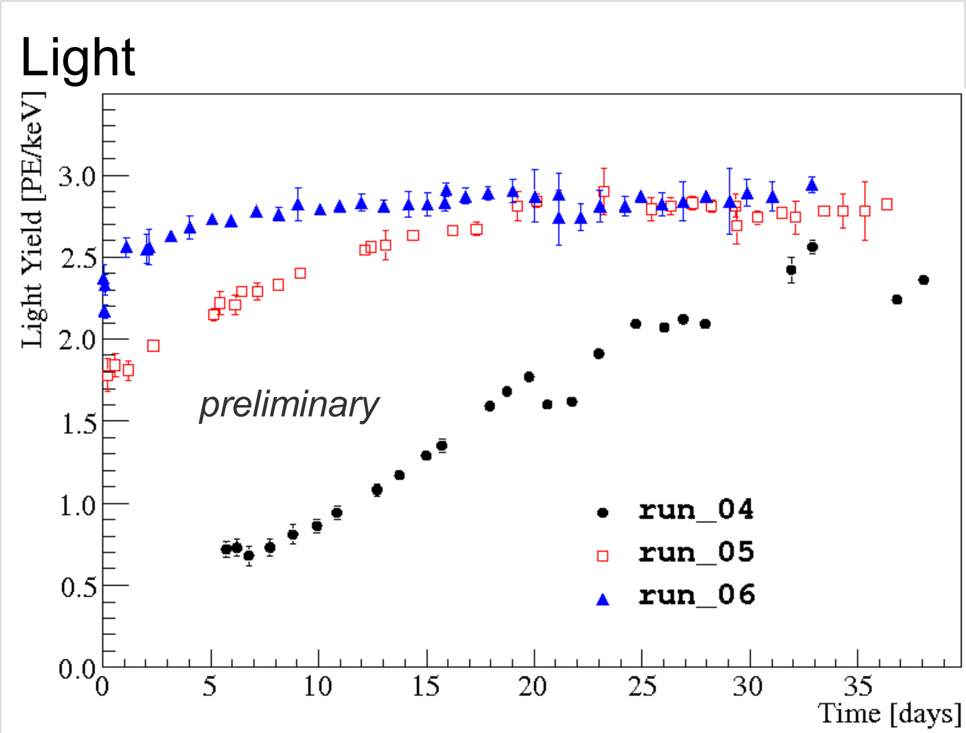


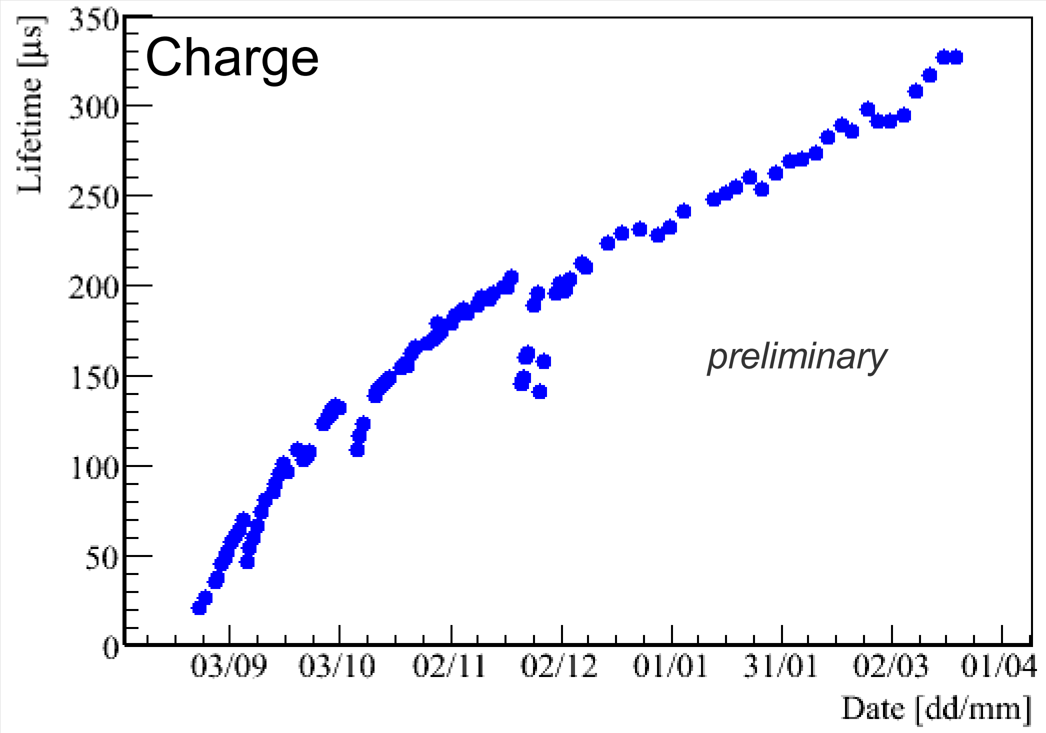
PTR cooling provides excellent stability

Slow Control System records:

- Temperatures
- Pressures
- Flow rates
- Xe Level
- TPC HV
- PMT HV
- DAQ rate
- Vacuum
- Rn level
- status of all important systems
- ...

Ongoing LXe Purification

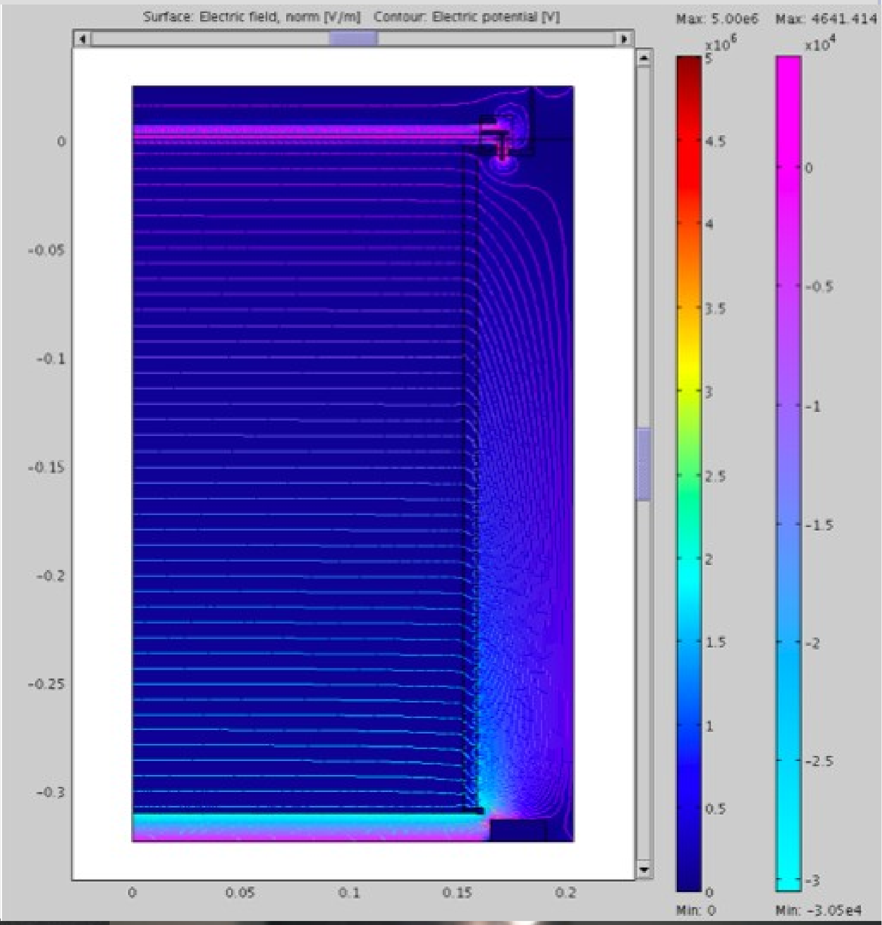




- Light yield is related to $H_2$0 content in LXe
- Continuous improvement to lower levels (baking, GXe circulation, $H_2$0 measurements)
- Charge yield related to O_2 content ➞ continuous purification

TPC: Electric Fields

- cathode: -30kV → drift field 1kV/cm
- anode: extraction field ~5kV
- field inside TPC was optimized in simulations for field homogeneity → 40 double field shaping rings
- anode stack optimized for
  - optical transparancy
  - S2 energy resolution (+4%)
- hexagonal mesh structures, pitch cathode 5mm, anode 2.5mm



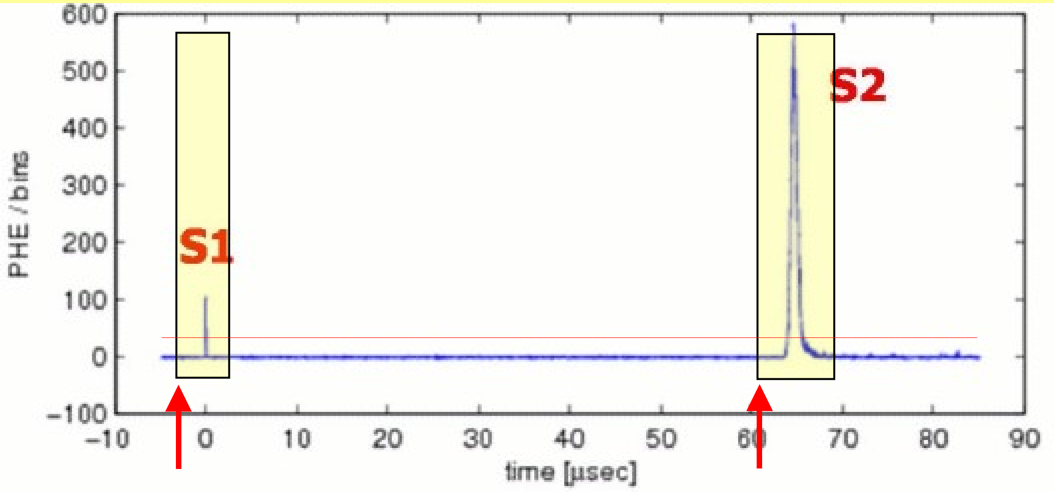
Data Acquisition

Requirements:

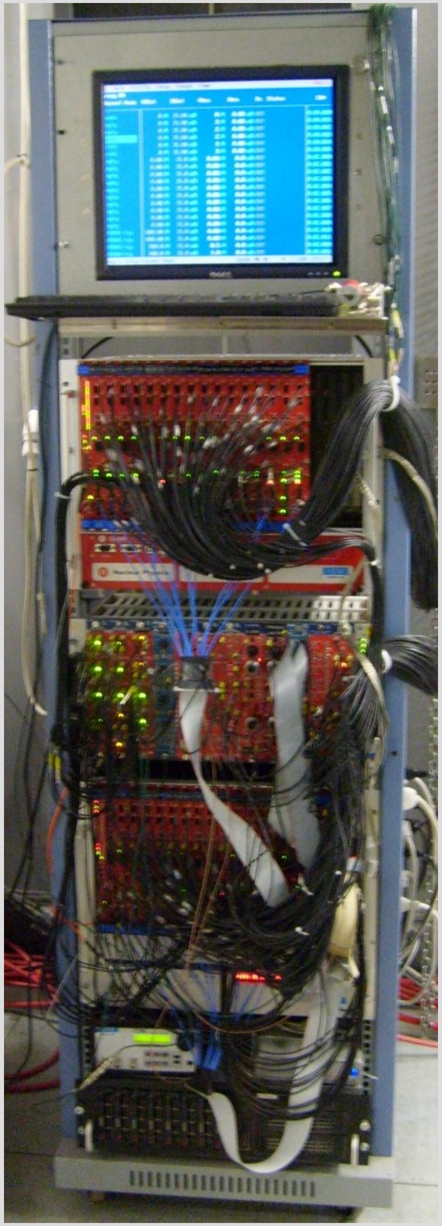
- digitize full waveform (320µs) of 242 PMTs
- no deadtime
- higher rate capability for calibration

CAEN V1724 Flash ADC: 14bit, 100MHz

- circular buffer → no deadtime
- on board FPGA: *Zero Length Encoding*



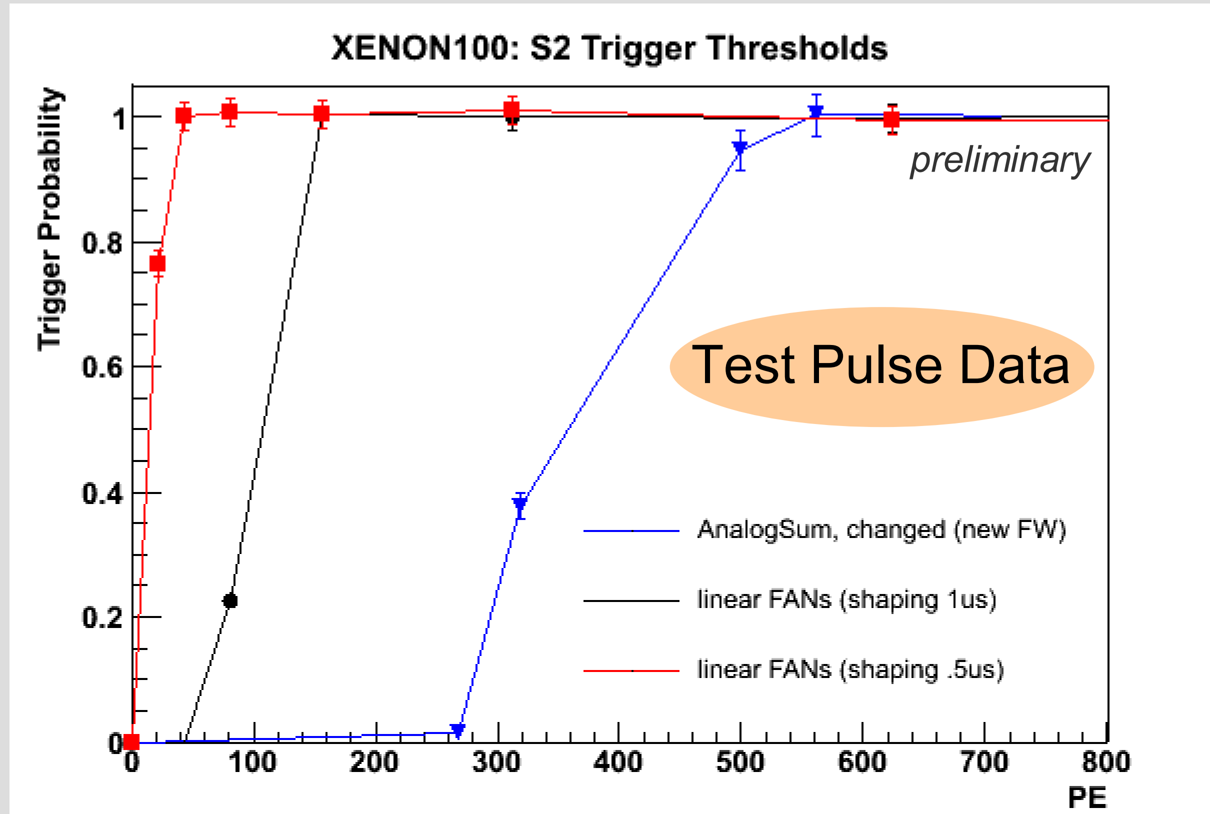
⇒ calibration rates ~20 Hz possible

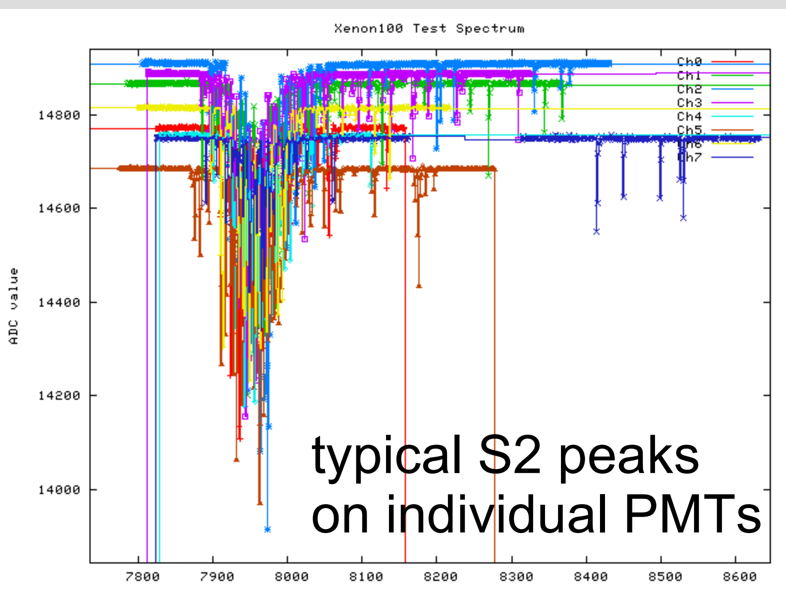


Low Trigger Threshold (S2)

XENON10

- S2 trigger efficiency 100% above 100 PE
- threshold of 300 PE used in WIMP analysis





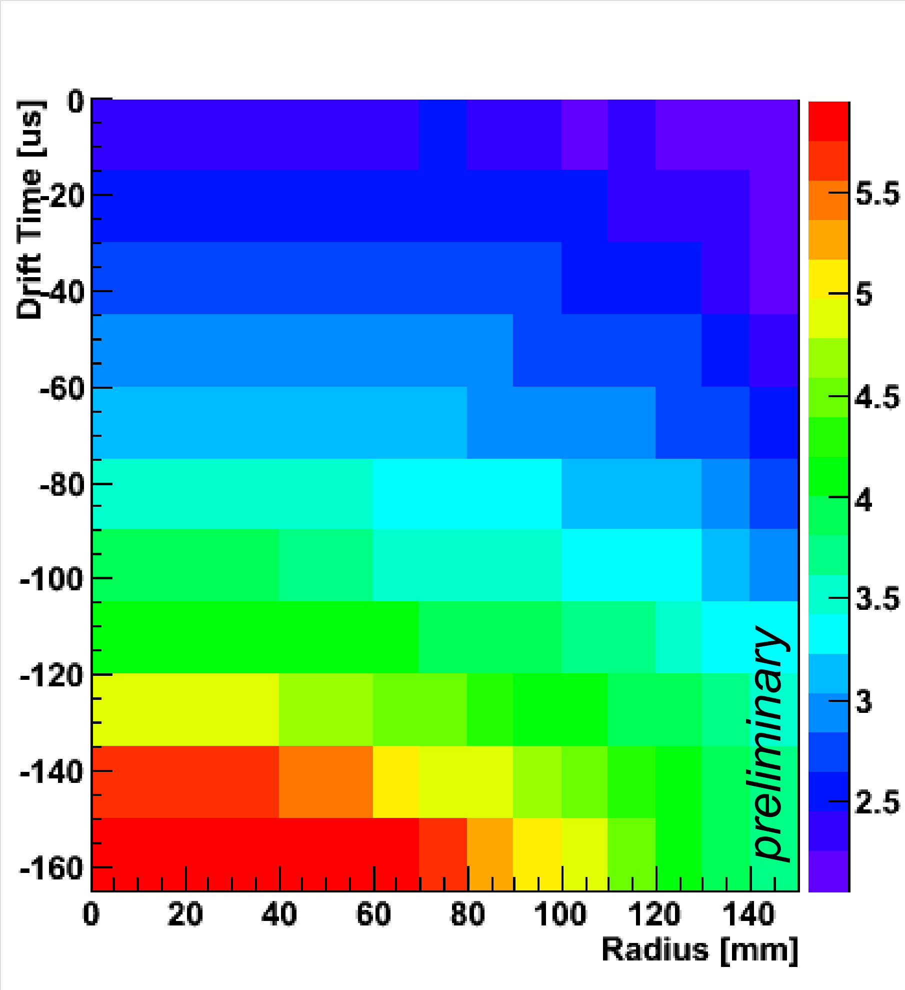
XENON100
similar S2 threshold

Averaged Light Yield

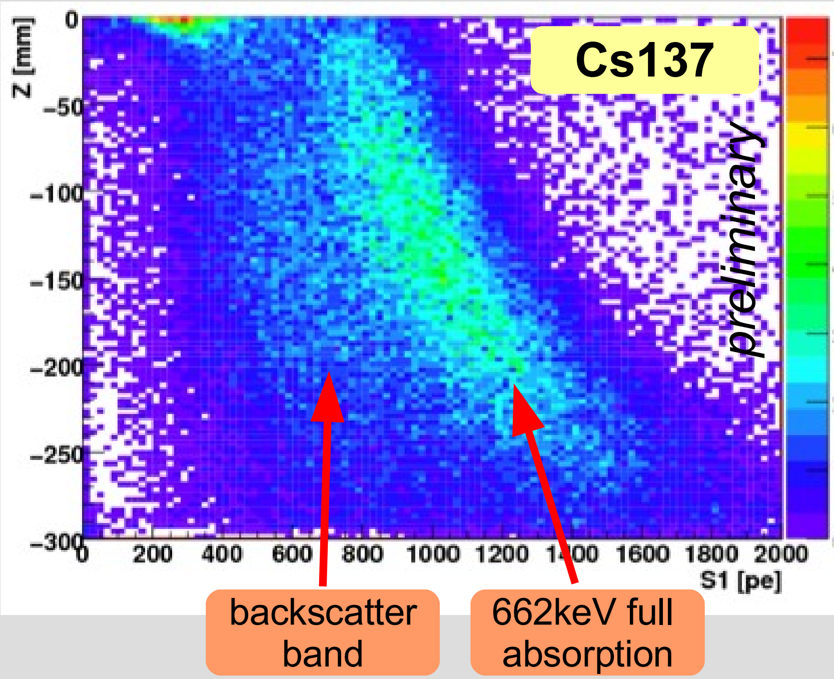
- Light collection is position dependent
- measured with Cs137, 40 keV, and 164 keV from AmBe data
- vertex reconstruction allows to obtain volume average
- maximal light yield reached corresponds to

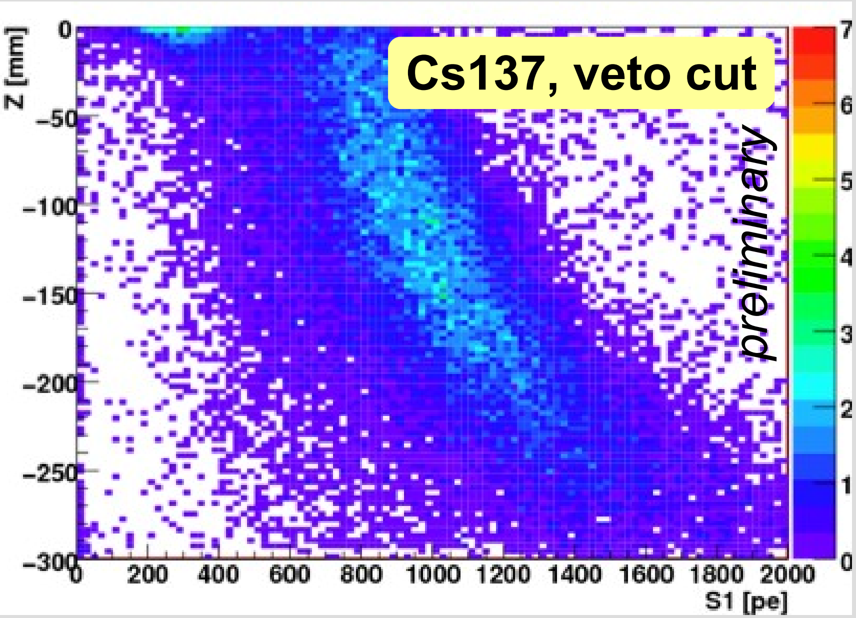
  4.5 PE/keV (zero field) @ 122 keV

  → 80% of XENON10
  (as expected from design)



Active Veto

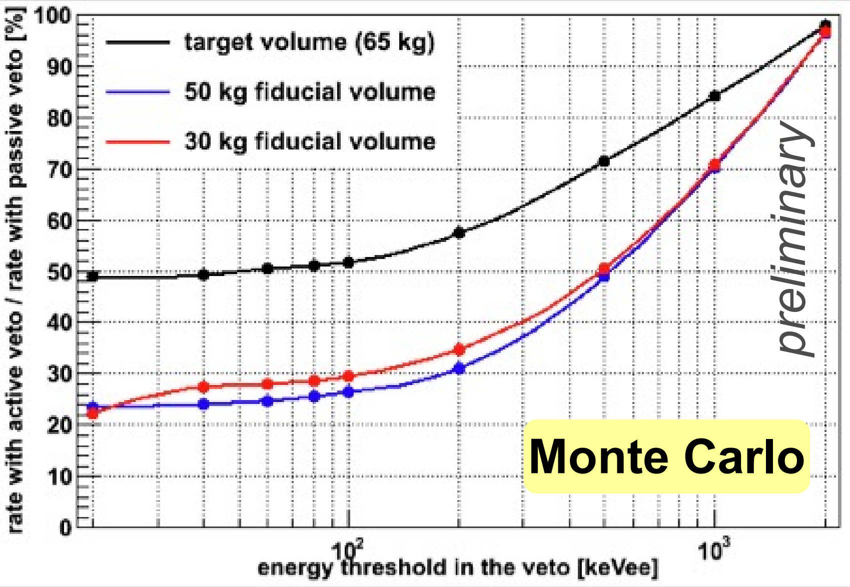




TPC is surrounded by 100 kg LXe layer (>4 cm)

➞passive shield

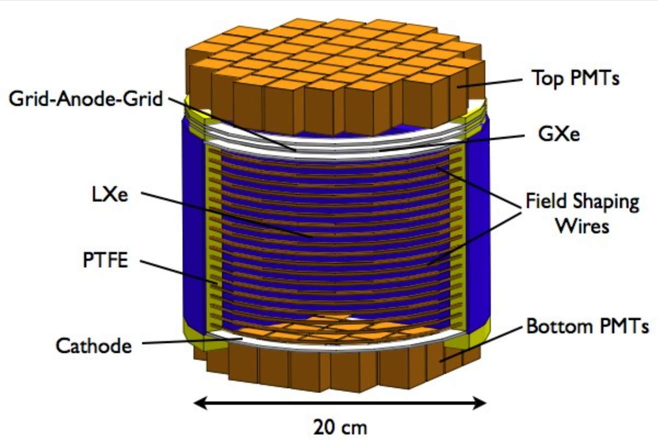
➞+64 PMTs: active veto

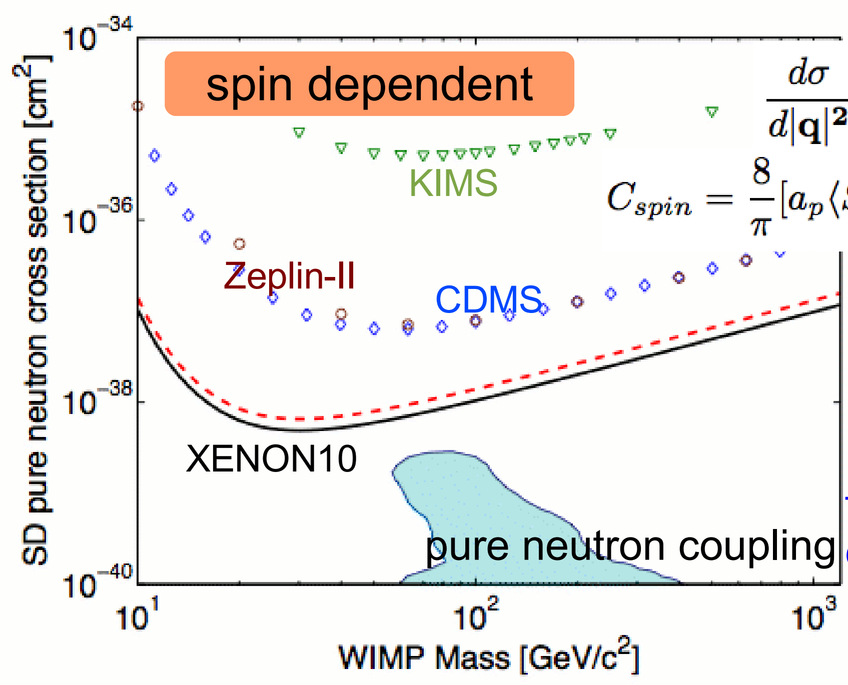


Reminder: XENON10 Results

- successful operation at LNGS 2006/07
- 15 kg dual phase detector, 5.4kg in fiducial volume
- Results:

Spin Independent:
PRL 100, 021303 (2008)
Spin Dependent:
PRL 101, 091301 (2008)





$$\frac{d\sigma}{d|\mathbf{q}|^2} = \frac{C_{spin}}{v^2} G_F^2 \frac{S(|\mathbf{q}|)}{S(0)}$$

$$C_{spin} = \frac{8}{\pi}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2 \frac{J+1}{J}$$

New best limits for pure neutron couplings (a_p=0)