9:00-9:30

Direct searches for dark matter

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Prologue

- For the last several months, direct dark matter experiments have been a very exciting subject.
  - Indications of low mass DM (a few ~ 10 GeV)?
    - DAMA/LIBRA, CoGeNT, (CRESST-II)
  - Limits and exclusions?
    - CDMS-II, EDELWEISS, XENON10, XENON100
- Many papers: 'try' to reconcile those results and show indications of dark matter in various scenarios
- In my talk, however, I will not explain the various efforts to reconcile the conflicting experiments.
- Instead, I will discuss on what experimentalists should do in order to clarify or strengthen the observed results.

Galactic Dark Matter

- Isothermal Halo Model (Standard Halo Model)
  - a single component isothermal sphere with a Maxwellian velocity distribution

$$f(v)dv = \frac{4\pi v^2}{(v_0^2\pi)^{\frac{3}{2}}} e^{-\frac{v^2}{v_0^2}} dv$$

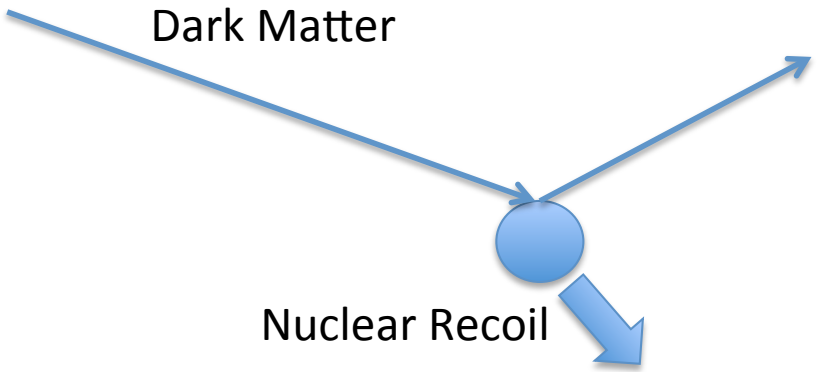
Typical Values:

- V_0 = 220km/s
- $\langle v_{DM}^2 \rangle$ = 270km/s
- Escape speed, $v_{esc} \sim$ 550km/s
- Density: ρ_x = 0.3 GeV/cm^3

Values and uncertainties of these astrophysical parameters have been revisited and reevaluated, and still under the discussion

$$\phi \sim 10^5/cm^2/s \cdot (\frac{100GeV}{m_\chi})(\frac{\rho_\chi}{0.4GeV/cm^3})$$

Direct Detection

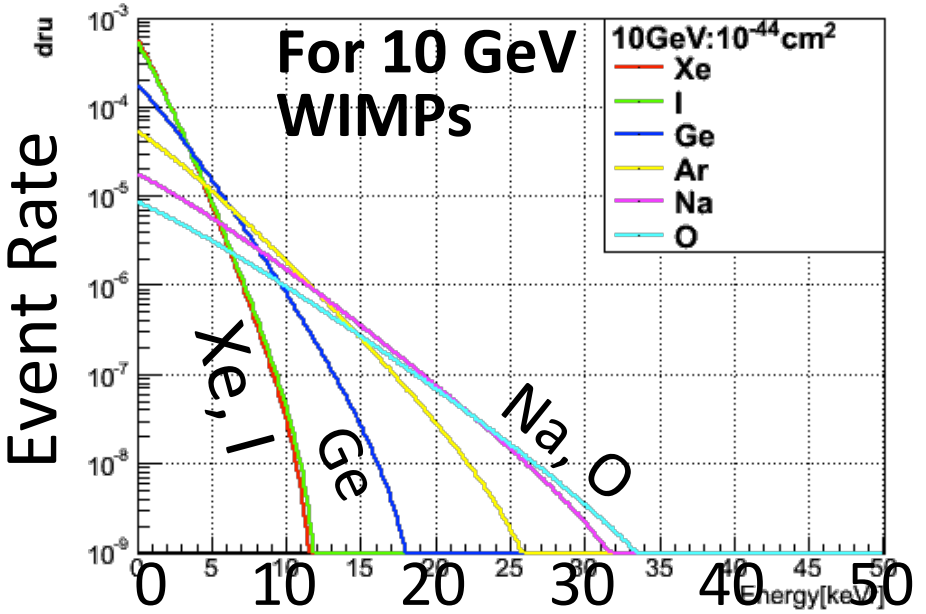


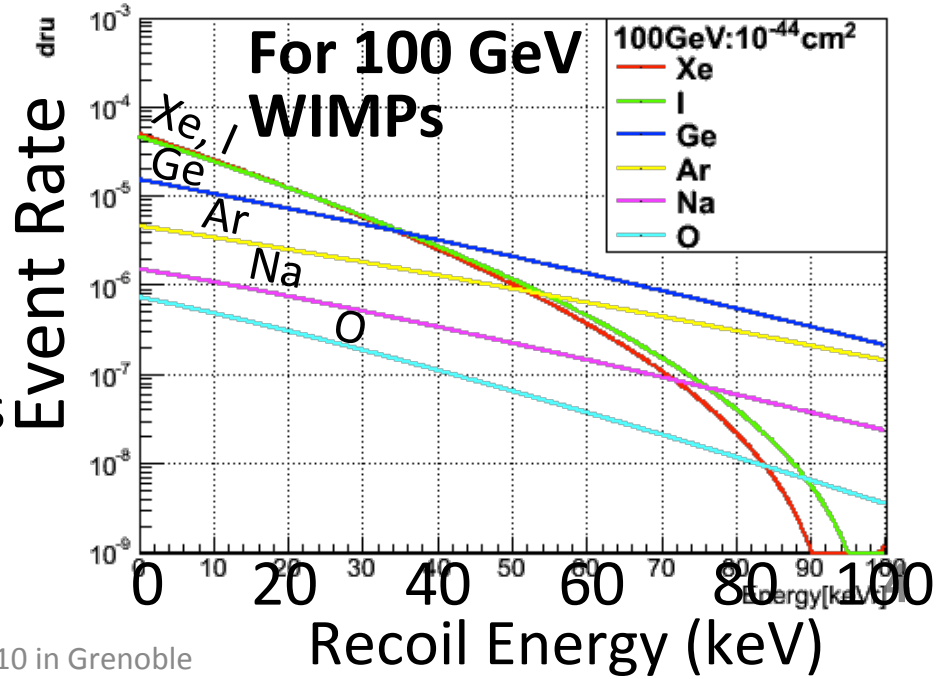
- Direct searches : Observe Nuclear Recoils
  - χ + N ➔ χ + N
- Recoil Energy:

  ➔Kinetic energy of DM

$$E_R = \frac{M_\chi v^2}{2} \frac{4M_\chi M_A}{(M_\chi + M_A)^2} \frac{(1 - cos\theta)}{2}$$

  - 1~100 keV
  - For low mass DM, sp. become very soft for large target masses like Xe, Ge,,
    - Loose efficiency unless lowering the threshold





Event Rate

$$R \sim \sigma_{\chi-N} \times n < v > \propto \sigma_{\chi-N} \times (\frac{\rho}{M_x}) \times \int v f(v) dv$$

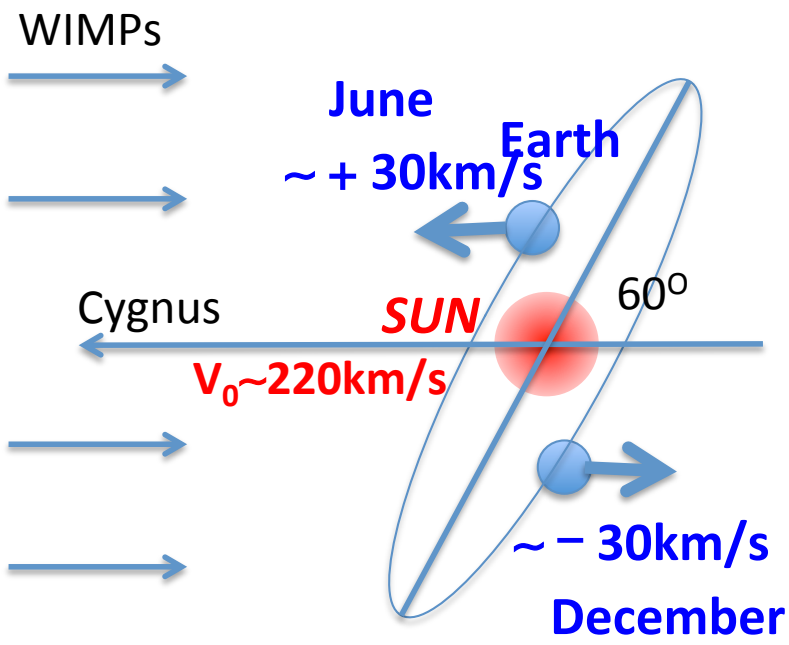
$$\sigma_{\chi-N} = \sigma^{SI}_{\chi-N} + \sigma^{SD}_{\chi-N}$$

$$\sigma^{SI}_{\chi-N} = A^2 \frac{\mu^2_{\chi-N}}{\mu^2_{\chi-p}} \sigma^{SI}_{\chi-n} \qquad \sigma^{SD}_{\chi-N} = \frac{\lambda^2 J(J+1)}{0.75} \frac{\mu^2_{\chi-N}}{\mu^2_{\chi-p}} \sigma^{SD}_{\chi-n}$$

TYPICAL:

- ~0.1 ev/day/100kg-Xenon
  for m_χ = 50 GeV and $\sigma_{SI}=10^{-44}$ cm^2
  with 10keV$_{NR}$ threshold, 30% eff

- Seasonal variations of the velocity: ±30km/s ➔
  < ~ 10% modulation effects
  - depend upon spectrum shape, trigger efficiency, analysis cuts and so on

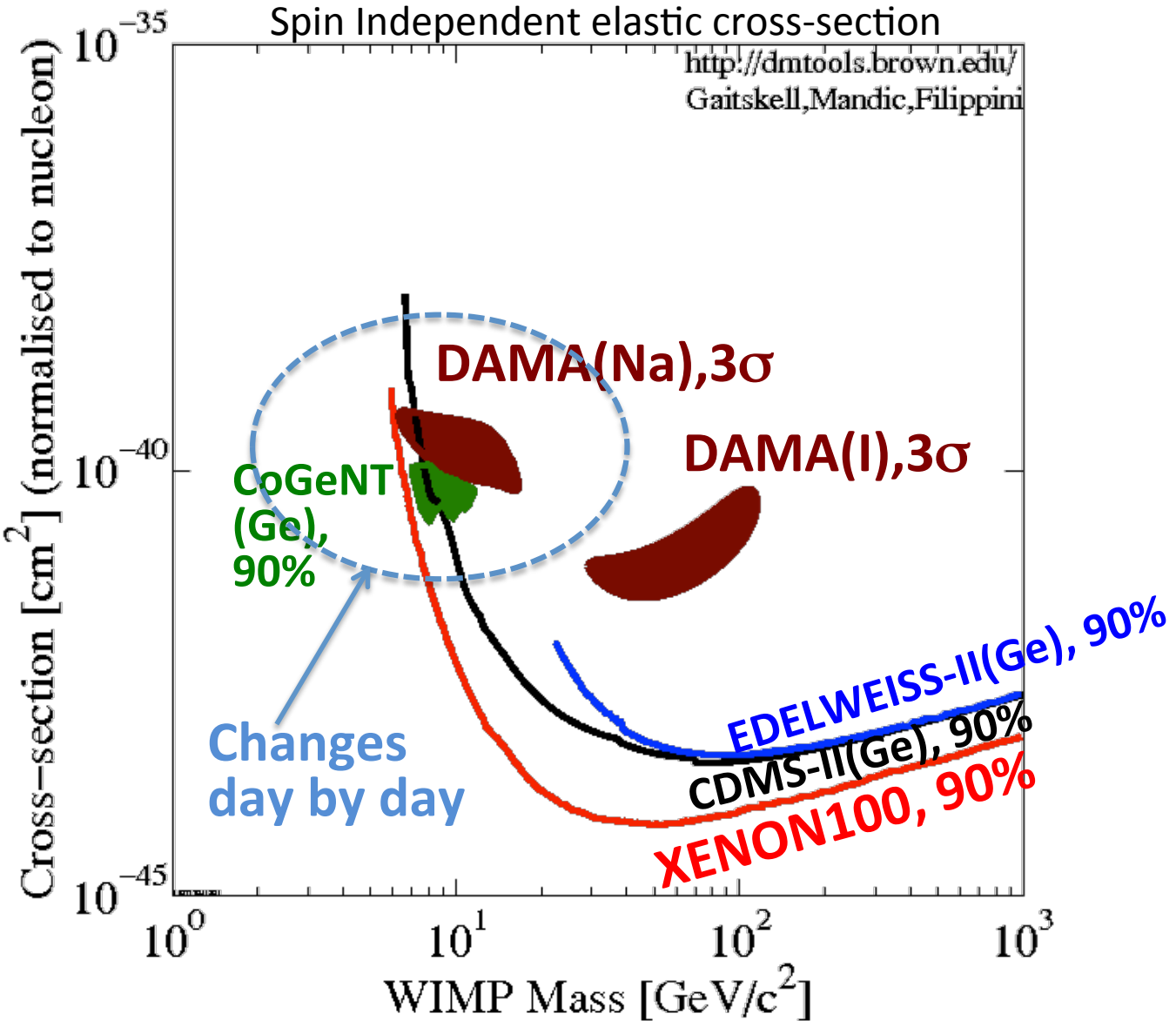


Recent Status

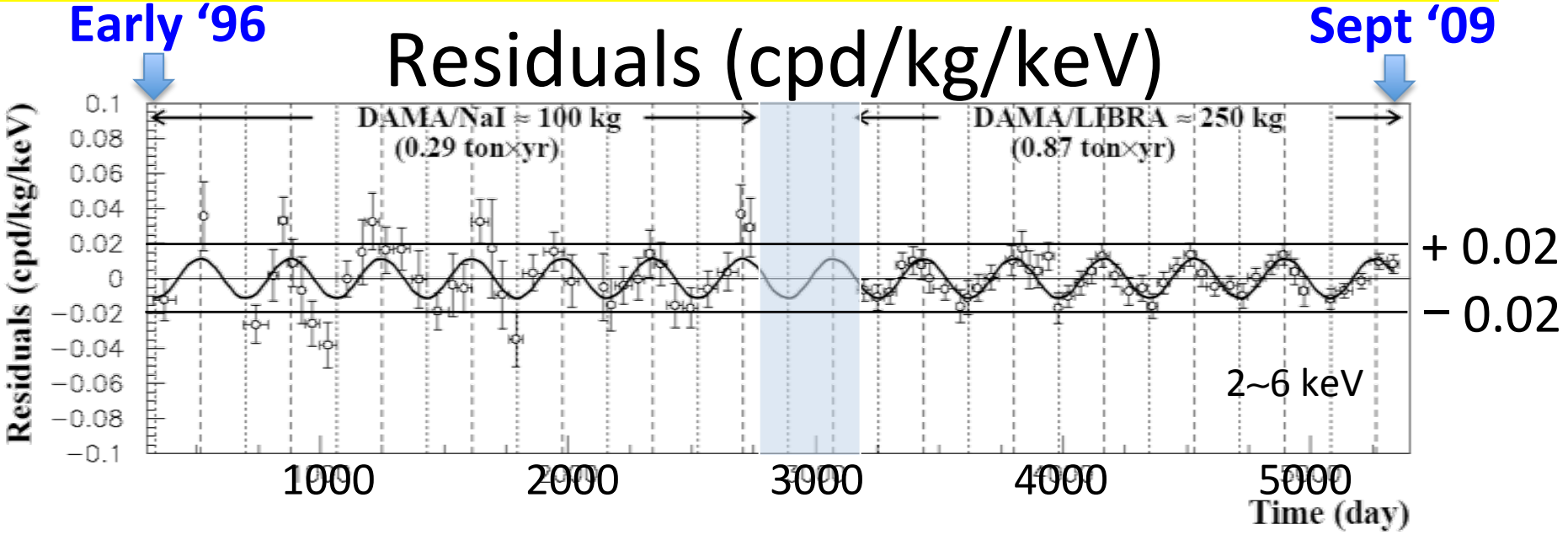
Sorry,
We did not plot all the results

CRESST-II:
Wait until their FINAL results

Low threshold Analysis by CDMS-II (LE) and XENON-10 (LE)

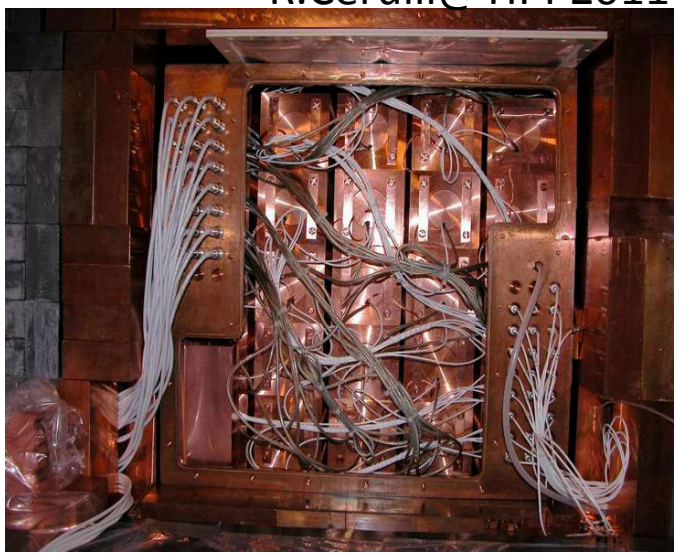


DAMA/LIBRA



- DAMA/LIBRA: <u>High purity low BG NaI</u>
  - Single module: 9.70 kg
  - 5x5=25 modules, (10.3x10.3x25.4)cm^3
- ~250kg NaI(Tl) for DAMA/LIBRA
- Total exposure: 1.17 ton-yr (13 cycles)
  - 427,000 kg-days

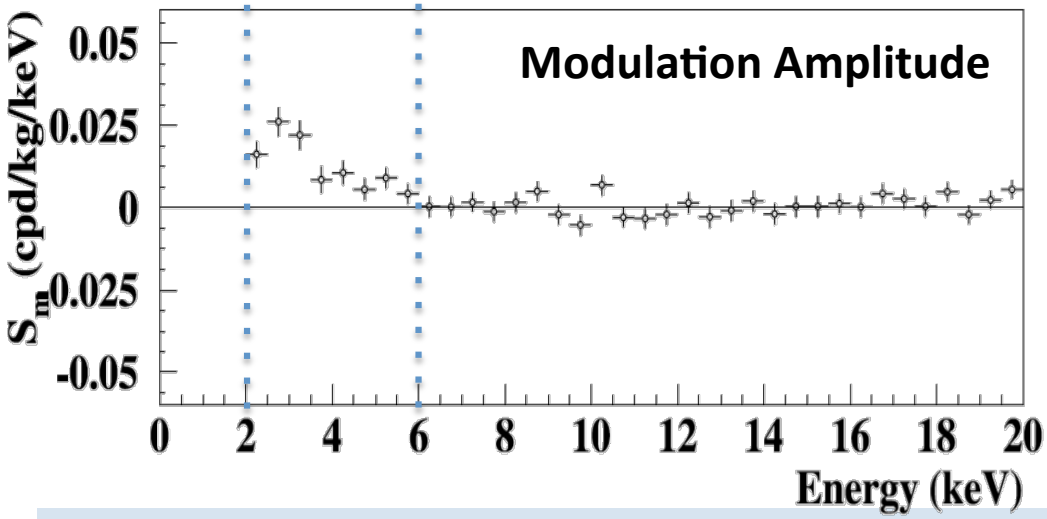
R.Cerulli@TIPP2011



View at the end of DAMA/LIBRA

Results

- Data selection:
  - Noise cuts
  - Select single-hit events
- Modulation (**8.9σ**)
  - $S_k=S_0+S_m\cos\omega(t-t_0)$
  - Amplitude(S_m):for 2~6 keV
  - 0.0116±0.0013 cpd /kg / keV (dru)
  - Phase (peak): 146±7 days
    (DM_{peak}:June-2: 152.5 days)
  - Period: 0.999±0.002 yr.

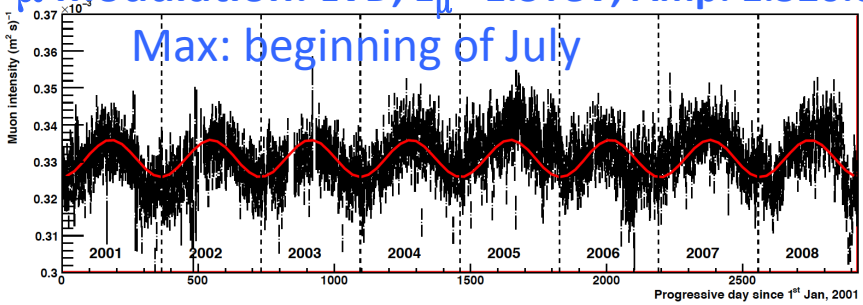


- Effects to mimic modulation ?

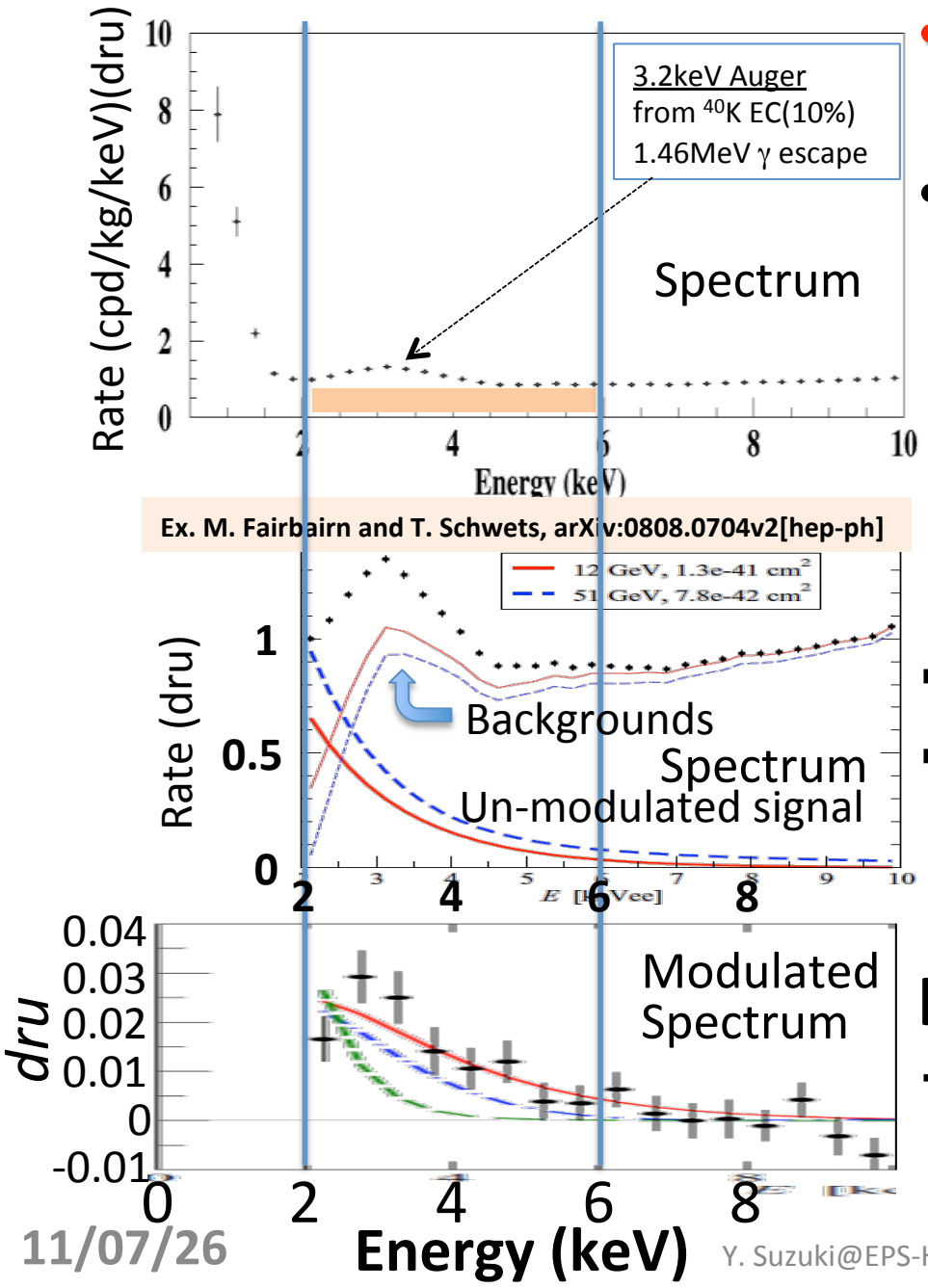
(~1.2x10^{-2} dru)

Temperature: < 10^{-4} dru	No!
Rn: < 2.4x10^{-6} dru	No!
Noise: < 10^{-4} dru	No!
Energy scale < 2 x 10^{-4} dru	No!
Efficiency: < 10^{-4} dru	No!
Backgrounds	No!
← > 6keV & multi-hits: <10^{-4} dru	
μon flux variation: < 3x10^{-5} dru	No!

μ modulation: LVD, E_μ> 1.3TeV, Amp: 1.5±0.6%



Question: Where is the un-modulated part of signal, S_0 ?



- ***Must be in somewhere underneath of the spectrum !***
- In most of the elastic scattering cases, $S_0(E)$ monotonically goes down as energy increase, then backgrounds must sharply goes down below 3~4 keV.

➔**This may not be natural**

➔**<u>Simple Elastic Scattering interpretation may have a internal inconsistency?</u>**

Inelastic ? → also strong tension

→ Other scenarios ???

Also similar study: V. A. Kudryavtsev et al. J. Of Phys. Conf. Ser. 203(2009)012039

DAMA/LIBRA

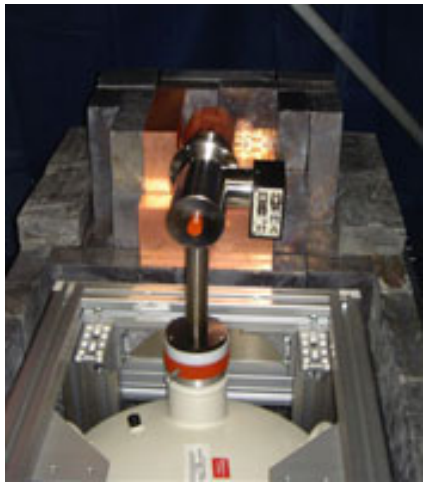
- DAMA/LIBRA has shown the beautiful modulation effect
- If they are able to identify all the remaining BG and estimate the un-modulated part of the signal, it will strengthen even the observed modulation

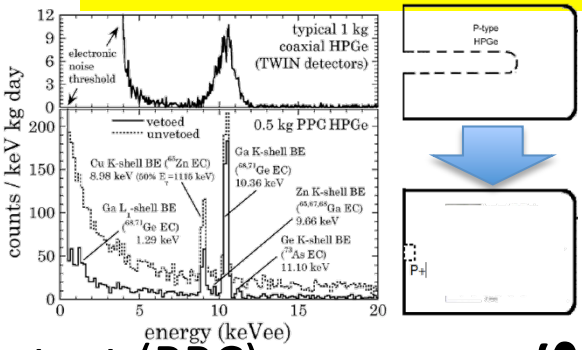
DAMA (Future)

- Upgrade in Sept 2008 (partial) and in Oct/Nov. 2010.
  - New-Digitizers 1 GS/s, 8bits
  - Replacement of all the PMTs w/ high QE
- ➔ Keep taking data !

CoGeNT

Coherent Germanium Neutrino Telescope

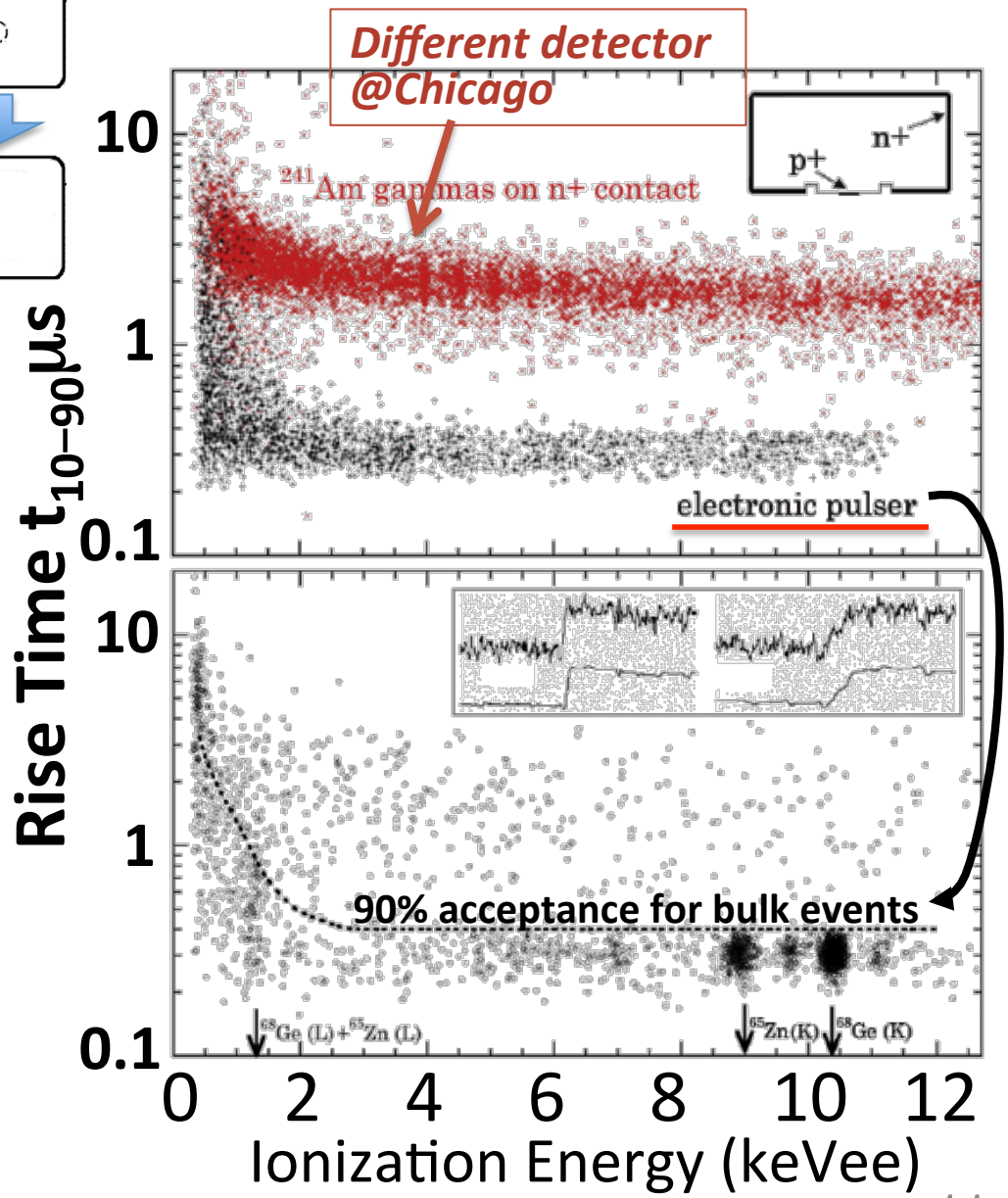




- P-type Point Contact (PPC) germanium detectors: 440g
  - High resolution (low C)
  - Obs. Cosmogenic peaks
- Threshold ~ 0.4 keVee (lowest)
- No Nuclear Recoil separation
- Reject surface events

  (~external γ's)
  - (n+) 1mm: dead, 1mm transition

  ← rise time difference:
  - bulk (0.3 μs ~ 2 μs @low energy)
  - Surface (2 μs ~ 4μs @low energy)



CoGeNT

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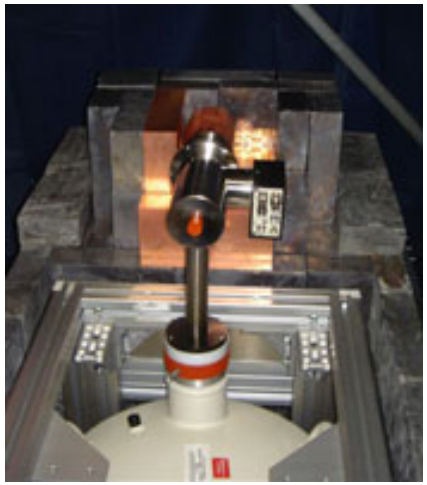

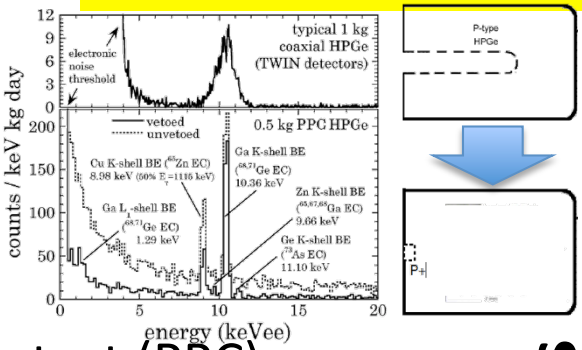

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  ← rise time difference:
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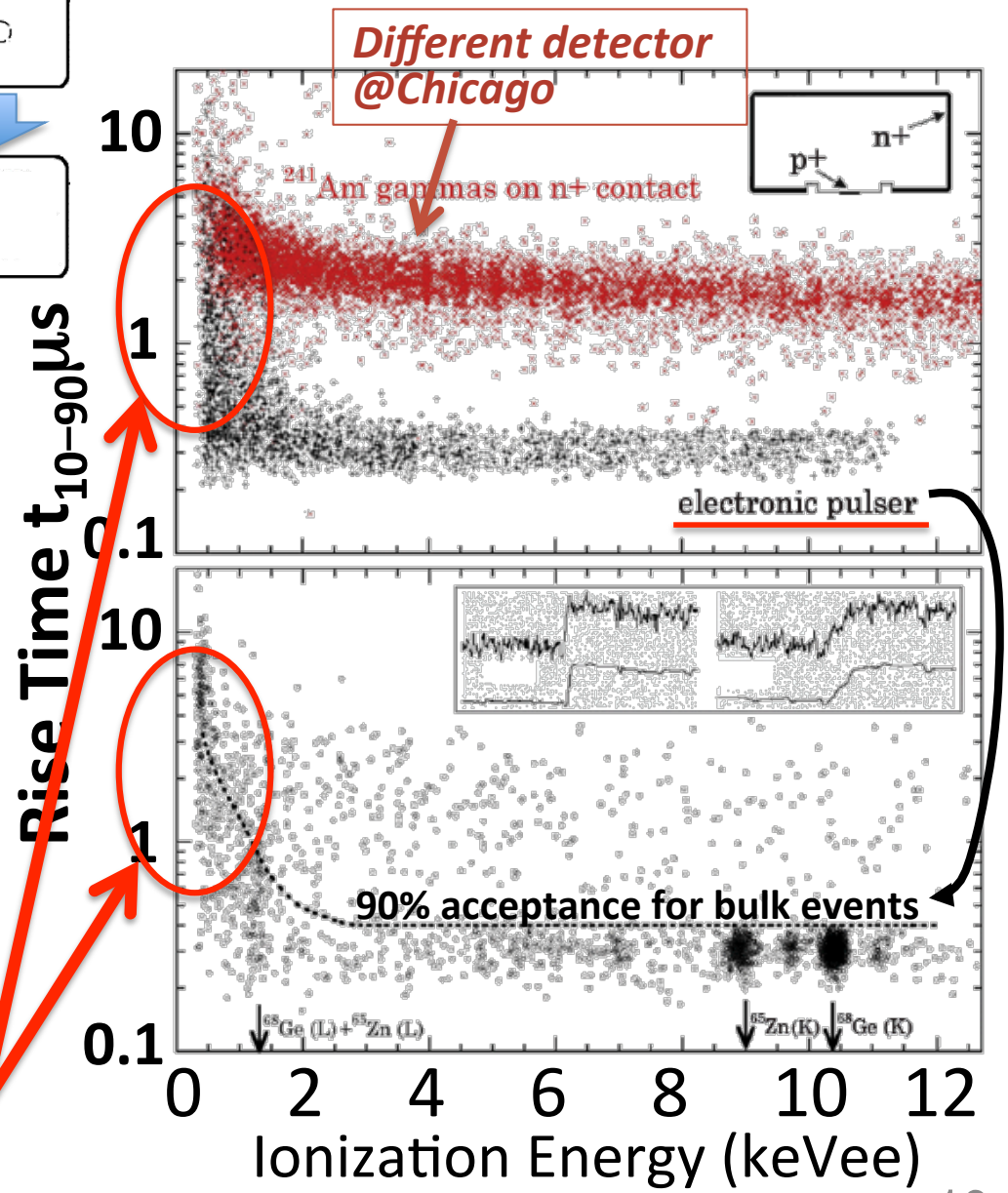
  - Surface (2 μs ~ 4μs @low energy)

Leakage from surface events should be evaluated

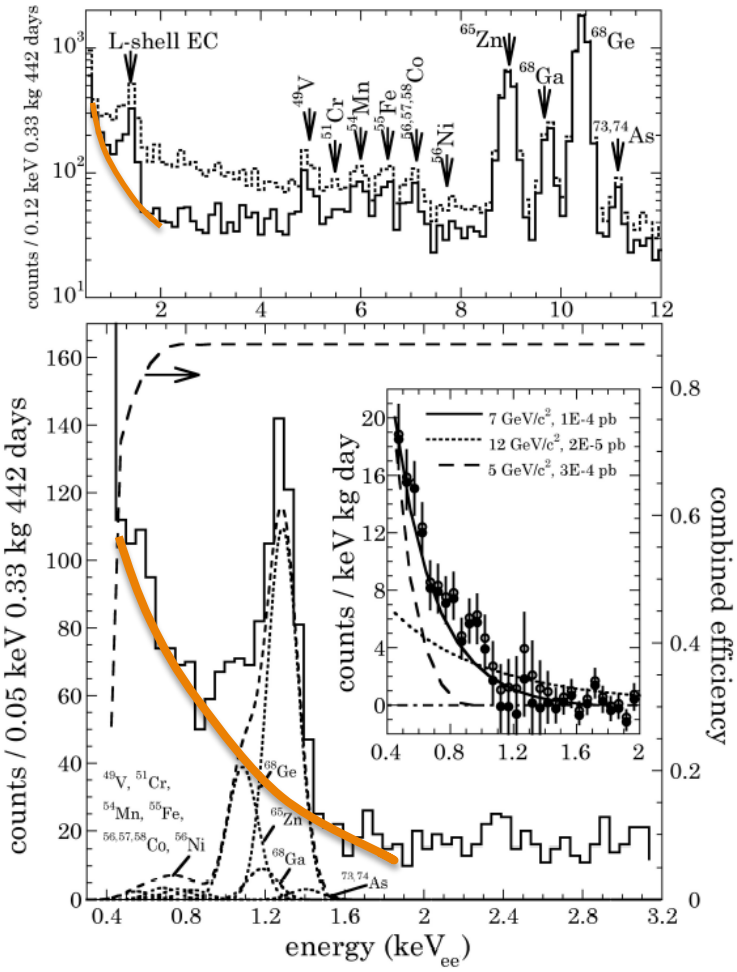


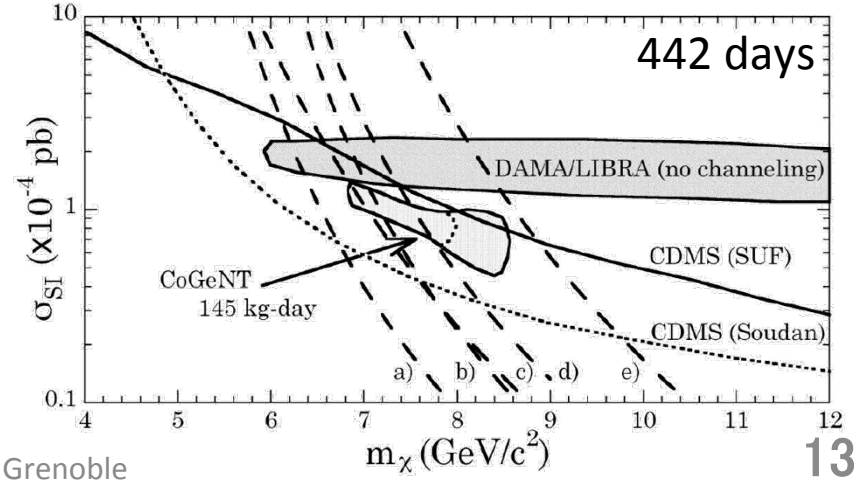
- After the timing cut, they found irreducible excess below 3 keV (unknown BG or….)
- Either electron events or NR
- Known Backgrounds
  - L-shell EC below ^{65}Zn (<10%)
  - Neutron(~0.1%)
  - Leakage of the surface events:

    no evaluation

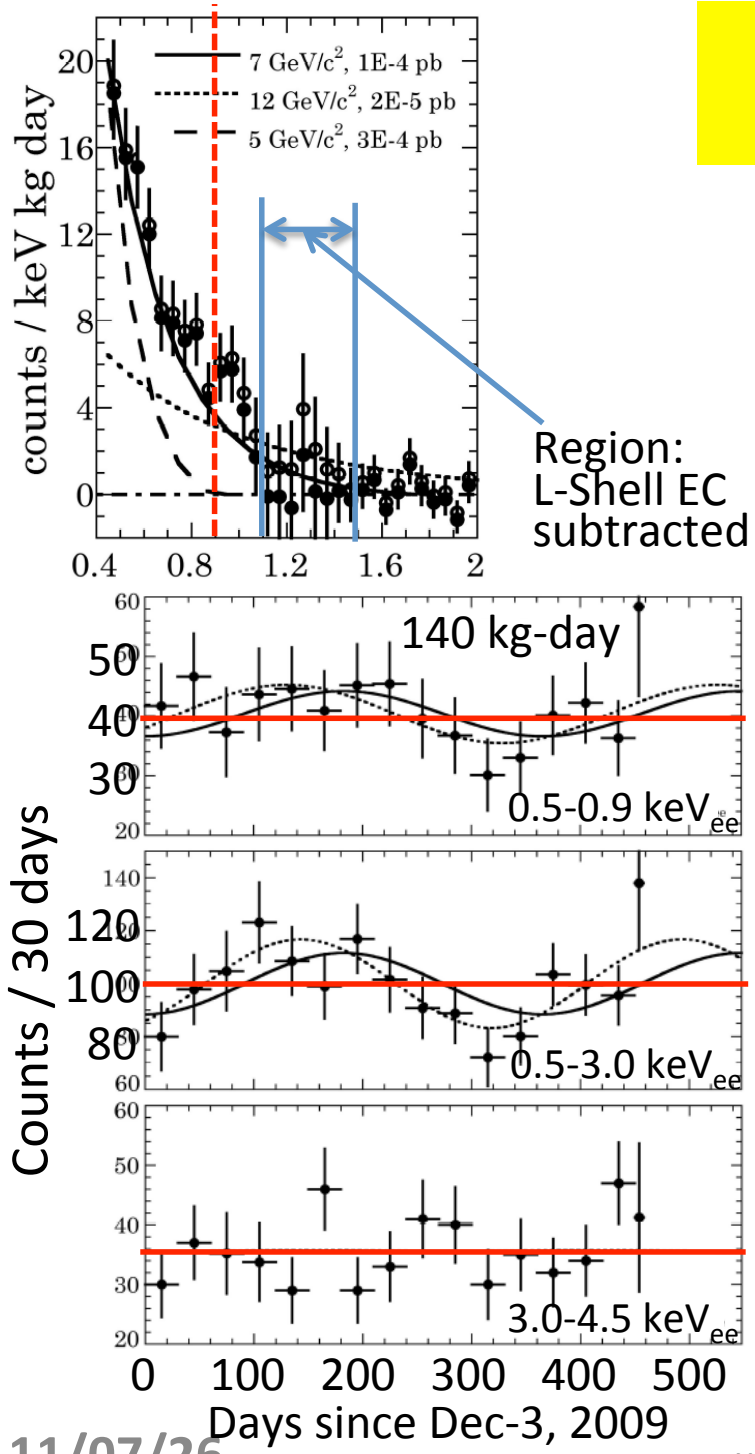
    They said that any such contamination should be modest (PRL106,131301)

➔ Need clear and quantitative evaluation of the leakage from the surface events





CoGeNT modulation



- Data: Dec-4th 2009 ~ March-6th 2011 (442 effective days)
- Assume: all the unknown excess is 'signal'
- Modulation (0.5 – 3.0 keVee)
  - χ^2/d.o.f. = 7.8 /12 (80% C.L. Accept.)
  - χ^2/d.o.f. = 20.3 /15 (85% C.L. Reject.) for null hypothesis
  - 99.4% C.L. (2.8 σ)
- Amplitude: 16.6±3.8% (347±29 days periods)
  - Minimum: Oct 16±12 d
- Modulation between 0.5 -3.0 keV may be too strong

➔ Wait more data

- CoGeNT Next:

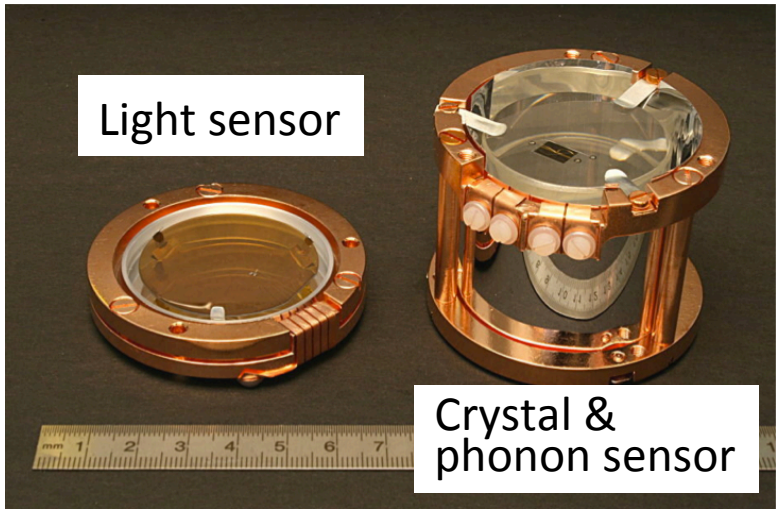
  ➔ 4 crystals (C4)

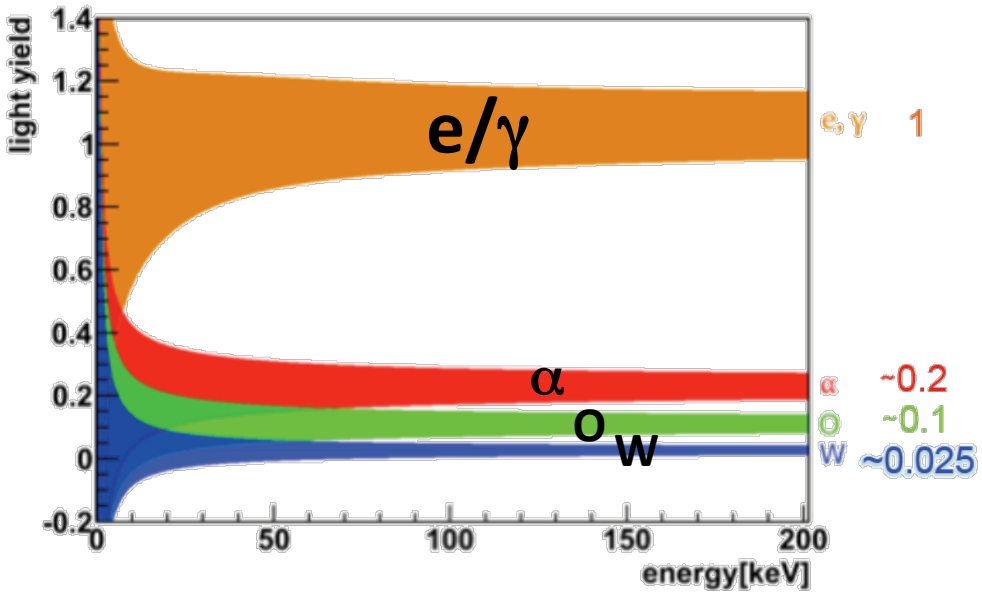
CRESST-II

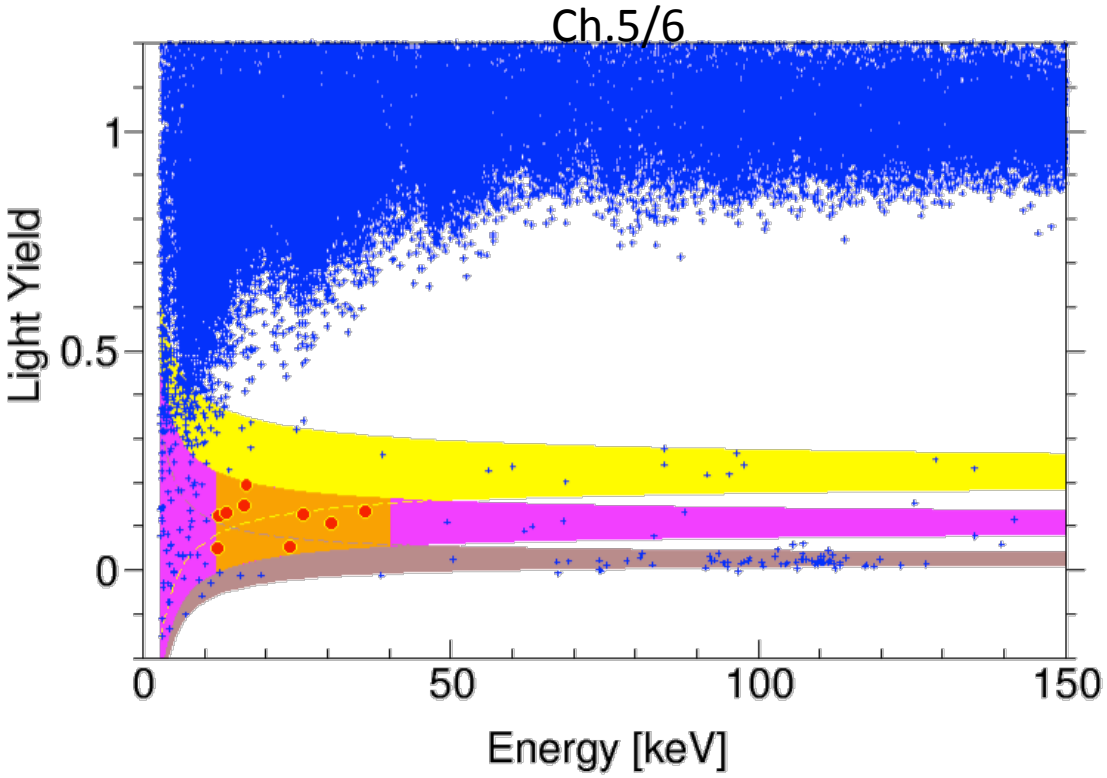
- Final results @TAUP2011
- $CaWO_4$(Multi-material target)
  - up to 10 kg, 33 crystals, (0.3kg each)
  - phonon (~10 mK)
  - Scintillation

    ➔ Reduced light output for nuclear recoils

    ➔ Light output decreases with increasing mass number of recoiling nucleus
- Run32
  - June 2009 – April 2011
  - > 700kg*days
  - 10 detector modules

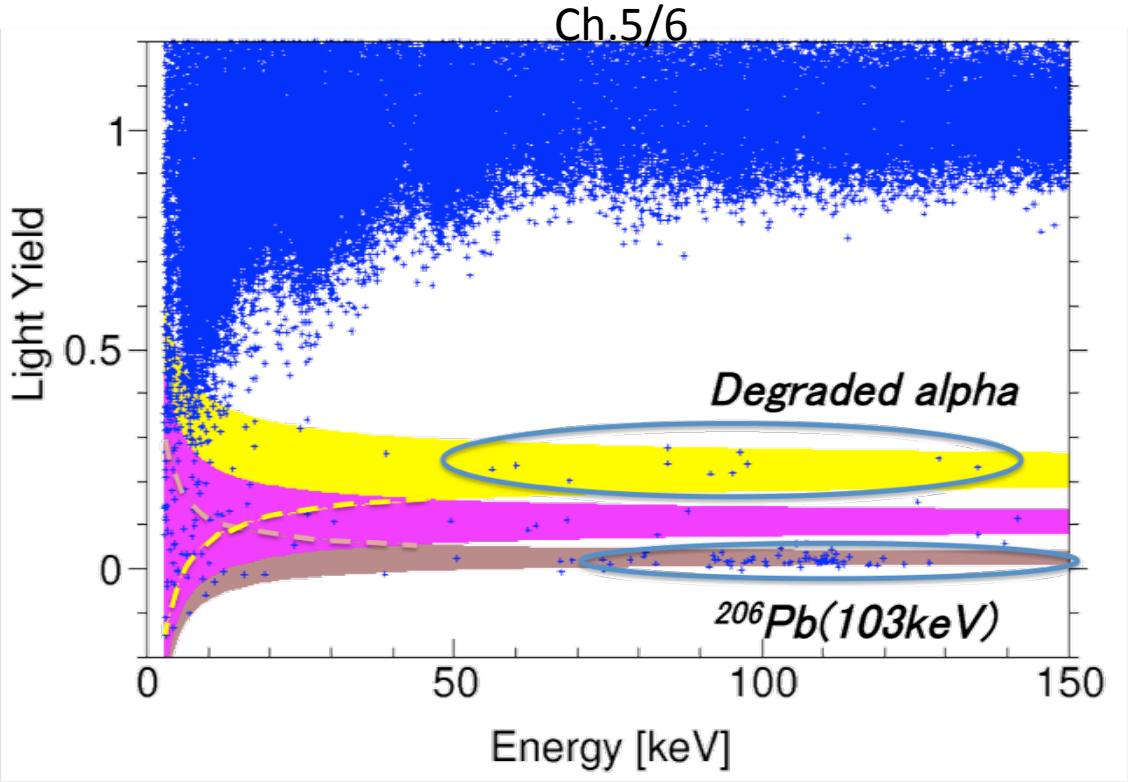






- CRESST (Future)
  - New run with reduction of BG
    - Improved detector holder (clamps)
    - Additional neutron shielding
    - Start fall in 2011
  - CRESST III : 20 kg of CaWO4 in upgraded cryostat, not funded

- O-band events
  - 50 events
  - 4.6 σ
- Estimated BG (~61%(30ev))
  - e/γ events: 15%
  - Neutron events (O) 30%
  - α related: 16%
    - Degraded α events
    - ^{210}Po→ ^{206}Pb(103keV) +α(out)
  - "room for signal": 39%
  - No errors shown yet
- Wait Taup2011

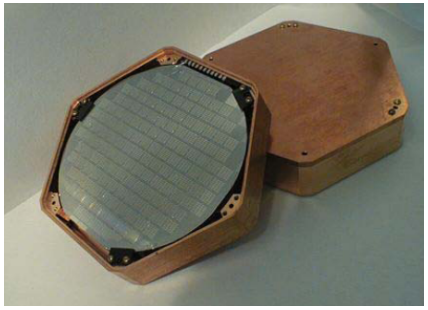


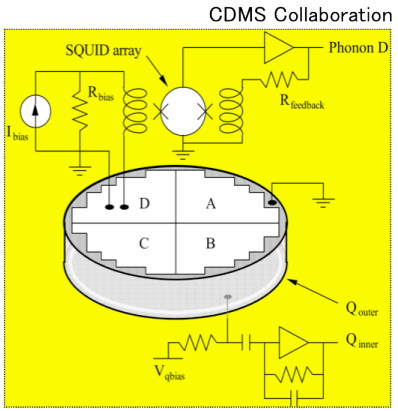
- CRESST (Future)
  - New run with reduction of BG
    - Improved detector holder (clamps)
    - Additional neutron shielding
    - Start fall in 2011
  - CRESST III : 20 kg of $CaWO_4$ in upgraded cryostat, not funded

- O-band events
  - 50 events
  - 4.6 σ
- Estimated BG (~60%(30ev))
  - e/γ events: 15%
  - Neutron events (O) 30%
  - α related: 16%
    - Degraded α events
    - ^{210}Po→ ^{206}Pb(103keV) +α(out)
  - "room for signal": 39%
  - No errors shown yet
- Wait Taup2011

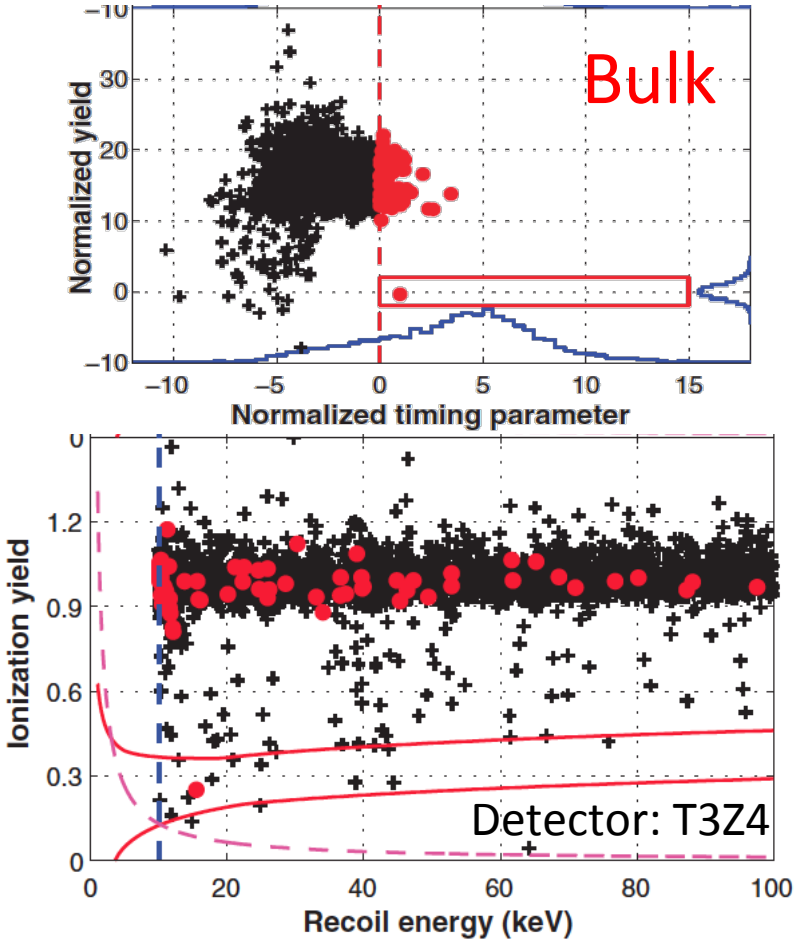
CDMS-II

- Ge(&Si) detector (~10mm thick and ϕ=76mm)
- 230g x19 ~ 4 kg
- Ionization and phonon (<50mK)
  - Ionization yield ➔ 1 in 10^4 raj. for γ's
  - Timing cut ➔ <u>surface events (>10^6 raj.)</u>
- 10 keV threshold & < 100keV
- Data: 612kg-days
- 2 events found
- Backgrounds: 0.9±0.2
  - 0.8±0.1±0.2 surface events
  - 0.1 neutron events





Z-sensitive
Ionization and
Phonon-mediated

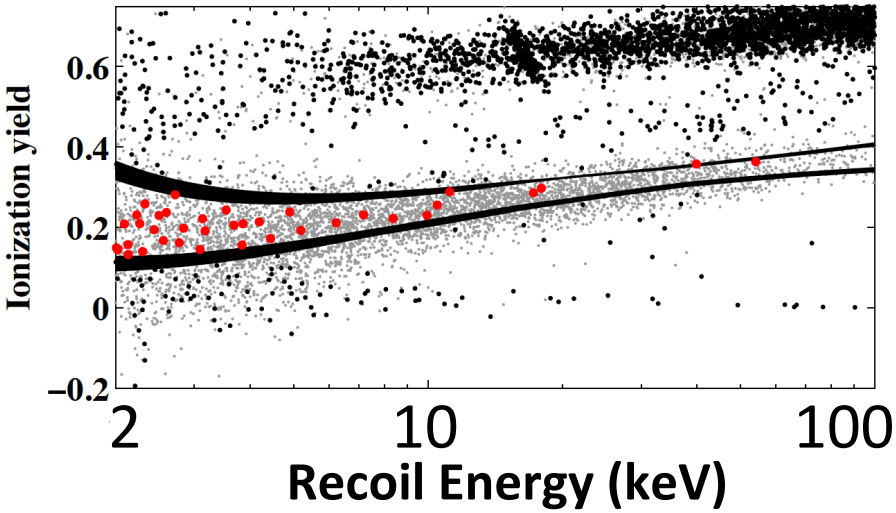


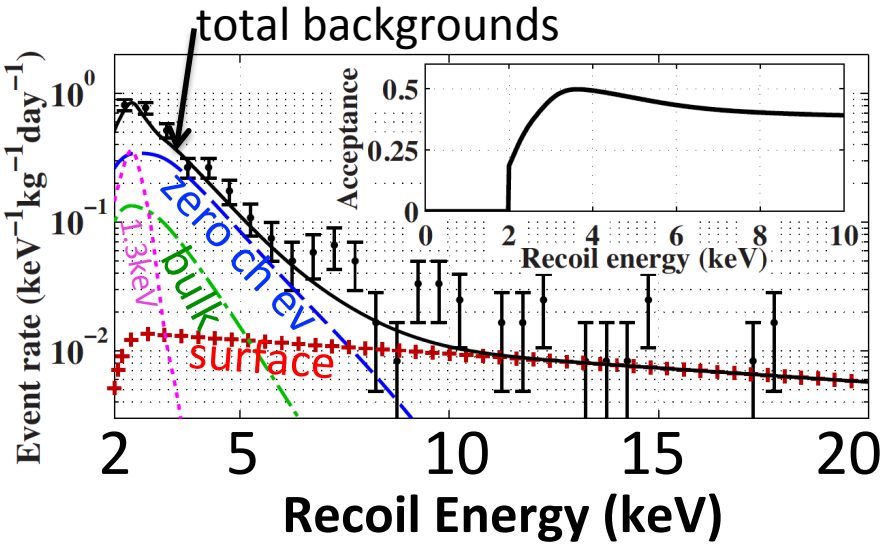
CDMS-II low threshold

- 2 keV threshold
- Only 8 low BG Ge detectors
  - Others: veto
- 241kg-days
- Remaining event shape: similar to a WIMP signal, but,

➔Un-rejected electron events

  - Zero-charge events (close to edge)
    - Charge → by side wall, not readout electrode
    - Phonon fiducialization does not work @LE ➔ remain as zero ch ev.
  - Remaining surface events
  - bulk events
  - 1.3 keV lines (L-shell EC)





Recoil energy scale assumes that the ionization signal is consistent with a nuclear recoil

CDMS-II low threshold

- 2 k
- On
  - –
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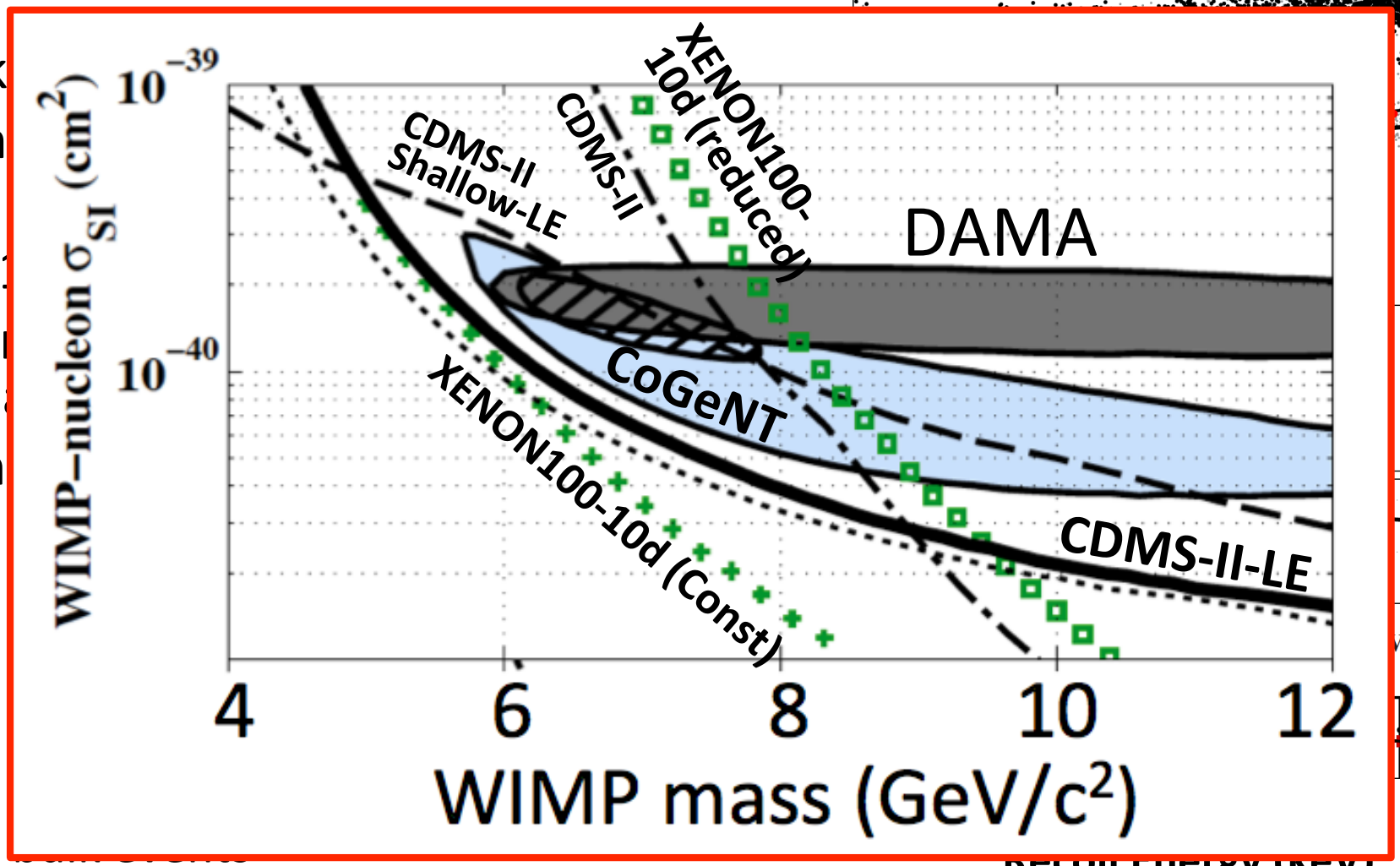
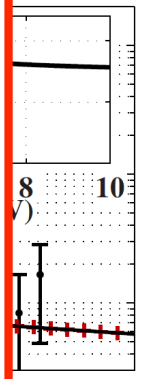
- Re
  to
- ➔ Un
  - –
  - –
  - –
  - 1.3 keV lines (L-shell EC)





Recoil energy scale assumes that the ionization signal is consistent with a nuclear recoil

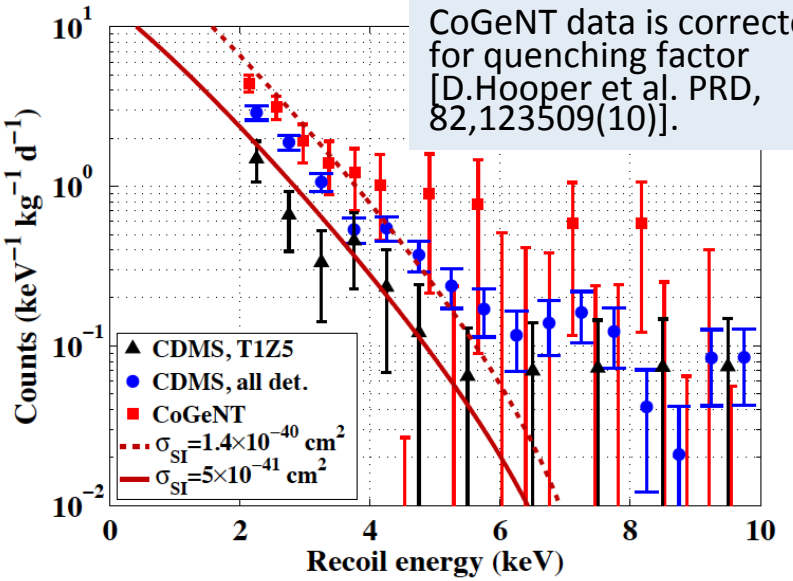
Comparison between CDMS and CoGeNT

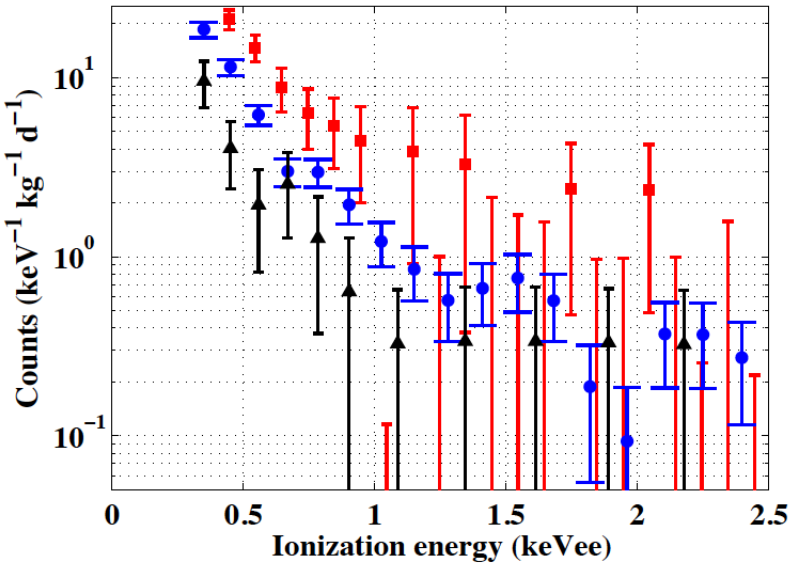
- Acceptance corrected
- CDMS selected as NR
- CDMS: Consistent with backgrounds
  - Surface, zero charge, EM bulk….
- CoGeNT: no separation for NR and EM.

➔

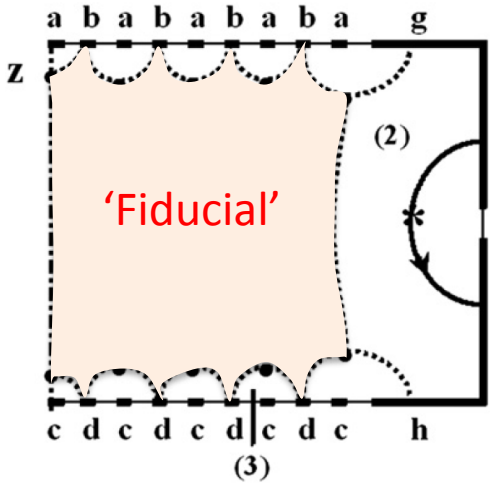
- If CoGeNT 'signal' is NR, inconsistent with CDMS, and majority is backgrounds.
- If CoGeNT 'signal' is EM, CDMS cannot tell much.

CoGeNT data is corrected for quenching factor [D.Hooper et al. PRD, 82,123509(10)].

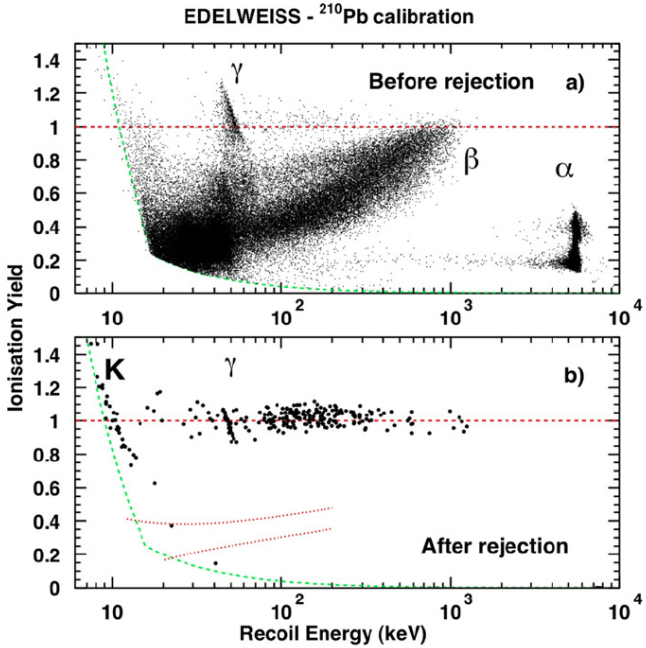




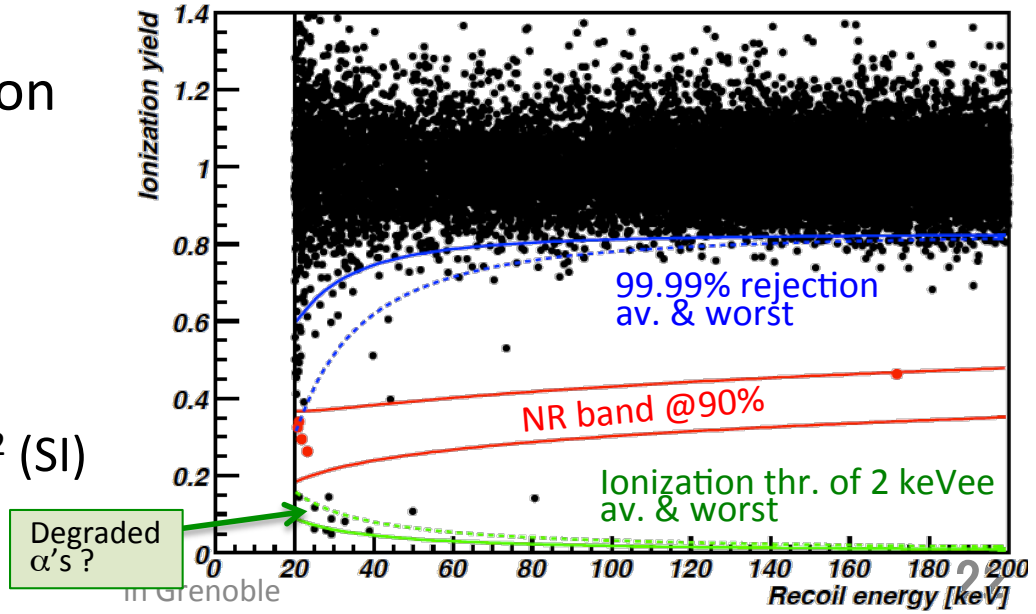
EDELEWEISS-II



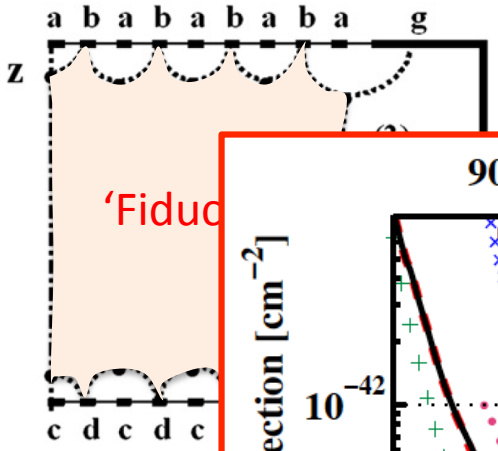
400g x 10 Ge= 4 kg (1.6kg:fid.)
Phonon+ *charge collection electrodes w/ interleaved geometry (Ge-ID)*
➔ reject of near surface events
Rej, Rate: 6×10^{-5}



- Threshold: $E_{NR} < 20$keV
- ~14 months of running: 384kg*day
- Found: 5 Nuclear Recoil events
- < 3.0 BG events
  - γ-BG leak (<0.9), surface (0.3), muon induced(0.4), neutron(1.4)
- Combined Analysis w/ CDMS-II
- Next Step:
  - Next EDELWEISS-III
    - 26kg (40 x 800g) aiming 10^{-45}cm^2 (SI)
    - Start installation in 2012

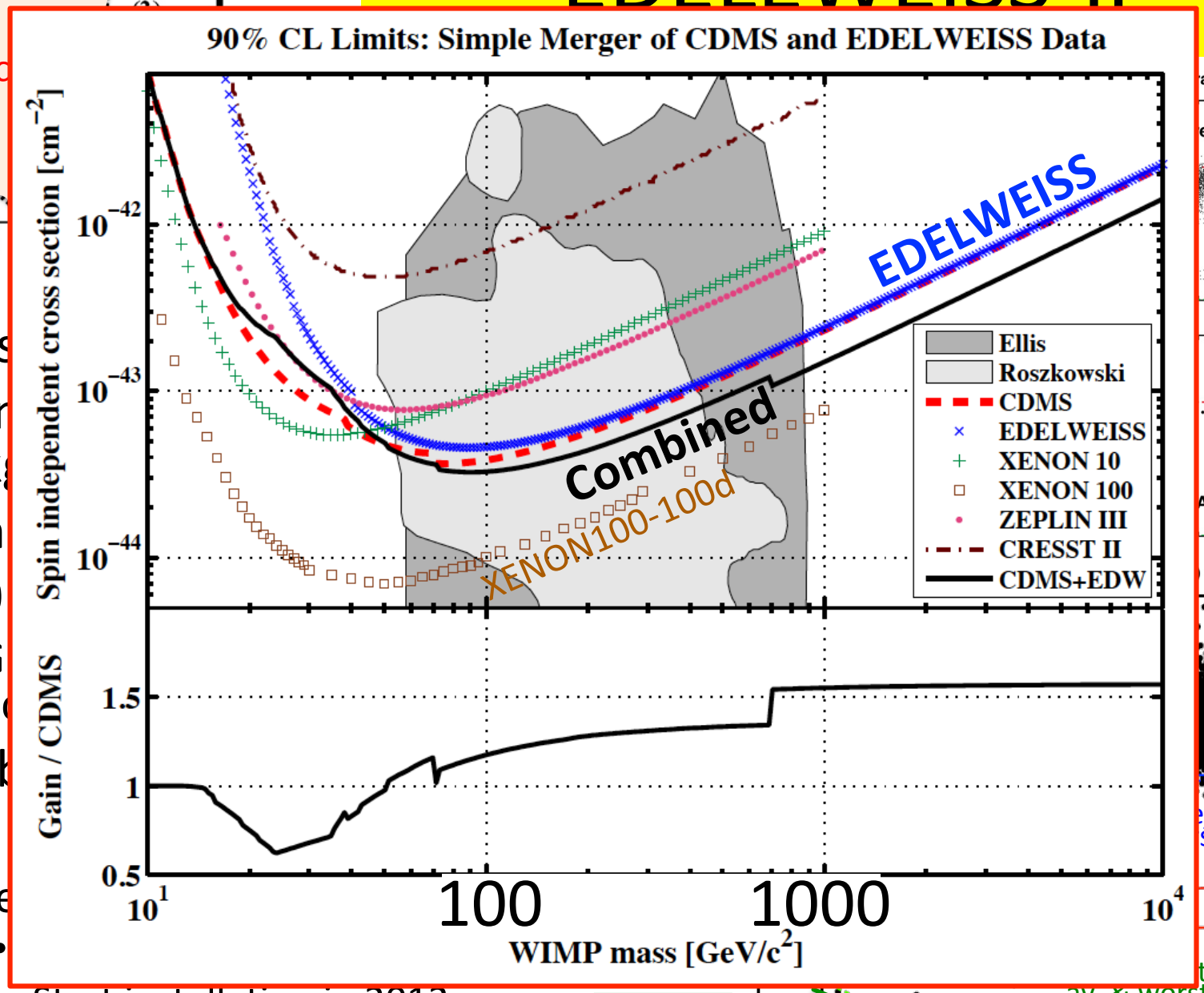


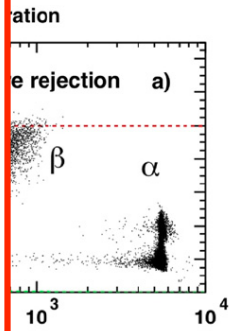
EDELEWEISS-II

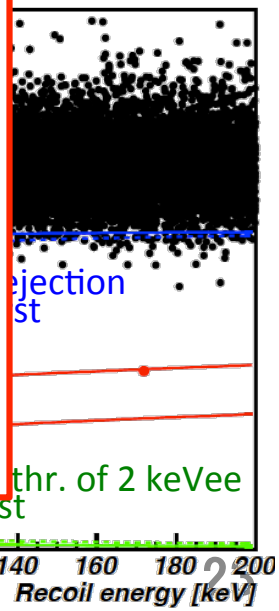


'Fiduc

- Thres
- ~14 r
  384k
- Foun
- < 3.0
  γ-BG
  indu
- Comb
- Next
  - Ne
    - Start installation in 2012

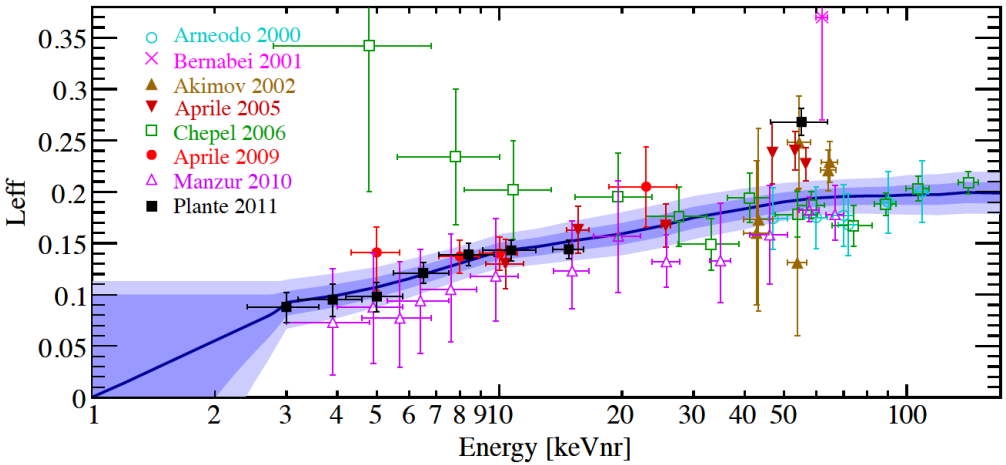




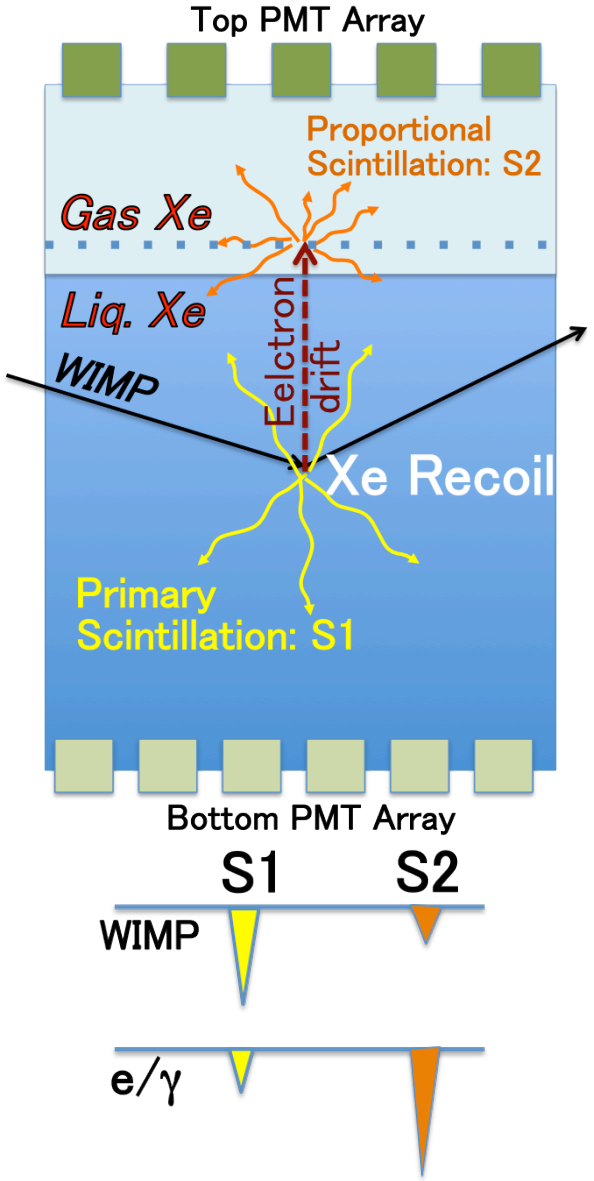


XENON-100

- Simultaneous detection of light (S1) and charge (as S2)
  - Ionization e's → S2 (prop. Scinti.)
- S2/S1 →NR and EM discri: ~1/1000
- Pos. Res.: (x,y):<3mm, z: 0.3mm
- $L_y(122keV_{ee})=(2.20\pm0.09)pe/keV_{ee}$
- $E_{NR}=((S1/S_{NR})/(L_y/S_{ee}))(1/\mathcal{L}_{eff})$
  - S_{NR}=095, S_{ee}=0.58: electric field QF
  - $\mathcal{L}_{eff}$: Scintillation efficiency



2 phase
liquid Xenon detector

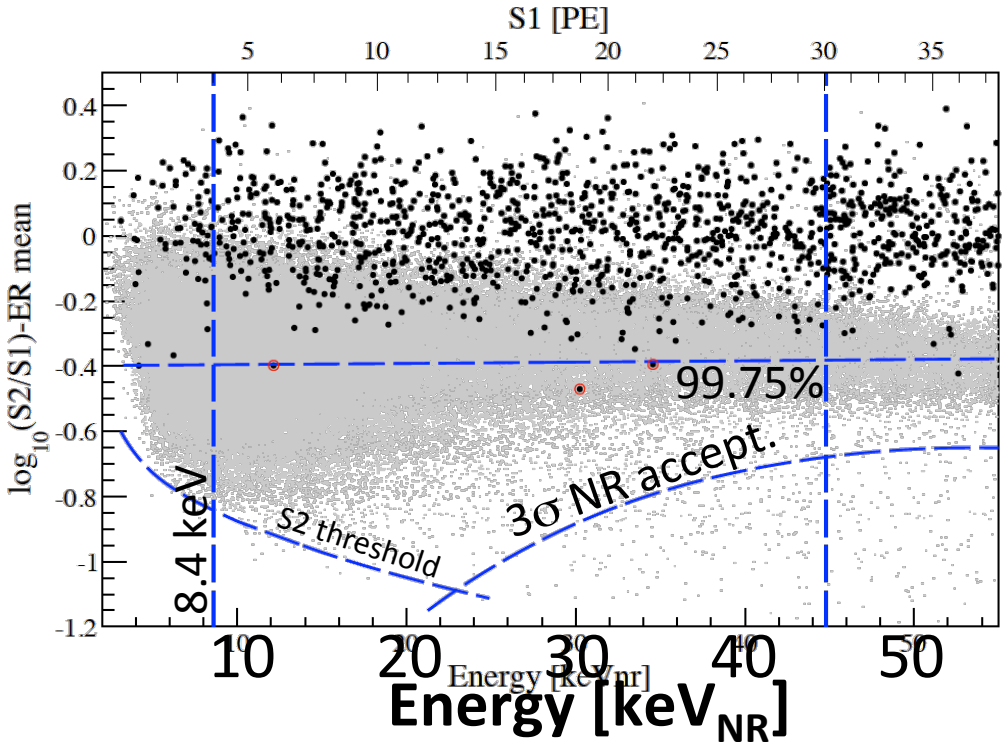


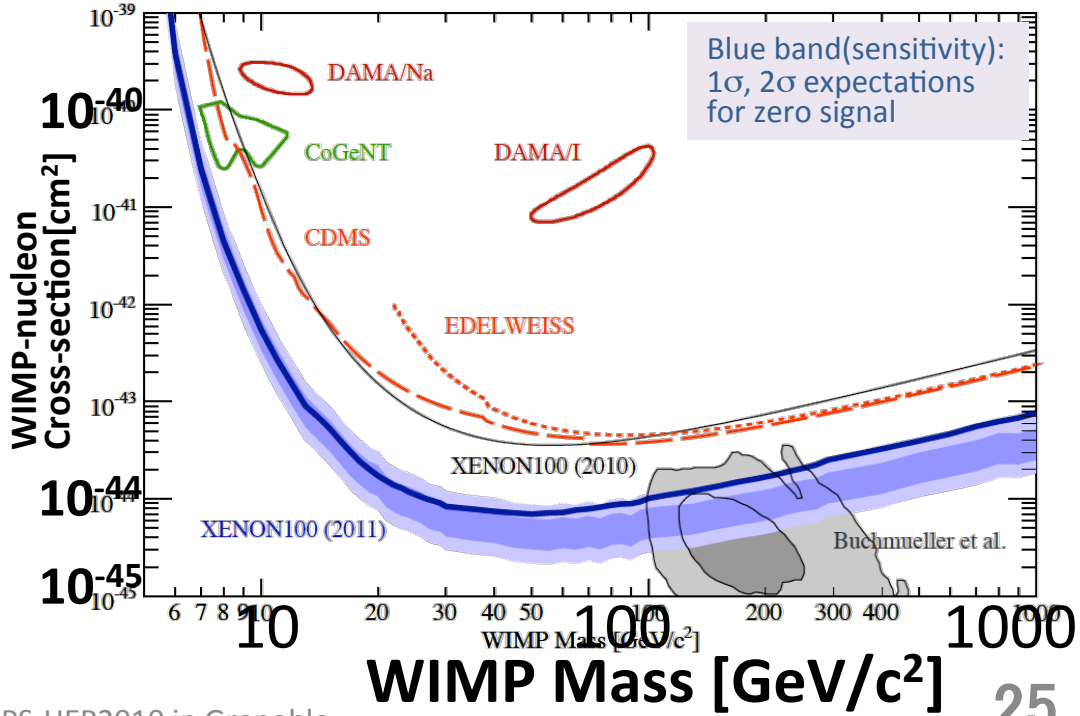
$(S2/S1)_{WIMP} < (S2/S1)_{\gamma}$

enoble

- 100.9 live days (till June in 2010) w/ 48 kg fiducial mass (62kg) ➔ 1471kg-day
- BG <5x10^{-3} ev/keV$_{ee}$/kg/day before signal discrimination
- 3 events remain after S2/S1 selection (99.75% EM rejection)
- Expected BG: 1.8±0.6
  - ^{85}KR: 1.14±0.48
  - Others: 0.56(+0.21/-0.27)

- XENON is moving to XENON1T in preparation



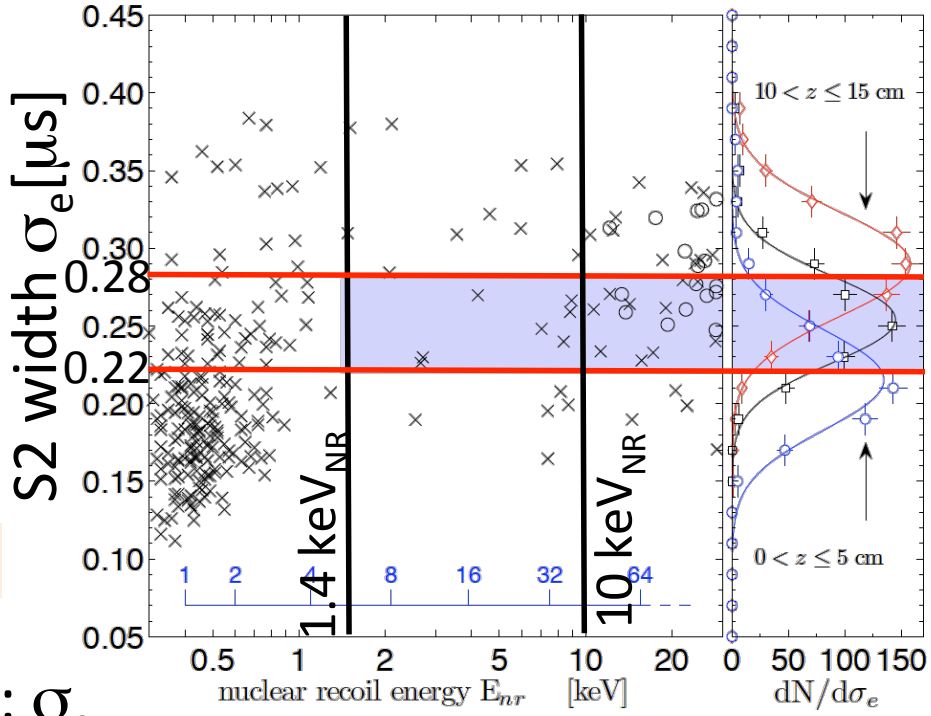


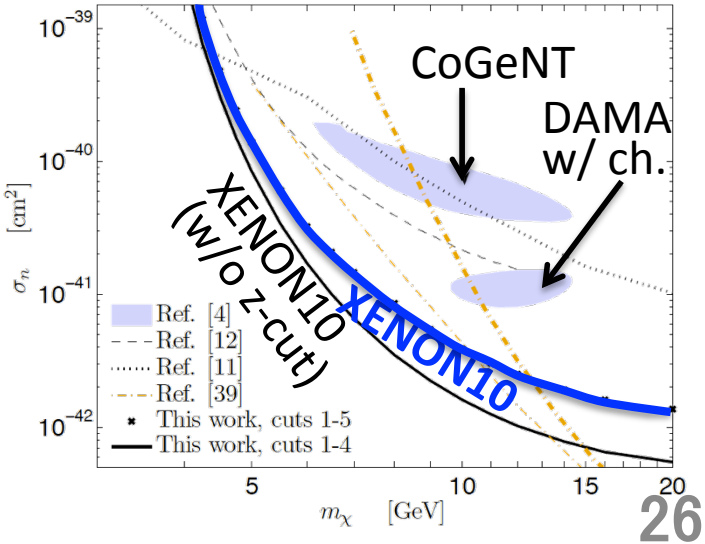
XENON10 low mass

- S2 only analysis
  - S1: 10% efficiency
  - $E_{NR} = S2/(Q_y * G_g)$
    - G_g: gas gain in pe/e$^-$
    - Q_y: NR charge yield in e$^-$/keV
  - No NR-EM discrimination
  - 'No' z- reconstruction
    ➔ Tight xy cut ➔ 1.2 kg fid.
    ➔ crude edge rej. by S2 width: σ_e
  - 12.5 days (15 kg-days)
  - 1.4 keV_{NR} thr. (5 electrons)
- 7 events remained (BG)
- Conservative analysis

Target mass 13.7kg

Take lower value of Q_y





Current players of the game

Experimentð	Target	Threshold	Total Exposure	Recoil Identification	Main body of Signal ?	Modul ation
DAMA/LIBRA	NaI	2.0 keV_{ee}	427,000 kg-days	(NR+EM)	Not identified	O
CoGeNT	Ge	0.5 keV_{ee}	140 kg-days	(NR+EM)	O?	O
CRESST	$WCaO_4$	10.0 keV	>700 kg-days	NR	O? (not official)	
CDMS-II	Ge/Si	10.0 keV	612 kg-days	NR		
CDMS-II (LE)	Ge	2.0 keV_{NR}	241 kg-days	(NR+reducedEM)		
EDELWEISS	Ge	20.0 keV	384 kg-days	NR		
XENON100	Xe	8.4 keV_{NR}	1471 kg-days	NR		
XENON10 (LE)	Xe	1.4 keV_{NR}	15 kg-days	(NR+reducedEM)		

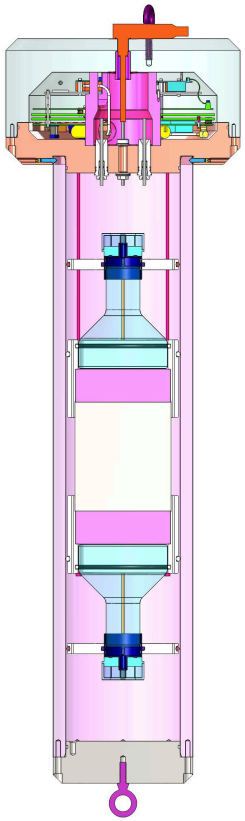
Current and Future direct WIMP Search experiments

35 programs (not complete list : sorry for those projects I have missed)

Experiments	site	Target & mass	technology	Achieved (cm^2)	Sensitivity (cm^2)	Status & comments	Year to start
Xenon							
ZEPLIN-III	Boulby	Xe: 8kg	two phase		SI: 10^{-43}	Stop in 5- 2011	results soon
XENON100	LNGS	Xe: 48kg	two phase		SI: $7x10^{-45}$		On going
XENON1T	LNGS	Xe: 1t	two phase		SI: 10^{-47}		2015
XMASS	Kamioka	Xe: 100kg	single phase		SI: 10^{-45}	commissioning	On going
XMASS-1.5	Kamioka	Xe: 1ton	single phase		SI: 10^{-46}		2013
XMASS-II	Kamioka	Xe: 10ton	single phase		SI: 10^{-47}		2016
PANDA-X	Jing Ping	Xe: 25kg	two phase		SI: 10^{-45}		> 2013
LUX	SUSEL	Xe: 100kg	two phase		SI: $<10^{-45}$	Surface lab	2012
LZS	SUSEL/ SNO	Xe: 1ton	two phase		SI: 10^{-47}		2015
Ar							
WARP	LNGS	Ar:140kg	two phase		SI: $5x10^{-45}$	commissioning	
DarkSide50	LNGS	DAr: 50kg	two phase		SI: 10^{-45}	prototype	
ArDM	Canfranc	Ar: 850kg	two phase			Prototype	2011
DEEP3600	SNOLAB	Ar: 1ton	Single phase		SI: 10^{-45}		2012
MiniCLEAN	SNOLAB	Ar: 150kg	Single phase		SI: 10^{-44}		2011
DARWIN	Europe	Ar or Xe: tons	two phase		SI: $<10^{-47}$		
MAX	DUSEL	Ar and Xe			SI:$<10^{-47}$	R&D	

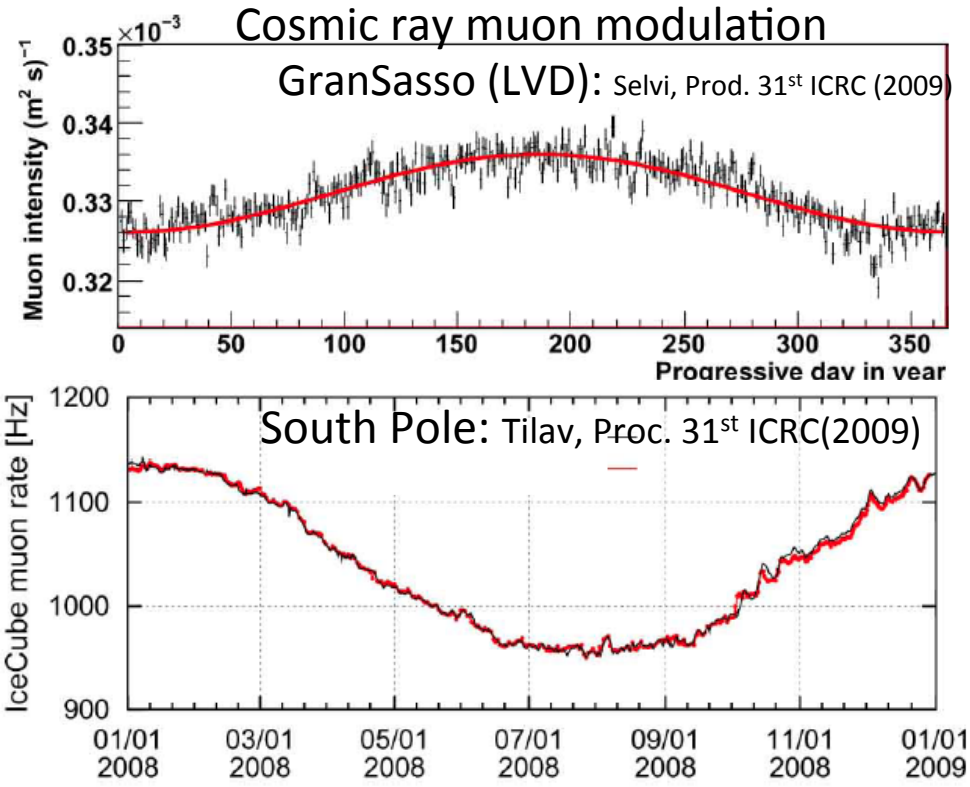
Experiments	site	Target & mass	technology	Sensitivity (cm^2)	Achieve (cm^2)	Status & comments	Year to start
Ge							
Super-CDMS	SOUDAN	Ge: 15kg	char+phonon	SI: $5x10^{-45}$			2011
Super-CDMS	SNOLAB	Ge: 100kg	char+phonon	SI: $3x10^{-46}$			2015
CoGeNT-C4	SOUDAN	Ge: 4kg	charge			installation	2011
CDEX	Jing Ping L	PC-Ge:10 kg	charge	SI: 10^{-43}		1kg test	
Bubble Chamber							
PICASSO	SNOLAB	C_4F_{10}: 2.6kg	BC	SD: $2x10^{-37}$			On going
SIMPLE	Rustrel	C_2ClF_5: 26 kg	BC			Test 0.2kg	Install 2012
COUPP	SNOLAB	60kg	BC			4kg test	2011
Scintillation (+phonon)							
DAMA	LNGS,	NaI: 250kg	Scintillation	SI: 10^{-40}			On going
KIMS	Yang Yang	CsI: 104.4kg	Scintillation	SD:10^{-38}			On going
CINDMS	Jing Ping L	CsI(Na)	Scintillation			R&D	
CRESST-II			Sintill+phonon				On going
ROSEBUD	Canfranc	Al_2O_3 etc.	Scintill+phonon			R&D	
DM-Ice	South pole	NaI:>250kg	Scintillation	Test DAMA		Prototype: 17kg	?
EURECA	LSM	Multi-T: 1ton	many	SI: 10^{-46}		Phase-I: 150kg	2015
Tracking							
Drift-III	Boulby	CS2:4kg,24m^3	TPC	SD: 10^{-40}			?
DM-TPC		CF4	PMT+TPC			Prototype test	
NewAGE	Kamioka	CF4	microTPC			Prototype test	
MiMac	LSM	CF4	microTPC			Prototype	2011 1m^3
Cygnus	World?		Tracking			White paper	

Test directly DAMA and GoGeNT



DM-Ice

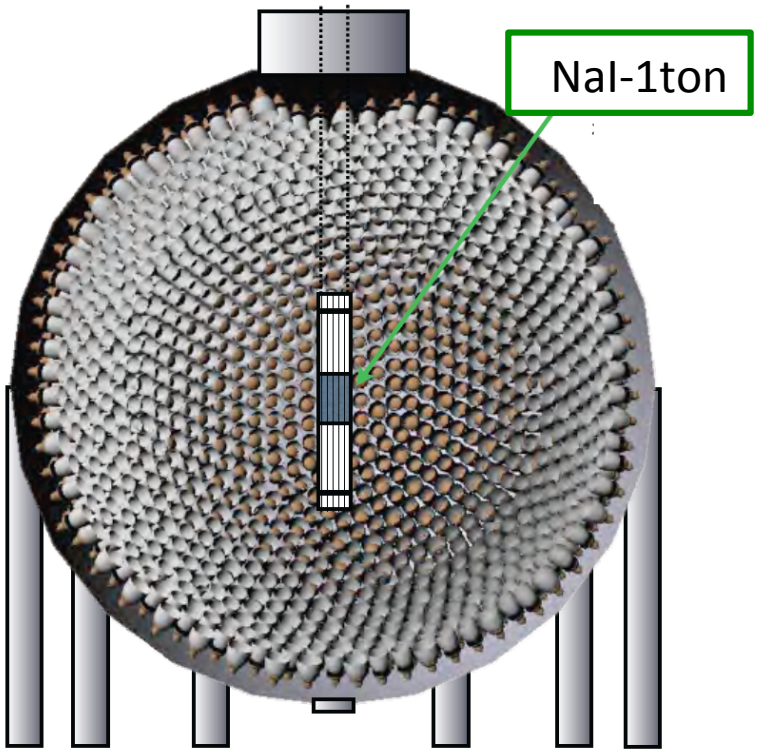
- Test directly DAMA
- NaI detector
  @South pole:
- **Cosmic modulation is opposite**
- Dec-2010 ~ :
  - Feasibility test
  - 8.5kgx2 NaI from NAIAD
- Inside BG: 5~10 times higher than DAMA
- ICE is clean:
  - U/Th: ppt
  - K: ppb



- Need to make low BG crystal
  - ✓ U/Th may be ok, but
  - ✓ K is more serious: need <ppt?
- R&D for low BG PMT

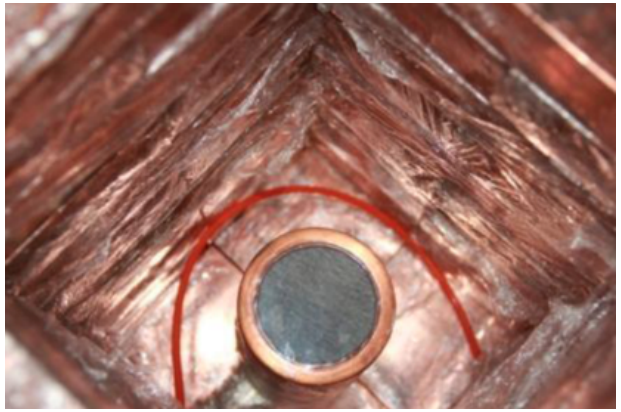
- Place NaI in KamLAND (or Borexino)

KamLAND-NaI



CEDX: Point Contact Ge detector

- Jing Ping Lab. in China



- 20g is running
- 1kg is testing !
- Aim to check GoGeNT results

'Standard' WIMPs search experiments should go on

100kg ➔ 1tons ➔ multi-tons ; sensitivity down to 10^{-47} cm^2 (SI)

XENON, XMASS, EURECA, Darwin, MAX, LZD, ……

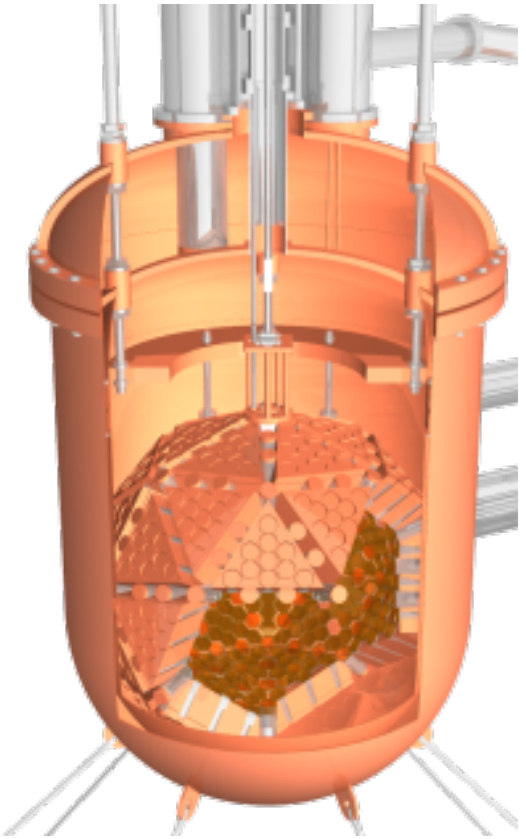
Status of XMASS

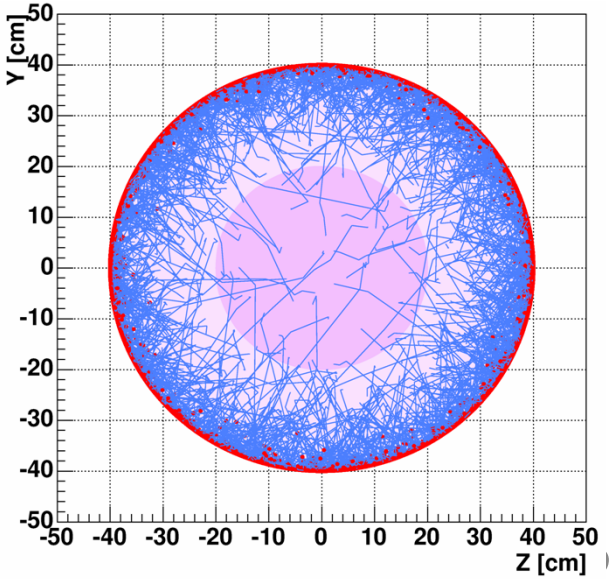
- Sorry we have no results to show today! Now in *commissioning*
- Need a few more months !

XMASS:

single phase liquid Xenon detector

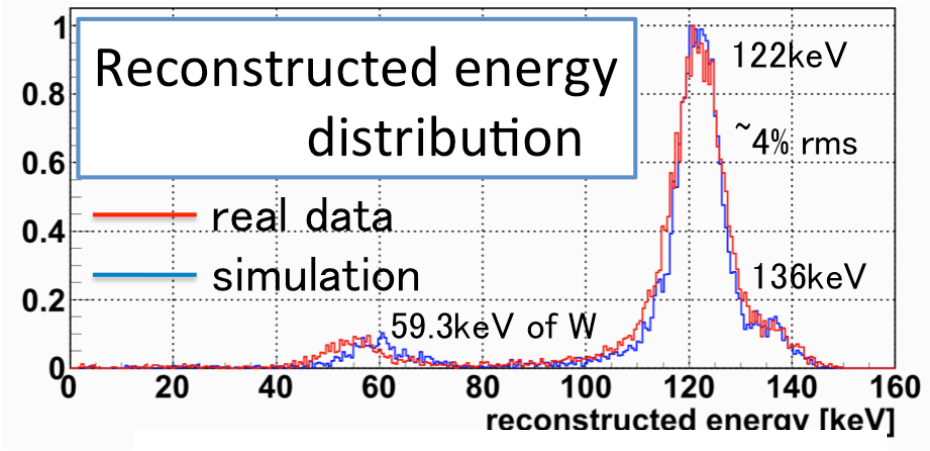
- Mass inside of the light sensor: 850kg
- Fiducial mass: 100 kg
- By simple self-shielding effect
  - 10^{-4} c/day/kg/keV (dru) for NR and EM
  - Further selection on NR or statistical identification of NR is possible

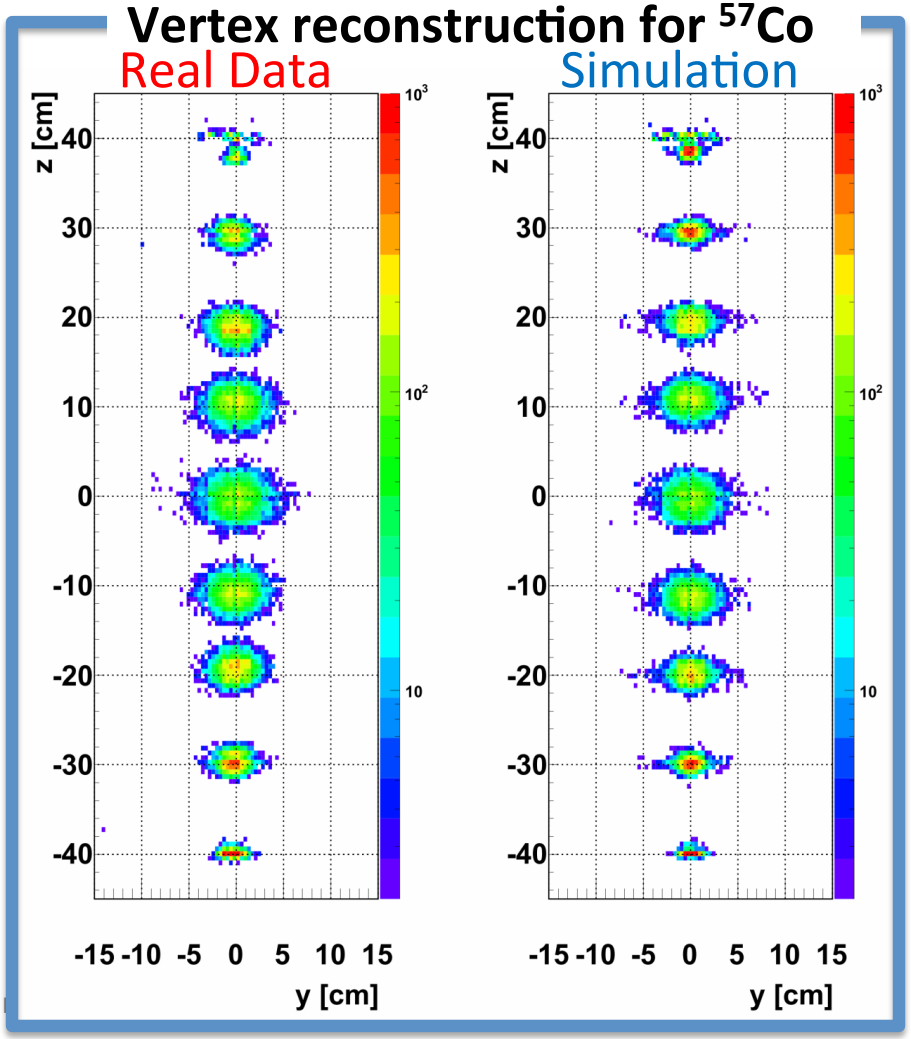


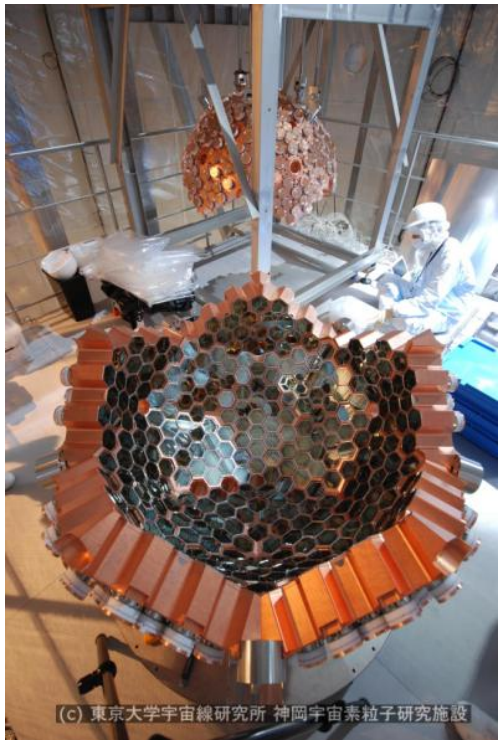


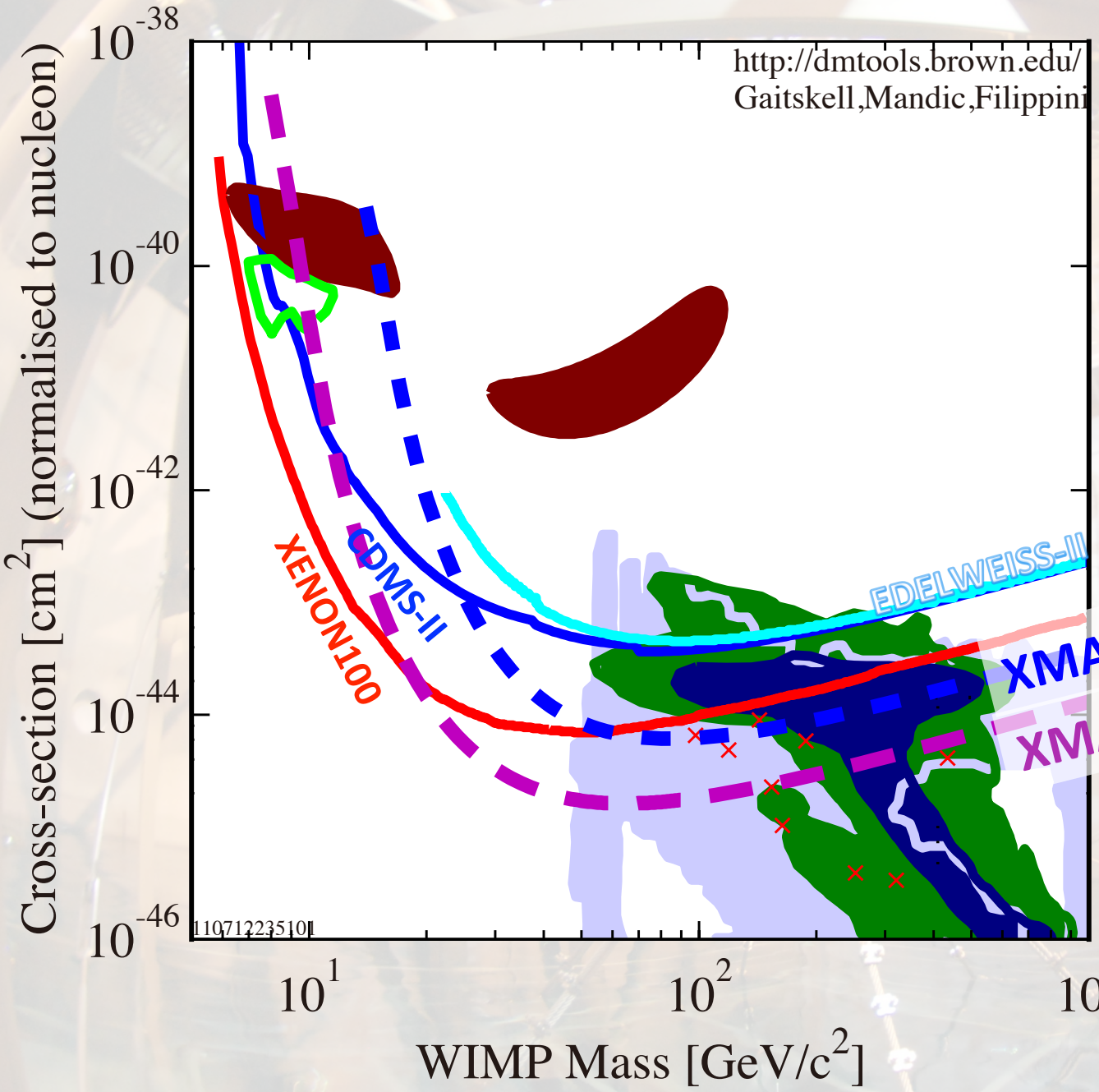
XMASS: Measured property

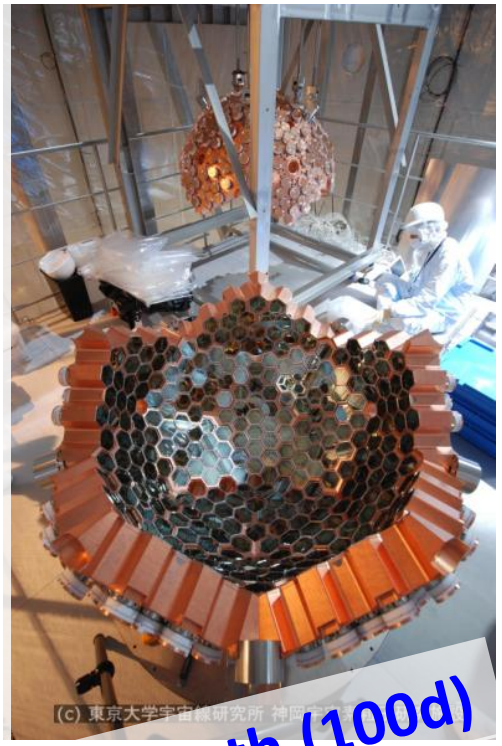
- Reconstructed energy
  - ~4% rms @122 keV
- 15.1±1.2 ph-electrons/keV
- Position resolution (122keV)
  - 1.4cm RMS (@z=0cm)
  - 1cm RMS (±20cm)
- BG reduction
  - Low BG PMT
  - Material screening 250 pieces
  - Kr: distillation
  - 10mh x 10m ϕ ωater tank
- BG measured
  - ^{222}Rn: 8.2±0.5mBq
  - ^{220}Rn: < 0.28mBq






(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設





Note: ~15 pe/keVee
May be much lower
threshold is possible

Summary

- Direct dark matter search experiments are in a very exciting and interesting stage: Some indications for low mass DM, but there are conflicting results.
- People tried to reconcile those results: Many many papers.
  - Inelastic DM, Isospin violating DM, Mirror DM, Composite DM, Resonant DM, SD inelastic DM, Complex Scalar DM, Astrophysical parameters, and so on….
- But experimentally we need more studies on those data and understand backgrounds especially.
- We may need new experiments in order to firmly establish or to reject the indications.
- Hope we will resolve the situation in a few years.
- But, WIMPs search in general should go on step by step by increasing its sensitivity
  - from 100kg size detectors to 1 ton, multi-ton class detectors

Direct dark matter search experiments will be attractive for the next few years

Stay tuned !

Sorry, I could not cover
direct search experiments
for axion or axion-like particles
because of the limited time

Backup

Backgrounds

Key Issue of the experiments !

- Many:
  - detector dependent
  - but common techniques to reduce backgrounds