Dark Matter Searches

F. Arneodo
INFN-LNGS

Outline

- Why we search for Dark Matter
- Indirect searches
- Direct searches (I will not cover everything!)
- The future
- Conclusions

Not a recent problem

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

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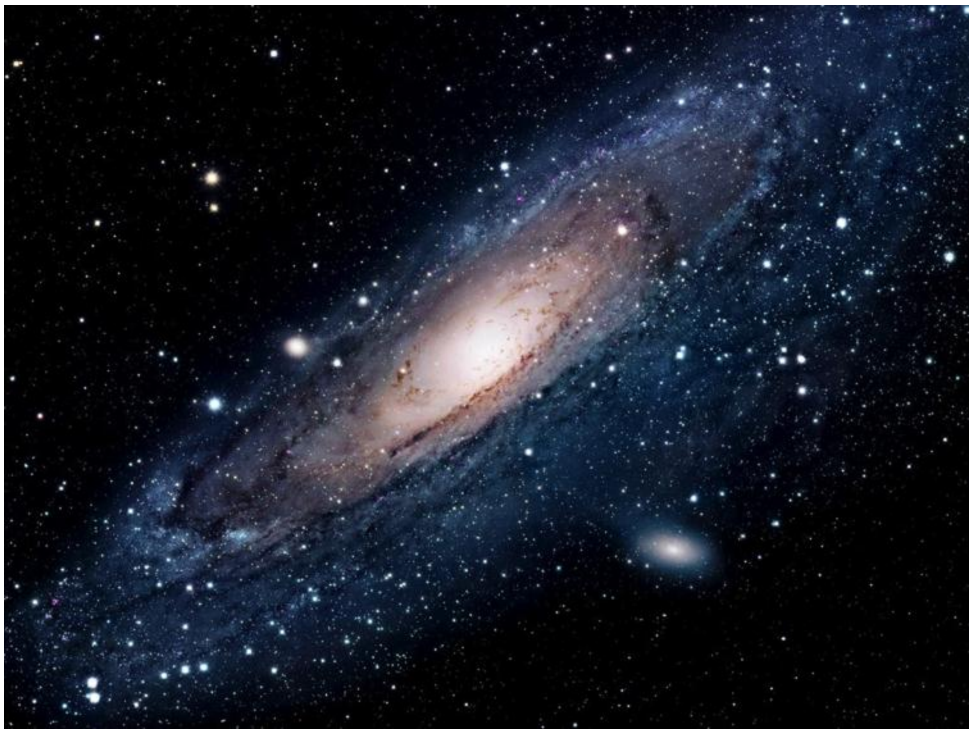
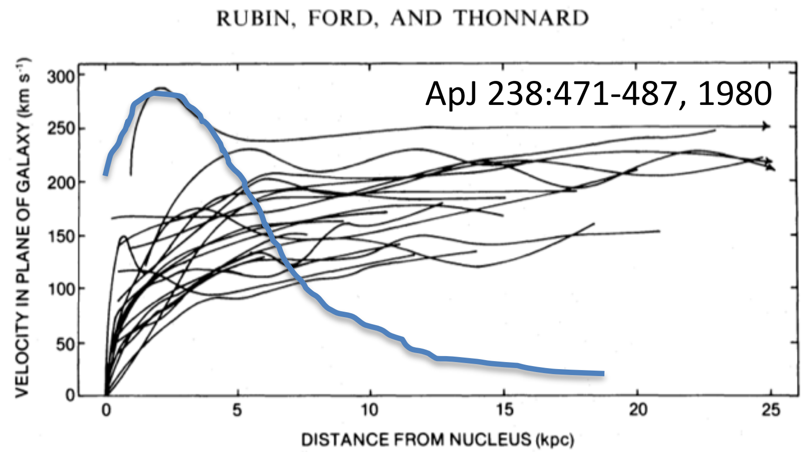
ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

Where's the mass of the Universe gone?

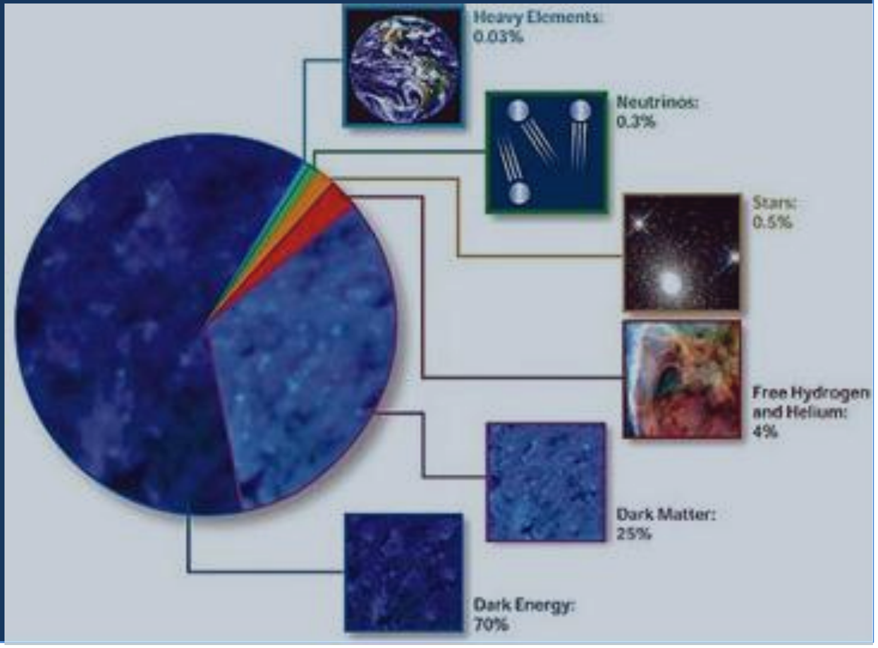




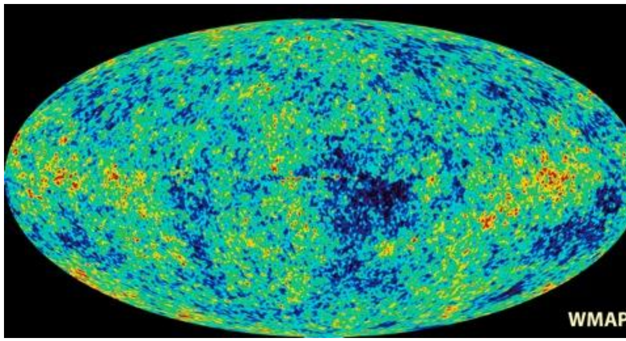
Estimated local DM density:
~0.3 – 0.6 GeV/cm^3

Dark Matter and the standard cosmological model

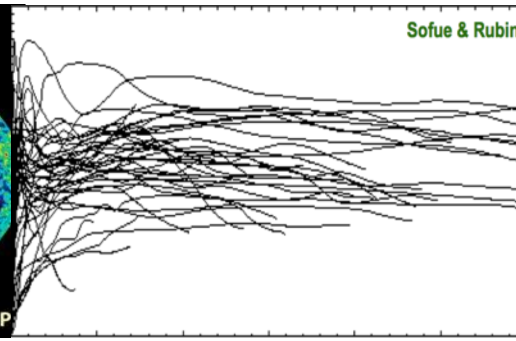
- "ΛCDM"
- $\Omega_{Total} = \Omega_m + \Omega_\Lambda = 1.02 \pm 0.02$
- $\Omega_m = 0.27 \pm 0.02$
- $\Omega_\Lambda = 0.73 \pm 0.04$
- $\Omega_b = 0.046 \pm 0.001$
- $\Omega_\nu < 0.0076$



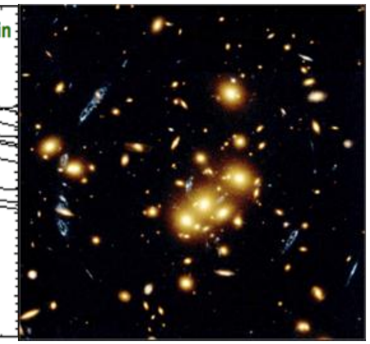
Several hints, and strong too



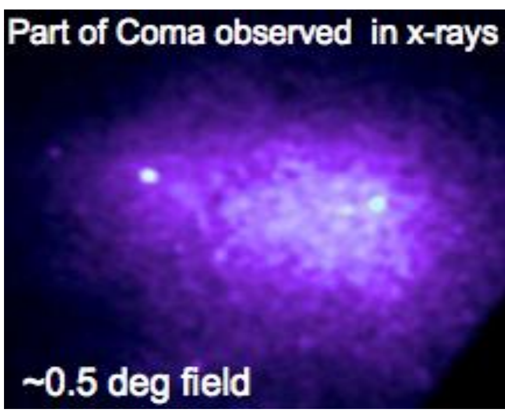
CMB anisotropies



Dynamics

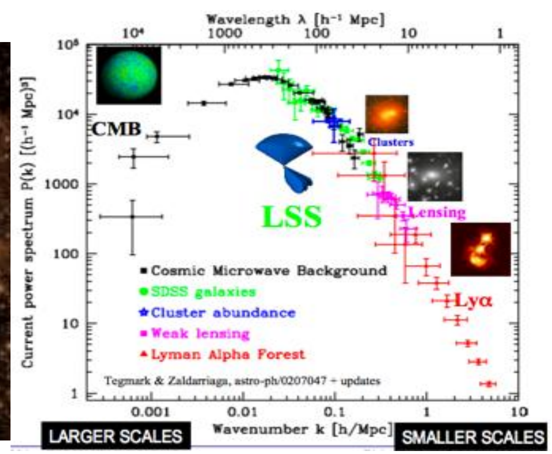


Lensing



Absorption lines

Structure formation

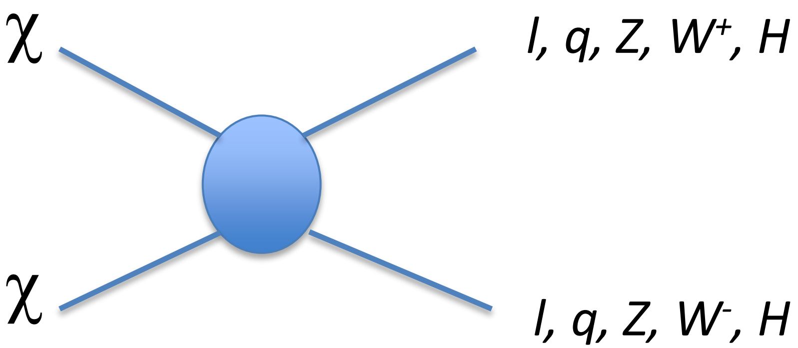


Spectrum

Cold Thermal Relics and the Weak Scale

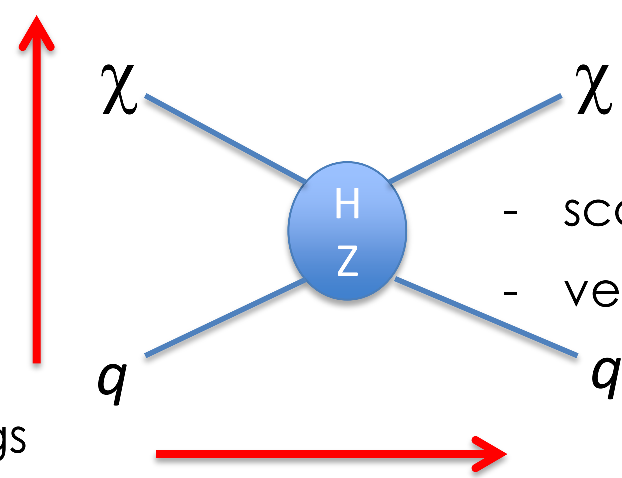
- if a **massive, weakly interacting particle** (WIMP) existed in the early Universe
- it was in equilibrium as long as the **reaction rate** was larger than the **expansion rate**
- after "freeze-out", we are left with a **relic density**
- An interaction and a mass at the weak scale [O(100GeV)] could satisfy the present observations
- SSM lightest particle could be a candidate

How to search for Dark Matter



Detection of products of particles annihilation

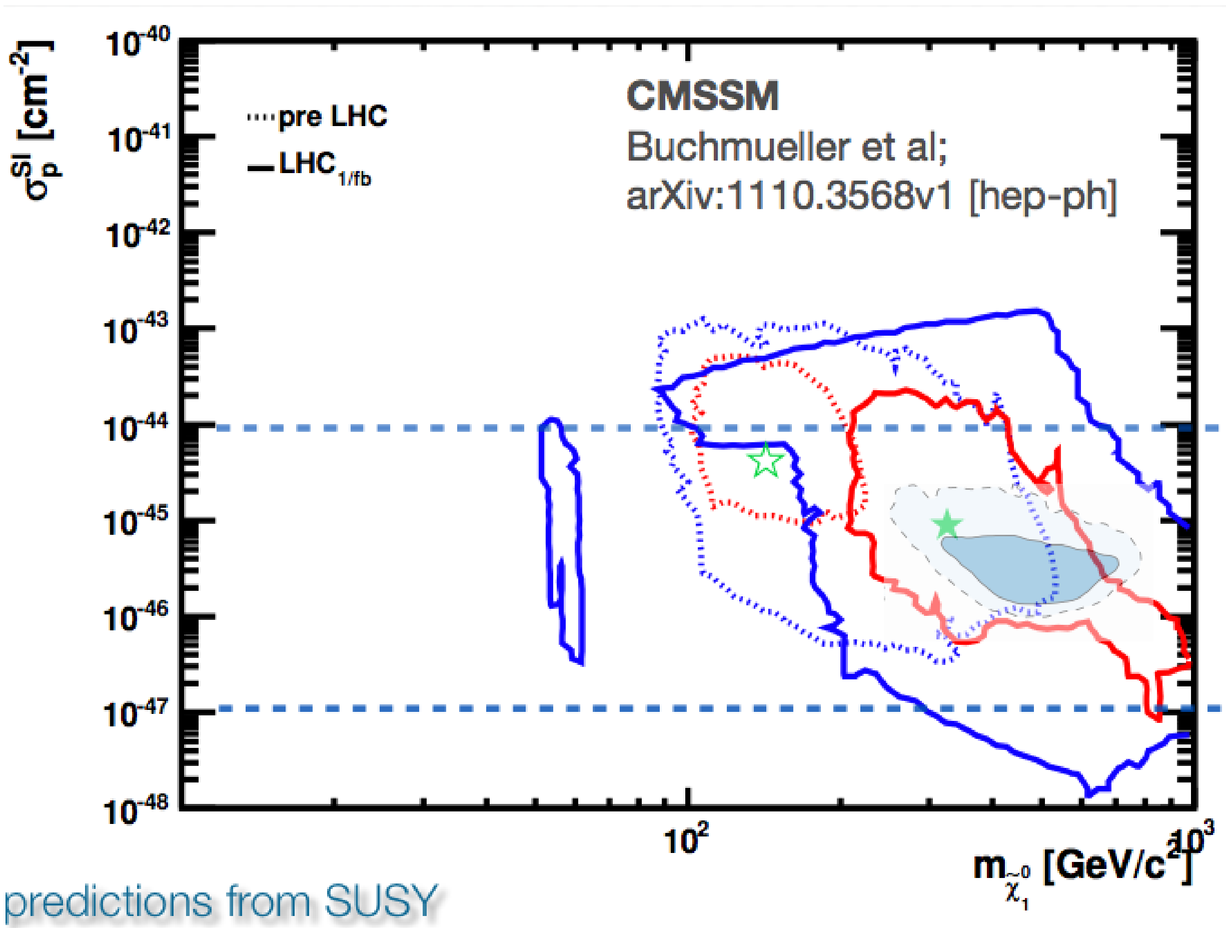
Production at LHC



- scalar coupling (SI) $\propto A^2$
- vector coupling(SD) $\propto J(J+1)$

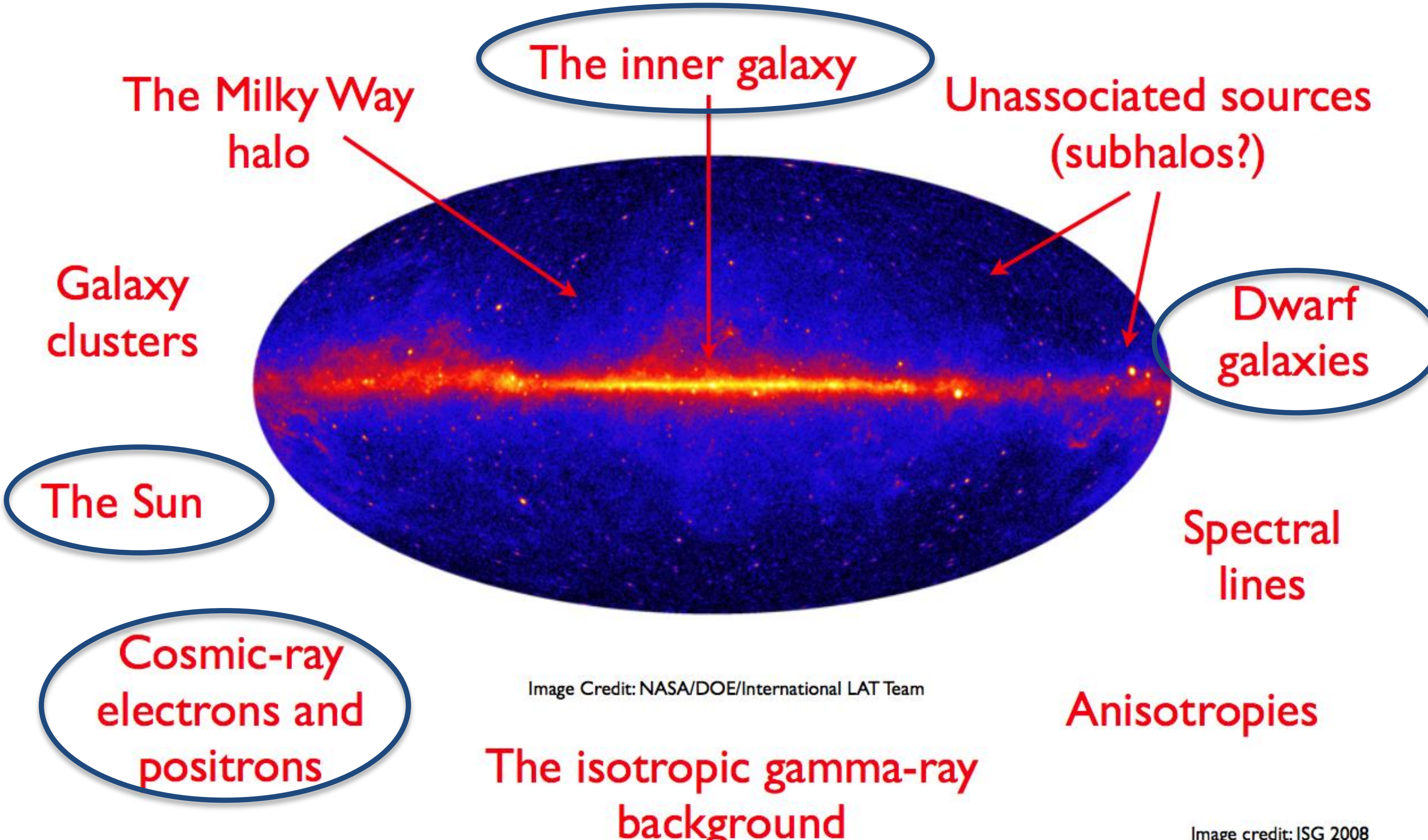
Detection of scatterings on specific targets

A competitive field



Roszkowski, DM jubilee, 2012

DM indirect search: the targets



From J. Siegal-Gaskins, IDM Chicago 2012

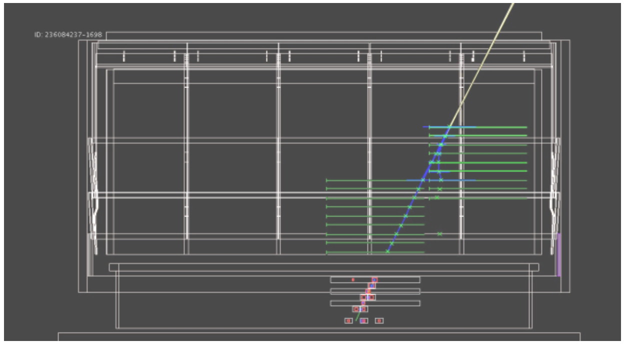
The instruments

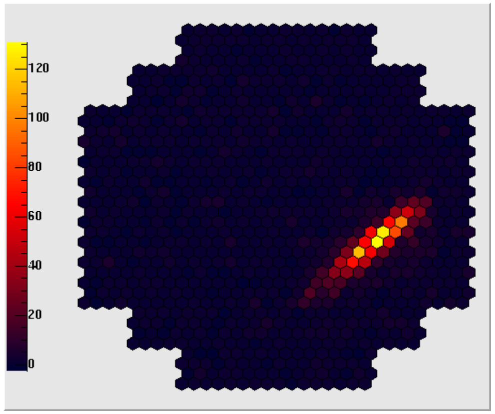
1 - 300GeV

10 GEv –TeV scale

FERMI gamma ray telescope

HESS Telescopes in Namibia



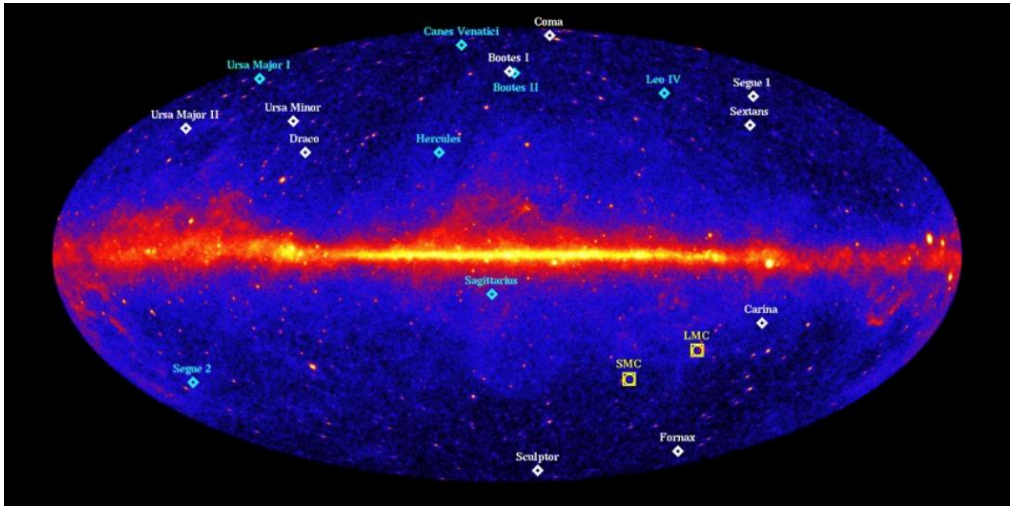


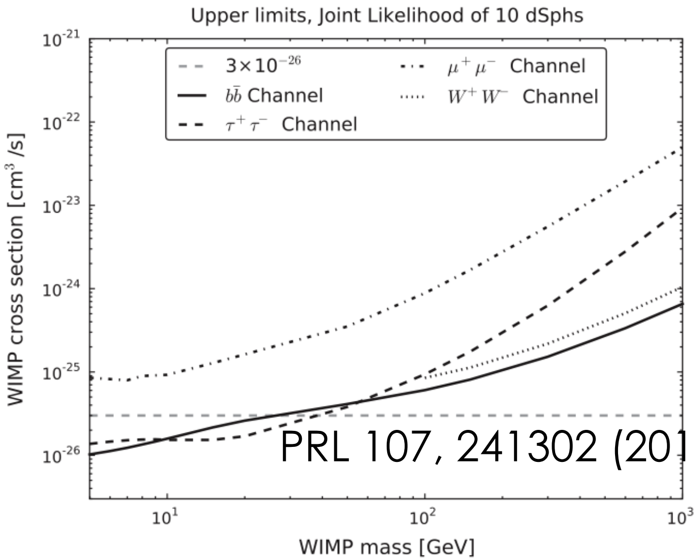
Hess web site

Dwarf spheroidal galaxies

- Very high M/L ratio (~100)
  - ➢ High content of Dark Matter
- No excess radiation observed

➢ Upper limits

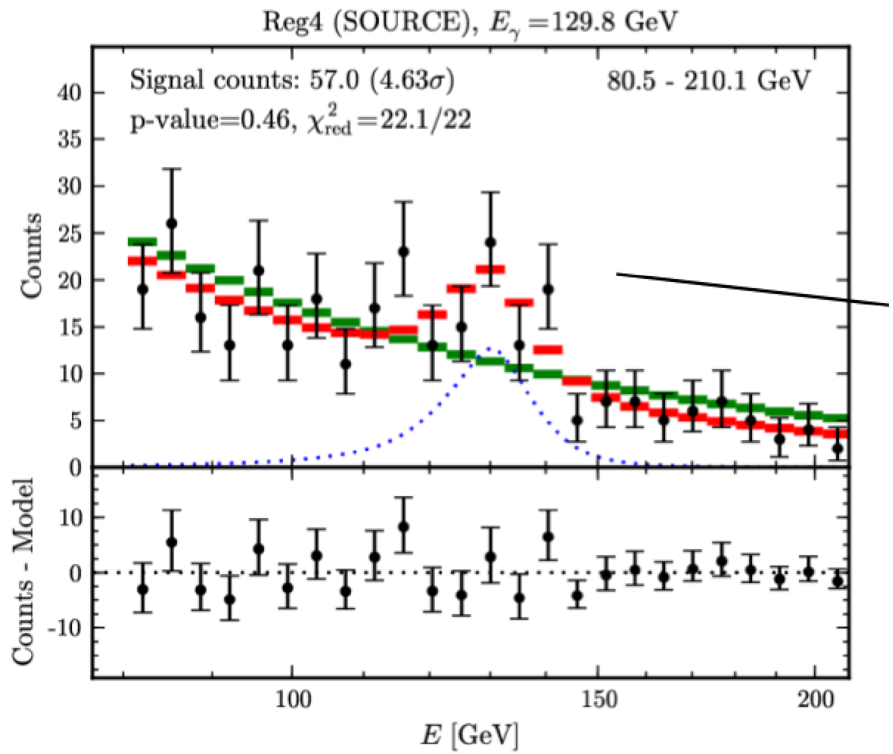


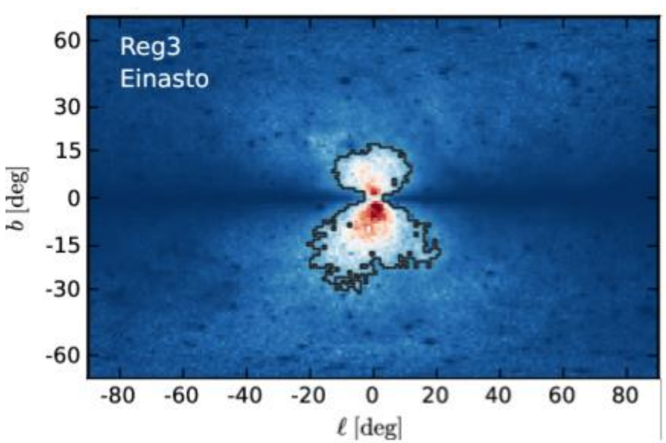


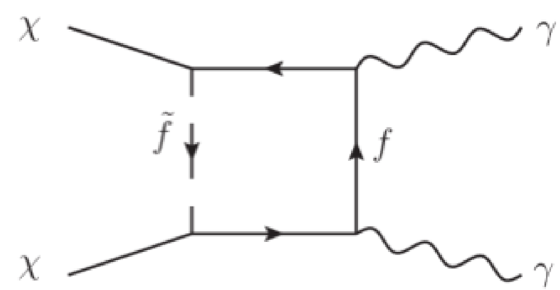
PRL 107, 241302 (2011)

The Galactic Center

- Line @130GeV found in FERMI public data by C. Weniger.
- Slight off axis from GC (1.5°).
- Instrumental effect?
- Consistent with standard Einasto profile
- Waiting for confirmation by HESS-II.
- (after all it's only 50 photons…)



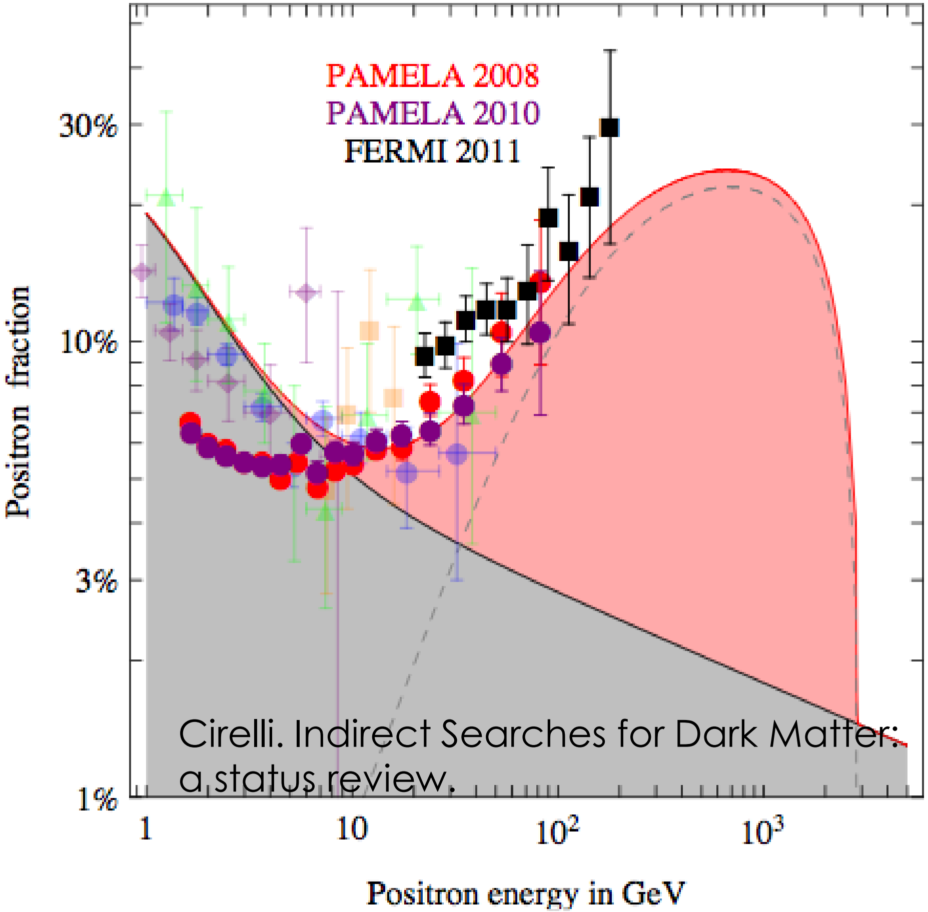




Christoph Weniger

Anti-matter

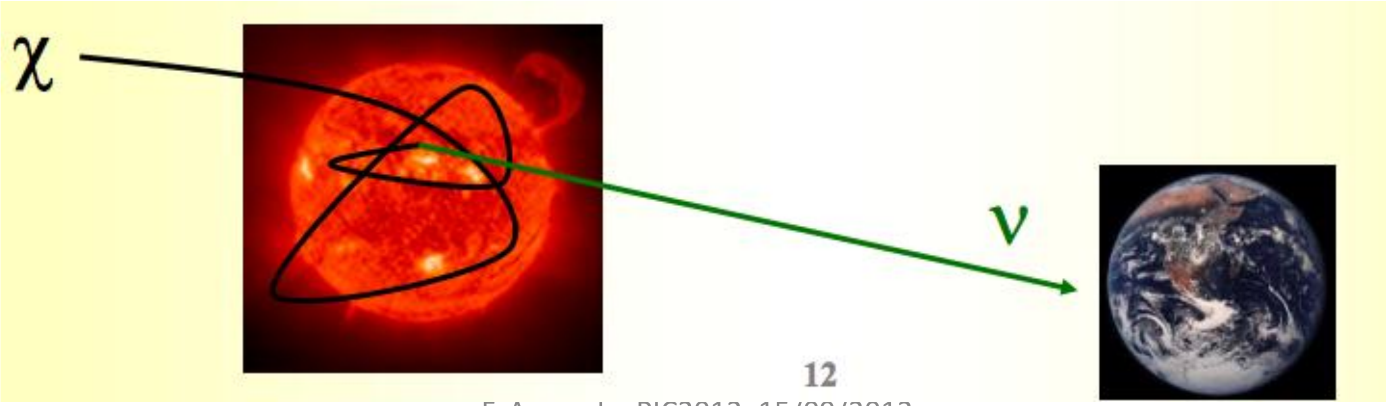
- DM annihilation signature: excess of antiparticles.
- Positron excess in PAMELA, FERMI data.
- But not antiproton excess!
- Backgrounds (from secondary CR production) not entirely understood.
- Best fit (halo model, diffusion, annihilation, etc) gives “leptophilic” DM candidate 3TeV mass and (too) high annihilation X-sec.
- Hard to reconcile with ‘standard’ WIMP, but models do exist that accommodate everything.



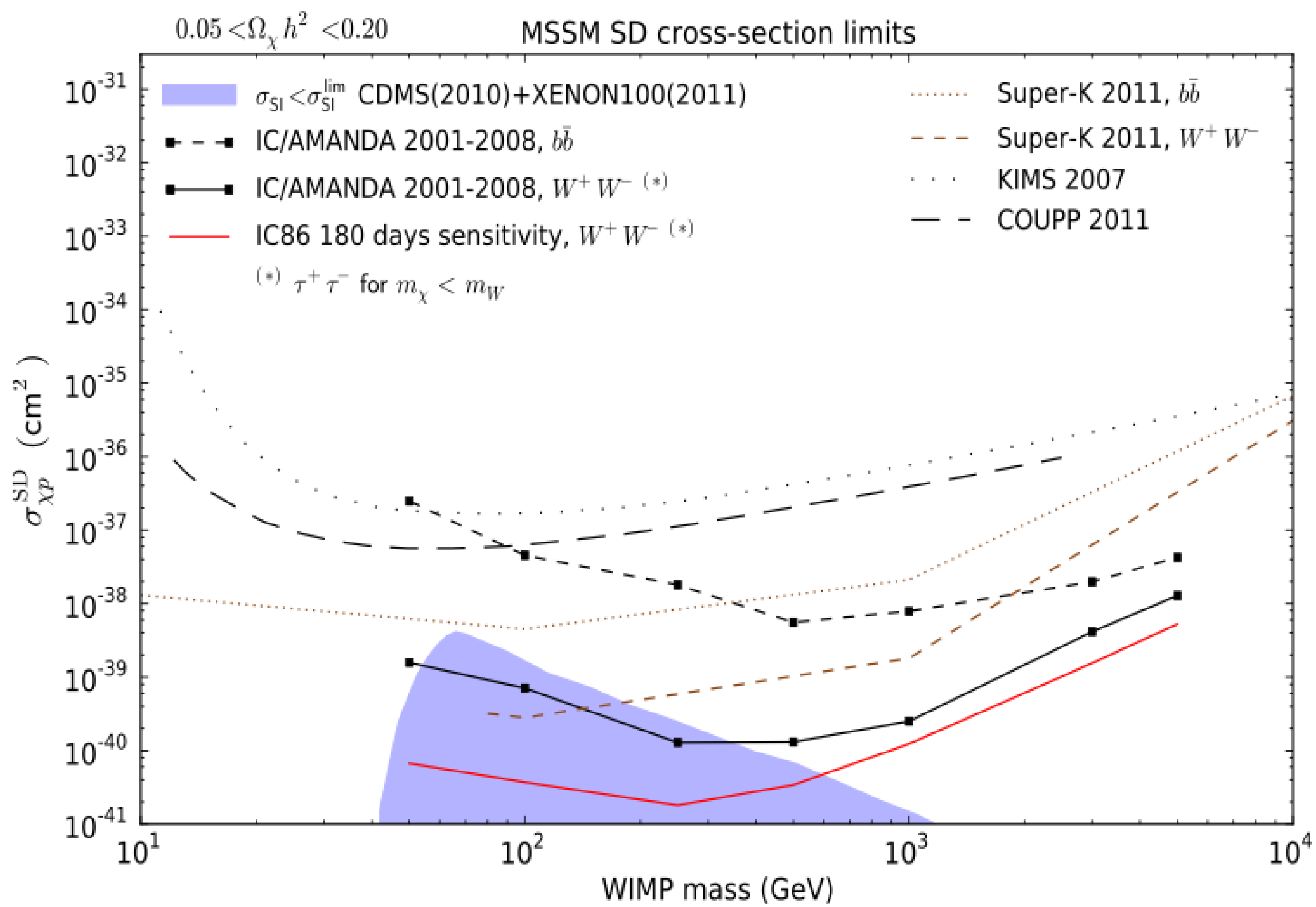
Cirelli. Indirect Searches for Dark Matter: a status review.

Neutrinos from the Sun

- WIMPs are swept up, slowed and captured by the Sun as the Solar System moves about the halo.
- Halo structure has been averaged out.
- Neutralino annihilation would result in anomalous neutrino flux from the Sun. (High energy neutrinos!!)
- Neutrino telescopes may do the job.
- Sun is essentially a proton target



Limit on SD interactions



arxiv:1112.1840

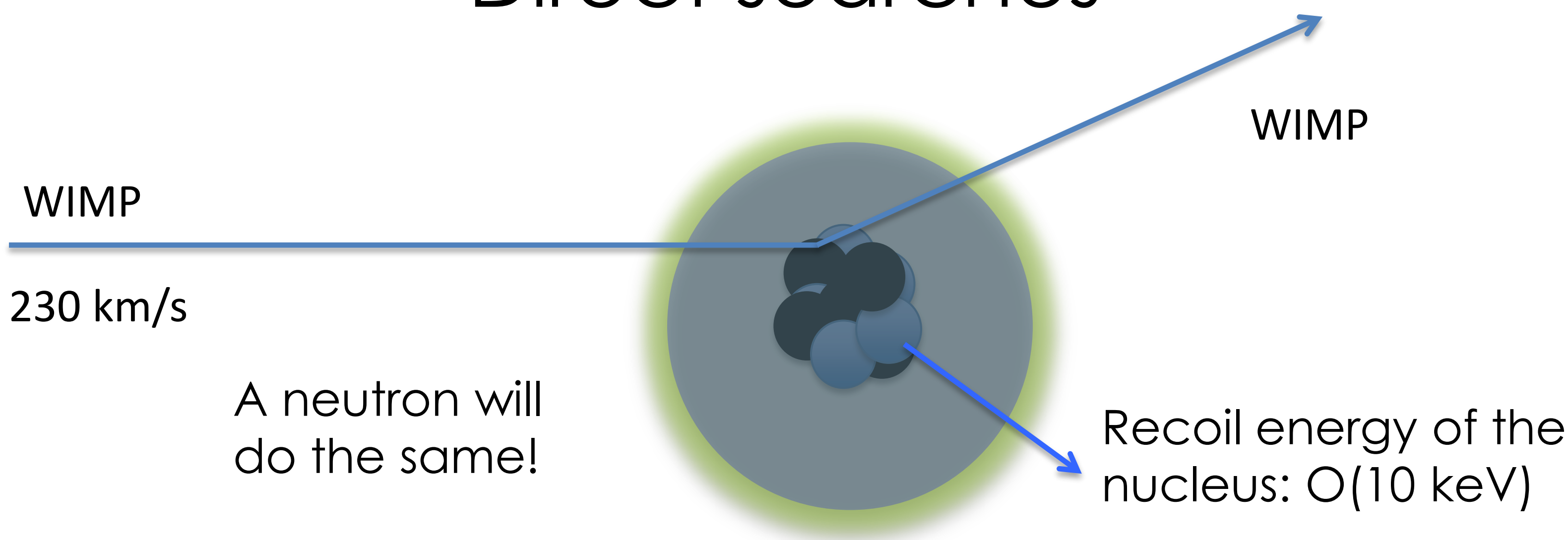
Direct detection

- $\rho_{halo} \sim 0.3 GeV\ cm^{-3}$
- 3000 WIMPs m^{-3} (100 GeV)
- WIMP flux: $10^5\ cm^{-2}s^{-1}$ (230 km/s)

Several halo models:

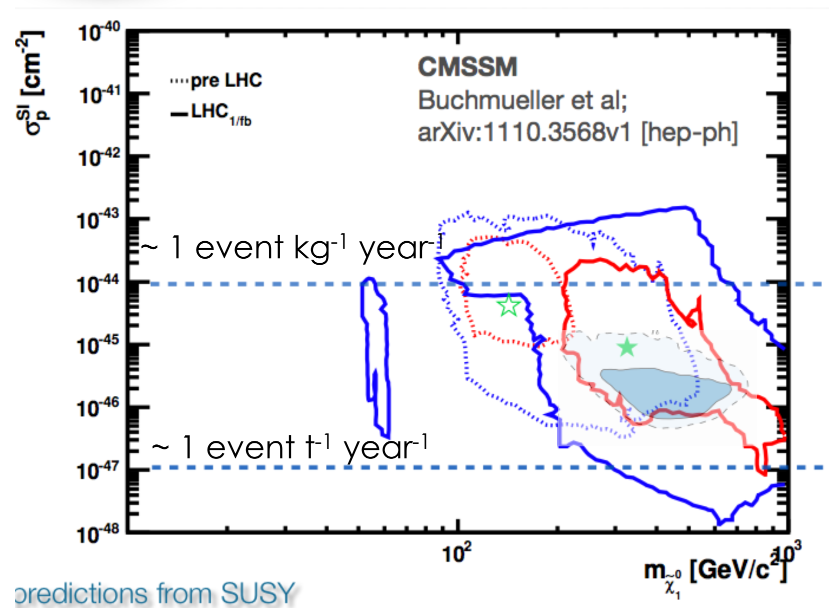
- Navarro-Frenk-White (n-body simulation)
- Einasto (mathematical)
- Burkert (best fit on rotational curves)

Direct searches



Expected rate

$$R \approx N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} < v >$$



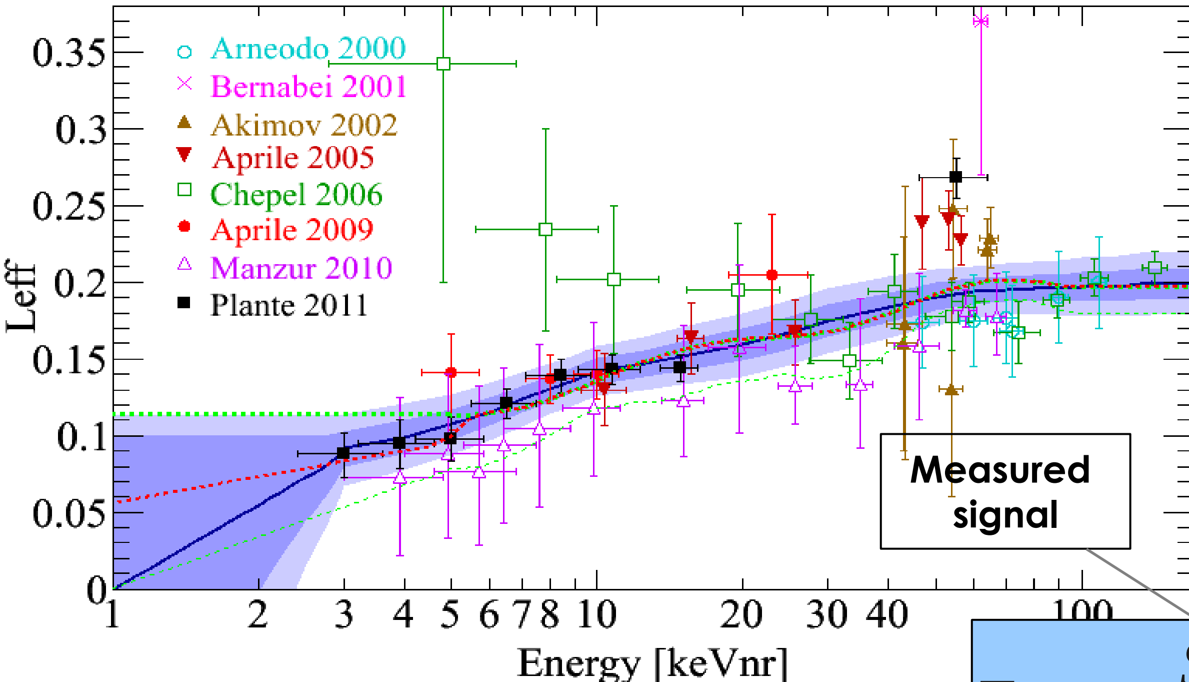
- N = number of target nuclei in a detector
- ρ_χ = local density of the dark matter in the Milky Way
- <v> = mean WIMP velocity relative to the target
- m_χ = WIMP mass
- $\sigma_\chi N$ =cross section for WIMP-nucleus elastic scattering

The four enemies of the DM warrior-hunter

(paraphrasing C. Castaneda)

1. Cosmic rays
   - Go deep underground!
2. Low energy gammas
   - Add copper and lead (preferably roman!)
   - Find a smart discrimination technique
3. Neutrons!
   - Add water or polyethylene to stop them
4. Energy scales!
   - Calibrations are crucial and difficult

Energy Scale: the case of liquid xenon



$$E_{nr} = \frac{S1}{L_y \cdot L_{eff}} \cdot \frac{S_e}{S_r}$$

Measured signal

Light quenching due to electric field for gammas @122keV

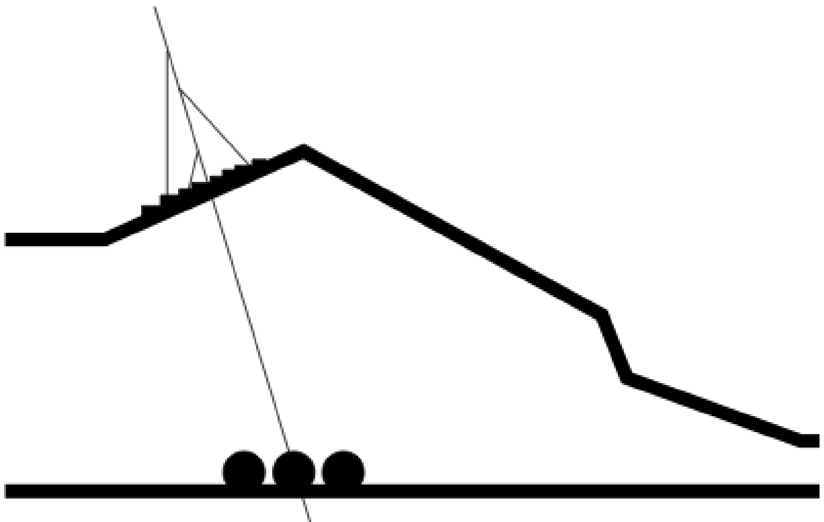
Light quenching due to electric field For nuclear recoils

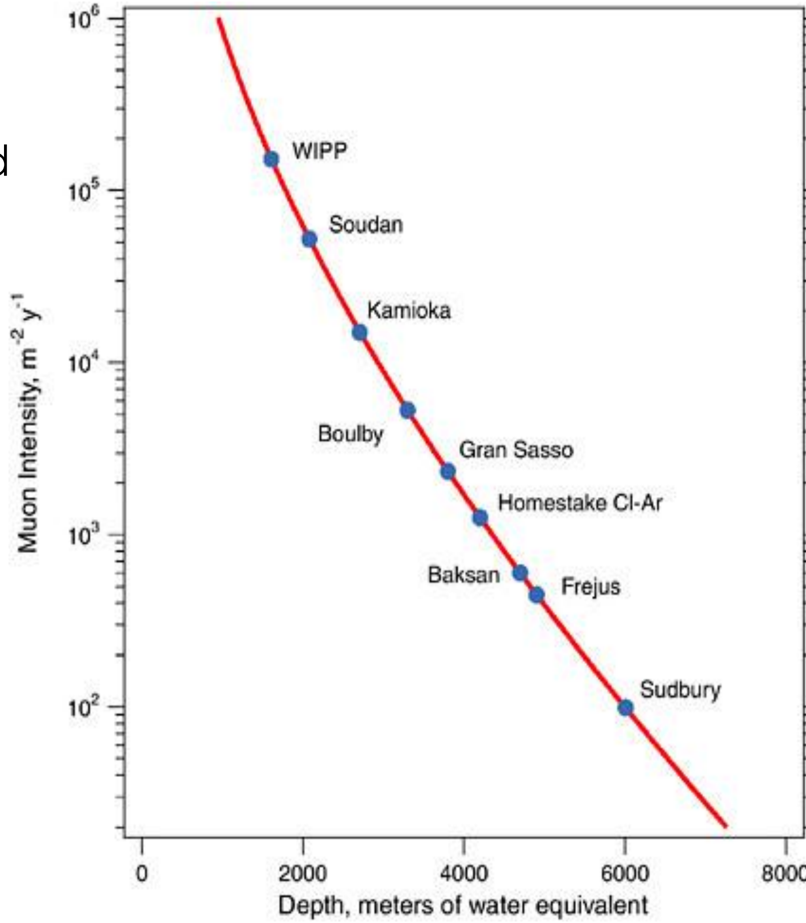
Light yield for gamma @122 keV

Scintillation eff. for nr at 0 field

Need for adequate shielding!

- Cosmic ray flux would kill any signal
  - Underground laboratories needed
- Additional radiopure shielding, plus background reduction and discrimination techniques
  - Pb, Cu for gamma rays
  - Water or polyethilene for neutrons
  - Sometimes active muon veto

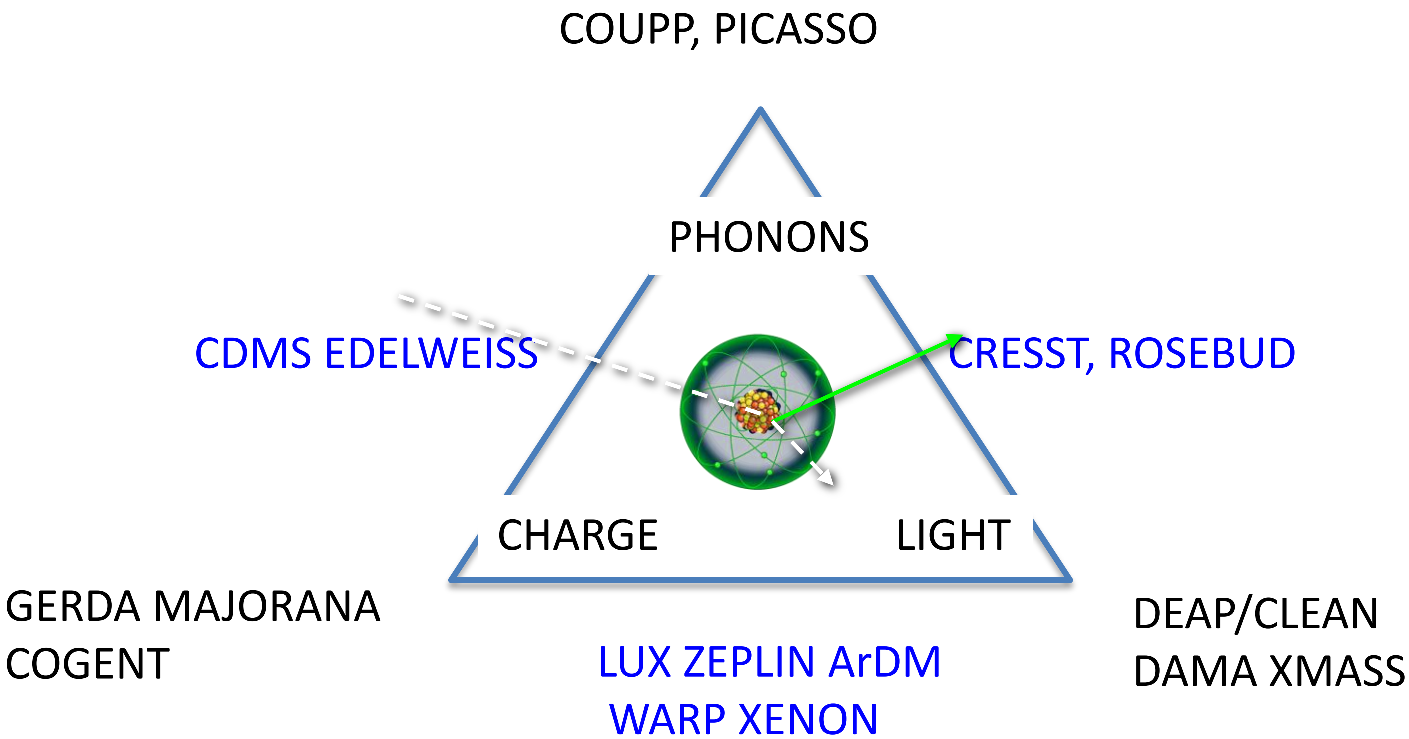




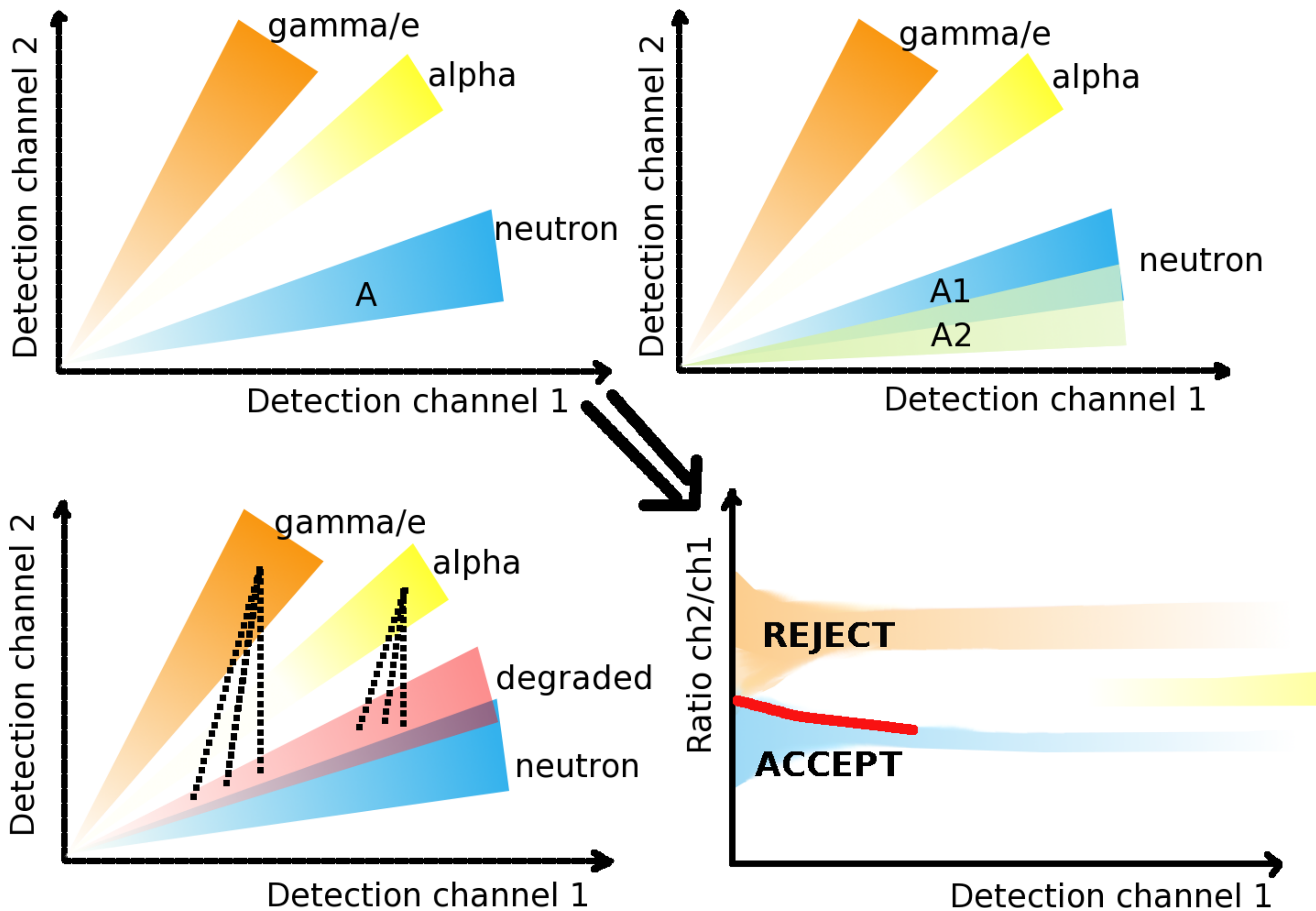
"Good mines are getting hard to find now. So many physics projects require them".
(Michael Crichton, *Timeline*)

The world wide race

Better two signals than one?

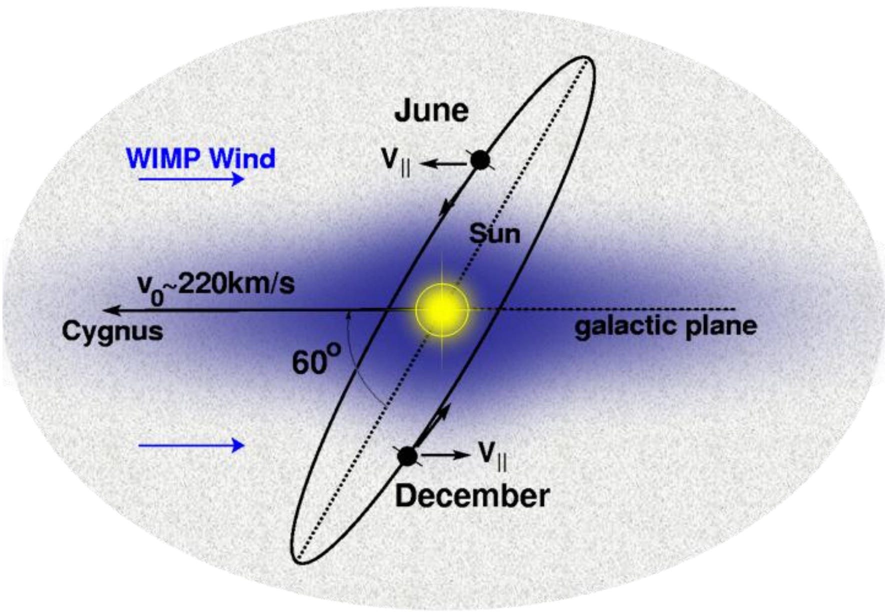


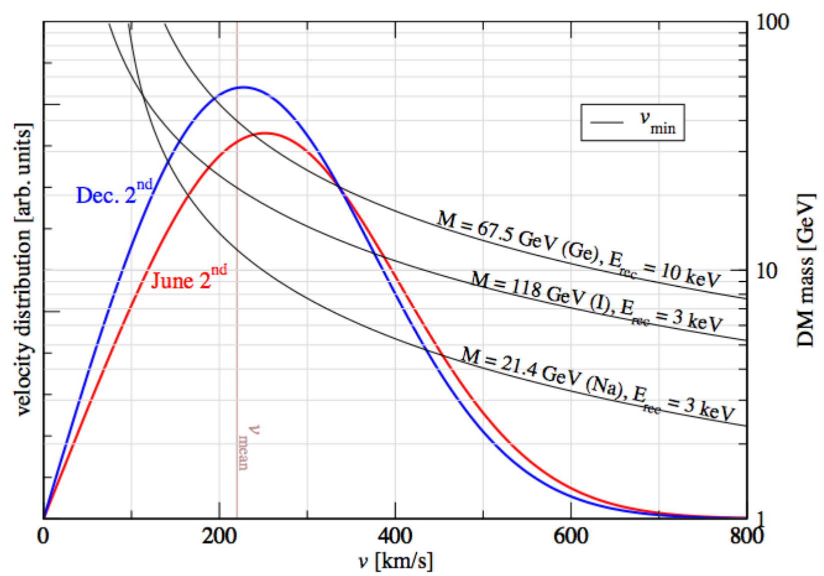
Active background discrimination with 2 channels



Courtesy E. Pantic

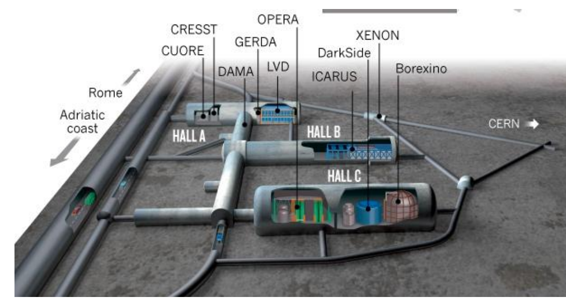
Looking for signatures: the "annual modulation" story



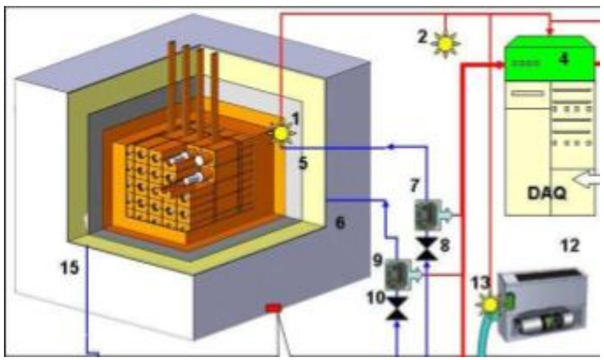


From T.Schwetz

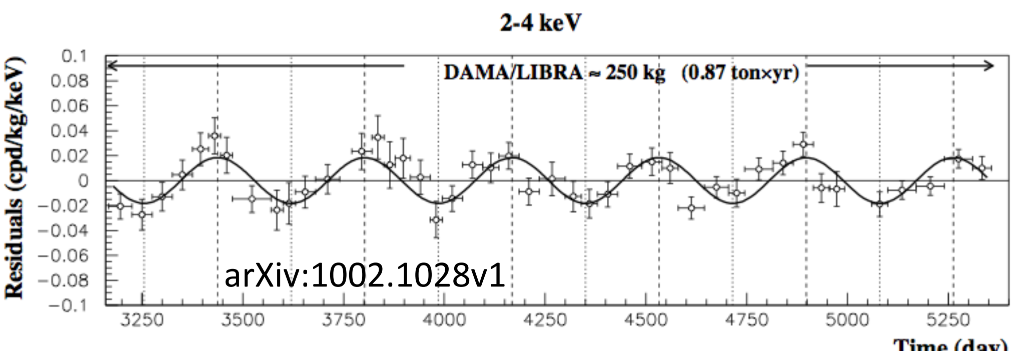
Light only: DAMA @Gran Sasso

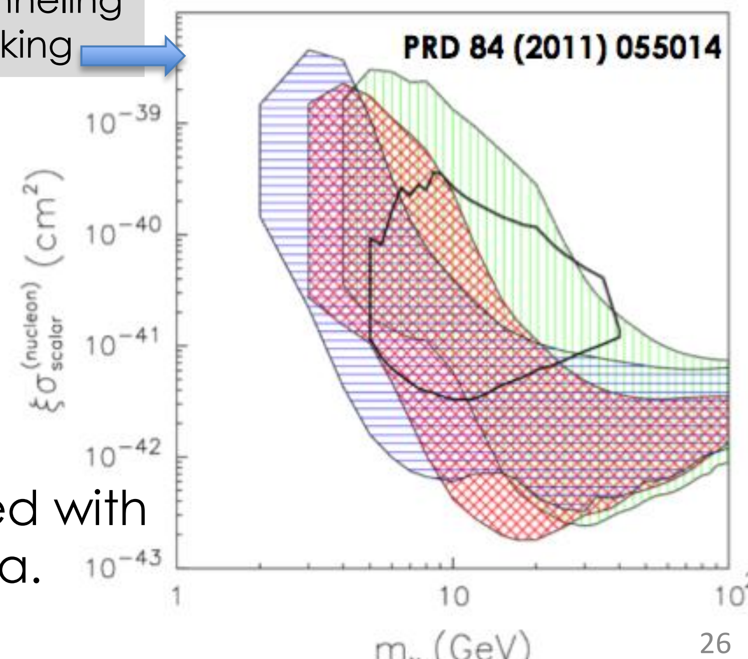


- 250 kg NaI, 0.82 tons-year
- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- 5.5-7.5 pe/keV
- Two PMTs, coincidence at the single pe
- Modulation effect, ~9 σ



- Green: no channeling
- Blue: with channeling
- Red: more cooking





Recent developments: old ETL PMTs replaced with higher QE Hamamatsu. Waiting for new data.

DM Ice

ark atter
DM-Ice-17 deployed in 2010

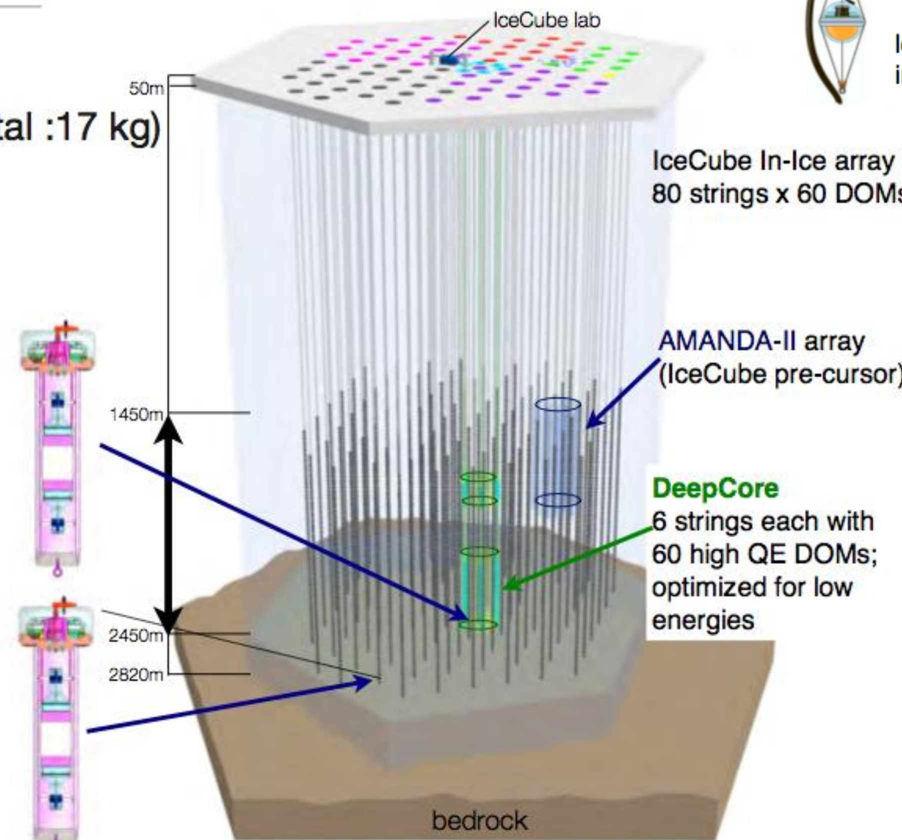
Detectors:

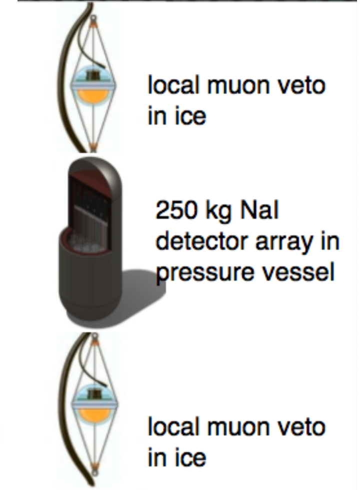
- Two 8.5 kg NaI detectors (total :17 kg)
- crystals from NAIAD

Goals:

- Assess the feasibility of deploying NaI(Tl) crystals in the Antarctic Ice for a dark matter detector
- Establish the radiopurity of the antarctic ice / hole ice
- Explore the capability of IceCube to veto muons

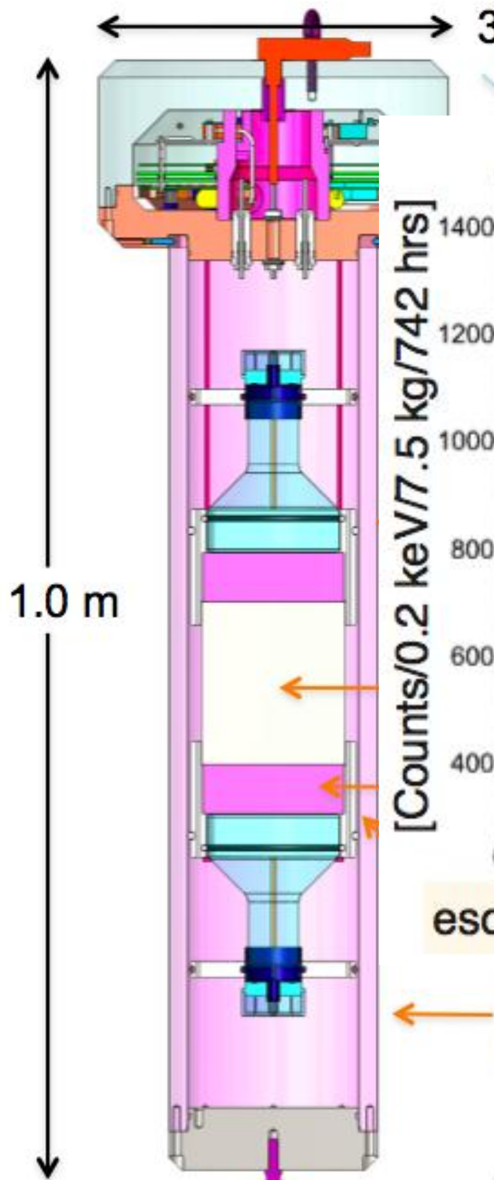
Installed Dec. 2010

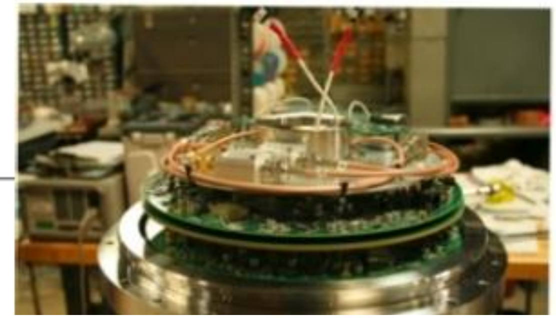


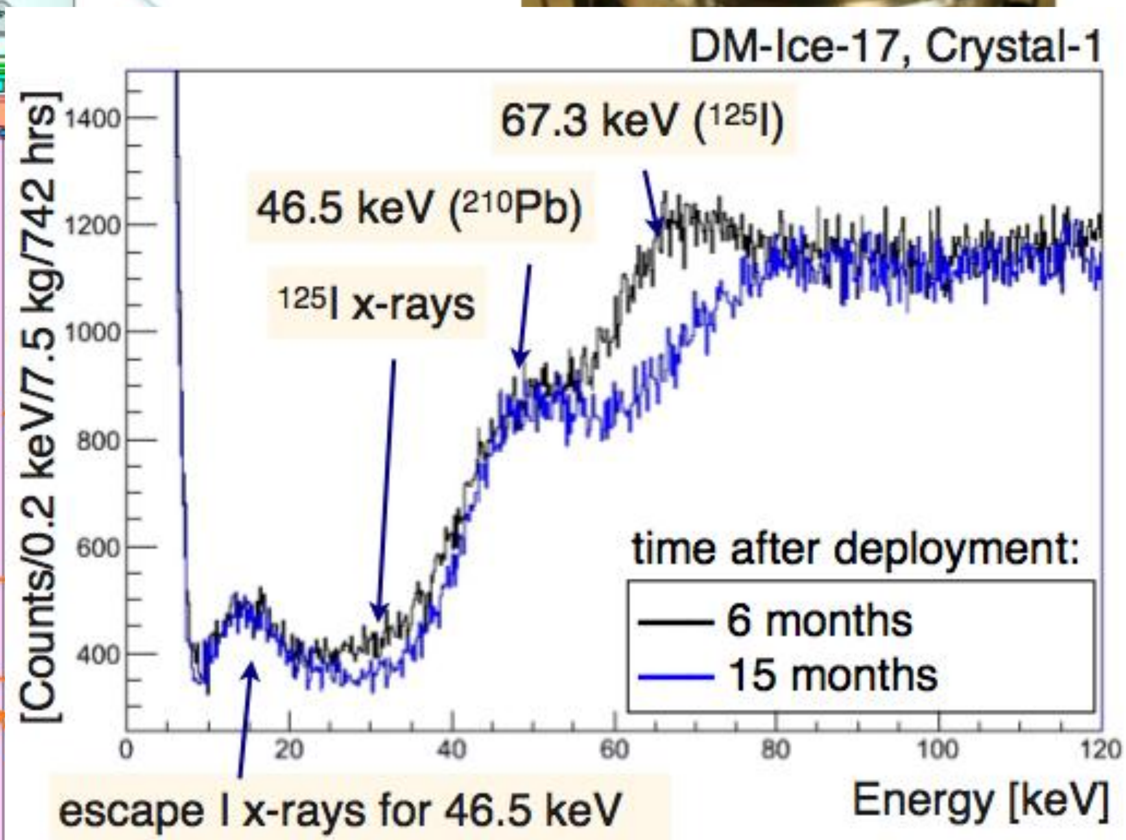


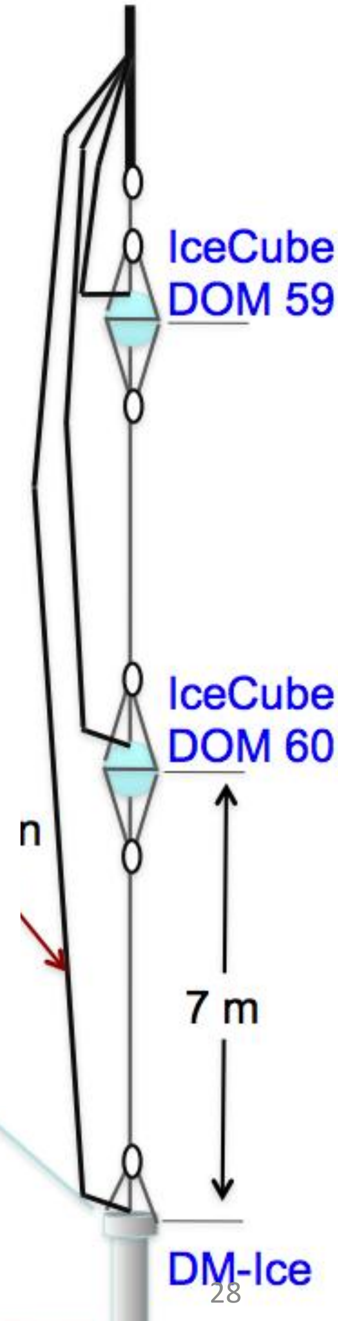
From R. Maruyama, TAUP 2011

DM-Ice-17 Detector

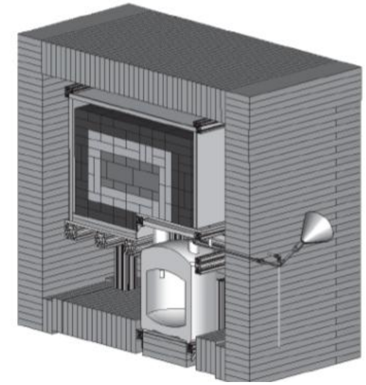




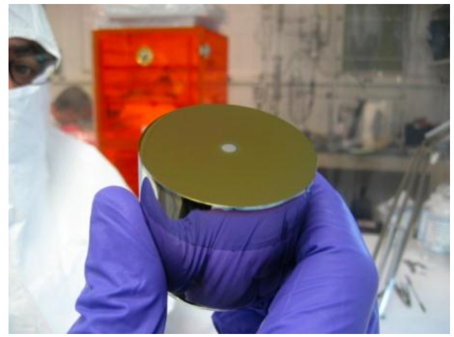




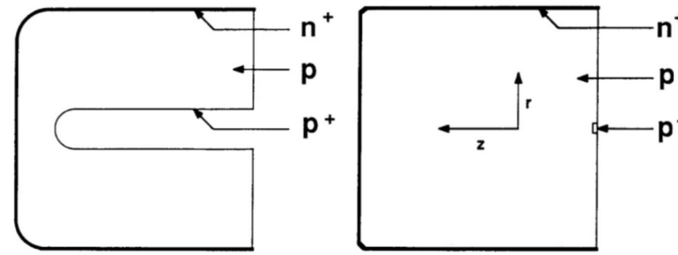
Charge only: CoGeNT

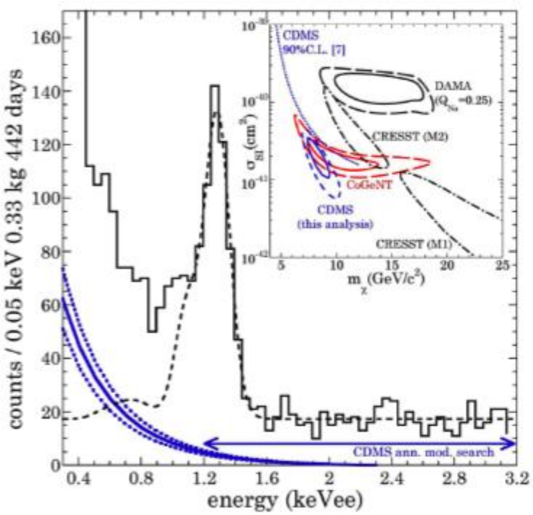


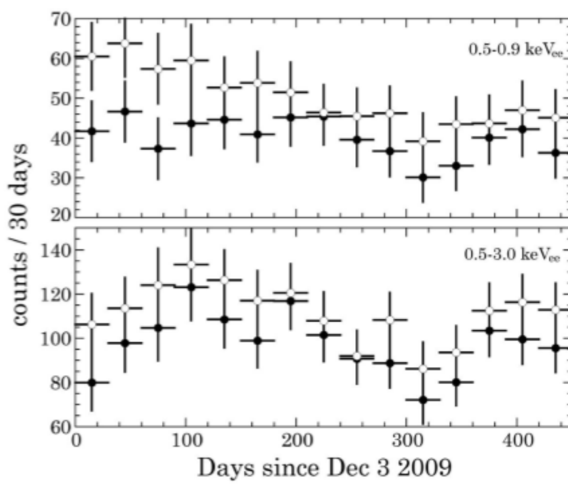
- **Soudan laboratory**, 2100 mwe
- 330 g HPGe, 450 d
- P-type Point-Contact (P-PC)
- Threshold: 400 eV !!
- Unexplained "background"
- Modulation compatible with Dama?

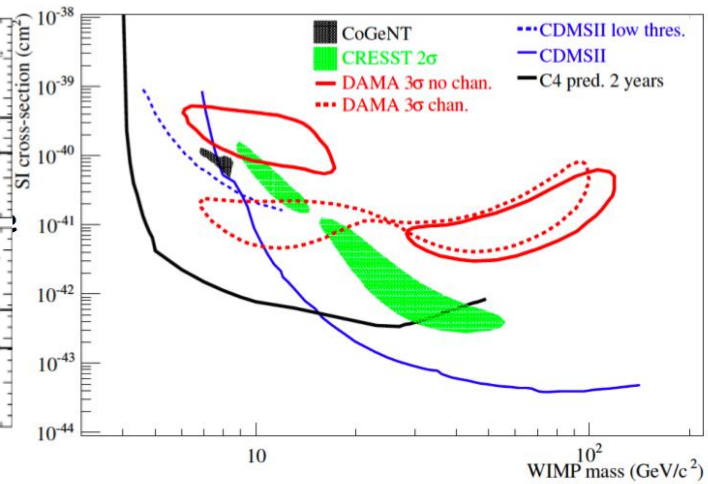


- P-type Point-Contact (P-PC) Germanium
- Geometry: low-capacitance, noise; long charge drift times





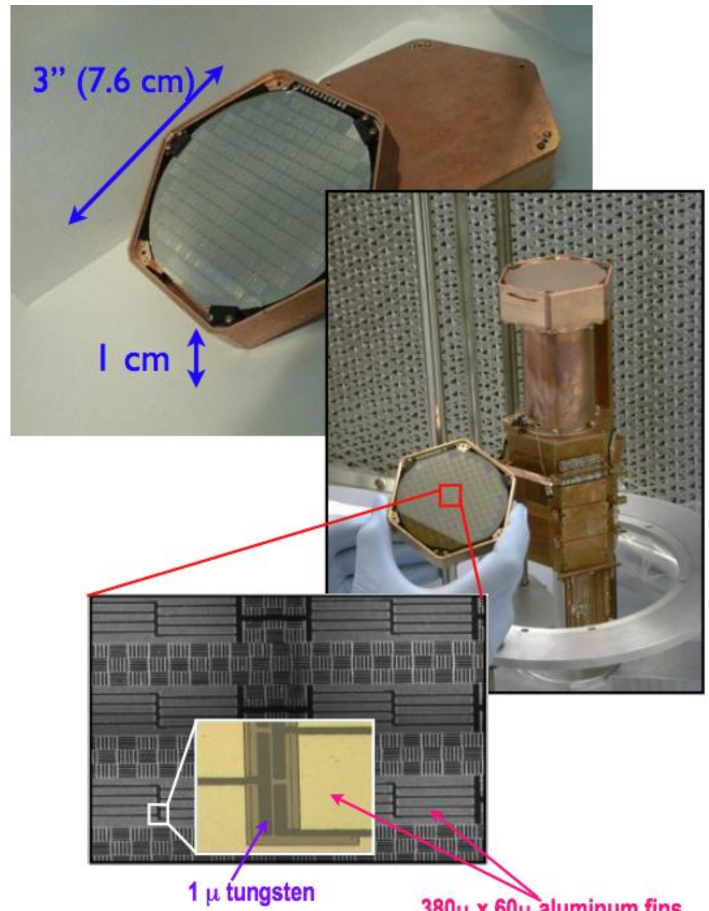




Charge & Phonons: CDMS @Soudan

Installed and
operating in Soudan since June
2006.
-4.75 kg of Ge, 1.1 kg of Si

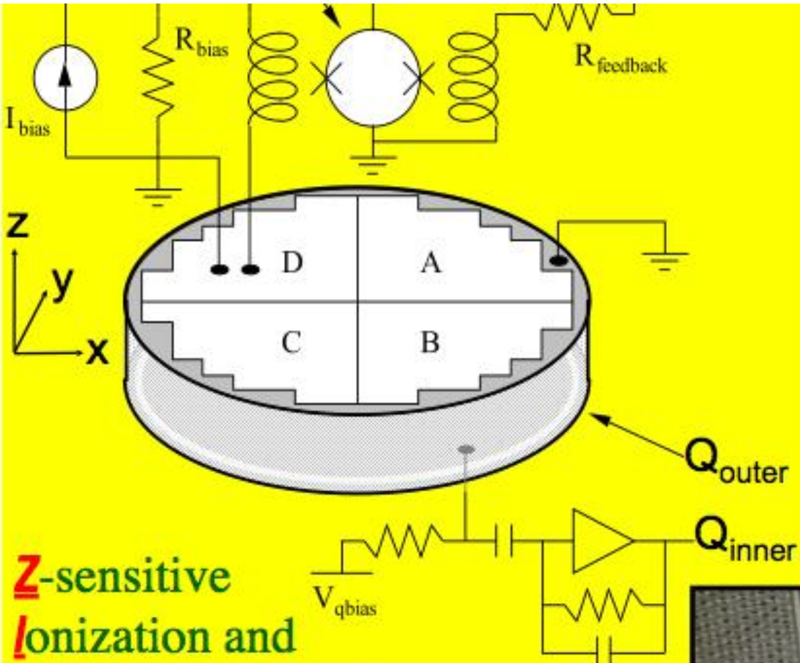
- **Z**-sensitive **I**onization and **P**honon mediated
- **230 g Ge** or **100 g Si** crystals (1 cm thick, 7.5 cm diameter)
- Photolithographically patterned to **collect athermal phonons** and **ionization signals**
  - xy-position imaging
  - Surface (z) event rejection from pulse shapes and timing
- **30 detectors** stacked into **5 towers** of 6 detectors



19 Jodi Cooley, SMU, CDMS Collaboration

40 mK operating temperature.
Shielded by a muon veto, Pb and
polyethilene

CDMS-II



Z-sensitive
Ionization and
Phonon-mediated

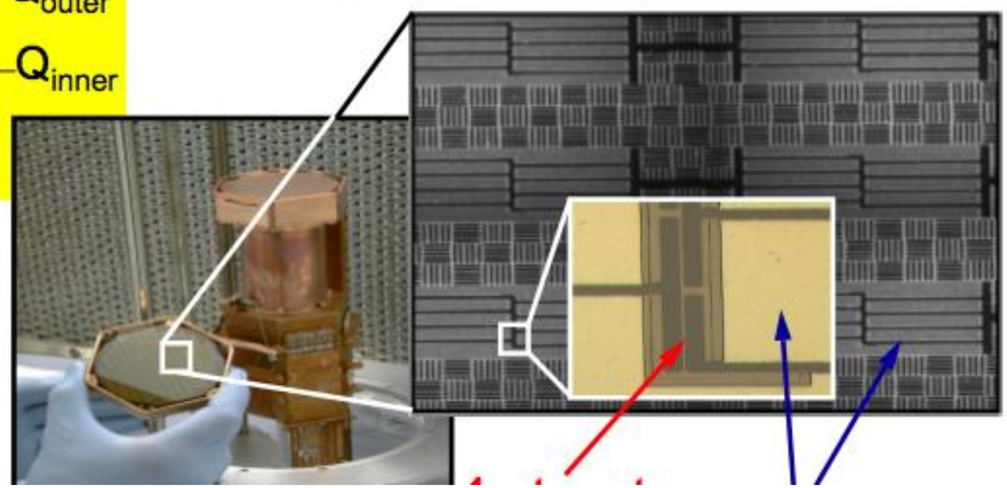
Measure ionization in low-field (~volts/cm) with segmented contacts to allow rejection of events near outer edge

1 cm thick x 7.5 cm diameter

Photolithographic patterning

Collect athermal phonons:

- Crystal lattice vibrations
- Speed of sound in crystal ~ 1 cm/ms results in measurable delays between the pulses of the 4 phonon channels => position sensitivity



CDMS active background rejection

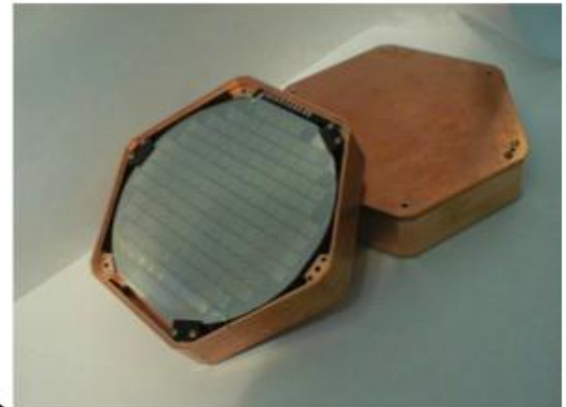
Detectors with excellent event-by-event background rejection

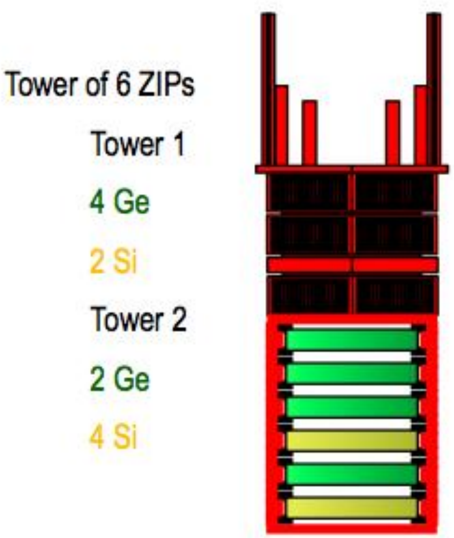
Use charge/phonon AND phonon timing

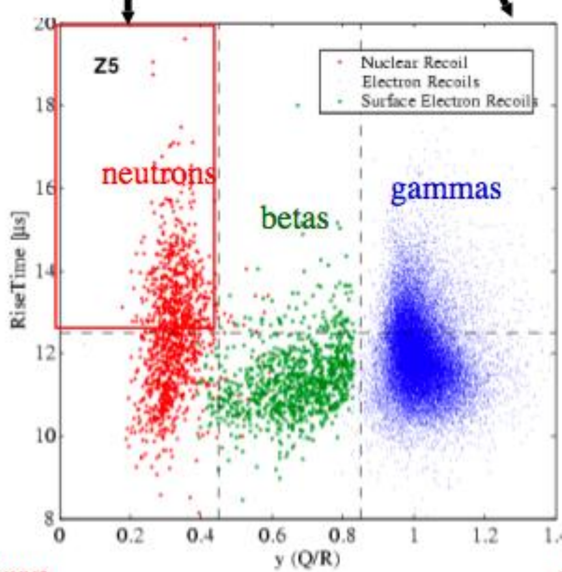
Measured background rejection:

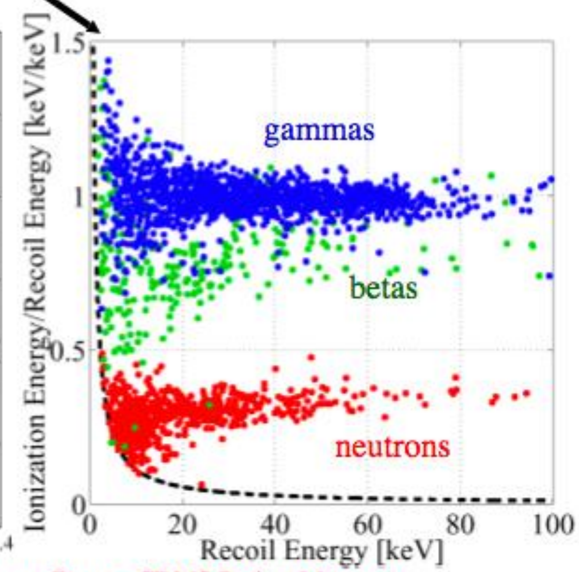
99.9998% for γ's, 99.79% for β's

Clean nuclear recoil selection with ~ 50% efficiency







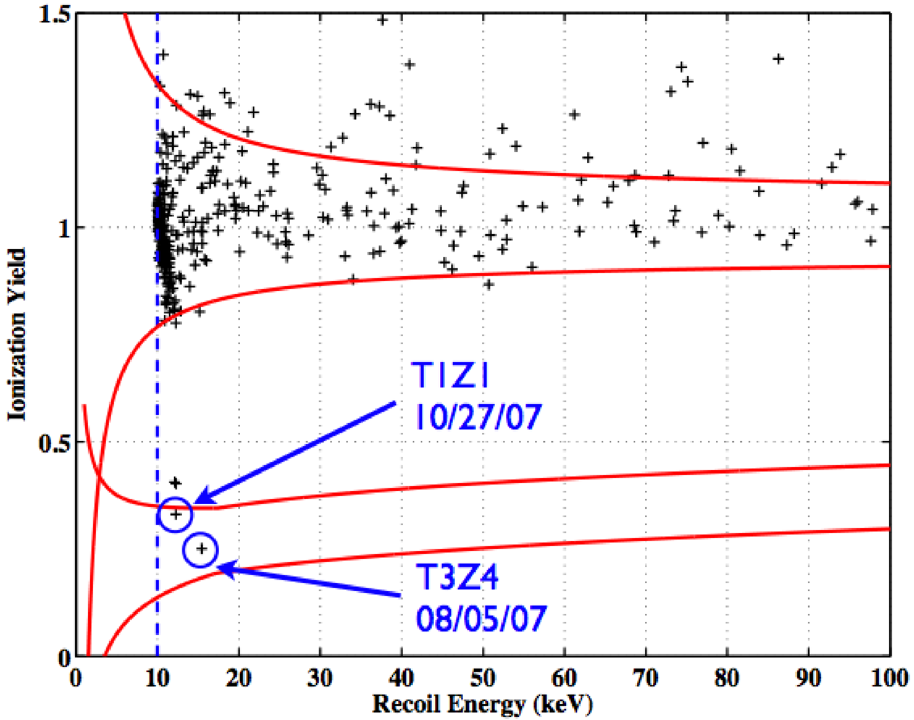


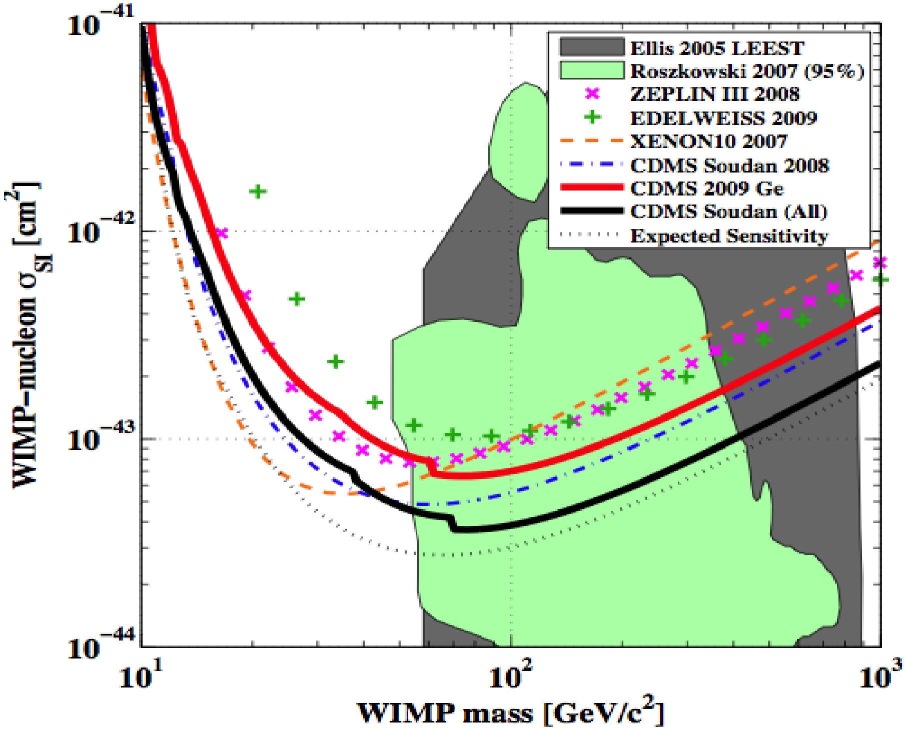
PPD Engineering Meeting - July 14,

Dan Bauer - CDMS Project Manager

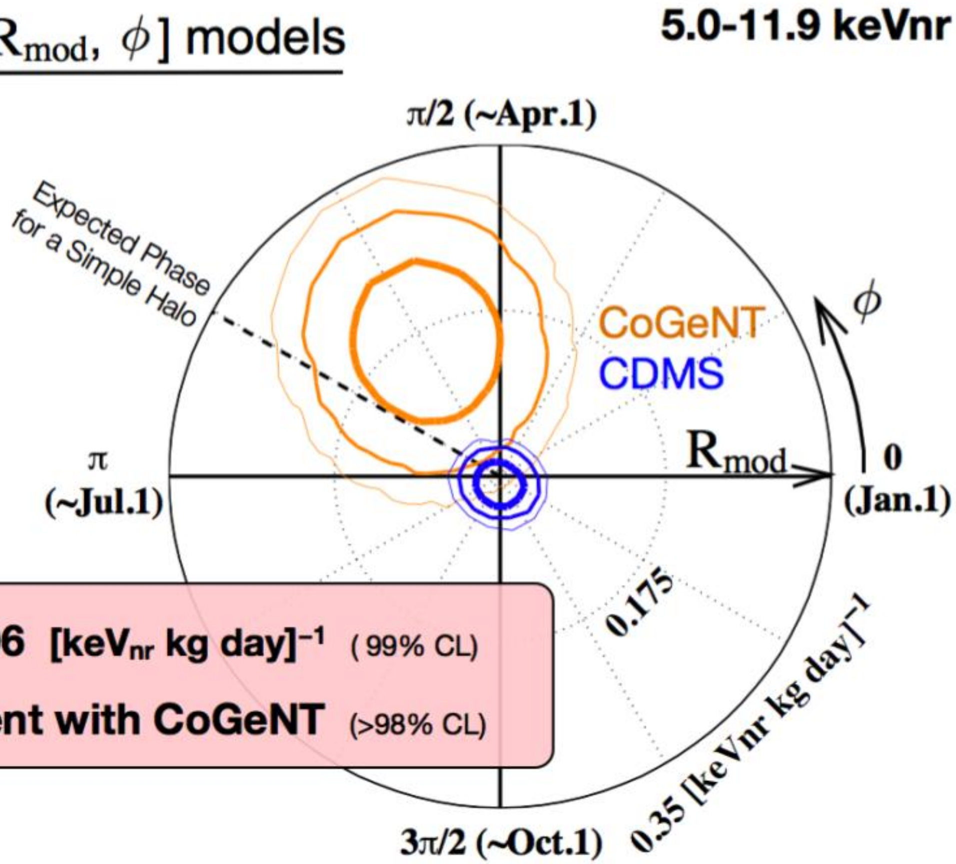
CDMS results, 2009

- 2 years of data taking, ~191kg year
- surface events = 0.8±0.1(stat)±0.2(syst).
- Expected neutrons = 0.1 ±0.05(syst).
- Observed: 2 events



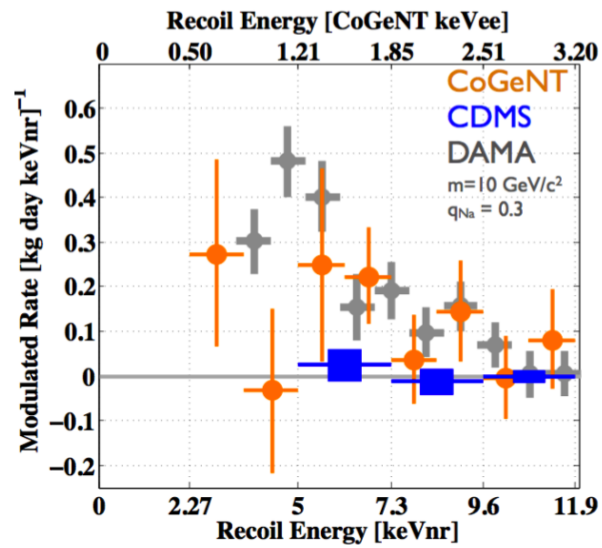


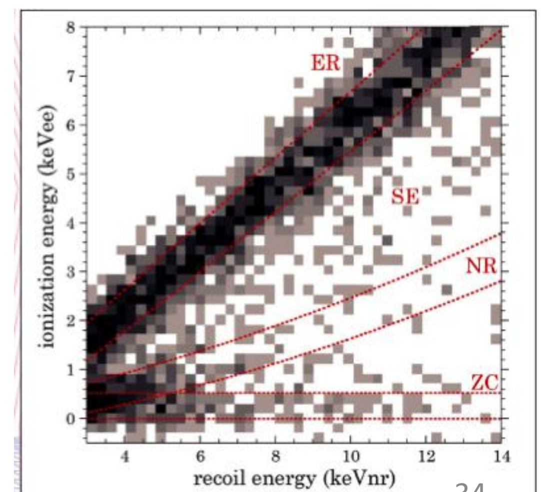
Tension with COGENT



R_{mod} < 0.06 [keV_{nr} kg day]$^{-1}$ (99% CL)

inconsistent with CoGeNT (>98% CL)

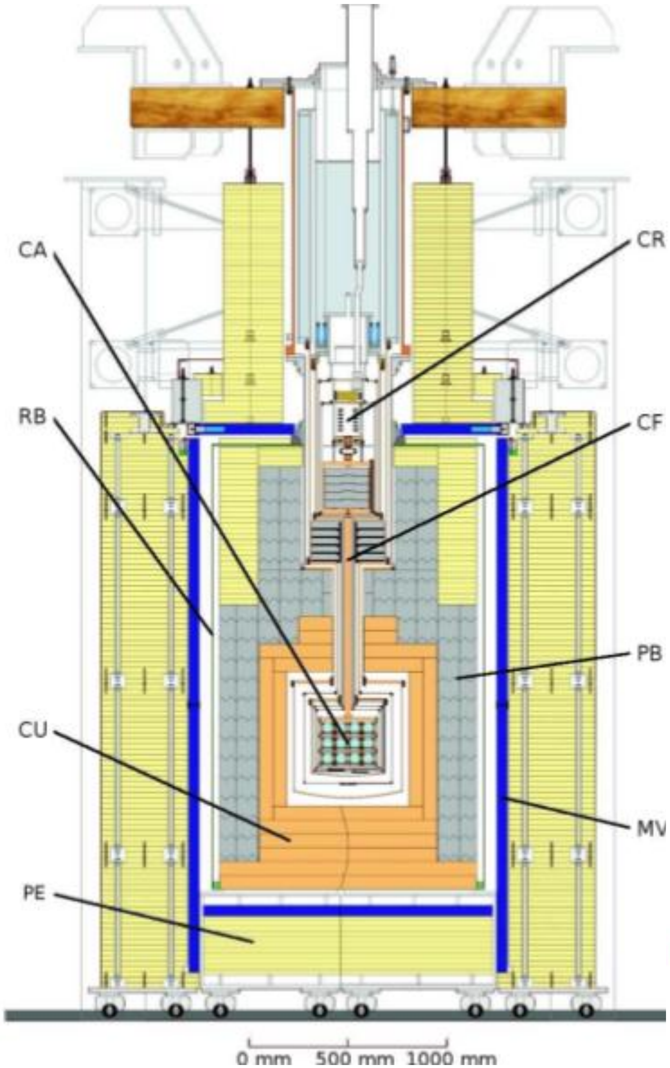




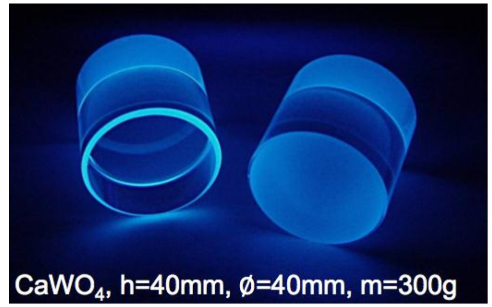
Criticism by Fields and Collar: low energy NRs are disregarded

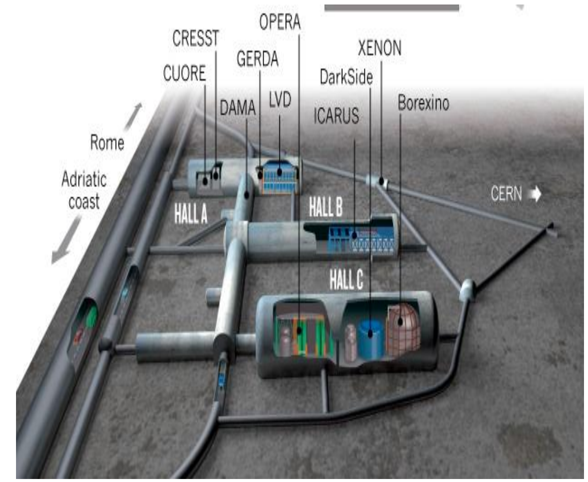
Scott Hertel, IDM 2012

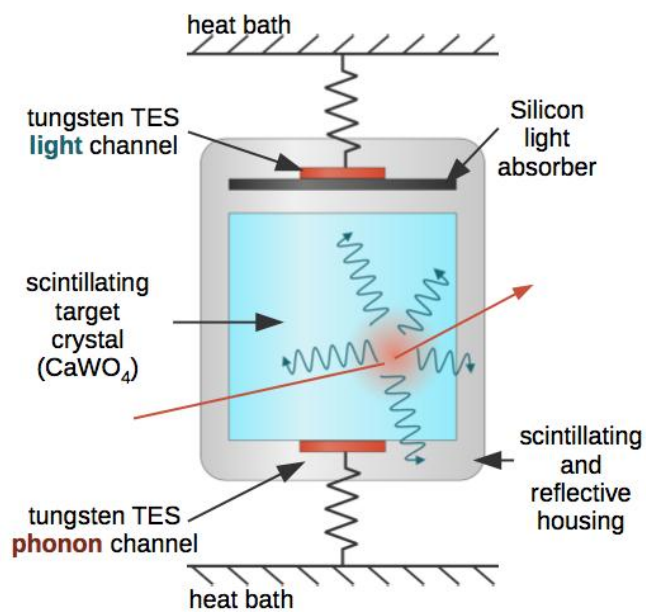
Phonons&Light: CRESST @LNGS



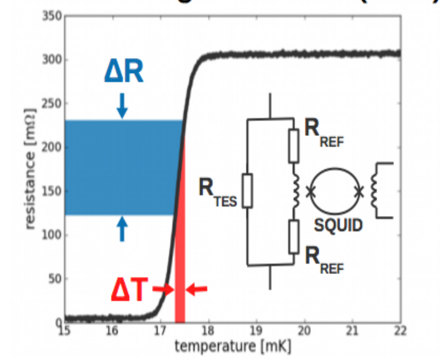
Calcium Tungstate







Transition Edge Sensors (TES)

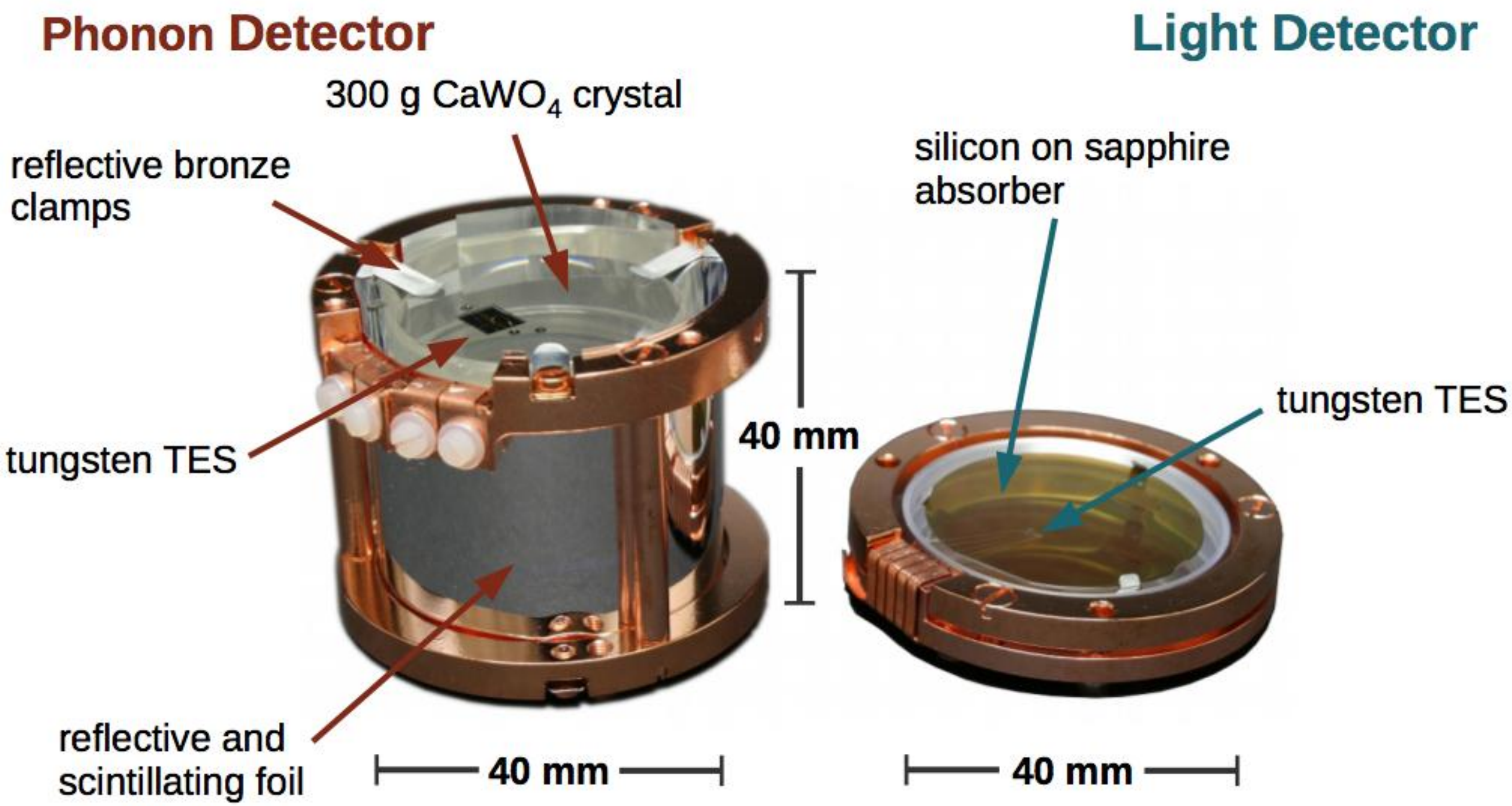


Advantages Of Our Detectors

- **precise calorimetric measurement** of deposited energy
- **low** energy **threshold** and **excellent** energy **resolution**
- possibility to use **different materials**

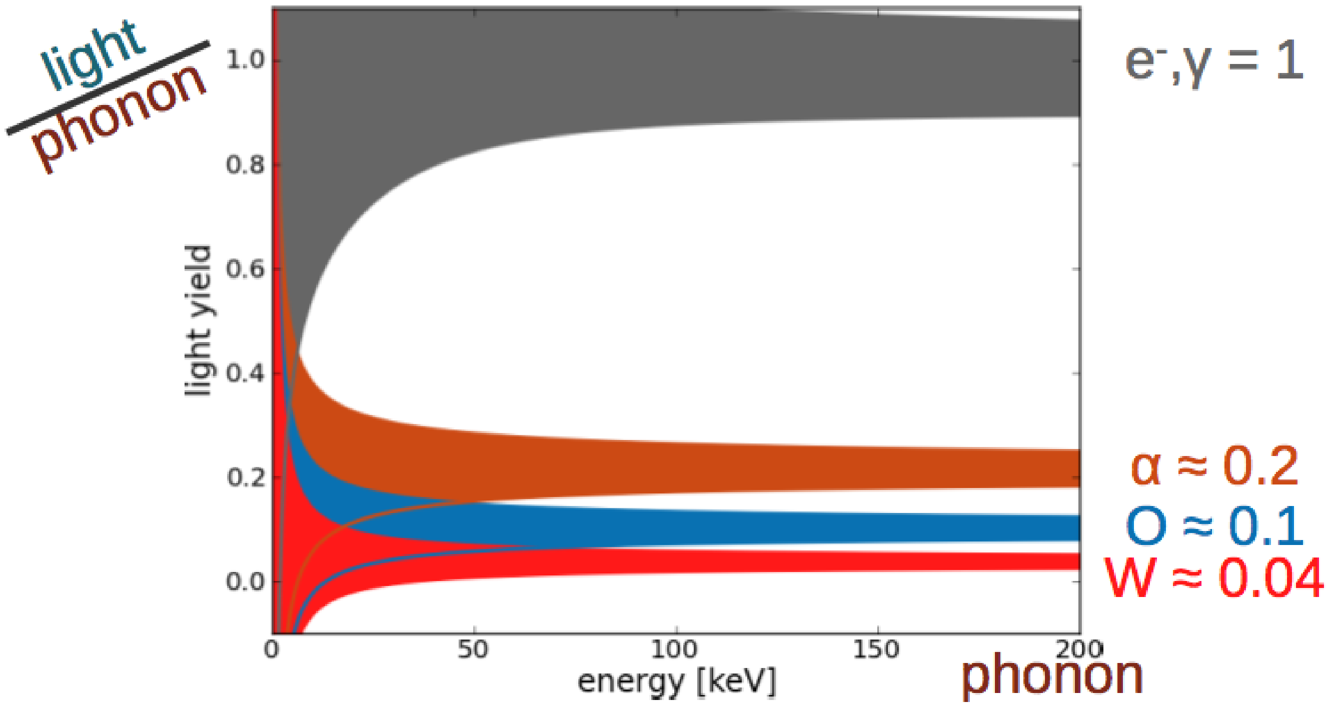
From C. Strandhagen, IDM 2012

CRESST detectors



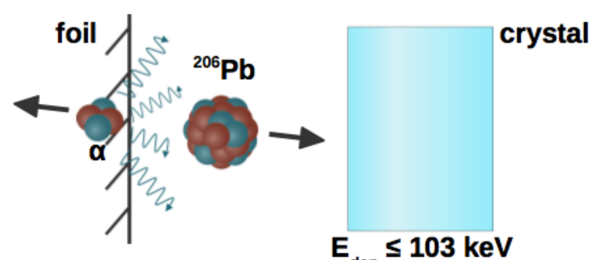
From C. Strandhagen, IDM 2012

CRESST active discrimination



- ^{210}**Po decay** on surface

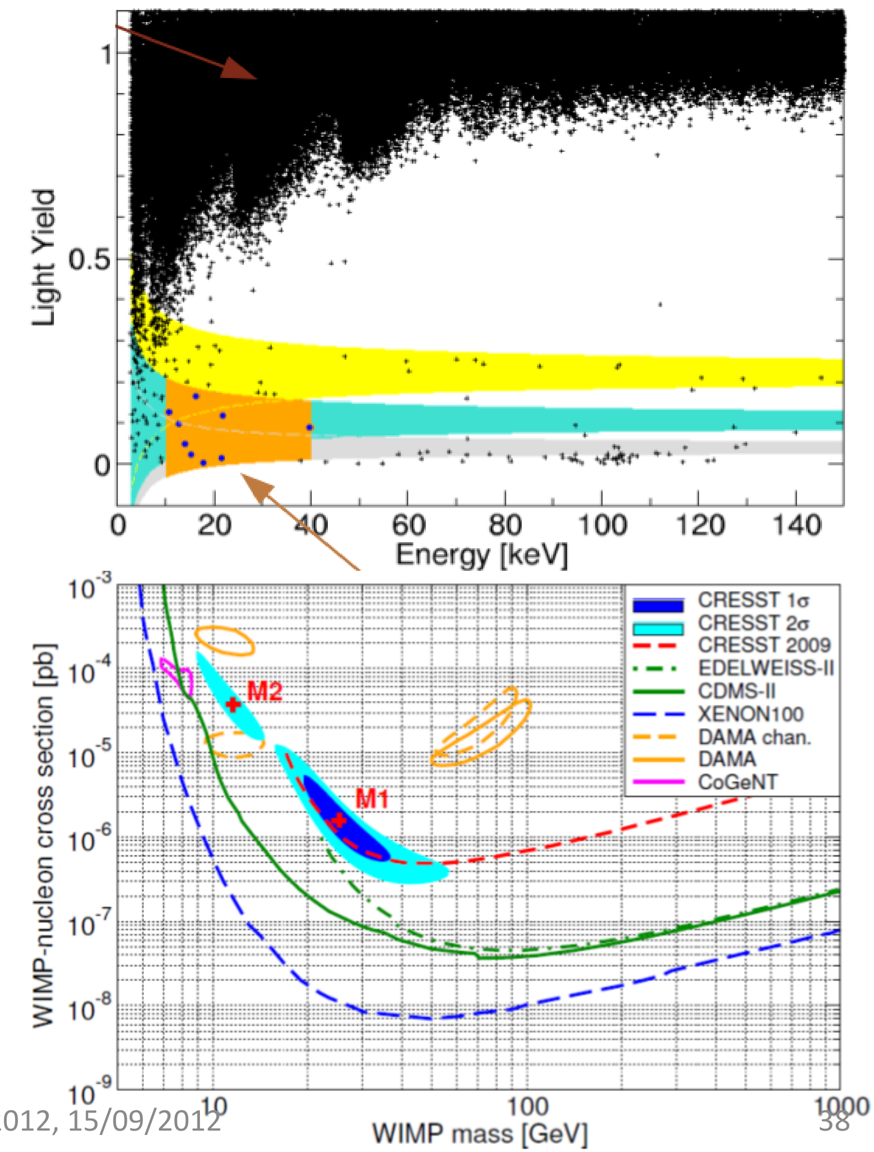
^{210}Po → ^{206}Pb (103 keV) + α (5.3 MeV)



From C. Strandhagen, IDM 2012

CRESST results

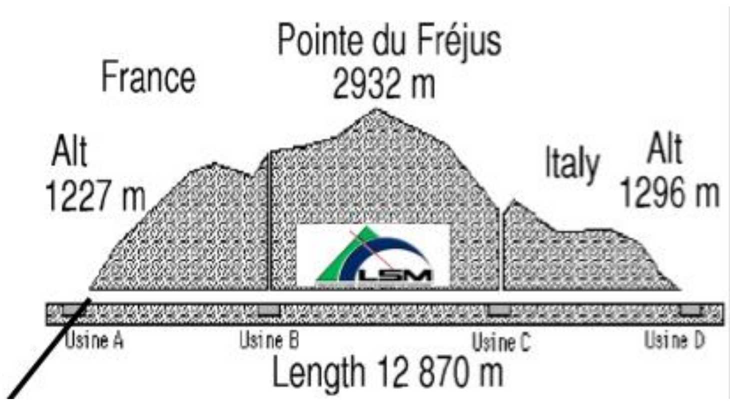
- ~730 kg days
- 67 events in acceptance region (all detectors)
- Background sources:
  - γ leakage (8.00 ± 0.05)
  - ^{206}Pb recoils (15 ± 5)
  - α from ^{210}Po decay (11.5 ± 2.5)
  - neutrons (7.5 ± 6)
- 4.7 σ significance
- WIMPs ?
  - two solutions found depending on composition of recoil spectrum

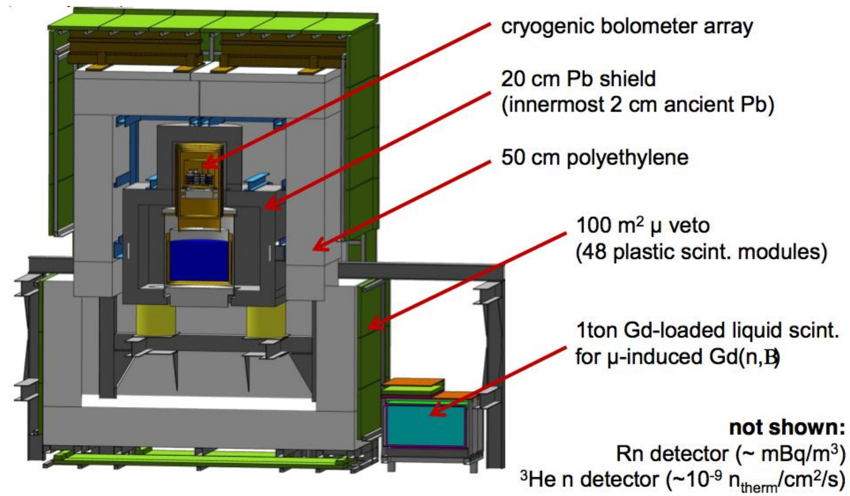


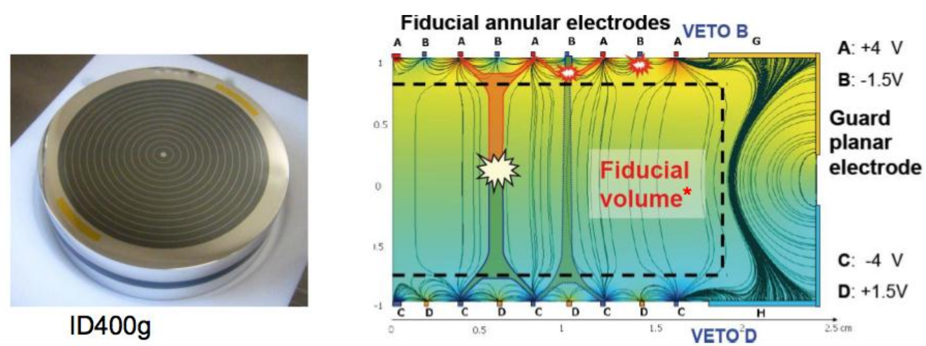
From C. Strandhagen, IDM 2012

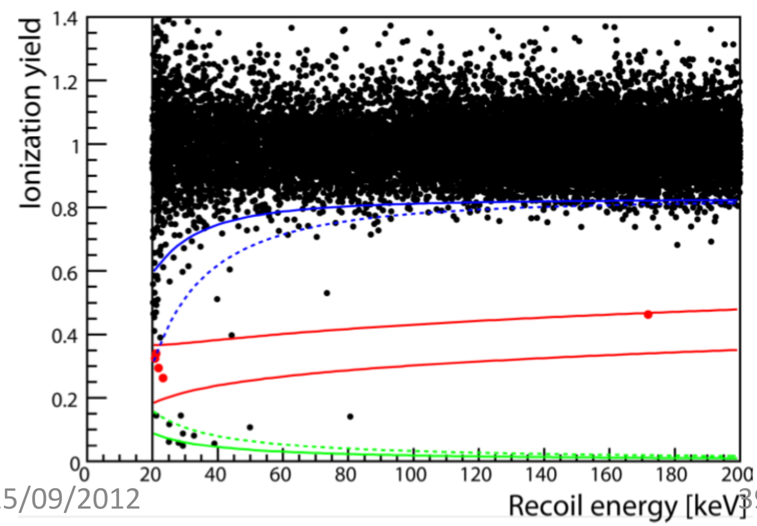
EDELWEISS @Modane

- 10 Ge detectors, 400g each
- total exposure of 384 kg·d

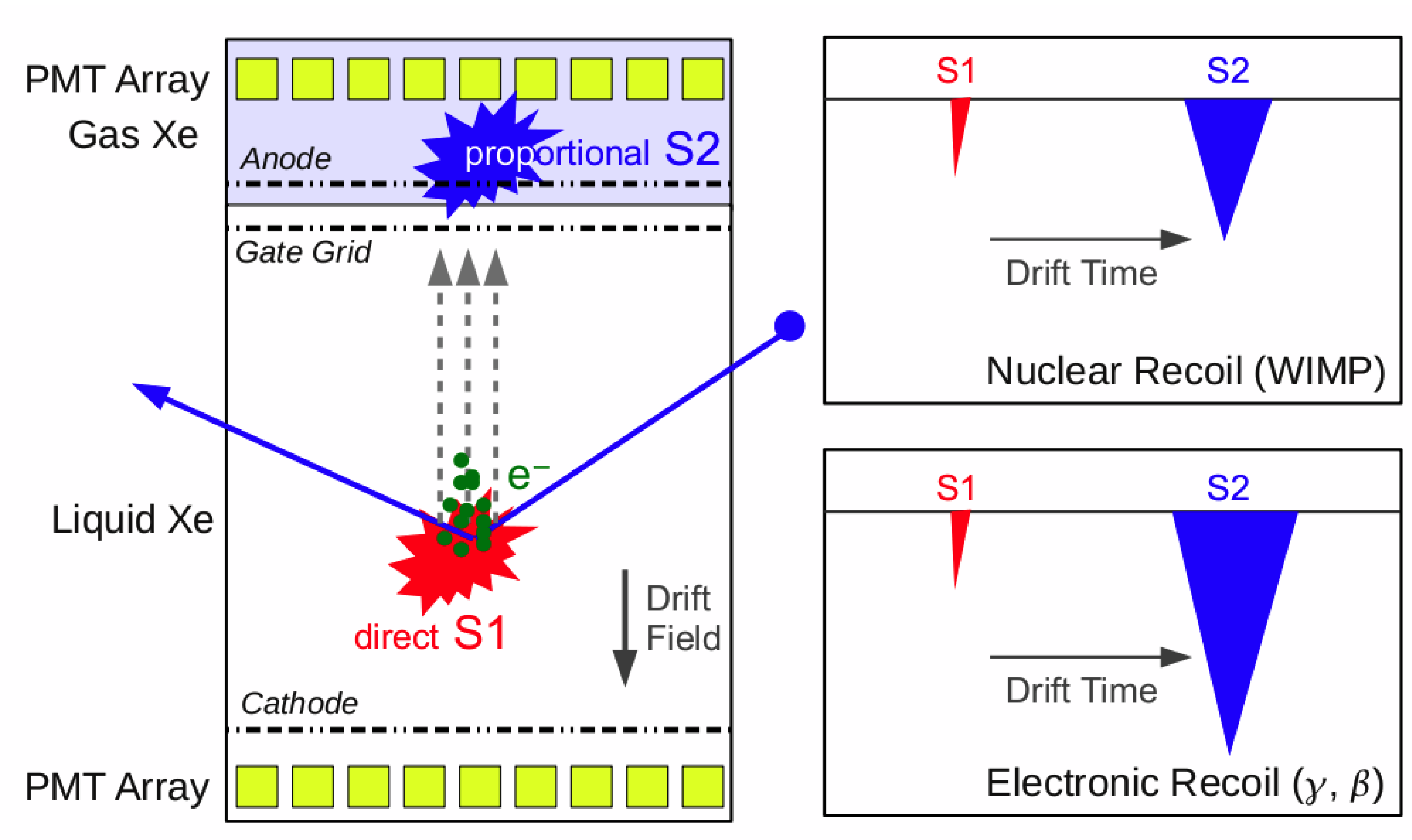




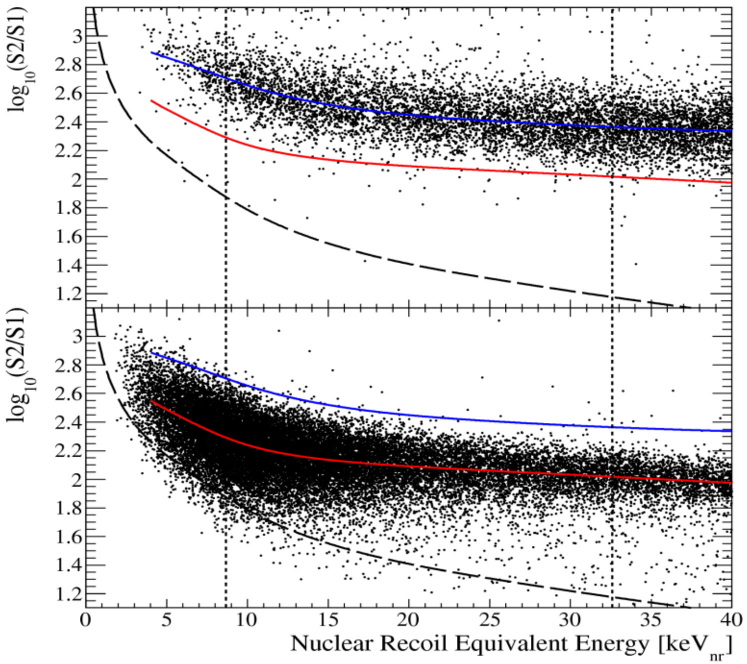




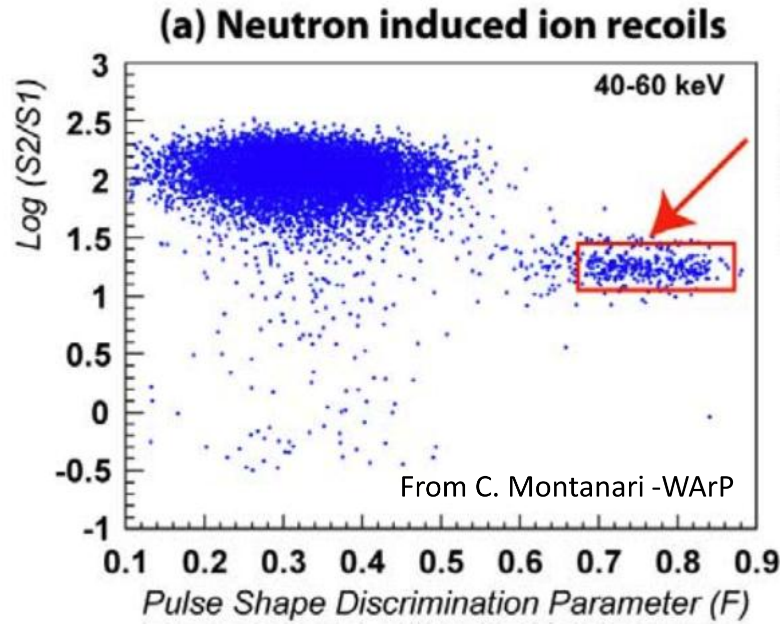
The wonders of double phase TPCs



The power of discrimination

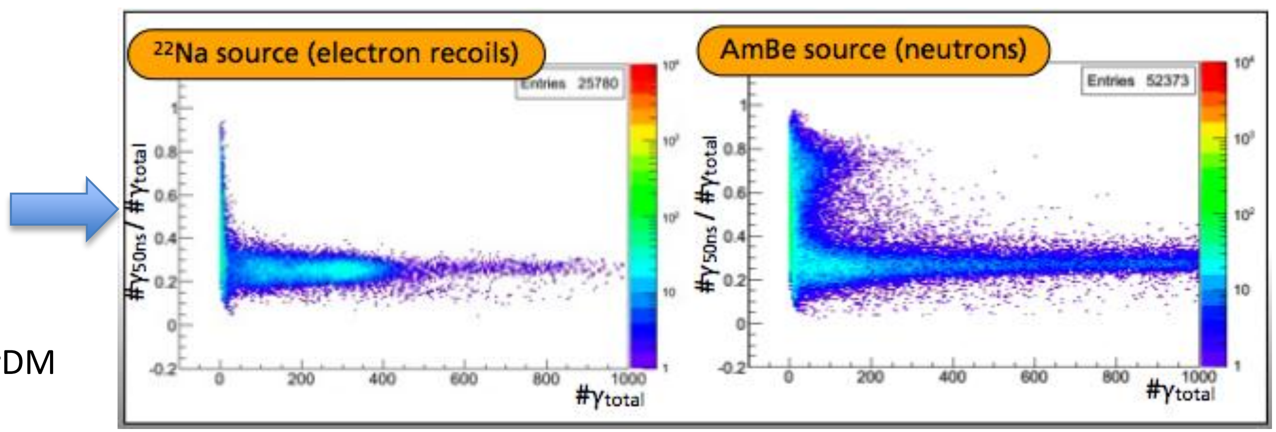


Xenon: double phase discrimination



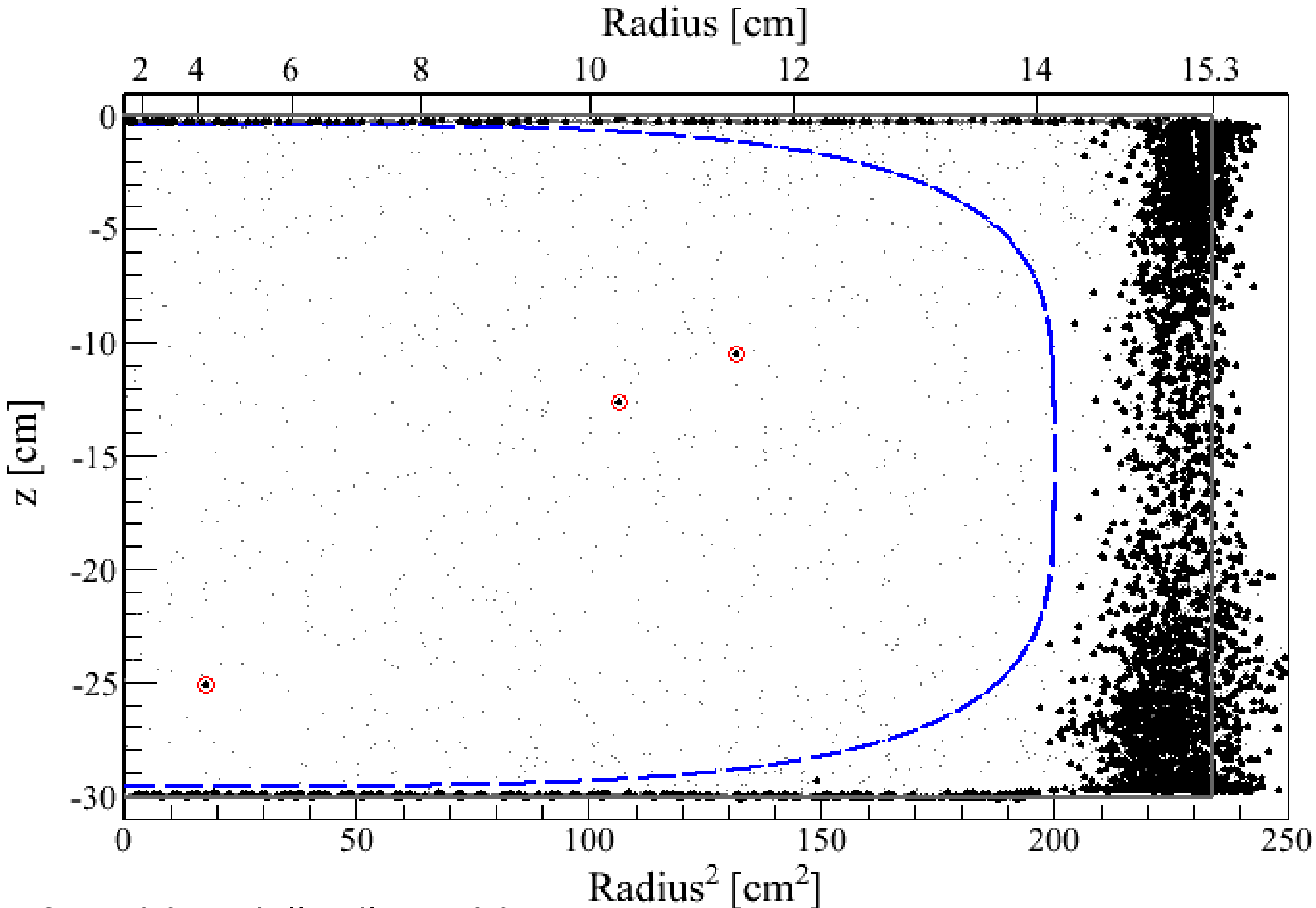
Argon: double phase + PSD

Pulse Shape Discrimination in liquid Argon



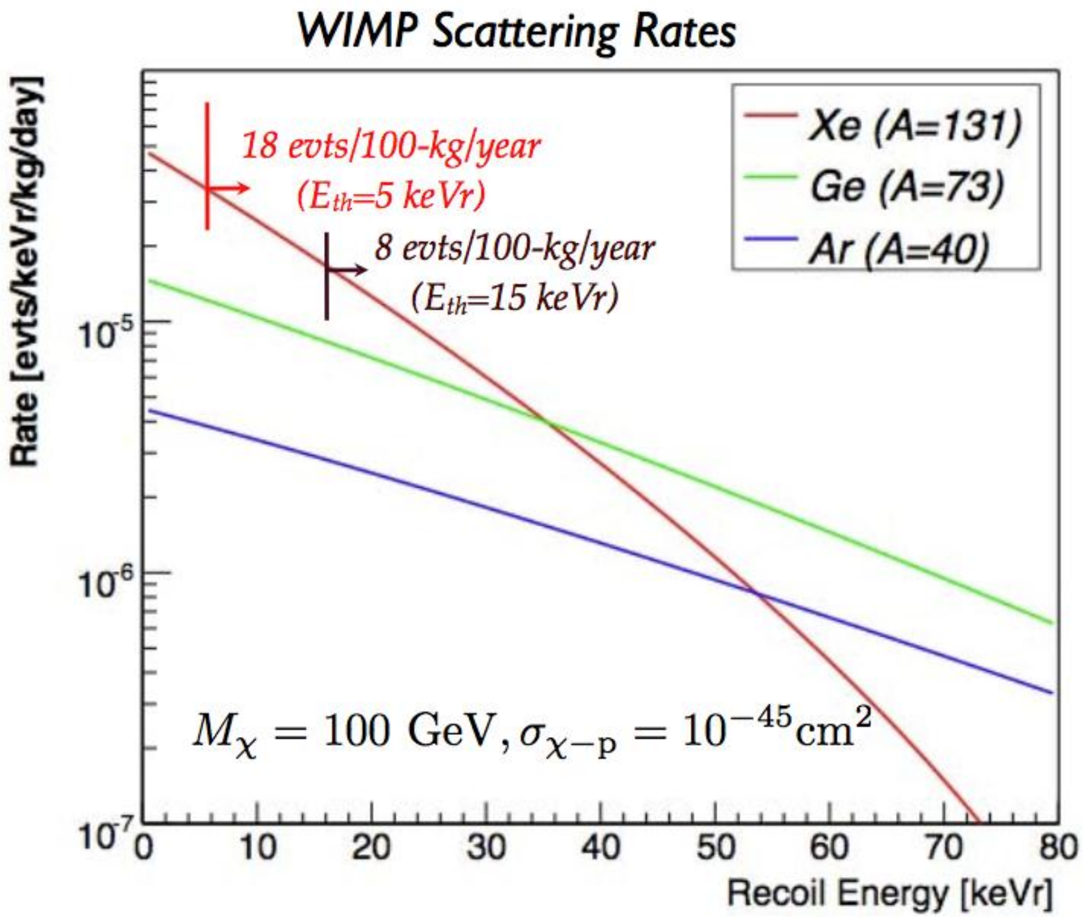
From L. Epprecht, ArDM

...and of a self shielding TPC



XENON100 unblinding, 2011

Argon vs Xenon



Argon vs Xenon

Argon	Xenon
Cheap	Not so cheap
Most impurities frozen (87K)	Easily polluted (165K)
➢ But cryogenics is more difficult	➢ But easier cryogenics
Scintillation light at 125nm	Scintillation light at 178nm
➢ Needs wavelength shifting	➢ No need for shifting
Low A	High A
➢ low cross section for WIMPS	➢ Ideal for SI and SD interactions ➢ High shielding power
Presence of ^{39}Ar @ 1Bk/kg	No natural radioactive isotopes
➢ Need to find or produce depleted Ar	➢ But presence of Kr (distillation needed)
Very good at PSD	Not especially good at PSD

Noble liquids detectors: LAr

WArP Gran Sasso: Sensitive volume of 100 l

Active and passive muon veto system

Successful operation of first prototype

Program presently stopped

Dark Side @Gran Sasso:

10 l prototype running

50 l detector in preparation

Use of depleted Ar

ArDM@CanFranc:

850 kg target

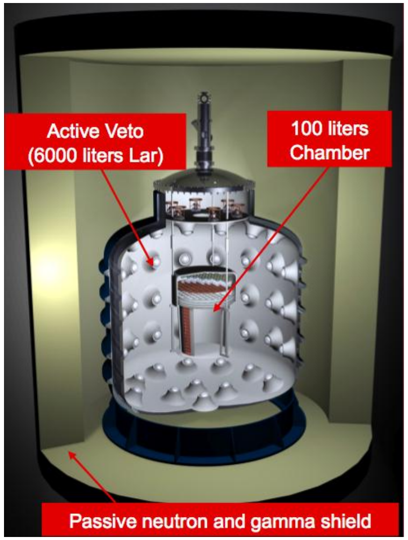
Just installed in Canfranc

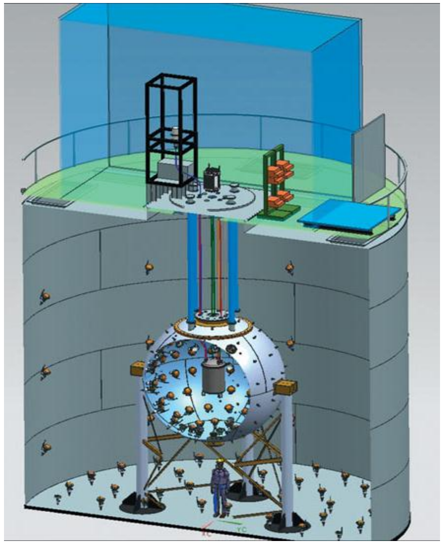
Operations to be started in 2013

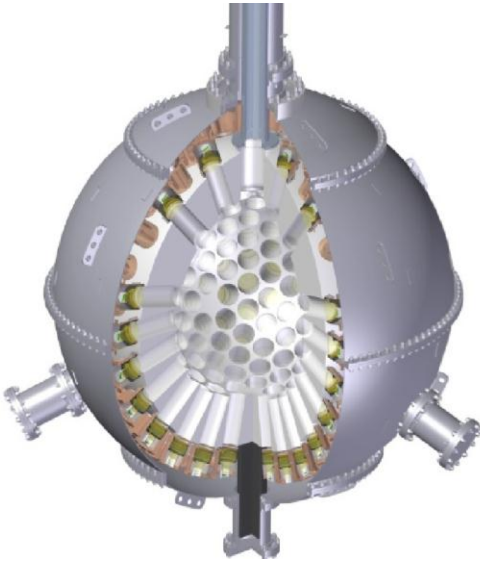
DEAP/CLEAN @SNOLab

3600kg Lar

Single phase







Noble liquids detectors: LXe

XENON @ Gran Sasso

62 kg in fiducial volume

Best limits on SI

One tonne module in preparation

XMASS @ Kamioka

835kg LXe, single phase; water shielding;

642 PMTs

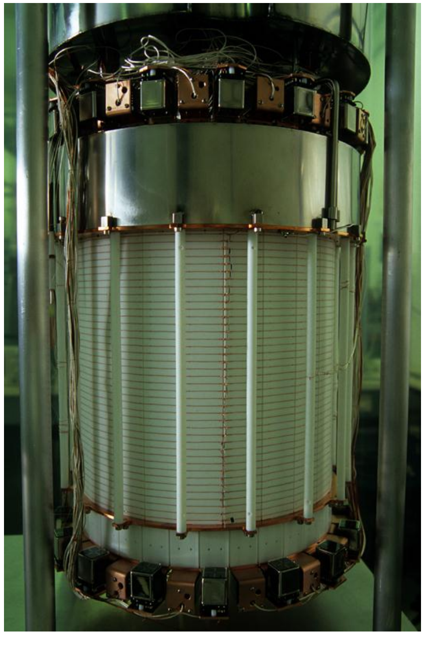
LUX @ Soudan

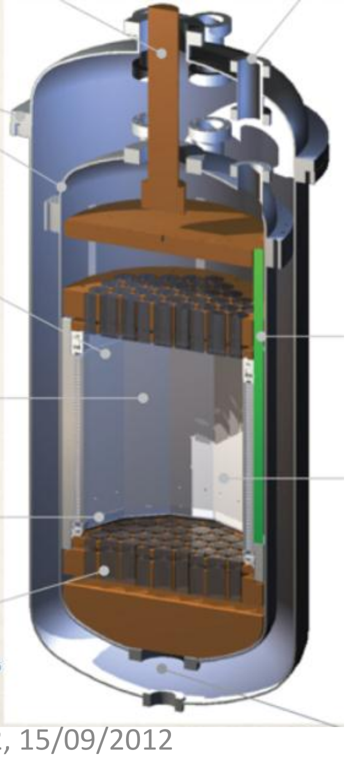
100kg fiducial

Moved underground in July 2012

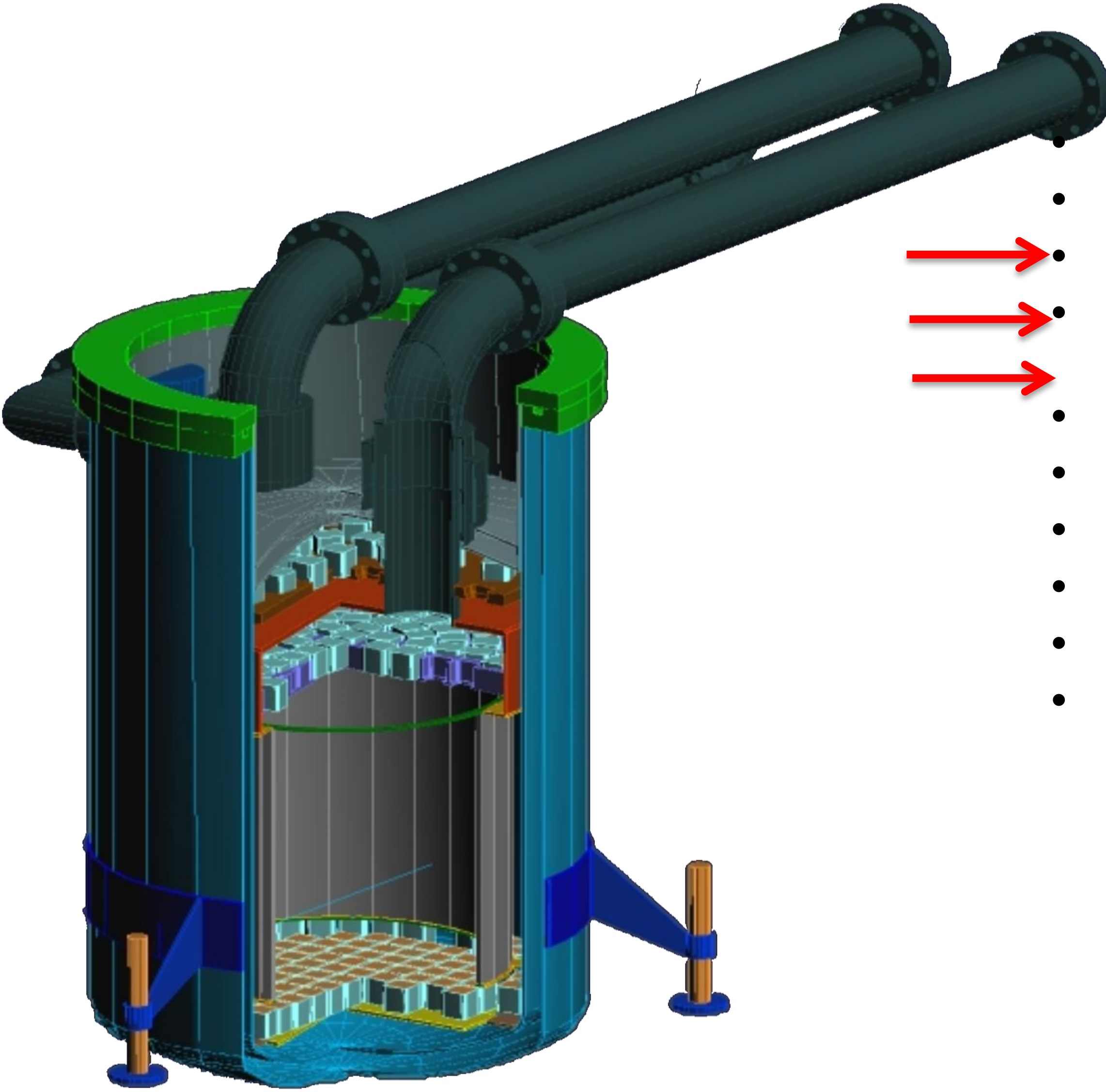
ZEPLIN @Boulby

6kg fiducial, double phase, ended 2011



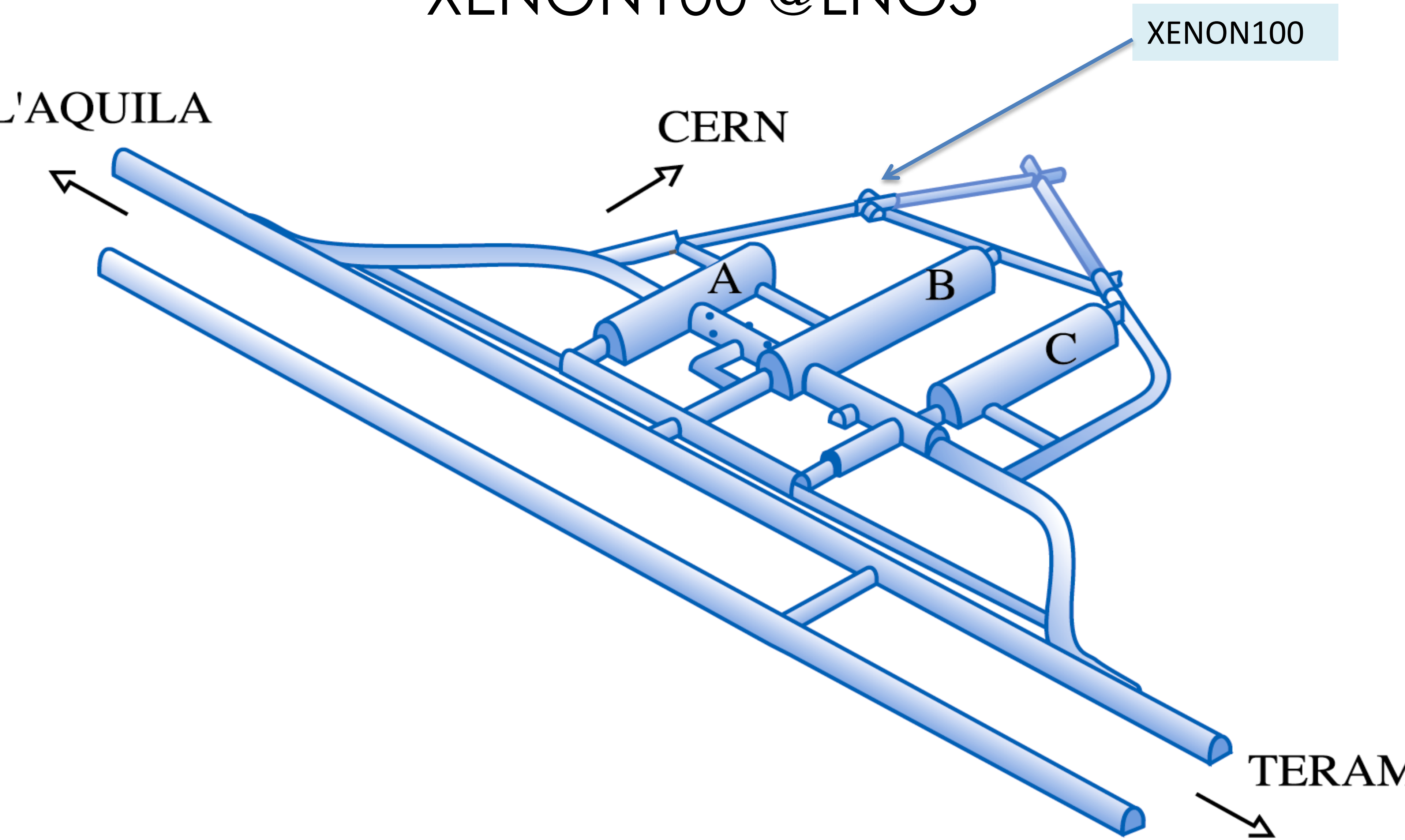


The XENON100 Detector



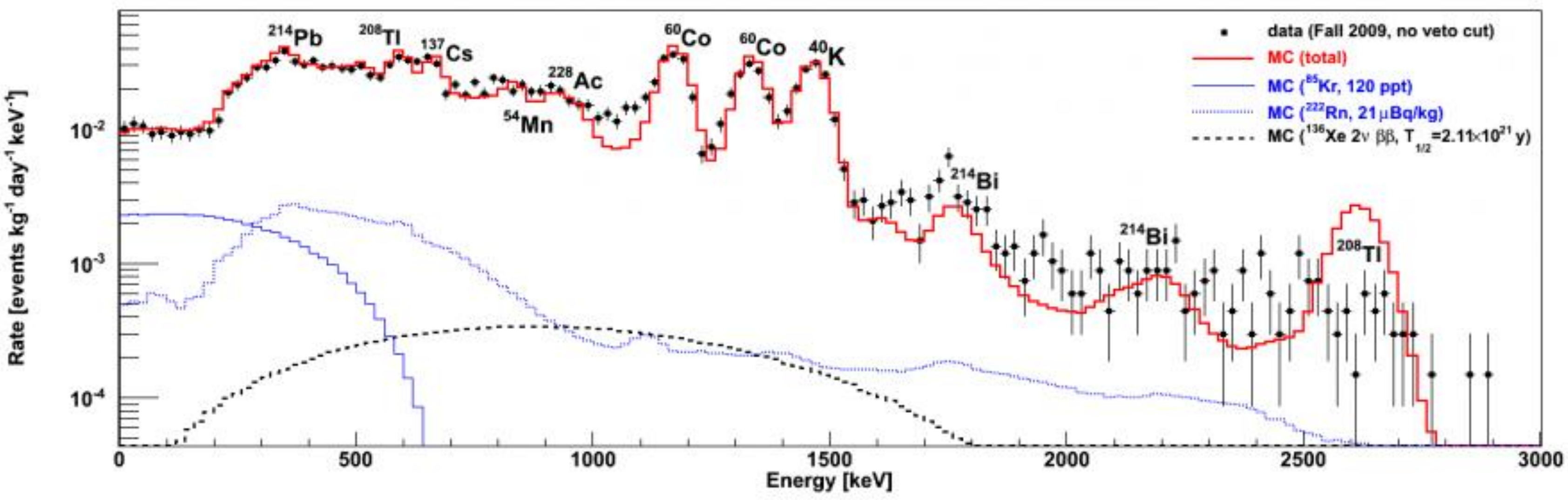
- 100 x less background than XENON10
- 10 x more fiducial mass than XENON10
- Cryocooler and FTs outside shield
- Materials screened for low radioactivity
- LXe scintillator active veto system
- Improved passive shield system
- Dedicated Kr Distillation Column
- TPC with 30 cm drift x 30 cm diameter
- 162 kg ultra pure LXe - 62 kg as target
- 1” square PMTs with ~1 mBq (U/Th)
  - R8520-06-Al 1
  - 98 PMTs in the gas phase
  - 80 in the liquid, below the cathode
  - 64 in the veto

XENON100 @LNGS

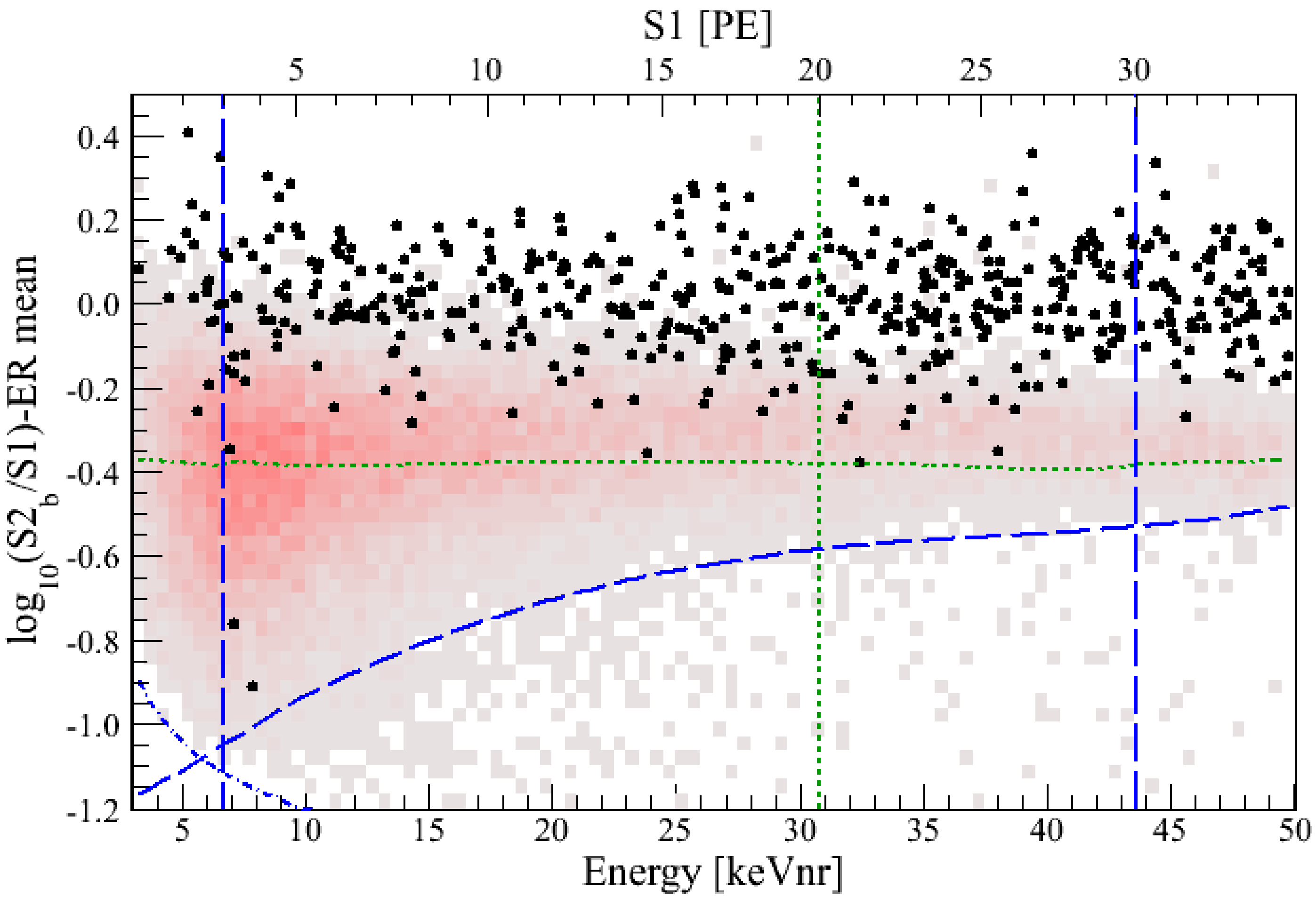


XENON100 @LNGS

Background in XENON100

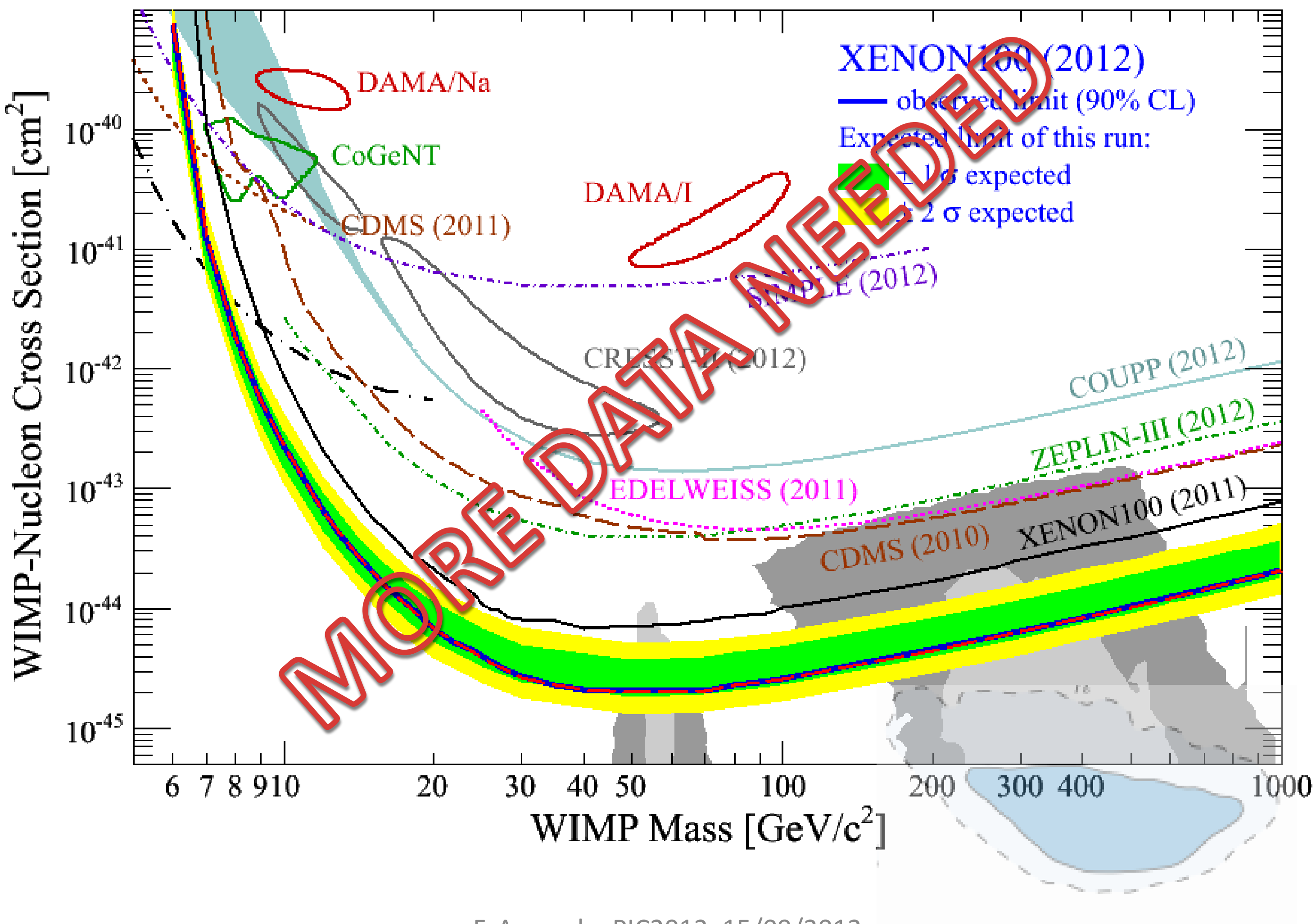


2012 XENON100 unblinding results



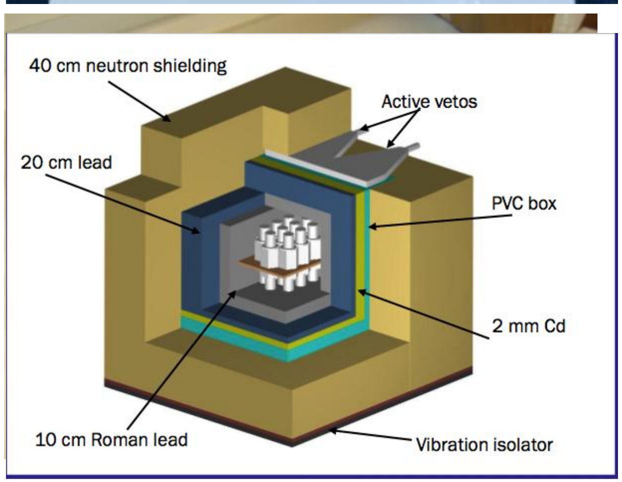
- **22**
- **2 events observed in the signal region with (1±0.2) expected**
- **No events below the signal threshold**

Present scenario



The Future I: more data from inorganic crystals

- DM ice
- ANaIs @Canfranc

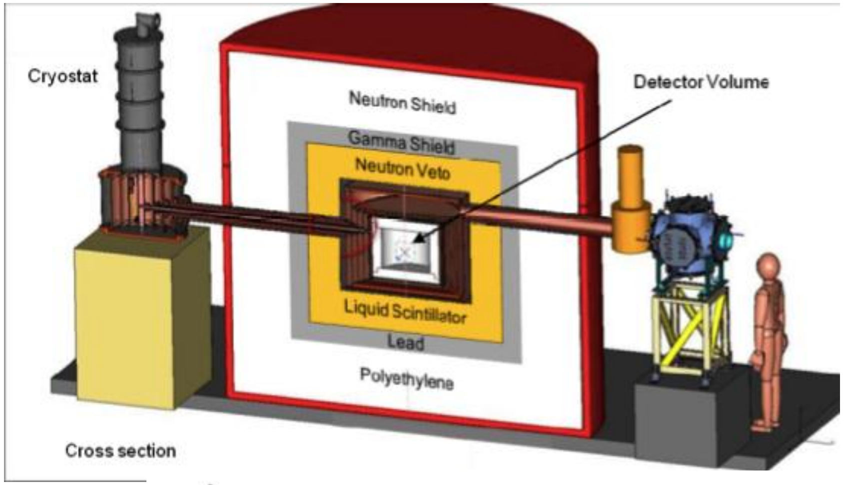


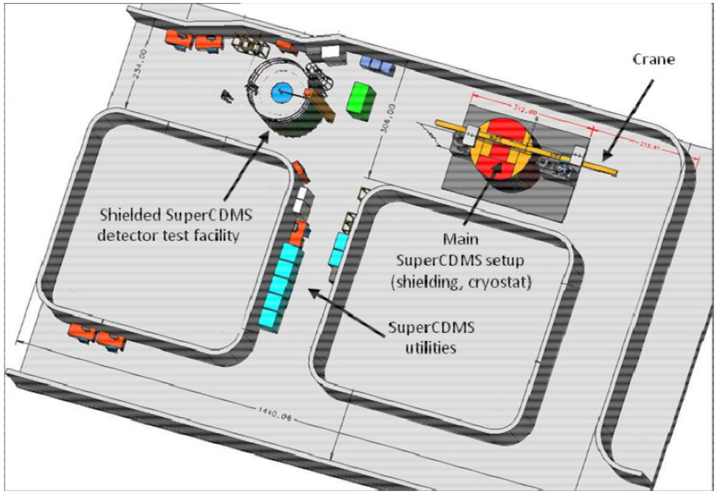
- KIMS @Yangyang (South Korea)

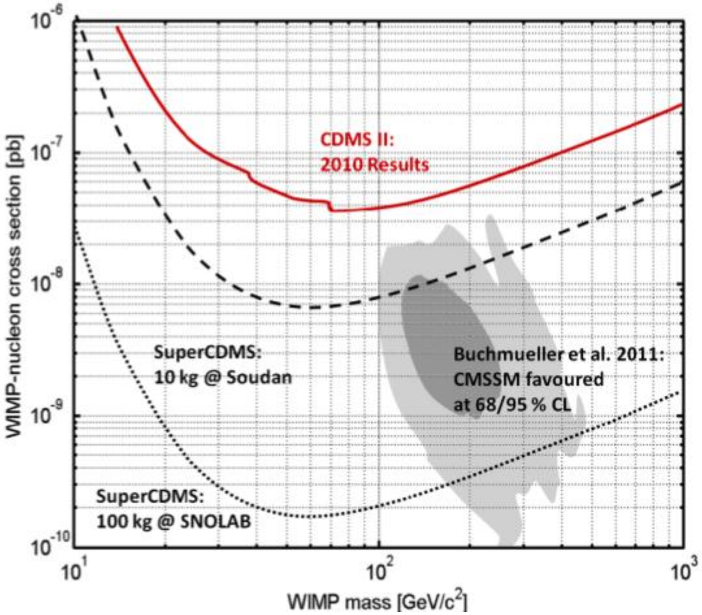
- 12 crystals of CsI, 100kg total
- No annual modulation seen
- Upgrades planned with NaI, more mass, less background

The future: Super CDMS

- New 600 g detector modules
- New sensor layout, interleaved charge and phonon sensors
- 15 detectors already in operation
- Soudan laboratory too shallow for the new measurements
- 100 kg proposed for SNOLab
- Projected sensitivity is competitive







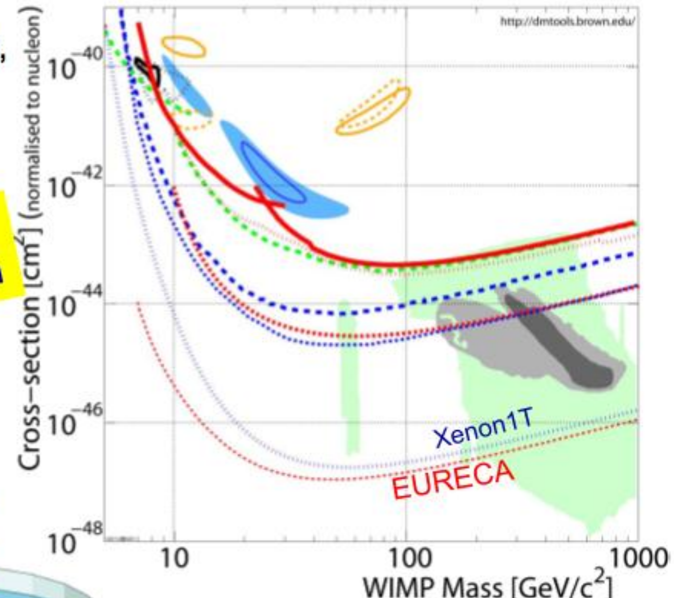
The future: EURECA

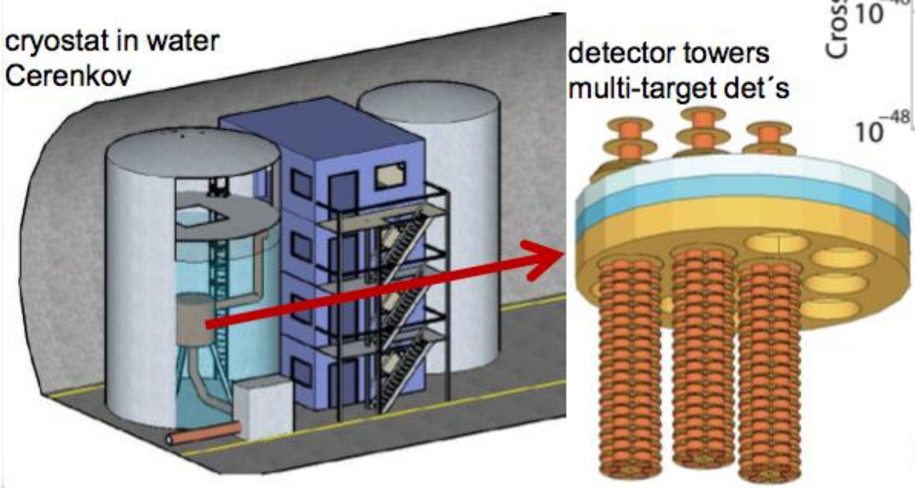
beyond EDELWEISS-III: EURECA

KIT Karlsruhe Institute of Technology

- EURECA goal: 10^{-10}-10^{-11} pb, 150kg → 1000kg, multi-target, bgd ~ 10^{-3} evts/(kg.y)
- EDW, CRESST, ROSEBUD, + others…
- coordinated cooperation with SuperCDMS (1st joint meeting Oct 7, 2011)
- CDR in summer 2012
- facility type (DM, 0νββ,...)
- part of European ASPERA roadmap

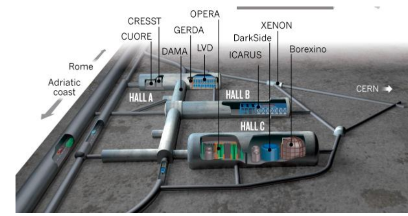
→H Kraus this afternoon



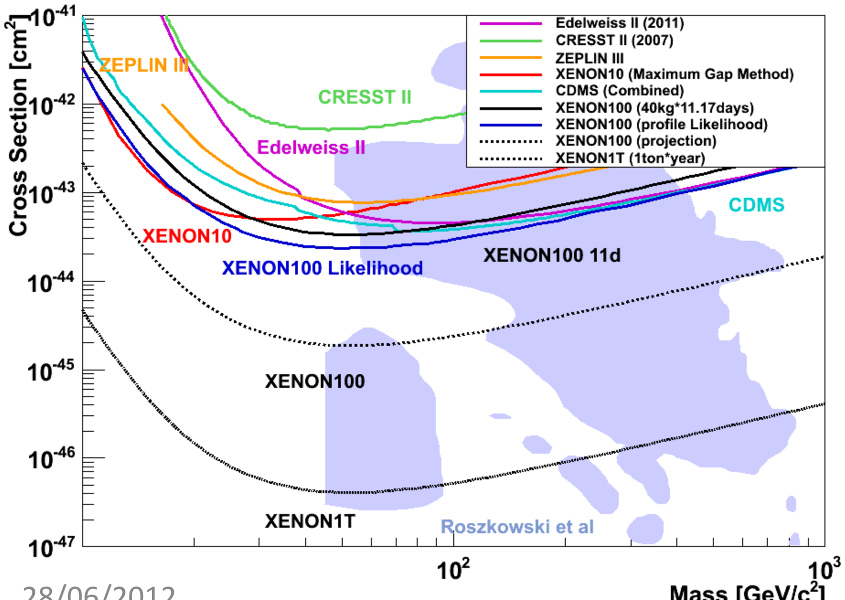


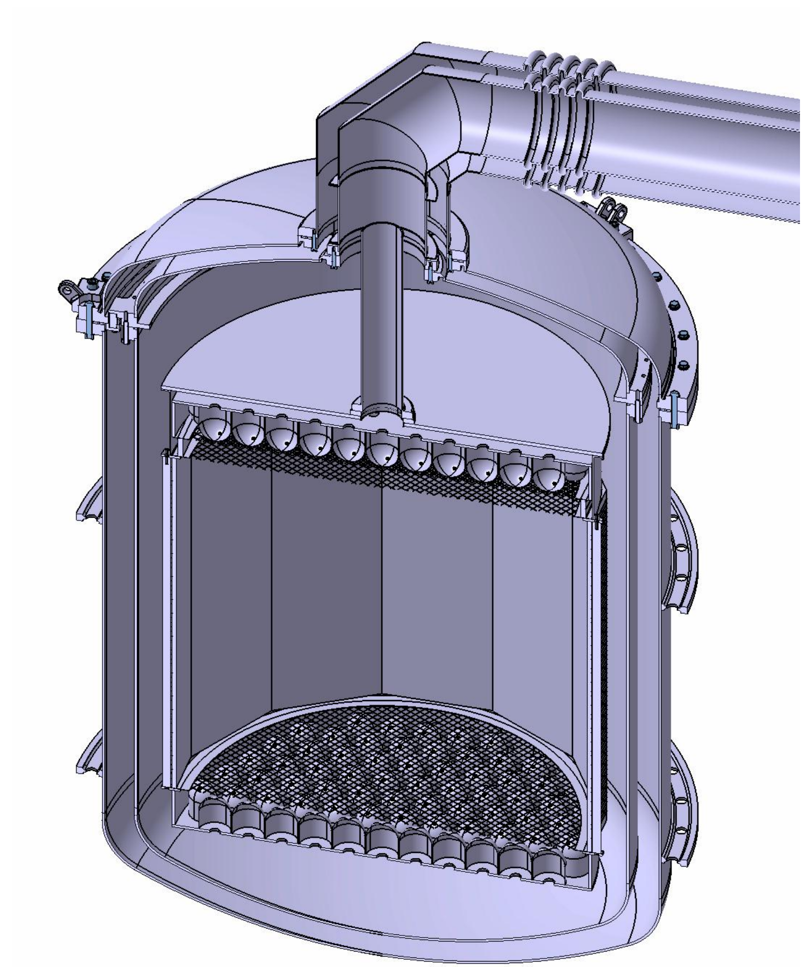
ANR HELMHOLTZ ASSOCIATION Alliance for Astroparticle Physics ASPERA Science & Technology Facilities Council bmb+f Förderschwerpunkt Astroteilchenphysik

Future projects: XENON1T @Gran Sasso

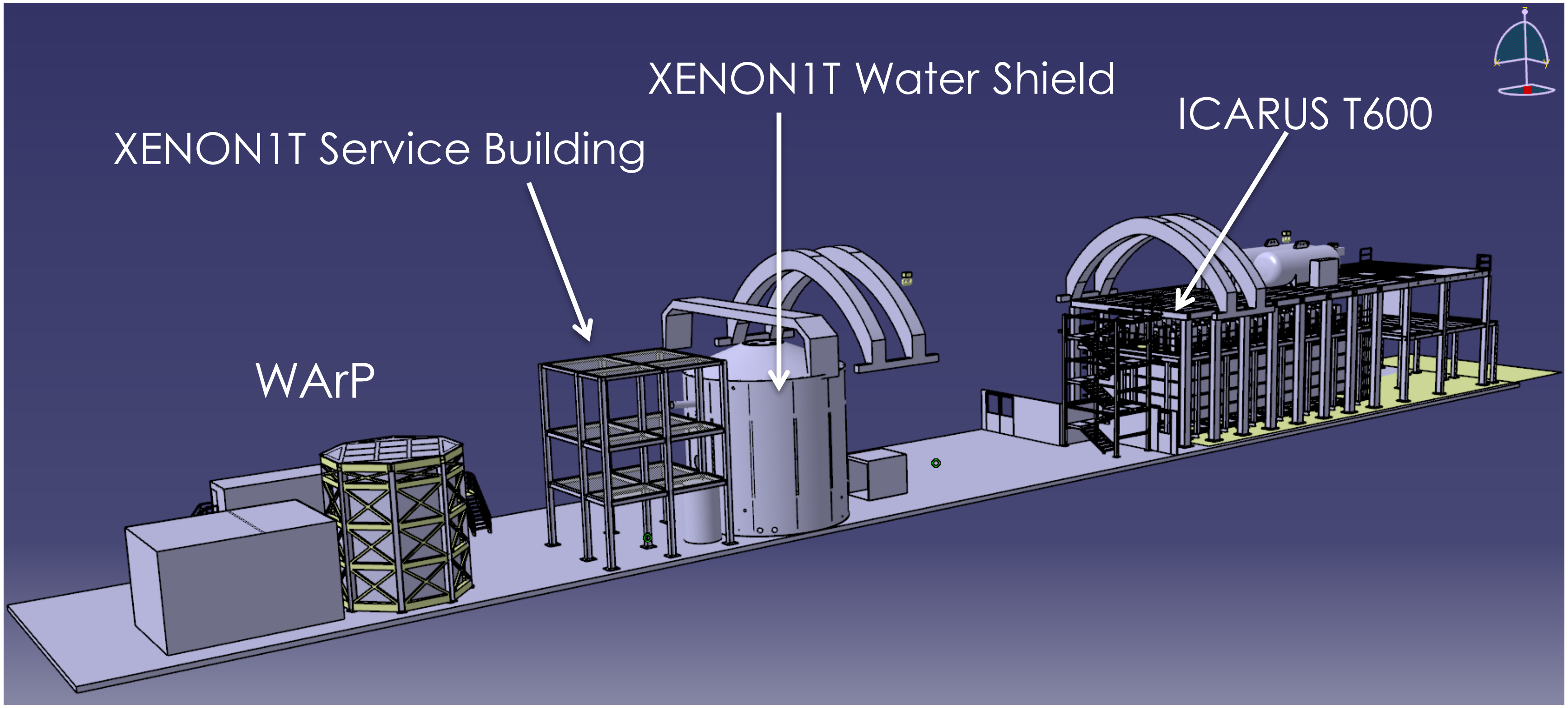


- Larger target masses are needed to explore the WIMP allowed region
- 2.5 t of liquid xenon are possible with the same technology
- Backgrounds must be totally under control (especially neutrons)
- Neutron rate in fiducial volume must be < 1evt/year



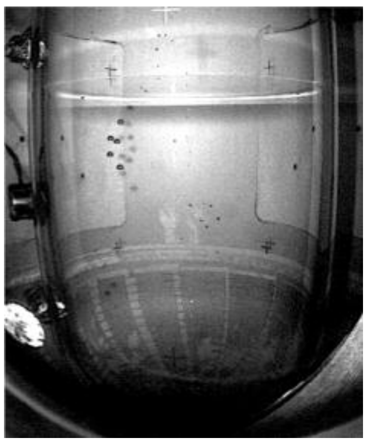


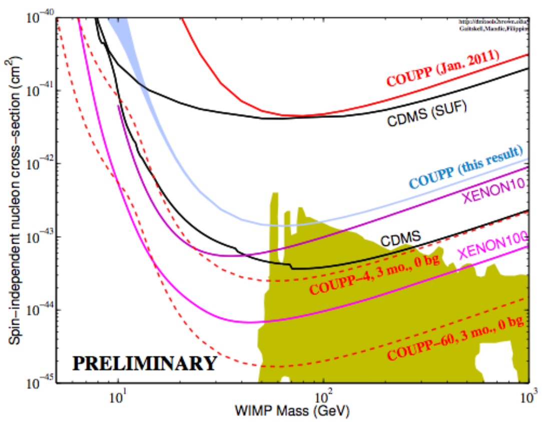
Gran Sasso Hall B, end of 2013



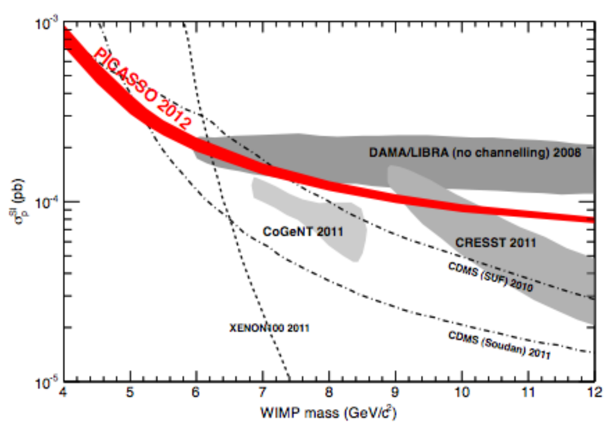
The future: "alternative" detectors

COUPP
a bubble chamber

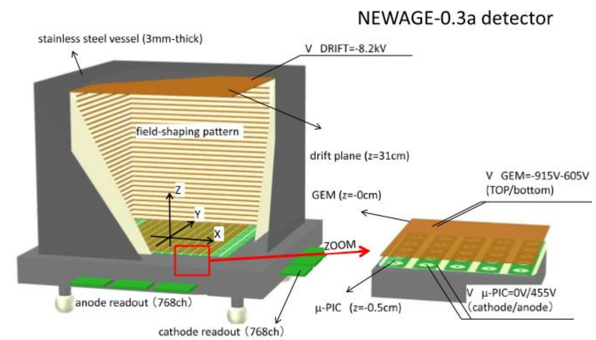


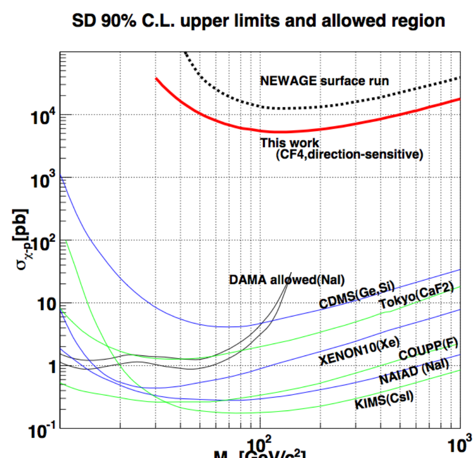


PICASSO@SNO
superheated droplets



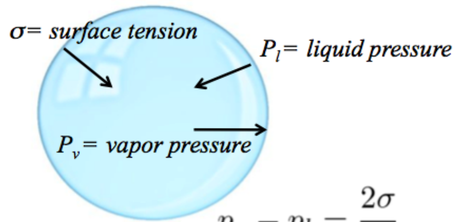
Directional detectors,
Newage, Drift, DMTPC





COUPP

- CF_3I bubble chamber
- Bubble nucleation
- No sensitivity to electron recoils !
- Development phase @Fermilab
- 4 kg module now @SNOlab



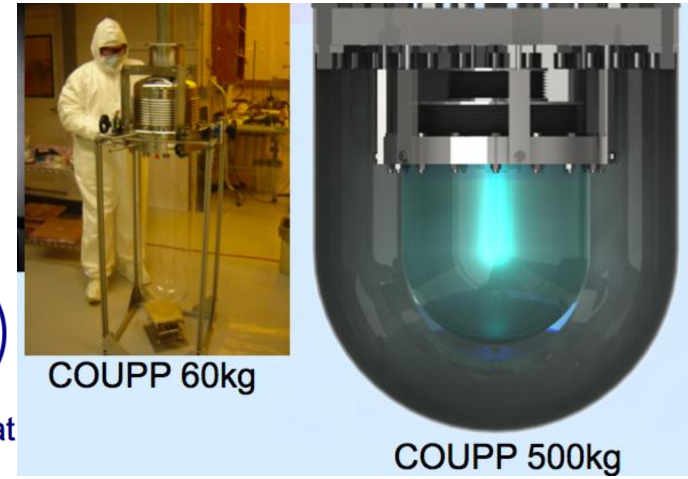
$$p_v - p_l = \frac{2\sigma}{r_c}$$

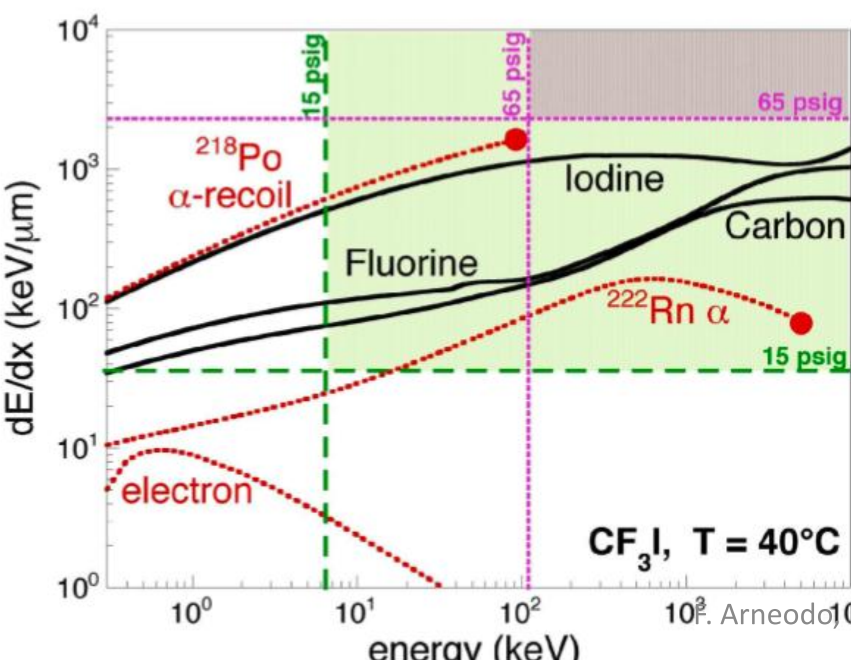
$$E_{th} = 4\pi r_c^2 \left(\sigma - T\frac{\partial \sigma}{\partial T}\right) + \frac{4}{3}\pi r_c^3 \rho_v h$$

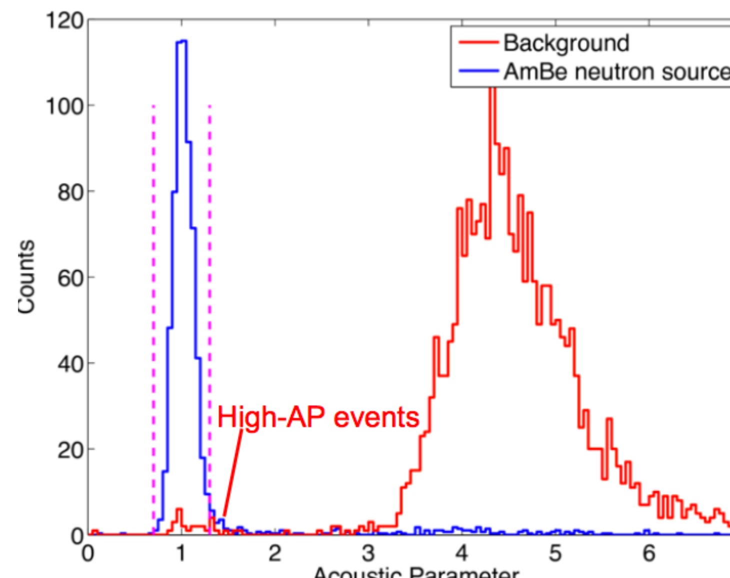
Surface energy

Latent heat

Seitz "Hot Spike" Model
Phys. Fluids 1, 2 (1958)

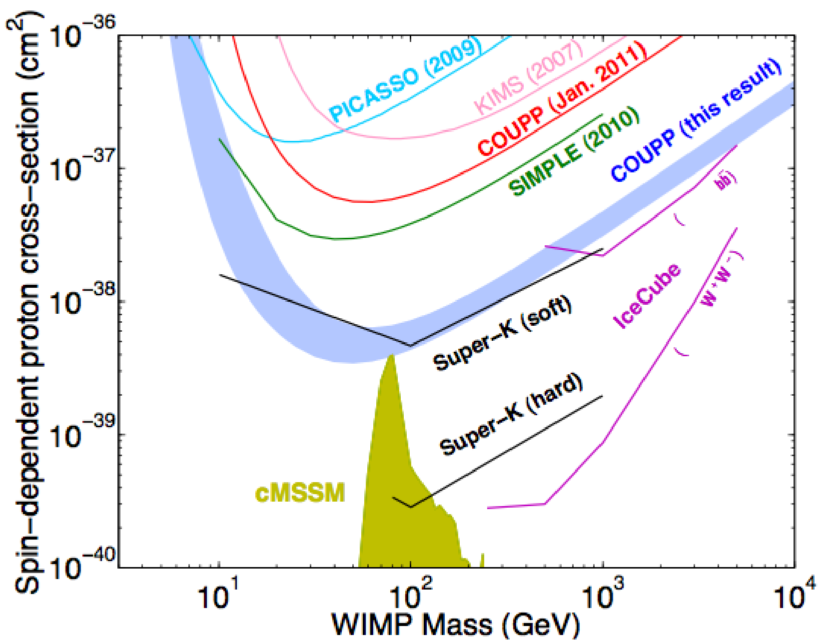


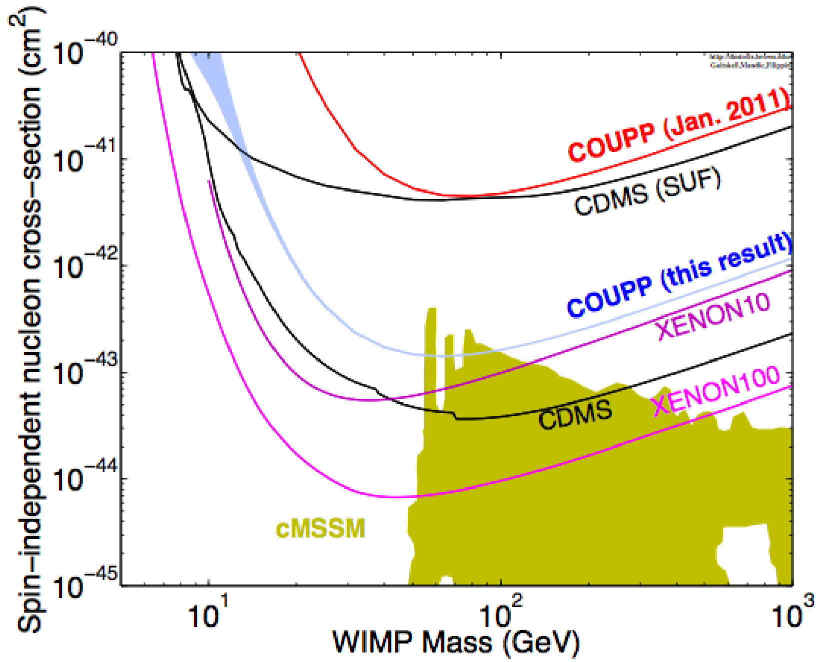




Michael B. Crisler: IDM 2012

COUPP limits

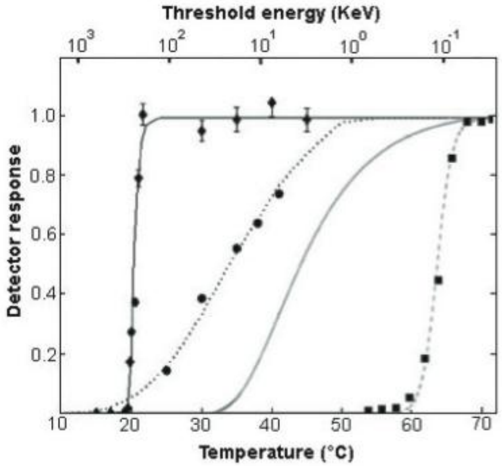


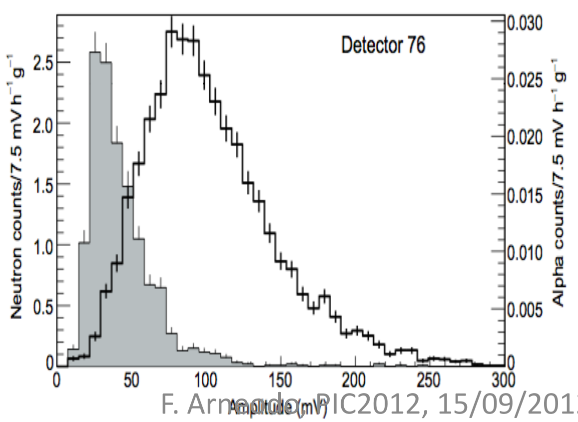


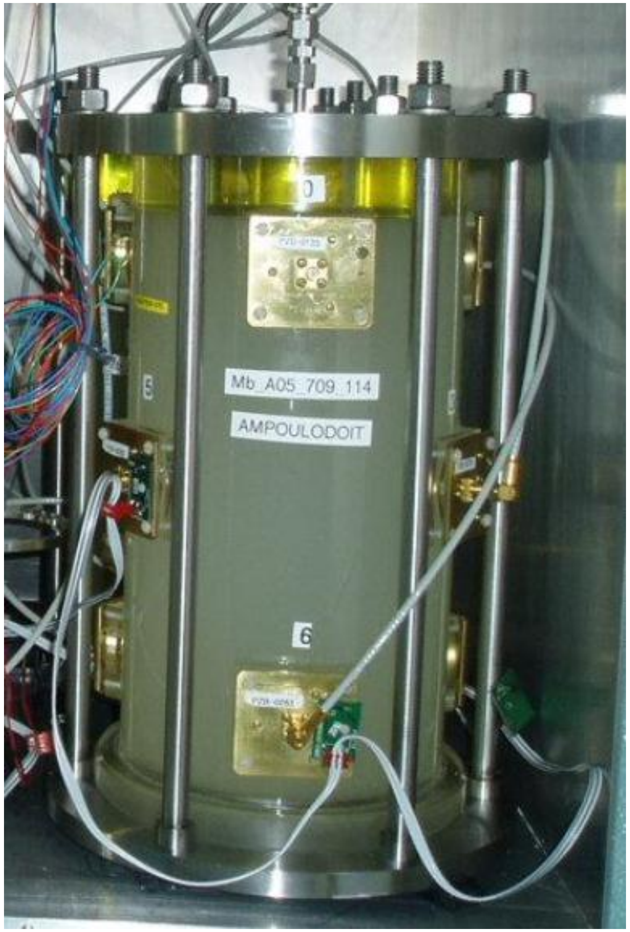
arXiv:1204.3094v1

PICASSO

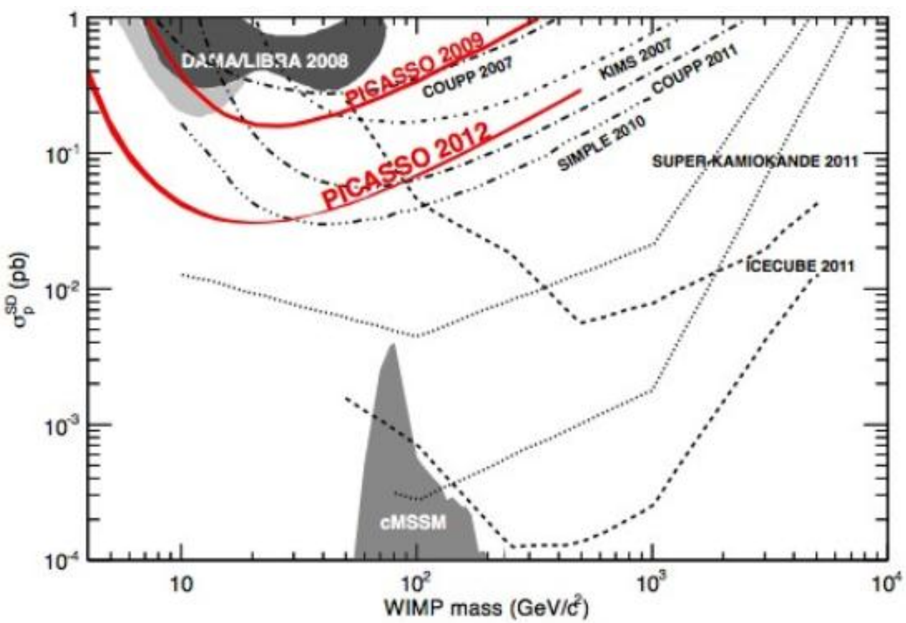
- Contains gel matrix to keep superheated freon (C_4F_{10}) droplets suspended.
- Each droplet is like a mini-bubble chamber
- Larger dE/dx will initiate phase transition and cause bubble to explode.
- Acoustic discrimination.



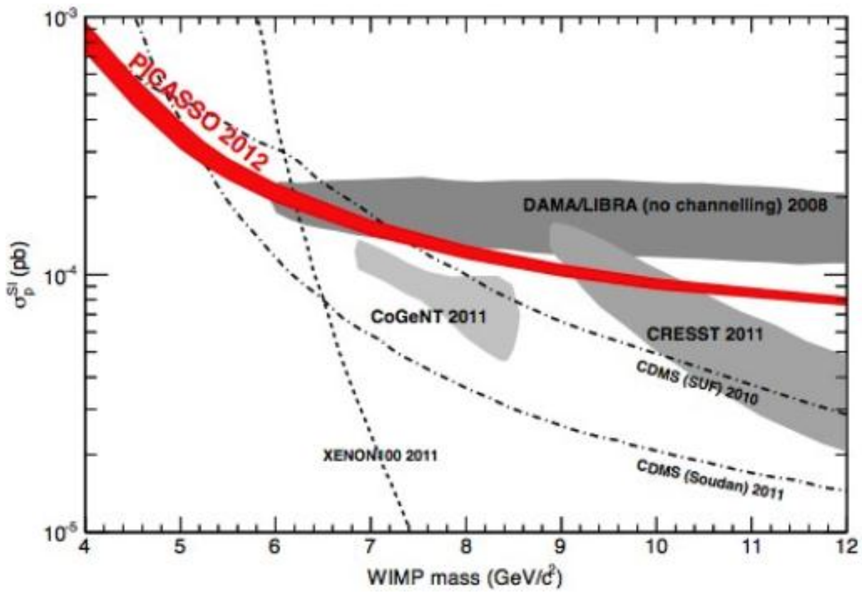




PICASSO results



SPIN DEPENDENT



SPIN INDEPENDENT

Conclusions

- Controversial and intriguing experimental scenario
- Highly challenging field, encompassing very different experimental techniques
- Some hints of signal but inconsistent up to now
- Lots of tension and competition among experiments
- Very important to check systematics, backgrounds, and energy scales
- A discovery within the next five years is very likely

Thank you!

Overview of the GLAST- LAT detector

Precision Si-strip Tracker (TKR)

measure photon direction

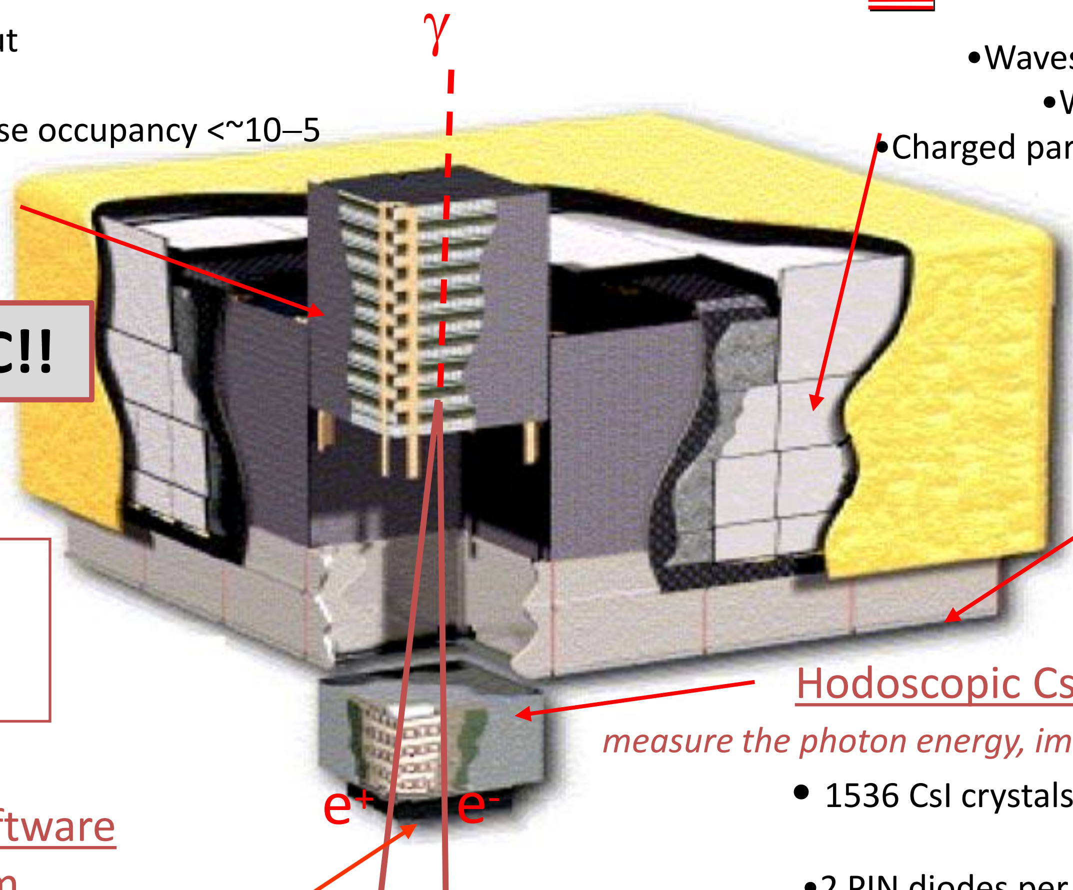
- ~10K (18XY tracking planes) 6” single-sided SSD
- 880,000 channels (total)
- 228 mm pitch, digital readout
- self-triggering
- hit efficiency > 99% with noise occupancy <~10–5
- 1.5 X0 total
- power <210 μ

Segmented Anticoincidence Detector (ACD)

reject background of charged cosmic rays

- 89 tiles – 1 cm thick
- 2 phototubes per tile
- Waveshifting fiber embedded
- White Tetratec wrapping
- Charged particle efficiency > 0.9997
- Power < 31 W total

DATA ARE PUBLIC!!



GRID

Mechanical backbone

LAT:
4 x 4 modular array
3000 kg, 650 W

Hodoscopic CsI Calorimeter(CAL)

measure the photon energy, image the shower

- 1536 CsI crystals (8 layers) 2x2.7x33 cm^3
- 6.1 104 channels
- 2 PIN diodes per end; 2 gain ranges each
- ~ 1500 kg
- self-triggering
- 8.5 X0 total
- power (total) < 91 W

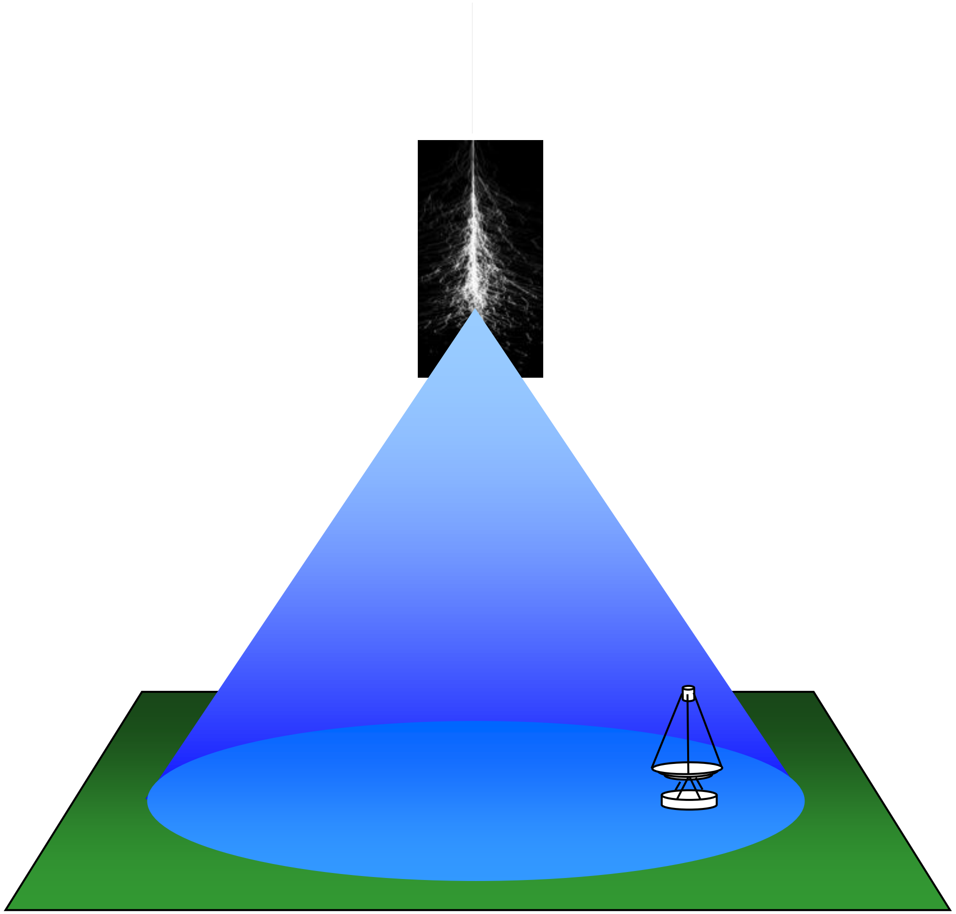
Electronics & Flying Software

Data Acquisition System

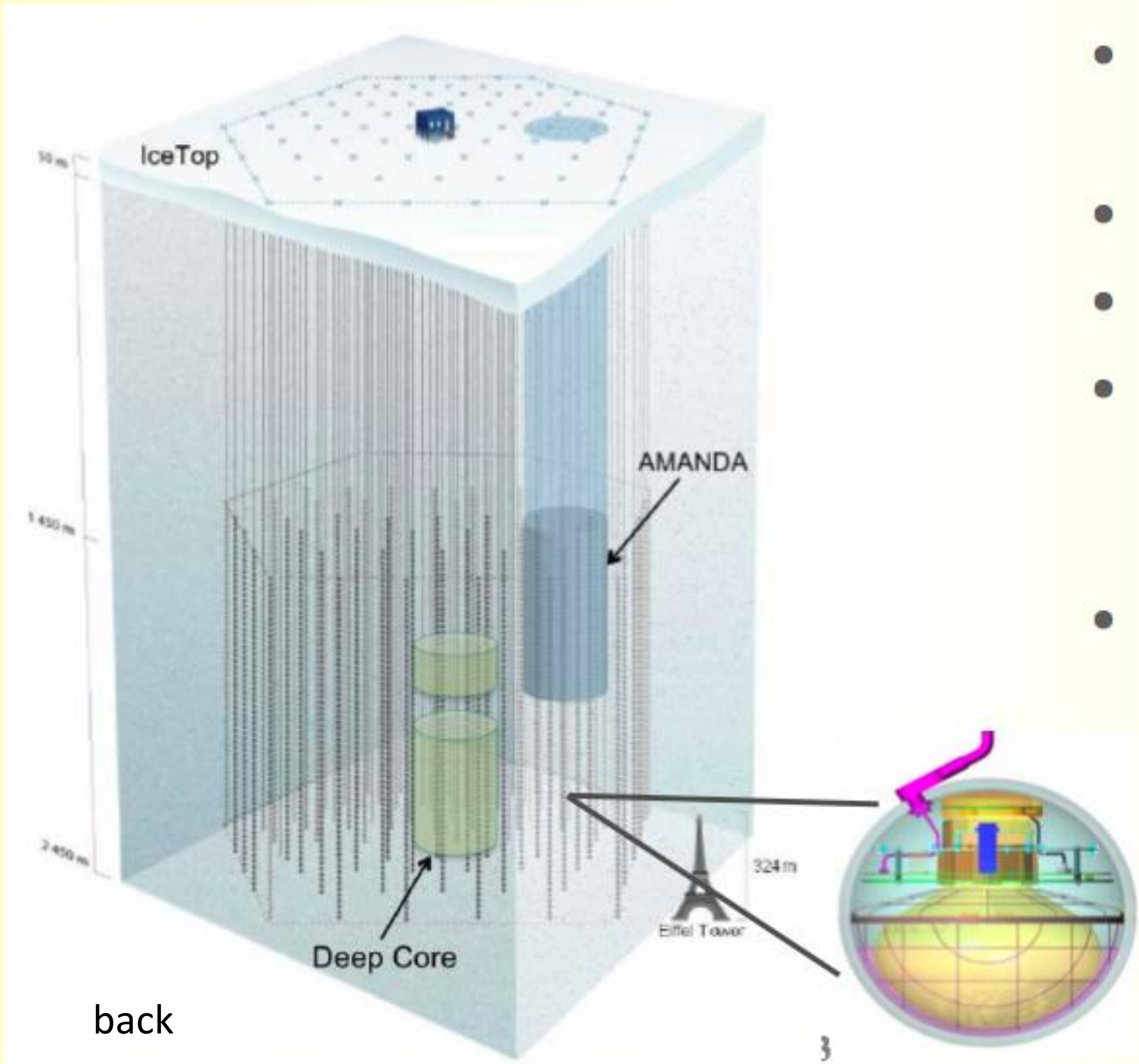
process events from 16 towers, apply trigger selection to reduce L1T rate from ~4KHz to ~30Hz

3-300GeV energy range

Atmospheric Cherenkov technique



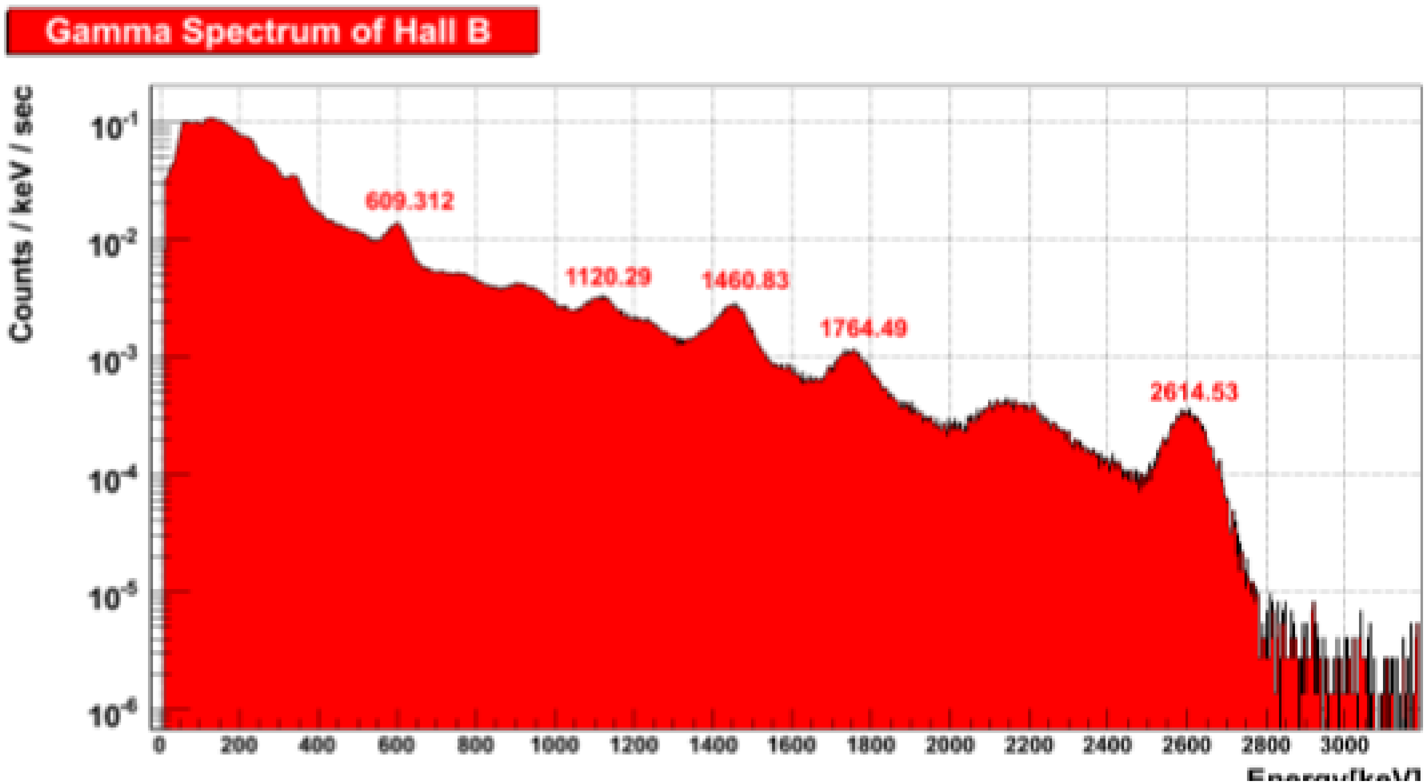
THE ICECUBE OBSERVATORY



- Detector completion in 2010-2011
- Cubic km, 86 strings
- 1450 m – 2450 m
- IceCube
  - 125 m string spacing
  - 17 m sensor spacing
- DeepCore
  - 70 m string spacing
  - 7 m sensor spacing
  - Higher QE sensors

Digital Optical Module (DOM)

back


Gamma Spectrum of Hall B
Counts / keV / sec
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
609.312
1120.29
1460.83
1764.49
2614.53
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000