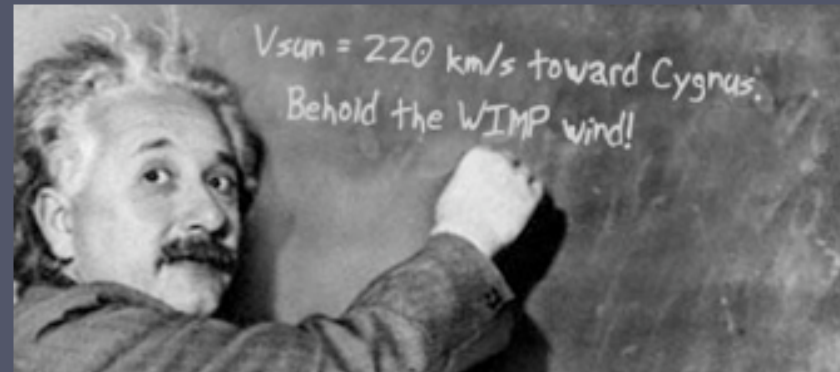
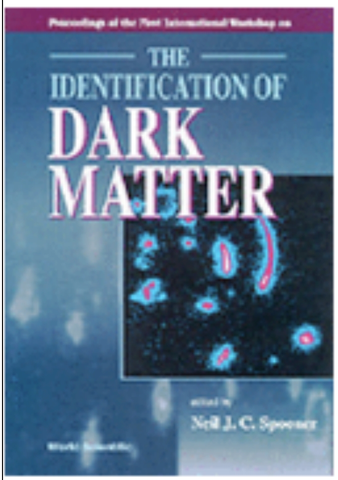
# Towards a Massive Directional Dark Matter Detector




Neil Spooner, University of Sheffield




## Proceedings of the First International Workshop on the Identification of Dark Matter (Sheffield 8-11 September 1996)

by Spooner, Neil (Edits)

Assessment of the progress in indentifying dark matter was the objective of the first "International Workshop on the Identification of Dark Matter", in particular to consider what techniques, both observational and experimental, are being used, how successful they are and what new techniques will ... Show more

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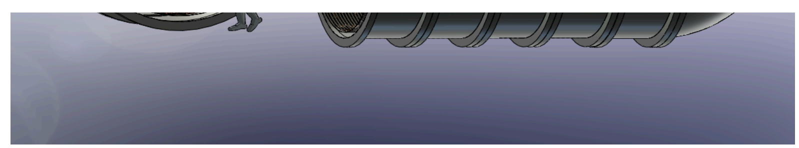

# CYGNUS Cooperation links most groups interested in directionality

- Interest in directional detection rapidly increasing
- DRIFT (US-UK), MIMAC (France), (CAST), NEWAGE (Japan), DMTPC (US), Emulsions (Japan), Micromegas (Spain); Theory groups....

CYGNUS2007
22-24 July 2007,
Boulby, UK

CYGNUS2009
11-13 June 2009,
Boston, USA

Cooperation on join document towards scale-up

**The Case for a Directional Dark Matter Detector**

**International Journal of Modern Physics A**
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THE CASE FOR A
DIRECTIONAL DARK MATTER DETECTOR AND
THE STATUS OF CURRENT EXPERIMENTAL EFFORTS

S. AHLEN,[1] N. AFSHORDI,[23,31] J. B. R. BATTAT,[*,15] J. BILLARD,[11]
N. BOZORGNIA,[3] S. BURGOS,[21] T. CALDWELL,[15,22] J. M. CARMONA,[12,13]
S. CEBRIAN,[12,13] P. COLAS,[4] T. DAFNI,[12,13] E. DAW,[26] D. DUJMIC,[15] A. DUSHKIN,[2]
W. FEDUS,[15] E. FERRER,[4] D. FINKBEINER,[6] P. H. FISHER,[15] J. FORBES,[21]
T. FUSAYASU,[16] J. GALAN,[12,13] T. GAMBLE,[26] C. GHAG,[5] I. GIOMATARIS,[4]
M. GOLD,[18] H. GOMEZ,[12,13] M. E. GOMEZ,[7] P. GONDOLO,[29] A. GREEN,[20]
C. GRIGNON,[11] O. GUILLAUDIN,[11] C. HAGEMANN,[18] K. HATTORI,[10]
S. HENDERSON,[15] N. HIGASHI,[10] C. IDA,[10] F. J. IGUAZ,[12,13] A. INGLIS,[1]
I. G. IRASTORZA,[12,13] S. IWAKI,[10] A. KABOTH,[15] S. KABUKI,[10] J. KADYK,[14]
N. KALLIVAYALIL,[15] H. KUBO,[10] S. KUROSAWA,[10] V. A. KUDRYAVTSEV,[26]
T. LAMY,[11] R. LANZA,[15] T. B. LAWSON,[26] A. LEE,[15] E. R. LEE,[18] T. LIN,[6]
D. LOC ... MARTOFF,[27]
F. MAY ... MONROE,[15]
B. MORG ... NAKAMURA,[10]
M. NAKAM ... A,[10] K. NIWA,[17]
S. M. ... PUSHKIN,[21]
M. ROBIN ... O,[7] T. SAHIN,[15]
R. SAN ... SAWANO,[10]
G. SC ... EN-IFFT,[21]
N. J. ... KAHASHI,[10]
A. TAKEDA,[28] T. TANIMORI,[10] K. TANIUE,[10] A. TOMAS,[12,13] H. TOMITA,[1]
K. TSUCHIYA,[10] J. TURK,[18] E. TZIAFERI,[26] K. UENO,[10] S. VAHSEN,[14]
R. VANDERSPEK,[15] J. VERGADOS,[8] J. A. VILLAR,[12,13] H. WELLENSTEIN,[2]
I. WOLFE,[15] R. K. YAMAMOTO[15] and H. YEGORYAN[15]

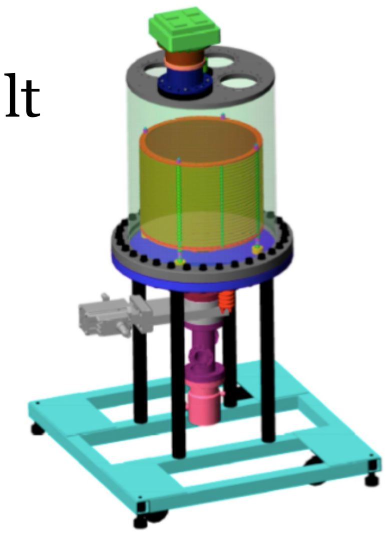
[1] *Boston University, Boston, MA 02215, USA*
[2] *Brandeis University, Waltham, MA 02453, USA*
[3] *University of California Los Angeles, Los Angeles, CA 90095, USA*
[4] *CEA Saclay, Cédex, France*
[5] *University of Edinburgh, Edinburgh, EH9 3JZ, UK*
[6] *Harvard University, Cambridge, MA, 02140, USA*
[7] *Universidad de Huelva, Campus El Carmen, 21071 Huelva, Spain*
[8] *University of Ioannina, Ioannina, Gr 451 10, Greece*
[9] *Institute of Particle and Nuclear Studies, KEK, Tsukuba, Japan*
[10] *Kyoto University Kitashirakawa-oiwakecho, Sakyo-ku, Kyoto, 606-8502, Japan*
[11] *Laboratoire de Physique Subatomique et de Cosmologie,*
*Université Joseph Fourier Grenoble 1, CNRS/IN2P3,*

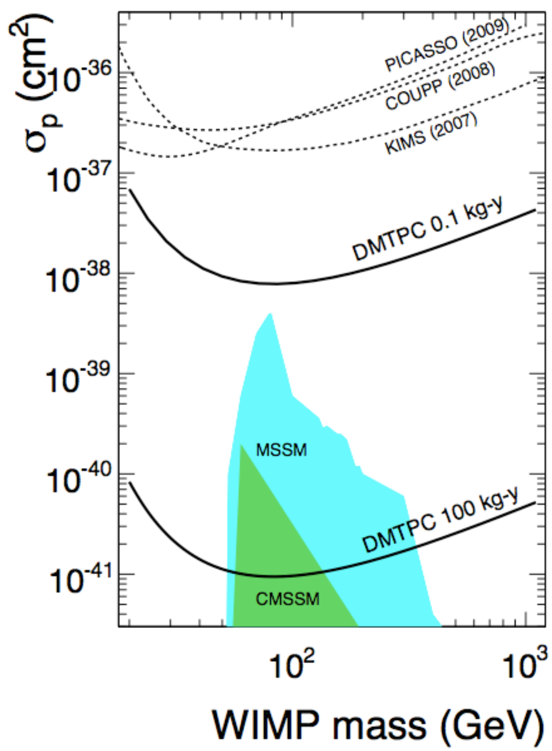
**White Paper**
**112 authors**

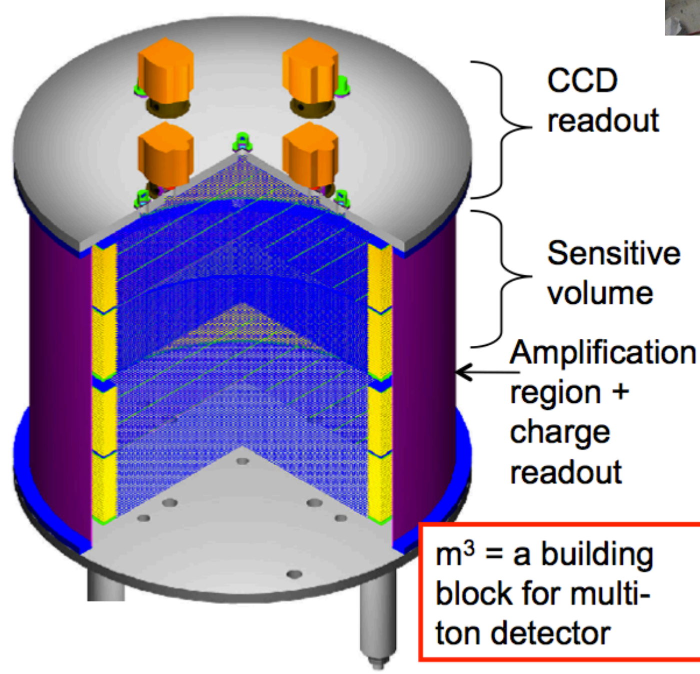
CYGNUS2011, June 8-10, Aussois, France

# DM-TPC  Future

- Going underground to WIPP with 20 lt detector now constructed ($CF_4$)
- Cubic meter design underway
  - Attention to radiopurity, material selection, high-purity copper, non-thoriated welds
  - Higher vacuum, more stable gain
  - PMT signal 3D track recon, worm veto





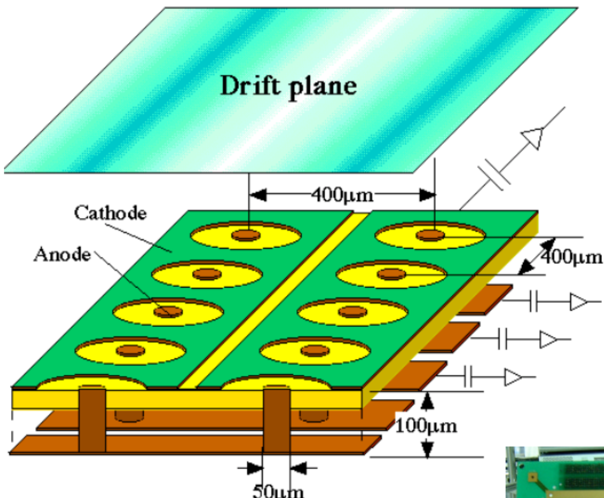



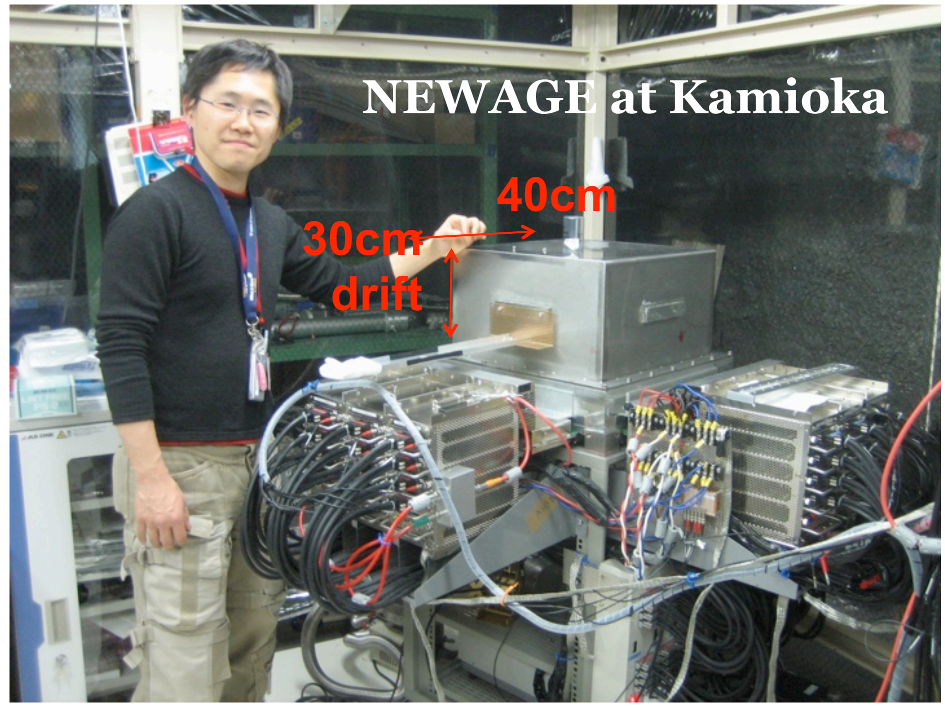

1 $m^3$ design with $CF_4$

# NEWAGE

**Kyoto University – Japan**

$CF_4$ filled 3D imaging gaseous TPC detector using micro-pattern pixellated readout ('µ-PIC')

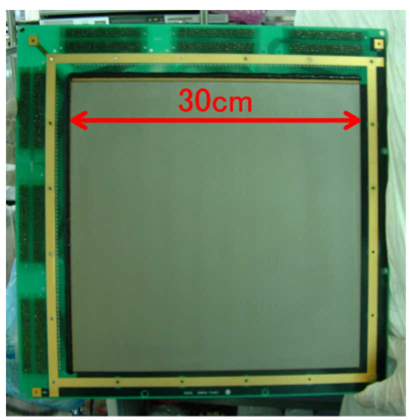



$CF_4$ gas @ 0.2 bar (aiming for 0.05 bar soon)

Now running in Kamioka

Key device: Kyoto designed µ-PIC readout – 400µm resolution



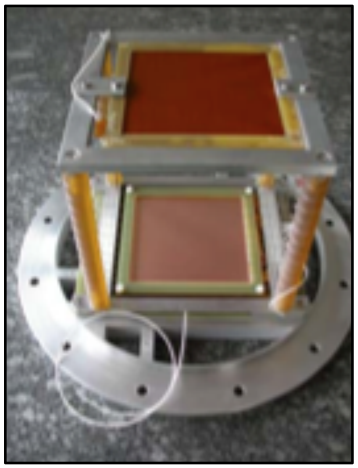

Aiming for 1m³ detector operating @ kamioka by 2013

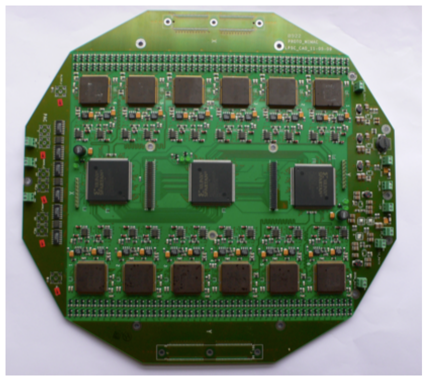
**PLB 654 (2007) 58 (Miuchi *et.al.*)**
**Preprints: physics/0701085**

# MIMAC

MIcro-tpc MAtrix of Chambers

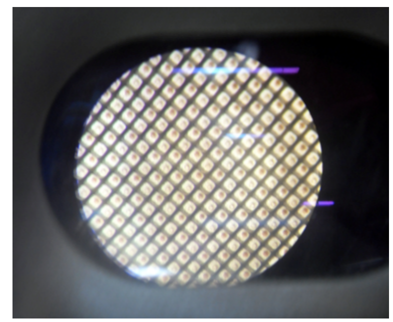
LPSC (Grenoble) CEA-Saclay (IRFU) IRSN (Cadarache) (D. Santos et al.)





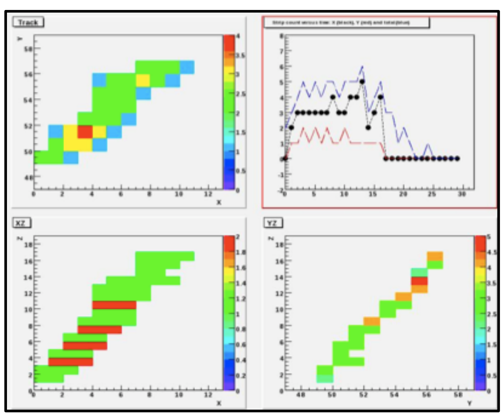
$CF_4$ and $CF_4$ + $CHF_3$ filled 3D imaging gaseous TPC detector using micro-TPC

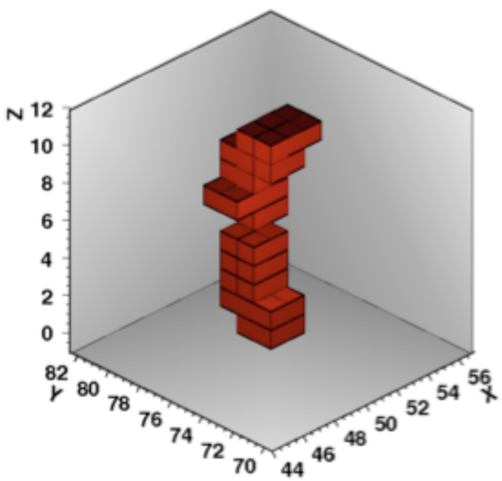
Developing 10x10 cm² pixelized anode



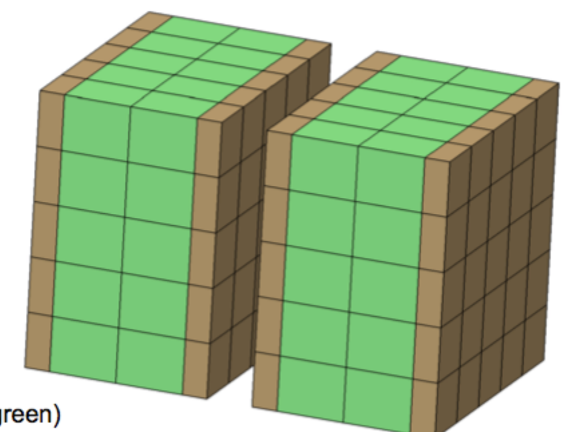
$^{19}$F Recoil (~40 keV), 50 mbar CF4 + CHF3 (30%)

5.9 keV electron track






towards 1 m$^3$



Chambers (green)
Electronics (grey)

# DRIFT IIa-e progress….

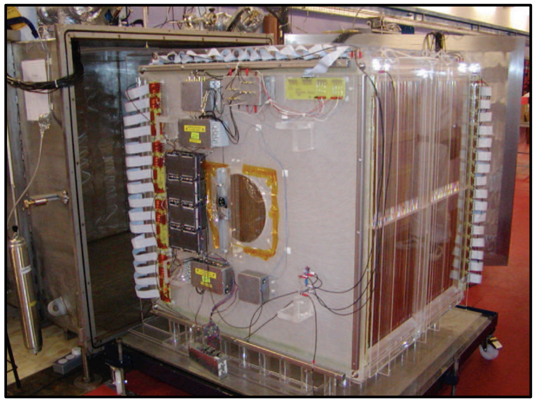
**US, UK groups and Boulby**

- Low threshold potential (< 3 keV, S-recoil)
- Directional signatures (and 3D reconstruction)
- Head-tail (sense) is feasible, and verified by theory
- Radon backgrounds (RPR) understood reduced
- *Fiducialisation via +ve ions looks to work*
- *Thin cathode works*
- Neutron backgrounds understood
- Stable and safe operation with $CS_2$ and $CF_4$
- Competitive SD WIMP-P limits <u>with directionality</u>


B. Morgan, A.M. Green and N.J.C. Spooner, Phys Rev D71 (2005) 103507
P. K. Lightfoot, N. J. C. Spooner et al., Astropart. Phys. 27 (2007) 490
S. Burgos et al., Astropart. Phys. 28 (2007) 409
N.J.C. Spooner, J. Phys. Soc. Japan, 76 (2007) 11101
E. Tziaferi et al., Astropart. Phys. 27 (2007) 326
K. Pushkin et al., (2008) arXiv:0811.4194
S. Burgos et al., Nucl. Instrum. and Meth. in Phys. Res. A 584 (2008) 114
S. Burgos et al., JINST 4 (2009) P04014
S. Burgos et al., Nucl. Instrum. and Meth. in Phys. Res. A600 (2009) 417
S. Burgos et al., Astroparticle Physics 31 (2009) 261
P. Majewski, D. Muna, D.P. Snowden-Ifft, N.J.C. Spooner (2009) arXiv:0902.4430

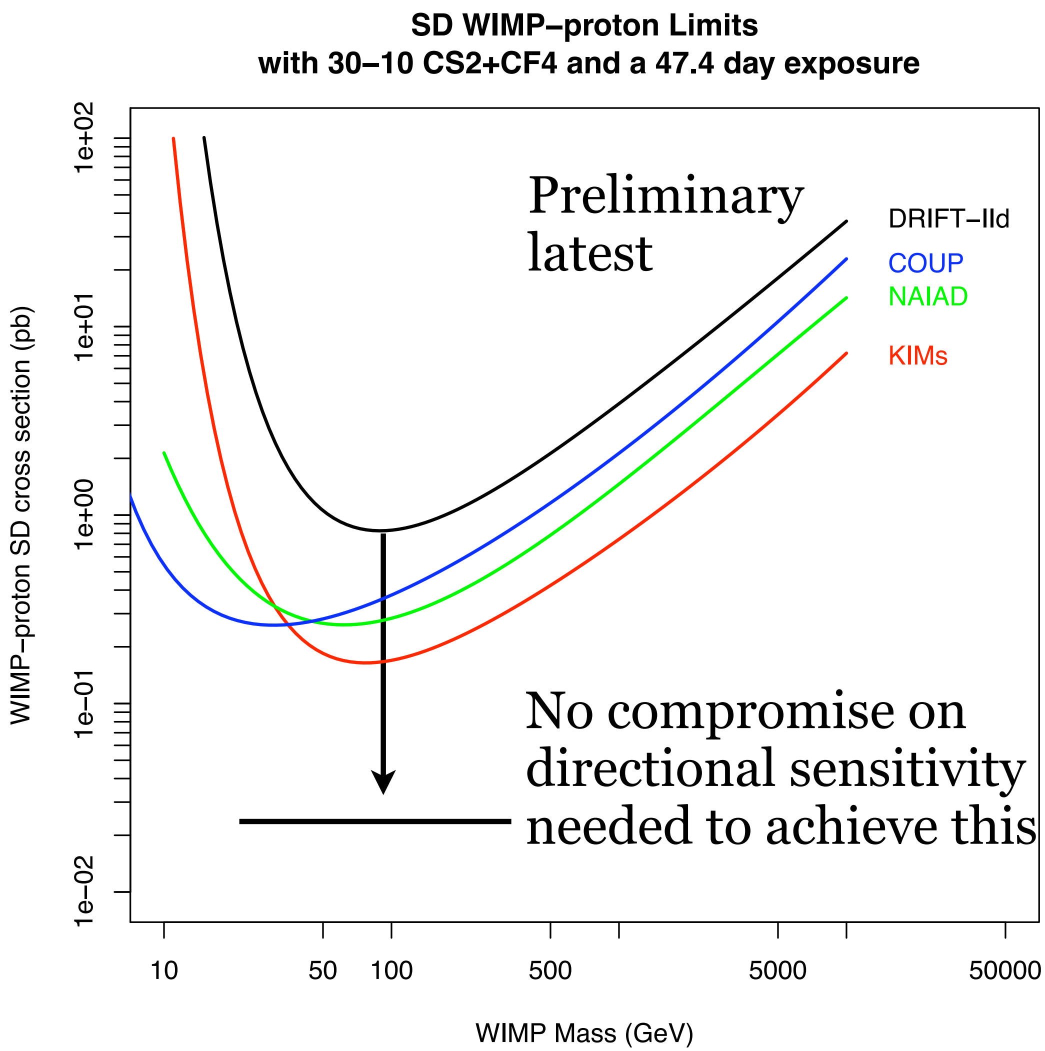

- See previous talks

BIG PROGRESS in the last 2 years



→ Ready to design scale-up to DRIFT III - 25m$^3$

# DRIFT IId status




# NEXT

x40-50 reduction in background (RPR) expected with thin cathode

i.e. ~ 0.02 pb assuming remaining RPRs distributed the same

This would take 2000 days live time

**DRIFT II is now volume limited…. not background limited**

Ready to design scale-up to DRIFT III - $25 m^3$

# DRIFT III Concept

## Larger size with lower cost

- Modular design to allow approach to ton-scale
- DRIFT-III module of 4 kg - 24 $m^3$
  *(DRIFT-II: 1$m^3$, 0.14 kg $CS_2/m^3$)*
- One DRIFT-III module well suited to Boulby
- Large number fits 30m x 150m DUSEL "Standard Lab Module" or new tunnel excavation at Boulby


- advantages of no cryogenics
- multiplexed electronics
- neutron shielding

cost split evenly:

- vacuum vessel
- electronics
- gas system

NB: current cost of complete DRIFT II module (with shielding) ~ $80K

Extrapolation gives ~$250K for DRIFT III module (with shielding)

# DRIFT III Directionality

## How Many WIMPs Needed to see a directional signal?

**Green & Morgan 'PRD '08, arXiv:0711.2234**
**Green & Morgan, Astropart. Phys '07, astro-ph/0609115**
**Morgan & Green, PRD '06 ,astro-ph/0508134**
**Morgan, Green & Spooner, PRD '05, astro-ph/0408047**

go for
3D with head-tail
discrimination

| difference from baseline configuration | $N_{90}$ | $N_{95}$ |
|---|---|---|
| none | 7 | 11 |
| $E_{\rm T} = 0$ keV | 13 | 21 |
| no recoil reconstruction uncertainty | 5 | 9 |
| $E_{\rm T} = 50$ keV | 5 | 7 |
| $E_{\rm T} = 100$ keV | 3 | 5 |
| $S/N = 10$ | 8 | 14 |
| $S/N = 1$ | 17 | 27 |
| $S/N = 0.1$ | 99 | 170 |
| 3-d axial read-out | 81 | 130 |
| 2-d vector read-out in optimal plane, raw angles | 18 | 26 |
| 2-d axial read-out in optimal plane, raw angles | 1100 | 1600 |
| 2-d vector read-out in optimal plane, reduced angles | 12 | 18 |
| 2-d axial read-out in optimal plane, reduced angles | 190 | 270 |

assuming optimal
position sensitivity

Conclusion from directional analysis: positive identification using a diurnal signal can occur with a few 10s of events using only information only x and z with head-tail information

$\Delta Z/\Delta X$ + Head-Tail

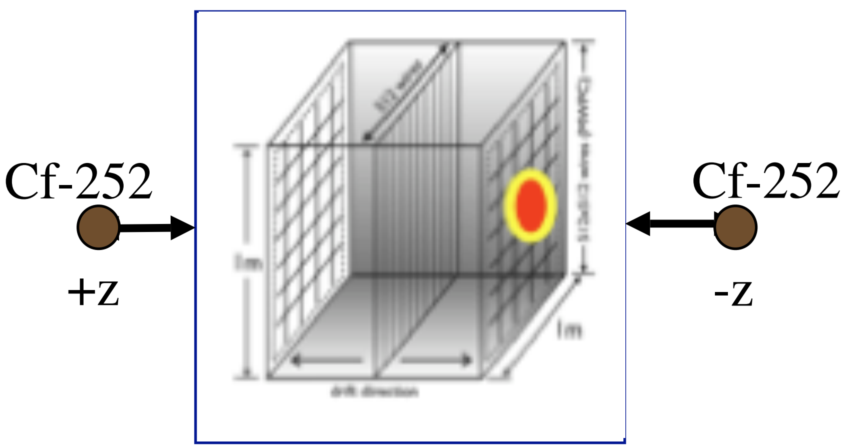
# DRIFT II result…

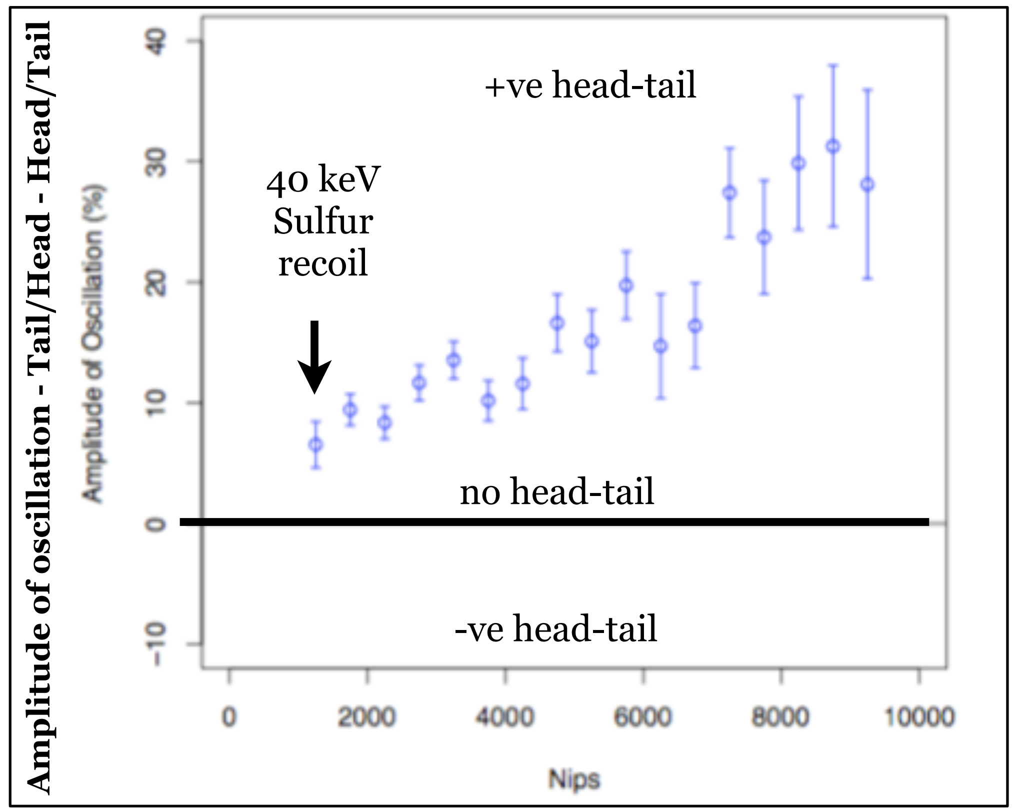
## DRIFT II Head-Tail Results

Experiment: S. Burgos et al., Astroparticle Physics 31 (2009) 261

Theory: P. Majewski, D. Muna, D.P. Snowden-Ifft, N.J.C. Spooner (2009) arXiv:0902.4430

Directed neutron runs (DRIFT IIc)

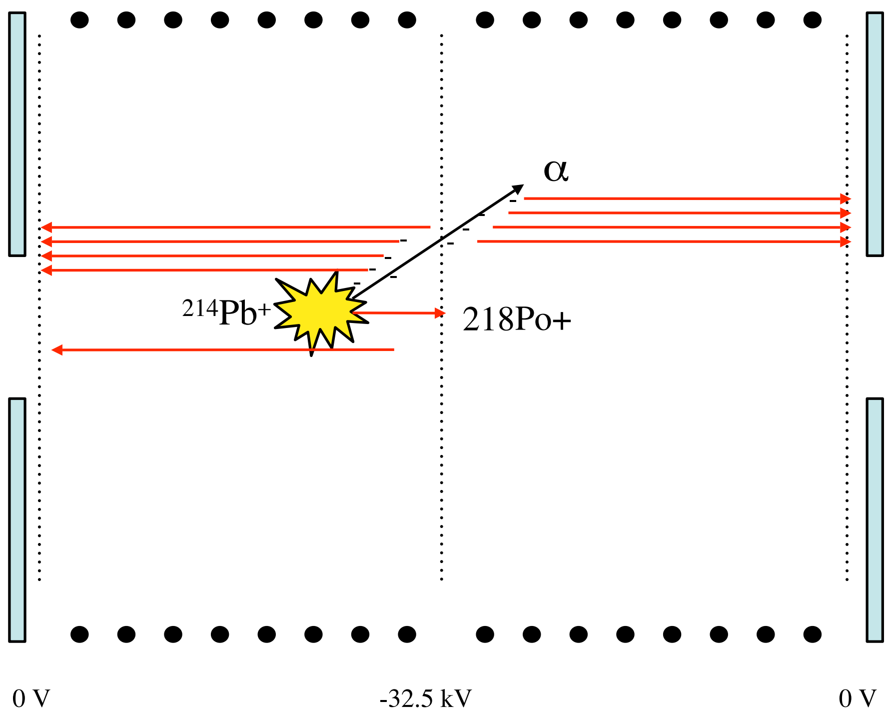


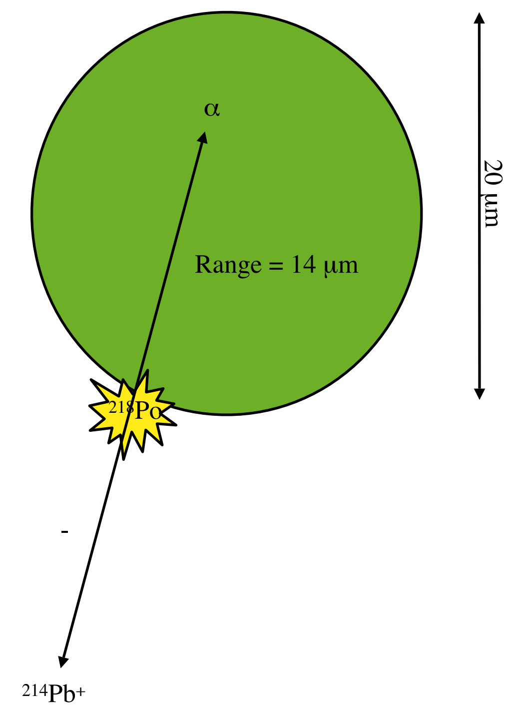

Clear head-tail discrimination (in 1 $m^3$ at low energy)!

# DRIFT III Radon

The Radon Progeny Recoil challenge




## Multiple attack on radon needed



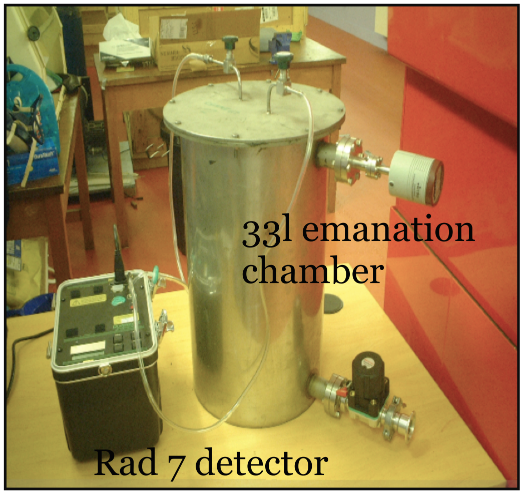

Solutions from DRIFT II:

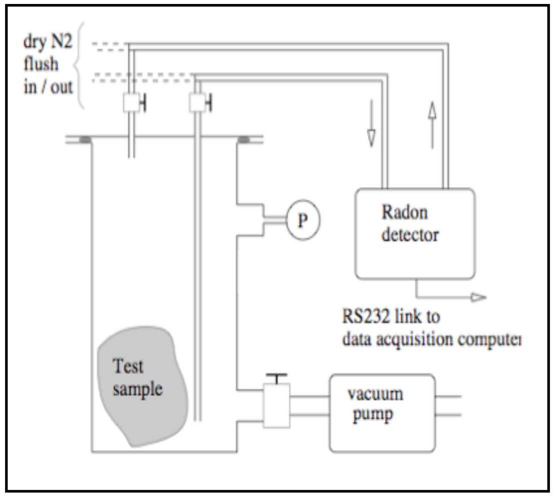
(1) Radon emanation materials control
(2) Nitric etching process cleaning
(3) Thin cathode understood
(4) +ve ion detection for fiducialisation

# DRIFT II result…

## (1) Rn Emanation Facility

Facility built to assess radon emanation and allow reduction

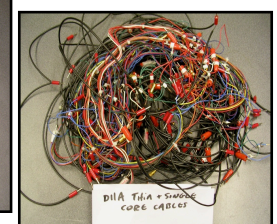


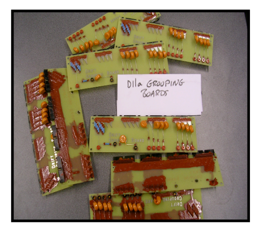



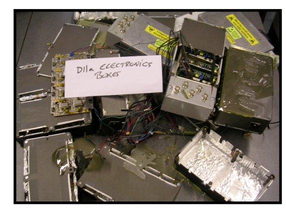

*DIIa samples:*

| Sample (Emanating into vacuum) | Fill gas | Emanation time (days) | Humidity (%) | Raw result ($Bq/m^3$) | Adjusted result (Rn atoms.$s^{-1}$) |
|---|---|---|---|---|---|
| RG58 coax cables (72m) | Dry N2 | 12.5 | 24 | 9.4 +/- 0.7 | 0.36 +/- 0.03 |
| Electronics boxes | Dry N2 | 12 | 37 | 1.5 +/- 0.3 | 0.05 +/- 0.01 |
| Ribbon cables | Dry N2 | 6.5 | 23 | 10.1 +/- 0.7 | 0.50 +/- 0.03 |
| Grouping Boards | Dry N2 | 10 | 37 | 0.3 +/- 0.2 | <0.02 * |
| Single core & thin coax cables | Dry N2 | 7 | 19 | 1.3 +/- 0.3 | 0.04 +/- 0.02 |
| Field cage parts | Dry N2 | 7 | 33.3 | 0.6 +/- 0.2 | <0.03 * |
| | | | | Total | 0.95 +/- 0.05 |

* The limit of sensitivity of the method (see above)







- Main offenders = Ribbon cables and Coax. cables
- Total of items measured = 0.95 +/- 0.05 Rn atoms.$s^{-1}$:

# DRIFT II result...

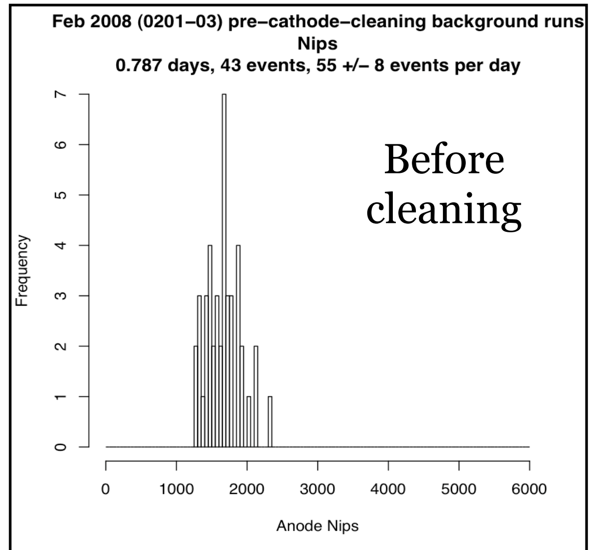
## (2) Nitric cleaning developed

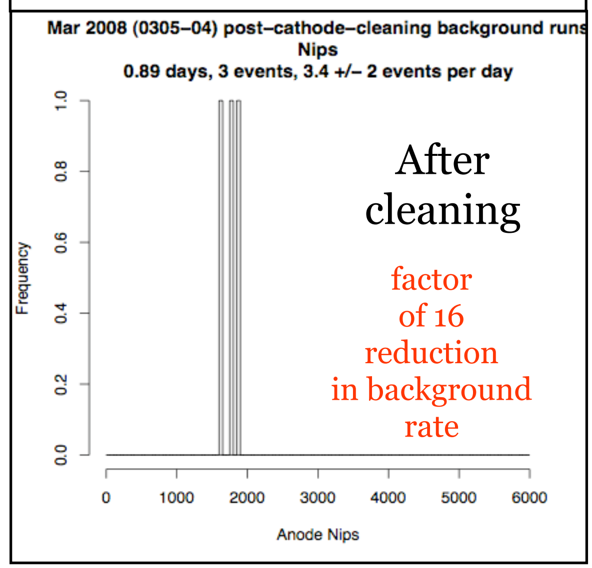
Facility built to remove MWPC and Cathode background events attributed to recoils of $^{210}Pb$ plated out on the detector.  Likely region for build-up of $^{210}Pb$ is on the cathode wires.


Johanna Turk ( University of New Mexico )

Mark Pipe ( University of Sheffield )

Kirill Pushkin ( Occidental College )



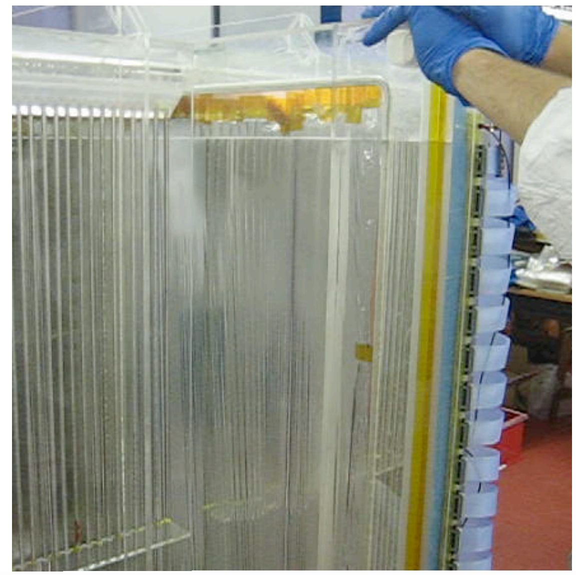

Now applied same cleaning procedure to the MWPC grid and anode wires.

# DRIFT II result...

## (3) Thin cathode developed

Use of multi-panel 0.9μm thick DRIFT cathode

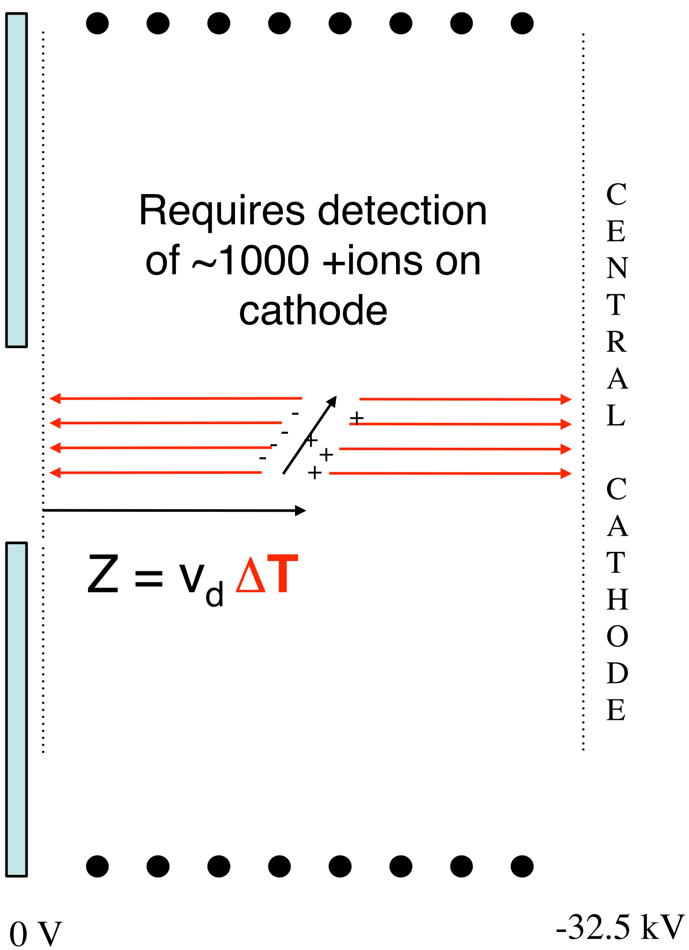
cathode tested at full voltage (32.5kV)



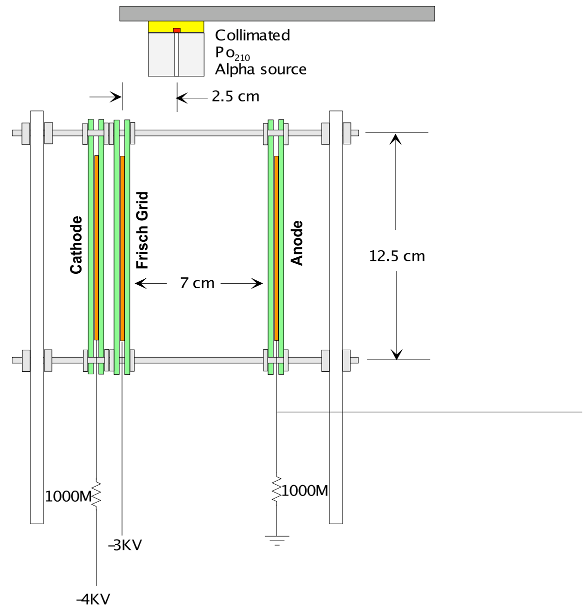
Latest data shows expected ~x30 reduction in RPRs

# DRIFT II result… (4) Z-fiducialisation developed

Z-fiducialisation by +ve ion detection demonstrated to give **ΔT** measurement

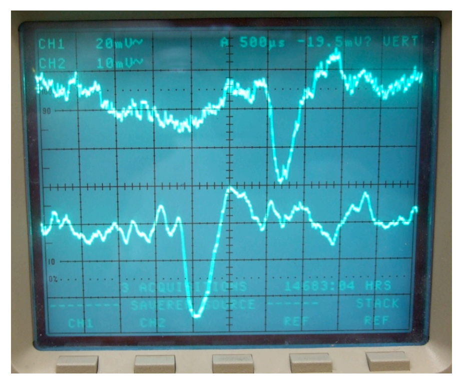



Eric Lee, UNM (2009)




Cathode

Anode



Retrofit to DRIFT IIc underway now

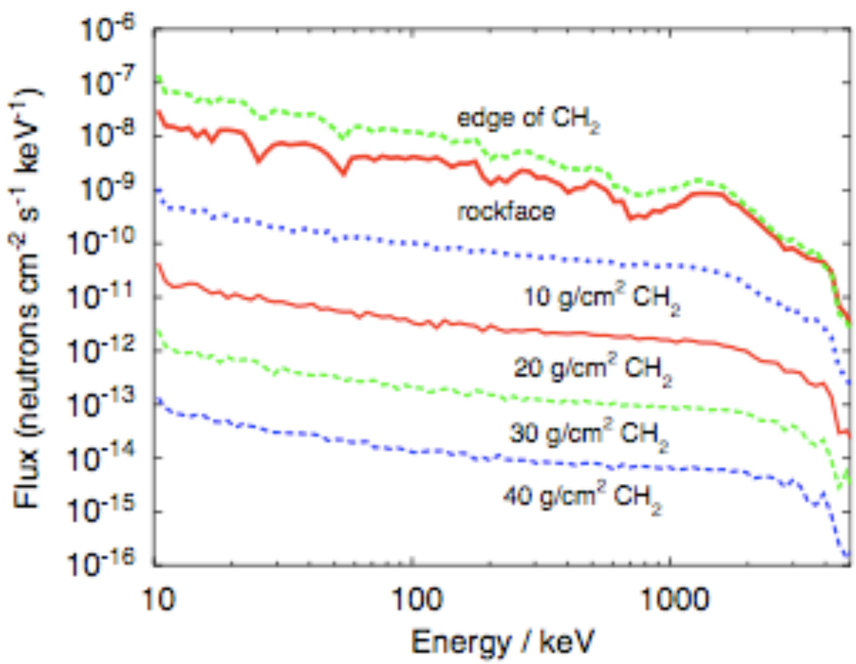
# DRIFT Neutrons (1) (external from rock)

## Neutrons are next most important background

Recoil rates expected in a single DRIFT II module due to neutrons from the surrounding rock calculated using modified SOURCES

## Assumptions

Simulated energy spectrum from spontaneous fission and alpha-n in NaCl in the surrounding rock due to U (60 ppb) and Th (130 ppb) contamination.




**Result** Nuclear recoil rates in DRIFT II module at 10–50 keV

Unshielded: $2.67 \times 10^3$ /yr

With 40 g cm$^{-2}$ $CH_2$: $1.10 \times 10^{-2}$ /yr

**Conclusion:** Salt is low in U, Th so fission is low but alpha-n reactions are high, on balance not much different to "normal" rock
Rock neutrons easy to shield with $CH_2$

# DRIFT Neutrons (2) (internal from detector)

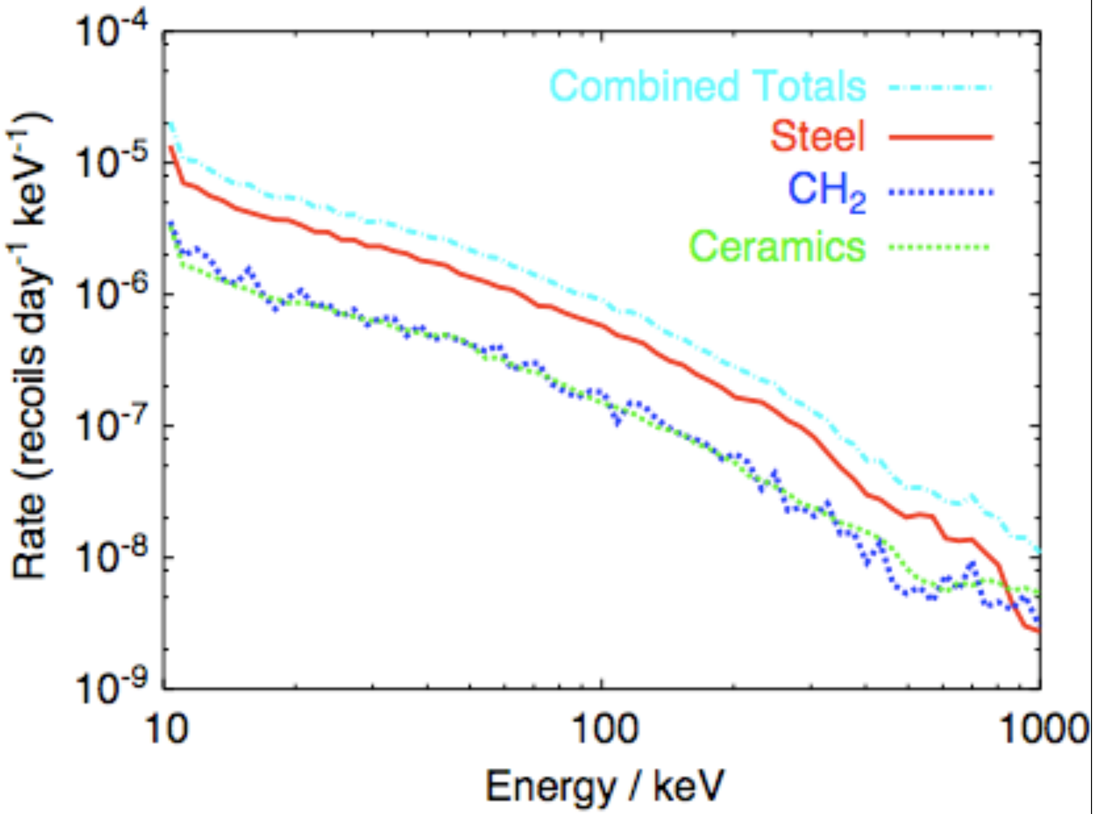
## Neutrons are next most important background

Extensive study with Monte Carlo simulation of fission and alpha-n reactions - production of neutrons via modified SOURCES

## Assumptions

DRIFT II construction materials

1 ppb U, 1 ppb Th is assumed as a source of alpha particles in steel




## Conclusion:

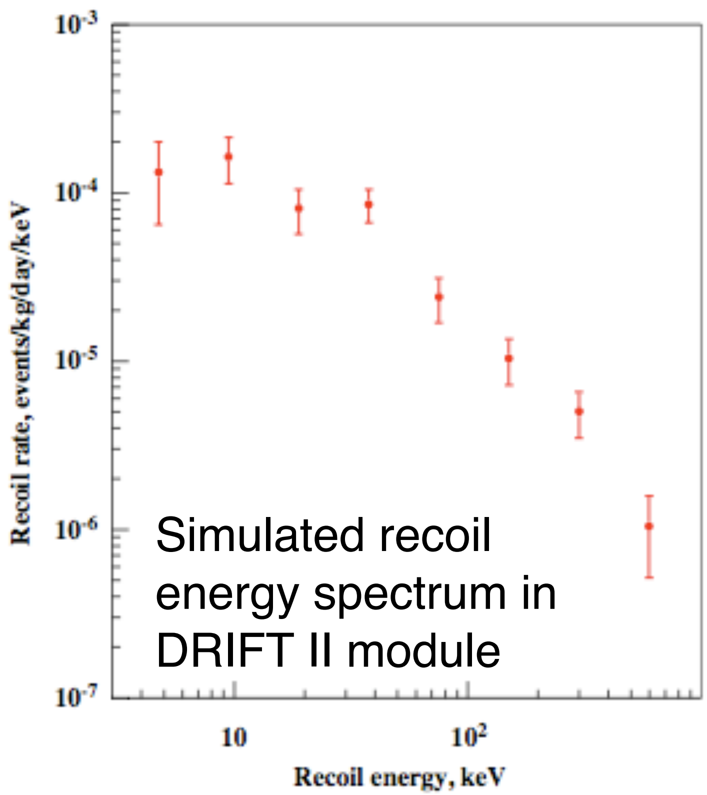
Nuclear recoil rates in a single DRIFT II module per year at 10–50 keV = $4.14 \times 10^{-2}$ per year

Steel vessel is dominant issue

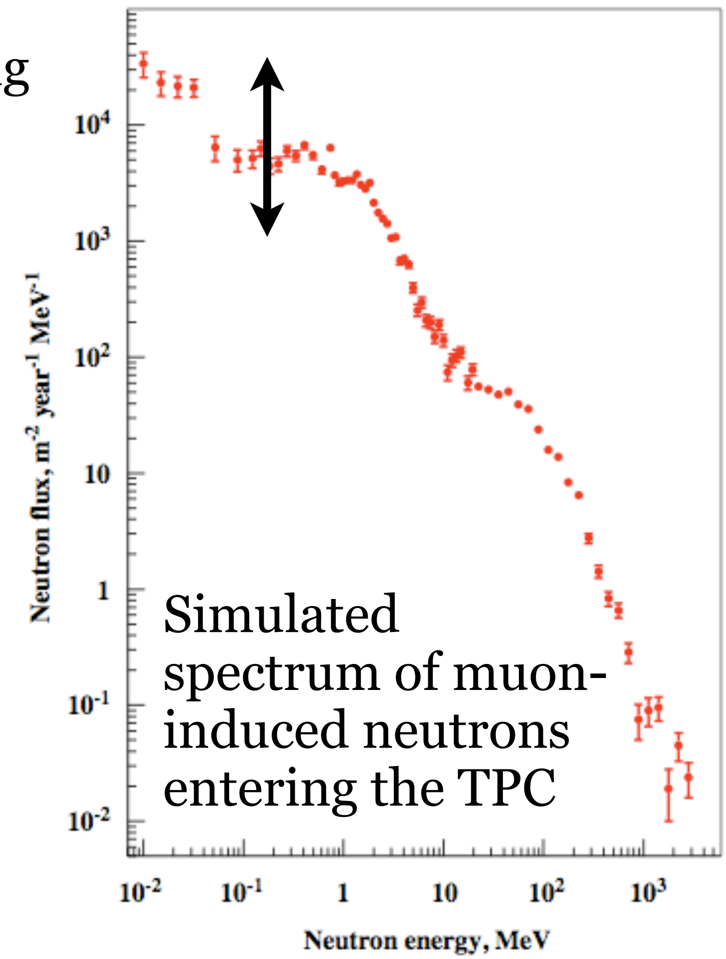
# DRIFT Neutrons (3)
## (external from muons)

### Assumptions

DRIFT II module with 40 g cm$^{-2}$ $CH_2$ shielding




### Neutrons from muons in the rock




### Conclusion:

Steel vessel contributes significantly (~x10) at low energy

# Neutron Summary

## Assumptions

Includes 40 g $cm^{-2}$ $CH_2$ shielding against rock neutrons (estimates)

## Result (prelim estimates for DRIFT III)

see M.J. Carson et al NIM A 546 (2005) 509–522

Estimated neutron backgrounds per year at 10-50 keV recoil energies

| | kg | Rock | Muons | Detector | Total |
|---|---|---|---|---|---|
| DRIFT II | 0.167 | 0.01 | 0.12 | 0.06 | 0.19 |
| DRIFT III module (as multiple DRIFT IIs) | 4.00 | 0.24 | 2.88 | 1.56 | 4.68 |
| DRIFT III module steel, no muon veto | *4.00* | *0.20* | *2.00* | *1.50* | *3.70* |
| DRIFT III module acrylic, no muon veto | *4.00* | *0.20* | *<1.00* | *<1.00* | *<0.4* |

## Conclusion for <u>single</u> DRIFT III module (prelim):

- Requires 40 $gcm^{-2}$ CH neutron shielding (like DRIFT II)
- Steel construction just about alright

  *optimization, selection, internal CH?*
- No need for muon active veto at Boulby for single module

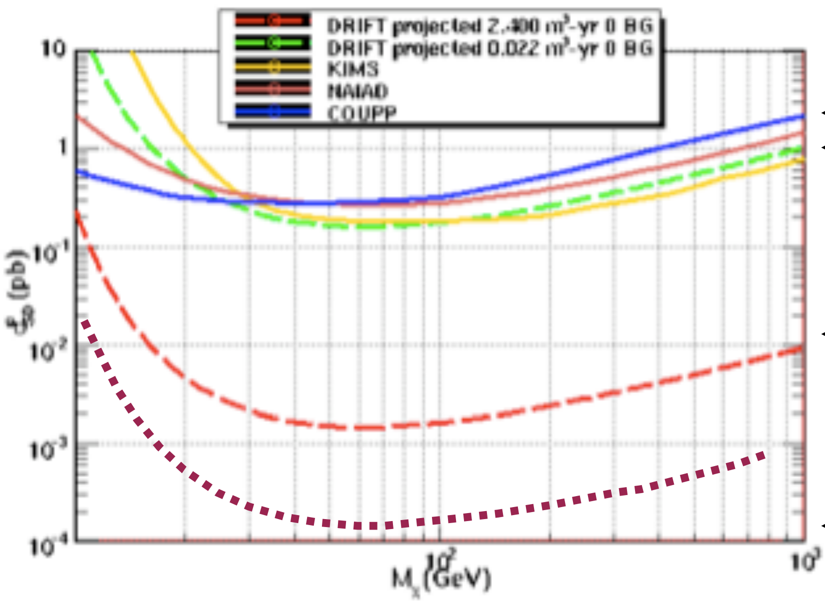
# DRIFT III Sensitivity

**with directional capability**

## SD Prediction

- Projected limits for a single DRIFT III module
- With no compromise on directional sensitivity

Expected WIMP-proton spin dependent sensitivity




← current limits

← DRIFT IId - 10 day run, zero background prediction

← DRIFT IId - 2.4 $m^3$-years, zero background prediction

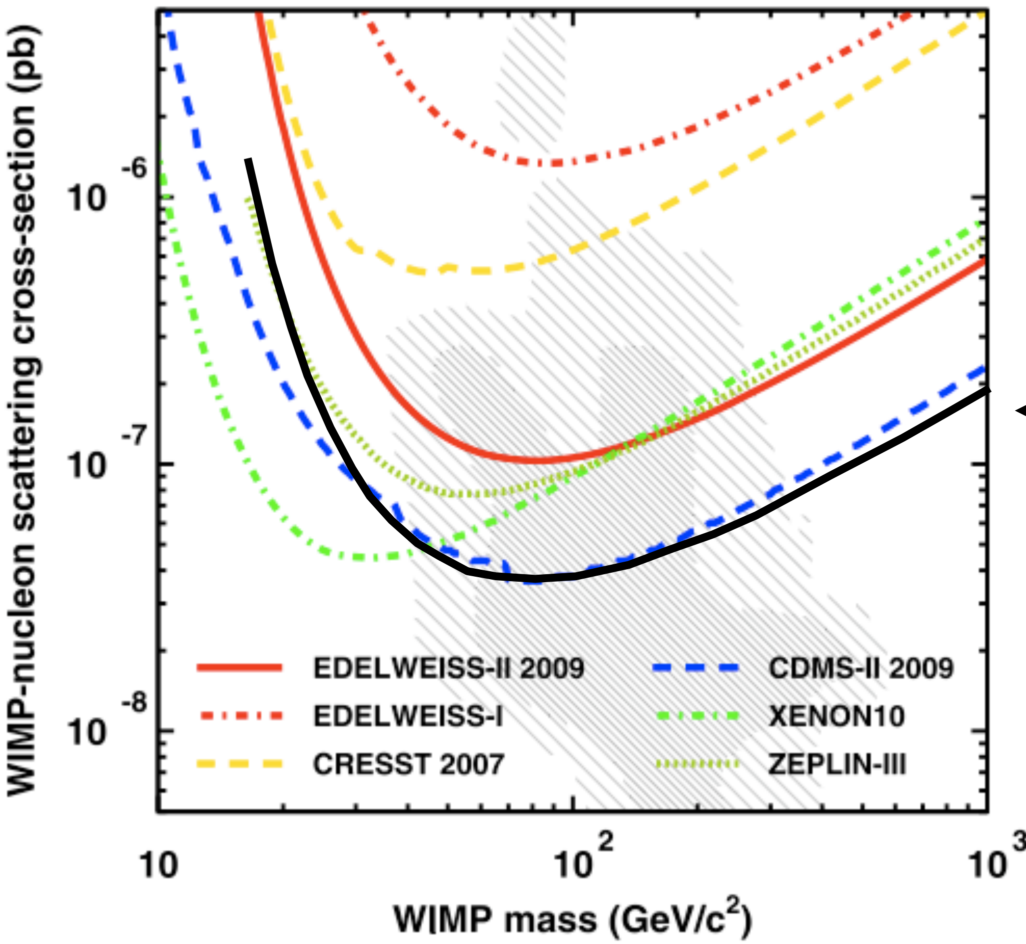
← DRIFT III module - 1 year run 4 kg.yr

# DRIFT III Sensitivity

## SI Prediction

**with directional capability**

- Projected limits for a <u>single</u> DRIFT III module (4kg)
- With no compromise on directional sensitivity

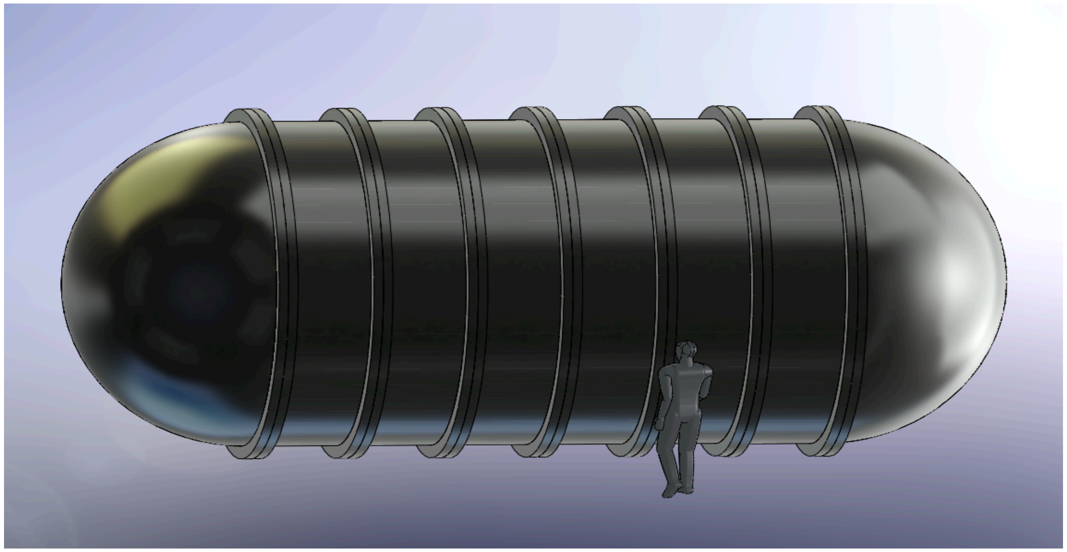



← DRIFT III module - 1 year run (4 kg.yr)

thanks to EDELWEISS for plot

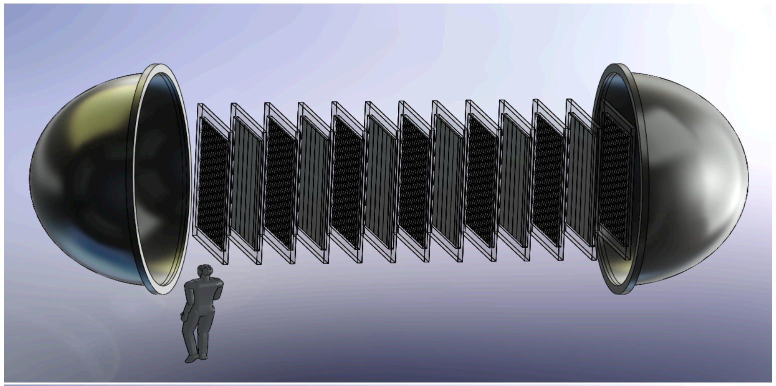
# DRIFT III Design

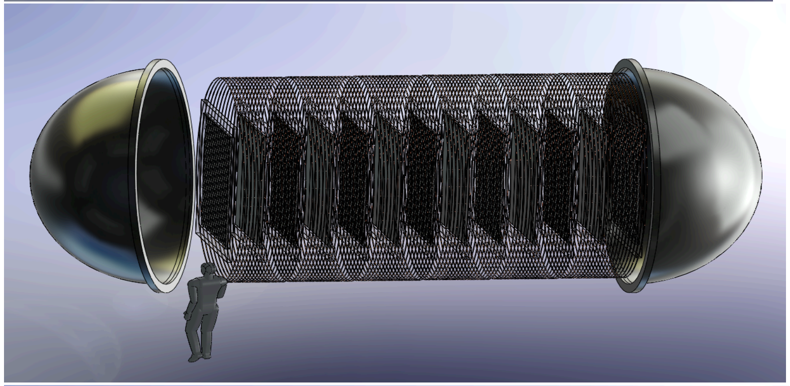
- 4kg fiducial mass, $CS_2$ -ve ion plus $CF_4$ (different target mixes)
- Thin low RPR central cathode (1 μm), partial segmentation
- Nitric acid process cleaning and radon emanation tests
- +ve ion detection for Z-fiducialisation
- 2 x 2m single plane anode with alternate grid wires, 1mm pitch reduced tension simplifies engineering (no strongback)
- Head-Tail sensitivity
- 2D readout but with 3D side veto using resistive wires
- $CH_2$ pellet shielding
- No gamma shielding needed

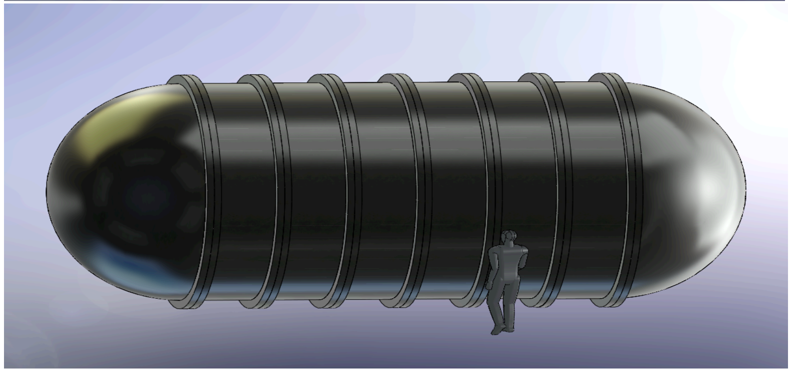


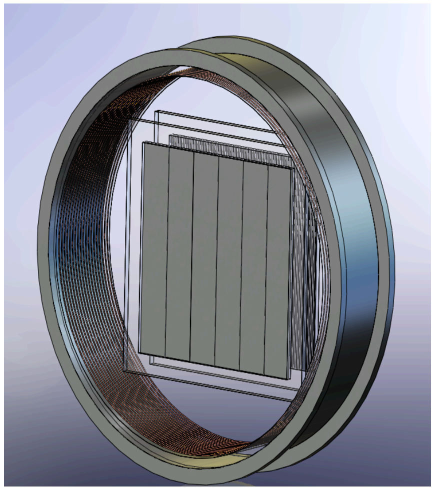
# DRIFT III Vessel

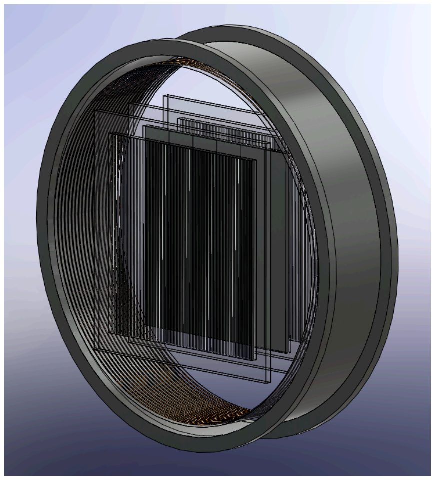
- Each DRIFT-III module composed of 6 segments footprint ~6 m by 3 m.
- Each detector segment observes 4 m$^3$ of gas or, at 40 Torr of $CS_2$, 0.67 kg of target mass
- 250 of these 4 kg modules gives 1 ton and would fit into a standard DUSEL module or 500m tunnel at Boulby











- Preference for hydrocarbon-based material

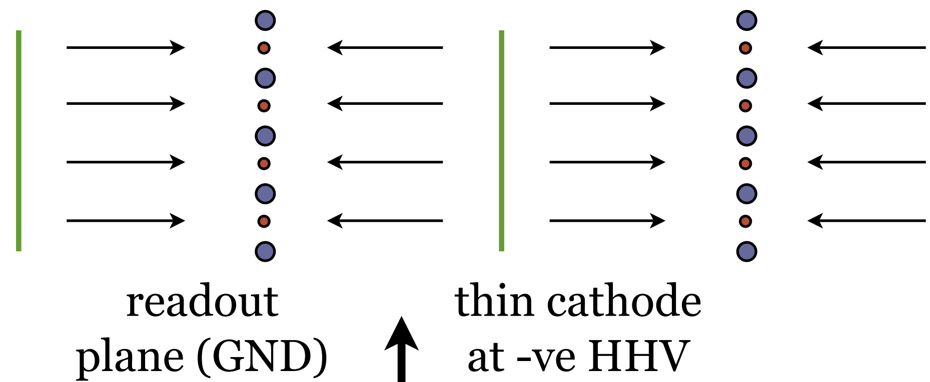
# DRIFT III Readout

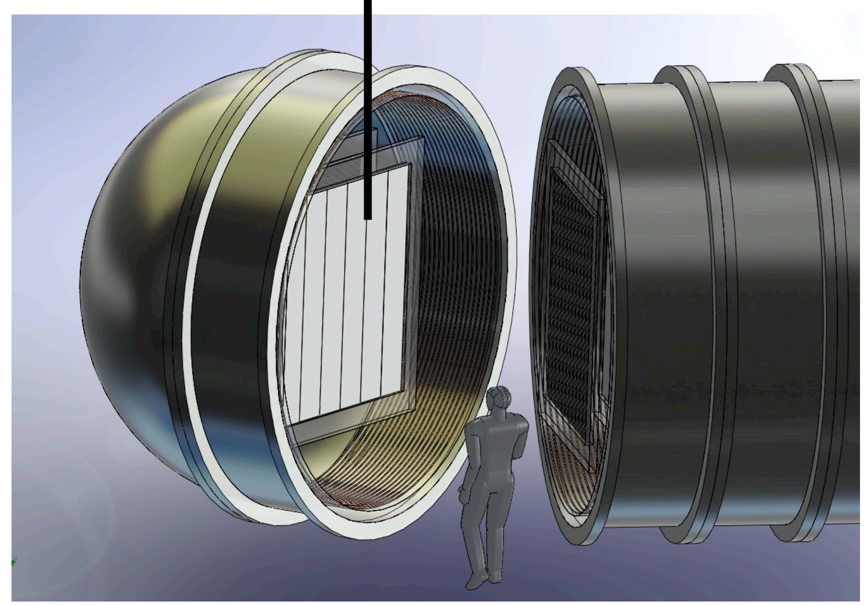
## Sense plane

- Transparent readout plane to sense two sides (eliminates the mechanical support "strong back")
- 20 μm diameter stainless steel wires on a 2 mm pitch
- X-wires, Y-resistive wires

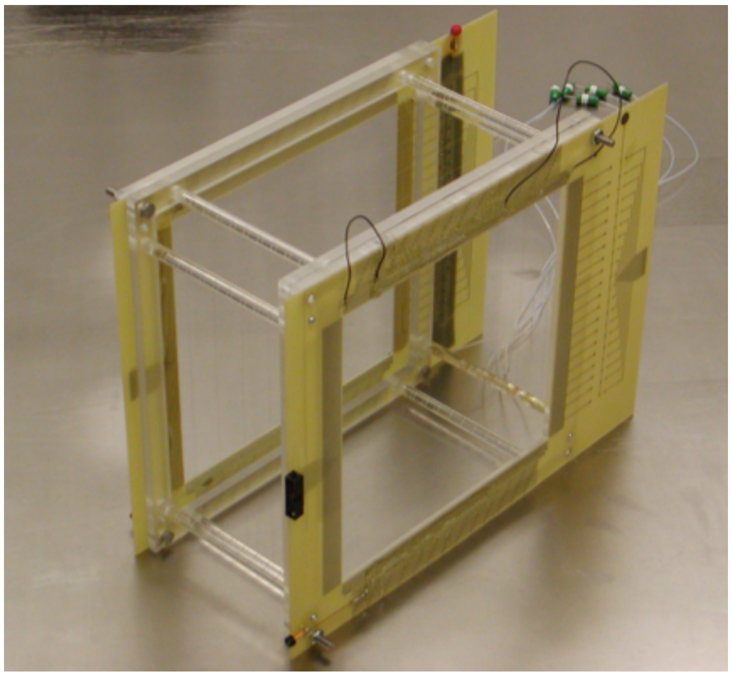
## Cathode

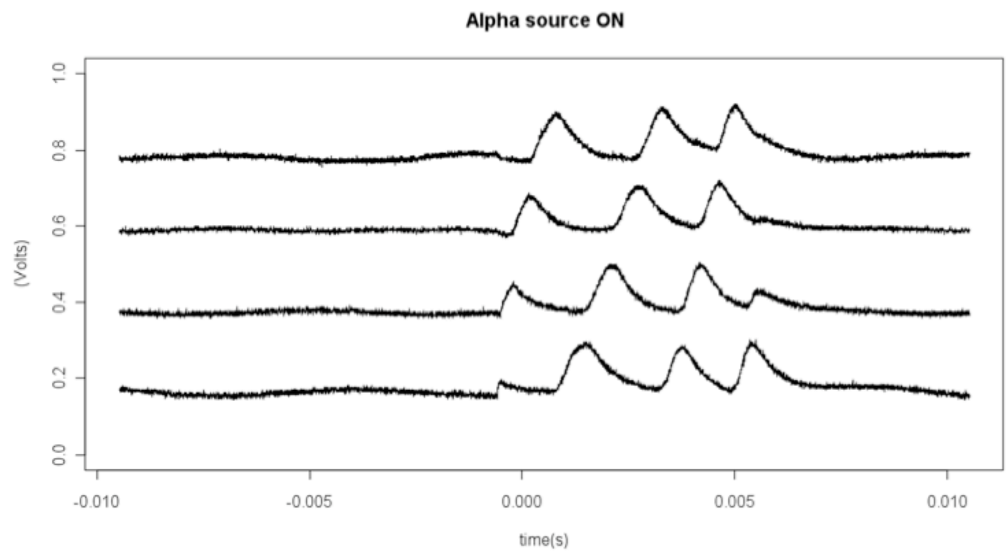
- 70 kV with well-engineered field cage and high-voltage system; diffusion (reduced by 40% c.f. DRIFT II)
- +ve ion detection - segmented to reduce the input capacitance for Z fiducialisation
- Orientation perpendicular to anode wires to give more y dimension information



# DRIFT III Readout R&D





# DRIFT III Gas and Safety

- Multiple targets possible with no change to detector (C, F, S…)
- $CS_2$ + $CF_4$ mixing system as demonstrated in DRIFT II
- Works with up to ~1% contamination (oxygen)
- Gas flow for removal of contamination and radon emanation control (R&D tasks)
- Handling and disposal of $CS_2$ (flammable toxic gas) and $CF_4$ a greenhouse gas is understood (e.g. at Boulby)
- Re-circulation and cleaning with a closed system is an R&D topic

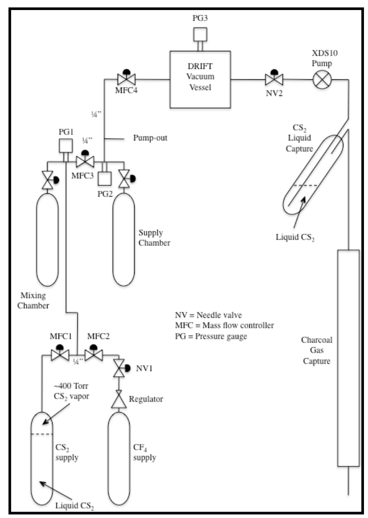
# DRIFT II result…

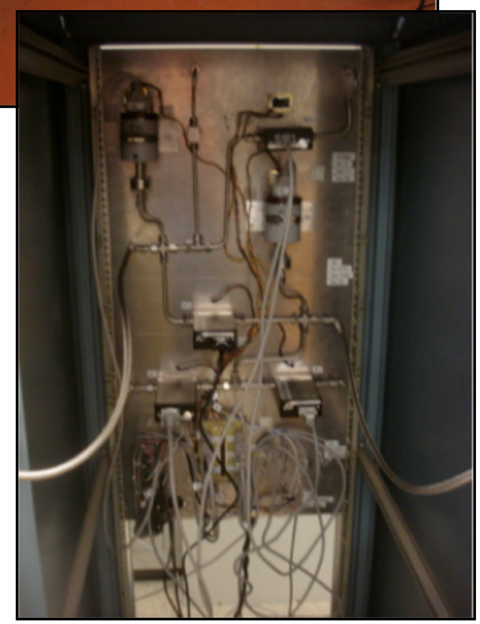
## $CS_2$-$CF_4$ Mixing underground

- Built a fully automated gas mixing system to supply a <u>continuous flow</u> of pre-mixed $CS_2$-$CF_4$ gas mixture to the vacuum vessel

- System of mass flow controllers and capacitance manometers to accurately control and monitor gas
- Fully automated and integrated into the current DRIFT slow control

- Installed at Boulby in May 2009
- Installed and working in 2 days
- Now taking $CF_4$ data



Installed at Boulby

# DRIFT III Shielding

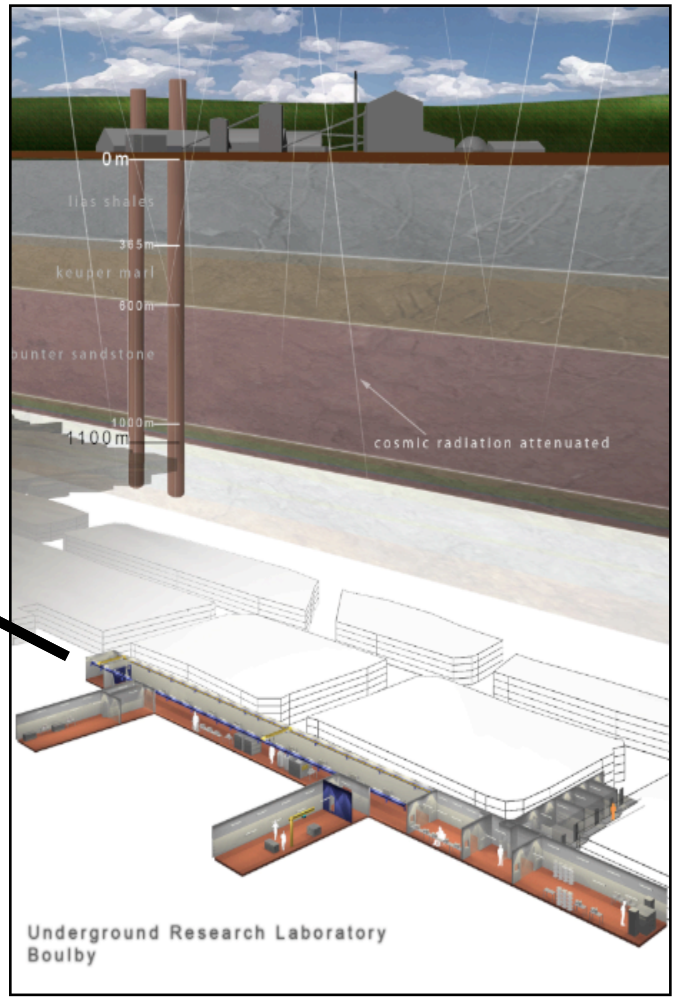
Simple and cheap poly pellet neutron shielding

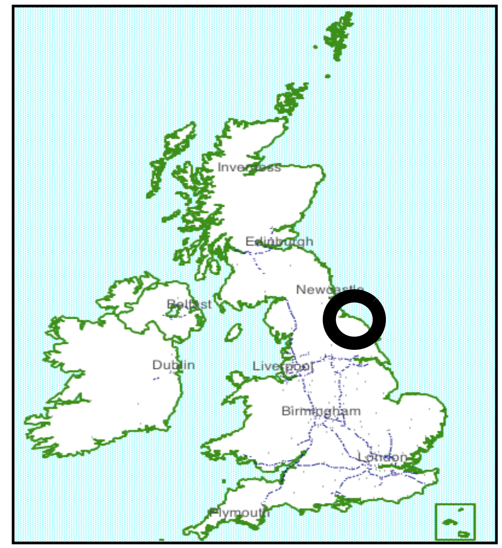
As for DRIFT II

# Boulby Mine Site

- Current site (1.1 km deep) hosts dark matter experiments in salt rock
- New excavation also to deeper levels, hard dolomite rock
- Suitable for large TPC!

- Extension to current laboratory being designed for DRIFT III

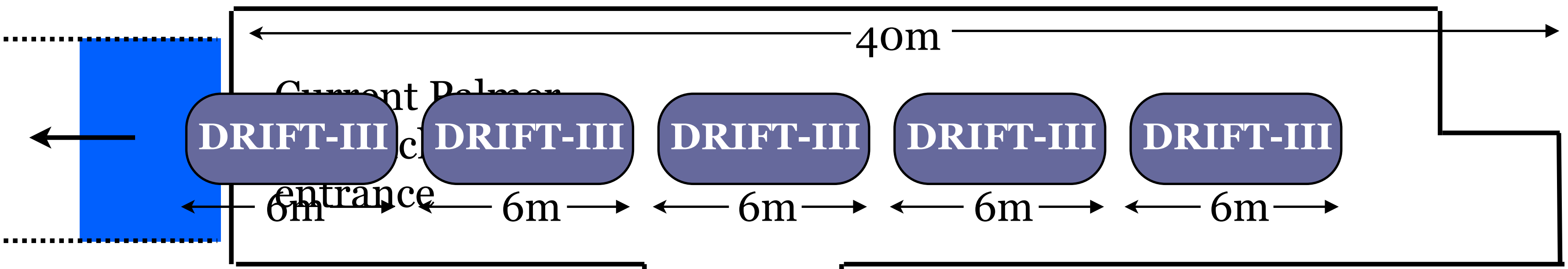



# DRIFT III Site?

- Site for first DRIFT III module identified at Boulby

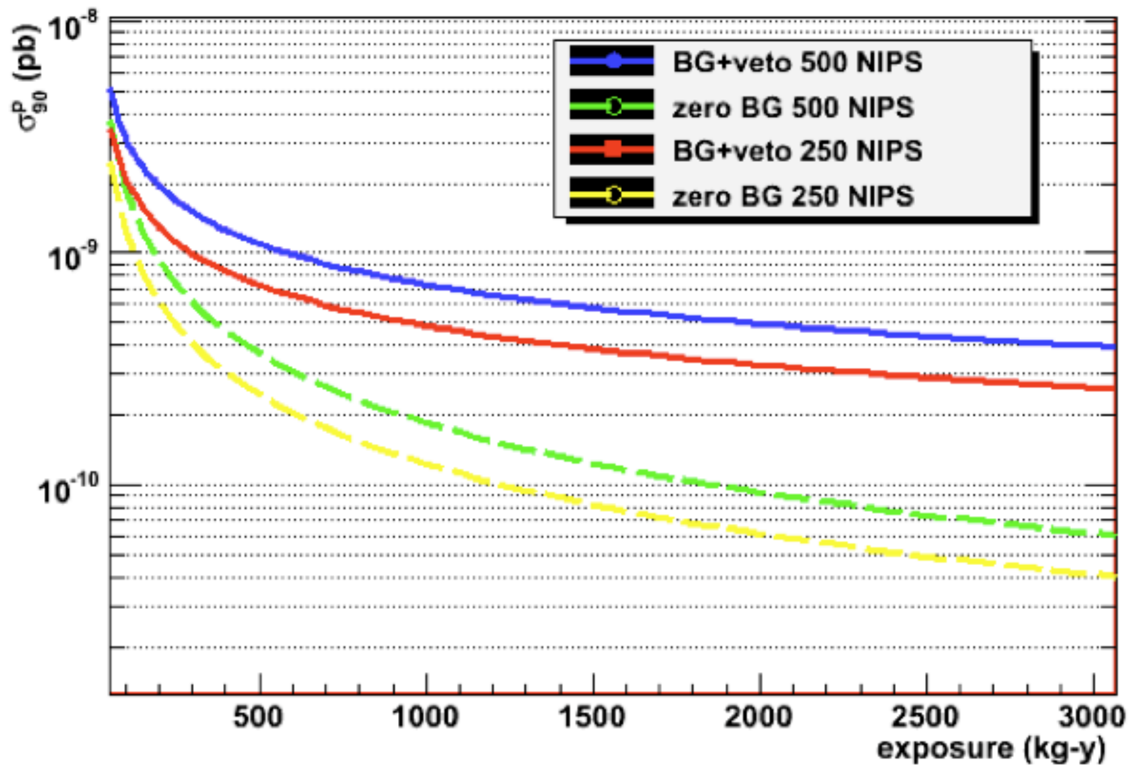
scale drawing




only simple infrastructure needed to house the detector

# Neutron Summary - ton scale

Conclusion for
ton-scale
DRIFT III
(250 modules):




Limits for 100 GeV WIMPs. The solid curves show that a large detector would be background limited due to neutrons produced by a steel vacuum vessel, even when an active veto (96% efficiency) is employed. Eliminating this source of neutrons will allow DRIFT-III to approach the zero-background limits (dotted curves). In the presence of zero or near-zero background, the threshold and efficiency determine the limit.

- Will need non-steel vessel and veto

# Scale-up Speculation (ultimate for SI)

1 ton directional target:

- Charge readout option - ~$10^6$ channels (with grouping)
- CCD concept - ~ 10,000 CCD cameras and optics

*SuperK size cavern device:*

- *10 ton (40 Torr)*
- *50 ton max*

*Ultimate - on scale of proton decay caverns:*

- *400 - 2000 ton directional target mass*

Excavation not a cost driver: \$20-50/m$^3$, \$250K/tonne target

Cost extrapolation from DRIFT III module: \$10K/m$^3$

$\Rightarrow$ ~\$4M/tonne (with scale factors)?

# Conclusion

- Development from DRIFT II to DRIFT III (x25) is now not a major technical leap; the main challenges are:
    - Vessel design (reduction of muon and detector neutrons)
    - Full implementation of z-fiducialisation (RPR reduction)
    - Gas recycling and handling underground
- CCDs, Micro-pix, Micromegas alternative readouts also possible