Directional Dark Matter Searches and Future

- Overview and CYGNUS
  - DM-TPC, NEWAGE, MIMAC
- progress with DRIFT
- DRIFT future
- Scale-up?

Neil Spooner
Dark Matter Signals and directionality

- Motion of the Earth through a static WIMP ‘halo’ -> Earth is subject to a ‘wind’ of WIMPs
- of average speed $\sim 220\text{km}s^{-1}$ coming roughly from the direction of the constellation Cygnus.
- The Earth’s rotation relative to the WIMP wind -> Direction changes by $\sim 90^\circ$ every 12 hours
Directional Dependence vs. Annual Modulation

Hard for a background to mimic the directional signal. (anisotropic backgrounds in lab are isotropic in Galactic rest-frame)

A WIMP directional signal could \textit{(in principle)} be detected with of order 10 events

[Copi, Heo & Krauss; Copi & Krauss; Lehner & Spooner et al.]

Towards WIMP Astronomy
How Many WIMPs Needed?

Dependence of number of events to reject isotropy (and detect a WIMP signal) at 90 (95)% c.l. in 90 (95)% of experiments, $N_{90}$ ($N_{95}$), on detector capabilities:

| difference from baseline configuration | $N_{90}$ | $N_{95}$ |
|---------------------------------------|----------|----------|
| none                                  | 7        | 11       |
| $E_T = 0$ keV                         | 13       | 21       |
| no recoil reconstruction uncertainty  | 5        | 9        |
| $E_T = 50$ keV                        | 5        | 7        |
| $E_T = 100$ 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 |

baseline configuration: 3-d vector read-out, 20 keV threshold, zero background, recoil reconstruction uncertainty taken into account

\{ upgraded and unrealistic \}

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

\{ assuming optimal position sensitivity \}
Advantages of Directionality

- 3D recoil direction, and sense (head-tail), full particle ID
- A definitive signal, linked to the galaxy, can not be mimicked
- Event by event background rejection, gamma, electron, recoil tracking in space and time (>10^6 gamma rejection)
- Low threshold, <5 keV nuclear recoil feasible
- Many targets possible, C, S, F, Xe... (SD)
- Room temperature operation, relatively known technology

Potential for other physics e.g. KK axions

B. Morgan, N.J.C. Spooner and K. Zioutous, Astropart. Phys. 23 (2005) 287
CYGNUS Cooperation links most groups interested in directional detection

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

CYGNUS2007 meeting
22-24 July 2007, Boulby, UK

CYGNUS2009
11-13 June 2009, Boston, USA

CYGNUS2011, June 8-10, Aussois, France
Cooperation on joint document towards scale-up
THE CASE FOR A DIRECTIONAL DARK MATTER DETECTOR AND THE STATUS OF CURRENT EXPERIMENTAL EFFORTS

112 authors

22 Directional detectors

N. Spooner

22.1 Direct dark matter detection technologies and transilience
22.2 The directional signature and statistics
22.3 Directional detector concepts
22.4 Gas detector physics – diffusion and straggling
22.5 TPC gamma background rejection and energy threshold
22.6 TPC neutron background rejection, solar neutrinos and radon
22.7 Chooz and other background
22.8 WIMP detection and directional sensitivity in practice
22.9 Head-tail recoil discrimination, theory and experiment
22.10 Experimental status and readout technology
22.11 Scale-up and a future WIMP telescope
Latest, e.g.:

| Collaboration | Technology | Target | Interactions | Head-tail | Readout | V (m³) |
|---------------|------------|--------|--------------|-----------|---------|--------|
| DRIFT        | NITPC      | CS₂, CS₂-CF₄ | SI/SD       | yes       | MWPC 2D + timing | 1 |
| DMTPC        | TPC        | CF₄     | SI/SD       | yes       | Optical (CCD) 2D + timing | 0.01 |
| NEWAGE       | TPC        | CF₄     | SI/SD       | no        | μPIC 2D + timing | 0.03 |
| MIMAC        | TPC        | ³He/CF₄ | SI/SD       | yes       | Micromegas 2D + timing | 0.00013 |
| Emulsions    | emulsions  | AgBr    | SI/SD       | no        | Microscope 3D | N/A |

5.9 keV electron track
DM-TPC 10-Litre
MIT, U Boston, U Brandeis - US

Low-pressure CF₄ TPC
- 50-75 torr: 40 keV F recoil ~2mm

Optical readout (CCD)
- Image scintillation photons produced in amplification region
- 2D, low-cost, proven technology

Amplification region
- Wire planes → mesh detector
- Woven mesh 25μm, 250μm pitch

CF₄ is ideal gas
- F: spin-dependent interactions
- Good scintillation efficiency
- Low transverse diffusion
- Non flammable, non toxic

10 L fiducial volume 20 cm drift 3.3 g at 75 torr
Charge and scintillation readout
DM-TPC head-tail

$^{252}\text{Cf}$ run with mesh detector @ 75 torr
Mesh-based detector: 2D projection of recoil

Stable data-taking at 75 torr
“Head-tail” effect down ~ 100 keV
Good data-MC agreement

Cf-252 neutrons

Astropart. Phys. 30 (2008) 58-64

Dujmic et al. Astropart. Phys. 30 (2008) arXiv:0804.4827
DM-TPC Surface run

- Surface run of 10 litre
- F SD WIMP-p limit ~2400pb
- CCD-specific backgrounds “worms”
DM-TPC Future

- Going underground to WIPP
- 2x larger detector under-construction
- 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
NEWAGE Concept
Kyoto University – Japan

CF$_4$ filled 3D imaging gaseous TPC detector using micro-pattern pixellated readout (‘μ-PIC’)

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

CF$_4$ gas @ 0.2 bar (aiming for 0.05 bar soon)

Now running in Kamioka
Aiming for 1m$^3$ detector operating @ Kamioka by 2013

PLB 654 (2007) 58 (Miuchi et.al.)
Preprints: physics/0701085
Directional sensitivity confirmed for ‘low energy’ recoils (>200keV) from $^{252}$Cf neutrons.

Also a $10^4 \sigma_{\text{WIMP-p}}$ SD limit based on isotropy of no-source recoil tracks >100-400keV

(PLB 654 (2007) 58)
MIMAC Concept

Developed a specific chip giving access to a 3D track reconstruction with a 300 μm spatial resolution.

Matrix of micromegas μTPC filled with $^3$He, CF$_4$, CH$_4$ or/and C$_4$H$_{10}$. A 10 kg $^3$He dark matter detector, or the equivalent mass of CF$_4$, with a 1 keV threshold (MIMAC) would be sensitive to SUSY models.

The x–y, y–z and x–z projections of a 5.5 MeV alpha track.

Quench tests with a dedicated ion beam.

Grenoble, Saclay - France
DRIFT
Dark Matter Search
(Directional Recoil Identification From Tracks)

Progress with DRIFT

- Overview
- New SD limits
- Fiducialisation and 24m³ DRIFT-III
DRIFT IIa-d

- 1 m³ active volume - back to back MWPCs
- Gas fill 40 Torr CS₂ => 167 g of target gas
- 2 mm pitch anode wires left and right
- Grid wires read out for Δy measurement
- Veto regions around outside
- Central cathode made from 20 μm diameter wires at 2 mm pitch
- Drift field 624 V/cm
- Modular design for modest scale-up

S. Burgos et al., Nucl. Instr. Meth. A 584, 114 (2008)
MWPC Concept in DRIFT

ΔX: Number of Anode Wires Crossed
ΔY: Progression across Grid Wires
ΔZ: Drift Time difference between start and end of track
Boulby Mine (UK)

- Current site (1.1 km deep) hosts dark matter experiments in salt rock
- But new excavation underway to deeper levels, hard dolomite rock
- Suitable for a large TPC!
Example 3D reconstruction (x-z and y-z projections) of a ~100 keV S recoil in DRIFT IIb (size of circles is indicative of the size of charge deposited).
(2) Low Energy Results

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

use of Savitzky-Golay
digital filter

$^{55}$Fe track reconstruction and digital polynomial smoothing - data fit to exponential decay(noise) plus Gaussians

Energy thresholds -->

Note these are not the trigger thresholds yet

| Source of Track          | Thres. Energy (keV) |
|--------------------------|---------------------|
| Electron                 | 1.23                |
| Alpha                    | 1.23                |
| Carbon nuclear recoil    | 2.15                |
| Sulphur nuclear recoil   | 3.46                |
(3) 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): +z, -z, +x, -y

Note: extrapolation indicates head-tail discrimination continues below current threshold

Clear head-tail discrimination (in 1 m³ at low energy)!

Theory Conclusion:
- expect head-tail
- expect more ionization at start (near interaction)
- depends on W

[Graph showing oscillation amplitude for different directions, with +ve and -ve head-tail values]
First low background runs of DRIFT-II see a recoil-like background ~200-600 / day (50-250 keV).

Increase with time consistent with Rn emanation.

Hypothesis: Recoil of radon progeny on central cathode - with alpha absorbed in wire.

S. Burgos et al., Astropart. Phys. 28 (2007) 409
RPR Reduction

Steps taken to reduce RPRs

(1) Reduce radon producing contaminants from vessel:

| Sample (Emanating into vacuum) | Fill gas  | Emanation time (days) | Humidity (%) | Raw result (Bq/m³) | 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 +/- 0.02               |
| Ribbon cables                  | Dry N2    | 6.5                    | 23           | 10.1 +/- 0.7       | 0.50 +/- 0.04               |
| Electronics & PCBs             | 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 +/- 0.5       |

S. Paling et al. (Sheffield)

(2) RPRs still produced from Pb isotopes plated out on cathode. Clean cathode with nitric acid

Together, these reduced the RPRs by 96% relative to D-IIa rate

D. Snowden-Ifft, Oxy, J. Turk, UNM
(PhD thesis 2008)
(3) RPRs have large pulse-widths as expected from maximally diffused tracks drifting from cathode. So, residual RPRs may be removed in analysis:
(5) CS$_2$-CF$_4$ Measurement Results

Measurements of Gain, W-value, Mobility, stability...

**e.g. Gain Tests**

From the known gain of the amplifier chain and the size of events gives us the gain for a single electron

- All mixtures total 40 Torr
  - Gas gain increases for added CF$_4$
  - Stability decreases
  - High gas gains even with 75% CF$_4$
  - Best stability with 50:50 mix or lower CF$_4$

- Need to run at lower voltages for stability of high voltage systems – lose MWPC gain
- Loss in MWPC gain is compensated for by improved gas gain.

---

Gas gain measurements using a single wire proportional counter

![Gas gain measurements graph](image)
CS$_2$-CF$_4$ Mixing Installed at Boulby

(M. Pipe et al., Sheffield)

- Built a fully automated gas mixing system to supply a continuous flow of pre-mixed CS$_2$-CF$_4$ gas mixture to the vacuum vessel
- Designed by Oxy-Sheffield
- 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
SD Limit 14.8 days (blind)

- Signal region chosen for zero expected events
- MC and Neutron calibration
- Blind analysis
  30-10 CS$_2$-CF$_4$ 2009/2010 Shielded WIMP runs
  14.8 days, 2050 events, 138 +/- 3 events per day

Preliminary 02/10

SD WIMP-proton limit (blind)

MC for 100 GeV WIMPs and region of acceptance

Signal region

WIMP Mass (GeV) vs. WIMP-proton SD cross section (pb)

DRIFT-IIId

COUP
NAIAD
KIMs

Preliminary 02/10
Latest SD Limit 47.2 days (unblind)

**SD WIMP–proton Limits**
with 30–10 CS2+CF4 and a 47.2 day exposure

0 events detected resulting in an upper limit of 2.44 (double-sided) by Feldman and Cousins. Gas mass = 0.134 kg Fraction of fluorine by mass = 0.241Run time = 47.2 days

**DRIFT**: 1.5 kg-days (CF4)
with full directional sensitivity
25keV F threshold

**DRIFT**: 1.2 pb minimum
c.f.

**NEWAGE**: 5400 pb
**DM-TPC**: 2400 pb

**No compromise on directional sensitivity needed to achieve this**
DRIFT What Next

(1) Main thrust is RPR elimination:
   (a) reduction of intrinsic radon/RPR contamination
   (b) improved PSD/position analysis and cuts
   (c) introduction of alpha-transparent cathode
   (d) full z-fiducialisation via +ve ion

(2) Upgrade/streamlined electronics and gas system

(3) DRIFT III scale-up design
    \[24 \, \text{m}^3\]
    \[\text{in 4 m}^3 \, \text{segments}\]

(4) 1 tonne directional target:
Electronics Upgrade  
(E. Daw, M. Robinson, Sheffield)

Aim: lower noise, better PSD for track reconstruction, simplification to allow multiple module operation, integrated slow control and safety

(1) Analogue Upgrade

(2) Digital Upgrade

14 bit, better pulse shape accuracy, lower dead-time for calibration, reduced cabling and noise, integrated slow control, improved web interface
Thin Cathode

Alpha transparencies for different cathode materials and thicknesses

| Cathode Type            | Fraction Lost (%) Po 214 (7.69 MeV) | Fraction Lost (%) Po 218 (6 MeV) |
|------------------------|--------------------------------------|----------------------------------|
| 20 micron steel wire   | 37                                   | 41                               |
| 20 micron quartz fiber | 8.6                                  | 14                               |
| 8.2 micron quartz fiber| 3.4                                  | 5.1                              |
| 6.5 micron quartz fiber| 2.6                                  | 4.1                              |
| 10 micron mylar sheet  | 9.1                                  | 13                               |
| 2 micron mylar sheet   | 1.8 (1.6)                            | 2.7 (2.5)                        |
| 1.5 micron mylar sheet | 1.4                                  | 2.0                              |
| 0.9 micron mylar sheet | 0.8                                  | 1.2                              |

Current: With 0.9 micron thick cathode the projected RPR rates would drop from current rate of 138/day to between 0.5/day to 3.5/day
Thin Cathode Installation at Boulby last week

Multi-panel 0.9μm thick DRIFT cathode
cathode tested at full voltage (32.5kV)
Thin Cathode Limit Prediction

x40-50 reduction in background (RPR) expected

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

No compromise on directional sensitivity needed to achieve this
Z-fiducialisation

Z-fiducialisation by measuring $\Delta T$:

$Z = v_d \Delta T$

Requires detection of \( \sim 1000 \) ions on cathode

0 V \hspace{2cm} -32.5 \text{ kV}

Eric Lee, UNM (2009)
Z-fiducialisation test

Expected delay = 1.5 milliseconds

Anode

Cathode

CS$_2$ – 40 Torr

Collimated
Po$_{30}$
Alpha source

6.5 cm

12.5 cm

1000M

-3KV

-4KV

Frisch Grid

7 cm

6.5 cm
Z-fiducialisation test

Expected delay = 1.3 milliseconds
Z-fiducialisation test

Expected delay = 1.1 milliseconds
Z-fiducialisation test

Expected delay = 0.8 milliseconds
Z-fiducialisation test

Expected delay = 0.6 milliseconds
**Z-fiducialisation test**

Anode

Cathode

Expected delay = 0.4 milliseconds

CS₂ – 40 Torr

Collimated
P₀₂₁₀
Alpha source

1.5 cm

12.5 cm

7 cm

Cathode

Frisch Grid

Anode

1000M

-3KV

-4KV
Z-fiducialisation test

Expected delay = 0.1 milliseconds
Z-fiducialisation test

Expected delay = 0.0 milliseconds

CS₂ – 40 Torr

Collimated
PO₃⁰
Alpha source

0.5 cm

12.5 cm

7 cm

-4KV

-3KV

1000 M

1000 M
Z-fiducialisation test

Results from cathode readout scheme: detection of $\sim 950$ $^+$ions produced with an $N_2$ laser

Detection of $\sim 500$ $^+$ions at 54% has now been achieved
**SD Sensitivity of DRIFT IIId**

- Plan is to run for 2.4 m³-years of exposure (started)
- Simulations are in progress – understand the expected behavior in the mixed gas

Expected WIMP-proton spin dependent sensitivity

![Graph showing current limits and predictions for DRIFT IIId runs.](Image)

- **current limits**
- **DRIFT IIId - 10 day run, zero background prediction**
- **DRIFT IIId - 2.4 m³-years, zero background prediction**

**with directional capability**
Scale-up Speculation (ultimate for SI)

1 Tonne

- A 1 Tonne target (10keV Thresh, 0 bg) would give $10^{-10}\text{pb}$ (raw) & $>10^{-9}\text{pb}$ (halo) SI sensitivity.
- Vol = 2,500–10,000 m$^3$ (160–40 Torr).
- 1/30th-1/120th volume of LNGS
- 4/3$^{rd}$ – 1/3$^{rd}$ the size of MINOS

Bigger

SuperK size cavern device:
  - 10 tonnes (40 Torr)
  - 50 tonnes max

Ultimate - on scale of proton decay caverns:
  - 400 - 2000 tonne directional target mass

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

Cost extrapolation from DRIFT IId: €50K/m$^3$

$\Rightarrow \sim$€40M/tonne (with scale factors)???
The Ultimate Dream Detector?
halo sensitivity at $10^{-12}$ pb

| Basic numbers for worst case cross section |
|-------------------------------------------|
| **Exposure, Mass** | 1000 ton.yr (galactic confirmation), 10,000 ton.yr (halo confirmation) |
| **Depth** | $>4000$ mwe (ignores statistical discrimination of neutrons via isotropy) |
| **(if) Gas technology** | go for 1 atm. (easier vessel?) |
| ![50 μm track μm gas readout (interpolation)](image) | 3 kg/m$^3$ target |
| | 1cm readout plane spacing (2d/3d) |
| | diffusion subtraction |
| **Caverns** | 3 caverns of 2km x 10m x 5m |

Low background components ok: Lucite, Cu, Kapton
Conclusions

• BIG PROGRESS in the last year
  ▫ Event by event discrimination - FIRST COMPETITIVE SD LIMITS
  ▫ Directional signals possible at 1 m$^3$ scale
  ▫ Head-tail (sense) exists and is understood at 1 m$^3$ scale
  ▫ Low recoil thresholds feasible (e.g. 2 keV S-recoil) at 1 m$^3$ scale
  ▫ Negative ion (low diffusion) operation with other targets demonstrated, in particular Fluorine (CS$_2$-CF$_4$)
  ▫ Solution to Z-fiducialisation and RPR reduction

• More international activity
  ▫ DM-TPC
  ▫ NEWAGE
  ▫ MIMAC, CAST
  ▫ CYGNUS cooperation and conference series on directional dark matter successful and expanding

• Large scale-up design studies underway
  ▫ e.g. 24m$^3$ DRIFT III module