Direction-Sensitive Direct Dark Matter Search

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Topical workshop on DARK MATTER

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DM direct detection

Expected direct DM signals

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Target: $^{19}$F

- $\sigma x p = 0.1$ pb
- $P_D = 0.3$ GeV/$c^2$/cm$^3$
- $v_0 = 220$ km/s
- $v_E = 247$ km/s (Jun.)
- $v_{esc} = 650$ km/s

SIGNAL

$E_R < \sim 100$ keV

“mainstream” talks tomorrow
“original” literatures: late 1980s

**Physical Review D**

**Particles and Fields**

Third series, volume 37, number 6
15 March 1988

Motion of the Earth and the detection of weakly interacting massive particles

David N. Spergel*  
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 September 1987)

\[ \frac{dR}{dE \, d \cos \gamma} = \frac{\rho_0 \sigma_0}{\sqrt{\pi}} \frac{(m_x + m_n)^2}{2m_x m_n v_{halo}} \times \exp \left\{ -\frac{[(v_E + v_\odot) \cos \gamma - v_{\min}]^2}{v_{\text{halo}}^2} \right\} \]. (7)

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Detection of Dark Matter Using Low Pressure Gas Detectors (TPC's)

G. Masek, K. Buckland, M. Mojaver  
Physics Department, University of California, San Diego 92093


**Fig. 2:** Set up for observing low energy (kev) ion tracks. The circled region is the location of the differential pumping holes.

30 years later, many up-to-date detectors are begin developed.
Science
Direction-Sensitive Dark Matter Search concept “CYGNUS”

WIMP-WIND from “CYGNUS”
Clear Discovery
+ study the nature of DM after discovery
“CYGNUS” physics towards discovery

Potential to search beyond the “neutrino floor”†

† neutrino-nucleus coherent scattering really exists!

Observation of coherent elastic neutrino-nucleus scattering


F. Mayer et al. / Physics Reports 627 (2016) 1–49
“CYGNUS” physics after discovery

Astrophysics ①

- standard halo (1-r) + co-rotating halo (r)

Discrimination of anisotropy in dark matter velocity distribution with directional detectors

Keiko I. Nagao*, Ryota Yakabe†, Tatsuhiro Naka‡, Kentaro Miuchi§

Target: F

$M_{\text{WIMP}} = 60 \text{GeV}$

standard “spectrum” in AD era

Chi2 ($r_{\text{tmp}} = 0.3$)
"CYGNUS" physics after discovery

Astrophysics

ex. Sagittarius stream

Our GALAXY

standard HALO

standard HALO + stream

galactic coordinate

streams, halo model...
“CYGNUS” physics after discovery

Particle physics

Test the interaction by scattering angle

Some operators are distinguishable
“CYGNUS” physics after discovery

Particle physics

- inelastic scattering

iDM (inelastic scatterings dark matter) and normal dark matter (FFeDM (form factor elastic dark matter)) show different angular DISTRIBUTION
Experiments
Experimental concept

Recoil nuclear track detection $< 100$keV

challenge: short track

- a few mm in low pressure gas
- a few 100 nm in solid

Most typical “CYNGUS”: low pressure gas TPC
(time projection chamber)

2D readout + timing $\rightarrow$ 3D tracking
Cygnus, nonTPC

NEWSdm [Japan+Italy]
- Emulsion (20~50nm crystal)
- Good position resolution
- Large mass
- No time resolution

ZnWO$_4$ [Italy, Japan]
- Columnar recombination
- Large mass
- Need to confirm in low energy

DeCANT [Italy]
- Carbon nano tube
- Large mass
- Proof of concept is ongoing

DM
Φ~10nm
~10μm

Liq Ar [Italy, Japan]
- "Anisotropic" scintillator
- Large mass
- Need to confirm in low energy

\[\text{Arxiv:1406.4825}\]
DRIFT: pioneer of “CYGNUS” concept

early 2000s ~
- large TPC
- low BG study

Measurement of carbon disulfide anion diffusion in a TPC
Tohru Ohnuki\textsuperscript{a,b,}, Daniel P. Snowden-Ifft\textsuperscript{a,}, C. Jeff Martoff\textsuperscript{b}
\textsuperscript{a}Department of Physics, Occidental College, 1600 Campbell Road, Los Angeles, CA 90041-3314, USA
\textsuperscript{b}Department of Physics, Temple University, 1900 N. 13th Street, Philadelphia, PA 19122-6082, USA
Received 15 May 2000; received in revised form 13 November 2000; accepted 14 November 2000

Neutron recoils in the DRIFT detector
D.P. Snowden-Ifft\textsuperscript{a,b,}, T. Ohnuki\textsuperscript{a,b,}, E.S. Rykoff\textsuperscript{a,b,}, C.J. Martoff\textsuperscript{a,b}
\textsuperscript{a}Physics Department, Occidental College, 1600 Campus Road, Los Angeles, CA 90041, USA
\textsuperscript{b}Barton Hall, Temple University, 1900 N. 13th St., Philadelphia, PA 19122-6082, USA
Received 5 July 2002; received in revised form 11 October 2002; accepted 27 November 2002

- 2mm pitch multi-wire proportional chamber
- not very direction-sensitive
NEWAGE: always direction-sensitive

New general WIMP search with an Advanced Gaseous tracker Experiment

- μ-PIC(MPGD) based TPC
- 3-D tracks SKYMAP
- CF$_4$ gas for SD search

Proposal  PLB 578 (2004) 241

First direction-sensitive limits

- PLB654 (2007) 58

Underground results


Phase for “low BG detector”
Cygnus, gas TPCs

- MWPC (2mm pitch)
- First started direction-sensitive method
- Underground
- Low background
- Large size (1m³)

- Pixel readout (ATLAS FE-I4) chip
- R&D in the surface lab

- optical (CCD) readout
- R&D in the surface lab

- Micromegs (~400μm pitch)
- quenching factor measurement
Technologies
State-of-the-Art
Main Background

From directional analysis: C and D below

SKYMAP @ detector coordinate

lower energy

reason: absolute “Z” position cannot be measured...
absolute Z position...

- For 2-phase xenon detector: trigger timing \( t_0 \) is given from \( S_1 \)
- For self-triggering TPC: \( t_0 \) cannot be detected
  \( \rightarrow \) Z-fudicialization is not possible
breakthrough for “z” detection

- minority peaks “discovery” (Occidental college group)
- O$_2$ addition to CS$_2$+CF$_4$ gas
  - CS$_2$ : used as negative ion gas for small diffusion
  - CF$_4$ : added as dark matter target
  - O$_2$ : accidentally mixed

several species of ions with different velocities

z-fidutialzation realized at last!

but… CS$_2$ gas is toxic, volatile, flammable
2nd breakthrough (2015)

- SF$_6$ gas
  - SF$_6$: famous insulator gas (safe gas)
  - found to have minority carriers

First Studies of SF$_6$ in a TPC

NGUYEN PHAN, ERIC LEE
UNIVERSITY OF NEW MEXICO

2017 JINST 12 P02012

- averaged waveform
- minority carrier is really minor

Fiducialization?

- 9% faster than larger peak
- SF$_5$?
World-wide SF$_6$ activities

- Wide varieties of MPGD (micro patterned gaseous detectors)
- Very active, new comers are welcome!

New Mexico
- Thick (400um) GEM (3 × 3cm$^2$)
- CERN 0.5mm pitch, Φ0.3mm
  - Gas gain
    - 2000@30Torr
    - 30,40,(60) Torr

Kobe
- Thin (100um) GEM (10 × 10cm$^2$) Scienergy, 140um pitch, Φ70um
  + μ-PIC (10 × 10cm$^2$) DNP, 400um pitch strip readout
- Triple thin (100um) GEM Scienergy, 140um pitch, Φ70um
  - Gas gain
    - 2000@20Torr

Wellesley
- Micromegas (10 × 10cm$^2$)
- CERN (gap 128um and 256um)
  - Gas gain
    - 300@40Torr
    - 2300@40Torr

Frascati
- Triple thin (50um) GEM (3 × 3cm$^2$)
- CERN, 50um pitch, Φ30um
  - Gas gain
    - 5000@175Torr, 2000@370Torr

Sheffield
- Thick (400um) GEM (50 × 50cm$^2$)
- UK, 0.5 um pitch Φ0.3um
  - Gas gain
    - 6000@30,40Torr
“CYGNUS”
concept to collaboration
2007 ~ biannual workshop
2007 Boulby, UK
2009 Boston, USA
2011 Aussois, France
2013 Toyama, Japan
2015 LA, USA
2017 Xichang, China

The CYGNUS Galactic Directional Recoil Observatory Proto-Collaboration Agreement

Now that conventional WIMP dark matter searches are approaching the neutrino floor, there has been a resurgence of interest in the possibility of introducing recoil direction sensitivity into the field. Such directional sensitivity would offer the powerful prospect of reaching below this floor, introducing both the possibility of identifying a clear signature for dark matter particles in the galaxy below this level but also of exploiting observation of coherent neutrino scattering from the Sun and other sources with directional sensitivity. There has also been significant progress recently in development of technology able to record the directional information from nuclear recoils at low energy (sub-100 keV) necessary for these goals. This includes progress on improving the sensitivity of low pressure gas time projection chamber technology but also on novel ideas with higher density targets, such as ultra-fine grain emulsions, scintillation materials, columnar recombination with noble gas targets and concepts using nano-technology. Such world-wide directional expertise, if pooled together and directed at converging on an optimised design, likely at multiple underground sites and different
We the undersigned agree to work together on the CYGNUS programme, noting that this does not automatically imply participation in the CYGNUS collaboration when that is formed.

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50 researches signed so far.
CYGNUS-KM vessel: modular approach
low BG gas chamber with $40 \times 40 \text{cm}^2$ windows
chamber ready, will be in Kamioka late 2018
your detectors are welcome!
AXIONs

- gas detectors are useful for decay-search (volume matters) → KK axion

Searches for solar Kaluza–Klein axions with gas TPCs


First experimental limit (not by gas detector, though)
SUMMARY

- Direction sensitive dark-matter search

  - For the discovery and further investigation
  - Gas TPC and other detectors

  - R&Ds are actively ongoing