CYGNUS: Imaging of low-energy nuclear recoils in gas TPCs

for directional dark matter searches, neutrino detection, and more

Sven Vahsen (University of Hawaii)

https://arxiv.org/abs/2102.04596
The Power of Directionality

• An experiment that can measure the direction of nuclear recoils...

• Can positively identify galactic origin of a potential dark matter signal w/ only 3-10 recoil events ($\sim 10^3$ x stronger effect than annual oscillation)

• Can Distinguish dark matter and solar neutrinos $\rightarrow$ penetrate neutrino floor

• Can do neutrino physics

Many potential benefits, but experimentally challenging!
Ideal experiment: 3D-vector-directionality
<table>
<thead>
<tr>
<th>Name</th>
<th>Detector, [TPC readout]</th>
<th>Directionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEWAGE</td>
<td>Gas TPC, GEM + μPIC</td>
<td>3d</td>
</tr>
<tr>
<td>DRIFT</td>
<td>Gas TPC, MWPC, NID</td>
<td>1.5d</td>
</tr>
<tr>
<td>MIMAC</td>
<td>Gas TPC, Micromegas + Strips</td>
<td>3d</td>
</tr>
<tr>
<td>DMTPC</td>
<td>Gas TPC, Optical readout</td>
<td>2d</td>
</tr>
<tr>
<td>D³</td>
<td>Gas TPC, 2xGEM + CMOS pixel</td>
<td>3d</td>
</tr>
<tr>
<td>New Mexico readout R&amp;D</td>
<td>Gas TPC, Optical readout, NID</td>
<td>2d</td>
</tr>
<tr>
<td>CYGNO</td>
<td>Gas TPC, 3xGEM + CMOS optical + PMT</td>
<td>3d / 2d+1d</td>
</tr>
<tr>
<td>NEWSdm</td>
<td>Nuclear Emulsions</td>
<td>2d</td>
</tr>
<tr>
<td>PTOLEMY</td>
<td>Graphene</td>
<td>2d</td>
</tr>
</tbody>
</table>

All directional experiments that have set DM limits use gas TPCs. Most TPC groups now working towards the CYGNUS project.
<table>
<thead>
<tr>
<th>Detector classes by directional information</th>
<th>[ \text{Indirect} ]</th>
<th>[ \text{Recoil imaging} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistical</strong></td>
<td><strong>Event-level</strong></td>
<td><strong>Demonstrated</strong></td>
</tr>
<tr>
<td>Modulation-based directionality</td>
<td>Indirect recoil event directionality</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Anisotropic scintillators</td>
<td>Nuclear emulsions</td>
<td>Proposed</td>
</tr>
<tr>
<td>‣ No event-level directions</td>
<td>‣ 2d recoil tracks, without head/tail</td>
<td></td>
</tr>
<tr>
<td>‣ Exploits modulation of DM with respect to crystal axes</td>
<td>‣ No event times information recorded</td>
<td></td>
</tr>
<tr>
<td>Columnar recombination</td>
<td>Gas TPC</td>
<td></td>
</tr>
<tr>
<td>‣ Event-level 1d directions</td>
<td>‣ Head/tail measurable</td>
<td></td>
</tr>
<tr>
<td>‣ No head/tail</td>
<td>‣ 1d, 2d or 3d</td>
<td></td>
</tr>
<tr>
<td>‣ Direction and energy are not independent</td>
<td>‣ Independent energy/direction measurement</td>
<td></td>
</tr>
<tr>
<td>DNA detector</td>
<td>Crystal defects</td>
<td></td>
</tr>
<tr>
<td>‣ 3d recoils without head/tail</td>
<td>‣ 3d track topology</td>
<td></td>
</tr>
<tr>
<td>‣ No event times recorded</td>
<td>‣ Head/tail measurable</td>
<td></td>
</tr>
</tbody>
</table>

The Power of High Definition (HD) gas TPCs

Capabilities resulting from HD charge readout

- 3D directionality
- Head/tail
- Electron rejection
- Nuclear Recoil ID
- 3D fiducialization

3D vector directionality possible in gas TPC w/ highly segmented readout planes – HD TPCS

Want: segmentation (here: 50 x 250 µm) < diffusion (~200-500 µm) < recoil length (~mm)

Compact, directional neutron detectors capable of high-resolution nuclear recoil imaging, NIMA 2019.
https://doi.org/10.1016/j.nima.2019.06.037

3/18/21
Sven Vahsen, CPAD Workshop
Proto Collaboration formed:
- **55 signed members** from the US, UK, Japan, Italy, Spain, China
- **Six US faculty members**
- Close collaboration and regular meetings on detector R&D and physics studies

**New collaborators welcome!**

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Sven Vahsen, CPAD Workshop
Opportunities for a long-term physics program

New physics opportunities for each factor 10 increase in exposure (yellow = measurement/observation)

- Migdal Effect measurement
- Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) at either NuMI or DUNE
- Competitive DM limits in SI and SD
- CEvNS from solar neutrinos
- Efficiently penetrating the LDM $\nu$ floor
- Observing galactic DM dipole
- Measuring DM particle properties and physics
- Geoneutrinos
- WIMP astronomy

Extensive concept paper on 1000 m$^3$ detector: https://arxiv.org/abs/2008.12587
Focused on technical feasibility and WIMP searches
Wider physics potential being explored as part of US Snowmass process

https://arxiv.org/abs/2102.04596
Detector Performance Requirements

(if targeting solar neutrinos and $m \approx 10$ GeV Dark Matter)

- Event-level recoil directionality
  - angular resolution $\leq 30$ degrees
  - excellent head/tail sensitivity
- Rejection of internal electron backgrounds
  - by factor $\geq 10^5$ for 1000 m$^3$ detector
- All of above down to $E_{\text{recoil}} \approx 5$ keV
- Energy resolution $\sim 10\%$ at 5.9 keV
- Timing resolution $\sim 0.5$ h

# detected WIMP events required to exclude $\nu$-hypothesis at 90% CL

Assumptions: $m_\chi = 10$ GeV, He:SF$_6$ gas
Key issue: WIMP sensitivity depends on electron rejection

Electron rejection rises exponentially with ionization energy. When combined with flat bkg spectrum, will determine CYGNUS energy threshold for background free operation.

Majd Ghrerar et al., arxiv.:2012.13649
Improved, physically motivated observables for electron rejection. Requires HD readout.
CYGNUS: Experimental Approach

- Gas Time Projection Chamber
  - ~1-10 m$^3$ unit cells
  - ~100-1000 such cells. Flexible form factor.

- Gas mixture 1:
  - SF$_6$:4He:X, p<=1 atm
  - Reduced diffusion via negative ion drift (SF$_6$ gas)

- Gas mixture 2:
  - CF$_4$:4He:X, p<=1 atm
  - Trades diffusion for higher gain

- Fluorine: SD WIMP sensitivity

- Helium target
  - SI, low mass WIMP sensitivity
  - Longer recoil tracks, extending directionality to lower energies

- 3D fiducialization techniques
  - SF$_6$ minority carriers
  - charge cloud profile

Both electronic and optical charge readout being investigated: CYGNUS HD and CYGNO
But what is the optimal TPC charge readout technology?

Strip readout has almost same performance as pixel readout, but at approx. one order of magnitude lower cost

Helium recoils in 755:5 He:SF$_6$

Comparison of TPC charge readout technologies

Pixel readout extracts the entire directional information left after diffusion (red and yellow curves overlap fully).

Strip readout has almost same performance as pixel readout, but at approx. one order of magnitude lower cost.

Helium recoils in 755:5 He:SF$_6$

Result of cost vs performance analysis

Best raw performance – optimal for precision studies of nuclear recoils

Best directional WIMP sensitivity per unit cost – optimal for large detectors!

probably insufficient performance for solar neutrino physics

TPC charge readout technology

Current U.S. efforts

• DRIFT experiment
  • Pioneering directional TPC
  • MWPC charge readout
  • First to demonstrate negative ion drift, fiducialization via minority carriers → background free
• Readout R&D on HD TPCs
  • U. New Mexico
  • Wellesley
  • U. Hawaii
• Quenching factor measurements
  • Duke/ TUNL
Extensive prototyping with HD pixel readout completed @ U. Hawaii, culminating in BEAST TPCs. Due to high spatial resolution and single-electron sensitivity, these prototypes remain in use for quenching factor measurements and precision studies of nuclear recoil physics. Planning to evaluate GridPix charge readout ~Summer 2021 (see next talk).
Demonstration: Dark Matter limit with BEAST TPC directional neutron detectors (low gain)

Double GEM + pixel readout, *even at gain ~1500*, already has outstanding performance. At gain >20k, can detect single electrons. But is this level of performance worth the cost?
New US effort: CYGNUS HD – two detectors
Cost-effective scale up via existing collider technologies
CERN strip micromegas, CERN VMM3a hybrids, CERN SRS readout

Construction ongoing!

CYGNUS HD “Keiki” - factor 1000 scaleup of BEAST TPC
Evaluation of components for follow-on 1m³ detector
CYGNUS HD Keiki readout plane

- Vacuum vessel interior: 50 x 50 cm
- Strip micromegas sensitive area: 20x20 cm
- 200 micron pitch
- 1000 x-strips, 1000 y-strips
- 16 Front end-cards
  - 8 on x-side
  - 8 on y-side
- 8 HDMI connectors
  - 4 on x-side
  - 4 on y-side
- Hybrids on back of readout plane, to allow tighter packing in large detector
- Iterating readout plane design with CERN
- Plan to evaluate 1) resistive, diamond like carbon x/y strips and 2) x/y strips w/ dielectric protection

Digitize inside vessel, custom HDMI feedthroughs
CYGNUS HD-1 Demonstrator

- 1000 liter sensitive volume
- 2 x 50 cm drift
- Unit-cell technology demonstrator for future, large CYGNUS neutrino/DM observatory
- 1.5 x 1.5 x 1.5 m internal volume.
- May go underground
- CERN strip micromegas readout, 2 x 1m²
- Custom feedthroughs with ~20 HDMI connectors

Vacuum vessel design ongoing at vendor
Yesterday’s background ➔ today’s signal?

• HD gas TPC *excellent* at identifying electron-recoil events
• So far, treated as background
• But they could be an important new signal
• A *vector-directional* signal
• CYGNUS study ongoing!

3/18/21

Sven Vahsen, CPAD Workshop
Conclusion

• HD gas TPCs suitable for directional DM, neutrino detection, and precision measurement
• Potential for a rich, long-term physics program based on incremental scale-ups
• CYGNUS concept paper and new review of directional detection:
  https://arxiv.org/abs/2102.04596
• CYGNUS US
  • performing recoil physics measurements with small, UHD detectors
  • building next generation strip detectors to demonstrate scaleup
• CYGNUS now exploring complementary electron recoil signatures
• Planning Snowmass mini-workshop on directional detection in Fall 2021
CYGNUS HD: MPGD gas TPCs for nuclear recoil imaging

1st generation, proof of concept

2011-2013

μD³ (~1 cm³)

2013

~2.5 cm³

2013

~ 20 cm³

2014

2 x 60 cm³

2015

8 x 40 cm³

2nd Generation: compact directional neutron detectors. currently operating @ KEK, Japan.

3rd Generation: Optimized for dark matter

2021

3rd Generation: Optimized for dark matter

120 cm

150 cm

CYGNUS HD 1 Demonstrator (1 m³)

CYGNUS HD “Keiki” (40 liters)

3rd Generation: Optimized for dark matter

2020

Extensive prototyping with pixel chip readout completed

Due to high spatial resolution and single-electron sensitivity, these prototypes remain in use for precision studies of nuclear recoil physics

Now constructing 3rd generation detectors w/ CERN strip micromegas readout to achieve DM + solar neutrino sensitivity at reduced cost

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