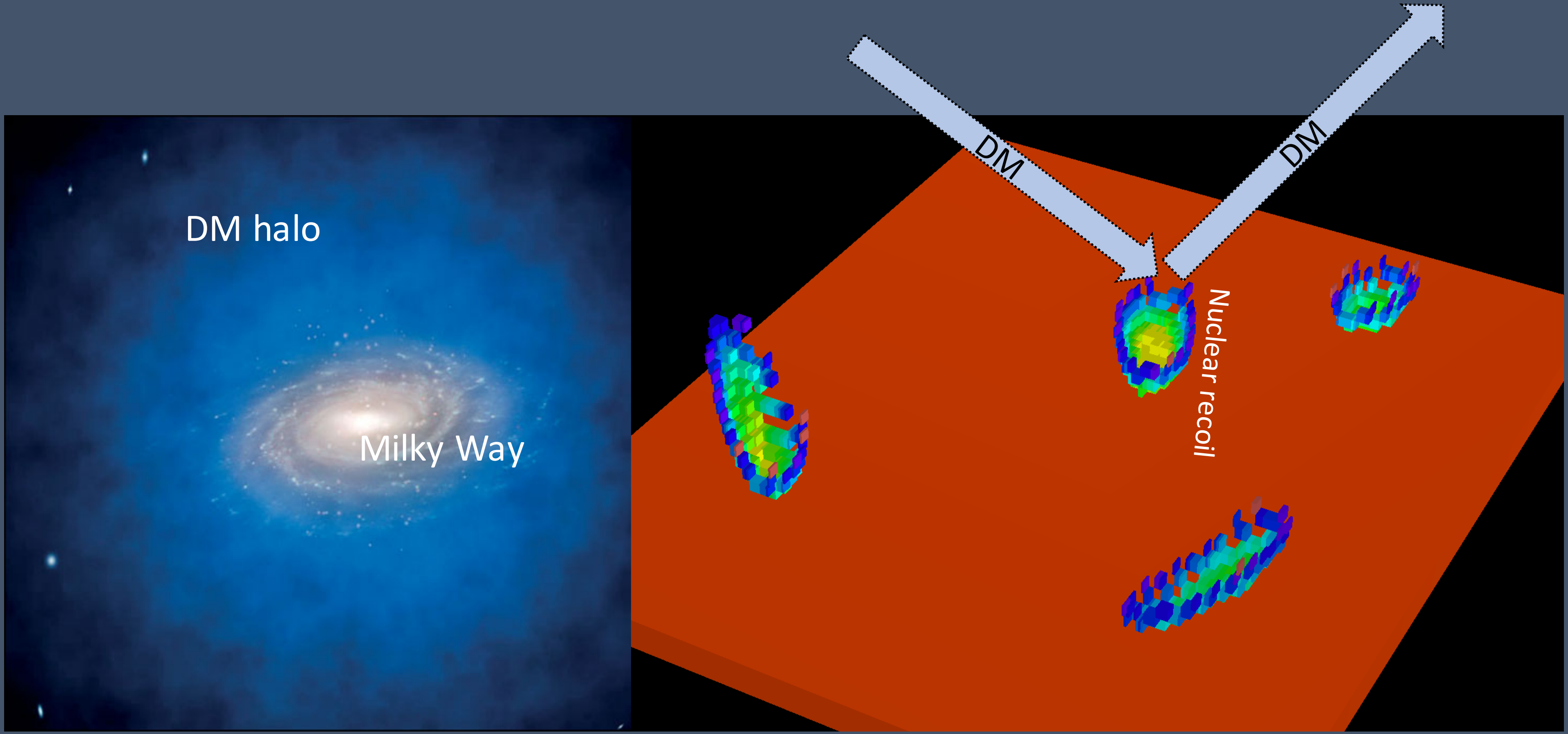
Directional Dark Matter Detection



Sendai Symposium, March 2019

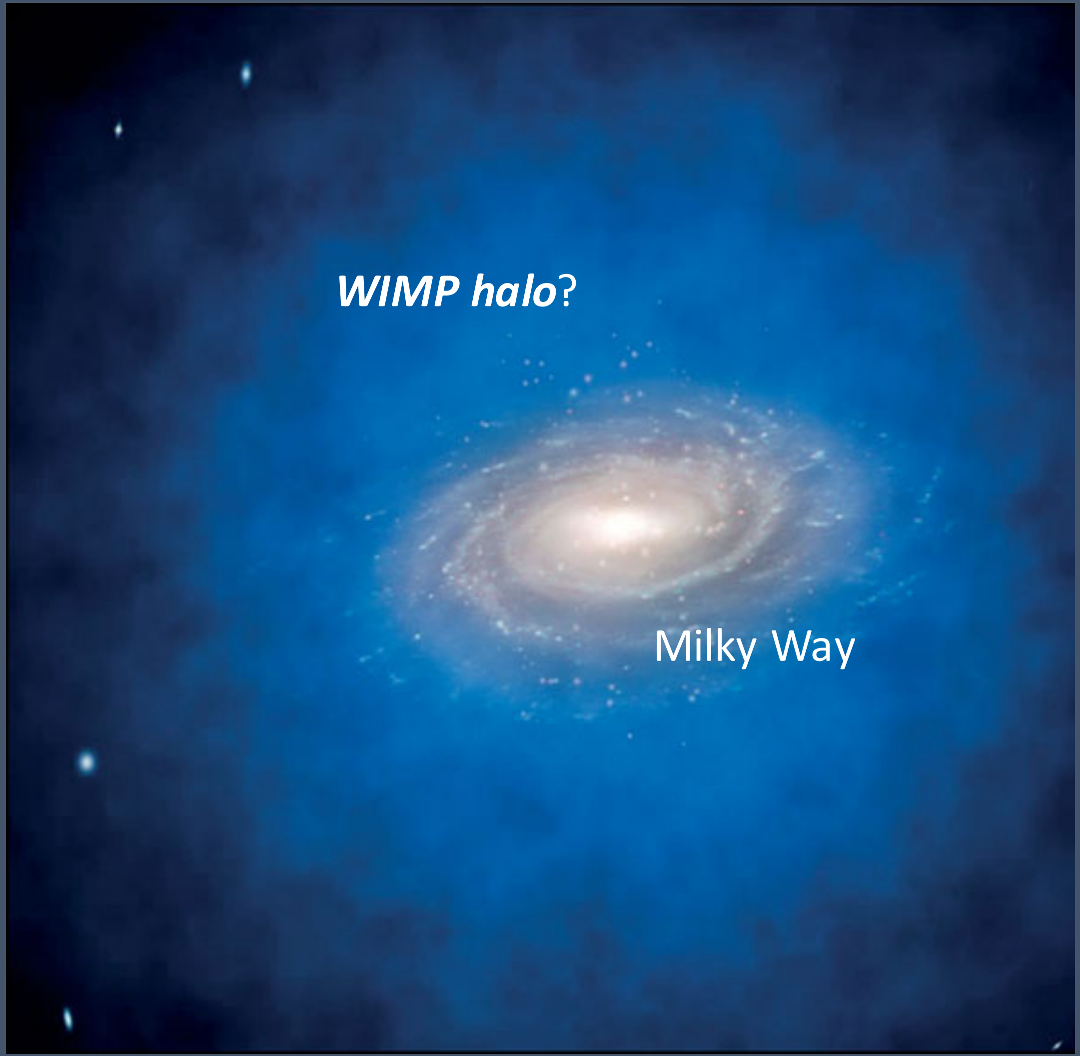
Sven Vahsen (University of Hawaii)

Outline

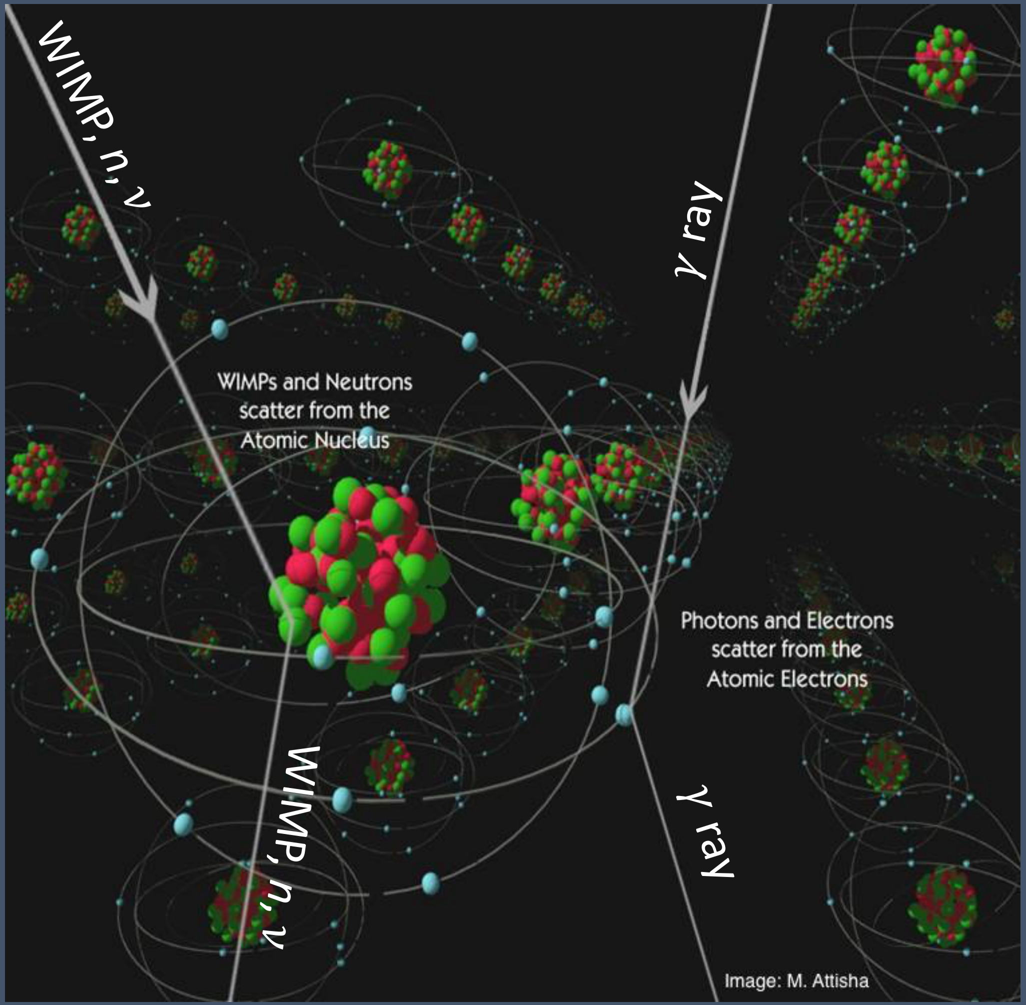
- Challenges in direct detection of DM
- Motivation for directional detectors
- Technological approaches
- CYGNUS

Do we live in a *WIMP halo*?

- Dark Matter exists
  - Overwhelming evidence at distance scales from Milky Way to visible universe
  - All gravitational
- WIMPs are one hypothesis
- Direct Detection seeks to answer
  - Does the local Milky Way DM halo contain WIMP-like particles?
  - What are their properties?
  - What is their local density and velocity distribution ?



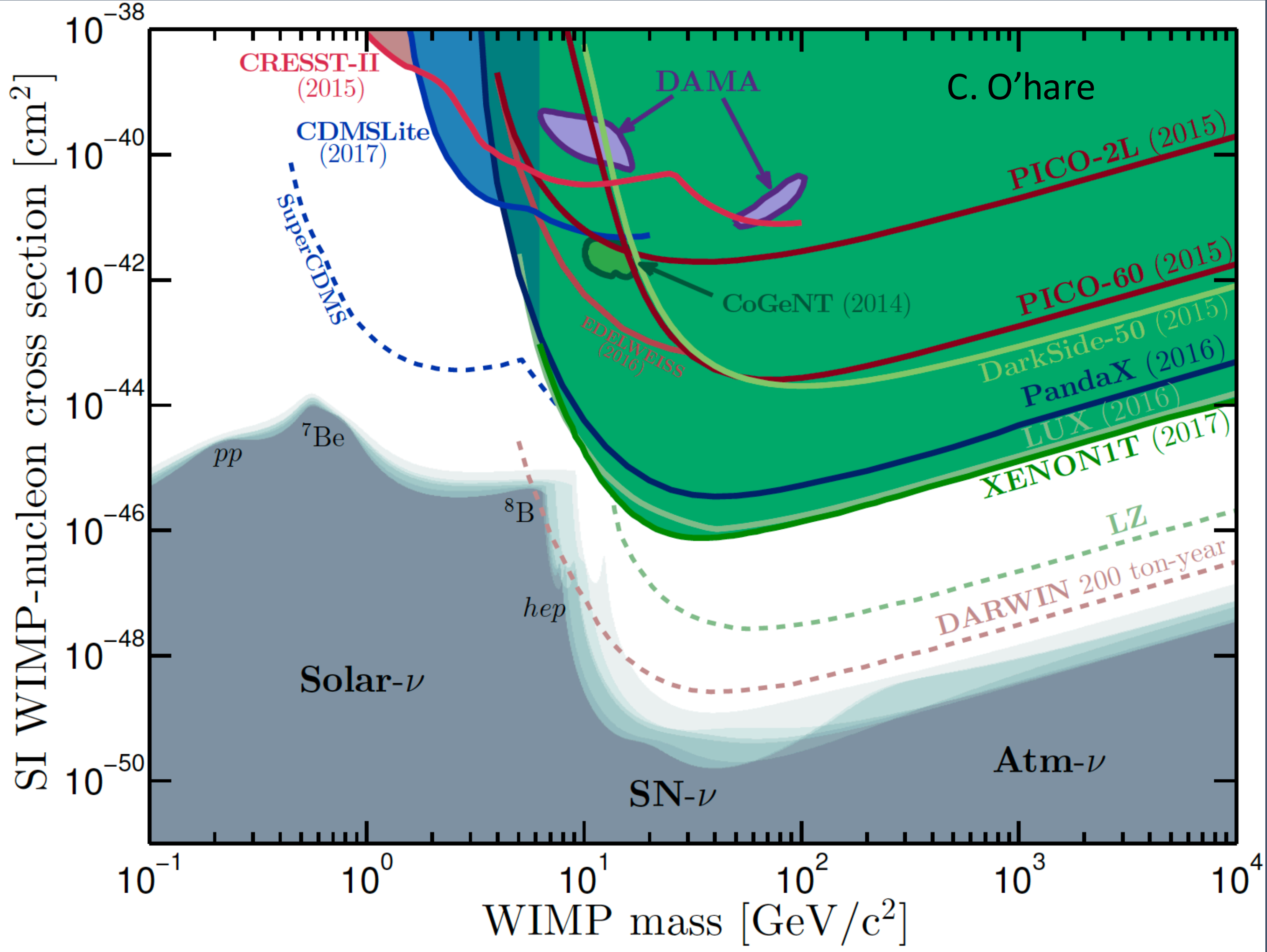
Challenges



- Huge detectors
- Stringent requirements on
  - Shielding
  - Radiopurity
  - Background rejection

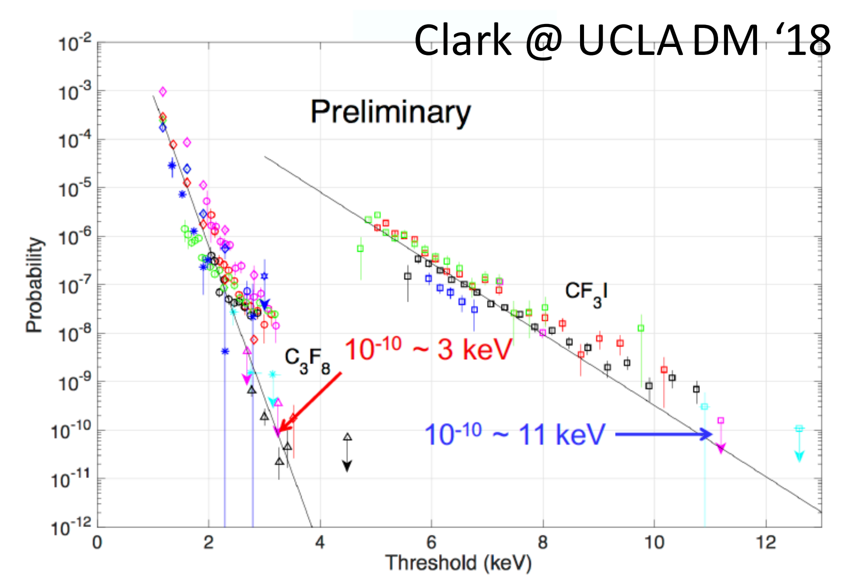
SI, elastic, WIMP/nucleon Scattering: Experimental Status

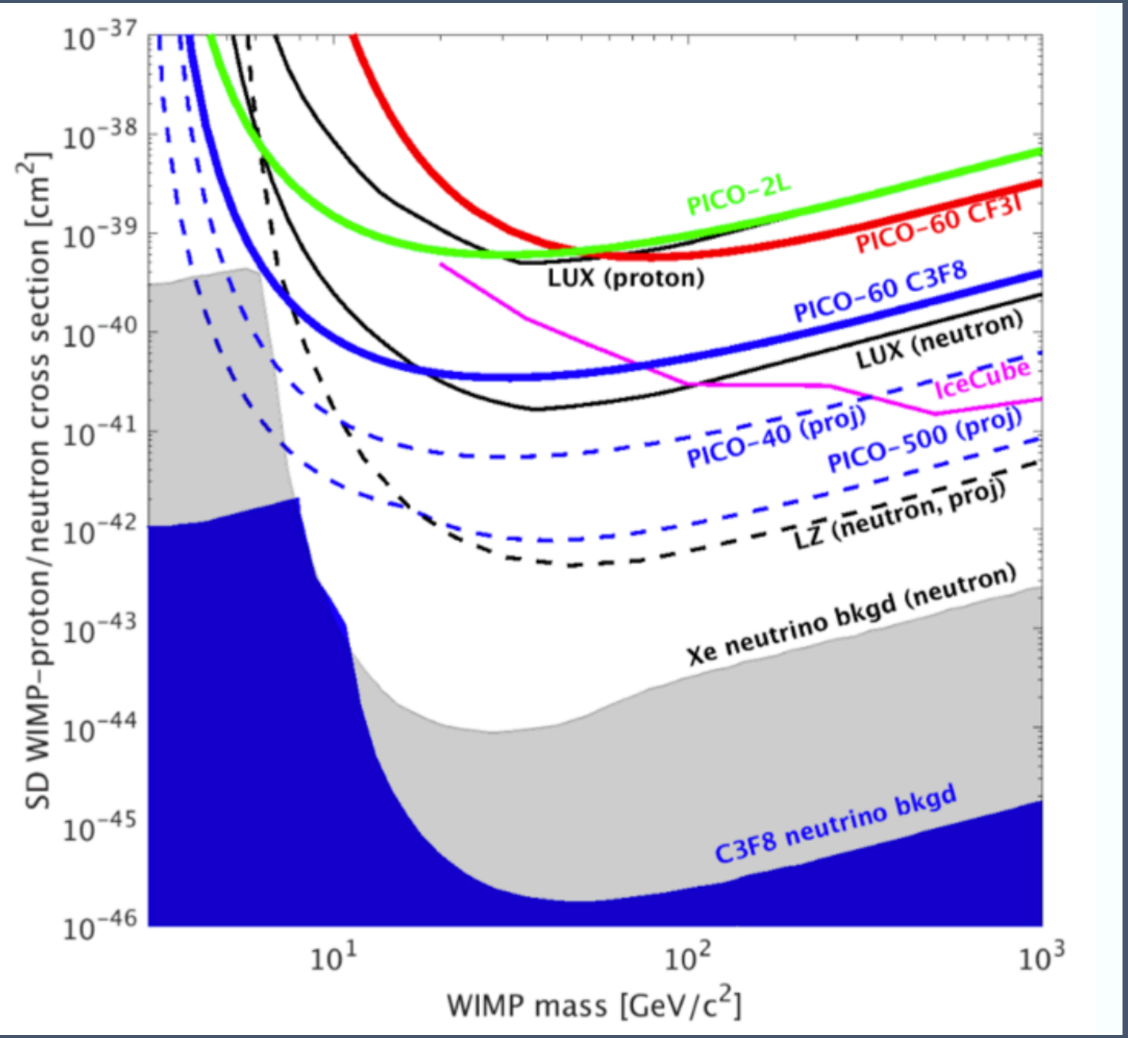
- Best limits now < 0.1 zB
- Noble liquid experiments most sensitive at m~50 GeV/c²
- Solid targets leading around m~5 GeV/c²
- Controversial signals suggesting m~10 GeV



SD, elastic, WIMP/nucleon Scattering: Experimental Status

- Bubble chambers with fluorine targets are taking the lead
- Excellent gamma rejection at low energies

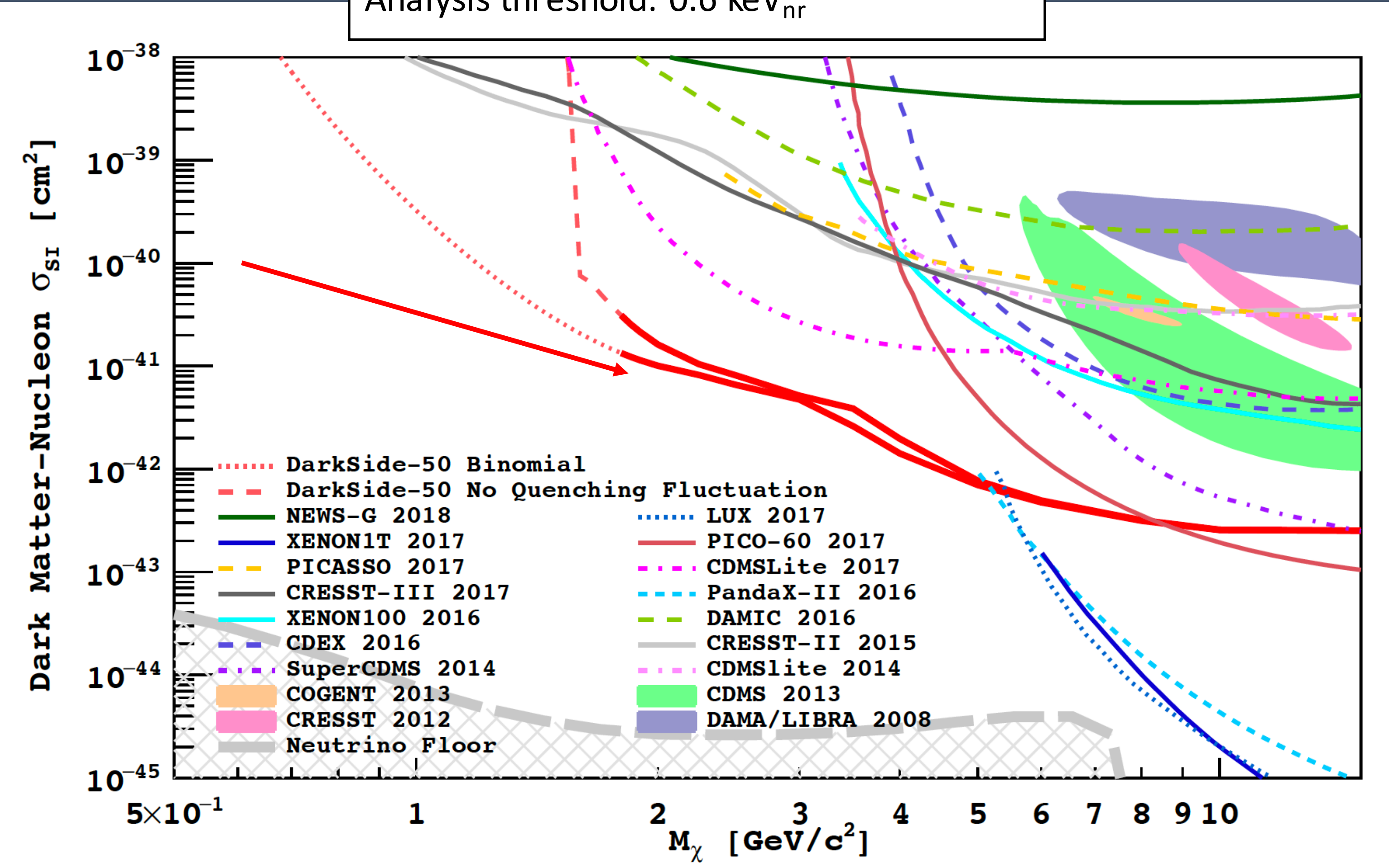




Recent Limits: Low mass

arxiv: 1802.06994
Darkside-50 ionization (S2) only analysis
Analysis threshold: 0.6 keV_{nr}

- Ionization-only analyses from noble liquid experiments
- Dedicated, often, ionization-based experiments, including gas targets
- Often
  - lack of particle ID at lowest (keV) energies
  - Uncertainty about low-energy sensitivity



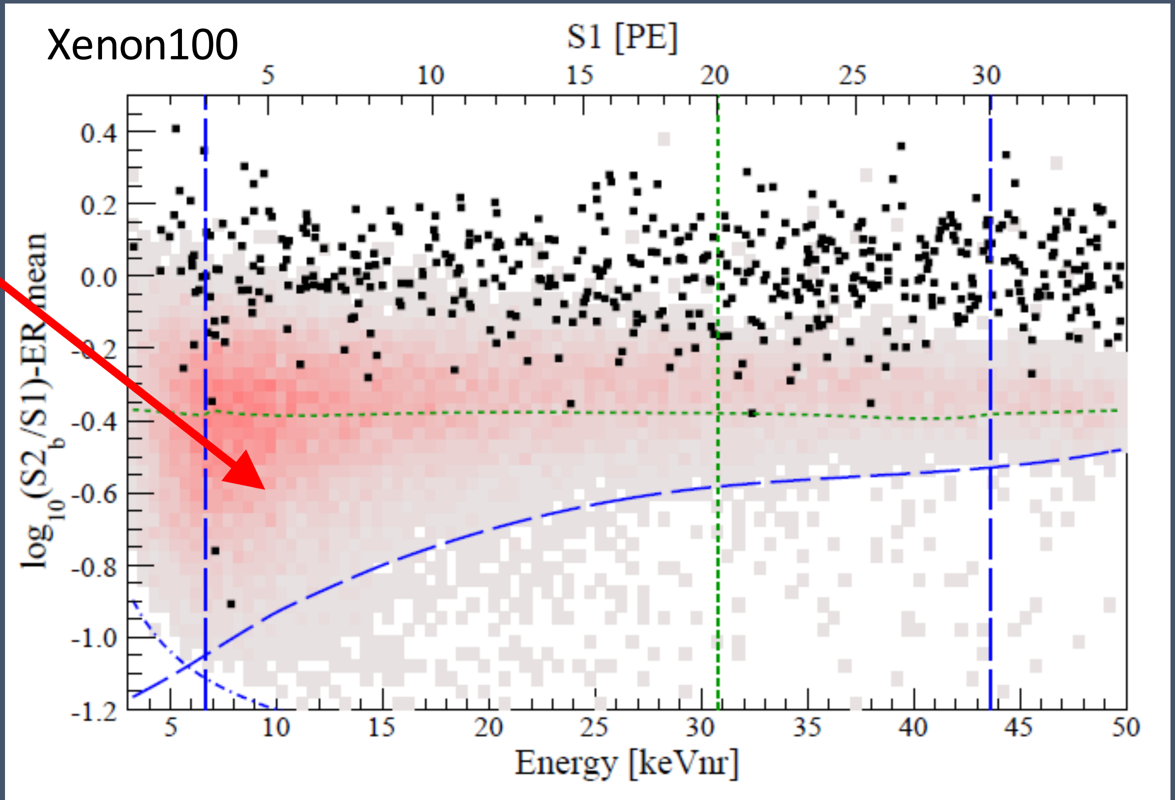
Summary of Status and Challenges

- G2 experiments will probe cross-sections within factor 10-100 of the neutrino floor for m > 1 GeV/c^2
- Challenges to further progress in this mass range
  - Irreducible neutrino background
  - Lack of particle ID in ionization-only experiments for E $\sim<$ 10 keV
  - Lingering controversial signals from DAMA / lack of clear discovery signal
  - Calibrations at lowest recoil energies
  - Ever stricter requirements on radio purity and background rejection

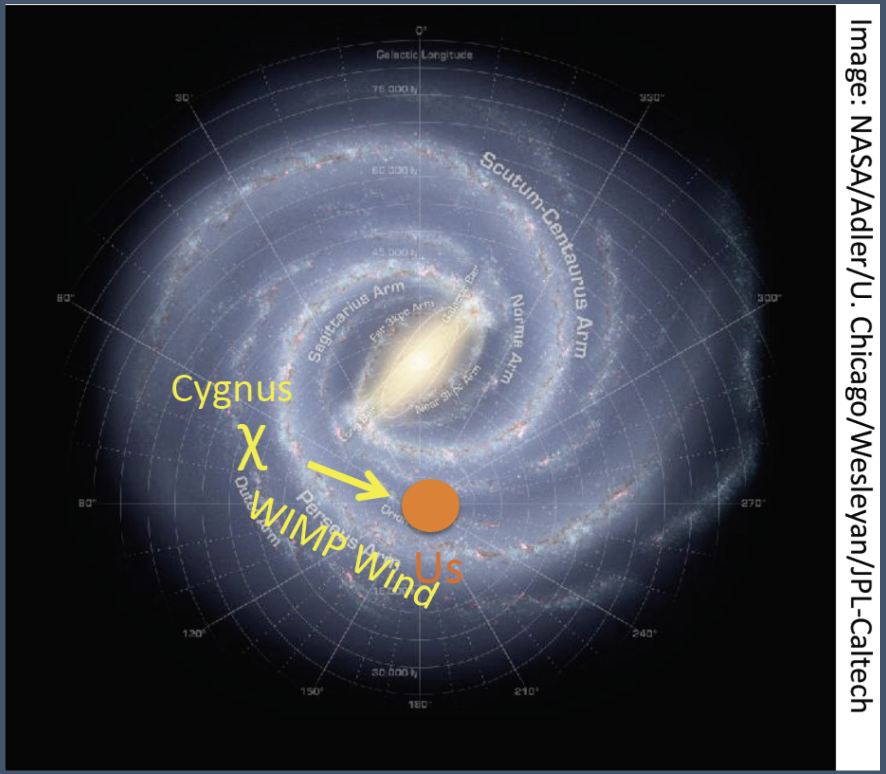
Motivation for Directional Detectors

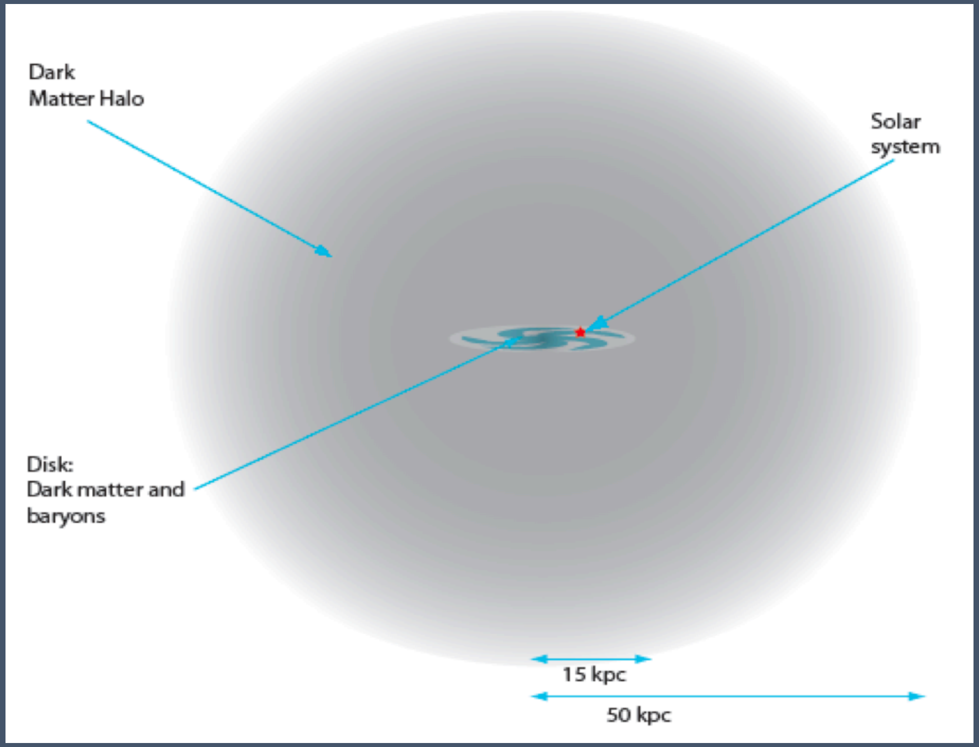
Non-directional WIMP search

- Observable: excess count rate over predicted BG in signal region
- Requires ultra-clean detectors & precise understanding of remaining backgrounds
- Single-scattering neutrons produce identical events to WIMPs



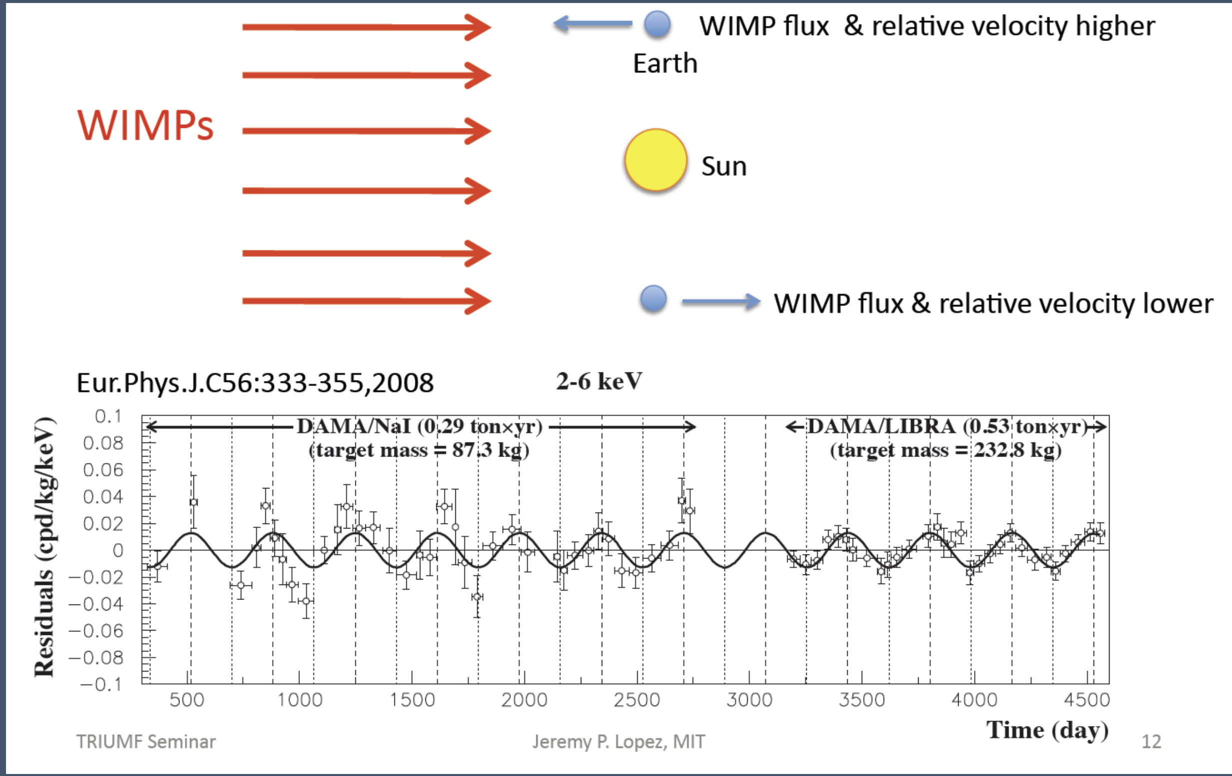
The WIMP Wind





- ~220 km / s
- blows from CYGNUS
- provides two additional WIMP signatures…

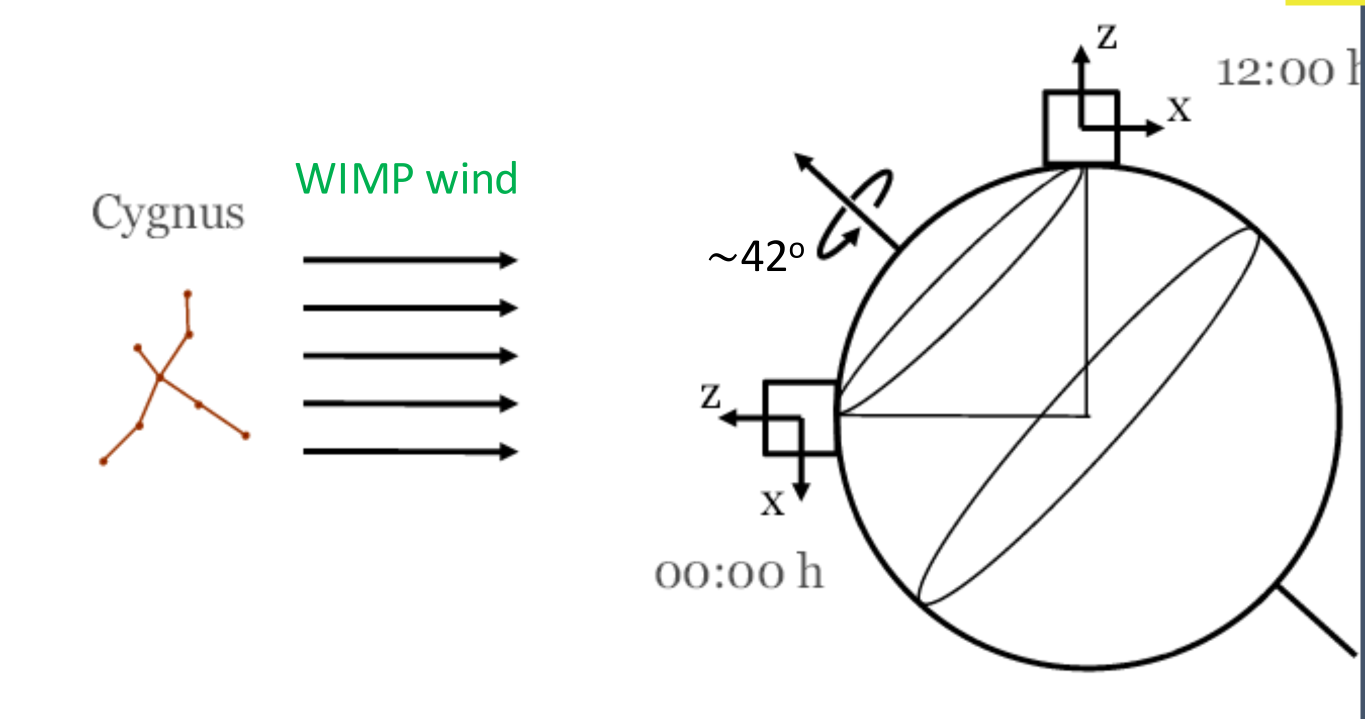
Annual Rate Modulation



- ***due to motion of earth around sun***
- ***%-level effect***
- requires thousands of signal events, and %-level control of BGs and gain

Diurnal (Daily) Directional Oscillation

Spergel PRD 37,1353 (1988)

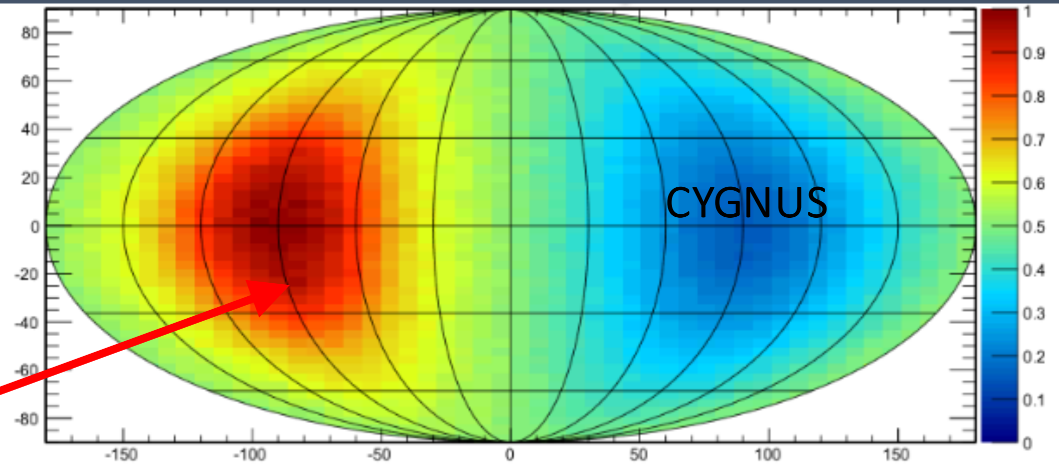


- oscillation of the mean recoil direction, due to rotation of earth
- order 1 effect
- oscillation period = sidereal day ≠ solar day
- no known background with this signature

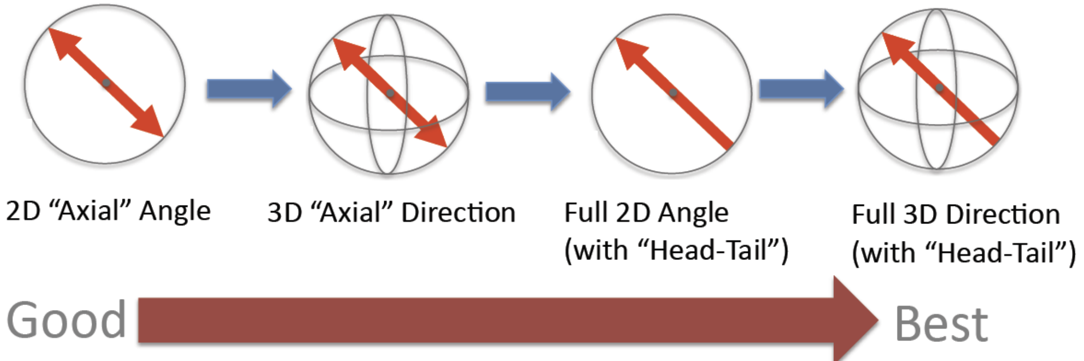
The Galactic Dipole

- The diurnal directional oscillation is equivalent to a dipole in galactic coordinates
- Recoils Point away from constellation CYGNUS
- Need ~10 3D vector events to reject isotropy.

Physics Reports 627 (2016)

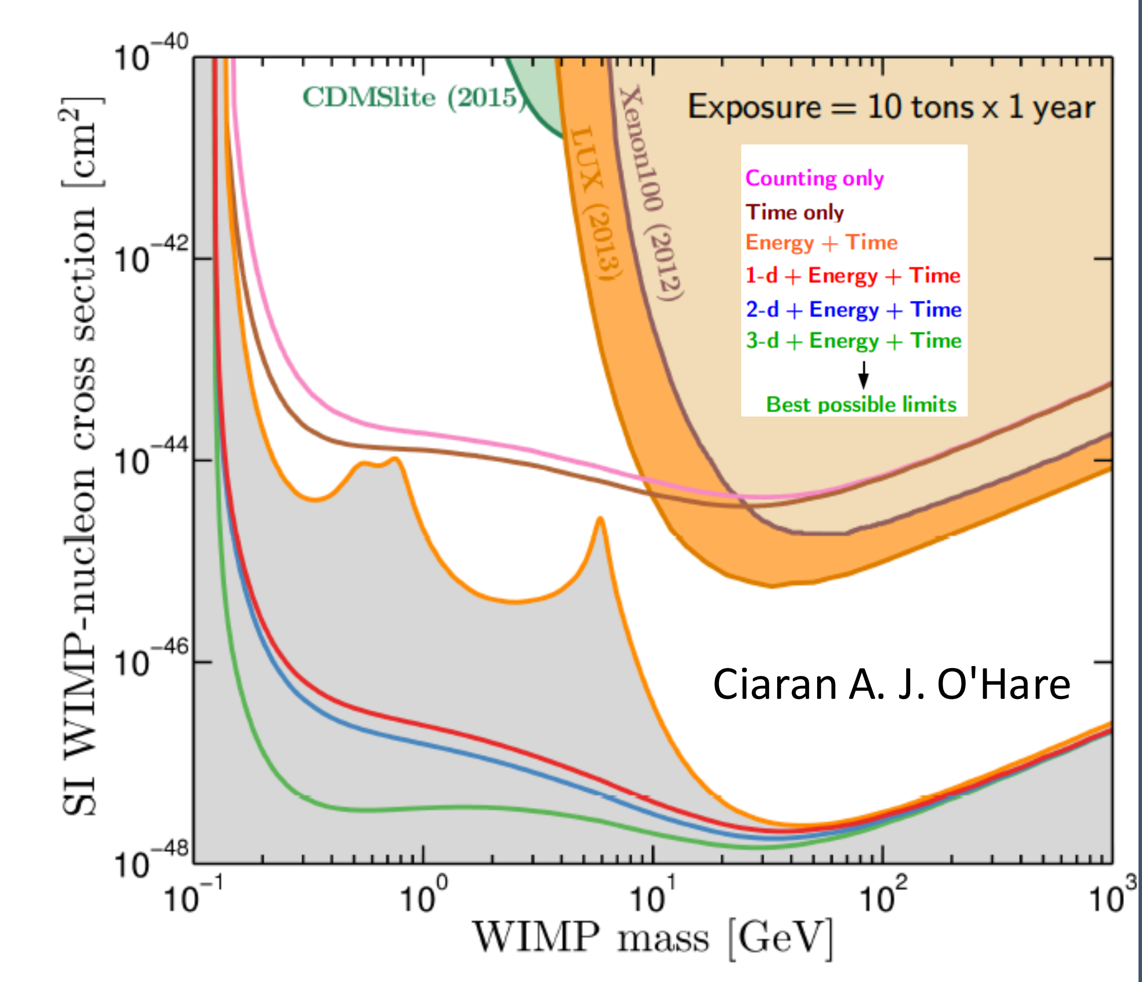


Sky map in galactic coordinates of recoils from 100 GeV WIMPs on ^{19}F, E>50 keV



Galactic dipole: - strongest predicted direct detection signature
- can unambiguously demonstrate cosmological origin of signal

Penetrating the neutrino floor



Readout strategies for directional dark matter detection beyond the neutrino background
[Ciaran A. J. O'Hare](), [Anne M. Green](), [Julien Billard](), [Enectali Figueroa-Feliciano](), [Louis E. Strigari]()

- Directionality significantly enhances the DM sensitivity below neutrino floor
  - 3D again "best"
- But note:
  - True Figure of Merit: sensitivity / unit cost
  - A realistic detector has strongly energy-dependent directionality. This was not considered in past studies.

Technological Approaches

Achieving Directionality

- *Detectors that reconstruct the recoil trajectory*
  - *Gas-based TPCs*
  - *Nuclear Emulsions*

  See next two talks

  - *Crystal defect spectroscopy*
  - *DNA strand detector*
  - *Planar targets (graphene)*
- *Detectors that indirectly determine the recoil direction*
  - *Anisotropic scintillators*
  - *Columnar recombination*
  - *Carbon nanotubes*

- Event-by-event recoil tracking in condensed matter is hard, but not impossible

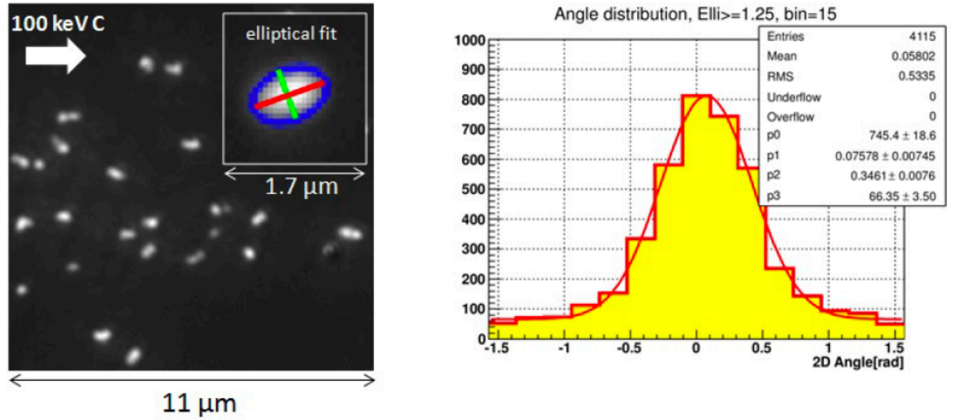


Figure 24: Left: Optical microscope image of 100 keV C ion tracks. Right: The corresponding distribution of major axis orientation determined from elliptical shape fitting for events whose ratio of lengths of major and minor axes exceeds 1.25.

Physics Reports 662 (2016)

Prototypes and Experiments (list is probably not comprehensive!)

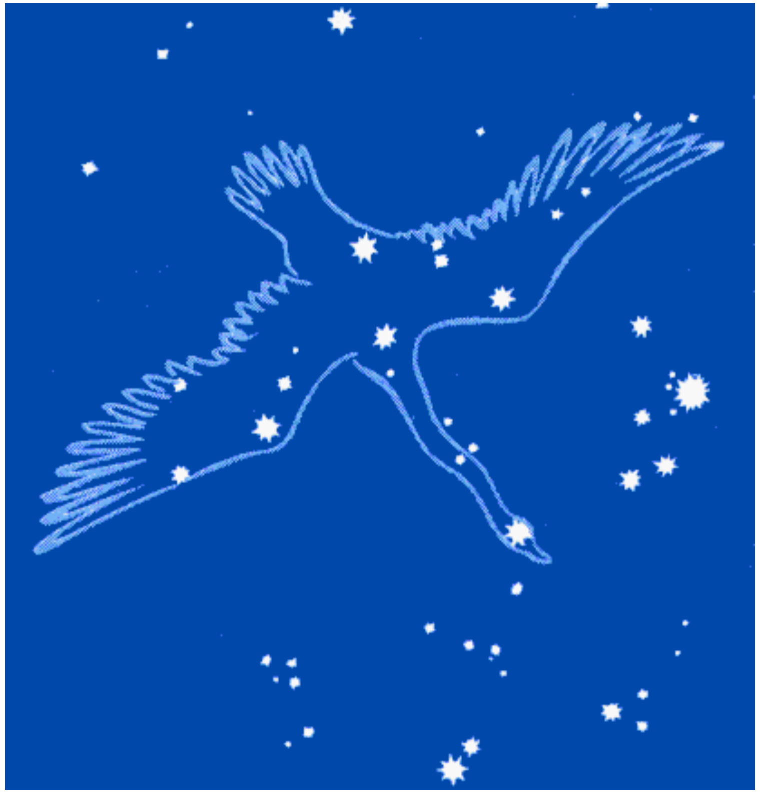
Name	Technology	Directionality	Status
NEWAGE	Gas TPC, strip readout	3d	Running underground
DRIFT	Gas TPC, NID, wire readout	1.5d	Running underground
MIMAC	Gas TPC, strip readout	3d	Ran underground, scaling up
DMTPC	Gas TPC, optical readout	2d	Ran underground, scaled up, stopped
D^3 / Hawaii readout R&D	Gas TPC, pixel readout	3d	Prototypes evaluated, ran above-ground
New Mexico readout R&D	Gas TPC, NID, optical readout	2d	Prototypes evaluated
LEMON, ORANGE, INITIUM, CYGNO	Gas TPCs, CMOS + PMT optical readout	3d	Prototypes evaluated, funded to scale up
NEWSdm	Nuclear Emulsions	2d	Prototyping / going underground
PTOLEMY	Graphene	2d	Prototyping / going underground

All directional that have set limits use <=1m^3 gas TPCs
NEWAGE: best limit using directionality
DRIFT: best limit with a directional detector

CYGNUS

The CYGNUS Proto-Collaboration

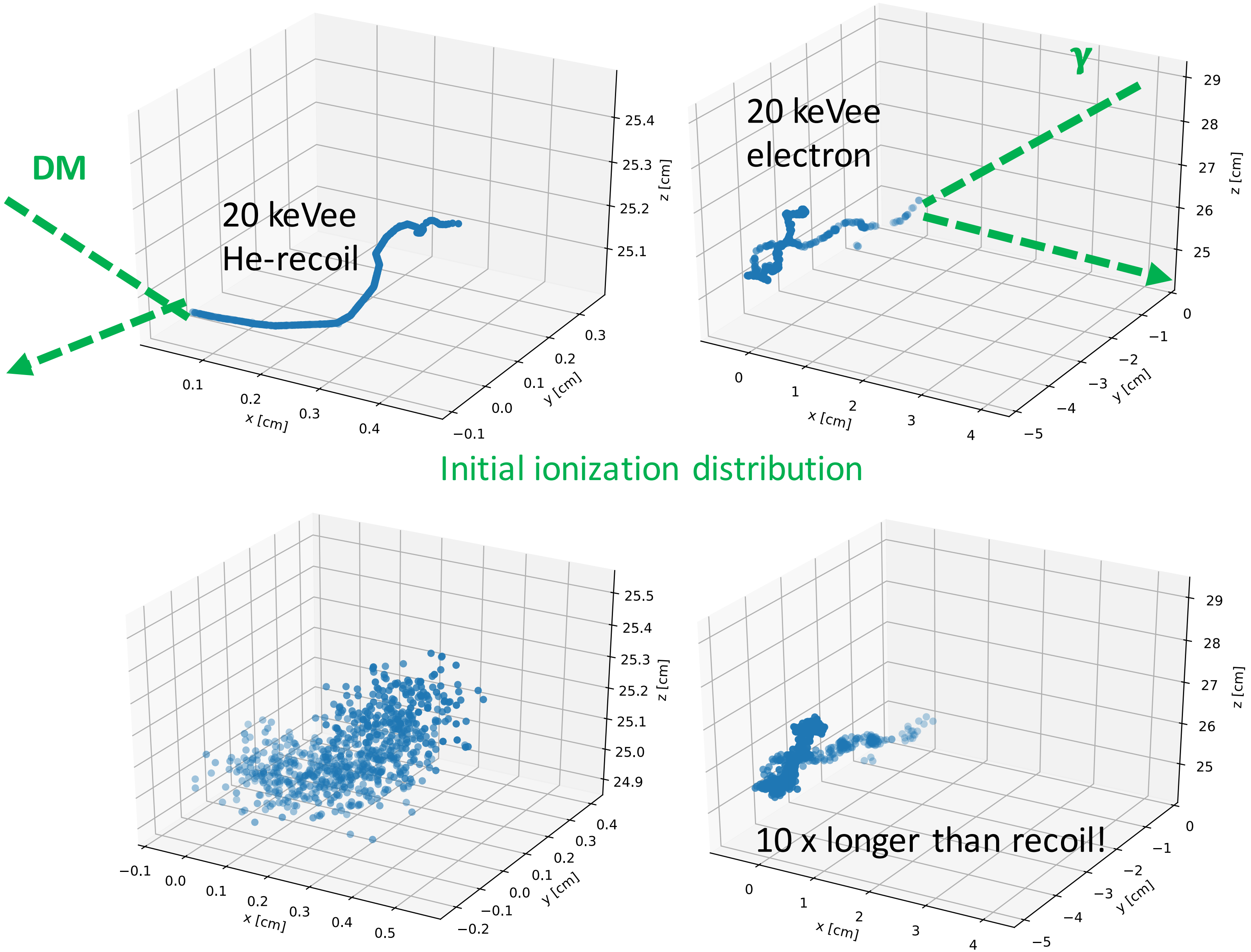
- Recently, many of the groups working on directional dark matter detection formed CYNUS
- 45 signed members from the US, UK, Japan, Italy, Spain, China, Australia
- Steering group:
  - Neil Spooner (Sheffield, UK)
  - Sven Vahsen (Hawaii, USA)
  - Kentaro Miuchi (Kobe, Japan)
  - Elisabetta Baracchini (GSSI/INFN, Italy)
  - Elisabetta Barberio (Melbourne, Australia)



The dark matter wind is expected to come from the constellation Cygnus.

The main idea

- Direct DM detection w/ Gas based TPCs
- Measure spatial ionization distribution resulting from nuclear recoils
- Advantages:
  - Axial Directionality
  - Head/tail
  - Background rejection
    - Particle ID
    - 3D fiducialization
- Technologically challenging, but now achievable via multiple technologies



charge cloud after 25 cm drift in gas TPC

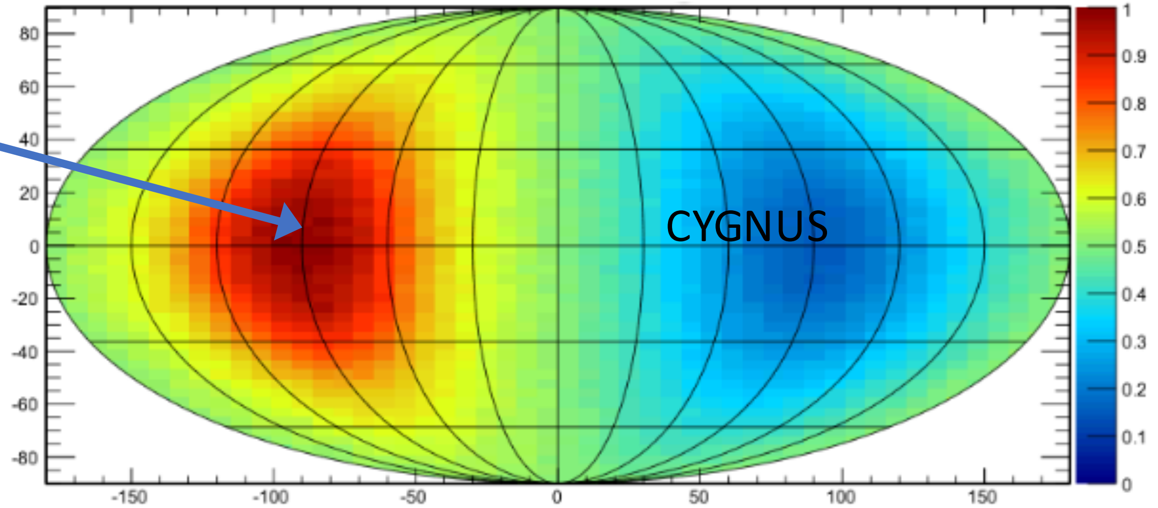
CYGNUS vision and long-term goal

> 1000 m^3 directional nuclear recoil detector capable of

exposure

- Setting competitive DM limits
- Observing galactic dipole ⇔ diurnal oscillation in lab
- Detecting solar neutrinos
- Efficiently penetrating the ν floor
- Measuring DM particle properties and physics
- Measuring Geoneutrinos
- WIMP astronomy

A review of the discovery reach of directional Dark Matter detection
[Physics Reports 627 (2016)]

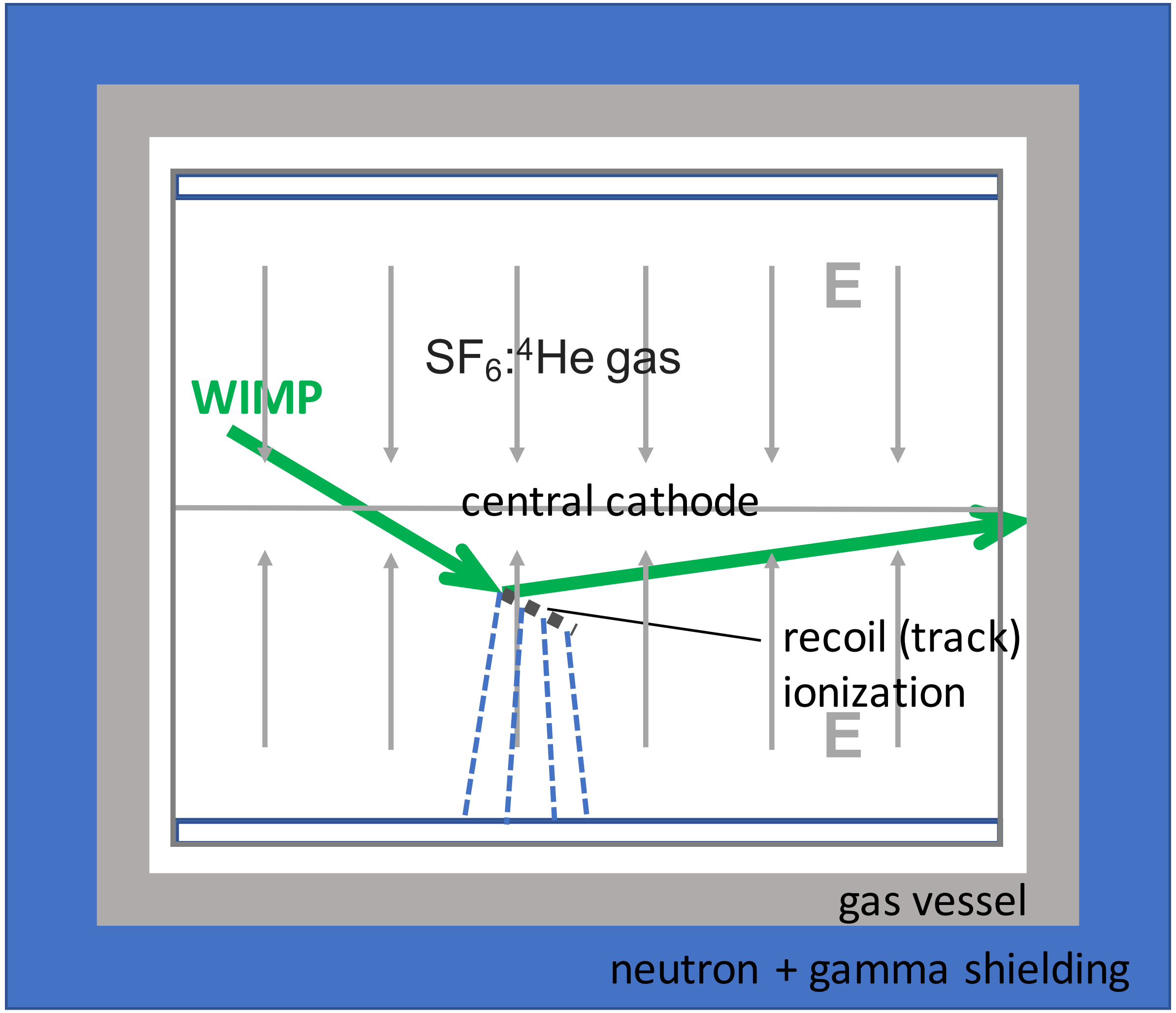


Sky map in galactic coordinates of recoils from 100 GeV WIMPs on ^{19}F, E>50 keV

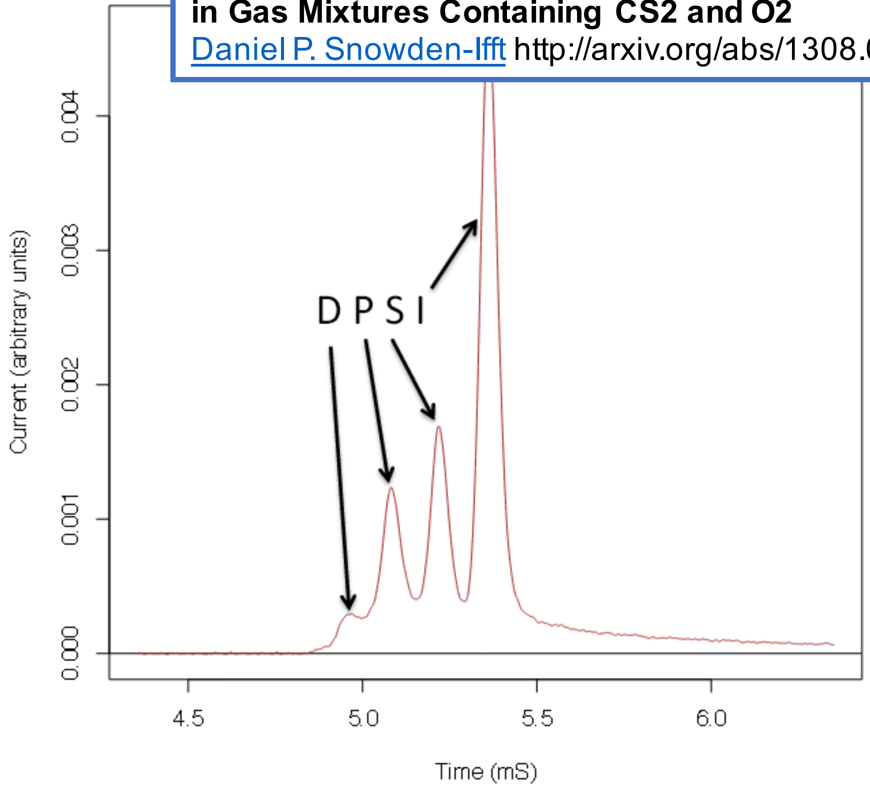
Galactic dipole: - strongest predicted direct detection signature
- unambiguous proof of cosmological origin

CYGNUS: Experimental Approach

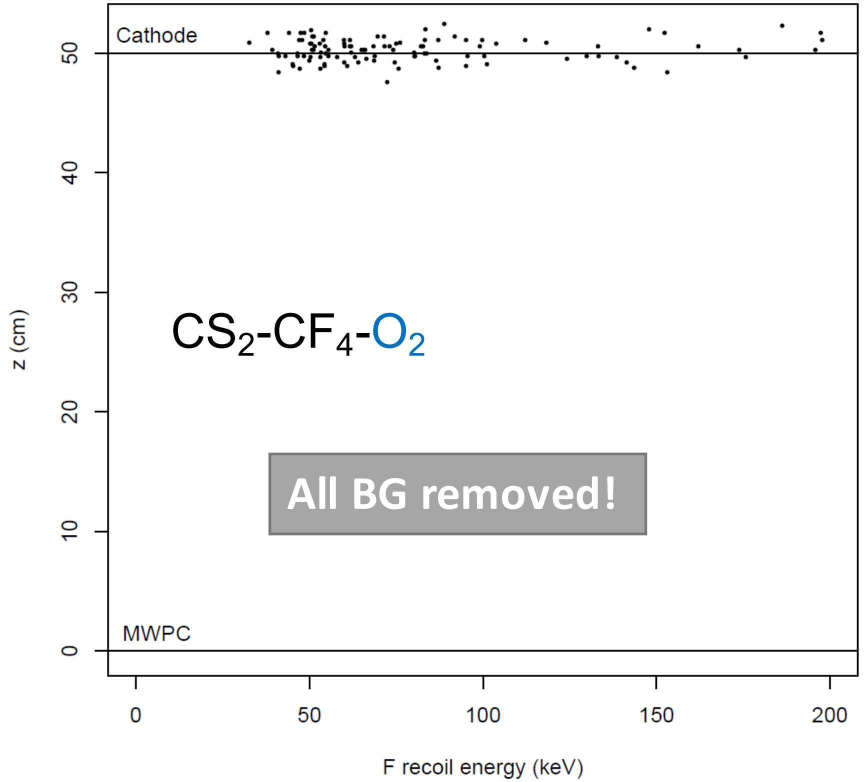
- Gas Time Projection Chamber
- Gas mixture: SF_6:^{4}He, p~1 atm
  - Possibility of switching between higher density (search mode) gas and lower density gas mixtures for (improved) directional confirmation of WIMP signal
- Reduced diffusion via negative Ion drift (SF_6 gas)
- Redundant 3D fiducialization
  - SF_6 minority carriers
  - charge cloud profile
- Helium target
  - Improved sensitivity to low mass WIMP
  - Longer recoil tracks, extending directionality to lower energies
- Multiple readout plane options have been successfully demonstrated



3D Fiducialization I: Minority Carriers



Discovery of Multiple, Ionization-Created Anions in Gas Mixtures Containing CS2 and O2
Daniel P. Snowden-Ifft http://arxiv.org/abs/1308.0354



CS_2-CF_4-O_2

All BG removed!

- Game changer for directional WIMP search via gas TPC
- Utilizes timing - works with any charge readout (1D,2D,3D)
- First discovered in CS_2
- Now also demonstrated in pure SF_6 & CF4 + SF_6 mixtures
- Incredibly lucky: SF_6 is also non-toxic, non-flammable, not corrosive, has gain, thermal diffusion, and is a good SD target (!)

The novel properties of SF_6 for directional dark matter experiments

N.S. Phan, R. Lafler, R.J. Lauer, E.R. Lee, D. Loomba, J.A.J. Matthews and E.H. Miller

Published 17 February 2017 • © 2017 IOP Publishing Ltd and Sissa Medialab srl

Journal of Instrumentation, Volume 12, February 2017

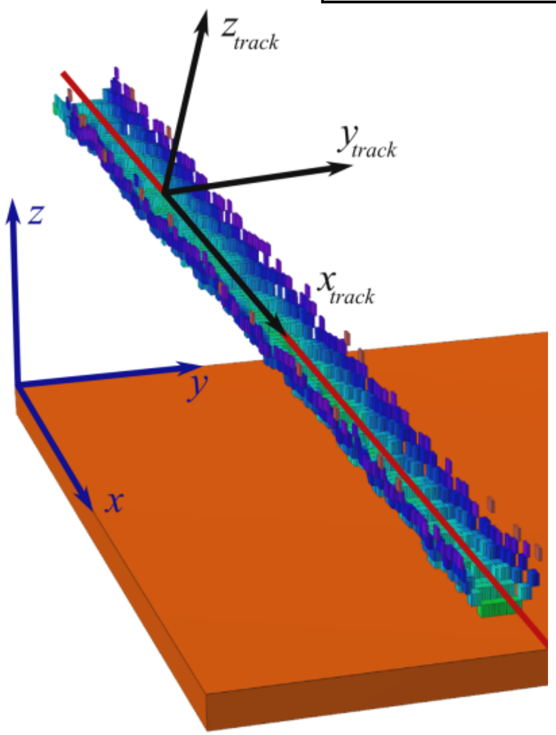
3D Fiducialization II: Charge Cloud Reconstruction

Nuclear Instruments and Methods in Physics Research A 789 (2015) 81–85

P.Lewis (U. Hawaii)

- Measuring charge-profile (*not width)* of track, enables accurate measurement of transverse diffusion, which depends on drift length

→ obtain absolute position in drift direction



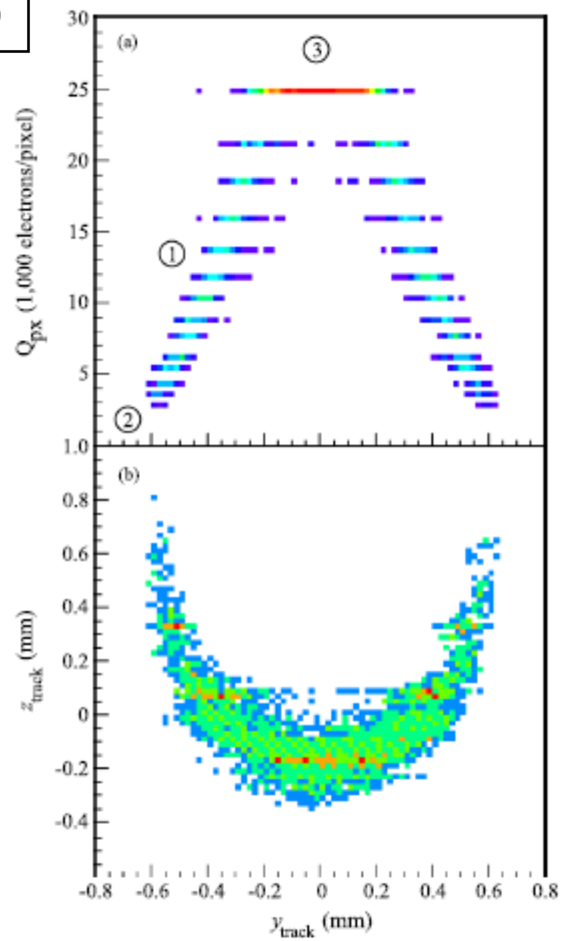


Fig. 2. Corrected pixel charge (Q_{px}) profile (a) and shell coordinates (b) for a single horizontal track from the near alpha source. Label 1 of the profile plot (a) corresponds to the Gaussian, label 2 to the threshold, and label 3 to the saturation regions of the profile. The U-shaped shell in plot (b) is very roughly the bottom half of the track in space, described in Section 2.1. These plots are two-dimensional histograms where the counts per bin are encoded by brightness: the outside points of each distribution (blue online) have the lowest count number, the center points (yellow and red online) have higher count numbers. (References to color apply to the web version of this article.)

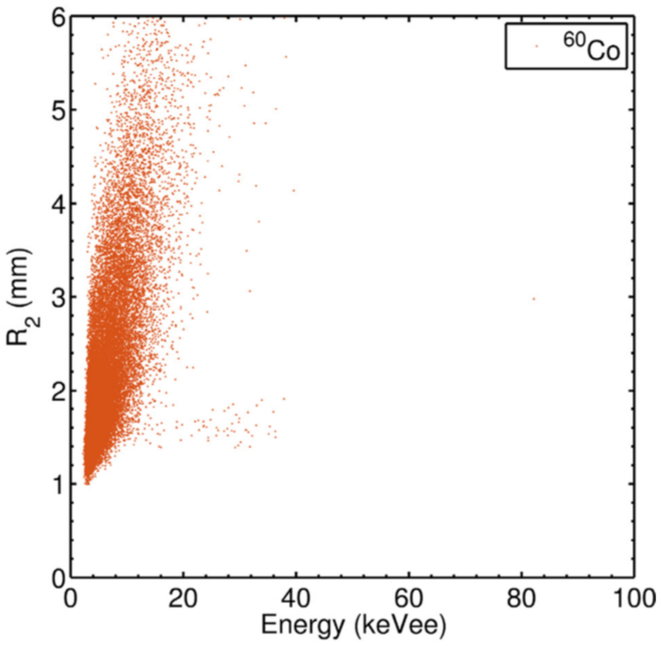
- Requires high resolution readout of charge density → only 2D, 3D
- However, should work with any gas
- Published version utilized “chopped” alphas, but has since been extended by grad student to also work with recoil events (unpublished)

2D electron rejection (experiment)

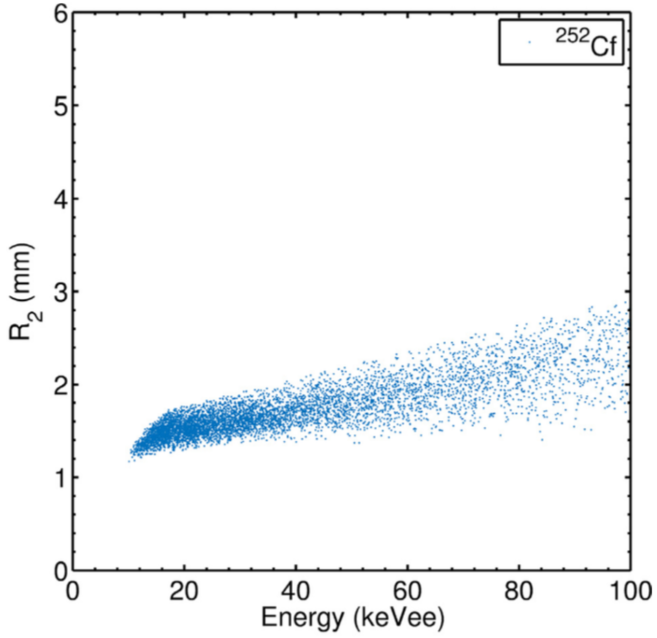
- On right: 2D optical readout in 100 torr CF_4
  - F versus electron recoils
  - $\sigma = 0.35$ mm readout resolution, incl. diffusion
  - Using range-energy signature, electron event rejection factor < 3.9 x 10^{-5} around 10 keVee
  - *It's a limit – all available electron events rejected*!
- Extrapolating to CYGNUS
  - 20 torr SF6 + 740 torr Helium: 50% longer tracks
  - 50 cm of thermal drift ($\sigma = 0.55$ mm): 50% higher

→expected same discrimination in CYGNUS

- Should improve with 3D charge *cloud tomography, i.e.*, going beyond range-energy signature.
- *Follow-up experimental work with 3D readout needed.*
- *Both directionality and BG rejection are strongly gas density dependent. Can operate in search mode (higher density) and confirmation mode (lower density)*



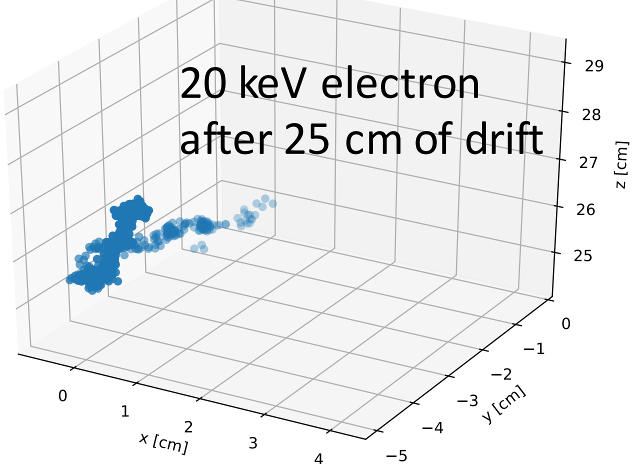
(b) ^{60}Co data post CCD cuts

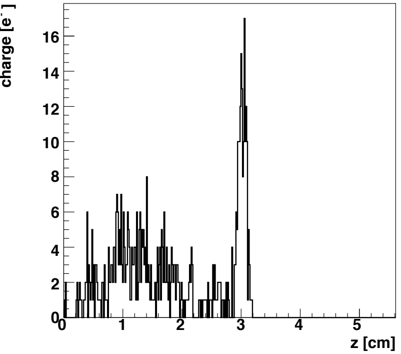


(b) ^{252}Cf data post selection cuts

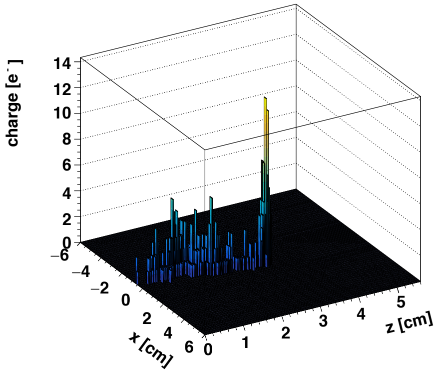
GEM-based TPC with CCD imaging for directional dark matter detection
N.S. Phan, et. al., Astroparticle Physics, 84 (2016)

Six types of TPC charge readouts

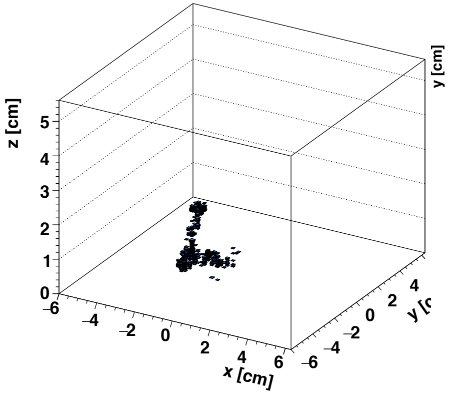




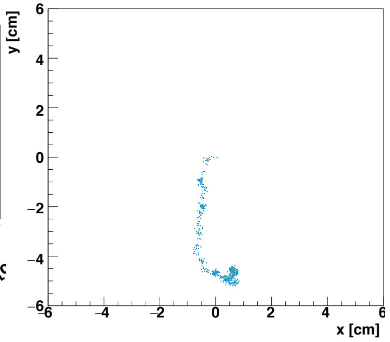
1D GEM



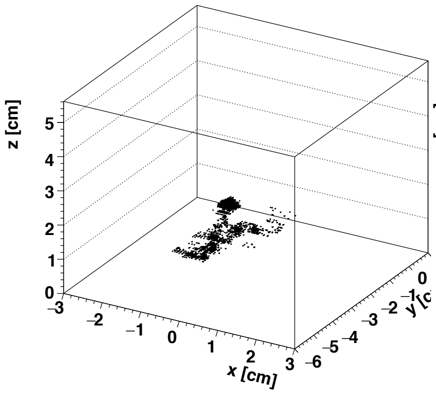
1.5 D: wires



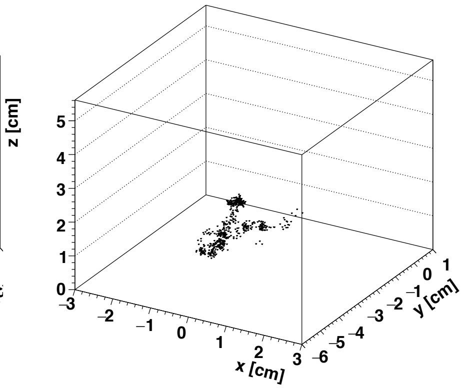
3D pads



2D optical



3D strips



3D pixels

Worse performance
Lower cost

Best compromise? Simulation study to find out

Better performance
Higher cost

Input Parameters: Diffusion, gain, etc

Gas mixture	SF_6	SF_6:^{4}He
Gas pressure [torr]	20	20:740
W [eV / ion pair] used in reconstruction	35.45	35.45
Transverse diffusion, σ_T [µm/$\sqrt{\text{cm}}$]	116.2	116.2
Longitudinal diffusion, σ_z [µm/$\sqrt{\text{cm}}$]	116.2	116.2
Drift velocity [µm/µs]	140	140
z binning (assume 1MHz sampling) [μm]	140	140
Mean avalanche gain	9000	9000

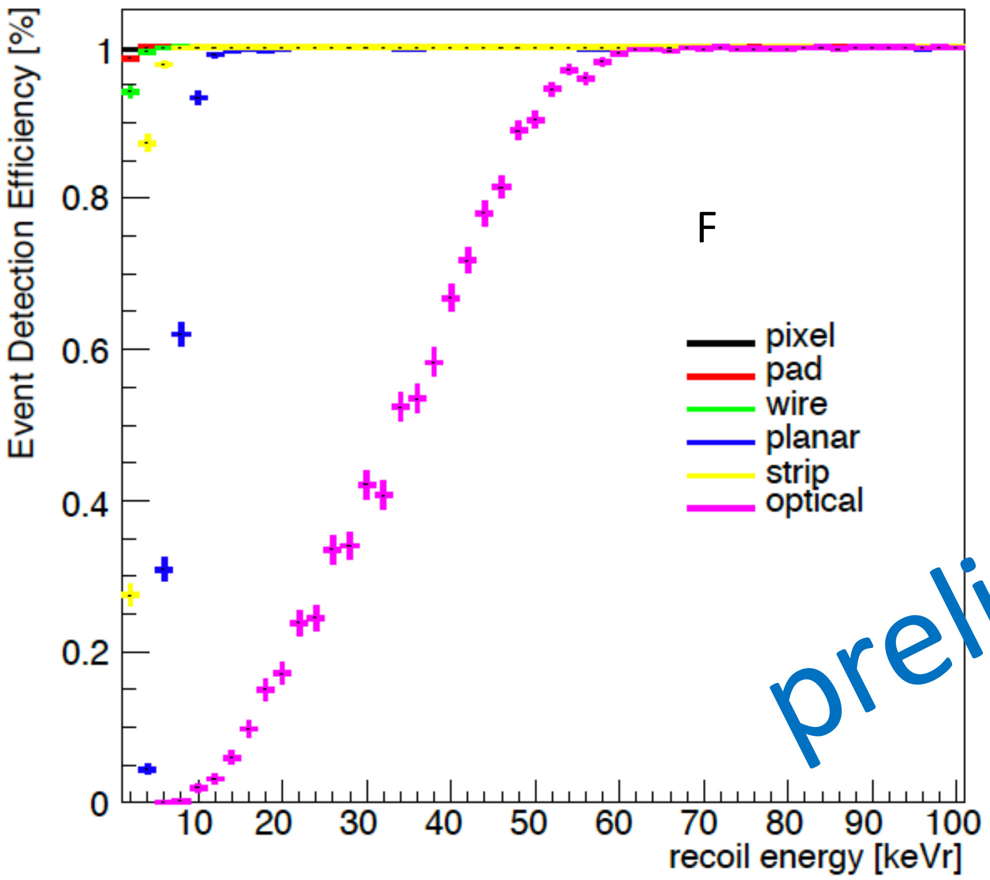
Input Parameters: Readouts

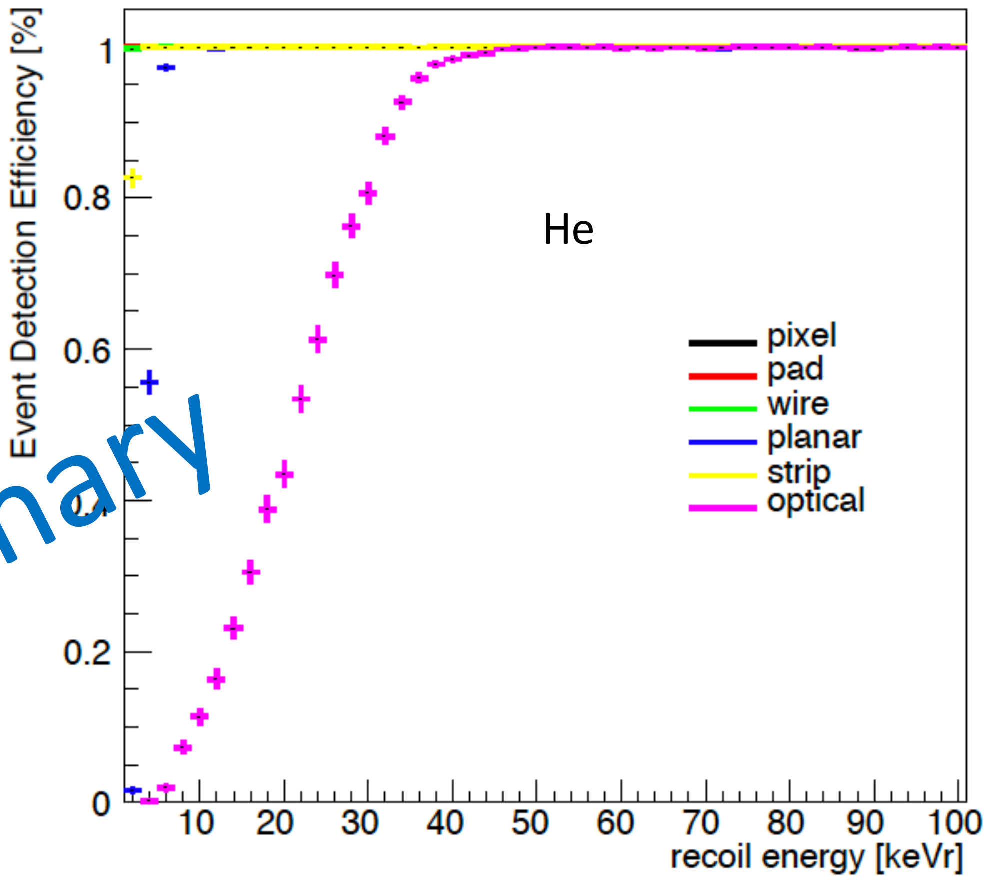
TABLE III. TPC readout technologies being simulated, and readout-specific parameters that are used in the simulation of each. The capacitance listed is that for a single detector element, which determines the noise level. For the optical readout, a loss factor of 1000 is used to account for photon yield, geometric optical acceptance, optical transparency, and quantum efficiency.

Readout type	Dimensionality	Segmentation $(x \times y)$	Capacitance [pF]	σ_{noise} in 1 μs $[e^-]$	Threshold/σ_{noise}
planar	1d (z)	10 cm $\times$ 10 cm	3000	18000	3.09
wire	2d (yz)	1 m wires, 2 mm pitch		800	4.11
pad	1d (z)	3 mm $\times$ 3 mm		375	4.77
CCD	2d (xy)	200 μm $\times$ 200 μm	n/a	20 photons	5.77
strip	3d (xyz)	1 m strips, 200 μm pitch	500	2800	4.61
pixel	3d (xyz)	200 μm $\times$ 200 μm	0.012 - 0.200	42	5.77

Results: Detection efficiency

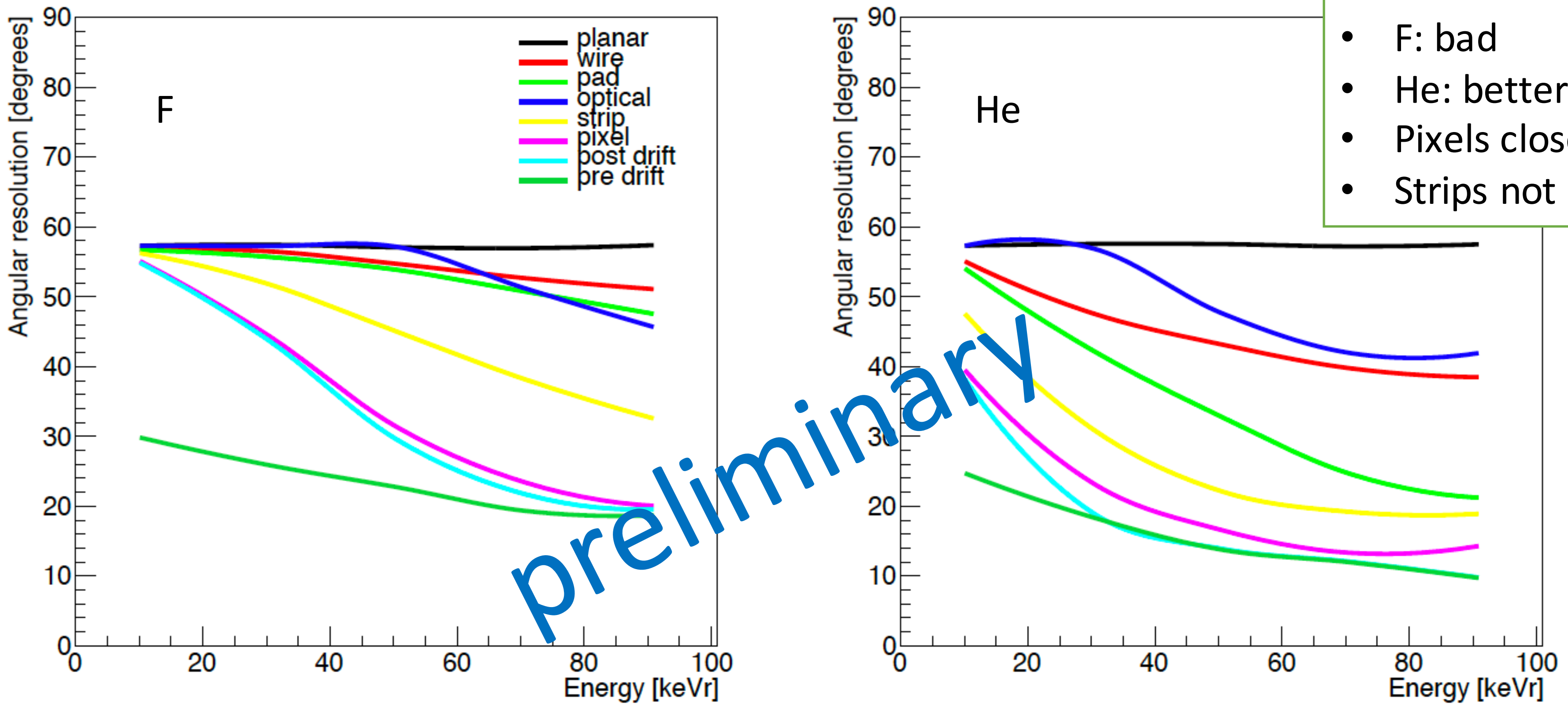
Ok, but NID *gain on low side*
CCD and planar suffers from this





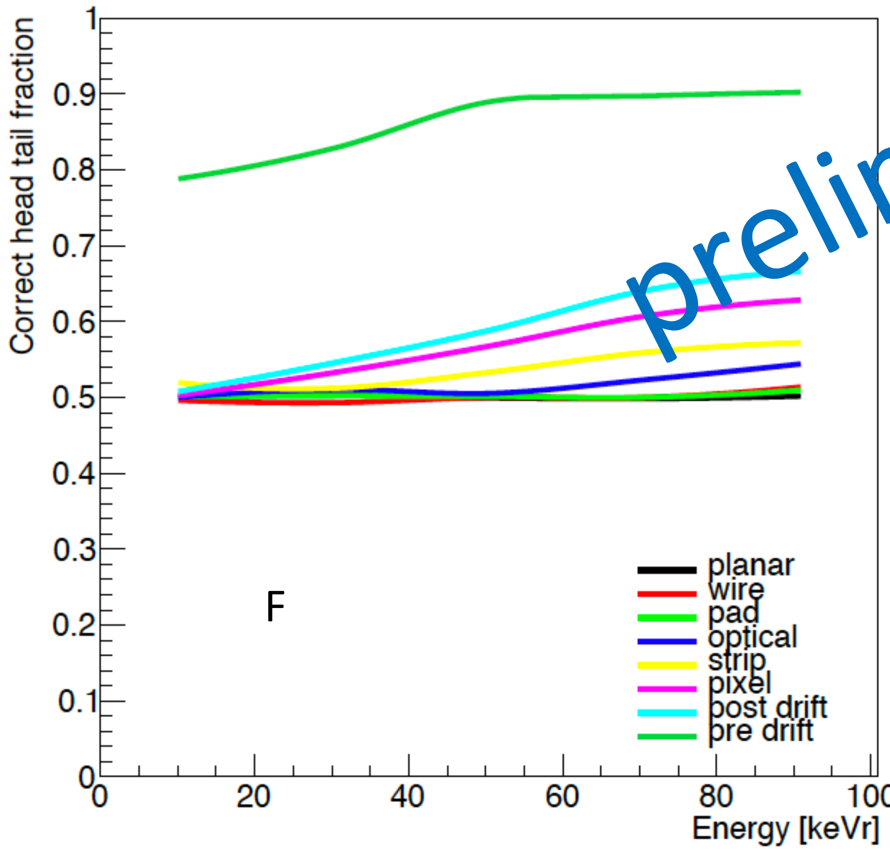
preliminary

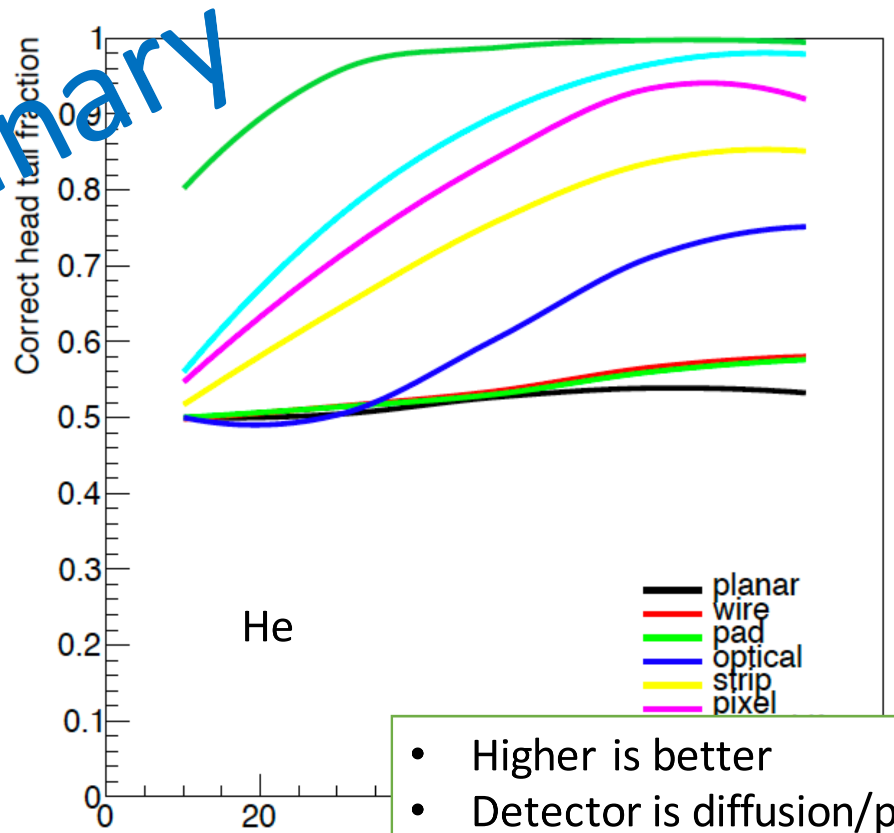
Results: Axial Vector Angular resolution



- Lower is better
- Detector is pressure/diffusion limited
- F: bad
- He: better
- Pixels close to optimal
- Strips not bad

Results: Head/tail recognition efficiency





- Higher is better
- Detector is diffusion/pressure limited
    - especially for F
    - He: better
- *only pixels, strip, and CCD do OK*

Results: 3D Electron Rejection Factors

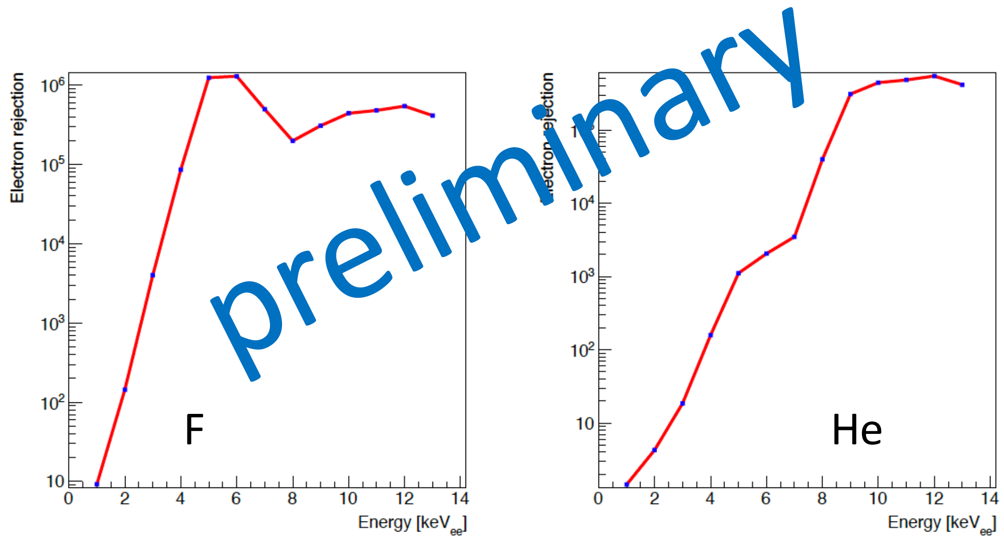


FIG. 19. Electron rejection factors versus electron-equivalent observed energy for fluorine recoils (left) and helium recoils (right), before diffusion of drift charge, utilizing the fitted-track length versus energy signature only. For each energy bin, a variable minimum track length that retains 50% of the nuclear recoils is applied. The plateaus in the rejection curves seen above 7 keV$_{ee}$(fluorine) and 10 keV$_{ee}$(helium) should be considered lower limits - all simulated electron events were rejected.

- Nice!
- Gets somewhat worse after diffusion
- Algorithm can be improved

Final Result: Sensitivity per Unit Cost

TABLE IV. Summary of main performance parameters and estimated detector cost at equal directional sensitivity, for the simulated TPC charge readout technologies. Results assume a 20:740 He:SF_6 gas mixture at 760 torr at room temperature, gain of 9000, charge diffusion of 116 $\mu m/\sqrt{cm}$, and 50 cm drift length.

Charge readout	pre diff.	post diff.	pixels	strips	pads	wires	planar	CCD
event detection threshold (F) [keVr]	0	0	< 2	3	< 2	<2	8	35
event detection threshold (He) [keVr]	0	0	< 2	3	< 2	< 2	8	35
directionality threshold (F) [keVr]	16	30	30	80	> 100	100	> 100	> 100
directionality threshold (He) [keVr]	8	10	10	20	45	25	> 100	> 100
electron rejection threshold (F)[keVee]	1	4	-	-	-	-	-	-
electron rejection threshold (He)[keVee]	2.5	4.5	-	-	-	-	-	-
exp. penalty, exclude isotropy, 10 GeV WIMPs (He)	9	38	53	182	1512	319	$>$10k	$>$10k
exp. penalty, exclude neutrinos, 10 GeV WIMPs (He)	9	31	48	157	4897	857	$>$10k	$>$10k
exp. penalty, exclude isotropy, 100 GeV WIMPs (He)	7	23	53	107	1658	1570	$>$10k	$>$10k
exp. penalty, exclude neutrinos, 100 GeV WIMPs (He)	7	28	71	107	1274	255	$>$10k	$>$10k
average relative exposure penalty factor	n/a	n/a	1	2.46	41.5	13.3	$>$178	$>$ 178
approx. cost per unit readout area [US $/$m^2$]	n/a	n/a	400k	15k	5k	5k	0.050k	60k
total readout cost (US $)	n/a	n/a	800M	73M	415M	133M	$>$178M	$>$213M
total volume cost (US $)	n/a	n/a	5M	12M	207M	67M	$>$9B	$>$ 9B
total detector cost, constant WIMP sensitivity (US $)	n/a	n/a	805M	86M	663M	200M	$>$9B	$>$ 9B
total detector cost, 1000 m^3 volume (US $)	n/a	n/a	805M	35M	15M	15M	$>$5.1M	$>$ 125M

preliminary

Conclusion/recommendation: build a 1000 m^3 detector with *strip* readout for $35M

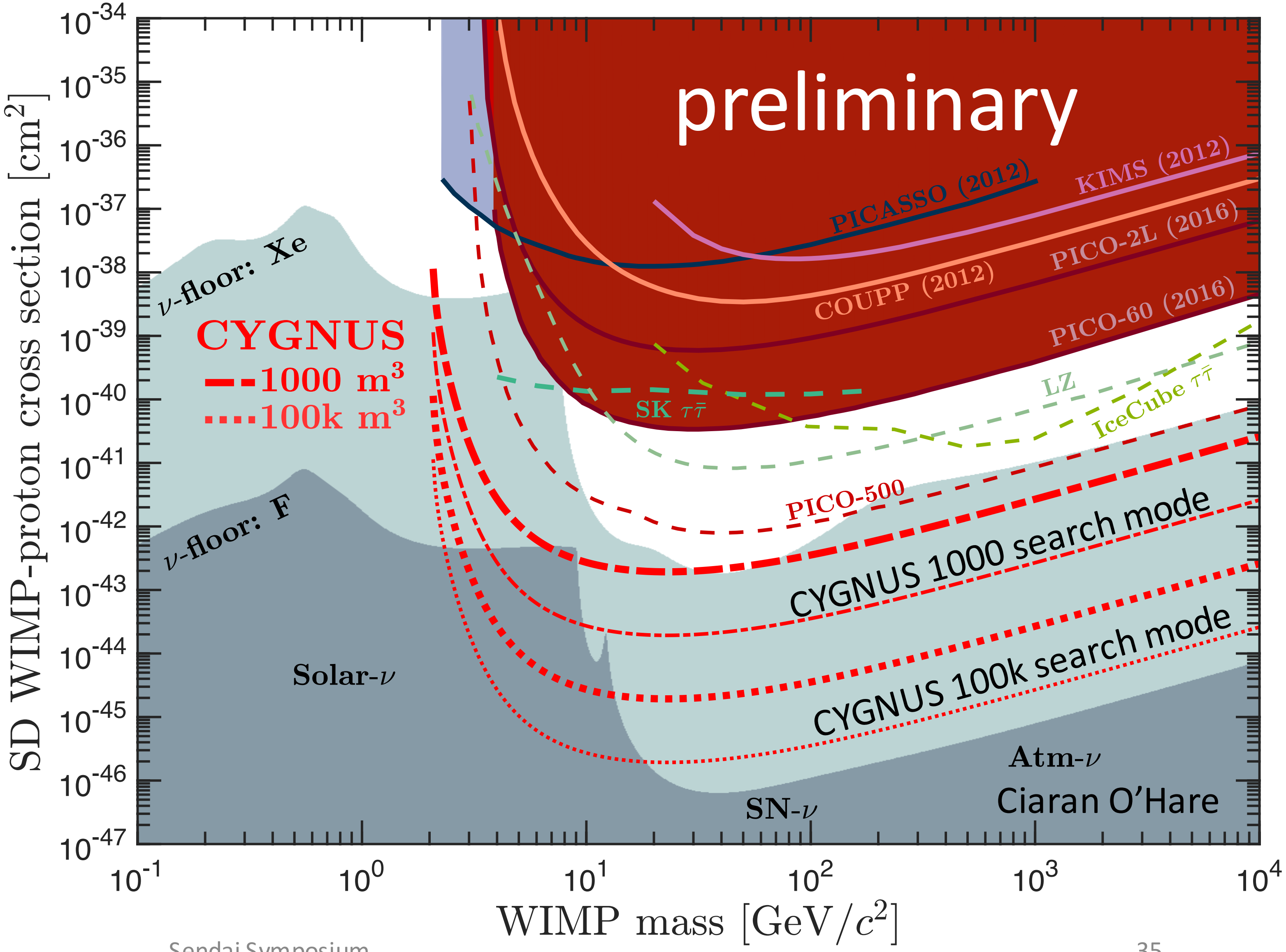
CYGNUS SD Sensitivity

CYGNUS 1000: 10m x 10m x 10m
CYGNUS 100k: ~2 x DUNE target volume

- Assumptions
  - 3 years of running time
  - 3 keVr F threshold
  - 1 keVr He threshold
  - Directional mode:

    20 torr SF_6
    740 torr 4-He
  - Search mode:

    200 torr SF_6
    740 torr 4-He
- Should see solar ν events
- Discoveries can be investigated in directional mode

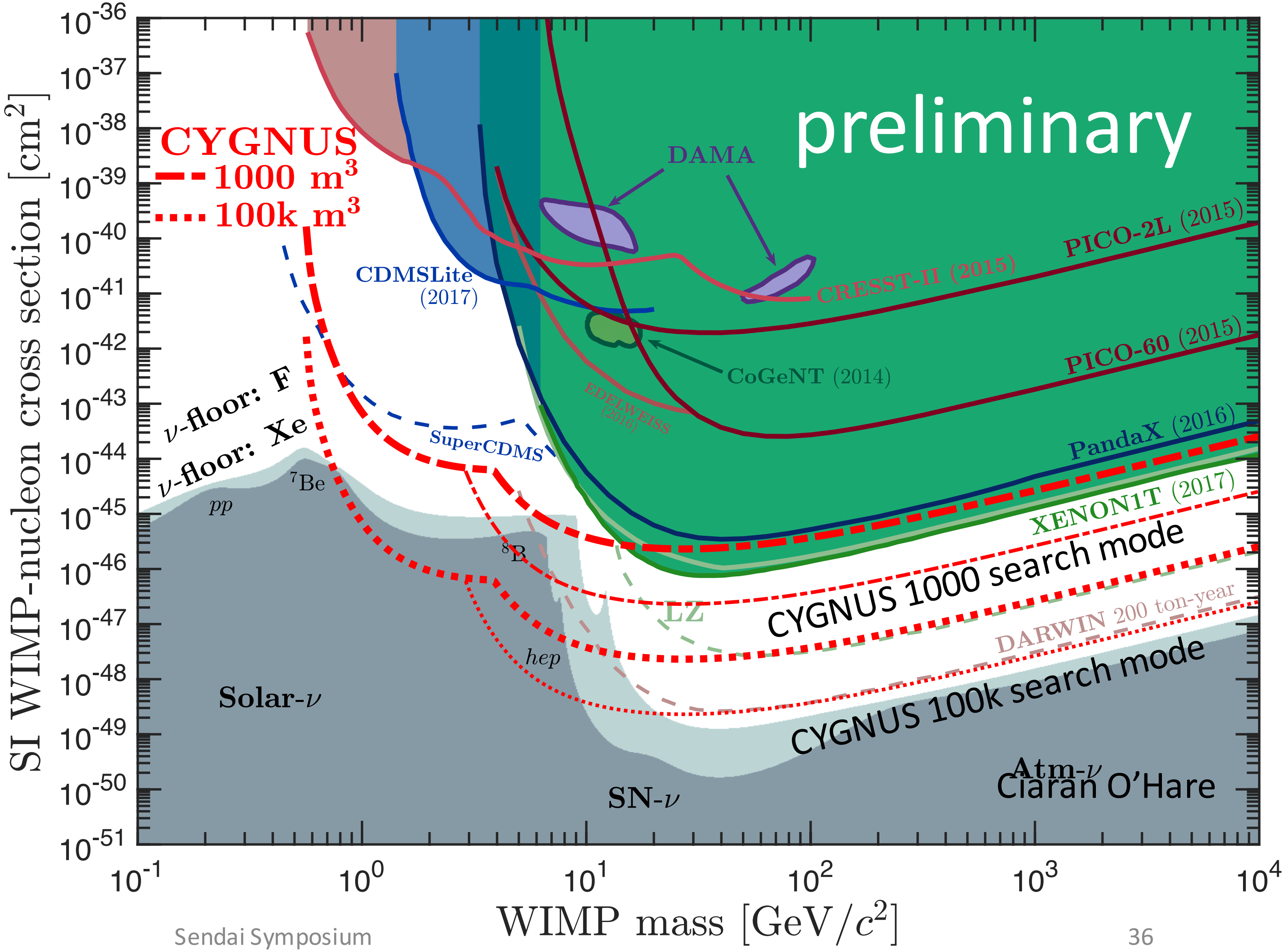


CYGNUS SI Sensitivity

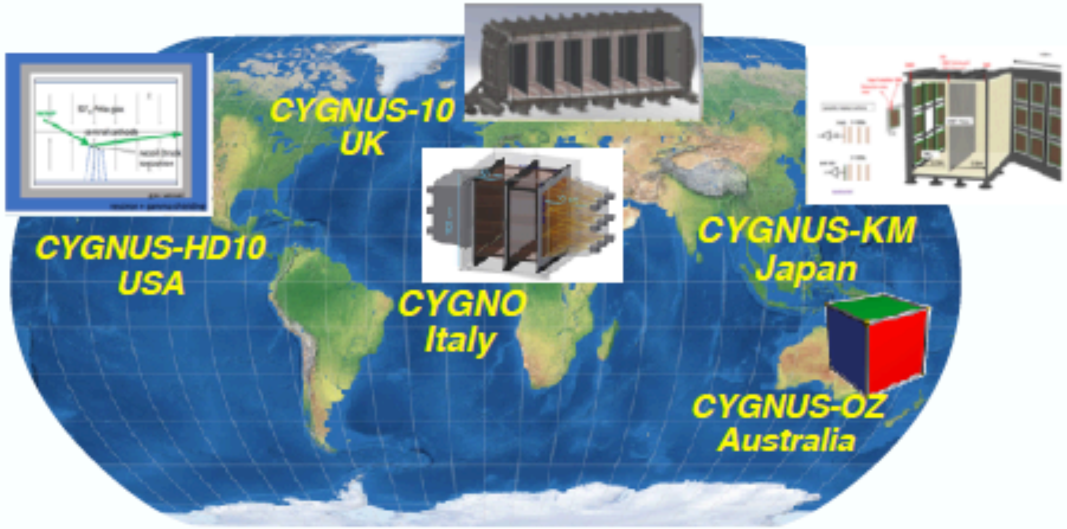
- Assumptions
  - 3 years of running time
  - 3 keVr F threshold
  - 1 keVr He threshold
  - Directional mode:

    20 torr SF_6
    740 torr 4-He
  - Search mode:

    200 torr SF_6
    740 torr 4-He
- Should see solar ν events
- Discoveries can be investigated in directional mode



CYGNUS-TPC vision



A multi-site Galactic Nuclear Recoil Observatory at the ton-scale to probe Dark Matter below the Neutrino Floor and measure ^{8}B solar Neutrinos <u>with directionality</u>

Since fall 2016

- Helium/Fluorine-based gaseous TPC for sensitivity to low mass WIMP region for both SI and SD couplings
- Goal of zero background operation after electron/gamma rejection and fiducialization at O(keV)
- Directional and gamma/electron rejection thresholds at O(keV)

Summary

- Many novel ideas for achieving directionality have been proposed and studied
- Much of the worldwide directional detection community merged into CYGNUS
- Work on strawman design of CYGNUS 1000 gas-TPC detector nearly complete
  - Competitive SI and SD sensitivity. Extends to low WIMP masses thanks to He
- CYGNUS 1000 would be the first step towards a large-scale, distributed recoil observatory, capable of
  - unambiguously demonstrating the cosmological origin of a putative WIMP signal
  - effectively penetrating the neutrino floor
  - eventually, WIMP astronomy
- Please join: Directional Detection Workshop in Roma (Italy) at Sapienza on June 24-25-26th 2019.