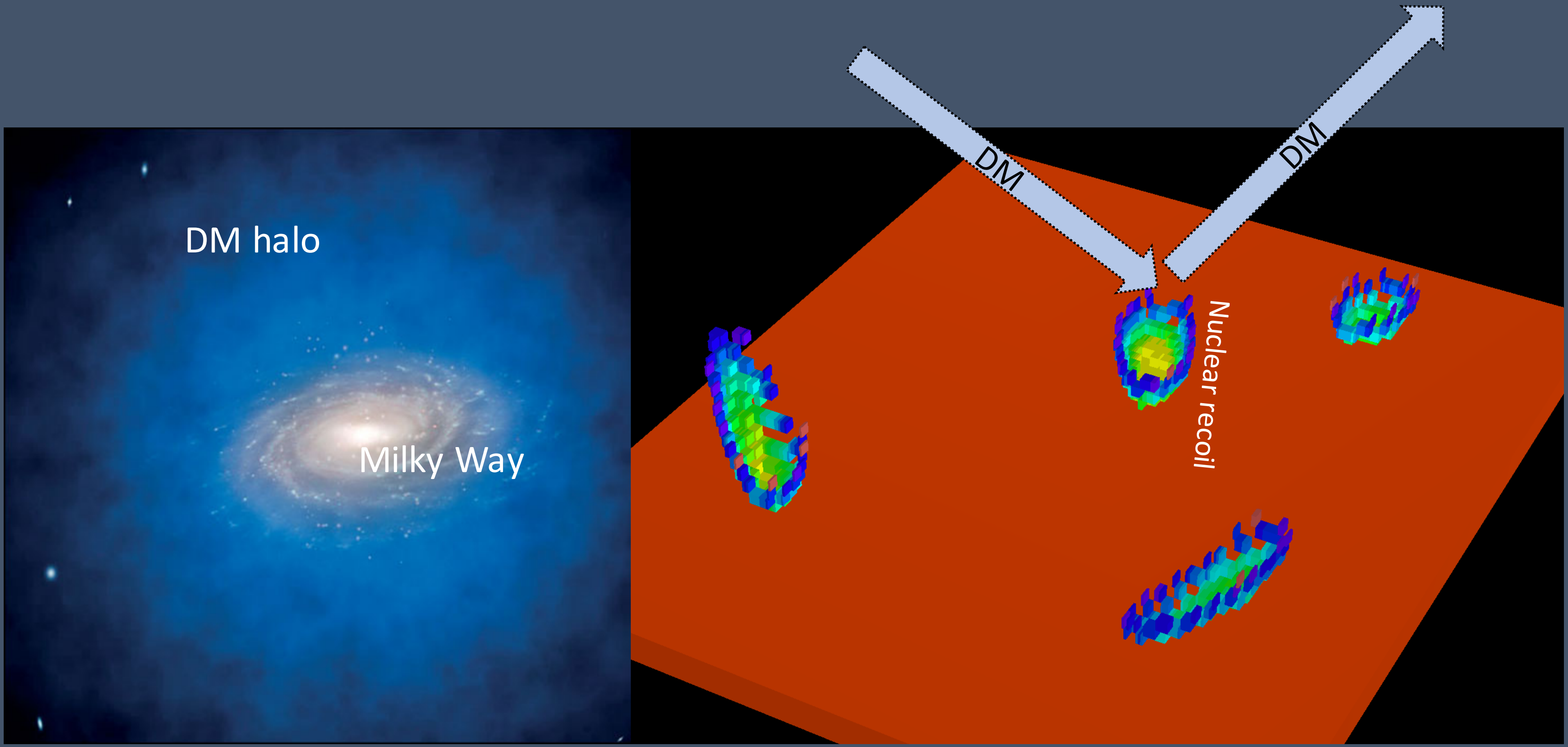
Status of the CYGNUS TPC Project



CYGNUS 2019, 7th Workshop on directional dark matter searches, Rome, Italy

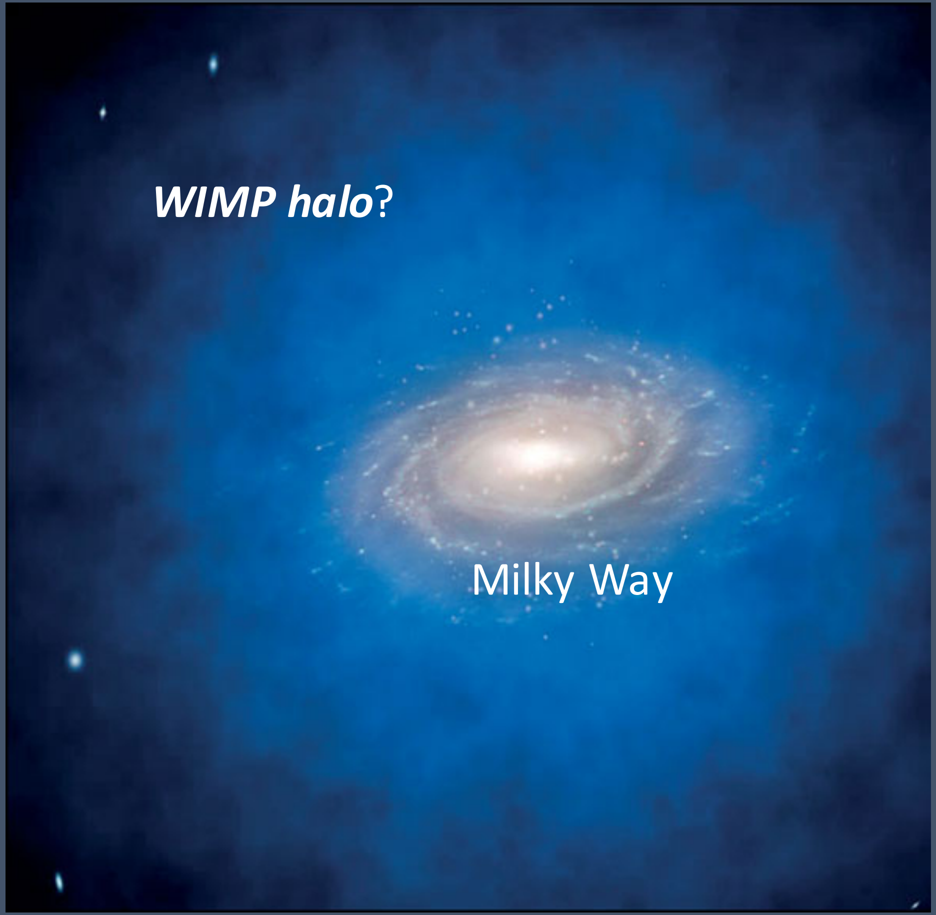
Sven Vahsen (University of Hawaii) for the CYGNUS proto-collaboration

Outline

- Challenges in direct DM searches
- Motivation for directional searches
- CYGNUS TPC project
- TPC Readouts comparison
- CYGNUS sites

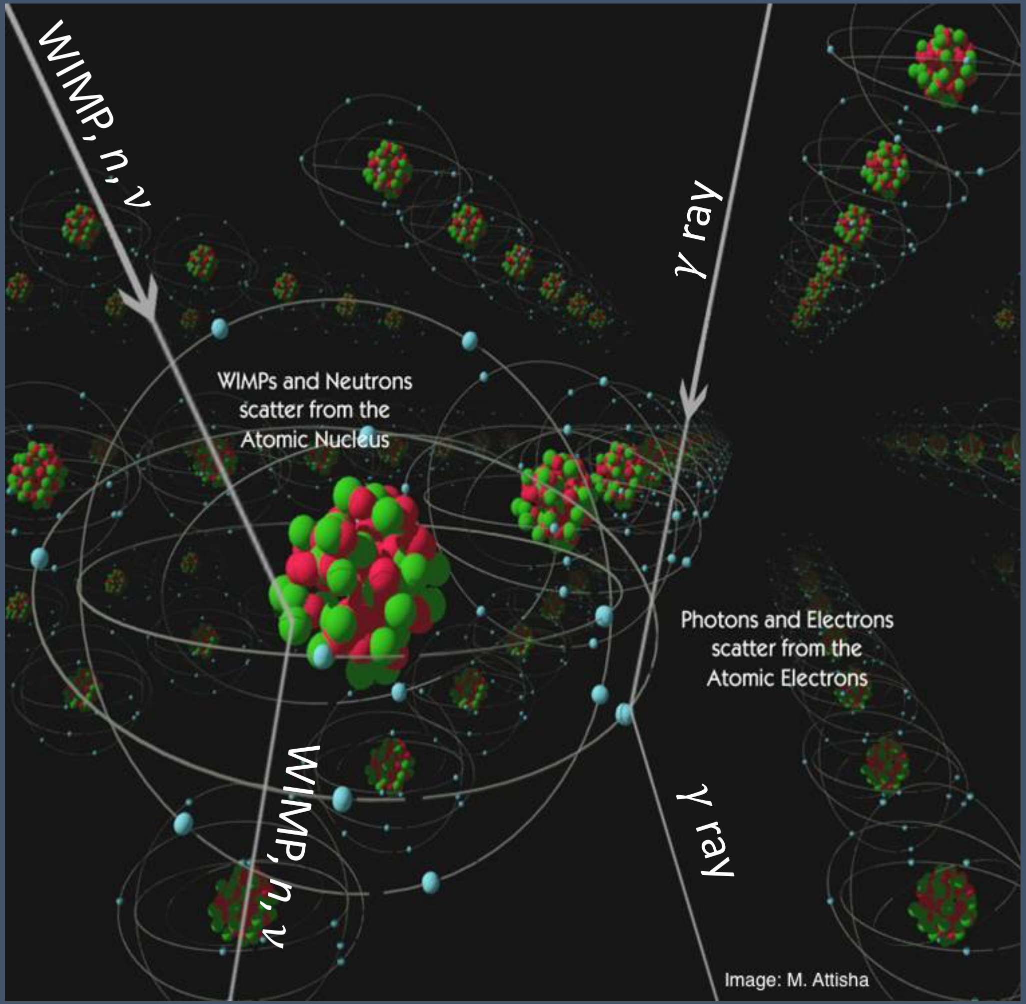
Do we live in a *WIMP halo*?

- We already know Dark Matter exists
- WIMPs are one hypothesis
- Goal of Direct DM Detection: answer
  - Does the local Milky Way DM halo contain WIMP-like particles?
  - What are their properties?
  - What is their local density and velocity distribution ?



Direction-sensitive experiments are ideally suited to answer these questions

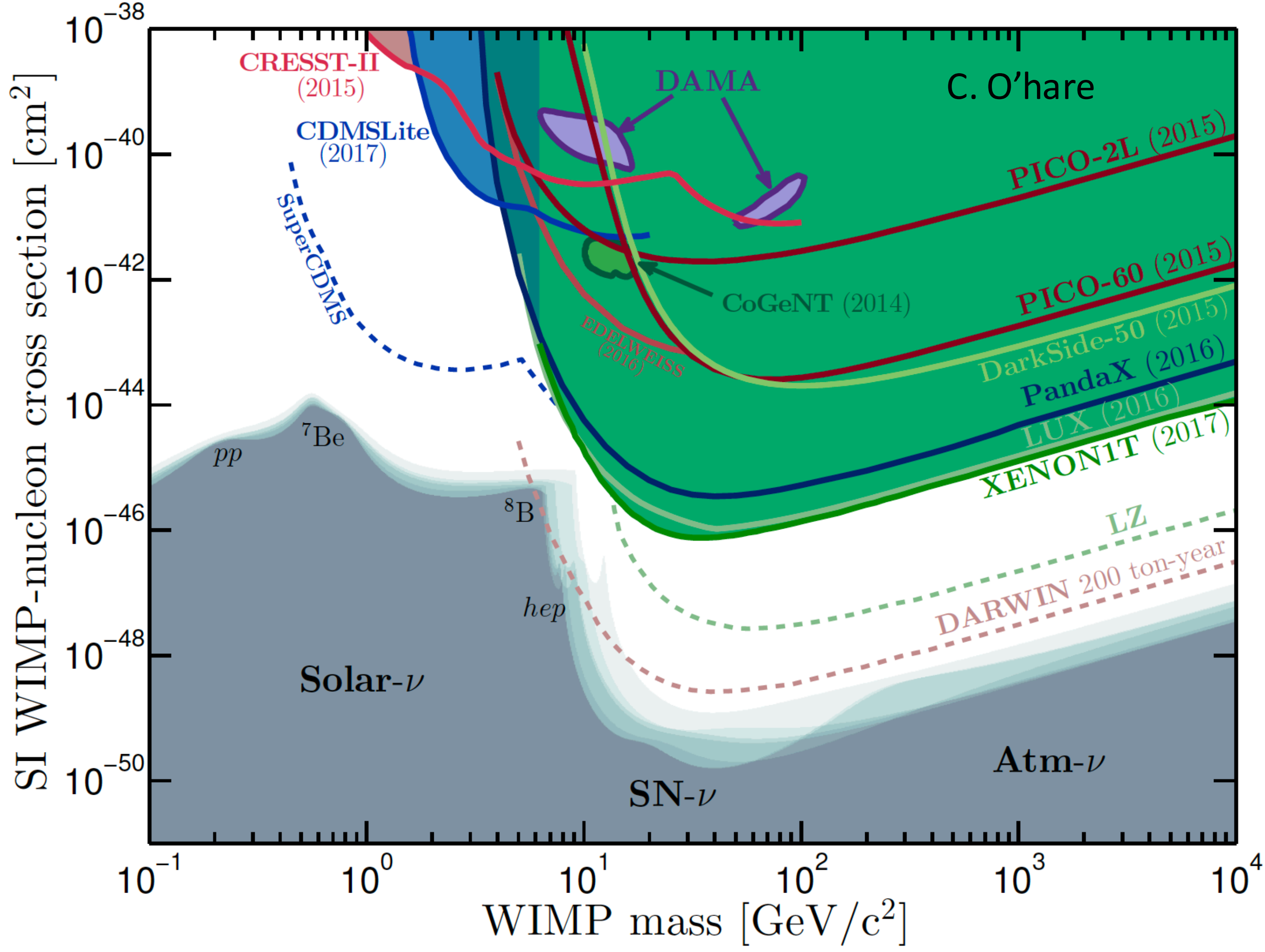
Experimental Challenges



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

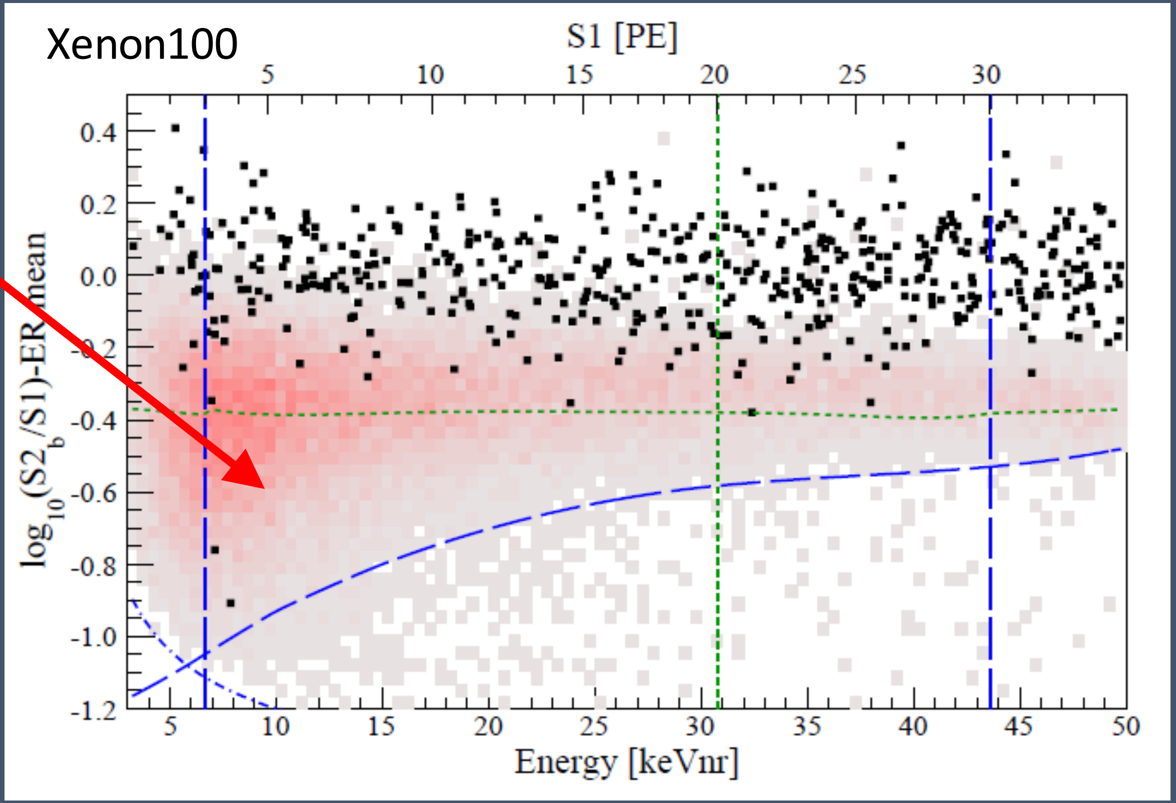
SI, elastic, WIMP/nucleon Scattering: Experimental Status

- Best limits now < 0.1 zB
- Noble liquid experiments most sensitive at m~50 GeV/c^2
- Solid targets leading around m~5 GeV/c^2
- Controversial signals suggesting m~10 GeV



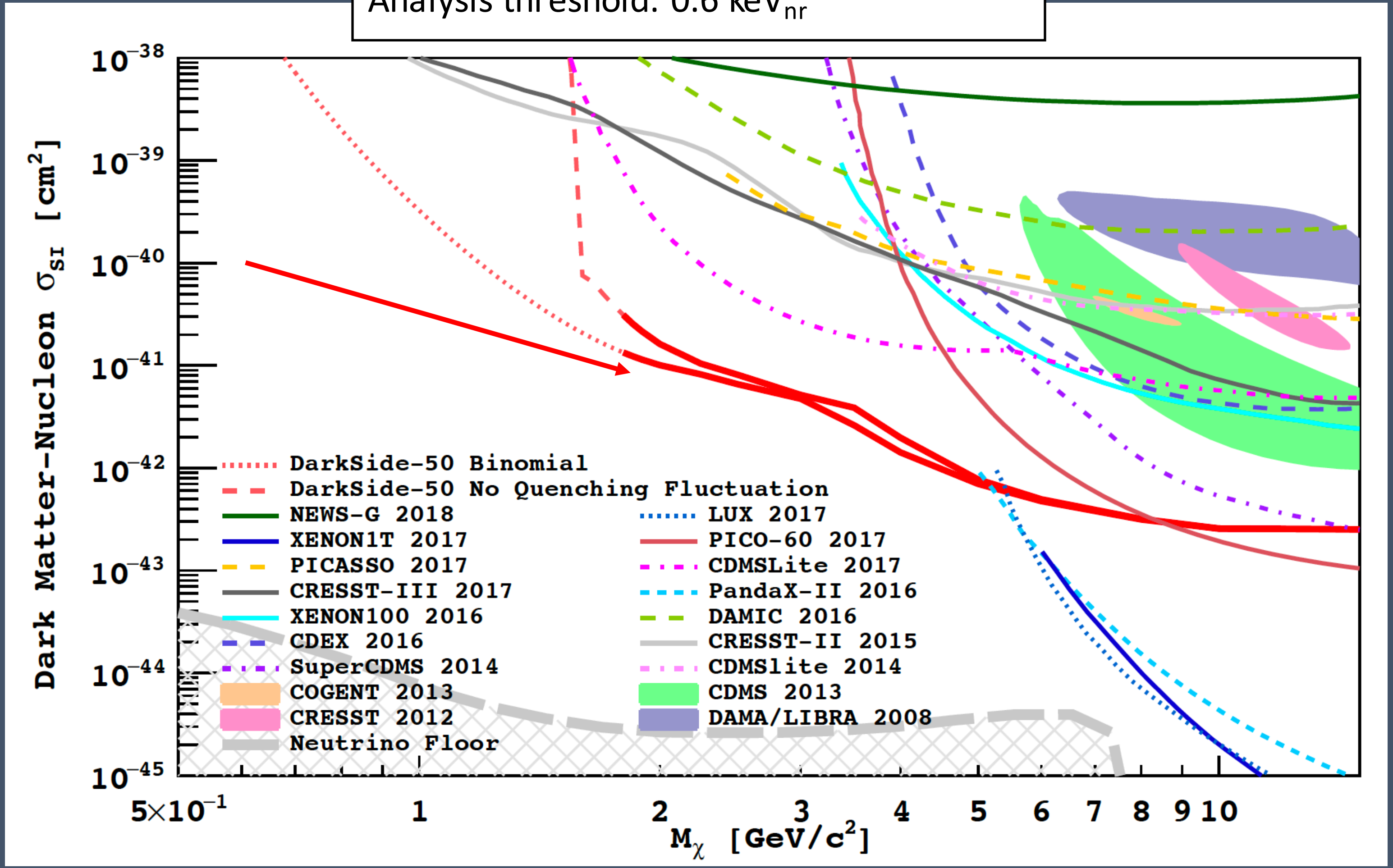
Non-directional WIMP search

- 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
- Does not demonstrate cosmological origin



Recent Limits: Low mass

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



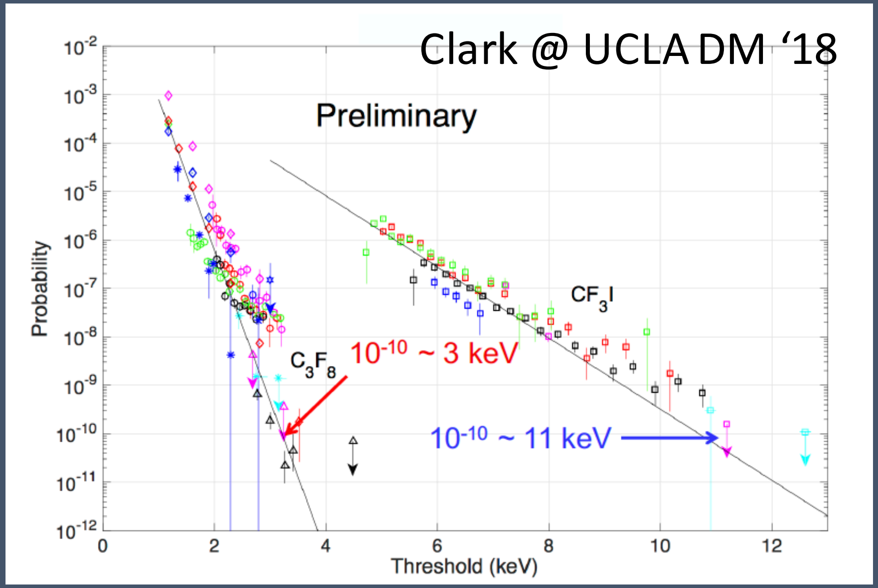
arxiv: 1802.06994

Darkside-50 ionization (S2) only analysis

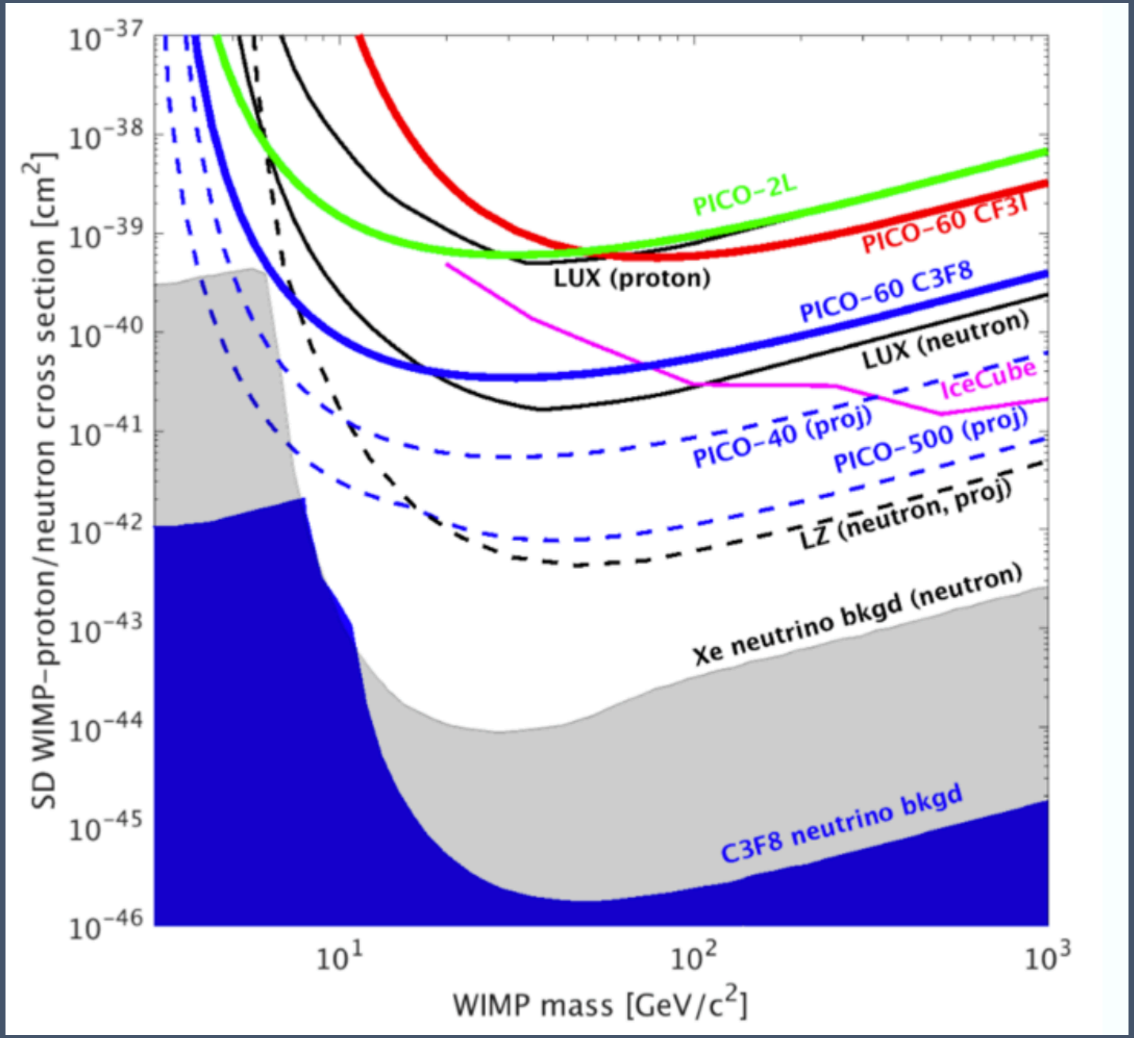
Analysis threshold: 0.6 keV$_{nr}$

SD, elastic, WIMP/nucleon Scattering: Experimental Status

- Bubble chambers with fluorine targets taking the lead
- Excellent gamma rejection at low energies
- But, *no energy measurement, which is important for penetrating neutrino floor*



Clark @ UCLA DM ‘18



Summary of Direct Detection Status

- Current DM experiments will probe cross-sections within factor 10-100 of the neutrino floor for m > 1 GeV/c^2
- There are significant challenges to further progress
  - Neutrino background
  - Lack of particle ID in ionization-only experiments for E ~< 10 keV
  - Lingering controversial signals from DAMA
  - Uncertain calibrations at lowest recoil energies
  - Ever stricter requirements on radio purity and background rejection
  - Lack of clear discovery signal that demonstrates cosmological origin

Motivation for Directional Detectors

The WIMP Wind

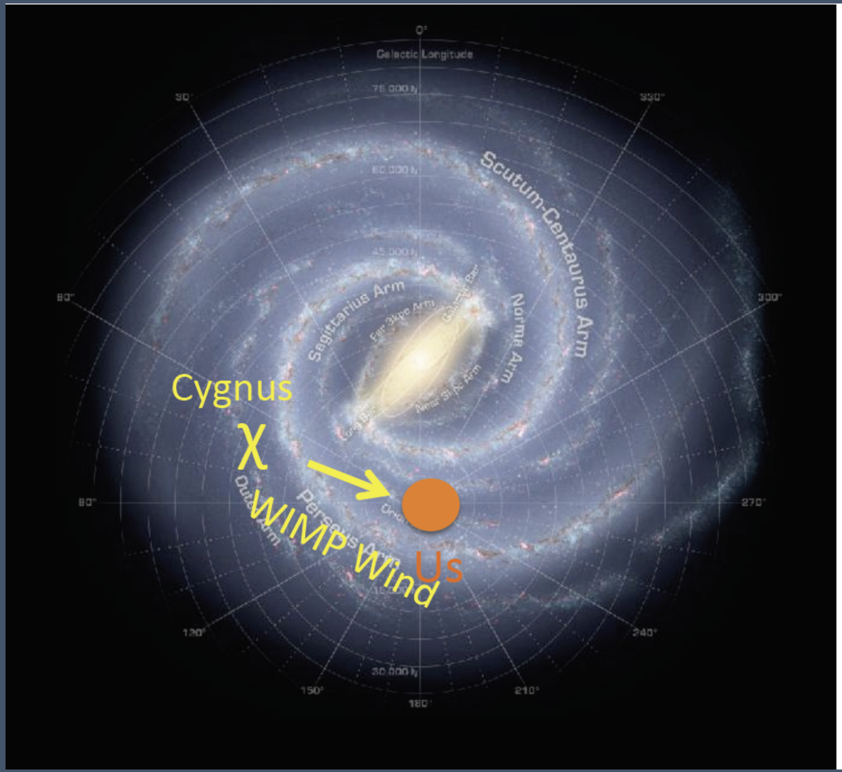
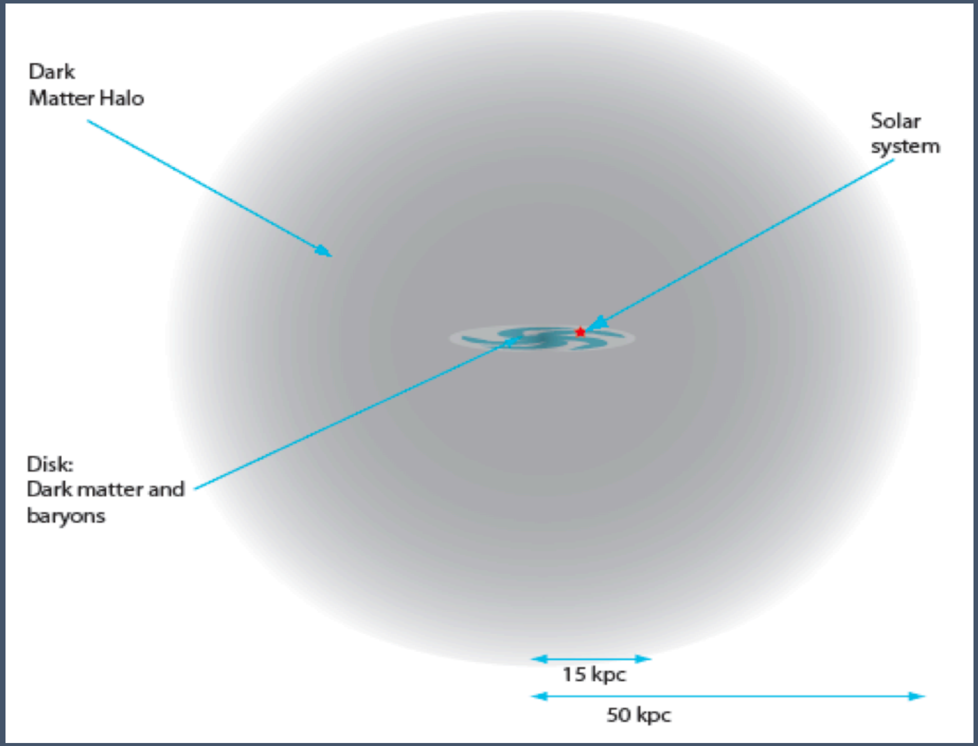
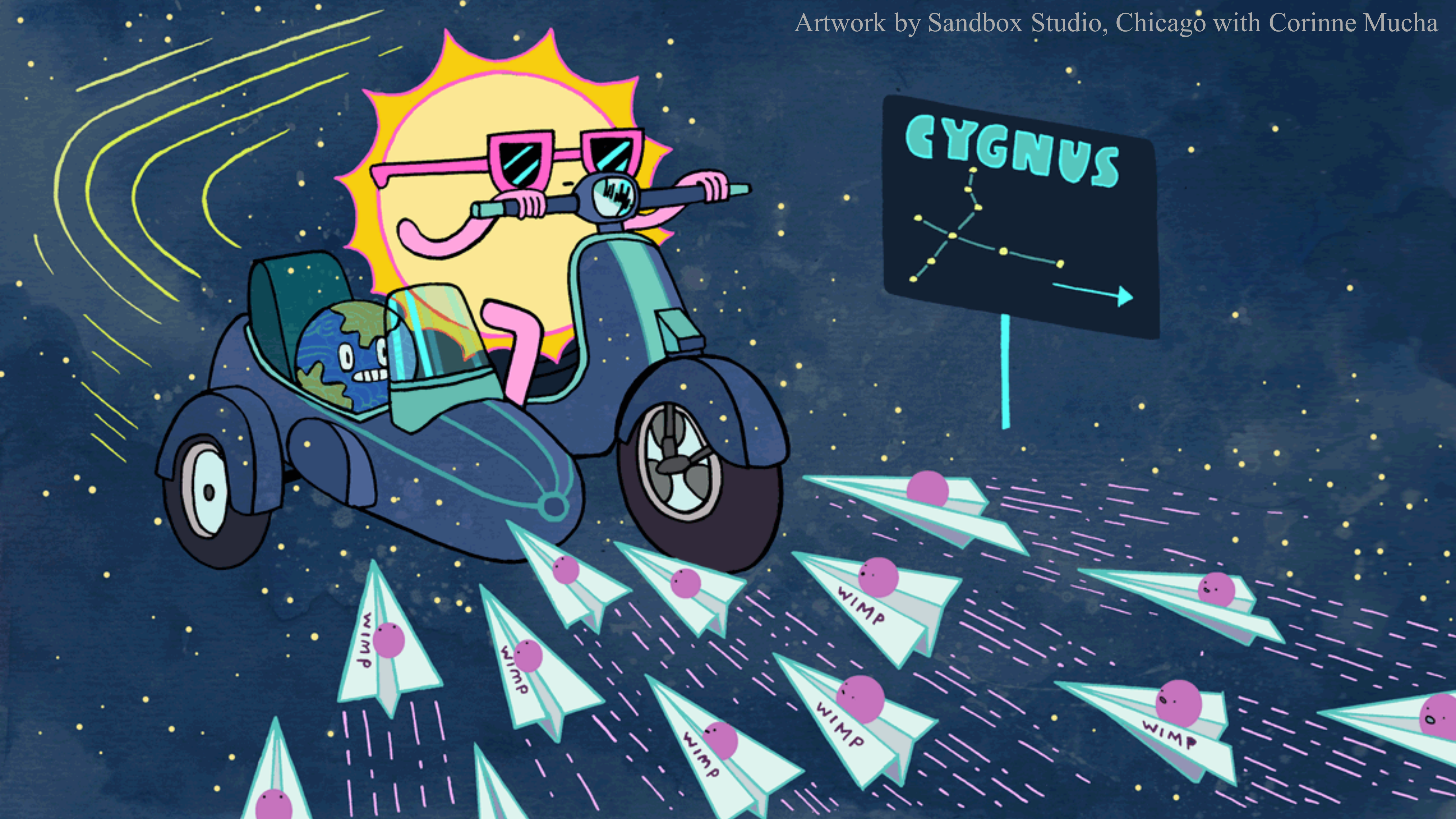


Image: NASA/Adler/U. Chicago/Wesleyan/JPL-Caltech

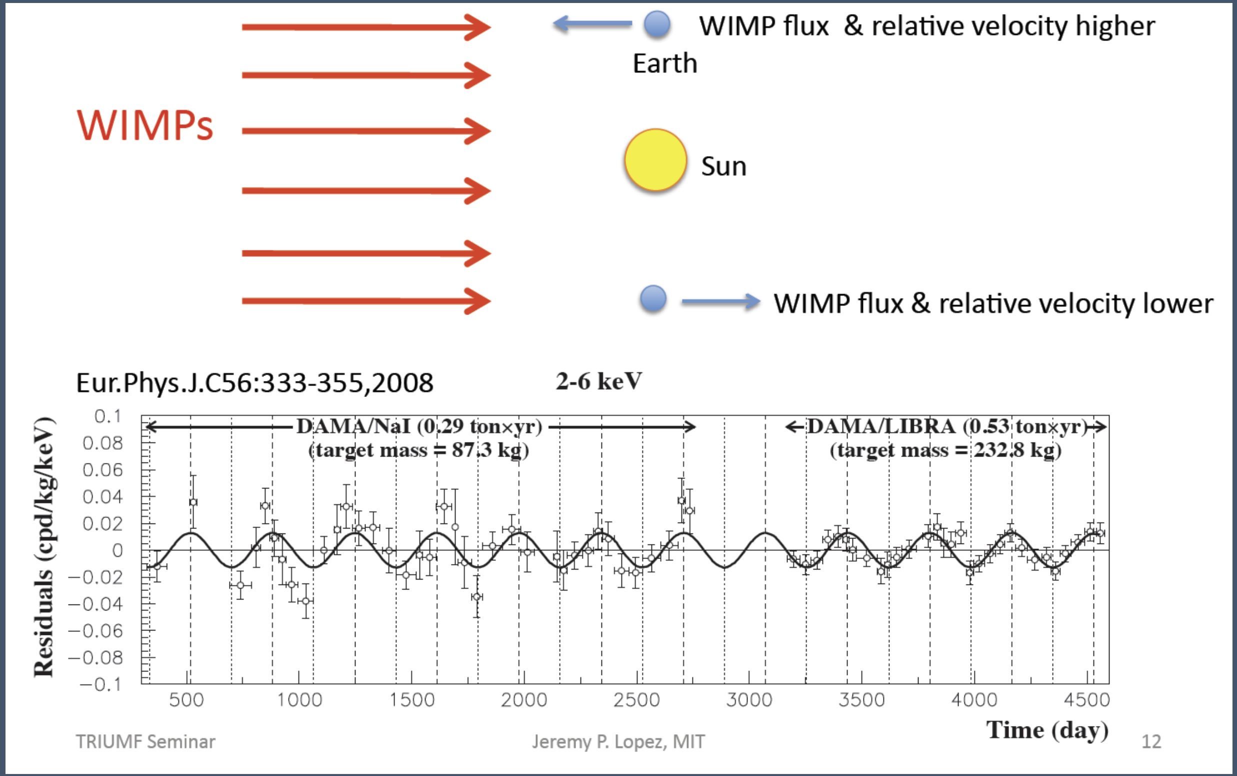


- ~220 km / s
- blows from CYGNUS
- provides two additional WIMP signatures…



Artwork by Sandbox Studio, Chicago with Corinne Mucha

Annual Rate Modulation



Eur.Phys.J.C56:333-355,2008

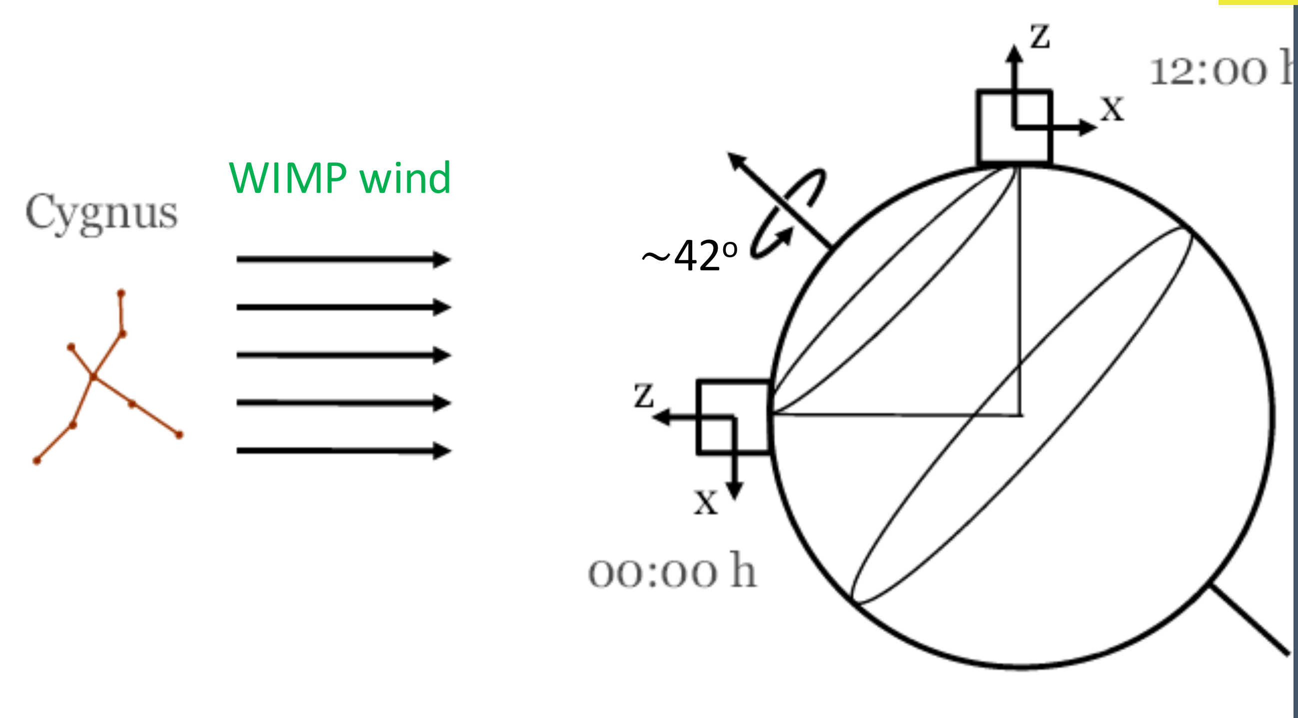
TRIUMF Seminar Jeremy P. Lopez, MIT 12

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

→ *does* demonstrate cosmological origin, but small magnitude, and not a robust signature

Diurnal (Daily) Directional Oscillation

Spergel PRD 37,1353 (1988)

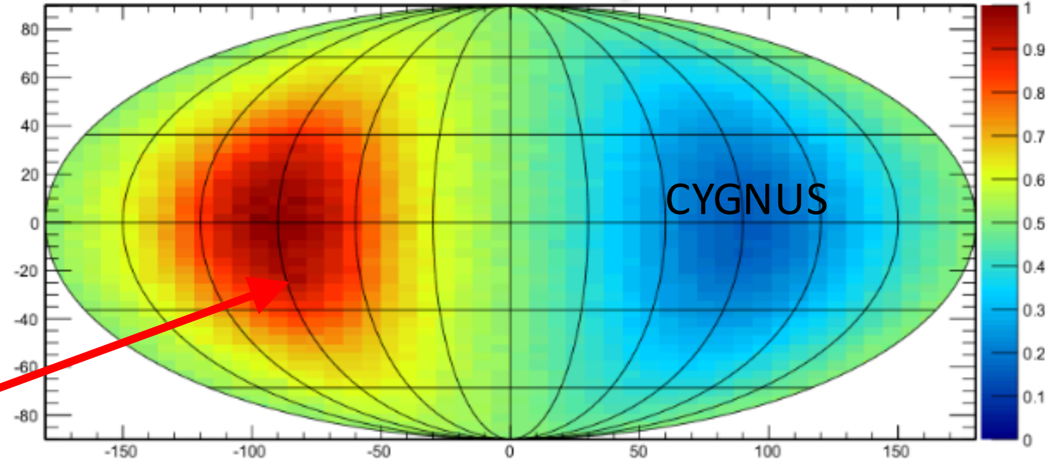


- oscillation of the mean recoil direction, due to rotation of earth
- order 1 effect
- oscillation period = sidereal day ≠ solar day
- no known background with this signature

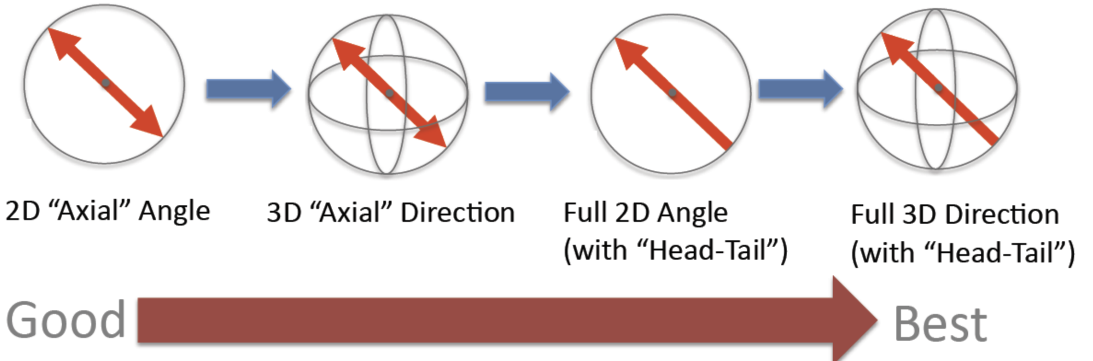
The Galactic Dipole

- 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)

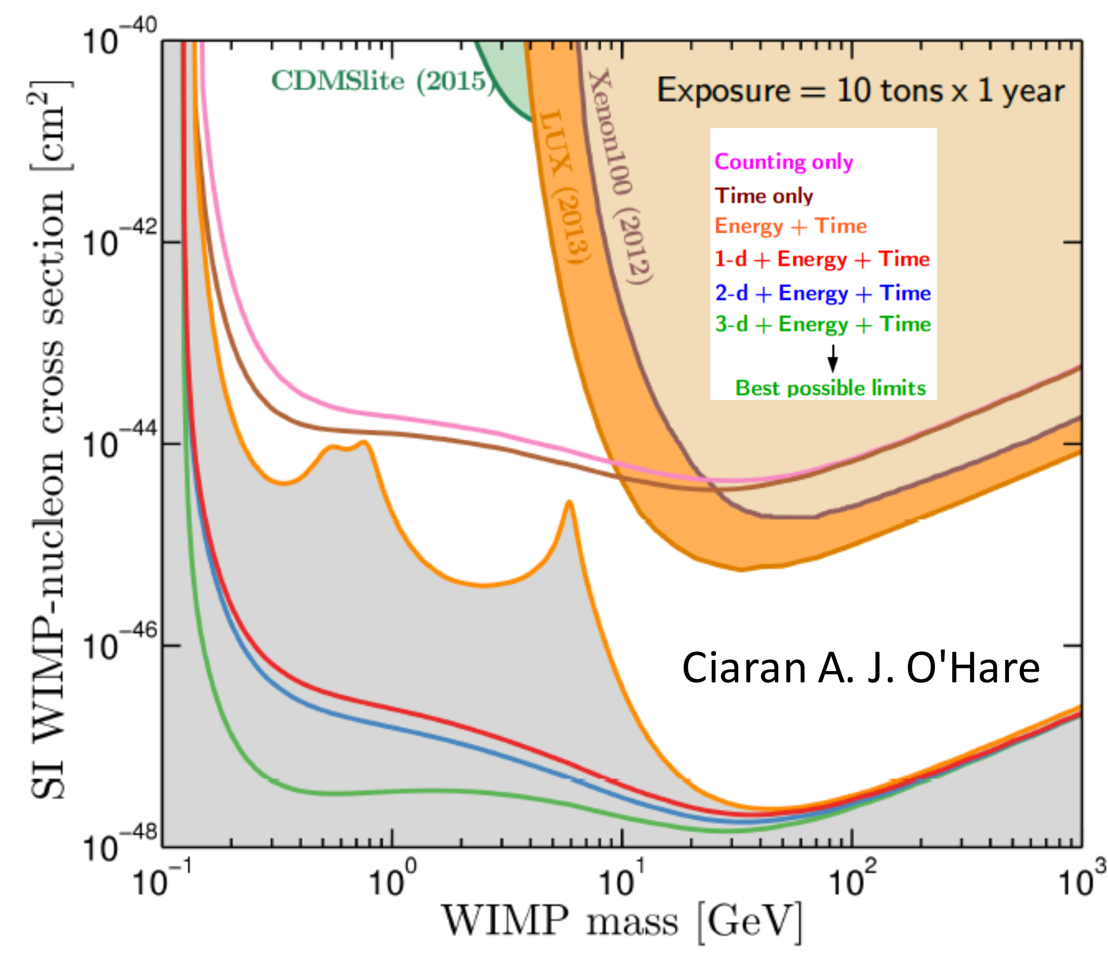


Sky map in galactic coordinates of recoils from 100 GeV WIMPs on ^{19}F, E>50 keV



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

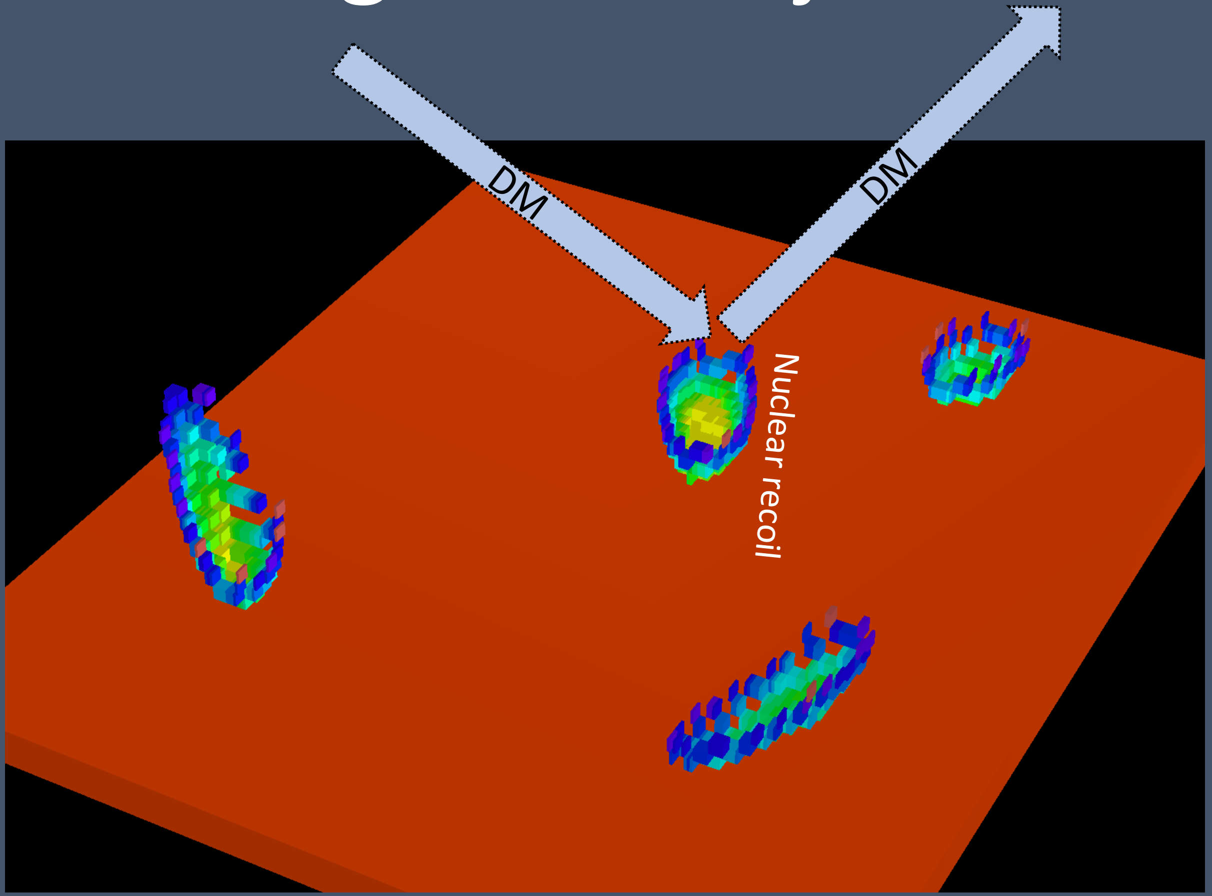
Penetrating the neutrino floor

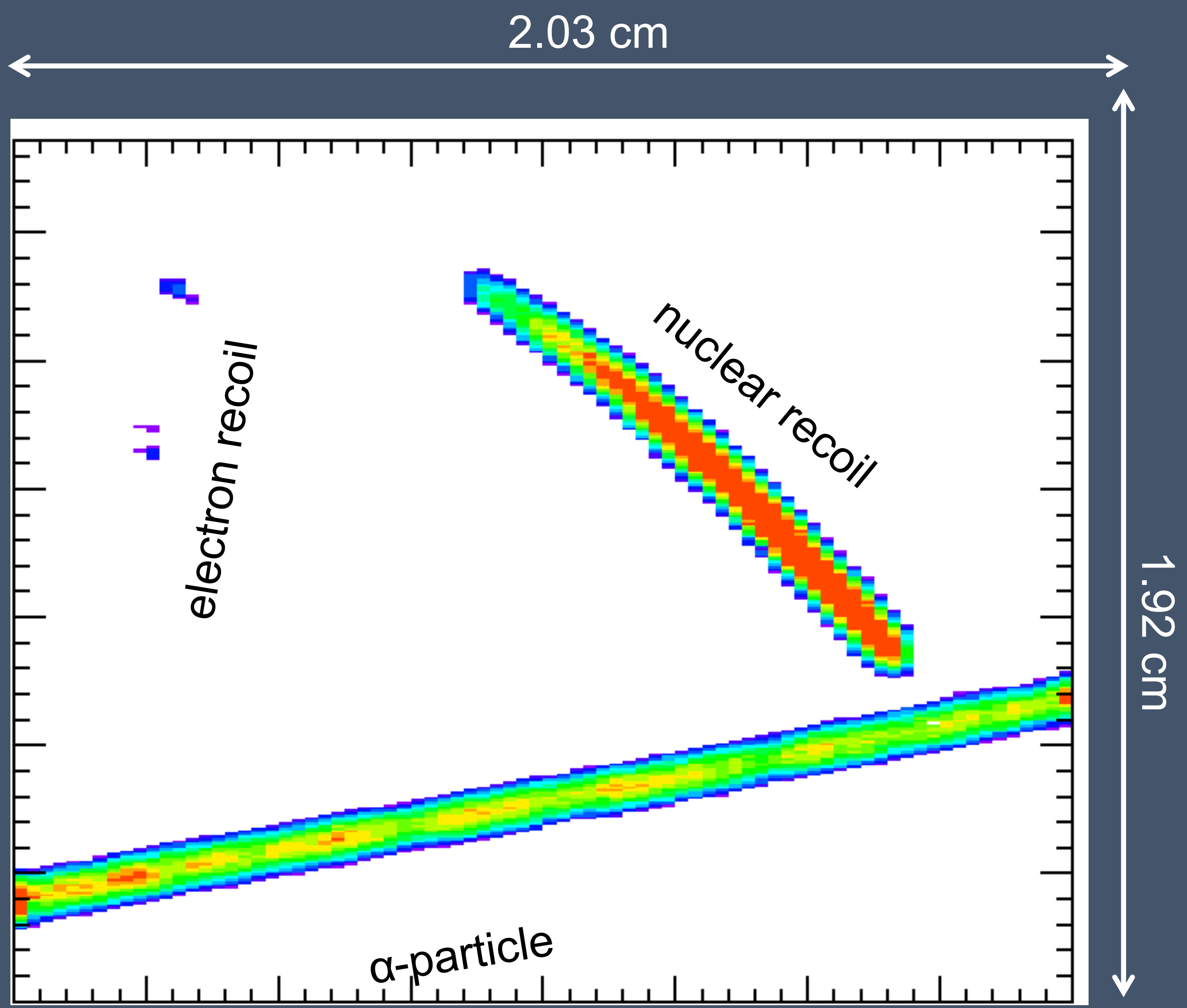


Readout strategies for directional dark matter detection beyond the neutrino background
Ciaran A. J. O'Hare, Anne M. Green, Julien Billard, Enectali Figueroa-Feliciano, Louis E. Strigari

- 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.

Background rejection



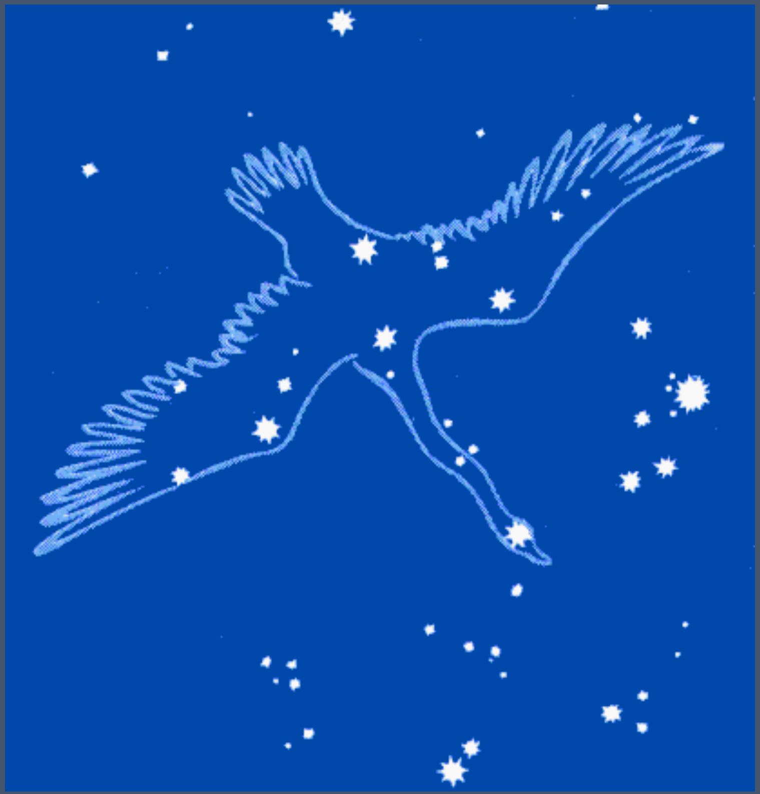


3D vector directionality can be achieved with high-definition (HD) 3D TPC charge readout
Detectors capable of this have excellent electron recoil / nuclear recoil separation as a “free bonus”

CYGNUS

The CYGNUS Proto-Collaboration

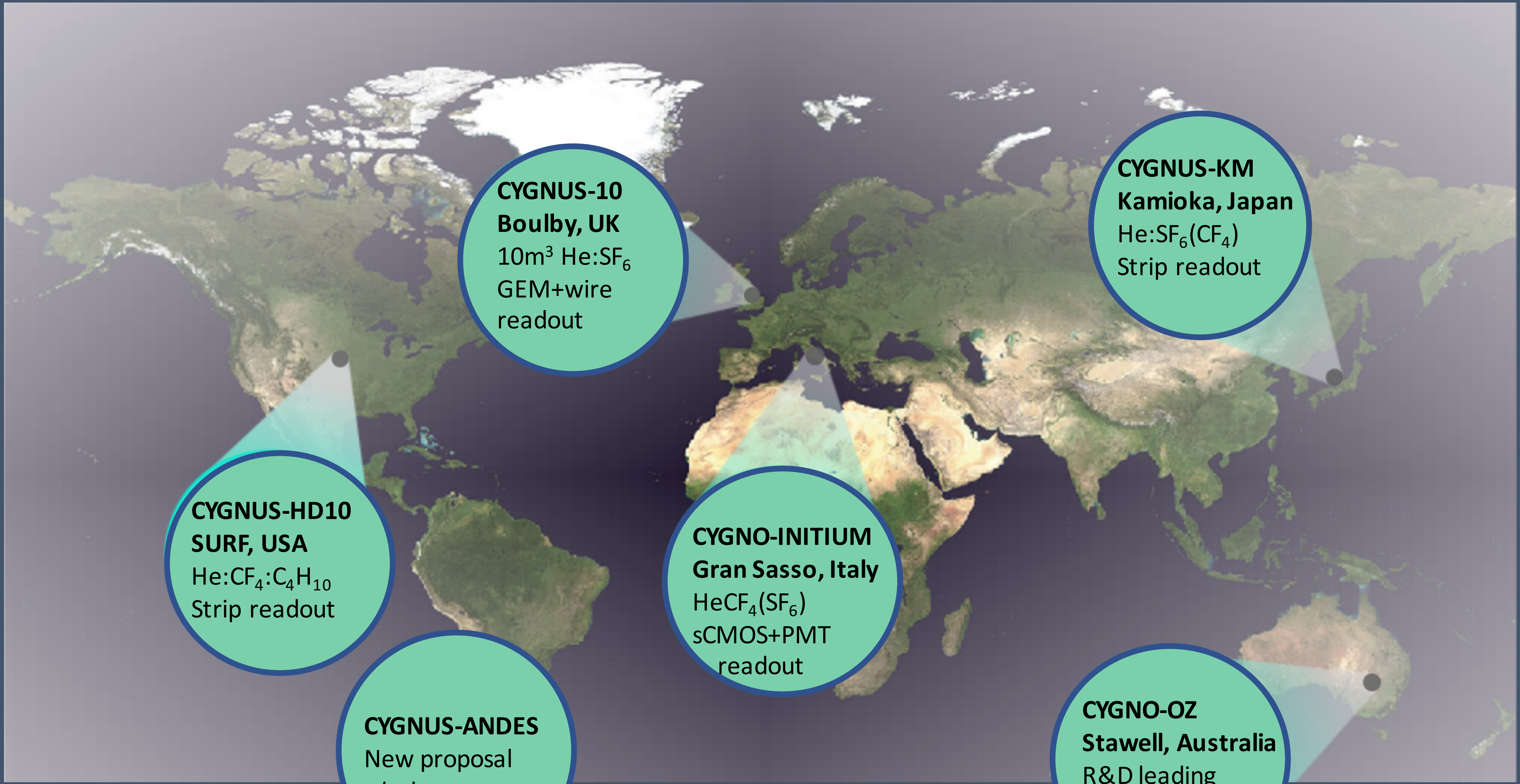
- As outcome of CYGNUS workshops, we have formed the CYGNUS proto-collaboration
- >50 signed members from the US, UK, Japan, Italy, Spain, China
- Focused on gas TPCs
- Close collaboration and regular meetings
- Encourage new members to join



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

CYGNUS Vision: Multi-site Galactic Recoil Observatory

with directional sensitivity to WIMPs and neutrinos



CYGNUS-10
Boulby, UK
10m^3 He:SF_6
GEM+wire
readout

CYGNUS-KM
Kamioka, Japan
He:SF_6(CF_4)
Strip readout

CYGNUS-HD10
SURF, USA
He:CF_4:C_4H_{10}
Strip readout

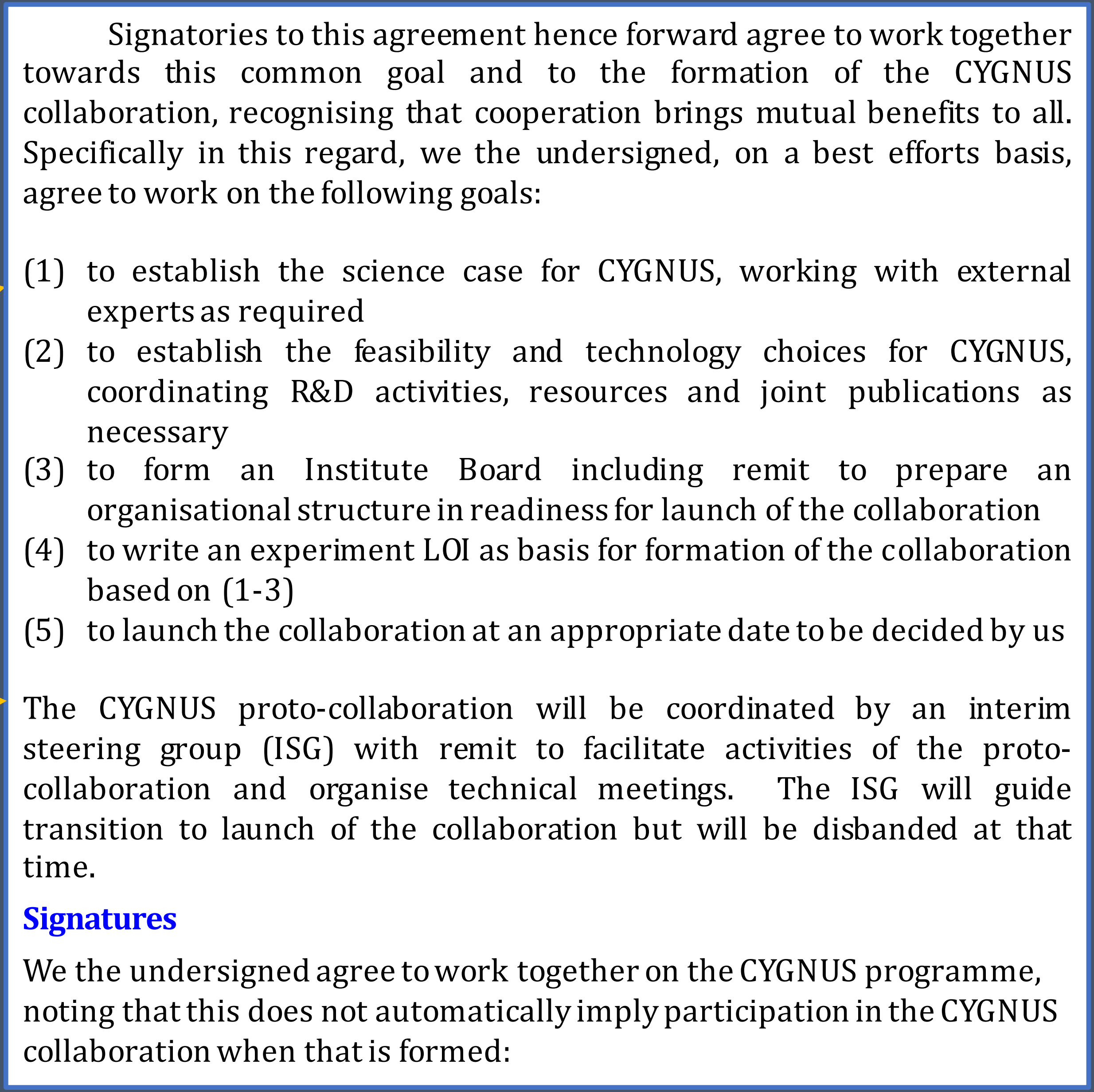
CYGNO-INITIUM
Gran Sasso, Italy
HeCF_4(SF_6)
sCMOS+PMT
readout

CYGNUS-ANDES
New proposal
t.b.d.

CYGNO-OZ
Stawell, Australia
R&D leading
to 1m^3

What we have agreed to

- 52 members have signed The CYGNUS Galactic Directional Recoil Observatory Proto-Collaboration Agreement
- (1) Finished
- (2) Ongoing
- (3-5) Next
- Interim Steering group:
  - Neil Spooner (Sheffield, UK)
  - Sven Vahsen (Hawaii, USA)
  - Kentaro Miuchi (Kobe, Japan)
  - Elisabetta Baracchini (GSSI/INFN, Italy)
  - Greg Lane (Melbourne, Australia)



Signatories to this agreement hence forward agree to work together towards this common goal and to the formation of the CYGNUS collaboration, recognising that cooperation brings mutual benefits to all. Specifically in this regard, we the undersigned, on a best efforts basis, agree to work on the following goals:

(1) to establish the science case for CYGNUS, working with external experts as required

(2) to establish the feasibility and technology choices for CYGNUS, coordinating R&D activities, resources and joint publications as necessary

(3) to form an Institute Board including remit to prepare an organisational structure in readiness for launch of the collaboration

(4) to write an experiment LOI as basis for formation of the collaboration based on (1-3)

(5) to launch the collaboration at an appropriate date to be decided by us

The CYGNUS proto-collaboration will be coordinated by an interim steering group (ISG) with remit to facilitate activities of the proto-collaboration and organise technical meetings. The ISG will guide transition to launch of the collaboration but will be disbanded at that time.

Signatures

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:

Science Case Paper – Task (1)

CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

E. Baracchini,[1,2,3] P. Barbeau,[4] J. B. R. Battat,[5] B. Crow,[6] C. Deaconu,[7] C. Eldridge,[8]
A. C. Ezeribe,[8] D. Loomba,[9] W. A. Lynch,[8] K. J. Mack,[10] K. Miuchi,[11] F. M. Mouton,[8] N. S. Phan,[12]
C. A. J. O'Hare,[13,14] K. Scholberg,[4] N. J. C. Spooner,[8] T. N. Thorpe,[6] and S. E. Vahsen[6]
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(Dated: June 20, 2019)

Now that conventional weakly interacting massive particle (WIMP) dark matter searches are rapidly approaching the neutrino floor, there has been a resurgence in interest towards detectors with directional sensitivity. A large enough detector with such a capability introduces the possibility of identifying a clear signature of dark matter particles with signals weaker than the neutrino background. All the while fulfilling a dual purpose in measuring these neutrinos from the Sun and other sources through the novel channel of coherent neutrino-nucleus scattering. We present here, for the first time, a detailed analysis of the potential for observing a directional nuclear recoil signal using low-pressure gas time projection chamber (TPC) technology at energies below 10 keV, as well as for discriminating against electron backgrounds in this regime, as required for low-mass WIMP and solar neutrino observations. Furthermore, we present analysis of the background and technological requirements for such a detector, along with a full cost-benefit analysis to identify the optimal choice of detector readout technology. We describe how a large-scale directional nuclear recoil observatory, which we call CYGNUS, has the potential to open a new field in observational cosmology.

I. INTRODUCTION

A wide range of astrophysical observations across Galactic and cosmological scales indicate that dark matter (DM) dominates the mass budget of the Universe. While the gravitational evidence for DM is very strong (for a review, see Ref. [1]), its particle identity remains unknown. A definitive detection of particle DM is expected to be a gateway to physics beyond the standard model. Being of such fundamental importance, the quest to uncover the nature of DM remains one of the most important experimental challenges in contemporary

claimed [2–11]. As detectors become sensitive to lower masses and weaker cross sections, the previously negligible neutrino background will become important, potentially swamping any WIMP signal. Models which give signals weaker than the neutrino background are said to live beyond the 'neutrino floor', a theoretical boundary beyond which convential DM detectors cannot probe.

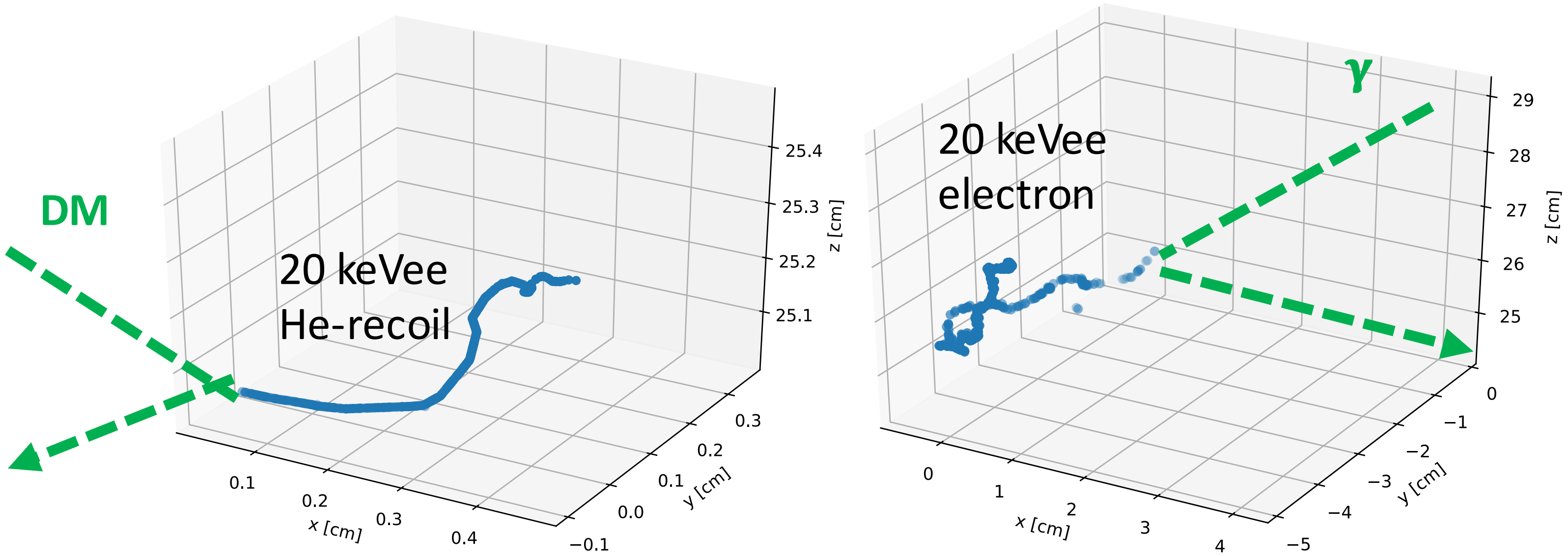
DM detectors with *directional sensitivity*—the ability to reconstruct the directions of WIMP-induced recoil events—have the potential to address two of the main challenges to current detection techniques: (1) the difficulty of positively identifying detected interactions as be-

- 55 pages
- Complete, revising
- Intended for PRD

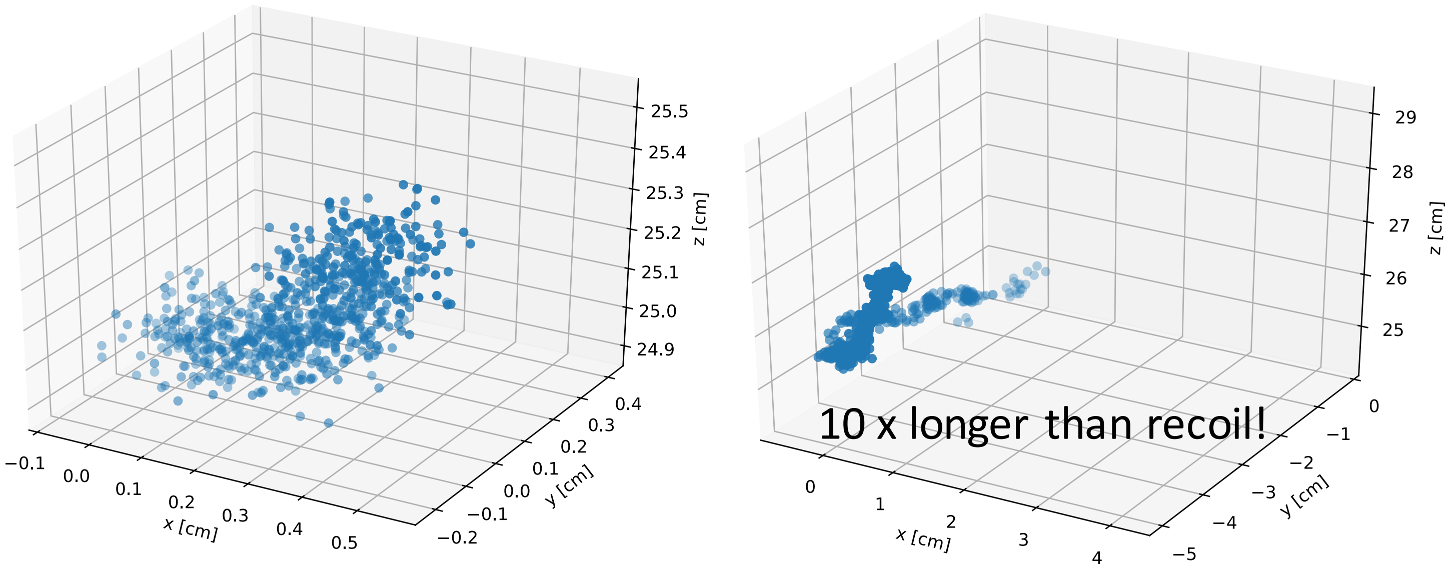
- Some results in this talk. Also see talk by O'Hare, this conference.

The main idea

- Direct DM detection w/ Gas target 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



Initial ionization distribution



charge cloud after 25 cm drift in gas TPC

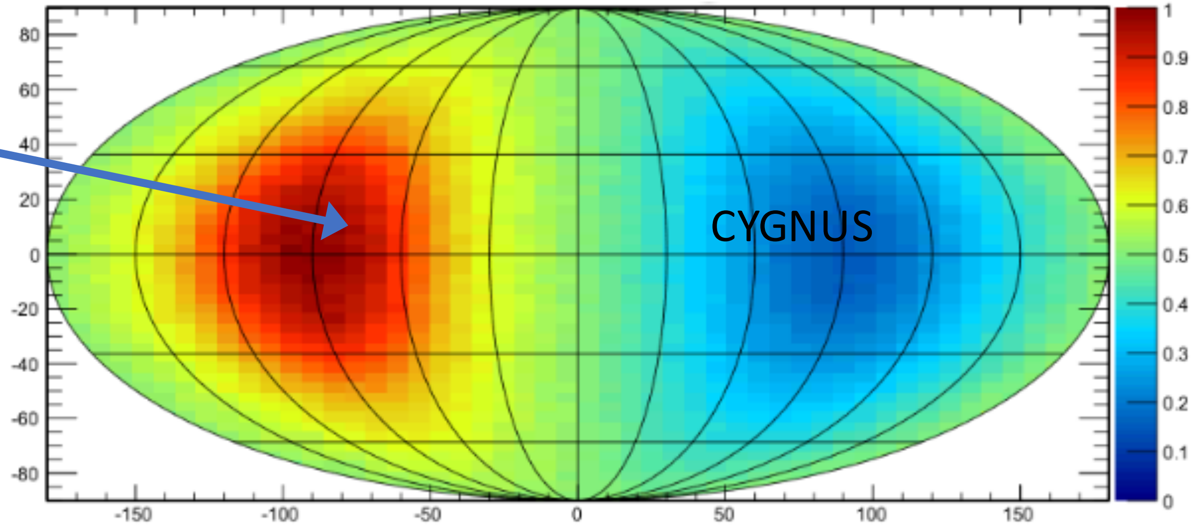
CYGNUS vision and long-term goal

> 1000 m^3 directional nuclear recoil detector capable of

exposure

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

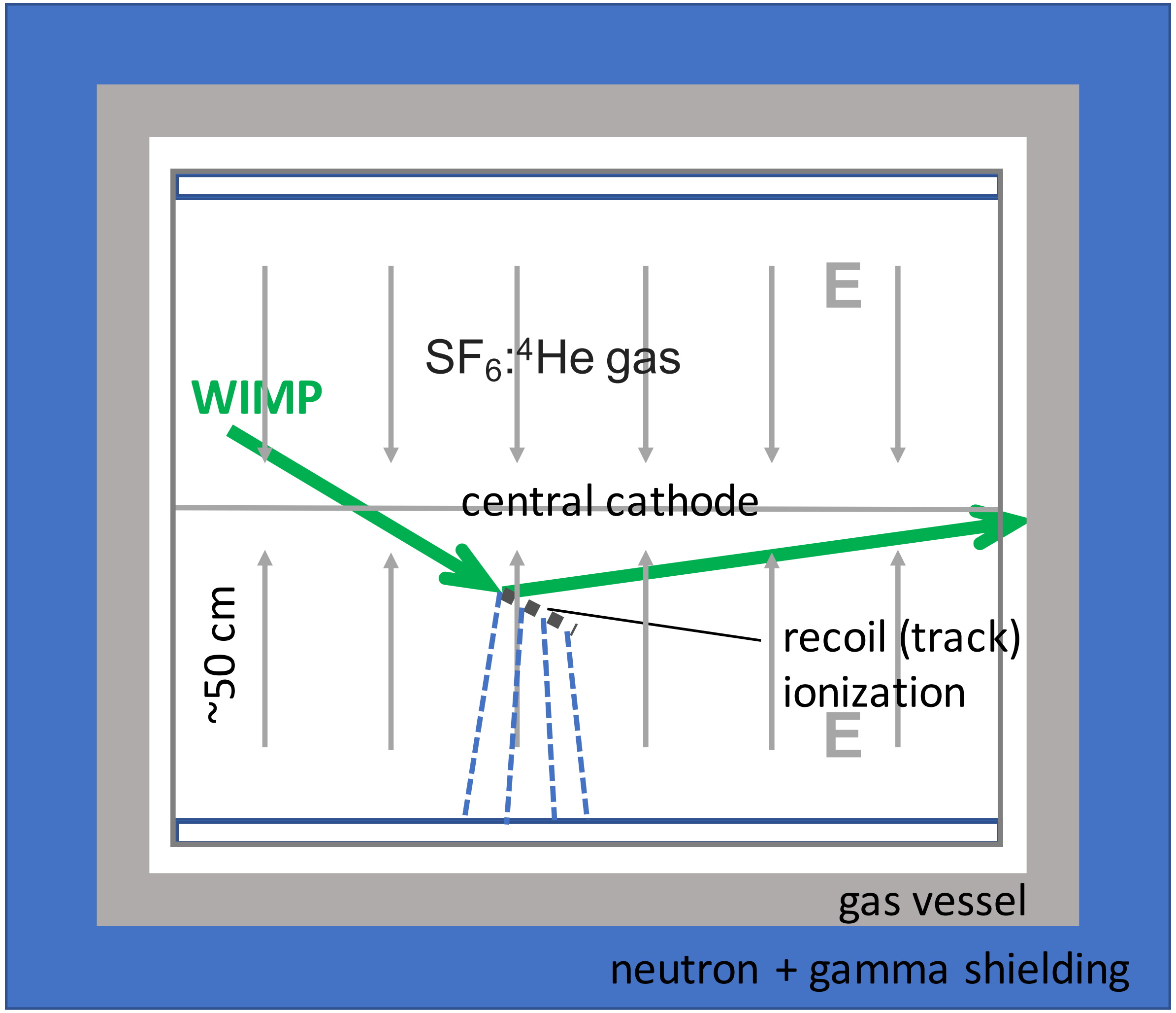
A review of the discovery reach of directional Dark Matter detection
[Physics Reports 627 (2016)]



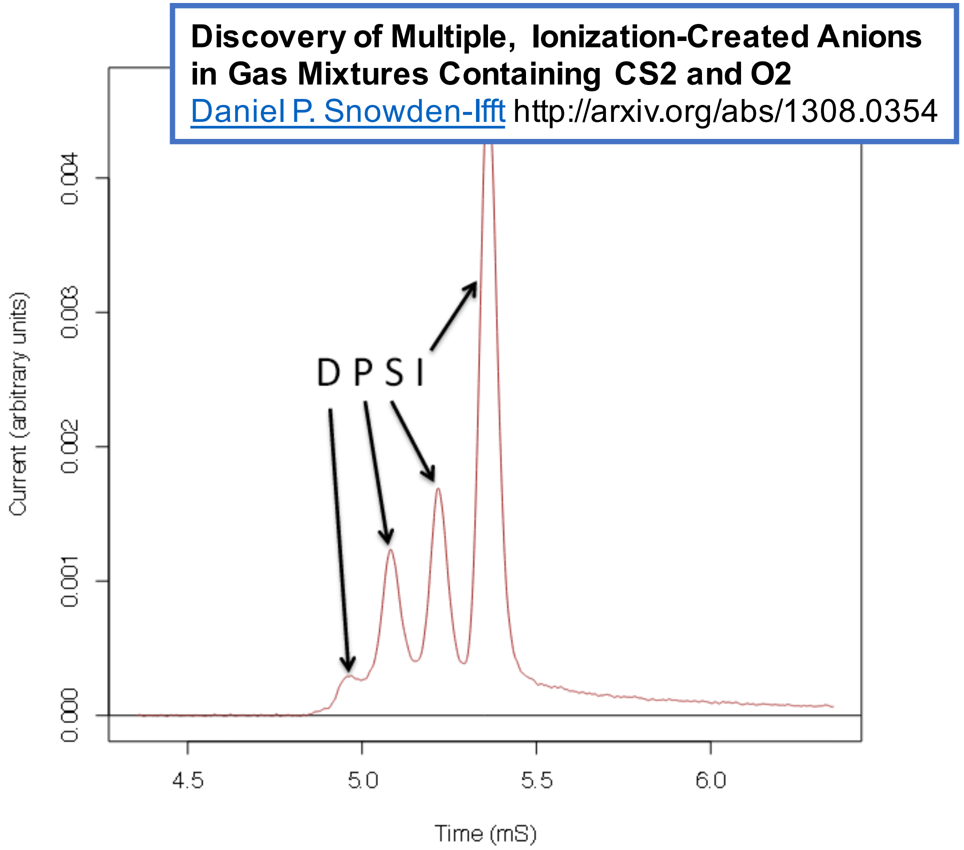
Sky map in galactic coordinates of recoils from 100 GeV WIMPs on ^{19}F, E>50 keV

CYGNUS: Experimental Approach

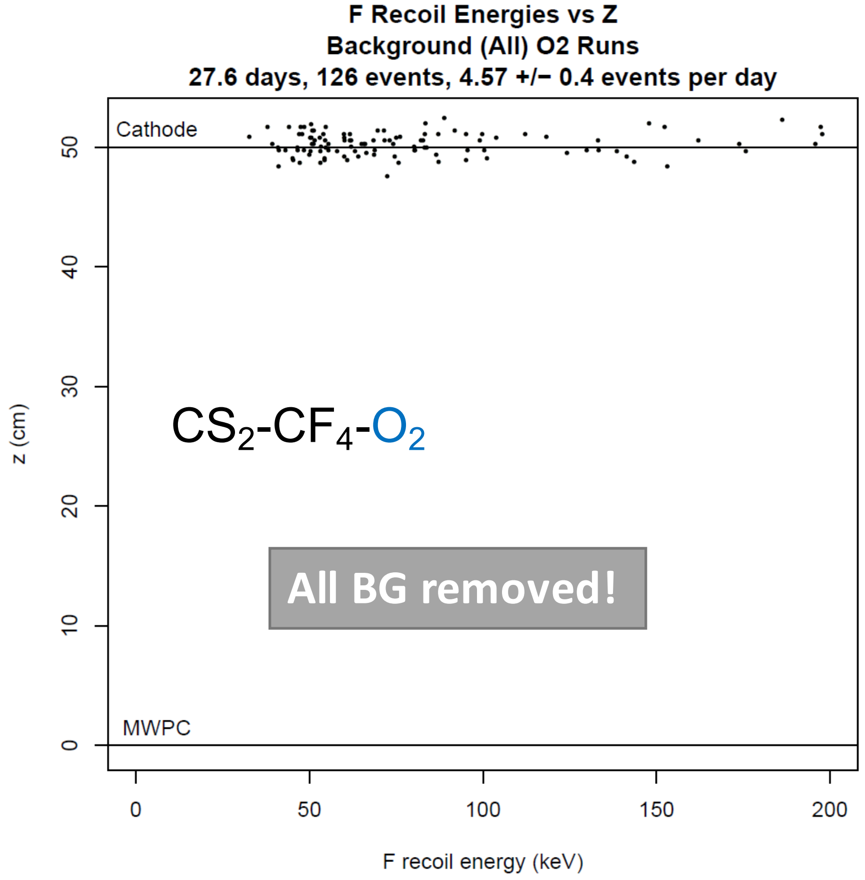
- Gas Time Projection Chamber
- Order $1 m^3$ unit cells
- Gas mixture: SF_6:^4He, p~1 atm
- Reduced diffusion via negative Ion drift (SF_6 gas)
- Fluorine: SD WIMP sensitivity
- Helium target
  - SI, low mass WIMP sensitivity
  - Longer recoil tracks, extending directionality to lower energies
- Redundant 3D fiducialization
  - SF_6 minority carriers
  - charge cloud profile
- 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



F Recoil Energies vs Z
Background (All) O2 Runs
27.6 days, 126 events, 4.57 +/− 0.4 events per day

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

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

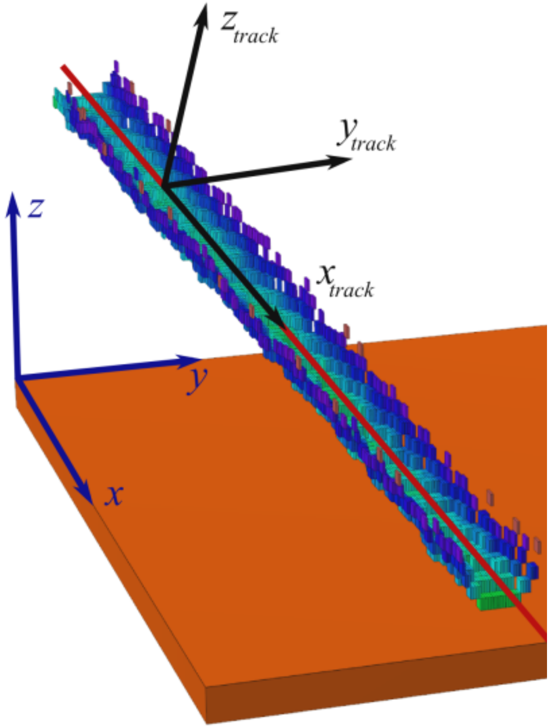
Journal of Instrumentation, Volume 12, February 2017

3D Fiducialization II: Charge Cloud Reconstruction

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

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

→ obtain absolute position in drift direction



P. Lewis (U. Hawaii)

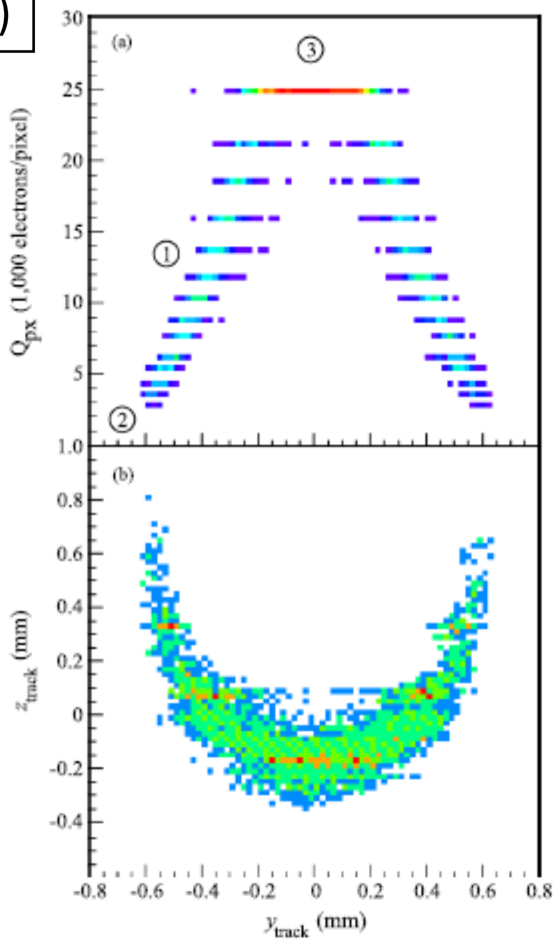


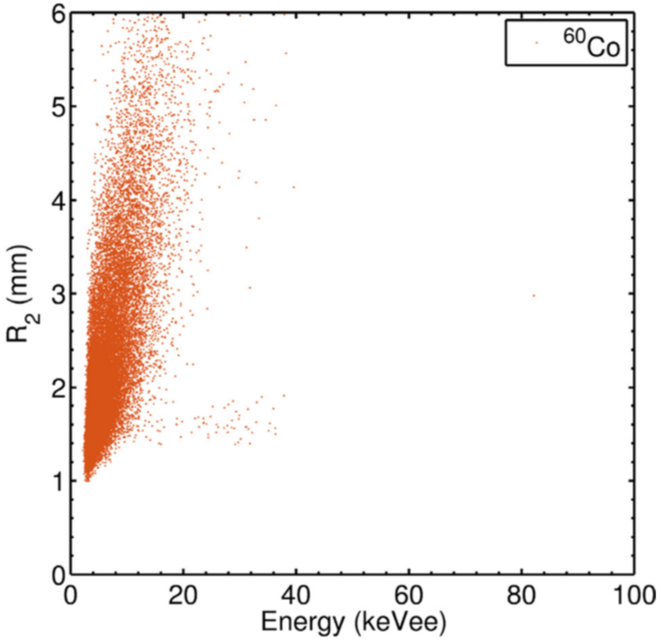
Fig. 2. Corrected pixel charge (Q_{px}) profile (a) and shell coordinates (b) for a single horizontal track from the near alpha source. Label 1 of the profile plot (a) corresponds to the Gaussian, label 2 to the threshold, and label 3 to the saturation regions of the profile. The U-shaped shell in plot (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 I. Seong to also work with recoil events (unpublished)

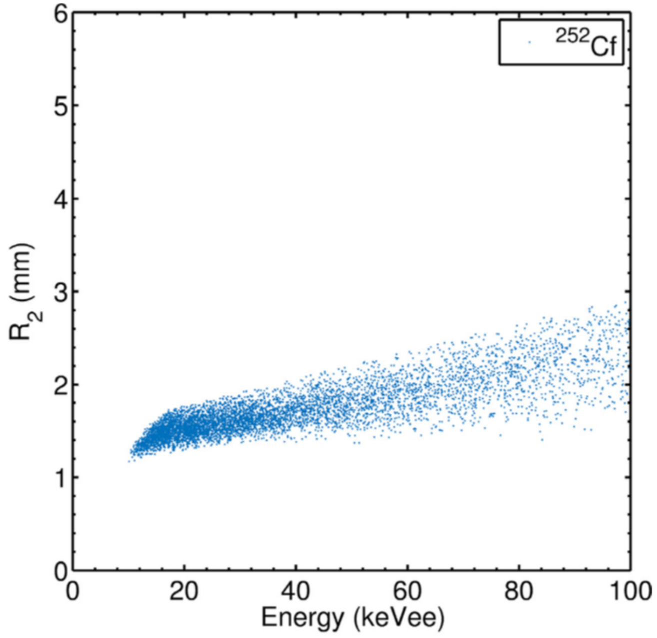
2D electron rejection (experiment)

- 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 < 3.9×10^{-5} around 10 keVee
  - *It's a limit – all available electron events rejected*!
- Extrapolating to CYGNUS
  - 20 torr SF_6 + 740 torr Helium: 50% longer tracks
  - 50 cm of thermal drift ($\sigma = 0.55$ mm): 50% higher
  - Expect similar performance

→Should improve with 3D reconstruction and going beyond range-energy signature.



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



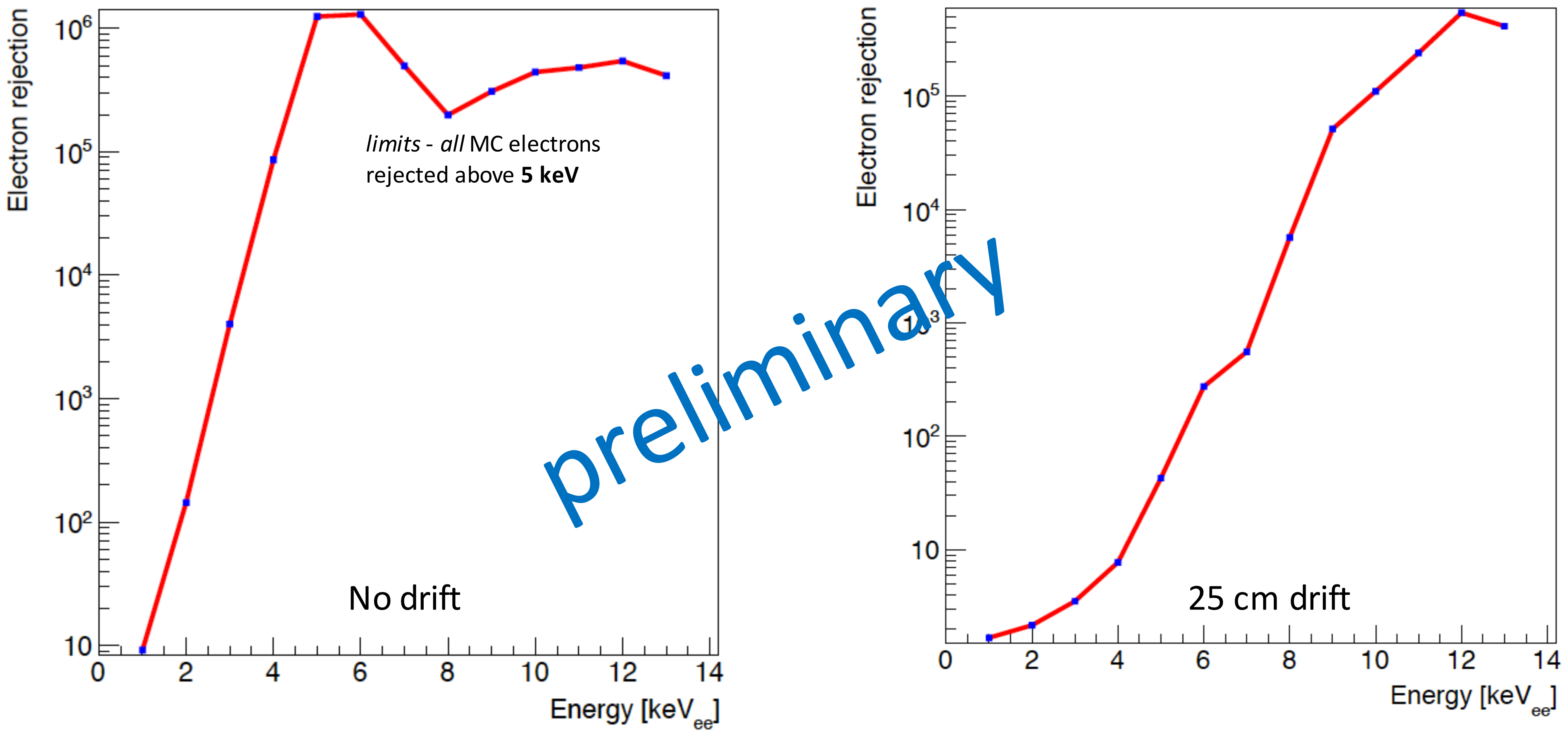
(b) ^{252}Cf data post selection cuts

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

3D electron rejection (simulation) per 1keVee

20 torr SF_6 + 740 torr Helium

Evaluated at Flourine-recoil effiency of 50.0%



limits - *all* MC electrons rejected above **5 keV**

No drift

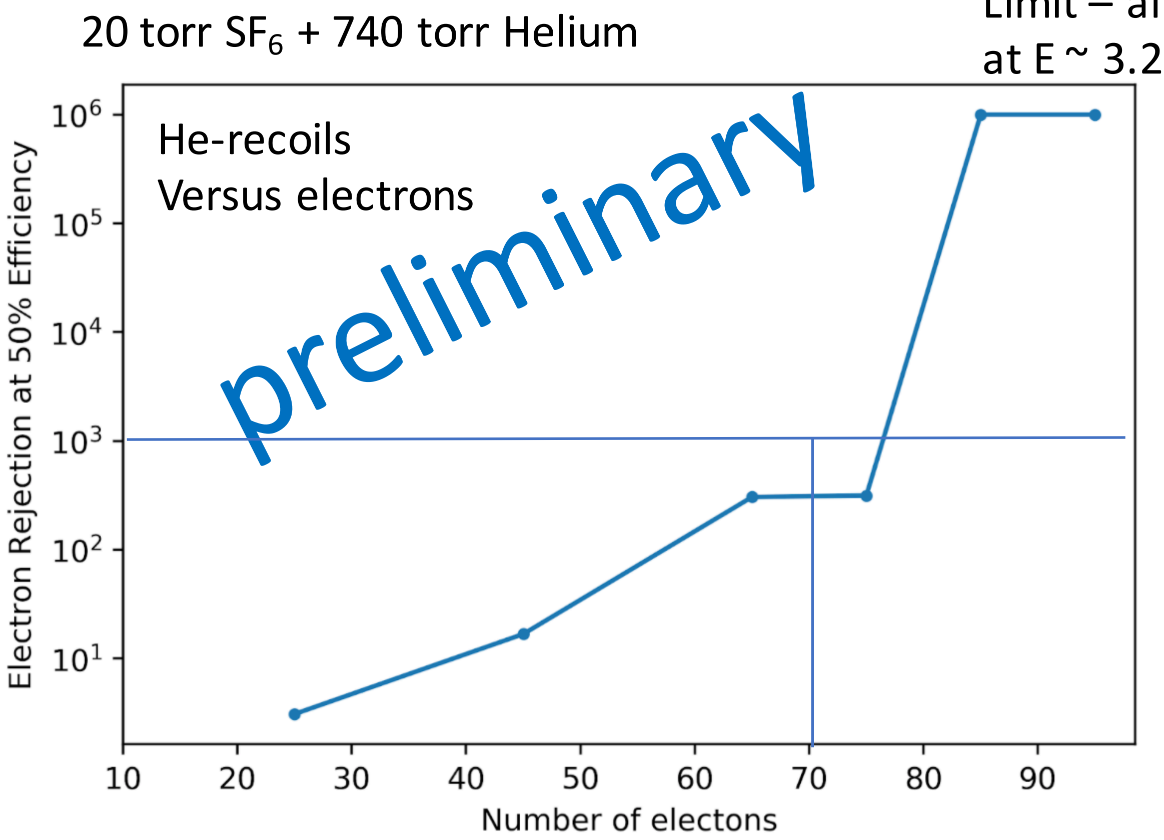
25 cm drift

3d-range versus energy signature: good electron rejection down to 2-5 keVee (depending on drift length)

3D Electron Rejection with Deep Learning

Includes 100 micron diffusion + HD 3D detector.

Huge improvements
May be possible with
machine learning!
More work needed.

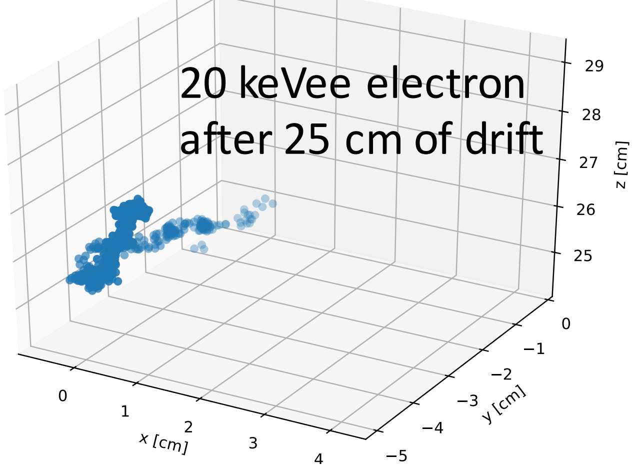


Limit – all electrons rejected at E ~ 3.2 keVee

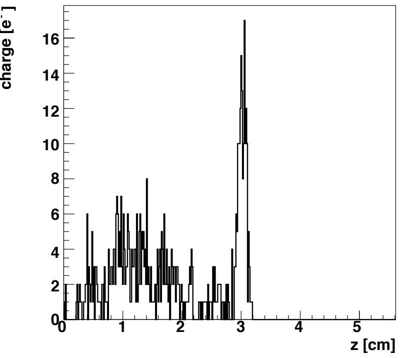
For 1000 m^3 detector:
after copper shielding,
expect 1-2 x 10^4
gammas/year/ 10 keV →
need 10^3 rejection factor
per 1keV bin

- Statistically significant electron rejection down to <=1 keVee

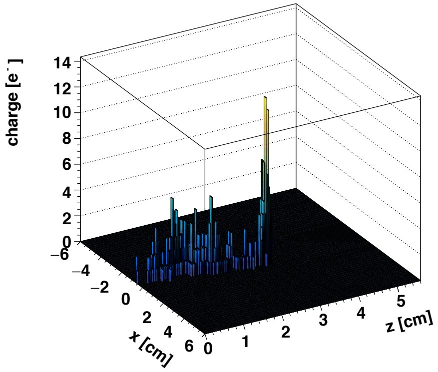
Six types of TPC charge readouts



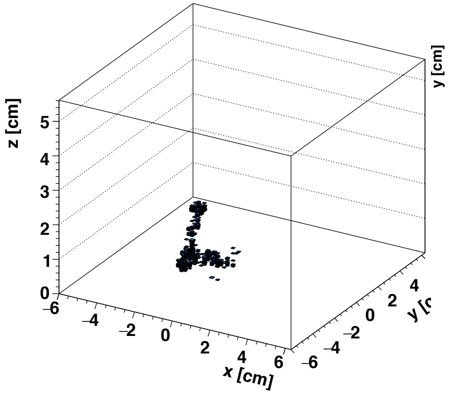
20 keVee electron
after 25 cm of drift



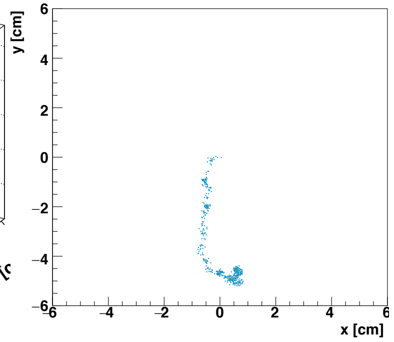
1D GEM



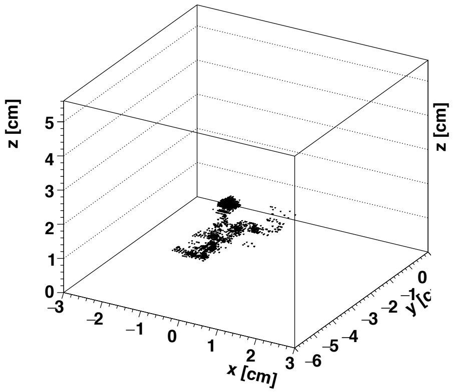
1.5 D: wires



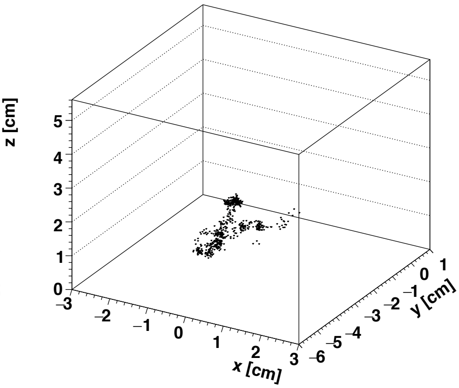
3D pads



2D optical



3D strips



3D pixels

Worse performance
Lower cost

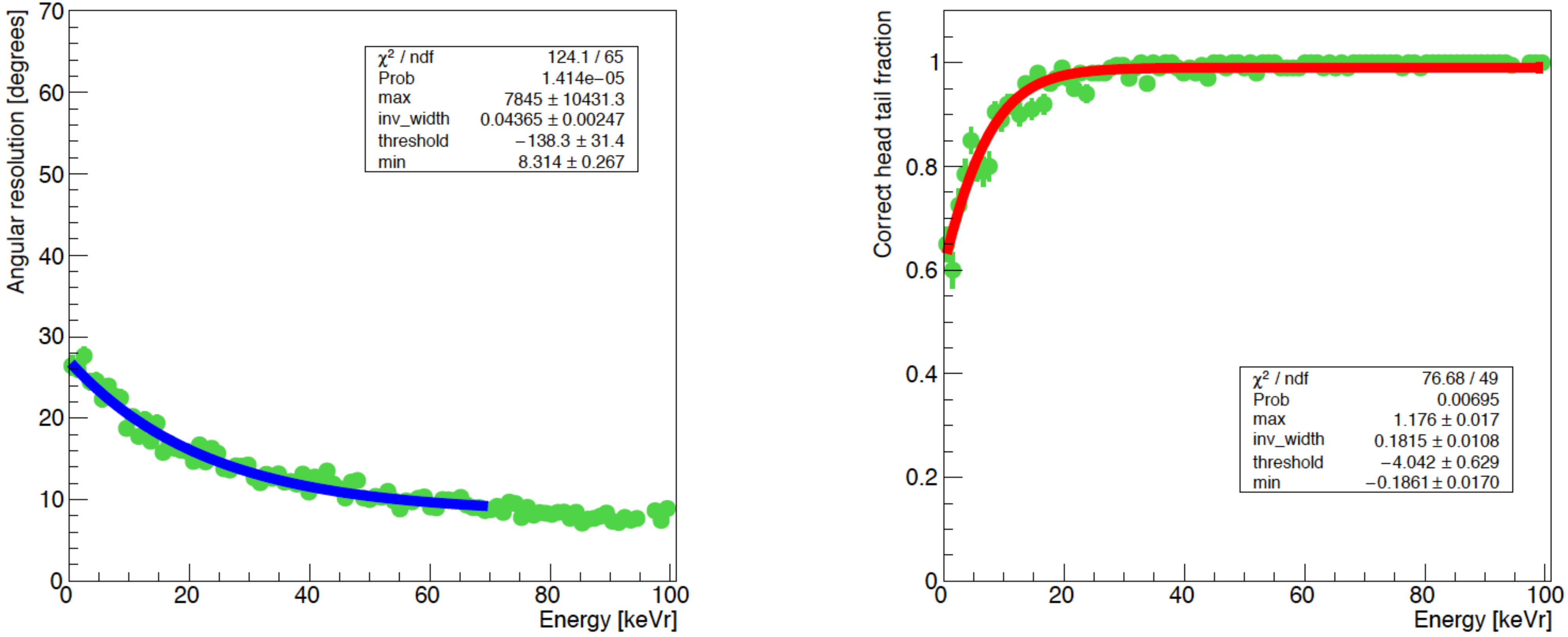
Best compromise? Simulation study to find out

Better performance
Higher cost

New gas mix: He+SF6 755+5. Pre-drift

straggling + reconstruction algorithm

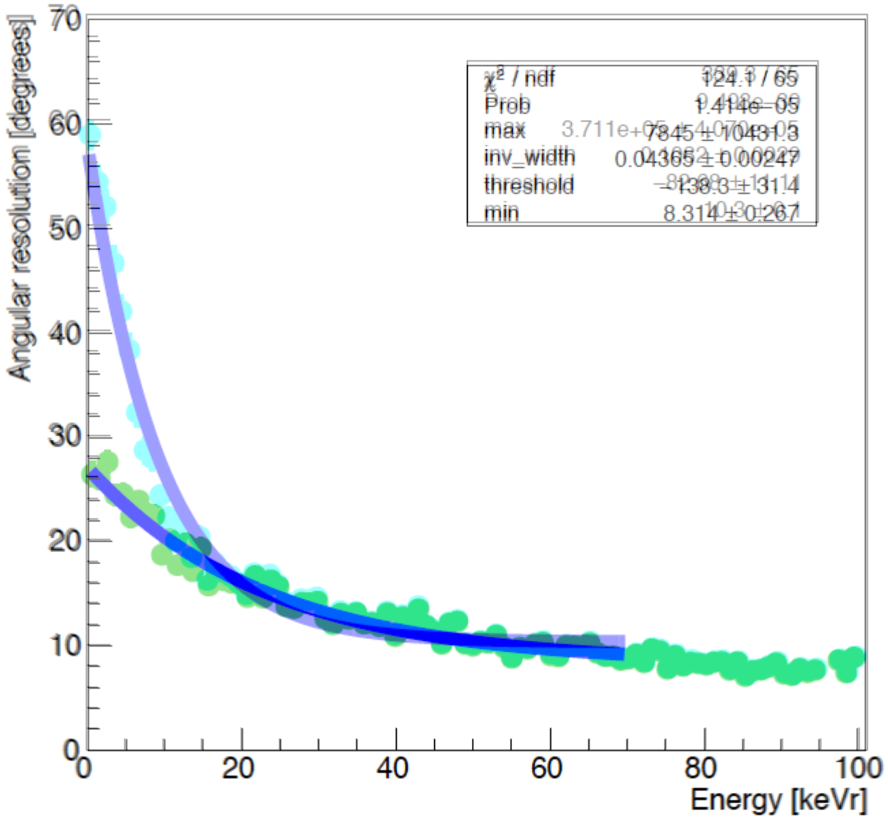
Helium recoil

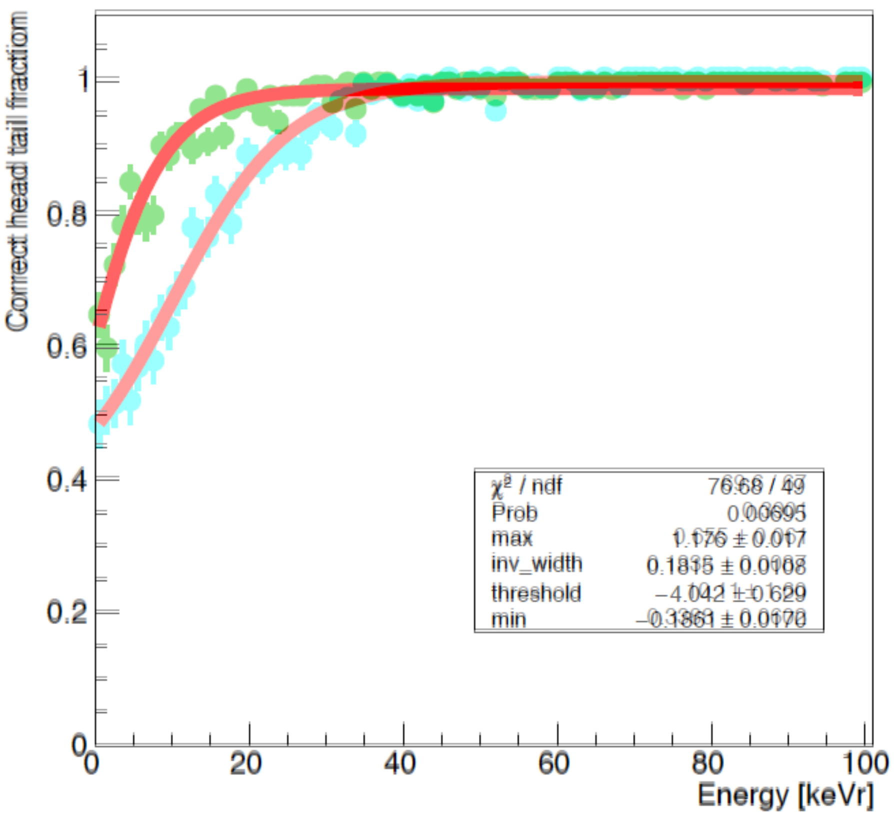


New gas mix: He+SF6 755+5. Post-drift.

straggling + reconstruction algorithm + diffusion

Helium recoil

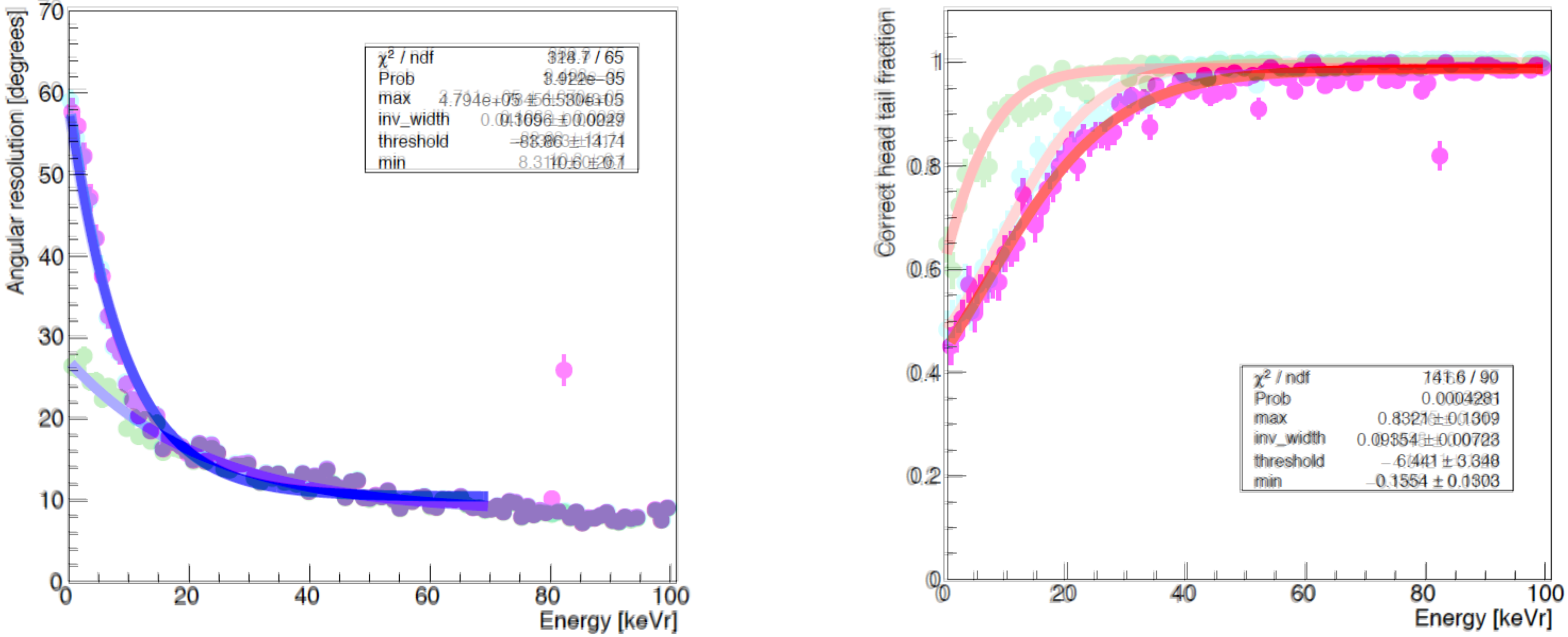




New gas mix: He+SF6 755+5. Pixel readout.

straggling + reconstruction algorithm + diffusion + readout performance

Helium recoil



Directionality is diffusion limit. Pixel readout essentially extracts all information present after diffusion.
Possible paths to improved directionality: 1) lower diffusion 2) improved reconstruction algorithms 3) hydrogen

Final Result: Sensitivity per Unit Cost

20 torr SF_6 + 740 torr Helium

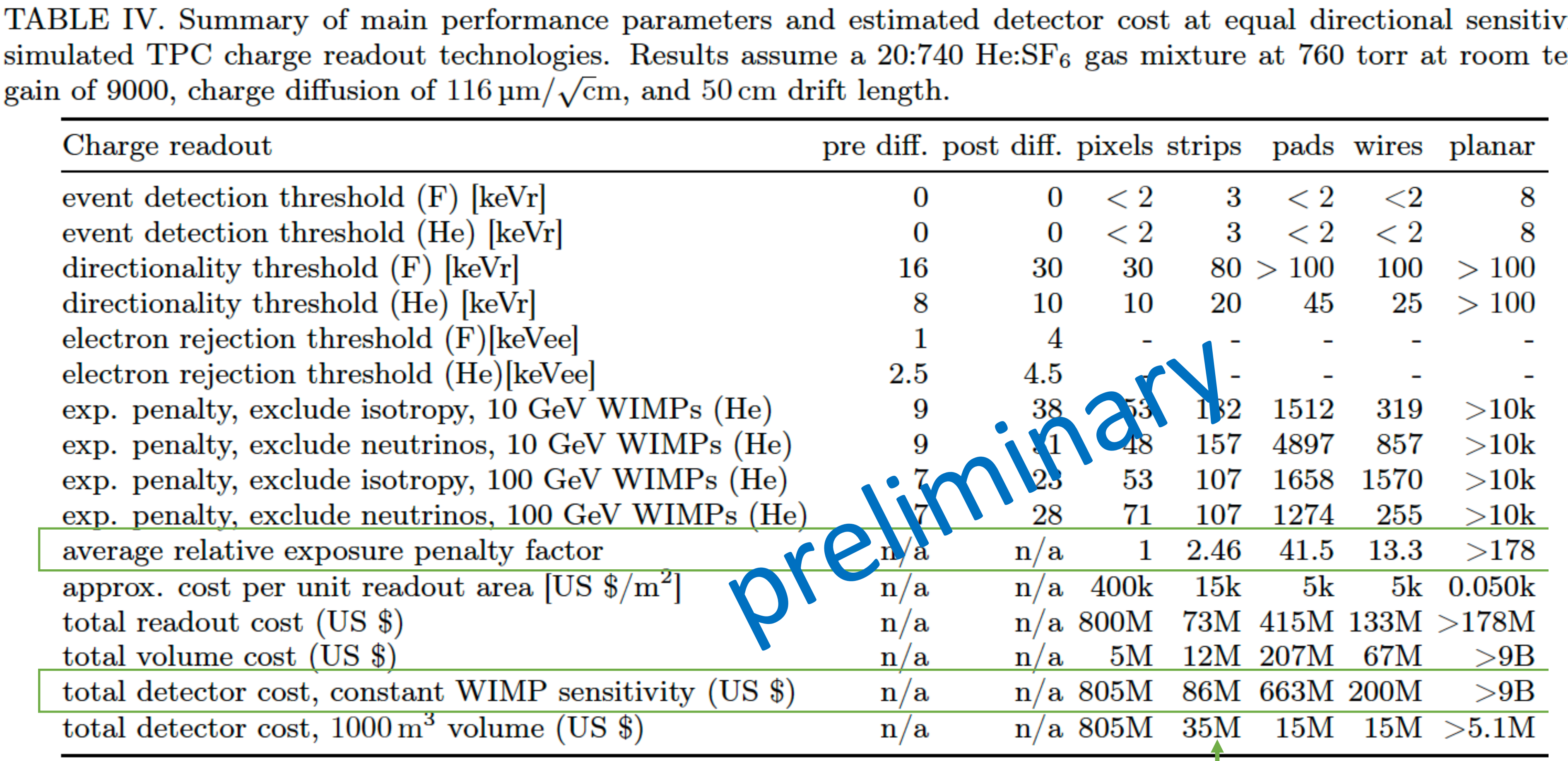


TABLE IV. Summary of main performance parameters and estimated detector cost at equal directional sensitivity, for the simulated TPC charge readout technologies. Results assume a 20:740 He:SF_6 gas mixture at 760 torr at room temperature, gain of 9000, charge diffusion of 116 μm/$\sqrt{\text{cm}}$, and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

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

preliminary

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

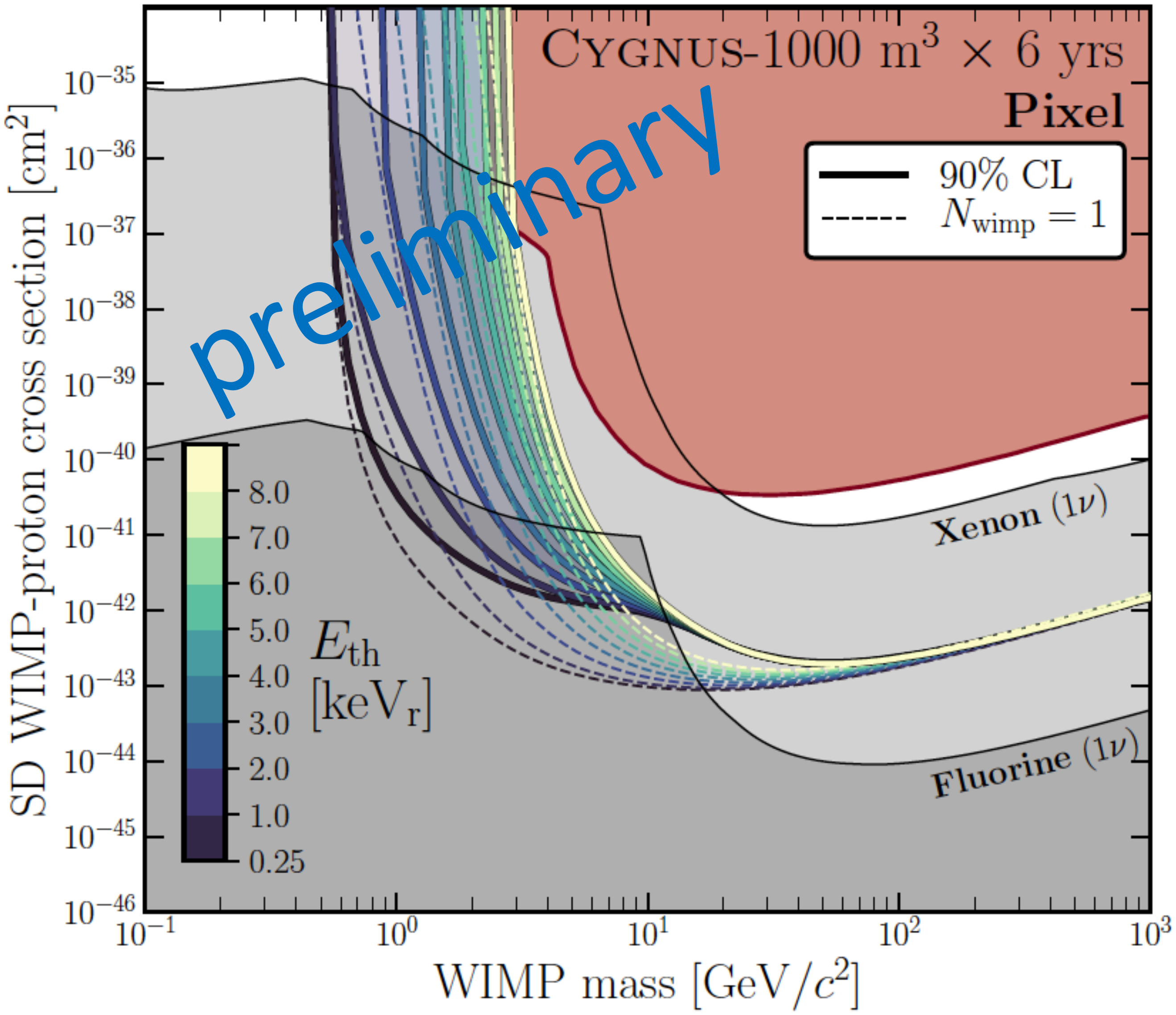
CYGNUS SD Sensitivity

CYGNUS 1000: 10m x 10m x 10m

He+SF$_6$ 755+5

- Significant improvement in SD WIMP reach over existing experiments
- Both for high and low WIMP masses
- Sensitive well below Xe neutrino floor – where LXe experiments are not sensitive
- Low-energy reach depends strongly on electron rejection

Ciaran O'Hare



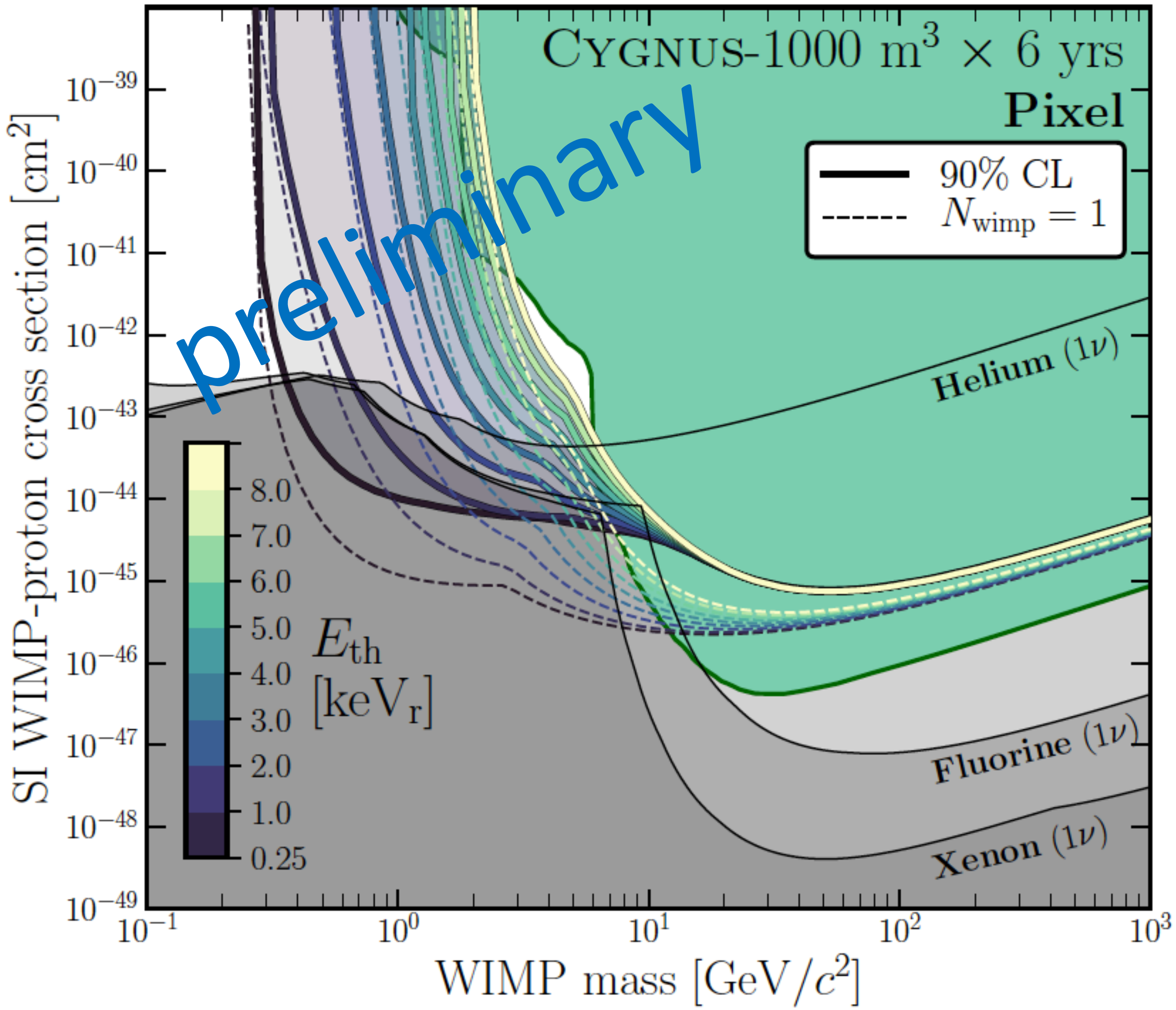
CYGNUS SI Sensitivity

CYGNUS 1000: 10m x 10m x 10m

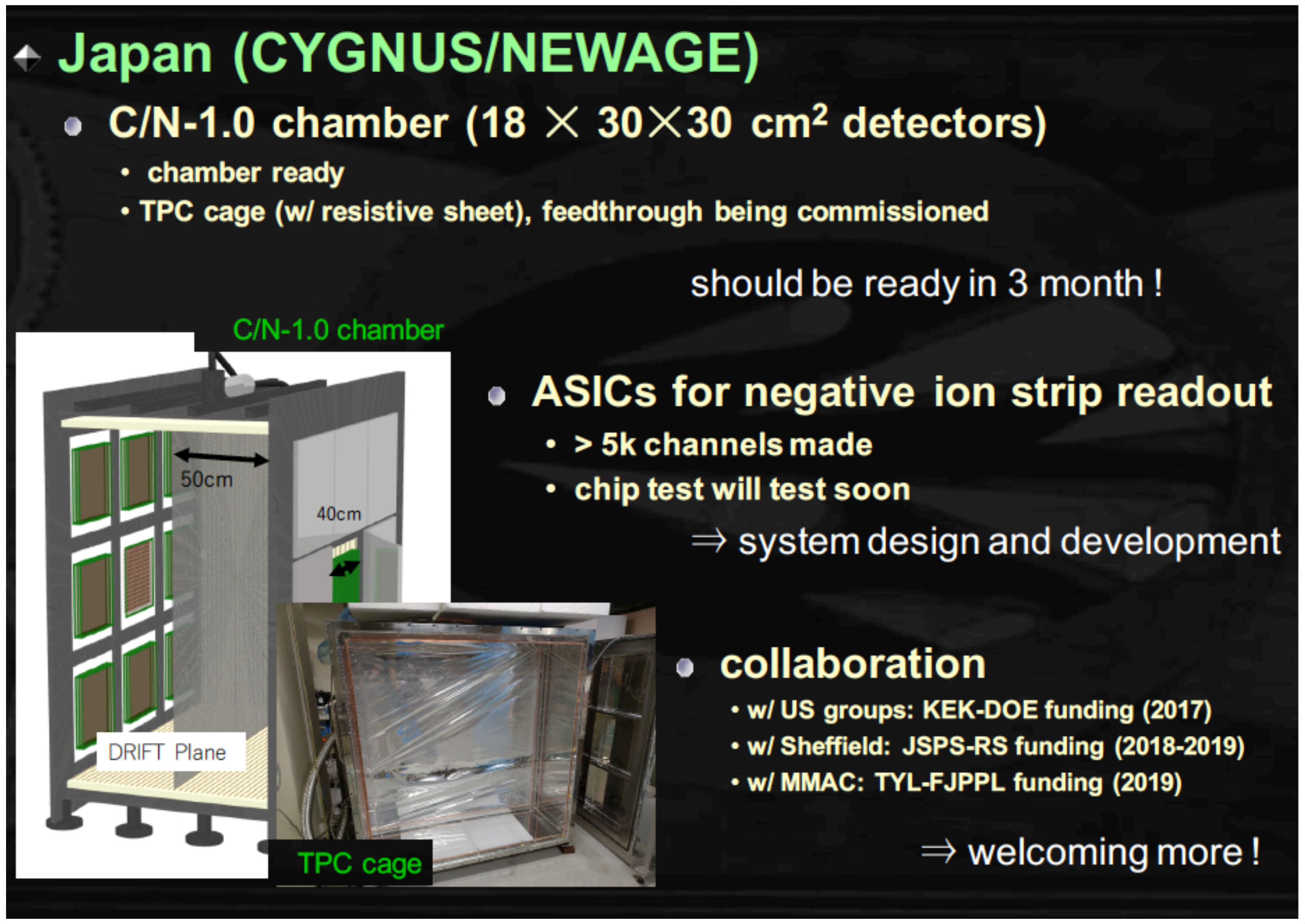
He+SF_6 755+5

- Main improvement is in WIMP *mass* reach
- Need more F in gas mixture to be competitive at higher masses
- Improvement depends strongly on electron rejection
- Expect 10-50 neutrino recoil events, (CEvNS) both He and F

Ciaran O'Hare



CYGNUS Japan



Japan (CYGNUS/NEWAGE)

- C/N-1.0 chamber (18 × 30×30 cm^2 detectors)
  - chamber ready
  - TPC cage (w/ resistive sheet), feedthrough being commissioned

should be ready in 3 month !

- ASICs for negative ion strip readout
  - > 5k channels made
  - chip test will test soon

⇒ system design and development

- collaboration
  - w/ US groups: KEK-DOE funding (2017)
  - w/ Sheffield: JSPS-RS funding (2018-2019)
  - w/ MMAC: TYL-FJPPL funding (2019)

⇒ welcoming more !

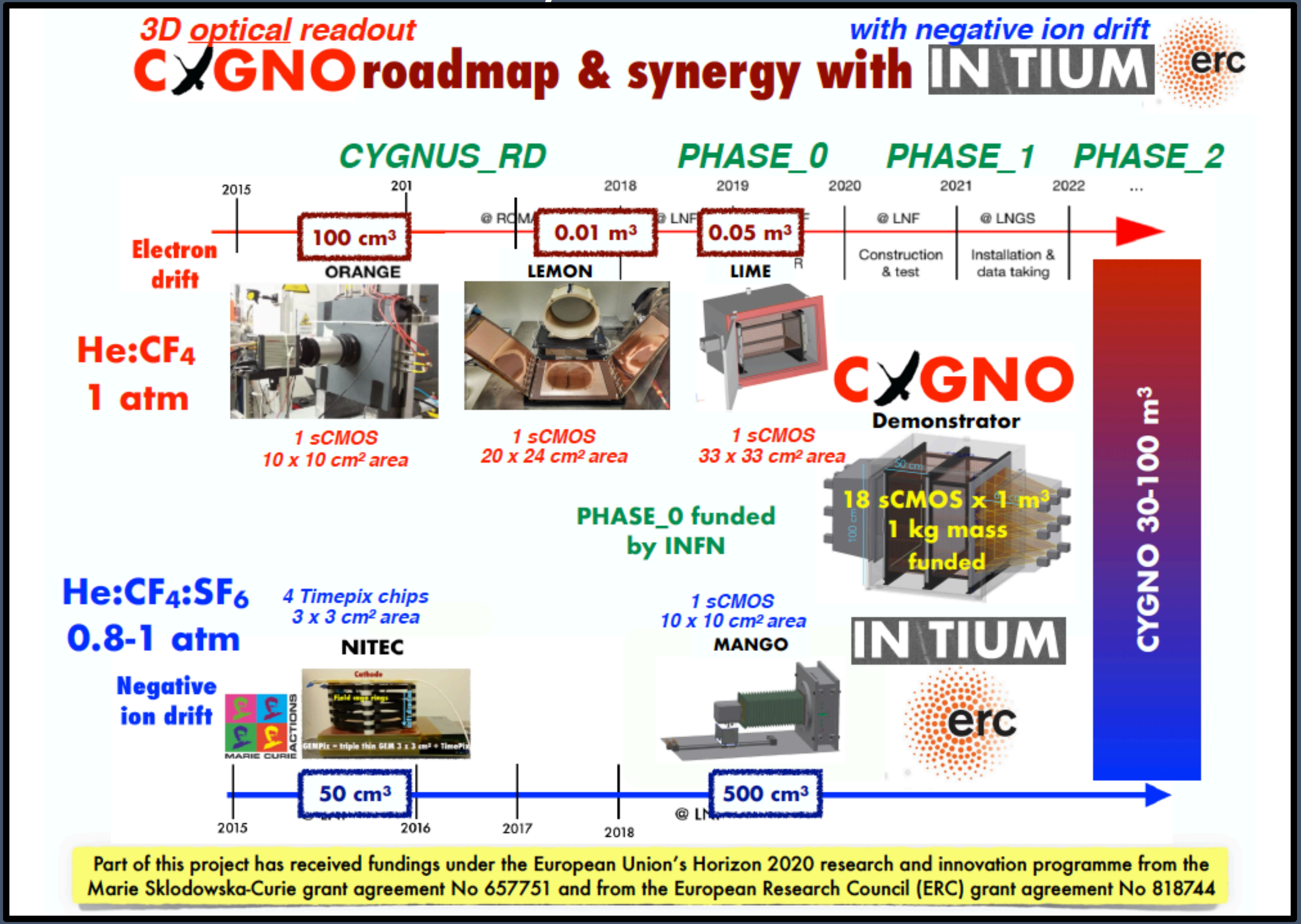
- Focusing on strip and pixel readout
- NEWAGE detector already running underground
- 1-m^3 chamber funded and in place, detector construction ongoing
- Intended site: Kamioka

CYGNUS U.K.

Underground at Boulby

- Focusing on GEM and wire readout
- 1-m^3 exists (DRIFT)
- 10-m^3 proposed
- Extensive clean lab space available underground at Boulby Mine --- and easy to excavate more

CYGNUS Italy



3D optical readout

CYGNO roadmap & synergy with INITIUM

with negative ion drift

erc

CYGNUS_RD *PHASE_0* *PHASE_1* *PHASE_2*

2015 201 2018 2019 2020 2021 2022 ...

Electron drift

100 cm³ ORANGE

@ ROMA

0.01 m³ LEMON

@ LNF

0.05 m³ LIME

@ LNF Construction & test

@ LNGS Installation & data taking

He:CF$_4$ 1 atm

1 sCMOS 10 x 10 cm² area

1 sCMOS 20 x 24 cm² area

1 sCMOS 33 x 33 cm² area

CYGNO Demonstrator

18 sCMOS x 1 m³ 1 kg mass funded

PHASE_0 funded by INFN

He:CF$_4$:SF$_6$ 0.8-1 atm

Negative ion drift

MARIE CURIE ACTIONS

4 Timepix chips 3 x 3 cm² area

NITEC

1 sCMOS 10 x 10 cm² area

MANGO

INITIUM

erc

50 cm³ 500 cm³

2015 2016 2017 2018

@ LN

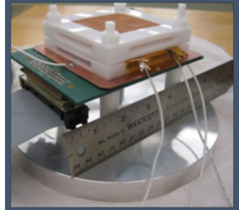
CYGNO 30-100 m³

Part of this project has received fundings under the European Union's Horizon 2020 research and innovation programme from the Marie Sklodowska-Curie grant agreement No 657751 and from the European Research Council (ERC) grant agreement No 818744

- Focusing on optical readout
- Two parallel R&D paths
  - electron drift
  - negative ion drift
- 1-m^3 scale funded as demonstrator for 30-50 m^3
- Intended site: Gran Sasso

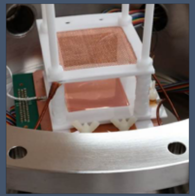
CYGNUS U.S.

2011-2013



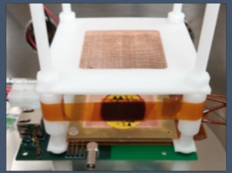
μD^3 (~1cm^3)

2013



~2.5 cm^3

2013



~ 20 cm^3

1st generation,
proof of concept

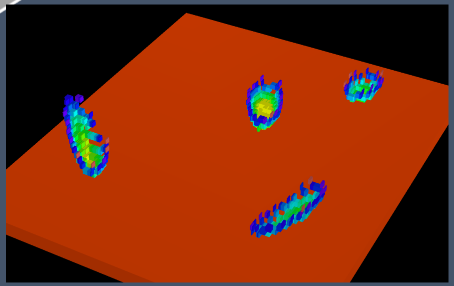
2014

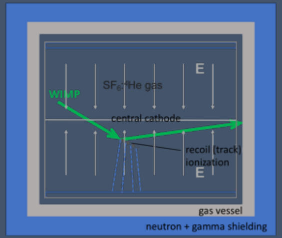
2 x 60 cm^3

2015

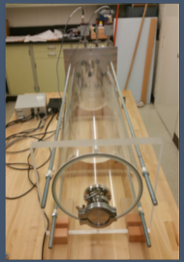
8 x 40 cm^3

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





proposed: CYGNUS HD1 → 10

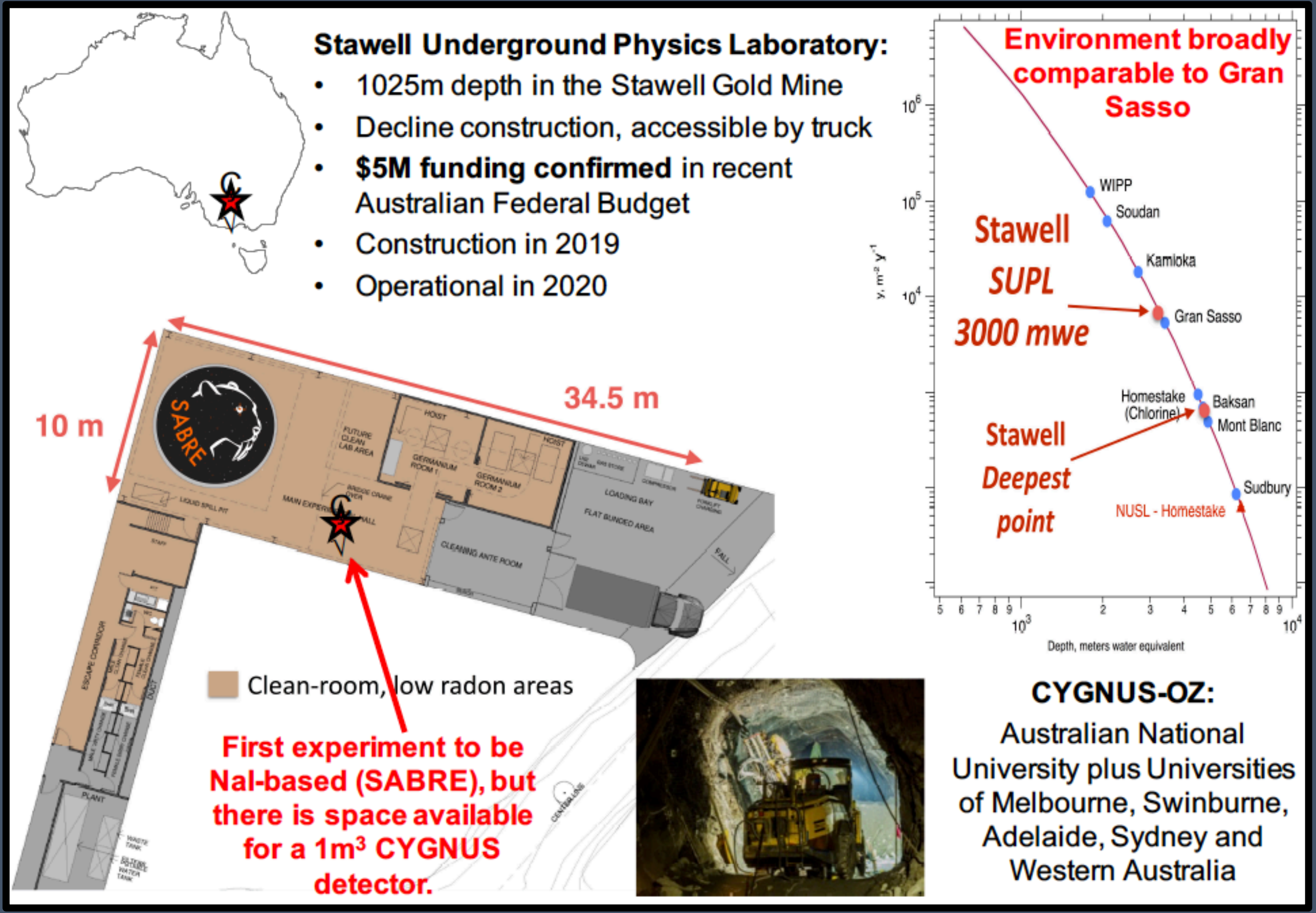


New prototype Fall 2019

3rd Generation: Optimized for dark matter

- Focusing on pixel, strip readout (HD)
- Extensive prototyping completed
- CYGNUS HD1 1-m^3, demonstrator for 10 m^3, proposed
- Intended site: SURF

CYGNUS-Australia



Stawell Underground Physics Laboratory:

- 1025m depth in the Stawell Gold Mine
- Decline construction, accessible by truck
- **$5M funding confirmed** in recent Australian Federal Budget
- Construction in 2019
- Operational in 2020

Environment broadly comparable to Gran Sasso

Stawell SUPL 3000 mwe

Stawell Deepest point

Clean-room, low radon areas

First experiment to be NaI-based (SABRE), but there is space available for a 1m³ CYGNUS detector.

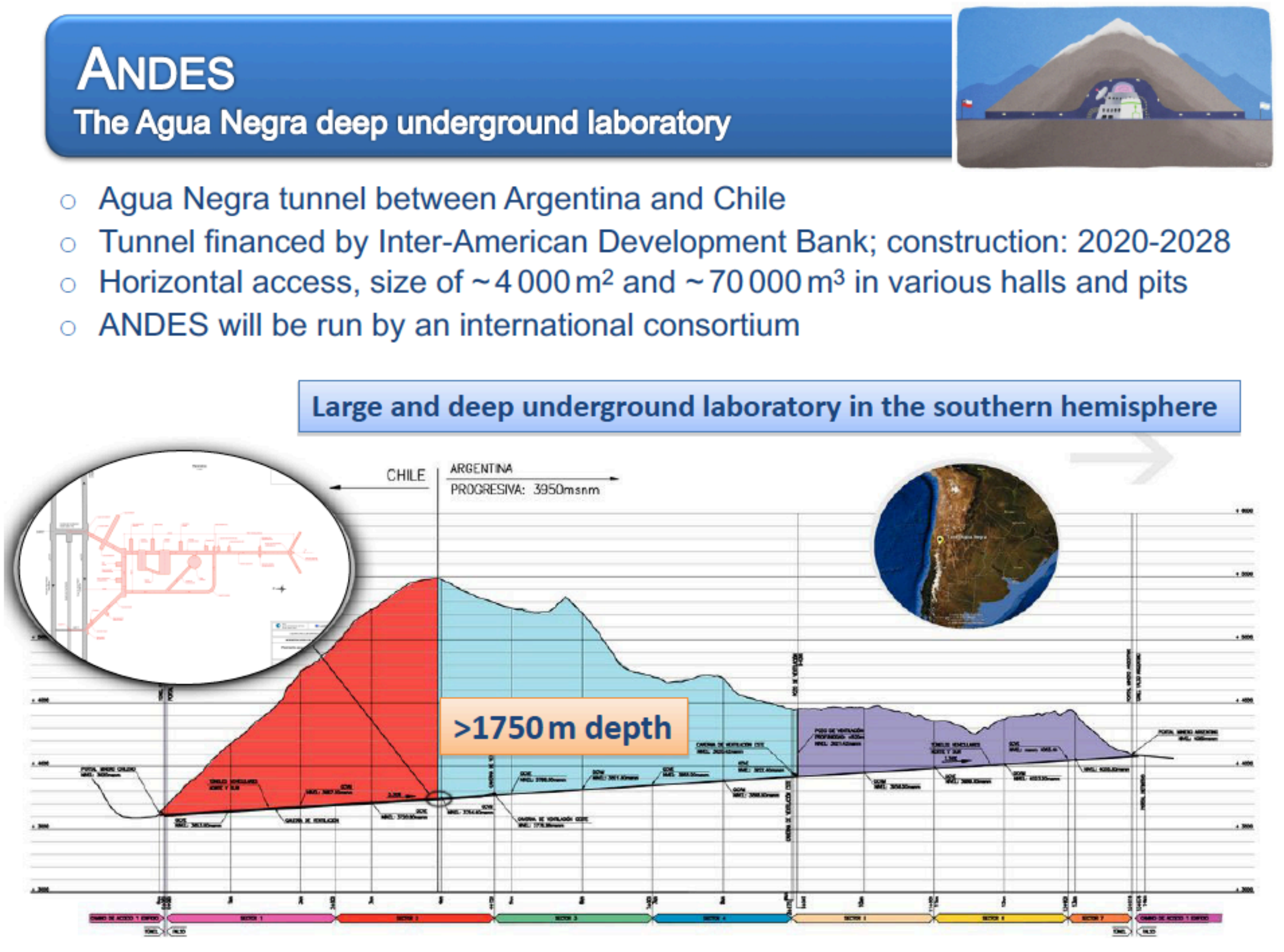
CYGNUS-OZ:

Australian National University plus Universities of Melbourne, Swinburne, Adelaide, Sydney and Western Australia

- New lab, operational next year
- Space available for planned 1-m^3 CYGNUS gas TPC

CYGNUS *ANDES*

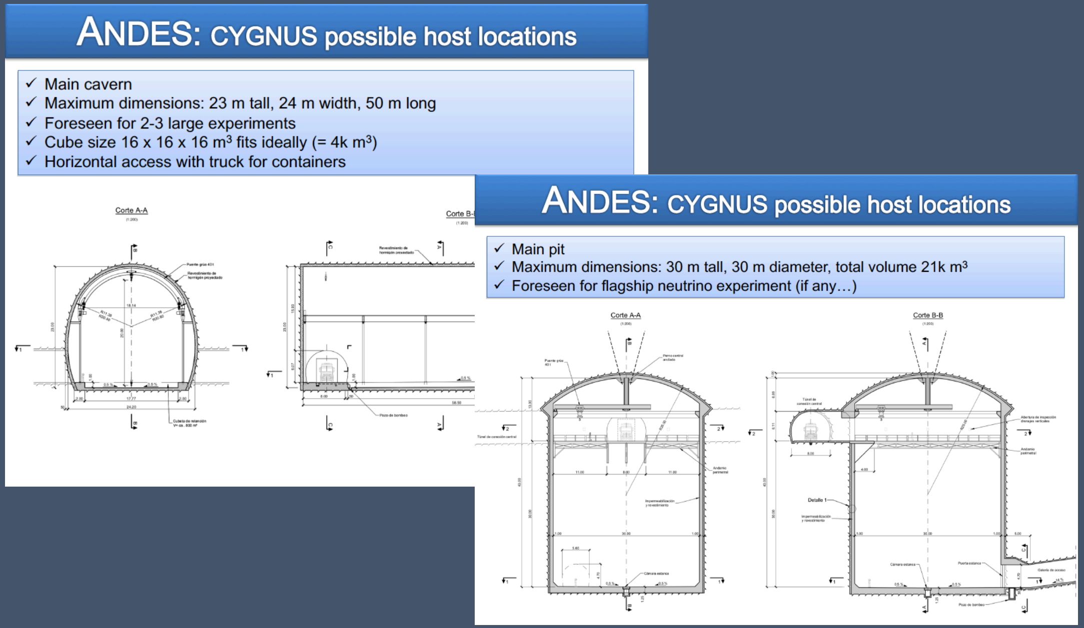
- Future lab
- Significant space suitable for for CYGNUS 1000 m^3 and beyond



ANDES
The Agua Negra deep underground laboratory

- Agua Negra tunnel between Argentina and Chile
- Tunnel financed by Inter-American Development Bank; construction: 2020-2028
- Horizontal access, size of ~4 000 m^2 and ~70 000 m^3 in various halls and pits
- ANDES will be run by an international consortium

Large and deep underground laboratory in the southern hemisphere



ANDES: CYGNUS possible host locations

- ✓ Main cavern
- ✓ Maximum dimensions: 23 m tall, 24 m width, 50 m long
- ✓ Foreseen for 2-3 large experiments
- ✓ Cube size 16 x 16 x 16 m^3 fits ideally (= 4k m^3)
- ✓ Horizontal access with truck for containers

ANDES: CYGNUS possible host locations

- ✓ Main pit
- ✓ Maximum dimensions: 30 m tall, 30 m diameter, total volume 21k m^3
- ✓ Foreseen for flagship neutrino experiment (if any…)

Conclusion & Summary

- Much of worldwide directional detection community merged into CYGNUS
- Work on science case for 1000 m^3 detector nearly complete
  - Unique sensitivity in both SD (cross section) and SI (mass), in a single detector, with improved electron rejection expected at low masses
- 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
  - neutrino physics
  - eventually, WIMP astronomy
- Important next steps:
  - Experimentally demonstrate directional performance and electron rejection
  - Move from strawman design to technical designs
  - Evaluate complementary physics opportunities in more detail