What Next Dark Matter GdI
10th July 2014

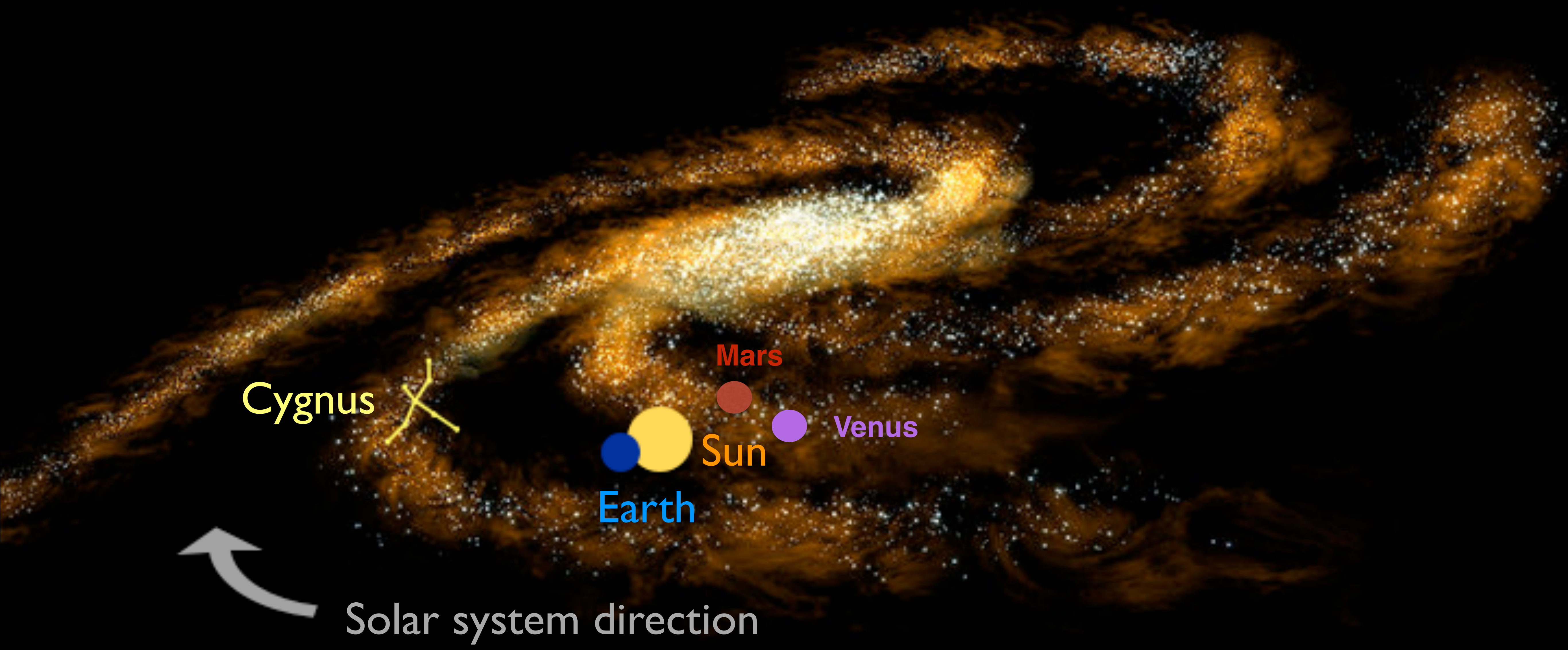
NITEC: a Negative Ion Time Expansion Chamber for directional dark matter searches

Programma "SIR"
Decreto del 23 gennaio 2014 prot. n. 197
Protocollo: RBSI14N9OV

Programma Per Giovani Ricercatori
"Rita Levi Montalcini"
PROPOSTA DI CONTRATTO
Codice: PGR1335VLA

Elisabetta Baracchini
ICEPP, The University of Tokyo

In collaboration with G. Bencivenni, D. Dominici, F. Murtas

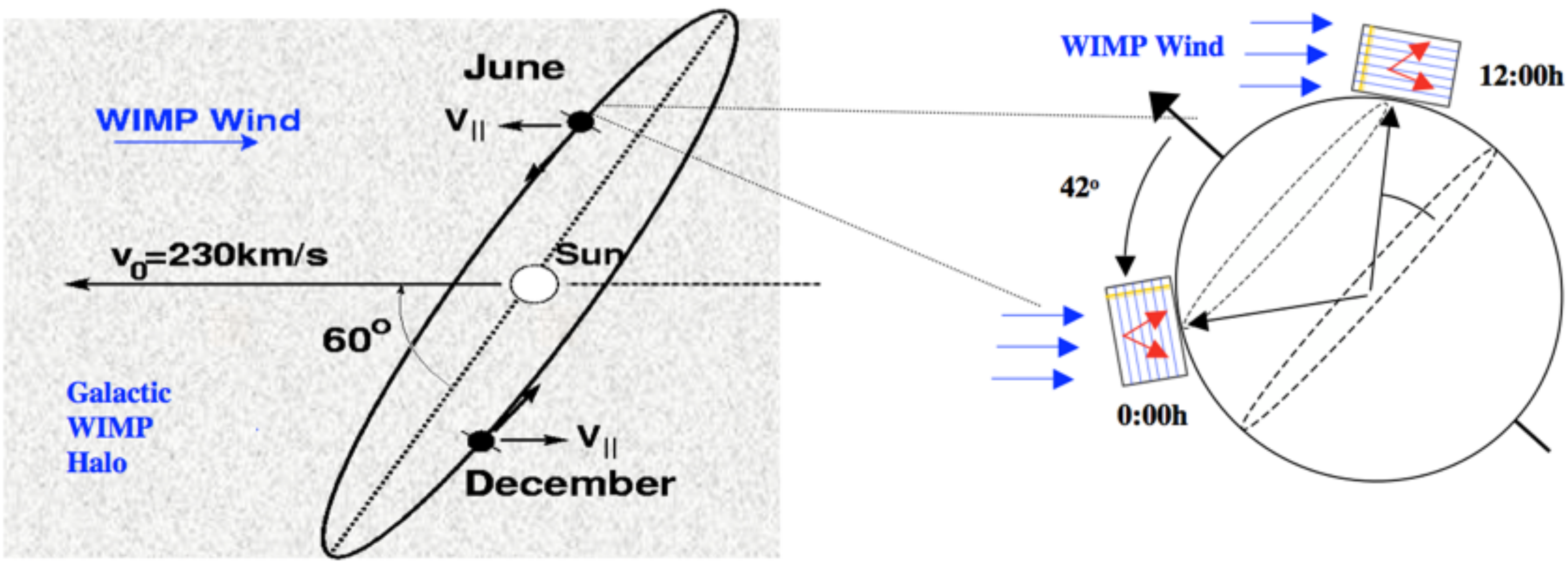


Men are from Mars, Women are from Venus
.....and WIMPs are from Cygnus :)

A very powerful observable

- *Annual Modulation:* as a result of Earth motion relative to WIMP halo; rate modulation with a period of 1 year and phase ~2 June; large mass required (~2% effect)

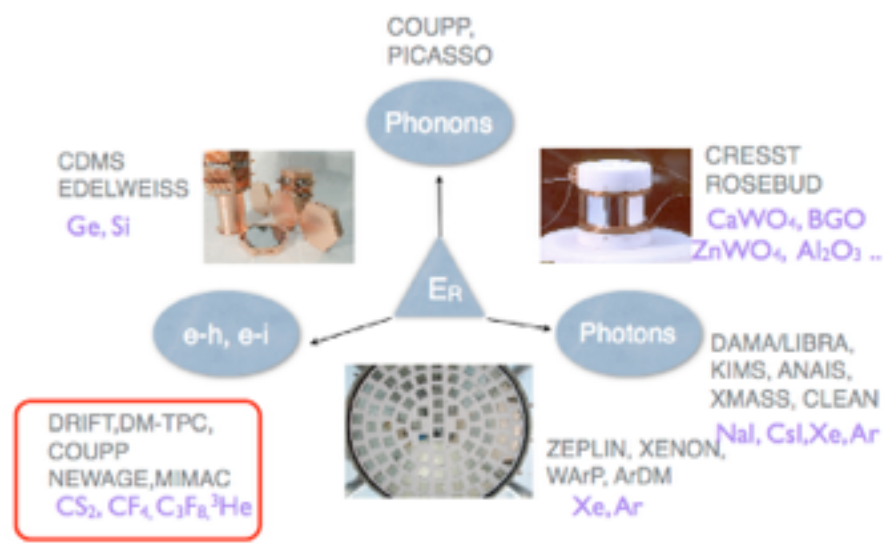
- *Diurnal Direction Modulation:* Earth rotation about its axis, oriented at angle w/respect to WIMP "wind", change the signal direction by 90 degree every 12 hrs. ~30% effect.



NO BACKGROUND can mimic a directional correlation with an astrophysical source

Gaseous Directional Detectors

you need a (low pressure) gas detector in order to observe a nuclear recoil track



- Gas Typically allow for low energy thresholds
- Gaseous detectors easily allow for different targets: just fill with different gas
- Directionality allows to perform WIMP astronomy and constraint WIMP properties
- Directional gaseous detectors potentially provide the best observables of any DM experiment:
  - total charge collected indicates energy of the recoil
  - comparison b/w track path and energy provide excellent rejection of alphas and electrons
  - the track itself indicates the axis of the recoil
  - measurement of charge (and dE/dx) along the path allows to infer the sense of direction

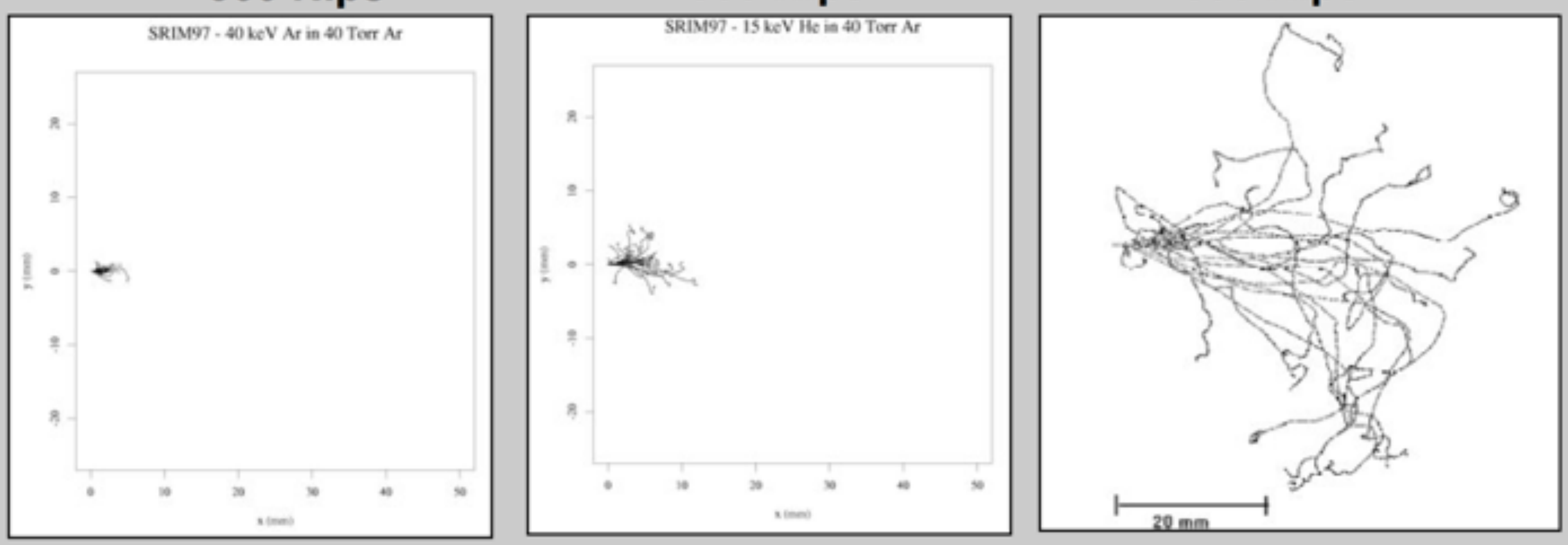
much more efficient means to actively suppress background than any other experimental approach

Gaseous Detectors Particle Identification

Particle Identification

simulation

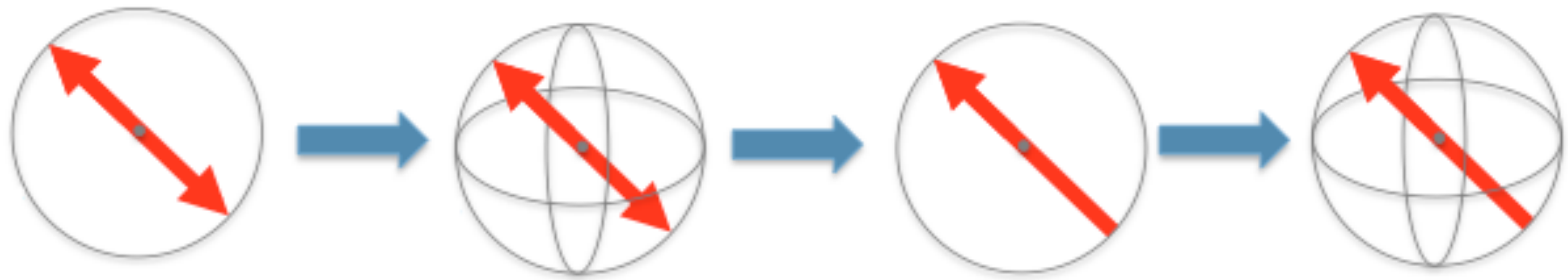
40 keV Ar recoils from WIMPs 500 Nips	15 keV as from radioactivity 500 Nips	13 keV e^-s from radioactivity 500 Nips



Key points: it's range discrimination - no doubt

Key points: start at high pressure for events then low pressure for direction

Direction



2D "Axial" Angle | 3D "Axial" Direction | Full 2D Angle (with "Head-Tail") | Full 3D Direction (with "Head-Tail")

Good → Best

- Few events needed for discovery of directional signal
- Can deal with background contamination
- Can better constrain DM mass/halo parameters

A. M. Green, B. Morgan, Astropart.Phys.27:142-149,2007
J. Billard, F. Mayet, D. Santos, arXiv:1009.5568

A WIMP directional signal could ***(in principle)*** be detected with of order 10 events
[Copi, Heo & Krauss; Copi & Krauss; Lehner & Spooner et al.]

Gaseous Directional Detectors

Collaboration	Technology	Target	Amplification + Readout	Volume (m^3)	Country
DRIFT	NITPC	CS_2, CS_2:CF_4	MWPC	1	UK-US
DMTPC	TPC	CF_4	mesh chambers + Optical CCD	0.02	UK-US
NEWAGE	TPC	CF_4	Micro Pixel Chamber μPIC	0.02	Japan
MIMAC	TPC	$^3He/CF_4$	pixelized Micromegas	0.006	France
D^3 (prototype)	TPC	CF_4	double GEM + pixel	1×10^{-6}	US
NITEC	NITPC	CS_2/CH_3NO_2:CF_4	triple GEM + pixel	0.005	Italy

Current experimental challenges

- 3D track reconstruction, possibly with sense determination (not available to all experiments and for most limited > 100 keVnr)
- Lowest possible energy threshold (current >= 50 keVnr w/ directionality, >=20 keVnr without)
- Possibility to be scaled to large active mass with low costs (all except DRIFT limited to <= 25 cm drift length)

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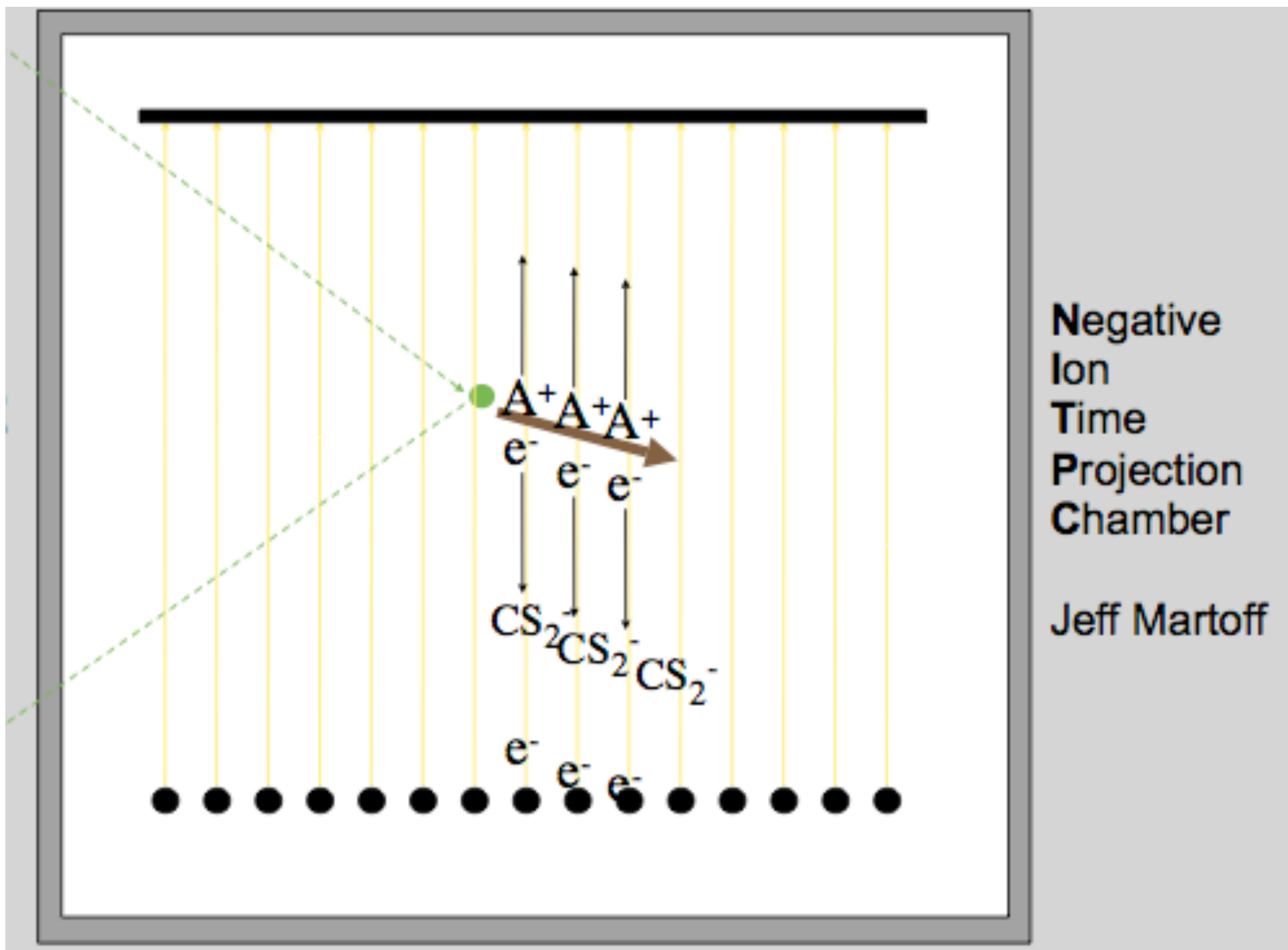
NITEC main features:

- Negative Ion Time Projection Chamber ---> to overcome conventional TPC volume limitations (~> 50 cm drift length) and improve position and energy resolution
- Triple GEM amplification with pixelated readout ---> for the state of the art spatial, time and energy resolution (sense determination via charge and dE/dx measurement along path)
- Explore the use of Nitromethane (CH_3NO_2), recently suggested as a more benign, lower Z electron capture agent --> possibility of using NITEC as X-ray polarimeter in the 1-10 keV band or neutrinoless double beta decay detector and easier gas handling

Negative Ion concept



< 0.5 mm diffusion achieved over 0.5 m drift length (NIM A 440 355, NIM A 463) w.r.t. 10 mm obtained with electrons

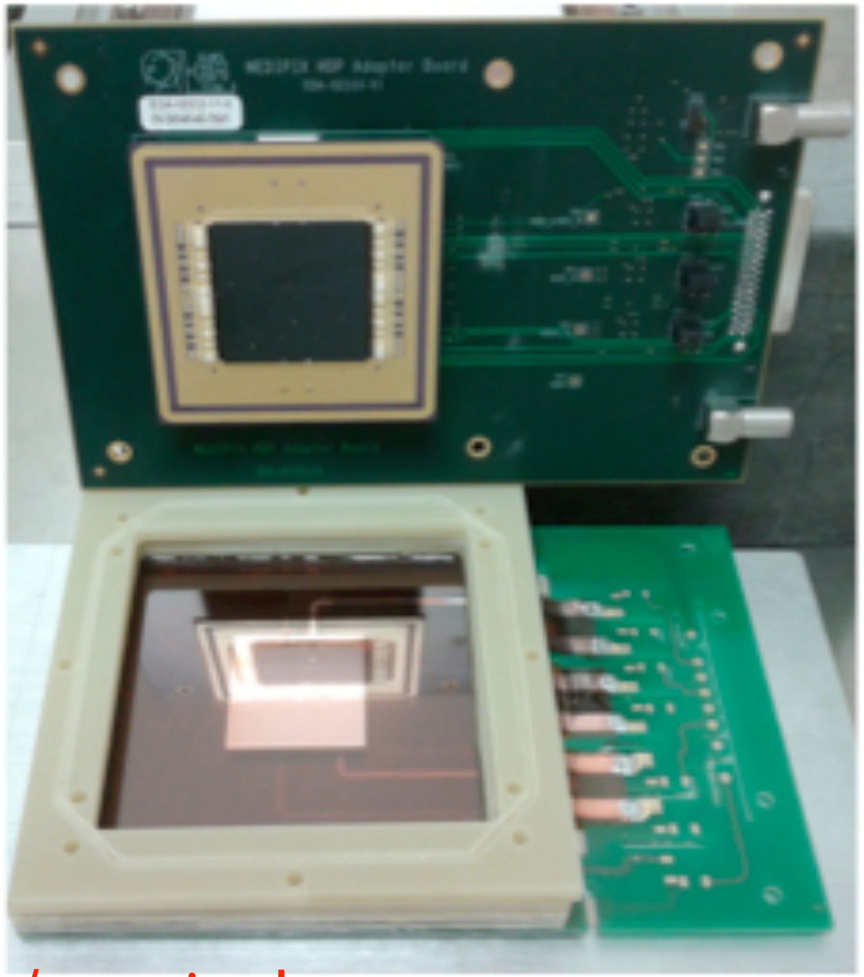
- Mixture of target gas + electronegative gas (typically CS_2)
- Primary ionization electrons are captured by the electronegative molecules at O(100) um
- Anions drift to the anode (where normal electron avalanche multiplication occur) acting as the effective charge carrier instead of the electrons
- Thanks to the much higher anions mass w.r.t. electrons, longitudinal and transversal diffusion can be reduced to thermal limit w/out any magnetic field

GEMPix

- The GEM is a micro pattern gas detector, thin holes are etched in a kapton foil and a potential is placed across it
- Very large electric field around the holes which creates an electron avalanche
- Couple a timepix asic for readout of a triple Gas Electron Multipler (GEM) detector

Triple GEM

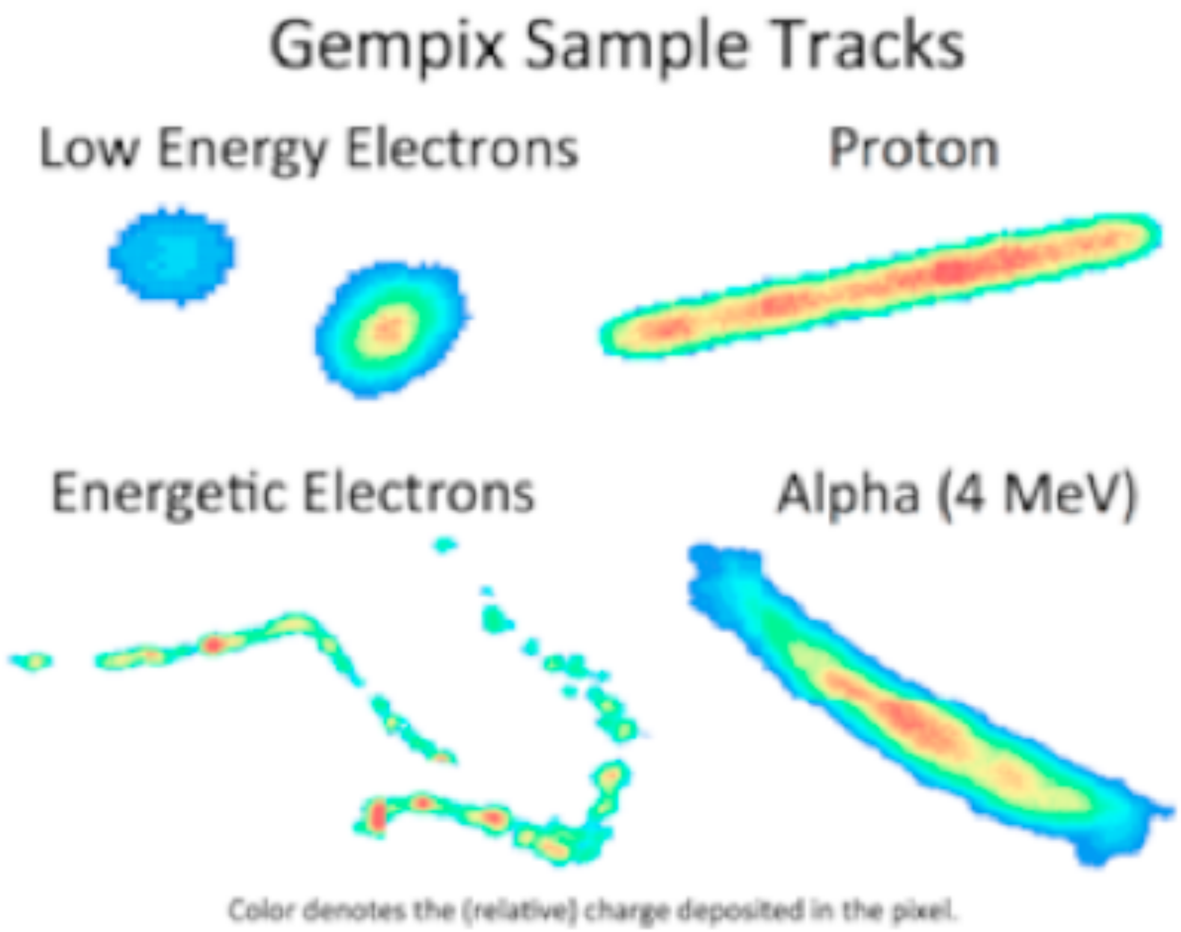
Quad Timepix ASIC

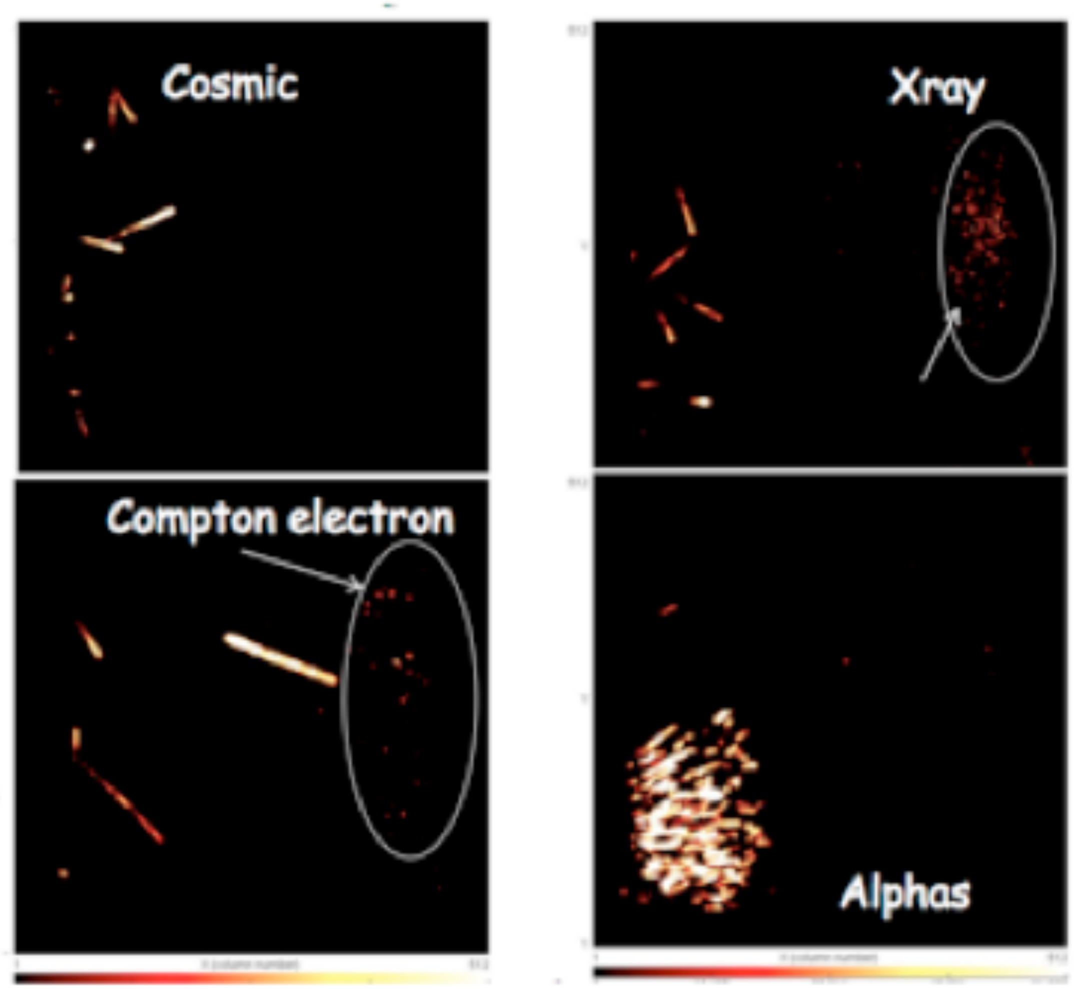


https://web2.infn.it/GEMINI/index.php/gempix-detector

GEMPix performances

5ns time resolution, 200 um spatial resolution, sensitivity to single ionization cluster, possibility to measure time AND charge for each pixel cluster at the same time





These pictures were taken with radiactive sources of ^{55}Fe Cesium and Americium

Using a gas mixture of $Ar/CO_2/CF_4$ 45/15/40

With a gain of 6000 and an induction field of 2 kV/cm

CNAO
CERN
ARDENT
INFN

Possibility of customizing GEMPix to our needs for the full length prototype in collaboration with LNF electronic department, starting from the results of Phase I (see later)

Negative Ion + GEMPix = NITEC

- At moderately high reduced fields, anions drift at about 100 m/s, compared to about 10^4 m/s for electron in typical atmospheric pressure drift chamber conditions
- Excellent GEMPix time, energy and spatial resolutions
- Slow anions speed + typical separation of primary ionization clusters in gas + GEMPix performances = Time Expansion Chamber
  - Single ionization clusters drift slowly and can be individually observed with high precision: a relative time expansion between ionization process and signal readout has effectively been achieved
- Single ionization cluster observation can provide excellent dE/dx information, improved position resolution and possibility of superior energy resolution for low energy radiation (< 1 keV)

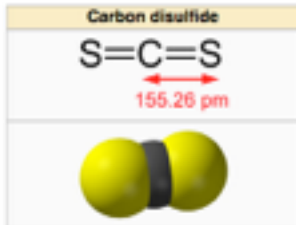
We believe that all these features combined will allow low energy threshold (~< 30-50 keVnr) and good 3D track reconstruction WITH directionality

"The Time Expansion Chamber and single ionization measurement" (A.H.Walenta, IEEE TNS 26 73)
"Suppressing drift chamber diffusion without magnetic field" (C.J.Martoff et al, NIM A 440)

Nitromethane as alternative electron capture agent

CS_2

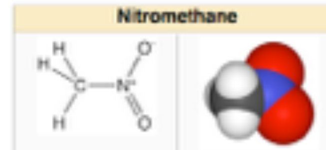
Carbon disulfide



Hazards	
MSDS	External MSDS
EU Index	006-003-00-3
EU classification	
R-phrases	R11, R36/38, R48/23, R62, R63
S-phrases	(S1/2), S16, S33, S36/37, S45
NFPA 704	
Flash point	−30 °C (−22 °F; 243 K)
Explosive limits	1.3–50%
LD_{50}	3188 mg/kg

CH_3NO_2

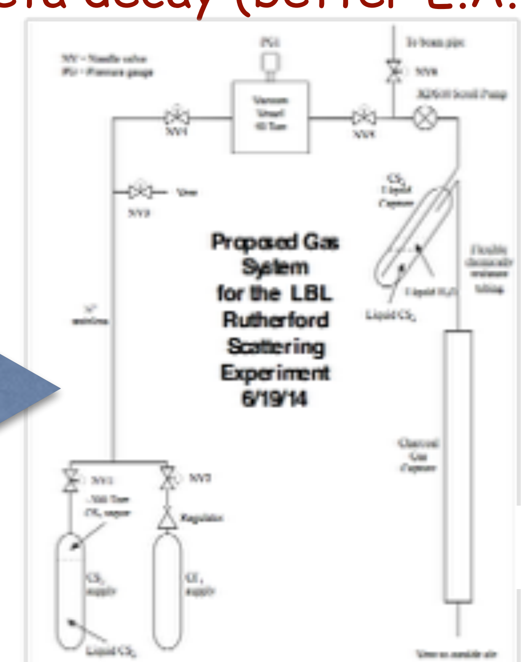
Nitromethane



Hazards	
MSDS	External MSDS
R-phrases	R5 R10 R22
S-phrases	S41
Main hazards	Flammable, harmful
NFPA 704	
Flash point	35 °C (95 °F; 308 K)

- Nitromethane is more benign and less dangerous than CS_2
- With Nitromethane, NITEC could be used also as
  - X ray polarimeter @ 1-10 keV (lower Z gases produce clearer signals)
  - Ultra high energy resolution (~0.005 FWHM) NITEC for neutrinoless double beta decay (better E.A.)

Already in contact with DRIFT community, who provided us with their gas system specifics and safety issues



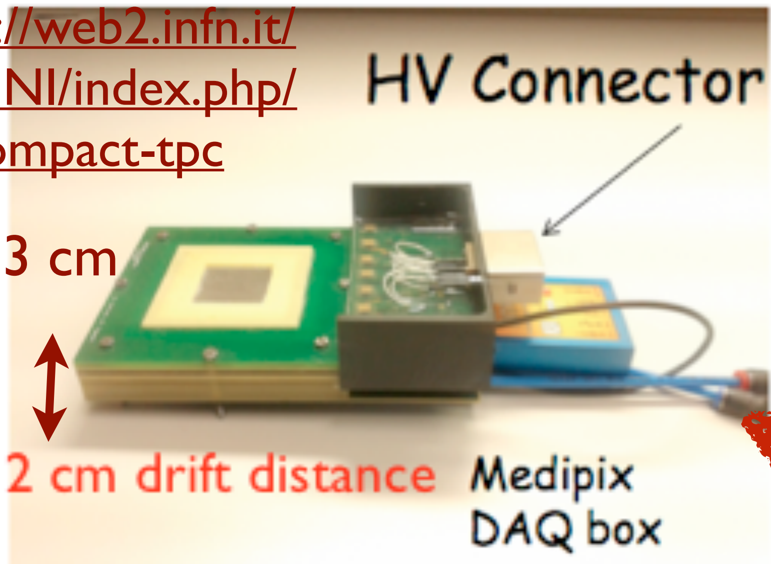
TASK SPECIFIC JOB HAZARD ANAYLSIS (TSJHA)

Staged Approach

Year 1	Year 2	Year 3

Phase I: Small prototype studies

https://web2.infn.it/GEMINI/index.php/compact-tpc



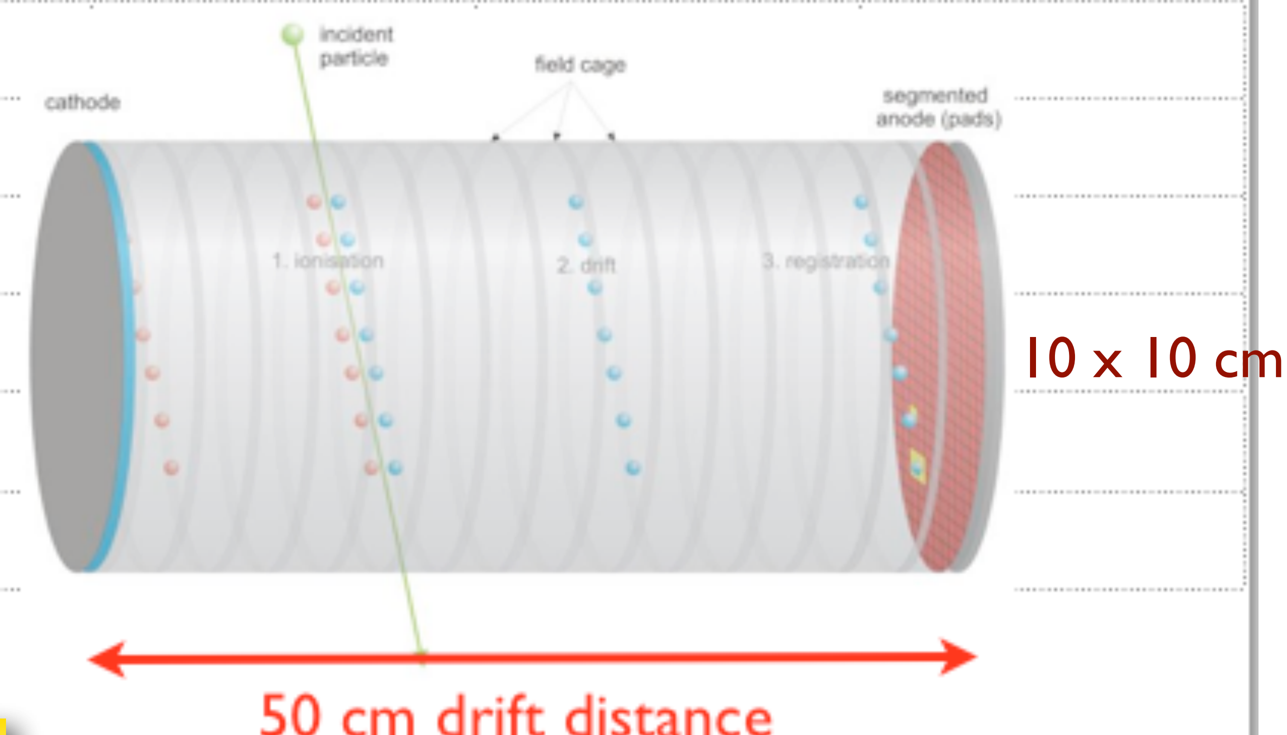
Employ an already existing small TPC prototype with GEMPix readout to prove its feasibility as Negative Ion TPC.

Study its working points, possible use of CH_3NO_2 and measure small prototype performances

Phase II: Design, development and performance assessment of NITEC

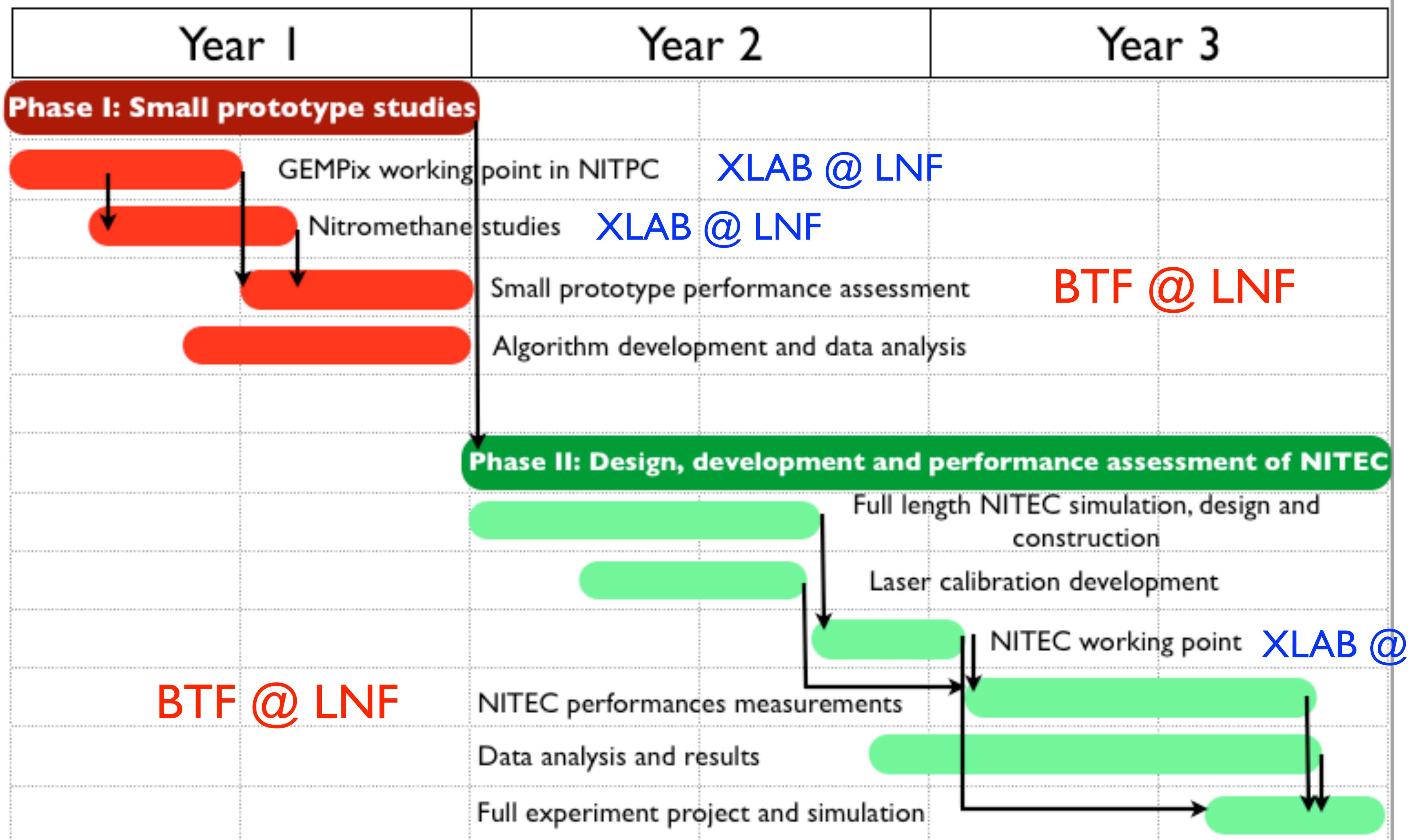
Starting from all the information obtained in phase I, design, build and commission a full length (50 cm drift distance) NITEC prototype

Measure its performances as directional DM detector



Full experiment project & simulation

Staged Approach



BTF & XLAB measurements fundamental in order to asses small and full length prototypes overall performances and response to signal-like (n@BTF) and background-like particles

Measurements @ BTF

- Measurements of spatial, time and energy resolution of the detector
- We have very long signal (slow ion drift) <---> we would need to optimize bunch length and repetition rate for our tests
- We look for very low energy processes <---> we would benefit from lower energy positrons/electrons/photons
- n@BTF pivotal for measuring detector response to signal-like particle: neutrons are just lighter WIMPs :)
  - In particular, crucial 3D track reconstruction, angular resolution and sense determination as a function of the energy threshold
  - In this respect, we would highly benefit from tagging the outgoing neutron and measuring its final direction and from a very precise knowledge of its energy

Already in contact with BTF community for future improvements and upgrade of the infrastructure (see NITEC talk at First BTF Users Workshop)

https://agenda.infn.it/conferenceDisplay.py?confId=7359

Costs & Manpower

SIR Contract

- Contract for PI for 3 years @ LNF
- Contract for Postdoc for 3 years @ LNF
- 18 person-months by permanent and temporary employees
  - Dr. G. Bencivenni, Dr. D. Domenici, Dr. F. Murtas
  - Total of 90 person-months for full project
- Budget to (fully) cover the project:
  - Gas system, laser calibration system, PCs, DAQ
  - Full length prototype fabrication and operation (GEMPix, vessel, HV system, vacuum pump)
  - Travel & conferences
- ~ 800 kEUROs budget

Awaiting for evaluation

Will apply also to Group 5 call for young scientists and Marie Curie

Rita Levi Montalicini Contract

- Contract for PI for 3 years @ University
  - Either Roma La Sapienza or Roma 3 or L'Aquila
  - Possibility to be hired as assistant professor after
- 55k EUROs budget (on top of PI contract)
  - Laser calibration system, PCs & DAQ
  - Travel & conferences
- Full endorsement from LNF with availability for use of LNF resources and facilities for prototype realization and tests


INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati
www.lnf.infn.it
Il Direttore

tel. + 39 06 9403 2223
fax + 39 06 9403 2582
email: prot@lnf.infn.it

Il sottoscritto Umberto Dosselli, nato a Lovere (BG) il 6 Ottobre 1955, e domiciliato per la carica in Frascati (RM), Via E. Fermi 40, nella sua qualità di Direttore dei Laboratori Nazionali di Frascati (LNF) dell'INFN, in relazione al progetto: *"NITEC: a Negative Ion Time Expansion Chamber for directional dark matter searches"*, codice: PGR1335VLA, presentato dalla Dottoressa Elisabetta Baracchini per il Programma per Giovani Ricercatori "Rita Levi Montalcini", dichiara:

- estremo interesse da parte dell'Istituto in generale e di parte dello staff permanente in particolare alla collaborazione con la Dottoressa Baracchini per lo sviluppo e la realizzazione dei prototipi proposti nel progetto di cui sopra;
- disponibilità all'utilizzo delle risorse dei Laboratori, quali camere pulite e supporto dai dipartimenti elettronico e di officina meccanica, per la costruzione dei prototipi;
- disponibilità all'utilizzo delle infrastrutture Beam Test Facility (BTF) e X LAB dei Laboratori per test e caratterizzazione dei prototipi.

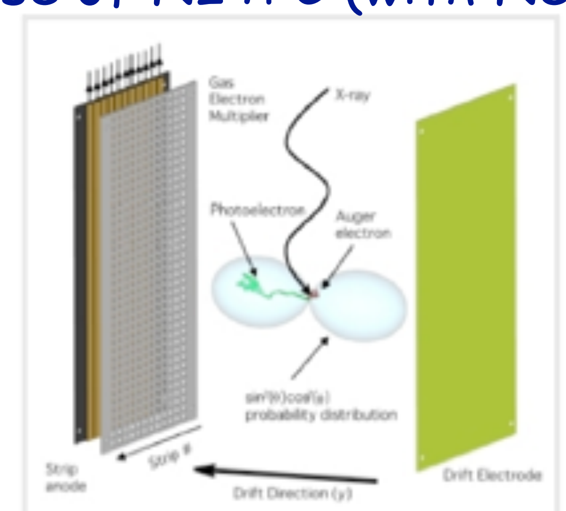
In fede,

LABORATORI NAZIONALI DI FRASCATI DELL'INFN
IL DIRETTORE
Dott. Umberto Dosselli

Not only DM: alternative NITEC applications

X ray polarimetry

- A photoelectron is emitted preferentially aligned with the electric field of the incident photon
  - Measurement of photoelectron direction provide information on photon polarization state
- Very few measurements of X ray polarization
- Can probe exotic astrophysical processes with the strongest gravitational and magnetic fields
- The community has just started to explore the use of NITPC (with Ne) [arXiv:1107.3079]



Neutrinoless double beta decay searches

- A NITEC capable of counting each primary free electron liberated in a Xe gas by an ionizing event, will approach the intrinsic fluctuations in the conversion of energy to ionization [D.Nygren, JPCS 65 012003]
- Even with counting efficiency significantly less than 100%, a 5 x 10^{-3} FWHM energy resolution could be achieved
- First tests with a 17 bar Xe conventional TPC show very encouraging results (1% FWHM) [A. Goldschmidt et al, IEEE NSSCR 1409]

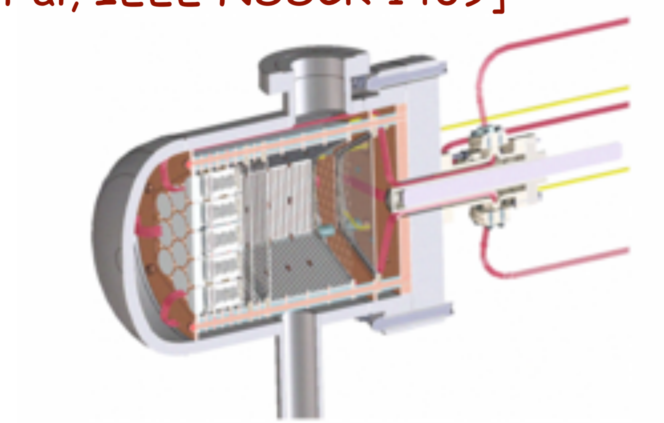


Fig. 1. Cross section of the TPC. Wire meshes separate the 19-PMT array from several regions, beginning at the mesh in front of the PMT array, from left to right; a 5 cm buffer region, an 8 cm drift region, a 3 mm EL gap, and another 5 cm buffer region. (Drawing by Robin LaFever.)

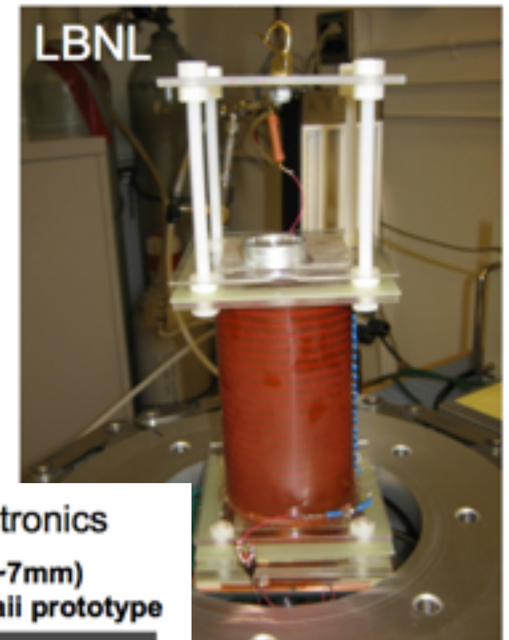
Domande per il GdI: possiamo puntare a WIMP di qualche GeV?

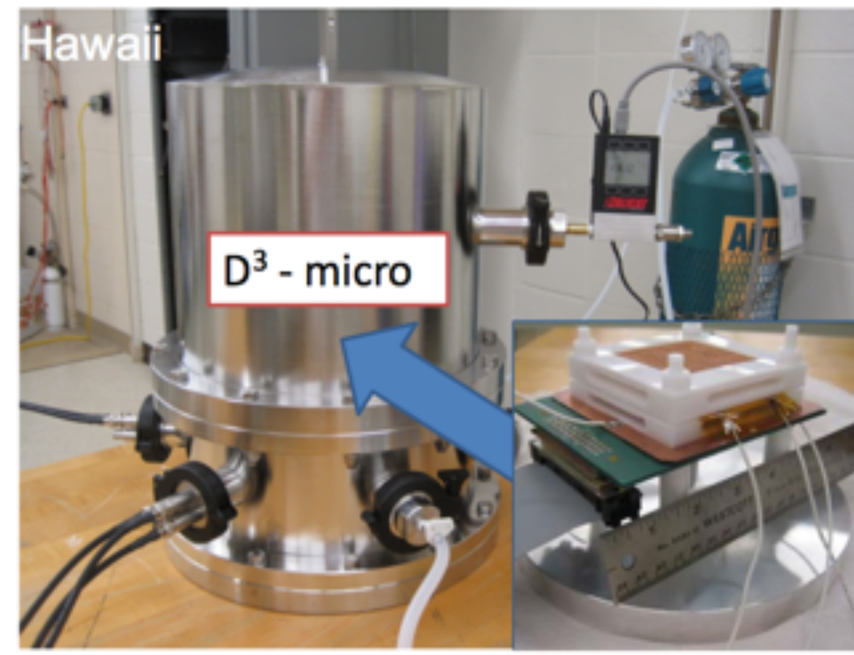
A close cousin: D^3 experiment

- Hawaii / LBNL collaboration (S. Vahsen / J. Kadyk, M. Garcia-Sciveres)
- Gas TPCs - drift charge read out w/ GEMs & ATLAS pixel electronics
- Small (1-10 cm^3) prototypes built to investigate feasibility of direction-sensitive DM search with this type of detector.
- Ongoing since ~Fall 2010 – youngest gas-target DM TPC effort

5. Energy Threshold

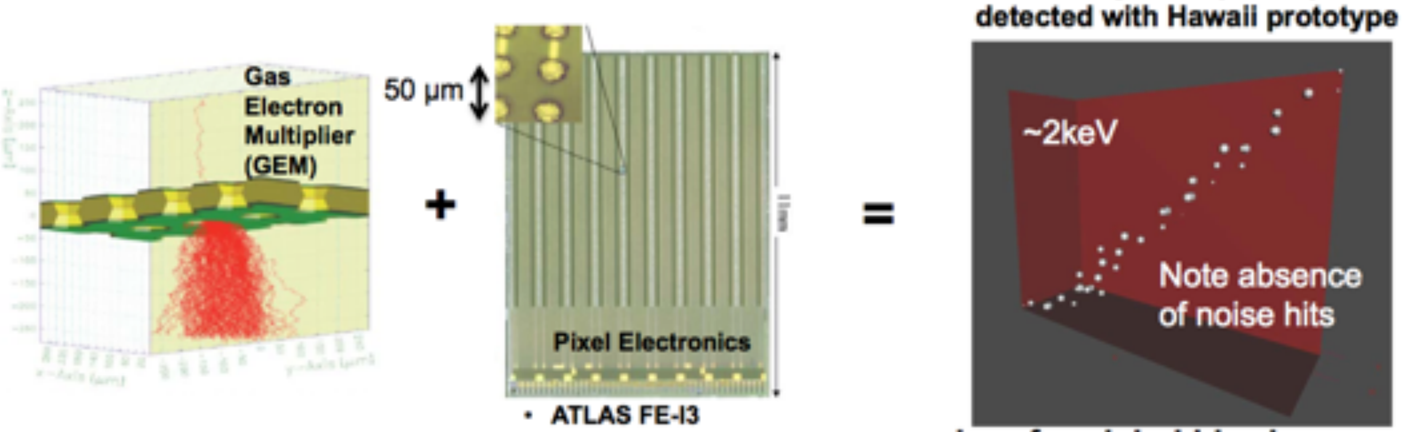
- Not yet measured. Goal is *directional* threshold of 10keV or lower. Non-directional threshold can be of order a few times 100 eV.





- Drift charge amplified with double layer of GEMS, detected with pixel electronics
- Gain ~20k, threshold ~2k e^-, noise ~ 100 e^-

Cosmic ray track (~7mm) detected with Hawaii prototype



- ATLAS FE-I3
- 50x400 μm pixels
- Sampling at 40 Mhz

size of each bubble shows amount of ionization measured

Advantages of this approach

- Full 3D tracking w/ ionization measurement for each spacepoint → **improved directional sensitivity and rejection of alpha particle backgrounds**
- Pixels ultra-low noise (~100 electrons), self-triggering, and zero suppressed → **virtually noise free at room temperature** → low demands on DAQ
- High-single electron efficiency → may be **suitable for (ultra?) low-mass** WIMP searches

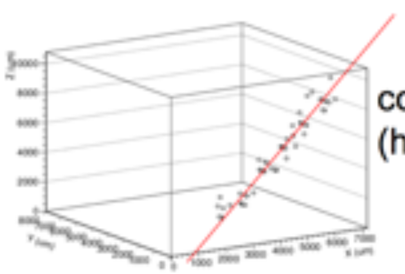
March 2013, Sven Vahsen   Pre-Snowmass DM Workshop @ SLAC

arXiv: 1110.3444
arXiv: 1110.3401

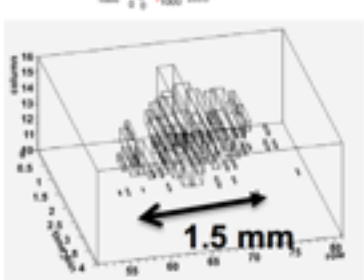
D^3 prototype performances

March 2013, Sven Vahsen   Pre-Snowmass DM Workshop @ SLAC

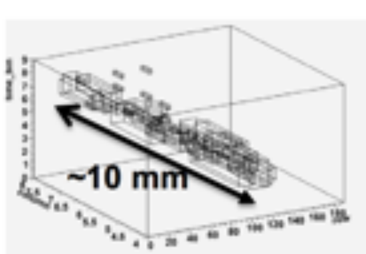
- Due to combination of high single-electron efficiency and low noise, expect low threshold operation, and good sensitivity to low-mass WIMPs
- Mostly excellent
  - Point resolution ~200 µm
  - Angular resolution ~ 1 degree for 5-10 mm tracks
  - Gain resolution ~5-10%
  - Gain stability <2%



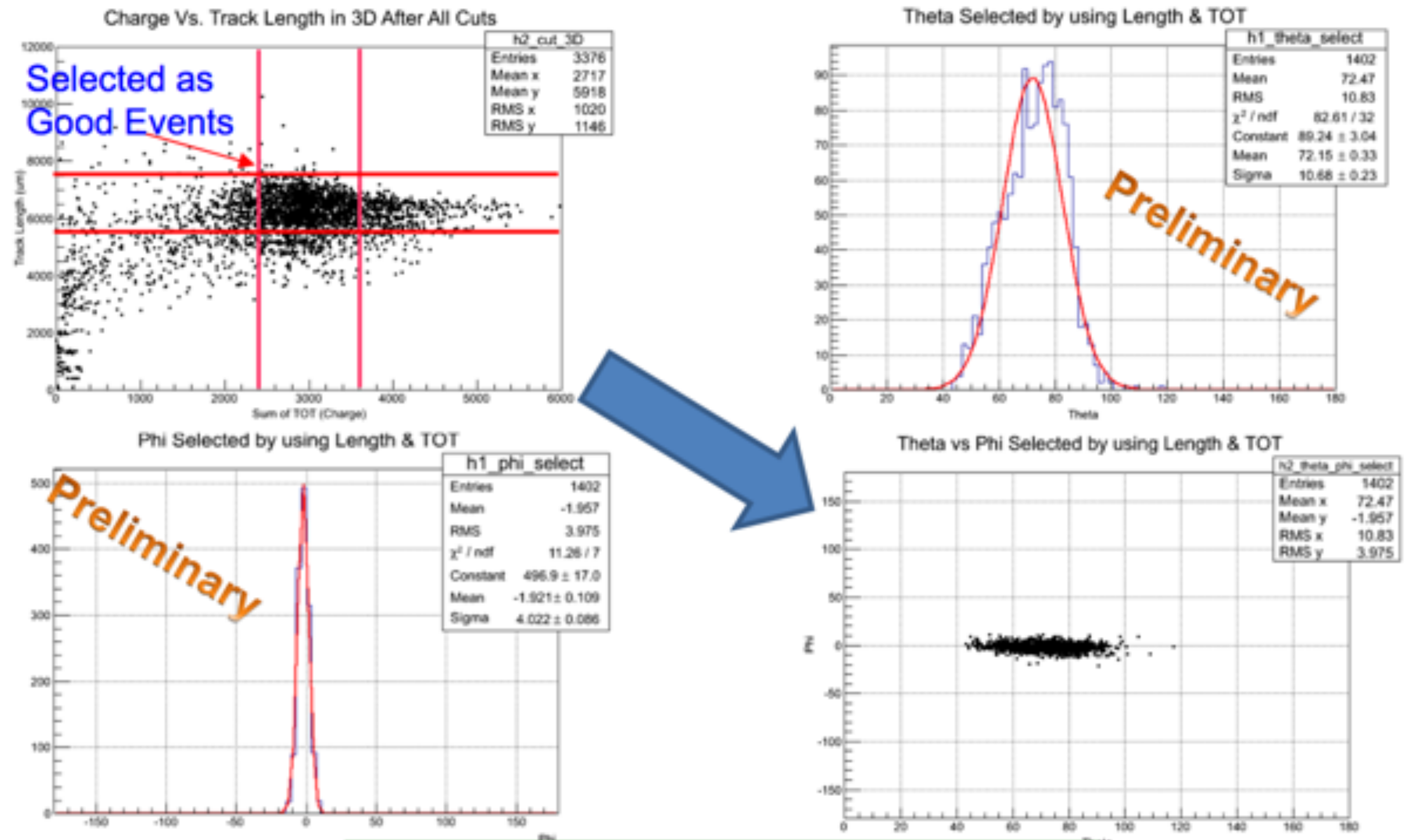
cosmic muon (high gain mode)



He-recoil candidate (low gain)



RPR event? (low gain)



upper limits: $\sigma_\theta = 10.68°, \sigma_\phi = 4.022°$

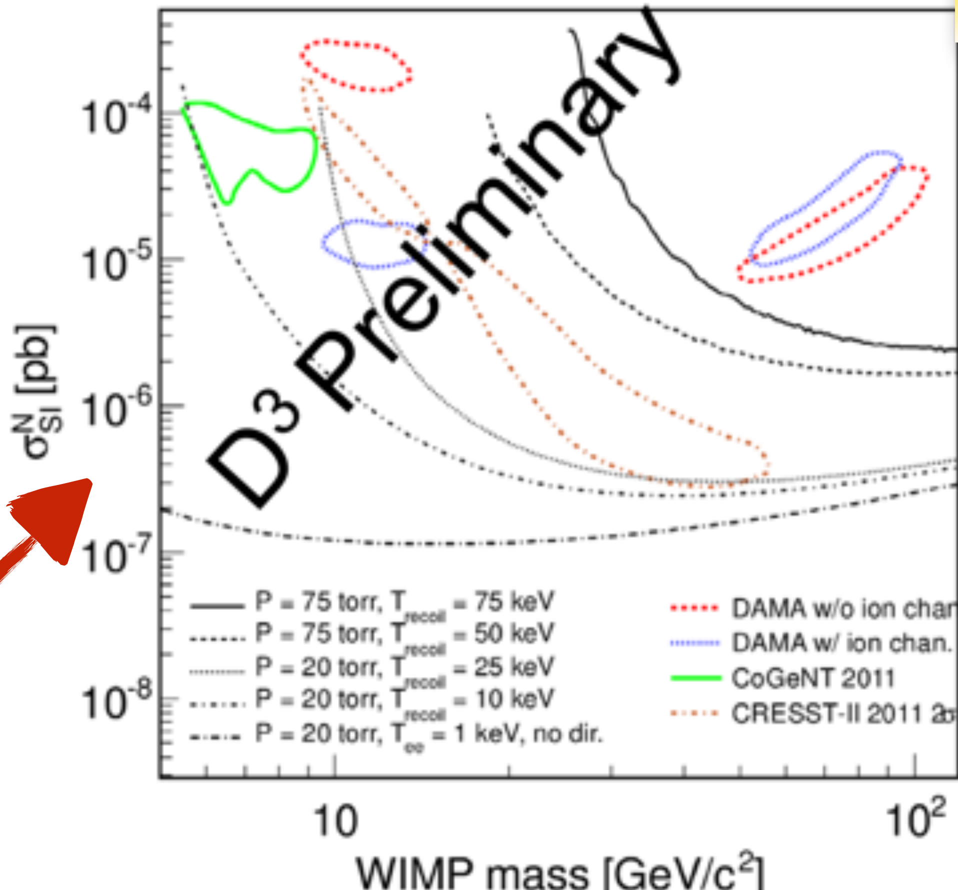
$$\sigma_{angle} = \sqrt{\sigma^2_{detector} + \sigma^2_{straggling} + \sigma^2_{source\ cone} + \sigma^2_{source\ size}}$$

- Selected events clearly point back to a single source
- Analysis still ongoing, but expect to obtain $\sigma_{\phi\ detector}$ ~1°
- σ_Θ too large - reduce TPC drift velocity

Preliminary conclusion: performance mostly *better* than expected.

D^3 expected sensitivity

arXiv: 1110.3444



Estimated sensitivity to spin-independent WIMP-nucleon scattering, 3-m³ directional dark matter detector, running for 3 years with 33 cm drift length and CF_4 gas, for four different track reconstruction thresholds and for non-directional analysis.

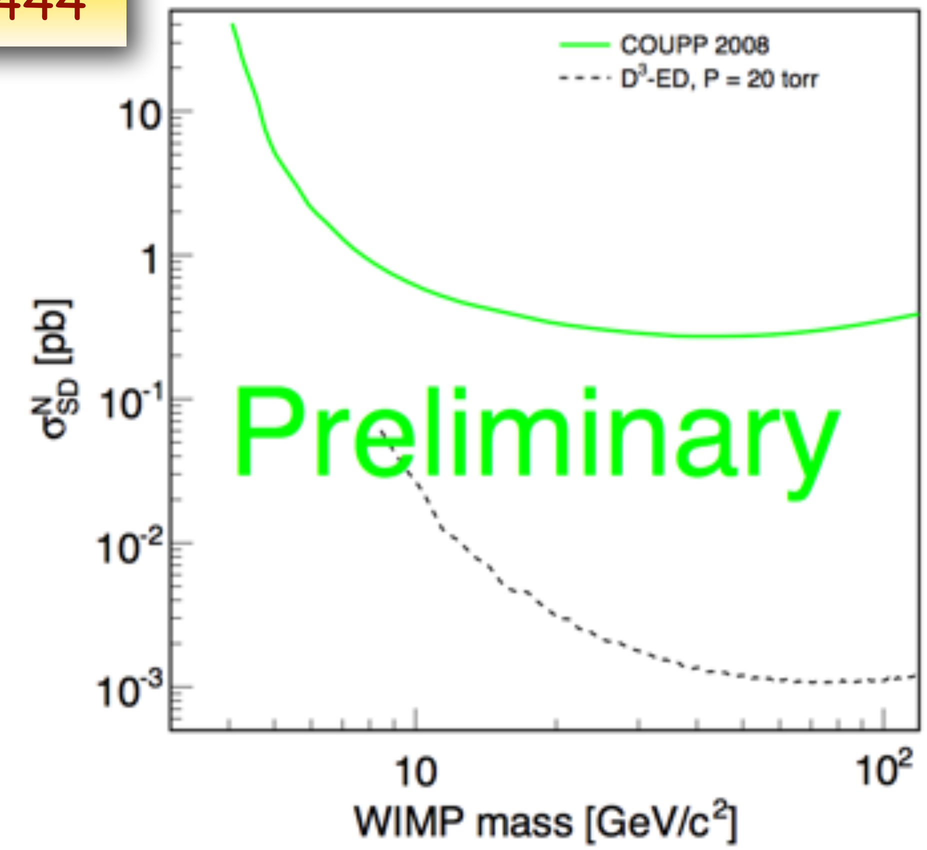


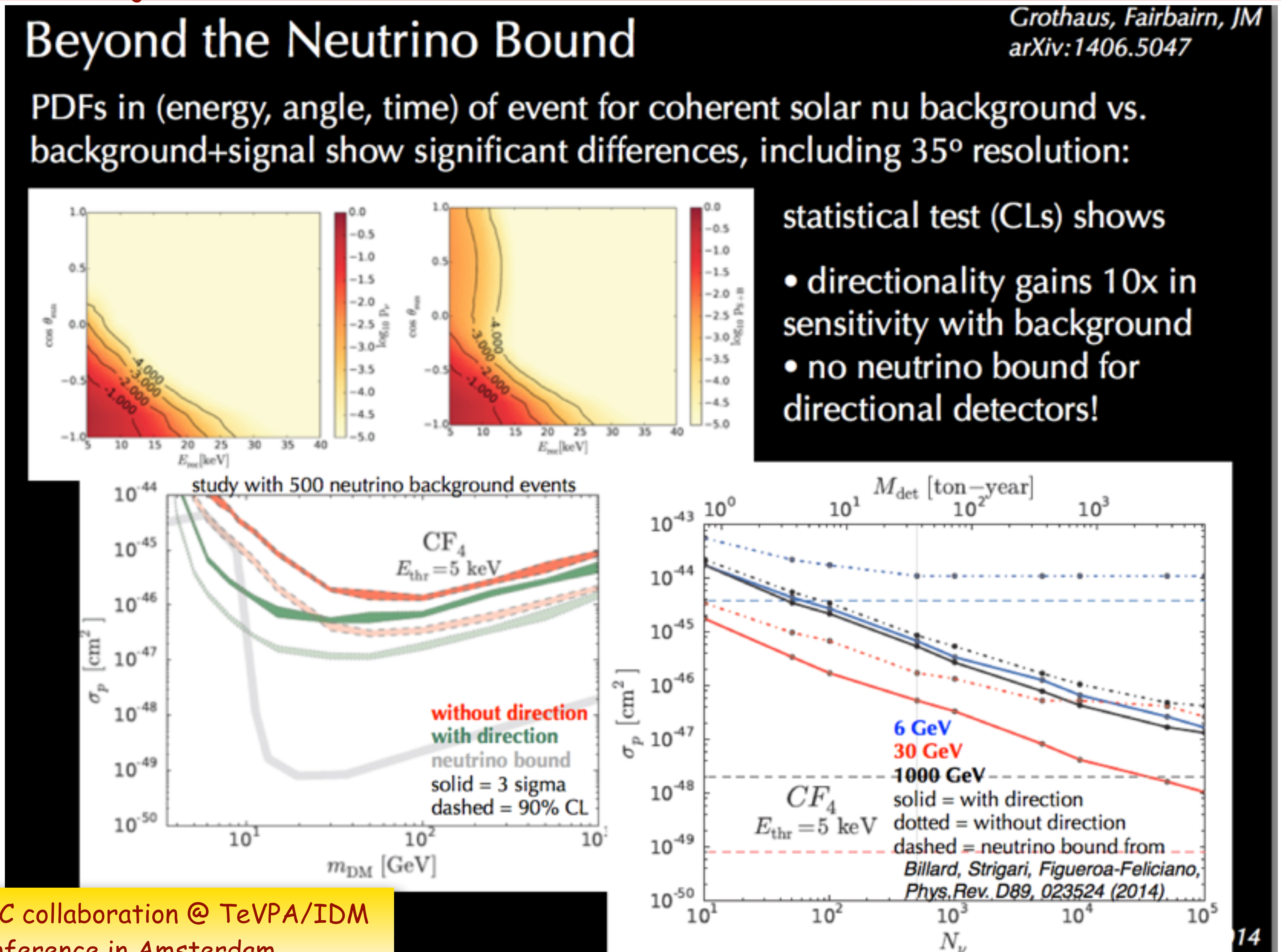
Fig. 5. D^3 cross section limit as a function of the WIMP mass for one recoil produced by a WIMP detected in three m^3. The detector is divided into nine sub-detectors with a maximum drift distance of 33.33 cm for ED-CF_4 and NID-CS, the SI case on the left and for the SD case on the right. The D^3 reach plot is compared to the non-directional experiments DAMA/LIBRA [13], CoGeNT [14] and CRESST-II [15] for the SI case and to COUPP[16] for the SD case.

Directional sensitivity to low masses AND non directional sensitivity to VERY LOW masses

March 2013, Sven Vahsen Pre-Snowmass DM Workshop @ SLAC

Domande per il GdI: e' possibile battere il fondo di neutrini?

Beyond Neutrino Bound



from DMTPC collaboration @ TeVPA/IDM Conference in Amsterdam

What happens after 3 years?

- Further larger prototype(s) with improved (larger pixels, lower costs) readout in order to get to a full experiment (1-3 m3) to be hosted in Gran Sasso Laboratories in ~ 5 years

  …I am an optimist, am I not? :D

- Development and optimization of NITEC for alternative applications (HPXe for neutrino-less double beta decay searches my first choice, X-ray second one)
- Exploitation of NITEC full length prototype to study columnar recombination effect in order to explore the possibility of using this technique for a HP gas (or even liquid) next generation directional DM detector

  lots of questions to be answered still, but extremely interesting

- …and then lets' see what's next :)

Message is: we want to develop a Negative Ion TPC with GEMPix readout and study which is its best application (in my heart, directional DM searches)

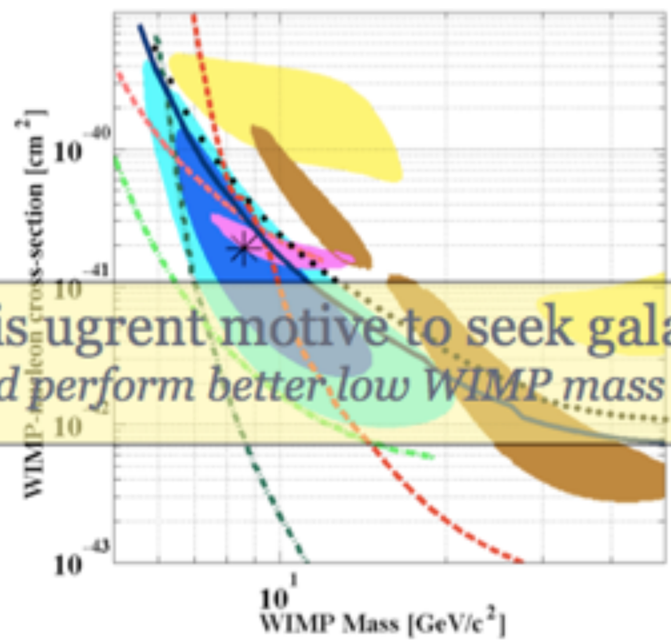
Backup slides

Current enigmatical experimental situation

Claims for detection

Excitment and Confusion in WIMP World

- Currently 6 direct search experiments see events above expected background - DAMA/LIBRA, CoGENT, CRESST, CDMS/Edelweiss
  and three/four claim detection of WIMP DM



There is ugrent motive to seek galactic signals
and perform better low WIMP mass searches

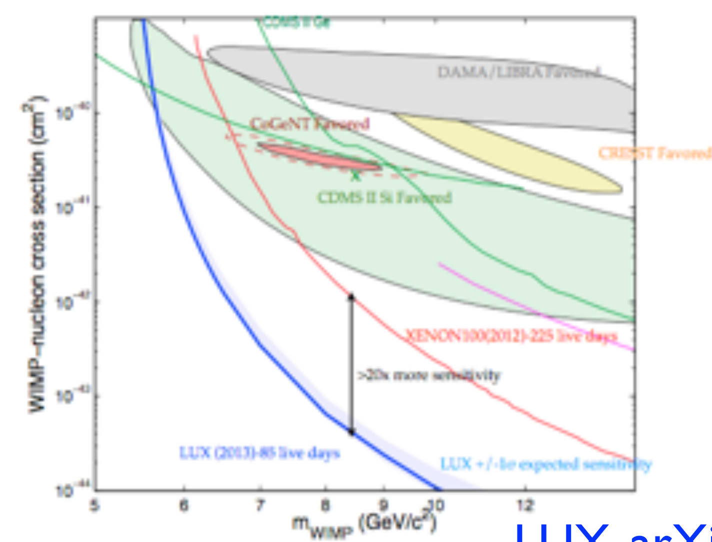
- There is also indirect claimed evidence, e.g. the spectrum of gamma rays from the region surrounding the Galactic Centre peaks at a few GeV, consistent with a ~7-10 GeV dark matter particle annihilating largely to leptons

CDMS, arXiv:1304.4279; COGENT, arXiv:1208.5737v3; CRESST-II, EPJ C72:1971; DAMA/ LIBRA, JCAP 0904:010

D. Hooper et al, PRD, 84 123005

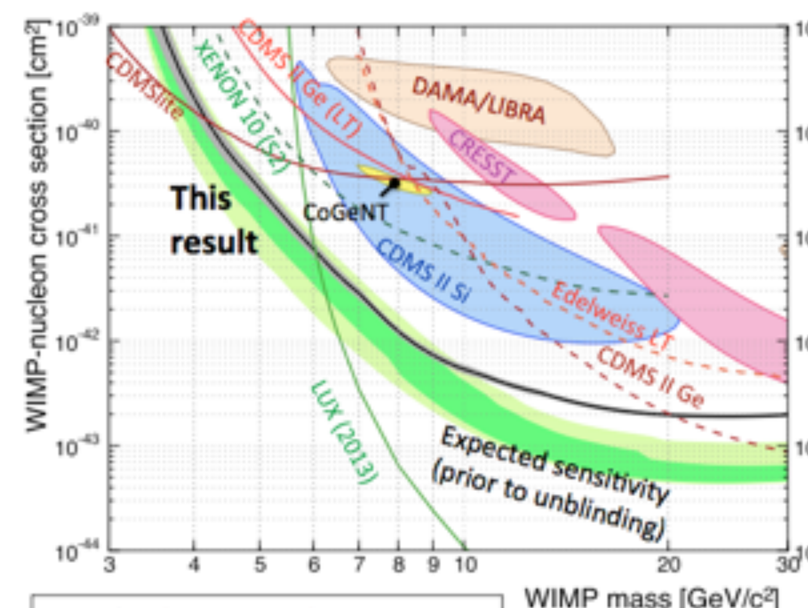
Inconsistent exclusion limits

Low-Mass Limit



LUX, arXiv:1402.3731

- LUX data is inconsistent with putative signals from CoGeNT and CDMS II Si



- CoGeNT strongly disfavored in model-independent scenario
- CDMS II (Si) disfavored under assumption of standard halo model and A^2 coupling
- Explores new parameter space below 6 GeV/c^2
- Competitive constraint for Ge up to 20 GeV/c^2; dedicated HT analysis yet to come
- Disagreement between limit and sensitivity at high WIMP mass due to events on T5Z3.
- For CDMSlite: please see: PRL 112, 041302 (2014)

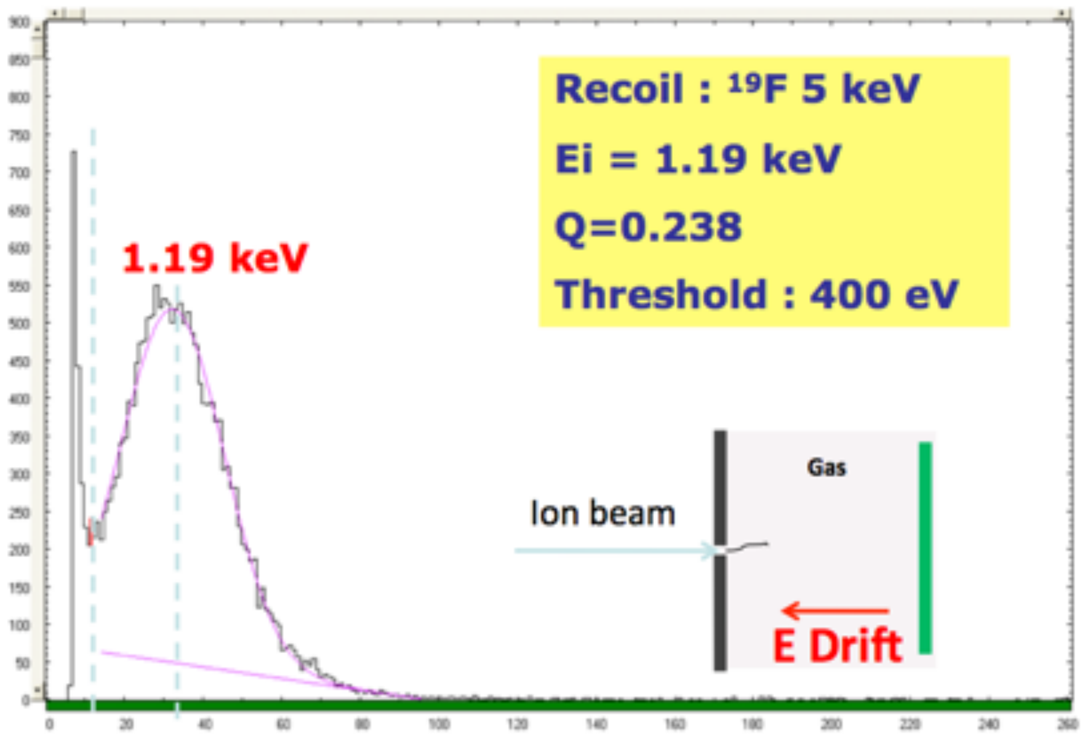
Gray bands: propagated systematic unc. from fiducial volume + nuclear recoil energy scale + trigger efficiency

UCLA February 2014 14

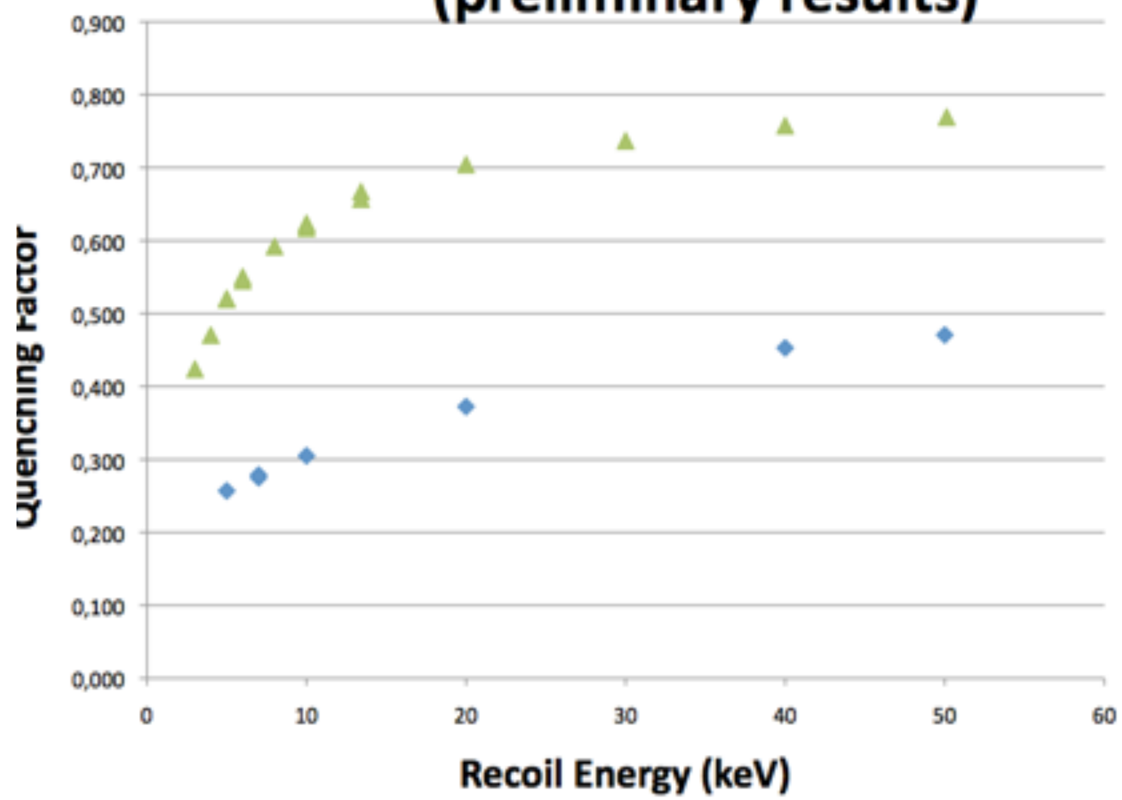
SuperCDMS, arXiv:1402.7137

Quenching Factor

Ionization Quenching Measurements:
5keV ^{19}F Recoil in 60 mbar
40mbar CF_4+16.8mbar CHF_3+1.2 mbar Isobutane



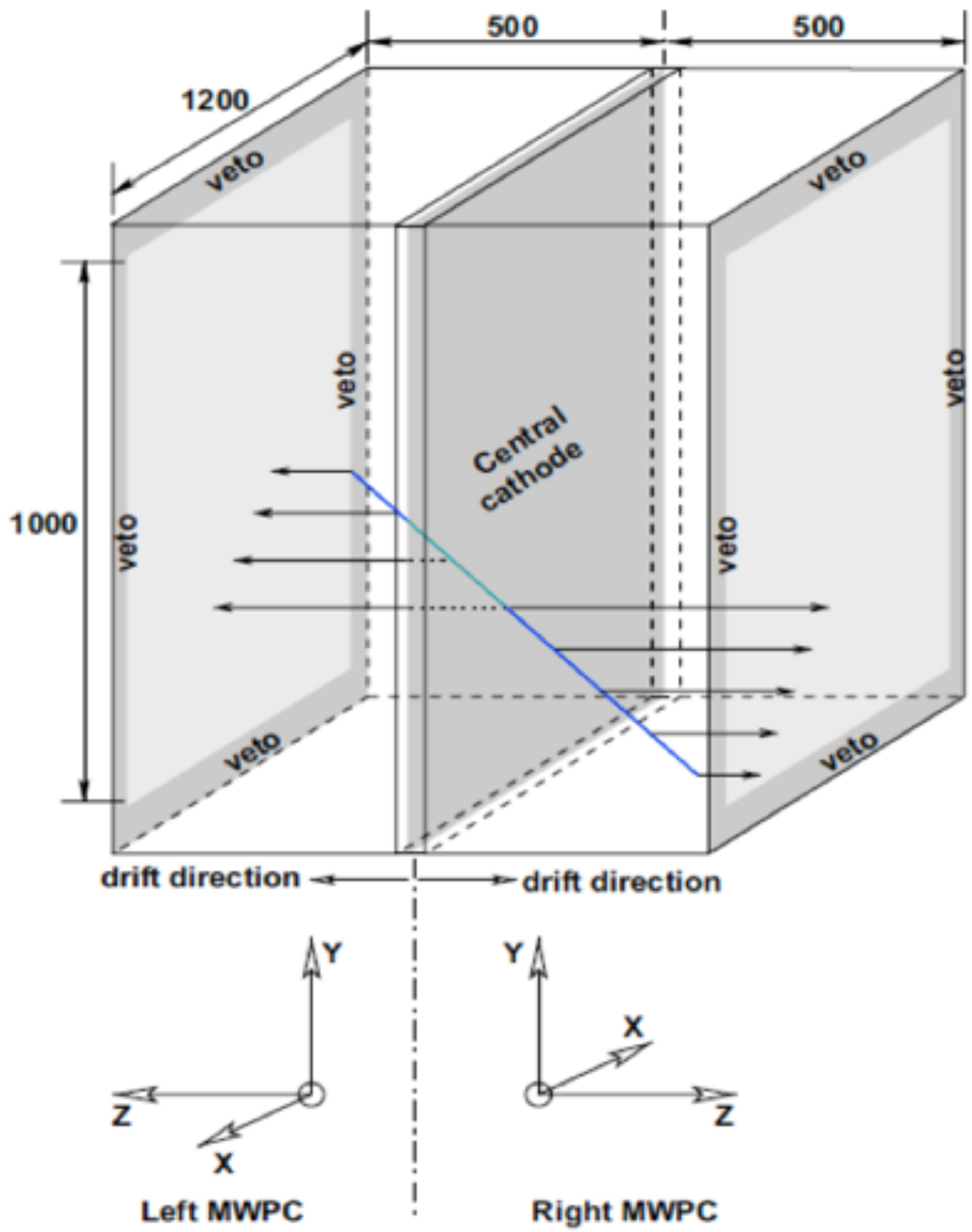
Ionization Quenching Factor for Fluorine in pure CF4 at 50 mbar (preliminary results)



from MIMAC collaboration measurement @ LPSC Grenoble

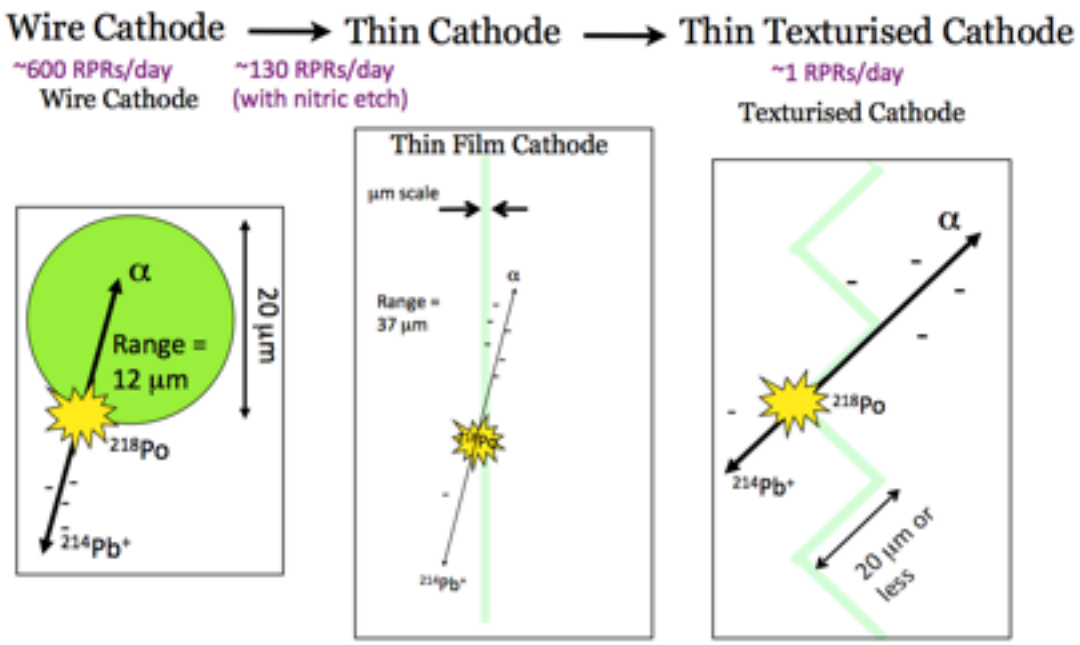
DRIFT

Technology evolution - DRIFT IIa, b, c, d...e, DRIFT III



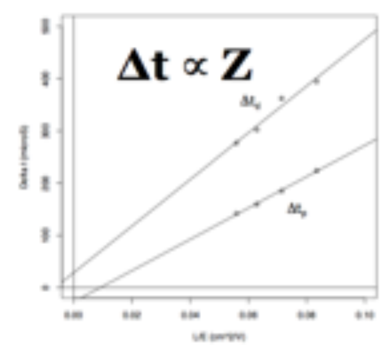
- 1 m^3 Negative ion TPC read out by two MWPCs.
- Electronegative drift gas (CS_2) with J=1/2 target gas (CF_4) to probe SD interactions whilst maintaining low diffusion.
- The shared central cathode defines two 624 V/cm drift regions.
- Every 8th wire grouped.
- > 67 cm polypropylene pellet neutron shielding on all sides.
- Current iteration: DRIFT-IId is running at Boulby Mine in Cleveland, UK.
- Next iteration: DRIFT-IIe being installed, with first data coming later this year.

DRIFT IId Upgrades



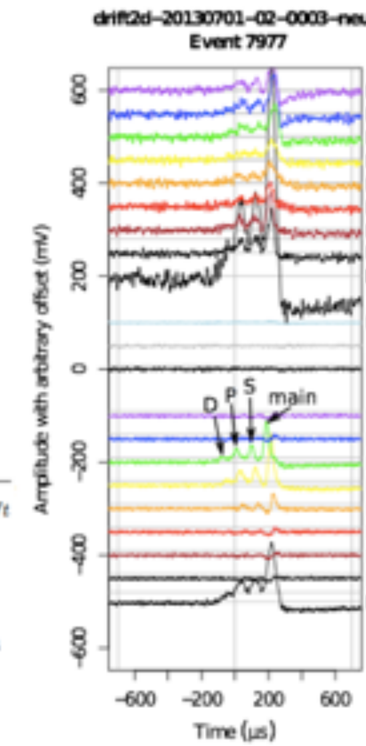
The concept:
Give the alphas **no** place to hide in a **texturized** aluminized Mylar thin film

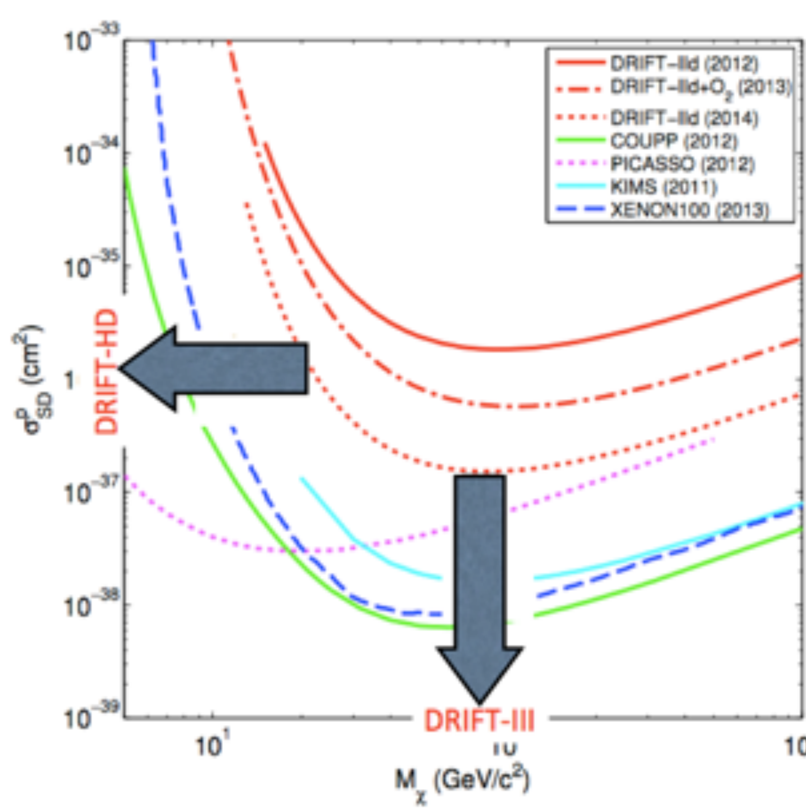
- **1% oxygen** added to normal 30:10 Torr CS_2: CF_4 mixture
- Appearance of "minority carrier" peaks **earlier** than the "majority" peak, carrying ~1/2 of the total charge (see Snowden-Ifft Rev. Sci. Instr. 85 (2014))
- Timing between main peak and minority peaks gives **absolute Z information** on events
- This allows rejection of RPR events that originate near the cathode at z = 50 cm or MWPC planes at z = 0 cm



$$z = (t_m - t_p)\frac{v^{m}_{drift}v^{p}_{drift}}{v^{m}_{drift} - v^{p}_{drift}}$$

Example event display from minority carrier data. The main peak and the earlier 'S', 'P' and 'D' minority peaks can be seen on LA 3, 4, 5 and 6.





← Z-fiducialisation "by-eye" analysis

DRIFT-IId is currently background limited

DRIFT III

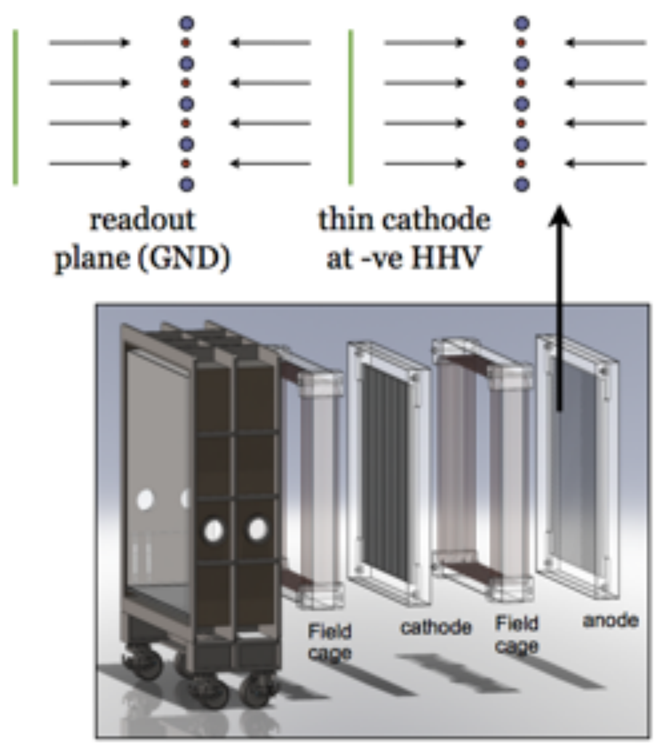
DRIFT III Specifications - 24m³

- <1 background event/year/24m³ (neutron, gamma, Rn control)
- directional threshold <40 keV_{recoil}
- head-tail sensitivity
- 1 mm wire separation in single plane - Δx and Δz < 200 μm
- full fiducialisation and all wires read out

DRIFT III Readout

Sense plane 2m x 2m

- Transparent readout plane to sense two sides (eliminates the mechanical support "strong back")
- 20 μm anode (50 μm grid) diameter stainless steel wires on a 1 mm pitch
- X-wires, Y-veto strip
- Head-Tail sensitivity
- 2D readout but with 3D side veto

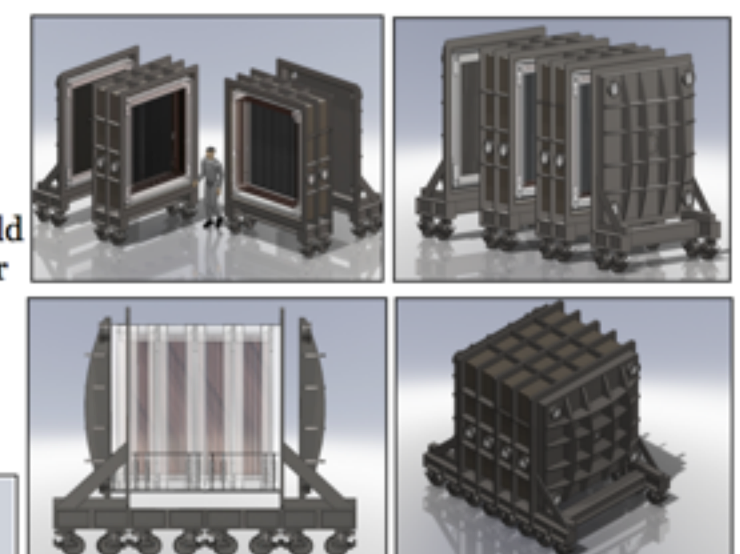


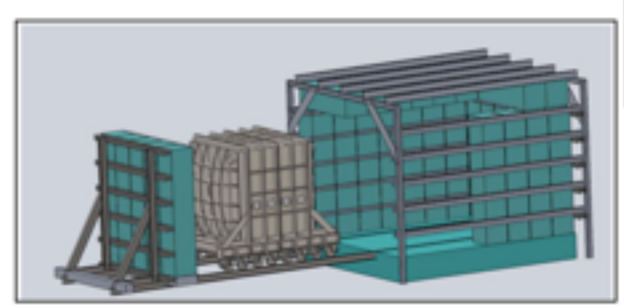
Cathode

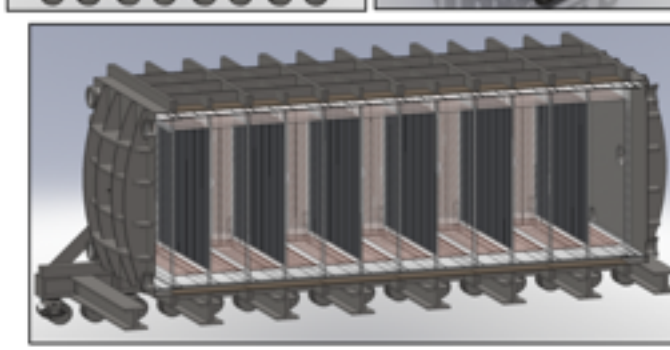
- 35 kV with well-engineered field cage and high-voltage system
- Texturised thin film
- Partial segmentation

DRIFT III Unit Design and Modularity

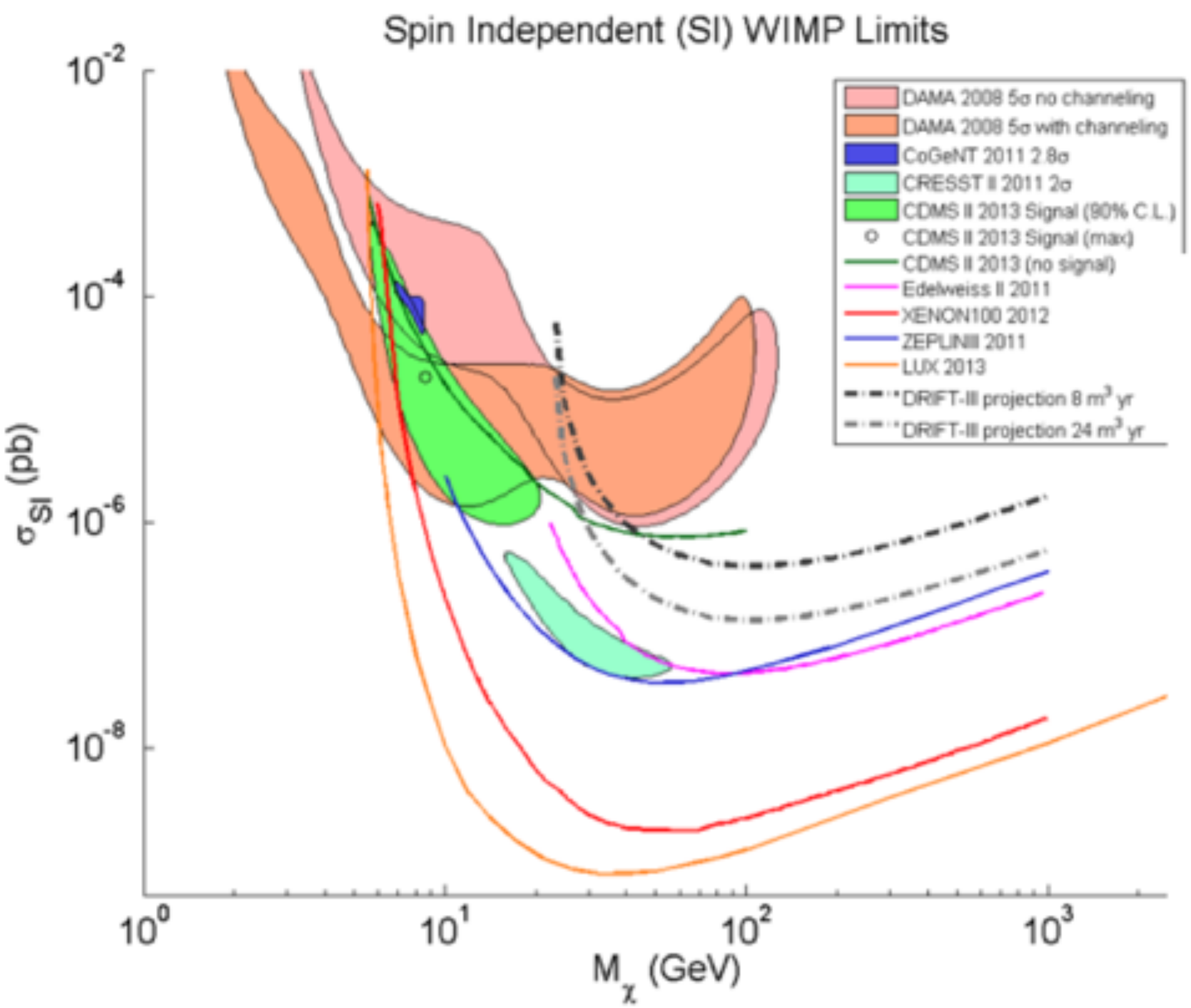
- Unit cell of 8 m³
- Modular design, 3 unit cells to give 4 kg target - 24 m³
- 250 of 4 kg modules gives 1 ton would fit into a standard DUSEL module or 500m tunnel at Boulby
- Water shield

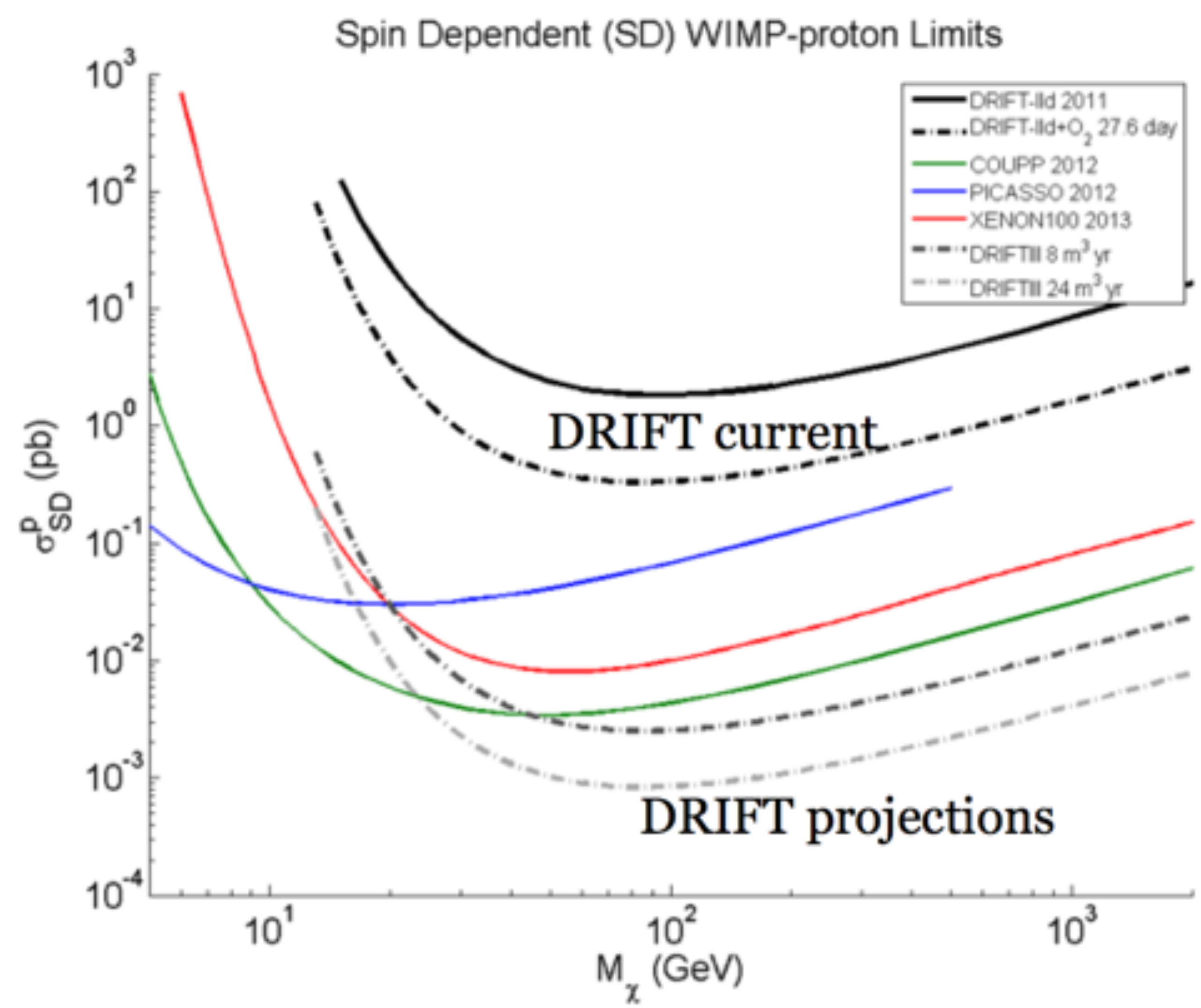






DRIFT Goals

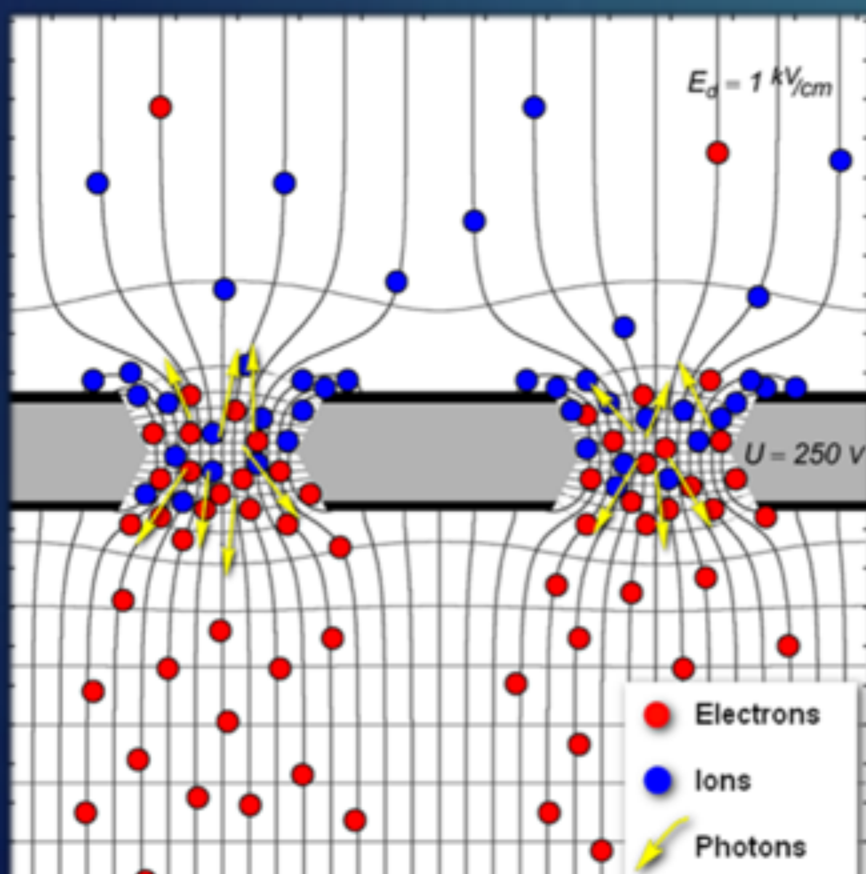


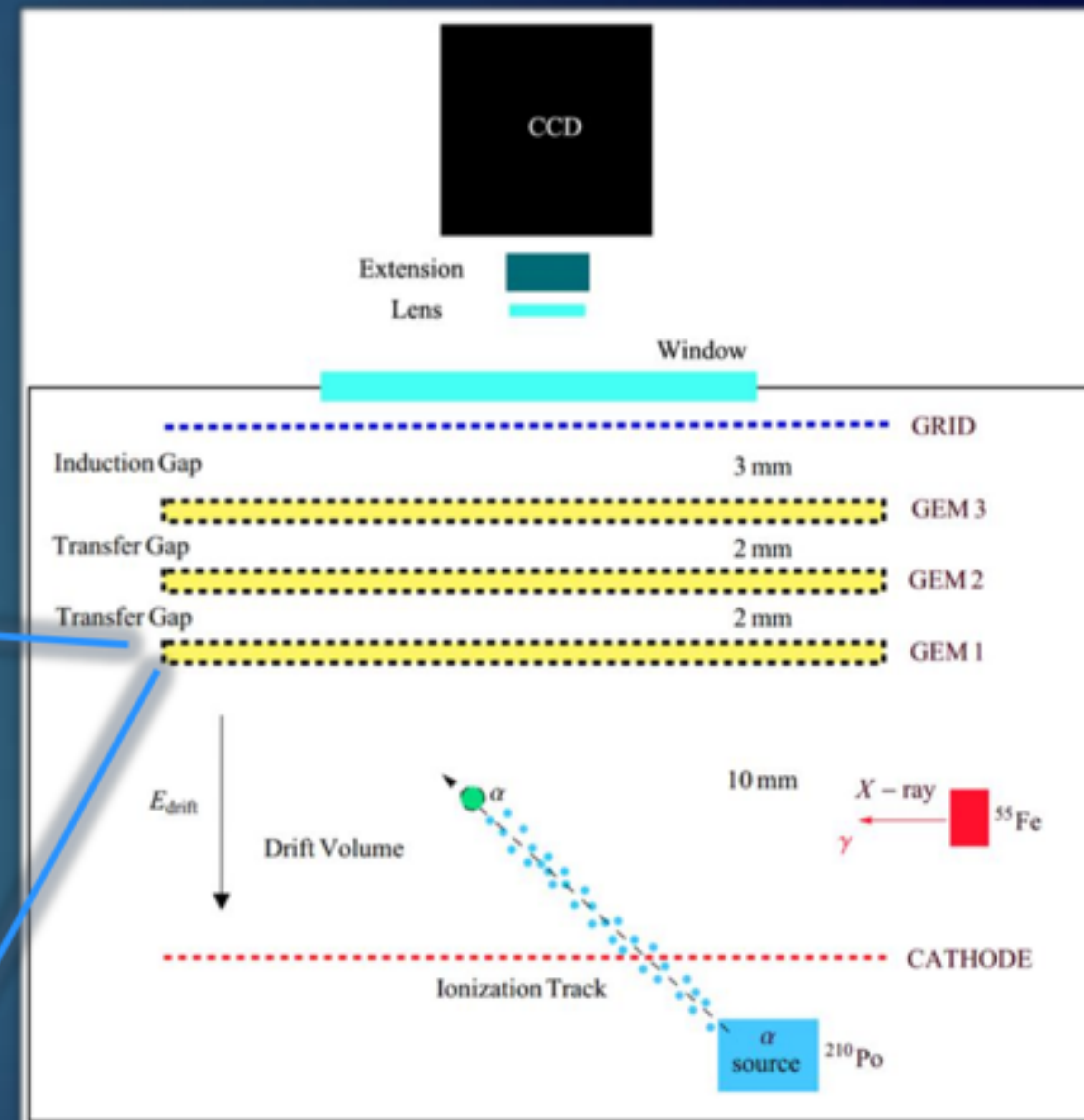


PLEASE NOTE: only DRIFT has directionality in these plots

Latest R&D

- Triple GEM (gas electron multiplier) low pressure TPC with optical readout.
  - Three 7 cm x 7 cm CERN GEMs (140 μm pitch, 50-70 μm hole dia., ~ 50 μm thick)
  - FLI Back-illuminated CCD (13 μm pix., 1024 x 1024) + 58 mm F 1.2 Nikon lens.
  - 1 cm conversion gap, 3 cm x 3 cm imaging area.
  - 100 Torr CF_4 gas.





Nguyen Phan ----- TeVPA/IDM 2014 Amsterdam

from people in DRIFT collaboration

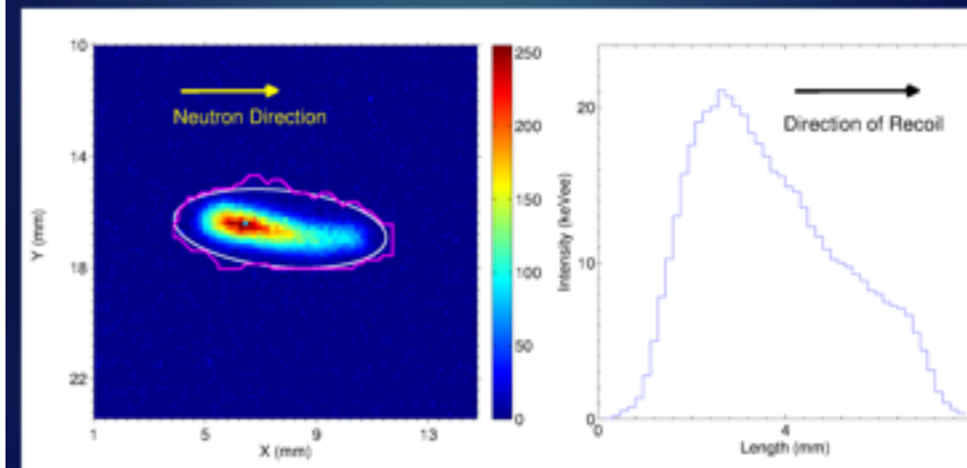
Performances

Directionality

8

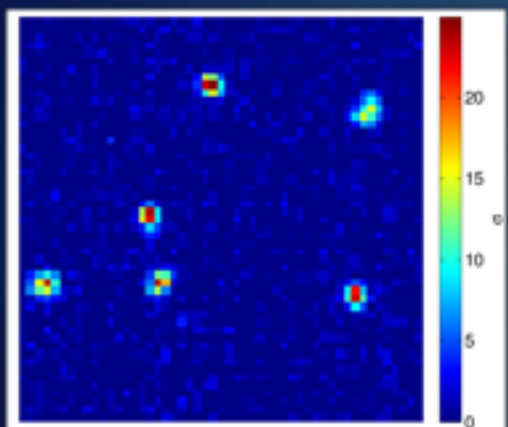
Skew: $S = \frac{\mu_3}{\mu_2^{3/2}}$

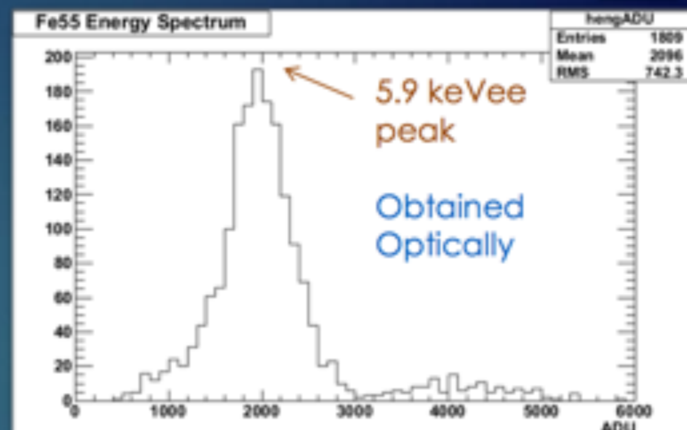
Orientation Angle: α



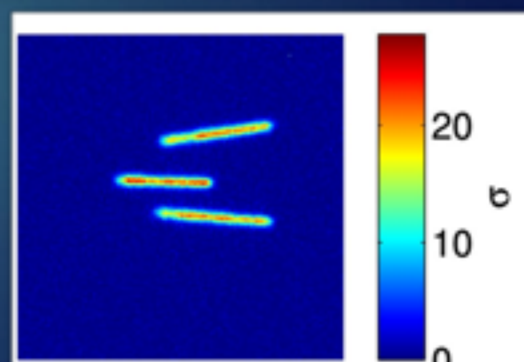
^{55}Fe and ^{210}Po Calibrations

4





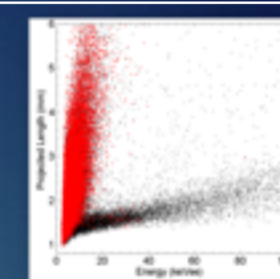
- ^{55}Fe energy spectrum (obtained optically via CCD) and image of tracks at 16x16 pixel binning .
- Alpha track segments (right) at 6x6 binning and max stable gain (~ 10^5).
  - Excellent signal-to-noise (SNR), Peak SNR > $25\sigma_{im}$
- Energy Resolution: 35 % (FWHM) at 5.9 keVee.
- Diffusion: σ ~ 350 μm, mostly from GEM stages.



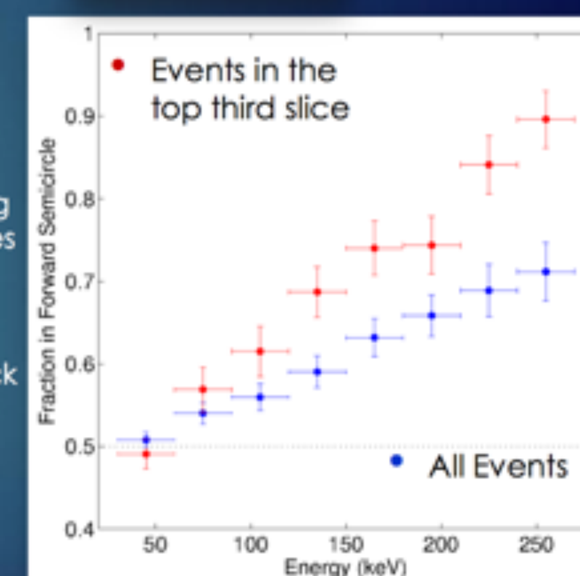
- Discrimination down to ~ 10 keVee (~ 25 keV). Recoil energy assumes fluorine and Hitachi quenching factors (Hitachi, Rad. Phys. & Chem. 77 (2008)).
- Electronic recoils have small dE/dx but large fluctuations → low S/N could lead to confusion with nuclear recoils.

Head-Tail (Sense)

9



- Head-tail sensitivity down to 60 keV.
- Multiple scatterers not taken into account.
- How do we improve it?
  - Straggling -- Target choice. Less straggling for lighter targets (e.g. He) vs. heavier ones (e.g. F).
  - Projection Effect --- 2D vs. 3D
  - Pressure --- Lower pressure to increase track lengths.
  - Resolution/Diffusion



The fraction of nuclear recoil events in the forward half-circle from the ^{252}Cf data run.

from people in DRIFT collaboration

Other gaseous directional detectors

DMTPC

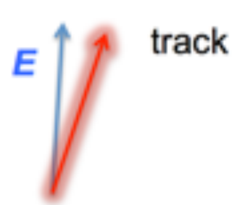
The DMTPC detector is a dual conventional TPC with ~ 20 cm drift distance, filled with pure CF4 at 75 Torr, based on optical read out. The electron liberated by the recoiling nuclei drift towards the amplification region, where photons are produced together with electrons in the avalanche process with a ratio of 1:3. CCD cameras record the projection of the 3D nuclear recoil on the 2D amplification plane and PMTs measure the length of the recoil in the drift direction. The cathode and ground planes are meshes with 256 um pitch that provide ~ 5 x 10^{4} gas gain and whose signal is digitized as well. The recoil energy and angle reconstruction resolution are 15% and 40 degrees at 80 keV. The gamma rejection power is 1.1 x 10^{-5}. The head-tail direction is correctly measured on 60% of the tracks with an energy threshold between 60 and 80 keV, and up to 90% at 200 keV. The optical readout is definitely a powerful and innovative tool, nonetheless the electron diffusion limits the maximum drift distance of the DMTPC to about 25 cm. Moreover, the anode mesh voltage increase is limited due to spontaneous discharges (which also produce ghost images in the CCD) and event-triggered discharges due to the Rather limit.

NEWAGE and MIMAC

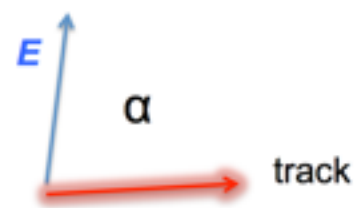
NEWAGE and MIMAC detectors are conventional TPCs read out by pixelized anode with pixel dimension of ~200 um. The amplification stage is made of GEM and Micromegas respectively, both reaching ~ 5 x 10^{4} gas gain. The dimensions of the existing detectors are 23 x 28 x 31 cm3 and 25 x 10.8 x 10.8 cm3 (times 2 since MIMAC is a bi-chamber) respectively. NEWAGE runs on pure CF4 and has energy resolution of 70% FWHM and angular resolution of 55 degrees (RMS), gamma rejection power of 8 x 10^{-6} and a nuclear track detection efficiency of 80%, all of the above at 100 keV equivalent alpha recoil. Both these detectors make use of the highly performing pixelated readout, which can provide very good spatial resolution. Nonetheless their drift distances (and thus volumes) are necessarely limited to ~ 30 cm due to the electron diffusion.

Columnar Recombination in HPXe

- <u>Columnar Recombination</u> (CR) occurs when:
  - A drift electric field *E* exists;
  - Tracks are highly ionizing;
  - Tracks display an approximately linear character;
  - The angle α between *E* and track is small:
  - **Recombination** ≈ dot-product of vectors E and "track"



Substantial CR



~No CR

CR Exists!

Evidence for columnar recombination in **α-particle** tracks in dense xenon gas.

FWHM depends on E-field and density!

Bolotnikov & Ramsey NIM **A 428** (1999) pp 391-402

G. C. Jaffe: Annalen der Physik, **42,** p 303, (1913)

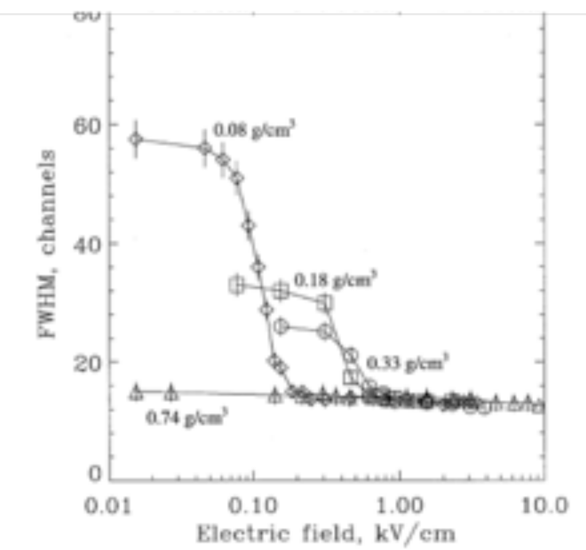


Fig. 5. FWHM of the peaks in pulse-height spectra of the amplitude of the light signals versus the electric field strength measured at 0.08 g/cm³ (diamonds), 0.18 g/cm³ (squares), 0.33 g/cm³ (circles), and 0.74 g/cm³ (triangles).

28 May 2013

- Define (*electrostatic*) ***Columnarity "C"***
- ***C*** = $\mathcal{R}/r_0$
  - – $\mathcal{R}$ = the nuclear recoil track *range*
  - – r_0 = Onsager radius $r_0 = e^2/\varepsilon\,\mathcal{E}$, where $\mathcal{E}$ is electron energy (usually taken as kT)
  - – in xenon gas for ρ ≈ 0.05 g/ cm³:
    - r_0 ~ 70 nm
    - $\mathcal{R}$ ~ 2100 nm for 30 keV nuclear recoil (SRIM result)
    - ***C ≈ 30*** in this example

We want C to be fairly large, i.e. C > 10

- This condition is probably met for KE ≥ 20 keV in xenon gas for ρ ≈ 0.05 g/ cm³, or less
  - – ~2% of LXe density
  - – Hopeless for LXe density: ρ = 3.1 g/ cm³ → C<1

- The signal **R** is fluorescence (scintillation)
  - – Observed in noble gases and some molecules
  - – Noble gas: VUV (85 – 173 nm) – difficult,...
  - – *Desired: Recombination signal is UV, not VUV*
  - – Molecular fluorescence: 280 - 500 nm
  - – Very few gaseous molecular candidates:
    - *Trimethylamine (TMA)*
    - *Triethylamine (TEA)*
    - *Tetrakis-dimethylamino-ethylene (TMAE)*
    - *Others?*

D.R.Nygren
J.Phys.Conf.Ser. 460 (2013) 012006

Columnar Recombination in HPXe

Nuclear Recoils: extracting directionality

- Rapidly falling energy spectrum of recoils
  - Kinetic Energies < 40 keV for xenon
  - But, Head-on collisions have more energy
- Substantial scattering along trajectory
  - But, where directionality is retained, energy loss high
  - Majority of energy lost to "heat" – quench factor ~5
- Ambipolar diffusion holds most of the electron population
  - A few primary electrons wander off and are lost
- Excitations outnumber ionizations by large factor
- Primary excitations contain no directional information!

What to do! ?

Exploit Atomic/Molecular Dynamics

- **Primary Xe excitations**: these must be converted to ionization – to serve as recombination sites!
  - Use Penning effect: excitations → ionization
  - Xenon: TMA (and maybe TEA) are candidates
- **Primary Xe ions:** Xe^+ are rapidly neutralized by charge exchange with Penning molecules
  - Ionization potential of TMA ≤ first excited state of Xe*
  - Ionic image transformed to TMA^+ molecular image
- Columnar recombination occurs on TMA^+ ions

Detecting Directionality

Xe_{nr} + Xe → Xe + heat
→ Xe*
→ Xe^+ + e^-

Xe* + TMA → Xe + TMA^+ + e^- (Penning effect)
Xe^+ + TMA → Xe* + TMA^+ (Charge exchange)

TMA^+ + e^- → TMA* → TMA + photon (~300nm)

- Columnar Recombination with TMA leads to UV
  - TMA, TEA, fluoresce strongly in 280 – 330 nm band
- **The Directionality signal is contained in the ratio of recombination/ionization = R/I**
  - More recombination implies less ionization & vice versa
- R signal is intrinsically optical
  - Convert I signal to scintillation by electroluminescence
- All signals detected optically
  - I signal is separated in time by drift interval

- **No track visualization required !**
  - **R/I** determined before drift
  - Simplified readout plane possible
  - TPC scale can be arbitrarily large

Figure of Merit: $\mathcal{M} = V_{det}/V_{track}$

$\mathcal{M} \sim 10m^3/10\mu m^3 \sim 10^{18}$ for CR-based system

D.R.Nygren
J.Phys.Conf.Ser. 460 (2013) 012006