東京大学
THE UNIVERSITY OF TOKYO

What Next LNGS: prospettive per il ruolo scientifico del LNGS
15th- 16th October 2014

NITEC: a Negative Ion Time Expansion Chamber for very rare events 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

Istituto Nazionale di Fisica Nucleare
Bando n. 16555
Concorso per il finanziamento di n. 6 progetti per giovani ricercatrici/ricercatori nell'ambito delle linee di ricerca e sviluppo tecnologico proprie dell'Ente (acceleratori, elettronica/informatica, rivelatori, interdisciplinare)

MARIE SKŁODOWSKA-CURIE ACTIONS
Individual Fellowships (IF)
Call: H2020-MSCA-IF-2014

Elisabetta Baracchini
International Center for Elementary Particle Physics (ICEPP)
The University of Tokyo

In collaboration with G. Bencivenni, D. Domenici, F. Murtas
(Laboratori Nazionali di Frascati)

LNF

What this is, what this is not

This is not an approved experiment with funds and a collaboration

This is a proposal for an R&D with which I applied to 4 grants, in collaboration with (some people from) LNF

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

3 yr for PI + 3 yr for a postdoc
800k budget (including salaries)
results?????

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

3 yr for PI
no budget
results????

Istituto Nazionale di Fisica Nucleare
Bando n. 16555
Concorso per il finanziamento di n. 6 progetti per giovani ricercatrici/ricercatori nell'ambito delle linee di ricerca e sviluppo tecnologico proprie dell'Ente (acceleratori, elettronica/informatica, rivelatori, interdisciplinare)

2 yr for PI
75k/yr budget
apertura sigla in CSN5
results by end 2014

MARIE SKŁODOWSKA-CURIE ACTIONS
Individual Fellowships (IF)
Call: H2020-MSCA-IF-2014

2 yr for PI
19k (+15 k overhead) budget
results by February 2015

- Full endorsement from LNF
- Already in contact with BTF community for future upgrade of the facility, that could benefit NITEC calibration (improvement in the neutron beam line)
- Already in contact with the directional DM gaseous detector community (DRIFT collaborators already provided us with gas system specifics and safety issues)


INFN Istituto Nazionale di Fisica Nucleare
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Il Direttore

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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

The concept

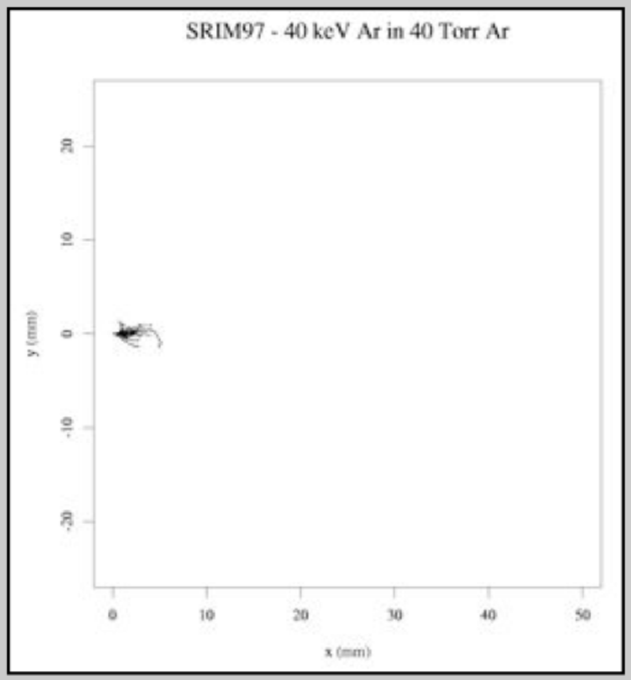
Gaseous TPC

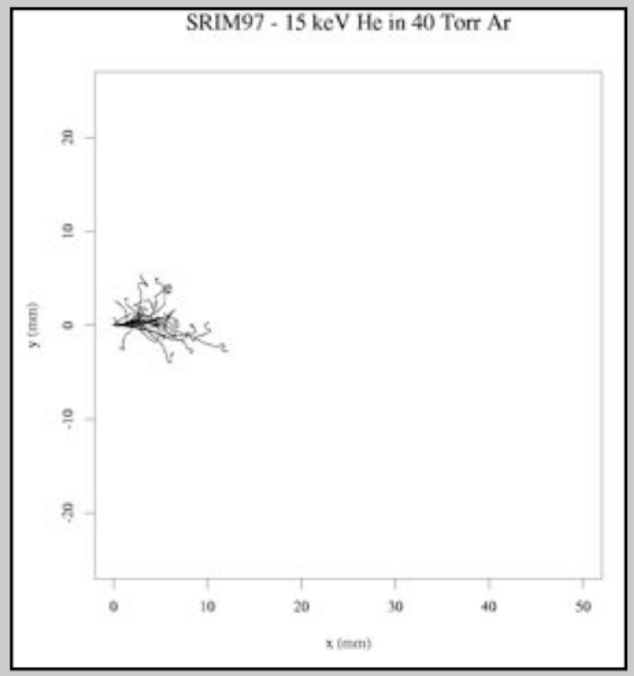
From DRIFT experiment

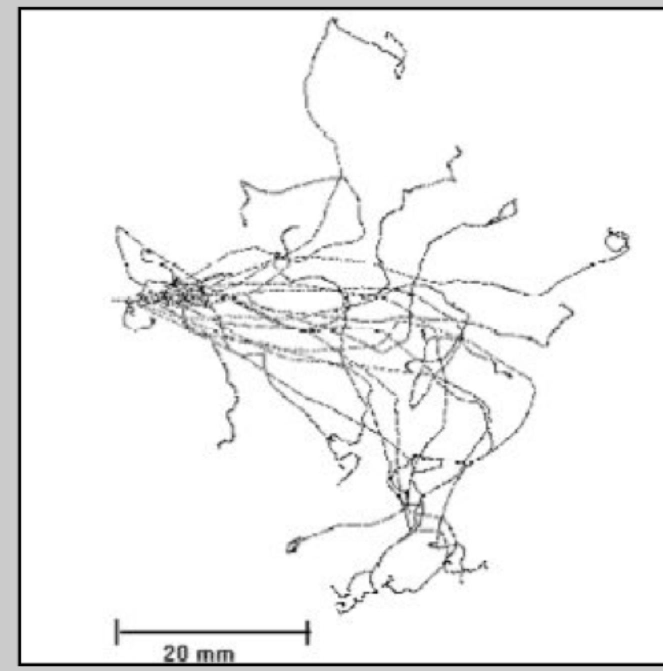
Particle Identification

simulation

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





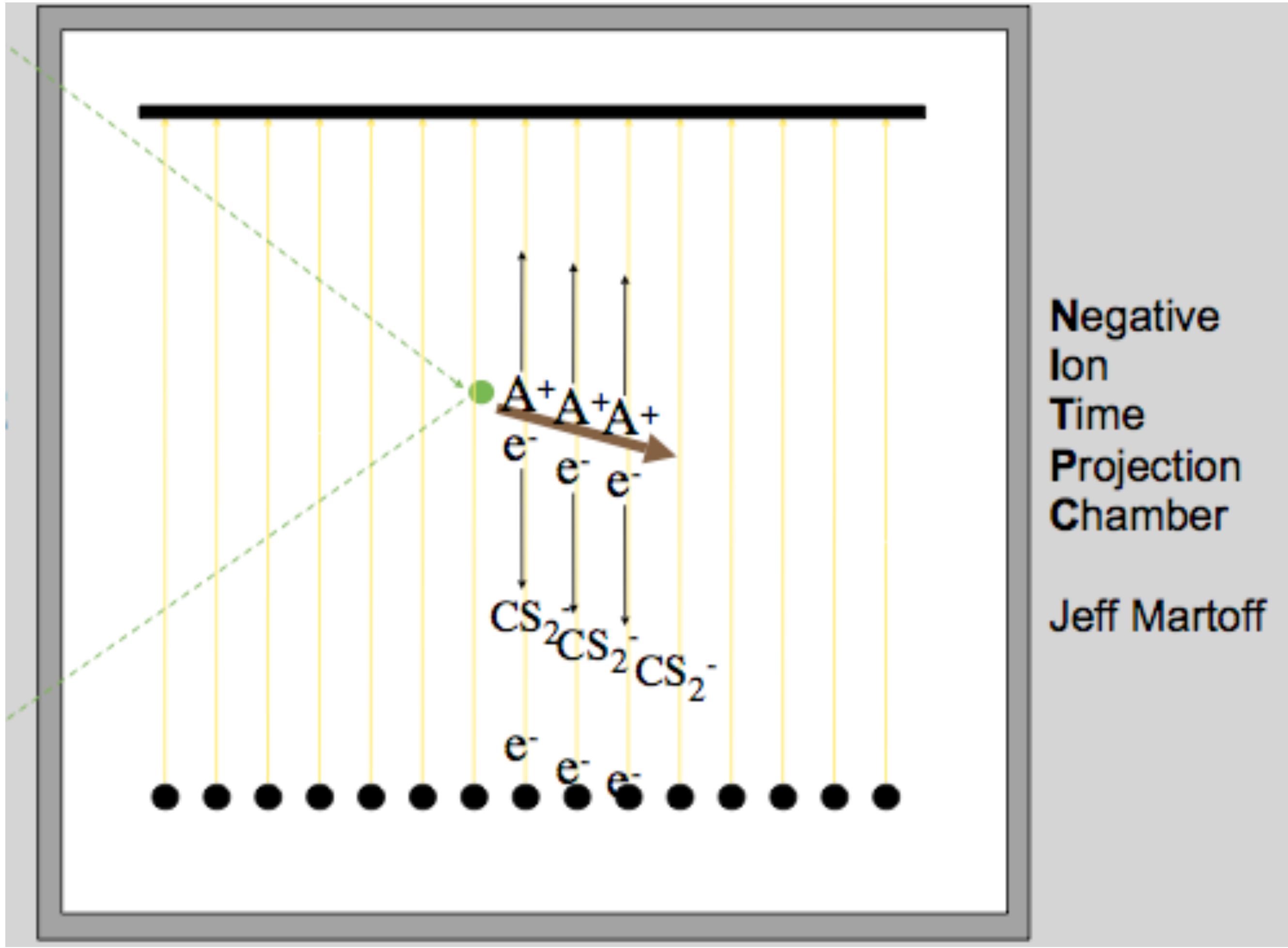


Key points: it's range discrimination - no doubt

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

To exploit gaseous TPC PID capabilities

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

To address TPC typical volume limitations

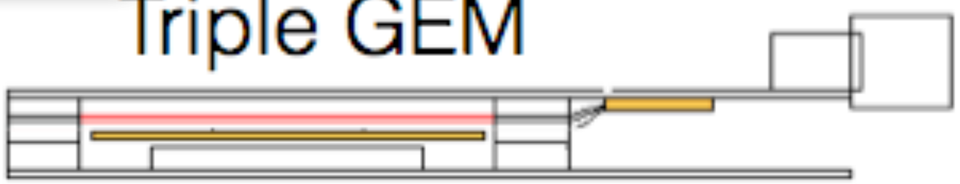
Amplification & Readout

GEMPIX

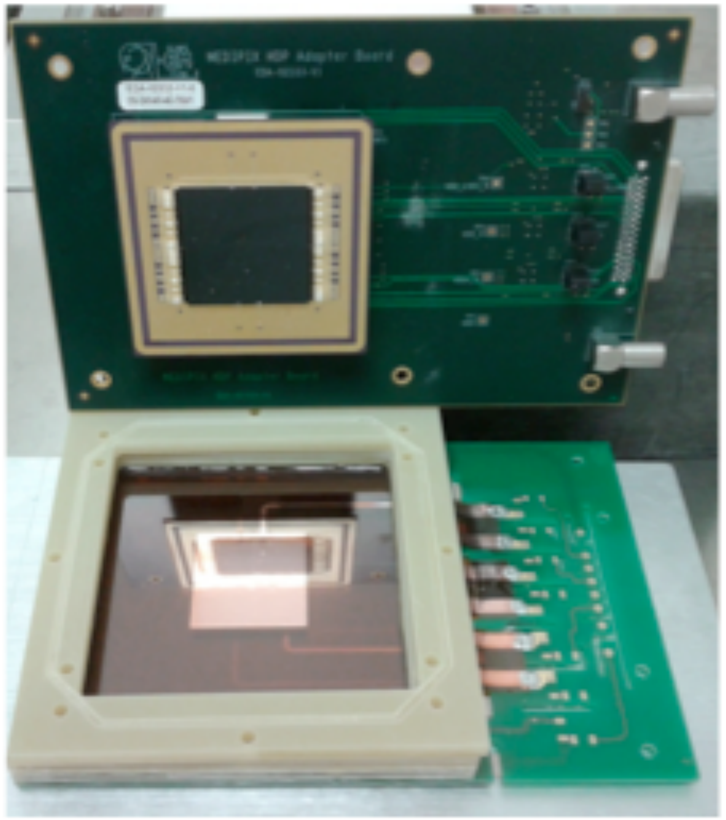
- The GEM is a micro pattern gas detector, thin holes are etched in a kapton foil and a potential is placed across it
- Very large electric field around the holes which creates an electron avalanche
- Couple a timepix asic for readout of a triple Gas Electron Multipler (GEM) detector

Developed by LNF in collaboration with CERN

Triple GEM



Quad Timepix ASIC

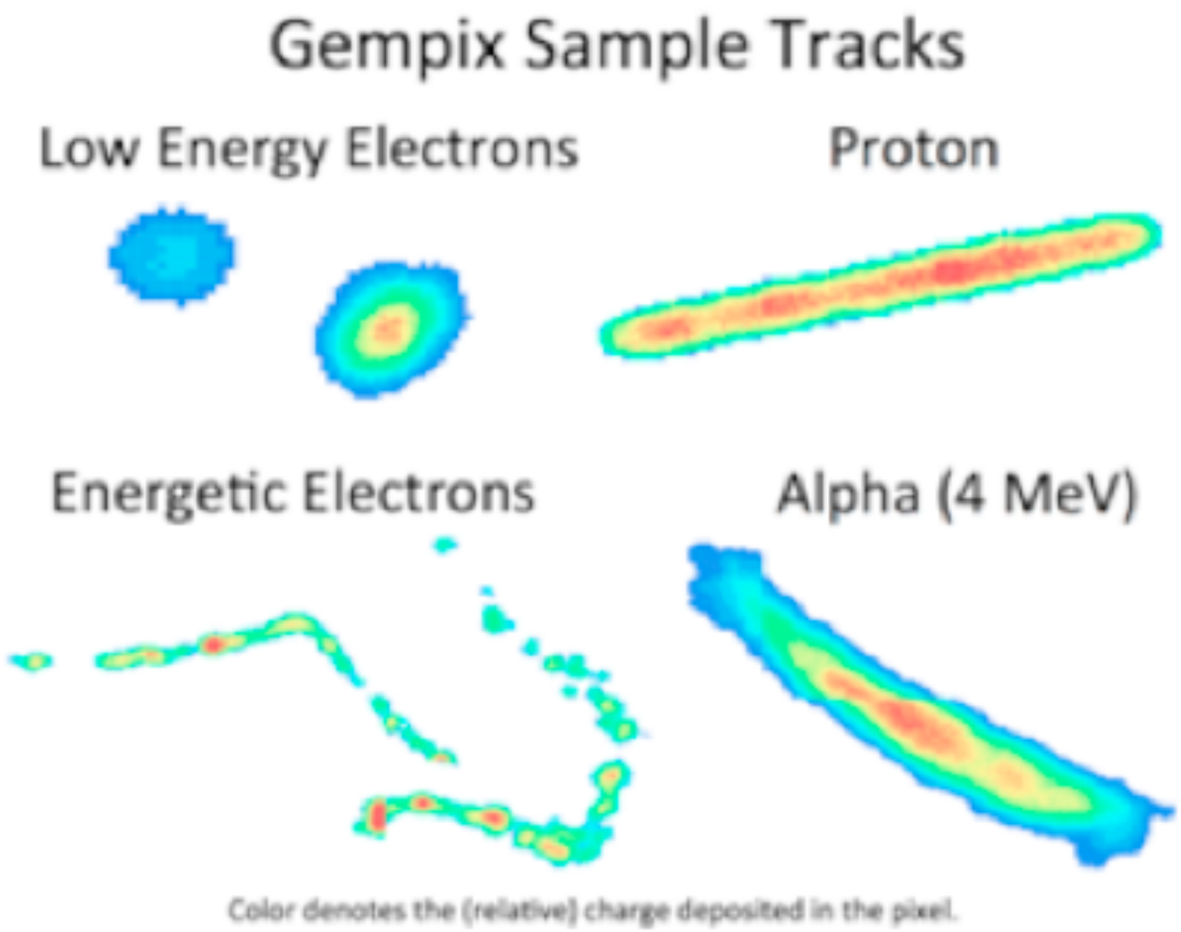


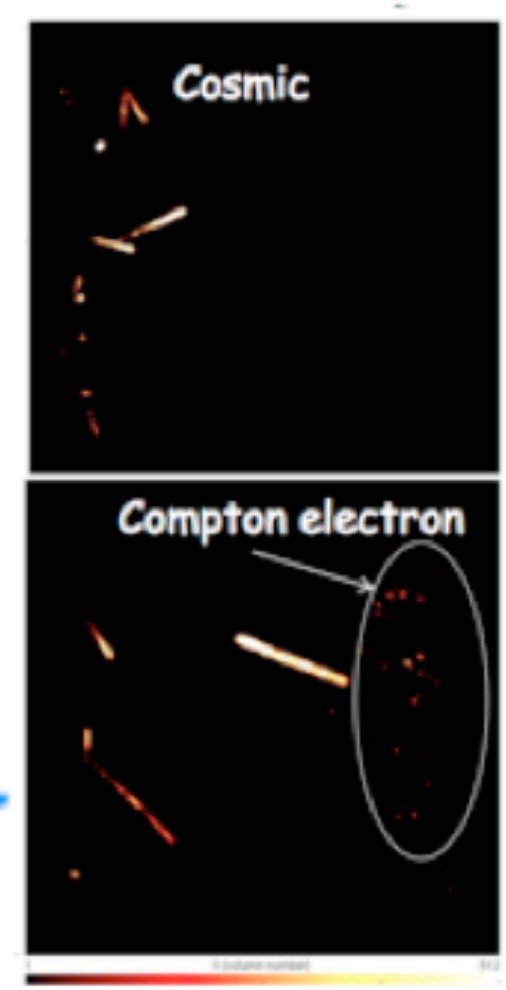
https://web2.infn.it/GEMINI/index.php/gempix-detector

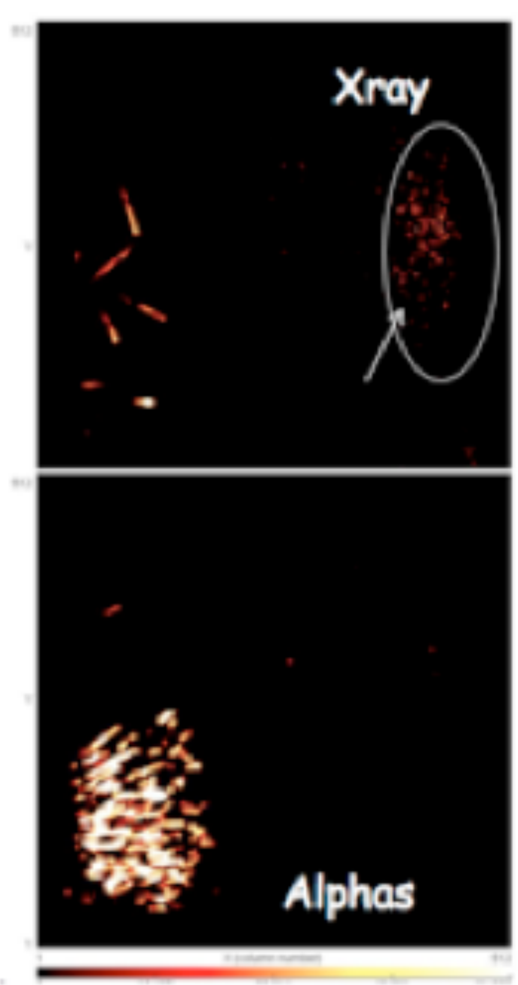
For the state-of-the-art amplification & readout

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 fielc 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)

Time Expansion Chamber

- 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)

Applications

What to do with NITEC?

- Highly reduced diffusion of the event image carriers thanks to their higher mass
  - Larger allowed drift distances, hence active detector volumes
  - Slower drift bring improved tracking and energy resolutions
- State-of-the-art readout
  - GEMs high gain combined with high stability
  - Pixel readout for high spatial, energy and time resolution

↓

Directional DM detector — what the grant requests are about

OR

Neutrino-less double beta decay detector

Ultra High Energy resolution NITPC

- 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 5×10^{-3} FWHM energy resolution could be achieved
- A good capture agent for HPXe would be Nitromethane (see later)
- First tests with a 17 bar Xe conventional TPC show very encouraging results (1% FWHM) [A. Goldschmidt et al, IEEE NSSCR 1409]

This kind of R&D is not included in the grant requests due to the limited timescale and budgets

NEXT collaboration R&D

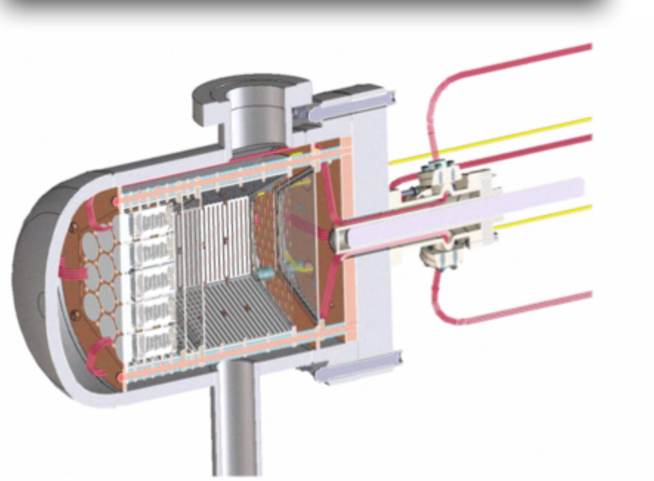
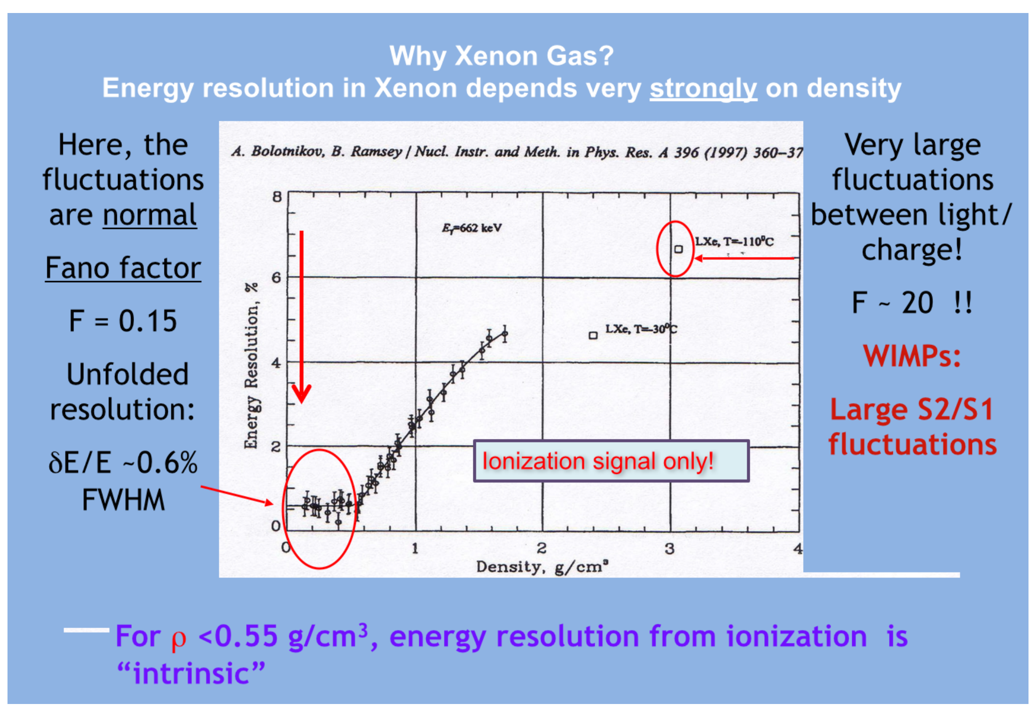
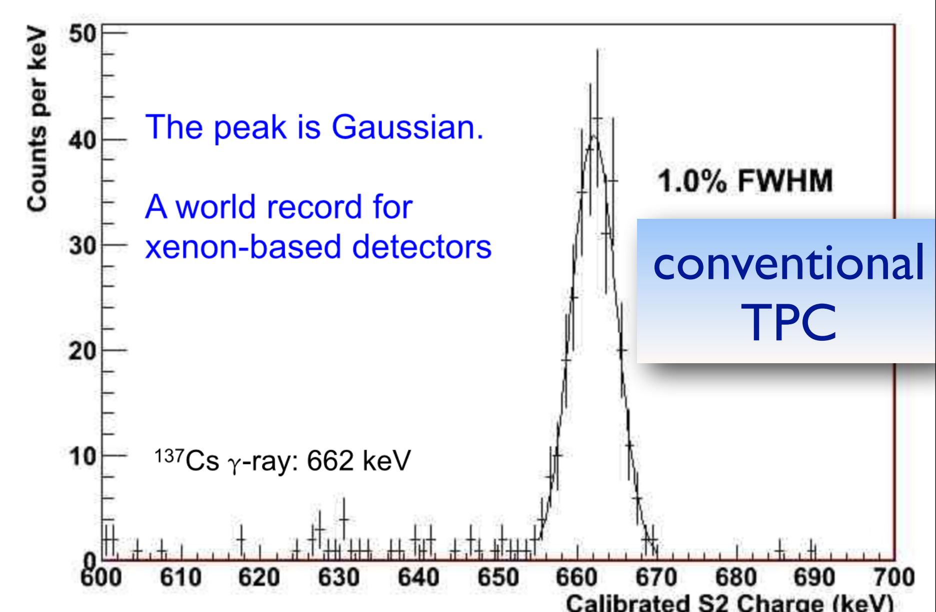


Fig. 1. Cross section of the TPC. Wire meshes separate the 19-PMT array from several regions, beginning at the mesh in front of the PMT array, from left to right; a 5 cm buffer region, an 8 cm drift region, a 3 mm EL gap, and another 5 cm buffer region. (Drawing by Robin LaFever.)





The project: directional DM detector proof of concept

As in the SIR grant request

Gaseous Directional DM 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	NITPC	CS_2/CH_3NO_2:CF_4	triple GEM + pixel	0.005	Italy

NITEC main features:

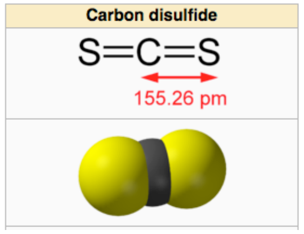
- Negative Ion Time Projection Chamber ---> to overcome conventional TPC volume limitations (~> 50 cm drift length) and improve position and energy resolution
- Triple GEM amplification with pixelated readout ---> for the state of the art spatial, time and energy resolution (sense determination via charge 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 neutrino-less double beta decay detector and easier gas handling

C. J. Martoff et al, NIM A 598

Nitromethane as alternative electron capture agent

CS_2

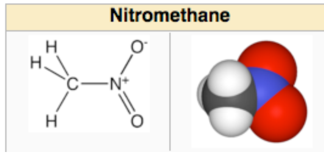
Carbon disulfide



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

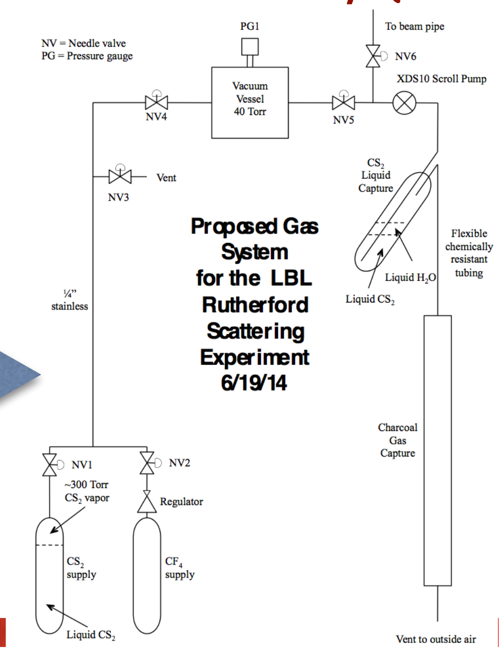
Nitromethane



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 neutrino-less double beta decay (better E.A.)

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



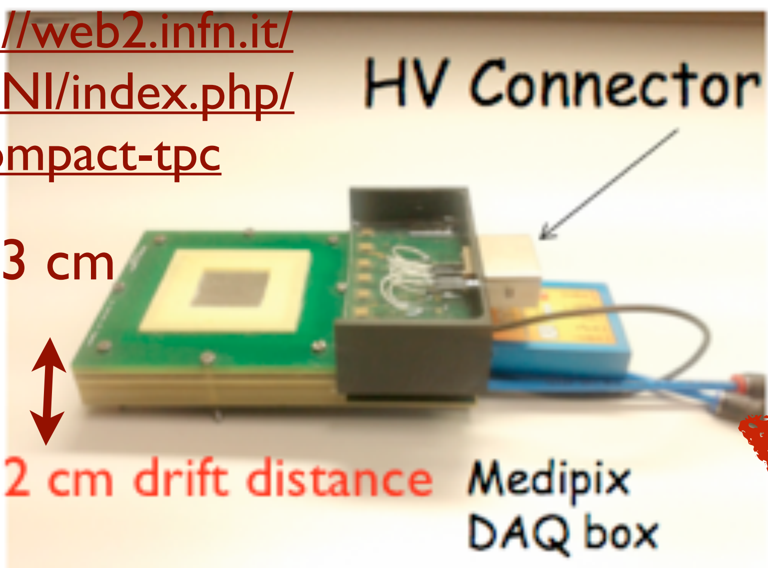
TASK SPECIFIC JOB HAZARD ANAYLSIS (TSJHA)

Staged Approach

Year 1	Year 2	Year 3

Phase I: Small prototype studies

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



3 x 3 cm

2 cm drift distance

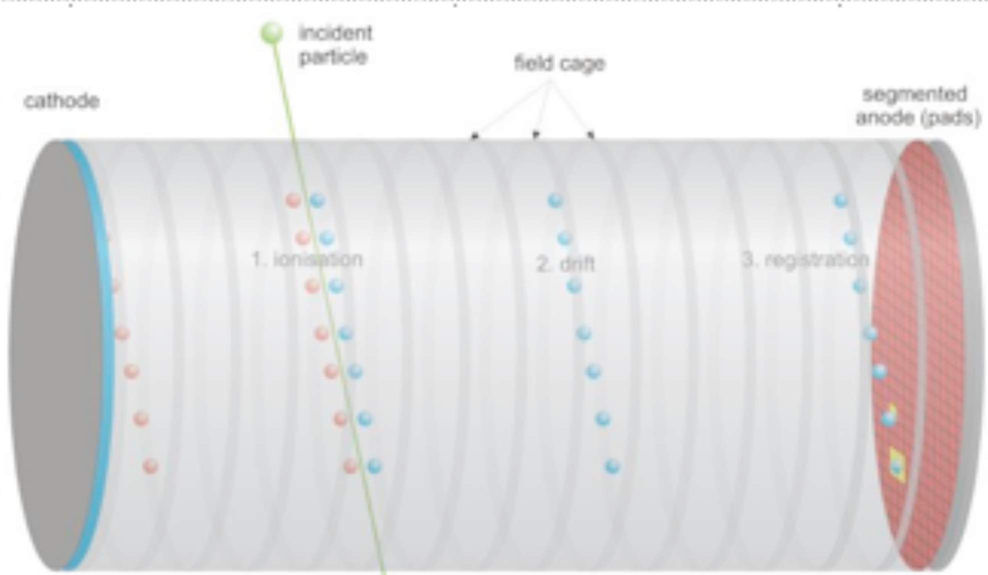
Employ an already existing small TPC prototype with GEMPix readout to prove its feasibility as Negative Ion TPC.

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

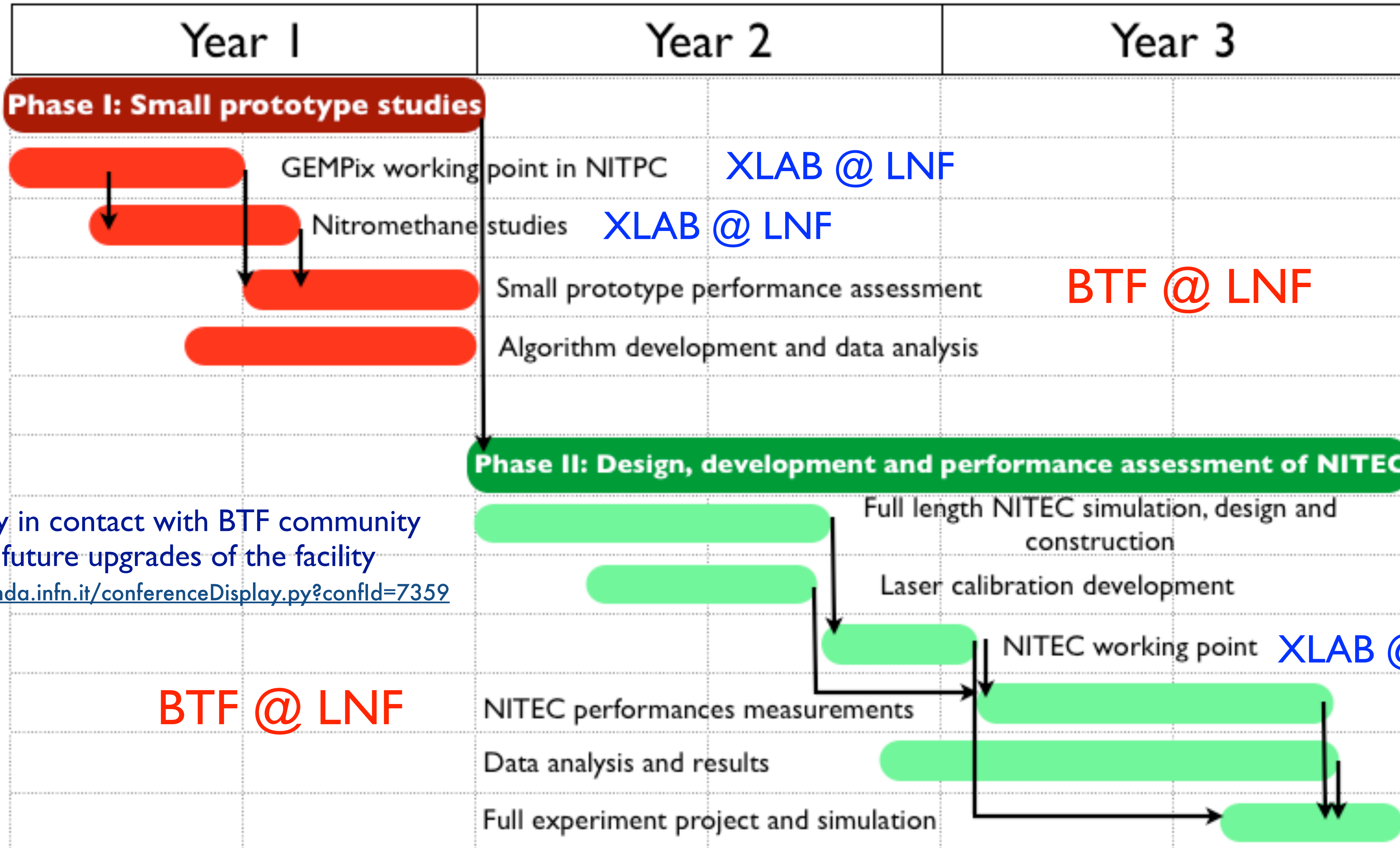


10 x 10 cm

50 cm drift distance

Full experiment project & simulation

Staged Approach



Already in contact with BTF community for future upgrades of the facility
https://agenda.infn.it/conferenceDisplay.py?confId=7359

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

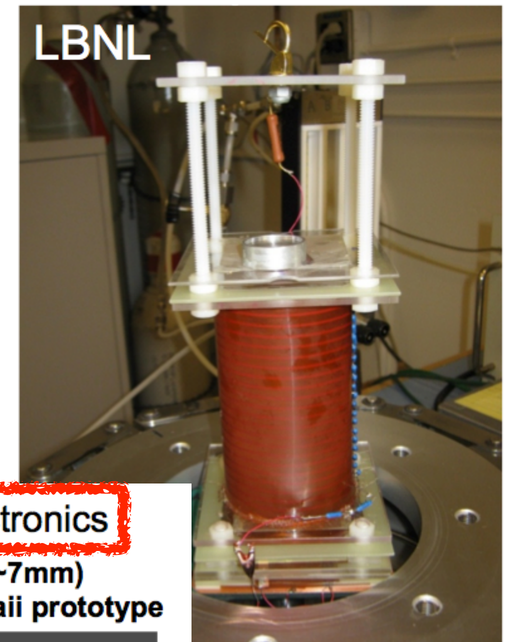
Expected performances

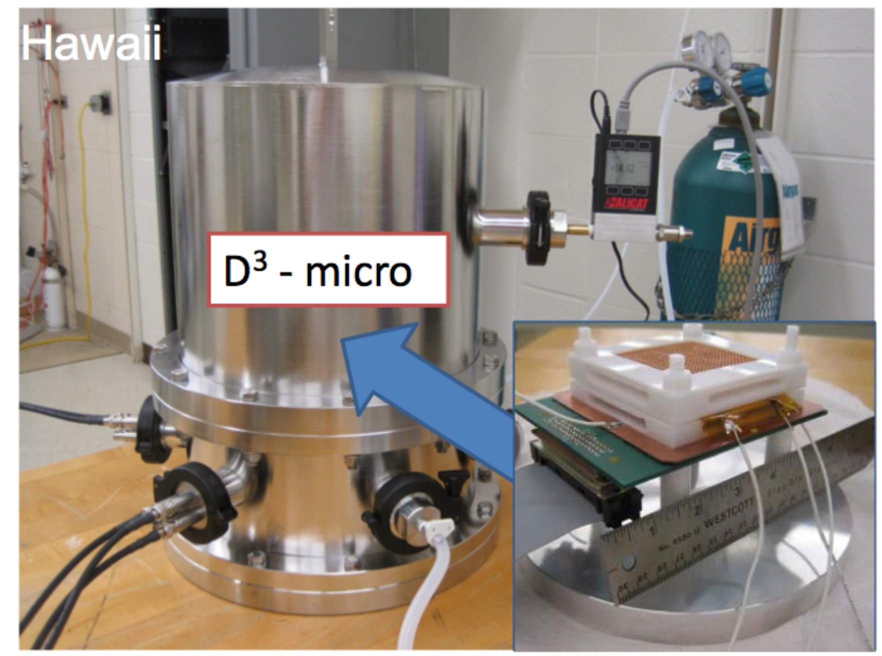
A close cousin: D^3 experiment

- 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

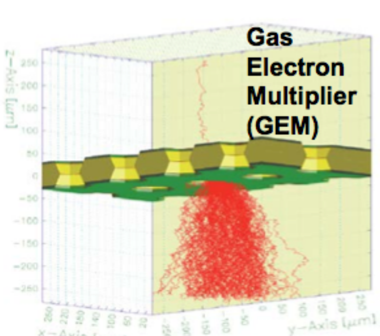
5. Energy Threshold

- 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^-



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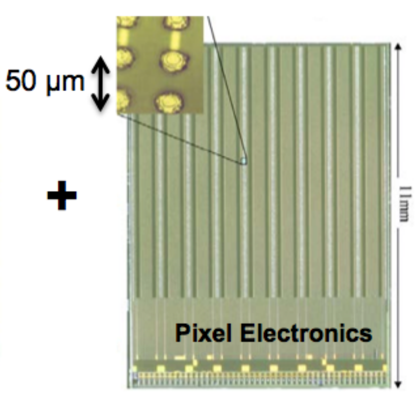
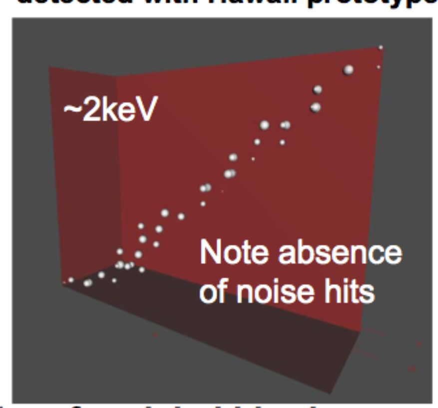


- ATLAS FE-I3
- 50x400 μm pixels
- Sampling at 40 Mhz

=

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



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

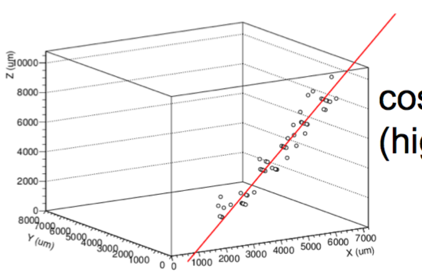
March 2013, Sven Vahsen Pre-Snowmass DM Workshop @ SLAC

arXiv: 1110.3444
arXiv: 1110.3401

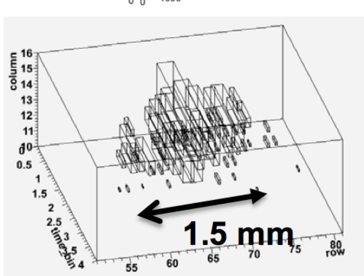
D^3 prototype performances

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

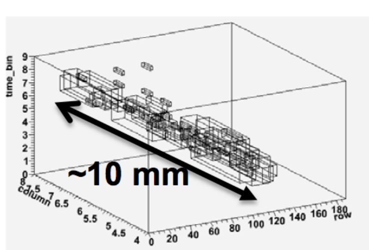
- Due to combination of high single-electron efficiency and low noise, expect low threshold operation, and good sensitivity to low-mass WIMPs
- Mostly excellent
  - Point resolution ~200 µm
  - Angular resolution ~ 1 degree for 5-10 mm tracks
  - Gain resolution ~5-10%
  - Gain stability <2%



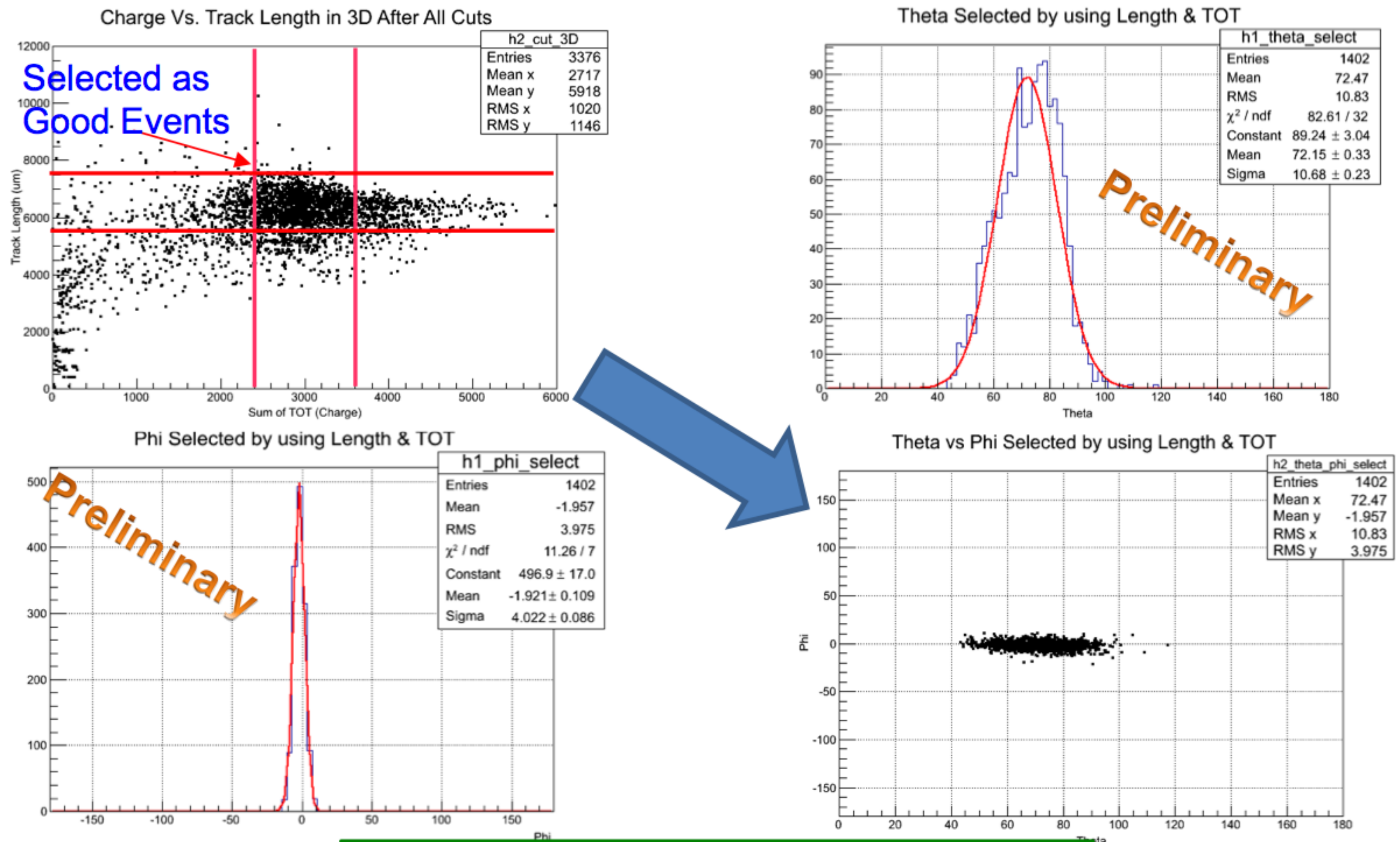
cosmic muon (high gain mode)



He-recoil candidate (low gain)



RPR event? (low gain)



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

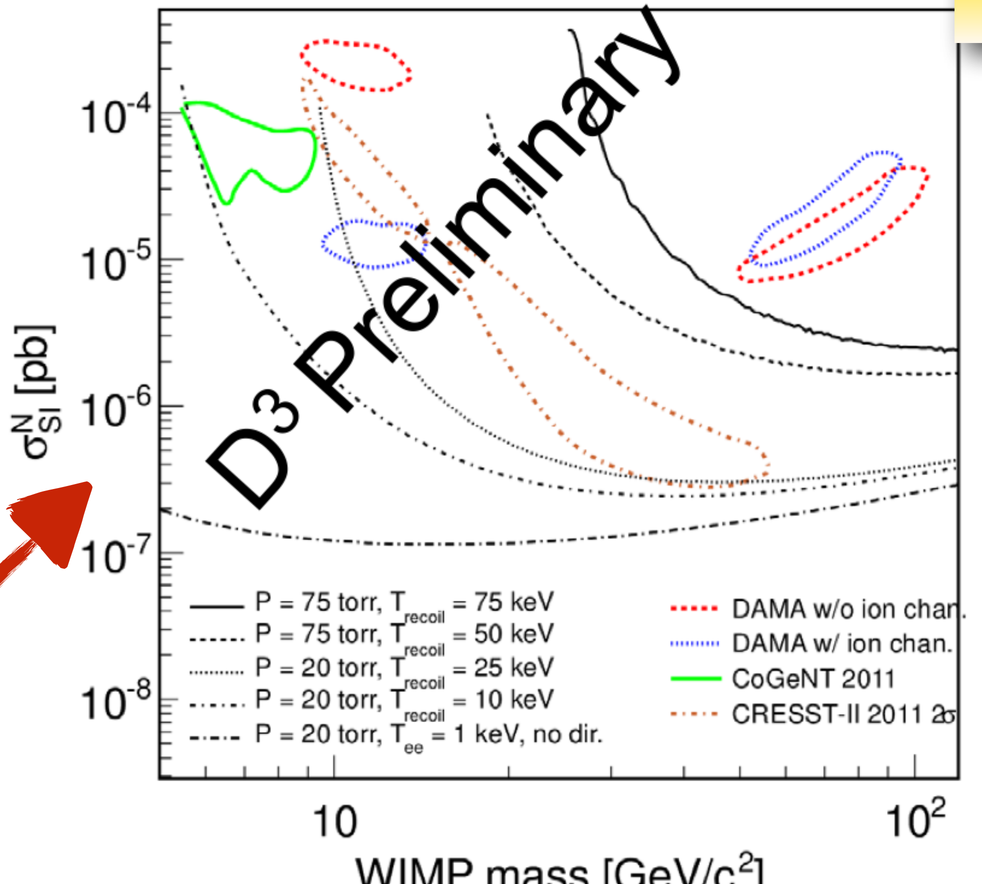
$$\sigma_{angle} = \sqrt{\sigma^2_{detector} + \sigma^2_{straggling} + \sigma^2_{source\ cone} + \sigma^2_{source\ size}}$$

- 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.

D³ 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.

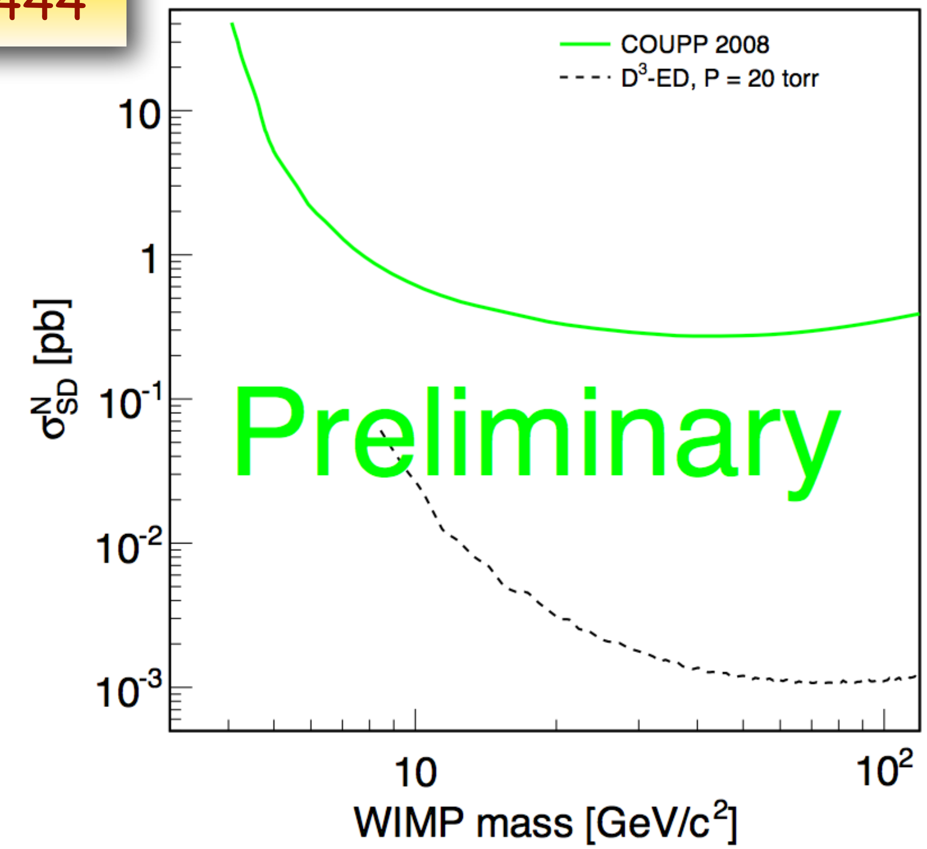


Fig. 5. D³ cross section limit as a function of the WIMP mass for one recoil produced by a WIMP detected in three m³. The detector is divided into nine sub-detectors with a maximum drift distance of 33.33 cm for ED-CF_4 and NID-CS, the SI case on the left and for the SD case on the right. The D³ reach 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

Two words about neutrino bound

Beyond neutrino bound

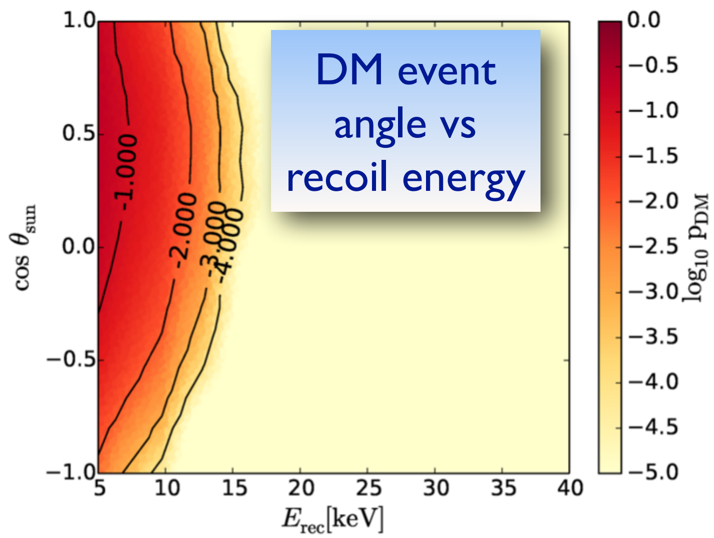


FIG. 1: Two dimensional dark matter probability distribution ρ of recoil energy and event angle for a 6 GeV dark matter particle in a CF_4 detector with 5 keV threshold in September.

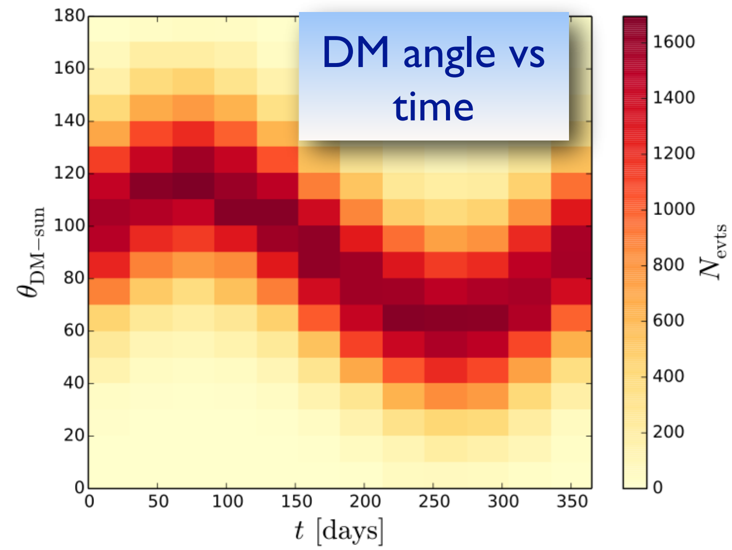


FIG. 2: Distribution of the angle between the incoming dark matter velocity and the Earth-Sun direction over the year for events above a 5 keV threshold in a CF_4 detector. For each month 1×10^4 dark matter events have been simulated. The maximum of the distribution follows the expected pattern as described in the text.

arXiv:1406.5047
from DMTPC collaborators

$$\tilde{Q} = \frac{p_{b+s}(n)}{p_b(n)} \frac{\prod_{j=1}^{n} \frac{sS_t(t_j)+bB_t(t_j)}{s+b} \; \frac{sS^{(t)}_{\theta,E}(\theta_j,E_j)+bB_{\theta,E}(\theta_j,E_j)}{s+b}}{\prod_{j=1}^{n} B_t(t_j)\; B_{\theta,E}(\theta_j,E_j)}$$

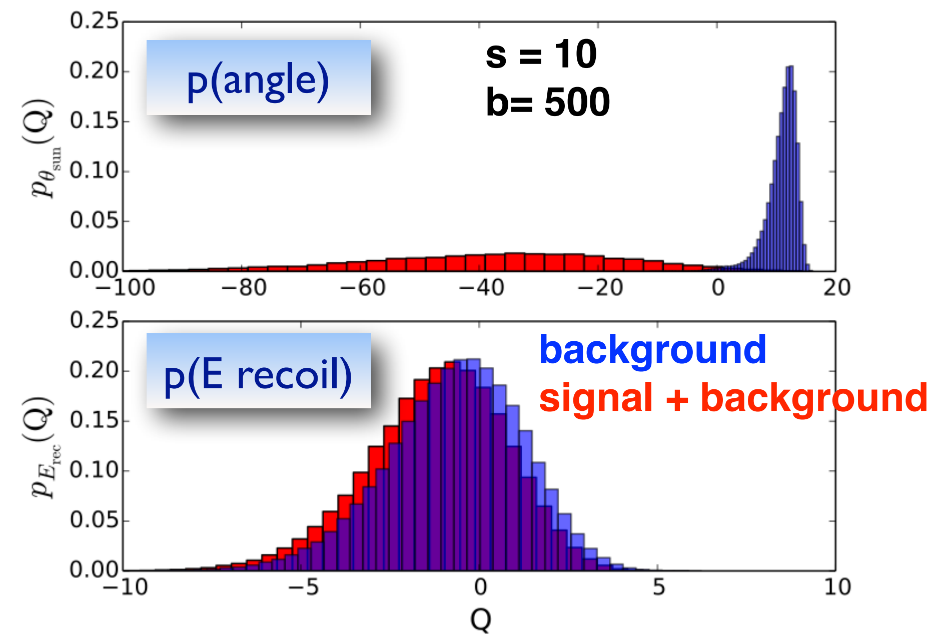


FIG. 6: The normalised background only distribution $p_B(Q_B)$ (blue) and signal plus background distribution $p_{SB}(Q_{SB})$ (red) including angular information (top) and excluding angular information (bottom) for s=10 and b=500 for a 6 GeV dark matter particle in a CF_4 detector. The gain in sensitivity when using directionality is clearly visible in the separation of the two distribution in the upper plot.

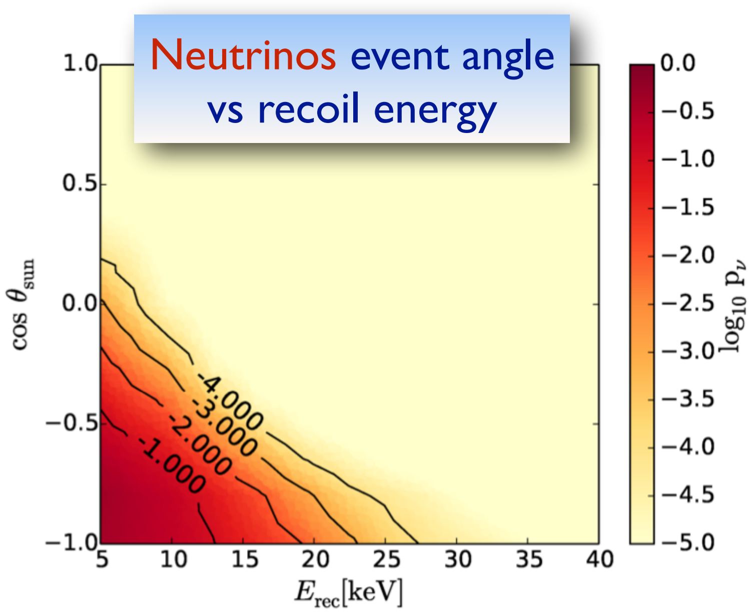


FIG. 5: The two dimensional probability distribution ρ of recoil energy and event angle of neutrinos in a CF_4 detector with 5 keV threshold.

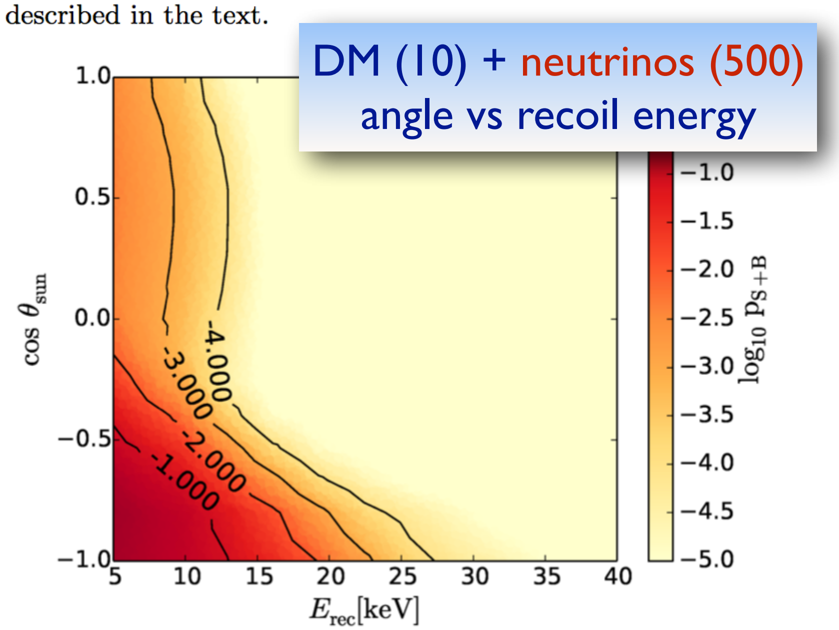


FIG. 7: The combined two dimensional probability distribution ρ of the recoil energy and event angle for a 6 GeV dark matter particle and neutrinos in a CF_4 detector. The expected signal rate is fixed to s=10 and the expected background rate to b=500.

CF_4 detector with 5 keV energy threshold for a 6 GeV DM particle

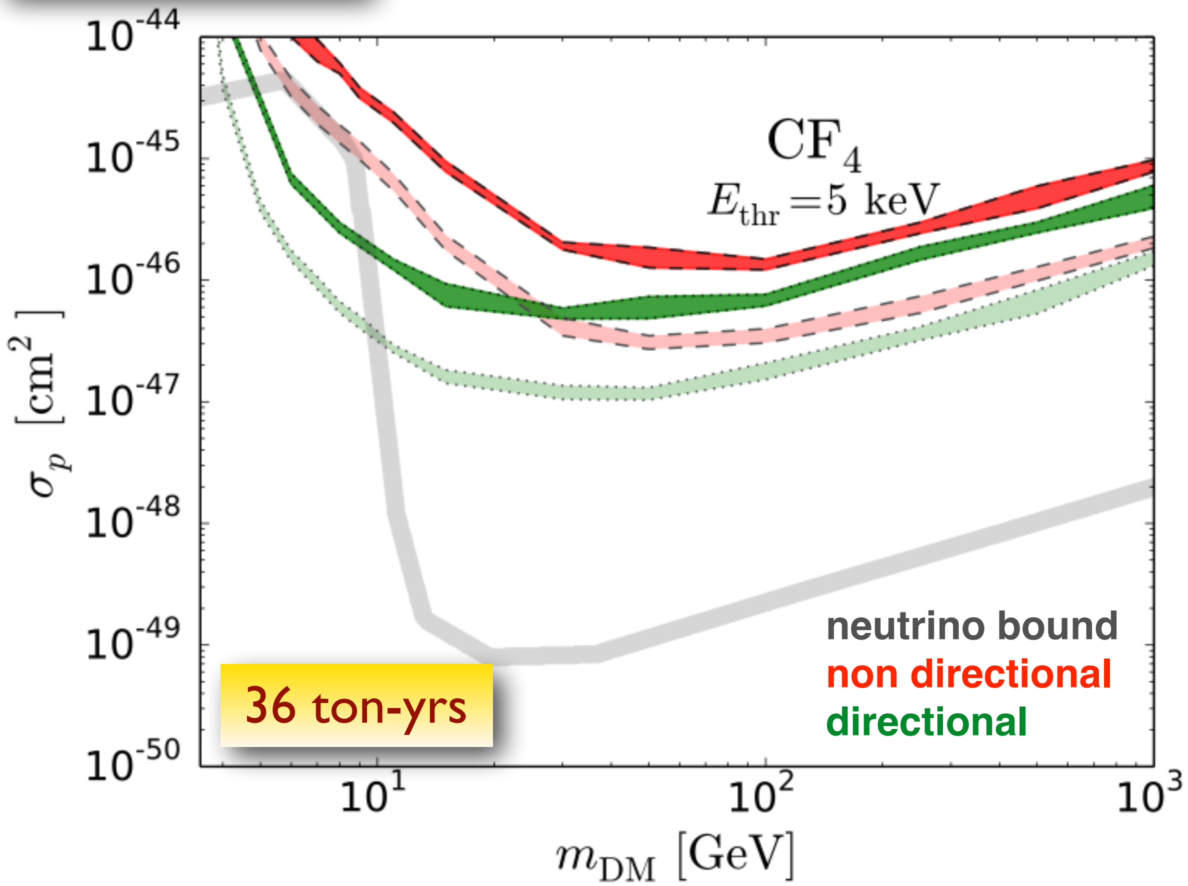
Expected sensitivity

CF₄ detector

signal events = 10
background events= 500

3 sigma discovery
90% C.L.

Xe detector



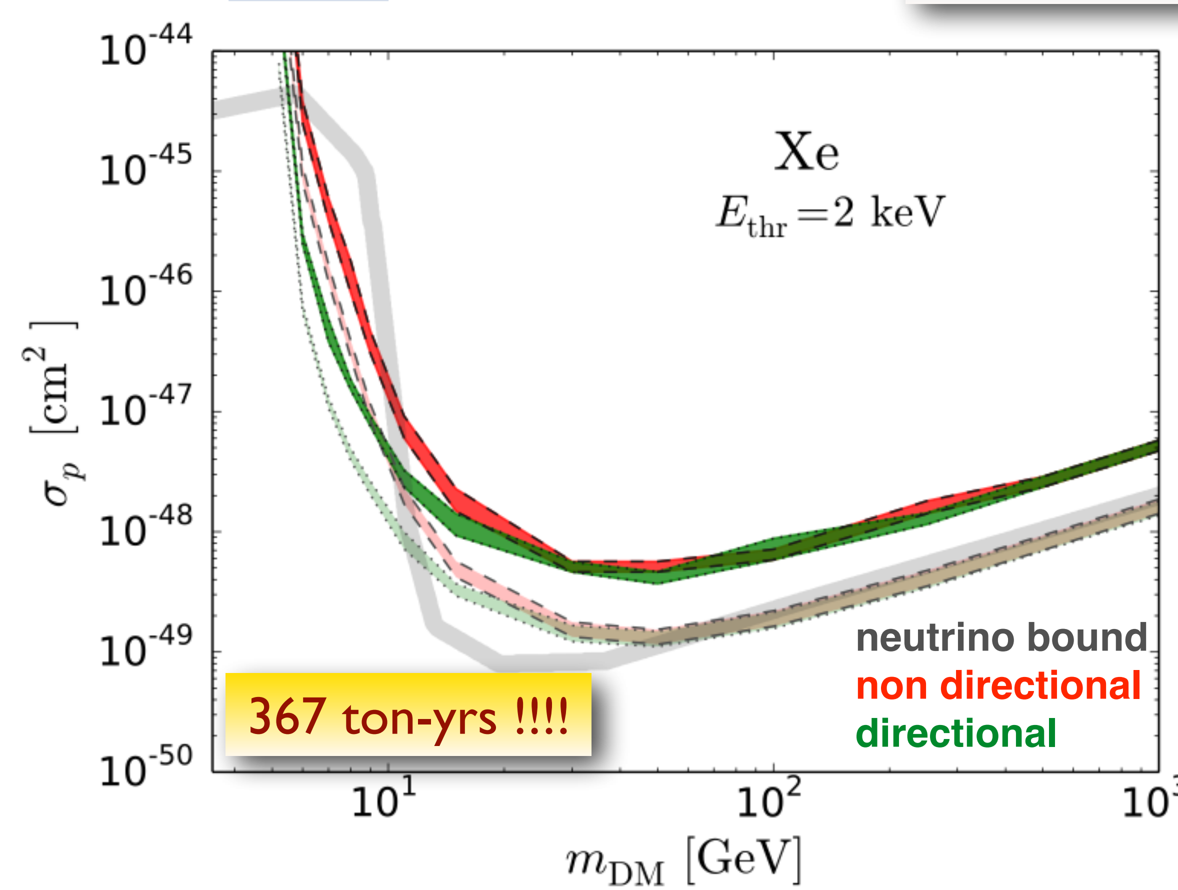


FIG. 8: Estimated sensitivity limits at 3σ level for a nondirectional (red band) and directional (green band) CF_4 detector with 36 t-yrs exposure and 5 keV energy threshold resulting in 500 expected neutrino events. The fainter bands indicate corresponding sensitivity limits at 90% CL, the grey curve is the neutrino bound.

FIG. 9: Estimated sensitivity limits at 3σ level for a nondirectional (red band) and directional (green bands) Xenon detector with 367 t-yrs exposure and 2 keV energy threshold resulting in 500 expected neutrino events. The fainter bands indicate corresponding sensitivity limits at 90% CL, the grey curve is the neutrino bound.

Directionality gains 10x in sensitivity in presence of background!!!!

Directional information is less significant in heavy target material (Xenon) based detectors, since solar neutrinos can give recoil energies up to approximately 5 keV with an heavy nucleus.

What next?

Successful proof of concept of NITEC — **~ 3 yrs**

- If interest is found in the scientific community, develop a project for a full (1 m^3??) experiment to be hosted, for example, at LNGS
- Consequent development of customized amplification & readout with optimized pixel size (400-500 um) and electronics tailored on a triple GEM amplification
- Possible new larger prototype for additional optimization studies

DM directional experiment

- New prototype (able to sustain high pressure)
- New target material
- New study and optimization needed for a customized amplification & readout system
- New ERC, SIR, Rita Levi Montalcini, gruppo 5, Marie Curie grants to apply

(if HPXe is used, both can be done with same prototype)

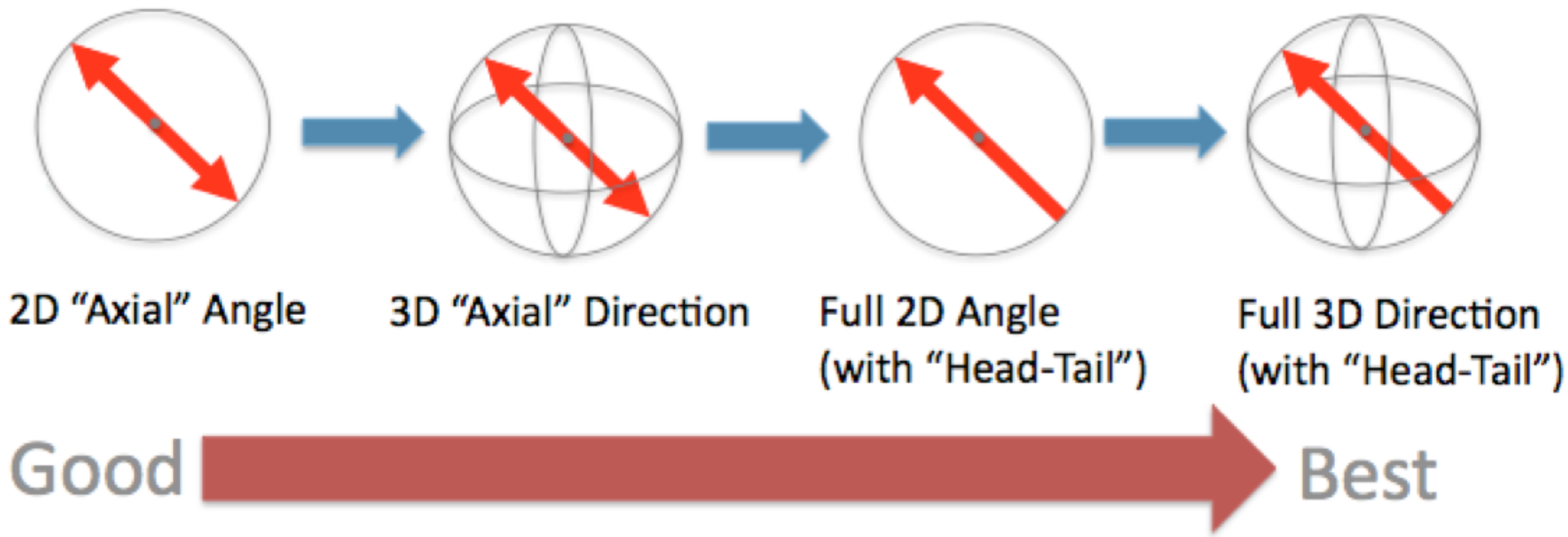
Neutrino less double beta decay detector proof of concept

Use NITEC to study columnar recombination potentialities

BONUS: italian and international MPGS R&D communities already working on chip optimization for GEM and Micromegas readouts

Backup

Direction



- 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.]

Measurements @ BTF

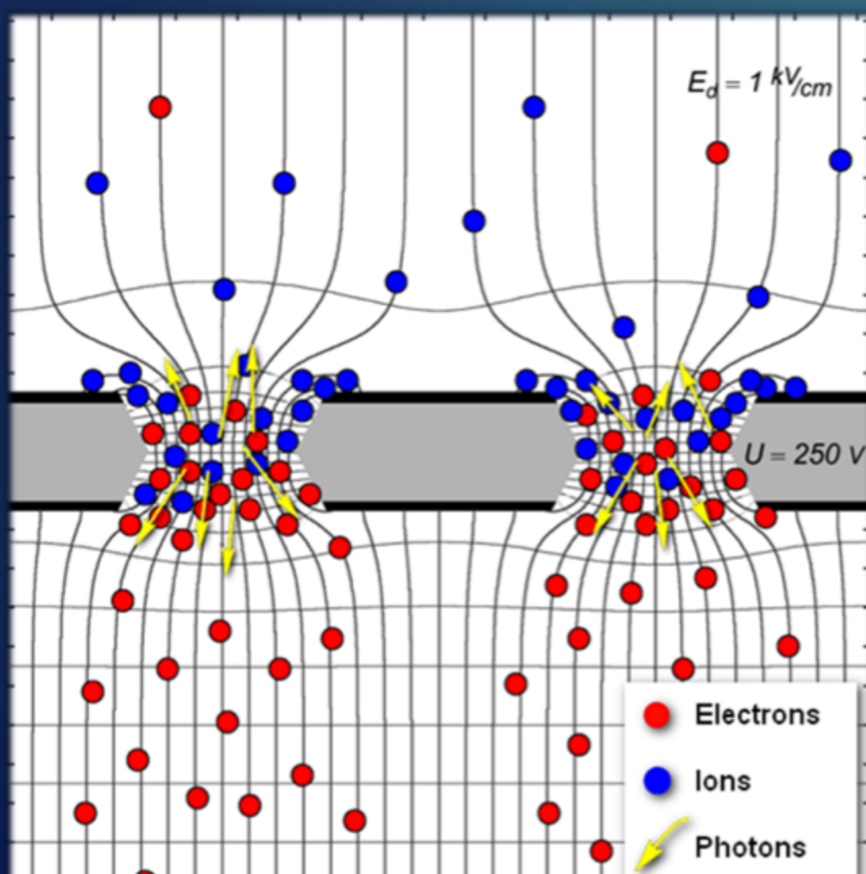
- Measurements of spatial, time and energy resolution of the detector
- We have very long signal (slow ion drift) <---> we would need to optimize bunch length and repetition rate for our tests
- We look for very low energy processes <---> we would benefit from lower energy positrons/electrons/photons
- 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

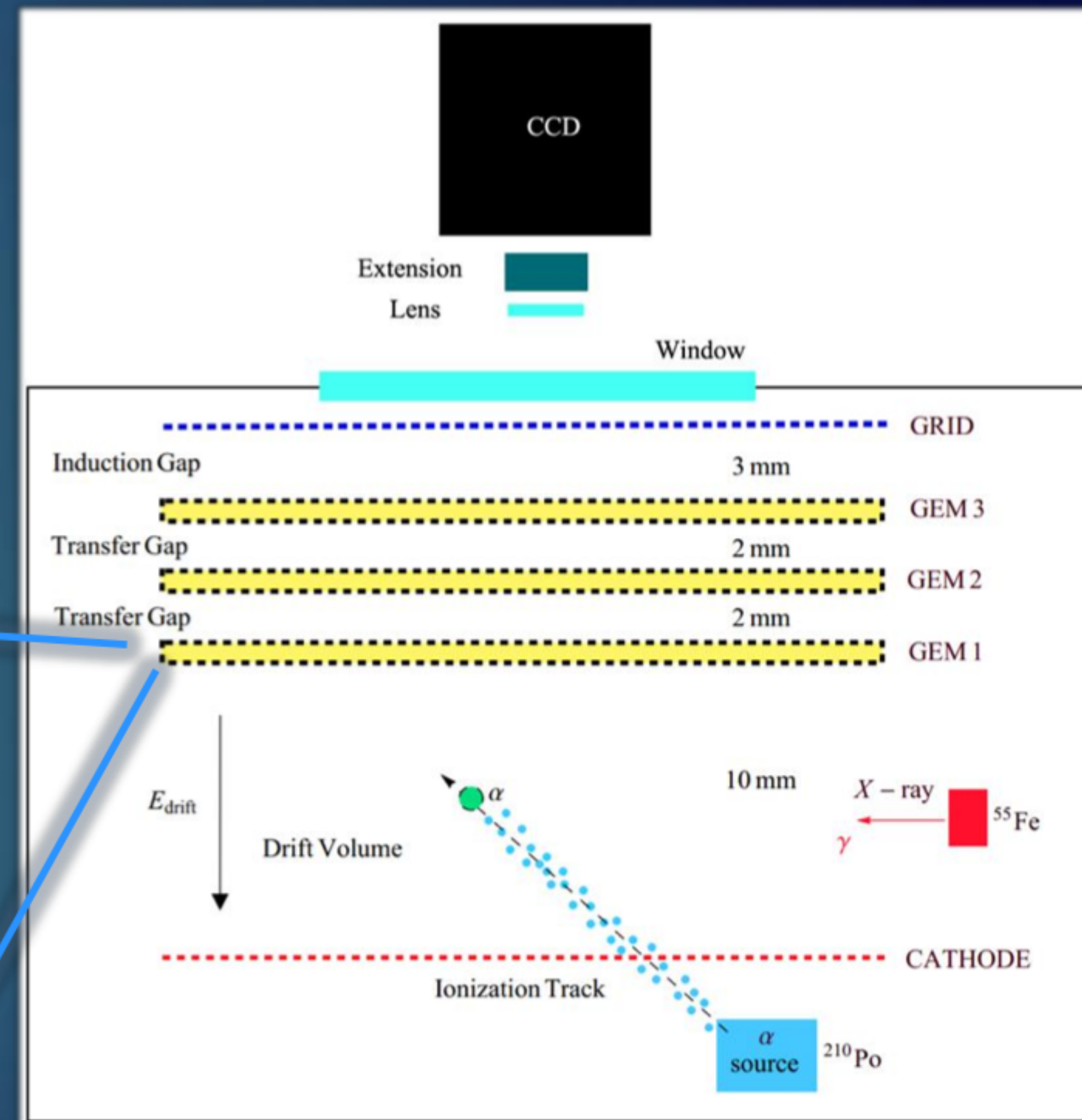
Already in contact with BTF community for future improvements and upgrade of the infrastructure (see NITEC talk at First BTF Users Workshop)

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

GEM TPC for DM 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.





from people in DRIFT collaboration

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

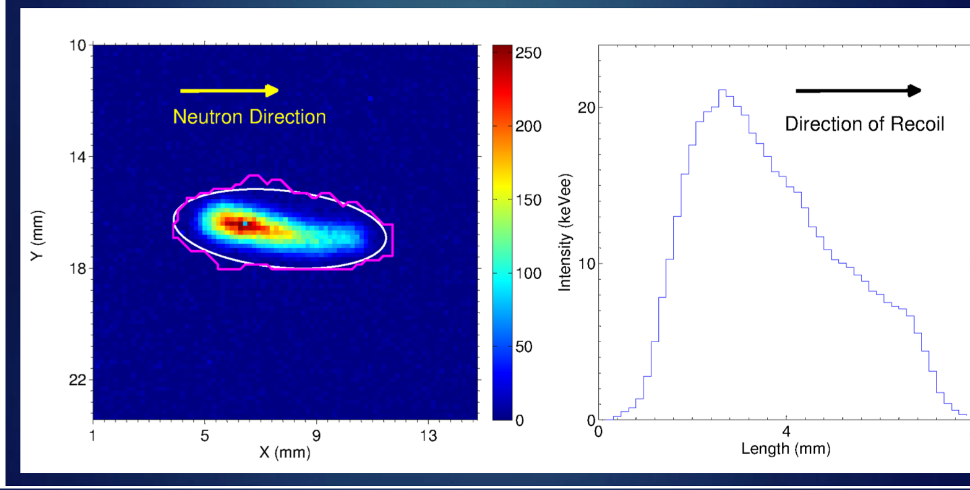
Performances

Directionality

8

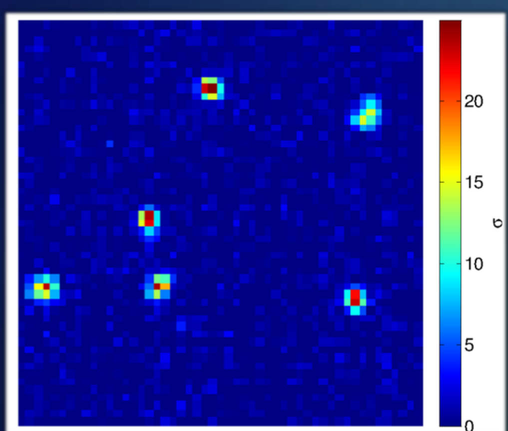
Skew: $S = \frac{\mu_3}{\mu_2^{3/2}}$

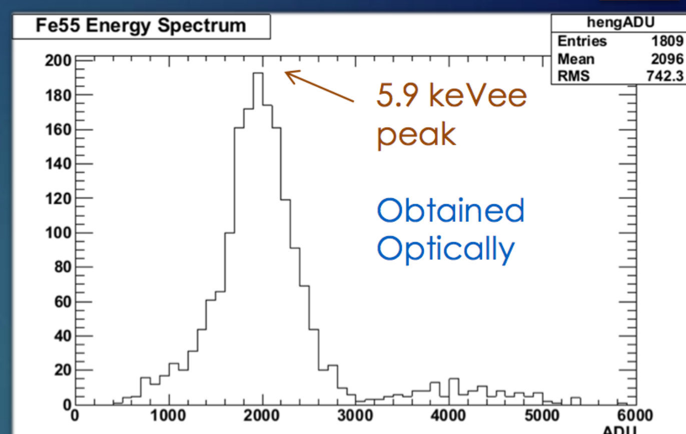
Orientation Angle: α



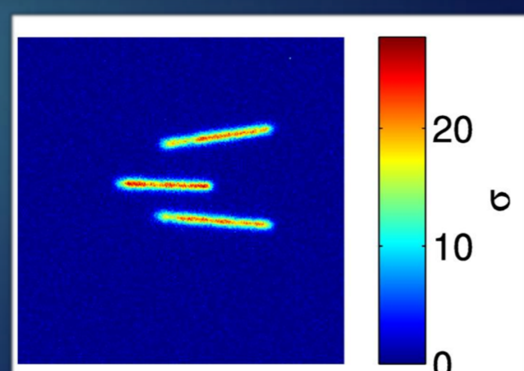
^{55}Fe and ^{210}Po Calibrations

4





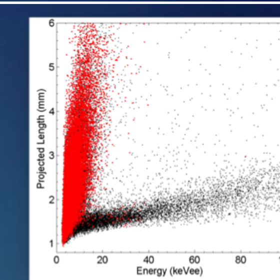
- ^{55}Fe energy spectrum (obtained optically via CCD) and image of tracks at 16x16 pixel binning .
- Alpha track segments (right) at 6x6 binning and max stable gain (~ 10^5).
  - Excellent signal-to-noise (SNR), Peak SNR > $25\sigma_{im}$
- Energy Resolution: 35 % (FWHM) at 5.9 keVee.
- Diffusion: σ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



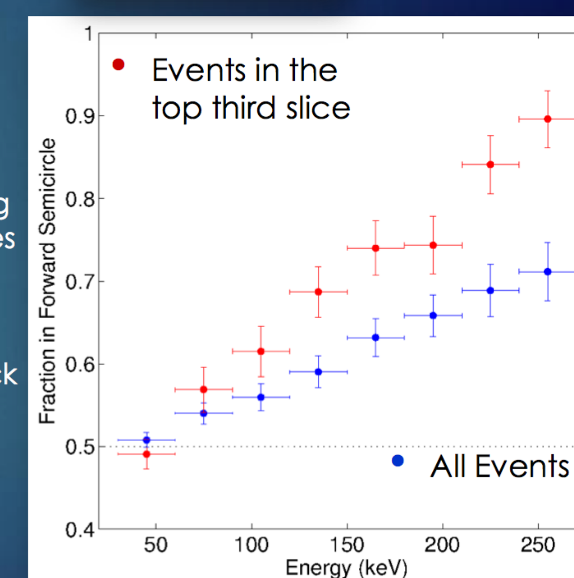
- Discrimination down to ~ 10 keVee (~ 25 keV). Recoil energy assumes fluorine and Hitachi quenching factors (Hitachi, Rad. Phys. & Chem. 77 (2008)).
- Electronic recoils have small dE/dx but large fluctuations → low S/N could lead to confusion with nuclear recoils.

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

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)

28 May 2013

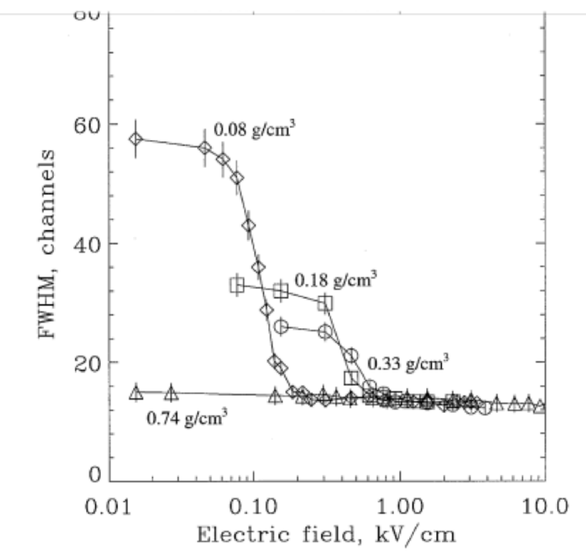


Fig. 5. FWHM of the peaks in pulse-height spectra of the amplitude of the light signals versus the electric field strength measured at 0.08 g/cm³ (diamonds), 0.18 g/cm³ (squares), 0.33 g/cm³ (circles), and 0.74 g/cm³ (triangles).

- 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

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