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

NITEC

a Negative Ion Time Expansion Chamber for very rare events searches

7th Symposium on large TPCs for low-energy rare event detection
Amphi Buffon, Paris
15th - 17th December 2014

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 Laboratori Nazionali di Frascati (INFN)

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

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

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

erc
European Research Council
ERC-2015-StG

- Full endorsement from LNF
- Already in contact with BTF community for improvement in the neutron beam line
- Ready to start as soon as fundings will be available


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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

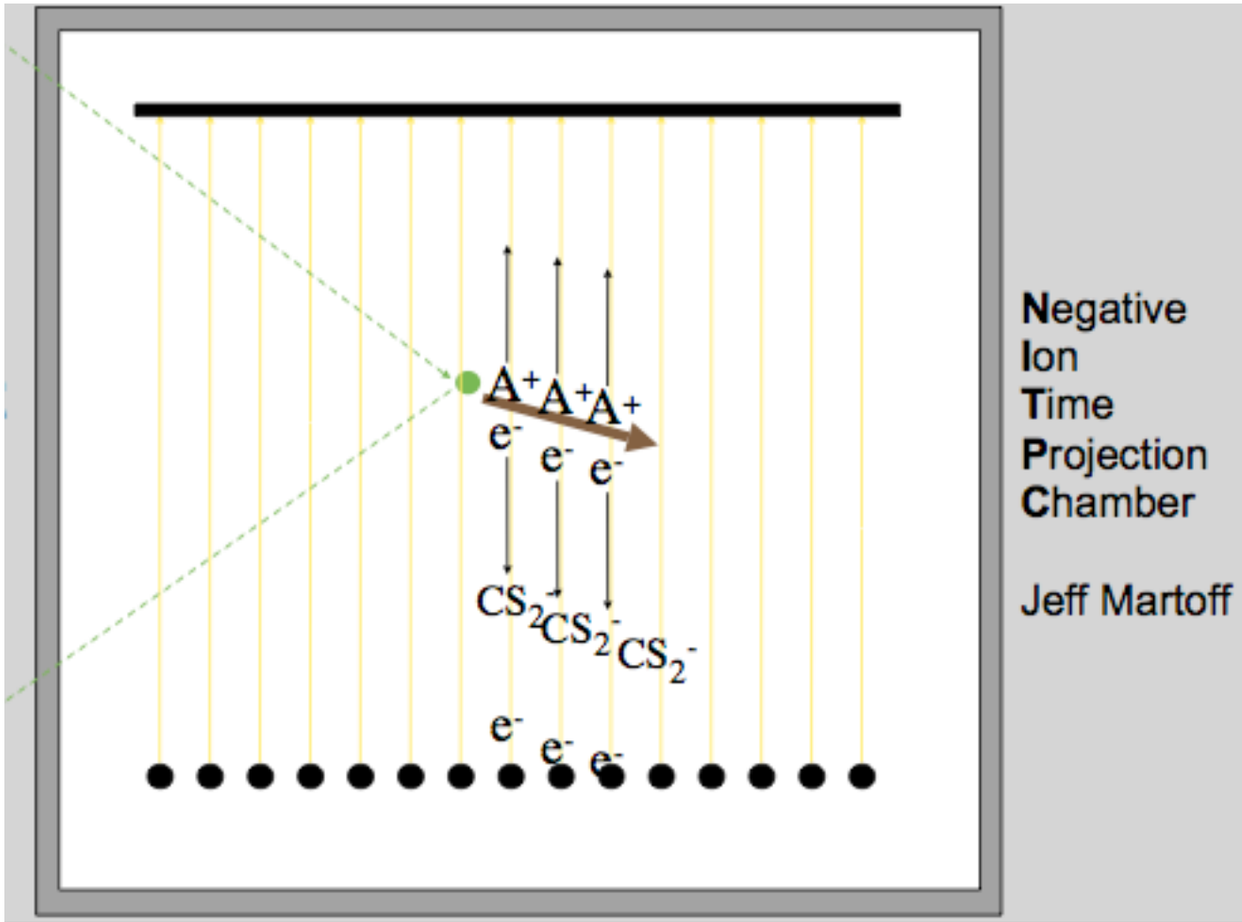
…mainly because my current position in the MEG experiment does not allow me to freely pursue this project….

Approach

- TPC with negative ion drift
- Charges signal through triple GEM amplification and CMOS pixel readout (GEMPix)
- Light signal with SiPM

- Larger allowed drift distance
- Powerful background rejection through tracking
- Superior energy resolution

Negative Ion drift



< 0.5 mm diffusion achieved over 0.5 m drift length w.r.t. 10 mm obtained with electrons (no magnetic field)

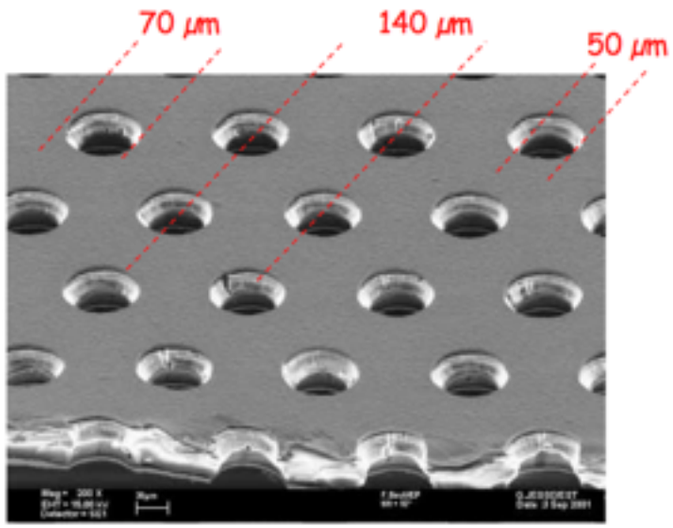
J. Martoff et al., NIM A 440 355

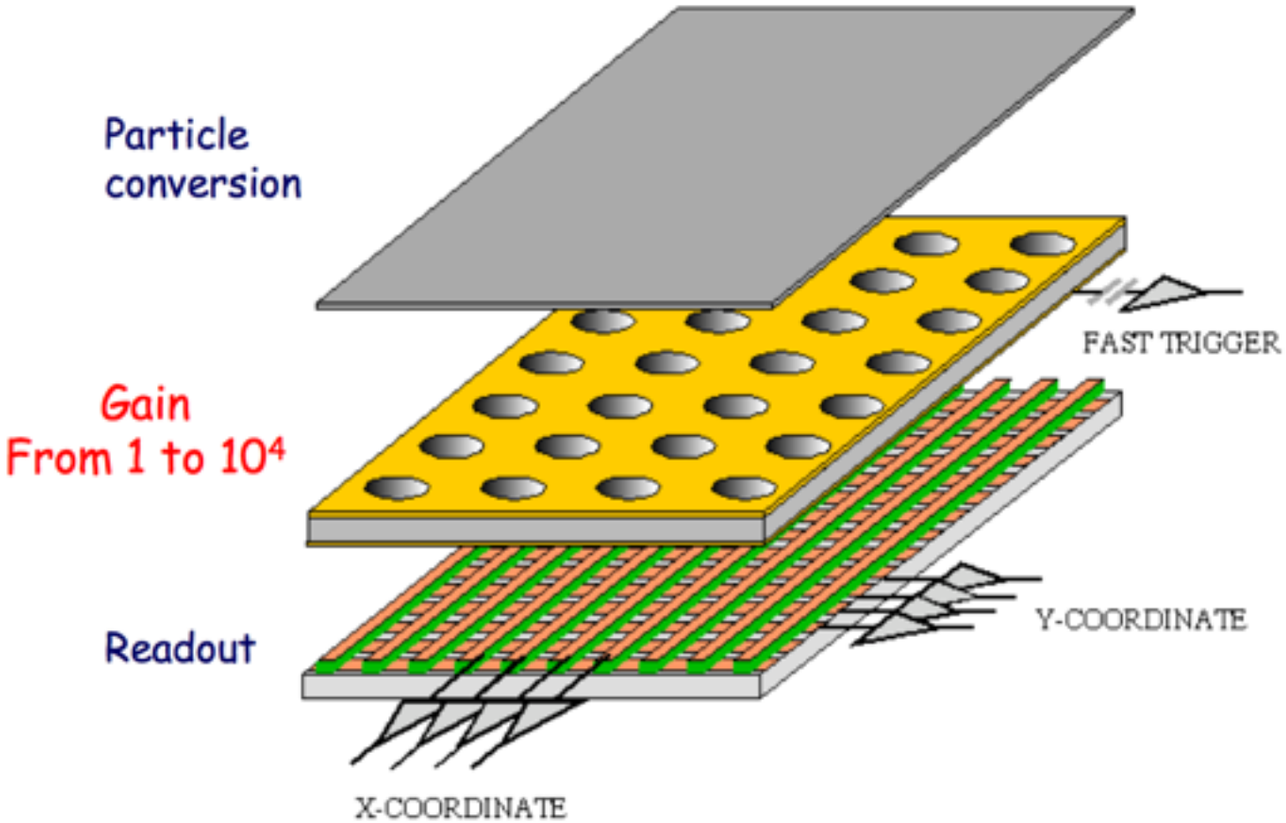
T. Ohnuki et al., NIM A 463

- 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 acting as the effective image carrier instead of the electrons
- Thanks to the much higher anions mass w.r.t. electrons, longitudinal and transversal diffusion is reduced to thermal limit w/out any magnetic field
- At the anode, the electron is stripped from the anion and normal electron avalanche occurs

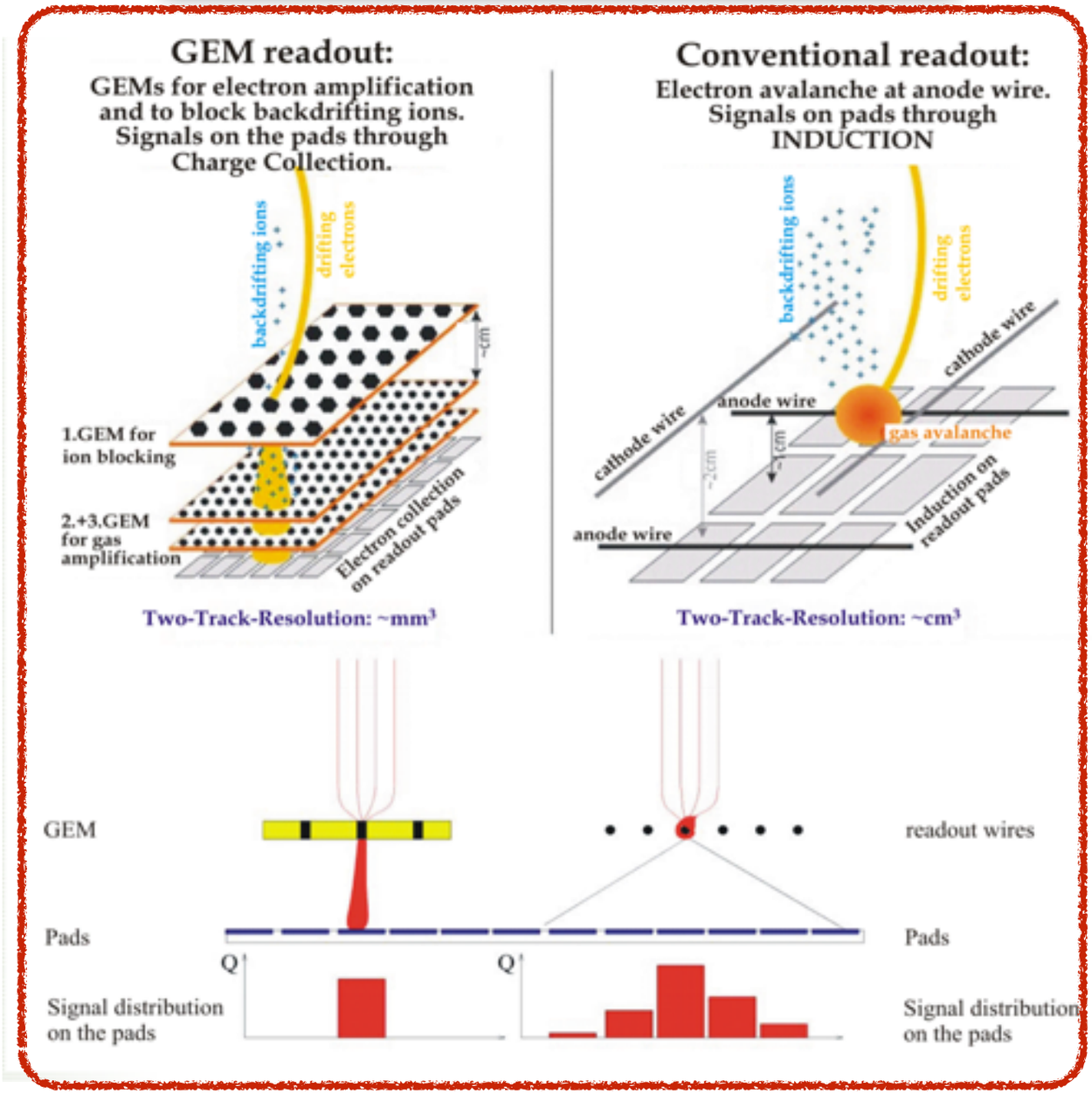
Address TPC typical volume limitations

GEM Amplification

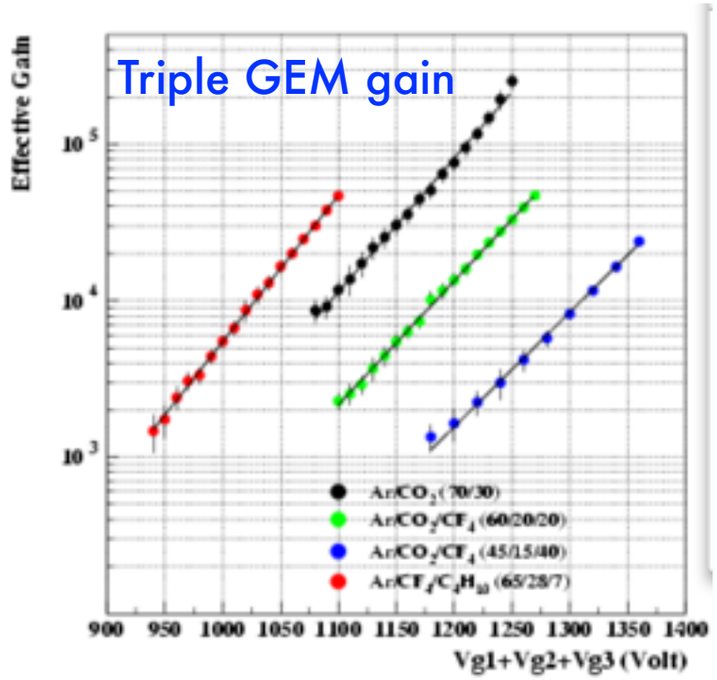




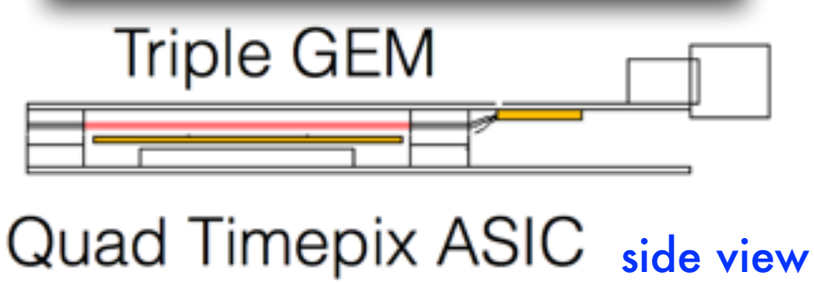
GEM amplification advantages



GEMPix

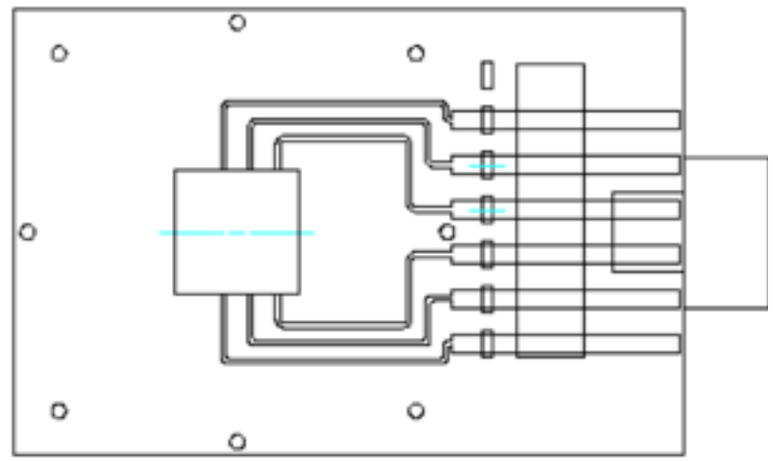


Triple GEM detector with HV filters and connector

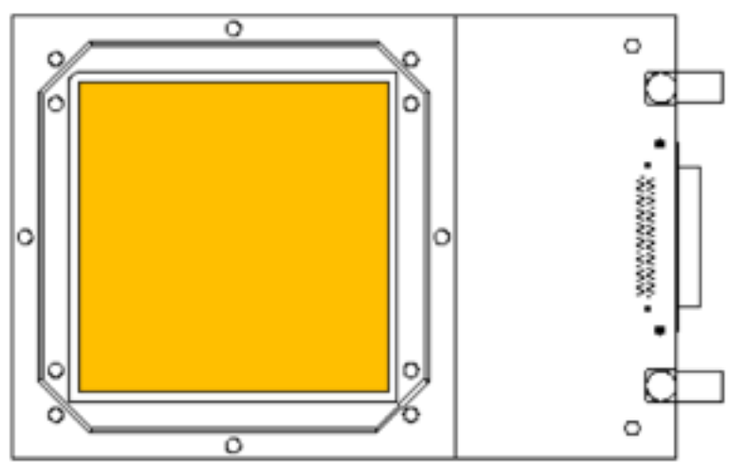


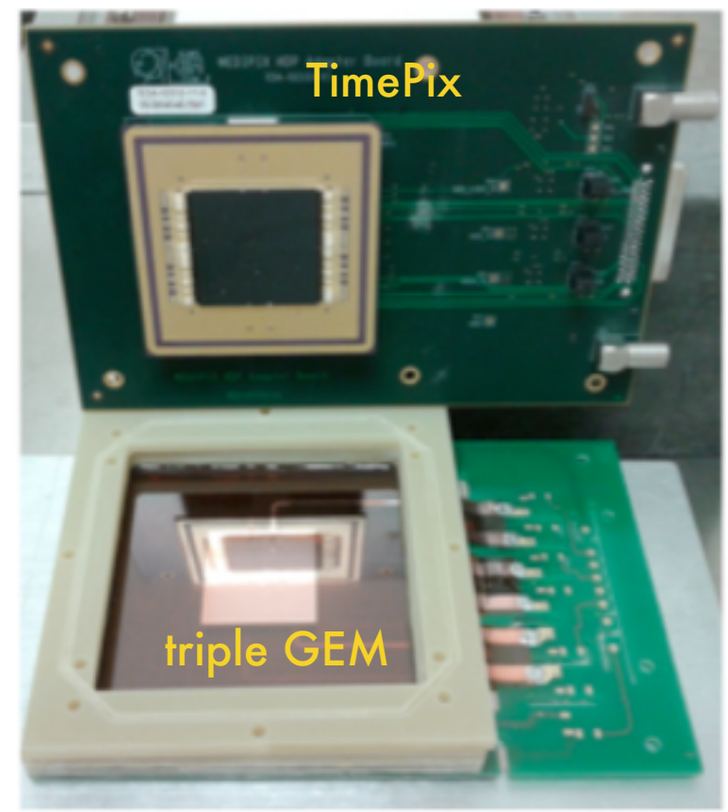
Quad Timepix ASIC board with naked devices (i.e. no silicon)

Developed by LNF in collaboration with CERN



top view





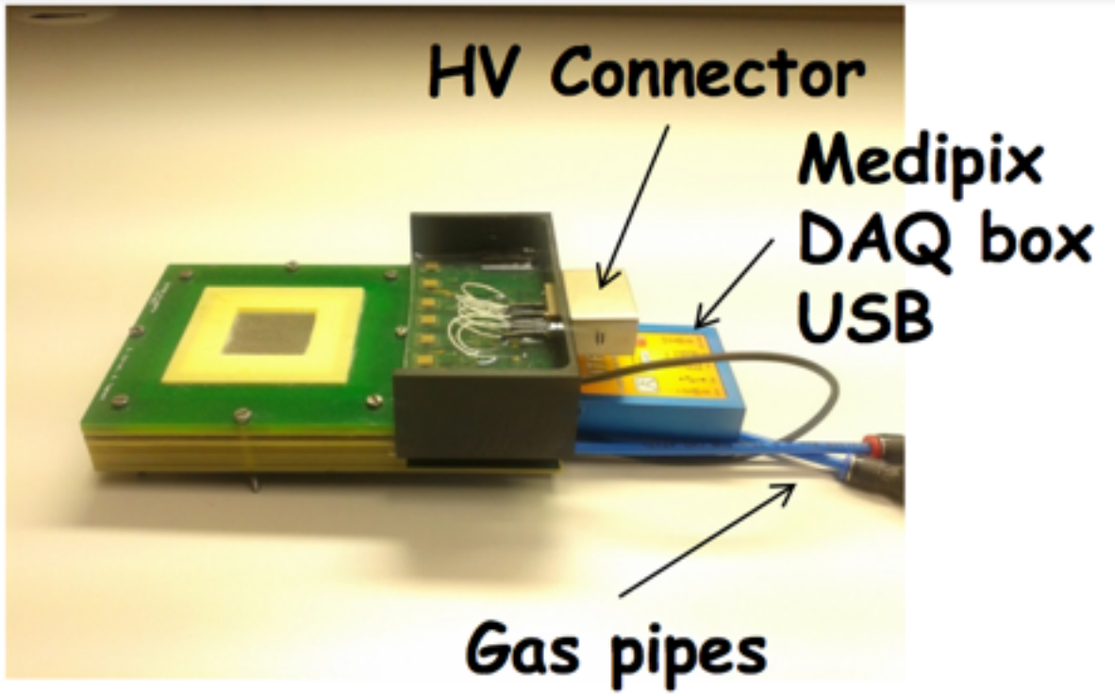
pixel size 55 x 55 um

Quad Timepix (512 x 512 pixels) = 4 Timepix chips (256 x 256 pixels each)

GEMPix TPC performances

- Single particle counting mode, Time over Threshold or Time of Arrival mode
- 5 ns time resolution, O(200) um spatial resolution, sensitivity to single ionization cluster
- Up to now, potentialities explored only in beam monitoring, dosimetry and low energy x ray imaging

Already existing 3 x 3 x 2 cm drift distance TPC equipped with GEMPix readout

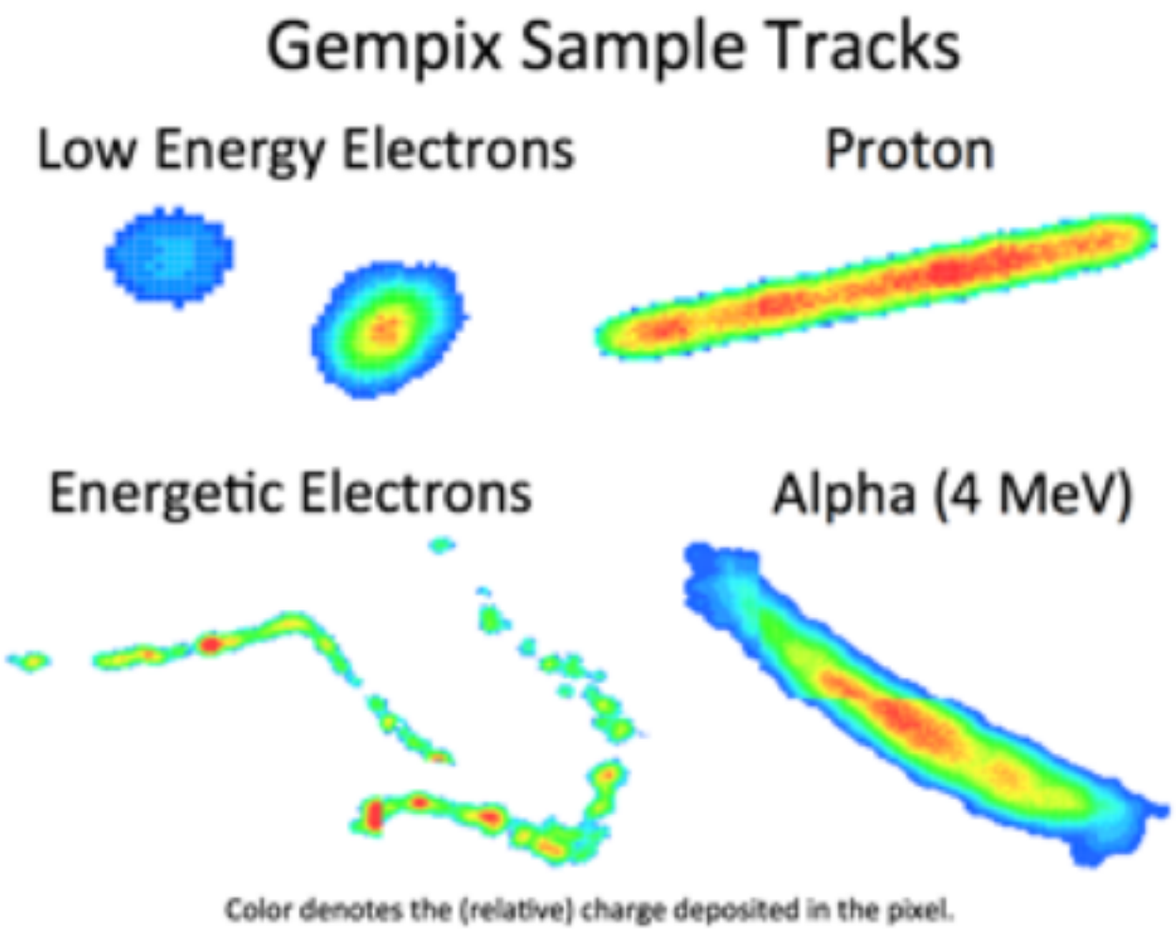


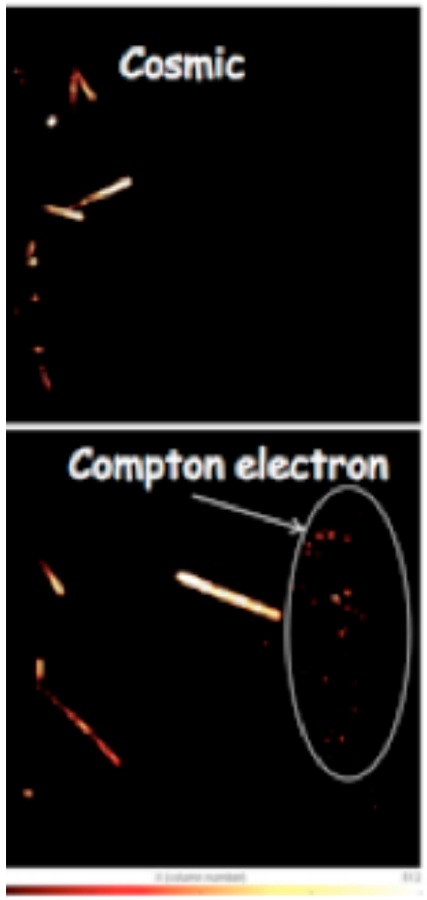
https://web2.infn.it/GEMINI/index.php/gempix-detector

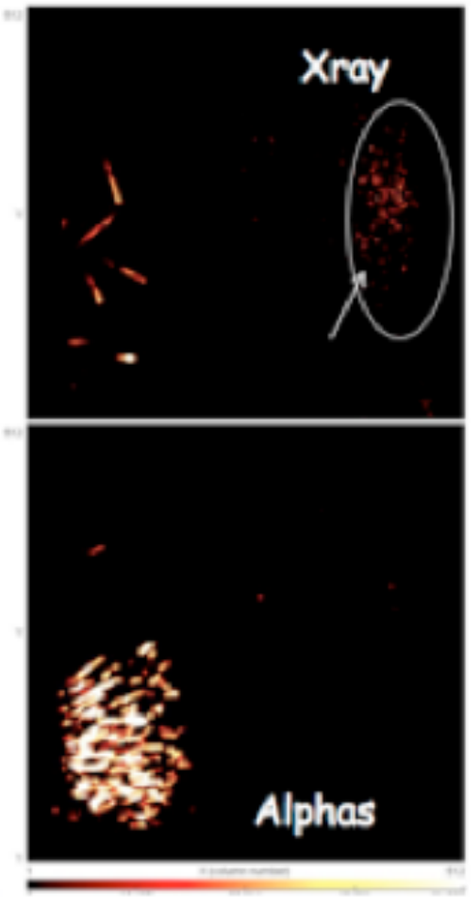
- Timepix clock can run at 1, 10 or 50 Mhz (100 as well, but unstable)
- Timepix counter depth is 11810 —> limits total acquisition time —> is ok for negative ion slow drift as well

GEMPix TPC performances

(Time over Threshold)







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

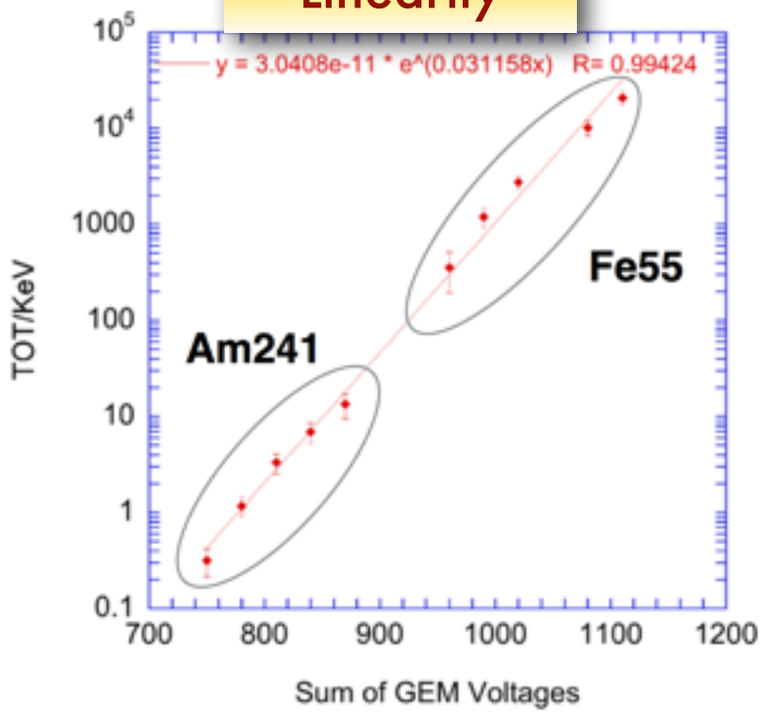
With a gain of 6000 and an induction field of 2 kV/cm

CNAO
CERN
ARDENT
INFN

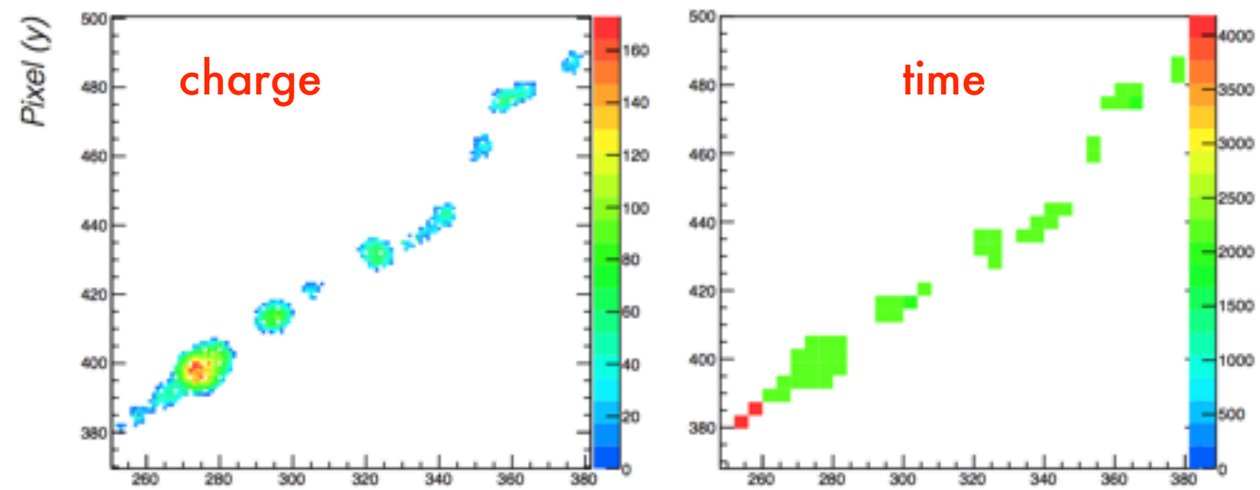
Please note:
these are DATA, not MC

GEMPix TPC performances

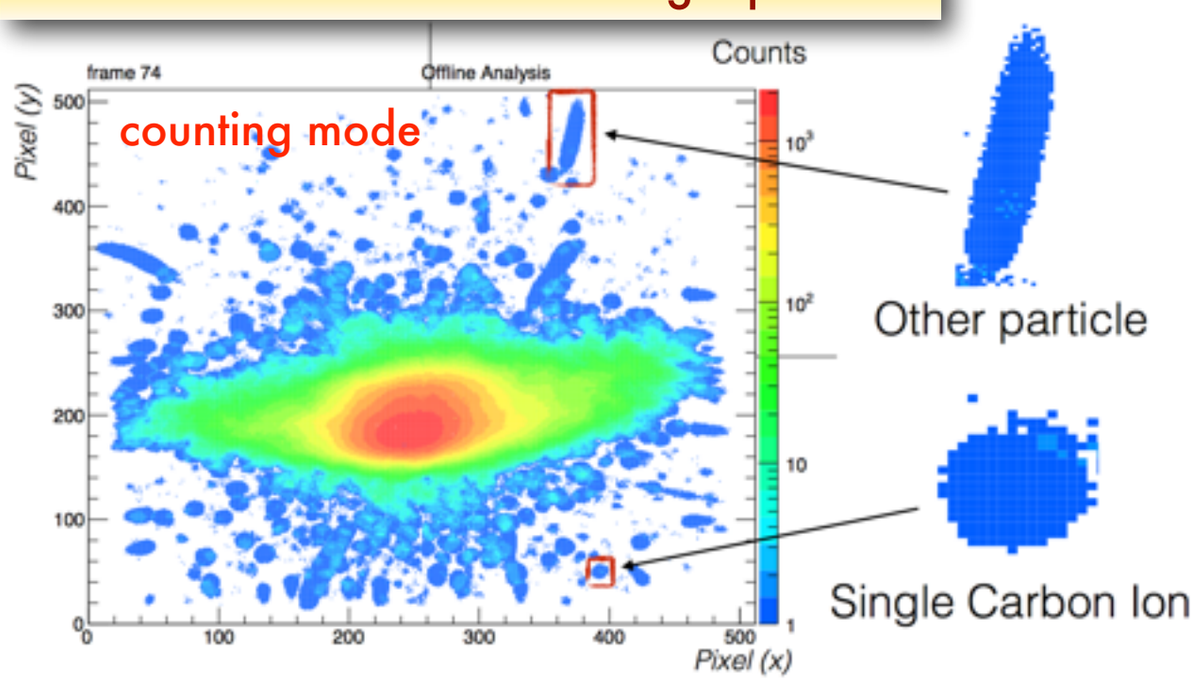
Linearity



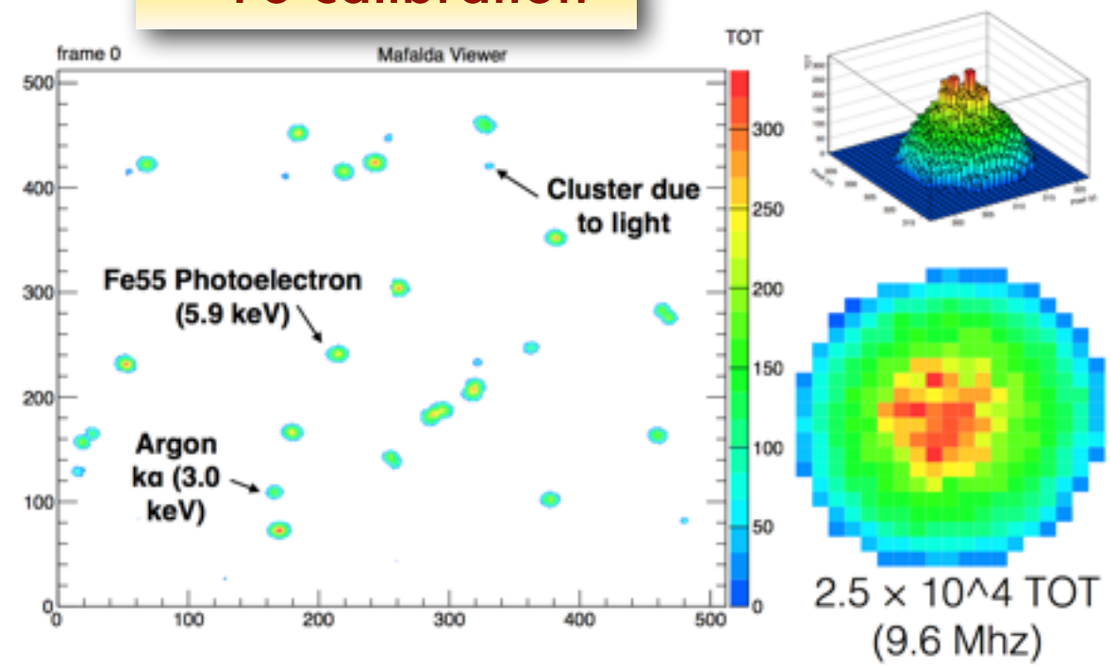
1 out of 16 pixels in Time of Arrival mode (100 ns res)



As beam monitor down to single particle



^{55}Fe calibration



GEMPix future: Timepix3

	Timepix (2006)	Timepix3 (2013)
Pixel arrangement	256 x 256	
Pixel size	55 x 55 μm^2	
Technology	250nm CMOS - 6Metals	130nm CMOS - 8Metals
Acquisition modes	1) Charge (iTOT) 2) Time (TOA) 3) Event counting (PC)	1) Time (TOA) AND Charge (TOT) 2) Time (TOA) 3) Event counting (PC) AND integral charge (iTOT)
Readout Type	1) Full-Frame	1) Data driven (DD) 2) Frame (FB)
Zero suppressed readout	NO	YES
Dead time per pixel	> 300µs readout time of one frame	> 475ns Pulse measurement time + packet transfer time **~600x**
Minimum timing resolution	10ns	1.562ns **6.4x**
On-chip Power pulsing (PP)	NO	YES
Minimum detectable charge	~750e-	>500e- **1.5x**
Output bandwidth	1 LVDS ≤200Mbps 32 CMOS ≤3.2Gbps	1 to 8 SLVS @640Mbps DDR ≤5.2Gbps **1.6x**

A 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)

"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)

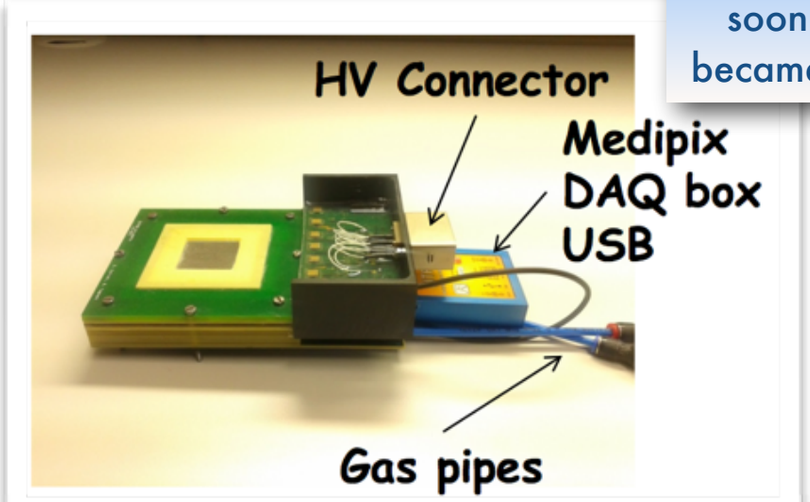
R&D with GEMPix TPC

Depending on starting date, a new TPC **5 cm drift distance** equipped with **Timepix3** could be available

First phase of the project: study GEMPix behavior in a negative ion configuration with an already existing TPC developed by LNF

- $CF_4 + CS_2$ / $CF_4 + CH_3NO_2$
- Xe / Xe + CH_3NO_2 / Xe + TMA / Xe + other??

Ready to start as soon as funds became available

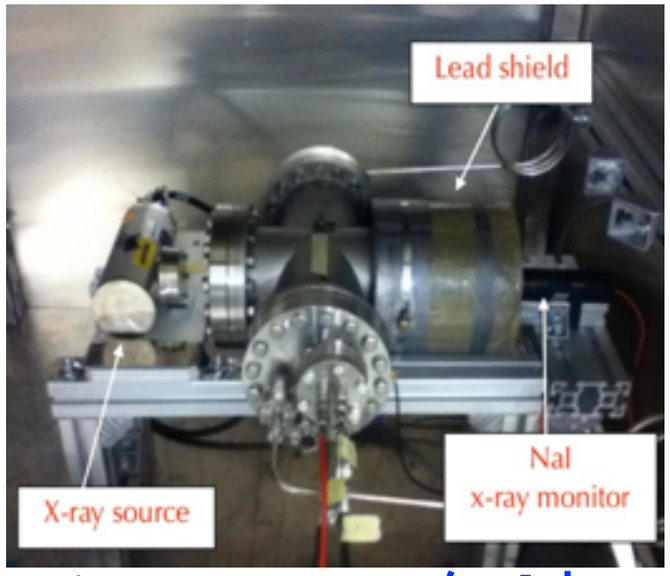


https://web2.infn.it/GEMINI/index.php/gempix-detector

In order to:

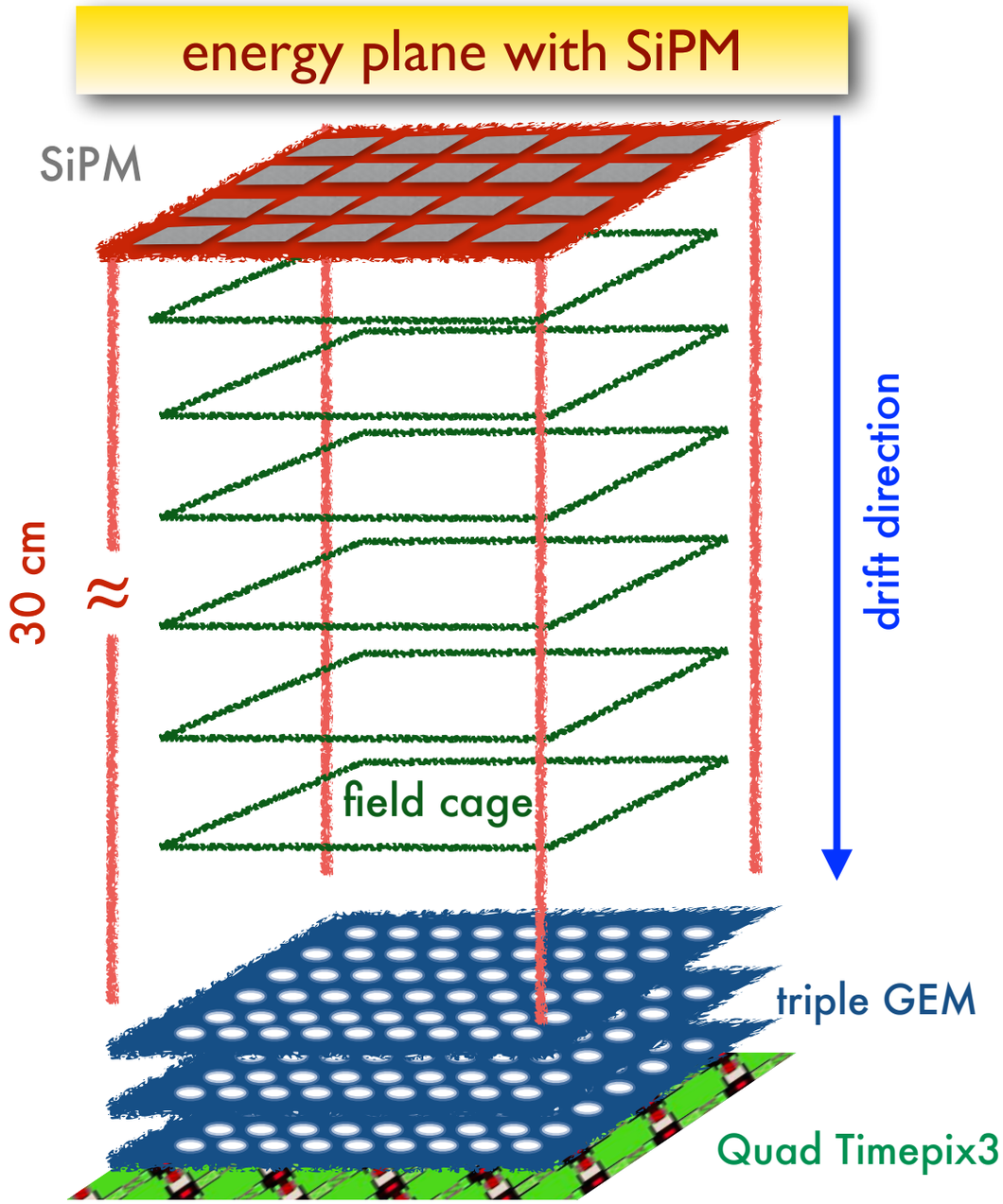
- Study for the first time GEMPix in negative ion configuration with CS_2
- Study the potentialities of CH_3NO_2 as capture agent
- Search for a suitable capture agent for Xe
- Study GEMPix operation in HPXe
- Collect crucial information for the design and optimization of NITEC prototype

First phase expected to last 12-18 months



Tests at various pressures (< 1 bar - 5/10 bar)

Full NITEC concept

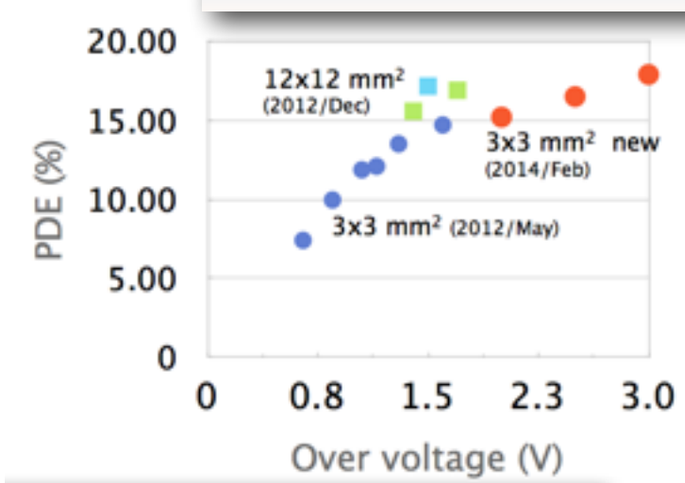


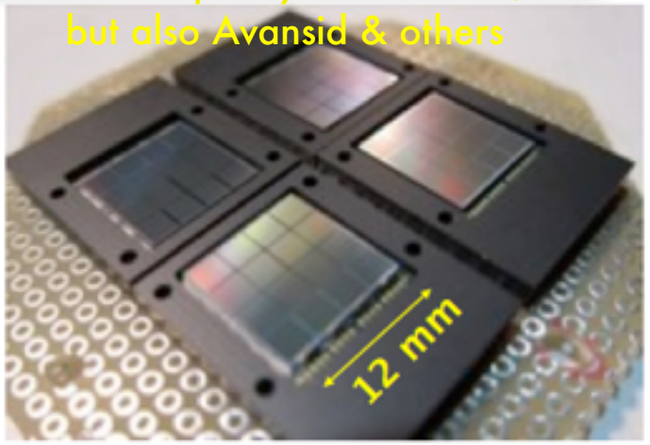
6 x 6 / 10 x 10 cm^2

tracking plane with GEMPix

- Optimized design on the basis of the preliminary studies with the small prototype
- (Possibly) GEMPix with optimized pixel size and electronics tailored for rare events search application
- Exploit NEXT separate charge and light collection concept, *but with:*
  - Negative ion transport
  - Charge amplification instead of electroluminesce for the tracking plane
  - SiPM readout for the energy plane

SiPM with 1 p.e. detection & > 15% PDE now commercially available





NITEC potentialities

Directional Dark Matter Gaseous Detector

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	0.0011	Italy

+ HPXe????

NITEC main features:

- **Negative Ion Time Projection Chamber** –> larger allowed drift length
- **Time Expansion Chamber** –> improved position resolution and possibly superior energy resolution thanks to slow ions motion and possibility of observing single ionization cluster
- **Triple GEM amplification with CMOS pixel readout** –> for 3D track reconstruction and sense determination via dE/dx (time??) measurement along path
- **SiPM light readout** –> measure of the start of the event, placement of track along the drift direction and fiducialization, and possibly improved energy resolution thanks to measurement of scintillation light

We believe that all these features combined will allow low energy threshold (~< 30-50 keV) and good 3D track reconstruction WITH full directionality (i.e. sense determination)

NITEC potentialities

Neutrino-less double beta decay detector

	Isotope	Mass [kg]	B'	FWHM [keV]	Lab [keV]	Status	Start	$S_5^{0\nu}$ [10^{26}y]	$\langle m_\nu \rangle$ [meV]
CUORE	^{130}Te	206	29	5	LNGS	P	2014	2.1	73
GERDA I	^{76}Ge	18	23	4.5	LNGS	R	2012	1.1	184
GERDA II		40	1.2	3		D		2.1*	133
MJD		30	1.2	3	SUSEL	P	2014	2.6*	67
EXO	^{136}Xe	200	1.9	100	WIPP	R	2011	1.2	115
SuperNEMO	^{82}Se	100-200	0.08	120	LSM	D	2013-2015	0.8	90
KamLAND-Zen	^{116}Cd	400	9	248	Kamioka	R	2011	0.33	220
		1000	9	248		D	2013-2015	0.59	164
SNO+	^{150}Nd	44	1.8	229	Sudbury	D	2013	0.08	310
SNO+ II		131	1.8	303	Sudbury	D	2013	0.08	310
NEXT		100	0.2	13	Canfranc	D	2014	5*	56

Tab.2 *List of some of the most developed ββ(0ν) projects. 5 years sensitivity at 90% C.L. Experimental phases are indicated as running (R), progress (P) or development (D). Asterisk signals 0B condition. B' is the background per unit of isotope mass in units of 10^{-3} counts/keV/kg/y.*

HP gaseous TPC "a la NEXT", *but with:*

- Negative Ion Time Projection Chamber –> larger allowed drift length
- Time Expansion Chamber –> improved position resolution and possibly superior energy resolution thanks to the possibility of observing single ionization cluster D.Nygren, JPCS 65 012003
- Triple GEM amplification with CMOS pixel readout for tracking plane –> can GEMPix gain stability and general excellent performances be competitive with EL options??
- SiPM light readout sensitive to VUV light for the energy plane–> can existing commercial VUV SiPM be competitive with WLS coating and PMT readout??? PLUS: SiPM will have nearly 100% coverage w.r.t. 30% for PMT in NEXT

The negative ion drift is clearly an advantage worth exploring for this search field as well
Negative ion + GEMPix could make charge amplification competitive with EL: worth studying

NITEC prototype as a tool

Use the developed prototype to study columnar recombination in HPGXe (and other???)

- Columnar Recombination (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"

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

- 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

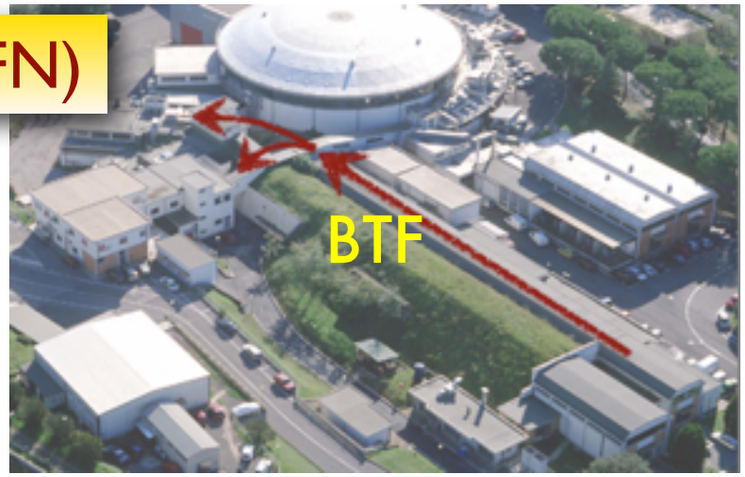
See also Nakajima's talk yesterday

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

- Do we really need TMA if we can be sensitive to VUV light?
- How does this interplay with negative ion transfer?
- Can we study columnar recombination in other gases at HP ? (CF_4 ??)
- ???? so many questions to answer!!!

Facilities & research team

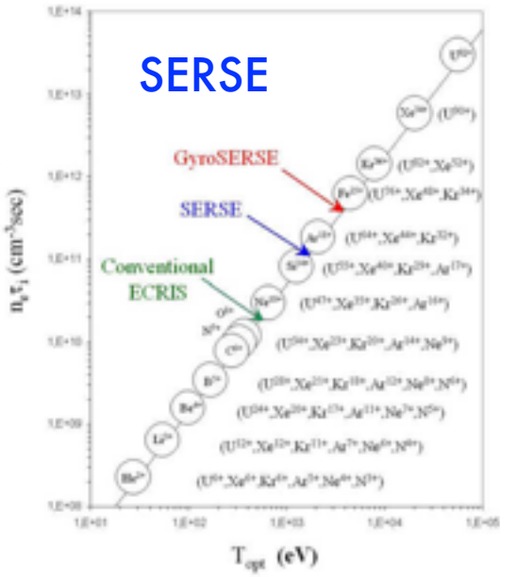
NITEC to be developed at Laboratori Nazionali di Frascati (INFN)



- Beam Test Facility (BTF) and X LAB at LNF to characterize the prototype and measure its response to signal like and background like particles
  - BTF: electrons, positrons, protons and NEUTRONs with definite energy and intensity, down to single particle operation mode
  - XLAB: highly collimated monochromatic x ray beam with energy down to 5.9 keV
- Ion source available at Laboratori del Sud INFN facility
- LNF collaborators to this project long standing tradition in design and manufacturing of:
  - Gaseous detector with GEM amplification for large high energy physics experiment (KLOE, LHCb, RD51) since 2000
  - GEM technology coupled to CMOS pixel readout (GEMPix, GEMINI project)

Already in contact with BTF community for future improvements in the neutron beam line to tag outgoing neutrons
(see NITEC talk at First BTF Users Workshop)

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



Ion	Current (eμA)
N^{6+}	160
$^{15}N^{7+}$	25
O^{6+}	720
O^{7+}	105
Ne^{8+}	170
Ne^{9+}	14
Ar^{11+}	120
Ar^{16+}	2
Ca^{12+}	52
Ca^{14+}	6
Ni^{17+}	18
Kr^{22+}	10
Kr^{26+}	1
Ta^{27+}	10

Tab. 2 - Typical currents (in eμA) produced by CAESA

CESAR

Conclusions

We propose an R&D project for an original Negative Ion Time Expansion Chamber for very rare event searches with triple GEM amplification and CMOS pixel readout for the charge signal and SiPM readout for the light signal

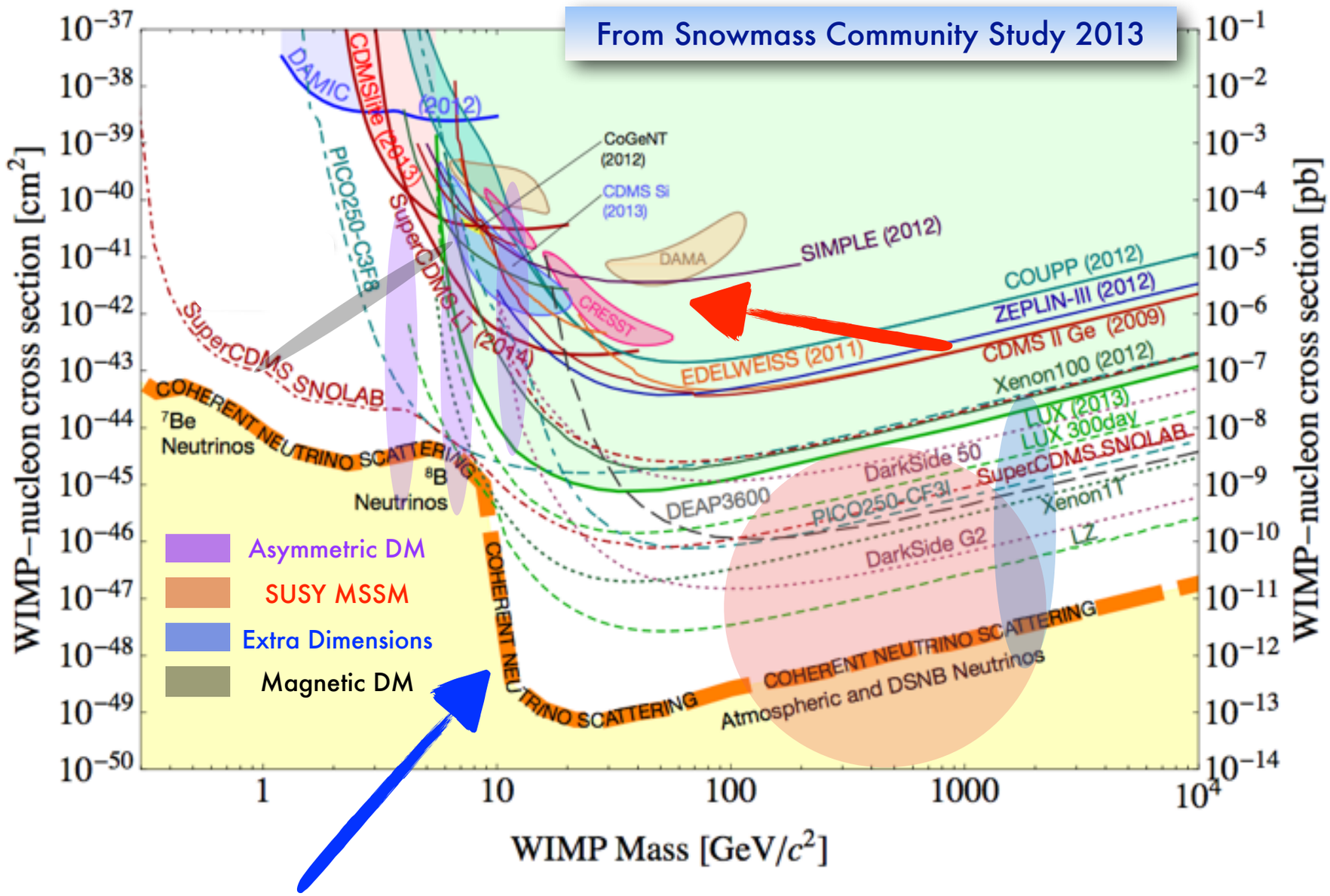
- Large allowed drift distance + improved tracking and energy resolution thanks to slow drift + possibly superior energy resolution + track directionality (and sense) measurement capabilities:
  - Very appealing DM directional detector
  - Very appealing neutrino-less double beta detector "a la NEXT"
  - Very appealing X-ray polarimeter

High versatility

- Short and long term impact of the R&D:
  - Expand knowledge on NITPC:
    - with GEM amplification and pixel readout
    - with CH_3NO_2 (and possibly other) capture agents (plan to measure ion transport properties)
    - a NITPC with Xenon???
  - Explore possibility of alternative realization of NEXT SOFT concept
  - Development of MPGD optimized and with tailored electronics for rare events searches
  - Study columnar recombination processes in XPHe and possibly other HP gases

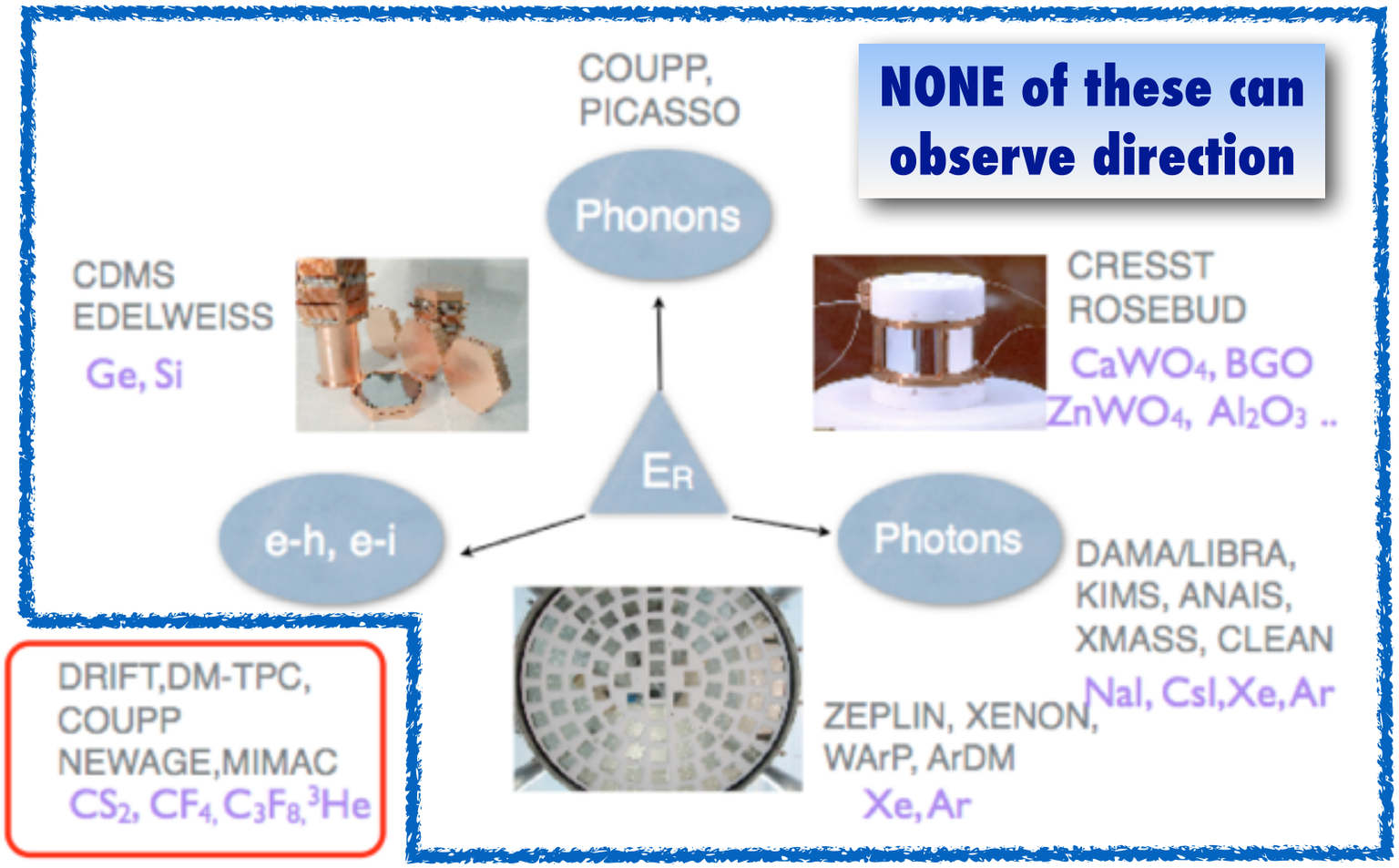
Backup

DM Past, present and future issues



- Enigmatical experimental situation: claims for detection inconsistent with exclusion limits
- The "Neutrino-bound": when DM detector will start to be sensitive to solar neutrinos background, neutrinos will give EXACTLY same detector response as a signal like particle

DM Direct Detection Experiments



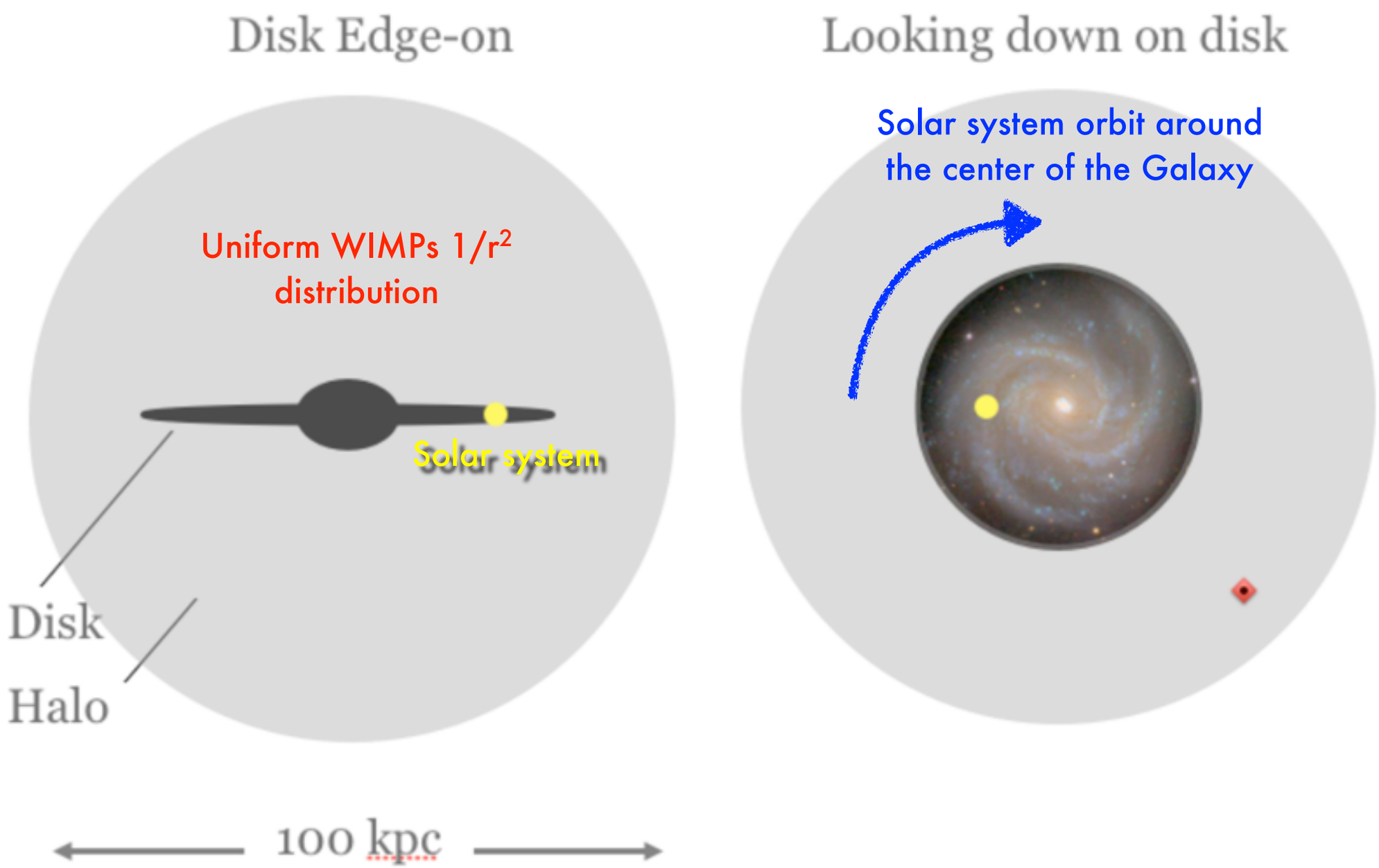
DRAWBACK: small masses

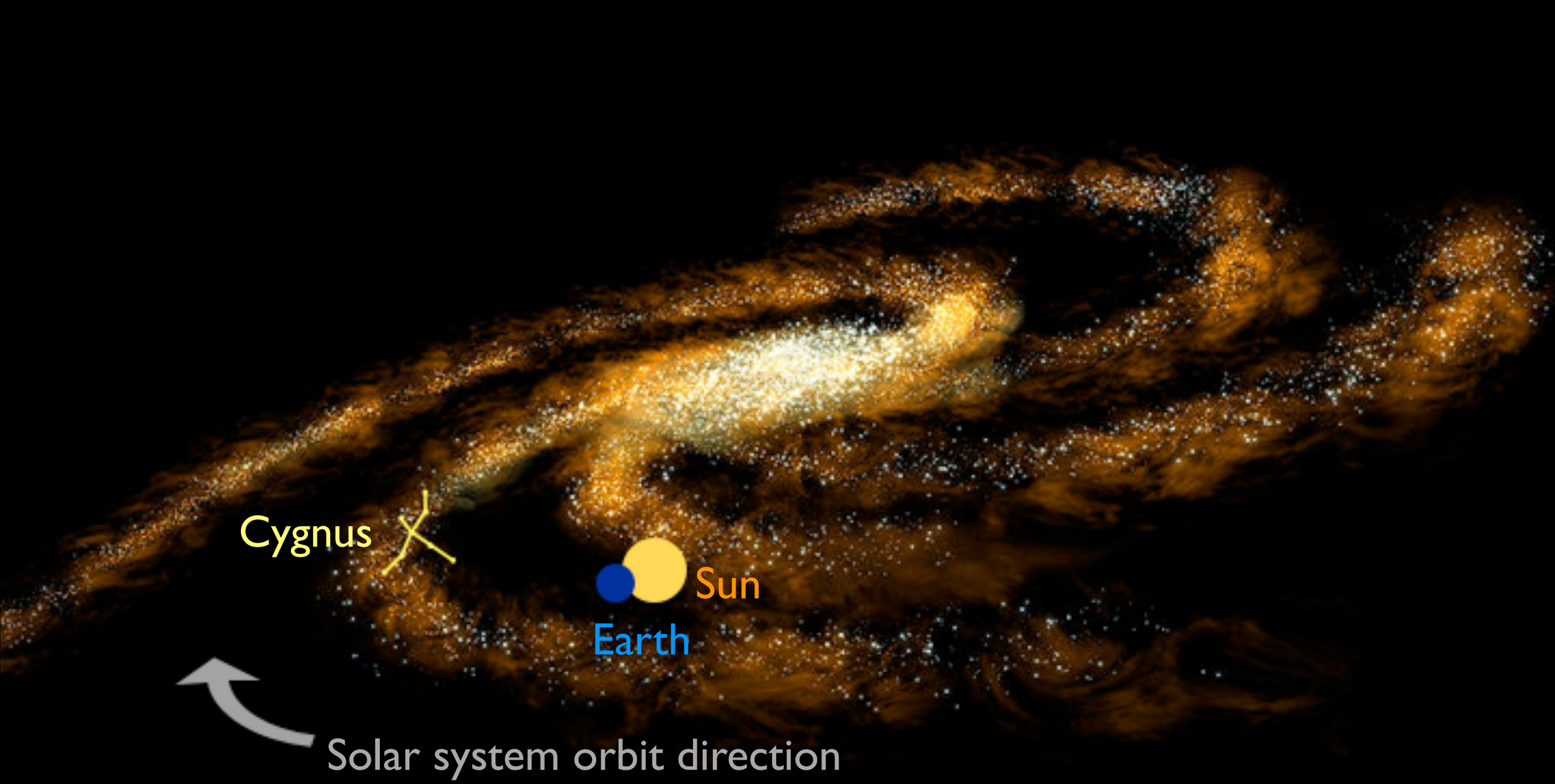
Low pressure gas detector in order to observe direction at these energies

- 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

All these information offer much more efficient means to actively suppress background than any other experimental approach

WIMPs in our Galaxy



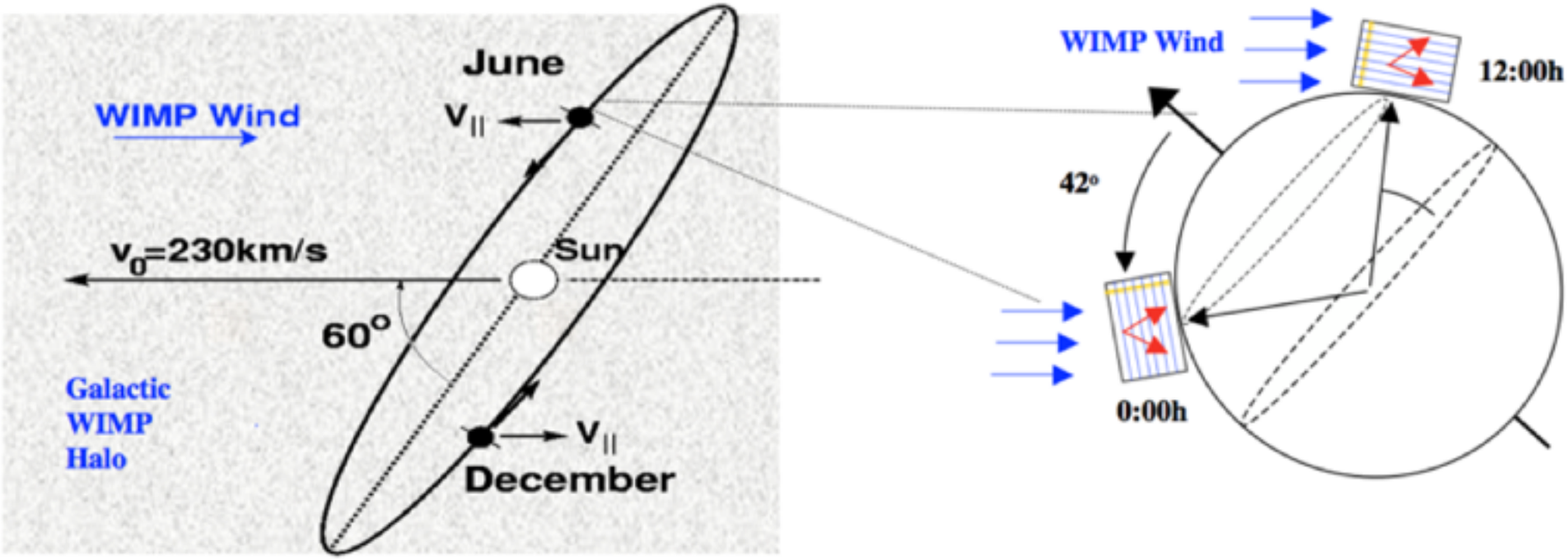


Men come from Mars, Women come from Venus
.....and WIMPs come from Cygnus

An additional 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.*

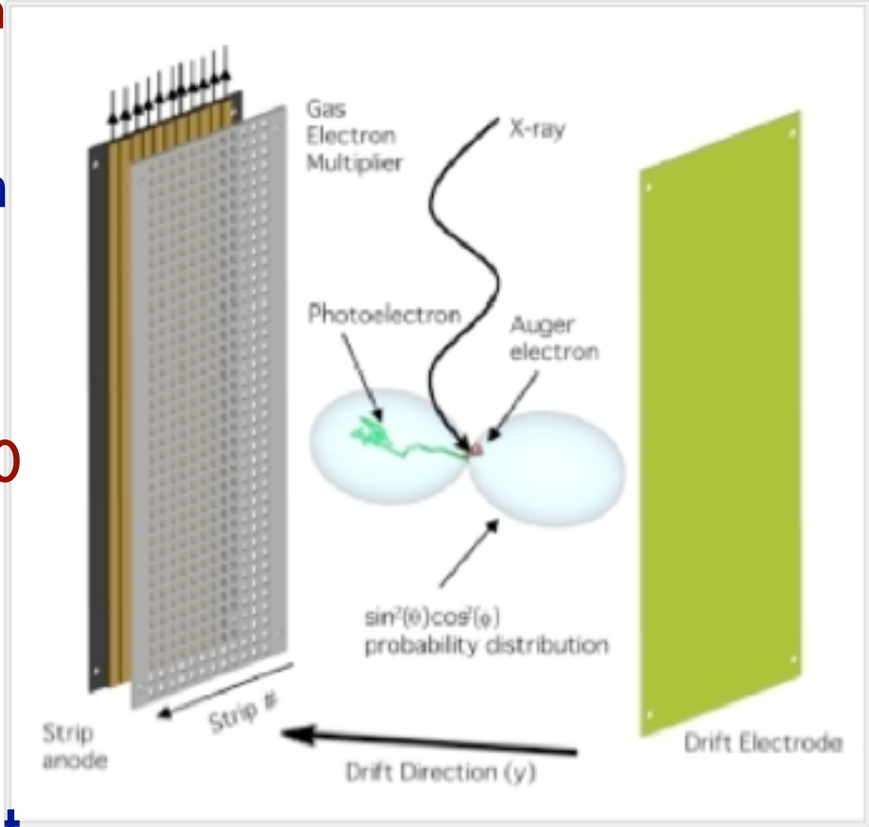


No background <u>whatsoever</u> can mimic a directional correlation with an astrophysical source

PLUS: directionality is the only tool that allows to reject the neutrinos background from the Sun

X ray polarimetry in space

- 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 (and old) measurements of X ray polarization with limited techniques
  - Bragg diffraction at 45°, too narrow energy band
  - Thomson scattering at 90°, loss of efficiency for energies <10 keV
- Can probe exotic astrophysical processes with the strongest gravitational and magnetic fields
- A NITEC could observe not only static <u>but also transient sources</u> (GRB, SGR, black holes) thanks to the larger allowed drift distance
- The community has just started to explore the use of NITPC (with Ne) [arXiv:1107.3079]

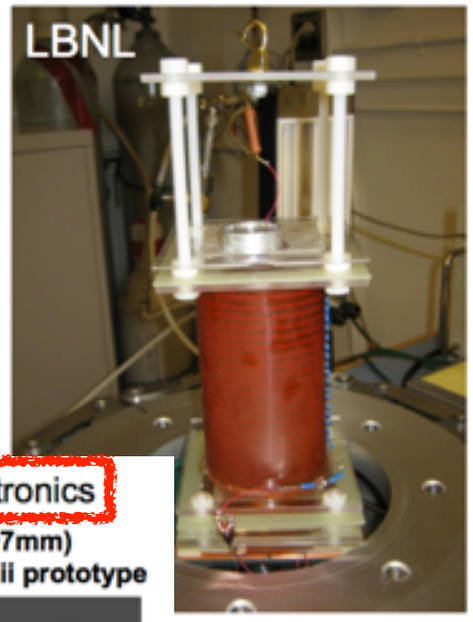


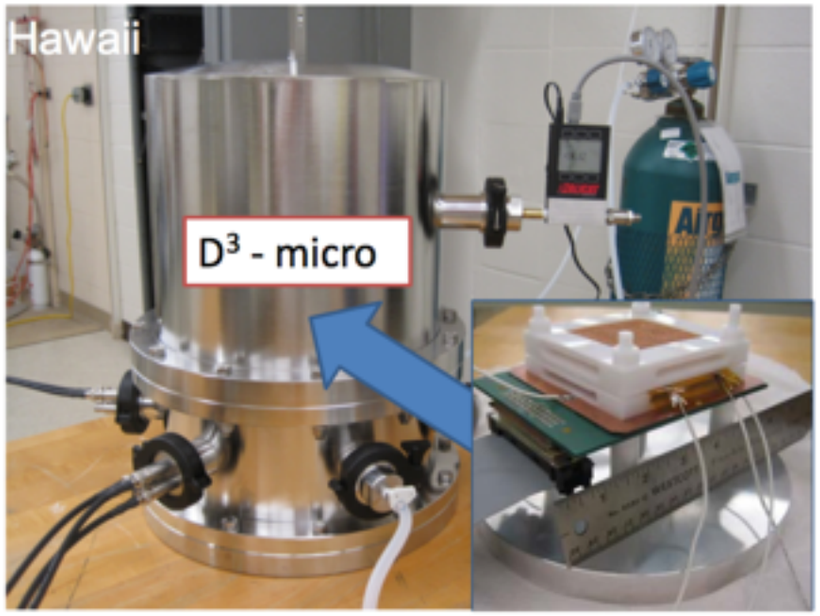
A close cousin: D^3 experiment

5. Energy Threshold

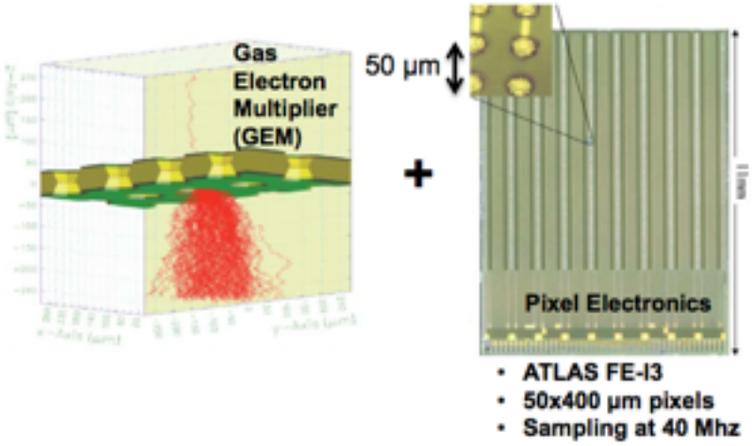
- Not yet measured. Goal is *directional* threshold of 10keV or lower. Non-directional threshold can be of order a few times 100 eV.

- 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

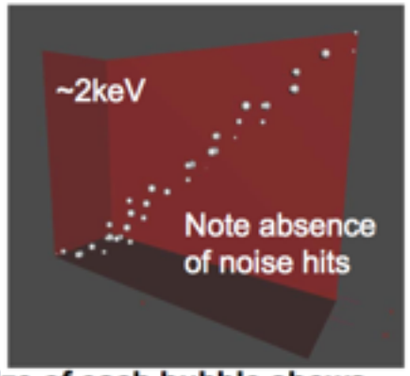




- Drift charge amplified with double layer of GEMS, detected with pixel electronics
- Gain ~20k, threshold ~2k e^-, noise ~ 100 e^-



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



size of each bubble shows amount of ionization measured

arXiv: 1110.3444
arXiv: 1110.3401

Advantages of this approach

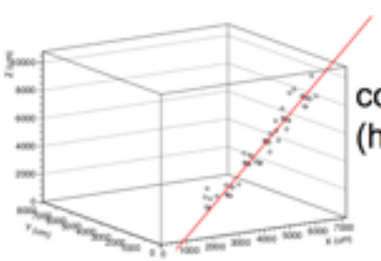
- Full 3D tracking w/ ionization measurement for each spacepoint → **improved directional sensitivity and rejection of alpha particle backgrounds**
- Pixels ultra-low noise (~100 electrons), self-triggering, and zero suppressed → **virtually noise free at room temperature** → low demands on DAQ
- High-single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

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

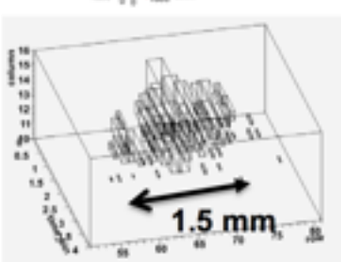
D^3 prototype performances

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

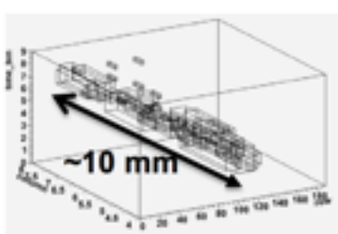
- Due to combination of high single-electron efficiency and low noise, expect low threshold operation, and good sensitivity to low-mass WIMPs
- Mostly excellent
  - Point resolution ~200 µm
  - Angular resolution ~ 1 degree for 5-10 mm tracks
  - Gain resolution ~5-10%
  - Gain stability <2%



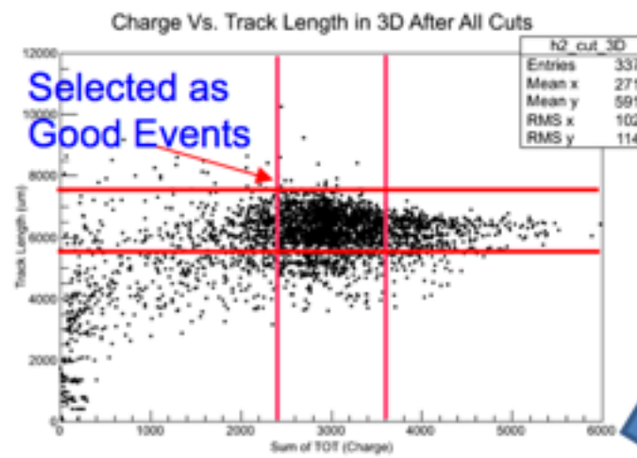
cosmic muon (high gain mode)

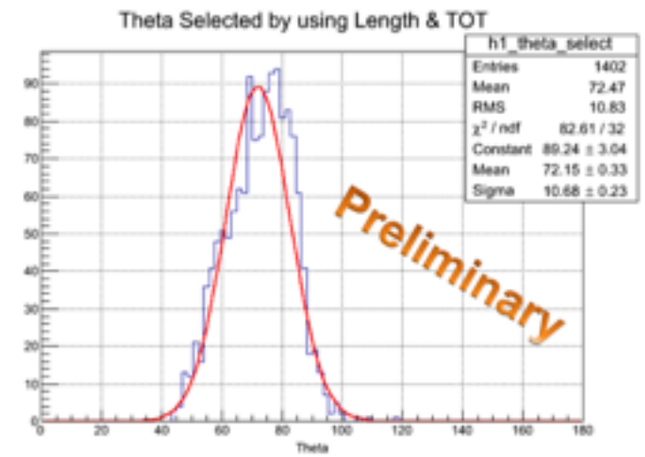


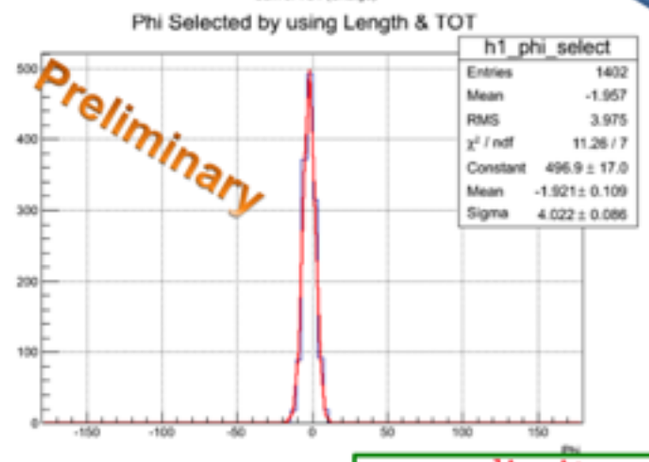
He-recoil candidate (low gain)

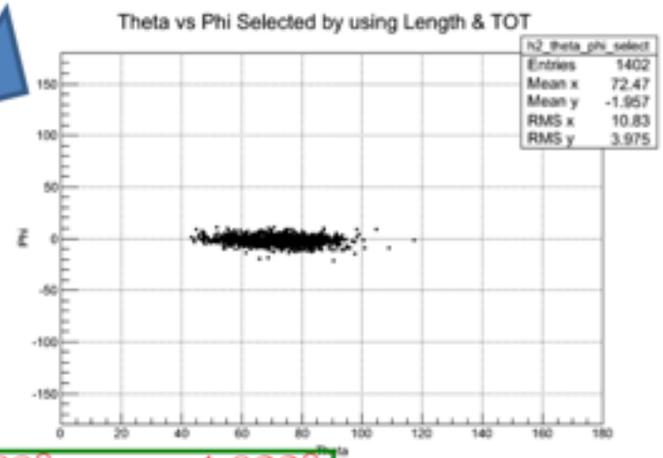


RPR event? (low gain)









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

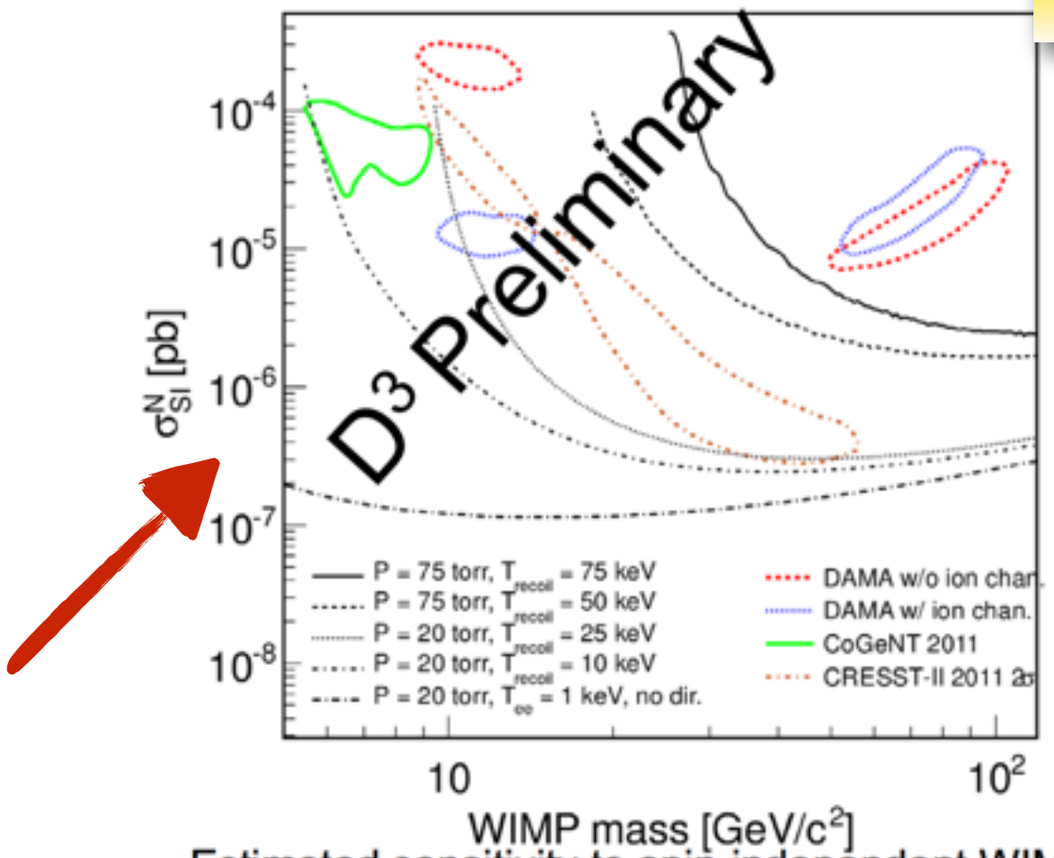
$$\sigma_{angle} = \sqrt{\sigma^2_{detector} + \sigma^2_{straggling} + \sigma^2_{source\ cone} + \sigma^2_{source\ size}}$$

- 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.

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.

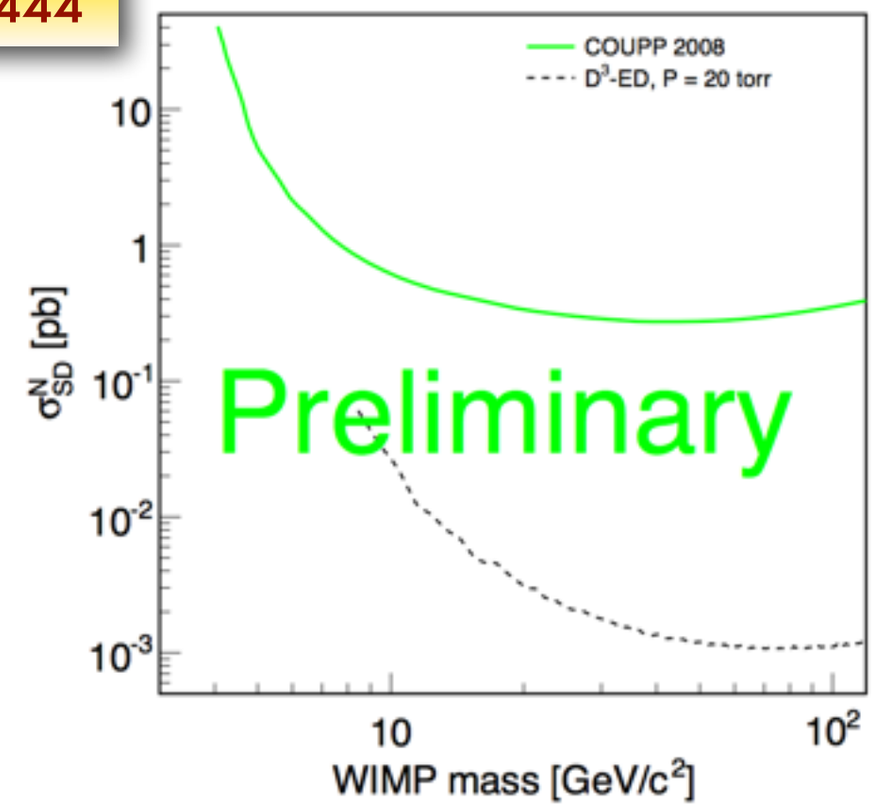


Fig. 5. D^3 cross section limit as a function of the WIMP mass for one recoil produced by a WIMP detected in three m^3. The detector is divided into nine sub-detectors with a maximum drift distance of 33.33 cm for ED-CF_4 and NID-CS, the SI case on the left and for the SD case on the right. The D^3 reach 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

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

Beyond Neutrino Bound

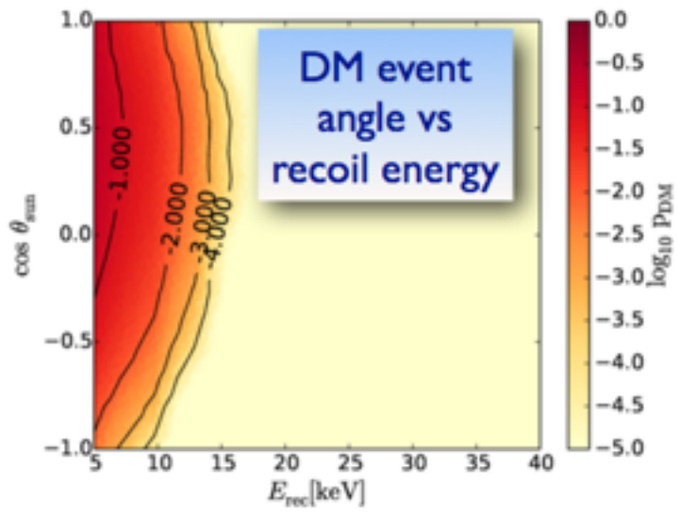


FIG. 1: Two dimensional dark matter probability distribution ρ of recoil energy and event angle for a 6 GeV dark matter particle in a CF_4 detector with 5 keV threshold in September.

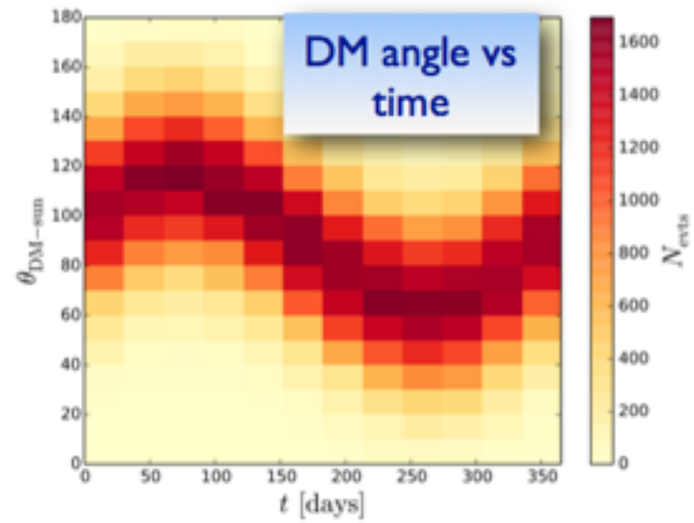


FIG. 2: Distribution of the angle between the incoming dark matter velocity and the Earth-Sun direction over the year for events above a 5 keV threshold in a CF_4 detector. For each month 1×10^4 dark matter events have been simulated. The maximum of the distribution follows the expected pattern as described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

arXiv:1406.5047
from DMTPC collaborators

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

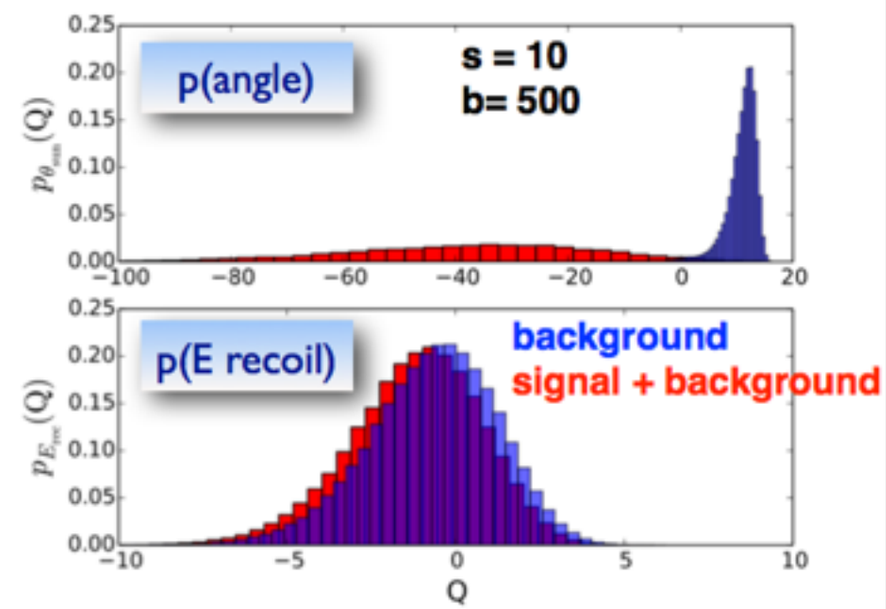


FIG. 6: The normalised background only distribution $p_B(Q_B)$ (blue) and signal plus background distribution $p_{SB}(Q_{SB})$ (red) including angular information (top) and excluding angular information (bottom) for s=10 and b=500 for a 6 GeV dark matter particle in a CF_4 detector. The gain in sensitivity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

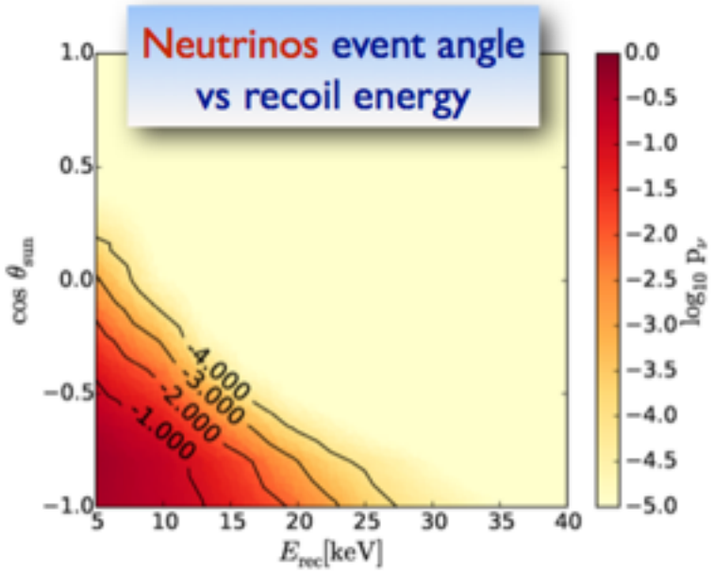


FIG. 5: The two dimensional probability distribution ρ of recoil energy and event angle of neutrinos in a CF_4 detector with 5 keV threshold.

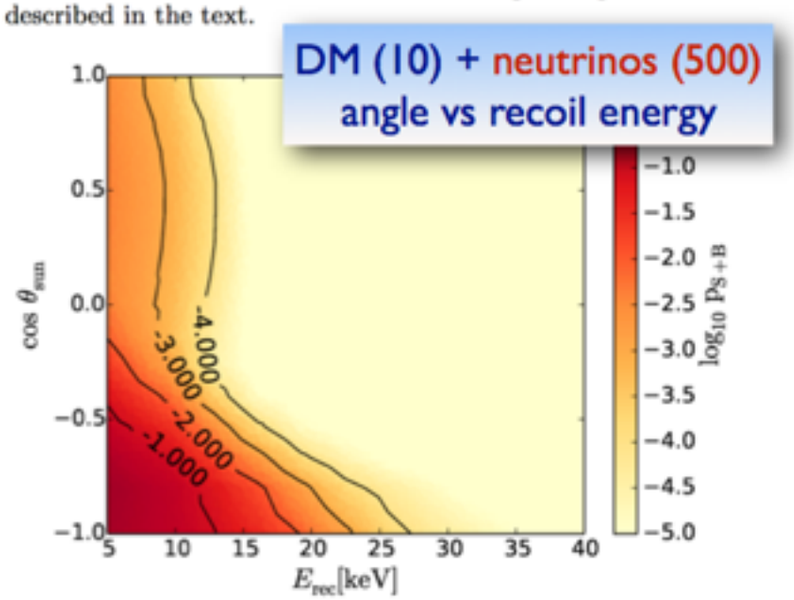


FIG. 7: The combined two dimensional probability distribution ρ of the recoil energy and event angle for a 6 GeV dark matter particle and neutrinos in a CF_4 detector. The expected signal rate is fixed to s=10 and the expected background rate to b=500.

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

Beyond Neutrino Bound

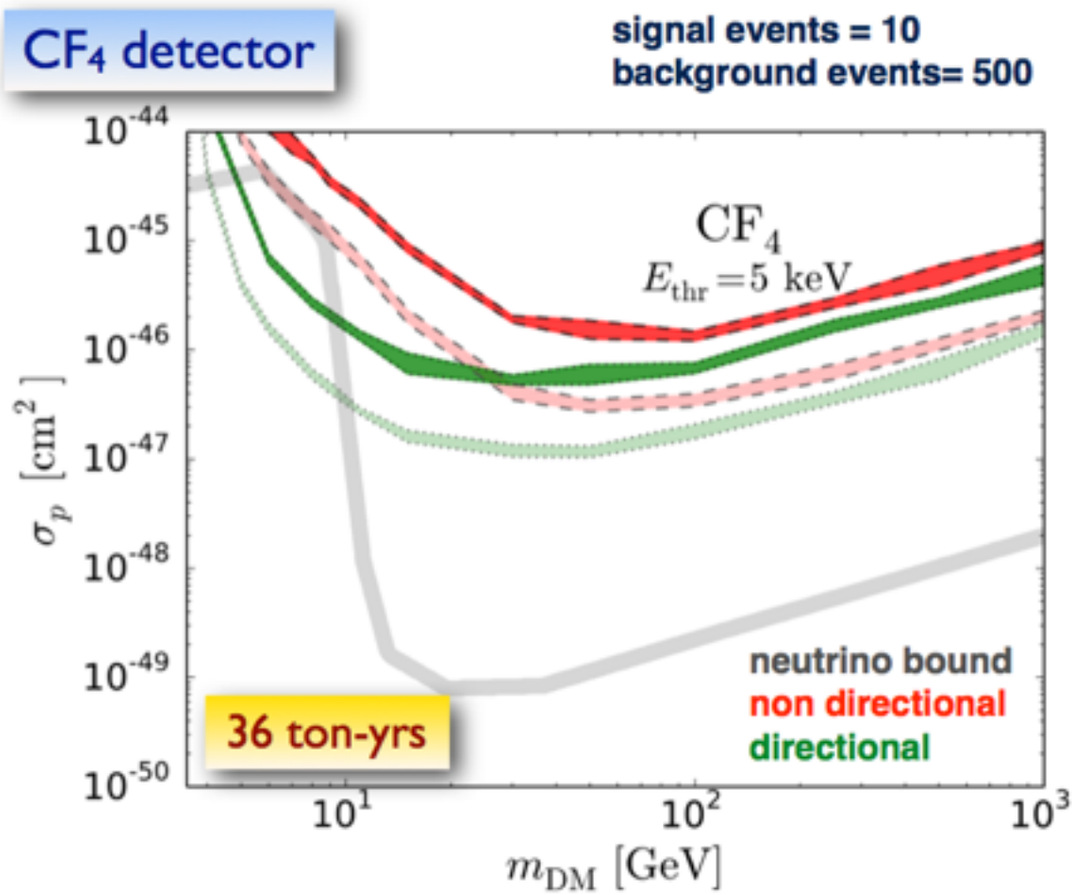


FIG. 8: Estimated sensitivity limits at 3σ level for a nondirectional (red band) and directional (green band) CF_4 detector with 36 t-yrs exposure and 5 keV energy threshold resulting in 500 expected neutrino events. The fainter bands indicate corresponding sensitivity limits at 90% CL, the grey curve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

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

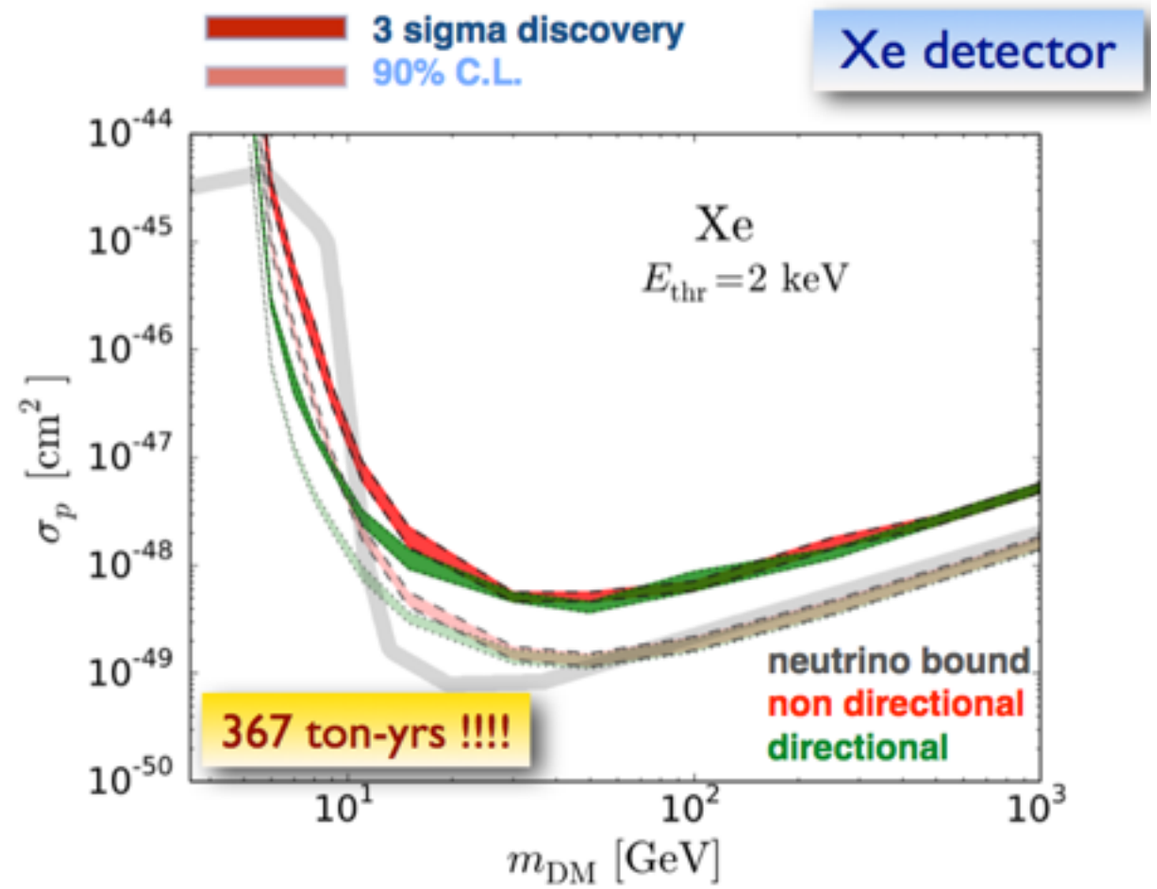


FIG. 9: Estimated sensitivity limits at 3σ level for a nondirectional (red band) and directional (green bands) Xenon detector with 367 t-yrs exposure and 2 keV energy threshold resulting in 500 expected neutrino events. The fainter bands indicate corresponding sensitivity limits at 90% CL, the grey curve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

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.

Columnar Recombination in HPXe

- Columnar Recombination (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"

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)

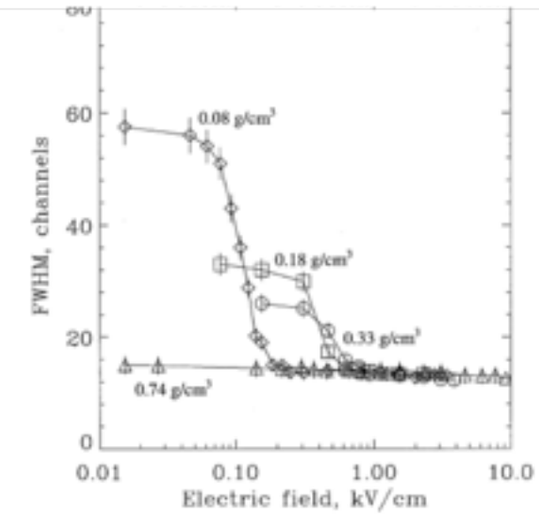


Fig. 5. FWHM of the peaks in pulse-height spectra of the amplitude of the light signals versus the electric field strength measured at 0.08 g/cm³ (diamonds), 0.18 g/cm³ (squares), 0.33 g/cm³ (circles), and 0.74 g/cm³ (triangles).

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 $\rho \approx 0.05$ g/ cm³:
    - $r_0 \sim 70$ nm
    - $\mathcal{R} \sim 2100$ 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 $\rho \approx 0.05$ g/ cm³, or less
  - ~2% of LXe density
  - Hopeless for LXe density: $\rho = 3.1$ 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

$$Xe_{nr} + Xe \rightarrow Xe + heat$$
$$\rightarrow Xe^*$$
$$\rightarrow Xe^+ + e^-$$

$$Xe^* + TMA \rightarrow Xe + TMA^+ + e^- \quad \text{(Penning effect)}$$
$$Xe^+ + TMA \rightarrow Xe^* + TMA^+ \quad \text{(Charge exchange)}$$

$$TMA^+ + e^- \rightarrow TMA^* \rightarrow TMA + photon\ (\sim 300nm)$$

- 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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