暗物质的方向探测

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2011年12月20日

内容

- 暗物质直接探测现状
- 暗物质方向探测的物理动机
- 暗物质方向探测的实验状况

暗物质类型的多样性 → 暗物质信号的多样性

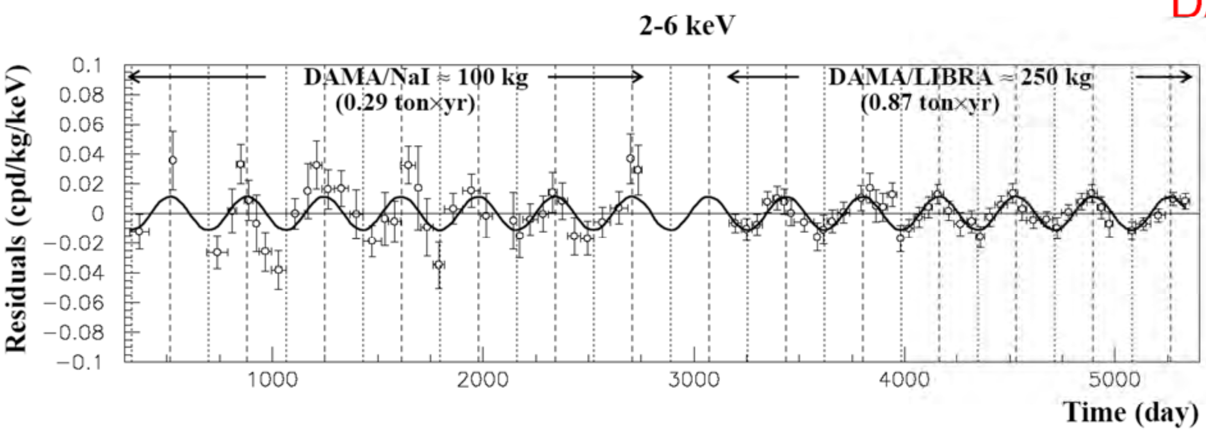
- Cold Dark Matter (CDM)
  - WIMPs (e.g., neutralino from MSSM)
  - Axions
  - axion-like
  - MACHOs
- Warm Dark Matter (WDM)
  - sterile neutrinos
  - gravitinos.
  - axino
- Hot Dark Matter (HDM)
  - Neutrinos

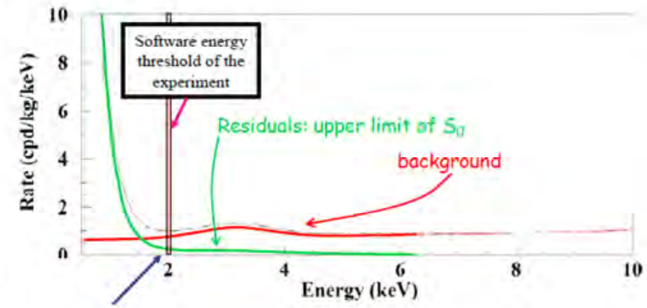
暗物质可轻可重,可热可冷

- Nuclear recoil
  - SI elastic
  - SD elastic
  - inelastic
- Electron recoil
- E. m. component （e-, γ, x-ray)

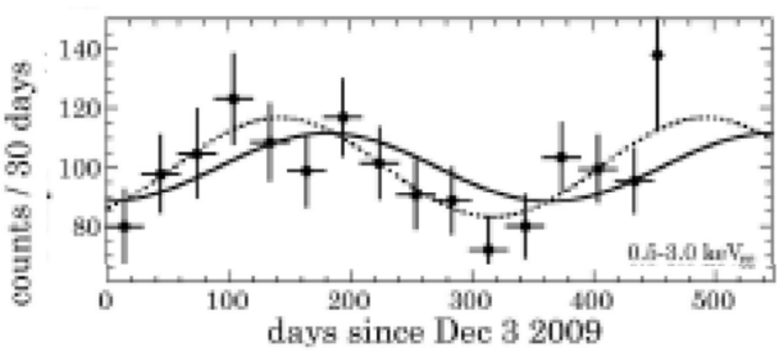
年调制信号:模型无关

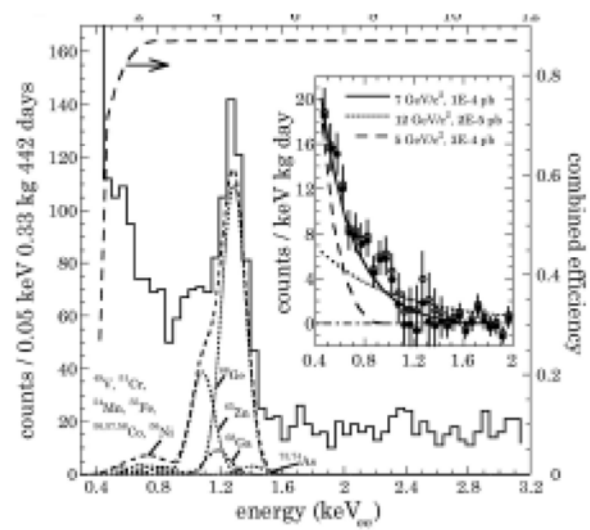
DAMA





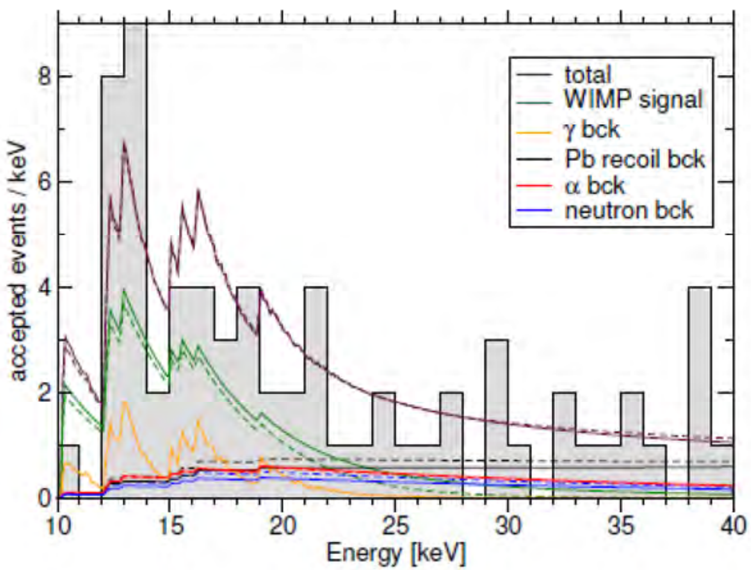
COGENT



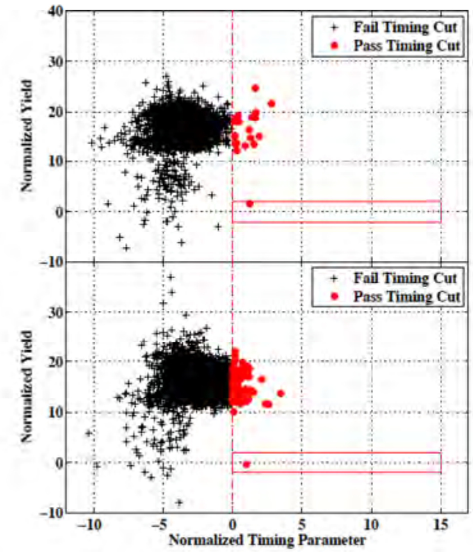


只考虑核反冲

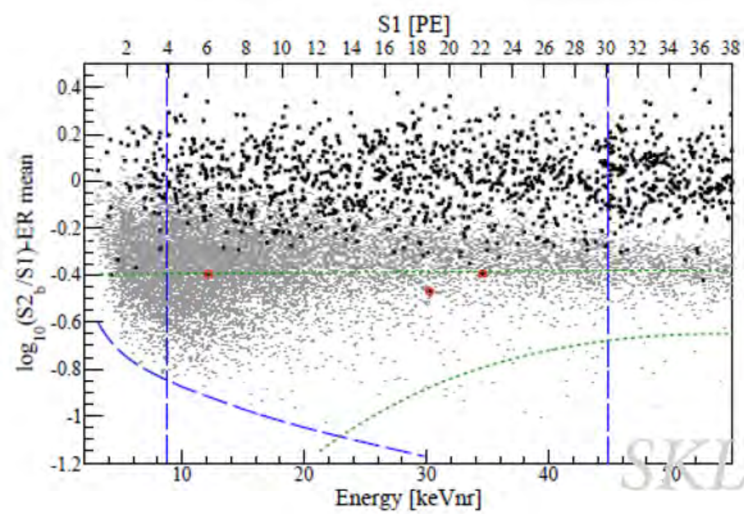
CRESST II



CDMSII



XENON100



DAMA,CoGeNT年调制信号与light neutralinos一致

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11

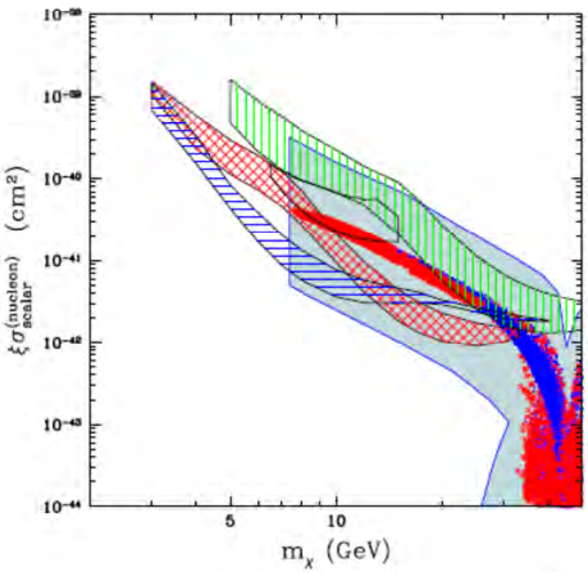


FIG. 6: $\xi\sigma_{\rm scalar}^{\rm (nucleon)}$ as a function of the neutralino mass. The experimental annual-modulation regions are obtained as explained in the caption of Fig.1, except that here the used DF is an isothermal sphere with the following values for the parameters: $\rho_0 = 0.34$ GeV cm^{-3}, $v_0 = 220$ km sec^{-1}, $v_{esc} = 650$ km sec^{-1}. The theoretical scatter plot displays the whole sample of neutralino configurations: (red) crosses denote SUSY configurations with a neutralino relic abundance which matches the WMAP cold dark matter amount ($0.098 \leq \Omega_\chi h^2 \leq 0.122$) while (blue) dots denote the configurations where the neutralino is subdominant ($\Omega_\chi h^2 < 0.098$) (these two sets of configurations were shown separately in Fig.5). The scatter plot has been evaluated for $g_{d,\rm ref} = 290$ MeV. The (light-blue) flag–like region denotes the extension of the scatter plot upwards and downwards, when the hadronic uncertainties are included (see text).

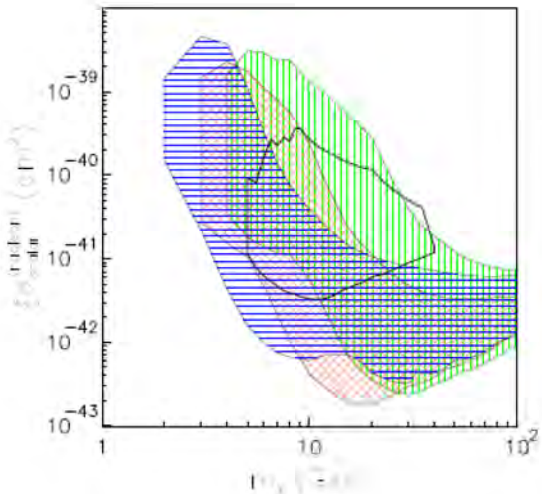


FIG. 7: Regions in the $\xi\sigma_{\rm scalar}^{\rm (nucleon)}$ vs m_χ plane allowed by DAMA experiments in the three considered instances for the Na and I quenching factors, including all the DFs considered in Ref. [14] and the same uncertainties as in Refs. [24, 25] for a WIMP with a pure SI coupling. The hatchings (and colours) of the allowed regions are the same as those in Fig. 1. These regions represent the domain where the likelihood–function values differ more than 7.5 σ from the null hypothesis (absence of modulation). It is worth noting that, depending on other possible uncertainties not included here, the channeled (blue) horizontally–hatched region could span the domain between the present channeled region and the unchanneled one. The allowed region obtained for the CoGeNT experiment, including the same astrophysical models as in Ref. [24, 25] and assuming for simplicity a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters, is also reported and denoted by a (black) thick solid line. This region is meant to include configurations whose likelihood–function values differ more than 1.64 σ from the null hypothesis (absence of modulation). This corresponds roughly to 90% CL far from zero signal. See text.

- DAMA/LIBRA :7–8 GeV <~ m_χ <~50 GeV,
- CoGeNT: 7–8 GeV <~ m_χ <~(15-20) GeV.
- CRESST 和CDMS事例: 在同样的区域内
- 与LHC最近结果给出的质量限制相一致

从这些实验结果我们得到什么启示？

- 暗物质直接探测要求探测器达到低本底、低阈能、大规模、长期稳定的运行
  - 阈能：DAMA-2→1keVee, CoGeNT-0.4keVee, CRESSTII-10keVr
  - 探测器自身放射性本底：DAMA~1ppt→0.01ppt
  - 规模：DAMA/LIBRA 250kg→1ton
  - 稳定性： DAMA/LIBRA已得到13个周期的年调制
- 还没有明确的结论，面临着更多的问题
  - 暗物质信号的多样性？(DAMA闪烁光, CoGeNT电离, CRESSTII闪烁光+声子)
  - 暗物质作用是不是只有核反冲?
  - 暗物质是不是轻的?
  - 核反冲是自旋无关(SI)还是自旋相关的(SD)?
  - ...

但是有迹象表明，我们正接近暗物质物理发展史上的一个里程碑

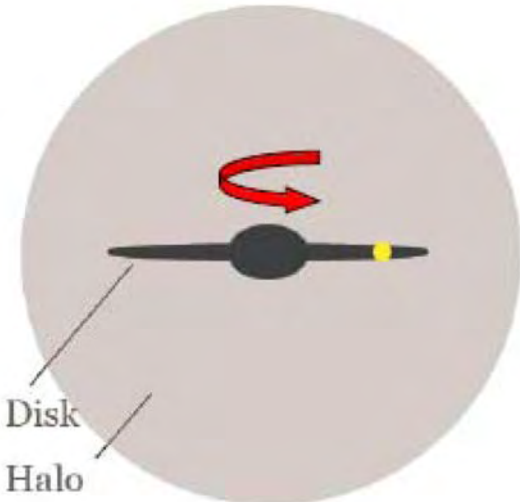
根本问题

到目前为止，没有实验能保证本底压得足够低了

→新方法?

→测量方向将对于压低本底和信号挑选非常有利

银河系暗物质方向



银河系中太阳运行指向银经90°银纬0°，大致是天鹅座方向

→在地球上看，***暗物质流强具有各向异性，而本底是各向同性的***

Direct→ Directional:

直接的→方向的

$$\frac{dR}{dE_R} \rightarrow \frac{d^2R}{dE_R d\Omega_R}$$

Physics Letters B 691 (2010) 156–162

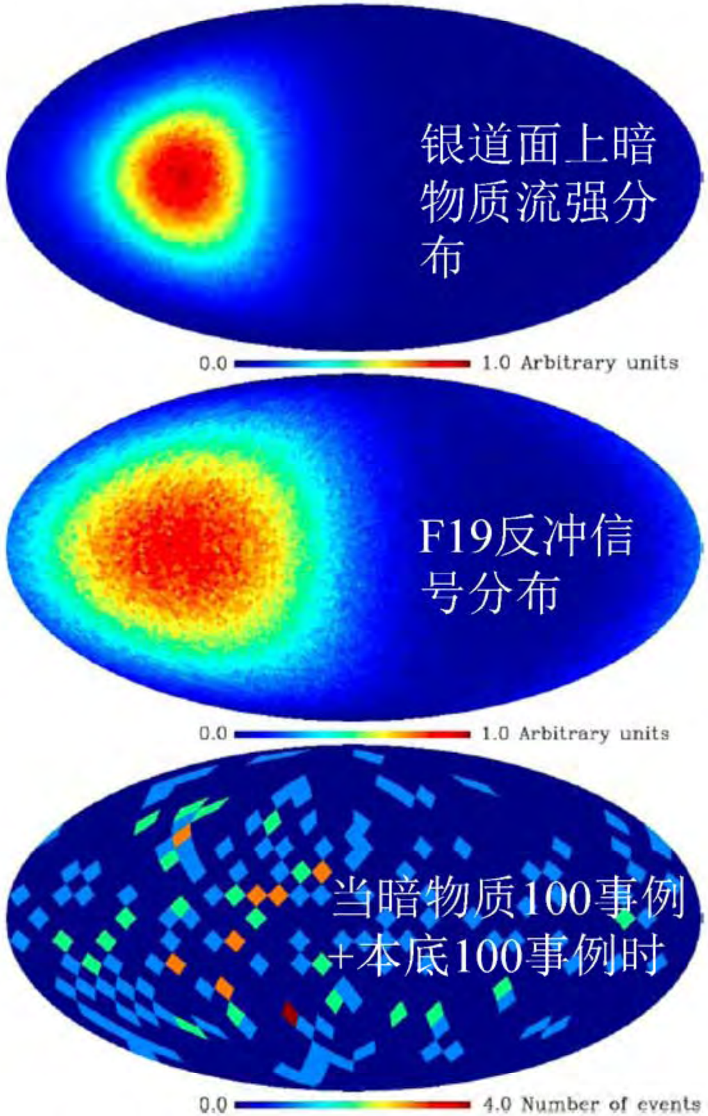


Fig. 1. From top to bottom: WIMP flux in the case of an isothermal spherical halo, WIMP-induced recoil distribution and a typical simulated measurement: 100 WIMP-induced recoils and 100 background events with a low angular resolution. Recoils maps are produced for a ^{19}F target, a 100 GeV c^{-2} WIMP and considering recoil energies in the range 5 keV $\leqslant E_R \leqslant$ 50 keV. Maps are Mollweide equal area projections.

暗物质天文学

- 地球上看暗物质流强分布具有各向异性
- 虽然核反冲后方向会有一定的模糊，但是信号分布仍然保持了各向异性
- 对探测器角分辨的要求并不很高，几十公斤CF_4的一年观测就可对于SD模型有很强的约束

For an elastic axial cross-section on nucleon, σ_n $= 1.5 \times 10^{-3}$ *pb and a 100 GeVc*$^{-2}$ *WIMP mass*, an exposure of ~ 7 × 10^3 kg day in 3He and ~1.6 × 10^3 *kg day in CF4*, *angular resolution*~ 15◦ (FWHM),

暗物质类型的确定

通过方向观测，可以对暗物质质量、作用截面、halo特性(速度分布)做很强的限定

比如30kg•year CF4可以得到

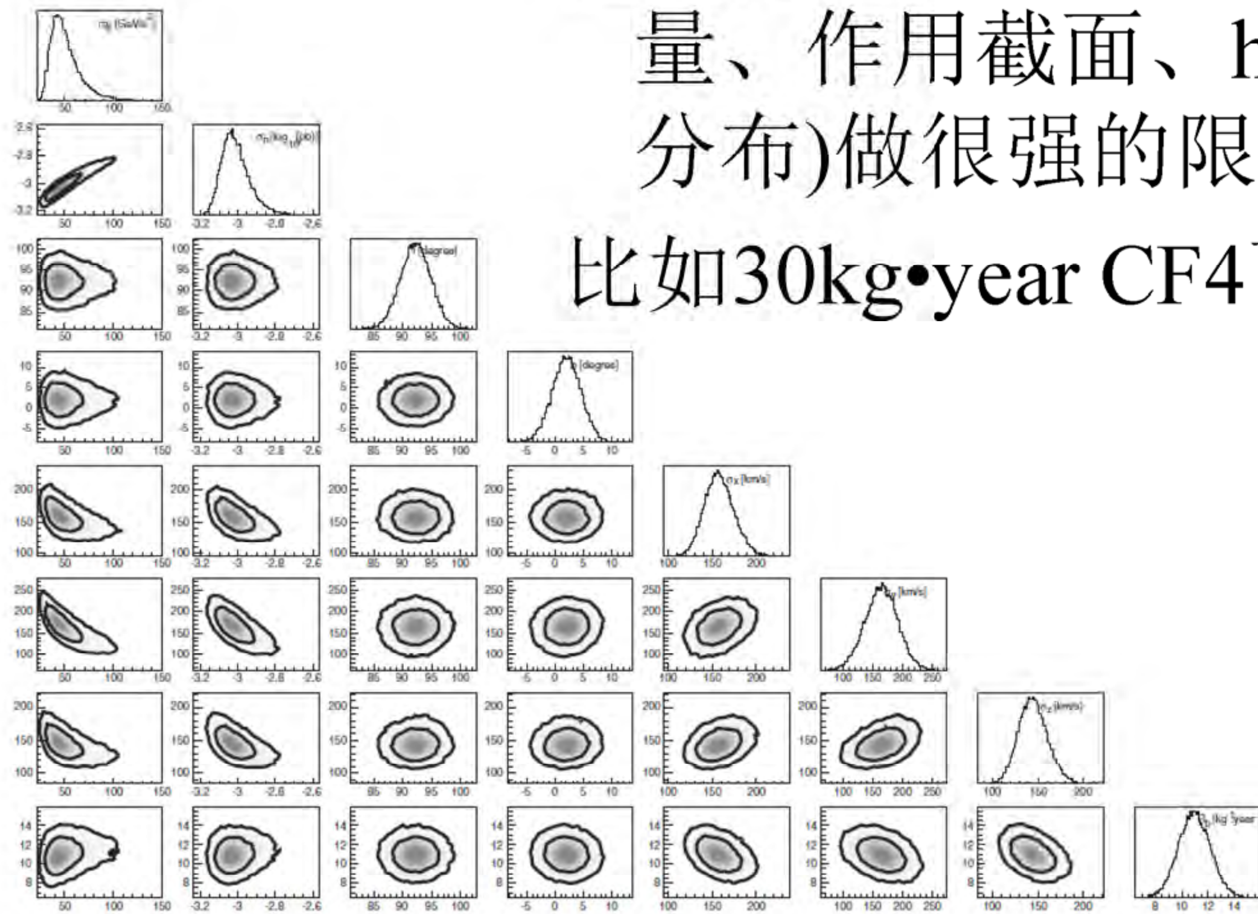


FIG. 3. Marginalized distributions (diagonal) and 2D correlations (off-diagonal) plots of the 8 parameters from the analysis of simulated data in the case of an isothermal halo with a WIMP mass of 50 GeV.c^{-2} and a WIMP-nucleon cross section $\sigma_n = 10^{-3}$ pb.

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暗物质信号的日调制

CYGNUS2009 white paper

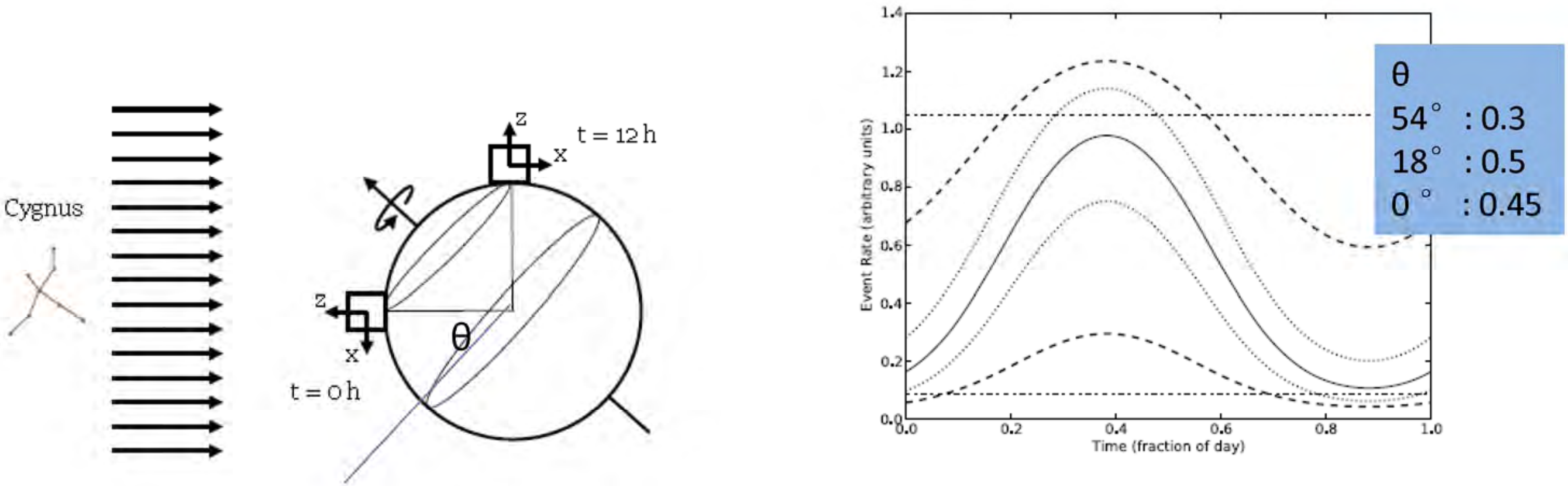


Fig. 2. (left) The daily rotation of the Earth introduces a modulation in recoil angle, as measured in the laboratory frame. (right) Magnitude of this daily modulation for seven lab-fixed directions, specified as angles with respect to the Earth's equatorial plane. The solid line corresponds to zero degrees, and the dotted, dashed, and dash-dot lines correspond to $\pm 18^\circ$, $\pm 54^\circ$ and $\pm 90^\circ$, with negative angles falling above the zero degree line and positive angles below. The $\pm 90^\circ$ directions are co-aligned with the Earth's rotation axis and therefore exhibit no daily modulation. This calculation assumes a WIMP mass of 100 GeV and CS_2 target gas. (from Ref. 13).

日调制

cygnus2009Whitepaper

- 所有的本底都不会有日调制
- 日调制幅度比年调制大很多
- 只需少量带方向的事例就可以区分 DM 信号和本底.

靶物质的选择

SI： $M_{target} \rightarrow M_{DM}$

Light DM ← Heavy DM

	F	Na	Si	Ar	Ca	Ge	I	Cs	Xe	Ba
A	19	23	28	36	40	72,73,74	127	133	129,131	137,138

SD: **σ~spin factor**

	^{23}Na	^{127}I	^{19}F	^{73}Ge	^{129}Xe	^{131}Xe
Spin factor	0.041	0.007	**0.647**	0.065	0.124	0.055
Unpaired nucleon	p	p	**p**	n	n	n

理论上：作用截面SD比SI高**6个量级**

实验上：给出的上限SD比SI高**6个量级**

→SD 是“浅矿”

SKLTP

靶物质的选择

- 低阈能要求尽可能长的径迹
  - 靶核要轻
  - 气压要低
- 对SD来说，H, He3, F19自旋因子大，大部分实验选择CF4，有的用He3;
- 对SI来说，CS2是个不错的选择，漂移的是负离子，可以压低扩散，从而得到更长的径迹

非弹性散射

arXiv:0906.0002v2 [astro-ph.CO]

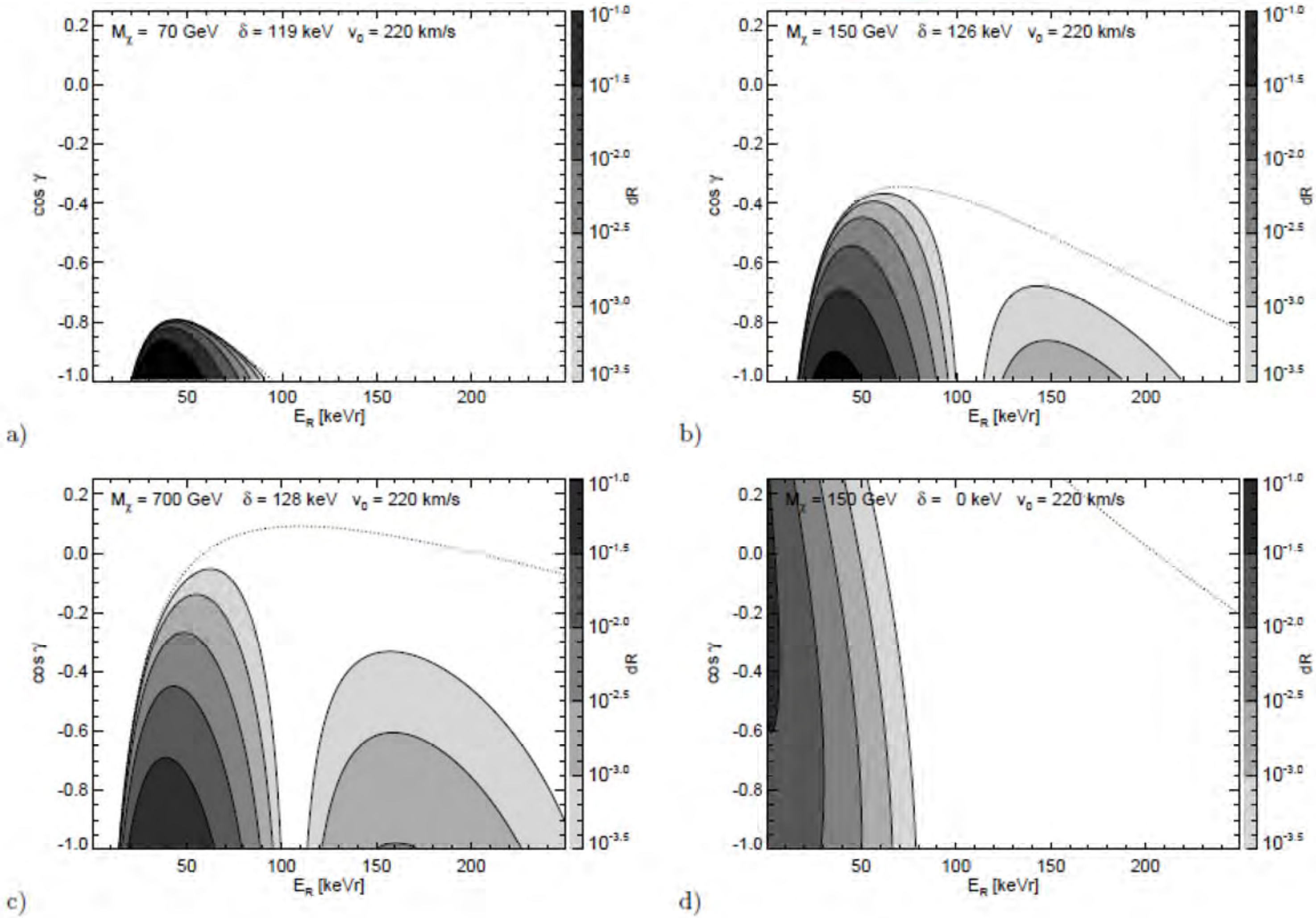
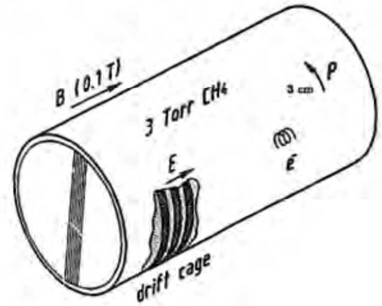


FIG. 1: Differential rates $dR/(dE_R\, d\cos\gamma)$ for the benchmark models given in Table I for v_{esc} = 500 km/s, as well as for an elastic WIMP. In each case, the differential rate is normalized so that the total rate is unity. Outside the region indicated by the dashed line, scattering events are kinematically forbidden.

方向探测思想的产生与发展

- D.N.Spergel(1988): 提出方向探测的想法
- G. Gerbier, J. Rich, M. Spiro and C. Tao (1990): 提出用气体TPC测核反冲方向
- K. N. Buckland, M. J. Lehner, G. E. Masek, and M. Mojaver(1994)： 第一个做成用于暗物质方向探测的低气压TPC



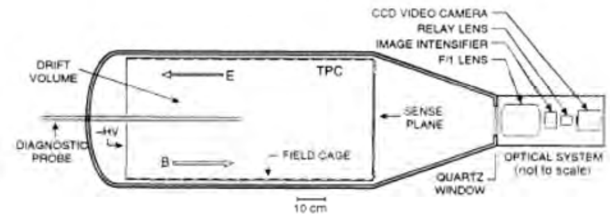


FIG. 1. A schematic view of the low pressure TPC and optical system.

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The case for a directional dark matter detector and the status of current experimental efforts

S. AHLEN,[1] N. AFSHORDI,[22,30] J. B. R. BATTAT,[14] J. BILLARD,[11] N. BOZORGNIA,[3] S. BURGOS,[20] T. CALDWELL,[14,21] J. M. CARMONA,[12] S. CEBRIAN,[12] P. COLAS,[4] T. DAFNI,[12] E. DAW,[25] D. DUJMIC,[14] A. DUSHKIN,[2] W. FEDUS,[14] E. FERRER,[4] D. FINKBEINER,[6] P. H. FISHER,[14] J. FORBES,[20] T. FUSAYASU,[15] J. GALAN,[12] T. GAMBLE,[25] C. GHAG,[5] I. GIOMATARIS,[4] M. GOLD,[17] H. GOMEZ,[12] M. E. GOMEZ,[7] P. GONDOLO,[28] A. GREEN,[19] C. GRIGNON,[11] O. GUILLAUDIN,[11] C. HAGEMANN,[17] K. HATTORI,[10] S. HENDERSON,[14] N. HIGASHI,[10] C. IDA,[10] F. J. IGUAZ,[12] A. INGLIS,[1] I. G. IRASTORZA,[12] S. IWAKI,[10] A. KABOTH,[14] S. KABUKI,[10] J. KADYK,[13] N. KALLIVAYALIL,[14] H. KUBO,[10] S. KUROSAWA,[10] V. A. KUDRYAVTSEV,[25] T. LAMY,[11] R. LANZA,[14] T. B. LAWSON,[25] A. LEE,[14] E. R. LEE,[17] T. LIN,[6] D. LOOMBA,[17] J. LOPEZ,[14] G. LUZON,[12] T. MANOBU,[9] J. MARTOFF,[25] F. MAYET,[11] B. McCLUSKEY,[25] E. MILLER,[17] K. MIUCHI,[10] J. MONROE,[14] B. MORGAN,[29] D. MUNA,[19]

CYGNUS2009 white paper:
USA,France,UK,Spain,Greece, Japan,Canada
7个国家，30个单位，112名成员
提出1ton方向探测器

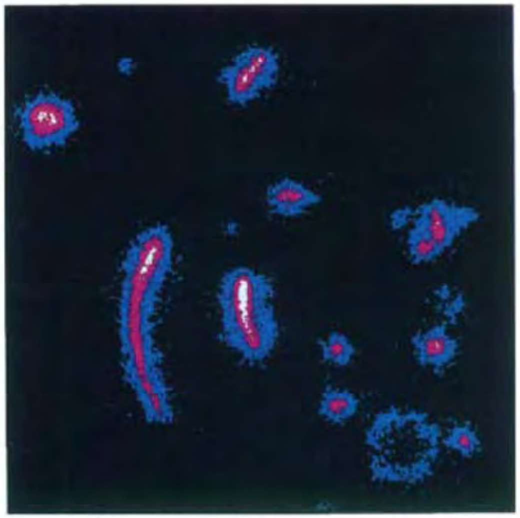
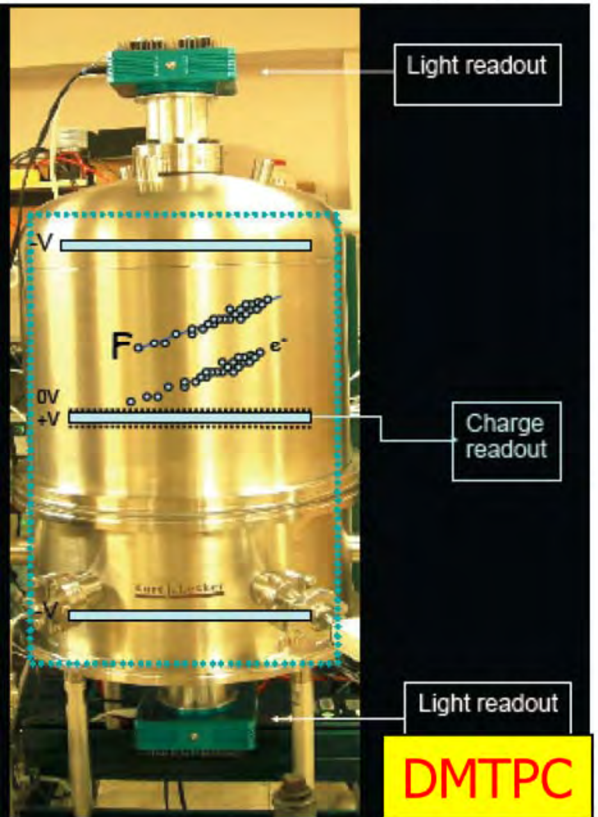
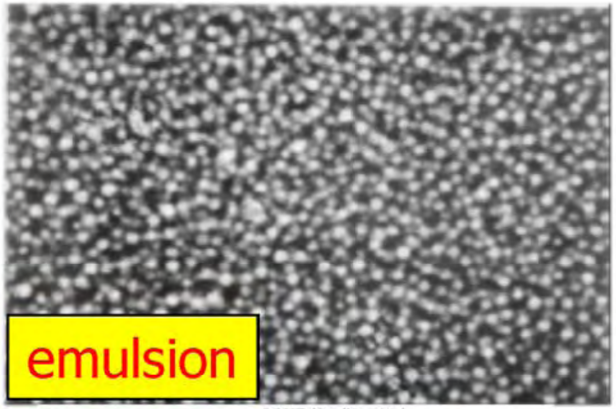


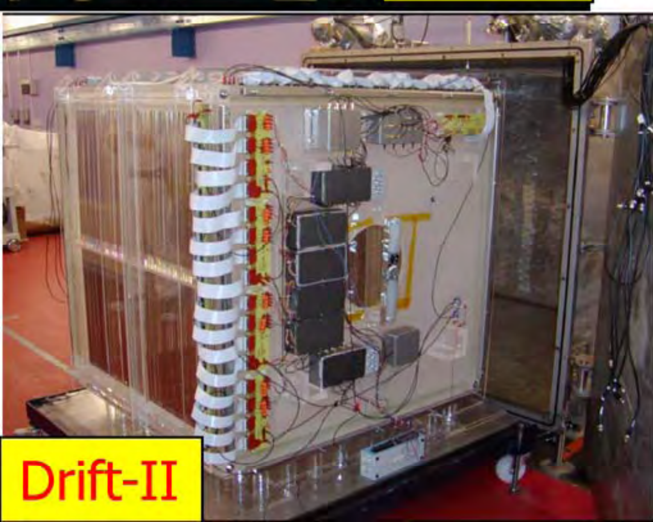
FIG. 2. A false color CCD image resulting from a ^{252}Cf neutron source. The colors black, blue, red, and white represent the order of increasing light intensity levels. The area displayed represents a 25 cm by 25 cm section of the detector plane. See the text for a description of image features.

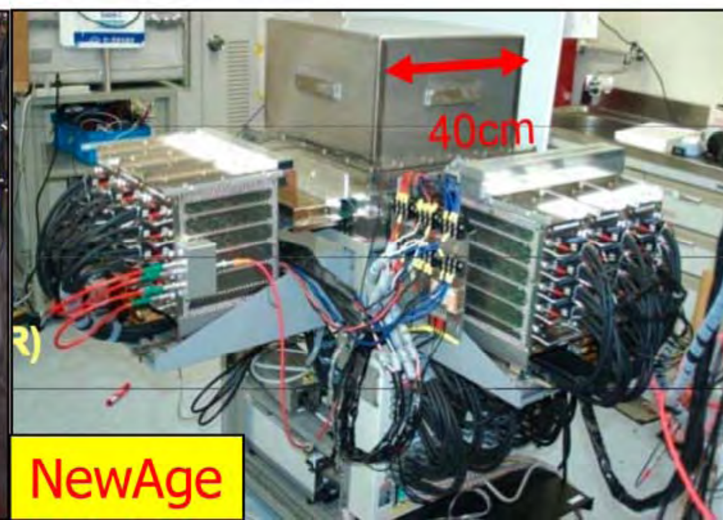
CYGNUS2009

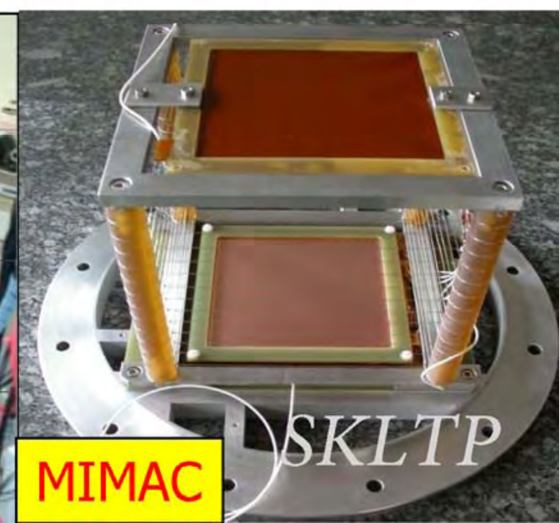
CYGNUS2011





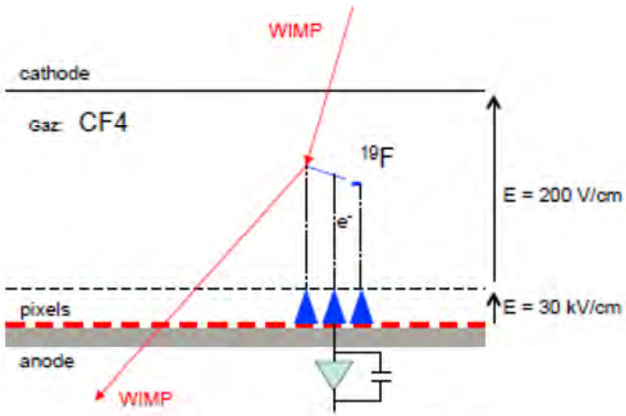


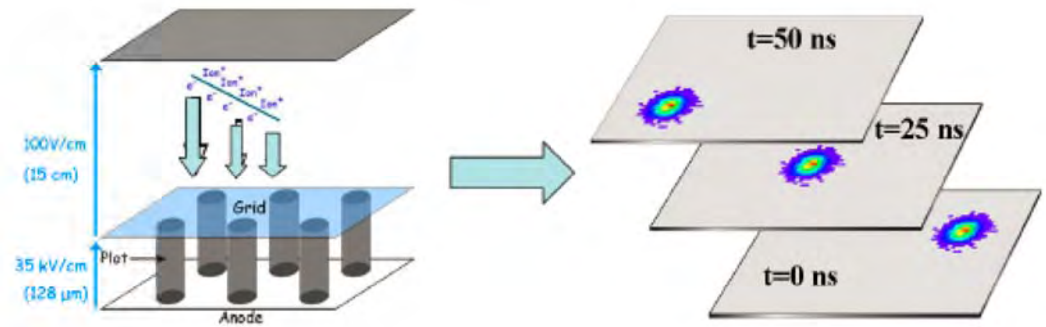




MIMAC

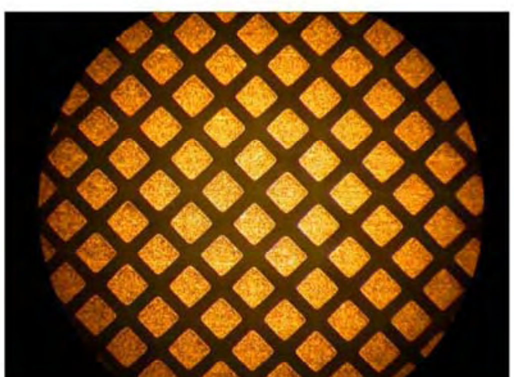
MIcro-tpc MAtrix of Chambers



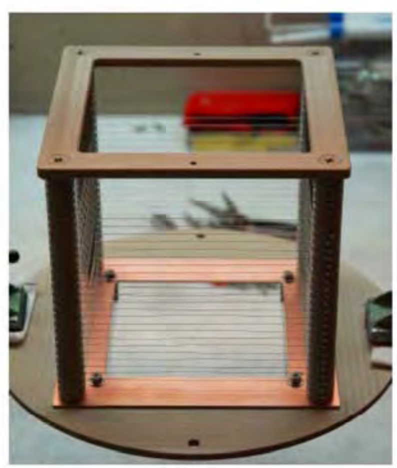


Micromegas(Micromesh Gas Structure): 33 cm2 active area, segmented in 300 µm pixels.

MIMAC 100x100 (v2)

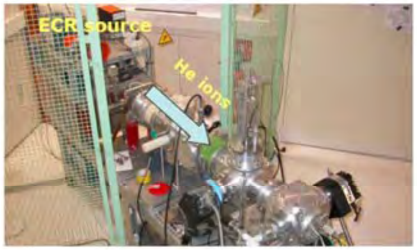


Drift volume – charge collection

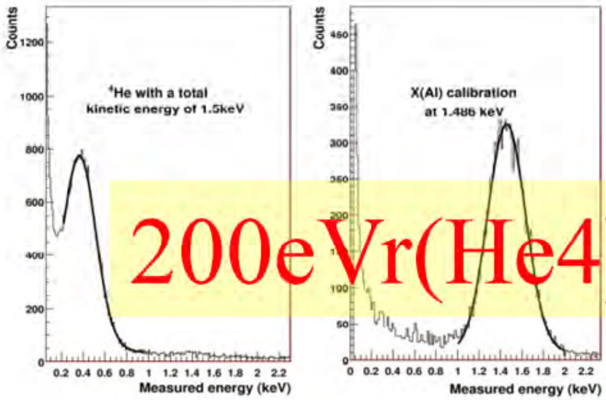


Bi-chamber module (Modane)
2x (10x10x25 cm^3)
(November 2011 !)

MIMAC
Quenching factor & E_{th} !

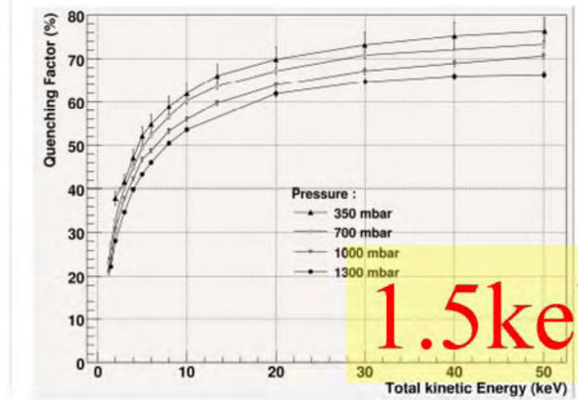


Detection of ^4He (recoils) of 1.5 keV !!
(95% ^4He + 5% iso) at 700mbars

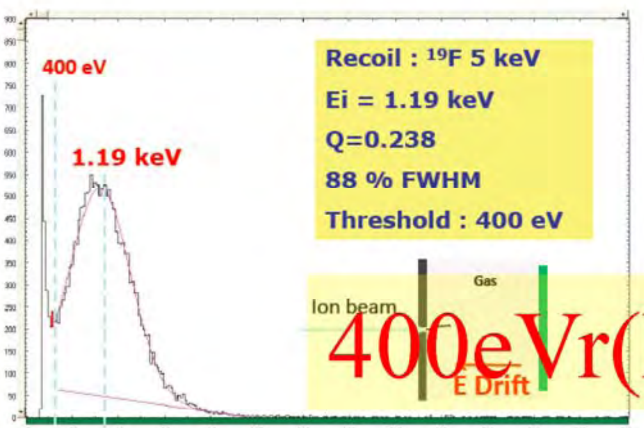


IQF Measurement of ^4He in 95% ^4He + 5% C_4H_{10} as a function of the pressure

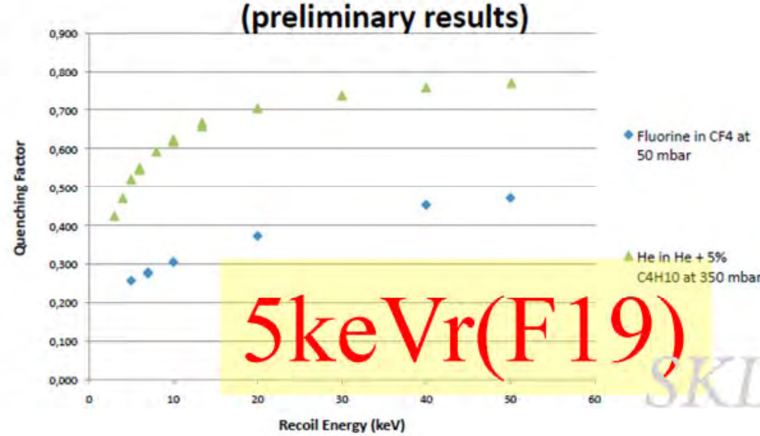
D. Santos et al. arXiv:astro-ph0810.1137



5keV ^{19}F Recoil in 60 mbar
40mbar CF4+16.8mbar CHF3+1.2 mbar Isobutane



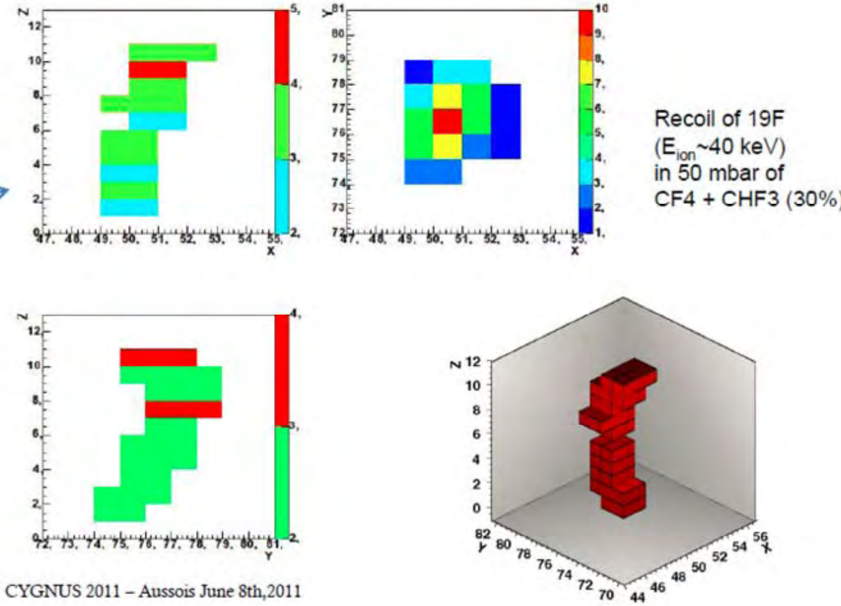
Ionization Quenching Factor for Fluorine in pure CF4 at 50 mbar (preliminary results)



MIMAC

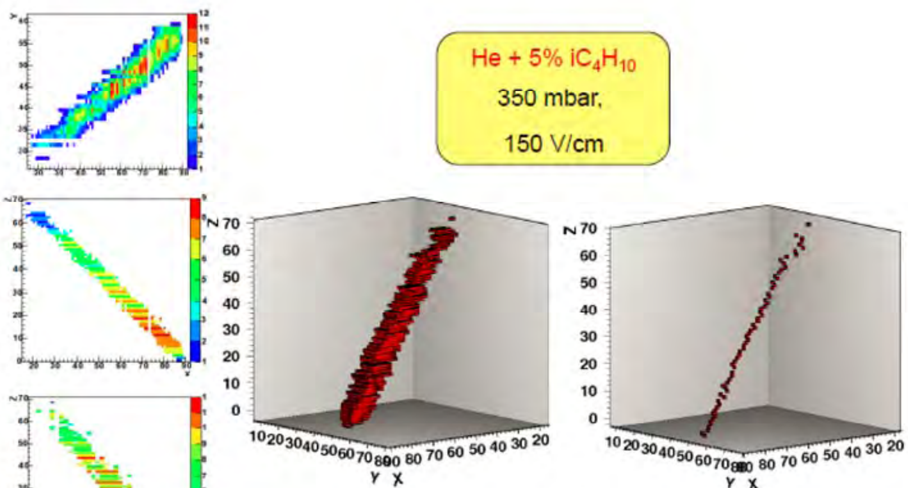
Not only direction of nuclei recoil

But also direction of electron recoil



CYGNUS 2011 – Aussois June 8th,2011

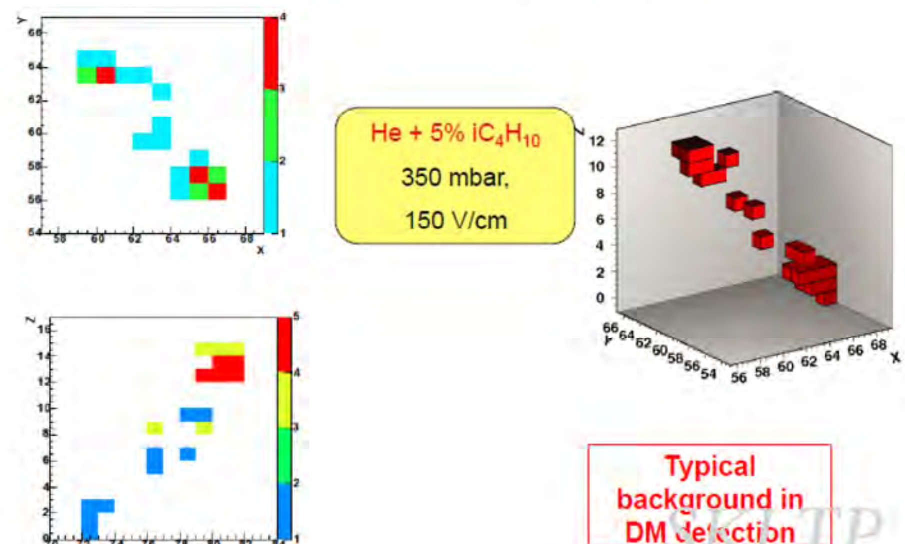
3D track : **Alpha 5,5 MeV** (^{222}Rn)



CYGNUS 2011 – Aussois June 8th,2011

D. Santos (LPSC Grenoble)

3D Track : 5.9 keV electron (^{55}Fe)

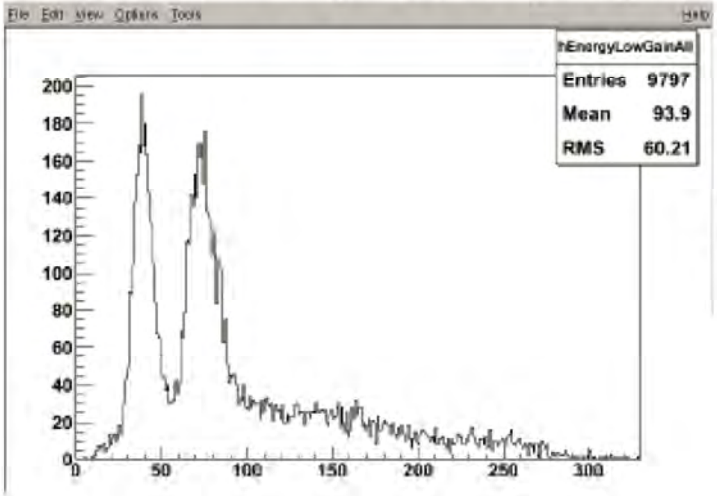


CYGNUS 2011 – Aussois June 8th,2011

D. Santos (LPSC Grenoble)

MIMAC

Calibration from X rays: 3.05 keV (^{109}Cd) et 5.96 keV (^{55}Fe)



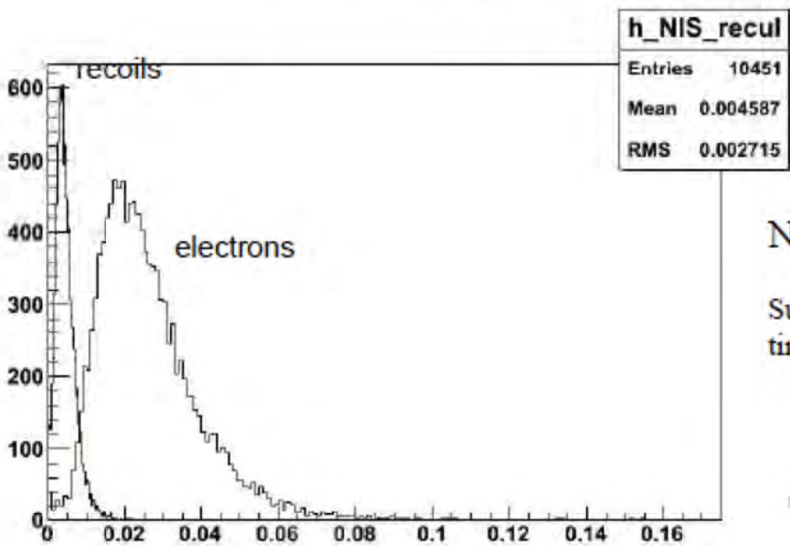
Each event has its associated track…

Energy resolution: 12% at 1.486keV (Al27), 5% at 5.96keV (Fe55)

Normalized Integrated Straggling (NIS)

(a new degree of freedom for e-recoil discrimination)

(The adition of partial deflections along the measured track, normalized by its total energy)

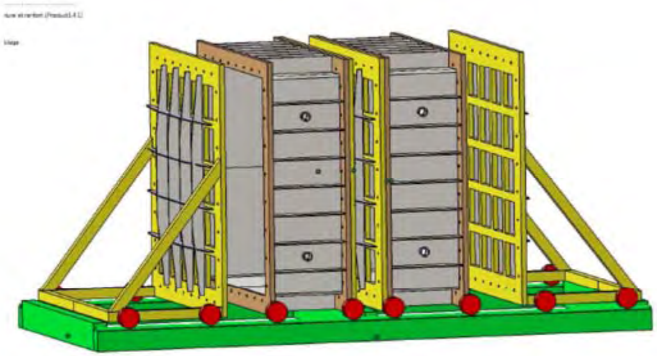


NIS= $\Sigma (\Delta\theta_i) / E$

Summed over all the time samples of a track

SKLTP

MIMAC – 1m^3

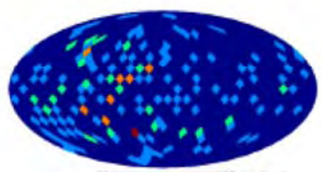


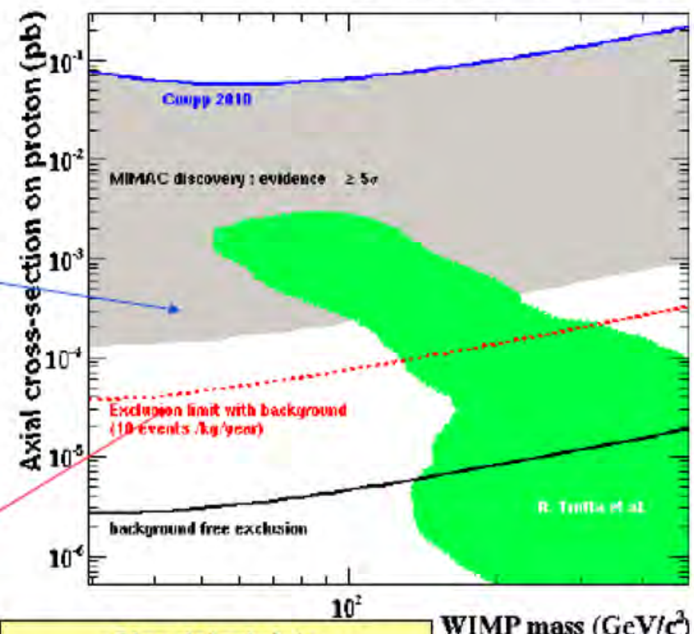
MIMAC

J. Billard *et al.*, PLB 2010

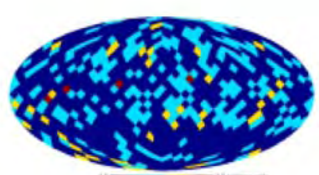
J. Billard *et al.*, PRD 2010

- ***discovery (5σ)***
  Up to 10^{-4} pb





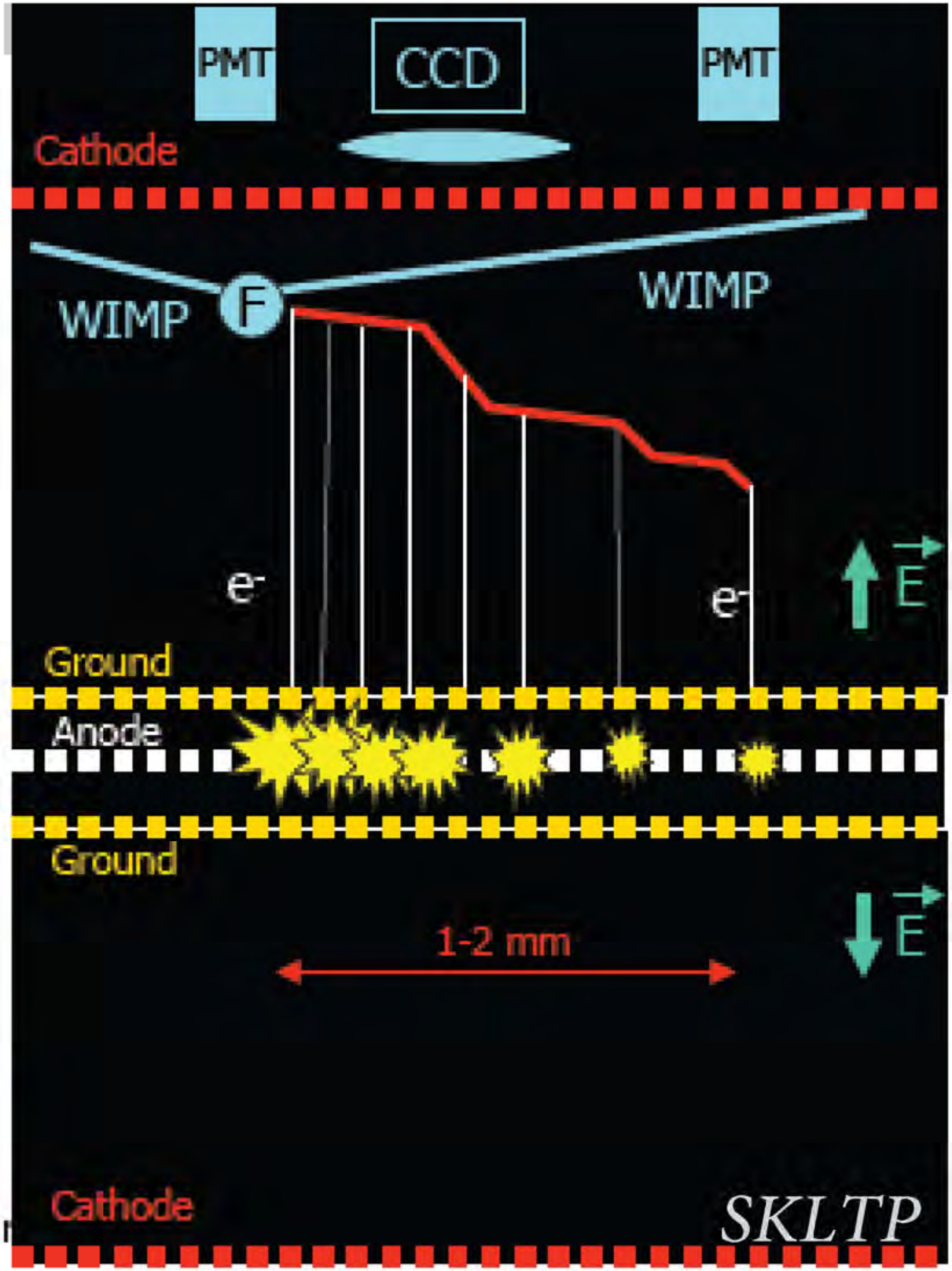
- **exclusion**
  Up to 10^{-6} pb



Simulated data
- 30 kg.year CF_4
- Recoil energy [5, 50] keV
- Angular resolution : 15°

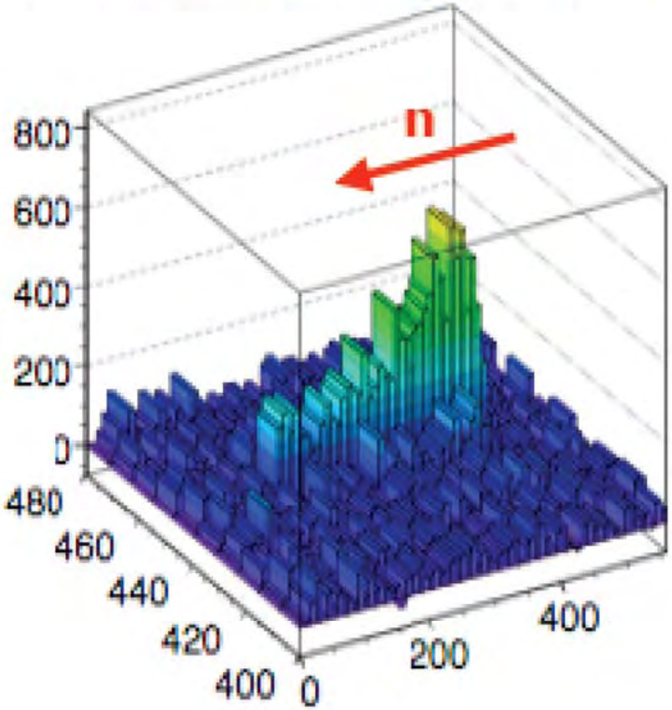
DM-TPC

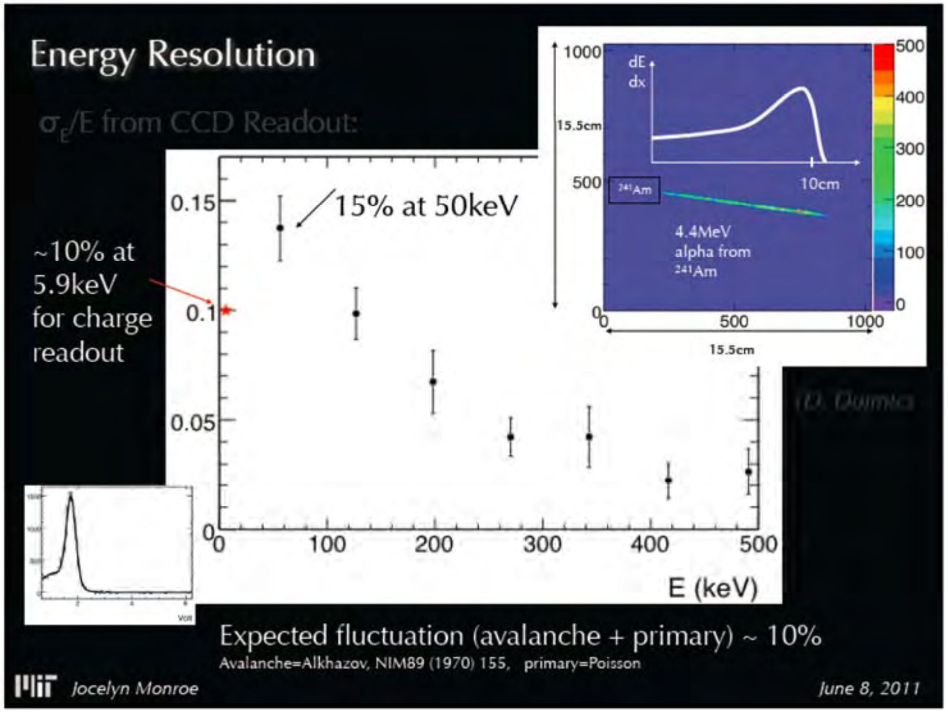
- 低气压 CF4 （自旋相关）
  - 50 torr: F recoil ~2mm @ 40 keV
- 光学读出 (CCD,1536×1024)
  - 2D径迹测量(100pixels~6mm)
  - 能量测量， σ_E/E~15% @ 50 keV
- PMT和电荷读出（漂移室20cm直径）
  - 触发，
  - 能量测量， σ_E/E~10%@ 5.9 keV
  - (Z方向测量)



- Head-tail sensitivity for neutron-induced recoils above 100 keV
- 本底排除~2/10^6
- 阈能50 keV（P=100 torr）
- 角分辨~15^o @ 100 keV

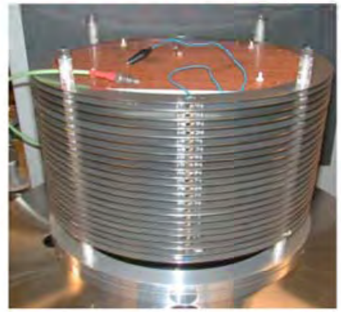
DM-TPC

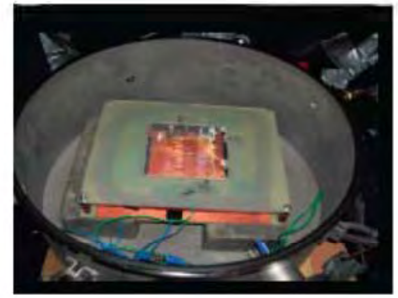




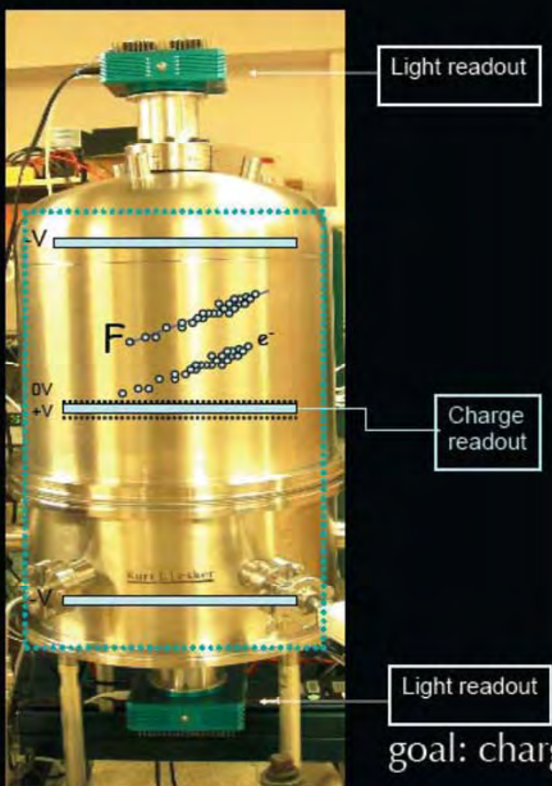
DMTPC

- DMTPC 10-liter, 3.3g (75torr)





TPC Readout

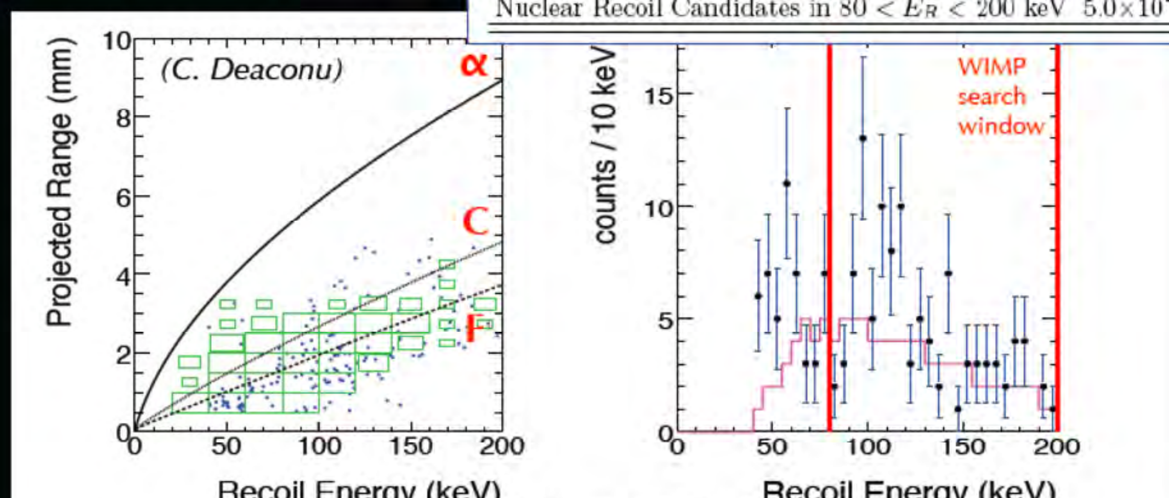


goal: charg

Surface Run Results

nuclear recoil selection cuts set using calibration data

Event Selection Cut	Rate (Hz)
All Tracks	0.43
Residual Bulk Images	0.15
CCD Interactions	4.4×10^{-3}
Alpha Candidates	8.2×10^{-5}
Nuclear Recoil Candidates in $80 < E_R < 200$ keV	5.0×10^{-5}



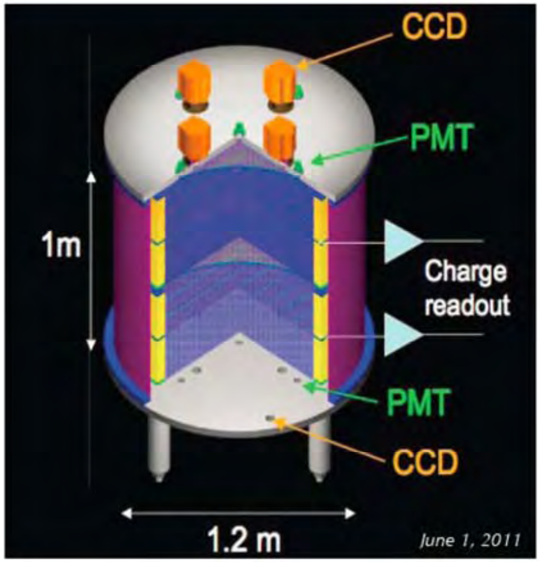
S. Ahlen et al., Phys. Lett. B 695 (2011)

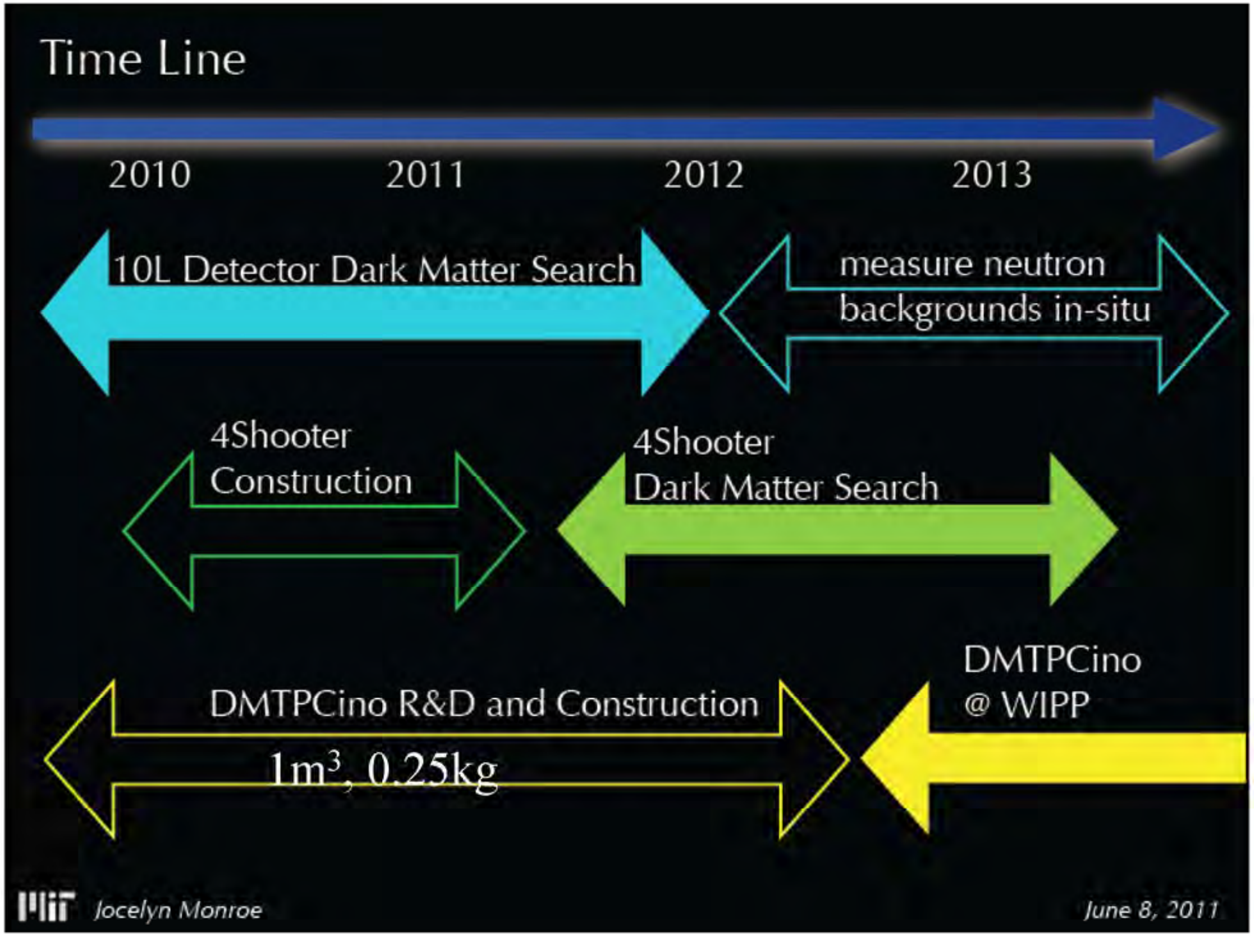
surface neutron flux measurement: T. Nakamura, T. Nunomiya, S. Abe, K. Terunuma, and H. Suzuki, J. of Nucl. Sci. and Tech. 42 No. 10, 843 (2005).

observed 105 events above 80 keV threshold chosen for dark matter search (threshold chosen for max. recoil efficiency), consistent with neutron prediction (74 events)

SKLTP

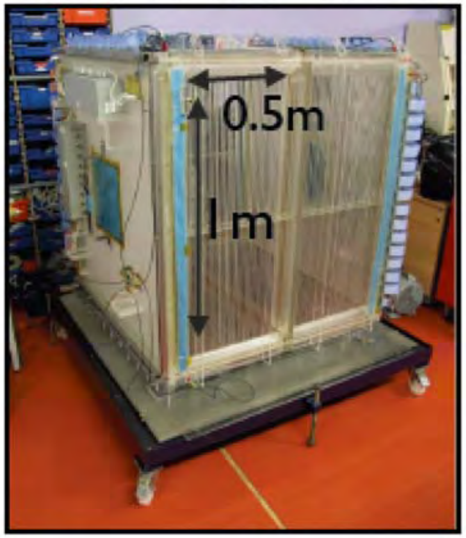
DMTPC

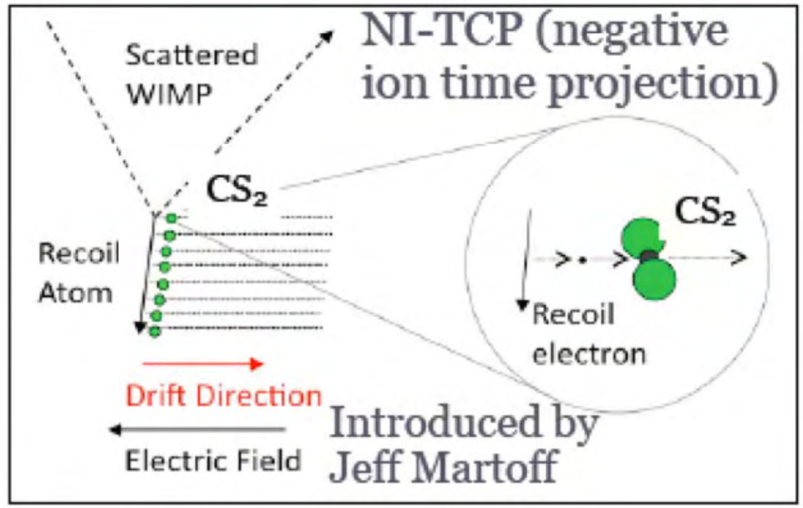

CCD
PMT
1m
Charge readout
PMT
CCD
1.2 m
June 1, 2011

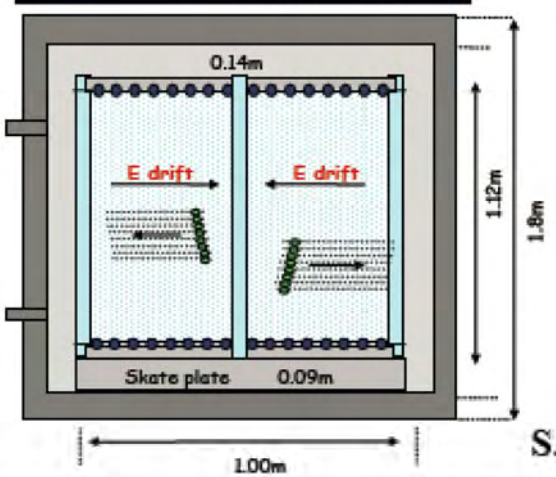

Time Line
2010
2011
2012
2013
10L Detector Dark Matter Search
measure neutron backgrounds in-situ
4Shooter Construction
4Shooter Dark Matter Search
DMTPCino R&D and Construction
1m3, 0.25kg
DMTPCino @ WIPP
Jocelyn Monroe
June 8, 2011

DRIFT

DRIFT II Concept



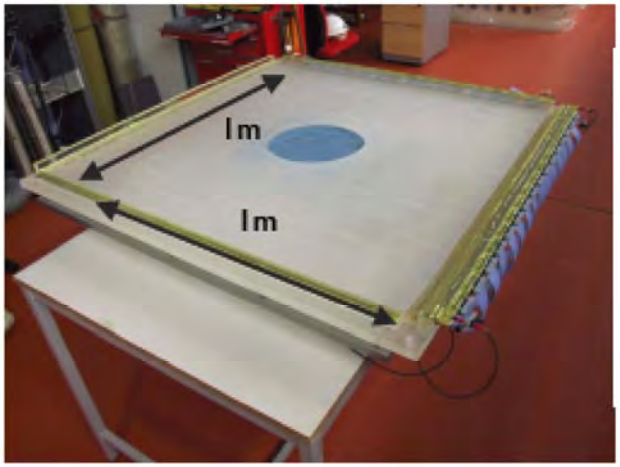


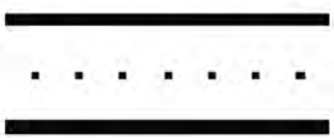


- 1 m³ active volume - back to back MWPCs
- Gas fill 40 Torr CS_2 => 167 g of target gas
- 2 mm pitch anode wires left and right
- Grid wires read out for Δy measurement
- Veto regions around outside
- Central cathode made from 20 μm diameter wires at 2 mm pitch
- Drift field 624 V/cm
- Modular design for modest scale-up

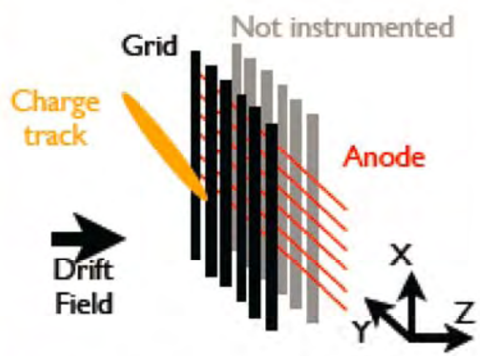
S. Burgos et al., Nucl. Instr. Meth. A 584, 114 (2008)

MWPC Readout

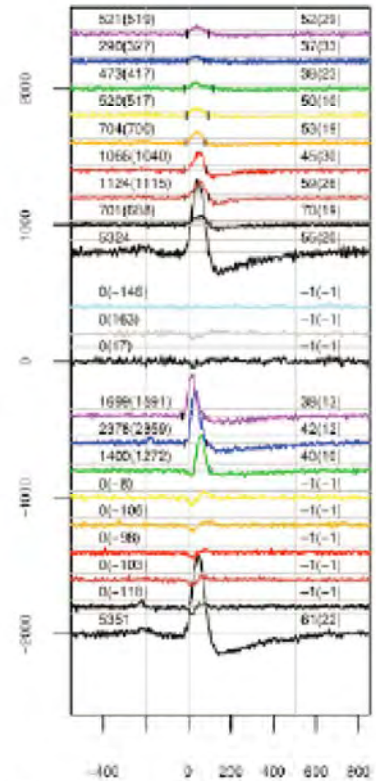




- Anode plane of 512 20μm wires with 2mm pitch
- 2 cathode planes of 512 100μm wires perpendicular to anode plane, 2mm pitch - one of which is read out



ΔX: Number of anode wires crossed
ΔY: Progression across grid wires
ΔZ: Drift time between start and end of track



Multiplexed to 18 channels of digitised waveform output for $1m^2$ readout plane

<u>Simple, cheap & scalable</u>

DRAFT

Operational in the Boulby Mine since 2001
DRIFT-I, DRIFT-IIa, DRIFT-IIb, DRIFT-IIc, DRIFT-IId

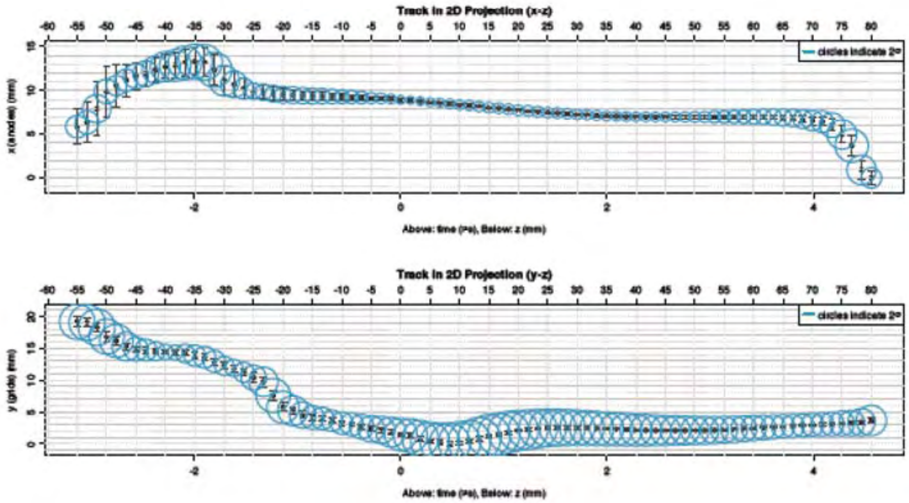
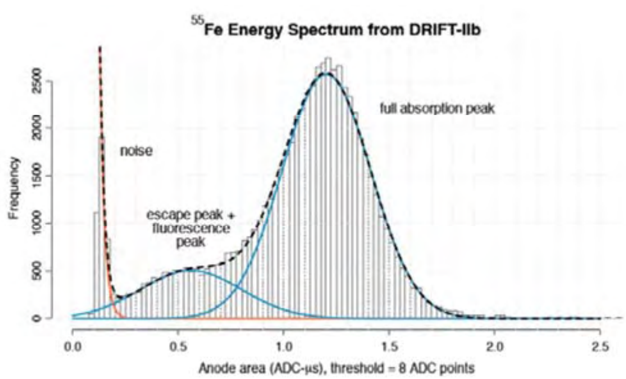
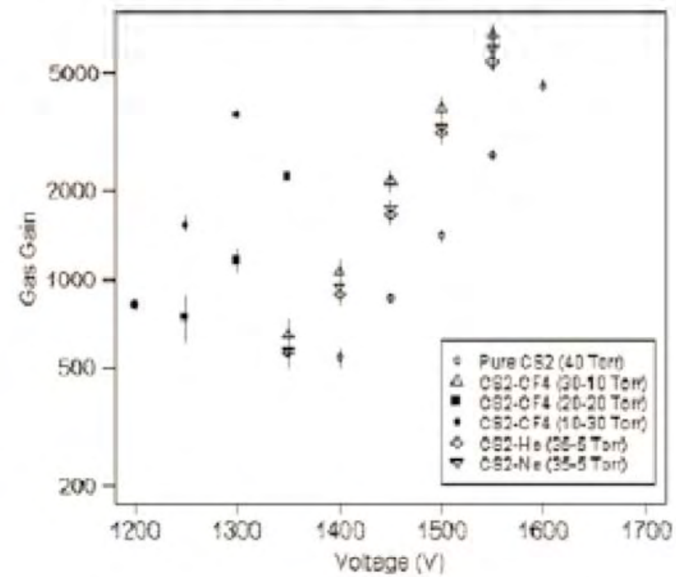


Fig. 8. Example 3D reconstruction (x-z and y-z projections) of a ~100 keV S recoil in DRIFT IIb (circle sizes indicate the amount of deposited charge).



- DRIFT-IId new set-up with CS_2/CF_4 (=DRIFT-IIb + gas mix system)



CS_2/CF_4 gain vs mixture

SKLTP

DRAFT

RPR(radon progenies) reduction

Sample (Emanating into vacuum)	Fill gas	Emanation time (days)	Humidity (%)	Raw result (Bq/m^3)	Adjusted result (Rn atoms.s^{-1})
RG58 coax cables (72m)	Dry N2	12.5	24	9.4 +/- 0.7	0.36 +/- 0.03
Electronics boxes	Dry N2	12	37	1.5 +/- 0.3	0.05 +/- 0.02
Ribbon cables	Dry N2	6.5	23	10.1 +/- 0.7	0.50 +/- 0.04
Electronics & PCBs	Dry N2	10	37	0.3 +/- 0.2	<0.02 *
Single core & thin coax cables	Dry N2	7	19	1.3 +/- 0.3	0.04 +/- 0.02
Field cage parts	Dry N2	7	33.3	0.6 +/- 0.2	<0.03 *
				Total	0.95 +/- 0.5

S. Sadler, S. Paling et al. (Sheffield)

- RPRs still produced from Pb isotopes plated out on cathode. Clean cathode with nitric acid

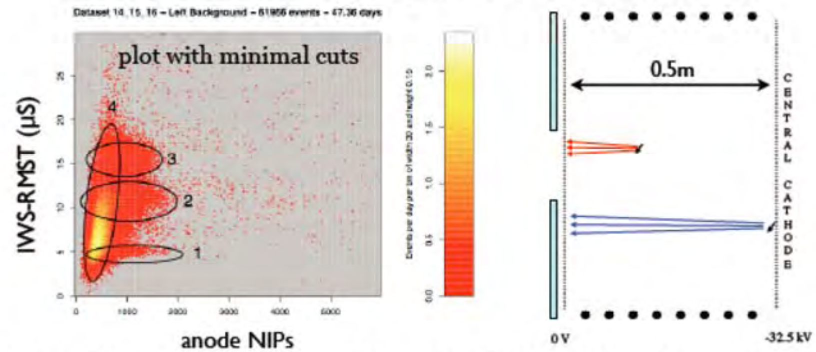
D. Snowden-Ifft, Oxy, J. Turk, UNM (PhD thesis 2008)

Together, these reduced the RPRs by 96% relative to D-IIa rate

- Use pulse z-direction shape shape

Separating out/reducing backgrounds

- Neutrons occur throughout the detector volume
- RPRs come from the central cathode or MWPC and suffer different diffusion - on average cathode RPRs have higher width (IWS-RMST)

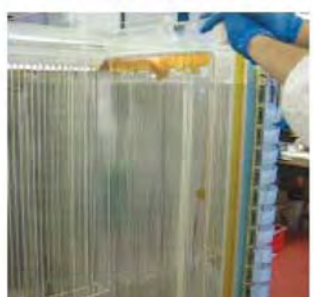


Plots with reduced cuts help explain various backgrounds at low recoil energy: (1) MWPC sparks, (2) MWPC RPRs (3) central cathode RPRs (4) betas

DRIFT IId 0.9μm cathode

Use of multi-panel 0.9μm thick DRIFT cathode

cathode tested at full voltage (32.5kV)

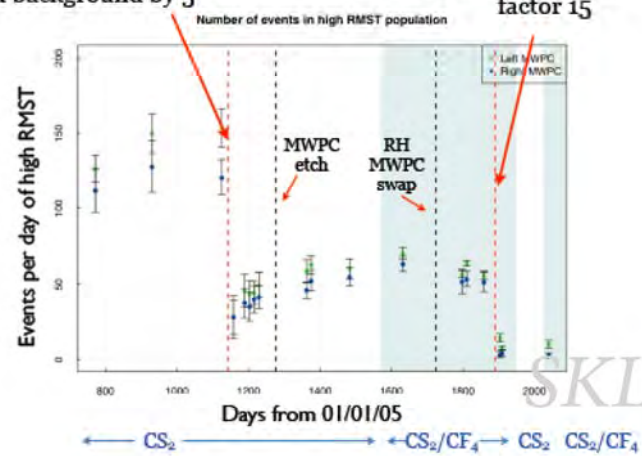


Backgrounds rates vs. time

For instance cathode RPR region (higher IWS-RMST) vs. time

nitric acid etch of cathode reduced background by 5

thin film cathode reduces by further factor 15



SKLTP

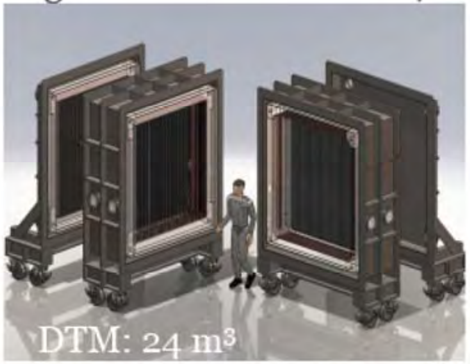
DRAFT

DRIFT III Module (DTM) Concept

Larger size with lower cost/m³

- Modular design to allow approach to ton-scale
- 4 kg target - 24 m³

- One DTM well suited to Boulby
- Large number fits 30m x 150m DUSEL "Standard Lab Module" or new tunnel excavation at Boulby for 1 ton



- advantages of no cryogenics
- multiplexed electronics
- neutron shielding

cost split evenly:

- vacuum vessel
- electronics
- gas system

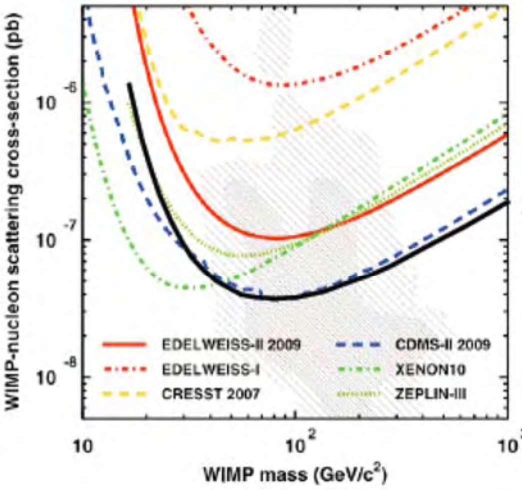
NB: current cost of complete DRIFT II module (with shielding) ~ $80K
Extrapolation gives ~$250K for DTM (with shielding)

DTM Sensitivity

with directional capability

SI Prediction

- Projected limits for one DTM (4kg)
- With no compromise on directional sensitivity



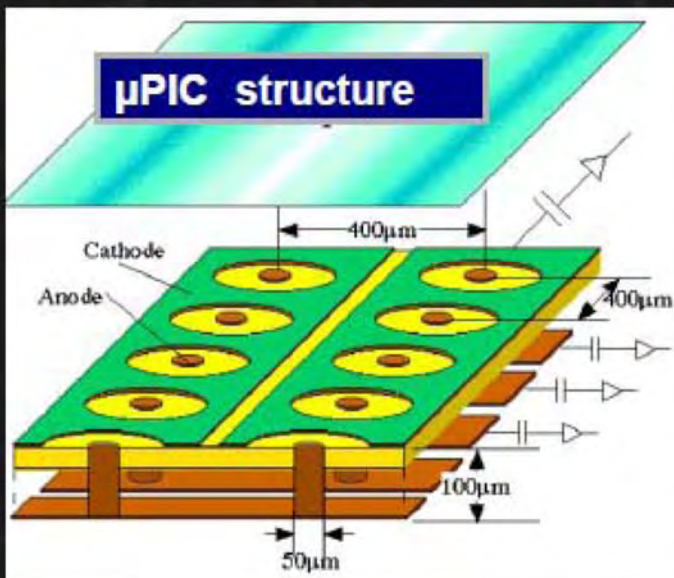
← DTM - 1 year run (4 kg.yr)

thanks to EDELWEISS for the plot

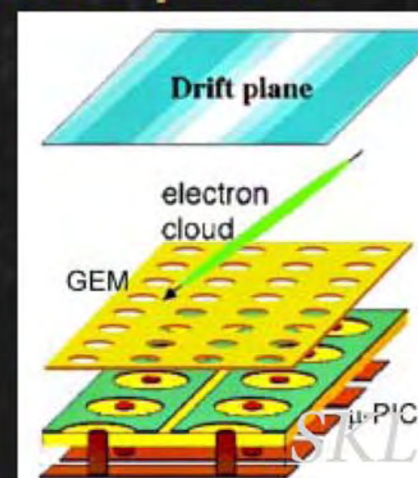
SKLTP

NEWAGE

- μ PIC (developed in Kyoto)
  (one of the Micro Patterned Gaseous Detectors)

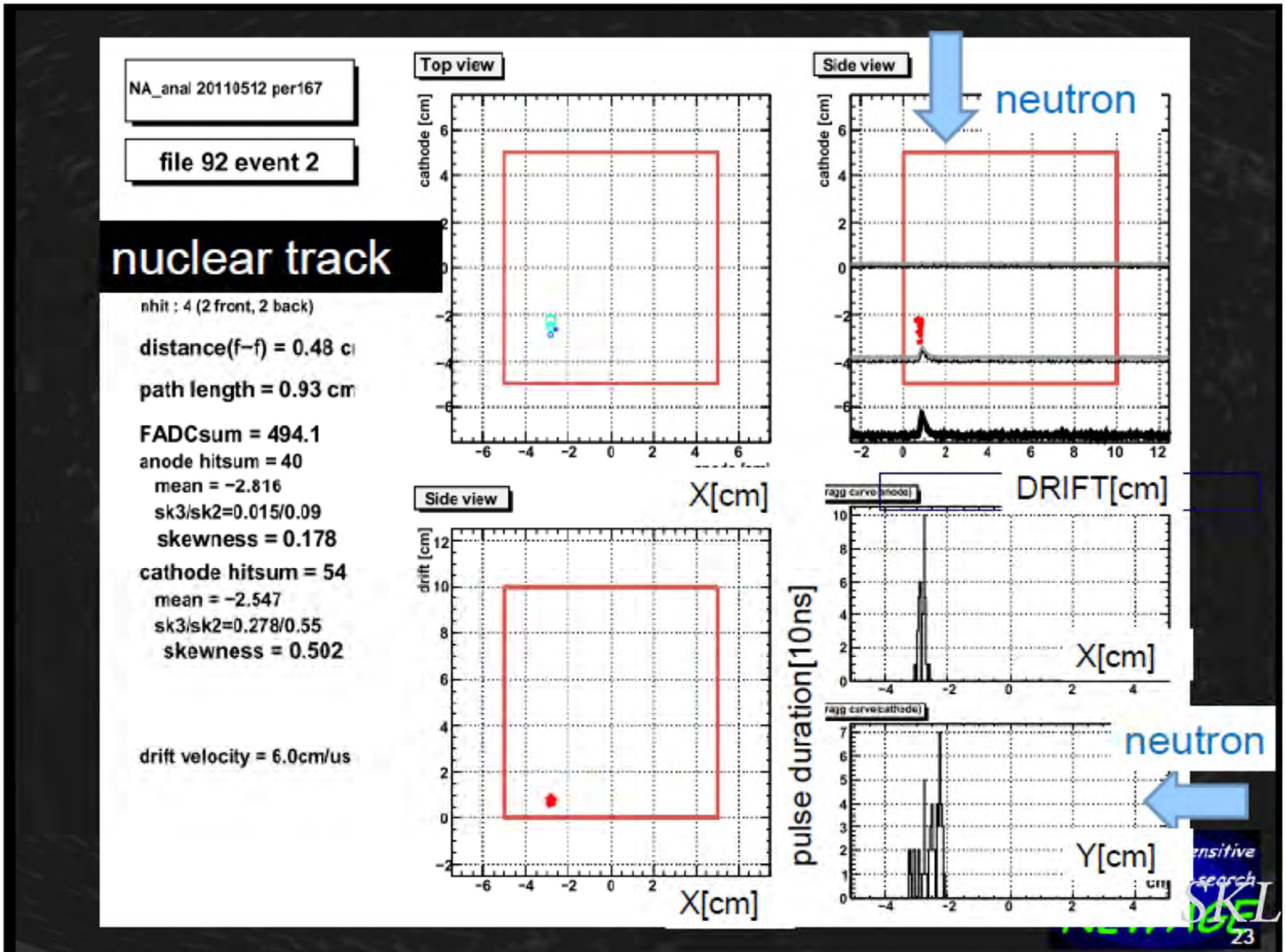


- μPIC SPECs
  - 30 × 30cm^2
  - Gas amplification + readout
  - 400μm pitch
  - 768+768 readouts
  - with GEM (sub amplifier)
  - 3D tracks
  - CF_4



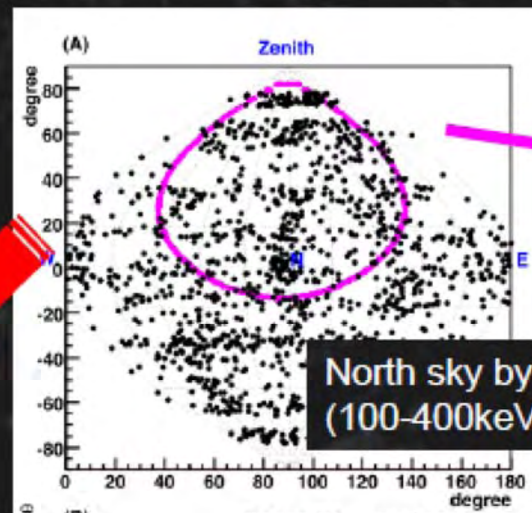
- NEWGAE History
  - Proposal PLB 578 (2004) 241
  - first result PLB 654 (2007) 58
  - underground result PLB 686 (2010) 11

NEWAGE

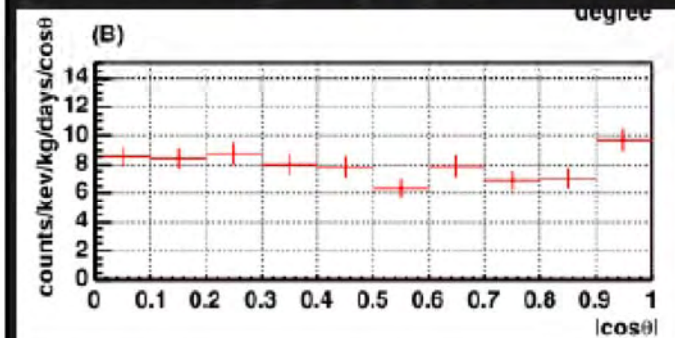

NA_anal 20110512 per167
file 92 event 2
nuclear track
nhit : 4 (2 front, 2 back)
distance(f−f) = 0.48 c
path length = 0.93 cm
FADCsum = 494.1
anode hitsum = 40
mean = −2.816
sk3/sk2=0.015/0.09
skewness = 0.178
cathode hitsum = 54
mean = −2.547
sk3/sk2=0.278/0.55
skewness = 0.502
drift velocity = 6.0cm/us
Top view
cathode [cm]
X[cm]
Side view
neutron
DRIFT[cm]
drift [cm]
pulse duration[10ns]
Y[cm]
23

NEWAGE

- First underground results
- The sky map
  - --> cosθ distribution
    - --> upper limits



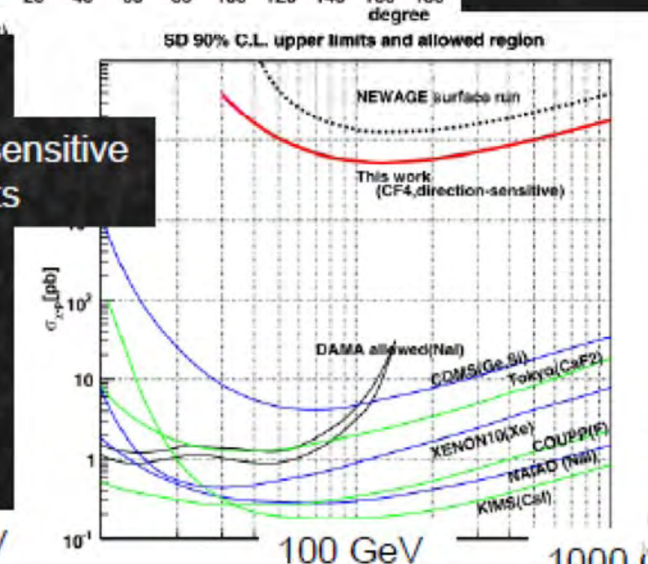
North sky by C and F nuclei (100-400keV)



Cosθ distribution

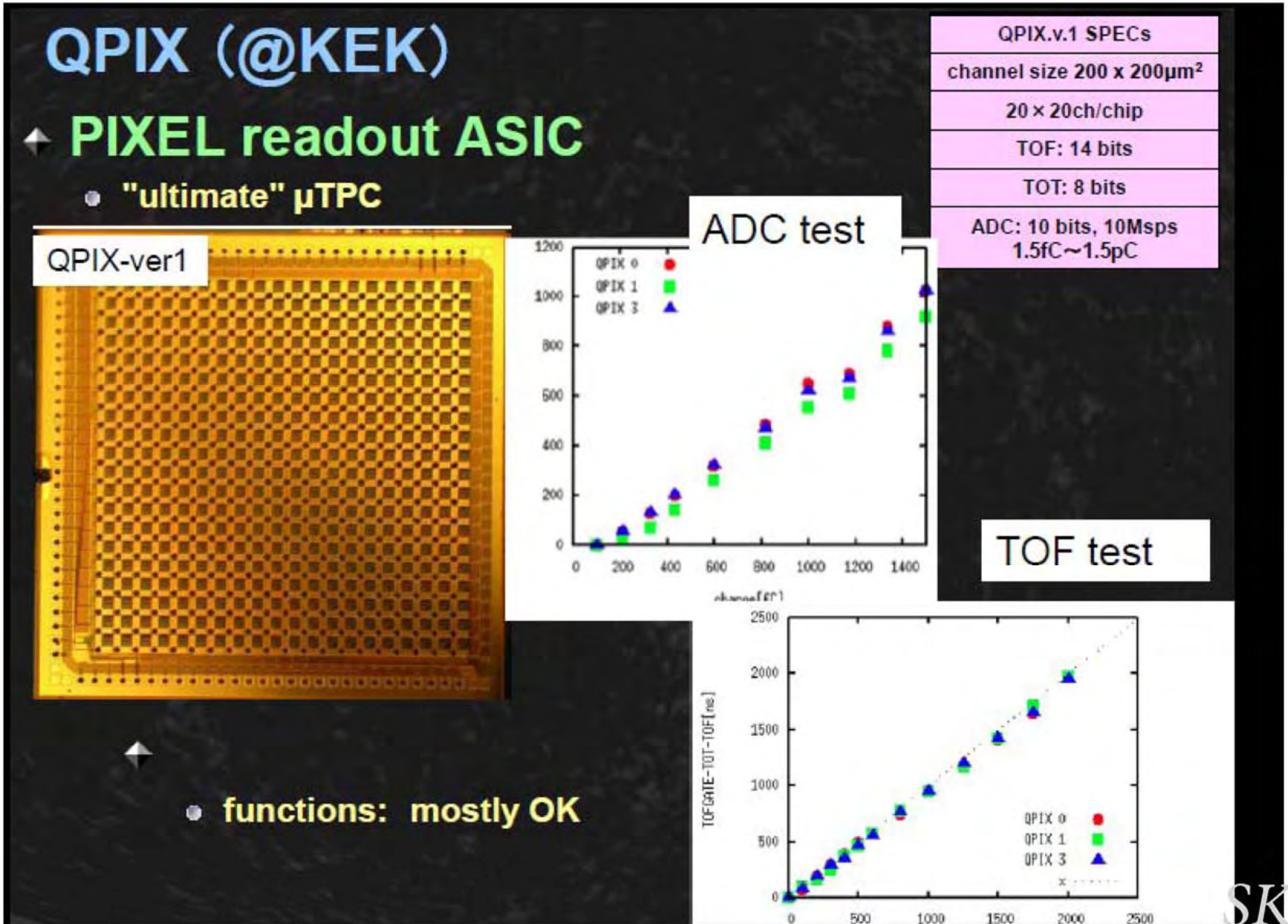
(100-400keV)

direction-sensitive upper limits

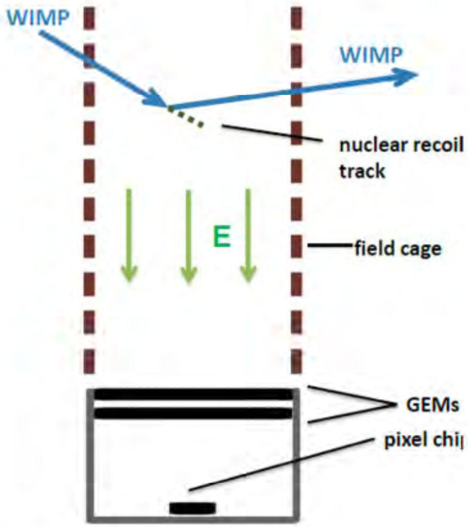


K. Miuchi June 9, 2011 CYGNUS 11

NEWAGE


QPIX (@KEK)
PIXEL readout ASIC
"ultimate" μTPC
QPIX-ver1
functions: mostly OK
QPIX.v.1 SPECs
channel size 200 x 200μm²
20 × 20ch/chip
TOF: 14 bits
TOT: 8 bits
ADC: 10 bits, 10Msps
1.5fC~1.5pC
ADC test
QPIX 0
QPIX 1
QPIX 3
0
200
400
600
800
1000
1200
1400
TOF test
TOFGATE-TOT-TOF[ns]
500
1000
1500
2000
2500
x

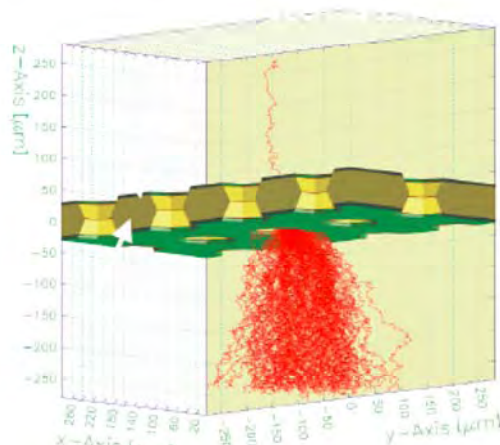
The Directional Dark Matter Detector (D3)

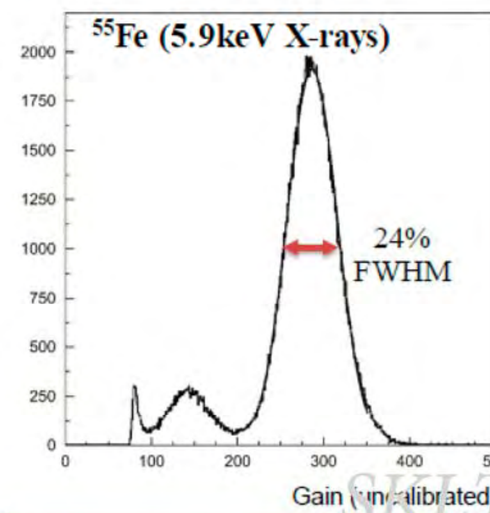


Amplification: Gas Electron Multipliers (GEMs)

- Off-the shelf GEMs from CERN
  - 5cm x 5cm x 60 µm
  - Hole spacing: 140 µm
- Electrons multiplied by avalanching
- ~100% area efficiency

- Reliable without sparking with single-GEM gain up to 300 (Ar/CO_2)
- Two GEMS in series: higher gain with less risk of sparking: 500V + 400V → gain = 40000





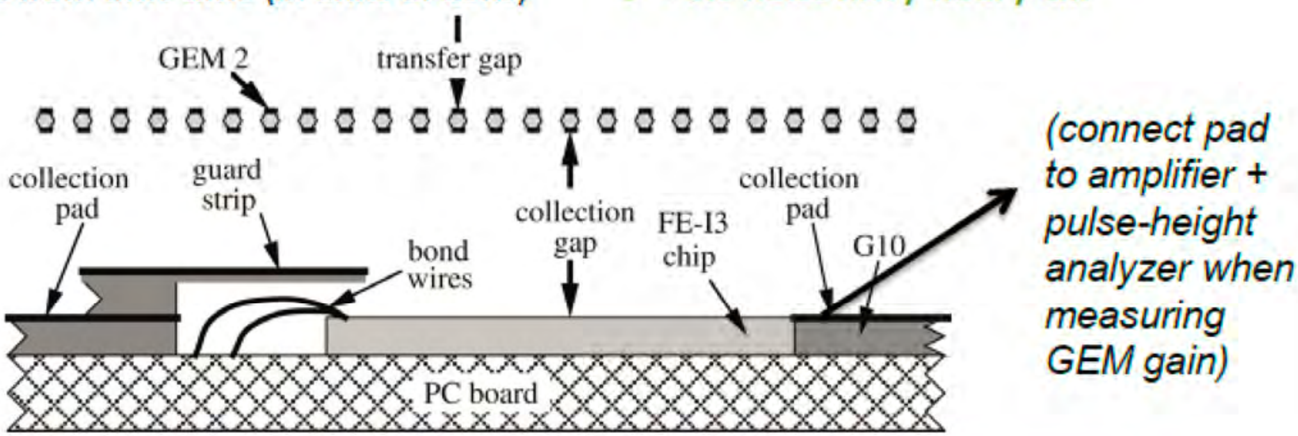
High gain, good resolution, stable, simulated and measured gain consistent

D3

Charge Collection: FE-I3 Pixel Chip

- Same Front End Chip as used in ATLAS Pixel Detector, but Gold/Aluminum plated
- Developed at LBNL, over ~7 years
- 2880 pixels of 50x400 μm. Each pixel
  - tunable, analog amplifier w/ digital controls, digital output logic
  - measures position, arrival time and amount of incident charge
- x/y from pixel coordinate
- Relative z from drift-time (in units of 25ns)

- Same DAQ chain as during ATLAS pixel detector production
- Pixel chip in self-trigger mode
- Read out 16 time bins after trigger
  - 16x 25ns*26 μm/ns = 10.4 mm (Ar/CO_2, 1kV/cm)
- **Very low noise: ~120 electrons**
- **2-3 pixels out of 2880 masked**
  → < 0.5 noise hits / hour / cm²



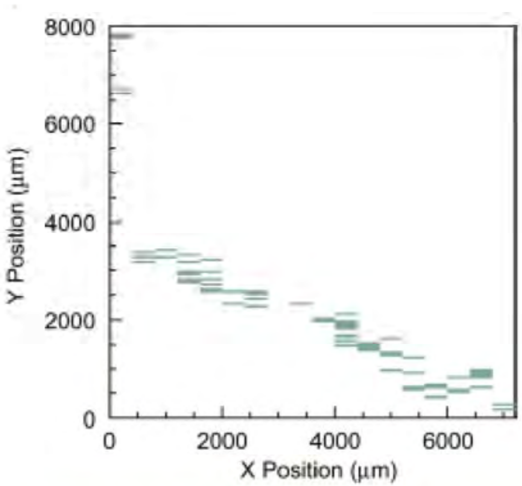
low noise level, compared to expected single-electron signal
low demand on downstream DAQ electronics when used for DM detection

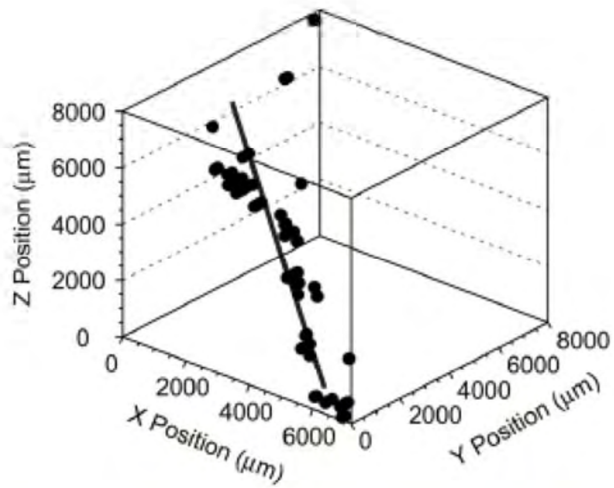
D3

Position Resolution with Cosmic Rays

- Large sample of cosmic rays
- Require >10 pixel hits
- 3D track at least 4.5mm long
- GEM Gain=9000, pixel threshold=1800e-

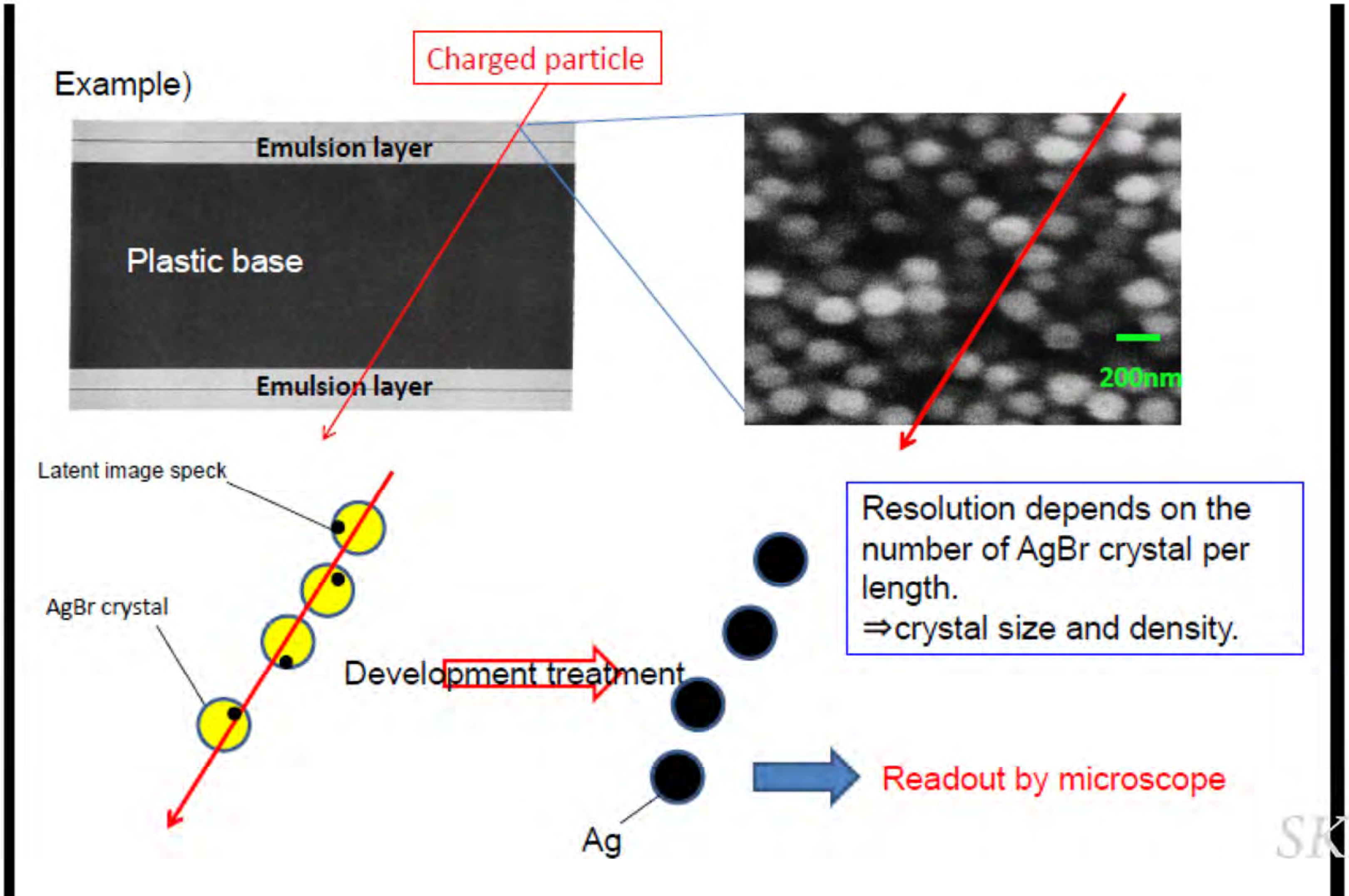
	track fit residual	Diffusion	$\sigma_{GEM+Pixel}$
σ_X (μm)	170	110	130
σ_Y (μm)	130	110	70
σ_Z (μm)	240	190	150





Unfolding diffusion, estimate single hit position resolution to 70 μm
(At collider detectors, would use magnet to keep diffusion < 100 μm.)

Nuclear Emulsion



Nuclear Emulsion

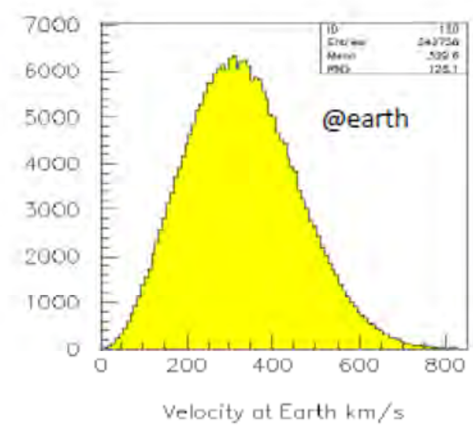
Requirement of resolution

Track length

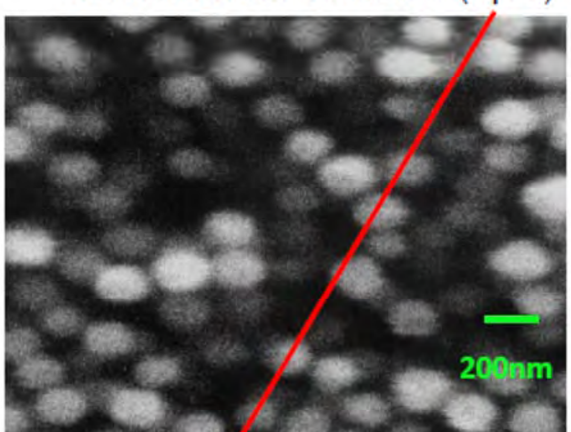
Maximum DM velocity<800km/sec

Recoil energy : 10-100keV order

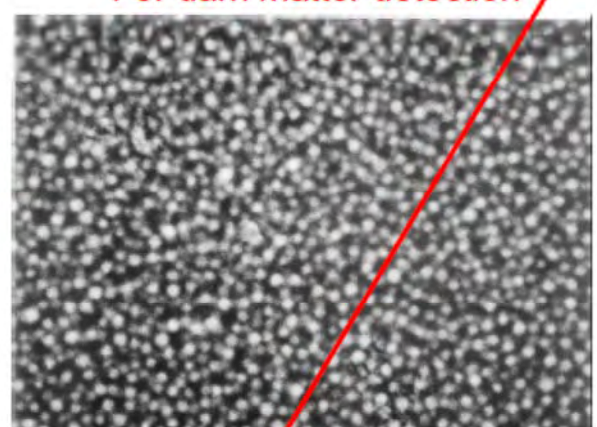
Track length < ~400nm



Usual nuclear emulsion (>μm)



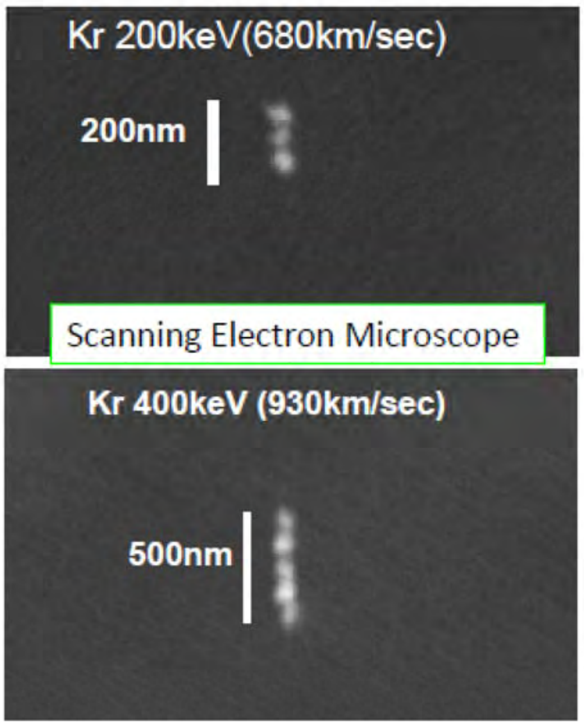
For dark matter detection

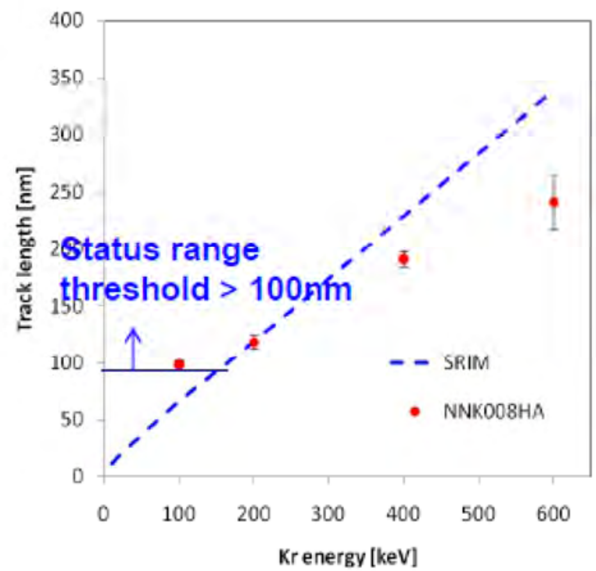


Until now, Fuji Film developed and produced

Nuclear Emulsion

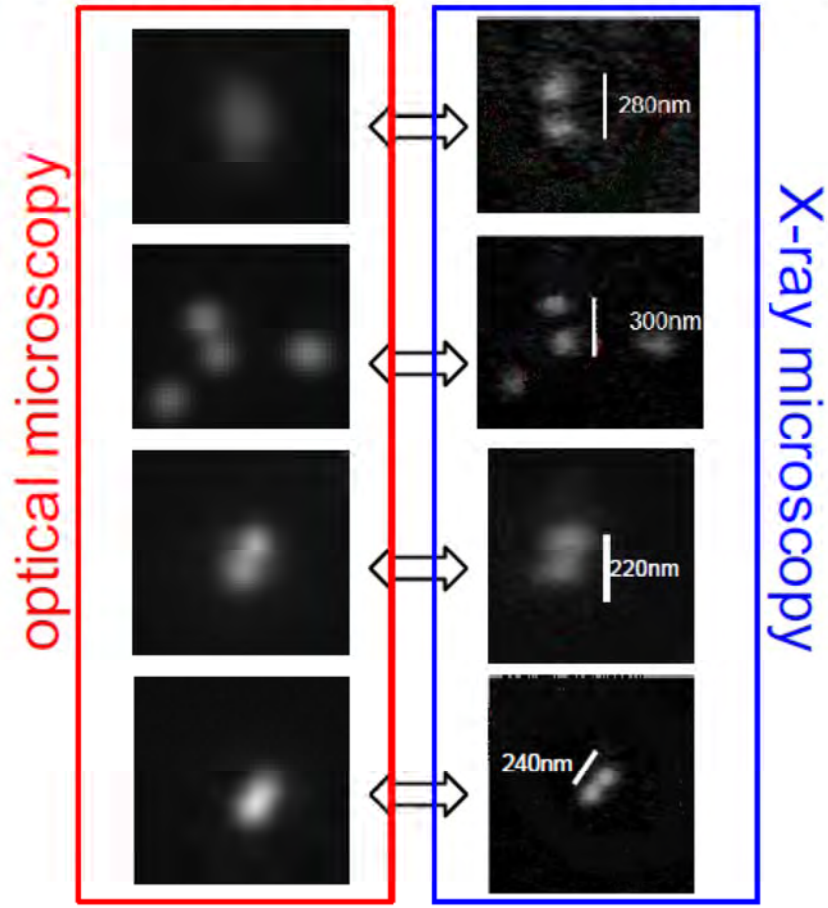
Checking of submicron track detection using low velocity Kr ions





Nuclear Emulsion

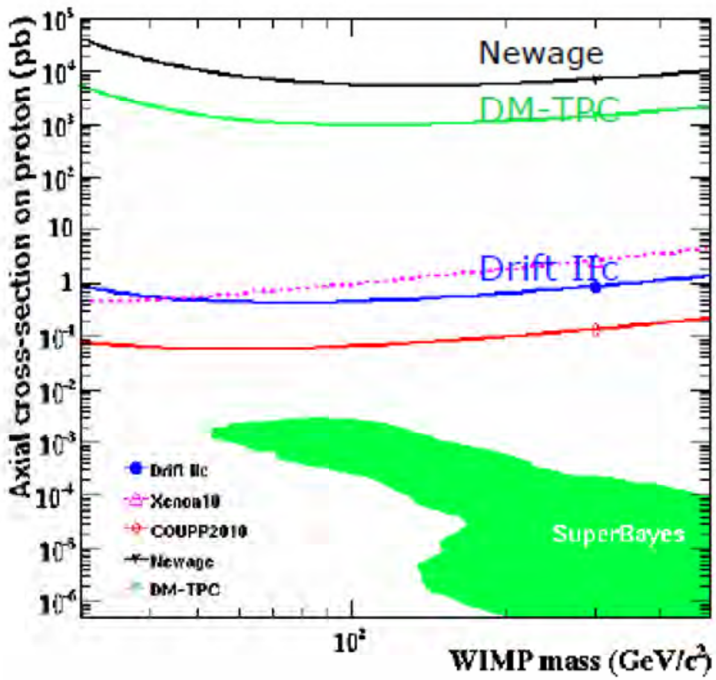
Matching of neutron recoil tracks between optical and X-ray microscopy



SKLTP

Table 1. Summary of existing directional dark matter detection experiments. TPC stands for Time Projection Chamber, NITPC stands for negative-ion TPC, and SI and SD refer to spin-independent and spin-dependent WIMP-nucleon interactions. The column labeled "head-tail" specifies whether the experiment has successfully demonstrated head-tail sensitivity. The last column lists the active volume for each experiment.

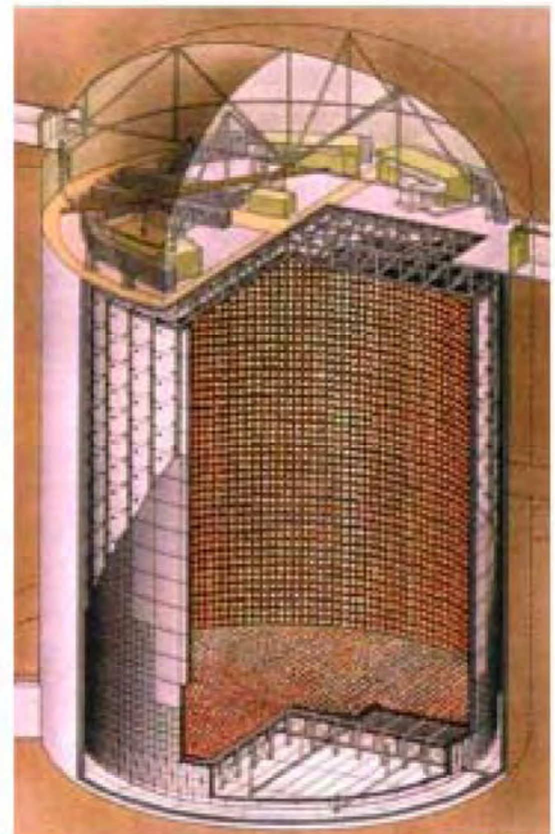
Collaboration	Technology	Target	Interactions	Head-tail	Readout	V (m^3)
DRIFT	NITPC	CS_2, CS_2-CF_4	SI/SD	yes	MWPC 2D + timing	1
DMTPC	TPC	CF_4	SI/SD	yes	Optical (CCD) 2D	0.01
NEWAGE	TPC	CF_4	SI/SD	no	μPIC 2D + timing	0.03
MIMAC	TPC	^{3}He/CF_4	SI/SD	yes	Micromegas 2D + timing	0.00013
Emulsions	emulsions	AgBr	SI/SD	no	Microscope 3D	N/A
D3	TPC	CF4	SI/SD		GEM	



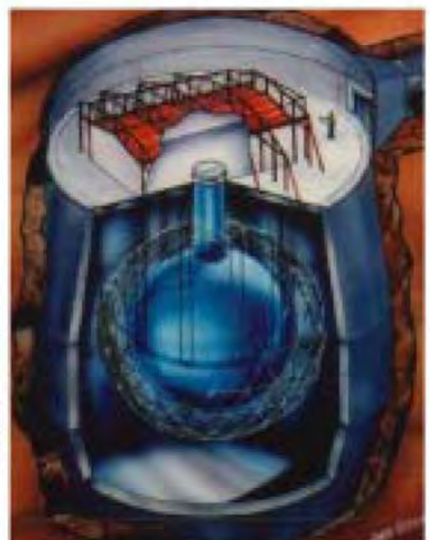
1吨气体探测器很大吗？

--- “这个可以大”
--- “这个真不大”
而且几十公斤•年就可得到显著成果

Super-K
40 x 40 x 40 m³

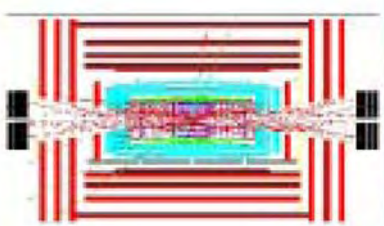


SNO
21 x 21 x 34 m³



DMTPC
16 x 16 x 16 m³

CMS
15 x 15 x 22 m³



1吨气体探测器很贵吗？

CYGNUS2009 white paper:

- 1ton方向探测器， 需$150M
- DAQ and readout is likely to be a (or the) major cost driver.
  - a 1 ton target at 40 Torr and 2 mm resolution would require 10^7 readout channels for a charge readout concept, each requiring fast ADC output. Allowing for increased pressure and better position resolution could see this rise to 10^9 channels per ton.
  - The CCD option would require of order 10,000 CCD cameras per ton plus associated optics
- 目前阶段，几十公斤探测器就可得到较好的物理结果，这需要几个M $

Miniworkshop in Tsinghua

Mini-workshop on directional DM detectors

Nov. 15-16, 2011

清华大学理科楼 B-406 房间

主席Charling Tao

MIMAC people + Tsinghua , IHEP, SJTU, USTC等

晶体：仍有可能

Anisotropic crystal scintillators

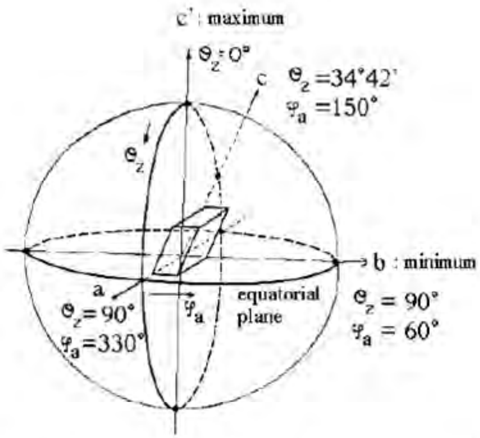


Fig. 2. A schematic representation of the crystal axes of anthracene. The *quenching factor* is maximal in the direction of the c'-axis, which is perpendicular to the *ab* plane [8]

- light response of Anisotropic crystal scintillators to particles (p, α, recoil nuclei, · · ·) depends on their impinging direction with respect to the crystal axes.
- For example: organic crystal

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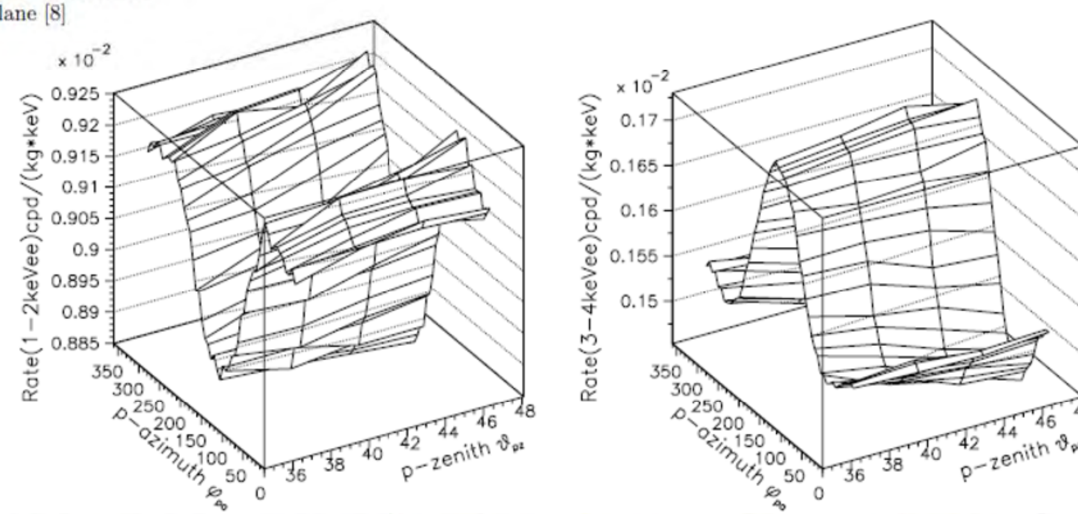

Fig. 5. Example of the expected rate, in the 1–2 keV and 3–4 keV energy windows, versus the detector's (or Earth's) possible velocity directions. As in Fig. 4, this example refers to the particular case of a WIMP mass assumed to be equal to 50 GeV, a WIMP–proton cross section assumed to be equal to $3 \cdot 10^{-6}$ pb and a model framework assumed to be as given in the text. As previously explained, there is a strong dependence on the "polar-azimuth" (ϕ_{pa}) that induces a diurnal variation of the rate

Questions as summary

- Which targets are more efficient ? Heavy or light, SI or SD?
- How to reach low energy threshold?

highlight: MIMAC已经降到1.5keVr(He4)-5keVr(F19)

- How to reach low background?
- How to increase target density?
- How to combine the new technologies?

暗物质直接探测:新型弱信号探测器的试验场

→aim: best S/N ratio