DM-TPC: a new approach to directional detection of Dark Matter

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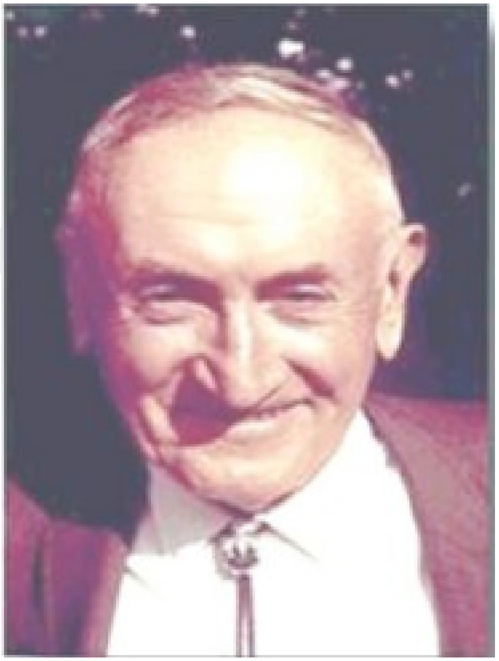
Outline:

- Introduction to Dark Matter
- Why directional detection of DM
- DM-TPC: detector concept
- Recent results: first evidence of “head-tail” effect
- Next step: toward a full-scale detector
- Conclusion

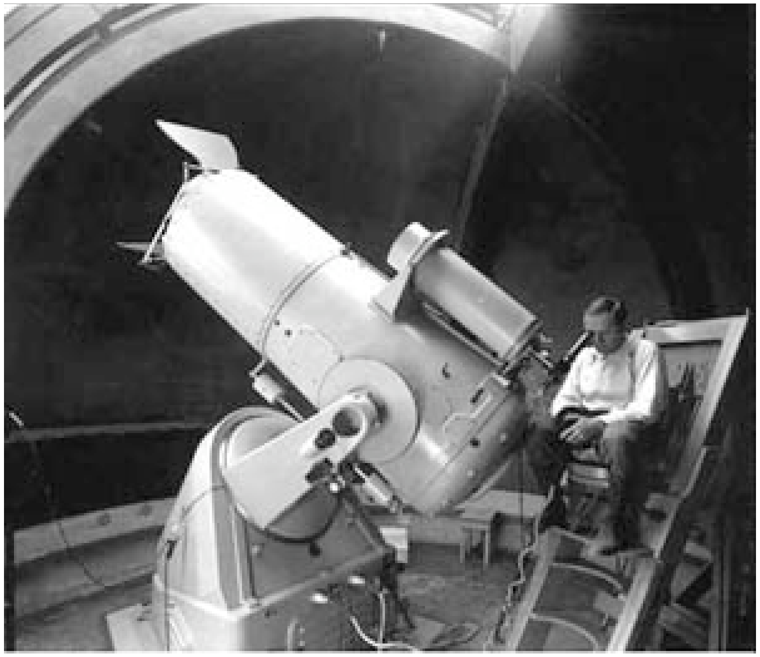
Fermilab, May 19 2008

First hints of Dark Matter



Fritz Zwicky (1933)

- Applying virial theorem to study of Coma cluster, he concluded that mass of galaxies in cluster was $O(10^2)$ what inferred from luminosity
- Explanation: substantial amount of matter not emitting light (Dark) must exist



Coma Cluster in ultraviolet and visible light from Sloan Digital Sky Survey/Spitzer Space Telescope

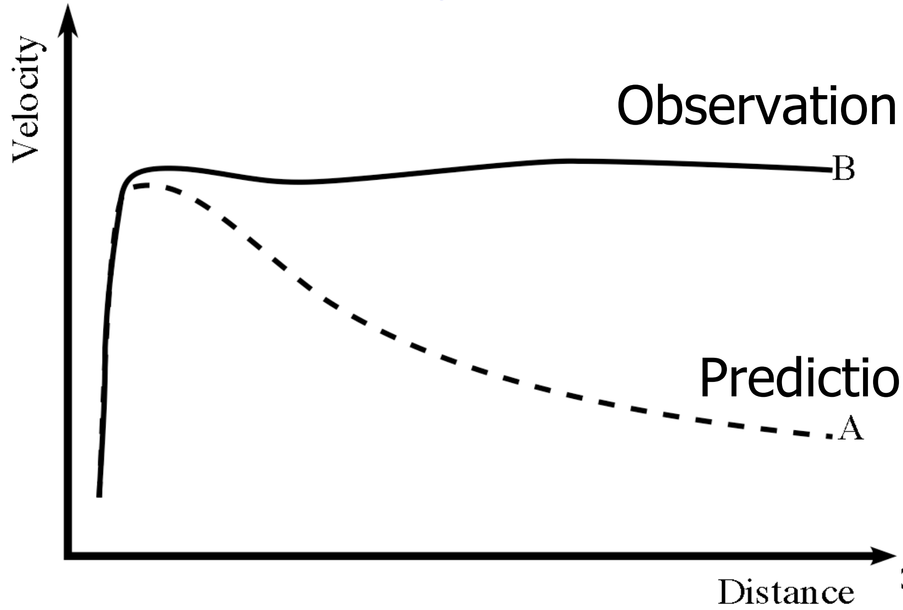
Strong evidence for DM

Vera Rubin et al. (1979)

- Study of rotational curve of spiral galaxies
  - Newtonian prediction for orbital velocity of galaxies

$$\frac{GMm}{r^2} = \frac{mv^2}{r} \Rightarrow \boxed{v \propto \frac{1}{\sqrt{r}}}$$

  - Observation: orbital velocity is flat outside central bulge
- Explanation: substantial amount of matter far from the center of the galaxy that is not emitting light (Dark Matter)



Even more convincing evidence…

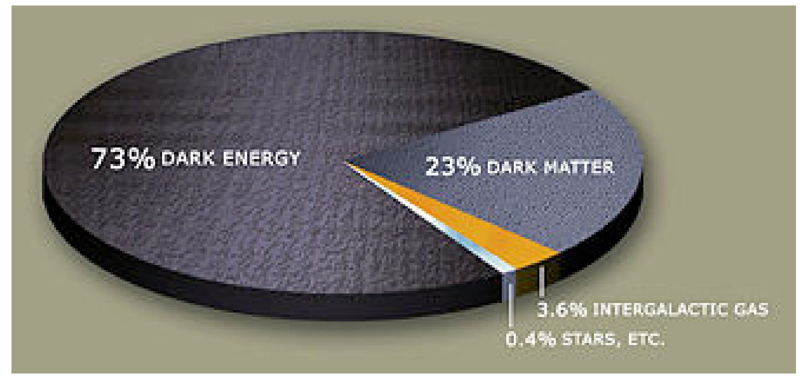
Bullet Cluster (2006)

- Two colliding clusters of galaxies
- Its components (stars, gas, and DM) behave differently during collision
  - Stars (optical) not greatly affected: small gravitational slow down
  - Hot gas (X-rays), larger mass, EM interactions: more dramatic slow down
  - DM (gravitational lensing), largest mass, <u>minimally</u> affected
- Conclusion: most of the mass in the cluster pair is in the form of weakly interacting Dark Matter

X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

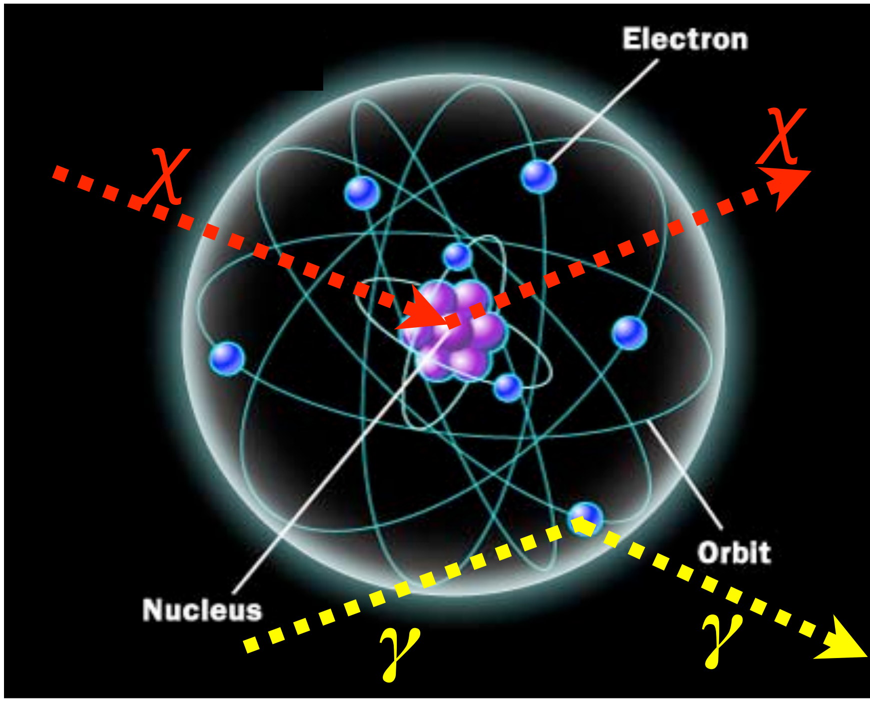
What is Dark Matter made of?

- Astronomy and cosmology tell us that Dark Matter accounts for a huge fraction of our Universe:
  - 23% of the energy
  - 82% of the mass



- What is Dark Matter?
  - Many candidates:
    - Baryonic DM (e.g.: non-luminous gas)
    - Non baryonic DM --- hot or cold
  - CMB data favor cold non-baryonic Dark Matter
    - Cold: large mass --> non-relativistic velocities
    - Non-baryonic: gravity and weak interactions --> new particle
    - Stable: maybe LSP?
- Weakly Interacting Massive Particles (WIMPs) are the most likely candidates

Direct detection of WIMPs



Signal:

$\chi \, N \rightarrow \chi \, N'$

Backgrounds:

$n \; N \rightarrow n \; N'$

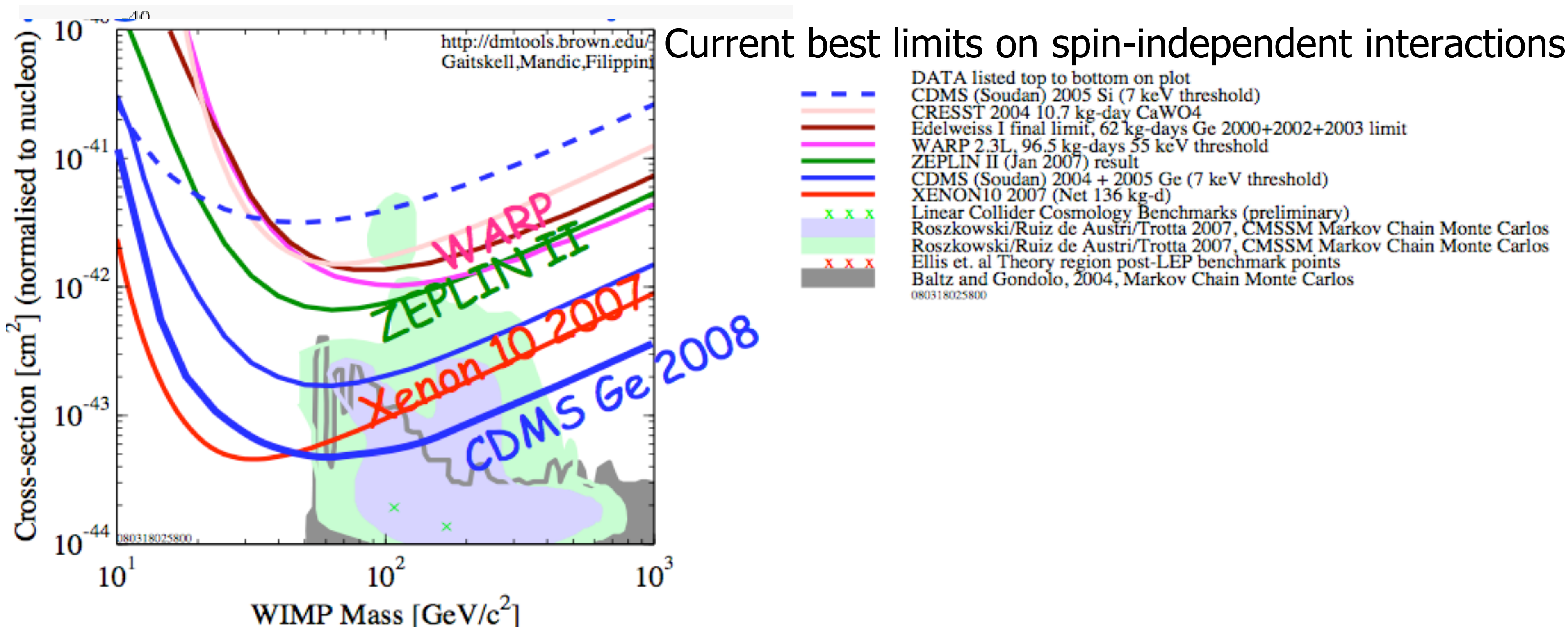
$\gamma \, e^- \rightarrow \gamma \; e^{-'}$

$N \rightarrow N' + \alpha, e^-$

$\nu \; N \rightarrow \nu \; N'$

- Basic principle: detect recoil of matter after elastic scatter with WIMP
- Different experiments use different techniques and materials
  - Ionization, scintillation, phonons
  - Si, Ge, CsI, Xe, Ar, CF_4, …
- Challenging measurements
  - Very low-energy recoils (10-100 keV), very weak interactions, many backgrounds

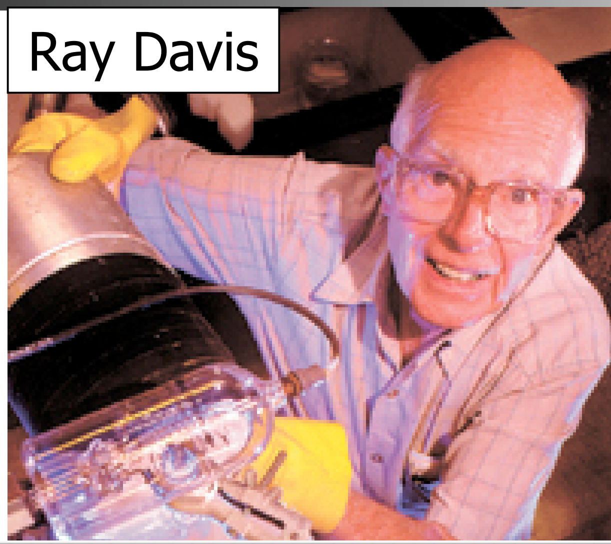
Present DM searches

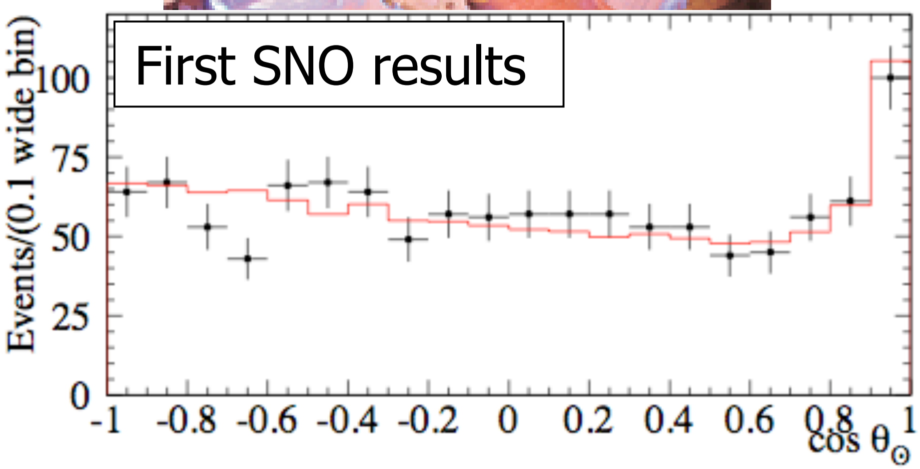


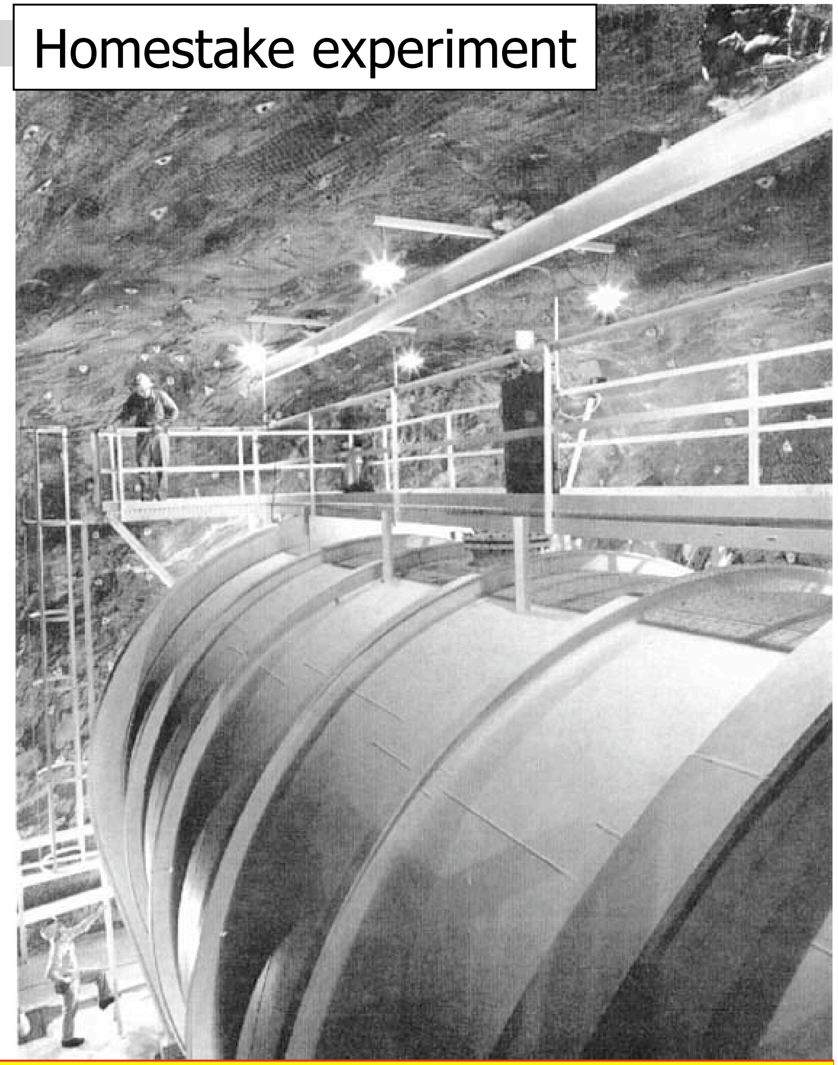
- Many experiments engaged in direct detection of DM
  - Recent progress: improved cross-section limits $\sigma_{SI} < 10^{-44}$-10^{-43} cm^2
- Intrinsic limitation of mainstream DM experiments
  - Counting experiments: zero-background assumed
  - Larger detectors will start to see several (irreducible) backgrounds

It may be very hard for a counting experiment
to provide unambiguous positive observation of Dark Matter

Situation similar to neutrino oscillations…



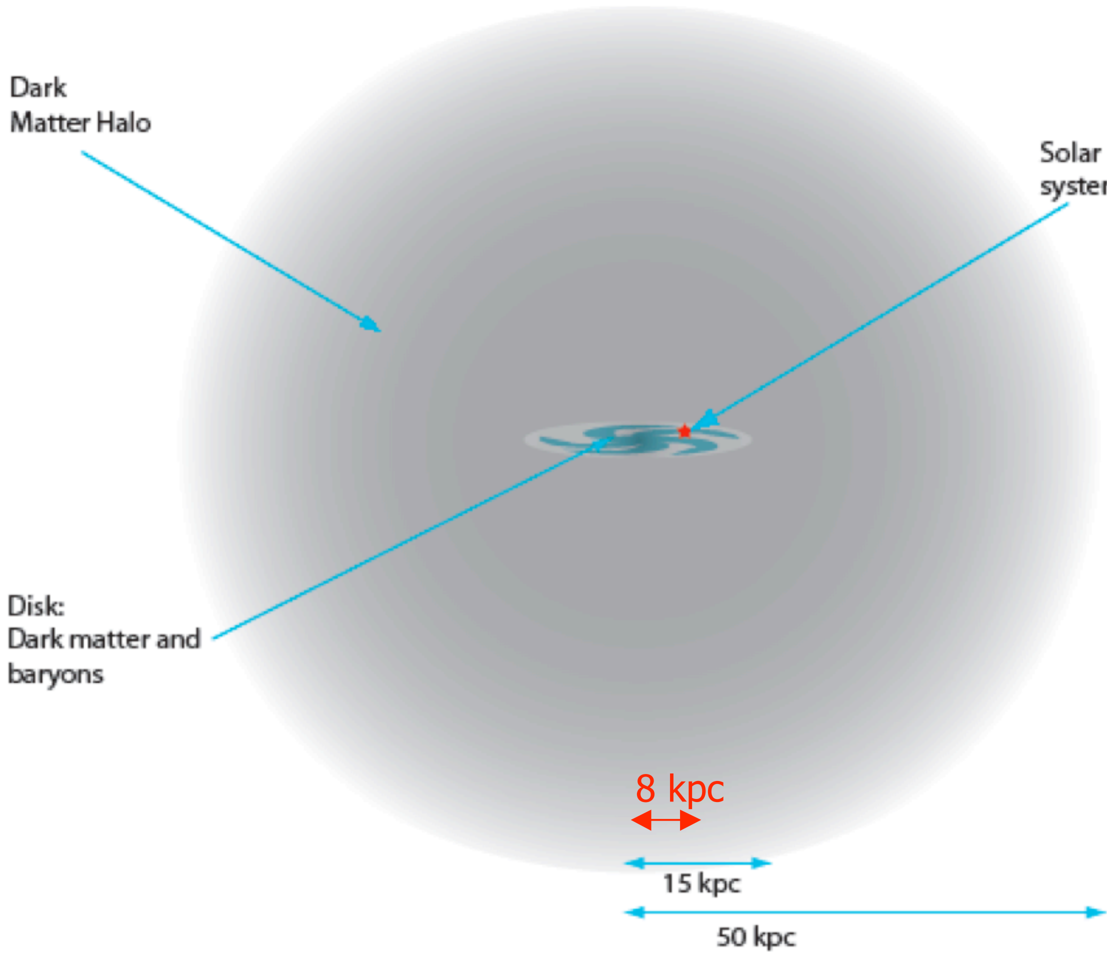




Oscillation of solar ν first observed by Davis in the 60’s in counting experiment, but decisive proof came in 2001 with water Cherenkov directional results

Dark Matter wind from Cygnus

The decisive proof of positive observation of DM requires correlation with astrophysical phenomena



A wind of Dark Matter from Cygnus

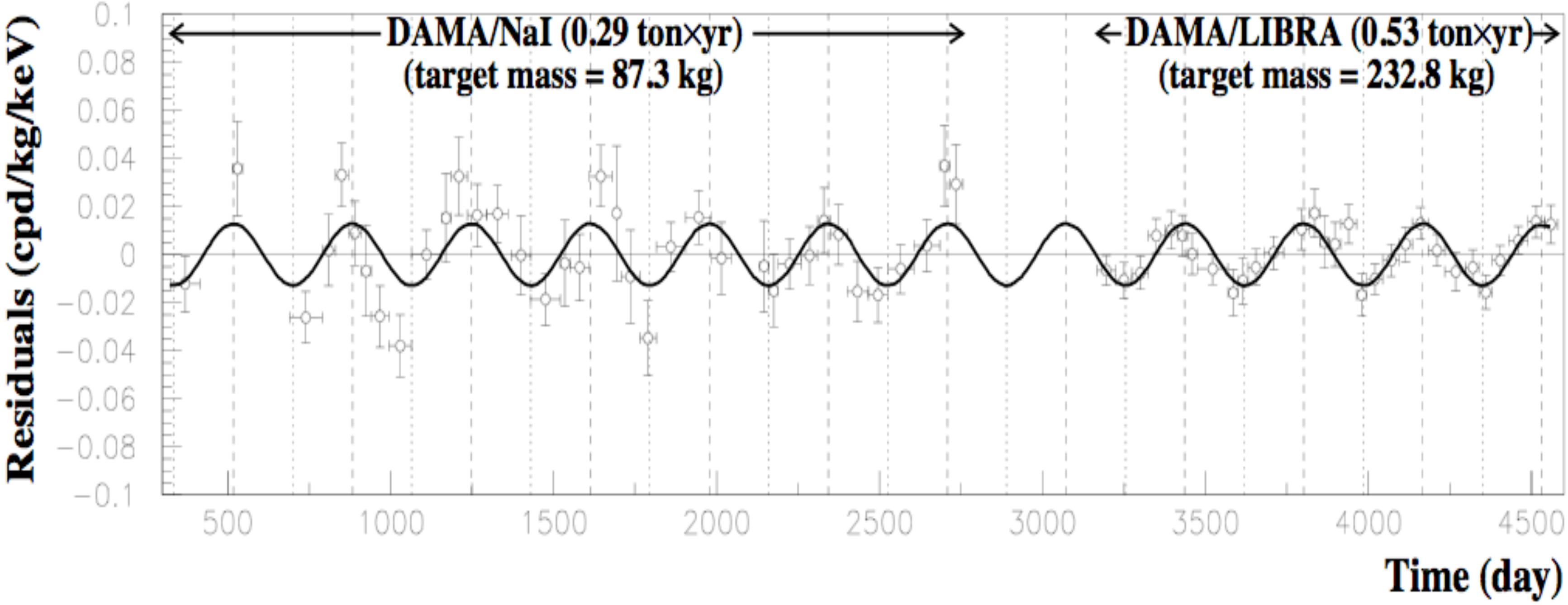
The decisive proof of positive observation of DM requires correlation with astrophysical phenomena

DM halo's reference frame

Solar system's reference frame

Dark Matter wind from Cygnus of 220 Km/s

Why not yearly asymmetry?



First observation of WIMPS??

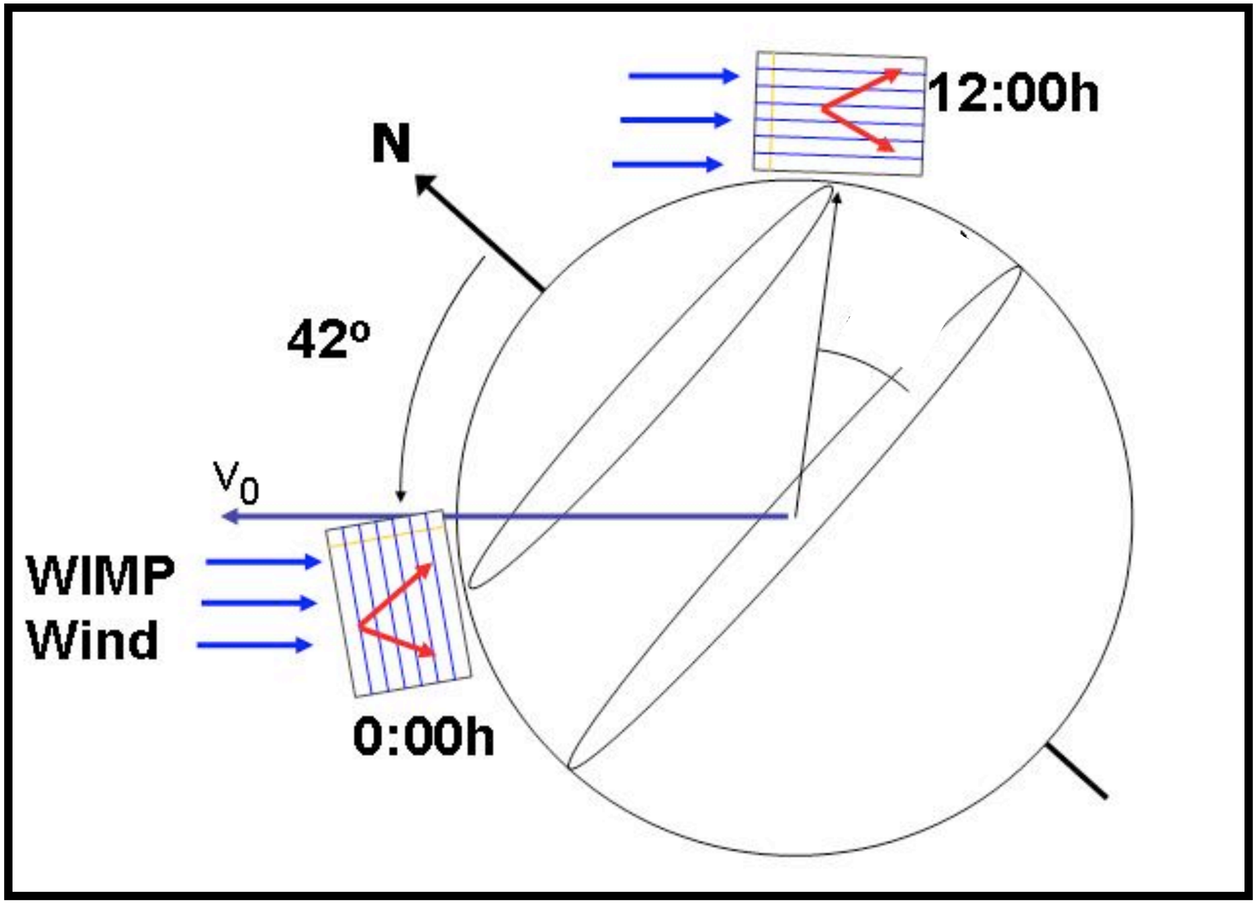
Yearly asymmetry:

- Small rate asymmetry: 2-10%
- Hard to disentangle from temperature dependent phenomena

Spergel PRD 37,1353 (1988)

Unambiguous signature of Dark Matter

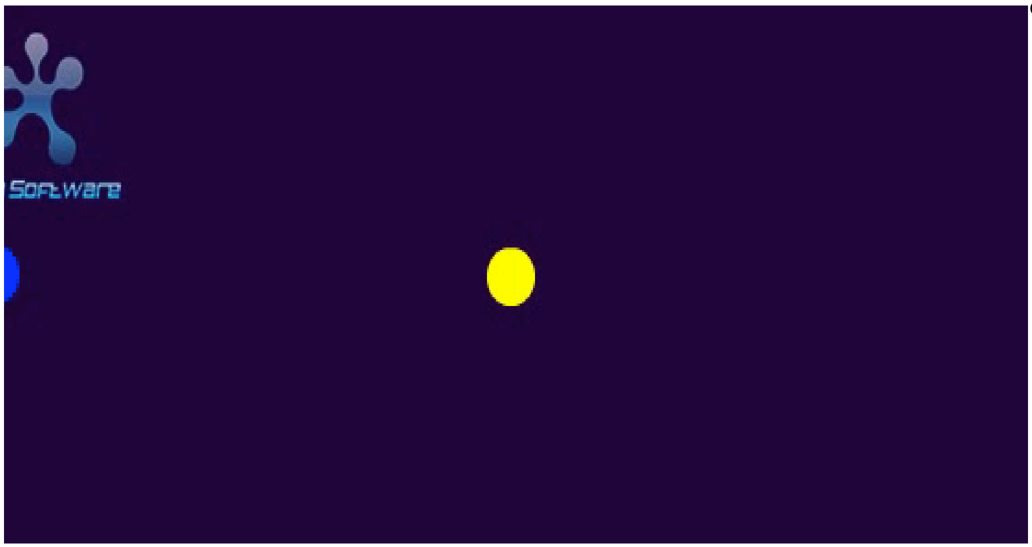
Daily asymmetry~30-100%!

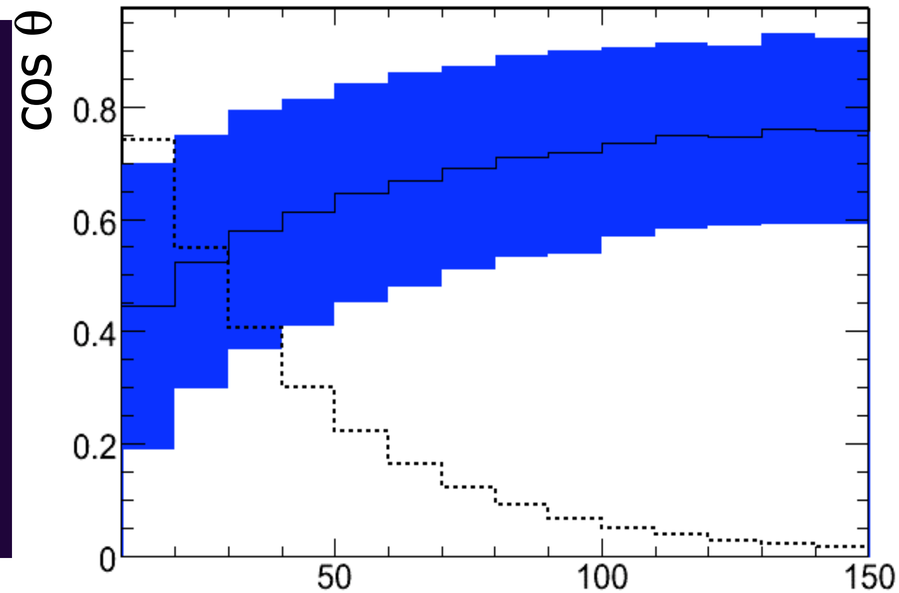


Only directional detection can correlate with Cygnus:
unambiguous positive observation of Dark Matter in presence of backgrounds

Directional Detectors

- Direction of incoming WIMP is encoded in direction of nuclear recoil



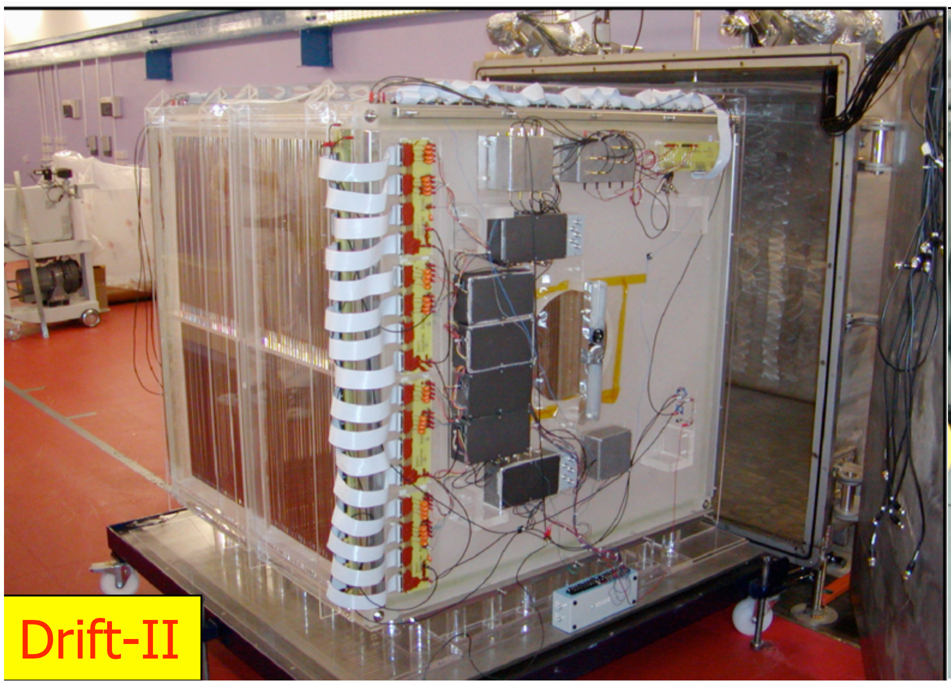


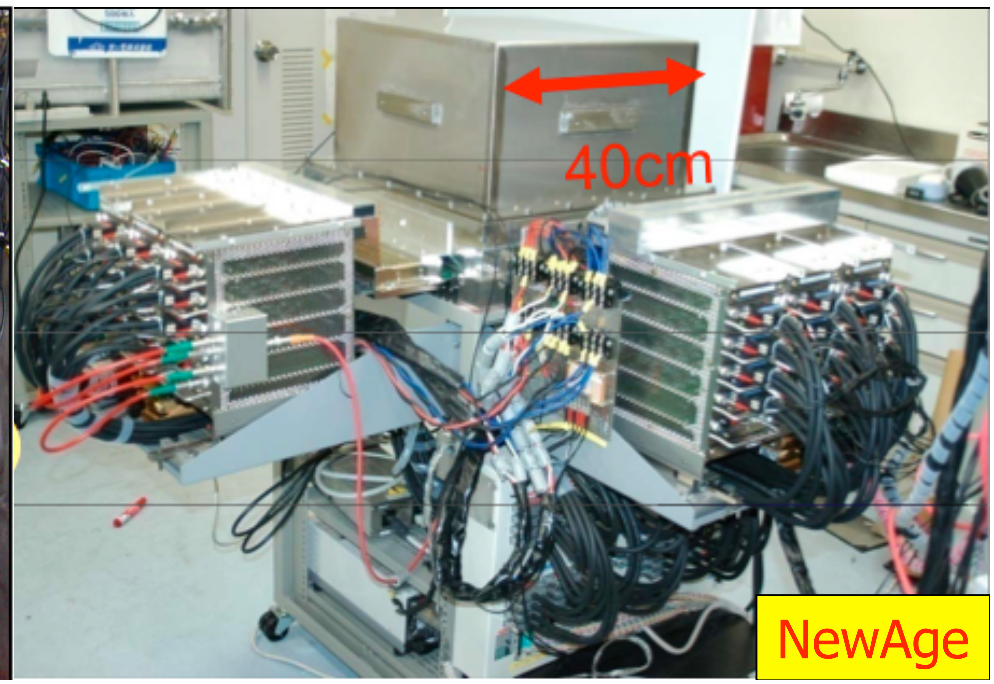
- How to detect the direction of recoils?
  - Low-pressure gaseous detectors
    - A 50 keV F in CF_4 @ 40 torr recoils ~2 mm

Other directional DM detectors

- DRIFT (Boulby, UK)
  - 1 m^3 (167 g) CS_2 low-pressure negative ion TPC
  - MWPCs for charge readout
- NewAge (Kamioka, Japan)
  - Low-pressure CF_4 TPC using μPIC readout

Limitation: $$ electronics





Spin-dependent interactions

- WIMPs can scatter elastically on nuclei via
  - Spin-independet interactions
    - cross-section scales with the mass of the nucleus squared: $\sigma \sim A^2$
  - Spin-dependent interactions
    - cross-section is nonzero only if the nucleus has a nonzero spin
- Spin-dependent interactions may be enhanced by orders of magnitude compared to spin-independent
  - E.g.: in models in which LSP has substantial Higgsino contribution

Chattopadhyay and D.P. Roy, Phys. Rev. D 68(2003) 33010
Murakami B. and J.D. Wells, Phys. Rev. D 64 (2001) 15001
Vergados, J., J. Phys. G 30 (2004) 1127

- Weaker limits for spin-dependent interactions
  - Limits on spin-independent x-section: $\sim 10^{-44}$-10^{-43} cm^2
  - Limits on spin-dependent x-section: $\sim 10^{-37}$-10^{-36} cm^2

7 orders of magnitude!

Spin-dependent searches are promising and almost unexplored

Our goal

Develop a novel detector for direct detection of Dark Matter with the following characteristics:

- Directionality
  - Unambiguous observation of DM in presence of backgrounds
  - Test DM models in our Galaxy ("DM astronomy")
- Spin-dependent interactions
  - Can be much enhanced wrt spin-independent interactions

To make this feasible we need:

- Low cost/unit volume
  - Directionality requires gaseous detectors: large volumes
- Easy to maintain
  - Very stable, safe, easy to operate underground
- Scalability
  - Modular structure

The DM-TPC Collaboration

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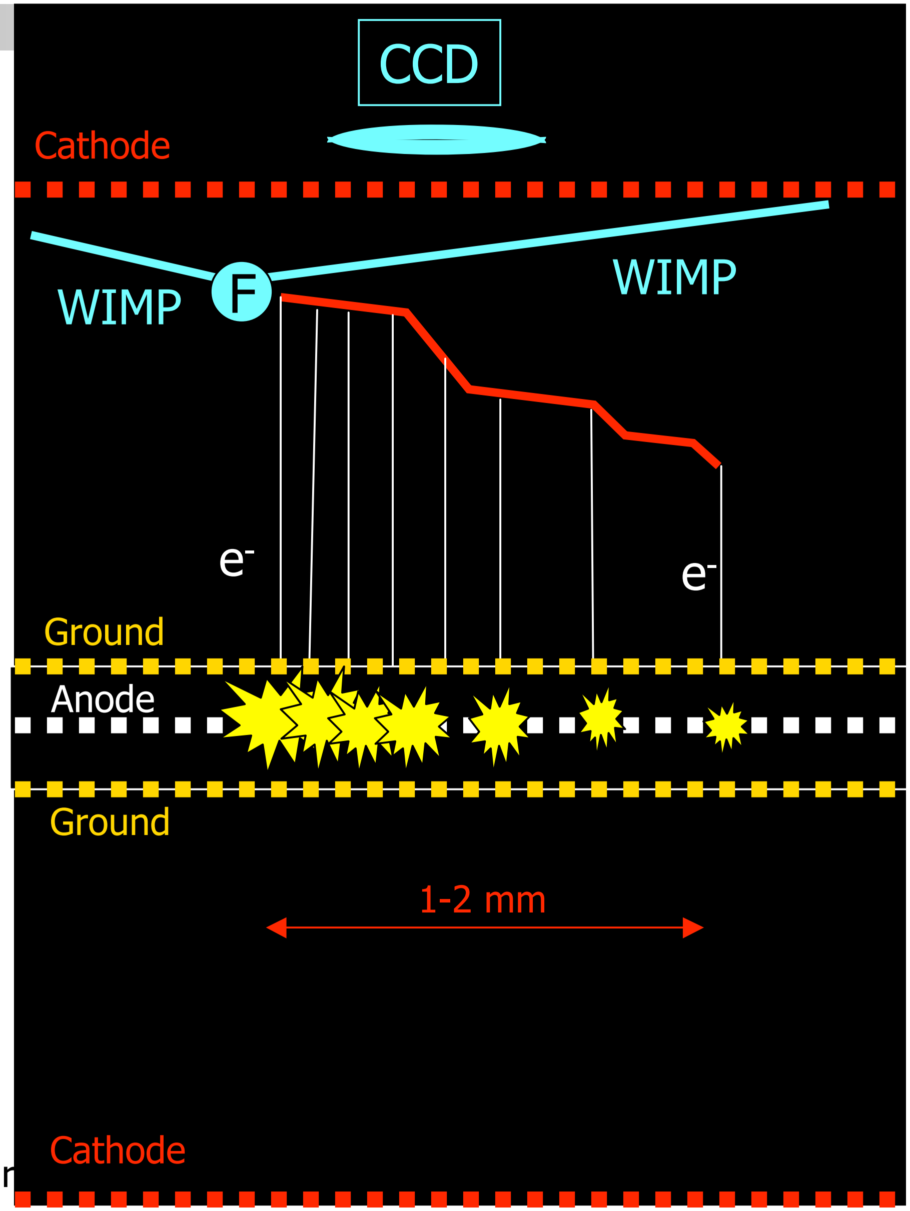
Note:
- * indicates undergraduate students
- [1] also Harvard University

DM-TPC: detector concept

- Low-pressure CF_4 TPC
  - 50-100 torr $\rightarrow$ F recoil ~1-2mm
- CF_4 is ideal gas
  - F: spin-dependent interactions
  - Good scintillation efficiency
  - Low transverse diffusion
  - Non flammable, non toxic
- CCD readout
  - Image scintillation photons produced in avalanche
    - $\#\gamma_{\text{scintillation}} \propto \# e_{\text{ionization}}$
  - Low-cost, proven technology
- Amplification region (camera) serves 2 drift regions

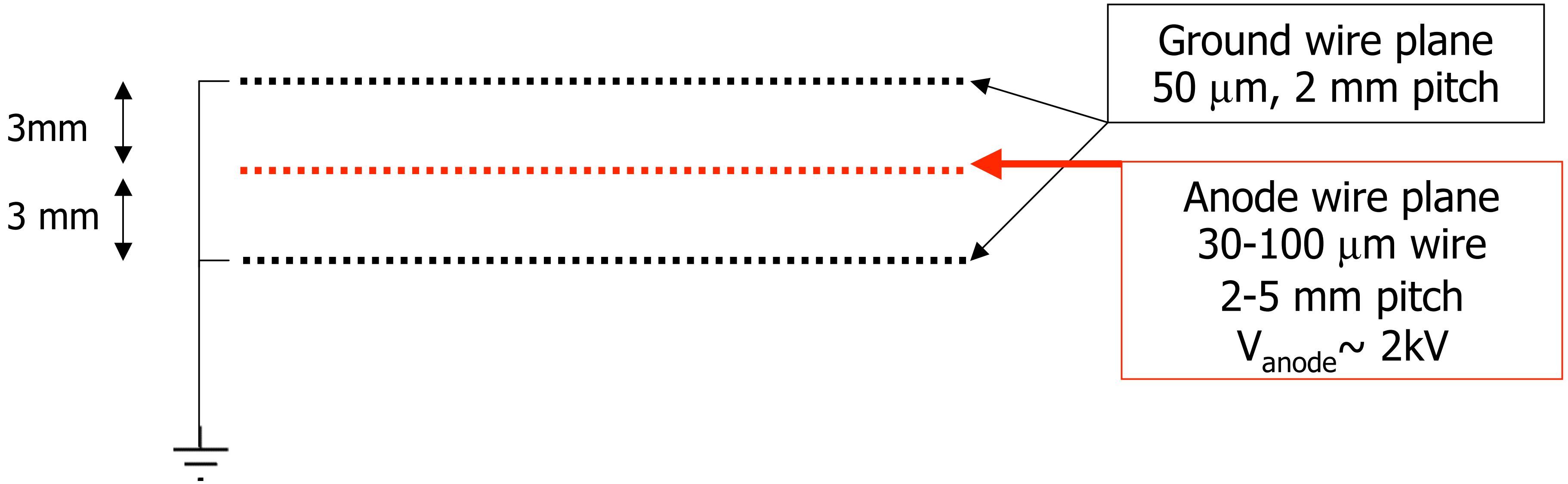


Animation by AnaMaria Piso

Detector concept

The amplification region

Original design: wire planes

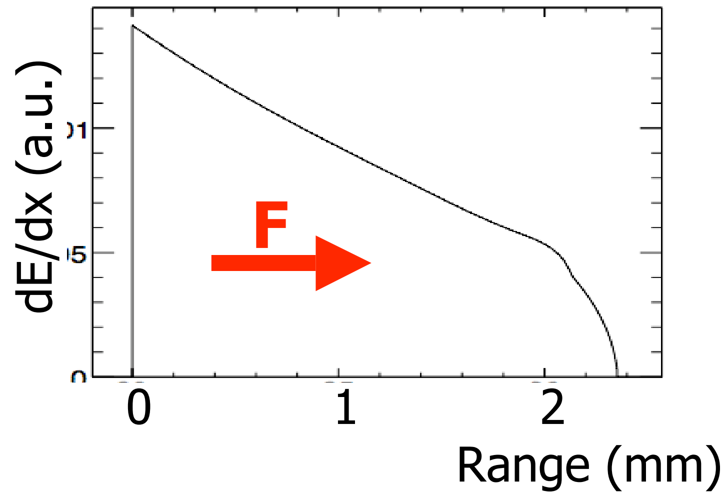


- Pros: simplicity, high gains (~10^4-10^5)

What we measure

3 fundamental measurements (in hand)

- E_{recoil} from total scintillation light
- Length of recoil
- Sense of direction (head-tail)
  - Gains an additional order of magnitude
    - A.Green, B.Morgan(astro-ph/0609115)
  - dE/dx decreases along recoil track
    - Low energy, below Bragg peak



Bragg curve for 80 keV F recoil from WIMP in CF_4

Additional features

- PMT provides length of recoil // v_{drift} and trigger

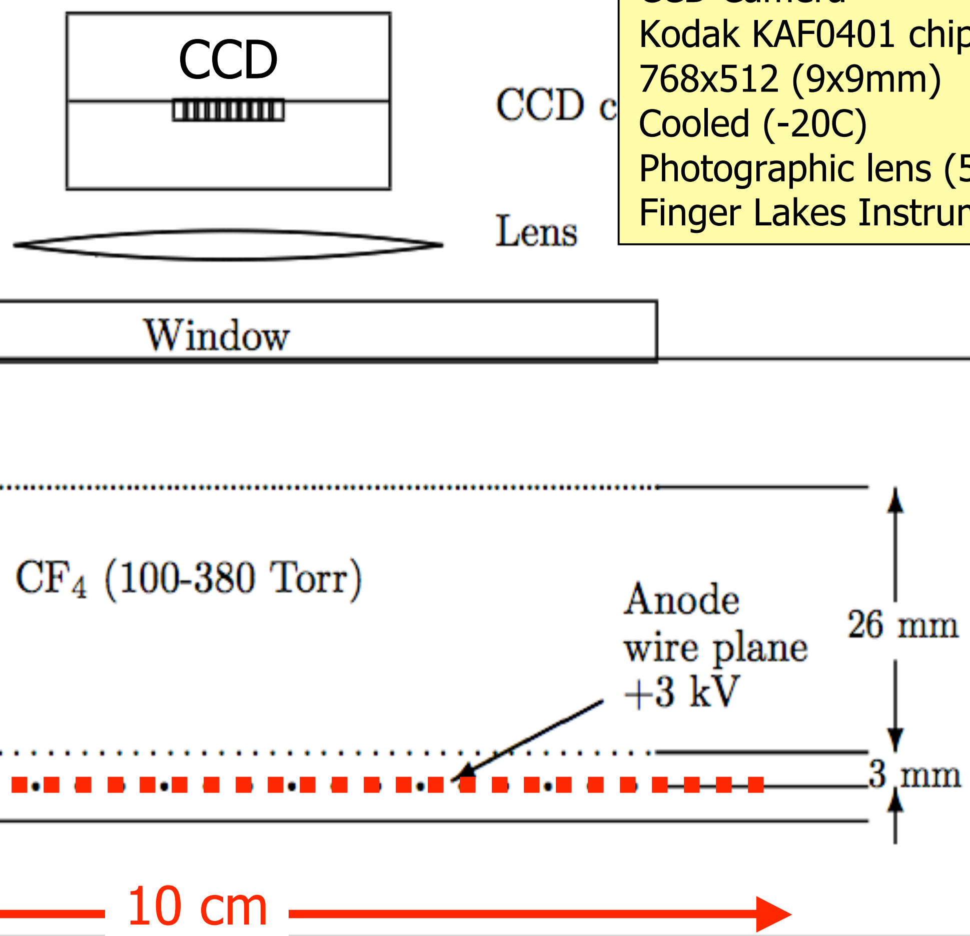
No existing experiment had demonstrated head-tail capability

- Our first goal: demonstration of head-tail

First prototype

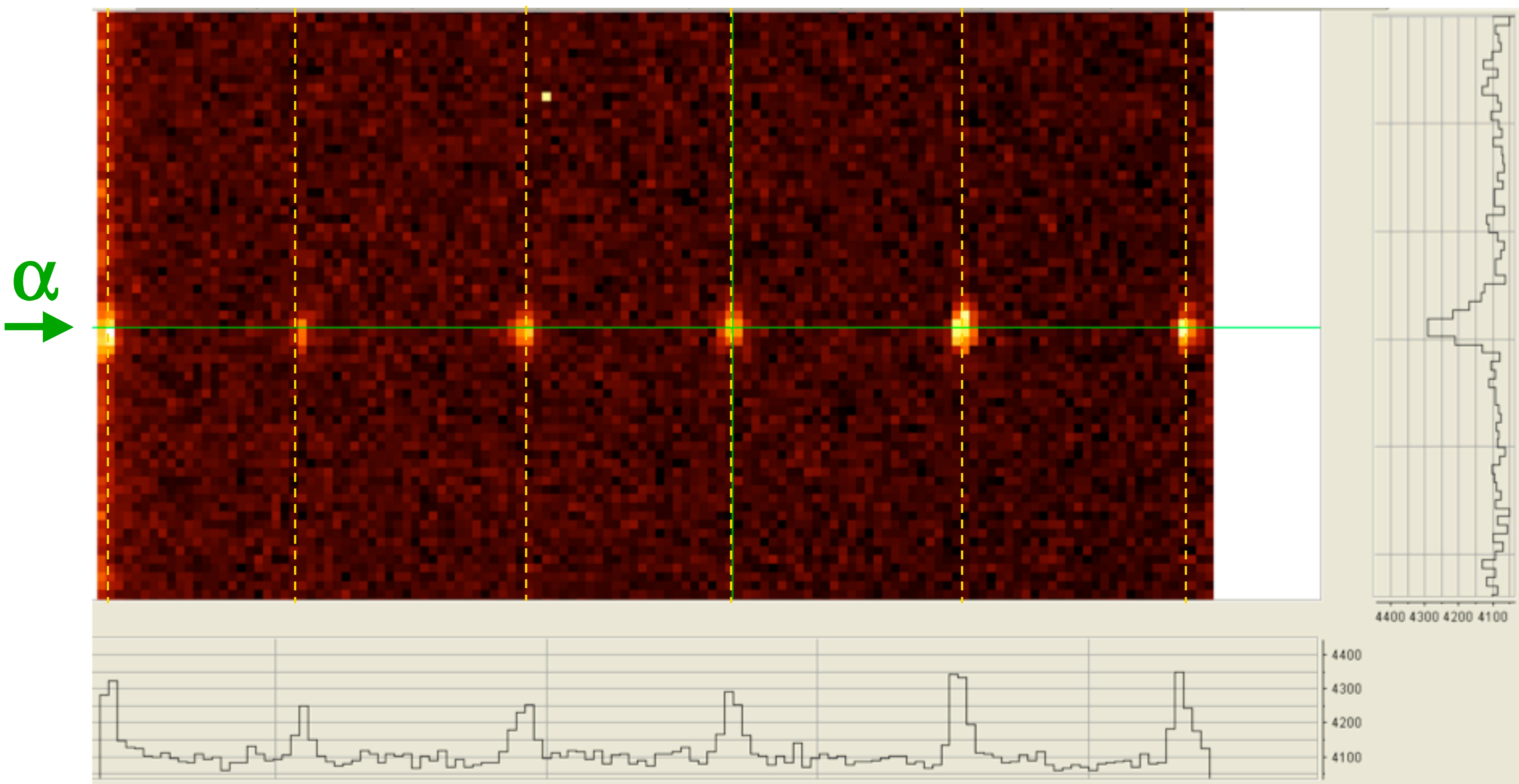
Drift distance: 2.6cm,
E=580 V/cm
Wire plane: 10x10 cm^2
Anode: 5 mm pitch, 100μm
Ground: 2 mm pitch, 50μm

CCD Camera
Kodak KAF0401 chip
768x512 (9x9mm)
Cooled (-20C)
Photographic lens (55mm)
Finger Lakes Instrumentation

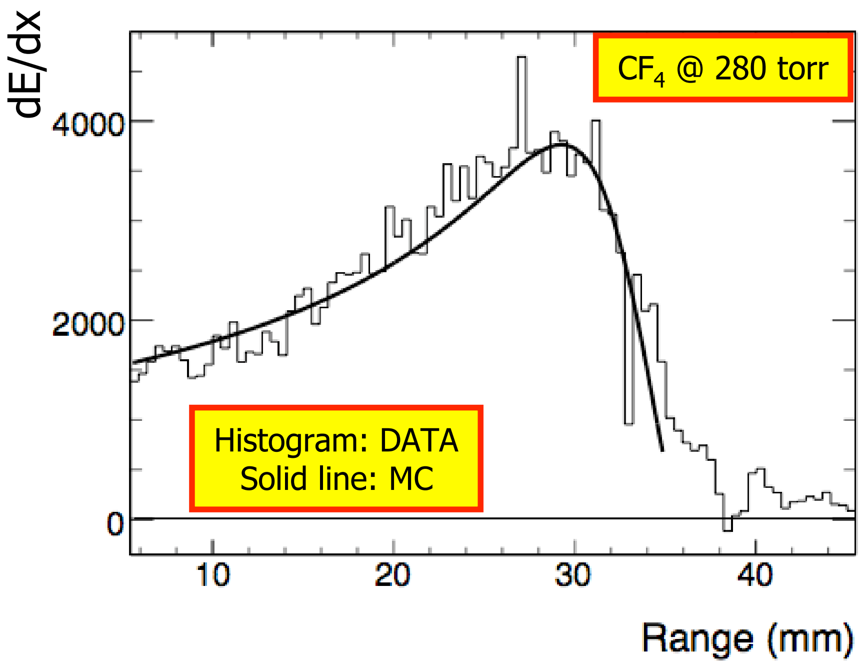


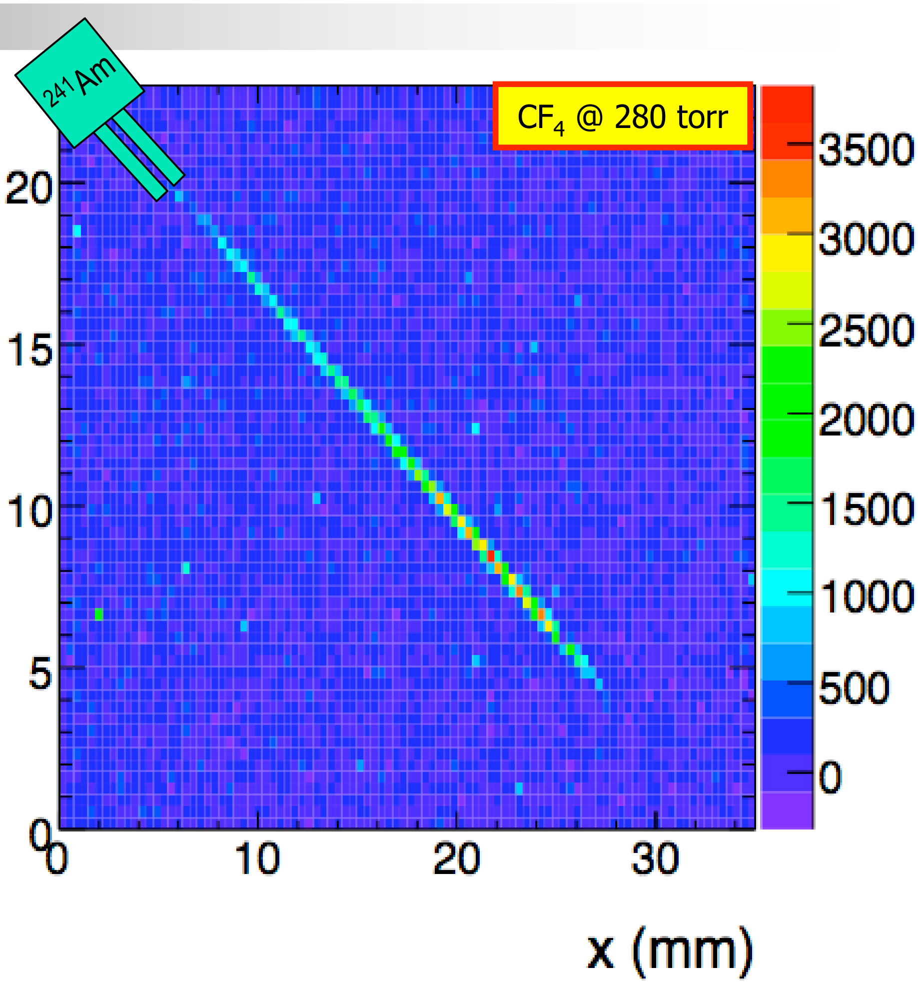
5.5 MeV alphas from ^{241}Am source

Alpha track traveling perpendicular to anode wires (vertical)



Bragg curve for 5.5 MeV alphas



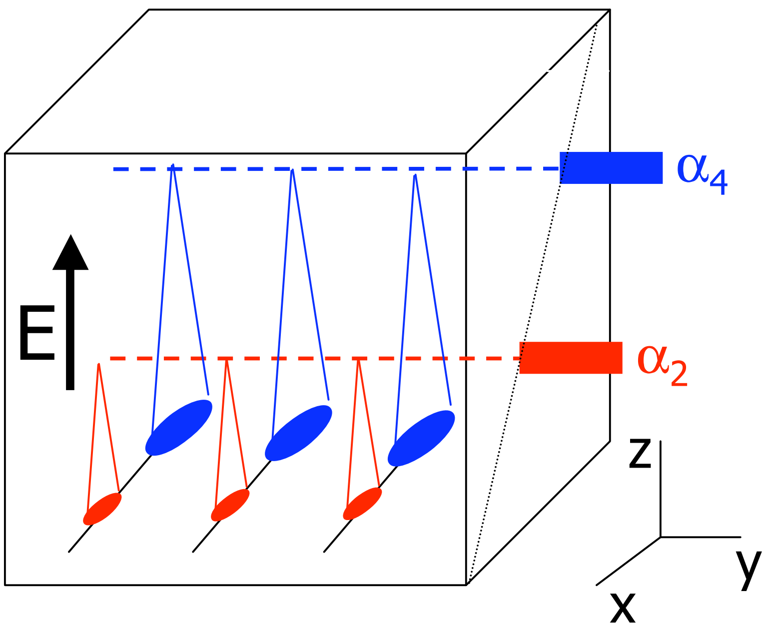


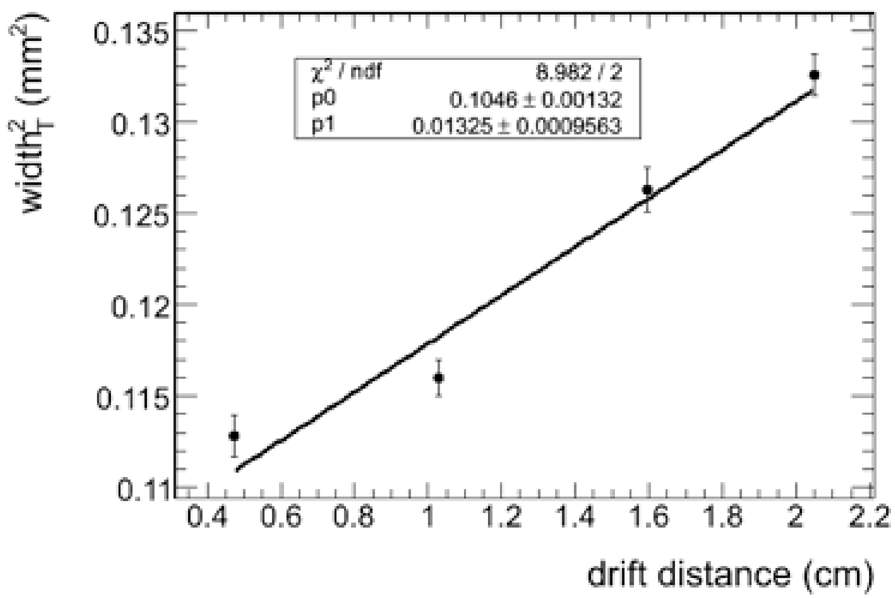
- Alphas emitted parallel to anode wires
  - Wire plane oriented at 45 degrees
- Compare measured dE/dx vs range of the track with SRIM simulation
  - Excellent DATA-MC agreement!

Well understood detector

Effect of diffusion on resolution

- Dark Matter recoils ~ 1-2 mm
  - Resolution<< 1mm; diffusion must be contained
- Resolution vs drift distance measured with 4 α sources



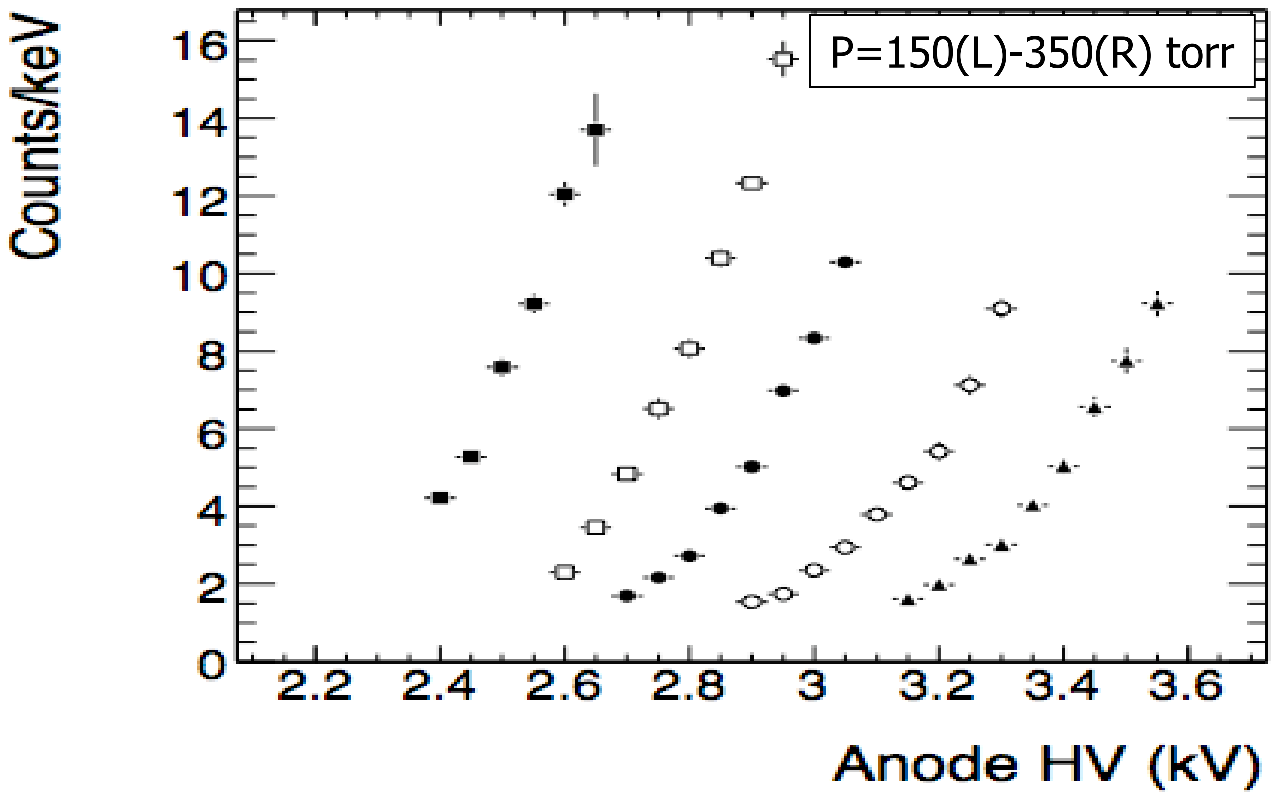


$$\sigma[\mu\text{m}] = 324 \oplus 36\sqrt{\Delta z}$$

Drift distance	Resolution
1 cm	340 μm
25 cm	670 μm

Light yield calibration with alphas

Photon yield/keV as a function of anode voltage:

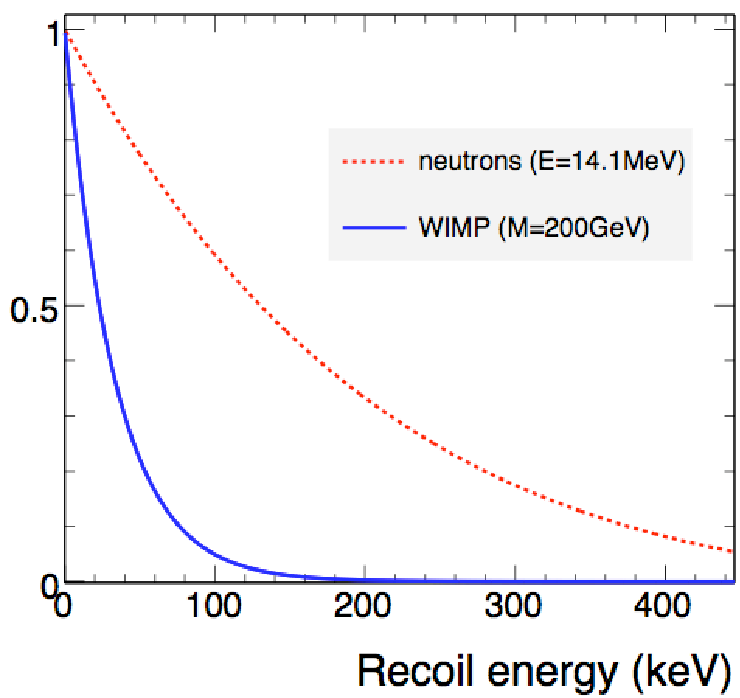


Stable operations for gas gain ~ 10^4-10^5

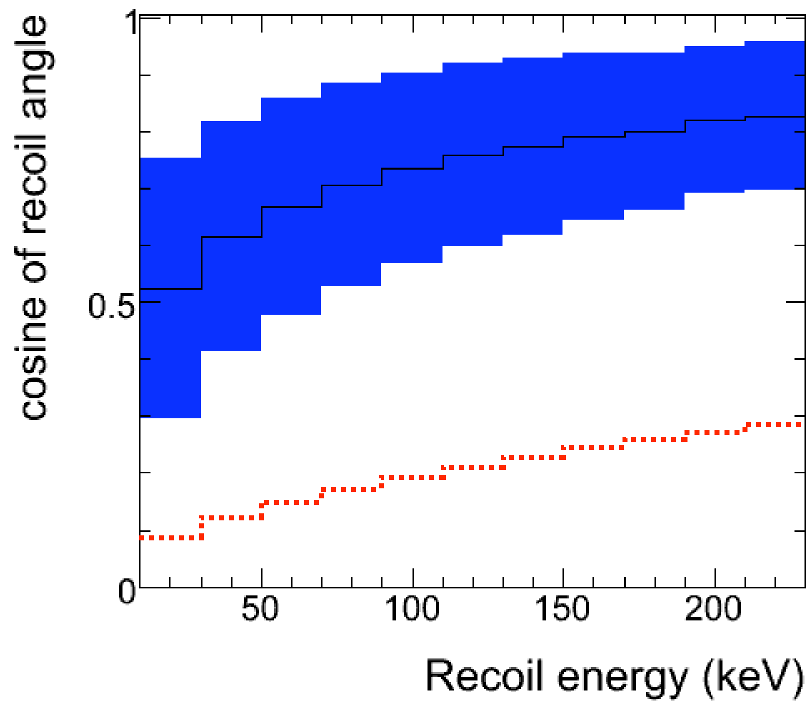
Recoils from low-energy neutrons

- Nuclear recoils by low-energy neutrons mimic Dark Matter
  - DM: F has lower energy but is better aligned with WIMP direction
- Neutron source: 14 MeV neutrons from D-T tube

Fluorine recoil energy

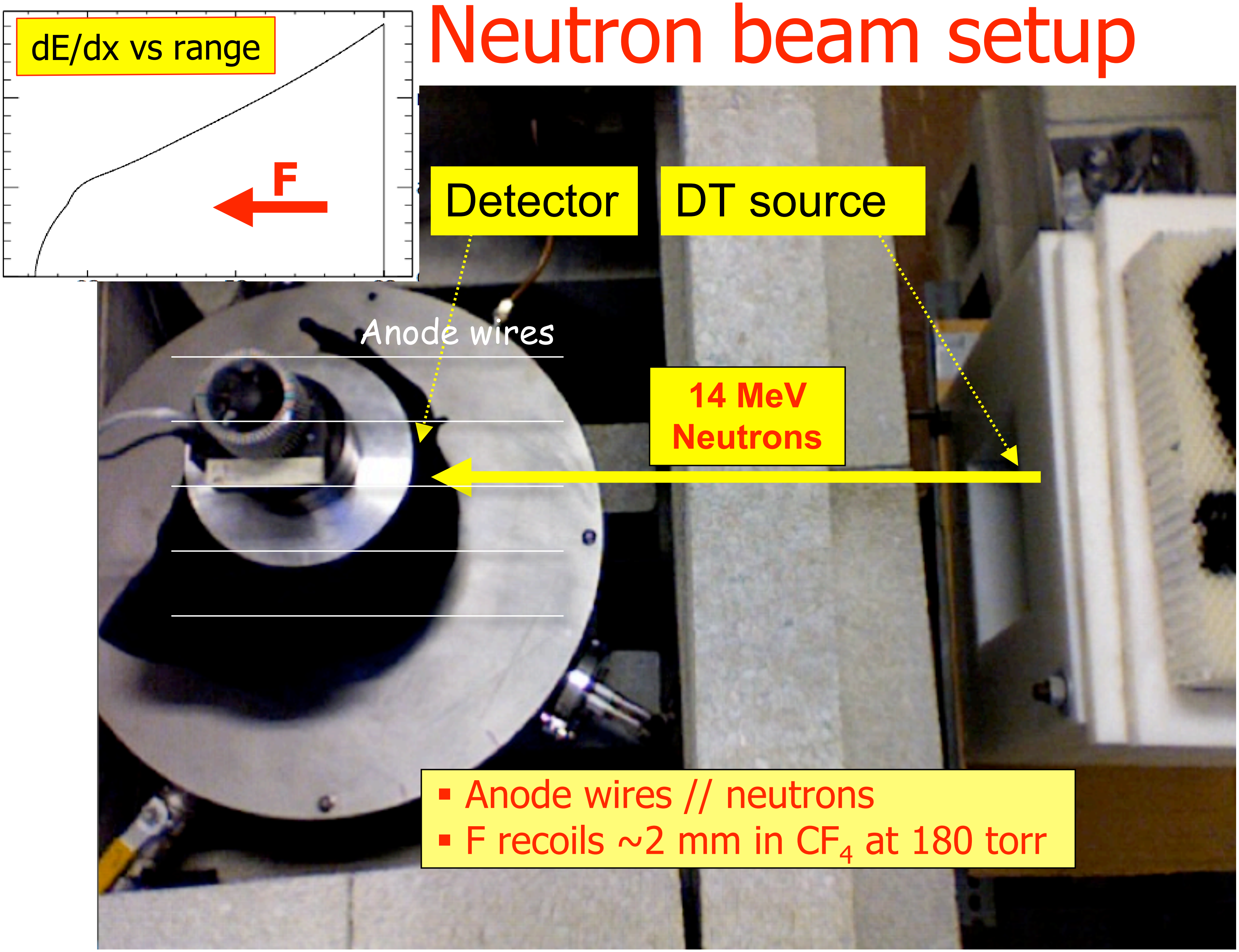


Fluorine recoil angle wrt wires



Blue band = spread in WIMP direction

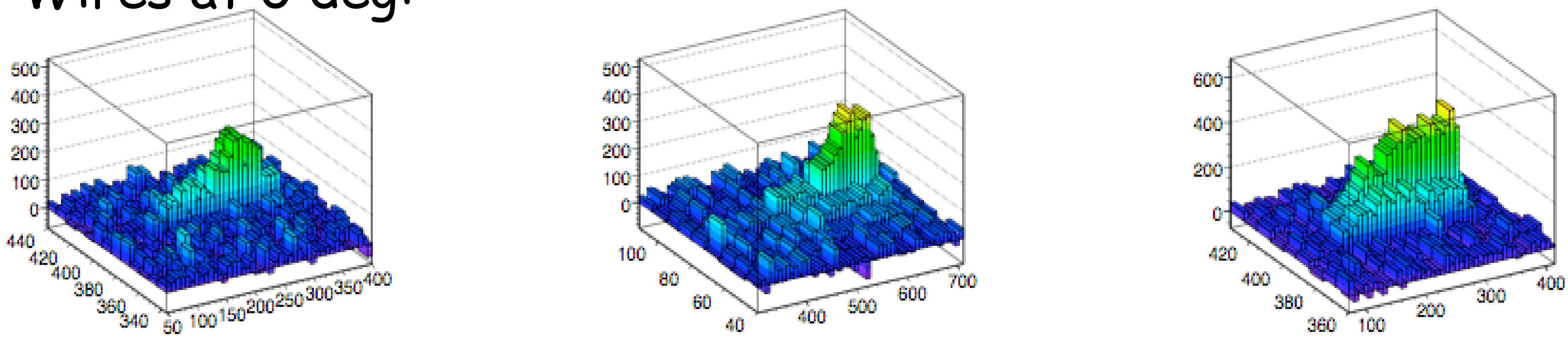
Neutron beam setup



NIM A584:327-333,2008

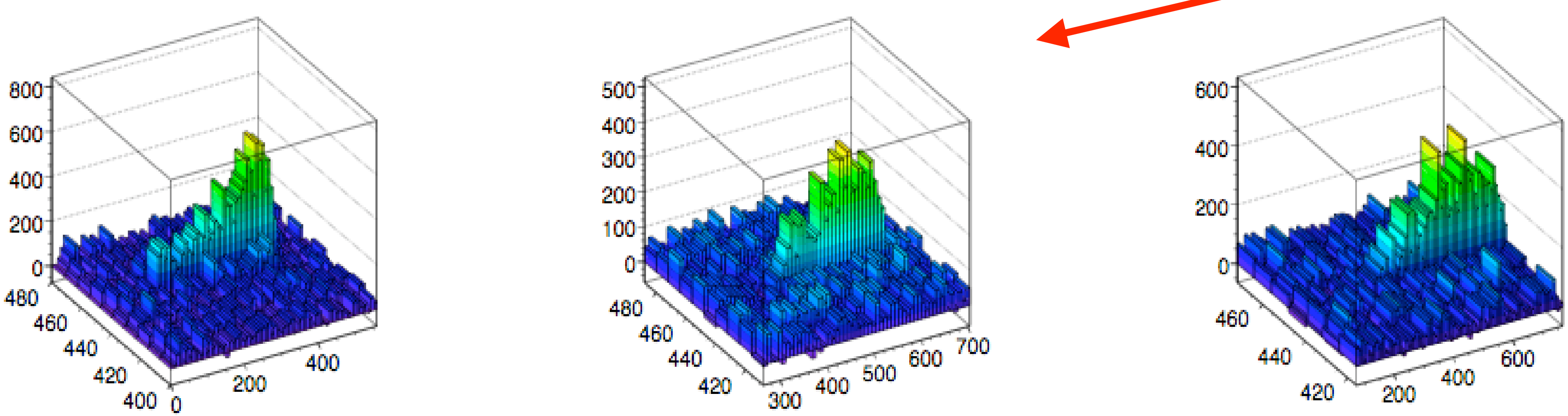
Observation of “head-tail” in F recoils

Wires at 0 deg:



Wires at 180 deg:

Direction of neutrons



ICHEP ’07, CYGNUS ’07

NIM A584:327-333,2008

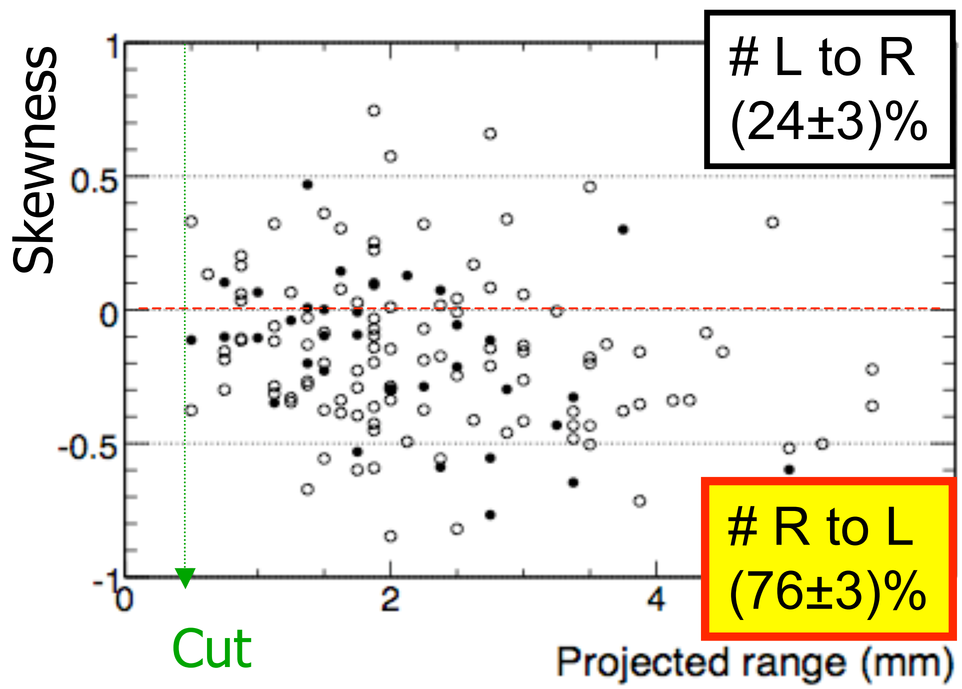
More quantitative results (DT)

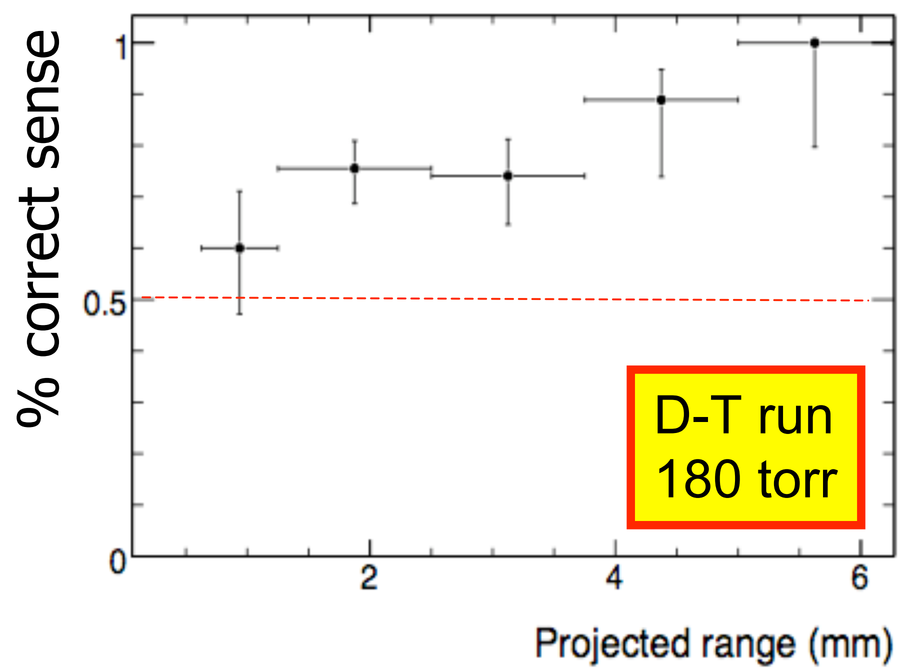
We measure skewness of light yield along wire

$$\gamma(x) = \frac{\mu_3}{\mu_2^{3/2}} = \frac{\langle (x - \langle x \rangle)^3 \rangle}{\langle (x - \langle x \rangle)^2 \rangle^{3/2}}$$

γ>0: neutron travels L to R

γ<0: neutron travels R to L



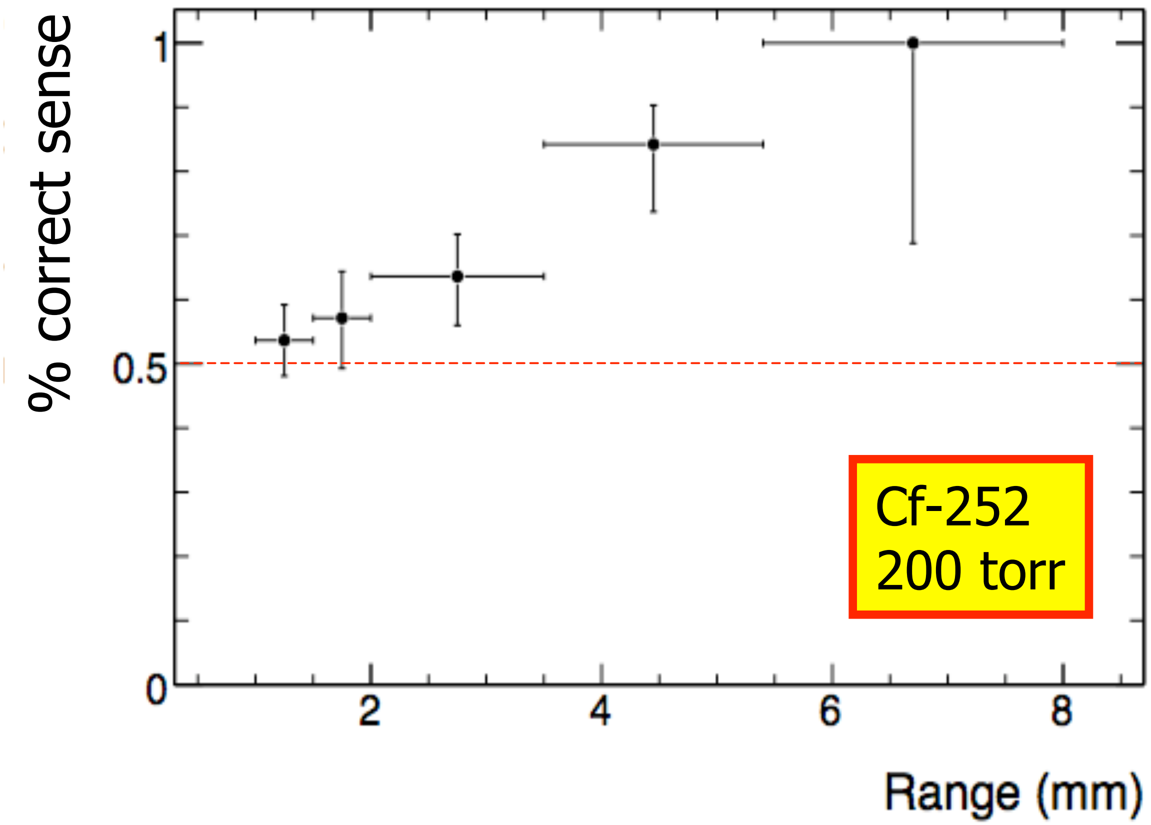


Black dots: wires @ 0 deg
Open circles: wires @180 deg

arXiv:0801.2687

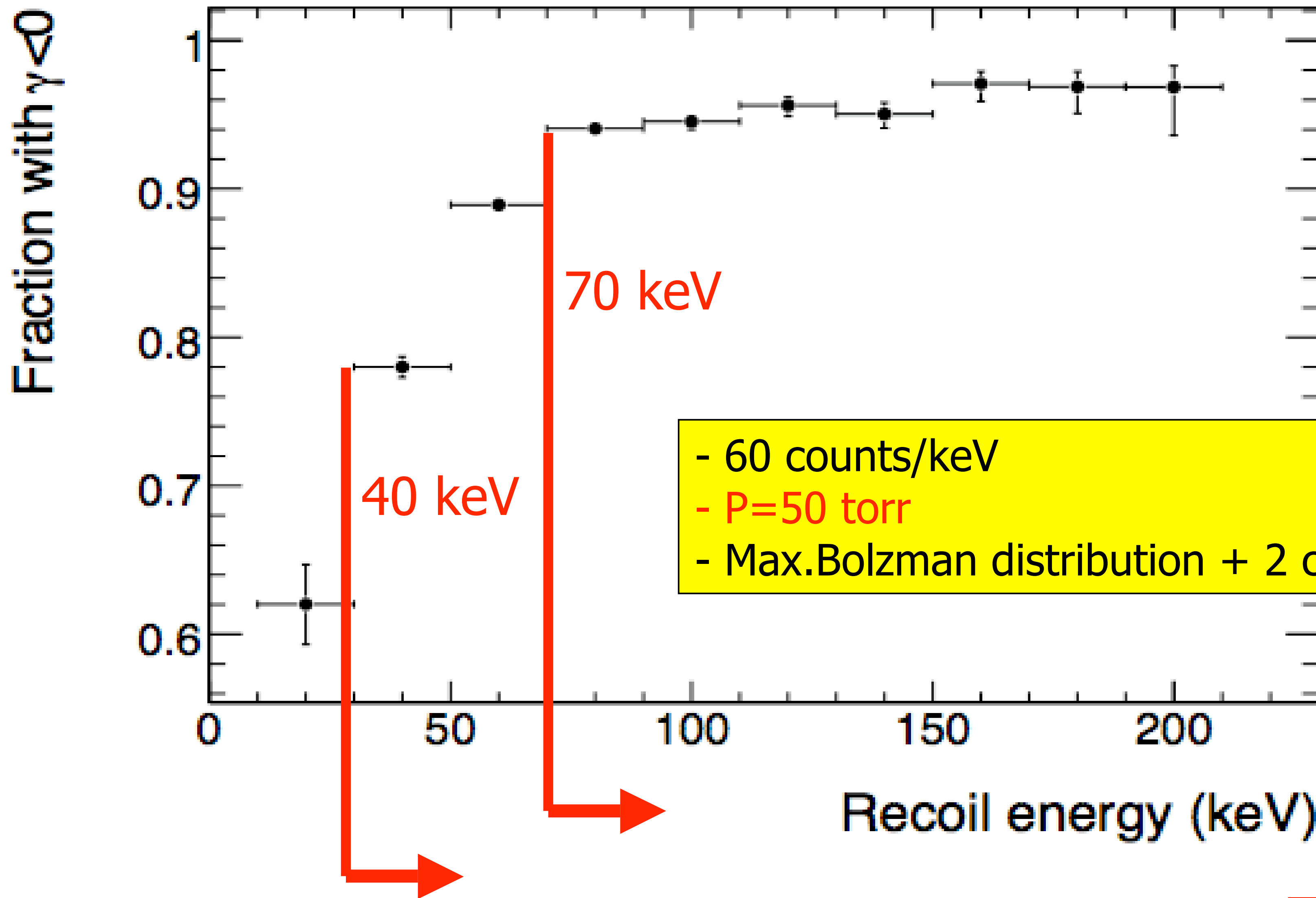
Head-tail with ^{252}Cf source

Very preliminary results (few hours run at P~200 torr)



Observed head-tail for E>200 keV

MC studies: 200 GeV WIMP



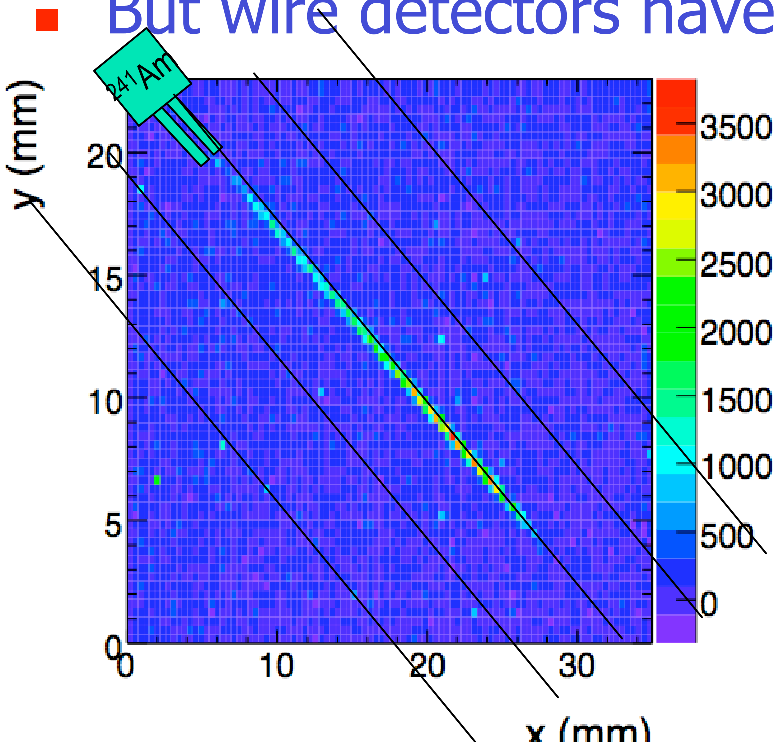
- 60 counts/keV
- P=50 torr
- Max.Bolzman distribution + 2 cm drift

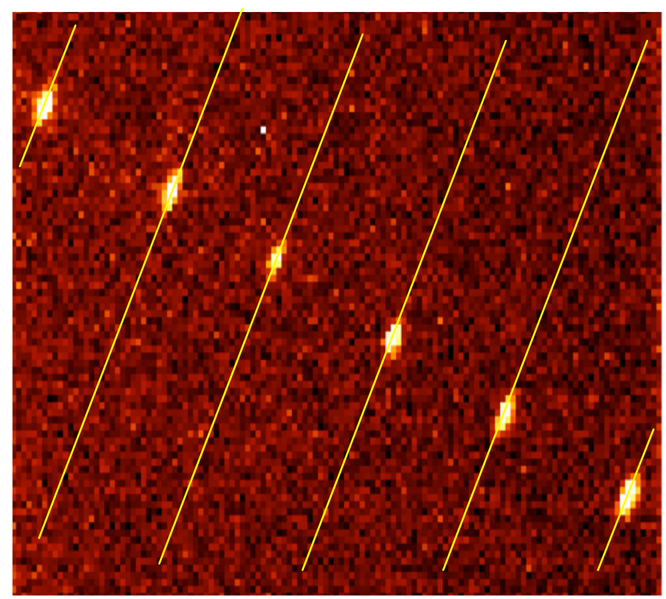
Background rejection

- Blind to gammas
  - 8 hours run with 8 μCi ^{137}Cs inside prototype: no evts
  - Rejection factor ~$2/10^6$
- Excellent discrimination against α and e-
  - By measuring both energy and length of recoil
    - For pressure of 50 torr
      - WIMP/neutrons: 30 keV --> 1 mm
      - electrons: 15 keV e- (same ionization) --> 30 mm
      - alphas: 7 keV α --> 1 mm (below threshold)
- Neutrons
  - Passive and active neutron shielding
  - Directionality!

Recent progress: wires --> meshes

- All results shown so far obtained with wire-based detectors
- But wire detectors have serious limitations….



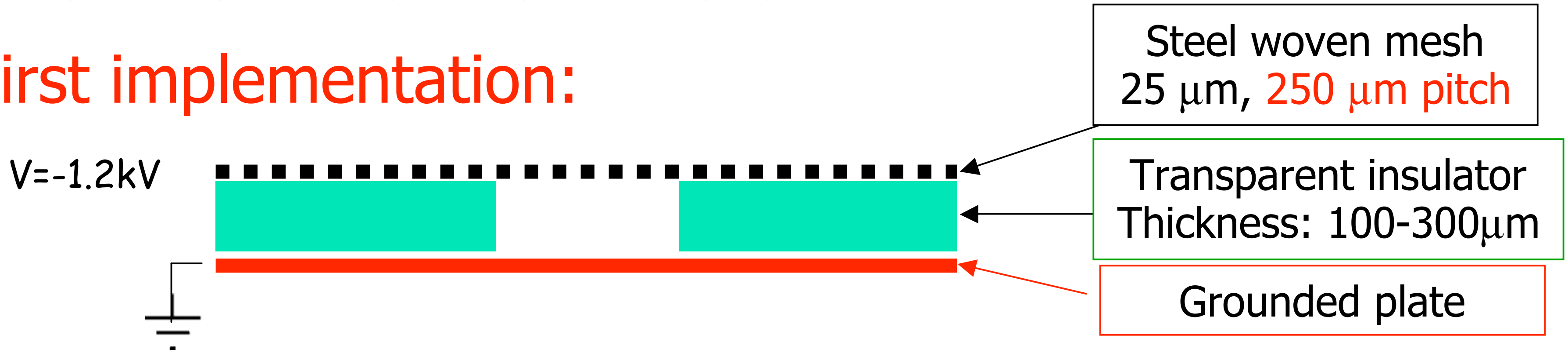


- We recently moved to mesh-based amplification regions

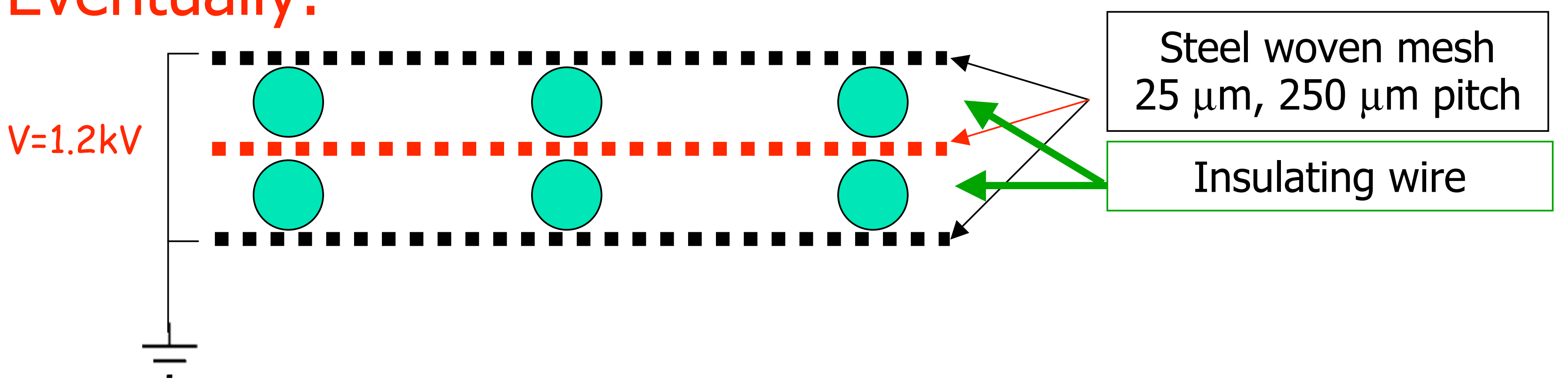
New amplification region: meshes

- Pros: additional coordinate at no additional readout cost
- Cons: some more R&D needed

First implementation:

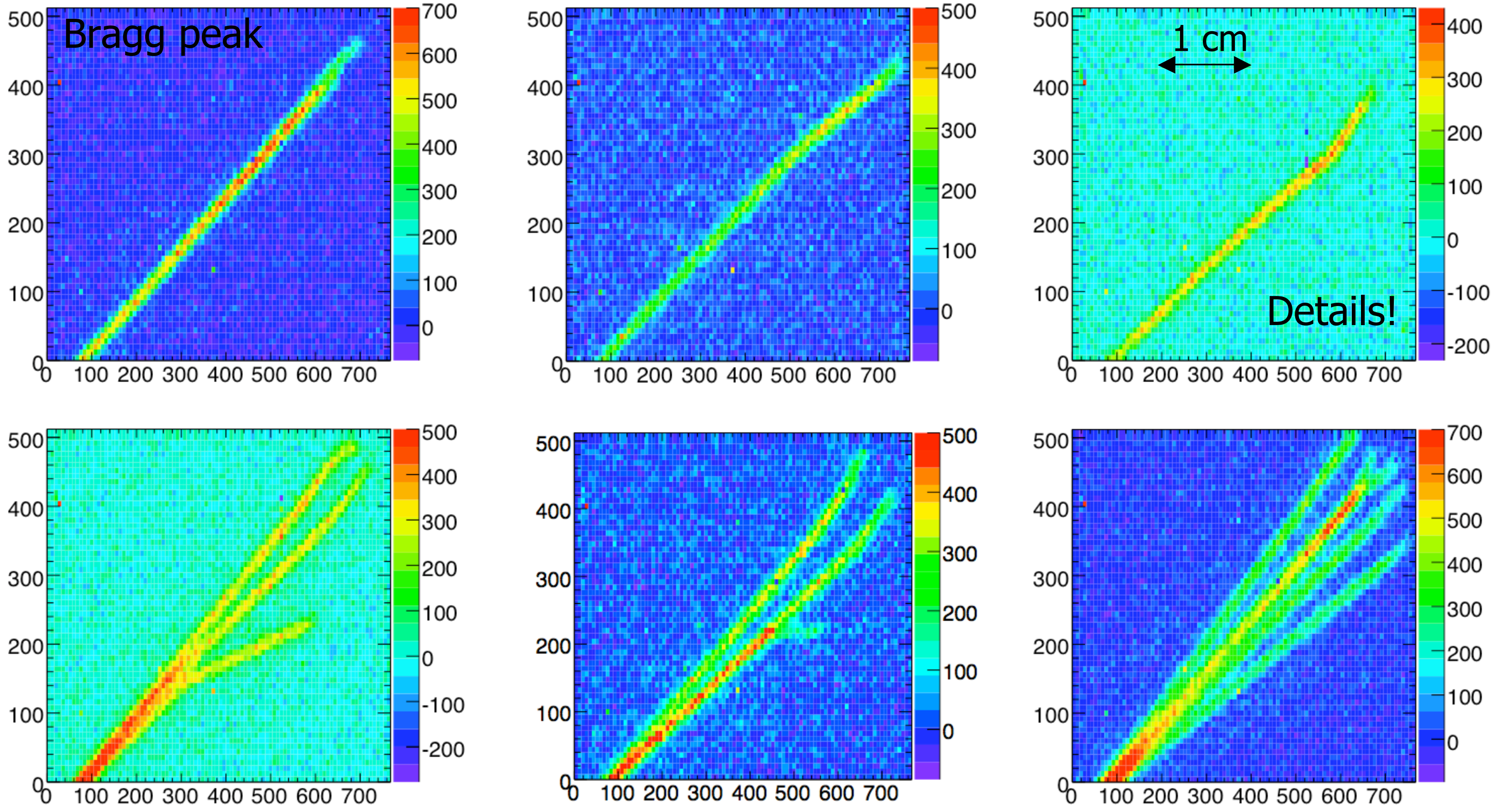


Eventually:



α particles with meshes

V_{anode}=2kV (E~1.5·10^5 V/cm)
0.3mm foil, 200Torr

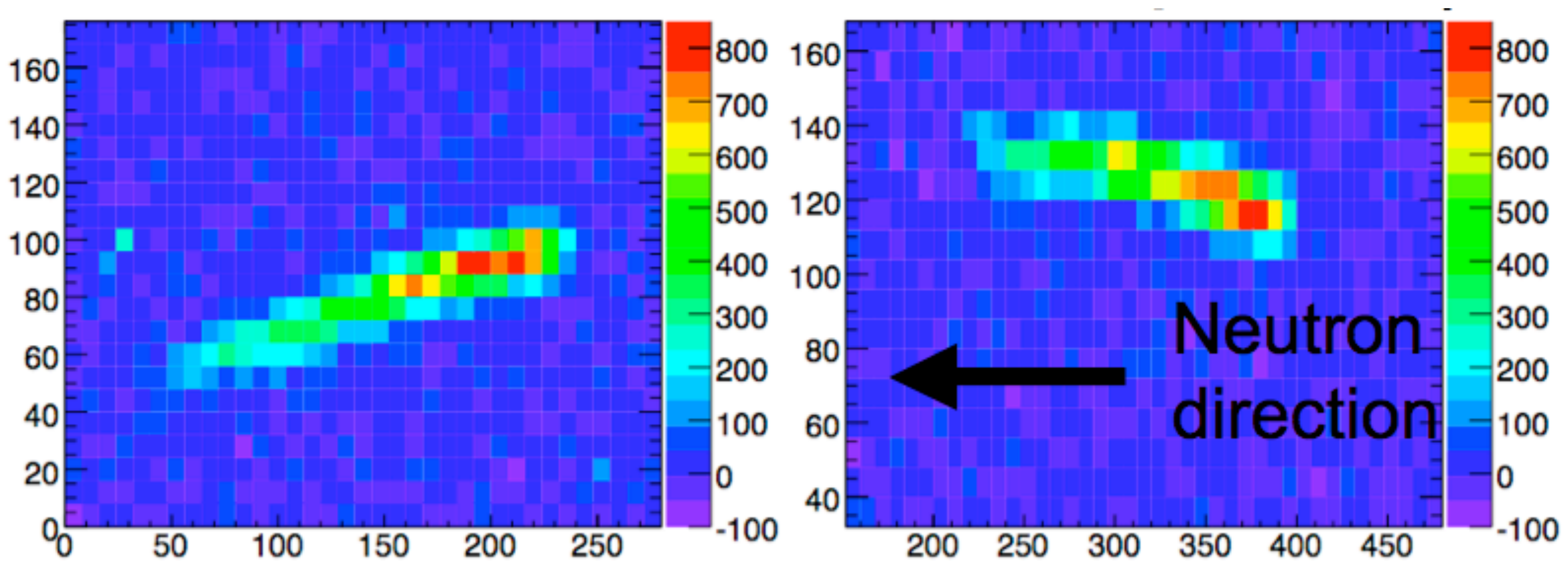


NB: 1D --> 2D at no additional cost!

arXiv:0804.4827 [astro-ph]

^{252}Cf neutrons
75 Torr

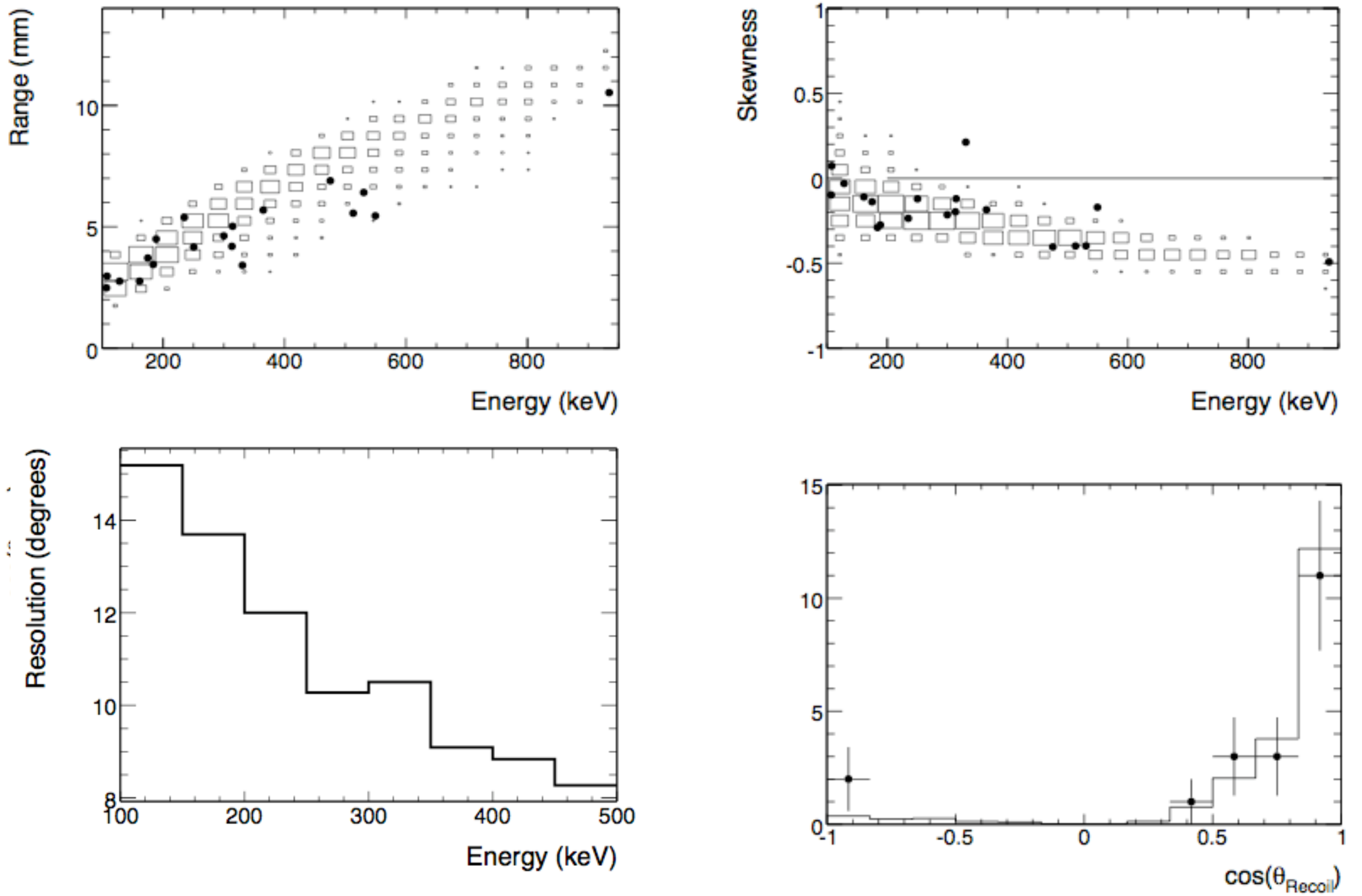
Beautiful nuclear recoils!



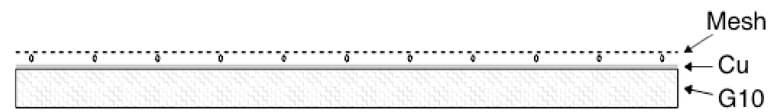
arXiv:0804.4827 [astro-ph]

^{252}Cf neutrons
75 Torr

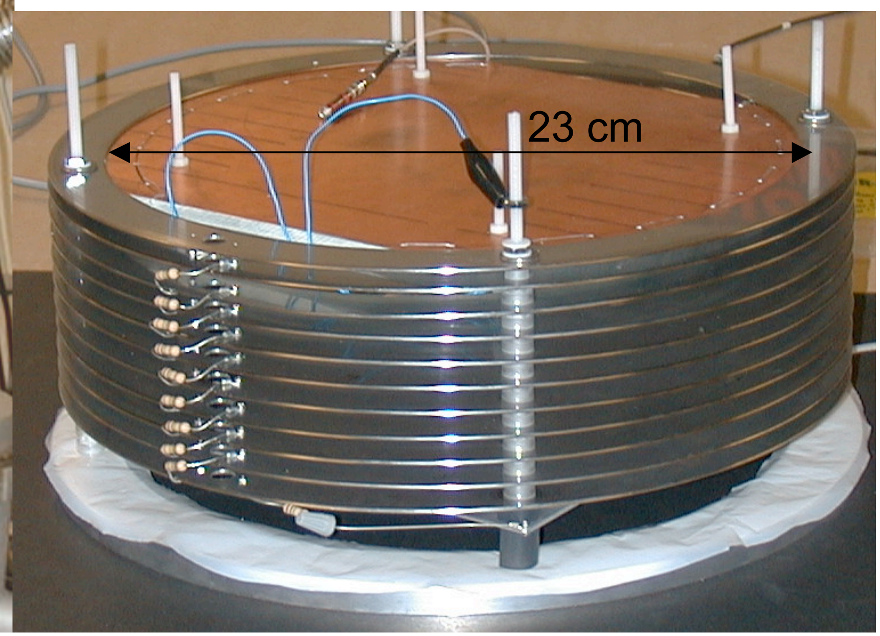
Mesh detector: short Cf run



DM-TPC: 2nd Generation

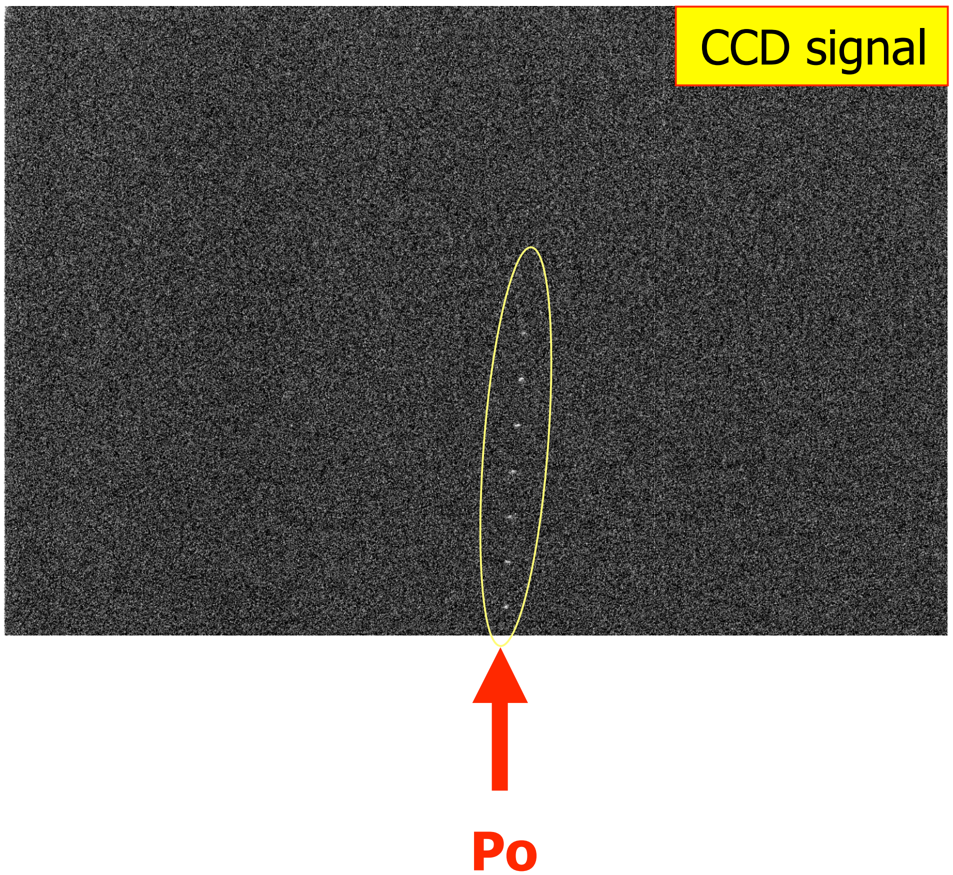


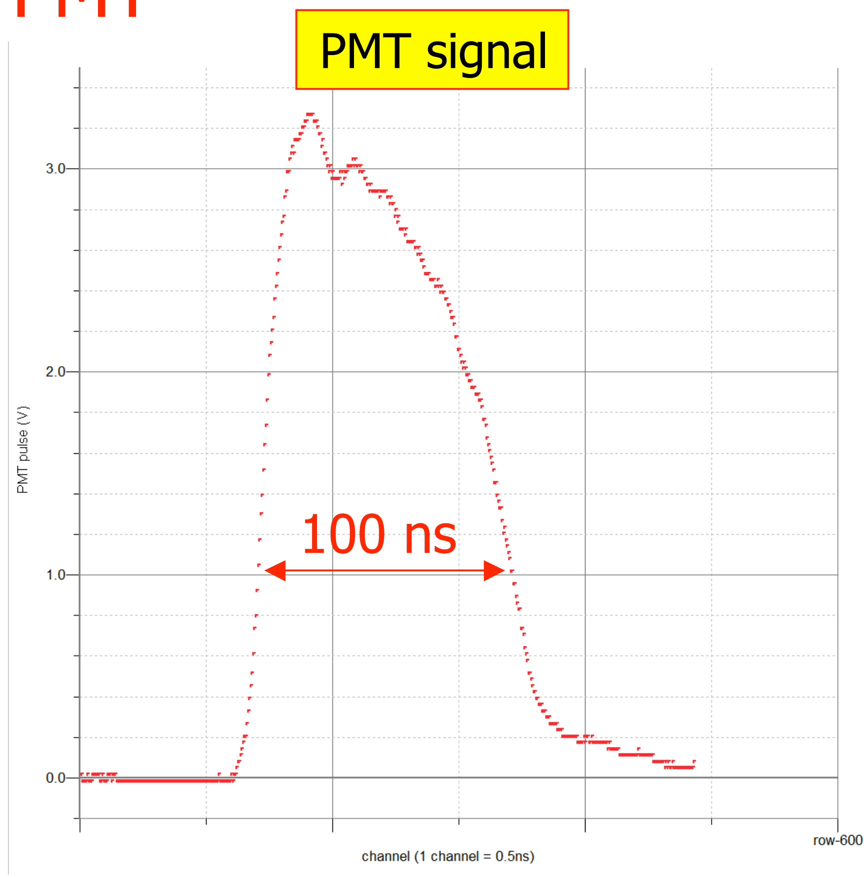
- Drift up to 25 cm
- Image view 16 cm O
- Mesh detector 23 cm O
    - 256 um pitch
    - 30 um wire O
    - 79% transparency



Some results from 2nd prototype

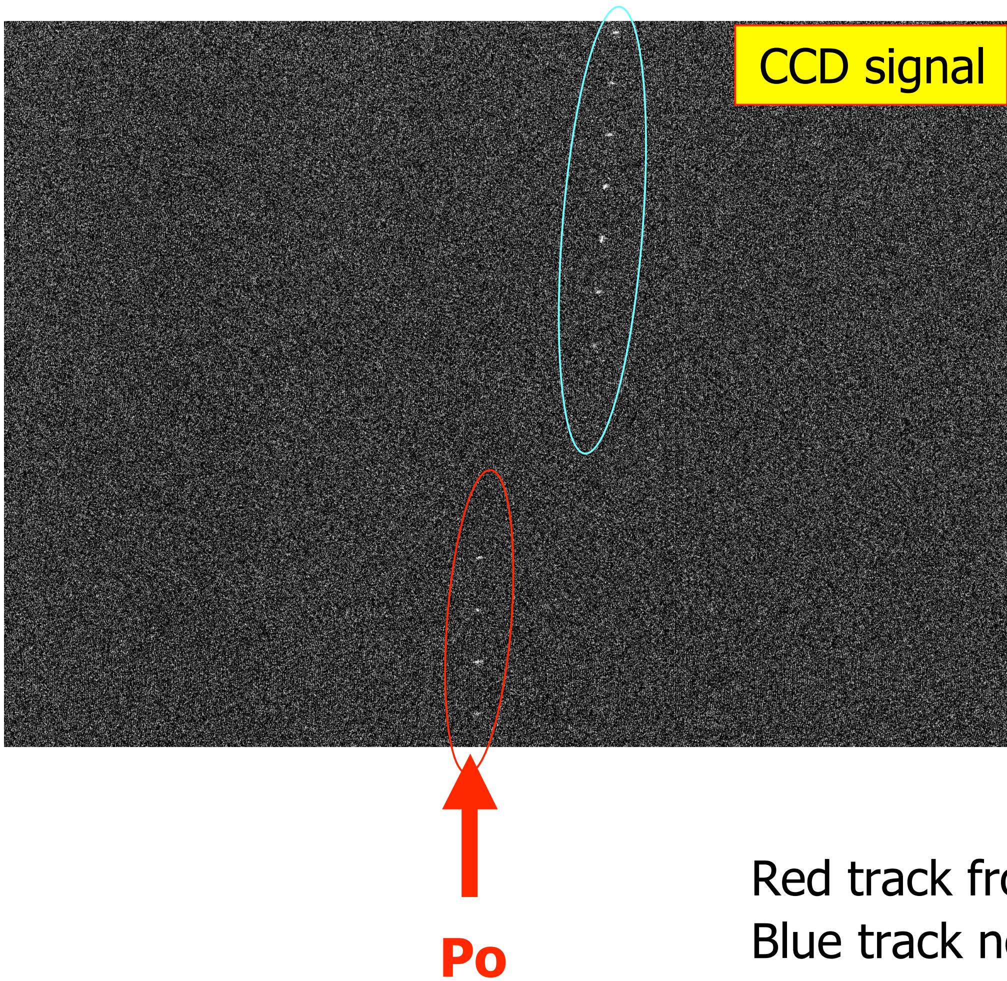
- Example: deployment of PMT

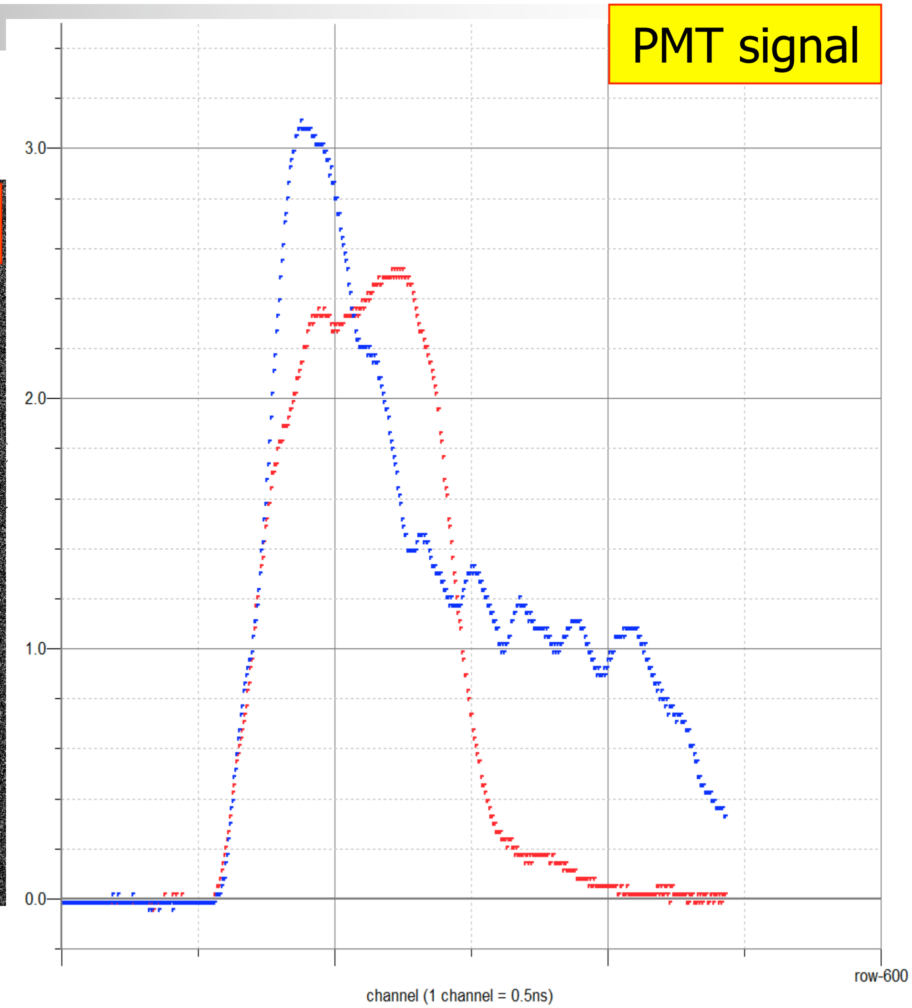




PMT signal skewed toward left: track tilted toward wire plane

More on PMT signal





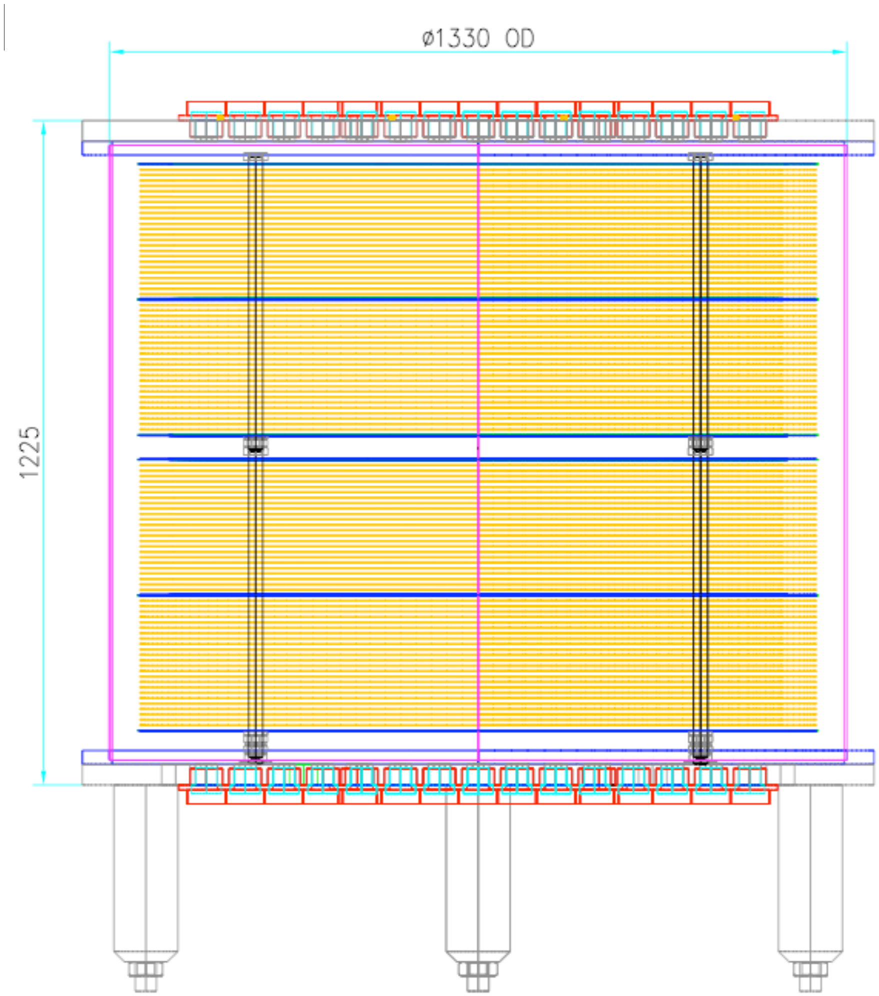
Red track from Po: narrow, small tilt away from plane
Blue track not from Po: wide, big tilt wrt wire plane

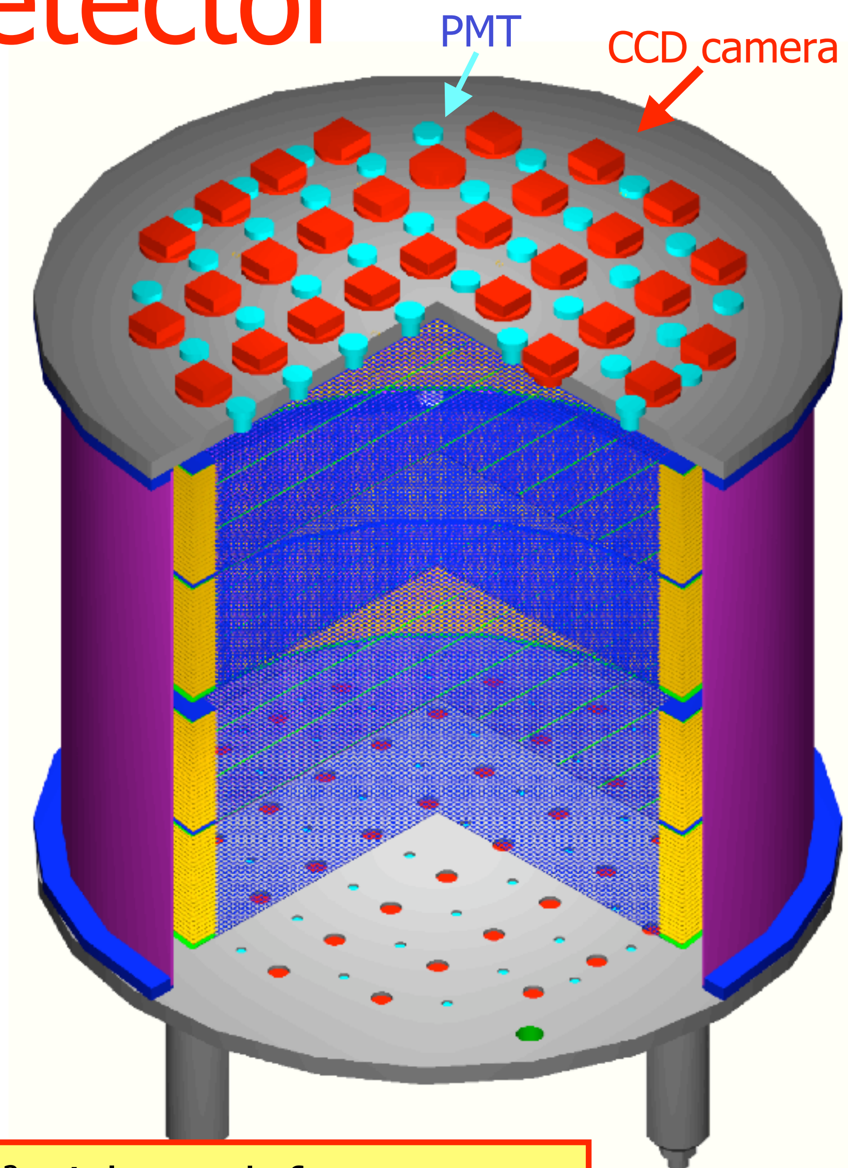
Next step: ~ m^3 detector

- Goals
  - **Set scientifically competitive limit on spin-dependent interactions with directionality**
  - Prove detector technology on realistic scale
  - Underground backgrounds studies
- Detector
  - Mass: 250-500 g/m^3 for P=50-100 torr
  - 1 year underground run: 90-180 kg-day / m^3
    - SIMPLE/PICASSO 2 Kg-day; CDMS 34(12) Kg-day for Ge(Si) runs
- Timescale
  - Design and build: 2008
  - Commissioning and underground run: 2009

Preliminary

Example: 1 m³ detector

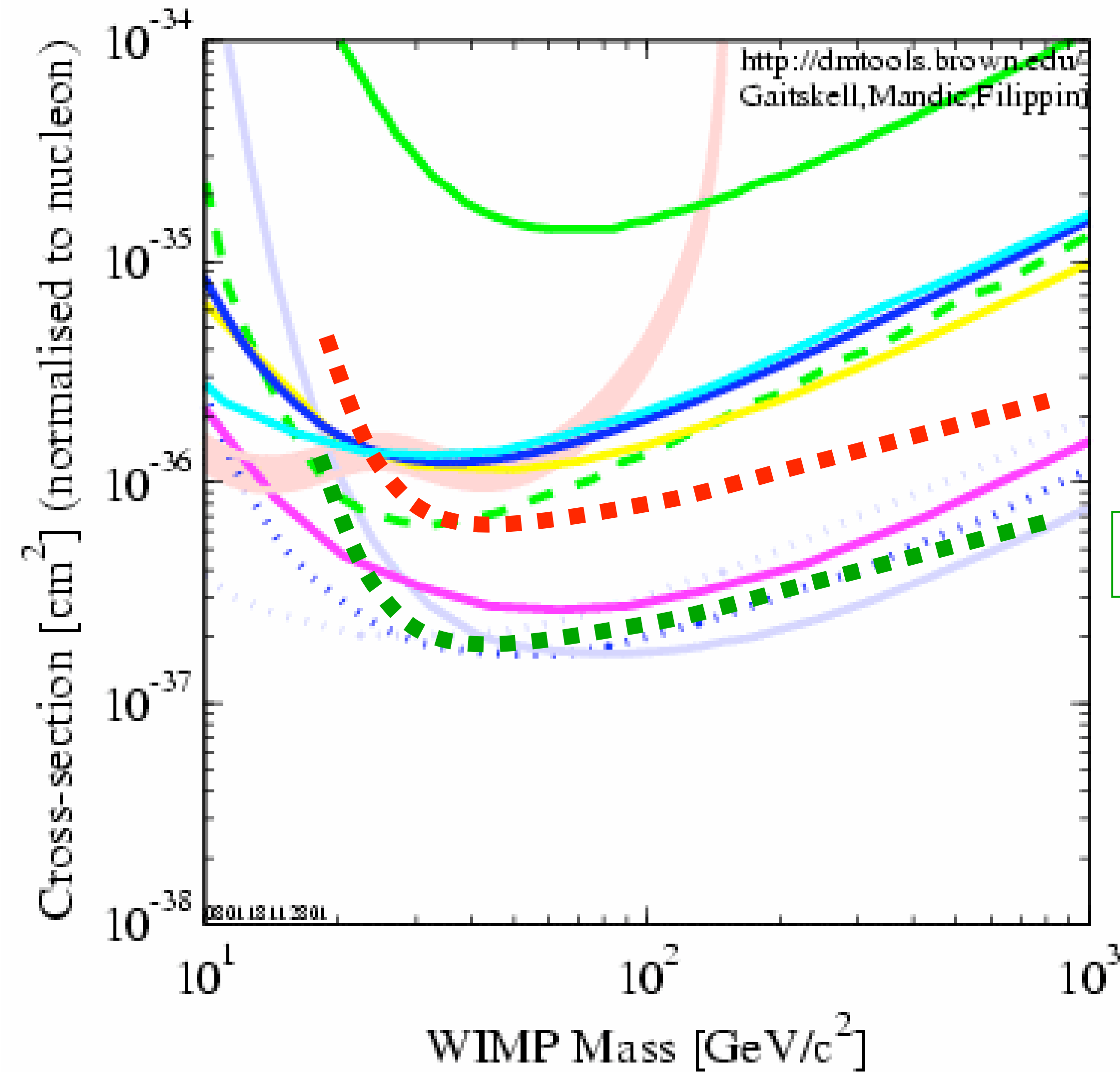




- 2 units --> 2 x (2 x 25) cm drift regions; 1m² triple mesh frames
- ~40 low-cost CCD cameras/plane; KAI220 chip & 0.95/25 lens; 20°C

Very preliminary

Sensitivity of 1 m^3 DM-TPC prototype



Current best limits on Spin-Dependent interaction

ZEPLIN II SD-proton
PICASSO SD-proton (2005)
Tokyo 2005 CaF2, SD-proton
SIMPLE SD-proton (2005)
DAMA 2003 NaI SD-proton (est.)
XENON10 SD-proton (preliminary)
NAIAD 2005 Final SD-proton
COUPP 2007 (5 keV threshold, 40 C) SD-proton (
KIMS 2007 - 3409 kg-days CsI SD-proton
COUPP 2007 (19 keV threshold, 30 C) SD-proton

DM-TPC surface (1 m^3)

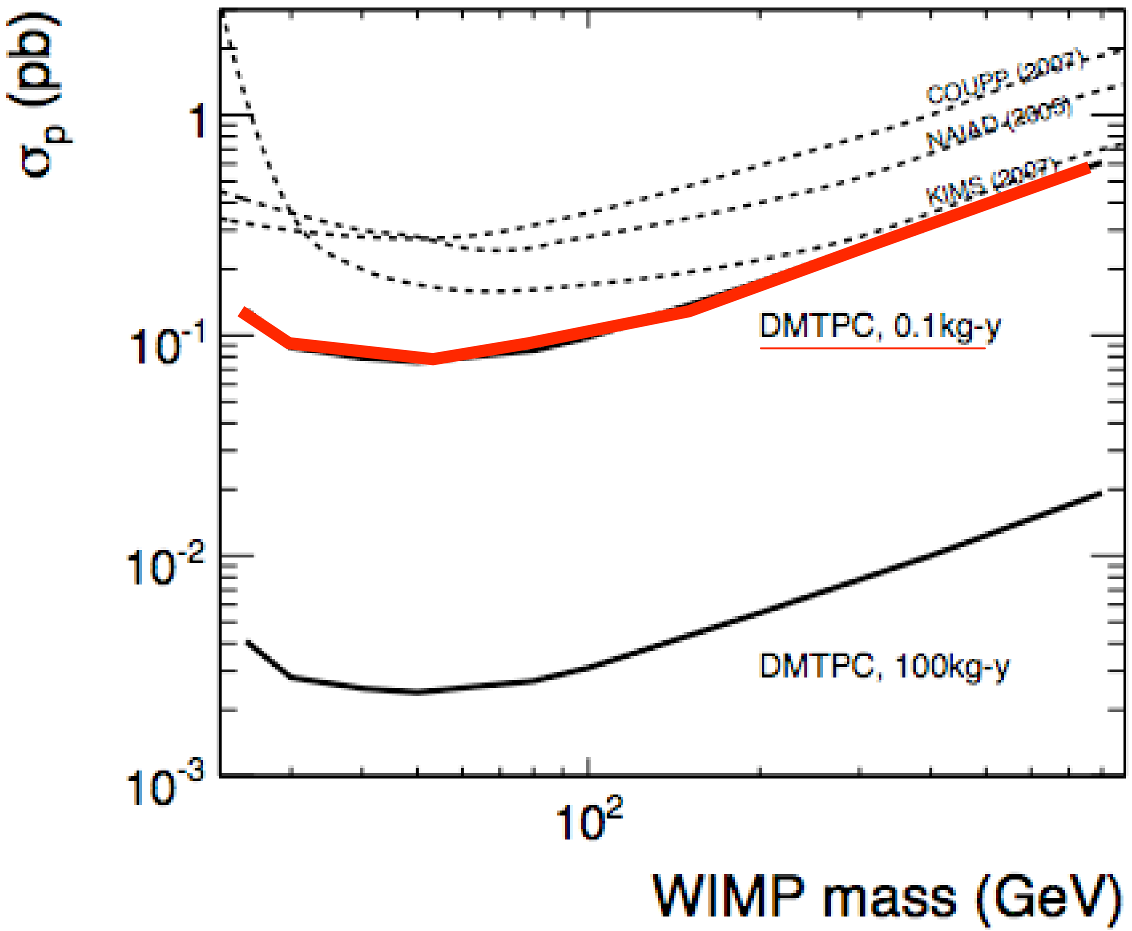
DM-TPC surface (4 m^3)

Assumptions:

- 1 year of data taking
- Threshold 40 keV
- P=100 torr

Very preliminary

Sensitivity 1 m^3 underground



Assumptions:

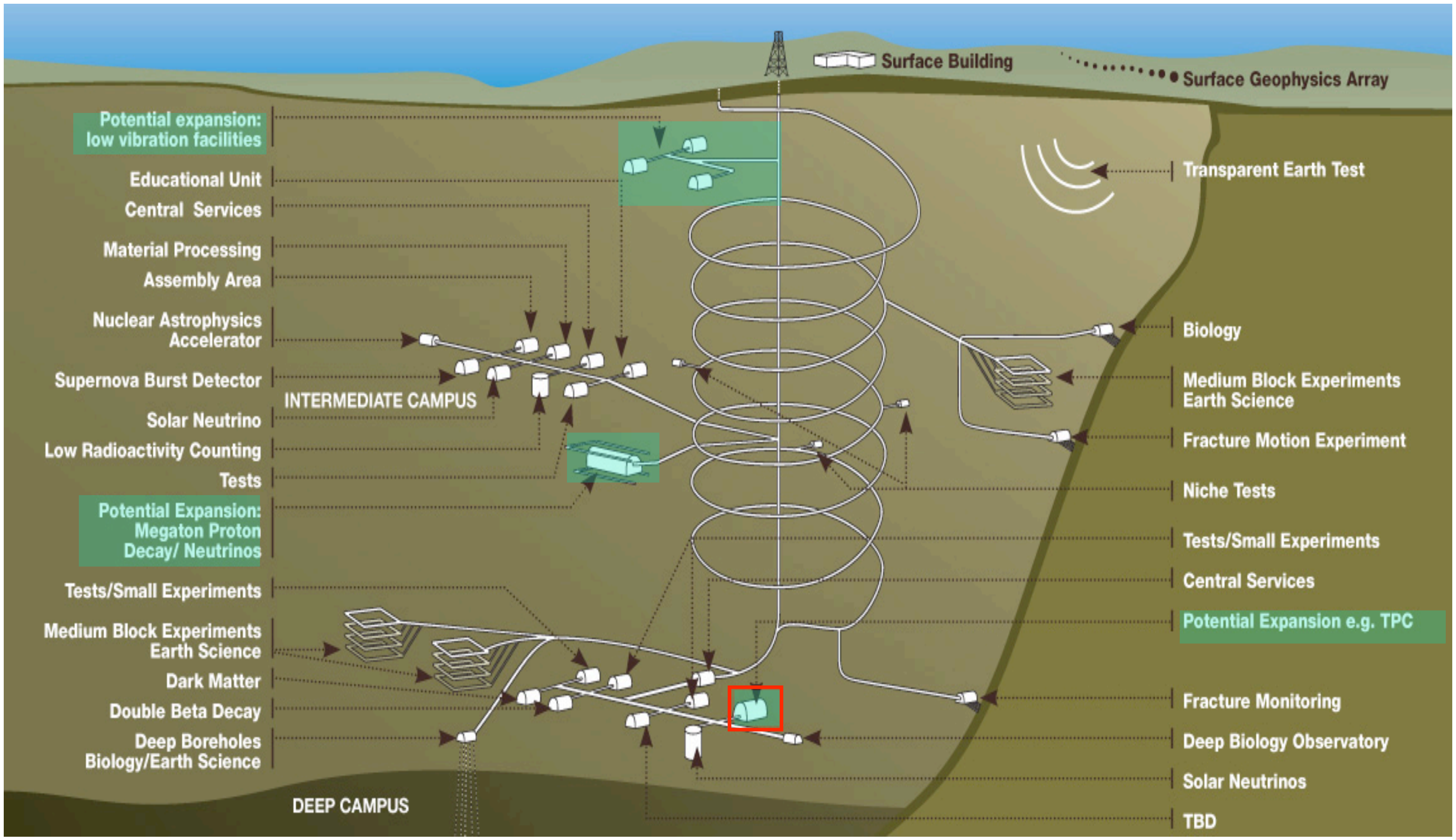
- Soudan-like depth
  (bkg 0.01/(keV-y-kg))
- Threshold 50 keV

Eventually: full scale detector

- Scale ~ O(100) m^3
  - Big for Dark Matter, but small w.r.t. LHC detectors or Super-K
  - Simple for HEP standards, e.g.: trigger rates ~ 1 Hz
  - Challenges: purity of materials!
- Mass
  - O(100) kg for P=50-100 torr
  - 3 years of running: exposure ~10^5 Kg day
  - Reach on SD interactions ~ 10^{-3} pb
- Very preliminary cost estimate
  - <~$100K/$m^3$
- Shielding
  - Active and passive shield: <$2M

Can we find space for it?

- Large DUSEL cavern at 6,000 mwe is ideal for our needs



From J. Kotcher's presenation at HEPAP meeting on 7/14/2007

Conclusion

- DM-TPC collaboration is making rapid progress toward development of new Dark Matter detector
  - Directionality, spin-dependent interactions, optical readout (<$)
- Prototype I proved detector concept (2006-2007)
  - First observation of head-tail effect in low-energy neutrons
    - NIM A584:327-333,2008
- ~1 m^3 module (2007-2009)
  - Design and build (2007-2008): meshes, PMT, better CCD…
  - One year of data taking underground (2008-2009)
    - Competitive limit on spin-dependent cross-section w/directionality
    - Study backgrounds, perfect detector design
- Large DM-TPC detector is an ideal candidate for DUSEL
  - Second generation DUSEL experiment
  - After WIMP discovery, first "WIMP astronomy" to test DM models