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

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Outline:

- Why directional detection of DM
- DM-TPC detector concept
- Recent results: first evidence of “head-tail” effect
- Toward a full-scale detector
- Conclusion

Rencontres de Blois, May 21, 2008

Spergel (1988)

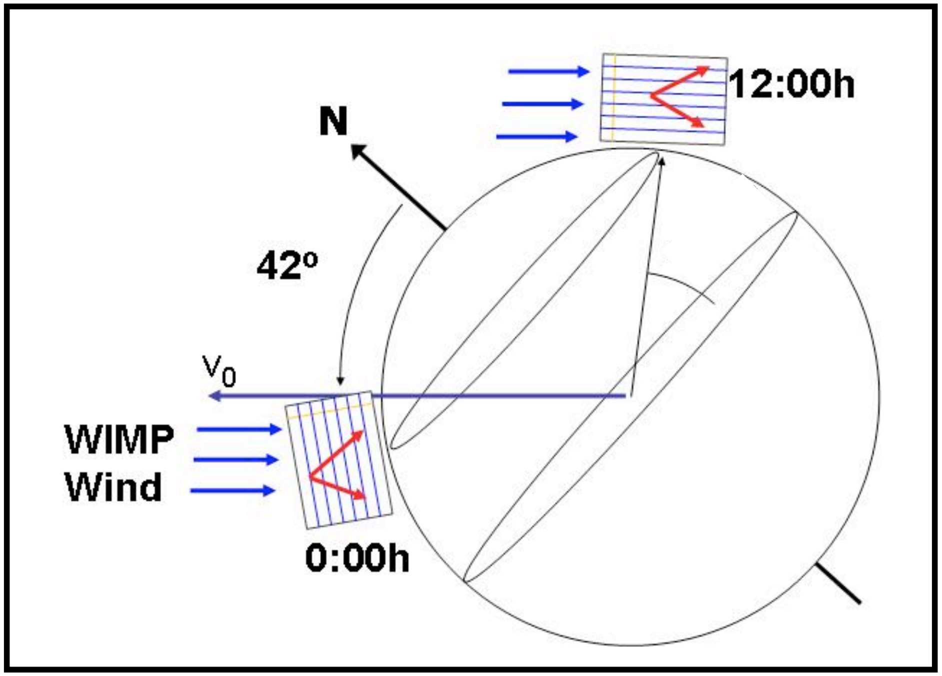
Goal #1: Directional detection of DM

In presence of backgrounds, the most convincing proof of direct observation of DM requires correlation with astrophysical phenomena

What to look for:
- WIMP wind of 220 km/s
- Direction: Cygnus

Clear signature:
- Daily asymmetry of 30-100%

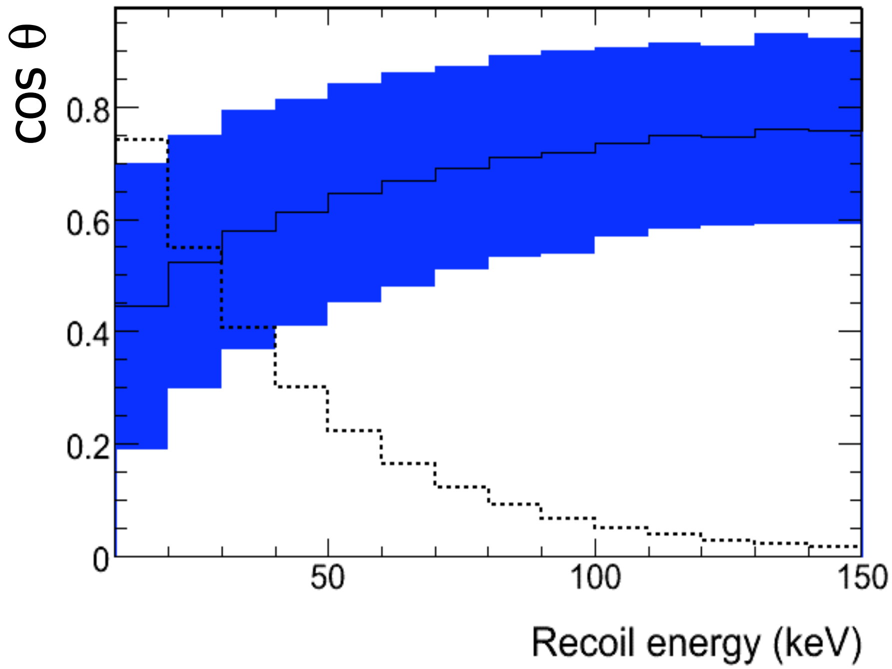
Experimental requirement:
- Directional DM detector

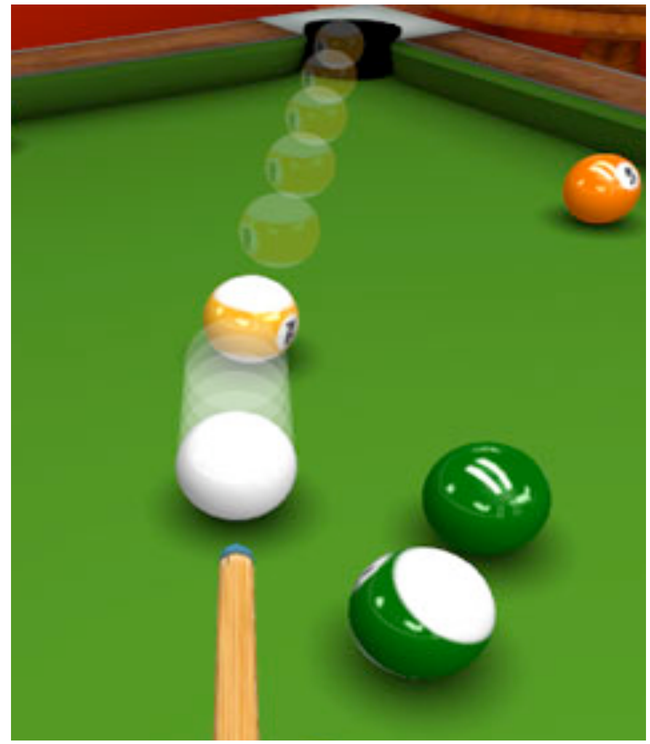


Directional detection provides:
1) Unambiguous positive observation of DM in presence of backgrounds
2) Test our understanding of DM (start "Underground WIMP astronomy")

Directional DM detectors

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





- How to detect the direction of recoils?
  - Solid/liquid detectors --> **low-pressure gaseous detectors**
    - A 50 keV F in CF_4 @ 40 torr recoils ~2 mm

Goal #2: Spin-dependent interactions

- WIMPs can scatter elastically on nuclei via
  - Spin-independet interactions
    - cross-section scales with the mass of the nucleus: $\sigma \sim A^2$
  - 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

DM-TPC Collaboration

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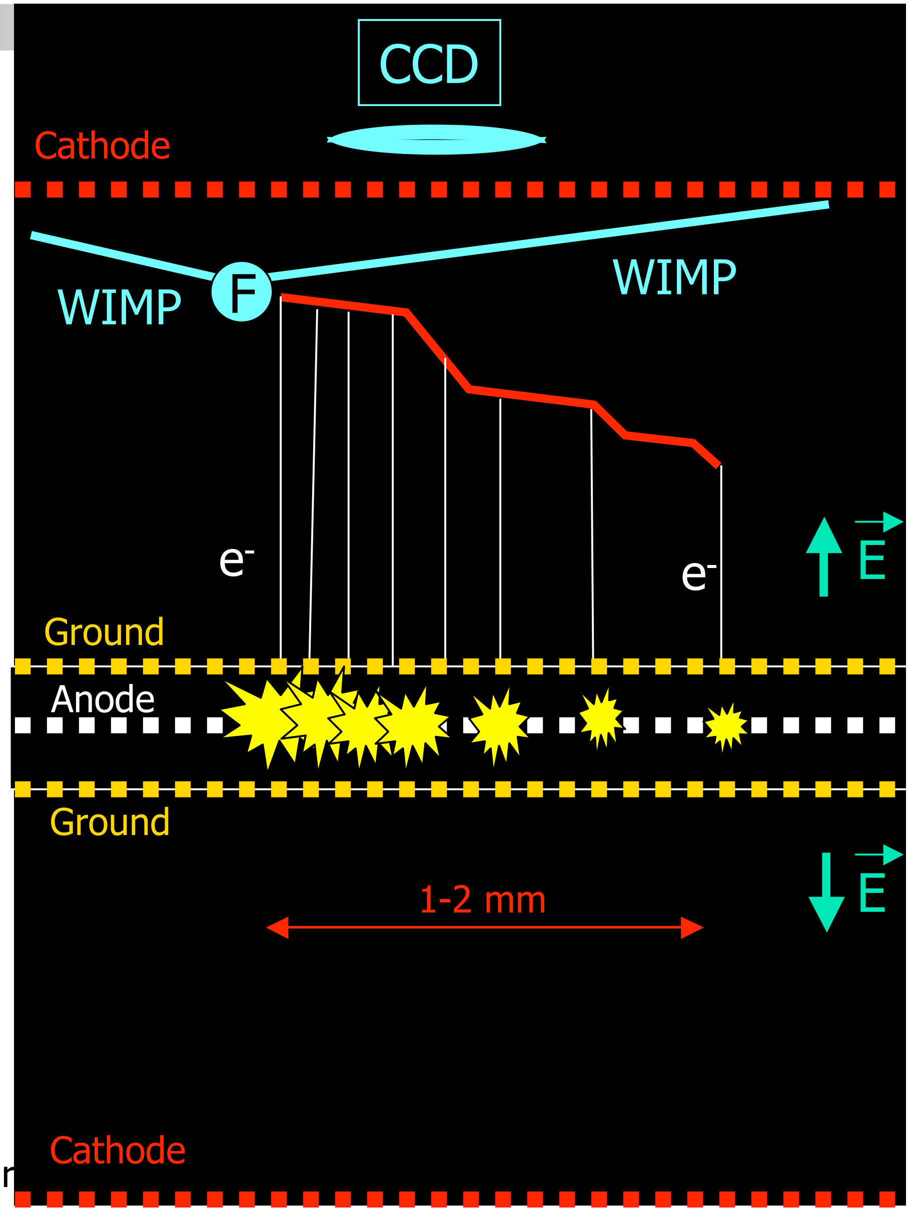
DM-TPC: detector concept

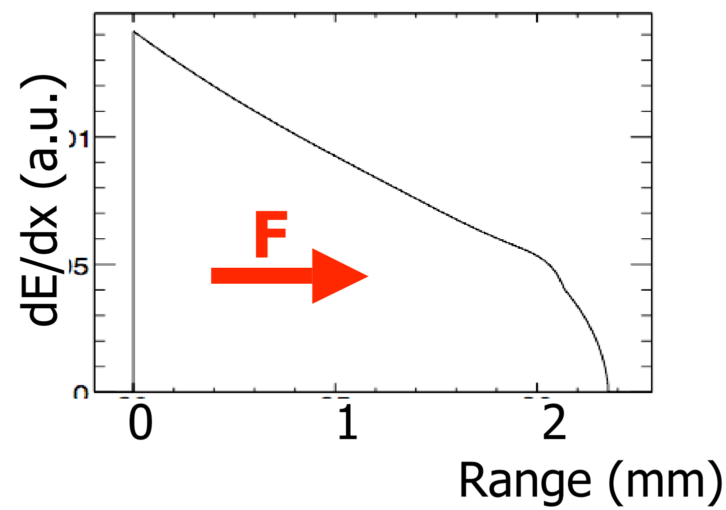
- Low-pressure CF_4 TPC
  - 50-100 torr $\rightarrow$ F recoil ~1-2mm
- Optical readout (CCD)
  - Image scintillation photons produced in avalanche
  - Low-cost, proven technology
- Amplification region
  - Wire planes --> mesh detector
  - Woven mesh 25μm, 250μm pitch
- CF_4 is ideal gas
  - <u>F: spin-dependent interactions</u>
  - Good scintillation efficiency
  - Low transverse diffusion
  - Non flammable, non toxic



What we measure

3 fundamental measurements (CCD)

- E_{recoil} from total scintillation light
  - Integral of CCD signal
- Reconsructs recoil track (in 2D)
  - Pattern recognition in CCD
- 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 measurements (PMT)

- 3rd coordinate of recoil (// v_{drift})
- Trigger

Background rejection

- Excellent rejection of 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
  - Underground data-taking
  - Passive and active neutron shielding
  - Directionality!

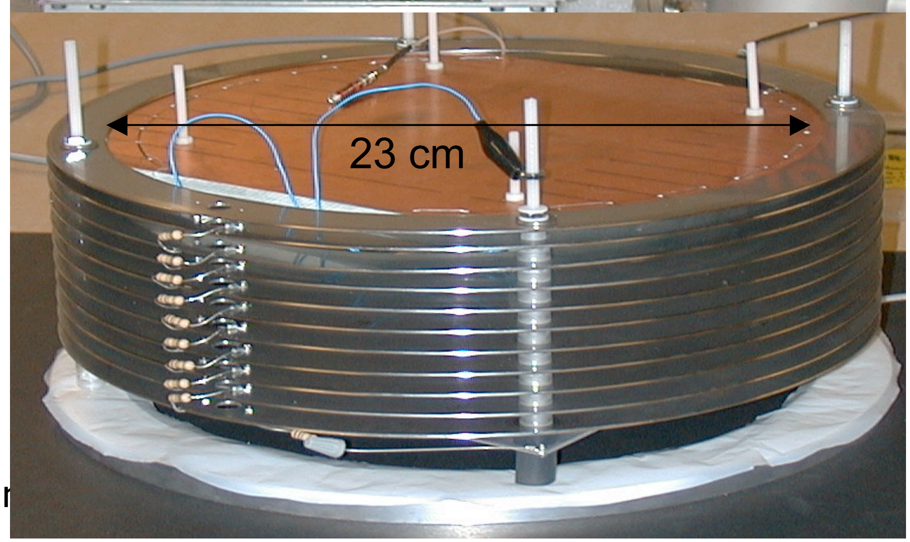
Prototypes

First generation prototype

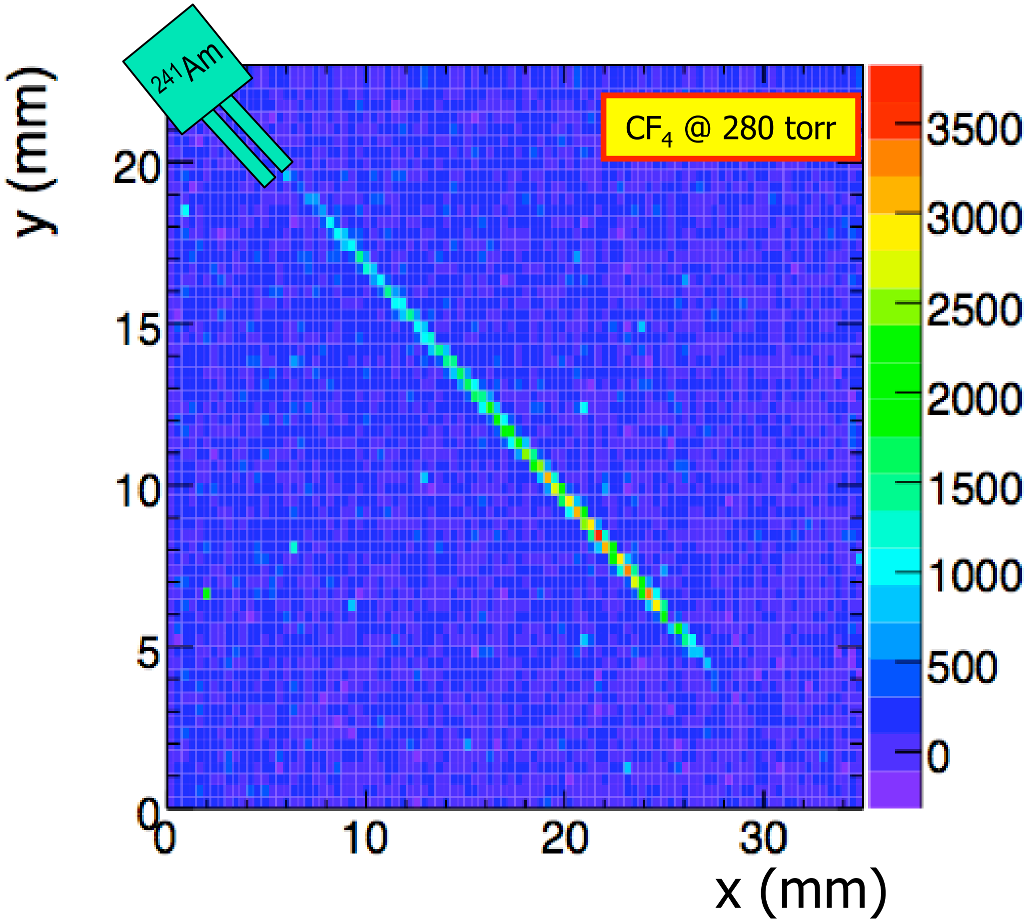
- Prove detector concept & first observation of "head-tail" effect
- 10x10 cm^2 wires planes
- Drift ~ 2.6 cm
- Camera: Finger Lakes Instrumentation; Kodak KAF0401 chip 768x512 (9x9mm) cooled @-20C; 55mm lens

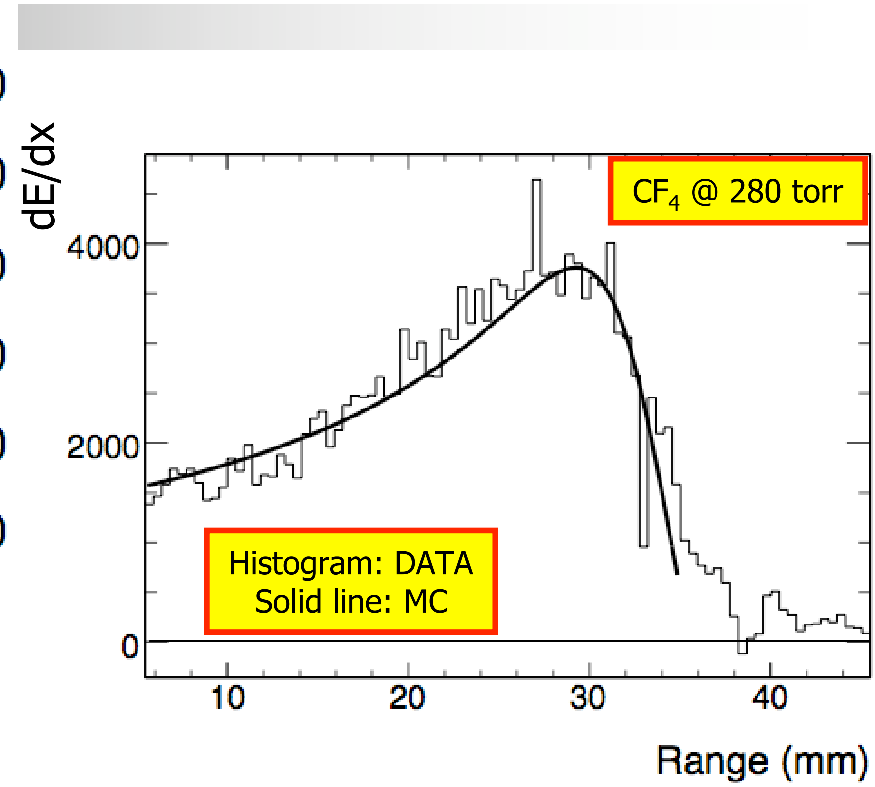
Second generation prototype

- ~20 cm diameter meshes
- Drift: up to 25 cm
- Camera: Apogee U2-ME
- Kodak KAF-1603ME, 1536x1024 pixels
- Lens: Schneider Xenon 0.95/17



Calibration: 5.5 MeV alphas from ^{241}Am





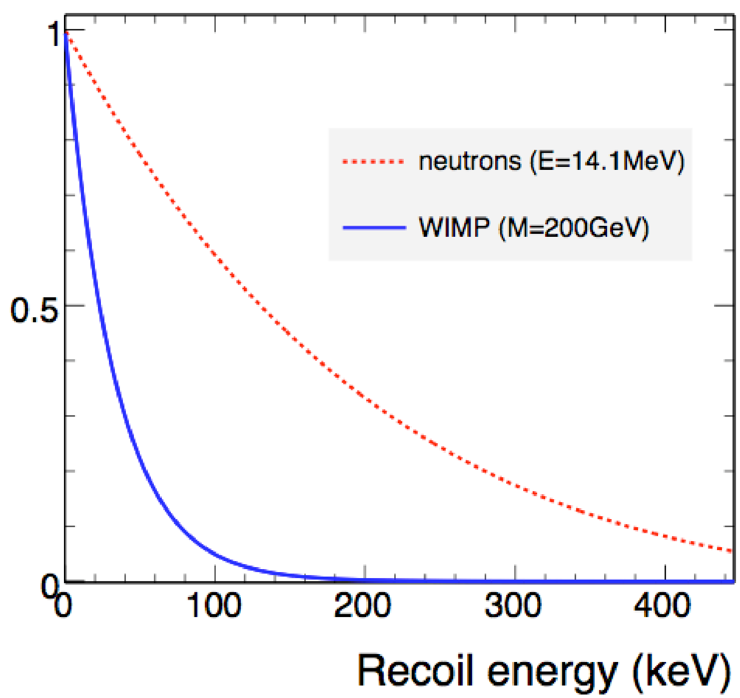
- Bragg peak of alphas: well understood detector
- Diffusion studies: max drift distance ~ 25 cm $\sigma[\mu m] = 324 \oplus 36\sqrt{\Delta z}$
- Light yield calibration: stable operations for gas gain ~ 10^4-10^5

Head-tail studies:

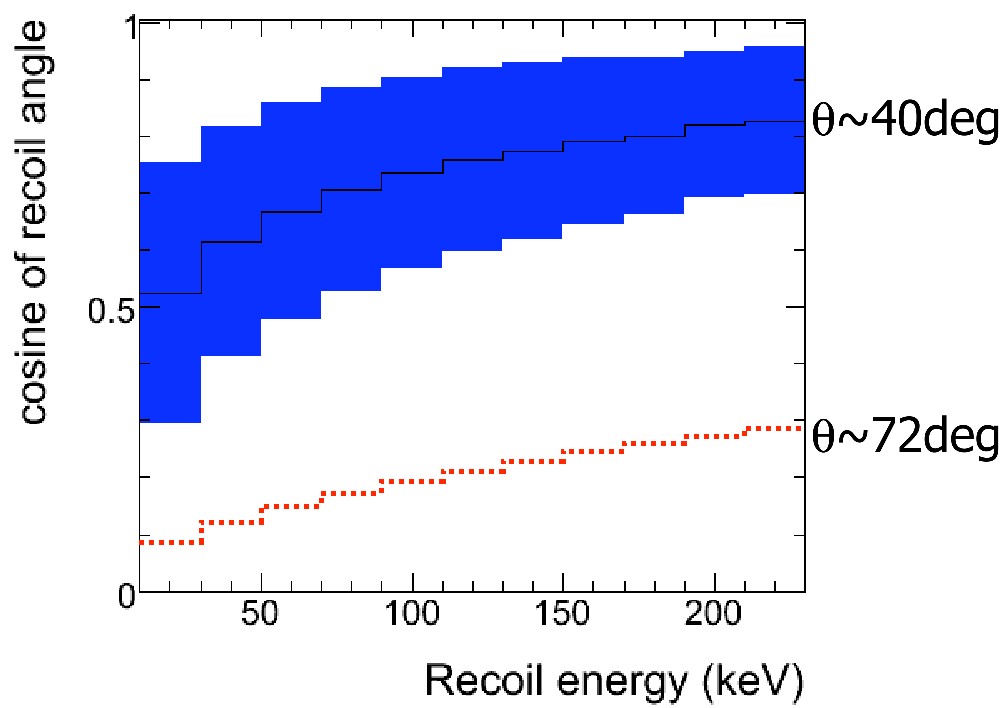
Recoils from low-energy neutrons

- Nuclear recoils using 14 MeV neutrons from D-T tube
  - DM: F has lower energy but is better aligned with WIMP direction
- Short runs with ^{252}Cf source

Fluorine recoil energy

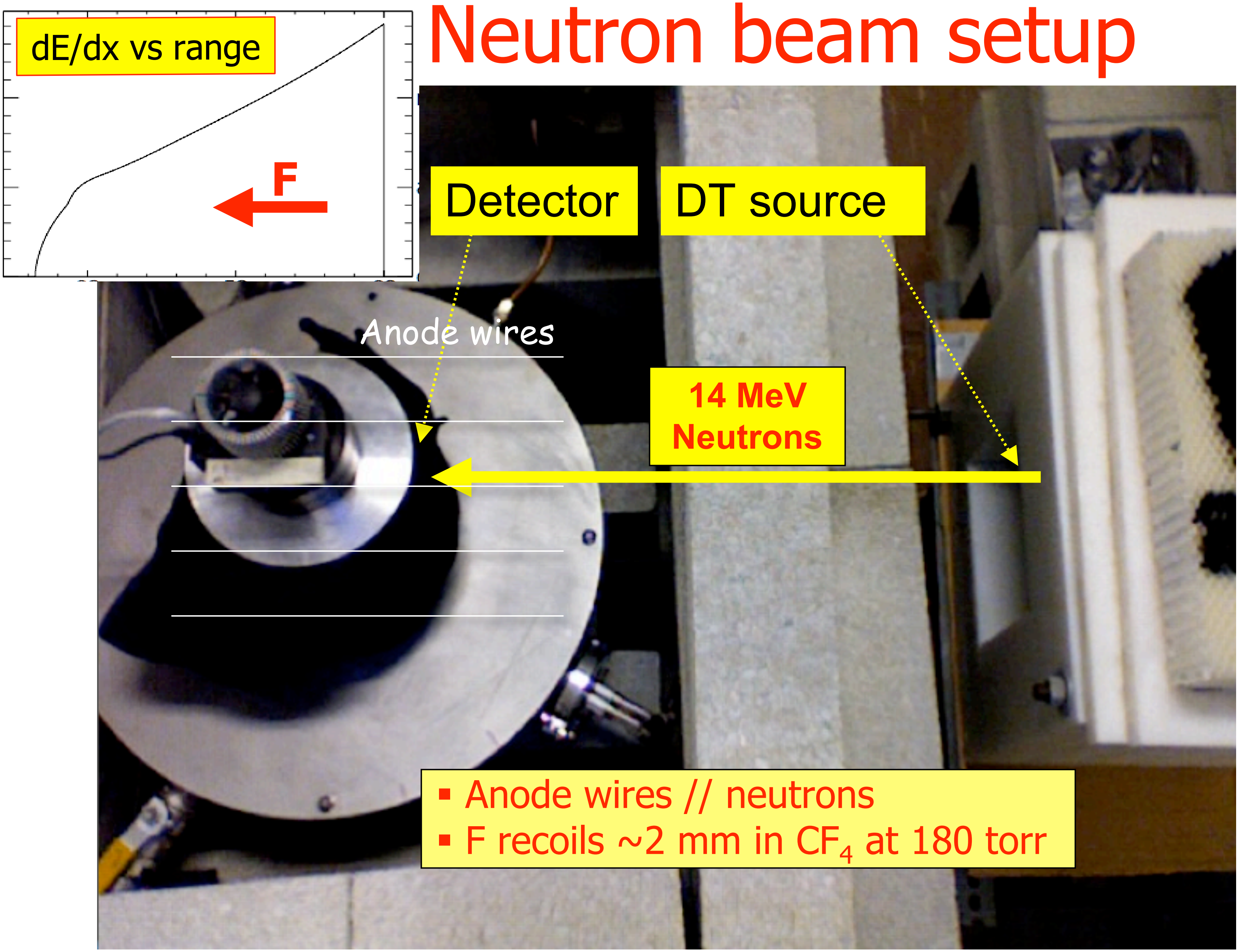


Fluorine recoil angle wrt wires



Blue band = spread in WIMP direction

Neutron beam setup



- Anode wires // neutrons
- F recoils ~2 mm in CF_4 at 180 torr

NIM A584:327-333,2008

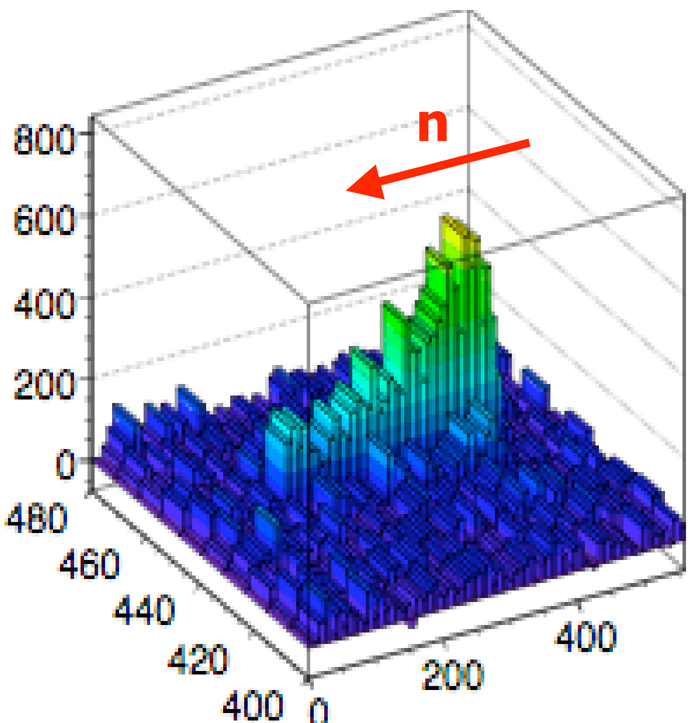
Observation of "head-tail" in F recoils

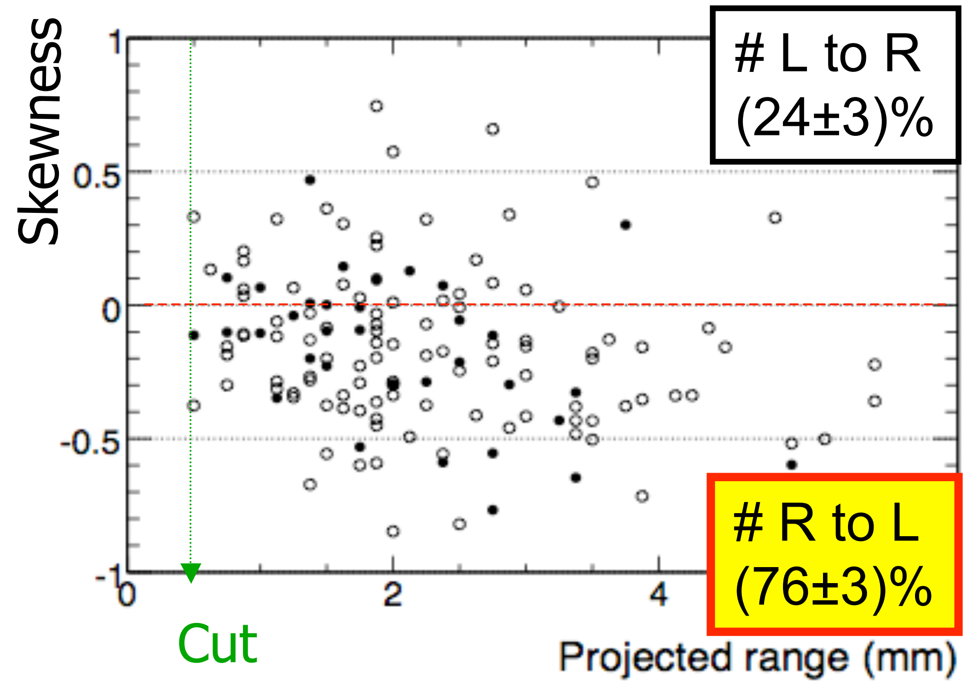
Measure skewness of light yield along wire

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

γ>0: neutron travels L to R

γ<0: neutron travels R to L





^{252}Cf run: head-tail observed for E>200 keV (P=200 torr)

arXiv:0801.2687

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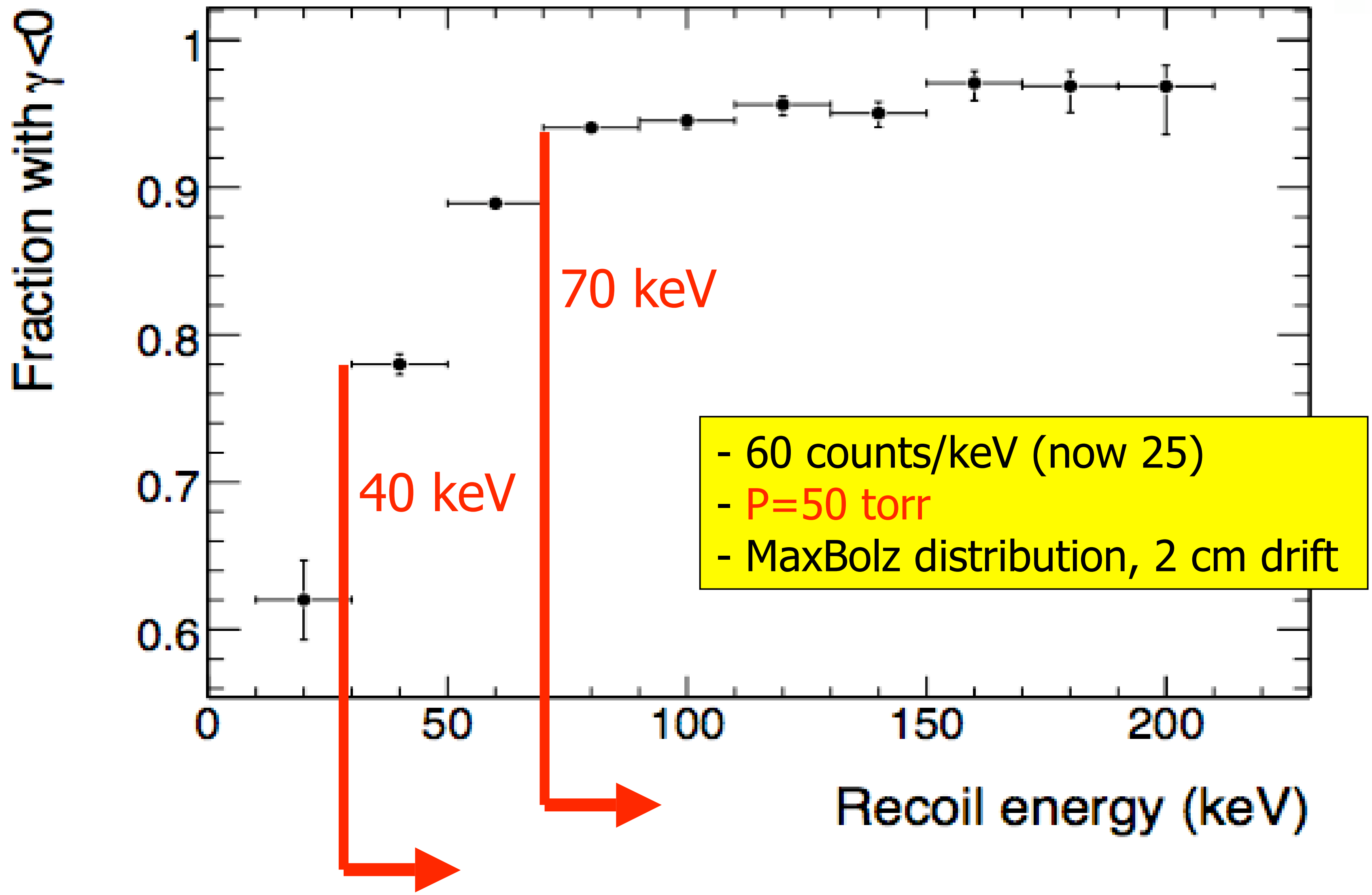
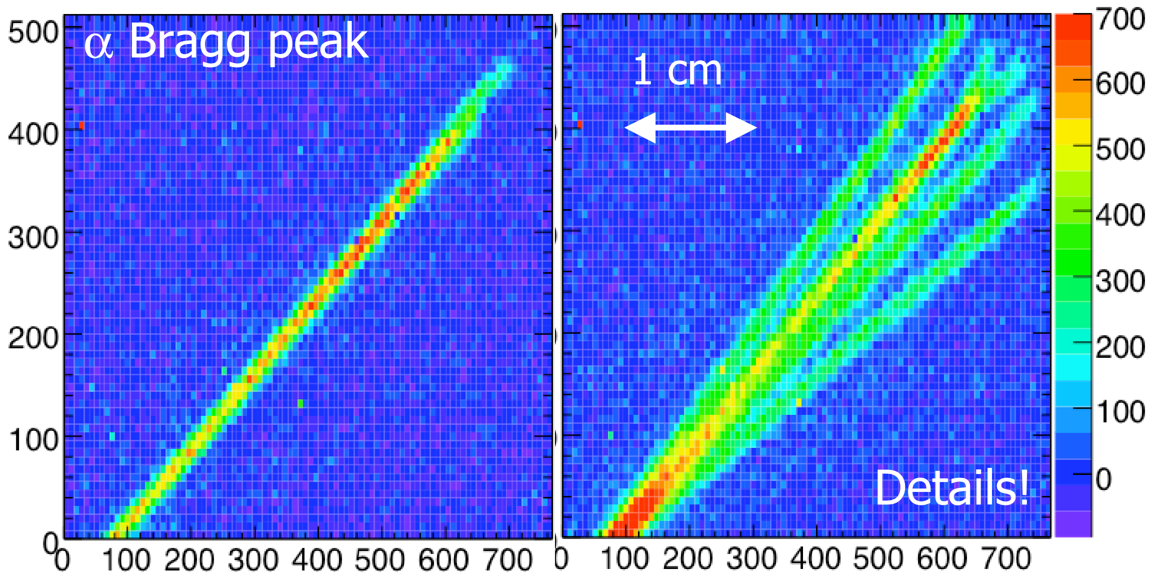
MC studies: 200 GeV WIMP



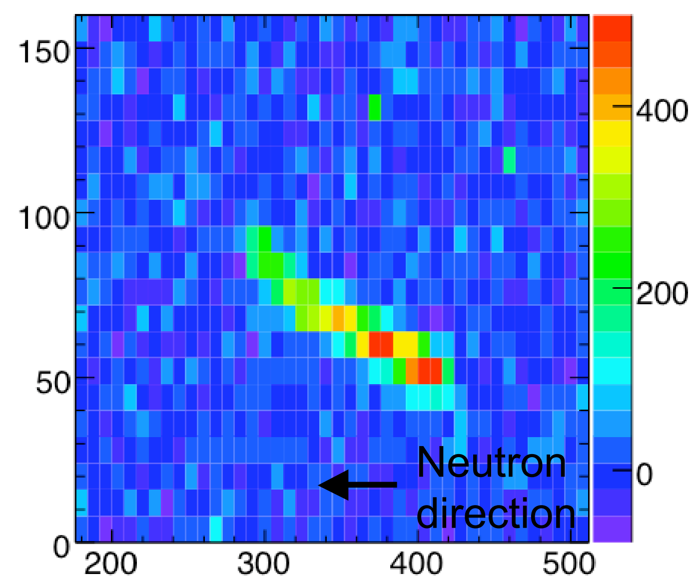
arXiv:0804.4827 [astro-ph]

Recent progress: mesh detectors

- Results shown so far obtained with wire-based detectors
- Recently we moved to mesh-based amplification region
  - 1D --> 2D at no additional cost!
  - Sensitive to a whole new level of details: "digital bubble chamber"
- Head-tail capability preserved



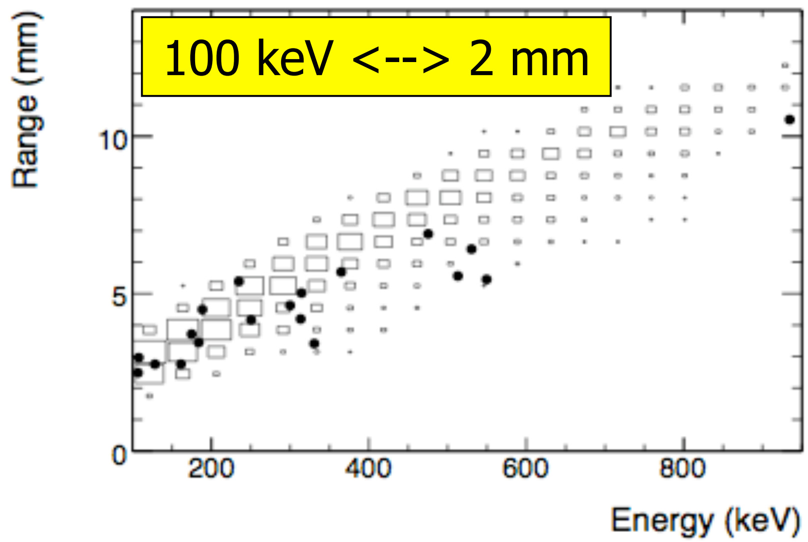
5.5 MeV alphas, 200 Torr, V_{anode}=2kV

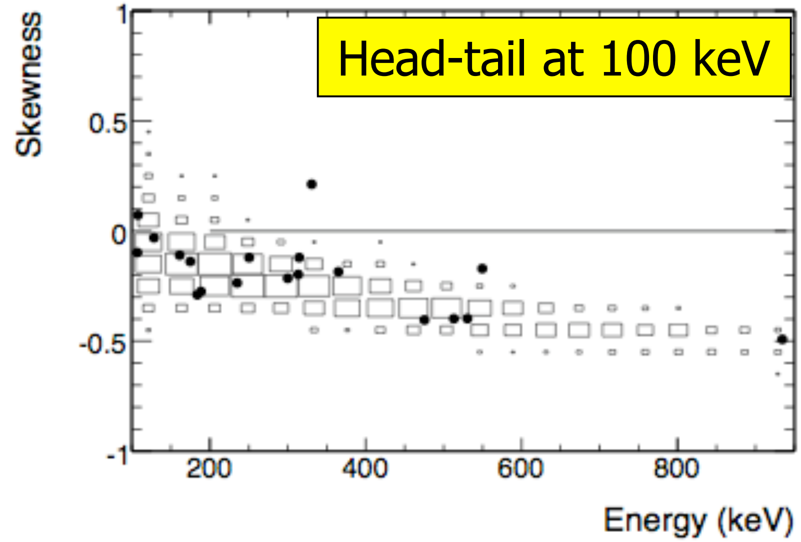


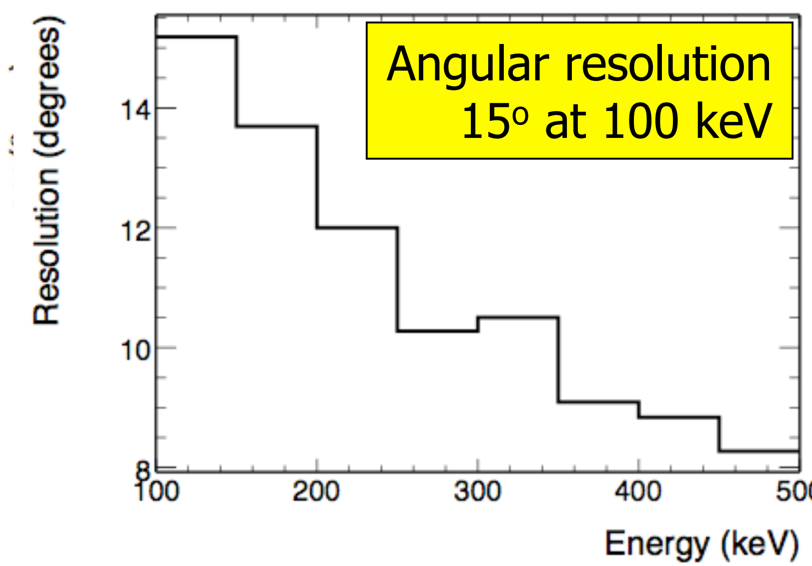
^{252}Cf neutrons, 100 Torr

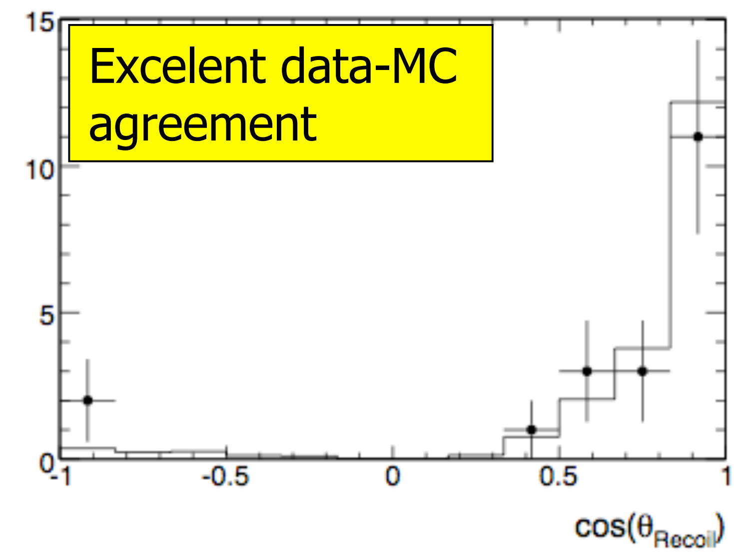
arXiv:0804.4827 [astro-ph]

Mesh detector: ^{252}Cf run @ 75 torr









Next step: ~ m^3 detector

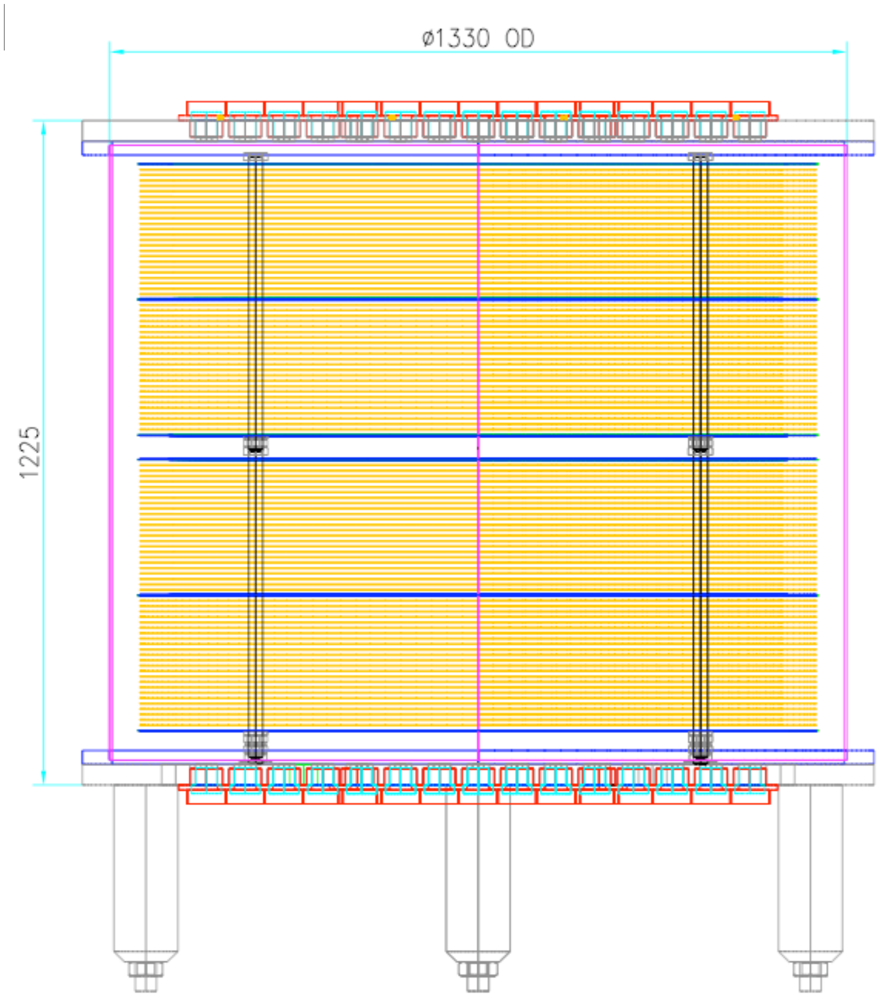
- Goals
  - Prove detector technology on realistic scale
  - Underground backgrounds studies
  - Set scientifically competitive limit on spin-dependent interactions with directionality

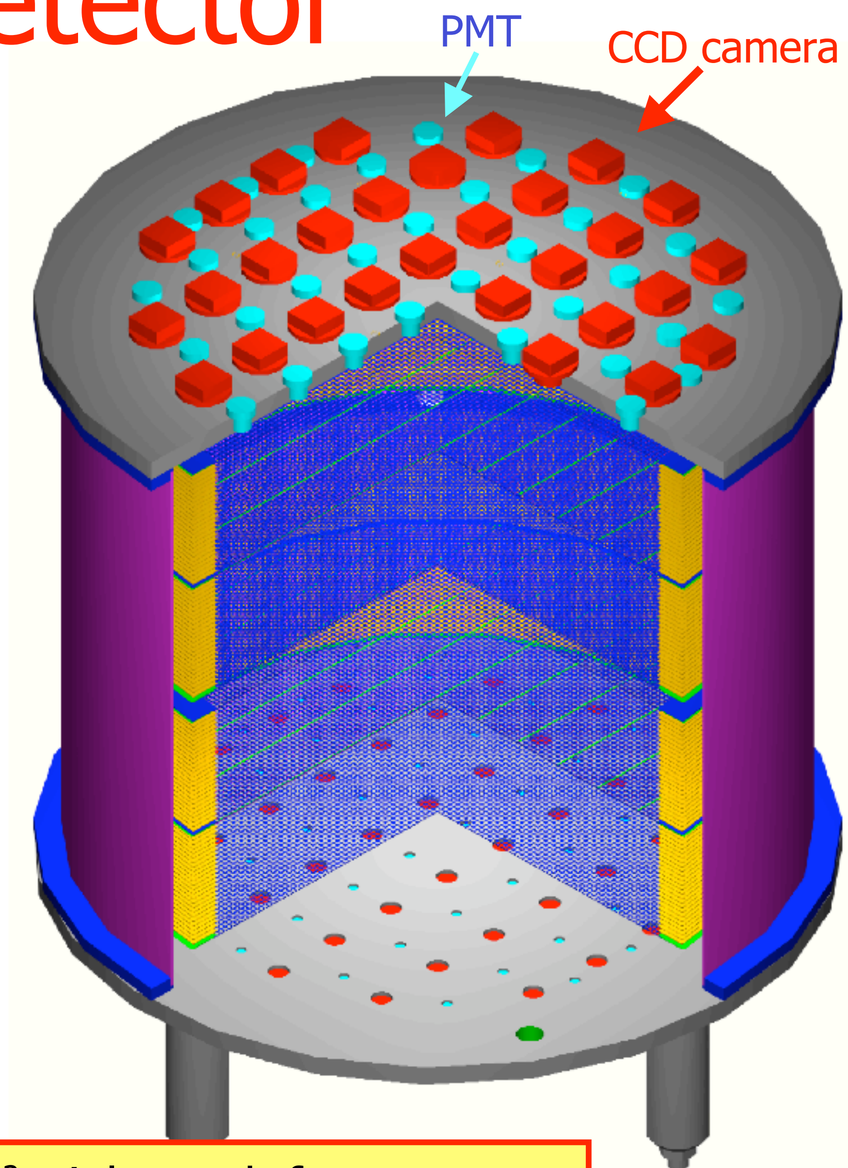
- Mass: 250-500 g/m^3
  - 1 year underground run: 90-180 kg-day / m^3

- Timescale:
  - Design and build: 2008
  - Commissioning and underground run: 2008-2009

Preliminary

Example: 1 m³ detector

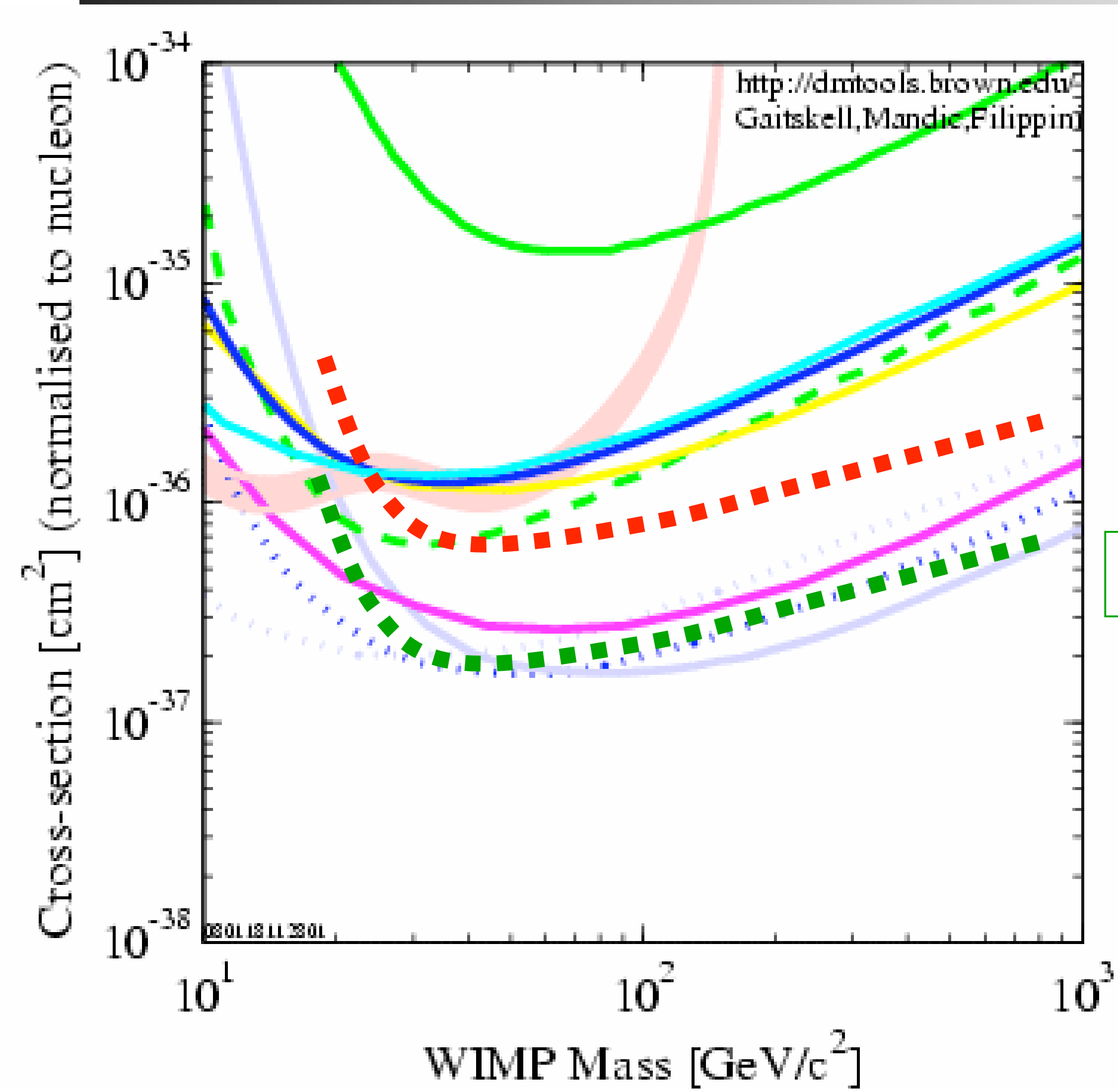




- 2 units --> 2 x (2 x 25) cm drift regions; 1m² triple mesh frames
- ~40 low-cost CCD cameras/plane; KAI220 chip & 0.95/25 lens; 20°C

Very preliminary

Sensitivity of 1 m^3 detector (surface run)



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 (1 m^3)

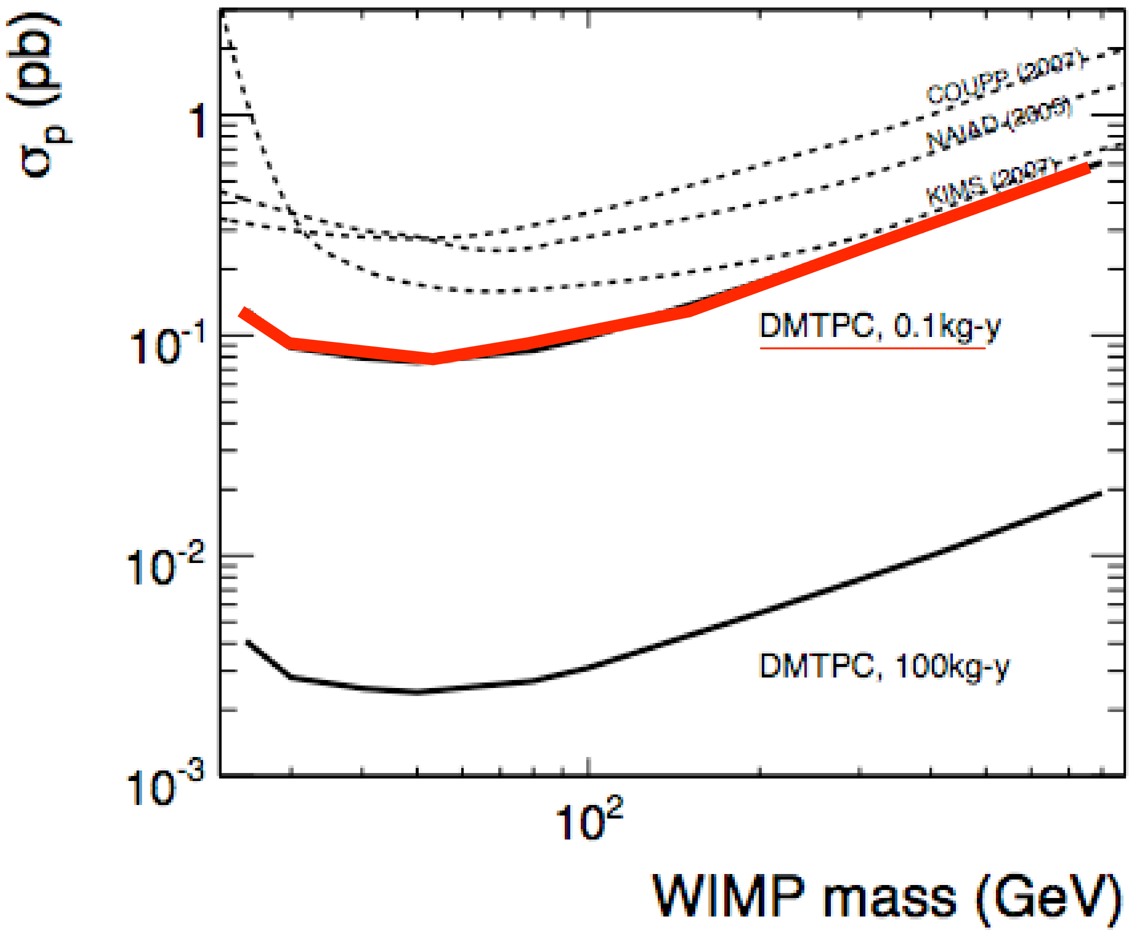
- - - - - DM-TPC (4 m^3)

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

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
- ~1 m^3 module (2008-2009)
  - One year of data taking underground
    - Study backgrounds, perfect detector design
    - Competitive limit on spin-dependent cross-section w/directionality
- Large DM-TPC detector is an ideal candidate for DUSEL
  - Size: O(10^2 kg)
  - Second generation detector: not only unambiguous observation of WIMPs, but with directionality start of "WIMP astronomy"