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

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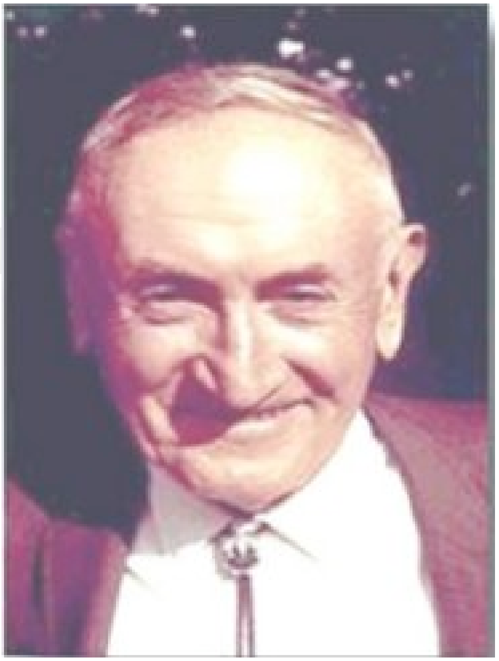
Outline:

- 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

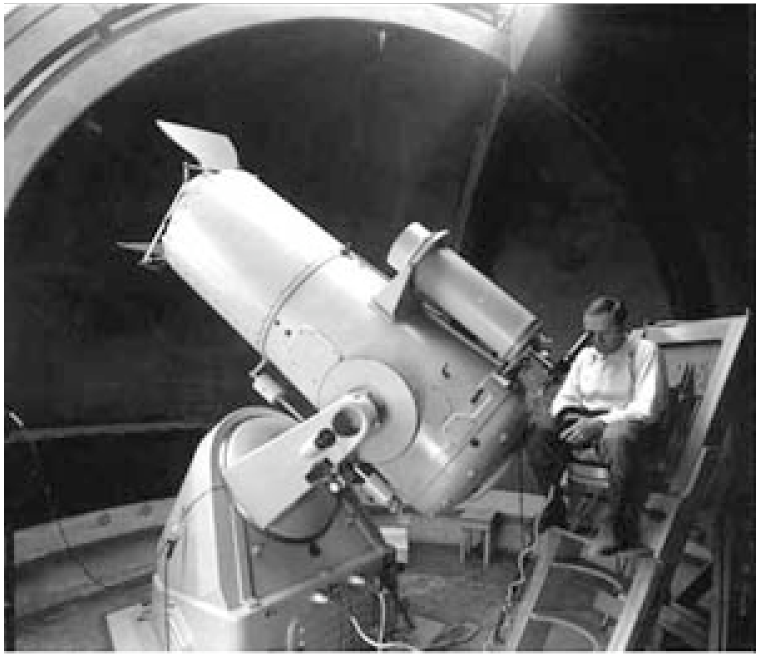
Orsay, Dec 16, 2008

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

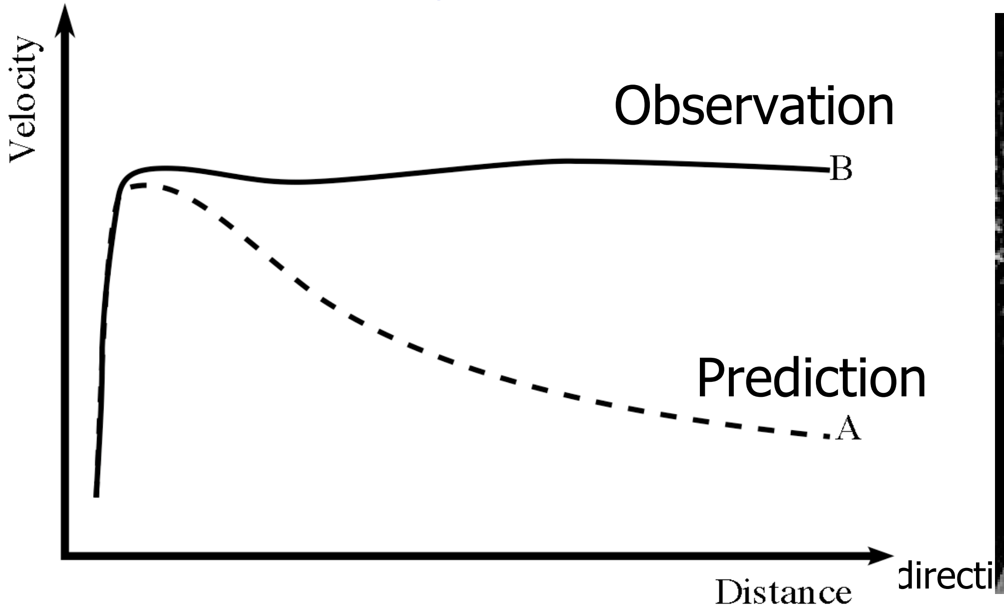
Strong evidence for DM

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…

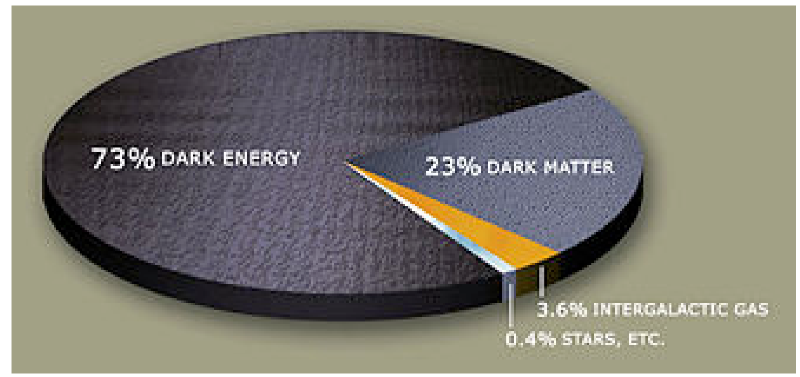
Bullet Cluster (2006)

- 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/STScl; ESO WFI; Magellan/U.Arizona/ D.Clowe et al
Optical: NASA/STScl; Magellan/U.Arizona/D.Clowe et al.;

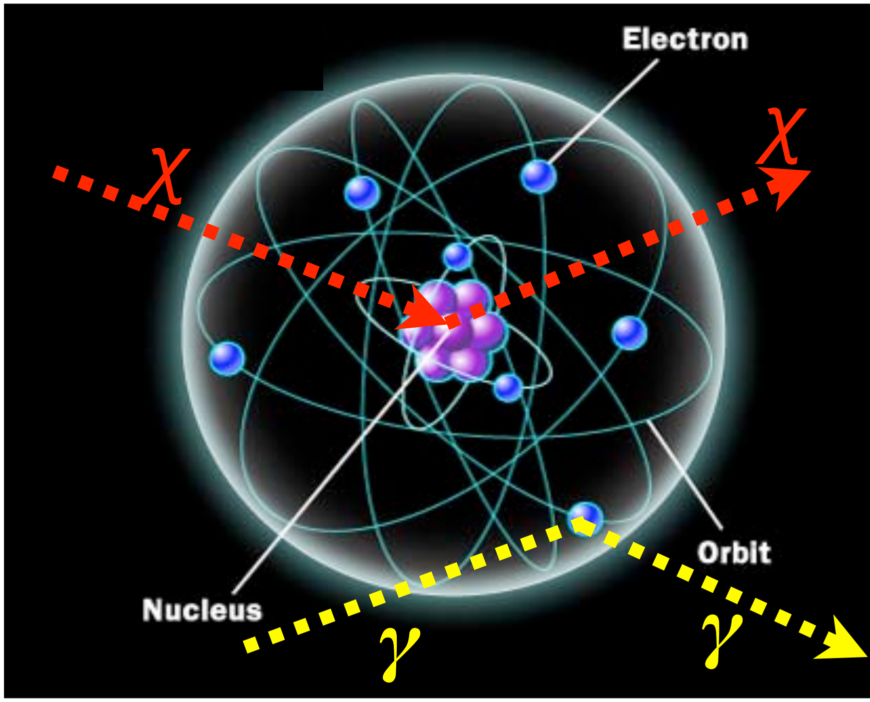
What is Dark Matter made of?

- 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:

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

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

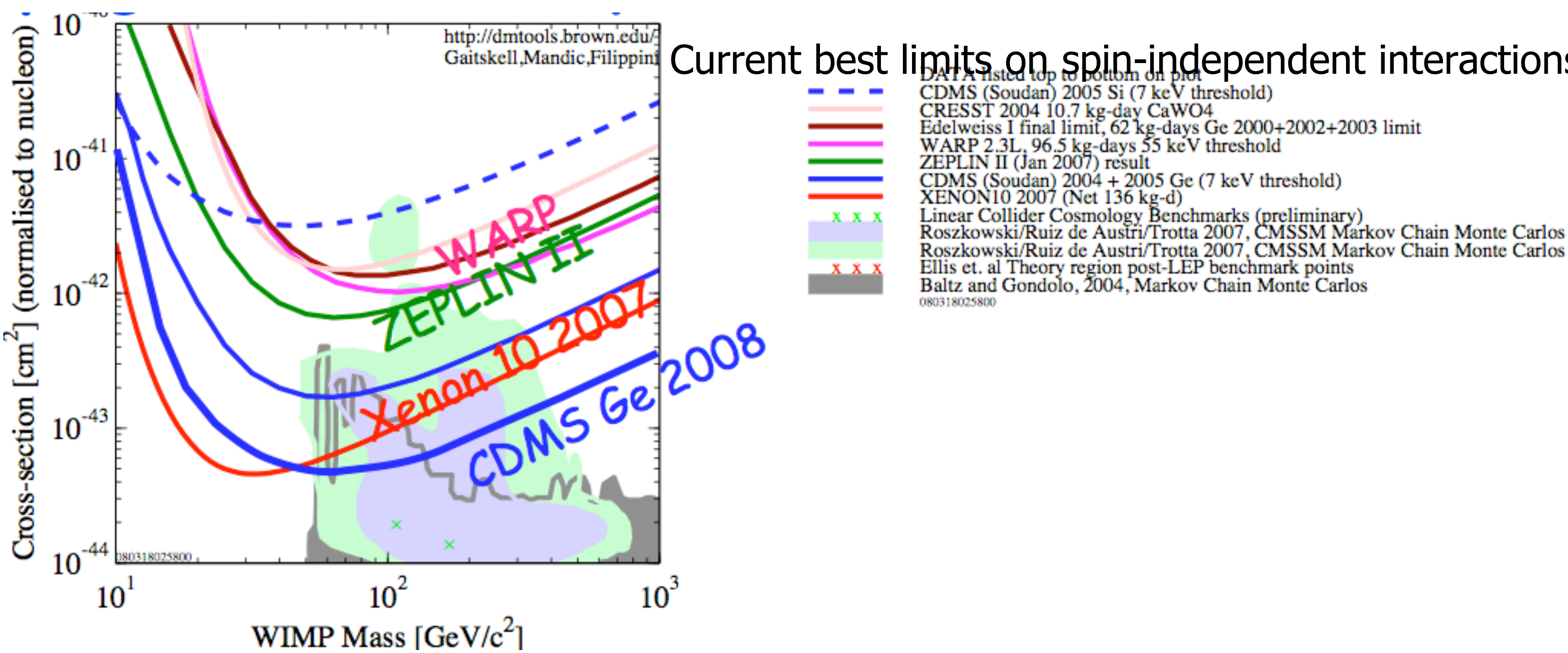
$$N \rightarrow N' + \alpha, e^-$$

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

- 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

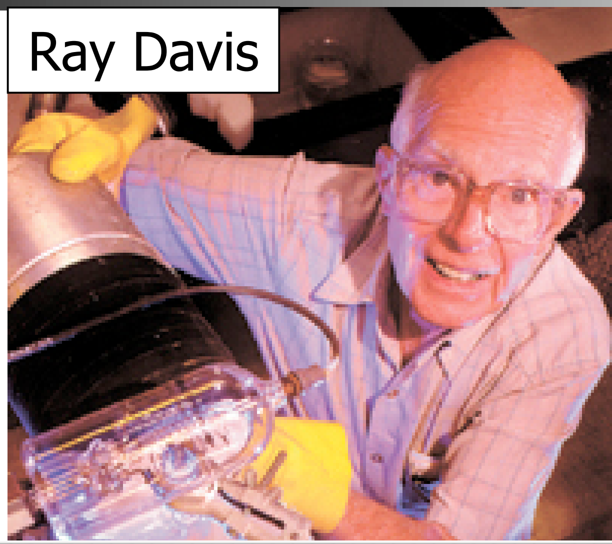
Current best limits on spin-independent interactions

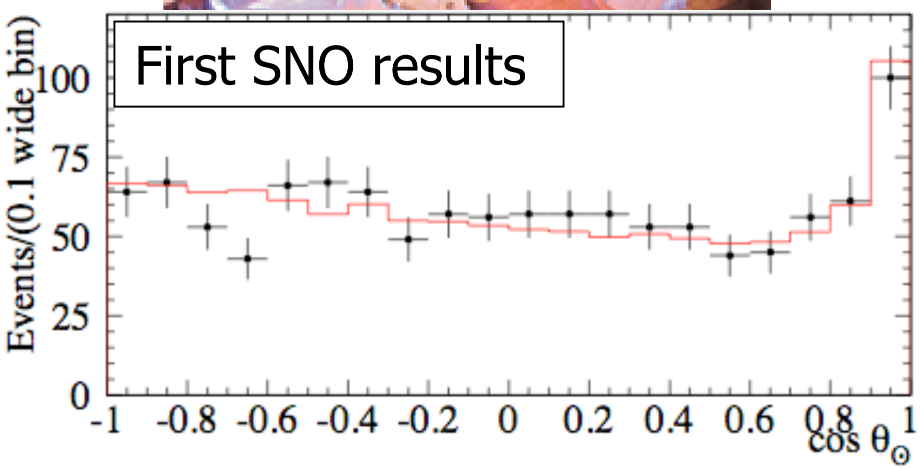


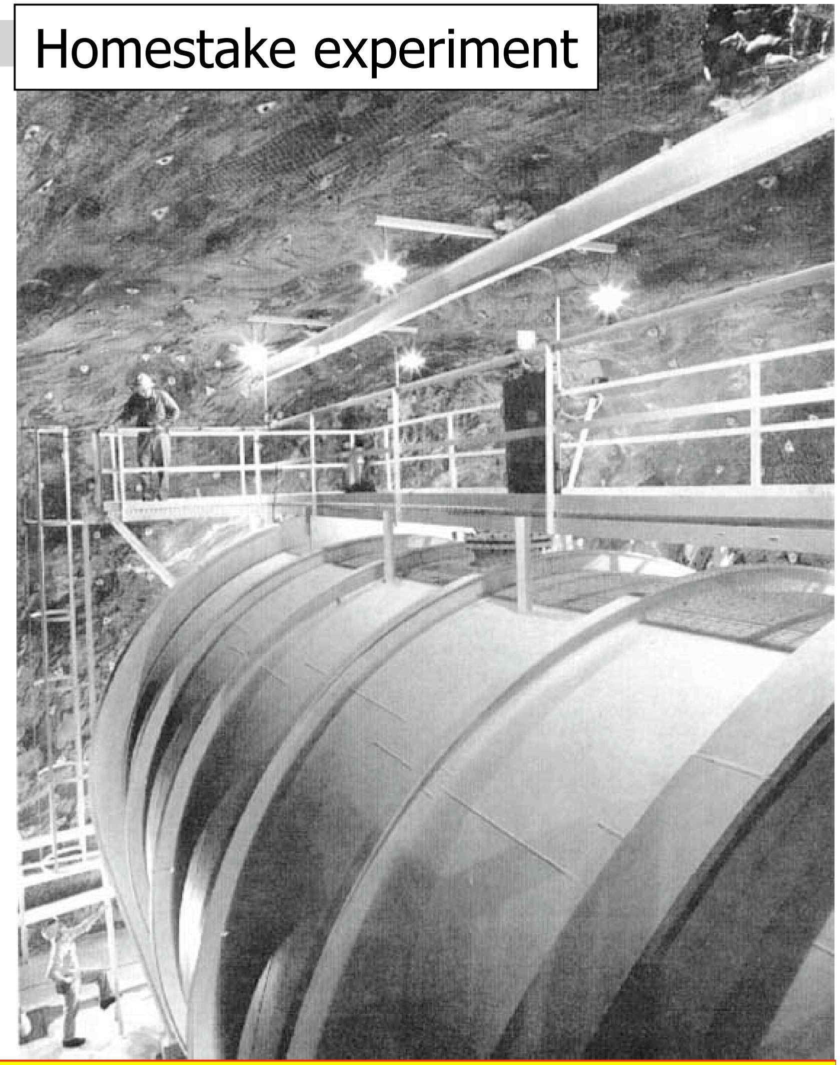
- Many experiments engaged in direct detection of DM
  - Recent progress: improved cross-section limits $\sigma_{SI} < 10^{-44}$-10^{-43} cm^2
- Intrinsic limitation of mainstream DM experiments
  - Counting experiments: zero-background assumed
  - Larger detectors will start to see several (irreducible)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

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

Situation similar to neutrino oscillations…



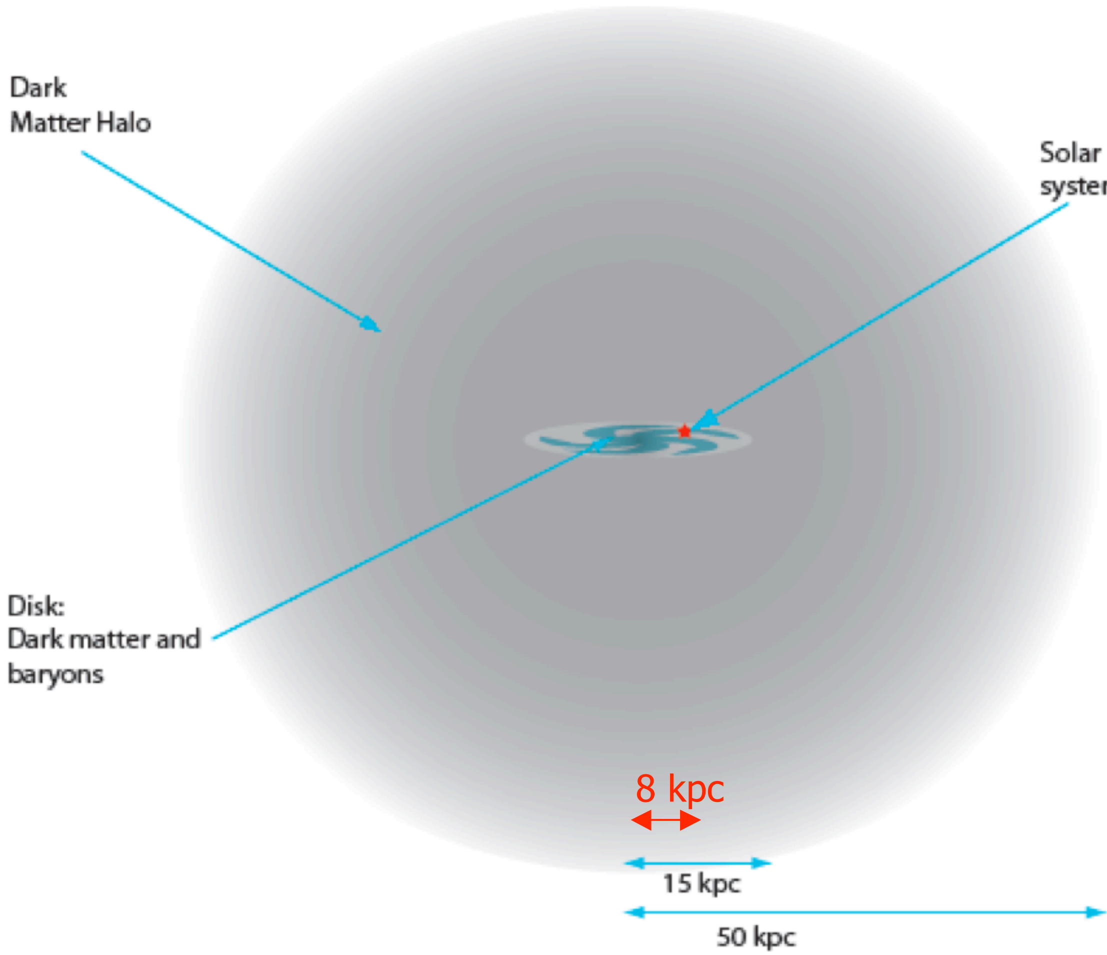




Oscillation of solar ν first observed by Davis in the 60's in counting experiment, but decisive proof came in 2001 with water Cherenkov directional results

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

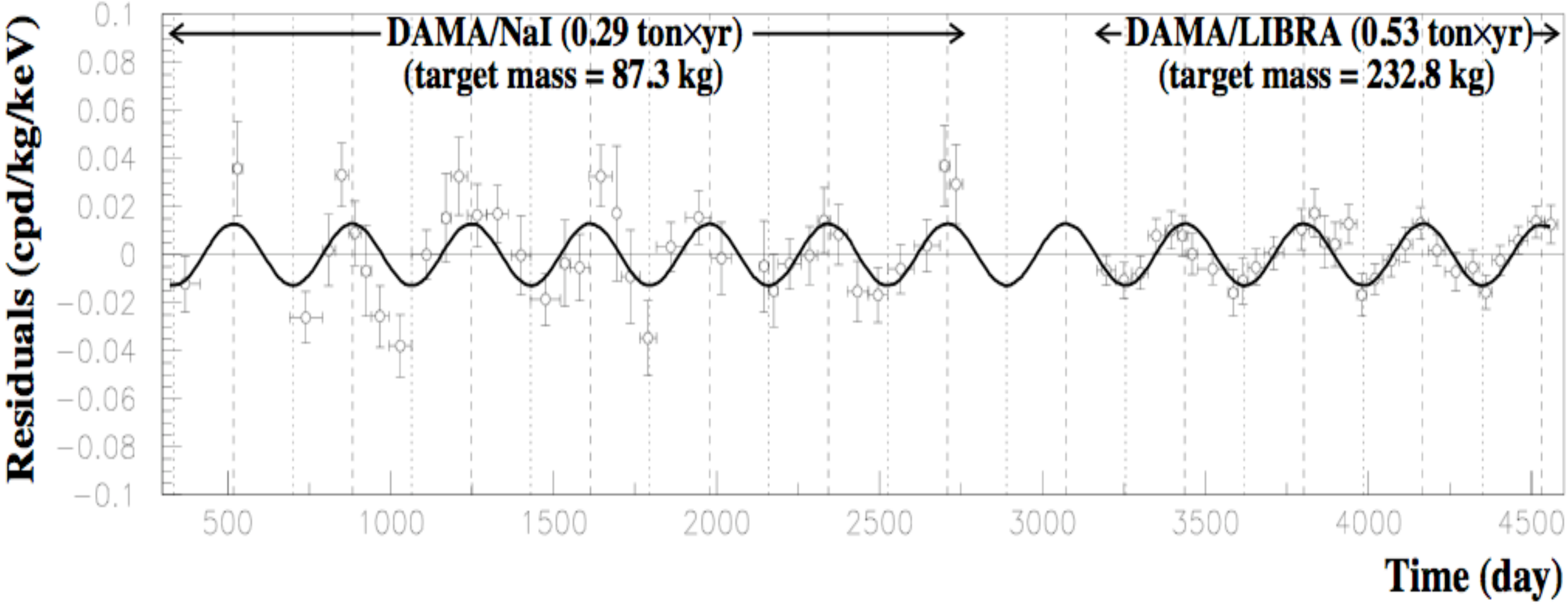
The decisive proof of positive observation of DM requires correlation with astrophysical phenomena

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??

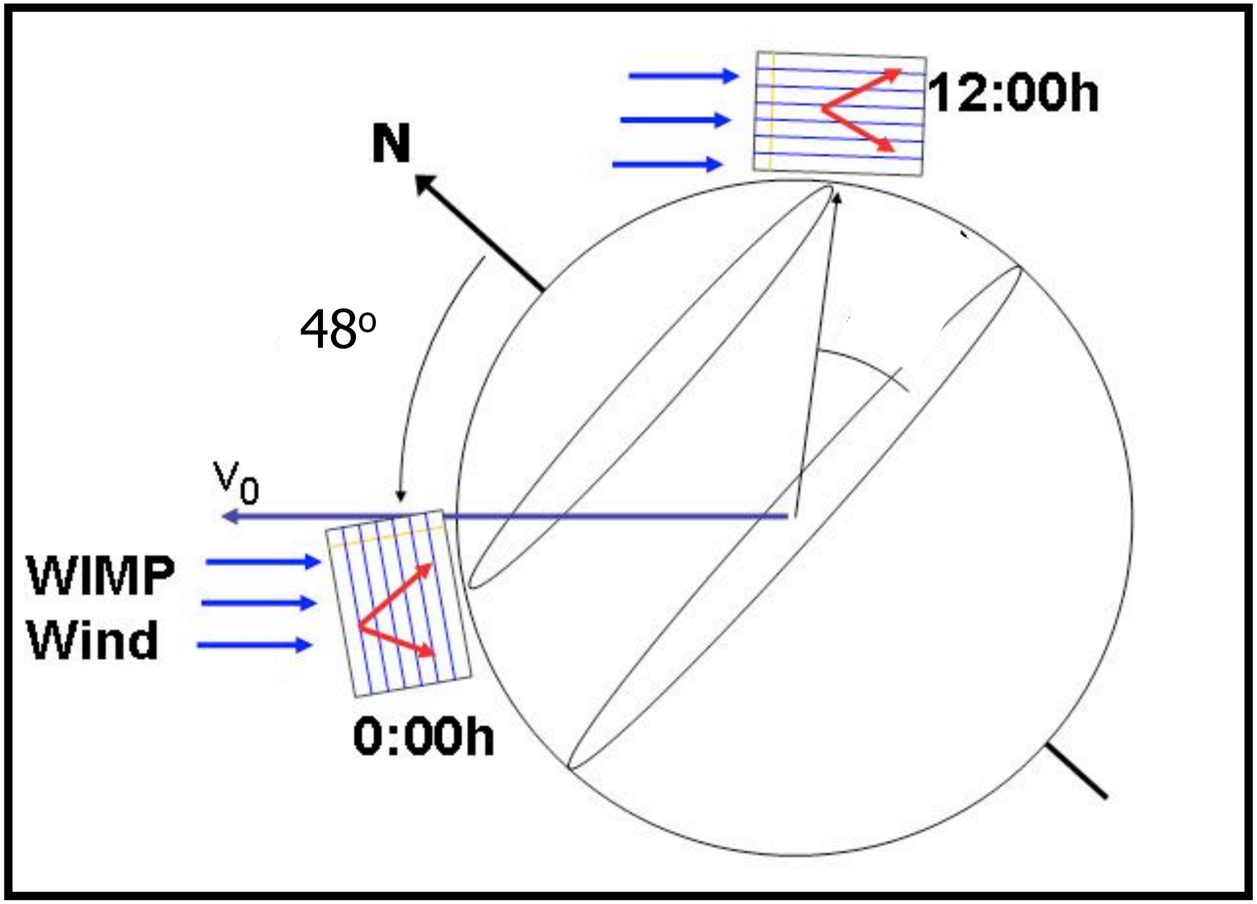
Yearly asymmetry:

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

Spergel PRD 37,1353 (1988)

Unambiguous signature of Dark Matter

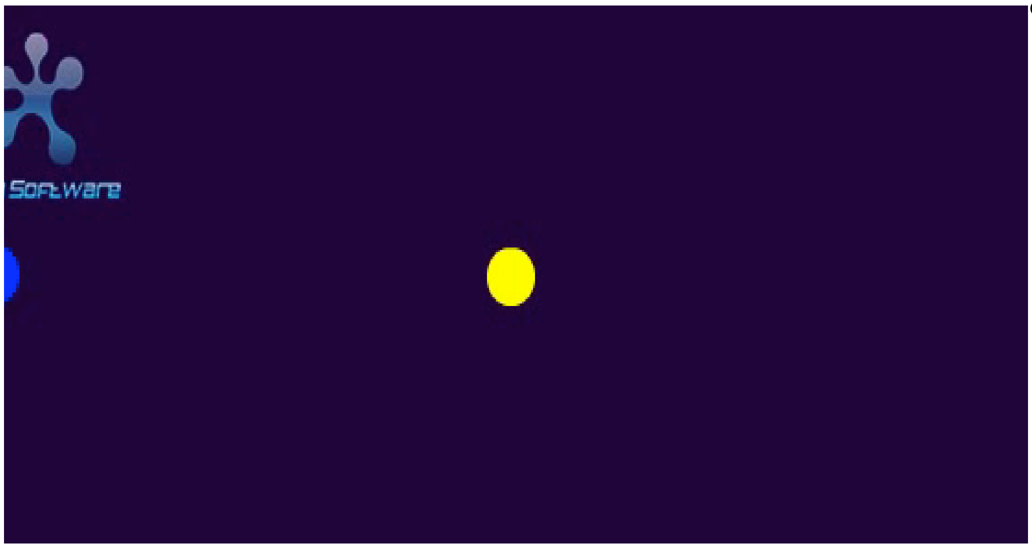
Daily asymmetry~30-100%!

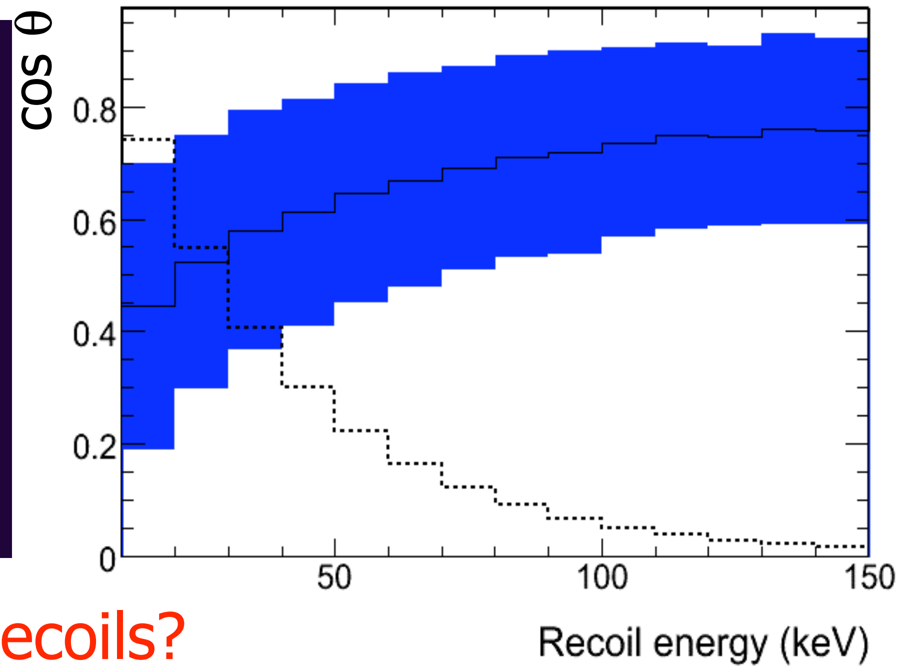


Only directional detection can correlate with Cygnus:
unambiguous positive observation of Dark Matter in presence of backgrounds

Directional Detectors

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



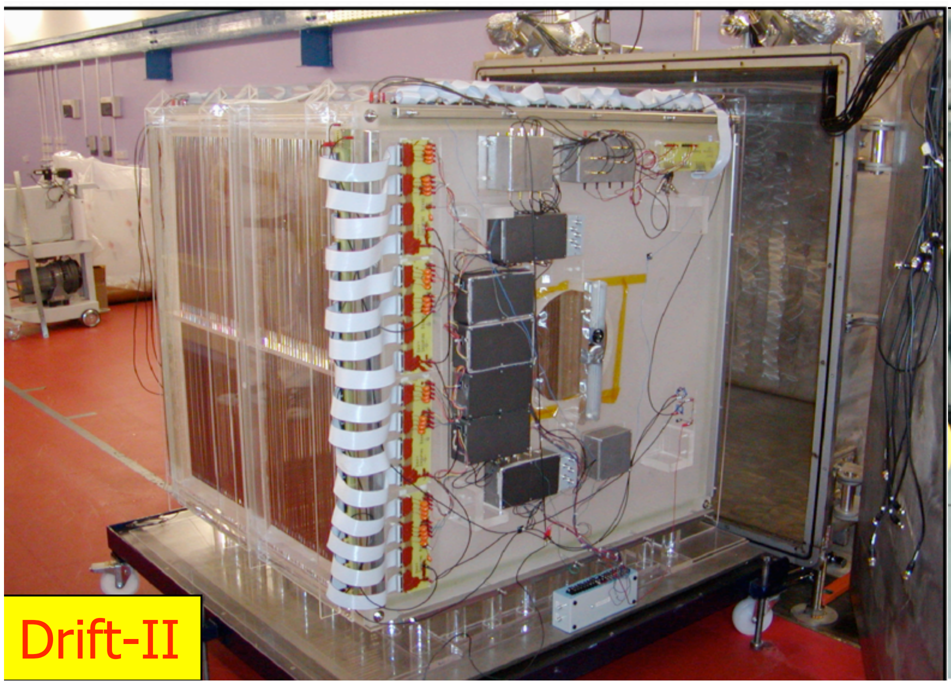


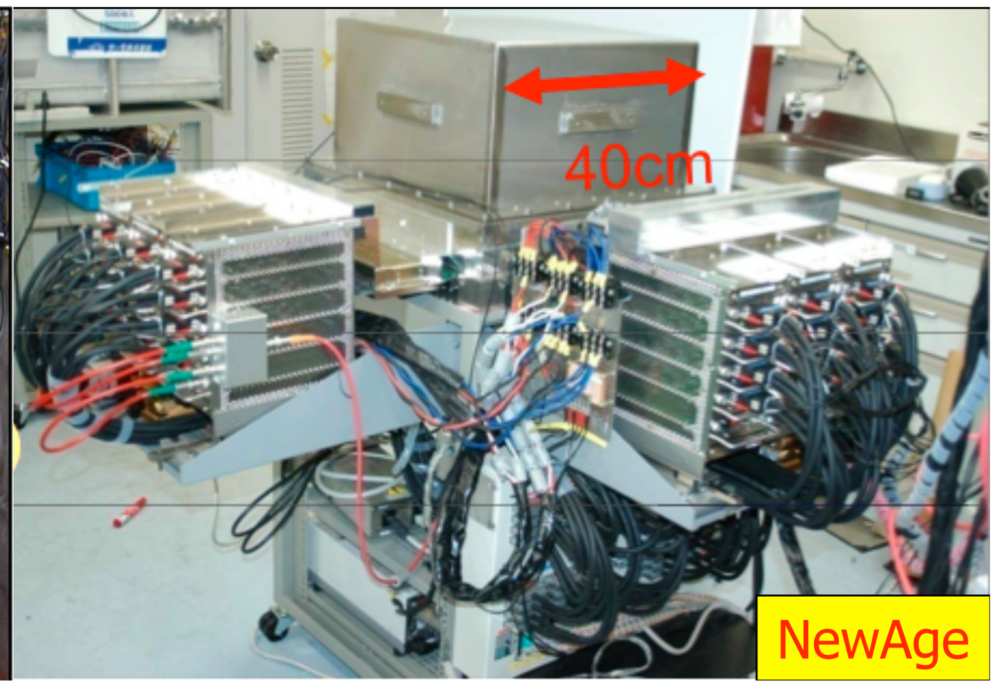
- How to detect the direction of recoils?
  - Low-pressure gaseous detectors
    - A 50 keV F in CF_4 @ 40 torr recoils ~2 mm

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-independent 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!

SD searches are promising and complementary to other DM efforts

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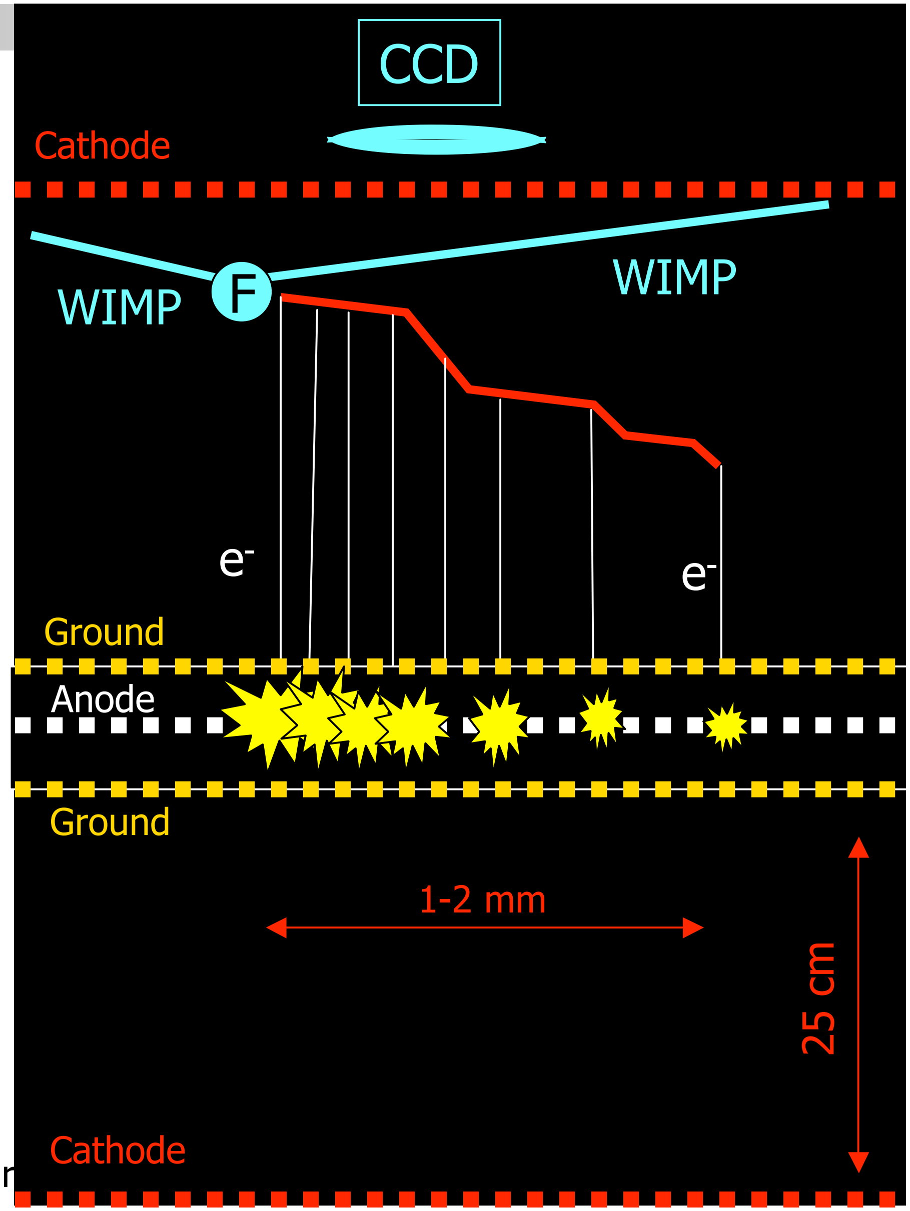
Note:
* indicates undergraduate students
[1] also Harvard University

DM-TPC: detector concept

- Low-pressure CF_4 TPC
  - 50-100 torr → 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
    - $\# \gamma_{\text{scintillation}} \propto \# e_{\text{ionization}}$
  - 2D, low-cost, proven technology
- Amplification region (camera) serves 2 drift regions

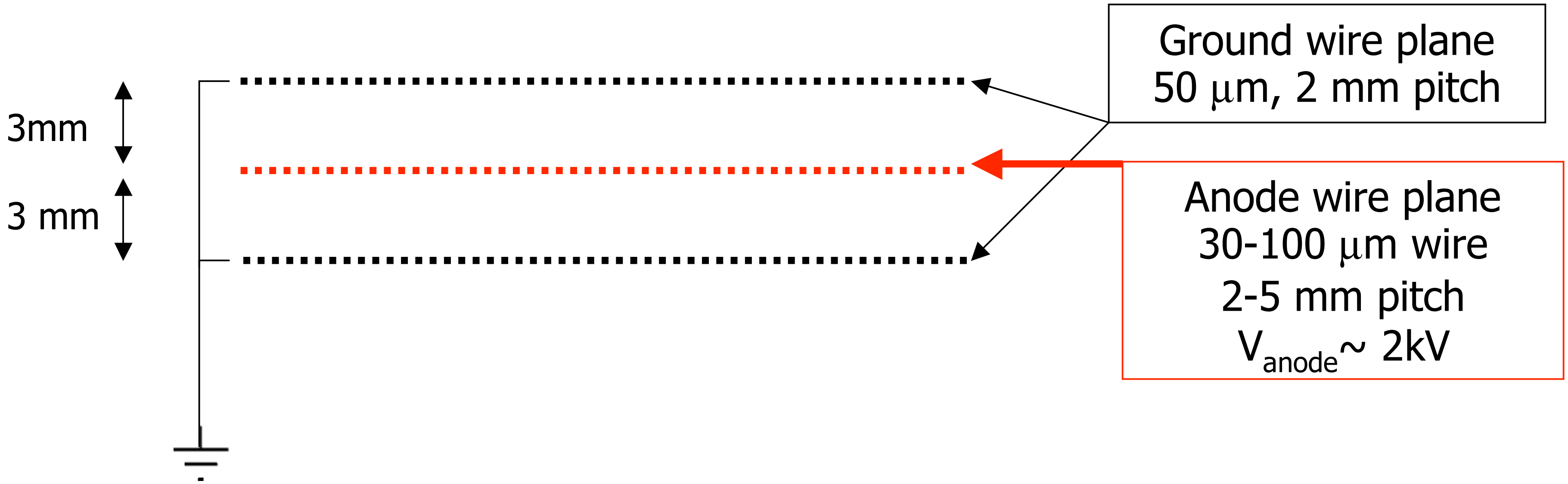


Animation by AnaMaria Piso

Detector concept

The amplification region

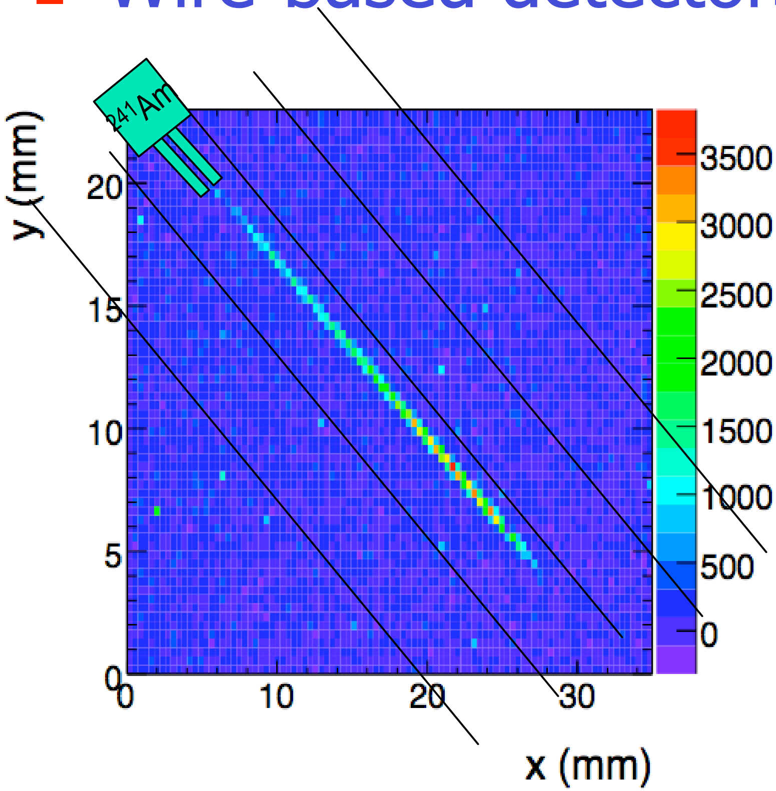
Original design: wire planes

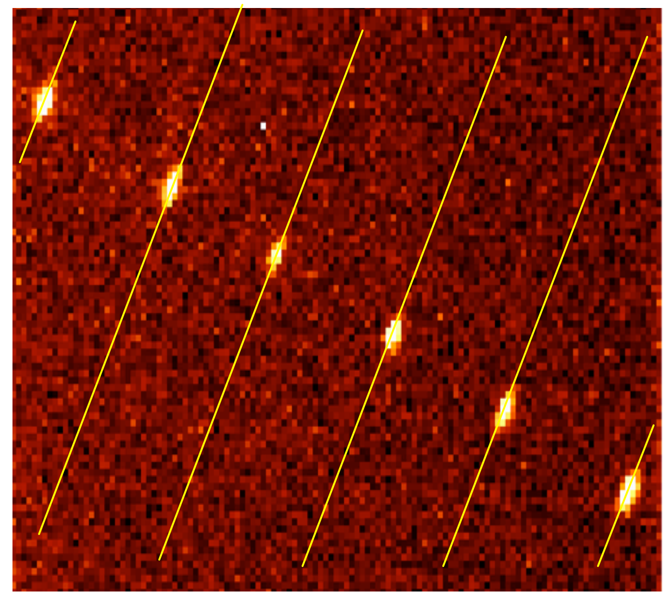


- Pros: simplicity, high gains (~10^4-10^5)

Limitations of wire-based amplification

- Wire-based detectors have serious limitations….





- 1D reconstruction of the recoil: not enough!

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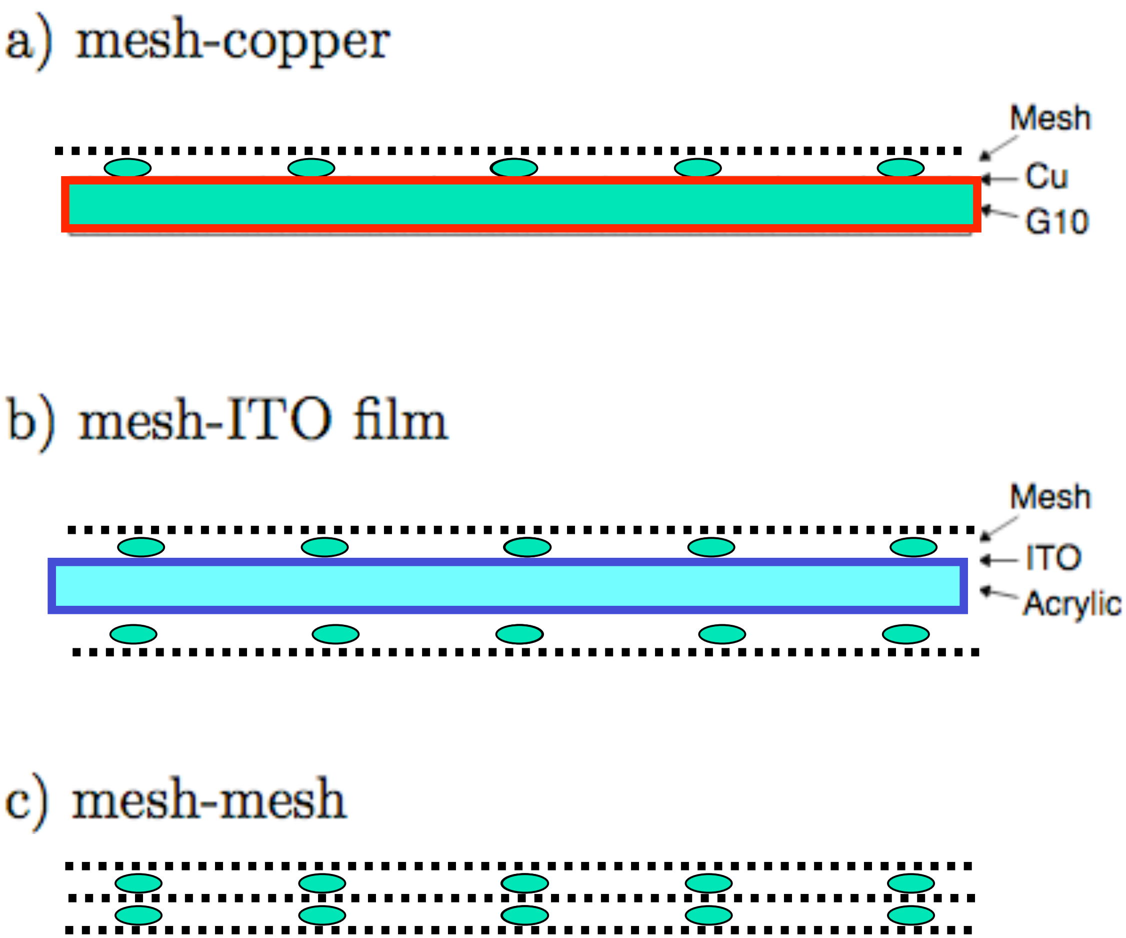
New amplification region: meshes

- Additional coordinate at no additional readout cost



Stainless steel woven mesh
- 28 μm, 256 μm pitch
- Optical transmittance 77%

Uniform spacing
- Fishing wire 0.54 mm Ø
- Pitch 2 cm

ITO: In2O3 (90%) SnO2 (10%)
- Optical transmittance 80%

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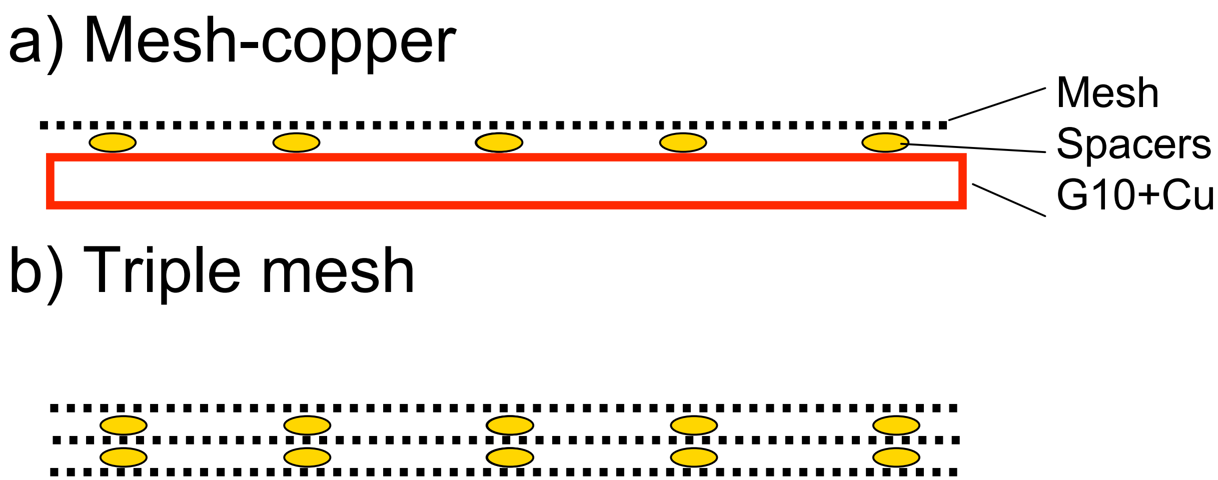
New amplification region: meshes

Additional coordinate at no additional readout cost



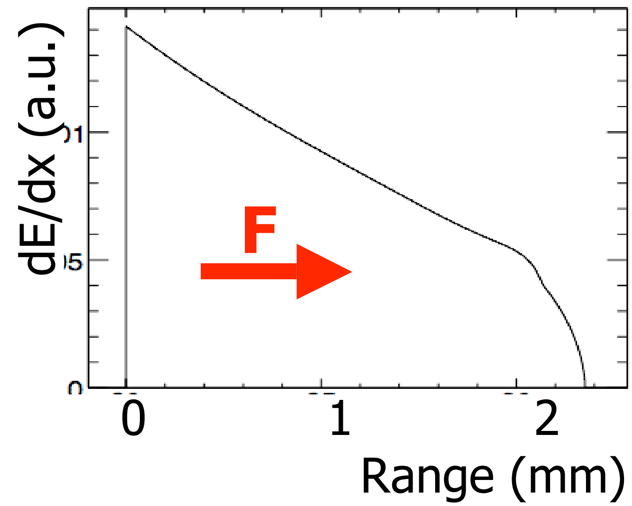
Stainless steel woven mesh
- 28 μm, 256 μm pitch, optical transmittance 77%

Uniform spacing
- Fishing wire 0.54 mm Ø, Pitch 2 cm

What we measure

CCD cameras measure

- E_{recoil} from total scintillation light
  - Integral of CCD signal ($\sigma_E/E\sim10\%$)
- Reconstruct recoil track (in 2D)
  - Pattern recognition in CCD
- Sense of direction ("head-tail")
  - Gains an additional order of magnitude
    - Green&Morgan '06, Alenazi&Gondolo '08)
  - dE/dx <u>decreases</u> along recoil track
    - Low energy, below Bragg peak



Bragg curve for 80 keV F recoil from WIMP in CF_4

Additional info from PMTs

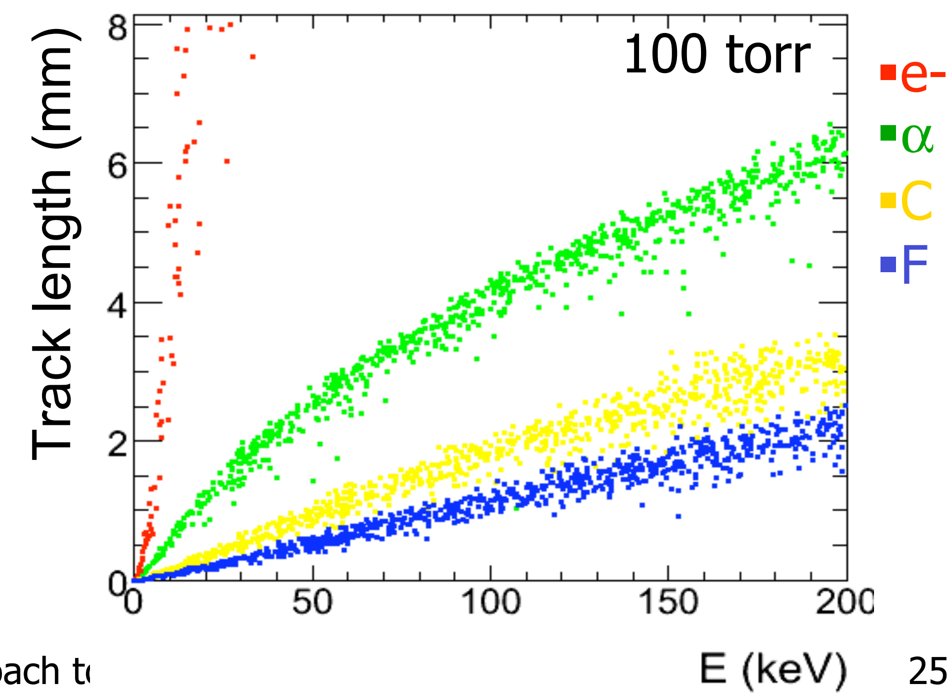
- 3rd coordinate of recoil (// v_{drift})
- Trigger

Electronic readout of the mesh

- Additional determination of E_{recoil} and trigger

Background rejection

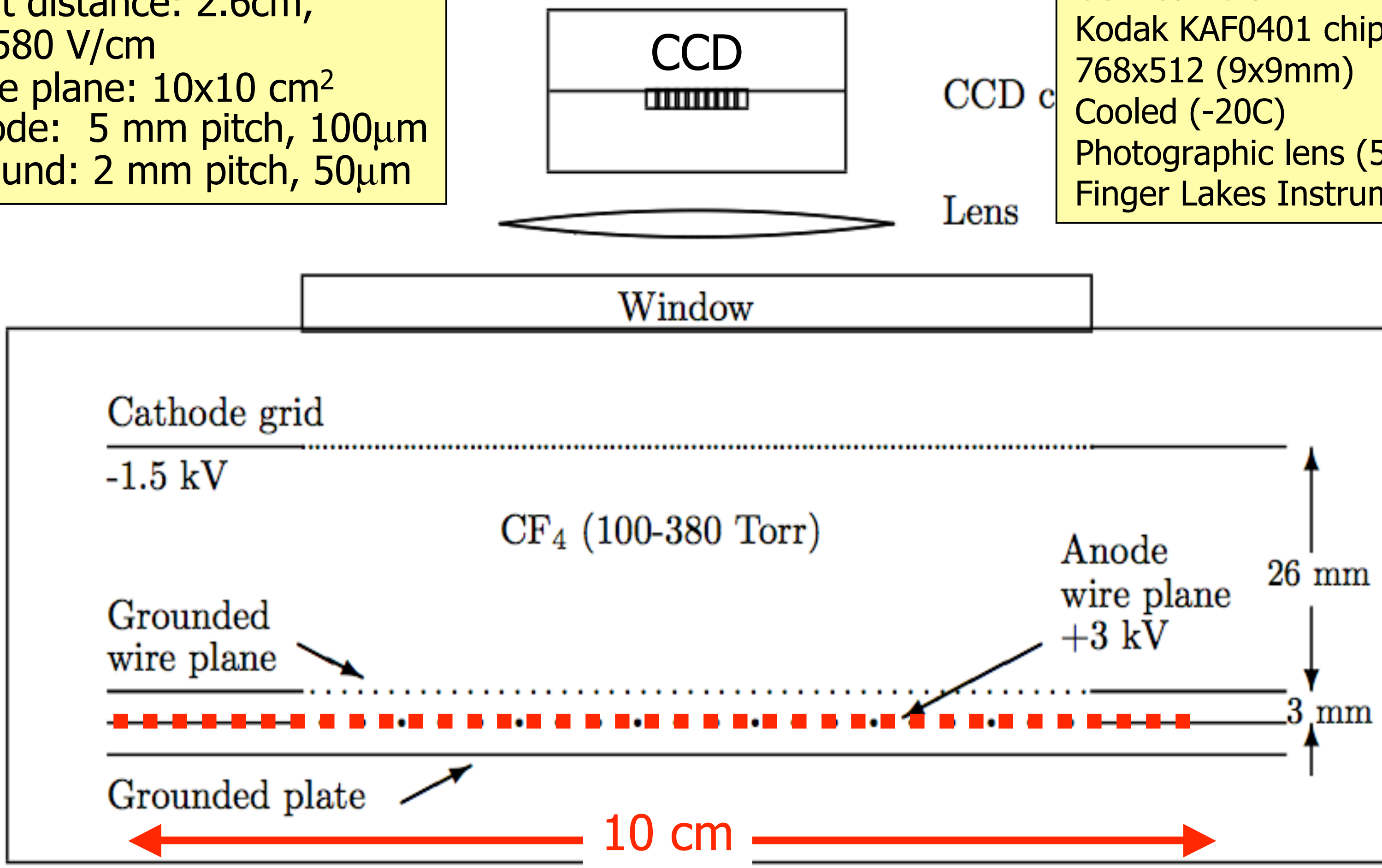
- Excellent rejection of gammas
  - 8 hours run with 8 μCi ^{137}Cs inside prototype: no evts
  - Rejection factor ~$2/10^6$ or better
- Excellent discrimination against α and e^-
  - By measuring both energy and length of recoil
- Neutrons
  - Underground cavern
  - Neutron shielding
    - Passive and active
  - Directionality!
- Neutrinos
  - Directionality!



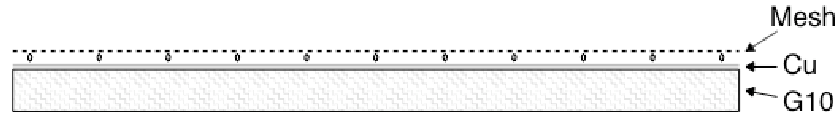
First generation prototype

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

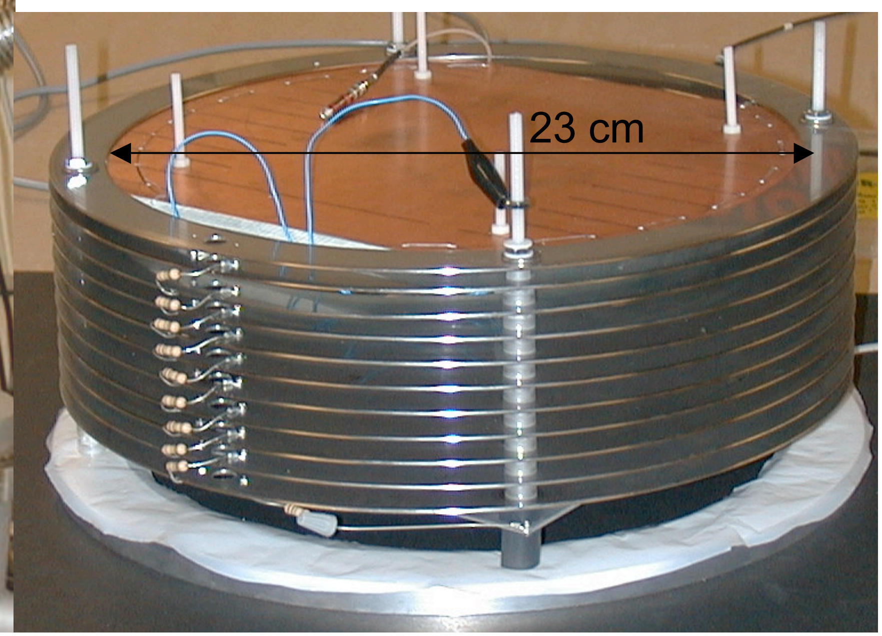
CCD Camera
Kodak KAF0401 chip
768x512 (9x9mm)
Cooled (-20C)
Photographic lens (55mm)
Finger Lakes Instrumentation



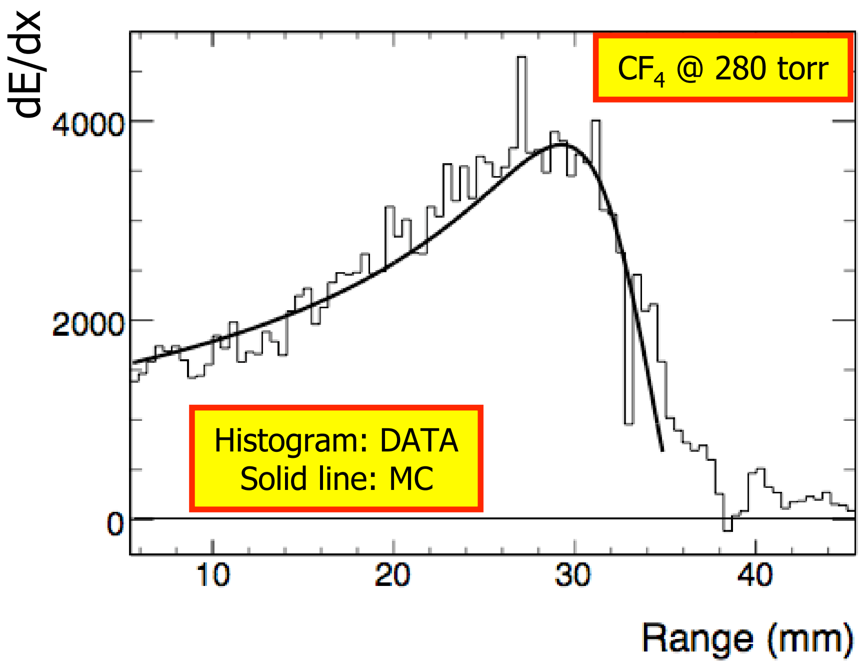
DM-TPC: 2nd generation prototype

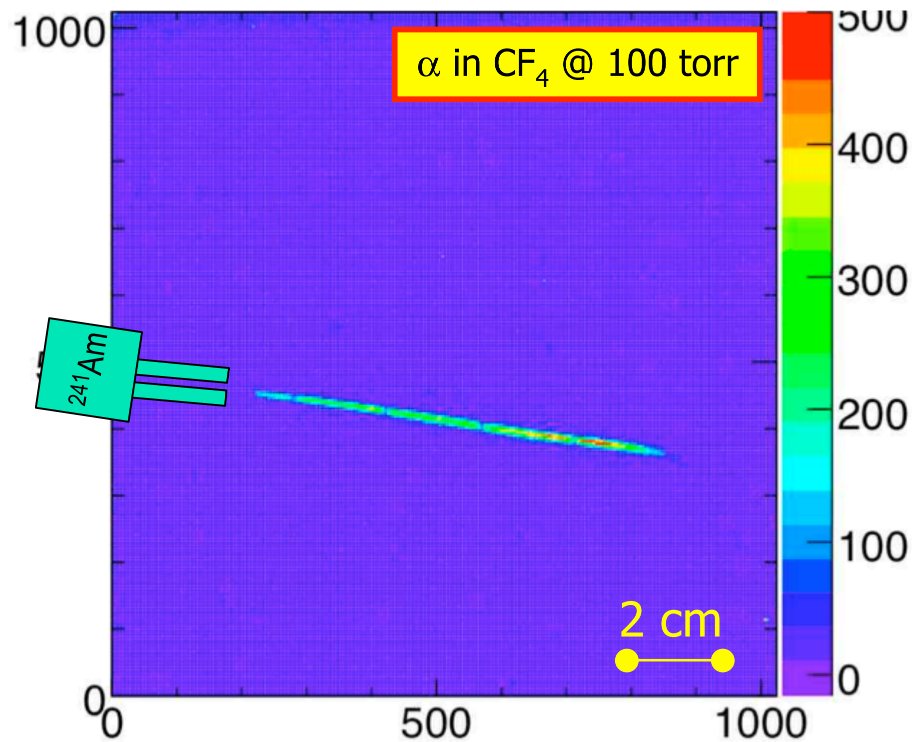


- Drift up to 25 cm
- Image view 16 cm Ø
- Mesh detector 23 cm Ø
  - 256 um pitch
  - 30 um wire Ø
  - 79% transparency



Bragg curve for 5.5 MeV α from ^{241}Am





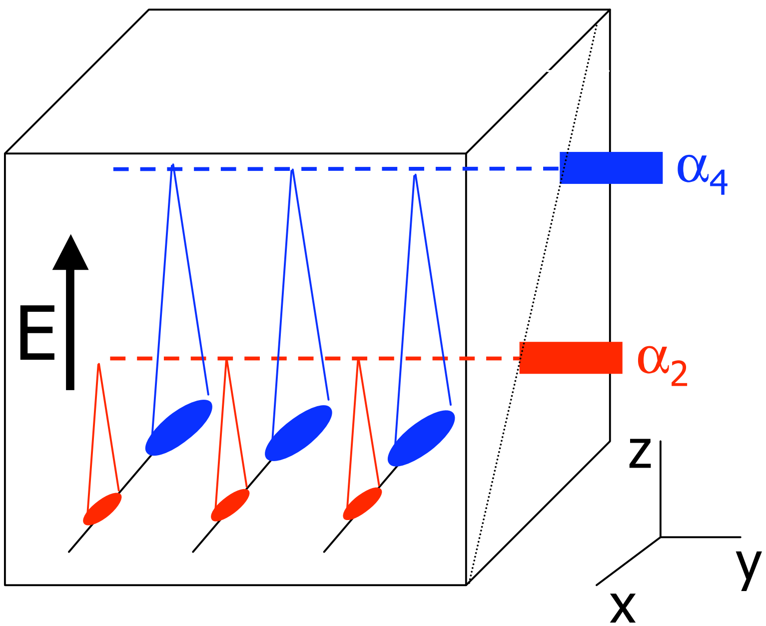
- Alphas emitted parallel to anode wires
  - Wire plane oriented at 45 degrees
- Compare measured dE/dx vs range of the track with SRIM simulation
  - Excellent DATA-MC agreement!

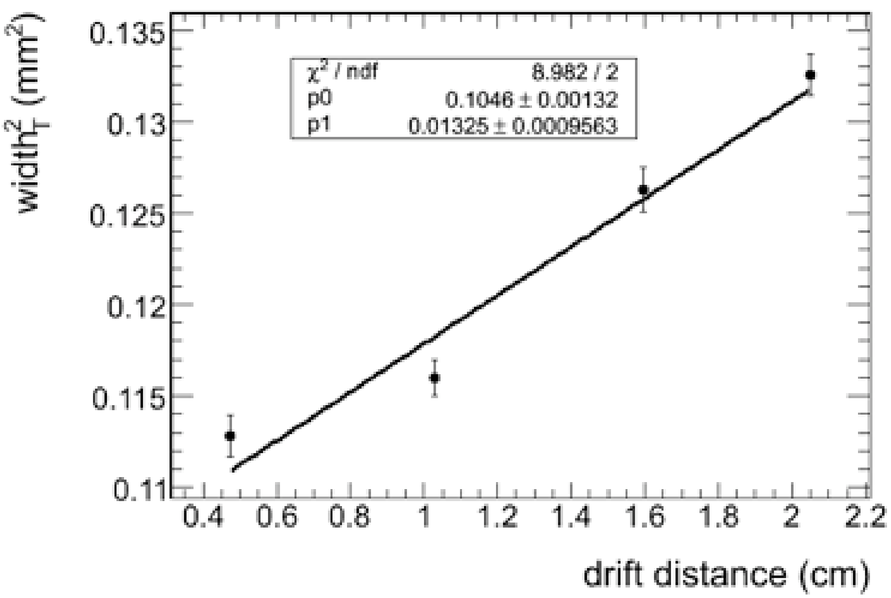
Well understood detector

NIM A584:327-333,2008

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





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

Drift distance	Resolution
1 cm	340 μm
25 cm	670 μm

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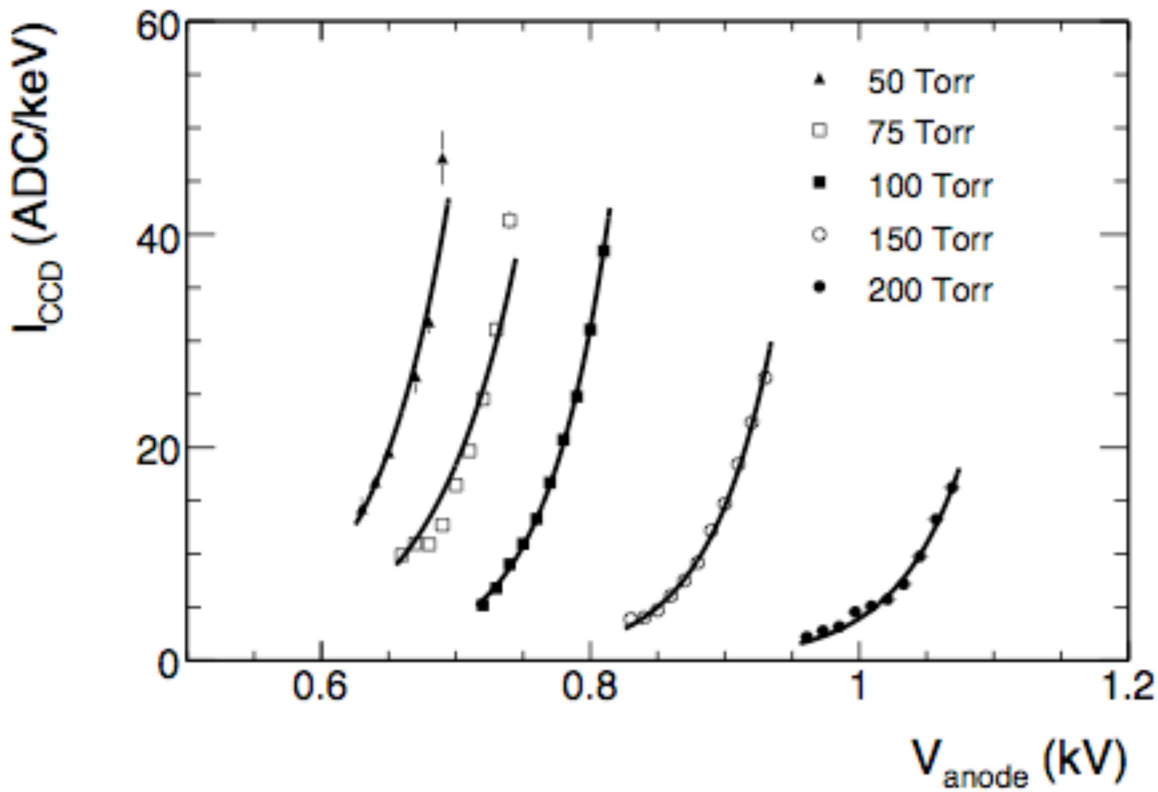
Light yield calibration with alphas

Photon yield/keV as a function of anode voltage

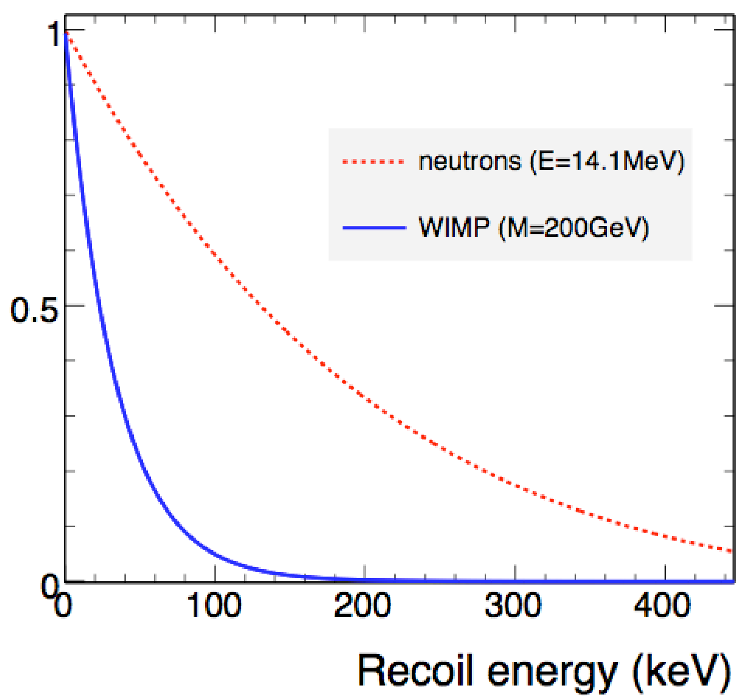


Stable operations for gas gain ~ 10^5

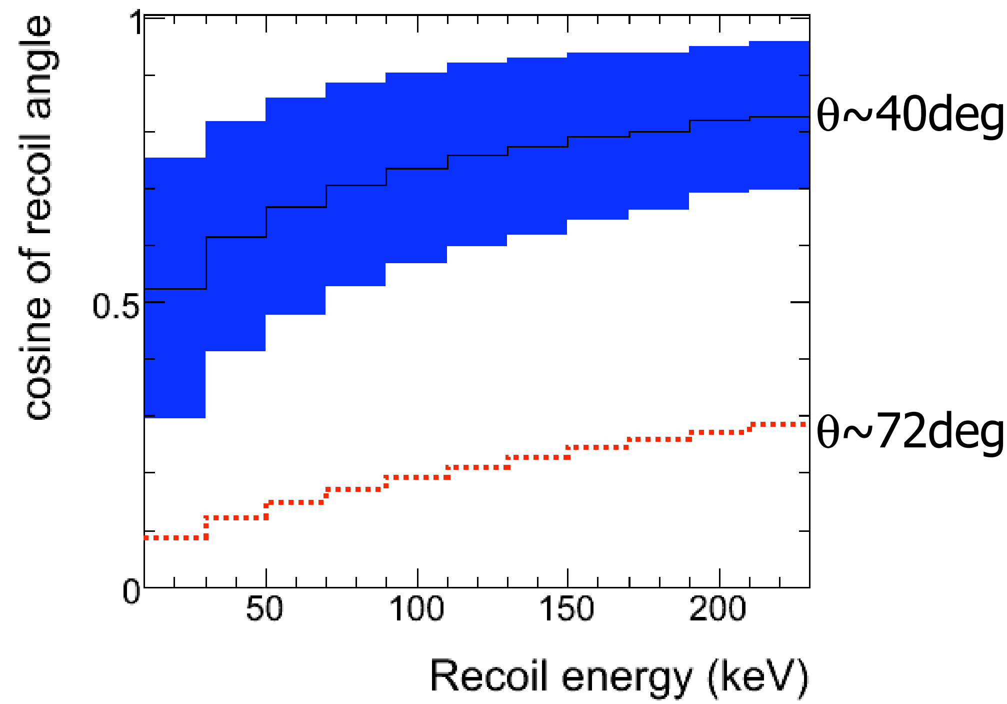
Recoils from low-energy neutrons

- Nuclear recoils by low-energy neutrons mimic Dark Matter
  - DM: F has lower energy but is better aligned with WIMP direction
- Neutron source #1: 14 MeV neutrons from D-T tube

Fluorine recoil energy

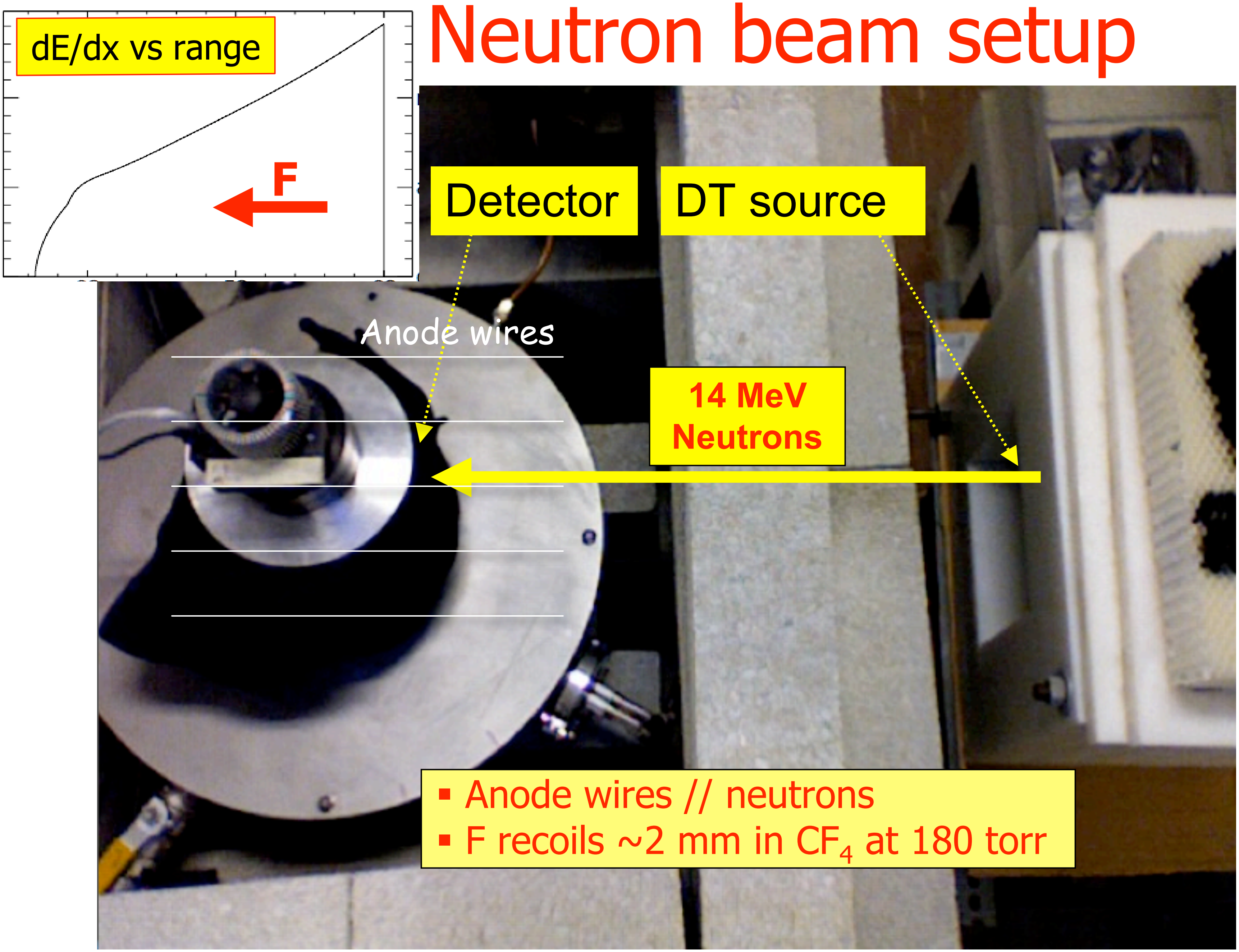


Fluorine recoil angle wrt wires



Blue band = spread in WIMP direction

Neutron beam setup

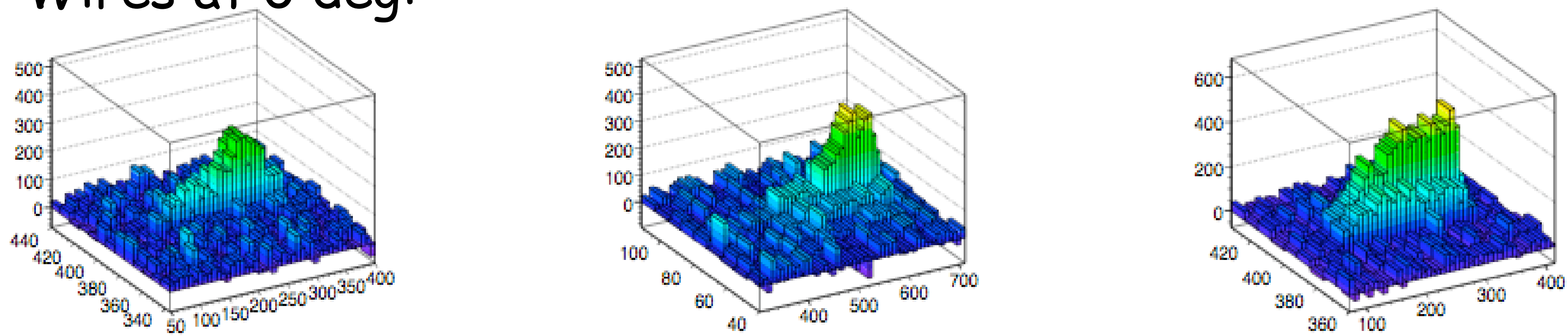


- Anode wires // neutrons
- F recoils ~2 mm in CF_4 at 180 torr

NIM A584:327-333,2008

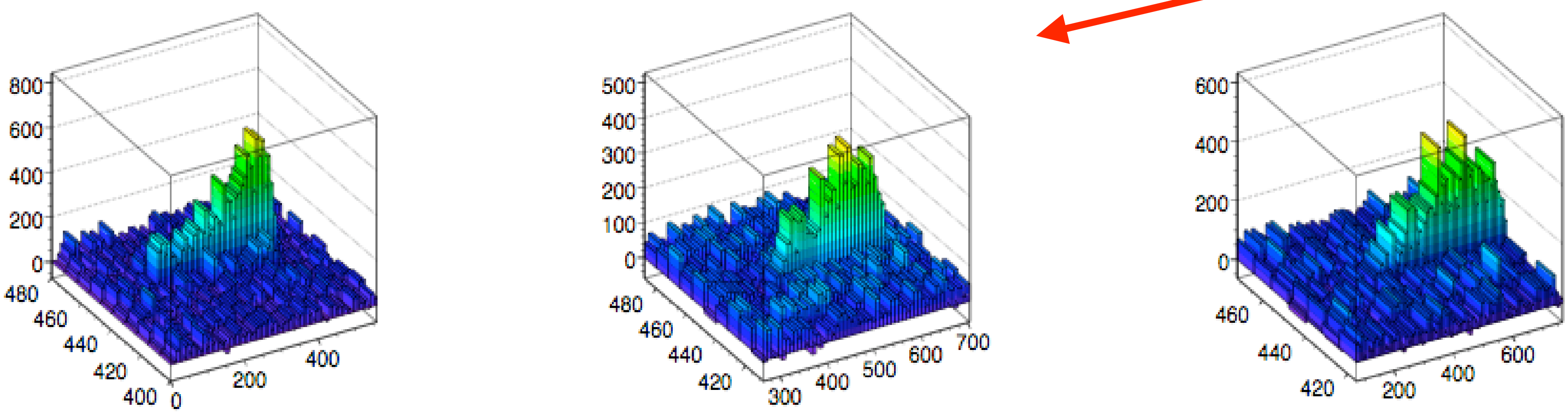
Observation of "head-tail" in F recoils

Wires at 0 deg:



Wires at 180 deg:

Direction of neutrons



ICHEP '07, CYGNUS '07

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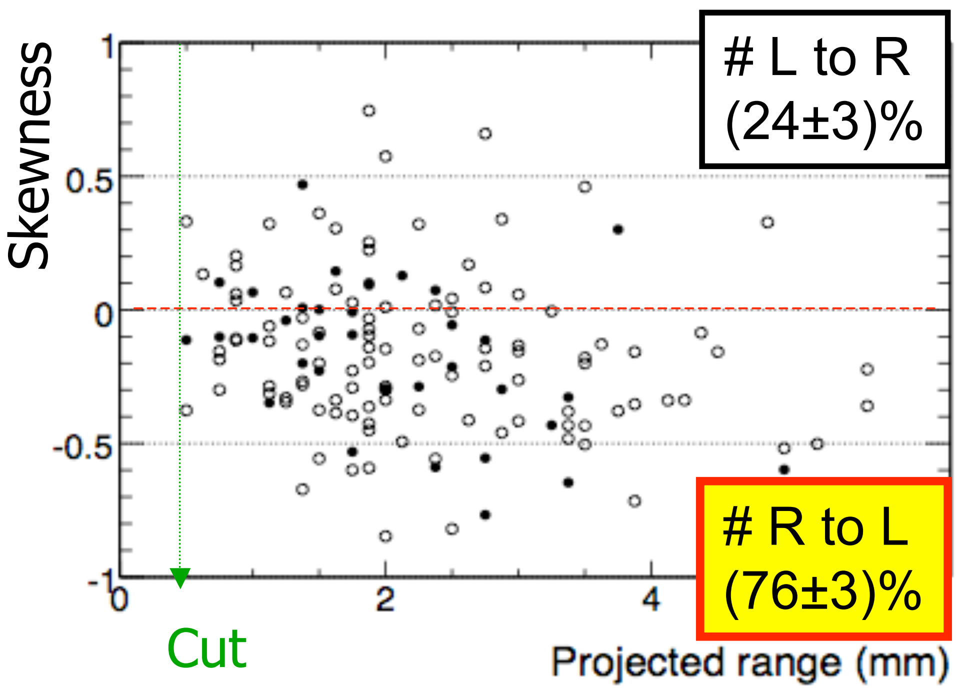
More quantitative results (DT)

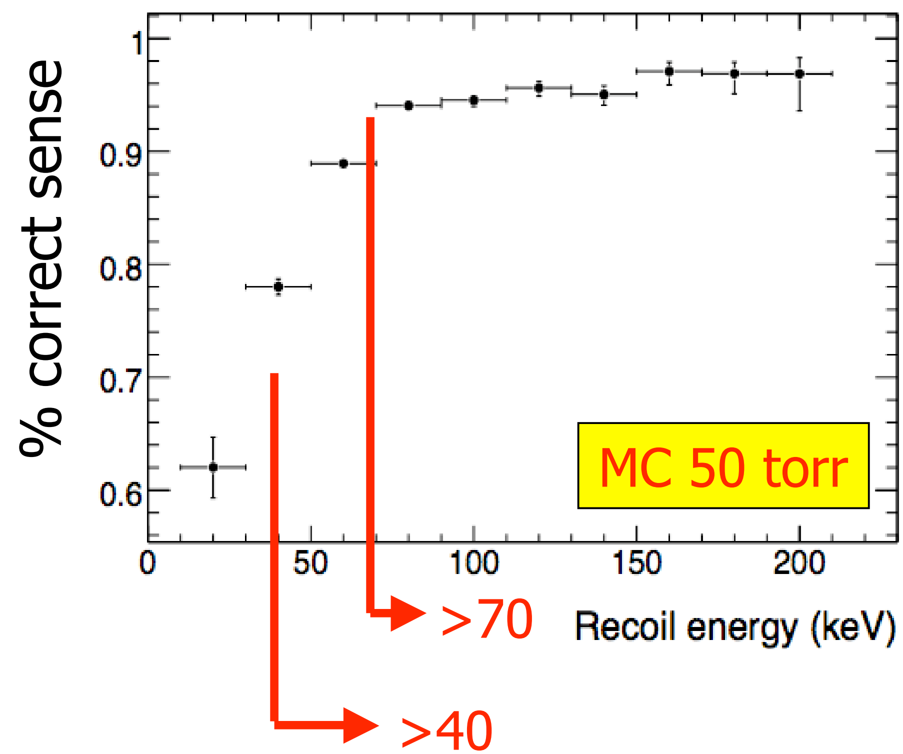
We measure skewness of light yield along wire

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

$\gamma > 0$: neutron travels L to R

$\gamma < 0$: neutron travels R to L

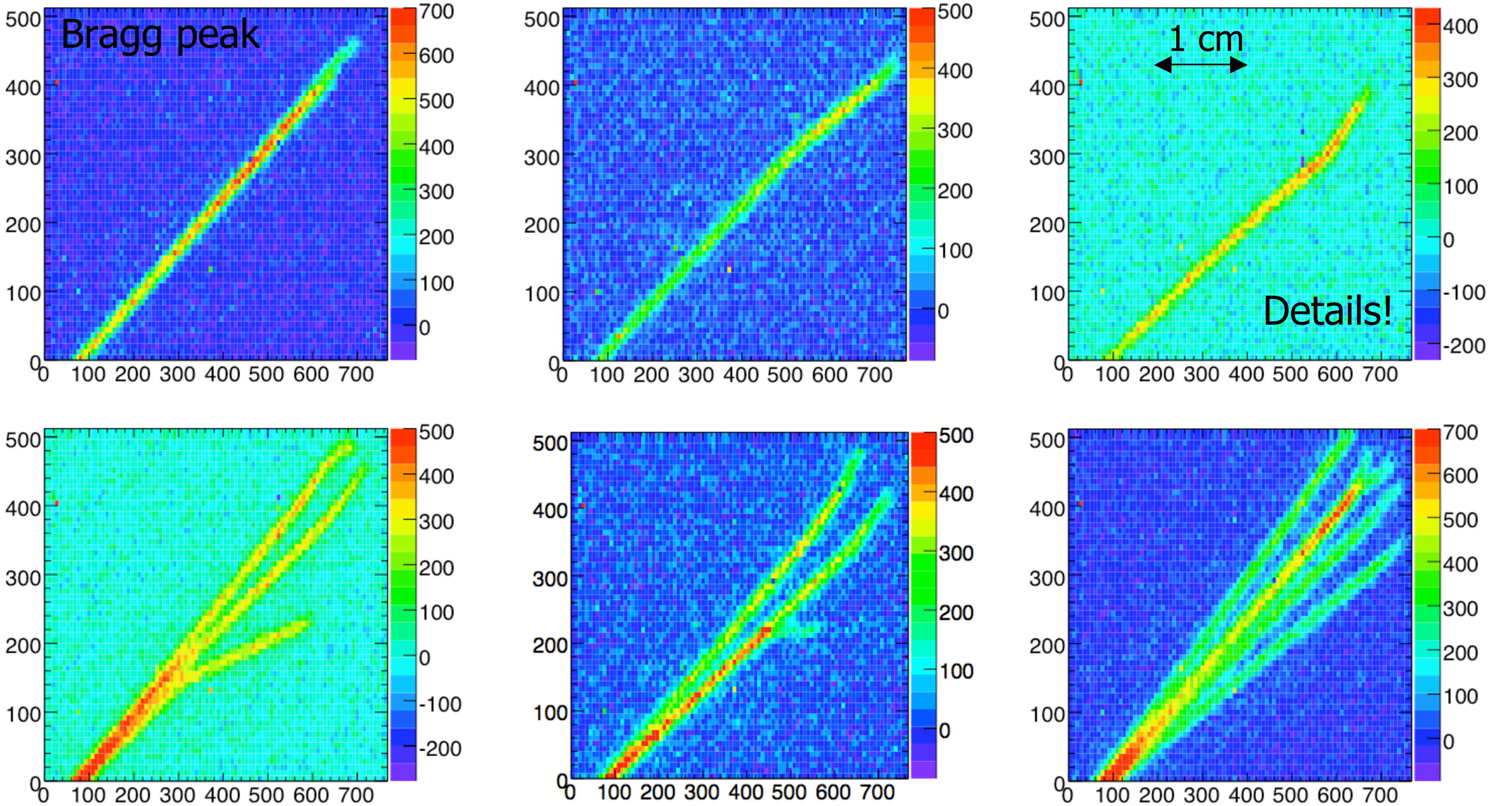




Black dots: wires @ 0 deg
Open circles: wires @180 deg

α particles with meshes

V_{anode}=2kV (E~1.5·10^5 V/cm)
300μm gap, 200Torr



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

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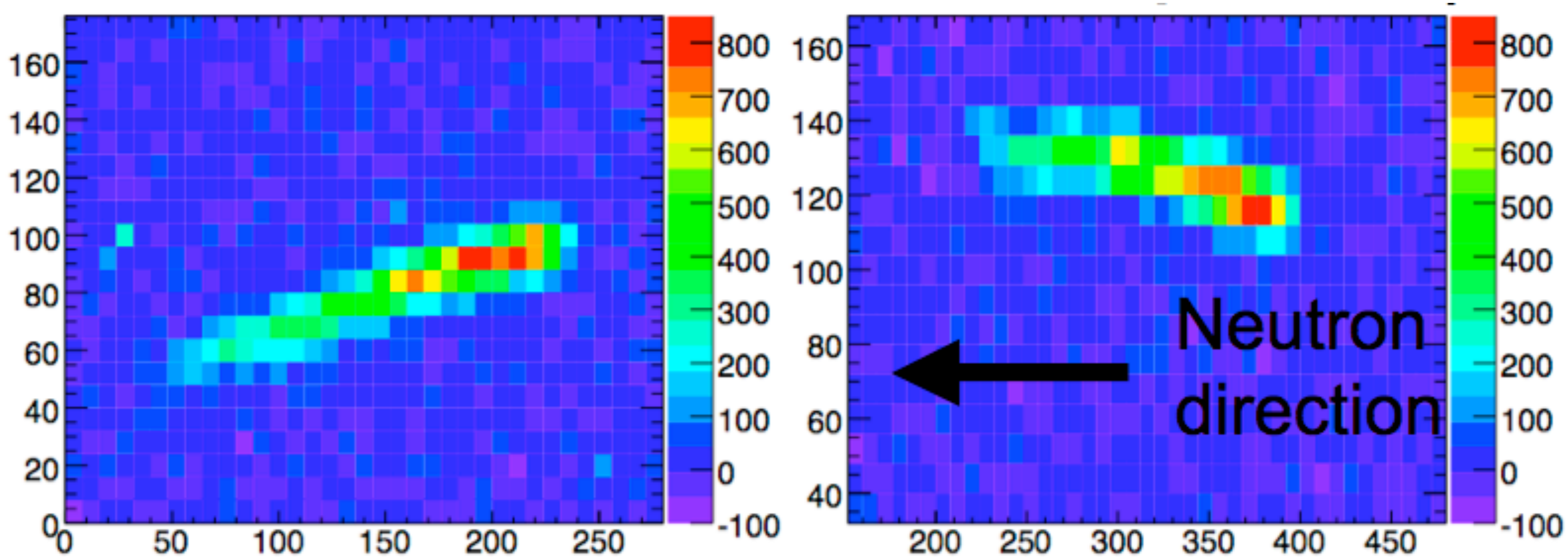
^{252}Cf run with mesh detector @ 75 torr

- Softer spectrum, closer to WIMP recoils
- Mesh-based detector: 1D→2D projection of recoil
- Stable data-taking at 75 torr
  - "Head-tail" effect down ~ 100 keV
- Excellent data-MC agreement



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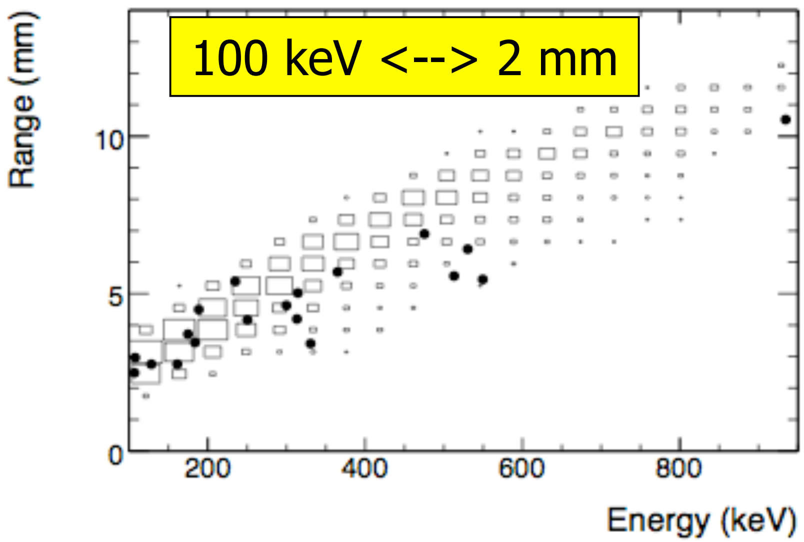
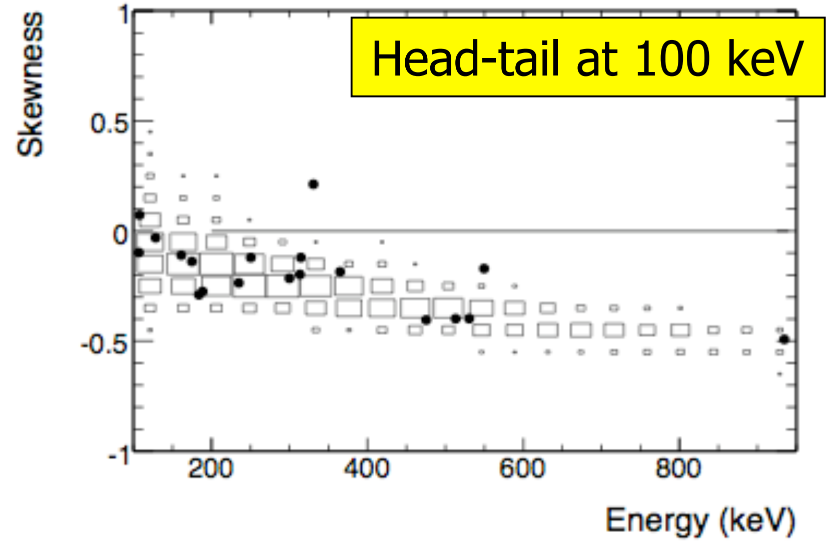
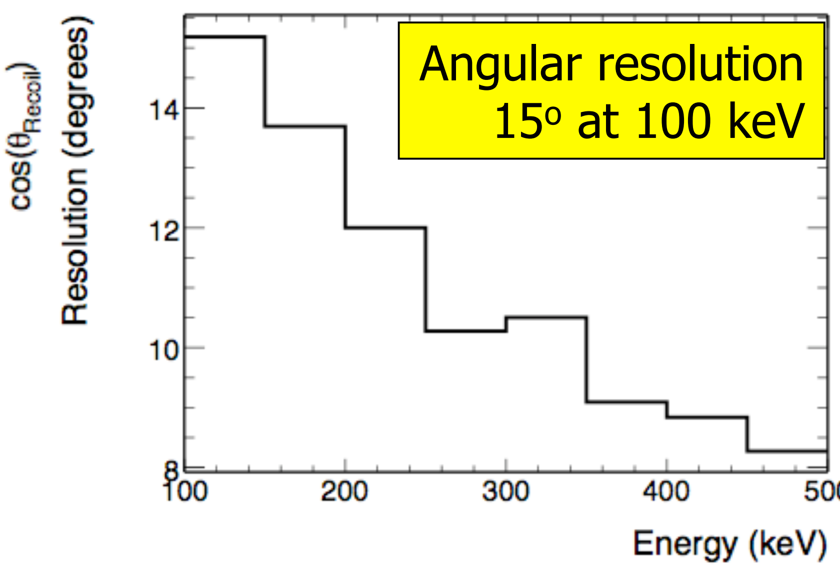
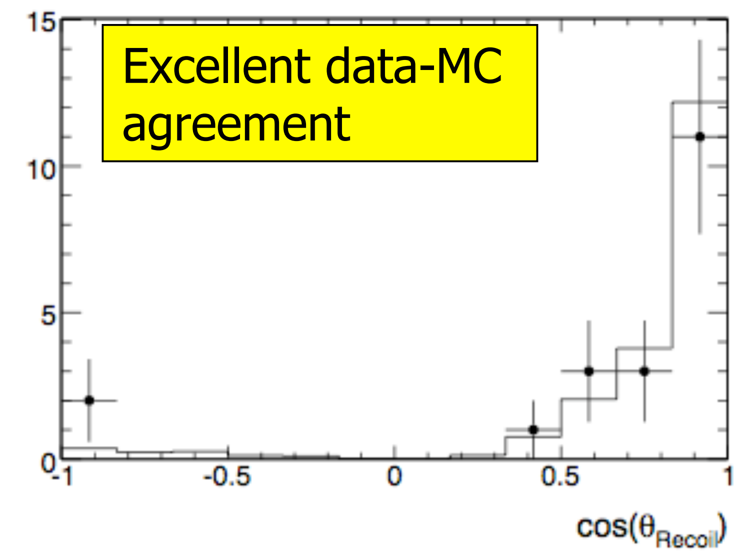
Mesh detector: ^{252}Cf run @ 75 torr



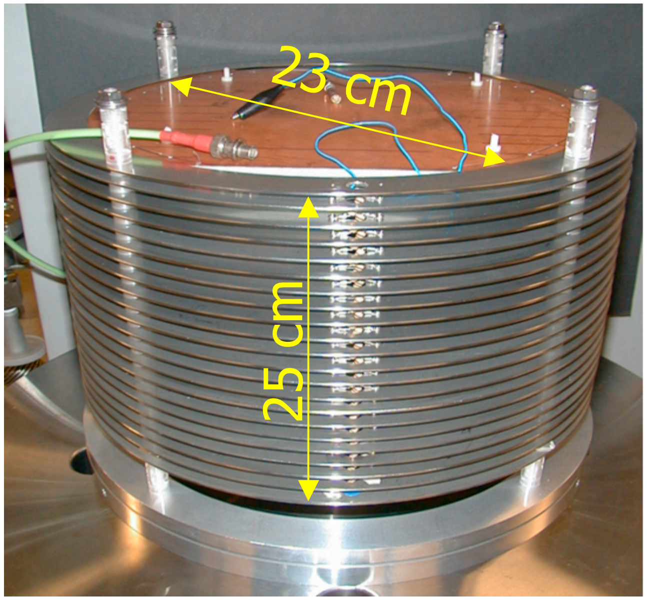






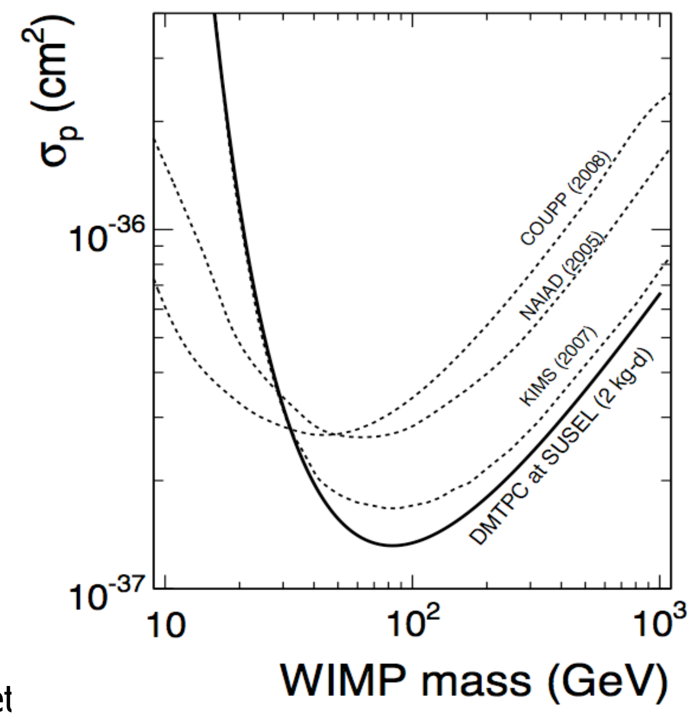
Next step: DM-TPC (10 liters)

- Active volume: 10 liters
  - Each drift volume: 23cm Ø, 25cm drift
  - 2 CCD cameras (top and bottom)
  - Triple mesh will double active volume
- P~100 torr; 1 year underground
  - Exposure of 2-4 kg-days



Goals of DM-TPC (10 liters)

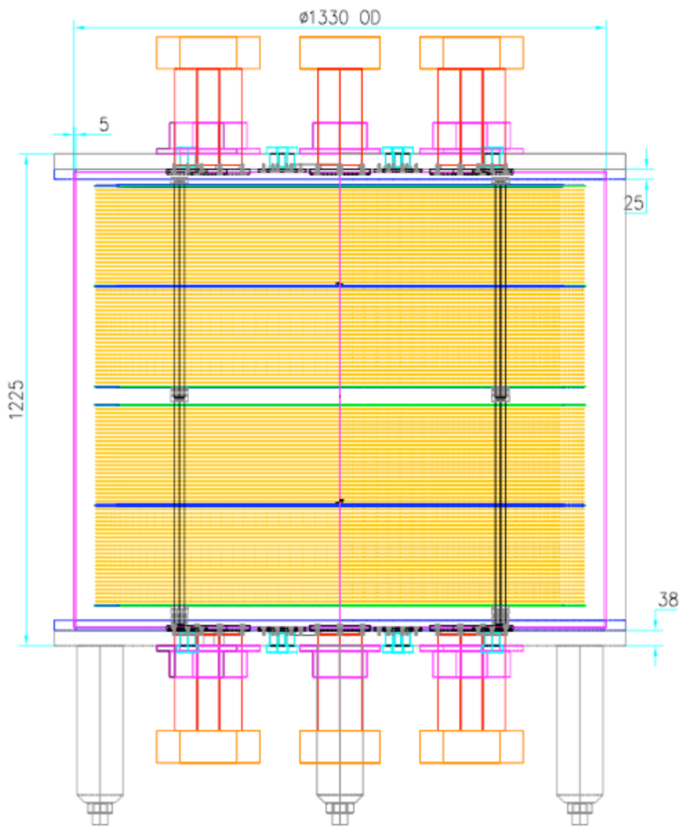
- Ready for underground run (starting in Spring 2009 at WIPP)
  - Detectors commissioned at MIT
  - > 1 month of surface data is being analyzed
- Module 1: study neutrons underground (no neutron shielding)
  - Gas mixture ^{4}He-CF_4 to enhance n interactions
  - Measure neutron <u>spectrum and direction</u> in underground cavern
    - Can identify 10% point source over bkg
    - Useful input for nearby DM experiments!
- Module 2: CF_4 (with neutron shielding)
  - Prove backgrounds-free operation underground
  - Set our first limit on SD WIMP interactions
    - Surprisingly good limits given limited mass due to large spin-factor of F and isotopic abundance
    - Directionality provides additional n rejection

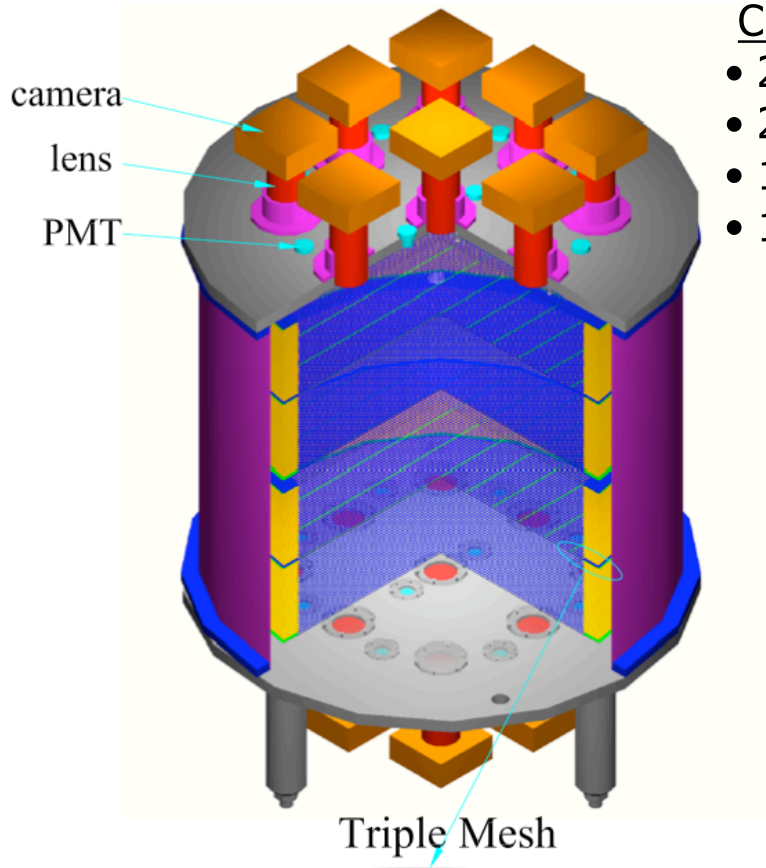


Next step: 1-m^3 detector

- Mass ~0.25-0.5 kg/m^3
- 1 year: ~100-200 kg d

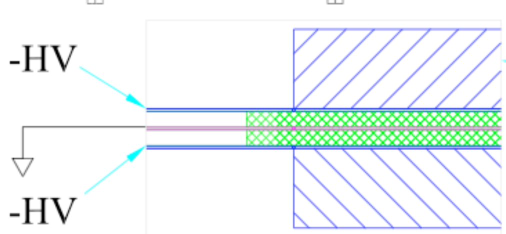
- Prove detector technology on a more realistic scale
- Set best limit on spin-dependent interactions with directionality

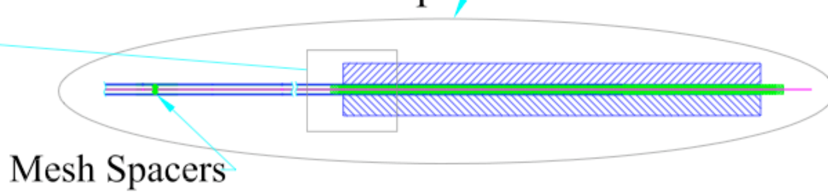




Current design:

- 2 amplification planes
- 2 drift regions / plane
- 10 CCD cameras/plane
- 10 PMTs/plane





Preliminary

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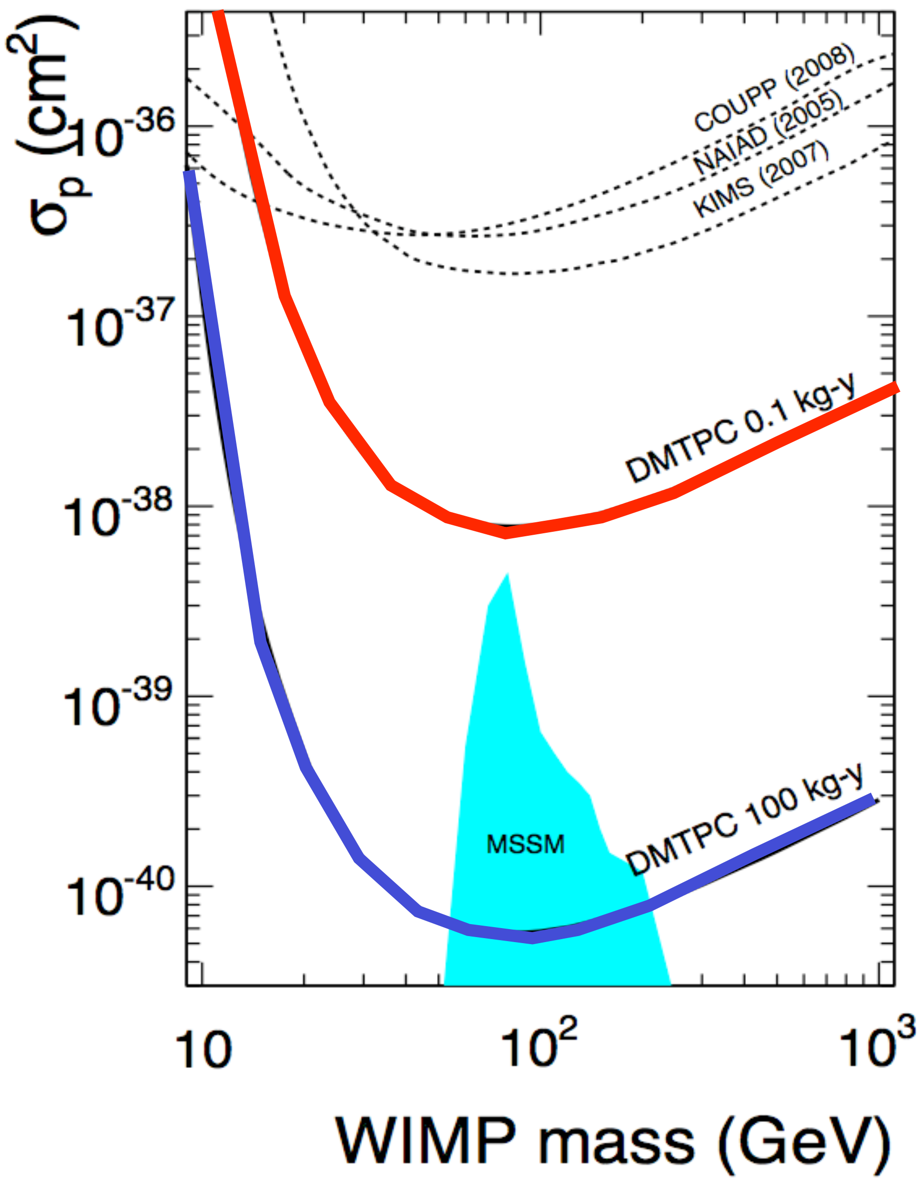
Sensitivity 1 m^3 underground



Assumptions:

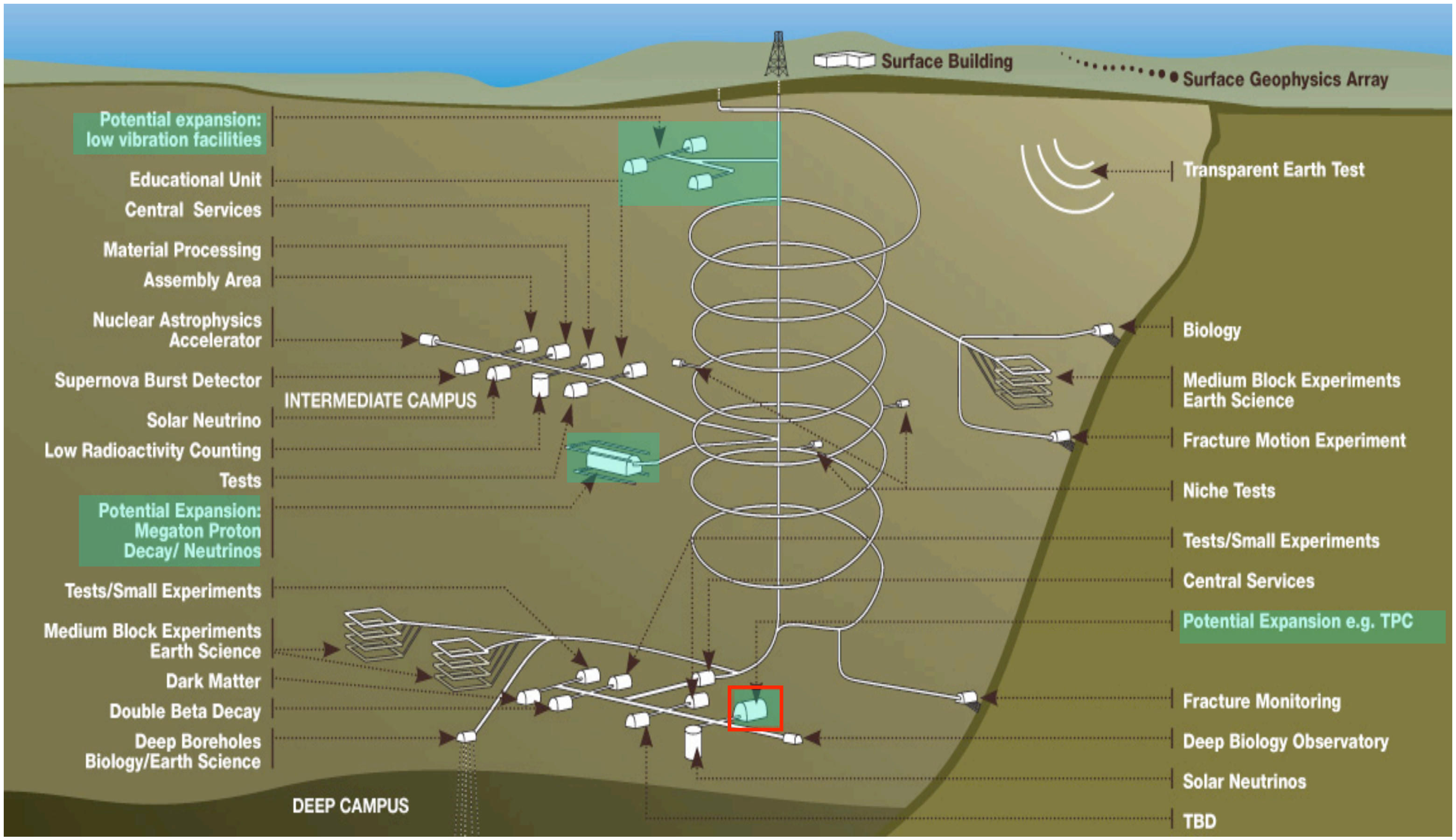
- 1 year data taking at 3,000 mwe
- Threshold 50 keV, P=100 torr
- Negligible background from detector material

Future detector:

- 100 kg-year at 3,000 mwe
- Threshold 50 keV
- Negligible background from detector material

Can we find space for it?

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



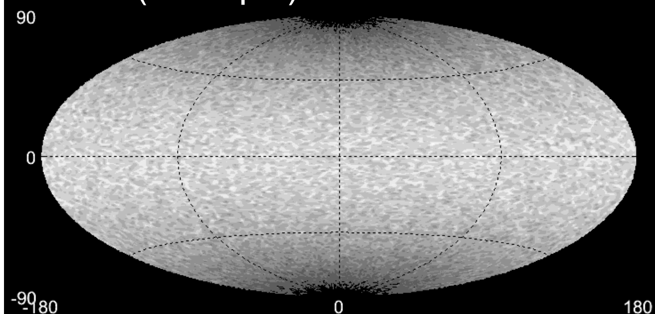
From J. Kotcher's presenation at HEPAP meeting on 7/14/2007

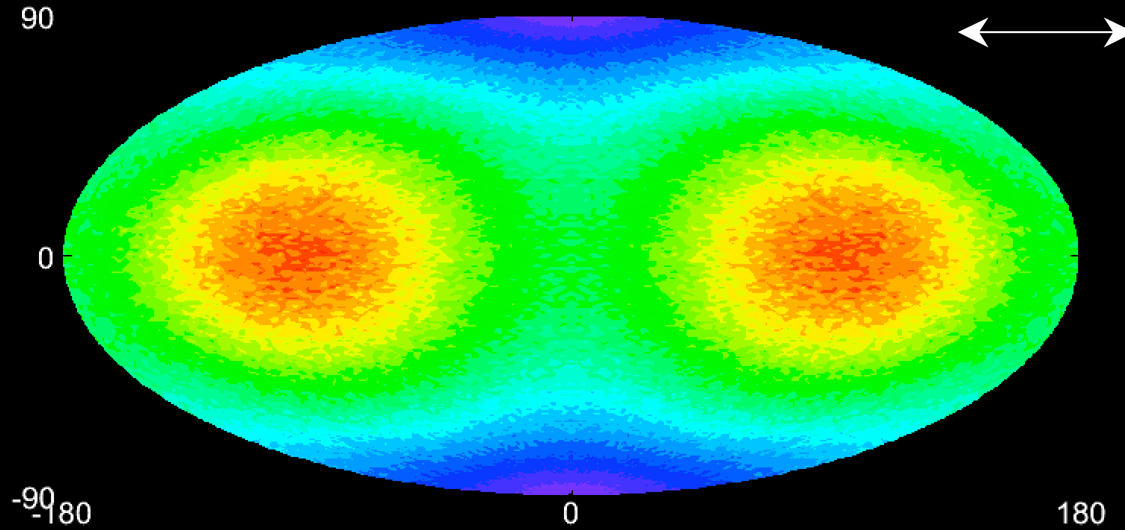
Conclusion

- DM-TPC collaboration is making rapid progress toward development of new Dark Matter detector
  - Directionality, spin-dependent interactions, optical readout (<$)
- One year ago (2007)
  - First prototype proved detector concept using wire planes (1D)
  - First observation of head-tail effect in low-energy nuclear recoils
- Now (2008)
  - Much superior detector images recoils in 2D
  - 2 10-liter modules ready for underground operation to study neutrons in cavern and set limits on σ_p^{SD}
  - 1-m^3 detector being designed; very competitive in σ_p^{SD} w/directionality
- Large O(10^2 kg) DM-TPC detector ideal candidate for DUSEL
  - Directionality: unambiguous observation of WIMPs
  - First DM observatory for underground WIMP astronomy

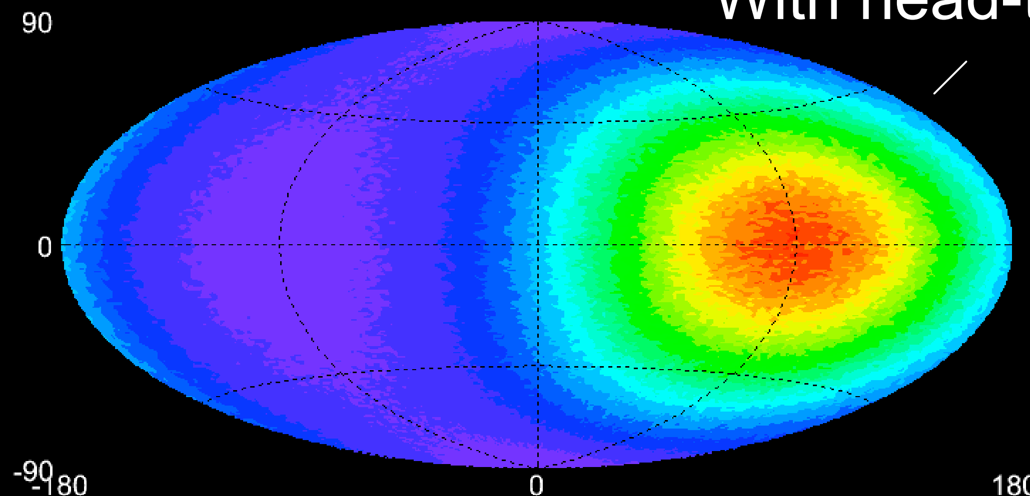
WIMP Astronomy: Sky Map

Background
(isotropic)





With head-tail



-------- Sky map -------