

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

Saclay, Dec 17, 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



Gabriella Sciolla

DM-TPC: a new approach to dir



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

Strong evidence for DM

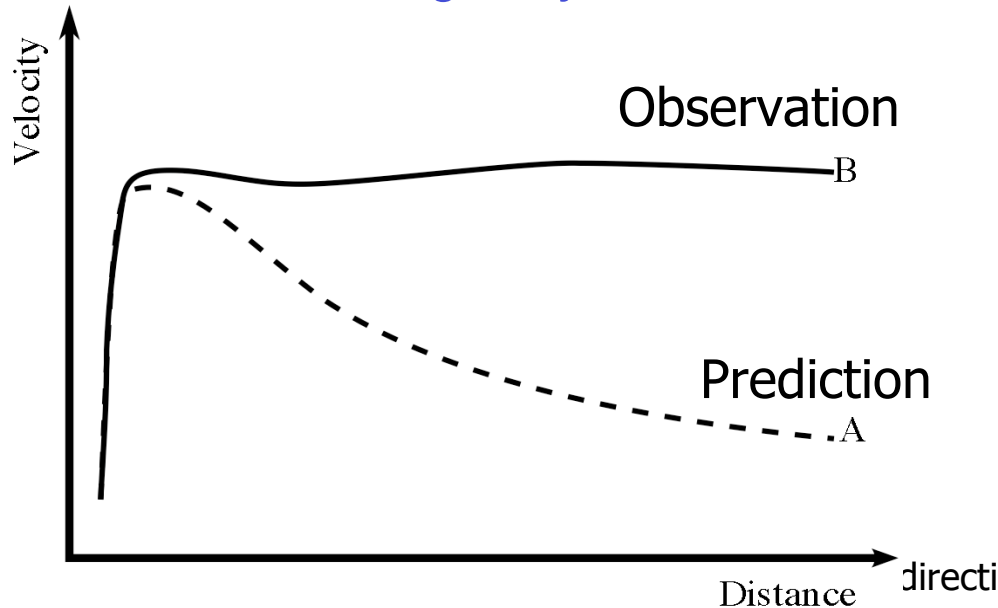


Vera Rubin et al. (1979)

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

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

- 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, minimally 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.;

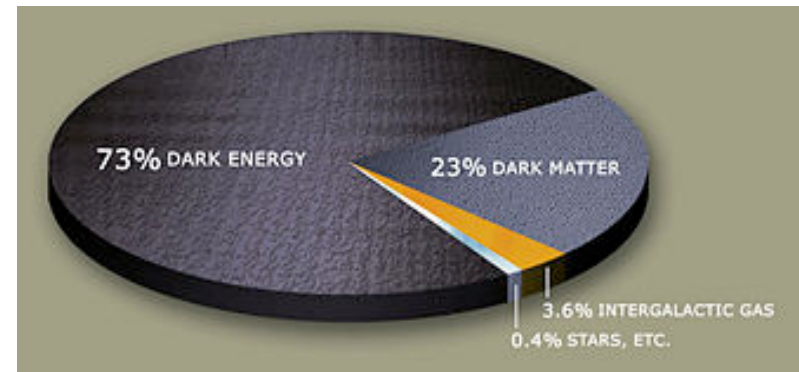
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al

Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

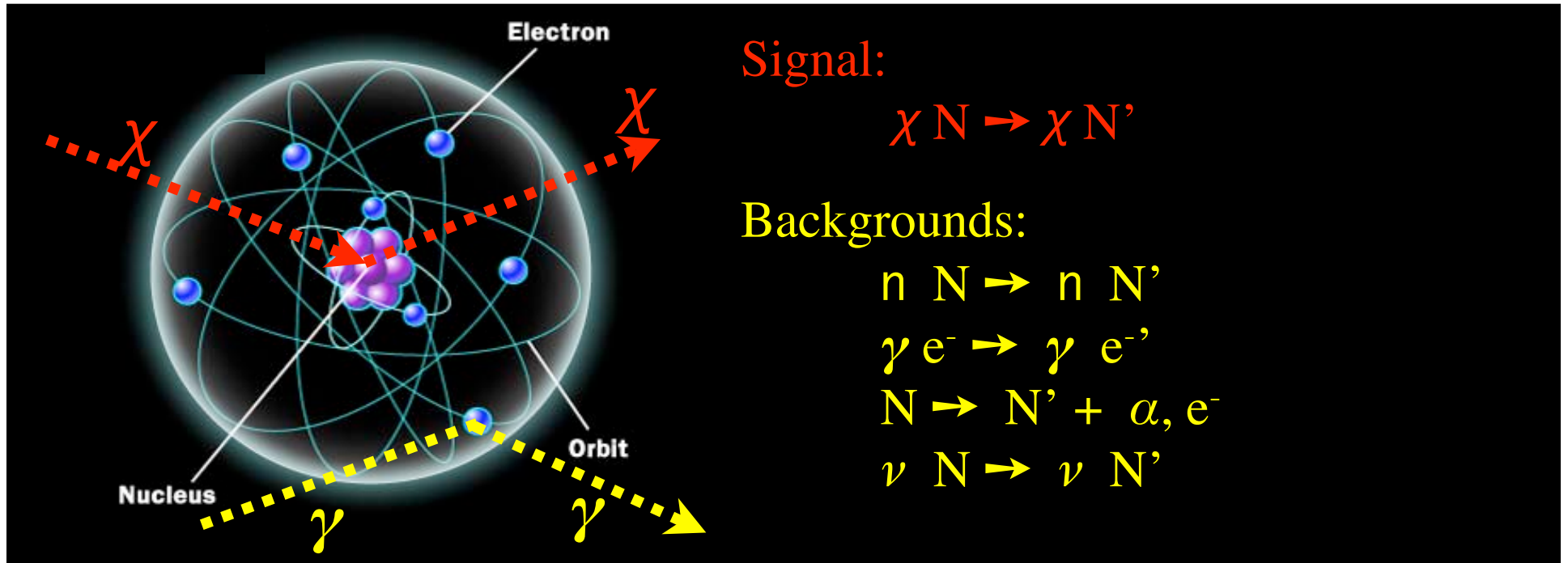


What is Dark Matter made of?

- 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



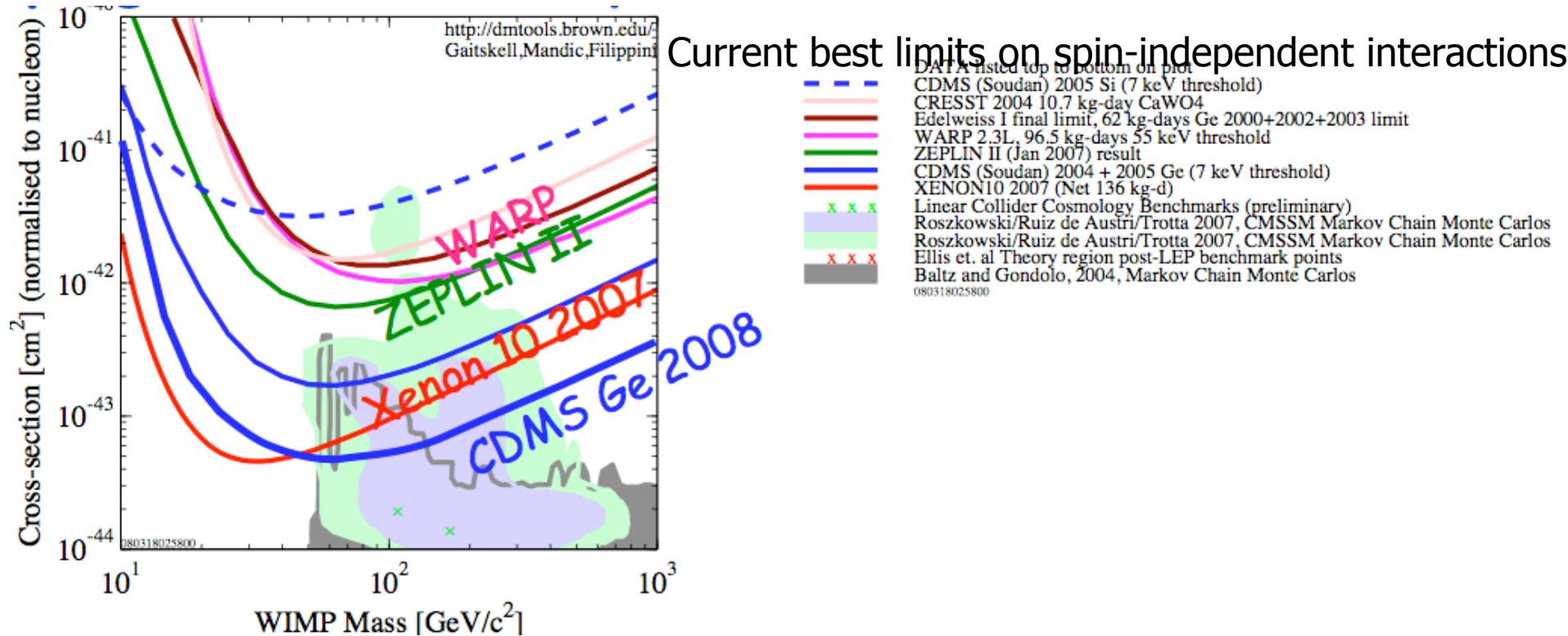
Direct detection of WIMPs



- 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, CF₄, ...
- Challenging measurements
 - Very low-energy recoils (10-100 keV), very weak interactions, many backgrounds

Present DM searches

Current best limits on spin-independent interactions

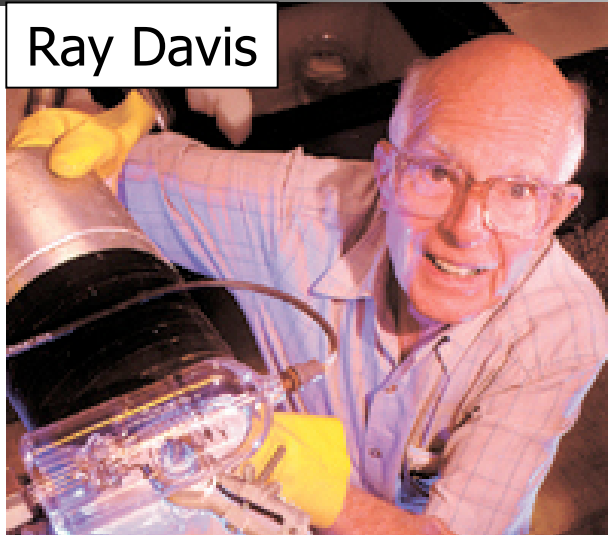


- Many experiments engaged in direct detection of DM
 - Recent progress: improved cross-section limits $\sigma_{SI} < 10^{-44}-10^{-43} \text{ cm}^2$
- Intrinsic limitation of mainstream DM experiments
 - Counting experiments: zero-background assumed
 - Larger detectors will start to see several (irreducible)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

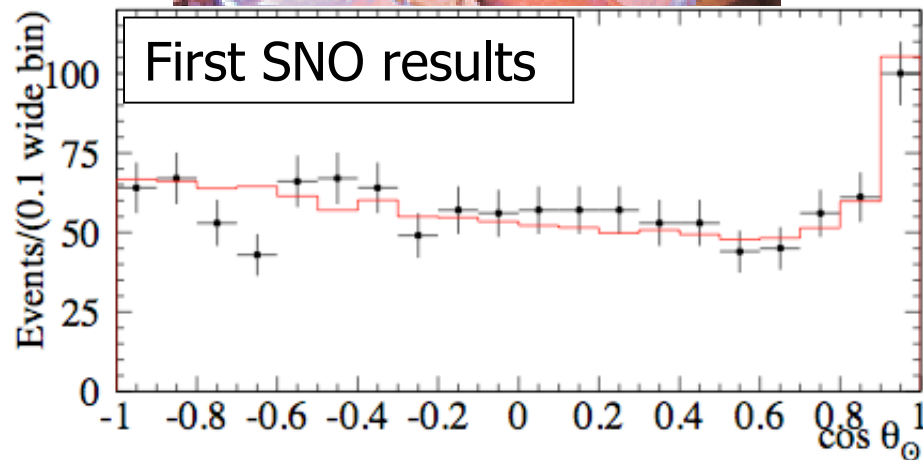
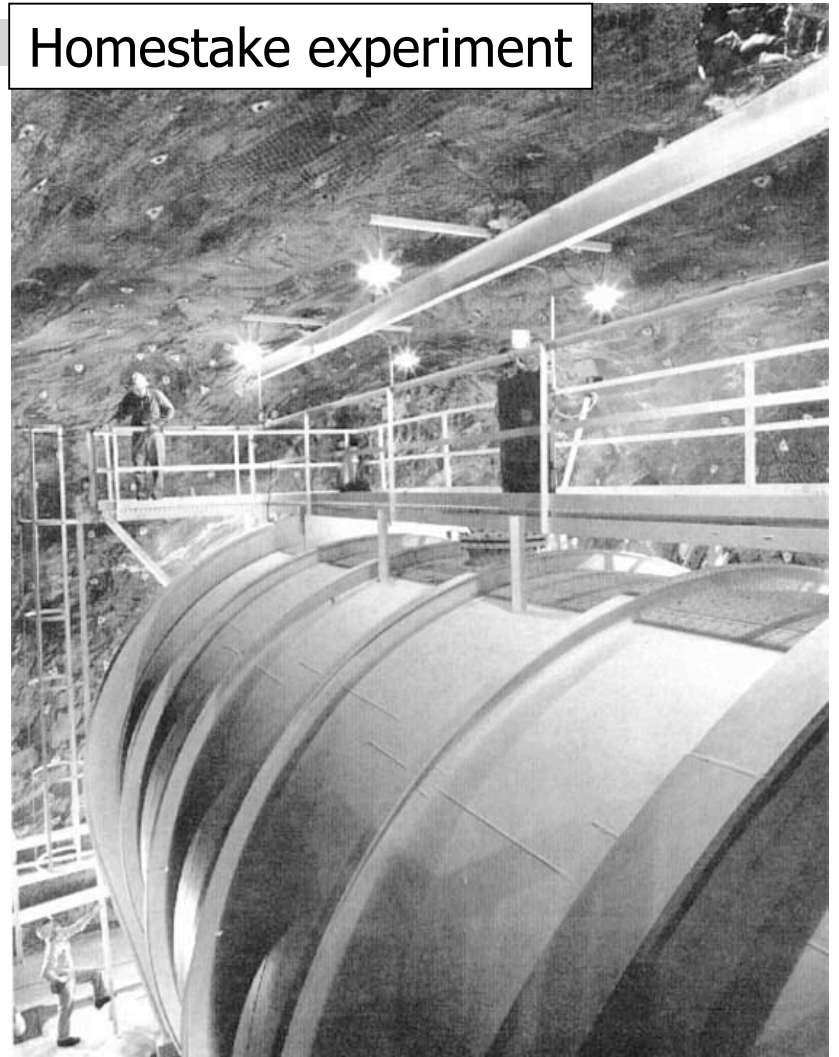
It may be very hard for a counting experiment
to provide unambiguous positive observation of Dark Matter

Situation similar to neutrino oscillations...

Ray Davis



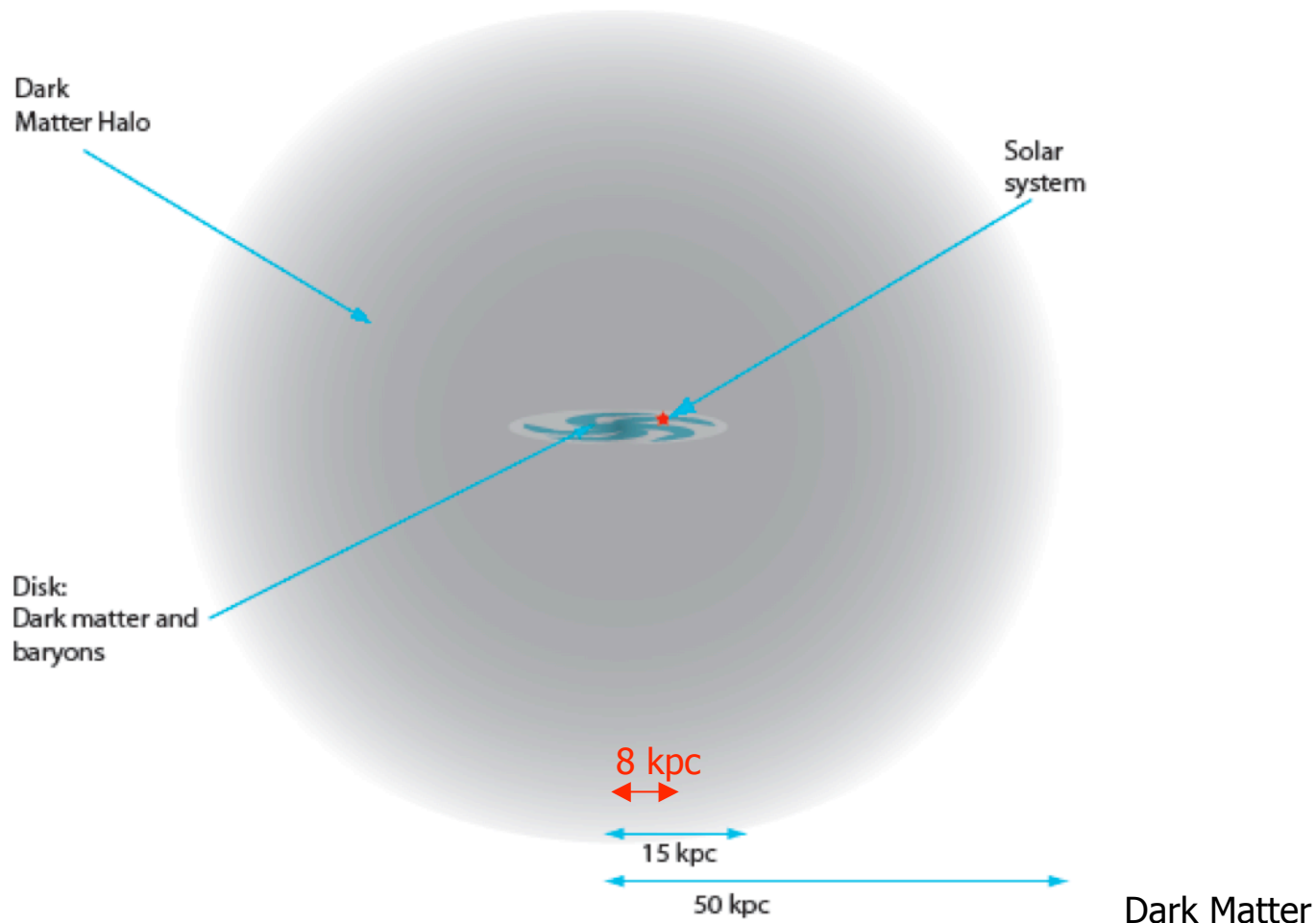
Homestake experiment



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

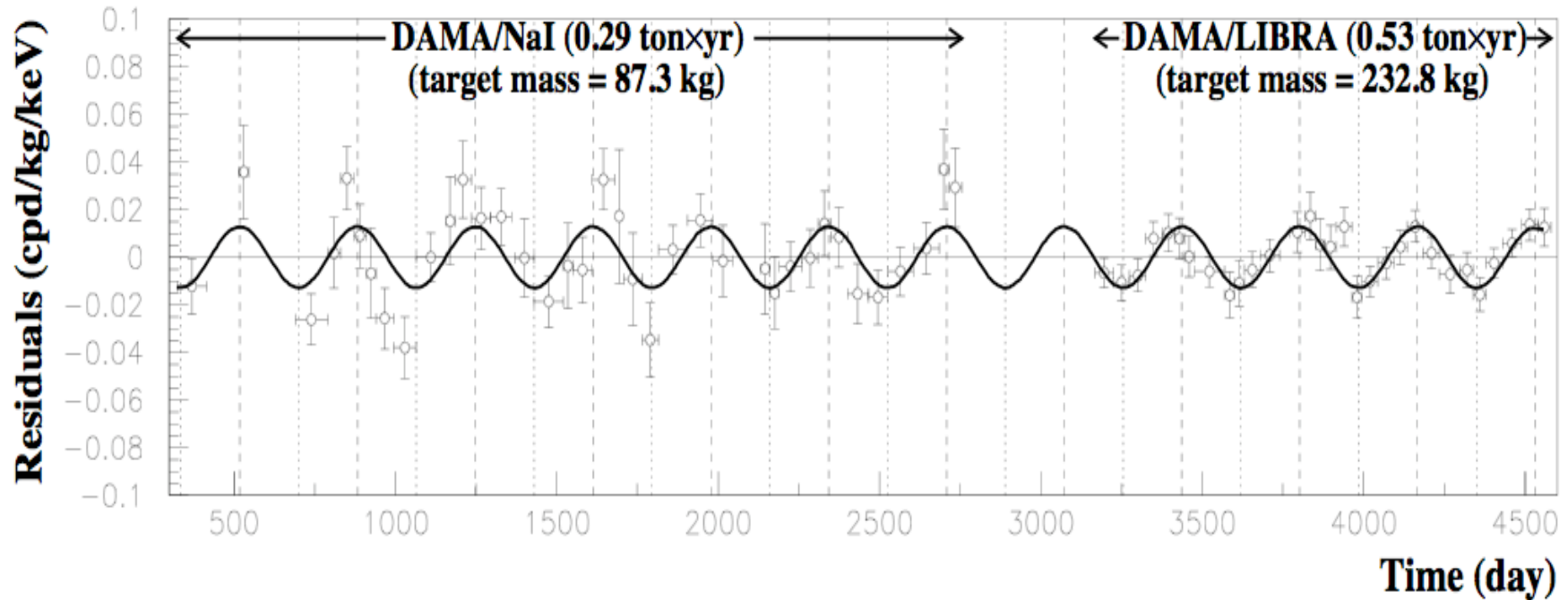
The decisive proof of positive observation of DM requires correlation with astrophysical phenomena

DM halo's reference frame

Solar system's reference frame

Dark Matter wind from Cygnus of 220 Km/s

Why not yearly asymmetry?



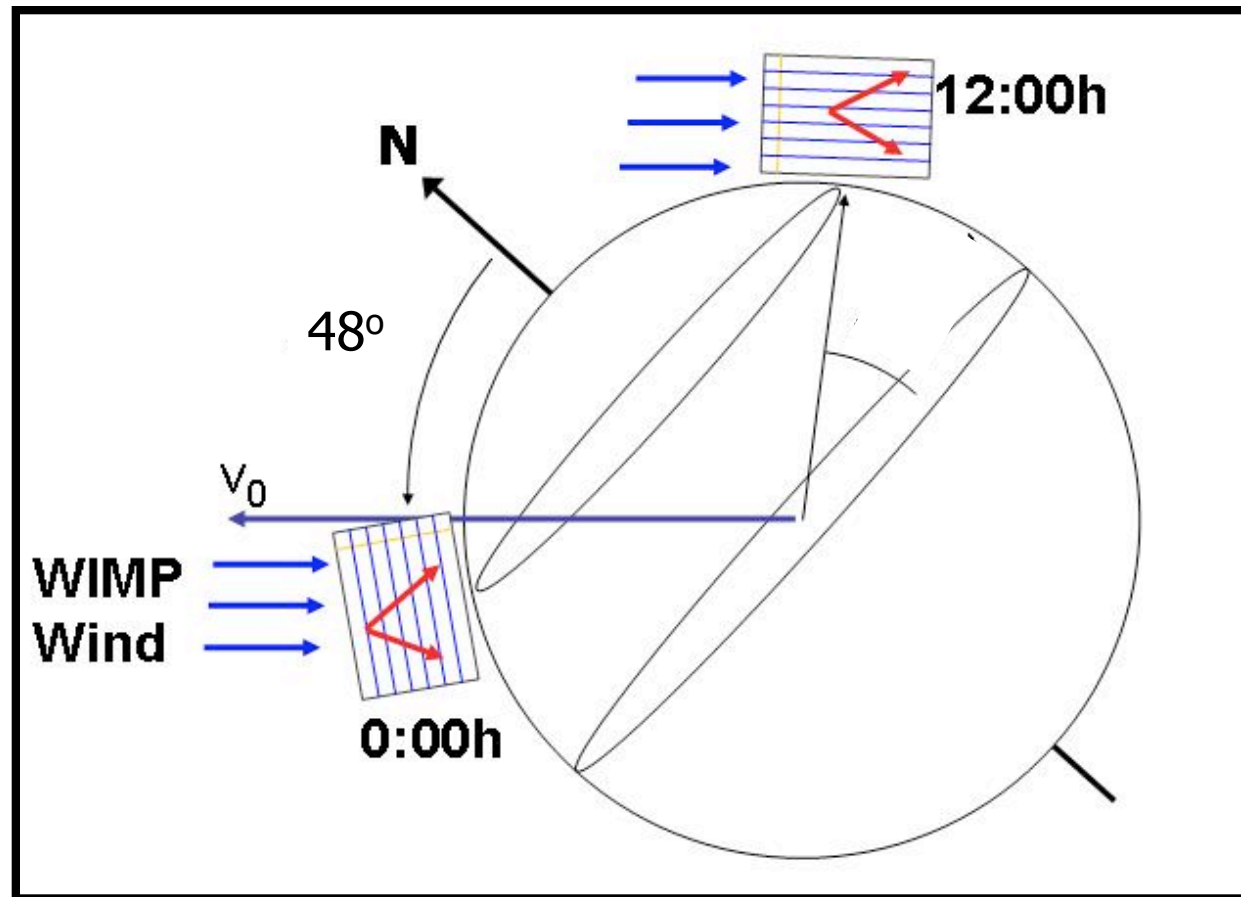
First observation of WIMPS??

Yearly asymmetry:

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

Unambiguous signature of Dark Matter

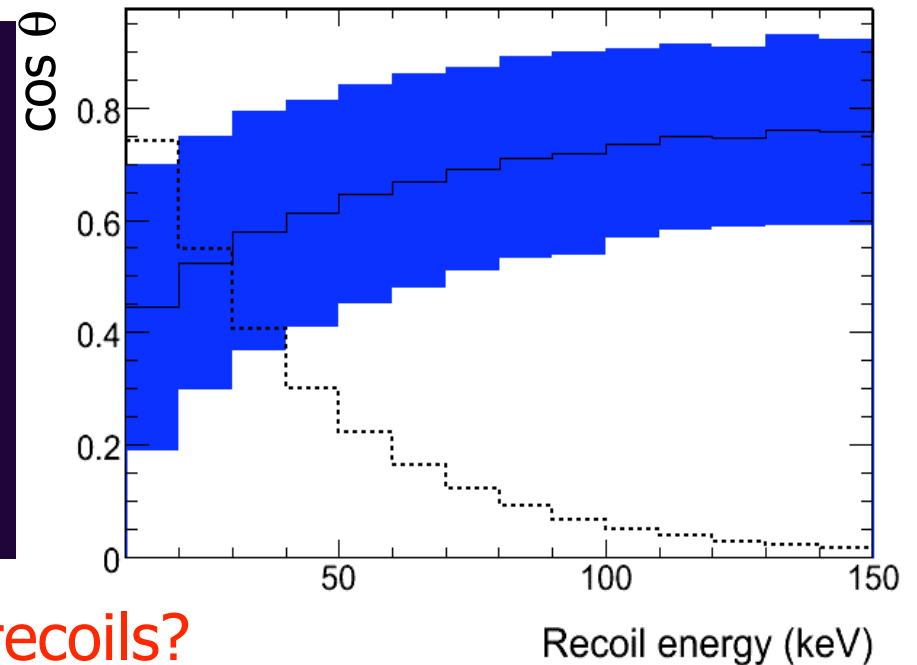
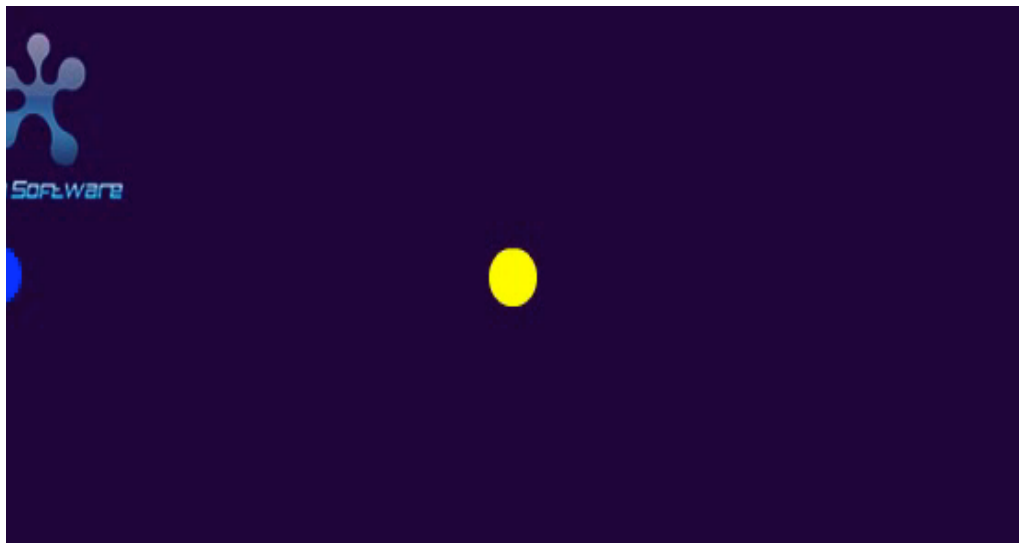
Daily asymmetry ~30-100%!



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

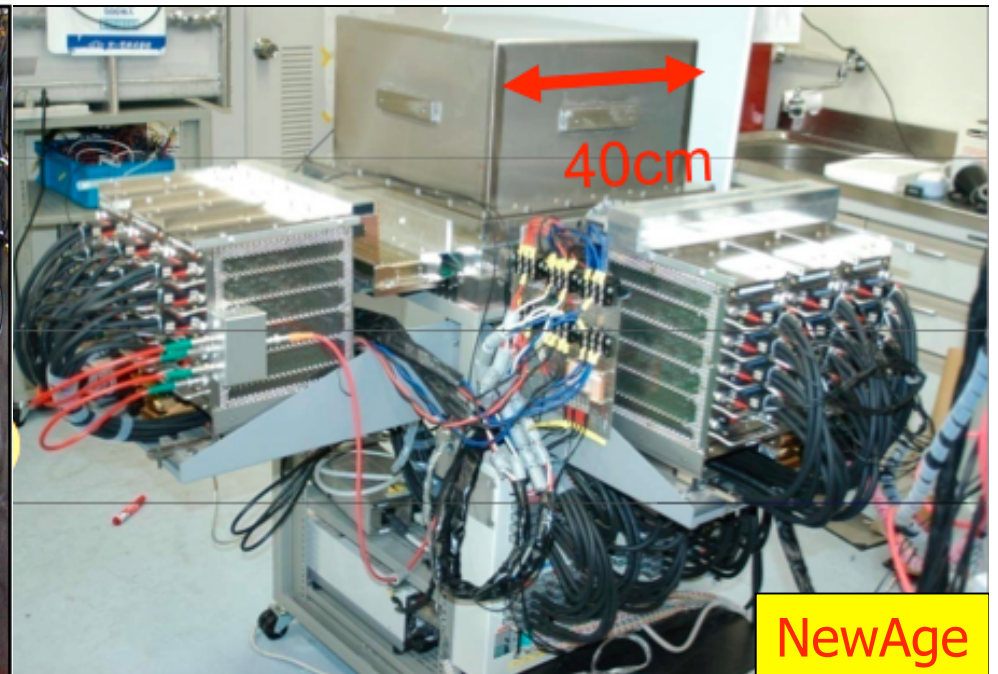
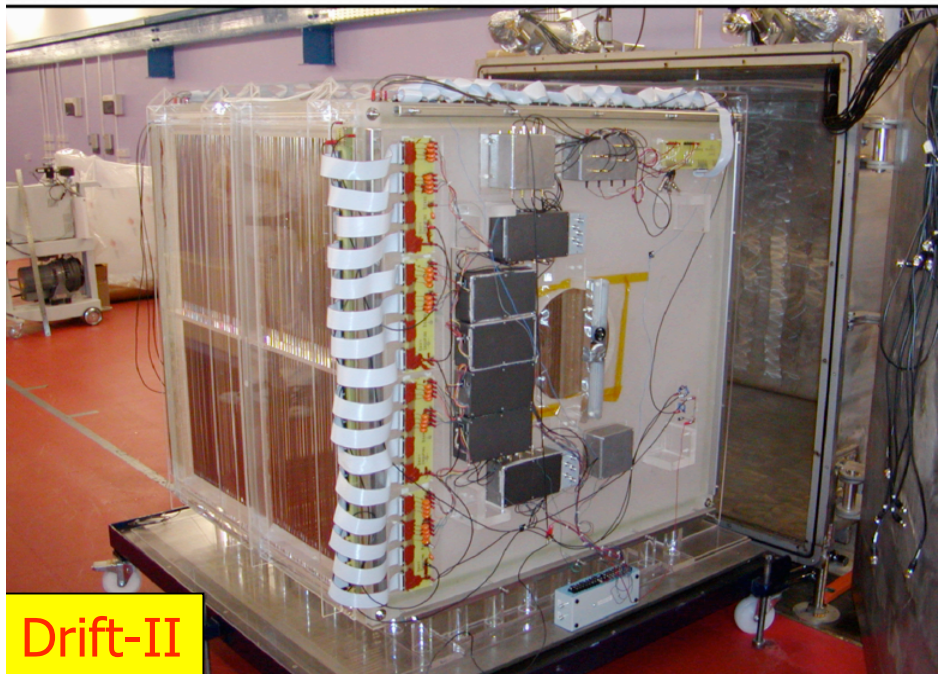


- How to detect the direction of recoils?
 - Low-pressure gaseous detectors
 - A 50 keV F in CF_4 @ 40 torr recoils ~ 2 mm

Other directional DM detectors

- DRIFT (Boulby, UK)
 - 1 m³ (167 g) CS₂ low-pressure negative ion TPC
 - MWPCs for charge readout
- NewAge (Kamioka, Japan)
 - Low-pressure CF₄ TPC using μ PIC 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: $\sim 10^{-44}-10^{-43} \text{ cm}^2$
 - Limits on spin-dependent x-section: $\sim 10^{-37}-10^{-36} \text{ cm}^2$
- 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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G. Sciolla, R. Vanderspek, R. Yamamoto, H. Yegoryan*
Massachusetts Institute of Technology

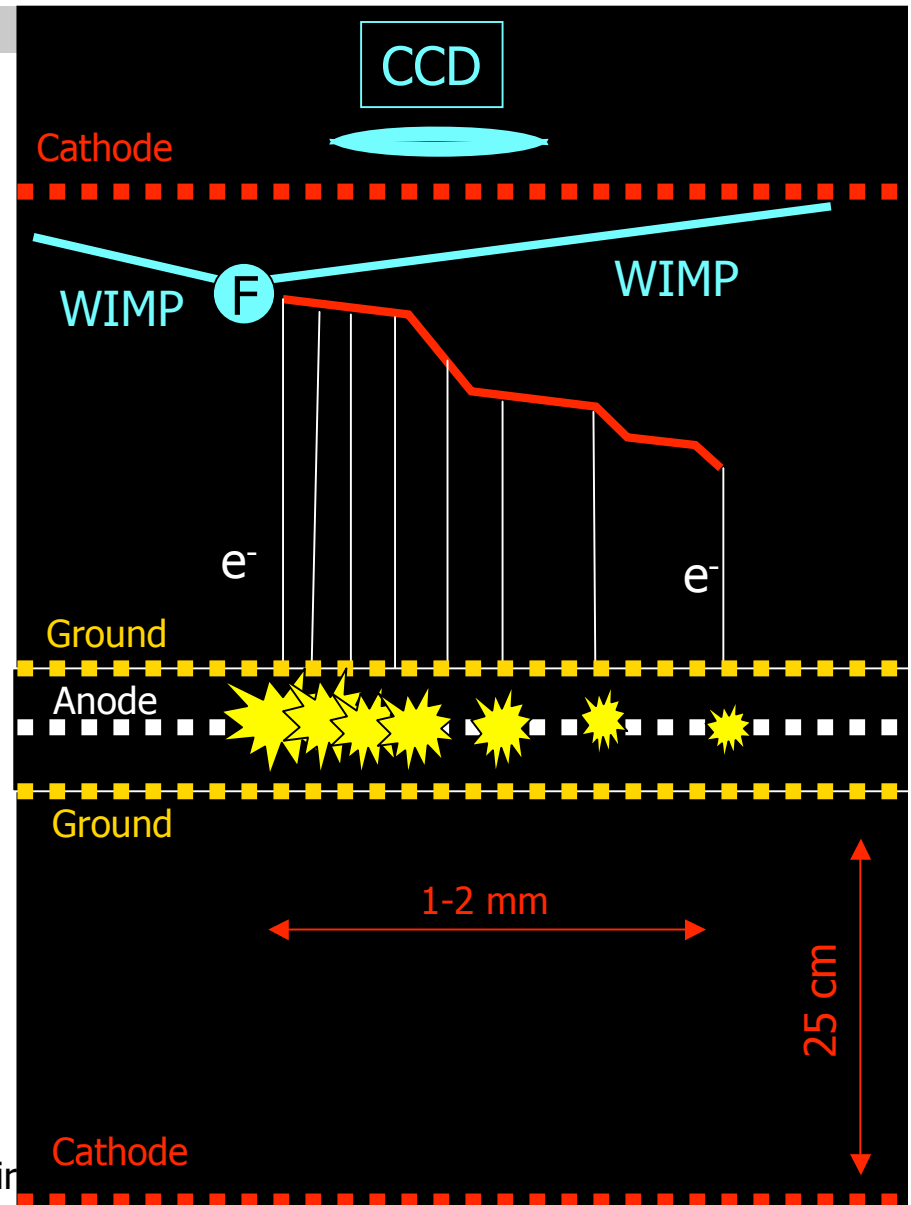
Note:

* indicates undergraduate students

¹ also Harvard University

DM-TPC: detector concept

- Low-pressure CF_4 TPC
 - 50-100 torr \rightarrow F recoil \sim 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

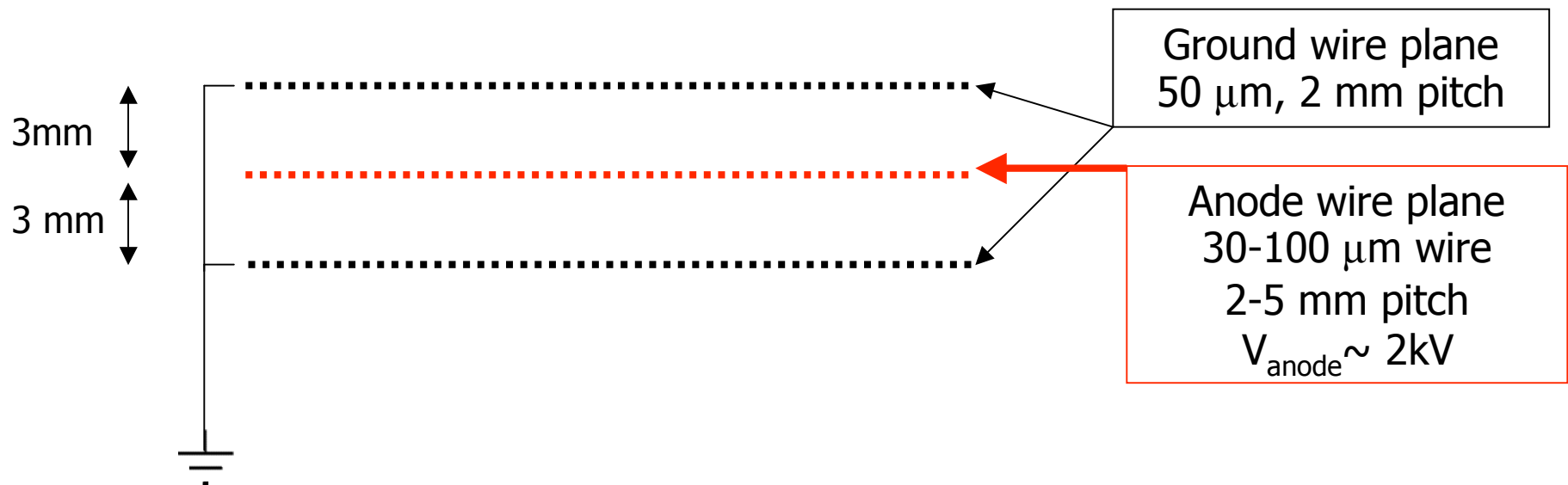
Detector concept



Moyea Software

The amplification region

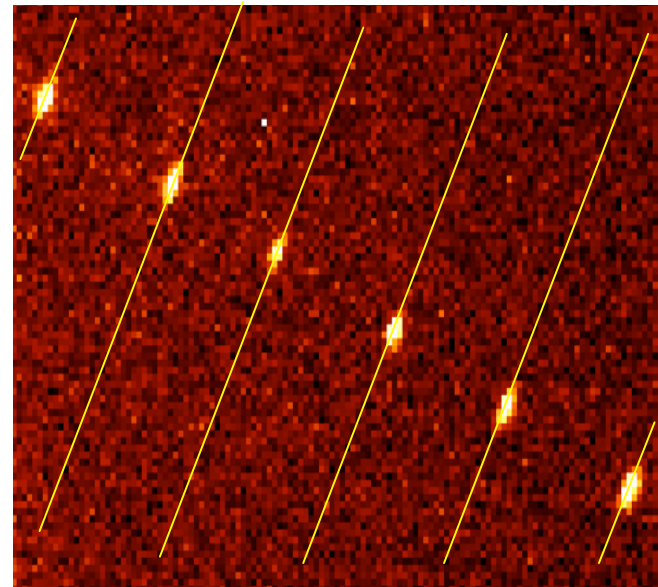
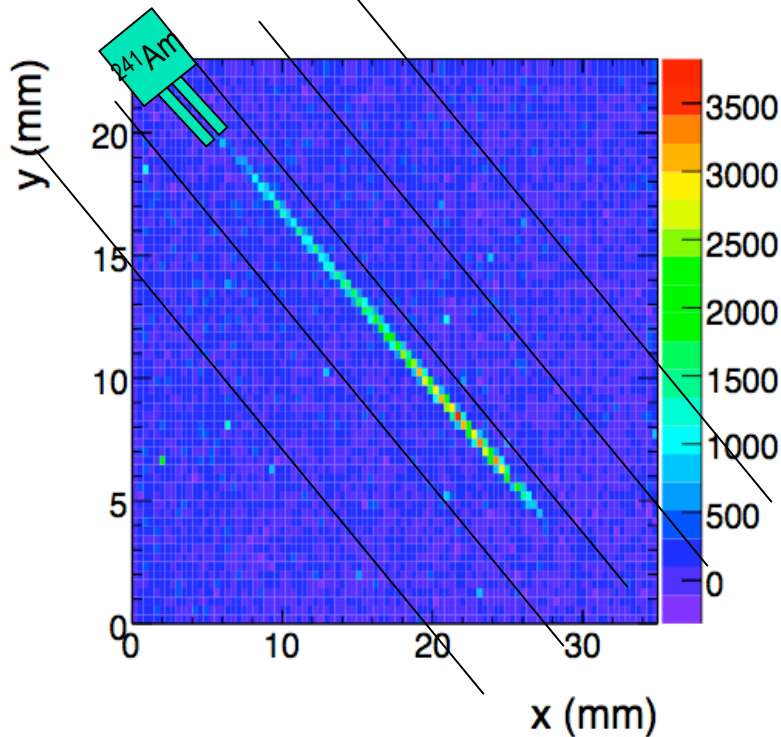
Original design: wire planes



- Pros: simplicity, high gains ($\sim 10^4$ - 10^5)

Limitations of wire-based amplification

- Wire-based detectors have serious limitations....

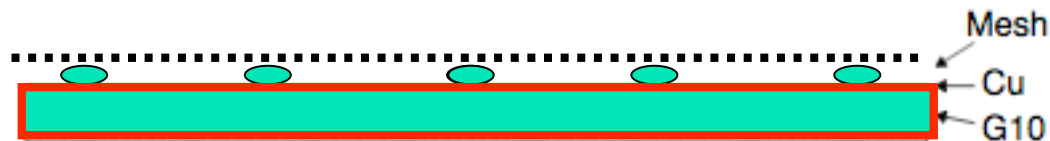


- 1D reconstruction of the recoil: not enough!

New amplification region: meshes

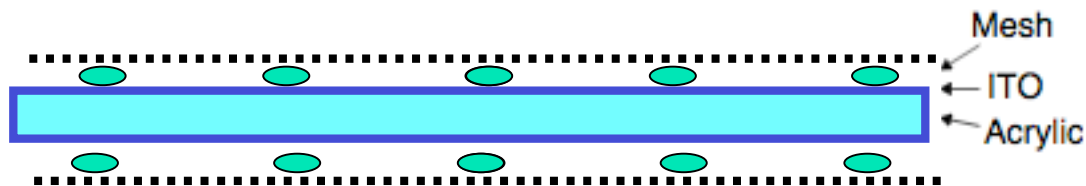
- Additional coordinate at no additional readout cost

a) mesh-copper



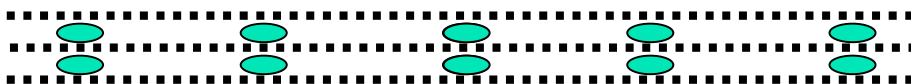
- Stainless steel woven mesh
- 28 μm , 256 μm pitch
 - Optical transmittance 77%

b) mesh-ITO film



- Uniform spacing
- Fishing wire 0.54 mm \varnothing
 - Pitch 2 cm
- ITO: In₂O₃ (90%) SnO₂ (10%)
- Optical transmittance 80%

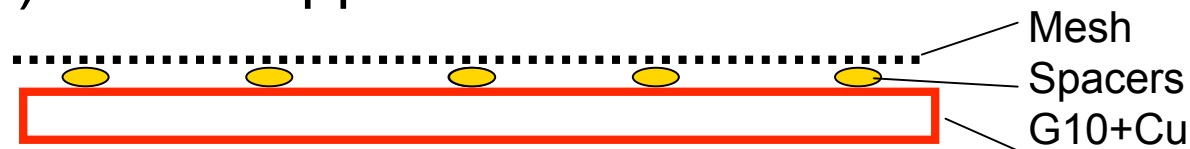
c) mesh-mesh



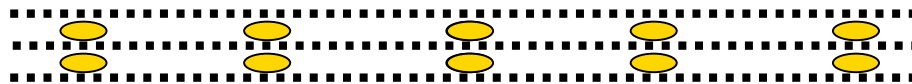
New amplification region: meshes

Additional coordinate at no additional readout cost

a) Mesh-copper



b) Triple mesh



Stainless steel woven mesh

- 28 μm , 256 μm pitch, optical transmittance 77%

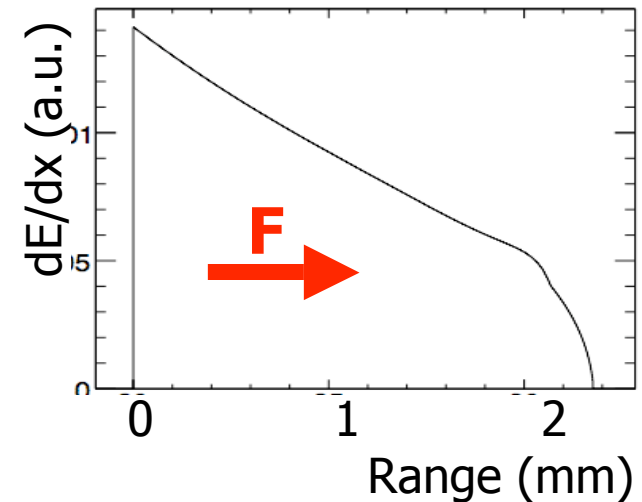
Uniform spacing

- Fishing wire 0.54 mm \varnothing , Pitch 2 cm

What we measure

CCD cameras measure

- E_{recoil} from total scintillation light
 - Integral of CCD signal ($\sigma_E/E \sim 10\%$)
- 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 decreases along recoil track
 - Low energy, below Bragg peak



Bragg curve for 80 keV
F recoil from WIMP in CF_4

Additional info from PMTs

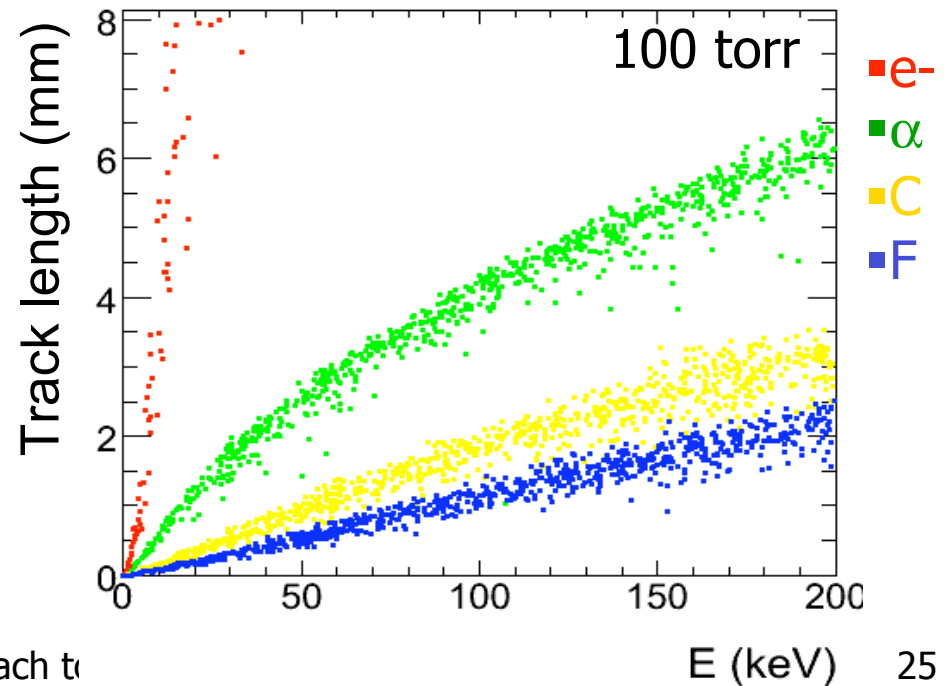
- 3rd coordinate of recoil ($\parallel v_{\text{drift}}$)
- Trigger

Electronic readout of the mesh

- Additional determination of E_{recoil} and trigger

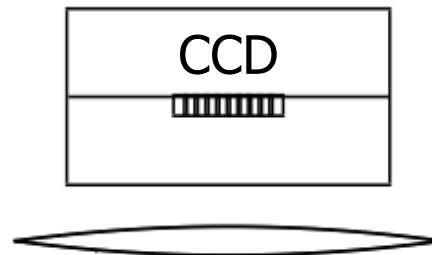
Background rejection

- Excellent rejection of gammas
 - 8 hours run with 8 μCi ^{137}Cs inside prototype: no evts
 - Rejection factor $\sim 2/10^6$ 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!



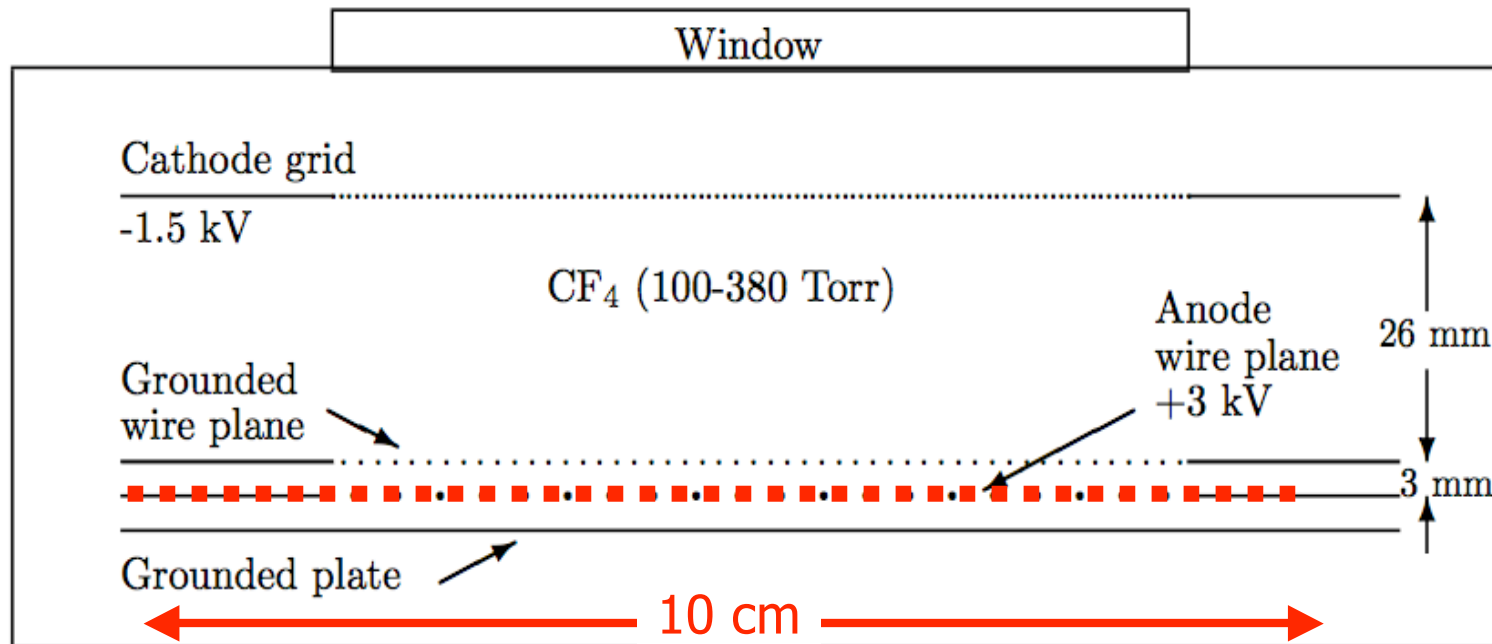
First generation prototype

Drift distance: 2.6cm,
 $E=580$ V/cm
 Wire plane: 10×10 cm²
 Anode: 5 mm pitch, $100\mu\text{m}$
 Ground: 2 mm pitch, $50\mu\text{m}$

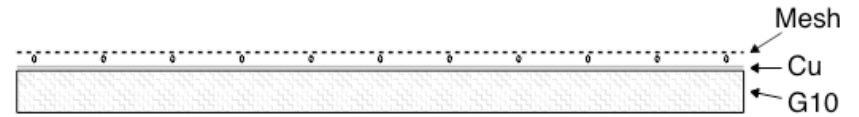


CCD c
 Lens

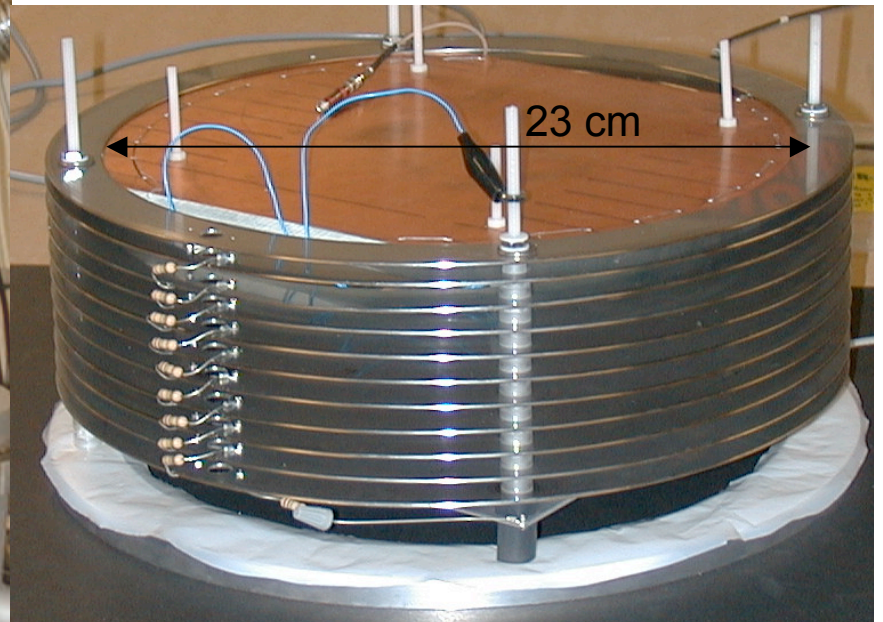
CCD Camera
 Kodak KAF0401 chip
 768x512 (9x9mm)
 Cooled (-20C)
 Photographic lens (55mm)
 Finger Lakes Instrumentation



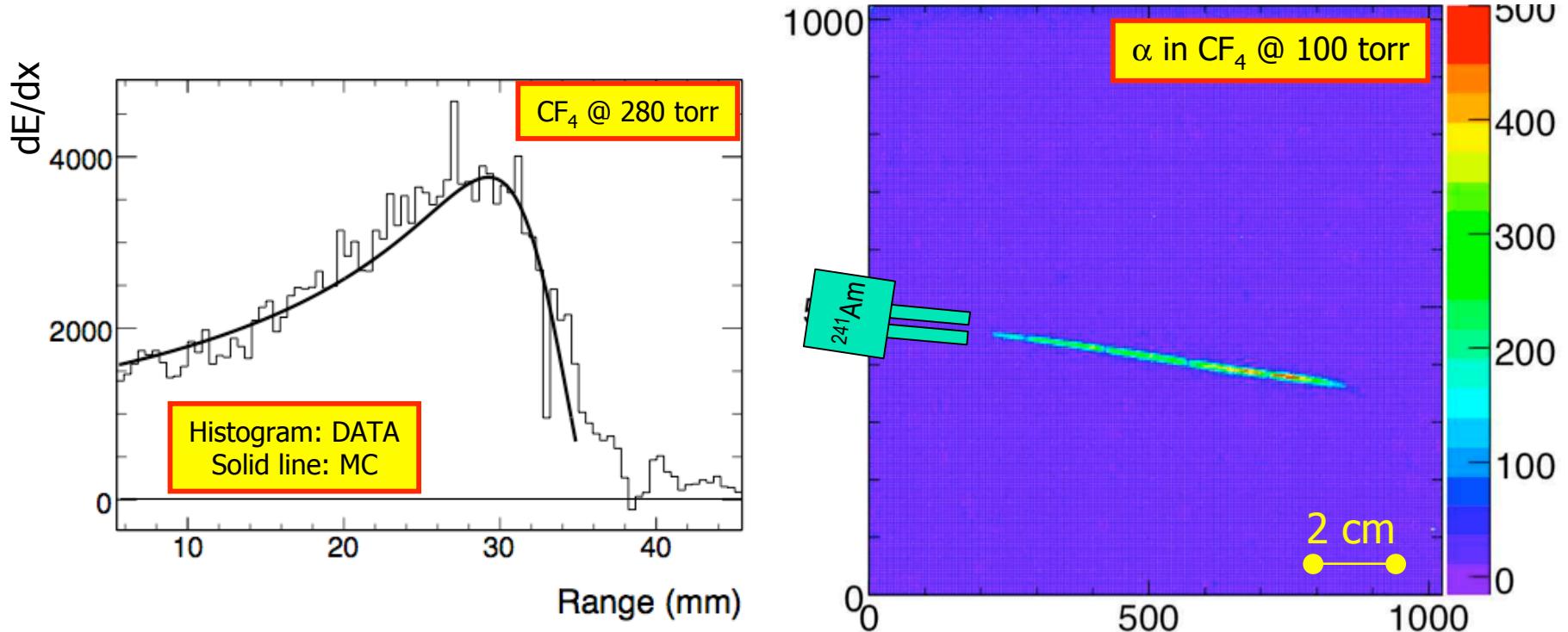
DM-TPC: 2nd generation prototype



- Drift up to 25 cm
- Image view 16 cm \varnothing
- Mesh detector 23 cm \varnothing
 - 256 μm pitch
 - 30 μm wire \varnothing
 - 79% transparency



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

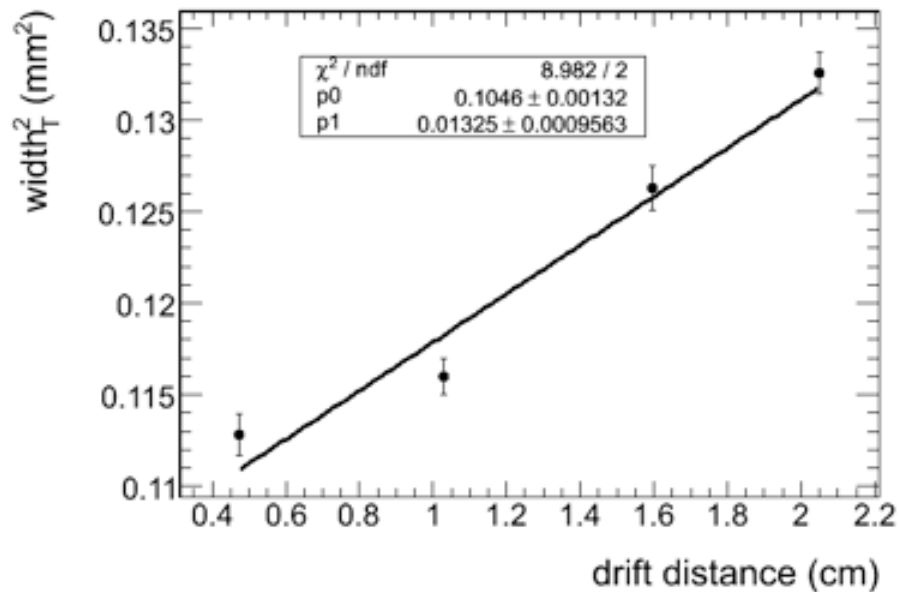
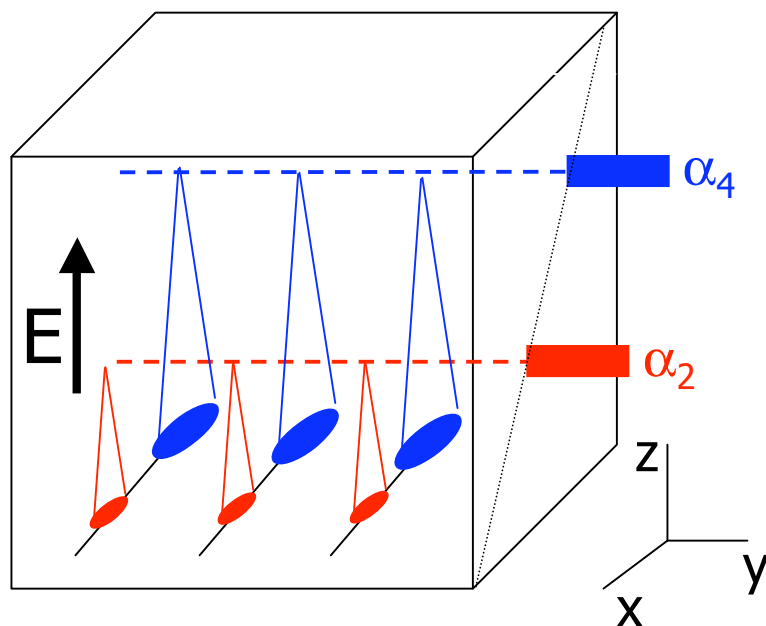


- Alphas emitted parallel to anode wires
 - Wire plane oriented at 45 degrees
- Compare measured dE/dx vs range of the track with SRIM simulation
 - Excellent DATA-MC agreement!

Well understood detector

Effect of diffusion on resolution

- Dark Matter recoils $\sim 1-2$ mm
 - Resolution $\ll 1$ mm; diffusion must be contained
- Resolution vs drift distance measured with 4 α sources

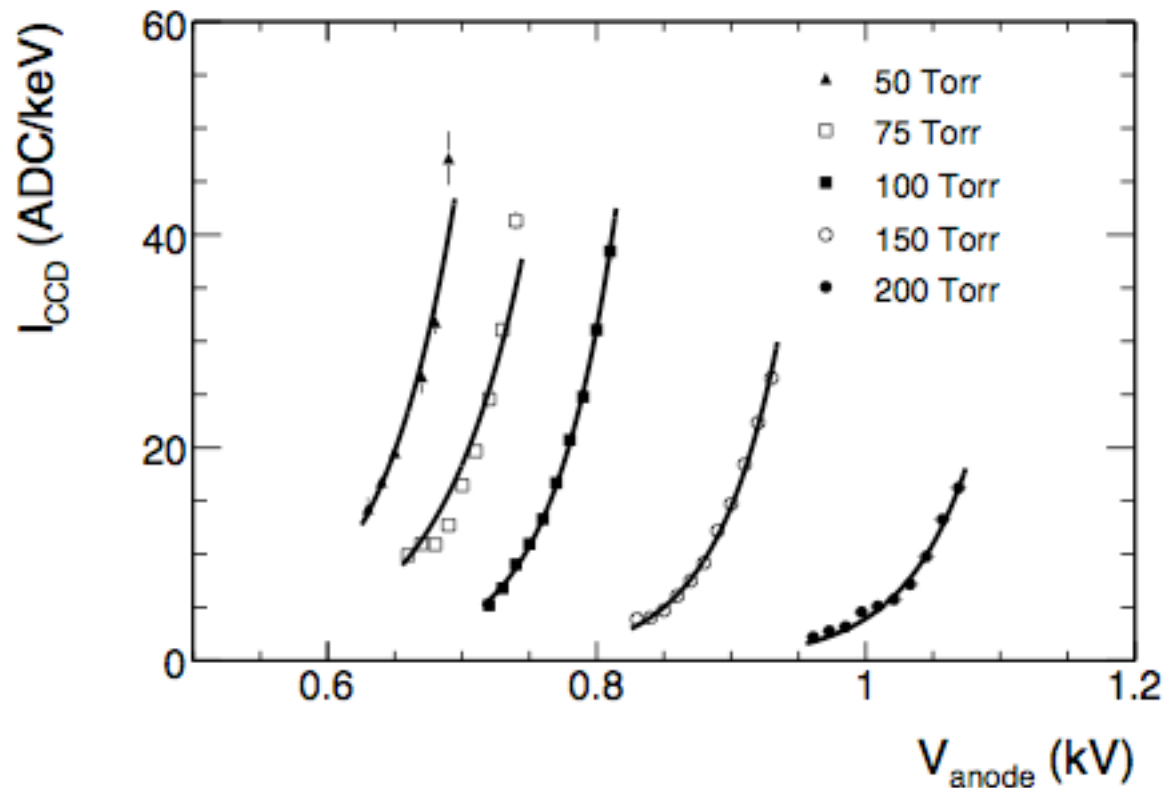


$$\sigma[\mu\text{m}] = 324 \oplus 36\sqrt{\Delta z}$$

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

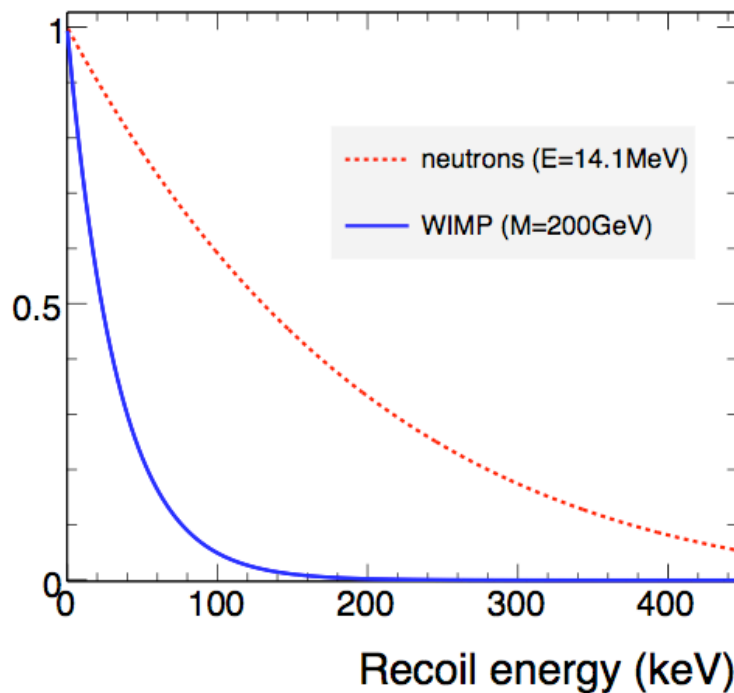


Stable operations for gas gain $\sim 10^5$

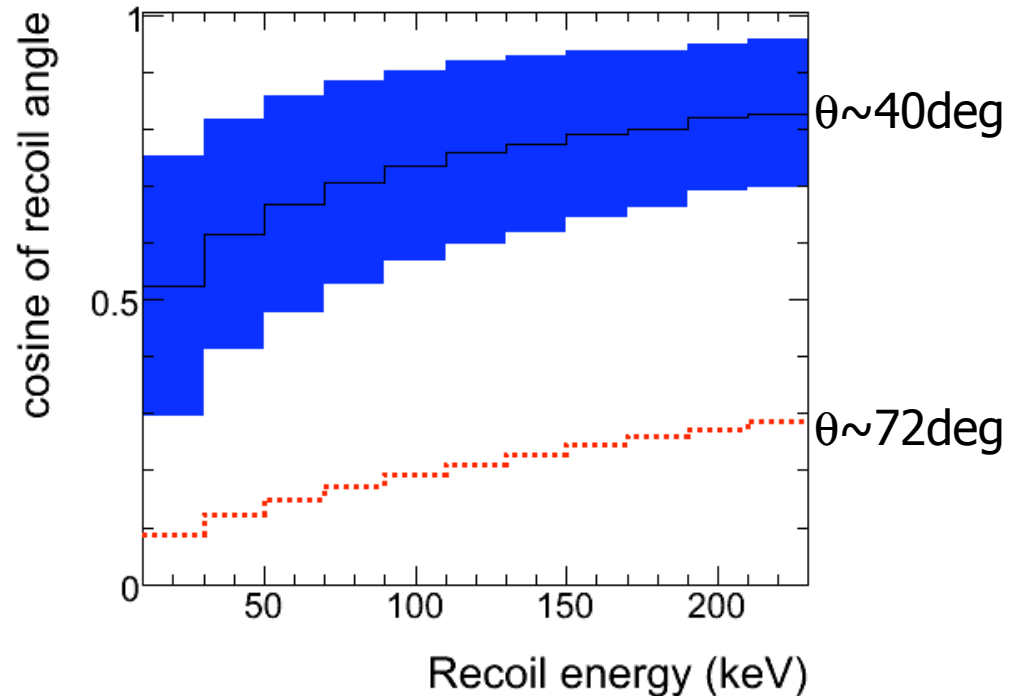
Recoils from low-energy neutrons

- 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

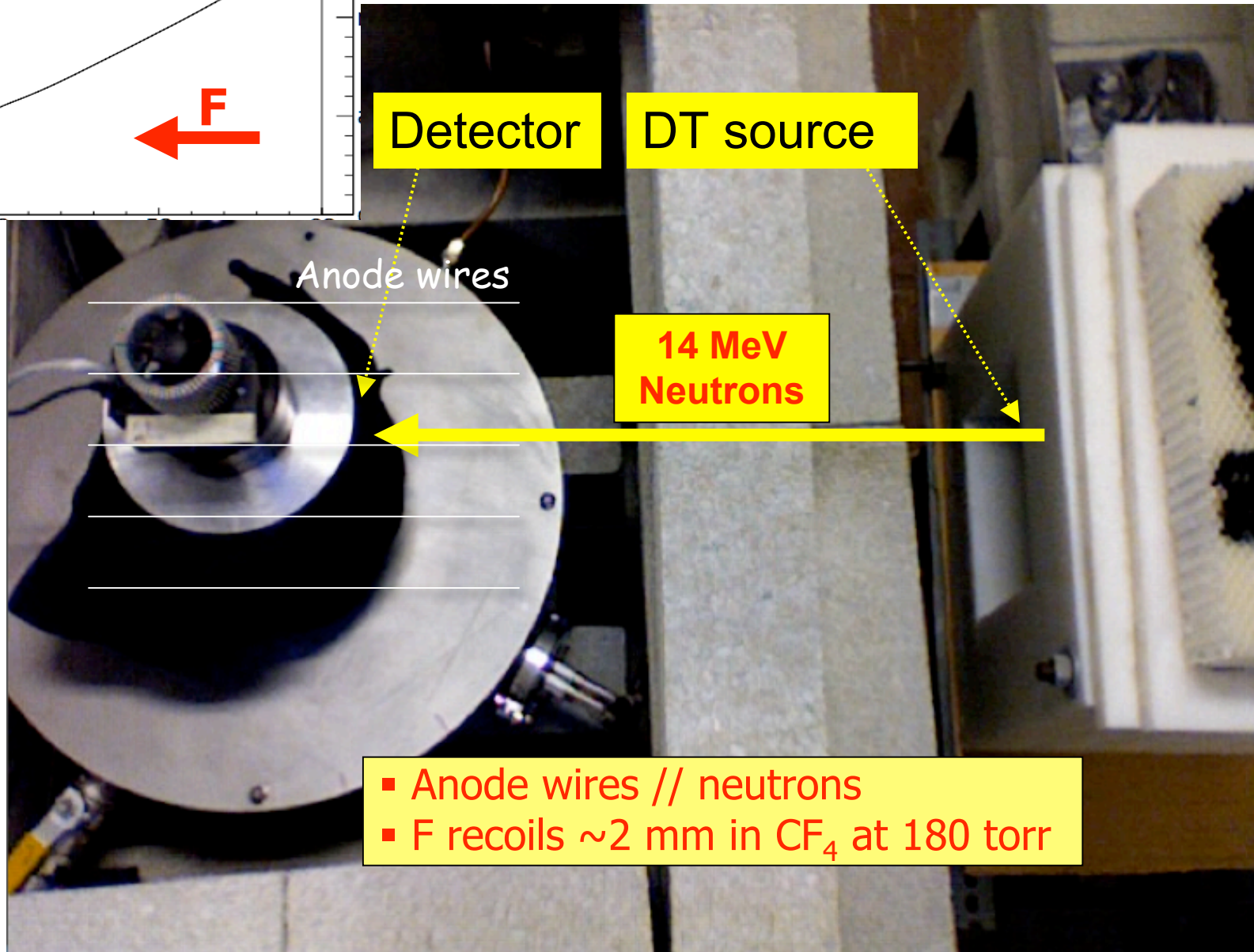
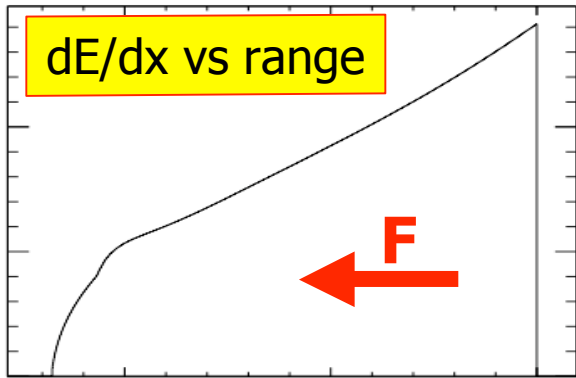
Fluorine recoil energy



Fluorine recoil angle wrt wires



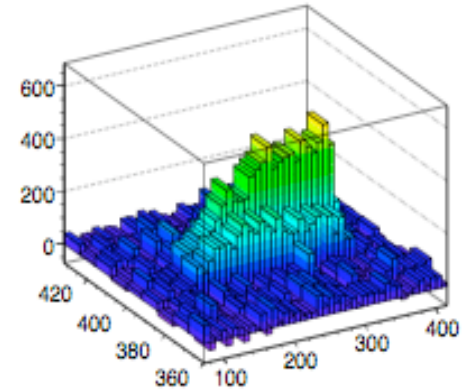
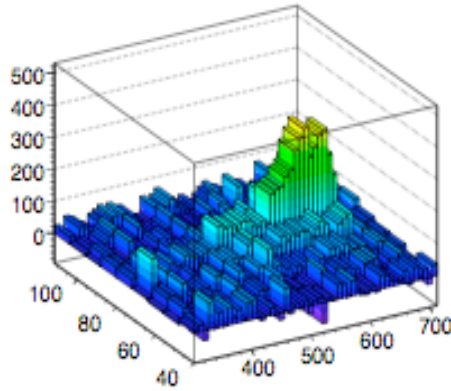
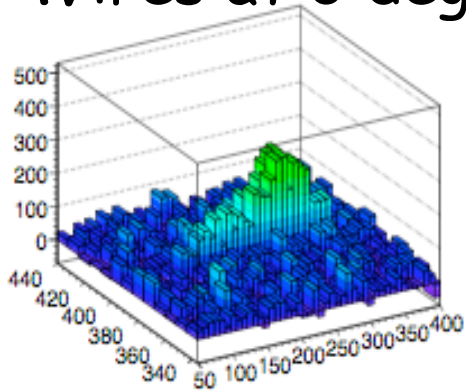
Neutron beam setup



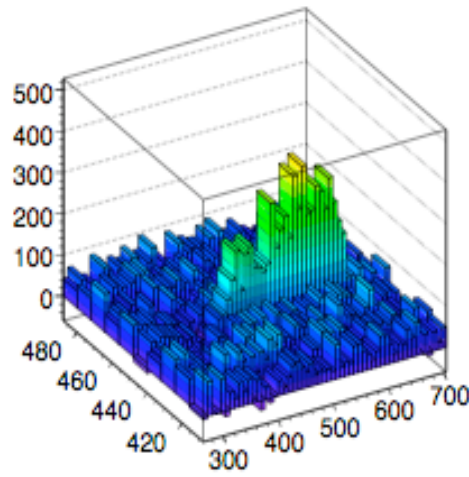
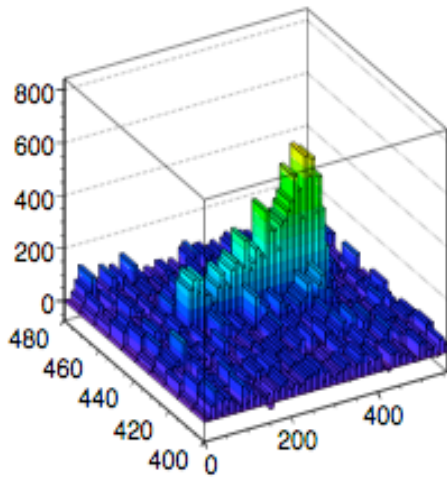
- Anode wires // neutrons
- F recoils ~ 2 mm in CF_4 at 180 torr

Observation of "head-tail" in F recoils

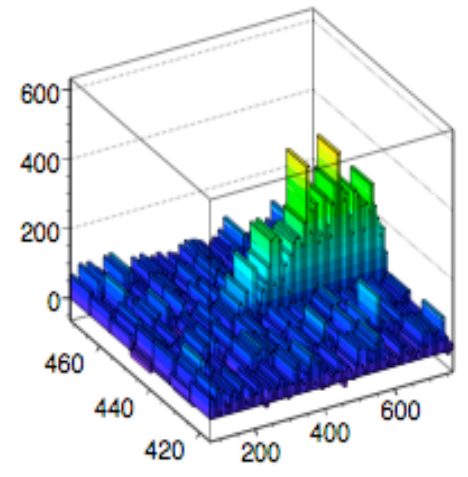
Wires at 0 deg:



Wires at 180 deg:



Direction of neutrons
←

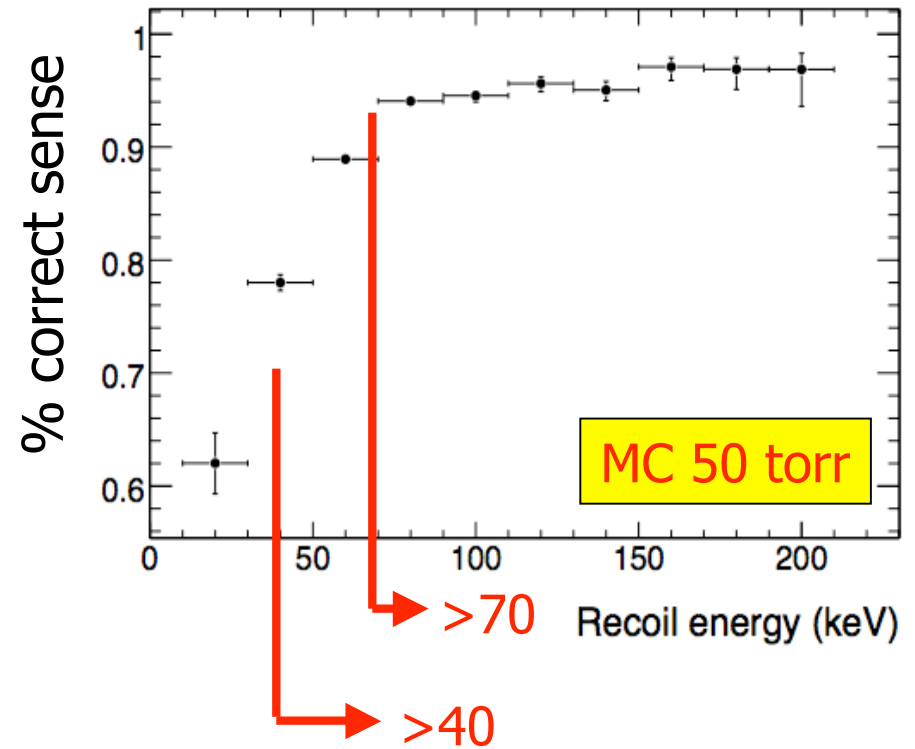
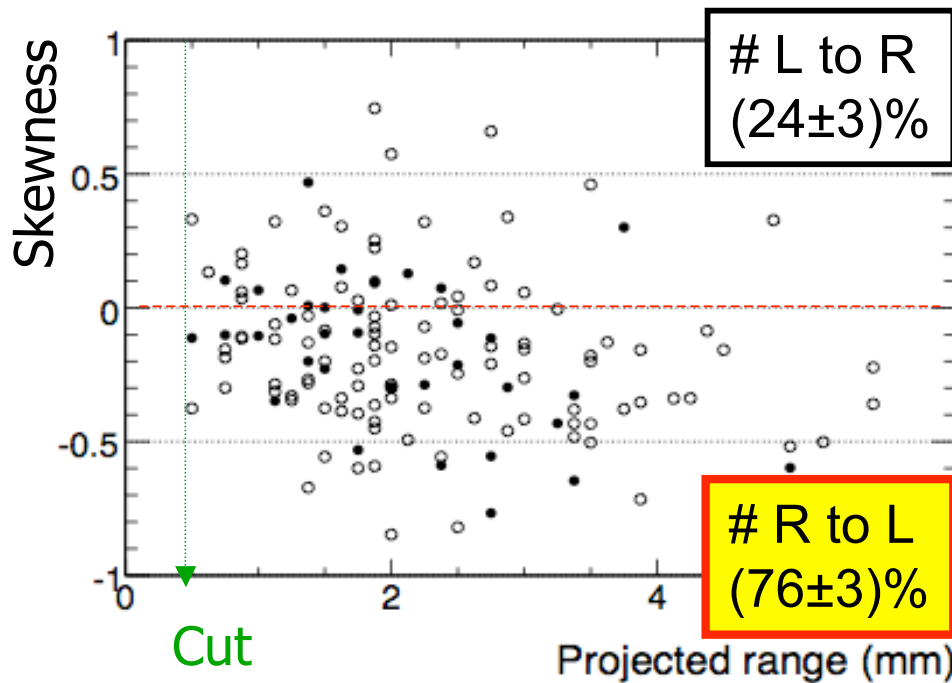


More quantitative results (DT)

We measure skewness of light yield along wire

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

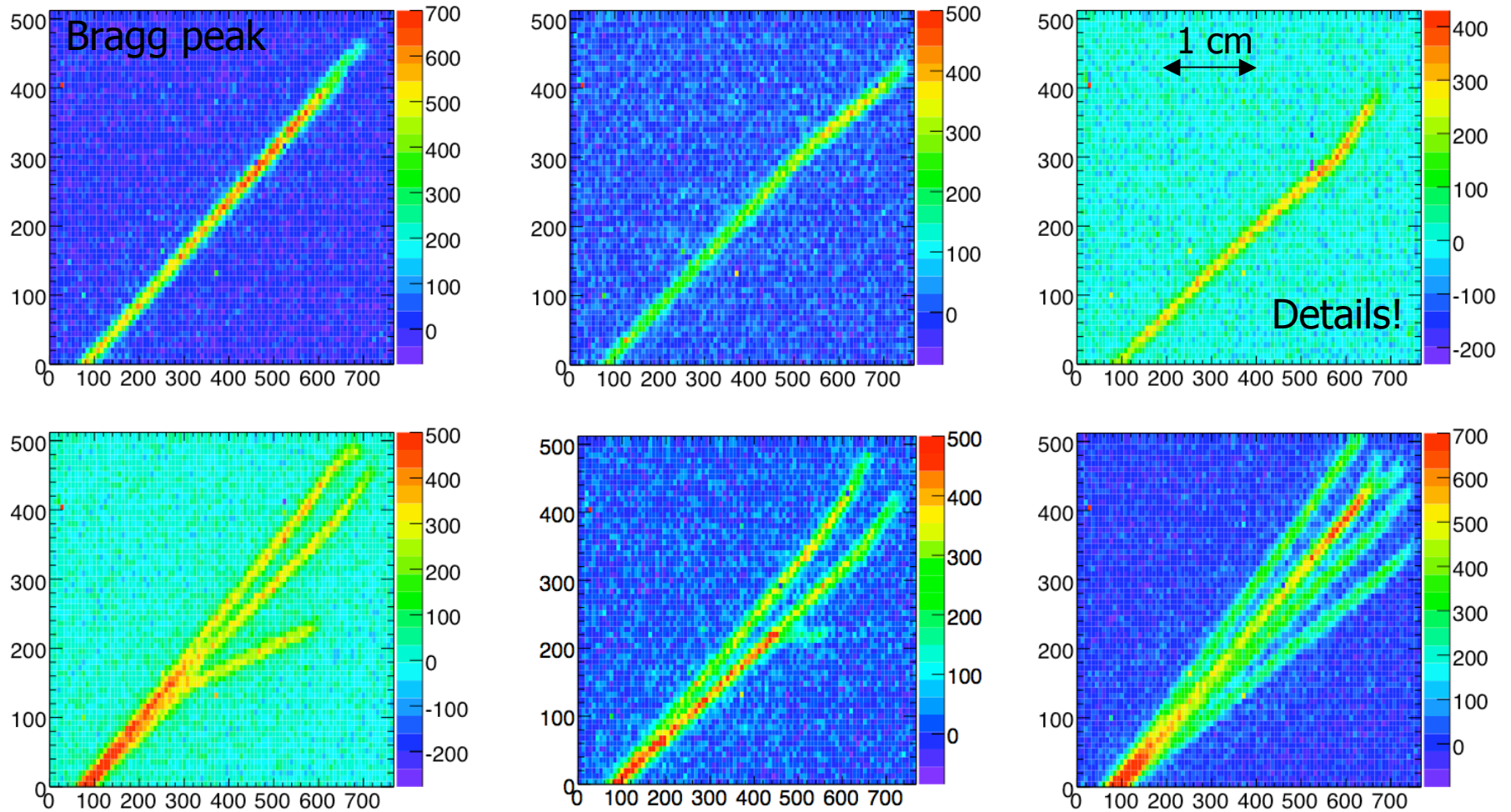
$\gamma > 0$: neutron travels L to R
 $\gamma < 0$: neutron travels R to L



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

$V_{\text{anode}} = 2\text{kV}$ ($E \sim 1.5 \cdot 10^5 \text{ V/cm}$)
300 μm gap, 200Torr

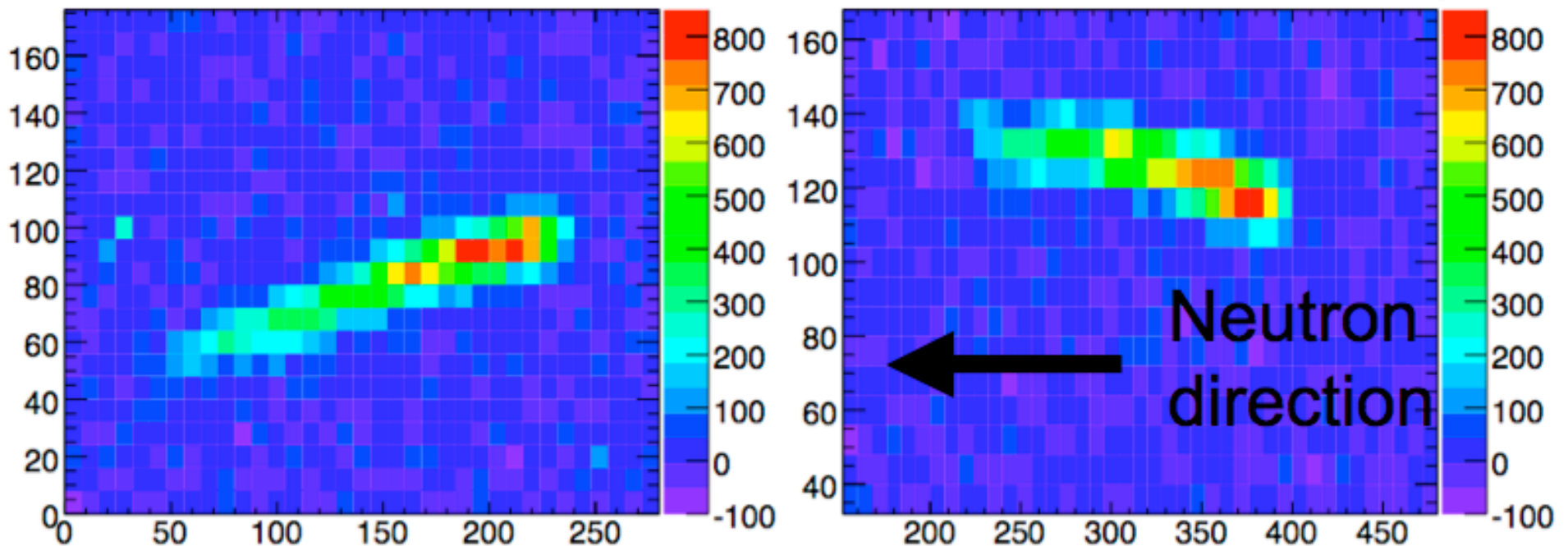
α particles with meshes



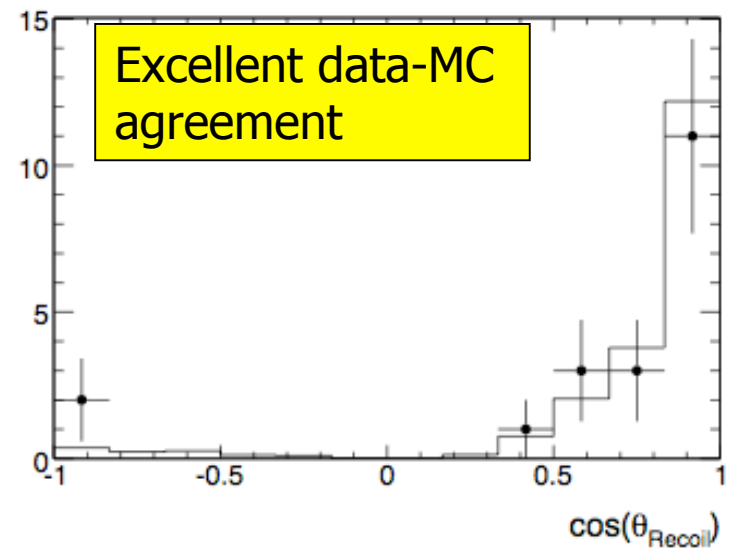
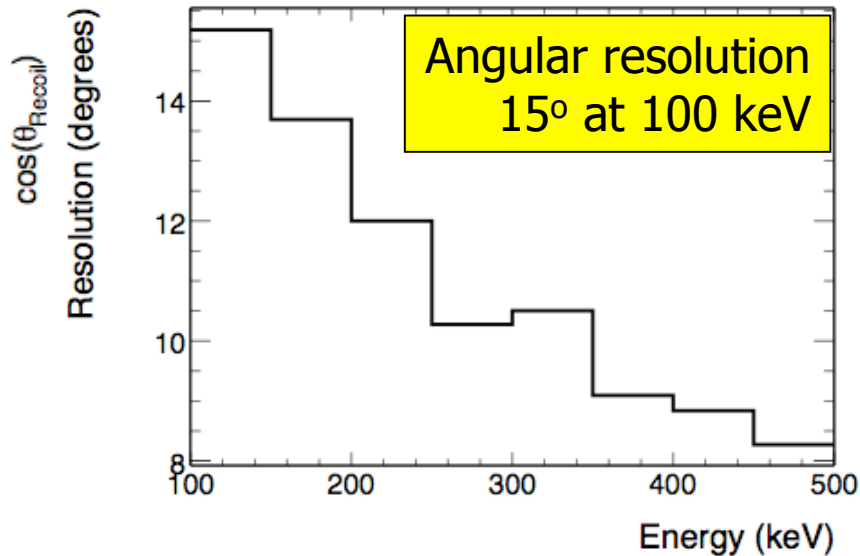
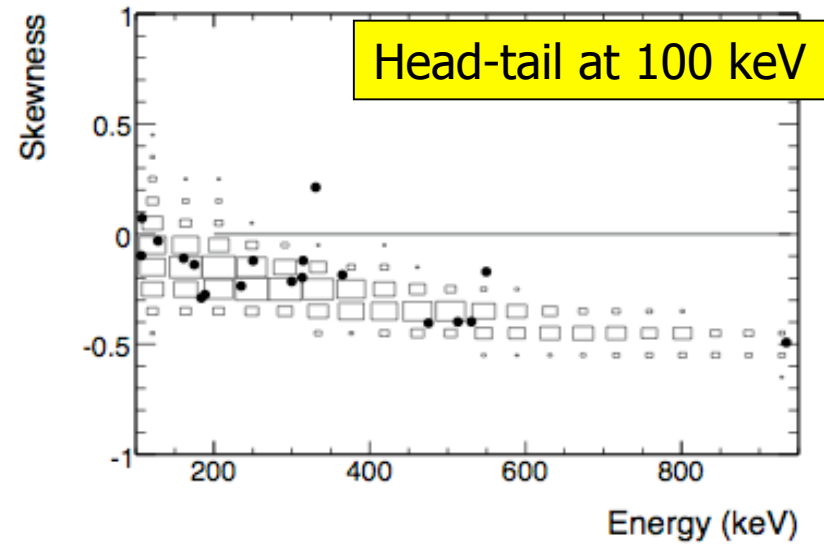
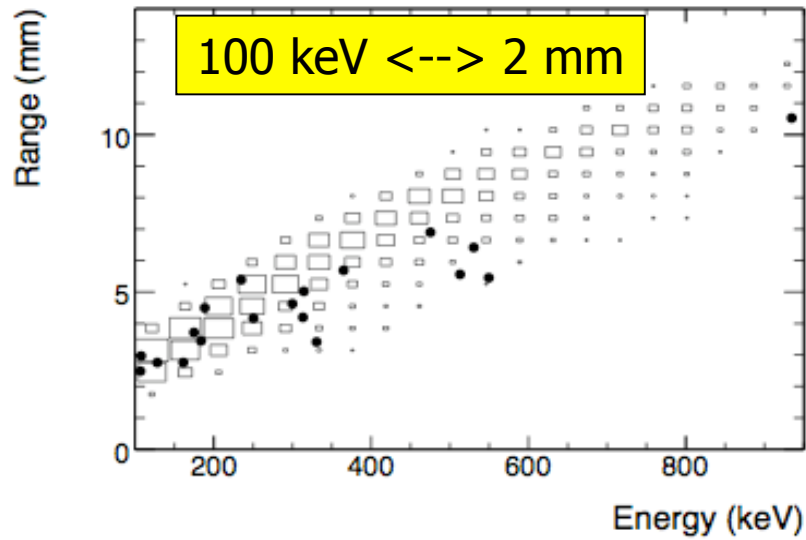
NB: 1D --> 2D at no additional cost!

^{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

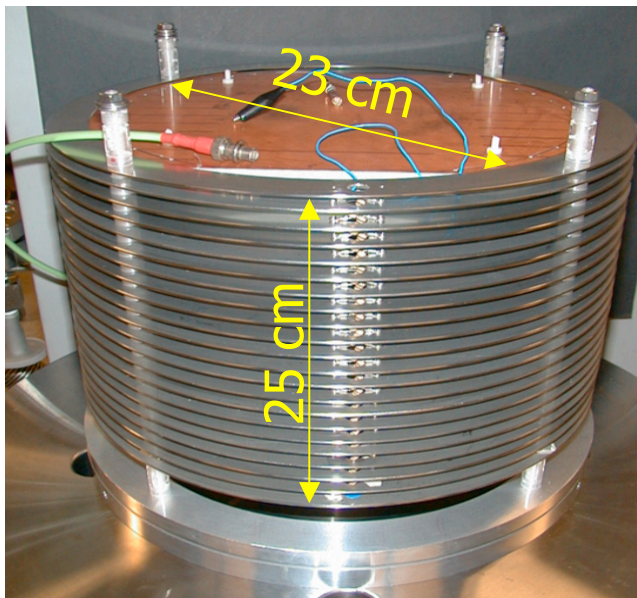


Mesh detector: ^{252}Cf run @ 75 torr



Next step: DM-TPC (10 liters)

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



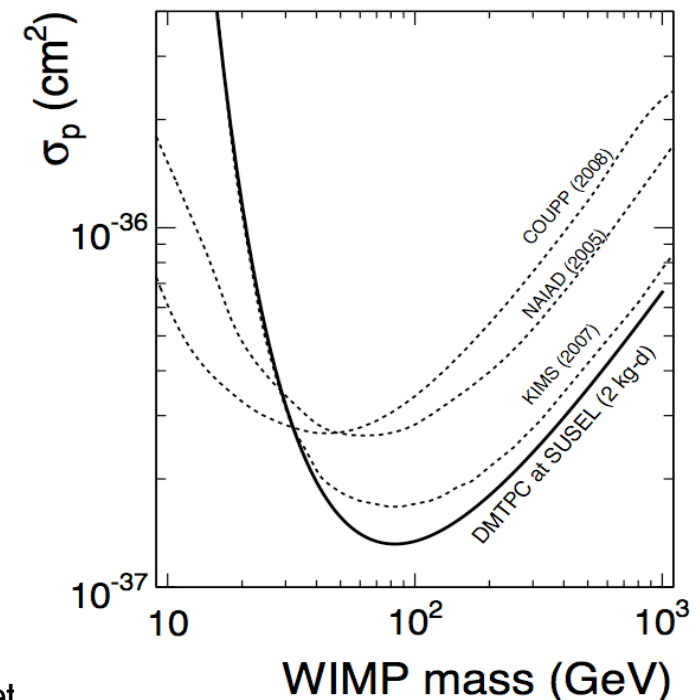
Gabriella Sciolla

DM-TPC: a new approach to directional



Goals of DM-TPC (10 liters)

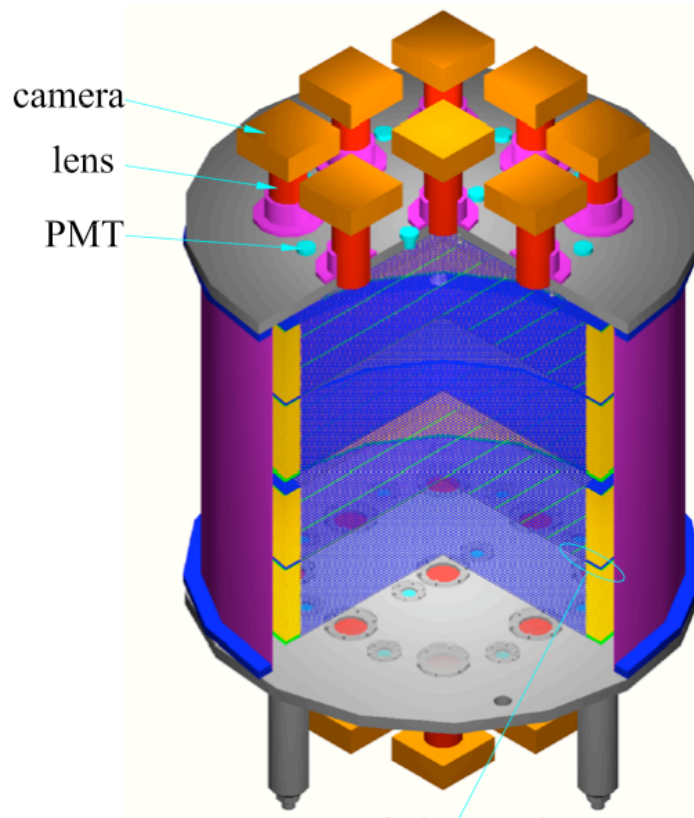
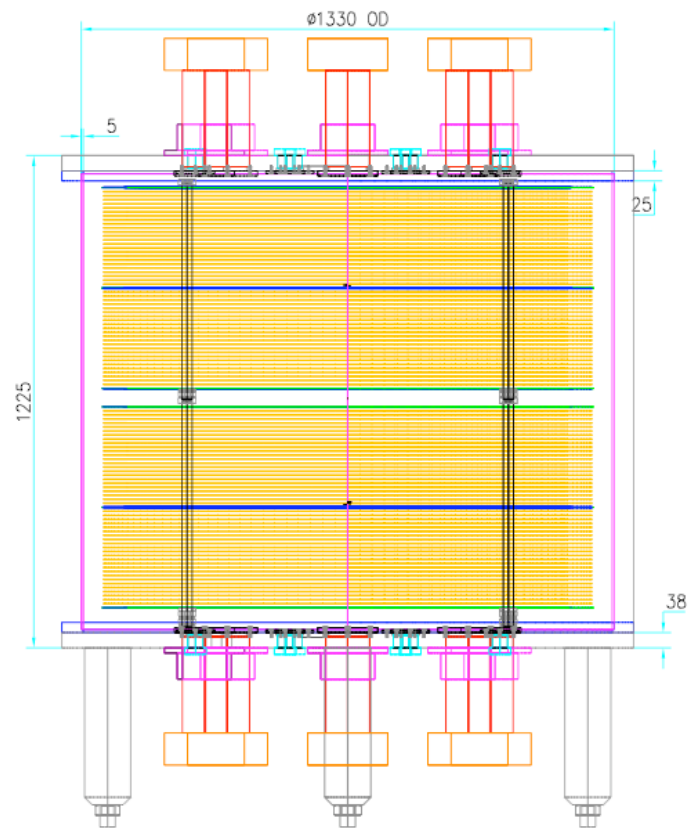
- Ready for underground run (starting in Spring 2009 at WIPP)
 - Detectors commissioned at MIT
 - > 1 month of surface data is being analyzed
- Module 1: study neutrons underground (no neutron shielding)
 - Gas mixture ^4He - CF_4 to enhance n interactions
 - Measure neutron spectrum and direction in 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-m³ detector

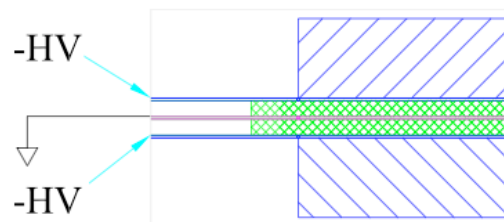
- Mass $\sim 0.25\text{-}0.5 \text{ kg/m}^3$
- 1 year: $\sim 100\text{-}200 \text{ kg d}$

- 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



Mesh Spacers

Triple Mesh

Preliminary

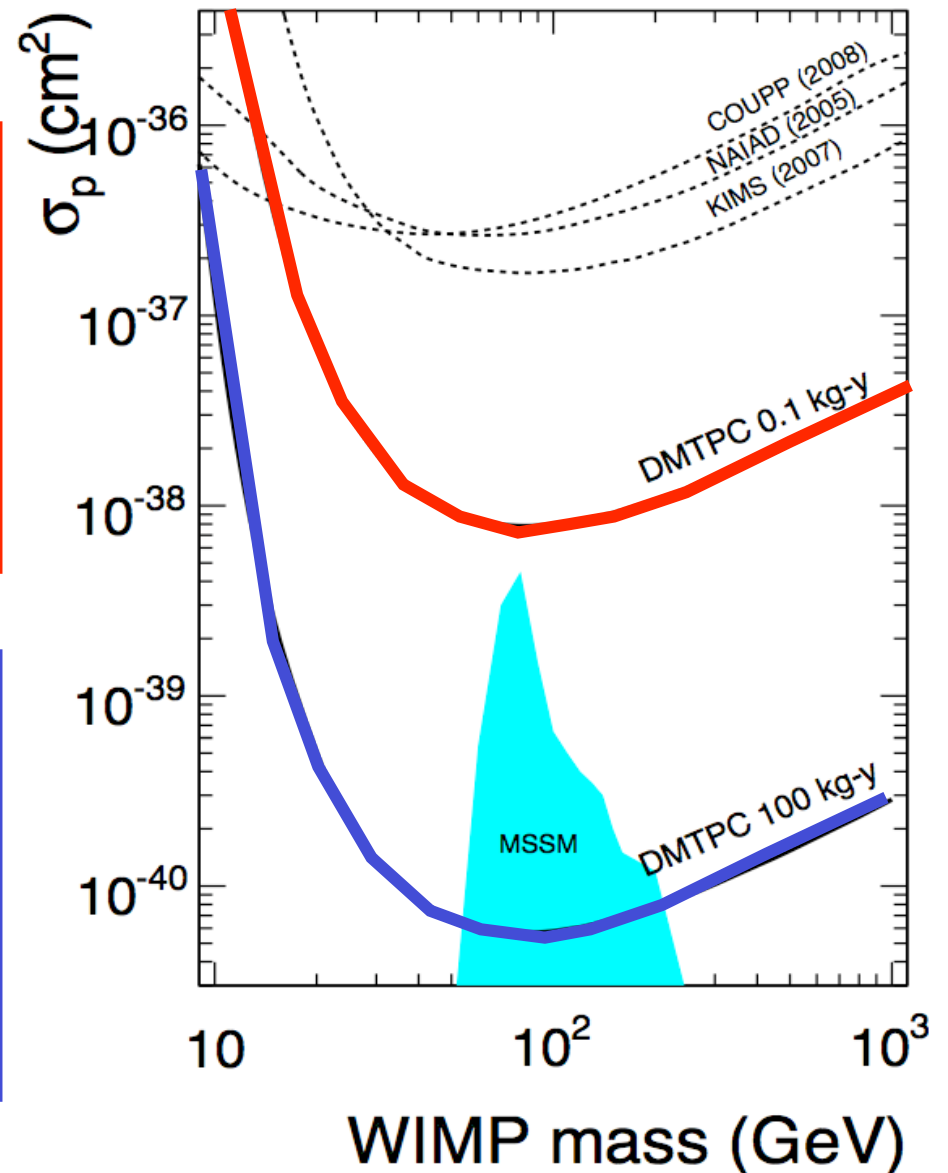
Sensitivity 1 m³ underground

Assumptions:

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

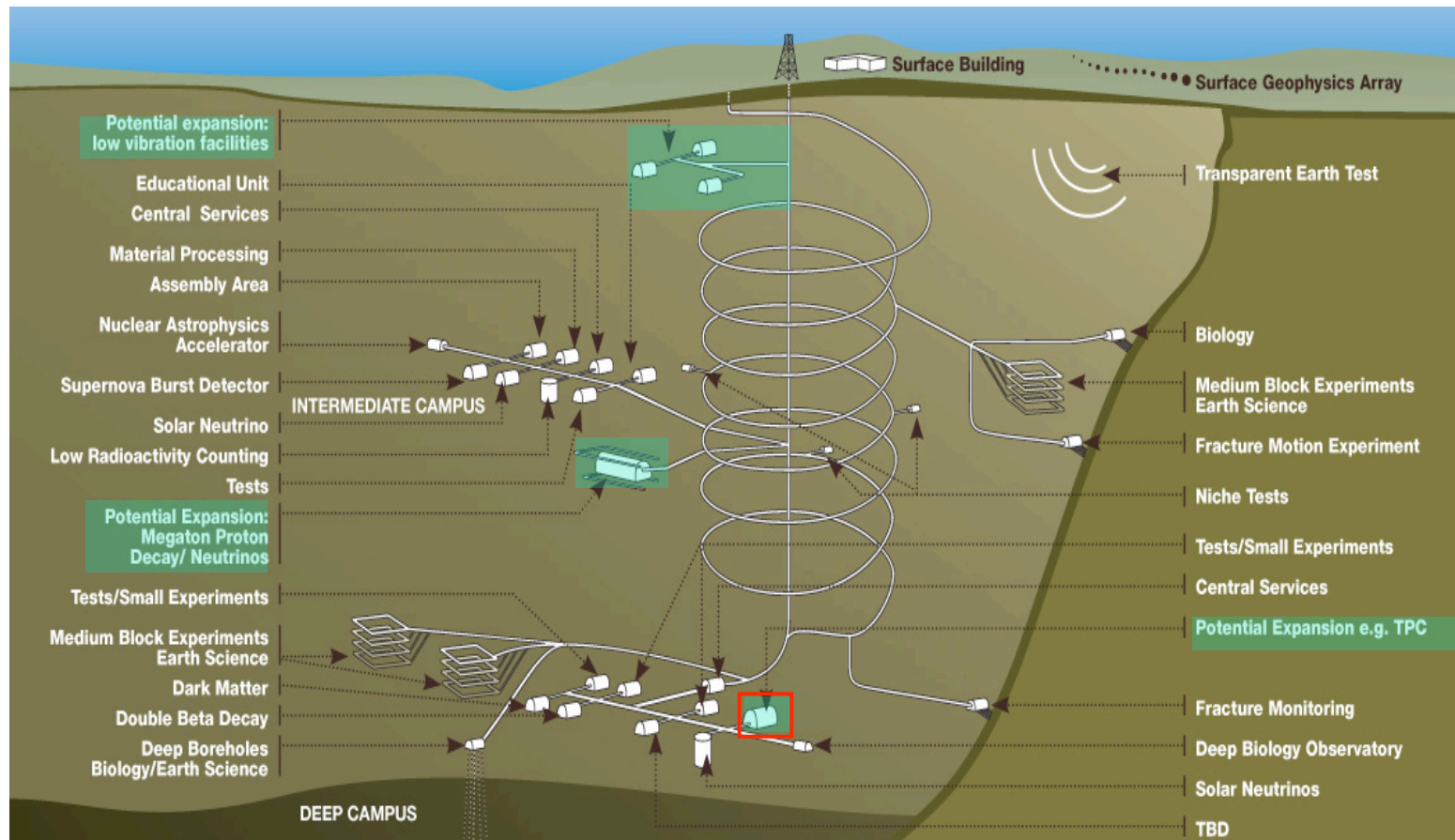
Future detector:

- 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 presentation at HEPAP meeting on 7/14/2007

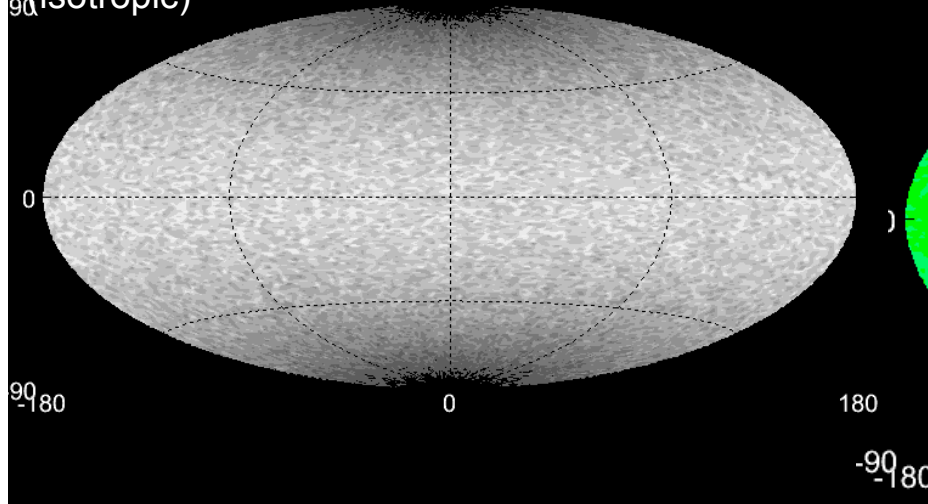
Conclusion

- 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-m³ detector being designed; very competitive in σ_p^{SD} w/directionality
- Large O(10² kg) DM-TPC detector ideal candidate for DUSEL
 - Directionality: unambiguous observation of WIMPs
 - First DM observatory for underground WIMP astronomy

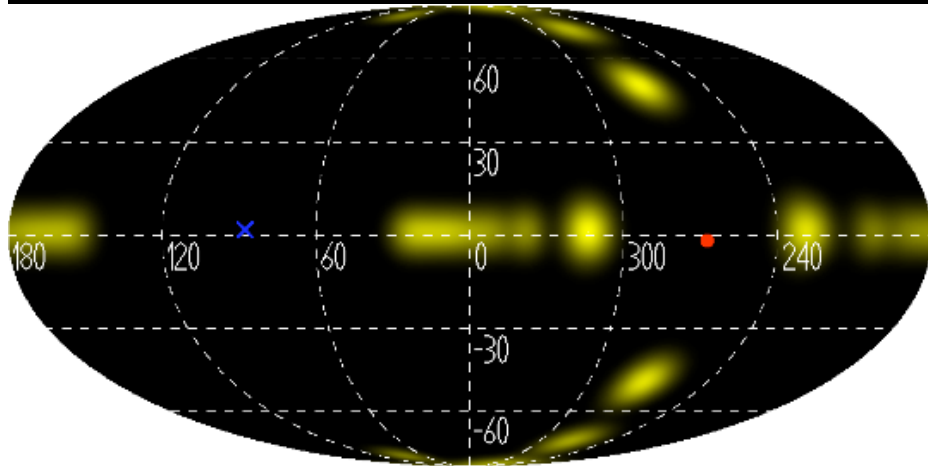
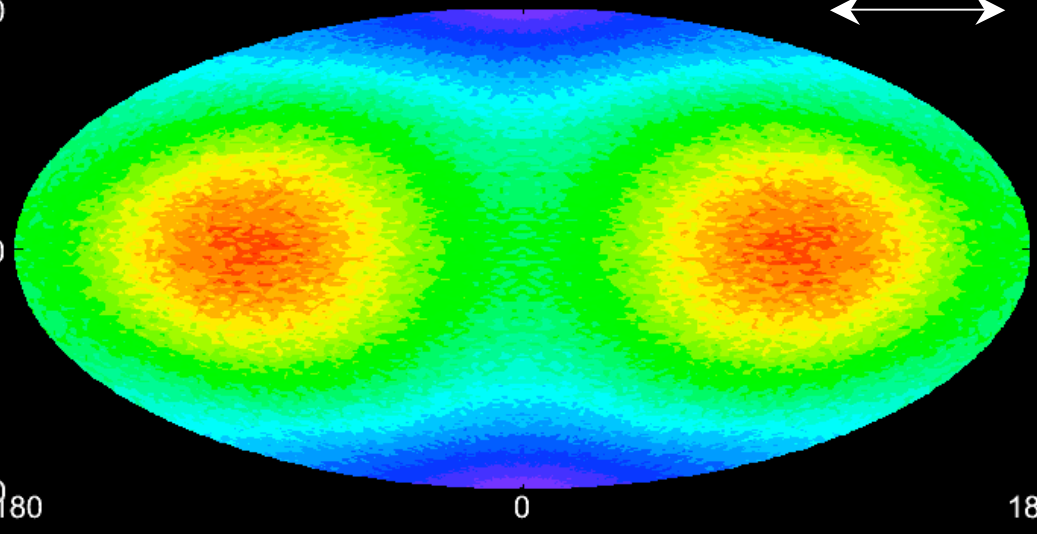
WIMP Astronomy: Sky Map

Background

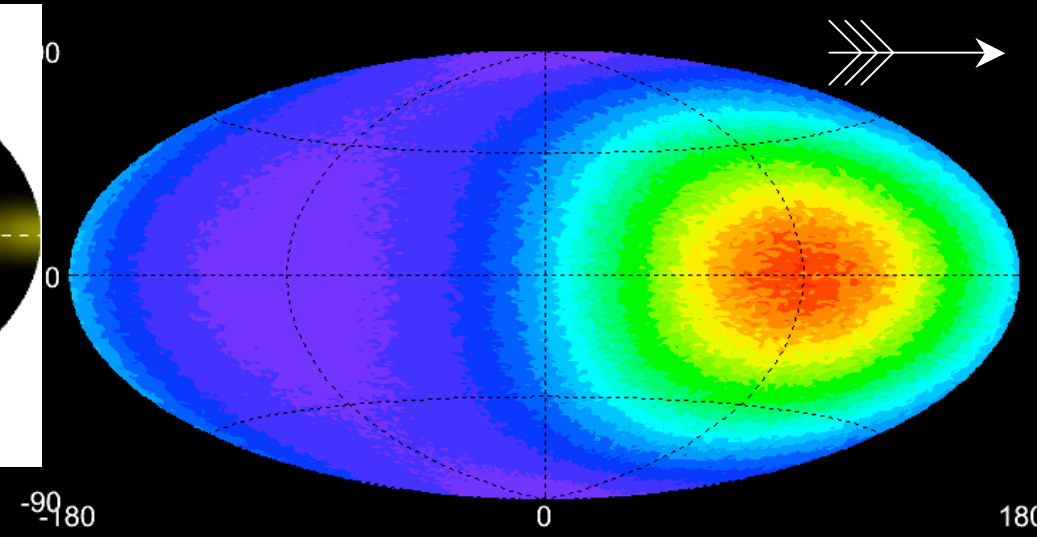
ρ_d (isotropic)



Dark halo - no head-tail



Sikivie's model (Gelmini, Gondolo 2001)



With head-tail