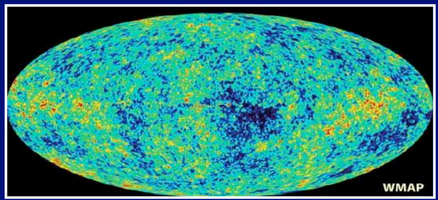
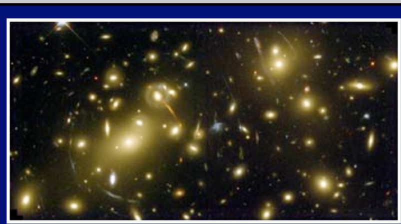
Dark Matter present and future

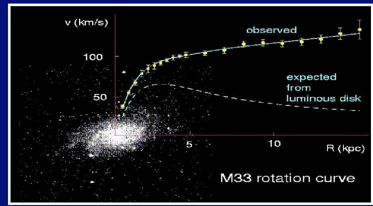
Neil Spooner - University of Sheffield

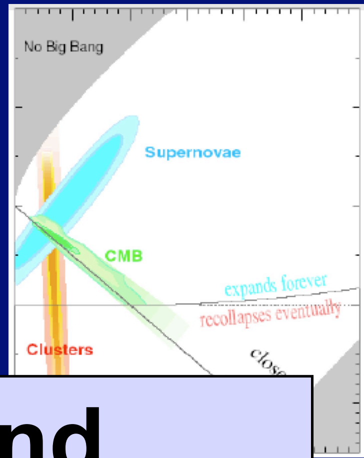


Concordance of the Universe









Contributions to Ω

Total (100%) $\Omega_0 = 1$

Stars 0.5%

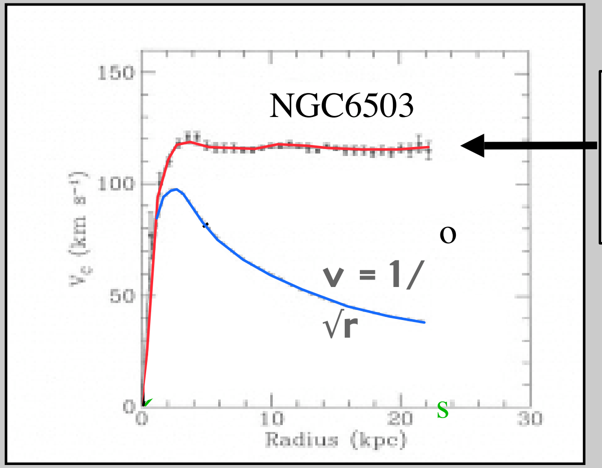
73% still missing

Three "dark" problems and >95% of the Universe is still unidentified

Weighing a Galaxy

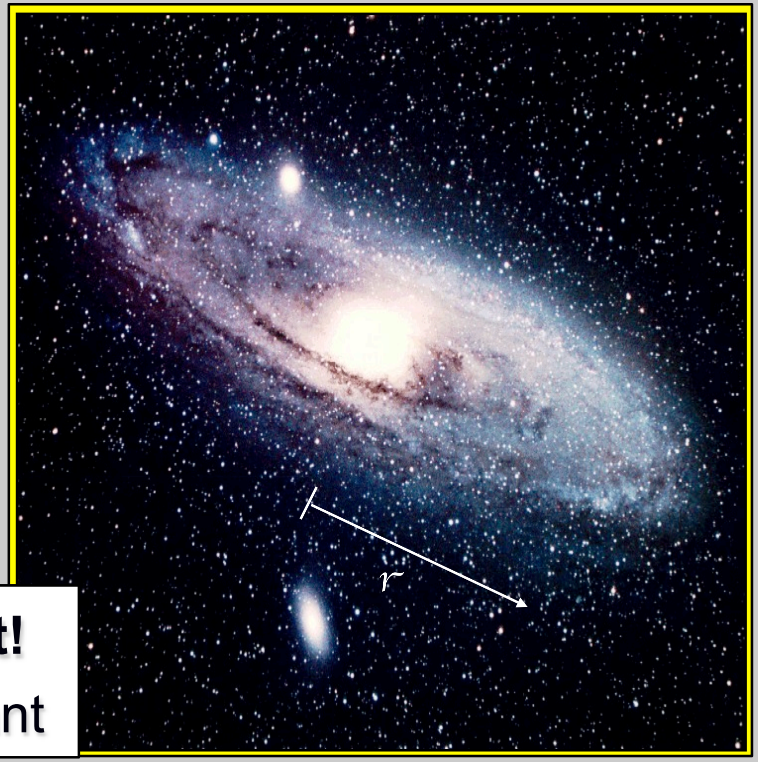
- **Use Doppler shift of star light to determine rotational velocity.**
- **Expect velocity to fall off with distance from centre**

$$v_c^2 = G_N \, M_{vis}/r$$



It doesn't!

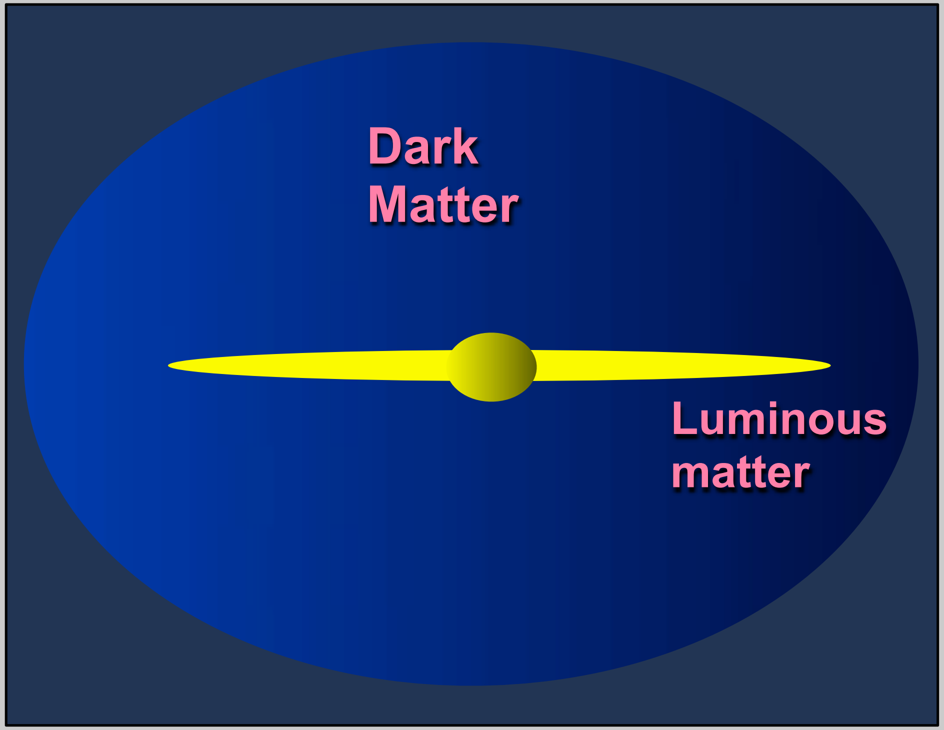
v ~ constant



There must be a lot of hidden (non-luminous)

DARK MATTER!

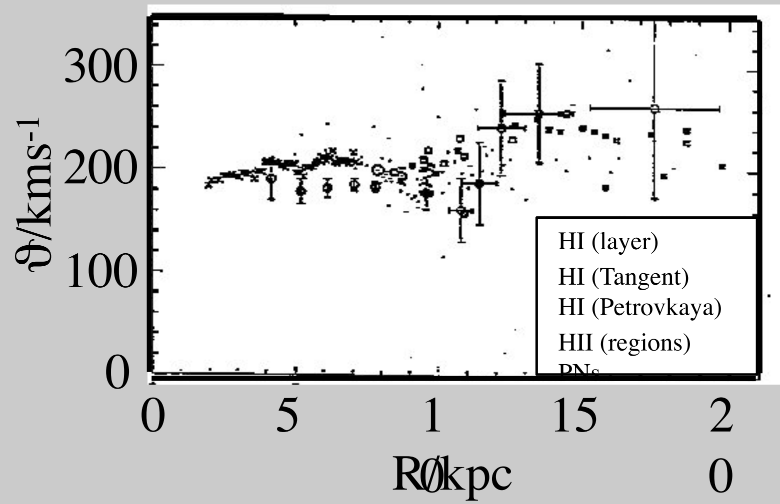
Weighing a Galaxy



- ~90% of the mass of galaxies is in the form of **DARK MATTER**
- Evenly distributed in a Dark Matter Halo

NGC6503

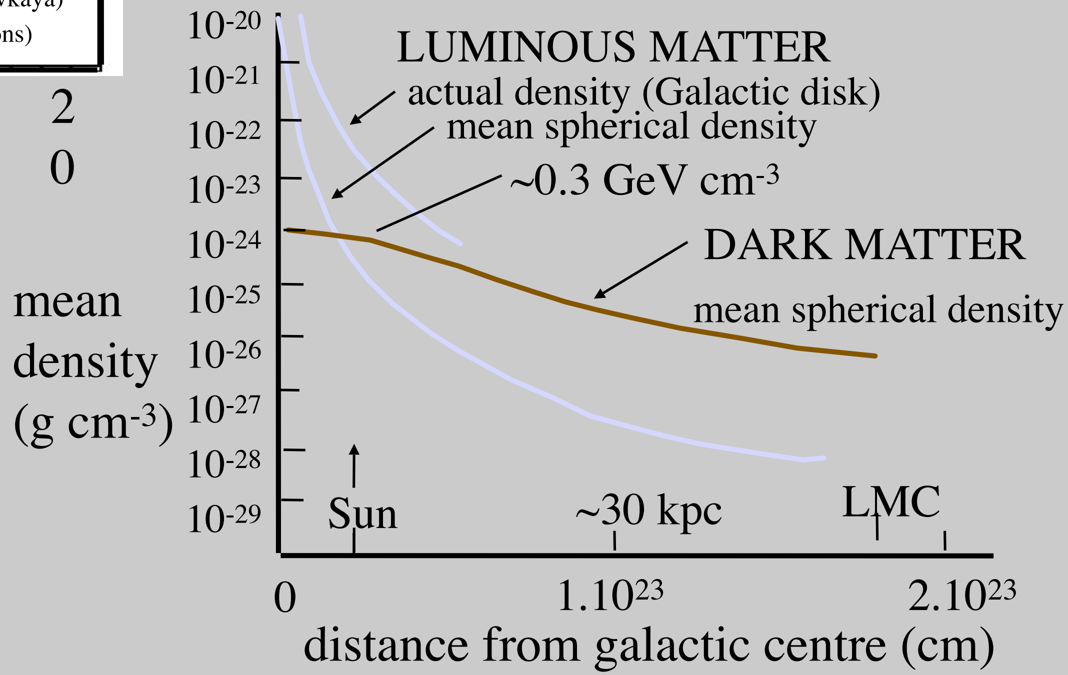
Dark Matter in our Galaxy



> 90% of our galaxy is dark matter

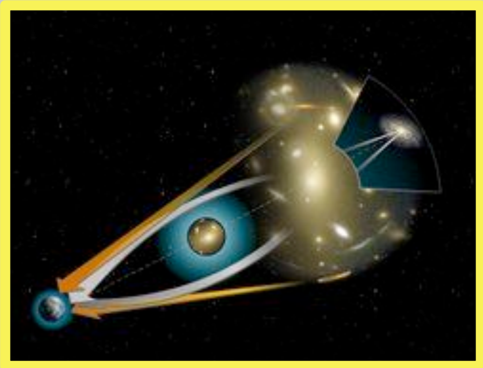
gives Ω_{halo} ~ 0.1

$$\Omega_a = \frac{\rho_a}{\rho_c}$$

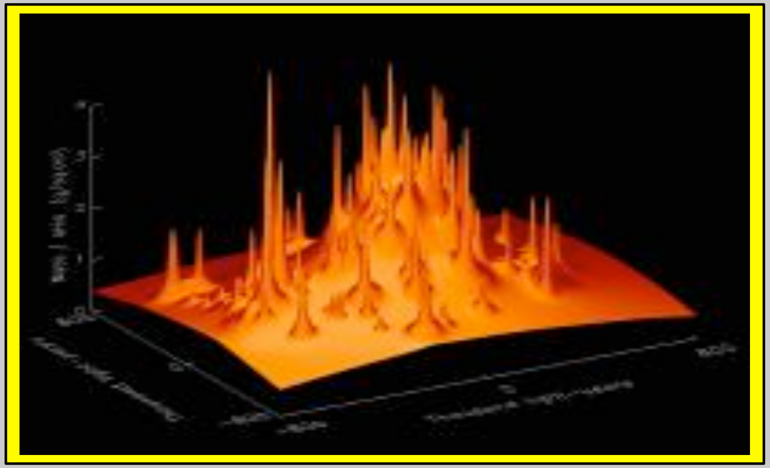


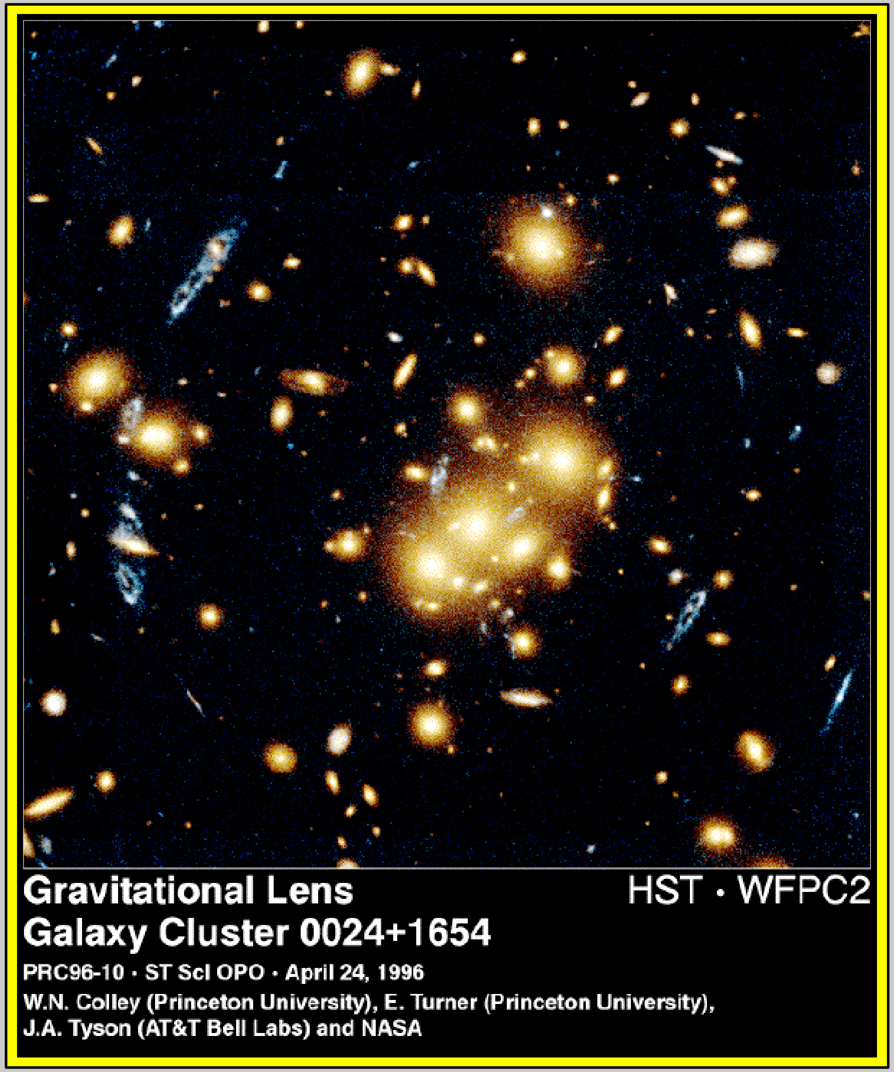
Weighing Galaxy Clusters

- **Now missing mass detected by ‘Gravitational Lensing.’**

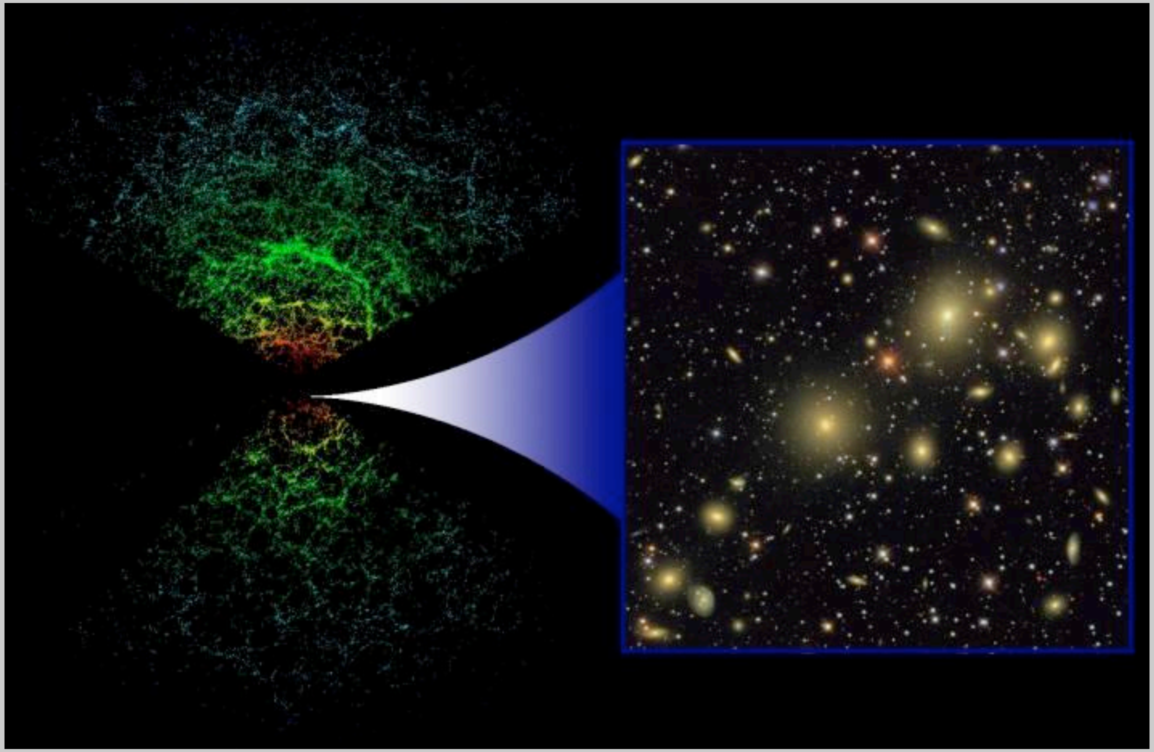


- **Distortion (rings or multiple images) caused by gravitational lens**

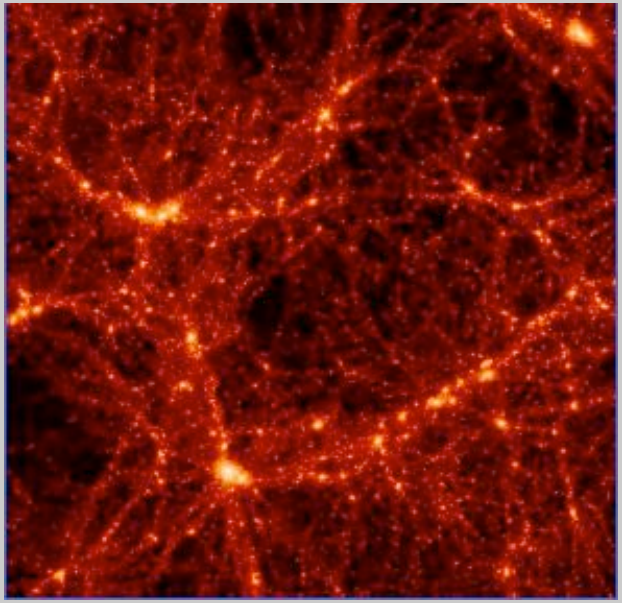




Models of Large Scale Structure



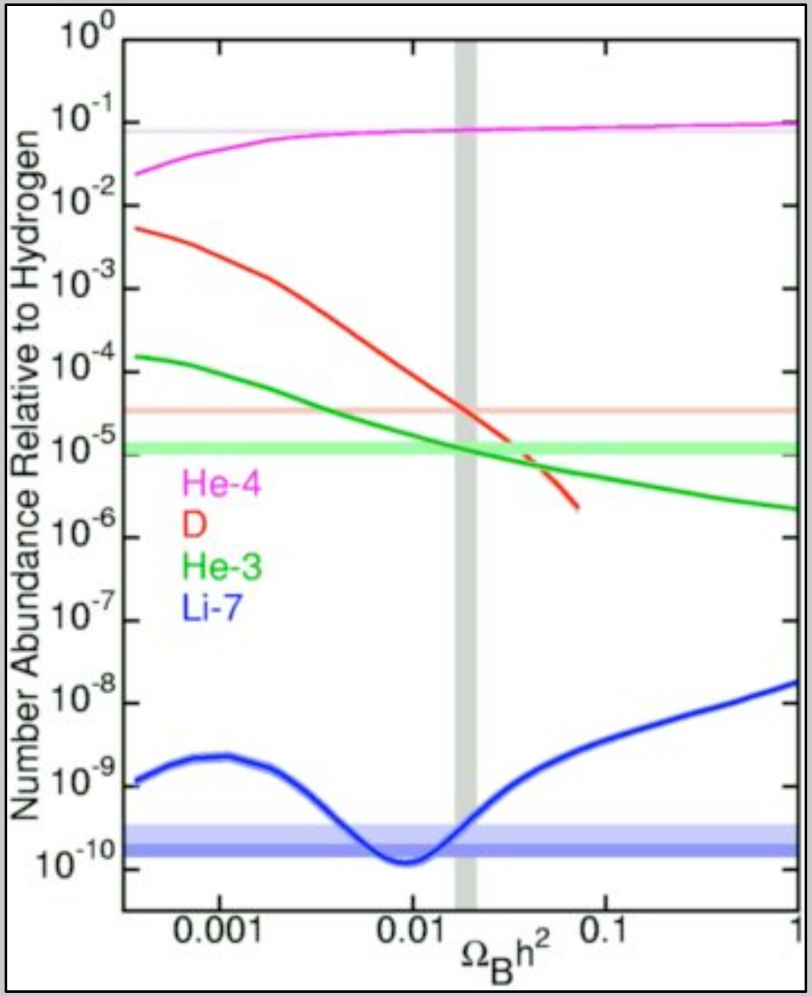
Observed large scale structure can be modelled only with cold dark matter



Sloan digital sky survey and VIRGO simulations for ΛCDM cosmology

Big Bang Nucleosynthesis

Nucleosynthesis simulations predict the abundances of light elements (D, He, Li) as a function of the baryon density.

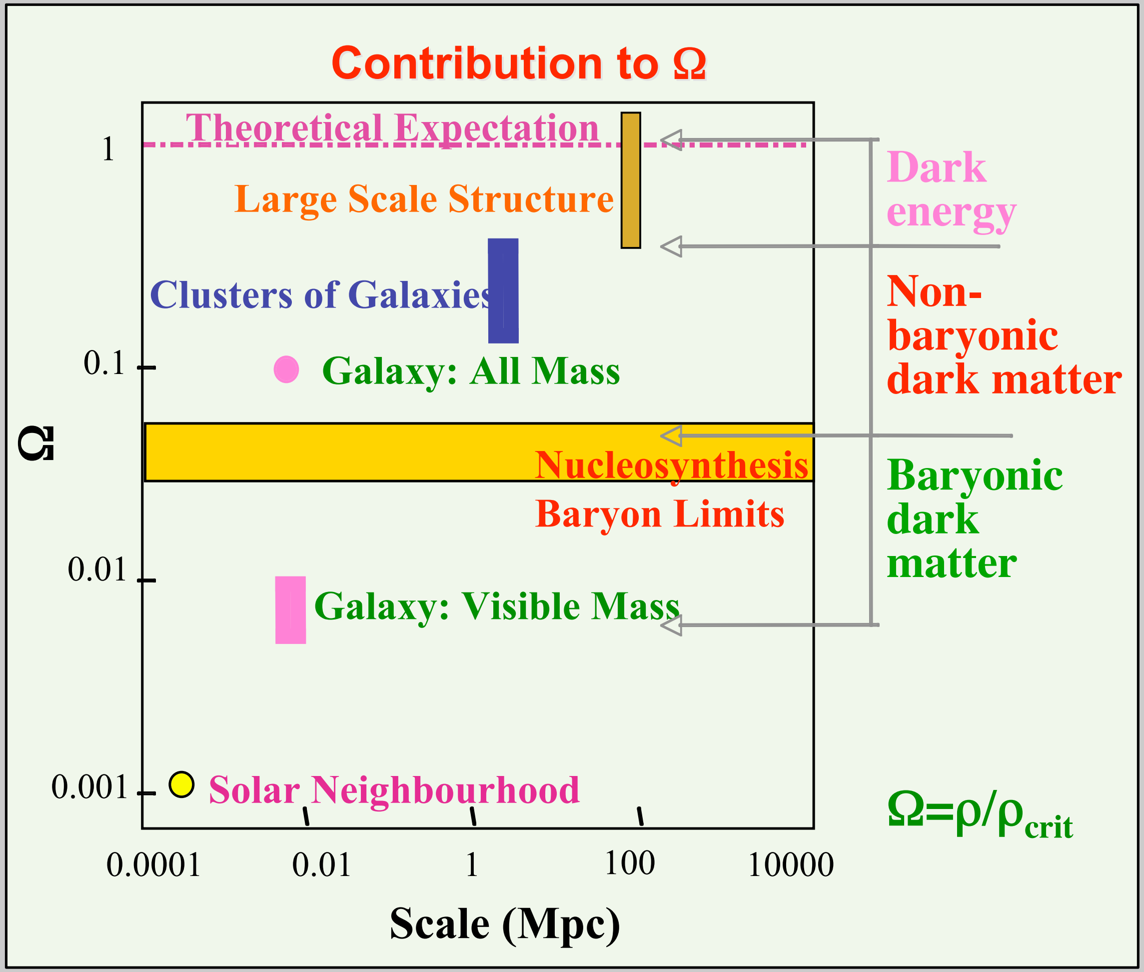


Measurements complicated by astrophysical production mechanisms, but primordial D abundance now give

$\Omega_b = 0.040 \pm 0.004$.

BB Nucleosynthesis

- $\Omega_{visible} \approx 0.005$
- $\Omega_{baryon} = 0.044 \pm 0.004$
  nucleosynthesis, WMAP
- $\Omega_{matter} = 0.27 \pm 0.05$
  WMAP, sky surveys
- $\Omega_{dark\ energy} = \Omega_{\Lambda} =$
  0.73 ± 0.04
  distant type Ia supernovae, WMAP
- $\Omega_{total} = 1.02 \pm 0.02$
  WMAP, inflation
- $h = 0.71 \pm 0.04$



Dark Matter Candidates

Ordinary Matter

- Gas or Dust?
- Small, faint stars (or near-stars)?
  - white dwarfs
  - red dwarfs
  - brown dwarfs
  - Jupiters
- Black Holes?

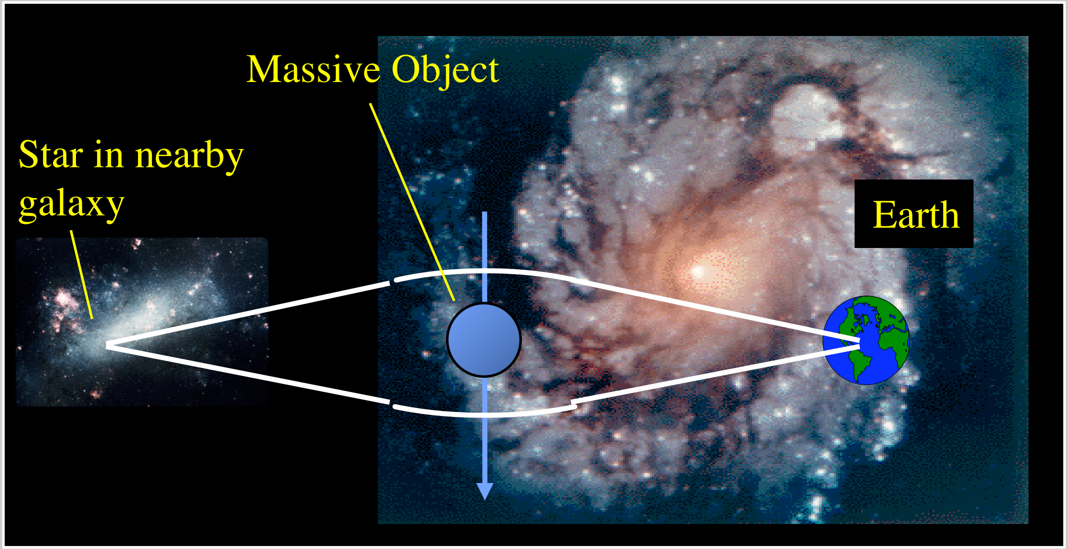
Exotic Particles

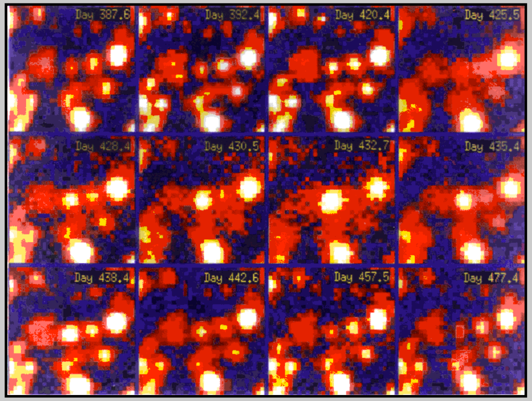
- Neutrinos (ν)
- **W**eakly **I**nteracting **M**assive **P**articles…

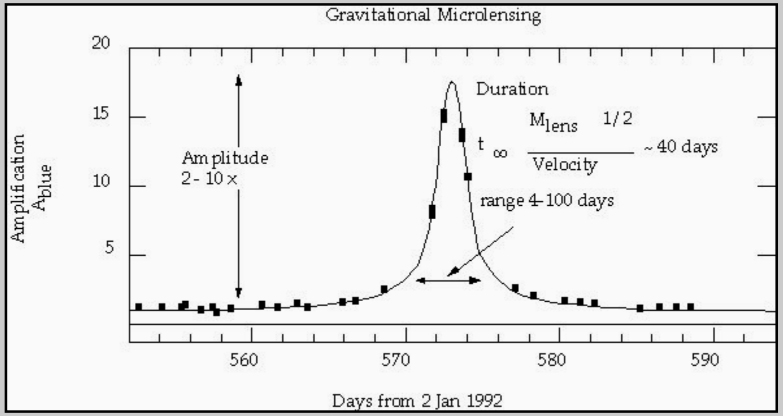
('WIMPs')

MACHOs?

- **Non-luminous massive objects can be found by 'Micro-lensing'**







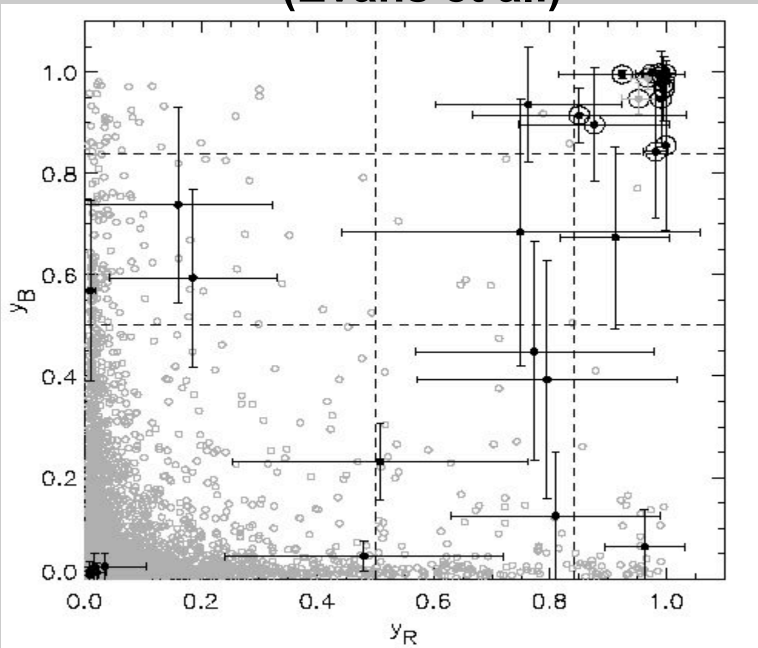
Signals Decline? - MACHOs

END of the MACHO ERA

"...the microlensing towards the LMC or Andromeda provide little if any evidence for any MACHO component in galaxy halos" - Evans et al. IDM2004

- MACHOs have had their day
  $f_{halo\ dm}$ ~20% and likely to fall
- M31, LMC experiments
  little if any evidence of MACHOs
- Could be other baryonic material
  -hydrogen flakes
  -supermassive black holes

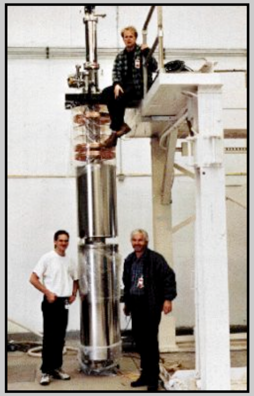
Neural network analysis (Evans et al.)

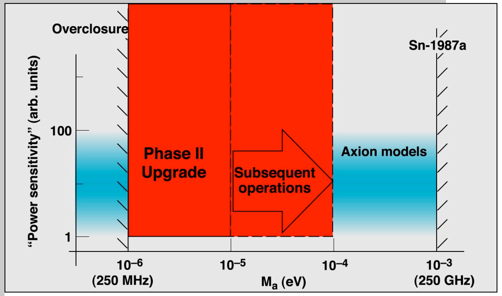


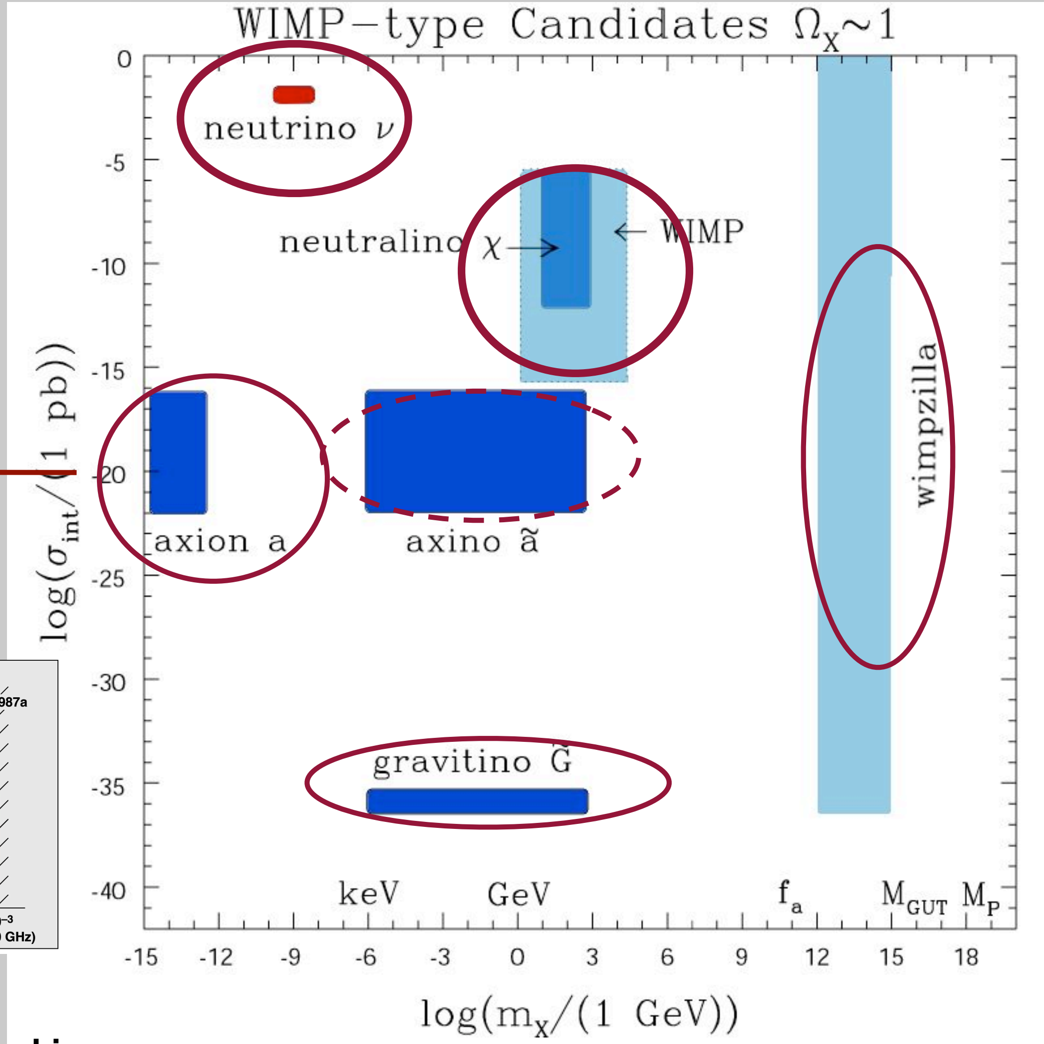
6 probably microlensing events
2 likely microlensing events
2 contaminations (Seyfert or variable star)
1 event looks perfect but known by EROS to repeat

Particle Candidates

ADMX







yuk!

thanks to L. Roszkowski

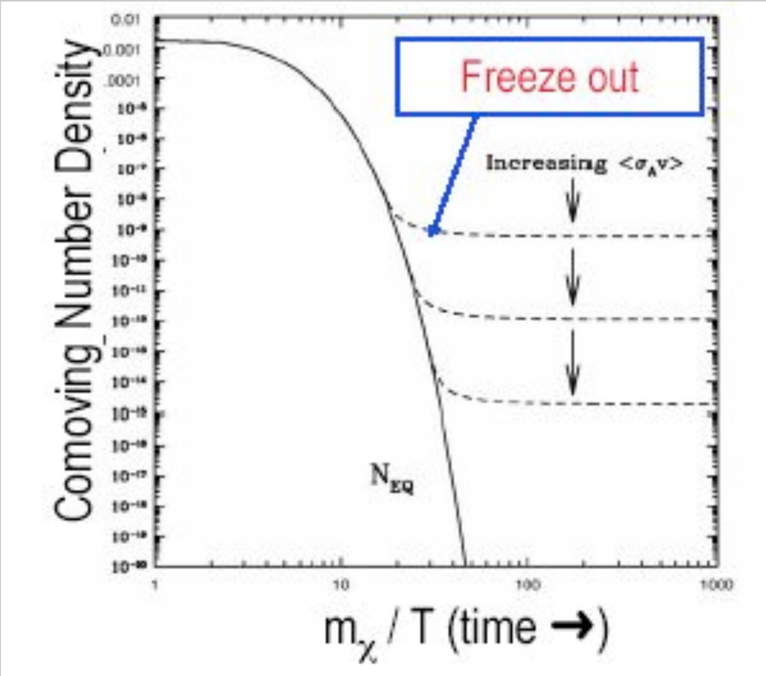
Why WIMPs and Neutralinos

PARTICLES IN THERMAL EQUILIBRIUM

Freeze out when annihilation rate ≈ expansion rate

$$\Omega_\chi h^2 = \frac{3\times 10^{-27} cm^3/s}{\langle \sigma_A v \rangle} \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}, \rho_\chi \approx \frac{M_{EW}^2 T^3}{M_{pl}}$$

So cosmology indicates generic WIMPs at W&Z scale



$\chi\chi \leftrightarrow \bar{f}f$

$N = N_{EQ} \sim e^{-m/T}$

=> $\Omega_\chi \sim 1$!

Supersymmetric dark matter

- Supersymmetry first formulated in the 1970s.
- Symmetry between fermions and bosons.
- Each SM particle has a 'superpartner' with identical quantum numbers apart from spin.
- R-Parity introduced to prevent rapid proton decay - must be conserved.
- => Existence of a stable Lightest Supersymmetric Particle.

$$\tilde{\chi}_i^0 = N_{i1}\tilde{B} + N_{i2}\tilde{W}^3 + N_{i3}\tilde{H}_1^0 + N_{i4}\tilde{H}_2^0$$

For SUSY to agree with Standard Model:

$$10GeV < M_\chi < 10^4 GeV$$

Searches for charginos and squarks at LEP and Tevatron:

$$M_\chi > 50GeV$$

- Most important SUSY particle for DM is the Neutralino.
- If this is the LSP, it is an ideal WIMP candidate.
- In most realistic SUSY models (i.e. no charged LSP), Neutralino IS LSP (otherwise sneutrino).

A natural candidate not invented to solve Dark Matter

Why WIMPs and Neutralinos

COSMOLOGY

There should be CDM - non-relativistic, no interactions with photons

collapse of density fluctuations start early

There should be Non Baryonic DM

Ω_m (LSS, CMBR, SN) ~ 7 x Ω_b (BBN, CMBR)

CMB alone requires non baryonic dark matter:

WMAP+... $\Omega_m h^2 = 0.14 \pm 0.02 \gg \Omega_b h^2 = 0.024 \pm 0.024 \pm 0.001$

anyway how do you hide the baryons?

PARTICLE PHYSICS

Standard model requires new physics at W&Z scale - supersymmetry - neutralino

BUT not only supersymmetry - e.g. Extra Dimensions - G. Servant et al.

LSP Neutralino - Majorana (self-annihilate) fermions (spin 1/2), R-parity

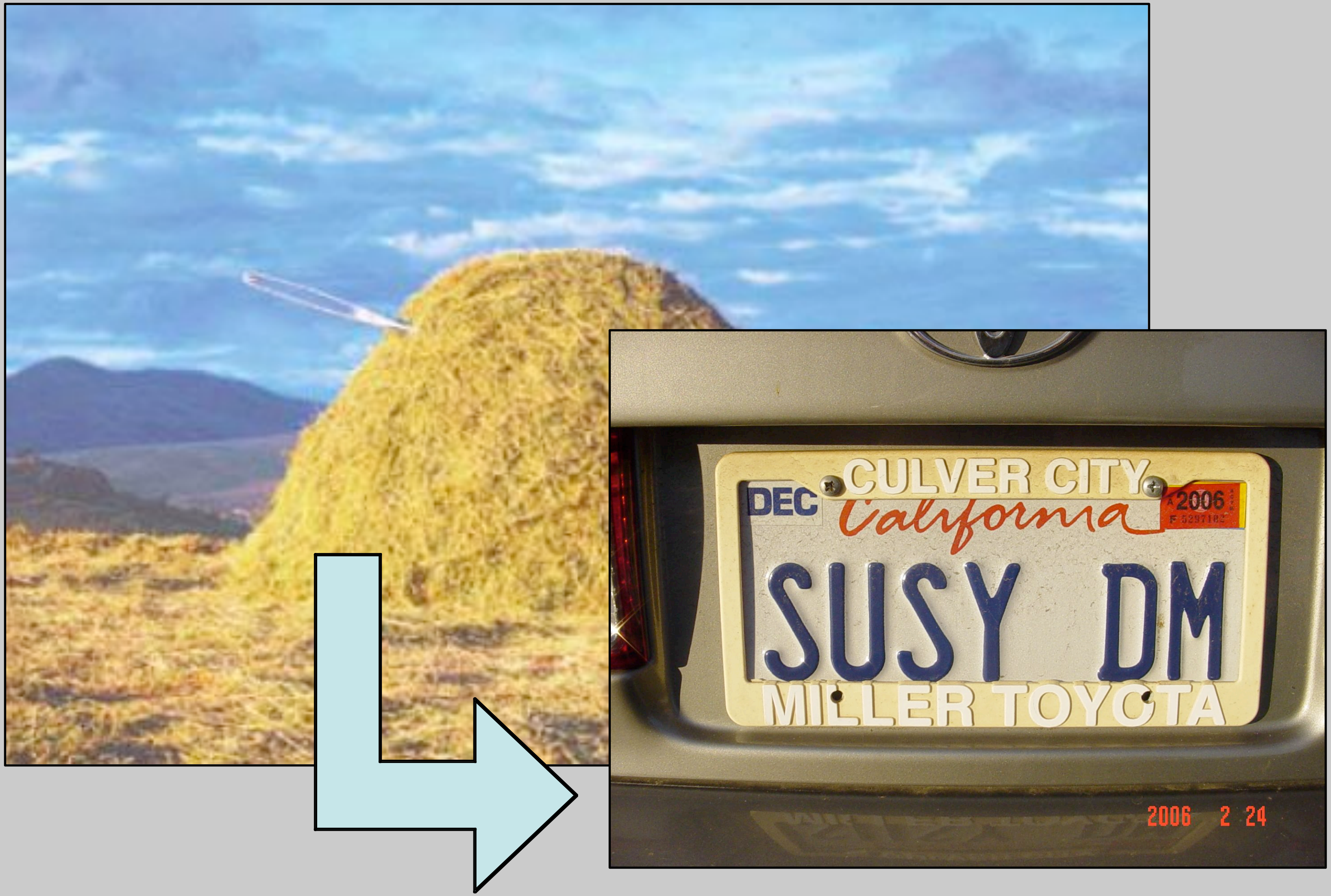
LKP interacts with SM particles and is stable because of KK parity

Applies as generic Bosonic Dark Matter candidate

Many papers now, e.g.:
Servant et al. ANL-HEP-PR-02-054, ANL-HEP-PR-02-032,Cheng CERN-TH/2002-157


Dark matter exists
and
we need a detector

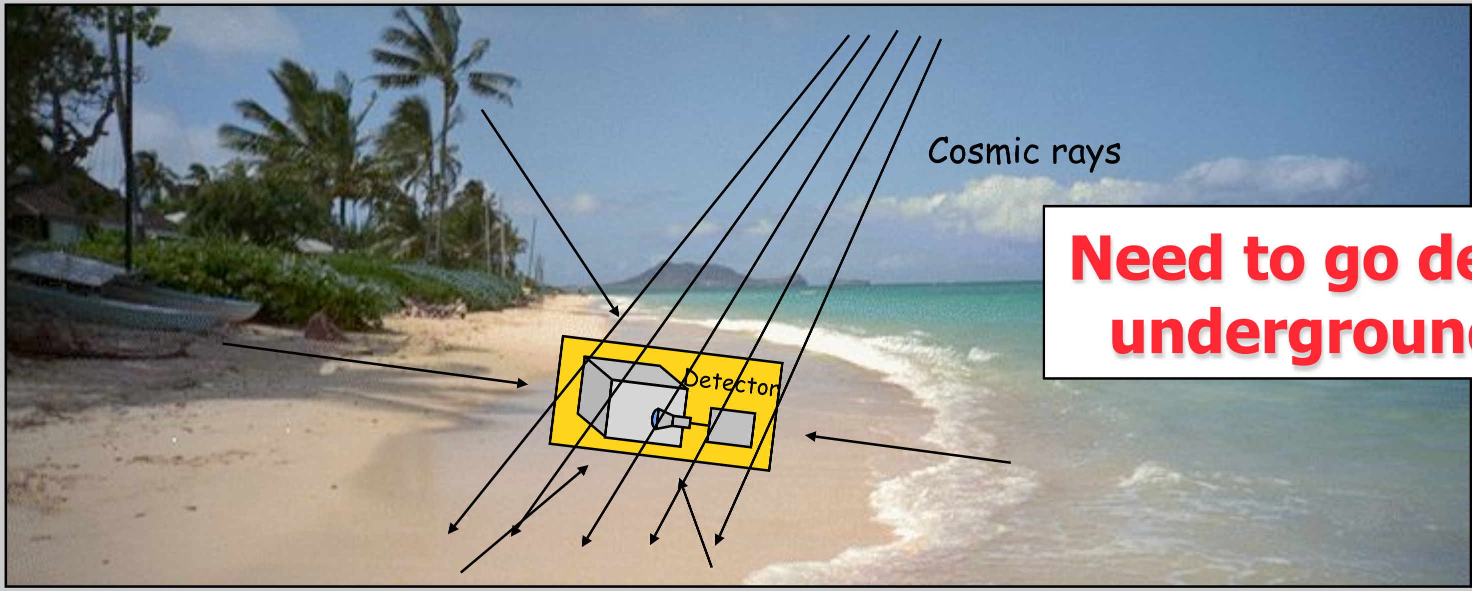
Aim and challenge



How to Detect a WIMP

- Not as simple as all that!
- For each DM event there are a >10^6 events from other sources

- Radiation from surroundings (α, β, γ, neutrons)
- Cosmic Rays. (especially Muons).

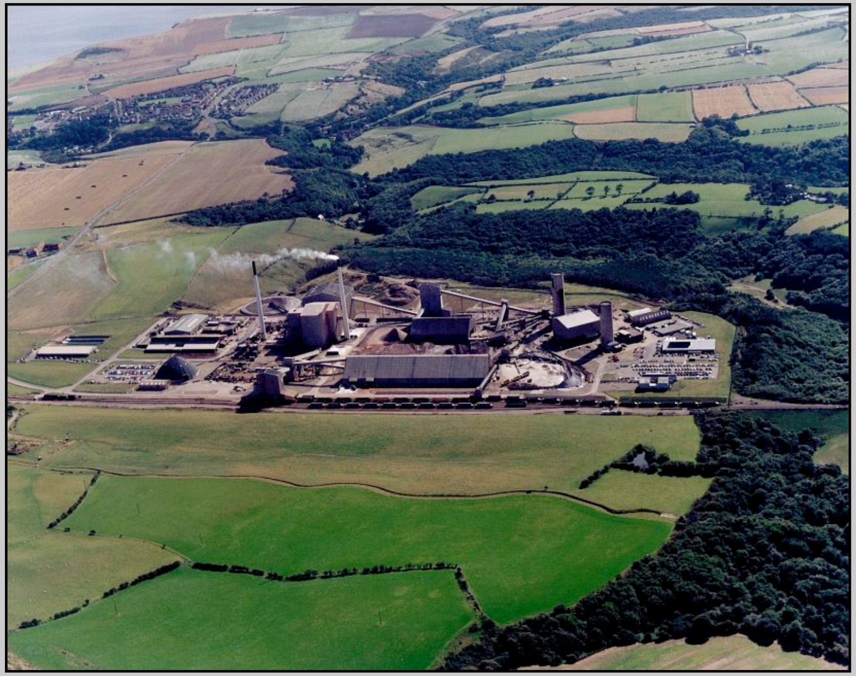


Need to go deep underground!

Boulby Mine Basics

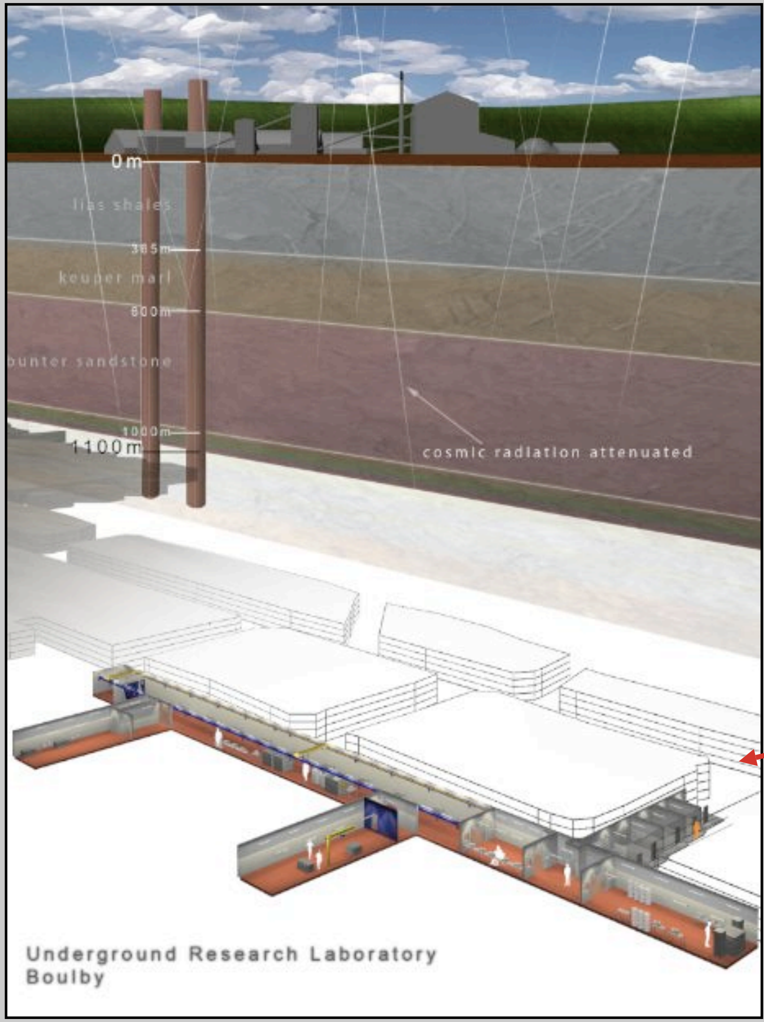
- A working potash and salt mine (Cleveland - North East England)
- Near - deepest mine in EU (850m-1.3km deep) (proposed 1.5-1.6 km)
- Unique environment for science (deep and low radioactivity)
- 940 mine staff + ~3000 local employment
- Durham - 75 mins; Sheffield - 105 mins; York - 60 mins

CLEVELAND POTASH



Boulby Laboratory

The JIF laboratory



Boulby - The JIF area - Jan 2005

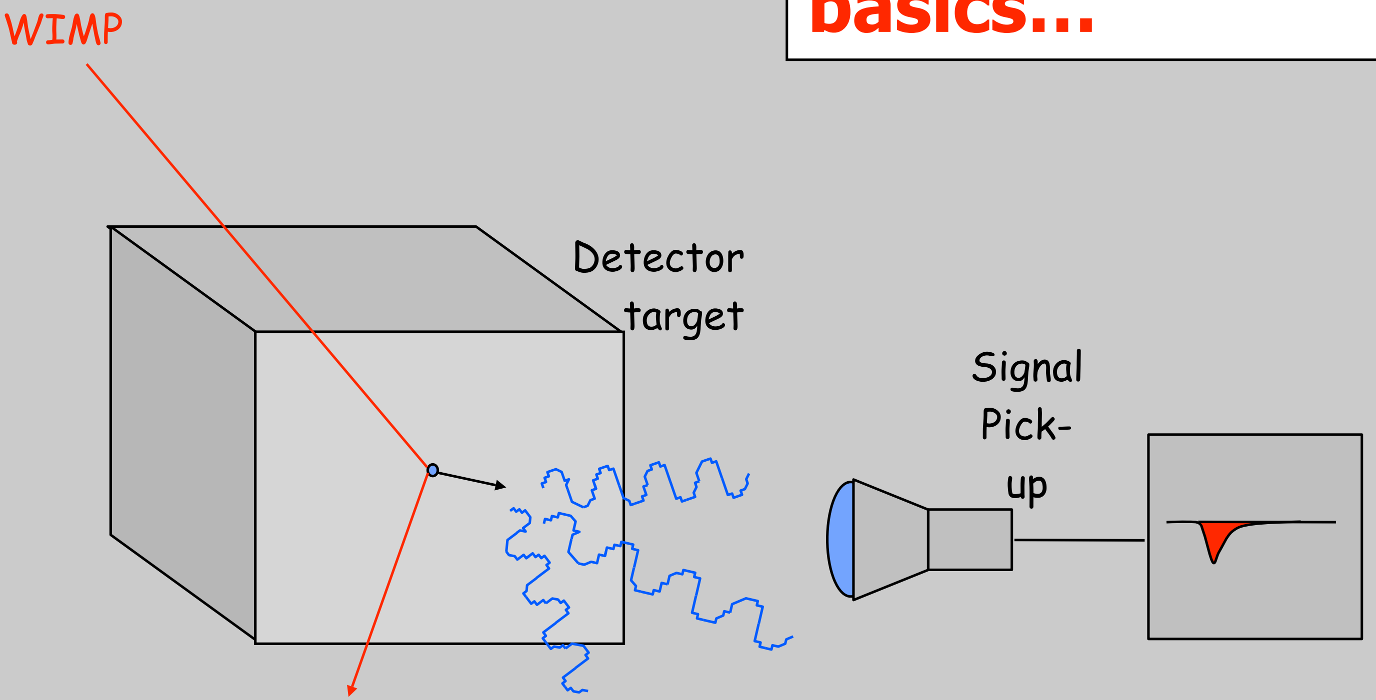
Low Background Lab

opened April 2003

Public Outreach

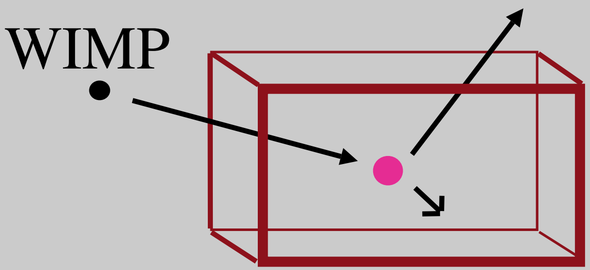
How to Detect a WIMP

Particle detection basics...



How to Detect a WIMP

Direct Searches

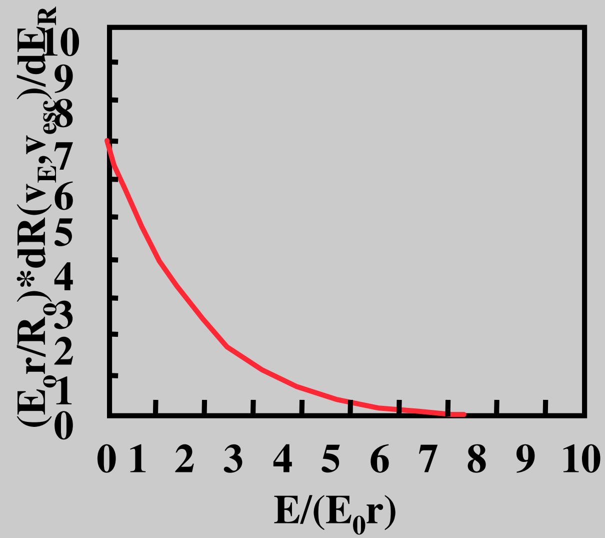


total event rate (point like nucleus)

$$\frac{dR}{dE_R} = \frac{R_o}{E_o r} e^{-E_R/E_o r}$$

kinematic factor
$$= 4M_D M_T/(M_D + M_T)^2$$

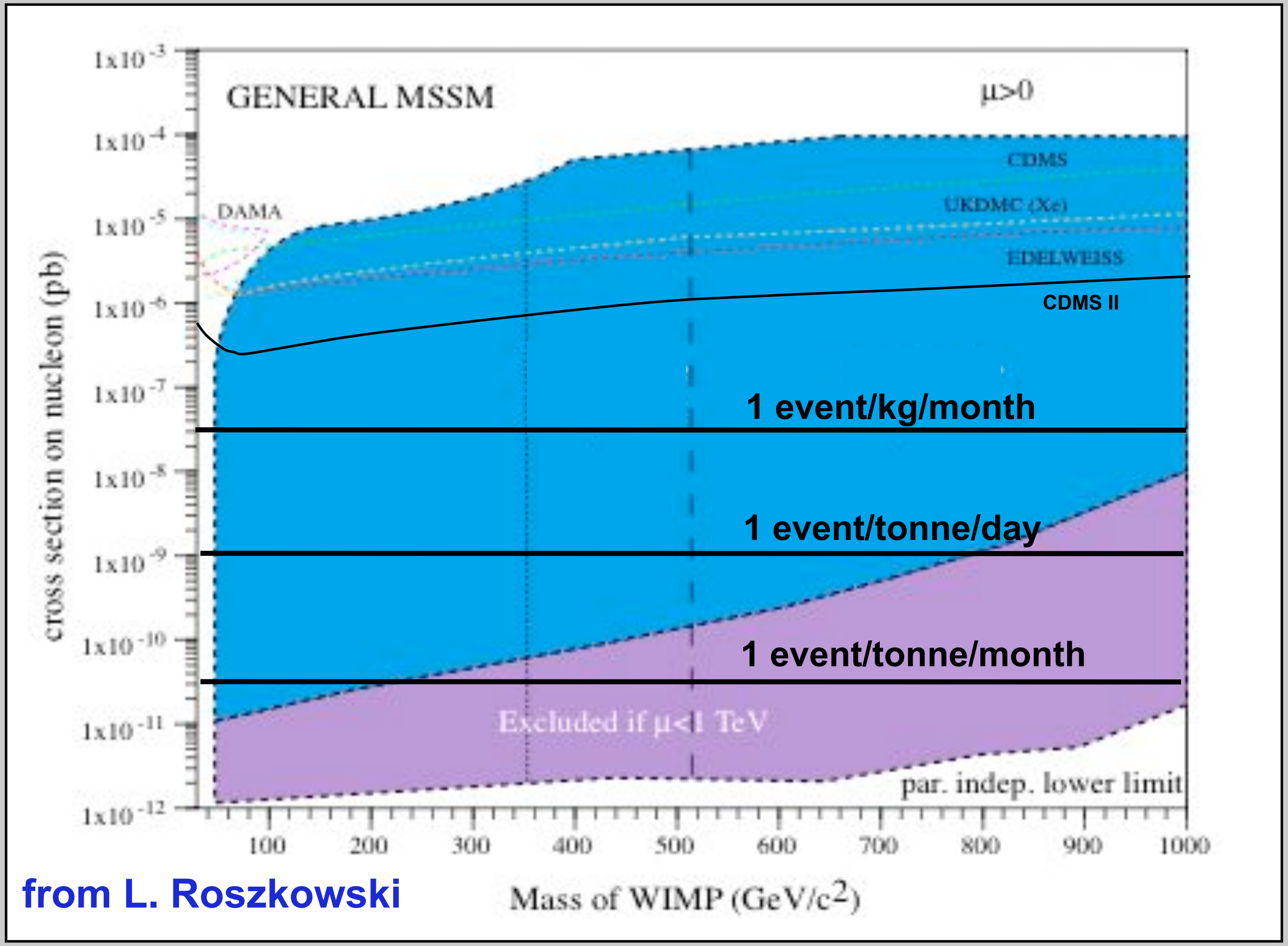
$$\left.\frac{dR}{dE}\right|_{obs} = R_o\, S(E)\, F^2(E)\, I(A)$$



featureless differential nuclear recoil energy spectrum

so need nuclear recoil discrimination, low background, <u>go underground</u>

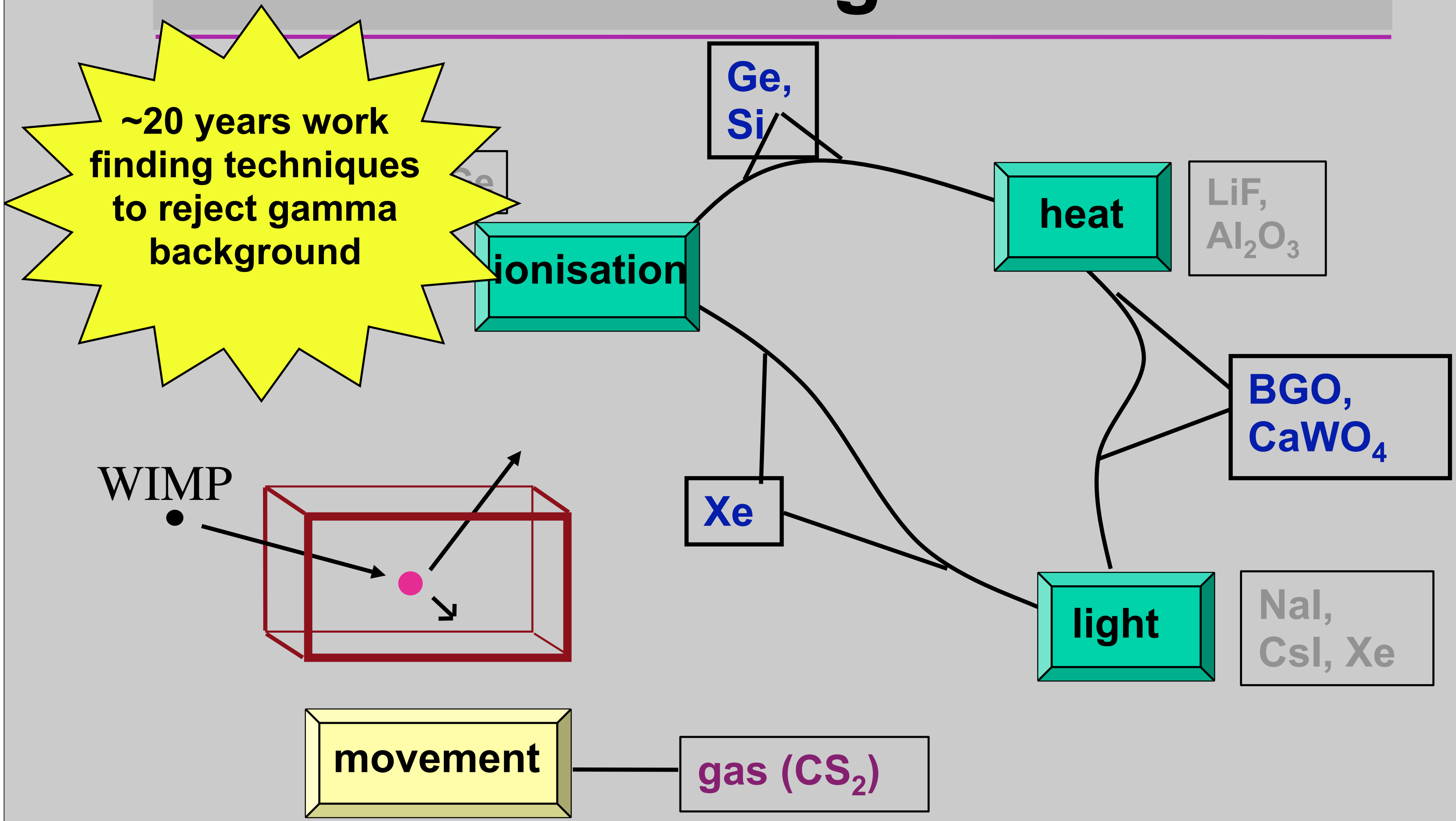
Aim and challenge



from L. Roszkowski

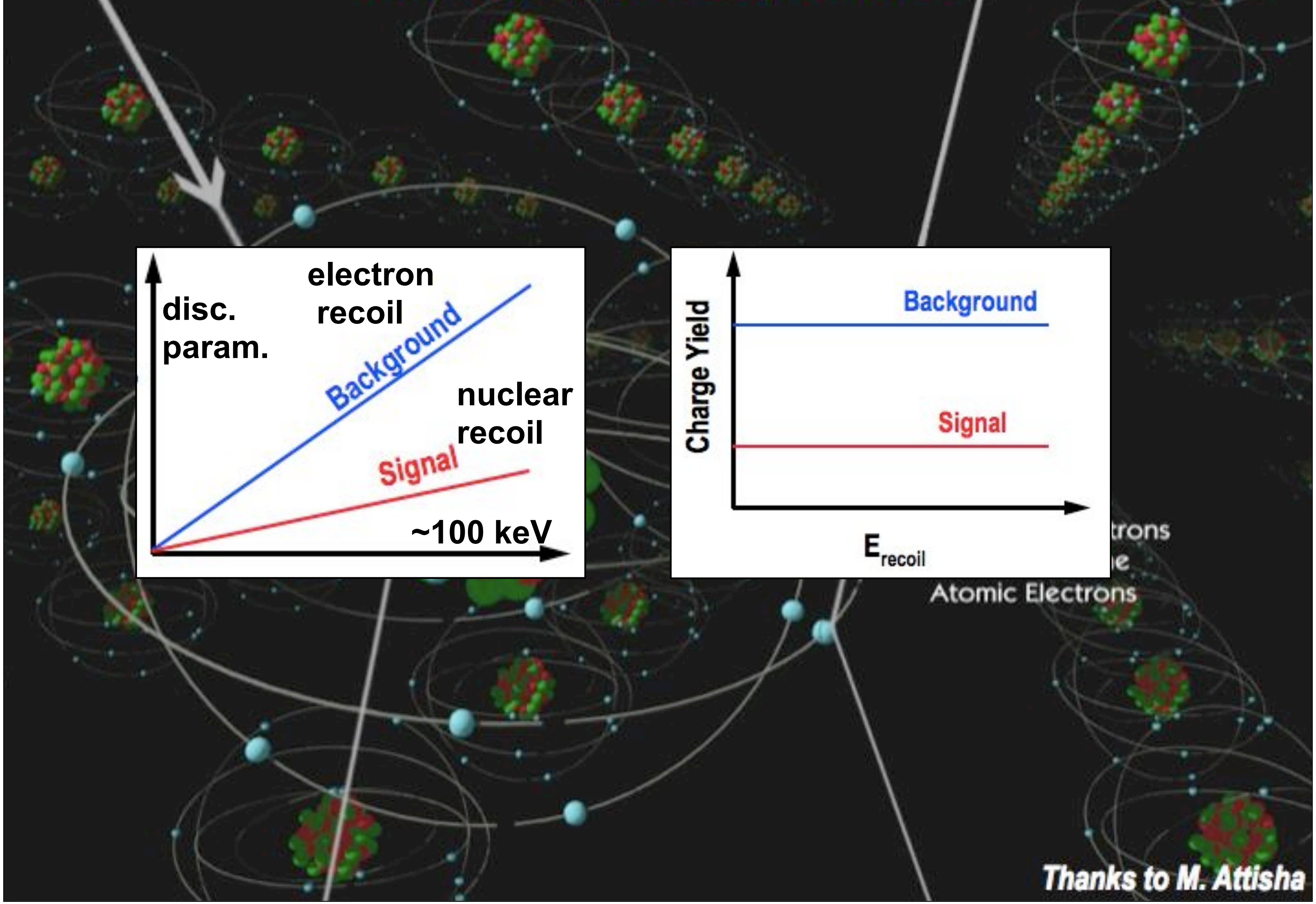
- Required <u>sensitivity</u> 10^{-7}-10^{-10}pb
- but need a good rate for detection statistics of x10 more

Technologies

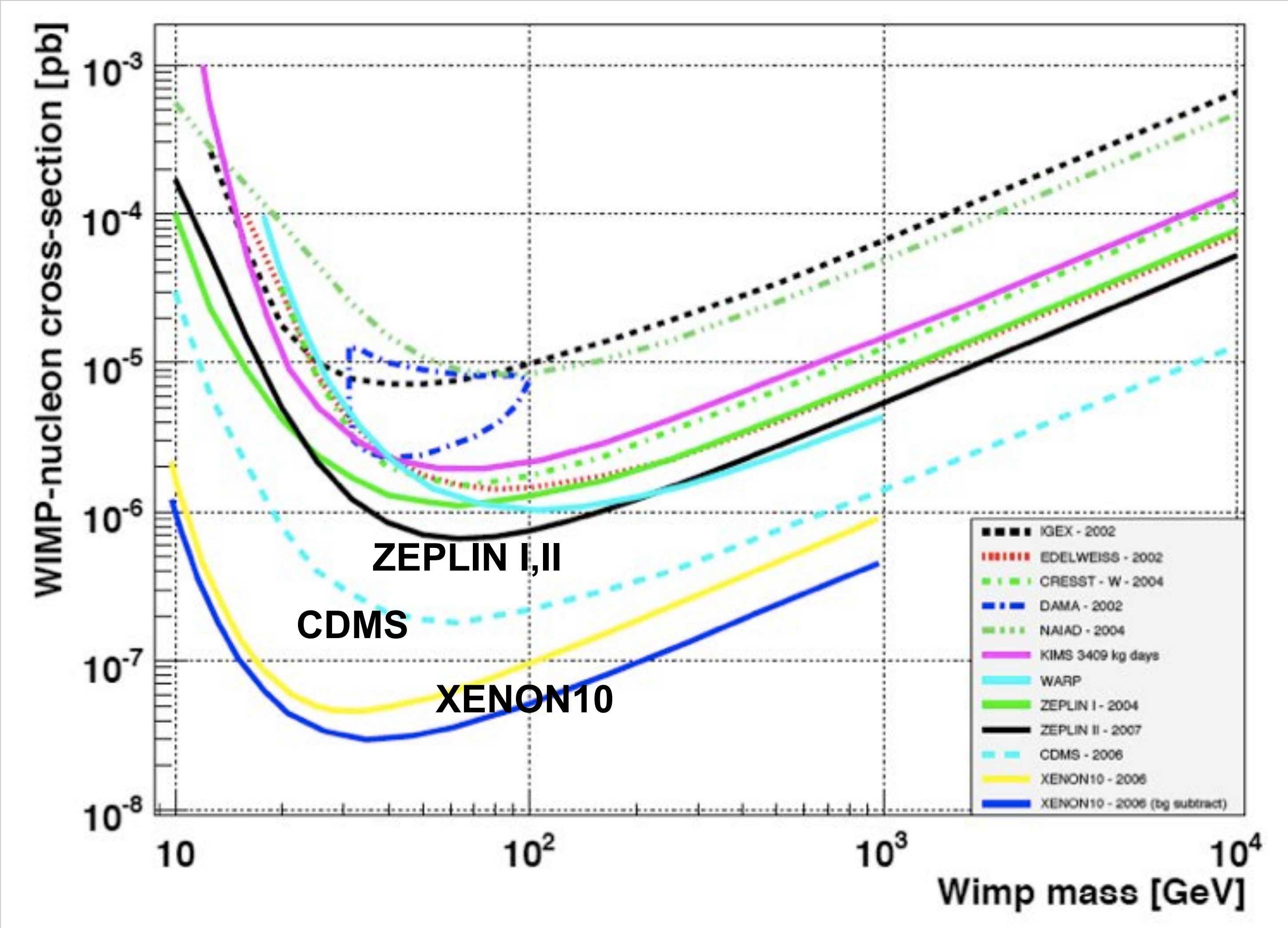


discrimination: none, statistical, event by event

Different types of particles

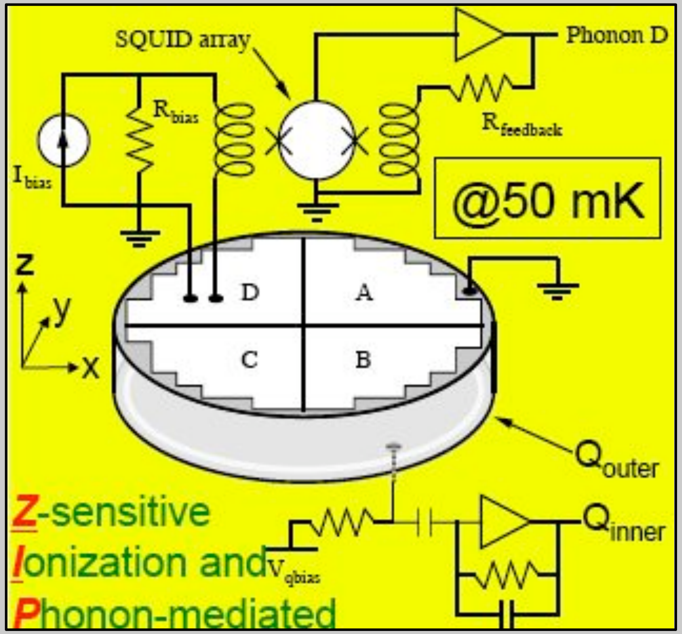


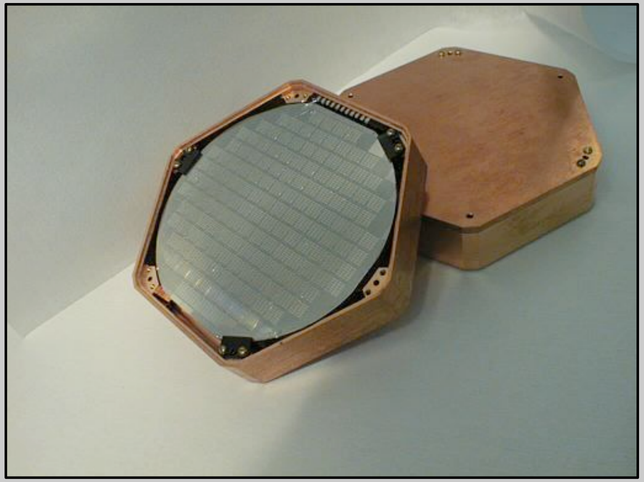
Results summary

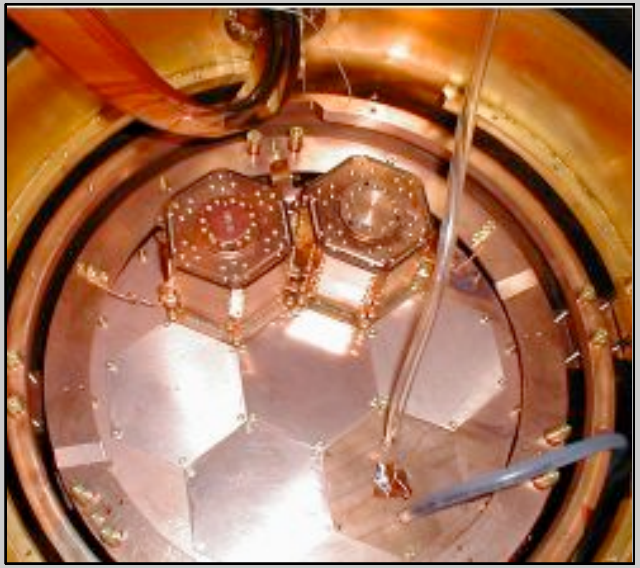


Ionisation-thermal

CDMS-II







CDMS (Soudan mine, USA).
High purity Ge and Si crystals operated at ~15mK temperature.

Measurement of ionisation and athermal phonons - heat.

Ionisation-thermal

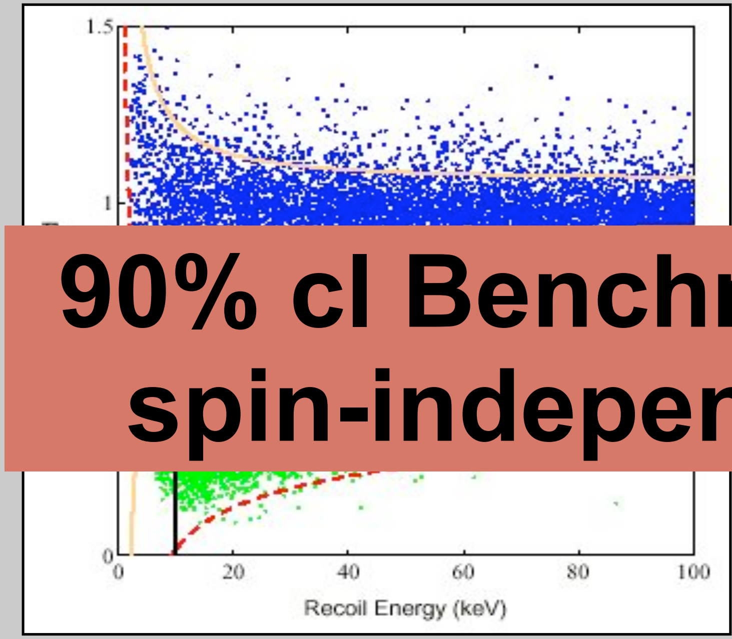
CDMS-II

• first Soudan runs

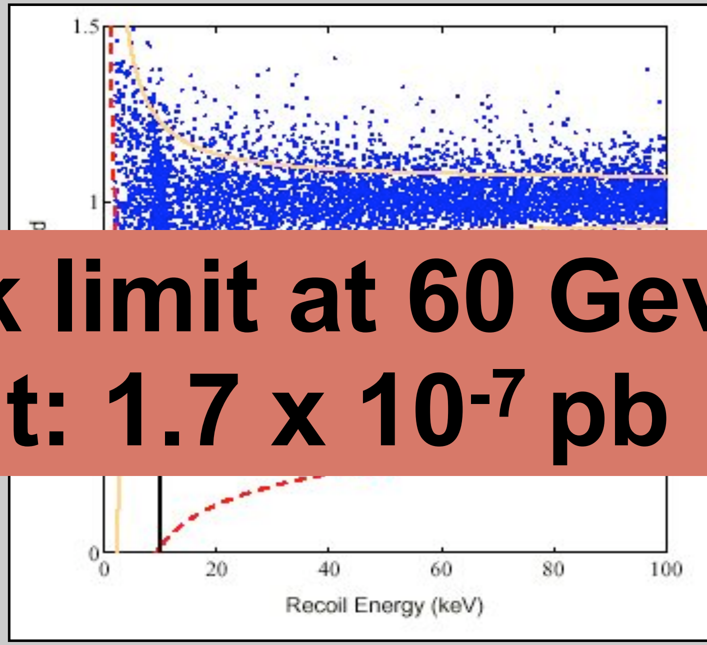
Recent world best result

ionisation yield calibration with ^{252}Cf on Z2,3,5

WIMP data for Z2,3,5 with same cuts

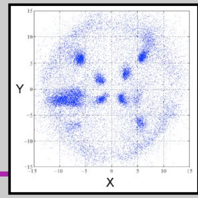


Tower 1
Previously

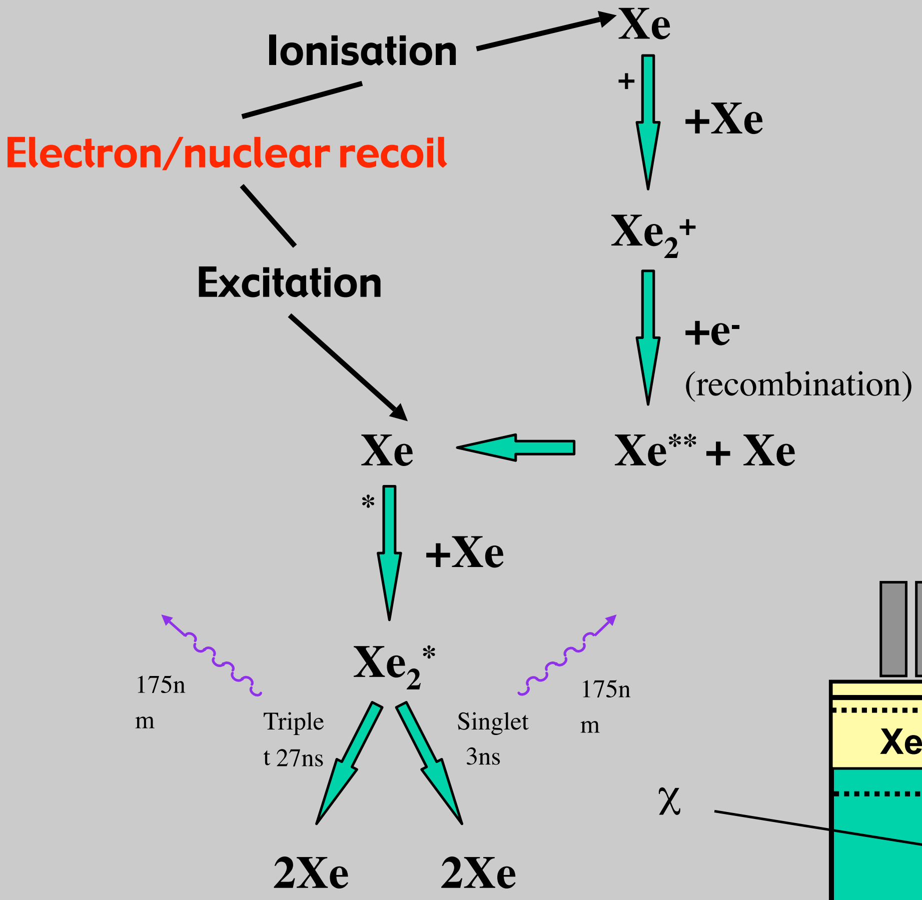


90% cl Benchmark limit at 60 Gev spin-independent: 1.7 x 10^{-7} pb

• low field with segmented contacts to allow rejection of near edge events
• collect athermal phonons - ZIP technology
• xy positioning and pulse shape analysis



Xenon Basics (and LAr)

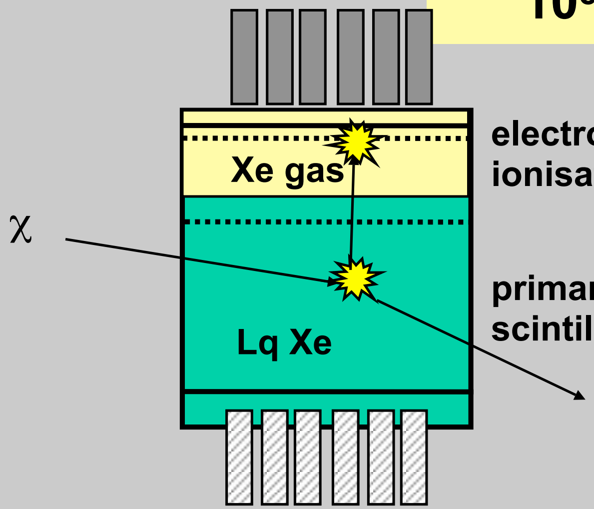


(1) Single Phase Experiments

DAMA Xe
ZEPLIN I (PSD)
XMASS I (no PSD)

(2) Double Phase

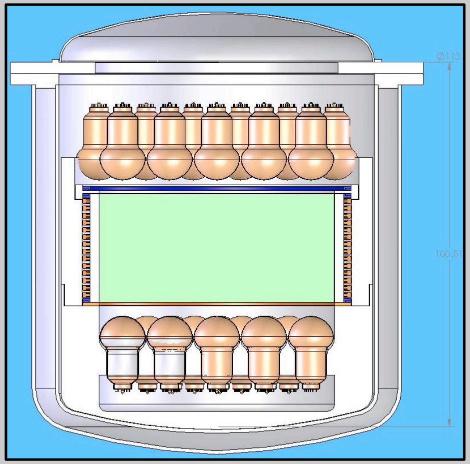
should give necessary $10^{5\text{-}6}$ γ rejection?



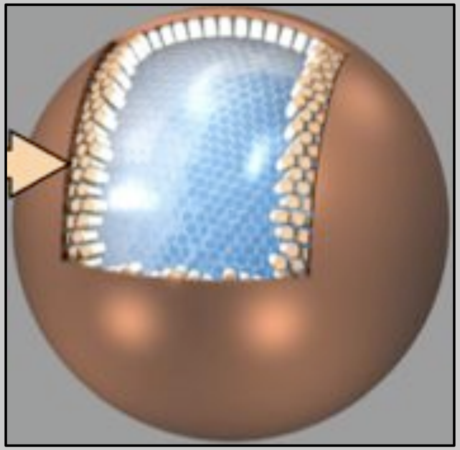
XMASS II
XENON 10,100
ZEPLIN II, ZEPLIN III

Multi-tonne LXe futures?

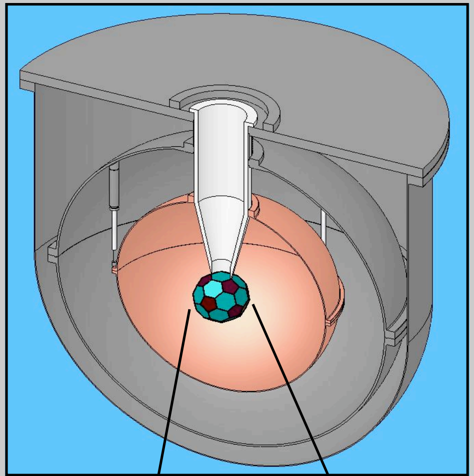
(1) two-phase with PMTs (ZEPLIN IV?)

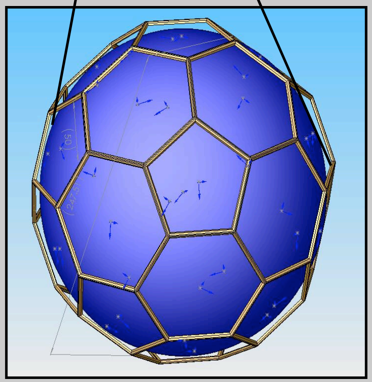


(2) one-phase with PMTs (XMASS)



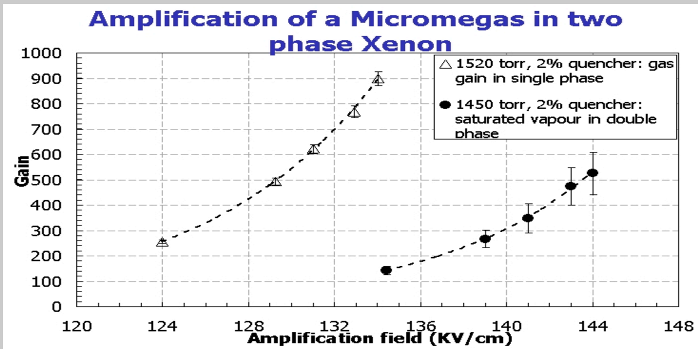
(3) one-phase with charge readout (CORE)



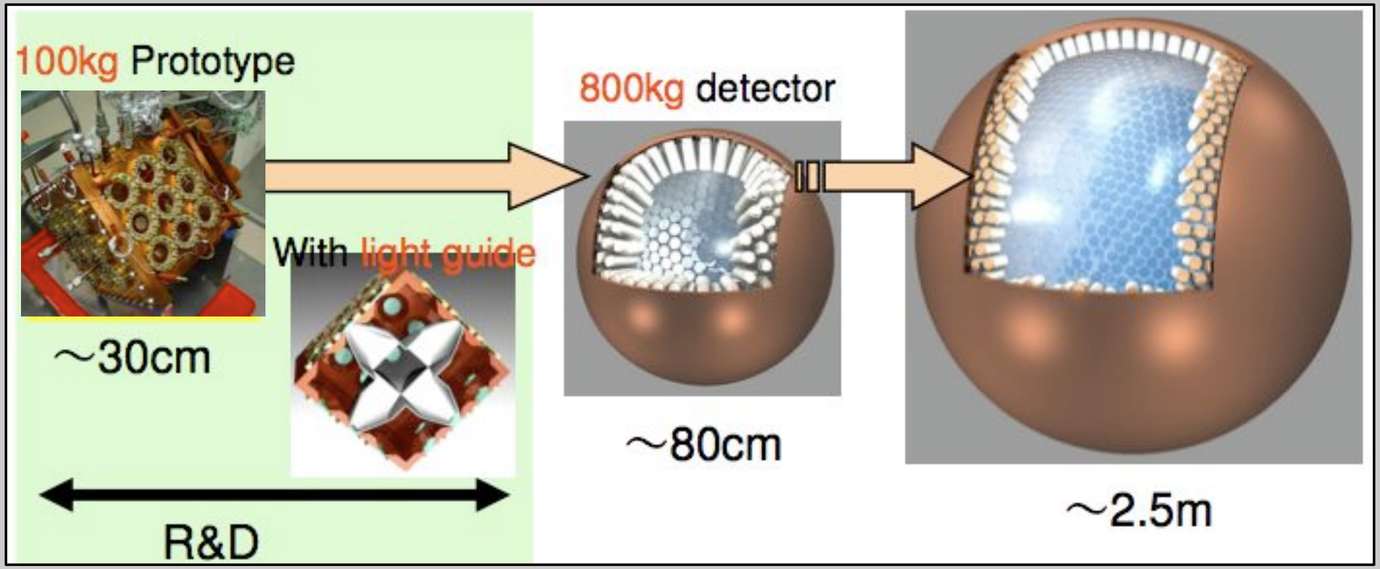


P. Lightfoot et al.
NIMA 554 (2005) 226

Pawel Majewski, Univ. of Sheffield Cryogenic Liquid Detectors for Future Particle Physics; LNGS, 13-14 III 2006

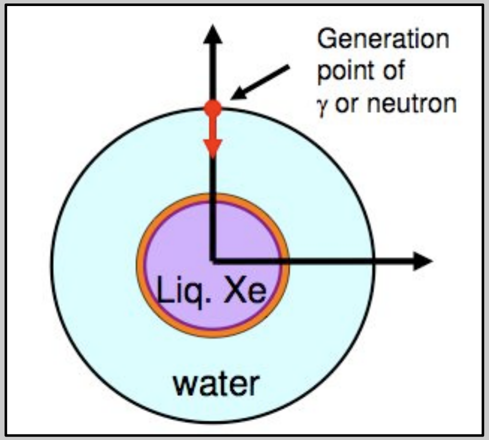


XMASS (Japan) - single phase



single phase

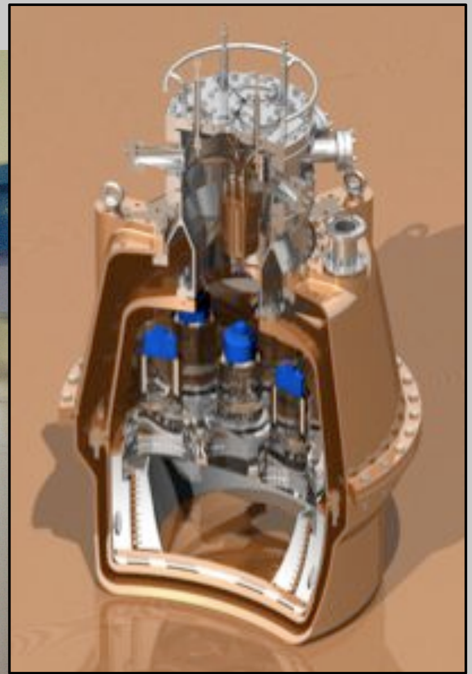
4 pe/keV
812 PMTs
in liquid



use basic PSD - poor discrimination
use passive shielding - LXe and water
use sphere - make BIG and uniform

how much passive shielding needed to suppress neutron and gamma background from PMTs?

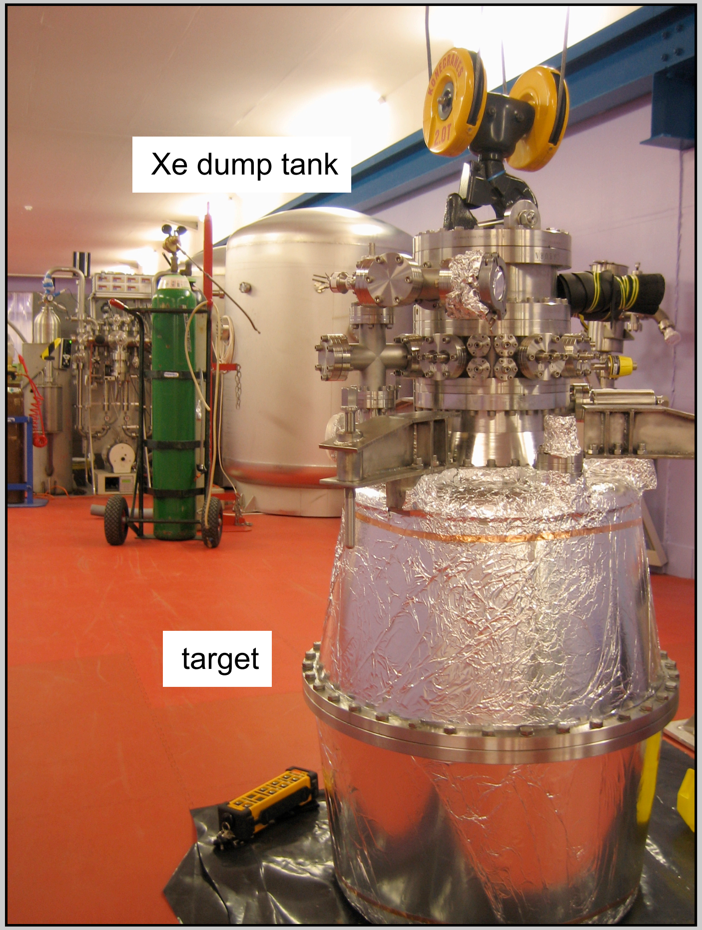
ZEPLIN II at Boulby

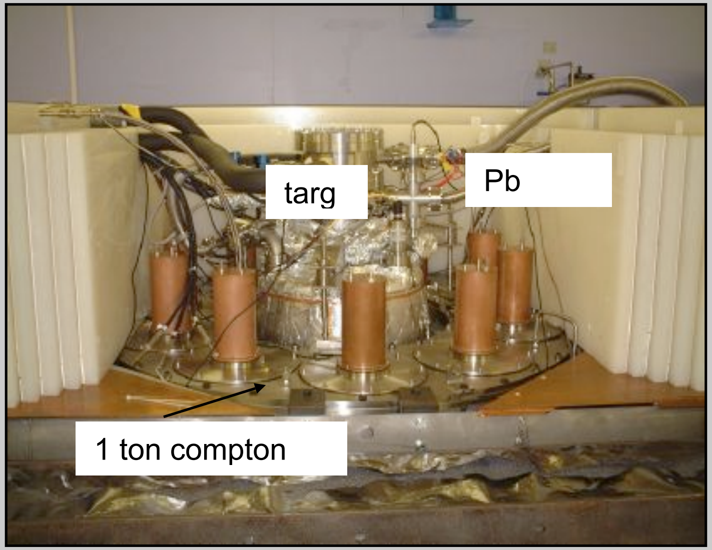


ZEPLIN II at Boulby

Jul-Aug 2005
final assembly

ZEPLIN II at Boulby



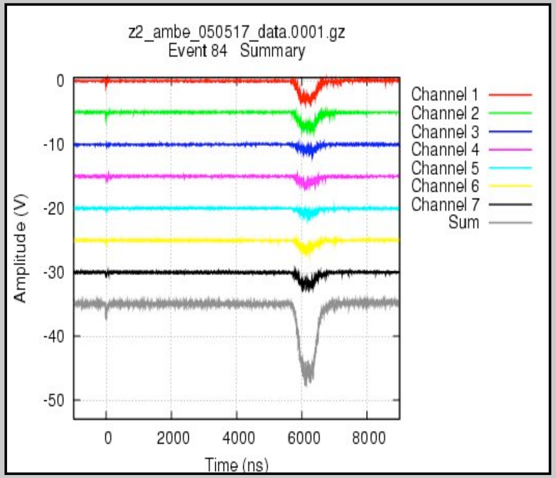


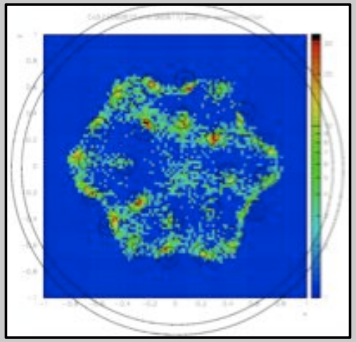
May-Jun 2005

ZEPLIN II Data

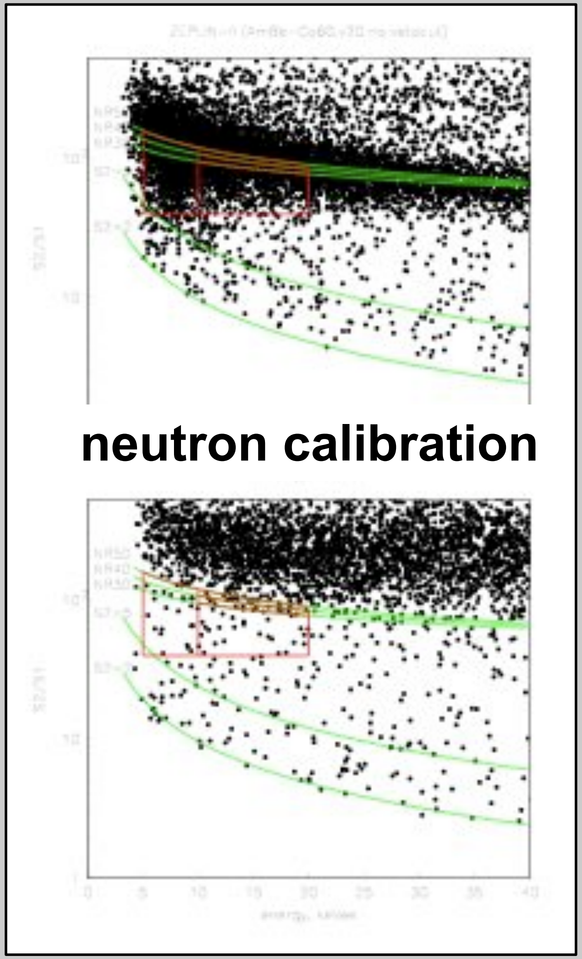
5 months continuous operation
~1 ton*day of DM data so far

~1.69 p.e./keV without field
0.55 p.e./keV with field

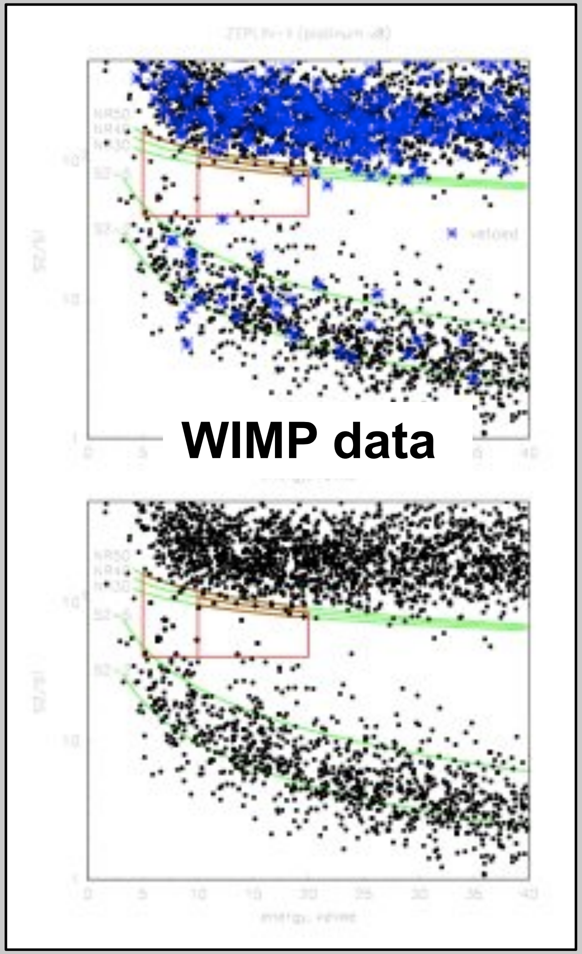




spatial reconstruction
LXe volume 30 kg

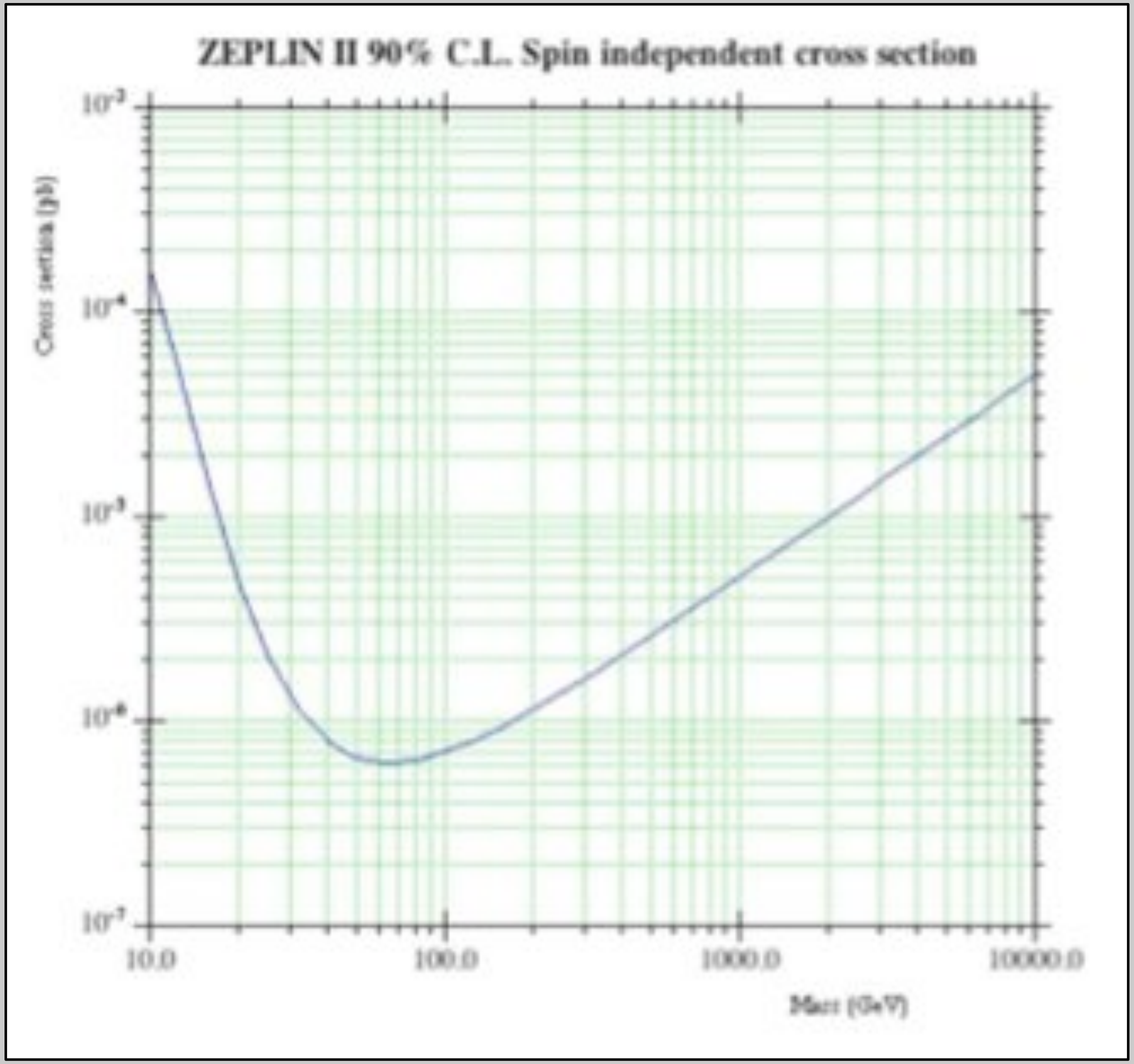


neutron calibration



WIMP data

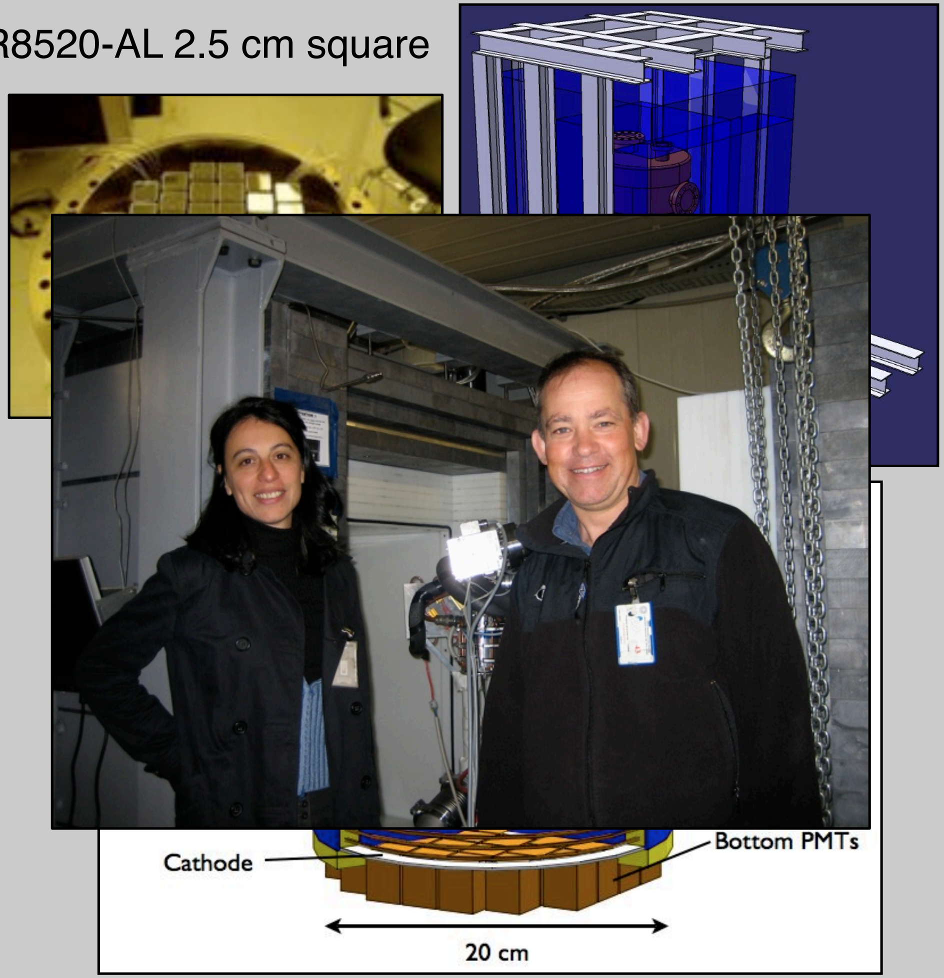
ZEPLIN II Result - run 1



XENON 10 at Gran Sasso

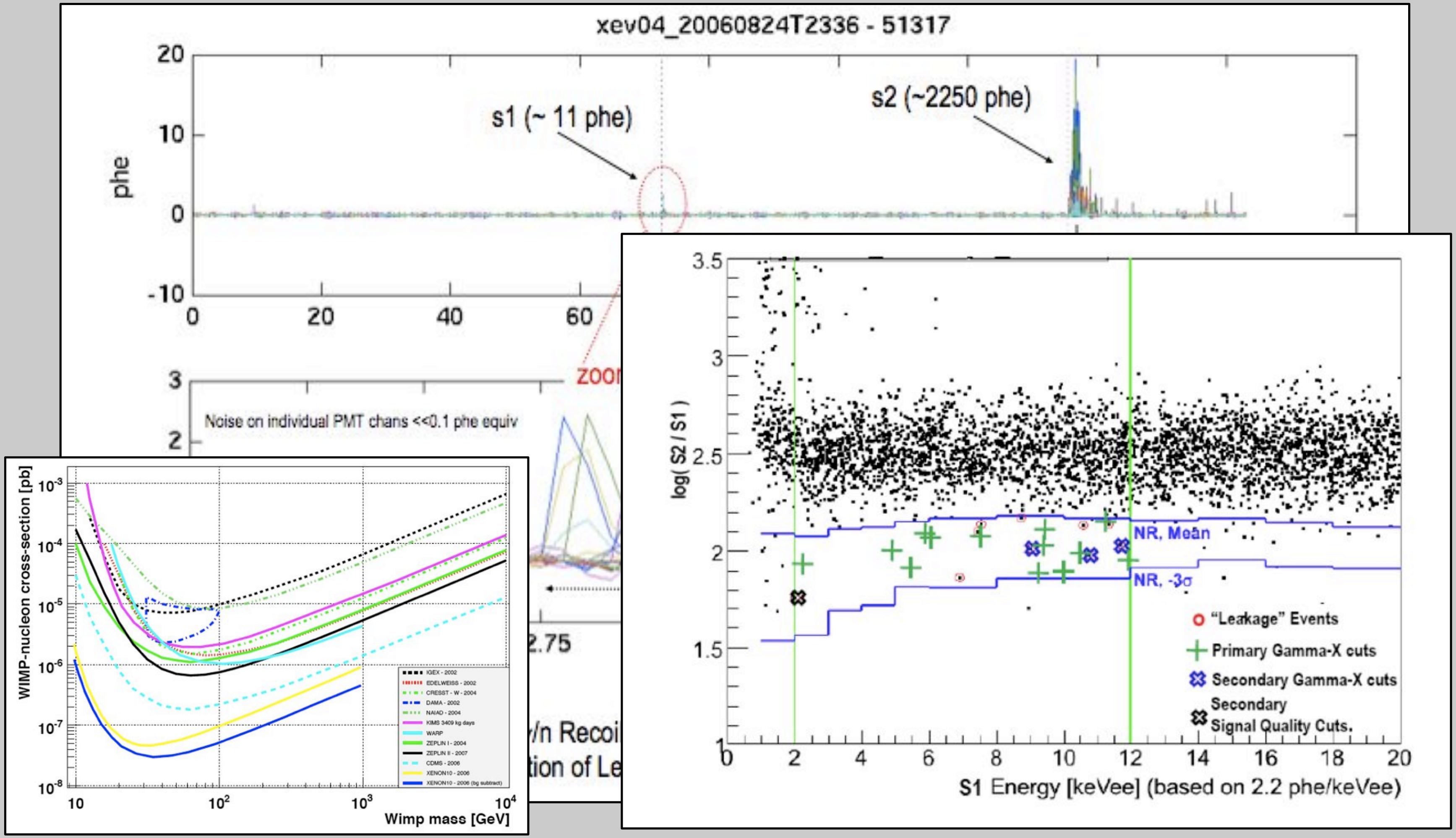
R8520-AL 2.5 cm square

- **10 kg target mass at LNGS**
- **89 LB tubes top and bottom**
- **First dark matter runs started**
- **XENON 100, 2007-2009, 100 kg**



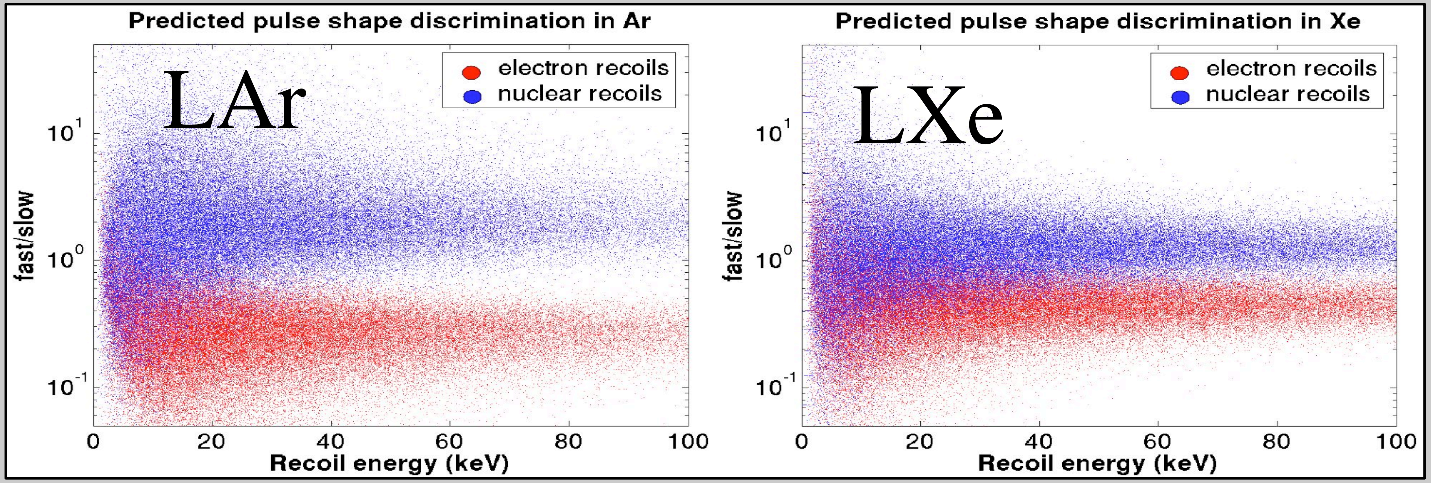
XENON 10 - two phase

Example prelim data - no neutron calibration yet



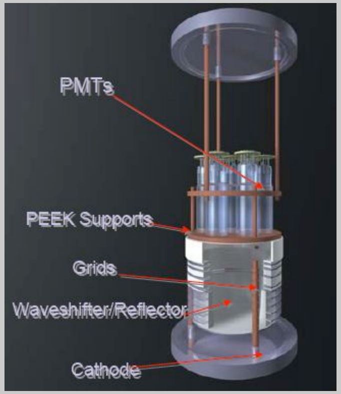
Liquid Argon

Better Discrimination than in LXe



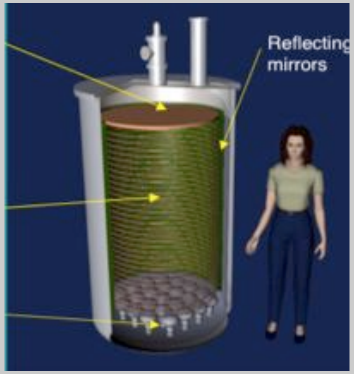
thanks to Tom Shutt

Compatible interests for other physics with LAr



WARP experiment

2.3 l argon prototype at LNGS.
Based on ICARUS.
Discrimination: S2/S1 + PSD.
Observed discrimination >10^5.
Expected discrimination >10^8.



ArDM experiment

800 kg DM prototype at CERN
First surface runs on schedule for 2007 at CERN

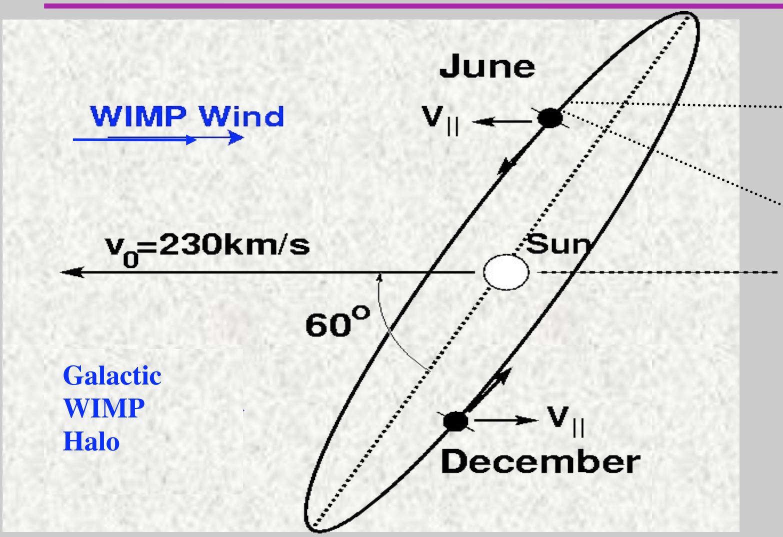
A SIGNAL!

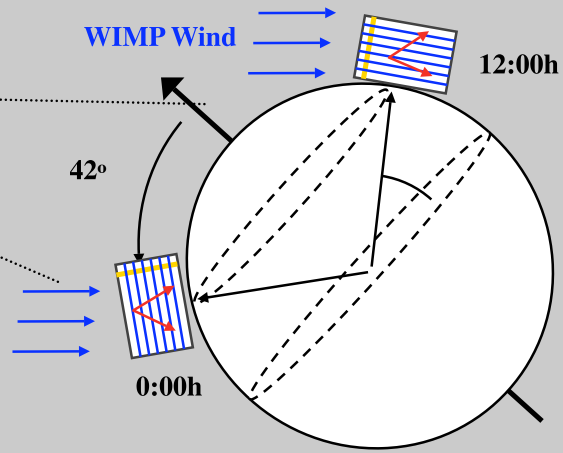
but can it be true?

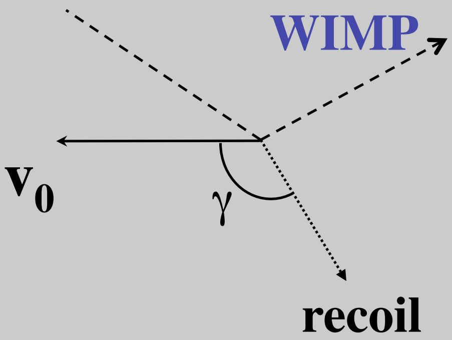
but is it galactic?

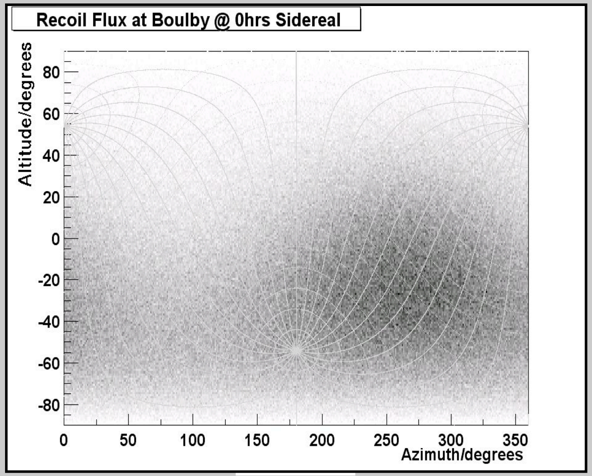
GAS
Directional

Motivation









A WIMP telescope?

Death of the Standard Model?

Models: many structures

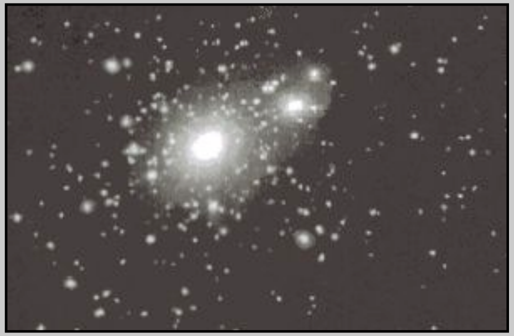
- velocity space anisotropy
- bulk rotation
- substructure, clumps
- ultra-small scale clumps
- triaxality, logarithmic ellipsoidal
- oblate vs. prolate
- late accreted sub-halos
- sub-structure on sub-pc scales
- spikes and caustics

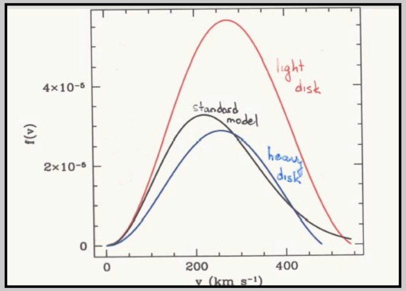
Evidence:

- rotation curves
- local kinematics, Oort constants,
- tracers: satellites
  (PNs, globular clusters, halo stars)
- IR maps

New satellite missions

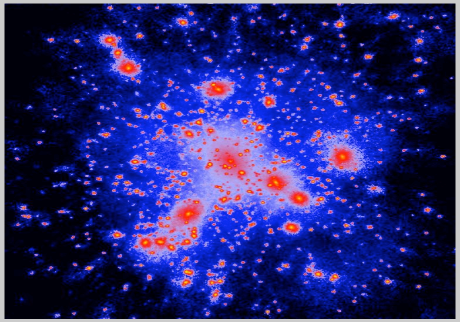
Clumps   **Moore et al.....**





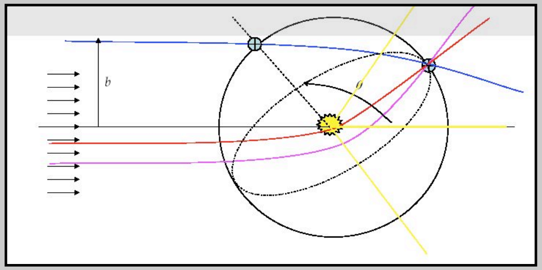
Stiff , Widrow et al..
Helmi et al, Evans et al...

Multicomponents



Tidal disruption streams - Sagittarius

K. Johnston et al, Sackett & Merrifield reviews
Freese, Gondolo et al.



Sun's influence

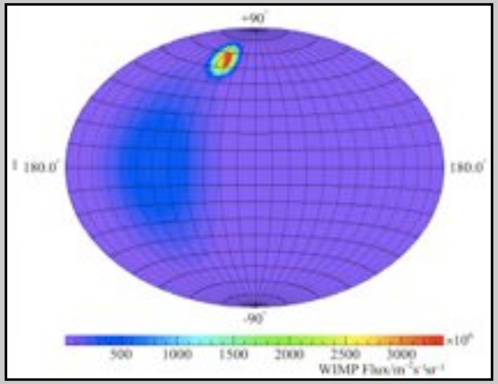
Fu-sin Ling et al.
Sikivie, Wick et al

Results for various halos

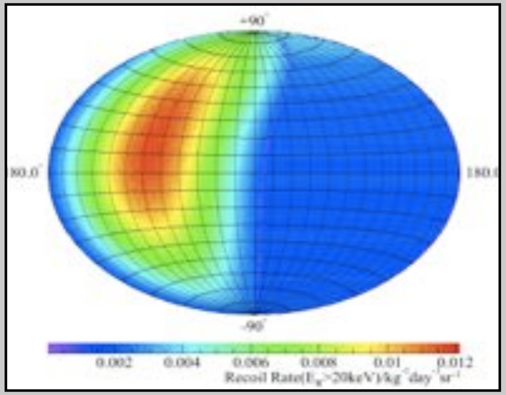
Our predictions for TPC-type detector with 200 μm resolution

B. Morgan et al., Phys. Rev. D71 (2005) 103507

input WIMPs



output recoils



Halo Model	N_{iso} for $(R_c, A_c) = (0.90, 0.90)$						
	Vectorial Statistics				Axial Statistics		
	$\mathcal{W}^*$	$\mathcal{A}$	$\mathcal{F}$	$\langle\cos\theta\rangle$	$\mathcal{B}^*$	$\mathcal{G}$	$\langle\lvert\cos\theta\rvert\rangle$
1	12	12	13	7	167	168	104
2	12	12	12	7	112	114	73
3	[illegible]	14	15	8	156	157	121
4	[illegible]	12	13	7	148	150	96
5	[illegible]	15	15	[illegible]	215	215	[illegible]
6	11	11	11	6	67	68	47
7	14	14	14	8	89	88	74
8	[illegible]	13	13	7	176	177	112
9	[illegible]	15	16	9	264	265	188
10	[illegible]	15	15	8	278	281	194
11	12	12	12	7	126	128	81
12	16	16	17	9	233	234	210
	N_{iso} for $(R_c, A_c) = (0.95, 0.95)$						
1	18	18	19	11	235	235	131
1 (no)	16	16	17	9	128	129	65
2	17	17	18	10	162	162	93
3	20	20	21	12	226	226	152
4	18	18	19	11	212	213	120
5	21	21	22	12	309	312	199
6	16	16	16	10	96	96	59
7	19	20	20	12	125	126	94
8	18	18	19	11	248	249	142
9	21	21	22	13	376	379	237
10	21	21	21	12	395	399	244
11	17	17	17	10	180	180	102
12	20	20	20	15	326	327	276

~100s detected WIMPs needed to identify halo model

~x10 fewer needed if there is head-tail sensitivity

experiments needed to test head-tail discrimination

Directional

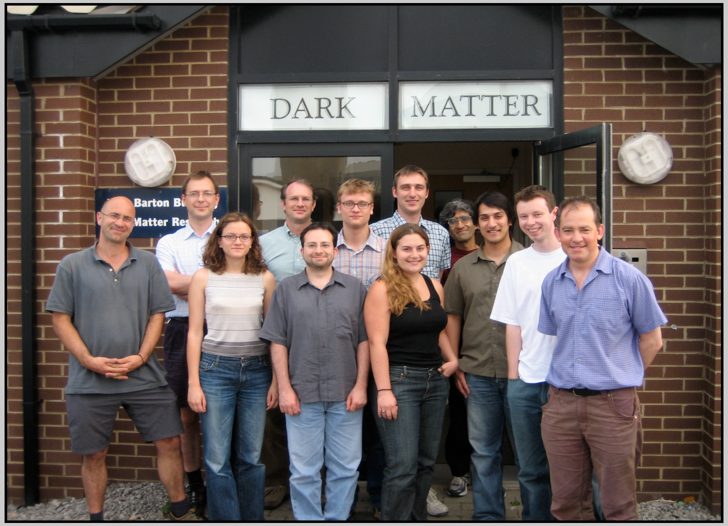
Recoil

Identification

From

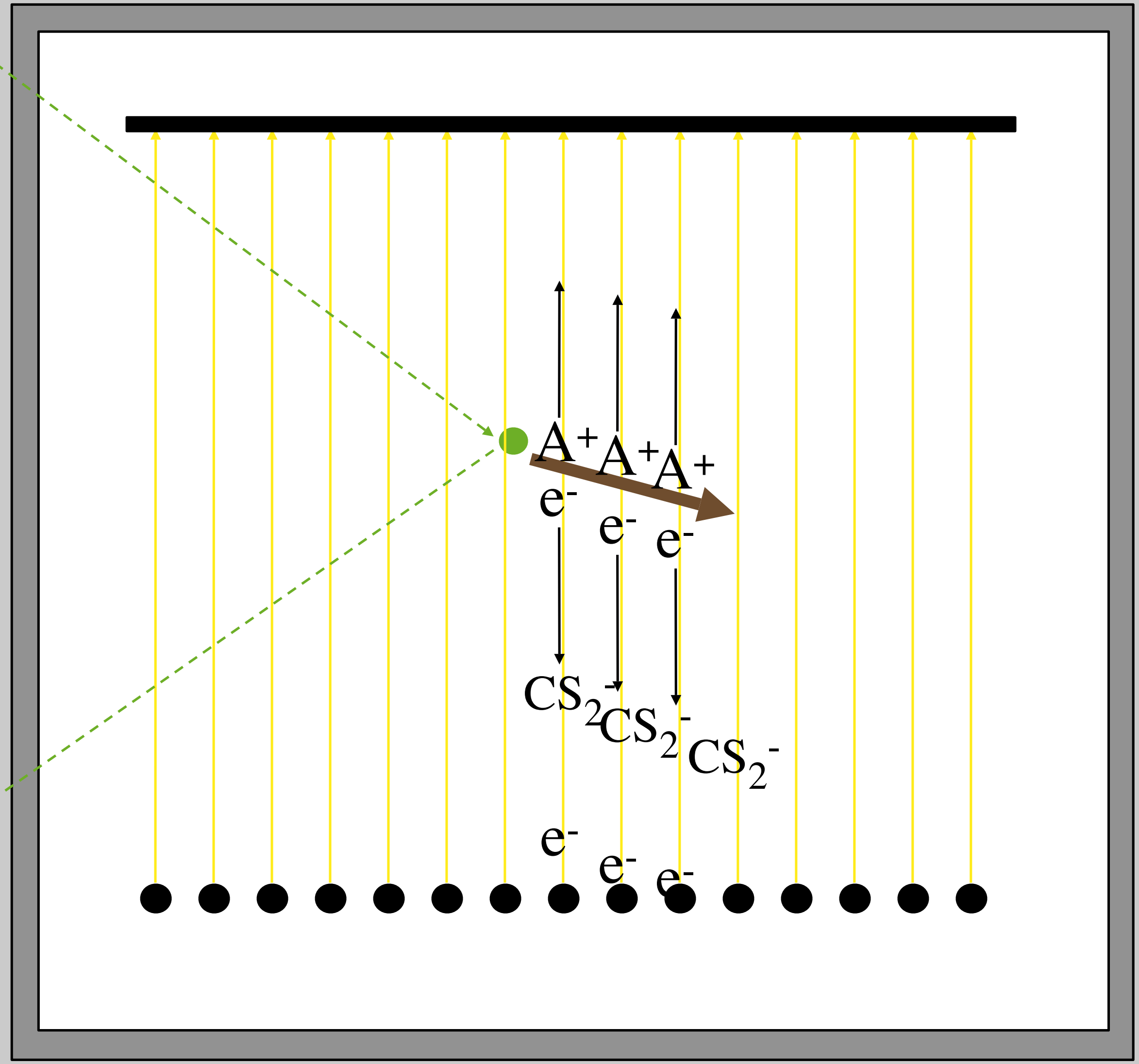
Tracks

On behalf of the
DRIFT collaboration



DRIFT

concept



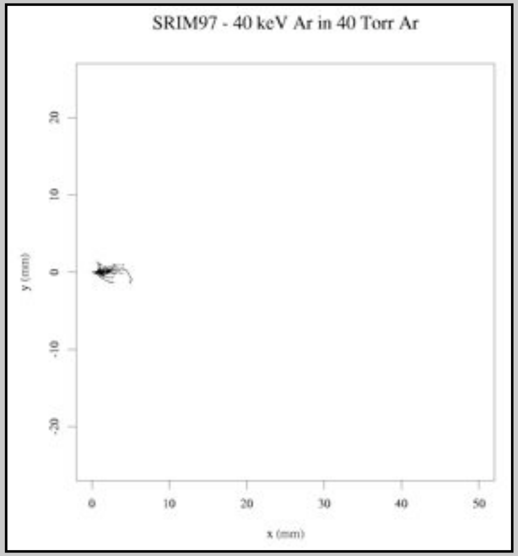
Negative
Ion
Time
Projection
Chamber

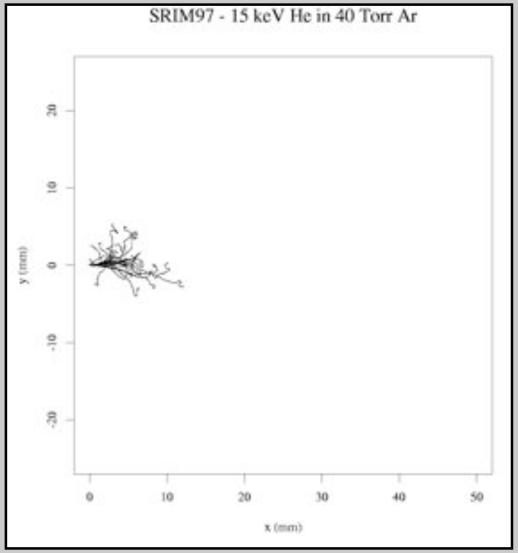
Jeff Martoff

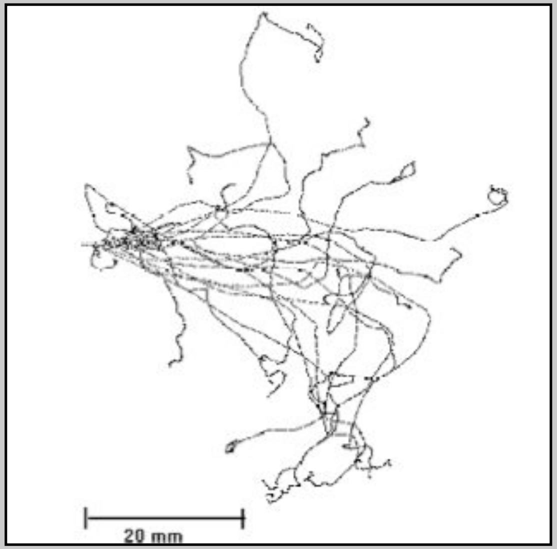
Particle Identification

simulation

40 keV Ar recoils from WIMPs 500 Nips	15 keV as from radioactivity 500 Nips	13 keV e^-s from radioactivity 500 Nips



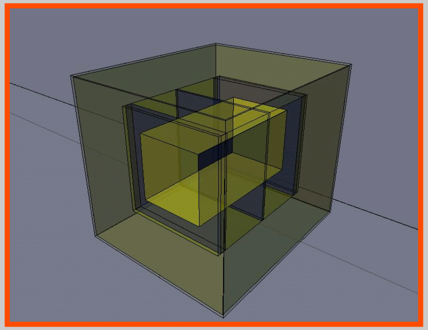


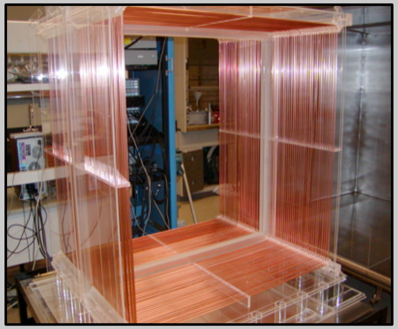


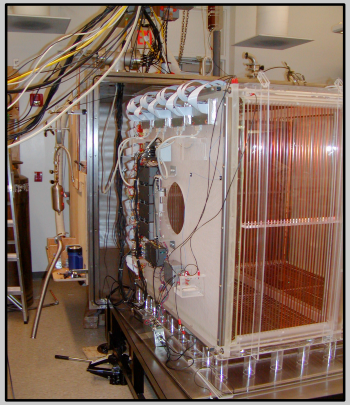
Key points: it's range discrimination - no doubt

Key points: start at high pressure for events
then low pressure for direction

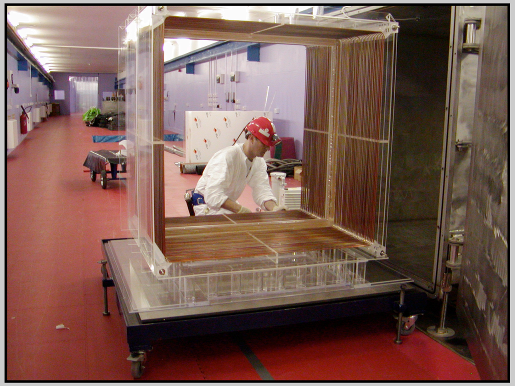
DRIFT IIa, built & run in 1 yr



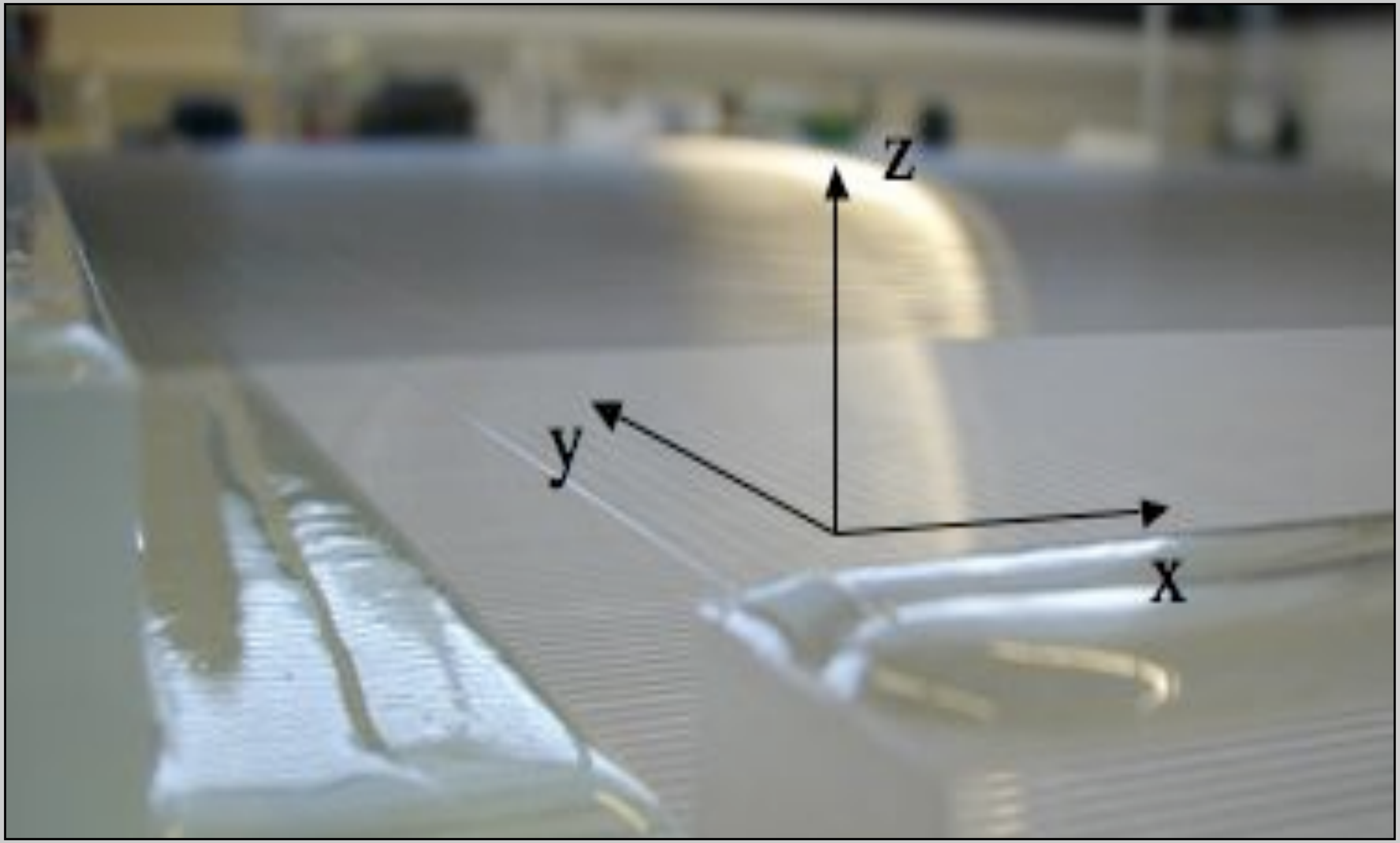




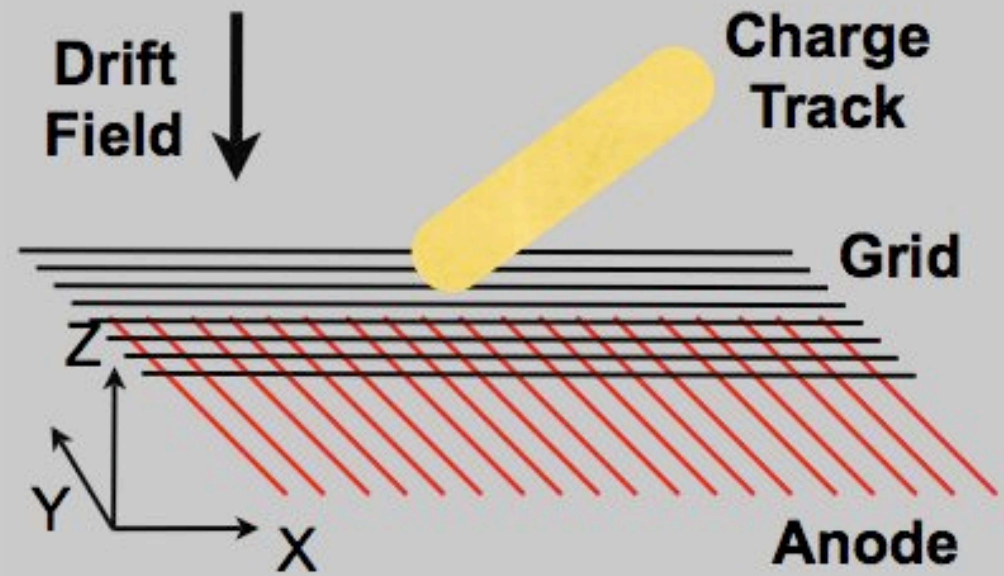
at the Boulby laboratory

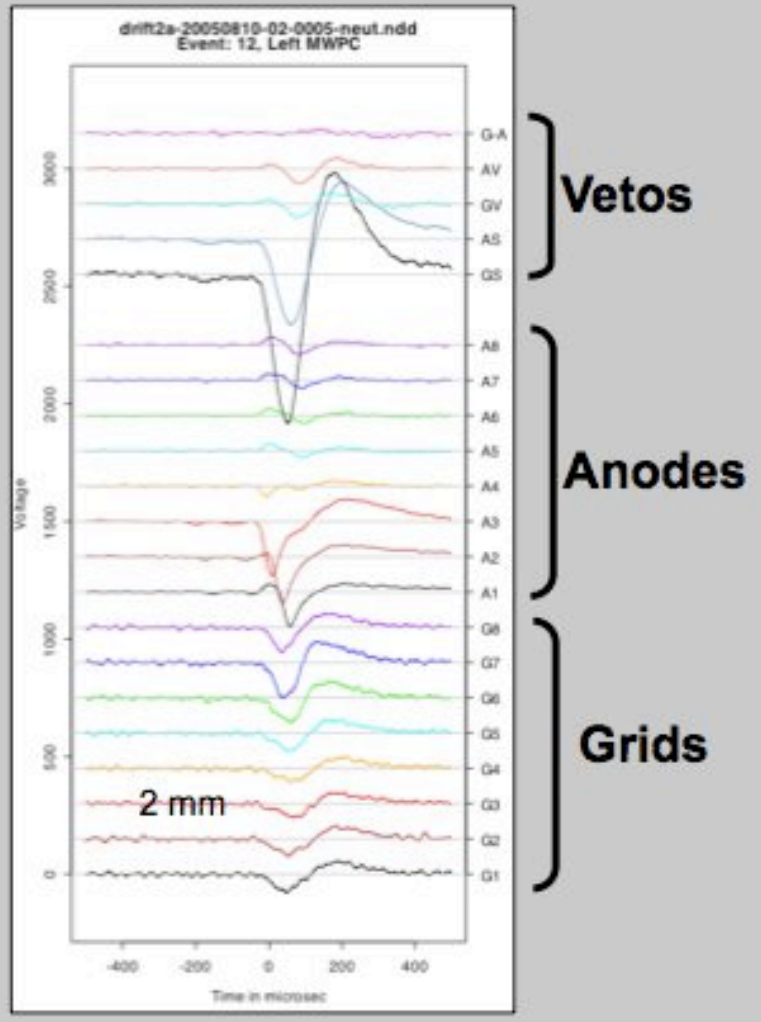


DRIFT - 3D readout



Directional Analysis

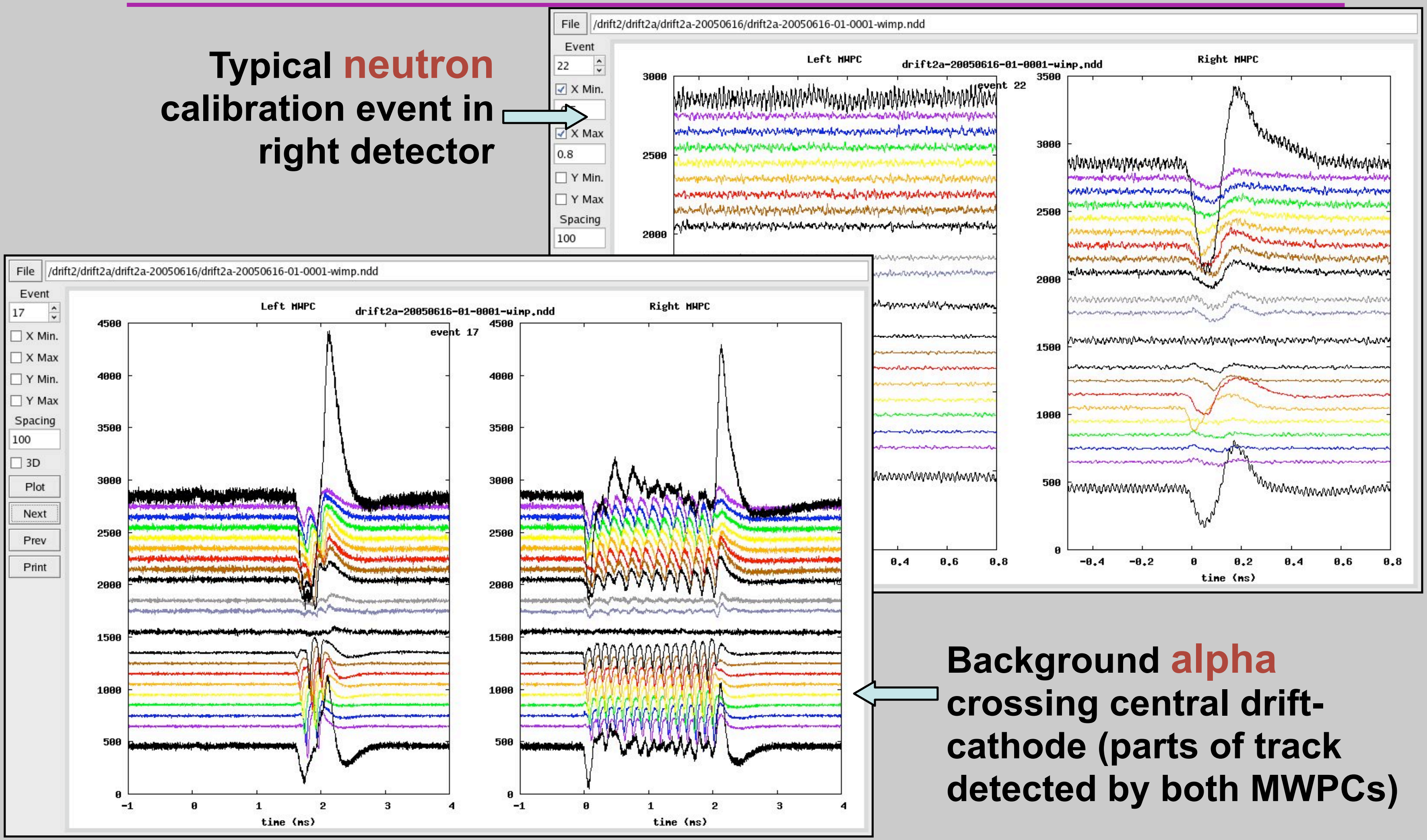




ΔX: Number of Anode Wires Crossed
ΔY: Progression across Grid Wires
ΔZ: Drift Time difference between start and end of track

DRIFT IIa - typical events

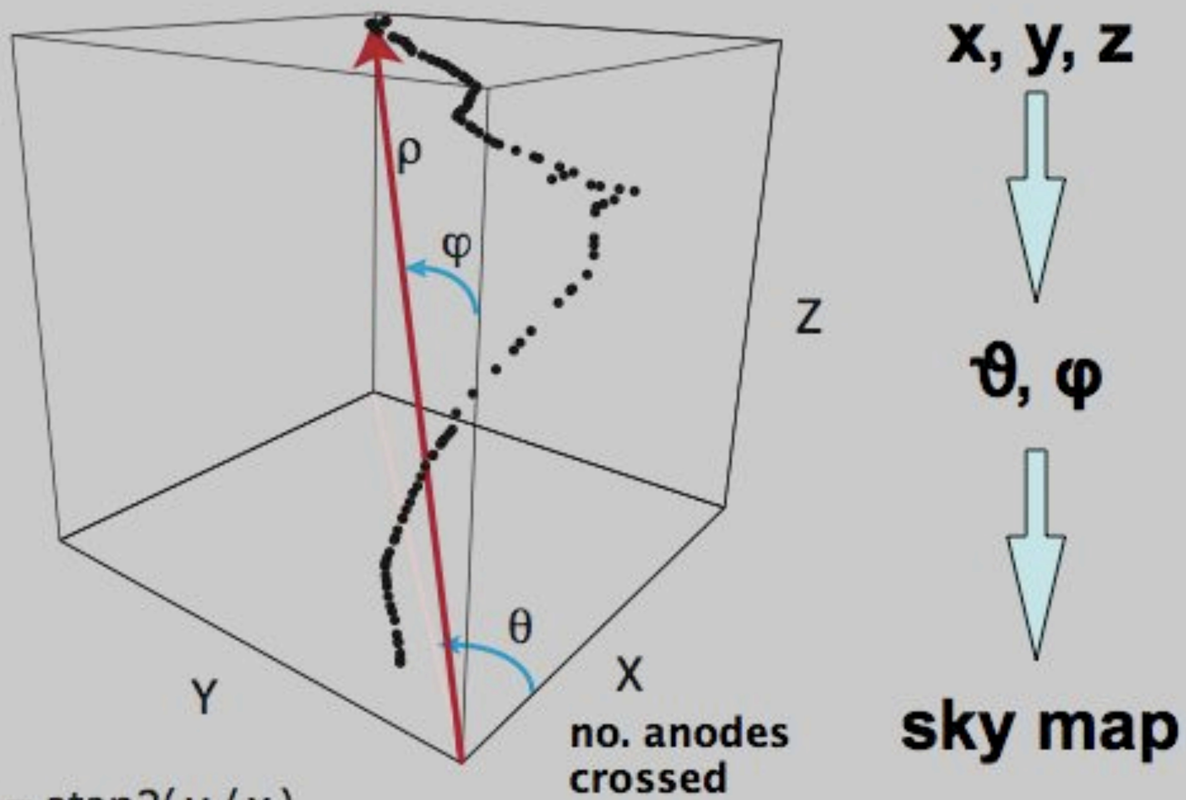
Typical neutron calibration event in right detector



Background alpha crossing central drift-cathode (parts of track detected by both MWPCs)

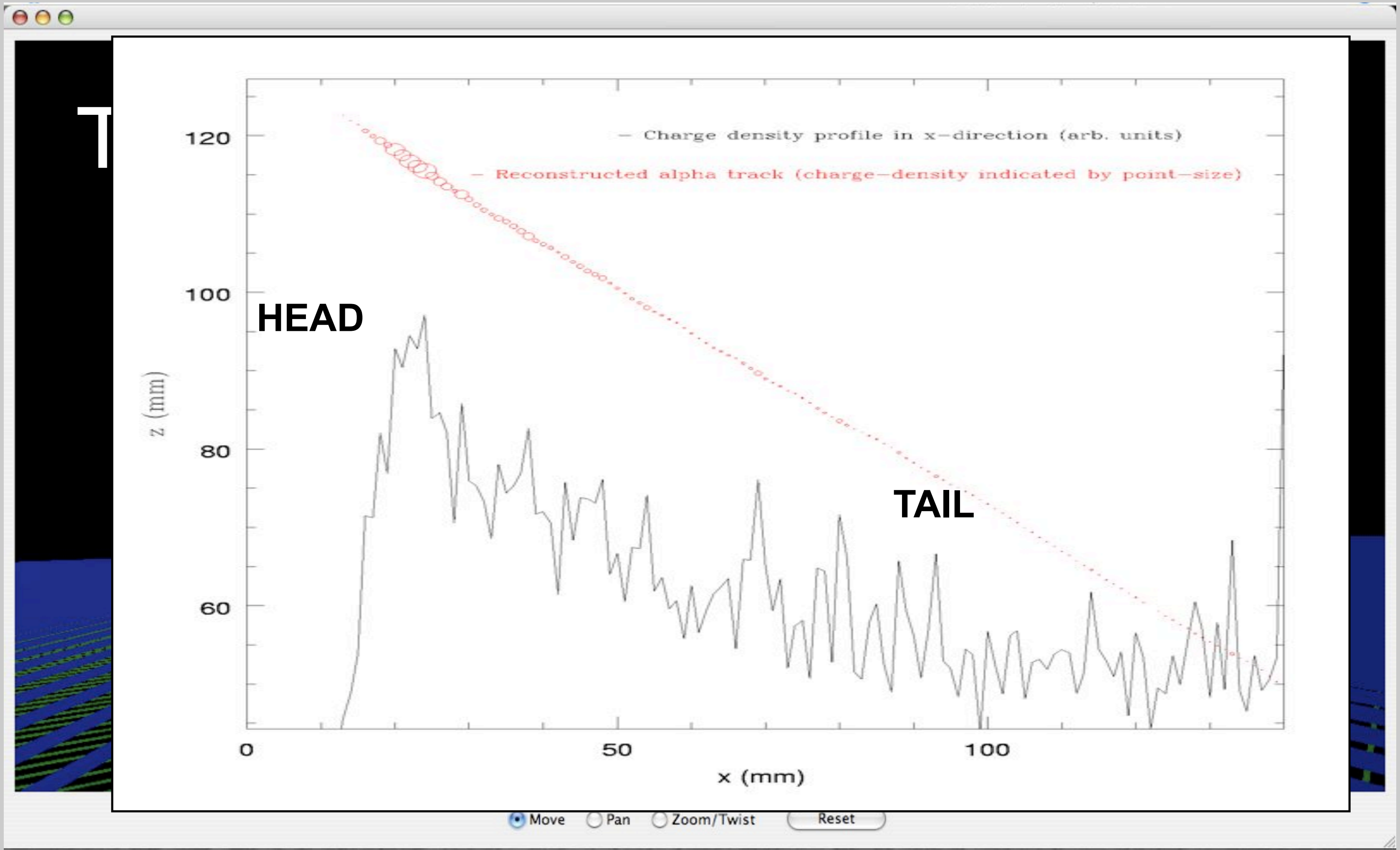
Track reconstruction

Minimum cuboid



$$\theta = \operatorname{atan2}(y/x)$$
$$\varphi = \operatorname{acos}(z/\rho)$$

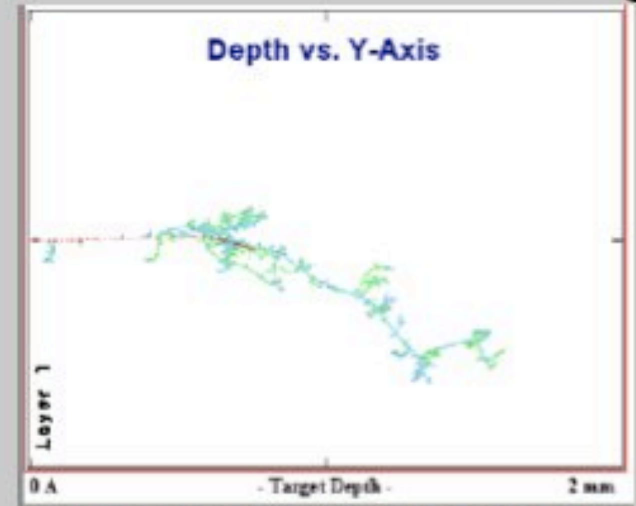
DRIFT track images



3D track MC of DRIFT IIa

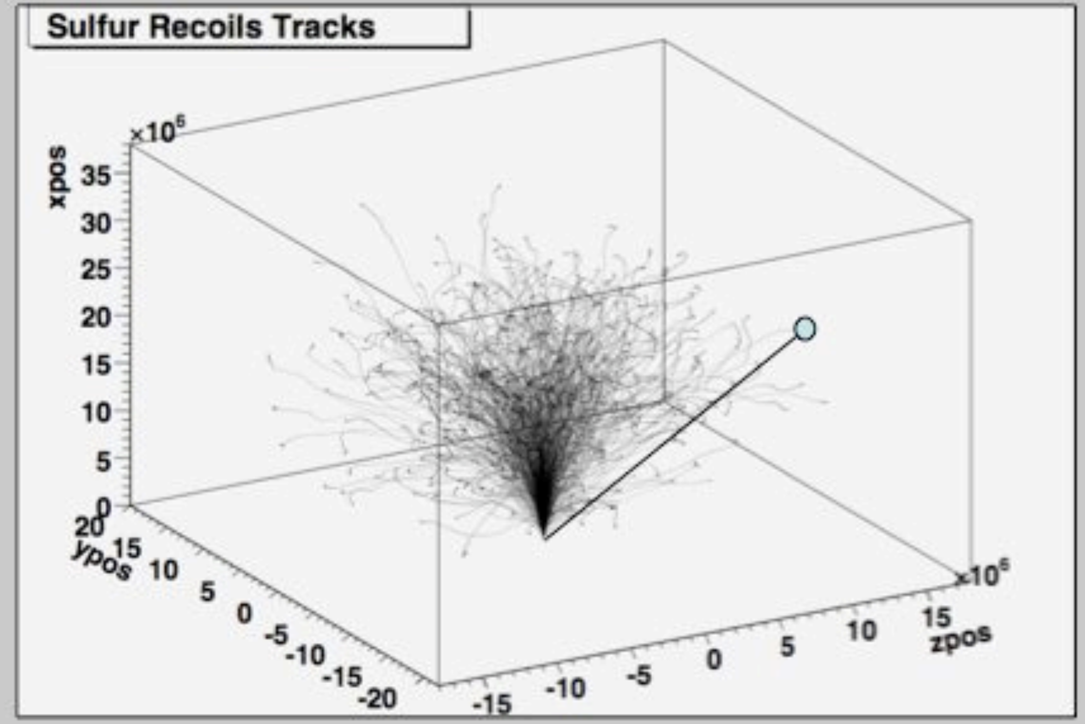
e.g: 100 keV S-recoils in DRIFT IIa @ 40 torr CS_2 (SRIM2006)

e.g. initial recoil directions along one axis



example S 100 keV track

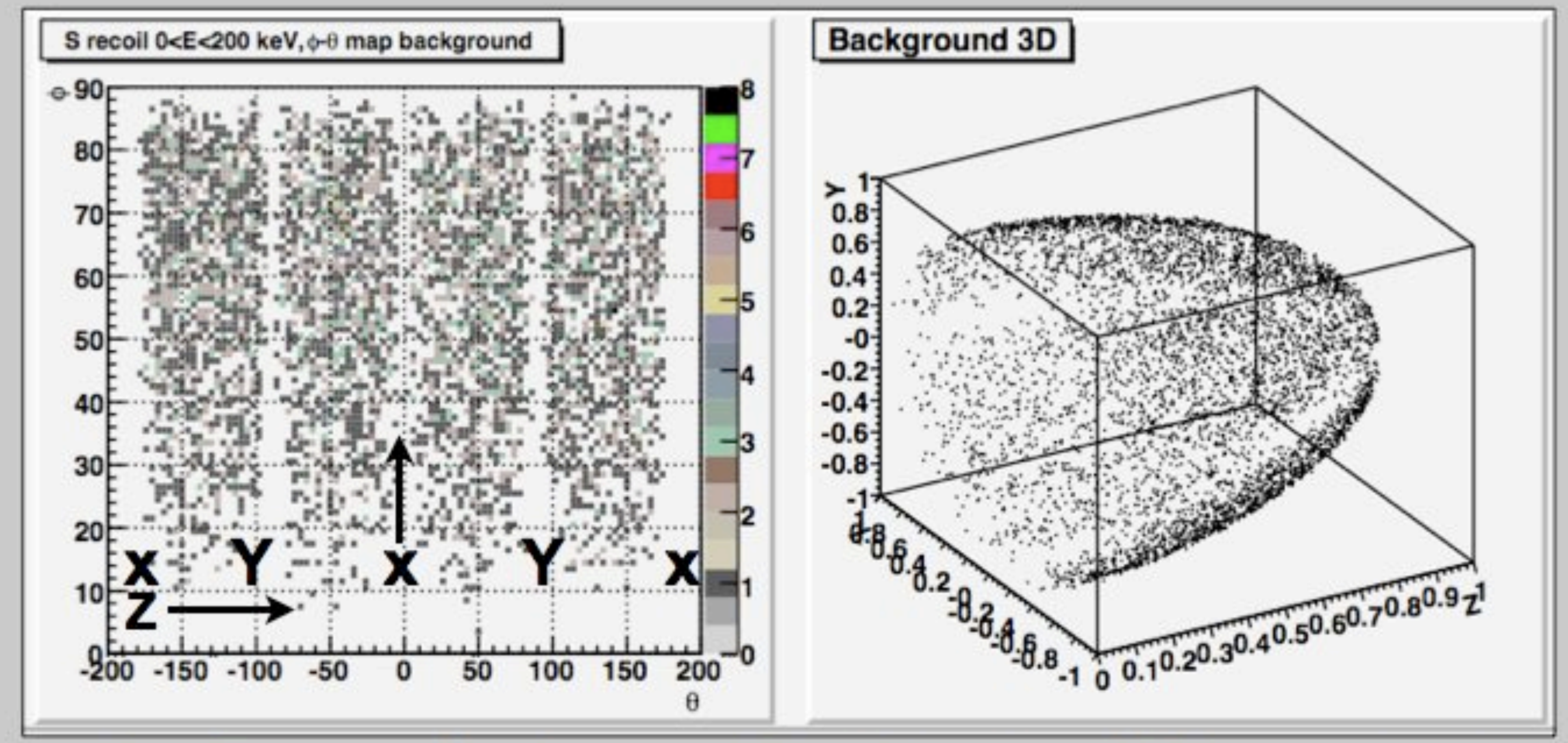
analysis assumes no head-tail (see later)



propagate through DRIFT IIa - find intrinsic angular resolution and response

3d (θ, φ) sky maps (simulation)

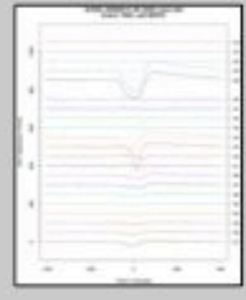
Output for random s-recoil directions of 0-200 keV



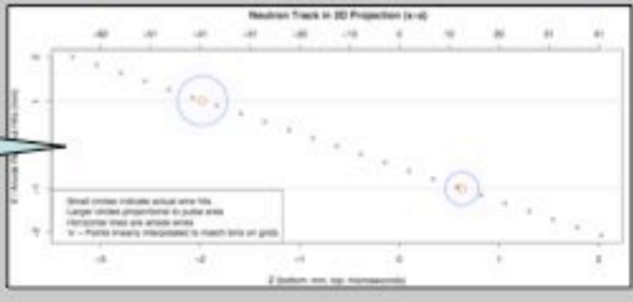
- gaps for events along x,y,z axis due to minimum cuboid
- depletion at low φ (cos φ effect)

3d S-recoil reconstruction

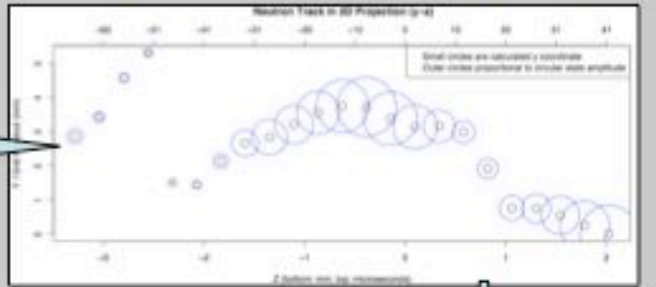
raw pulse

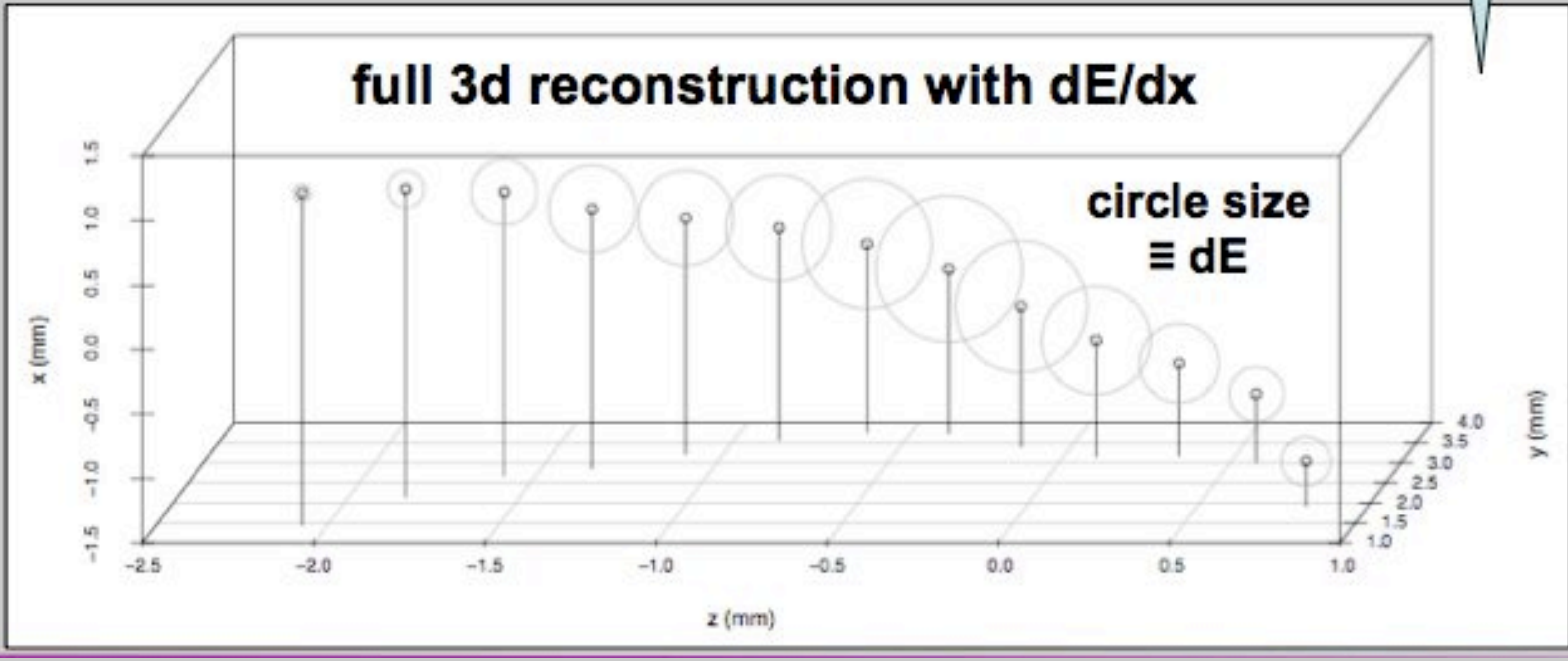


x-z reconstruction (anode)



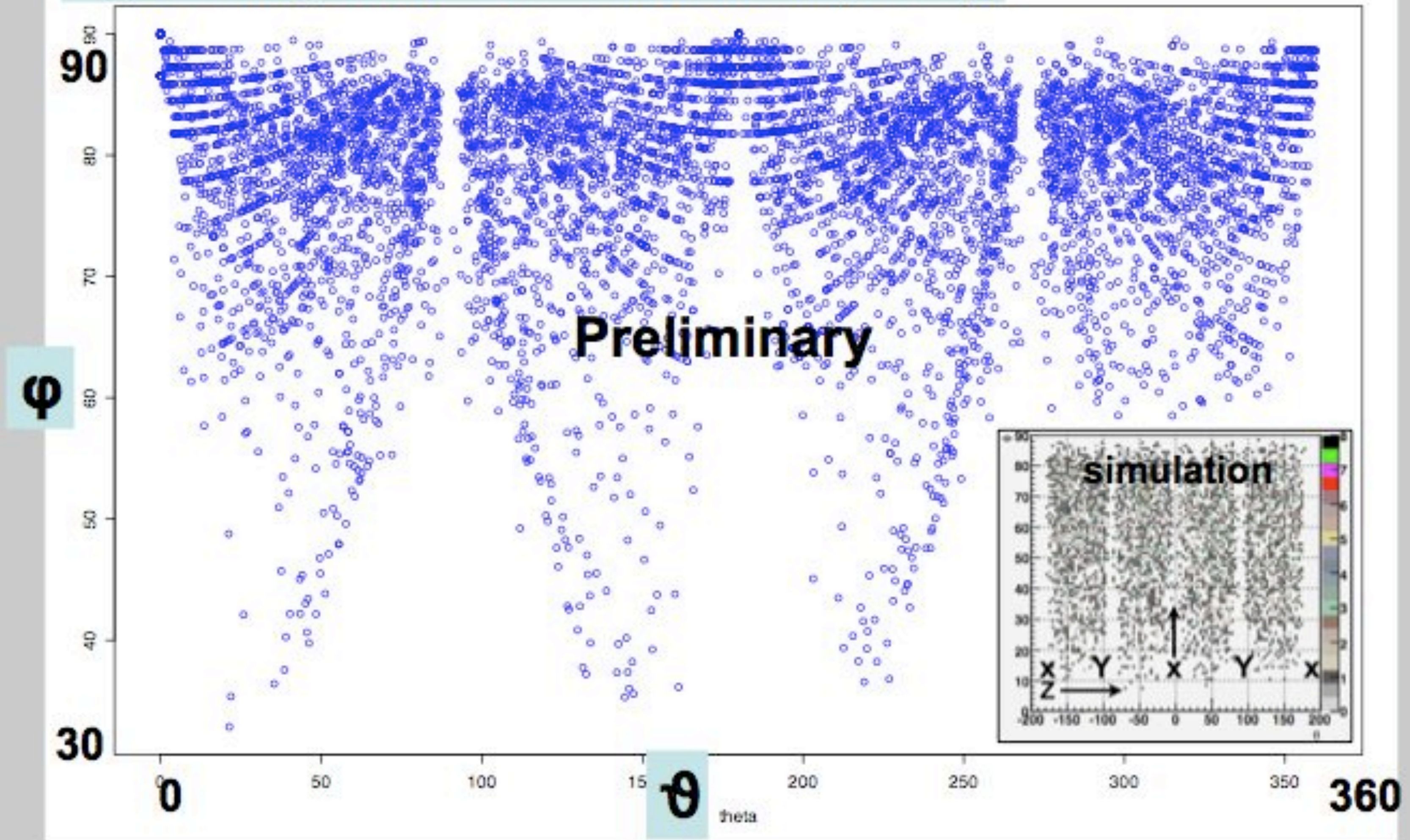
y-z reconstruction (grid)





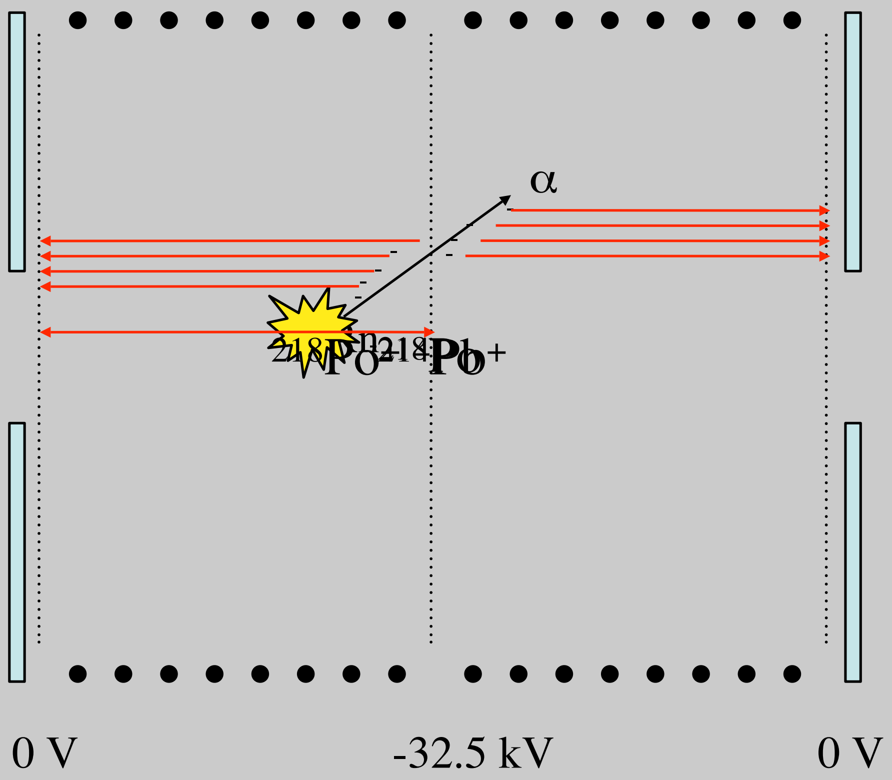
real 3d data map vs. simulation

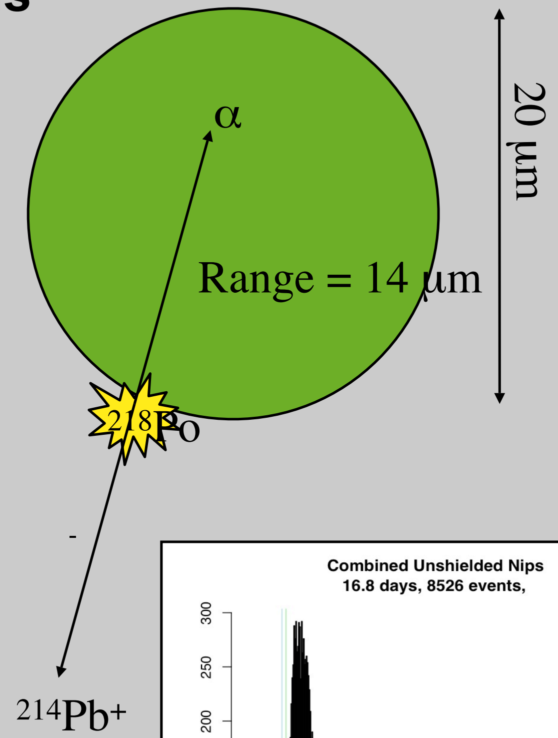
e.g. “background” run of 17th June (RPRs)

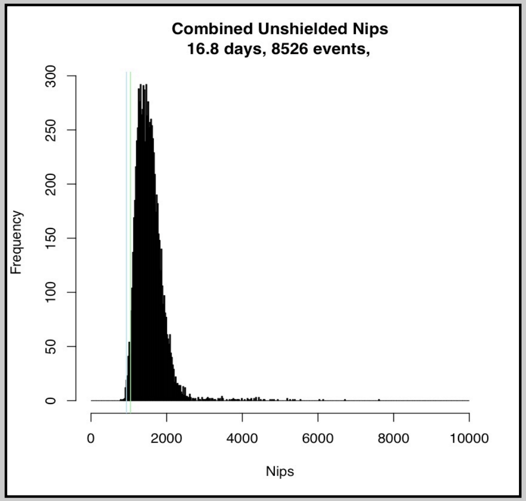


Radon Progeny Recoils

The Radon Progeny Recoil (RPR) Hypothesis

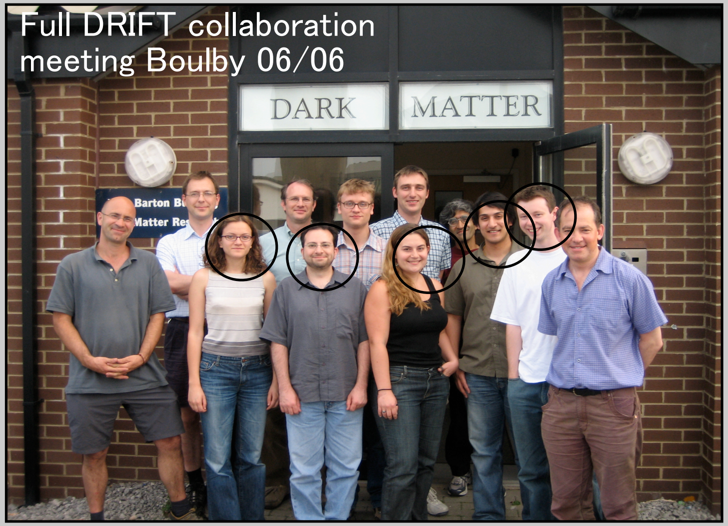






DRIFT IIb - in 5 days

DRIFT IIb with new radon control and RPR control



Full DRIFT collaboration meeting Boulby 06/06

NB: students are very active on DRIFT

Conclusion

Great progress in WIMP searches

But we will need a directional gas TPC detector to show definitively that WIMPs exist in the galactic halo!