Possible Backgrounds and Shielding Requirements for a Direct Dark Matter Search Experiment

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Plan of talk

- Brief overview of dark matter
- Strategies employed in dark matter search
- Current DM search experiments and recent results
- Mini-DINO experiment
- Backgrounds and shielding requirements
- Some results I have obtained

Evidence for dark matter

- Discrepancy in Galactic Rotation curves.
- Mass estimate using Gravitational lensing
- Evidence from colliding galaxy clusters
- Elemental abundance from BBN
- Cosmic Microwave Radiation

Rotation of Stars around Galactic Centers

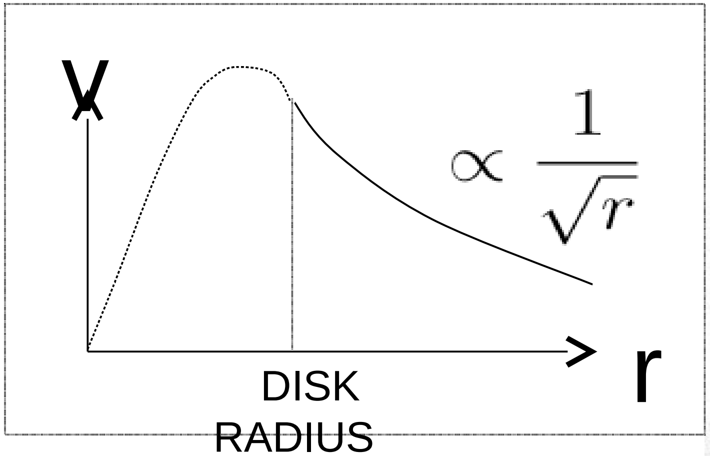
can measure how fast stars rotate around galactic centers by looking at the freq
of known spectral lines originating in the stars due to the Doppler effect.

Star’s motion towards you, relative to the galactic centre alters wavelength of light

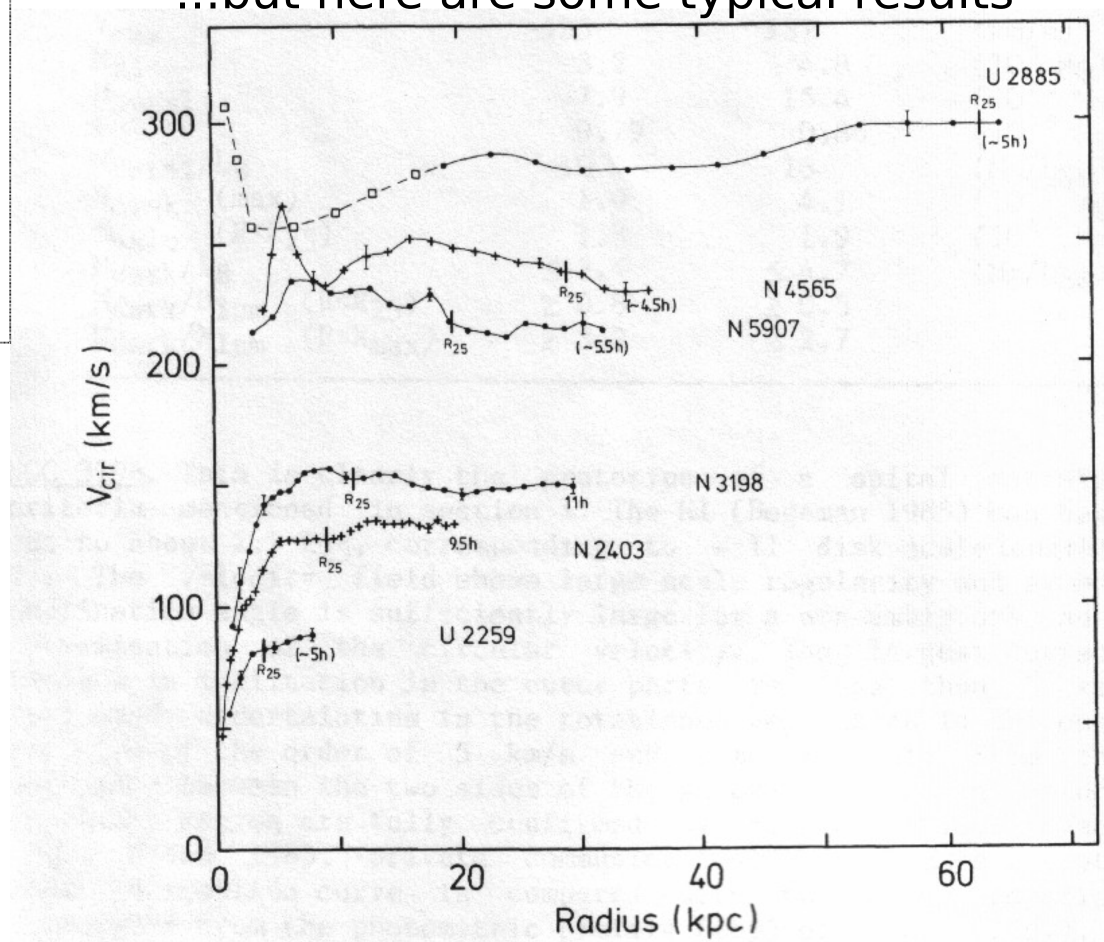
$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Some Results

This is what we expect....



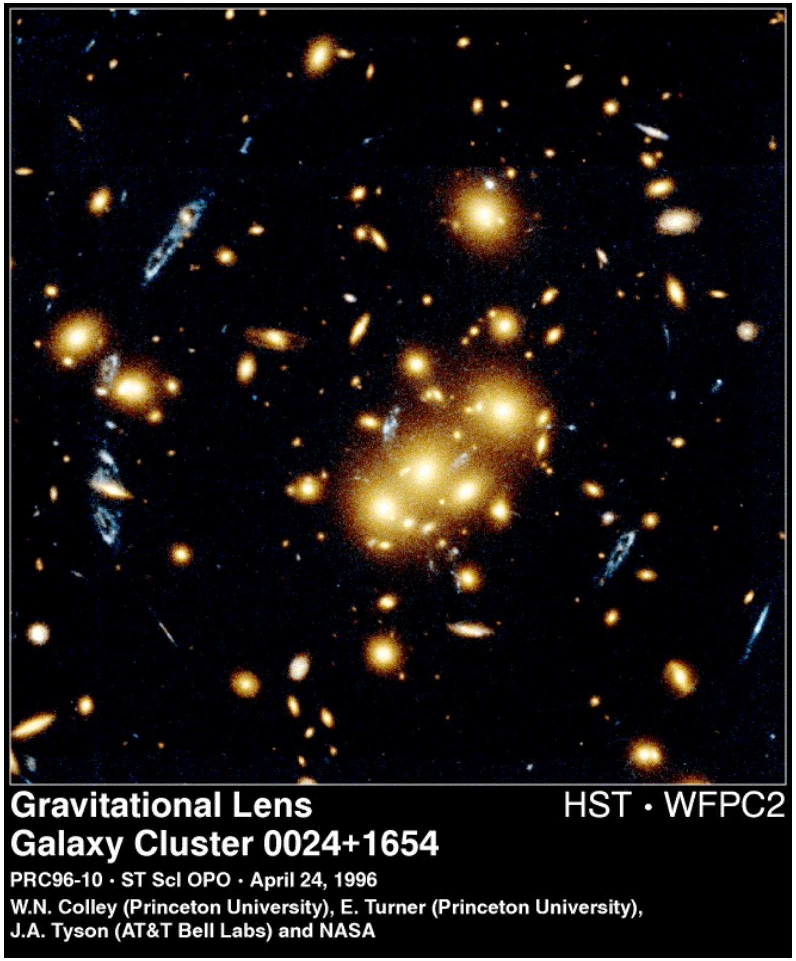
...but here are some typical results



Requires about 10 times as much dark matter than ordinary matter to explain the discrepancy

Gravitational lensing

- Study of gravitational lensing also points to the presence of dark matter about 5 times the mass of normal matter in Galaxy clusters.

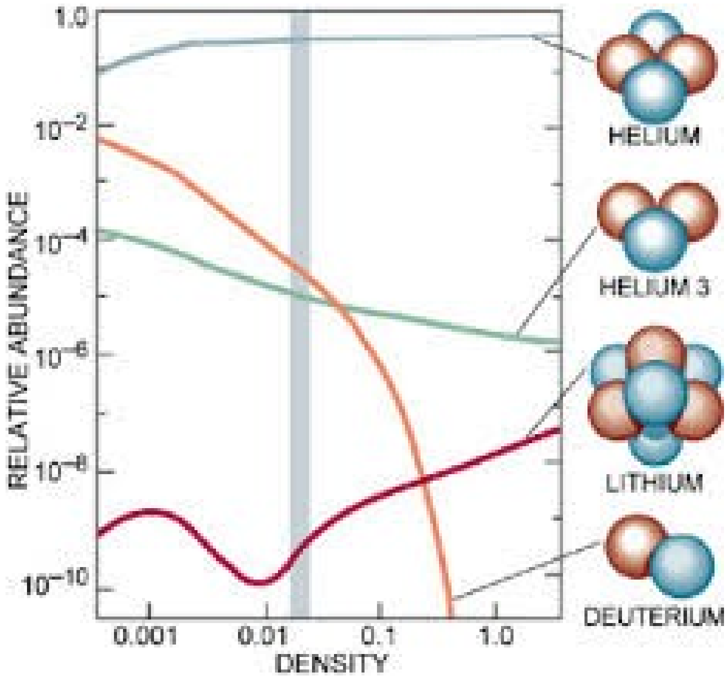


Evidence from colliding galaxy clusters

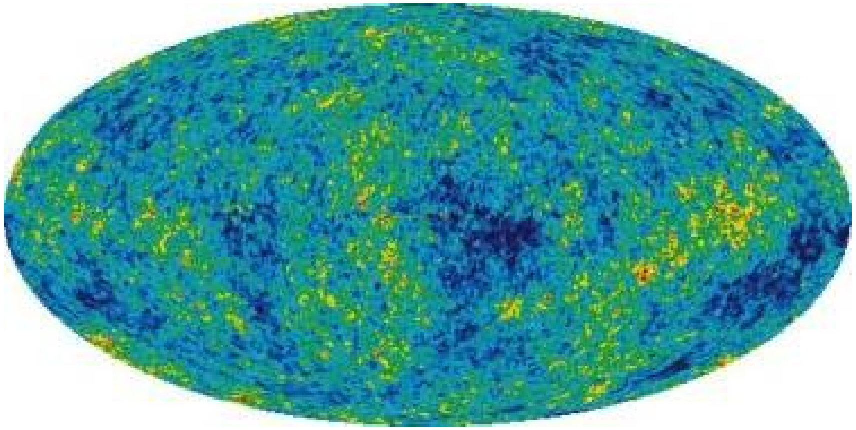
- Normal matter (shown in pink) measured from x-ray emissions gets separated from most of the mass in the form of dark mater (shown in blue) as estimated from gravitational lensing during galaxy cluster collision.

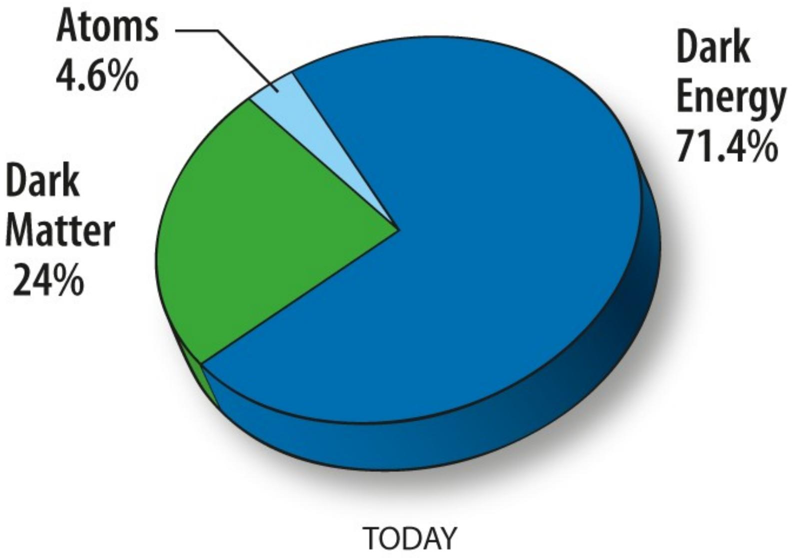
Big Bang Nucleosynthesis

- Study of light element abundances produced during big bang also shows that exotic dark matter abundance exceeds ordinary baryonic matter by a factor of about 5



Cosmic microwave background





Dark matter properties

- Non-baryonic
- Most evidence point to cold dark matter: large mass, slow moving, clumps together, aids structure formation
- Lifetime > age of the universe
- Self interaction cross section: must be small
- Interaction cross section with baryons: small
- Interaction cross sections with photons: zero

Most promising DM candidate: WIMP

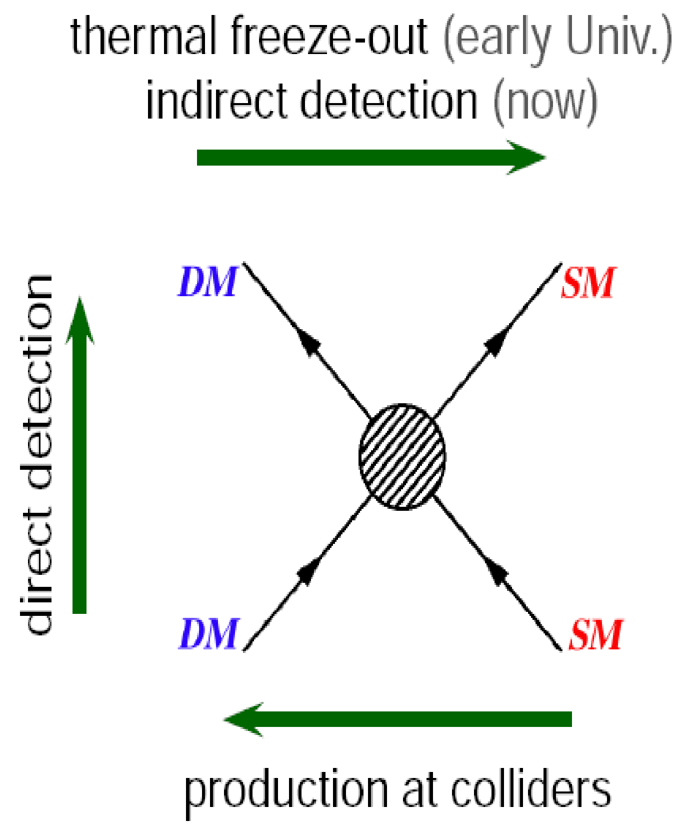
- As a result of thermal freeze out process a relic abundance of WIMPs is left behind
- For a particle with GeV-TeV mass, to obtain a thermal abundance matching observed dark matter density we need an annihilation cross section ~ pb
- Generic weak interaction scale cross section ~ pb
- This coincidence, sometimes referred to a WIMP miracle offer strong hints that dark matter may originate from electroweak scale physics
- Theories such as supersymmetry, invented for entirely different reasons predict stable particles which interact with EW scale cross-sections.

WIMPs from Supersymmetry

- Supersymmetry is one of the most theoretically appealing extensions of standard model
- Provides natural solution of hierarchy problem and restores the unification of couplings
- R-parity has to be preserved in Supersymmetry to prevent rapid proton decay.
- Another consequence of R-parity is that the superpartners can be produced and destroyed in pairs. This makes the lightest supersymmetric particle stable.
- Possible WIMP candidates from supersymmetry are 4 neutralinos the lightest of which is typically stable. These four states are mixtures of the bino and the neutral wino (which are the neutral electroweak gauginos), and the neutral higgsinos.
- Neutralinos are Majorana fermions and as such are their own antiparticles.

WIMP hunting strategies

- Indirect searches rely on WIMP pair annihilation from regions of high WIMP densities (e.g. Galactic center, solar core). Annihilation products: gamma rays, positrons, muons, neutrinos etc.
- Hadron colliders may produce WIMPS through decay of new particle. Detectable through missing energy.
- Direct detection involves WIMPS undergoing elastic scattering off nuclei of the detector material depositing small amounts of energy.



Direct detection of WIMPS

- WIMPS from dark matter halo will undergo elastic scattering off nuclei of the detector material.
- Energy spectrum and rate depends on the WIMP distribution in the dark matter halo as well as the target.
- Standard assumption: isothermal and spherical, obeys Maxwell Boltzmann velocity distribution
- Recoil energy ~ 10 -20 keV
- Event rate < 1 event/Kg/day

Experimental challenges

- Extremely low rate of scattering and low recoil energy.

- Requires detectors with very low energy (KeV) threshold and large target mass.

- Suppression of background from radioactivity and cosmic rays (Gamma, Neutron) requires deep underground sites, excellent shielding and use of radio-pure materials in construction.

- Residual backgrounds are to be suppressed using typical WIMP signatures such as :

  - Nuclear recoils, not electron recoils
  - Absence of multiple scattering
  - Annular modulation
  - Directionality

WIMP detection strategies

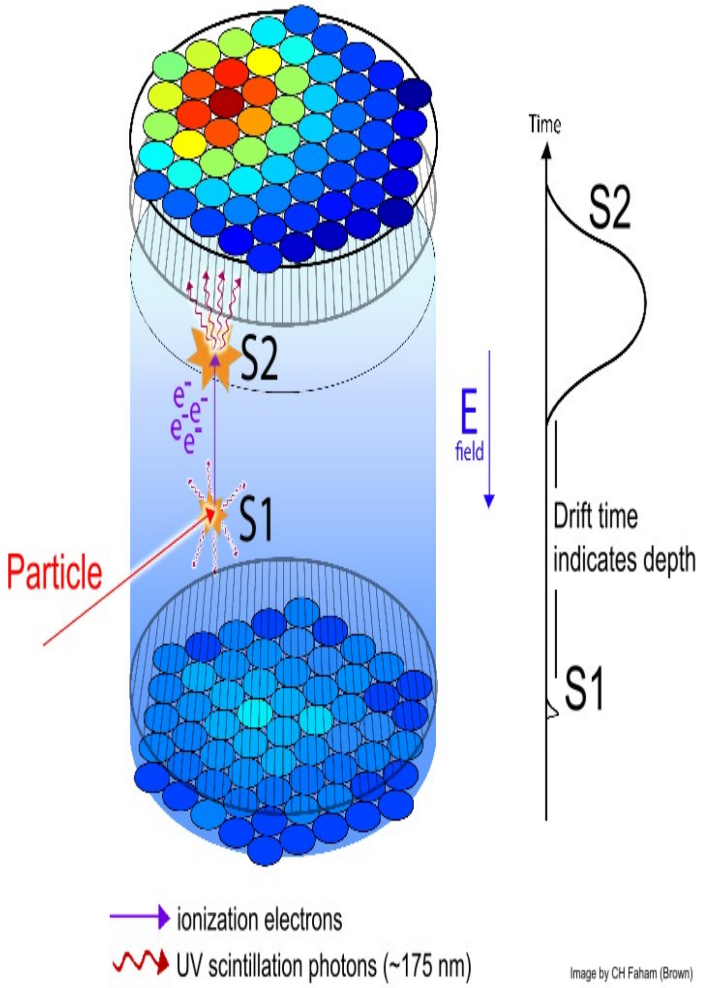
- There are three main detection strategies which can be employed to measure energy deposition in a detector (depending on the detector material).

  - **Scintillation detection**: a particle interacting within a scintillating target induces the emission of light produced by the de-excitation of exited atoms. This light can be detected by PMTs. Xenon is one popular scintillator.
  - **Ionization detection:** a particle interacting inside a target (Ge, Si) produces free electron-ion pairs that can be detected with a collecting drift field and a device sensitive to the electric charge.
  - **Phonon detection:** a particle interacting inside a detectors deposits energy with a subsequent increase of the temperature. Cryogenic apparatus working at very low temperature (around few mK) may be able to measure this small variation.

- Most modern experiments combine information from two of the three above channels for much better event by event background discrimination. The ratio between two channels can be used to distinguish between nuclear (due to a DM interaction) and electromagnetic recoils.

LUX Experiment : Scintillation + Ionization

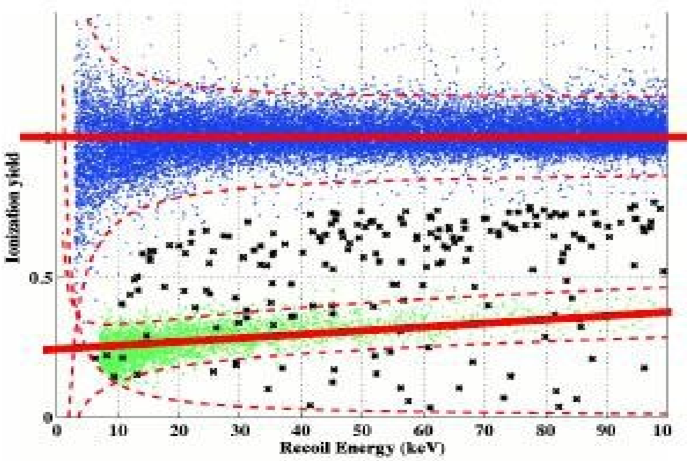
- Two phase time projection chamber.
- Contains 370 Kg xenon 1 mile underground in South Dakota
- PMTs collect prompt (S1) and proportional (S2) light. Signals proportional to energy.
  - S1-S2 delay Drift length
  - S2 light pattern Horizontal location
- S2/S1 ratio differs markedly between electron and nuclear recoils
  - Nuclear recoils have higher ionization density higher recombination probability higher S1 yield
  - >98.5% rejection of EM backgrounds
  - Detection threshold ~ 5 KeV



Super CDMS: Ionization + Phonon

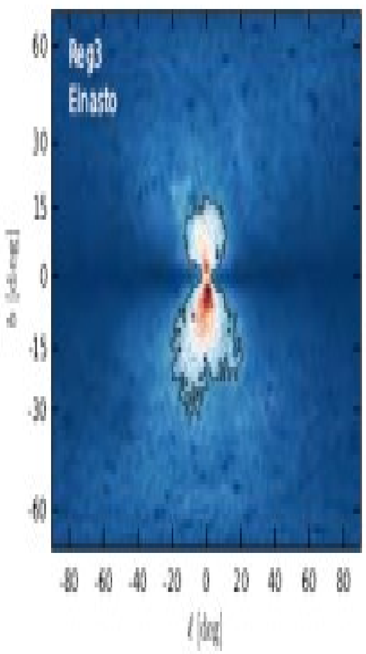
- The CDMS experiment uses cryogenic silicon and germanium detectors
- The recoiling nucleus from a dark matter interaction produces crystal lattice vibrations (phonons) and also electron-hole pairs.
- The phonon and charge signals are captured by electrodes applied to the face of the crystal using photolithography
- Phonon detection is accomplished with superconducting transition edge sensors read out by SQUID amplifiers
- Ionization signals are read out using a FET amplifier.
- The ratio of ionization signal to phonon signal differs for particle interactions with atomic electrons (for electron recoils Nc/Np ~ 1) and atomic nuclei (for nuclear recoils Nc/Np ~ 0.25).

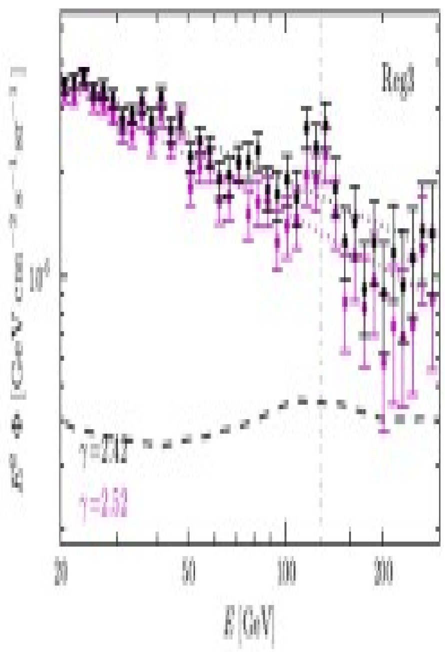
Charge to Phonon ratio



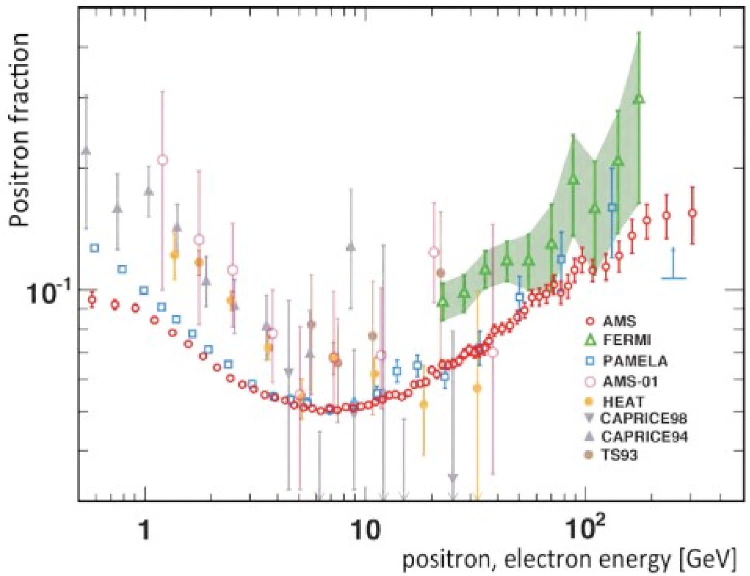
Some recent results: Indirect search

Fermi: 130 GeV photons coming from the galactic center.



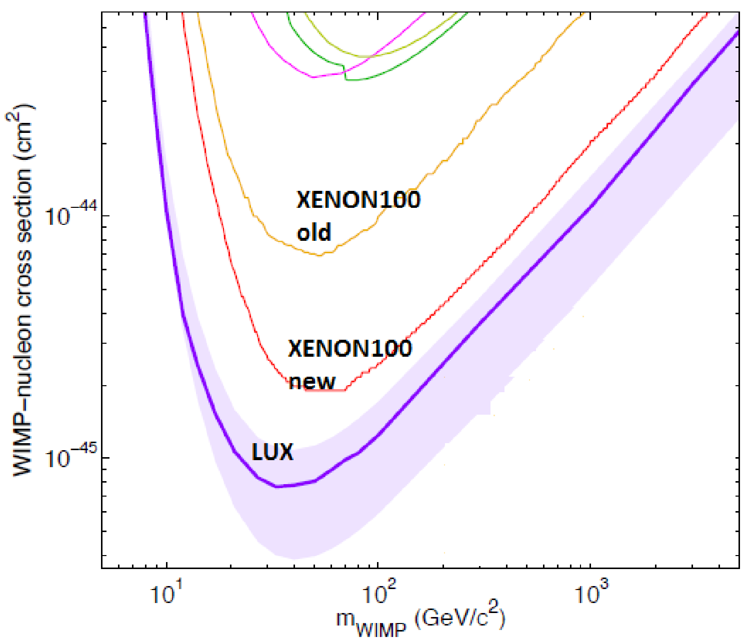


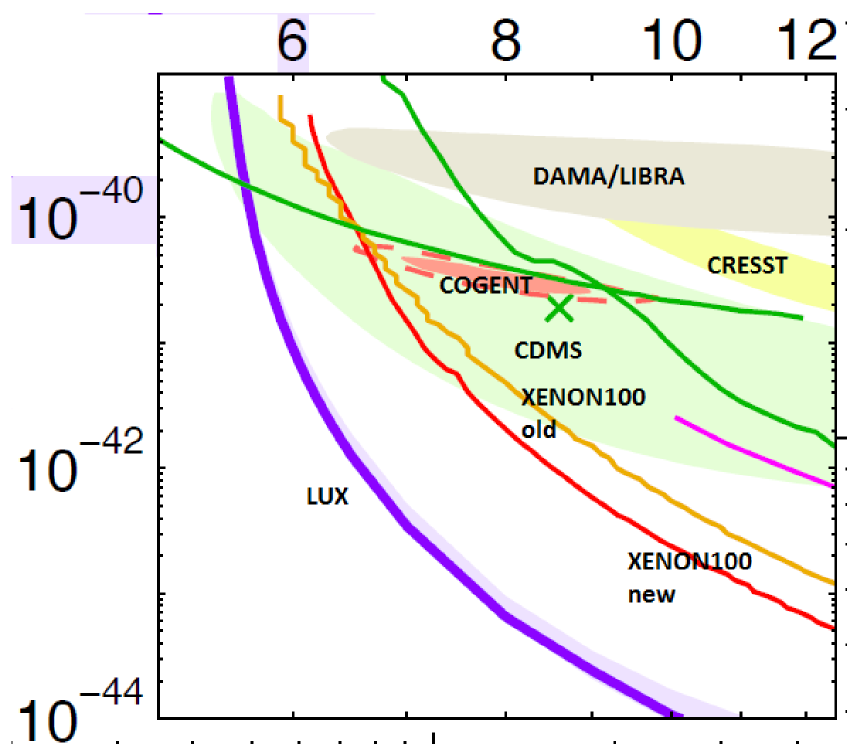
AMS-02: Increasing positron fraction above 10 GeV upto 350 GeV



Contradictory results !

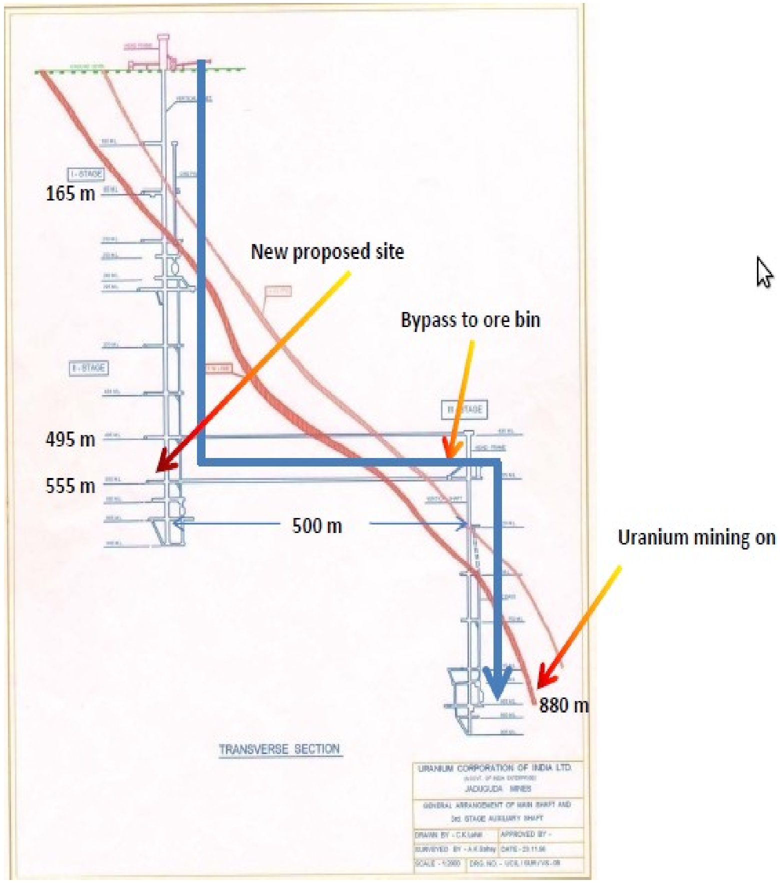
Direct search results: Exclusion plot
Recent LUX results rules out hints seen by other experiments





Mini-DINO

- A proposed direct dark matter search experiment to be set up at the UCIL, Jaduguda Mines.
- Based on CDMS detector technology. 15-30 Kg Si/Ge detector for detection of low mass (<10 GeV) WIMPs
- To be set up 550 m below ground



Sources of Background

- Background particle sources in a low background experiment can broadly be divided into two categories

- **Muon Induced**: particles that are produced promptly by a muon interaction in the experimental apparatus or surrounding material. These muons are produced in cosmic ray induced air showers. Goes down with depth.

- **Non-Muon induced**: This category consists entirely of particles resulting from radioactive decay of unstable isotopes. The products are primarily photons, electrons, and positrons. Neutrons are produced in small amounts by fission and (α, n) reactions, with the α's coming from radioactive decays.

Muon induced backgrounds

- Muons produce secondary particles by two different classes of processes :

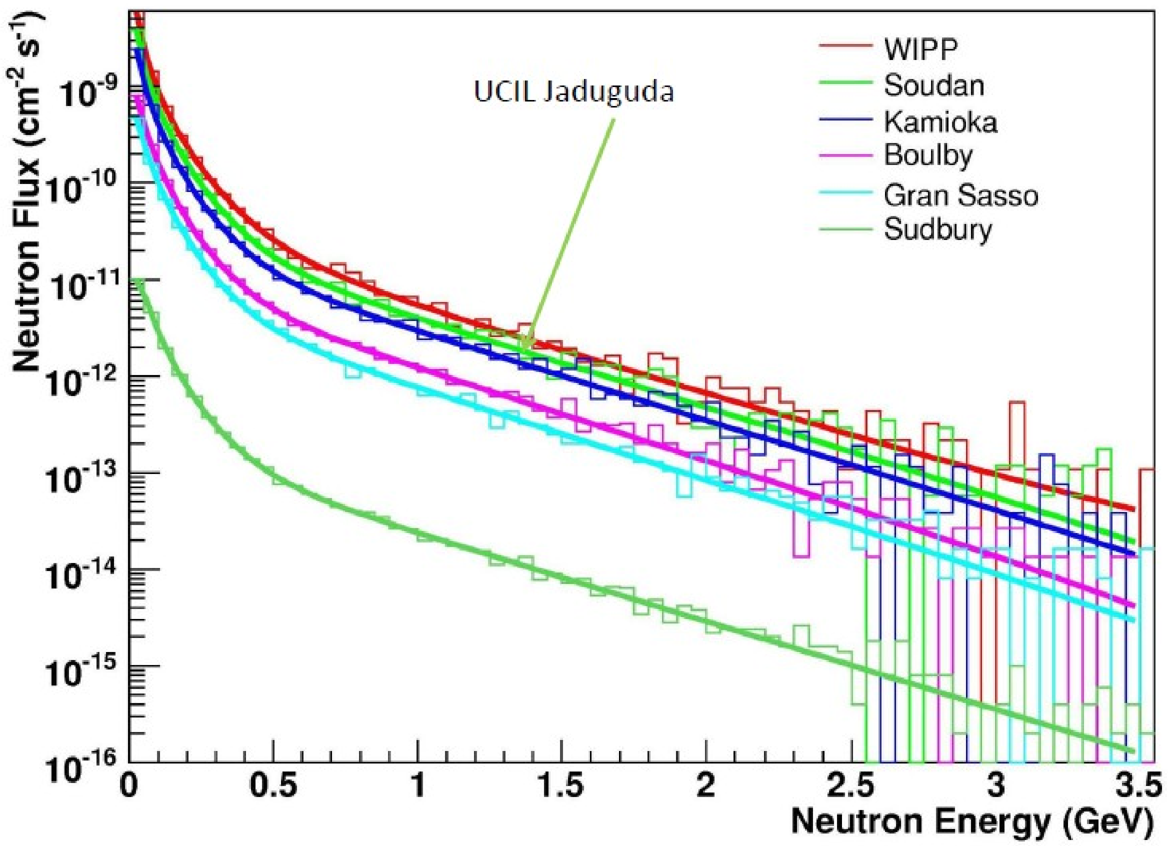
- **Fast-Muon Interactions** : Above several-hundred-GeV muon energy, muon interactions are dominated by radiative processes which eventually give rise to energetic electromagnetic and hadronic particles and showers. The processes are :
  - Bremsstrahlung
  - Pair Production
  - Photonuclear reactions
  - δ-ray production

- **Capture of Slow Muons** : Below several hundred GeV, ionization dominates. Once a muon has slowed down sufficiently, it may be captured by an atom. The muon may be captured by the nucleus via $\mu^- + p \rightarrow n + \nu_\mu$. The resulting excited nucleus de-excites by direct emission or evaporation of neutrons.

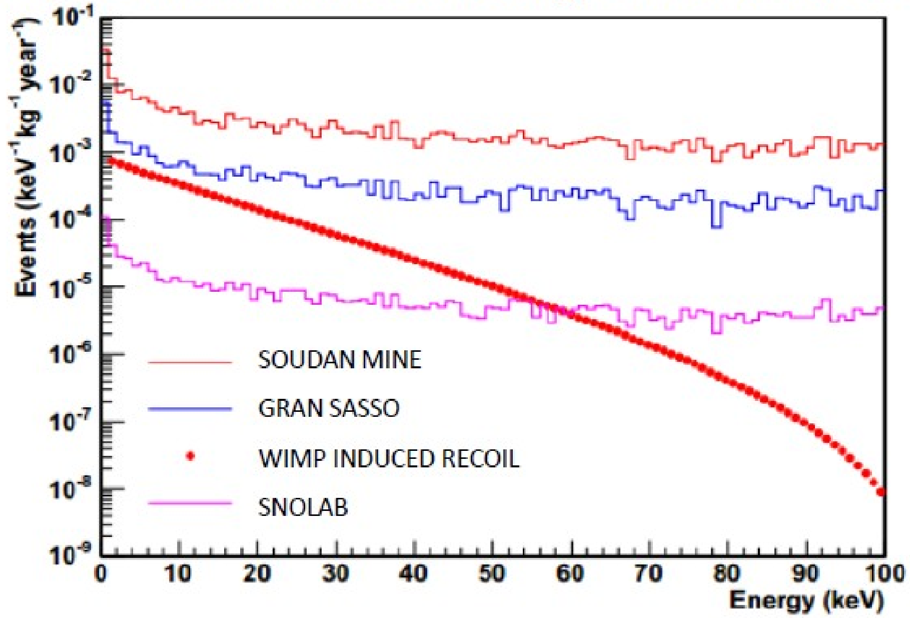
Non-Muon induced backgrounds

- There are three elements possessing radioactive isotopes with large naturally occurring abundances and long-lived decay products: uranium, thorium, and potassium.
- Uranium and thorium possess complex decay chains that include α, β, and γ emission.
- 40K potassium’s only naturally occurring radioisotope, decays via β decay or electron capture, the latter accompanied by a high-energy photon.
- Uranium and thorium chains and 40K yield photons with energies from tens of keV to 2.6 MeV. For any low-background experiment, these photons are an important source of background.
- In addition, it is necessary to avoid introducing, or else shield, any materials containing significant levels of other radioisotopes.

Underground neutron flux



Cosmogenic Neutron-induced Background Related to Depth



Source: CDMS II

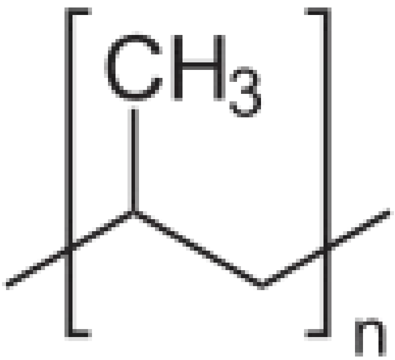
FIG. 22: The predicted event rates for spin-independent WIMP-nucleon scattering (dotted-line) in Ge assuming a WIMP-nucleon cross-section of $\sigma_p = 10^{-46} cm^2$ and a 100 GeV WIMP mass. Muon-induced neutron backgrounds are also displayed for comparison, indicating the need for greater and greater depth as experiments evolve in scale and sensitivity.

Shielding for Dark matter search

- Main sources of backgrounds are neutrons with recoil energies in the WIMP signal region.
- Ideal material to shield neutrons are hydrogen rich materials like polyethylene or water.
- Gamma rays are shielded using lead. But itself can be the location of high energy neutron interactions producing spallation neutrons which can mimic WIMP signals
- Passive shielding generally consists of alternative layers of polyethylene and lead.

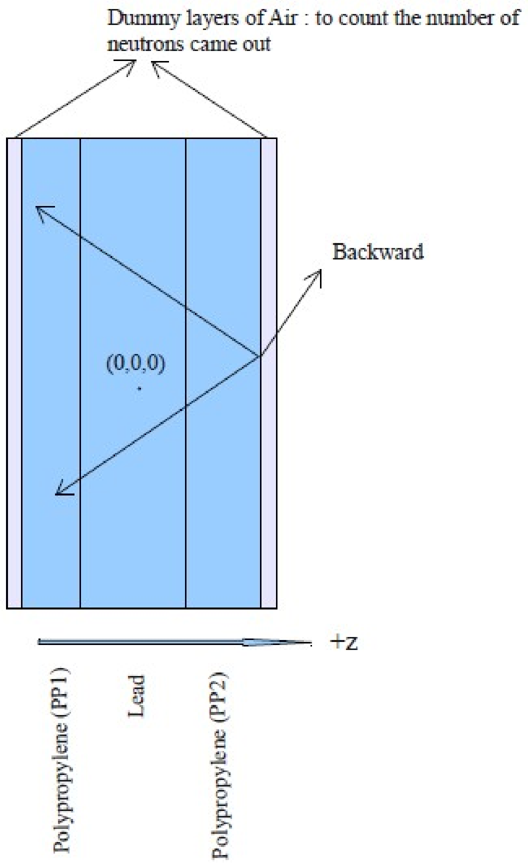
Neutron shielding material: Polypropylene (PP)

- Molecular formula : $(C_3H_6)n$
- Density: 0.95 gm/cm3
- Melting point: 130 C
- Rugged and very resistant to many chemical solvents, bases and acids.

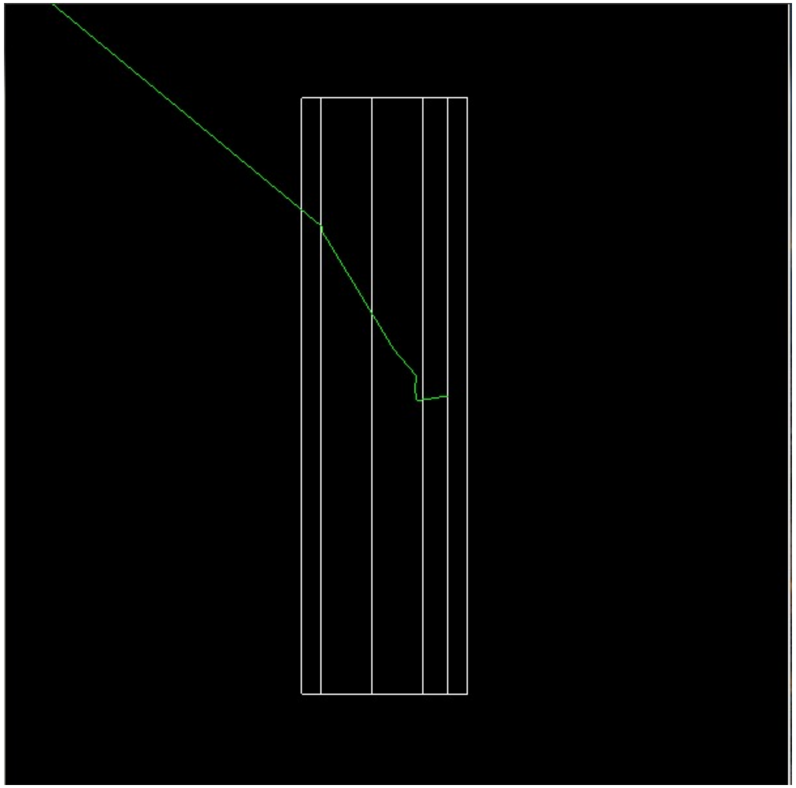


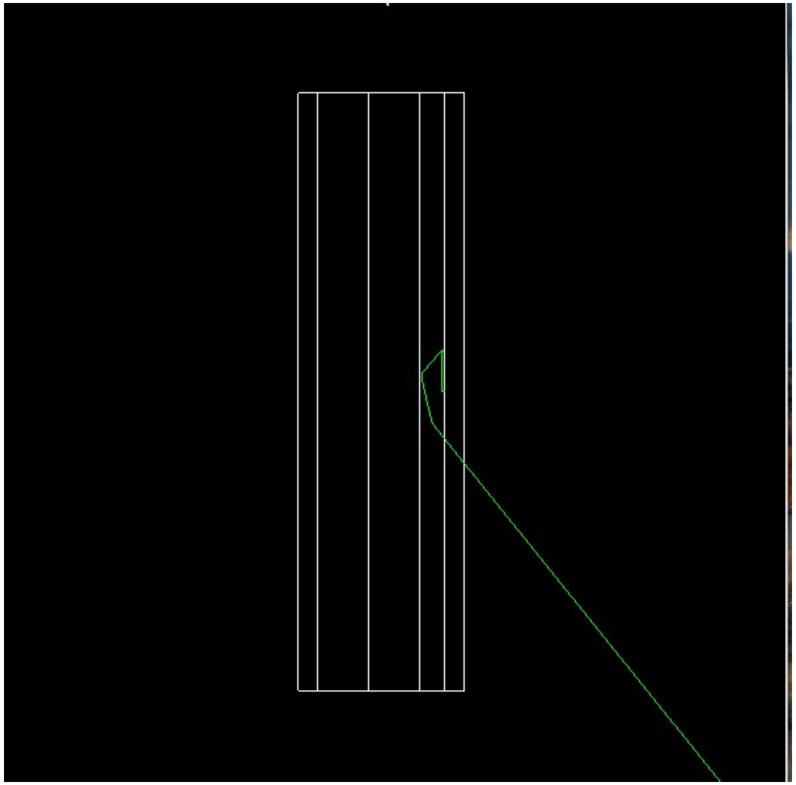
Geometry for GEANT4 simulation

- Poly -Lead-Poly layers
- Neutron gun vertex placed on top of the top polypropylene layer
- Thickness of layers, neutron energy and number can be varied
- The code counts the number of neutrons scattered in backward as well as forward directions.



Sample outputs: Neutron energy 1 MeV

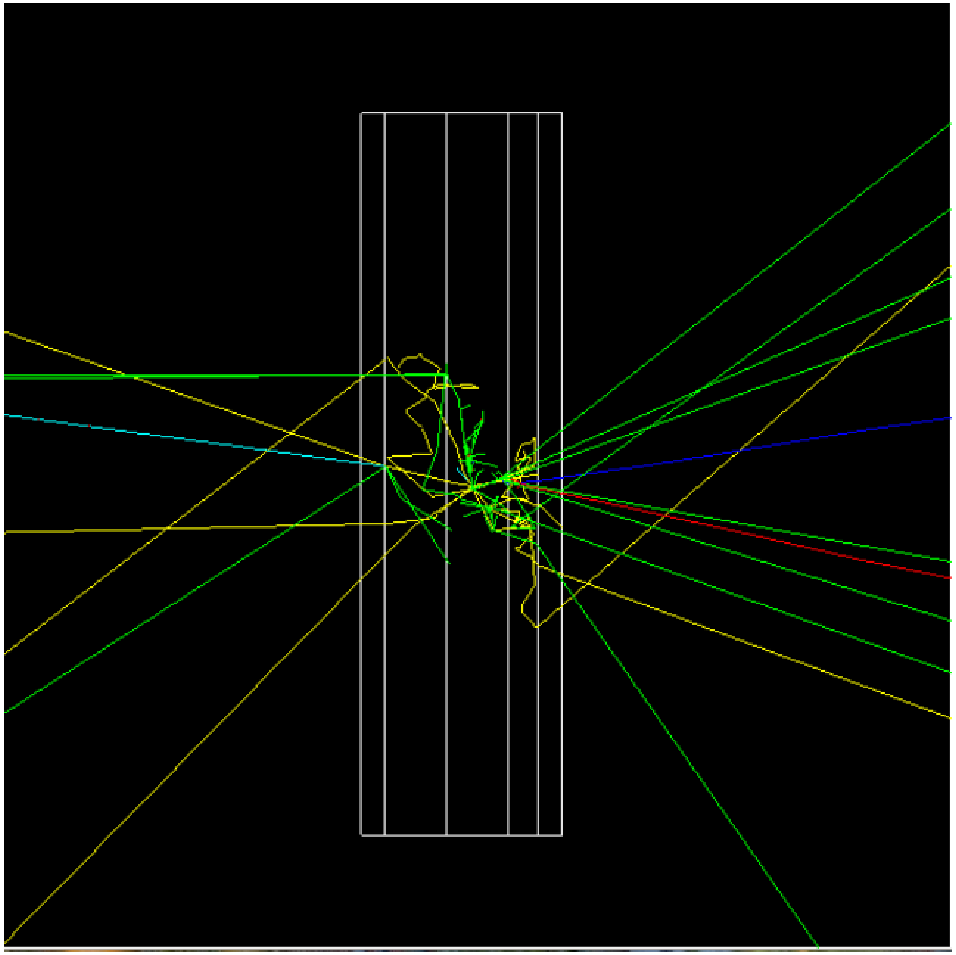




1 GeV event

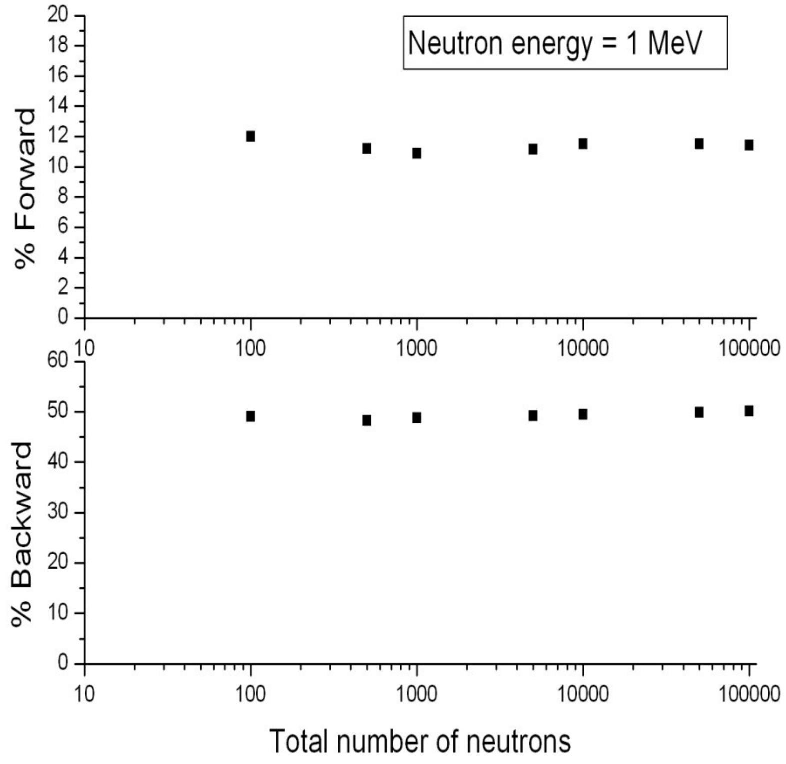
Color codes:

neutron : yellow
e- : red
e+ : blue
proton : cyan
gamma : green
pions : magenta

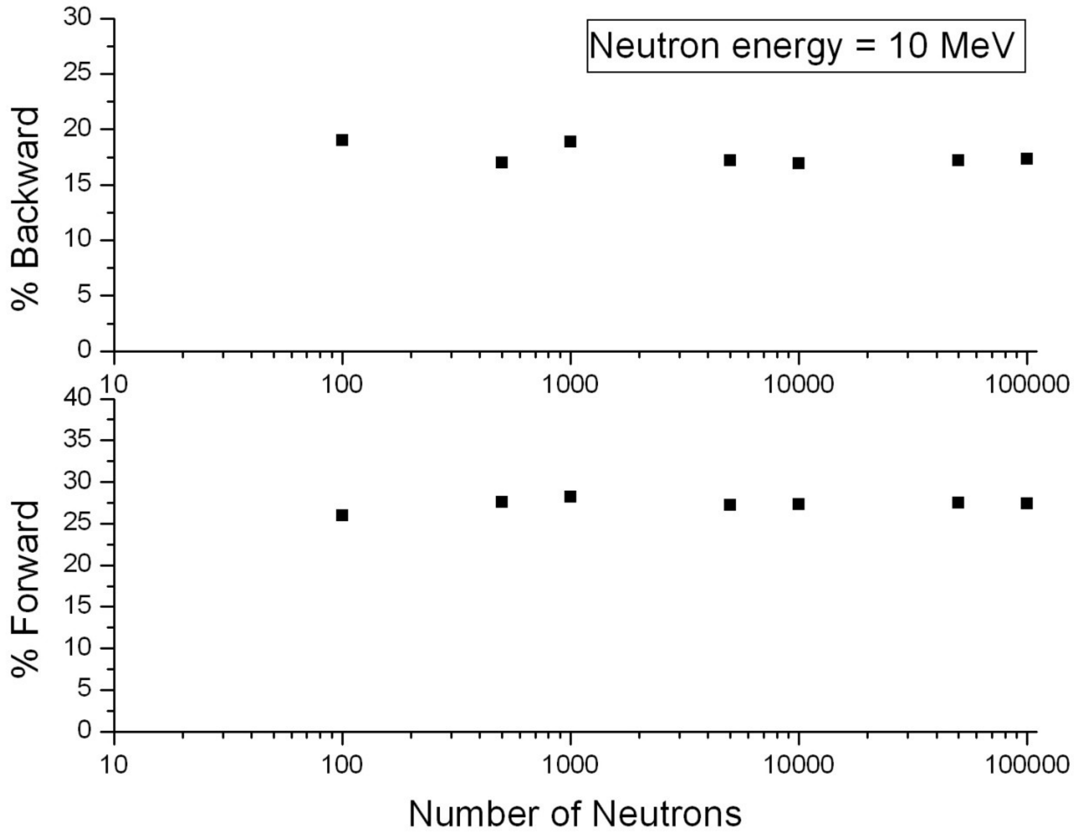


Neutron energy : 1 MeV

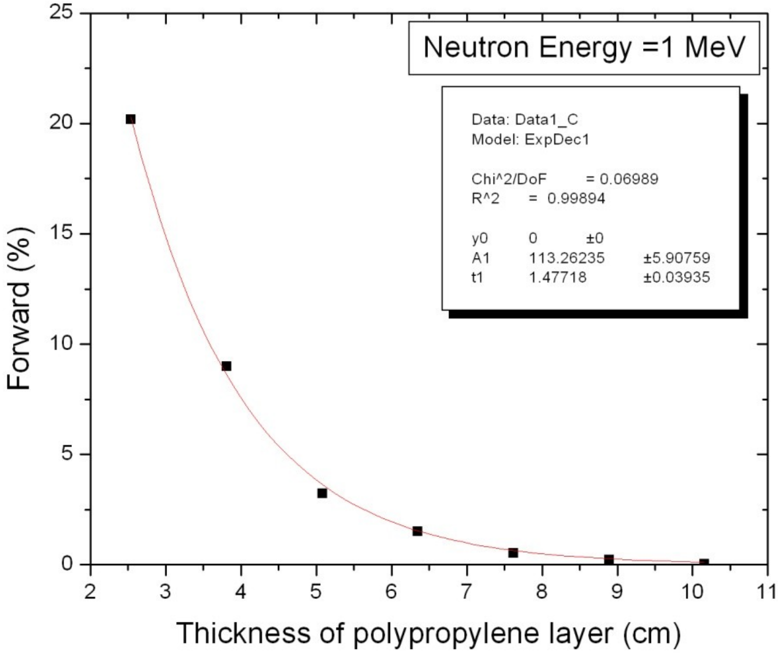
- Neutron number varied from 100 to 100000 to check how much is the statistical fluctuation
- 10000 neutrons was used for a particular run for all subsequent simulations.

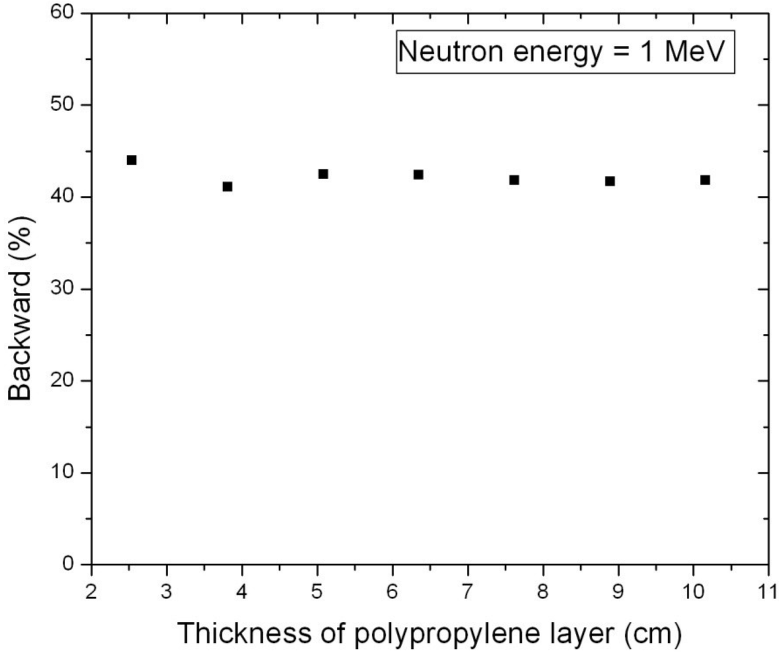


Neutron energy : 10 MeV

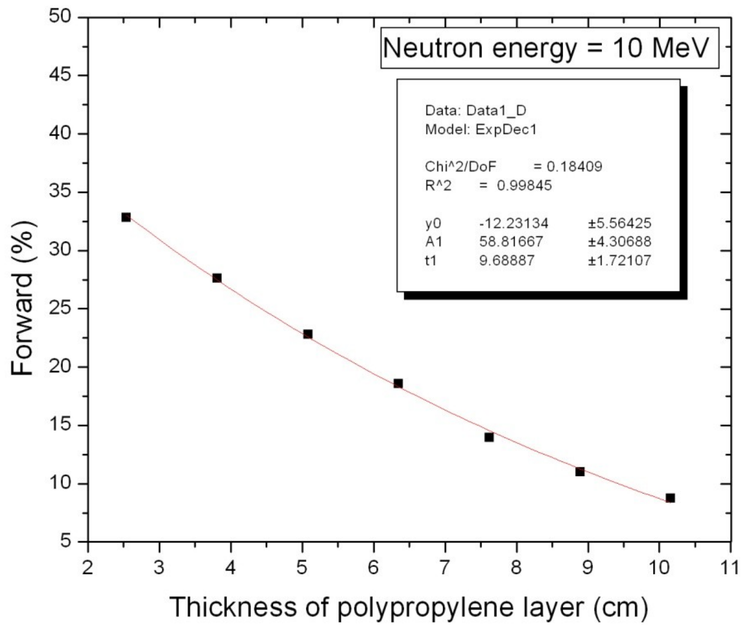


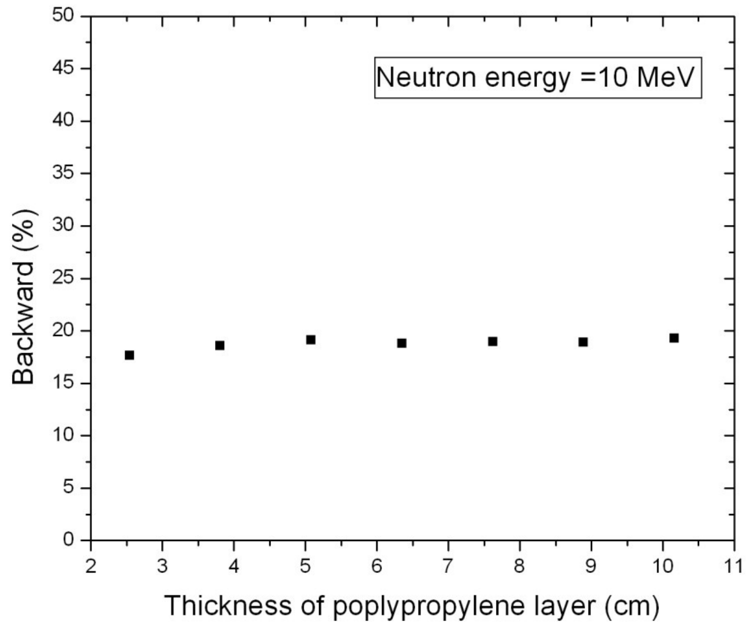
Neutron number variation with PP layer thickness (Neutron energy=1 MeV)



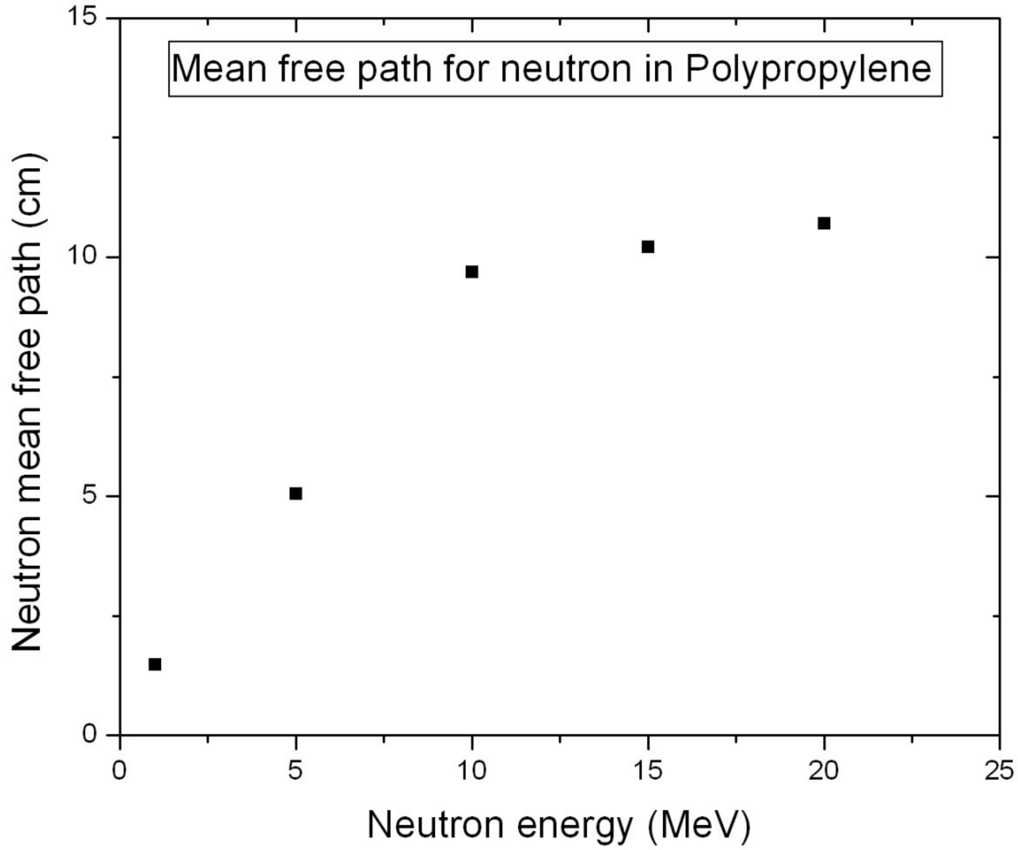


Neutron number variation with PP layer thickness (Neutron energy= 10 MeV)





Neutron mean free path in polypropylene



Future goals

- The neutron source distribution to be made isotropic
- Different detector geometries to be tried
- Effectiveness of other shielding materials to be studied

Thank you