Homestake DUSEL

Outline of Physics Topics Covered by DUSEL S4 Awards (for BGE)

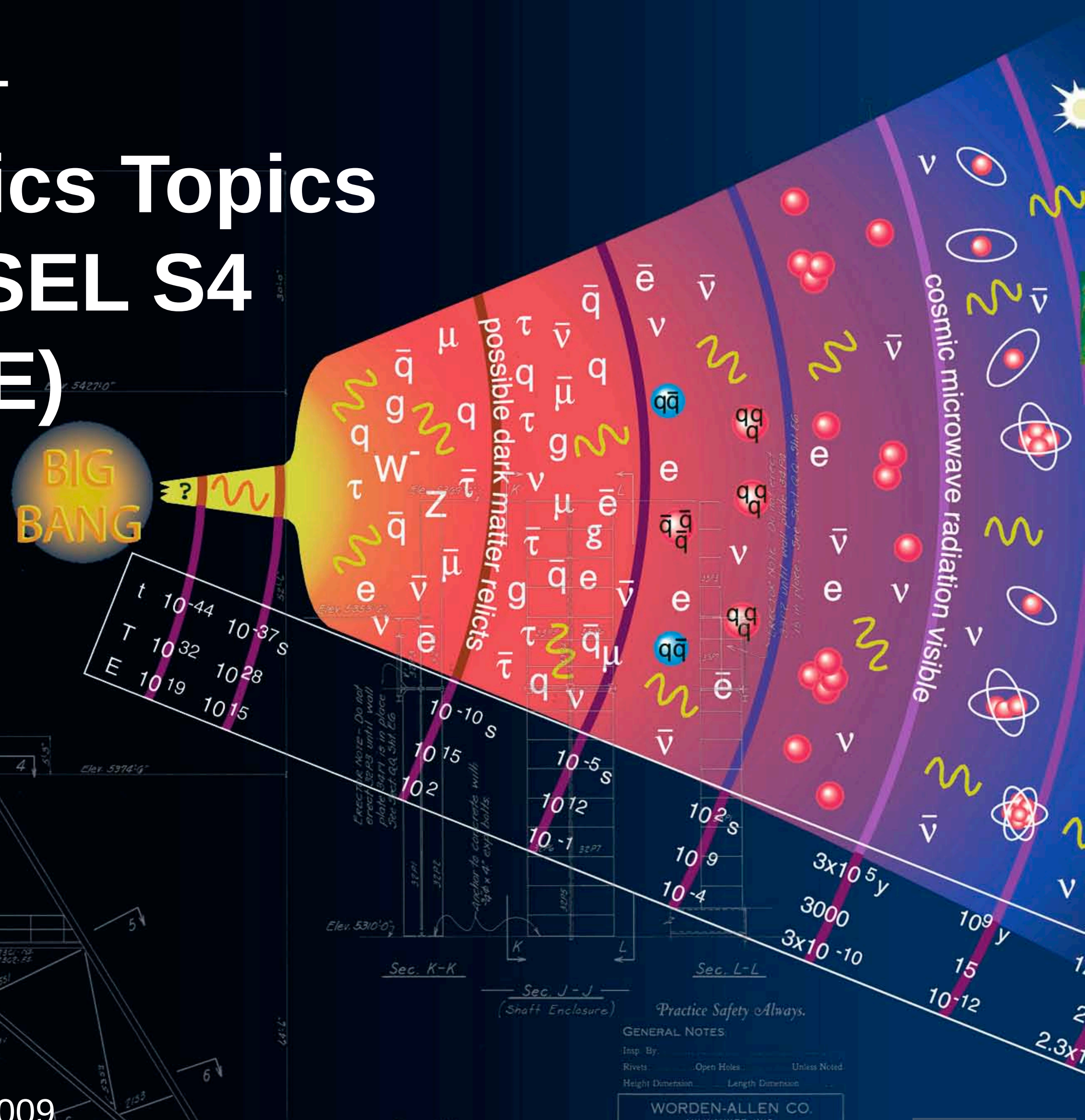


Figure Courtesy PDG and LBNL

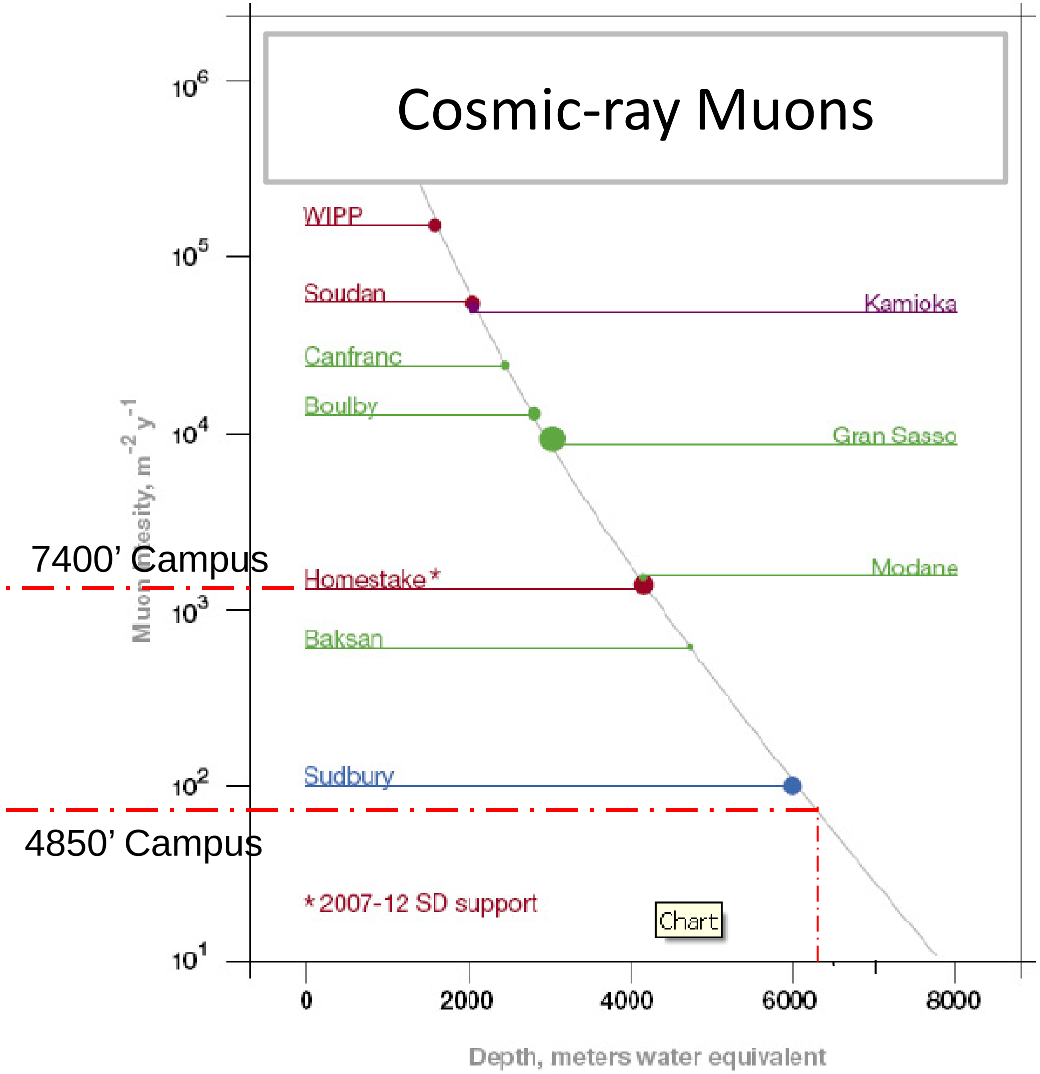
Hank Sobel for the DEDC

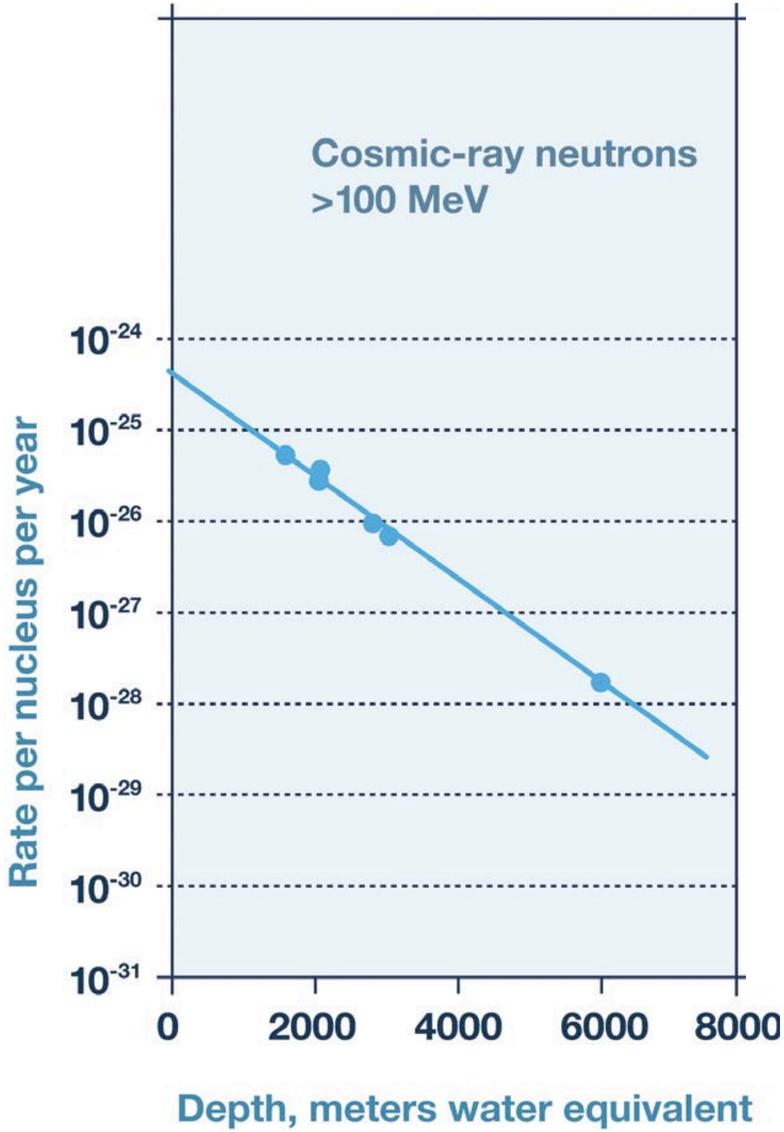
DUSEL Workshop Sept. 30 – Oct. 3, 2009

Physics – Science Questions in S4

- What is the Universe made of?
- What is Dark Matter?
- What is the origin of the elements in the cosmos?
- What are the fundamental properties and interactions of the three families of neutrinos and what can it tell us about the matter/antimatter asymmetry?
- Is ordinary matter inherently (un)stable?
- What is the spectrum of neutrinos from supernovae and the Big Bang, and what can this tell us about the history and evolution of our universe?

Major Motivation for Physics - Depth



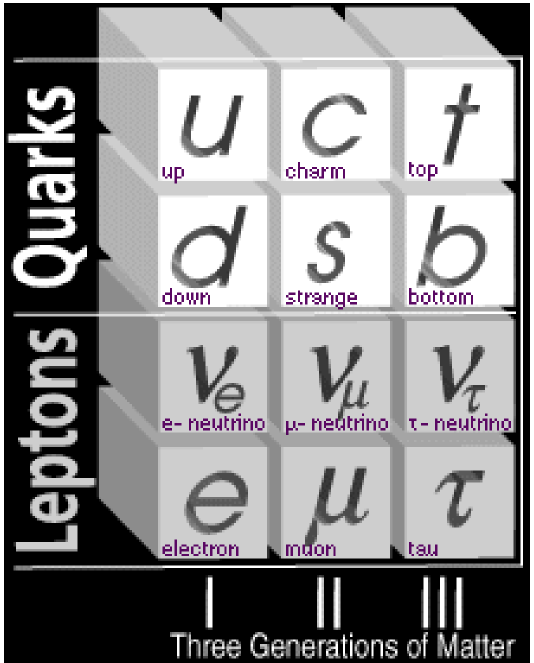


Physics S4 Awards

- LBNE – Water Cherenkov (neutrinos)
- COUPP – Dark matter
- GEODM – Dark matter
- LZ3 – Dark matter
- MAX – Dark matter
- EXO – Double beta decay (neutrinos)
- Majorana – Double beta decay (neutrinos)
- DIANA – Nuclear astrophysics accelerator
- AARM – Low background facility

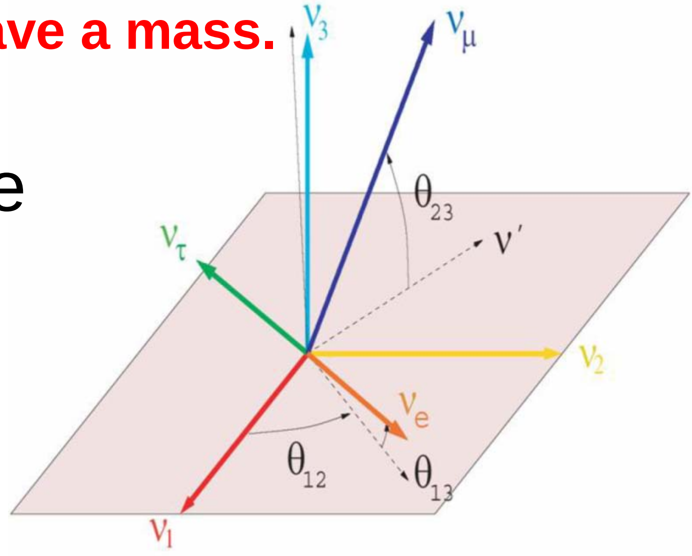
Long Baseline Neutrino Experiment

- There has been a revolution in Neutrino Physics.
  - Observation of Atmospheric Neutrino oscillations - Super-Kamiokande 1998.
  - Confirmation by K2K, MINOS.
  - Observation of Solar Neutrino oscillations (Chlorine, Super-K, SAGE, Gallex, SNO)
  - Confirmation by KamLAND



We now know that the flavors of neutrinos mix and that neutrinos have a mass.

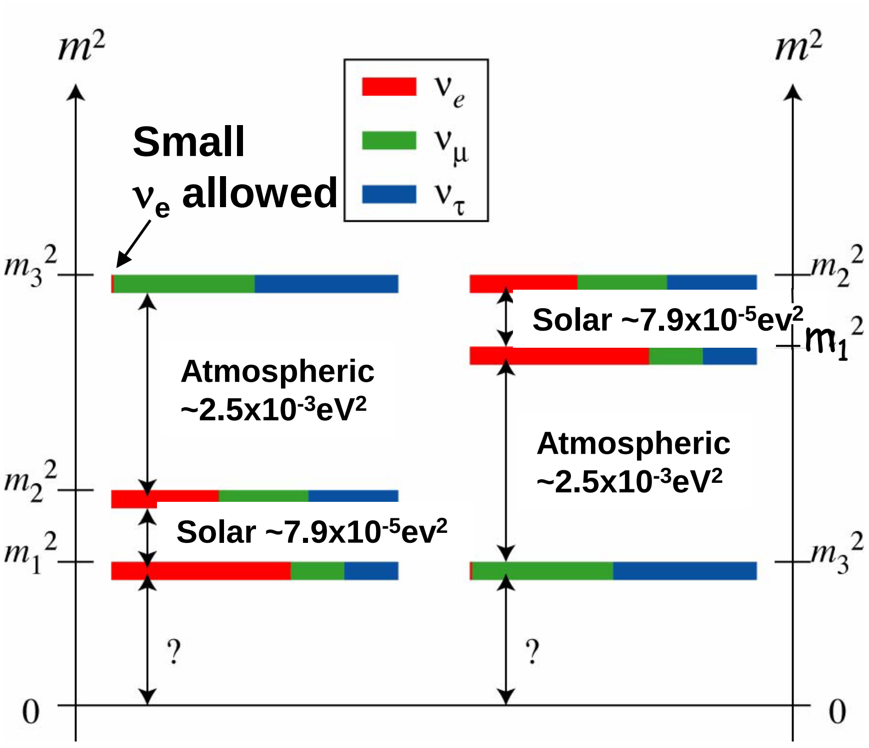
$$\nu_\tau \Leftrightarrow \nu_\mu \Leftrightarrow \nu_e$$



Remaining Questions

LB-L
- Mass hierarchy?
- How small is θ_{13}?
- CP Violation?

ββ
- Absolute mass scale?
- Dirac or Majorana?



Long Baseline Physics Program

Long baseline oscillation experiment can probe remaining unknown parameters.

- Neutrino interactions in the Earth probe the hierarchy. Need long travel distance
- CP violation may be observable with intense neutrino and anti-neutrino beams.
  - Signature of CP violation:

$$P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$

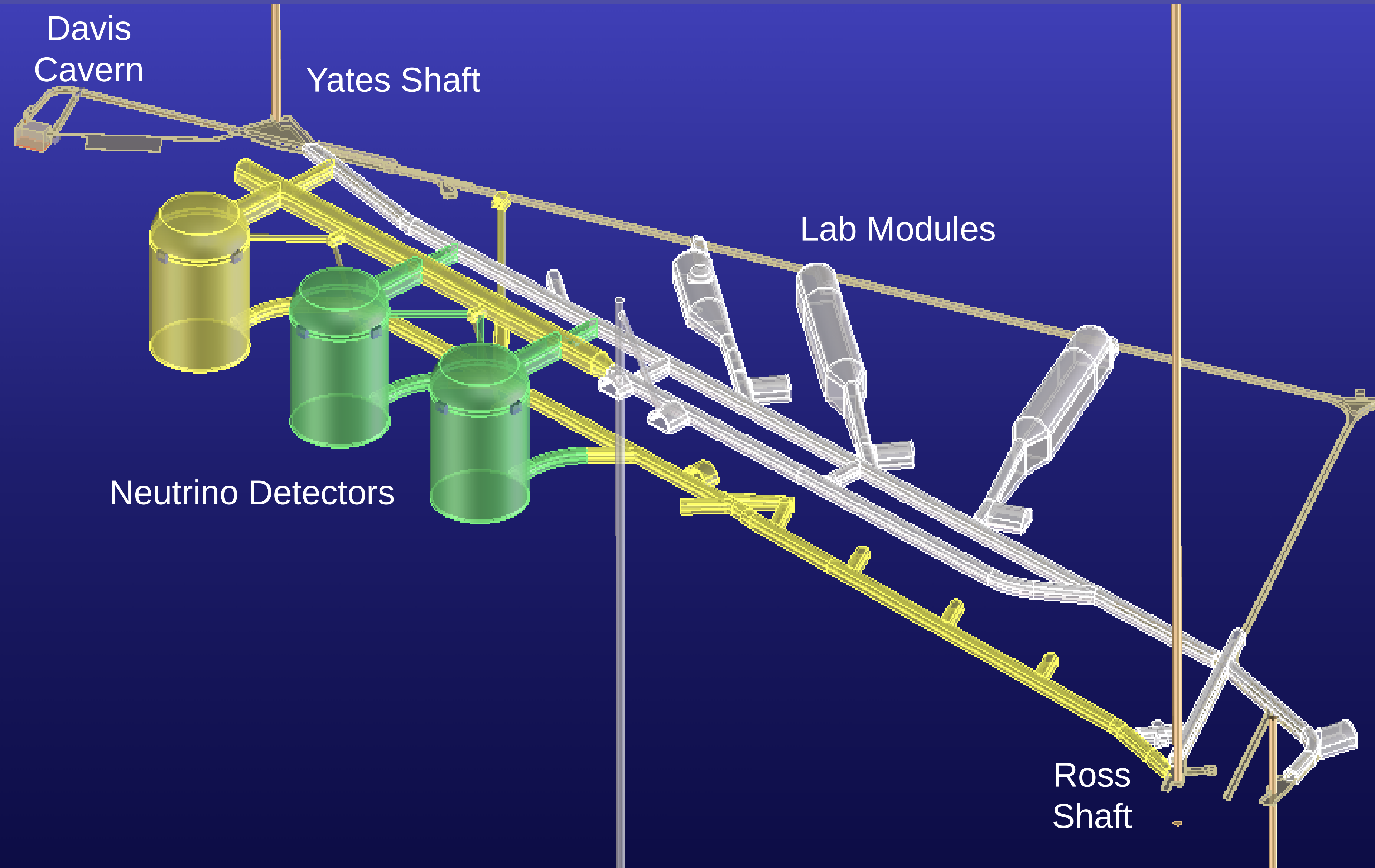
  - Rates are low, need very large detectors.

Sample Detector

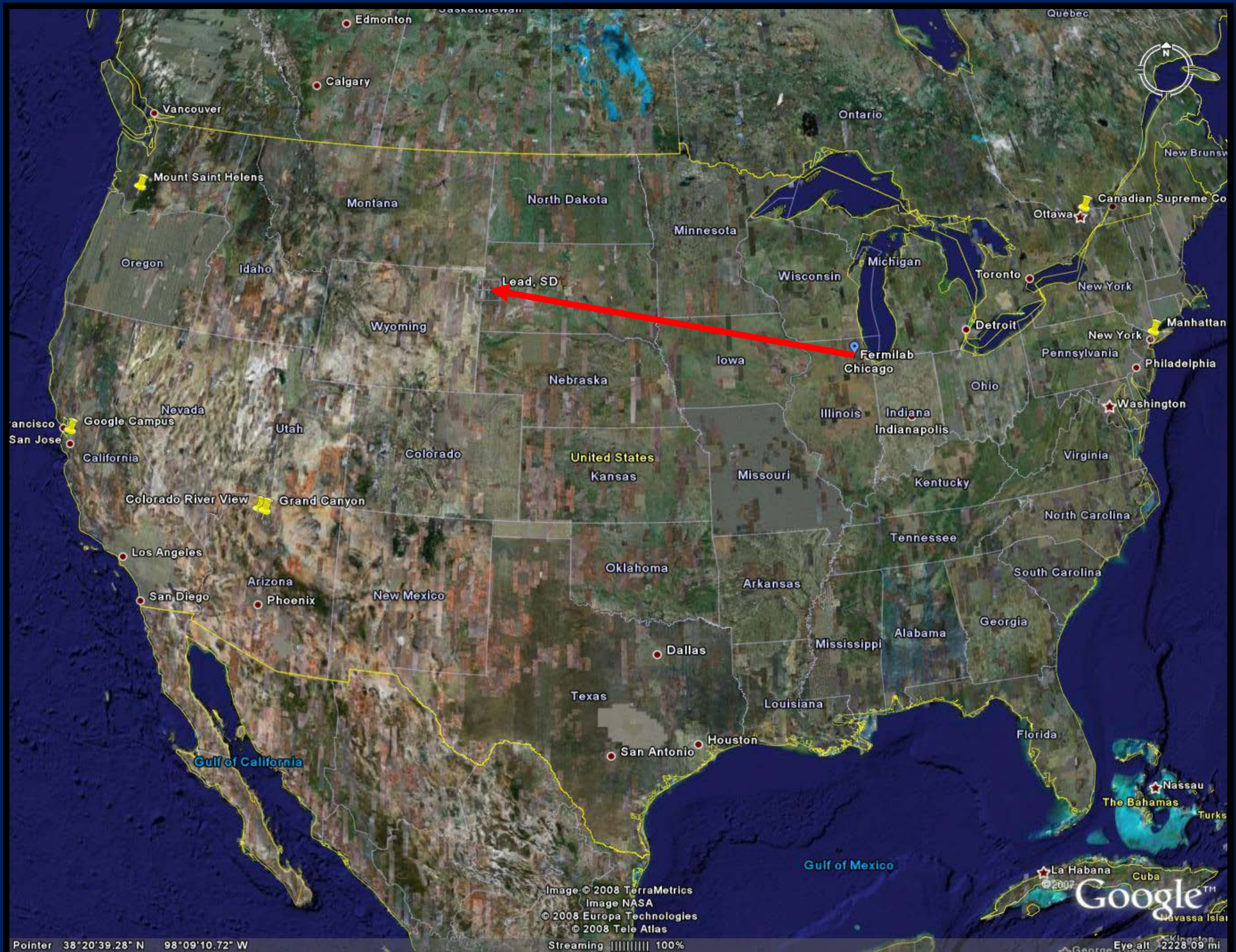
Super-Kamiokande
50,000 ton Water
Cherenkov Detector
in Japan

Too small, too close
(295 km)

Planned 4850 Level Layout



Neutrino Beam From Fermilab 1300 km Distant



Multi-purpose Detector

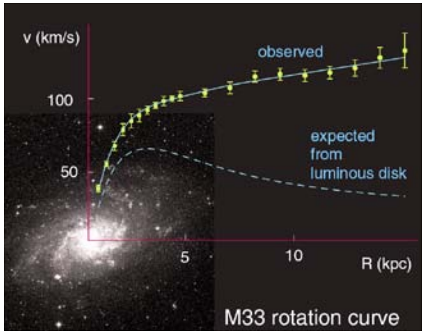
- Nucleon decay – Search for Grand Unification
- Supernova detection – many thousands of neutrinos detected for SN in our galaxy – understand SN mechanism.
- Relic Supernova – neutrinos from all past SN rattling around in the universe – information about star formation rate.
- Still more work to be done on Solar Neutrinos – observe Day/Night effect – regeneration in the Earth.

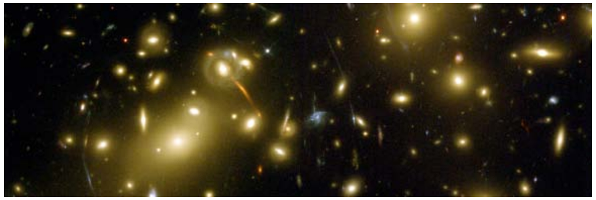
Low energy

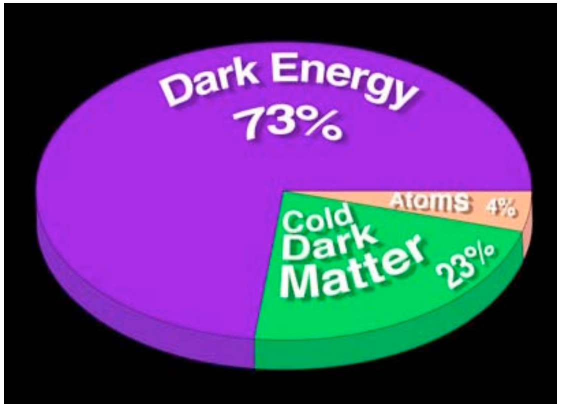
Dark Matter

Breakthroughs in cosmology have transformed our understanding of the Universe

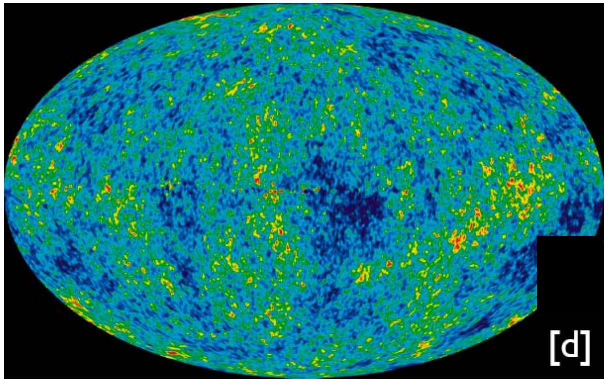
- •Spiral galaxies
  - •rotation curves
- •Clusters & Superclusters
  - •Weak gravitational lensing
  - •Strong gravitational lensing
  - •Galaxy velocities
  - •X rays
- •Large scale structure
  - •Structure formation
- •CMB anisotropy: WMAP







Evidence for Dark matter now overwhelming – amount becoming precisely known



Despite this progress, the identity of dark matter remains a mystery

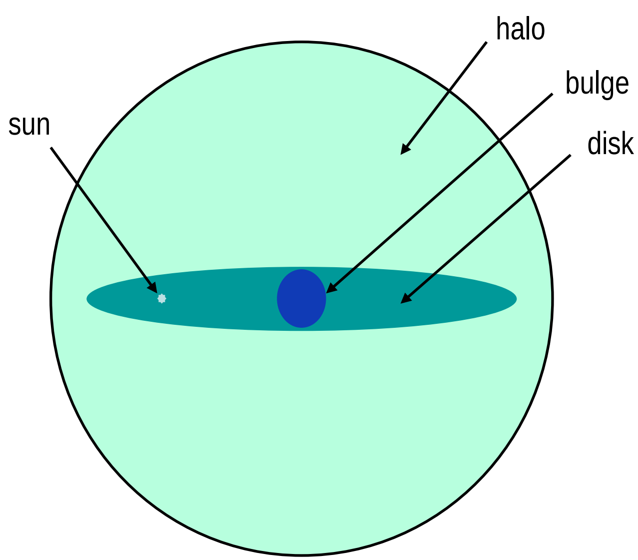
- Constraints on dark matter properties ⇨ the bulk of dark matter cannot be any of the known particles.
  - One of the strongest pieces of evidence that the current theory of fundamental particles and forces, is incomplete.
- Because dark matter is the dominant form of matter in the Universe, it plays a controlling role in galaxy formation and the evolution of the Universe.

➡ Dark matter plays a central role in both particle physics and cosmology

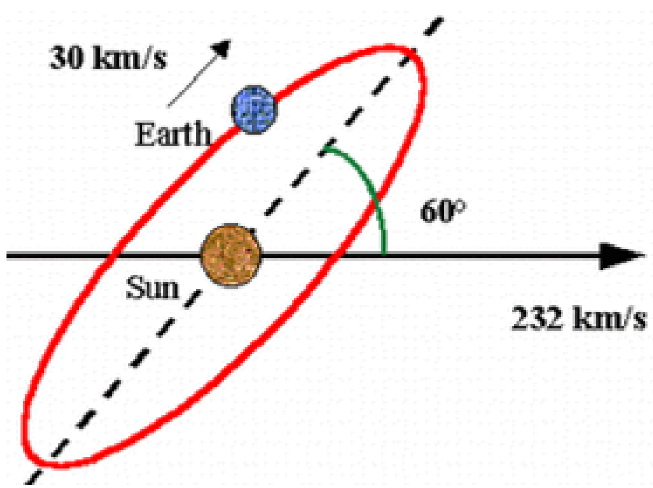
The discovery of the identity of dark matter is among the most important goals in basic science today.

WIMPs

- In many supersymmetric models, the lightest supersymmetric particle is, stable, neutral, weakly-interacting, mass ~ 100 GeV. All the right properties for WIMP dark matter!
- In addition: Ω_{DM} = 23% ± 4% stringently constrains models

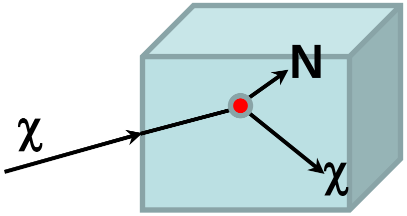


Dark matter responsible for galaxy formation (including ours). We are moving through a dark matter halo.



Usually assume spherical distribution with Maxwell-Boltzmann velocity distribution.
V=230 km/s, ρ=0.3 GeV/cm^3

Experimental Challenges



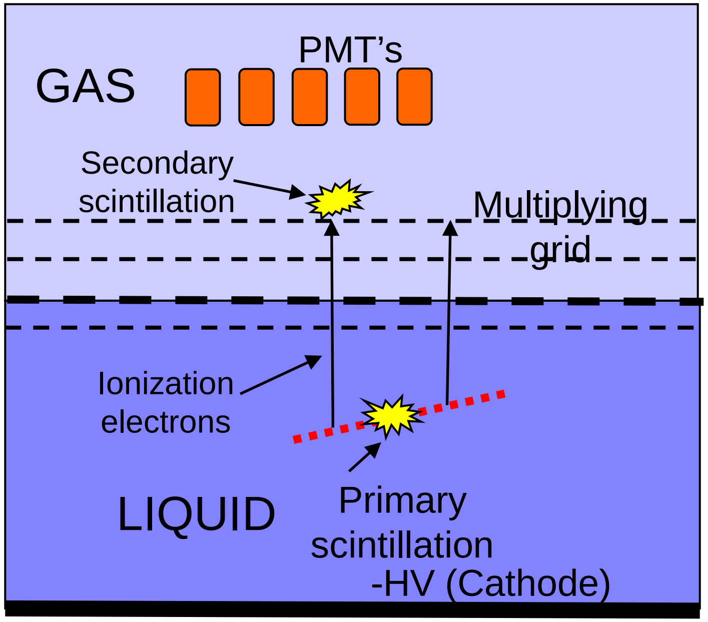
The WIMP "signal" is a low energy (10-100 keV) nuclear recoil.

- Overall expected rate is very small (limit now $\sigma < 10^{-43} cm^2$ gives less than 0.1 event/kg/day, some models go to ~ $10^{-48} cm^2$).
- Need a large low-threshold detectors which can discriminate against various backgrounds.
  - Photons scatter off electrons.
  - WIMPs and neutrons scatter off nuclei.
- Need to minimize internal radioactive contamination.
- Need to minimize external incoming radiation.
  - Deep underground location essential

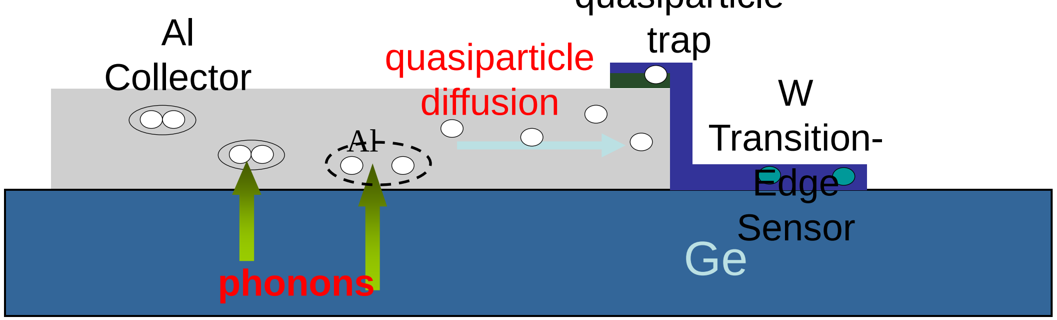
S4 Experiments in Dark Matter

MAX – Liquid Xe, Ar

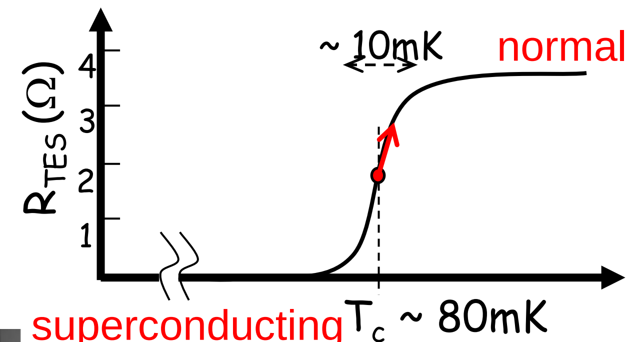
LZ3 – Liquid Xe



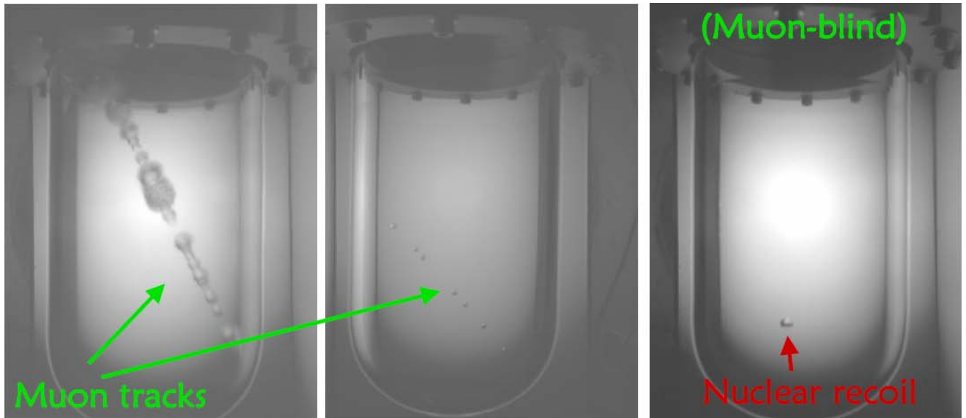
GEODM – Expansion of CDMS cryogenic Ge detectors



Quasiparticles heat up tungsten, resistance rises, current decreases sharply

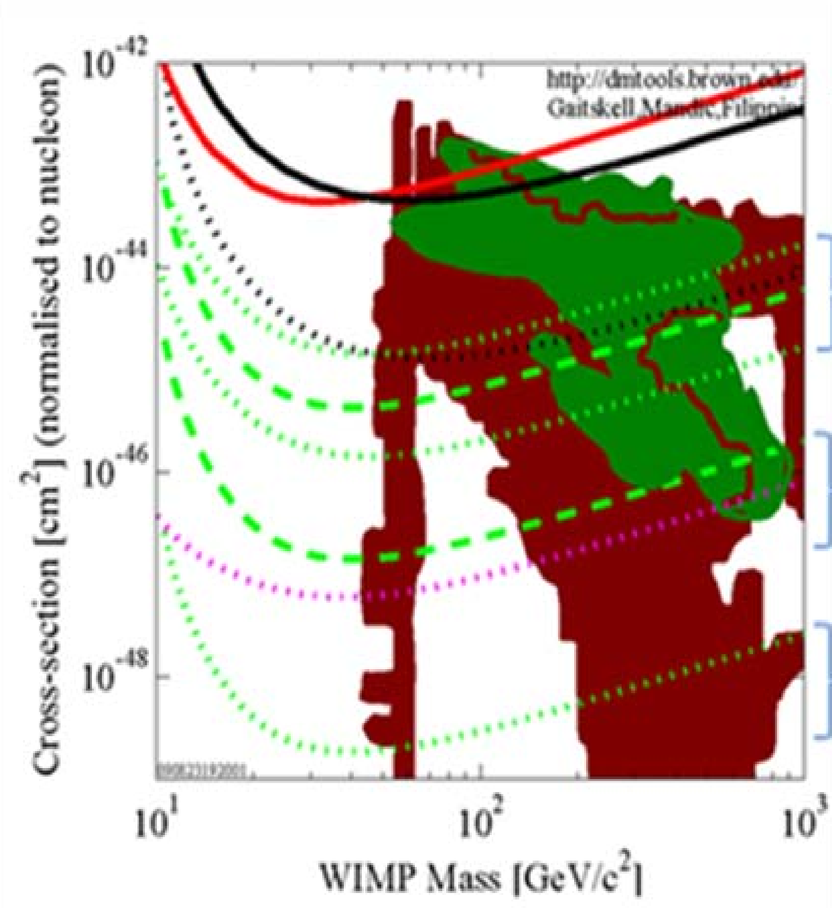


COUPP



- Based on room temperature bubble chamber of CF_3I. Other targets possible.
- Operate with threshold in dE/dx above sensitivity for MIP's.
- Not triggered by muons, electrons.

Experimental Program



Current status ~10^{-43} cm^2

Current experiments

Pre-DUSEL

2^{nd} Generation

4850' level

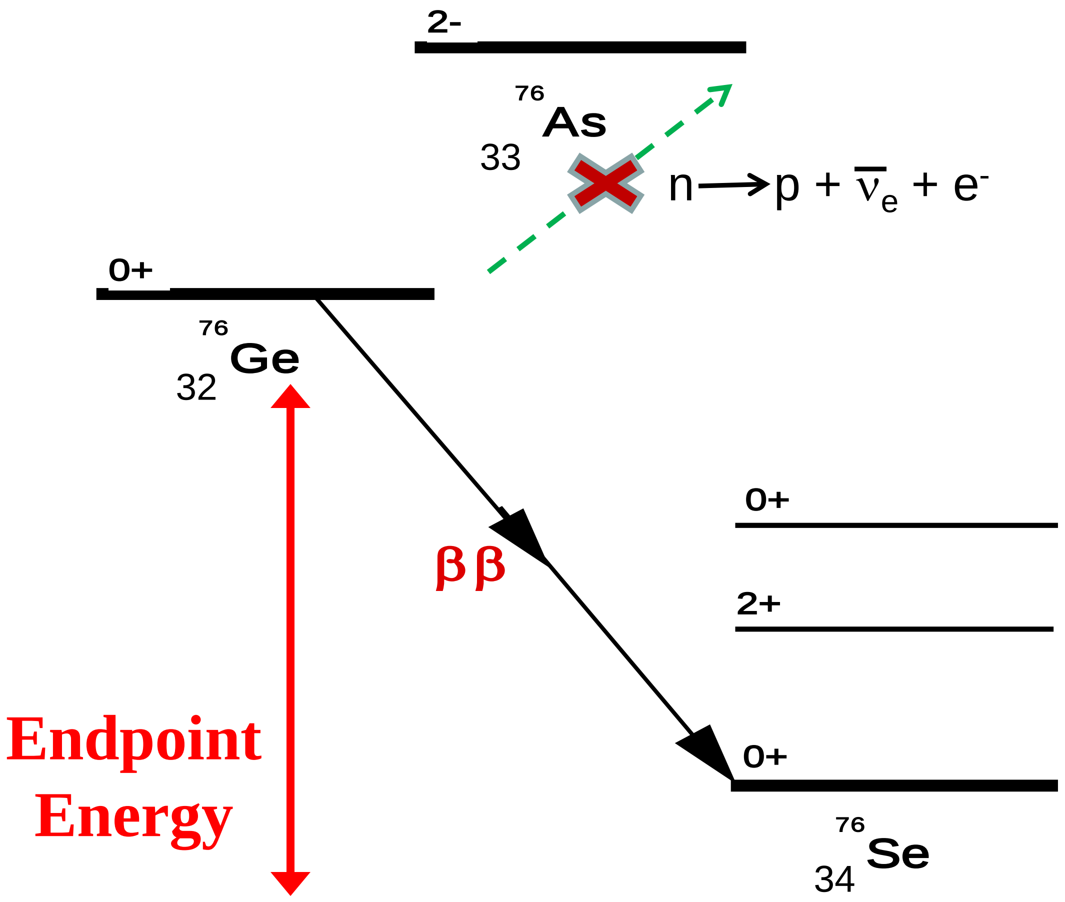
3^{rd} Generation

7400' level

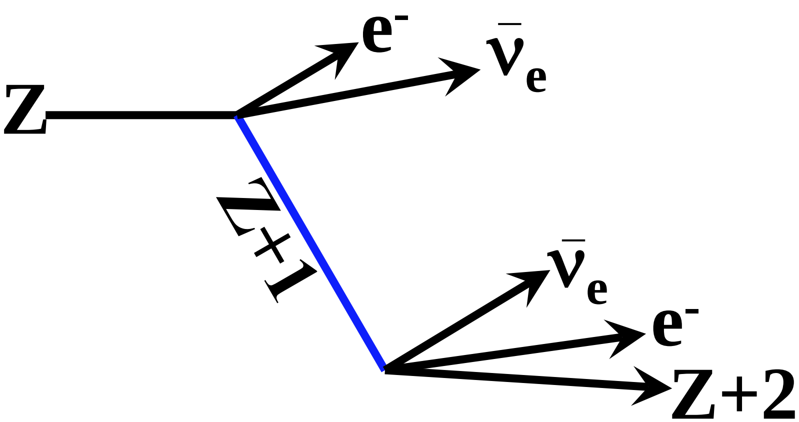
DUSEL

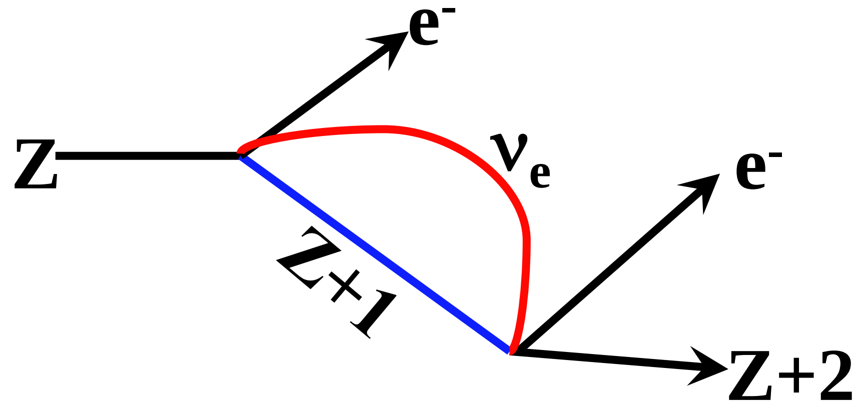
Double Beta Decay

In many even-even nuclei, β decay is energetically forbidden. This leaves ββ as the allowed decay mode.



Either 2ν or 0ν





$2n \longrightarrow 2p + 2\bar{\nu}_e + 2e^-$

$n \longrightarrow p + \bar{\nu}_e + e^-$

(RH $\bar{\nu}_e$)

(LH ν_e)

$\nu_e + n \longrightarrow p + e^-$

ββ(2ν): Allowed weak decay

ββ(0ν): requires massive Majorana ν

Difficulty

$\beta\beta(2\nu)$ rate first calculated by Maria Goeppert-Mayer in 1935.

- First observed directly in 1987.
- Why so long? Background

$$\tau_{1/2}(^{238}U, ^{232}Th) \sim T_{universe} \sim 14x10^9 yr$$

$$\tau_{1/2}(\beta\beta(2\nu)) \sim 10^{10}\ T_{universe}$$

- But next we want to look for a process with:

$$\tau_{1/2}(\beta\beta(0\nu)) \sim 10^{17}\ T_{universe}$$

Decay rate is proportional to square of neutrino mass

Close to a Discovery?

For at least one neutrino:

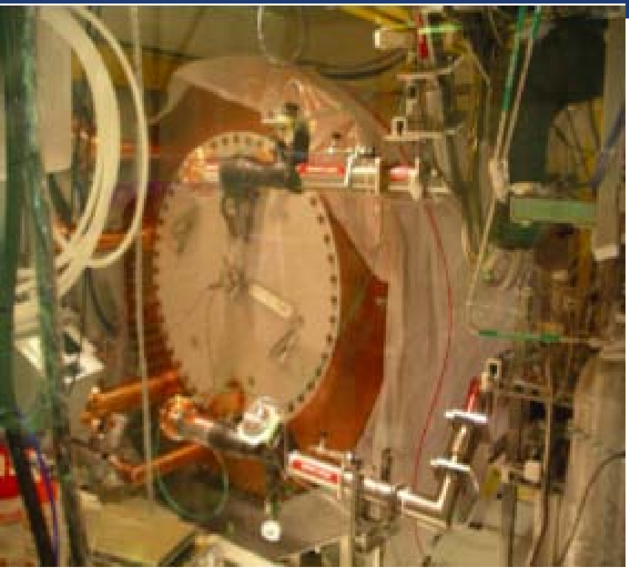
$$m_i > \sqrt{\delta m^2_{atmos}} \approx 50 meV$$

Capability of the technologies:

$$\langle m_{\beta\beta} \rangle \leq 50 meV$$

$< m_{\beta\beta} >$ in the range near 50 meV is very interesting.

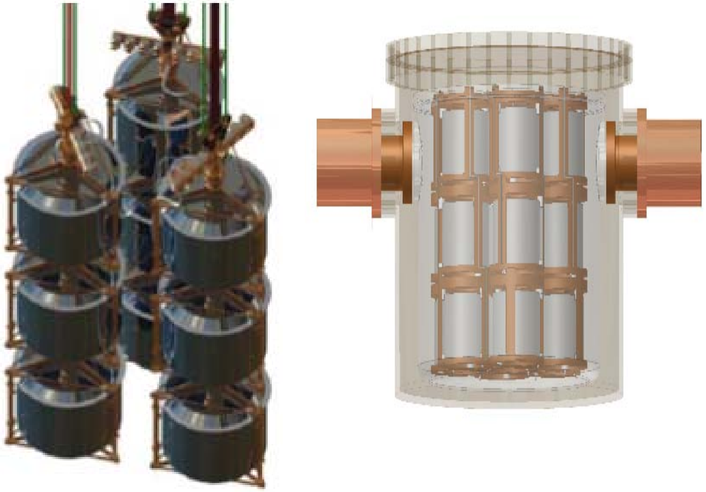
Double Beta Decay in S4



EXO - ^{136}Xe

$$\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_\nu^2$$

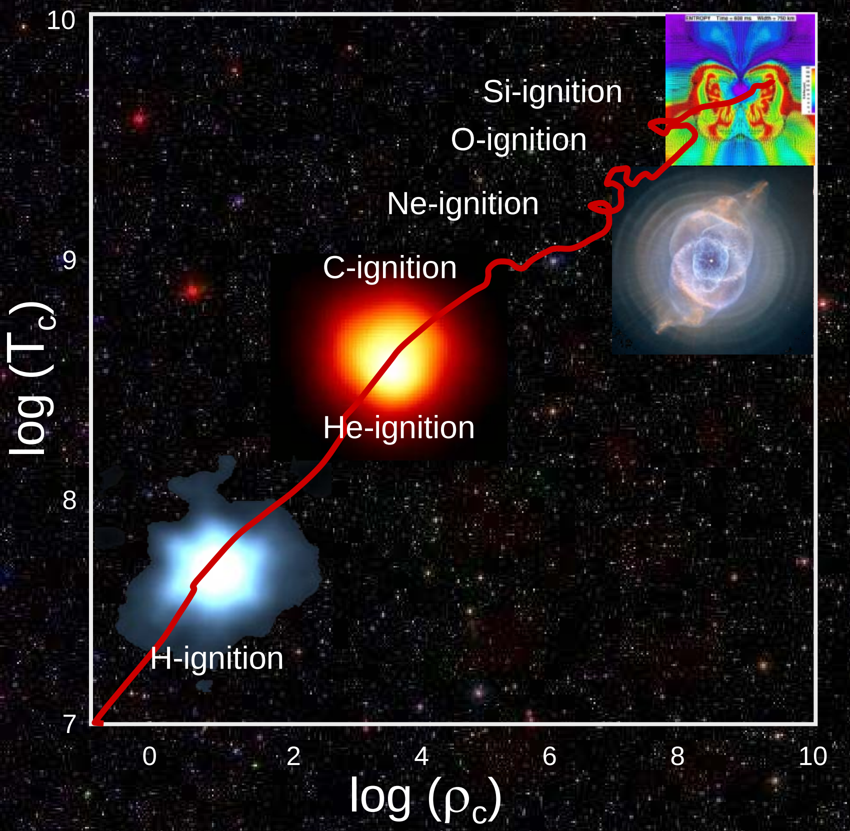
At least one neutrino has a mass >50 meV. These experiments will have a sensitivity below 50 meV.



GERDA/MAJORANA ^{76}Ge

- Very different techniques
- Backgrounds are different
- Nuclear matrix elements are different

Nuclear burning & stellar evolution



- What is the origin of the elements in the cosmos?
- What are the nuclear reactions that drive stars and stellar explosions?

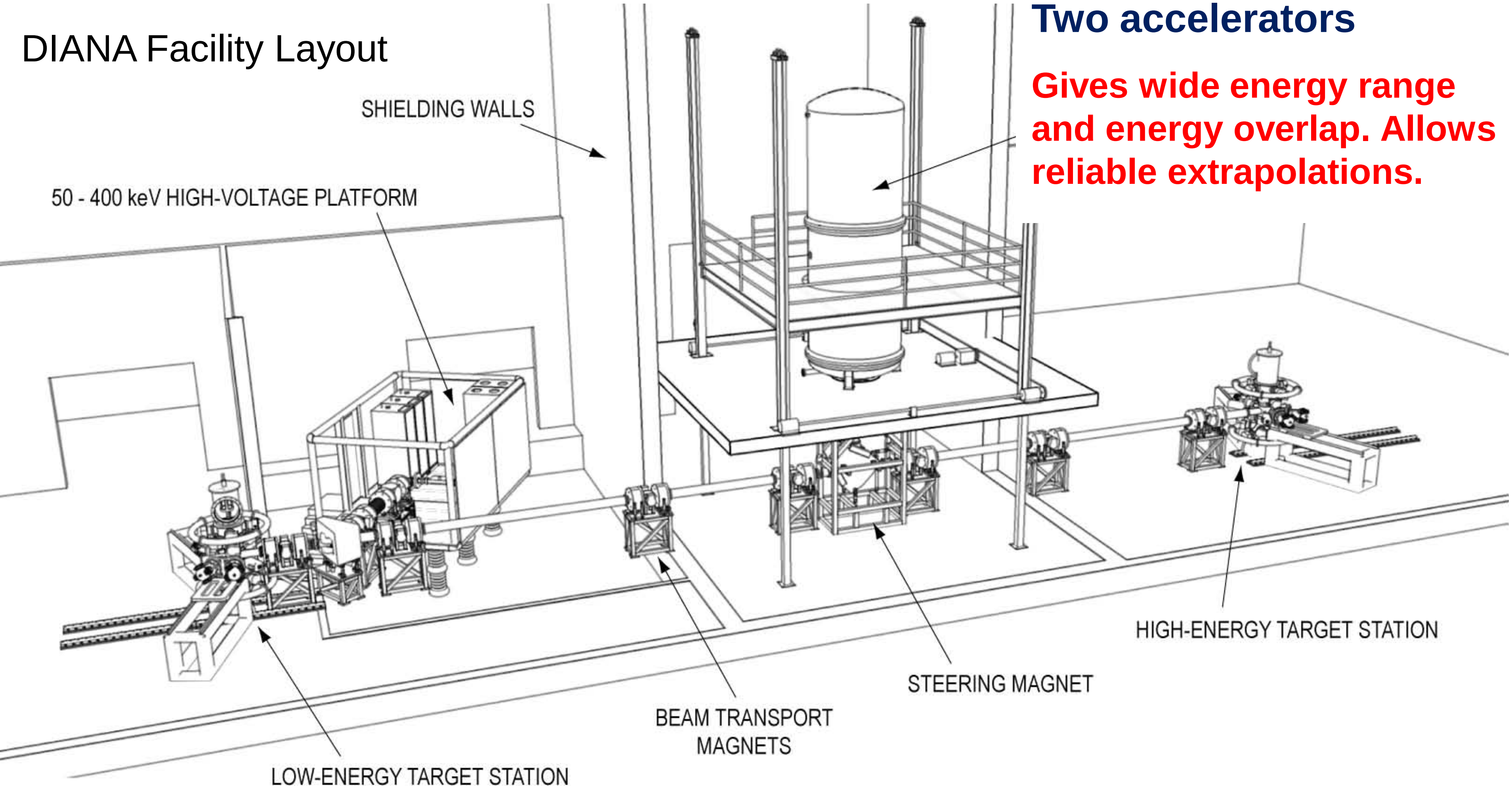
- Direct measurement of reaction rates on stable nuclei.
- Small cross sections and large natural backgrounds.
- Requires high-intensity beams and low backgrounds.

Dakota Ion Accelerators for Nuclear Astrophysics (DIANA)

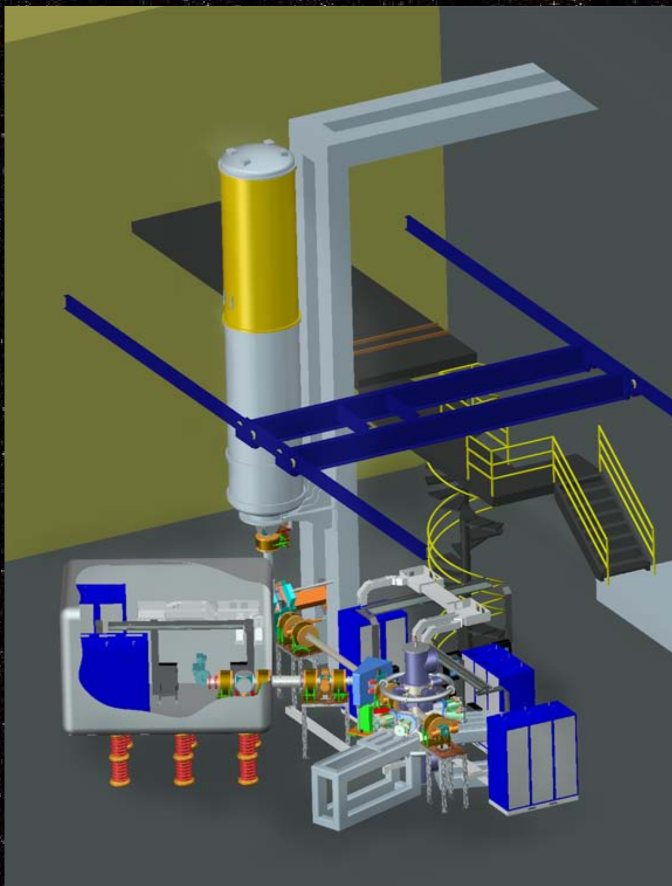
DIANA Facility Layout

Two accelerators

Gives wide energy range and energy overlap. Allows reliable extrapolations.



Flexibility and wide energy range will make it a unique facility world wide and enable a long experimental program



Critical reactions for:

- energy generation,
- time scale
- nucleosynthesis

Hydrogen Burning

$^{3}He(\alpha,\gamma)^{7}Be$ **(Sν)**
$^{3}He(^{3}He,2p)^{4}He$
$^{7}Be(p,\gamma)^{8}B$

$^{12}C(p,\gamma)^{13}N$
$^{14}N(p,\gamma)^{15}O$
$^{15}N(p,\gamma),(p,\alpha)^{16}O,^{12}C$

$^{17}O(p,\gamma),(p,\alpha)^{18}F,^{14}N$
$^{18}O(p,\gamma),(p,\alpha)^{19}F,^{15}N$
$^{19}F(p,\gamma),(p,\alpha)^{20}Ne,^{16}O$

Helium Burning

$^{12}C(\alpha,\gamma)^{16}O$
$^{16}O(\alpha,\gamma)^{20}Ne$
$^{20}Ne(\alpha,\gamma)^{24}Mg$

$^{18}O(\alpha,\gamma)^{22}Ne$
$^{22}Ne(\alpha,\gamma)^{26}Mg$
$^{24}Mg(\alpha,\gamma)^{28}Si$

$^{13}C(\alpha,n)^{16}O$
$^{22}Ne(\alpha,n)^{25}Mg$
$^{25}Mg(\alpha,n)^{28}Si$
$^{26}Mg(\alpha,n)^{29}Si$

(contribute to r process?)

The versatility of the facility will also allow to address

Heavy Ion Burning

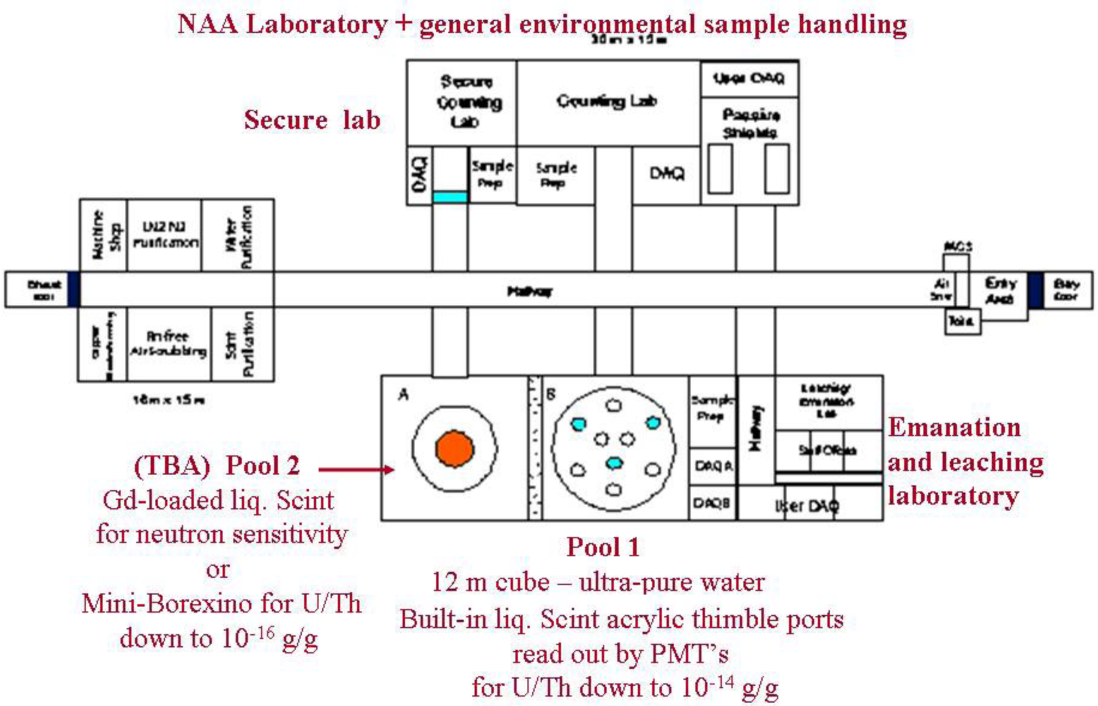
$^{12}C+^{12}C$
$^{12}C+^{16}O$
$^{16}O+^{16}O$

$^{17}O(\alpha,n)^{20}Ne$
$^{28}Si(\alpha,\gamma)^{32}S$
⋮

Low Background Counting Facility

S-4 proposal expected to develop a dedicated facility for the assay, control, and production of low radioactivity materials.

Figure E-16 from the Homestake Reference Design



Cost Efficient Sharing of

- Screening Detectors
- Cu electroforming
- Expert Personnel
- Materials Databases
- Simulation Software
- Characterization tools

Promote and foster

- Cross-cutting applications
- New Assay Techniques
- Training and Education

DUSEL Physics Program

- Wide range of physics already supported in S4
- Future opportunities for many other experimental programs. Some are:
  - Liquid argon technology for long baseline experiment
  - Gravitational wave detection
  - Solar neutrinos
  - Next generation dark matter detectors
  - 1 km vertical space
    - N Nbar oscillation
    - Mirror Matter Transition Search
    - Facility for physics of Cloud Formation