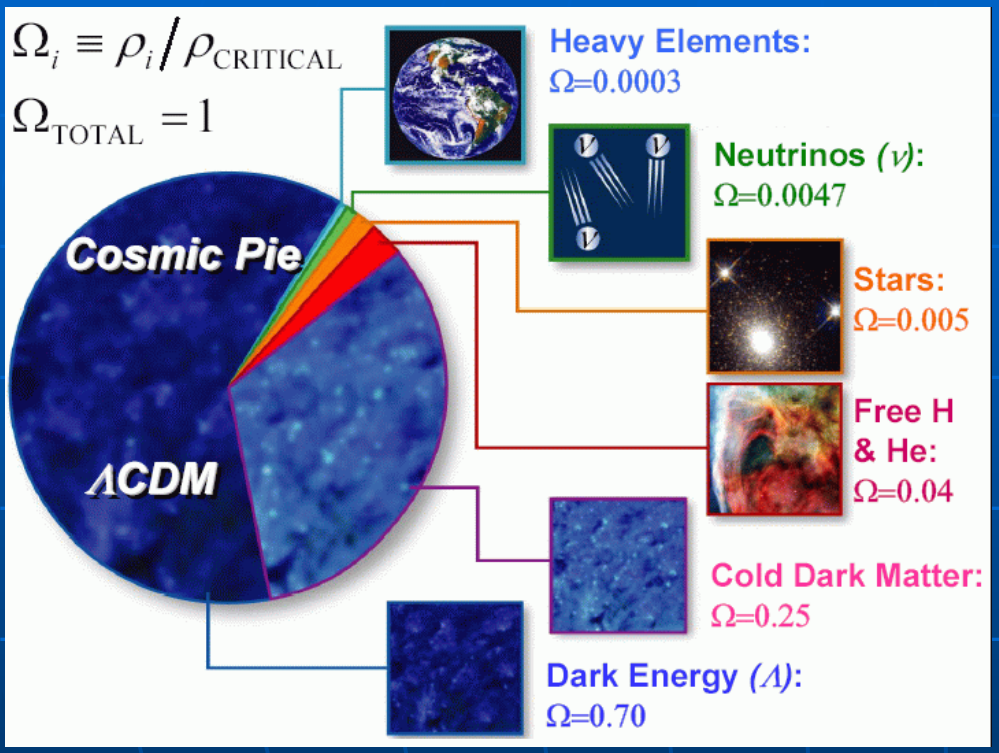
Particle Astrophysics at Fermilab

Brenna Flaugher
Fermilab Users Meeting
June 8,9 2005

Dark Energy, Dark Matter and UHECR



Dark Energy is the dominant constituent of the Universe (~ 70%)

Dark Matter is next (25%)

95% of the Universe is in Dark Energy and Dark matter for which we have no understanding

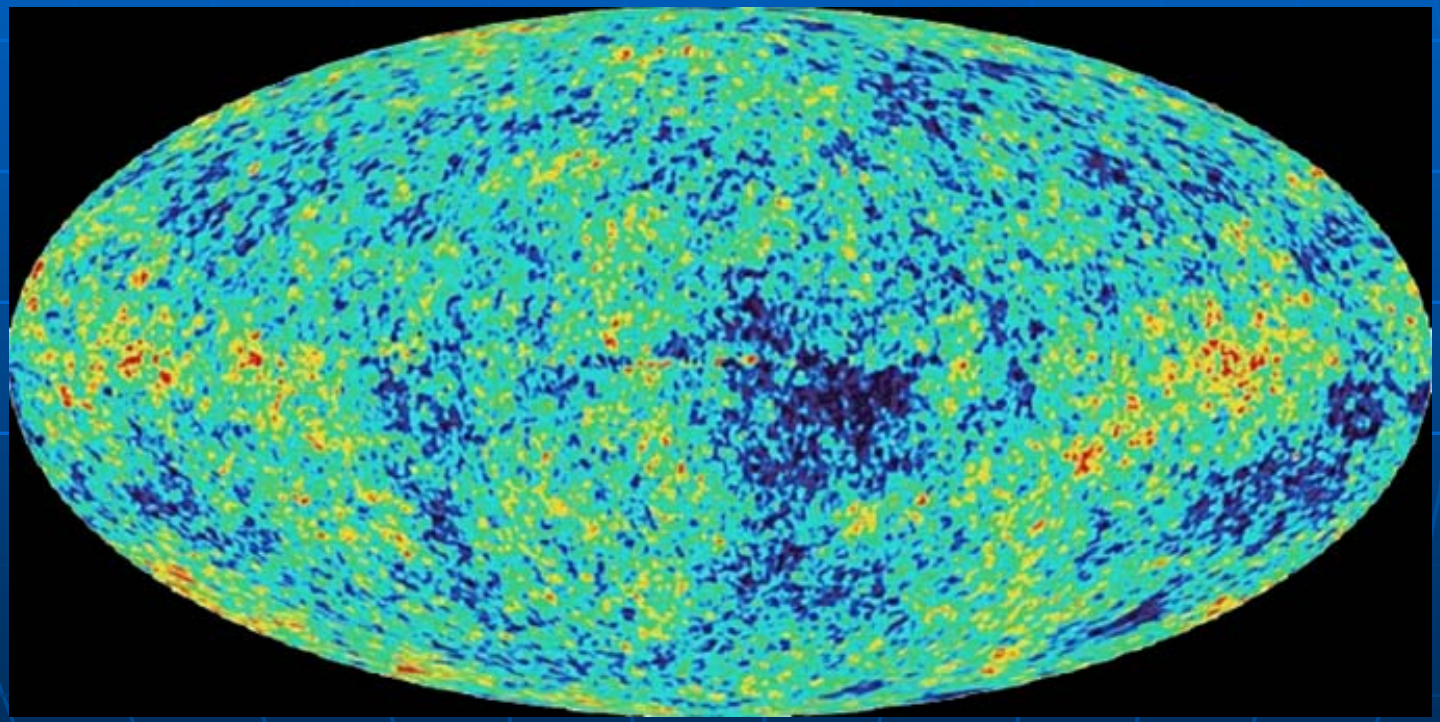
What are those Ultra High Energy ($>10^{19}$eV) Cosmic Rays?

- where do they come from?
- how are they produced?

Picture of the OLD universe

Quantum fluctuations grew during inflation – these led to galaxies & other structures

The CMB is the most distant light we'll ever be able to see, probes the initial conditions for structure formation.



WMAP measures the CMB radiation density field at z ~ 1000, ~13 billion years ago

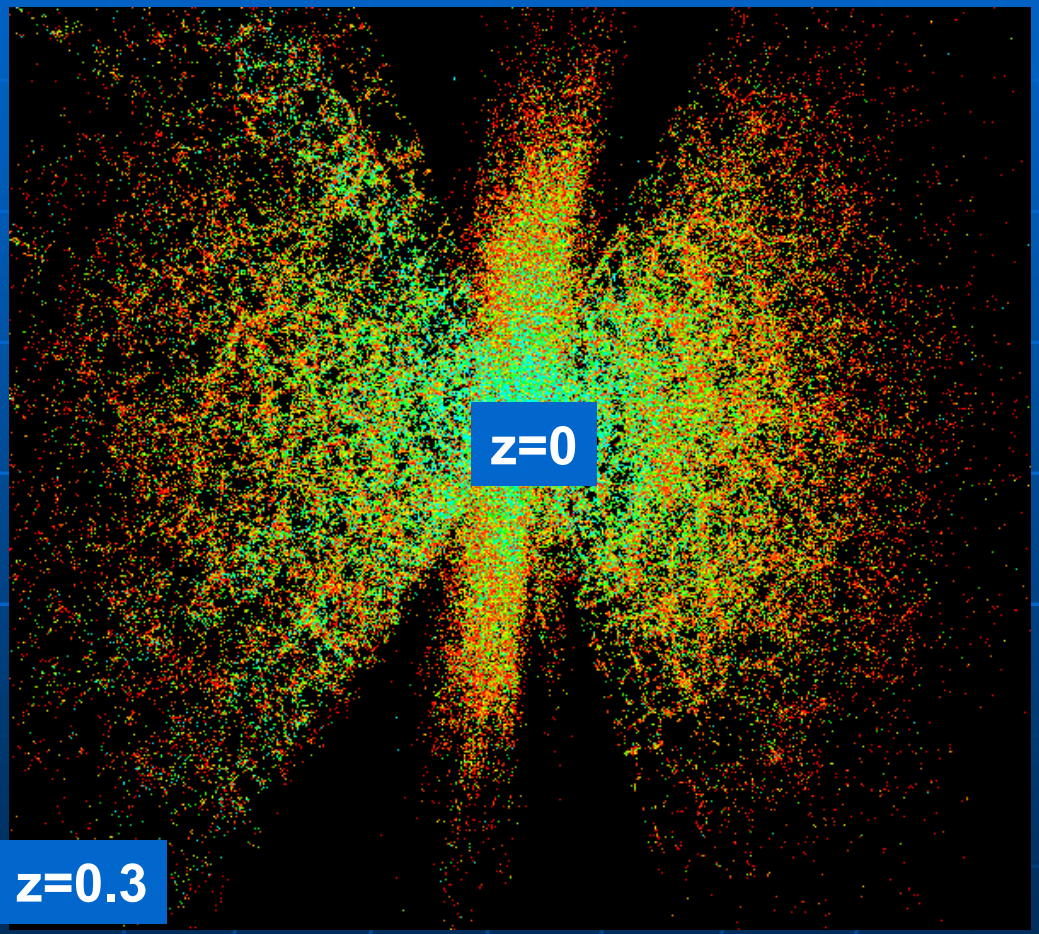
Picture of the RECENT universe

Sloan Digital Sky Survey measures the galaxy density field out to z ~ 0.3

filamentary structure is evident

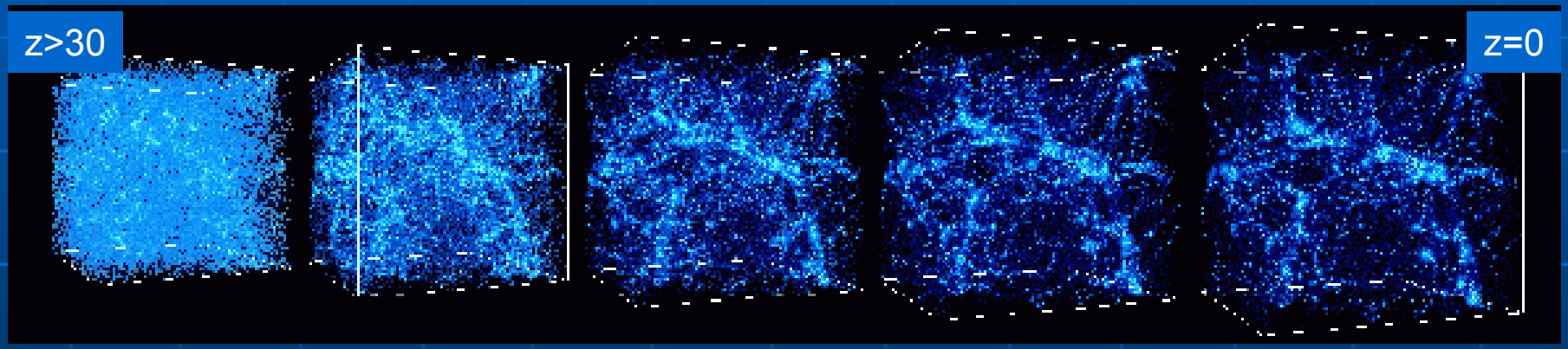
sample density drops off with z: fainter, harder to see

At z ~ 0.7 DE and DM are about equal, DE dominates now.



Dark Matter and Energy

- Expansion rate of the universe:
  $H^2(z) = H^2_0 \; [\Omega_M (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)}]$ (flat Universe, const. *w*,
  dark matter dark energy w = -1: cosm. const.)
- rate of growth of structure
  - mass, number and spatial distribution of galaxies as a function of z



- The parameter, $w = \mathbf{p}/\rho$, describes the evolution of the density of dark energy with redshift.
- Current Status: $\sigma(w) \sim 0.15$*, $w < -0.76$ (95%)

*** CMB+LSS+SNe; no *single* dataset constrains *w* better than ~30%**

A Cluster of Galaxies in SDSS Data

What is the cluster redshift?

What is the cluster mass?

not completely different from jet clustering in collider physics but also have depth (red shift) info.

Theoretical Astrophysics Group

- Founded in 1983 by Lederman and Schramm
  - Goal is to perform research at the confluence of astrophysics, cosmology, and particle physics
  - Rocky Kolb and Mike Turner + 3 post doc.
- Now
  - Scott Dodelson is head of the group
  - approximately 10-15 theoretical astrophysicists (5 FNAL staff, 5 PD, + users,visitors)
  - partially (~1/4) funded by a NASA Astrophysics Theory grant.
  - More than 1000 papers published!
- Strong connections to area Universities

Theory: Supports existing projects & helps initiate new ones

- Cosmological ν mass constraints (Beacom, Bell, & Dodelson 2004; SDSS Abazajian, Dodelson, Frieman, et al. 2004)
- Dark Energy: Models & Detection (Kolb et al. 2005; Battye & Weller 2005)
- Inflation (Kolb et al. 2004; Kadota & Stewart 2004)
- Dark Matter (Beacom, Bell & Bertone 2004; Bertone & Merritt 2005)
- Gravitational Lensing (Dodelson & Zhang '05; Zhang, Hui, & Stebbins '04)
- Strings (Greene, Jackson et al. 2004)

Sloan Digital Sky Survey (E885)

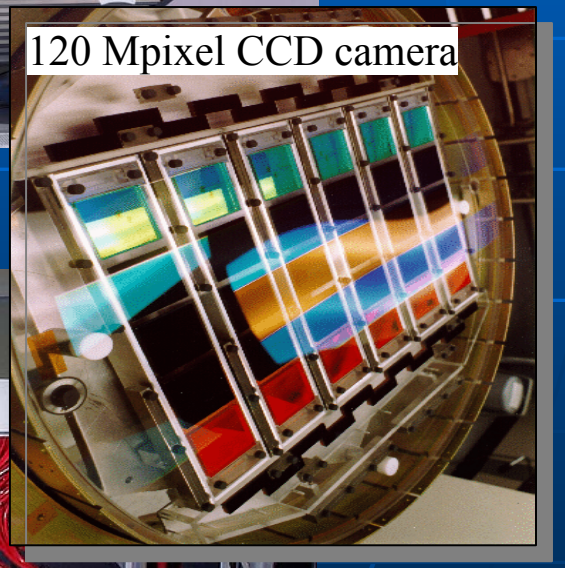
Fermilab involved since 1990

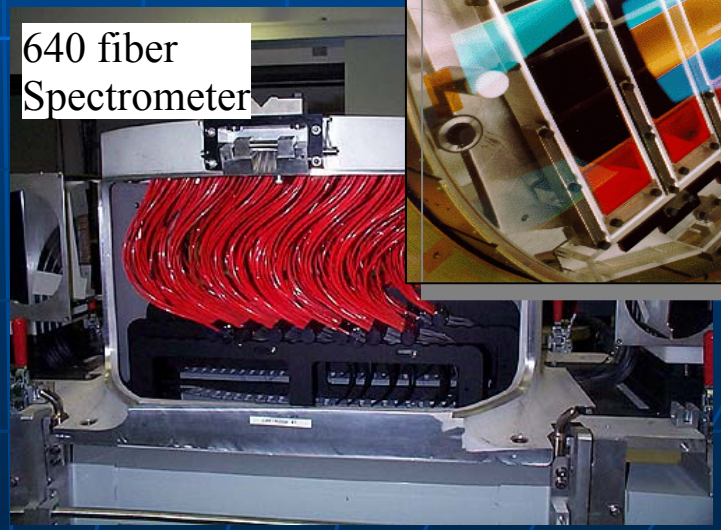
Goal: Study formation & evolution of galaxies and large scale structure
Understand the role of Dark Matter in shaping the universe

5 year mission: 2000-2005

Digital map of ¼ of sky in 5 wavelength bands
Spectra of 1 million galaxies,
100k Quasars

Public Data!





SDSS Impact

- Science publications:
  - 213 in the last year
  - ~ 50% were by people outside the Collaboration
- 20 PhD theses on SDSS data completed last year
- As of March 05, 660 refereed papers included SDSS or Sloan in their title and/or abstract. (~ 50% were actual analysis of SDSS data)
- These papers have been referenced over 12000 times including 14 papers referenced over 100 times each.
- Numerous articles in popular magazines
- With WMAP 2003 Science breakthrough of the year
- One appearance on David Letterman!

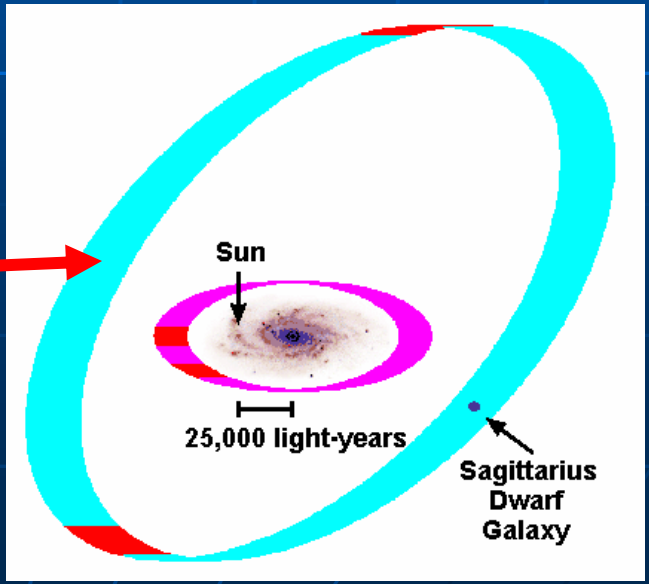
Sloan Digital Sky Survey

- 150 Scientists from 15 institutions

•Funding from: DOE/Fermilab, NSF, NASA, US Naval Observatory, Monbusho/Japan, Universities, Sloan Foundation, Max Planck Soc.

•Today: imaging 113% complete; spectroscopy 75% complete

- Received funding from NSF and Sloan Foundation for SDSS-II: 3 more years
  - Legacy (complete SDSS-I)
  - SEGUE (galactic structure)
  - SN (low/intermediate redshift)



The Pierre Auger Project (E881)

Goal: Measure the Highest Energy Cosmic Rays >10^{19} eV

Energy Spectrum - Direction – Composition

Two Large Air shower arrays

3000 km^2 in Mendoza, Argentina: construction underway

Auger North in Colorado or Utah: planning stage

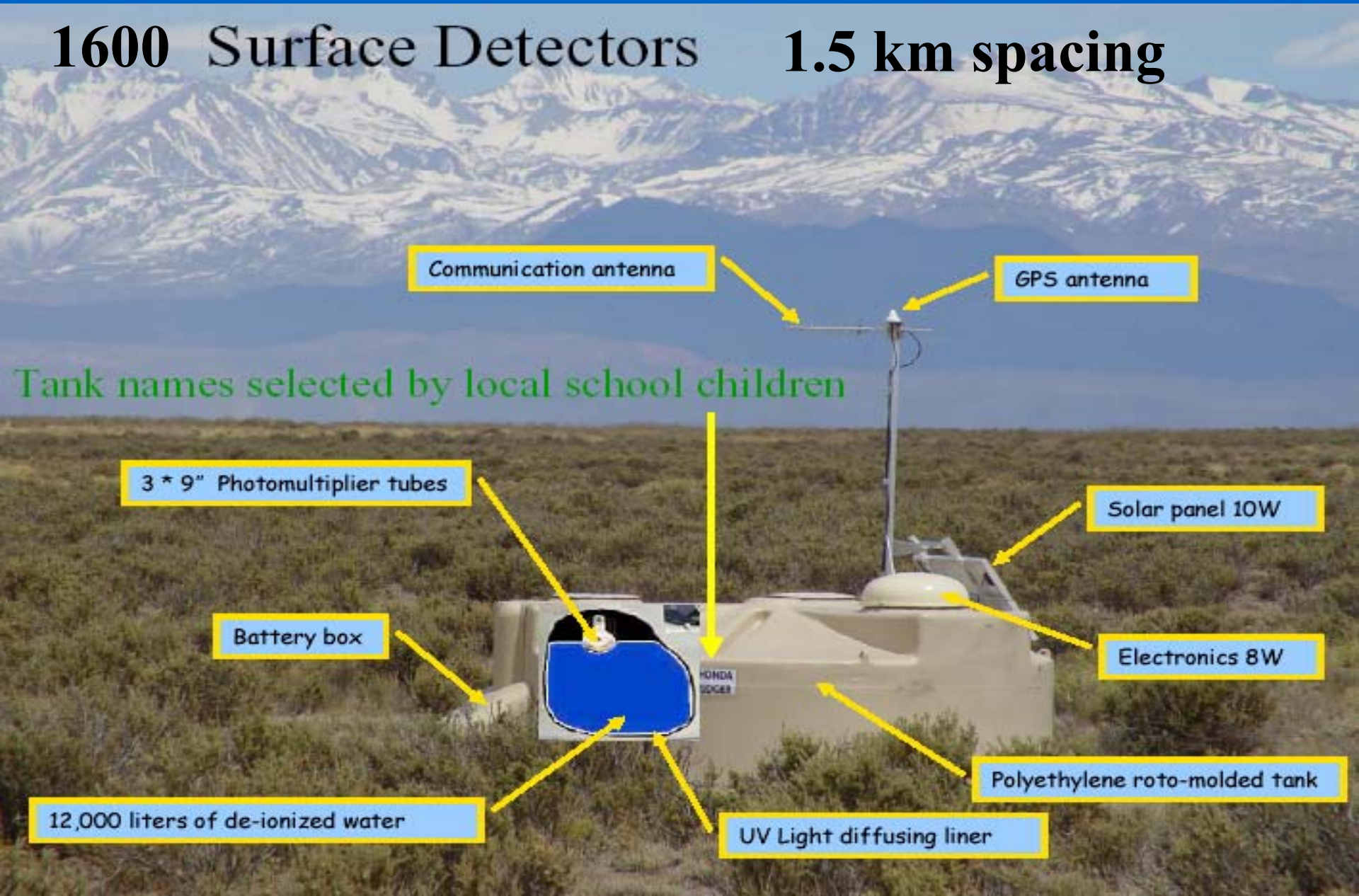
50 Institutions, >250 Scientists
Funding agencies: DOE, NSF and in 13 other countries.
US support is about 25% of the total

1st data coming in: submitted to 35 papers to International Cosmic Ray Conference Aug. 2005 Pune, India

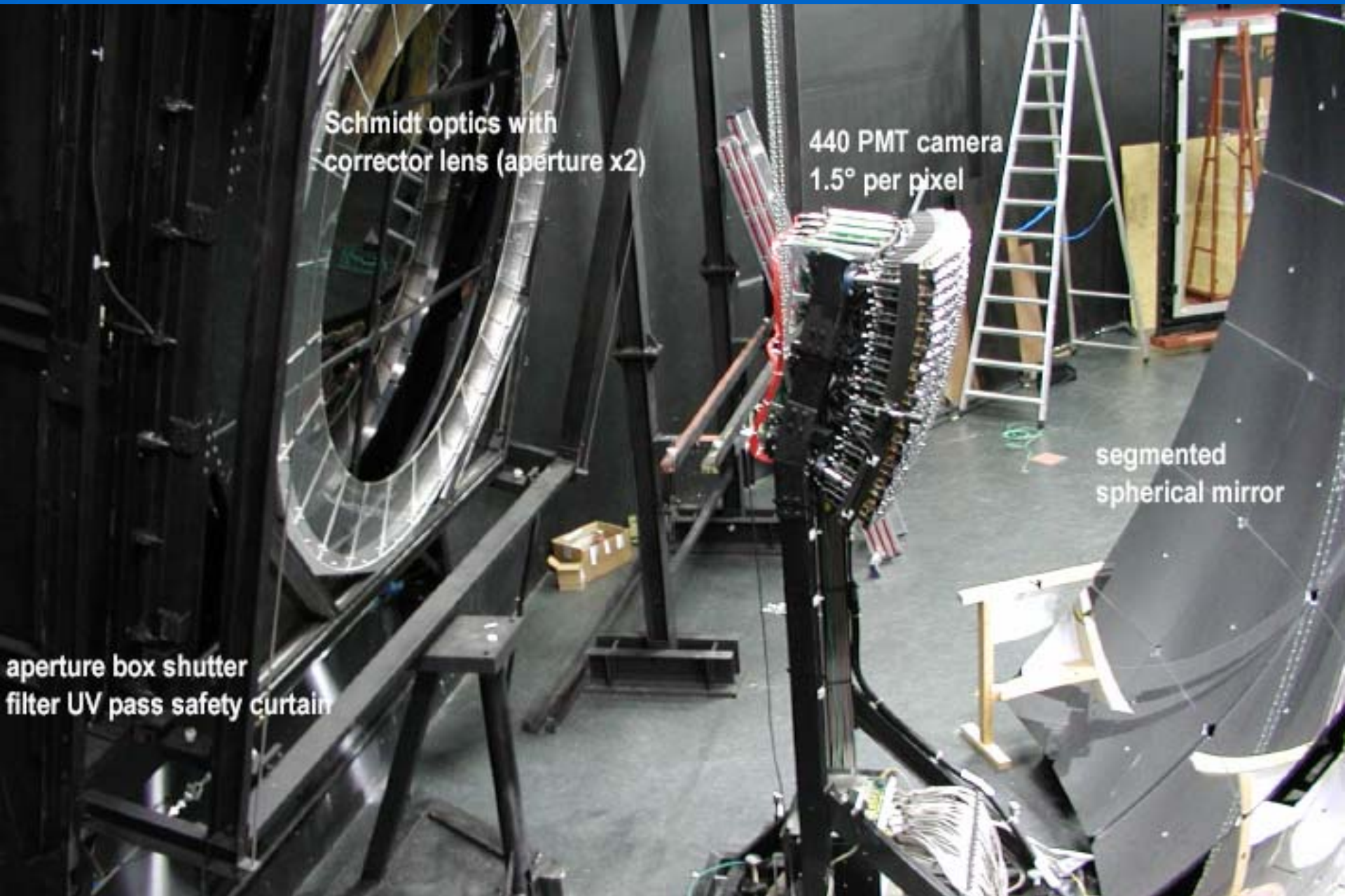
Fermilab has been involved since the inception in ~1994
Paul Mantsch (FNAL/TD) is project manager and will be giving the Auger highlight talk at ICRC

Pierre Auger Surface Detectors

1600 Surface Detectors **1.5 km spacing**

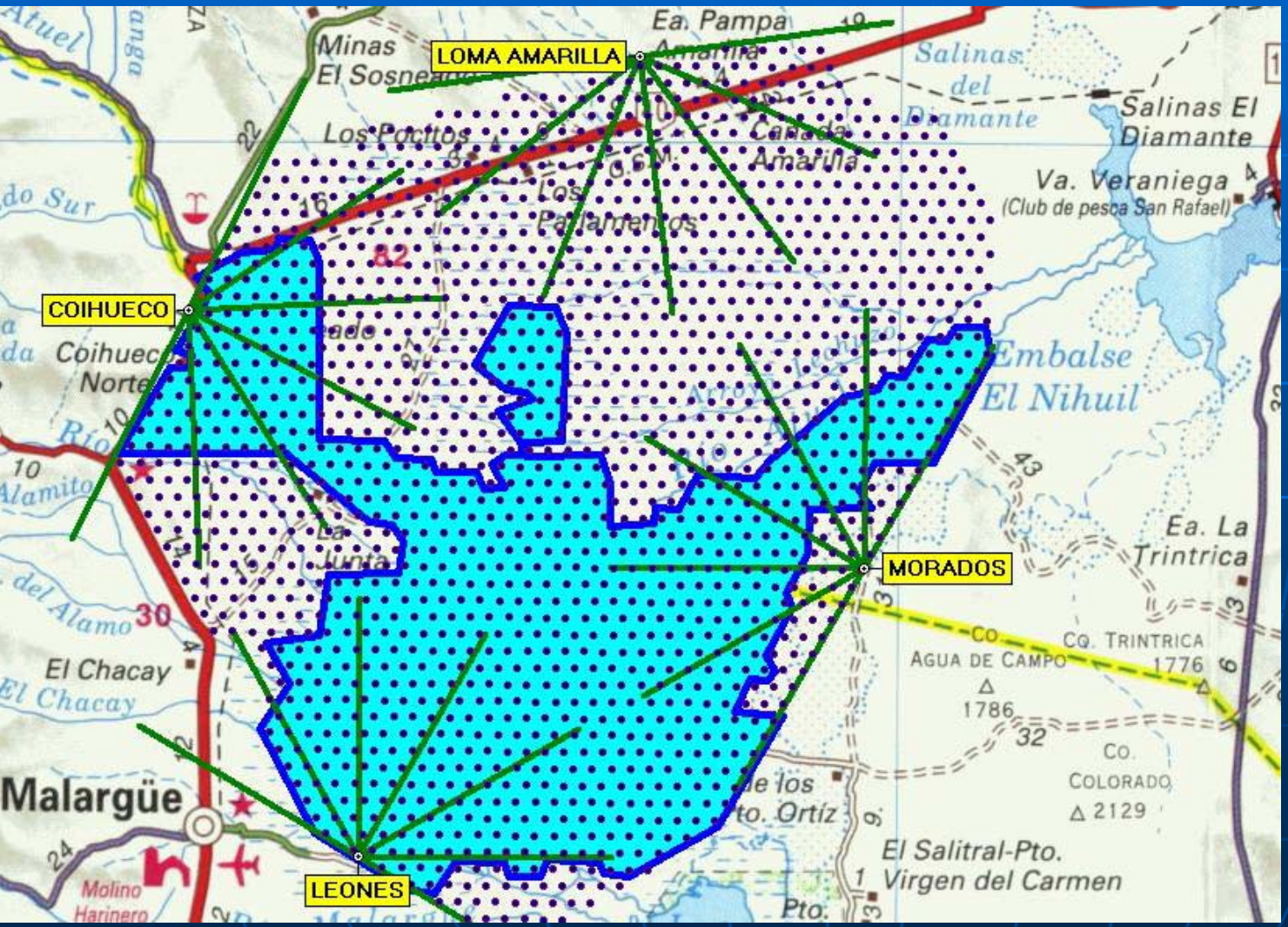


Pierre Auger Fluorescence Telescope



The Pierre Auger Project

Southern Site is already the worlds largest



726/1600 tanks and 18/24 telescopes sending data

Cryogenic Dark Matter Search(E891)

CDMS Mission:
Direct detection of Dark Matter Candidate: Weakly Interacting Massive Particles (WIMPS)

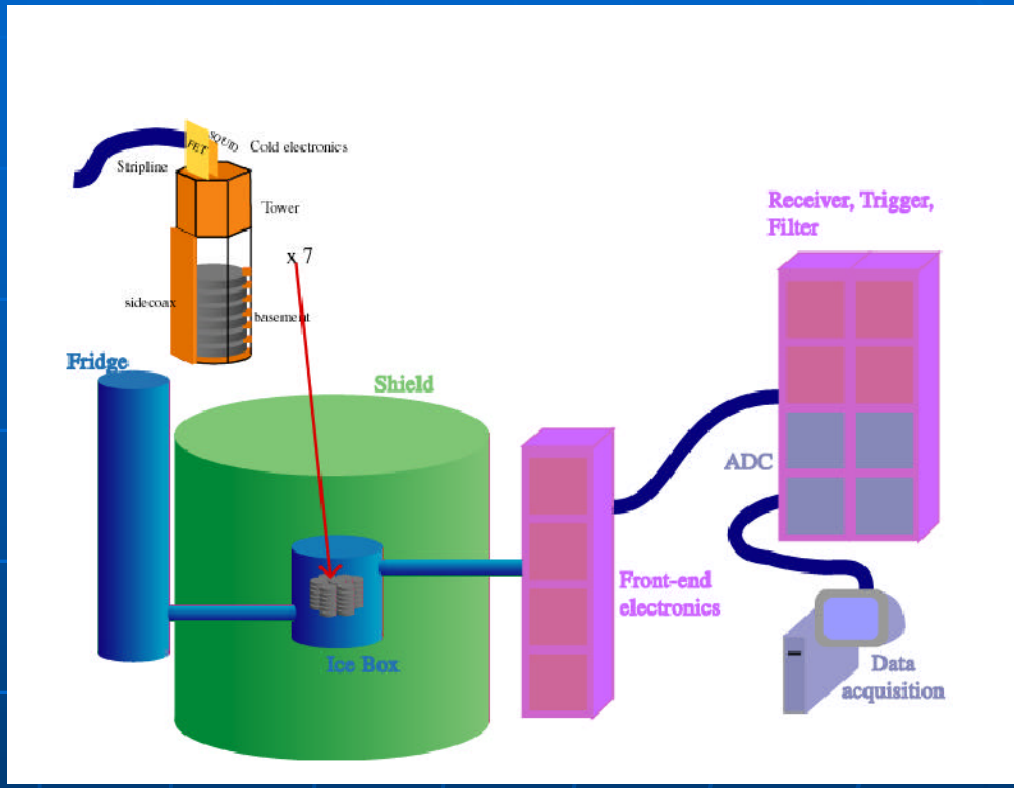
Need very low background:
Locate in Soudan Mine

1st data Oct. '03-Jan. 04:
1 tower: 1 kg Ge, 0.2kg Si
Improved world limit by x4!

Collaboration of ~ 50 Scientists
Funding: DOE, NSF and Universities
Dan Bauer (FNAL/PPD) is the project leader

CDMS in a Nut Shell

- Direct detection of a few WIMPS/year!
- Cryogenic towers of 6 Ge and Si detectors, < 50 mK
- Active Background Rejection
  - Detectors distinguish between nuclear recoils (WIMPS, neutrons) and electron recoils (backgrounds)
- Reject neutrons using
  - multiple scattering
    - Neutrons do, WIMPS don't
  - comparison of Ge to Si rates
    - Neutron cross sections similar, but WIMP cross sections x5 higher in Ge
  - depth
    - Neutrons mainly from cosmic ray interactions



Shielding

Layered shielding (Pb, polyethylene, Cu) against radioactive backgrounds and active scintillator veto (>99.9% efficient against cosmic rays).

CDMS - Status and Future

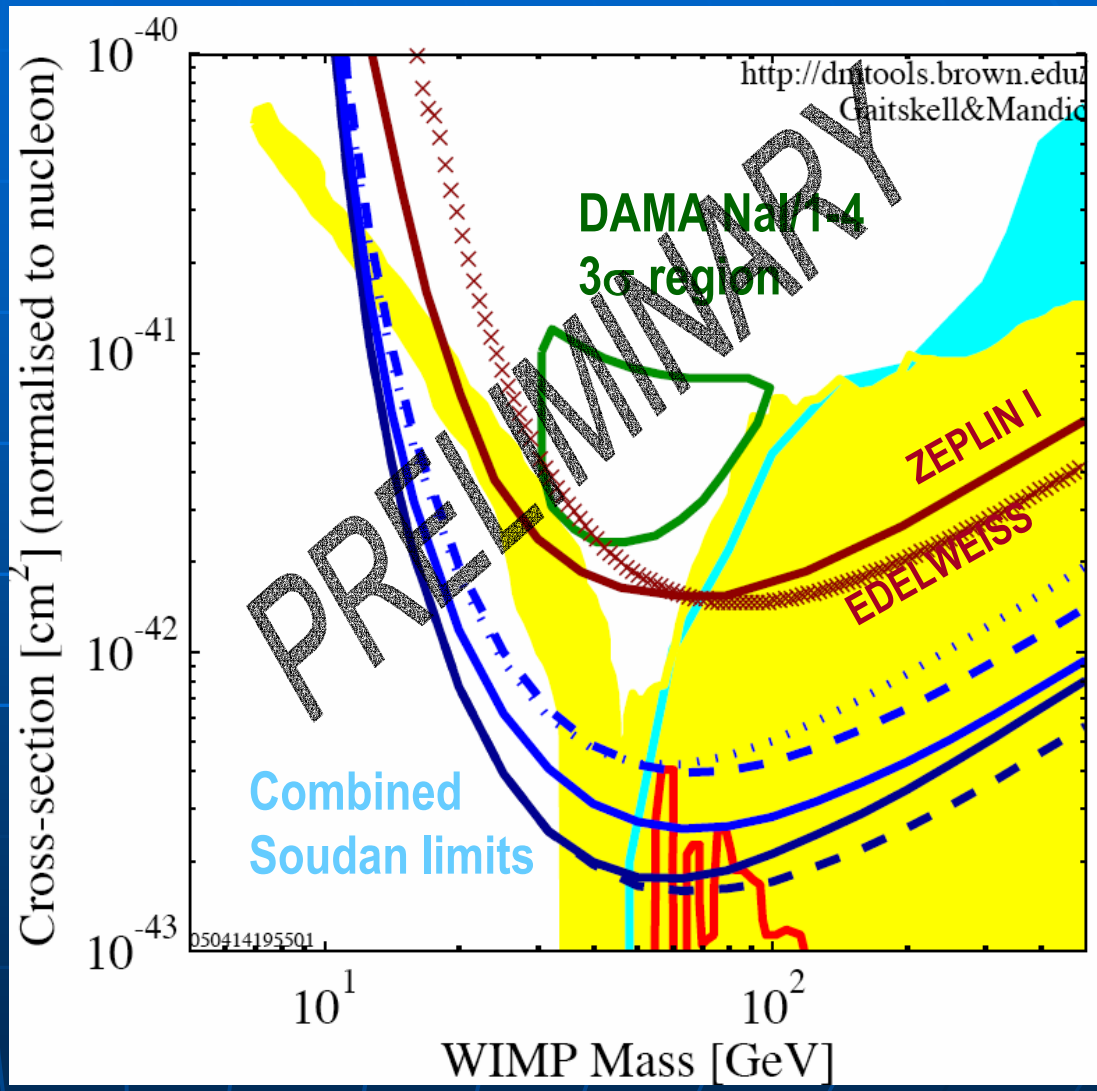
- March – August 2004: two towers

Just released preliminary result:

Best limit in the world by a factor of 10!

- Probing significant regions of MSSM model space
- Light-mass region largely ruled out
- NOW: Five towers installed (cold mid-June)
- Another factor of 10 available at Soudan by 2007

•After that will need to go deeper and bigger: Super CDMS (P947)

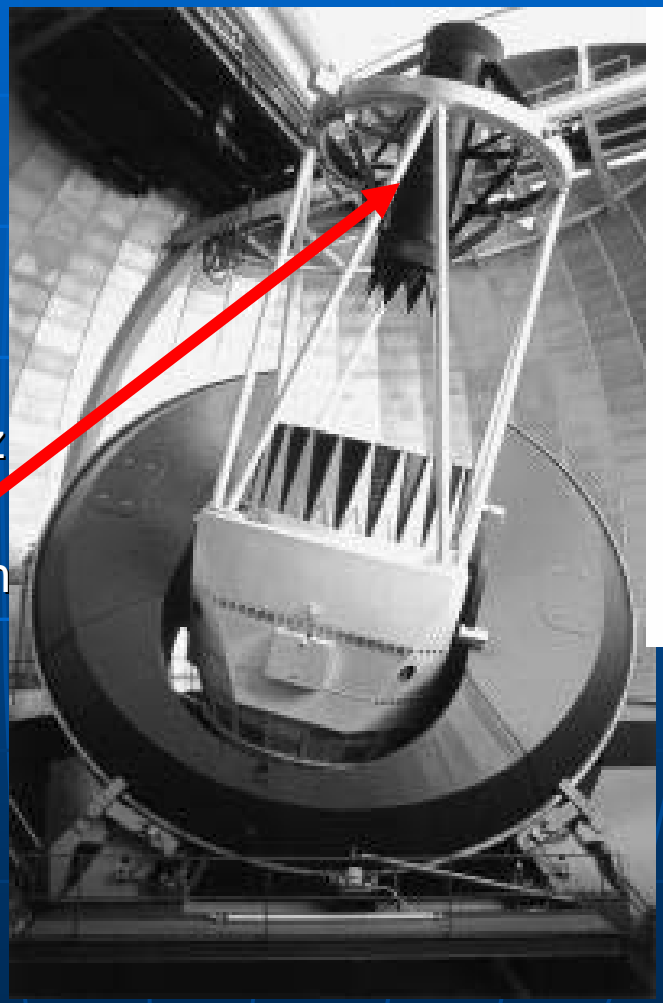


New Initiatives in Experimental Astrophysics

- Dark Energy Survey – P939 (proposal)
  - Started Fall of 2003
  - 2004: PAC, Director gave stage 1 approval pending funding
  - Fermilab is leading construction of the Instrument
  - UIUC is leading Data Management
  - goal is to be on the telescope in 2009
- SNAP – potential candidate for JDEM, the joint Dark Energy mission (DOE + NASA)
  - R&D lead by LBNL
  - Fermilab admitted to SNAP Collaboration in 2004

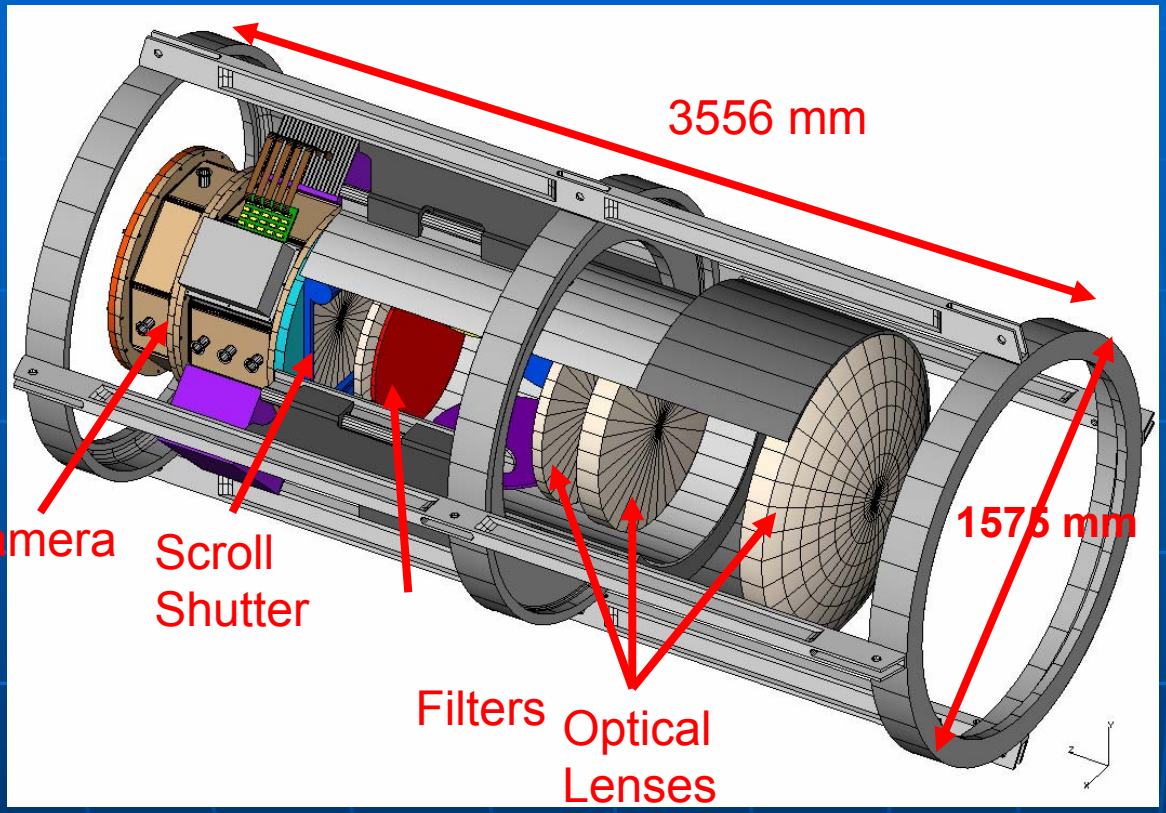
The Dark Energy Survey (DES)

- Proposal:
  - Perform a 5000 sq. deg. survey of the southern galactic cap
  - constrain w to ~ 5% with 4 complementary techniques
  - begin to constrain dw/dz
- New Equipment:
  - Replace the PF cage with a new 2.2 deg. FOV optical CCD camera
  - Instrument Cost ~$22.5M
- Time scale:
  - Instrument Construction 2005-2009
  - Survey 2009-2014

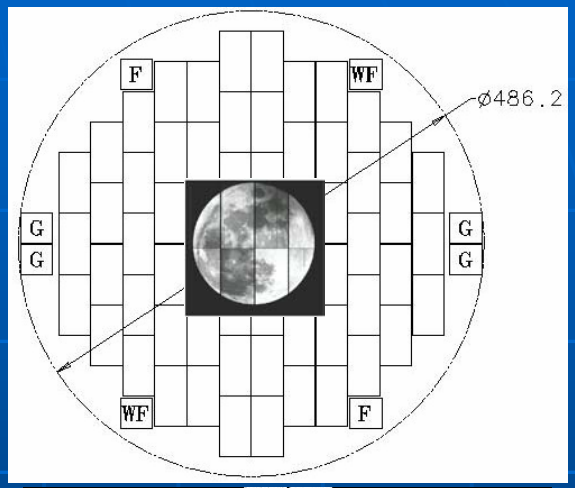


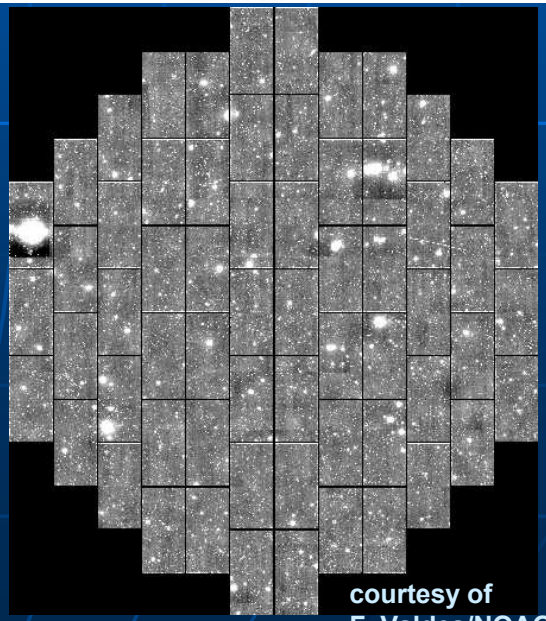
Use the Blanco 4M Telescope at the Cerro-Tololo Inter-american Observatory (CTIO)

DES Instrument



DES camera will be the largest of its time

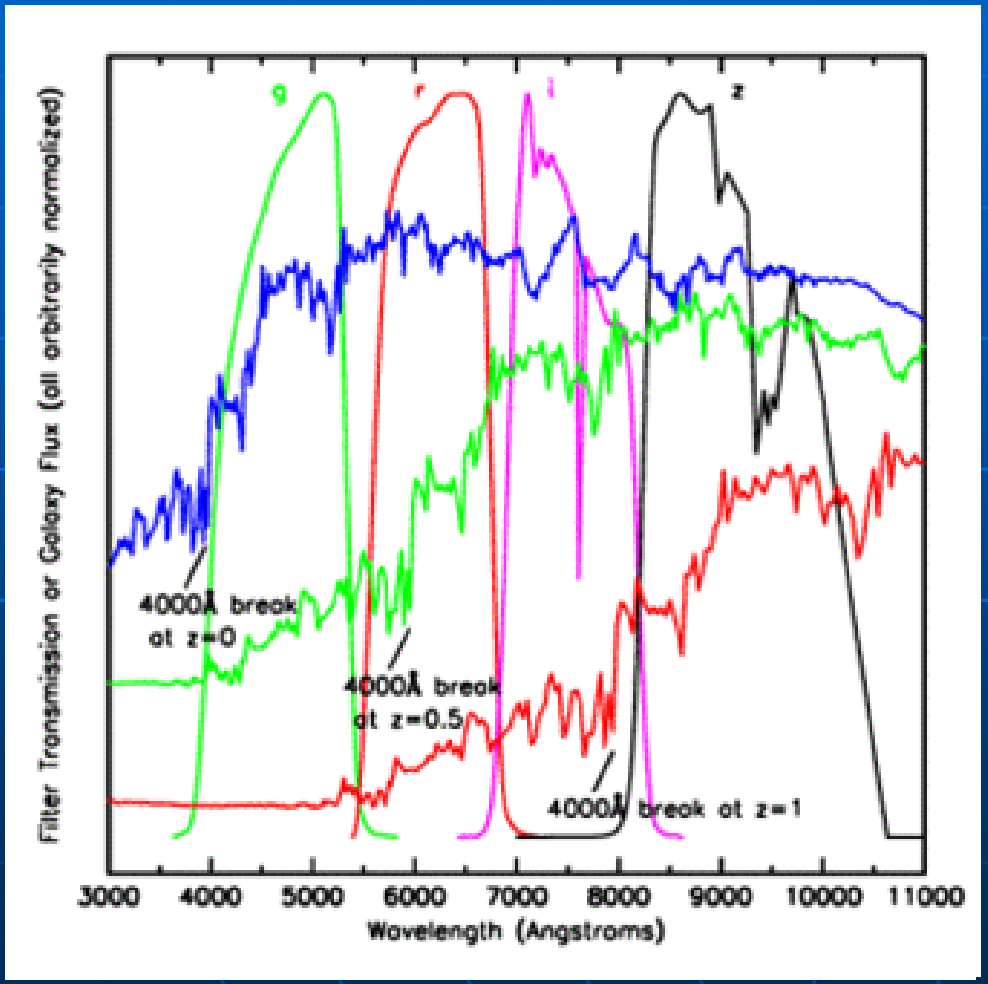




courtesy of
F. Valdes/NOAO

Each image: **3 sq. deg., ~ 20 Galaxy clusters**
~ 200,000 Galaxies, 500 Mega pixels (62 CCDs)
Each night ~ 300 GB of image data
Entire survey ~ 500 TB

Build on SDSS experience: photometric redshifts are useful!



Elliptical galaxy spectra at redshifts z = 0, 0.5, and 1.

The 4000 Å break in the spectrum moves with redshift

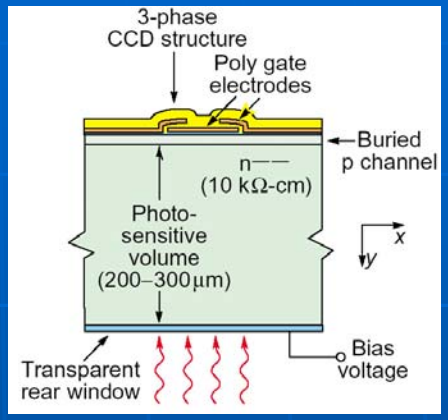
The difference in brightness of an object seen through the different filters gives a measure of the redshift

At a redshift of 1, only the z filter gets much light

This is not as precise as taking a full spectrum but it is MUCH faster and can go fainter
45 min for spectra, 55sec for photo-z

CCDs

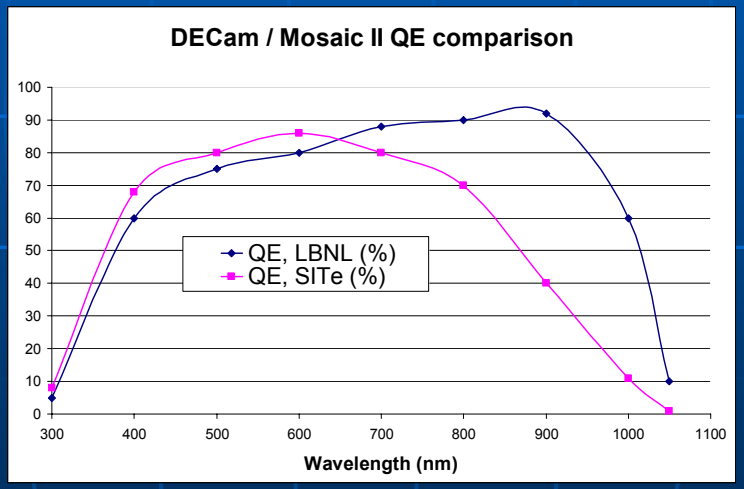
- **Reference Design: LBNL CCDs**
  - **QE> 50% at 1000 nm**
  - **250 microns thick**
  - **readout 250 kpix/sec**
  - **2 RO channels/device**
  - **readout time ~17sec**



LBNL CCDs in use on WIYN telescope. From S. Holland et al, LBNL-49992 IEEE Trans. Elec. Dev. Vol.50, No 1, 225-338, Jan. 2003

LBNL CCDs are much more efficient in high wave lengths (z-band: 825 - 1050nm)

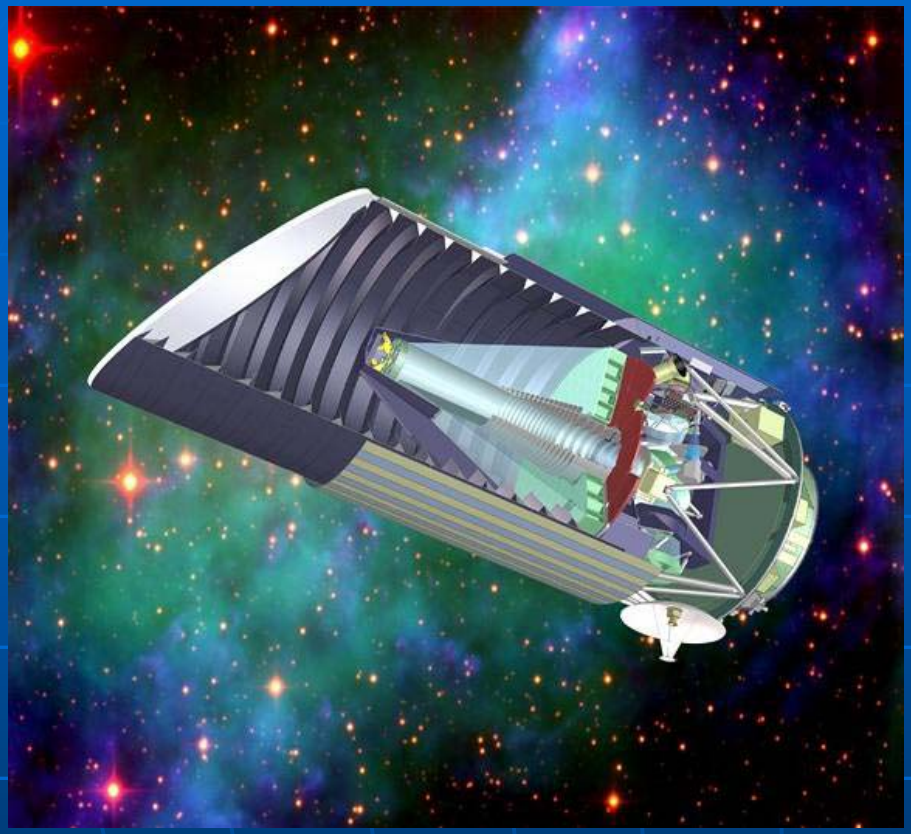
To get redshifts of ~1 DES will spend 46% of survey time in z –band

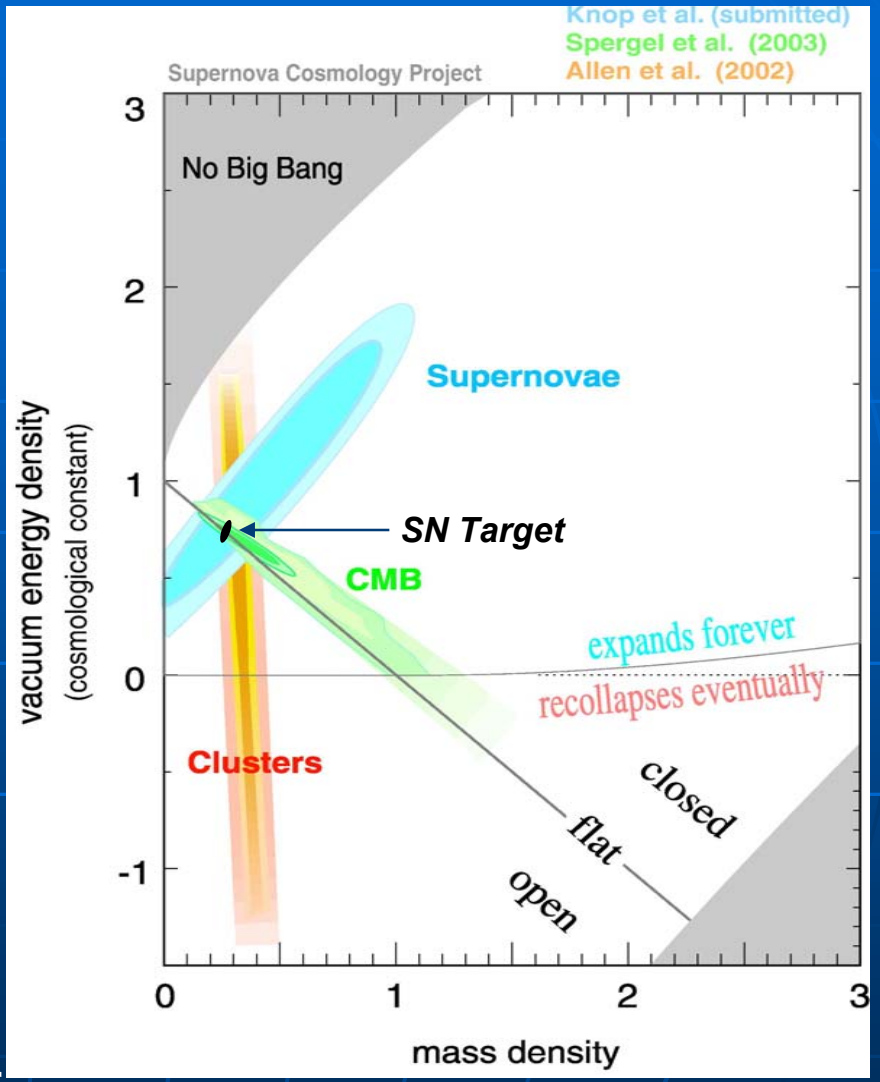


DES is the 1st production quantity application for LBNL CCDs

DES CCD design has already been used on telescopes in small numbers (3)
SNAP CCDs are the next generation, optimized for space

SNAP





- Discover and measure large numbers of supernovae, light curves and spectra, look back 3 - 10 Byrs (z=0.5 -1.7)
- Wide field survey: Weak lensing, cluster counts, angular PS
- Space-based: higher sensitivity, no smearing by earth's atmosphere

Fermilab Particle Astrophysics Center – Formed Jan. 1, 2005

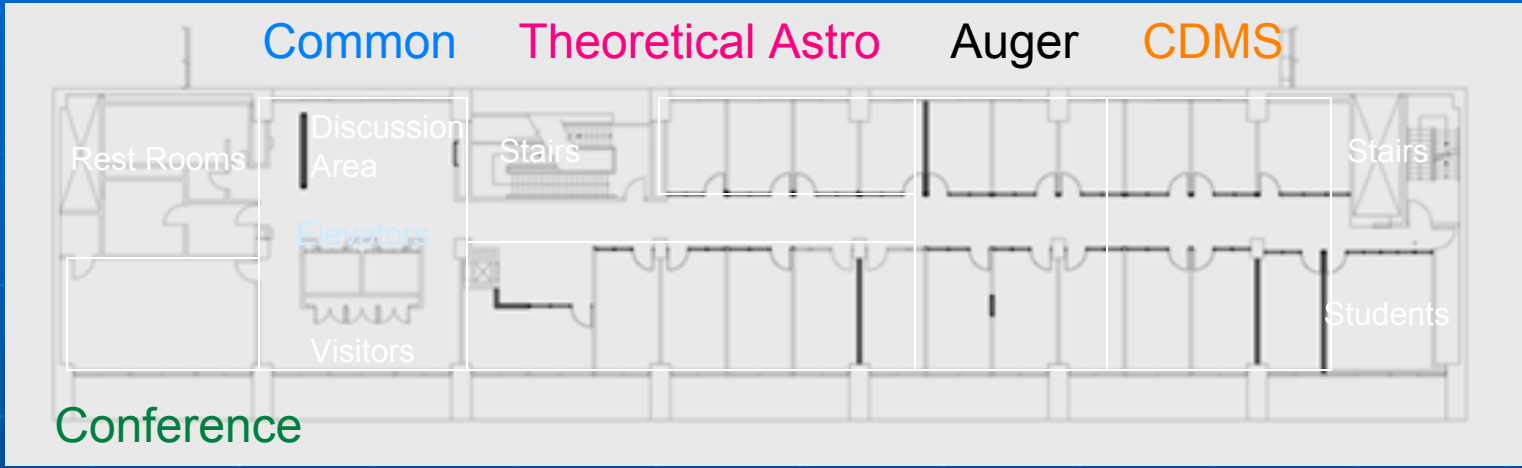
- Fermilab Particle Astrophysics Center goals:
  - to be an intellectual center that will serve to unify and to focus the astrophysics program at Fermilab, thereby enhancing the overall effectiveness of the effort and the recruiting power of the individual projects.
  - to provide the framework in which future efforts will be germinated, will be developed and will be advanced.
  - To become an internationally recognized center where scientists from Fermilab and the User Community can come to learn about and participate in the interface of particle physics and cosmology.

Fits well with Fermilab Mission and Long Range Plans

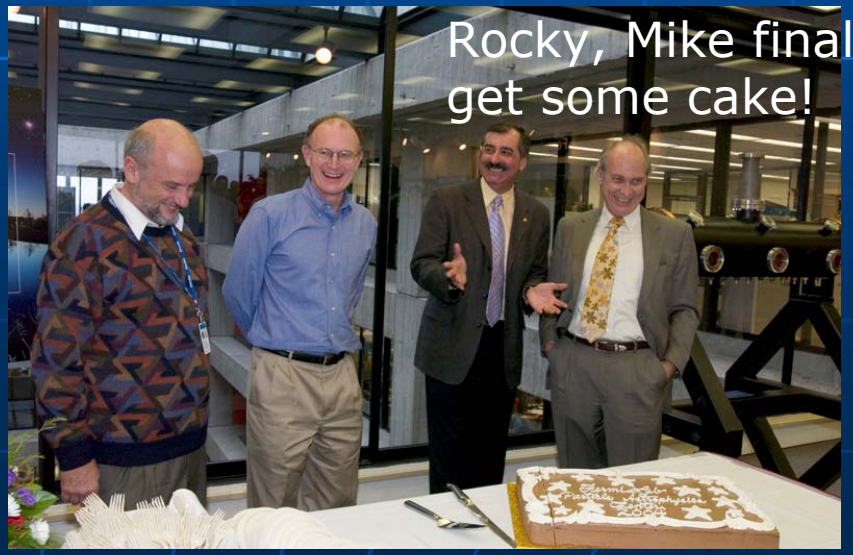
- Fermilab Mission statement
  - Fermilab advances the understanding of the fundamental nature of matter and energy by providing leadership and resources for qualified researchers to conduct basic research at the frontiers for high energy physics and related fields.
- Fermilab Long Range Plan May 2004:
  - Fermilab should substantially expand its leadership role in Particle Astrophysics, which provides probes of fundamental physics that complement accelerator experiments.

Particle Astrophysics Center

Location, location, location: WH6W+WH7W



Rocky Kolb is the director of the Particle Astrophysics Center
Proximity will facilitate discussions and use of common resources



Conclusions

- Very exciting time – cosmology is entering realm of "precision" measurements to compare to theoretical predictions and still there is no complete theory for Dark Matter and Dark Energy
- Fermilab has an active and successful role in both theoretical and experimental particle astrophysics
- The Particle Astrophysics Center provides an organizing structure to a wide and diverse field
- Fundamental questions we face today need to be attacked from both cosmology and from accelerators:
  - What in the nature of Dark Matter?
  - What is Dark Energy?
  - And what about those UHECR?

Extra Slides

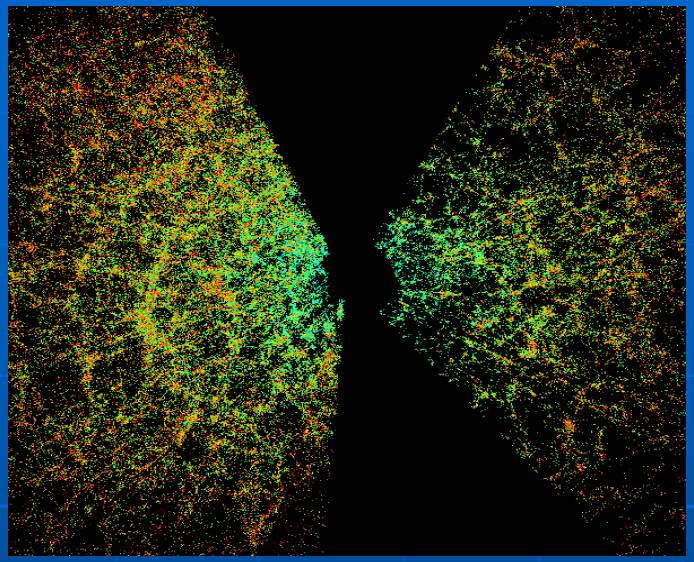
Particle Astrophysics Center

- Interdivisional – all divisions are involved in one or more of the projects. All individual astrophysics groups and projects continue to operate as before.
- Will assist Users community members who are involved in programs that are part of the Center
- Membership is open to all Fermilab employees who work on existing astrophysics projects and new initiatives
- Director of the Center will report on scientific matters to the Lab Director
- Director of the Center will be advised by a Steering committee which consists of the heads of the projects
- The Fermilab Director, with the advise of the director of the center and Steering committee, will recruit a distinguished visiting committee to advise him about the directions for research and to make suggestions concerning the progress of astrophysics at Fermilab

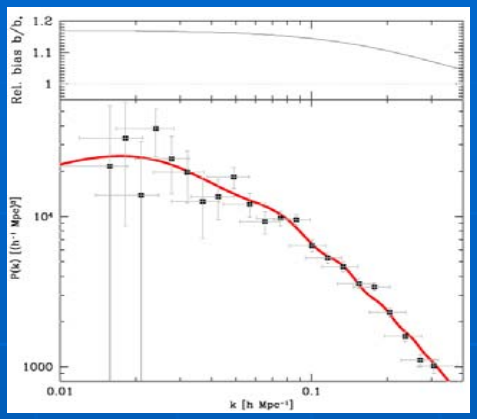
Theoretical Astrophysics

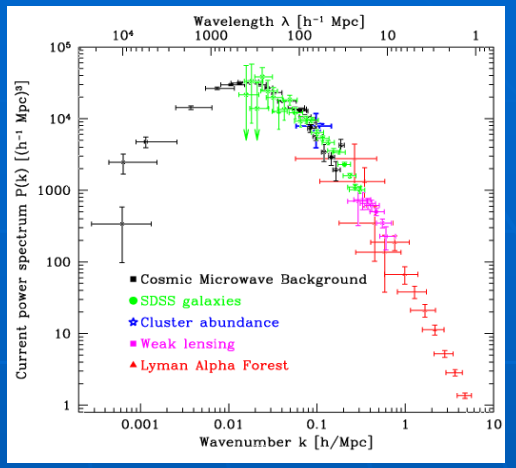
1. Alex Szalay, Professor Johns Hopkins University
2. Neil Turok, Professor DAMTP, University of Cambridge
3. Andreas Albrecht, Professor University of California, Davis
4. Keith A. Olive, Professor University of Minnesota
5. David Seckel, Associate Professor Bartol Research Institute
6. Lars G. Jensen, Associate Professor North Dakota State
7. Richard F. Holman, Professor Carnegie-Mellon University
8. David P. Bennett, Associate Professor Notre Dame
9. Marcelo Gleiser, Professor Dartmouth College
10. Albert Stebbins, Scientist II Fermilab
11. Edmund J. Copeland, Professor University of Sussex
12. Angela V. Olinto, Associate Professor University of Chicago
13. Dongsu Ryu, Professor Chungnam University, Korea
14. Scott Dodelson, Scientist II Fermilab
15. Ruth A. Gregory, Academic Staff University of Durham
16. David Salopek, Senior Researcher UBC
17. Esteban Roulet, Visiting Professor Valencia, Spain
18. Fay Dowker, Lecturer Queen Mary University of London
19. James Gelb, Assistant Professor UT, Arlington
20. Robert Caldwell, Assistant Professor Dartmouth College
21. Stephane Colombi, Scientist Institut d'Astrophysique, Paris
22. Igor Tkachev, Researcher CERN
23. Andrew Heckler, Assistant Dean, Ohio State University
24. Yun Wang, Assistant Professor University of Oklahoma
25. Istvan Szapudi, Assistant Professor University of Hawaii
26. Antonio Riotto, Professor INFN, Padova
27. Will Kinney, Assistant Professor SUNY Buffalo
28. Lam Hui, Associate Professor, Columbia University
29. Ewan Stewart, Assistant Professor Korea Advanced Inst.
30. Zoltan Haiman, Assistant Professor Columbia University
31. Pasquale Blasi, Faculty Osservatorio Astrofisico di Arcetri
32. Idit Zehavi, Assistant Professor Case Western Reserve
33. Ravi Sheth, Assistant Professor University of Penn
34. Patrick Greene, Assistant Professor UT, San Antonio
35. John Beacom, Assistant Professor Ohio State University

SDSS Impact



Distribution of Galaxies around Sun to z=0.15
(Blanton 2003)

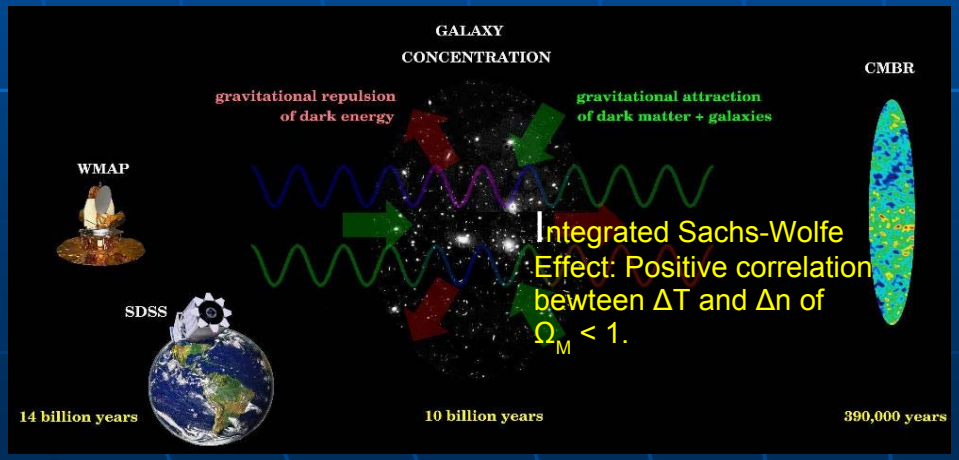




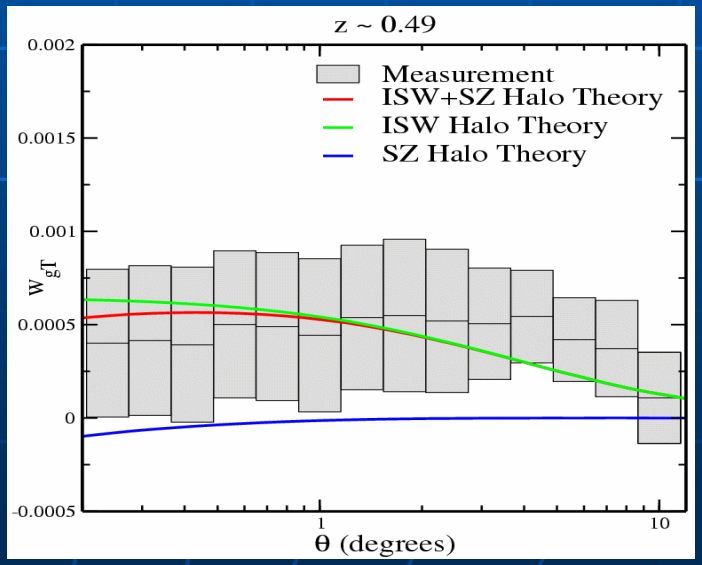
ΛCDM adjusted to L* galaxy

$\Omega_M h = 0.213 \pm .023$
σ_8 (gal) = 0.96 ± .02
n = 0.995

Three-dimensional Power Spectrum
(Tegmark et al 2003)



SDSS vs WMAP: Correlation of temp. fluctuations with galaxy counts
(Scranton et al. 2003)



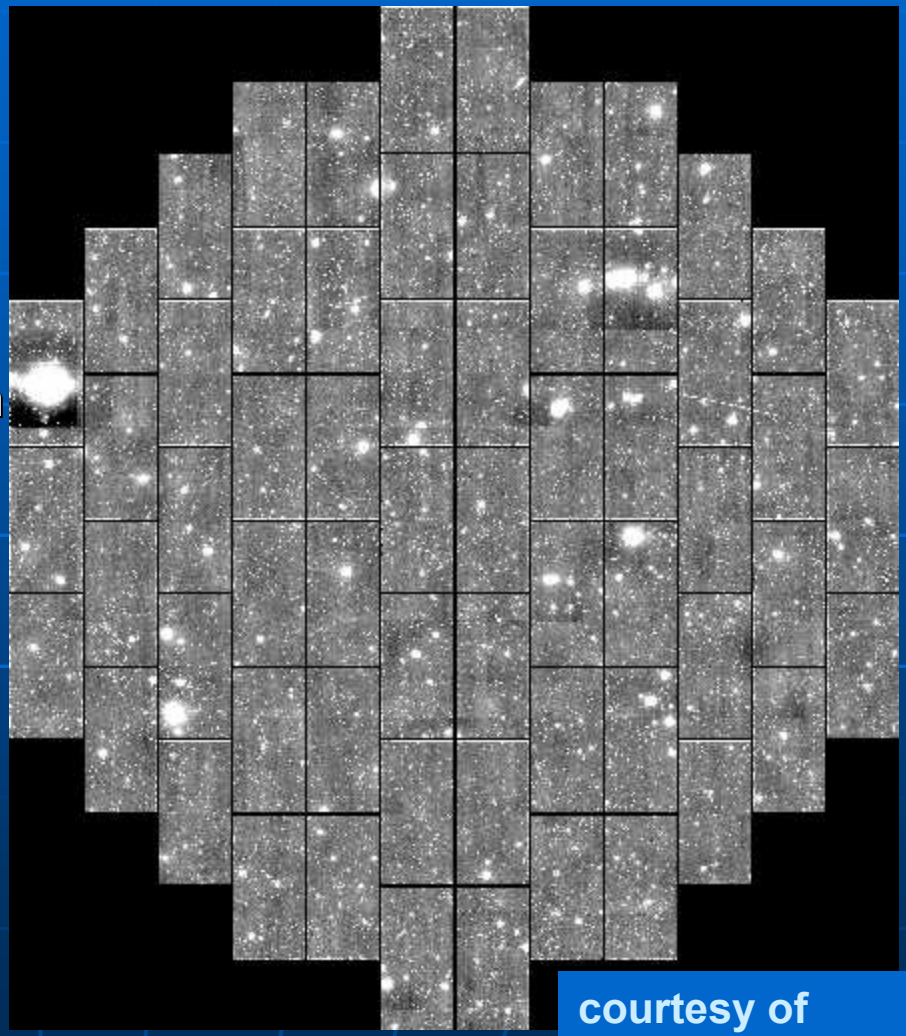
Strong evidence for dark energy dominated universe (ΛCDM)

DES Science

DES: Four Probes of Dark Energy

- Galaxy Cluster Counting: N(M,z)
  - Measure red shifts and masses
  - 20,000 clusters to z=1 with $M > 2x10^{14} M_{\odot}$
- Weak lensing
  - 300 million galaxies with shape measurements over 5000 sq deg.
- Spatial clustering of galaxies
  - 300 million galaxies to z = 1

    and beyond
- Standard Candles
  - 2000 SN Ia, z = 0.3-0.8



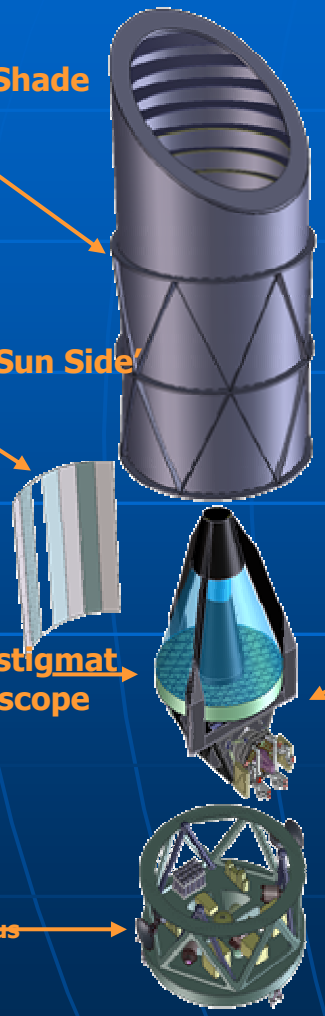
courtesy of F. Valdes/NOAO

Strawman Schedule

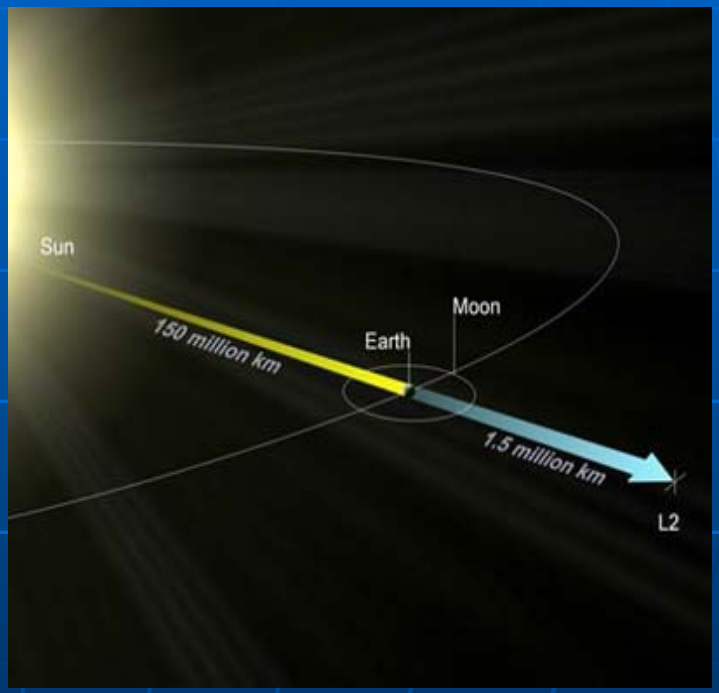
(assumes new funding in Year 0)

Year -1	Pre-phase A / Pre-conceptual planning (CD0)
	Conduct mission concept studies in anticipation of an AO
	Establish study office
Year 0	Phase A / Conceptual design
	NASA in-house mission concept definition study
	Write AO
Year 1	Issue AO; select investigations (CD1)
	Industry participation in spacecraft Phase A studies
Yr 2-3	Phase B / Preliminary design (CD2)
	Issue RFP or use RSDO; select prime contractor
Yr 4-8	Confirmation; Phase C/D / Final design (CD3) / Construction (CD4)
	Develop the mission, on time and on budget
Yr 9-11	Launch; Phase E / Operations
	Dark energy phase
Yr 12-14	General astronomical observing phase
Year 15	End of 6 year prime mission

The SNAP Observatory



Mission reference parameters	
Orbit	L2 halo orbit
Pointing stability	Within 0.02 arcsec; focal plane feedback
Time on target	87%
Calibration	Standard star network to AB 20 mag



Telescope reference parameters	
Focal Length	21.66 meters
Aperture	2.0 meters
Optical field	Annular, 6 to 13 mrad; 1.37 sq. deg.
Geometric blur	2.8 microns rms

Dark Energy Roadmap

Present to 2009: $\sigma(w) \sim 0.1$ (SNE+WMAP combined , ~0.3 alone)

- Supernovae: ESSENCE, CFHTLS, HST, SNF, SDSS,…many 100's of SNe Ia over z ~ 0.1-0.8
- Weak Lensing: Deep Lens, CFHTLS, ...: ~200-1000 sq. deg. deep multi-band imaging
- Cluster SZ: APEX, … ~200 sq. deg. survey

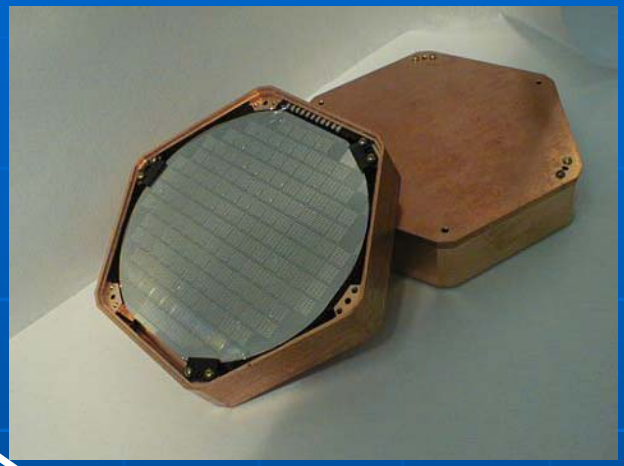
2009 to ~ 2014: DES will be in a unique position to constrain w to $\sigma(w) \sim 0.05$ using four independent techniques and 1st constraints on dw/dz

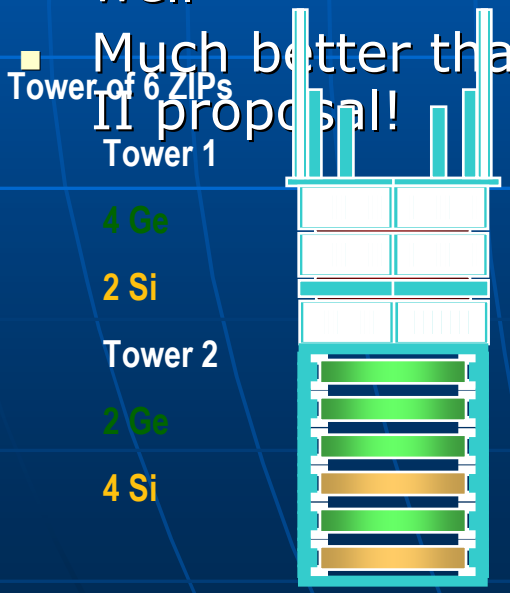
2014 and beyond: LST and JDEM will start to reach the next level of cosmological precision: ~1-2% on w and ~5% on dw/dz

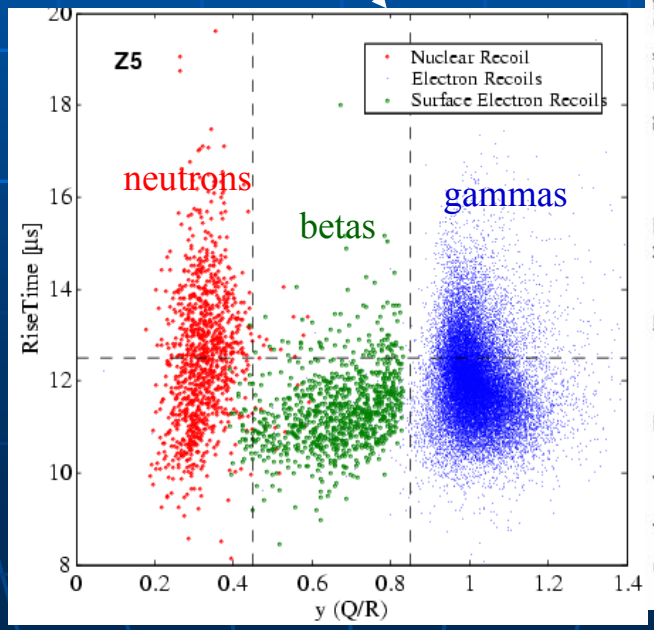
CDMS Active Background Rejection

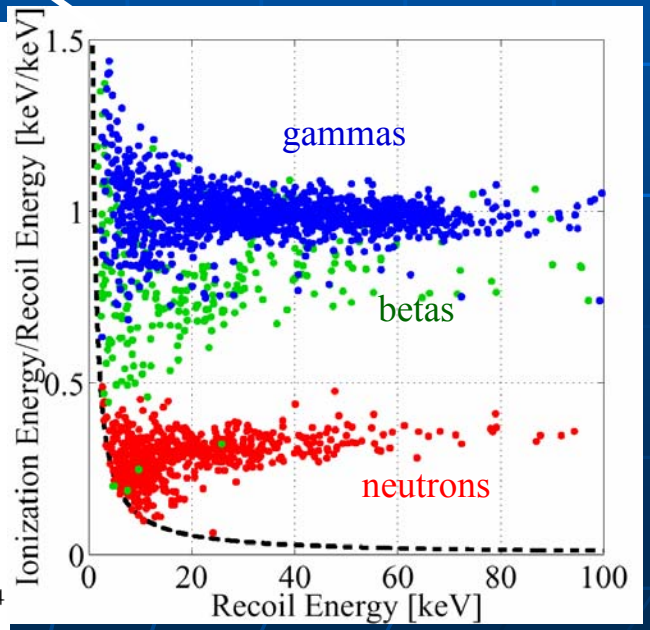
Detectors with excellent event-by-event background rejection

- Measured background rejection:
- 99.995% for EM backgrounds using charge/heat
- 99.4% for β's using pulse risetime as well
- Much better than II proposal!









First WIMP limits from CDMS II at Soudan

- Best in the world by x4!
- DAMA 'signal' is not due to spin-independent WIMP interactions
- Probing significant section of MSSM model space
- New results on spin-dependent WIMP-neutron cross sections