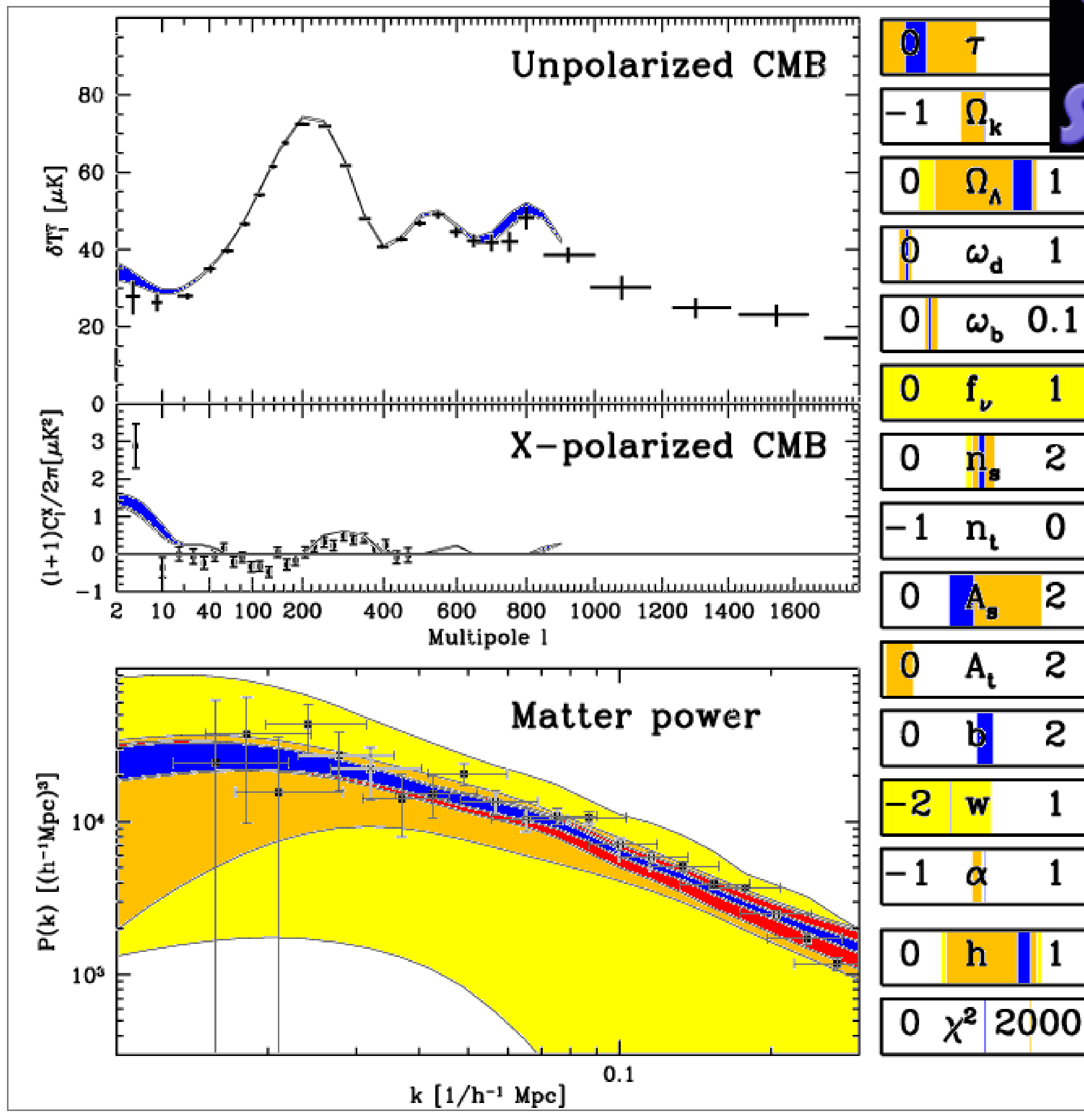
Future Directions in Ground Based Optical/IR Cosmology

James Annis
Experimental Astrophysics Group
Fermilab

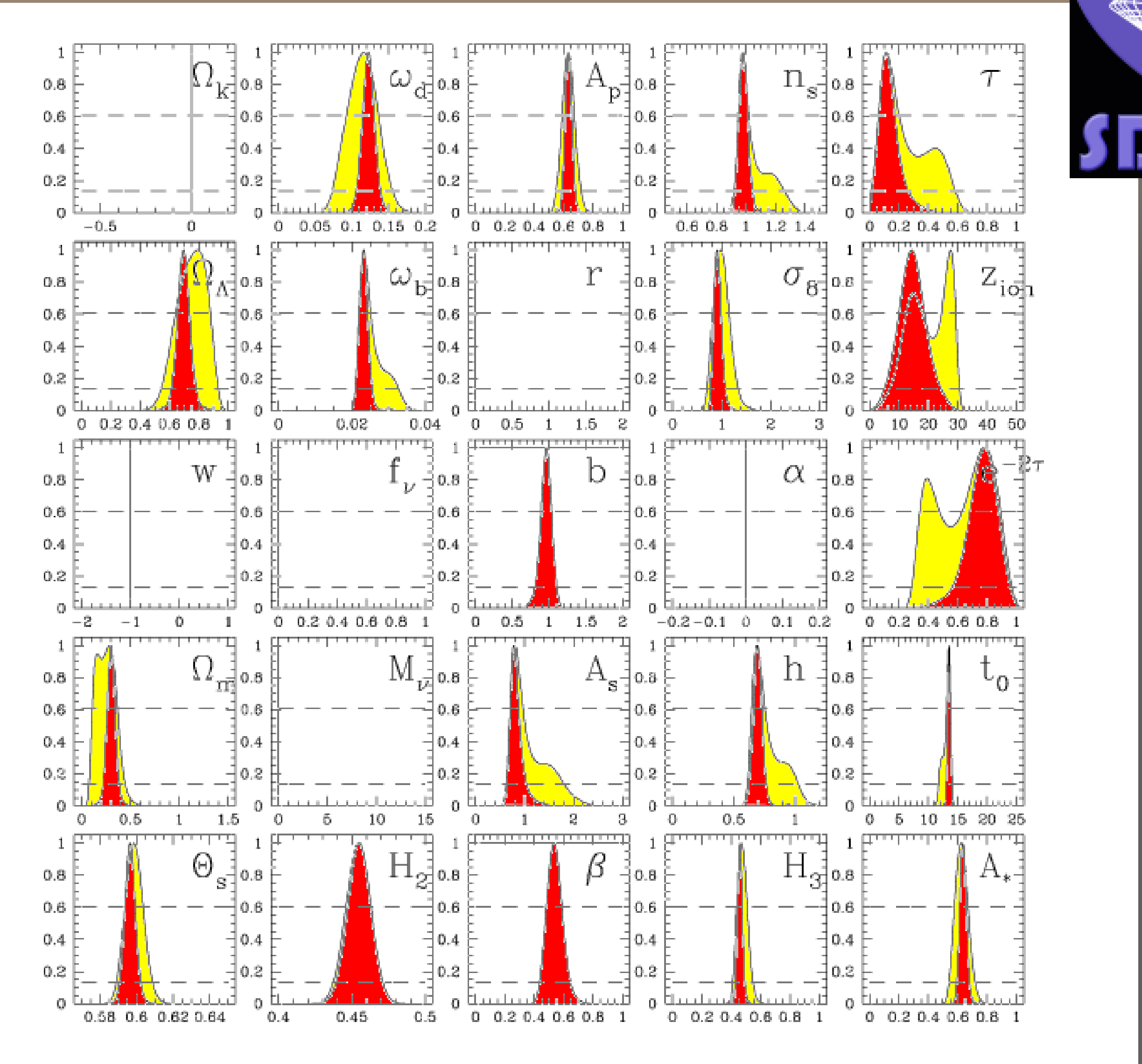
SDSS Cosmology



Tegmark/SDSS

Power Spectra provide sensitive probes of cosmology

SDSS Cosmology



Tegmark/SDSS

Constraining a wide range of physical parameters

Scientific Motivation

Create the ultimate map of the Universe:

⇒ *The Cosmic Genome Project!*

Study the distribution of galaxies:

⇒ What is the origin of fluctuations?

⇒ What is the topology of the distribution?

Measure the global properties of the Universe:

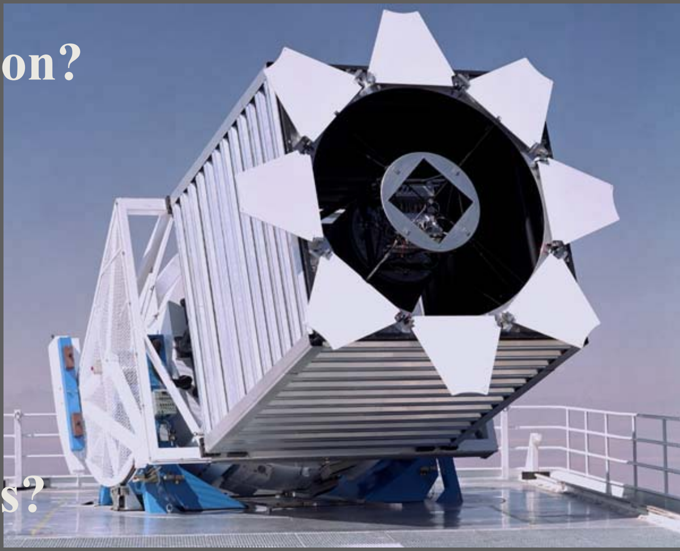
⇒ How much dark matter is there?

Local census of the galaxy population:

⇒ How did galaxies form?

Find the most distant objects in the Universe:

⇒ What are the highest quasar redshifts?



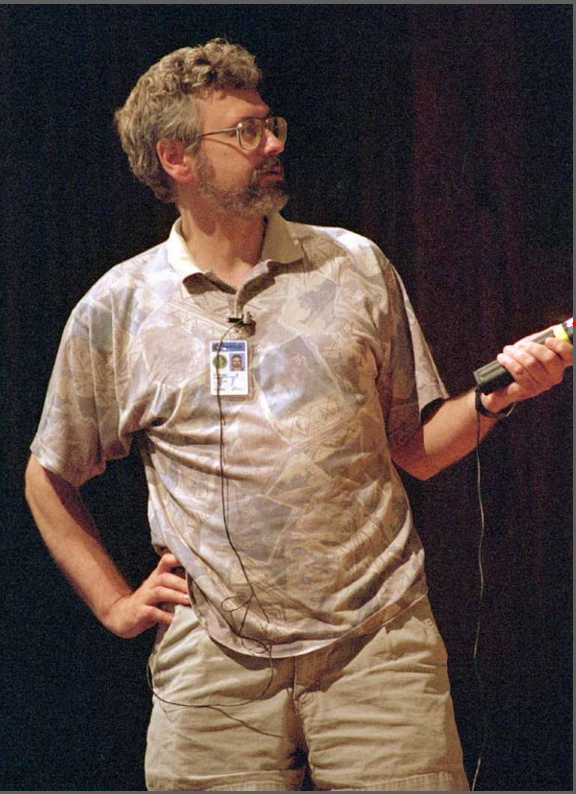
Fermilab's Role

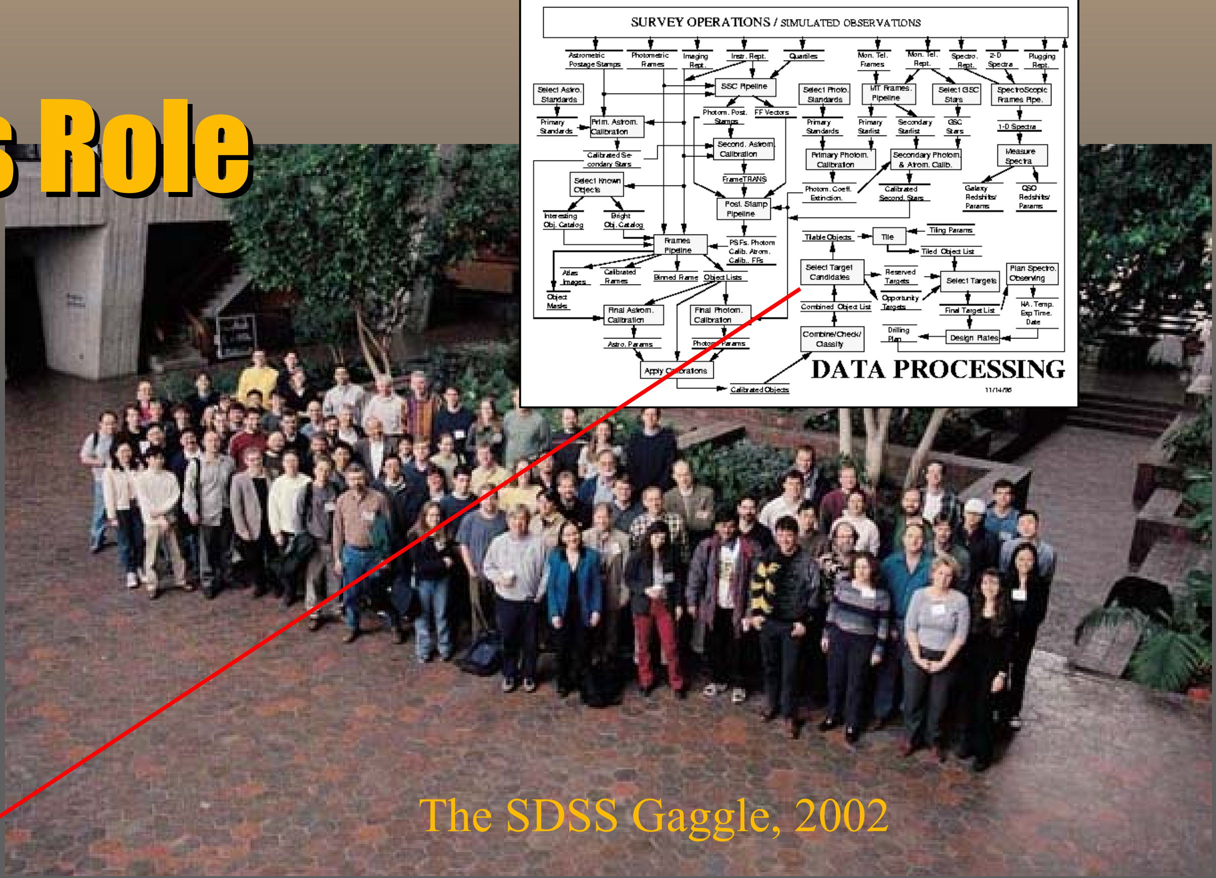
- Project Management
  - Project directed by a Fermilab scientist from 1997-2003
  - Current director has Fermilab/UC joint appointment
  - Project managed by Fermilab engineer since 1999
- Software System Design
  - Led by Fermilab scientist since 1991
  - Designed whole software environement
  - System worked when confronted with real data
- Data Processing and Distribution
  - Target selection and plates drilling on time
  - Data releases to collaboration and public
- Pipeline Development
  - Target section
  - Calibration pipelines
  - Image correction pipelines
  - and on and on
- Data Acquisition
  - Ambitous (in 1992) system delivered on time
  - Real time data analysis on astrometric data
  - Mountain top software
- Mountaintop Engineering
  - Plate handling system
  - Camera handling carts
  - Fiber mapper
  - Telescope maintenence
- Calibration
  - Calibration system design
  - Calibration system software
- Analysis
  - star/galaxy separation,

These are Fermilab's strengths

Fermilab's Role

Steve Kent, designer of the SDSS Pipeline system





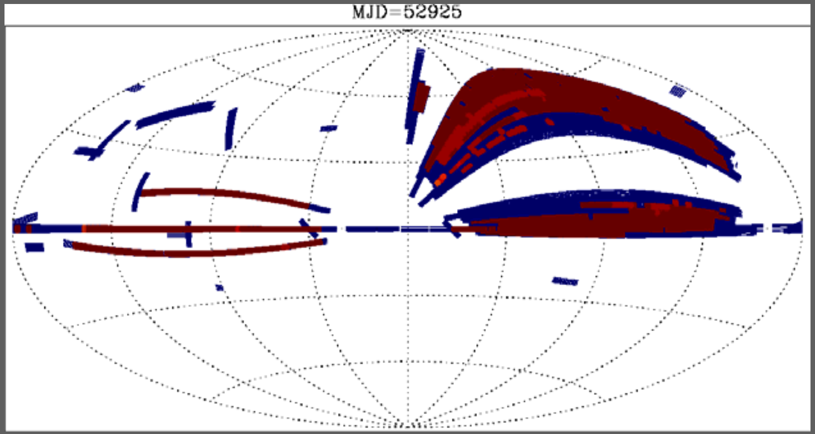
The SDSS Gaggle, 2002

Explaining large software projects to gaggles of astronomers.

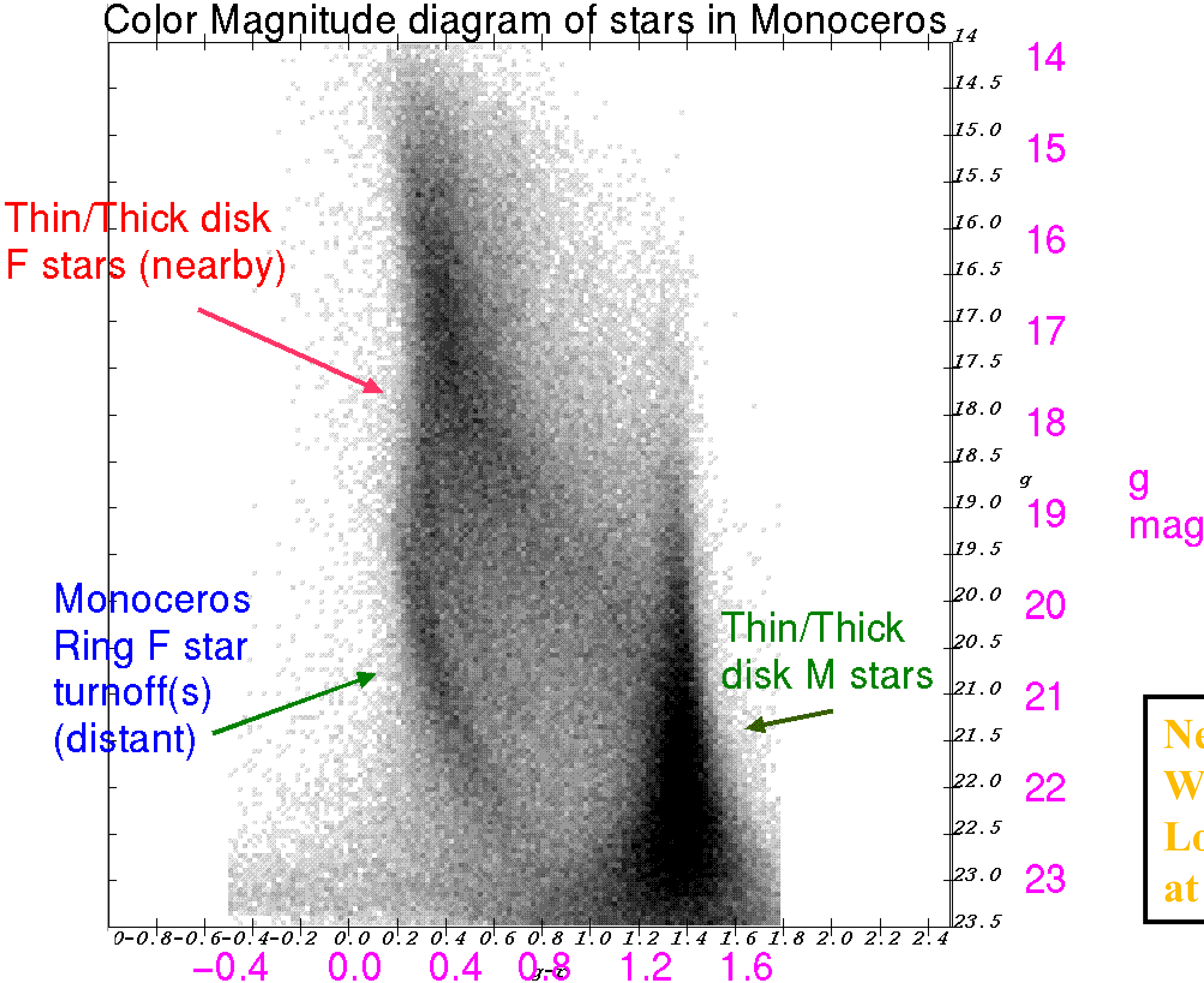
Another Fermilab strength

SDSS Extension

- New collaboration (new name?)
  - Starts 2005 (funding willing)
  - Primarily a 2-3 year spectroscopy project
  - 4000 sq-degrees of spectroscopy
  - 100/sq-degree

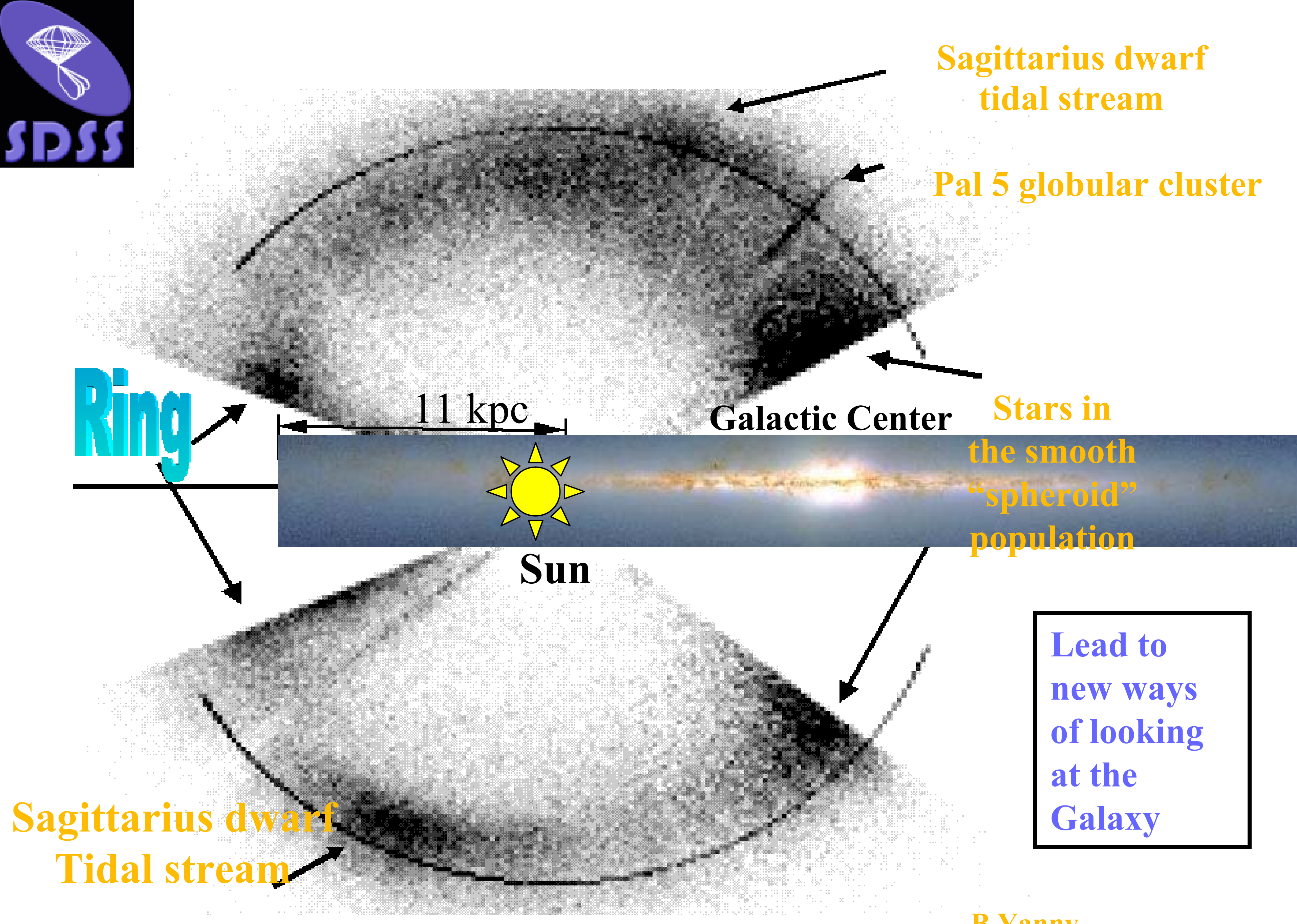


- Three core projects
  - Fill In the Gap
  - Structure of the Galactic Halo
  - Supernovae at 0.1 <= z <= 0.3



New Ways of Looking at Data

B Yanny

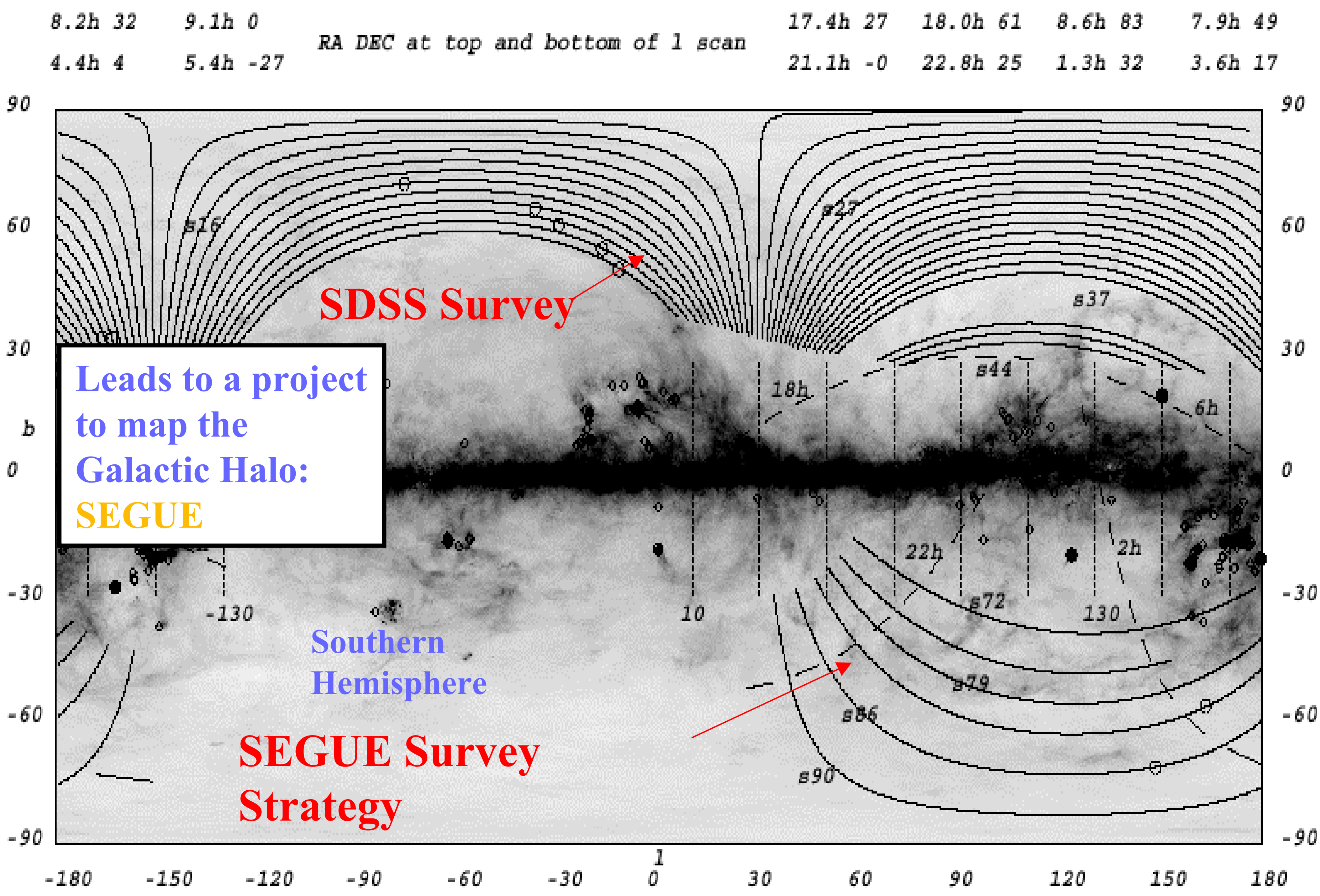


Lead to new ways of looking at the Galaxy

B Yanny

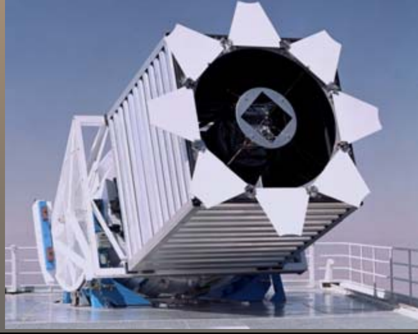
Leads to new structure in the halo of our Galaxy

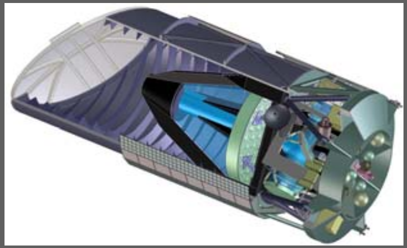
B Yanny

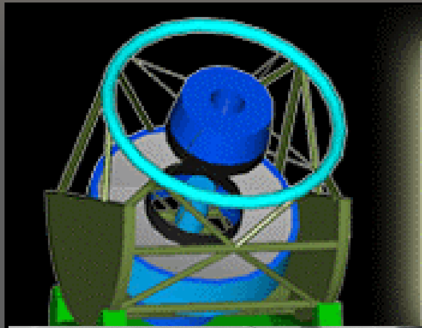


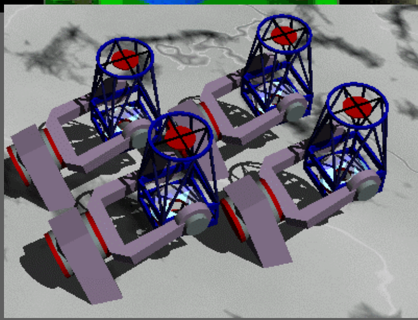
8.2h 32
4.4h 4
9.1h 0
5.4h -27
RA DEC at top and bottom of 1 scan
17.4h 27
21.1h -0
18.0h 61
22.8h 25
8.6h 83
1.3h 32
7.9h 49
3.6h 17
SDSS Survey
Leads to a project to map the Galactic Halo: SEGUE
Southern Hemisphere
SEGUE Survey Strategy
b
l

Context









- SDSS extension
  - 4000 sq-degrees of spectroscopy
- LSST
  - DMT/LSST 8m telescope, giant camera
  - PanSTARRS 4 1m telescopes, big cameras 2007?
- GSMT/CELT
  - 30meter ground telescope, deep spectroscopy
- JWST (aka NGST)
  - 6m space telescope,
  - infrared spectroscopy/imaging
- SNAP !
- WMAP
  - CMB, flying
- Planck
  - CMB: last word on fluctuations, but on to polarization

Scientific Motivation

Create the ultimate map of the Universe

$\Rightarrow$ *The SDSS was a start*

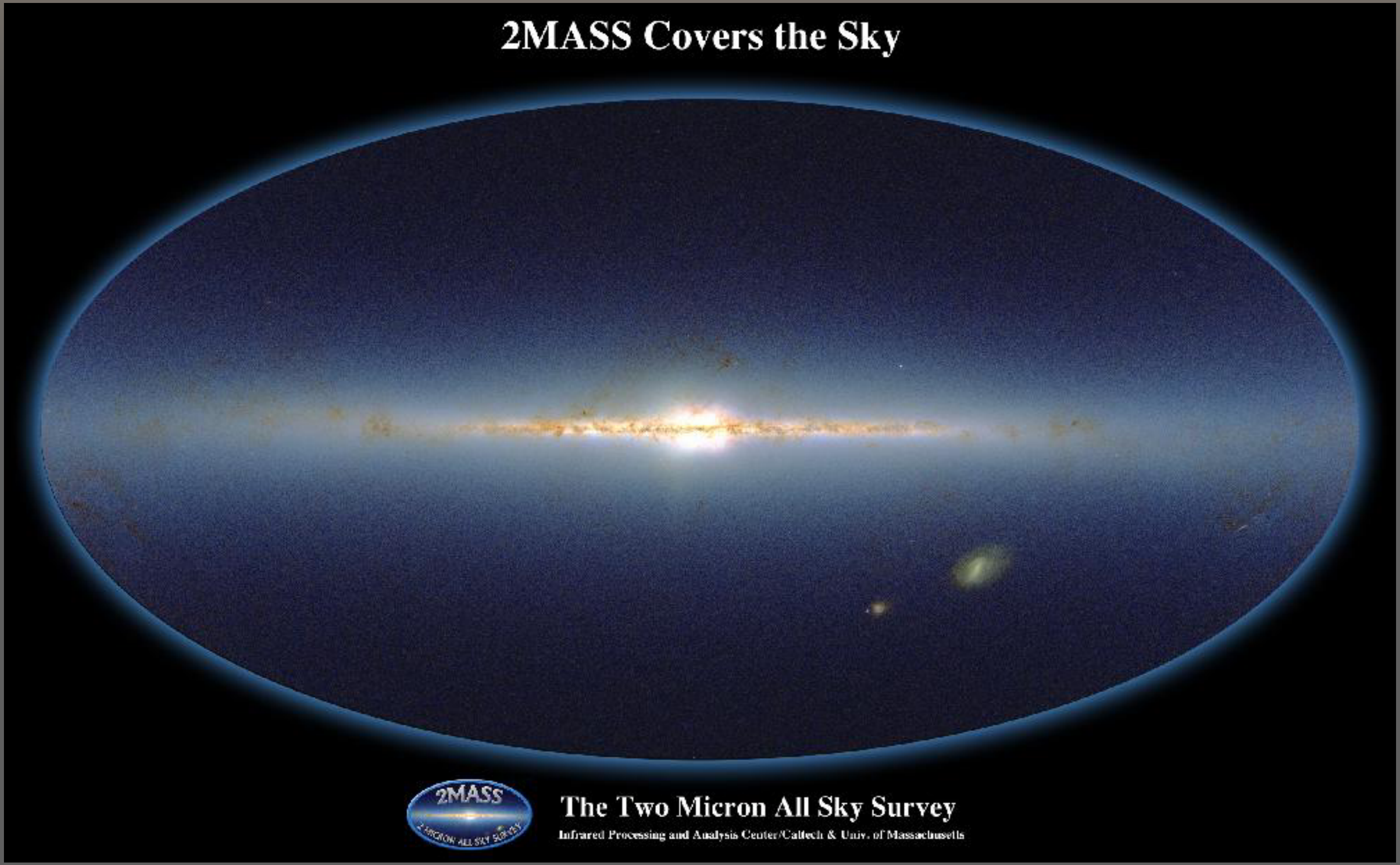
In order to study fundamental physics:

$\Rightarrow$ **What is the dark matter?**

$\Rightarrow$ **What is the dark energy?**

$\Rightarrow$ **What were the conditions during inflation?**

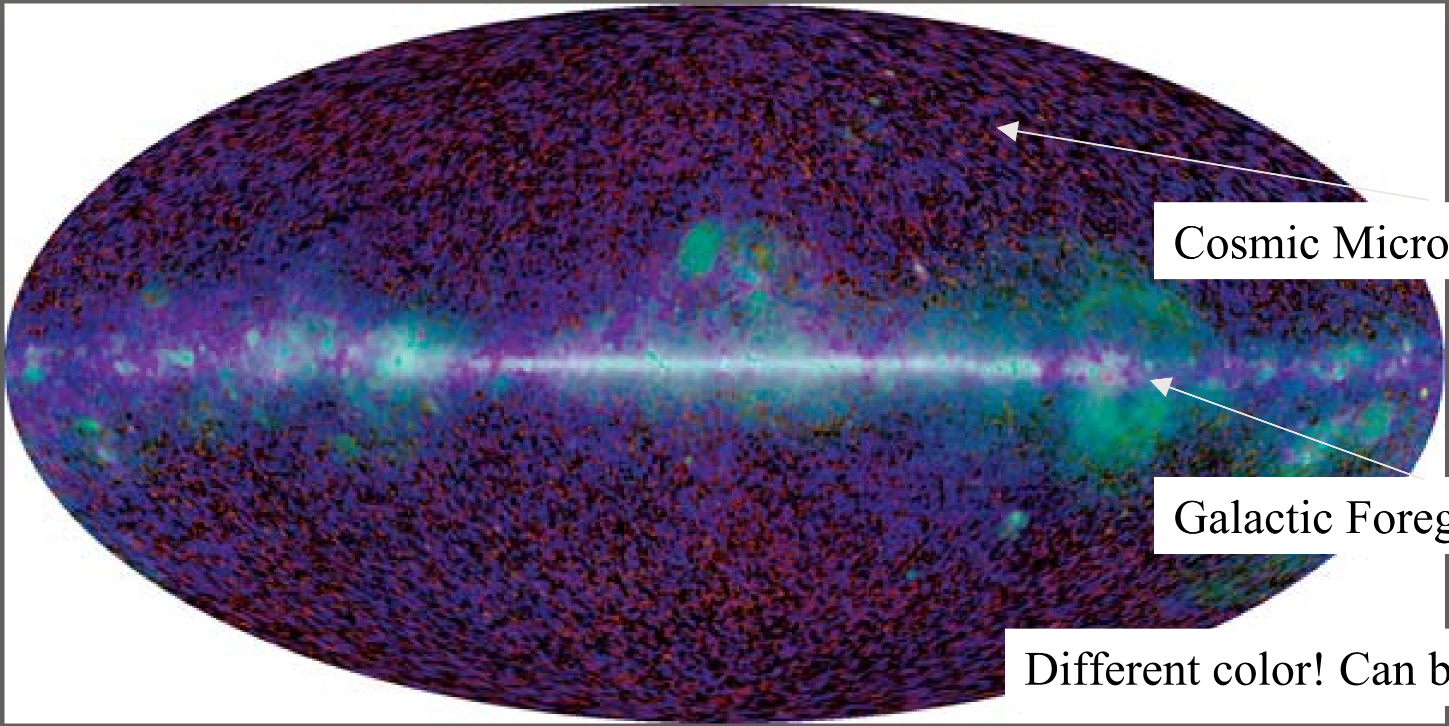
The Two Micron All Sky Survey



Too shallow to do much cosmology

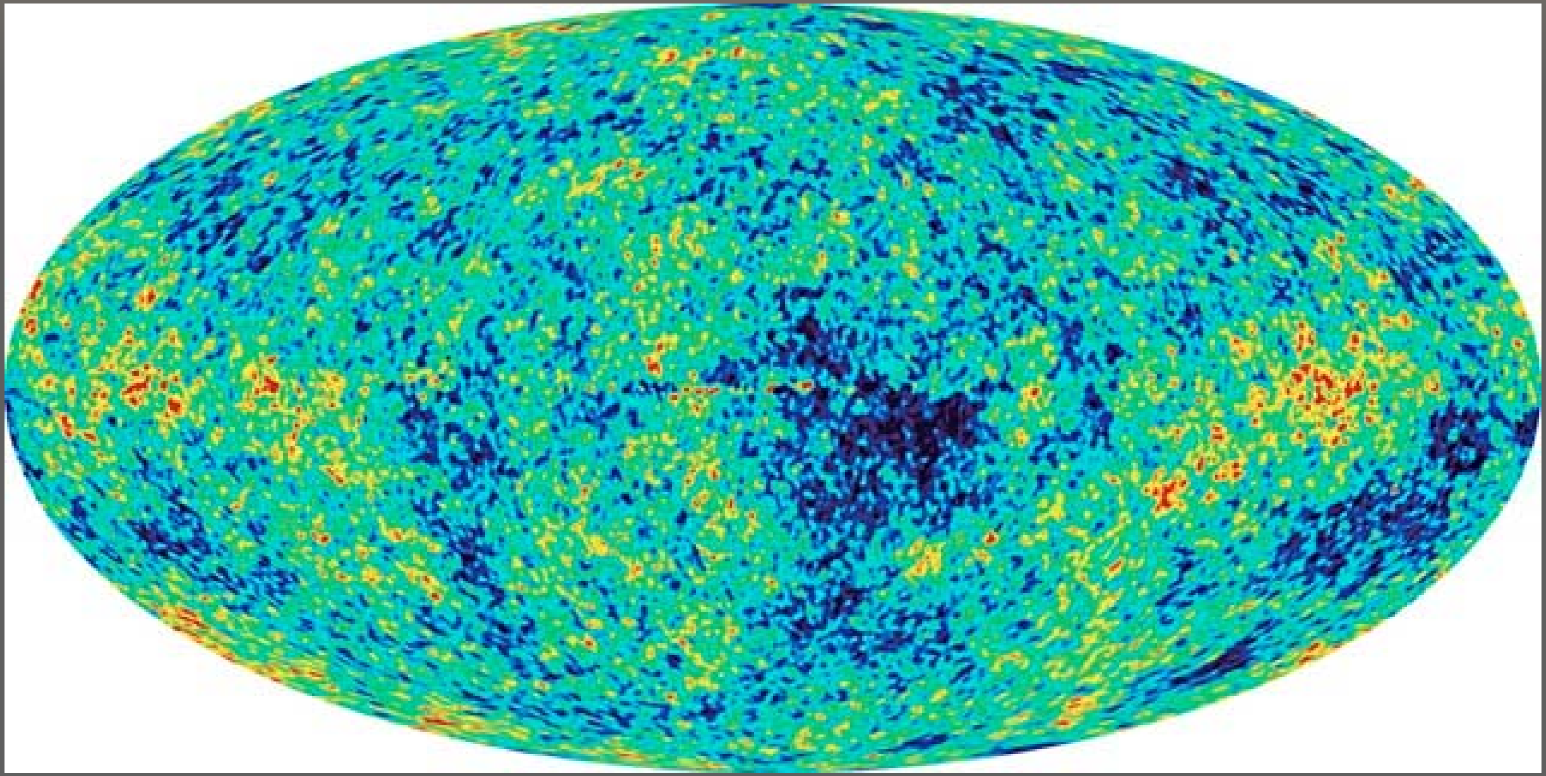
=> Sky coverage must be combined with depth

Wilkonsin Microwave Anisotropy Probe



The CMB is as deep as one can go

The Cosmic Microwave Background

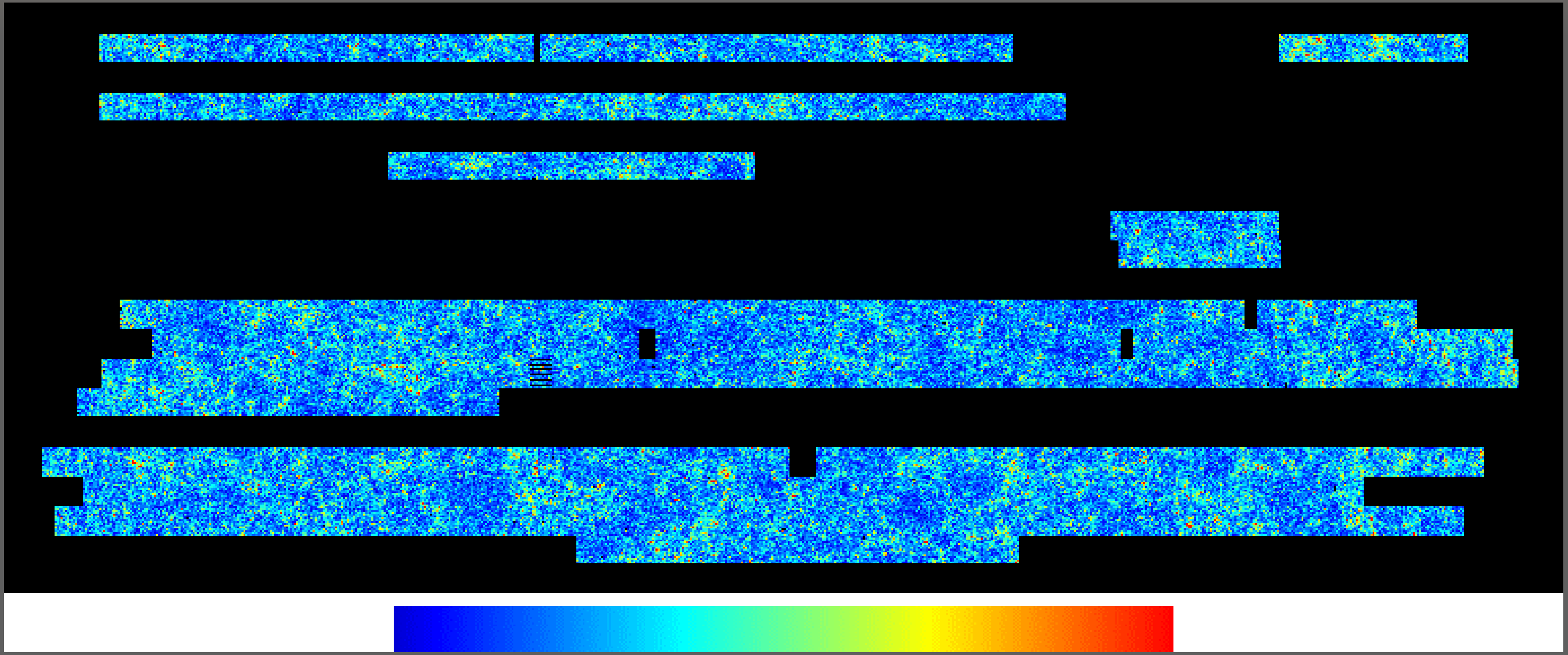


Imprint of density field at time of last scattering

Properties can be calculated from first principles!

WMAP Team

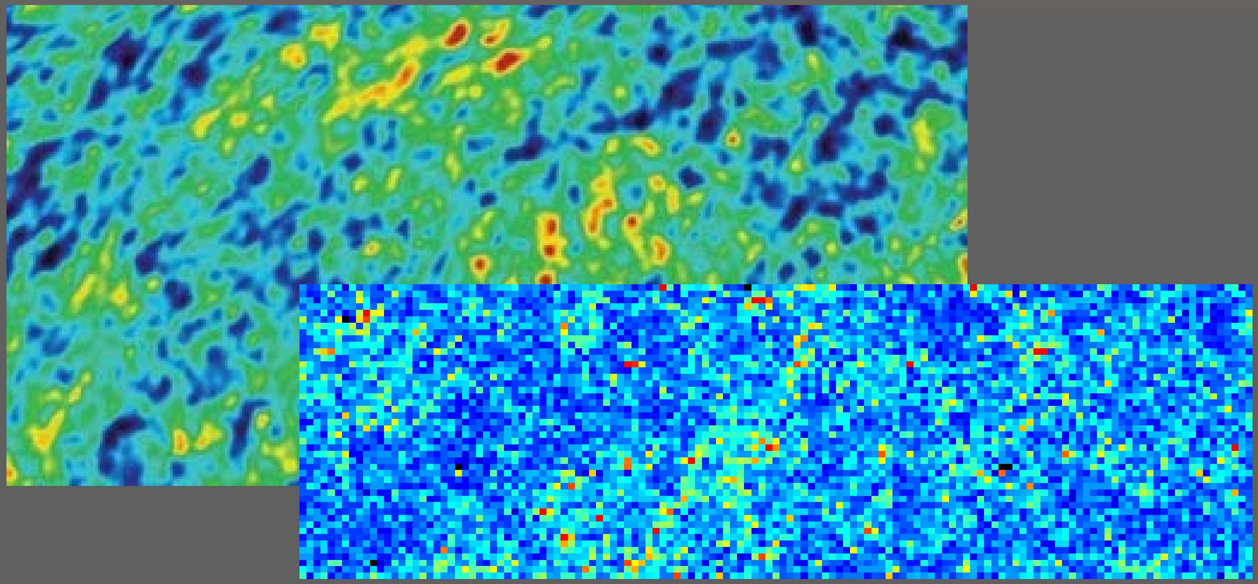
The SDSS DR1 Galaxy Map



Tracer of density field at z ~ 0.3

SDSS LSS Team

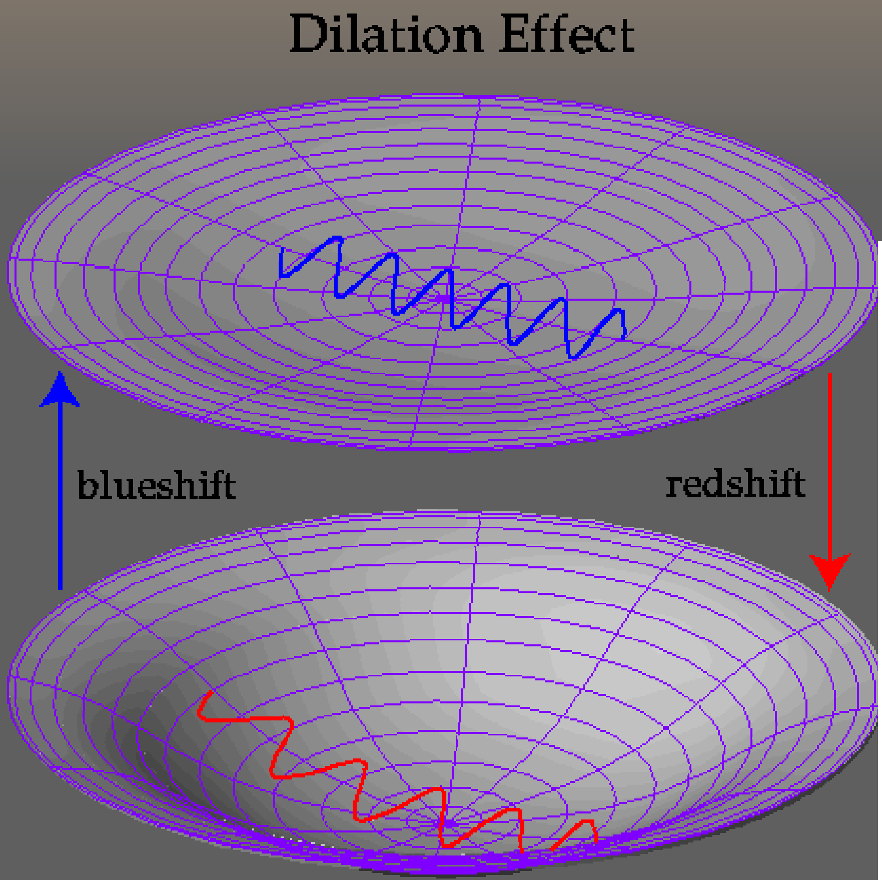
Cross correlate CMB & Galaxies

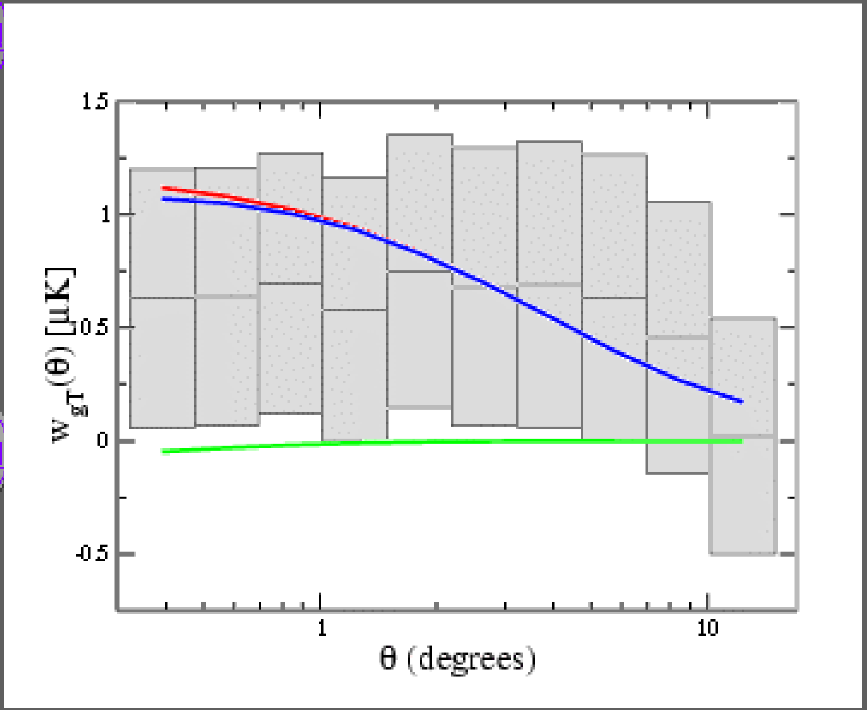


The large scale structure of galaxies and dark matter imprint the CMB photons as they pass to through

=> Cross correlate galaxies with CMB ?!

Integrated Sachs Wolf Effect



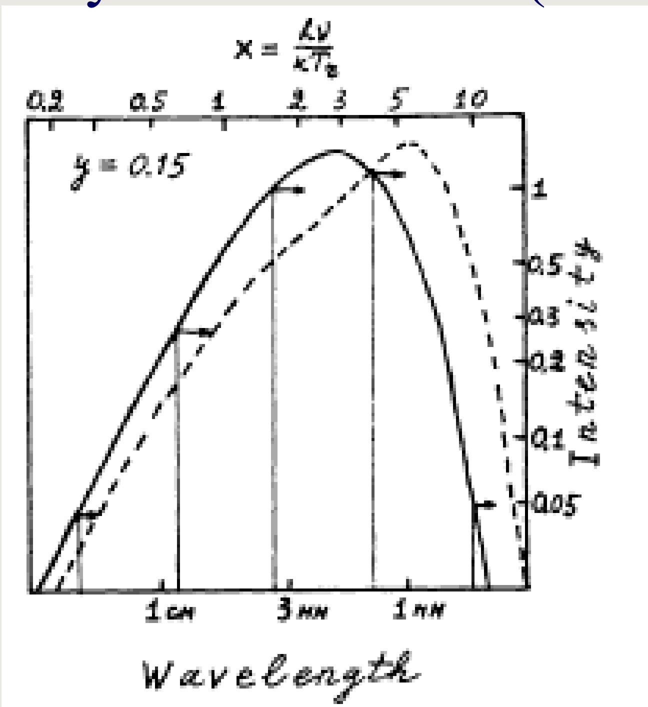


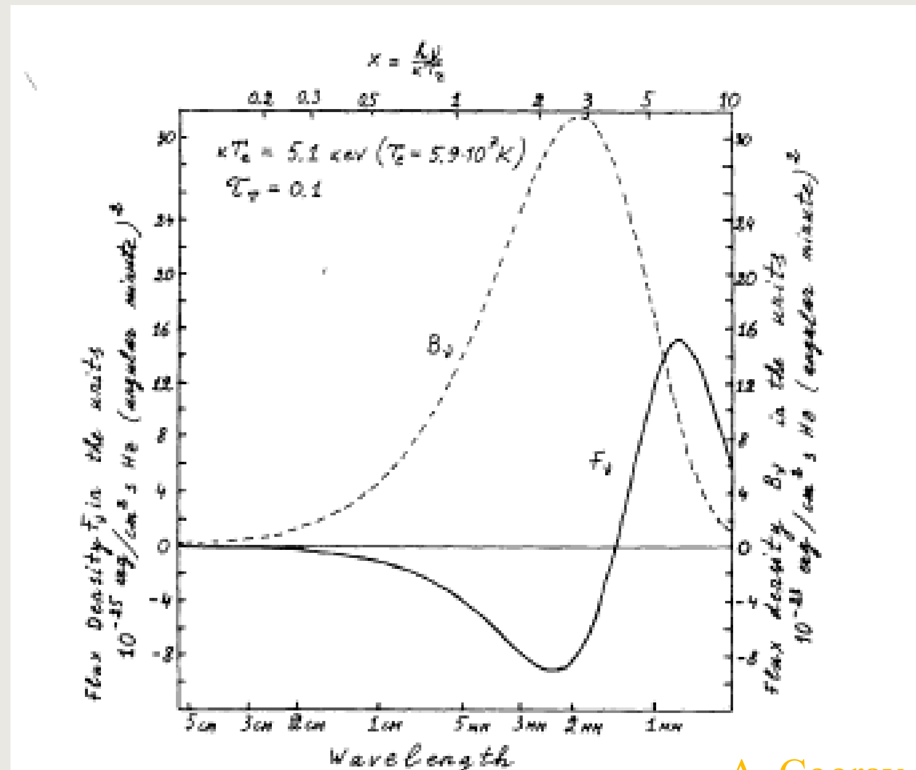
Red is predicted ISW. Green predicted SZ.

Sunyaev-Zeldovich Effect

⇒ *Scattering moves photons from low frequencies (RJ part of the frequency spectrum) to high frequencies (Wien regime)*

In the language of
Sunyaev-Zel'dovich (1980):





A. Cooray

Frequency shift the CMB blackbody

and the difference (wrt to CMB)

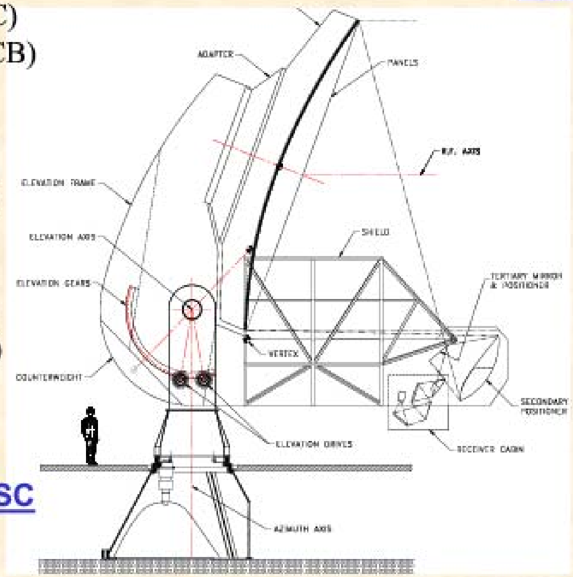
The South Pole Telescope

8m (10m) South Pole Telescope (SPT) and 1000 element bolometer array

PEOPLE

Carlstrom (UC)
Holzapfel (UCB)
Lee (UCB)
Leitch (UC)
Meyer (UC)
Mohr (UIUC)
Padin (UC)
Pryke (UC)
Ruhl (UCSB)
Spieler (UCB)
Stark (CfA)

NSF – OPP
Raytheon PSC
CfCP



Low noise, precision telescope

- 20 um rms surface over 8m
- 1 arcsecond pointing
- 1.25 arcminute at 2 mm
- 'chop' entire telescope
- 3 levels of shielding
  - 1 m radius on primary
    8 m precision surface
  - inner moving shields
  - outer fixed shields

SZE and CMB Anisotropy

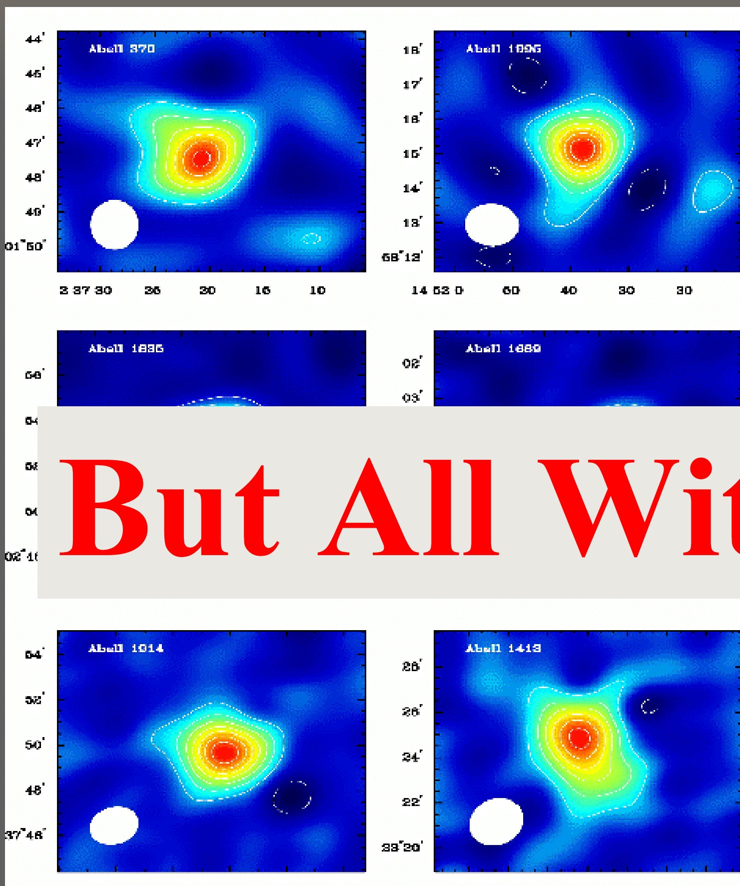
- at least two bands
  150 & ~250 GHz
- 4000 sq deg SZE survey
- deep CMB anisotropy fields
- deep CMB Polarization fields

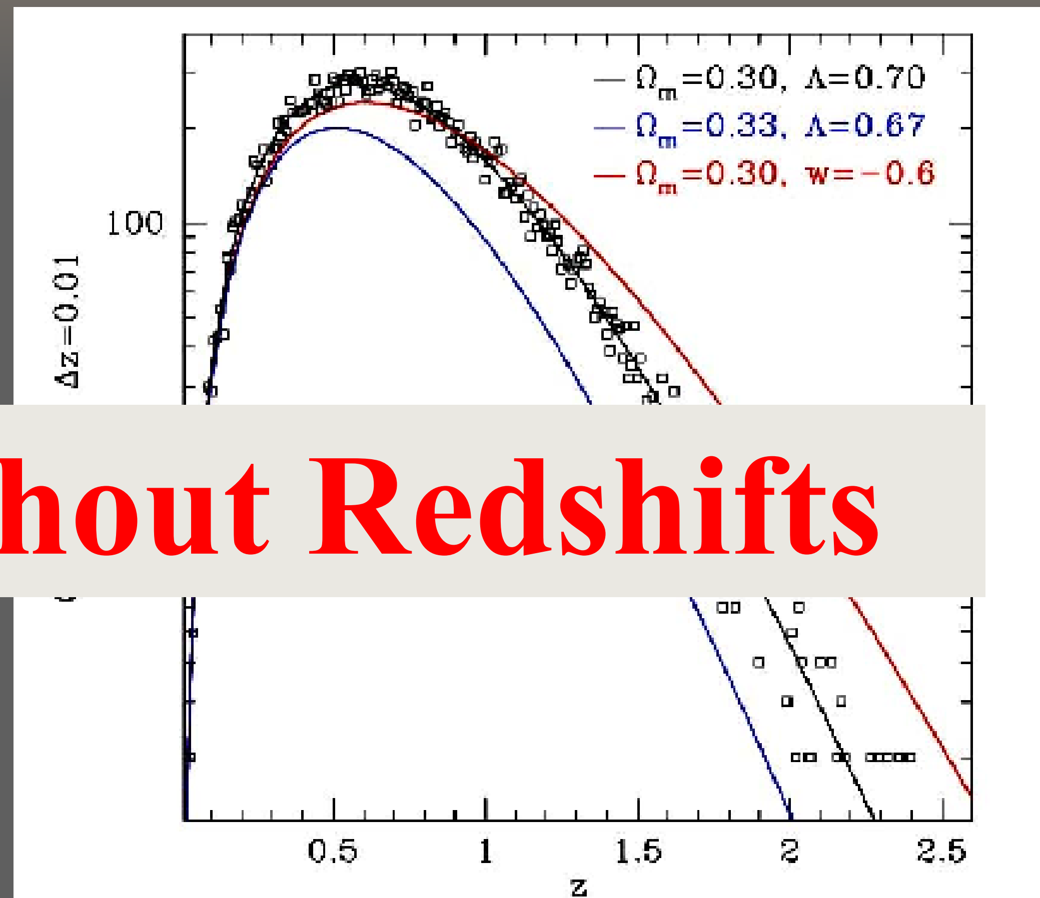
NSF-OPP Funded & scheduled for Nov 2006 deployment

J. Carlstrom

SPT 4000 sq degree Survey

Could be done in one austral winter



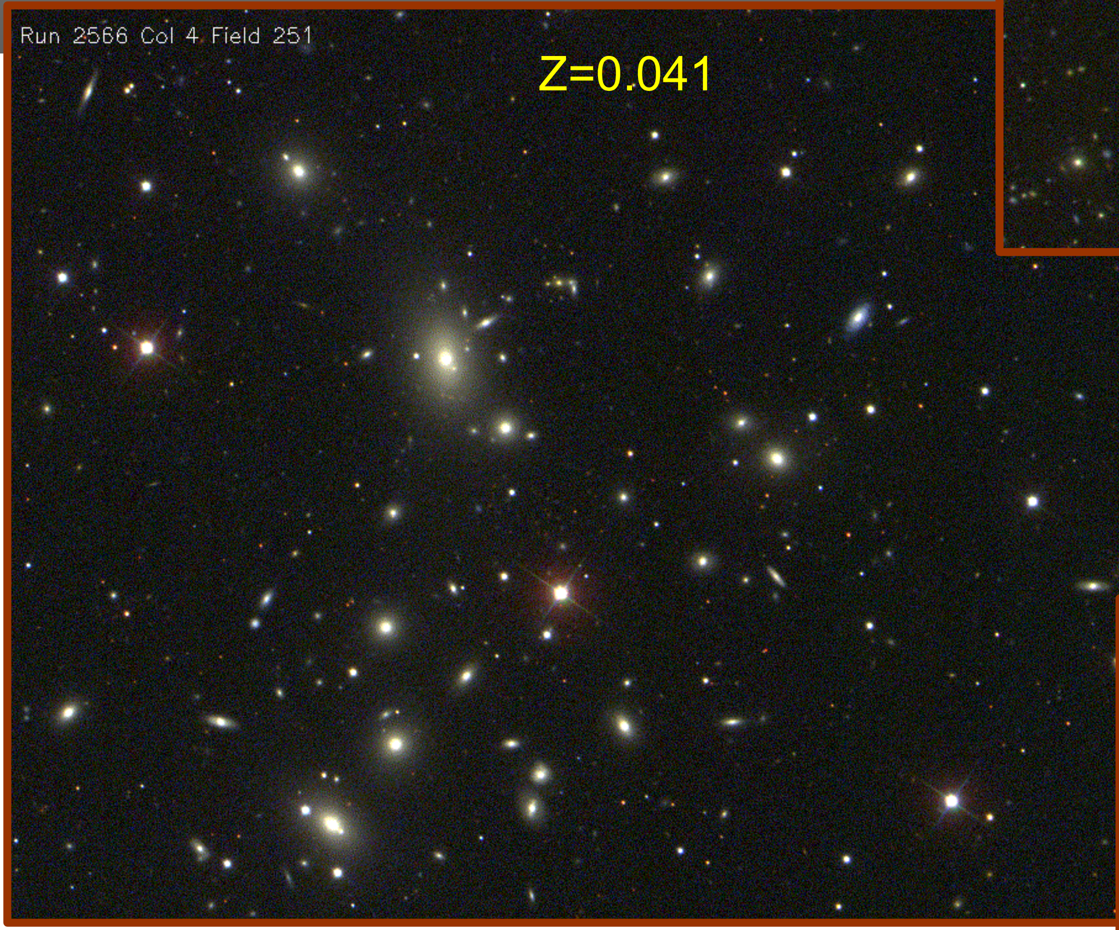


But All Without Redshifts

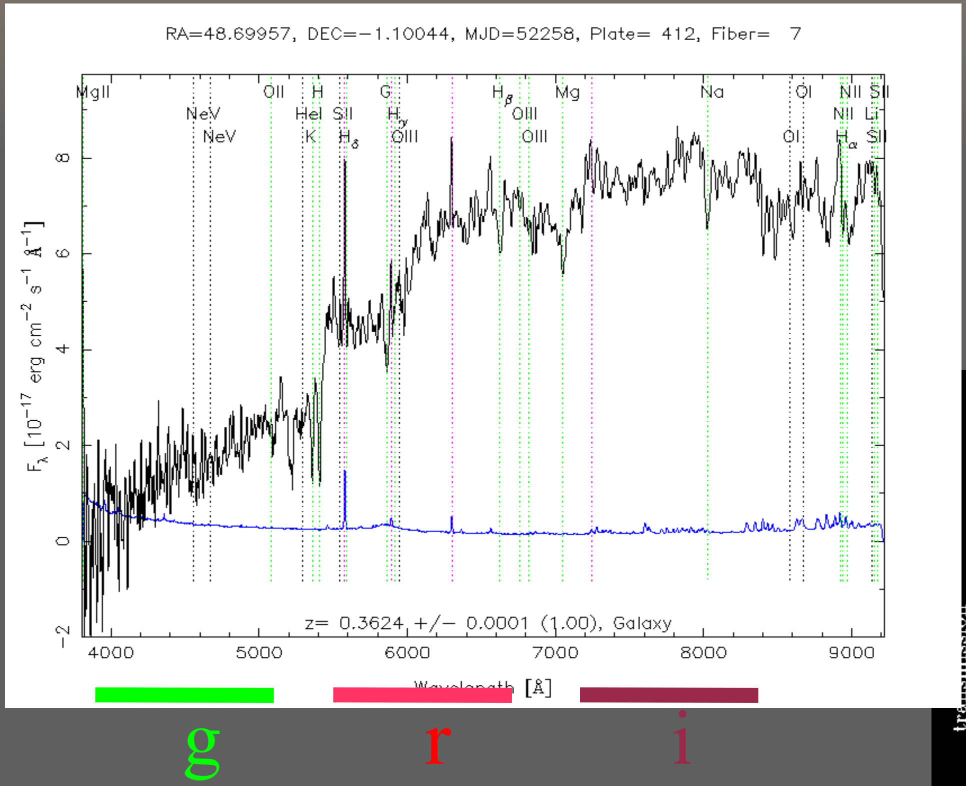
SZ observations of clusters

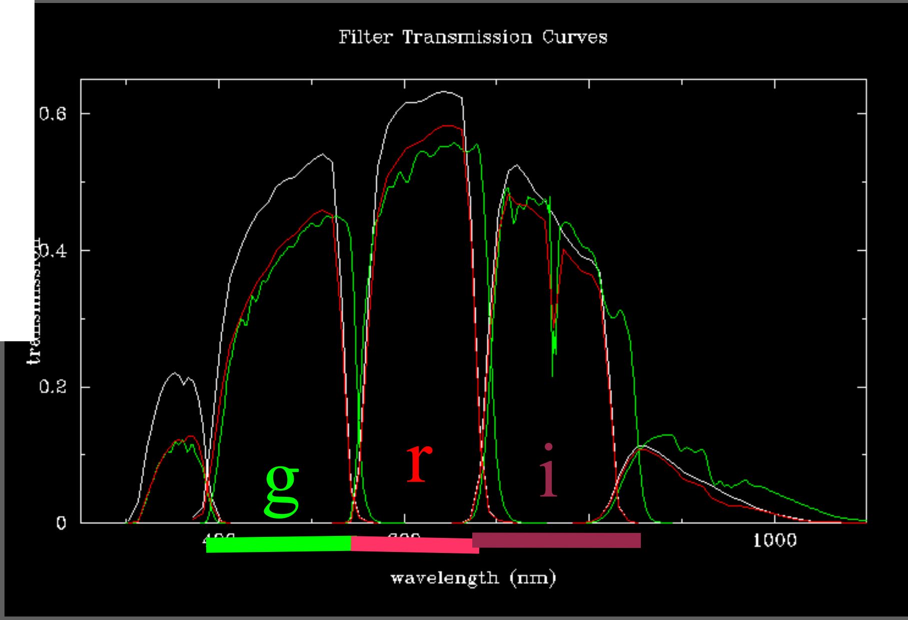
dN/dz for 4000 sq-degree
20,000 clusters, 80% z <= 1

Example color cluster images from the SDSS



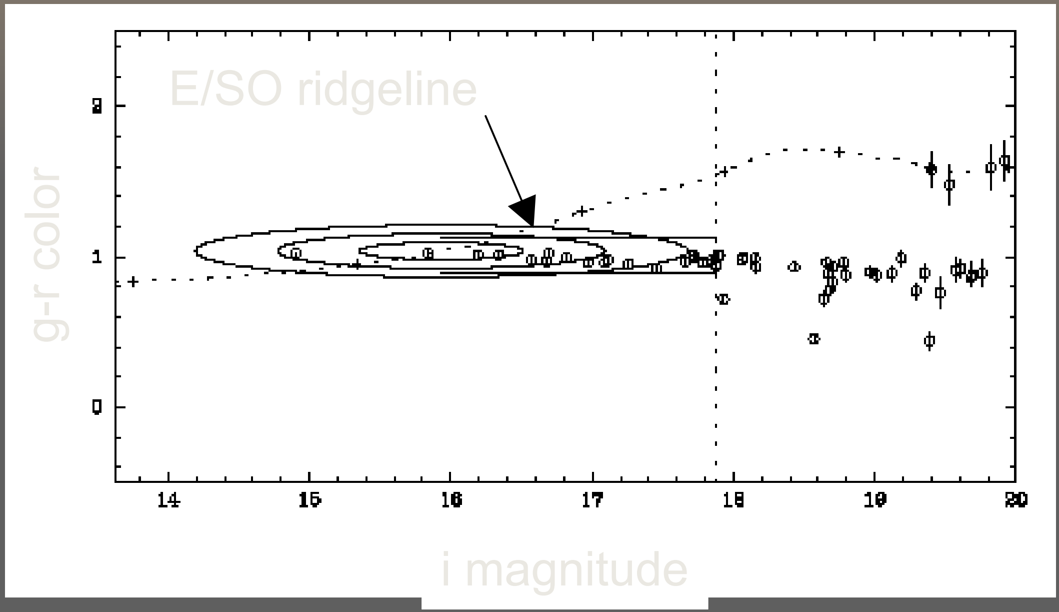
Elliptical Galaxy Spectrum

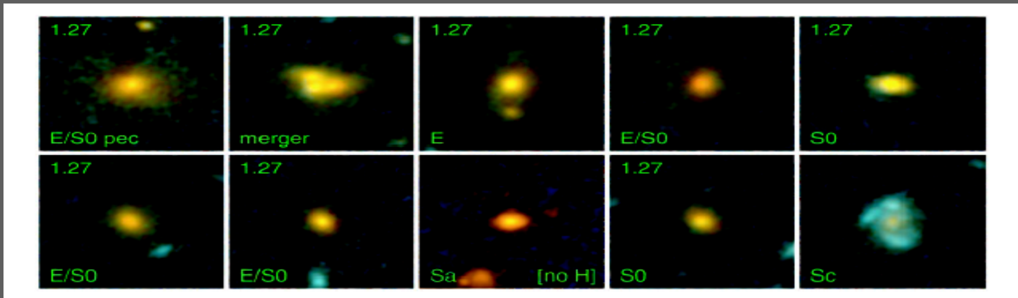




Finding red sequence clusters

- Clustering in position-color space essentially eliminates contamination by projection
- Gladders & Yee (2000), Goto et al. (2001), Annis et al. (2003)
- E/SO ridgeline provides extremely accurate ($\Delta z \approx 0.01$) photometric redshift
- Red sequence in place throughout SDSS volume and beyond, to z>1….

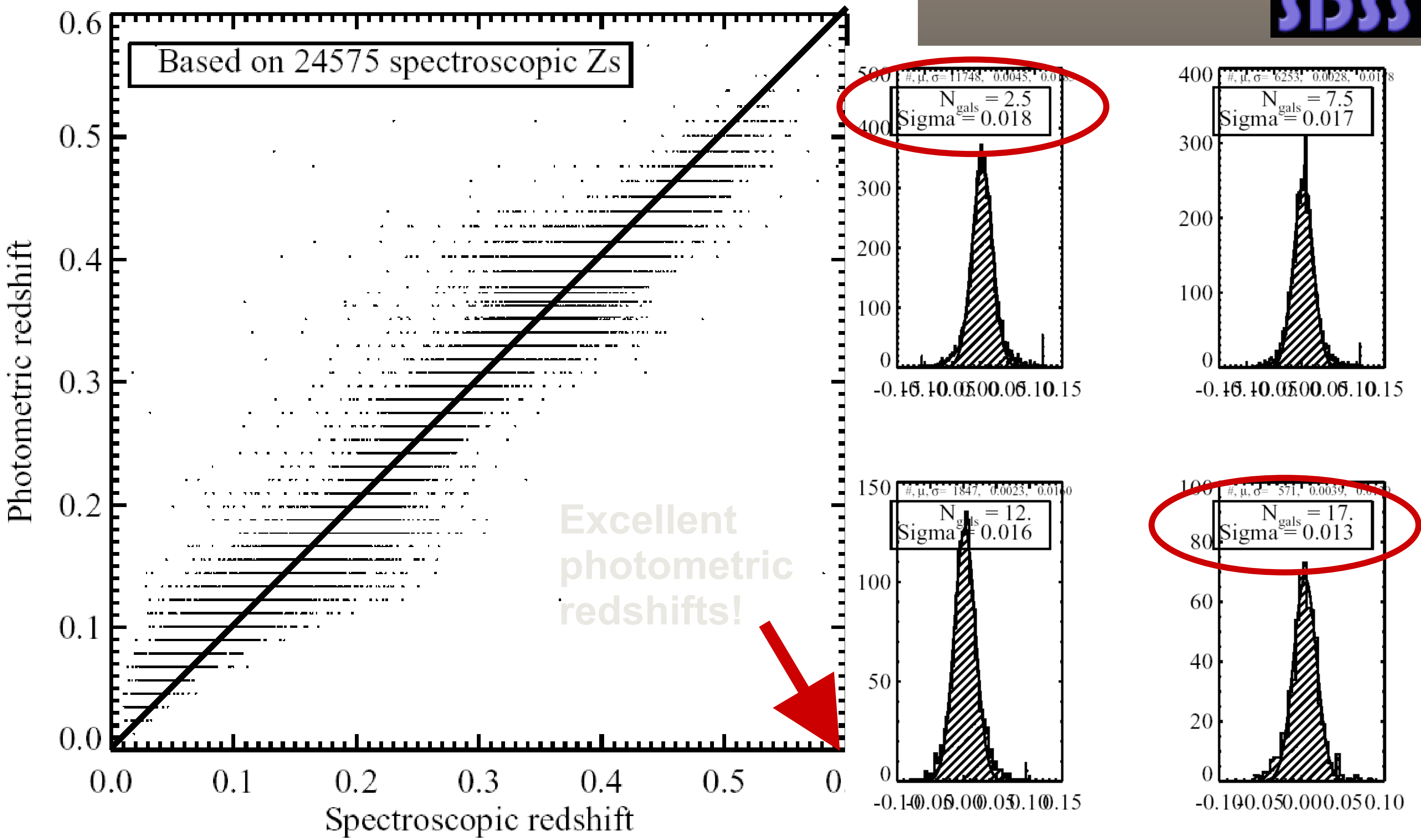




Red sequence galaxies at z=1.27
(van Dokkum et al, 2000)

T. Mckay

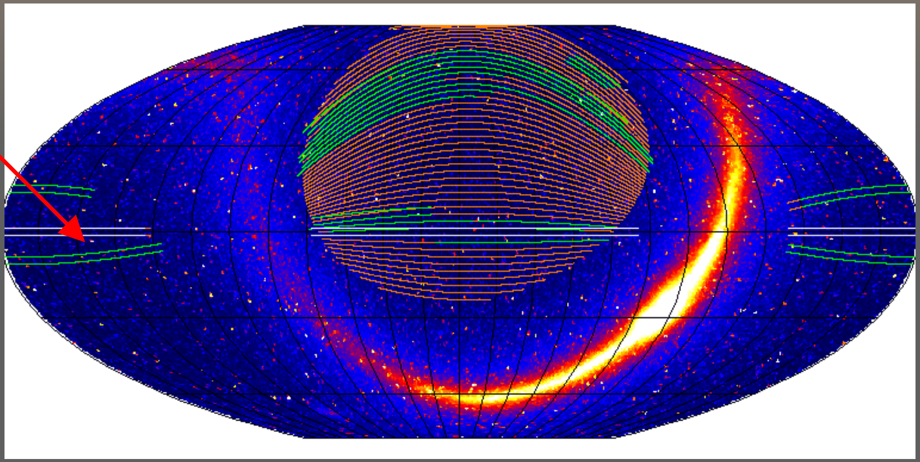
The maxBCG sample: redshift



T. Mckay

Limitations of Existing Instruments

SPT is at south pole, sees Southern Galactic Cap



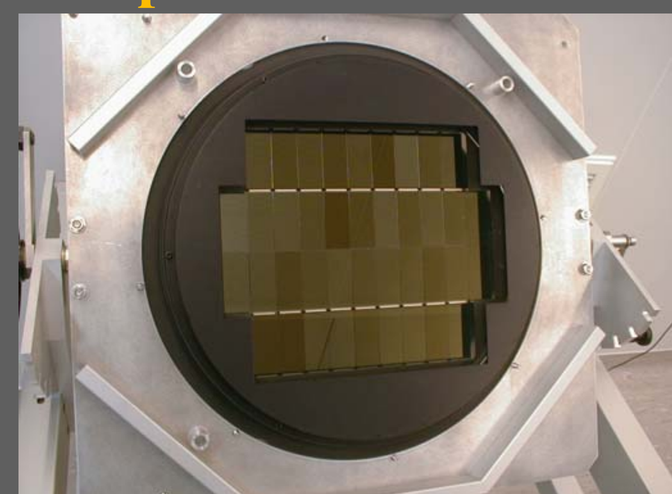
- SDSS: not deep enough
  - z = 0.3 – 0.5
  - wrong hemisphere, as are:
- CFHT Legacy Survey
  - 20 N declination (2 airmass @ -40 dec, meridian)
- PanStarrs
  - 20 N declination (2 airmass @ -40 dec, meridian)
- LSST
  - 2013 (?)
  - Will definitively survey they sky in optical

A Wide Field Imager on the CTIO Blanco 4

- Collecting area:10 m^2
- Prime focus:
  - f/2.87
  - 15 micron pixels => 0.267”/pixel
  - Field of view (diameter):
    - Current: 0.8 degree
    - Need: 1.8 degree

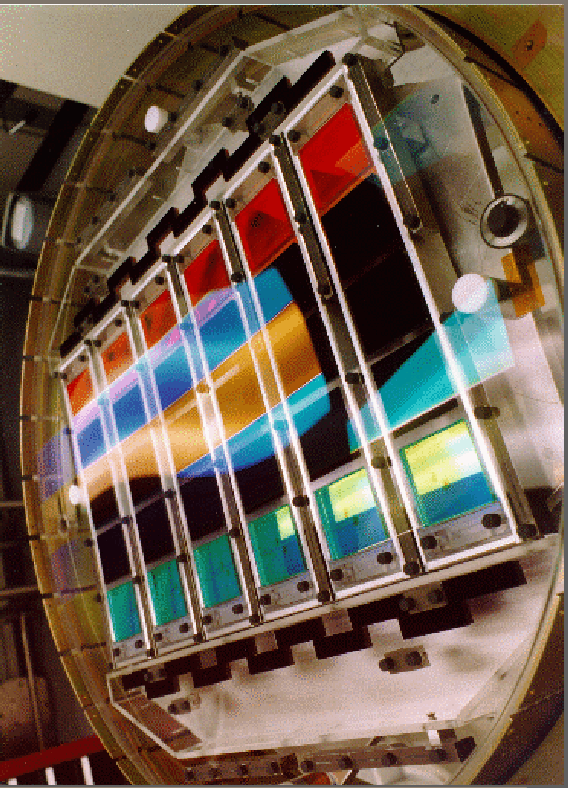
A project in which Fermilab could take a leadership role

- Need to build a 20k x 20k pixel Camera
  - 400 Megapixel
  - Big. State of the art last January: Megacam at 16k x 16k
  - 2007-2008?



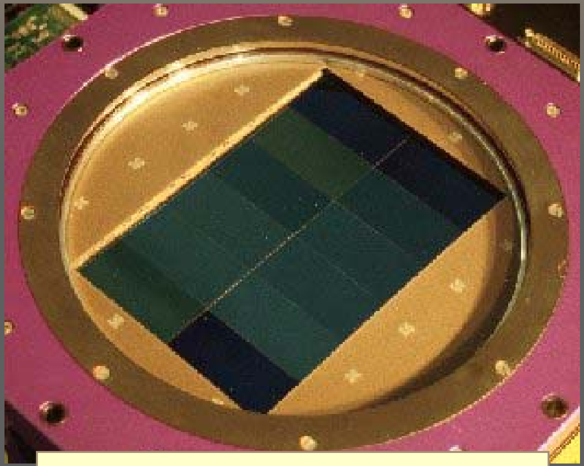
A four filter survey to i=24 over 4000 sq-degrees

Large format cameras



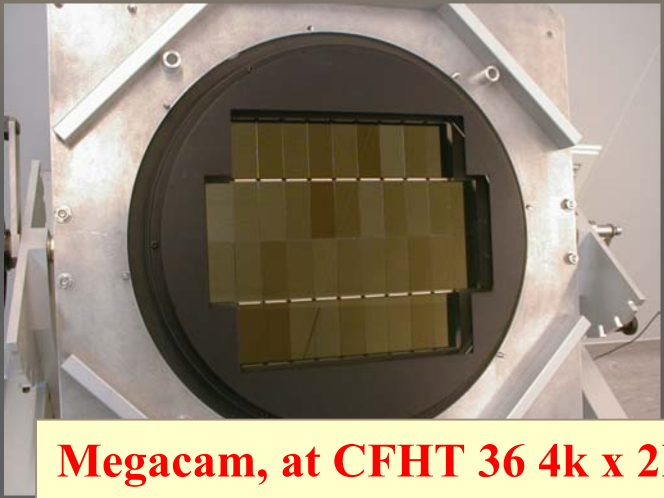
SDSS 30 2k x 2k

120 Megapix 1998



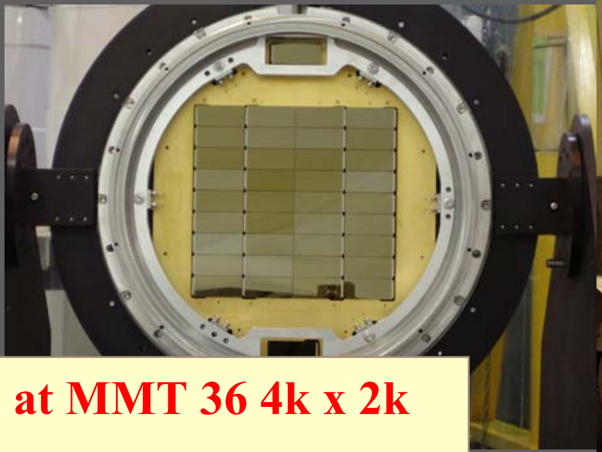
CFH12k 12 4k x 2k

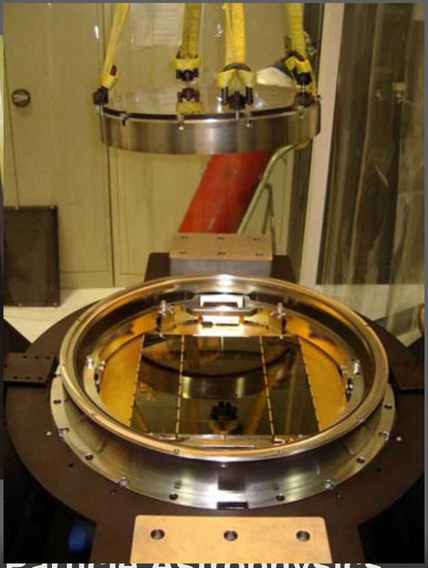
100 Megapix 2000



Megacam, at CFHT 36 4k x 2k

300 Megapix 2003

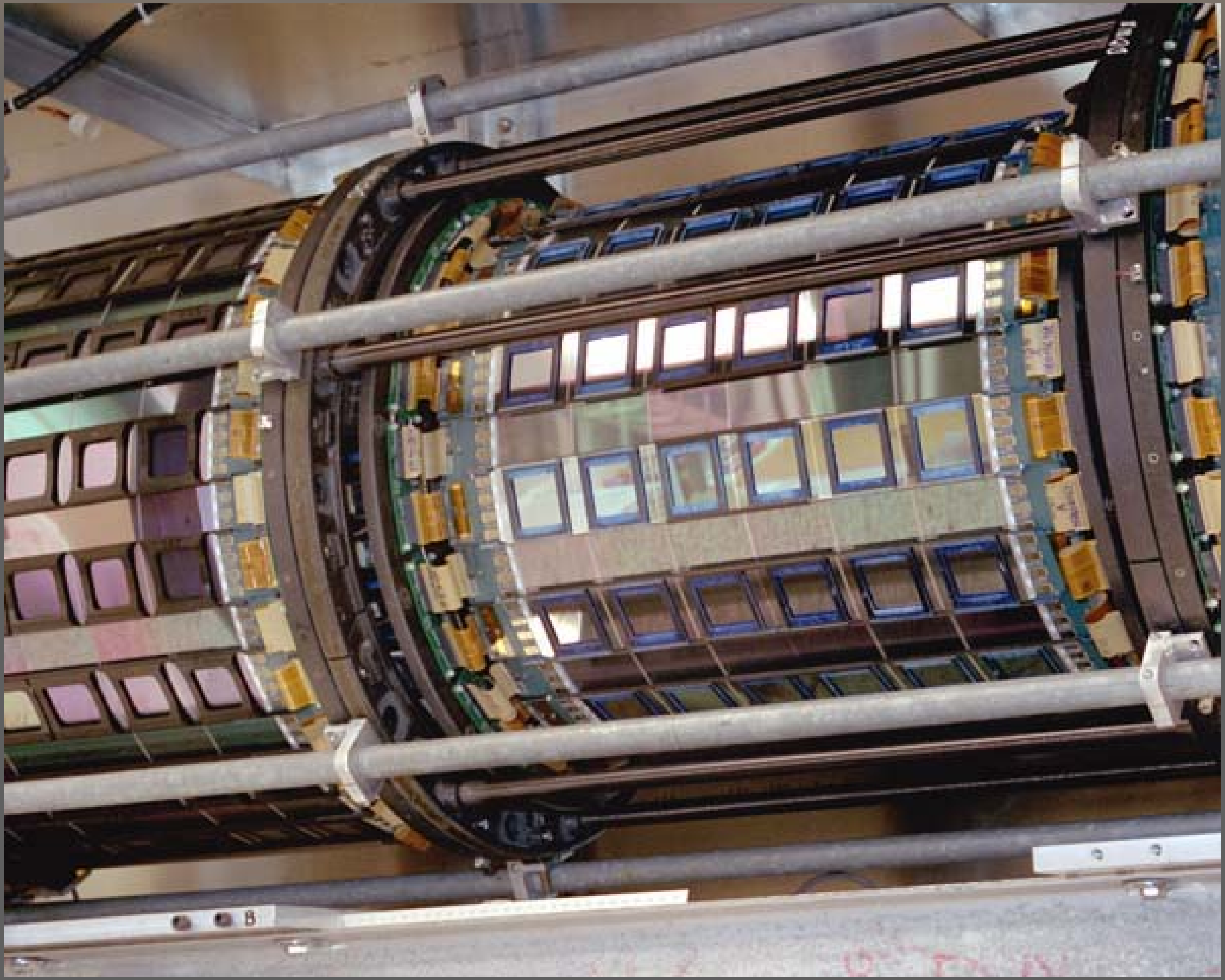




Megacam at MMT 36 4k x 2k

300 Megapix 2003

We can do that...



Elements of a Survey

Science case! for proposals

- Wide field corrector
- Camera
  - CCDs/detectors
  - Electronics
    - Readout
    - Control
  - Mechanical
  - Vacuum systems
  - Cooling systems
- Data acquisition system
  - Hardware
  - software
- Survey observation strategy
- Standard star strategy
- Science Software
  - Calibration pipeline
  - Coadd pipeline
  - Galaxy measurement pipeline
  - Cluster finding pipeline
- Data production
- Data distribution
- Simulation
- Science Analysis

Fermilab's Strengths

- Project Management
- Software System Design
- Data Processing and Distribution
- Pipeline Development
- Data Acquisition
- Mountaintop Engineering
- Calibration
- Analysis

We should add detector/camera construction!

CMB Optical Followup:

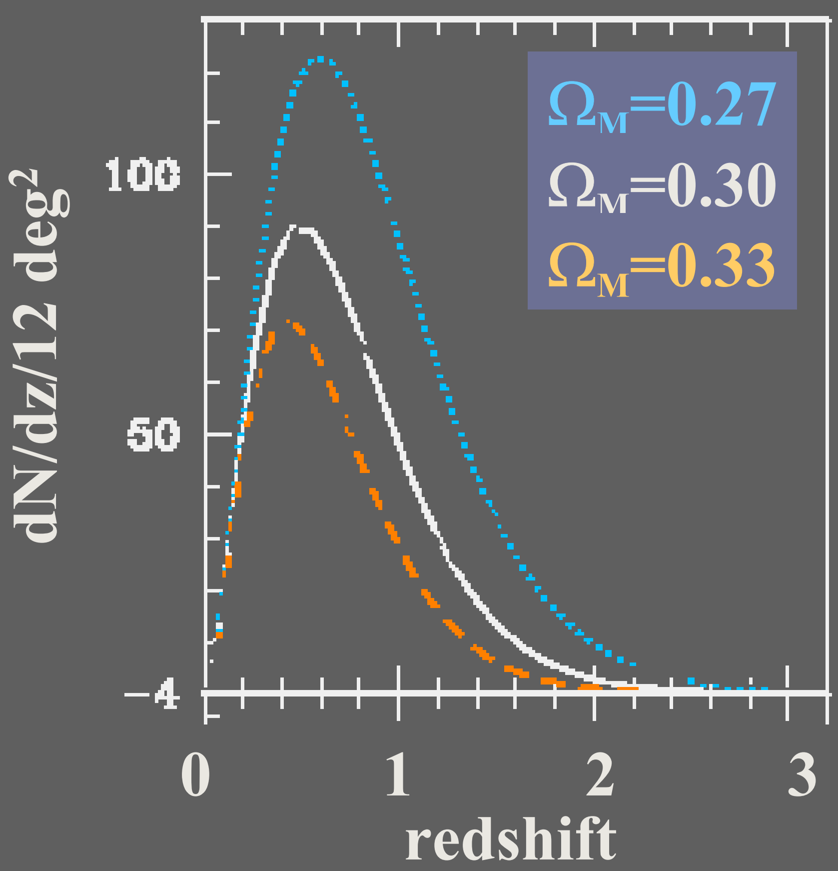
- One follows up by a 4000 square degree imaging survey, in 4 bandpasses, to i~24. This allows:

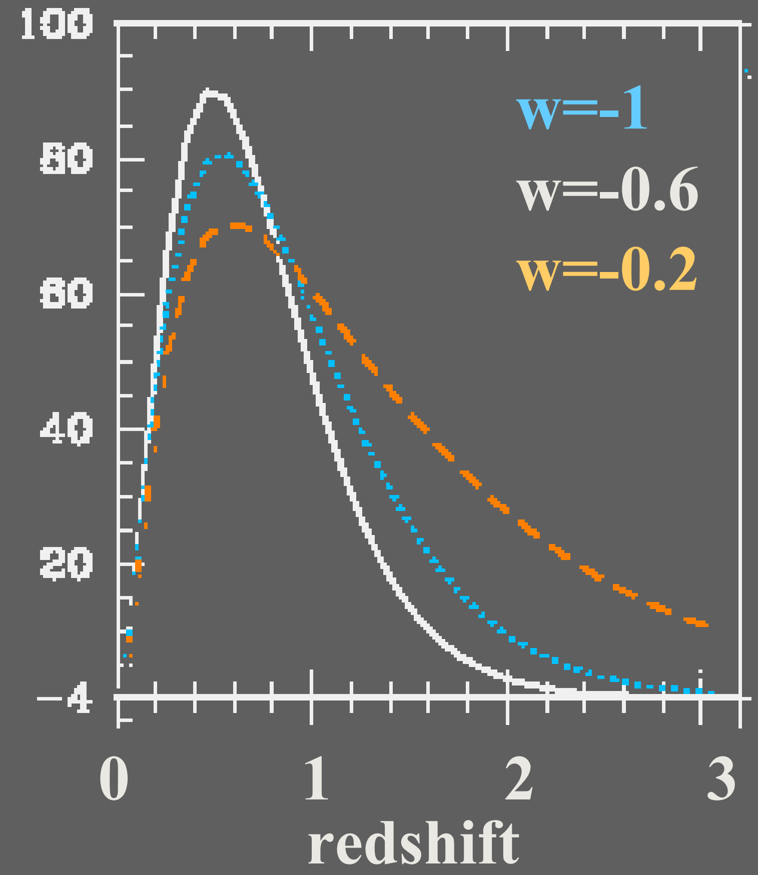
- Photometric redshifts for ~25,000 SZ clusters
- Optically selected sample of clusters
  - redshift and mass estimates
- Weak lensing mass estimates of these clusters
- Weak lensing cosmic shear measurements
  - with photo-z tomography
- Galaxy clustering on large scales to z ~ 1
- Galaxy-galaxy lensing

… and much more.

Sensitivity to Ω_M,w in SZE Survey

Haiman, Mohr & Holder 2001





overall scaling and σ_8 change

volume (low-z) + growth (high-z)

Cluster Power Spectra

- **High bias of galaxy clusters enables accurate measurement of cluster P(k):**

  $\Delta k/k=0.1 \rightarrow P(k)$ to 7% at k=0.1

  $k<0.2 \rightarrow P(<k)$ to 2%

- **Expected statistical errors from 25,000 clusters:**

  Ω_M ~ to 0.013 - geometrical test

  w ~ to 0.04 - geometrical test

  $\Omega_\nu h^2$ ~ to 0.002 - usual shape test

  → **Combine with dN/dM** **(Majumdar & Mohr 2003)**

- **Noteworthy for survey planning**
  - baryon rings are useful: contain ~ half the information
    make test robust (CMB, β)
  - photometric redshift (0.01) sufficient to recover most of the info
  - including knowledge of bias would much improve constraints
  - z < 1 clusters are best complement to CMB

An advantage unique to clusters?

- **A cluster sample can deliver <u>many</u> observables**

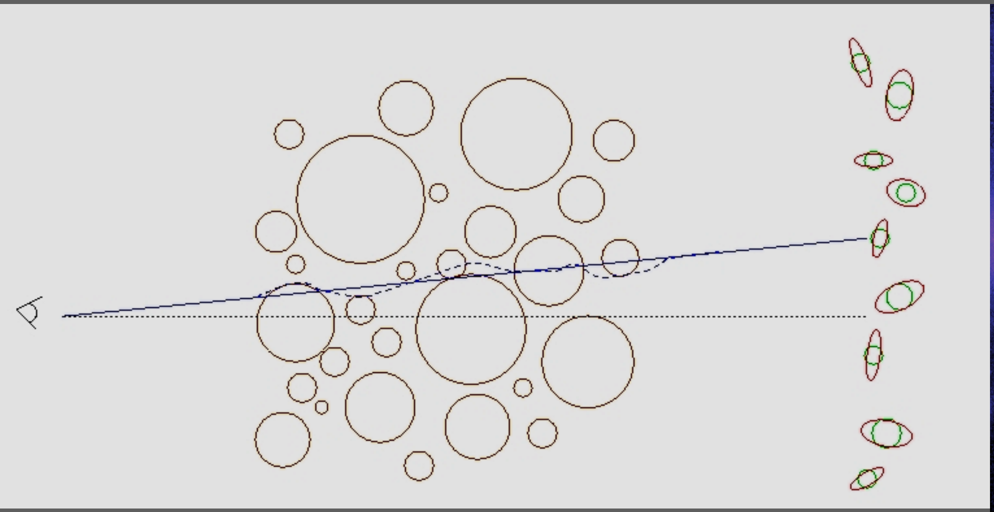
SZE decrement	X-ray flux
Angular size	Number of galaxies
Spatial distribution (2d, 3d)	Lensing signatures

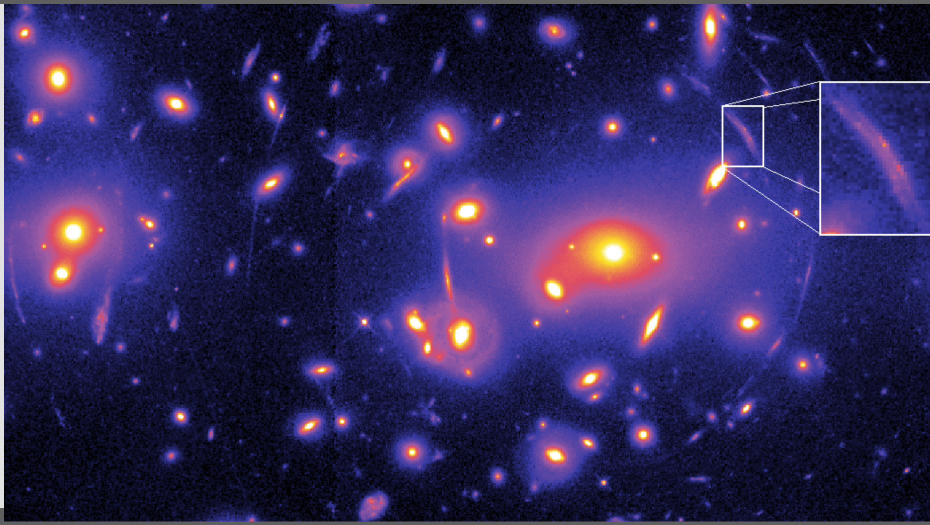
- **We can construct <u>several</u> cosmology tests**

dN/dz – abundance evolution (including mass function dN/dM)	**Best?**
P(k) – spatial power spectrum (including Alcock-Paczynski)	**better**
Scaling relations – between SZ/X-rays/sizes (including d_A measurement)	**good**

Simultaneous determination of cosmological and cluster structural parameters (with their evolution)

Weak Gravitational Lensing





Distortion Matrix:

$$\Psi_{ij} = \frac{\partial \delta\theta_i}{\partial \theta_j} = \int dz\, g(z) \frac{\partial^2 \Phi}{\partial \theta_i \partial \theta_j}$$

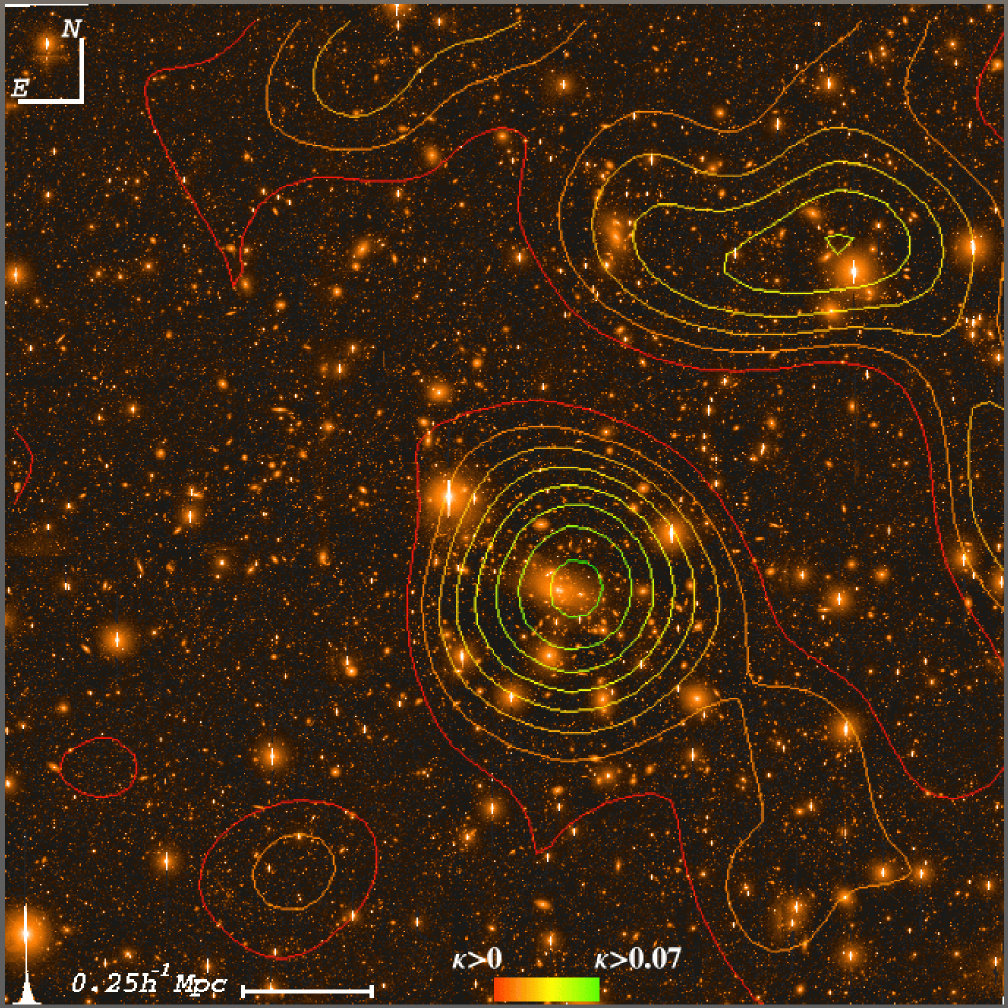
Theory

→ Direct measure of the distribution of mass in the universe, as opposed to the distribution of light, as in other methods (eg. Galaxy surveys)

Weak Gravitational Lensing Of Clusters

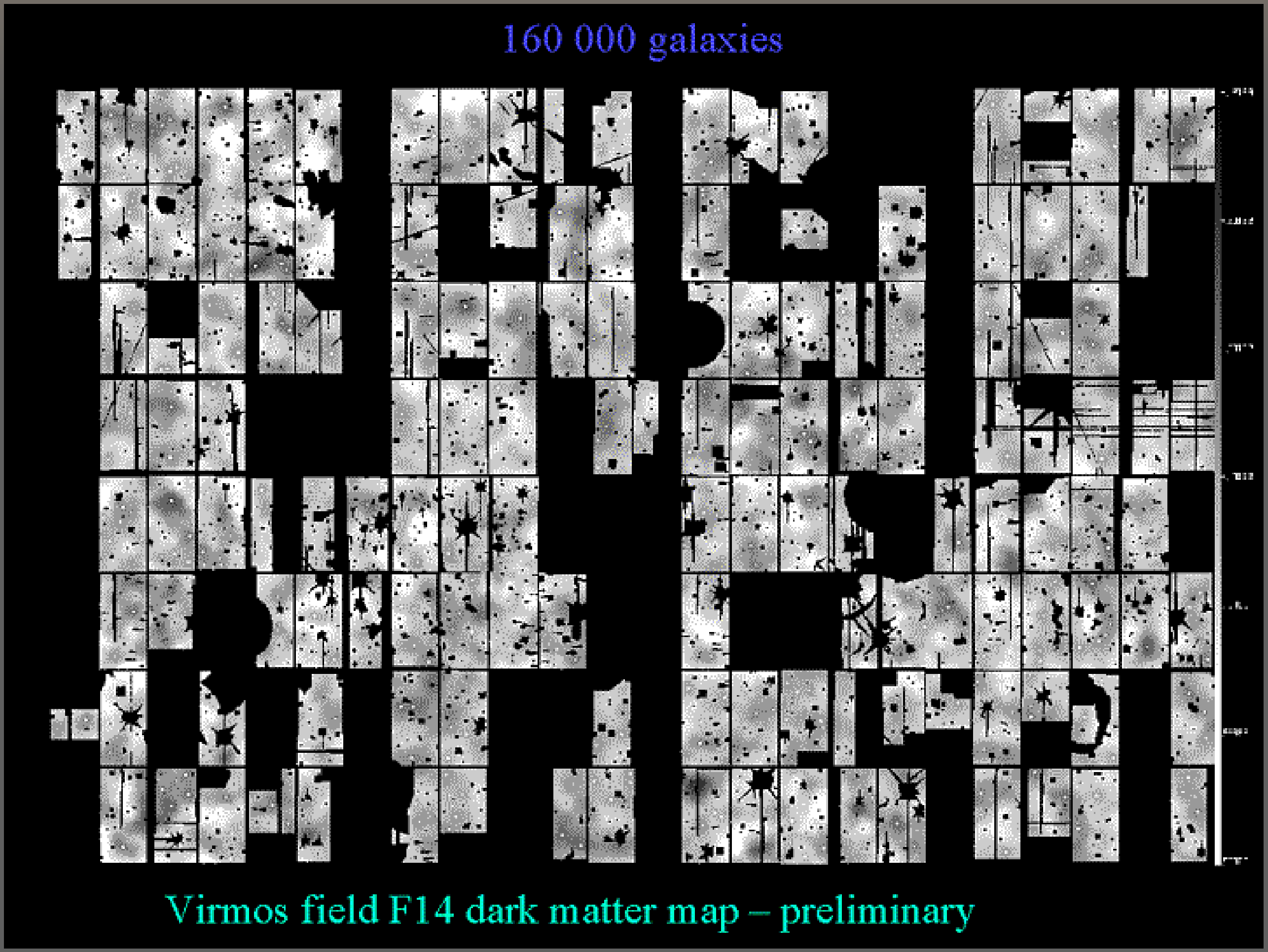
Abell
3667

z = 0.05



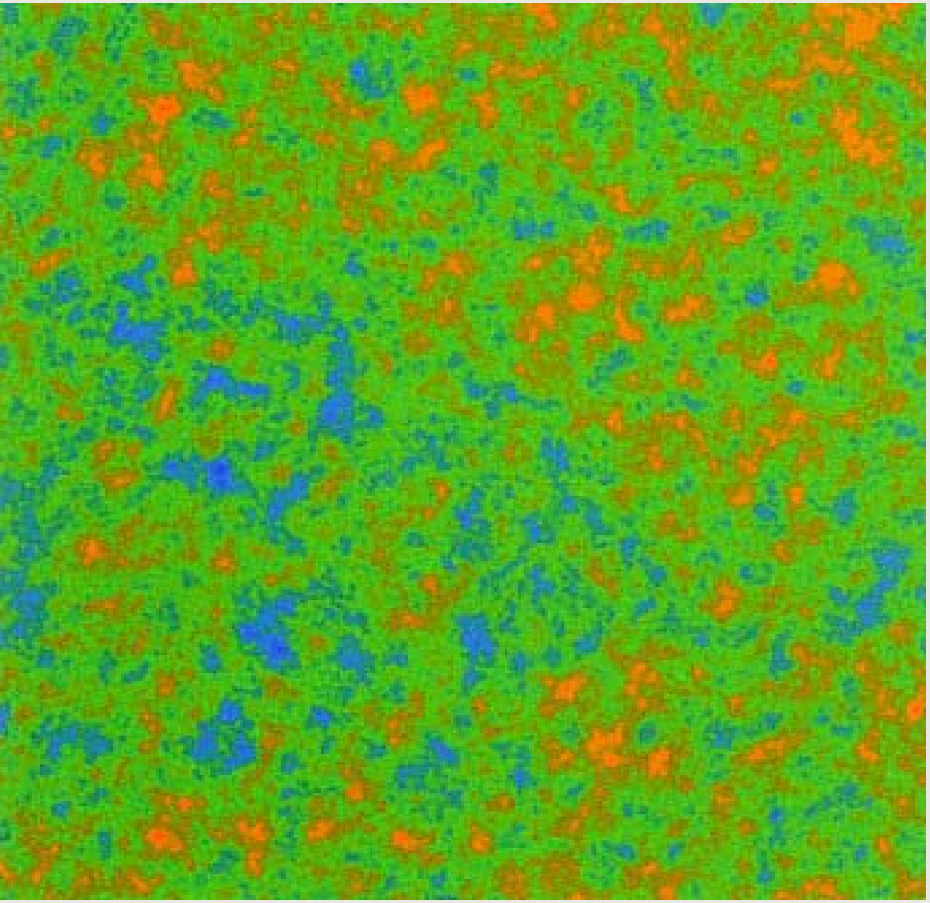
Joffre etal

Weak Gravitational Lensing of Large Scale Structure

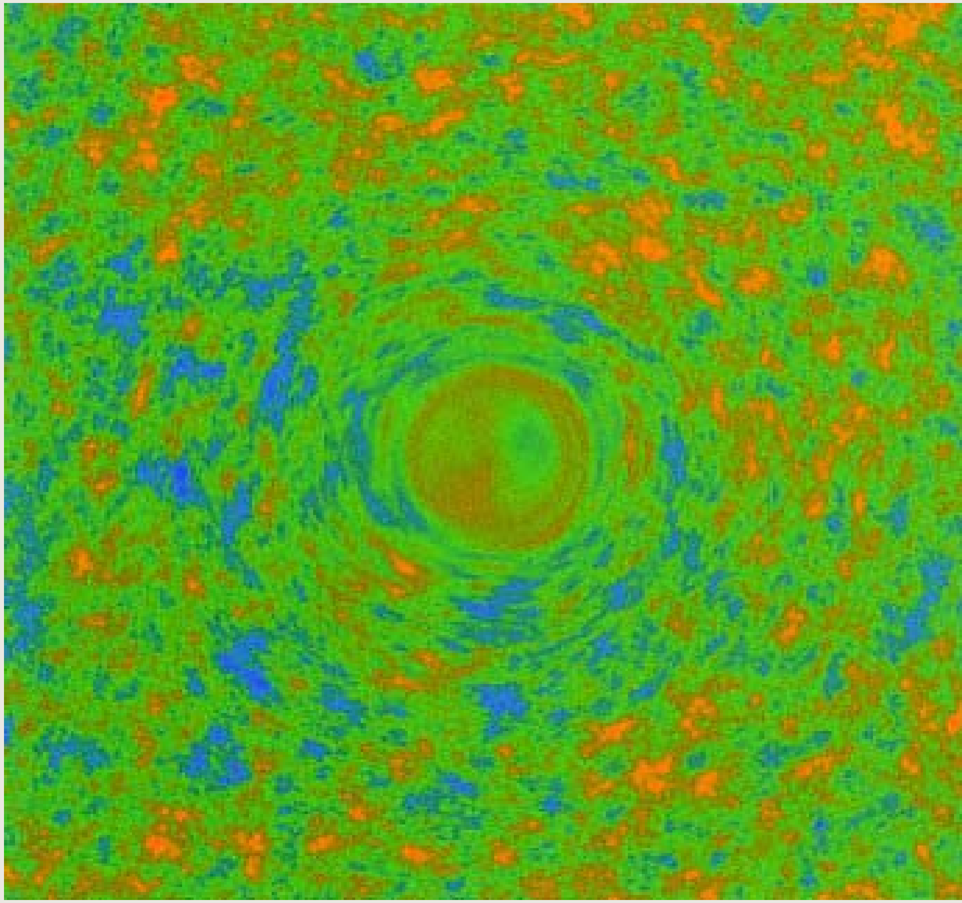


Pen

Weak Lensing in CMB



Temperature field



Lensed temperature field

Hu 2002

CMB/Galaxy/Weak Lensing Science

- Combine WL and SZ on cluster catalog
- Cross correlation of WL and secondary CMB
- Joint Analysis of CMB and WL power spectra
- Cross correlation of CMB and cluster catalog: SZ
- Cross correlation of CMB and galaxy catalog: ISW
- CMB polarization of CMB towards cluster catalog
- Cross correlate CMB polarization with galaxy catalog
- Power spectra of cluster catalog with photo-z
  - Redshifting Rings of Power (!)
- The Cosmology with Sunyaev-Zeldovich Cluster Surveys Conference

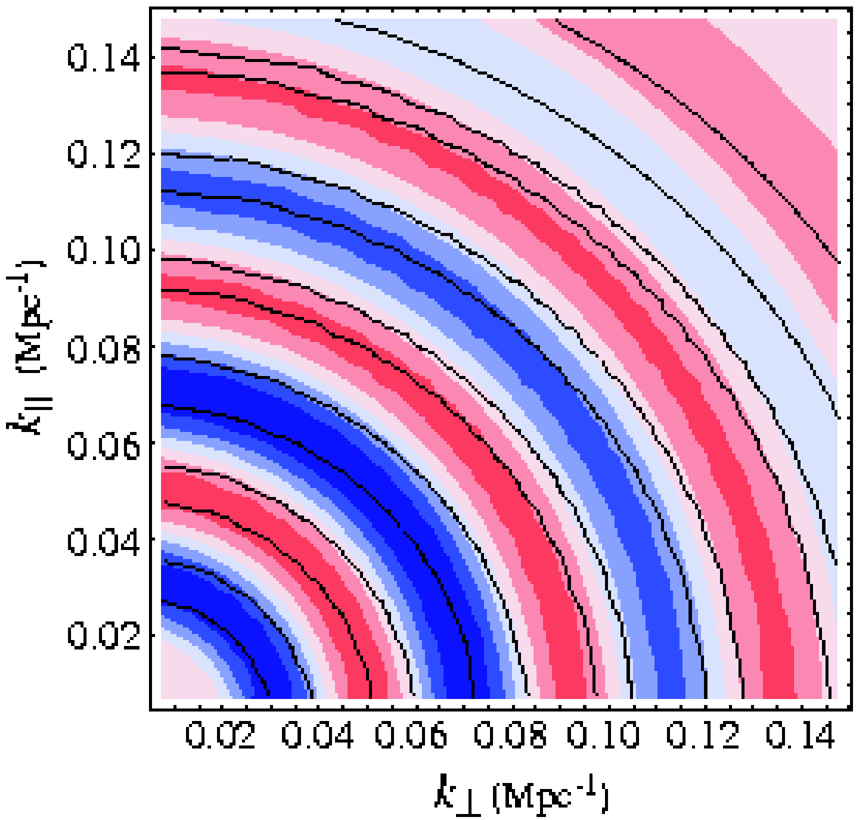
- Cooray 2003 (astroph/0305515)
- Takada and Sugiyama 2001 (astroph/0110313)
- Ishak et al 2003 (astroph/03084461)
- Komatsu et al 2000 (astroph/0012196)
- Scranton et al 2003 (astroph/0307335)
- Cooray and Baumann 2002 (astroph/0211095)
- Benabed et al 2000 (astroph/0003376)
- Hu and Haiman 2003 (astroph/0306053)
- http://bubba.ucdavis.edu/~sz03

A rich field with much interesting physics

Acoustic Rings in 2D

A measurement possible with just the imaging data

Hu & Haiman (2003)



Power spectrum is measured at fixed angular scale and redshift.

Inferred spatial scales depend on the assumed cosmology

Forms **purely geometrical test**, if CMB priors are used

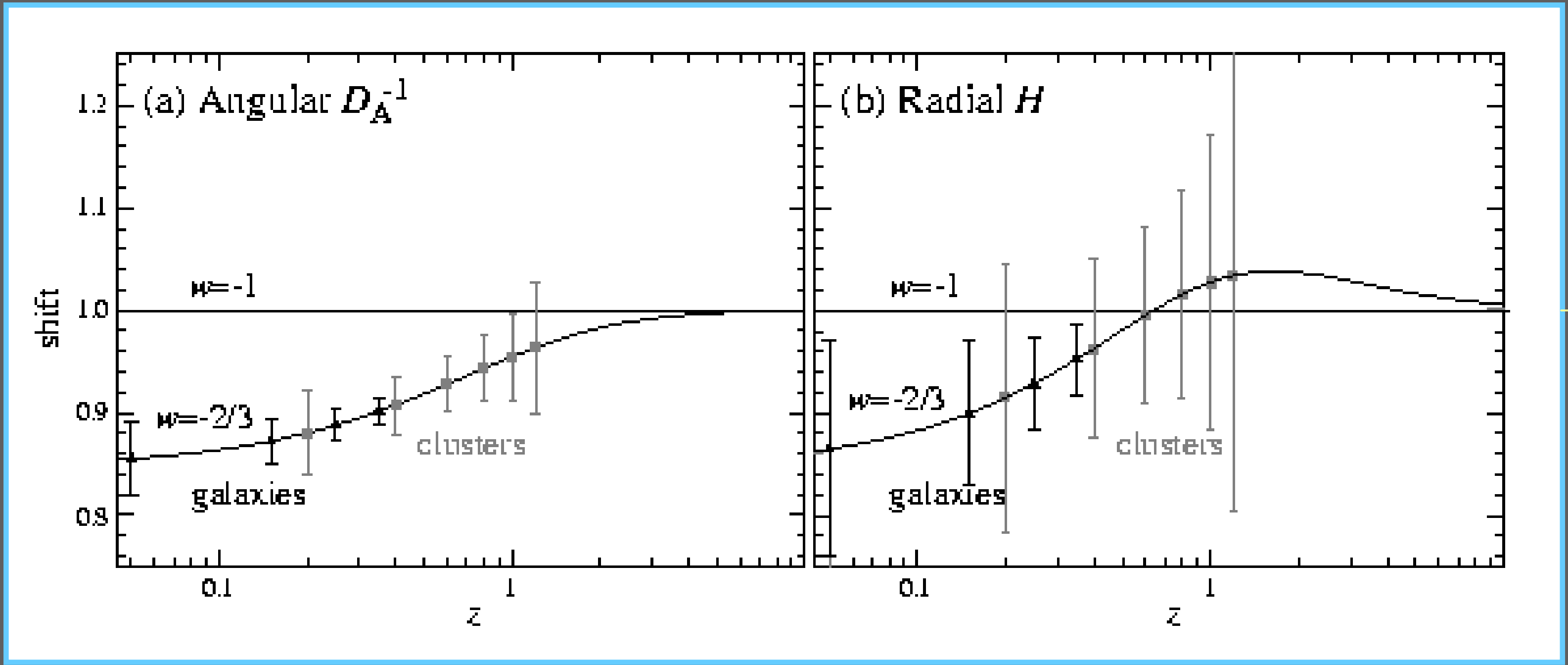
Insensitive to z-distortion

(c.f. Alcock-Paczynski test)

Haiman

Errors on $D_A(z)$ and $H(z)$

Hu & Haiman 2003



CMB priors

galaxies:	σ(w)=0.024	σ(Ω)=0.007
clusters:	σ(w)=0.040	σ(Ω)=0.013

Theorist's surveys:

Galaxies: 10,000 sq.deg

$M=10^{12.1}\ h^{-1}\ M_\odot$ at $0<z<0.1$ (SDSS main)

$M=10^{13.5}\ h^{-1}\ M_\odot$ at $0<z<0.4$ (SDSS LRG)

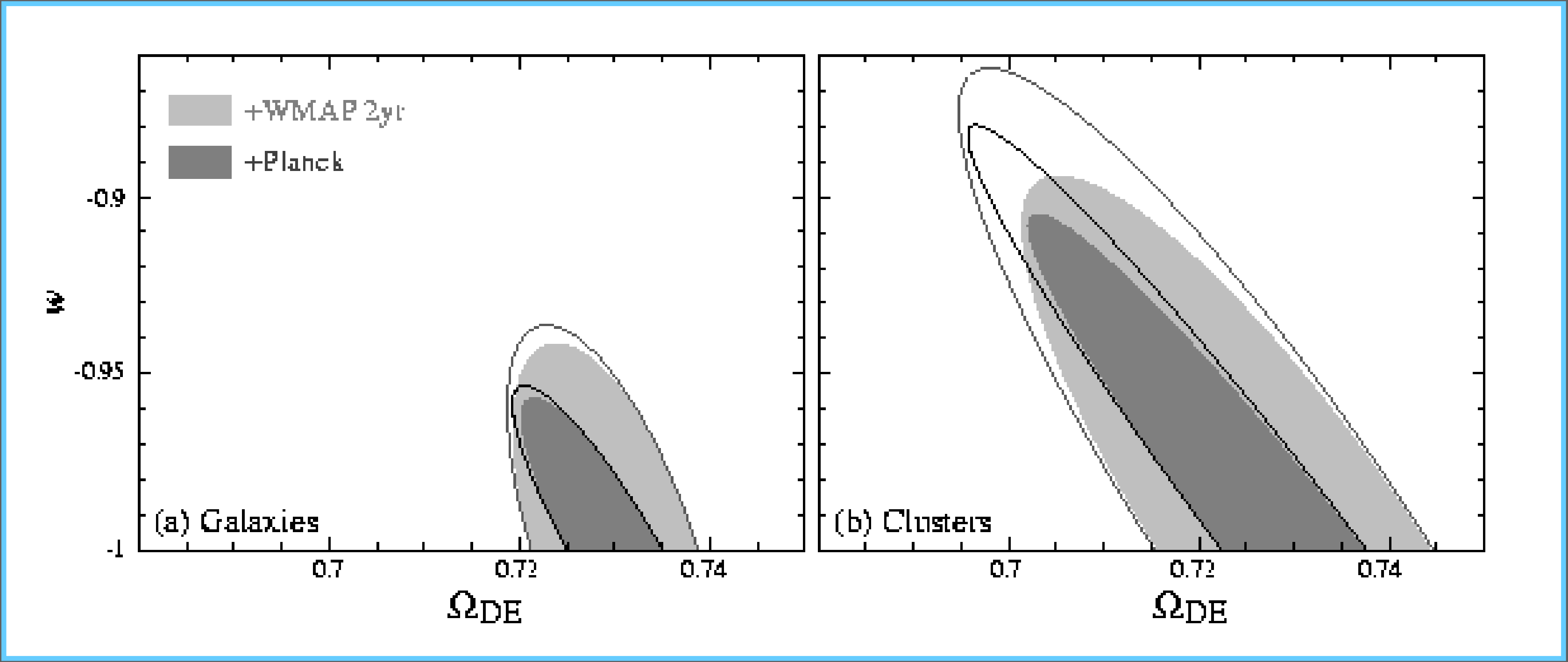
Clusters: 4,000 sq.deg

$M=10^{14.2}\ h^{-1}\ M_\odot$ at $0<z<1.3$ (SPT) - 25,000 clusters

Haiman

Errors on w and Ω_{DE}

Hu & Haiman 2003



Filled ellipses: b marginalized to an overall scaling
Empty ellipses: β, b marginalized (b separately in each Δz=0.1 bin)

galaxies:	σ(w)=0.024	σ(Ω)=0.007
clusters:	σ(w)=0.040	σ(Ω)=0.013

Haiman

SNAP

Is a fantastic project

See Physics Note

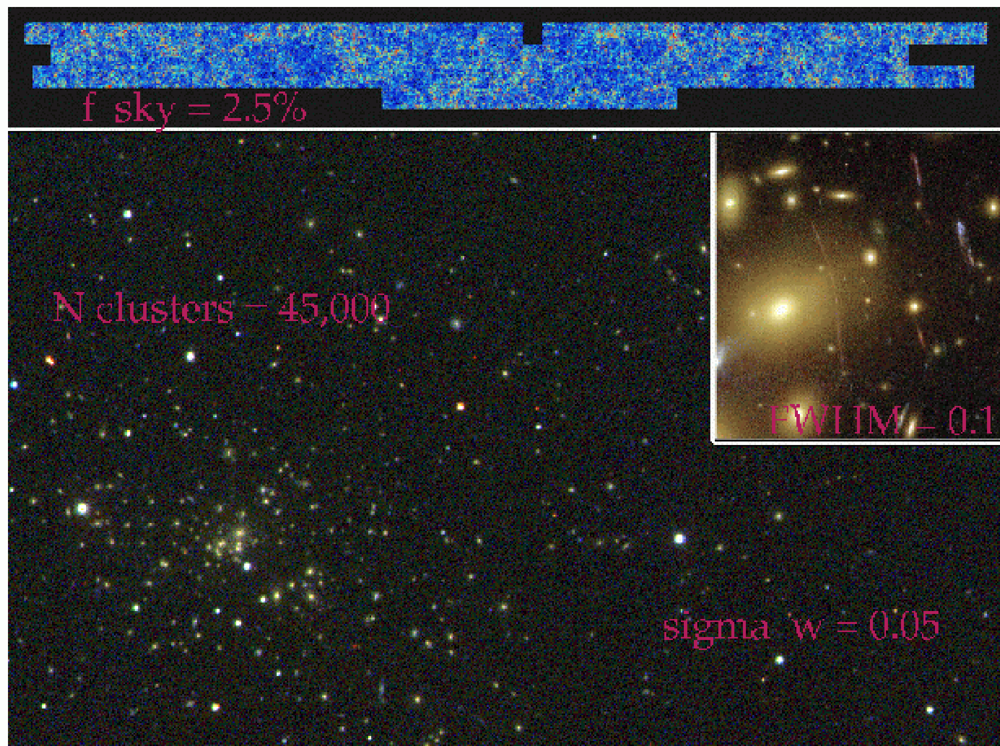
FN-739

Fermi National Accelerator Laboratory

Fermilab-FN-739

Annis et al 2003

Dark Energy Physics From A Space-Based Wide Area Sky Survey



Scientific Motivation

Create the ultimate map of the Universe

$\Rightarrow$ ***The SDSS was a start***

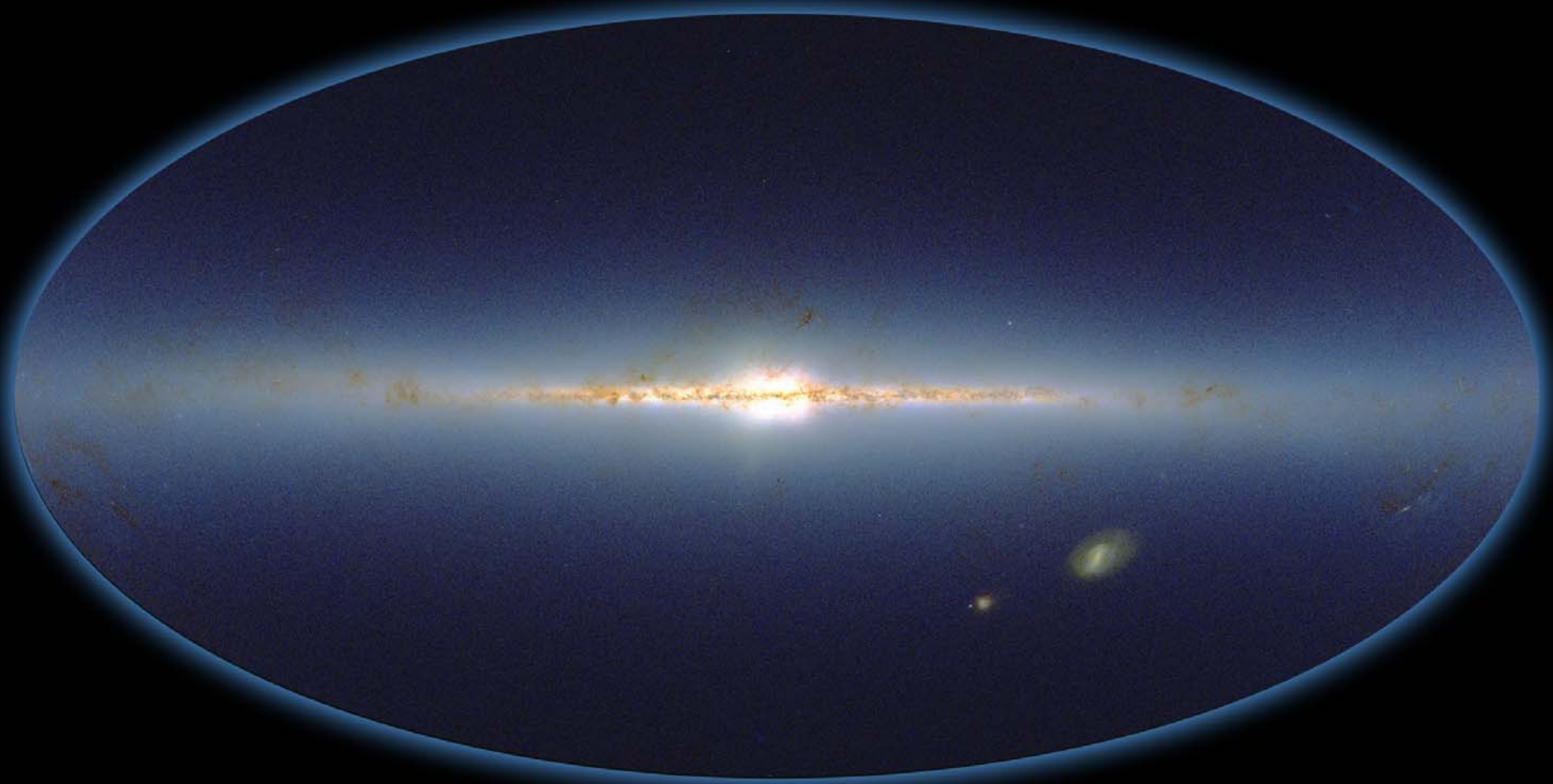
In order to study fundamental physics:

$\Rightarrow$ **What is the dark matter?**

$\Rightarrow$ **What is the dark energy?**

$\Rightarrow$ **What were the conditions during inflation?**

2MASS Covers the Sky



The Two Micron All Sky Survey

Infrared Processing and Analysis Center/Caltech & Univ. of Massachusetts

Planned Surveys: K band $R_H = 3/2$

Name	D	T	Ω	n		Survey
	m	sec	deg^2	#		years
UKIDSS	3.6	2000	0.21	1	R_H=3/4	12
Vista	4.0	1800	0.25	1	R_H=3/4	9
SNAP	2.0	140	0.06	3	R_H=3/4	1
SNAP	2.0	1500	0.06	3		11
Prime-midex	1.0	5000	0.25	4		7
Chicago LT	30.	6000	7.0	1		1
Prime-discovery	4.0	400	0.25	4		0.5

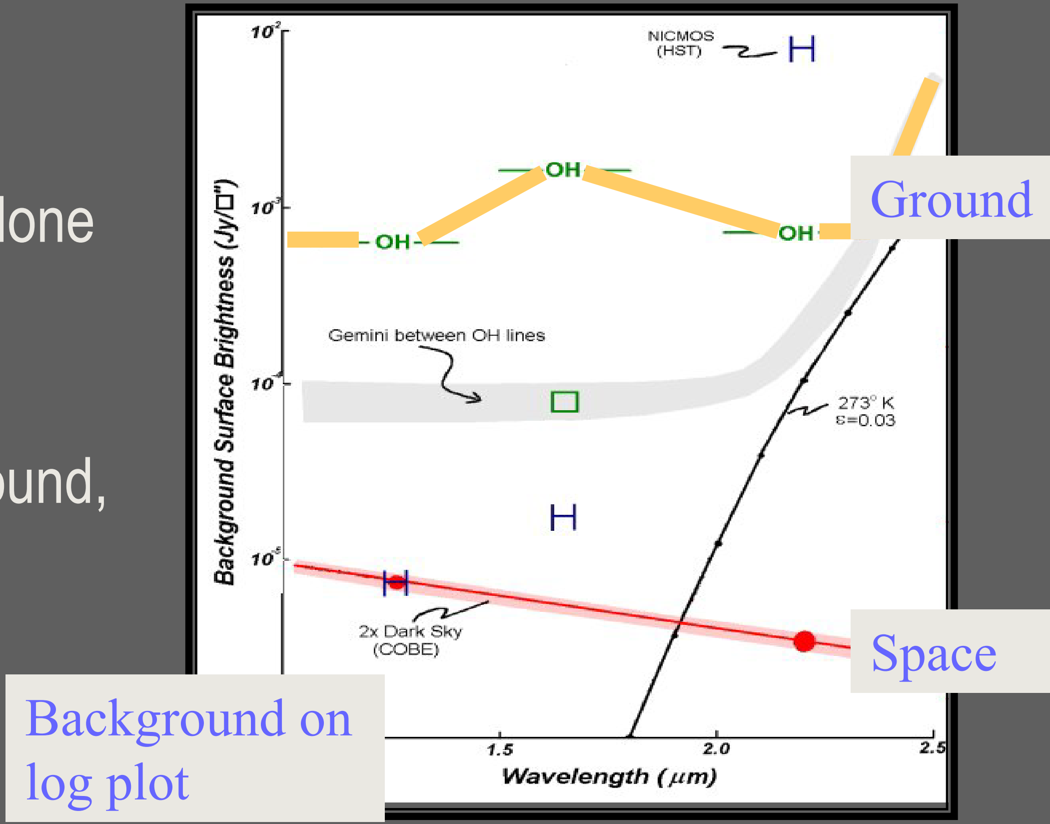
all need 3*survey to obtain photo-z data

Create the ultimate map of the Universe

Map all galaxies in the observable universe

- Photo-z's out to z=5 and down to 0.3 L-star
- Optical component can be done from ground with LSST
- Infrared impossible from ground, requires space based large infrared camera…

This is 2015+ thinking…



Changing the Way Astronomy is Done

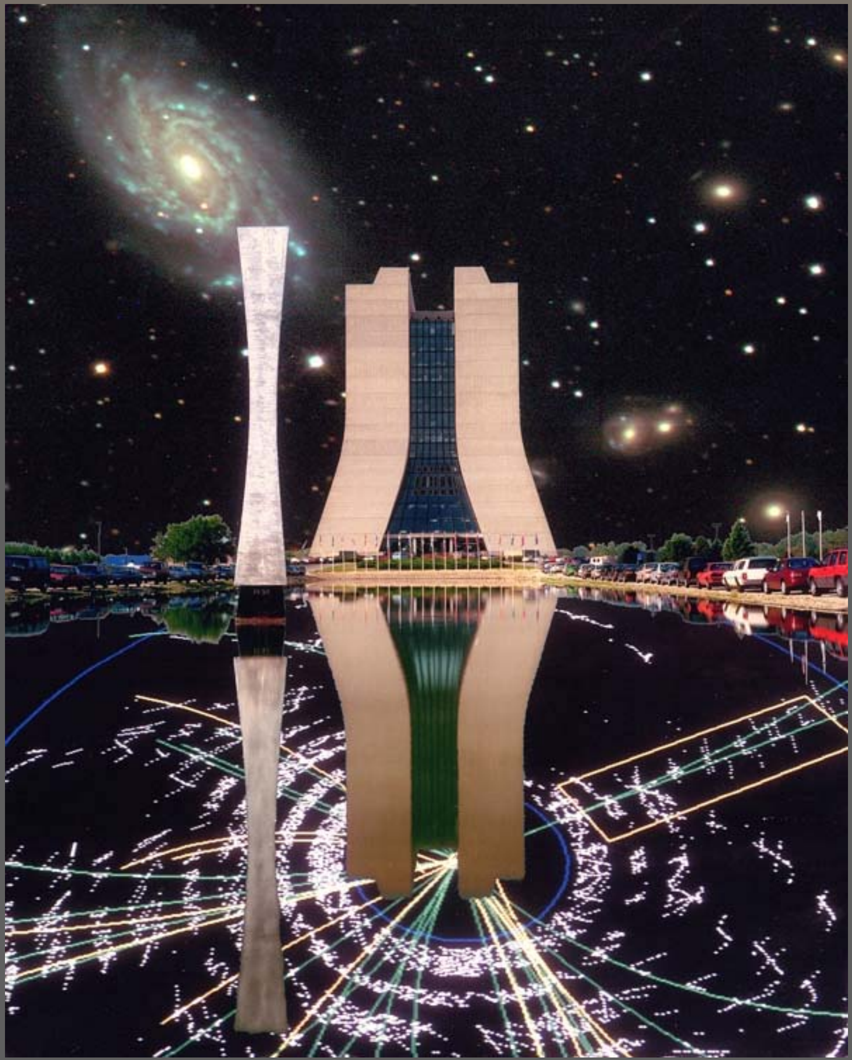
Surveys provide

The maximum amount of high-quality data

To the most scientists

For the lowest cost

To address the biggest problems of cosmology



Decadal Survey

Priorities in Astronomy and Astrophysics in the New Millenium

Ground-based	Cost (in millions of dollars)
Giant Segmented Telescope (GSMT)	350
Expanded Very Large Array (ELVA)	140
Large-Aperture Synoptic Survey Telescope (LSST)	170
Telescope system instrumentation program	50
Advanced Solar Telescope	60
Square Kilometer Array technology department	22
Combined Array for Research in Millimeterwave Astronomy (CARMA)	11
Very Energetic Radiation Imaging Telescope	35
Array System (VERITAS)	26
South Pole Submillimeter-Wave Telescope	50
National Virtual Observatory (NVO)	15
Laboratory astrophysics program	5
Low-Frequency Array	8
National theory postdoctoral program	6
Synoptic Optical Long-term Inverstigation of the Sun (SOLIS) expansion	8
Total ground-based	956

Space-based	Cost (in millions of dollars)
	1000
Next Generation Space Telescope (NGST)	800
Constellation-X Observatory	200
Terrestrial Planet Finder (TPF)	100
Gamma-ray large Area Space Telescope (GLAST)	300
Laser Interfermeter Space Antenna (LISA)	250
Solar Dynamics Observatory (SDO)	300
Energetic X-ray Imaging Survey Telescope (EXIST)	150
Advanced Radio Interferometry between Space and Earth (ARISE)	350
National Virtual Observatory (NVO)	45
Advanced Cosmic-ray Composition Experiment for Space Station (ACCESS)	100
Augmentation of astrophysics theory program	30
National theory postdoctoral program	40
Ultra-long duration balloons	14
	35
Total space-based	3714

Total 4670