Fermilab's Dark Energy Strategy: Past, Present, and Future

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Fermilab & U. Chicago

Fermilab Colloquium

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Cosmic Acceleration Timeline

- 1990's: Observational hints and theoretical suggestions (ΛCDM)
- 1998: Discovery (supernovae)
- 1998-2009: Confirmation and tightening of constraints
- 2010-: Address *why* is the Universe accelerating?
- Astro 2010: Ground+Space strategy for the long term

Fermilab:

Theory models

1st Dark Energy wkshop

SDSS & SDSS-II

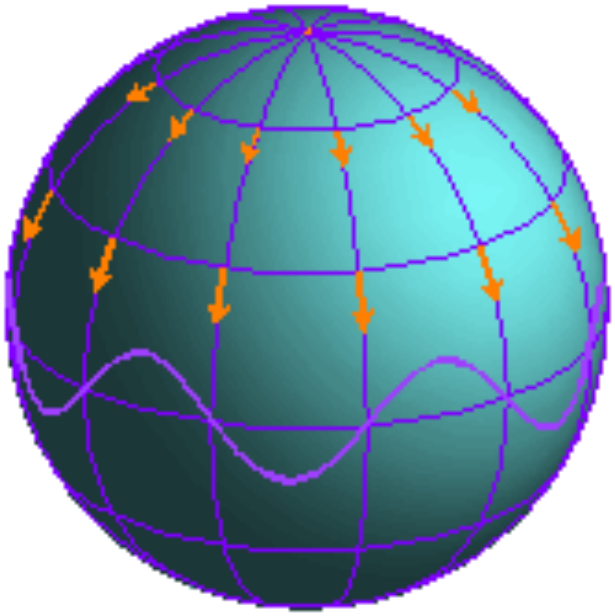
Dark Energy Survey

LSST, JDEM/WFIRST, BigBOSS, DESpec, 21 cm

The Expanding Universe

The only mode that preserves homogeneity and isotropy is overall expansion or contraction:

Cosmic scale factor $a(t)$



Distance between galaxies:

$$d(t) = a(t)r$$

where

$r =$ fixed (comoving) distance

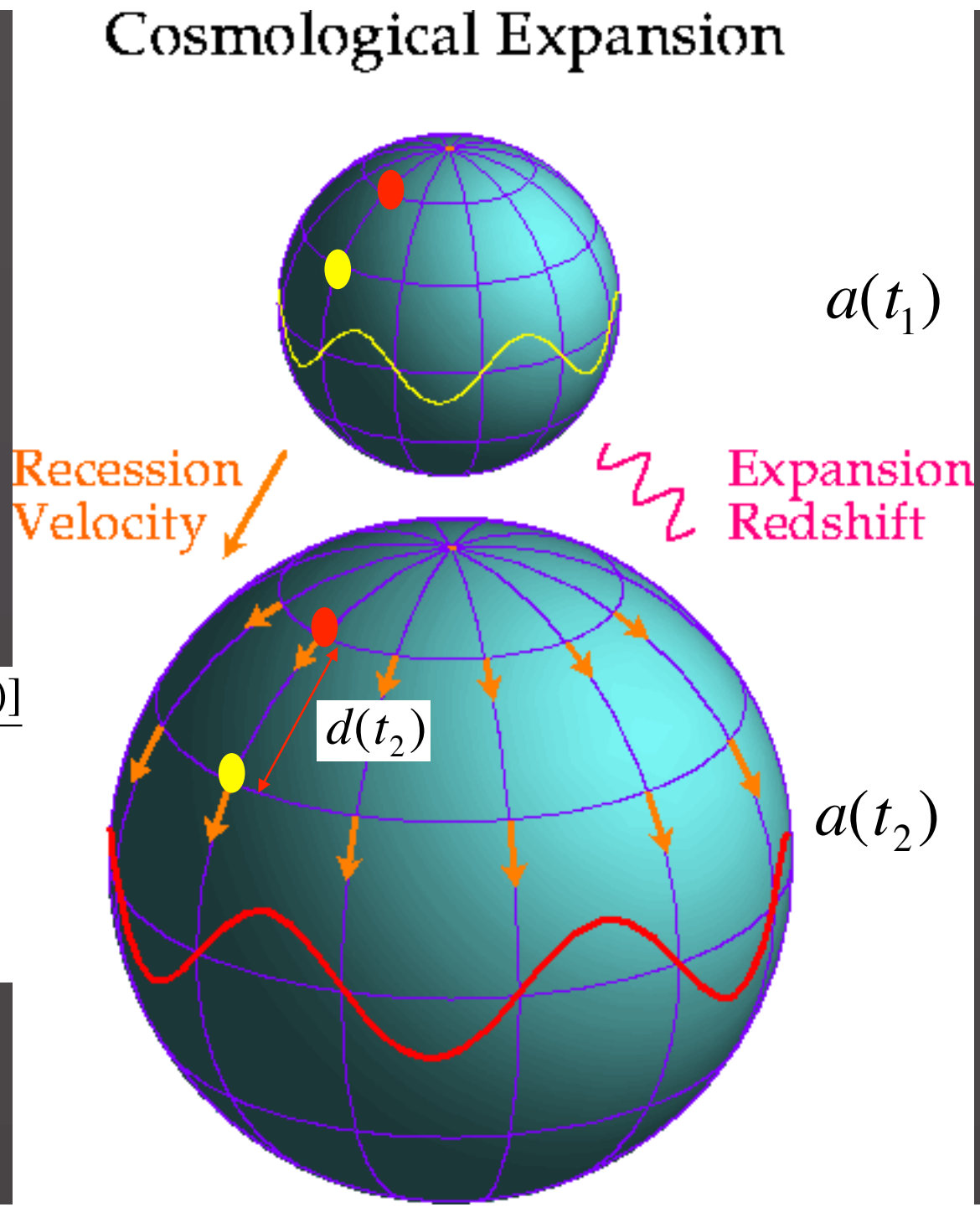
Recession speed:

$$v = \frac{d(t_2) - d(t_1)}{t_2 - t_1} = \frac{r[a(t_2) - a(t_1)]}{t_2 - t_1}$$

$$= \frac{d}{a}\frac{da}{dt} \equiv dH(t)$$

$$\approx dH_0 \text{ for `small' } t_2 - t_1$$

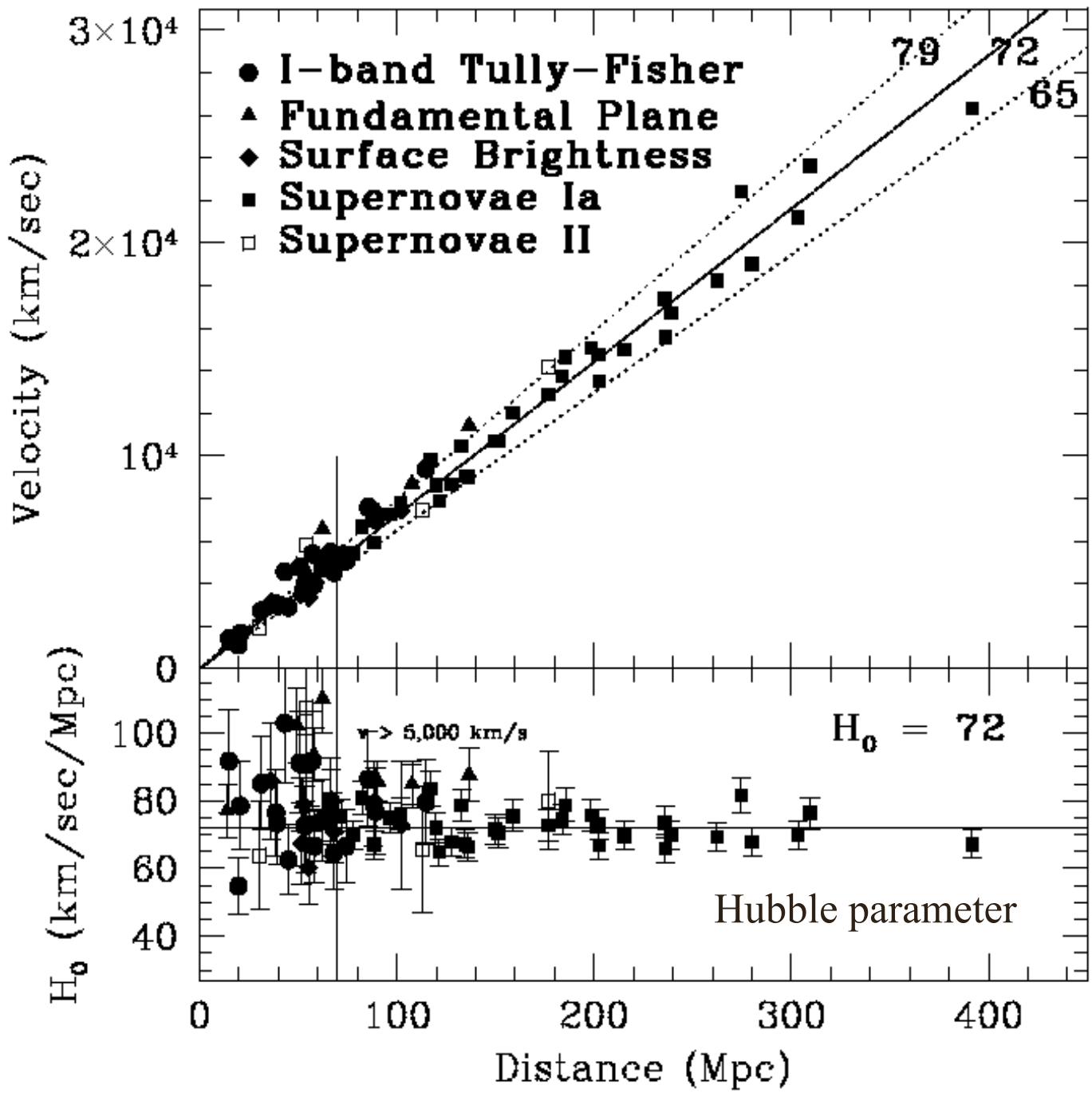
Hubble's Law (1929)



Modern Hubble Diagram

Hubble Space Telescope Key Project

Freedman etal



How does the expansion of the Universe change over time?

Gravity:

everything in the Universe attracts everything else

↓

expect the expansion of the Universe should slow down (decelerate) over time

Cosmological Dynamics

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\sum_i \left(\rho_i + \frac{3p_i}{c^2}\right)$$

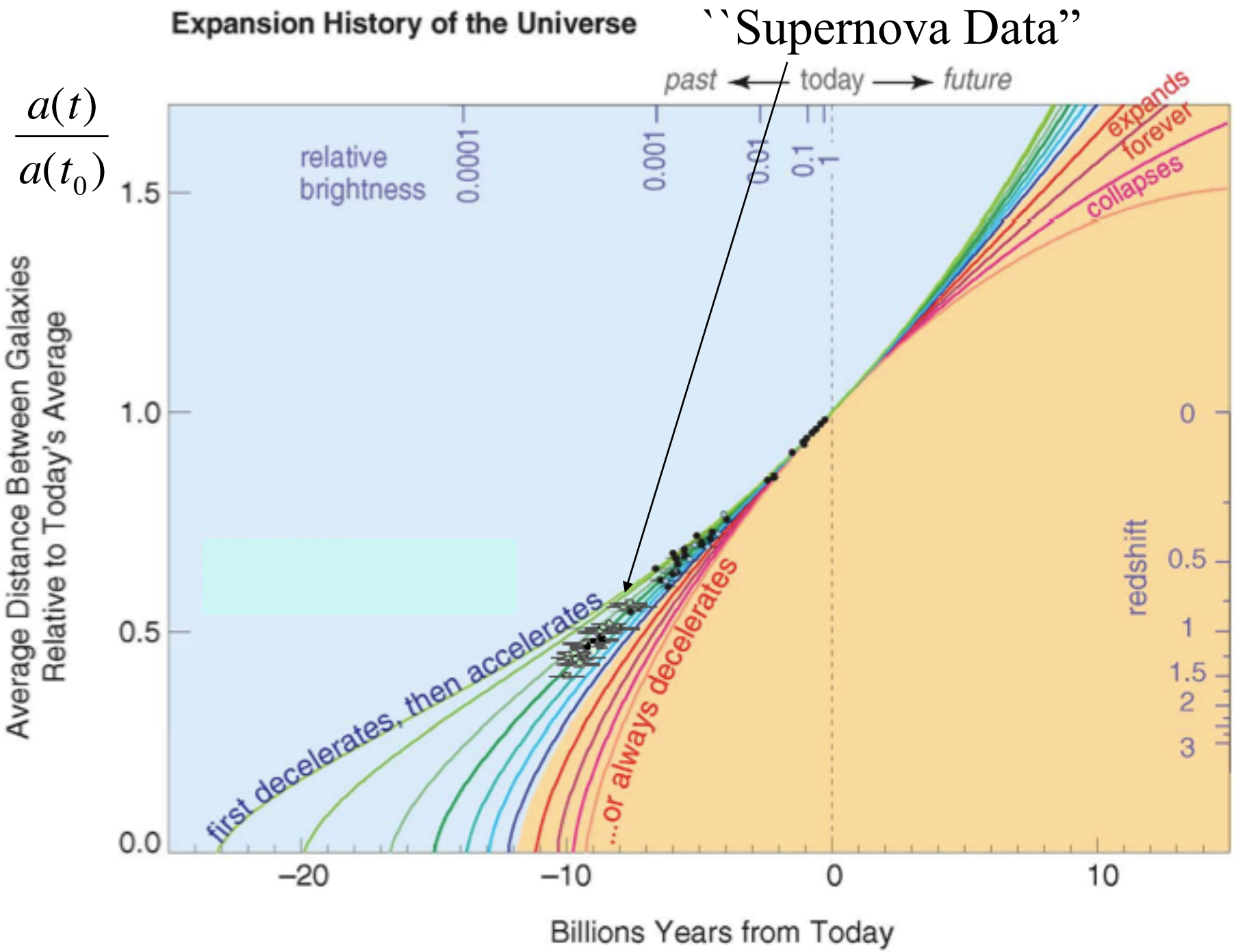
Friedmann Equation from General Relativity

Equation of state parameter: $w_i = p_i / \rho_i c^2$

Non-relativistic matter: $p_m \sim \rho_m \mathrm{v}^2,\ w \approx 0$

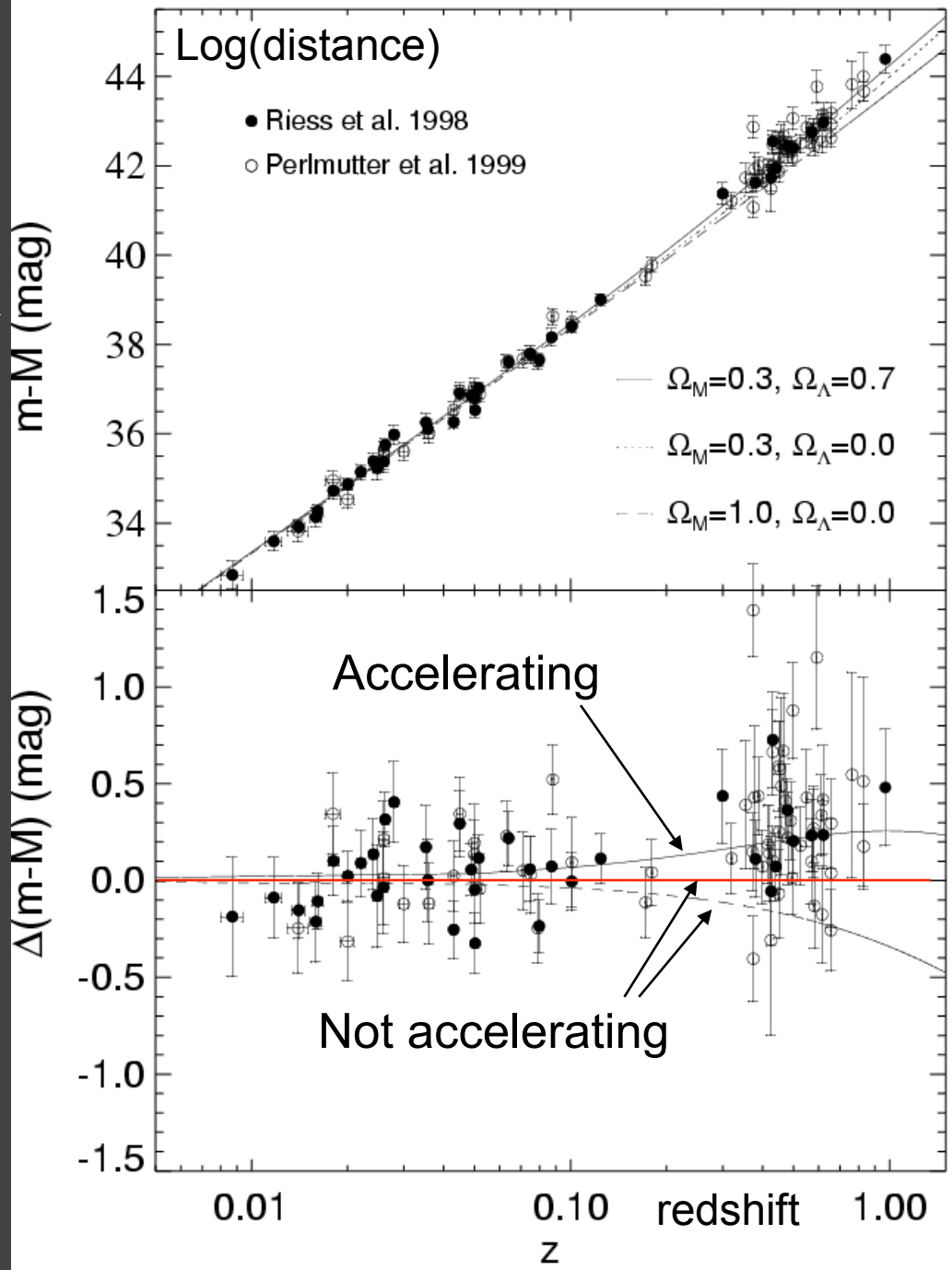
Relativistic particles: $p_r = \rho_r c^2 / 3,\ w = 1/3$

Dark Energy: component with negative pressure: $w_{DE} < -1/3$


Expansion History of the Universe
``Supernova Data"
past
today
future
$\frac{a(t)}{a(t_0)}$
relative brightness
0.0001
0.001
0.01
0.1
1
expands forever
collapses
first decelerates, then accelerates
...or always decelerates
redshift
0
0.5
1
1.5
2
3
1.5
1.0
0.5
0.0
Average Distance Between Galaxies Relative to Today's Average
–20
–10
0
10
Billions Years from Today

Discovery of Cosmic Acceleration from High-redshift Supernovae

Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected



$\Omega_\Lambda = 0.7$
$\Omega_\Lambda = 0.$
$\Omega_m = 1.$

Cosmological Constant and Acceleration

Einstein:

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Zel'dovich and Lemaitre:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

$$\equiv 8\pi G\left(T_{\mu\nu}(\text{matter}) + T_{\mu\nu}(\text{vacuum})\right)$$

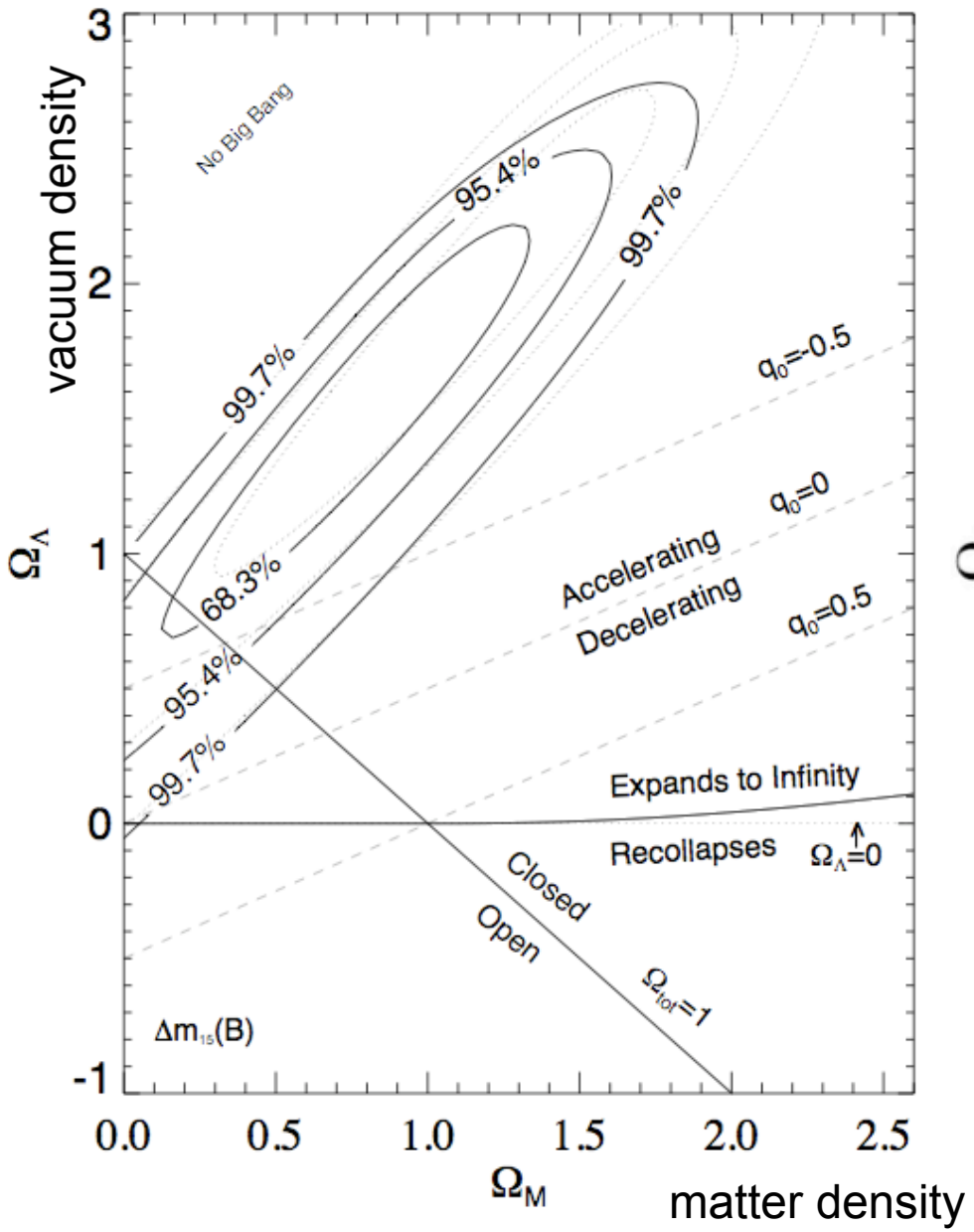
Vacuum Energy:

$$T_{\mu\nu}(\text{vac}) = \frac{\Lambda}{8\pi \text{G}} g_{\mu\nu}$$

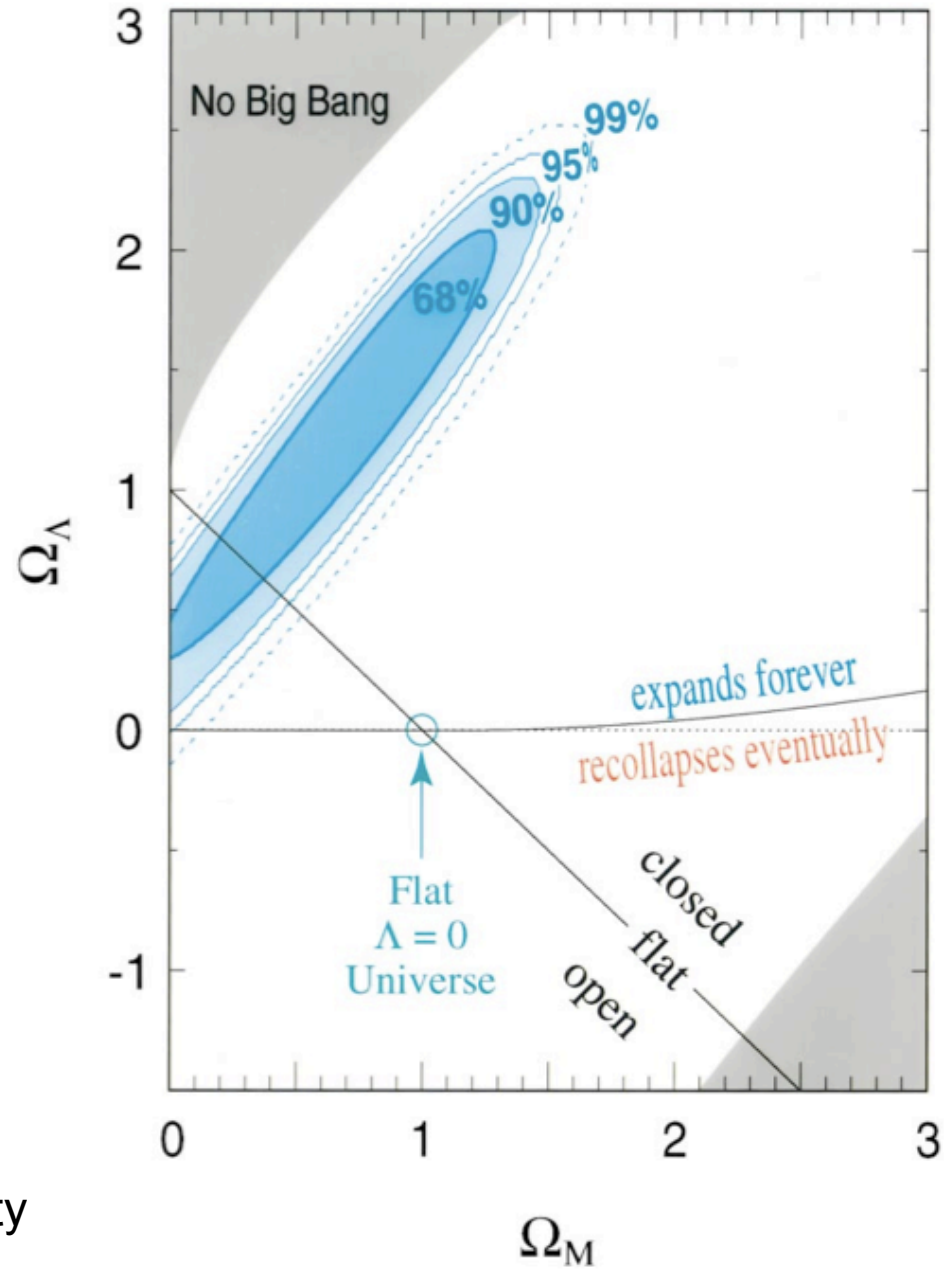
$$\rho_{\text{vac}} = T_{00} = \frac{\Lambda}{8\pi \text{G}}, \quad p_{\text{vac}} = T_{ii} = -\frac{\Lambda}{8\pi \text{G}}$$

$$w_{\text{vac}} = -1 \;\Rightarrow\; H = \text{constant} \;\Rightarrow\; a(t) \propto \exp(Ht)$$

Riess et al. (1998, AJ)

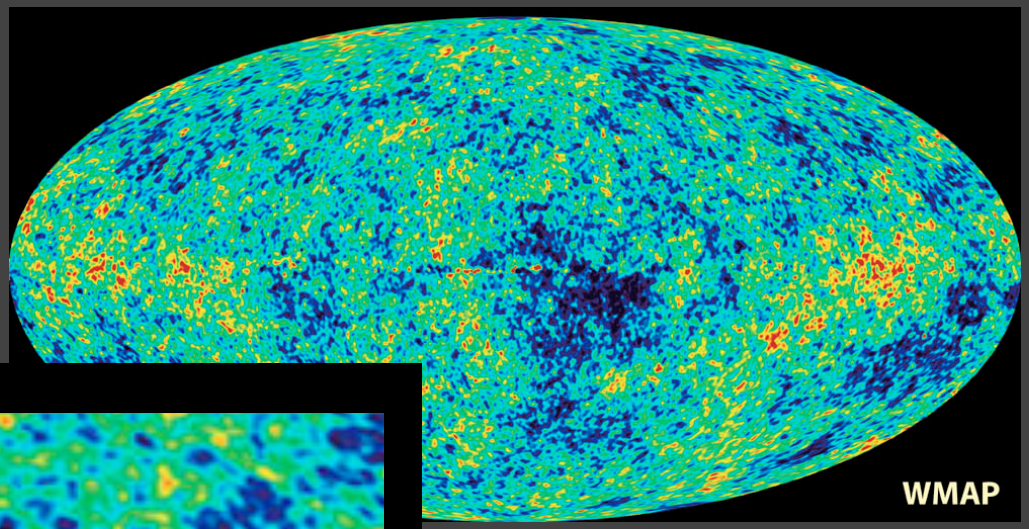


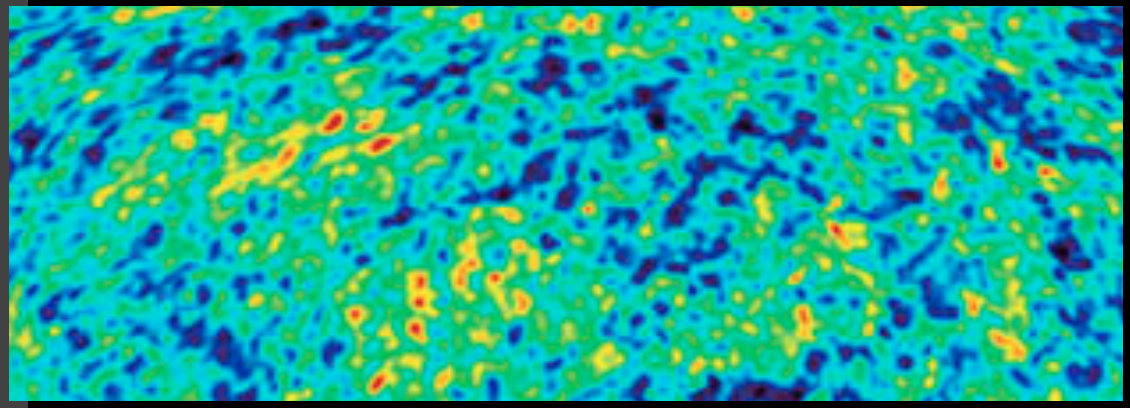
Perlmutter et al. (1999, ApJ)



CMB Anisotropies

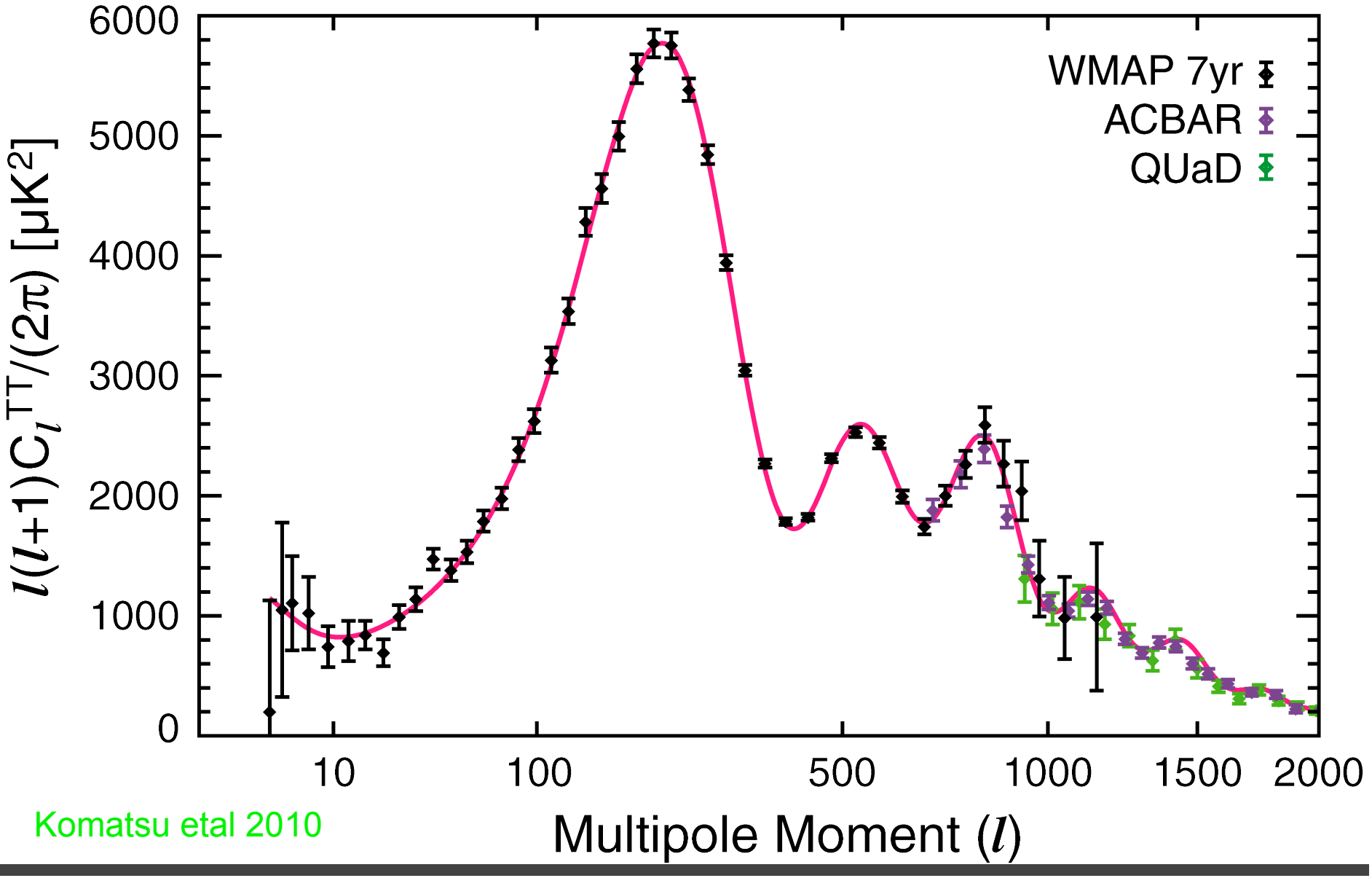
Temperature map of the Cosmic Microwave Background radiation





- There is a characteristic angular scale, ~ 1 degree on the sky, set by the distance sound waves in the photon-baryon fluid can travel just before H recombination: sound horizon $s \sim c_s t_{ls}$

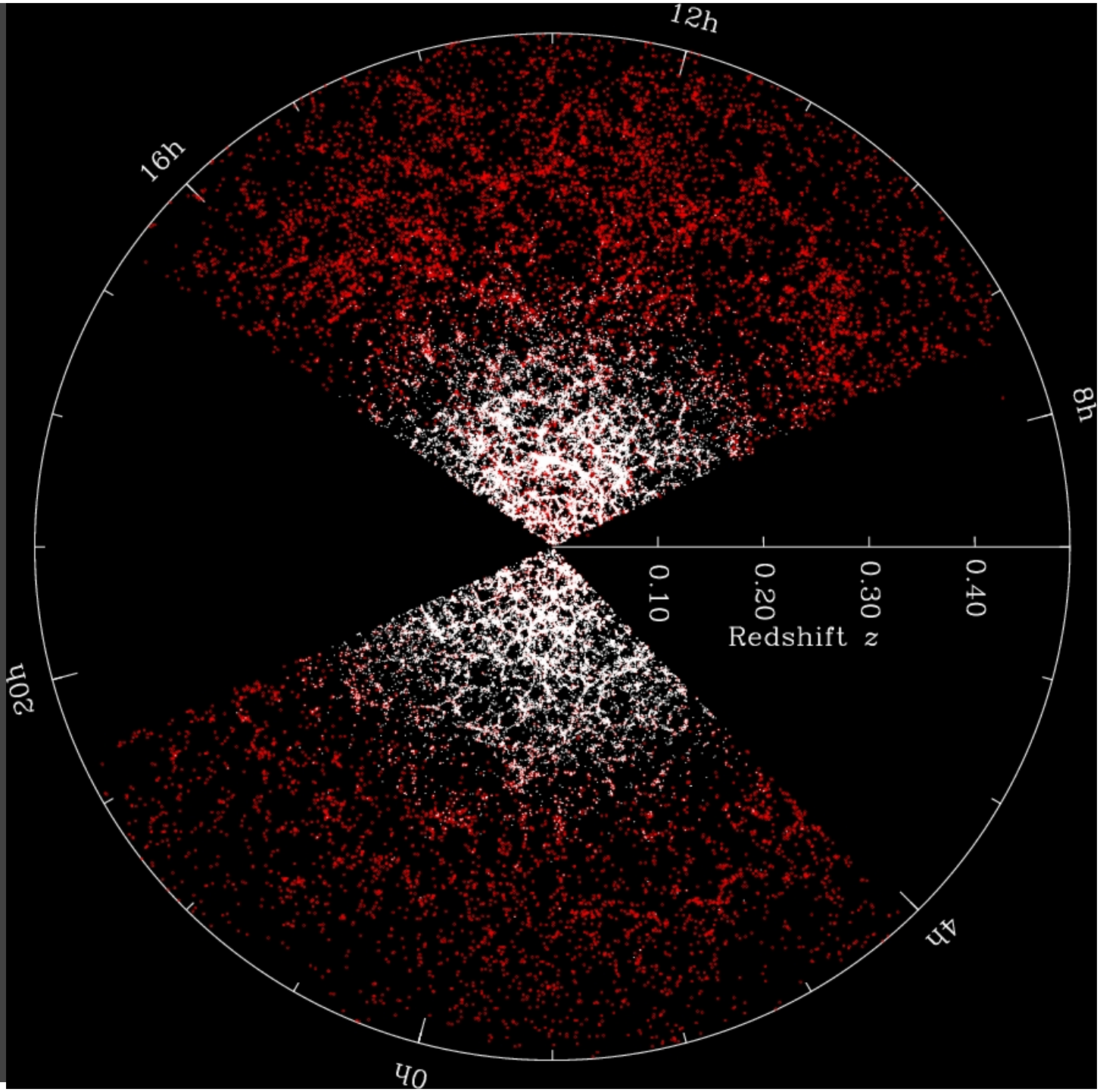
Current CMB Results



Komatsu etal 2010

SDSS Galaxy Distribution

Luminous Red Galaxies

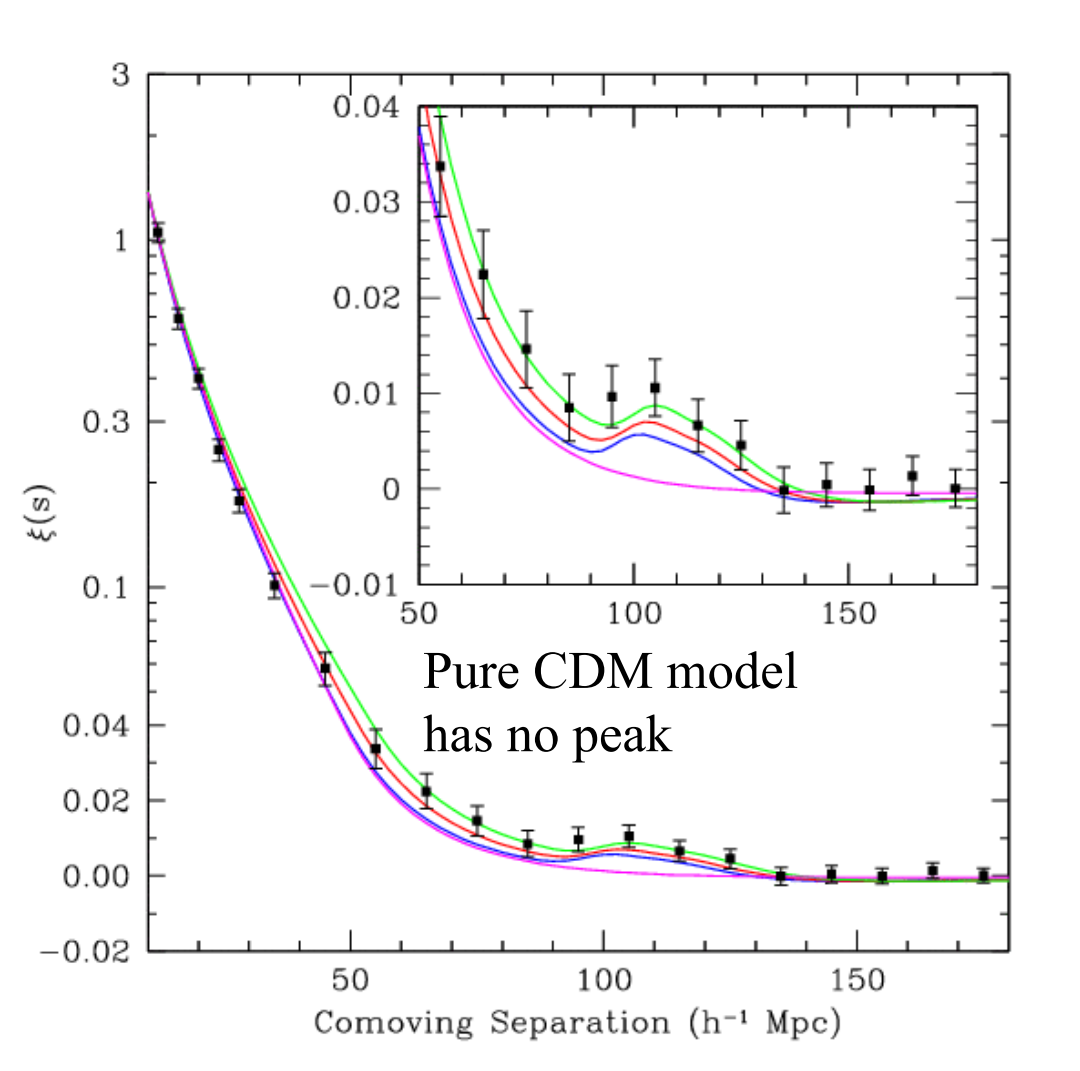


Large-scale Correlations of SDSS Luminous Red Galaxies

Redshift-space Correlation Function

$$\xi(r) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$$

Warning: Correlated Error Bars

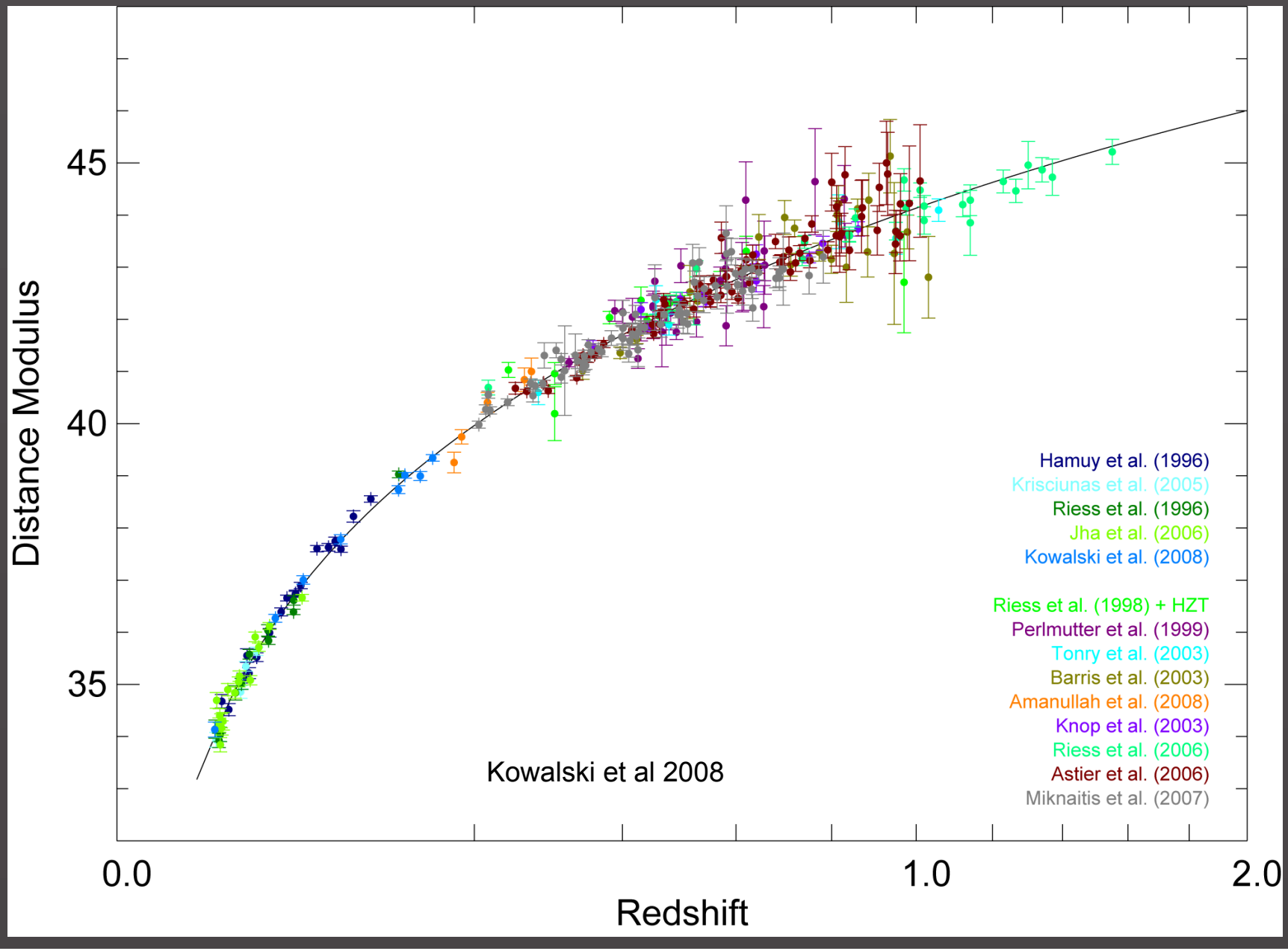


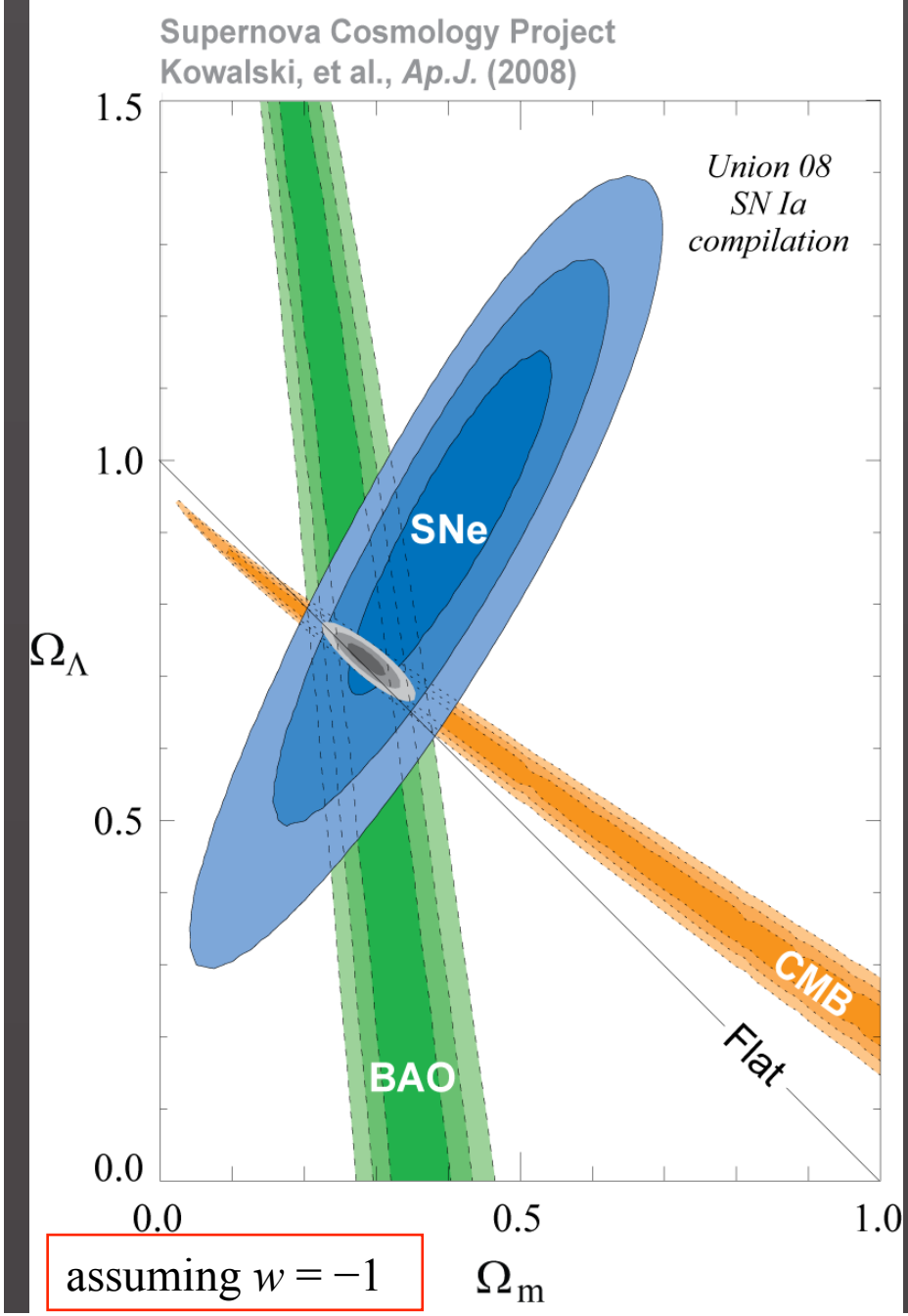
Baryon Acoustic Oscillations seen in Large-scale Structure:

mean distance to galaxies at z~0.35

Eisenstein, etal 2005

Recent Supernova Data





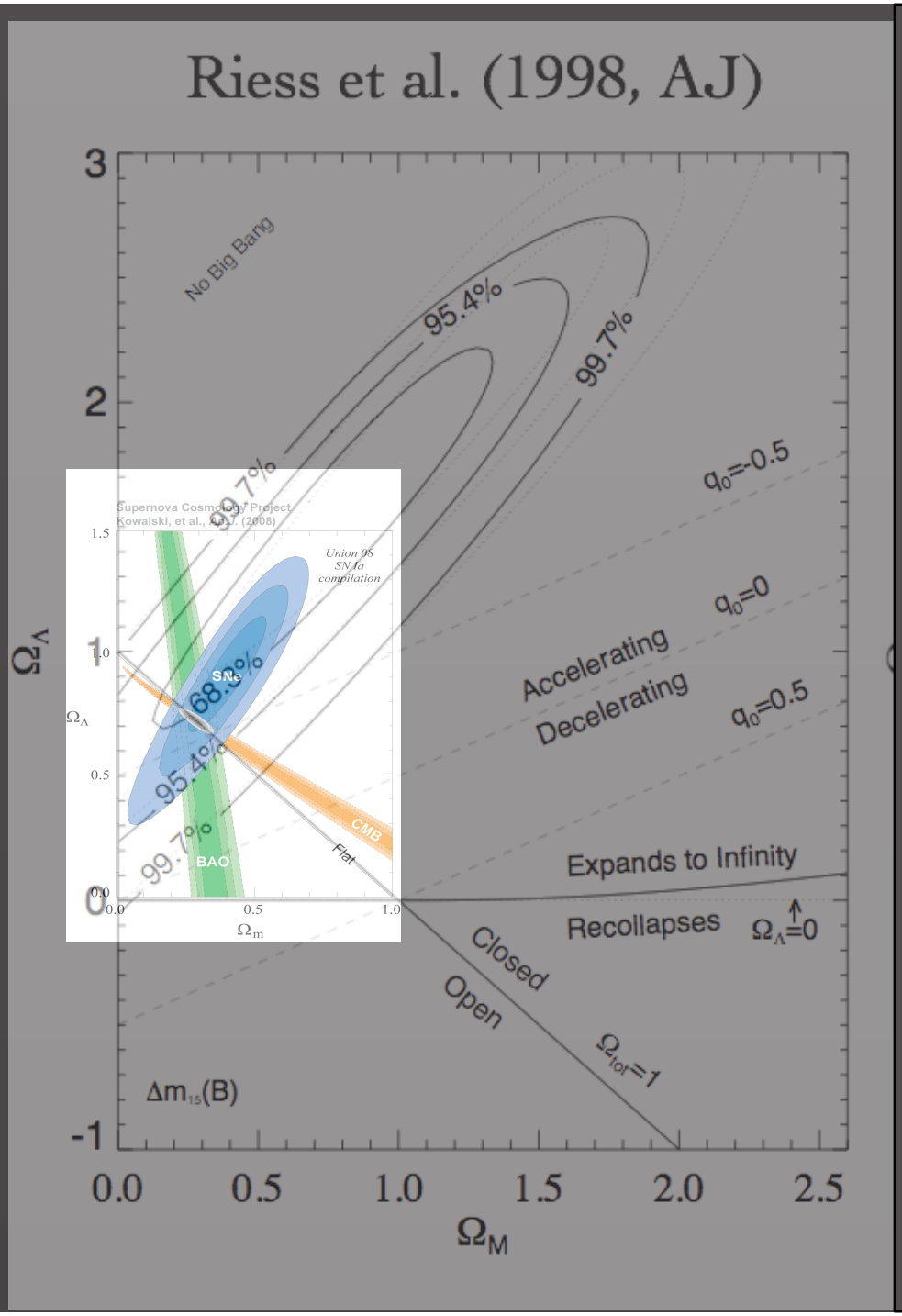
assuming $w = -1$

Recent Dark Energy Constraints

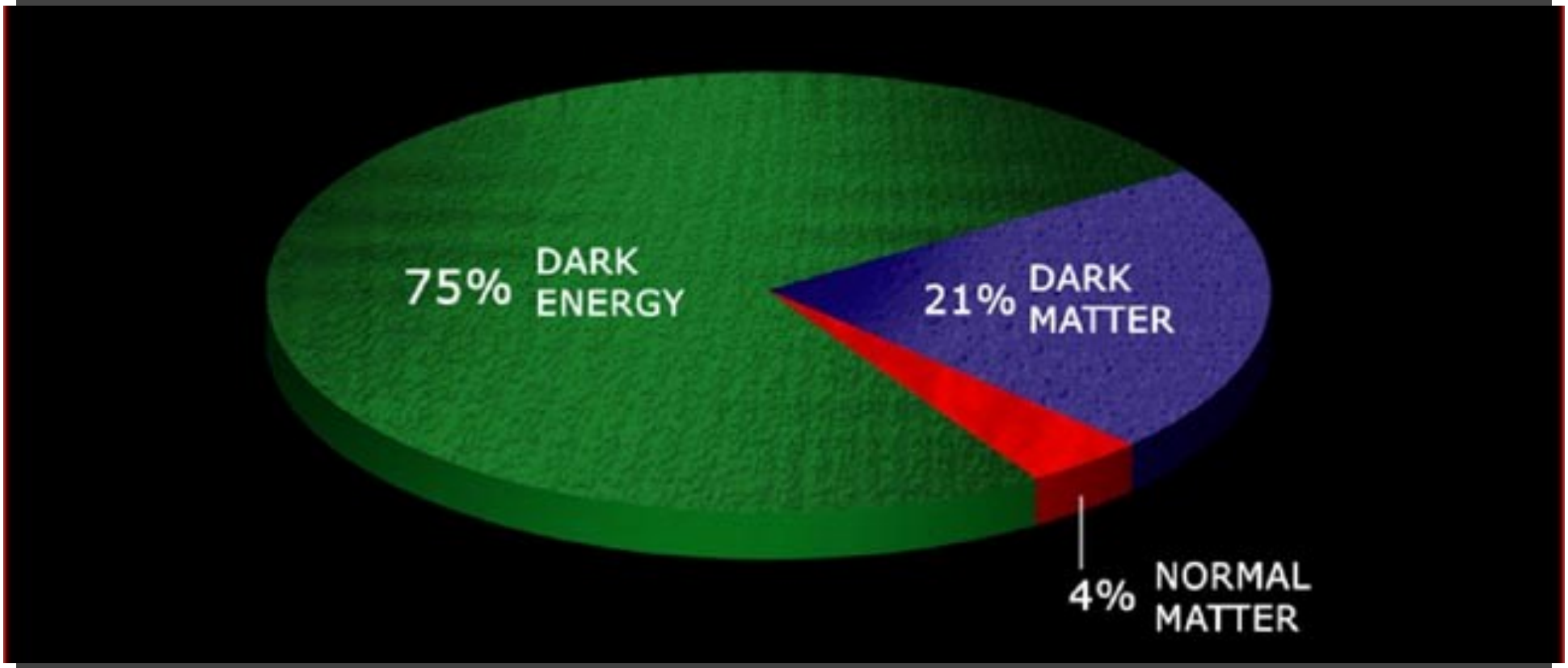
Constraints from Supernovae, Cosmic Microwave Background Anisotropy (WMAP) and Large-scale Structure (Baryon Acoustic Oscillations, SDSS)

Only statistical errors shown

Progress over the last decade



Components of the Universe



Dark Matter: clumps, holds galaxies and clusters together

Dark Energy: smoothly distributed, causes expansion of Universe to speed up

Cosmological Constant Λ as Dark Energy

Quantum zero-point fluctuations: virtual particles continuously fluctuate into and out of the vacuum (via the Uncertainty principle).

Vacuum energy density in Quantum Field Theory:

$$\rho_{vac} = \frac{\Lambda}{8\pi G} = \frac{1}{V}\sum \frac{1}{2}\hbar\omega = \int_0^M \hbar c(k^2 + m^2)^{1/2} d^3k \sim M^4$$

$$w_{vac} = \frac{p_{vac}}{\rho_{vac}} = -1, \quad \rho_{vac} = \text{ const.}$$

Pauli

Theory: $M \sim M_{Planck} = G^{-1/2} = 10^{28}\ \text{eV} \Rightarrow \rho_{vac} \sim 10^{112}\text{eV}^4$

Data: $\rho_{\text{vac}} < 10^{-10}\text{eV}^4$

Cosmological Constant Problem

Dark Energy: Alternatives to Λ

The smoothness of the Universe and the large-scale structure of galaxies can be neatly explained if there was a much earlier epoch of cosmic acceleration that occurred a tiny fraction of a second after the Big Bang:

Primordial Inflation

Inflation ended, so it was not driven by the cosmological constant. This is a caution against theoretical prejudice for Λ as the cause of current acceleration (i.e., as the identity of dark energy).

Light Scalar Fields as Dark Energy

Perhaps the Universe is not yet in its ground state. The `true' vacuum energy (Λ) could be zero (for reasons yet unknown). Transient vacuum energy can exist if there is a field that takes a cosmologically long time to reach its ground state. This was the reasoning behind inflation. For this reasoning to apply now, we must postulate the existence of an extremely light scalar field, since the dynamical evolution of such a field is governed by

$$t_d \sim \frac{1}{m} \ , \ t_d > 1/H_0 \ \Rightarrow \ m < H_0 \sim 10^{-33}\,\mathrm{eV}$$

JF, Hill, Stebbins, Waga 1995

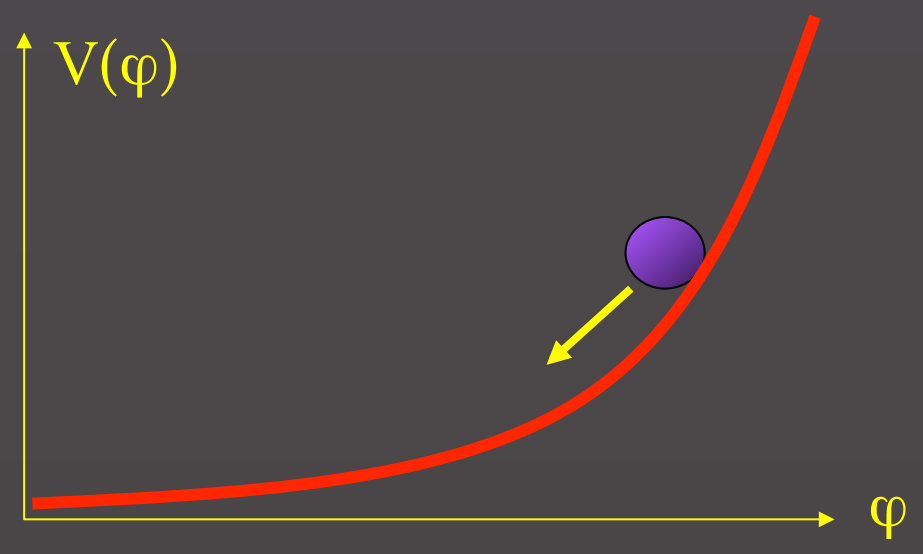
Scalar Field as Dark Energy (inspired by inflation)

- Dark Energy could be due to a very light scalar field φ, slowly evolving in a potential, V(φ):

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{dV}{d\varphi} = 0$$

- Density & pressure:

$$\rho = \tfrac{1}{2}\dot{\varphi}^2 + V(\varphi)$$
$$P = \tfrac{1}{2}\dot{\varphi}^2 - V(\varphi)$$



- Slow roll:

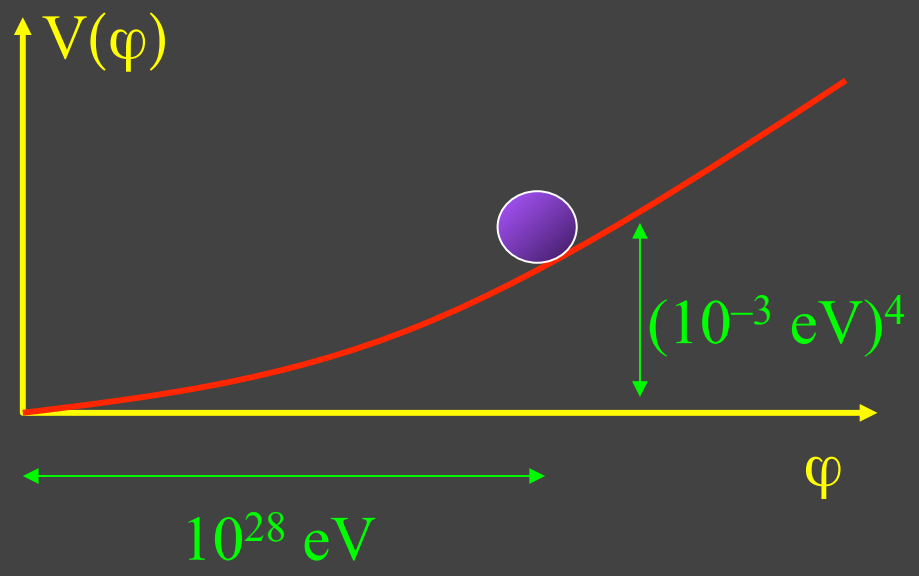
$$\tfrac{1}{2}\dot{\varphi}^2 < V(\varphi) \Rightarrow P < 0 \Leftrightarrow w < 0 \text{ and time - dependent}$$

Scalar Field Dark Energy

aka quintessence

General features:

$m_{eff} < 3H_0 \sim 10^{-33}$ eV $(w < 0)$
(Potential > Kinetic Energy)

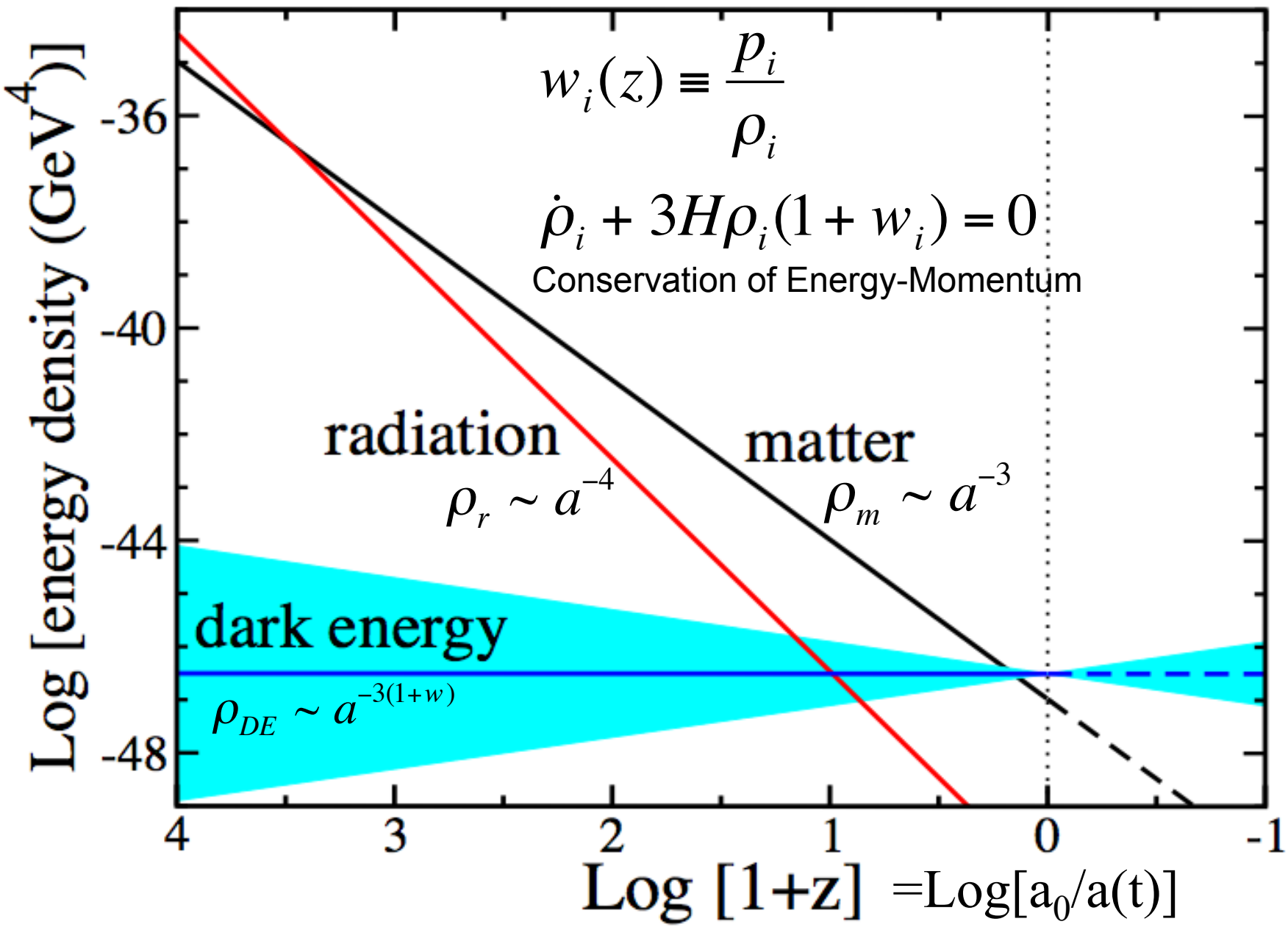


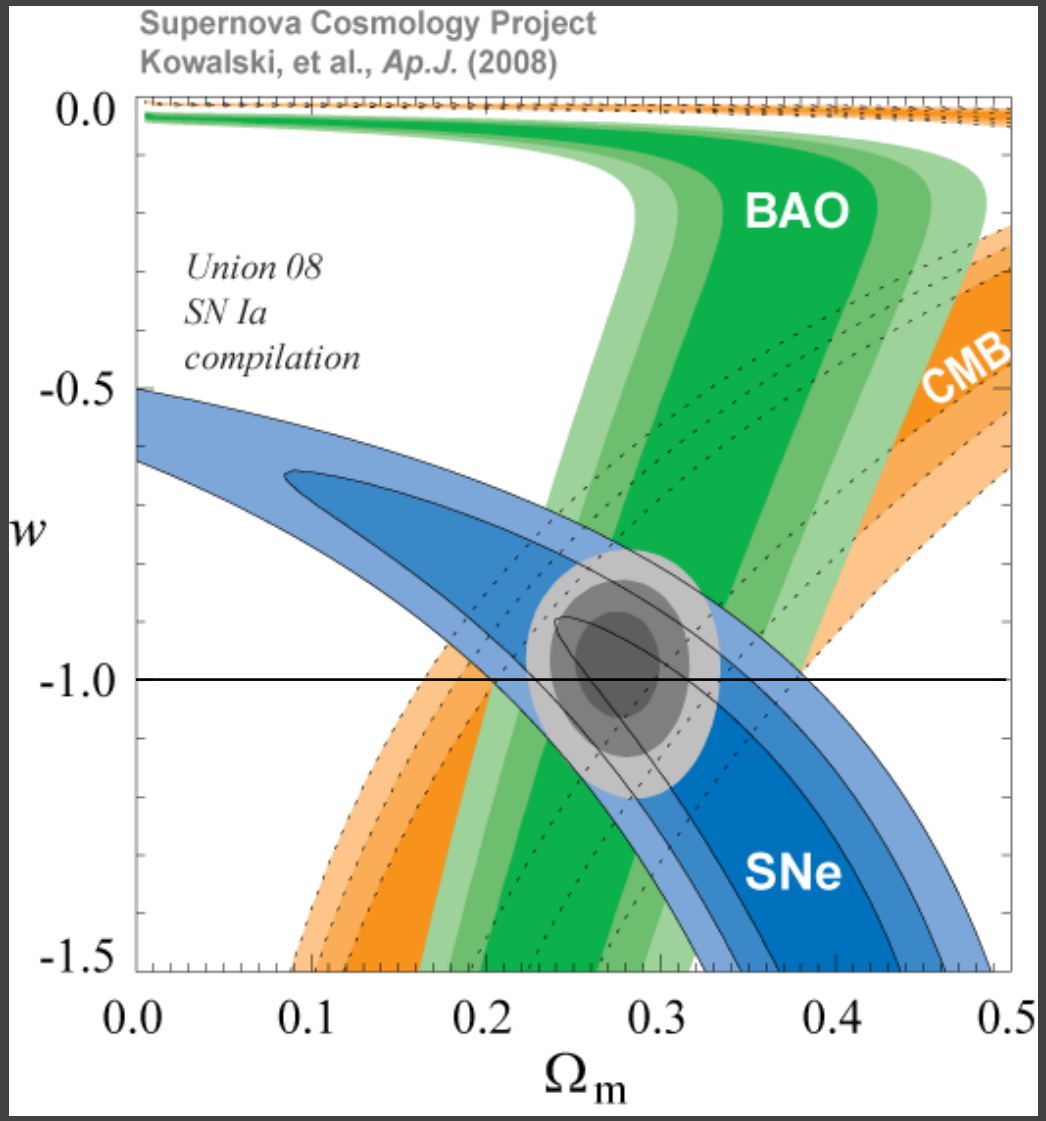
$V \sim m^2\varphi^2 \sim \rho_{crit} \sim 10^{-10}$ eV^4

$\varphi \sim 10^{28}$ eV $\sim M_{Planck}$

Ultra-light particle: Dark Energy hardly clusters, nearly smooth
Equation of state: usually, $w > -1$ and evolves in time
Hierarchy problem: Why $m/\phi \sim 10^{-61}$?
Weak coupling: Quartic self-coupling $\lambda_\phi < 10^{-122}$

Equation of State parameter *w* determines Cosmic Evolution





assuming flat Univ. and constant *w*

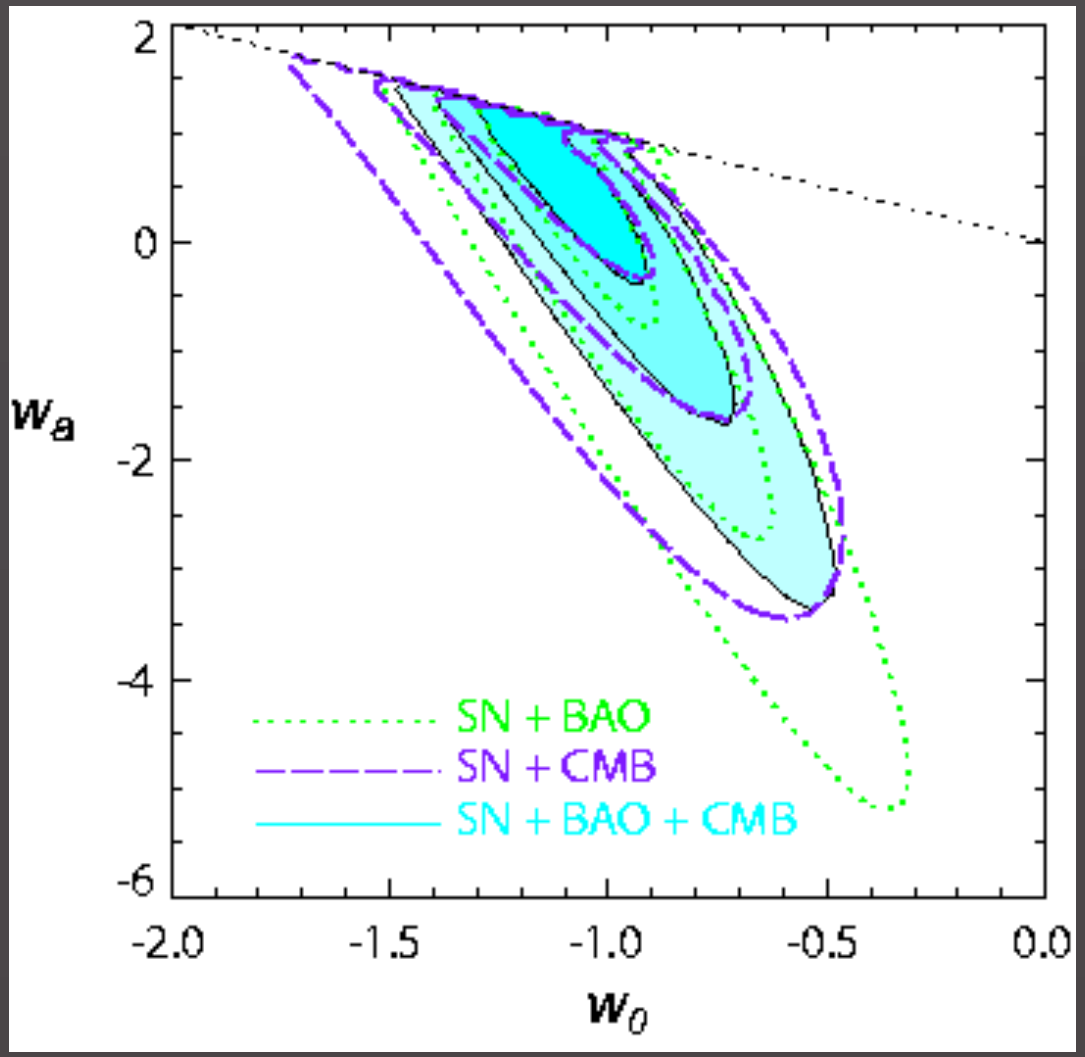
Only statistical errors shown

Much weaker current constraints on Time-varying Dark Energy

3-parameter model

$$w(z) = w_0 + w_a(1 - a) + \ldots$$

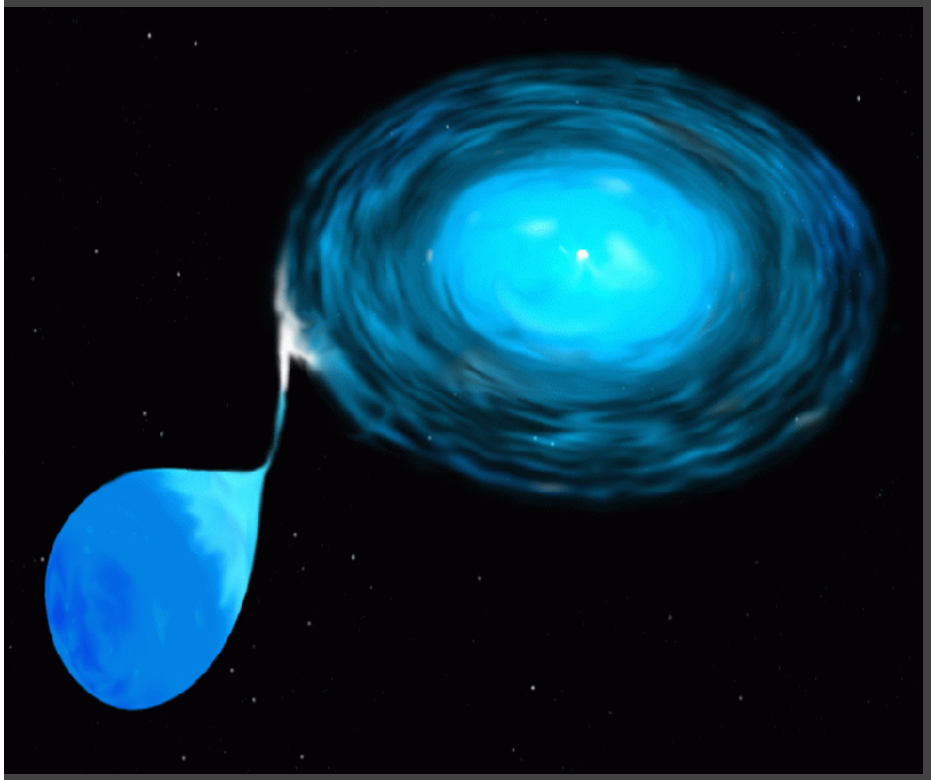
marginalized over Ω_m



Assumes flat Universe

Kowalski et al 08

Type Ia Supernovae



Thermonuclear explosions of White Dwarf stars

White Dwarf accretes mass from or merges with a companion star, growing to a critical mass~1.4M_{sun} (Chandrasekhar)

A violent explosion is triggered at or near the center, and the star is completely incinerated within seconds

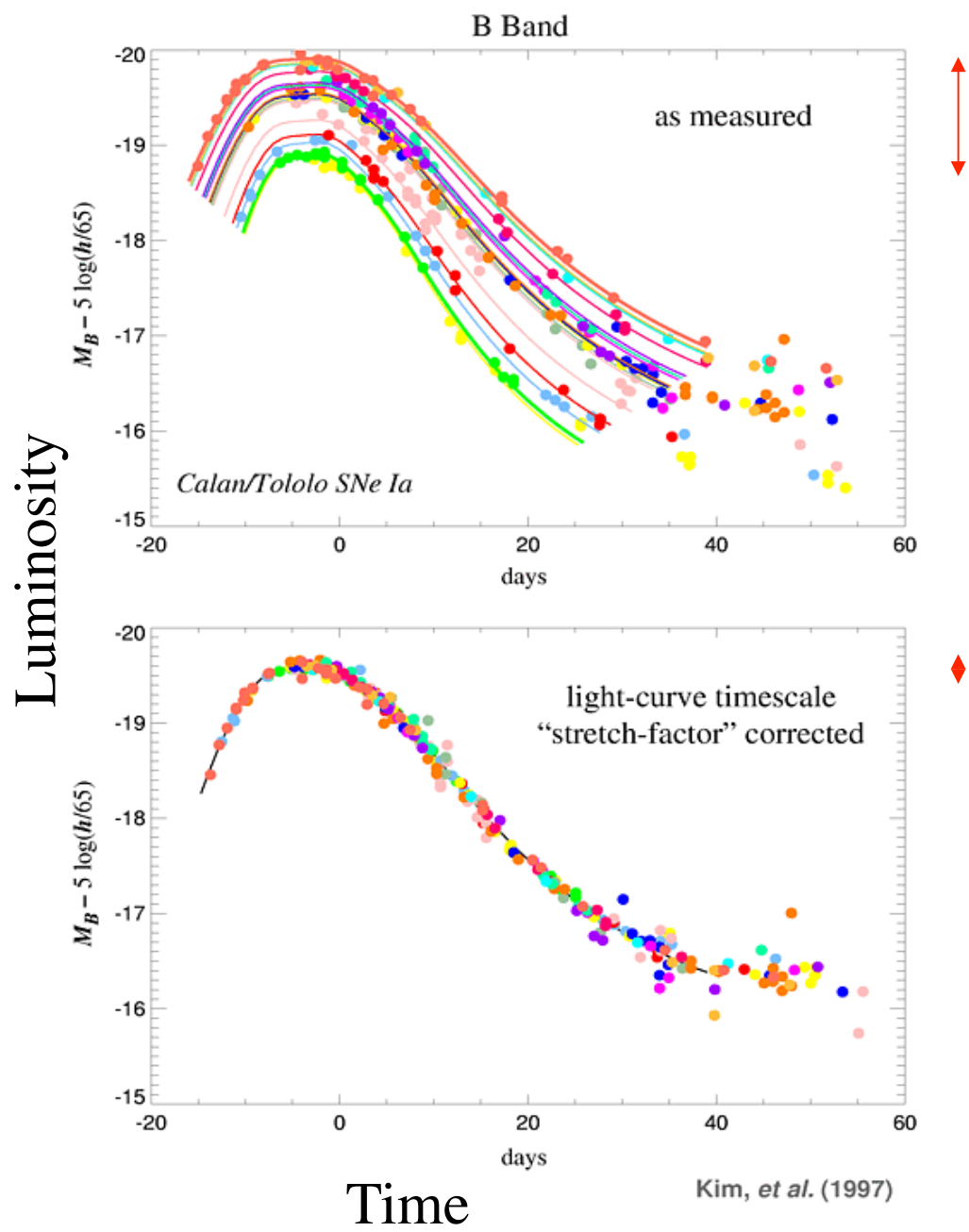
In the core, light elements are burned in fusion reactions to produce ~0.6M_{sun} Nickel. The radioactive decay of Nickel and Cobalt makes it shine for a couple of months

Type Ia SN
Peak Brightness
as calibrated
Standard Candle

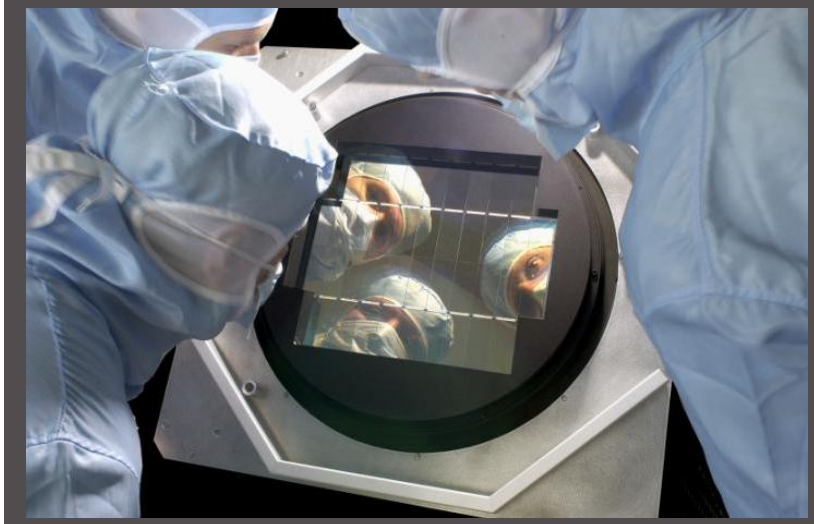
Peak brightness correlates with decline rate & color

Variety of algorithms for modeling these correlations

After correction,
σ~ 0.16 mag
(~8% distance error)



Supernova Legacy Survey (2003-2008)



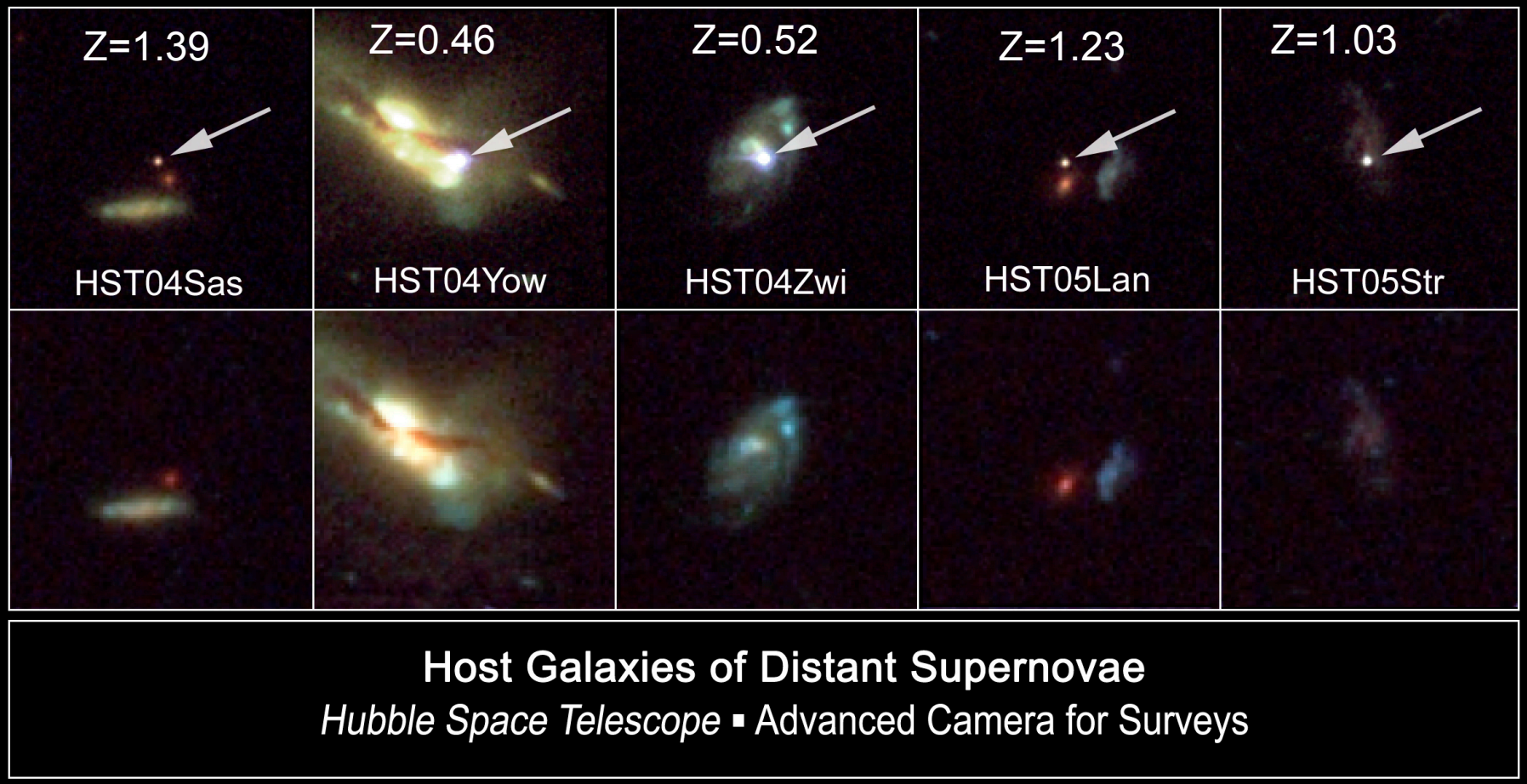
- ~400 distant SNe Ia to measure *w*
- Used 3.6-m CFHT+Megacam
- 36 CCDs with good blue response
- 4 filters *griz* for good K-corrections and color measurement
- Spectroscopic follow-up on 8-10m
- Astier etal (2006): published results based on ~70 SNLS SNe Ia (+Low-z) from 1st season
- 3-year results expected soon

The ESSENCE Survey

- Determine w to 10% or w!=-1
- 6-year project on CTIO 4m telescope in Chile; 12 sq. deg.
- Wide-field images in 2 bands
- Same-night detection of SNe
- Spectroscopy
  - Keck, VLT, Gemini, Magellan
- Goal is 200 SNeIa, 0.2<z<0.8

Wood-Vasey, etal (2007), Miknaitis, etal (2007): results from ~60 ESSENCE SNe (+Low-z)

Higher-z SNe Ia from ACS

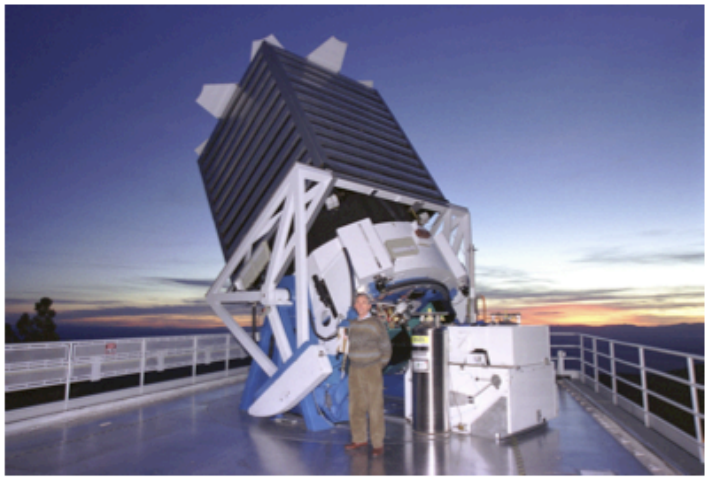


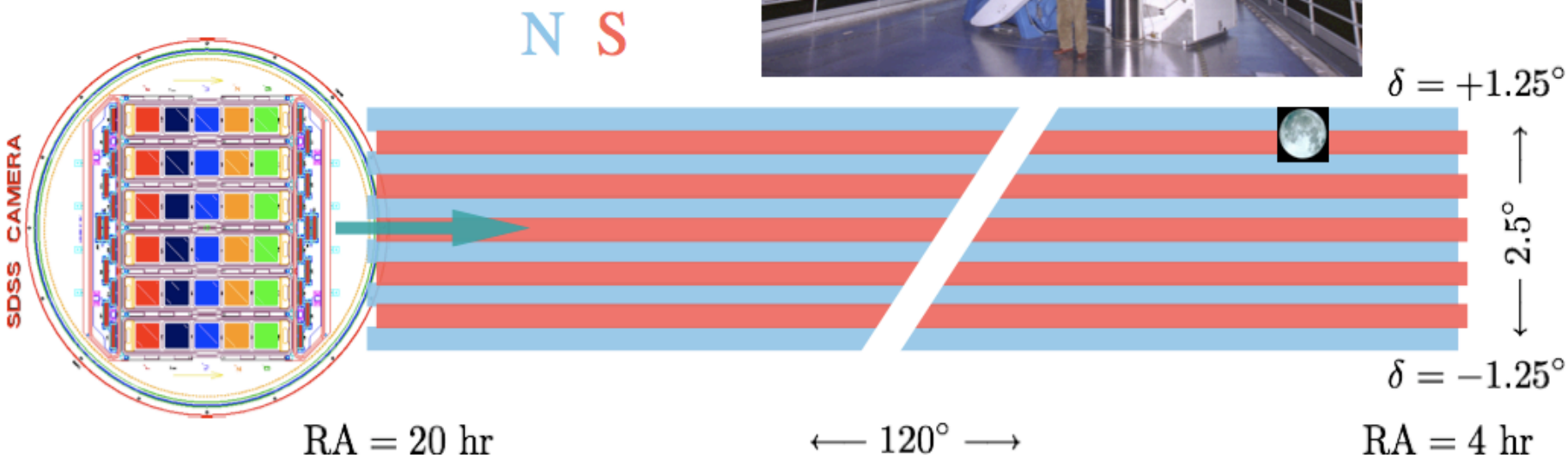
50 SNe Ia, 25 at $z>1$

Riess, etal

SDSS-II SN Survey

Frieman, et al (2008); Sako, et al (2008)

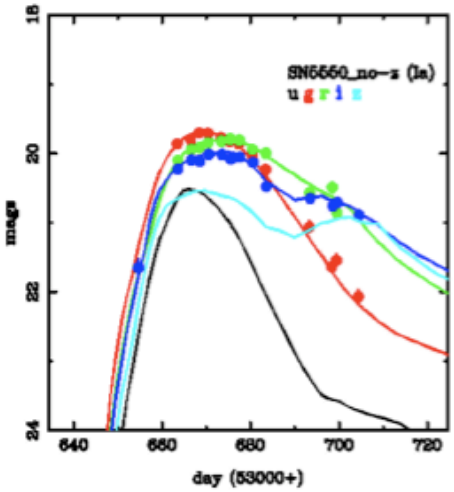


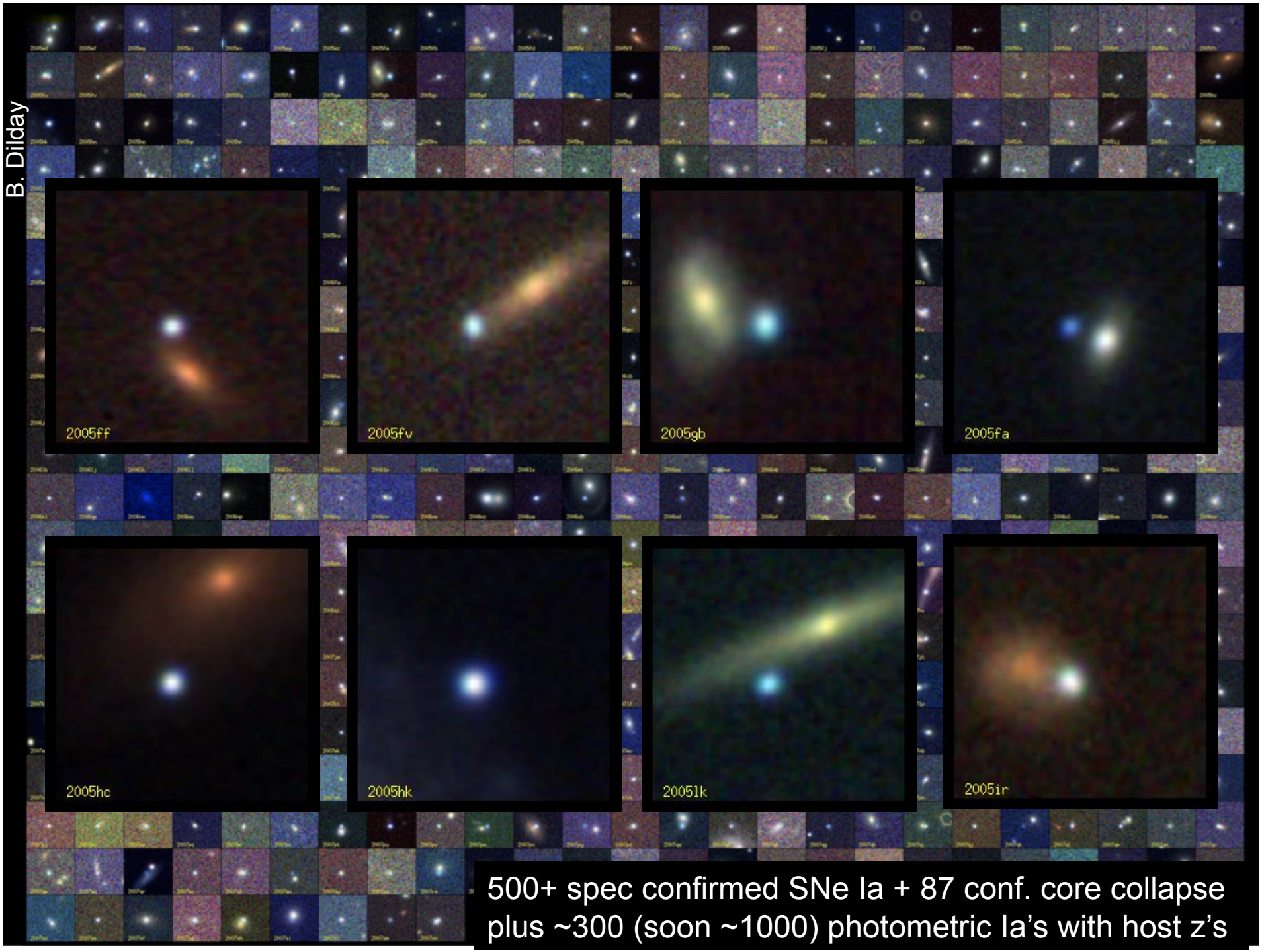


Use the SDSS 2.5m telescope

- September 1 - November 30 of 2005-2007
- Scan 300 square degrees every 2 days
- Obtain densely sampled multi-color light curves
- Results published from 2005 season

Kessler, et al 09; Lampeitl et al 09; Sollerman et al 09

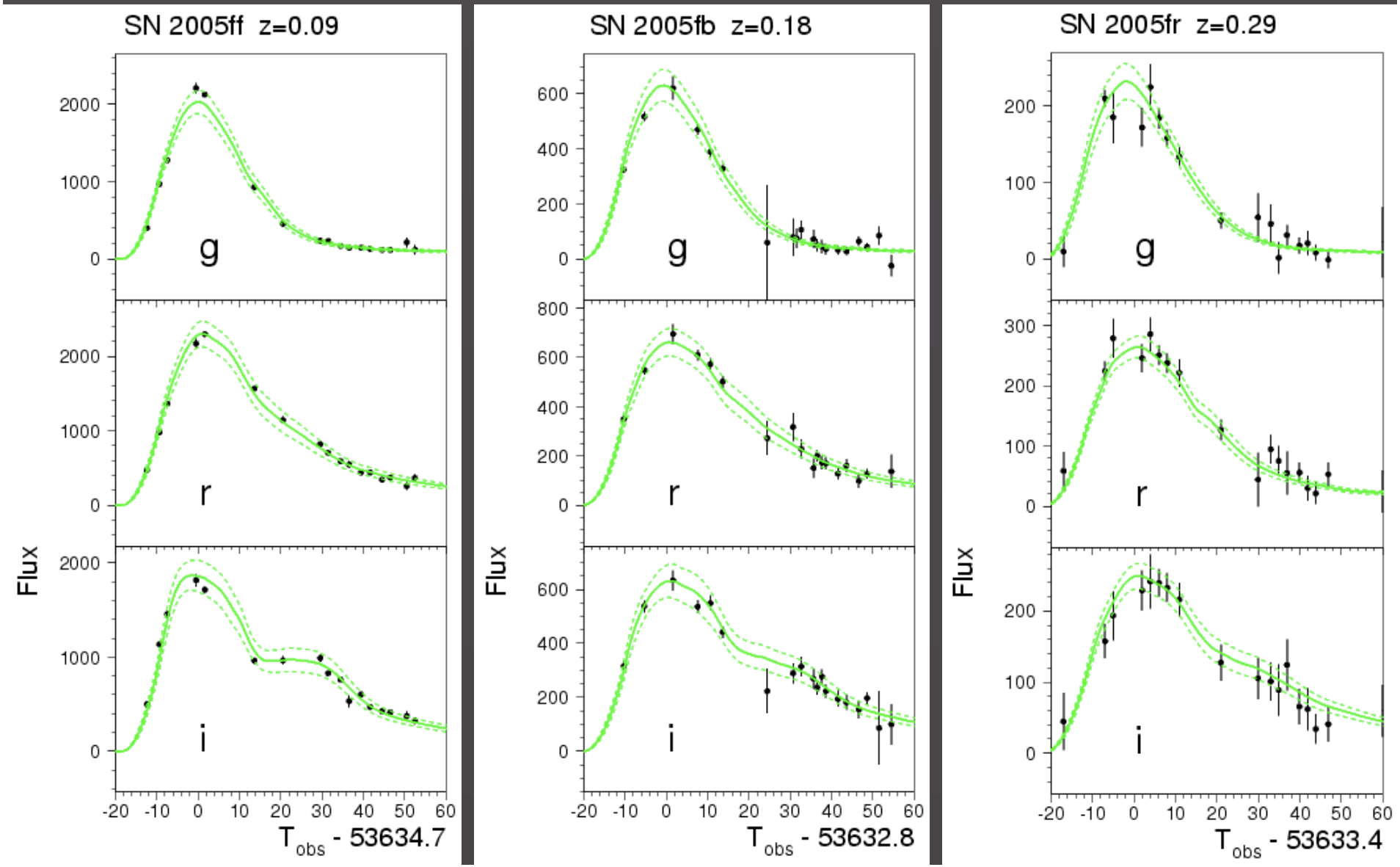




500+ spec confirmed SNe Ia + 87 conf. core collapse plus ~300 (soon ~1000) photometric Ia's with host z's

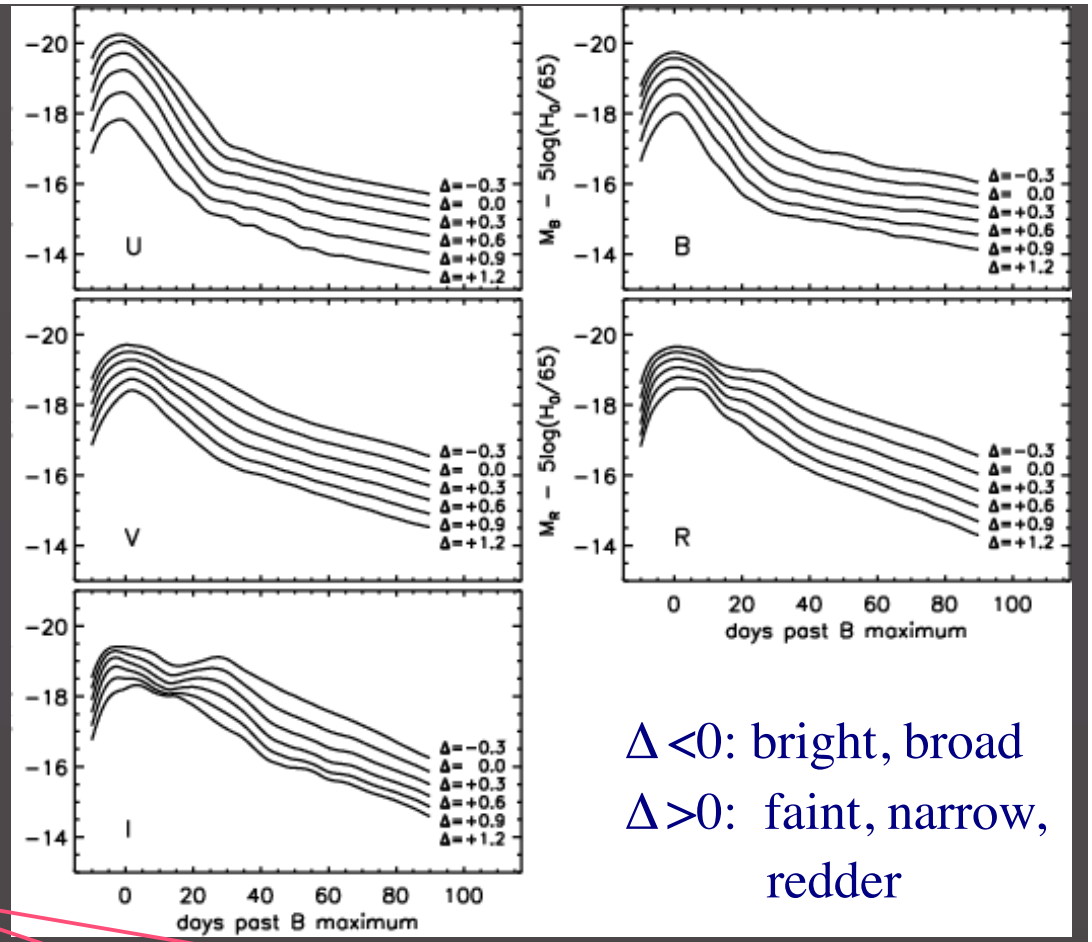
SDSS SN Photometry

Holtzman etal (2008)



MLCS2k2 Light-curve Templates

in rest-frame *j=UBVRI*;
built from ~100
well-observed, nearby SNe Ia



Δ <0: bright, broad
Δ >0: faint, narrow, redder

time-dependent model "vectors"
trained on Low-z SNe

observed passband

$$m^i_{\mathrm{mod}}(t-t_0) = \mu + M^j(t-t_0) + P^j(t-t_0)\Delta + Q^j(t-t_0)\Delta^2 + K^{ij}(t-t_0) + X^j_{host}(t-t_0) + X^i_{MW}(t-t_0)$$

fit parameters

Time of maximum | distance modulus | host gal extinction | stretch/decline rate

Guy et al

SALT-II Light-curve Fits

- Fit each light curve using rest-frame *spectral* surfaces:

$$\frac{dF_{\rm rest}}{d\lambda}(t,\lambda) = x_0 \times [M_0(t,\lambda) + x_1 \times M_1(t,\lambda)] \times \exp[c \times CL(\lambda)]$$

light-curve shape

color term

- Light curves fit individually, but distances only estimated globally:

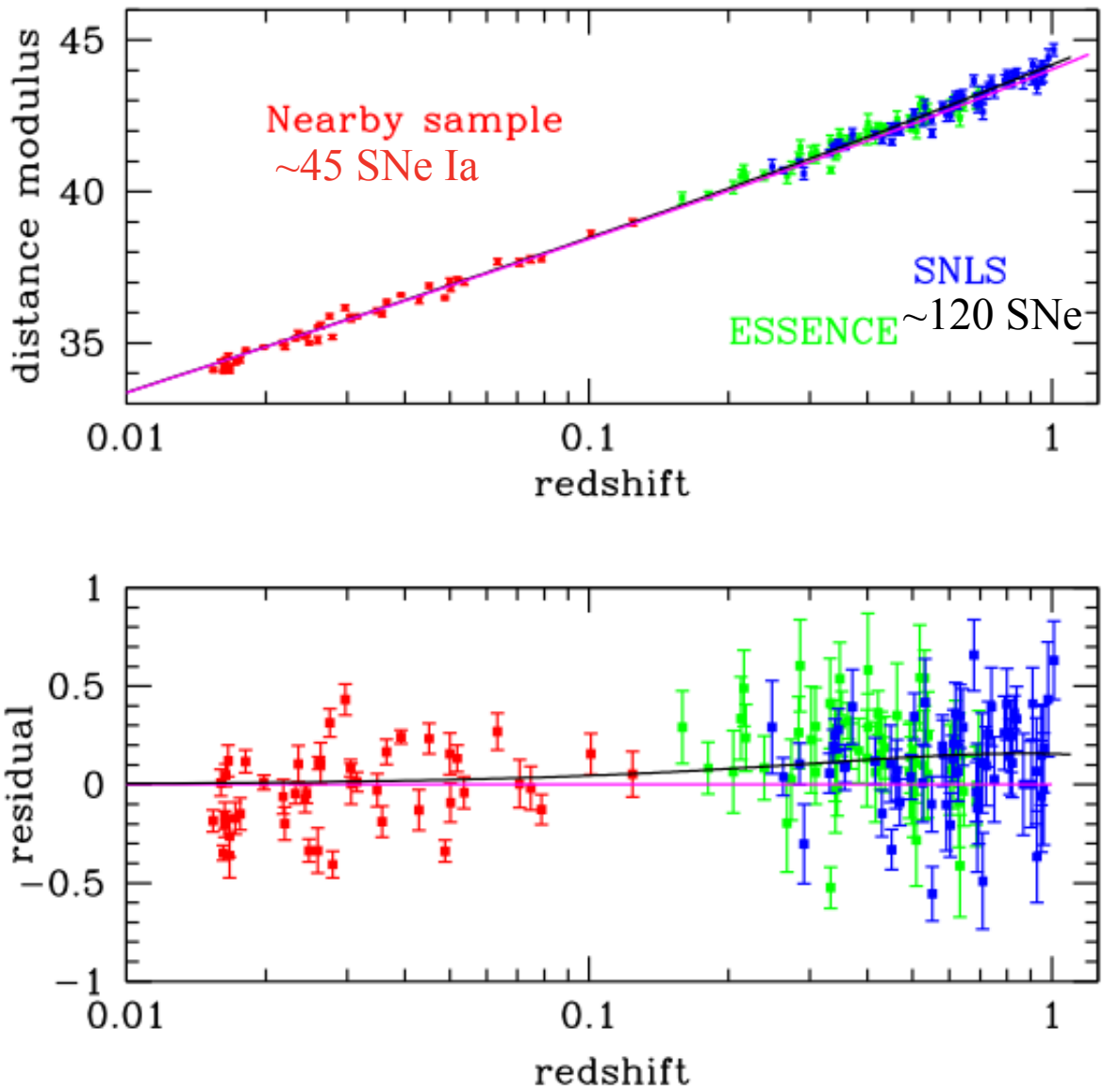
$$\mu_i = m^*_{Bi} - M + \alpha \cdot x_{1,i} - \beta \cdot c_i$$

$$\alpha \sim 0.15,\ \beta \sim 2.5$$

Global fit parameters, determined *along with* cosmological parameters by fit to Hubble diagram (so in principle you should not use SALT distance tables to test some other cosmological model)

•Differences from MLCS: not trained just on low-redshift data; flat priors on model parameters; color variations *not* assumed only from dust. *If* dust, then $\beta = R_V + 1$. Find $\beta \sim 2.5$ empirically.

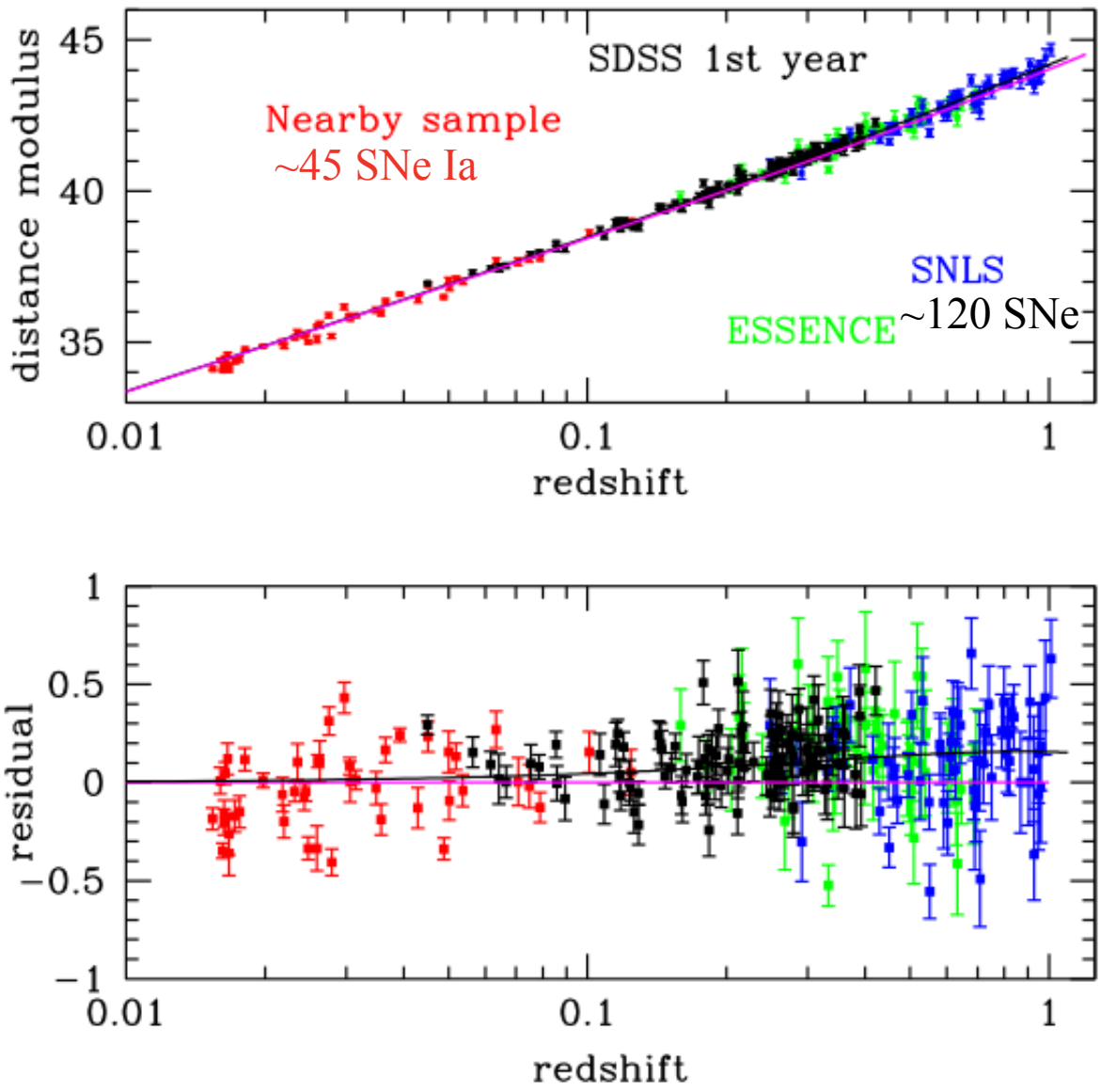
Hubble Diagram



Hubble Diagram with SDSS SNe

103 SNe Ia from first season that pass stringent light-curve quality cuts

Kessler etal (2009)
Lampeitl etal (2009)
Sollerman etal (2009)



SALT2

SDSS only:

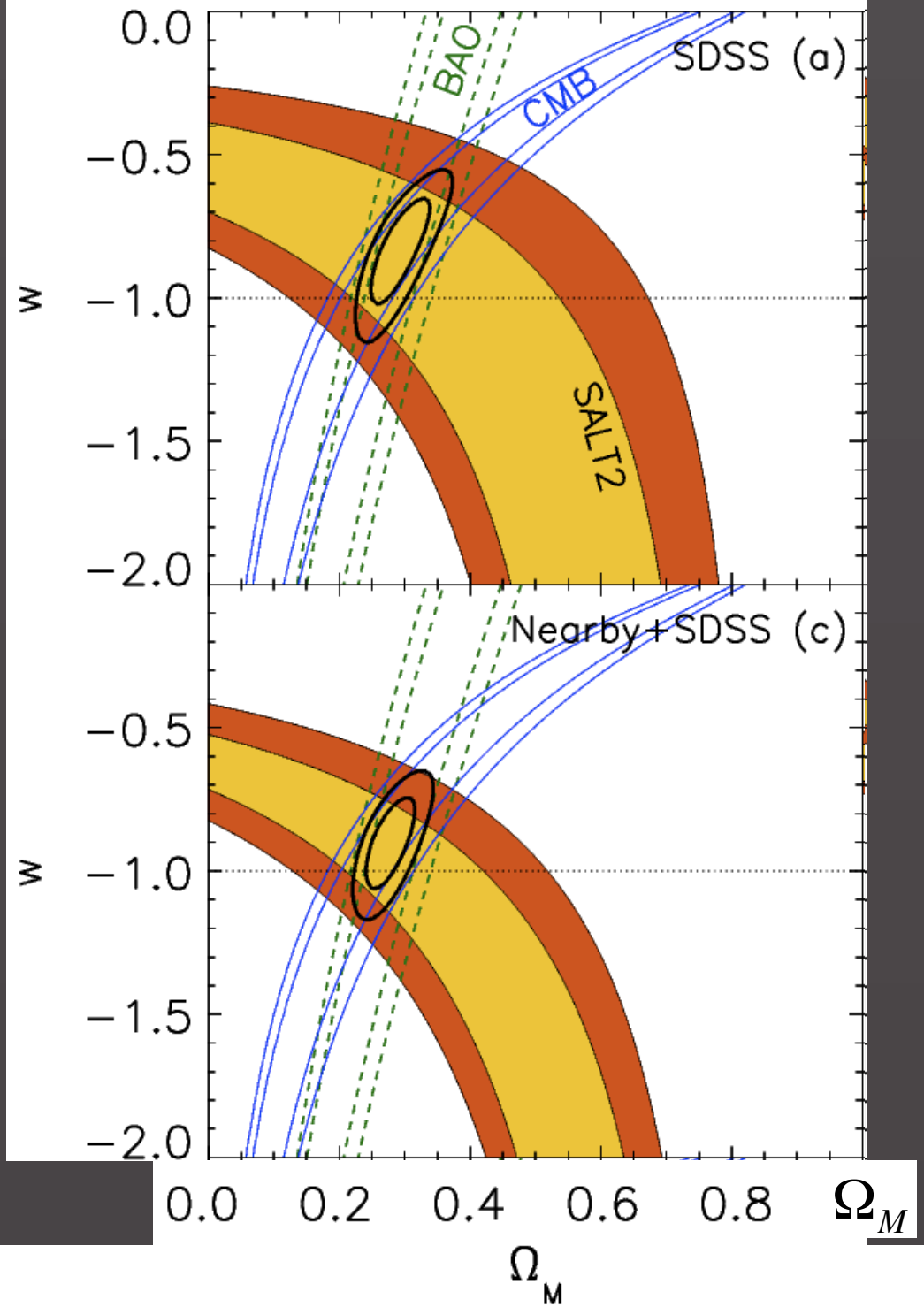
Nearby+SDSS:

MLCS

$$w = -0.93 \pm 0.13(\text{stat})^{+0.10}_{-0.32}(\text{syst})$$

SALT

$$w = -0.92 \pm 0.11(\text{stat})^{+0.07}_{-0.15}(\text{syst})$$



SALT/MLCS

Nearby+SDSS:

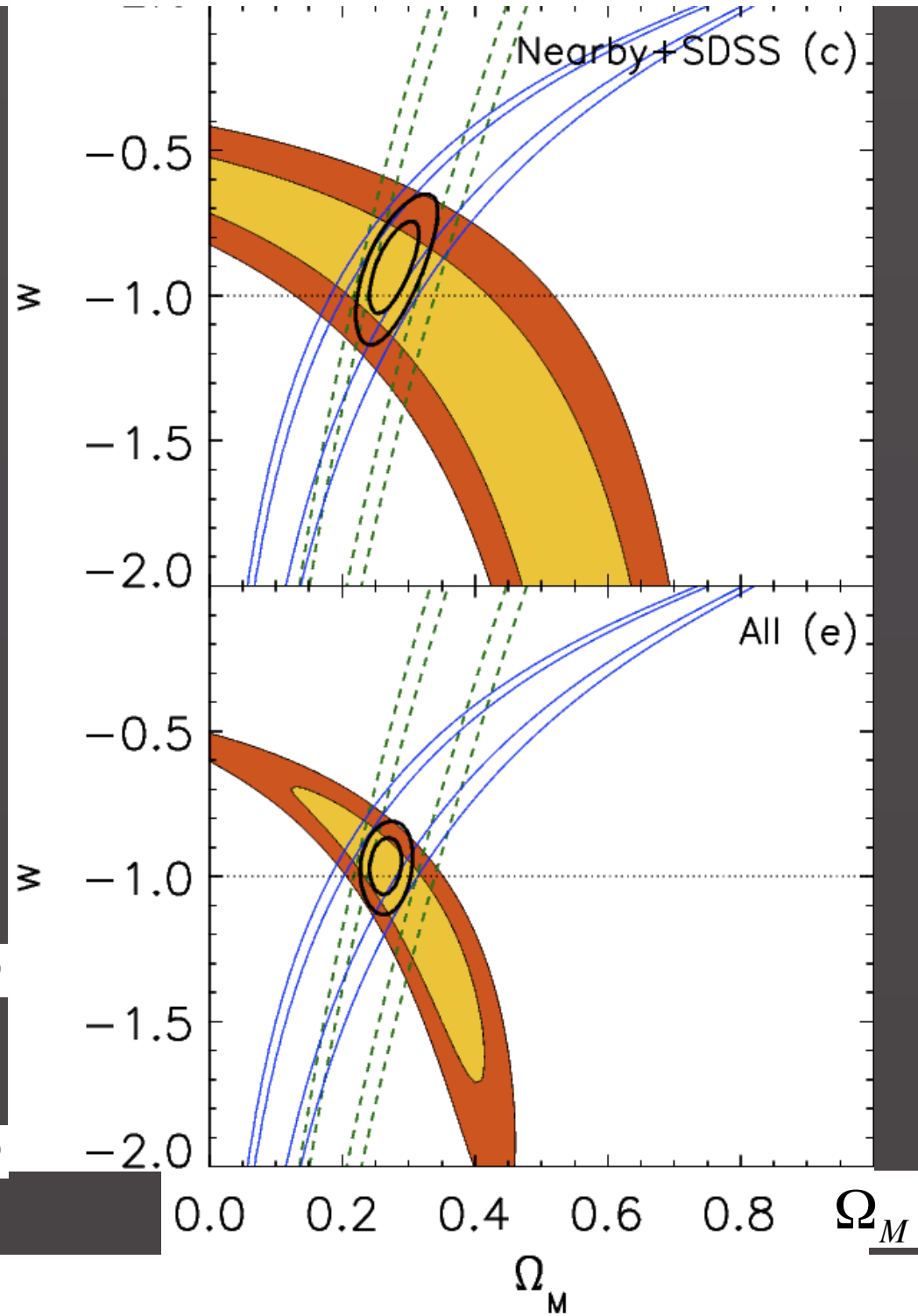
Nearby+SDSS+SNLS +ESSENCE+HST:

MLCS

$w = -0.76 \pm 0.07(\text{stat}) \pm 0.12(\text{syst})$

SALT

$w = -0.96 \pm 0.06(\text{stat}) \pm 0.12(\text{syst})$

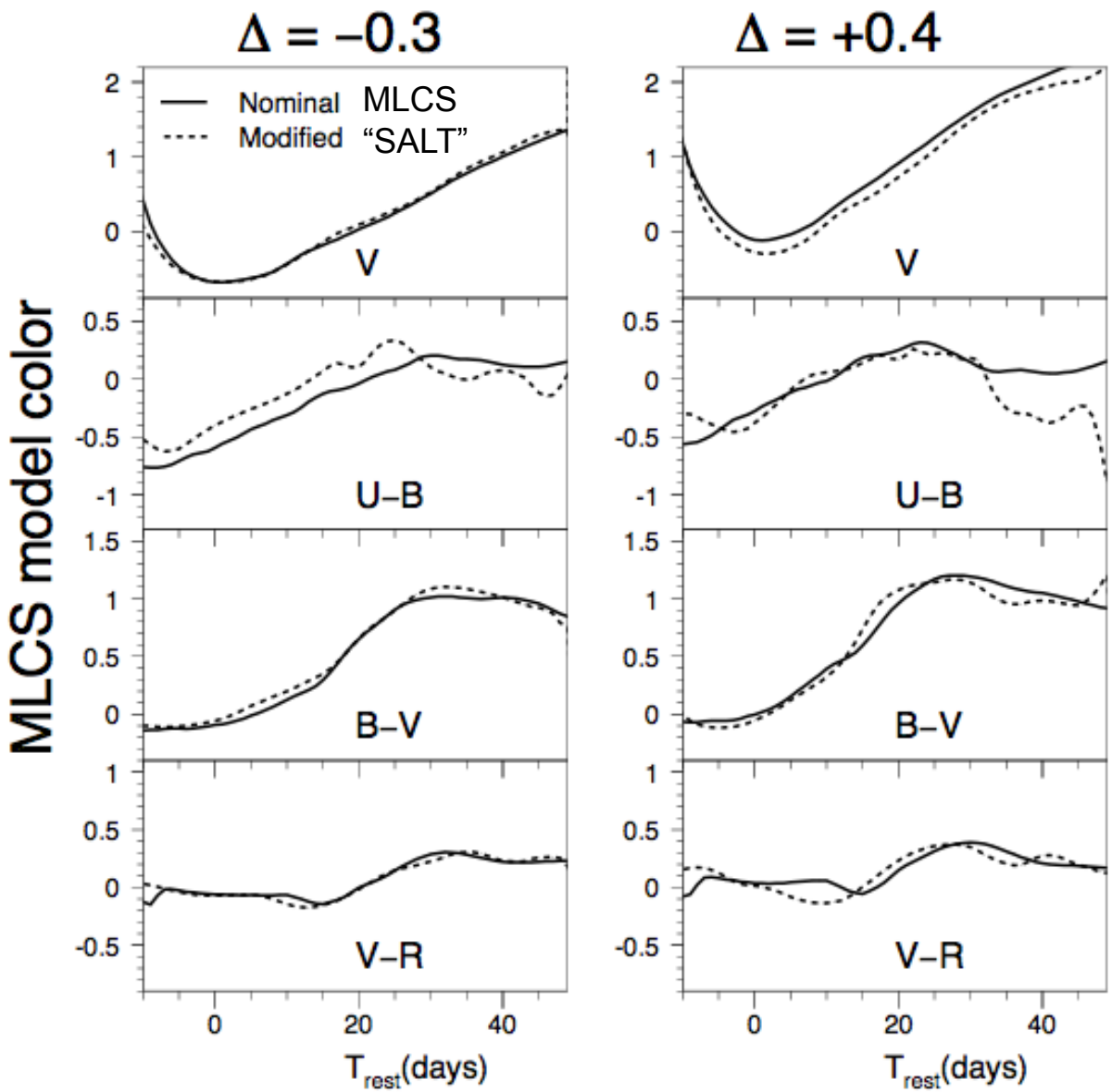


SALT vs MLCS template light curves

Diagnosis:

Large difference in Light-curve model in U-band

Use of prior on dust extinction in MLCS



What causes Cosmic Acceleration?

Three possibilities:

1. The Universe is filled with a negative-pressure component that gives rise to `gravitational repulsion':

   Dark Energy

2. Einstein's theory of General Relativity (gravity) is wrong on cosmic distance scales.

3. The Universe is inhomogeneous and only apparently accelerating, due to large-scale structure.

What can we probe?

- Probe dark energy through the history of the expansion rate:

$$\frac{H^2(z)}{H_0^2} = \Omega_m (1+z)^3 + \Omega_{DE} \exp\left[3\int (1+w(z))\, d\ln(1+z)\right] + \left(1-\Omega_m-\Omega_{DE}\right)(1+z)^2$$

- and the growth of large-scale structure: $\frac{\delta\rho(a)}{\rho}$

- Distances are often indirect proxies for *H(z)*:
  Form of *F* depends on spatial curvature

$$r(z) = F\left[\int \frac{dz}{H(z)}\right]$$

$$d_L(z) = (1+z)r(z)$$

$$d_A(z) = (1+z)^{-1} r(z)$$

$$\frac{dV}{dz\,d\Omega} = \frac{r^2(z)}{H(z)}$$

- Weak Lensing cosmic shear — Distance+growth
- Supernovae — Distance
- Baryon Acoustic Oscillations — Distance+*H(z)*
- Cluster counting — Distance+growth

www.darkenergysurvey.org

The Dark Energy Survey

- Study Dark Energy using
  4 complementary* techniques:
  I. Cluster Counts
  II. Weak Lensing
  III. Baryon Acoustic Oscillations
  IV. Supernovae

- Two multiband surveys:
  5000 deg^2 g, r, i, z, Y to 24th mag
  15 deg^2 repeat (SNe)

- Build new 3 deg^2 FOV camera
  and Data management sytem
  Survey 2012-2017 (525 nights)
  Camera available for community use the rest of the time (70%)

Blanco 4-meter at CTIO

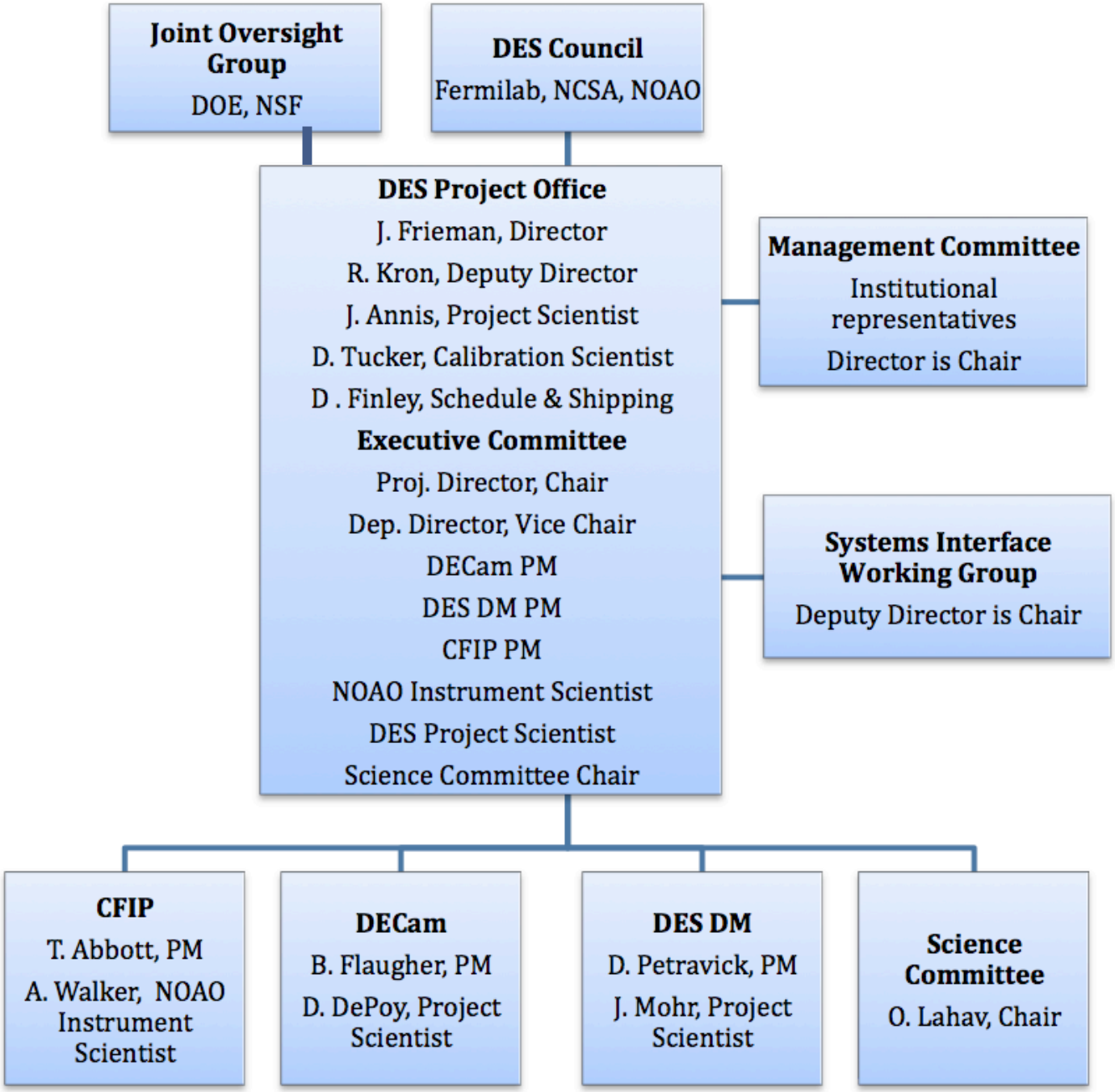
*in systematics & in cosmological parameter degeneracies
*geometric+structure growth: test Dark Energy vs. Gravity

The DES Collaboration

Fermilab
University of Illinois at Urbana-Champaign/NCSA
University of Chicago
Lawrence Berkeley National Lab
NOAO/CTIO
DES Spain Consortium
DES United Kingdom Consortium
University of Michigan
Ohio State University
University of Pennsylvania
DES Brazil Consortium
Argonne National Laboratory
SLAC-Stanford-Santa Cruz Consortium
Universitats-Sternwarte Munchen
Texas A&M University

Over 120 members
plus students & postdocs

Funding: DOE, NSF, STFC, MEC, FINEP, Excellence Cluster, collaborating institutions


Joint Oversight Group
DOE, NSF
DES Council
Fermilab, NCSA, NOAO
DES Project Office
J. Frieman, Director
R. Kron, Deputy Director
J. Annis, Project Scientist
D. Tucker, Calibration Scientist
D . Finley, Schedule & Shipping
Executive Committee
Proj. Director, Chair
Dep. Director, Vice Chair
DECam PM
DES DM PM
CFIP PM
NOAO Instrument Scientist
DES Project Scientist
Science Committee Chair
Management Committee
Institutional representatives
Director is Chair
Systems Interface Working Group
Deputy Director is Chair
CFIP
T. Abbott, PM
A. Walker, NOAO Instrument Scientist
DECam
B. Flaugher, PM
D. DePoy, Project Scientist
DES DM
D. Petravick, PM
J. Mohr, Project Scientist
Science Committee
O. Lahav, Chair

Project Timeline

3 Projects:

DECam (FNAL)

DES Data Management System (NCSA)

CTIO Facilities Improvement Project (telescope)

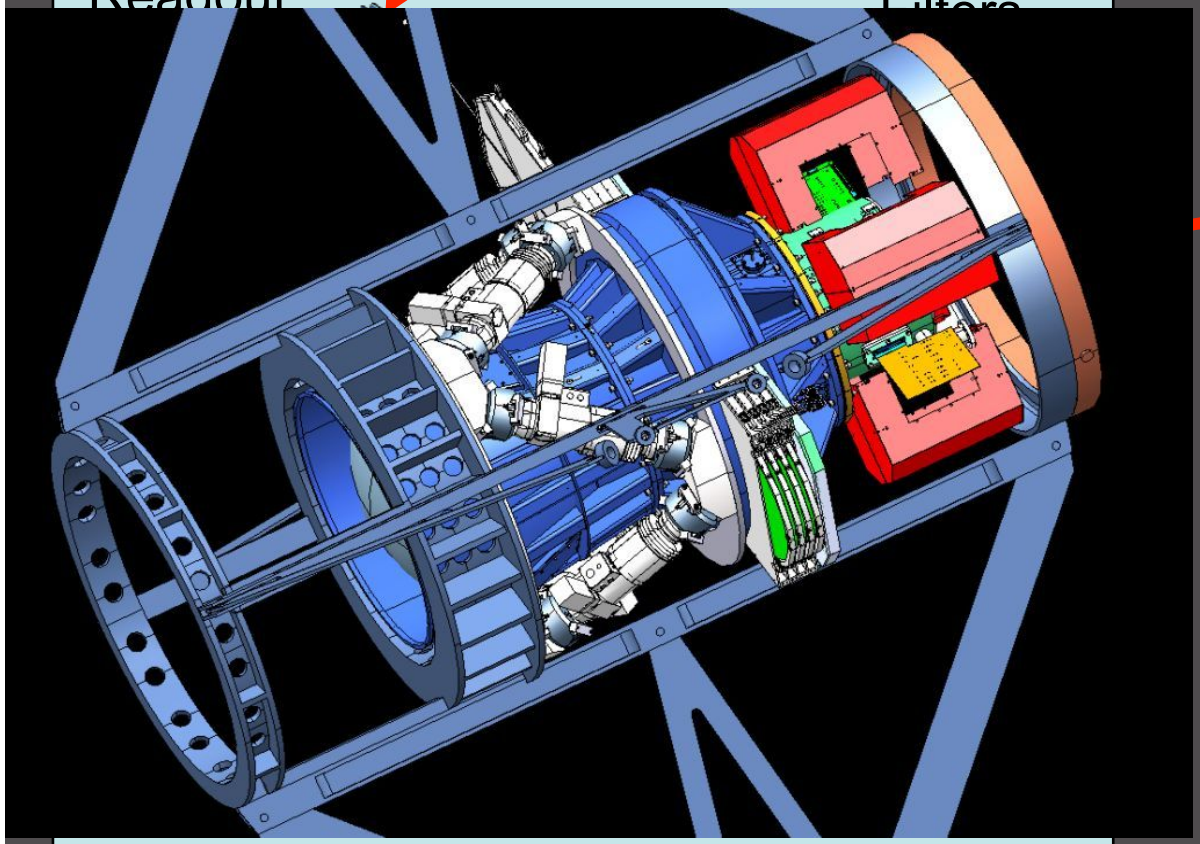
- Project initiated 2003
- DECam R&D 2004-8
- Camera construction 2008-11
- Final construction, testing, integration now on-going
- Ship components to Chile: Oct. 2010-June 2011
- Installation: Jan.-Oct. 2011
- First light: Oct. 2011
- Commissioning: Oct. 2011-Jan. 2012
- Survey begins: 2012

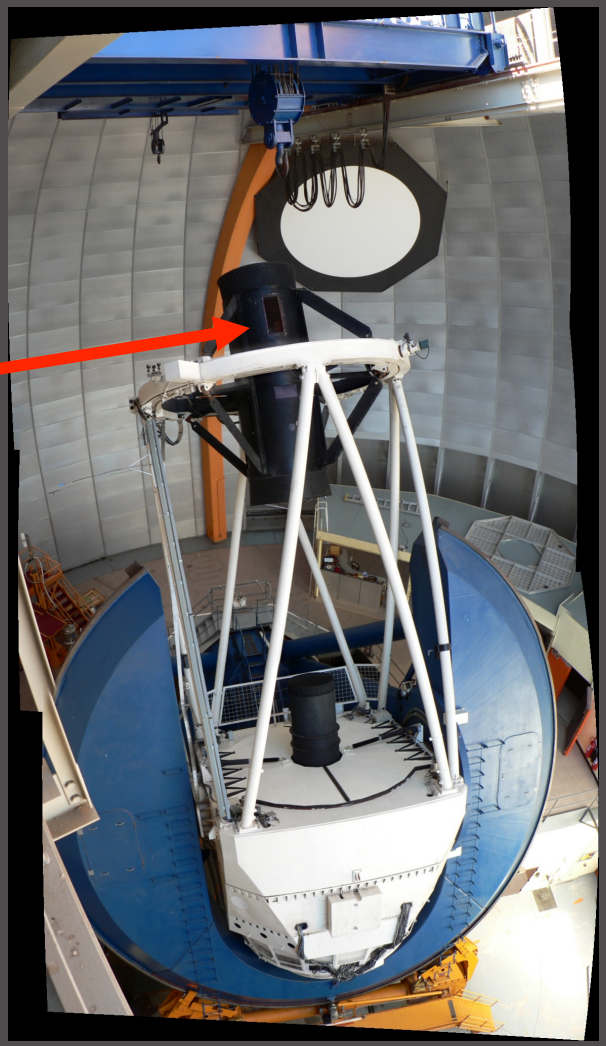
DES Instrument: DECam

CCD Readout

Mechanical Interface of DECam Project to the Blanco

Filters

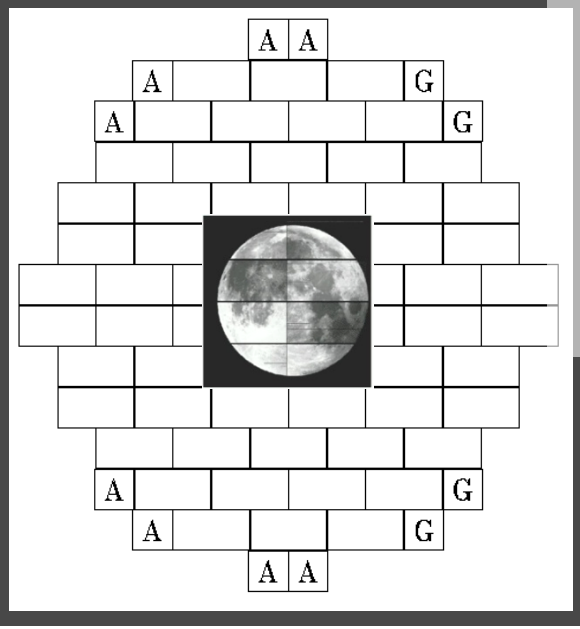


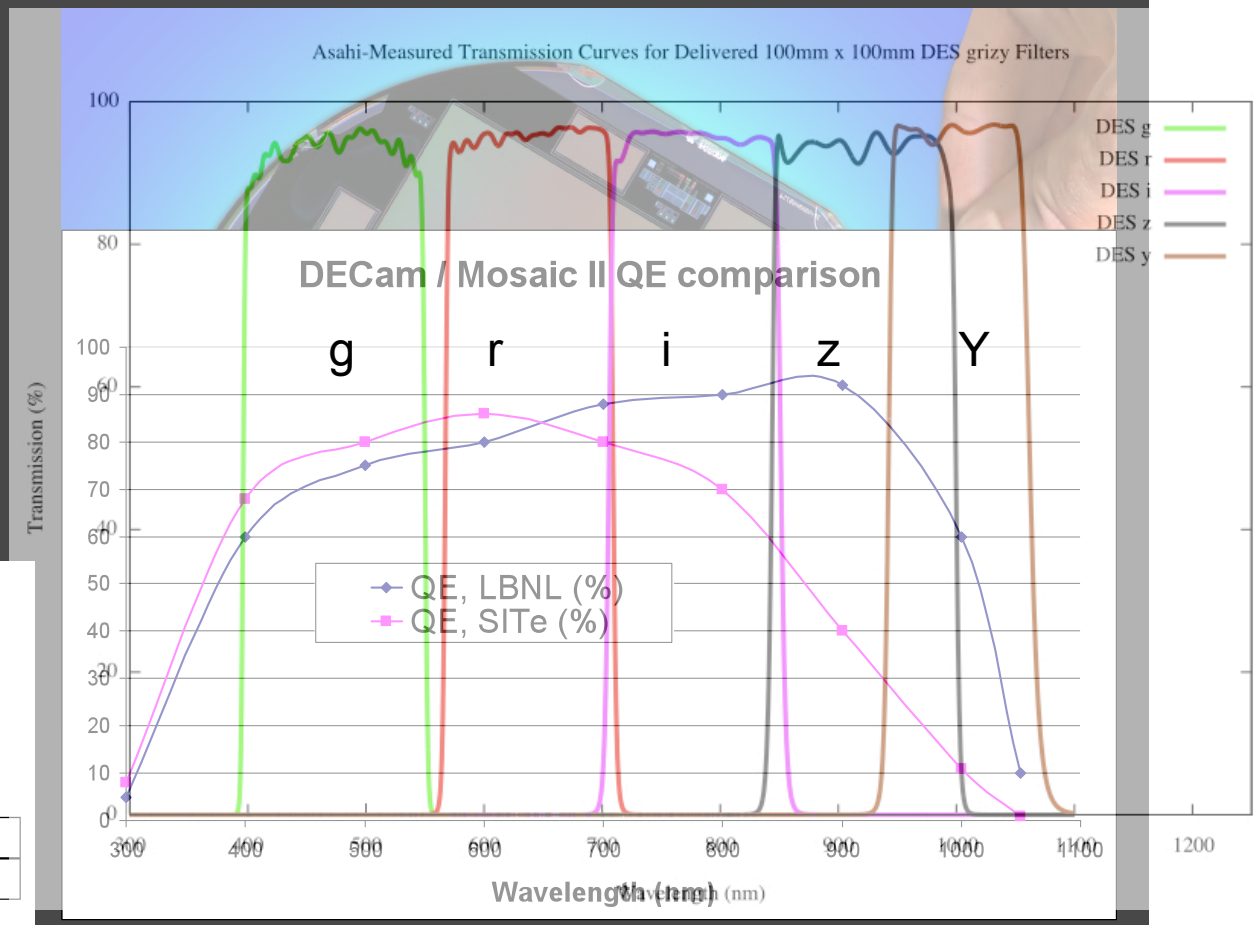


Designed for improved image quality compared to current Blanco mosaic camera

DES CCDs

- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.27”) pixel size
- 12 2kx2k guide and focus chips
- Excellent red sensitivity
- Developed by LBNL
- Packaged and tested at FNAL
- Read-time <17 sec with <15e read noise

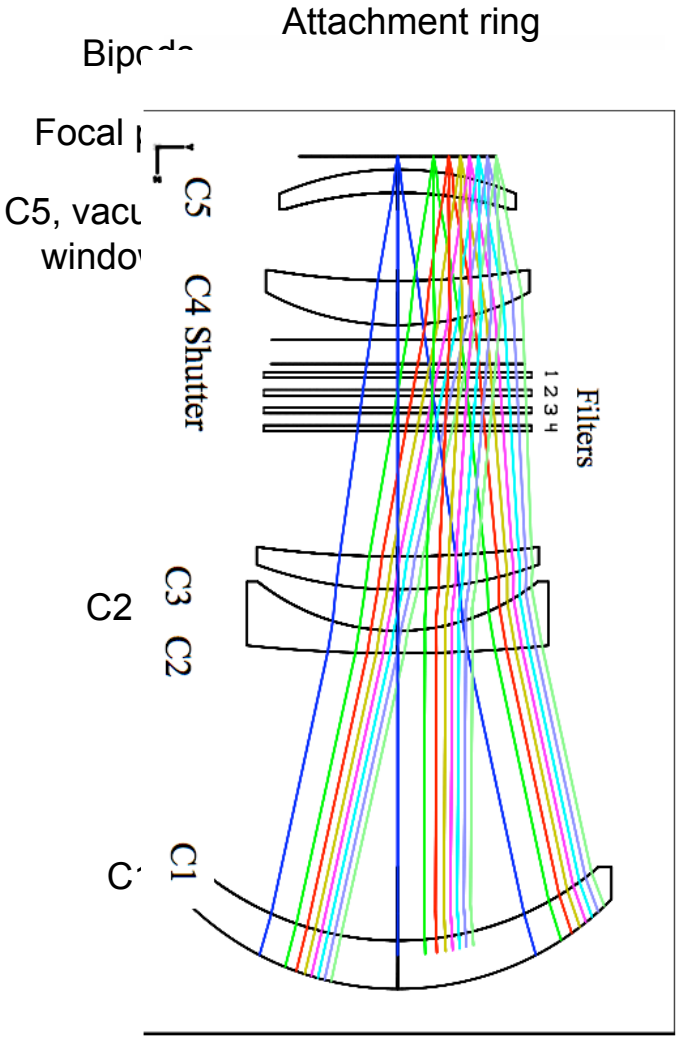




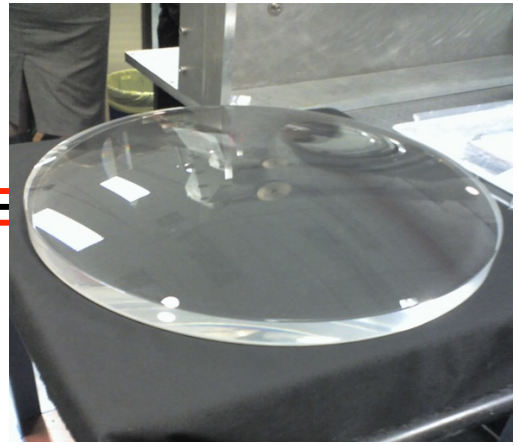
Now in hand: 114 packaged, science-grade CCDs

Optics

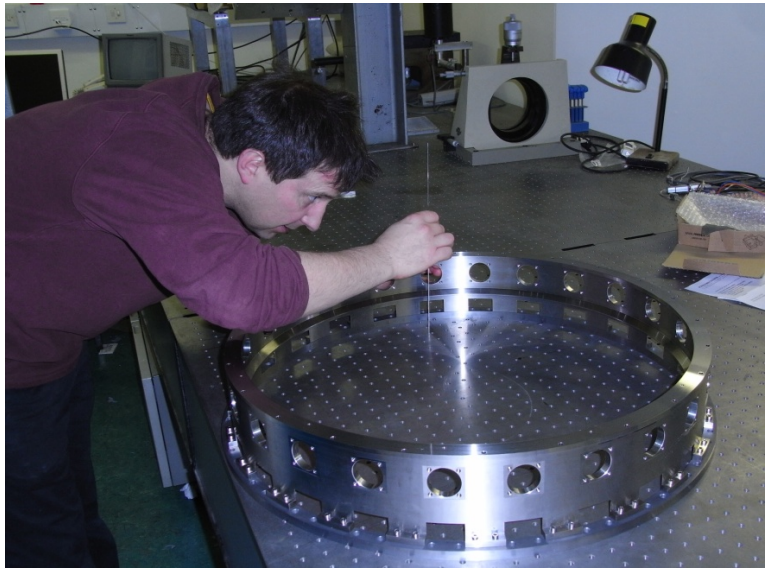
- Field of view: 2.2° diameter
  - 5 element optical corrector (fused silica)
  - – 2 Aspheres (one surface on C2 and C4)
  - – C1 is the largest: 980mm diameter
  - – C5 is imager window: 500mm diameter
- Pixel (15 μm) scale
  - – 0.26”/pixel (1” = 3.8 pix = 57 μm)
- Image quality Design FWHM: 0.27” (15 μm)
- Status
  - – C2, C3, C5 delivered June, July
  - – C1, C4 expected Oct. 2010

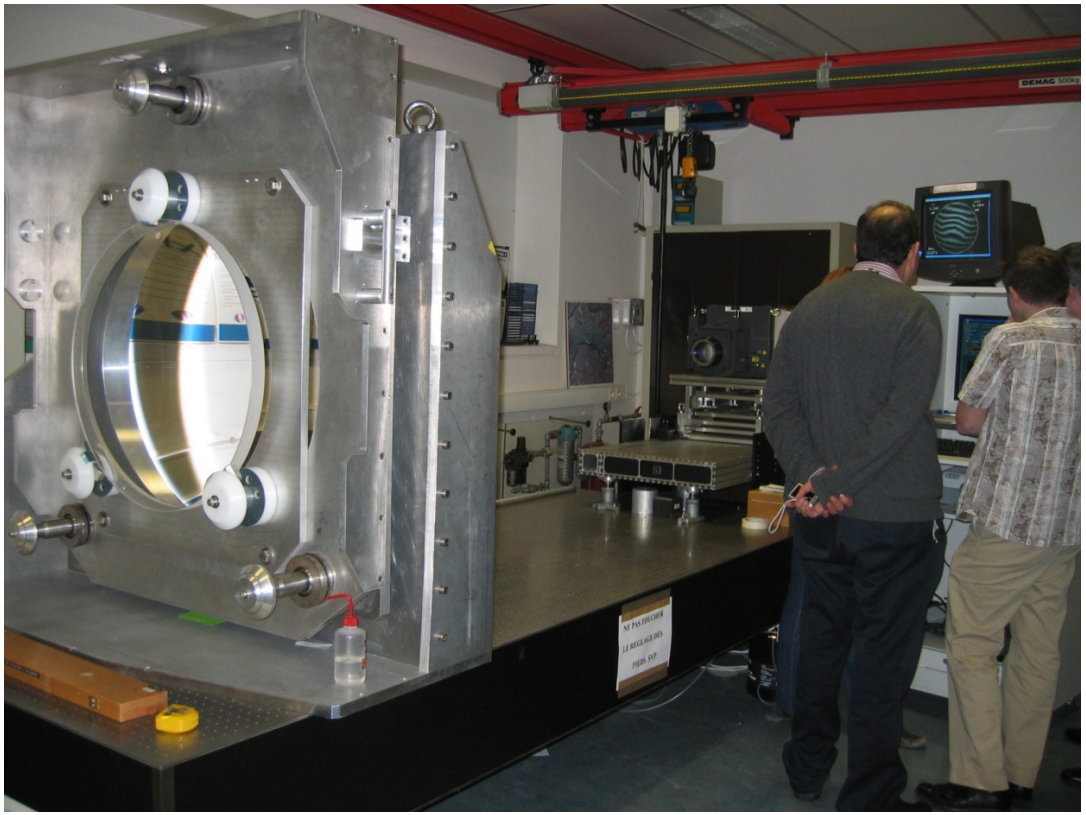


Lens Fabrication



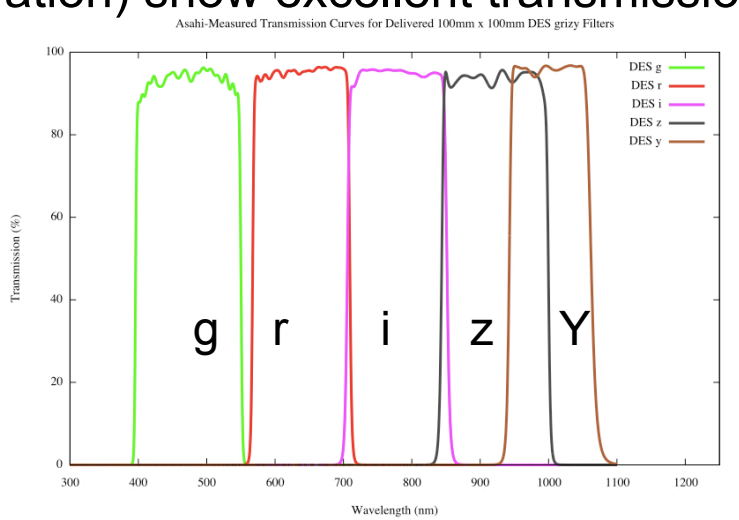
- C3 inspection at SESO April 2010
- C4 Cell inspection at UCL





Filters

- Filter contract awarded to Asahi in 2009
- 620mm substrate, 600mm clear aperture
- Delivery of all 5 filters (g,r,i,z,y) expected by Dec. 2010
- Asahi has built and commissioned a huge coating chamber as well as custom cleaning, polishing and testing equipment
- 100mm square filters from Asahi (for DES calibration) show excellent transmission



Shutter Arrived at Fermilab May 12th

DARK ENERGY SURVEY

Shutter Owners manual

Argelander-Institut für Astronomie

universitätbonn

Decam600

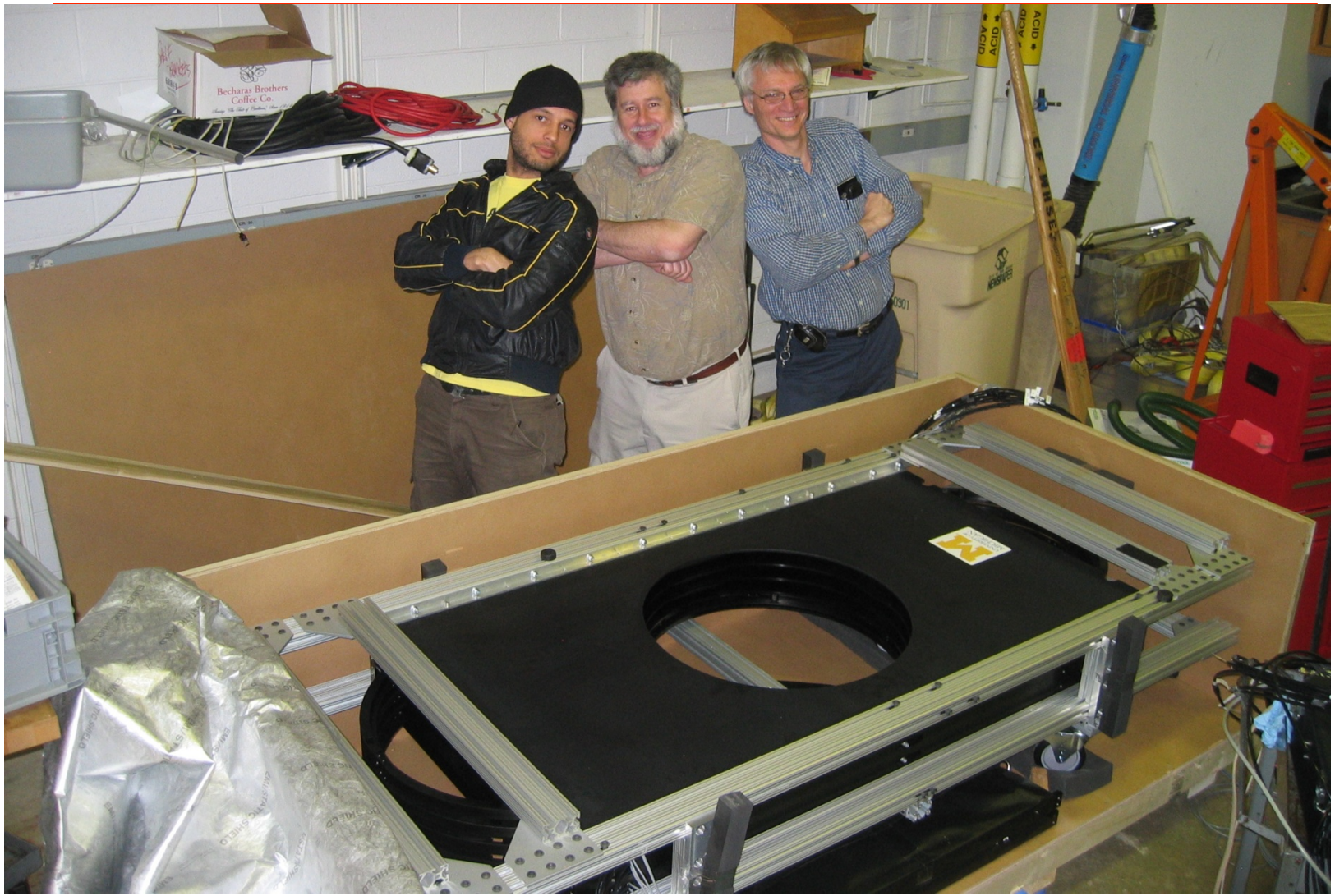
a Bonn Shutter for

the Dark Energy Survey camera

AIfA Instrumentation Group
Klaus Reif
(Vers. 1.0, April 2010)

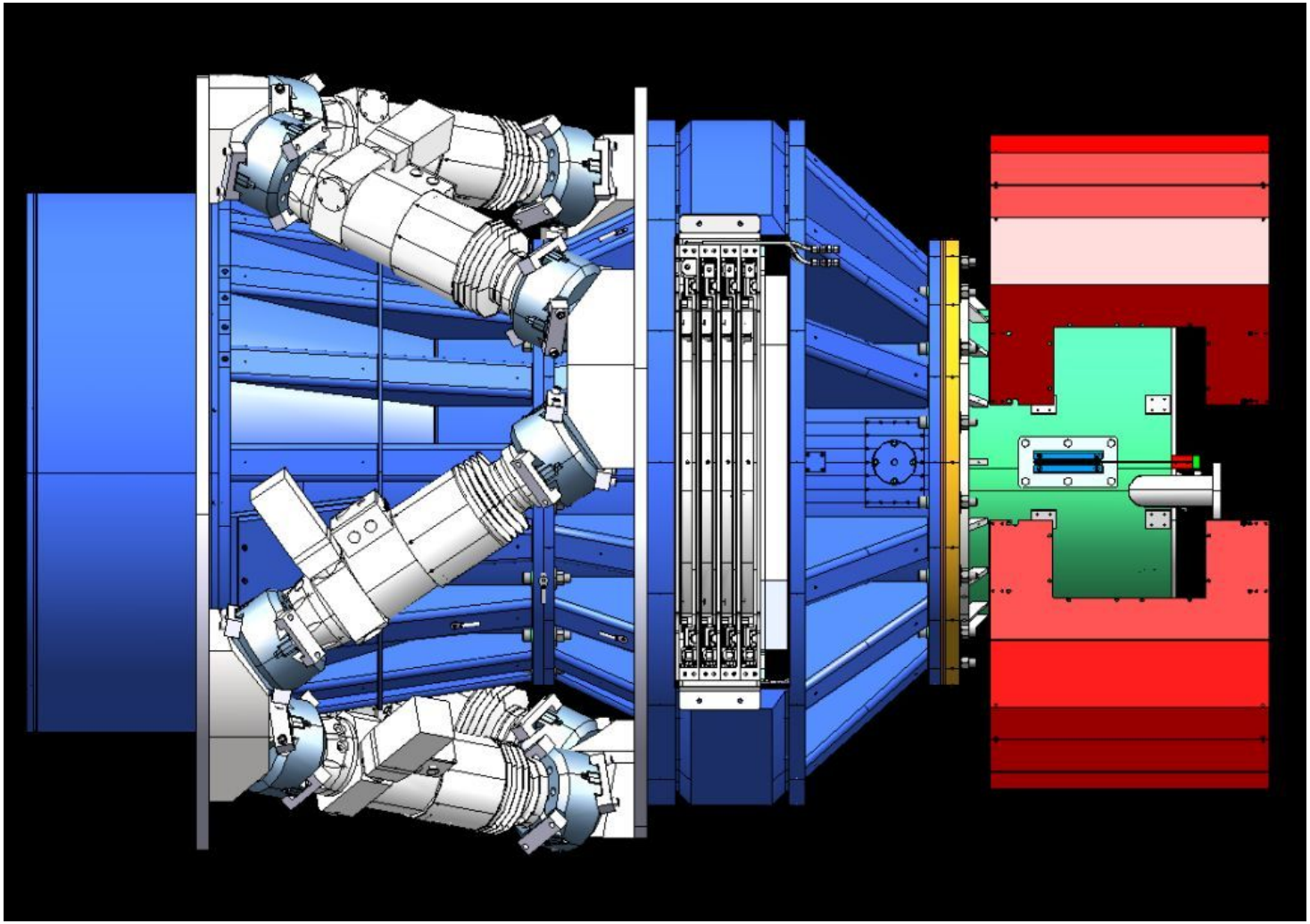
DARK ENEF
SURVEY

Filter Changer Mechanism (FCM) Arrived at Fermilab May 12th



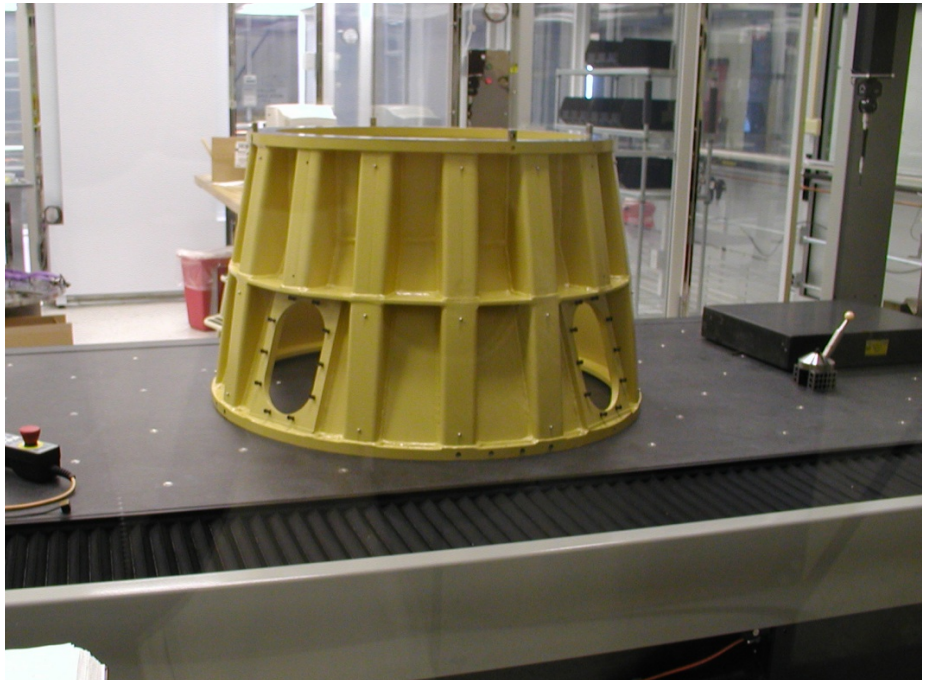
The optics and CCD imager are supported by the Barrel and positioned by the hexapod

DARK ENERGY SURVEY



Barrel

- Barrel has two pieces: Body and the Cone
- The Cone supports the first lens
- The Body supports the imager, FCM, shutter and is attached to the hexapod.
- We have two barrels
  - one will go to UCL for installation of the lenses
  - The other stays at Fermilab for the tests on the telescope simulator

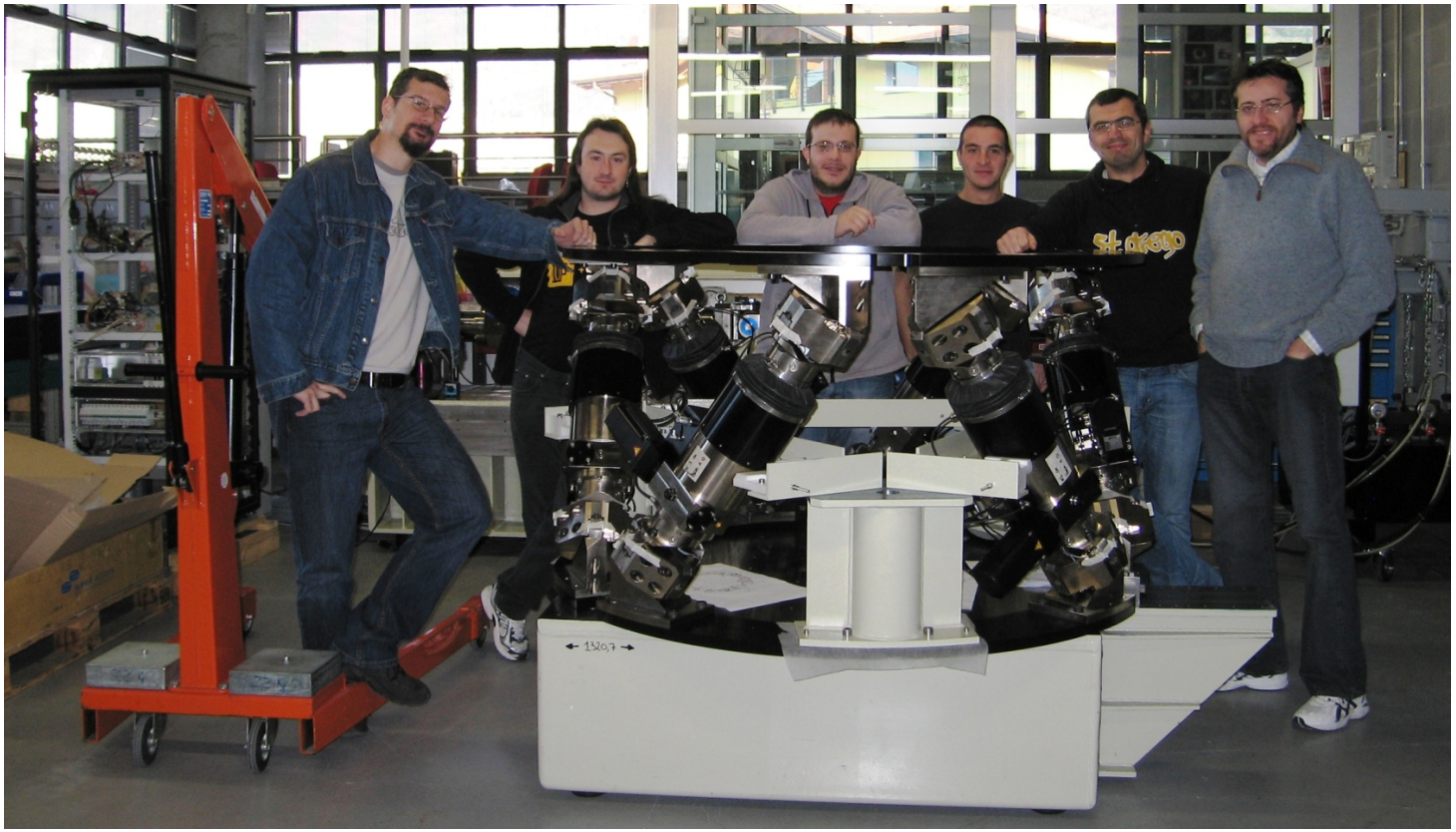


Hexapod

Arrived at Fermilab June10th

Adjusts optical alignment of camera wrt primary mirror

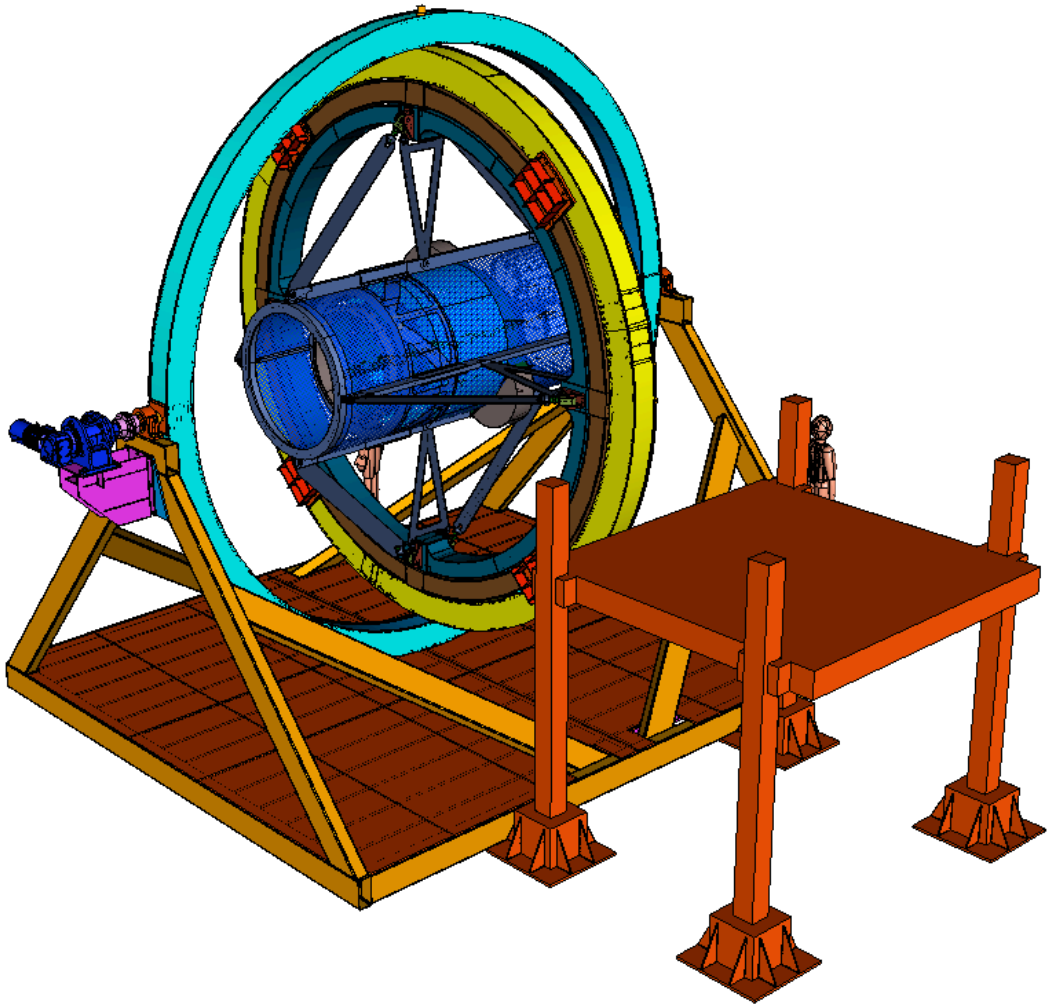
Use out of focus images (donuts)



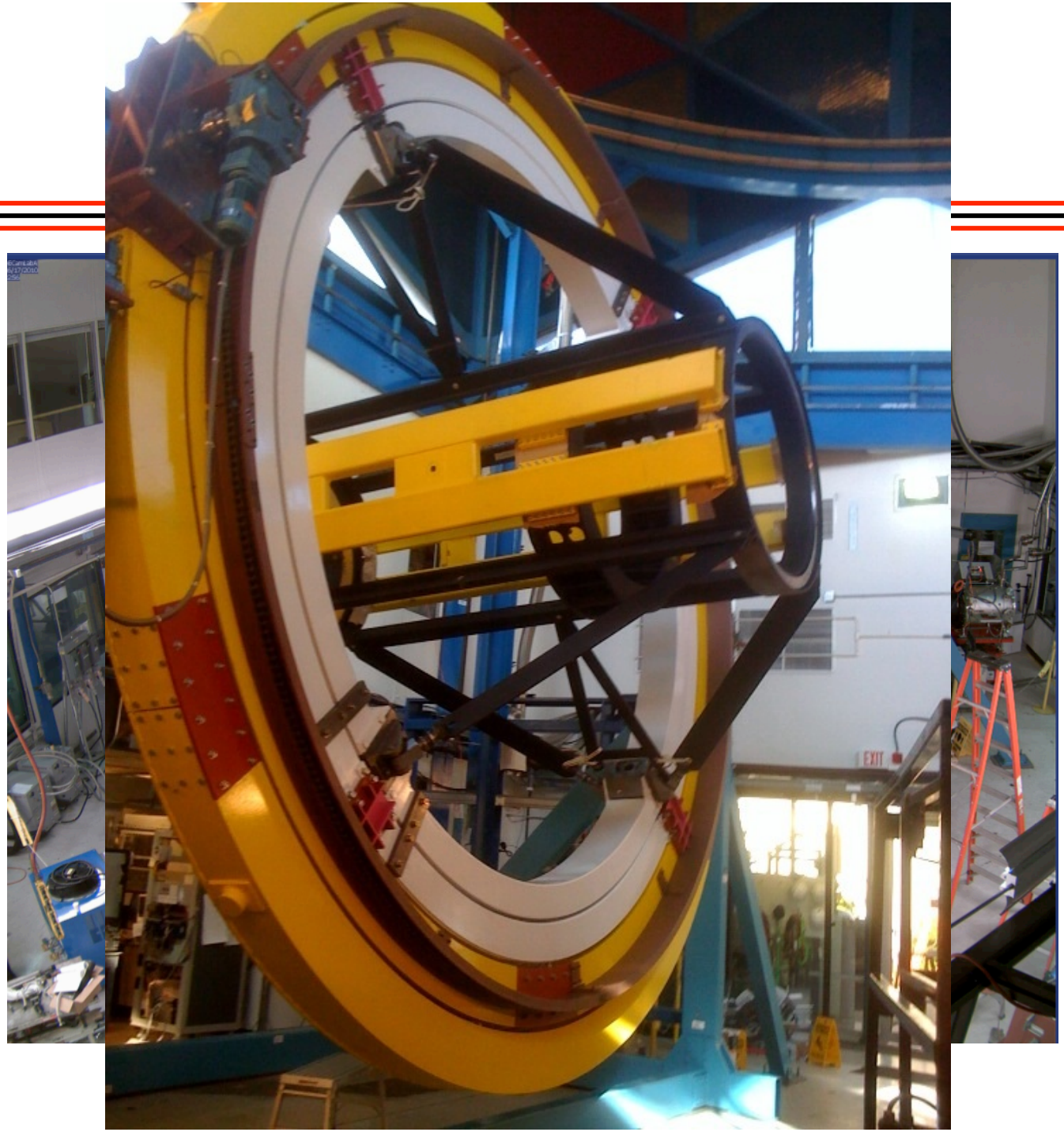
Telescope Simulator at Fermilab

DARK ENERGY SURVEY

- Provides platform for testing DECam operations and installation procedures prior to shipping to Chile



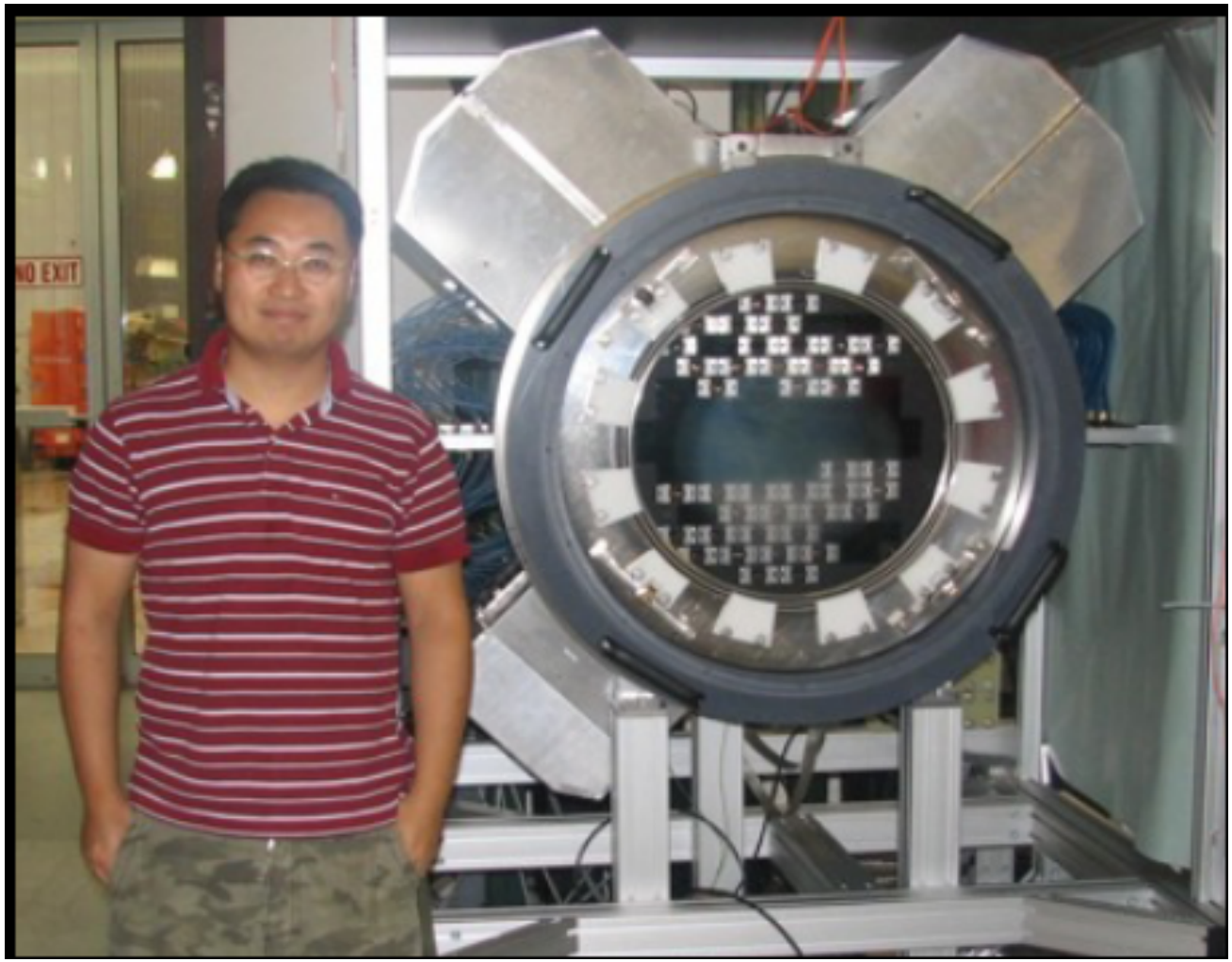
DARK ENERGY
SURVEY



DARK ENERGY
SURVEY

DECam Vessel

DARK ENERGY SURVEY



Fermilab postdoc
Jiangang Hao
with DECam

DARK ENERGY SURVEY

ENTREVISTA DIGITAL

Charla EN DIRECTO con Elvira Lindo, autora de 'Lo que me queda por vivir'

REPORTAJE

A la caza de la energía oscura

Un equipo internacional ultima una cámara para observar 300 millones de galaxias - Los científicos investigan por qué se acelera la expansión del universo

ALICIA RIVERA - Madrid - 15/09/2010

Vota ☆☆☆☆☆ | Resultado ★★★★½ 57 votos

Cuando los científicos tropiezan con una sorpresa, con algo que no comprenden, no se quedan de brazos cruzados, extasiados, sino que inmediatamente se ponen a inventar experimentos y observaciones para vencer el misterio, y más si se trata de un descubrimiento que altera en gran medida el conocimiento que tiene de la evolución del universo. Se trata de la energía oscura, cuya existencia se desconocía hace poco más de una década y que ahora atrae la atención de los cosmólogos de todo el mundo. No es para menos: según las observaciones más precisas realizadas, la energía oscura supone el 72% de todo el universo y no se sabe qué es ni a qué ley obedece, pero está ahí y se nota.

La noticia en otros webs

- webs en español
- en otros idiomas

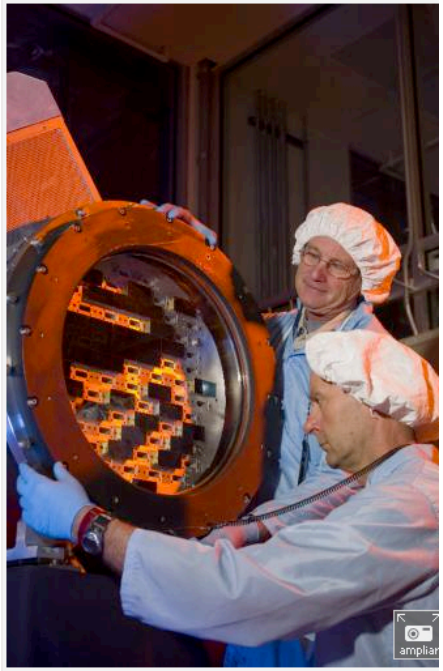
El aparato tiene 74 detectores CCD y cuesta 39 millones de euros

La constante cosmológica de Einstein puede explicar el efecto

Para intentar aclarar su naturaleza se están preparando media docena de cámaras astronómicas especiales. Una estará lista el año próximo. La están haciendo en EE UU y los astrónomos captarán con ella unos 300 millones de galaxias, algunas tan antiguas que emitieron la luz que ahora llega a la Tierra cuando el universo acababa de empezar, pocos miles de millones de años después del Big Bang. Se llama Dark Energy Camera y en el proyecto participan especialistas de varios países, incluida España.

"Nuestro objetivo principal es determinar la naturaleza de la energía oscura", explicó recientemente en el Centro Pedro Pascual de Benasque (Huesca) Josh Frieman, director del proyecto DES, que está haciendo la cámara estadounidense. "La energía oscura tiene dos efectos en los que nos basaremos para investigar su naturaleza: acelera la expansión del universo y modifica la velocidad a la que se forman las galaxias, y esto, a su vez, afecta al número de galaxias y a su distribución en el espacio. Así pues, contando las galaxias y midiendo su distribución obtendremos pistas sobre qué es".

Esa aceleración fue, efectivamente, la primera pista que encontraron dos equipos de astrónomos hace 12 años. Hasta ese momento, la cosmología venía a decir que el universo, que está en expansión desde hace 13.700 millones de años, se expandiría cada vez más despacio debido a la atracción gravitatoria de su propia materia. Pero en 1998



Expertos de Fermilab montan la cámara para estudiar la energía oscura (arriba) y el mapa del universo primitivo hecho por el telescopio *Planck*.- FERMILAB

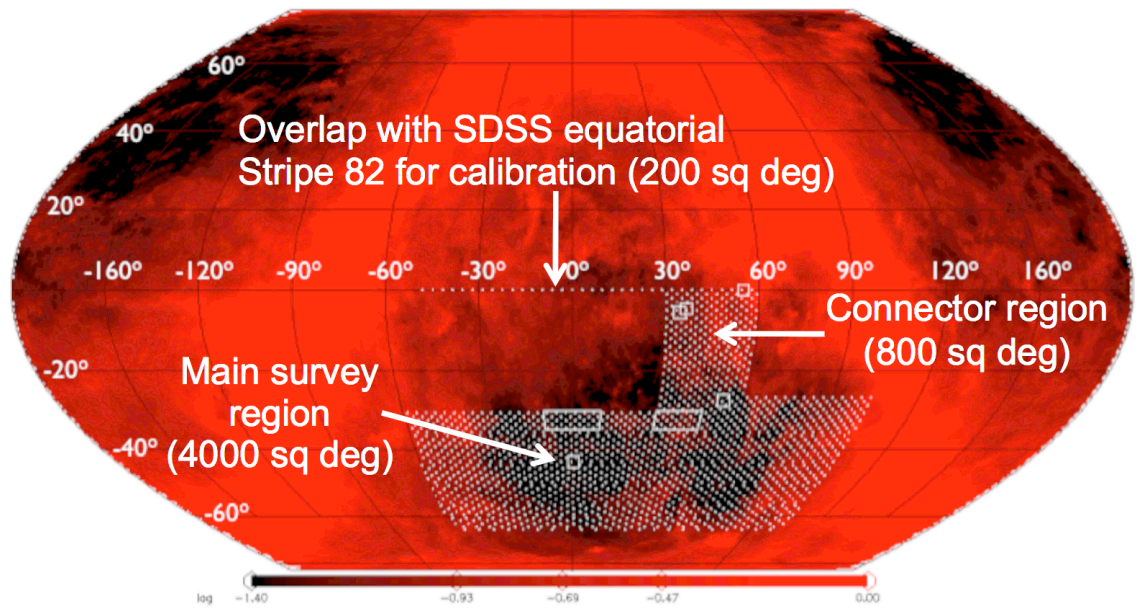
publicidad

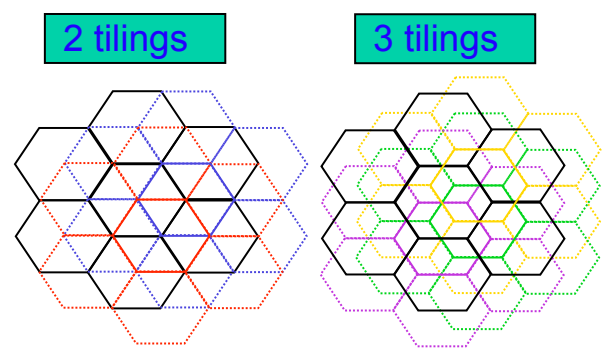
DES Observing Strategy

DARK ENERGY SURVEY

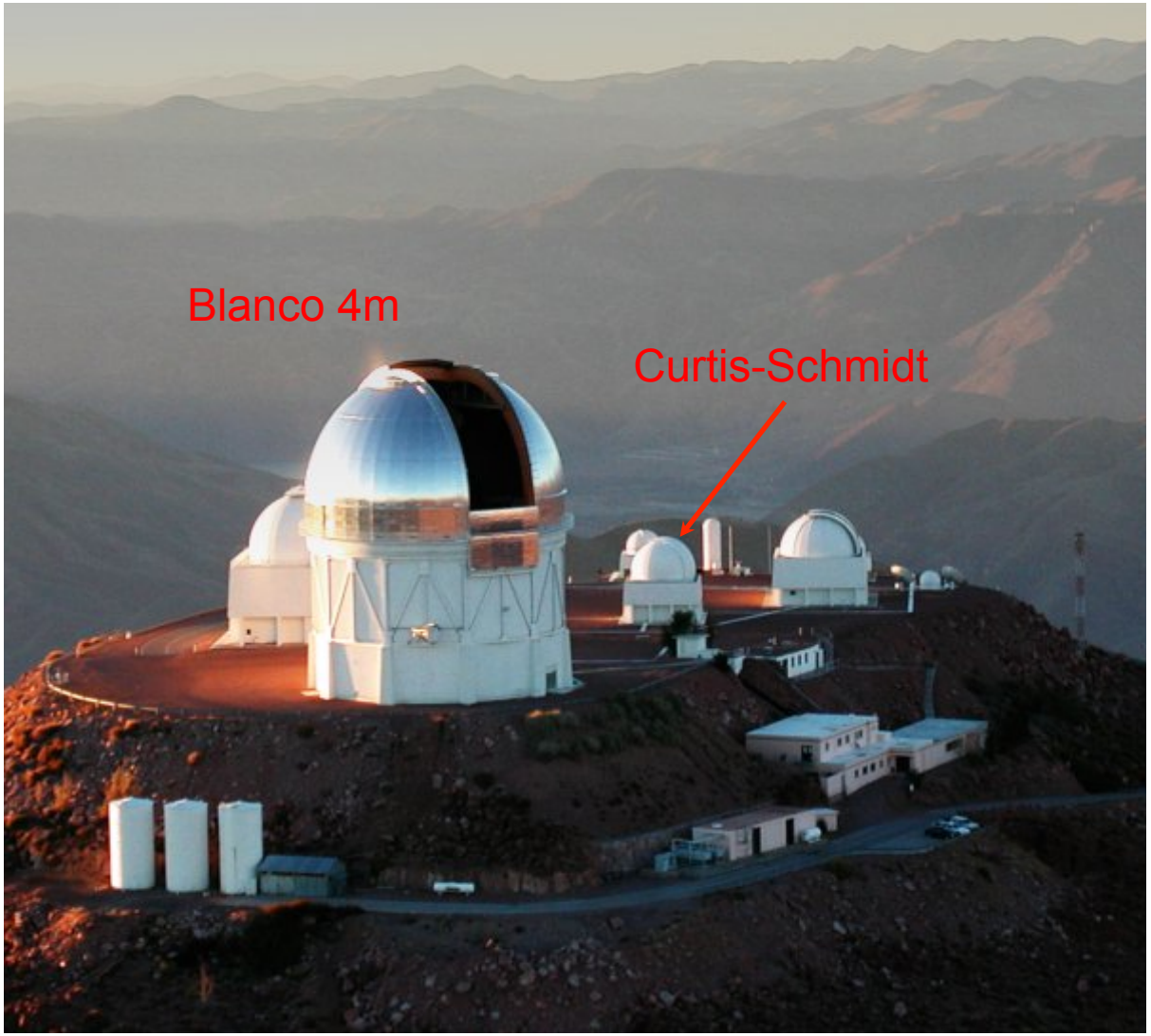
- 80-100 sec exposures
- 2 filters per pointing (typically)
  - *gr* in dark time
  - *izy* in bright time
- Multiple overlapping tilings (layers) to optimize photometric calibrations
- 2 survey tilings/filter/year
- Optimize Dark Energy science within the allotted 525 nights and where possible enable ancillary science, based on simulations

Survey Area 5000 sq deg



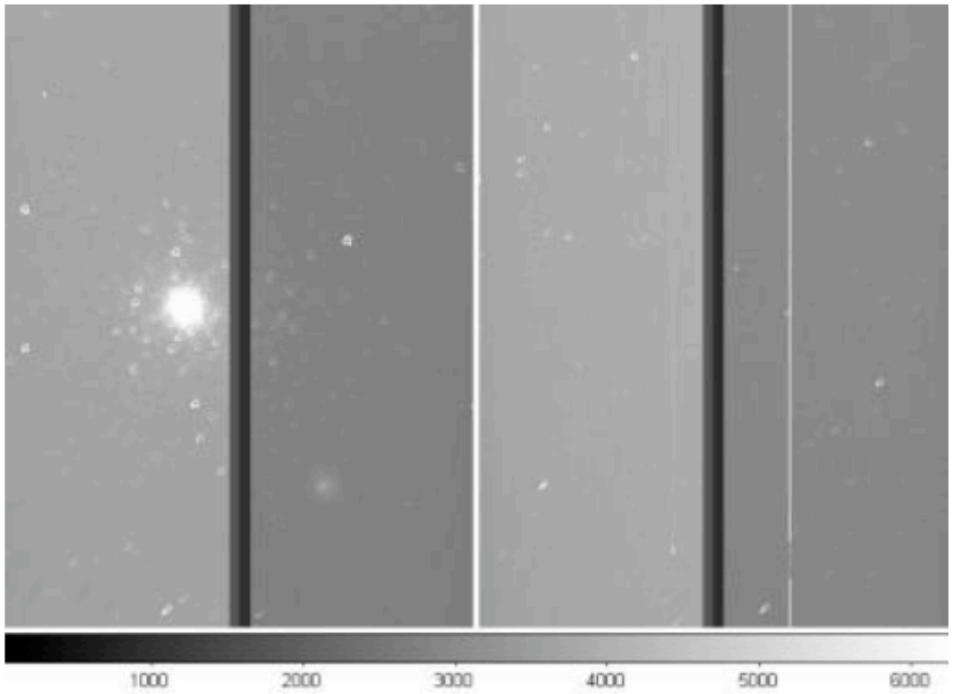


Calibration: PreCam Survey



A quick, bright survey in the DES footprint using a 4kx4k camera composed of DECam CCDs – “PreCam” - mounted on the U. Michigan Curtis-Schmidt Telescope at CTIO. Observations scheduled for Aug/ Sep 2010 and Nov 2010 - Jan 2011. Commissioning now.

PreCAM at CTIO



Clusters and Dark Energy

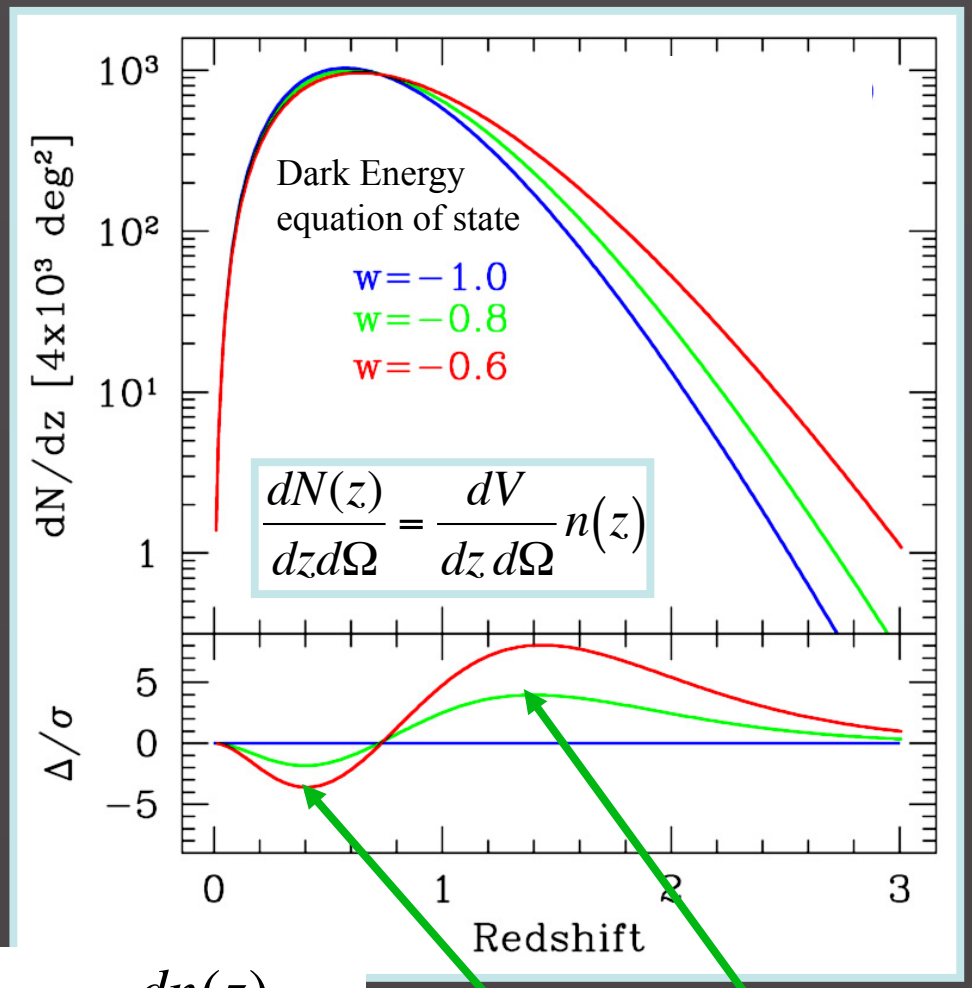
Number of clusters above observable mass threshold

- Requirements
  1. Understand formation of dark matter halos
  2. Cleanly select massive dark matter halos (galaxy clusters) over a range of redshifts
  3. Redshift estimates for each cluster
  4. Observable proxy that can be used as cluster mass estimate:

     $p(O|M,z)$

Primary systematic:

Uncertainty in bias & scatter of mass-observable relation



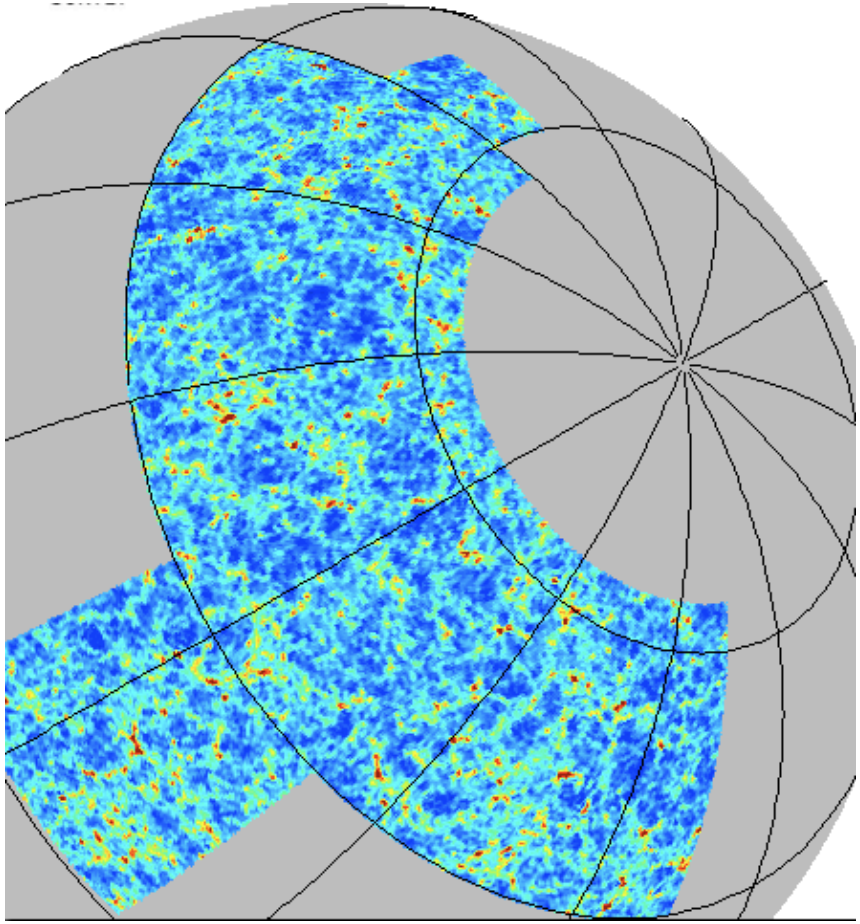
$$\frac{d^2N}{dz d\Omega} = \frac{r^2(z)}{H(z)} \int f(O,z) dO \int p(O \mid M,z) \frac{dn(z)}{dM} dM$$

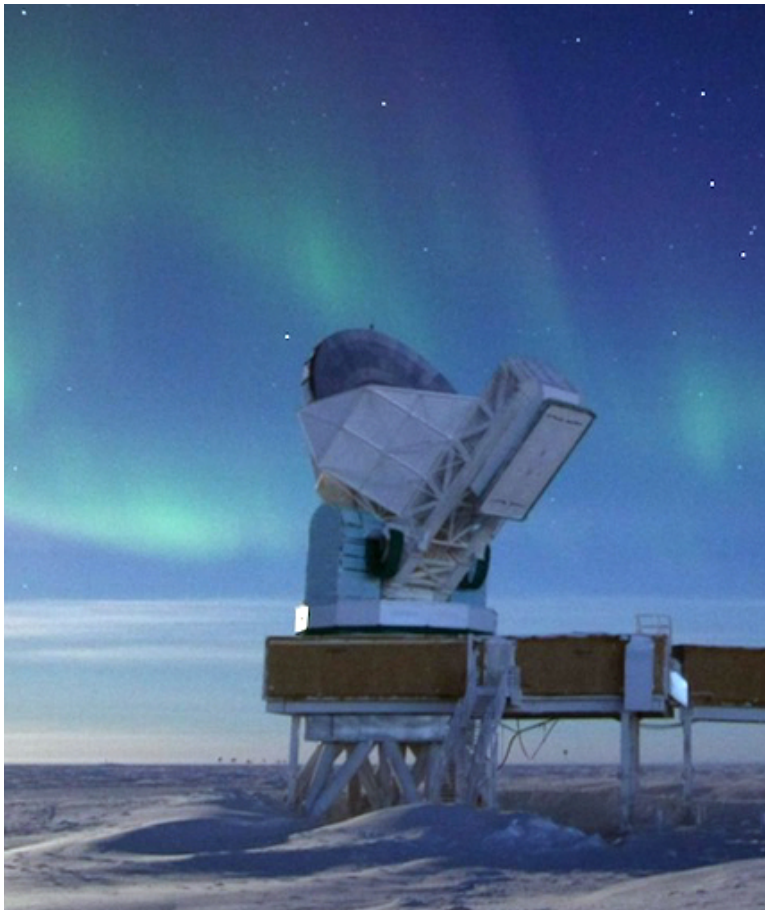
Volume

Growth

Kavli Institute
for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO

DES-SPT Synergy





DES survey area encompasses South Pole Telescope SZE Survey
~100,000 optical clusters to z>1: ~1,000 with SPT measurements

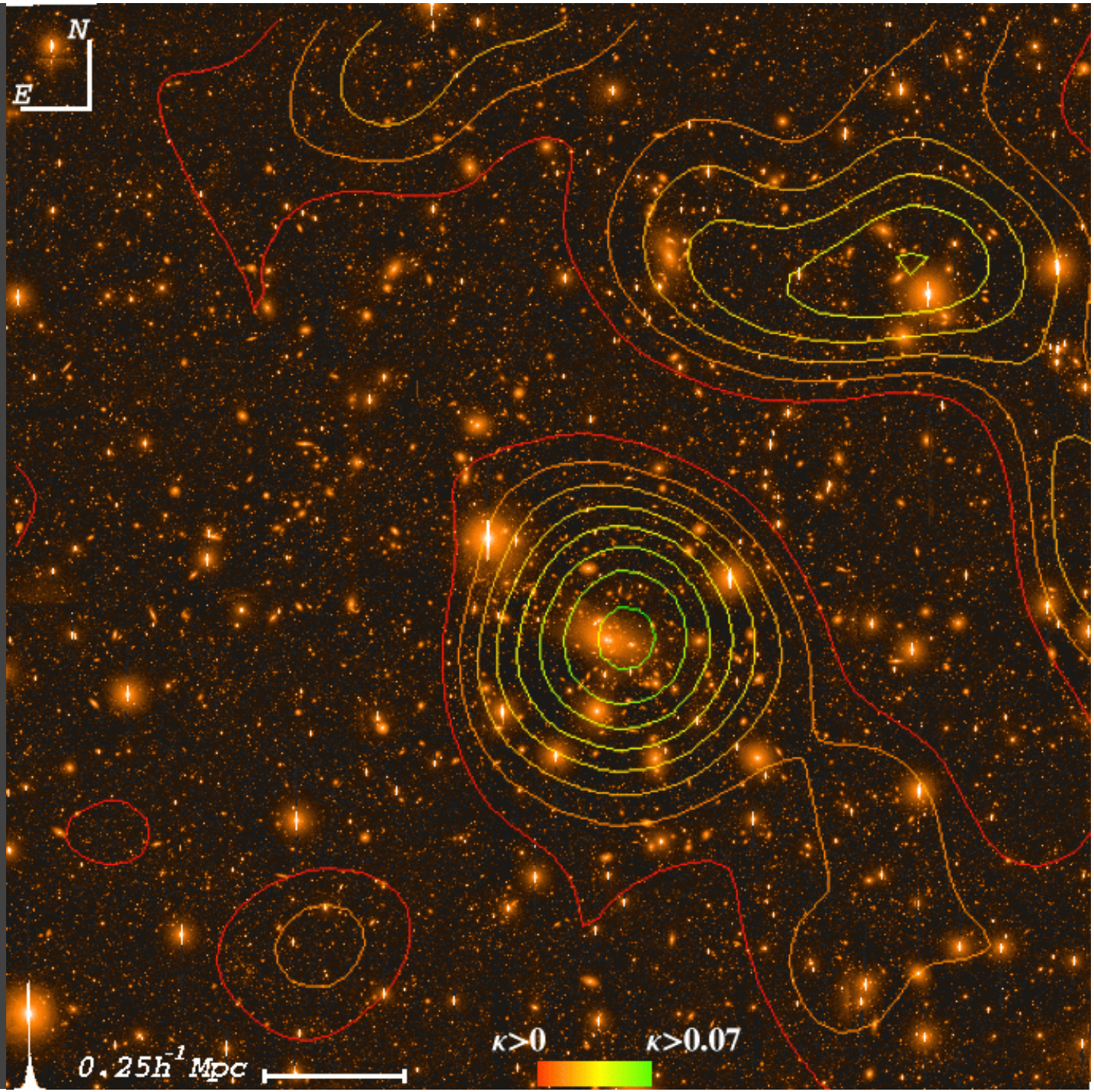
The National Science Foundation

THE KAVLI FOUNDATION

Mapping the Dark Matter in a Cluster of Galaxies via Weak Gravitational Lensing

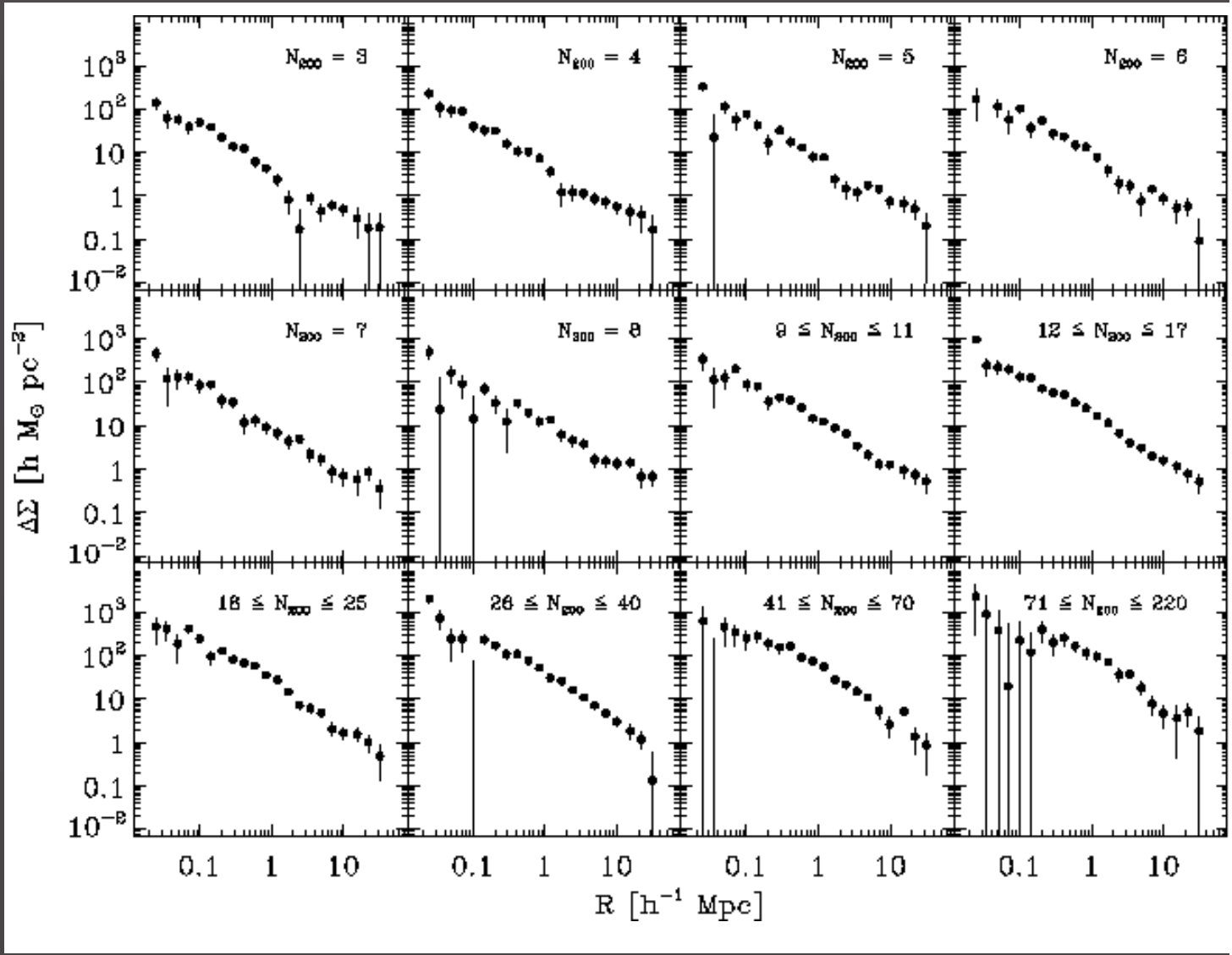
Data from Blanco 4-meter at CTIO

Joffre, etal



Statistical Weak Lensing by Galaxy Clusters

Mean Tangential Shear Profile in Optical Richness (N_{gal}) Bins to 30 h^{-1}Mpc

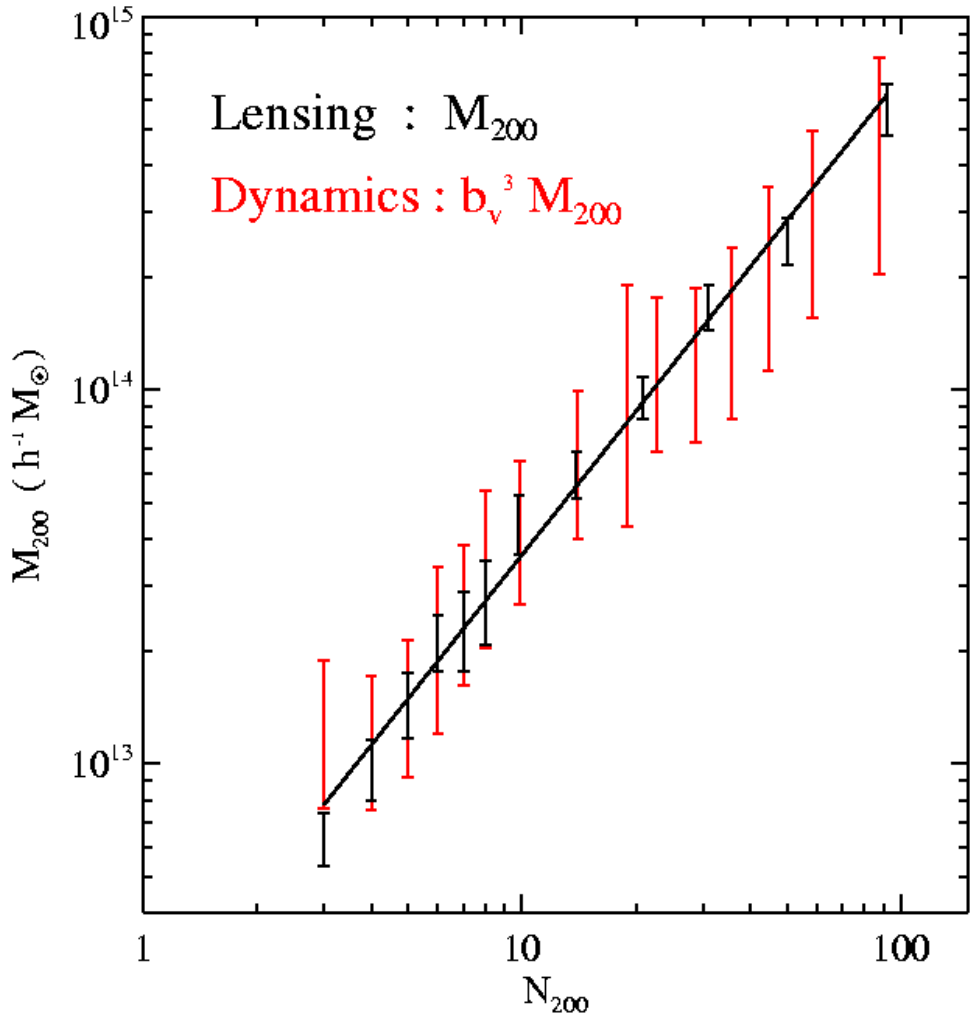


Sheldon, Johnston, etal SDSS

Statistical Weak Lensing Calibrates Cluster Mass vs. Observable Relation

Cluster Mass vs. Number of galaxies they contain

Future: use this to independently calibrate, e.g., SZE vs. Mass



Statistical Lensing eliminates projection effects of individual cluster mass Estimates

~50% scatter in mass vs optical richness

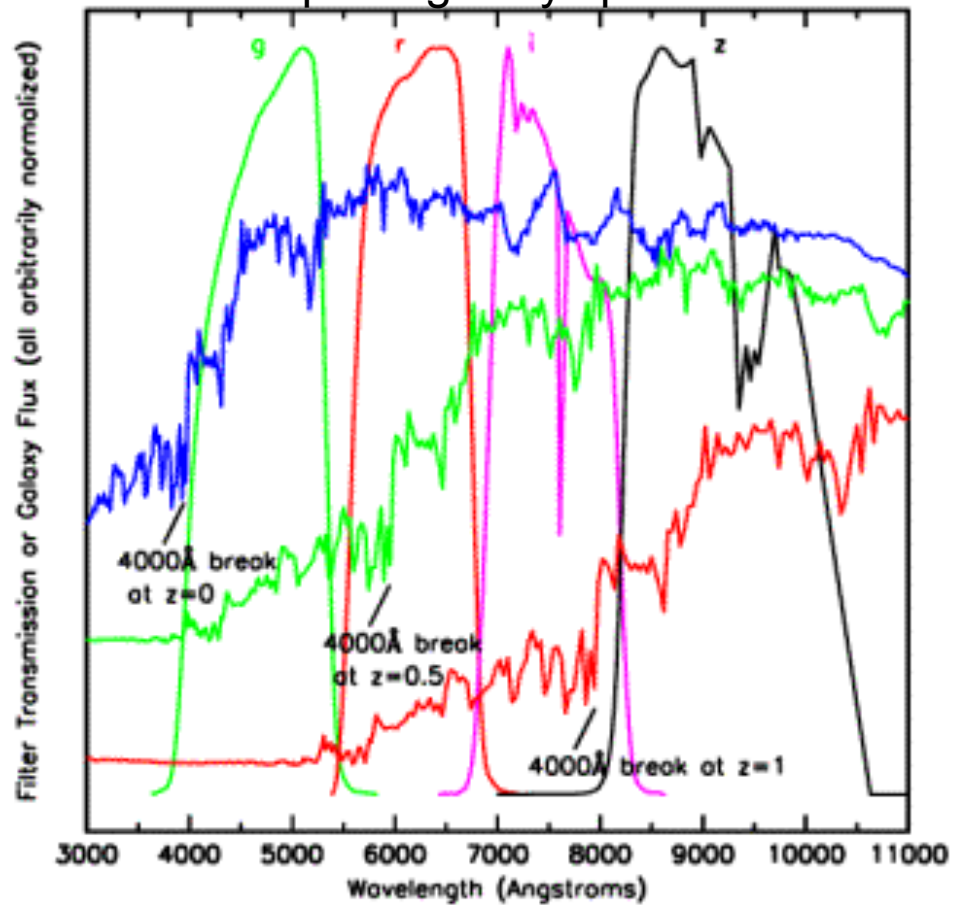
Johnston, Sheldon, etal

Photometric Redshifts

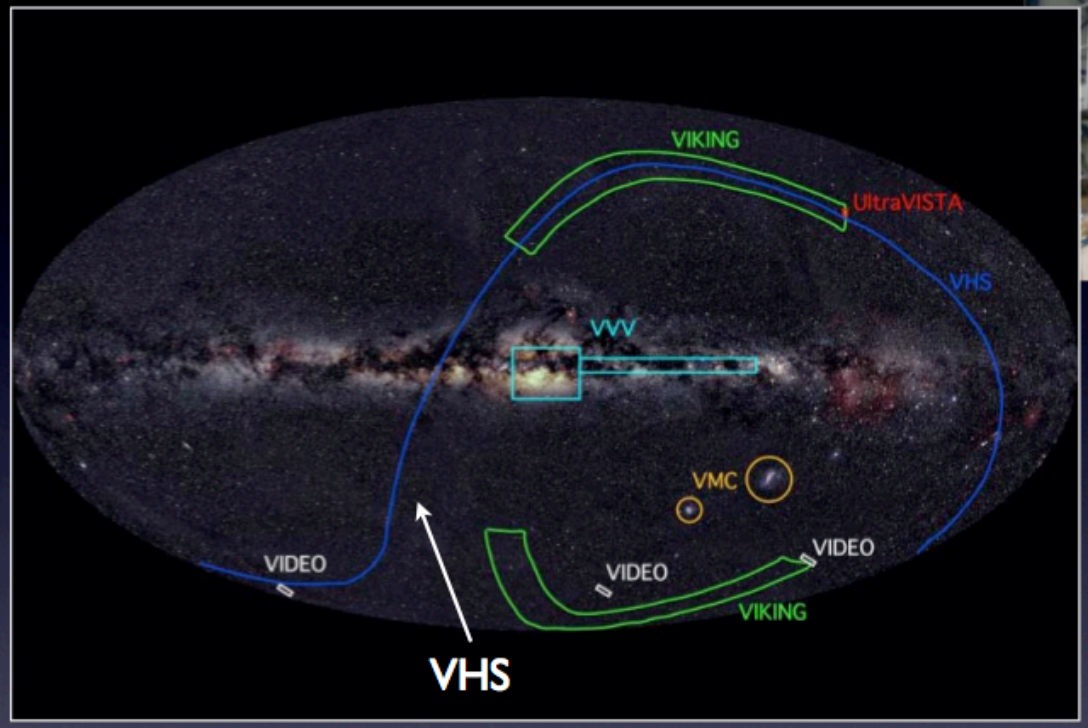
DARK ENERGY SURVEY

- Measure relative flux in multiple filters: track the 4000 A break
- Estimate individual galaxy redshifts with accuracy $\sigma(z) < 0.1$ (~0.02 for clusters)
- Precision is sufficient for Dark Energy probes, provided error distributions well measured.

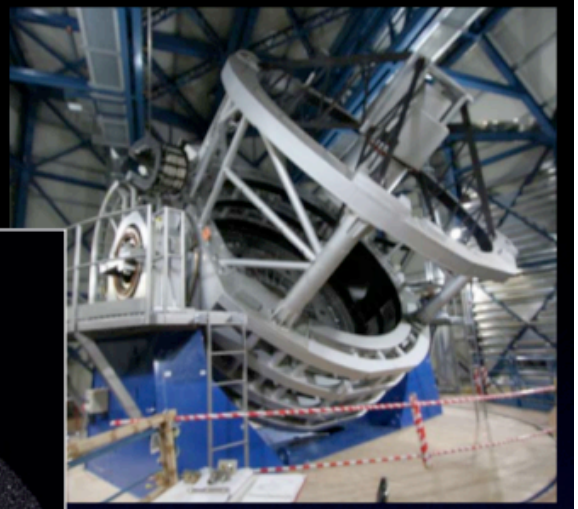
Elliptical galaxy spectrum



VISTA Hemisphere Survey



120 sec JHK exposures



VISTA

4.1m primary mirror
1.5deg field of view
16 2kx2k HgCdTe

VHS

380 nights over 5 yrs
120 sec JHK exposures
Richard McMahon, PI

VHS limiting magnitudes [AB system; 5σ]

	deg²	Y	J	H	K
VHS-DES	5000	21.9	21.2	20.8	20.2

DES collaborates with VHS: DES acquires Y imaging, VHS shares JHK data

Galaxy Photo-z Simulations

DARK ENERGY SURVEY

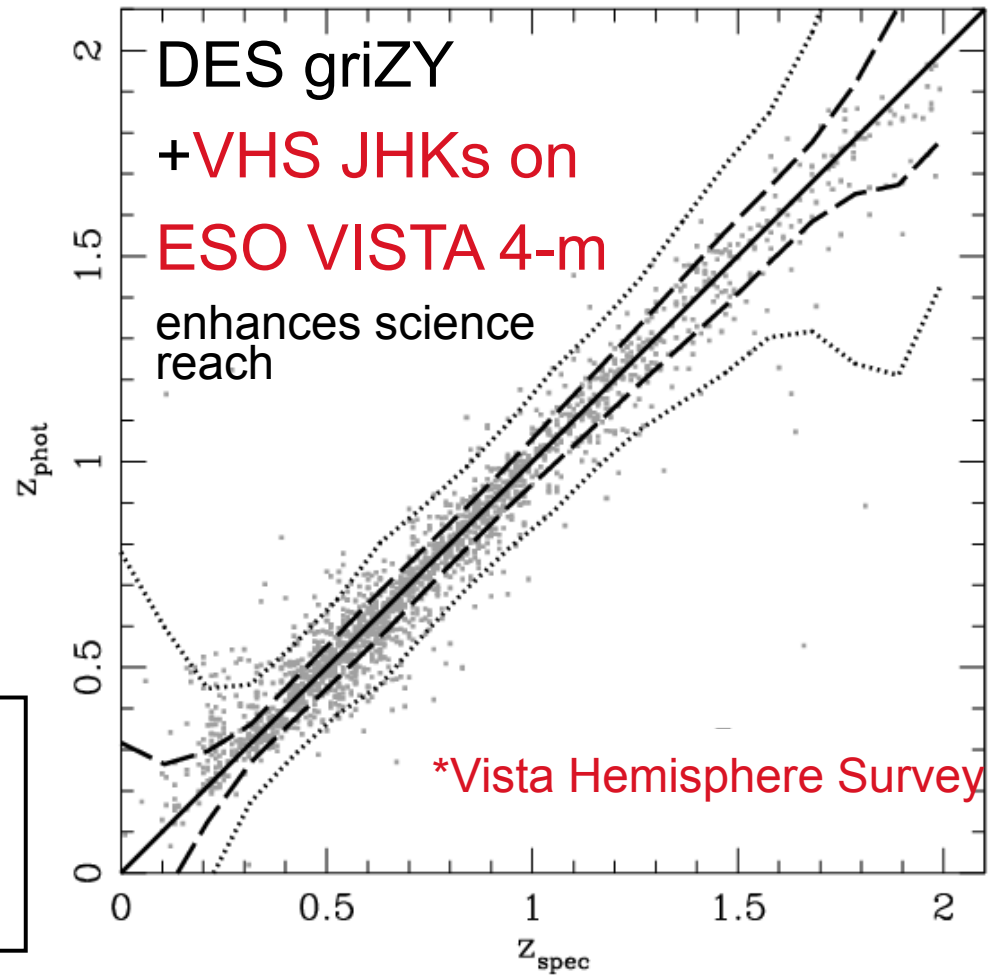
DES +VHS*

10σ Limiting Magnitudes

g	24.6		
r	24.1	J	20.3
i	24.0	H	19.4
Z	23.8	Ks	18.3
Y	21.6		

+2% photometric calibration error added in quadrature

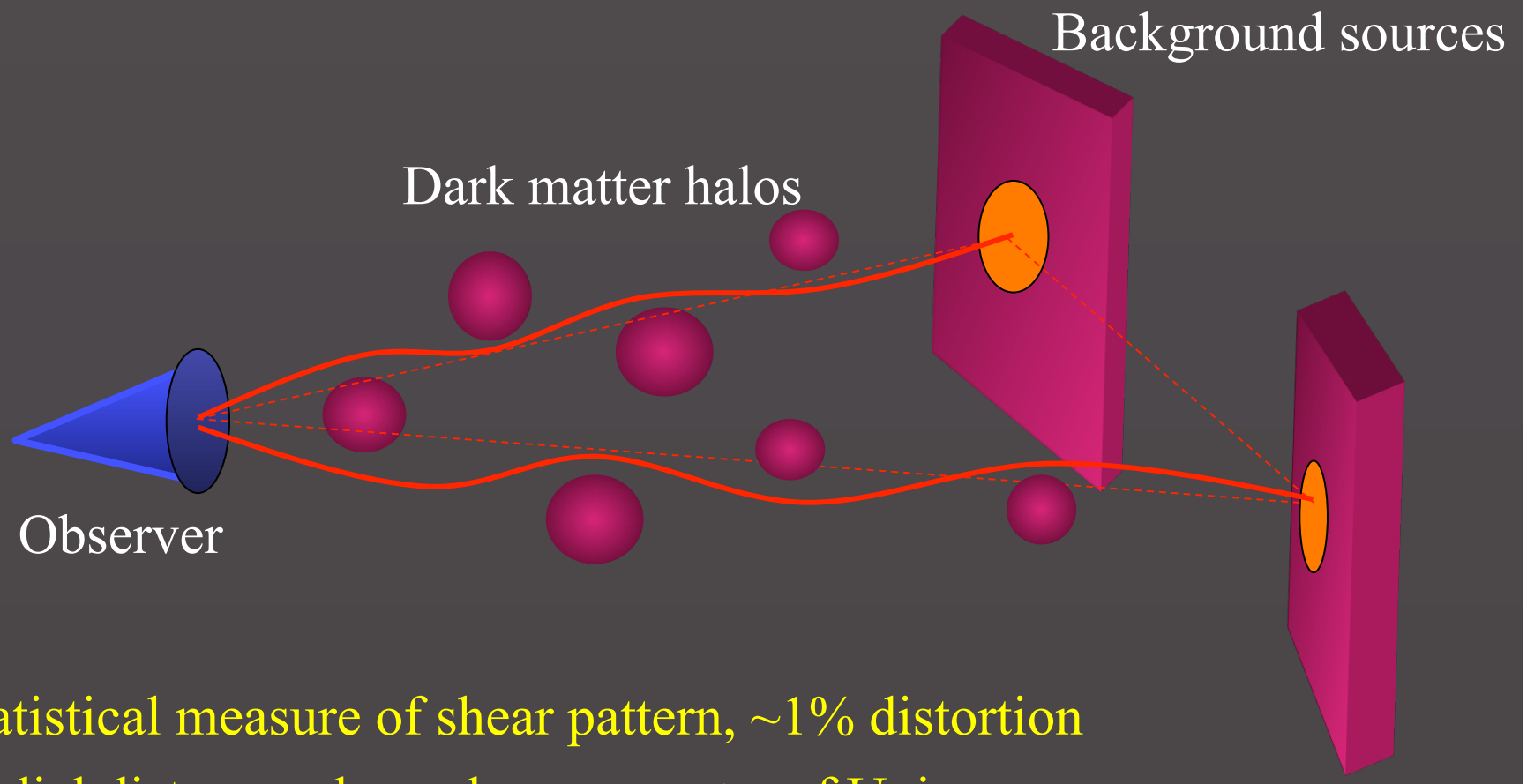
Photo-z systematic errors under control using *existing* spectroscopic training sets to DES photometric depth: low-risk



+Developed improved Photo-z & Error Estimates and robust methods of outlier rejection

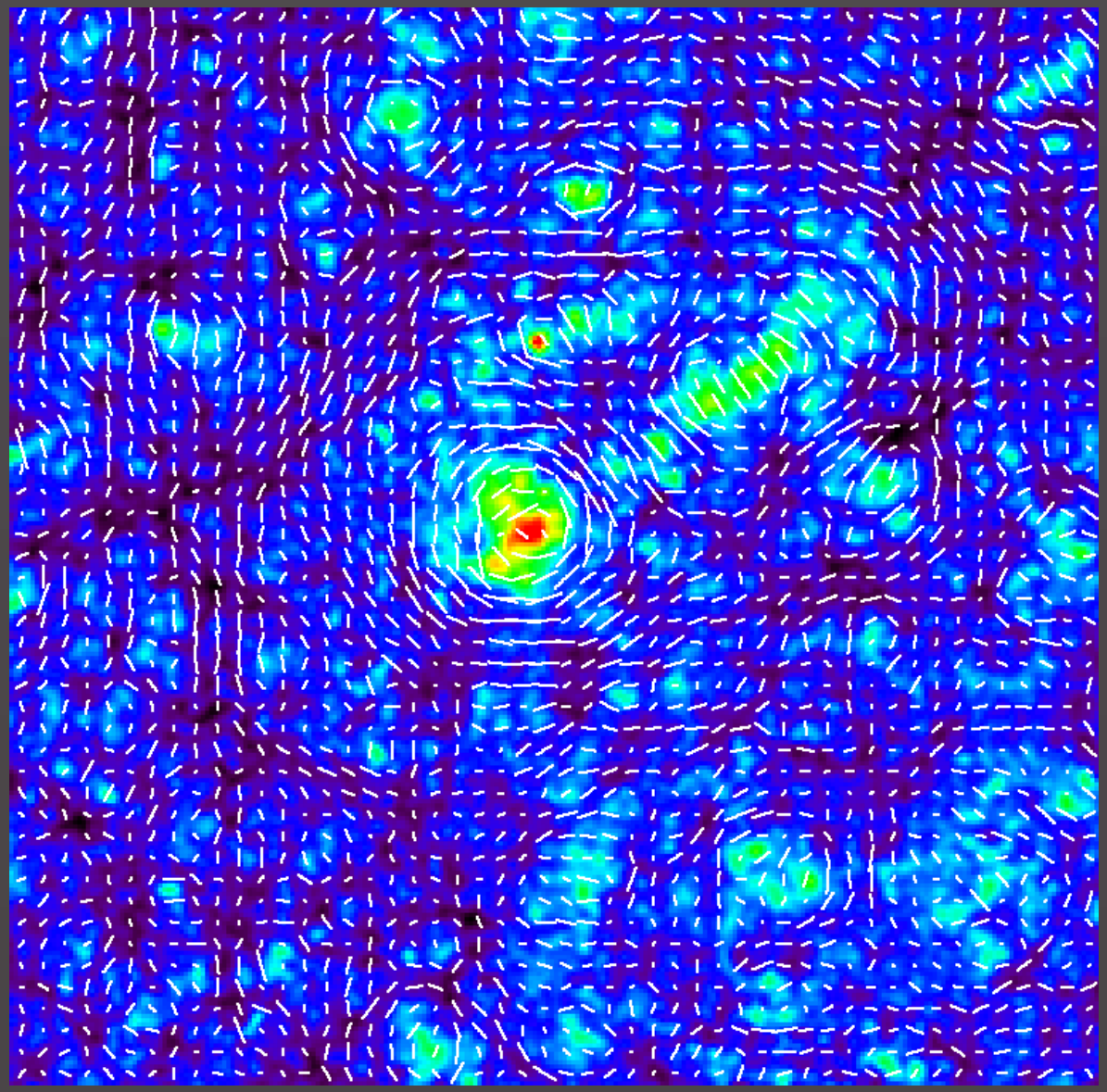
Oyaizu, Cunha, Lima, Frieman, Lin

Weak Lensing: Cosmic Shear



- Statistical measure of shear pattern, ~1% distortion
- Radial distances depend on *geometry* of Universe
- Foreground mass distribution depends on *growth* of structure

Weak lensing: shear and mass

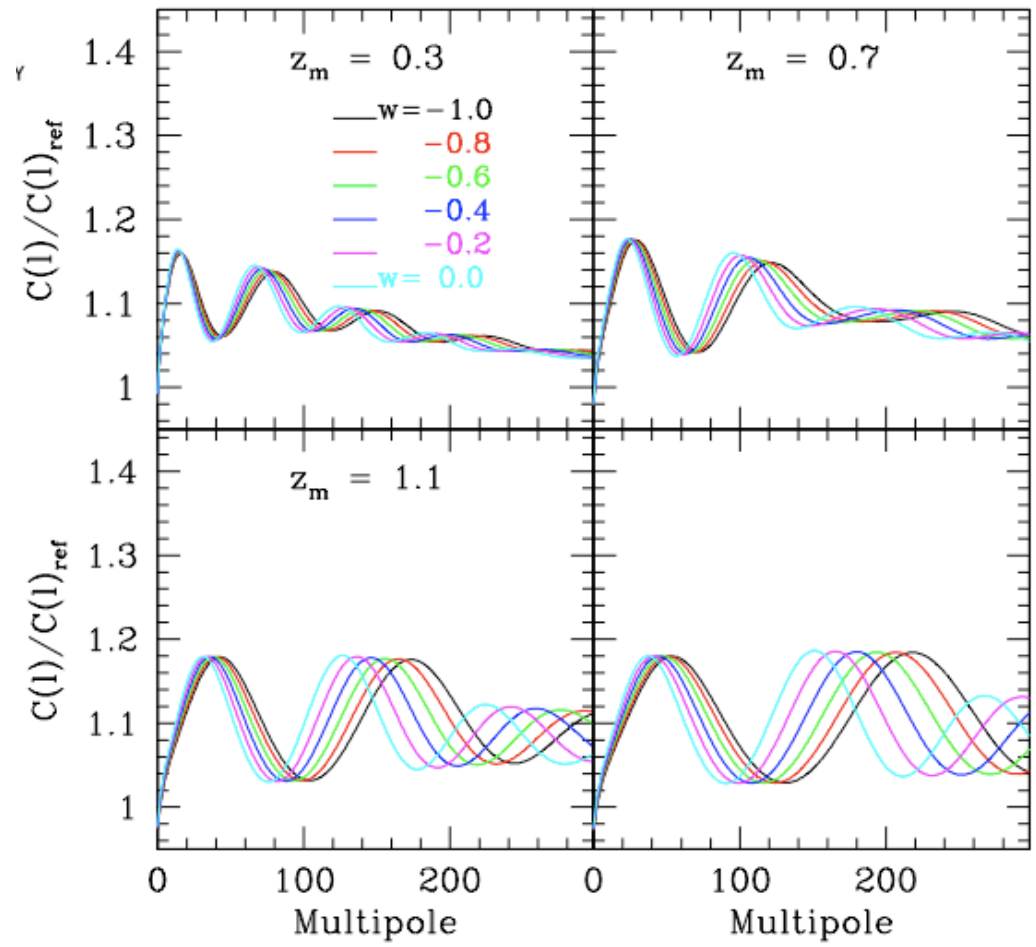


Takada

Baryon Acoustic Oscillations

DARK ENERGY SURVEY

Galaxy Angular Correlation Function in Photo-z bins

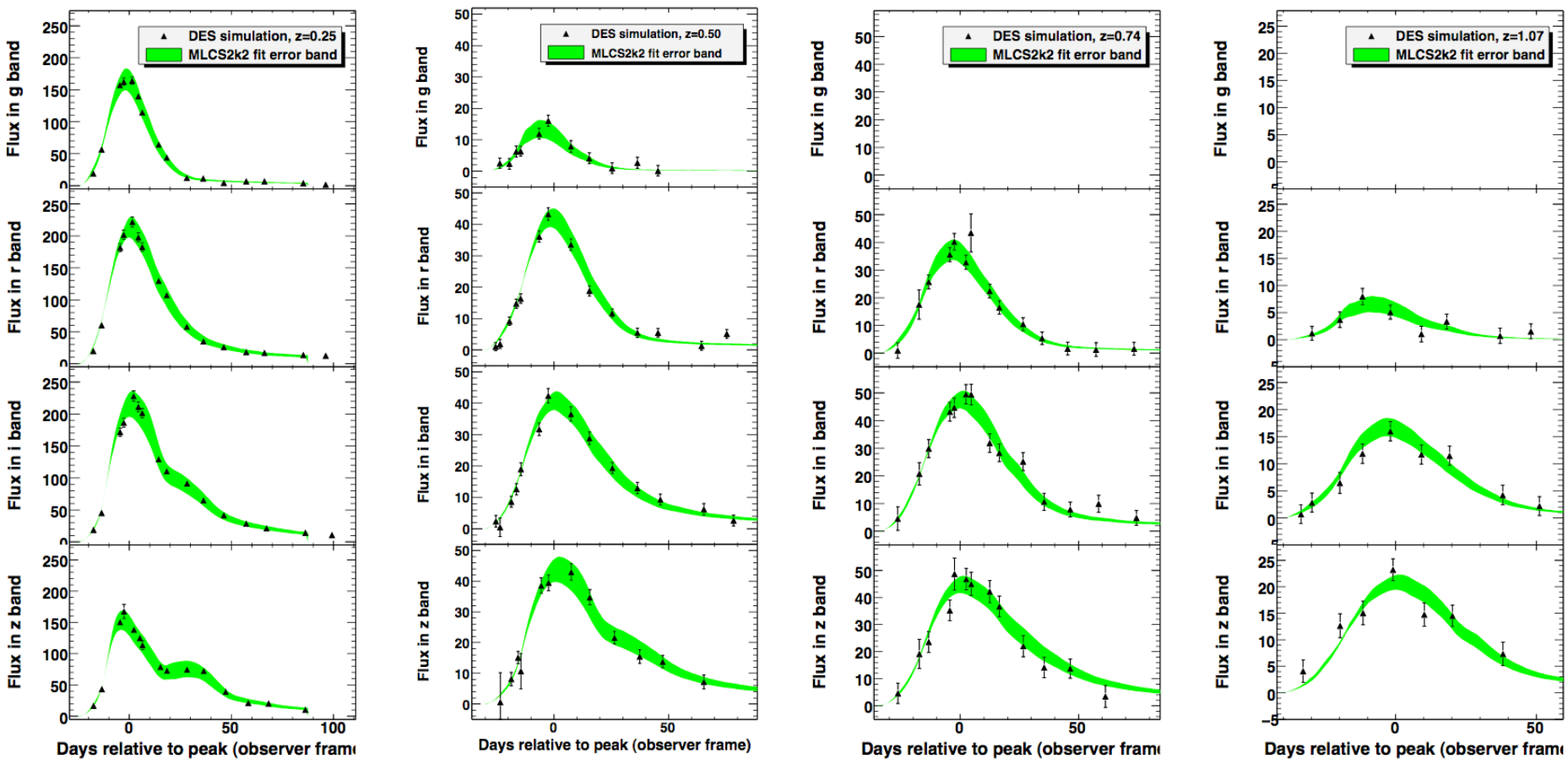


Systematics:
photo-z's, correlated photometric errors, non-linearity, scale-dependent bias

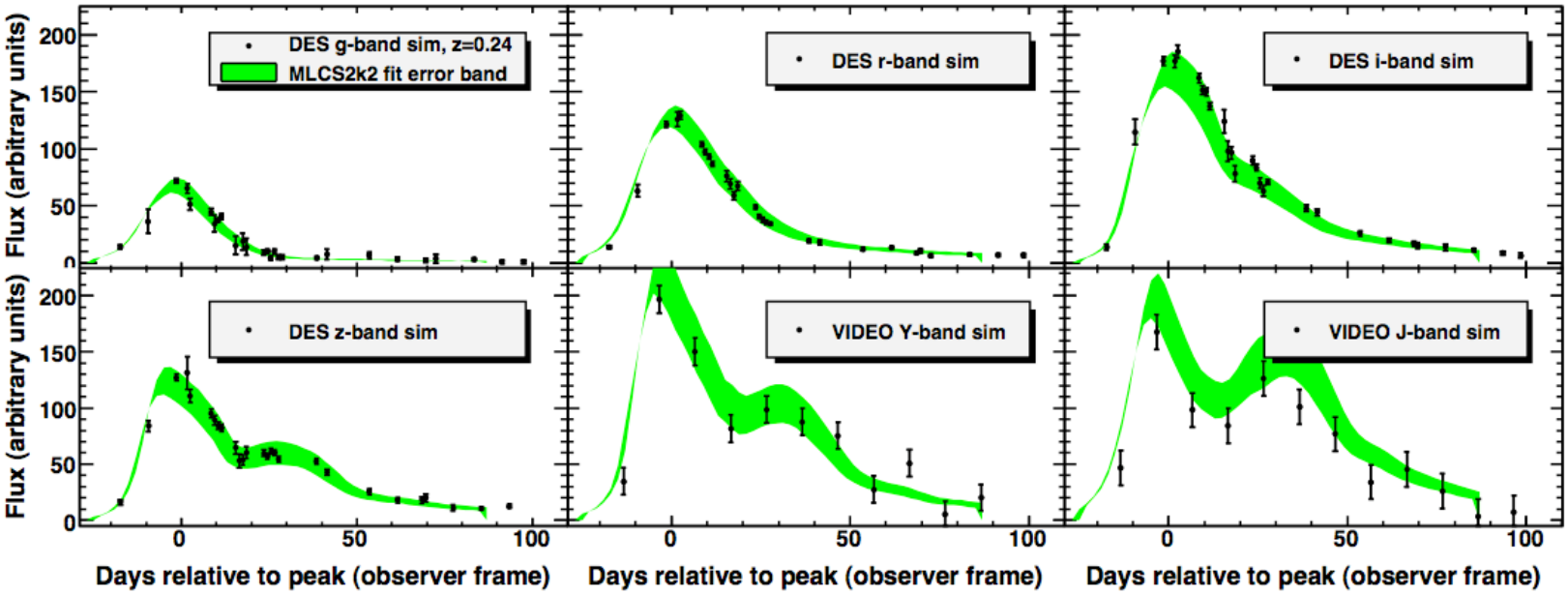
Fosalba & Gaztanaga

DES SN Simulated Light Curves

DARK ENERGY SURVEY



DES + VISTA VIDEO NIR

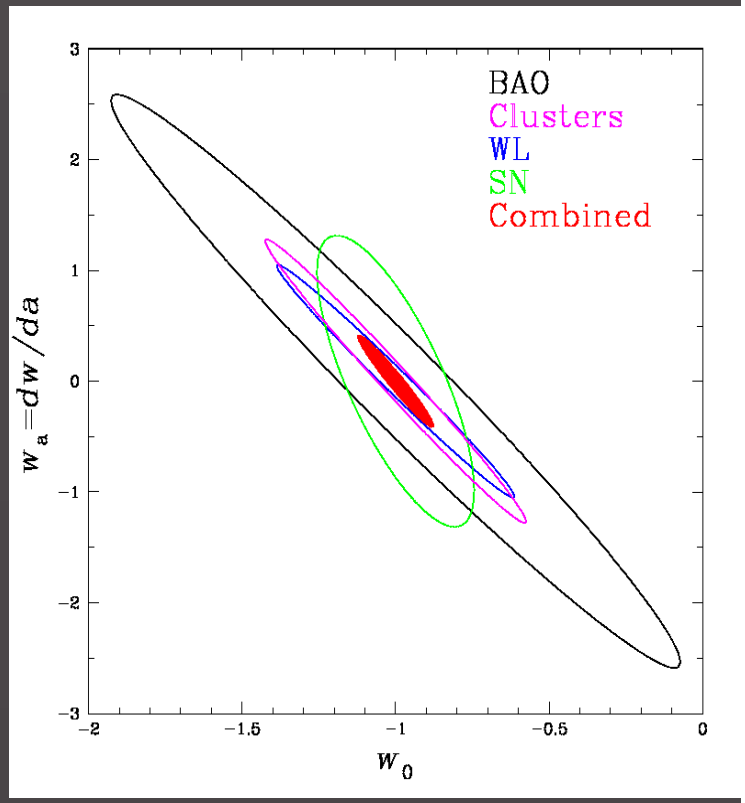


DES Science Program

Four Probes of Dark Energy

- Galaxy Clusters
  - ~100,000 clusters to z>1
  - ~10,000 with SZE measurements from SPT
  - Sensitive to growth of structure and geometry
- Weak Lensing
  - Shape measurements of 300 million galaxies
  - Sensitive to growth of structure and geometry
- Baryon Acoustic Oscillations
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- Supernovae
  - 15 sq deg time-domain survey
  - ~3000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

Forecast Constraints on DE Equation of State



Beyond DES

- LSST
- JDEM/WFIRST
- BigBOSS and/or DESpec
- 21 cm Intensity Mapping

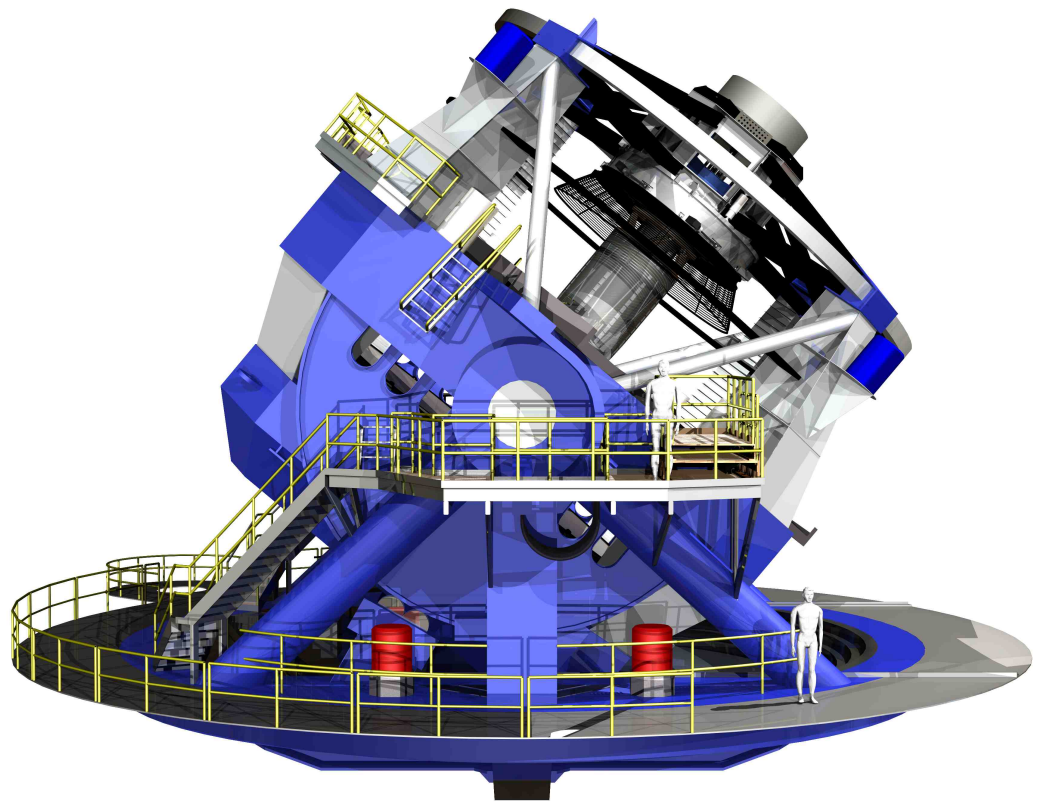
Large Synoptic Survey Telescope

Dedicated 8.4m telescope with 10 sq. degree field

Gigapixel camera will image ~1/2 sky in ugrizy every few nights

NSF/DOE/private

Top-ranked large ground project in Astro 2010



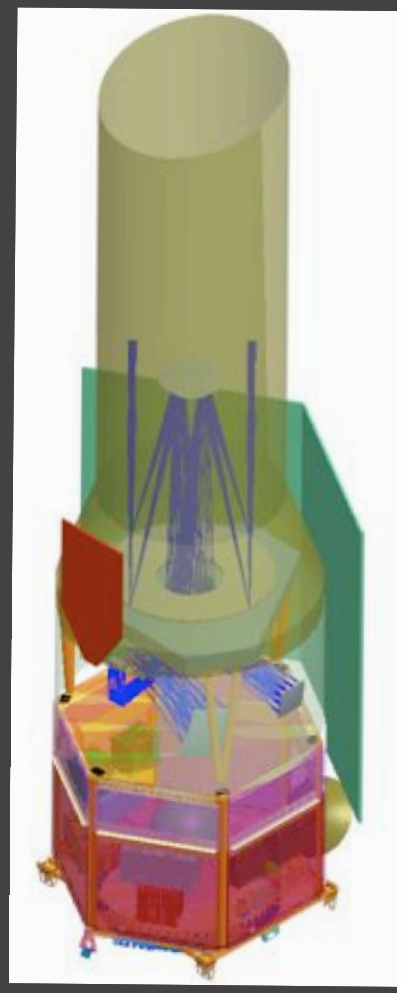
Fermilab in excellent position to help LSST succeed: SDSS/DES heritage; calibrations; data management, science

A Brief History of JDEM/WFIRST

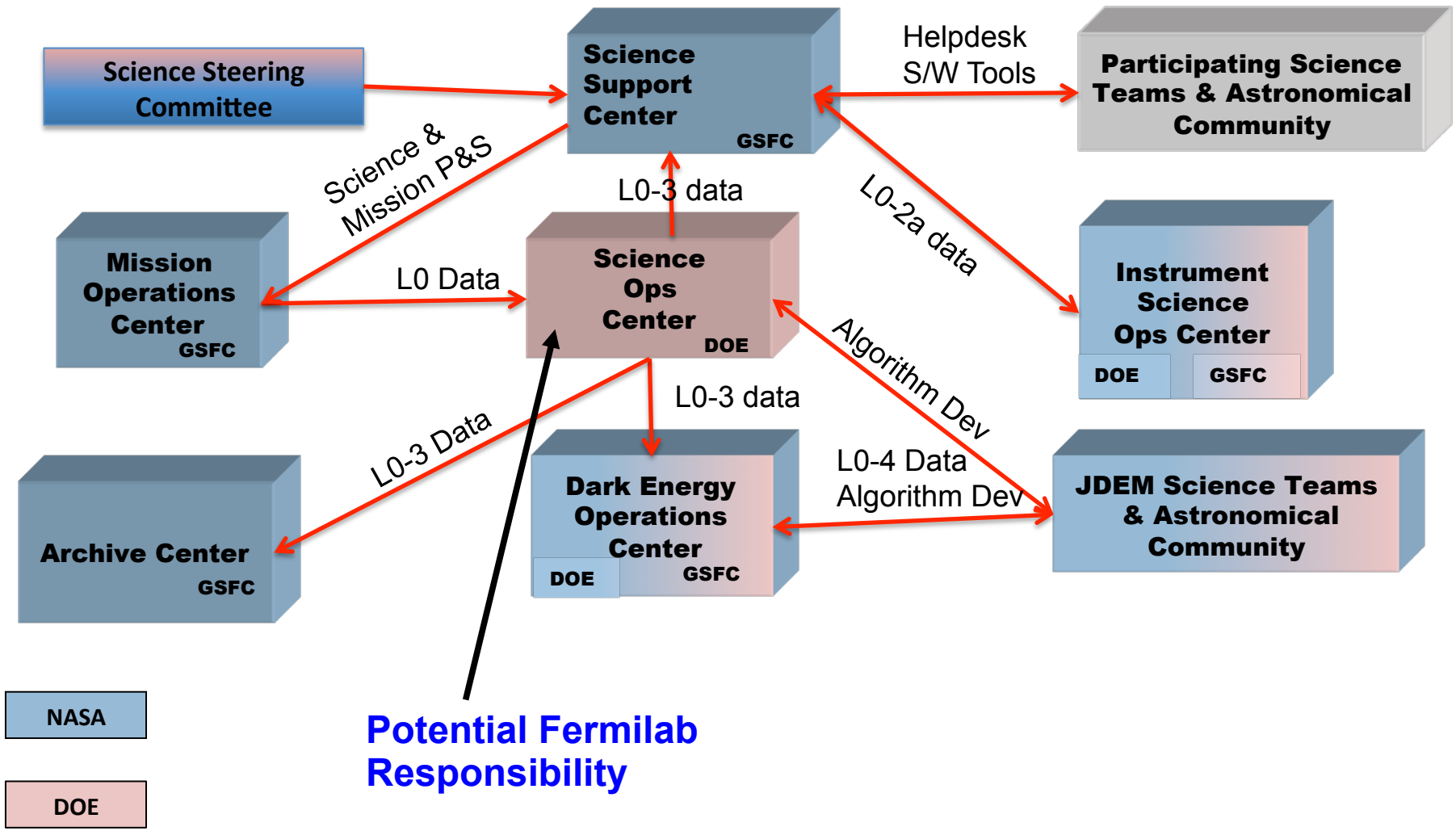
- 2000 SuperNova Acceleration Probe (SNAP) proposed by LBNL
- 2003 Joint Dark Energy Mission created between NASA/DOE
  - JDEM one of three “Beyond Einstein” probes
  - Three concepts eventually developed using a mix of three techniques (Weak Lensing, BAO, Supernovae)
    - SNAP, DESTINY, ADEPT FNAL joins SNAP
- 2007 BEPAC recommends JDEM “go first”
- 2008 NASA and DOE form JDEM Project Offices
- 2008 Agencies create Science Coordination Group to merge three concepts => JDEM-Omega design, submitted to Astro2010
- 2009 NASA creates ISWG to design a cheaper ``Probe-class” mission
- 2010 Astro2010 recommends WFIRST as top-ranked large space mission

WFIRST

- Based on JDEM-Omega design
- HgCdTe detectors for imaging & spectroscopy, 144 Mpixels
- 1.5-m telescope
- WL shapes for 2 billion galaxies
- BAO spectra for 200 million galaxies
- 2000 Supernovae
- Observing time split between Dark Energy, exoplanet microlensing, and NIR surveys



Ground System Architecture



DESpec

- Upgrade of DES: multi-object spectrograph for the Blanco 4-m, would deliver greater redshift precision (10^{-4} vs 0.1) for fraction ~10% of DES galaxies
- Enhance Dark Energy science reach of DES and LSST
- Use as much of the DECam infrastructure as possible (cage, barrel, hexapod, CCDs,…)
- ~20 HETDEX-like spectrographs, 4000 fibers
- Preliminary design and science studies underway

BigBOSS

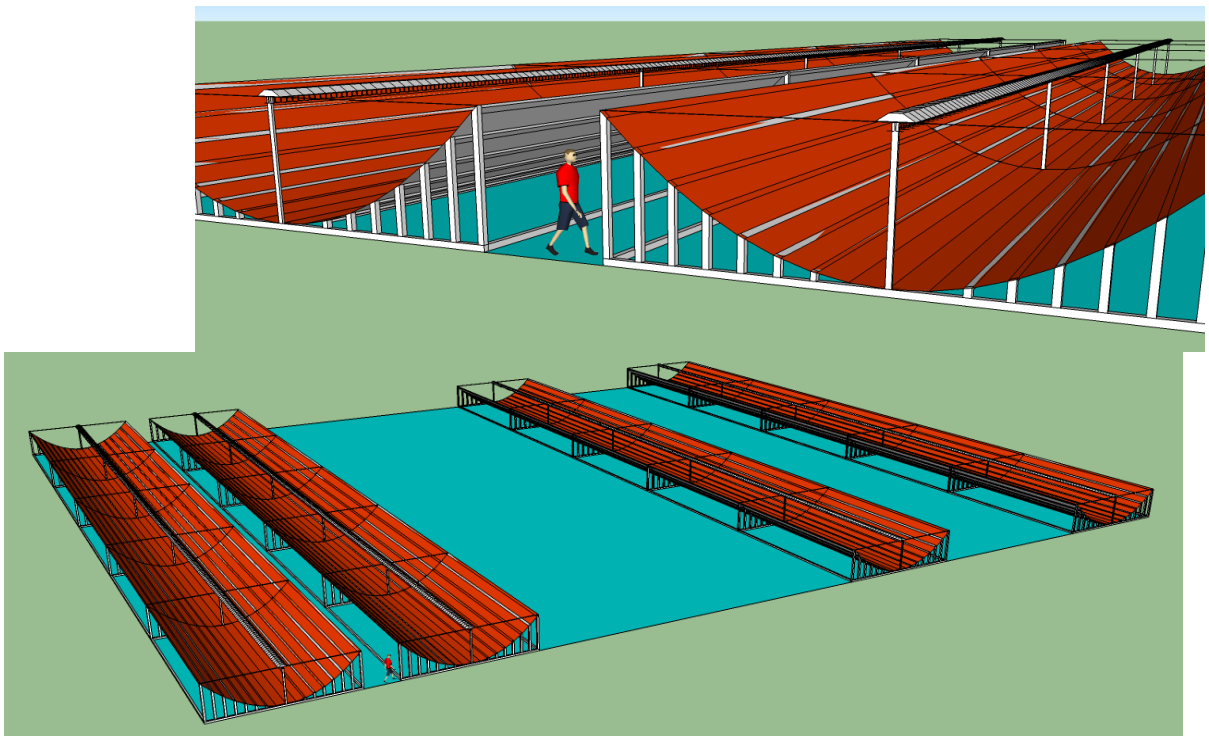
- LBNL-led concept for multi-object spectrograph for BAO survey to be mounted on the Kitt Peak 4-m telescope.
- Builds on experience with BOSS spectrographs for SDSS-III
- Larger optics, wider wavelength coverage, would likely not be an interchangeable instrument
- Northern hemisphere not optimal for DES, LSST targets
- Fermilab participating

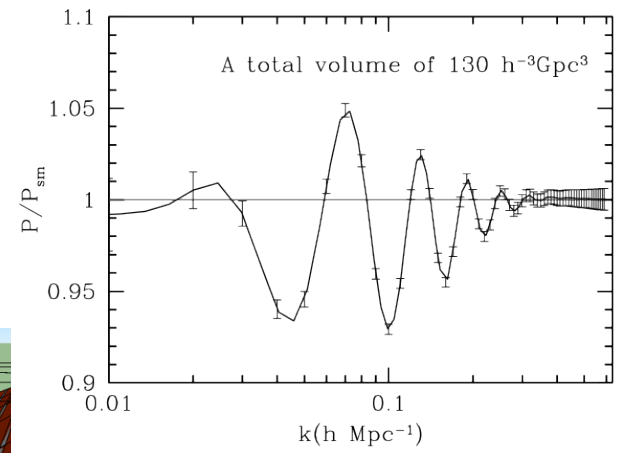
21 cm Radiation

- Arises from hyperfine transition in *neutral* hydrogen
  - ΔT=0.07 °K – hydrogen is never that cold, so it always glows
  - Weak transition – the whole universe is optically thin to it.
  - Is observed at 1.420 GHz at a redshift of z=0.
- Hydrogen is a tracer for the mass density of the universe
  - Less biased than galaxies (Marin,Gnedin,Seo & Vallinotto ApJ 718, 972)
  - Can measure large scale structure & BAO with an "all-sky" survey
  - Diffraction limits the resolution to ~20 arc-min for moderate (100 m) baselines so individual galaxies are not resolved, but BAO is large-scale
- The radio spectrum is dominated by "foregrounds" (i.e., broad-band emission mainly from synchrotron radiation). Removal of foreground radiation is a major experimental challenge.

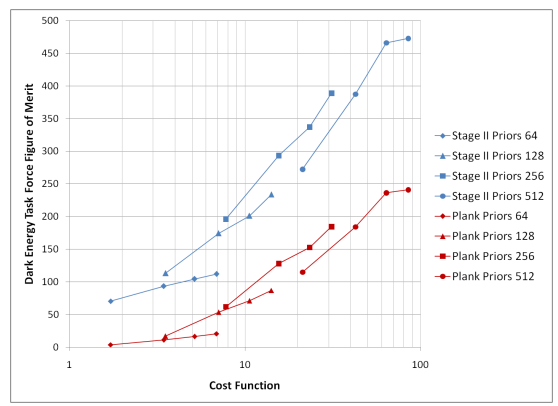
Strawman Design

Large scale multi-channel (~2048) interferometer array of uniformly spaced radio antennas.



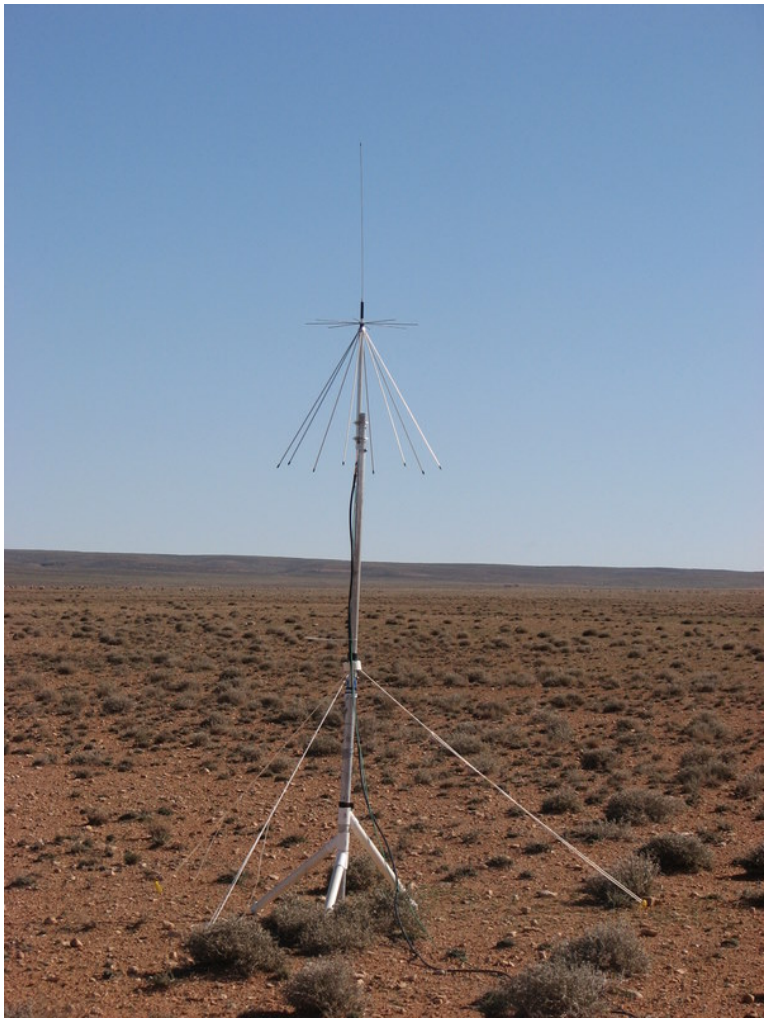


A projection of the accuracy that will be otained by the proposed 21 cm survey from Seo, et al., Astro-ph 0910-5007, to be published in ApJ.



Feasible DETF FoM's of 100 to 400

Site Testing



Conclusion

- Fermilab has been a leader in the study of Dark Energy and Cosmic Acceleration.
- With our collaborators, we're poised to take the next step in understanding the origin of cosmic acceleration with DES.
- Pursuing several `next-generation' options to make further progress
- Our goals are well-aligned with Astro2010, PASAG, and P5