Supernovae, Dark Energy, and New Astrophysics:
From Photons to Petabytes

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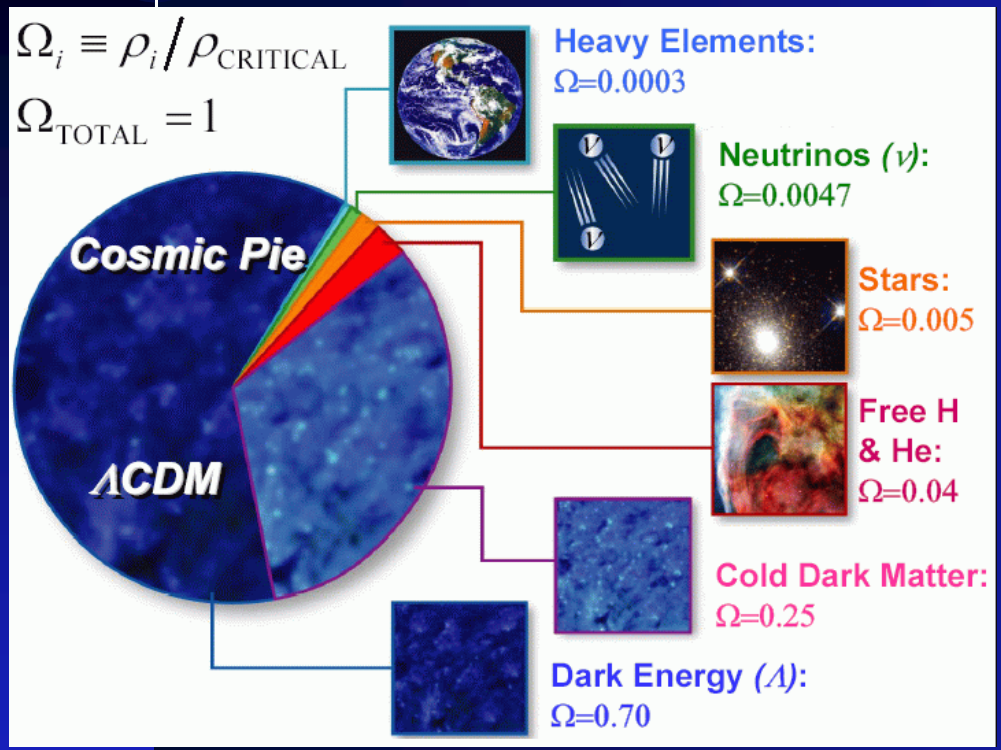
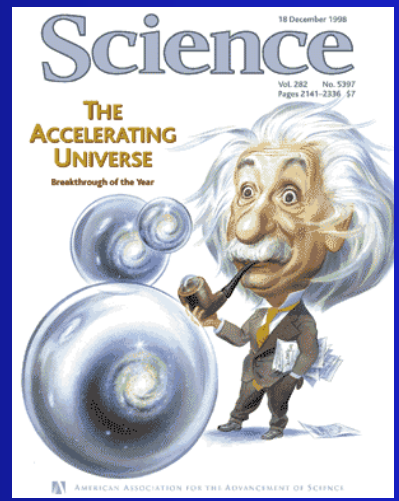
What we know…
and what we know we DON'T know!



Dark Energy is the dominant constituent of the Universe. Dark Matter is next.

95% of the Universe is in Dark Energy and Dark Matter, for which we have little or no detailed understanding.

1998 and 2003 Science Breakthroughs (?!!) of the year



How did we get in this mess?

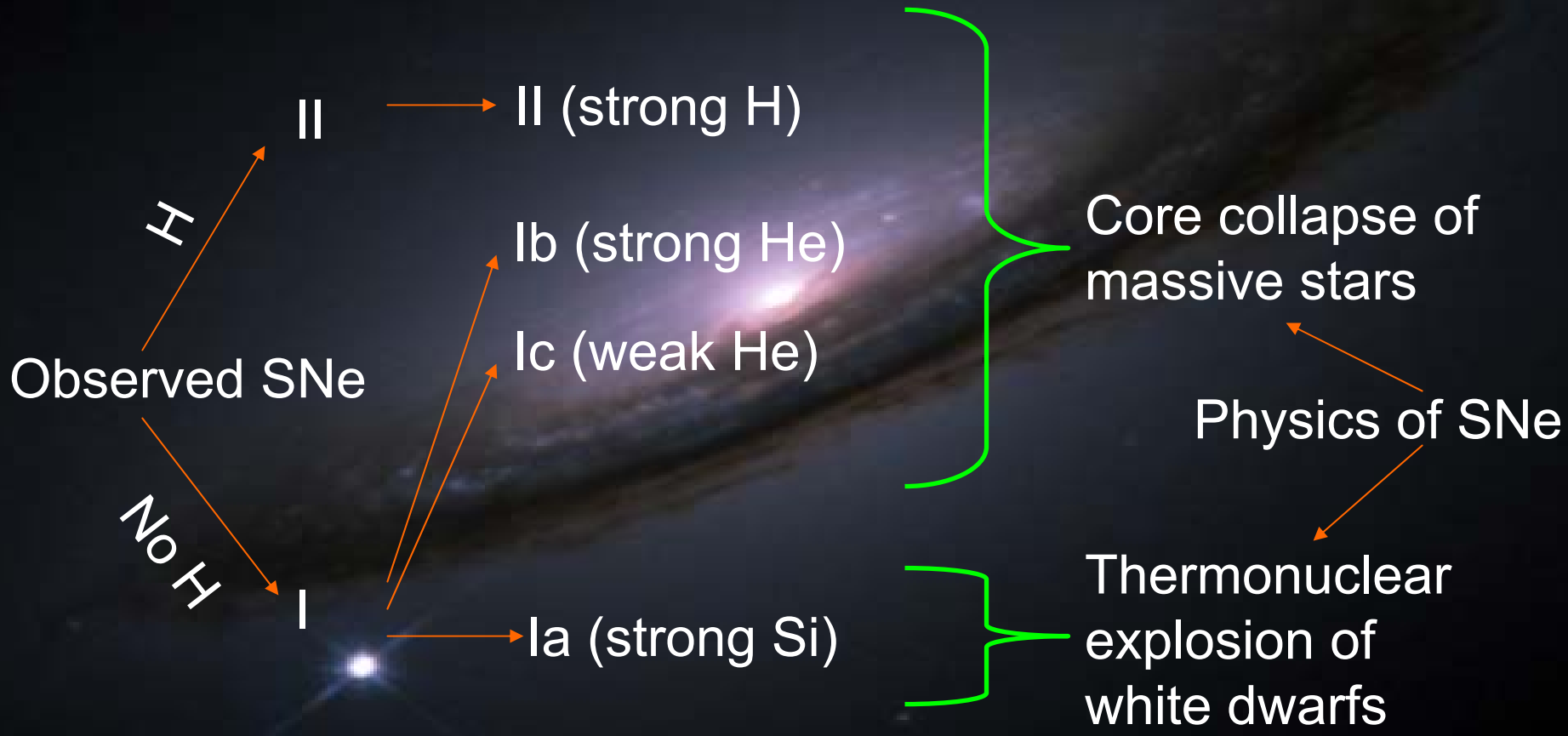
- Dark Matter?
  - Gravitational signature seen
  - But no detectable matter?
  - MACHOs? WIMPs?
- Dark Energy?
  - Went looking for deceleration; after all, we knew gravity works (even for Dark Matter), right?
  - Needed ways to measure large distances in the universe to demonstrate deceleration over time

Cosmic Yardsticks: A Supernova Primer

- Exploding stars are BRIGHT!
  - Often outshine the entire host galaxy (billions of stars)
  - Wilson (1939) suggested use as cosmological probes
- SNe come in a variety of observational "types"
  - Typing dates back to Minkowski, Zwicky, and Baade, ~1941
  - Originally five types: I - V
    - All based on SPECTROSCOPIC differences
  - Soon narrowed down to TWO types
    - With subtypes!
    - Still purely observational, purely spectroscopic

Traditional Supernova Classification

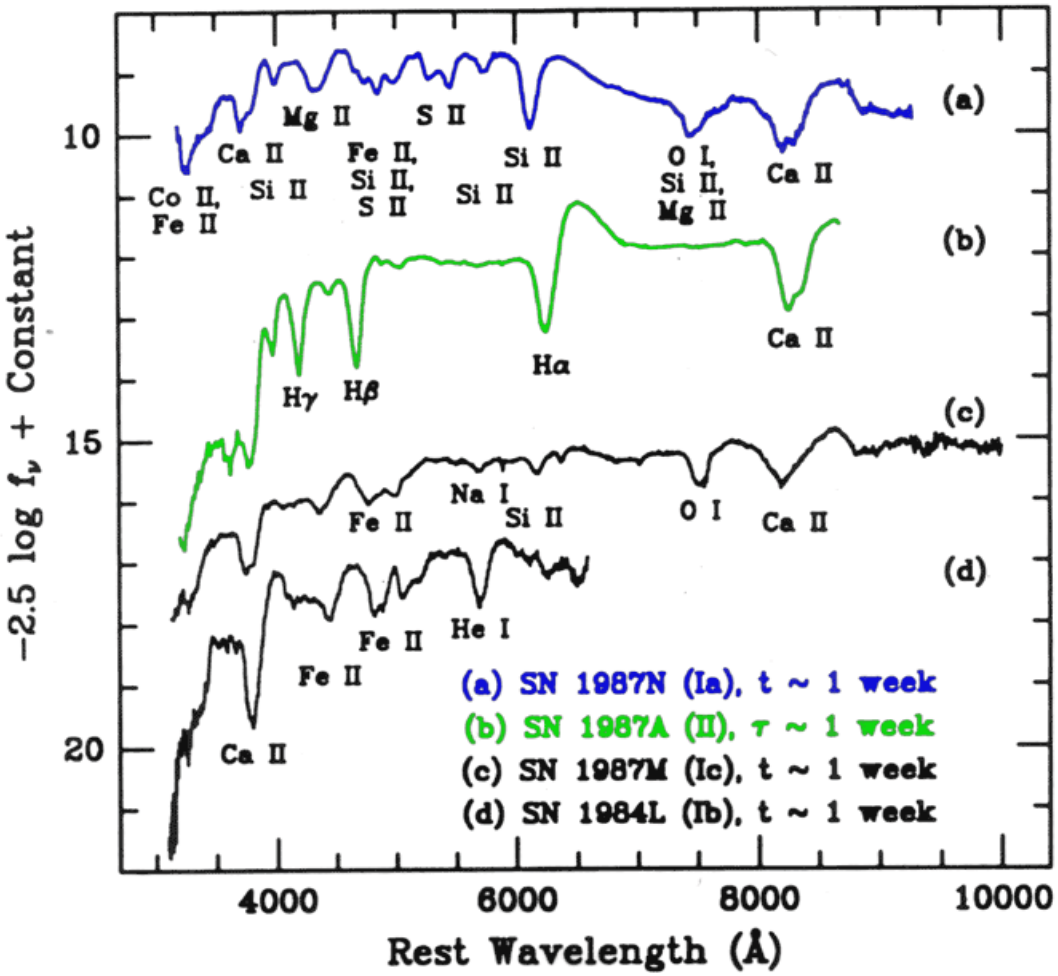
(spectroscopic)



SN1994D

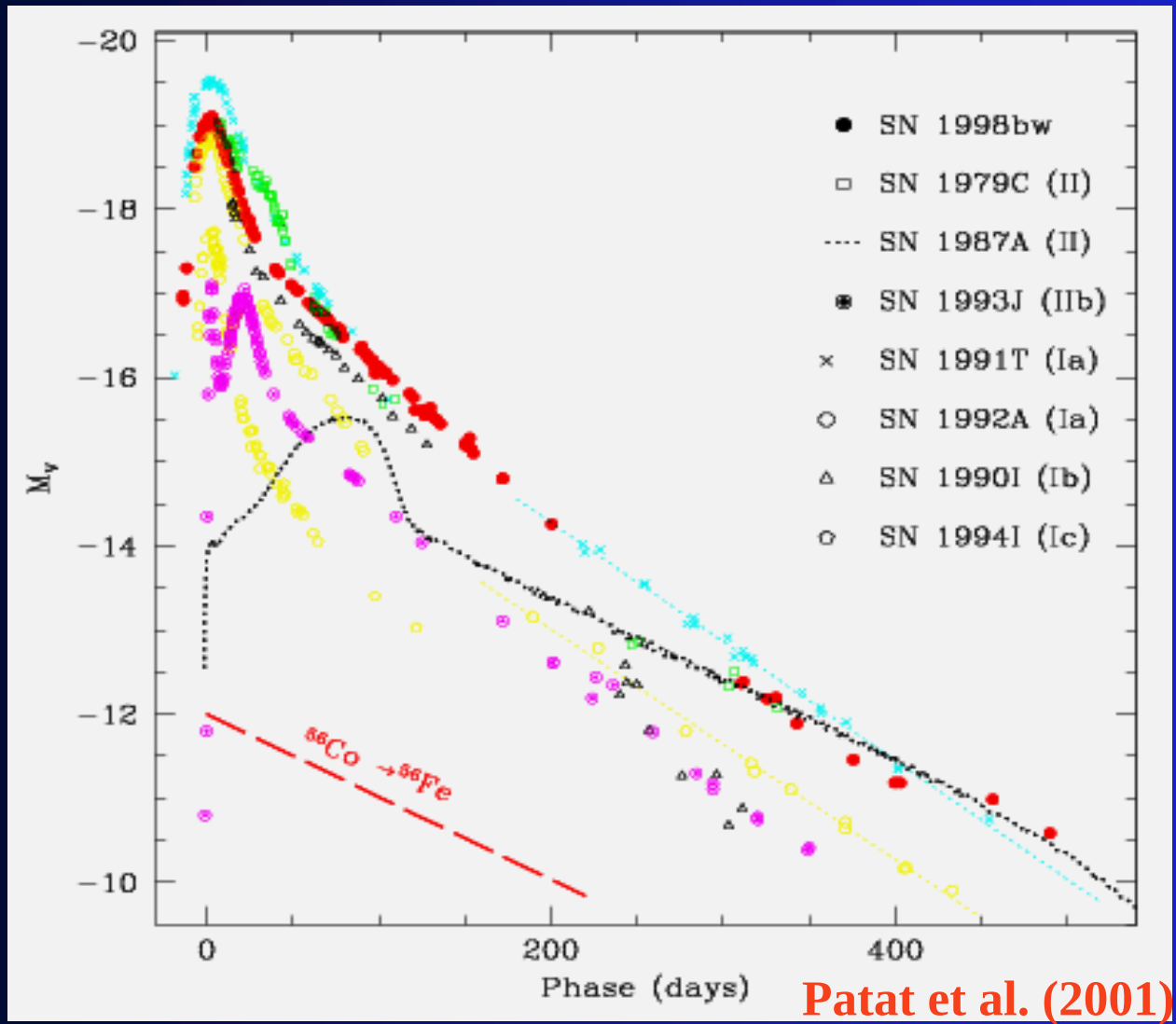
P. Challis, CfA

SN spectra at maximum light



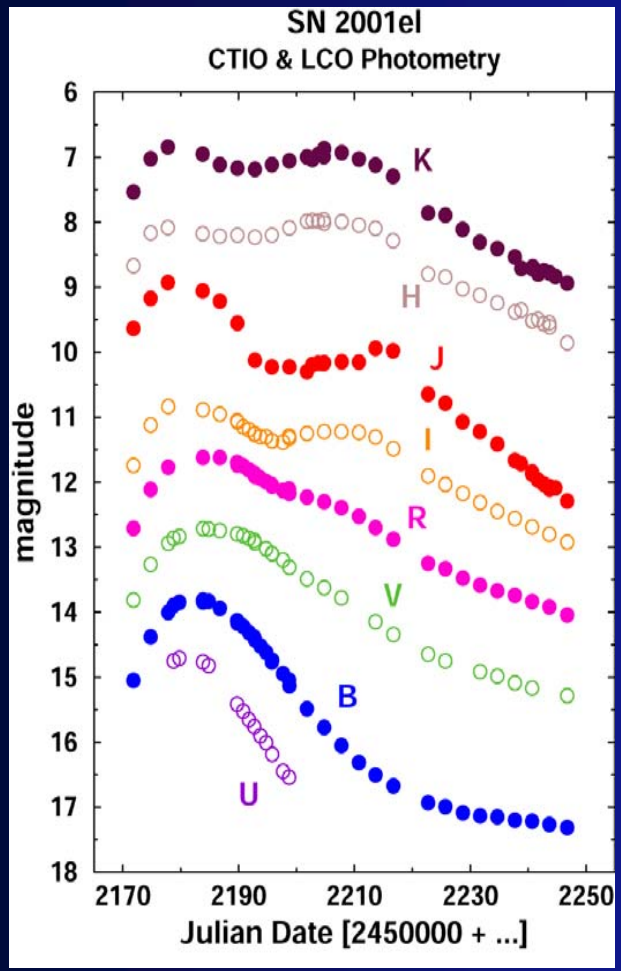
- Type Ia
- Type II
- Type Ic
- Type Ib

The variety of SN light curves

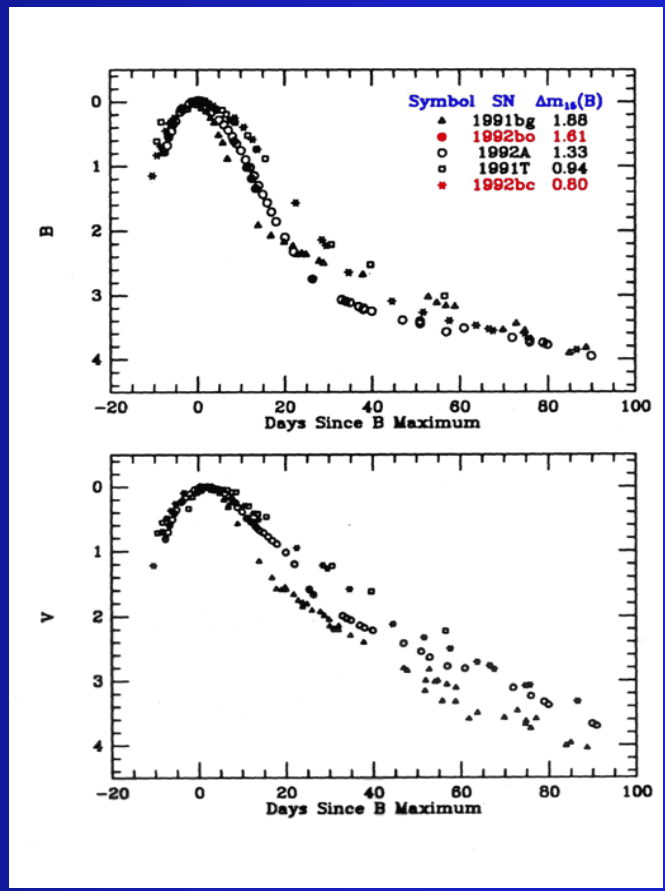


Patat et al. (2001)

Basic Type Ia Light Curves: Homogeneous? Not quite!

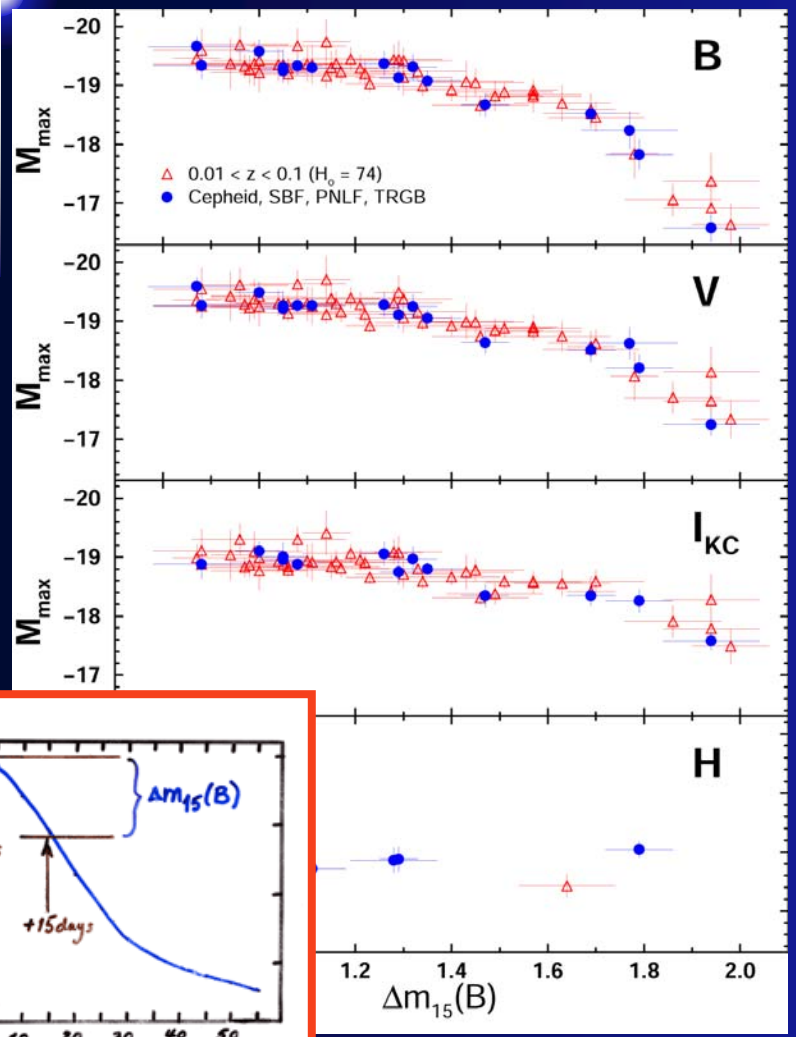


Krisciunas et al (2003)

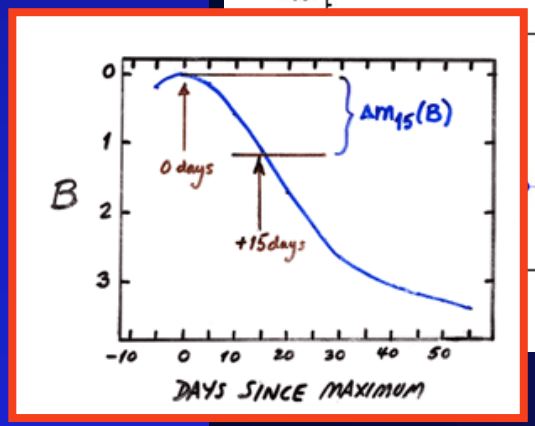


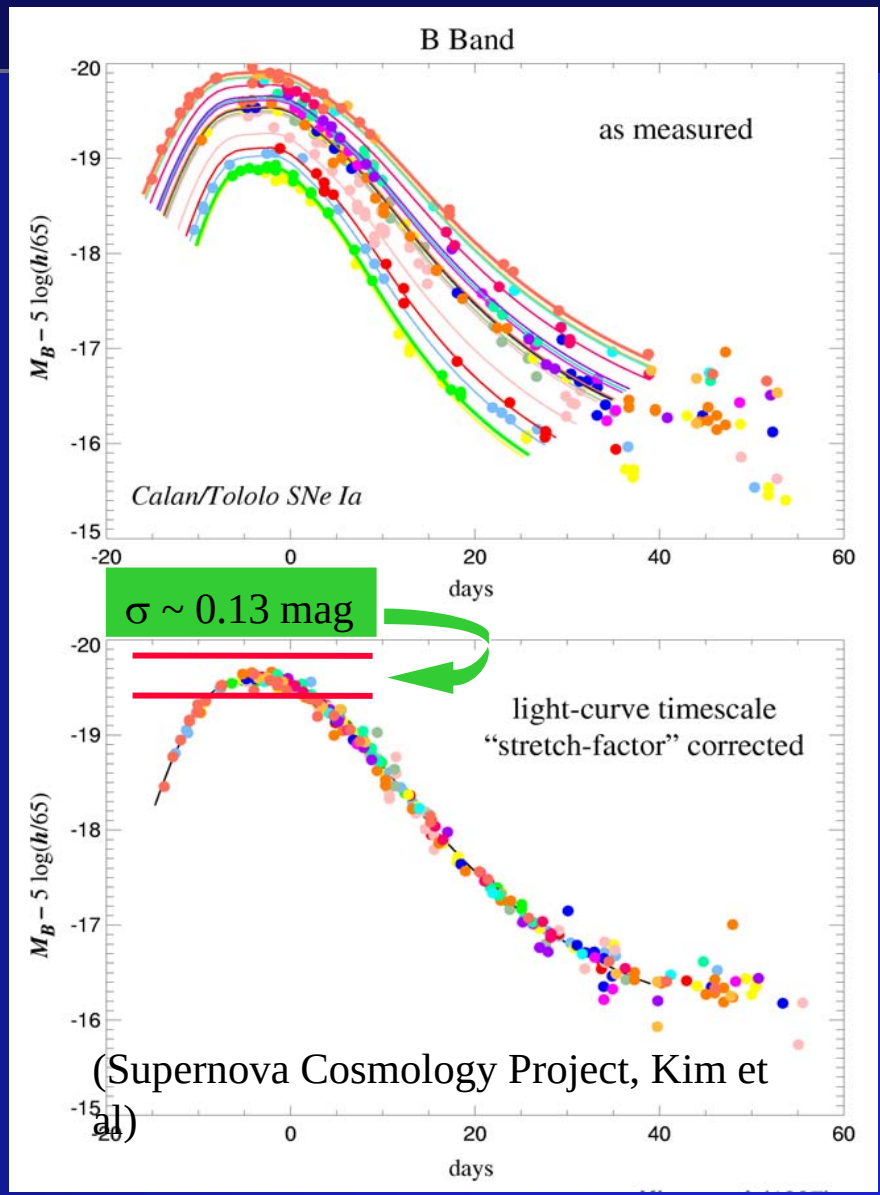
Diversity of Type Ia light curves (Calán/Tololo Survey)

Type Ia's show promise



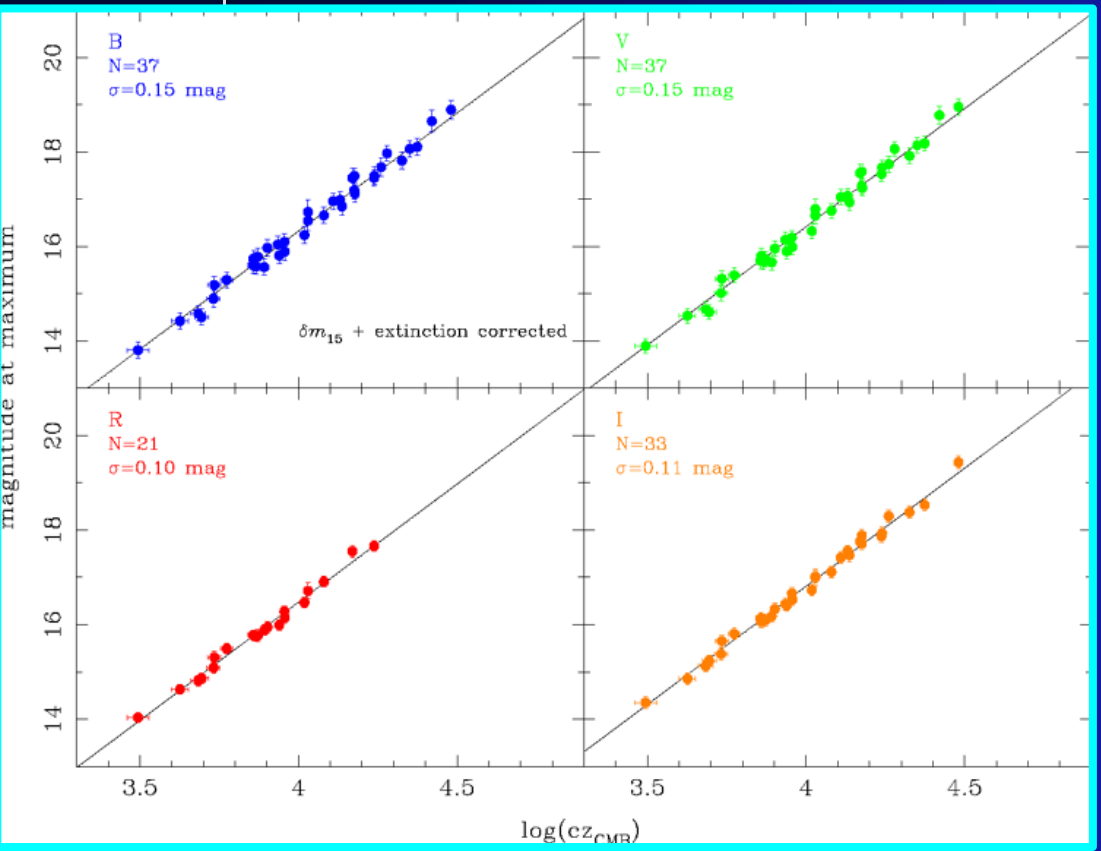
(Phillips, Hamuy et al.)



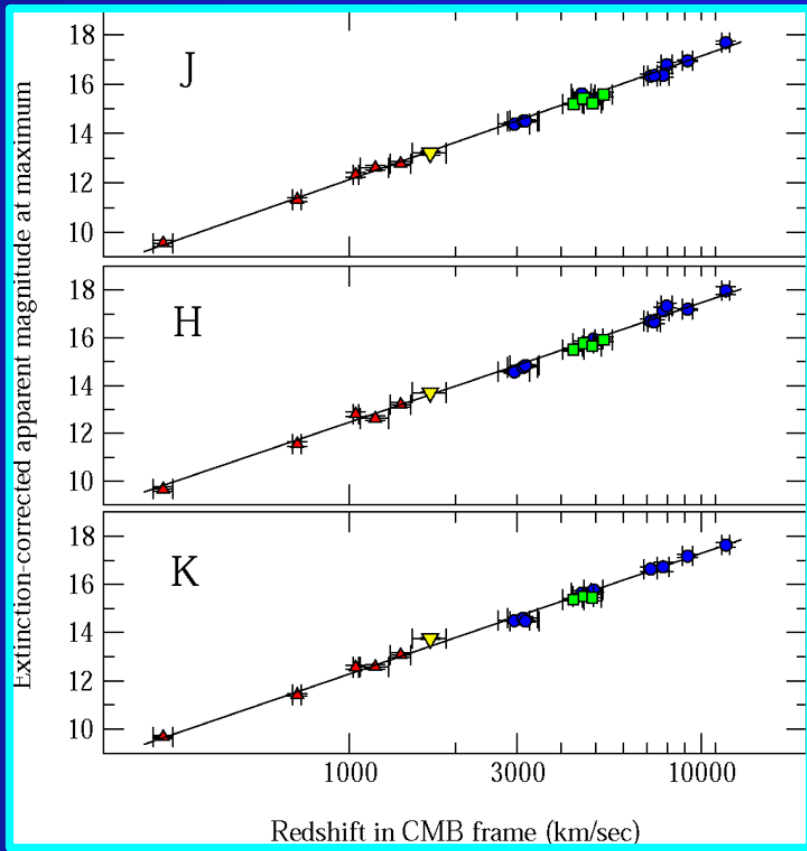


(Supernova Cosmology Project, Kim et al)

Type Ia SNe ARE precise standard-izable candles!



Prieto et. al. (2005)

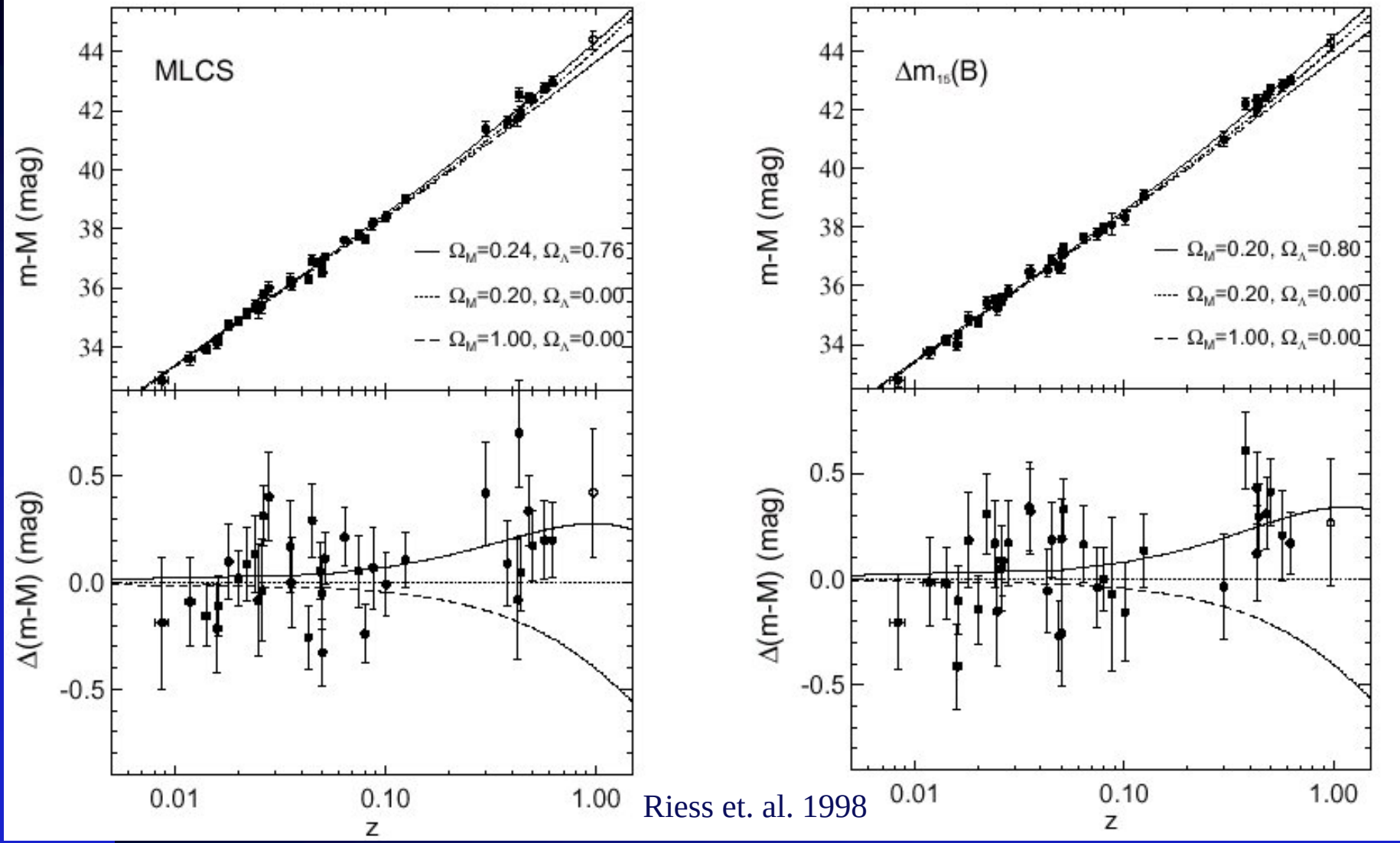


Krisciunas et. al. (2003)

Type Ia's and Cosmology

- Now have a precise tool
  - Measure distances to 10% with good lightcurves and mediocre spectroscopy
- Time to measure deceleration!
  - Supernova Cosmology Project efforts began in early 90s
  - High-z Team efforts began around 1995
  - Both using 4m telescopes to discover SNe, then obtain spectra with >4m telescopes, and obtain light curves with variety of 2m-4m telescopes

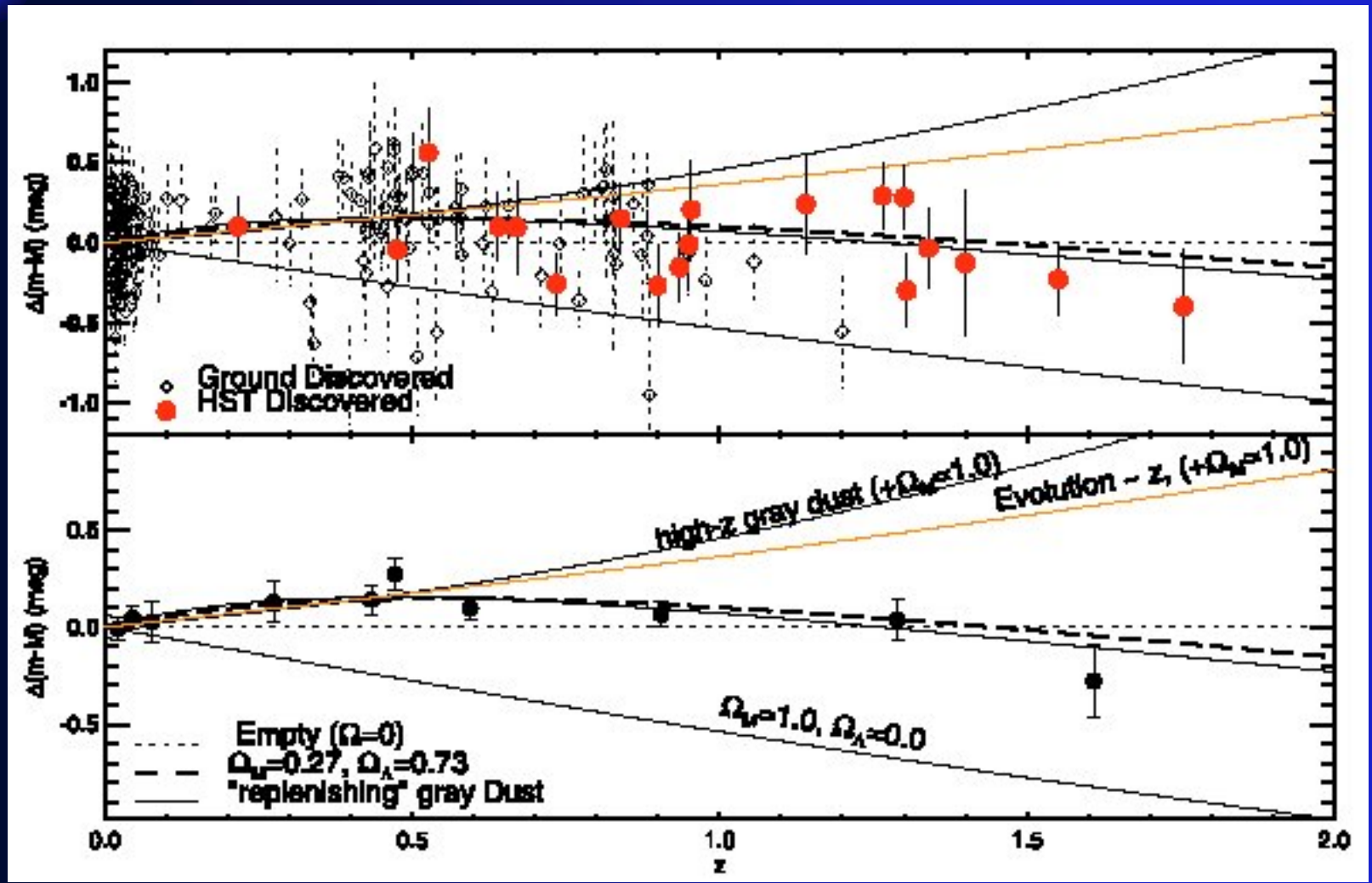
Surprise!
An ACCELERATING Universe!



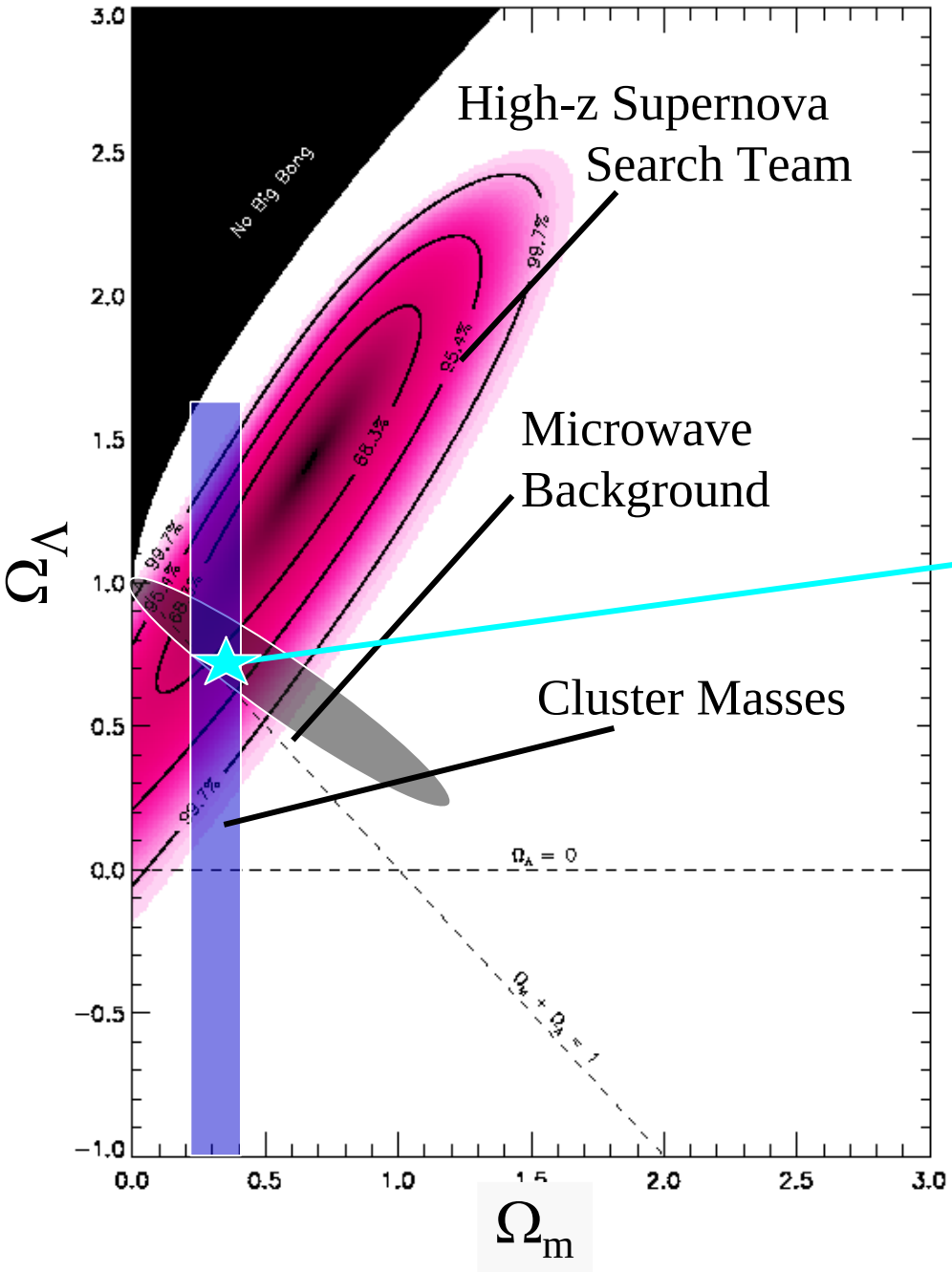
Riess et. al. 1998

Could it be Dust? Evolution?

"Higher-z" SN Team w/ HST, SN Ia @ z>0.5



Riess et al, ApJ, 2004



Insufficient mass to halt the expansion

Rate of expansion is increasing…

For flat Universe

$\Omega_{mass} + \Omega_\Lambda = 1$

"Best Fit" at

$\Omega_{mass} \sim 0.3$

$\Omega_\Lambda \sim 0.7$

Where are we going? A "Repulsive" Result

- In 1990s, began looking for deceleration
- Found expansion of Universe is accelerating!!!
- Implies something NEW!
- Regions of empty space REPEL each other?
  - "Cosmological constant"? Something gravitational?
    - Einstein's greatest blunder… OR NOT?!!
  - Something going on in the vacuum? Vacuum energy?
- Whatever it is, it points to
  - NEW FUNDAMENTAL PHYSICS!

Dark Energy's Equation of State

$P = w\rho$

- w = 0, matter
- w = 1/3, radiation
- w = – 1, Λ
- w = – N/3, topological defects?

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \sqrt{(1-\Omega_\Lambda)(1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}}\; dz'$$

For a flat Universe, luminosity distance depends only upon z, Ω_Λ, w. (assumes w is constant)

Dark Energy Models

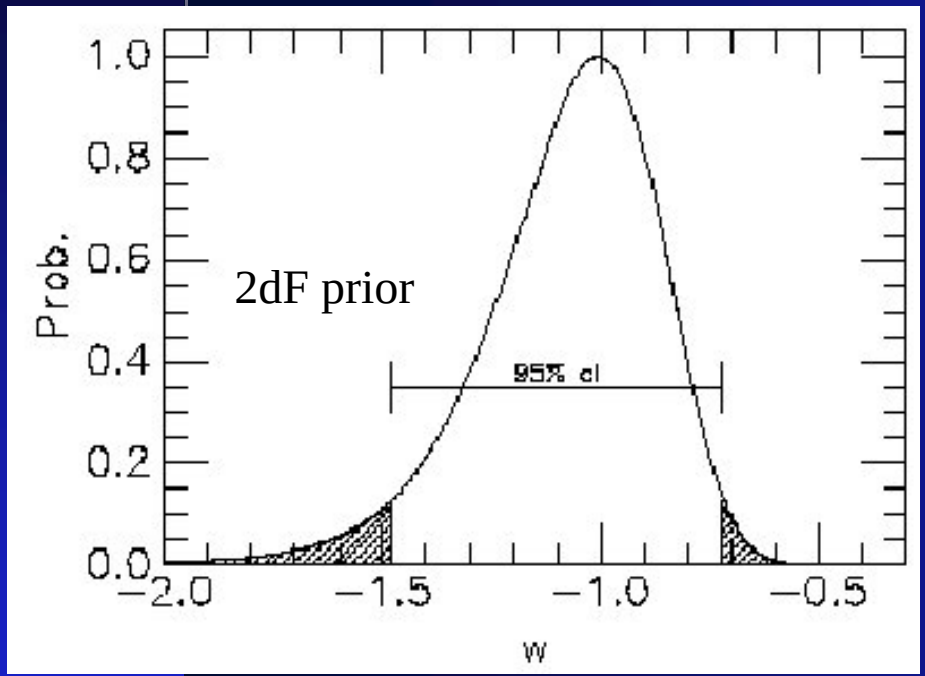
$w > -1$
- Quintessence
- Gravitational, e.g. R^{-n} with n>0 (Carroll et. al. 2004)

$w = -1$
- Cosmological Constant

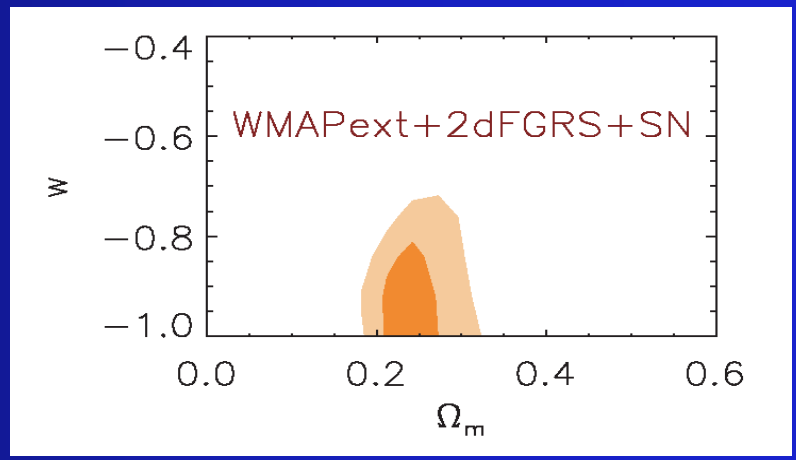
$w < -1$
- Exotic! (Carroll et. al. 2003)
  - In general unstable
  - Pair of scalars: “crossing” from w>-1 to w<-1
  - Physical issues

Early limits on w

- As of 2003, $w < -0.7$



Tonry et. al., astro/ph 0305008



Spergel et. al., 2003

Attacking the Question of Dark Energy

- "Classical" approach won't work
  - Not enough telescope time
  - Difficult to control calibrations & systematics
- LARGE SURVEYS
  - Goal: Provide large, uniform, well calibrated, controlled, and documented datasets to allow for advanced statistical analyses
  - Control calibrations & systematics to <1%
  - Larger collaborations provide both manpower and diverse expertise
    - Including traditional astronomers, physicists, mathematicians, and computer scientists

Sociology of Dark Energy

- Dark Energy may be pushing the universe APART
- But it is pulling the Astronomy, High Energy Physics (HEP), and Computer Science (CS) communities TOGETHER
  - HEP shared interest in fundamental physics
  - HEP experience in large datasets
  - CS interest in CPUs, Storage, Networks, and (of course) algorithms & optimization!

Dark Energy ROADMAP to understanding

- Today
  - ESSENCE at CTIO, large international group of astronomers
  - SNLS, Supernova Legacy Survey at CFHT, ditto
- Coming Soon (2008 – 2010)
  - Dark Energy Survey
    - Camera built by Fermilab, majority DOE funding
    - Data Management System led by NCSA
  - PanSTARRs I and IV
- The next BIG step (2014 – 2024)
  - LSST
    - Camera built by SLAC, Data Mgmt with NCSA,
    - NSF + DOE funding, inc. LLNL, Brookhaven, others
- Stepping UP
  - Space-based work: JDEM (SNAP and/or others)
    - NASA + DOE funding

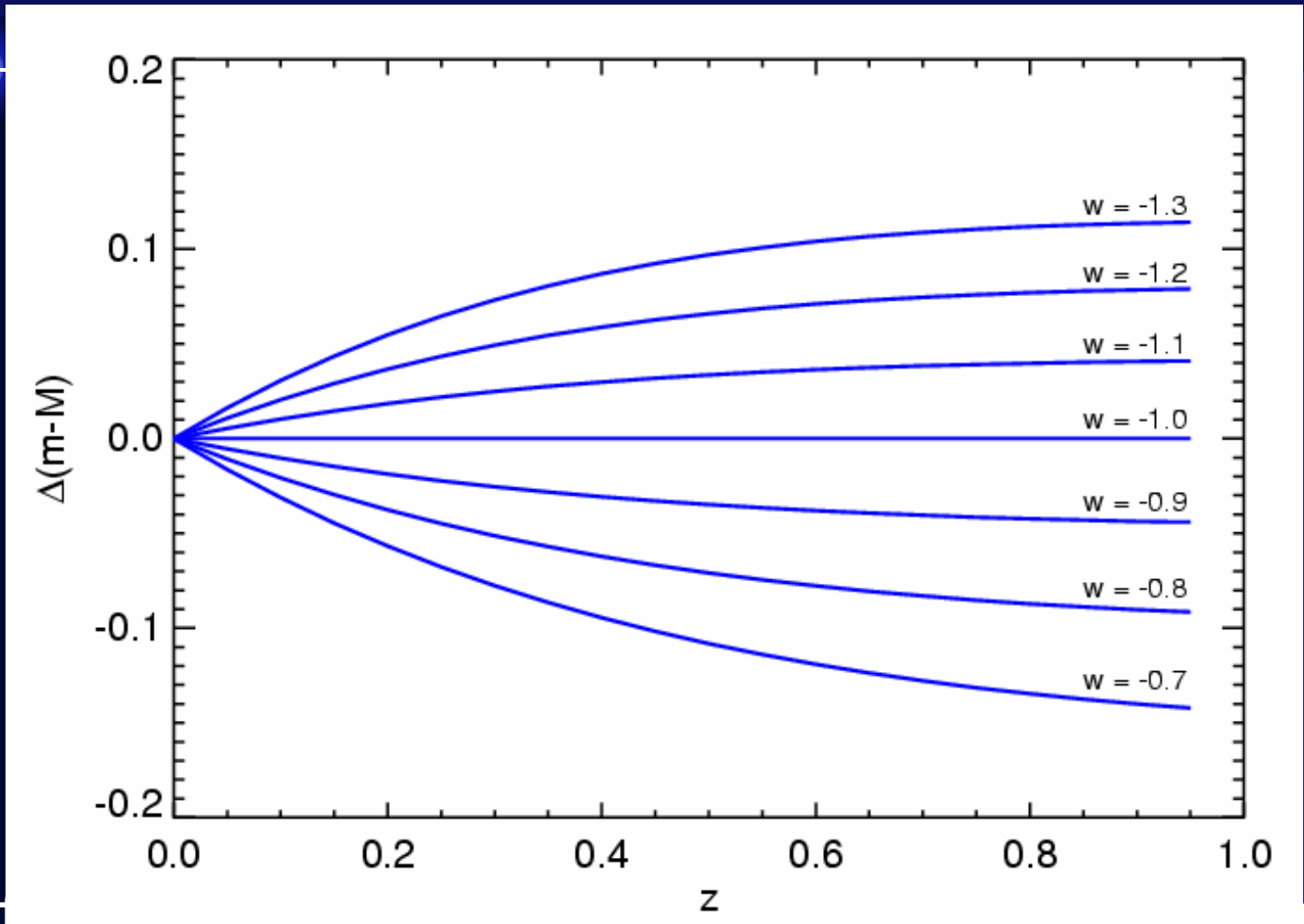
Today: ESSENCE (+SuperMACHO)

- Use a LARGE (~200 SNe), UNIFORM set of supernova light curves to allow us to study the evolution of the expansion of the universe
  - Constrain *w* to ~10%
- 30 half-nights per year for 5 years (2002-2006)
  - Control systematics by using ONE telescope
  - “Rolling search” - discovery & followup in same observations
- Use other half of nights to constrain possible DARK MATTER candidates
  - The ‘SuperMACHO’ project
  - Search the Large Magellanic Cloud for microlensing

ESSENCE Survey Team

Claudio Aguilera	*CTIO/NOAO*	Bruno Leibundgut	*ESO*
Andy Becker	*Univ. of Washington*	Weidong Li	*UC Berkeley*
Stéphane Blondin	*Harvard/CfA*	Thomas Matheson	*NOAO*
Peter Challis	*Harvard/CfA*	Gajus Miknaitis	*Fermilab*
Ryan Chornock	*UC Berkeley*	Jose Prieto	*OSU*
Alejandro Clocchiatti	*Univ. Católica de Chile*	Armin Rest	*NOAO/CTIO*
Ricardo Covarrubias	*Univ. of Washington*	Adam Riess	*STScI/JHU*
Tamara Davis	*Dark Cosmology Center*	Brian Schmidt	*ANU/Stromo/SSO*
Alex Filippenko	*UC Berkeley*	Chris Smith	*CTIO/NOAO*
Arti Garg	*Harvard University*	Jesper Sollerman	*Stockholm Obs.*
Peter Garnavich	*Notre Dame University*	Jason Spyromilio	*ESO*
Malcolm Hicken	*Harvard University*	Christopher Stubbs	*Harvard University*
Saurabh Jha	*SLAC/KIPAC*	Nicholas Suntzeff	*Texas A&M*
Robert Kirshner	*Harvard/CfA*	John Tonry	*Univ. of Hawaii*
Kevin Krisciunas	*Texas A&M*	Michael Wood-Vasey	*Harvard/CfA*

Equation-of-State Signal: where should we look?



Difference in apparent SN brightness vs. z

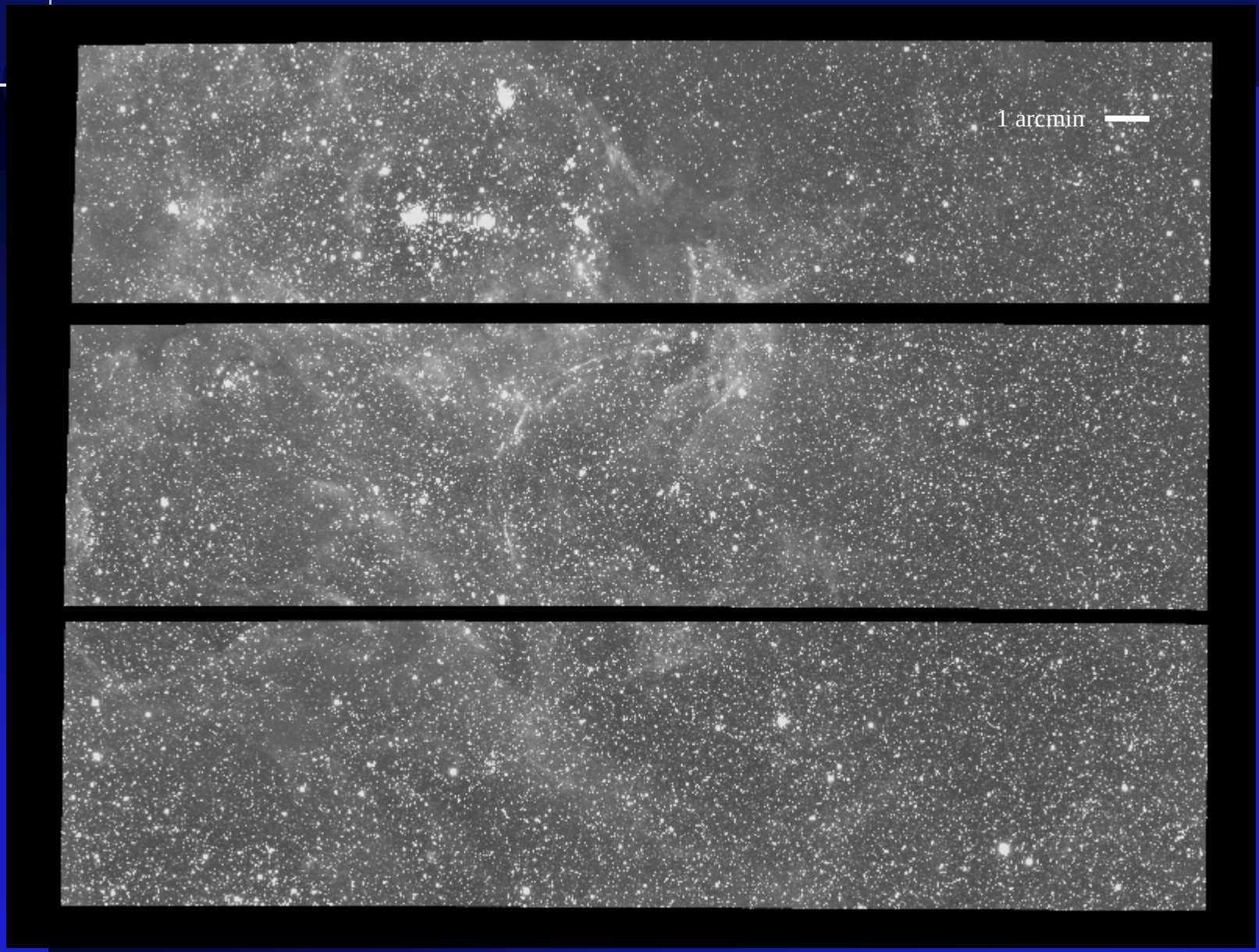
Ω_Λ=0.70, flat cosmology

The Strategy

- Repeatable
- Reliable
- Wide-field
- Multi-color
- Imaging

- CTIO Blanco 4m + MOSAIC II
- Every other night, Oct - Dec, 2002-2006

The Power of Difference Imaging



The Power of Difference Imaging: Light echos of SN 87a

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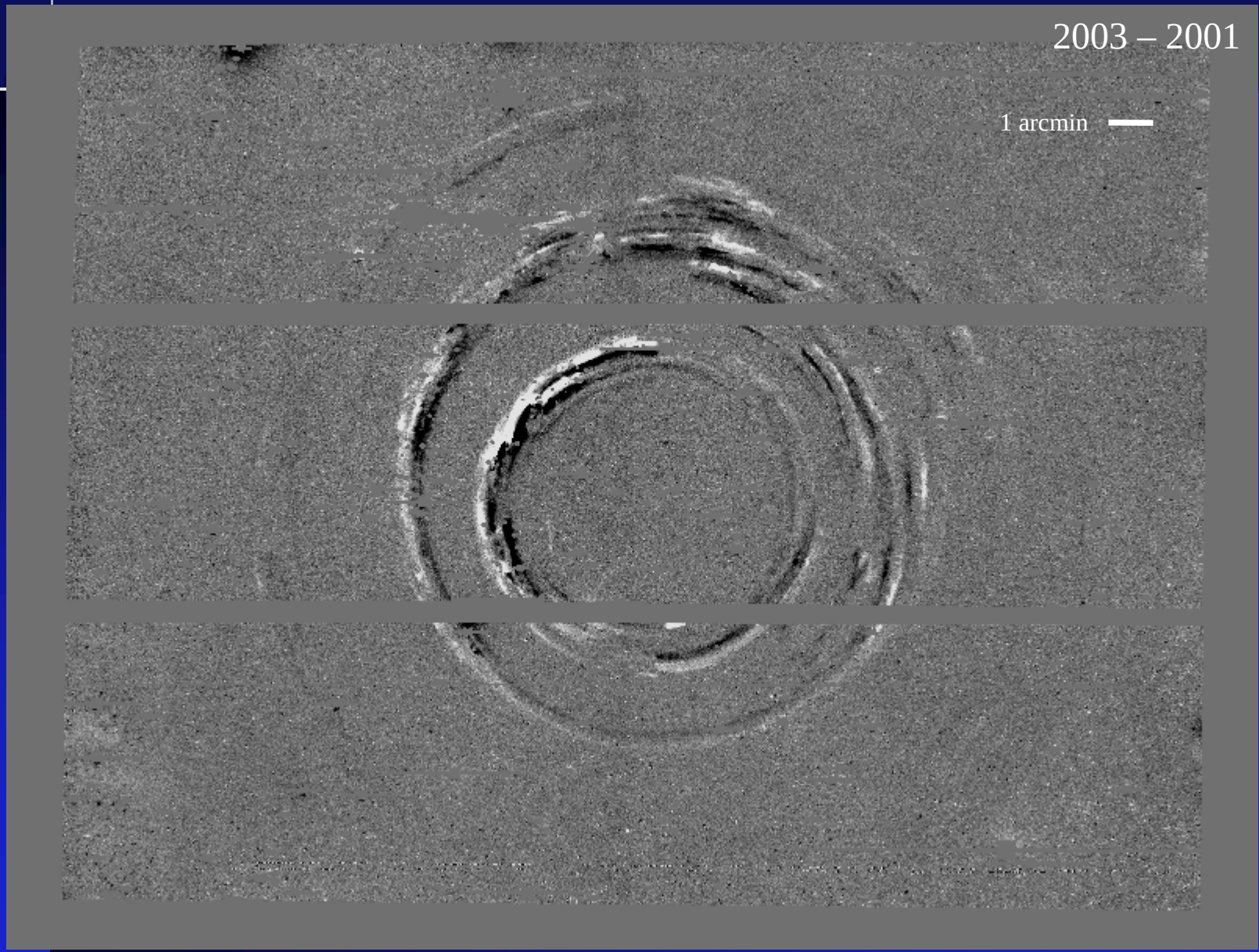
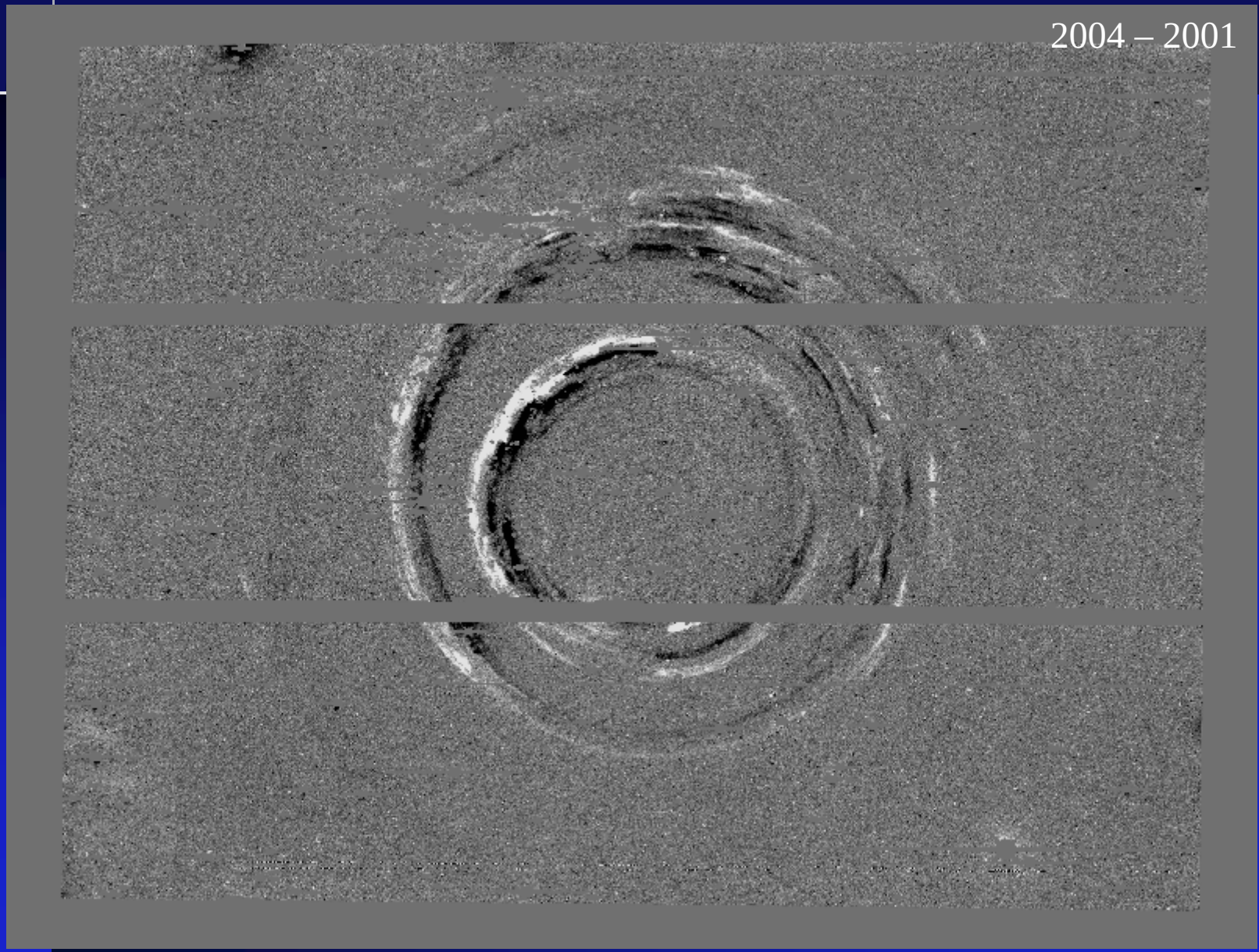
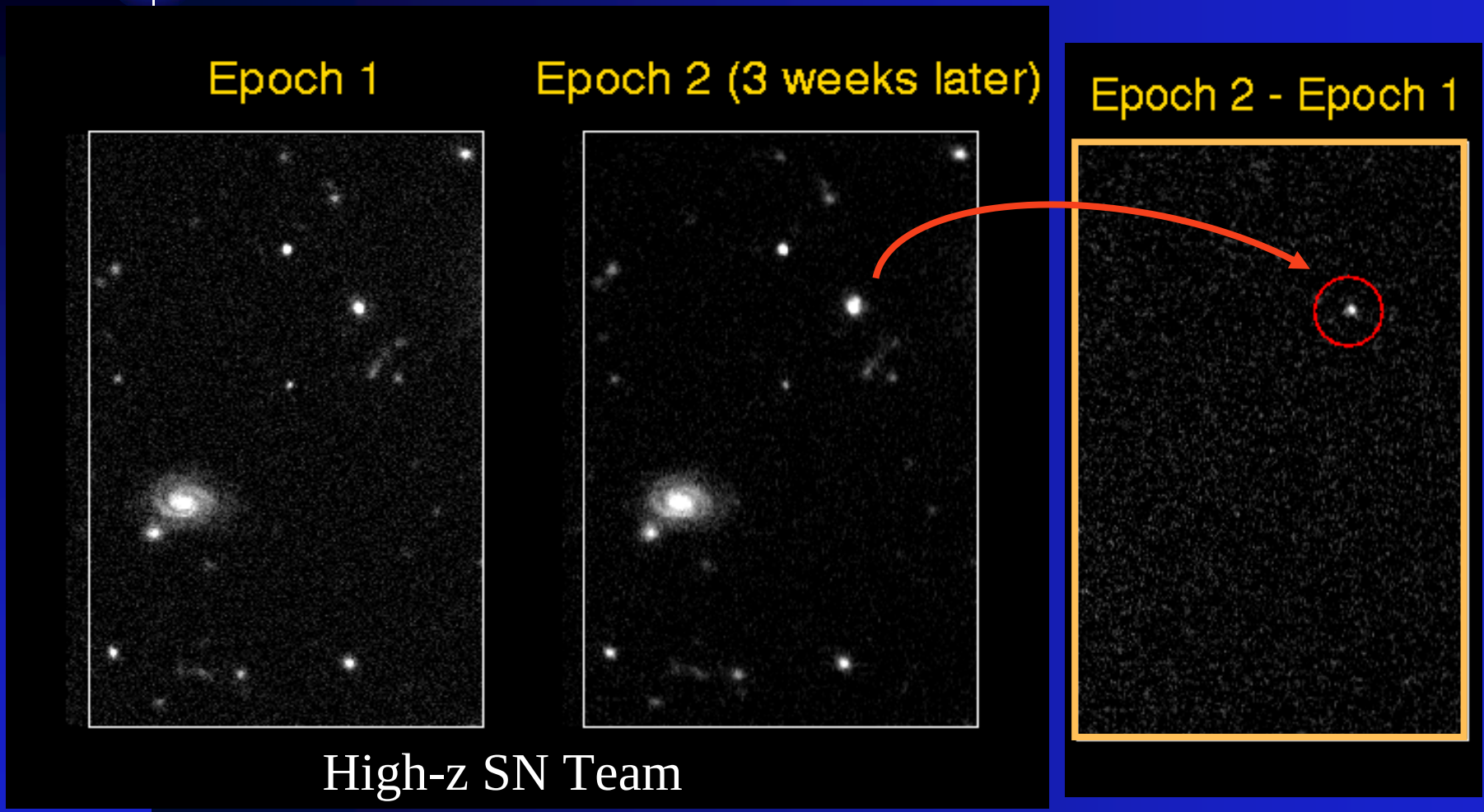


The Power of Difference Imaging: Light echos of SN 87a



Searching for Supernovae (and other transients)



The Experiment

CTIO 4m with Mosaic 8096x8096 imager:

150 half nights over 5 yrs.

3 lunations, every other night, avoiding full moon

Broadband *R* & *I* filters

32 fields, 0.36 arc-deg per field

13 sq-deg search

Exposures 200s *R*, 400s *I* (optimized for *w*)

+ *V* when needed

RI limits at S/N=7 - 23.5, 23.0

Remote observing from La Serena

Hardware for real-time reductions

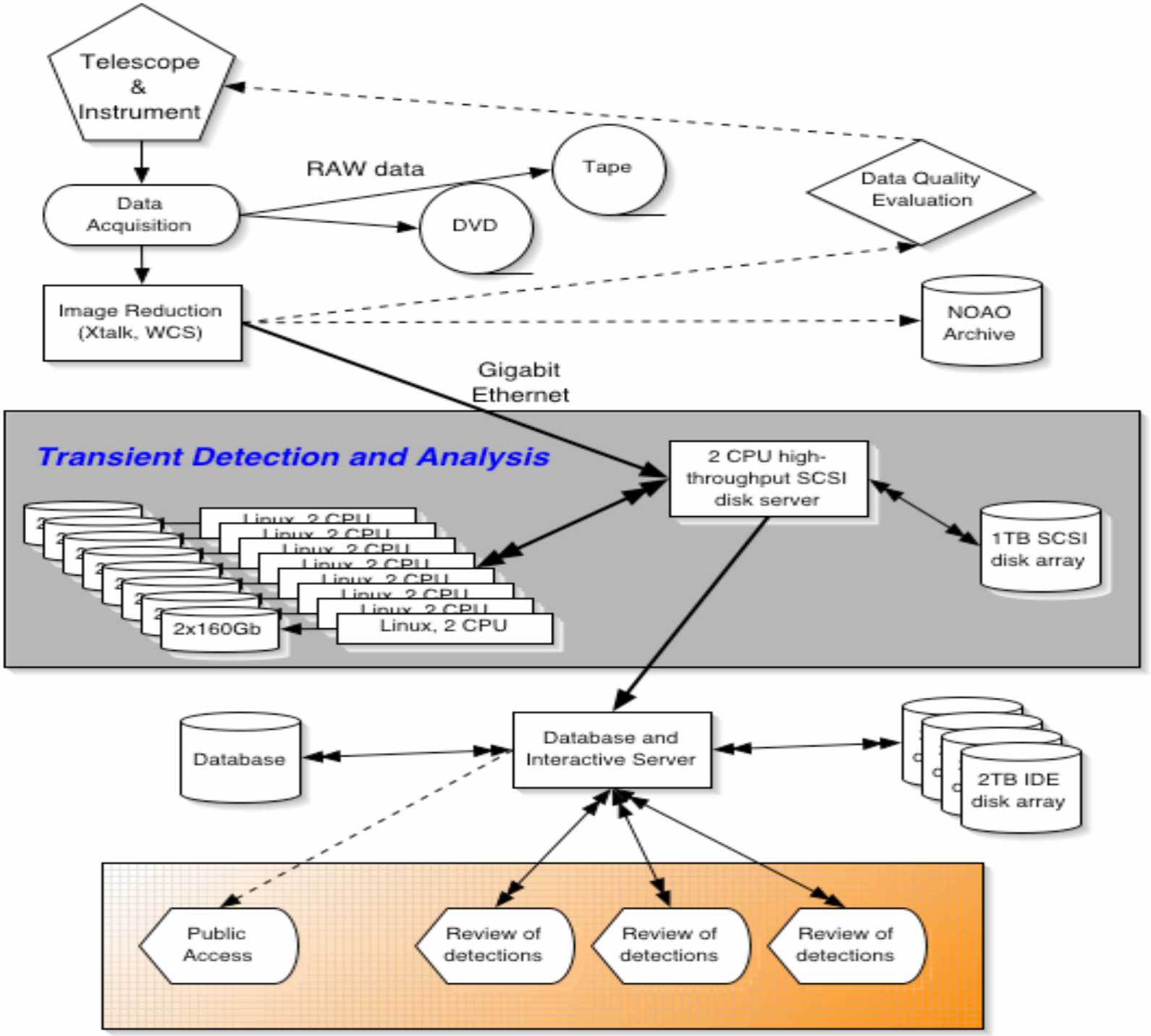
Dual networks
- 1 Gb/sec compute link
- 100 Mb/s admin link

10 compute nodes
- 2 x 1.2 GHz CPUs
- 1 GB RAM each
- 300 GB local IDE disk

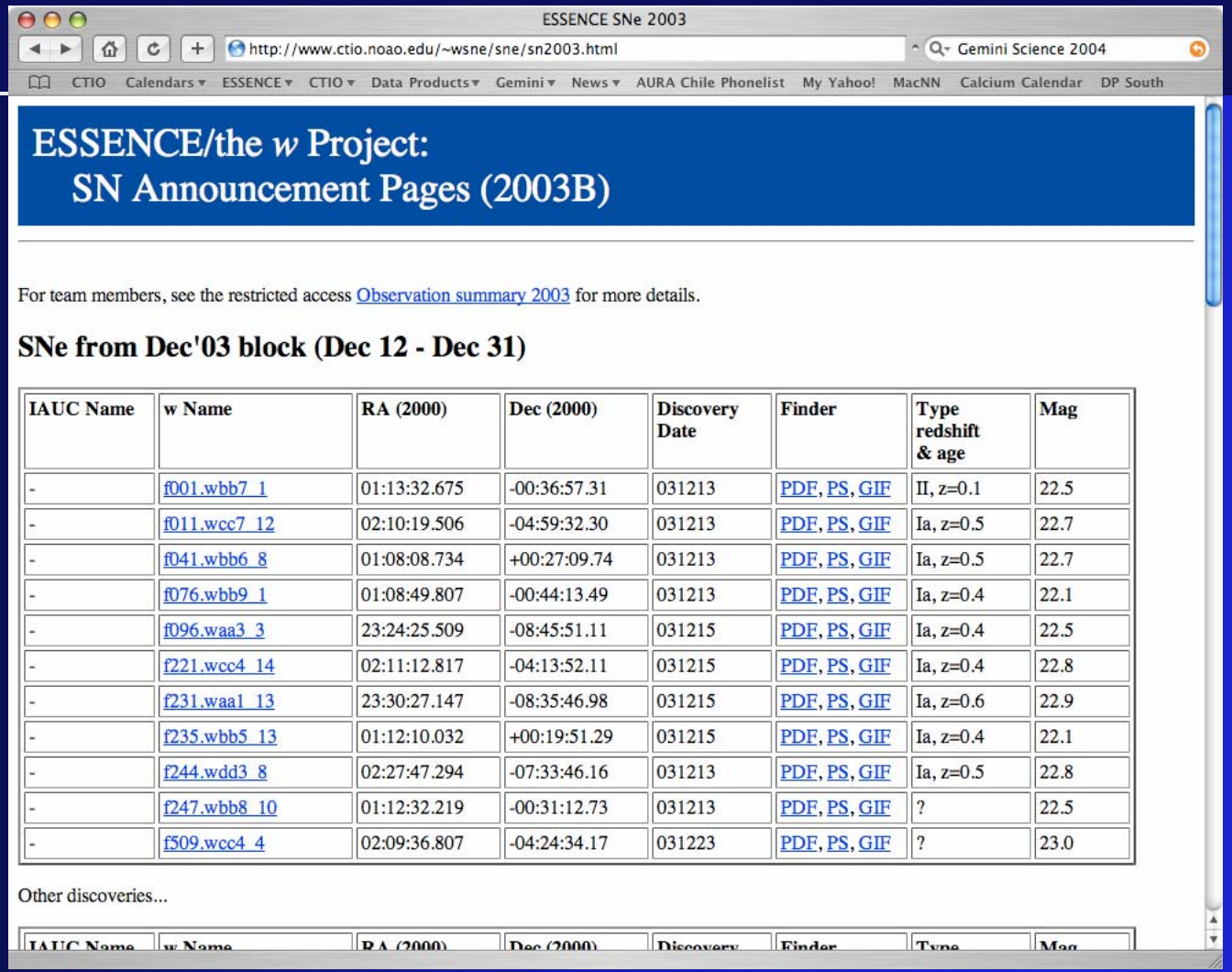
5x4 TB IDE RAID disk arrays

Additional ~6-8 TB online storage

= SN alerts & light curve fits <15 min after observation


Telescope & Instrument
RAW data
Tape
DVD
Data Acquisition
Data Quality Evaluation
Image Reduction (Xtalk, WCS)
NOAO Archive
Gigabit Ethernet
Transient Detection and Analysis
2 CPU high-throughput SCSI disk server
1TB SCSI disk array
Linux, 2 CPU
2x160Gb
Database
Database and Interactive Server
2TB IDE disk array
Public Access
Review of detections
Review of detections
Review of detections

Discoveries are announced immediately on our web site.



ESSENCE/the *w* Project: SN Announcement Pages (2003B)

For team members, see the restricted access Observation summary 2003 for more details.

SNe from Dec'03 block (Dec 12 - Dec 31)

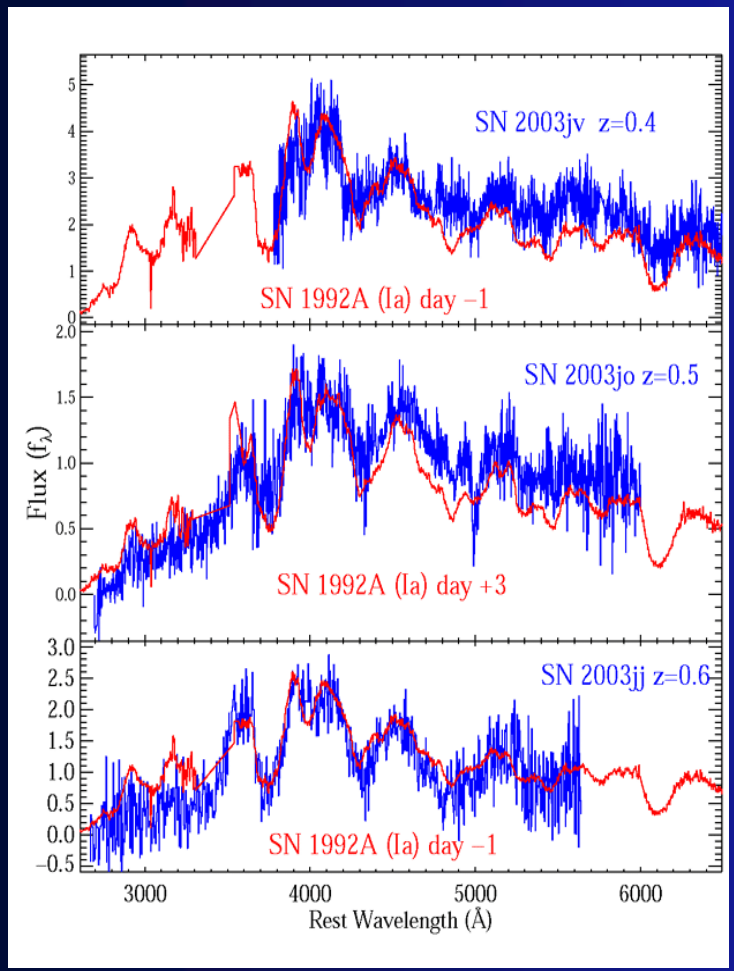
IAUC Name	w Name	RA (2000)	Dec (2000)	Discovery Date	Finder	Type redshift & age	Mag
-	f001.wbb7_1	01:13:32.675	-00:36:57.31	031213	PDF, PS, GIF	II, z=0.1	22.5
-	f011.wcc7_12	02:10:19.506	-04:59:32.30	031213	PDF, PS, GIF	Ia, z=0.5	22.7
-	f041.wbb6_8	01:08:08.734	+00:27:09.74	031213	PDF, PS, GIF	Ia, z=0.5	22.7
-	f076.wbb9_1	01:08:49.807	-00:44:13.49	031213	PDF, PS, GIF	Ia, z=0.4	22.1
-	f096.waa3_3	23:24:25.509	-08:45:51.11	031215	PDF, PS, GIF	Ia, z=0.4	22.5
-	f221.wcc4_14	02:11:12.817	-04:13:52.11	031215	PDF, PS, GIF	Ia, z=0.4	22.8
-	f231.waa1_13	23:30:27.147	-08:35:46.98	031215	PDF, PS, GIF	Ia, z=0.6	22.9
-	f235.wbb5_13	01:12:10.032	+00:19:51.29	031215	PDF, PS, GIF	Ia, z=0.4	22.1
-	f244.wdd3_8	02:27:47.294	-07:33:46.16	031213	PDF, PS, GIF	Ia, z=0.5	22.8
-	f247.wbb8_10	01:12:32.219	-00:31:12.73	031213	PDF, PS, GIF	?	22.5
-	f509.wcc4_4	02:09:36.807	-04:24:34.17	031223	PDF, PS, GIF	?	23.0

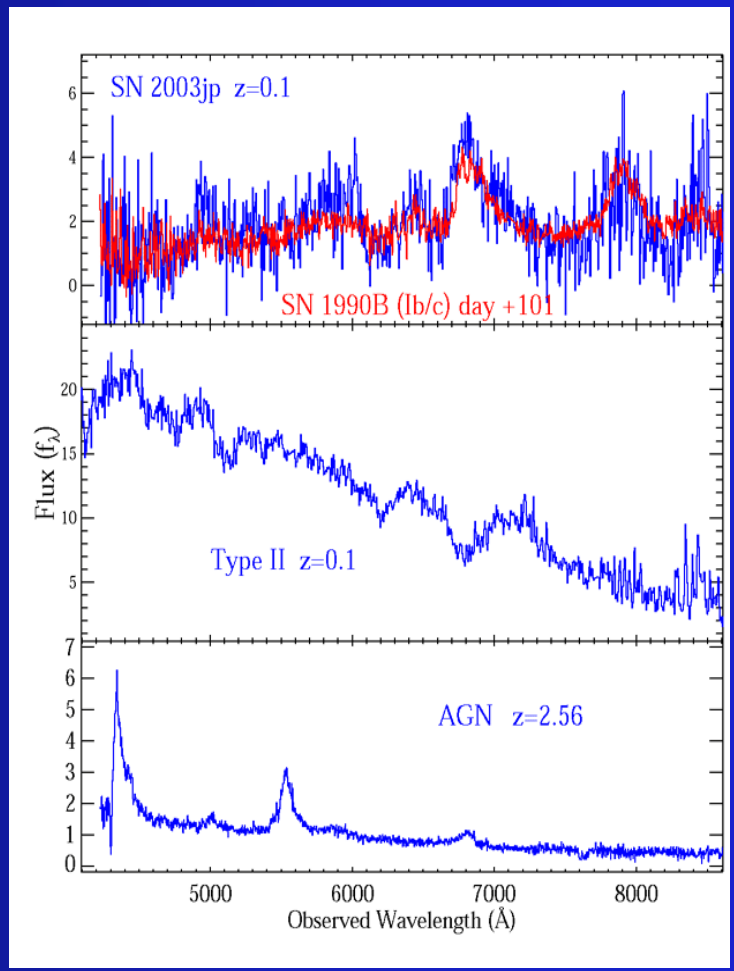
Other discoveries...

IAUC Name	w Name	RA (2000)	Dec (2000)	Discovery	Finder	Type	Mag

http://www.ctio.noao.edu/essence

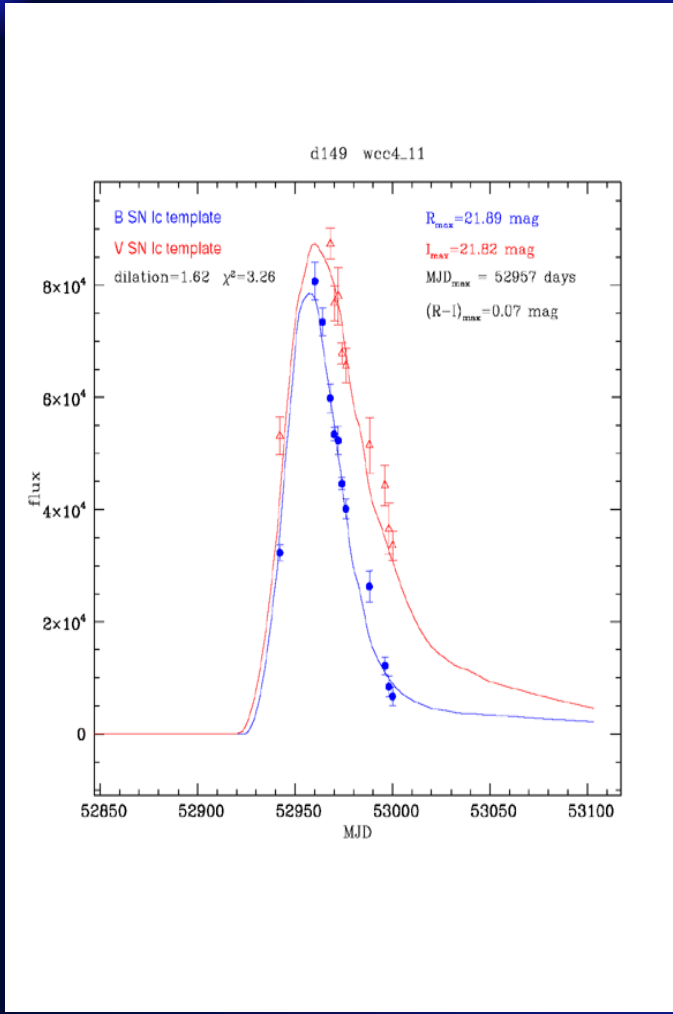
Spectra from 2003

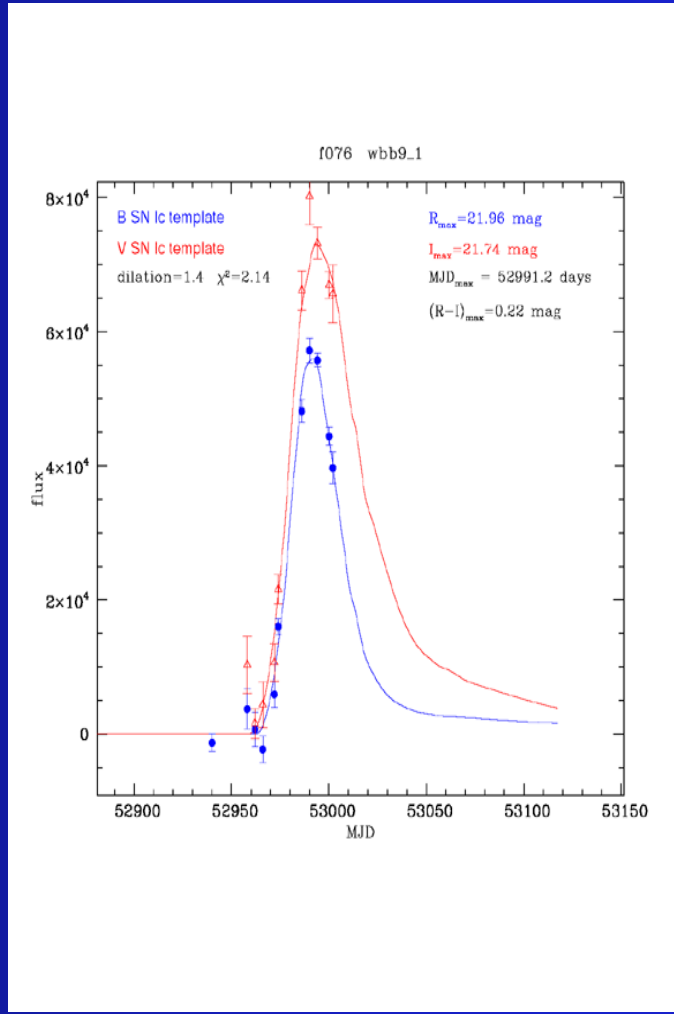




from Tom Matheson

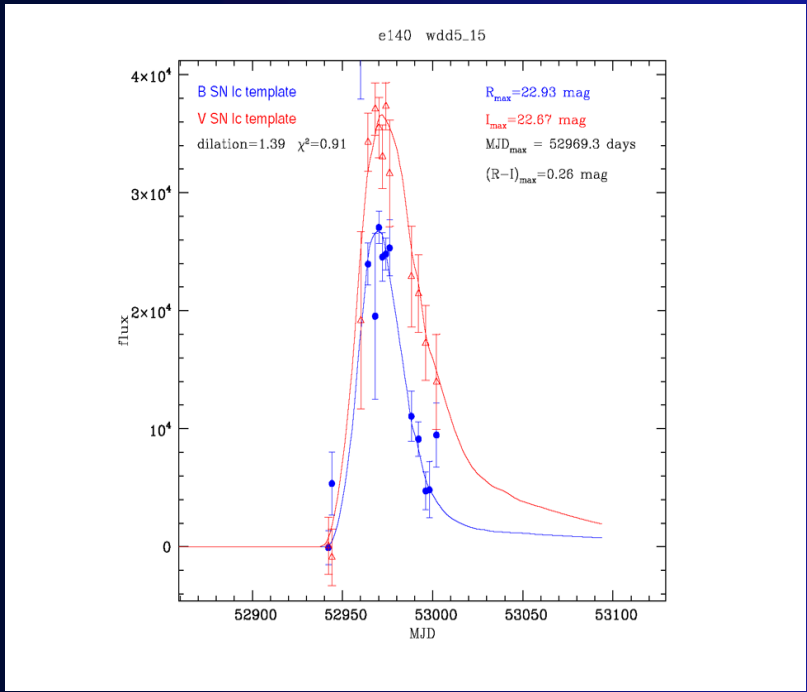
Sample light curves (I)



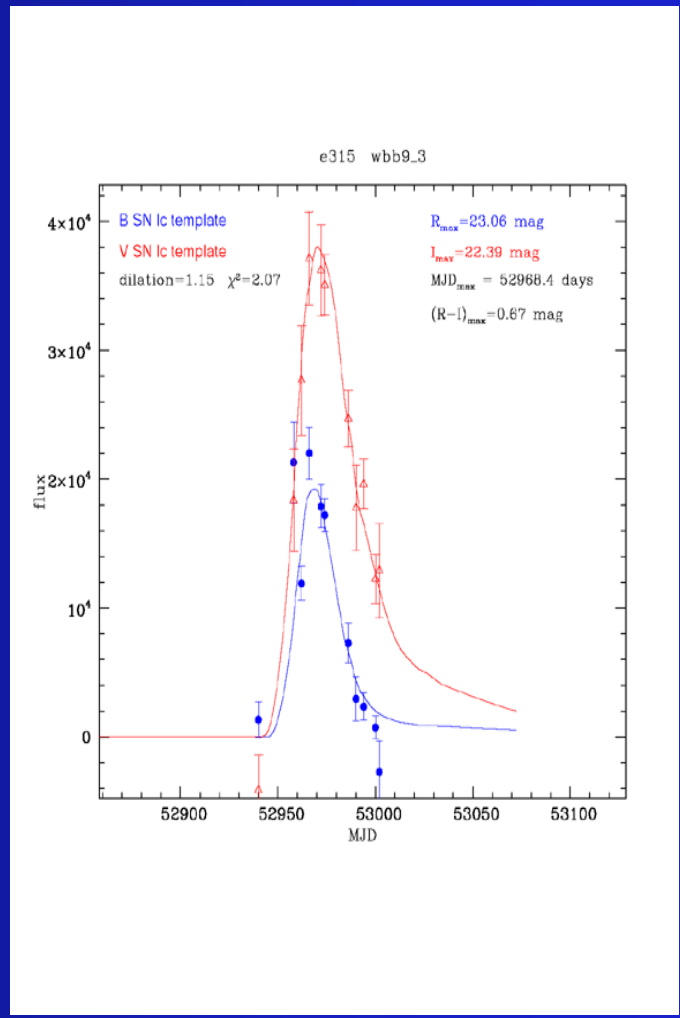


z = 0.34 Jose Luis Prieto z = 0.40

Sample Light Curves (II)



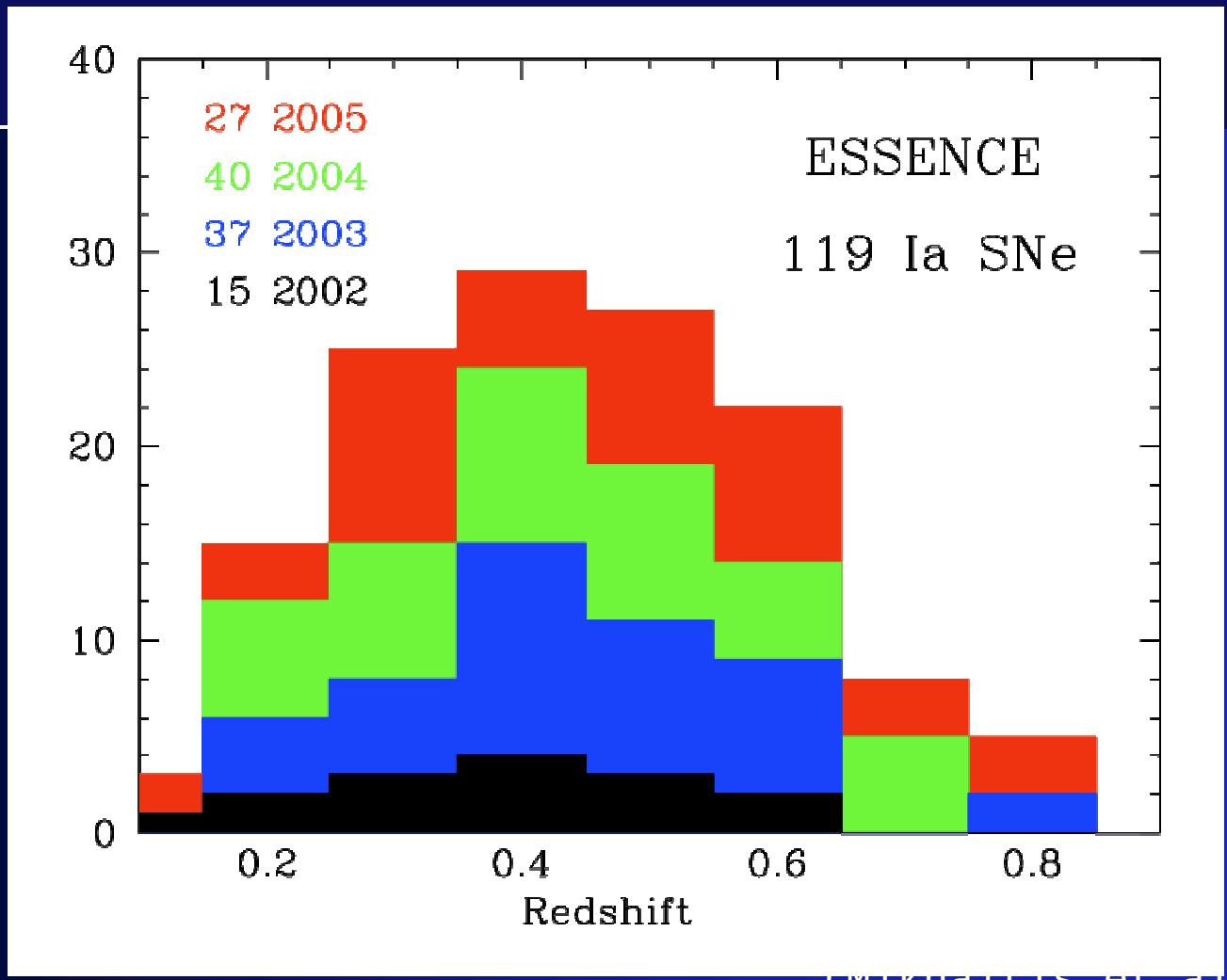
z = 0.61



Jose Luis Prieto

z = 0.82

ESSENCE SNe Ia To Date



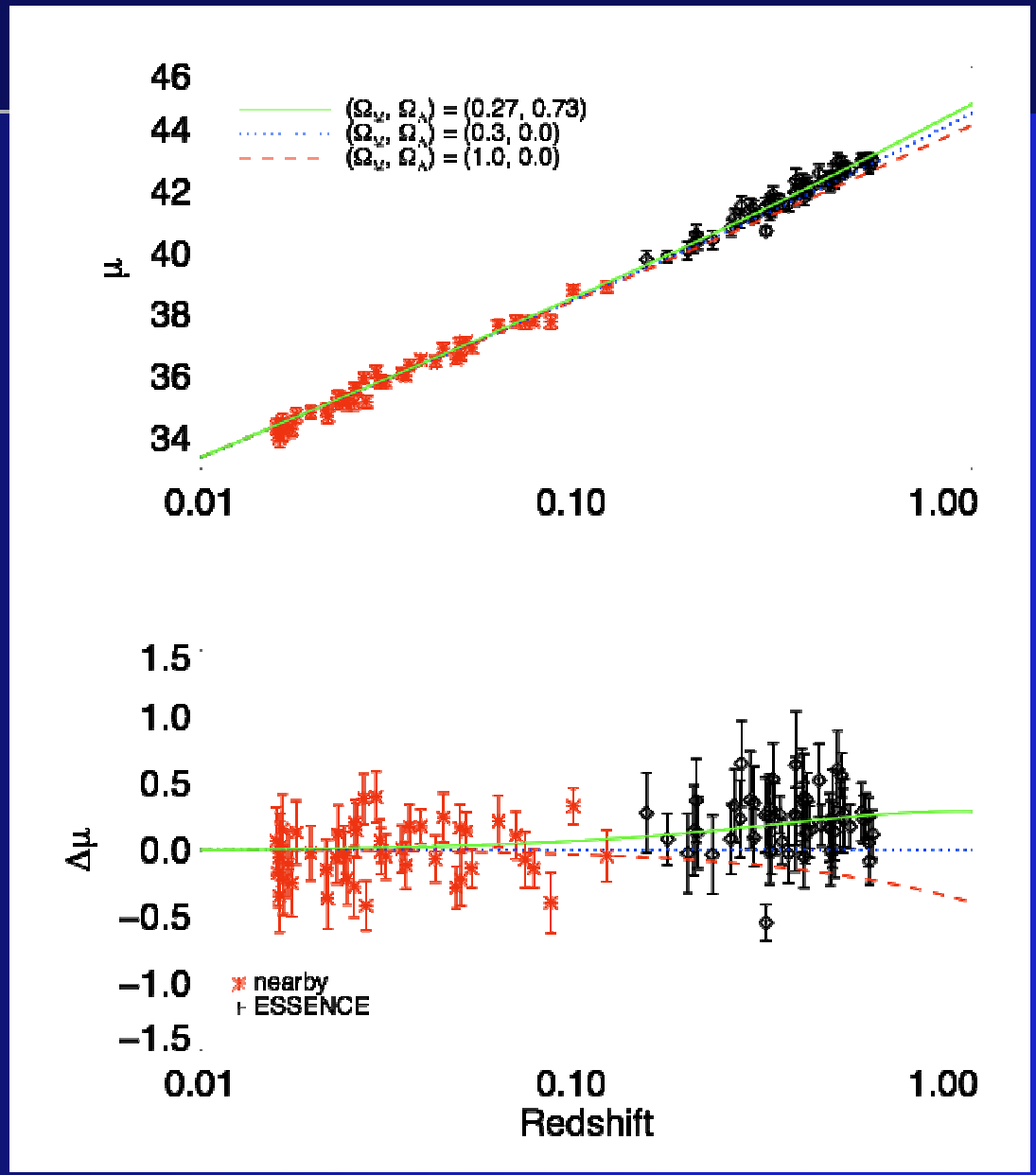
(Mikhailis et al., submitted to ApJ)

And just finishing up 2006 season with >50!

ESSENCE Hubble Diagram

Wood-Vasey et al., submitted to ApJ

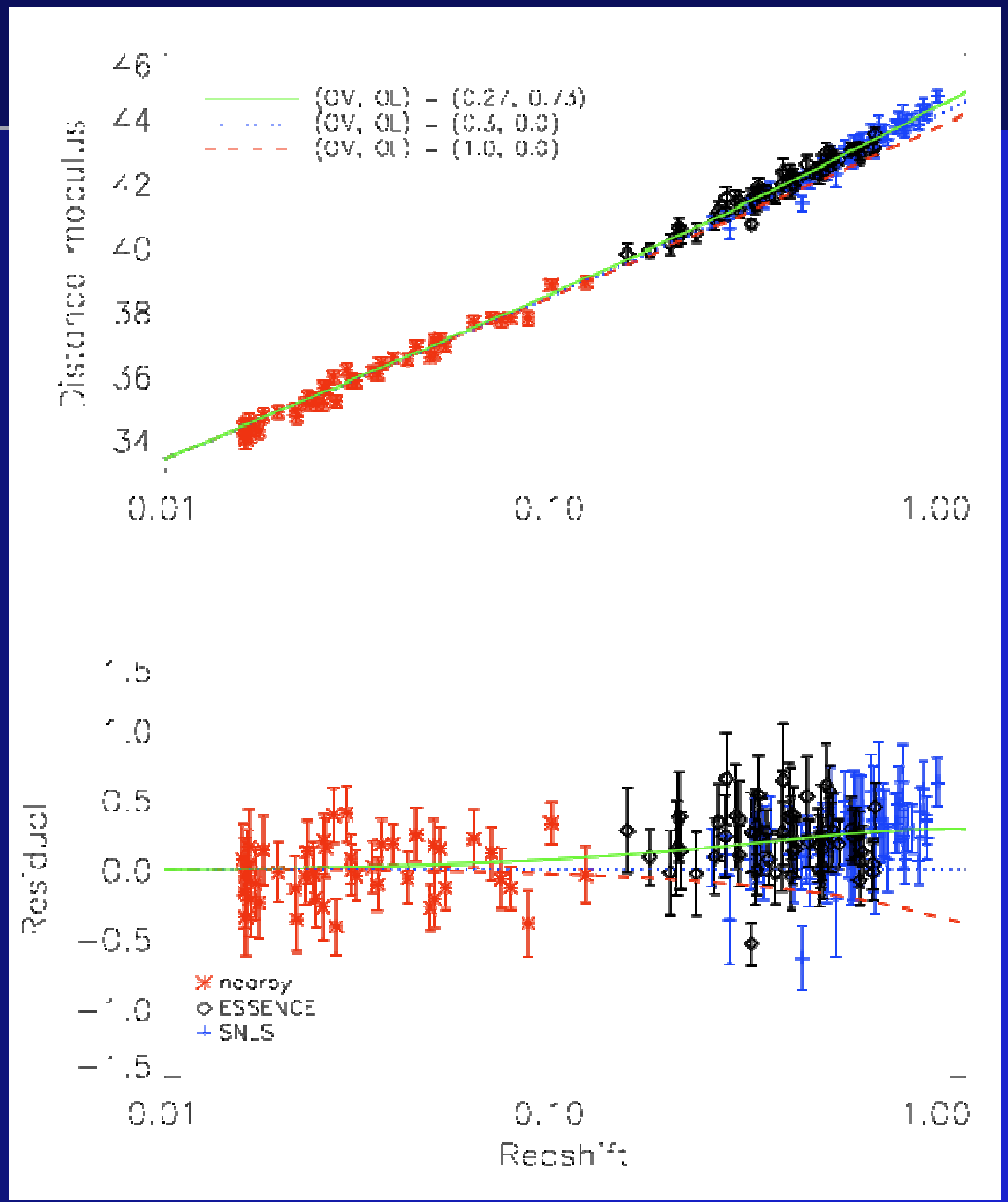
see also
Hamuy 1996, AJ
Riess 1999, AJ
Jha 2006, AJ

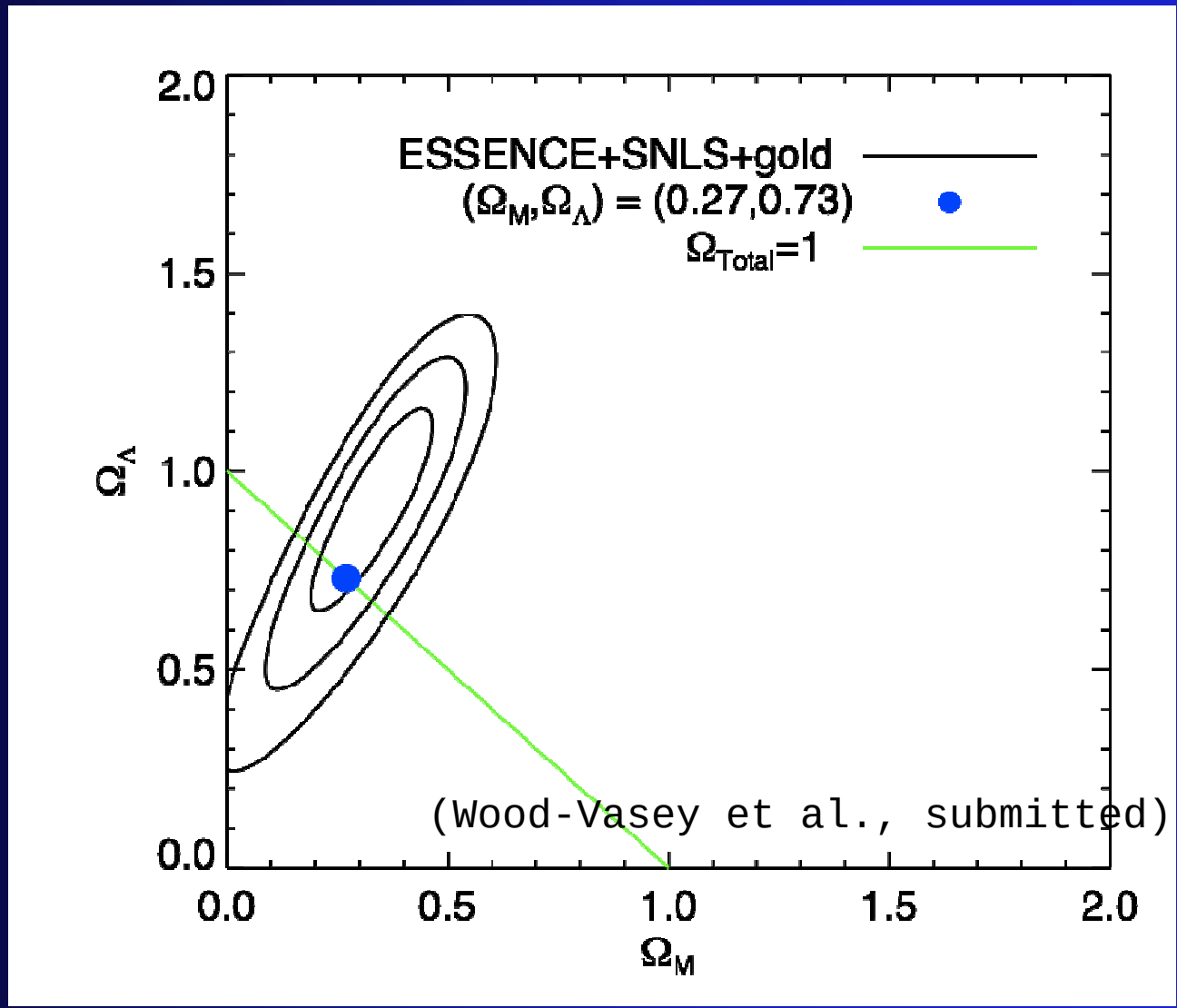


ESSENCE+SNLS Hubble Diagram

Wood-Vasey et al., submitted to ApJ

see also
Astier 2006, A&A
Hamuy 1996, AJ
Riess 1999, AJ
Jha 2006, AJ

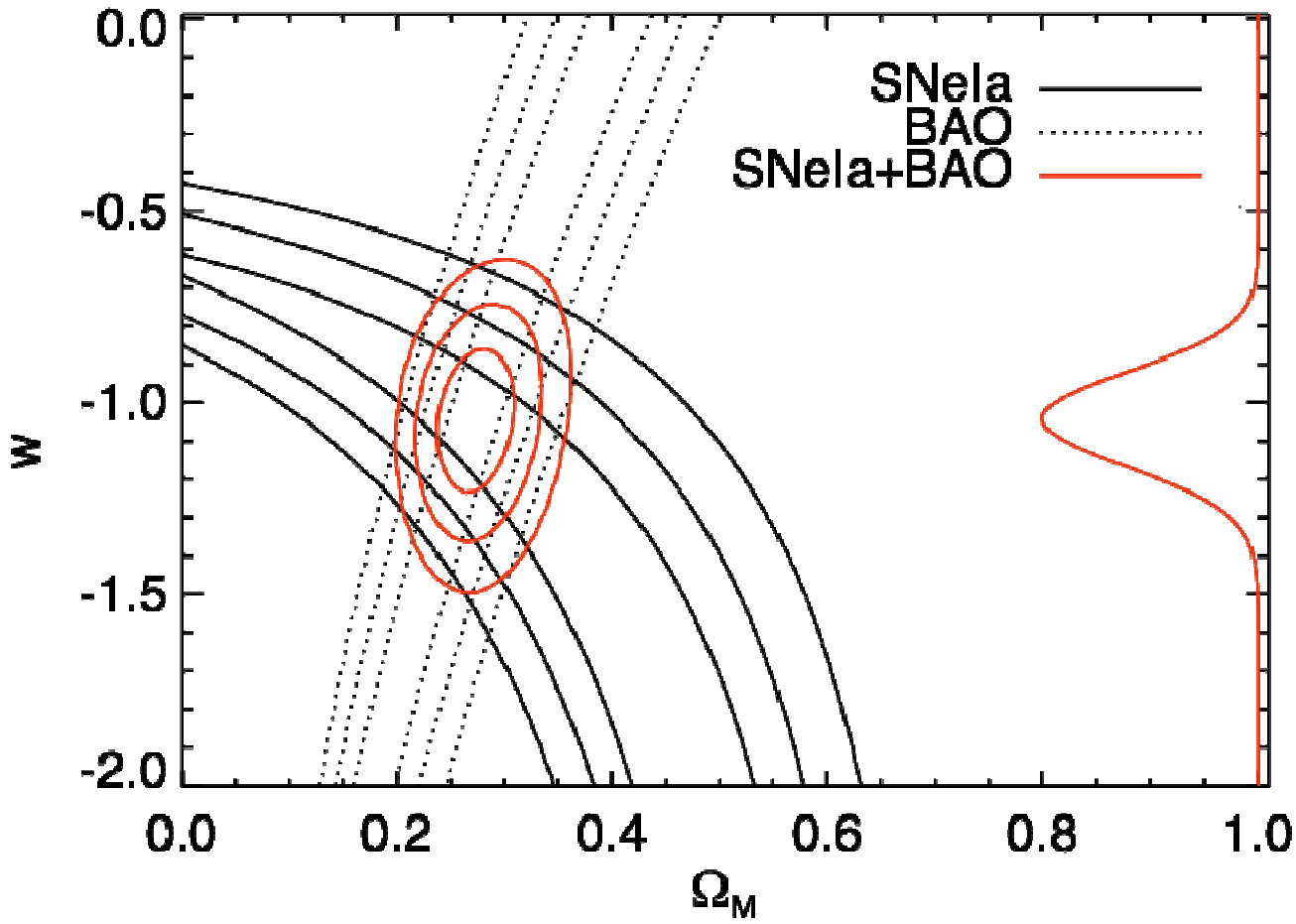




(see also Tonry03, Knop03, Riess04, Astier06)

ESSENCE SNe Only

w=-1.05 +- 0.11 +- 0.

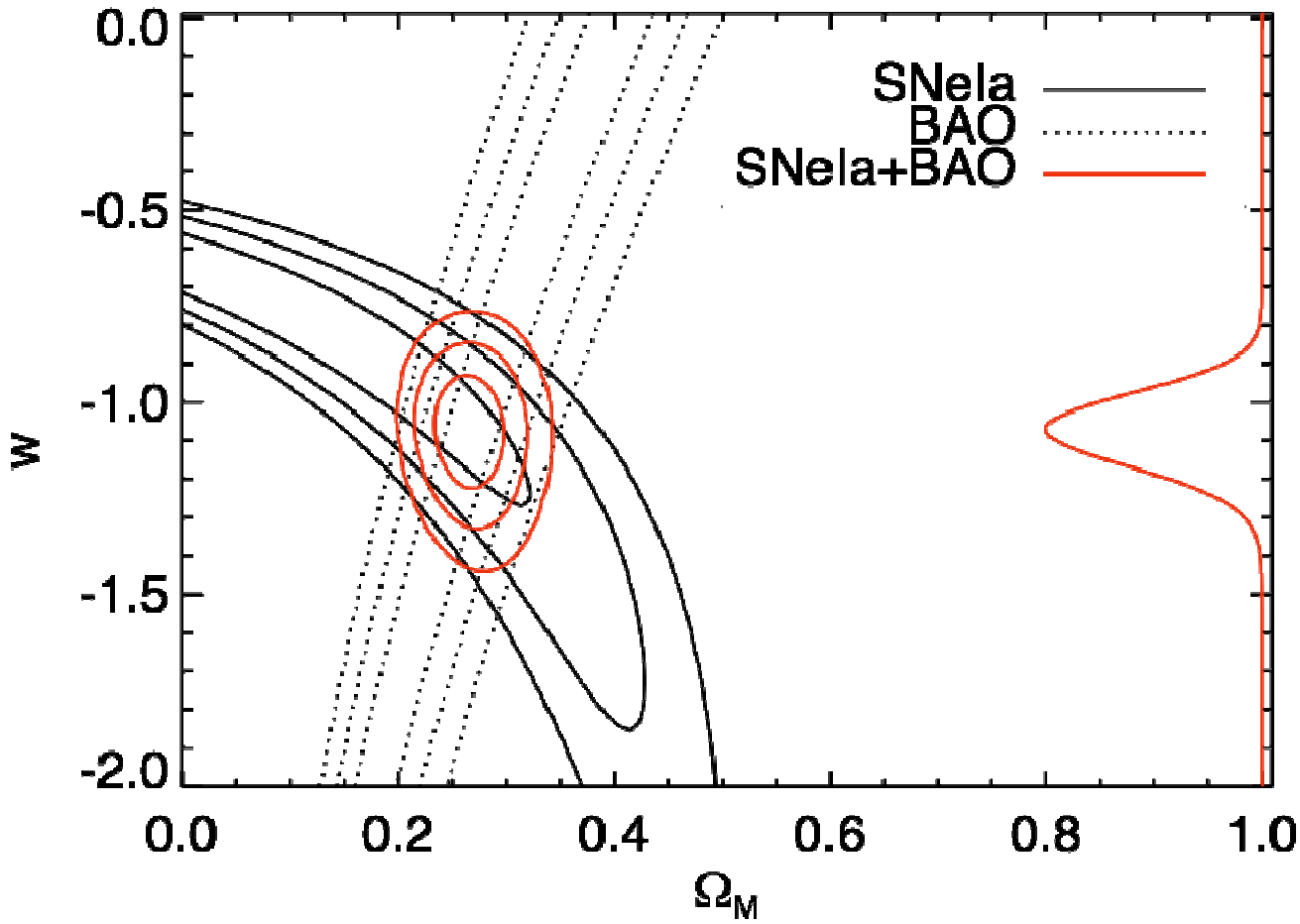


Assuming flat, isotropic, constant-w universe

(Wood-Vasey et al., submitted to ApJ)

ESSENCE + SNLS

w= -1.07 +- 0.09 +- 0.1



Assuming flat, isotropic, constant-w universe

(Wood-Vasey et al., submitted to ApJ)

Next Steps?

- DOE/NASA/NSF review options
  - Dark Energy Task Force Report

To dat … the
absenc … cus of our
efforts …

II. We recommend that the dark energy program have multiple techniques at every stage, at least one of which is a probe sensitive to the growth of cosmological structure in the form of galaxies and clusters of galaxies.

III. We recommend that the dark energy program include a combination of techniques from one or more Stage III projects designed to achieve, in combination, at least a factor of three gain over Stage II in the DETF figure of merit, based on critical appraisals of likely statistical and systematic uncertainties.

IV. We recommend that the dark energy program include a combination of techniques from one or more Stage IV projects designed to achieve, in combination, at least a factor of ten gain over Stage II in the DETF figure of merit, based on critical appraisals of likely statistical and systematic uncertainties. Because JDEM, LST, and SKA all offer promising avenues to greatly improved understanding of dark energy, we recommend continued research and development investments to optimize the programs and to address remaining technical questions and systematic-error risks.

Stage III: Dark Energy Survey

- Investigate Dark Energy using 4 complementary and independent methods
  - Galaxy Clusters
  - Baryon Acoustic Oscillations (BAO)
  - Weak Gravitational Lensing
  - Supernovae
- Combine the results to provide the best (to date) constraints on physics of Dark Energy
- Proposed plan: 5 year survey, 30% time, 2010-2015

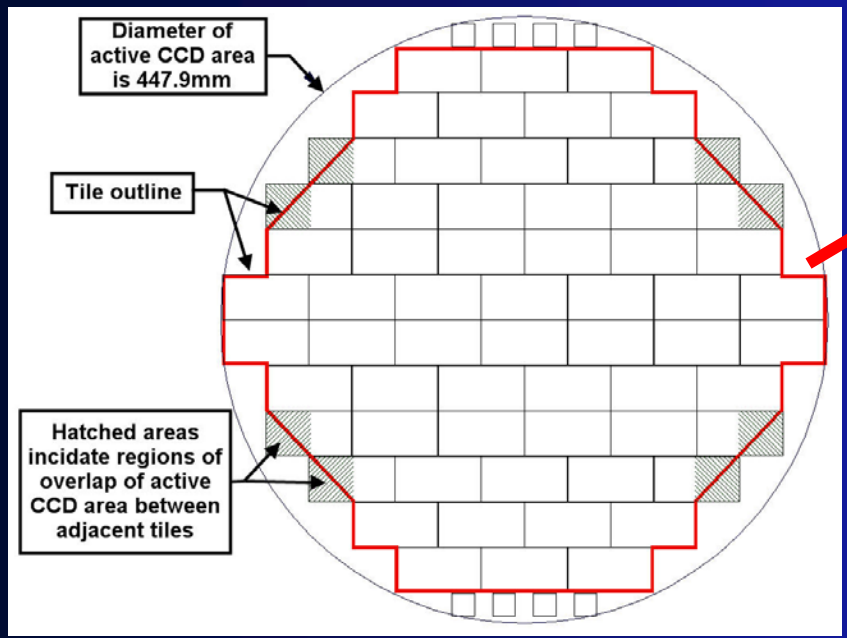
- Need new instrument for this experiment!
  - Dark Energy Camera (DECam) to go to the CTIO 4m

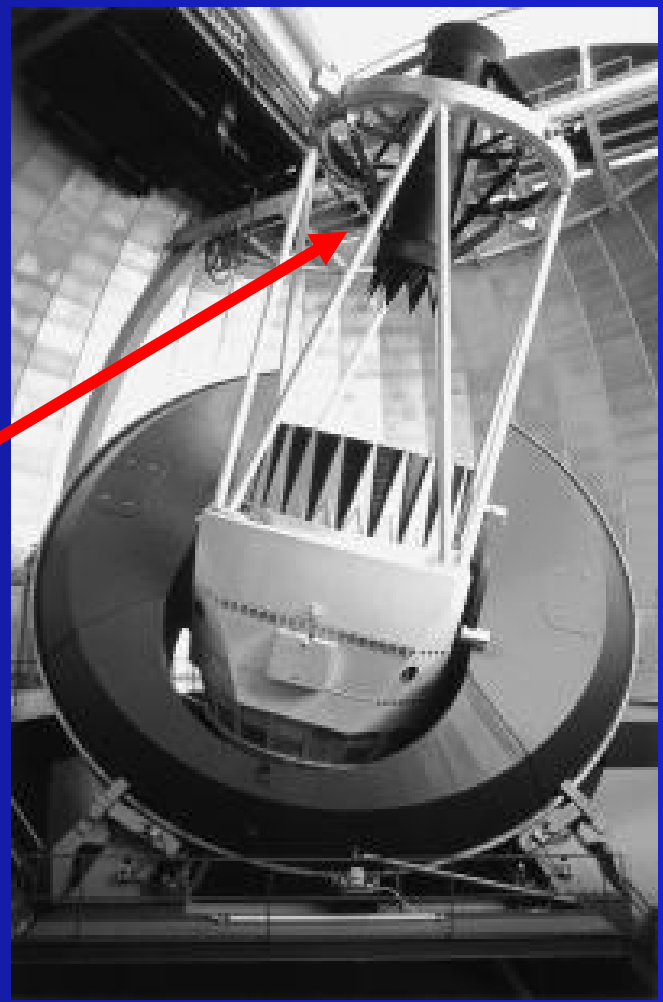
The Instrument: Dark Energy Camera

DARK ENERGY SURVEY

Focal Plane:

- 64 2k x 4k CCDs
  - Plus guiding and WFS
- 0.5 GIGApixel camera



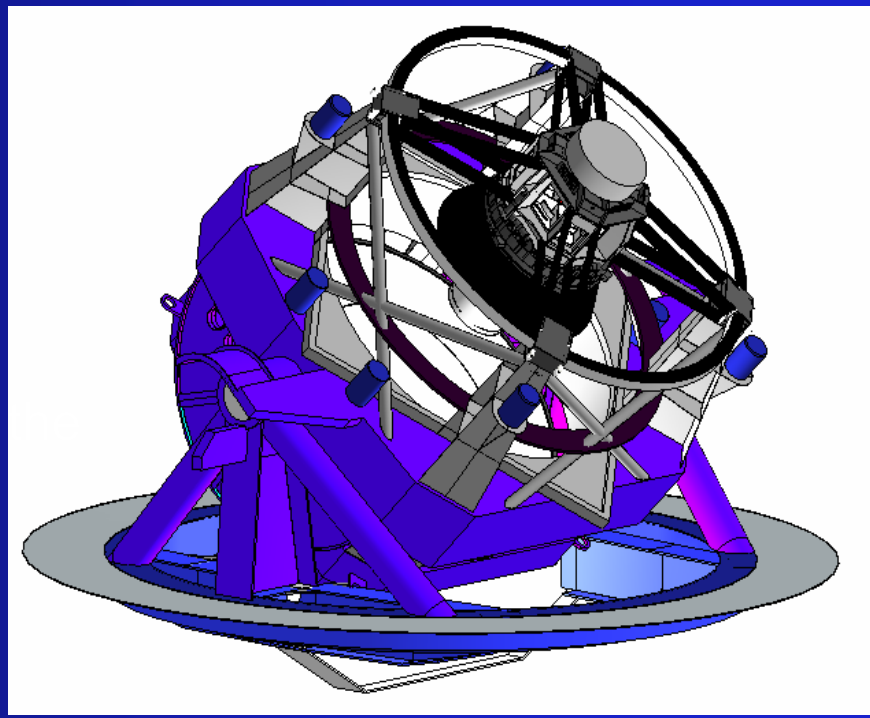


The Plan: Dark Energy Survey

- The Observations
  - A wide-field survey covering 5000 deg^2 in griz,
    - overlapping the 4000 deg^2 of South Pole Telescope SZ survey
    - Covers clusters, weak lensing, and BAO
  - A SN survey covering roughly 9 deg^2 in riz
    - Over 1000 Type Ia SNe to redshift z~1
- The Data
  - Total raw data after 5 yrs ~0.2 PB
  - TOTAL Dataset 1 to 5 PB
    - Reprocessing planned using TeraGrid resources
- Predicted results:
  - improved DE constraints on both *w* (to better than 8%) and *w'* (better than 27%)
  - Exploration of systematics for Stage IV experiments

Stage IV: LSST

- A facility to survey the sky
  Deep, Wide, and Fast
  - *8.2m telescope*
  - *3.5 degree field of view (diameter)*
  - *3.2 GIGApixel camera*
  - *2x15s images per field*
- Allows a broad range of science from **same** multi-wavelength survey data
- Precise control of systematics
- Rapid, public release of data



LSST Science Requirements Document: the Core Science

- Constraining Dark Energy and Dark Matter: multi-pronged approach
  - Weak lensing of galaxies as a function of redshift (cosmic shear)
  - Baryon Acoustic Oscillations
  - Distribution of dark matter clusters
  - Type Ia supernovae as “standardizable” candles
- Taking of Inventory of the Solar System
  - Potentially Hazardous Asteroids (PHAs)
  - Trans-Neptunian Objects & KBOs
- Exploring the Transient Optical Sky
  - Explosive events (GRBs, SNe, Novae, etc.)
  - Variables (RR Lyrae, Cephieds, etc.)
- Mapping the Milky Way
  - Proper motions & astrometric maps: Stellar Kinematics
  - Photometric maps: the Halo and Galactic streams

LSST Survey Overview

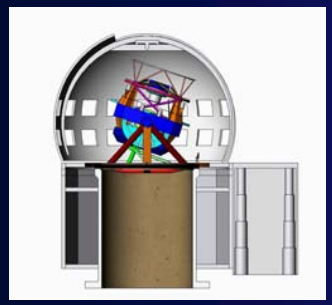
- 6-band survey: ugrizy covering 320-1050 nm
  - Frequent revisits in grizy
- Sky Area covered: >20,000 deg^2
  - 0.2 arcsec/pixel
- Each 10 deg^2 FOV revisited ~2000 times
- Limiting magnitudes
  - >27th AB magnitude @ 5σ
  - >24th AB magnitude per visit (2x15s exposures)
- Photometric precision: 0.01 mag (1%) requirement,
  - 0.001 goal
- Astrometric precision: 10 milliarcsec
  - for sources r < 22 or better

Massively Parallel Astrophysics

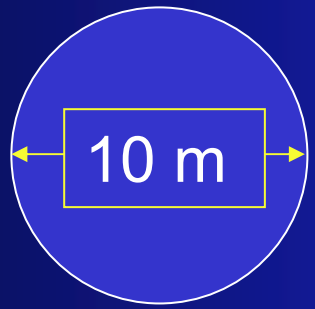
- Dark matter/dark energy via weak lensing
- Dark matter/dark energy via baryon acoustic oscillations
- Dark energy via supernovae
- Dark energy via distribution of mass peaks
- Galactic Structure encompassing local group
- Dense astrometry over 20000 sq.deg: rare moving objects
- Gamma Ray Bursts and transients to high redshift
- Gravitational micro-lensing
- Strong galaxy & cluster lensing: physics of dark matter
- Multi-image lensed SN time delays: separate test of cosmology
- Variable stars/galaxies: black hole accretion
- QSO time delays vs z: independent test of dark energy
- Optical bursters to 25 mag
- 5-band 27 mag photometric survey: unprecedented volume
- Solar System Probes: Earth-crossing asteroids, Comets, trans-Neptunian objects
- ***The unknown… in time domain and in static sky at 27th mag***

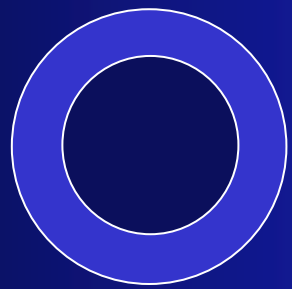
LSST: Deep, Wide, Fast

Keck Telescope



LSST

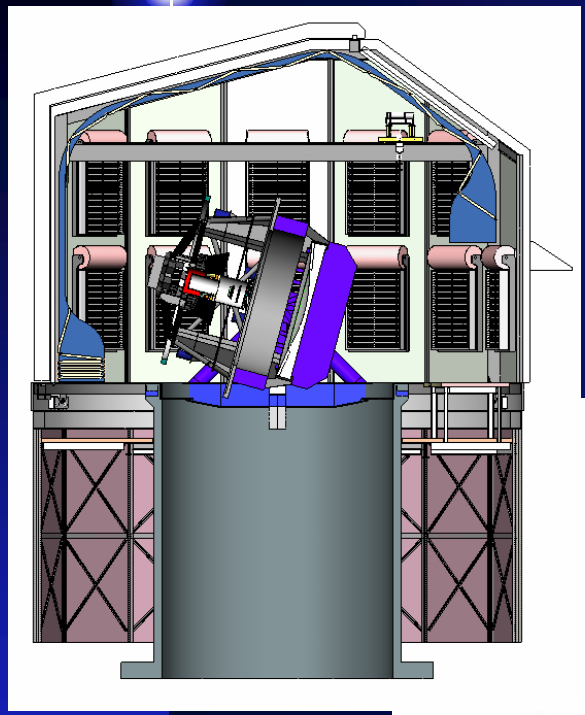




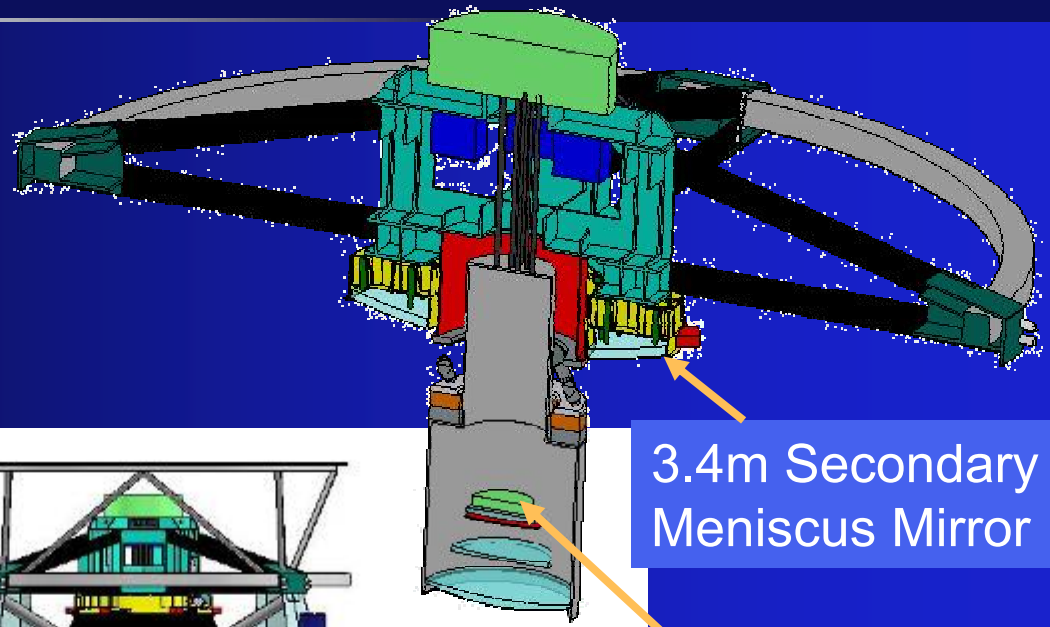
Field of view (FOV)

0.2 degrees

The Telescope

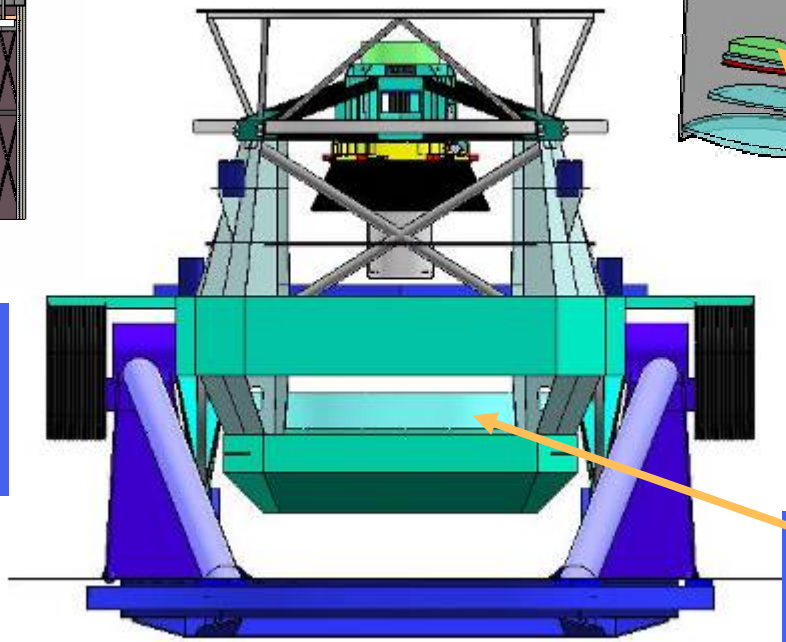


Alt-az configuration, 3-mirror design to achieve wide field



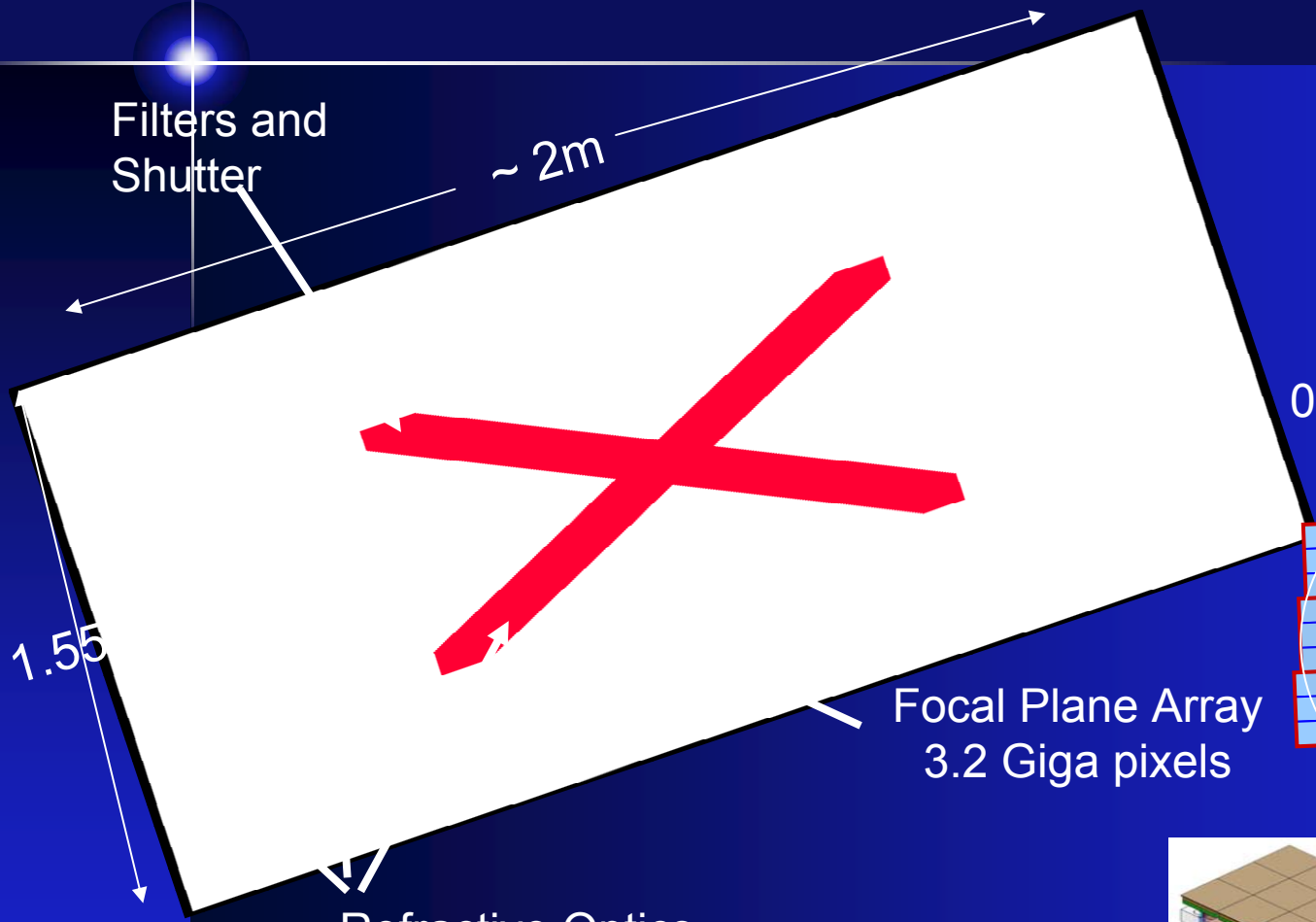
3.4m Secondary Meniscus Mirror

3.5° Camera



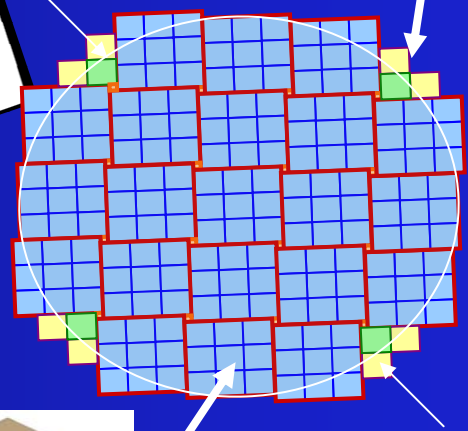
8.4m Primary-Tertiary Monolithic Mirror

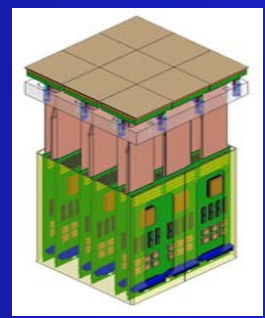
LSST Camera & Focal Plane



Wavefront Sensors and Fast Guide Sensors

0.634m Diameter





"Raft" of nine 4kx4k CCDs.

LSST Site in Northern Chile

LSST: Distributed Data Management

Long-Haul Communications
Data transport & distribution

Archive/Data Access Centers
Data processing, long term storage, & public access

Base Facility
Real time processing

Mountain Site
data acquisition, temp. storage

LSST: The Data Flow

- Each image roughly 6.5 GB
- Cad[illegible]
- 15 t[illegible]
  - [illegible] data center”
  - [illegible] timescale (15s), ~10-20Gbps
  - [illegible] within <24 hours, >2-10Gbps
- R[illegible]ME reduction, analysis, &
  - Send out ale[illegible]
  - Provide aut[illegible]
  - Processed [illegible]
- Just catalogs

All Data Public

All Alerts Public

DES, LSST, … and now for the REST of the Science

- Ongoing (ESSENCE, SuperMACHO, etc.) and future (DES, LSST, etc.) projects will provide PETABYTES of archived data
- Only a small fraction of the science potential will be realized by the planned investigations
- How do we maximize the investment in these datasets and provide for their future scientific use?
- How do we enable the “massively parallel astrophysics” experiments?

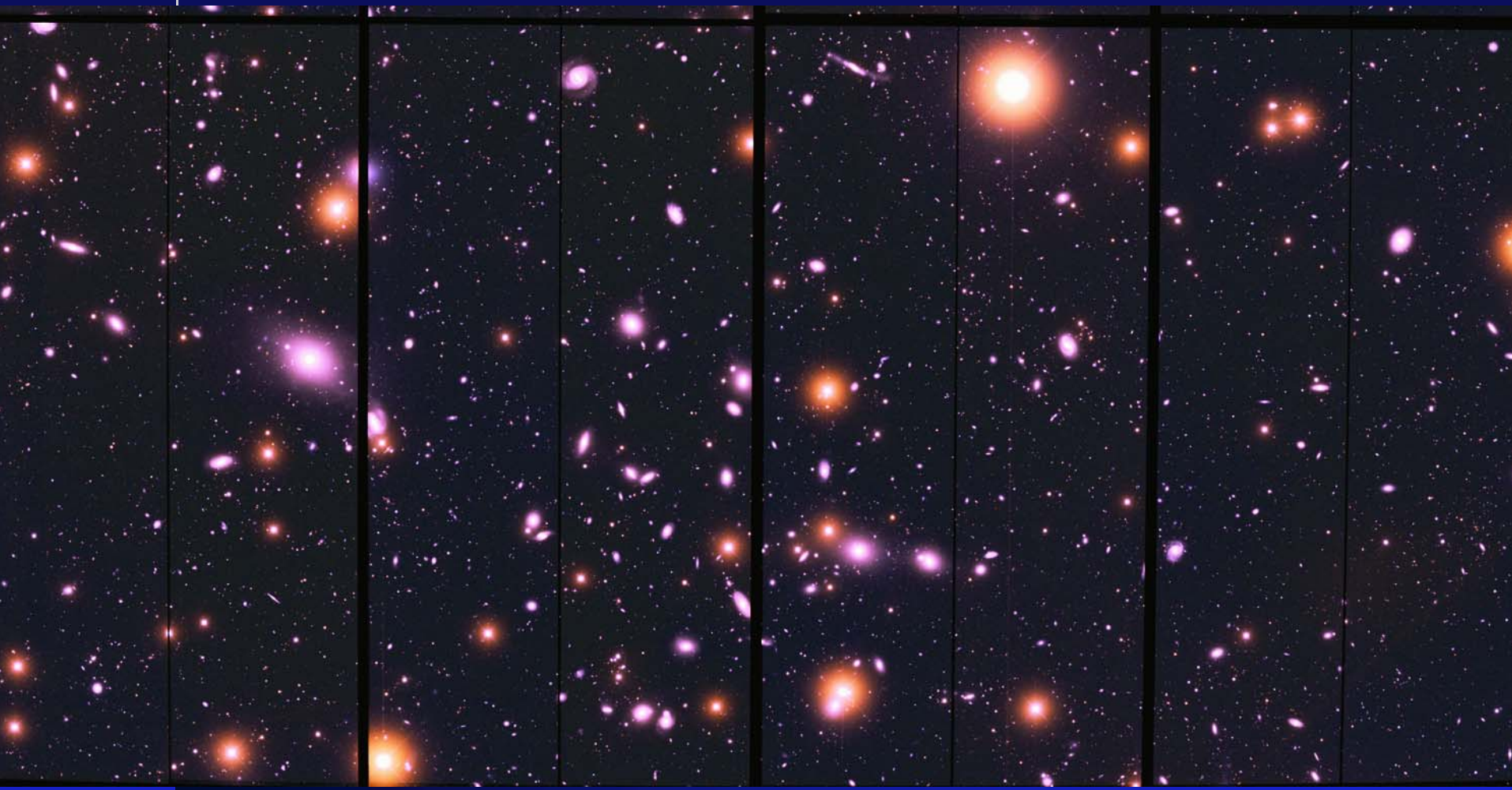
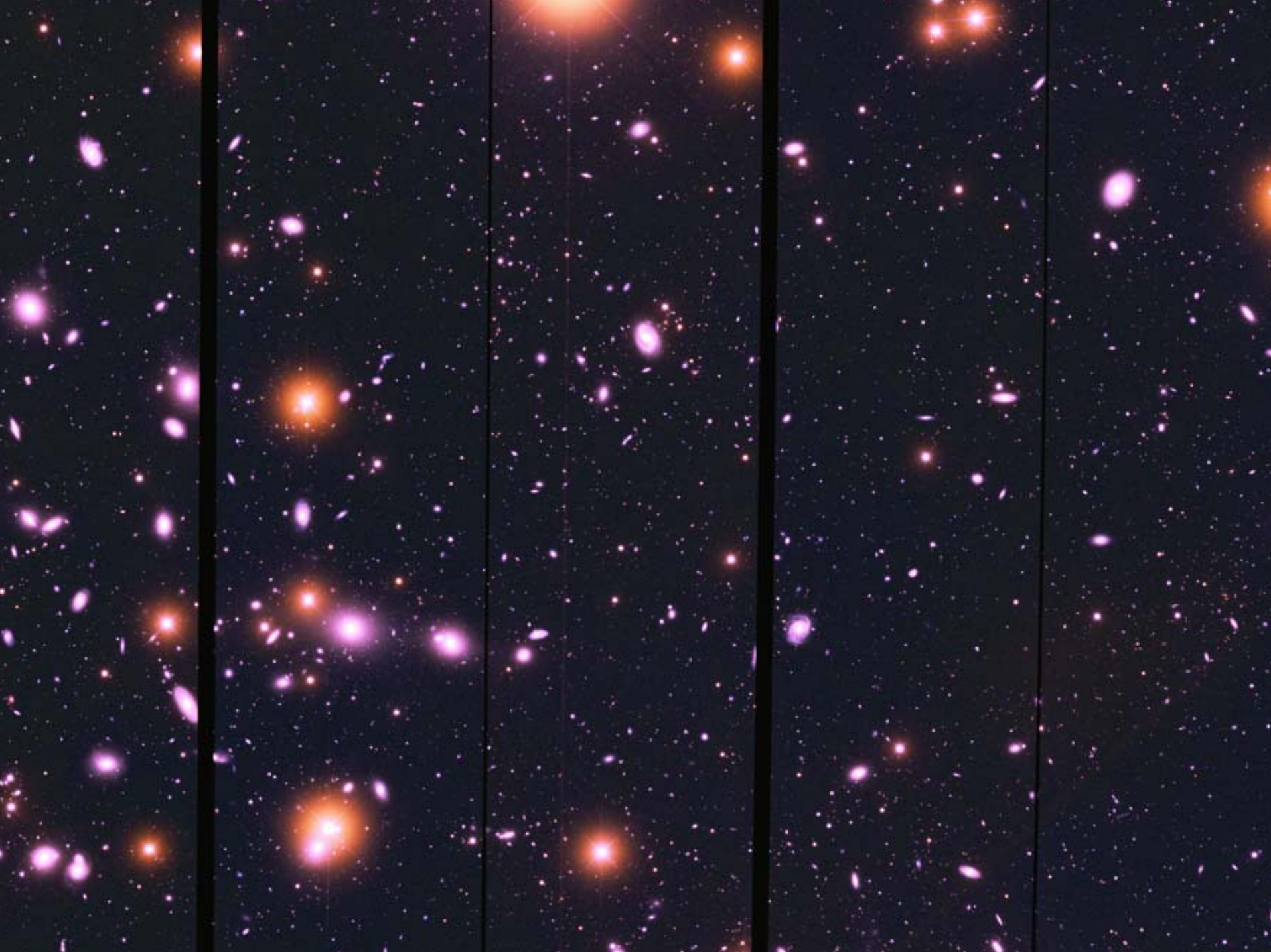
The Virtual Observatory

- What is VO?
  - Provides the framework for global access to the various data archives by facilitating the standardization of archiving and data-mining protocols.
  - Enables data analysis by providing common standards and state-of-the-art analysis tools which work over high-speed wide area networks
- What is VO not?
  - An organization funded to provide a single universal archive of all astronomical data
  - A provider of resources (storage, computation, bandwidth)

VO: A Global Effort

VO Challenges

- Provide Access to the Content
  - Multiple distributed archives, some on the scale of many petabytes
  - Archives provide content, the VO knits those resources together
- Provide the Standards
  - Allow variety of archives talk to each other
  - Develop generalized data model(s) for different instruments/different wavelengths

VO Challenges

- Provide the User Interfaces
  - Streamline data discovery, data understanding, data movement, and data analysis
- Support the Analysis
  - Support large queries across distributed DBs
  - Support statistical analysis across results (Grid)
- All the “boring” bits (infrastructure)
  - Security, handshaking, resource management