Probing Dark Energy

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Fermilab

Discovering the Nature of Nature

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AT THE UNIVERSITY OF CHICAGO

Dark Energy and the Accelerating Universe

Brightness of distant Type Ia supernovae, along with CMB and galaxy clustering data, indicates the expansion of the Universe is accelerating, not decelerating.

This requires *either* a new form of stress-energy with <u>negative effective pressure</u> *or* a breakdown of General Relativity at large distances:

DARK ENERGY

Characterize by its effective equation of state: $w(z) = p/\rho < -1/3$

and its relative contribution to the present density of the Universe: Ω_{DE}

Special case: cosmological constant: $w = -1$

Probing Dark Energy

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

$$H^2(z) = H^2_0 \; [\Omega_M (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)}]$$ (flat Universe)

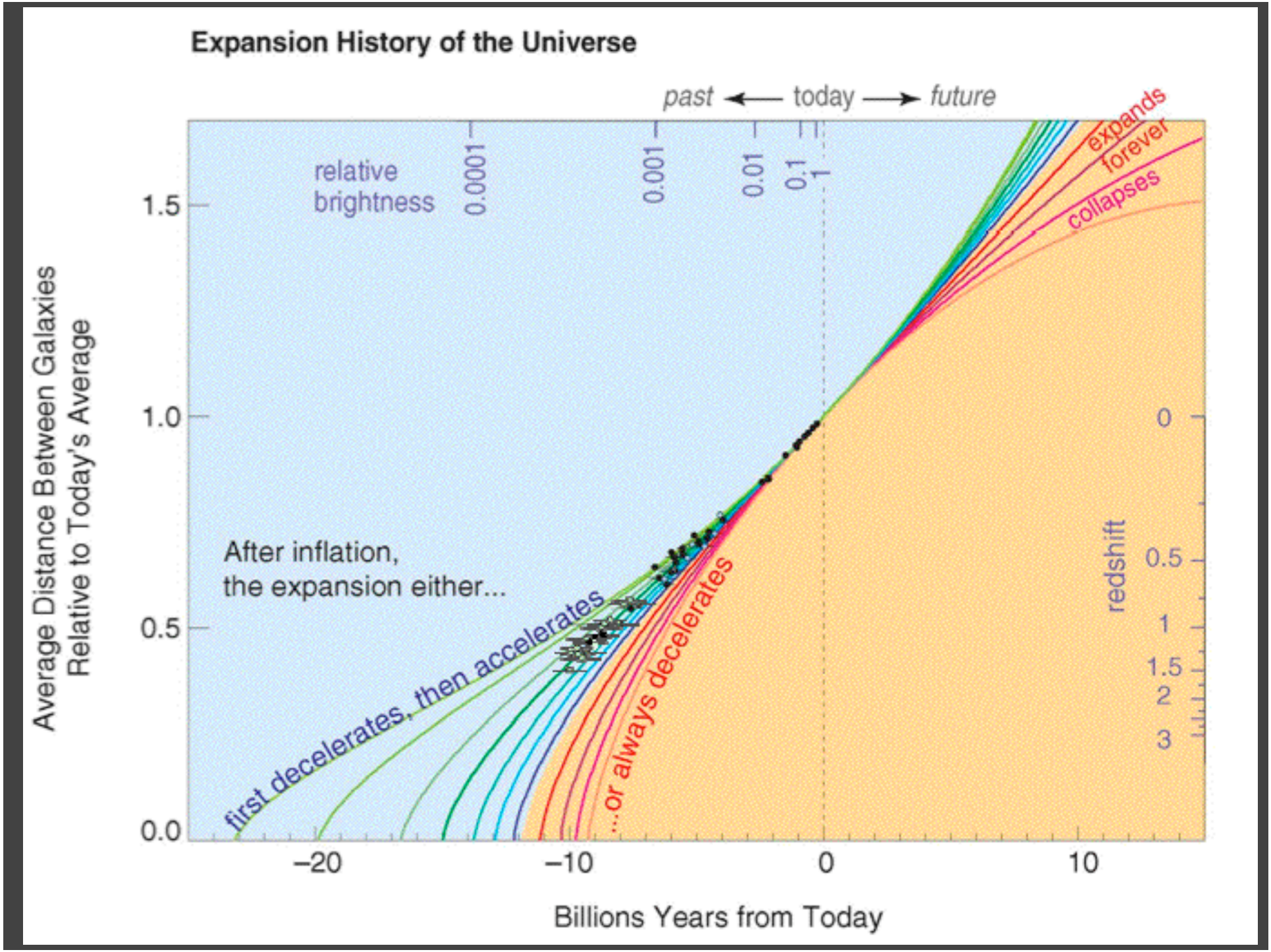
matter dark energy (constant w)

Geometric tests:

- Comoving distance $r(z) = \int dz/H(z)$
- Standard Candles $d_L(z) = (1+z)\, r(z)$
- Standard Rulers $d_A(z) = (1+z)^{-1}\, r(z)$
- Standard Population (volume) $dV/dz d\Omega = r^2(z)/H(z)$

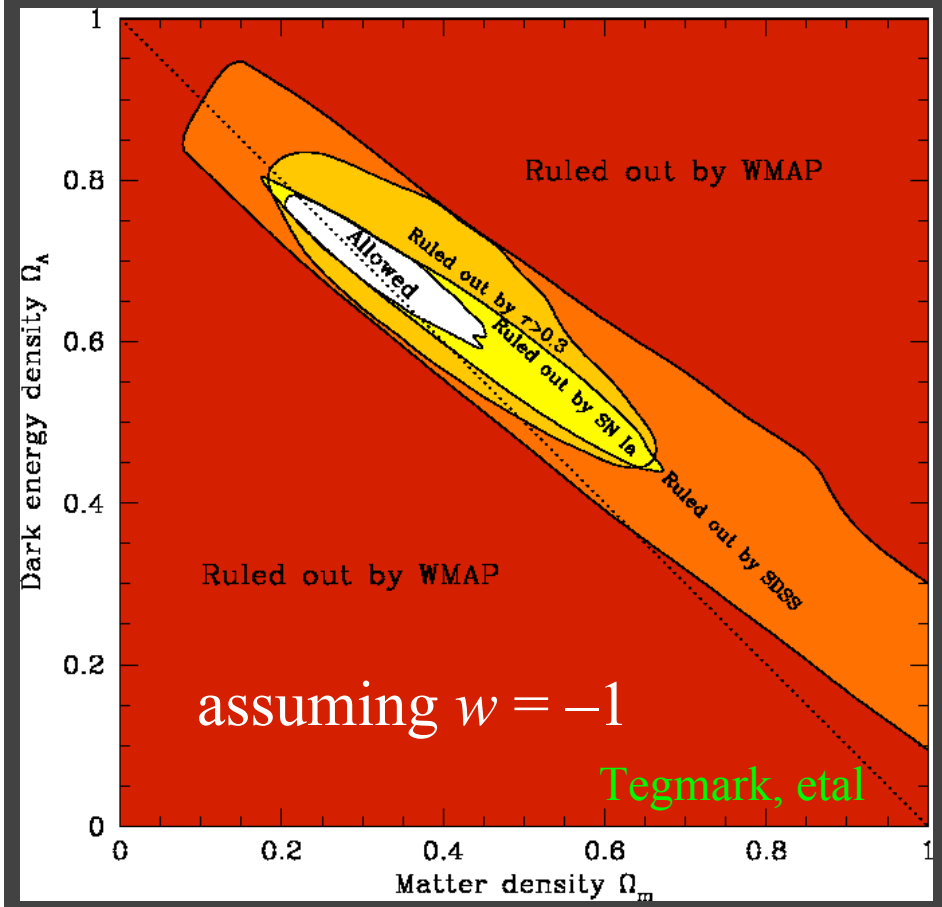
Structure based-tests:

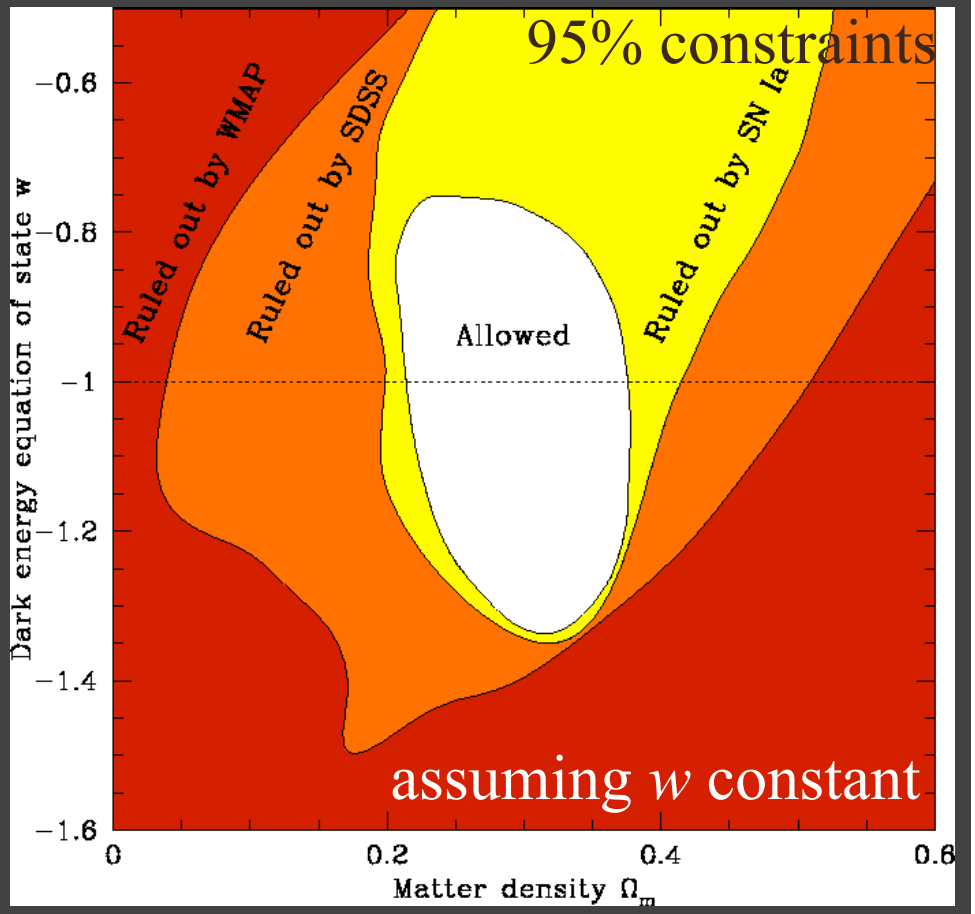
- The rate of growth of structure determined by H(z), by any modifications of gravity on large scales, and by other cosmological parameters


Expansion History of the Universe
past
today
future
relative brightness
0.0001
0.001
0.01
0.1
1
expands forever
collapses
After inflation, the expansion either...
first decelerates, then accelerates
...or always decelerates
redshift
0
0.5
1
1.5
2
3
1.5
1.0
0.5
0.0
−20
−10
0
10
Average Distance Between Galaxies Relative to Today's Average
Billions Years from Today

Dark Energy Constraints

$\sigma(w) \sim 0.15^*$, $w < -0.76$ (95%) with priors





<u>Key priors:</u> scale-free spectrum, no gravity waves, massless neutrinos, const. bias

Additional prior: flat Universe

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

Dark Energy: Stress Energy vs. Modified Gravity

Stress-Energy: $G_{\mu\nu} = 8\pi G\,[T_{\mu\nu}(\text{matter}) + T_{\mu\nu}(\text{dark energy})]$

Gravity: $G_{\mu\nu} + f(g_{\mu\nu}) = 8\pi G\, T_{\mu\nu}(\text{matter})$

Key Questions:

1. Is DE observationally distinguishable from a cosmological constant, for which $T_{\mu\nu}$ (vacuum) = $\Lambda g_{\mu\nu}/3$? Measure *w;* what precision is needed?
2. Can we distinguish between gravity and stress-energy?
3. If $w \neq -1$, it likely evolves: how well can/must we measure dw/da to make progress in fundamental physics?

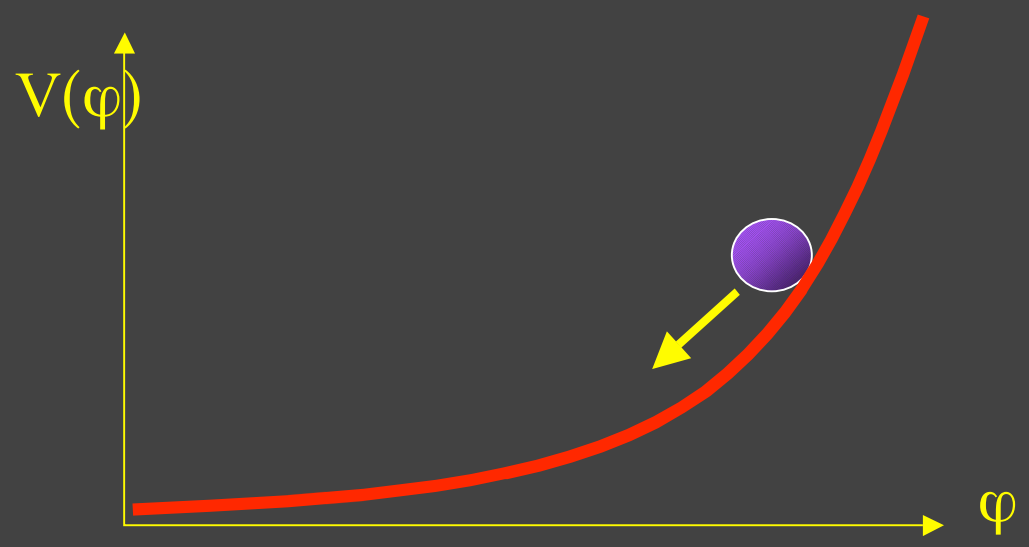
Scalar Field Dark Energy

- If Dark Energy is due to a scalar field, φ, evolving in a potential, V(φ):

$$\ddot{\varphi} + 3H\dot{\varphi} = -V'$$

- Density & pressure:

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



slide: A. Taylor

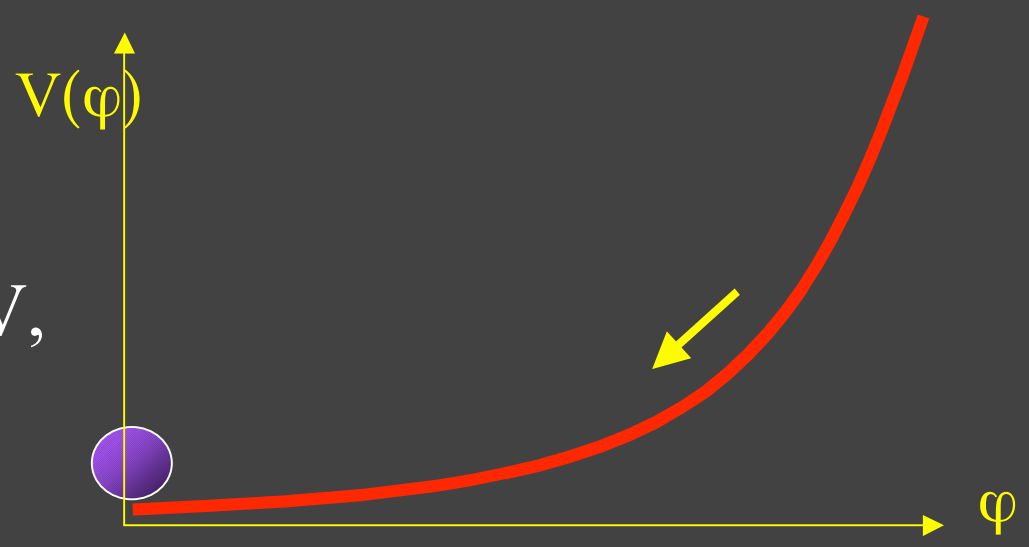
Dark Energy Dynamics

- Slow-roll: $3H\dot{\varphi} = -V'$
- Slow-roll parameter: $\varepsilon = \frac{\dot{\varphi}^2}{2V} \approx \frac{\Omega_V}{48\pi G}\left(\frac{V'}{V}\right)^2$
- Equation of State:

$$w \approx -1 + 2\varepsilon$$

- w measures slope of V, over a range

$$\Delta\varphi \approx \frac{\sqrt{\varepsilon}}{4} \approx 0.025 m_{PL}$$



Scalar Field Dark Energy

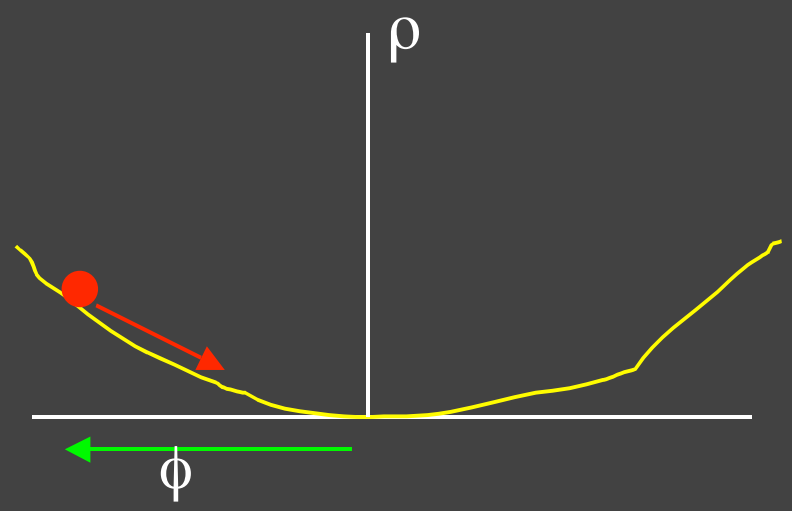
aka quintessence

General features:

$m_{eff} < 3H_0 \sim 10^{-33}$ eV ($w < 0$)
(Potential vs. Kinetic Energy:
`Slow roll' condition)

$\rho \sim m^2\phi^2 \sim \rho_{crit} \sim 10^{-10}$ eV^4

--> $\phi \sim 10^{28}$ eV $\sim M_{planck}$



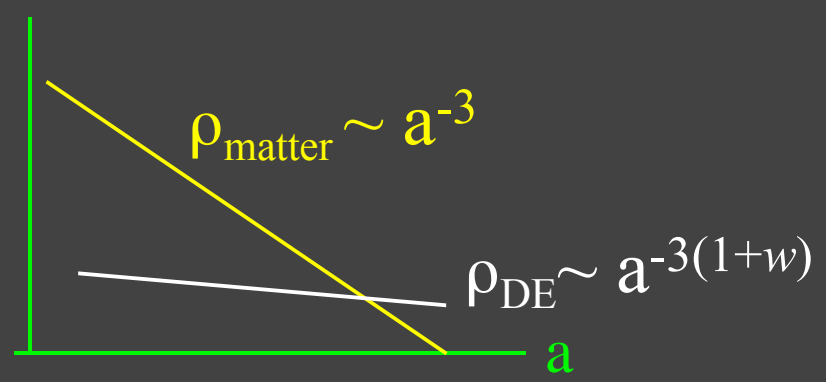
Ultra-light particle: Dark Energy hardly clusters, nearly smooth
Equation of state: usually, $w > -1$ and evolves in time
Hierarchy problem: Why $m/\phi \sim 10^{-61}$?
Weak coupling: Quartic coupling $\lambda < 10^{-122}$

The Cosmic Problems

Cosmological constant problem: why is the vacuum energy density at least 60-120 orders of magnitude smaller than expected? This problem predates DE.

$$\rho_{vac} = \Lambda/8\pi G = \pm(1/V)\,\Sigma\, h\omega/2 \sim \int^{M} h(k^2+m^2)^{1/2}\, d^3k \sim M^4 >> (.003\ \mathrm{eV})^4$$

Coincidence problem: why do we live at the `special' epoch when the dark energy density is comparable to the matter energy density?



Dark Energy & Inflation

Imagine you were living ~ 1 Hubble time after the onset of primordial inflation, at $t \sim 10^{-35}$ sec

(How) would you worry about the coincidence problem?

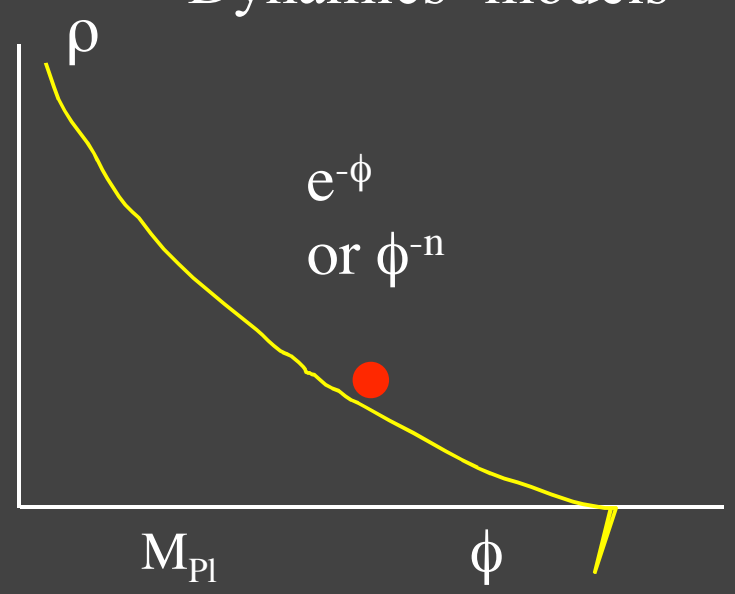
Inflation suggests existence of a new mass scale $M_{GUT} \sim 10^{15}$ GeV where we <u>expected</u> new physics of Unification, addresses early U. coincidence problem.

Does Dark Energy indicate a new mass scale in physics? $M_{VAC} \sim 10^{-3}$ eV

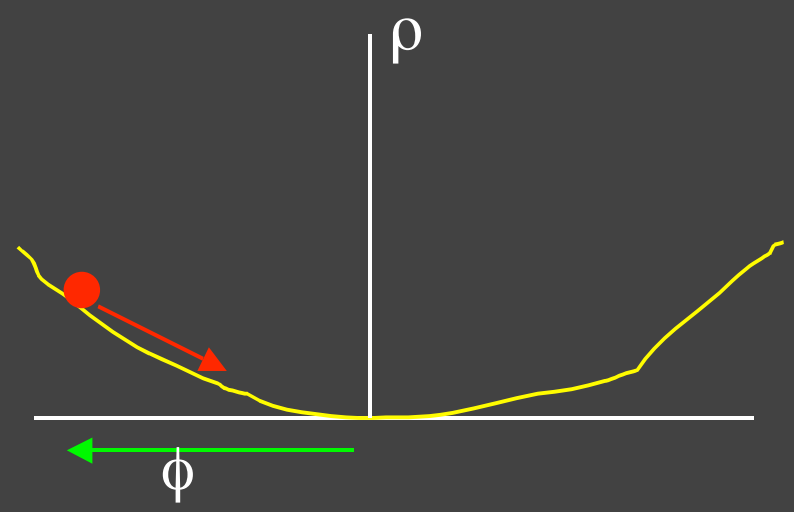
Alternative: dynamics, not mass scale.

Dynamical Scalar Field Models

`Dynamics' models



`Mass scale' models



Runaway potentials

DE/matter ratio constant (Tracker Solution) but coincidence and hierarchy problems remain

Ratra & Peebles, Caldwell, etal, Albrecht etal,…

Pseudo-Nambu Goldstone Boson:

Low mass protected by symmetry (ala axion)

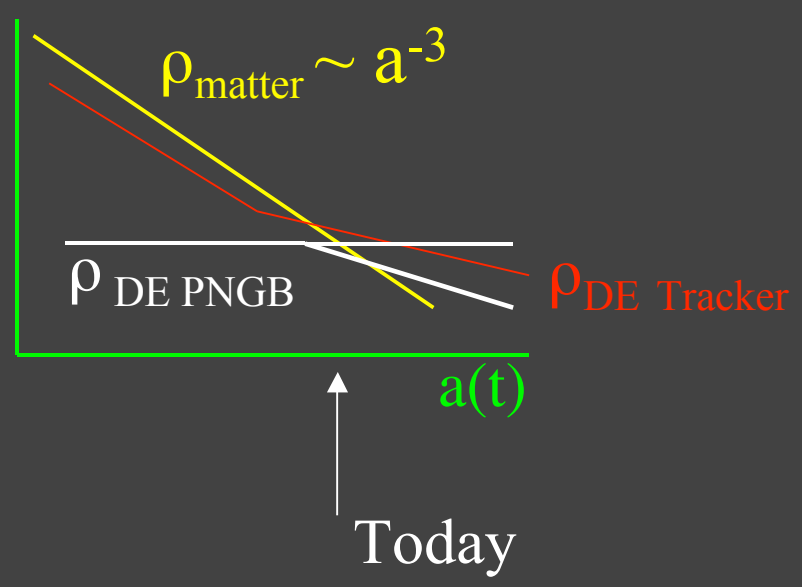
JF, etal

$$V(\phi) = M^4[1+\cos(\phi/f)]$$

$f \sim M_{planck}$ $\quad$ $M \sim 0.001$ eV

Second DE Coincidence Problem: is $w \neq -1$ natural?

If $w \neq -1$, why is the scalar field dynamics changing just around the time it begins to dominate the Universe?

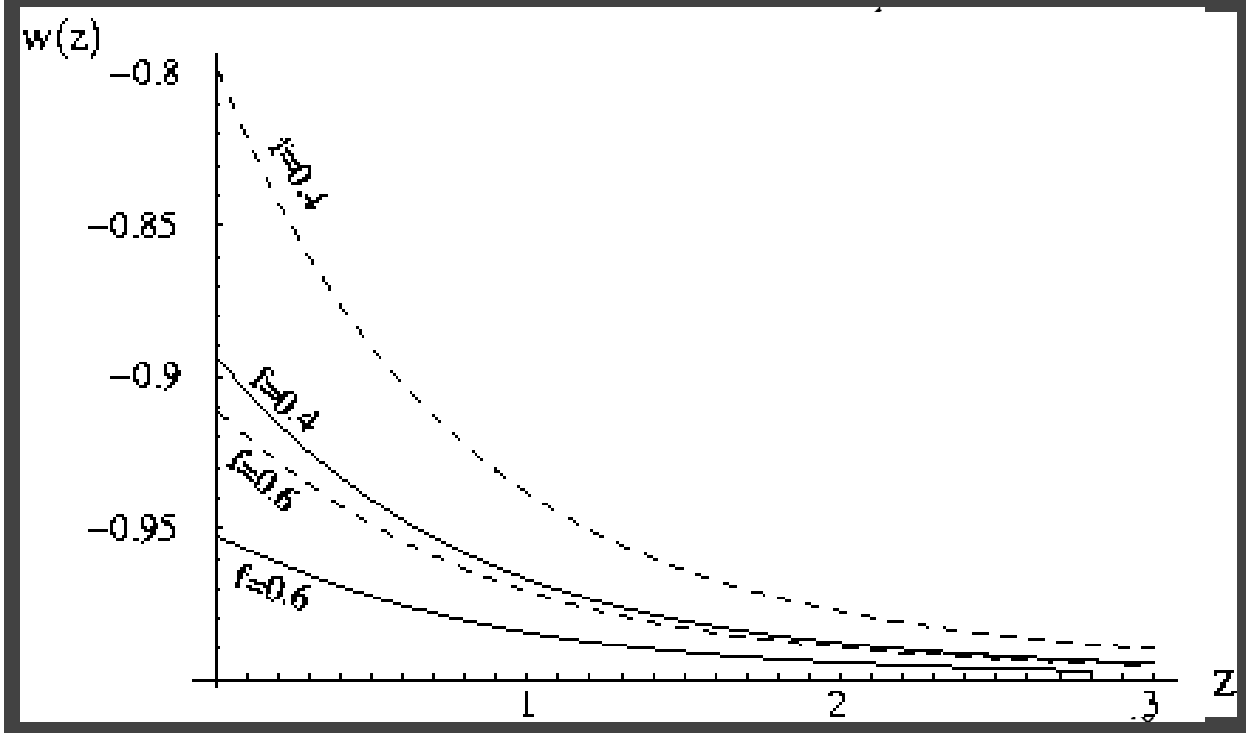


Axion (PNGB) Dark Energy

`The only symmetries in String Theory which might yield light scalars are axions.' (Banks & Dine)

In these models, coincidence problems indicate a new (effective) mass scale: e.g., 10^{-3} eV ~ $\exp(-2\pi^2/g^2)\, M_{SUSY}$

$m_a^2 \sim \exp(-8\pi^2/g^2)\, M_{SUSY}^4/M_{Pl}^2 \sim (10^{-33}\text{eV})^2$



$V(\phi) = M^4[1+\cos(\phi/f)]$

JF, Hill, Stebbins, Waga 95; Kim; Choi; Namura, etal, Hall, etal 05

There is little reason to assume that $w = -1$ is particularly likely.

Dark Energy Dynamics

- Time-evolution of *w*:

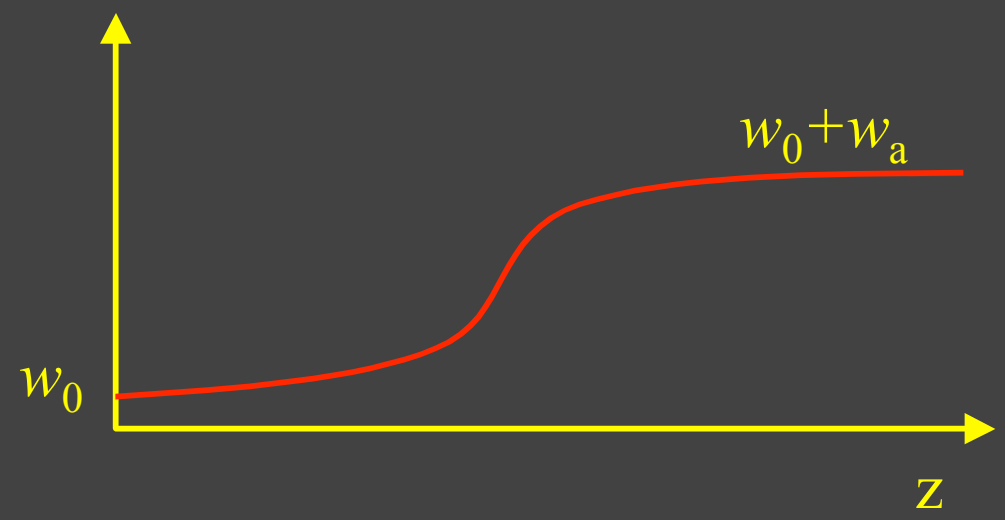
$$w(a) = w_0 + w_a(1-a)$$

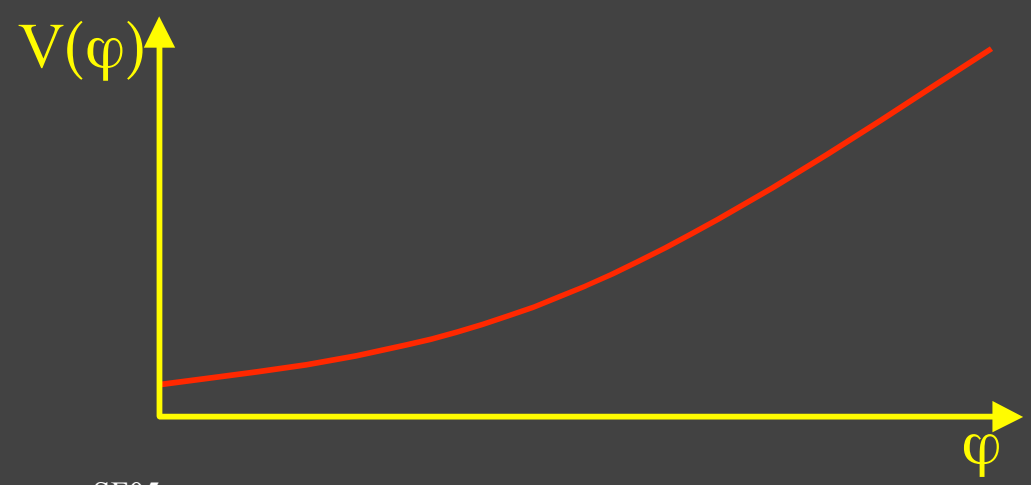
where

$$w_0 = -1 + 2\varepsilon$$

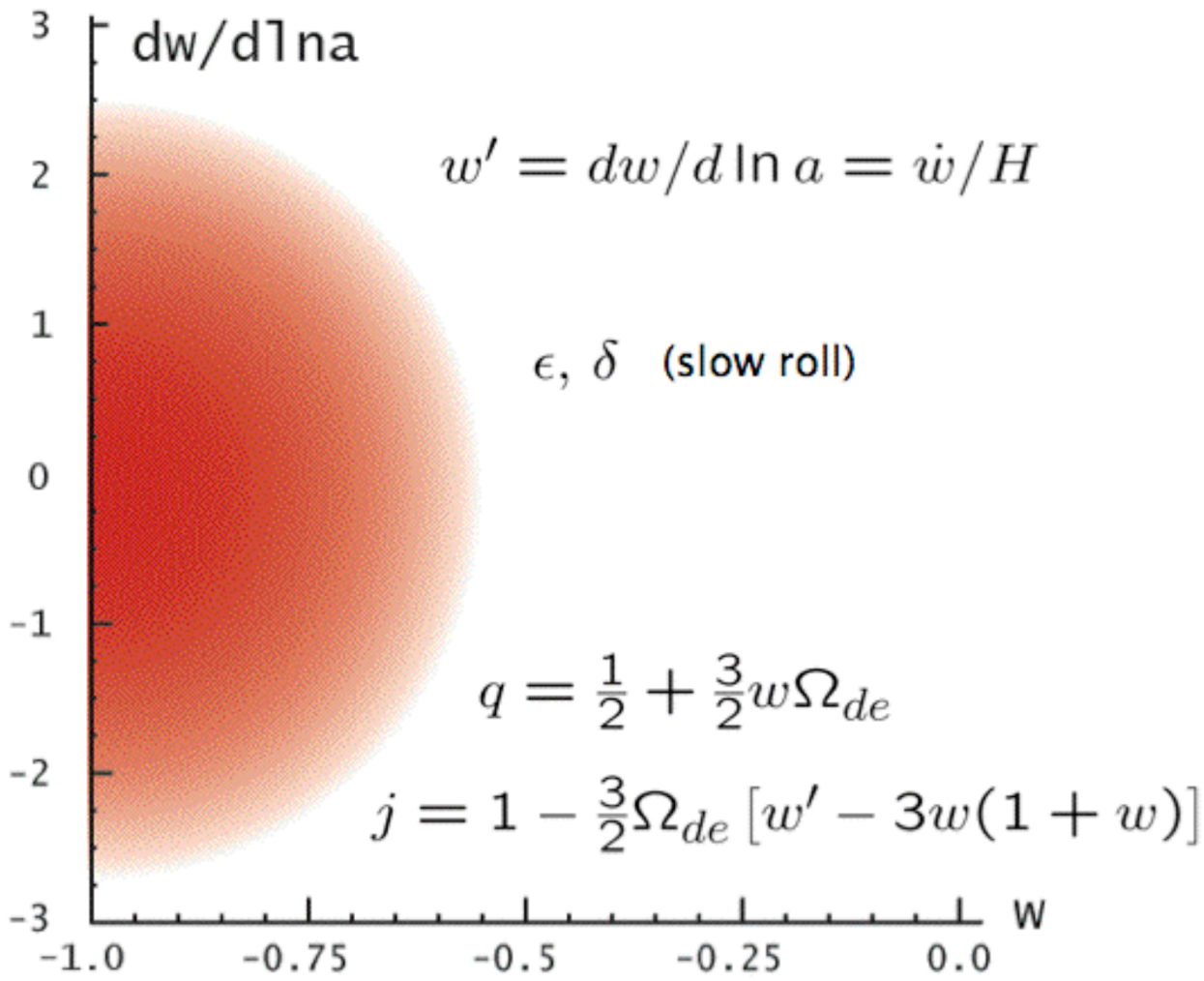
$$w_a = -24\varepsilon^2(\eta - 1)$$

$$\eta = \frac{VV''}{(V')^2}$$

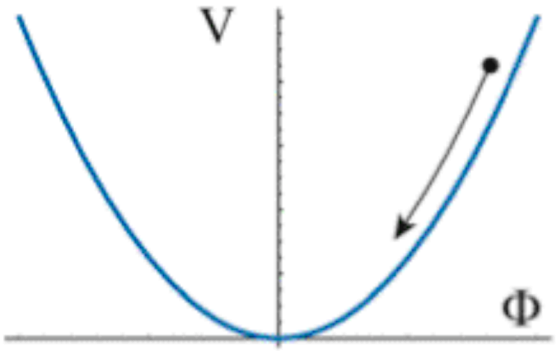




Dark Energy Constraints



Distinguish ***thawing*** and ***freezing*** fields

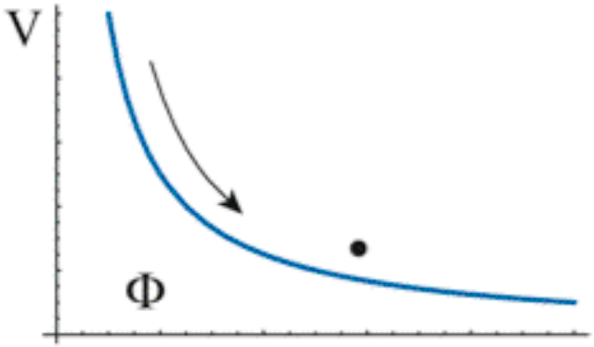


thawing

Field is critically damped until Hubble friction drops; ***w*** starts at -1 and grows larger

Any field near minimum, V=0 & V'=0

massive scalar, axion / pngb



freezing

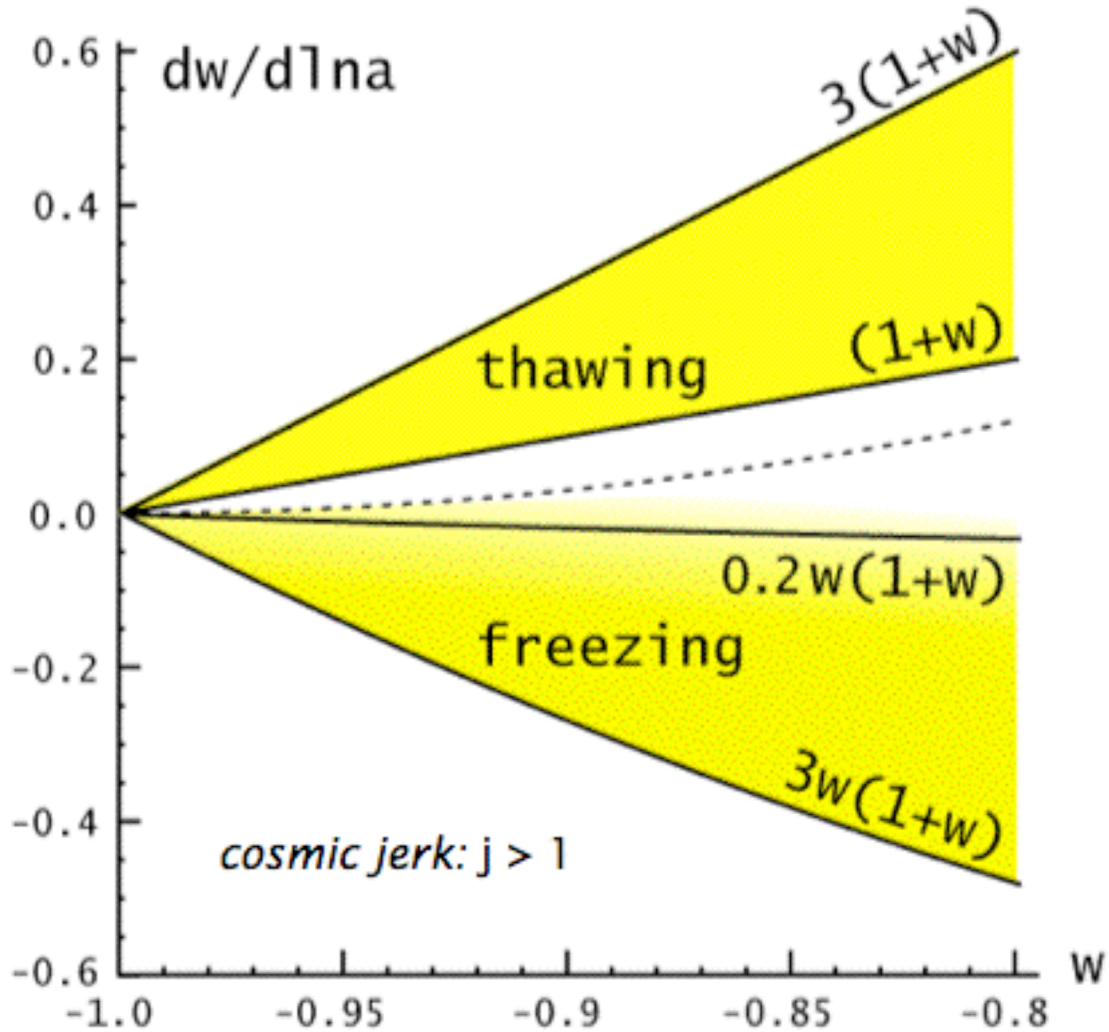
Field decays until curvature of potential causes field to slow; ***w*** evolves towards -1

"tracker" / runaway or vacuumless field

These are among the simplest, realistic quintessence models.

Distinguish ***thawing*** and ***freezing*** fields

- *bounds*
- *evolution*
- *trends*



Currently, there are no strong constraints on this phase diagram.

Caldwell & Linder

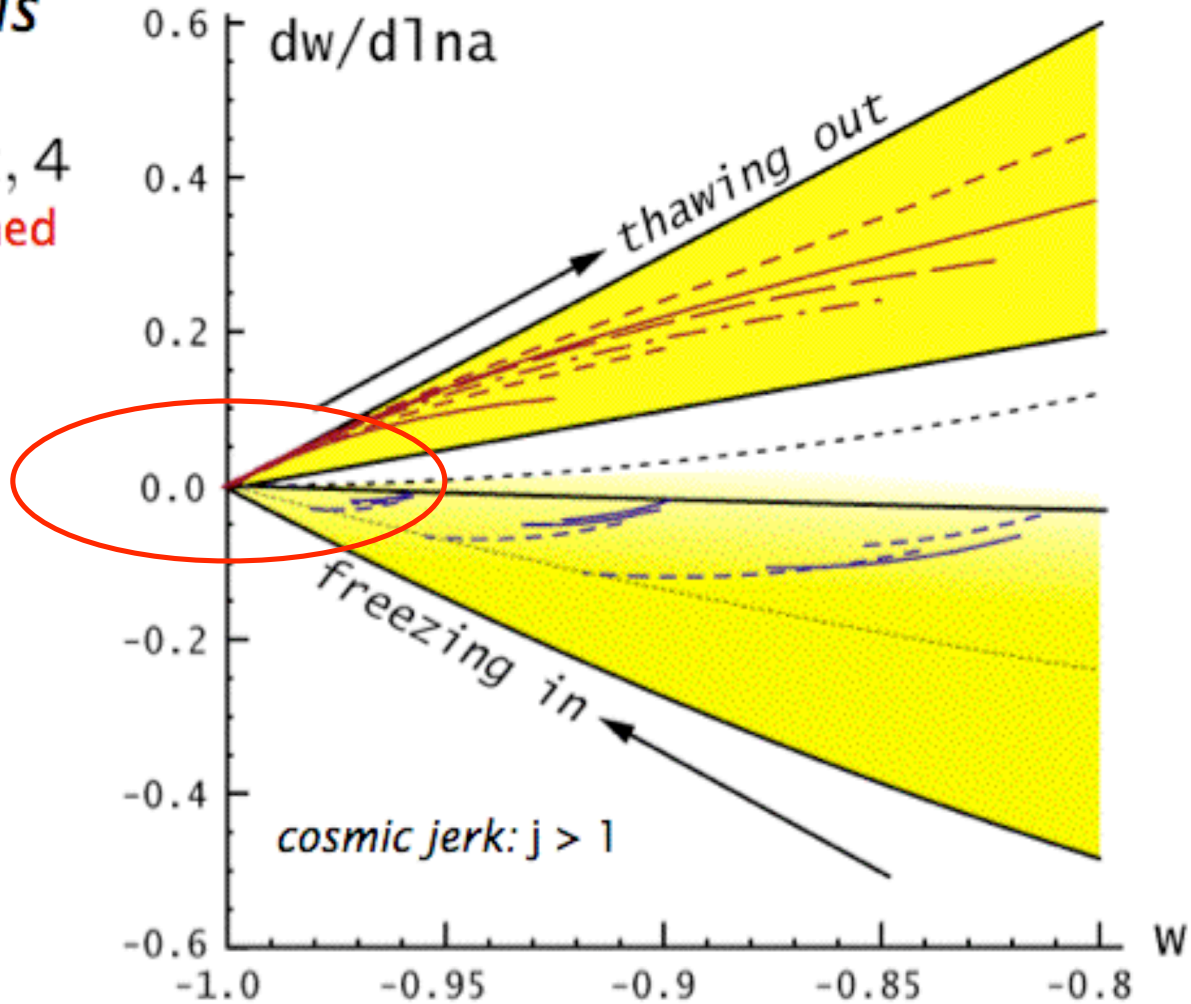
scalar field models

$V \propto \Phi^n,\ n = 1, 2, 4$
short-, dot-, long-dashed

$V \propto \cos^2(\Phi/2f)$
solid

$V \propto \Phi^{-n}$
solid

$V \propto \Phi^{-n} e^{\alpha\Phi^2}$
dashed



Caldwell & Linder

Ballpark goal of JDEM

Characteristic Energy Scale

$$E \equiv |V/V'|$$

$$= M_P/\sqrt{16\pi\epsilon}$$ *slow roll variable*

$$= M_P(1-w)\frac{\sqrt{\frac{3}{8\pi}\Omega_{de}(1+w)}}{w'+3(1-w^2)}$$

$$< M_P$$

$1+w \gtrsim 0.01$

0.2% difference from LCDM
in distance to z=1

Caveat: assumes $V_{min}=0$

Counterexamples: 2-axion models

Caldwell & Linder

IR-Modified Gravity Models

At large distances, gravity can leak off 3-brane into the bulk, infinite 5th dimension

Acceleration without vacuum energy on the brane, driven by brane curvature term:

$$S = M_5^3 \int d^5X \, |g_5|^{1/2} R_5 + M_{Planck}^2 \int d^4x \, |g|^{1/2} R$$

Cross-over from 4D to 5D gravity at scale: $r_c = M_{Planck}^2 / M_5^3$

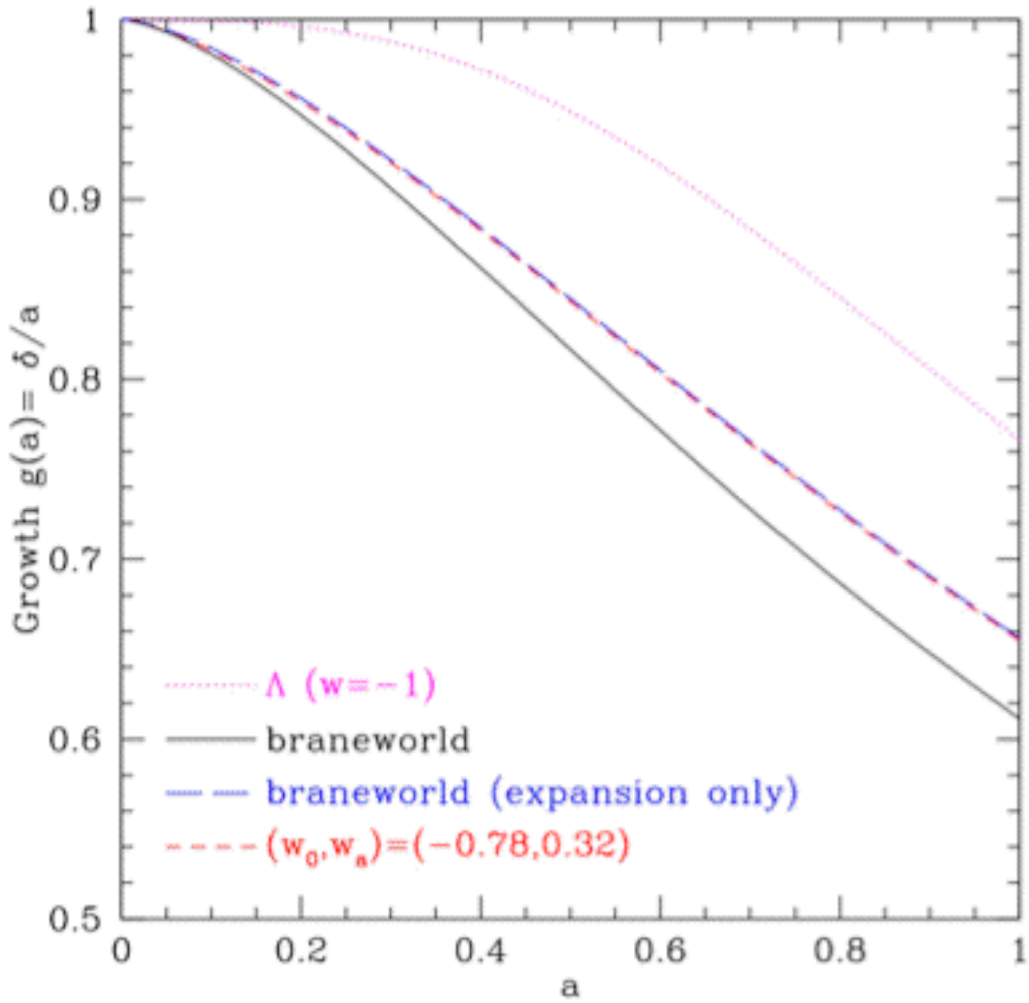
$$H^2 - H/r_c = \rho/3M_{Planck}^2 \qquad M_5 \sim 1 \text{ GeV} \rightarrow r_c \sim 1/H_0$$

Features: effective scalar-tensor gravity--> lunar laser ranging and growth of large-scale structure

Dvali, Gabadadze, Porrati

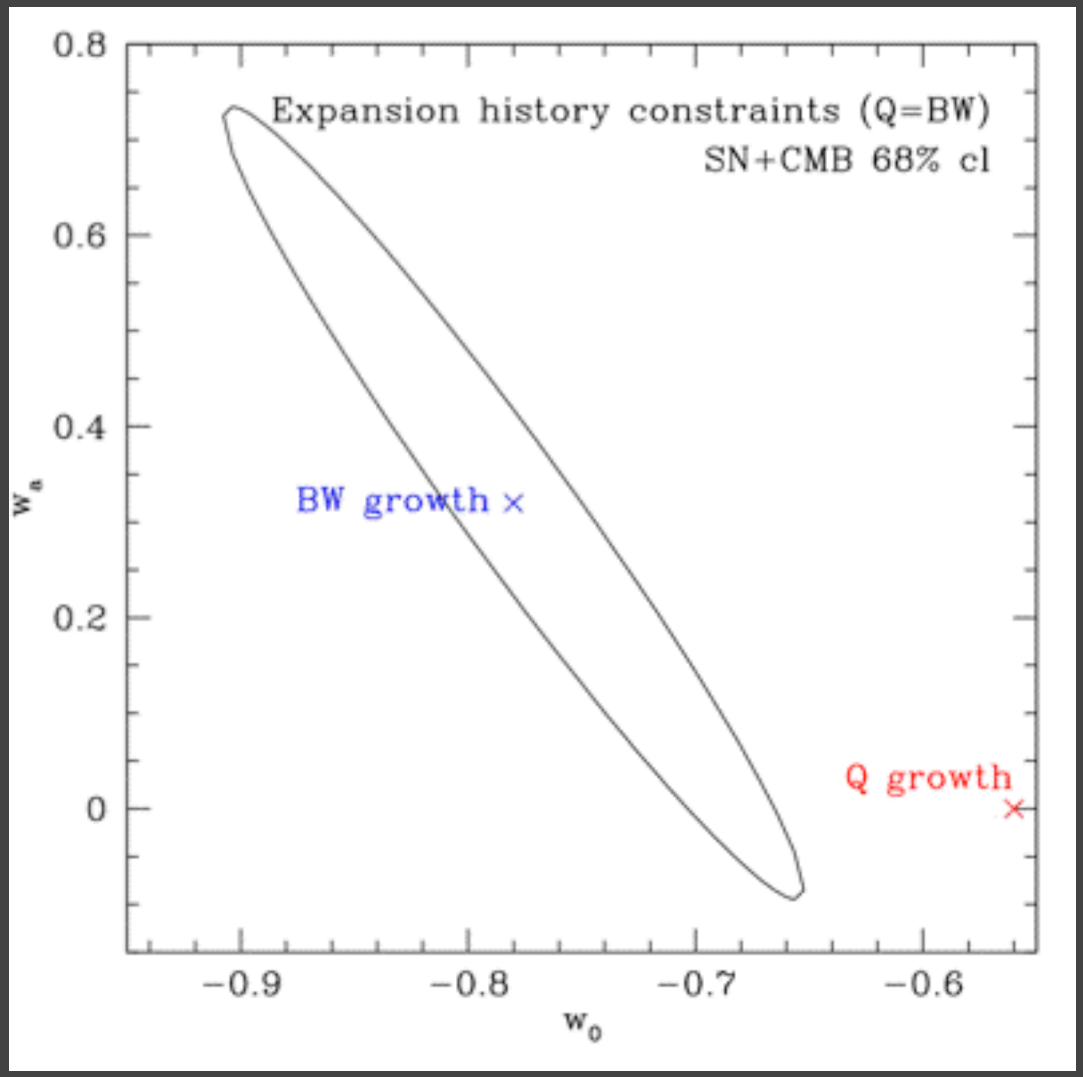
Beyond Expansion History

Growth of Perturbations probes H(z) and gravity



Linder

$$g'' + [5 + \tfrac{1}{2}\tfrac{d\ln H^2}{d\ln a}]g'a^{-1} + [3 + \tfrac{1}{2}\tfrac{d\ln H^2}{d\ln a} - \tfrac{3}{2}G\,\Omega_m(a)]\,ga^{-2} = S(a)$$


Expansion history constraints (Q=BW)
SN+CMB 68% cl
BW growth
Q growth
0.8
0.6
0.4
0.2
0
w_a
−0.9
−0.8
−0.7
−0.6
w_0

Probing Dark Energy

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

$$H^2(z) = H^2_0 \; [\Omega_M (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)}]$$

matter dark energy

(flat Universe)
(constant w)

Geometric tests:

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- Standard Population (volume) $dV/dz d\Omega = r^2(z)/H(z)$

Structure based-tests:

- The rate of growth of structure determined by H(z), by any modifications of gravity on large scales, and by other cosmological parameters

Probes of Dark Energy

- Supernovae
- Weak Gravitational Lensing
- Cluster Surveys

Will not cover:

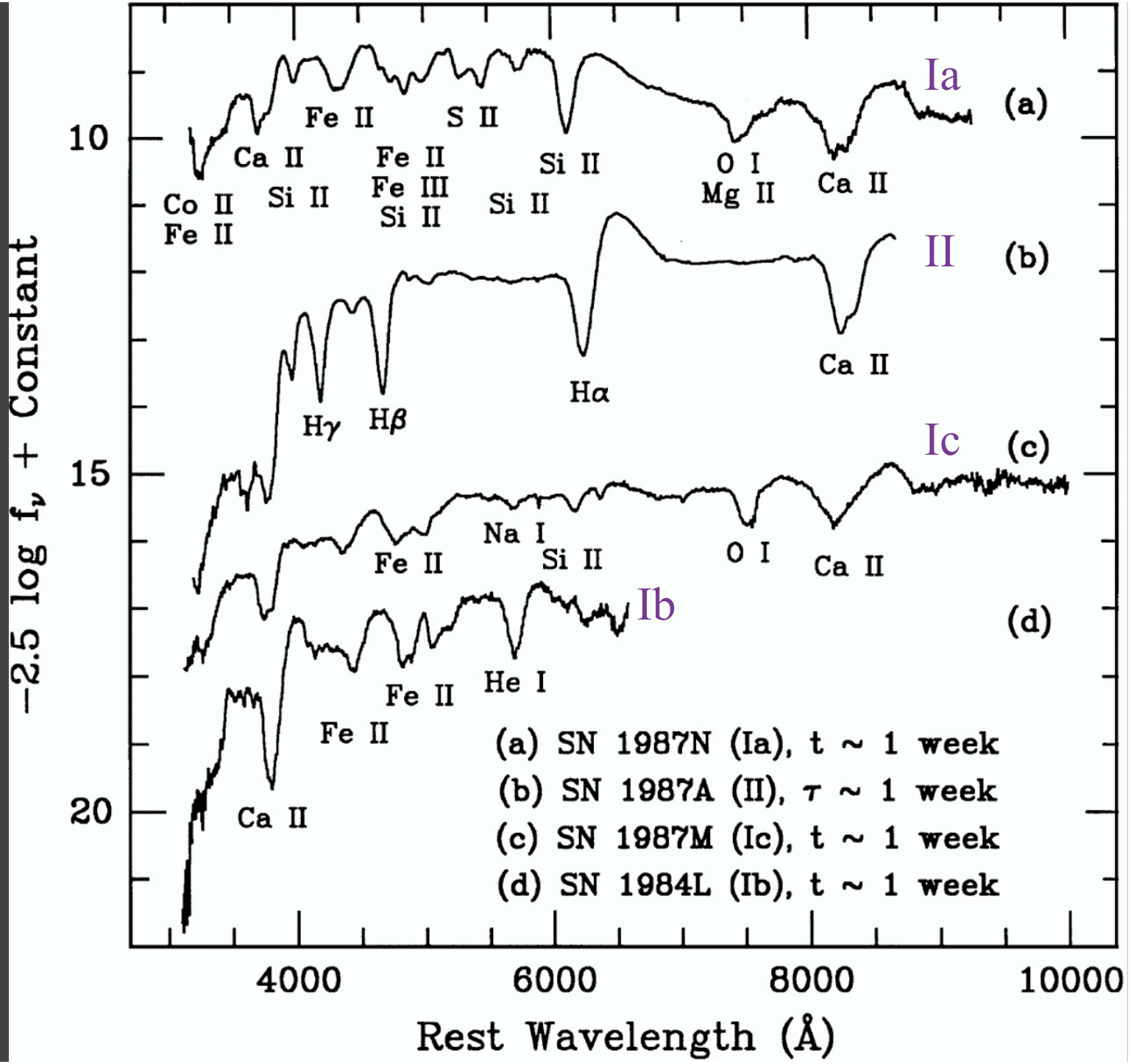
- Baryon Oscillations/galaxy clustering (see talk by Dan Eisenstein)
- Integrated Sachs-Wolfe
- CMB lensing

Classification of Supernovae

Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical mechanism	Nuclear explosion of low mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light curve	Reproducible	Large Variations		
Neutrinos	Insignificant	~ 100 x Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole ?		
Rate/h^2SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34
Observed	Total ~ 2000 as of today (nowadays ~200/year)			

Georg Raffelt, Max-Planck-Institut fur Physik (Munchen)

SN Spectra ~1 week after maximum



Filippenko 1997

Type Ia Supernovae

General properties:

- Homogeneous class* of events, only small (correlated) variations
- Rise time: ~ 15 – 20 days
- Decay time: many months
- Bright: M_B ~ – 19.5 at peak

No hydrogen in the spectra

- Early spectra: Si, Ca, Mg, ...(absorption)
- Late spectra: Fe, Ni,…(emission)
- Very high velocities (~10,000 km/s)

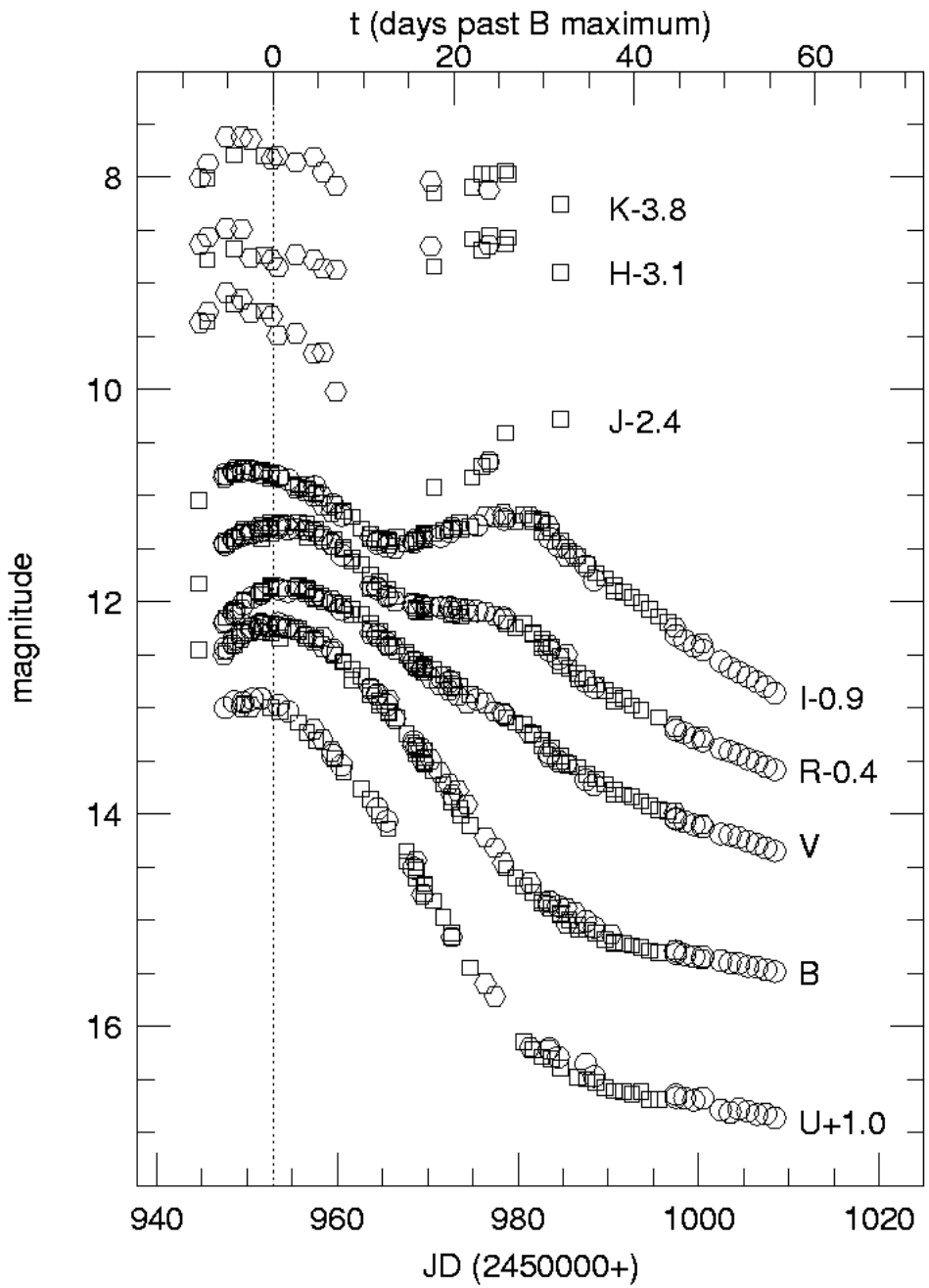
SN Ia found in all types of galaxies, including ellipticals

- Progenitor systems must have long lifetimes

*luminosity, color, spectra at max. light

SN1998bu

Light curve



Suntzeff, etal

Jha, etal

Hernandez, etal

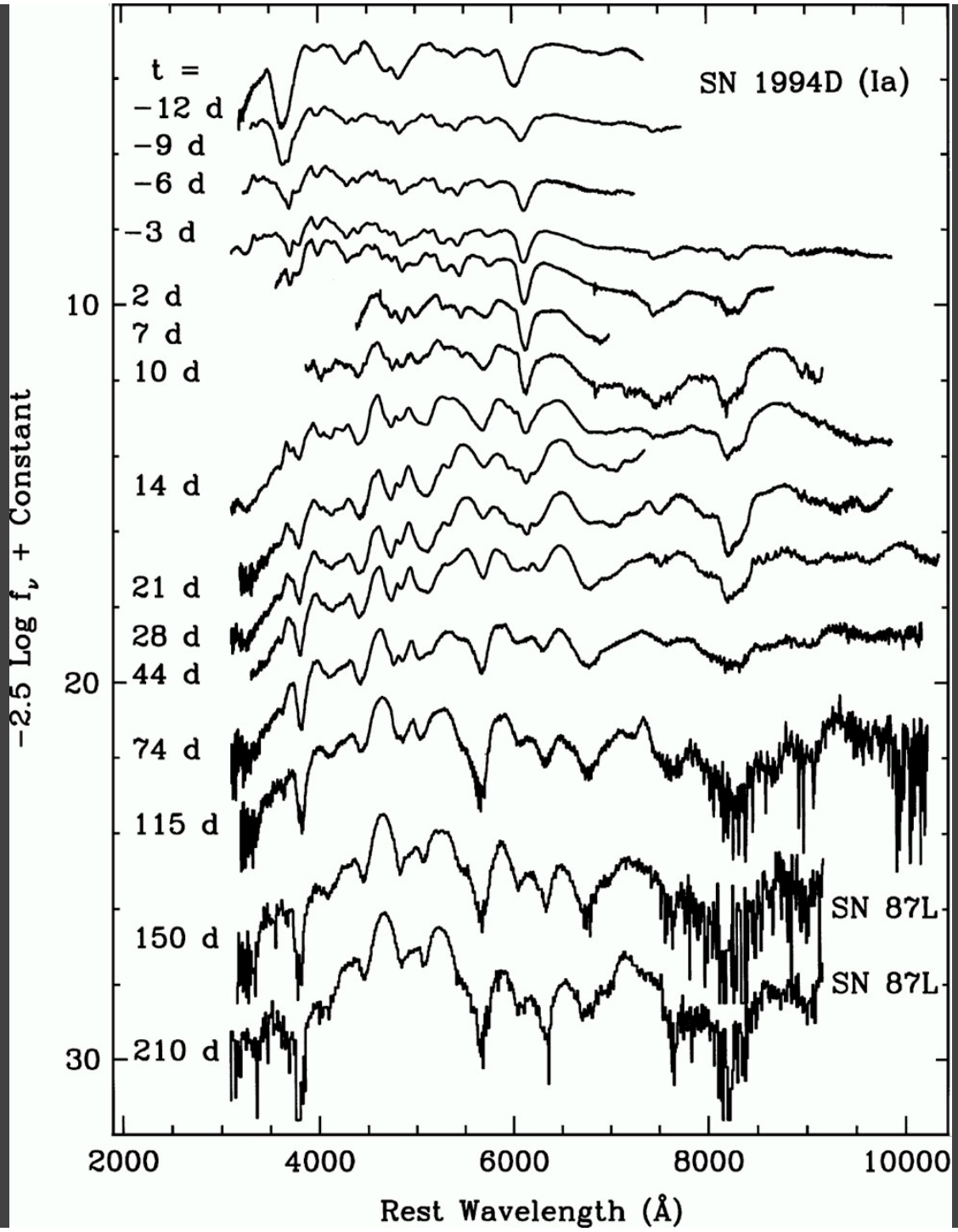
Nearby SN 1994D (Ia)

Spectral Evolution

Supernova Factory will produce library of ~300 Sne Ia with dense multi-epoch Spectrophotometry

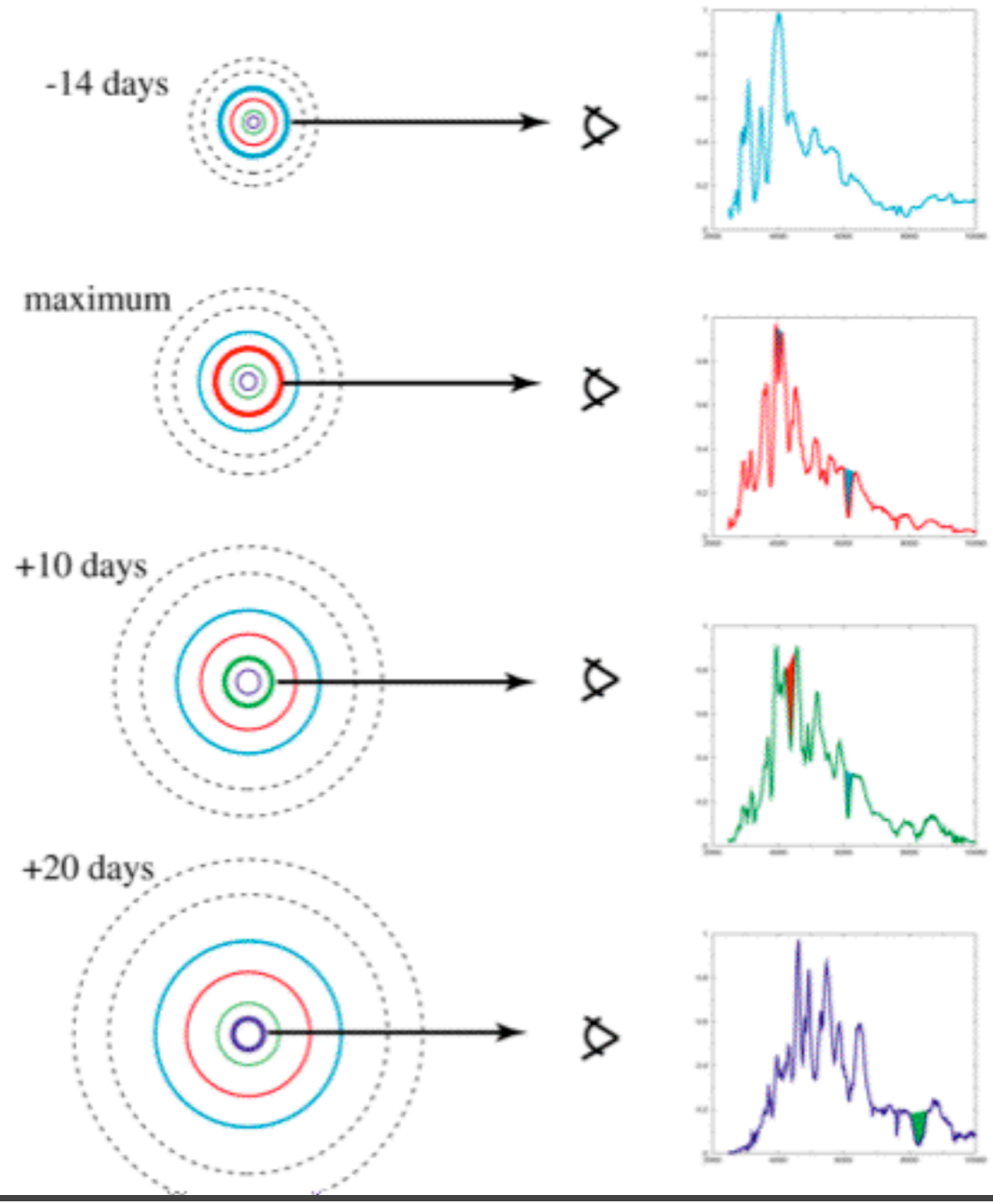
Patat etal 96

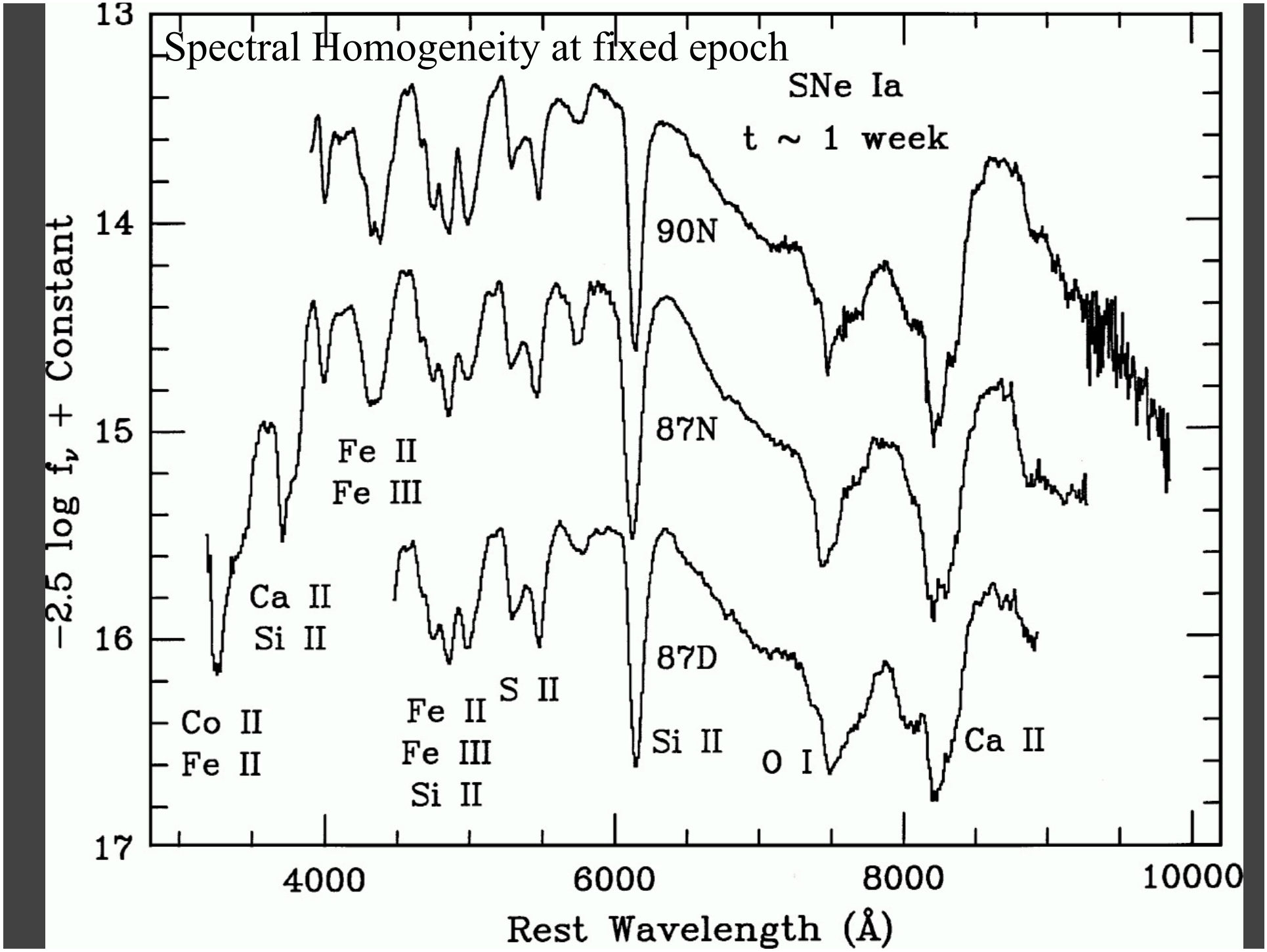
Filippenko 97



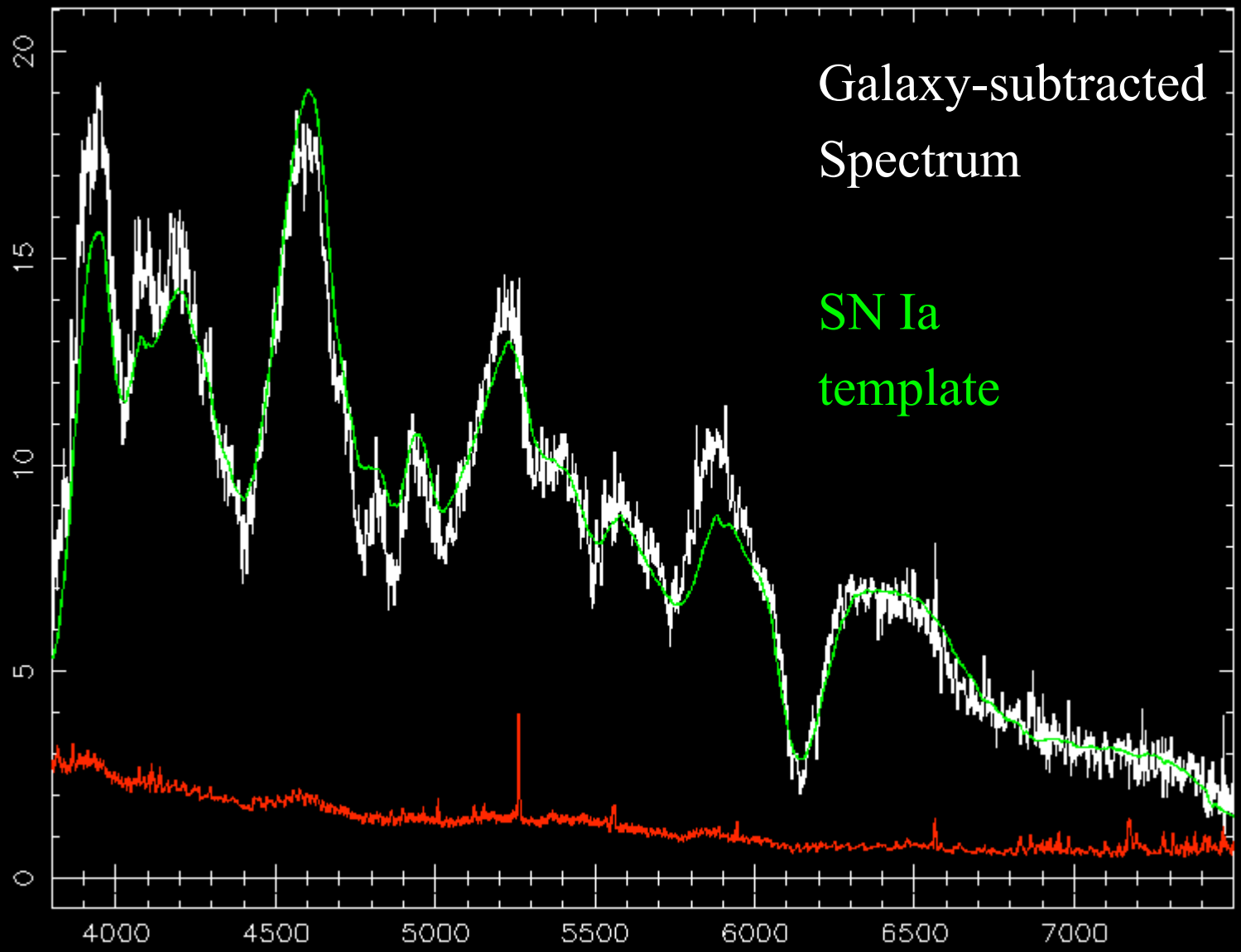
Layered Chemical Structure provides clues to Explosion physics

The Time Series of Spectra is a "CAT Scan" of the Supernova



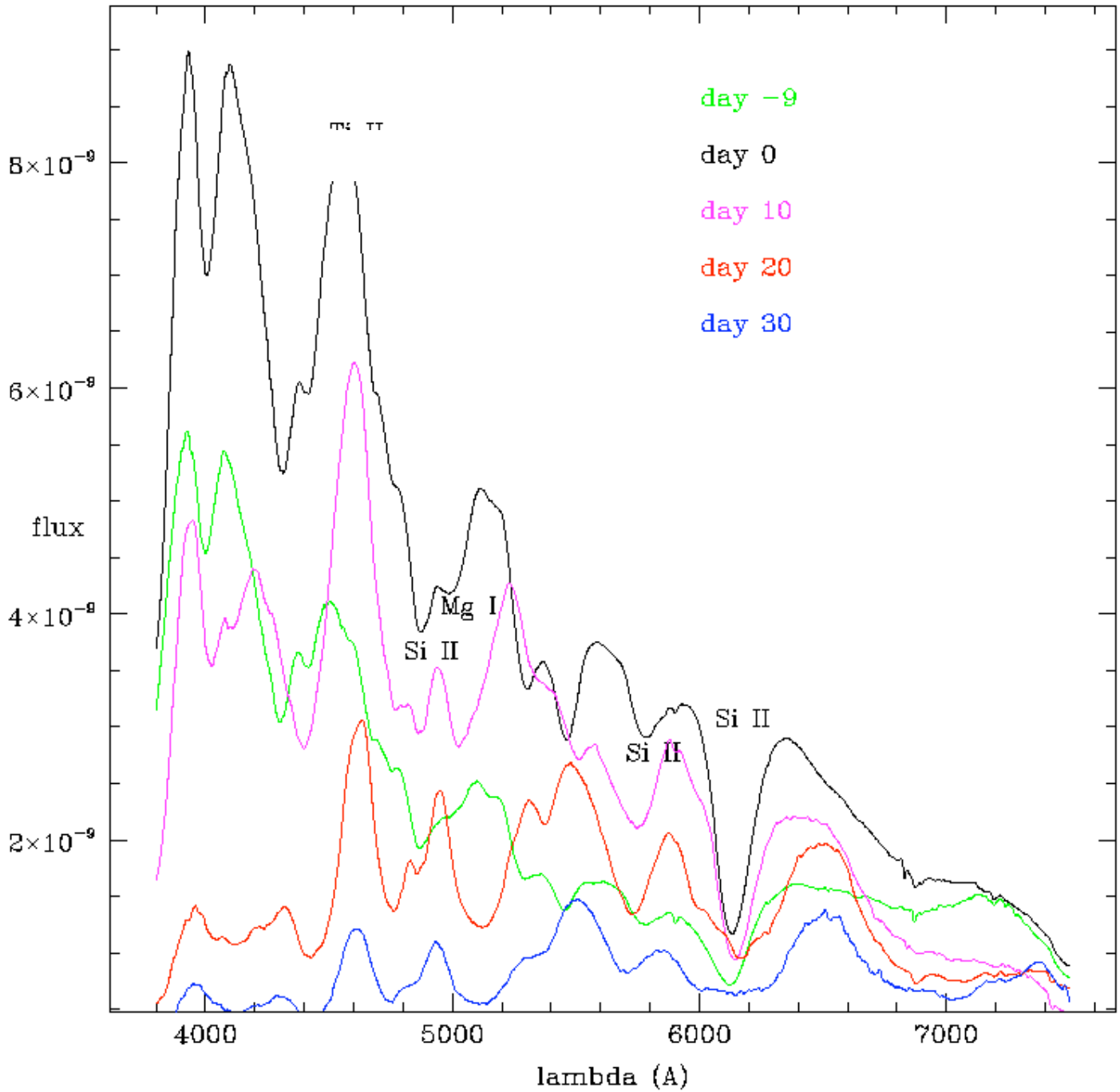

Spectral Homogeneity at fixed epoch
SNe Ia
t ~ 1 week
90N
87N
87D
Fe II
Fe III
Ca II
Si II
Co II
Fe II
Fe II
Fe III
Si II
S II
Si II
O I
Ca II
13
14
15
16
17
4000
6000
8000
10000
−2.5 log f_ν + Constant
Rest Wavelength (Å)

SN2004ar z = 0.06 from SDSS galaxy spectrum



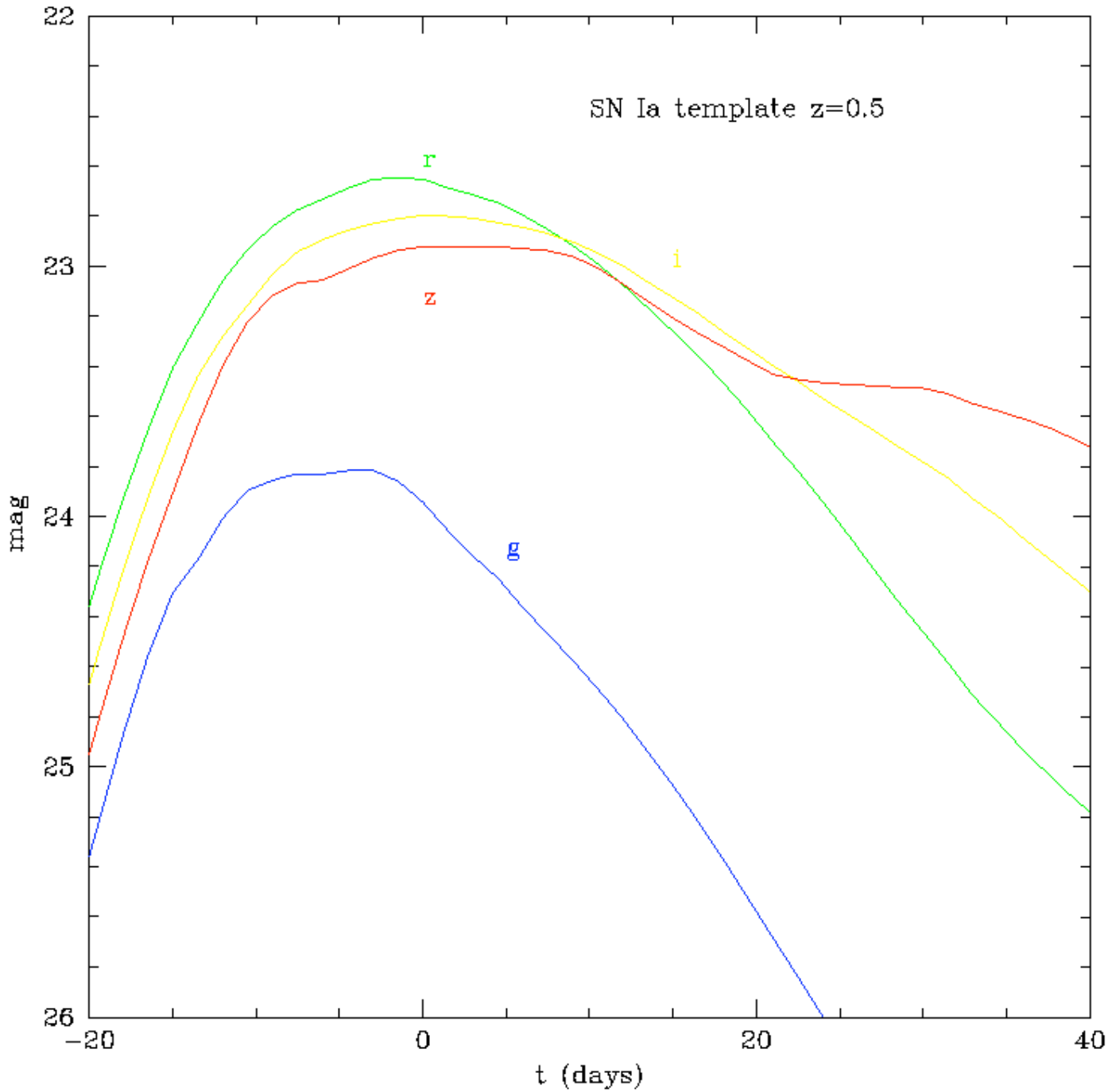
Composite Spectral Evolution (+modelling)

Use as templates



Nugent

Light Curves from Composite Template Spectral Sequence

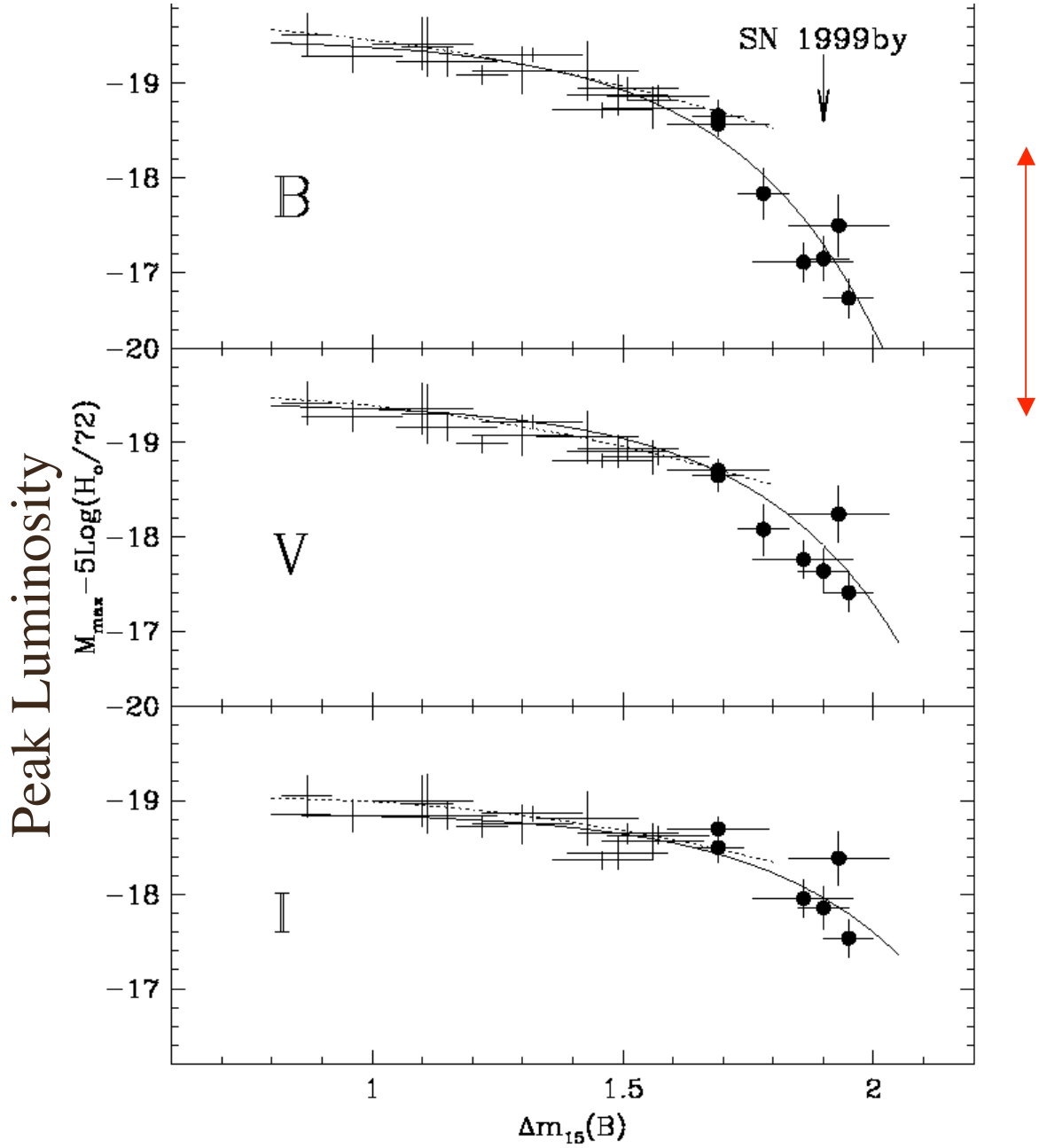


SN Ia Peak Luminosity Empirically correlated with Light-Curve Decline Rate

Brighter ←→ Slower

Use to reduce Peak Luminosity Dispersion

Phillips 1993



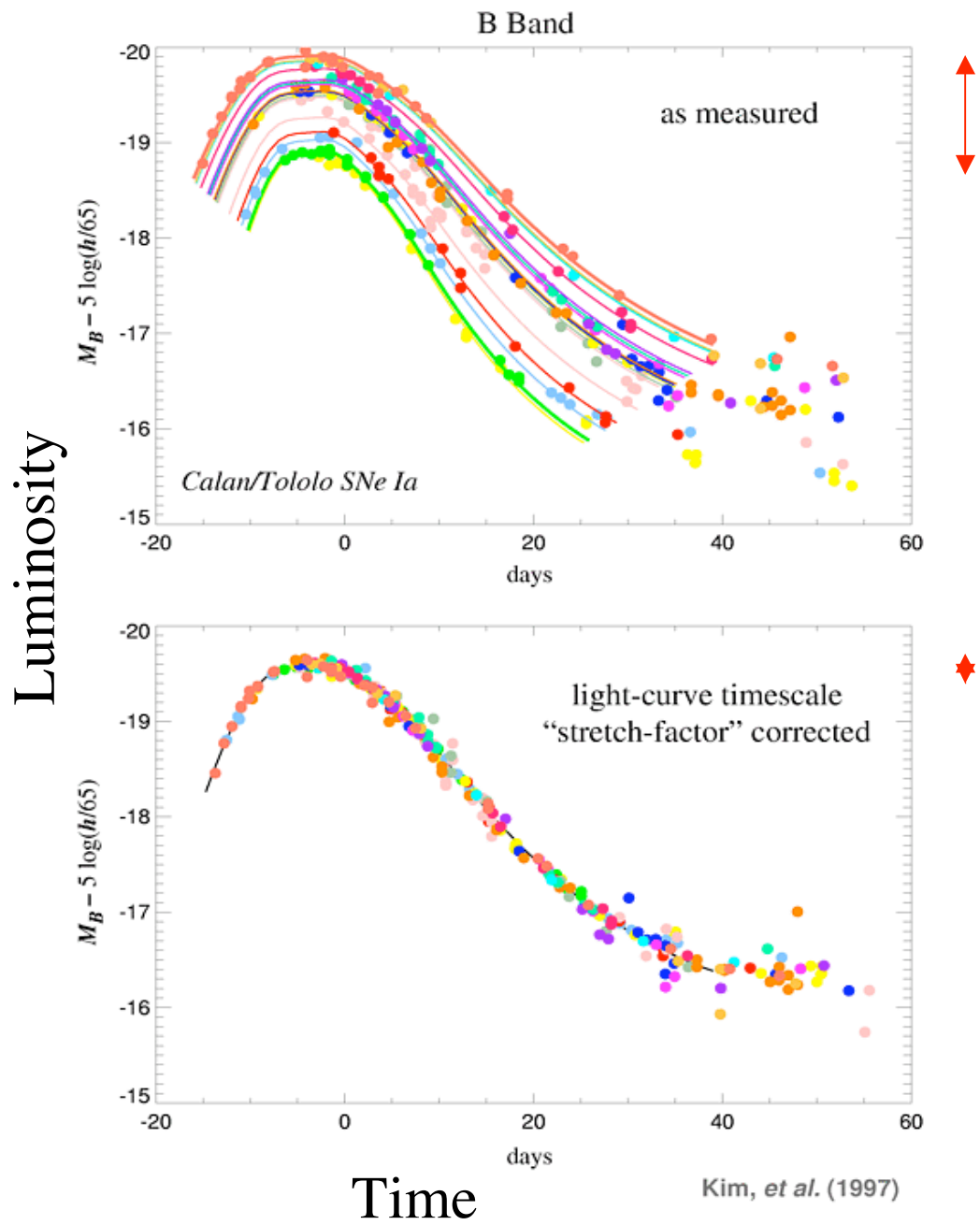
Garnavich, etal

Type Ia SN
Peak Brightness
as calibrated
Standard Candle

Peak brightness
correlates with
decline rate

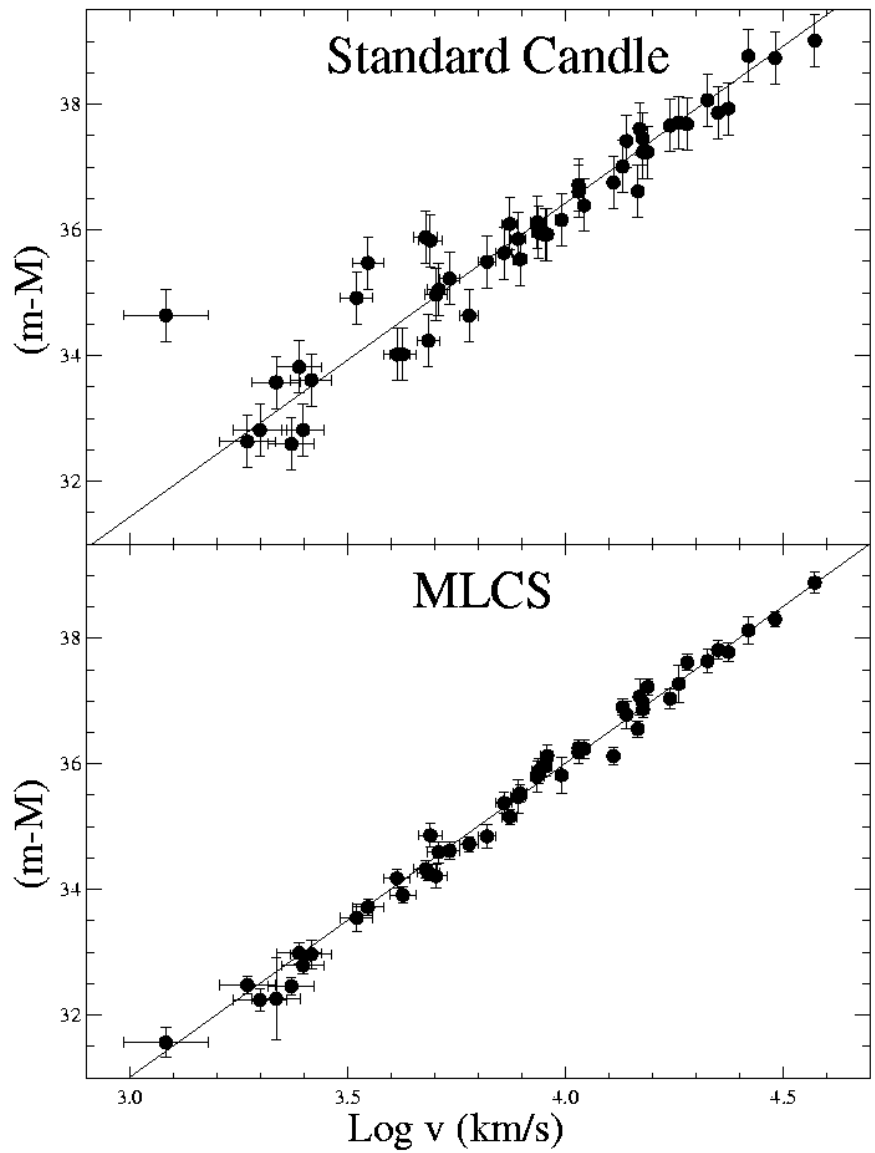
After correction,
σ~ 0.15 mag

(~7% distance error)



Correction for Brightness-Decline relation reduces scatter in nearby SN Ia Hubble Diagram

Riess etal 96



$$m(z) - M_B = -5\log(H_0) + 25 + 5\log[H_0 D_L(z, \Omega_m, \Omega_{DE}, w)] + K_{Bx} + A$$

Distance modulus

Luminosity Distance

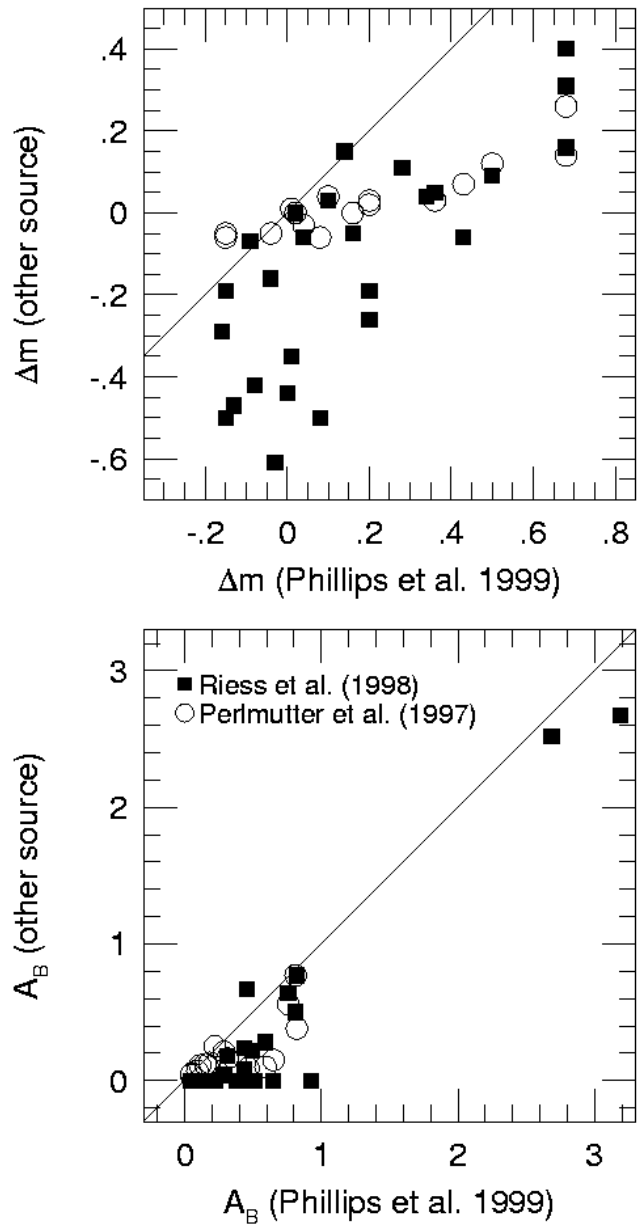
$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{[1 + \Omega_x((1+z)^{3w} - 1)]^{-1/2}}{(1+z)^{3/2}} \, dz$$

Caveat: Comparison of 3 Brightness-Decline Fitting Methods:

1. Δm_{15} (Phillips etal)
2. Stretch (Perlmutter etal)
3. MLCS (Riess etal)

Substantial differences on SN-by-SN basis seen in *nearby* and *distant* samples

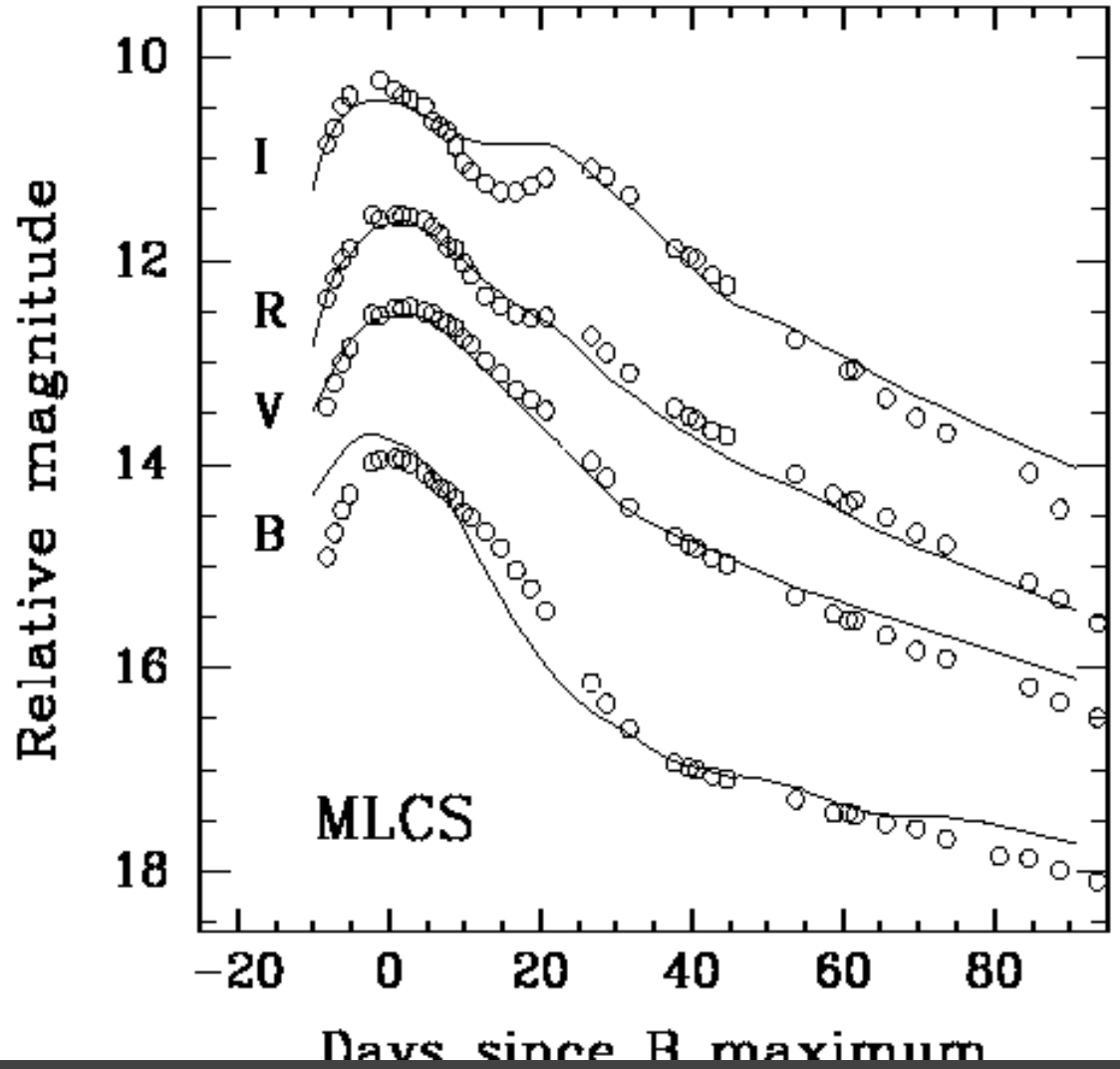
Yet cosmological results agree Liebundgut 2000



Caveat:
Peculiar SNe Ia that don't fit the Brightness-Decline relation

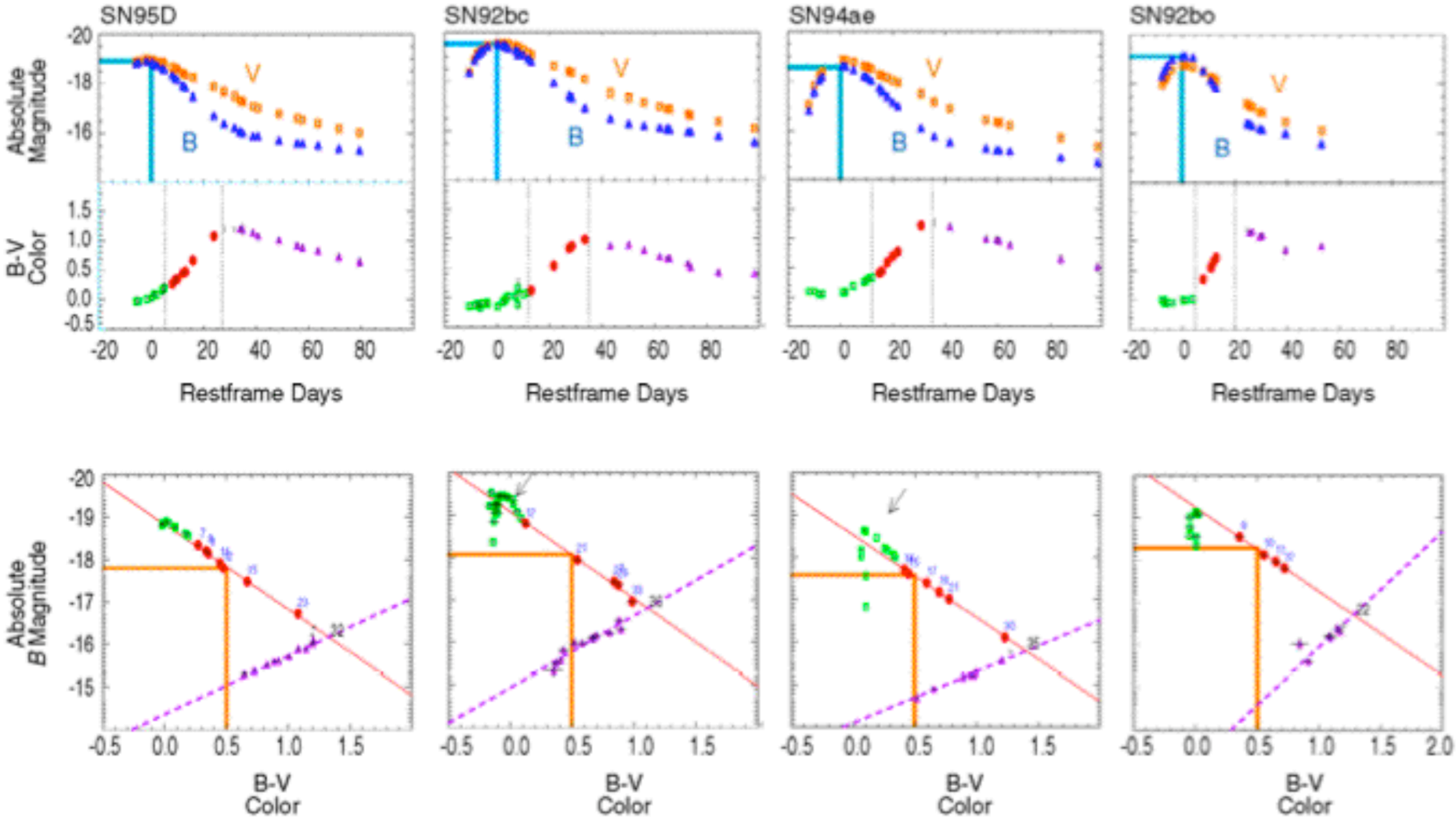
Sn2000cx

See also 2002cx



Li etal 01

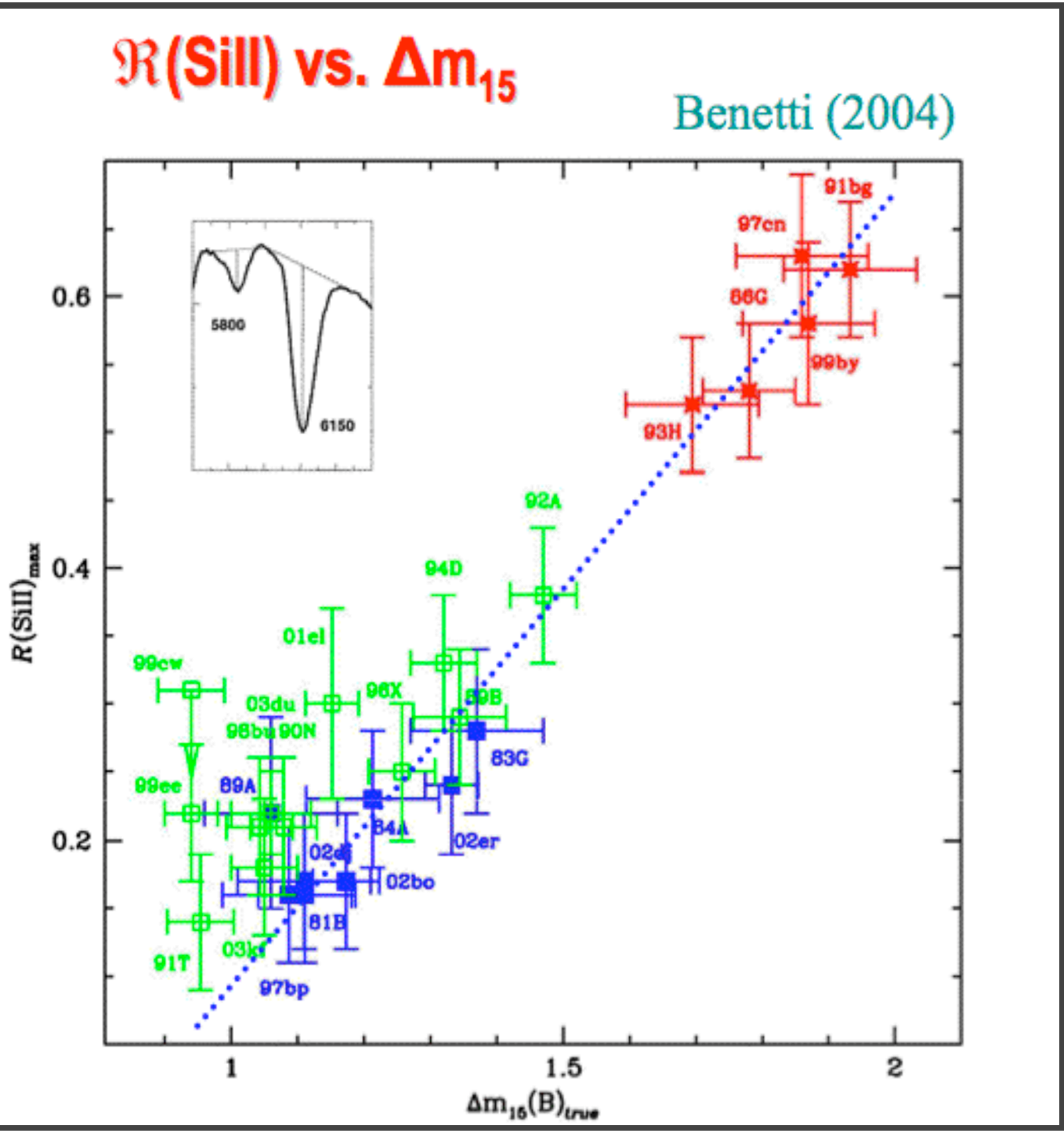
Color-Magnitude Intercept
Calibration Technique for Type Ia Supernovae



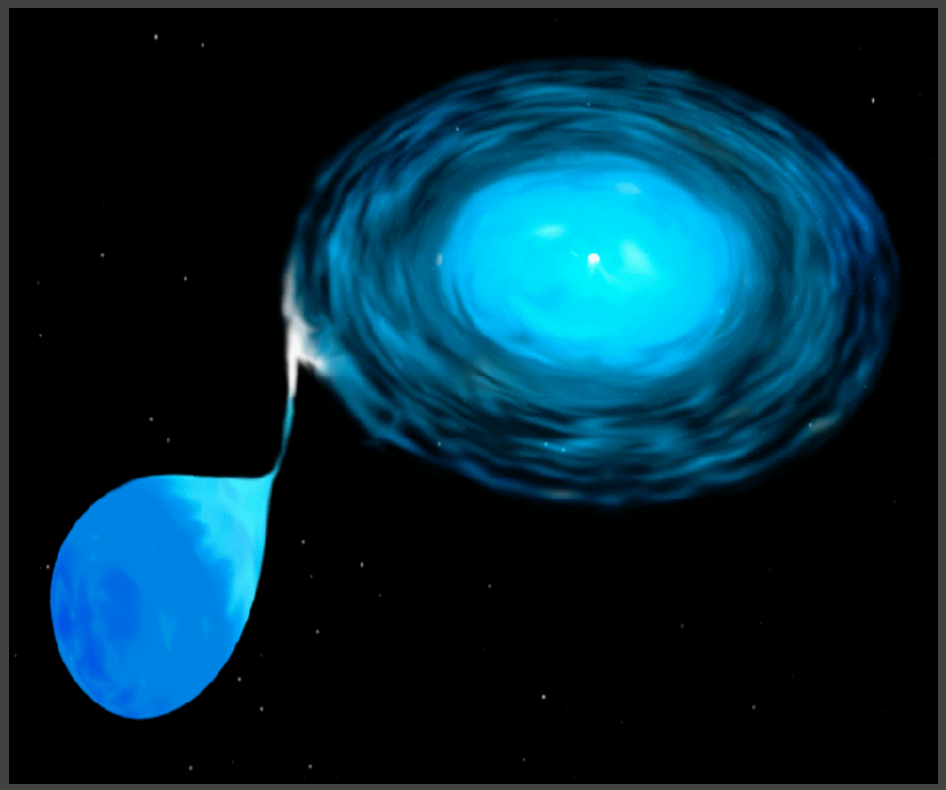
Wang, Goldhaber, Aldering, & Perlmutter (2003)

Spectral Correlations With Peak Luminosity

Possible Ia Subclasses based on velocity gradients



SN Ia Theory:



"Standard model":

- SNe Ia are thermonuclear explosions of C+O white dwarf stars.

Evolution to criticality:

- Accretion from a binary companion leads to growth of the WD to the critical Chandrasekhar mass (~ 1.4 solar masses).

After ~1000 years of slow thermonuclear "cooking", a violent explosion is triggered at or near the center; complete incineration within less than two seconds, no compact remnant

Chandrasekhar Mass Models

WD accretes H or He from non-degenerate companion, burns on the surface to C+O (alternate: WD binary merger)

When $M = M_{Ch}$, compressional heating--> thermonuclear instability: C, O burn explosively to ^{56}Ni (n=p) in the core → explosion driven by E_{kin} released from fusion reactions in a few seconds. Free expansion of unbound ejecta thereafter, with velocities ~10^4 km/sec.
Outer regions burn to Si, Ar, Ca,… seen in early spectra.

Radioactive decays: $^{56}Ni \xrightarrow{\text{days}} {}^{56}Co \xrightarrow{\text{months}} {}^{56}Fe$ + MeV photons
γ's downscatter, `thermalize'and escape as optical/NIR light: light curve

0th order homogeneity: M_{Ch} fully burned → $M_{Ni} \sim 0.6\ M_{sun}$
→ `fixed' L_{peak}

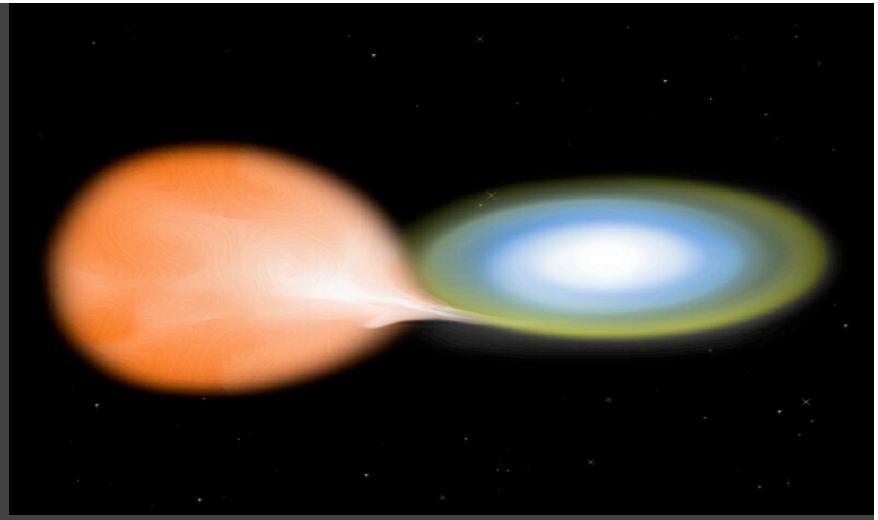
Chandrasekhar Mass Models

1st order diversity: spread in progenitor (pre-WD) Mass (1– 7 M_{sun})
→ spread in WD C/O → spread in M_{Ni} produced & E_{kin}
→ spread in L_{max}

Other diversity factors: varying accretion rates, rotation speeds, magnetic fields, metallicity

Correlation between L_{peak} and decline rate (Δm_{15}, LCS, stretch)
Increase M_{Ni} → increase L
Increase M_{Ni} → increase T → increase opacity → increase photon diffusion time → longer decline

Type Ia Supernovae



- Popular Explosion model
  - Deflagration: Subsonic burning turbulent, pre-expands WD, allowing production of intermediate-mass elements (in addition to Ni)
  - Delayed Detonation: Supersonic burning leads to layered chemical structure
- Main parameter: density at deflagration-detonation transition
- Parametrized models reproduce LC's, spectra reasonably well

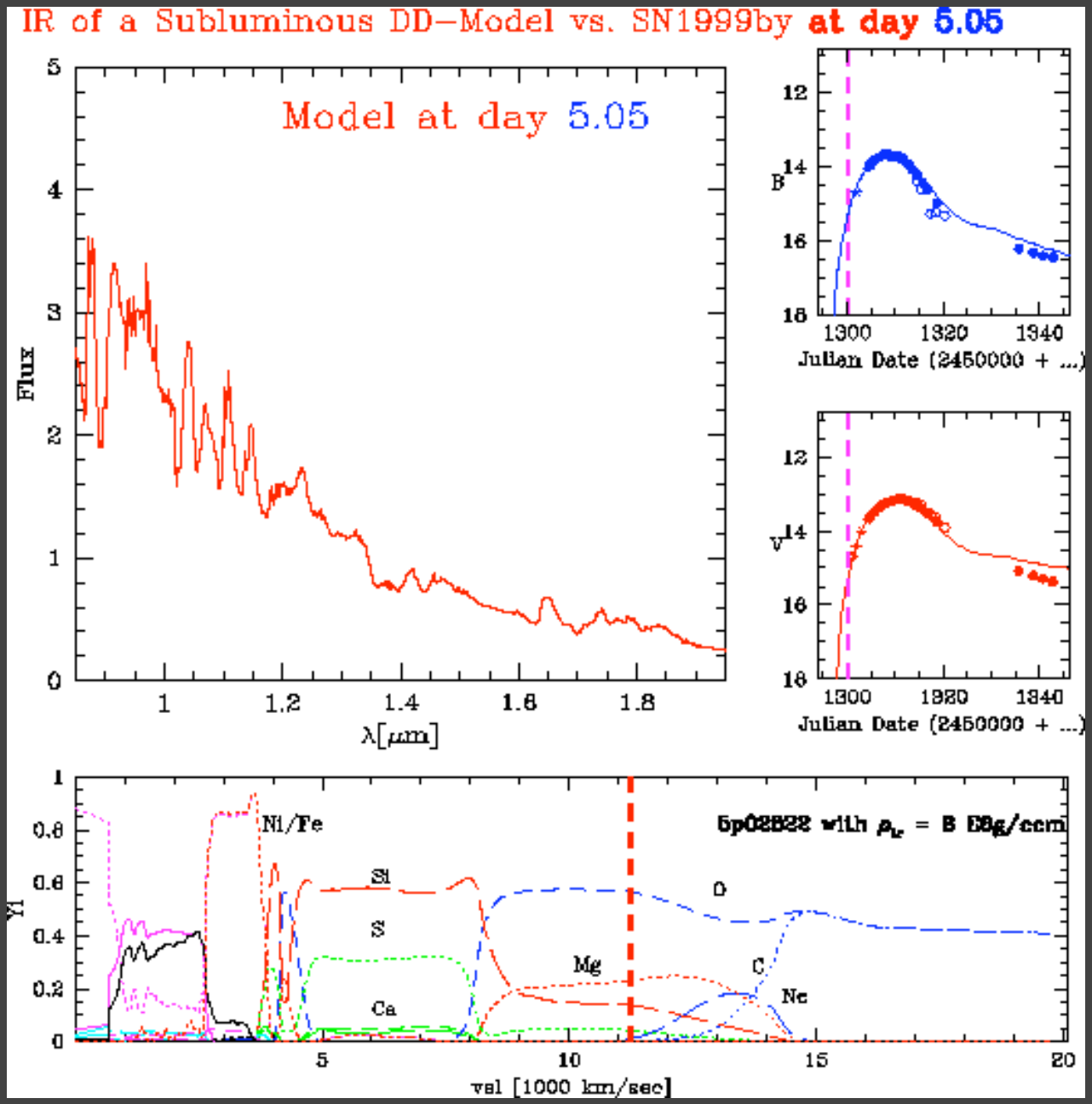
Khoklov, Hoflich, etal

Delayed-Detonation Model

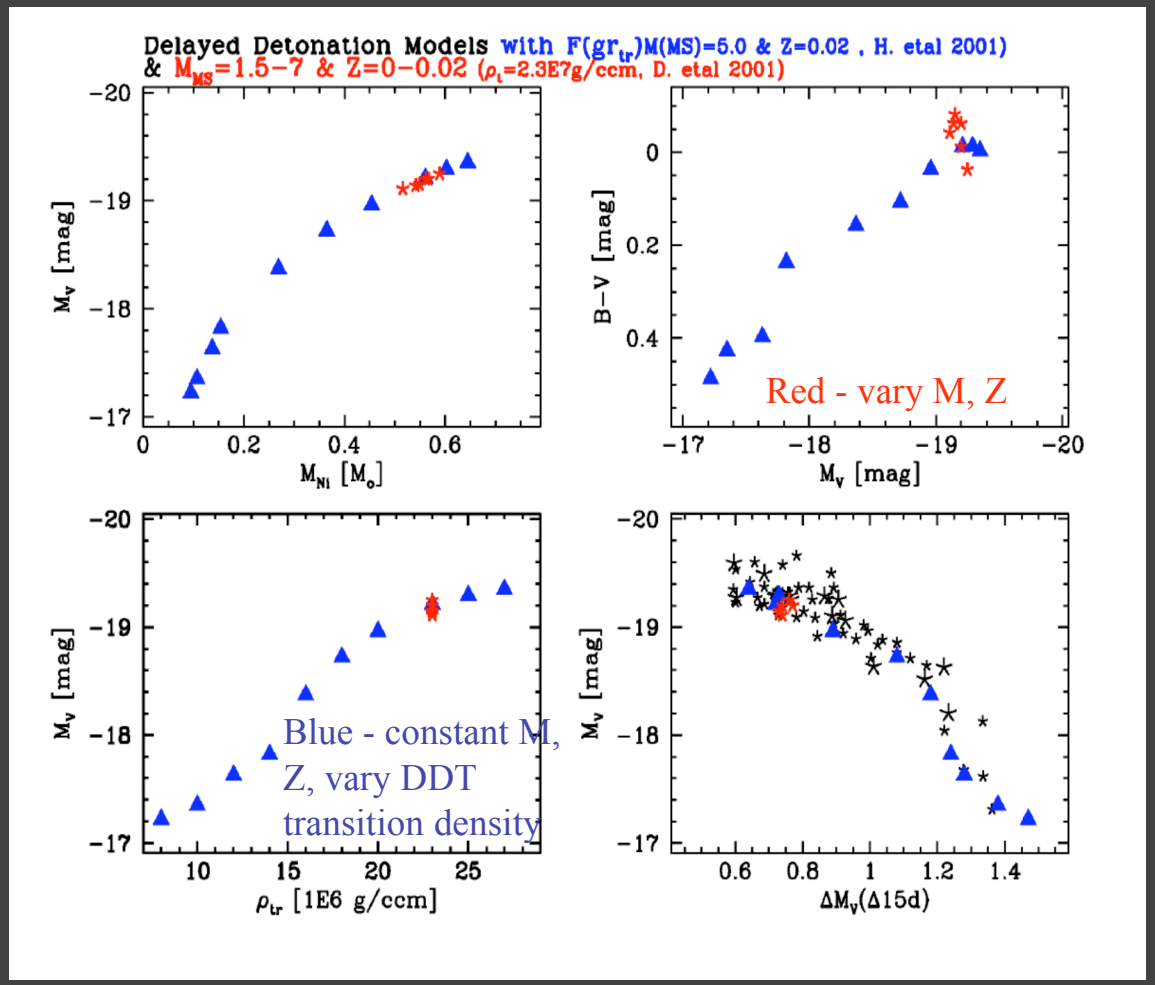
Subluminous SN 1999by

Model fit to B, V light curves (far right), *predicts* near IR spectral evolution.

Höflich et al.



The brightness/decline and color relations for Chandrasekhar-mass Delayed-detonation (DDT) models



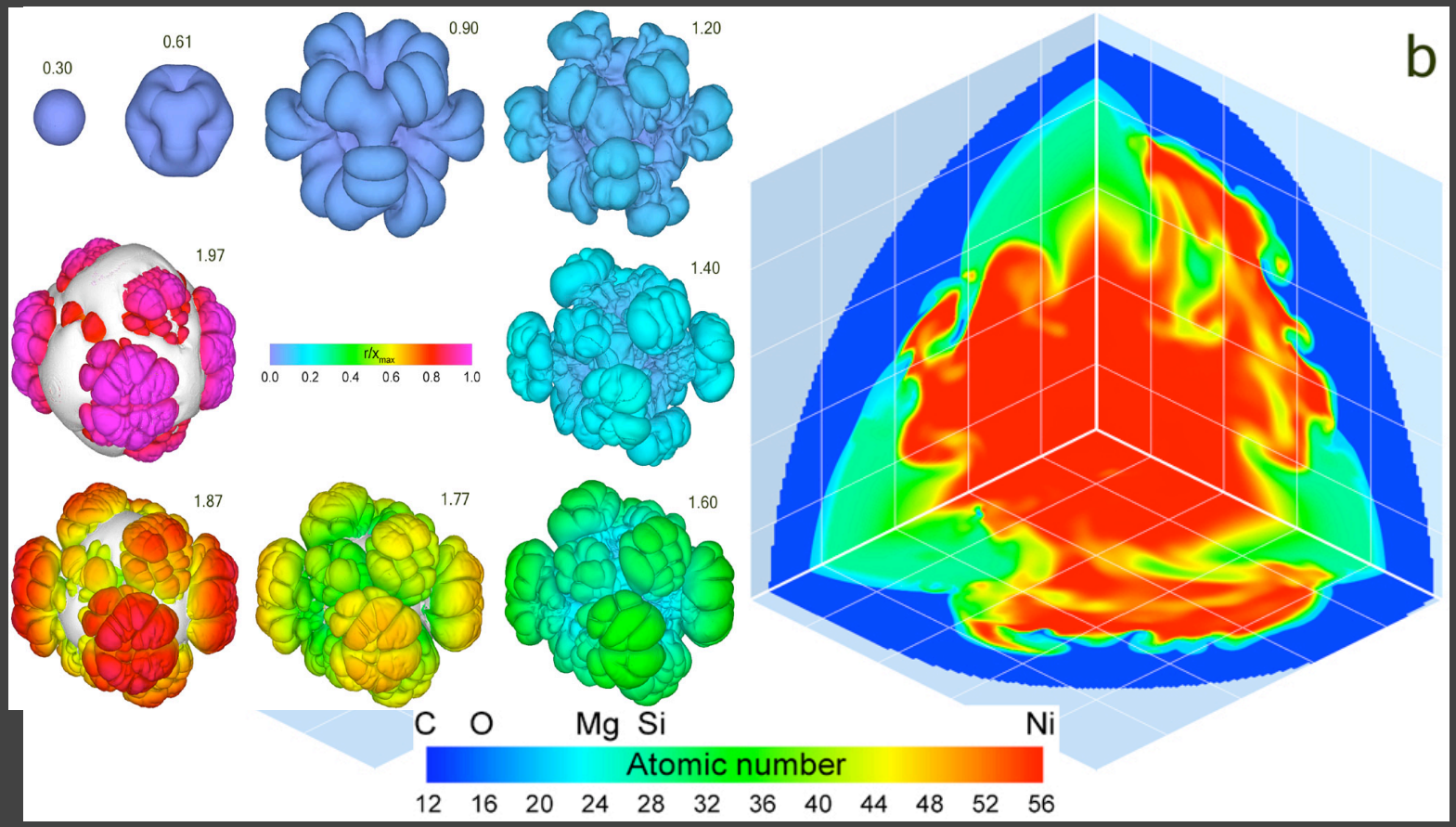
Hoflich, etal

- Small spread in brightness-decline requires similar explosion energies
- Progenitor metallicity (Z=0 ... solar) can produce systematics of about 0.3 mag.
- Color change of about 0.2 mag -> conflated with reddening

Turbulent 3-d Hydro w/ Radiation Transport

Deflagration is the engine of asymmetry

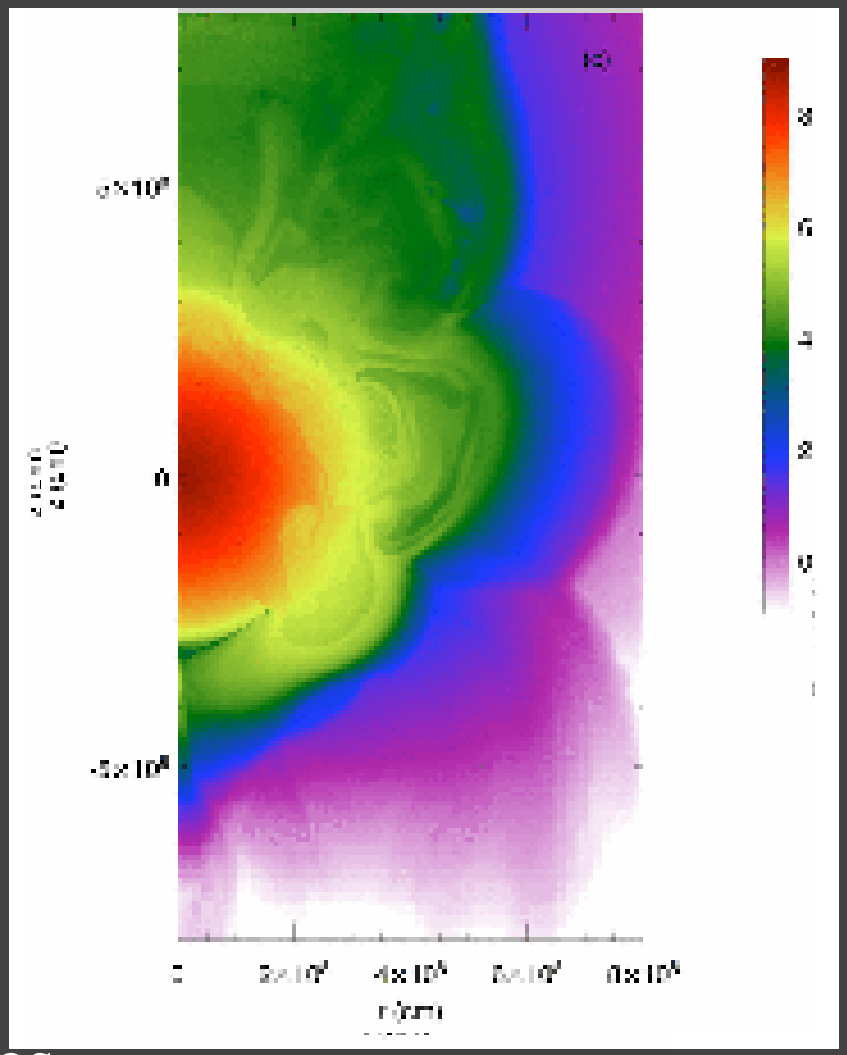
Detonation restructures the ejecta



Niemeyer, Hillebrandt, etal

Deflagration-Detonation Transition not Understood

Do we need to understand the explosion mechanism(s) in detail to have confidence in SN systematics? Perhaps not, but theory can point to observables to break degeneracies

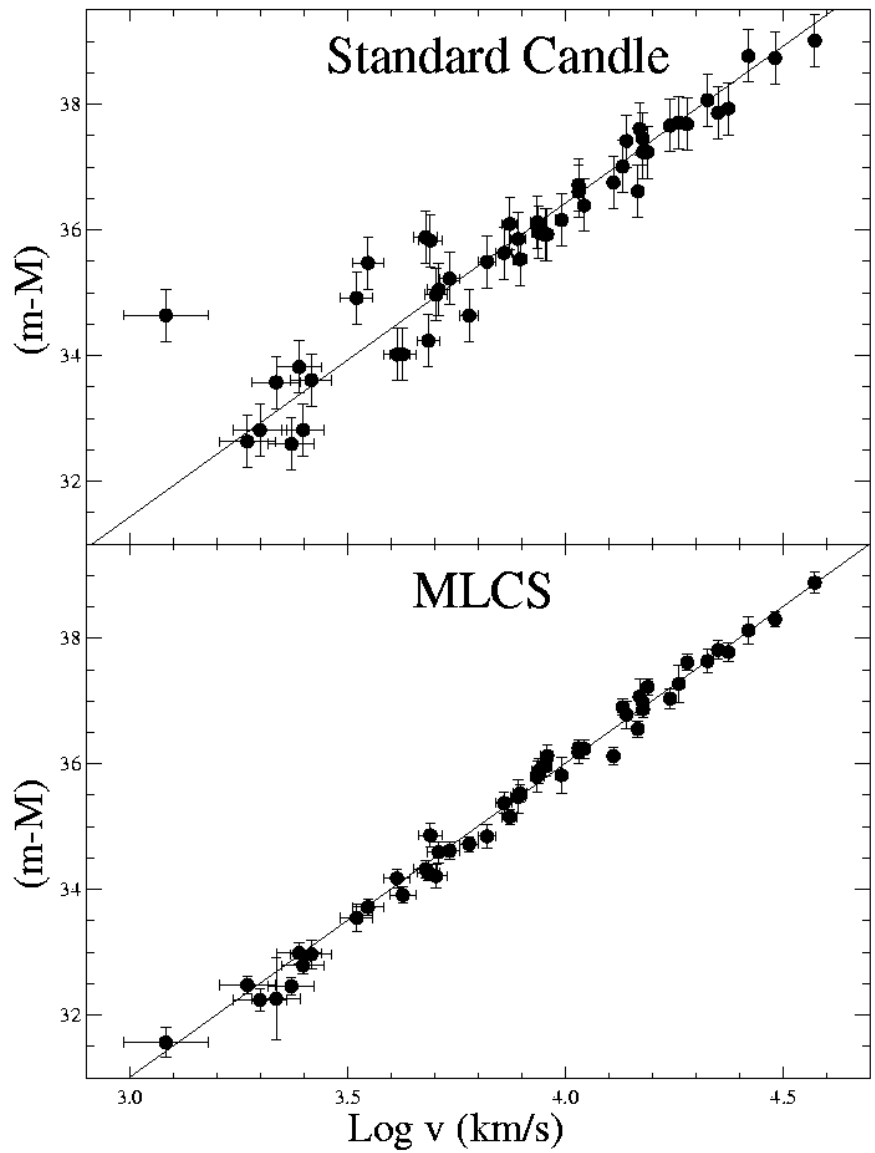


Gravitationally Confined Detonation: Deflagration Bubble rises, propagates around surface, then detonates

Plewa etal 04

Correction for Brightness-Decline relation reduces scatter in nearby SN Ia Hubble Diagram

Riess etal 96



$$m(z) - M_B = -5\log(H_0) + 25 + 5\log[H_0 D_L(z, \Omega_m, \Omega_{DE}, w)] + K_{Bx} + A$$

Distance modulus

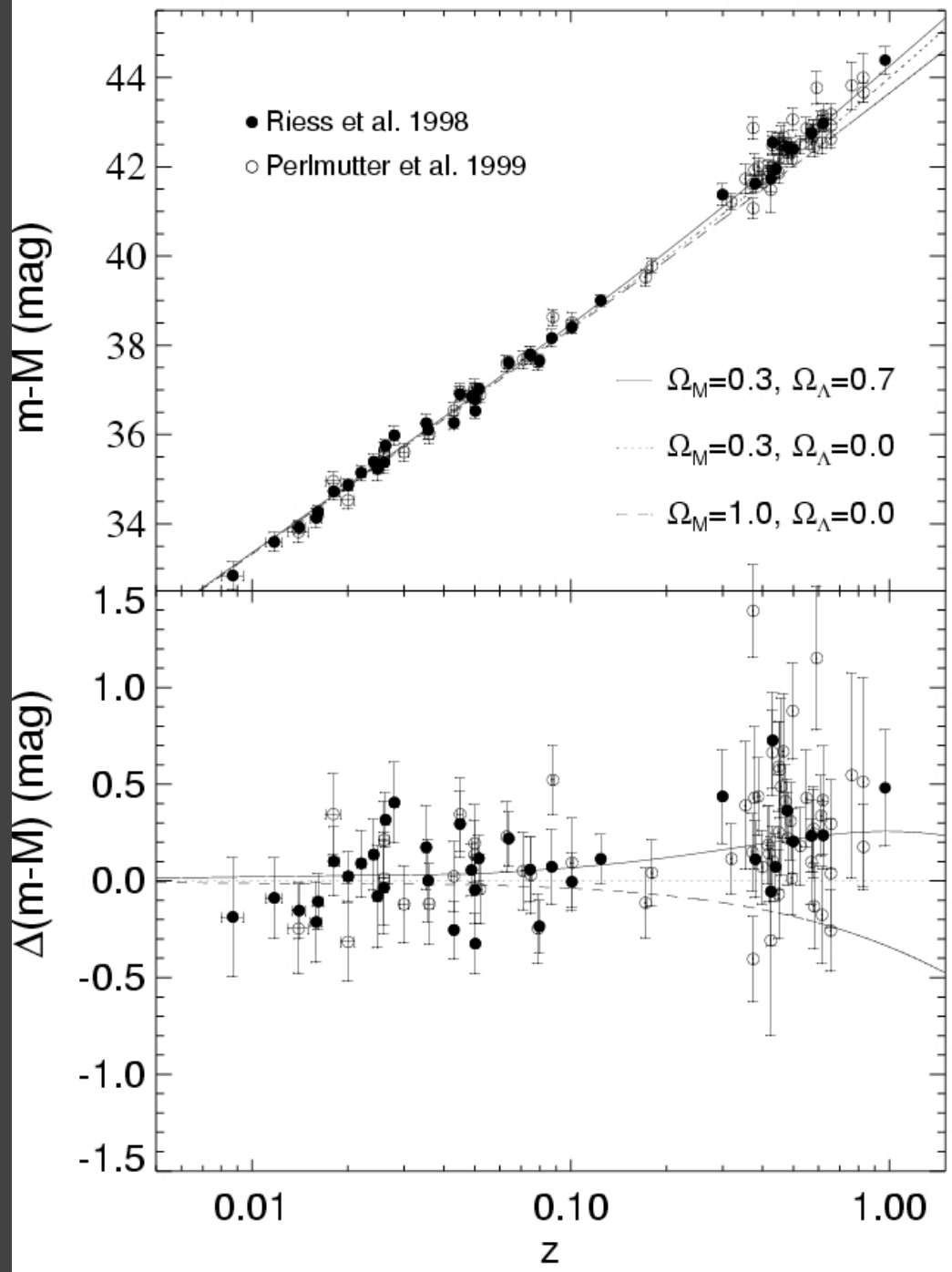
Luminosity Distance

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{[1 + \Omega_x((1+z)^{3w} - 1)]^{-1/2}}{(1+z)^{3/2}} \, dz$$

Dark Energy Discovery from High-redshift SNe Ia

Apply same Brightness-Decline relation at High-z

SNe at z~0.5 are ~0.25 mag fainter than in an empty Universe

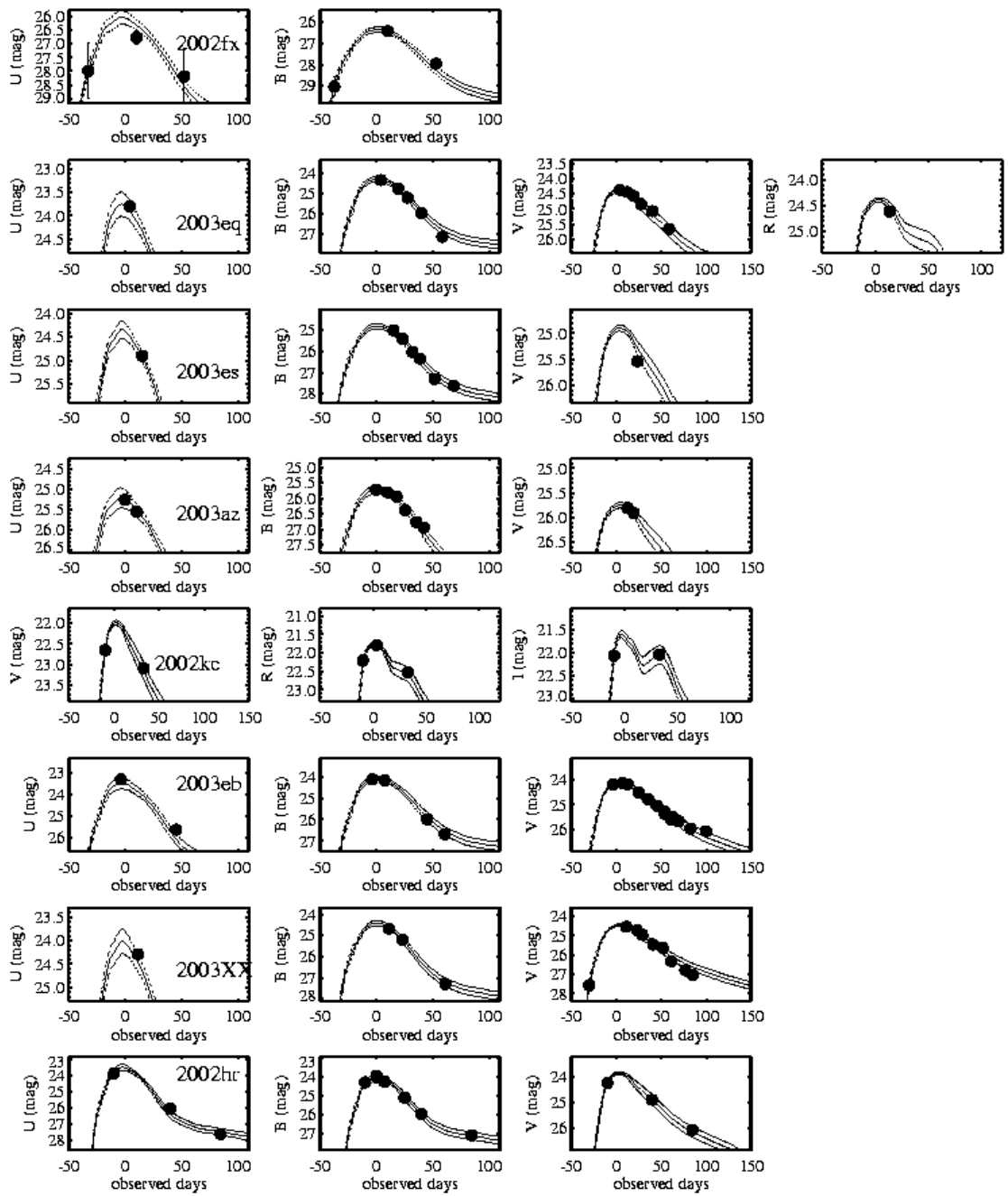


$\Omega_\Lambda = 0.7$
$\Omega_\Lambda = 0.$
$\Omega_m = 1.$

High-Redshift SN Light-curves: HST GOODS

z > 1

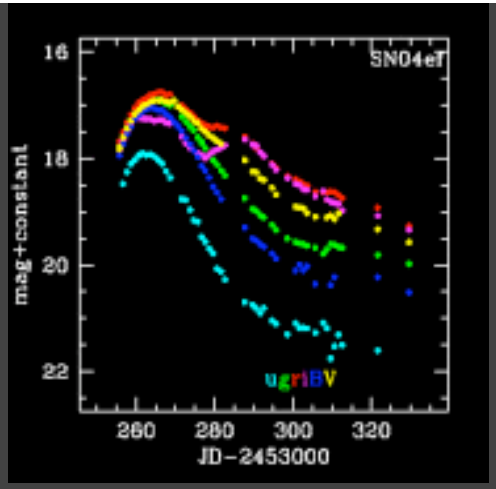
Riess etal 2004

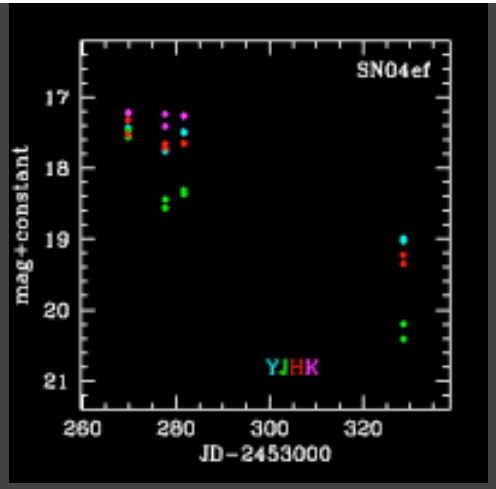


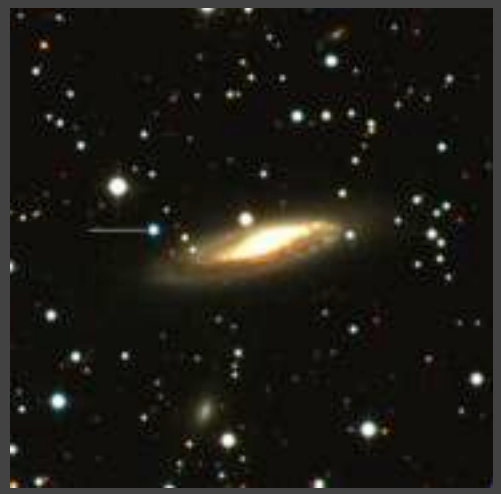
Carnegie Supernova Project

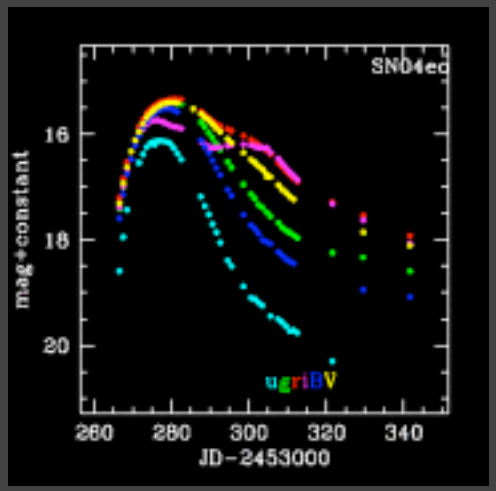
Nearby Optical+ NIR LCs

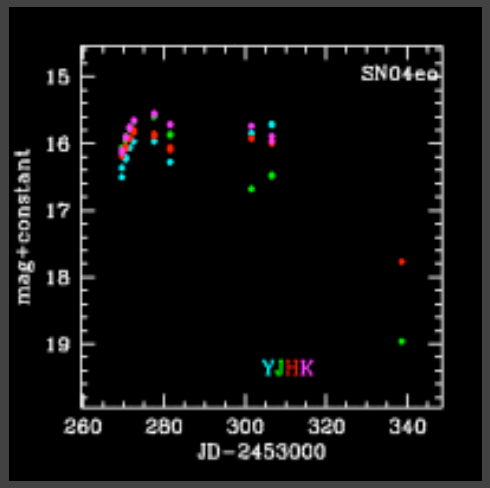
High-z samples still lower quality

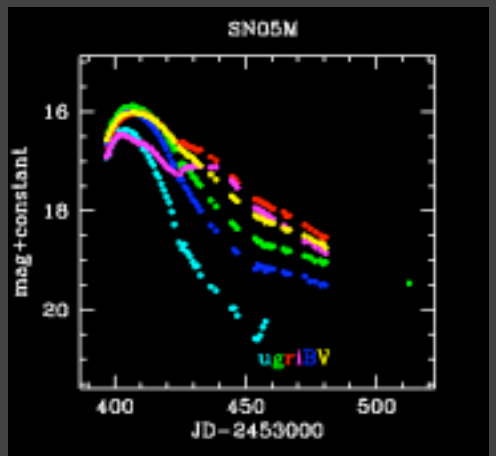


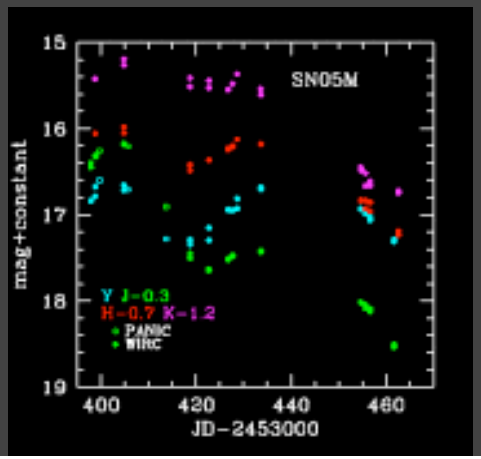


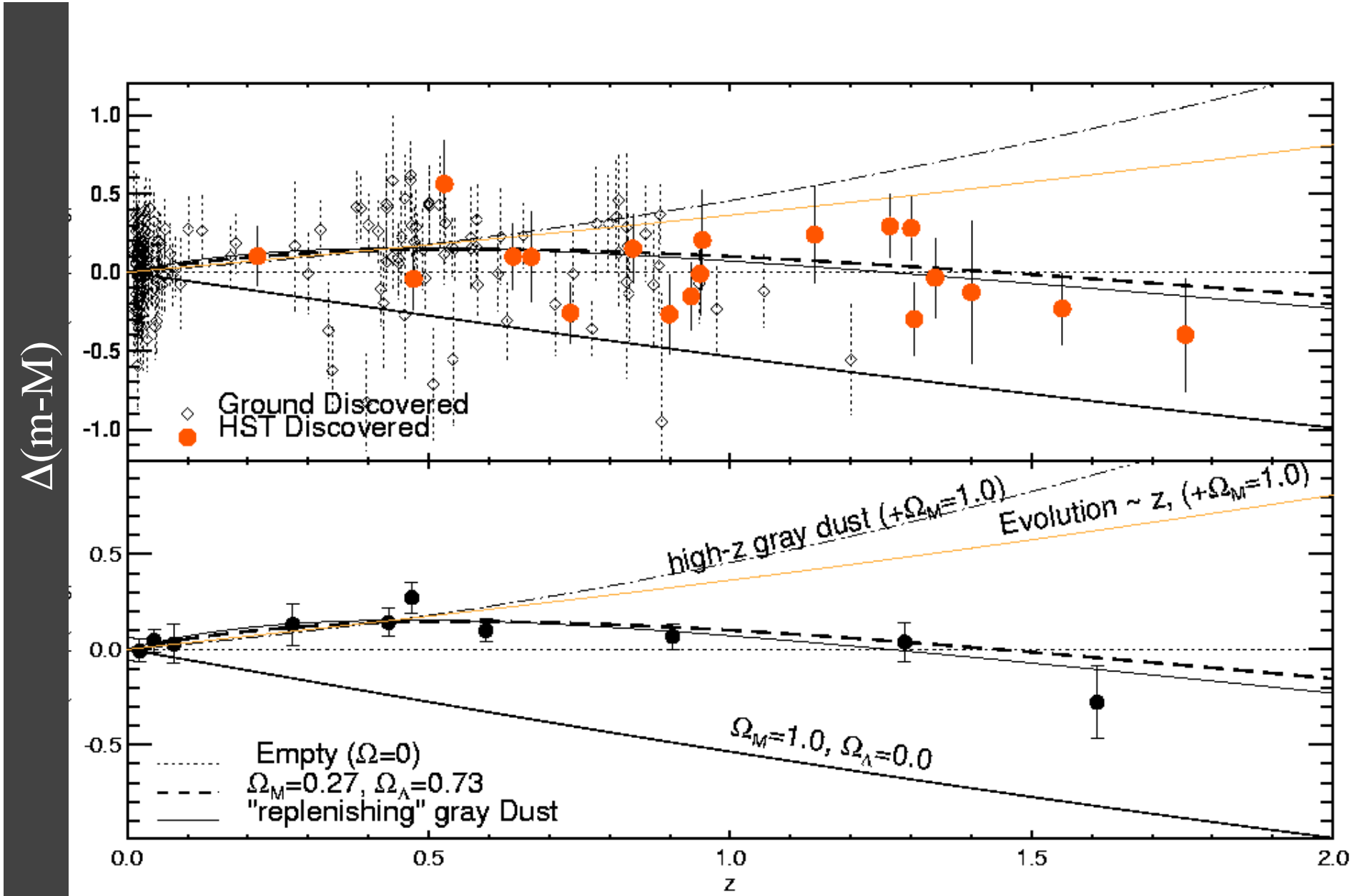












HST GOODS Survey (z>1)+

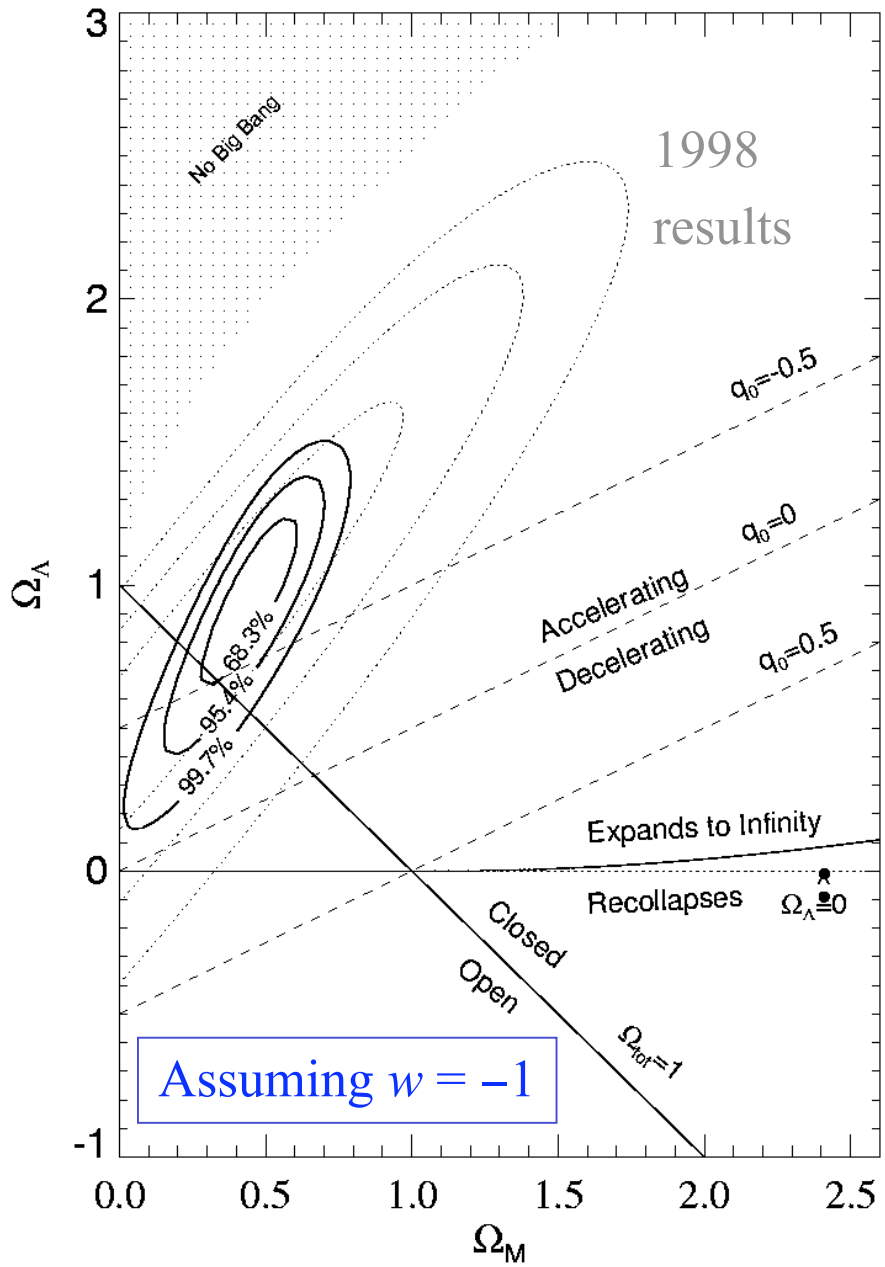
compiled ground-based SNe

Riess etal 04

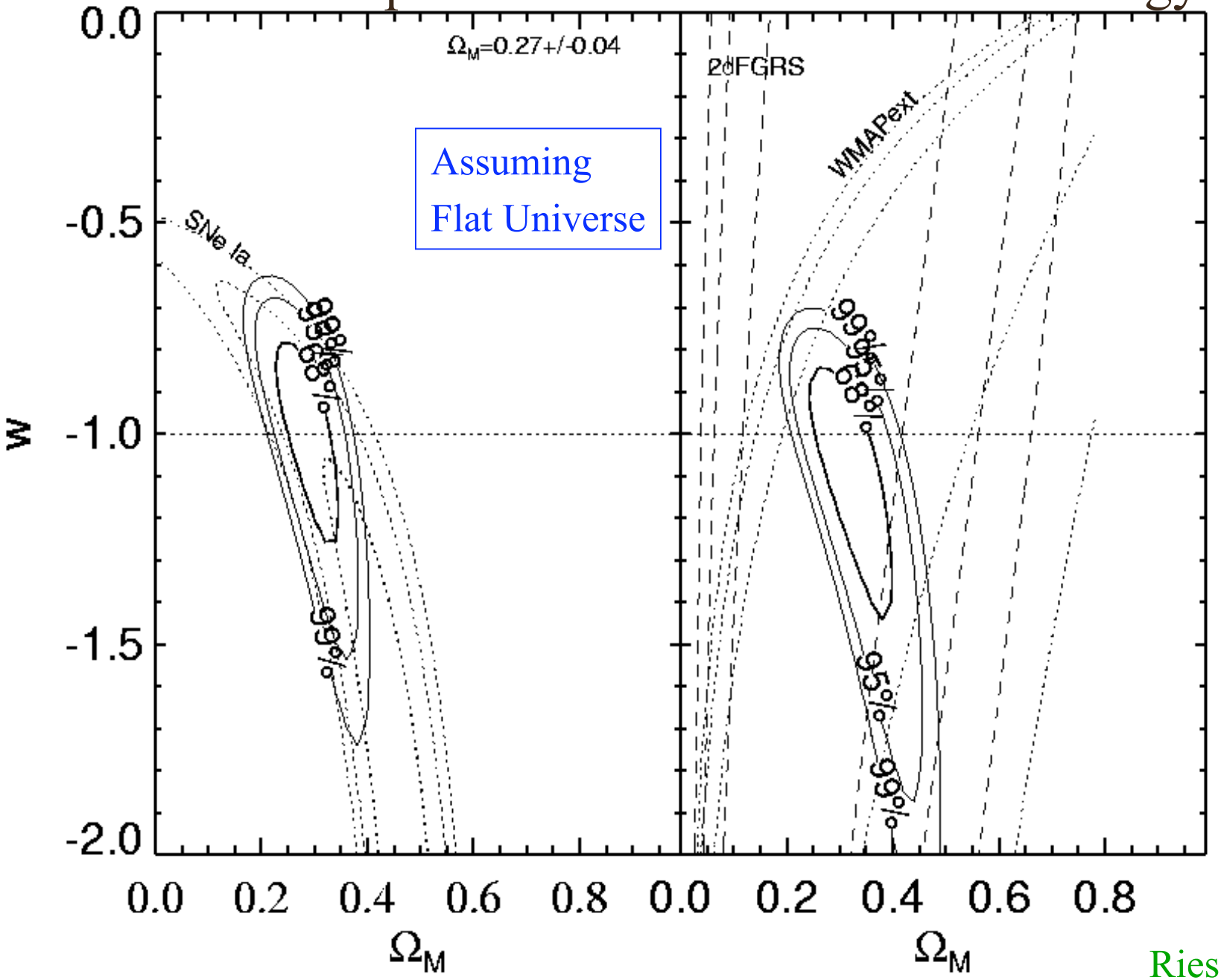
Current Cosmological Constraints

HST GOODS+
Ground-based Sne:
`Gold' sample of
157 SNe

Riess etal 04
See also: Knop etal 03
Tonry etal 03

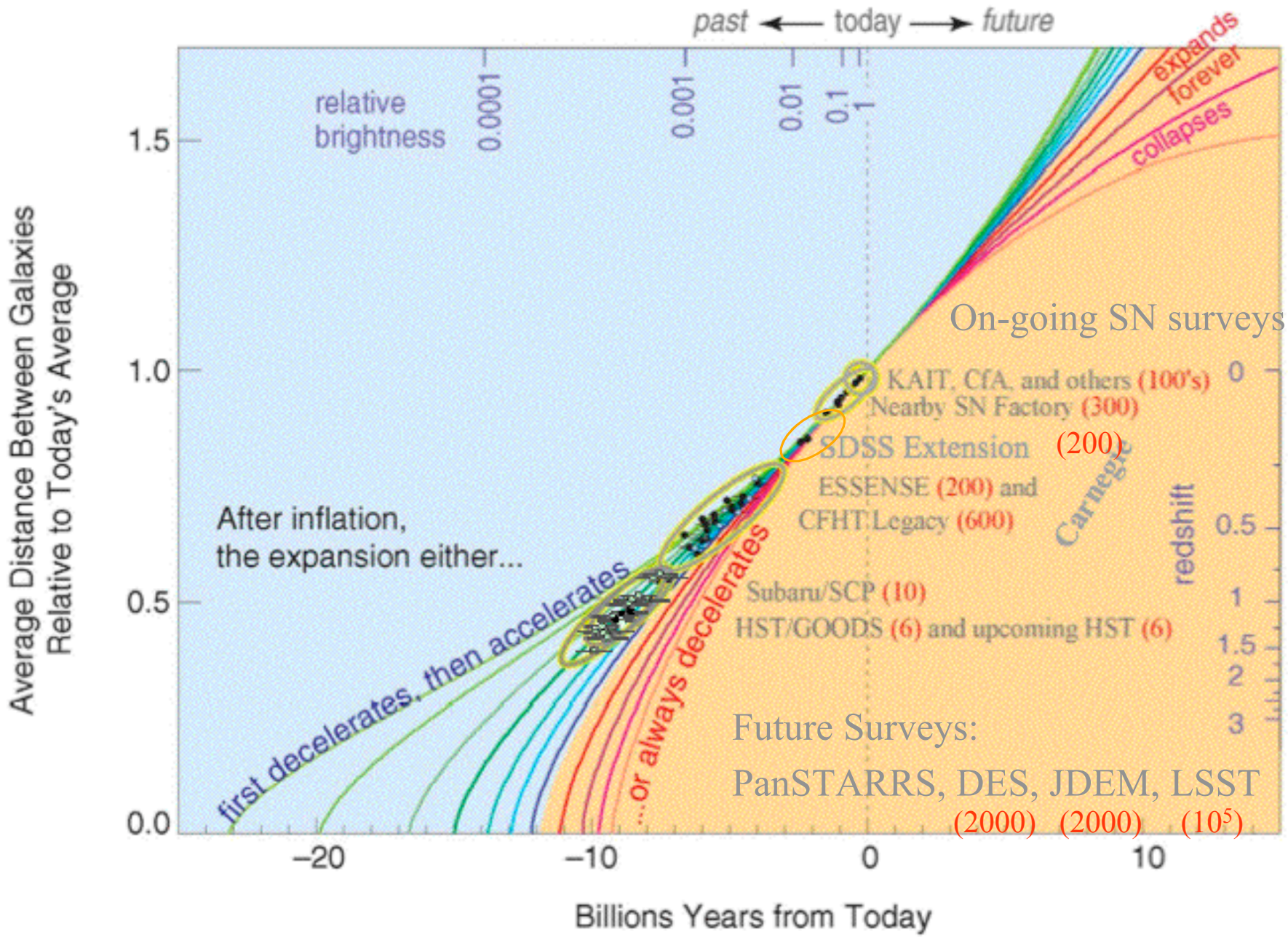


Recent Supernova Constraints on Dark Energy

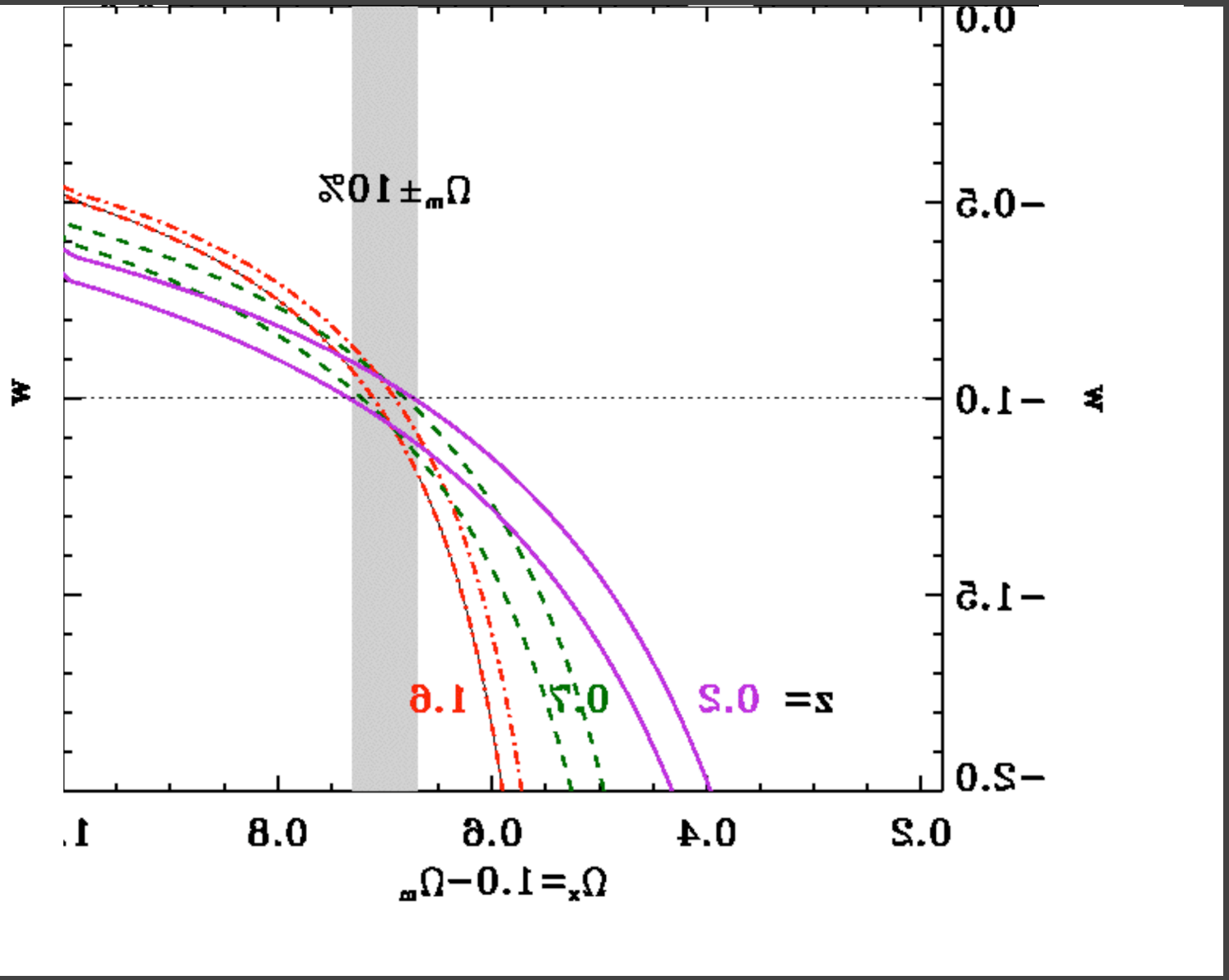


Riess, etal 04

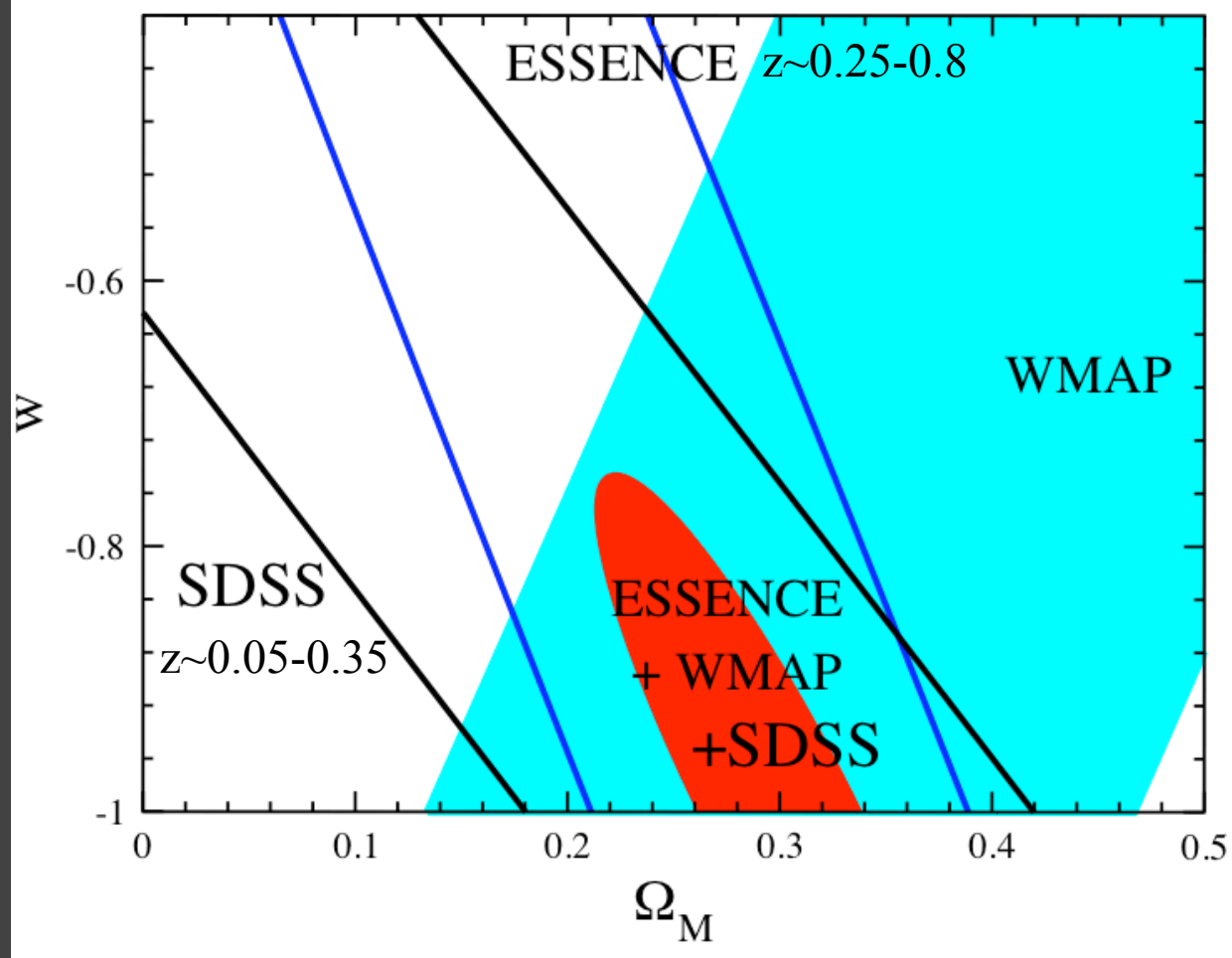
Where we're going



Need Broad Redshift Coverage to Break Degeneracies



Complementarity with CMB: Near-term



Forecast: $\sigma(w) = 0.1$ from SDSS+ESSENCE+WMAP+LSS

(statistical errors only, constant w, flat Universe)

SDSS and SDSS II

- SDSS I: April 2000-June 2005
- SDSS II: July 2005-2008
  - Legacy Survey (complete northern survey) ~10^6 redshifts
  - SEGUE (low-latitude survey of Milky Way)
  - Supernova Survey

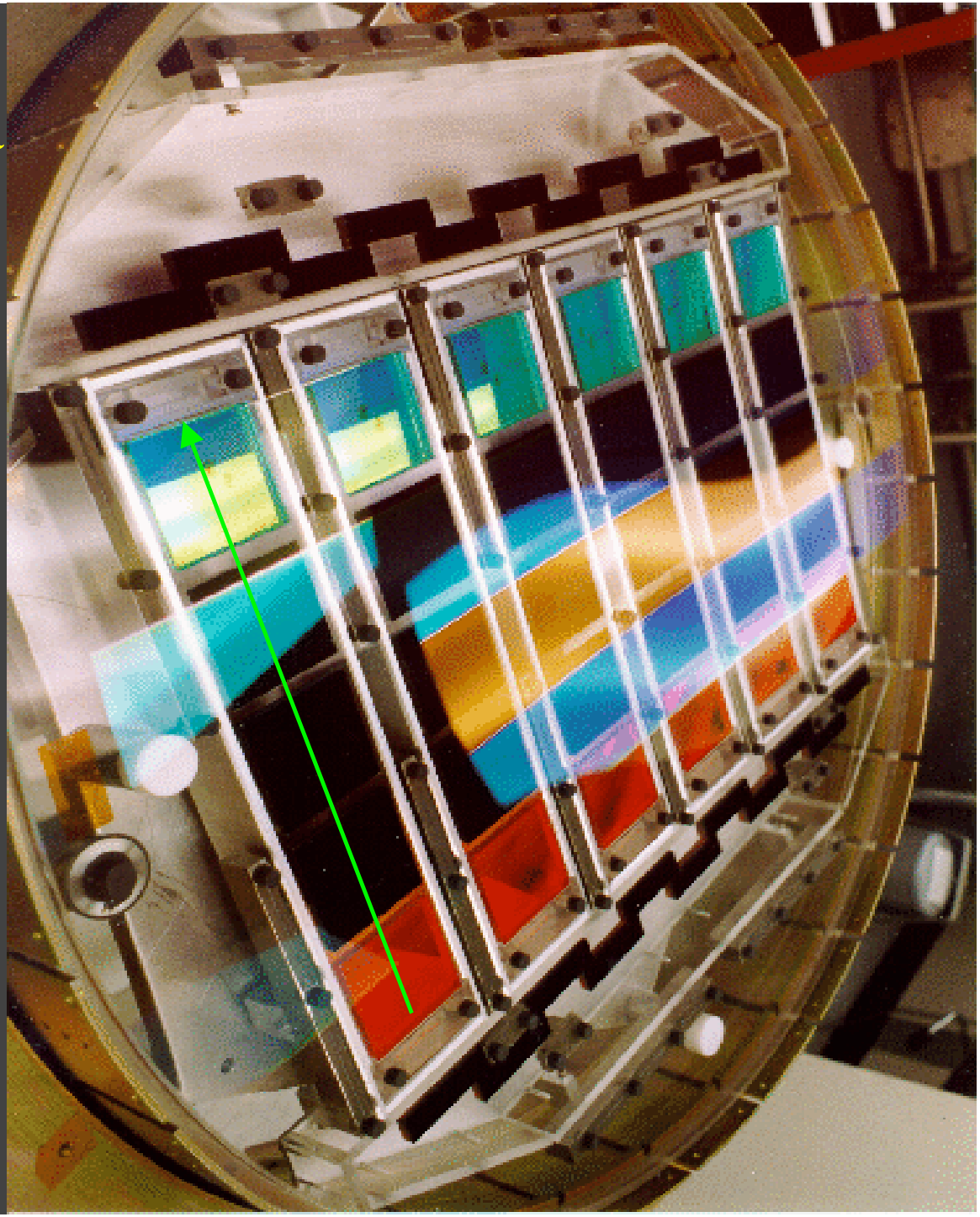
SDSS 2.5 meter Telescope

SDSS Imaging Camera

Top to bottom:

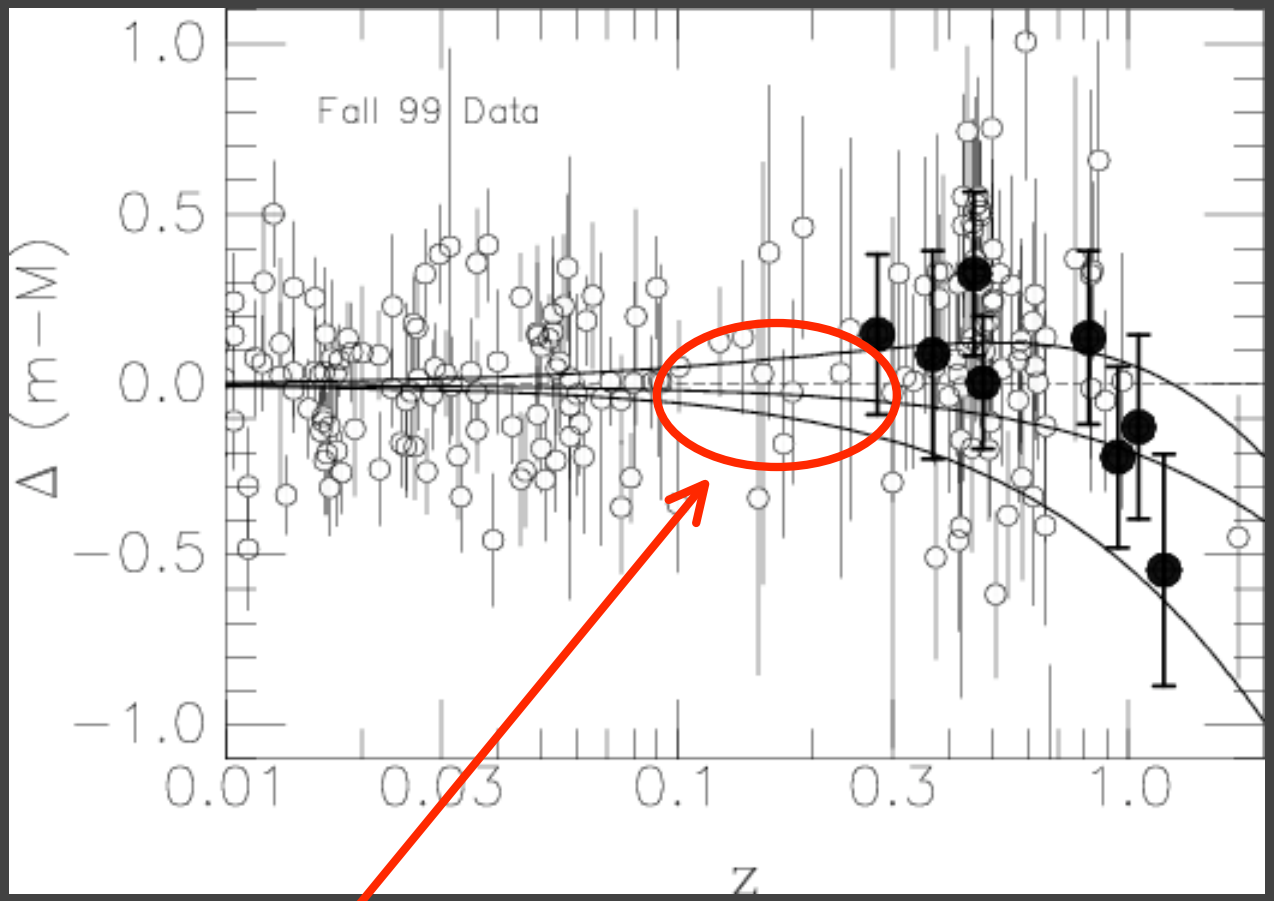
g’
z’
u’
i’
r’

Drift Scan Mode



Compiled Supernovae Ia Sample

Brightness relative to empty Universe: ($\Omega_m = \Omega_\Lambda = 0$)



Ω_m Ω_Λ

0.3, 0.7

0.3, 0.0

1.0, 0.0

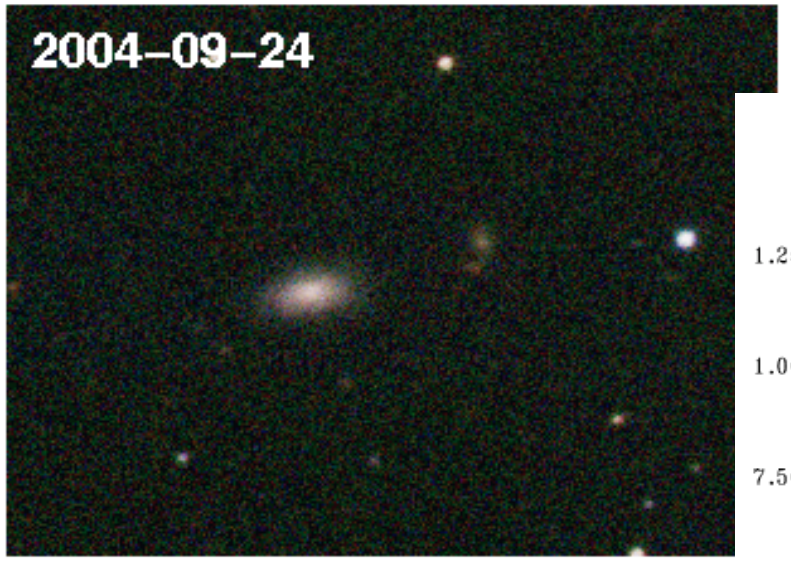
`Gold' sample of 157 SNe included only 6 between z = 0.1-0.3; SDSS naturally fills this gap

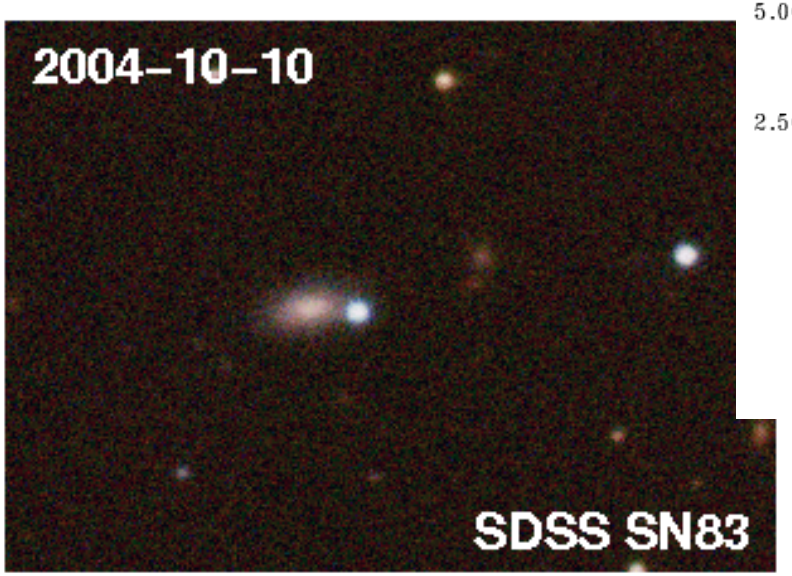
Tonry etal '03

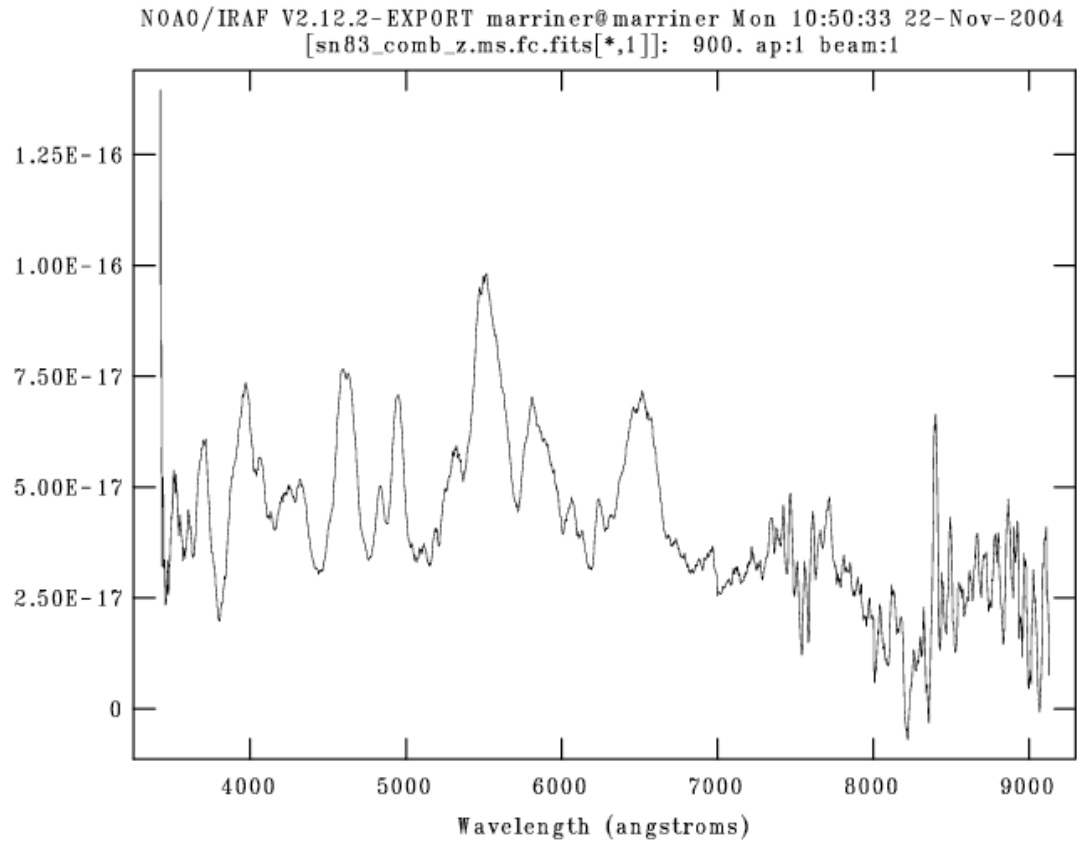
Riess etal '04

SDSS SN Science Goals

- Obtain ~200 *high-quality* SNe in the redshift desert:
  repeat multi-band data over ~250 square degrees
- Probe Dark Energy in *z* regime less sensitive to evolution than deeper surveys
- Study SN Ia systematics (critical for SN cosmology) with high photometric accuracy
- Search for additional parameters to reduce Ia dispersion
- Determine SN/SF rates/properties vs. *z*, environment
- Rest-frame *u*-band templates for z >1 surveys
- Study feasibility of cosmology with SN colors
- Database of Type II and rare SN light-curves



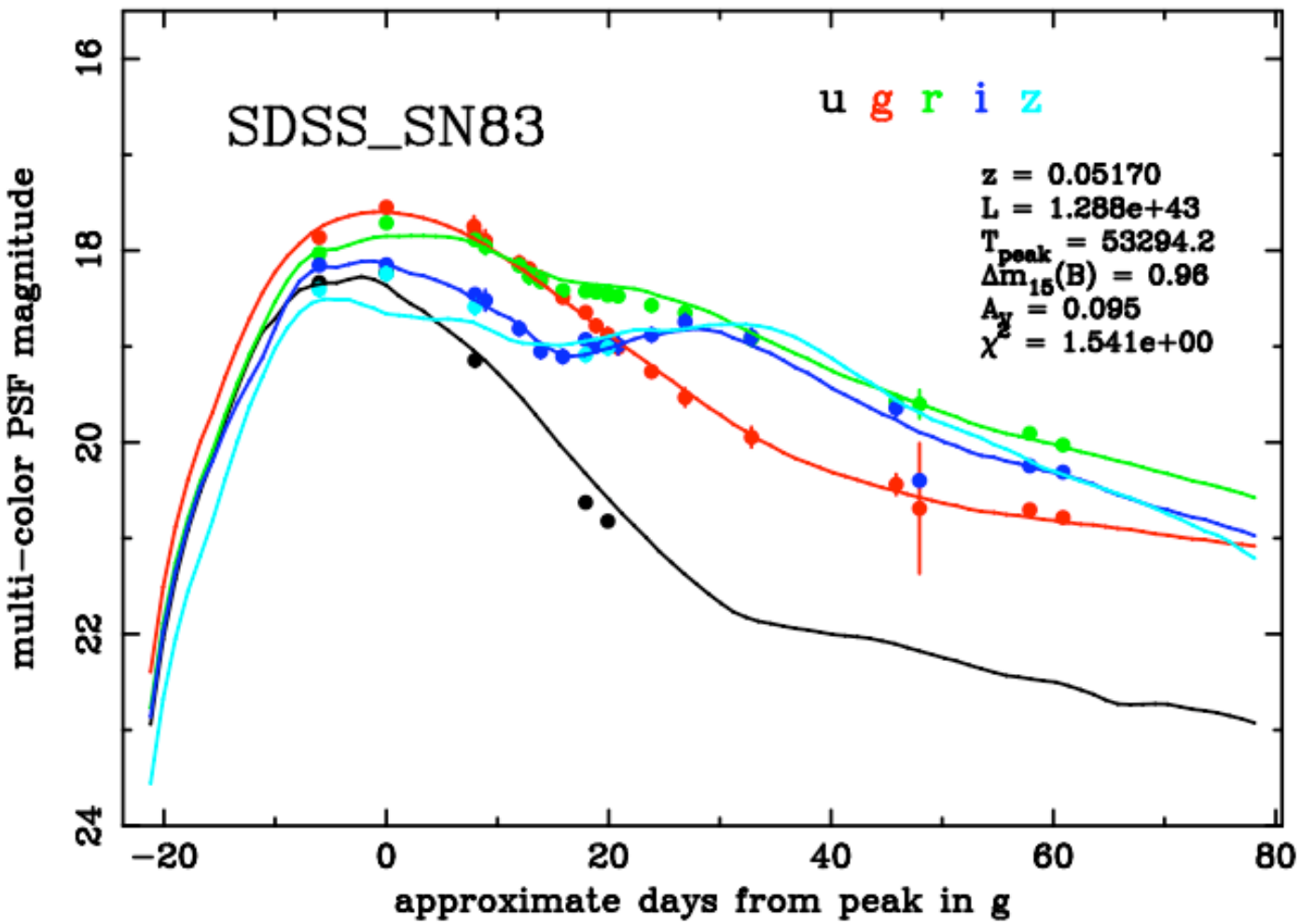




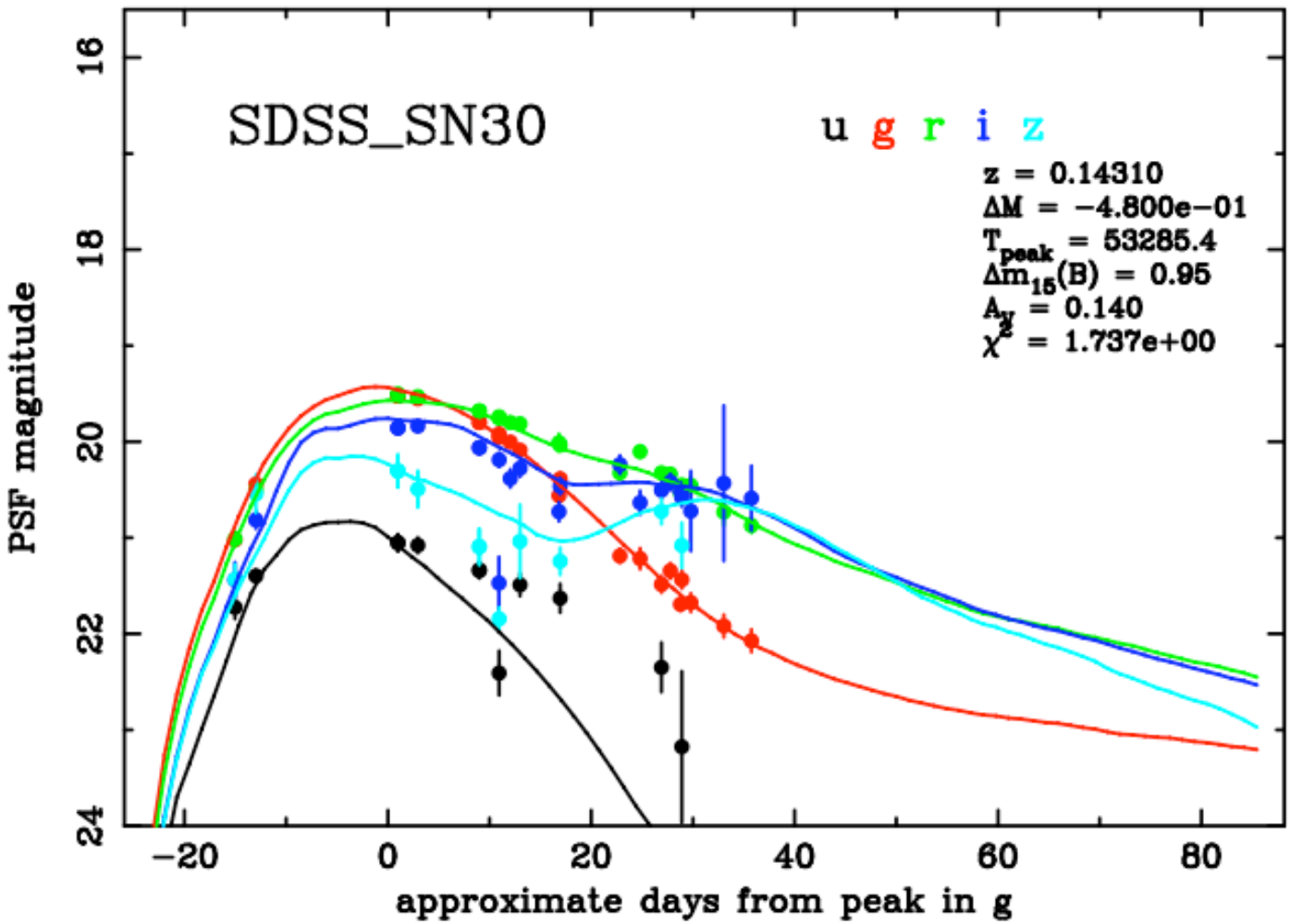
SN Ia z=0.0513

3 epochs of ARC 3.5m spectroscopy

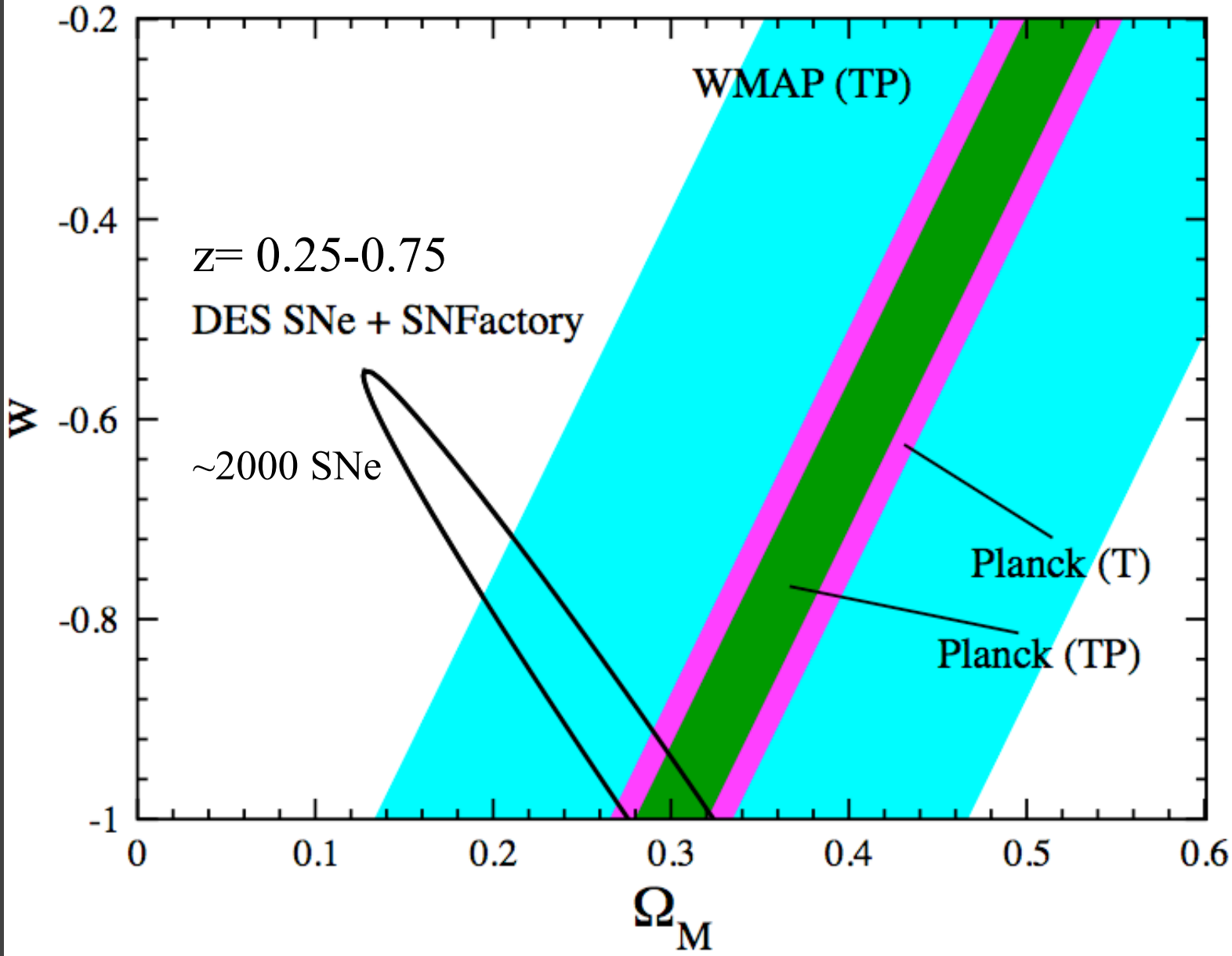
2004ie: Observed vs. Synthetic Light-curves (preliminary)



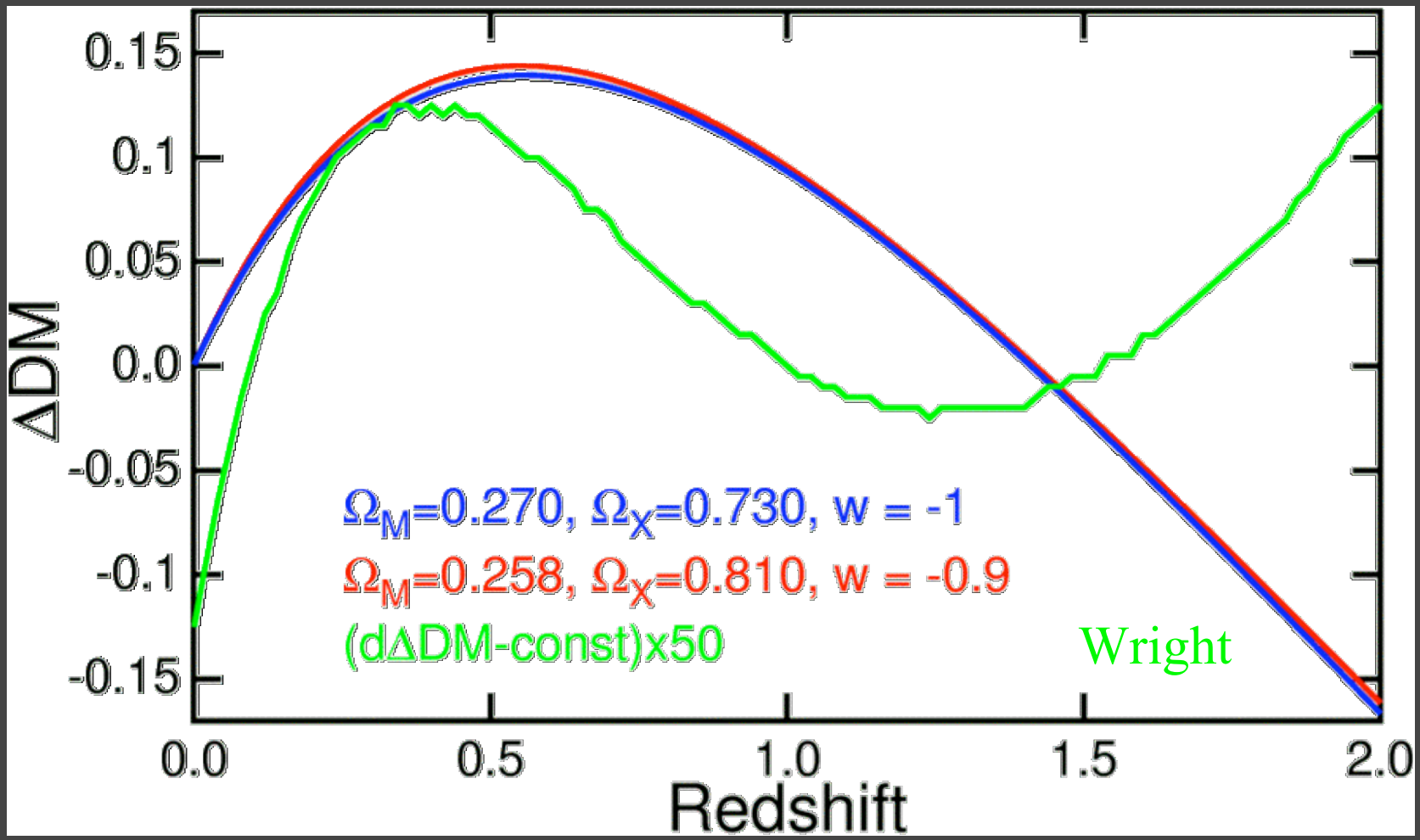
2004ia: Observed vs. Synthetic Light-curves (very preliminary)



Complementarity: CMB Anisotropy

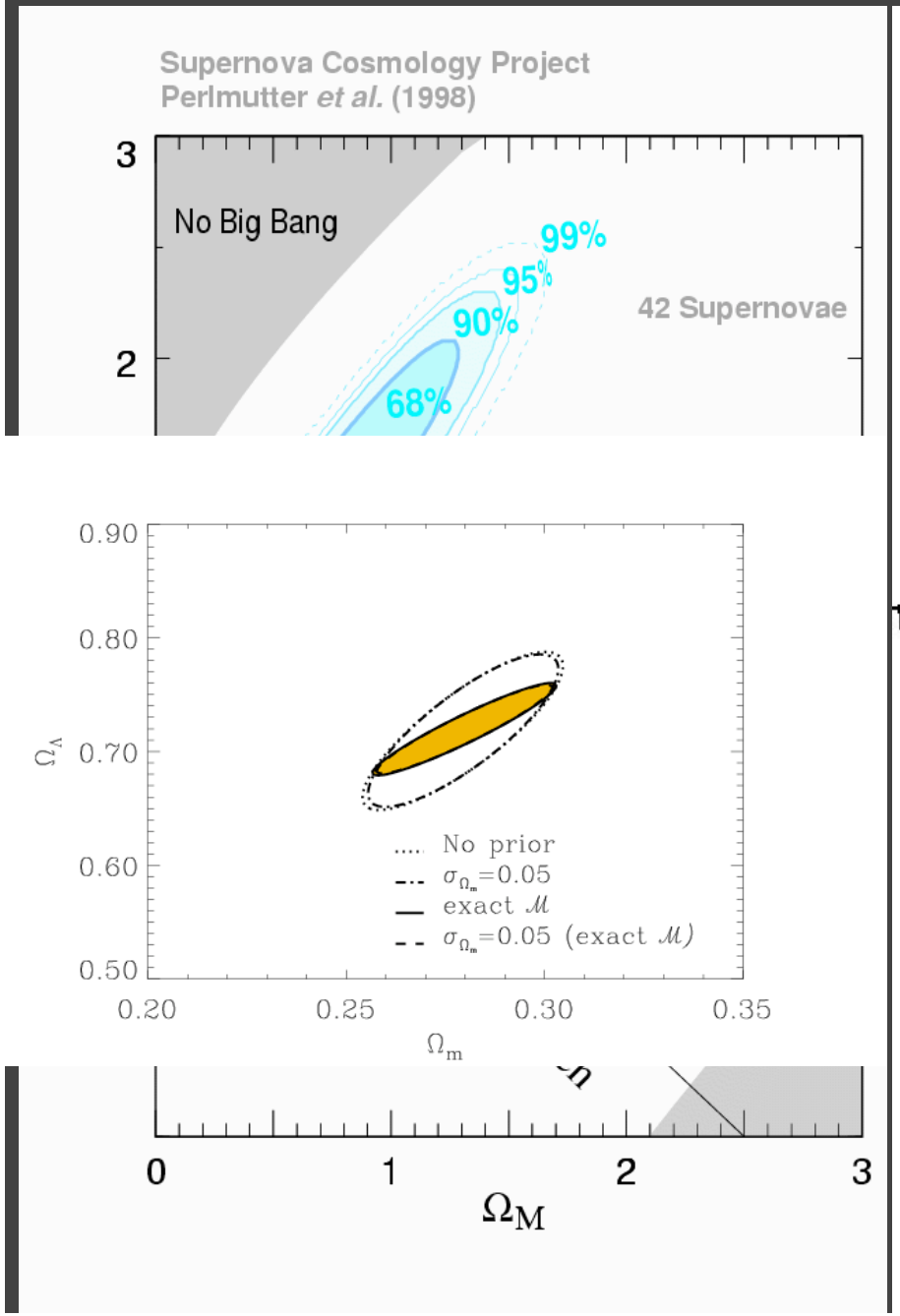


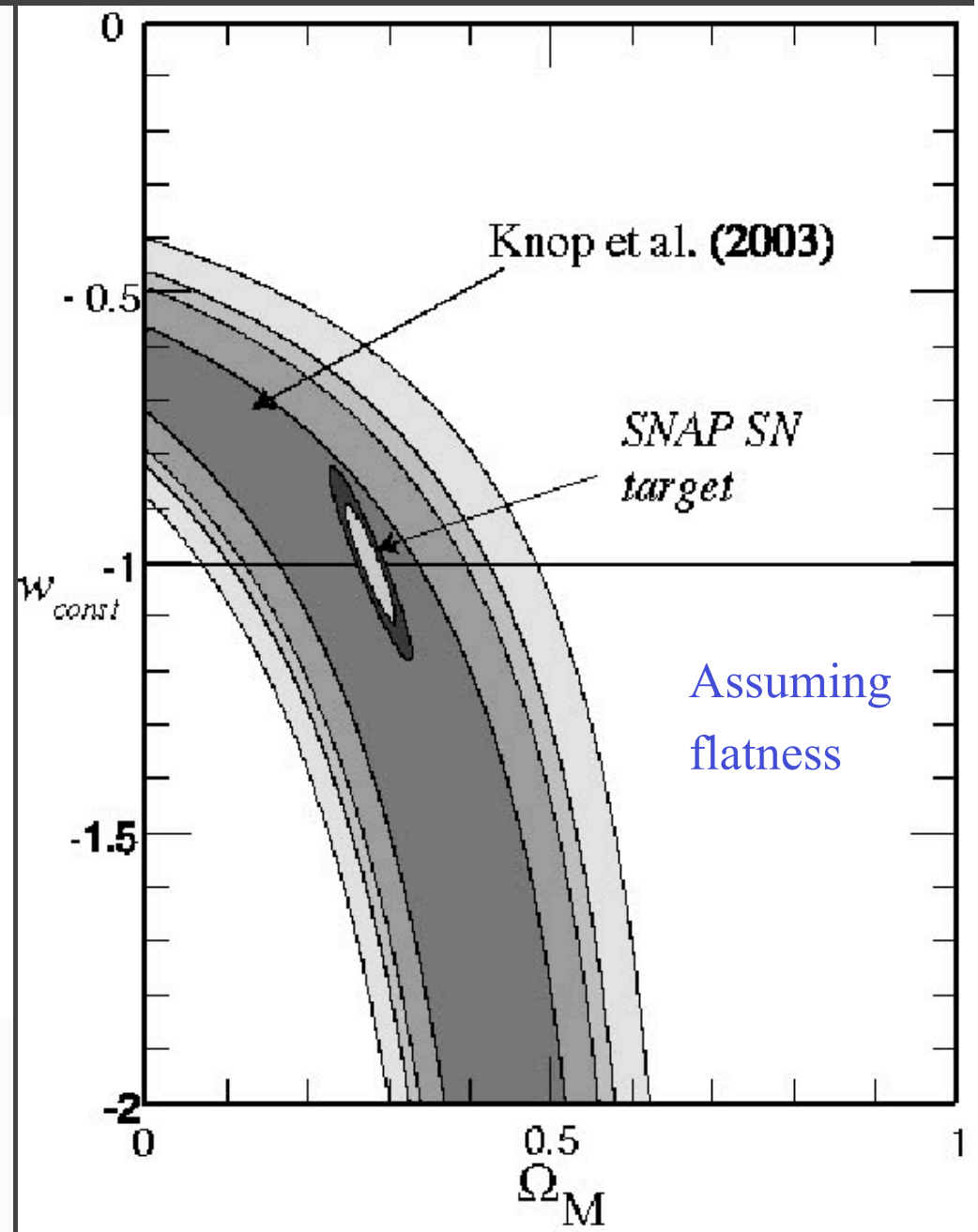
Non-flat comologies: further degeneracies



Models with w = -1 and -0.9 agree to within ± 2 millimag, after adjusting Ω_m, Ω_Λ and M (the absolute magnitude or Hubble constant). Need CMB prior on spatial geometry.

Dark Energy: Where we want to get

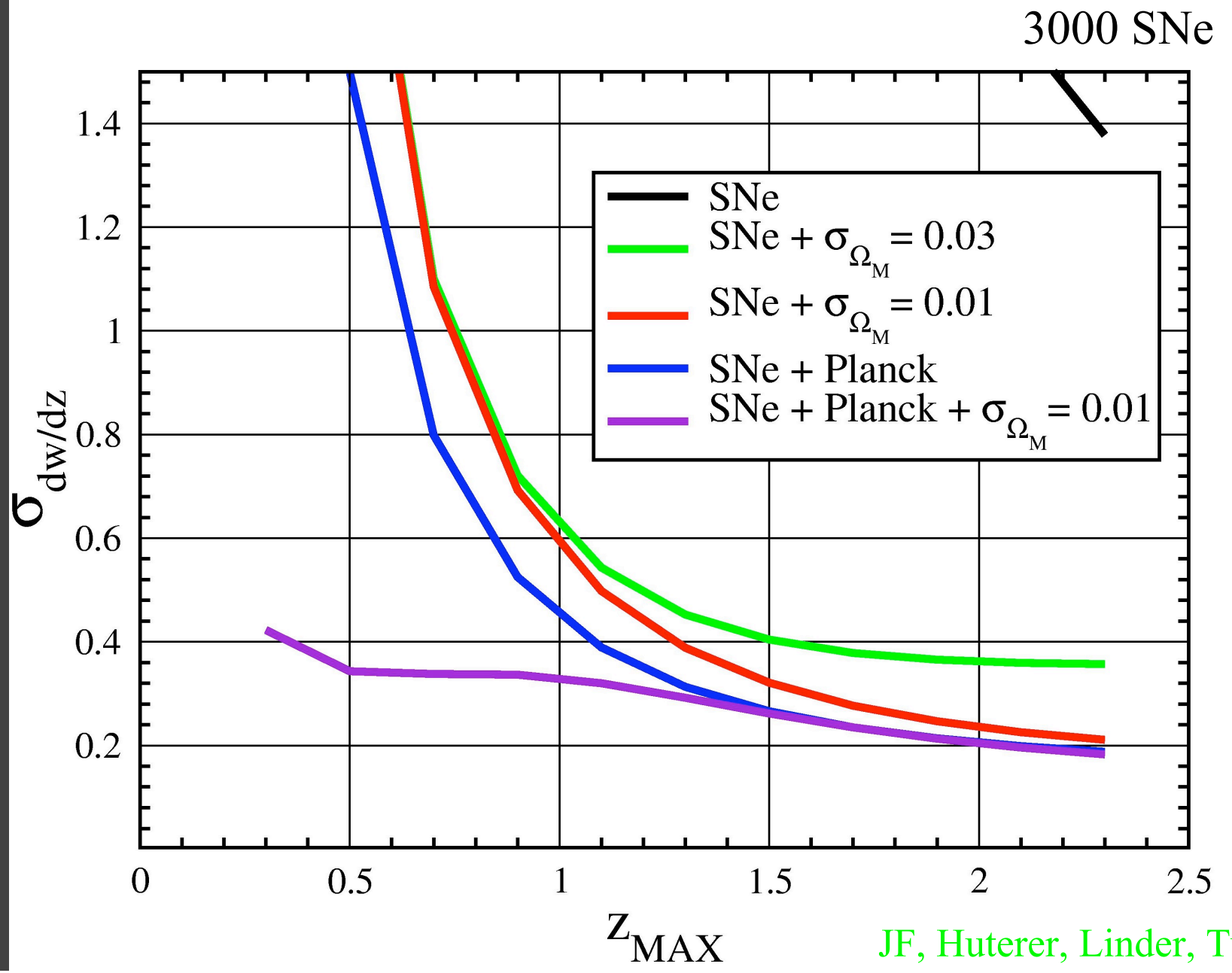




How do we get there?

- Goal: Determine w_0 to ~5% and dw/dz to ~10-20% with SNe.
- Statistical Requirement: ~1% relative distance measurements (2% flux) in Δz~0.1 redshift bins.
- Assume systematic error can be reduced to this level (to be demonstrated).
- This requires ~3000 SNe spread over z ~ 0.3-1.7 and a well-observed sample at low *z* to anchor the Hubble diagram.

Probing Dark Energy Evolution: 2% Mag Systematic Error Floors

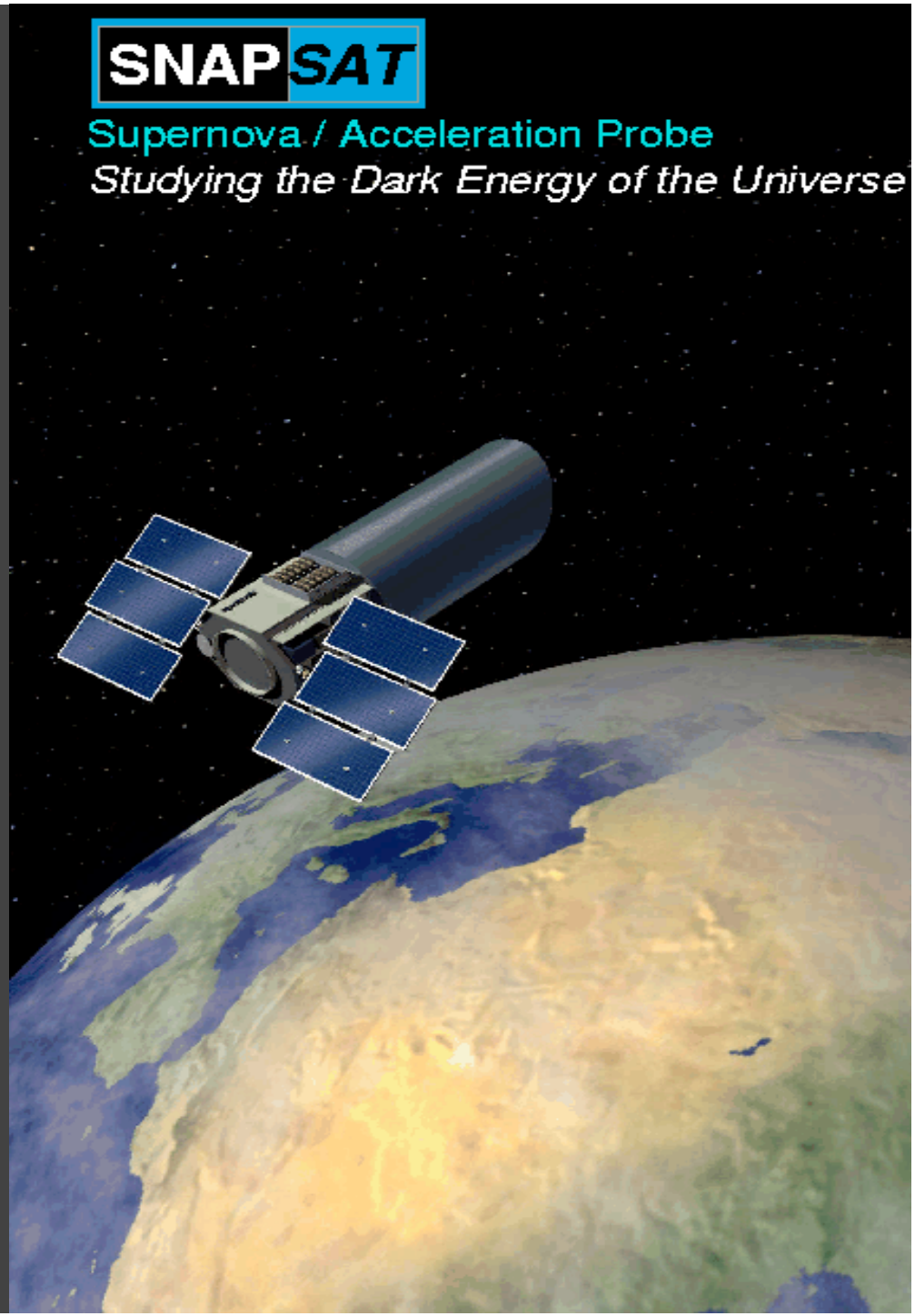


JF, Huterer, Linder, Turner

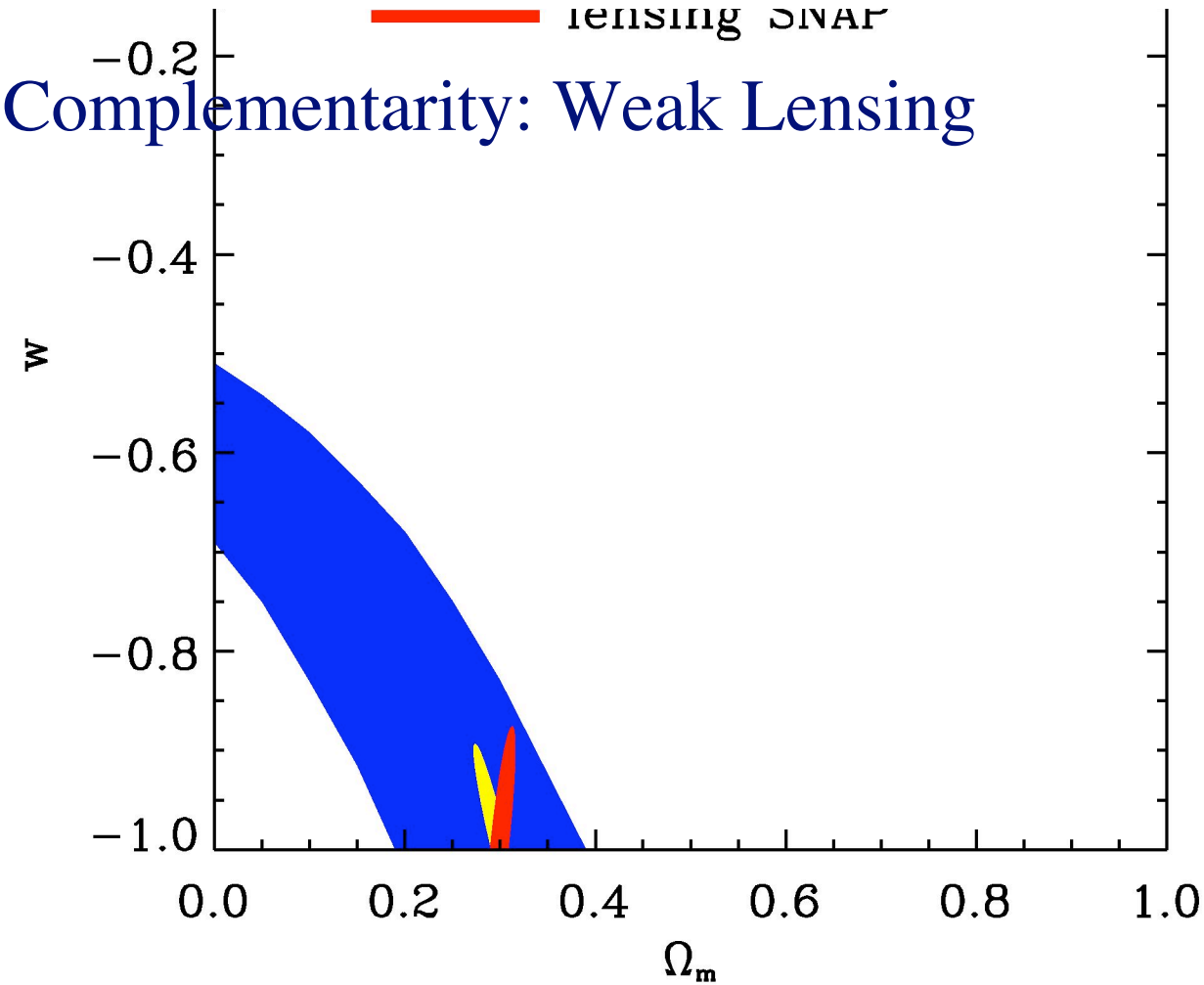
NASA/DOE Joint Dark Energy Mission (JDEM): observe ~3000 SNe Ia out to z ~ 1.7.
See also: DESTINY, JEDI

<u>Why Space?</u>
To probe z > 1, need NIR +Control systematics

Wide-field optical+NIR imager; O/IR spectrograph



Complementarity: Weak Lensing



Refregier etal 03

Type Ia Supernovae & Cosmology

Advantages:

- small dispersion in peak brightness (standardized candles)
- single objects (simpler than galaxies)
- can be observed over wide redshift range (bright)

Challenges/Systematic concerns:

- dust extinction (in or beyond host galaxy)
- chemical composition variations/evolution
- evolution of progenitor population
- photometric calibration, stability & host galaxy subtraction
- Malmquist bias
- environmental differences
- K correction uncertainties

Can we get there? Systematics Concerns

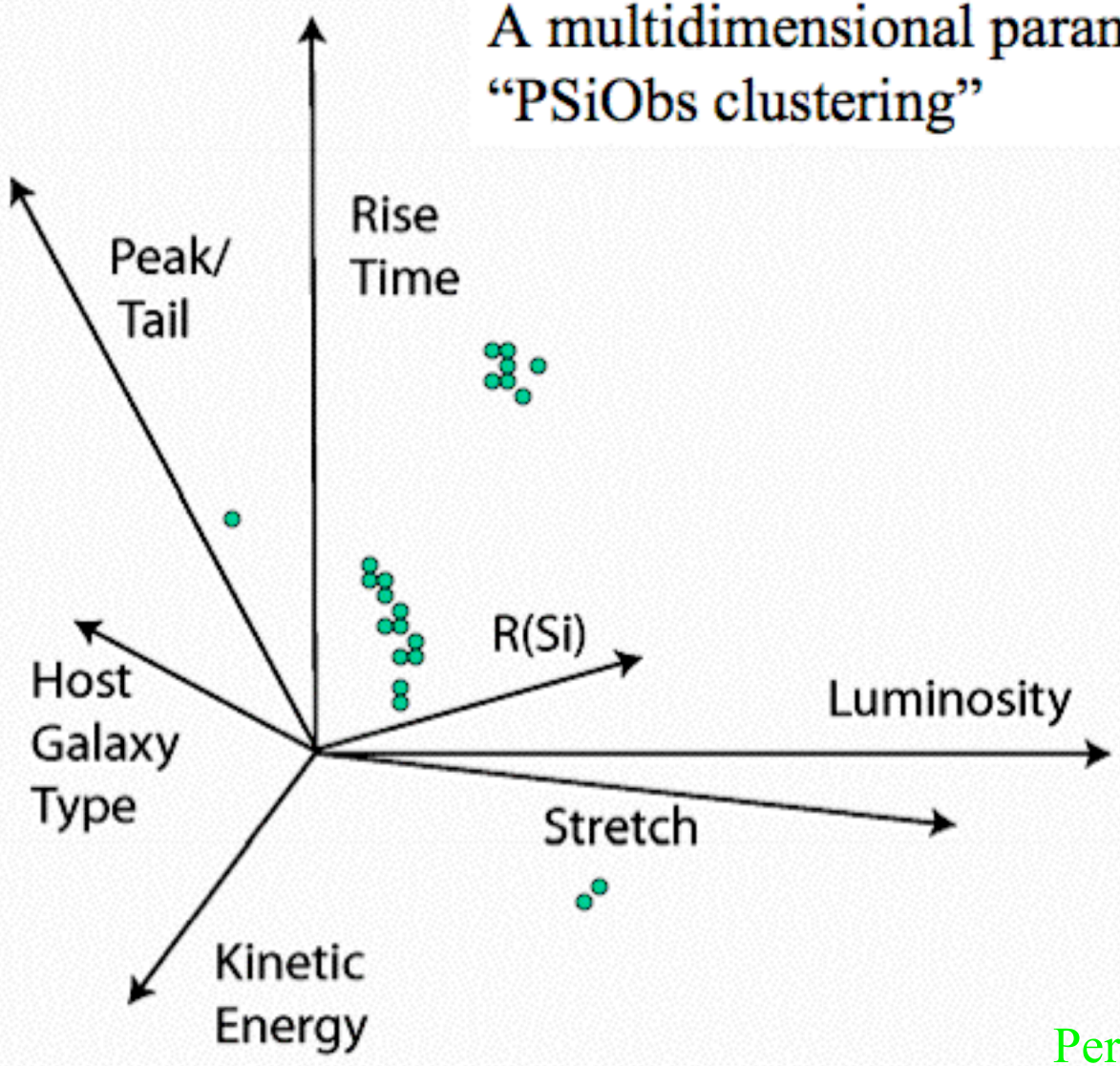
Luminosity Evolution:

We believe SNe Ia at z~0.5 are not intrinsically ~25% fainter than nearby SNe (the basis for Dark Energy). Could SNe at z~1.5 be 2% fainter/brighter than those nearby, in a way that leaves all other observables fixed?

Expectation: drift in progenitor population mix (progenitor mass, age, metallicity, C/O, accretion rates, etc).

Control: the variety of host environments at low redshift spans a much larger range of metallicity, etc, than the median differences between low- and high-z environments, so we can compare high-z apples with low-z apples, using host info., LC shape, colors, spectral features & spectral evolution, and *assuming* these exhaust the parameters that control L_{peak}.

A multidimensional parameter space: "PSiObs clustering"

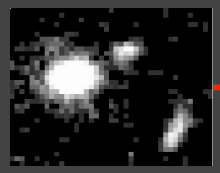


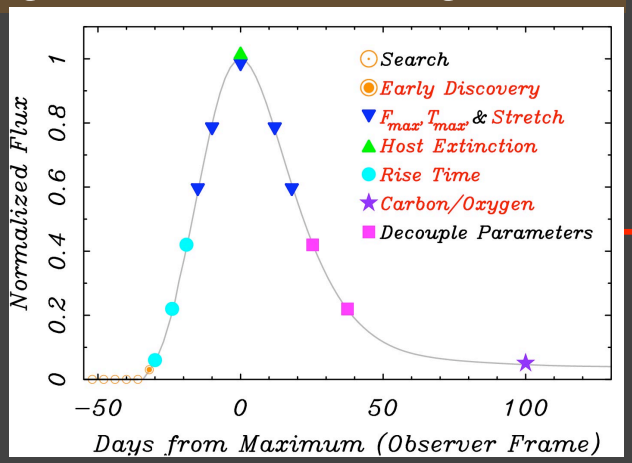
Perlmutter

SN Control of Systematics

Lightcurve & Peak Brightness

Images

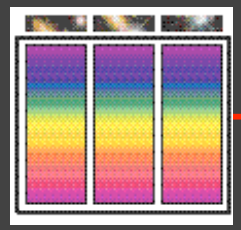


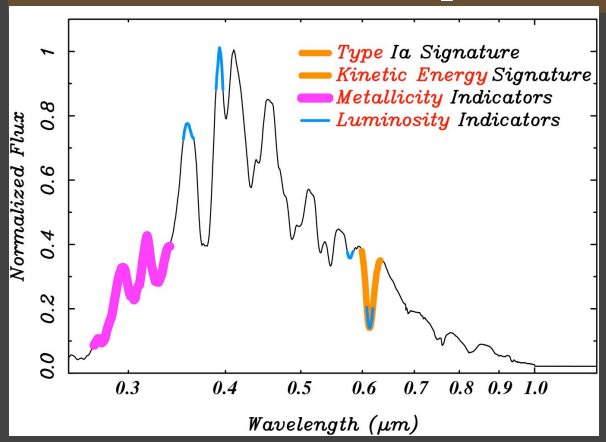


Dark Energy Properties

Redshift & SN Properties

Spectra





data → analysis → physics

Sort into Like Subsets

Group A:
* Si II in spectrum: type Ia
* elliptical host
* faint UV: high metallicity
* fast rise time: low Ni56 mass
* spectral feature velocities 9000 < v < 10000 km/s

⋮

Group B:
* Si II in spectrum: type Ia
* in core of late-type spiral host
* bright UV: low metallicity
* fast rise time: low Ni56 mass
* spectral feature velocities 9000 < v < 10000 km/s

⋮

Group C:
* Si II in spectrum: type Ia
* in outskirts of late-type spiral host
* bright UV: low metallicity
* long rise time: high Ni56 mass
* spectral feature velocities 8000 < v < 9500 km/s

⋮

• • •

Gro
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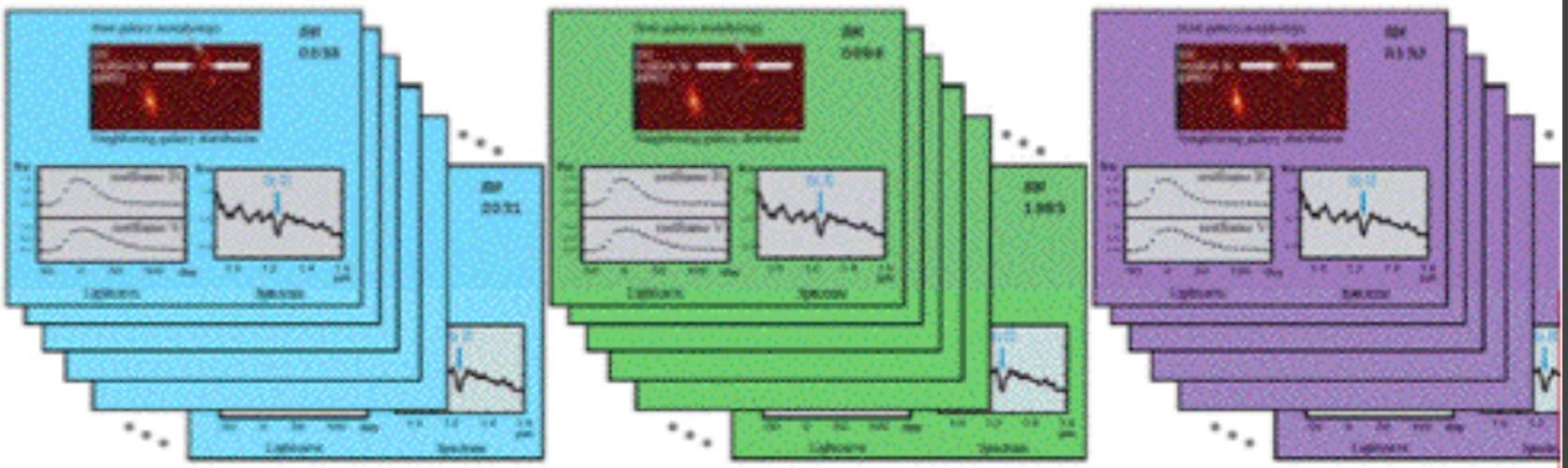
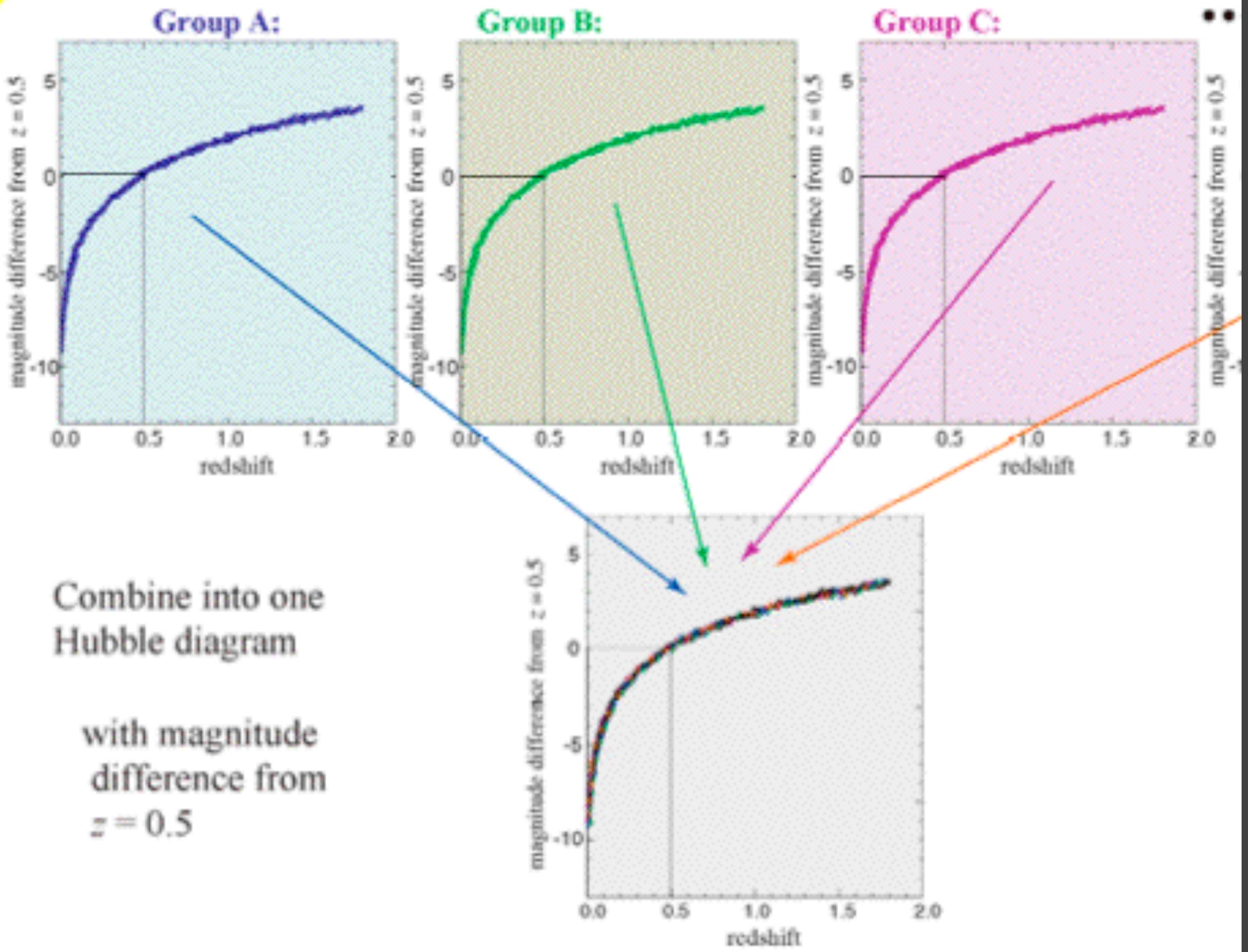


Each subset gets its own extinction-corrected Hubble diagram:



Combine into one Hubble diagram

with magnitude difference from $z = 0.5$

Can we get there? Systematics Concerns

Evolution Example:

SNe in spirals ~0.3 mag brighter on avg. than in ellipticals. Due to galaxy evolution, morphological mix at z=1.7 will be rather different than today, so mean SN L_{peak} will differ as well.

Control:

Out to z~0.8, LC-decline-corrected SNe show no E/S difference in corrected L_{peak}, within the errors: cosmology results robust to host morphology.

Also:

High-z Ia spectra appear very similar to those at low-z.

Note:

Require large variety of low-z Sne for control samples.

Can we get there? Systematics Concerns

Extinction:

Is high-z host galaxy dust similar to Milky Way dust?

Or could there by grey *intergalactic* dust that neither reddens nor increases the dispersion in peak magnitudes?

Control:

Compare rest-frame NIR data at high-z and low-z

Can we get there? Systematics Concerns

Other Issues:

Peculiar SNe Ia that don't fit the brightness-decline relation:

can they be recognized & removed at high-z? e.g., 2000cx, 2002cx.

Will contamination by other SN types (Ib/c) be under control?

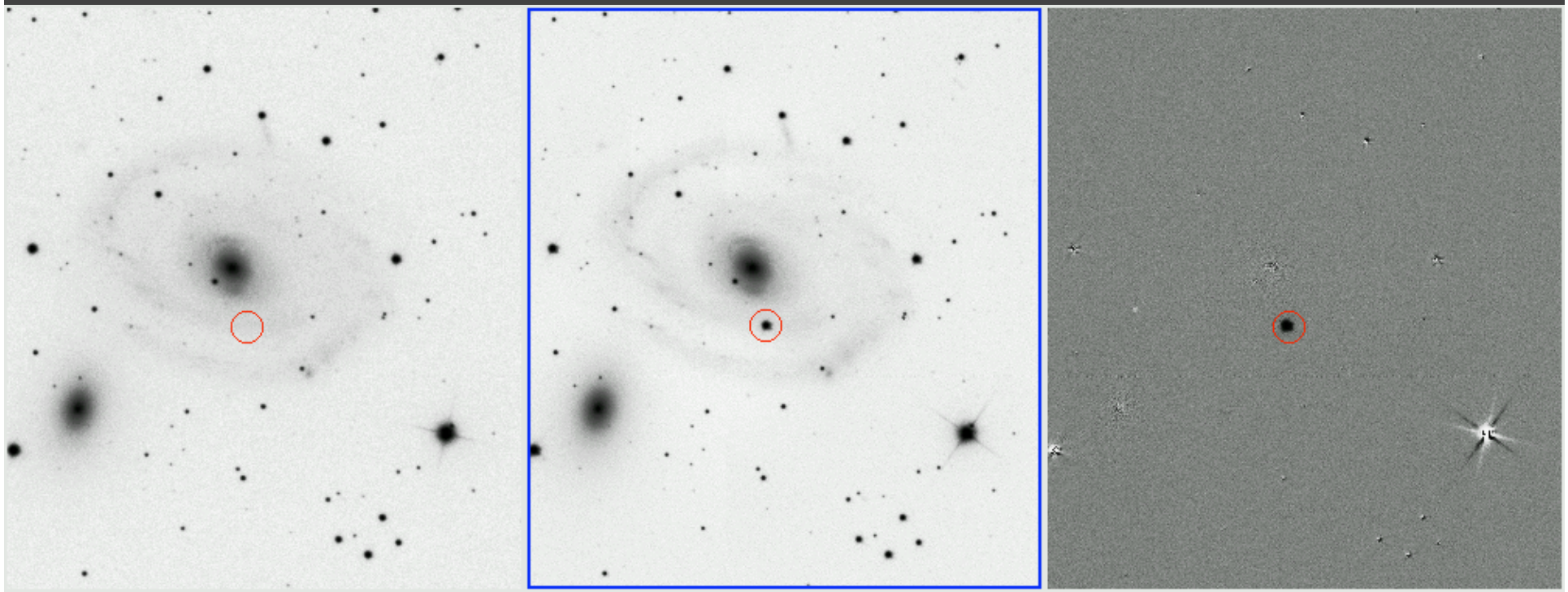
Malmquist bias

K-correction errors

Photometric calibration stability, color terms

Could host-galaxy subtraction be harder at high z?

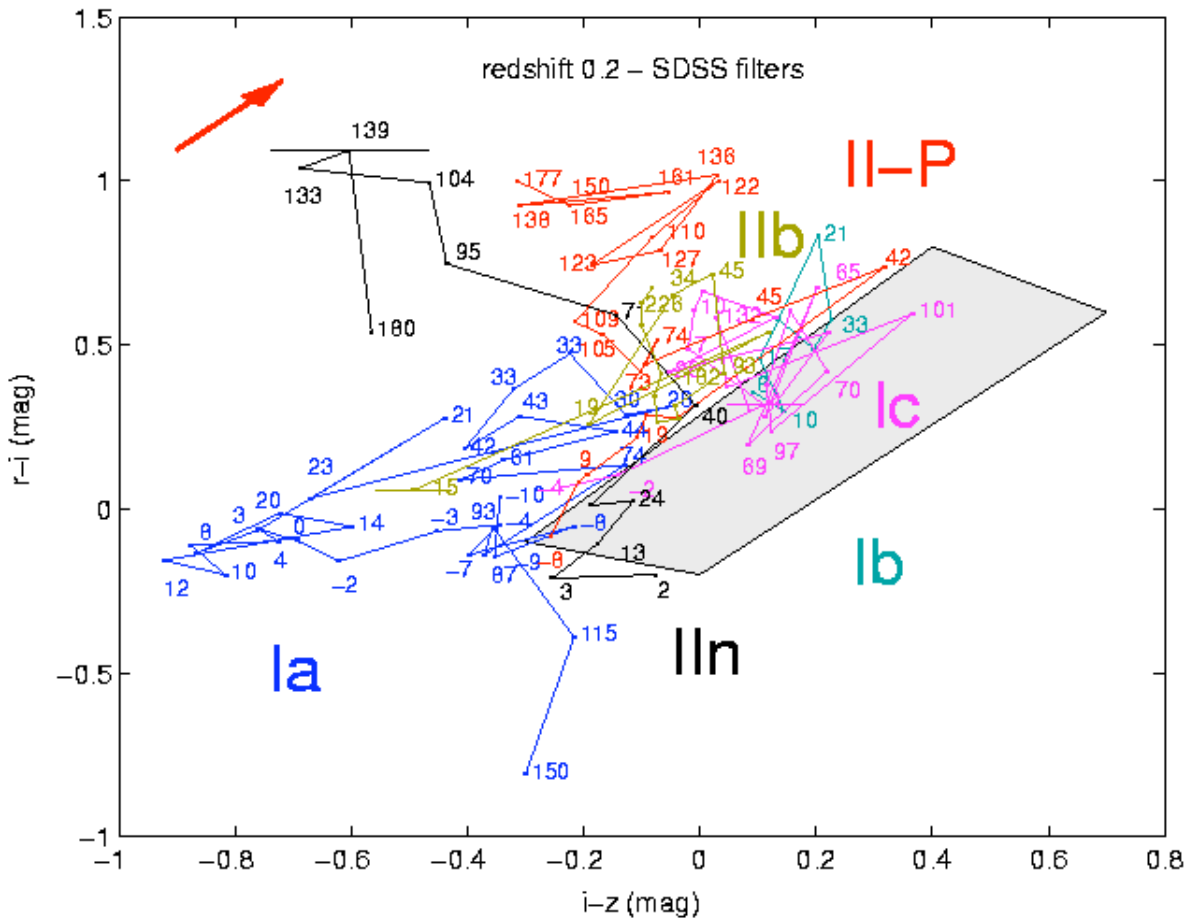
Finding SNe: Frame Subtraction



Before After Difference

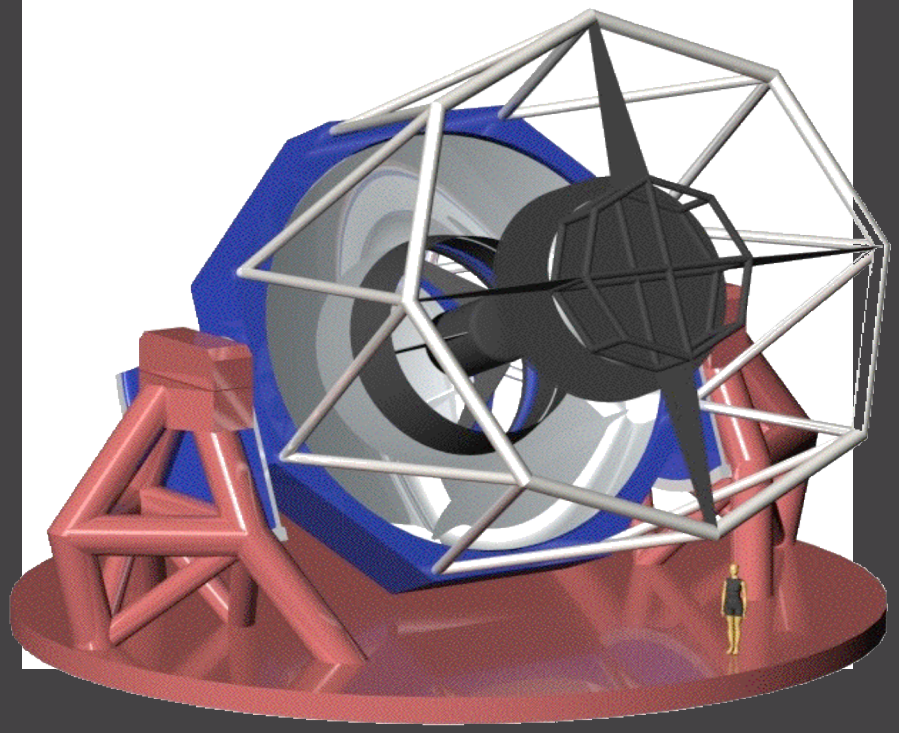
sn2002ha (Ia) z = 0.014 from LOTOSS seen in SDSS data (*g* band)

SN Typing & Dating with Colors



Poznanski, etal. (Van DenBerk, etal)

Can we do SN Cosmology with few/no spectra but very large numbers?



The Large Synoptic Survey Telescope (LSST)

Time-Domain Astronomy

survey visible sky every few nights

Weak Lensing

Cluster Counts

Galaxy Clustering

….

SNe Ia as Dark Energy Probes

- Purely geometrical: independent of structure formation paradigm (unlike clusters, weak lensing, LSS)
- Nearly orthogonal parameter degeneracy to structure-based probes: complementary to WL & CMB
- Best standardizable candles/relative distance indicators
- Lots of information in principle available per event to provide systematics cross-checks: multi-epoch spectrophotometry from near UV to near IR. How much of this information do we need for each SN at high z?
- Few % constraints on *w* will require exquisite control of observational systematics (from space), improved local SN templates, and improved LC analysis algorithms, and preferably better theoretical SN modeling

Structure-Based Probes of Dark Energy

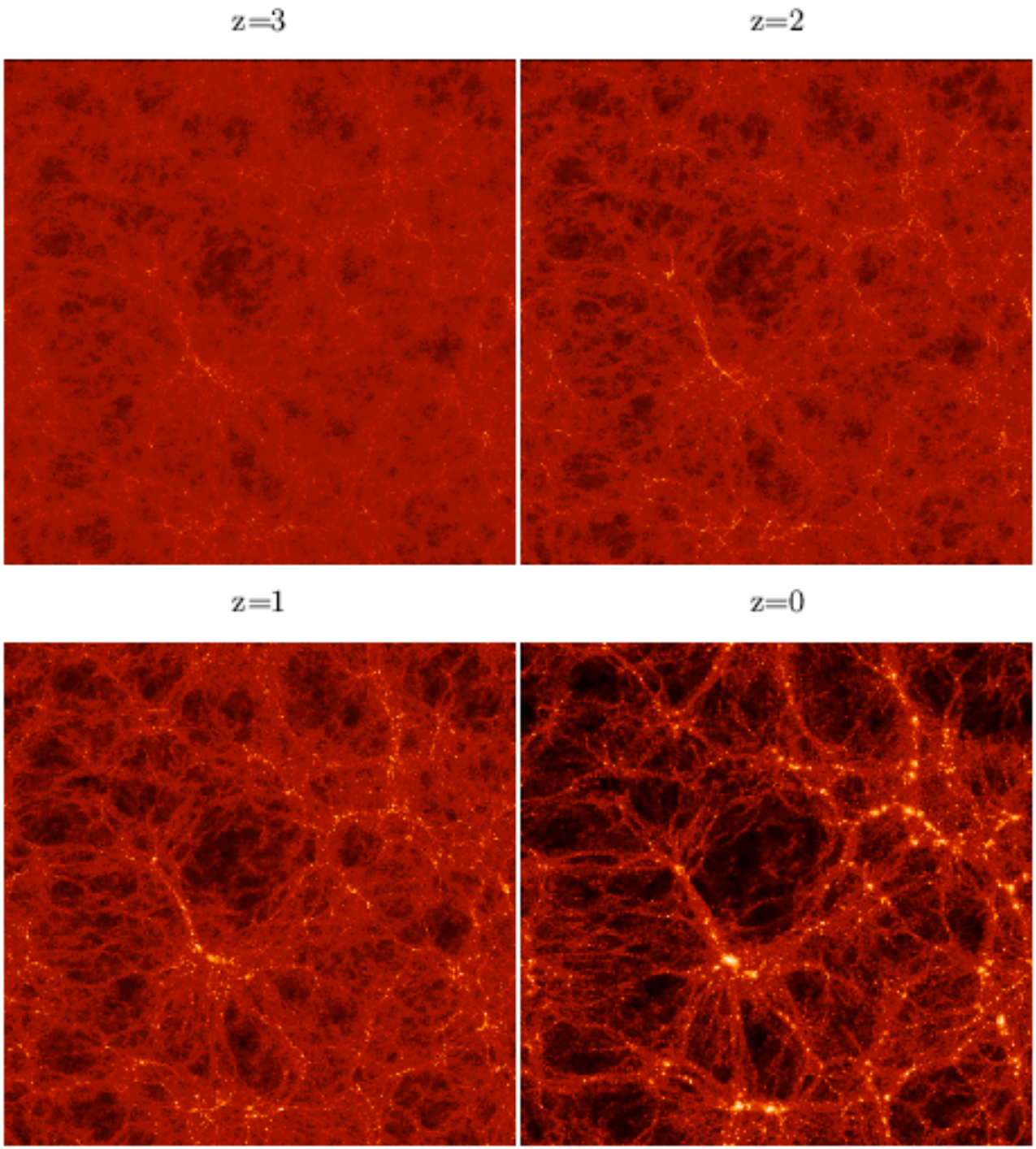
- Weak Gravitational Lensing
  - shear-shear correlations
  - galaxy-shear correlations
- Cluster Surveys

Evolution of Structure in a Cold Dark Matter Universe

Galaxies and Clusters form in sheets and filaments

Robustness of the paradigm recommends its use as a new Dark Energy probe

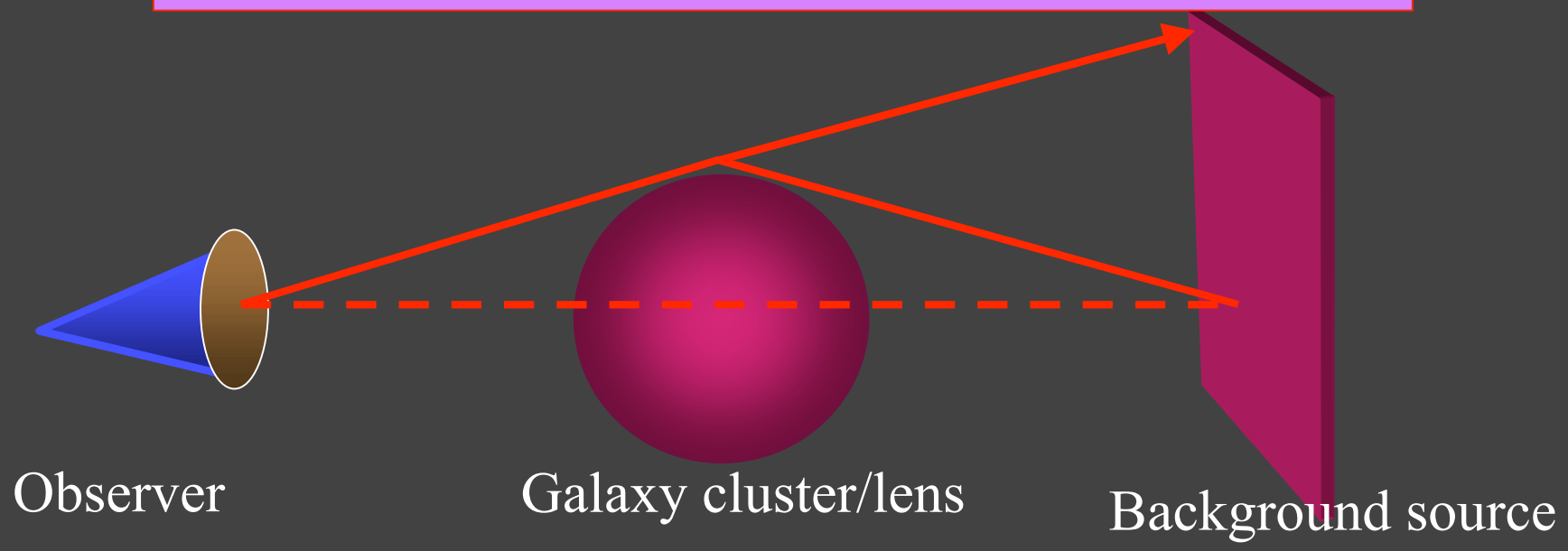
Price: additional parameters



Gravitational Lensing

- A simple scattering experiment:

$$ds^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Phi)dr_i dr^i$$



Effects of lensing

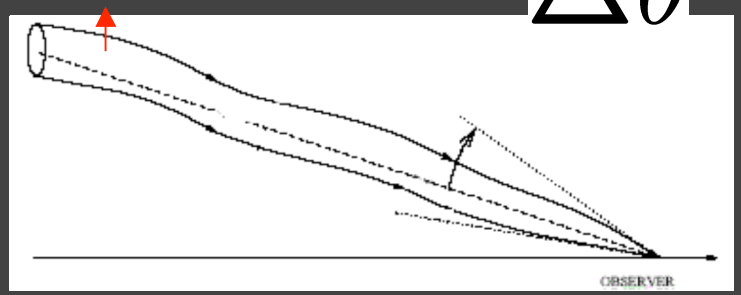
- Expansion + shear

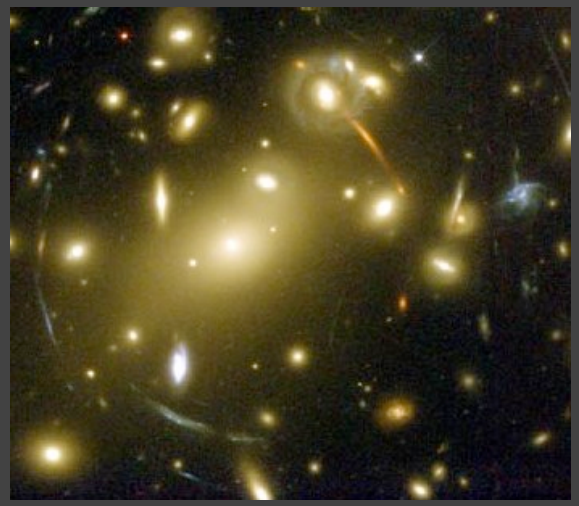
$$\Delta x_i = r \Delta\theta_j A_{ij}$$

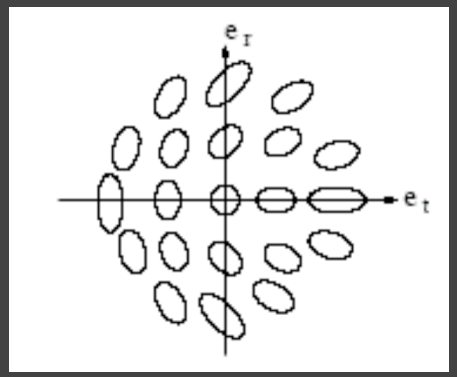
$$A_{ij} = \delta_{ij} - \phi_{ij}$$

Δx

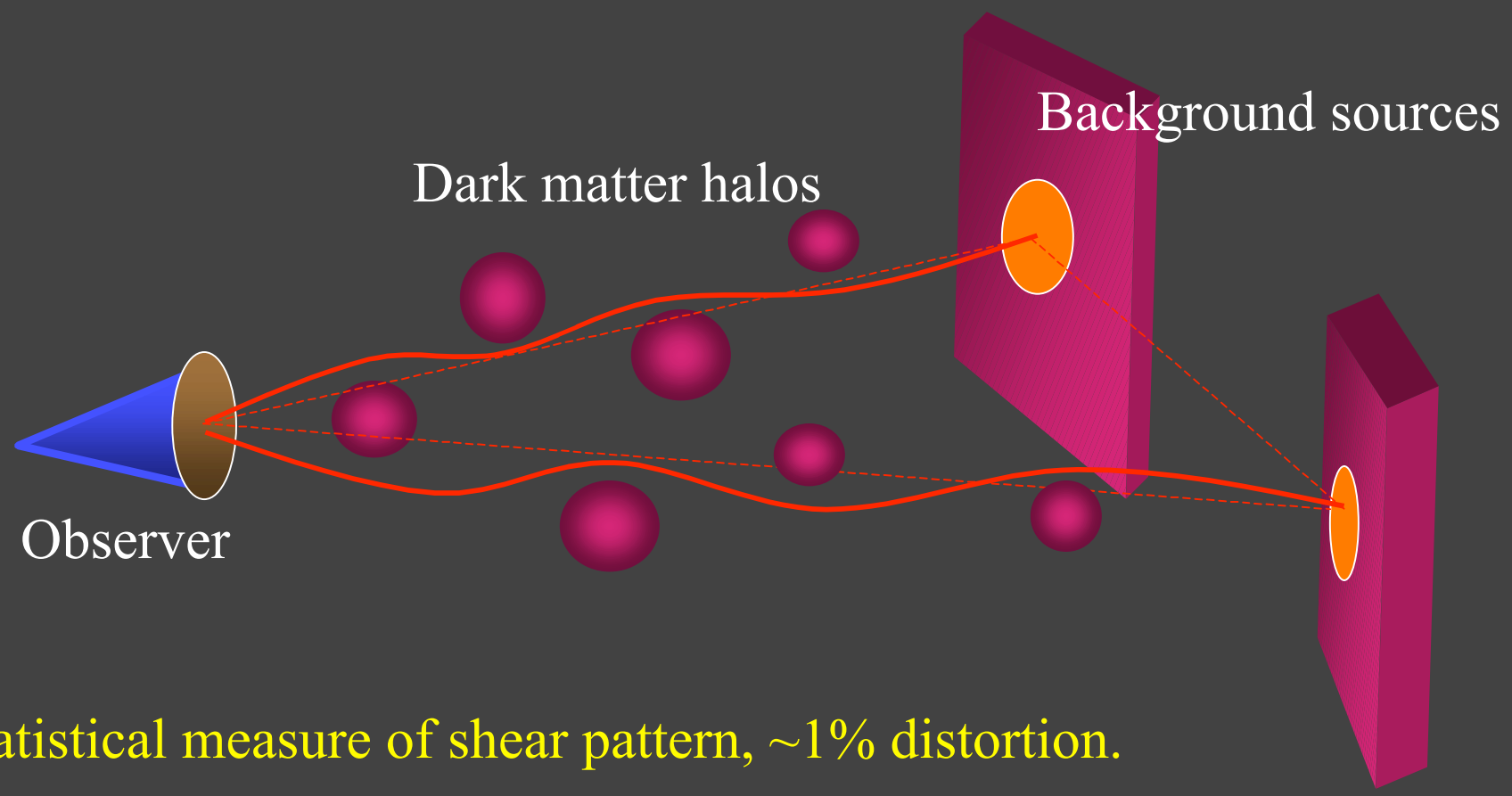
$\Delta\theta$







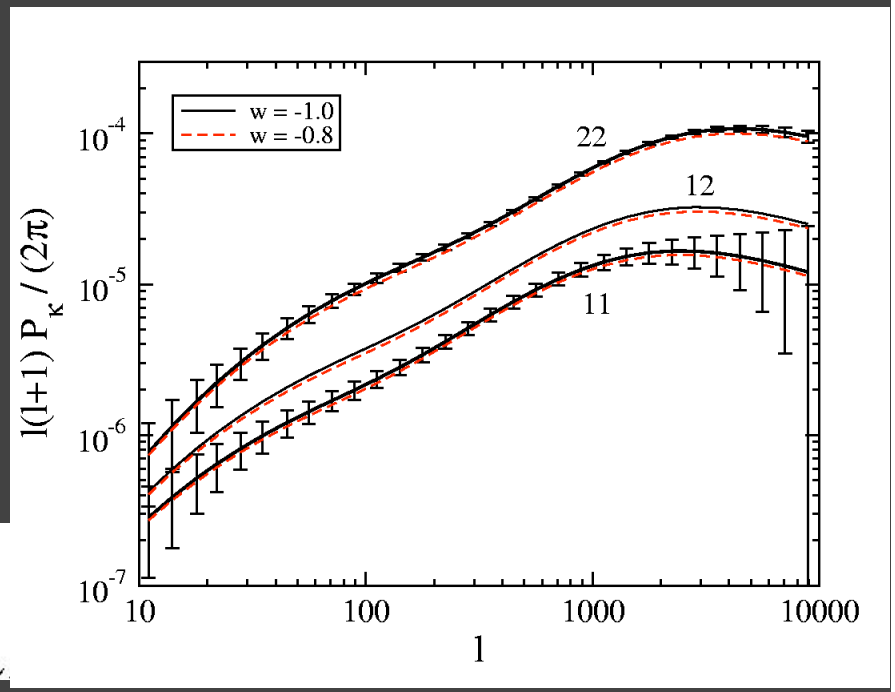
Cosmic Shear



- Statistical measure of shear pattern, ~1% distortion.
- Radial distances, r(z), depends on geometry of Universe.
- Dark Matter pattern & growth depends on cosmological parameters.

Weak Lensing Tomography

- Measure shapes for millions of source galaxies in photo-z bins
- Shear-shear & galaxy-shear correlations probe distances & growth rate of perturbations



$$C_\ell^{x_a x_b} = \int dz \frac{H(z)}{D_A^2(z)} W_a(z) W_b(z) P^{s_a s_b}(k = \ell / D_A; z)$$

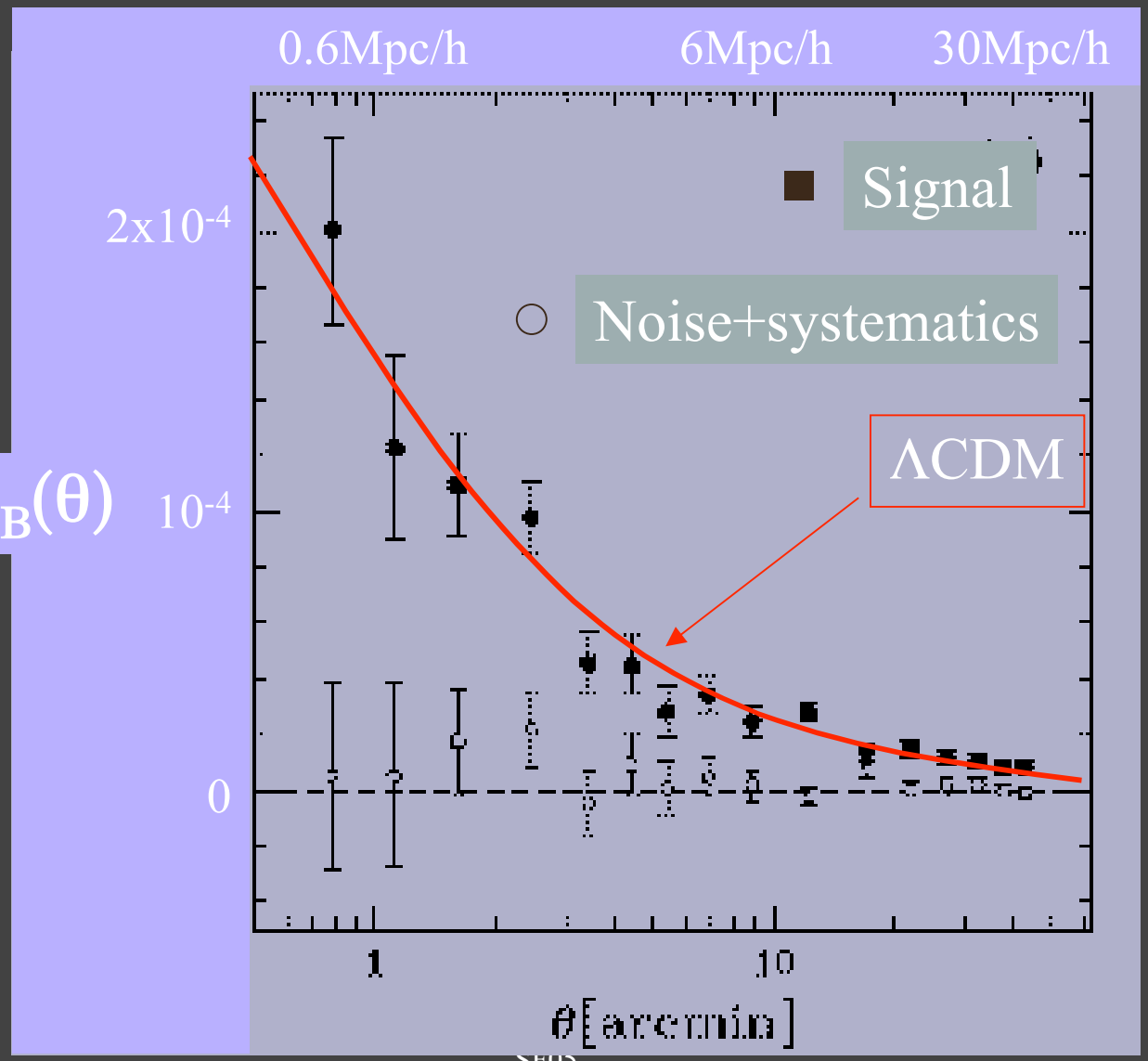
- Galaxy correlations determine halo model (galaxy bias) priors
- Requirements: Sky area, depth, photo-z's, image quality & <u>stability</u>

$$\Delta C_\ell = \sqrt{\frac{2}{(2\ell+1) f_{sky}}} \left(C_\ell + \frac{\sigma^2(\gamma_i)}{n_{eff}} \right)$$

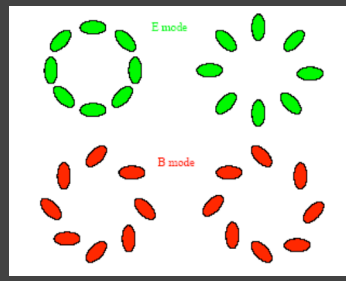
Cosmic Shear Correlations

van Waerbeke et al, 2005: Results from the VIRMOS-Descart Survey

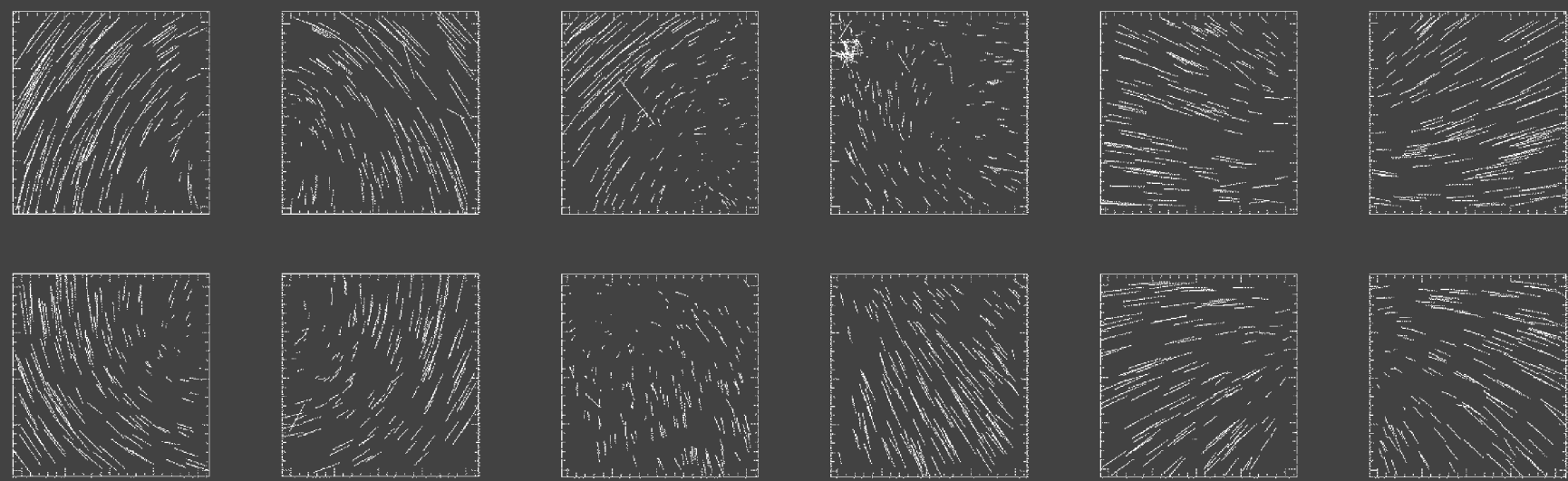
Shear Amplitude



- 55 sq deg
- z = 0.8



Improved Corrections for Anisotropic PSF



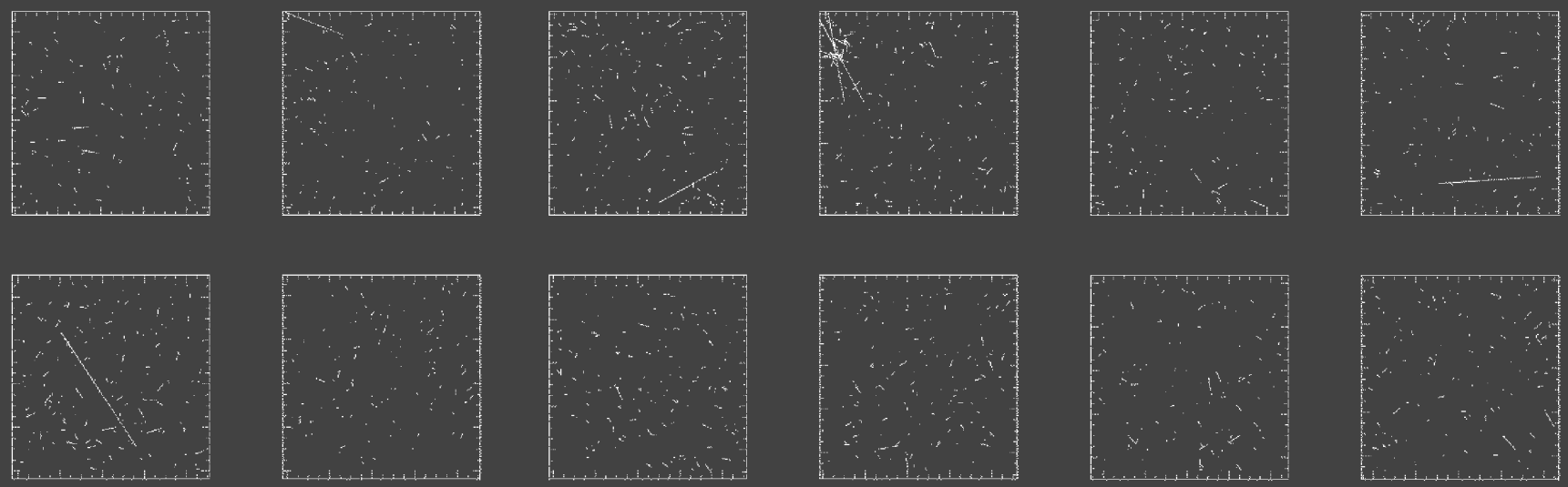
Focus too low Focus (roughly) correct Focus too high

- Whisker plots for three BTC camera exposures; ~10% ellipticity
- Left and right are most extreme variations, middle is more typical.
- Correlated variation in the different exposures: PCA analysis --> can use stars in all the images: better PSF interpolation

Jarvis and Jain

PCA Analysis

Jarvis and Jain



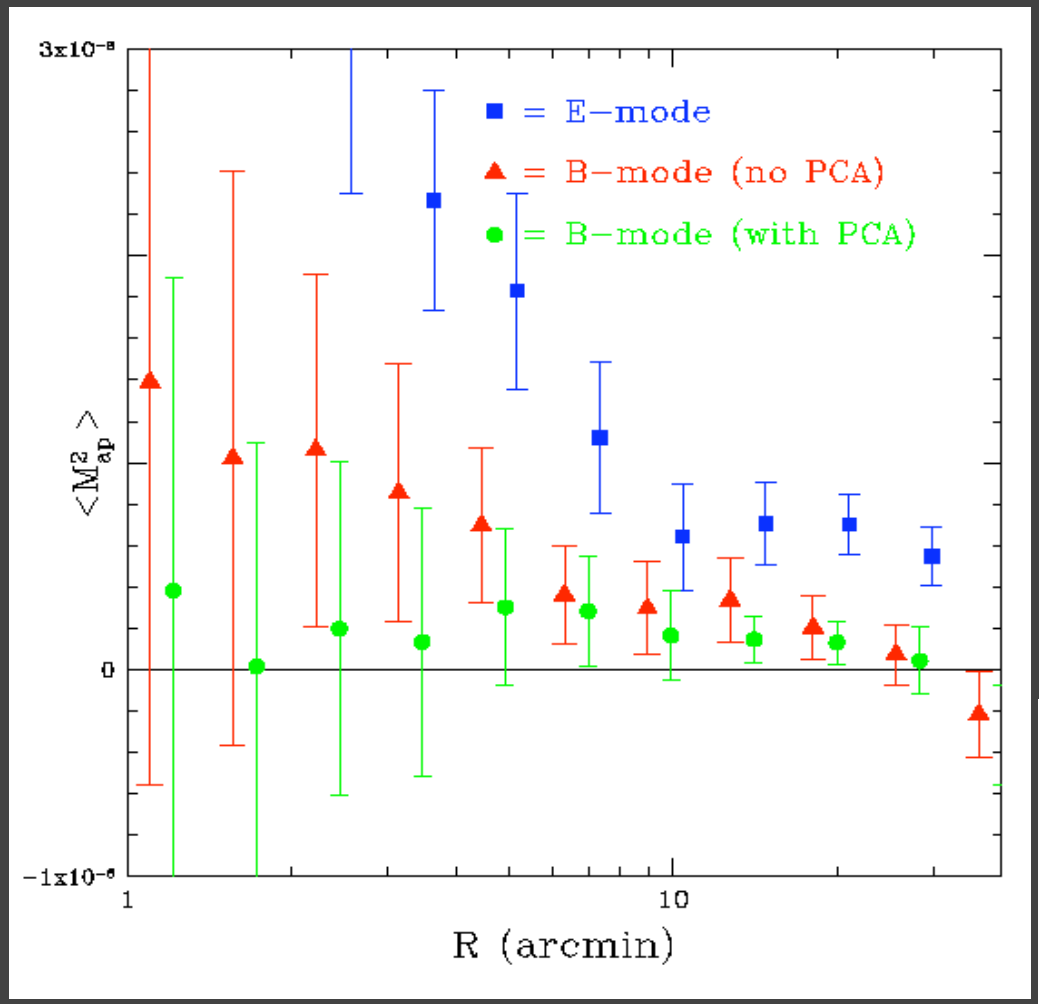
Focus too low Focus (roughly) correct Focus too high

Remaining ellipticities are essentially uncorrelated.

- Measurement error is the cause of the residual shapes.
- 1st improvement: higher order polynomial means PSF accurate to below 1arcmin.
- 2nd: Much lower correlated residuals on all scales

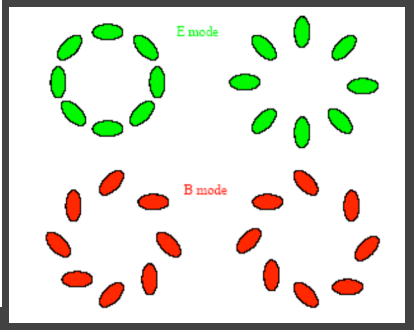
Test of PSF correction: star ellipticity correlation for Mosaic II

Jarvis and Jain



Results from 75 sq. deg. WL Survey with Mosaic II and BTC on the Blanco

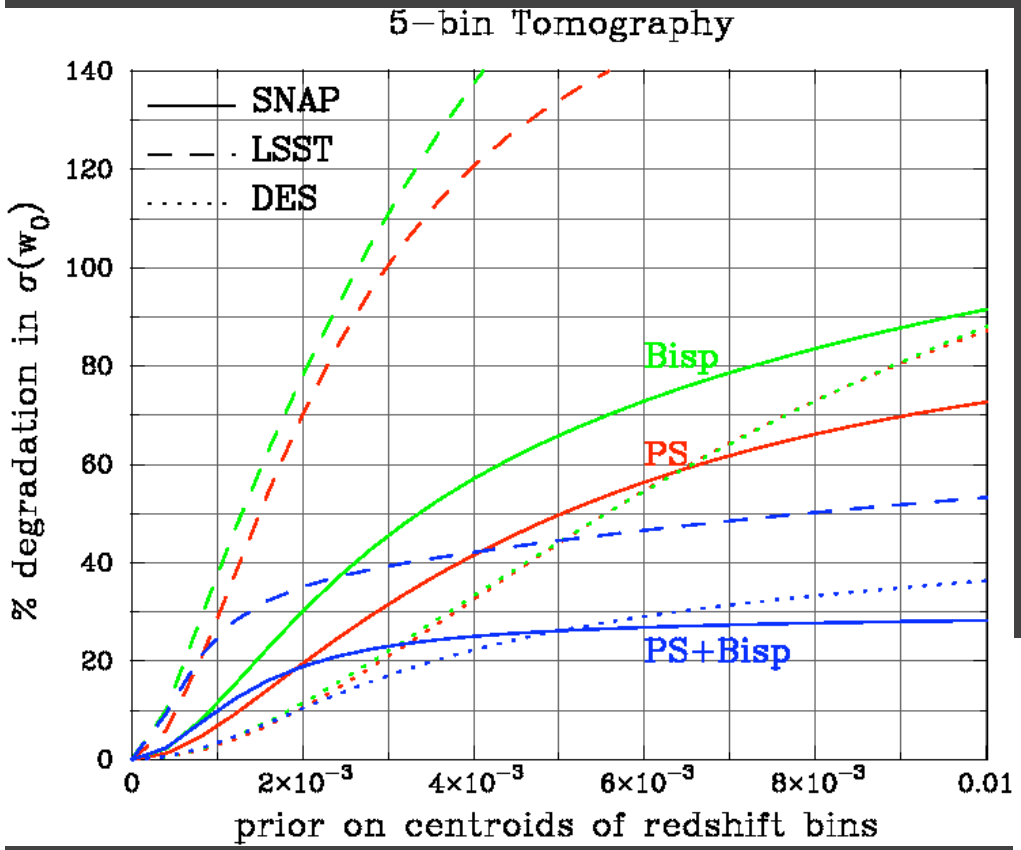
Bernstein, etal

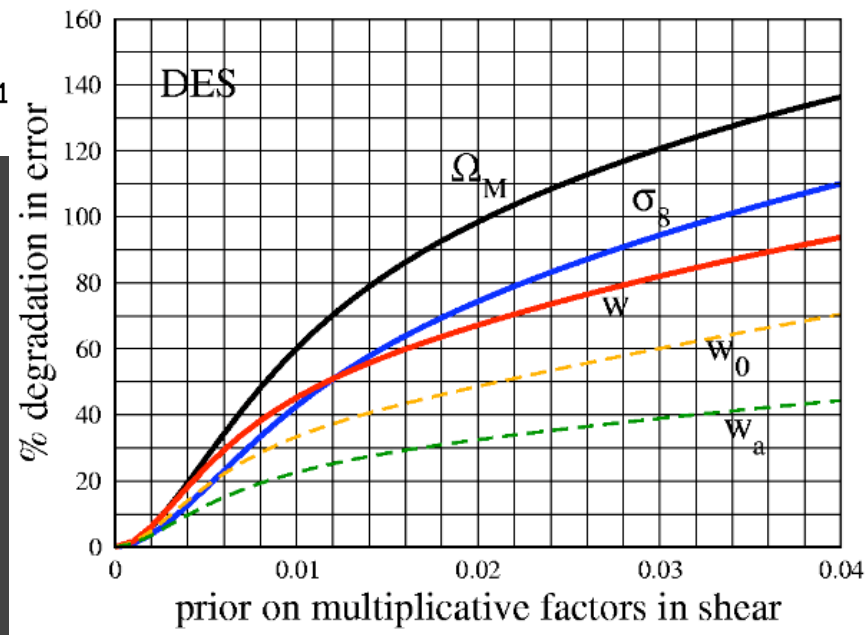


Corrected star ellipticity correlation is ~10-100 smaller than lensing signal.

Substantial improvement in additive shear error.

Effects of Systematic Errors in Photometric Redshifts and Shear Calibration on WL Constraints





- Photo-z error distributions determined from spectroscopic training sets to needed accuracy
- Calibration: lensing signal vs. galaxy angular size

Huterer, Takada, Bernstein, Jain

Galaxy Photo-z Simulations

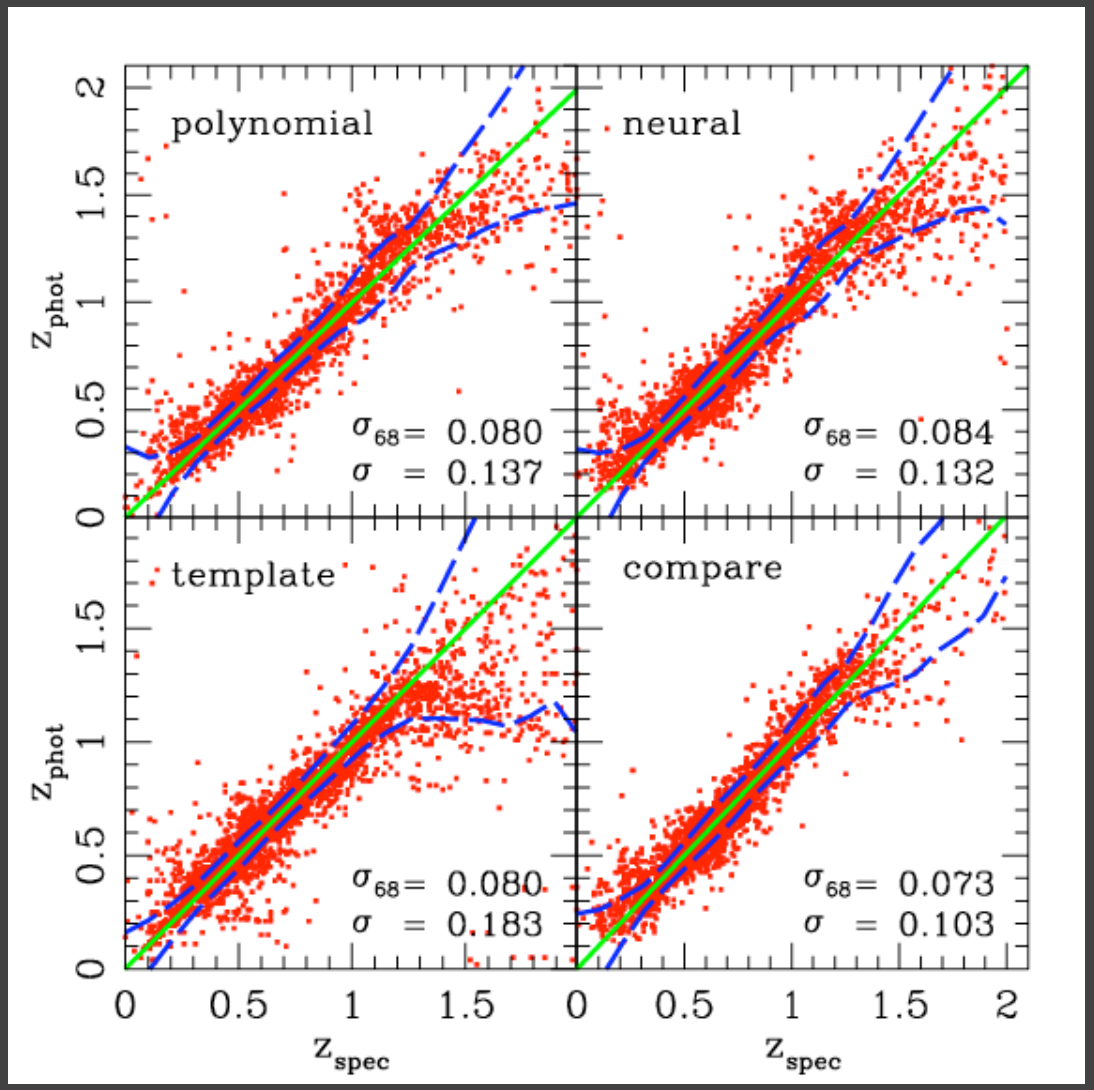
griz filters

10σ Limiting Magnitudes

g	24.6
r	24.1
i	24.0
z	23.9

+2% photometric calibration error added in quadrature

σ(z)~0.1 to z~1.3



Galaxy Photo-z Simulations

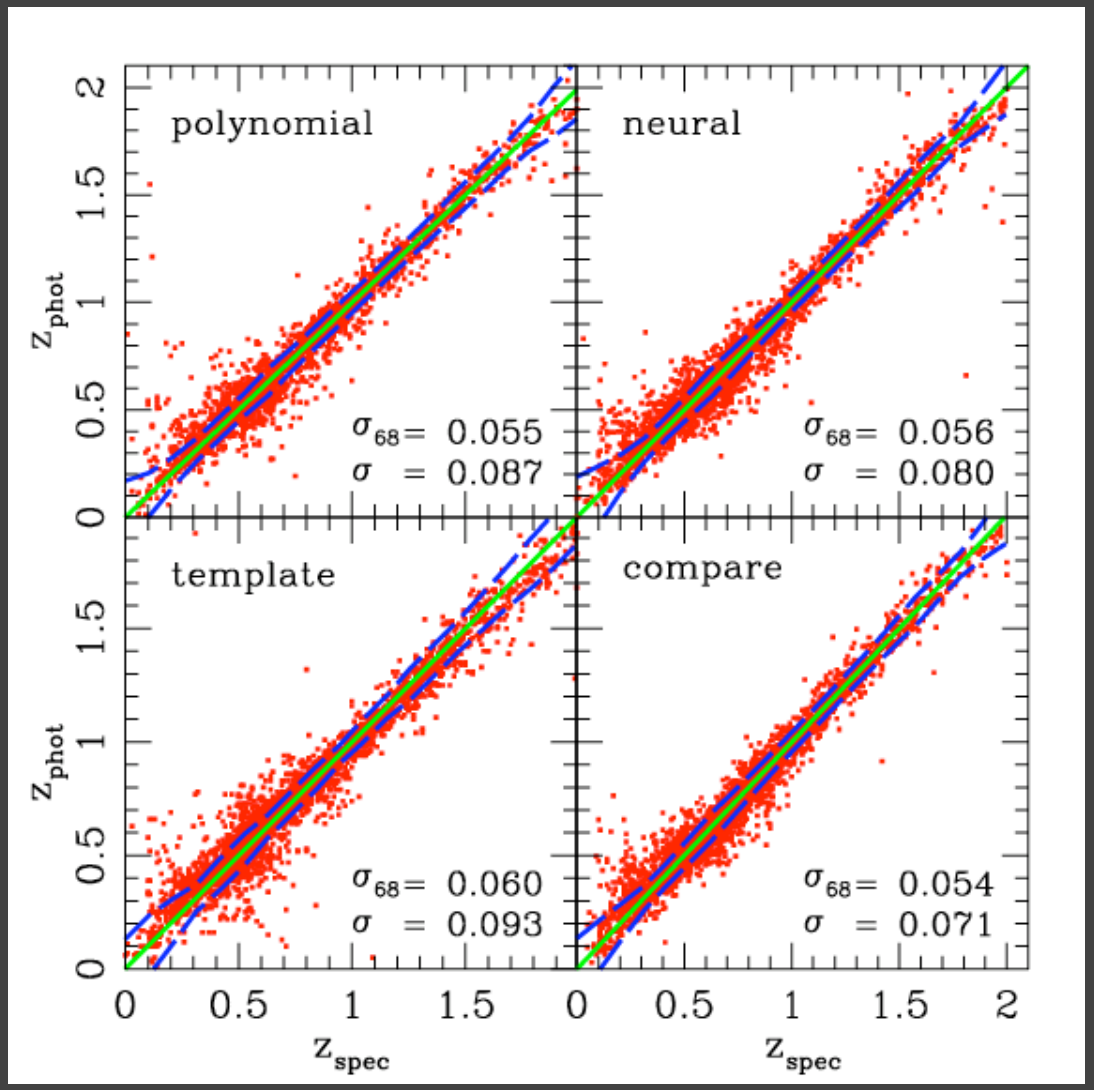
DES + VISTA
griz+YJHKs filters

10σ Limiting Magnitudes

Y	22.45
J	22.15
H	21.65
Ks	21.15

(~15 min exposures)
Single NIR band yields most of the benefit

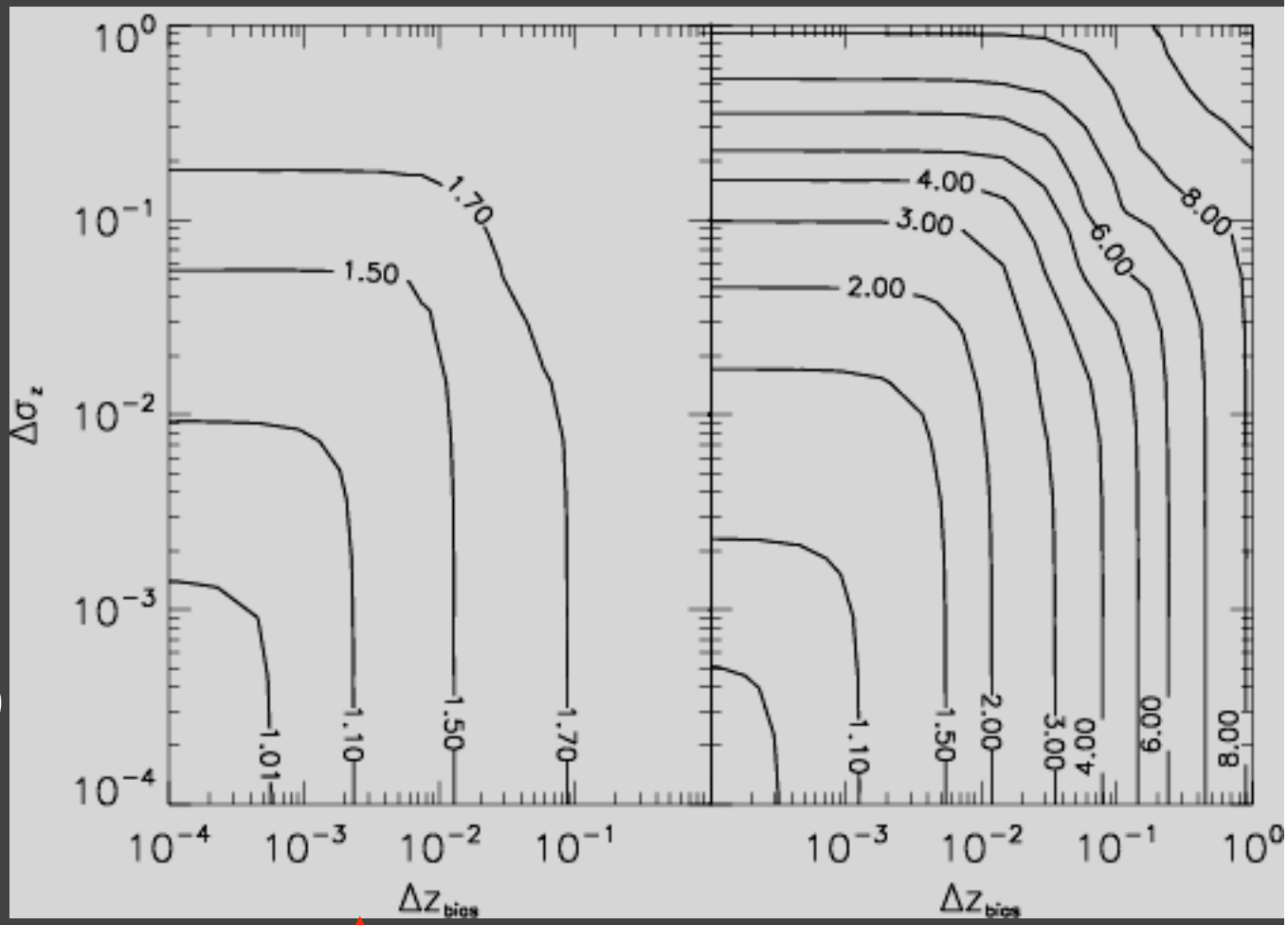
σ(z) ~ 0.07



Impact of Uncertainty in Photo-z Error Distribution on *w*

Spectroscopic `Training Set' needed to measure photo-z error distribution to required accuracy:

N ~ 50,000 - 100,000



Ma, Hu, & Huterer (2005)

The Dark Energy Survey

- Study Dark Energy using
  4 complementary* techniques:
  - Cluster counts & clustering
  - Weak lensing
  - Galaxy angular clustering
  - SNe Ia distances

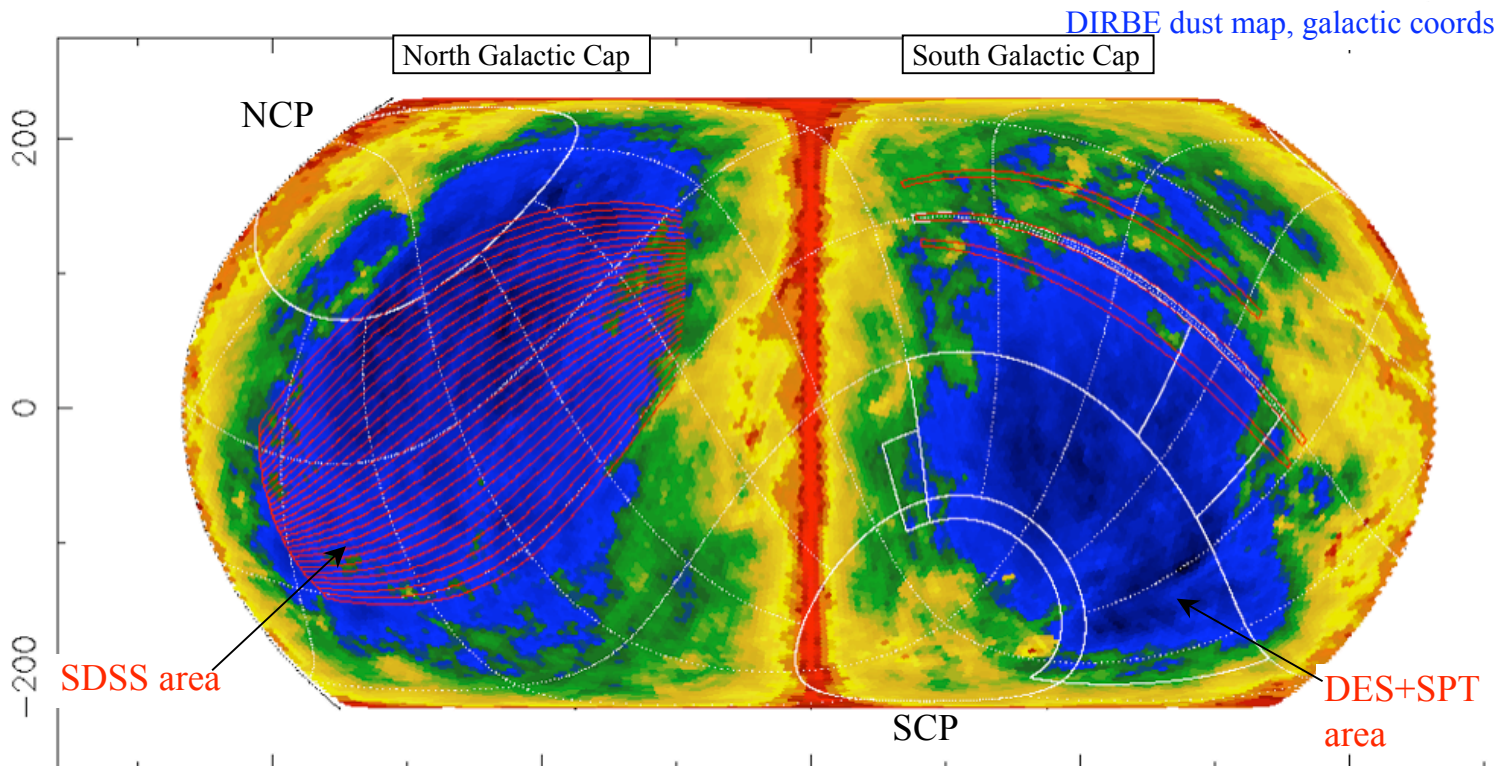
- Two multiband surveys:
  - 5000 deg^2 *g, r, i, z*
  - 40 deg^2 repeat (SNe)

- Build new 3 deg^2 camera
  - Construction 2005-2009
  - Survey 2009-2014 (525 nights)
  - Response to NOAO AO

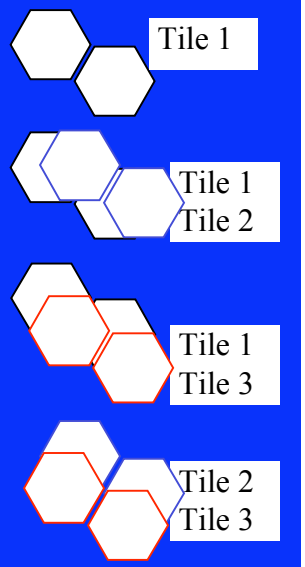
Blanco 4-meter at CTIO

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

The DES Survey Area



Observation strategy: multiple tilings of the sky



Massive overlap is basis for calibration strategy.
2 tiles/filter/year
1% photometry goal

Requirements

- Overlap 4000 sq-degree SPT SZE survey
- Overlap redshift surveys

g,r,i,z (10_, galaxies) = 24.6, 24.1, 24.3, 23.9
g,r,i,z (5_, psf) = 26.1, 25.6, 25.8, 25.4

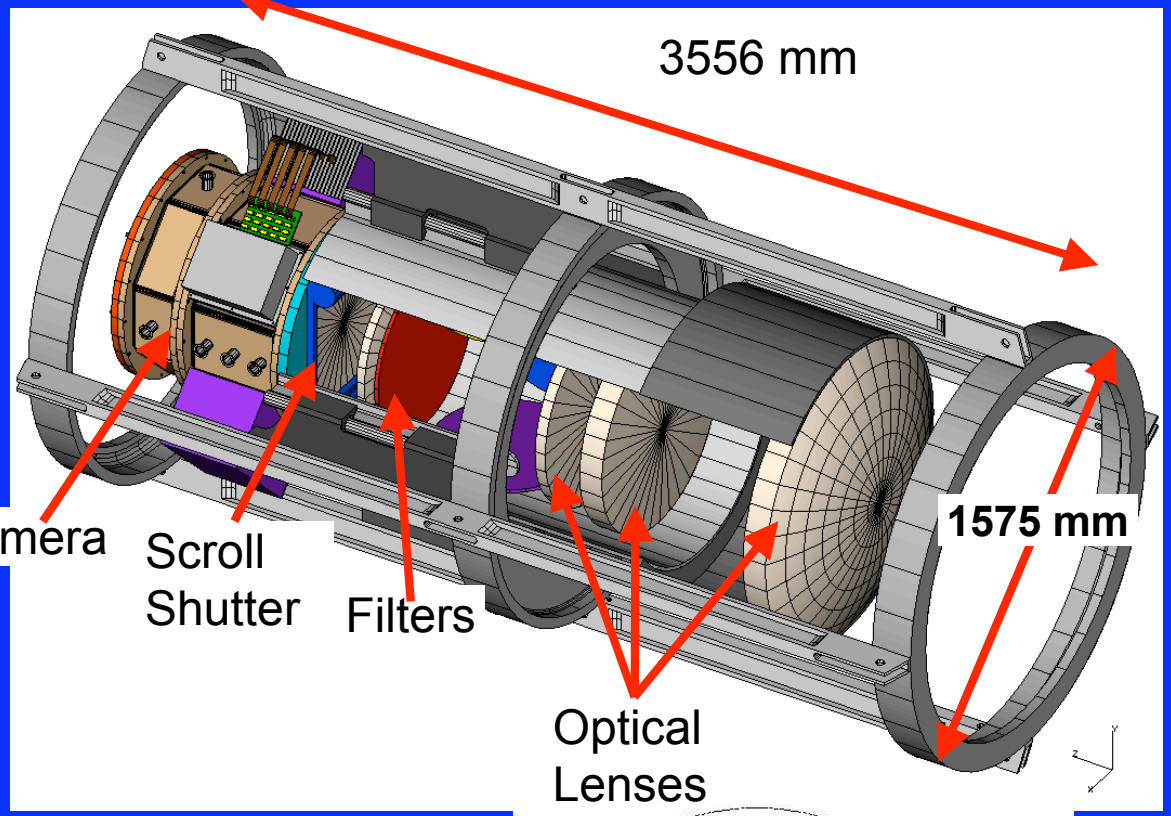
→ Photometric redshifts to z~1.3

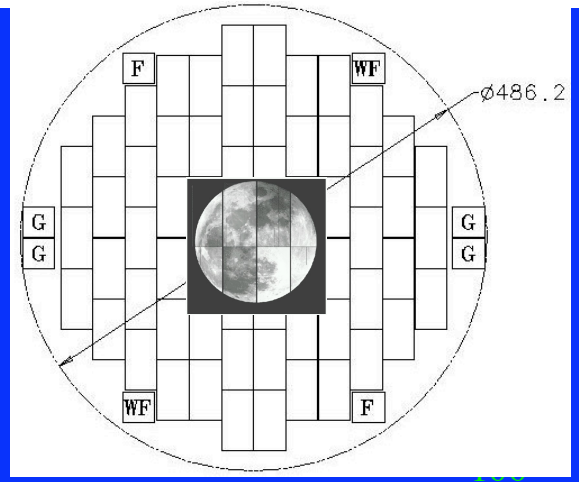
Survey Area

- 4000 sq-degrees: Main area — $-65 < \mathrm{Dec} < -30$ at $-60 < \mathrm{RA} < 105$; $-45 < \mathrm{Dec} < -65$ at $-75 < \mathrm{RA} < -60$
- 200 sq-degrees: SDSS Stripe 82 + VLT surveys — $-1 < \mathrm{Dec} < 1$ at $-50 < \mathrm{RA} < 50$
- 800 sq-degrees, photometric connection area — $-30 < \mathrm{Dec} < -1$ at $20 < \mathrm{RA} < 50$

The DES Instrument

- 62 CCD camera
- 2kx4k CCDs, 0.26”/pixel
- 17 second readout time
- 4 filters: *g,r,i,z*
- 5 optical element corrector
  - one aspheric surface
  - largest element is ~1m
  - UCL Optical Sciences Lab beginning design and engineering work



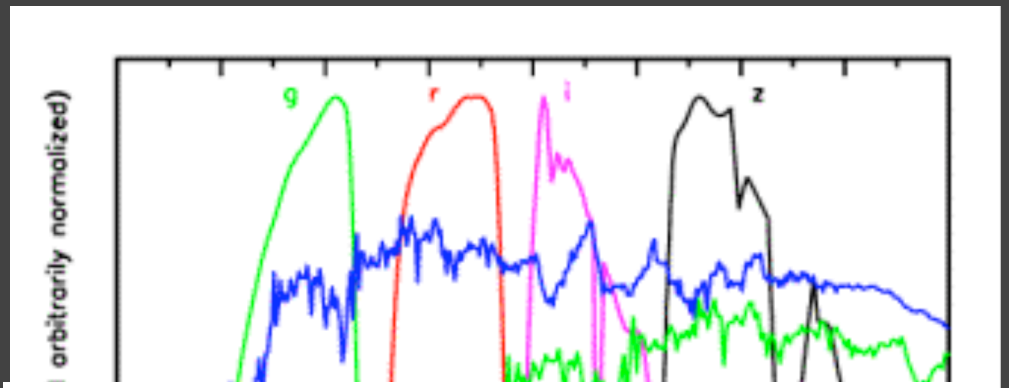


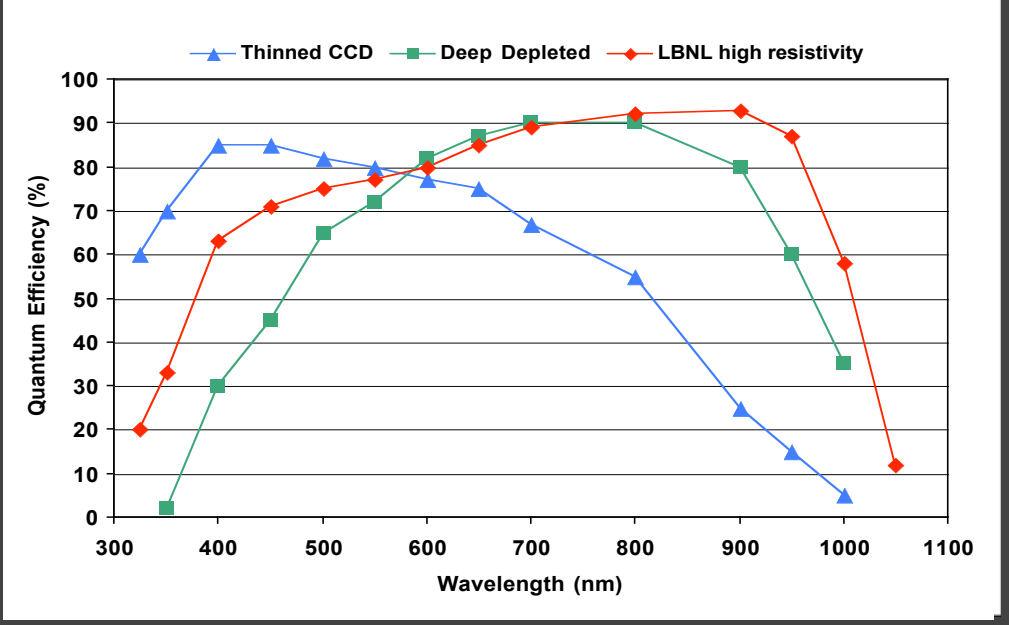
Instrument total cost:
$22.4M, includes:
~35% contingency
Equipment $11.4 M
Labor $7 M
Overhead $4 M

Optics and CCDs are the major cost and schedule drivers
Optics Total ~ $2M + $1M cont.
CCD Total ~ $2M + $1M cont.

Photometric Redshifts

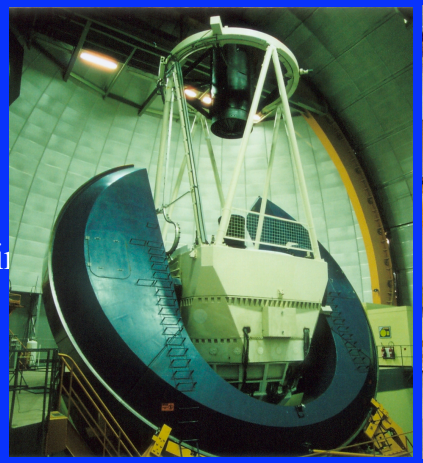
- Measure relative flux in four filters *griz*: track the 4000 A break
- Estimate individual galaxy redshifts with accuracy $\sigma(z) \sim 0.1$ (~ 0.02 for clusters)
- This is more than sufficient for Dark Energy probes, if biases can be controlled
- Note: good detector response in *z* band filter needed to reach z~1.3

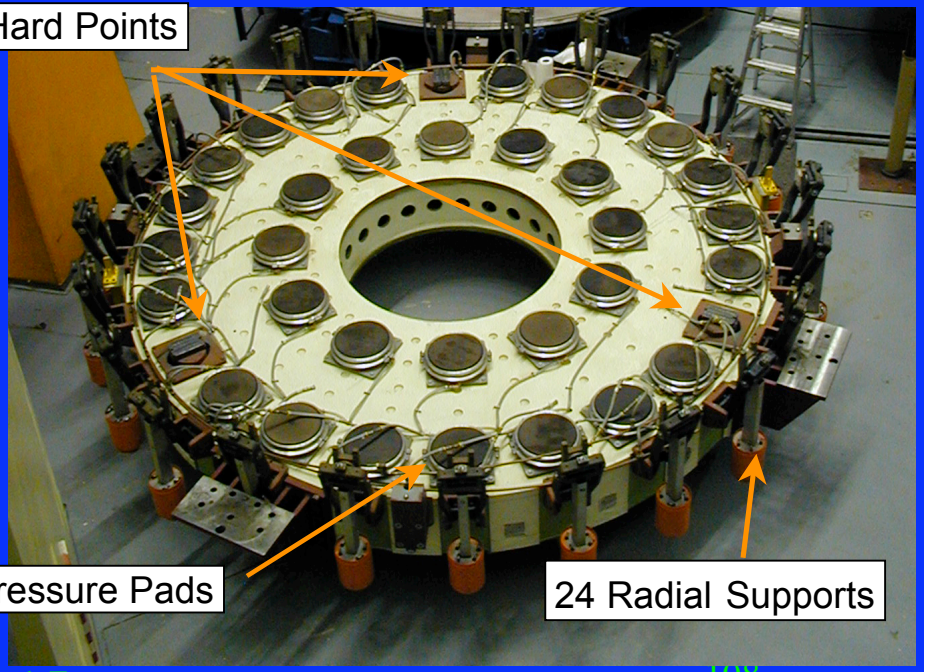




The DES Telescope

- NOAO/CTIO 4m Blanco telescope
  - 1970 era, equatorial mount
  - An existing, working telescope
  - On-going studies: finite element analysis, laser metrology, PSF pattern modeli
- Solid primary mirror
  - 50cm thick Cervit, 15 tons
- Mechanical mirror support system
  - radial: purely mechanical
  - axial: 3 load cell hard points + controllable support cells
- Primary cage
  - DES will replace entire cage
  - will have radial (alignment) movement
- Cerro Tololo
  - site delivers median 0.65" Sept-Feb
  - current Mosaic II+telescope delivers median 0.9" Sept-Feb



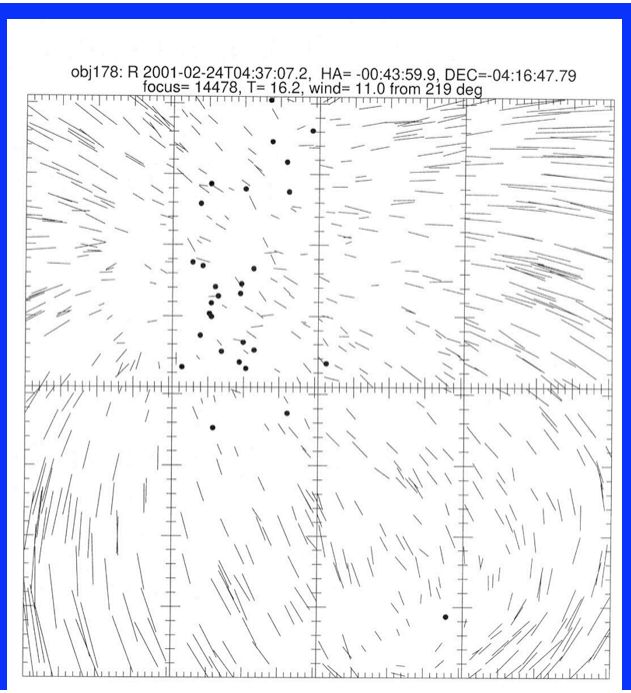


Understanding & Improving Blanco Image Quality

DARK ENERGY SURVEY

- Ray tracing model of Mosaic +corrector+primary
  - Reproduces PSF patterns & qualitatively explains PCA components
  - Focus errors coupled to primary astigmatism
  - Misalignment+ADC induces coma
  - Guiding errors
  - Trefoil distortions of primary due to mirror supports

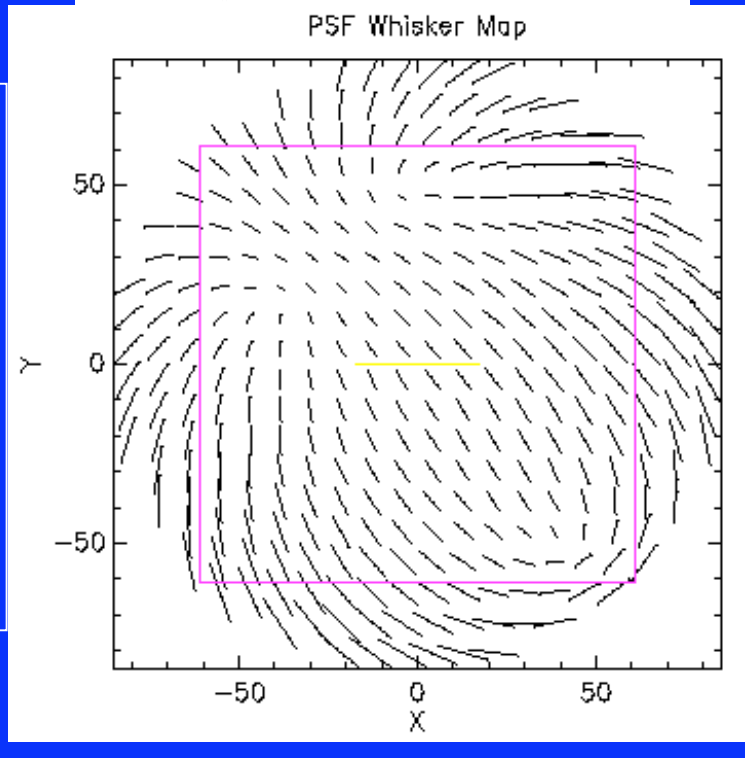
Mosaic II : an observed PSF pattern



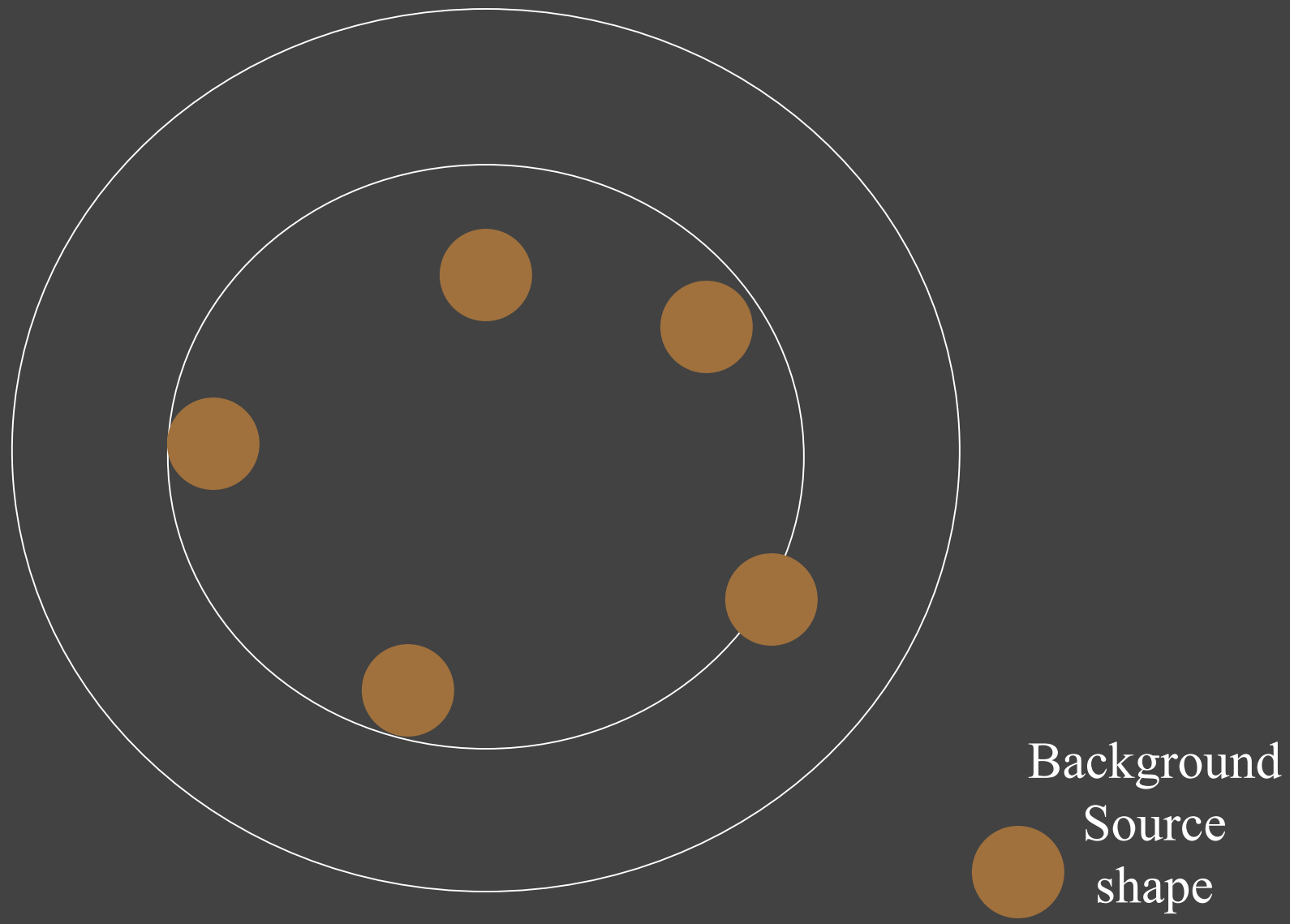
- Improvements for DES
  - New corrector with small & smoothly varying PSF
  - active focus sensors on focal plane
  - wavefront (curvature) sensors "
  - active control of prime focus cage tilt
  - active control of primary (low order)
  - fix radial support system
  - improved thermal environment (reduce local power dissipation)

Mosaic II optical model
ADC - neutral position axis to right
Primary misaligned by
0.2 mm x
-0.7 mm y
results in Coma

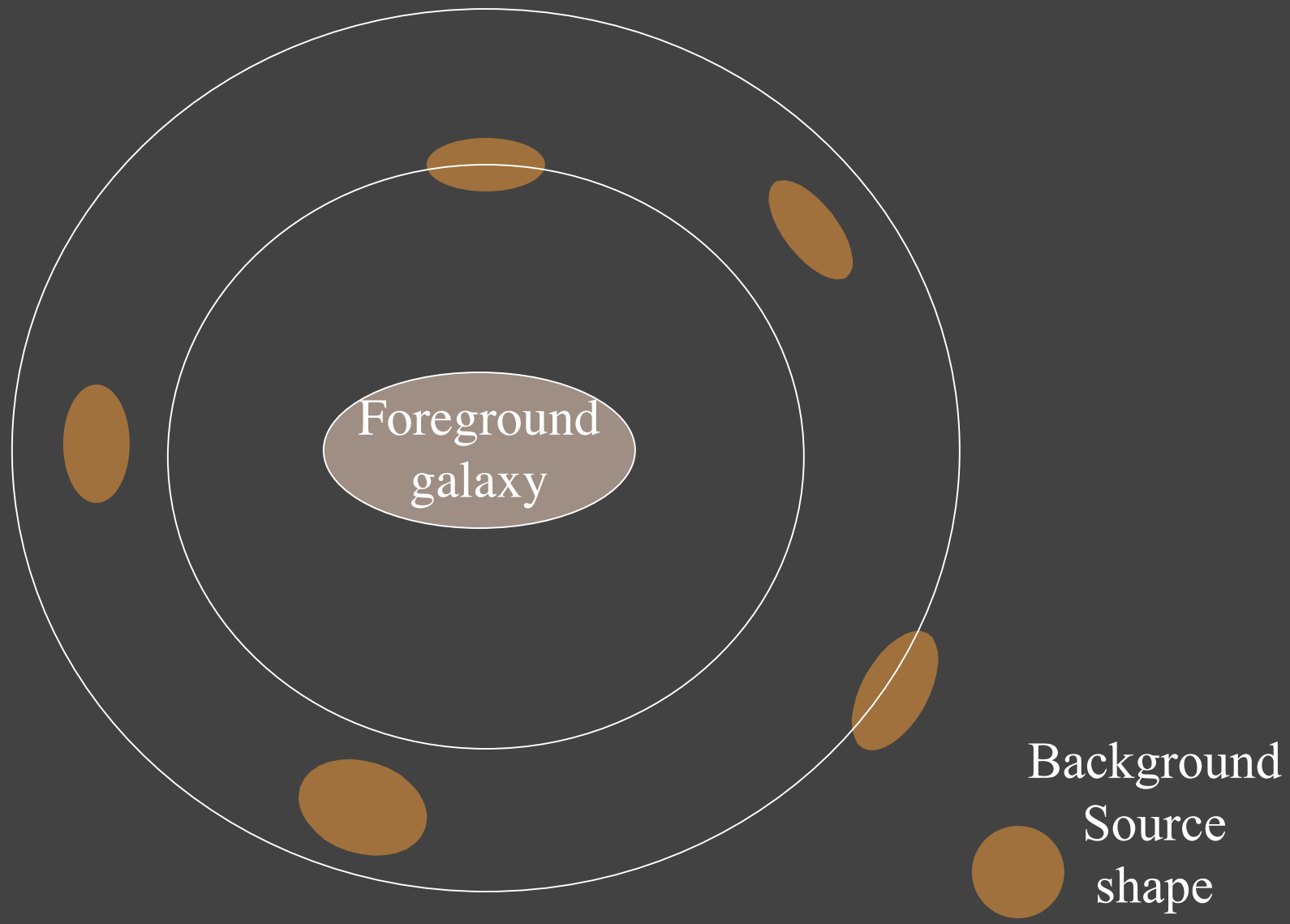
Offsets of this amount have been measured; possibly due to broken radial supports



Galaxy-shear Correlations

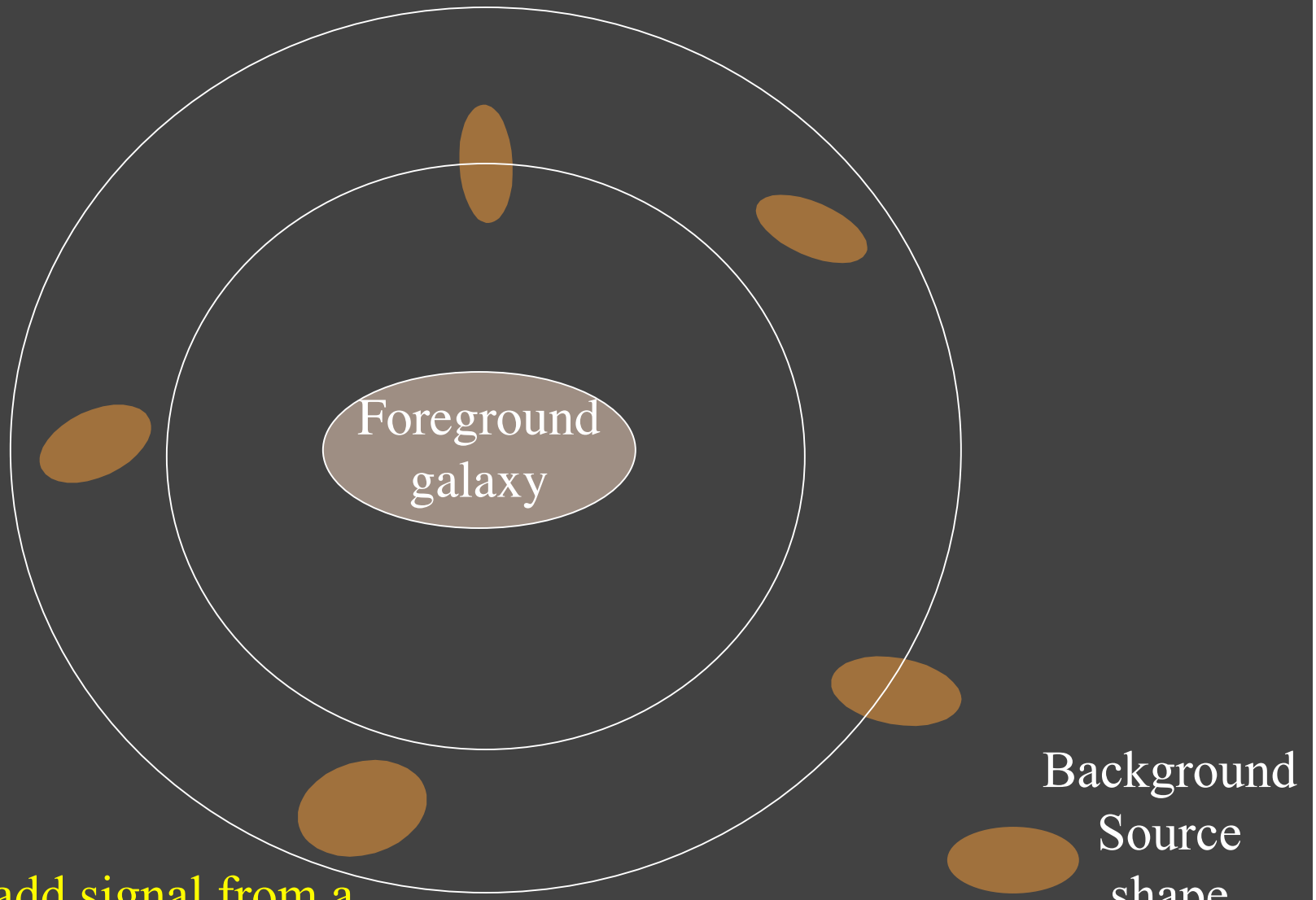


Galaxy-shear correlations



Note: the effect has been greatly exaggerated here

Lensing of real (elliptically shaped) galaxies

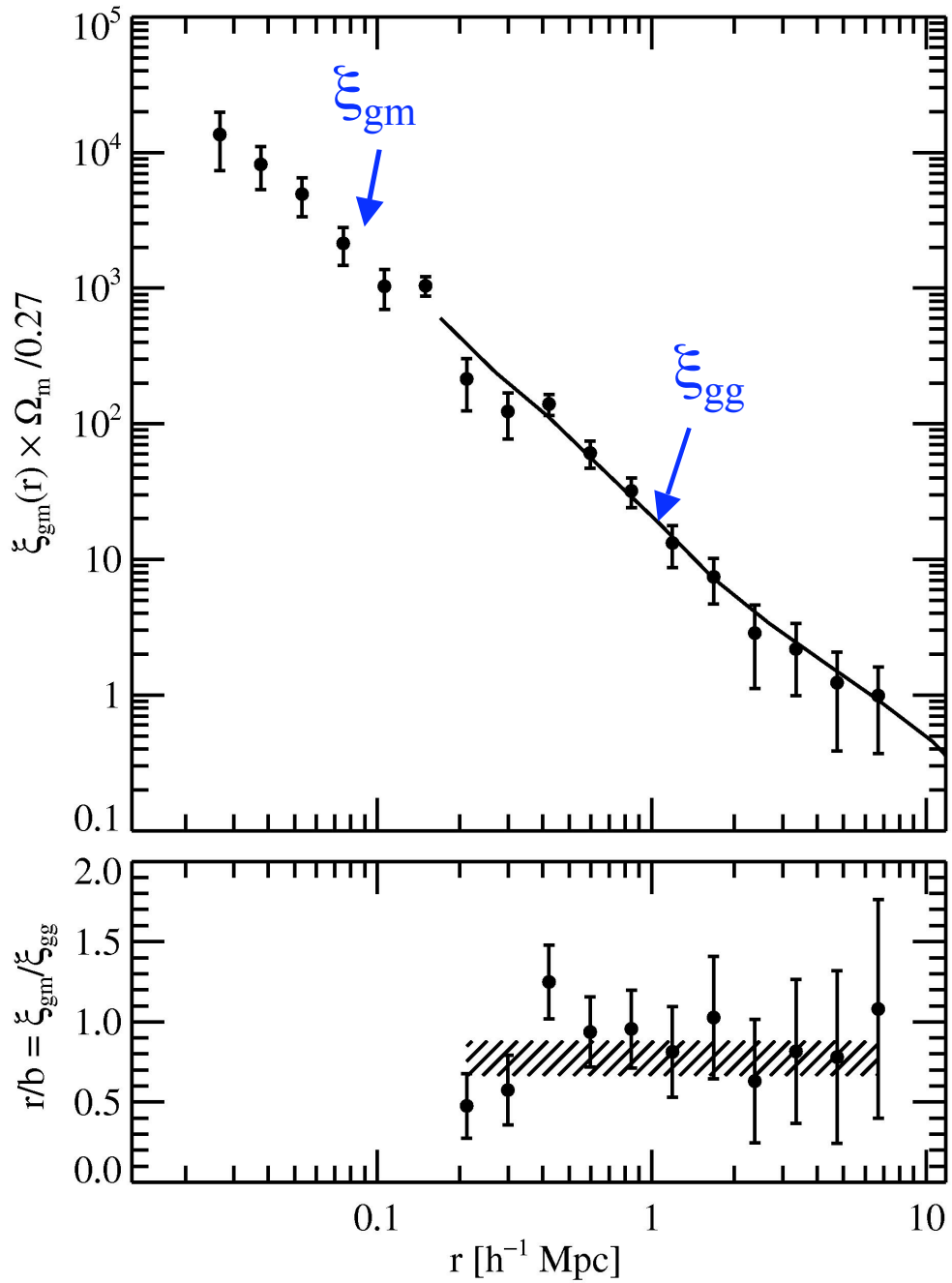


Must co-add signal from a large number of foreground galaxies

SDSS
Galaxy-mass vs.
Galaxy-galaxy
Correlations

weak lensing
8 million sources
100,000 lenses

Sheldon, Johnston, etal
Cf. Hoekstra, etal



Bias

Precision Cosmology with Large-scale Structure?

Requires a more nuanced treatment of:

- Bias as a function of galaxy type
- Redshift distortions
- Non-linear evolution of fluctuations

As well as very large sample sizes

We must jointly constrain cosmological and bias model parameters

"Halo Occupation" Model for Bias

Assume:

1. All galaxies live in dark matter halos.
2. Galaxy content of a halo is statistically independent of the halo's larger scale environment. Depends only on mass.

The bias of a certain galaxy class (type, luminosity, etc) is fully defined by:

- The probability distribution P(N|M) that a halo of mass M contains N galaxies

$\langle N \rangle_M$ $\quad$ $P(N|\langle N \rangle)$

- The relation between the galaxy and dark matter spatial distribution within halos

- The relation between the galaxy and dark matter velocity distribution within halos

<u>Halo Occupation Distribution</u>

Halo Model of Bias

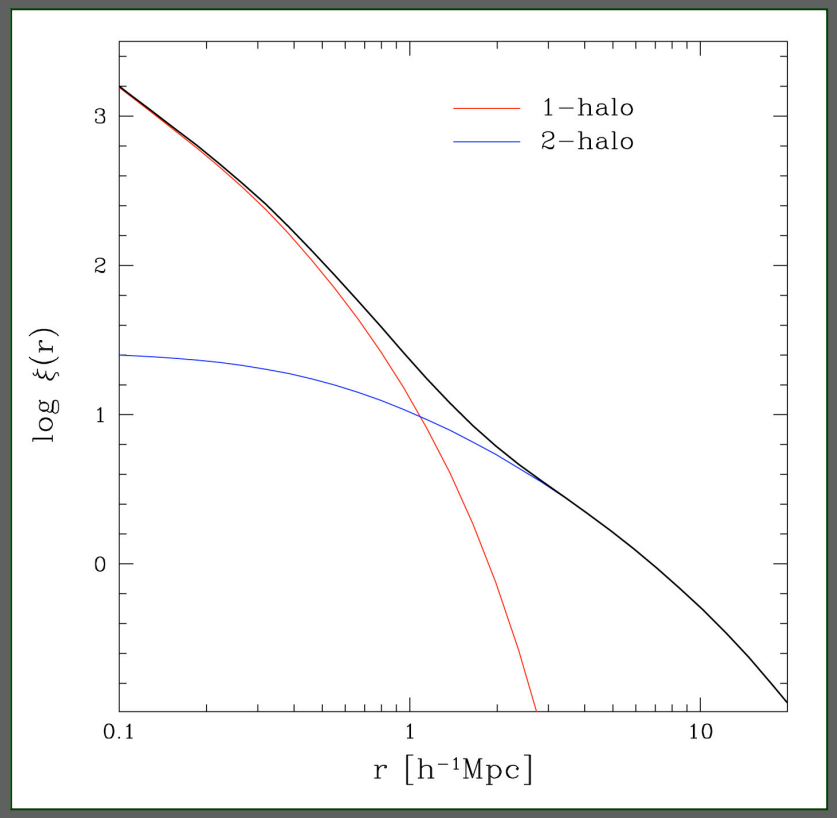
Two-point Correlations

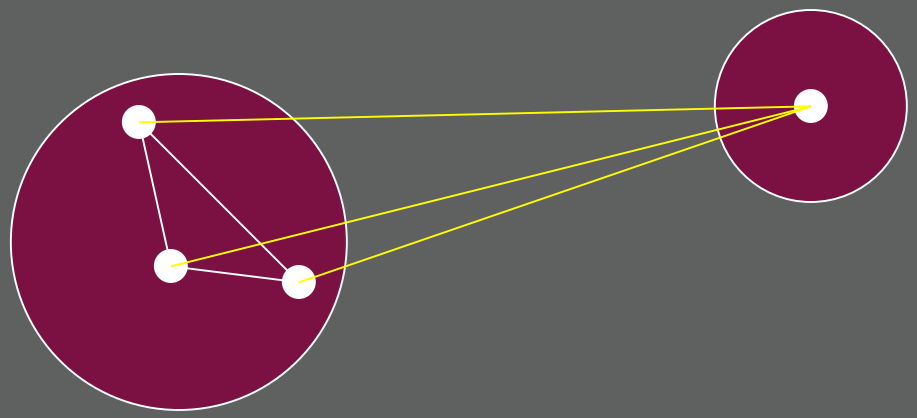
Large scales: All pairs from separate halos:

$$\xi_g(r) = b^2 \xi_m(r), \qquad b = \bar{n}_g^{-1} \int_0^\infty dM \frac{dn}{dM} \langle N \rangle_M b_h(M)$$

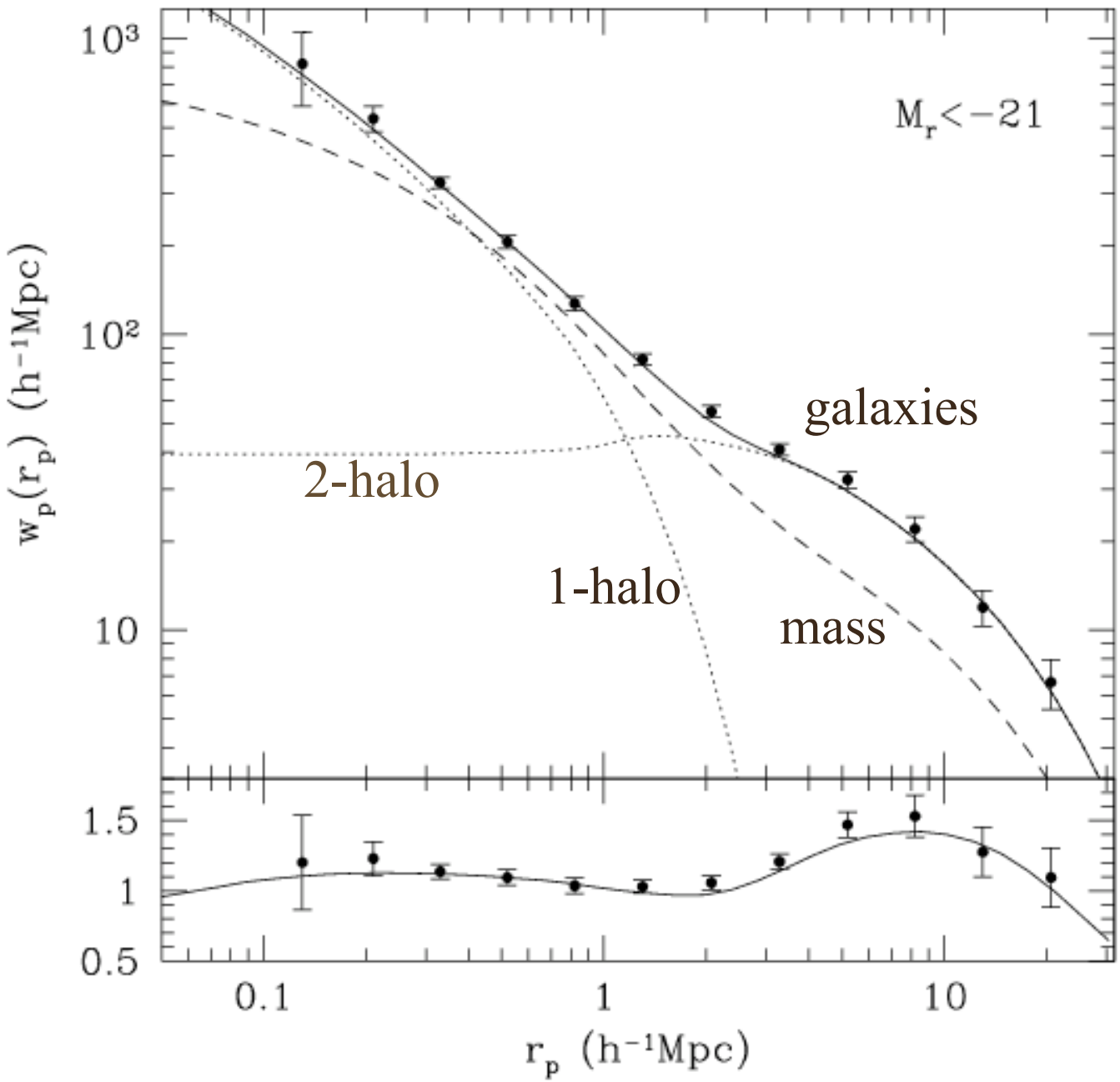
Small scales: All pairs from same halo:

$$\frac{\bar{n}_g^2}{2} \int_0^r \xi_{1\mathrm{h}}(r) 4\pi r^2 dr = \int_0^\infty dM \frac{dn}{dM} \frac{\langle N(N-1) \rangle_M}{2} F\left(\frac{r}{2R_{\mathrm{vir}}}\right)$$



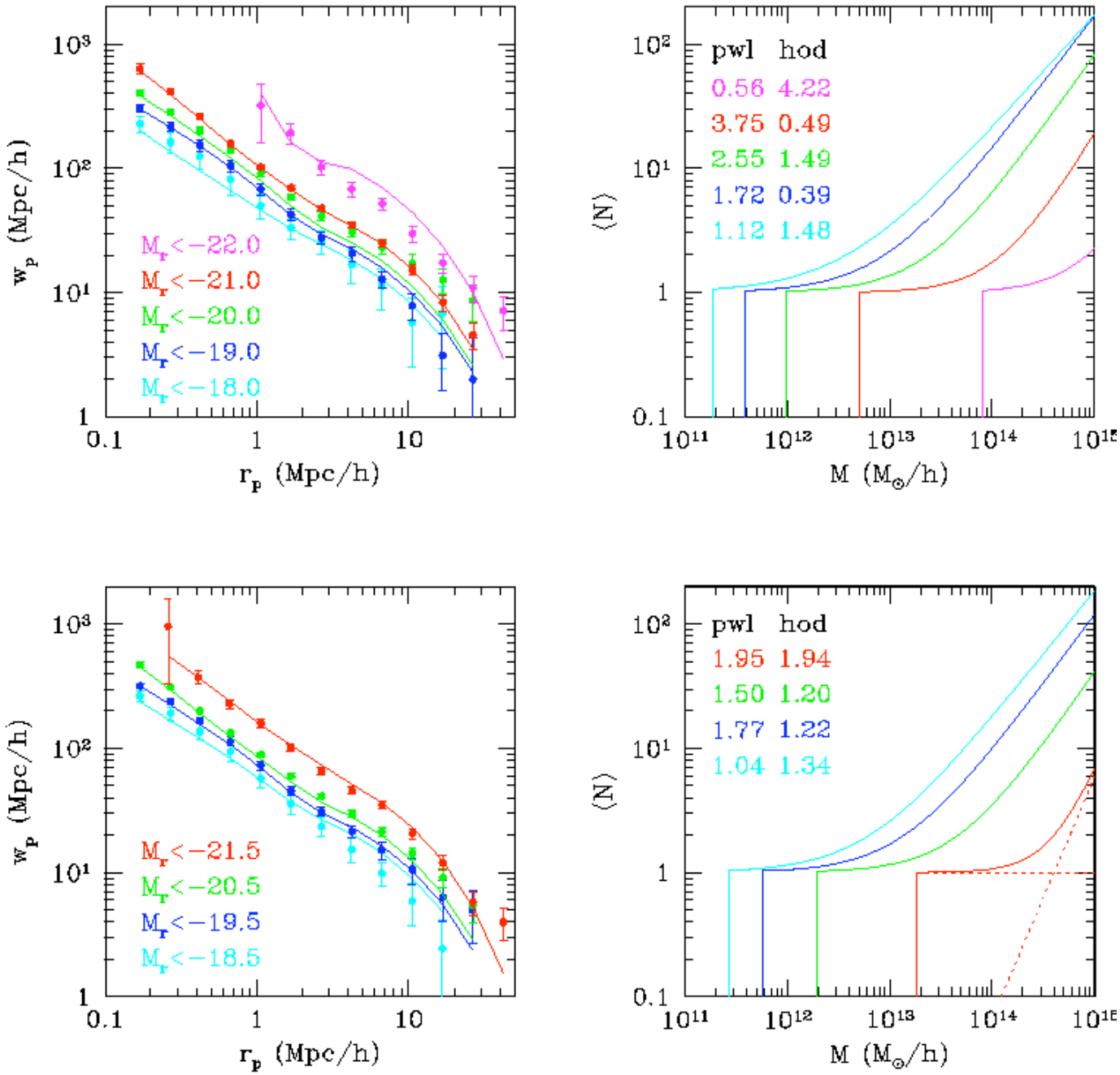


Halo Model fit to Clustering of Bright SDSS Galaxies



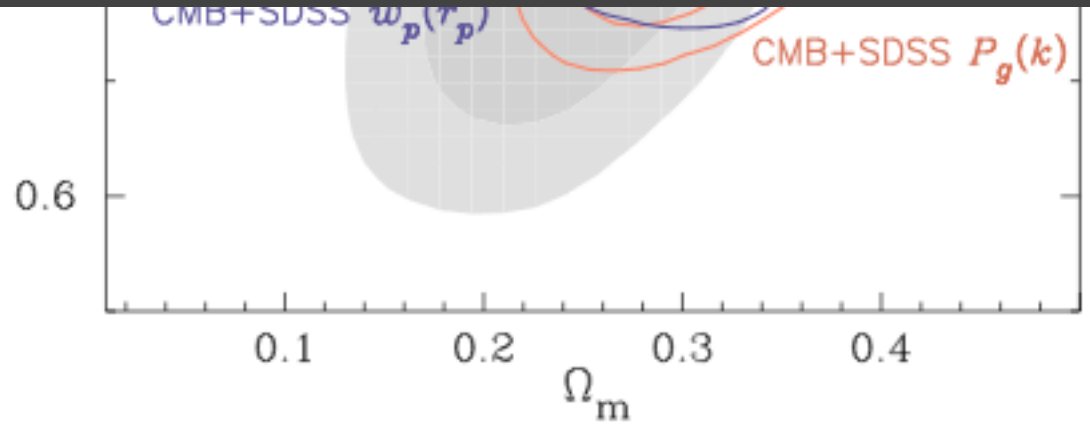
Zehavi etal

SDSS Galaxy-galaxy Correlations vs. Luminosity



Zehavi, Zheng, etal

Cosmological Constraints



Abazajian, etal

Cluster Redshift Distribution and Dark Energy

Constraints:

Raising w at fixed Ω_{DE}:

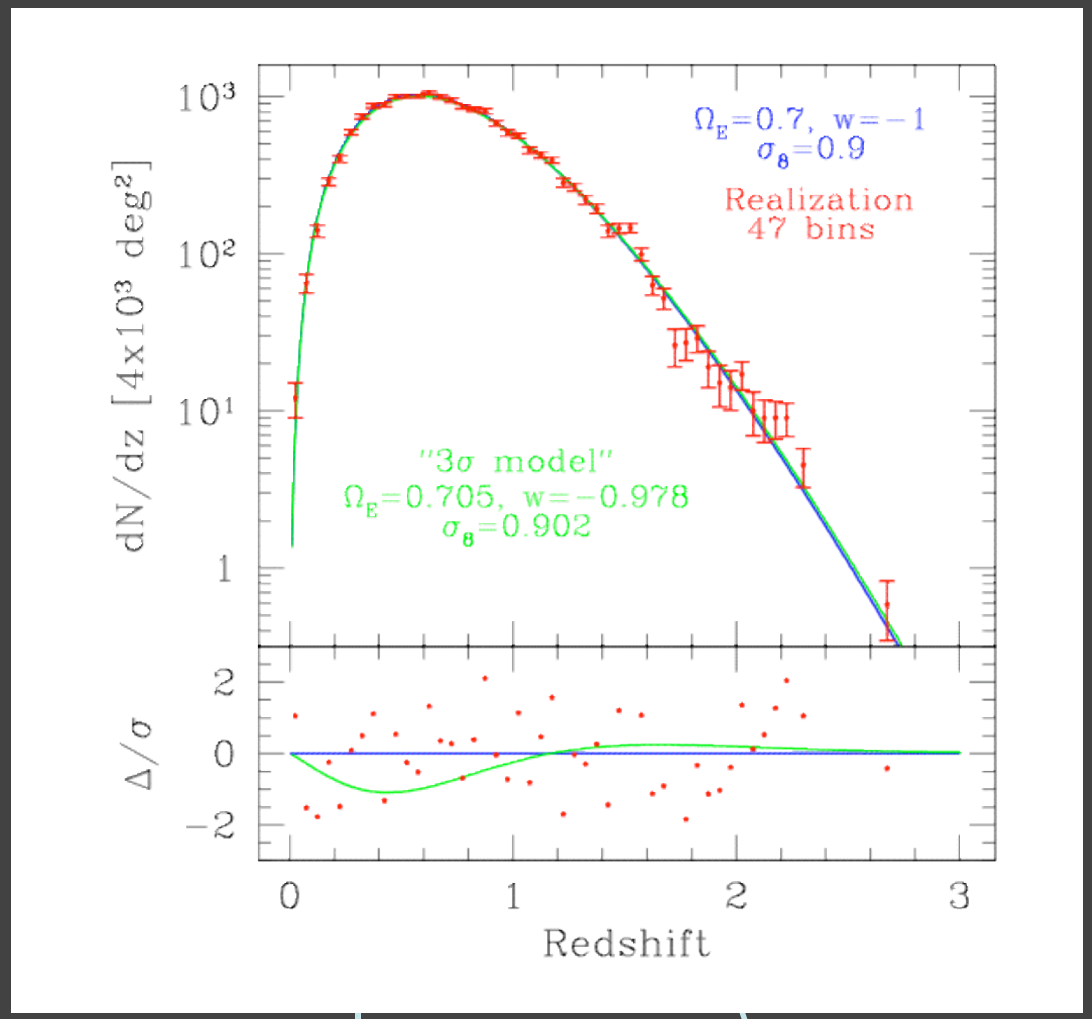
- decreases volume
- decreases growth rate of surveyed density perturbations

$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega} n(z)$$

$$\frac{dV}{dz\,d\Omega} = \frac{c}{H(z)} d_A^2 (1+z)^2 \qquad d_A \propto \int_0^z \frac{dz'}{E(z')}$$

$d_A(1+z)$ is proper distance

$H(z) = H_o E(z)$ is the Hubble parameter



Volume effect

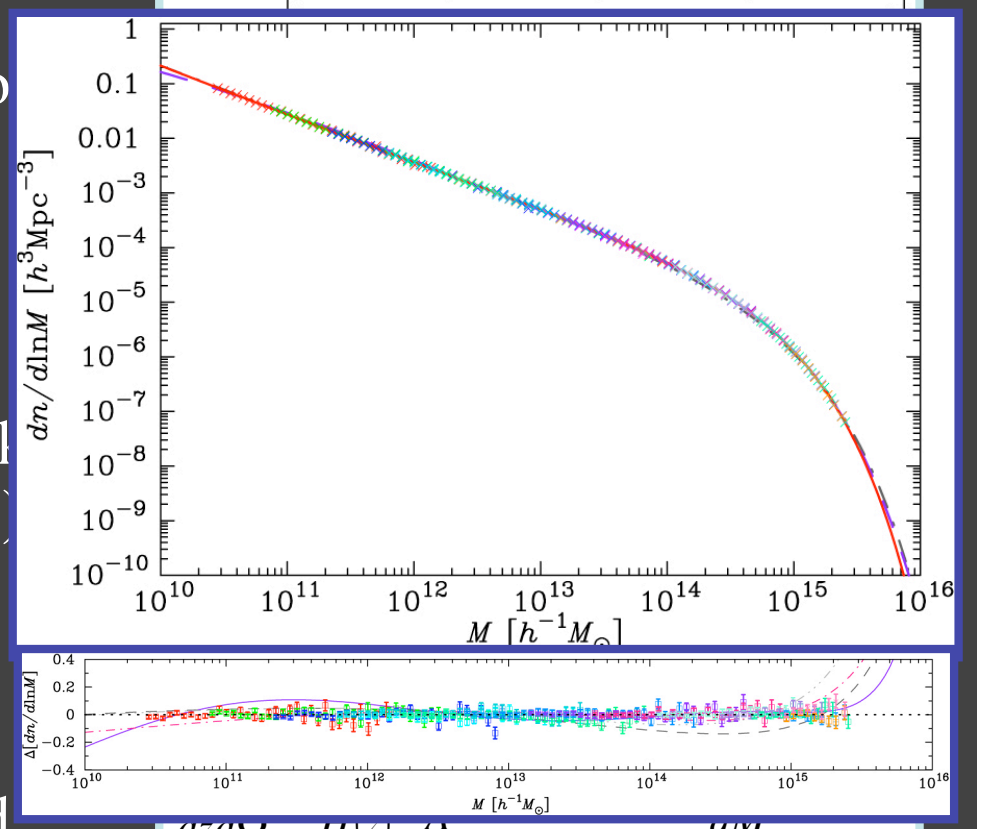
Growth effect

Mohr

Precision Cosmology with Clusters

- Requirements
  1. Quantitative understanding o the formation of dark matter halos in an expanding universe
  2. Clean way of selecting a large number of massive darl matter halos (galaxy clusters) over a range of redshifts
  3. Redshift estimates for each cluster (photo-z's adequate)
  4. Observables that can be used as mass estimates at all redshifts

Sensitivity to Mass

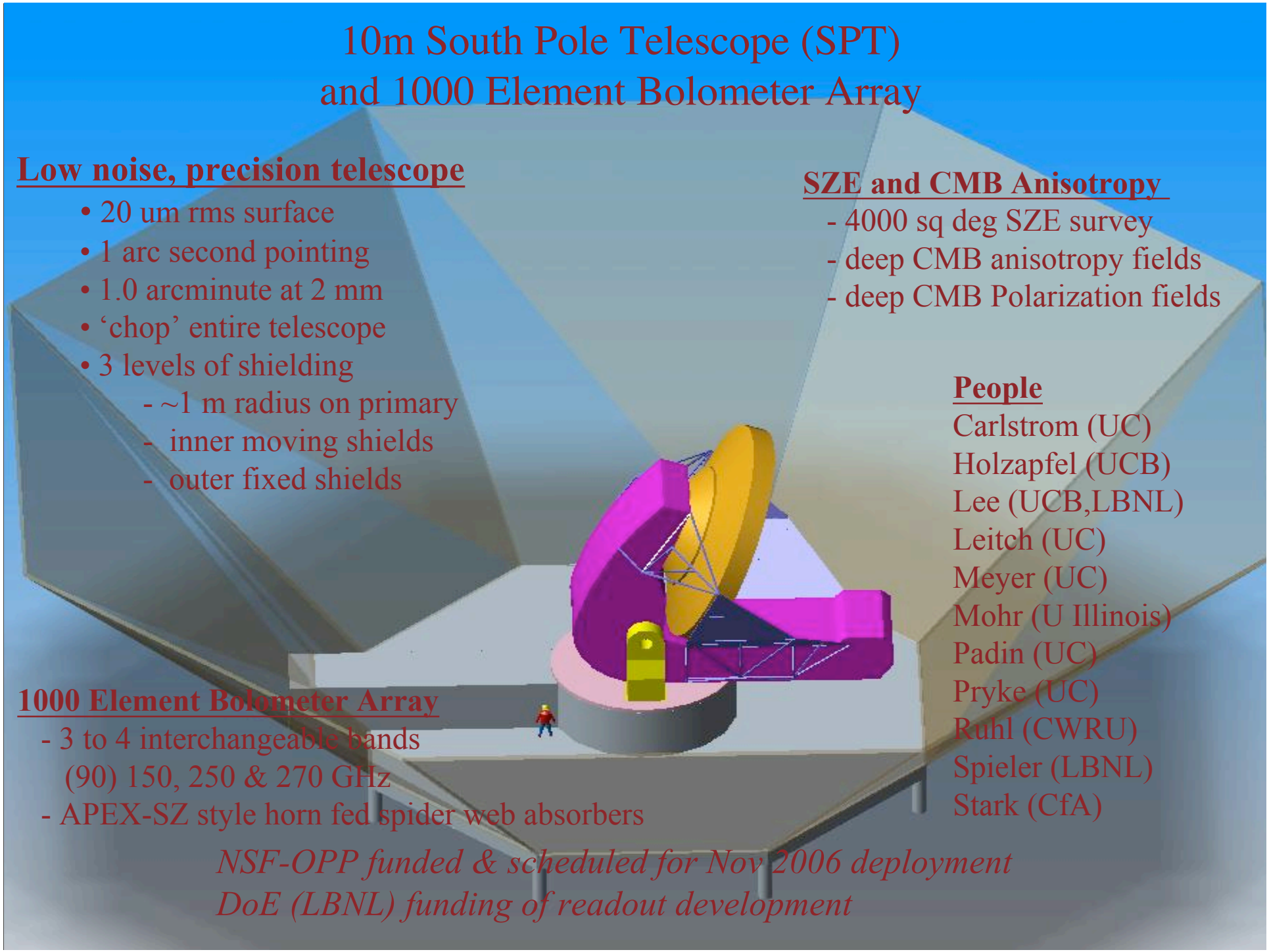


Warren etal

Jenkins etal

$$\frac{dn}{dM}(z, M) = 0.315\frac{\rho_0}{M}\frac{1}{\sigma_M}\frac{d\sigma_M}{dM}\exp\left[-|0.61 - \log(D_z\,\sigma_M)|^{3.8}\right]$$

10m South Pole Telescope (SPT) and 1000 Element Bolometer Array



Low noise, precision telescope

- 20 um rms surface
- 1 arc second pointing
- 1.0 arcminute at 2 mm
- 'chop' entire telescope
- 3 levels of shielding
  - ~1 m radius on primary
  - inner moving shields
  - outer fixed shields

SZE and CMB Anisotropy

- 4000 sq deg SZE survey
- deep CMB anisotropy fields
- deep CMB Polarization fields

People

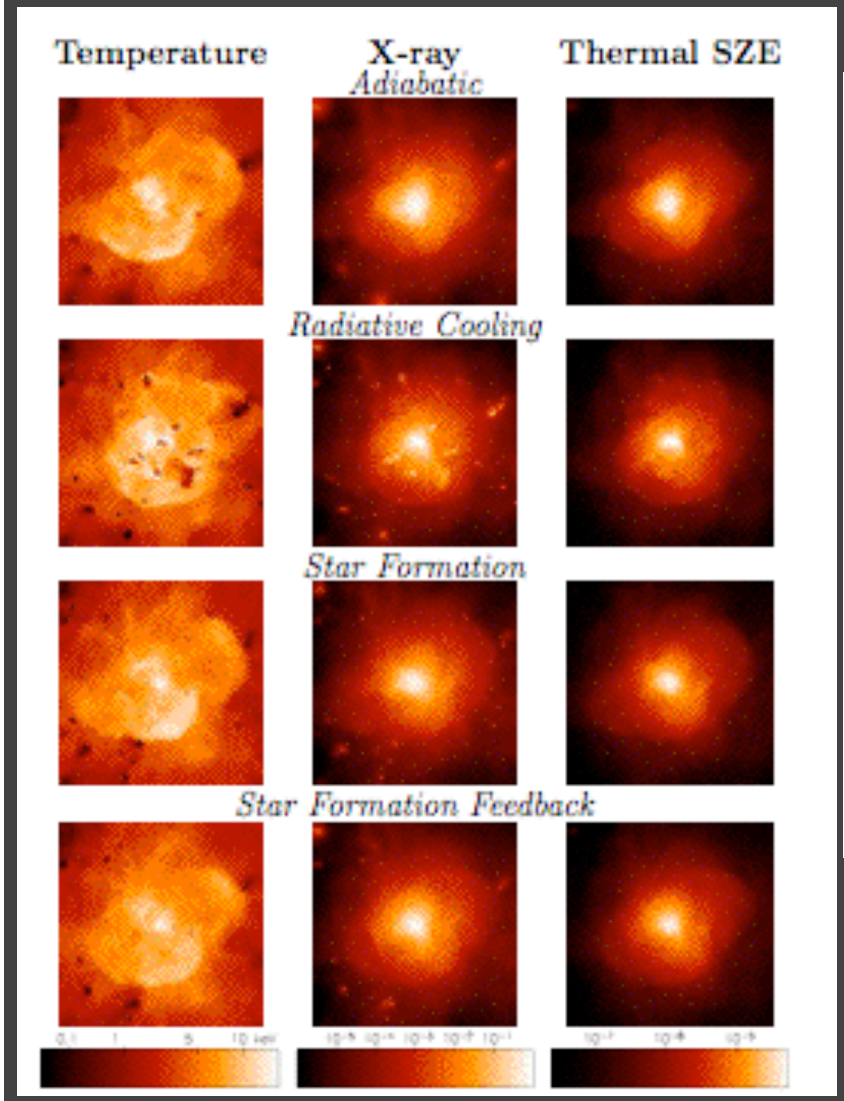
Carlstrom (UC)
Holzapfel (UCB)
Lee (UCB,LBNL)
Leitch (UC)
Meyer (UC)
Mohr (U Illinois)
Padin (UC)
Pryke (UC)
Ruhl (CWRU)
Spieler (LBNL)
Stark (CfA)

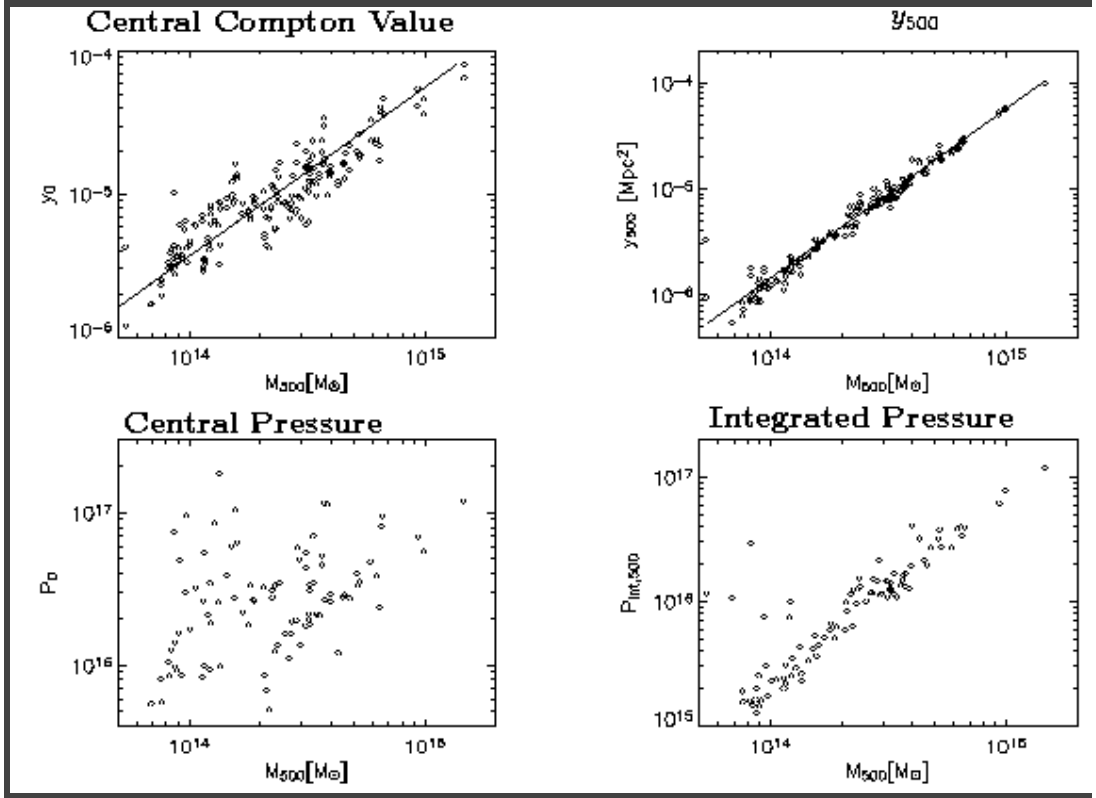
1000 Element Bolometer Array

- 3 to 4 interchangeable bands
  (90) 150, 250 & 270 GHz
- APEX-SZ style horn fed spider web absorbers

NSF-OPP funded & scheduled for Nov 2006 deployment
DoE (LBNL) funding of readout development

SZE vs. Cluster Mass: Simulations



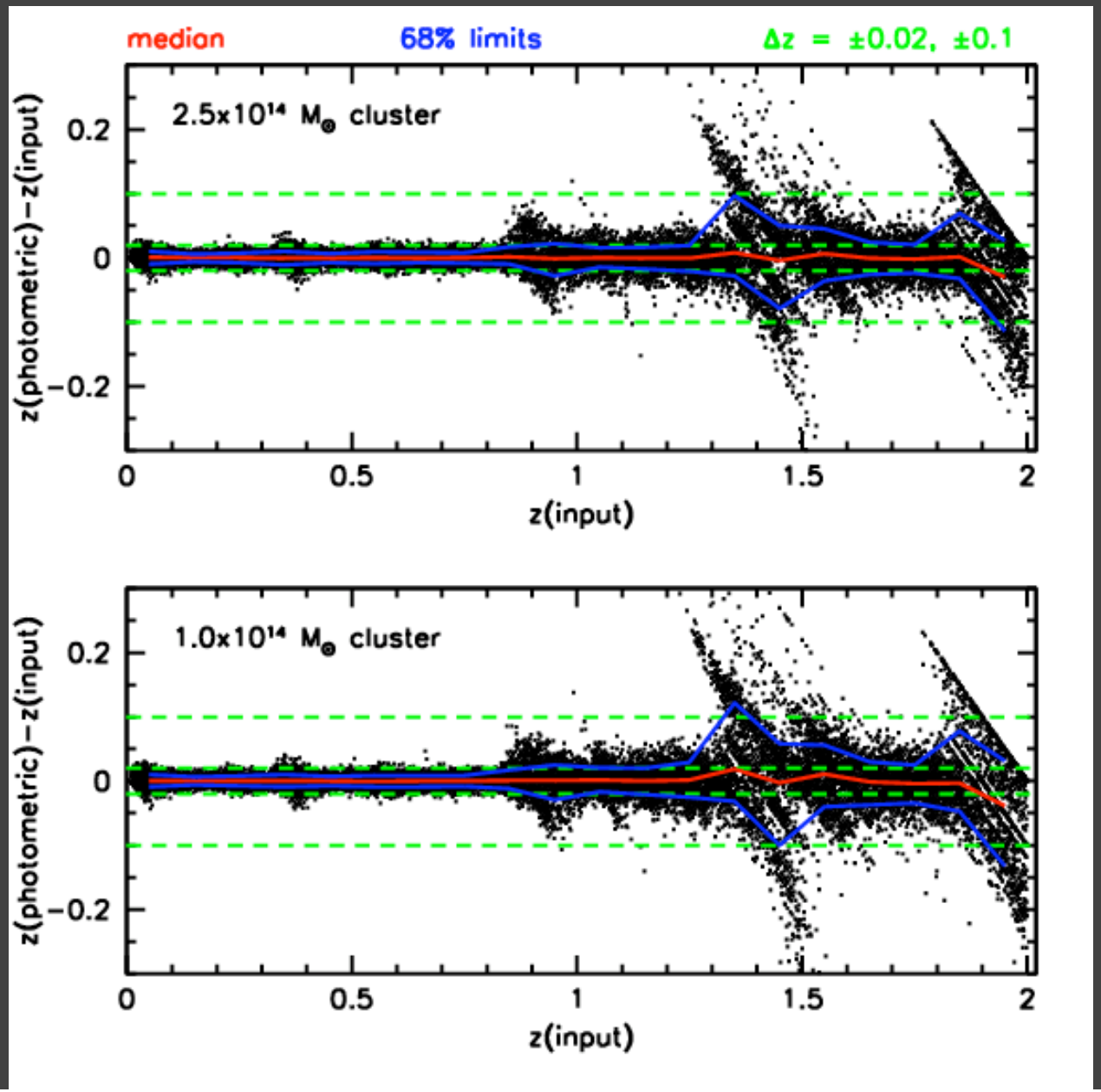


Integrated SZE flux decrement insensitive to gas dynamics in the cluster core

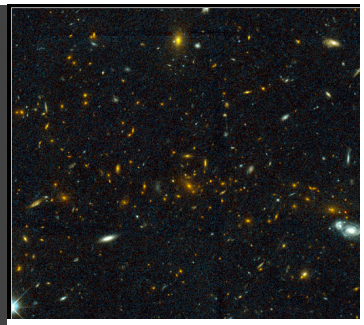
Motl, etal

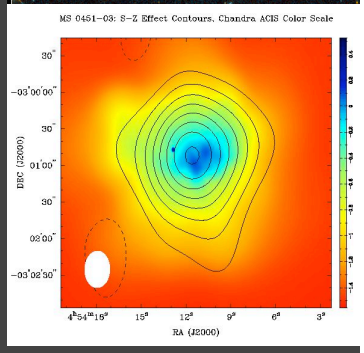
DES Cluster Photometric Redshift Simulations

$\sigma(z) \sim 0.02$
to $z=1.3$



Issues for Cluster Cosmology





- Techniques for Cluster Identification and Mass Determination:
  - Optical galaxy concentration: color-magnitude
  - Weak Lensing (e.g., aperture mass)
  - Sunyaev-Zel'dovich effect
  - X-ray flux

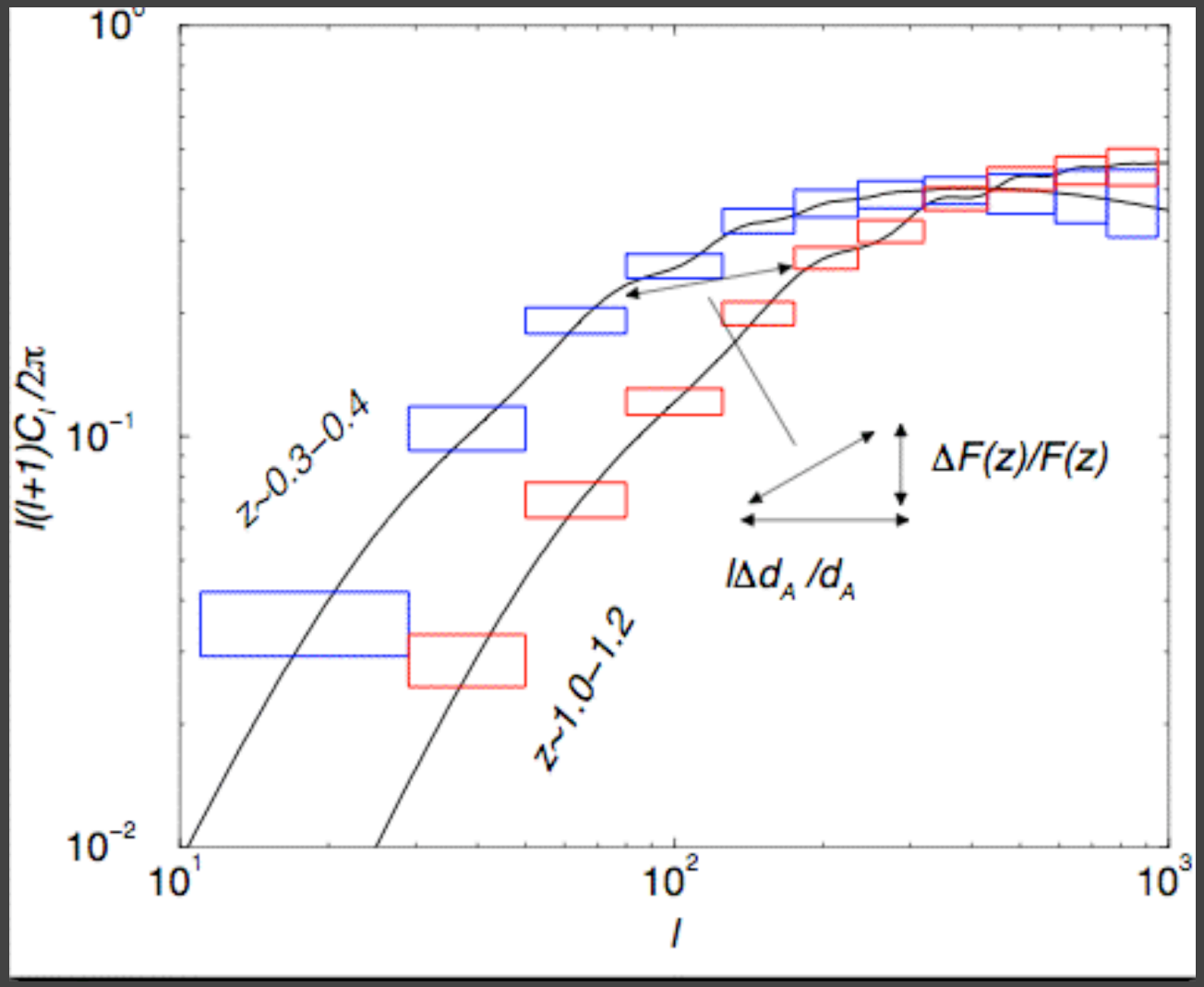
- Systematics:

1. Sample selection function: completeness & contamination
2. Statistical mass-observable calibration, scatter, & its evolution
3. Projection effects (for lensing-selected samples)
4. Photo-z systematics

- Controls:

1. Higher-resolution SZE studies (SZA); simulations w/ radio sources; multi-frequency SPT obs.; optical study of SZE selection function below shoulder
2. Self-calibration of mass-observable: clustering of clusters, shape of mass fn.
2. Weak Lensing mass calibration: Cluster-mass correlation function vs. SZE flux
4. Spectroscopic Training Sets

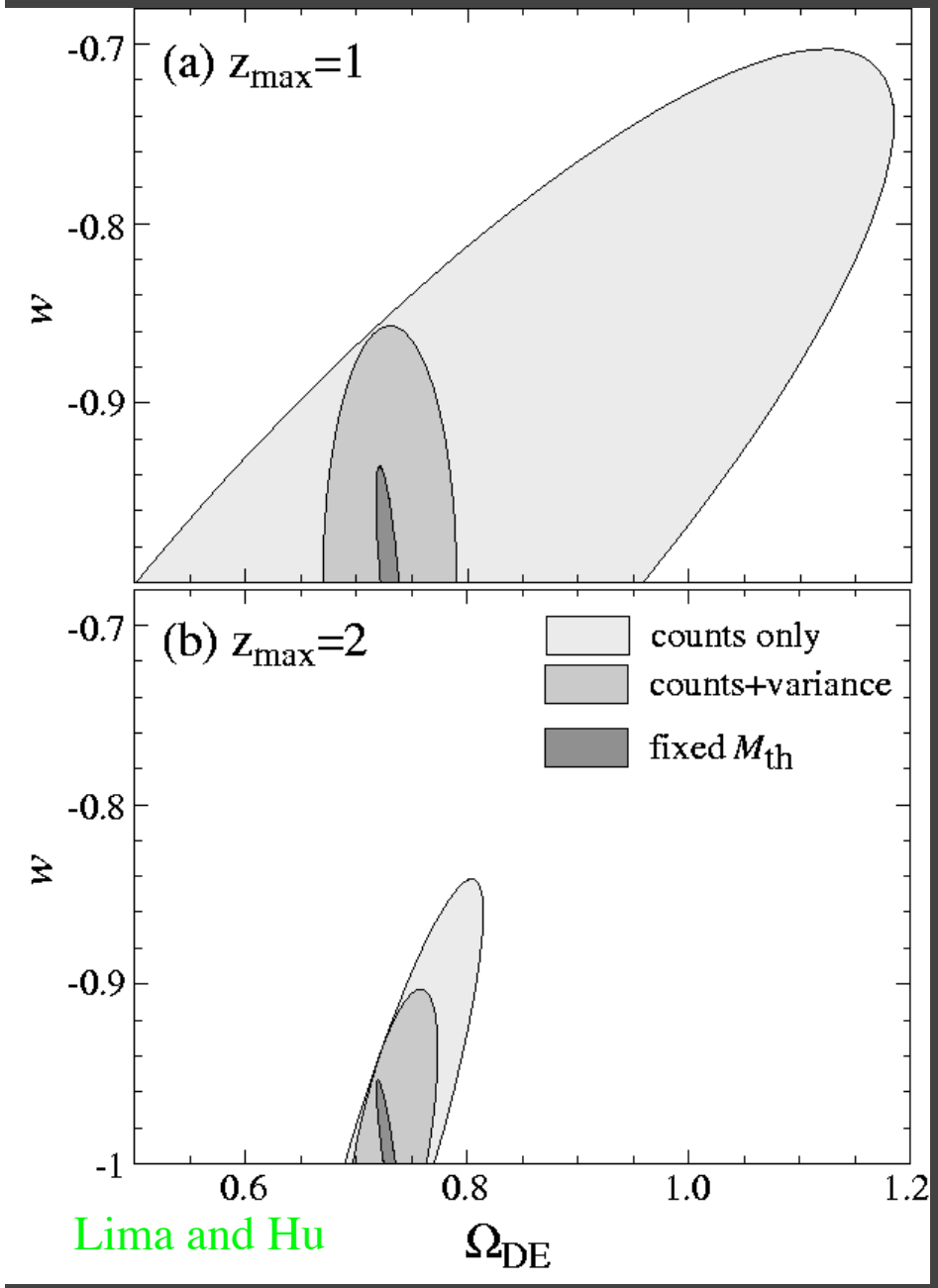
Cluster Angular Power Spectrum



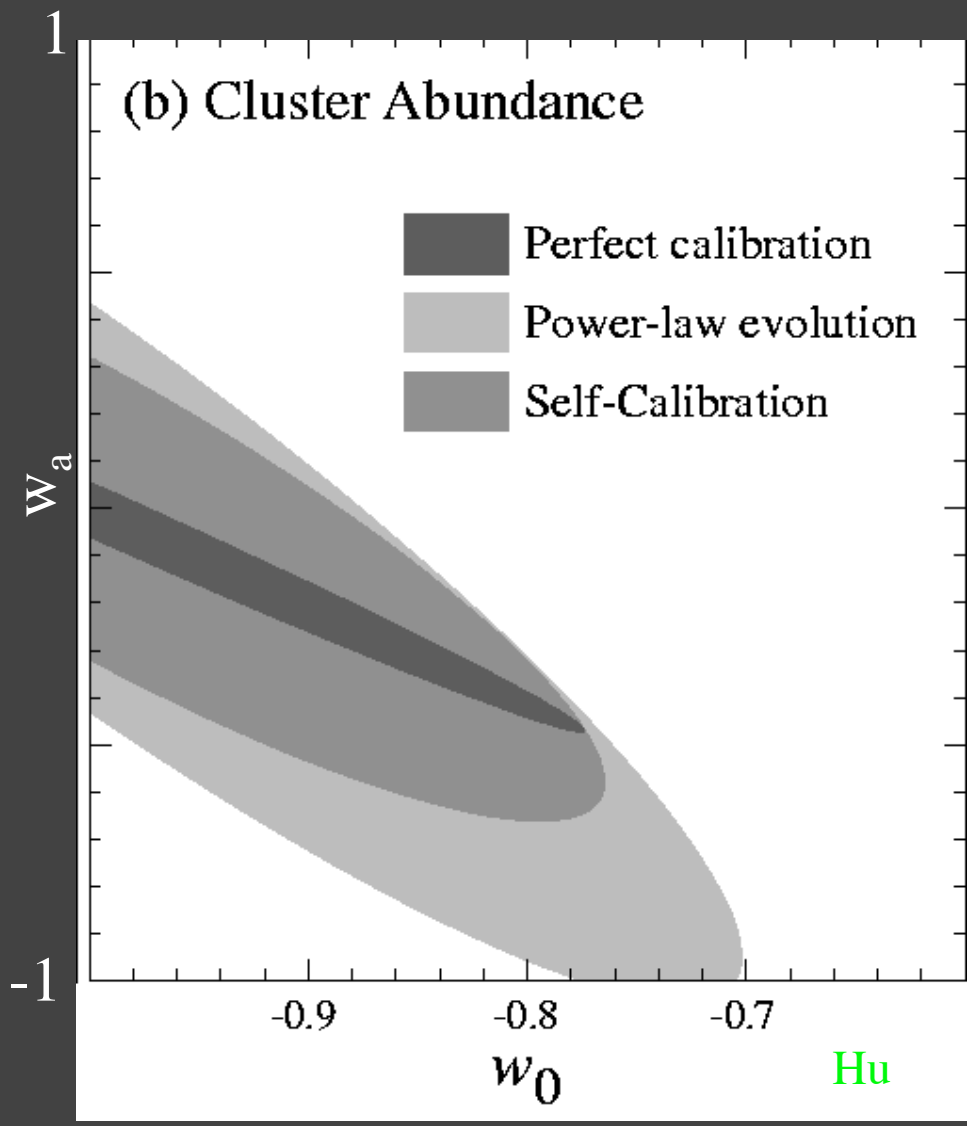
Cf. Baryon oscillations

Cooray etal 2001

Self-calibration with Clustering



Lima and Hu



Hu

4000 sq. deg. Survey

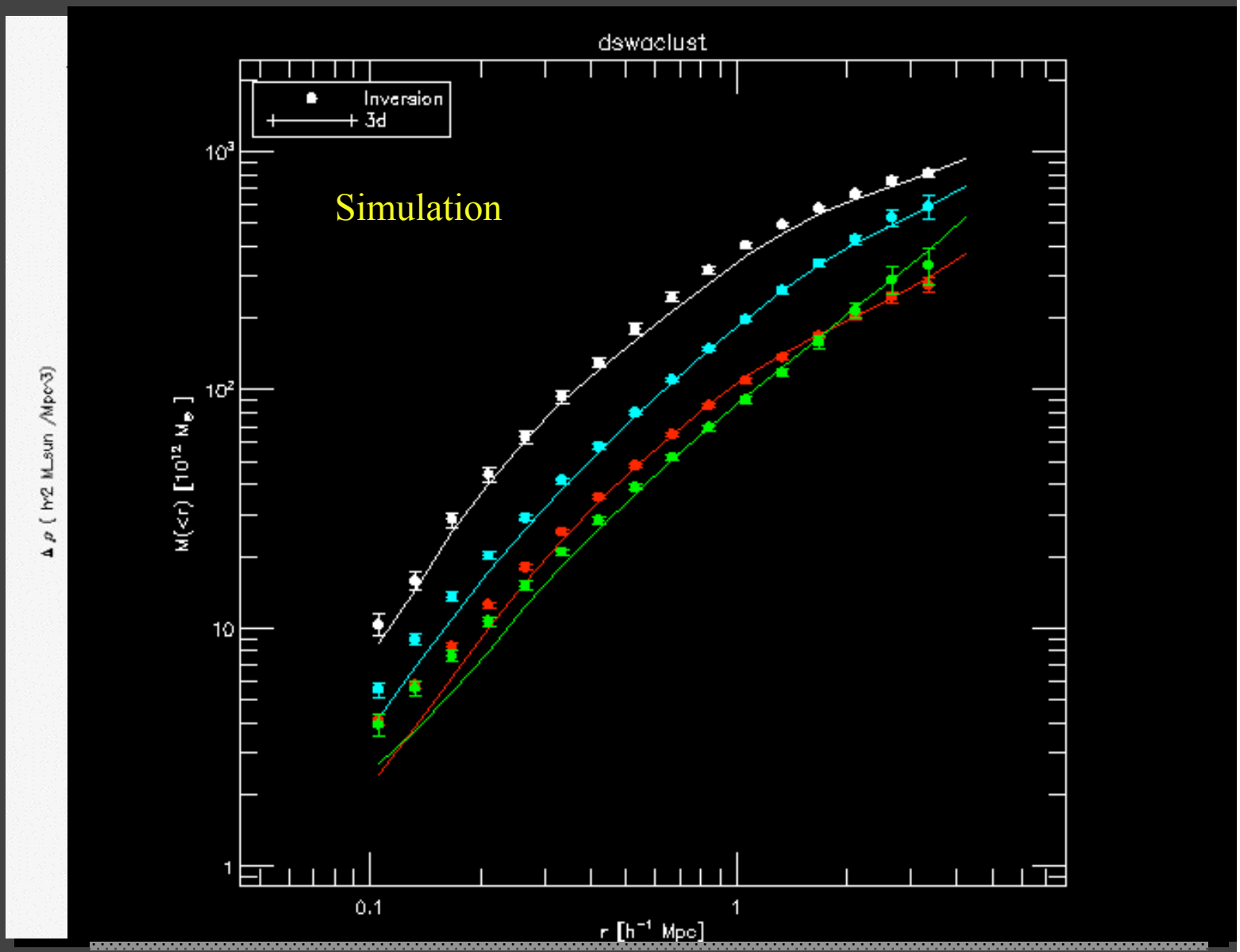
See also Majumdar & Mohr

Weak Lensing Statistical Mass Calibration

$\Omega_m \xi_{cm}$

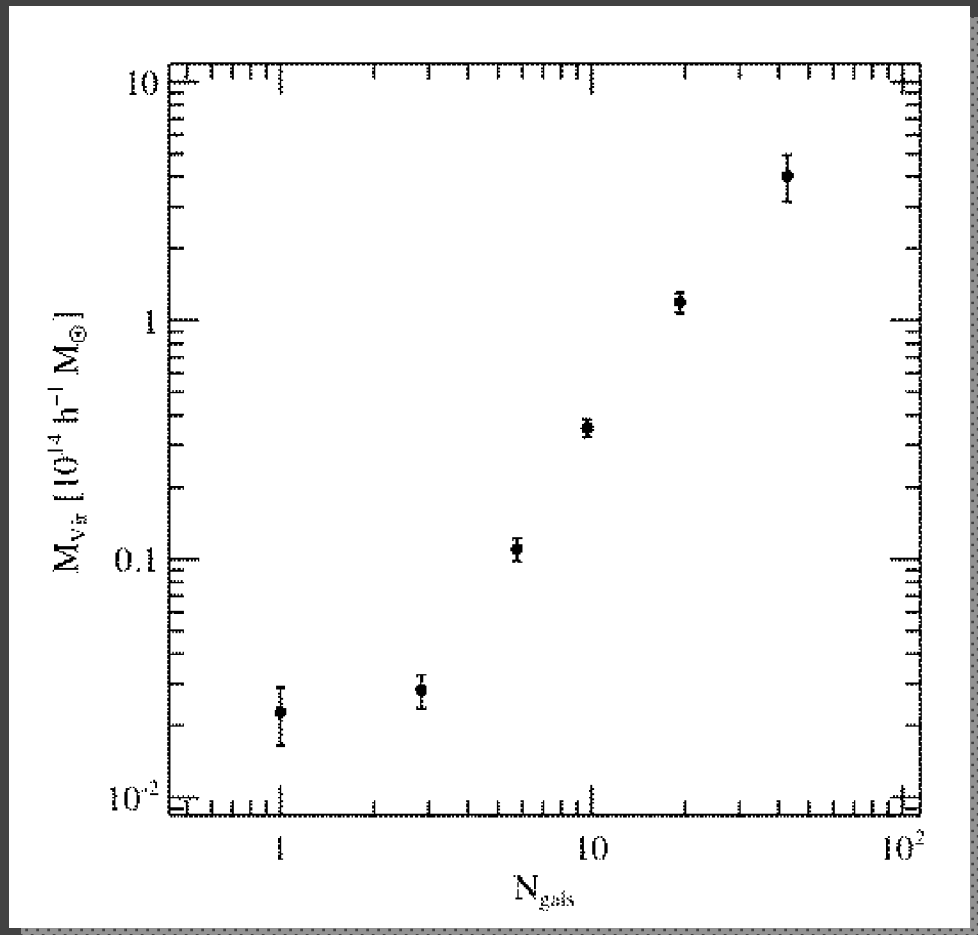
Preliminary SDSS Results

Simulations indicate this method accurately recovers statistical Cluster virial masses, immune to projection



virial radius

Lensing Calibrates Richness* vs. Cluster Virial Mass



SDSS preliminary (low-z)

*or any other observable

Johnston, Sheldon, etal