Probing Dark Energy

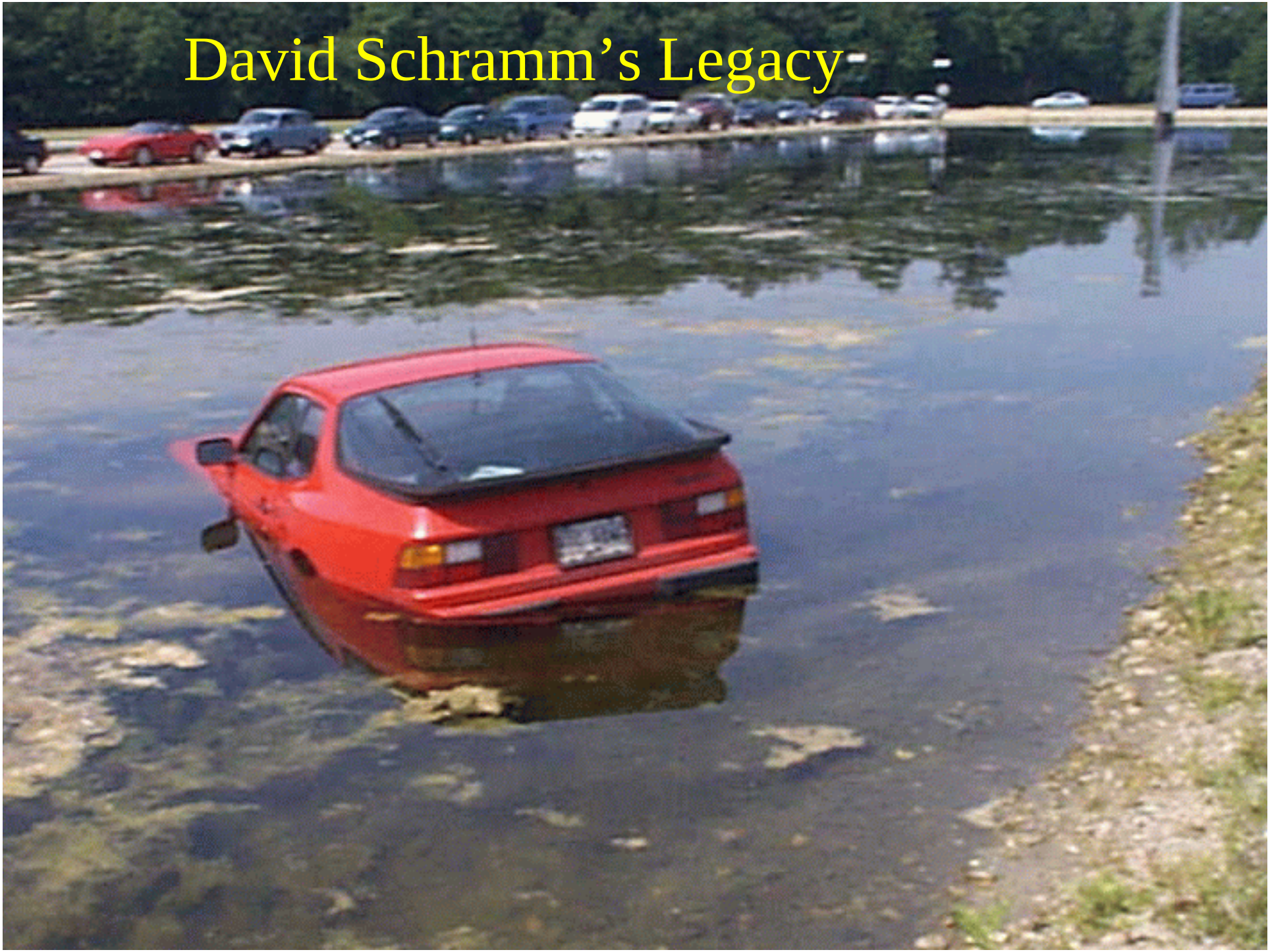
From Theory to Observation

Josh Frieman

KICP Inaugural Symposium

Dec. 11, 2005

David Schramm's Legacy

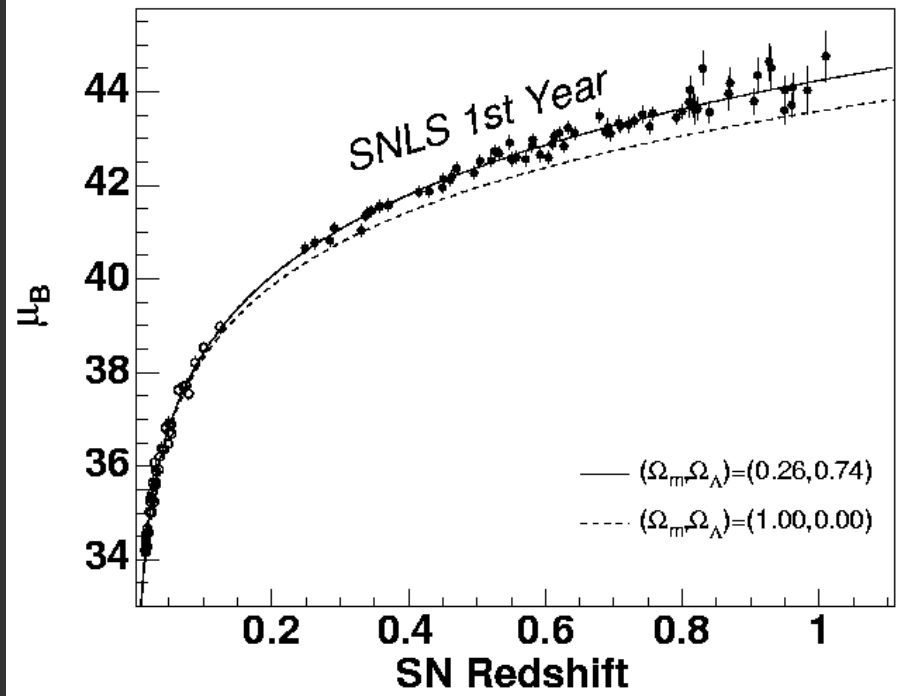


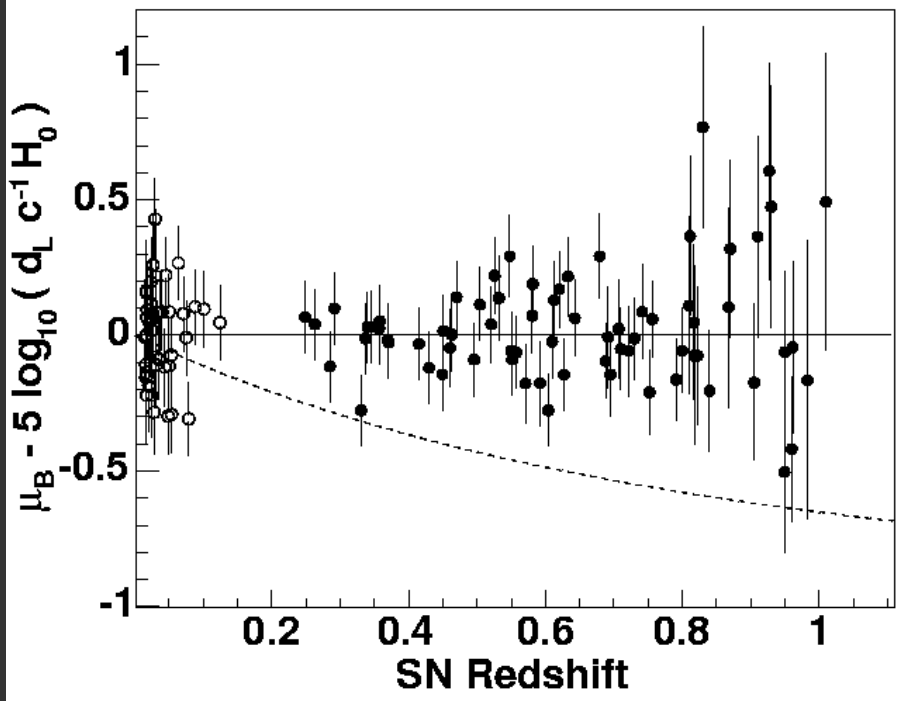
Supernova Hubble Diagram

CFHT Supernova Legacy Survey

Astier etal 05

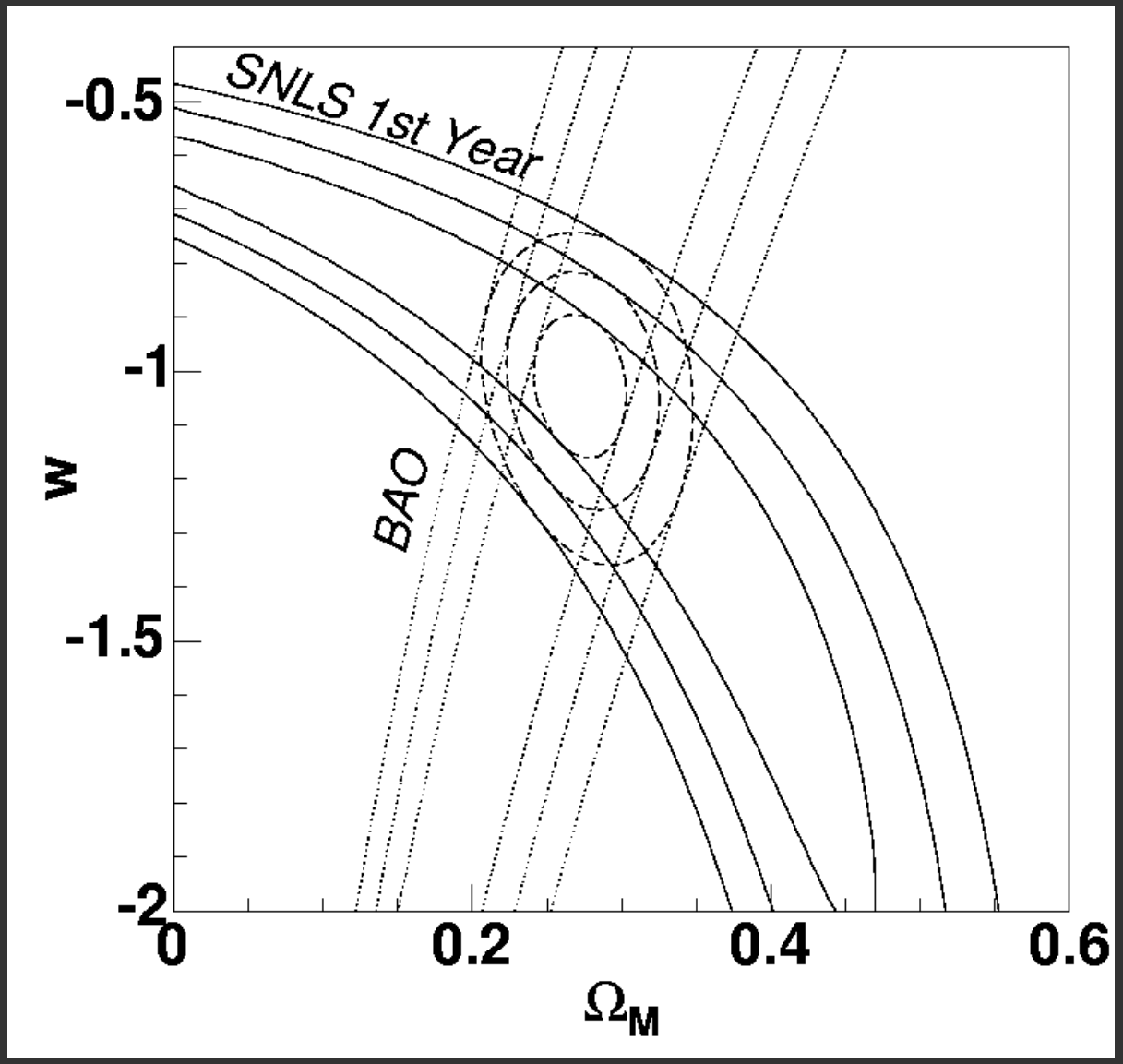
Previous talk by Isobel Hook





Is the game over?

Constraints on Dark Energy Equation of State



CFHT SNLS+
SDSS BAO

Astier etal 05

Probing Dark Energy: the Present

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

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

matter dark energy

flat Universe
constant *w*

2-parameter model

Geometric tests:

- Comoving distance $r(z) = F[\int dz/H(z)]$
- Standard Candles Supernovae $d_L(z) = (1+z)\, r(z)$
- Standard Rulers Baryon Oscillations $d_A(z) = (1+z)^{-1}\, r(z)$
- Standard Population Clusters $dV/dz d\Omega = r^2(z)/H(z)$

Probing Dark Energy: the Future

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

$$H^2(z)/H^2_0 = \Omega_M(1+z)^3 \quad \text{matter}$$
$$+ \Omega_{DE} \exp 3 \int(1+w(z))\, d \ln(1+z) \quad \text{DE}$$
$$+ (1- \Omega_M - \Omega_{DE})(1+z)^2 \quad \text{curvature}$$

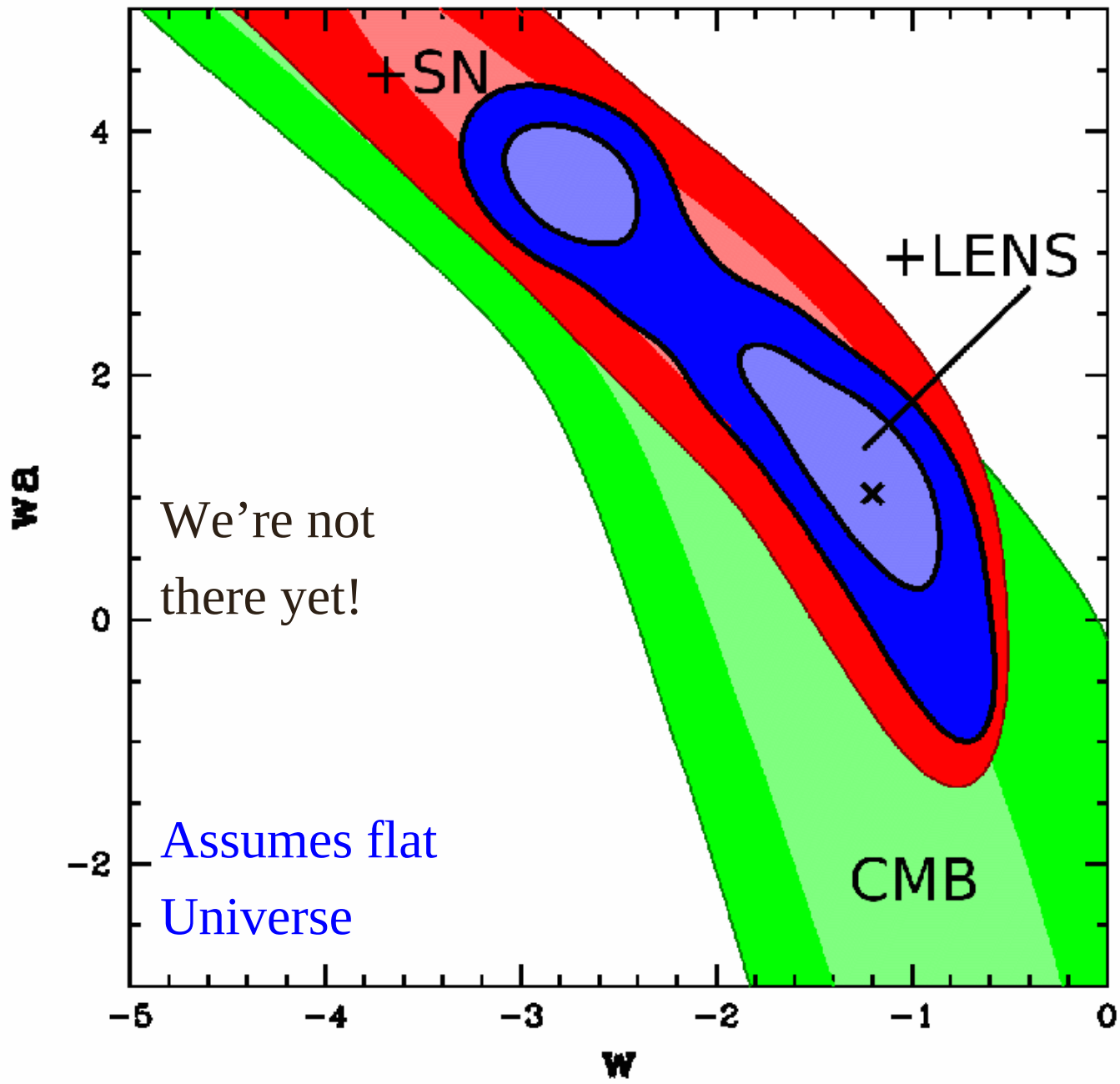
Parametrize: $w(a) = w_0 + w_a z/(1+z)$

- And through the growth rate of large-scale structure: $g=\delta/a$

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

Constraints on Time-varying Dark Energy

3-parameter model



Jarvis etal 05

Dark Energy Scenarios

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

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

$G_{\mu\nu} = f(T_{\mu\nu}(\text{matter}))$ Carroll's

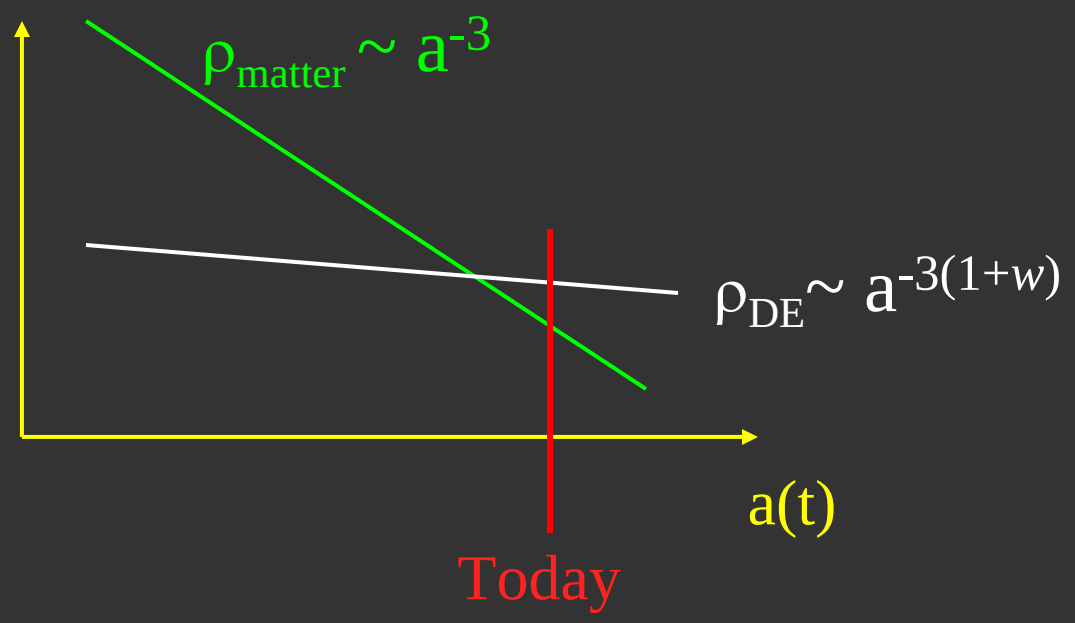
Inhomogeneity: apparent acceleration due to LSS Talk

Key Experimental Questions:

1. Is *w* observationally distinguishable from -1?
   What precision is needed? Depends on the answer.
2. Can we distinguish between gravity and stress-energy?
   Combine geometric w/ structure-based probes
3. If $w \neq -1$, it likely evolves: how well can/must we measure dw/da to make progress in fundamental physics?

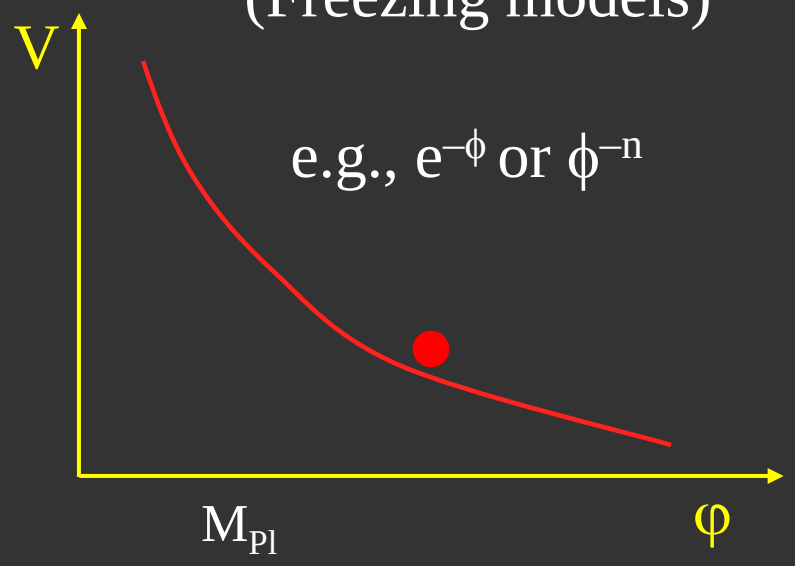
The Coincidence Problem

Why do we live at the `special' epoch when the dark energy density is comparable to the matter energy density?

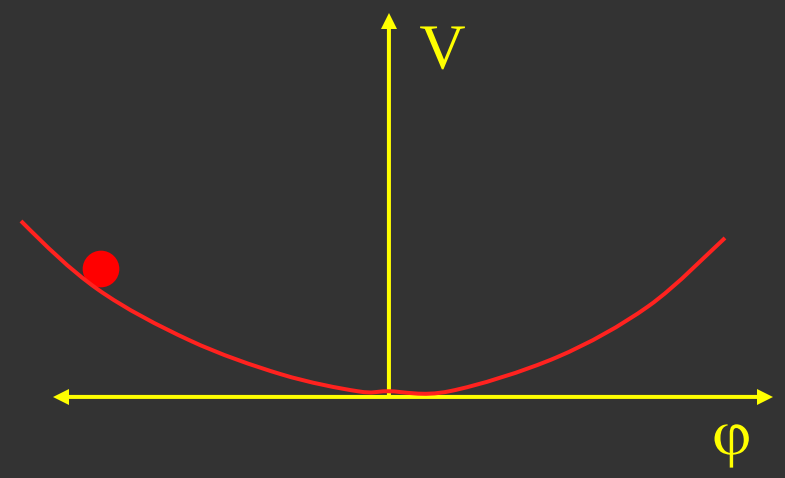


Scalar Field Models & Coincidence

`Dynamics' models
(Freezing models)



`Mass scale' models
(Thawing models)



<u>Runaway potentials</u>
DE/matter ratio constant
(Tracker Solution)

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

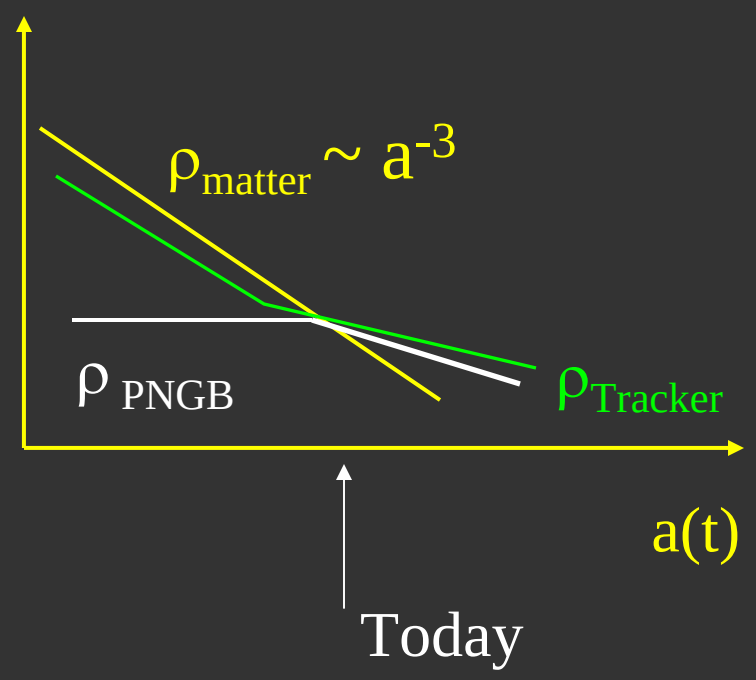
<u>Pseudo-Nambu Goldstone Boson</u>
Low mass protected by symmetry
(Cf. axion) JF, Hill, Stebbins, Waga

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

$f \sim M_{Planck}$ $M \sim 0.001$ eV $\sim m_\nu$

Second 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?

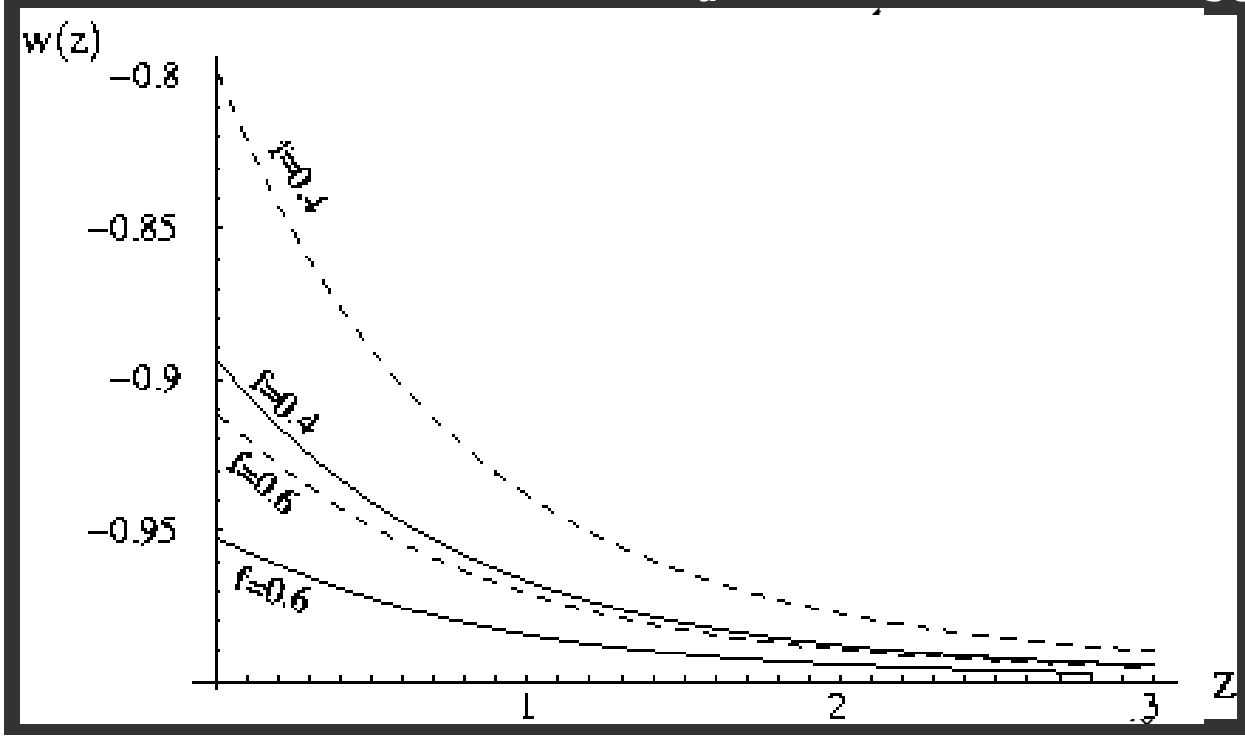


‘Axion’ (PNGB) Dark Energy

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

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

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



Hall etal

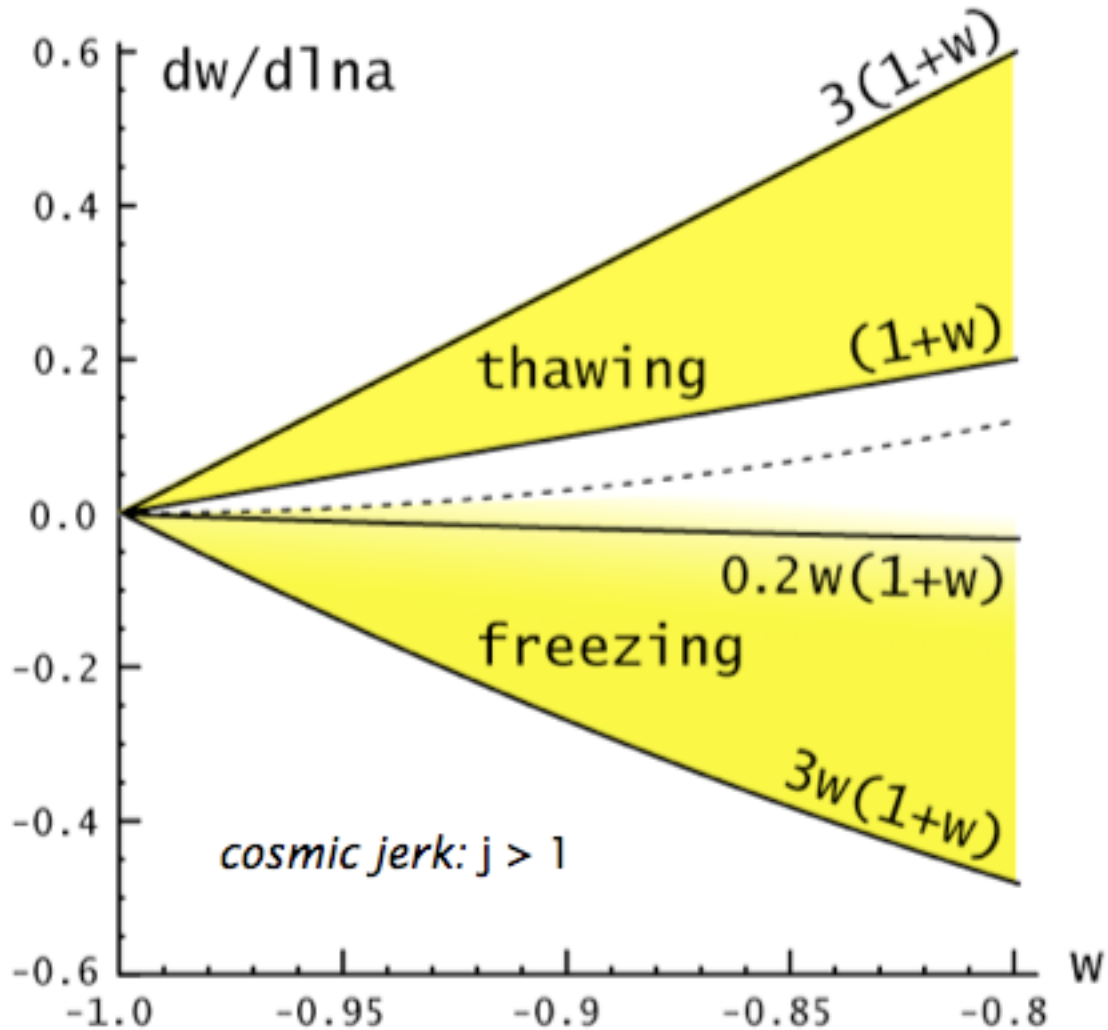
$V(\phi) = M^4[1+\cos(\phi/f)]$

See also
Kim; Choi; Namura, etal,
Kaloper & Sorbo,…

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

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

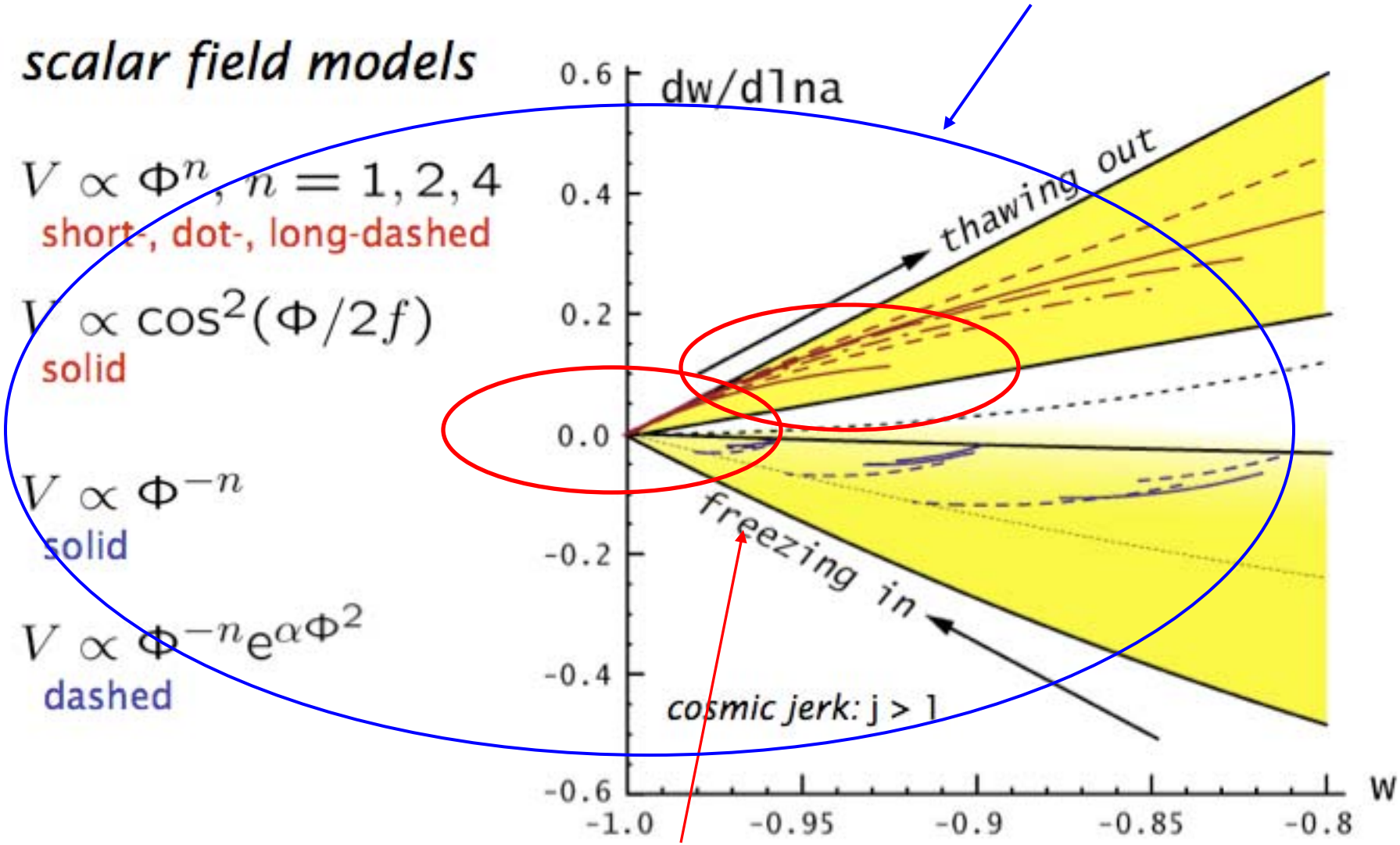
- *bounds*
- *evolution*
- *trends*



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

Caldwell & Linder

Goal for ~2011: SPT+DES



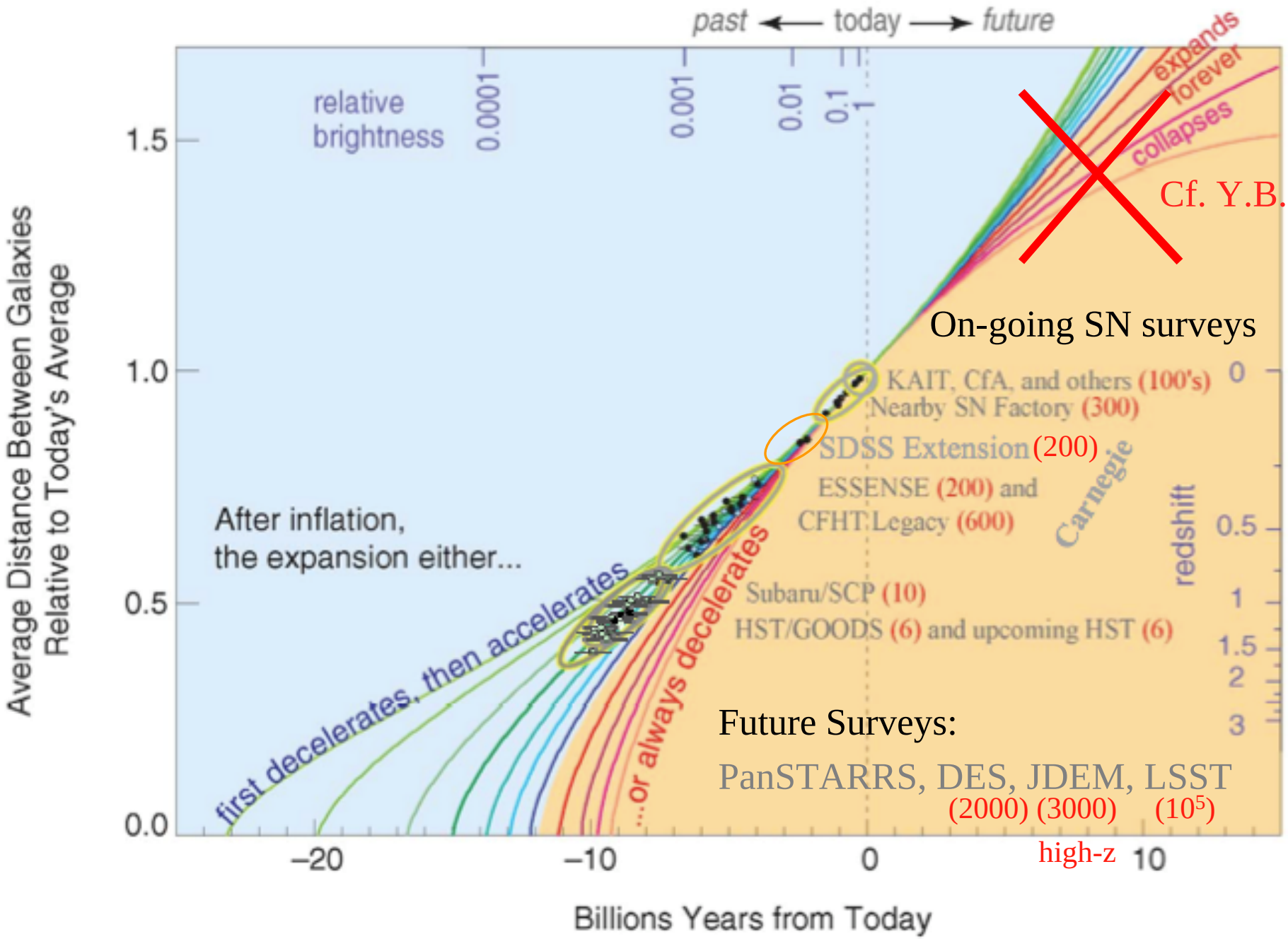
Caldwell & Linder

Goal for ~2015+: JDEM, LSST

Probes of Dark Energy

- Supernovae — Hook, Riess, Kowalski
- Weak Gravitational Lensing — Bernstein, Sheldon
- Cluster Surveys — Gladders
- Baryon Oscillations
- Integrated Sachs-Wolfe
- Other

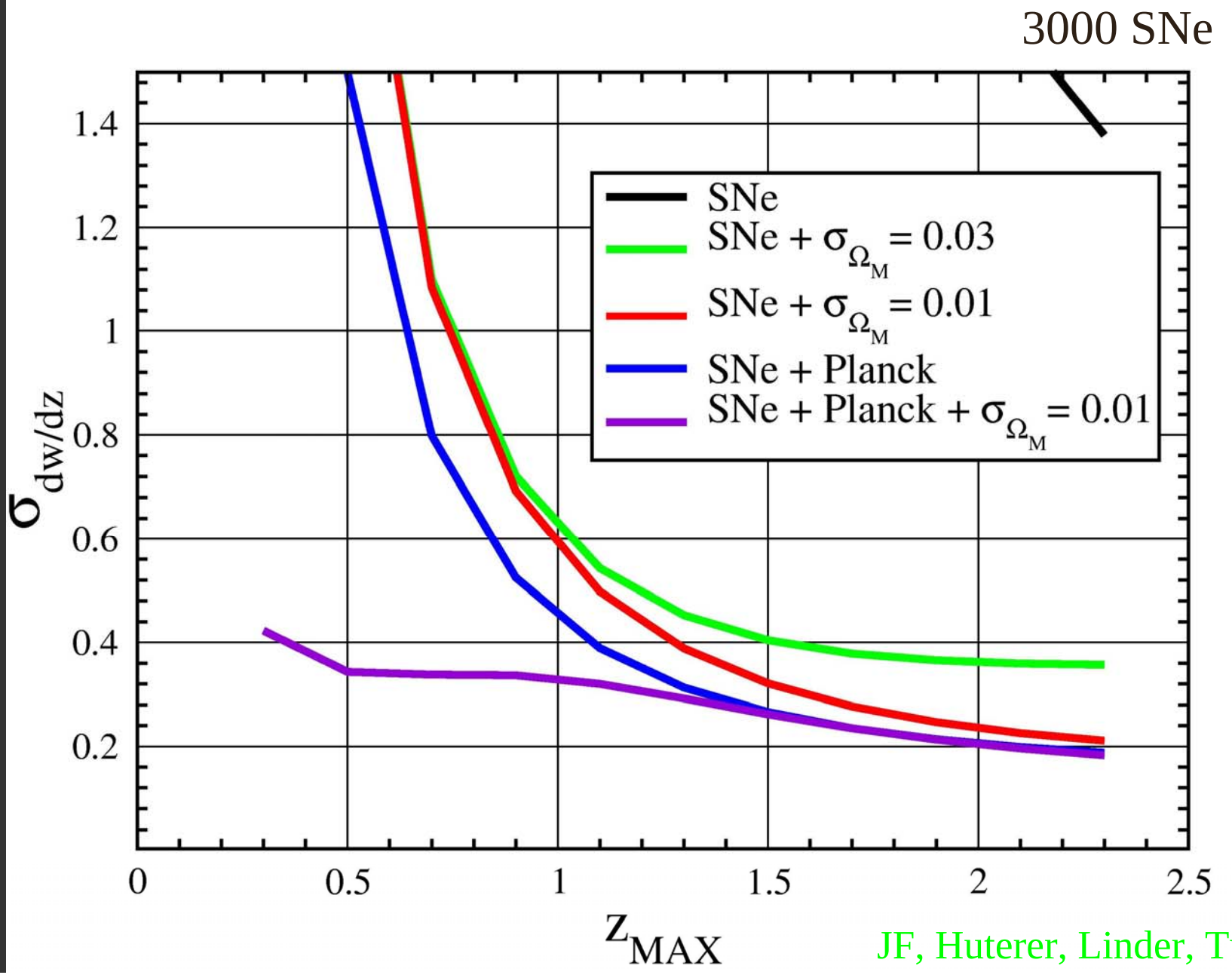
Supernovae: Where we're headed



Supernovae: the JDEM Future

- Goal: Determine w_0 to ~5% and w_a to ~20% (with CMB).
- Statistical Requirement: ~1% relative distance measurements (2% flux) in Δz~0.1 redshift bins.
- Assume systematic error can be reduced to this level.
  Kim, etal 04, Kim & Miquel 05
- Require ~3000 SNe spread over z ~ 0.3-1.7 and a well-observed sample at low z to anchor the Hubble diagram. Consequent requirements for NIR and photometric stability lead to a space-based mission.

Probing Dark Energy Evolution: 2% Mag Systematic Error Floors



JF, Huterer, Linder, Turner 03

Can we get there? Systematics Concerns

e.g., 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?* Key: Many observables per SN; which needed?

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

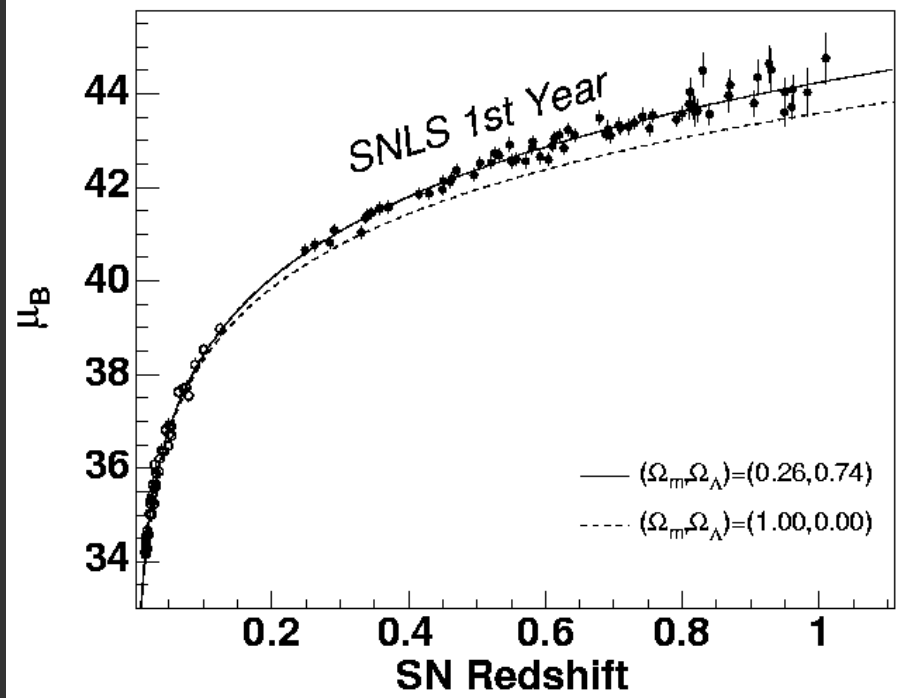
Control: the variety of host environments at low redshift spans a larger range of metallicity, etc, than the median differences between low- and high-z environments, so we can compare high-z apples with low-z apples, using host info., LC shape, colors, spectral features & spectral evolution, and *assuming*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

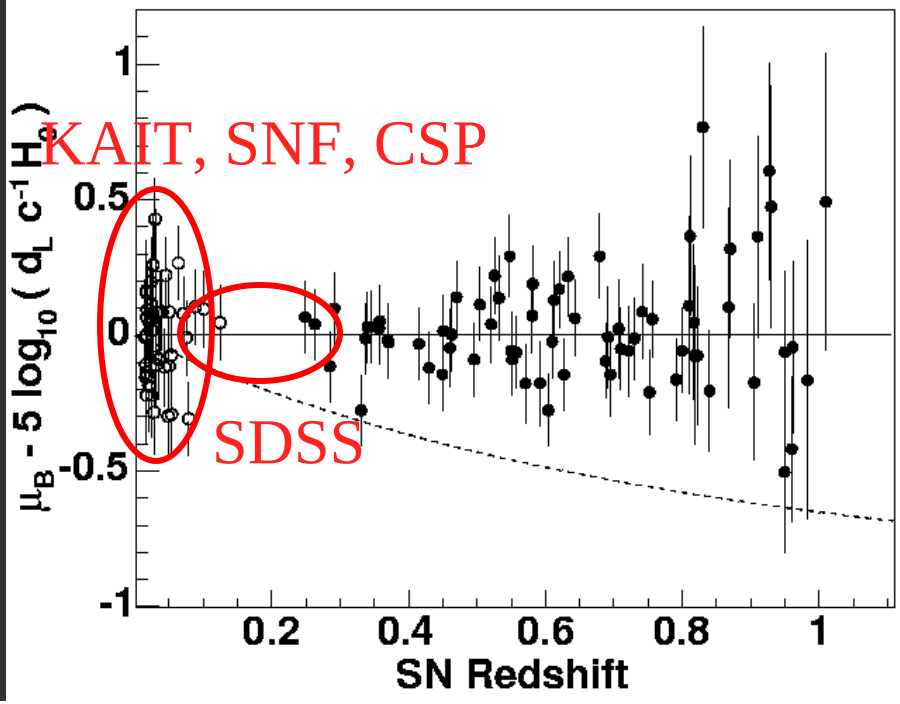
Supernova Hubble Diagram

CFHT Supernova Legacy Survey

Astier etal 05

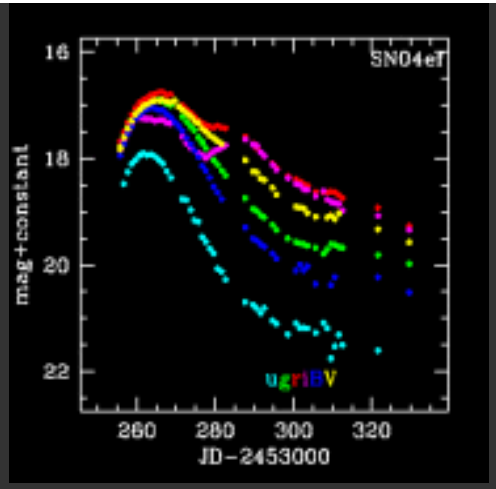
Needed: more, better data at low and Intermediate redshift

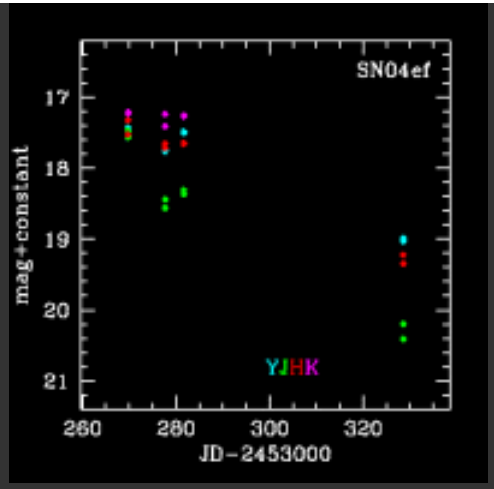


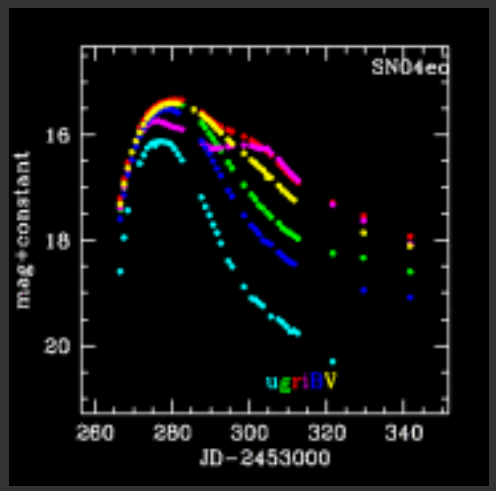


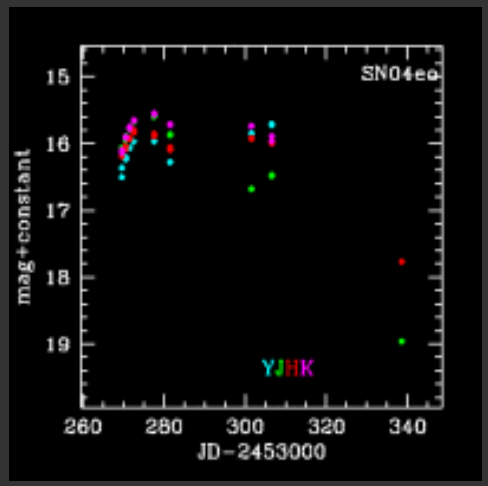
Carnegie Supernova Project

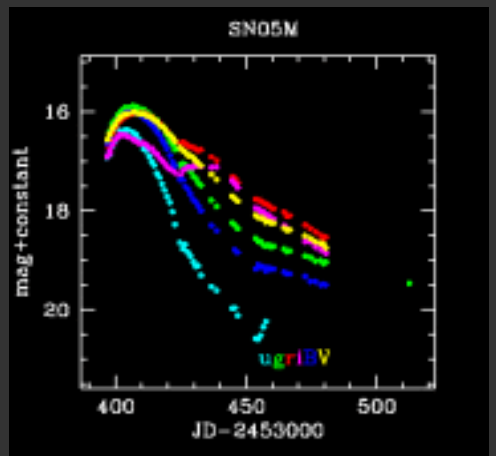
Nearby Optical+ NIR LCs

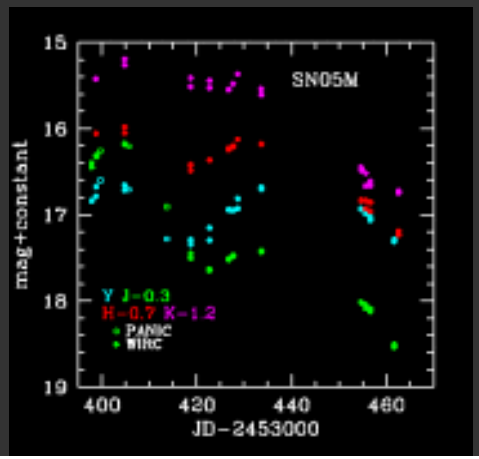












SDSS II Supernova Survey

Sept-Nov. 2005-7

- Obtain ~200 *high-quality* SNe Ia light curves in the `redshift desert' z~0.05-0.35: continuous Hubble diagram
- Probe Dark Energy in *z* regime less sensitive to evolution than, and complementary to, deeper surveys
- Study SN Ia systematics 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
- Database of Type II and rare SN light-curves (large survey volume with multi-band coverage)

SDSS Supernova Survey: First Season

http://sdssdp47.fnal.gov/sdsssn/snlist.php

Sept. 1 - Nov. 30, 2005:

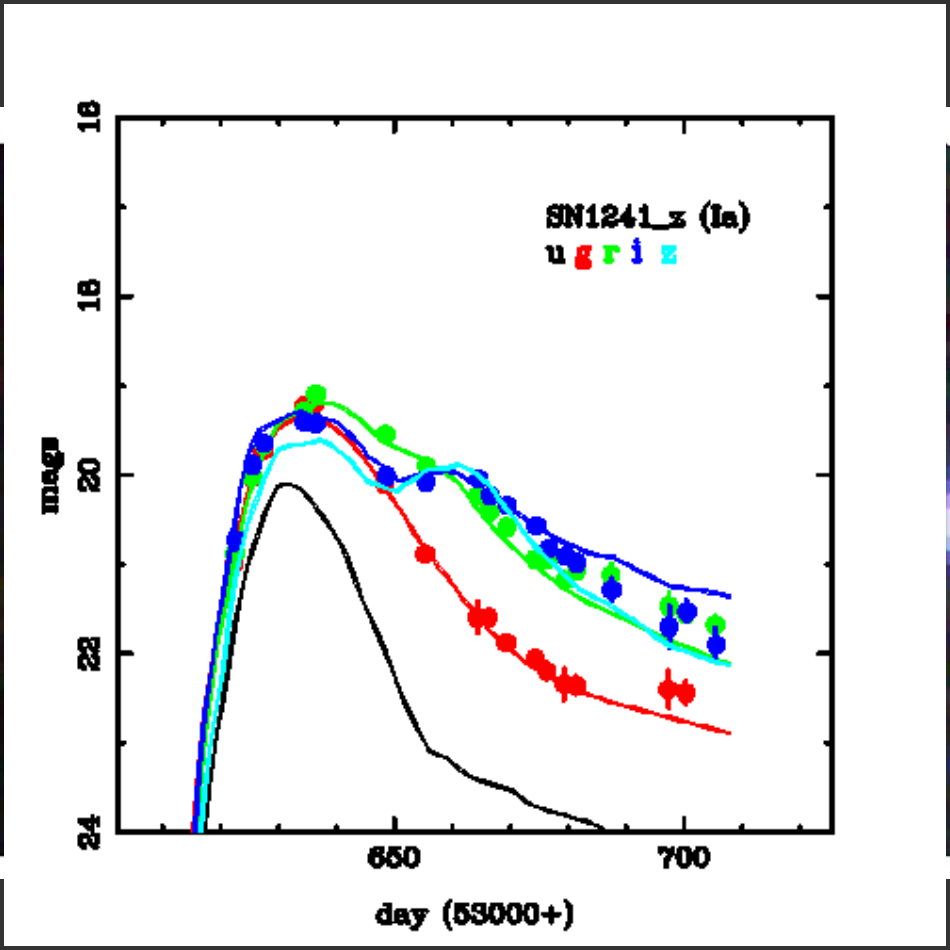
139 confirmed SNe Ia (including 13 `probable' Ia's)
additional unconfirmed but likely Ia's based on light curves
10 confirmed type II
6 confirmed Ib/c

Ia redshift range: 0.01-0.41, $\langle z \rangle$=0.2.
Very high Ia targeting efficiency for Ia's using multi-band light curve fitting (similar to SNLS algorithm).

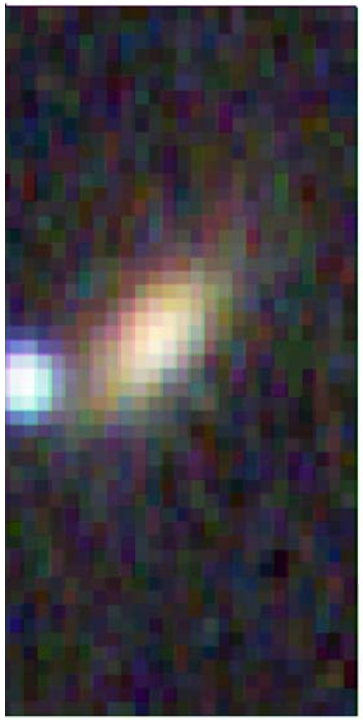
Composite gri images

SN 2005 ff

Before



After



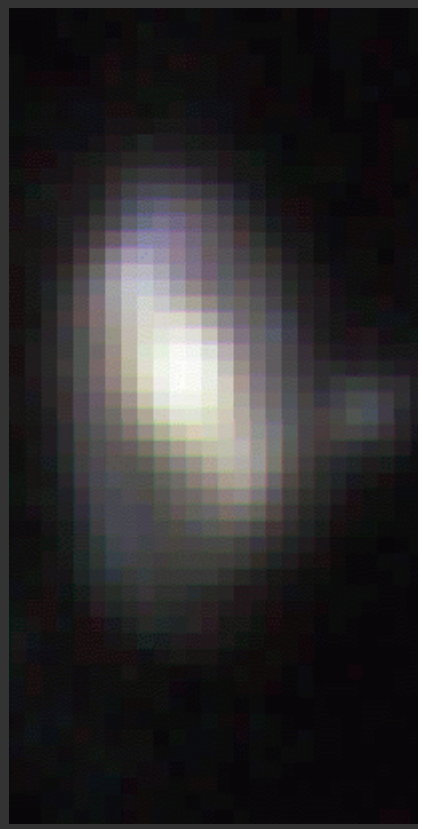
z = 0.07, confirmed at WHT

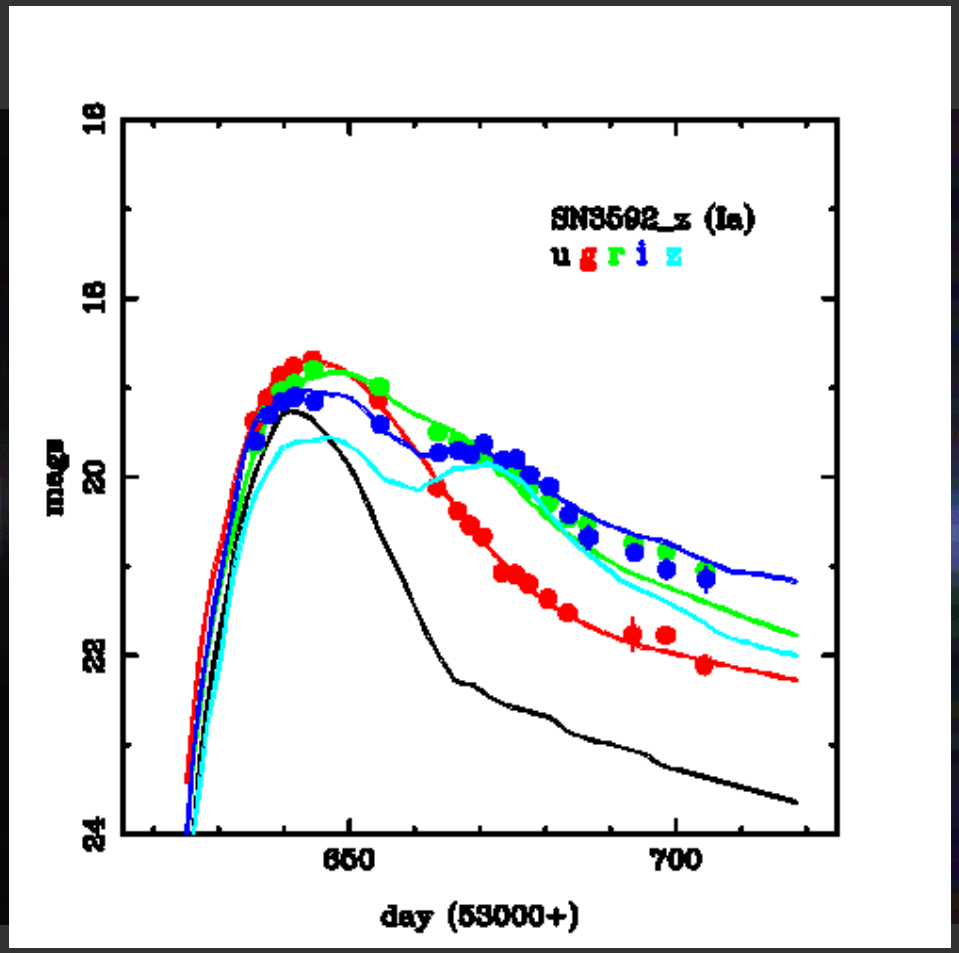
Preliminary gri light curve and fit from low-z templates

Composite gri images

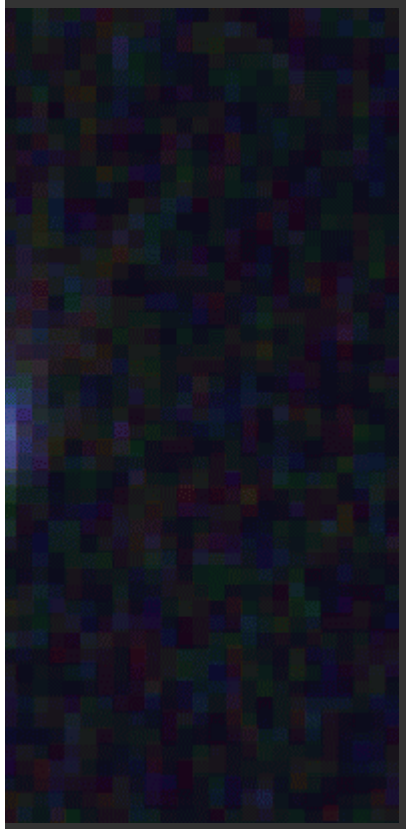
SN 2005 gb

Before





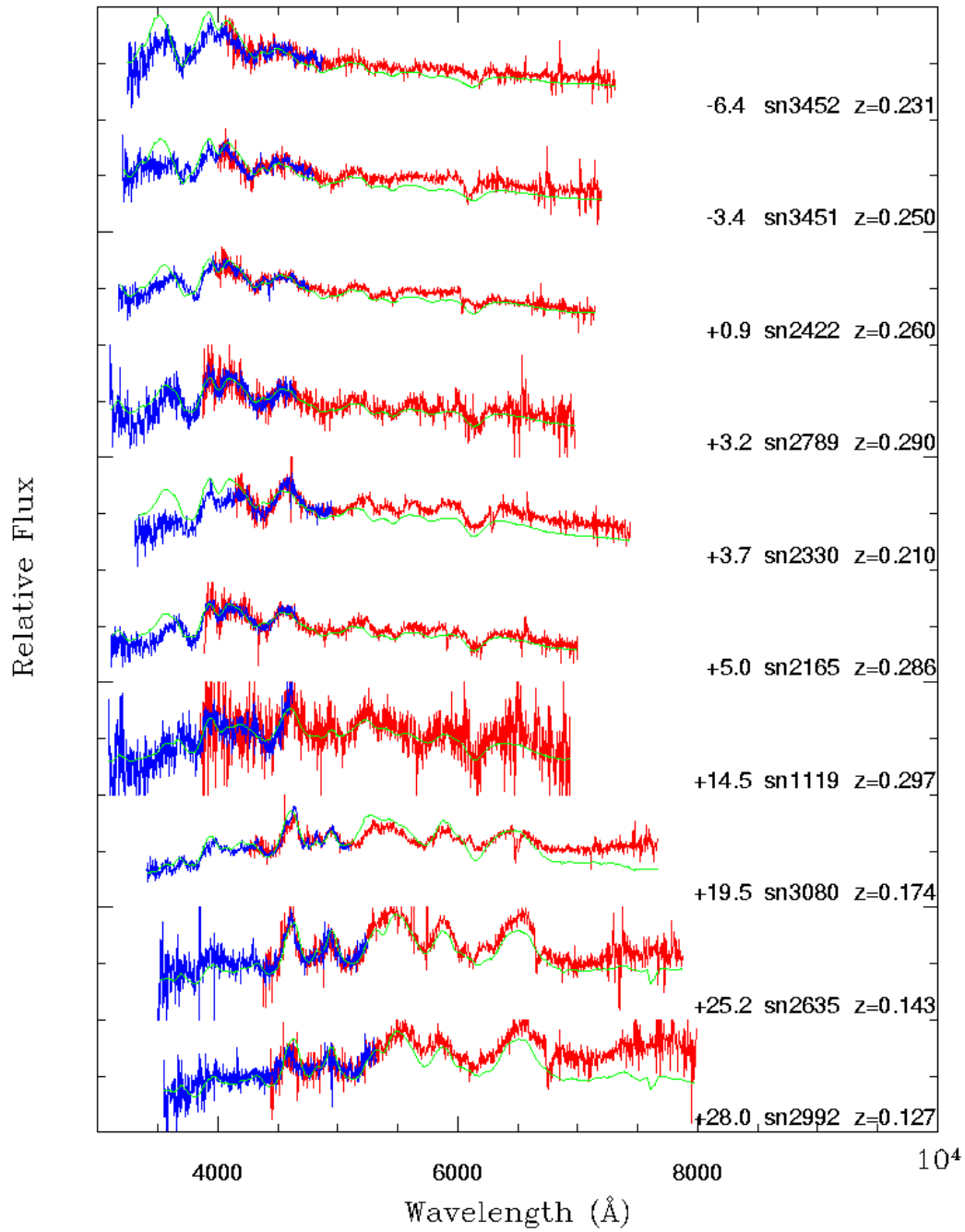
After



z = 0.086, confirmed at ARC 3.5m

Preliminary gri light curve and fit from low-z templates

Follow-up Spectra from Subaru



Conclusions

• Excellent prospects for increasing the precision on Dark Energy parameters from a sequence of increasingly complex, ambitious, and costly experiments over the next 5-15 years

DES+SPT, PanSTARRS, LSST, WFMOS, JDEM, Planck,…

• Exploiting complementarity of multiple probes (supernovae, clusters, weak lensing, baryon oscillations,…) will be key, especially given uncertainties in what the ultimate systematic error floors for each method will be.

• Encouraging progress in understanding and controlling systematic errors.

• What parameter precision is needed to stimulate theoretical progress? It depends in large part on what the answer is.