The Bright Future for Supernova Cosmology

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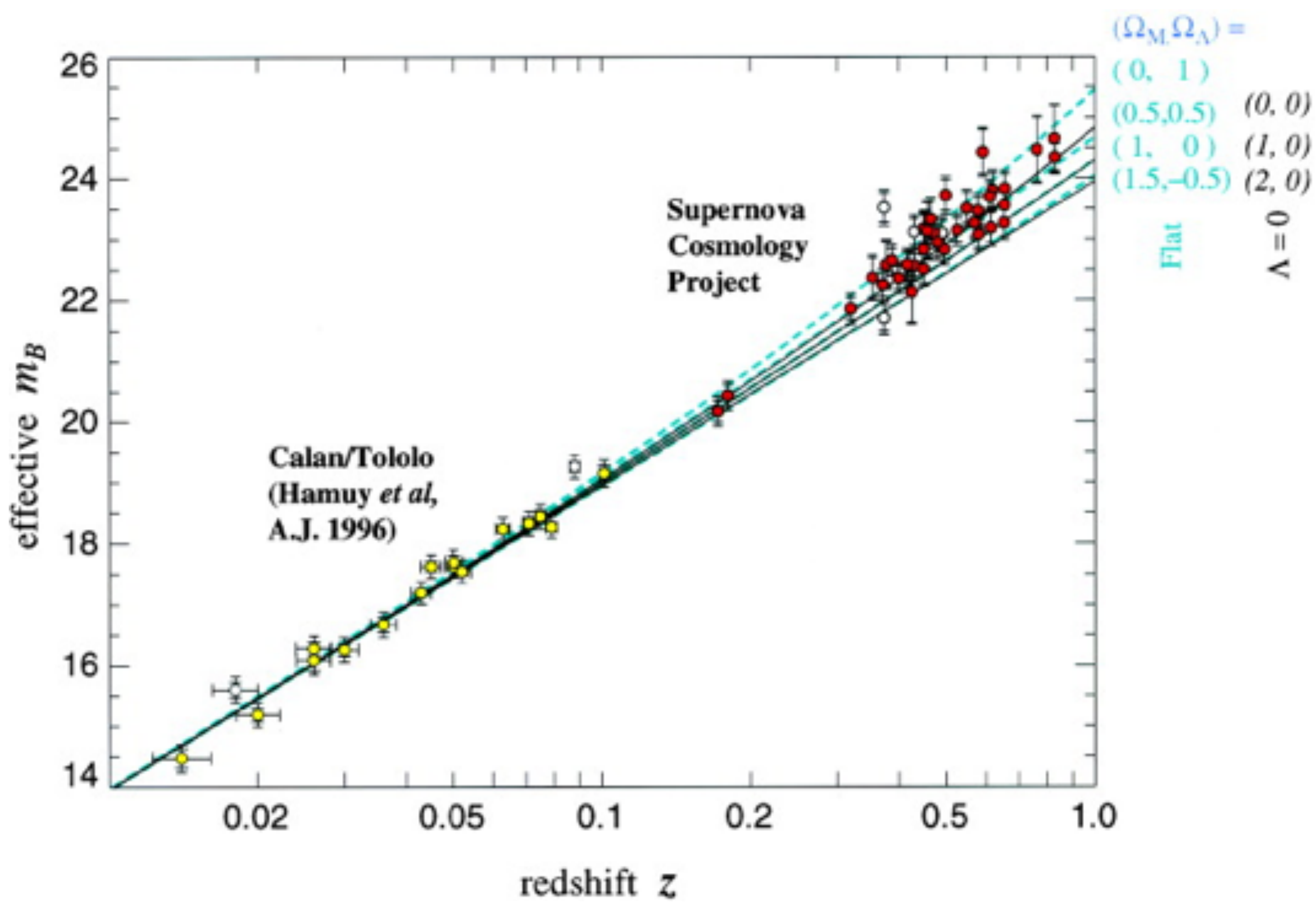
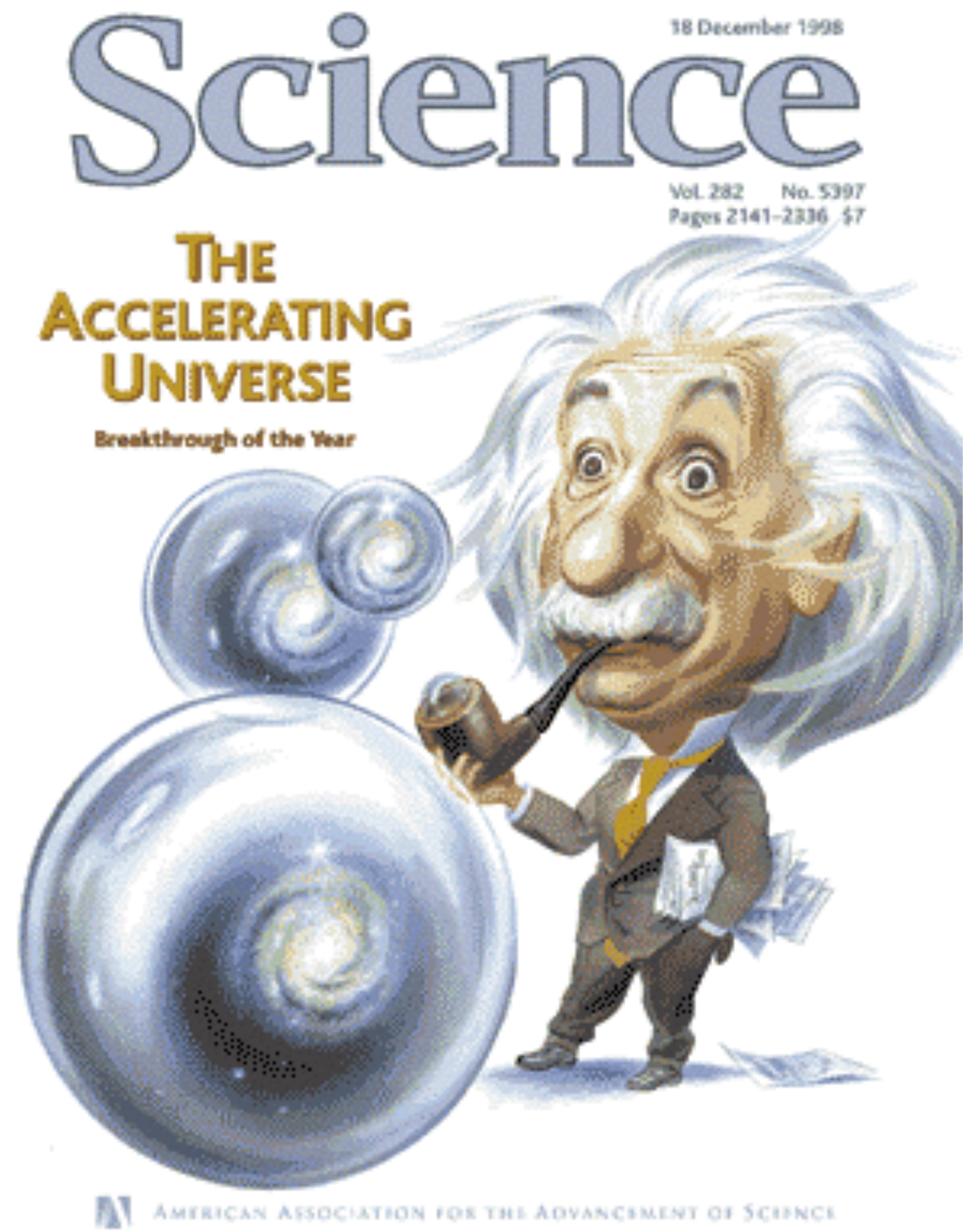
1998 Science Breakthrough of the Year





High-redshift supernovae fainter than expected
The Universe is accelerating

2017: Why Care About SN Cosmology - Fundamental Physics

- Addresses the major puzzle confronting physics today

- Cosmological Principle + General Relativity yields the Friedmann Equation

(Looks like: Kinetic Energy $H^2 = \frac{8\pi G}{3}\rho$ Gravitational Potential Energy)

- Supernova measurements show

$$H^2 \neq \frac{8\pi G}{3}\rho_{\text{known forms of energy}}$$

$$H^2 - F(H) = \frac{8\pi G}{3}\rho \text{ or } H^2 = \frac{8\pi G}{3}(\rho_{\text{known forms of energy}} + \rho_{\text{unknown forms of energy}})$$

DARK ENERGY

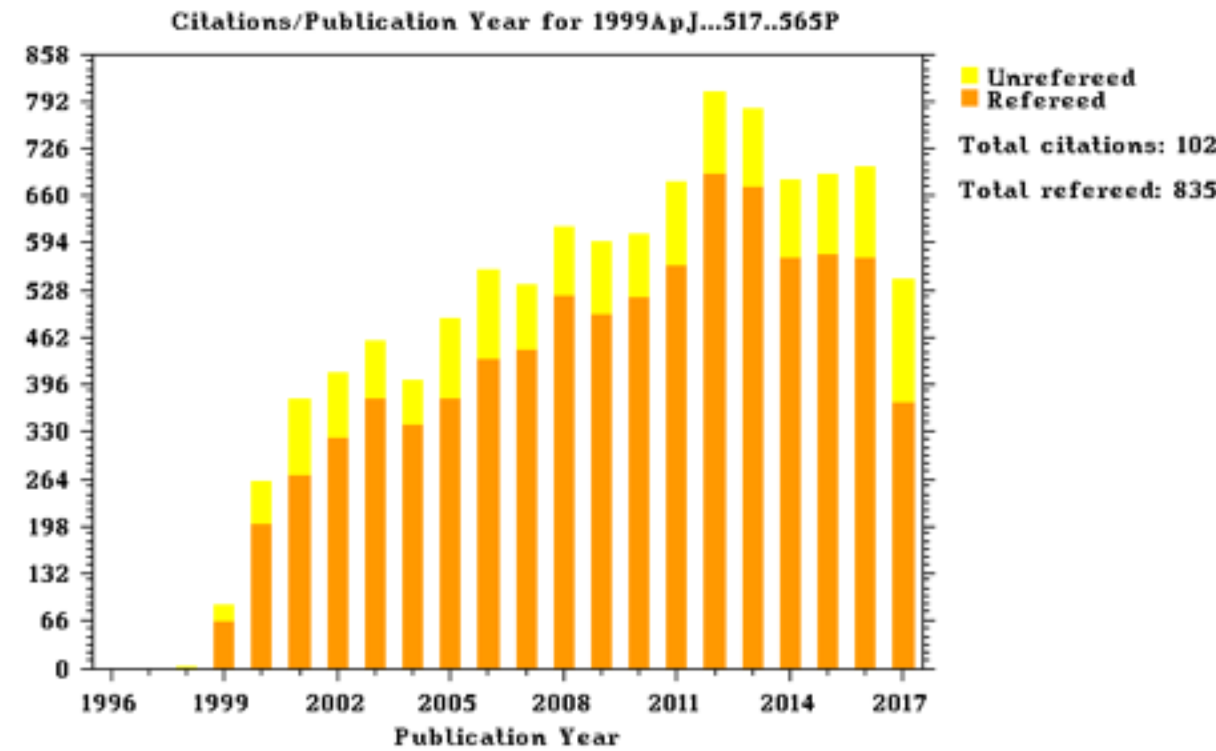
- Therefore

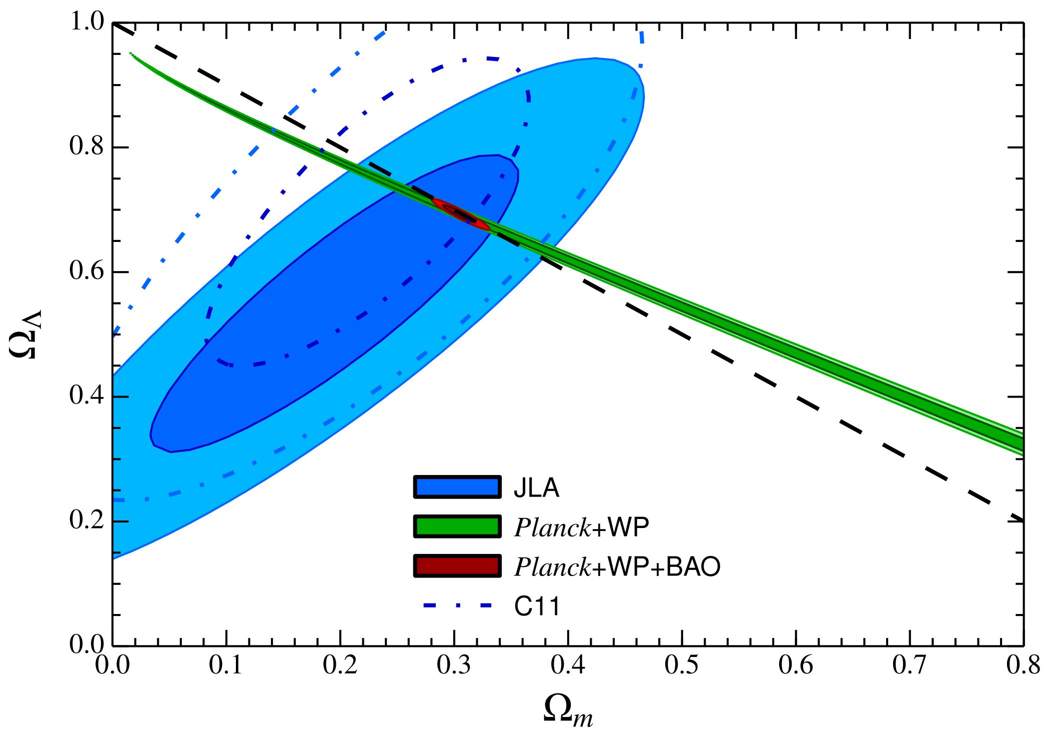
Modified Gravity!

Physics Beyond the Standard Model!

2017: Why Care About SN Cosmology - A Competitive Probe

- Original discovery of the accelerating universe made with Type Ia SNe
- Measure of the expansion history of the Universe with SNe Ia continue to be an important probe of dark energy
- Uniquely measures distances from 0<z<1.5 spanning accelerating and decelerating regimes



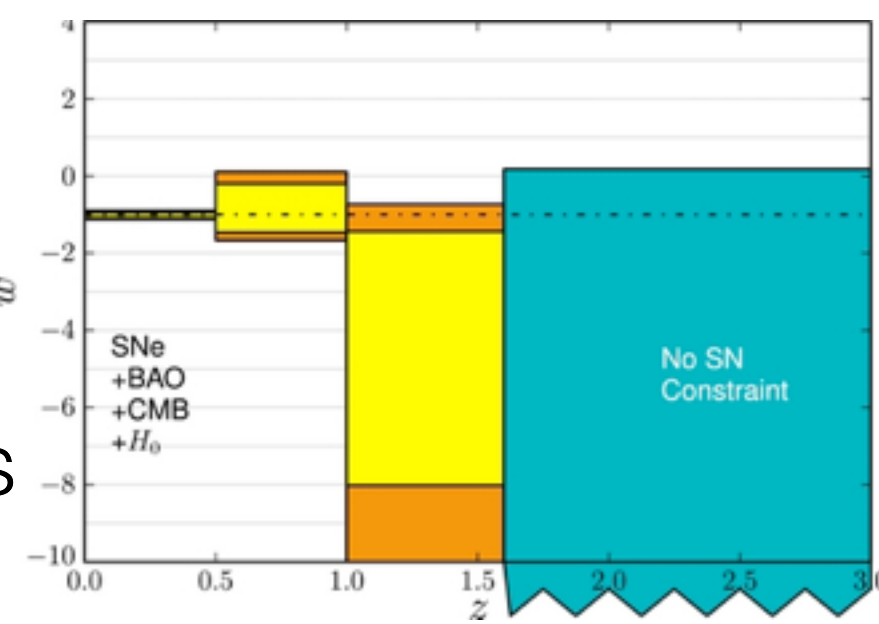


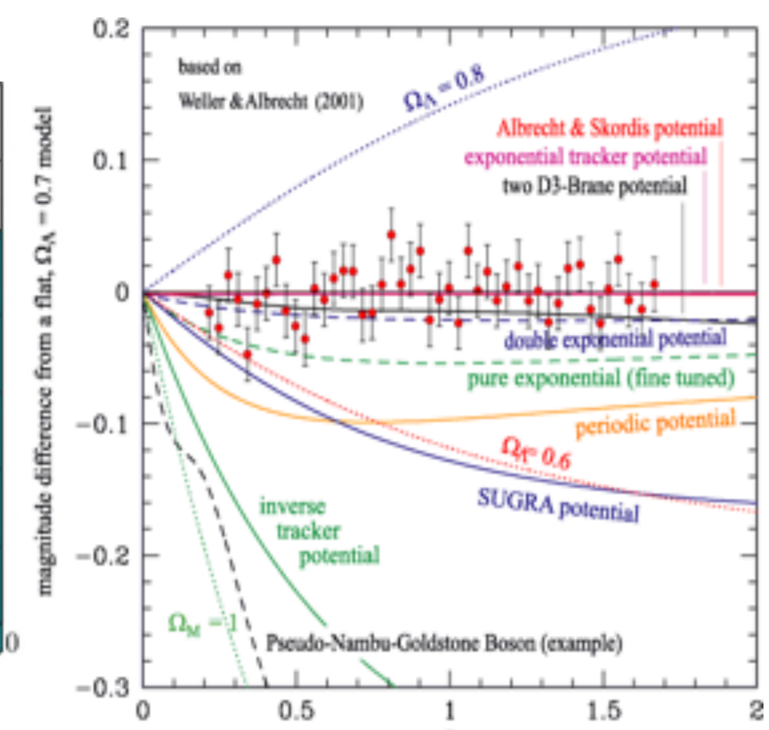
2017: Why Care About SN Cosmology - Can Do Better

- Decrease systematic uncertainty within the current redshift range to improve error budget
- Expand the redshift range to provide leverage for testing dark energy models

Uncertainty sources	$\sigma_x(\Omega_m)$	% of $\sigma^2(\Omega_m)$
Calibration	0.0203	36.7
Milky Way extinction	0.0072	4.6
Light-curve model	0.0069	4.3
Bias corrections	0.0040	1.4
Host relation[a]	0.0038	1.3
Contamination	0.0008	0.1
Peculiar velocity	0.0007	0.0
Stat	0.0241	51.6

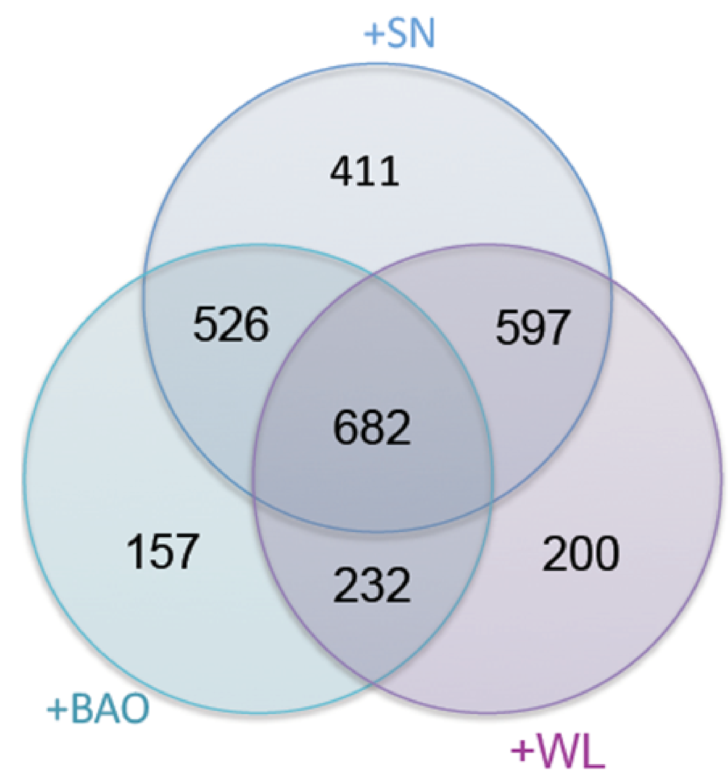
Betoule et al. (2014)



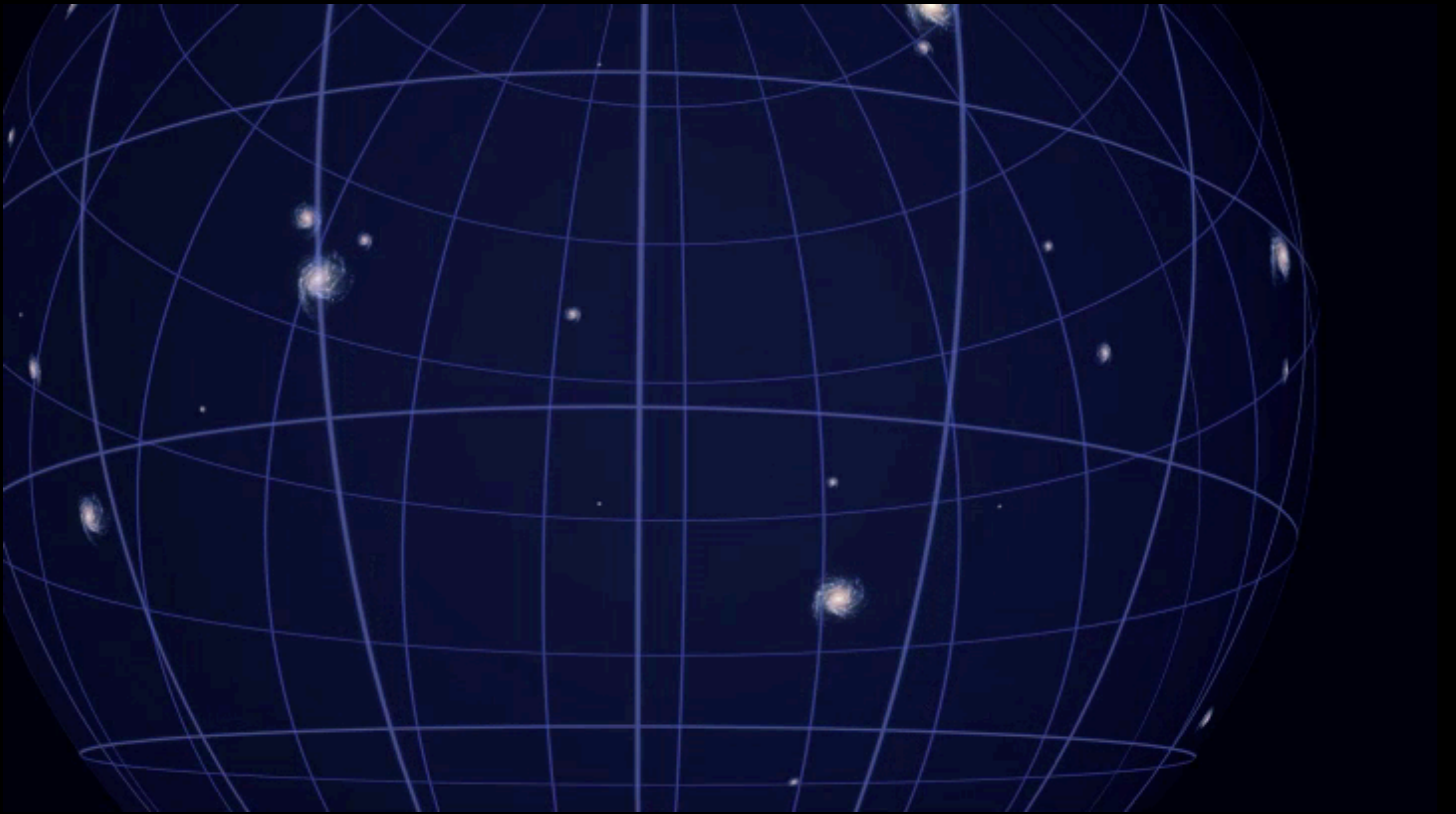


2017: Why Care About SN Cosmology - Major Experiments Planned

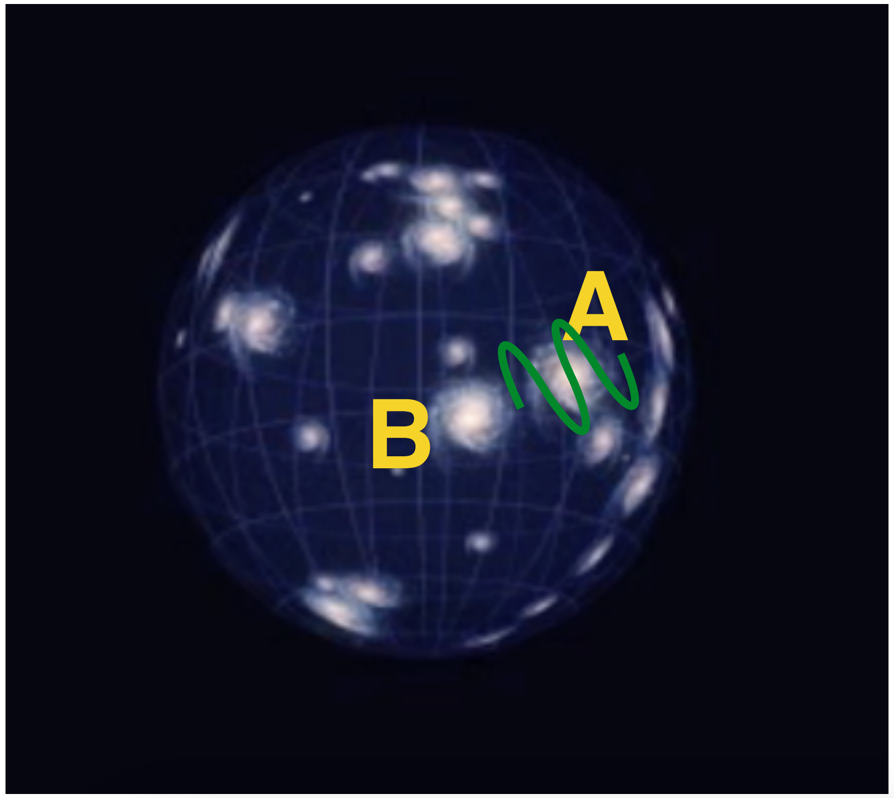
- Major future surveys will provide improved measurements
    - Important contribution when combined with other probes
    - Measured in terms of "Figure of Merit"
- Community support and funding for SN surveys
    - DES, LSST, WFIRST



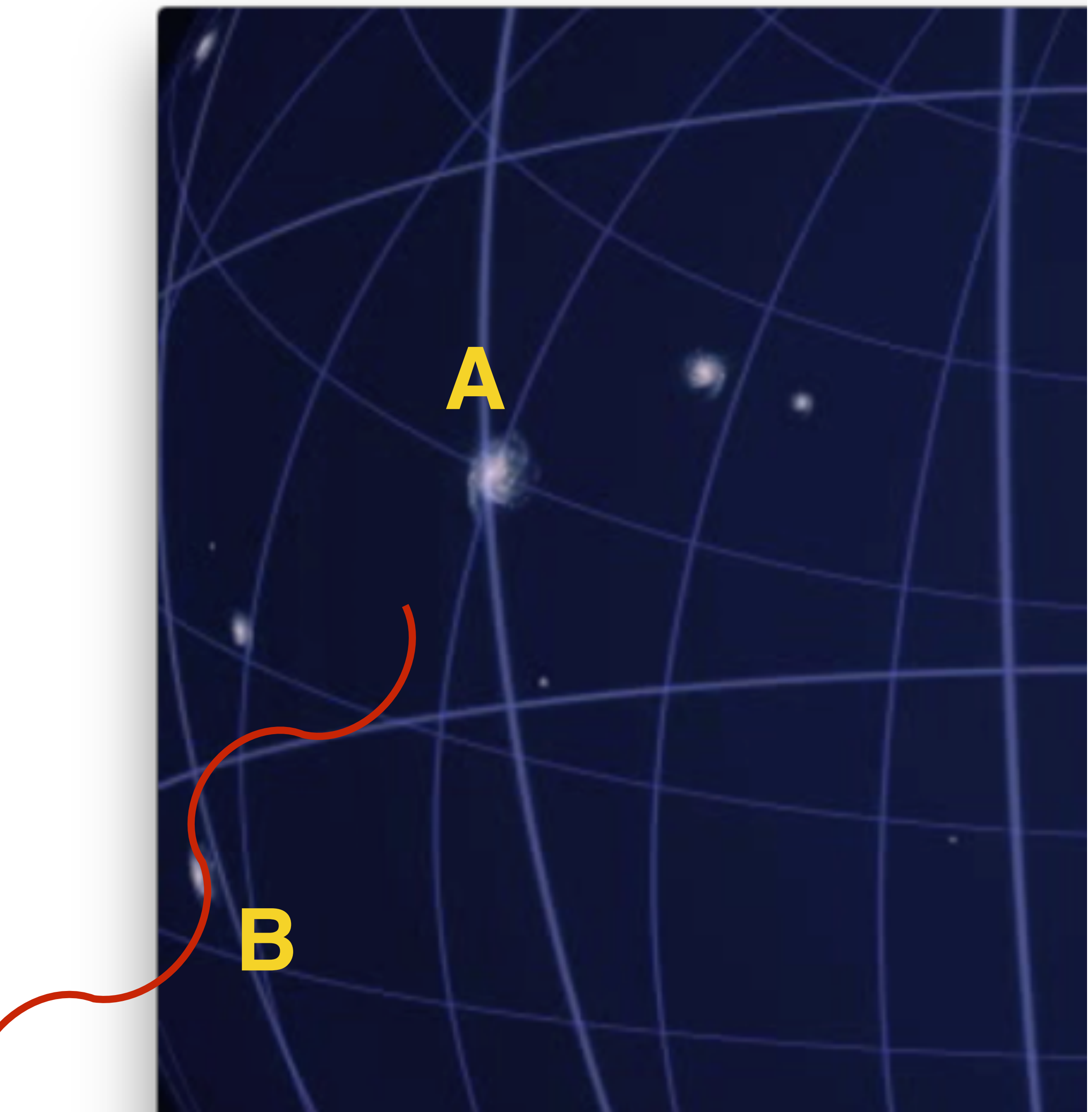
From WFIRST Final Report



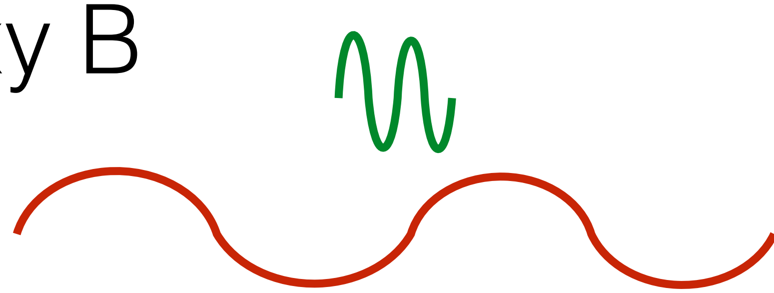
Redshift



As the Universe expands, light that starts from galaxy A…



… has its wavelength expanded by the time it gets to galaxy B



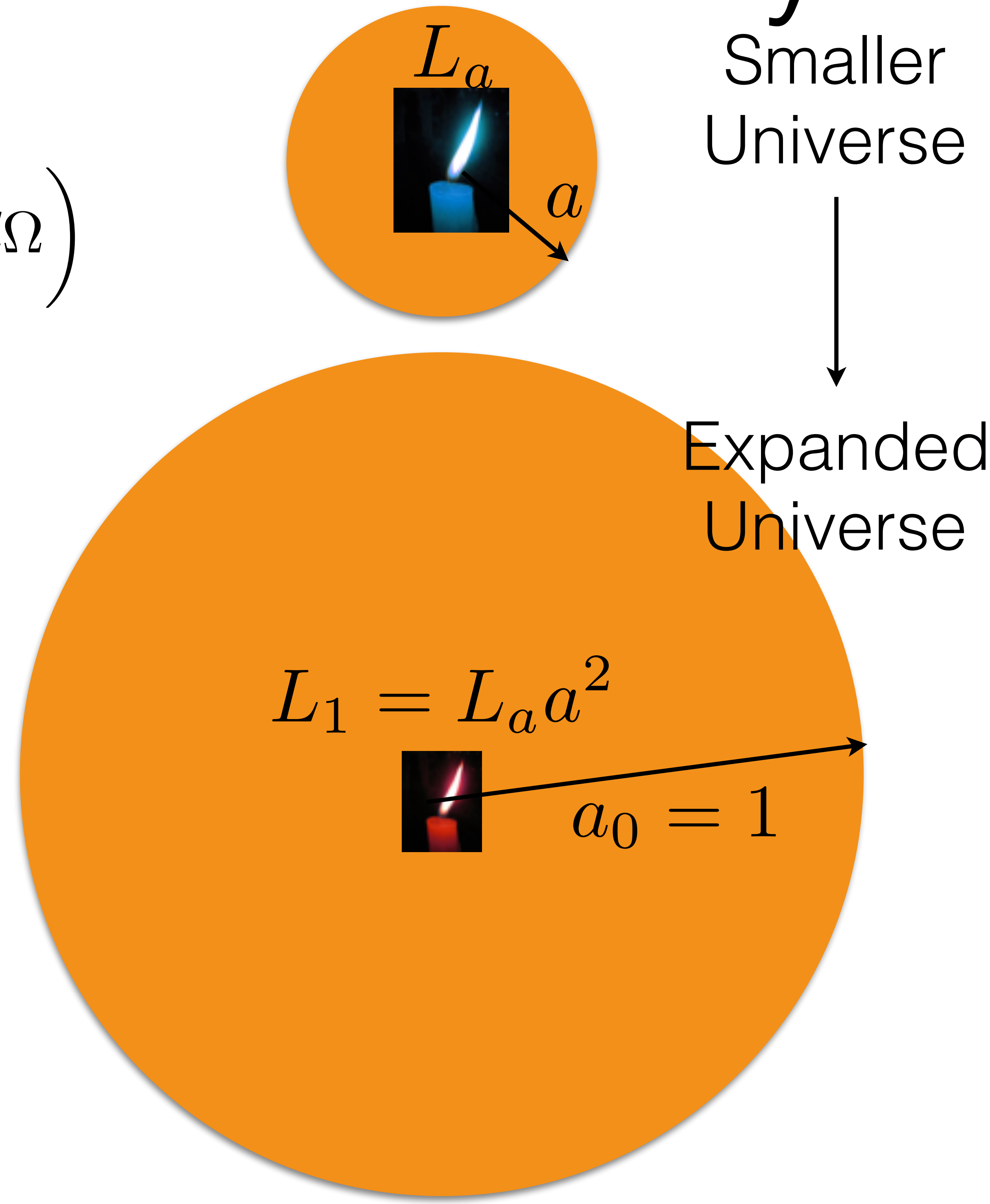
The relative increase in wavelength (redshift) is a measure of the relative change in size of the Universe

Redshift Directly Related to Observer-Frame Luminosity

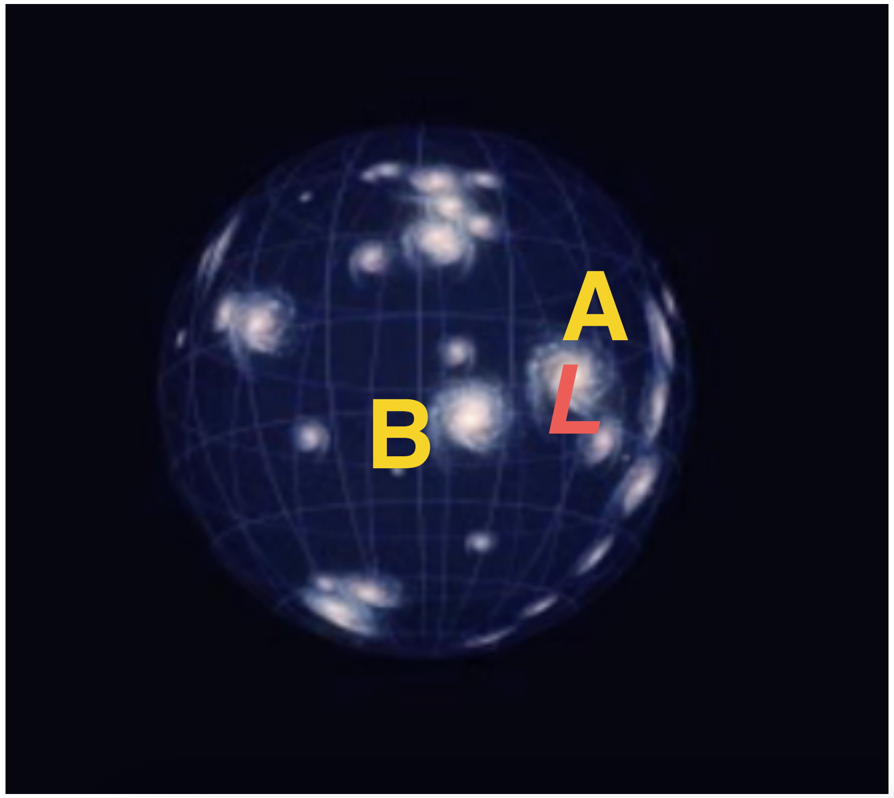
- Propagation of light described by the FRW metric

$$d\tau^2 = -dt^2 + a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega \right)$$

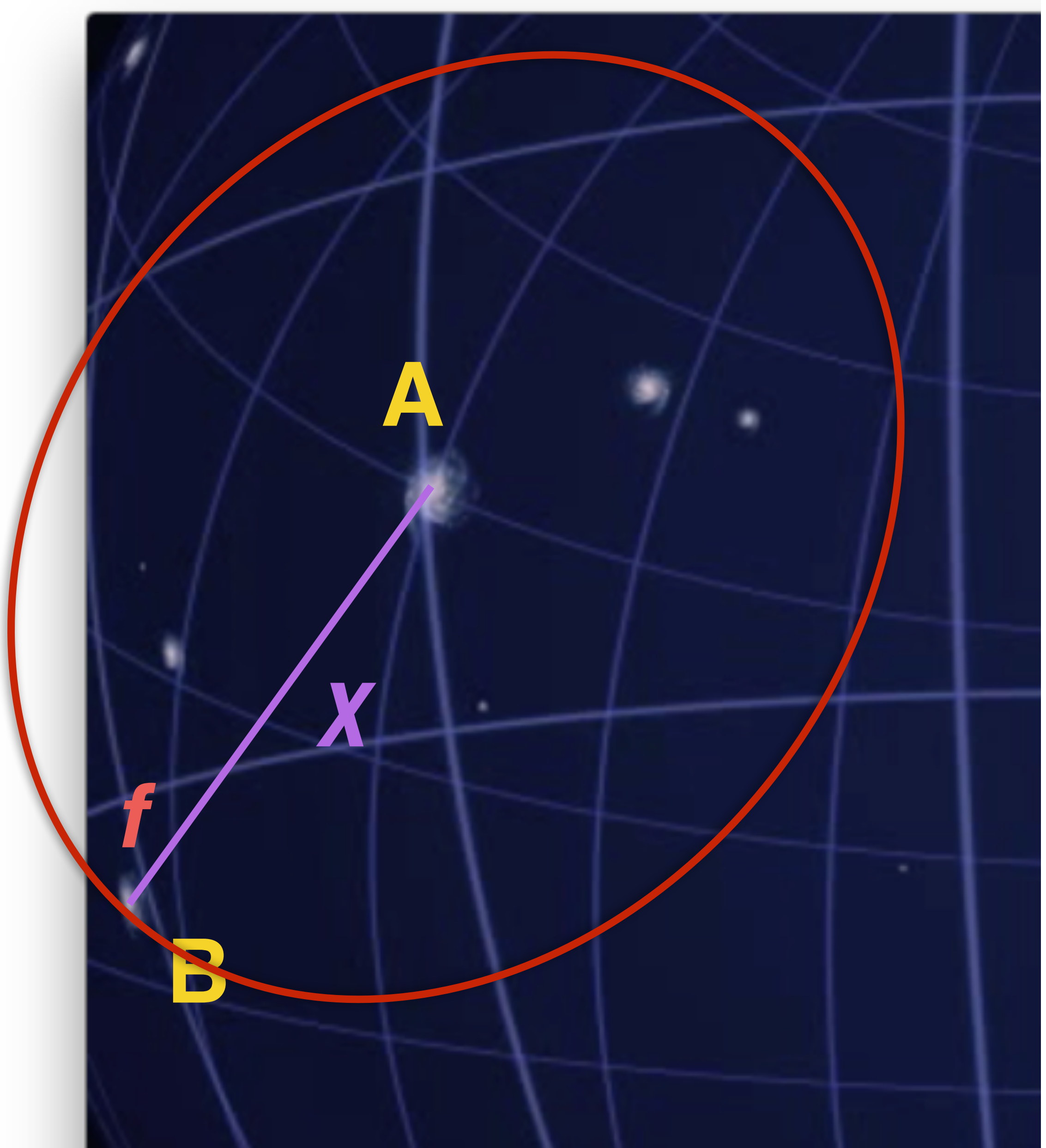
  - a(t) is the scale factor that describes the size of the Universe
  - Redshift $z = a^{-1} - 1$
- Photon energy proportional to a^{-1}
  - Redshift
- Clocks appear to move as a^{-1}
  - Time Dilation
- $L_1 = L_a a^2$



Light Cone and Flux



A source at galaxy A emits photons at some redshift, …



… that are now on a shell of a sphere centered around the source

The surface area of a sphere of radius χ is $4\pi\,\chi^2$

Photon flux diluted by the surface area

Surface Area of Light Cone Related to Flux

- Surface area of light cone described by the FRW metric

$$d\tau^2 = -dt^2 + a(t)^2\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega\right)$$

$$A = 4\pi\chi^2, \text{ where}$$

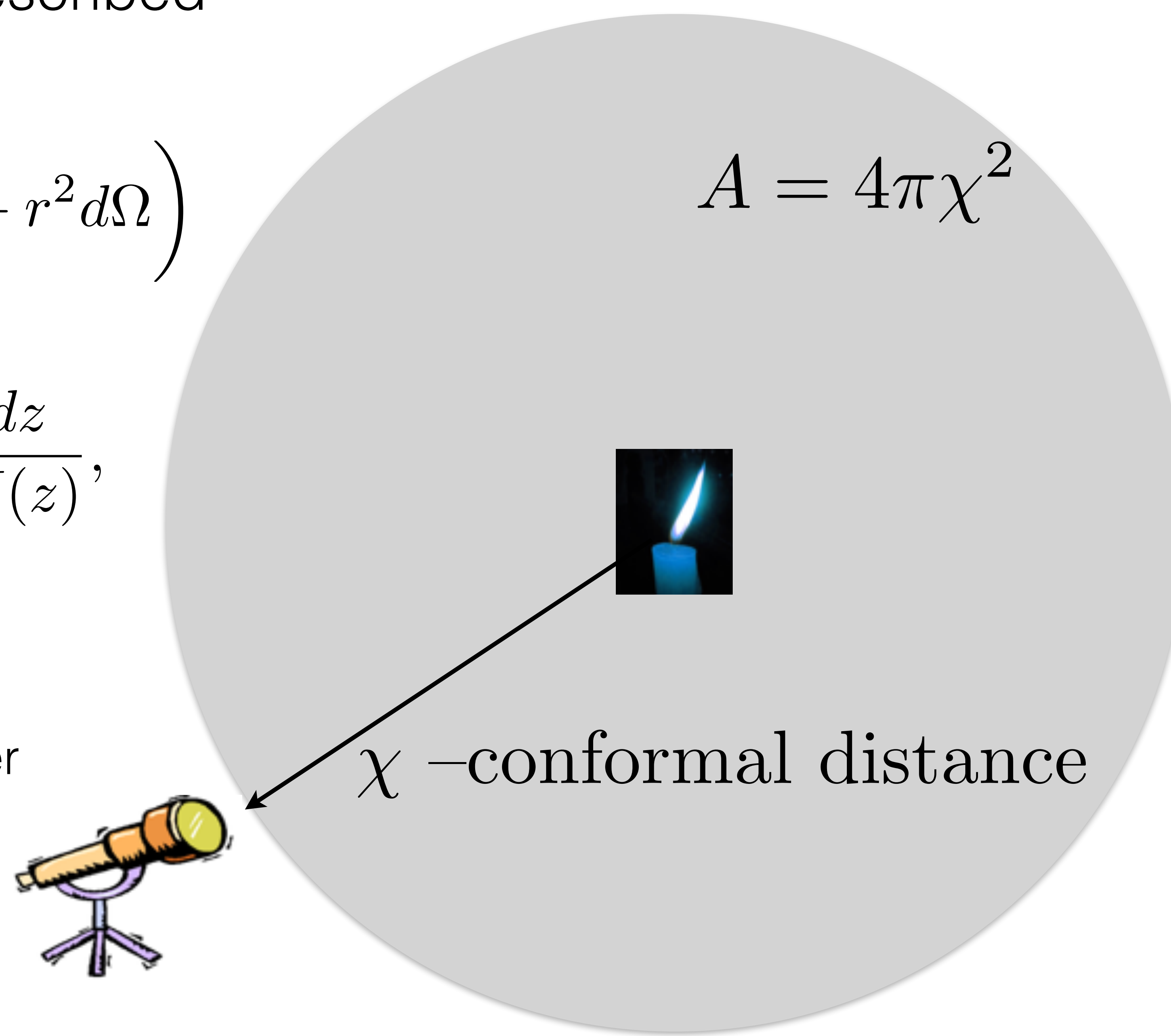
$$\int_0^\chi \frac{dr}{\sqrt{1-kr^2}} = \int_{t_e}^{t_o} \frac{dt}{a(t)} = \int_0^z \frac{dz}{H(z)},$$

$$z = \frac{1}{a} - 1$$

$$H = \frac{\dot{a}}{a}$$ Hubble parameter

- Piece 1 & Piece 2 give

$$f = \frac{L_a a^2}{4\pi\chi^2}$$



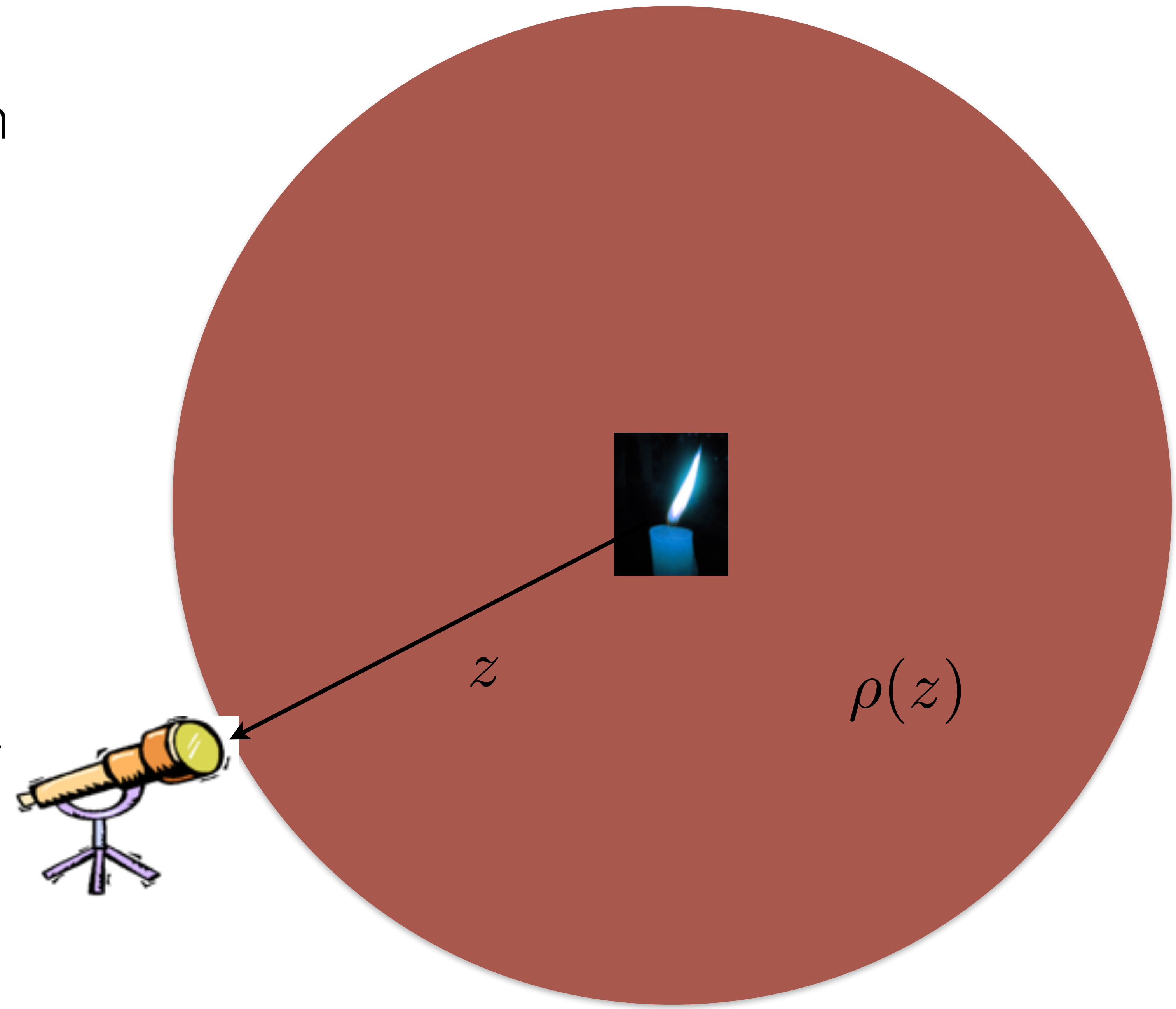
General Relativity Specifies *H* to Predict Flux

- Physics (General Relativity) provides expected evolution of a(t) based on the energy contents of the Universe
- Friedmann Equation:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho(a; \Omega_i, w_i, \ldots)$$

$$\int_0^\chi \frac{dr}{\sqrt{1-kr^2}} = \int_{t_e}^{t_o} \frac{dt}{a(t)} = \int_0^z \frac{dz}{H(z)}$$

$$f = \frac{L_a a^2}{4\pi\chi^2}$$



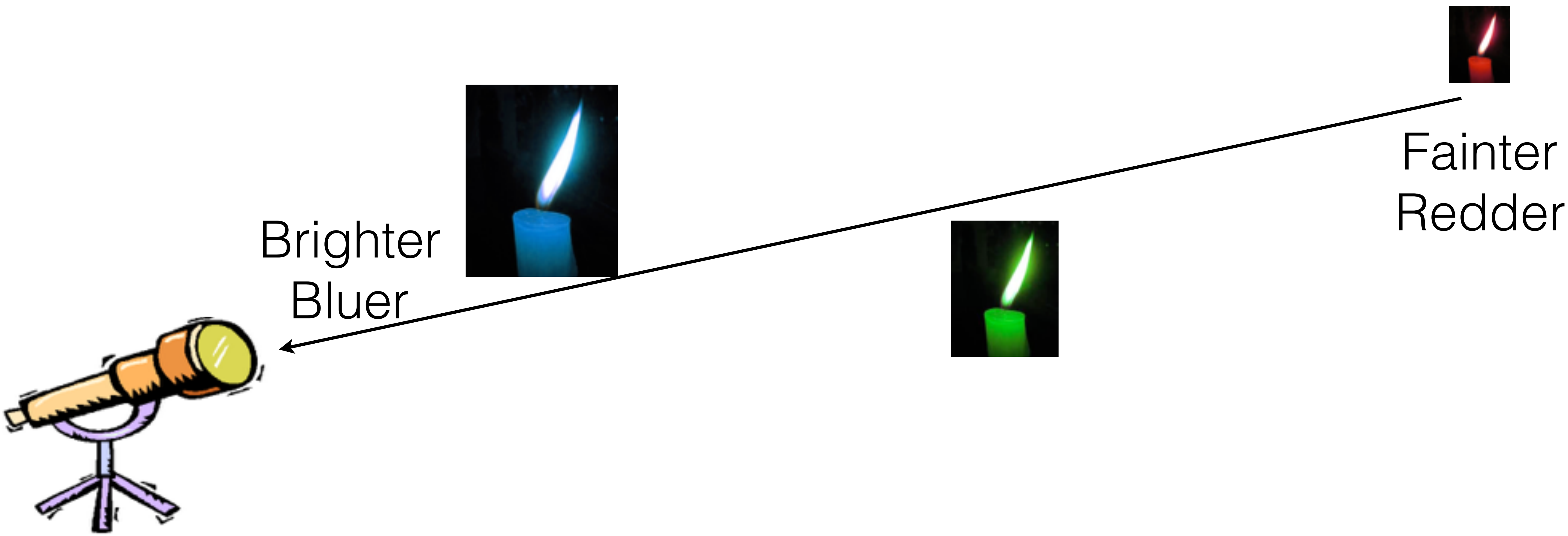
Hubble Parameter and the Matter Content

$$w \equiv p/\rho \qquad\qquad H^2 = H_0^2 \left(\sum_{i \in \text{energy states}} \Omega_i (1+z)^{3(1+w_i)} \right)$$

Dynamics depend on the equation-of-state of the sources of energy in the Universe

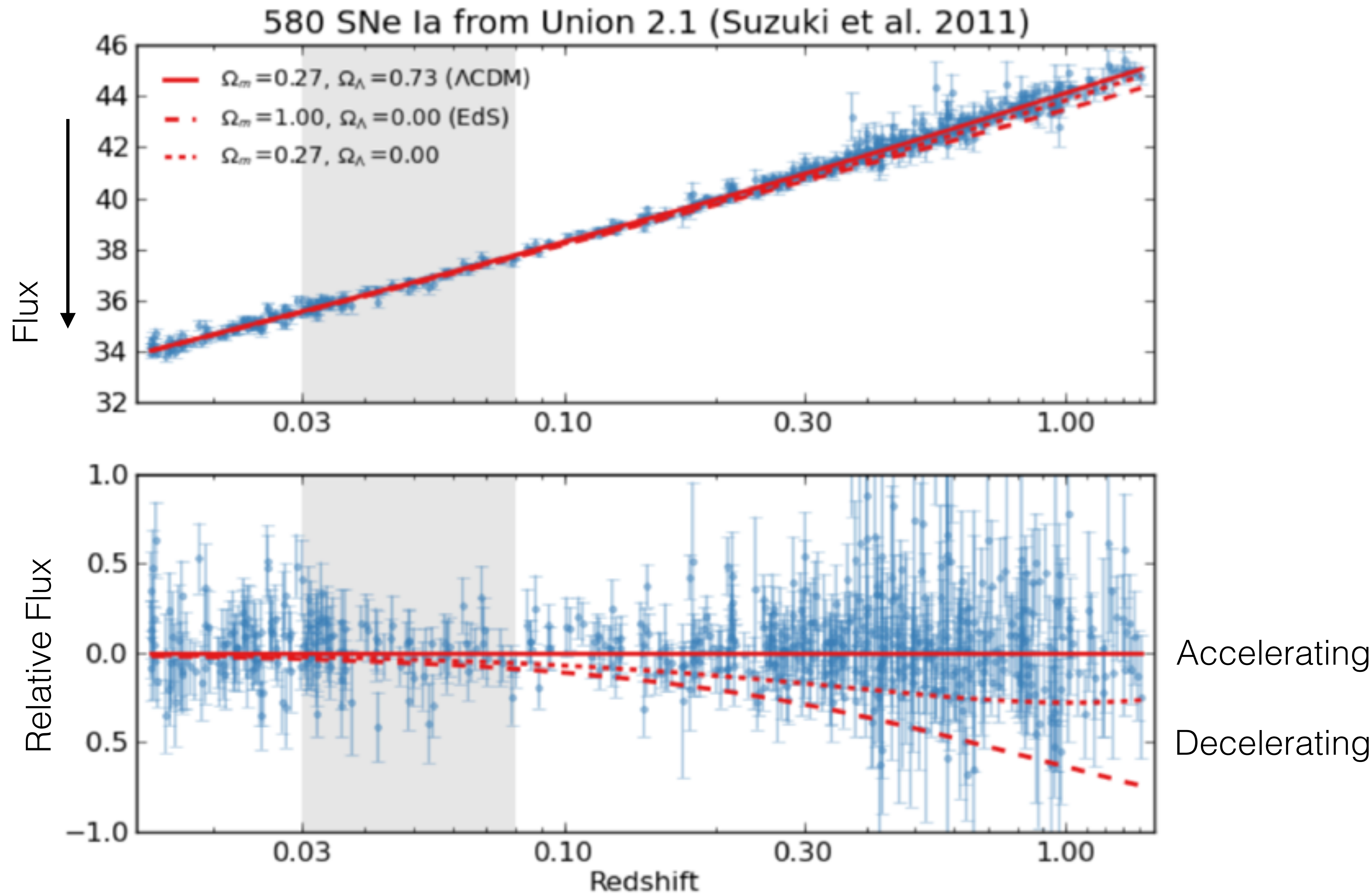
Energy State	Matter (CDM, Baryons)	Radiation (γ, ν)	Cosmological Constant Λ	"Dark Energy"	Curvature
$w=p/\rho$	0	1/3	-1	$w(a)$ modeled as: constant $w<-1/3$ $w=w_0+w_a(1-a)$	-1/3

Standard Candles



- For a set of standard candles of luminosity L
  - Measure flux f (magnitude)
  - Measure redshift z

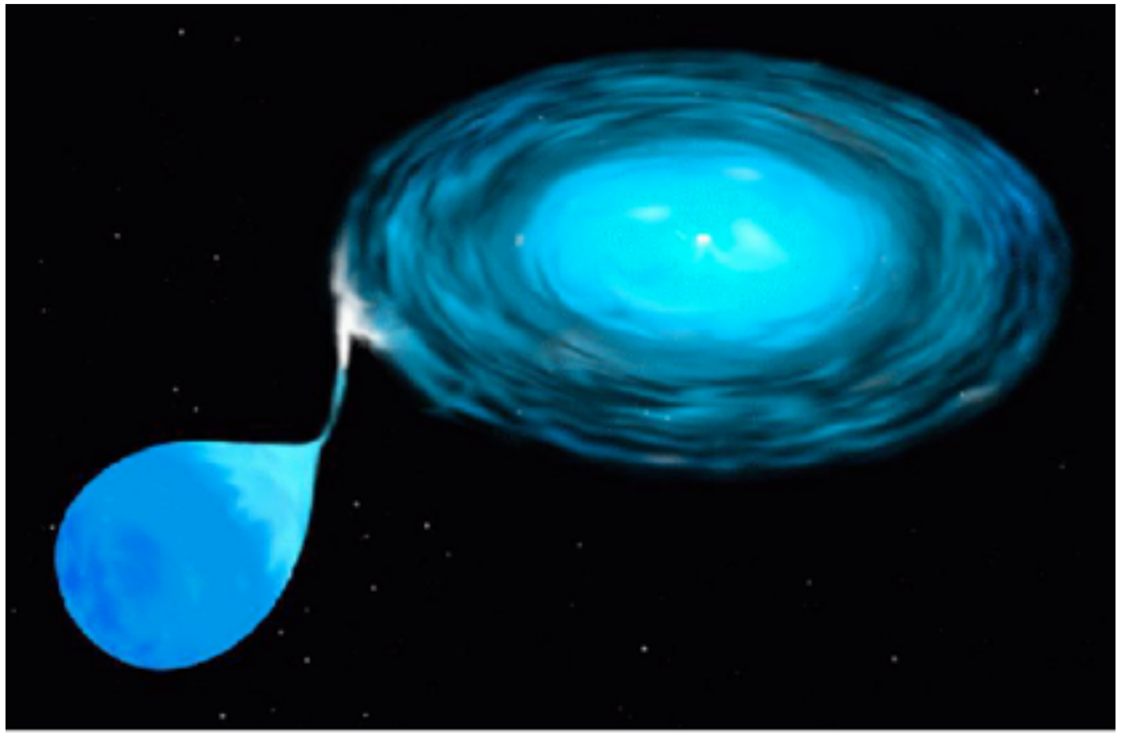
Hubble Diagram



Unexpected Energy In the Universe that is Gravitationally Repulsive

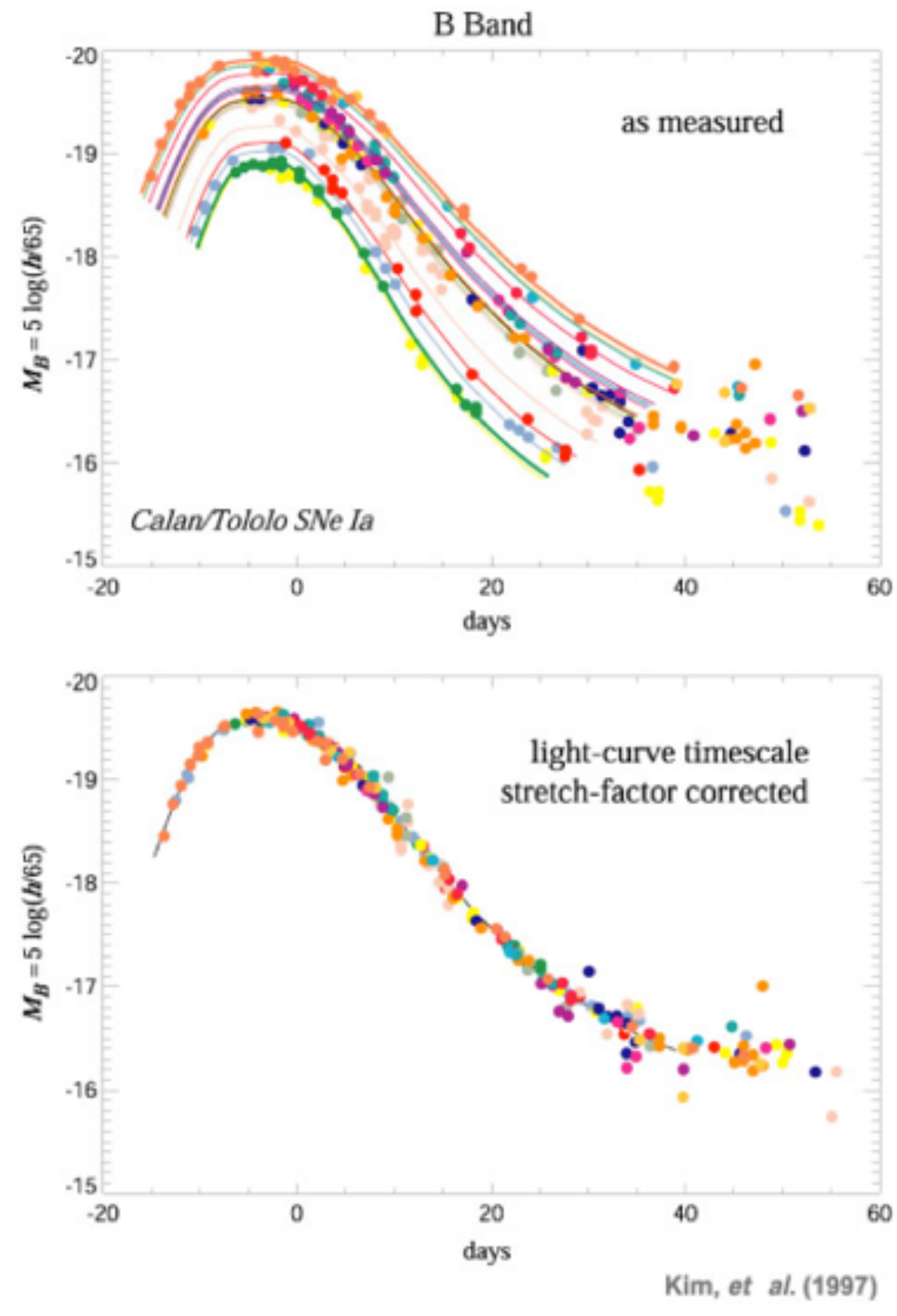
Type Ia Supernova

- Supernova without H, with Si
- C/O white dwarf gaining material from a binary companion
- As the white dwarf reaches the Chandrasekhar mass (1.4 solar mass) a thermonuclear runaway is triggered
  - Two burning phases: subsonic produce intermediate mass elements and supersonic produces ^{56}Ni
  - $>10^{51}$ ergs explosion energy disrupts star
  - Debris in homologous expansion
- Observed light from radioactive decay of ^{56}Ni to ^{56}Fe
- A homogeneous triggered bomb



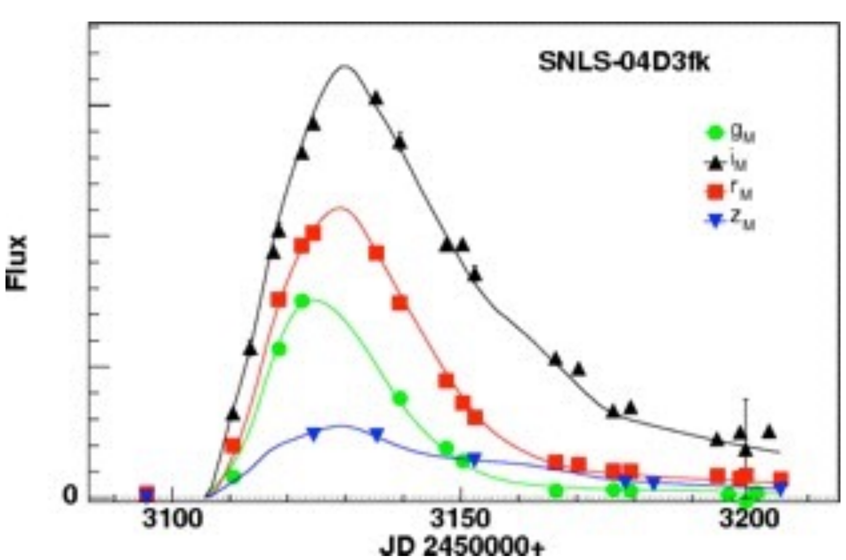
Supernovae Almost But Not Perfect Standard Candles

- Heterogeneity in supernova brightnesses and light curve shapes
- After correction for foreground dust supernovae have peak-magnitude dispersion of ~0.3 mag
- We can determine luminosity per object
- After correction for light-curve shape supernovae become “calibrated” candles with ~0.15 mag dispersion



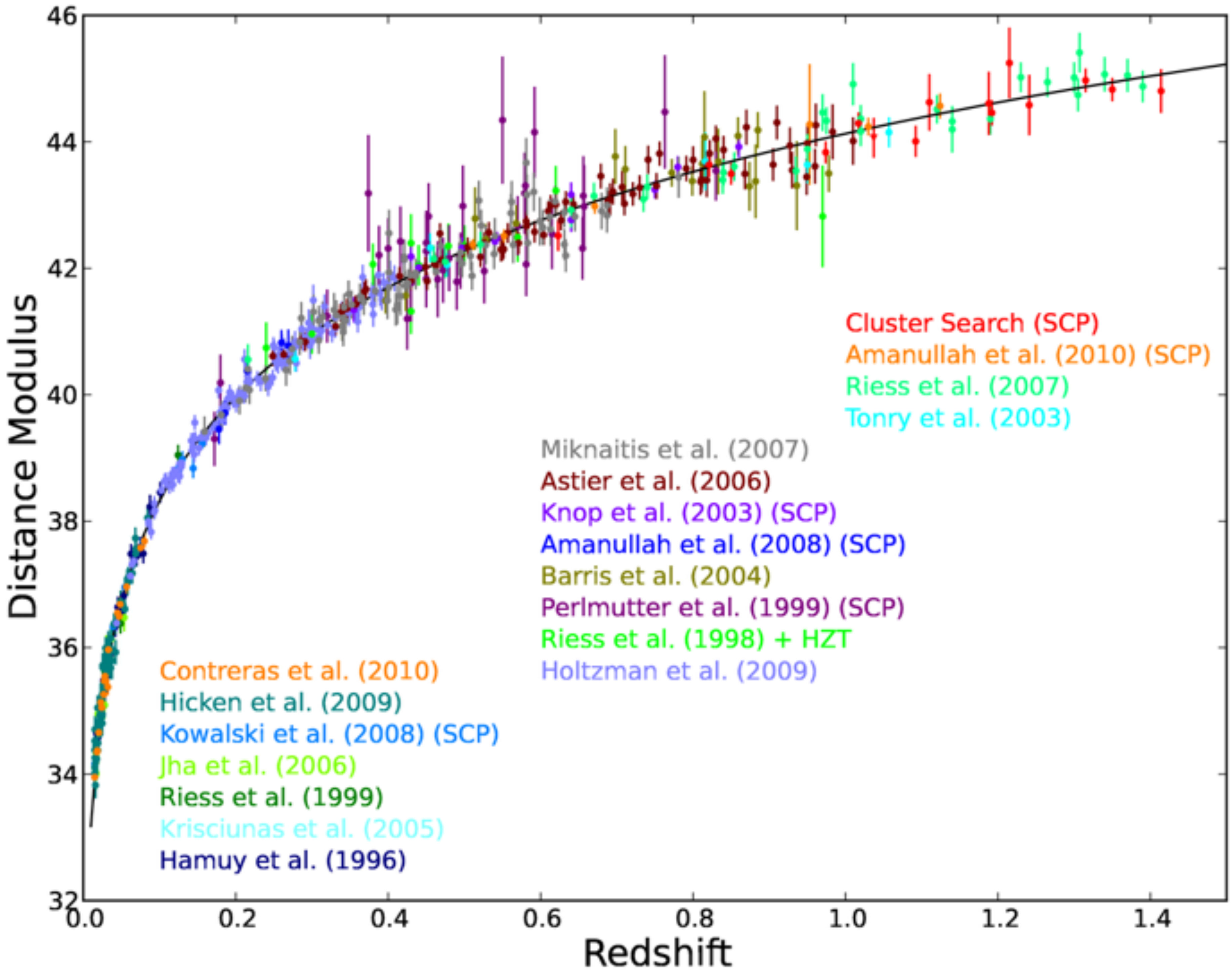
Estimating the Luminosity of the Standard Candle

- Supernova luminosities determined from fits of multi-band light curves
  - Depends on light-curve shapes and colors



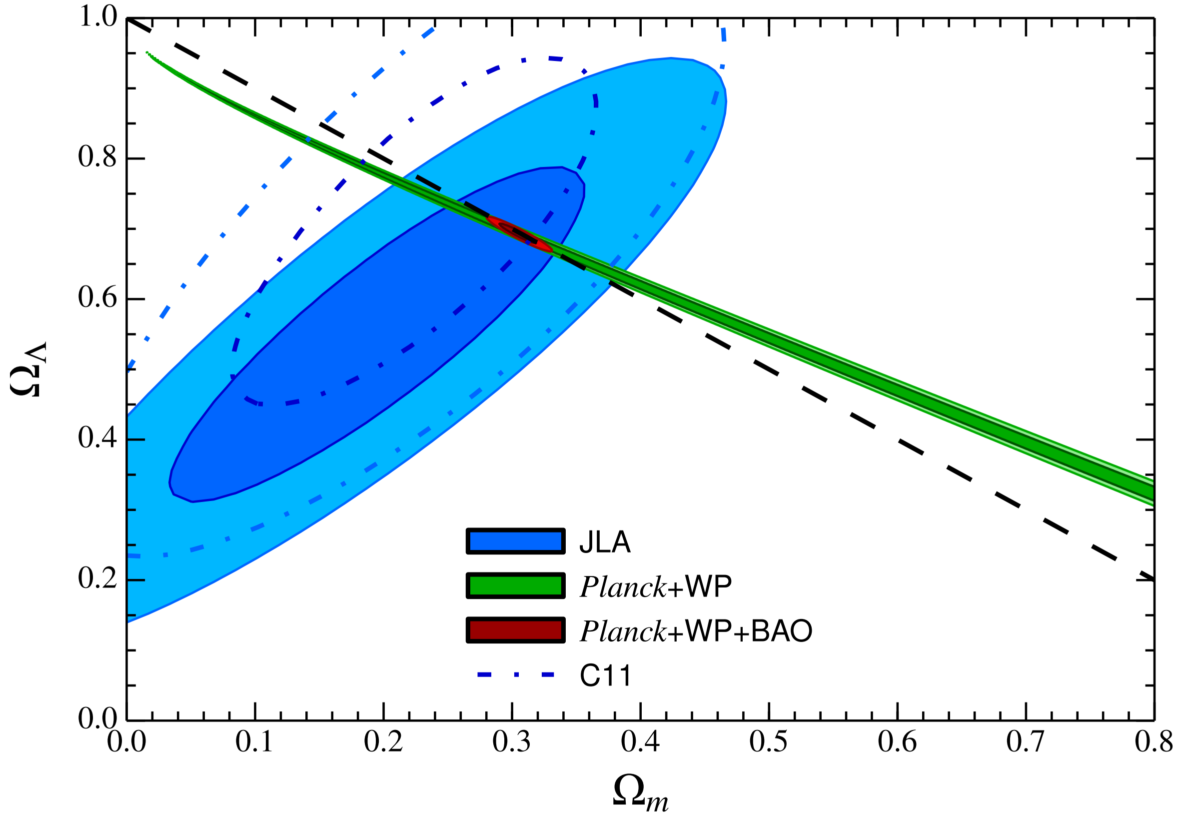
Luminosity

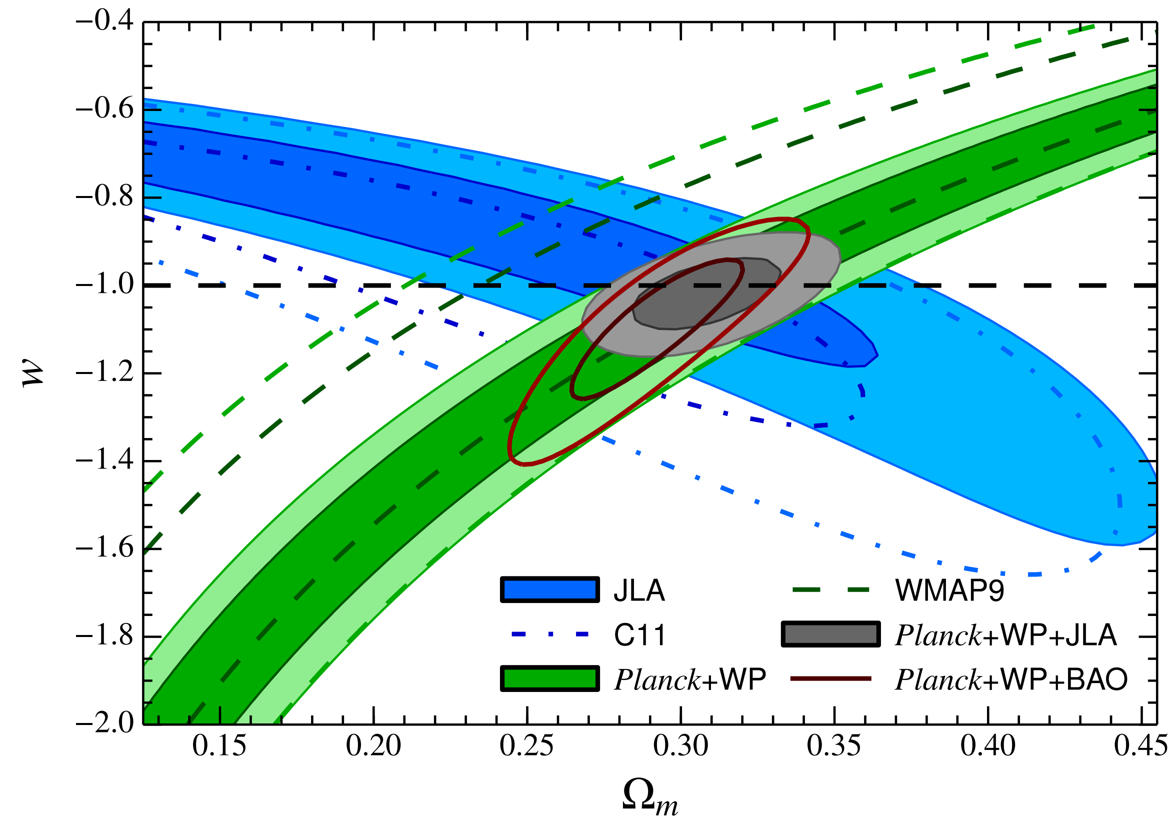
Supernova Hubble Diagram: Expansion History if the Universe



Dark Energy Parameter Estimates With Supernovae

- Sensitive to the acceleration of the universe
- Constrains the mass density, dark energy density, and a constant dark energy equation of state w





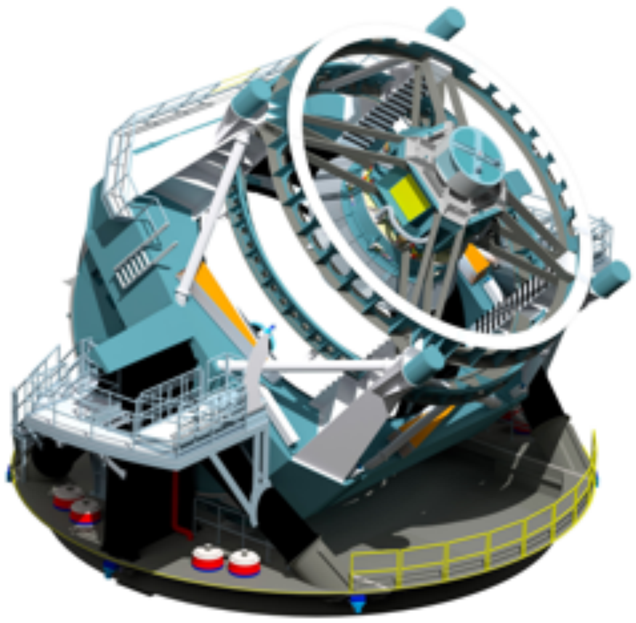
Betoule et al. 2014

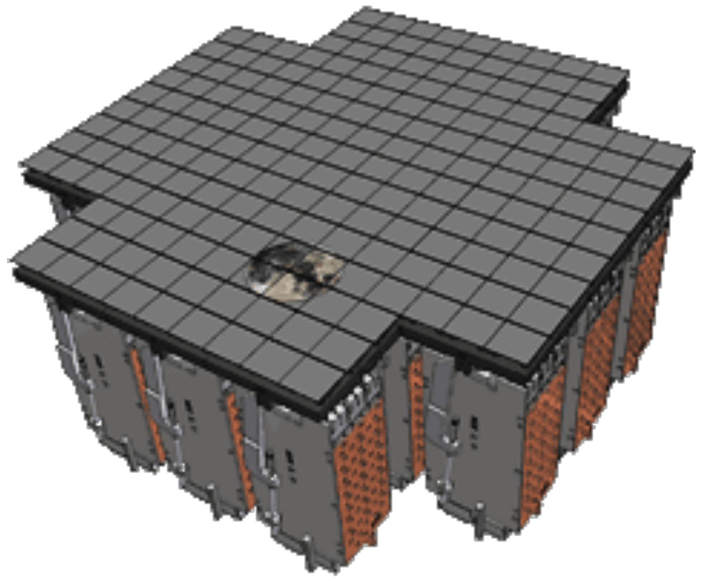
Publicly Available Datasets

- SDSS-II/SNLS3 Joint Light-Curve Analysis
    - http://supernovae.in2p3.fr/sdss_snls_jla/ReadMe.html
    - (Find the redshift bug!)
- Union 2.1
    - http://supernova.lbl.gov/union/
- Make a model for H(z) and write a paper

LSST

- Effective 6.7-m in Cerro Pachon Chile
- 10 sq deg CCD camera
- Survey start 2022
- 10-year survey
- 10 million transient alerts per night

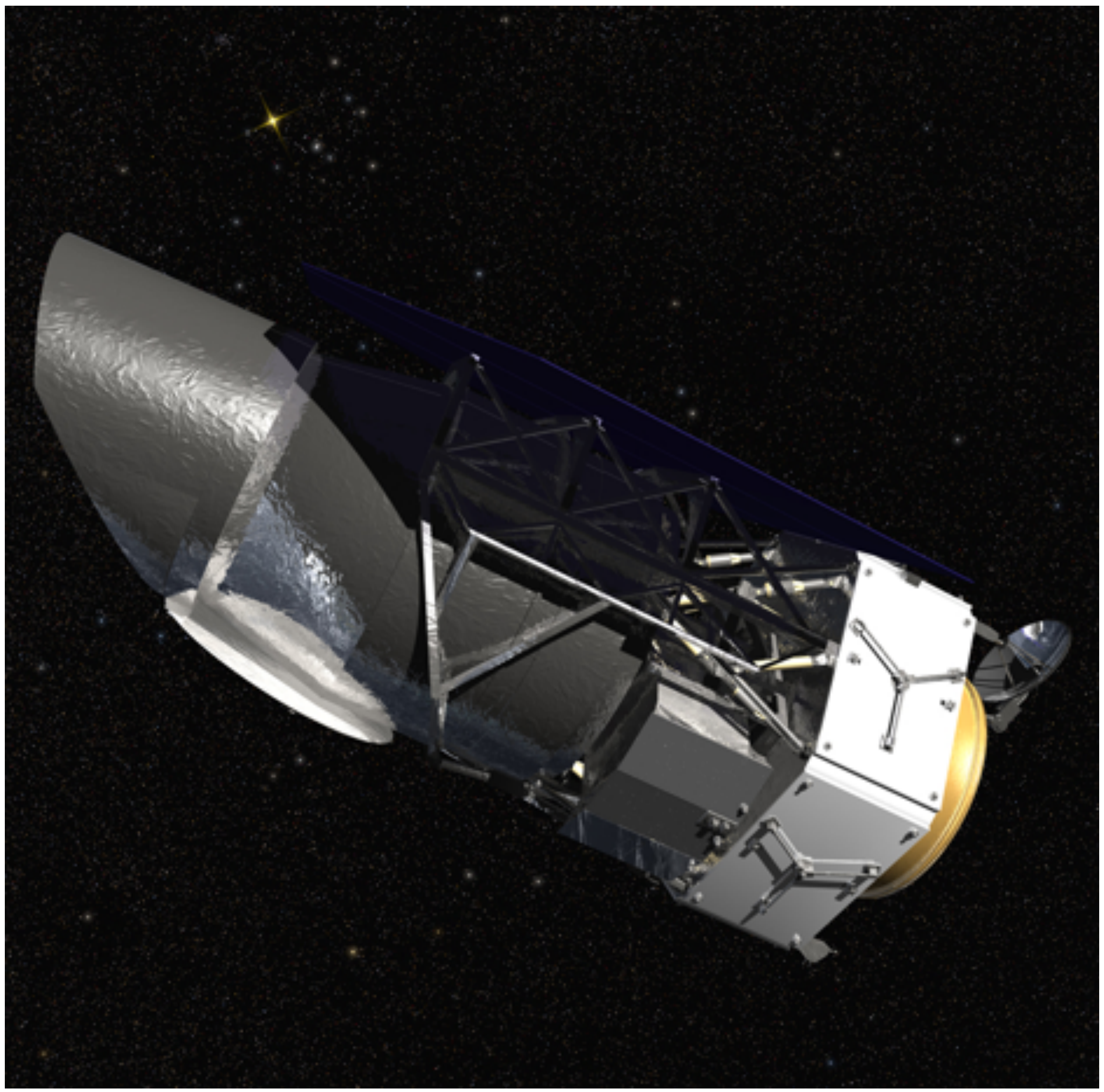




Ground-Based Cosmological SN Surveys

	DES SN		LSST	
	Wide	Deep	Main	Deep Drilling
Duration	5 CTIO Semesters		10 years	
Effective Mirror Diameter	3.6 m		6.7 m	
Solid Angle	8x3 sd	2x3 sd	18,000 sd	O(5)x9.6 sd
Depth/visit	24 *griz*	25 *griz*	24/25/24/23/22 *u/gr/i/z*	26.5/26/25.5/24.5 *gr/i/z/y*
Cadence	5 days/band	5 days/band	3 days	4 days/band
Numbers	2500	500	1,000,000	50,000

NASA WFIRST SN Program



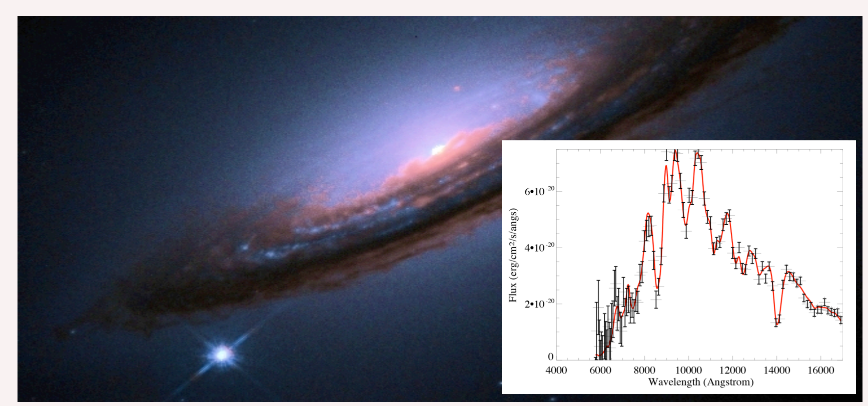
Supernova Survey

wide, medium, & deep imaging
+
IFU spectroscopy

2700 type Ia supernovae
z = 0.1–1.7

↓

standard candle distances
z < 1 to 0.20% and z > 1 to 0.34%



WFIRST+LSST SN Program

Increase number of supernovae by letting LSST do the discovery!

Supernova discovery

Supernova chromatic light curves

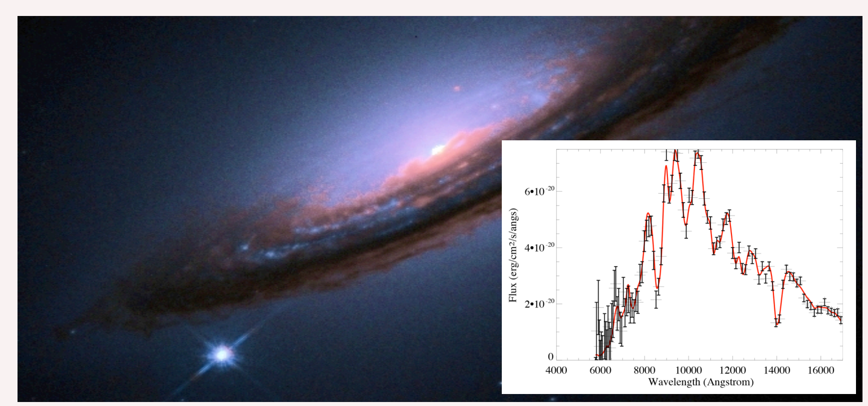
Supernova Survey

~~wide,~~ medium, & deep imaging
+
IFU spectroscopy

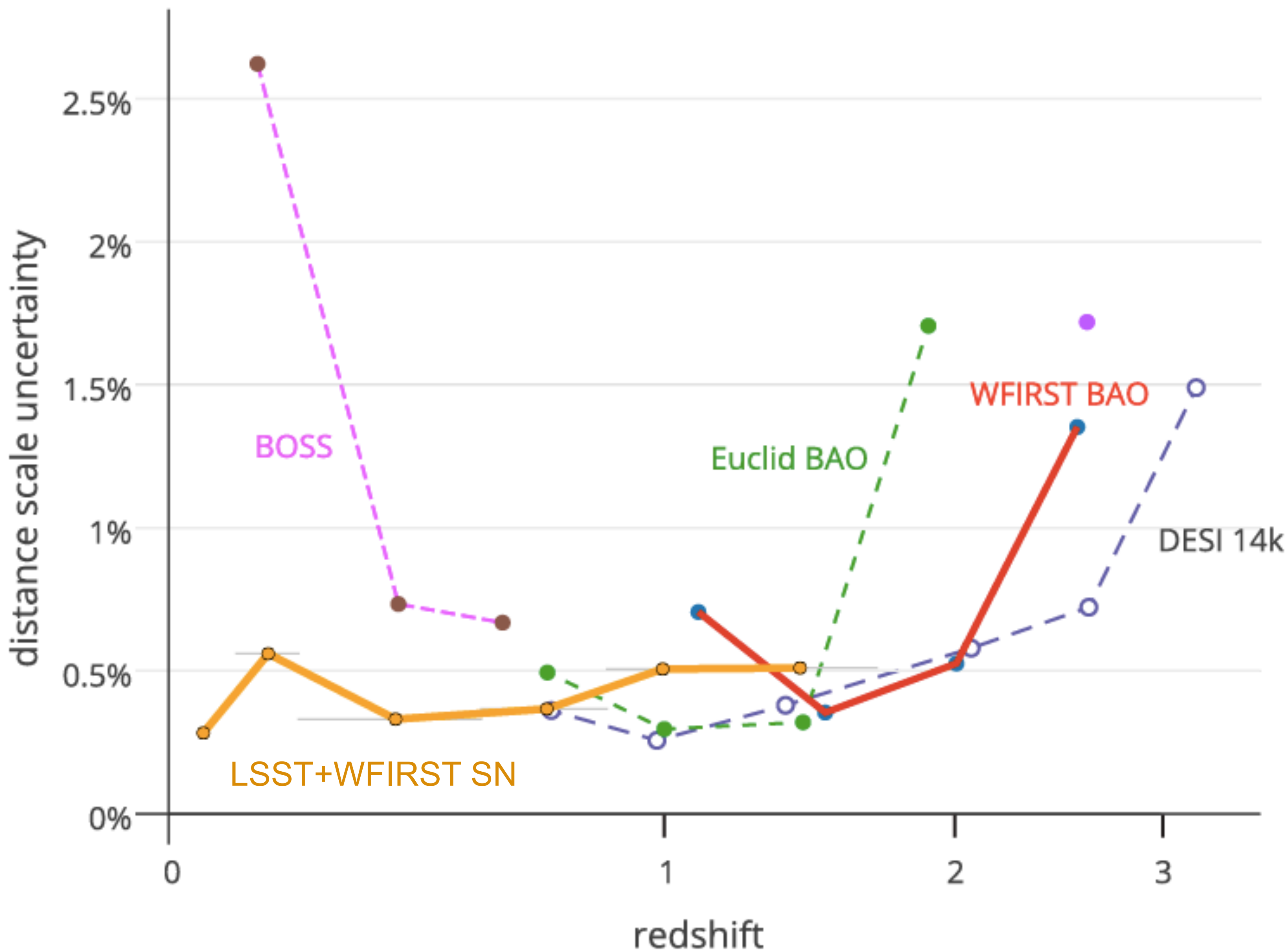
~~2700~~ 3200 type Ia supernovae
$z = 0.1–1.7$

↓

standard candle distances
$z < 1$ to 0.20% and $z > 1$ to 0.34%



Projections for LSST-WFIRST



Perlmutter 2016 LSST-DESC Collaboration Meeting

Opportunities for New Researchers in the Field

- Improve accuracy of SN Ia distances and reduce systematic uncertainties from SN luminosity model

- Supernova cosmology beyond the Hubble Diagram

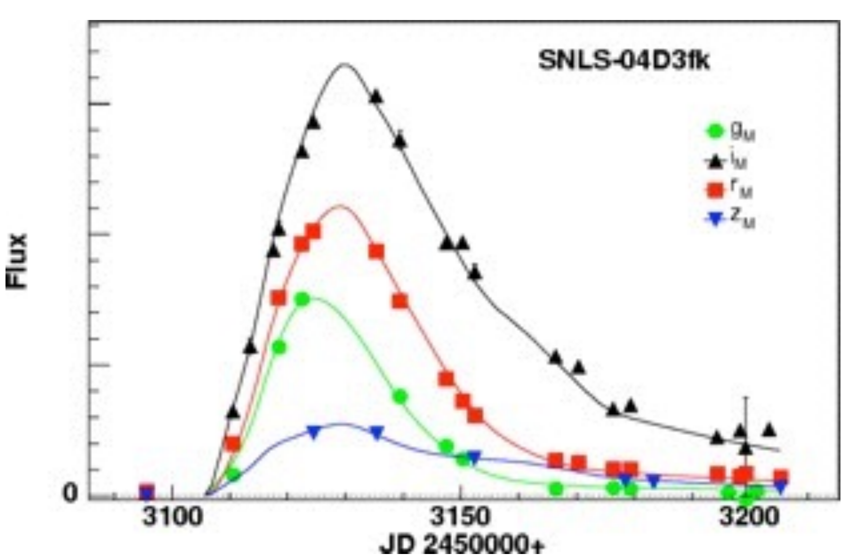
- Improve flux calibration of our observations

Opportunities for New Researchers in the Field

- Improve accuracy of SN Ia distances and reduce systematic uncertainties from SN luminosity model
  - ***Make a better SN Ia Model!***
- Supernova cosmology beyond the Hubble Diagram
- Improve flux calibration of our observations

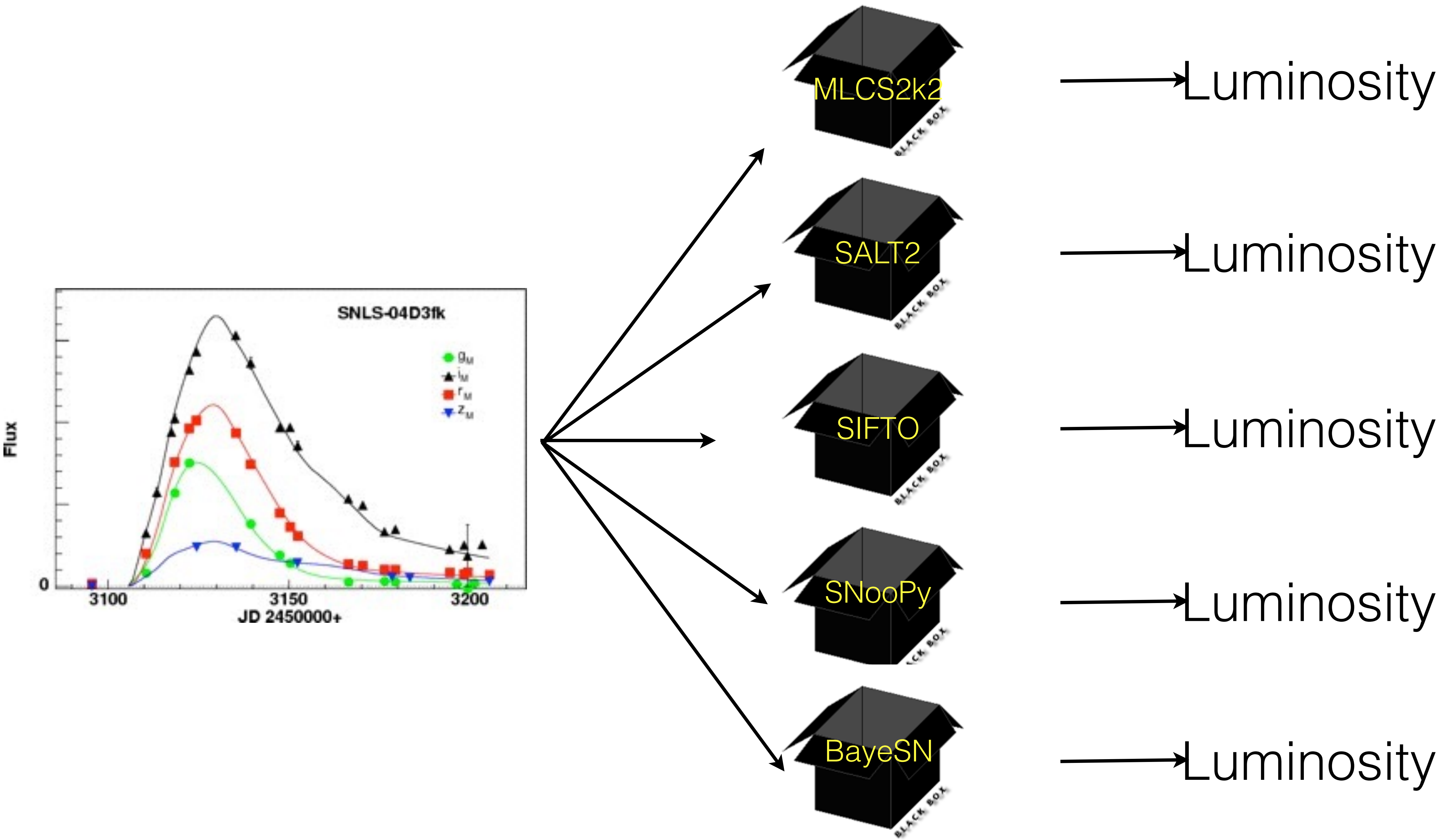
Uncertainty in SN Model

- Supernova distances determined from fits of multi-band light curves
  - Depends on magnitude at peak brightness, light-curve decline rate, and color



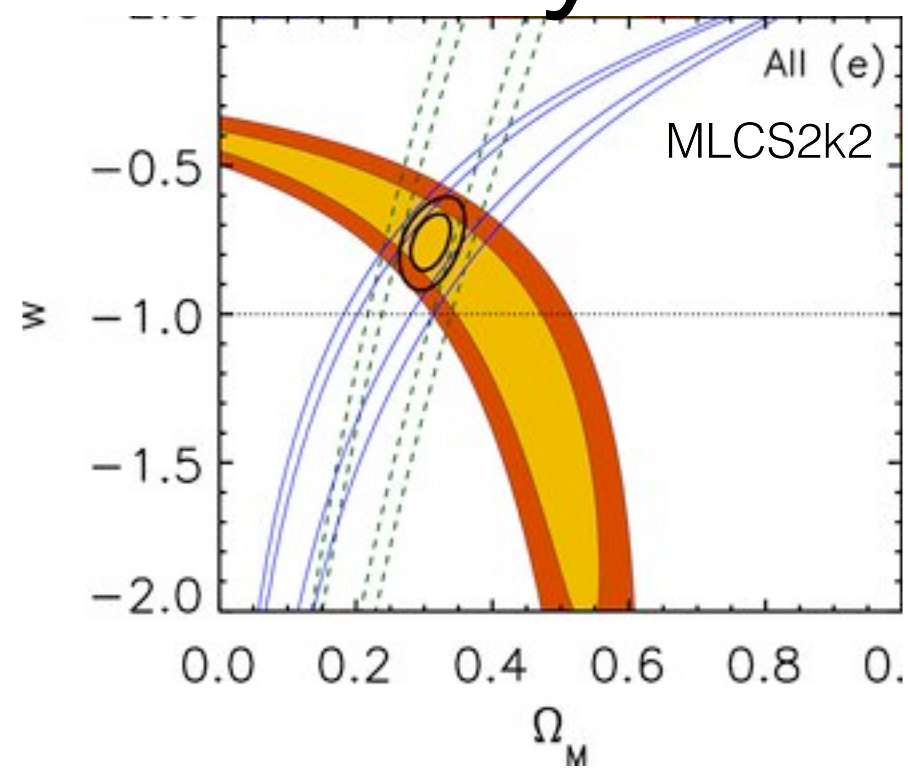
Luminosity

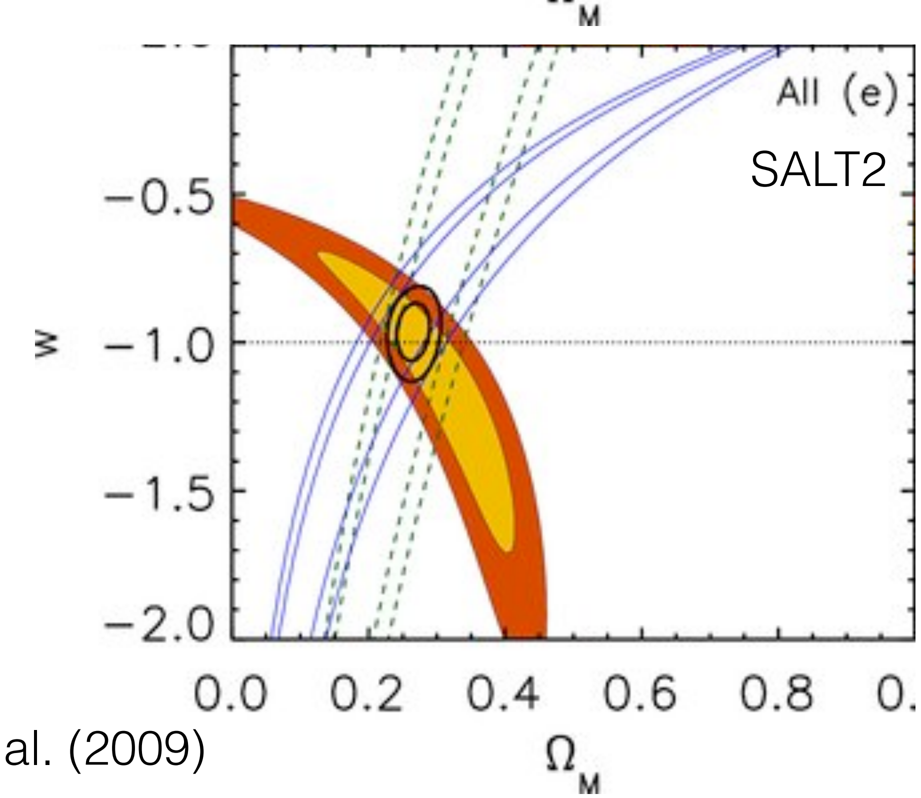
Uncertainty in SN Model



Uncertainty in SN Model Leads to Dark Energy Uncertainty

- Bulk of high-quality SN measurements in optical wavelengths and near peak
  - SNe less well understood in UV and NIR, well before and well after peak brightness
- Issue manifest in discrepancy of distances from different light-curve fitters
  - Inconsistent U-band templates
  - Different interpretation of color
  - Different priors





Kessler et al. (2009)

Make a Better SN Ia Model

- SN Ia models used for cosmology have two parameters: light-curve shape and color
- SN Ia are physically expected to and exhibit much more diversity: multi-color, spectral features, host-galaxy properties
- Sophisticated statistical techniques required to tease out signal (see e.g. Mandel et al. ApJ, 842, 93, 2017)

Fishing Expedition SN Ia Model

intrinsic magnitude

Spectral features determine absolute magnitude

intrinsic color

intrinsic magnitude covariance

$$\begin{pmatrix} U \\ B \\ V \\ R \\ I \end{pmatrix} \sim \mathcal{N}\left(\Delta + \begin{pmatrix} c_U + \alpha_U EW_{Ca} + \beta_U EW_{Si} + \eta_U \lambda_{Si} + \delta_U D \\ c_B + \alpha_B EW_{Ca} + \beta_B EW_{Si} + \eta_B \lambda_{Si} + \delta_B D \\ c_V + \alpha_V EW_{Ca} + \beta_V EW_{Si} + \eta_V \lambda_{Si} + \delta_V D \\ c_R + \alpha_R EW_{Ca} + \beta_R EW_{Si} + \eta_R \lambda_{Si} + \delta_R D \\ c_I + \alpha_I EW_{Ca} + \beta_I EW_{Si} + \eta_I \lambda_{Si} + \delta_I D \end{pmatrix}, C_c \right)$$

latent extrinsic color linear model

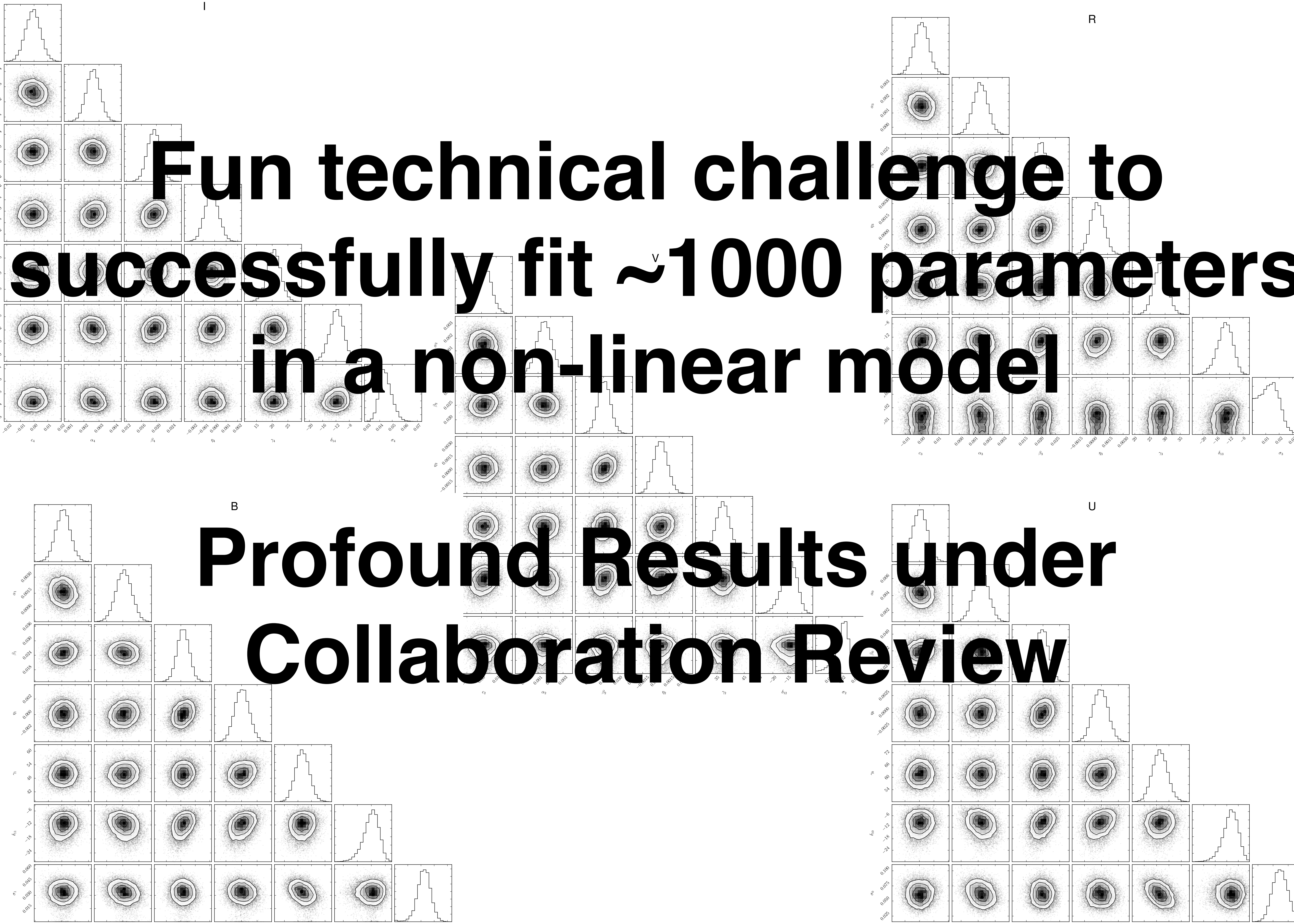
observed magnitudes

observed spectral features

$$\begin{pmatrix} U_o \\ B_o \\ V_o \\ R_o \\ I_o \\ EW_{Si,o} \\ EW_{Ca,o} \\ \lambda_{Si,o} \end{pmatrix} \sim \mathcal{N}\left(\begin{pmatrix} U + \gamma_U^0 k_0 + \gamma_B^1 k_1 \\ B + \gamma_B^0 k_0 + \gamma_B^1 k_1 \\ V + \gamma_V^0 k_0 + \gamma_V^1 k_1 \\ R + \gamma_R^0 k_0 + \gamma_R^1 k_1 \\ I + \gamma_I^0 k_0 + \gamma_I^1 k_1 \\ EW_{Si} \\ EW_{Ca} \\ \lambda_{Si} \end{pmatrix}, C \right)$$

data covariance

intrinsic spectral features



Fun technical challenge to successfully fit ~1000 parameters in a non-linear model

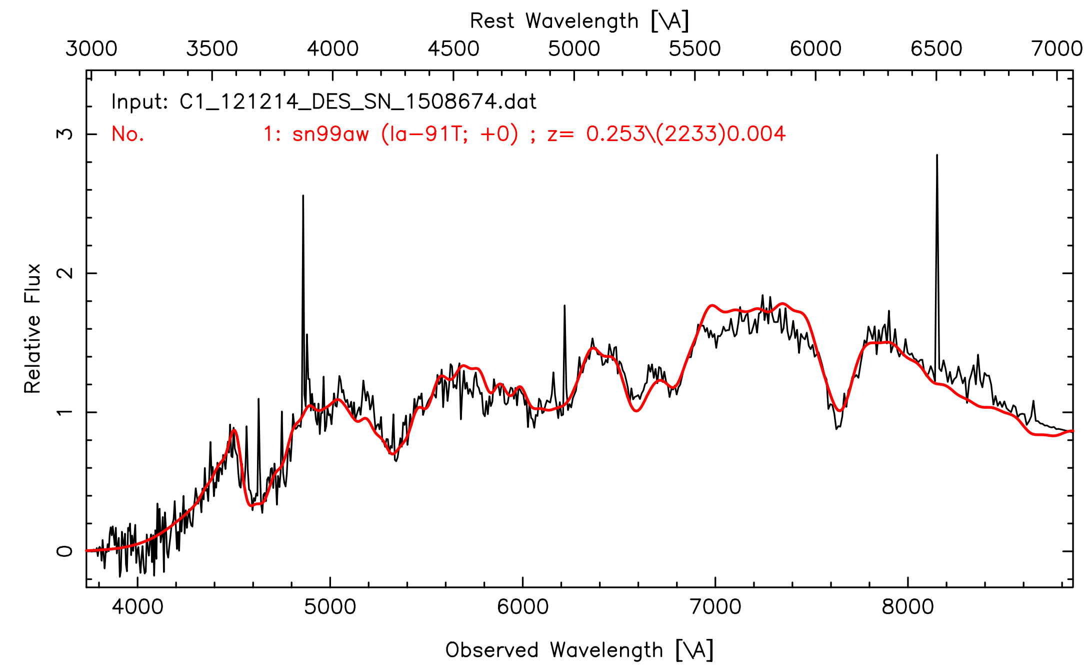
Profound Results under Collaboration Review

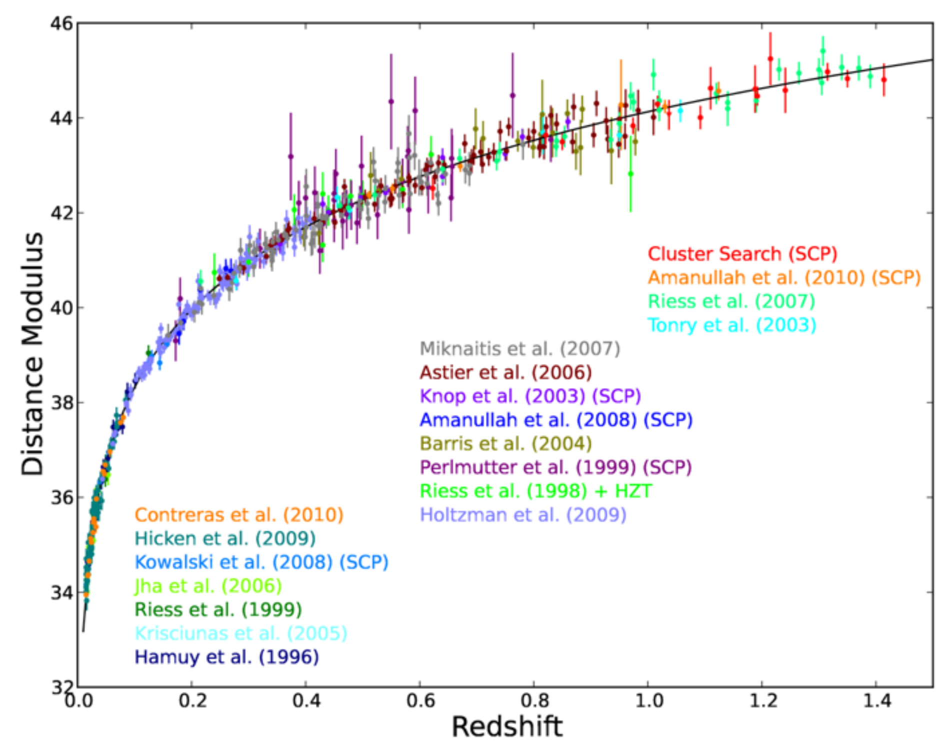
Opportunities for New Researchers in the Field

- Improve accuracy of SN Ia distances and reduce systematic uncertainties from SN luminosity model
  - ***Figure out how to do SN Ia cosmology with little spectroscopy!***
- Improve flux calibration of our observations
- Cosmology beyond the Hubble Diagram

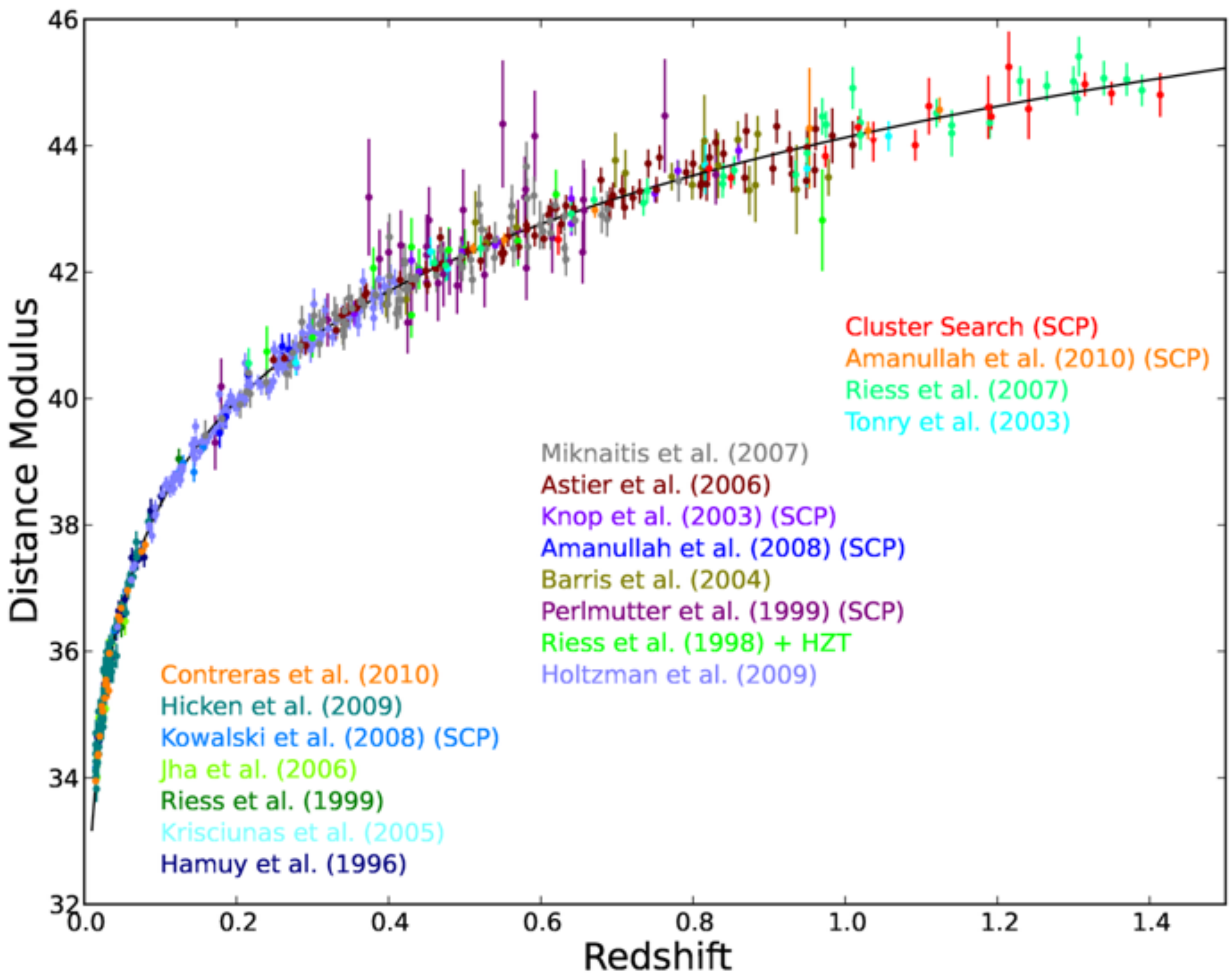
LSST Numbers Do Not Tell the Entire Story: Spectroscopy

- Spectroscopy used to make Hubble diagram
    - Transients typed as SNIa
    - Host galaxies identification
    - Highly precise redshift
- It takes more telescope time to spectroscopically type SNe than get light curves
    - Can't get spectrum of every LSST SN
- Not part of the imaging DES or LSST IMAGING surveys

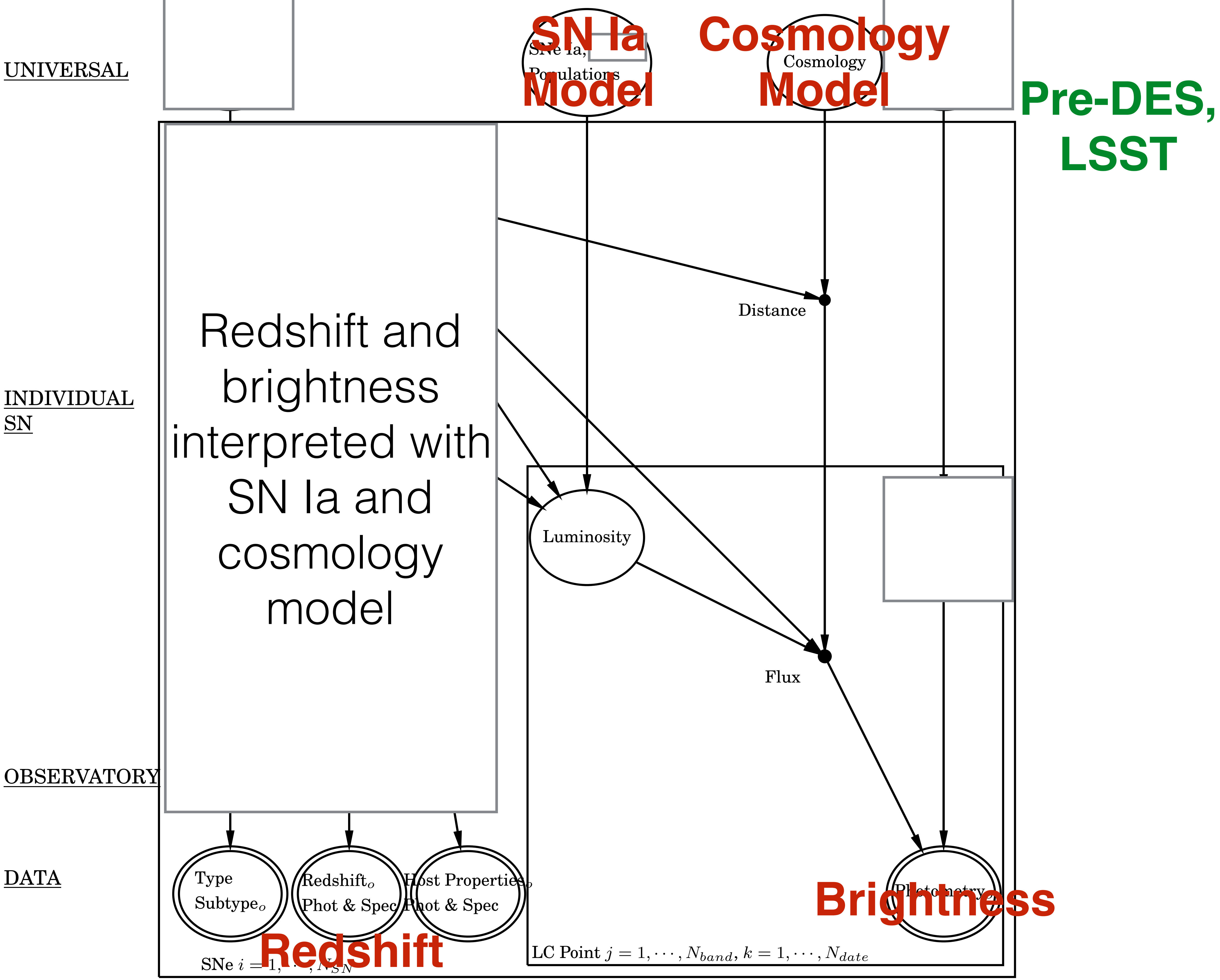


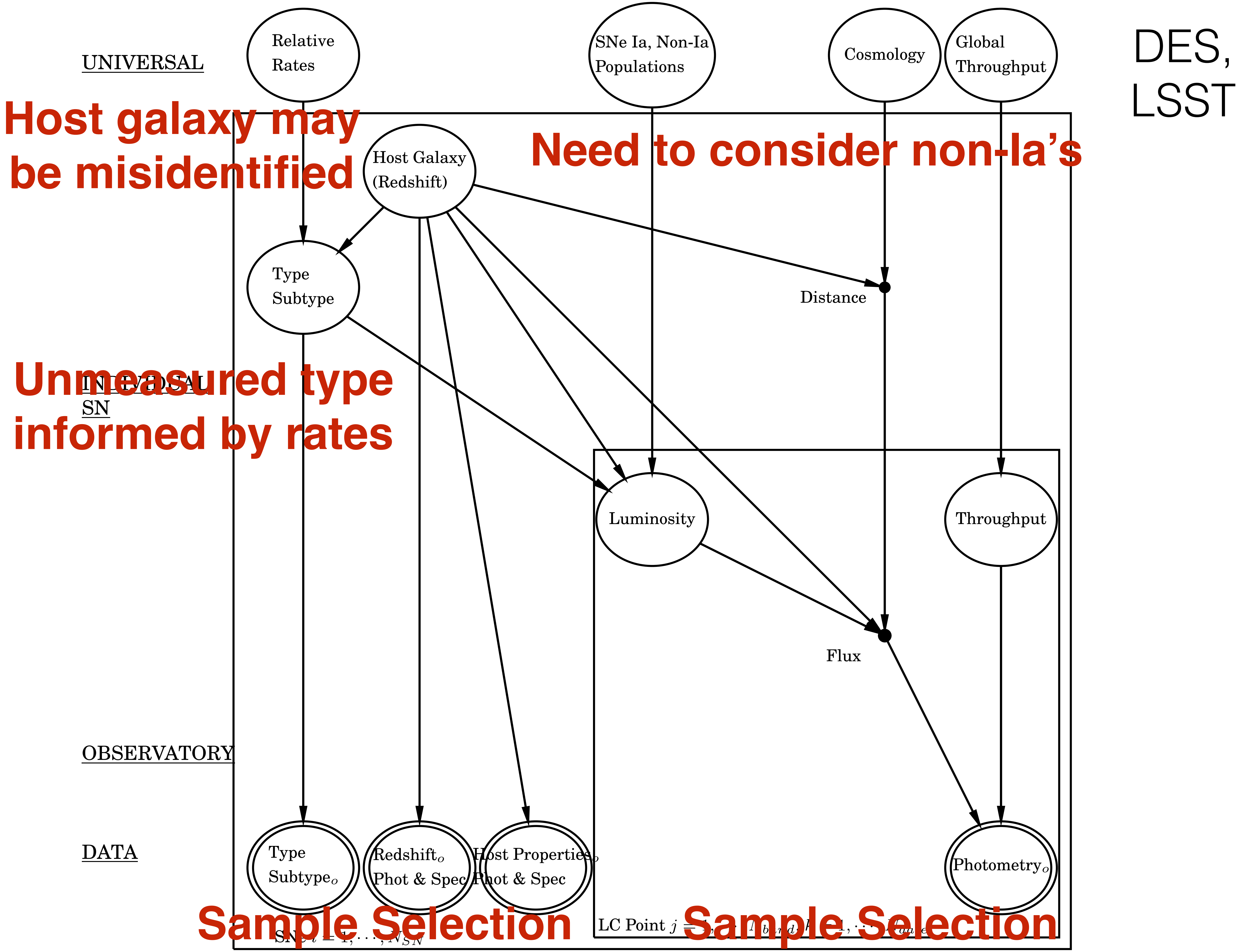


Numbers Do Not Tell the Entire Story: Incomplete Spectroscopy



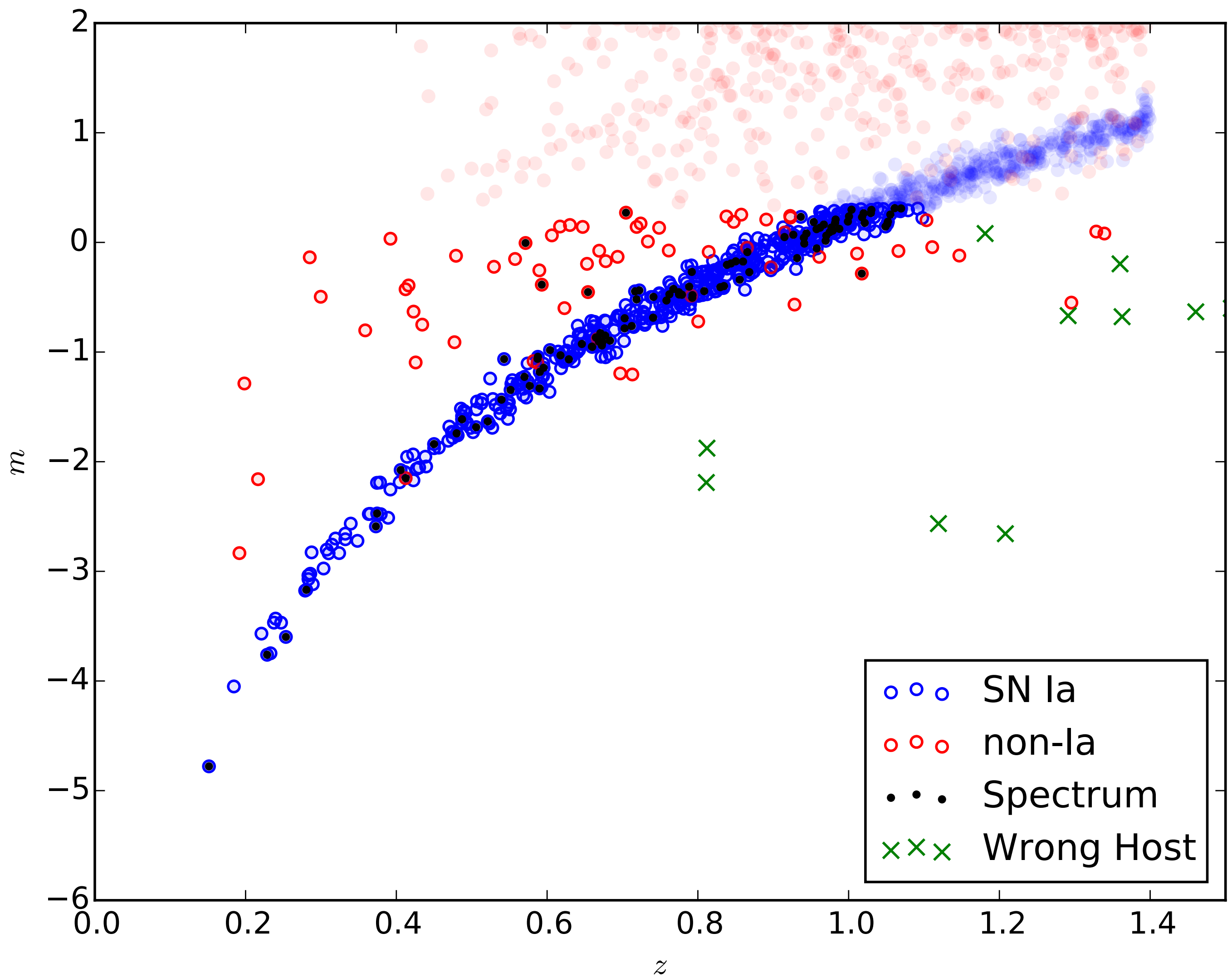
- DES Hubble Diagram (very preliminary!!)
  - has an impressive number of transients
  - is an impressive mess
- Mess is due to lack of spectroscopic completeness
  - Contamination from non-Ia's
  - Host galaxies misidentified
  - Highly uncertain redshifts
- It has NOT been established whether systematic uncertainties can be constrained to yield precision cosmology from these data

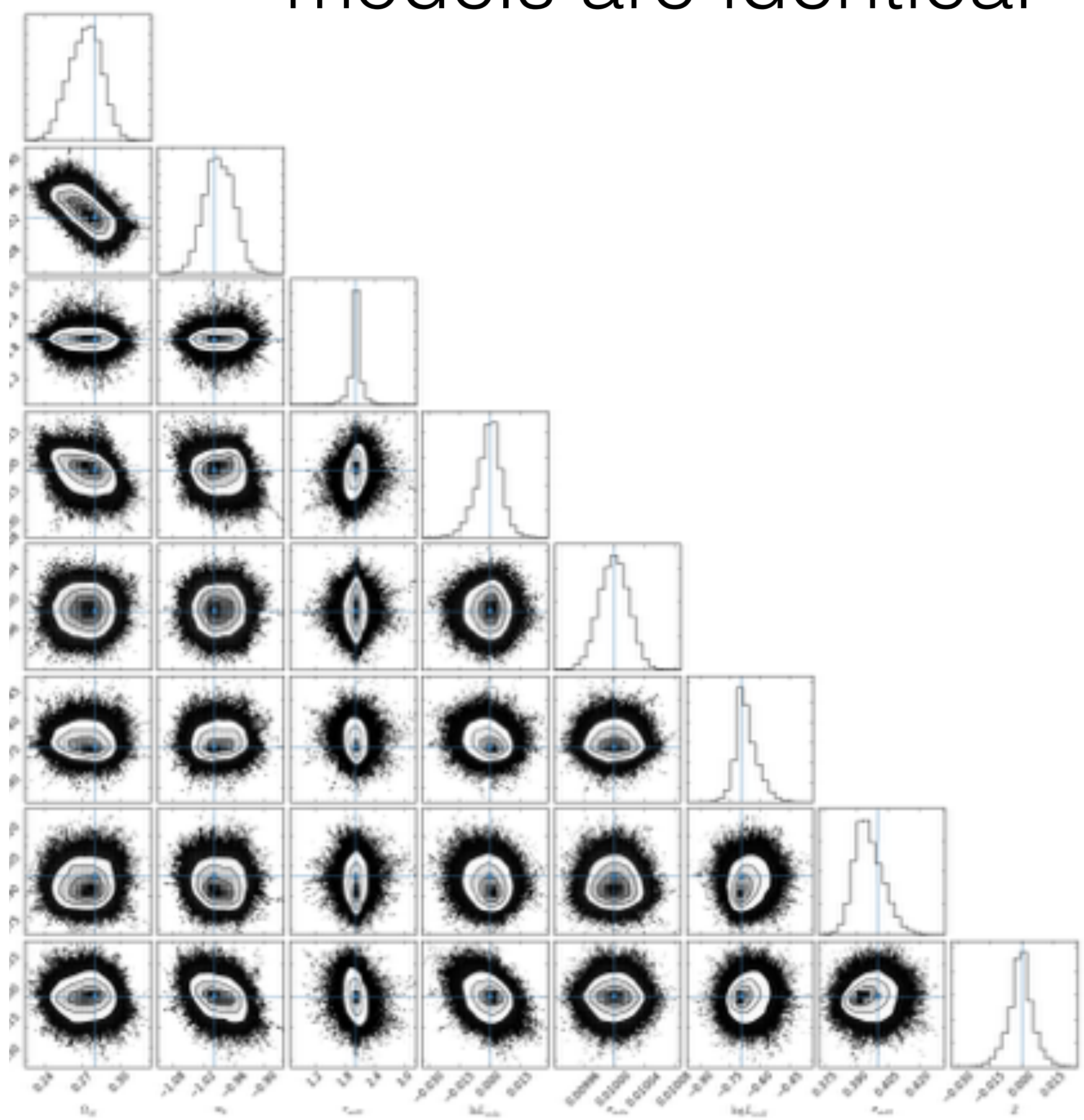

UNIVERSAL
INDIVIDUAL SN
OBSERVATORY
DATA
SN Ia Model
SNe Ia, Populations
Cosmology Model
Cosmology
Pre-DES, LSST
Redshift and brightness interpreted with SN Ia and cosmology model
Distance
Luminosity
Flux
Type Subtype$_o$
Redshift$_o$ Phot & Spec
Host Properties$_o$ Phot & Spec
Photometry
Brightness
Redshift
SNe $i = 1, \cdots, N_{SN}$
LC Point $j = 1, \cdots, N_{band}, k = 1, \cdots, N_{date}$


DES,
LSST
UNIVERSAL
Relative
Rates
SNe Ia, Non-Ia
Populations
Cosmology
Global
Throughput
Host galaxy may
be misidentified
Need to consider non-Ia's
Host Galaxy
(Redshift)
Type
Subtype
Distance
Unmeasured type
informed by rates
SN
Luminosity
Throughput
Flux
OBSERVATORY
DATA
Type
Subtype$_o$
Redshift$_o$
Phot & Spec
Host Properties$_o$
Phot & Spec
Photometry$_o$
Sample Selection
LC Point
Sample Selection

First-Generation Code Implemented

Simulated ugly Hubble Diagram → Input Cosmology IF Generative and simulated models are identical





Remains an unsolved problem

Opportunities for New Researchers in the Field

- Improve accuracy of SN Ia distances and reduce systematic uncertainties from SN luminosity model

- Supernova cosmology beyond the Hubble Diagram

    - ***Test General Relativity!***

- Improve accuracy of SN Ia distances

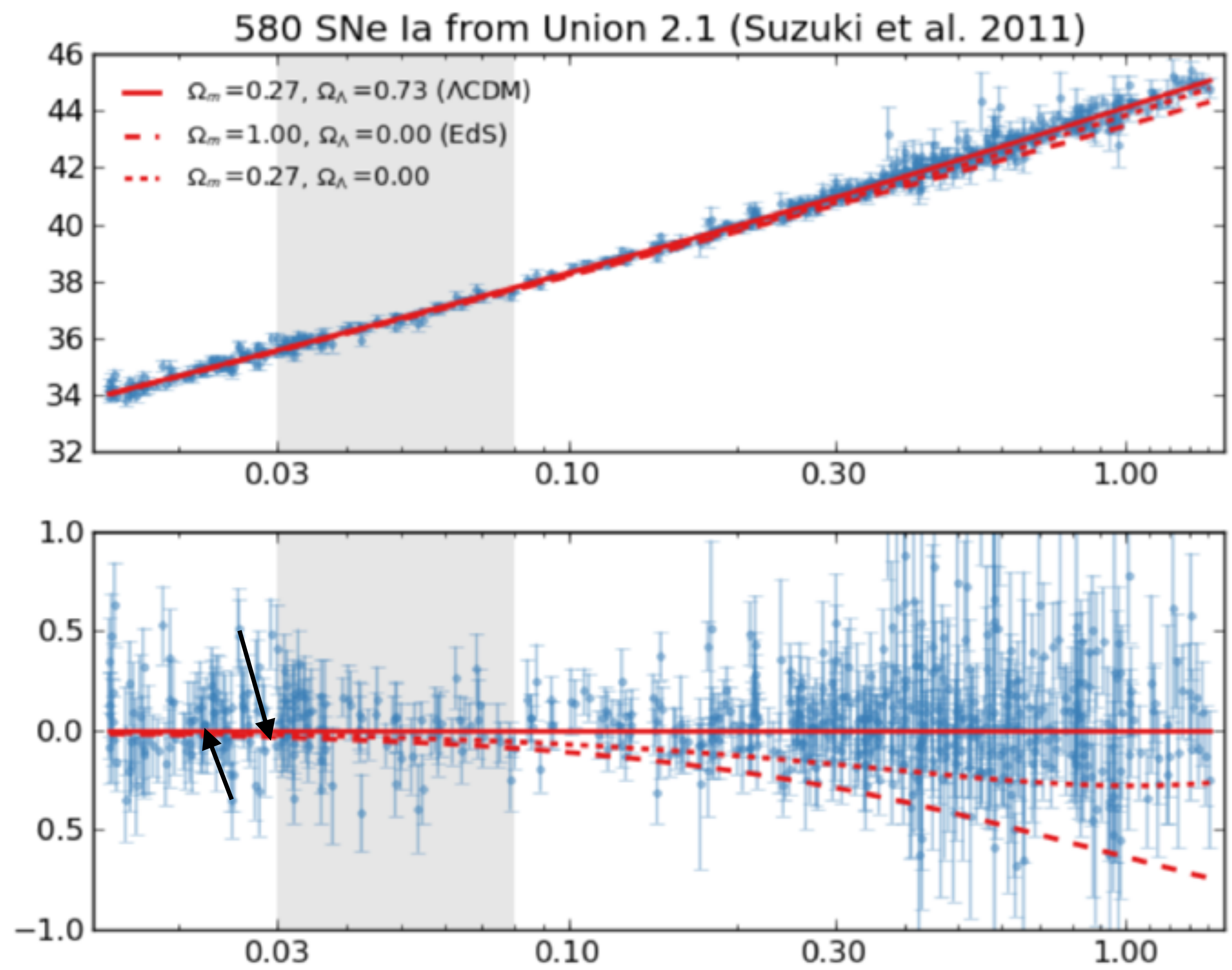
New LSST SN Probes of Cosmology: Peculiar Velocities

- Universe has mass overdenties that induce galaxy velocities on top of cosmological expansion
- Amplitude of extra motion related to
  - Amplitude of mass overdensities: σ_8
  - Rate at which gravity forms mass overdensities: $f(a)$
  - To first order not related to bias: b
- General Relativity found empirically to have a tight prediction for velocity amplitude

Millenium Simulation

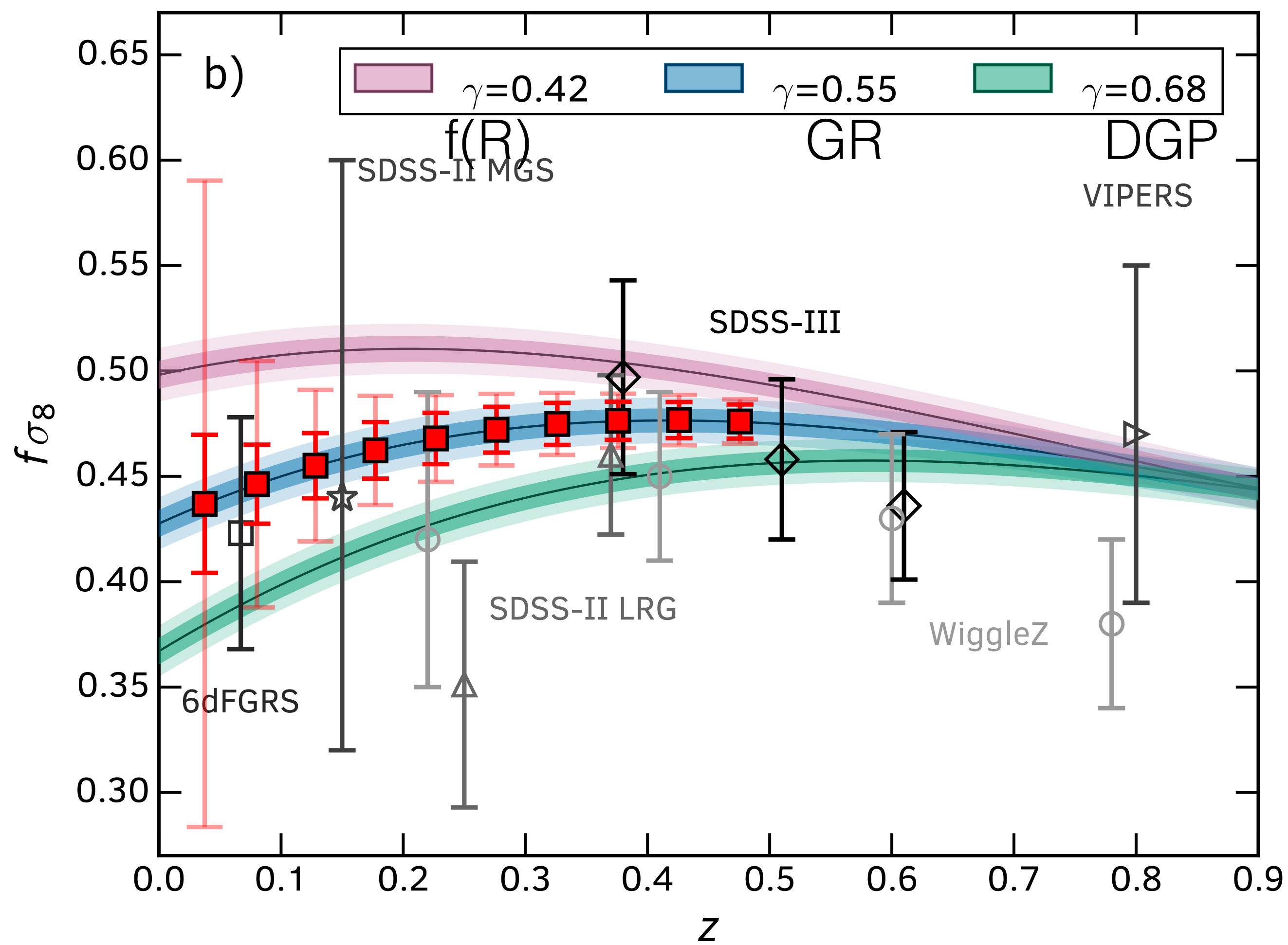
New LSST SN Probes of Cosmology: Peculiar Velocities

- Peculiar velocity = "peculiar distance"
- Transform Hubble diagram residuals to (line-of-sight) peculiar velocities



Measured Redshift (cosmological and line-of-sight peculiar velocity)

New LSST SN Probes of Cosmology: Peculiar Velocities



Howlett, Robotham, Lagos, Kim (submitted)

- Peculiar velocities of LSST-discovered SNe Ia tests GR and other gravity models

Opportunities for New Researchers in the Field

- Improve accuracy of SN Ia distances and reduce systematic uncertainties from SN luminosity model

- Supernova cosmology beyond the Hubble Diagram

  - ***Measure the Hubble Constant!***

- Improve accuracy of SN Ia distances

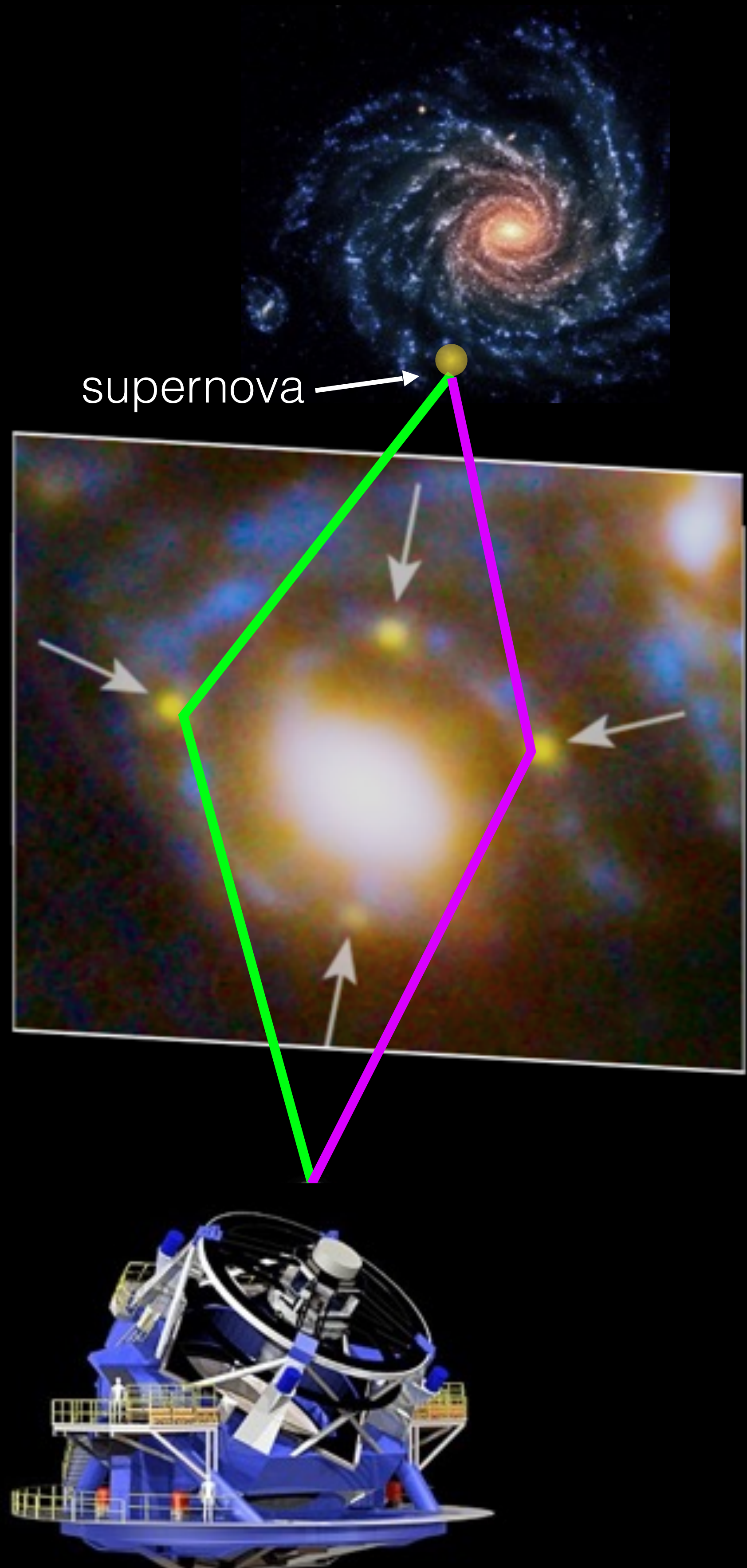
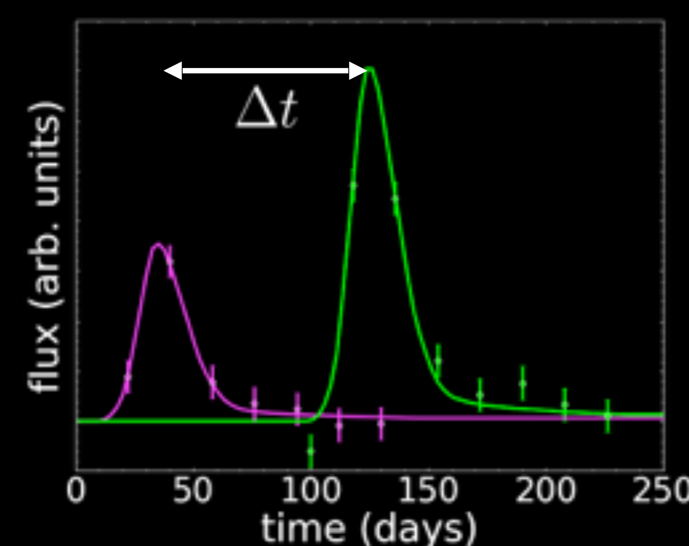
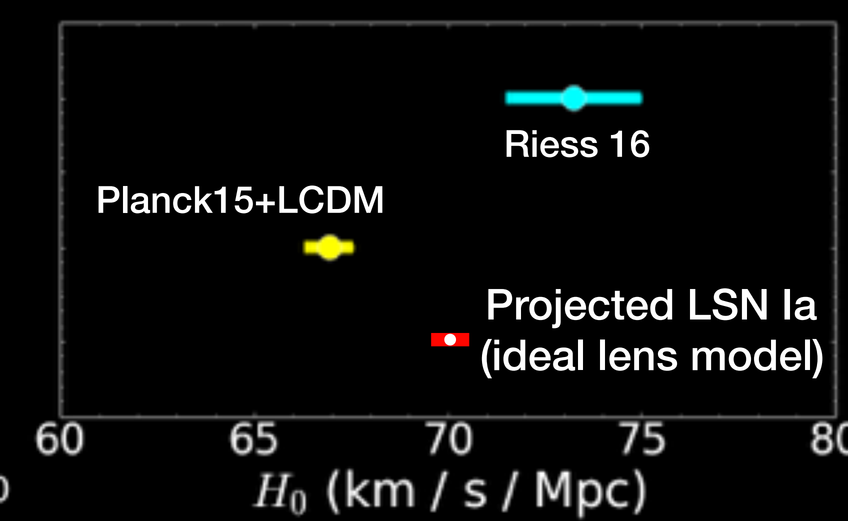


Image: Kelly et al. 2015 (Science)

Strong lensing creates multiple images.

If the source is variable, then time delays between the images can measured. This is a *dimensional* measurement, so we can measure H_0 (Refsdal 1964). We can also measure dark energy (Linder 2004, 2011).





$$\Delta t = \frac{D_l D_s}{D_{ls}} (1 + z_l) \phi$$

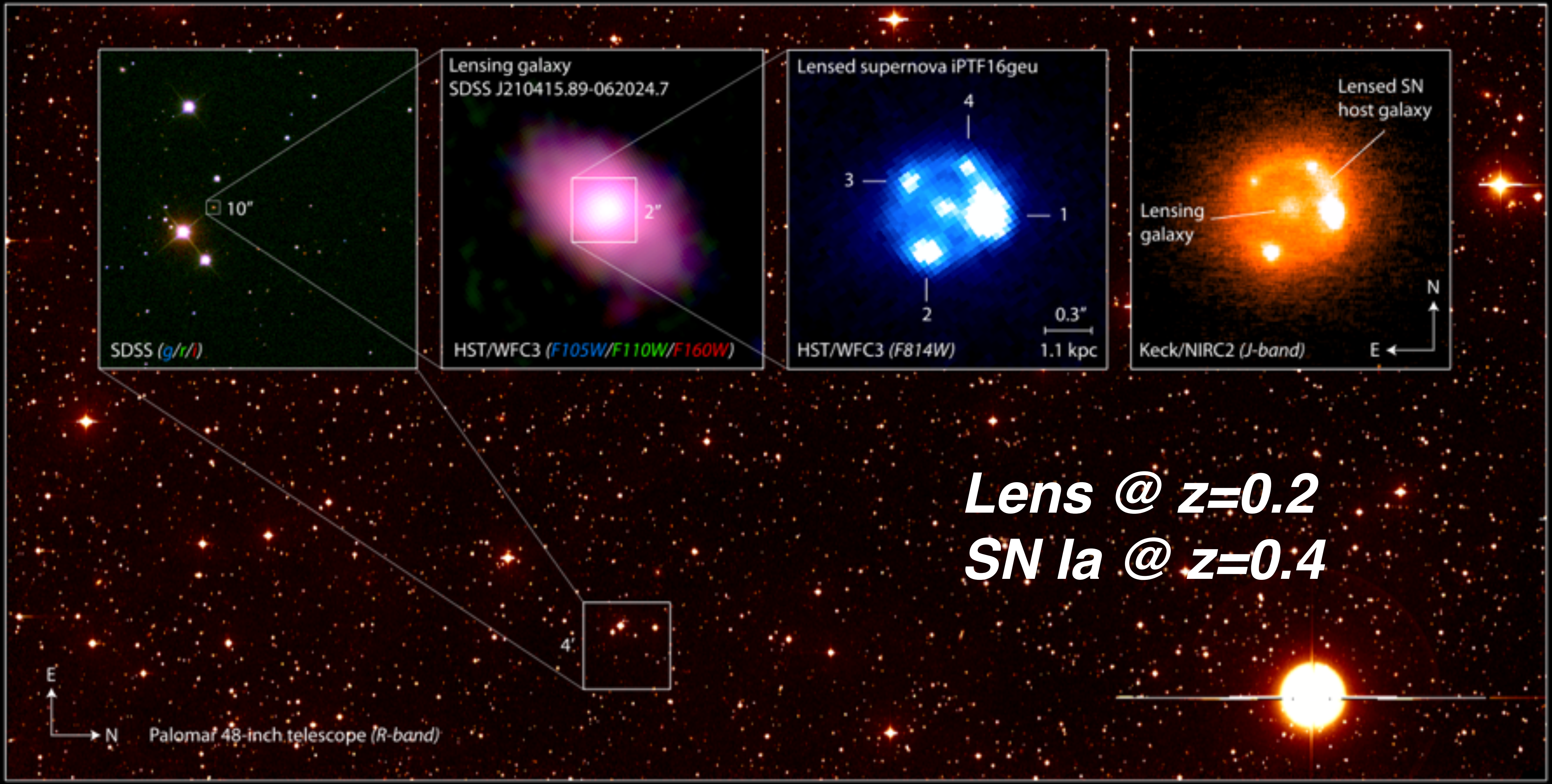
A unique cosmology distance probe

Depends on lens mass distribution

Seize the Day

Two very recent papers:

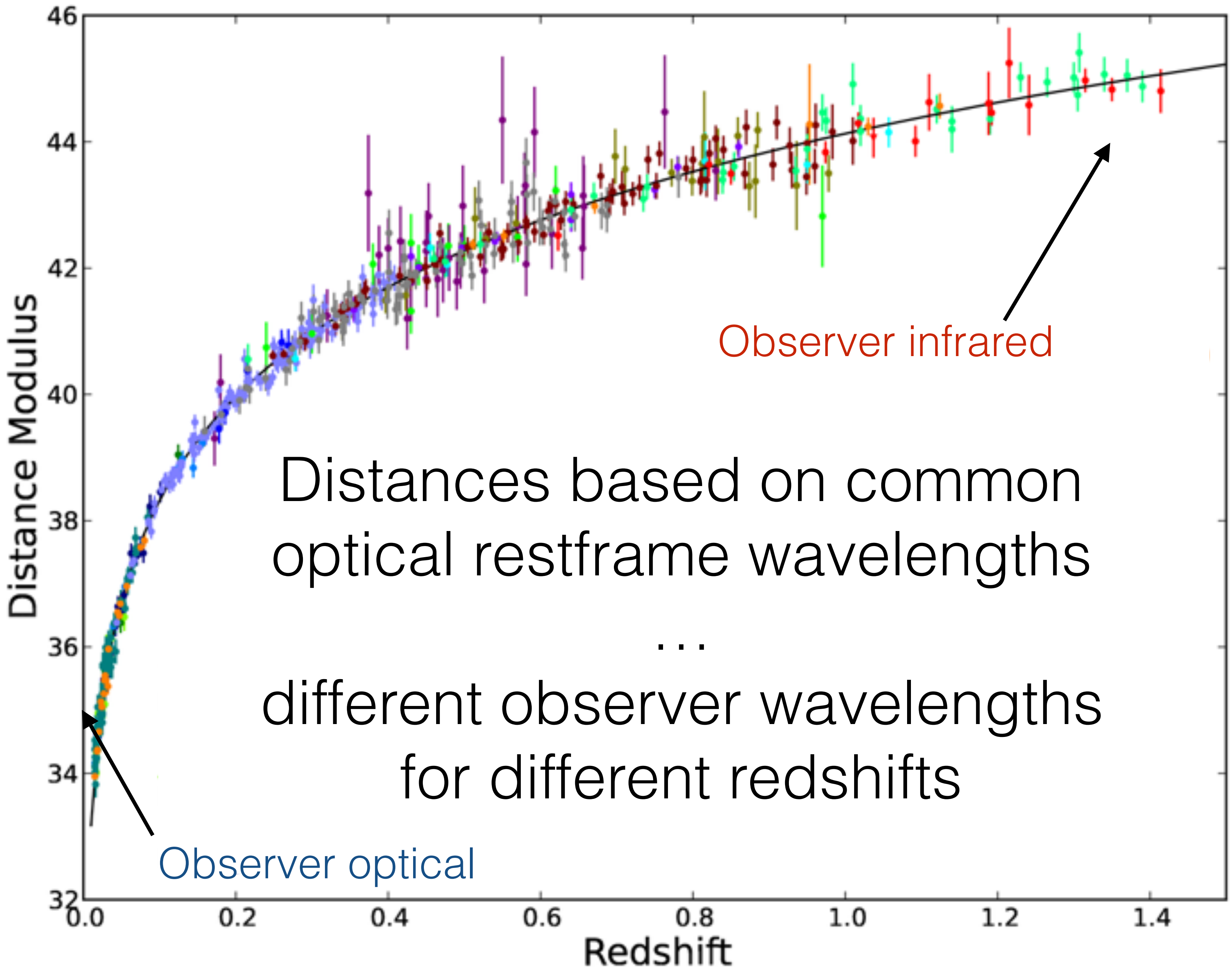
- Discovery of the first multiply lensed SN Ia – Goobar et al. (*Science* 2017)
- Novel method for increasing the discovery rate by an order of magnitude – Goldstein & Nugent (*ApJL* 2017)



Opportunities for New Researchers in the Field

- Improve accuracy of SN Ia distances and reduce systematic uncertainties from SN luminosity model
- Supernova cosmology beyond the Hubble Diagram
- Improve flux calibration of our observations
  - ***Calibrate of optical path tied to absolute flux standards***

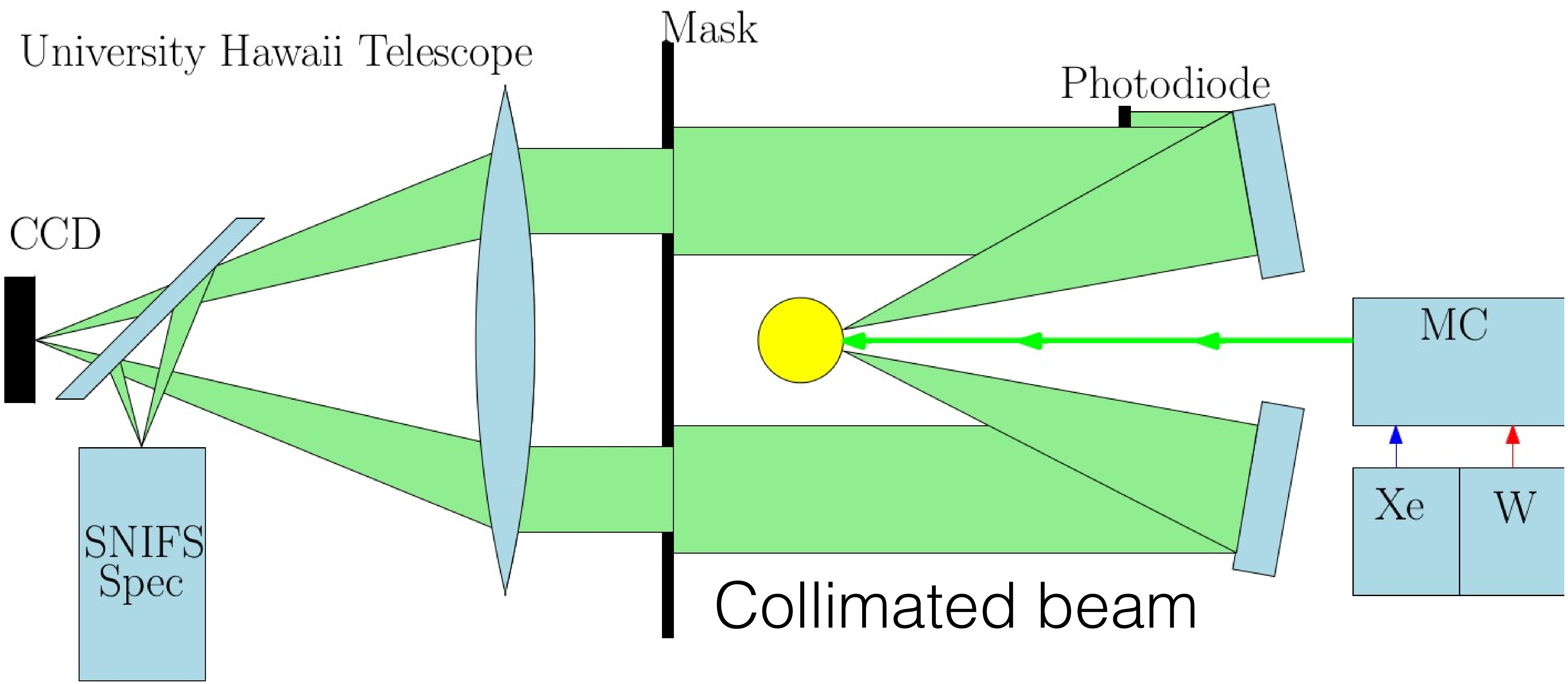
Relative SN Distances Require Color Calibration



Improved Calibration Needed

- Flux calibration one of the top limiting uncertainties for SN cosmology
- Precision SN cosmology needs <1% calibration over optical wavelengths
- Current flux calibration tied to modeling of white dwarfs — currently faced with limiting sources of uncertainty
- Goal: Tie next generation experiments to laboratory-calibrated standards

SCALA: NIST-Tracable Flux Calibration



Conclusions

- Type Ia Supernovae are and will remain a leading probe of dark energy
- Many challenges to overcome in order to realize improved constraints —> research opportunities