Supernova Cosmology & Supercomputing

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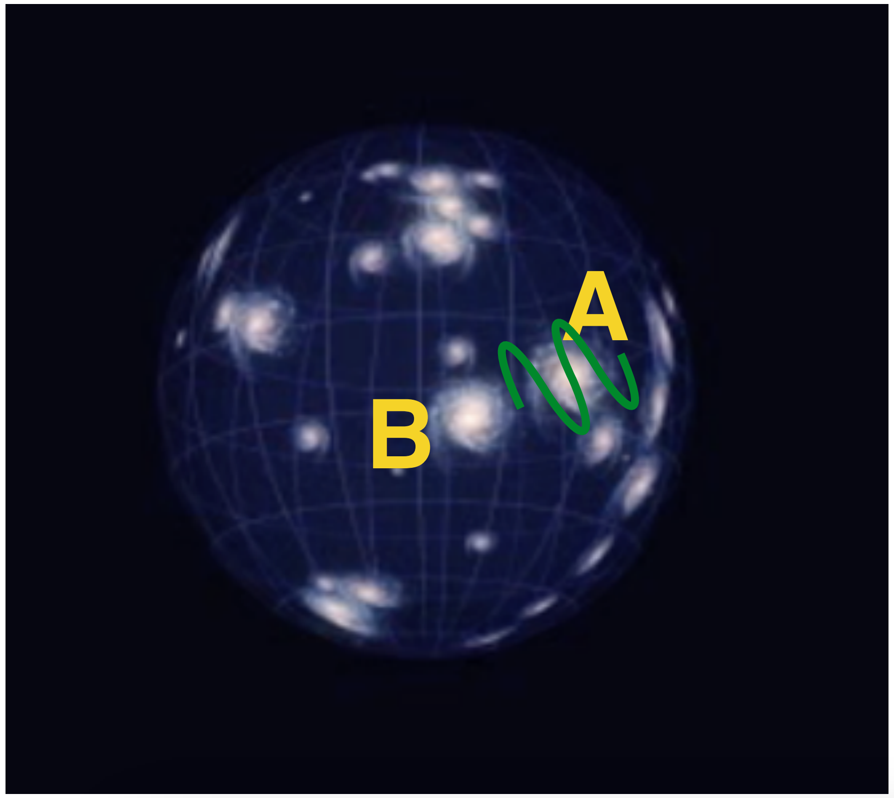
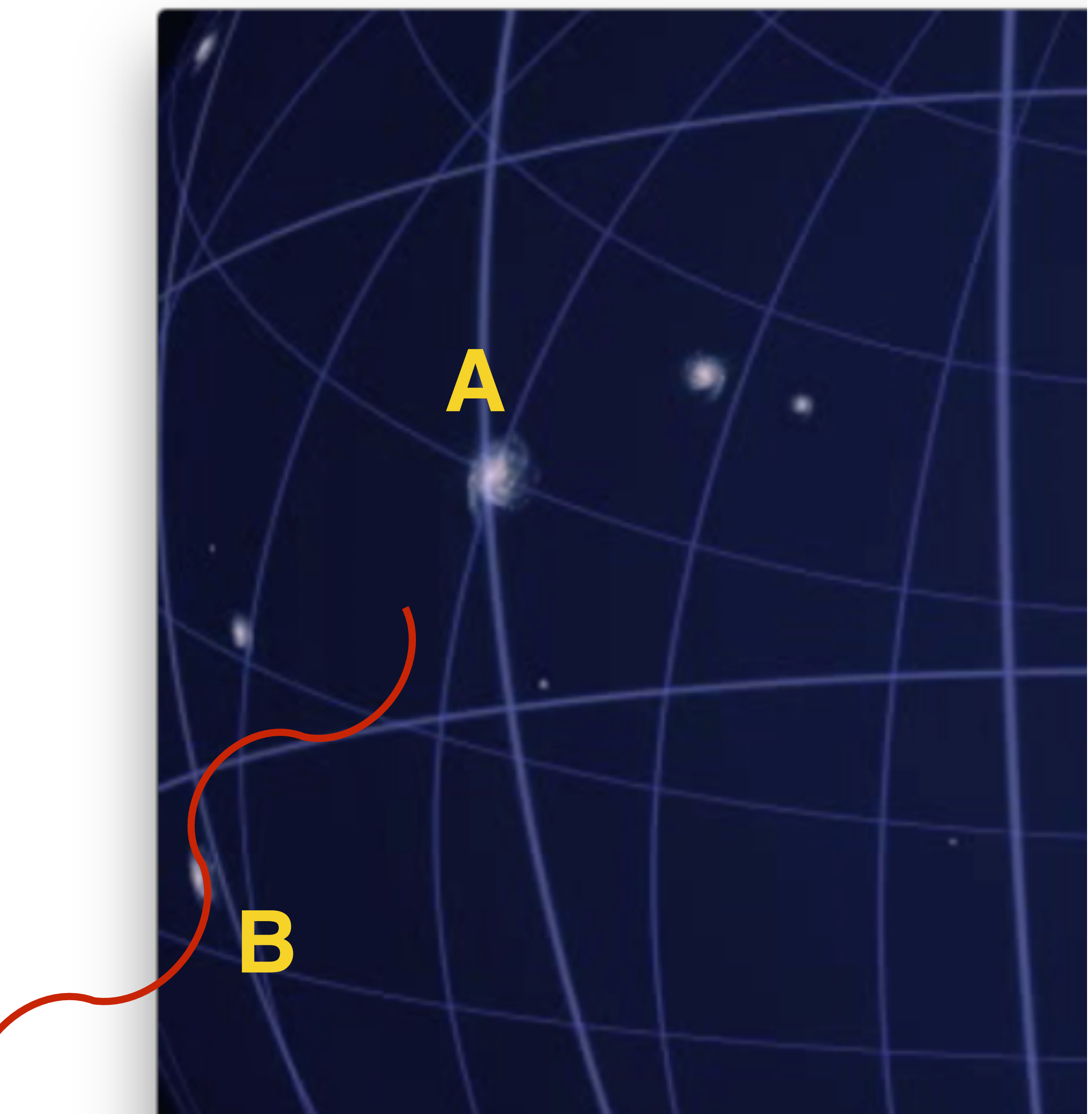
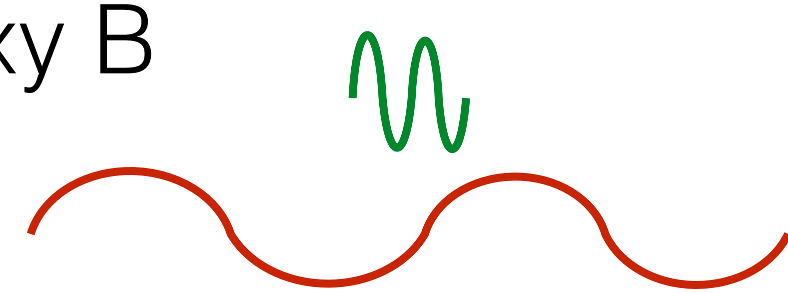
Redshift



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

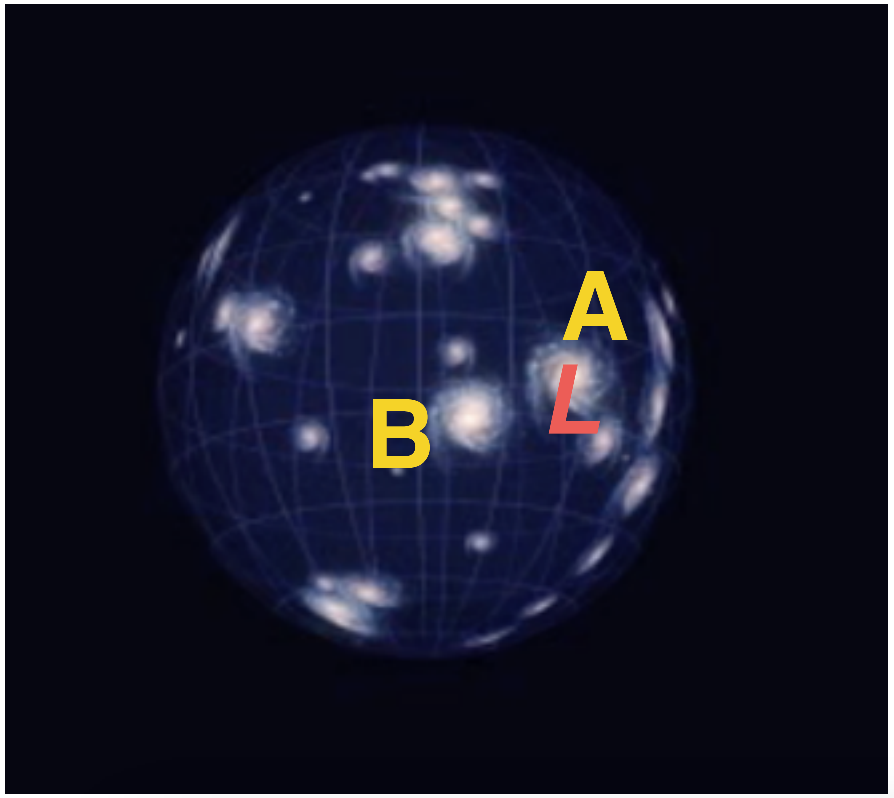
… has its wavelength expanded by the time it gets to galaxy B



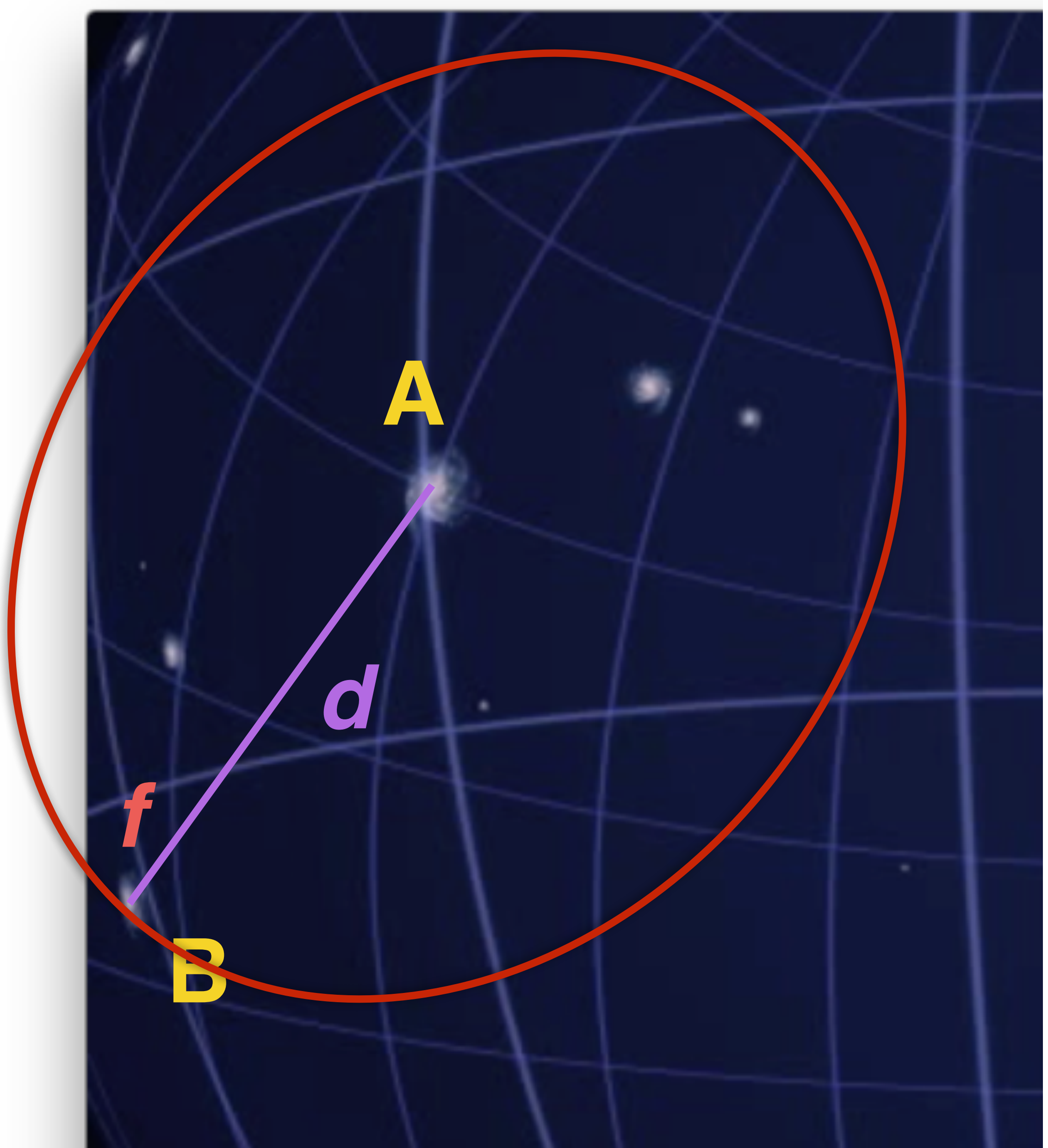


The relative increase in wavelength (redshift) is a measure of the relative change in size of the Universe

Light Cone and Flux



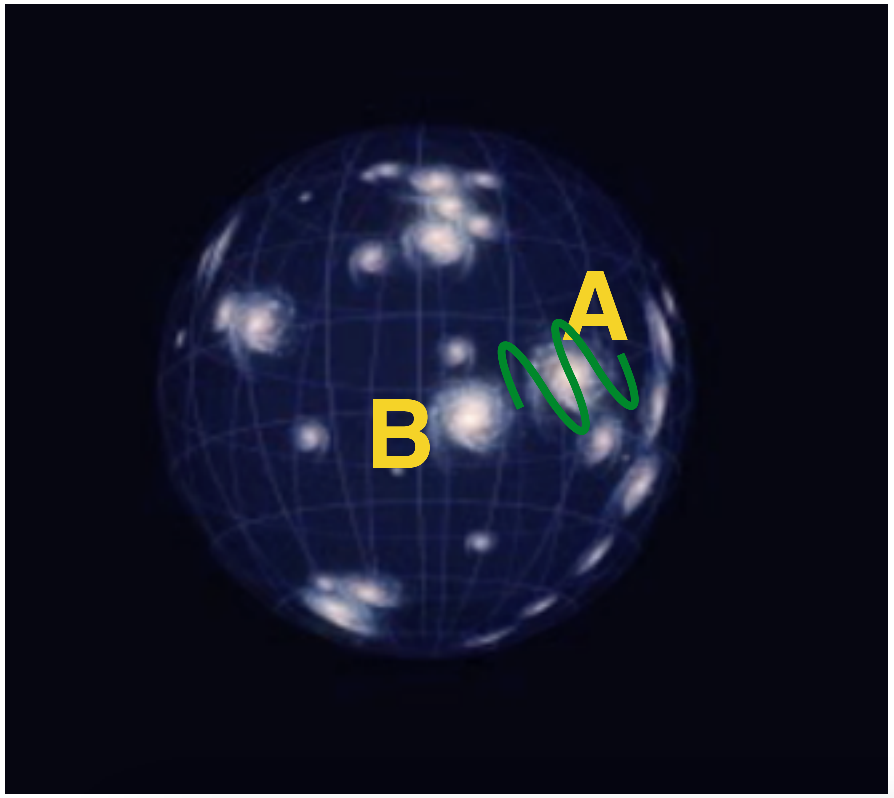
A source at galaxy
A emits photons at
some redshift, …



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

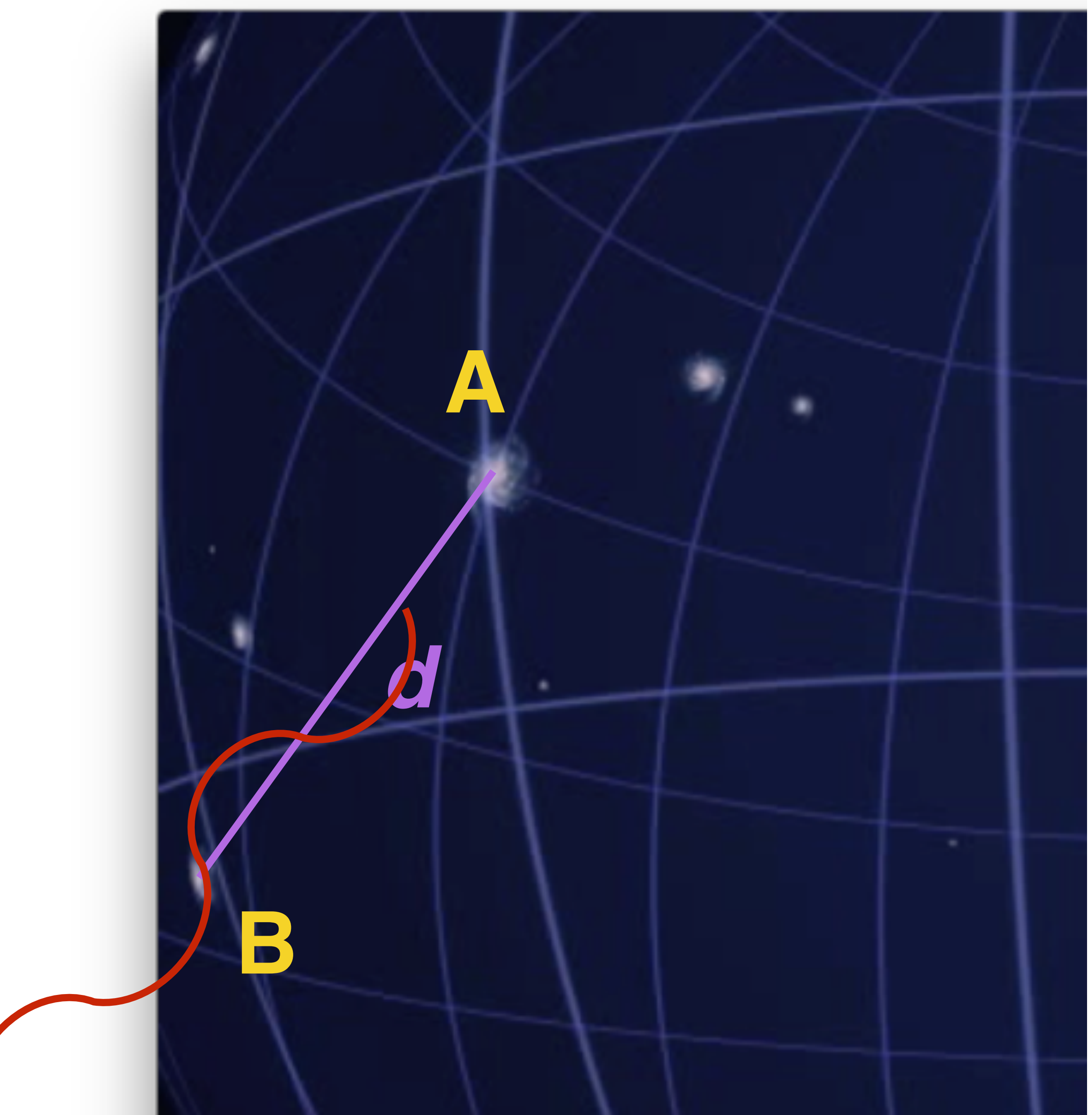
The surface area of a sphere of radius χ is $4\pi \chi^2$

Photon flux diluted by the surface area



Physics

Gravity predicts the relationship between redshift and distance

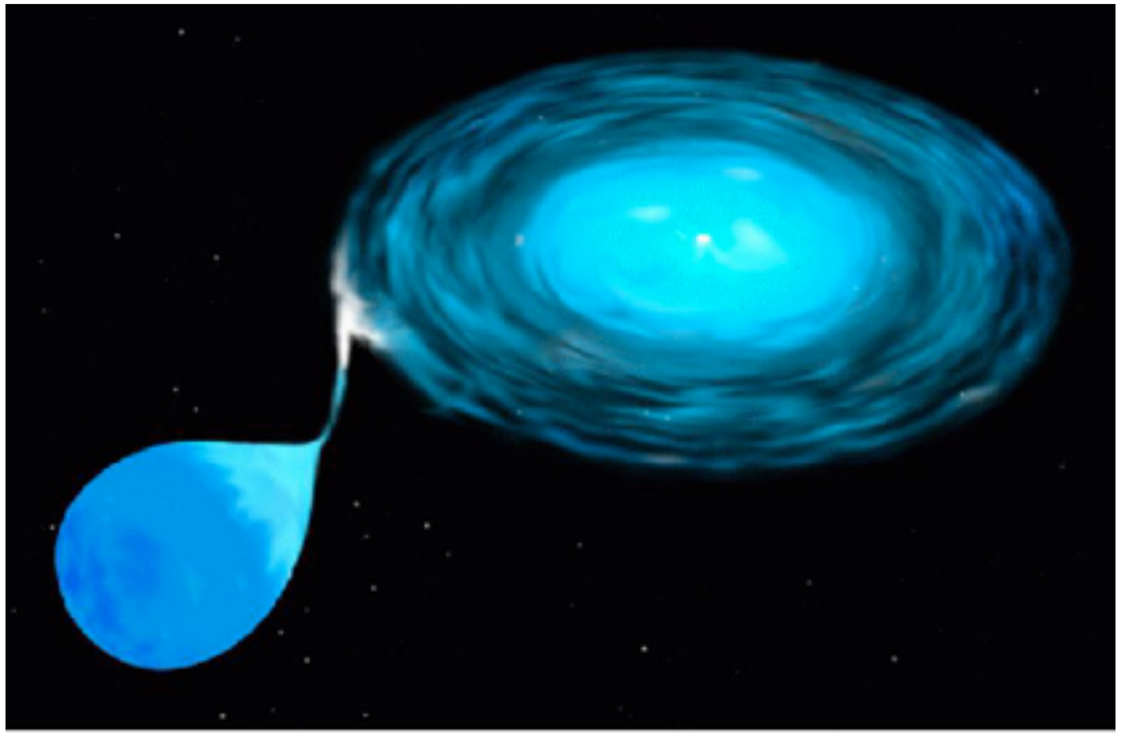


The relationship depends on:

- the geometry of the Universe
- All sources of energy in the Universe

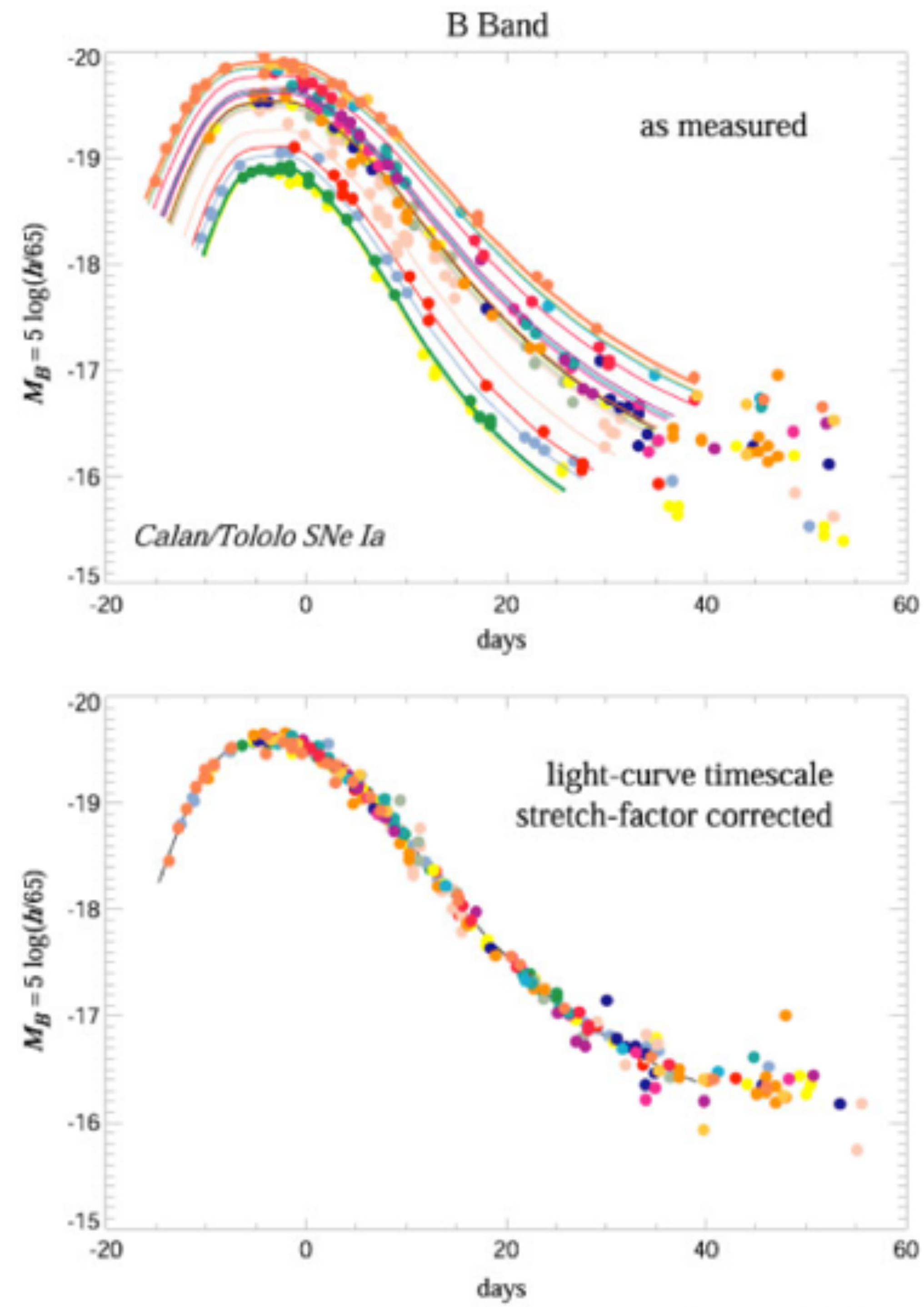
The Source: Type Ia Supernova

- 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

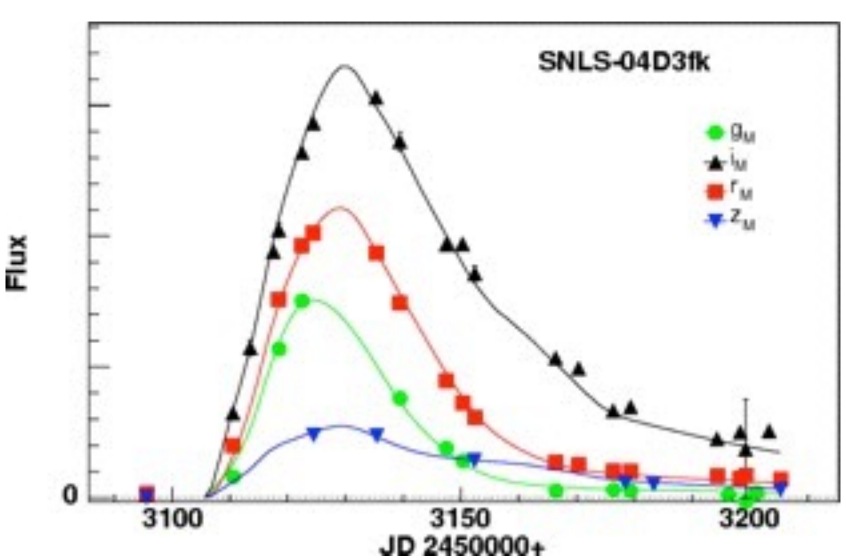
- Heterogeneity in supernova brightnesses and light curve shapes
- After correction for foreground dust supernovae have peak-magnitude dispersion of ~0.3 mag
- We can determine luminosity per object
- After correction for light-curve shape supernovae become “calibrated” candles with ~0.15 mag dispersion



Kim, *et al.* (1997)

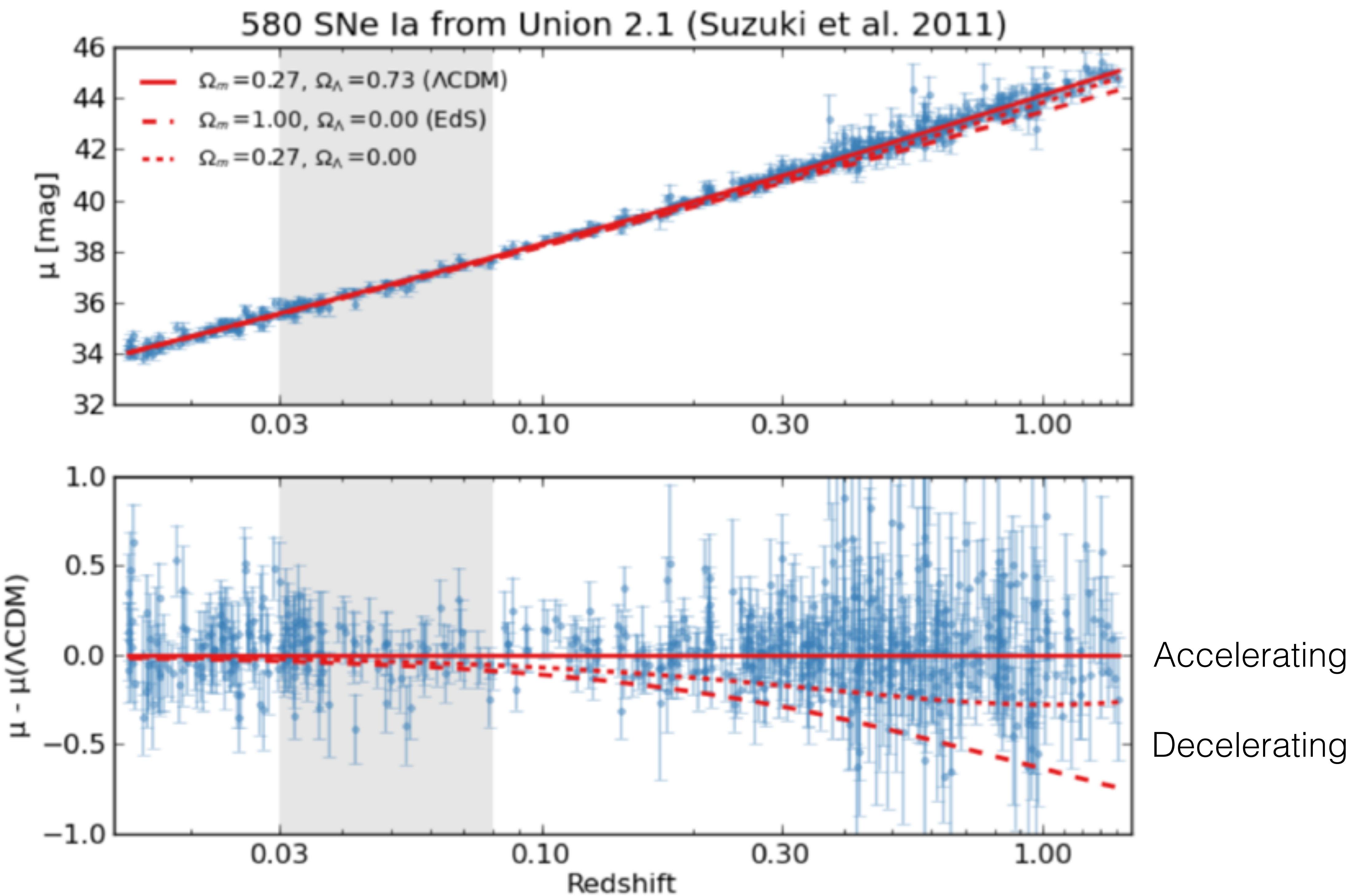
Estimating the Luminosity of the Standard Candle

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



Luminosity

Unexpected Energy In the Universe that is Gravitationally Repulsive



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

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

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

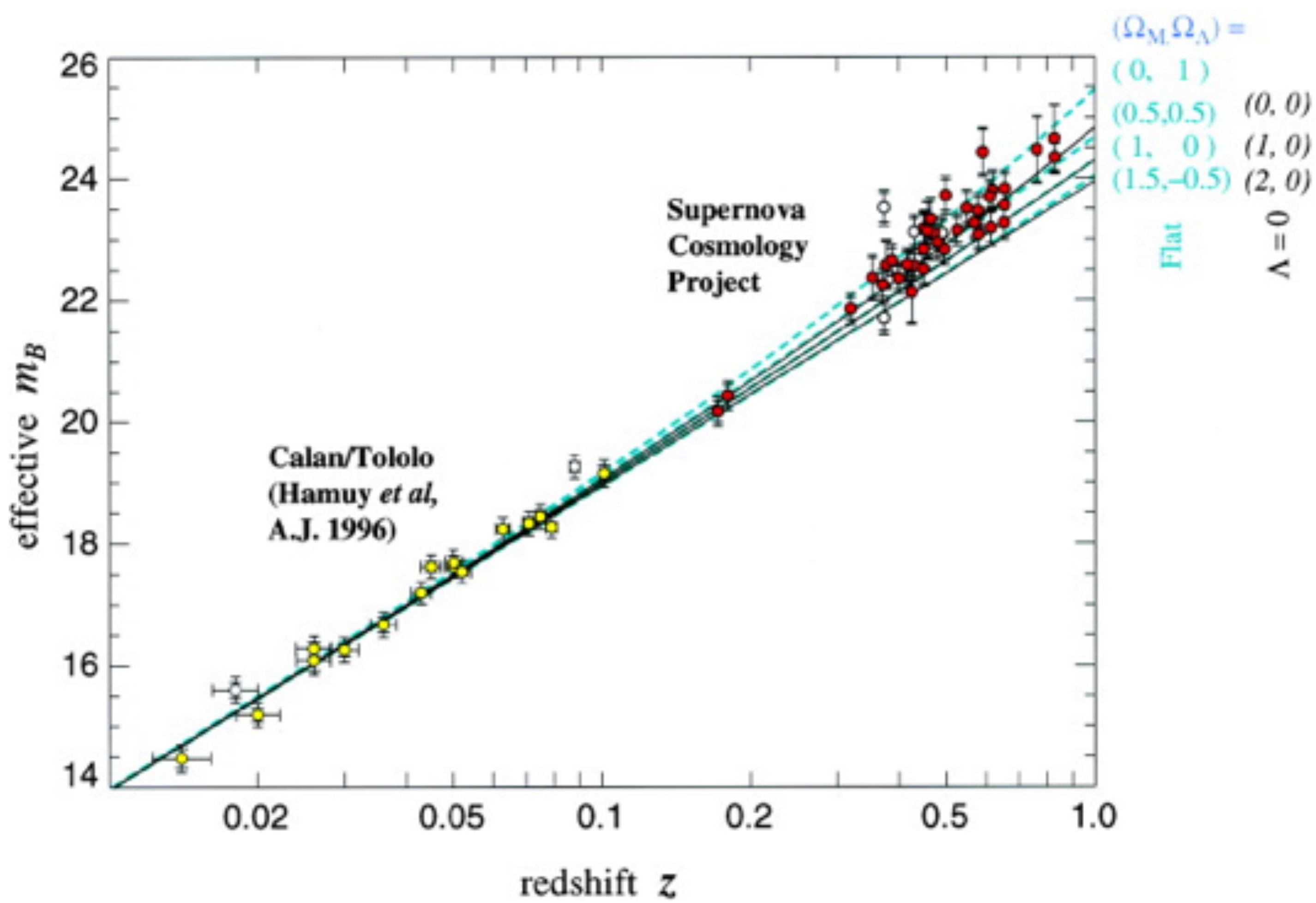
DARK ENERGY

- Therefore

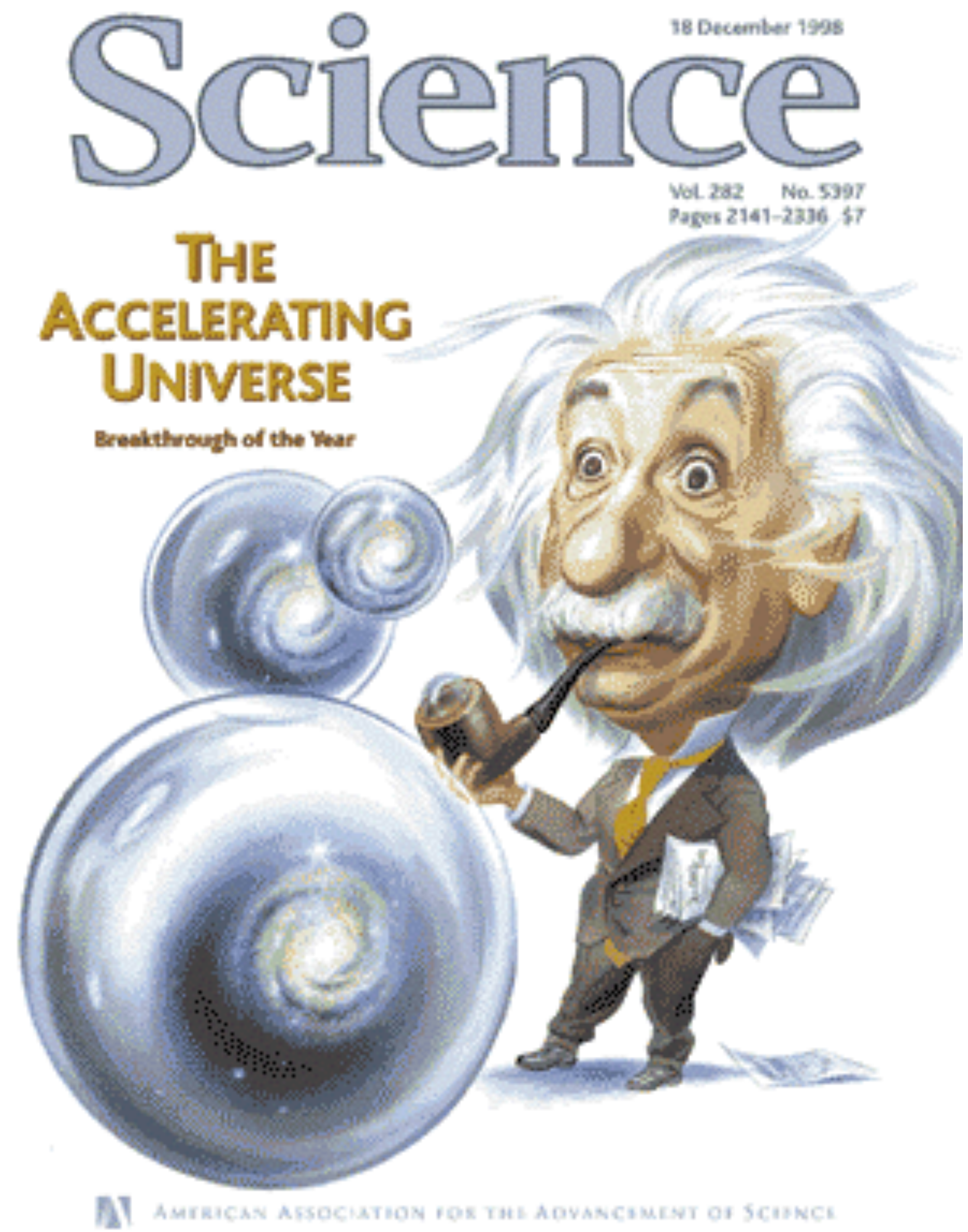
Modified Gravity!

Physics Beyond the Standard Model!

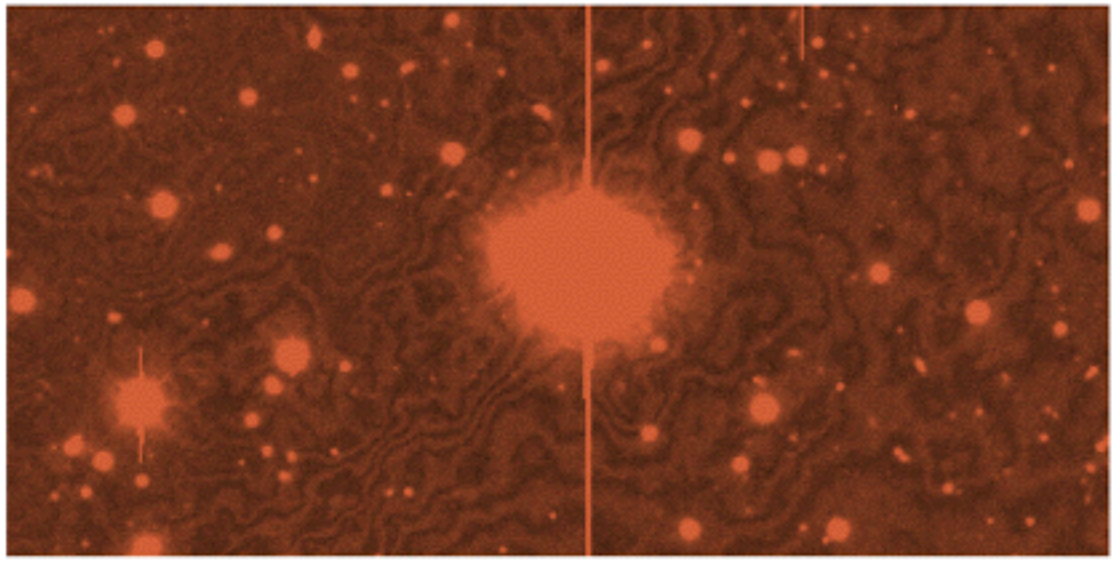
1998 Science Breakthrough of the Year

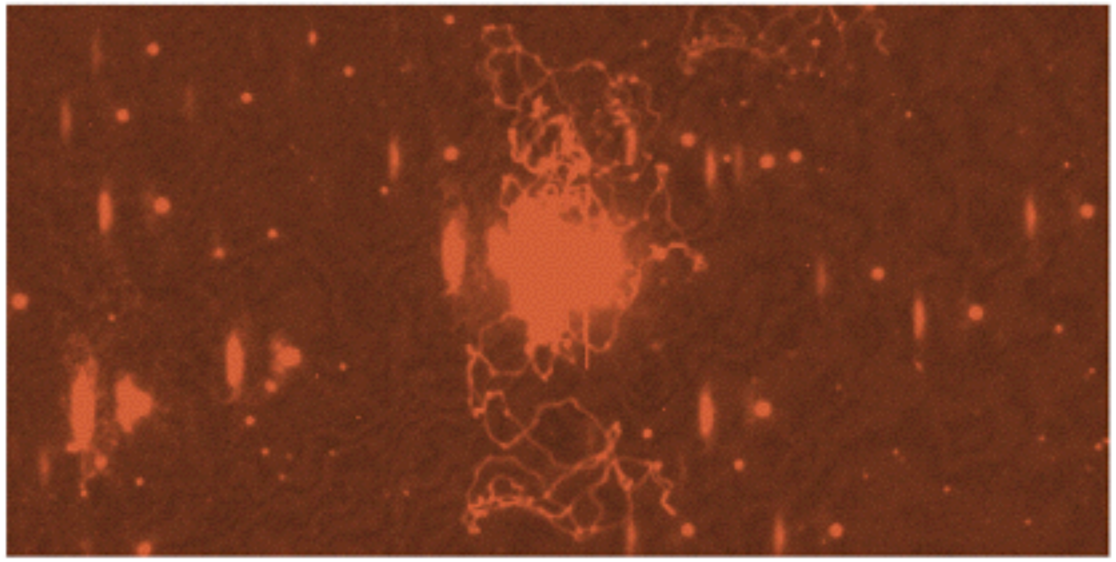


High-redshift supernovae fainter than expected
The Universe is accelerating




FUERZA
CHILE



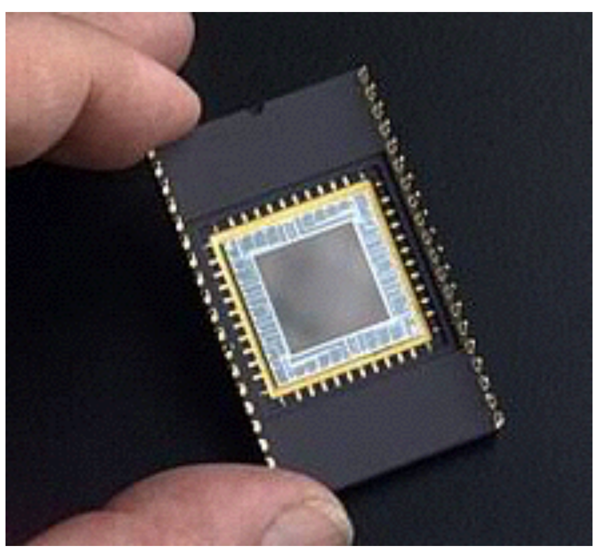



B

Evolution of SN Cosmology Computing

circa 1991

Data



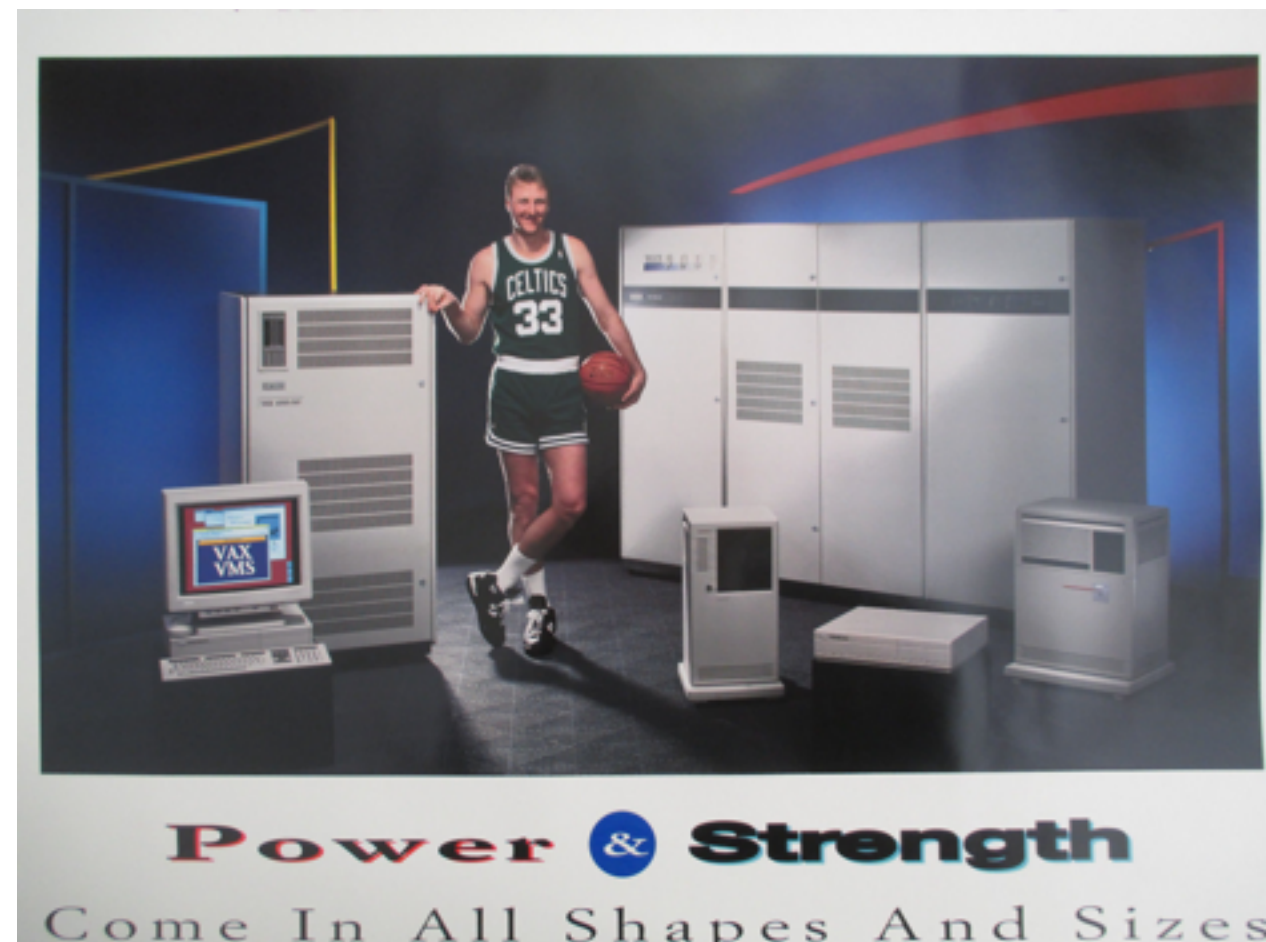
1 Mpix

Time-critical
Data Transfer

+

FedEx

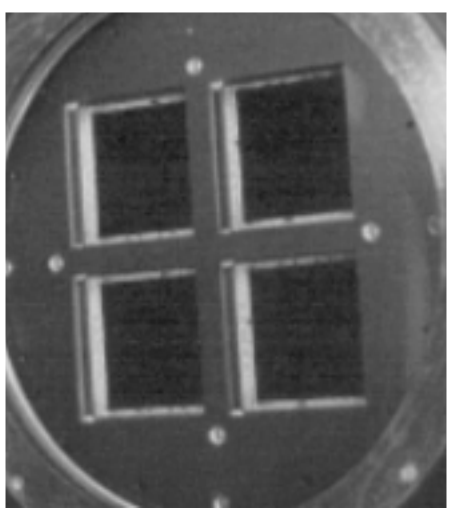
Computing



Evolution of SN Cosmology Computing

circa 1995

Data



16 Mpix

Time-critical Data Transfer

+

Computing

x5

… and in parallel rcp of lossy compressed data

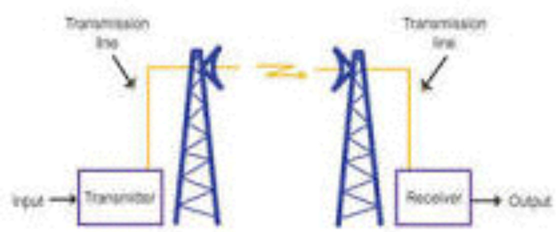
Evolution of SN Cosmology Computing

circa today

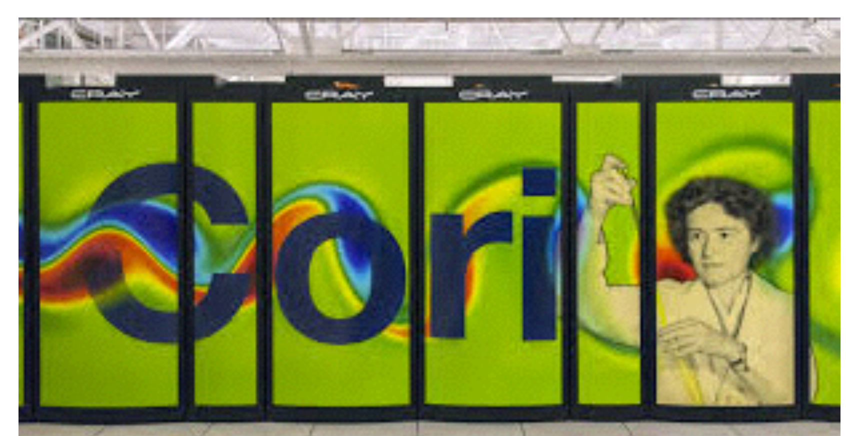
Data

520 Mpix

Time-critical
Data Transfer



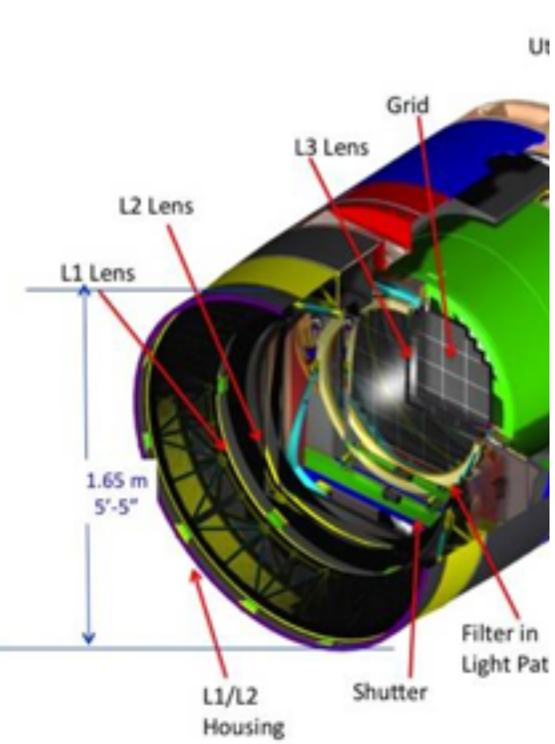
Computing



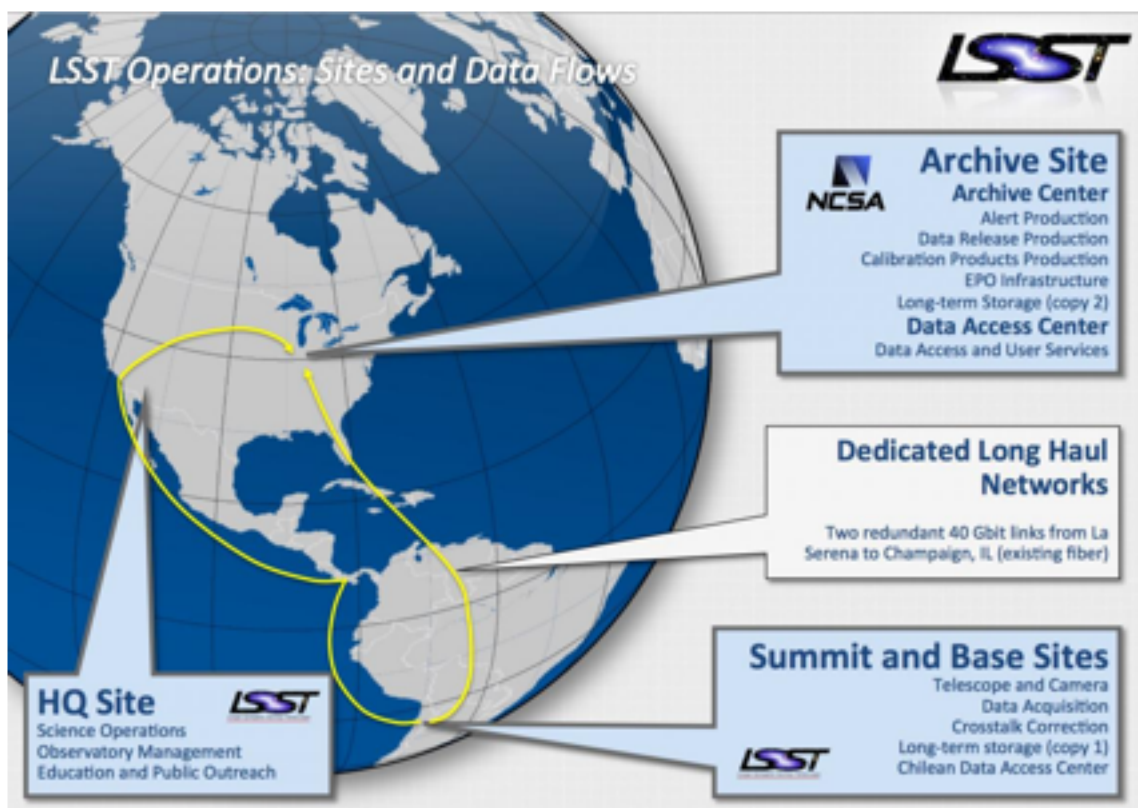
Evolution of SN Cosmology Computing

projected 2020s

Data	Time-critical Data Transfer	Computing



3.2 Gpix



Next generation NCSA

NERSC?

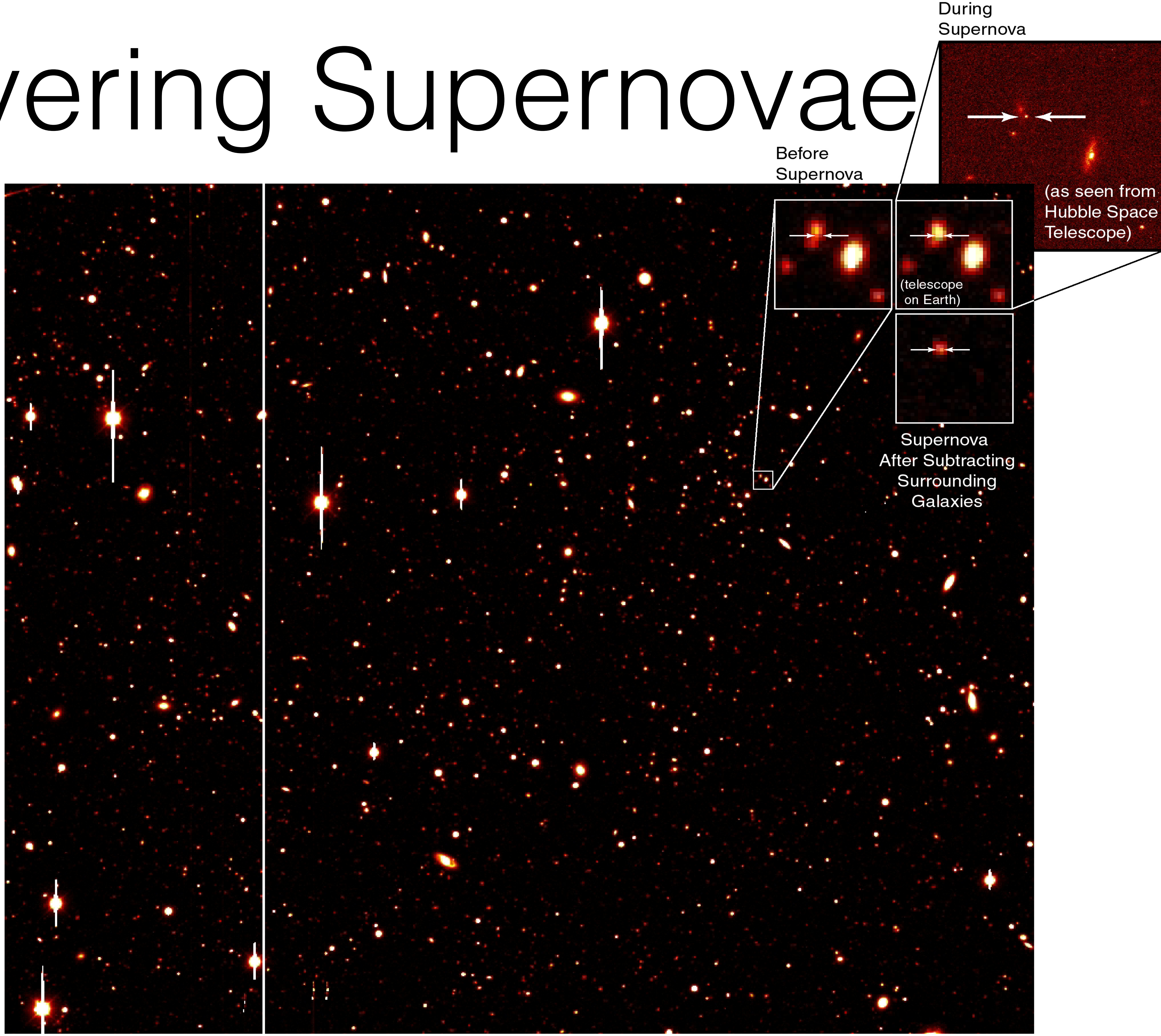
Examples of Computing in Supernova Cosmology

Discovering Supernovae

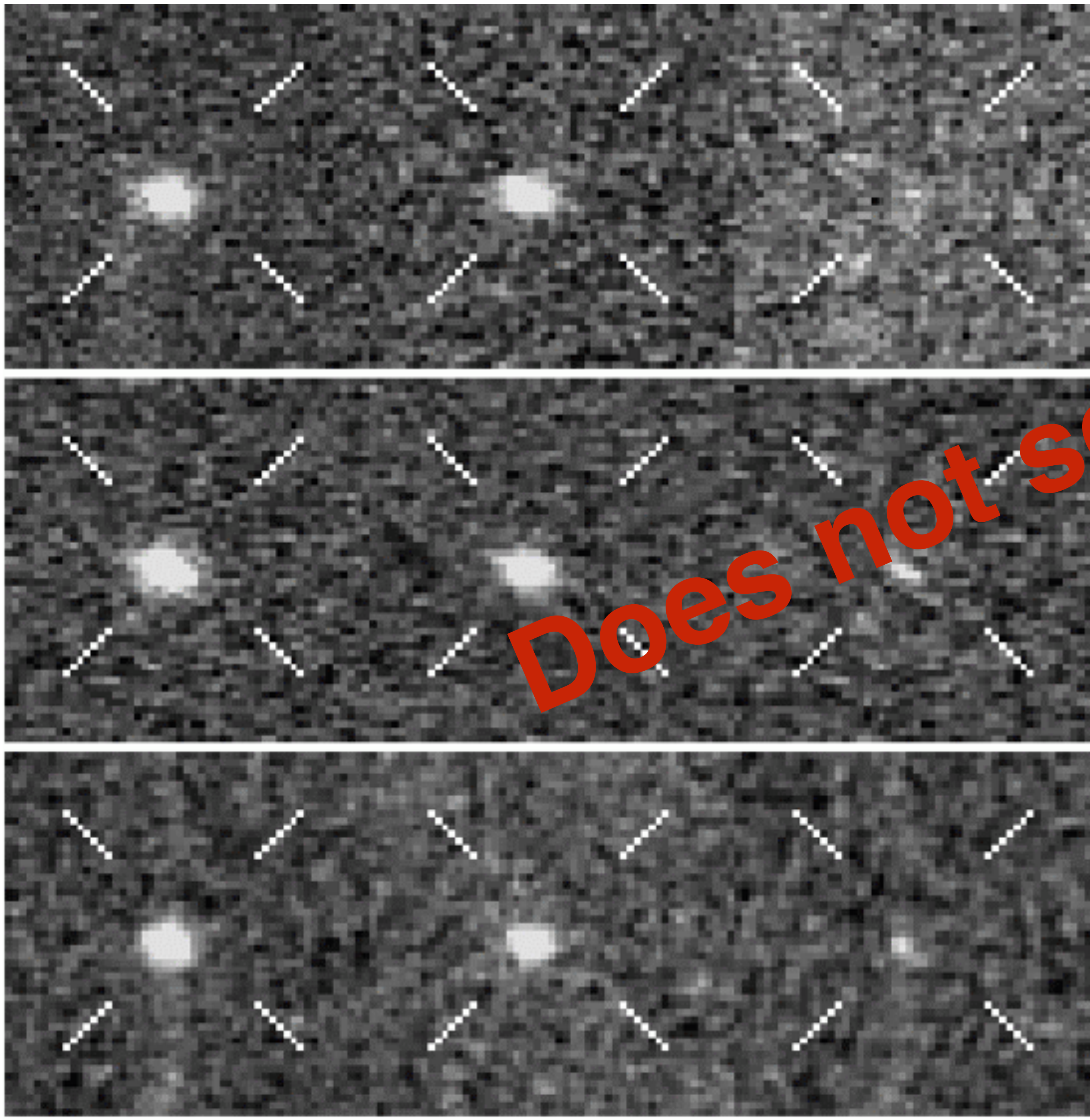
- Align and PSF-match reference and new pixellated images
- Subtract
- Discover new point sources

- Bigger imagers require more compute for this parallelizable operation

- Still using techniques from the 1980's — maybe time to try more statistically efficient but computationally difficult detection



Distinguishing Supernovae and Subtraction Artifacts: Human Scanning



Does not scale

Scanner	Nobody	No updates	All
Obj Id	451881		
srun	5582	sfield	339
trun	3325	tfield	71
rr	10	cc	2
ra	-5.543483	decl	-0.802113
gmag	22.390	g_delta	0.95
rmag	21.532	r_delta	0.68
imag	20.964	i_delta	0.41
Flags			
Ttl Objects	2477		
# Scanned	0		

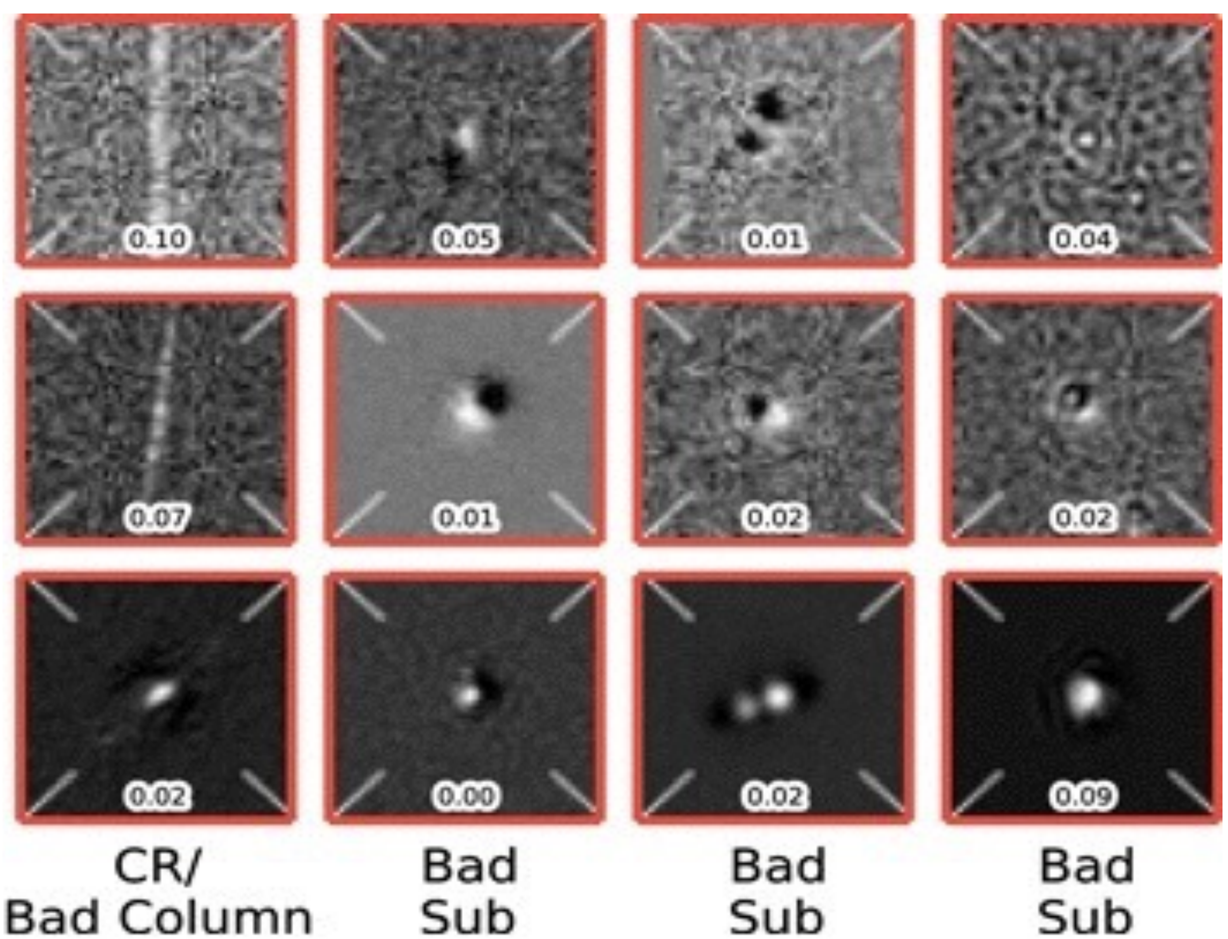
Back to initializing page.

Manual Scan Guide

- [0] None
- [1] Artefact
- [2] Moving

LBL Automatic Scanning Makes SN Searching Possible

In the first year of an ongoing survey humans spent many hundreds of hours identifying false positives



Goldstein et al. 2015

Now a computer does all the work!

autoScan DES Y1 Reprocessing Results

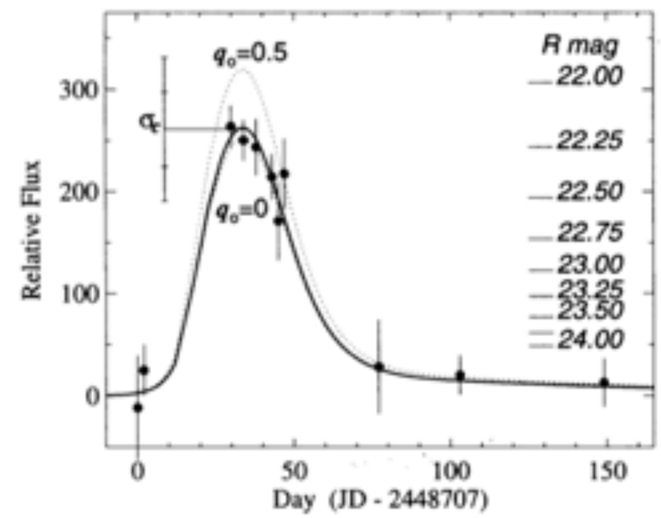
	No ML	ML ($\tau = 0.5$)
N_c[a]	100,450	7489
$\langle N_A/N_{NA}\rangle$[b]	13	0.34
ϵ_F[c]	1.0	0.990

The computer does an excellent job
Number of candidates reduced by over an order of magnitude …
with spurious events filtered out …
while maintaining high efficiency

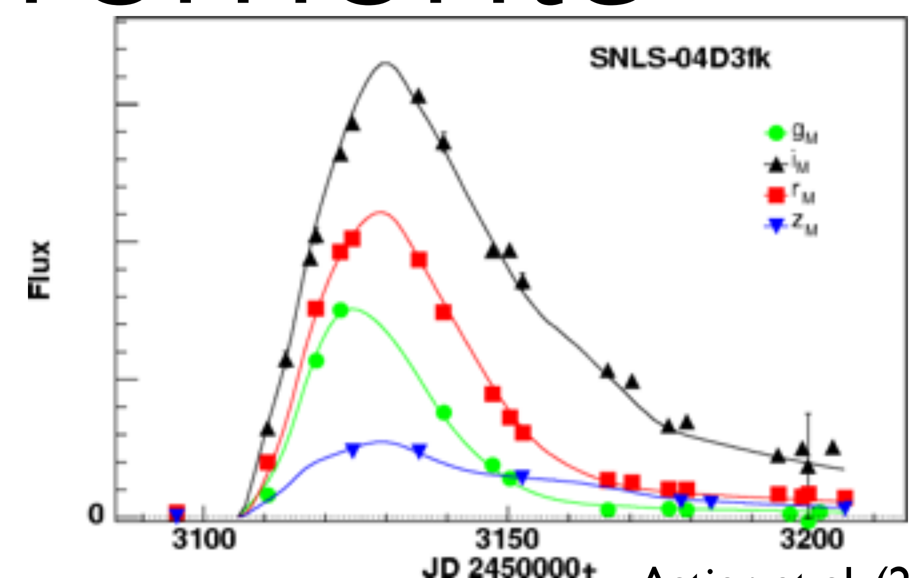
Leveraged LBL computing and machine learning expertise

After Discovery Supernovae Get More Measurements

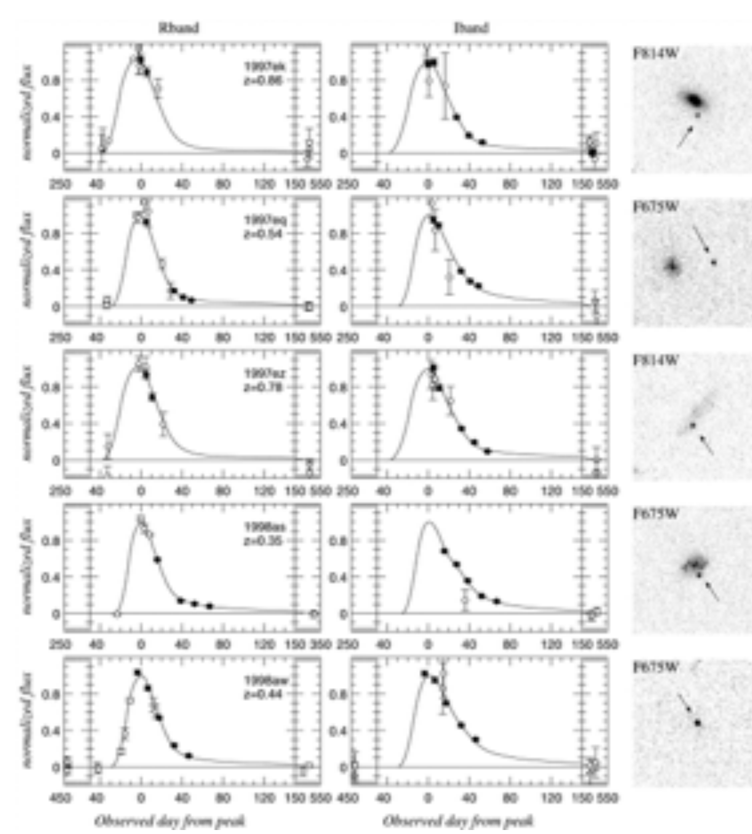
- Followup observations per supernova increasing
- More data processing
- More complicated data processing

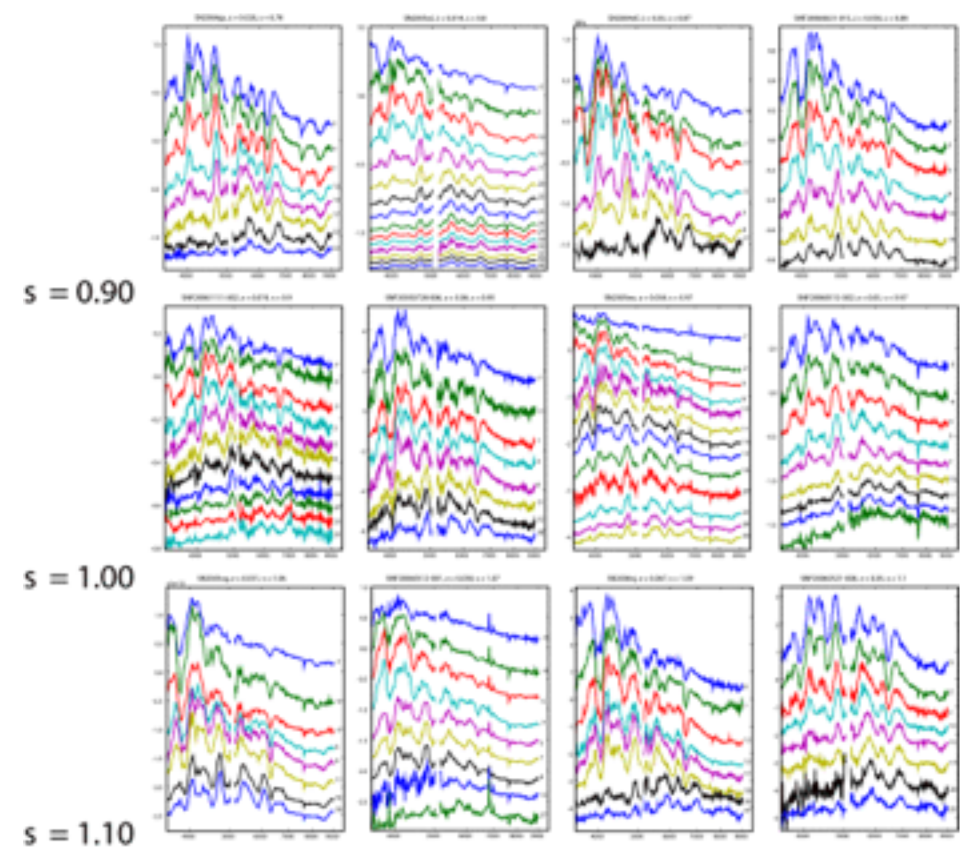


Perlmutter et al. (1995)



Astier et al. (2006)

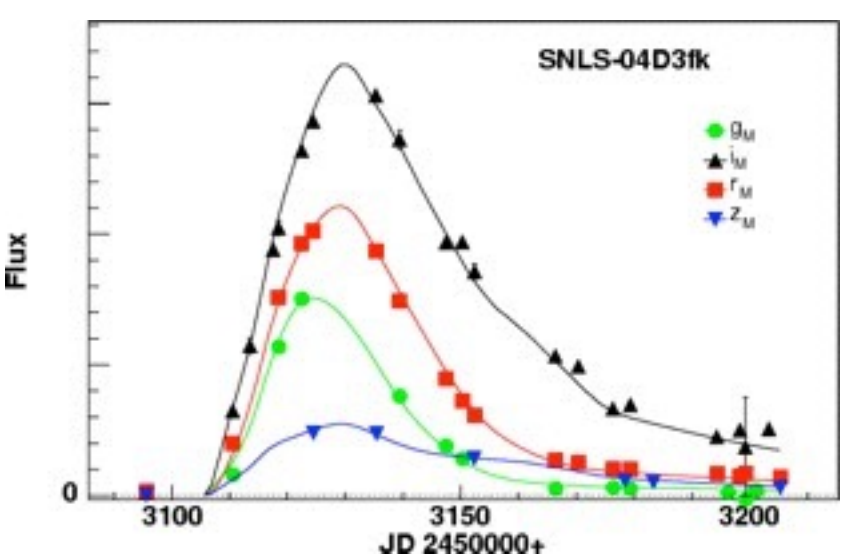

Knop et al. (2003)



Aldering et al. (2010)

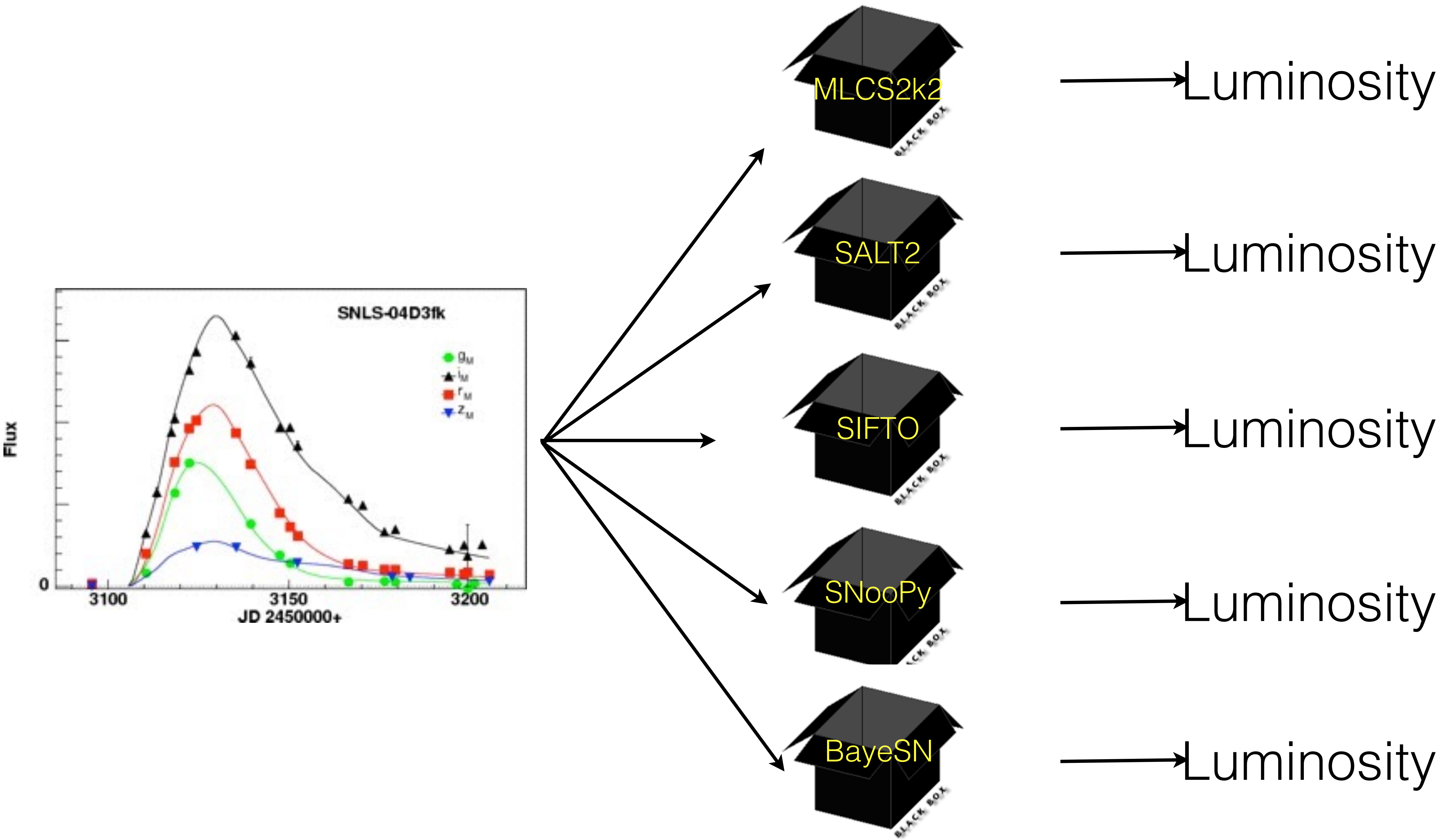
Uncertainty in SN Model

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



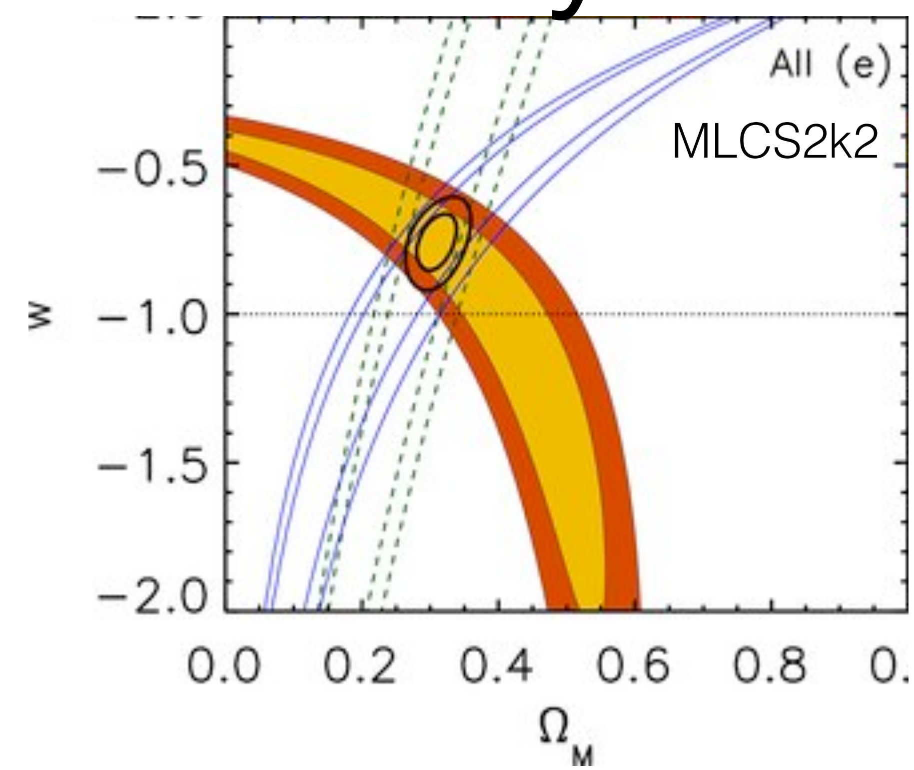
Luminosity

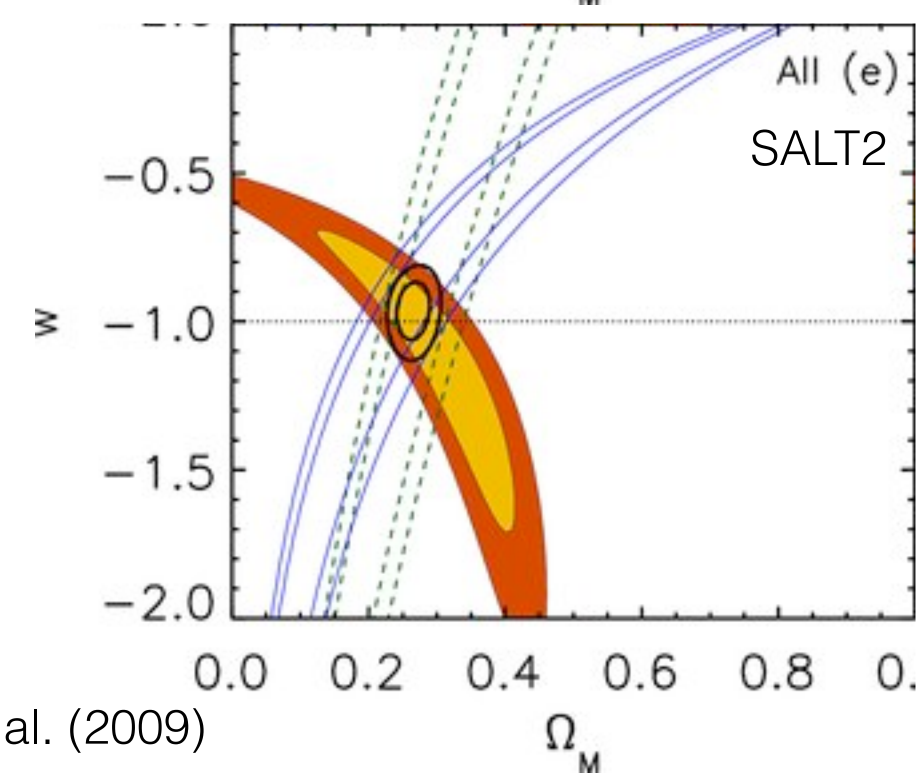
Uncertainty in SN Model



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

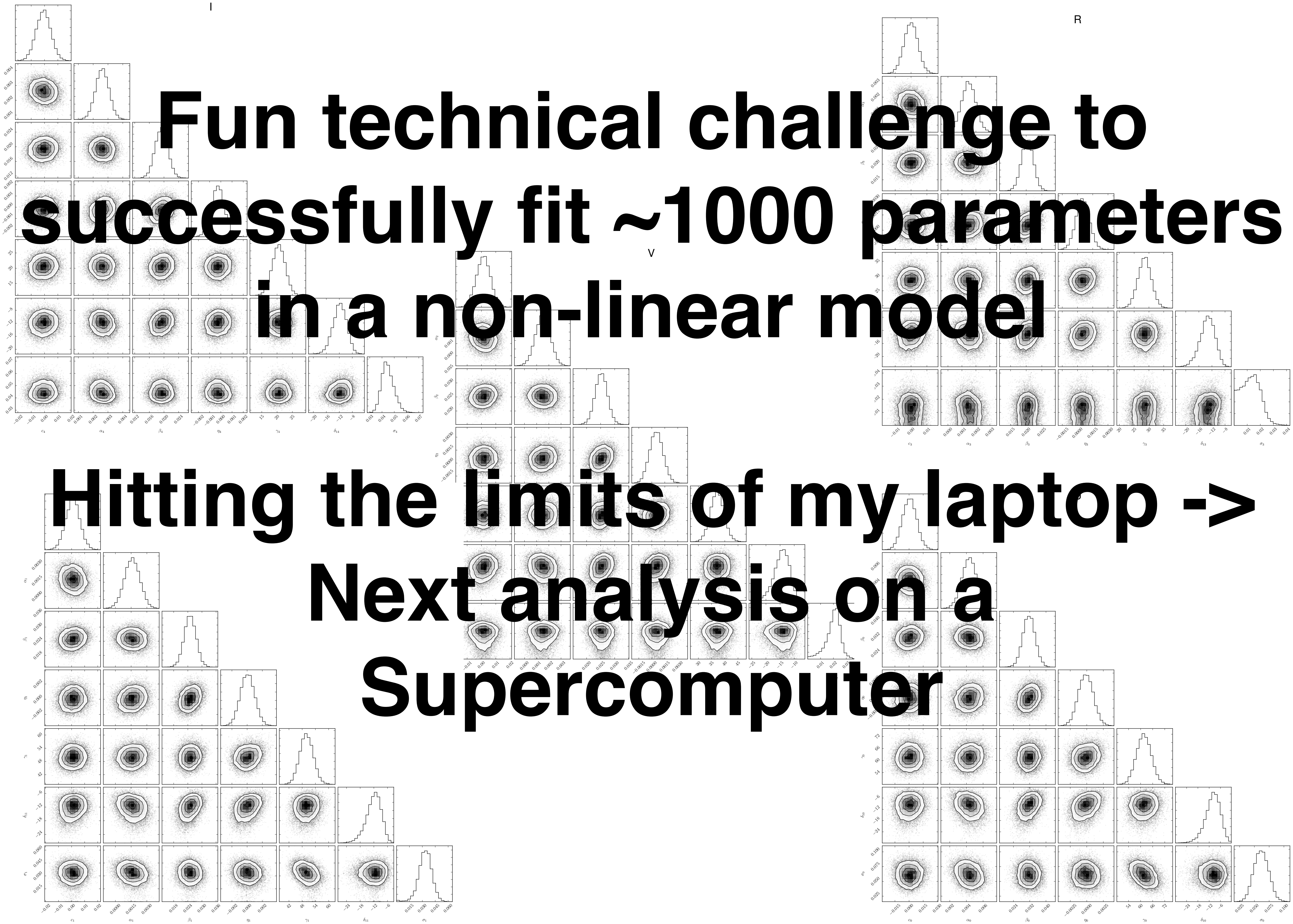
observed magnitudes

observed spectral features

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

data covariance

intrinsic spectral features

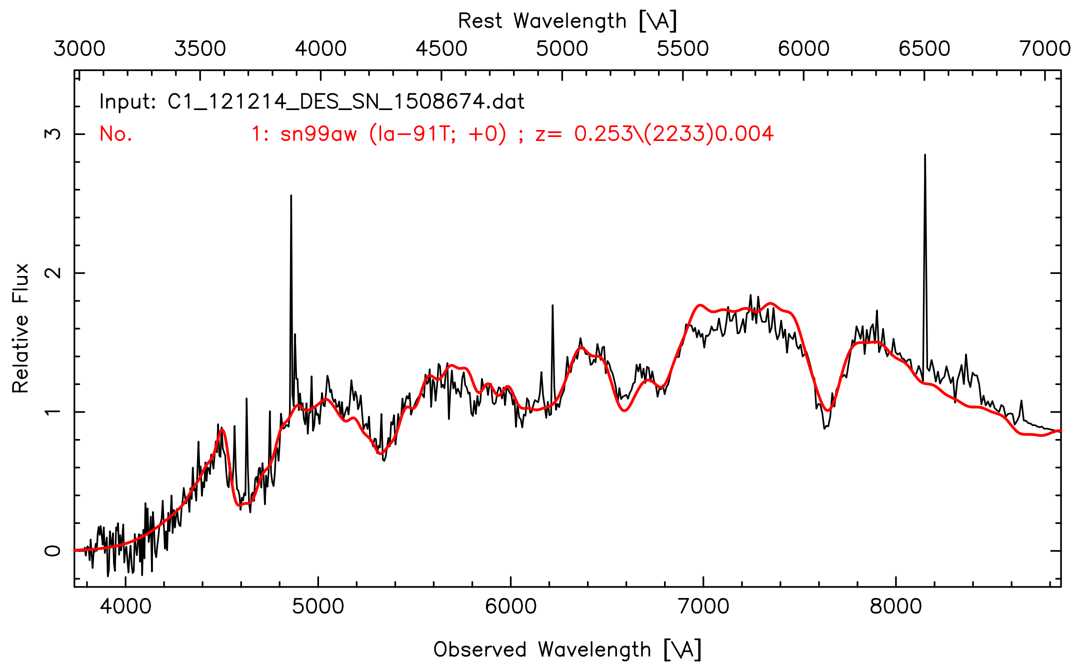


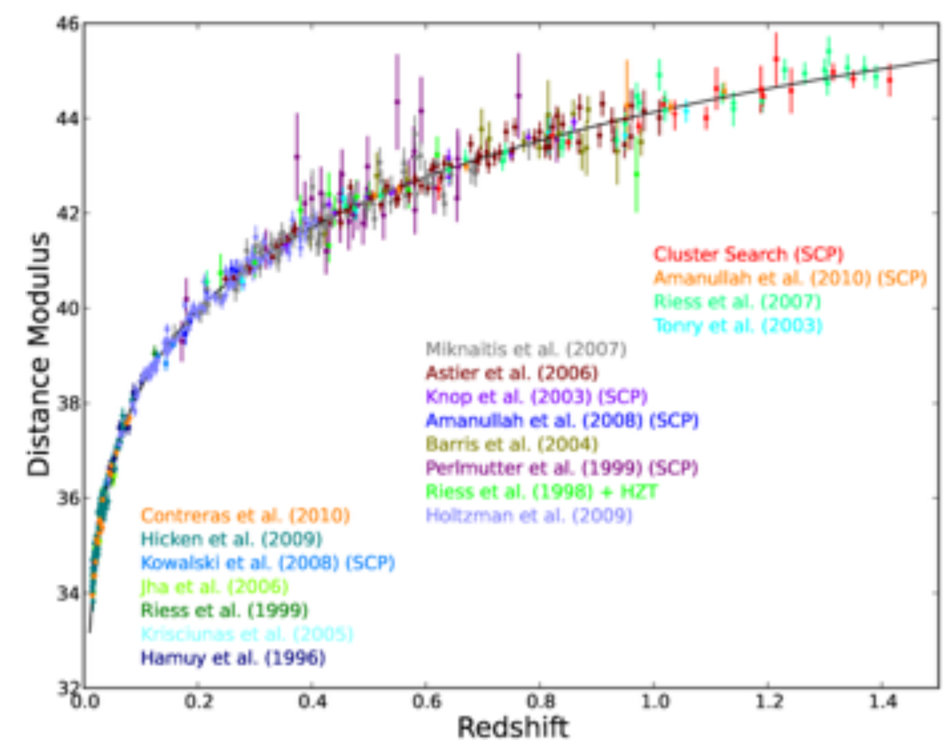
Fun technical challenge to successfully fit ~1000 parameters in a non-linear model

Hitting the limits of my laptop -> Next analysis on a Supercomputer

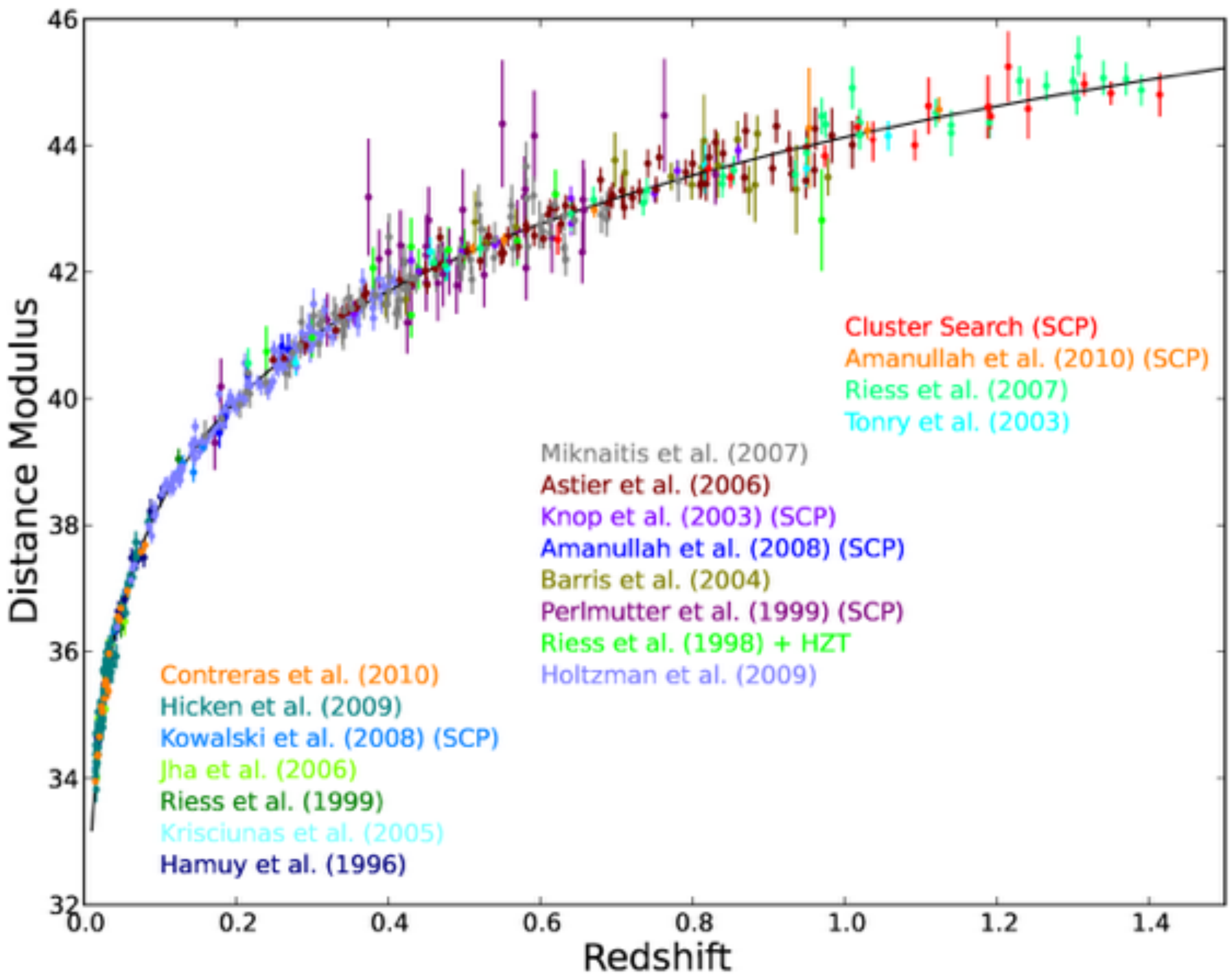
Imaging Surveys Not the Entire Story: Spectroscopy

- 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

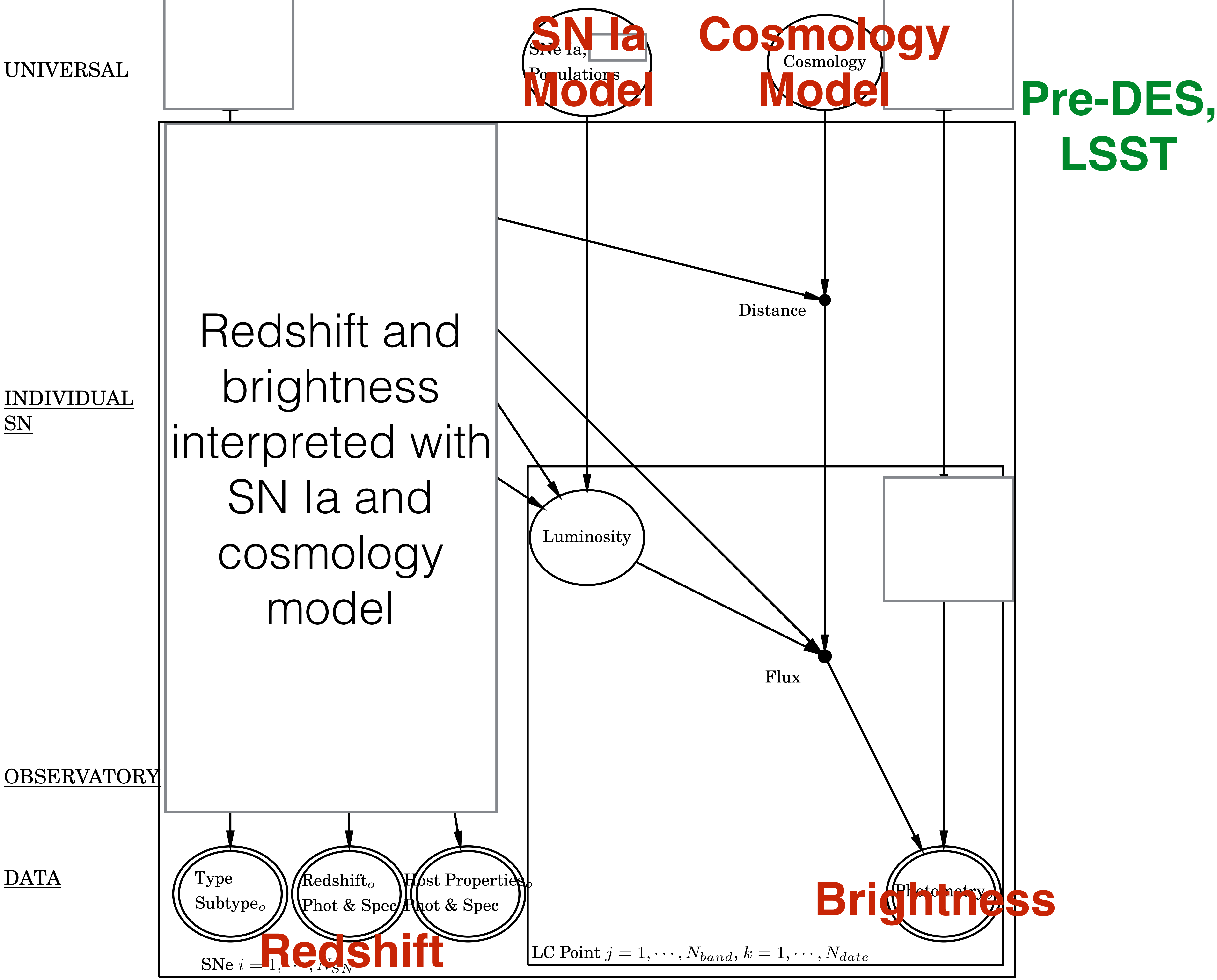


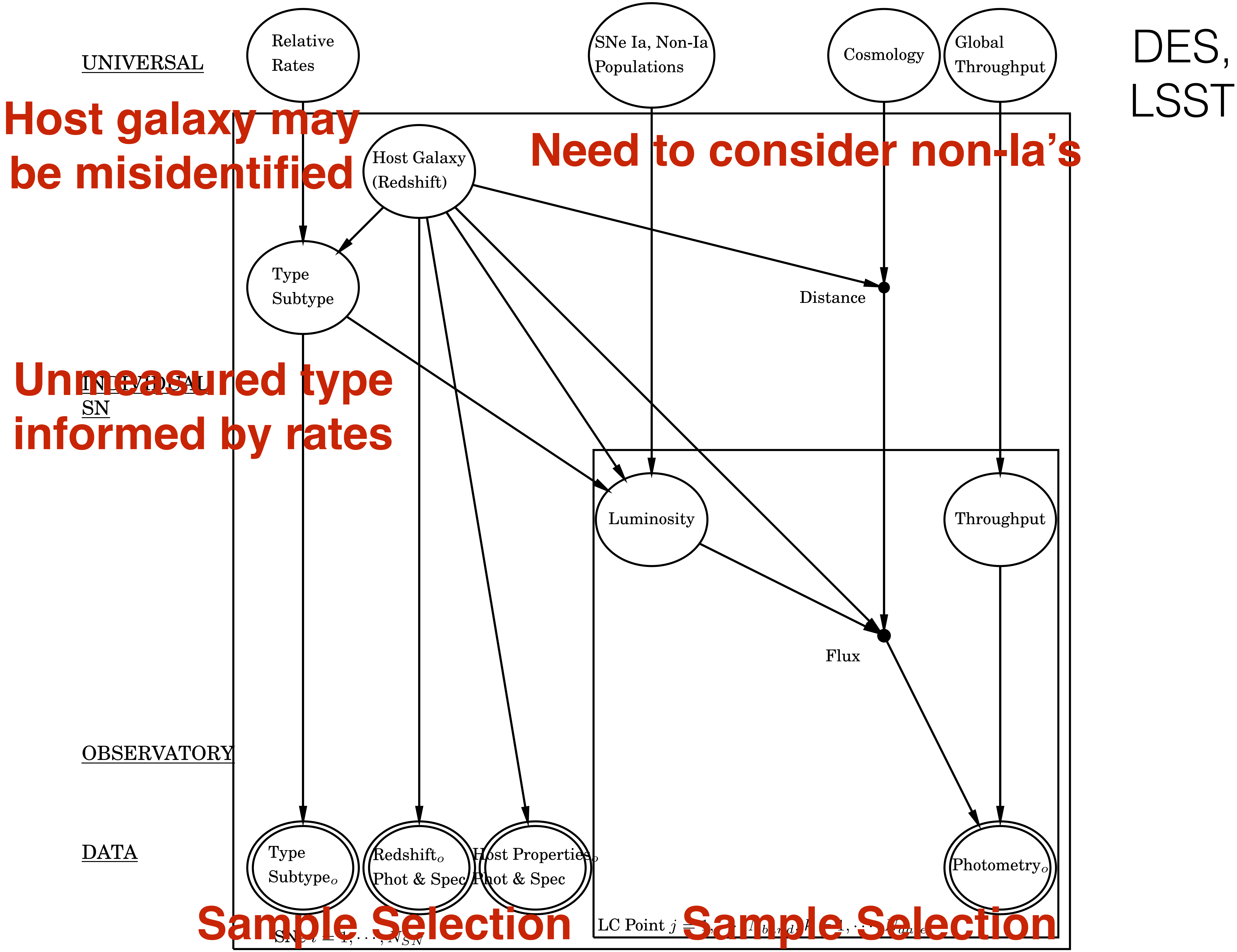


New Cosmology Analysis Required



- 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

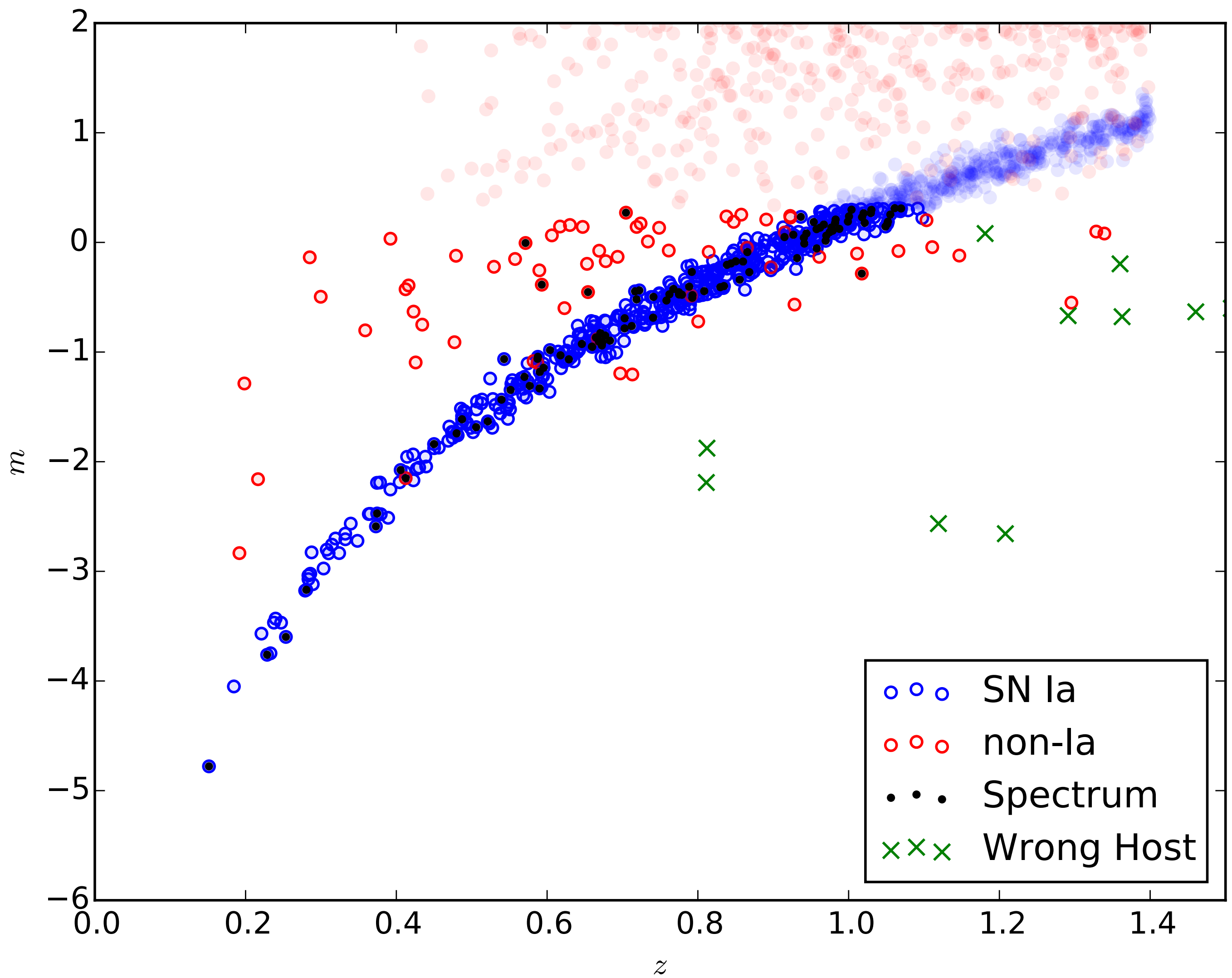

UNIVERSAL
INDIVIDUAL SN
OBSERVATORY
DATA
SN Ia Model
Cosmology Model
Cosmology
Pre-DES, LSST
Redshift and brightness interpreted with SN Ia and cosmology model
Distance
Luminosity
Flux
Type Subtype$_o$
Redshift$_o$ Phot & Spec
Host Properties$_o$ Phot & Spec
Brightness
Redshift
LC Point $j = 1, \cdots,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

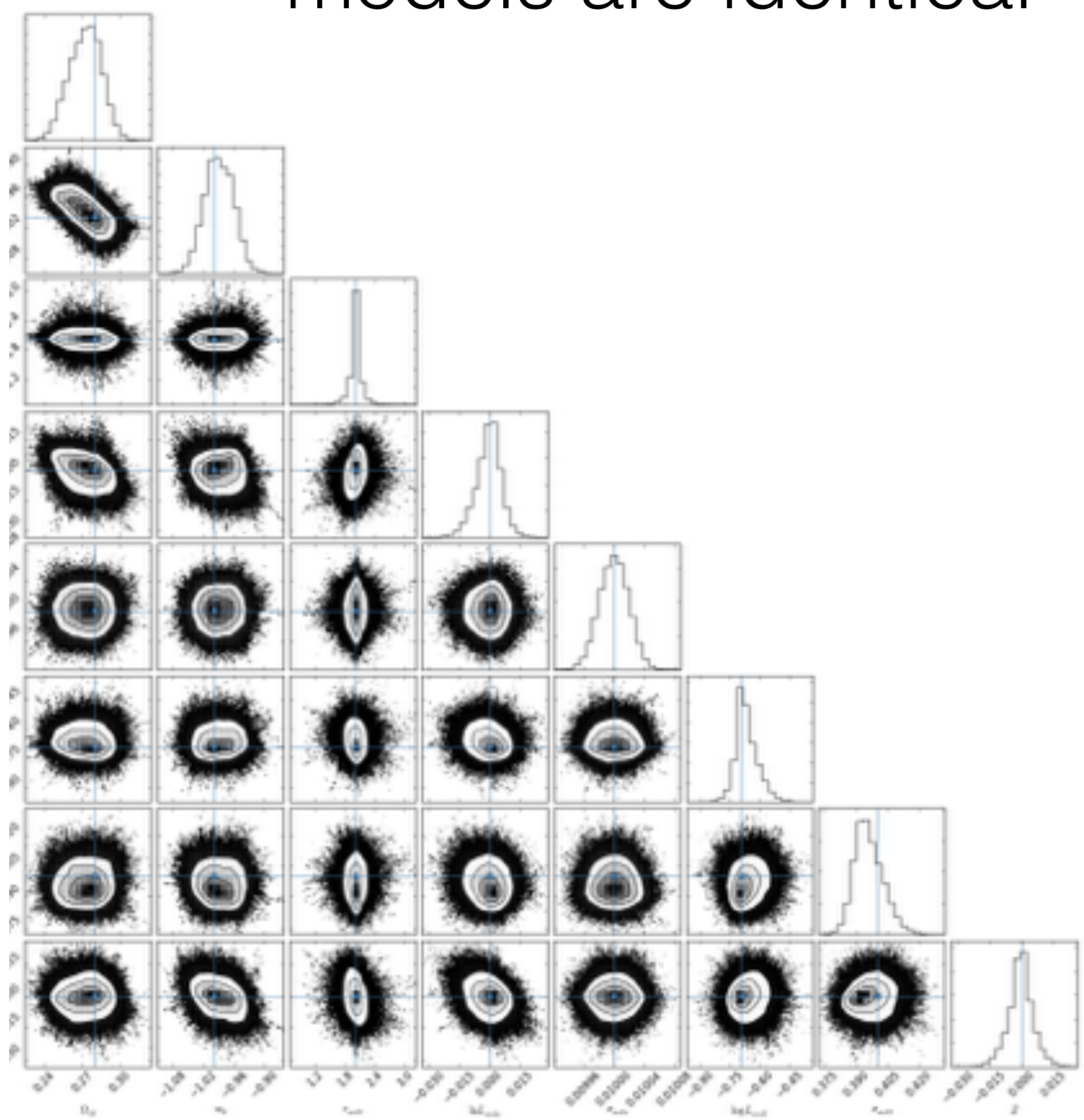


DES, LSST
UNIVERSAL
Relative Rates
SNe Ia, Non-Ia Populations
Cosmology
Global Throughput
Host galaxy may be misidentified
Host Galaxy (Redshift)
Need to consider non-Ia's
Type Subtype
Distance
Unmeasured type informed by rates
INDIVIDUAL SN
Luminosity
Throughput
Flux
OBSERVATORY
DATA
Type Subtype$_o$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

First-Generation Code Implemented

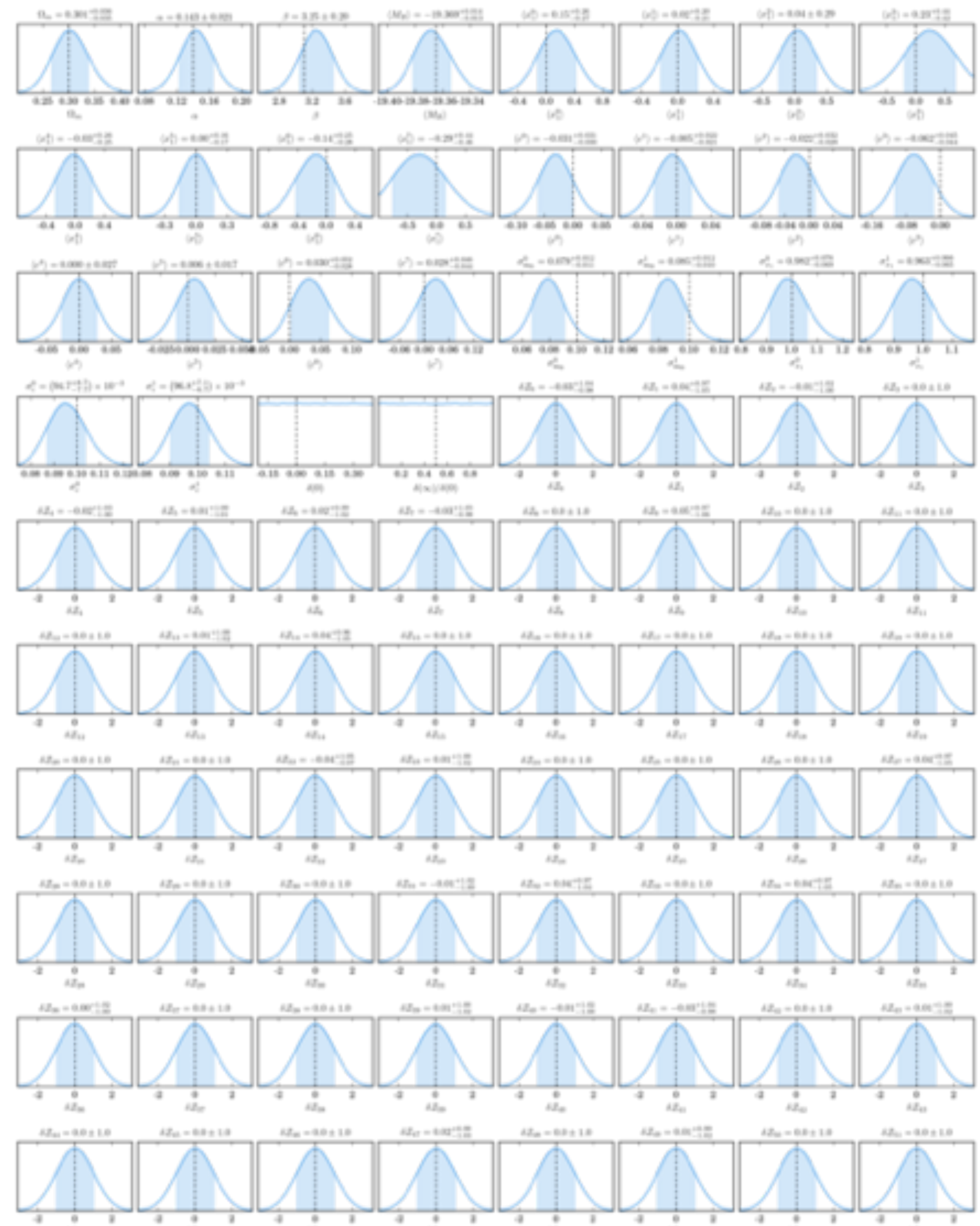
Simulated ugly Hubble Diagram → Input Cosmology IF Generative and simulated models are identical





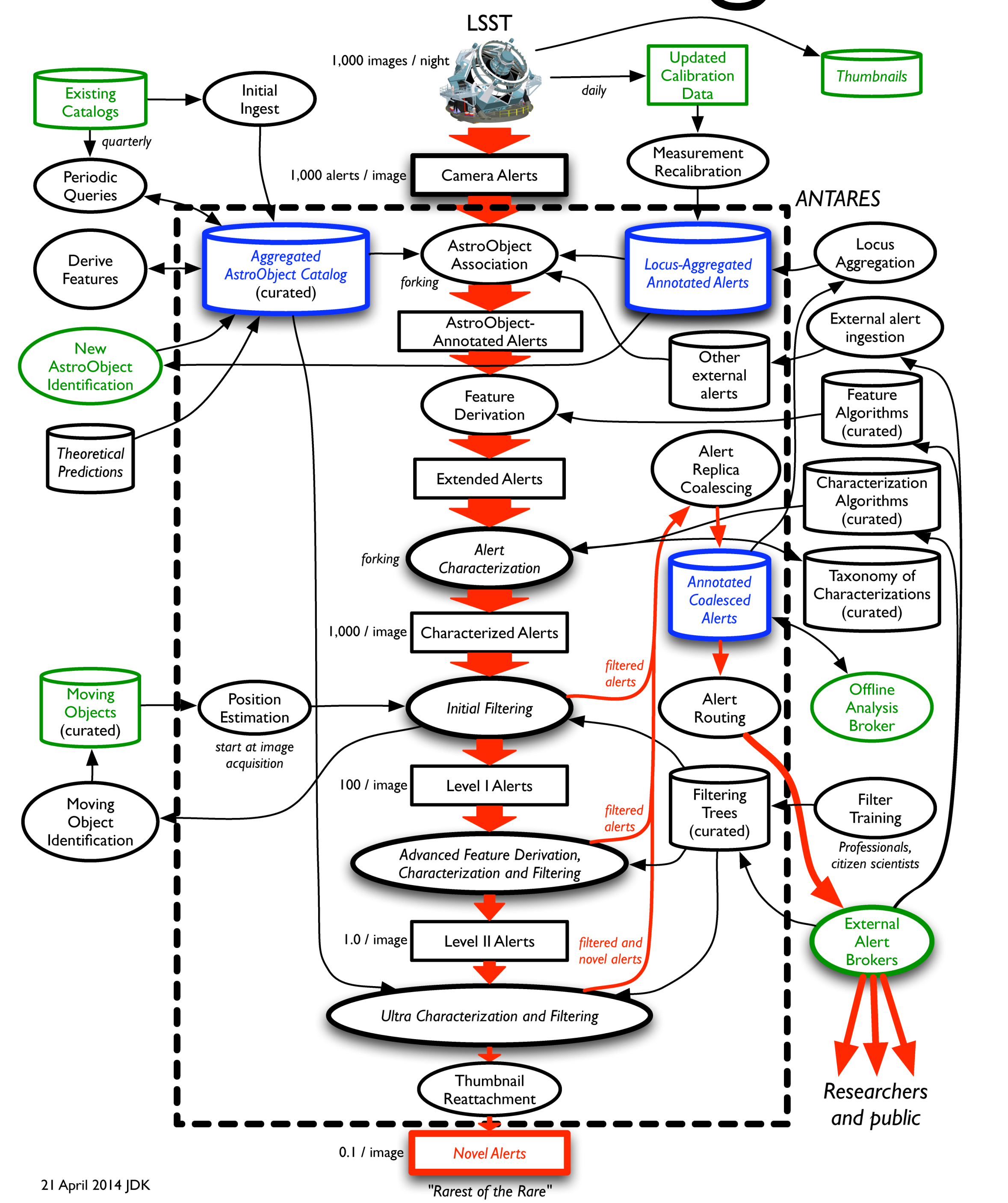
Cosmology Analysis Now Requires Supercomputing

- Implemented and tested analysis fitting ~1000 parameters
- Soon to be applied on real data
- Run at a computing center



Next Generation Supernova Experiments: A New Paradigm

- A Project releases 10M transient discovery alerts per night
- Each alert does not provide all available information that inform transient classification
- Challenge: Pick out the few objects that I am interested in
- Data volume and transfer requirements point to supercomputing facility



ANTARES: A Prototype Transient Broker System
Saha et al. (2014)

To Conclude…

- Computers enable otherwise inaccessible scientific discovery
- Supernova cosmology is now firmly in the supercomputing domain
- The vast majority of (supernova) cosmologists are not computing whizzes
- A user-friendly point of entry to supercomputer processing facilitates scientist and computer productivity