Computational Cosmology with Type Ia Supernova: an Observer's Perspective

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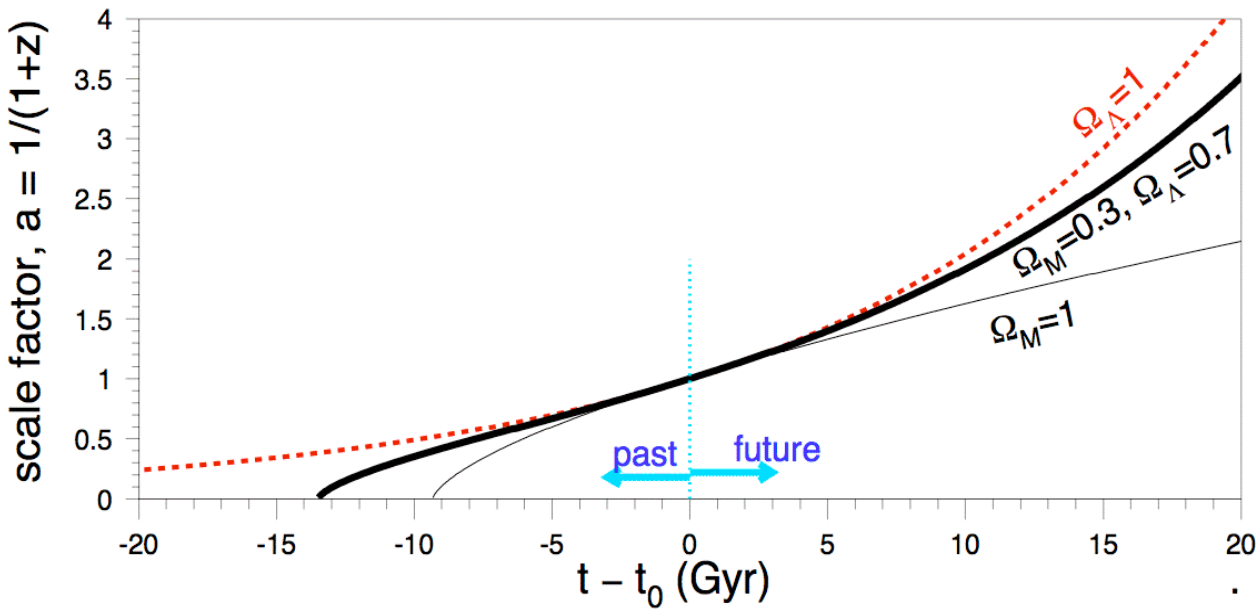
Motivation

- Type Ia SN (SN Ia) are used to make precision measurements of dark energy parameters (Ω_Λ , *w*, *w*' …)
- The brightness varies by more than 1 mag, but after empirical corrections the variation is ~0.1 mag … SN Ia are nearly ideal standard candles to measure a Hubble diagram.

Hubble Diagram Basics



Expansion history depends on w, Ω_Λ and Ω_M

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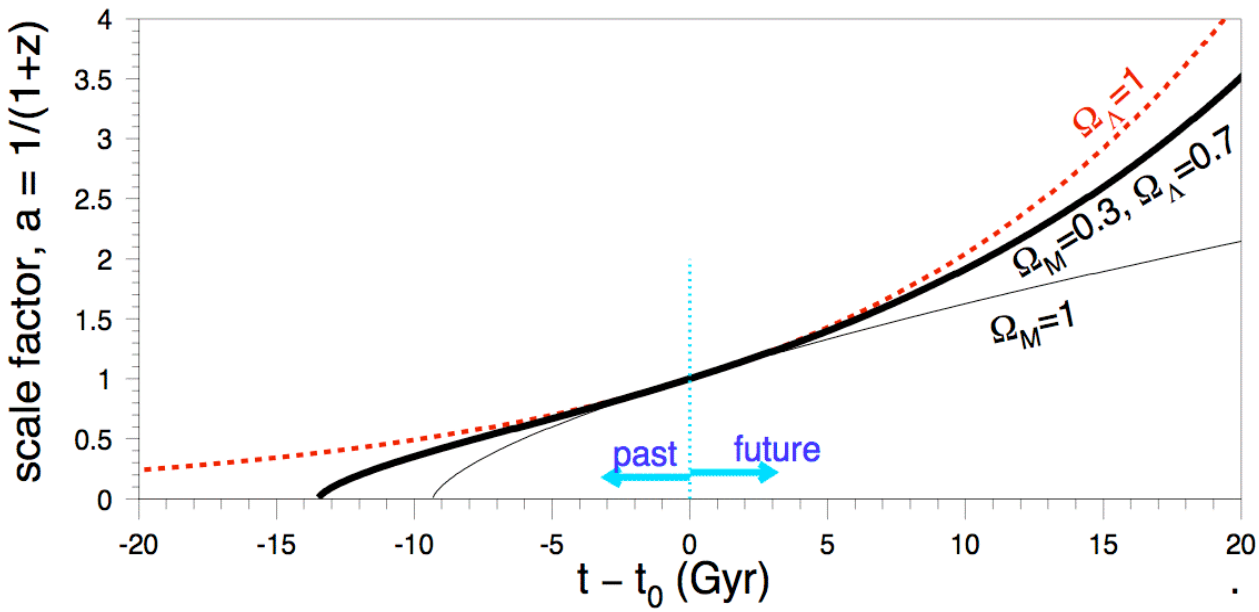

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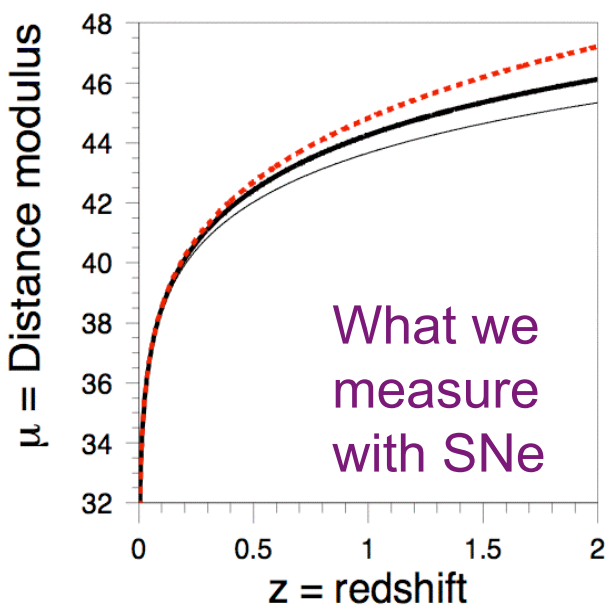
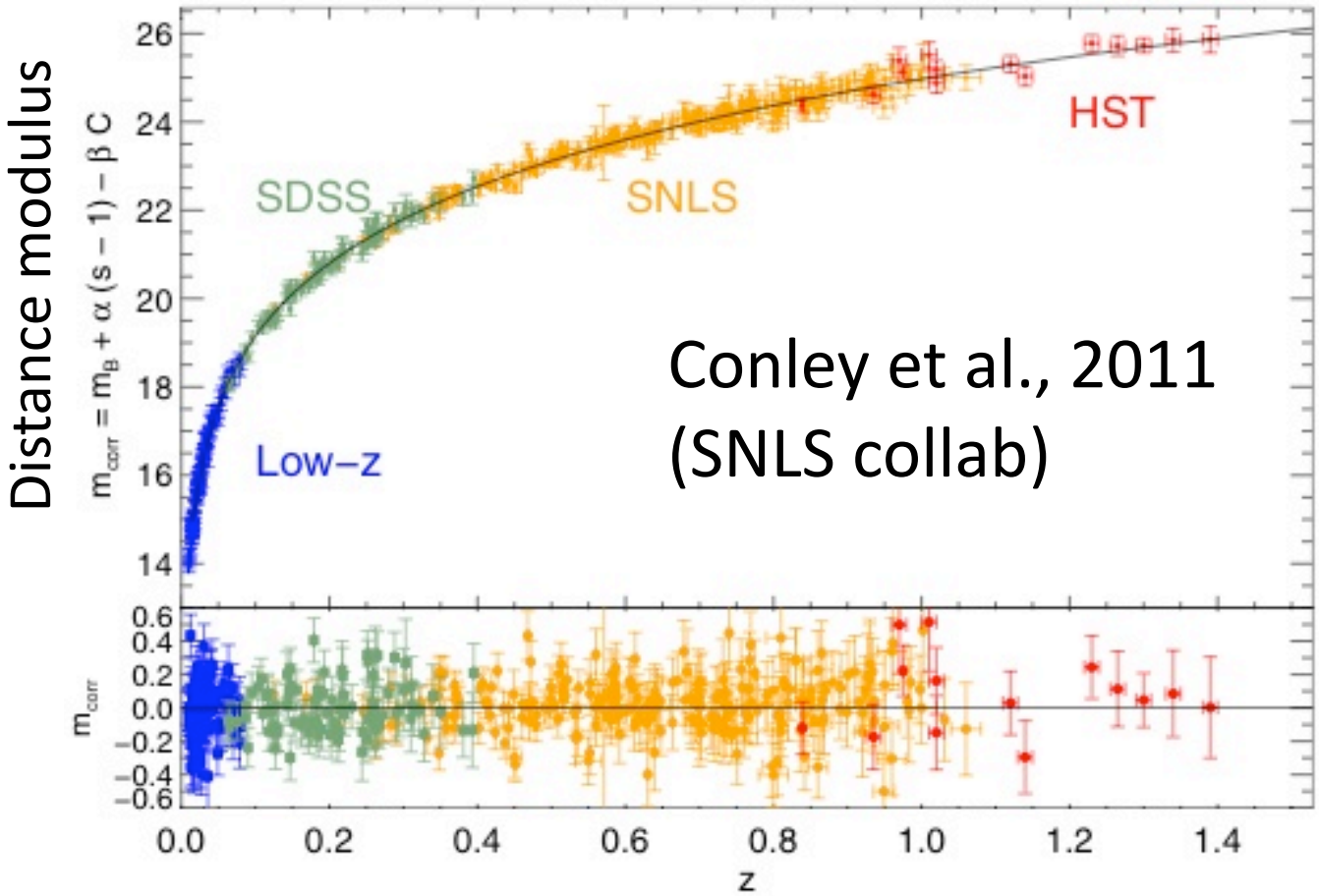


Flux $\propto \mathscr{L}/4\pi d_L^2$.

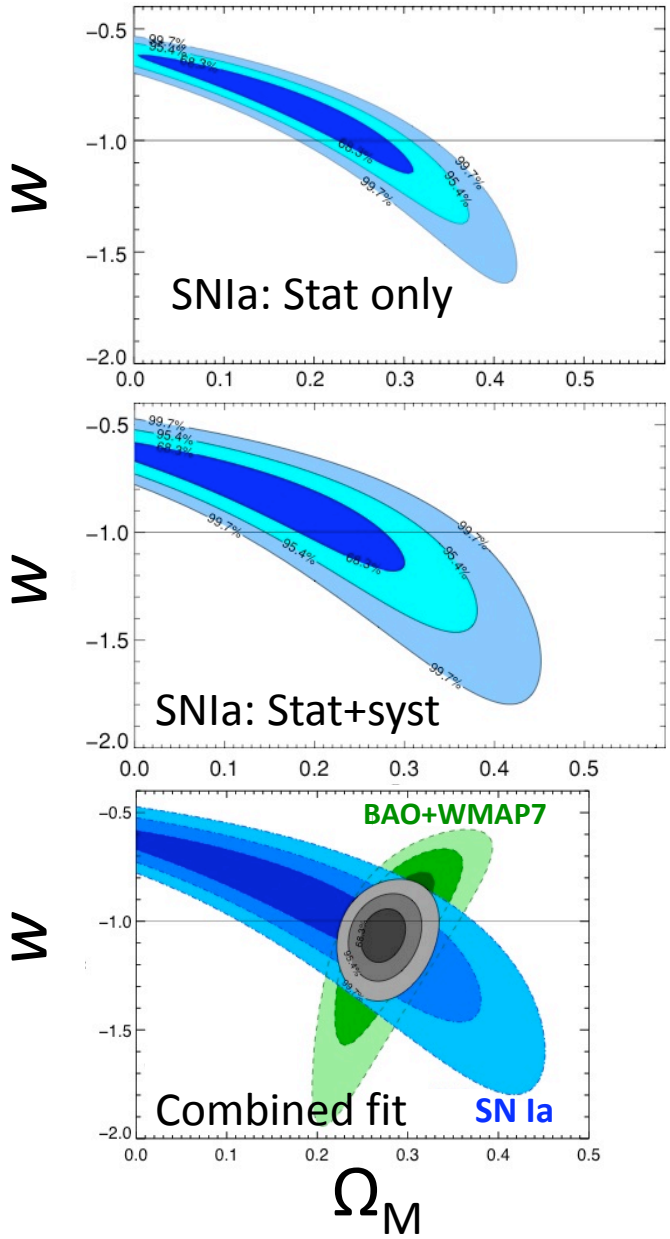
$d_L = (1+z)\int dz/H(z,\Omega_M,\Omega_\Lambda,w)$
for flat universe.
Distance modulus: $\mu=5\log(d_L/10pc)$

Recent Hubble Diagram with all [usable] Published Data

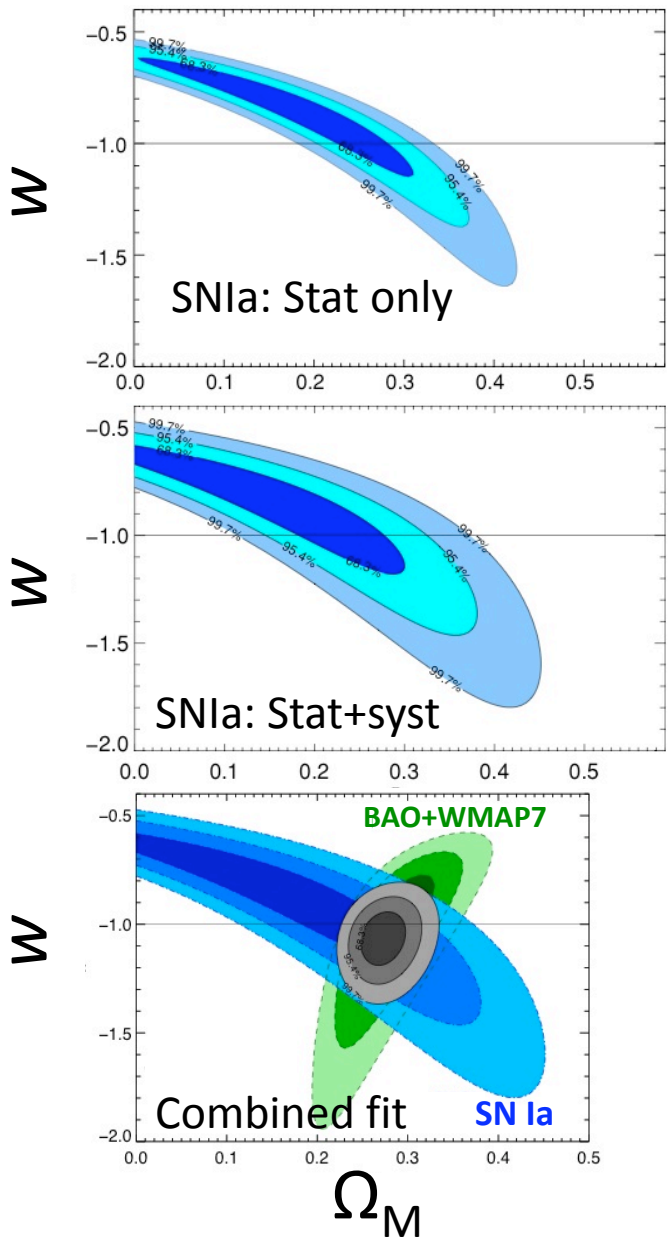


Conley et al., 2011
(SNLS collab)

Systematic Uncertainties (Conley et al., 2011)



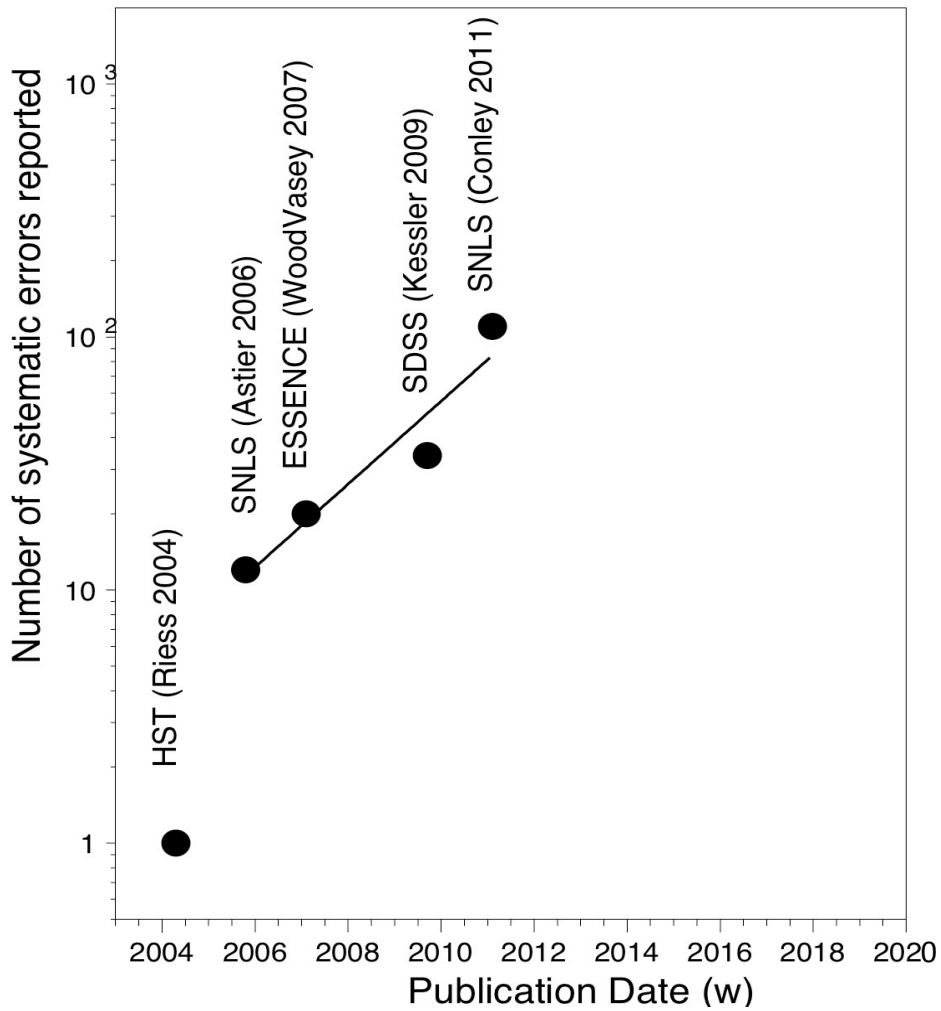
Systematic Uncertainties (Conley et al., 2011)



Source of Uncertainty	σ_w/σ_{stat}
Instrumental Calibration (mainly from old low-z set)	0.89
SN model	0.14 *
Peculiar velocities	0.17
Malmquist bias	0.26
Non-SNIa contamination	----
MW extinction	0.22
SN evolution	0.14 *
Host/SN-brightness correlation	0.28 *

* Potential improvement with input from explosion-model simulations

Systematic Uncertainties: more in-depth with each publication



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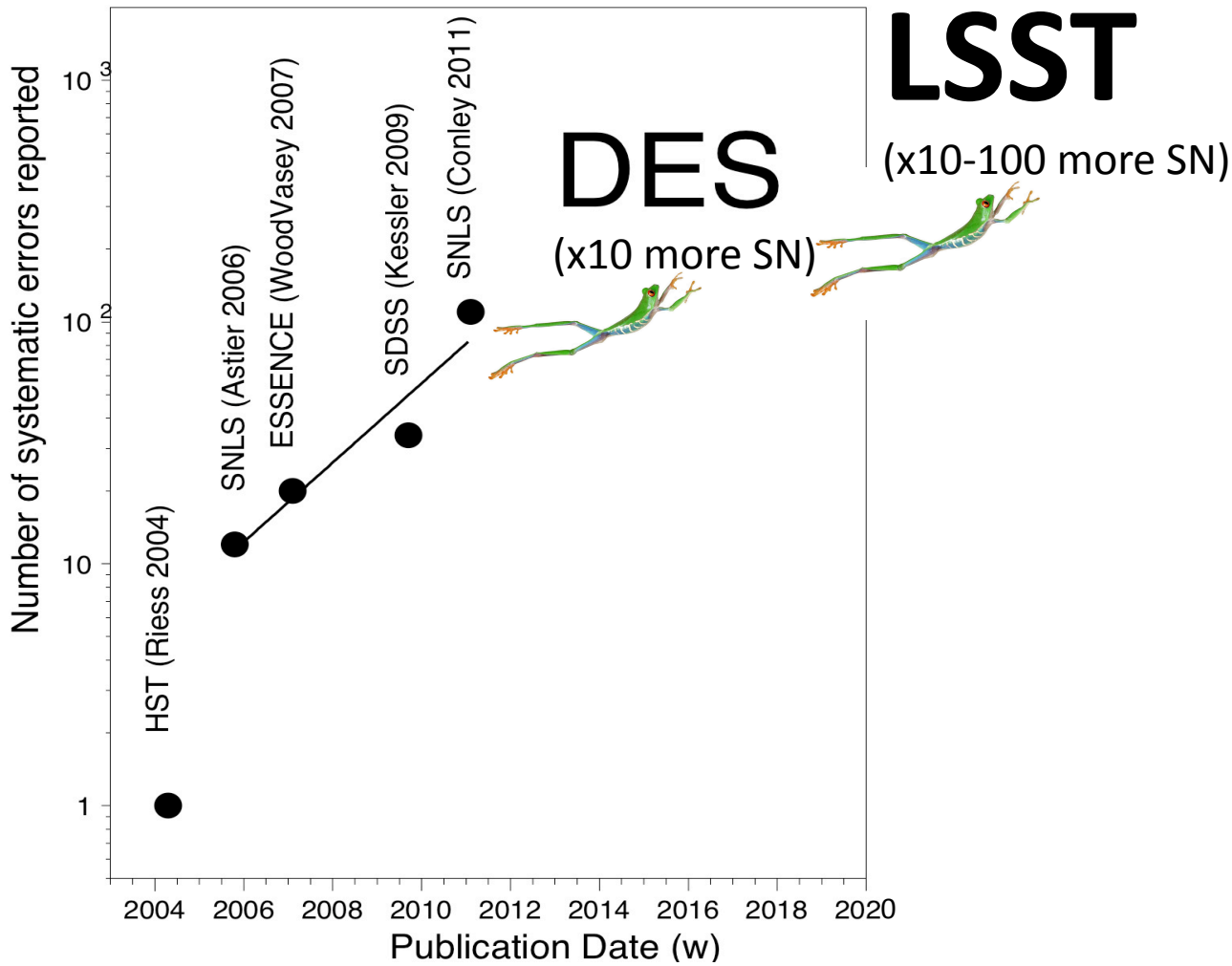
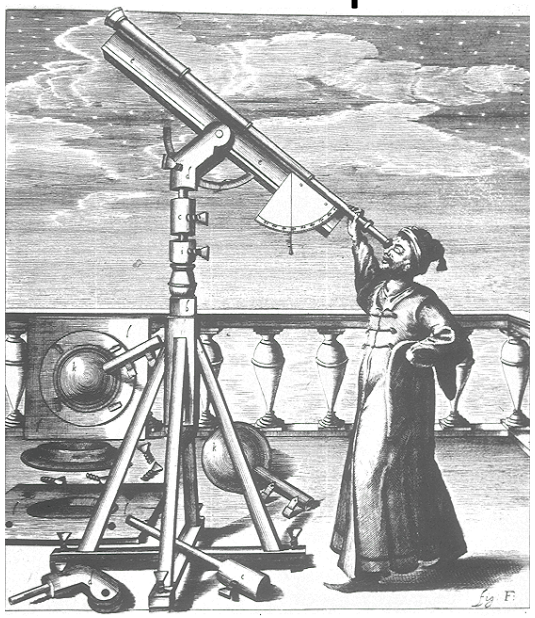


The “Apparatus”

Supernova

(Stuff in between:
dust and atmosphere)

Telescope



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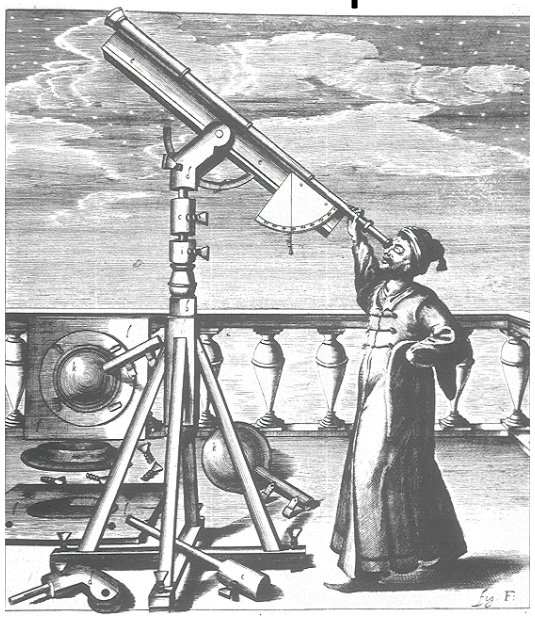
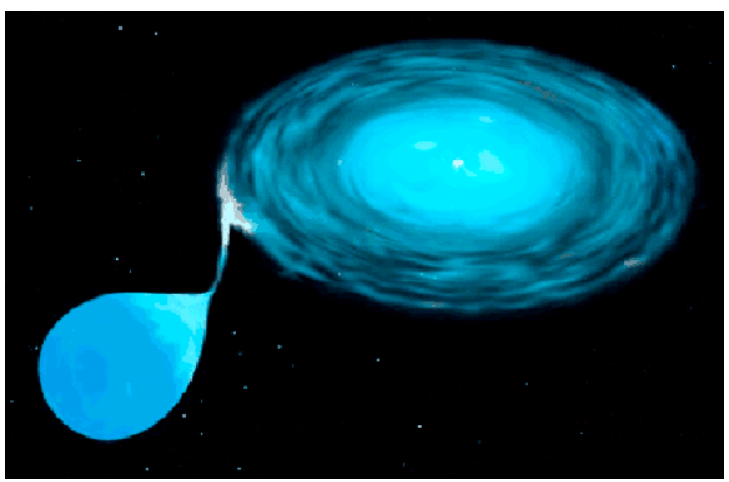


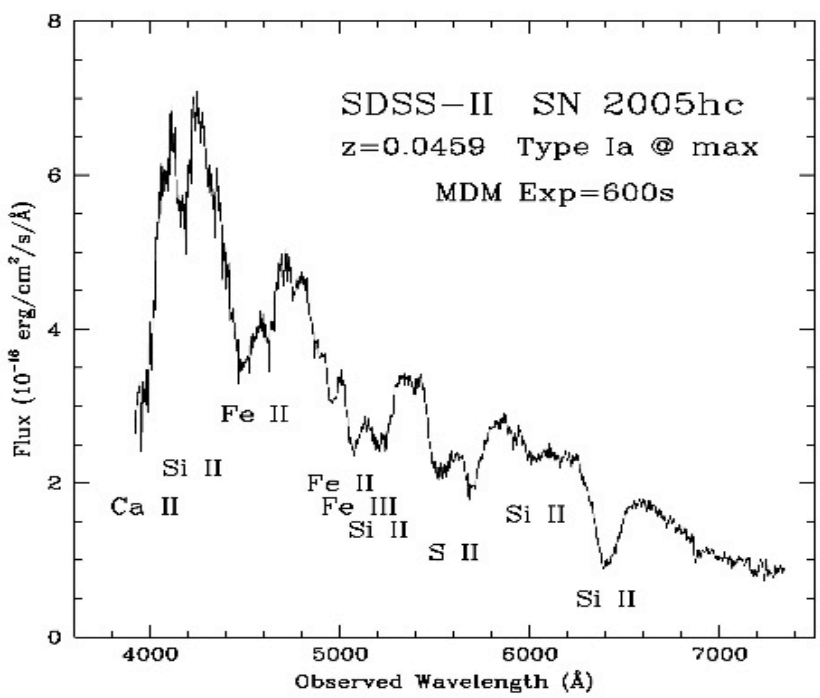
Tools to understand the ‘apparatus’ :

* SN: Simulations
* Telescope: Calibration

What is a Type Ia Supernova ?

- A CO white dwarf accretes matter from a large companion
- Upon reaching the Chandrasakar mass, it detonates and burns partly/mostly into iron-peak elements.
- Intermediate mass elements (Ca, Si ...) leave strong spectral features.





What Can we Hope to Learn From SN Explosion-Model Simulations

Question	Current knowledge
How do they detonate ?	Speculative
What drives the optical light curve ?	Heating ejecta by radioactive decay of ^{56}Ni and ^{56}Co
What drives the correlation between brightness and stretch/ color ?	^{56}Ni mass drives stretch correlation. Color correl. not understood.
Why is there 0.1 mag 'intrinsic' scatter after corrections … are there additional corrections ?	Speculative: Viewing angle ? Detonation location(s) ?

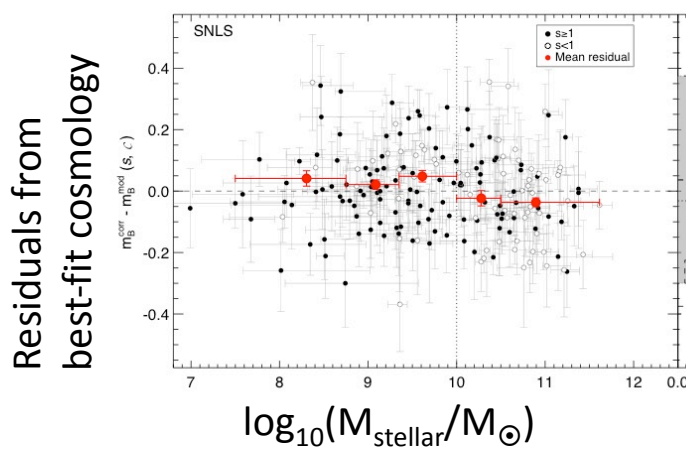
What can we Hope to Learn: Intrinsic (0.1 mag) Hubble Scatter

- For Hubble diagram fits for cosmological parameters, 0.1 mag scatter is assumed to be associated with 1 (of 3) fit parameters.
- Observationally we cannot rule out a more complex source of scatter

  (i.e., 3x3 covariance among fit parameters)
- Qualitative guidance from explosion-model sims could clarify the description of the scatter and its redshift dependence.

What can we Hope to Learn: Host/SN-brightness Correlation

- SN brightness depends (empirically) on host galaxy mass.
- Current "binary" correction is based on $M_{stellar}$ above or below 10^{10} $M_{\odot}$: true correlation is likely more complicated.
- SN simulations may reveal the underlying physics behind this empirically observed correlation.



Kelly et al., ApJ 715, 743 (2010)
Sullivan et al., MNRAS 406, 782 (2010)
Lampeitl et al, APJ 722, 566 (2010)

Overview of SN Ia Simulations

- Simulate explosion during first minute using hydro code. Output is map of velocity, density, composition.
- Simulate yield of radioactive elements that emit and absorb visible light.
- Use radiation transfer codes (Sedona, Pheonix) to simulate light curves and spectra from few days to months after explosion: MeV photons heat ejecta and radiate visible and IR light.

➔ **compare to data**

Groups Doing SN Ia Simulations

- University of Wuerzburg (Germany)
  [previously Max Planck Institute (Garching, Germany)]
  - Pure deflagration model
  - Sub-Chandrasekhar mass models
- University of Catalonia (Spain)
  - Pulsating reverse detonation model
- Naval Research Laboratory
  - Thermonuclear detonations
  - Deflagration-to-detonation transition (DDT) model
- UC Santa Cruz/LBNL/SUNY at Stony Brook
  - Smoldering phase
  - Turbulent nuclear combustion
  - Transition from turbulent nuclear combustion to distributed burning
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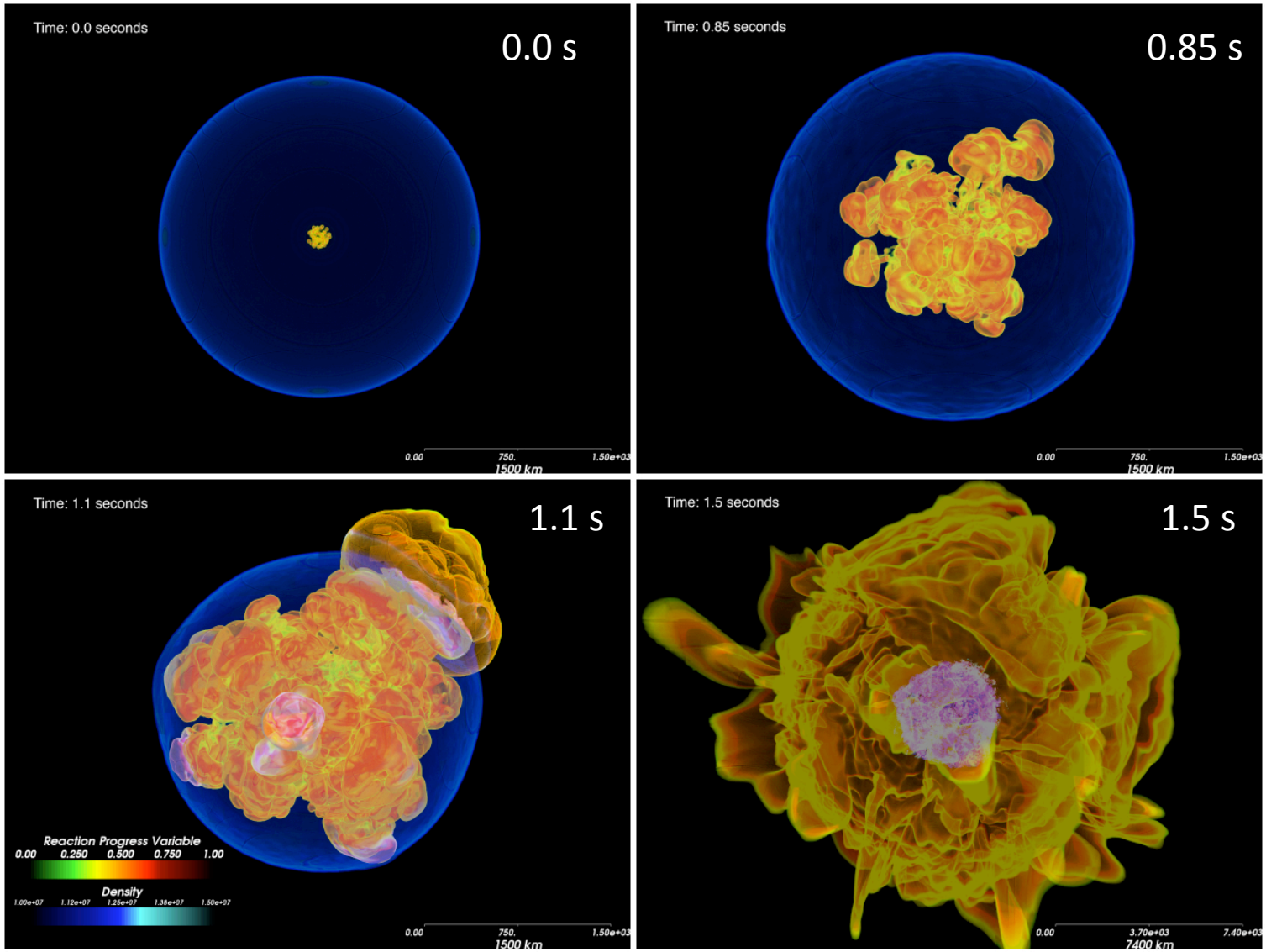
  - Deflagration-to-detonation transition (DDT) model
  - Gravitationally confined detonation (GCD) model

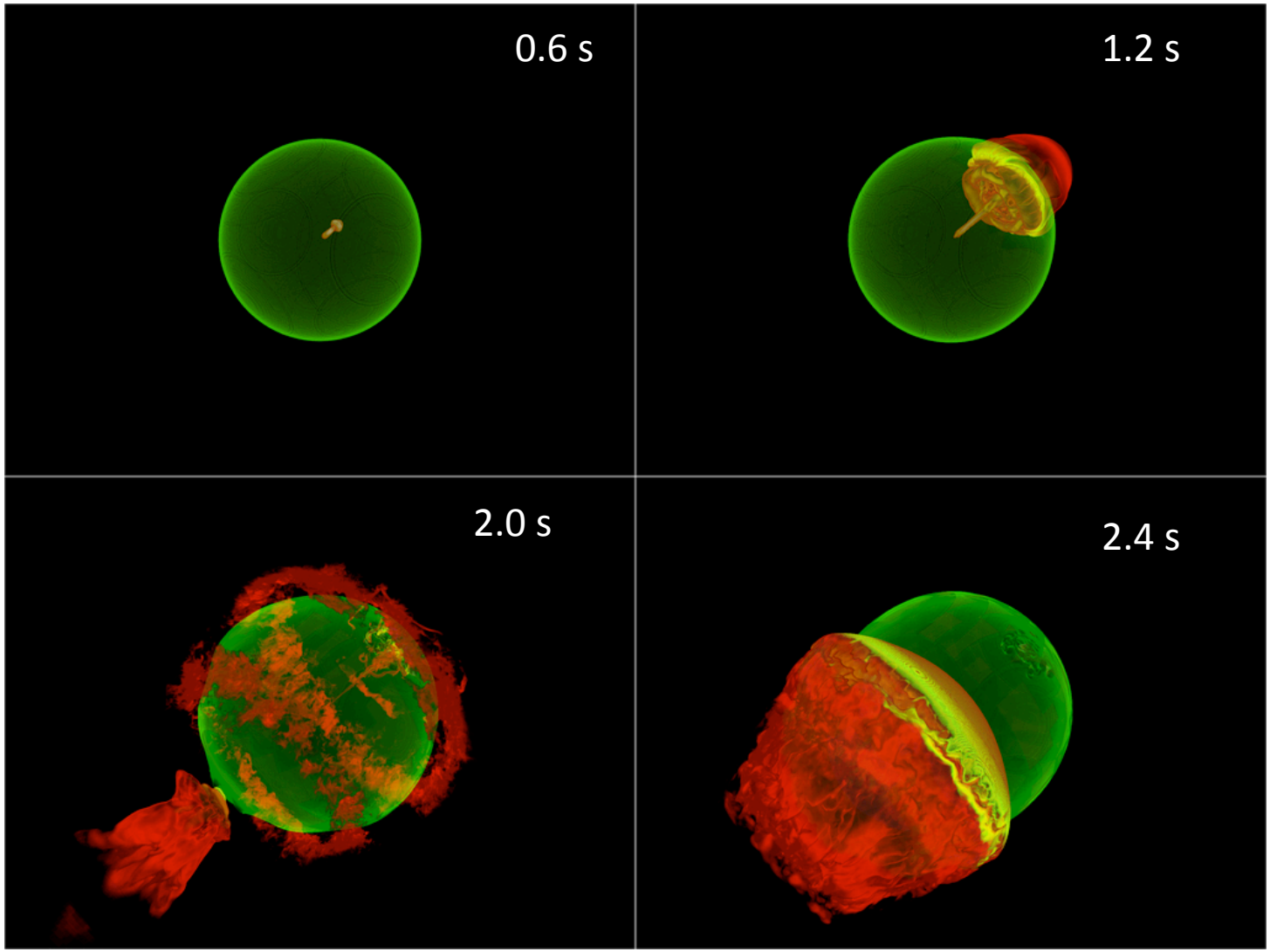
Computational Demands of Large-Scale 3D Type Ia Supernova Simulations

- High-resolution, 3D simulations of the SNIa explosion phase require ~ **100K-300K cpu-hours** on current machines; the radiation transfer phase requires more resources
- Each large simulation generates ~ **20-60 TB** of data
- Each of the past two years FLASH used ~ **80 M cpu-hrs** on *Intrepid* at ANL under DOE Office of Science INCITE program; a similar amount is expected this year
- FLASH generated ~ **3 PB** of data last year and expect to generate a similar amount this year; in-line analysis and intelligent triaging of data is therefore essential.

Deflagration to Detonation Transition Model (DDT)



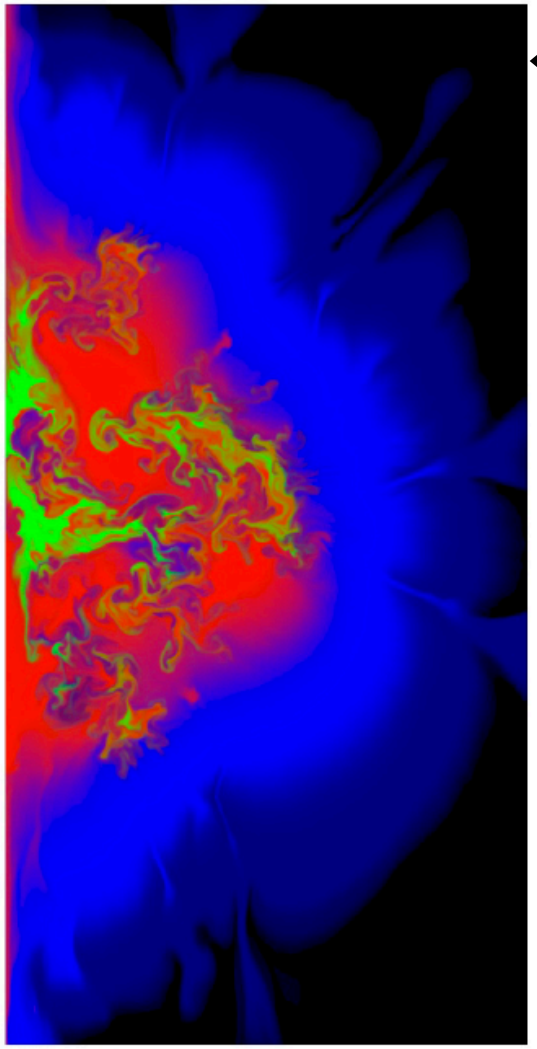
Gravitationally Confined Detonation Model (GCD)



Jordan et al. (2008)

Comparison of DDT and GCD

DDT



Kasen et al, 2009

- Turbulently mixed inner layers (Ni)
- Smooth outer layers (IME's)

- Si, Mg
- Stable Fe, Ni
- Radioactive ^{56}Ni

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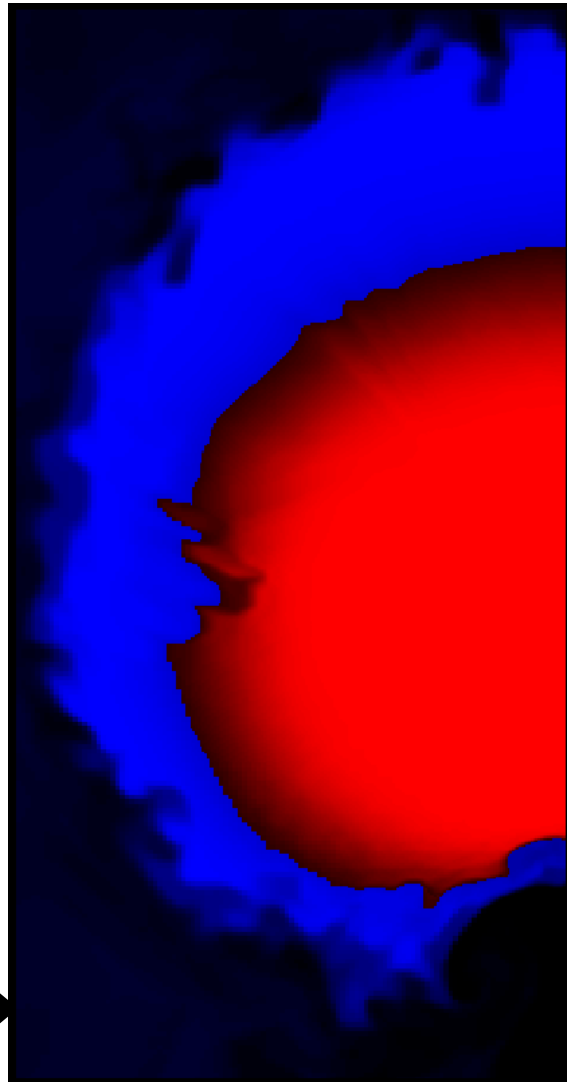
- Turbulently mixed outer layers (IME's)

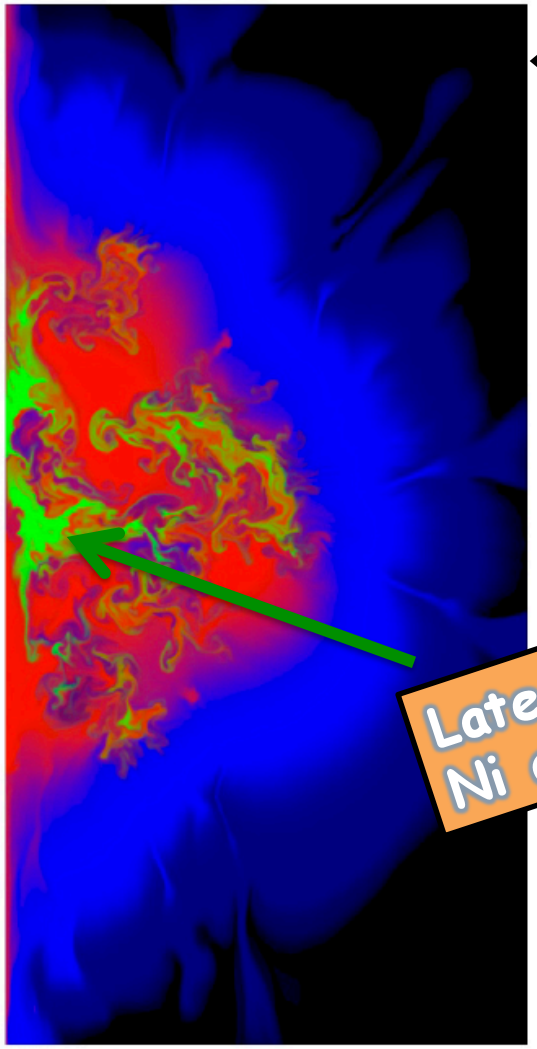
GCD



Jordan et al., in prep

Experimental Signatures

DDT



- Turbulently mixed inner layers (Ni)
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- Si, Mg
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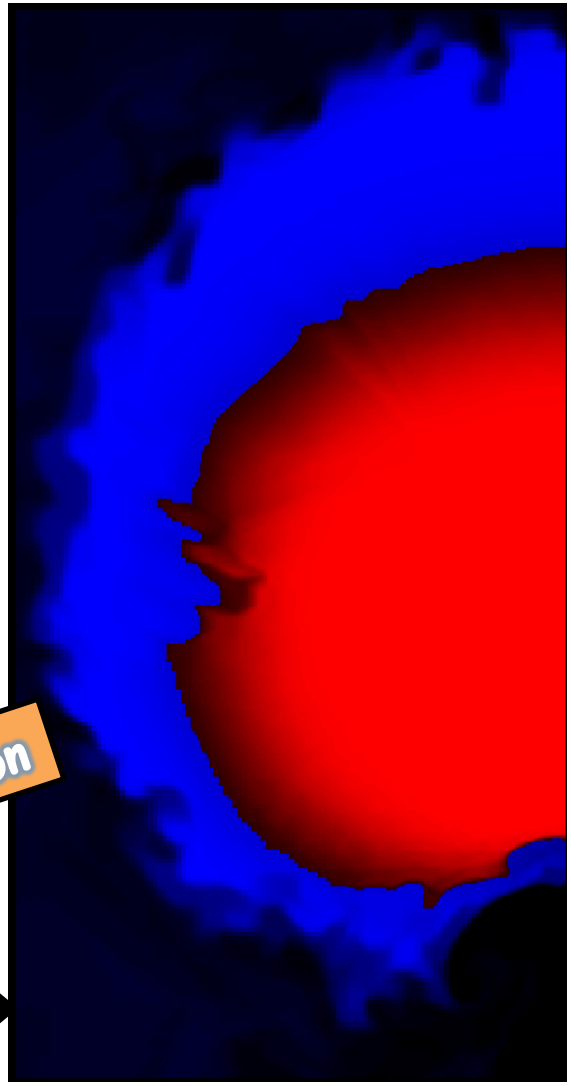
Late-time Ni absorption

polarization

- Smooth inner layers (Ni)
- Turbulently mixed outer layers (IME's)

GCD



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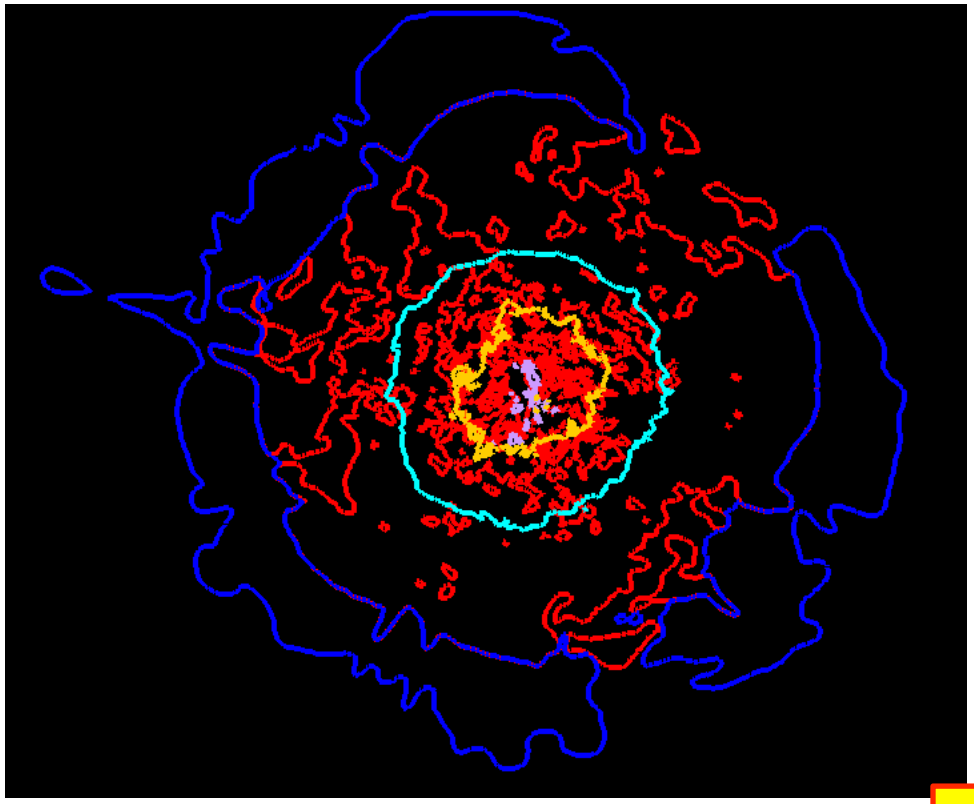
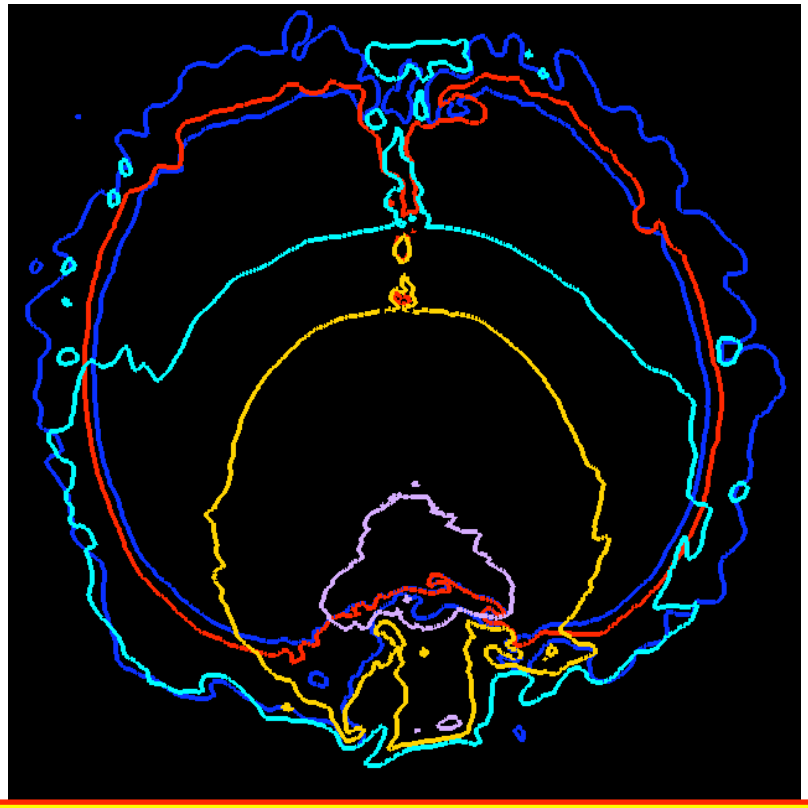
Comparison of DDT and GCD

DDT GCD

Ni contour (red), Si contour (blue)





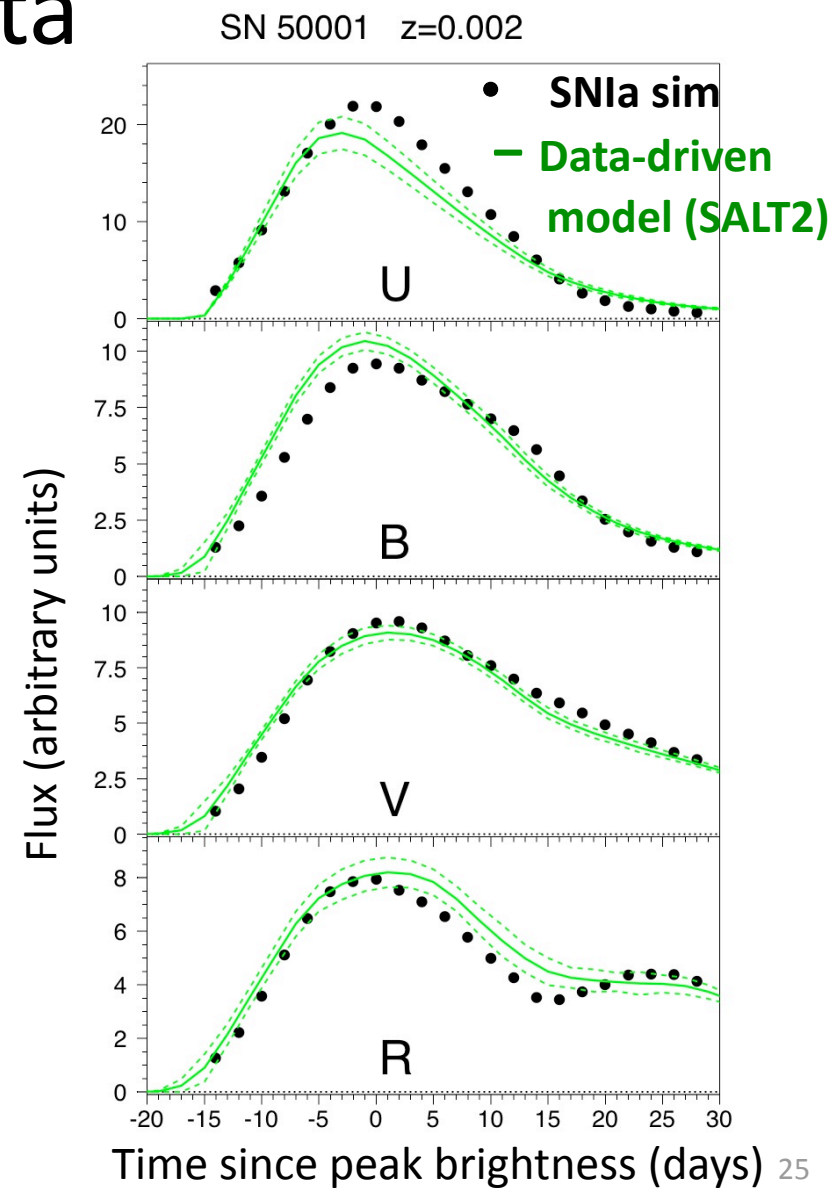
Recent polarization (Wang et. Al., 2006, 2007) and spectroscopic observations (Gerardy 2007) suggest a compositional structure like this.

Radiation Transfer

- Radioactive ^{56}Ni and ^{56}Co ($\tau_{½}$ = 6 and 77 days) heat the expanding envelope and radiate visible and IR photons.
- At early times the visible photons are trapped by the opaque envelope; later the expanding envelope becomes more transparent to the reservoir of visible photons.
- Spectrum is affected by millions of atomic absorption and emissions lines.
- Max 'visible' brightness occurs almost 3 weeks after explosion.

Comparing Predicted Light Curves to Data

- Synthesize photometric light curves from spectra generated by rad-transfer stage.
- Fit predicted light curves (from SNIa sim) exactly the same way that data are fit.



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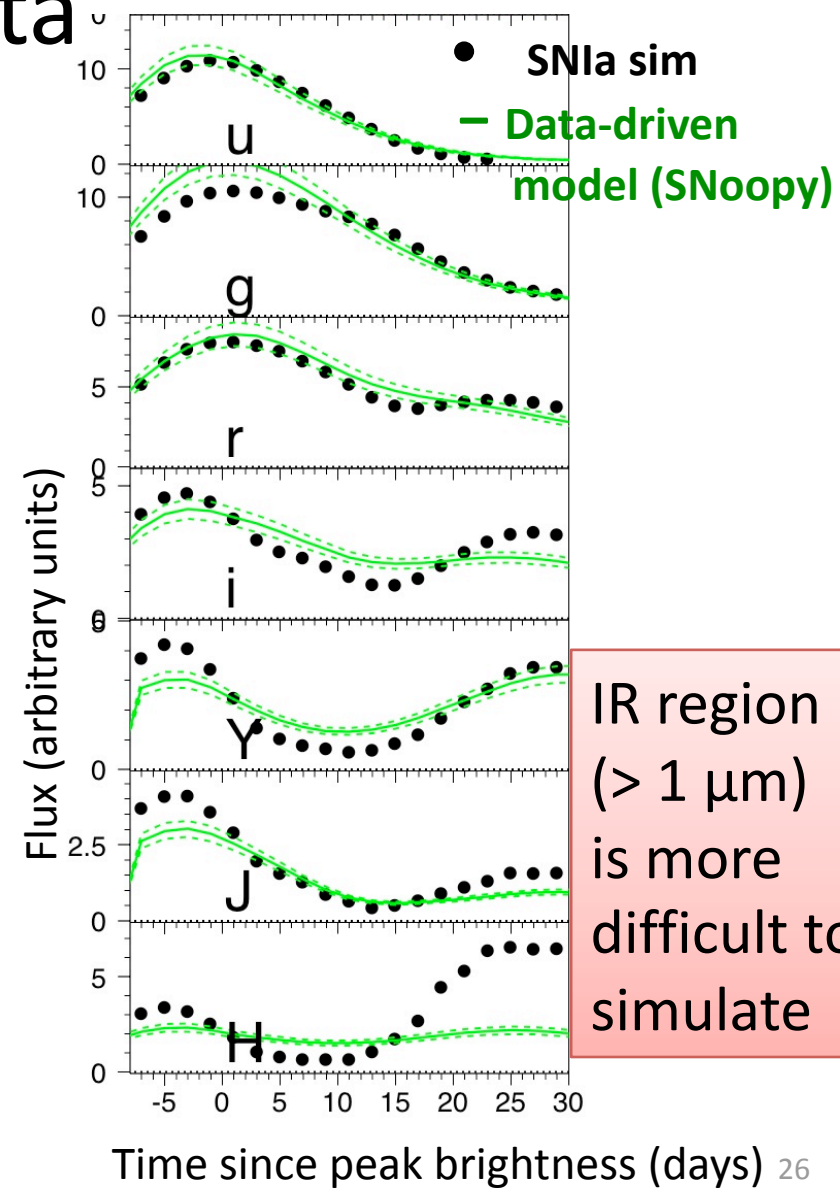
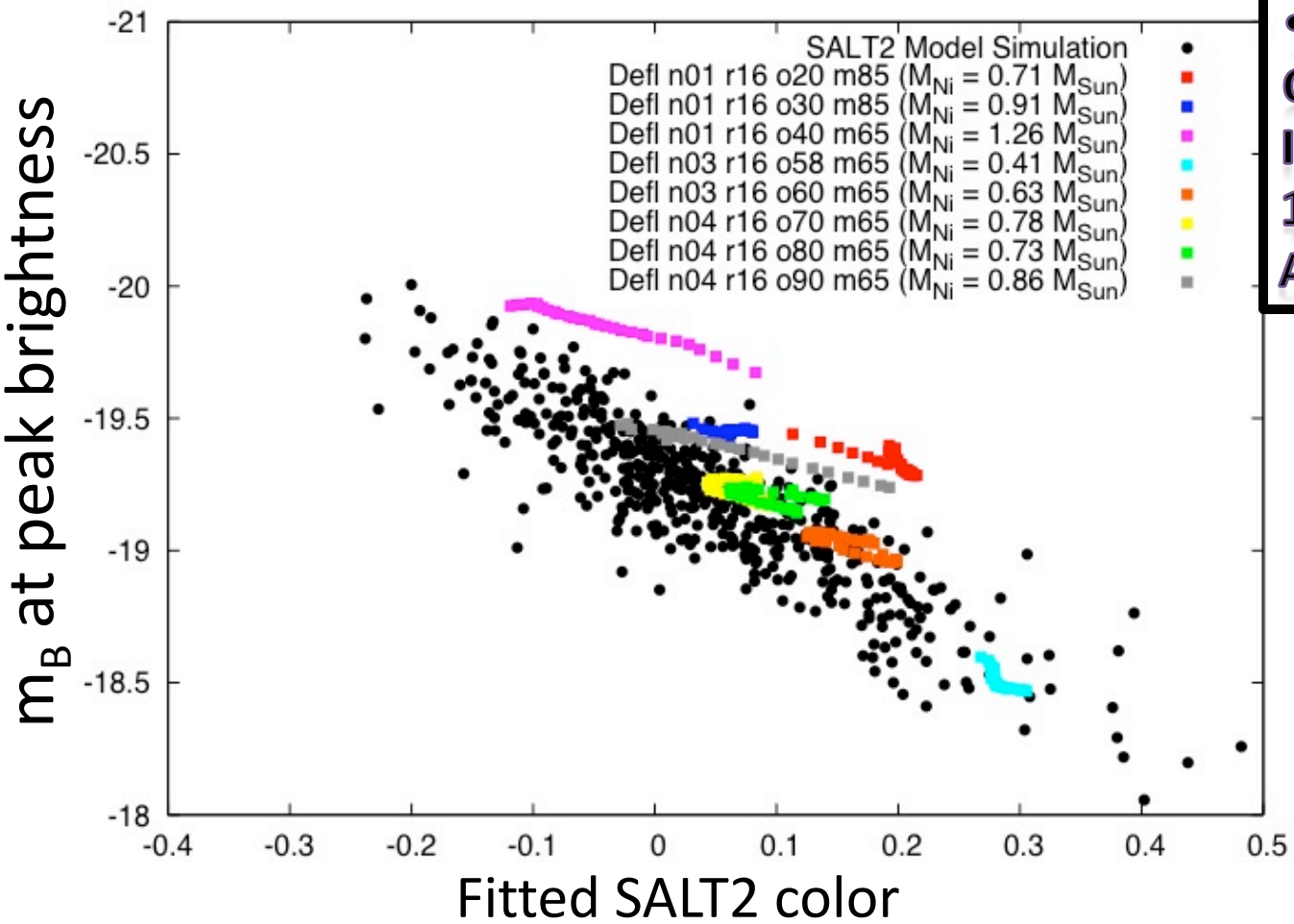


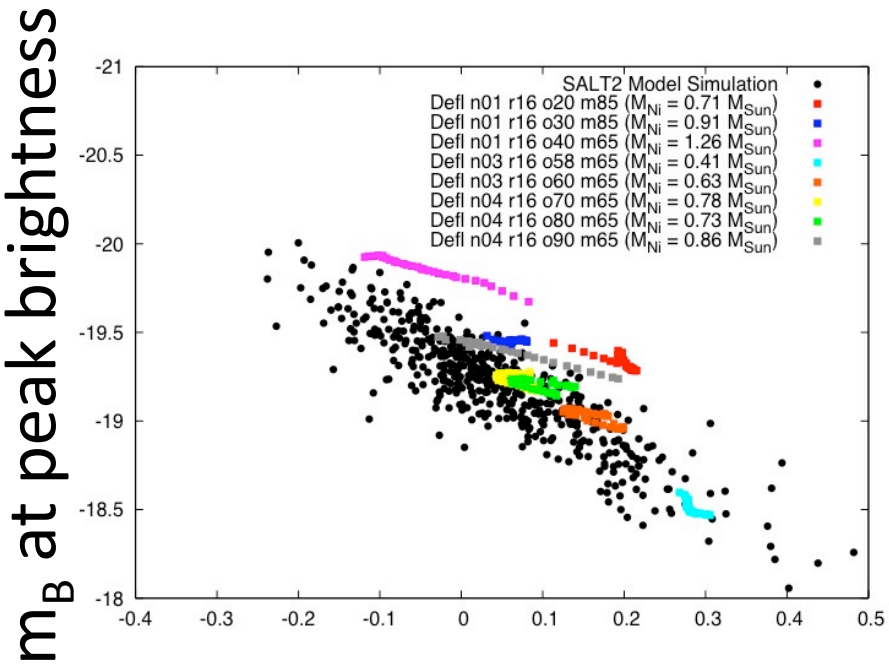
IR region (> 1 μm) is more difficult to simulate

Parameter Population

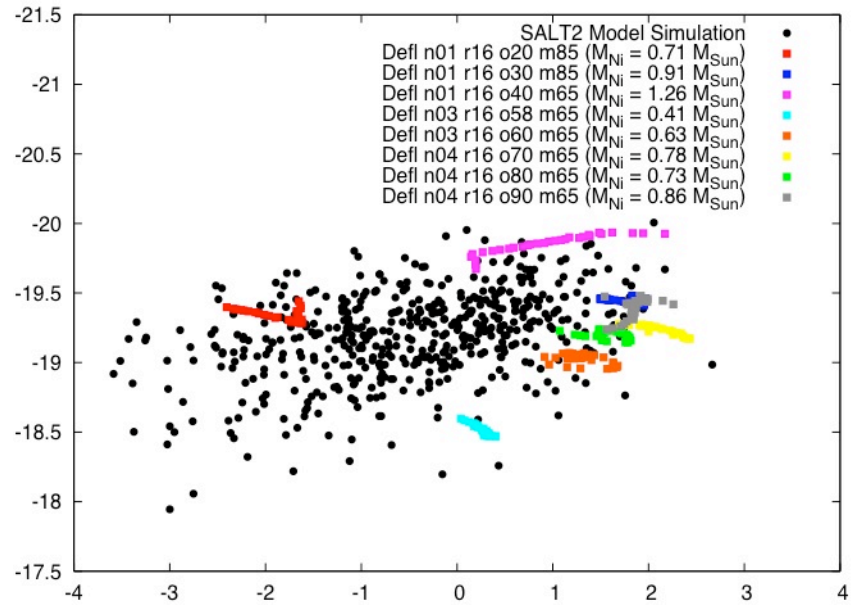


- **BEST ESTIMATE OF 'REALITY' FROM IDEAL SURVEY WITH 100% EFFICIENCY AND VERY HIGH S/N.**

Parameter Population



Fitted SALT2 color



Fitted SALT2 stretch (x_1)

Intermediate Goal:
determine population of underlying physics parameters (KE, ^{56}Ni mass, viewing angle …) that result in measured population of observable parameters.

Summary

- SNIa observations inform explosion-model simulations
- Explosion models have explained some observed features
  (stretch-brightness relation, why SNIa are so bright)
- DDT and GCD models are consistent with observations
  (pure deflagration model is disfavored)
- Testable predictions of DDT and GCD models may lead to better understanding of explosion mechanism.
- Dependence on viewing angle (GCD model) may partly explain intrinsic scatter.
- Predicted correlations between light curve properties and spectral features may lead to reduced scatter in the calibrated SNIa luminosity.

- Ultimate goals for explosion-model simulations:
  - understand explosion mechanism.
  - provide quantitative and/or qualitative input to SNIa-brightness relations and the source of intrinsic scatter.
  - understand population of observable parameters (stretch, color, …)