EXCELLENCE IN SCIENCE THE ROYAL SOCIETY

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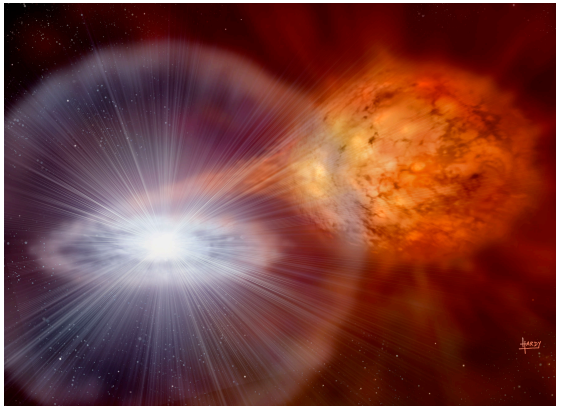
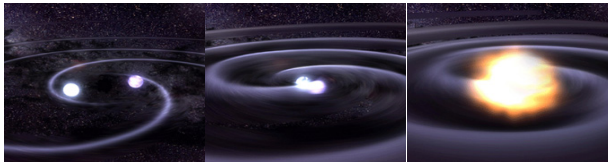
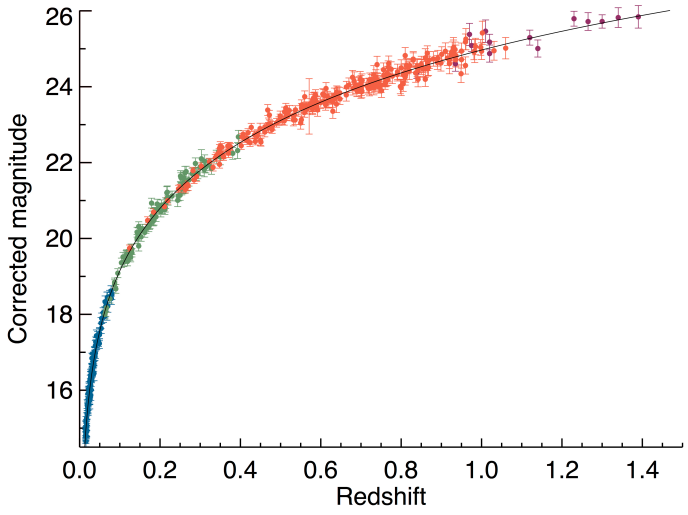
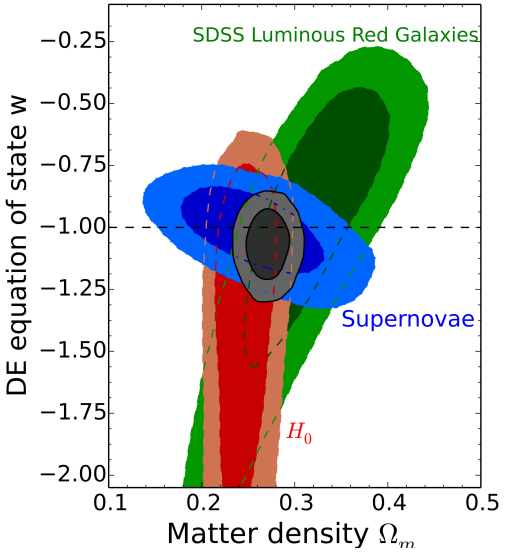
Astrophysics and supernova cosmology

Mark Sullivan, Southampton

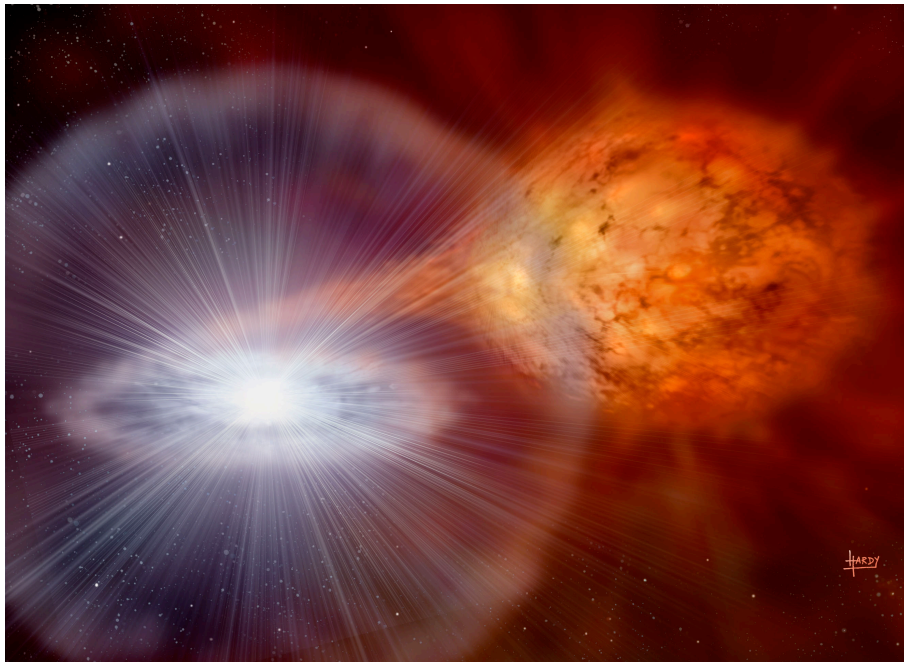








Type Ia Supernovae



Type Ia supernovae: thermonuclear explosions of CO white dwarfs

→ Approaches Chandrasekhar mass

→ C-burning ignited

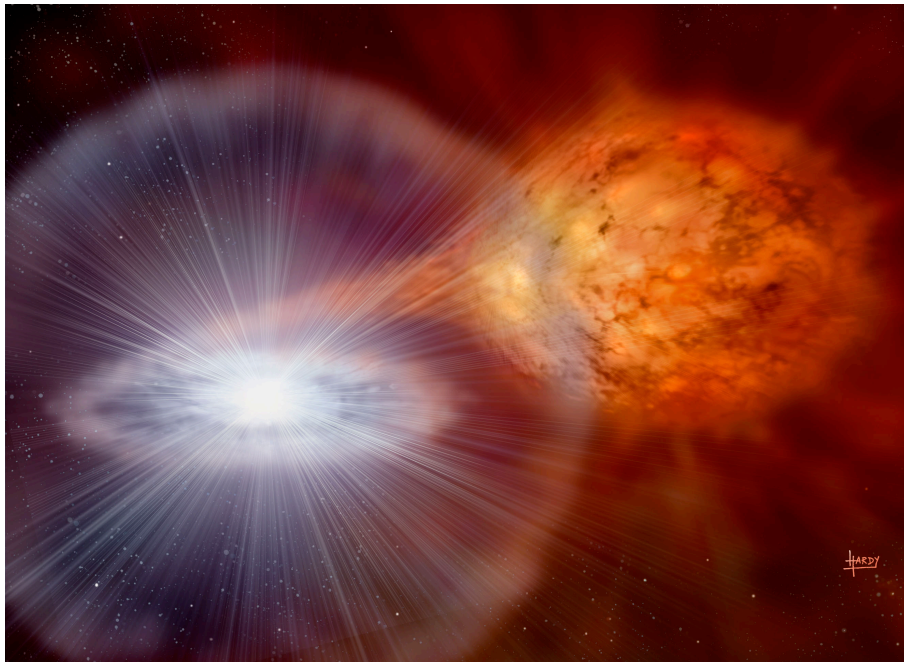
Resulting explosion is:

→ **Bright**: ~5-10 billion suns

→ **Powered by:** ^{56}Ni → ^{56}Co → ^{56}Fe

→ **Standardizable**: ≤5-6% in distance

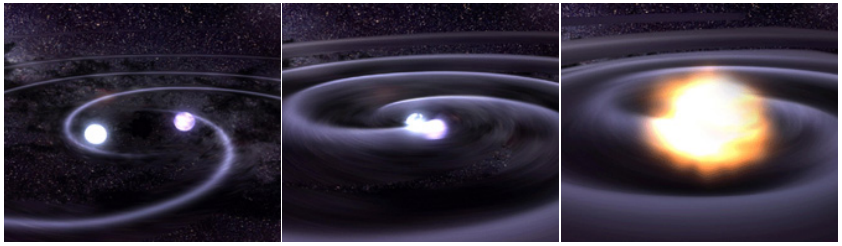
Type Ia Supernovae



Single degenerate?

and/or

Double degenerate?



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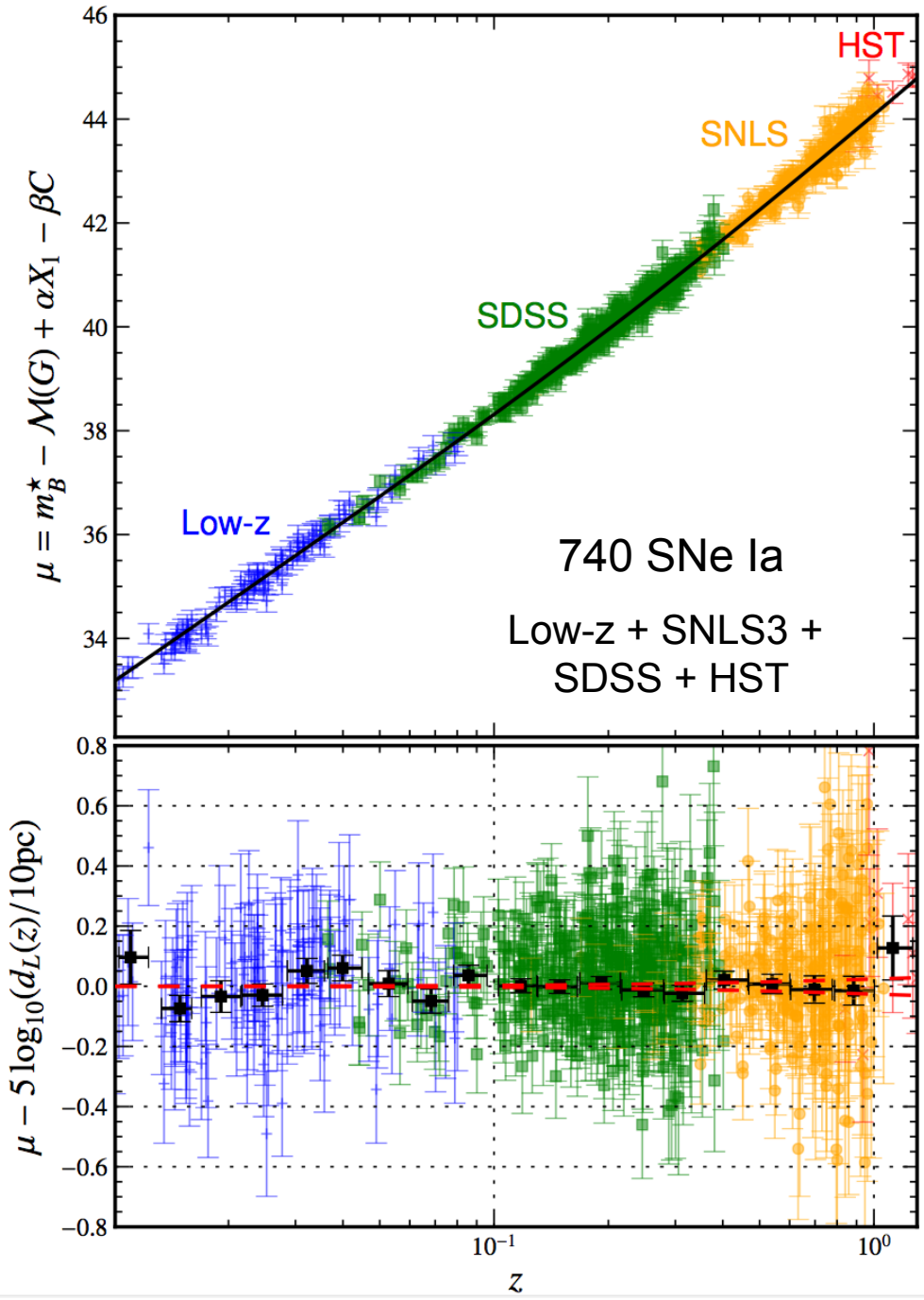
What are the progenitors of SNe Ia ?

Impact of progenitor diversity and physics?

Uncertain (In)~~Accurate~~ astrophysics?

- **Stellar evolution:** Pre-supernova stellar evolution
  - *White dwarf composition, age, metallicity*
- **Progenitors:** Configuration of system
  - *Single or double degenerate system*
- **Accretion:** Accretion process
  - *Mass transfer rate, composition of material*
- **Explosion:** Explosion physics
  - *Triggering conditions, ignition spots, flame propagation*
- **Aftermath:** Radiative transfer processes
  - *Ejecta composition, local environment, dust*



A modern day Hubble Diagram "JLA"

w = −1.018 ± 0.057 *(stat+sys)*
(SN+CMB)

w = −1.027 ± 0.055
(SN+CMB+BAO)

σ_{coh} = 0.08-0.11 mag
(4-6% in distance)

Betoule et al. 2014

Simplified SN systematic-error budget ("JLA")

Experimental | Astrophysical (non-SN) | Astrophysical (SN)

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

Photometric calibration is (by far) the dominant systematic uncertainty

Betoule et al. 2014

Experimental Astrophysical (non-SN) Astrophysical (SN)

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PS1 (Scolnic et al 2014)

Systematic	$\Delta\Omega_M$	Δw SN Only	Rel. Area
Stat. Only	0.000 ($\Omega_M = 0.223^{+0.209}_{-0.221}$)	0.000 ($w = -1.010^{+0.360}_{-0.206}$)	1.000
Calibration	0.024	−0.093	1.566
Color model	0.004	−0.023	1.117
Host gal.	0.006	0.000	1.035
Malmquist	0.004	−0.011	1.024
z_{min}	0.000	−0.004	1.020
MW extinction	0.001	−0.007	1.020
Syst.+Stat.	0.032 ($\Omega_M = 0.256^{+0.201}_{-0.174}$)	−0.108 ($w = -1.120^{+0.450}_{-0.357}$)	1.697

Photometric calibration is (by far) the dominant systematic uncertainty

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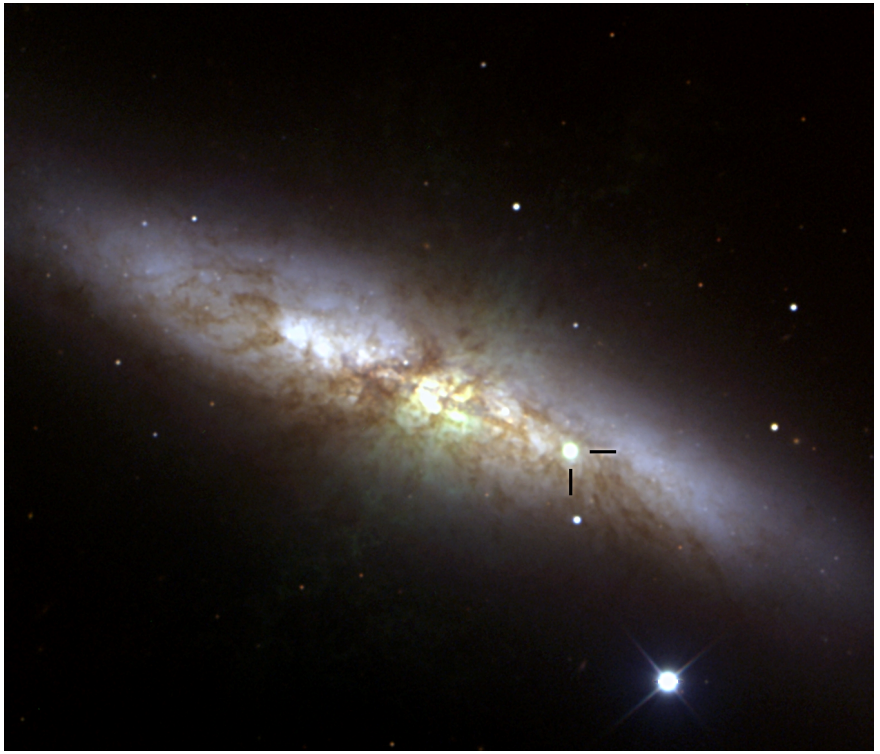
“Calibration is boring”

Astrophysics from nearby SNe

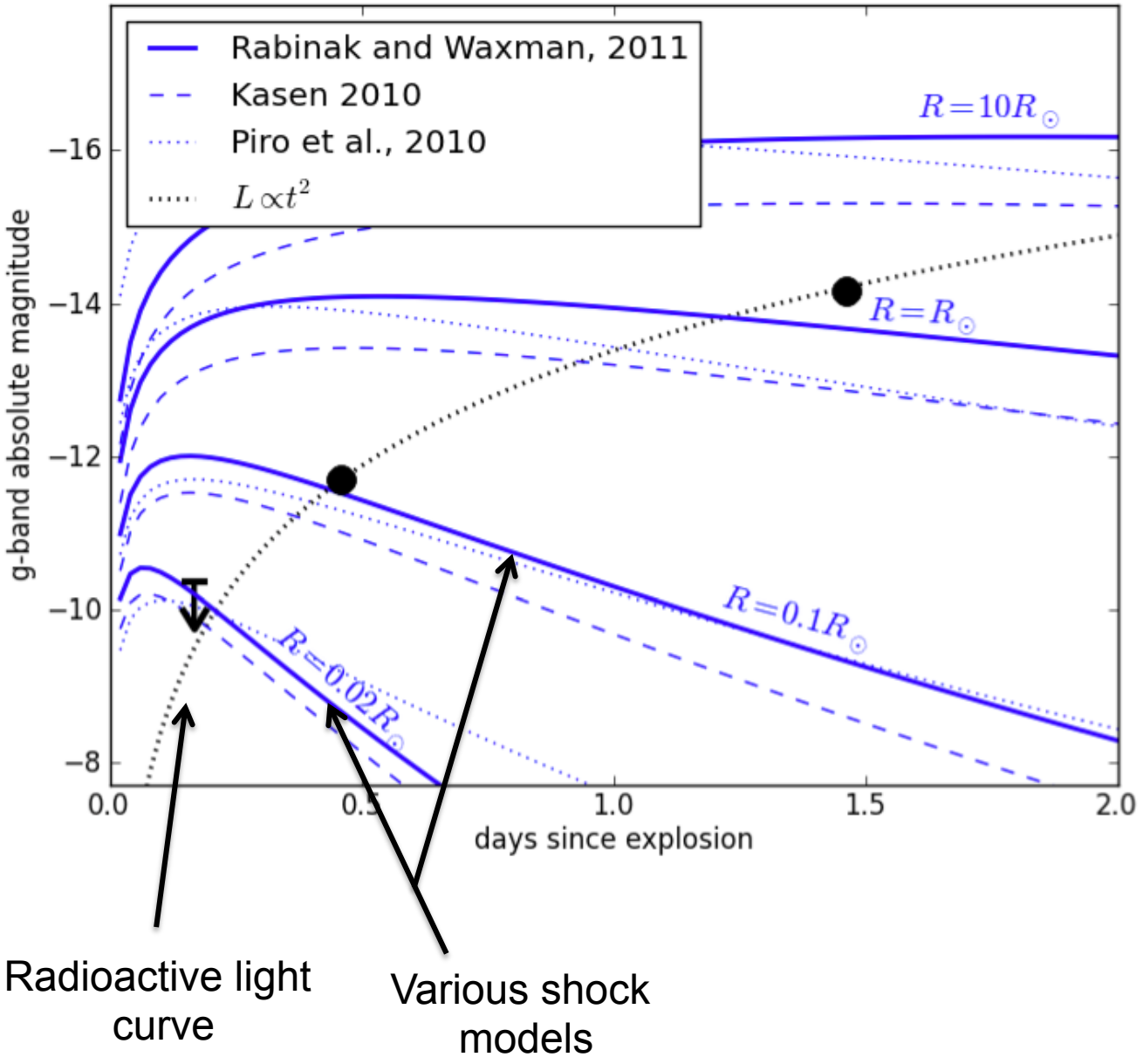
SN2011fe in M101

~6.5 Mpc



SN2014J in M82

~3.5 Mpc



SN2011fe: *It's a white dwarf*

Size constraint:
$R<0.02R_\odot$

i.e. a white dwarf

Carbon & oxygen in the very-early spectra:

i.e. a C-O WD

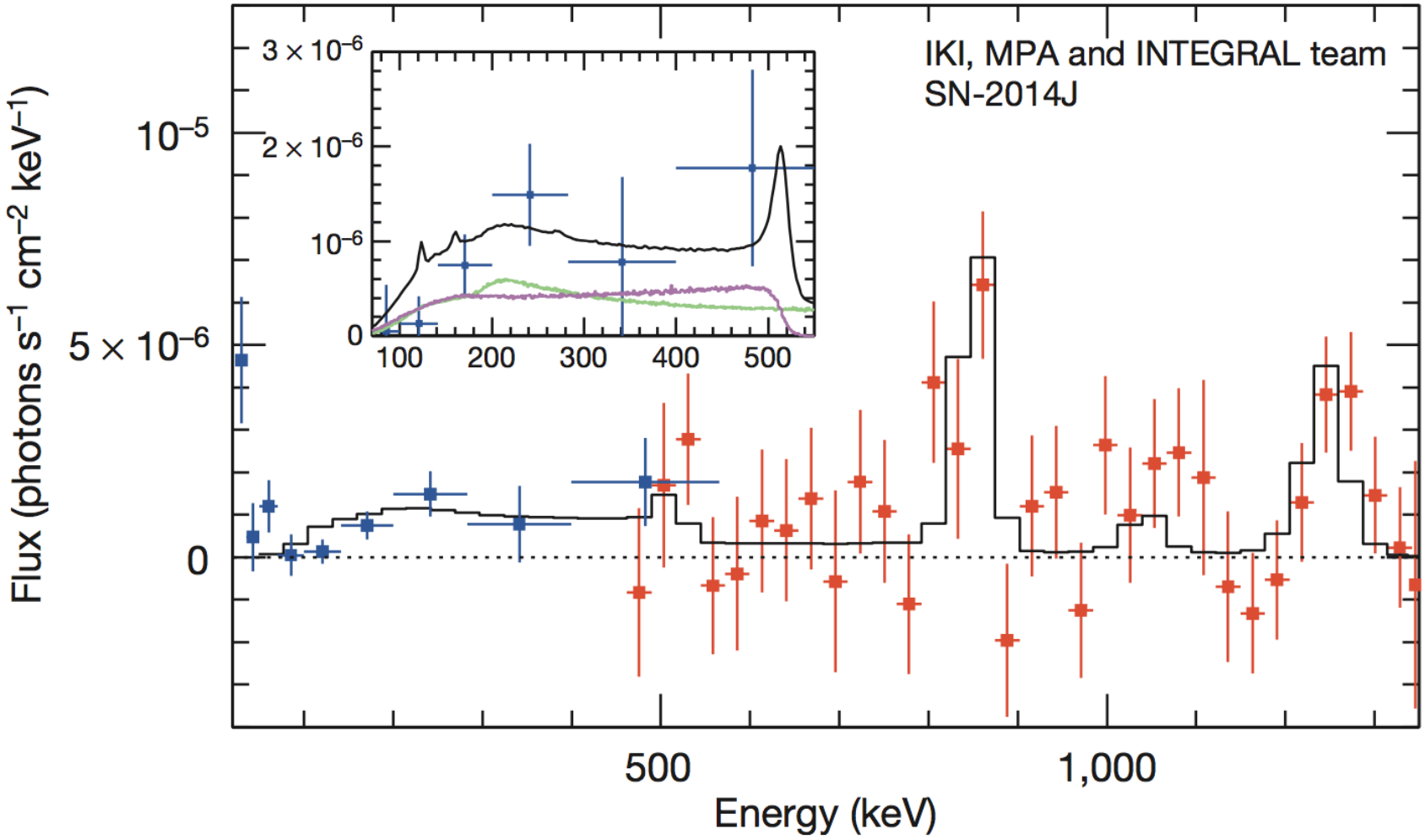
Nugent et al 2011, Nature
Bloom et al 2013

SN2014J:
It's ^{56}Ni

Strength of lines: $0.6M_{\odot}$ of ^{56}Ni

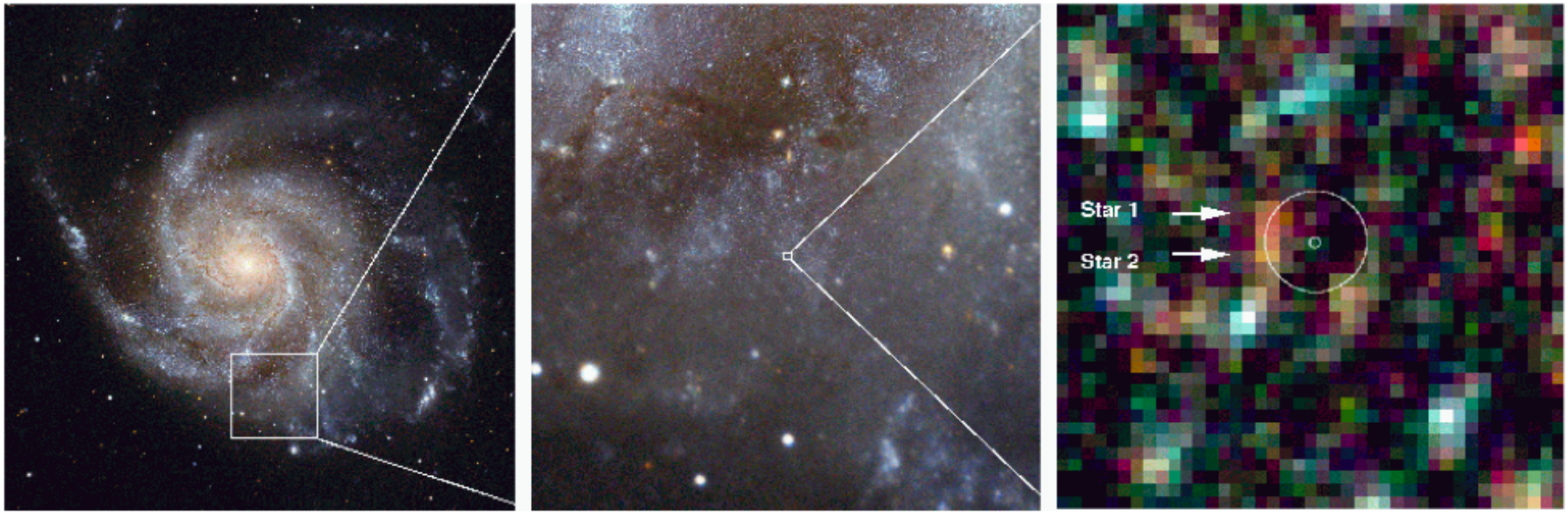
Width of lines: material moving at 10,000 km/s

Consistent with values inferred from optical



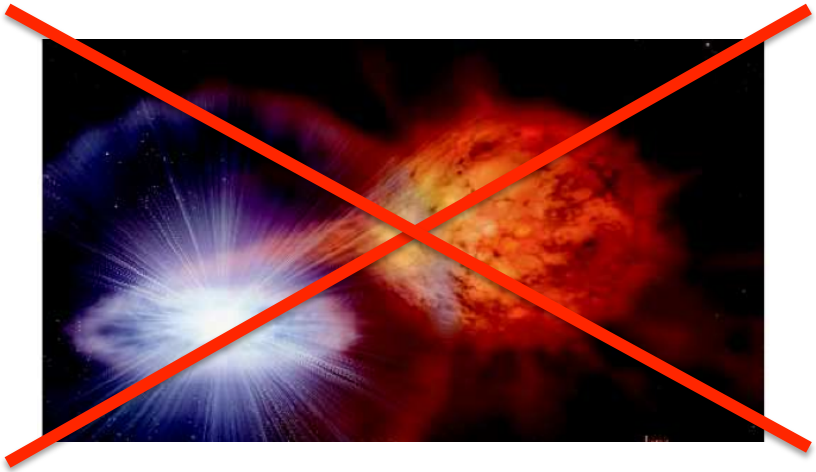
Churazov et al 2014, Nature

SN2011fe: Direct progenitor imaging



No progenitor (companion) star detected in HST imaging

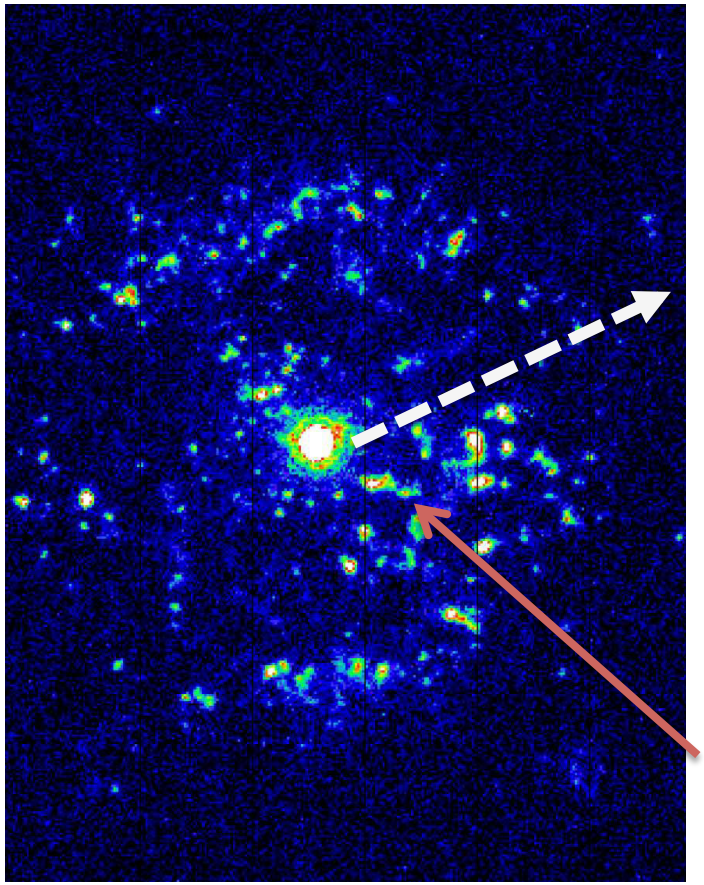
(complementary studies also place strict limits on SD scenarios)



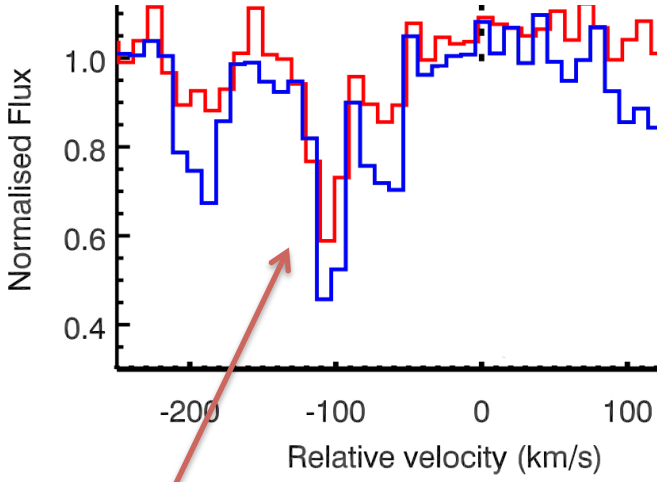
Li et al. 2011, Nature

Circumstellar material (CSM) around SNe Ia

CSM is (probably) a signature of a single degenerate system

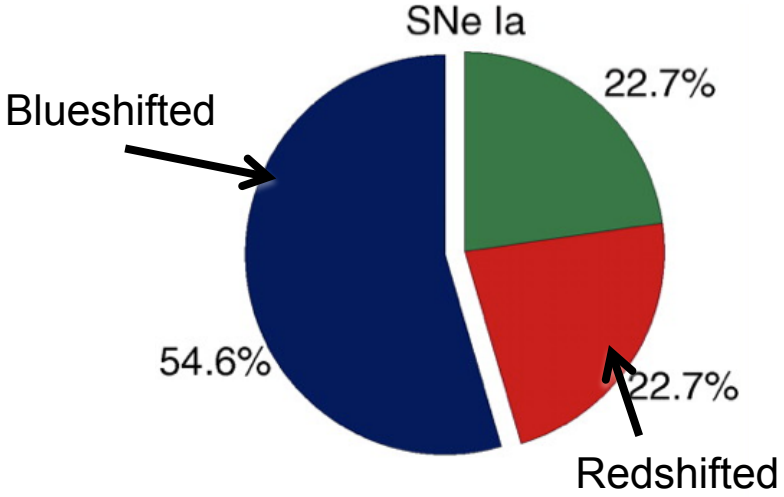


T Pyxidis, recurrent nova



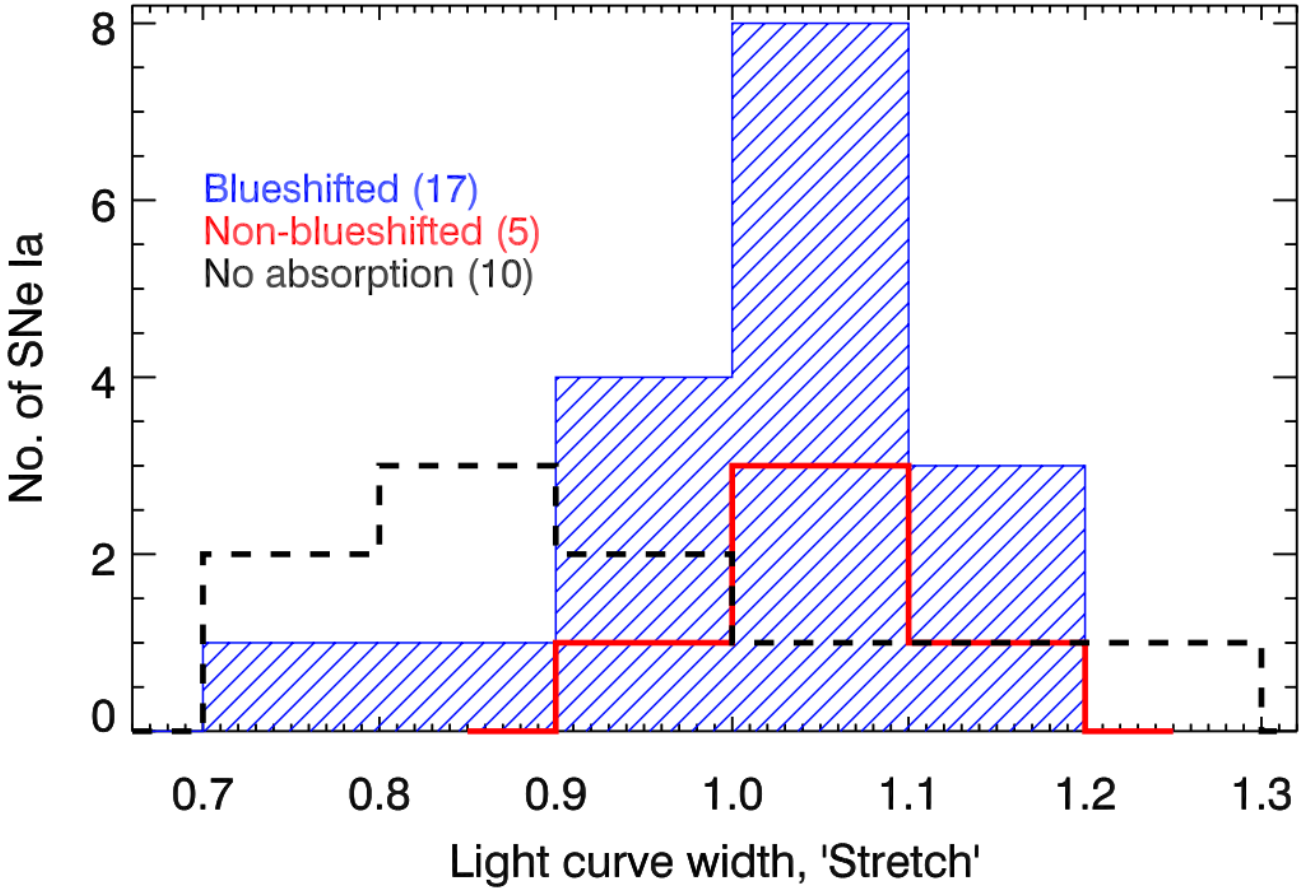
High resolution spectrum

Previous nova material



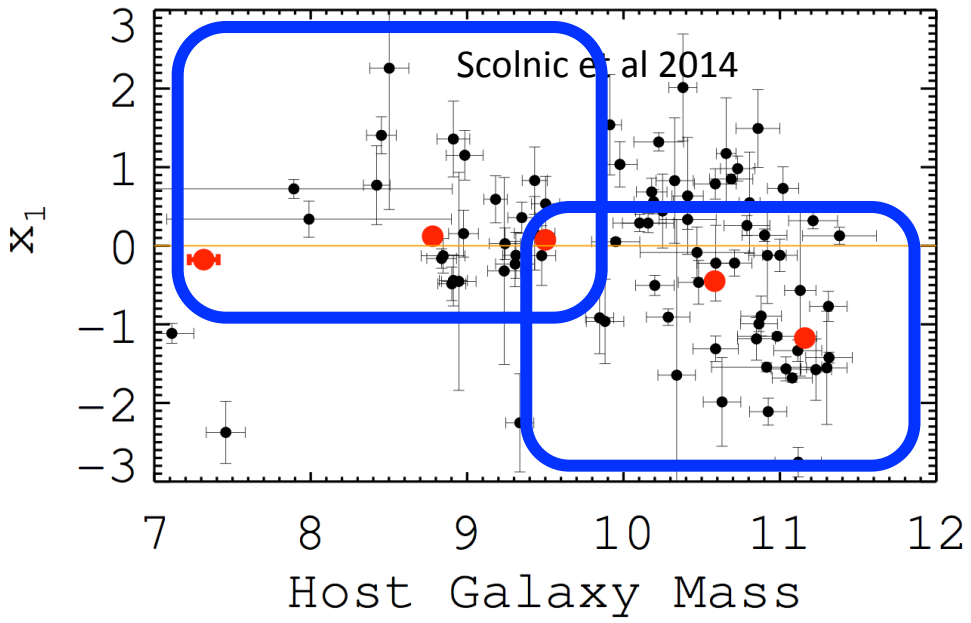
Sternberg et al. (2011), Science

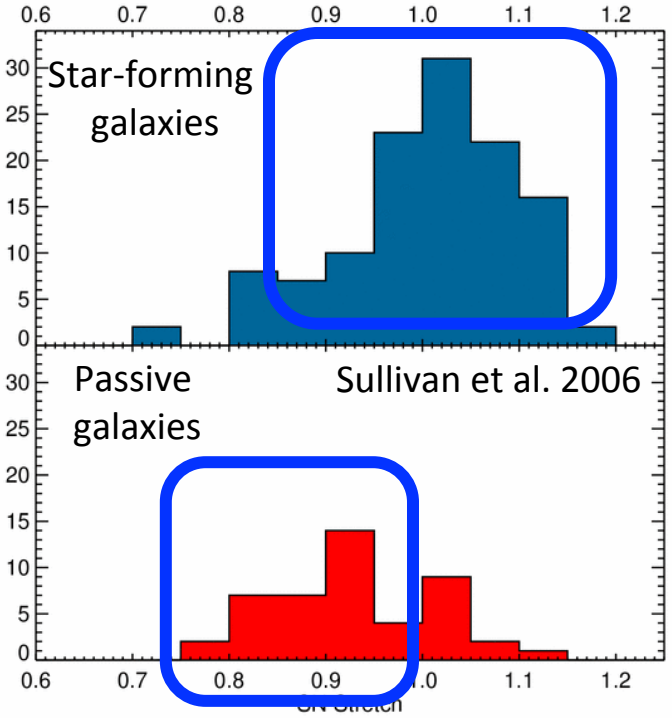
Link to progenitors?



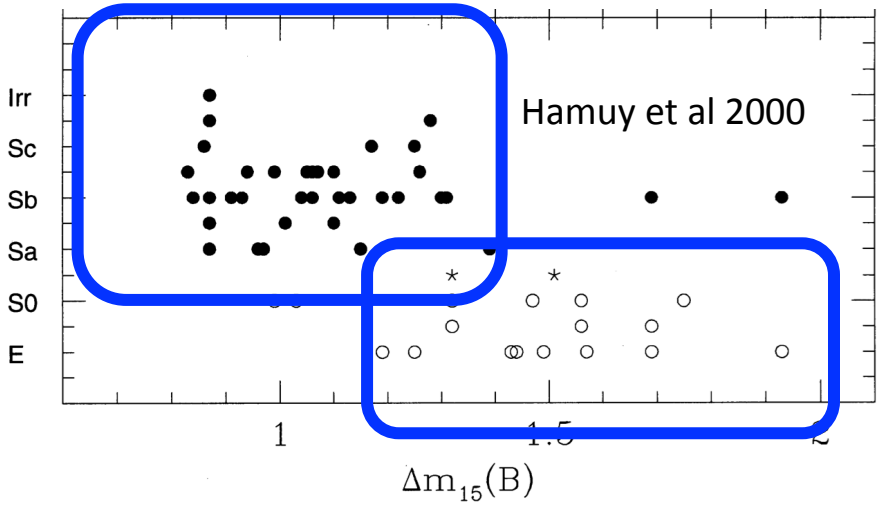
SNe Ia displaying blueshifted CSM have (on average) higher stretches: brighter SNe

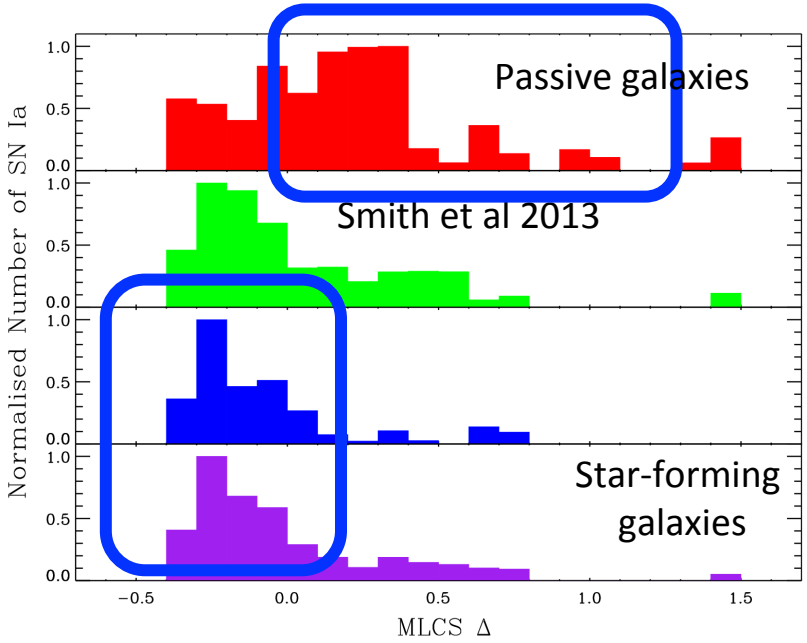
Maguire et al. 2013



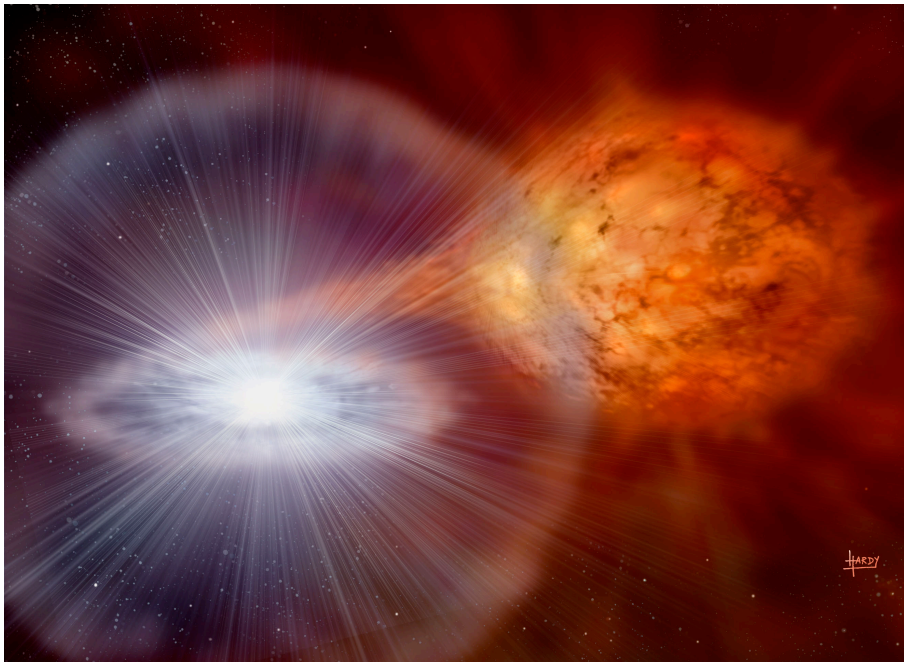


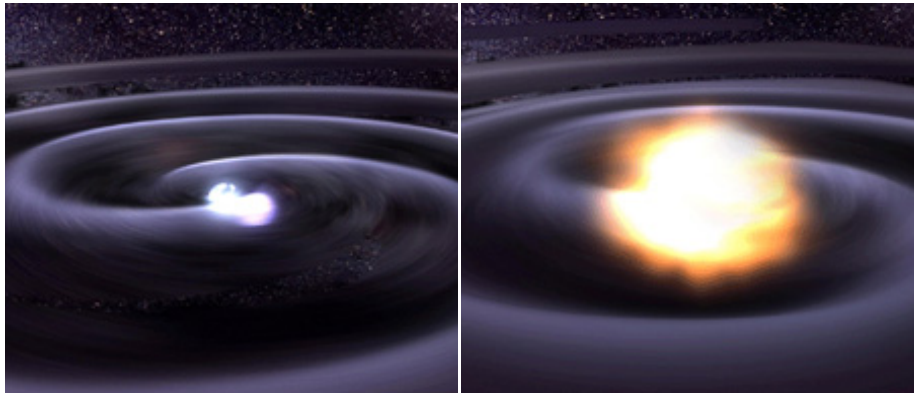
Light curve shape depends on host galaxy properties





More than one SN Ia progenitor system



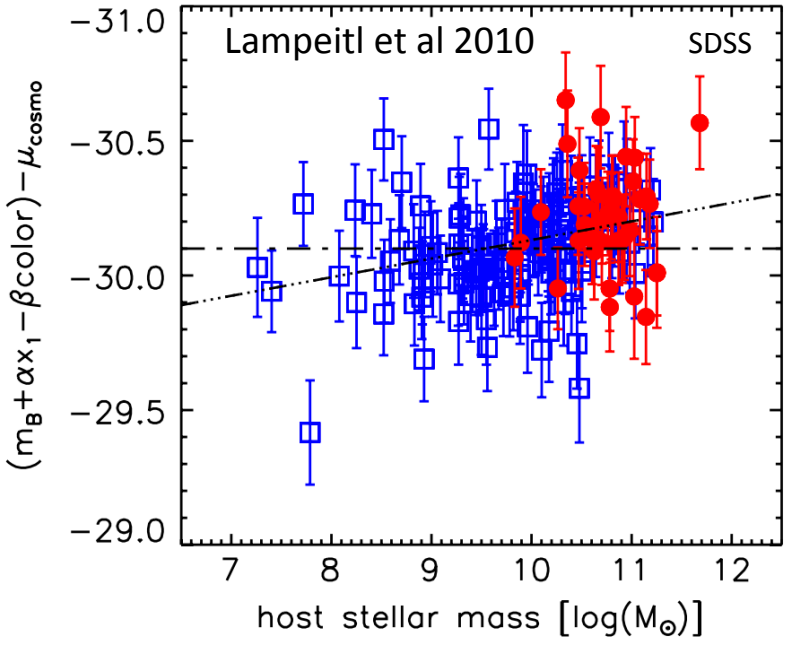


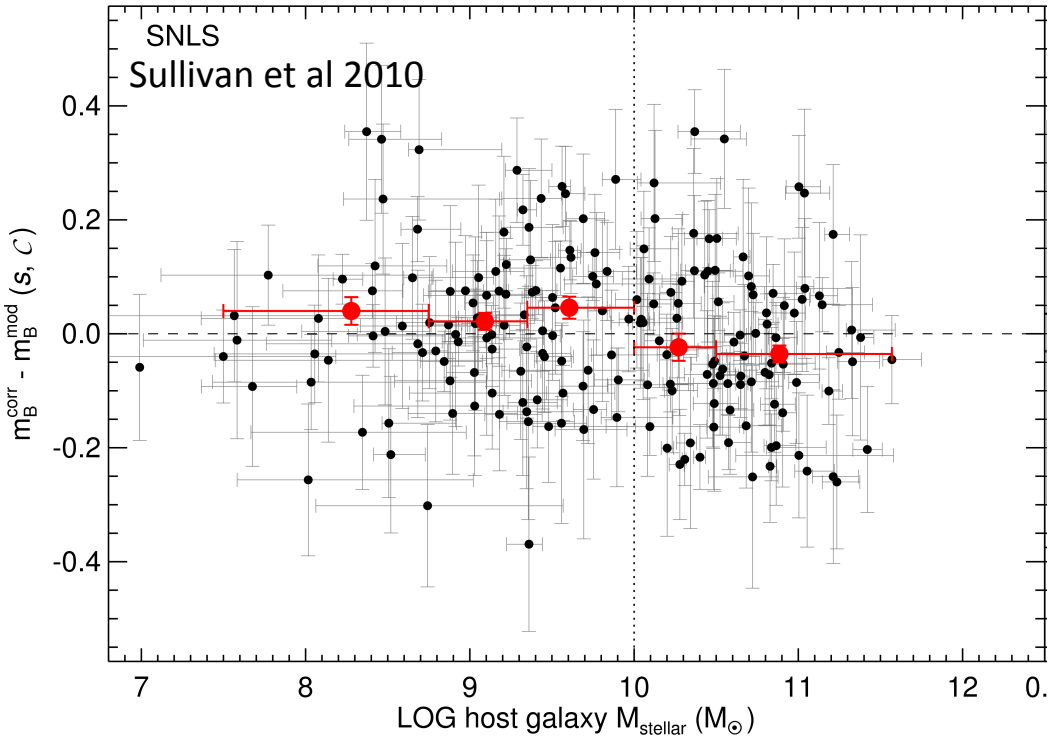
Over-luminous SNe Ia in young environments:

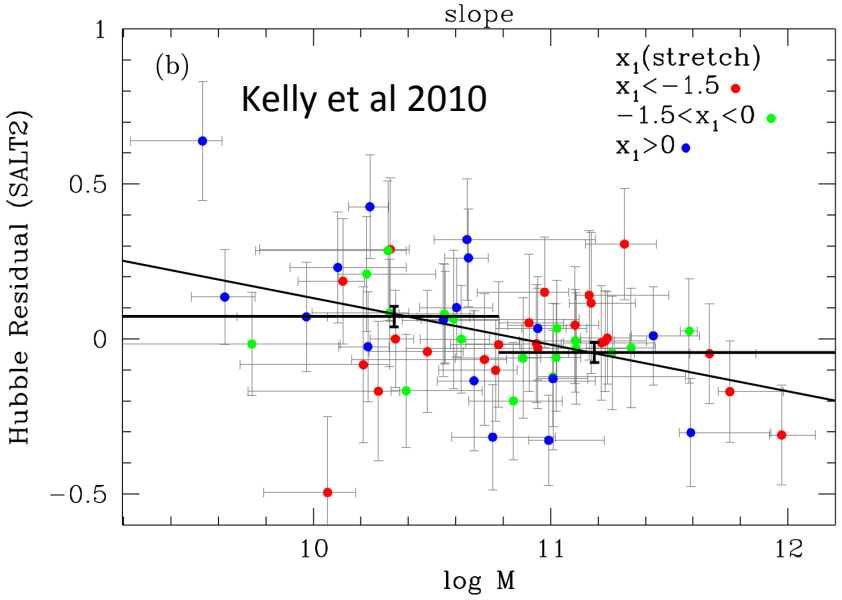
Evidence of being single degenerate?

Normal/under-luminous SNe in older environments:

Consistent with double degenerate?



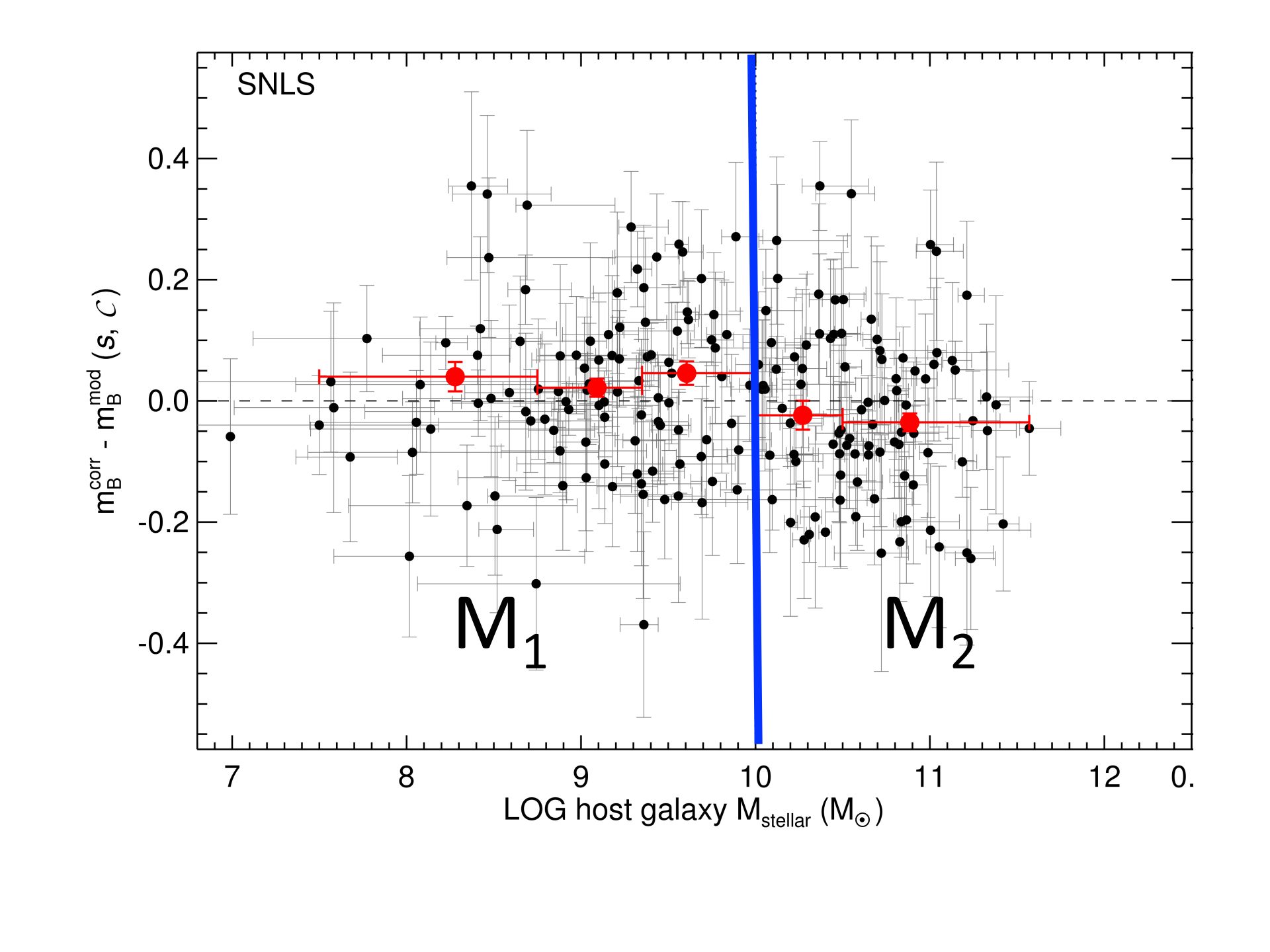




Hubble residuals depend on host galaxy properties

0.061 ± 0.012 mag

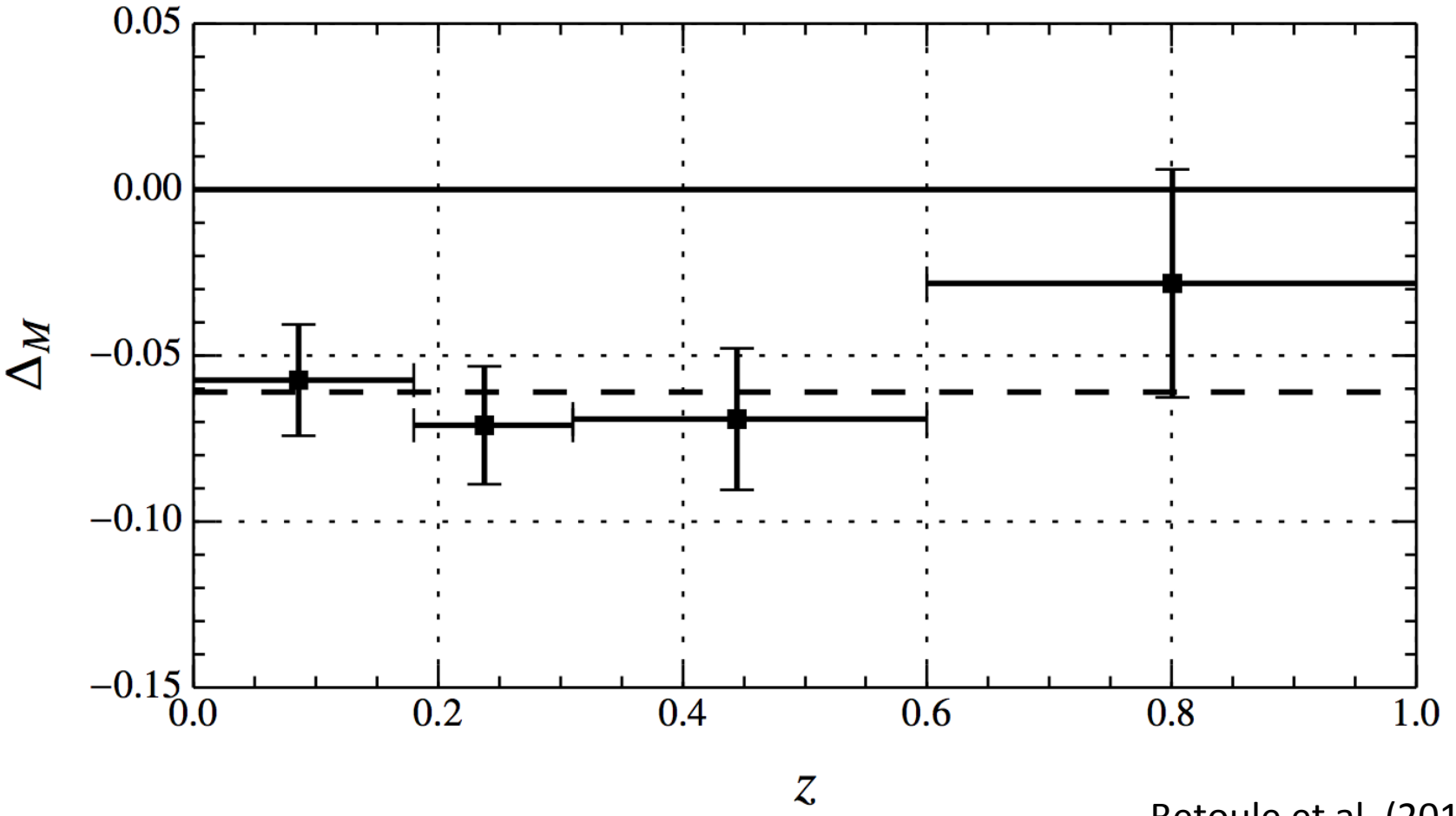
(See poster by Heather Campbell)


SNLS
0.4
0.2
0.0
-0.2
-0.4
$m_B^{corr} - m_B^{mod}(s, C)$
M1
M2
7
8
9
10
11
12
0.
LOG host galaxy $M_{stellar}$ ($M_\odot$)

Why use host stellar mass?

- Pros:
  - Easy to measure!
- Cons:
  - Almost certainly not the key physical variable
    - *"Everything" correlates with mass: age, metallicity, dust*
  - Host mass distribution affected by:
    - Selection effects
    - Field galaxy population demographics
  - A $10^{10} M_{\odot}$ host at z=0 is not the same as at z=0.8

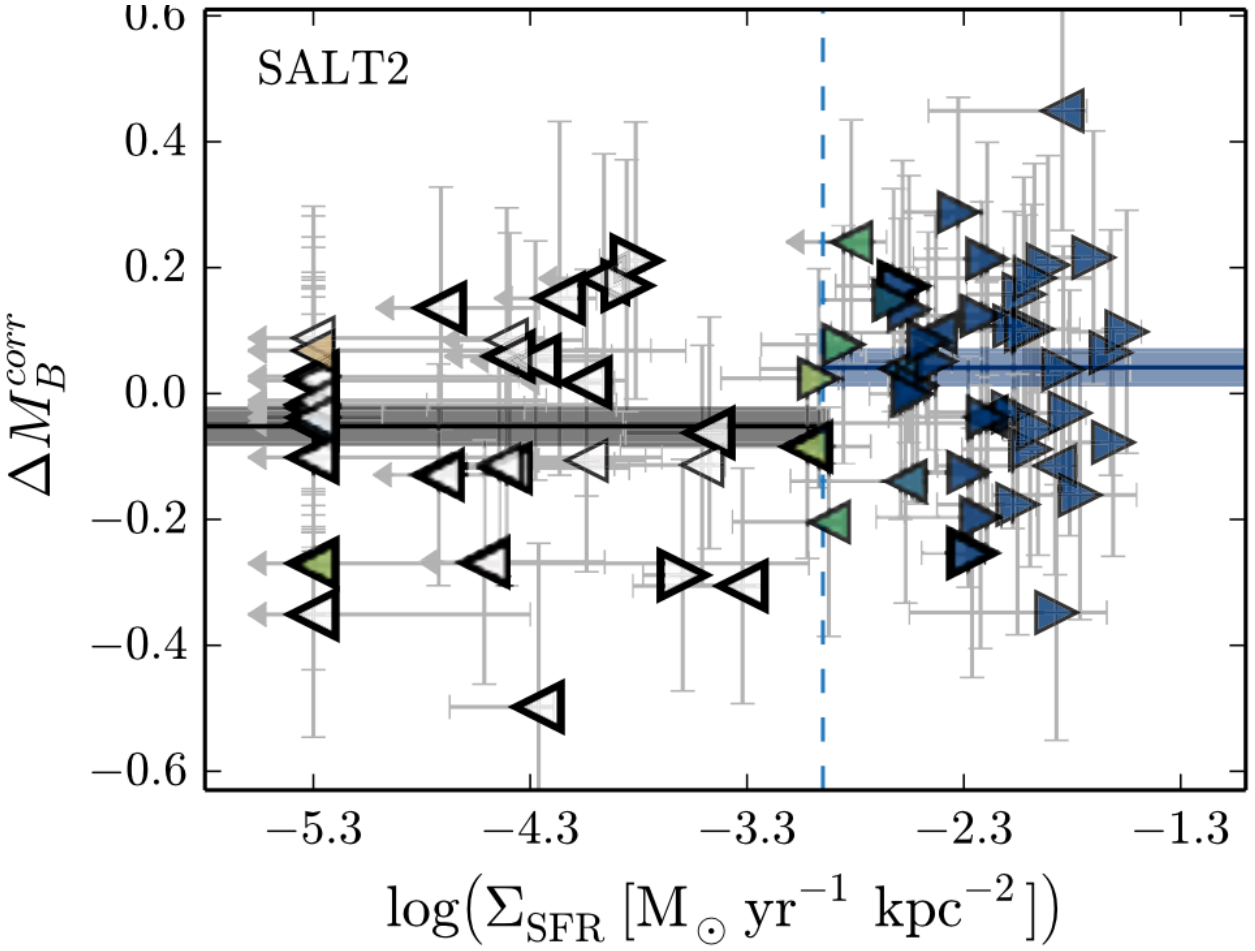
No evidence for mass-step evolution with redshift



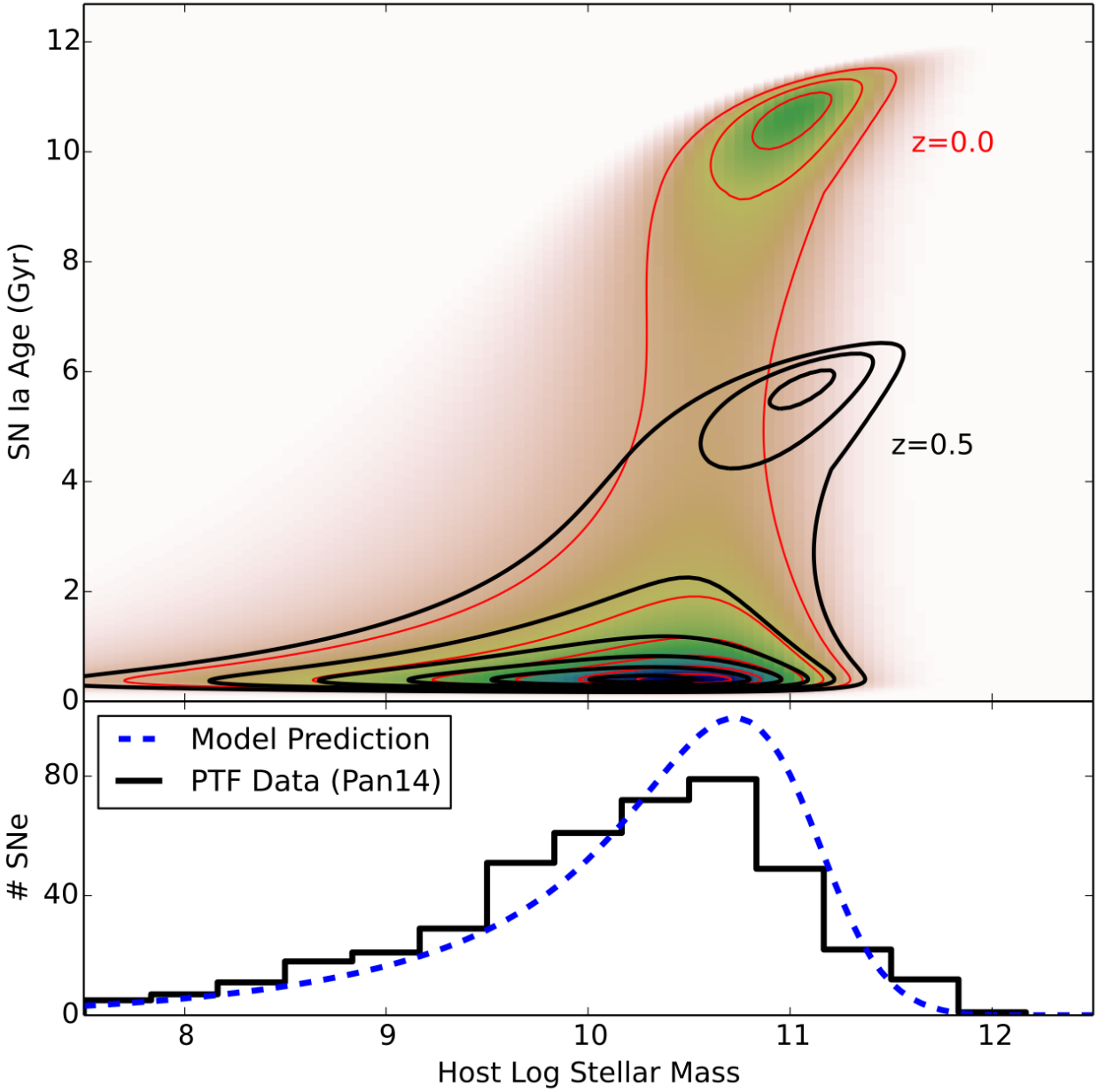
Betoule et al. (2014)

Correlation with local SFR (age)

Strong correlation between Hubble residuals and local star-formation rate



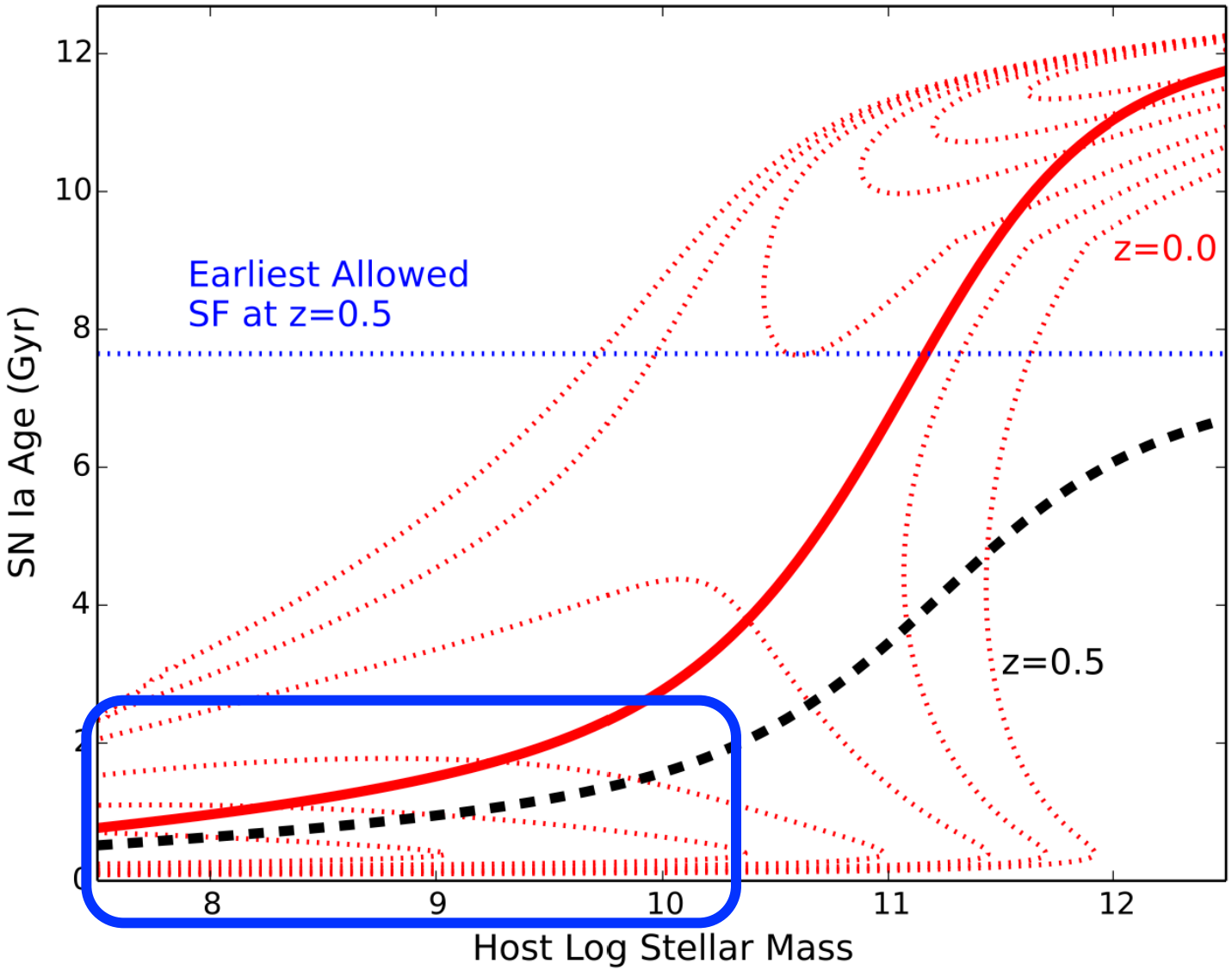
Rigault et al. (2015)



Simulation combining SN Ia formation rate and galaxy evolution

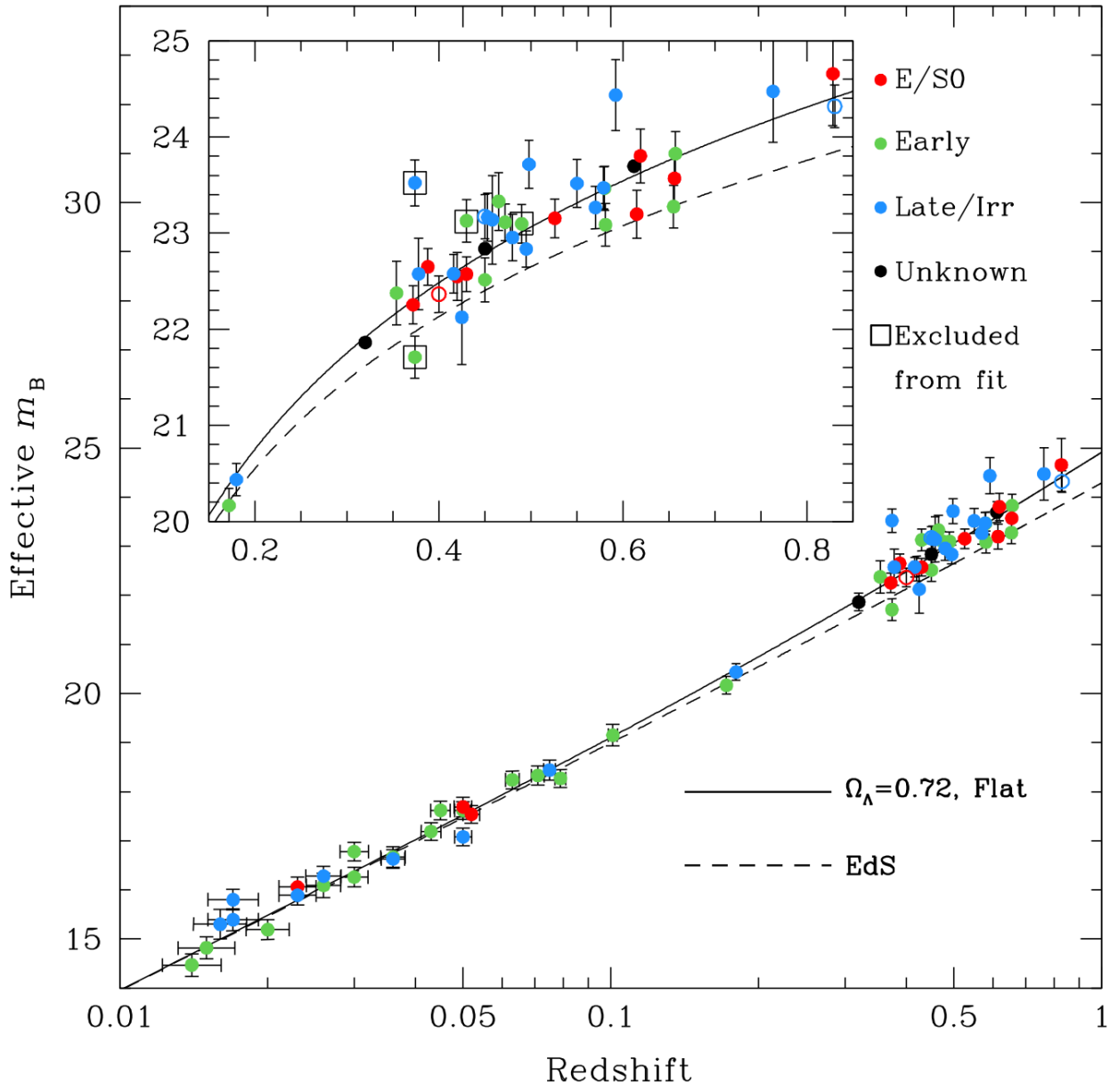
Result predicts SN progenitor age as a function of host stellar mass

Childress et al. (2014)



The most homogeneous SN Ia events are in lower mass galaxies

Childress et al. (2014)



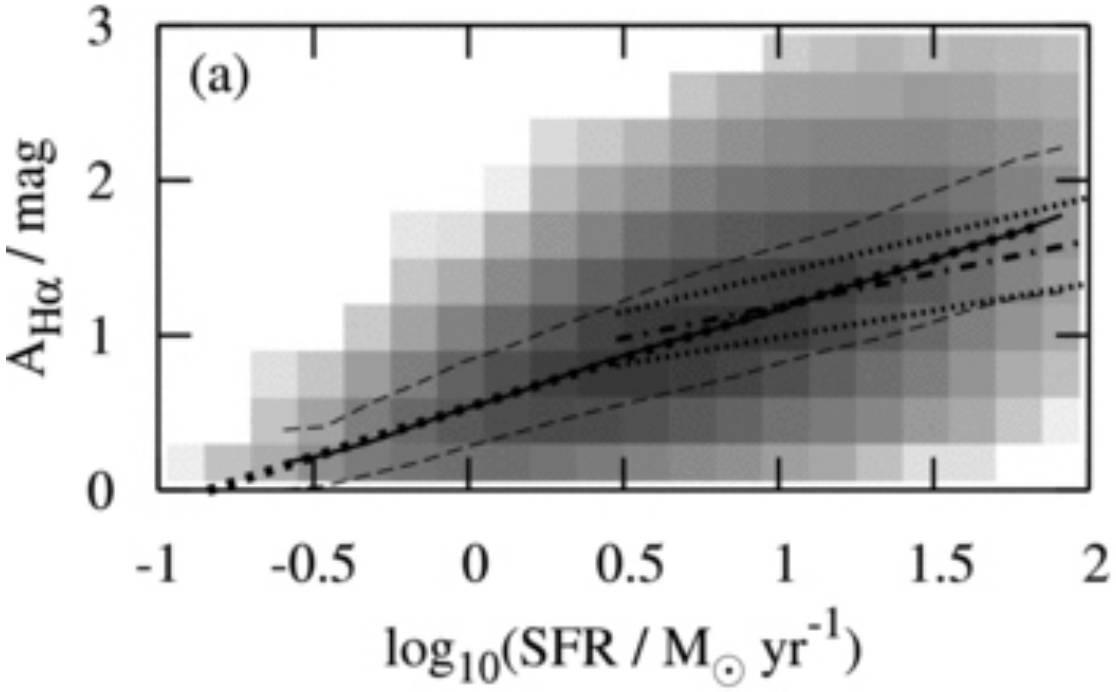
Earlier evidence suggested SNe Ia in E/S0s had low scatter

Improved colour corrections/handling improved SNe in spirals

Now no observational evidence that SNe Ia in E/S0s are "better"

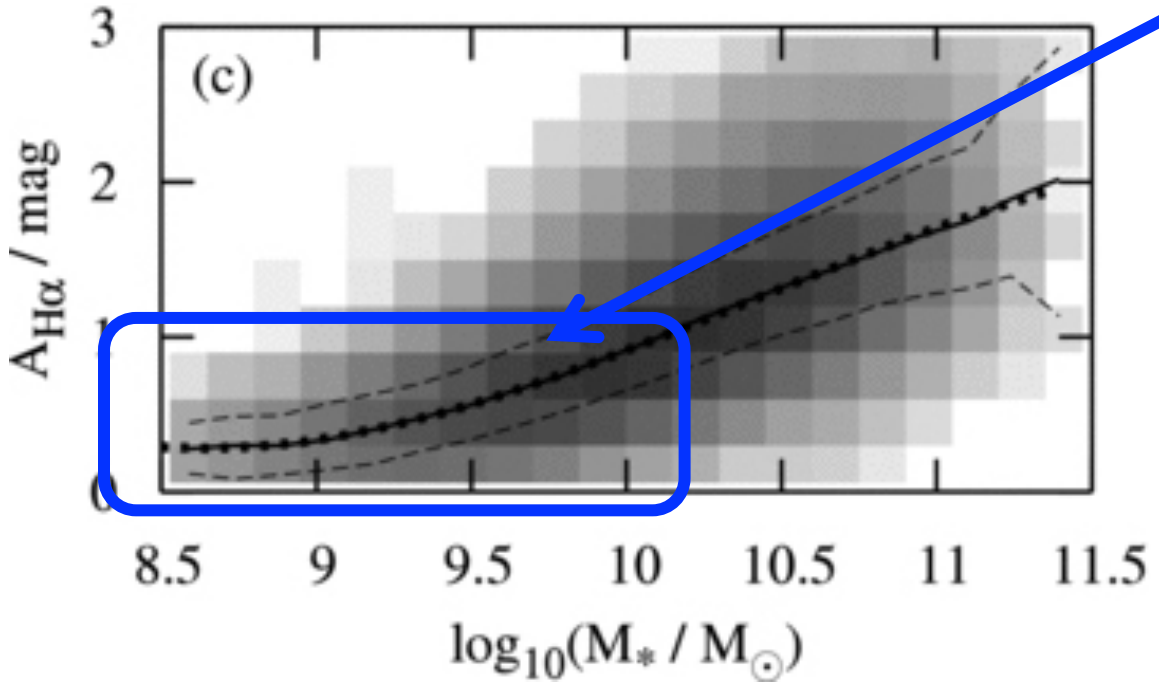
Sullivan et al. (2003)

(Relations for star-forming SDSS galaxies)



Dust versus SFR

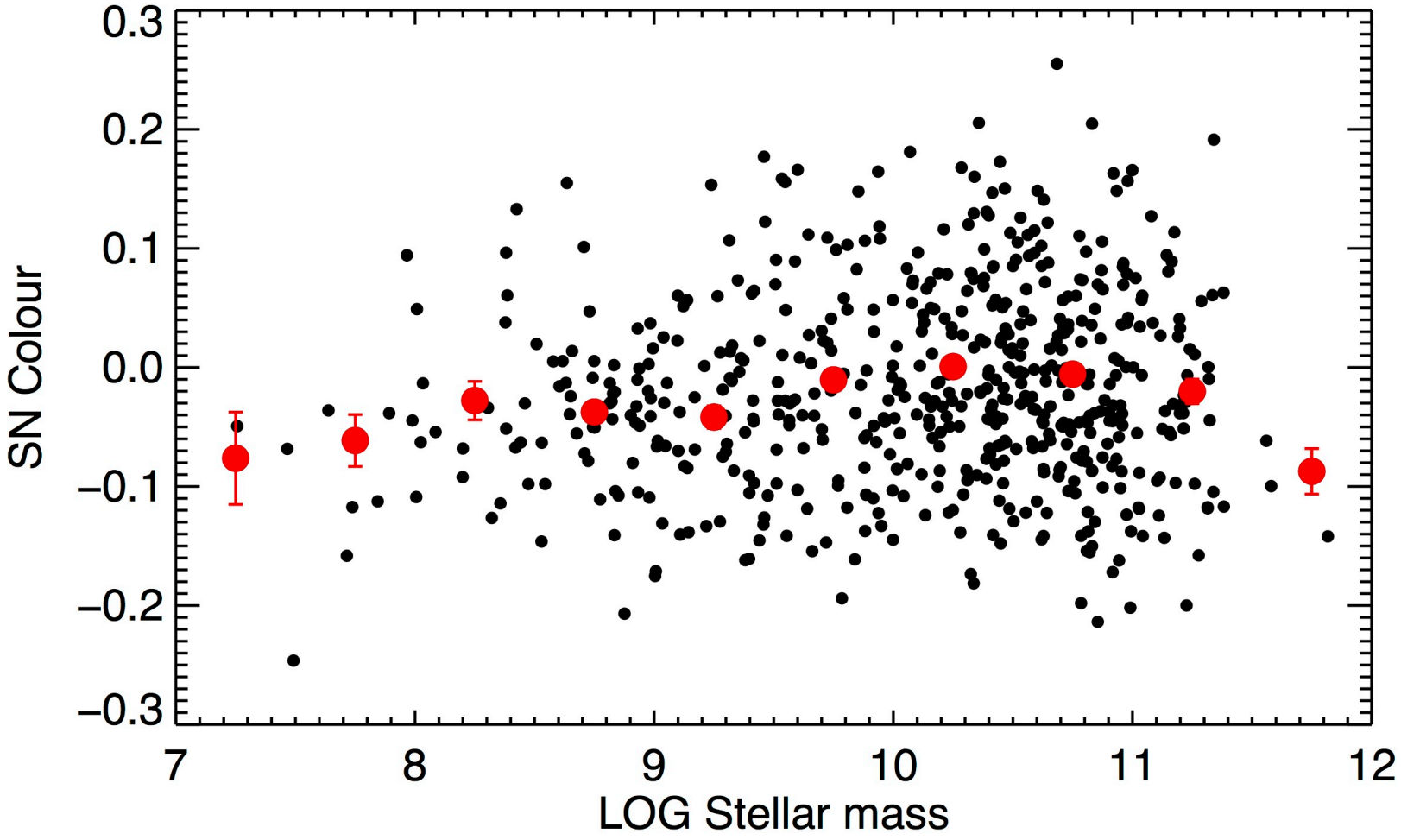
SN Ia events with low extinction are more likely to be in lower mass galaxies



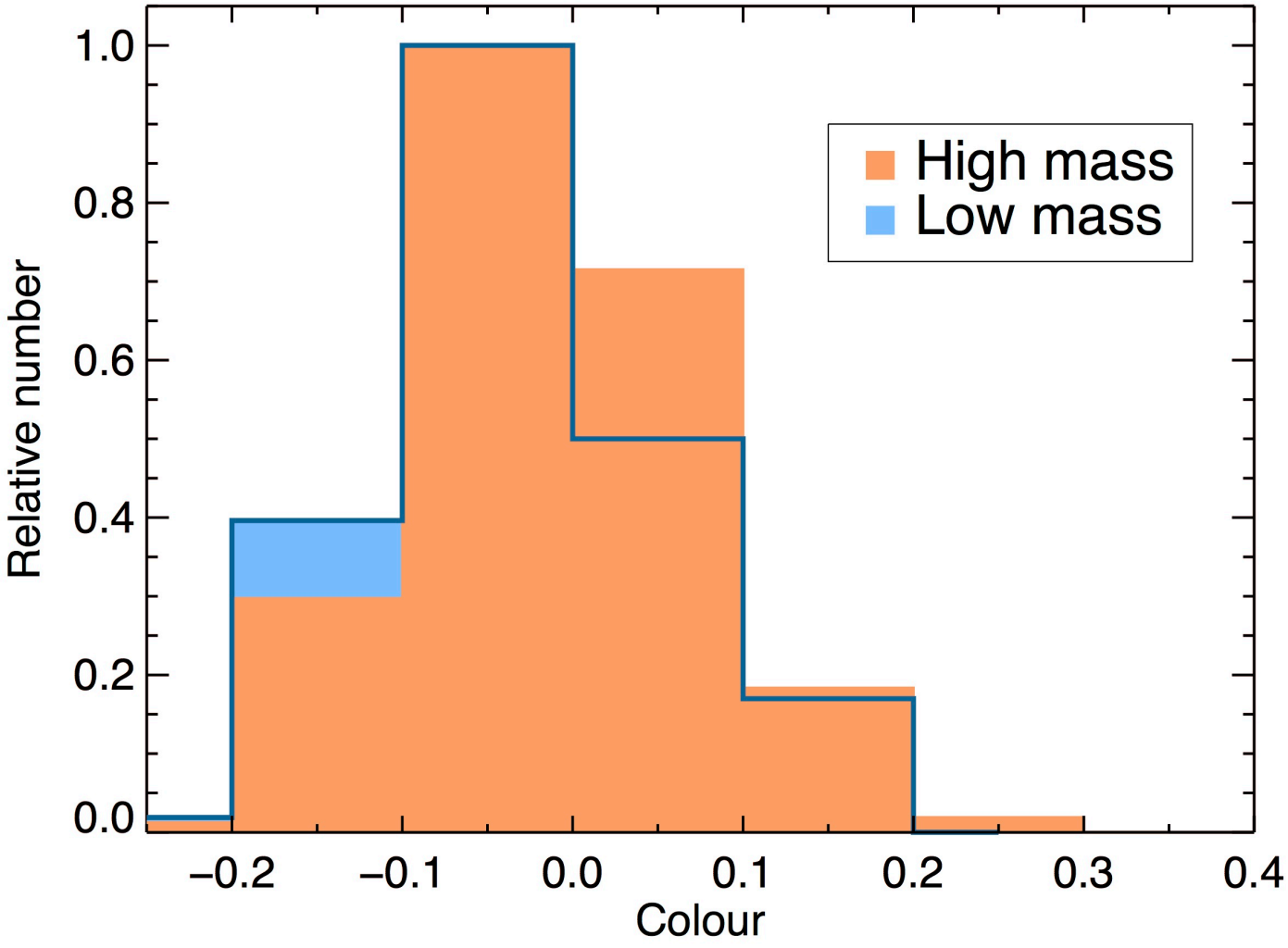
Dust versus stellar mass

Garn & Best (2010)

SN colour versus stellar mass



Betoule et al. sample



KS test: 2% chance from same population

Means differ at about 3.5σ

Betoule et al. sample

Summary

- SN Ia constraints on <w>: <w>≈-1 to <5.4% (flat), ~9% (non-flat)
  - Includes CMB, and all SN Ia systematics
  - In the current results, SNe Ia are an excellent probe of dark energy
- Astrophysical systematics are (currently) sub-dominant
- New low-redshift samples are revealing the SN physics:
  - Strong (direct) confirmation of the basic scenario
  - Evidence for diversity in SN Ia progenitors
- Selecting by environment may give more homogenous samples