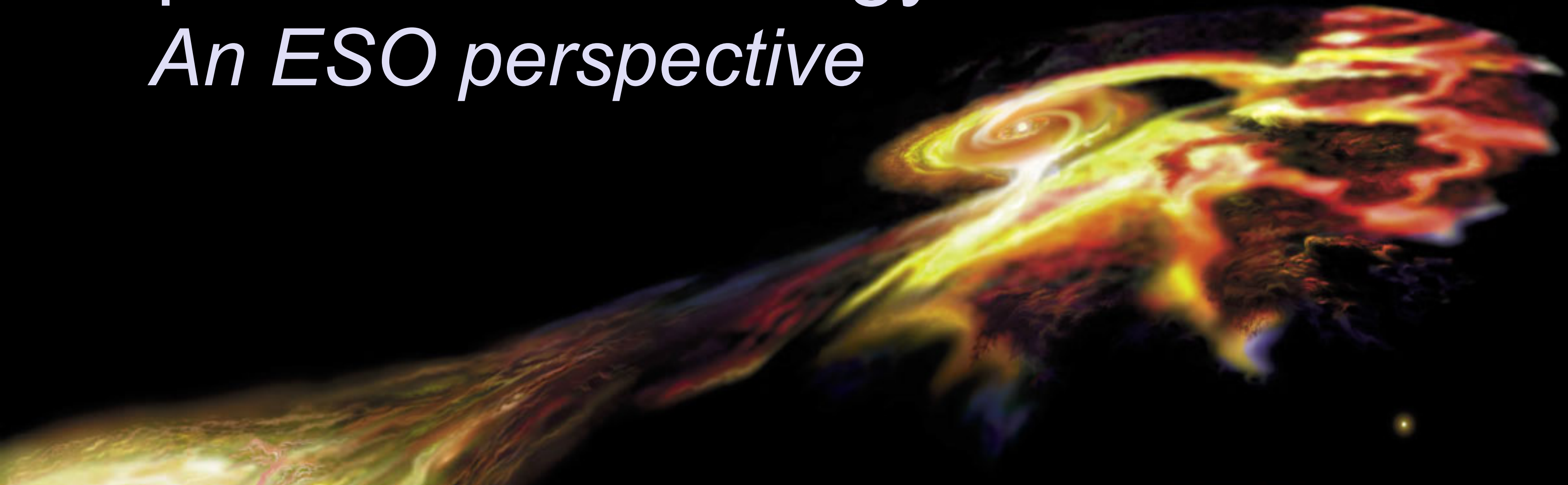
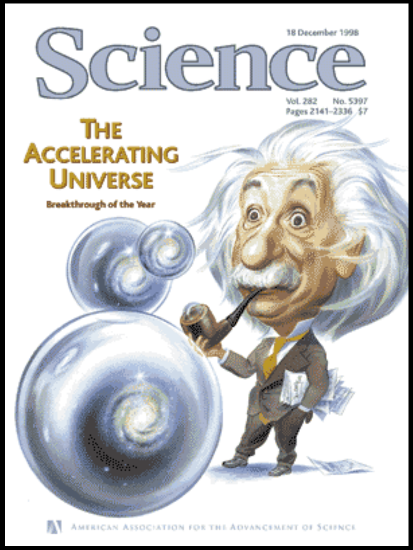
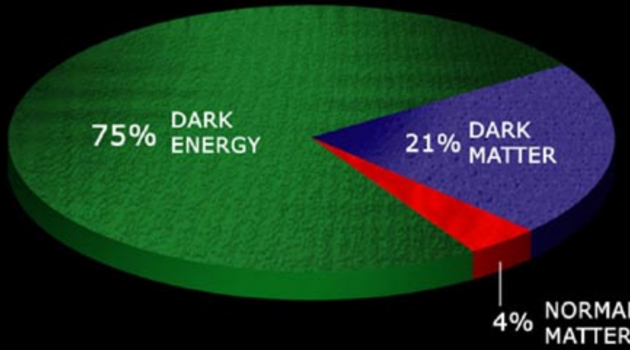
Supernova Cosmology:
An ESO perspective





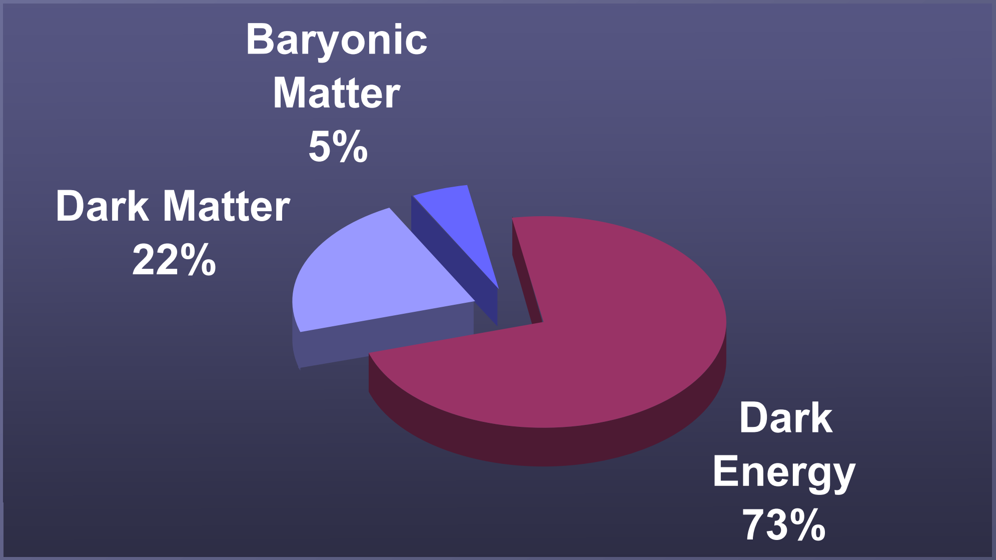


Mark Sullivan
(Oxford)

Supernova Cosmology

- ➜ Dark energy
  - Understanding the accelerating universe
- ➜ The ESO perspective
  - Early years – missed opportunities?
  - The 1990s
  - ESO's role in follow-up
- ➜ Supernova Legacy Survey
  - State-of-the-art constraints
  - Two ESO large programs
- ➜ Supernova physics
  - Type Ia supernova progenitor stars
- ➜ New surveys and ESO
  - PESSTO
  - DES
  - Euclid?

Nearly a century after Einstein, the "cosmological constant" is back in vogue



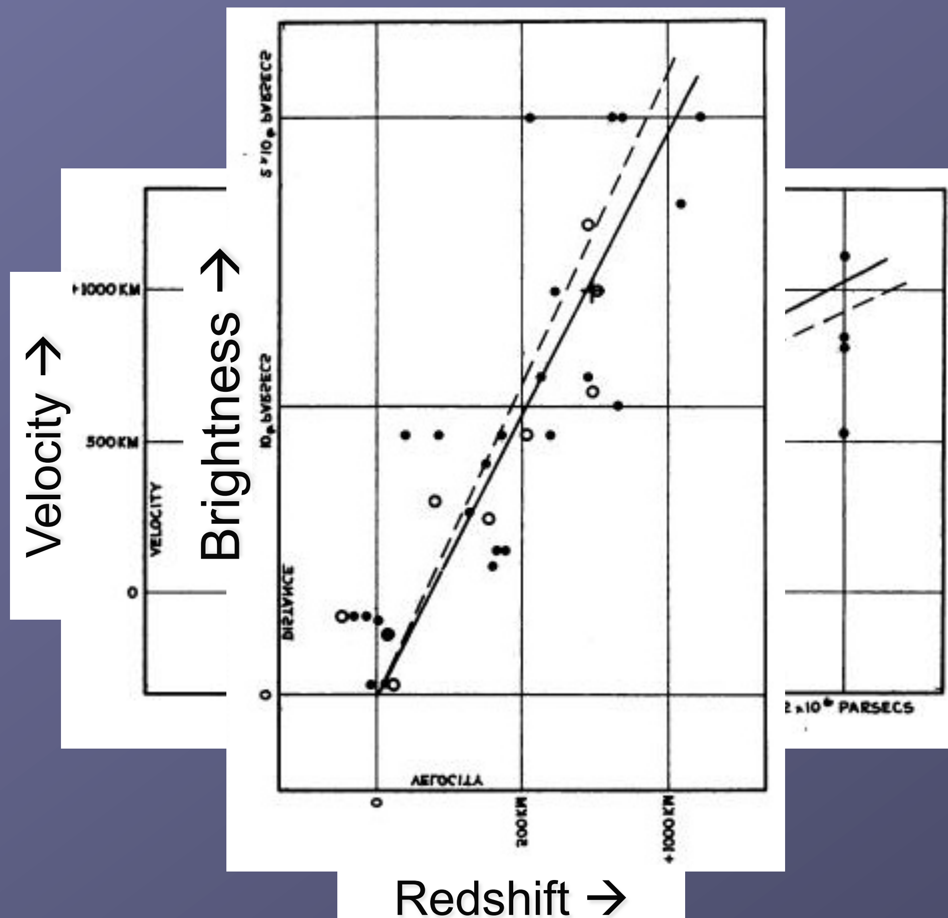
Deluge of astrophysical data show the expansion of the Universe is accelerating. What does this mean?

Gravity should act to slow the expansion!

1) *GR is incomplete – modified gravity on large scales?*

2) *"Λ", >70% of the Universe in an unknown form – "dark energy"*

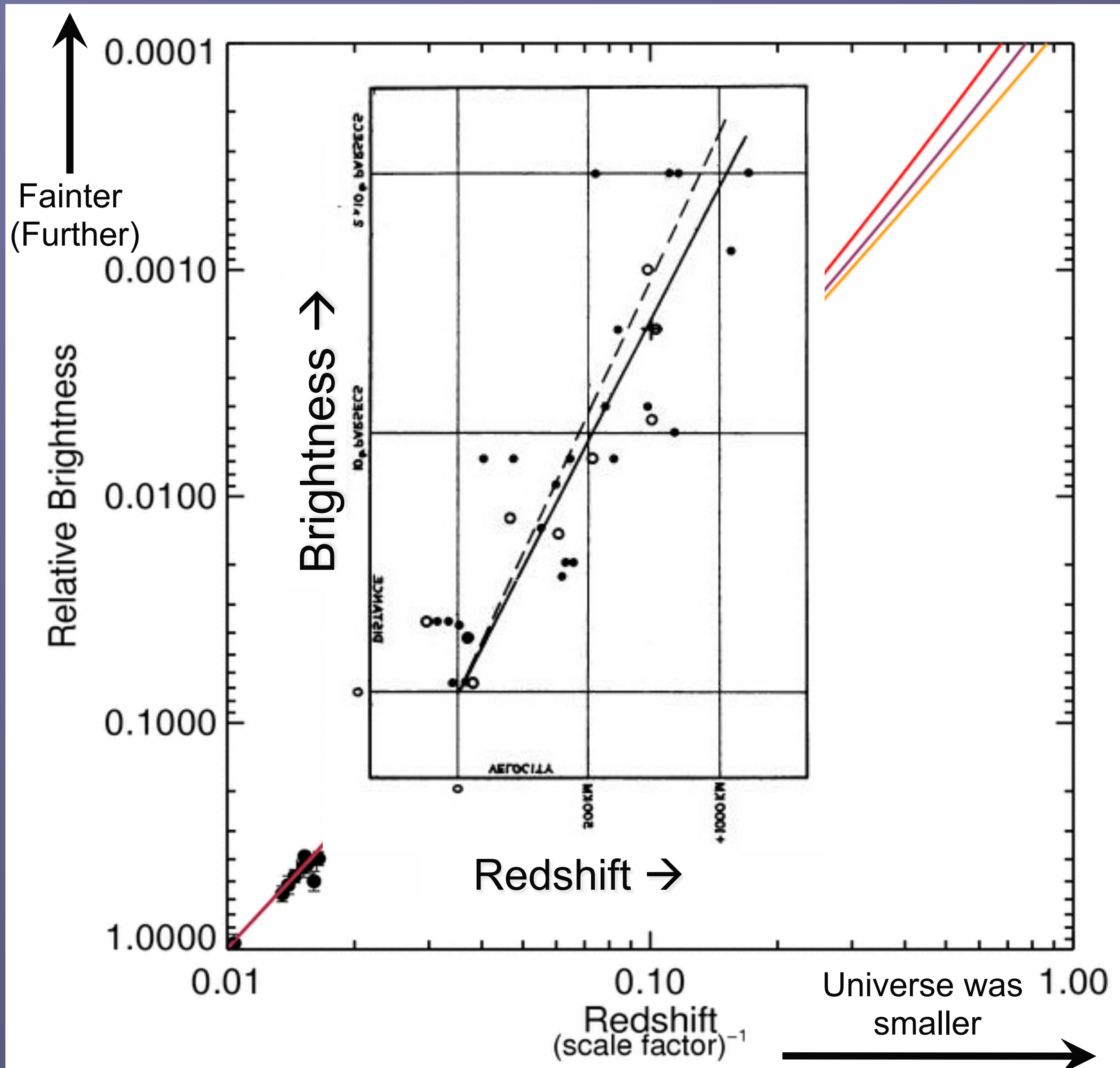
The standard candle



Standard candle: $$f = \frac{L}{4\pi d_L^2}$$

$$d_L \propto \left(z, w, \Omega_M, \Omega_{DE}\right)$$

The modern day Hubble Diagram



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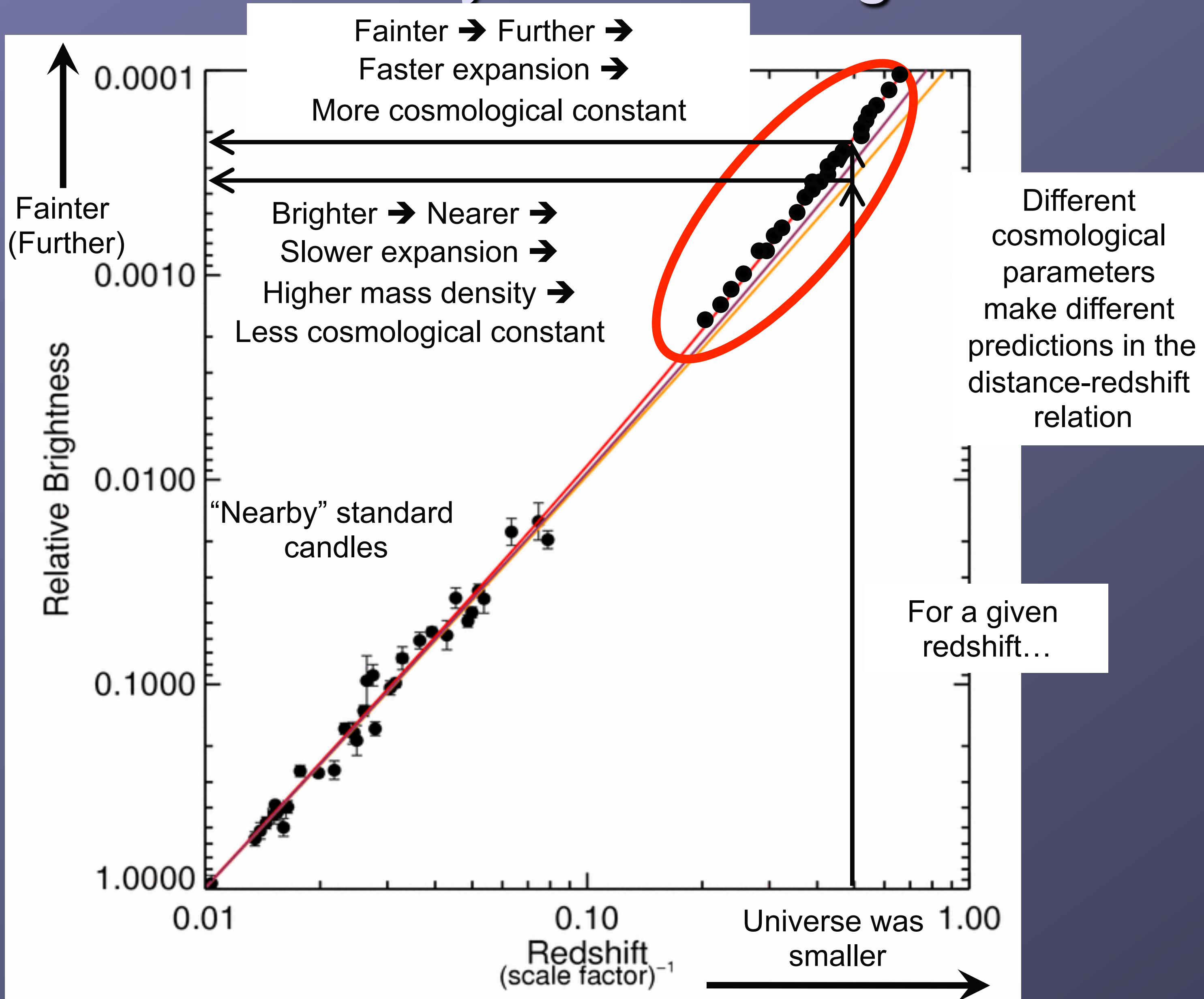
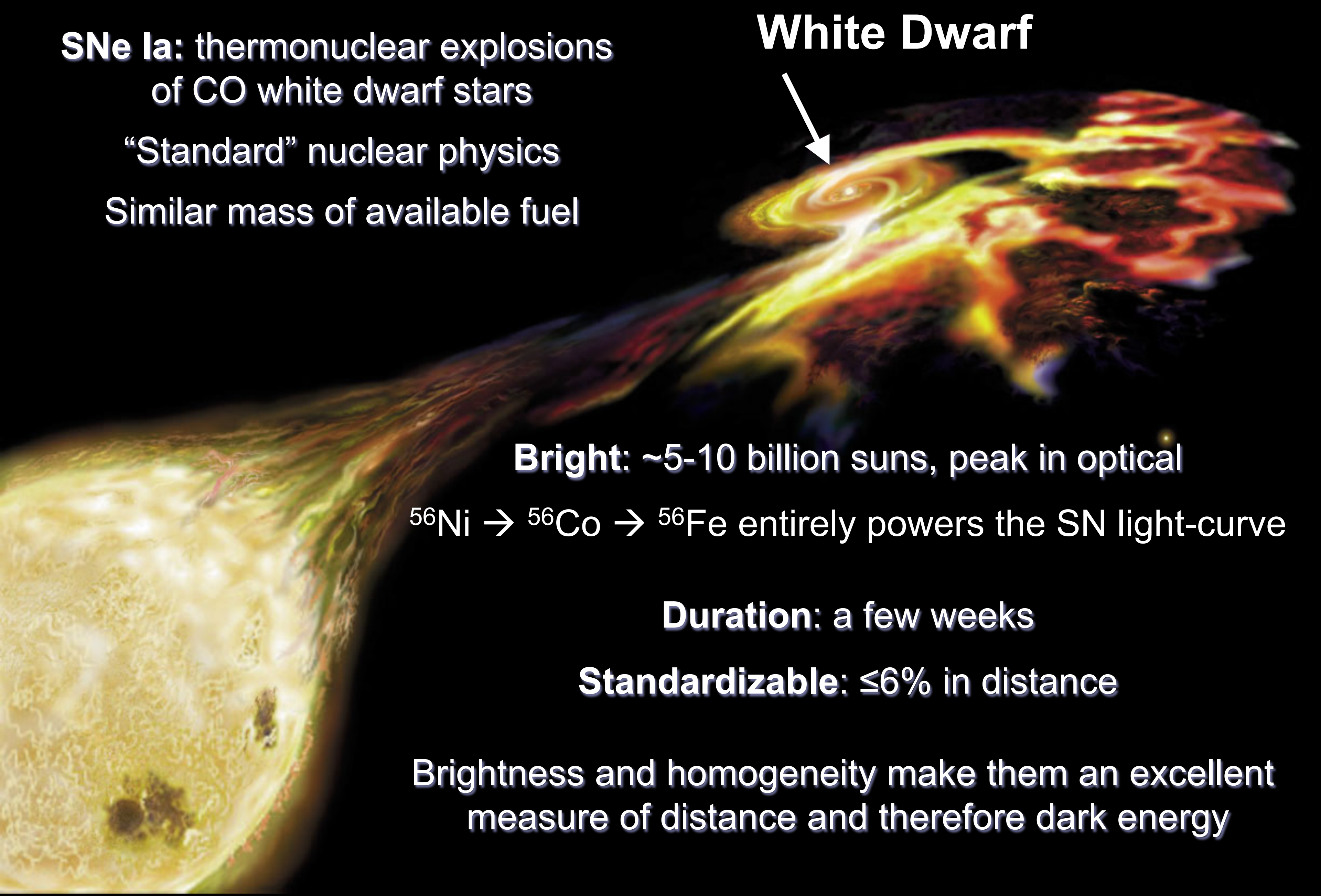


"Distance-
redshift"
relation

SNe Ia: thermonuclear explosions of CO white dwarf stars

"Standard" nuclear physics

Similar mass of available fuel



Bright: ~5-10 billion suns, peak in optical

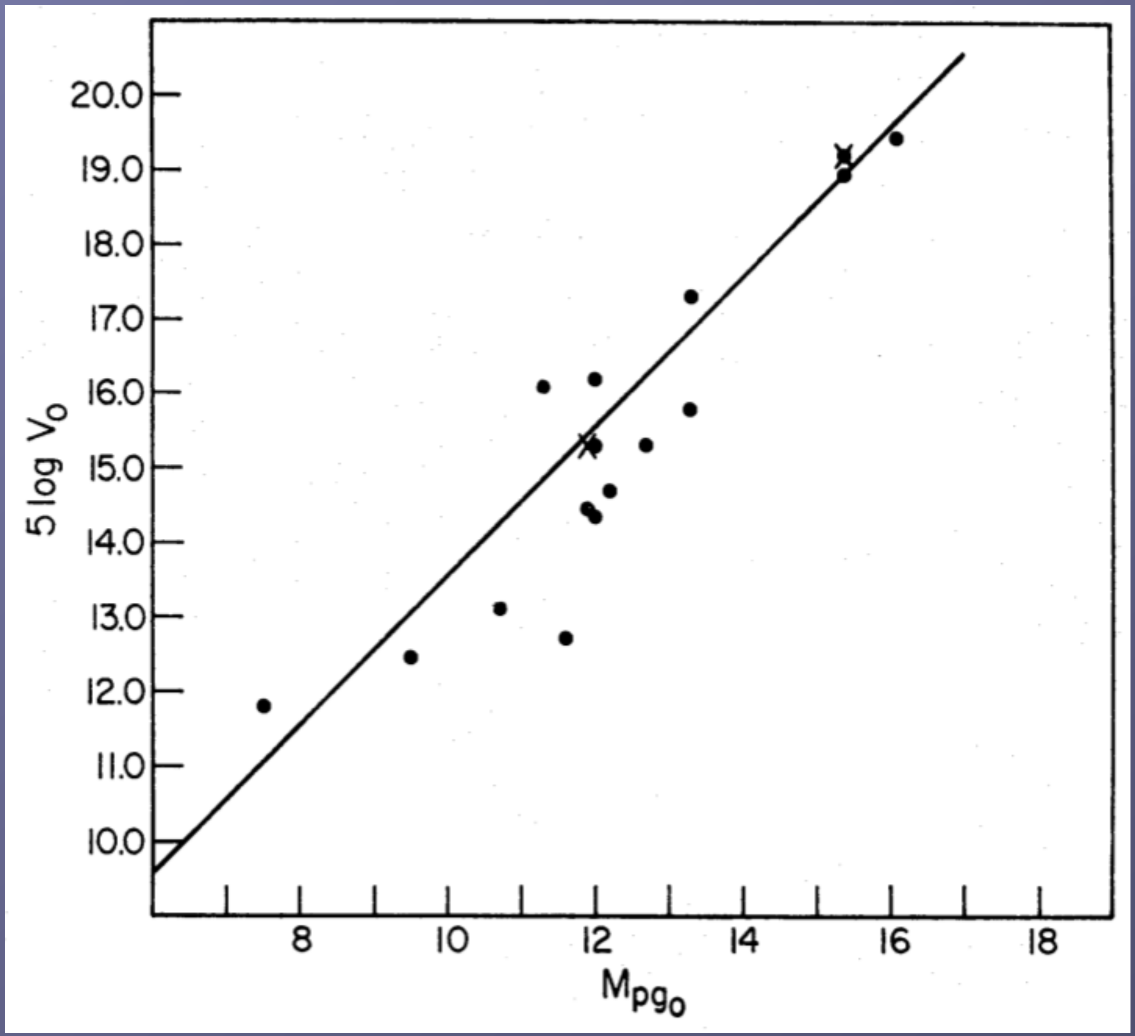
^{56}Ni → ^{56}Co → ^{56}Fe entirely powers the SN light-curve

Duration: a few weeks

Standardizable: ≤6% in distance

Brightness and homogeneity make them an excellent measure of distance and therefore dark energy

So why did it take so long?



SN Hubble diagrams go back to the 60s (and even earlier)

Type I SN Hubble Diagram

Observed dispersion 0.6mag (cf 0.14 today)

(Difference between EdS and Λ at z=0.5 is 0.45mag)

Kowal 1968

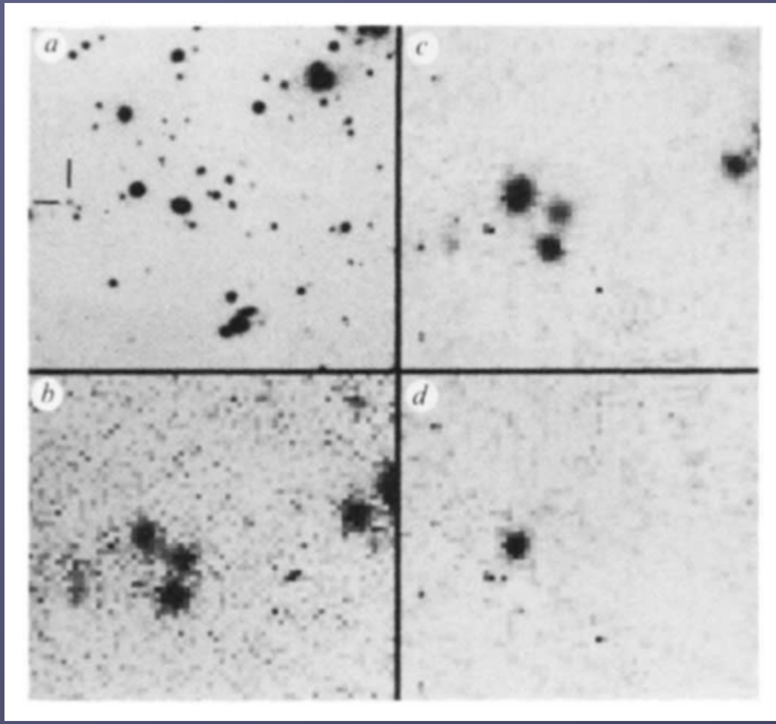
Finding and understanding SNe was hard

1. Large areas of sky need to be surveyed in short times
2. Need depth – R~23.0 @ z=0.5 for discovery and follow-up
3. Telescope scheduling must match the rise-time of the SNe
4. Significant data-flow generated
5. Reliable image subtraction methods

The Early Years – late 80s

- Danish 1.5m at La Silla
- Norgaard-Nielsen 1989
  - First concerted CCD search
  - A SN Ia at z=0.31
  - 60 galaxy clusters (more mass) over 2 years, 1 hour per month
  - Nearly 1000 hours on a 1.5m telescope!

The discovery of a type Ia supernova at a redshift of 0.31



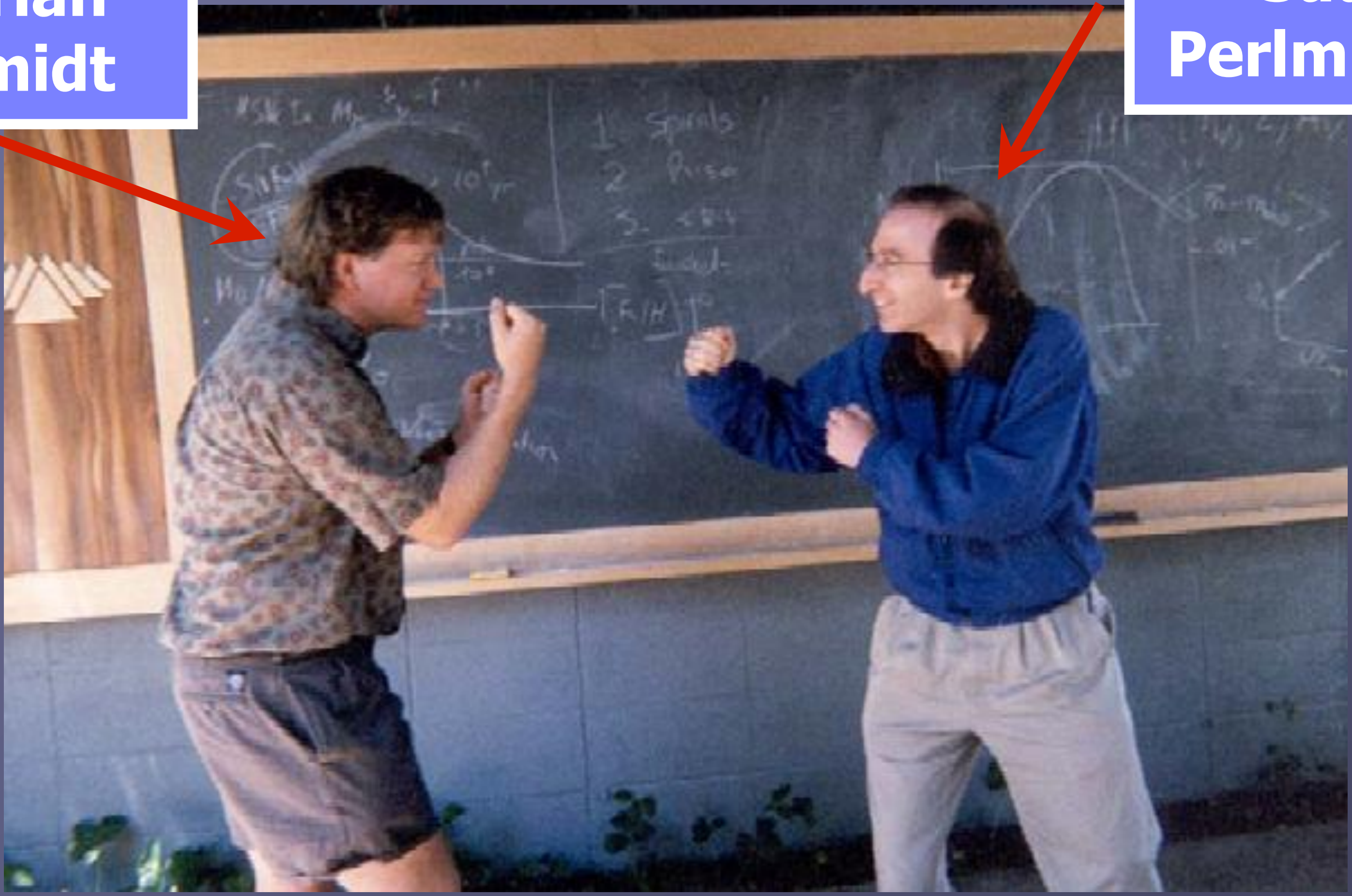
But this was the last large-scale “ESO-based” SN search effort

Cosmology – the 1990s

In the nineties, two teams chased the cosmological parameters

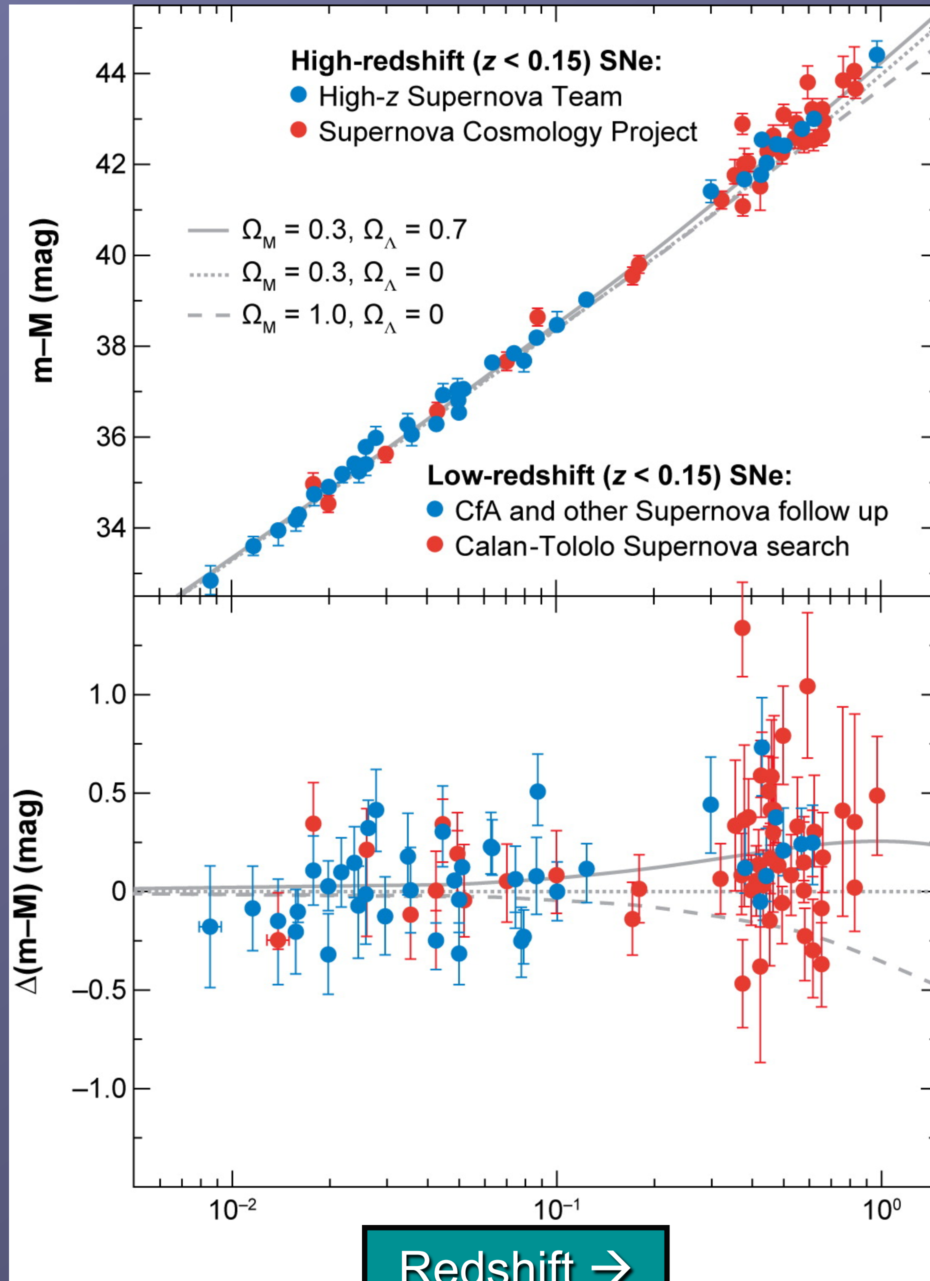
HZSST, led by Brian Schmidt

SCP, led by Saul Perlmutter



1998/9: Led to cosmological parameters

Apparent brightness →



Redshift →

The (then) "surprising" result of Ω_M=0.3 Ω_Λ=0.7

The teams that took these data were awarded the 2011 Nobel Prize for Physics

(Compilation from Frieman et al. 2008)

ESO and SN follow-up

- Large-format CCD cameras used for discovery were mostly US-based
- ESO played a critical role in follow-up spectra and light curves

(this reflects a continuing theme in SN cosmology)

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4] PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2] B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7] R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4] NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]

Imaging: ESO NTT/3.6m/1.5m

Spectra: ESO 3.6m

~6500 citations each

Imaging: ESO 3.6m

Spectra: ESO 3.6m

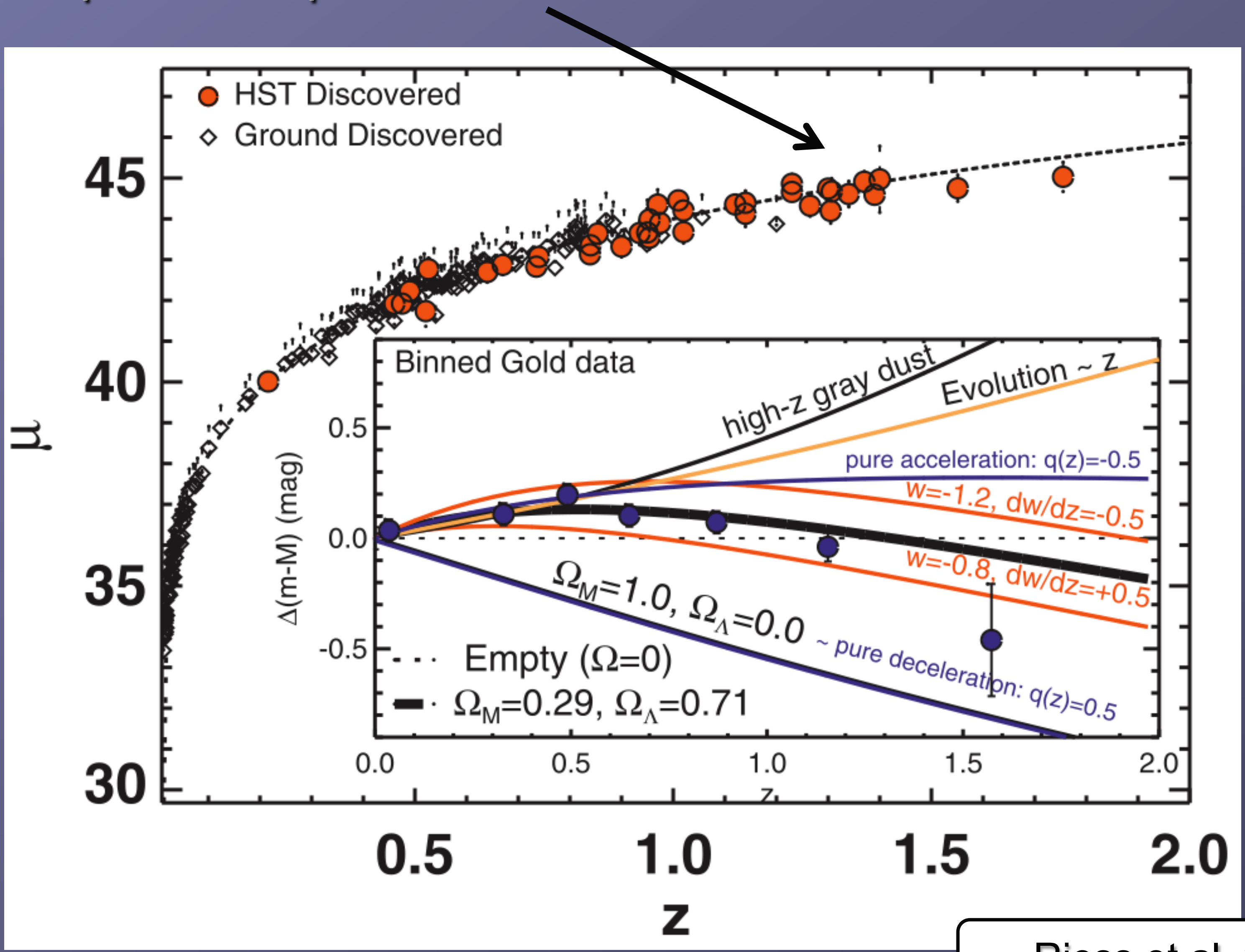
MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. PERLMUTTER,[1] G. ALDERING, G. GOLDHABER,[1] R. A. KNOP, P. NUGENT, P. G. CASTRO,[2] S. DEUSTUA, S. FABBRO,[3] A. GOOBAR,[4] D. E. GROOM, I. M. HOOK,[5] A. G. KIM,[1,6] M. Y. KIM, J. C. LEE,[7] N. J. NUNES,[2] R. PAIN,[3] C. R. PENNYPACKER,[8] AND R. QUIMBY

Institute for Nuclear and Particle Astrophysics, E. O. Lawrence Berkeley National Laboratory, Berkeley, CA 94720

To z>1

- VLT provided spectra for HST discoveries

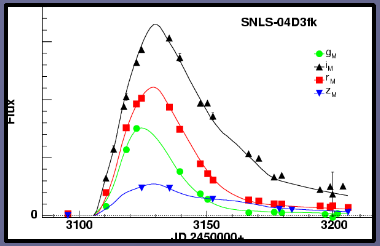


Riess et al. 2007

Supernova Legacy Survey: 2003—2008

Imaging

Distances from light-curves



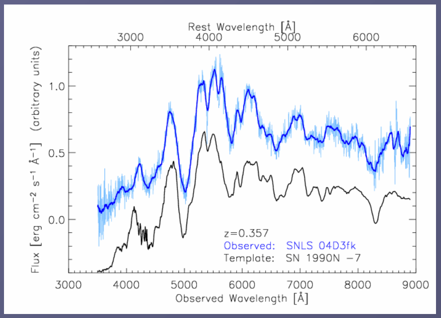
Discoveries **Lightcurves**

g'r'i'z' every 4 days during dark time

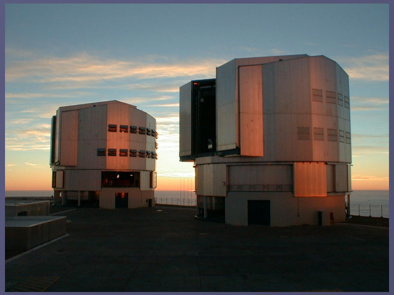
~1000 hours over 5 yrs

Spectroscopy

Redshifts → Distances from cosmological model



Gemini N & S (120 hr/yr)



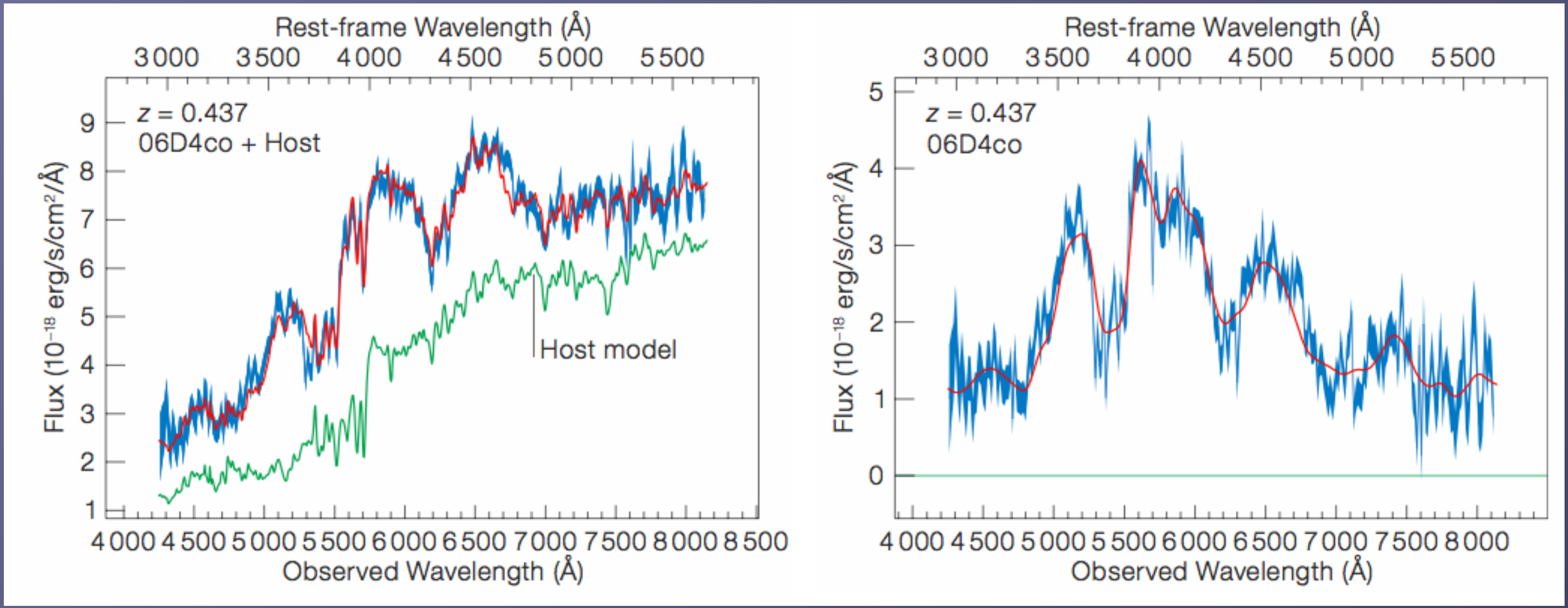
VLT (120 hr/yr)

Keck (8 nights/yr)

Magellan (15 nights/yr)

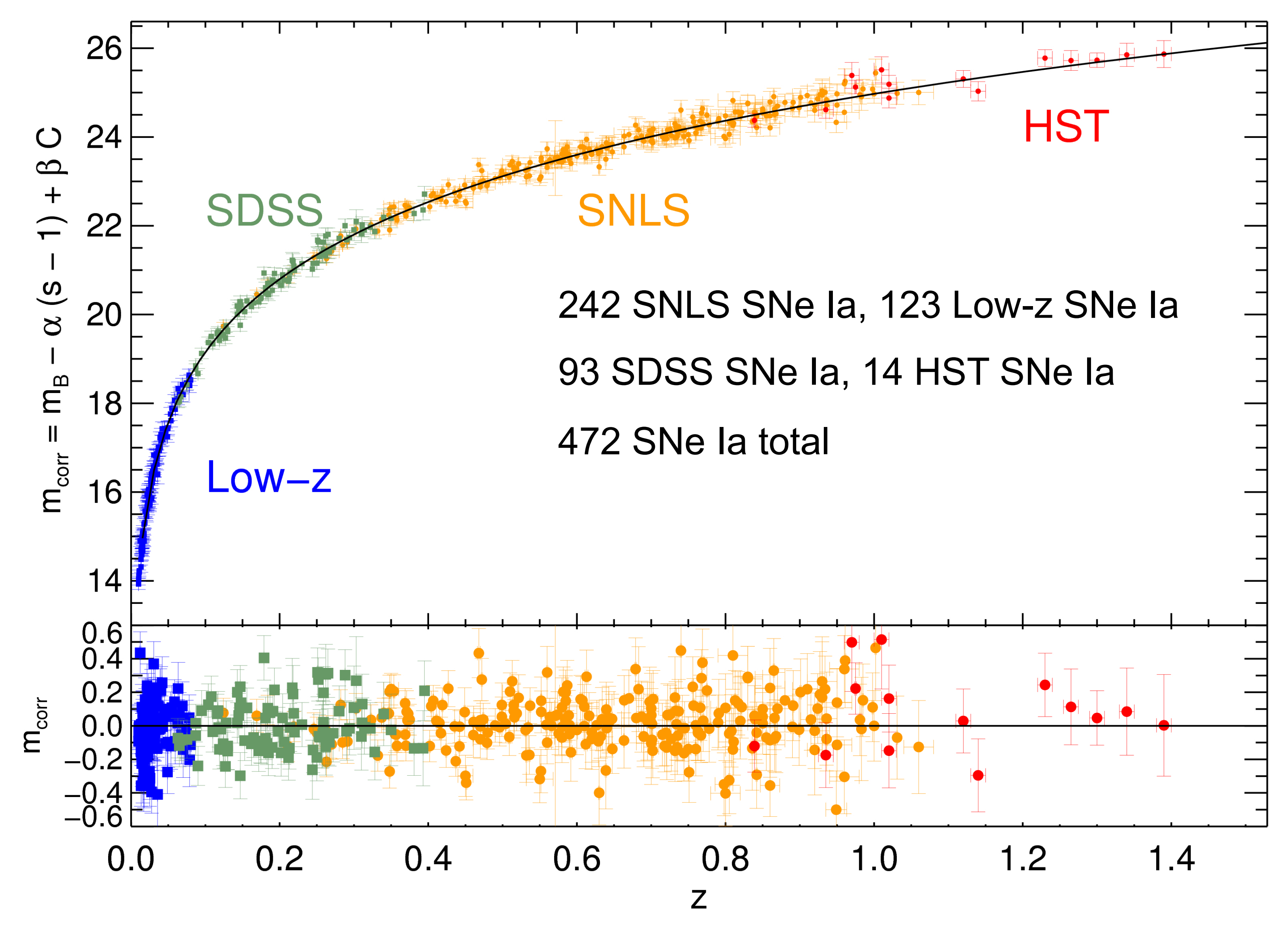
Two ESO Large Programs

- VLT ToO mode very effective
- FORS2 red sensitivity perfect for high-z SNe Ia
- 480 hr over 4 years (PI Pain)
  - >320 spectra, >200 SNe Ia
- Developed new techniques for analysis of high-z SN spectra



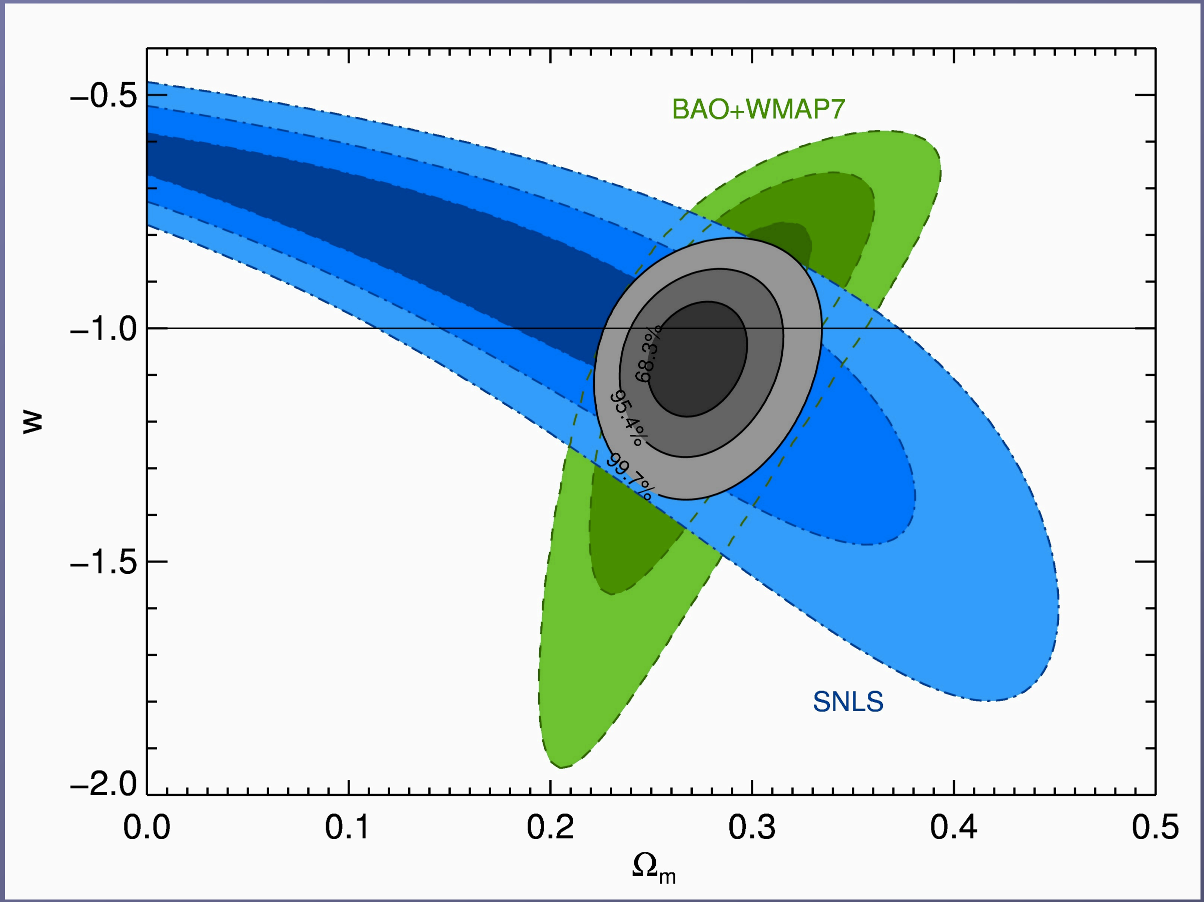
Balland et al. 2009

Supernova Legacy Survey: years 1-3



Conley et al. 2011

Supernova results



Recall: w=-1 is the cosmological constant

$$w = -1.061 \pm 0.069$$

Minus SNe:

$$w = -1.412 \pm 0.333$$

Consistent with cosmological constant

Error in w: **~7% w/ systematics**

SNe are essential for a meaningful measurement

Sullivan et al. 2011

Systematics

- → 170 systematic terms
  - "Calibration"
  - SN model (light curve fitters etc.)
  - Malmquist (selection) biases
  - SN "evolution" (alpha, beta, etc.)
  - Host-galaxy relation

Tractable, understood, and can be modelled

Packaged up in a covariance matrix

- → Stat only: w=-1.043 ± 0.054 – 5.2% measure
- → Stat + sys: w=-1.068 ± 0.081 – 7.6% measure
  - i.e. systematics are ~5.5%
- → Biggest systematic is photometric calibration
  - Stat + sys (no calibration): w=-1.048 ± 0.058 – 5.5%
  - i.e. systematics are only ~1.8%

Astrophysics of SNe Ia

How does the SN Ia progenitor influence the explosion?

What are the progenitors of SNe Ia?

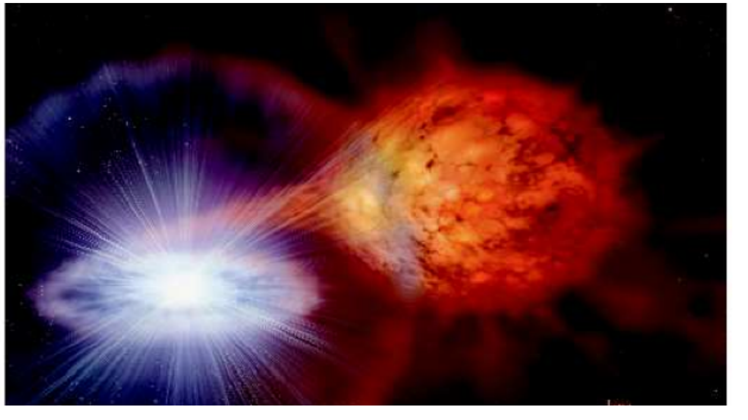
White-dwarf/white-dwarf merger (double degenerate; DD)

Accretion from a non-degenerate companion (single degenerate; SD)

Accretes from a wind (symbiotic channel)?

Roche Lobe over-flow?

Helium star channel?



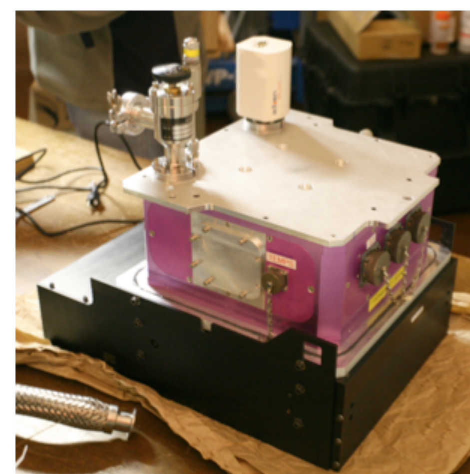
No progenitor has been found

Multiple progenitor types?!

- PTF11kly/SN2011fe:
  - Definitely *was not* a SD with a red giant companion

- PTF11kx:
  - Definitely *was* a SD with a red giant

Palomar
Transient
Factory



PTF 11kly / SN 2011fe

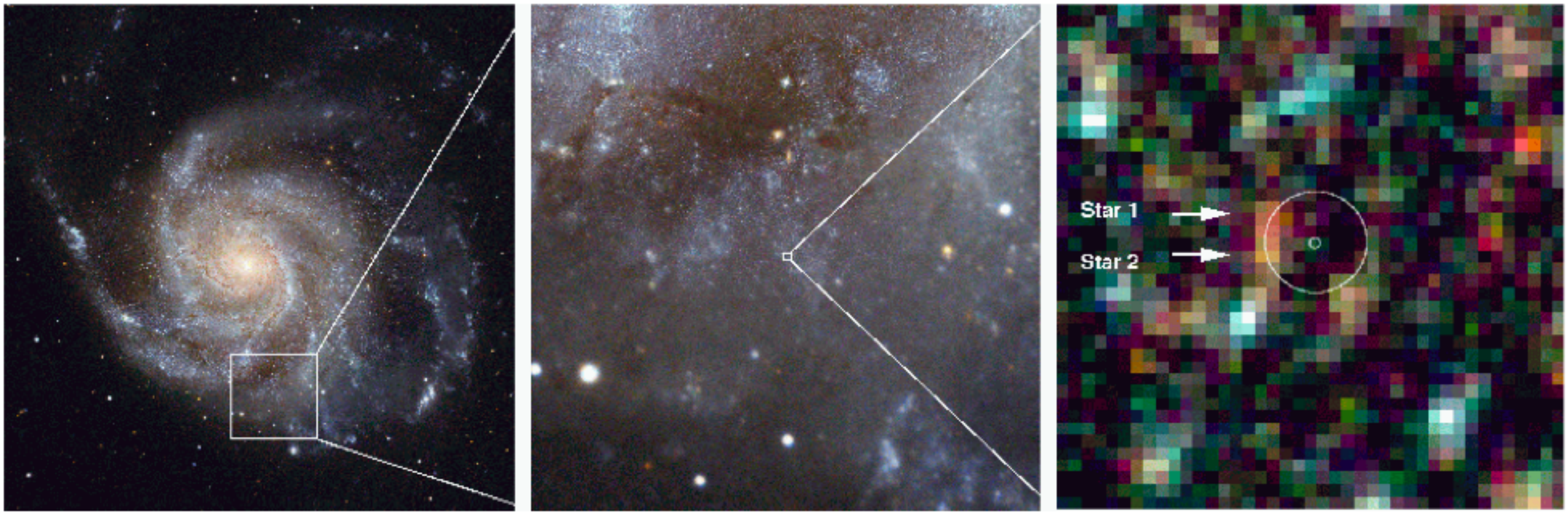
Transient located by PTF on night of August 23rd (Palomar)

Found in M101 – ~6Mpc

Went from non-detection to 17th magnitude in 24 hours.

NOTE: Northern hemisphere… so no ESO science to see here…

Direct progenitor imaging



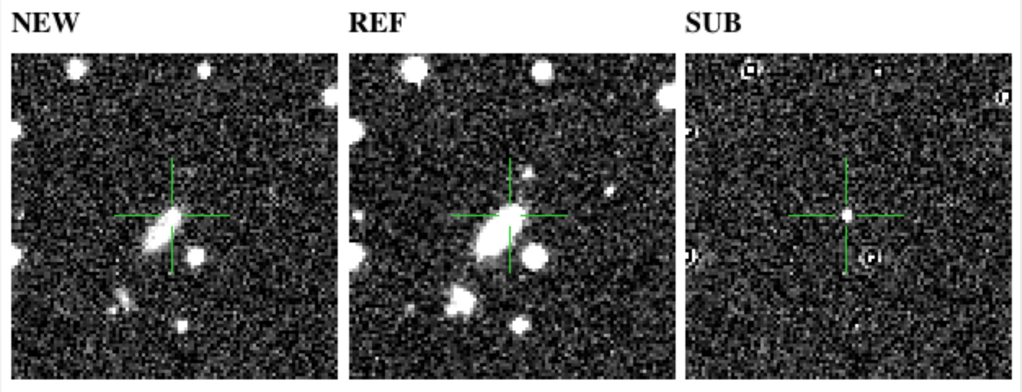
No progenitor (companion) star detected in HST imaging

10-100 times fainter limits than previous Ia progenitor studies

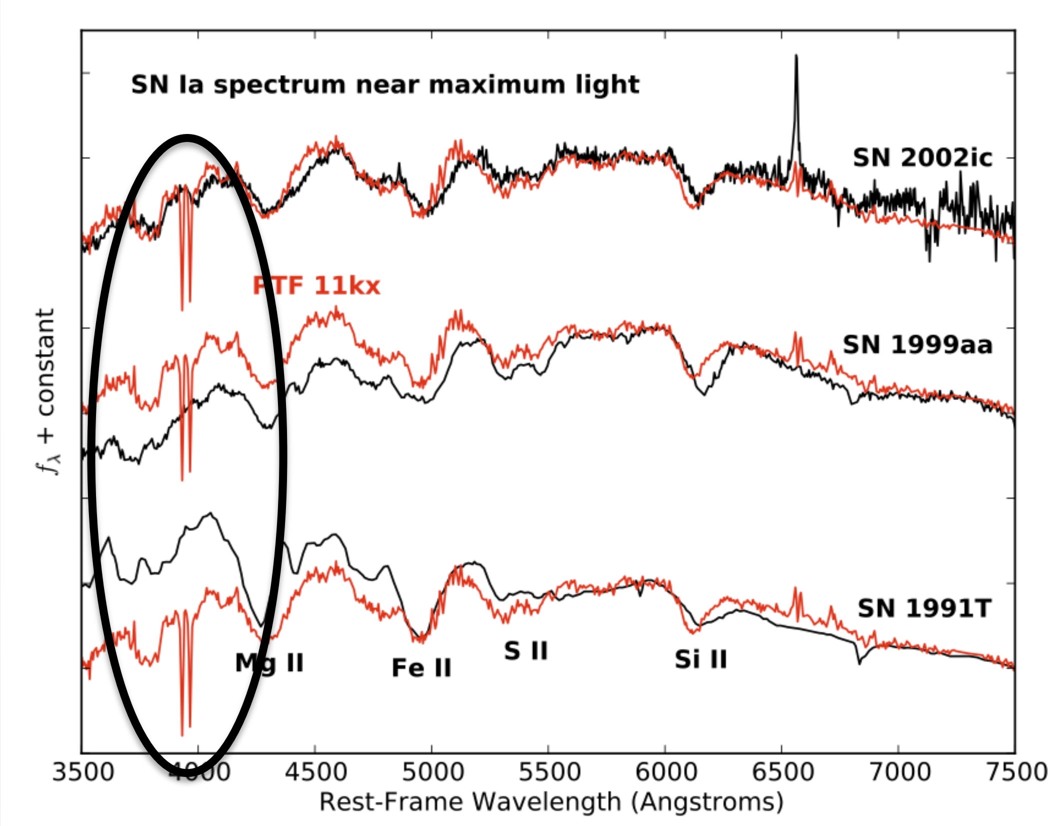
Other complementary studies also place severe limits on SD scenarios

Li et al. 2011

PTF11kx: a recurrent nova progenitor



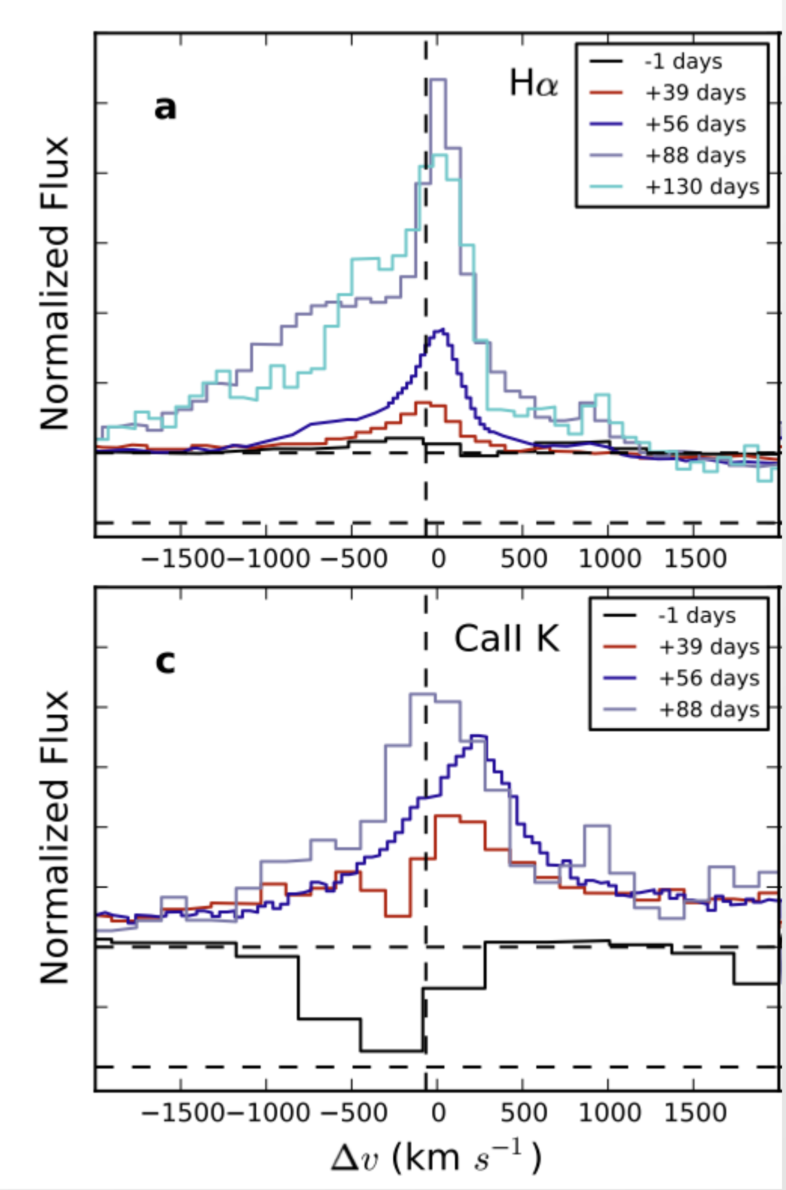
- SN Ia, z=0.047, slightly over-luminous
- Remarkable optical spectra; Ca H,K absorption
- Prompted detailed high-resolution study that revealed two CSM "shells"



Dilday et al. 2012, Science

Shells of material: Ca, H, Fe, Na, etc.

- Ca and H show different behaviour
- Hydrogen unambiguously points to a SD progenitor
- Ca II switches to emission in the later spectra – ejecta running into CSM

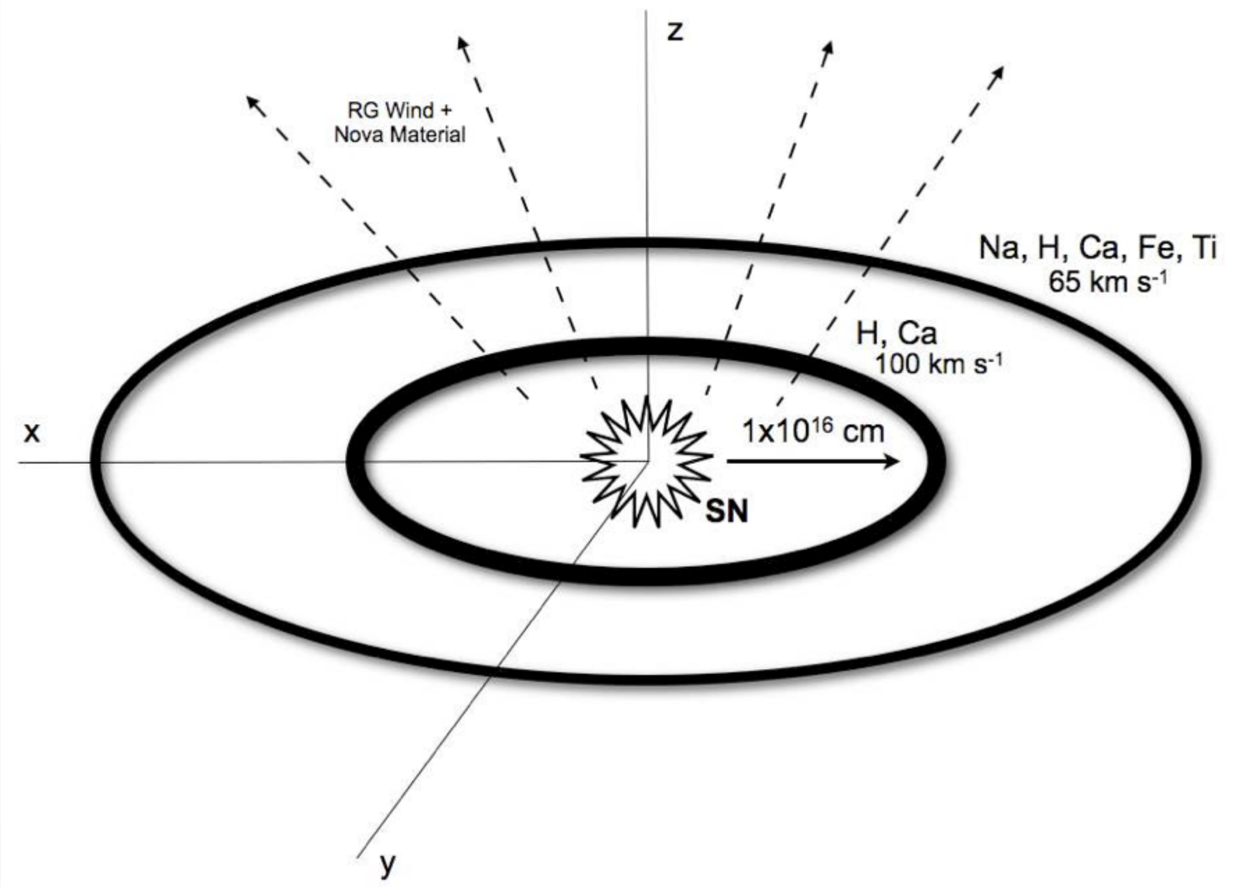


Dilday et al. 2012, Science

PTF11kx progenitor system

A SN Ia in a symbiotic nova system can explain all of these features: accretion onto a WD through the wind from a red giant star.

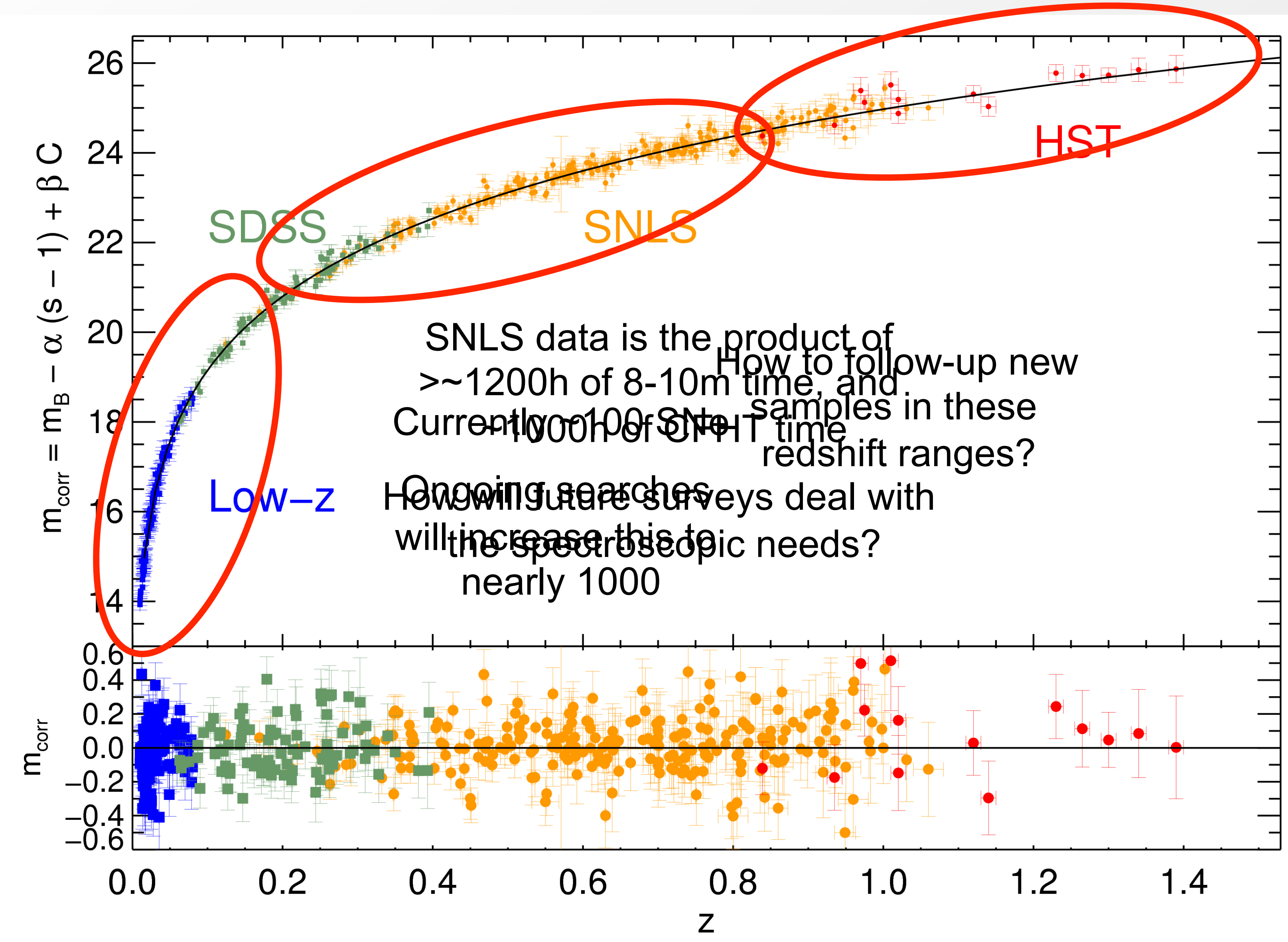
The wind populates the CSM



Direct evidence for a single degenerate companion, probably a red giant

Dilday et al. 2012, Science

SN cosmology in the next decade

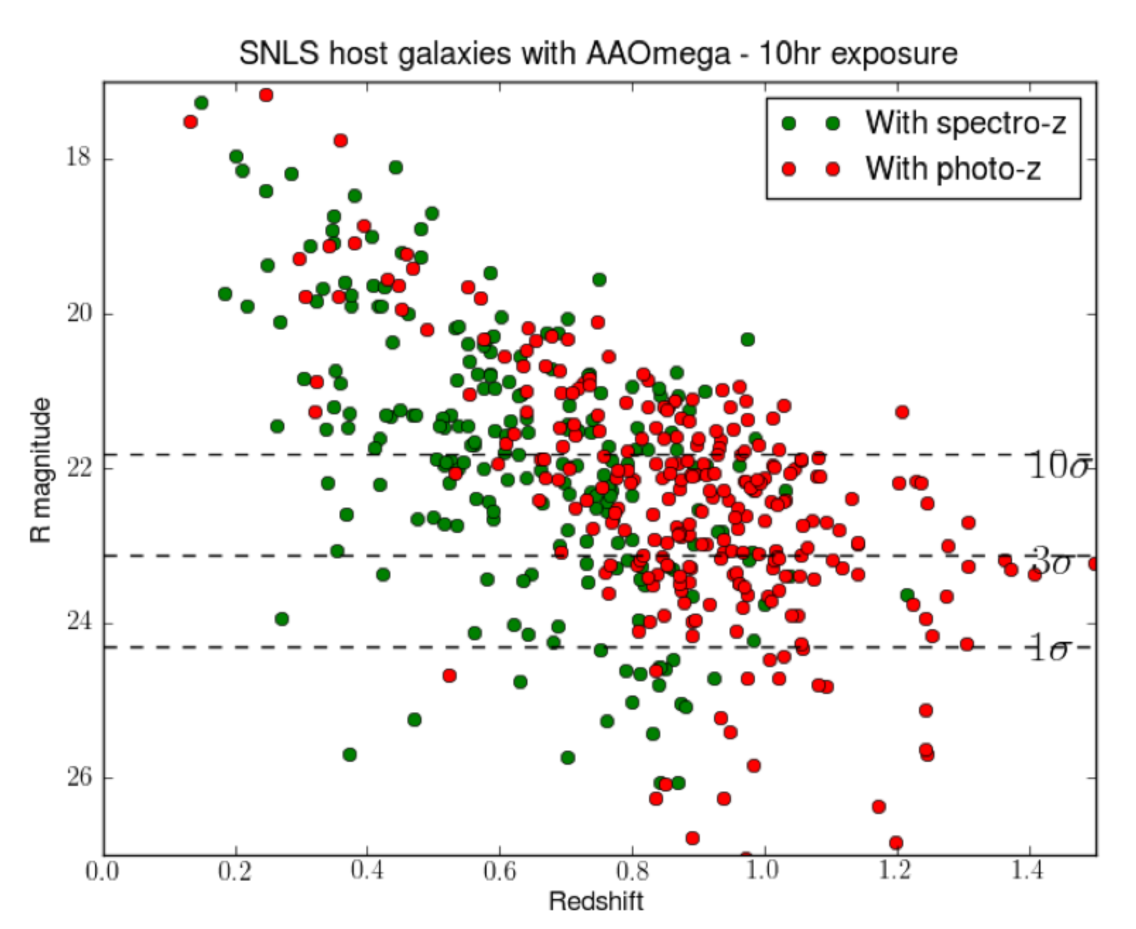


New high-z transients

- Dark Energy Survey: SNe Ia to z~1.2
  - Will provide a x5 increase in sample size over SNLS
  - Starts this Autumn
  - Spectroscopic time will be hard to come by
  - Photometric typing??
  - ESO could play a leading role: X-Shooter, FORS2, etc.

Follow-up of new high-z samples…

- How to follow-up the 1000s of objects detected?
  - Long-slit observations used only for SNe in faint hosts
  - MOSs can play a role providing spec-z for photometric typing



- Case study on AAOmega
- VIMOS or future facilities can be very competitive

Lidman et al. 2011

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- LSST
  - High US priority, optical transients
  - 8m imager. 100,000s of transients inc. 200,000 SNe Ia

- Euclid (ESA satellite)
  - Uncertain area, but Euclid SN case being developed
  - Centres around near-IR Hubble diagram; effects of dust lower

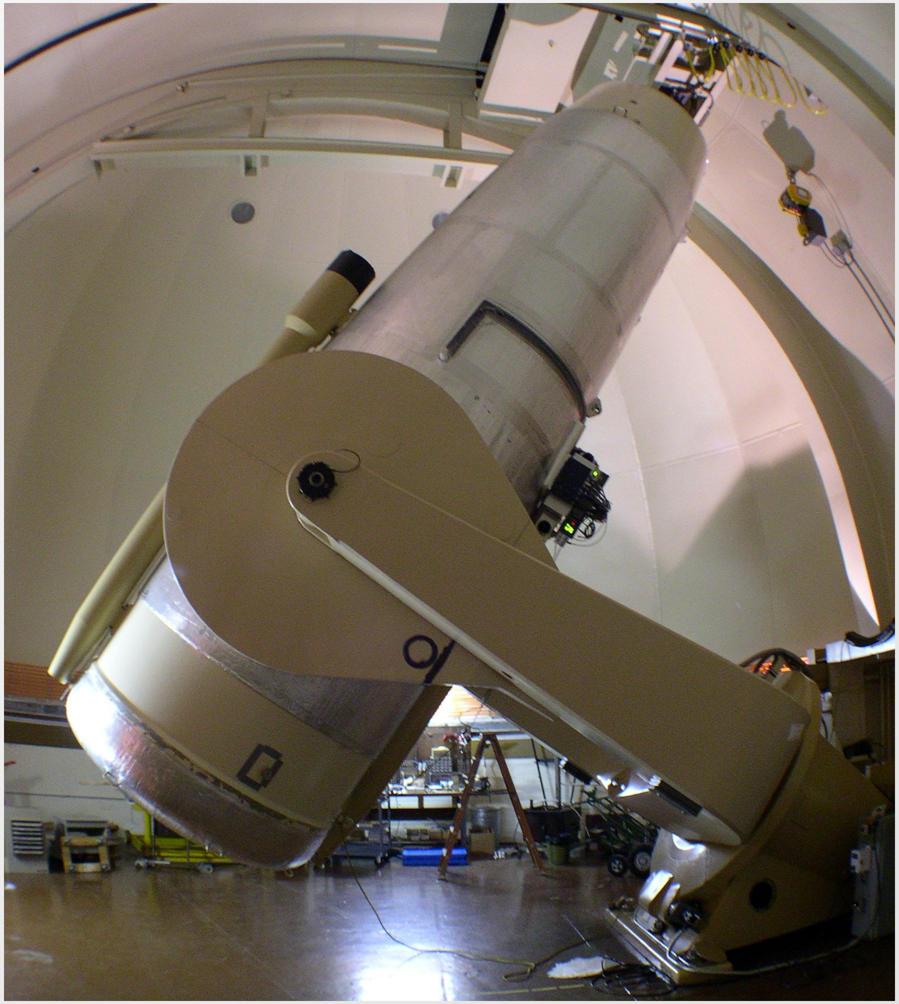
ESO Schmidt and LSQ Survey

- ESO Schmidt rides again
- 90% of time used for La Silla Quest variability survey

- ~10 sq deg camera; 112 CCDs
- Mag limit 21.5, seeing 1.7”
- 3000 sq deg, 2 day cadence

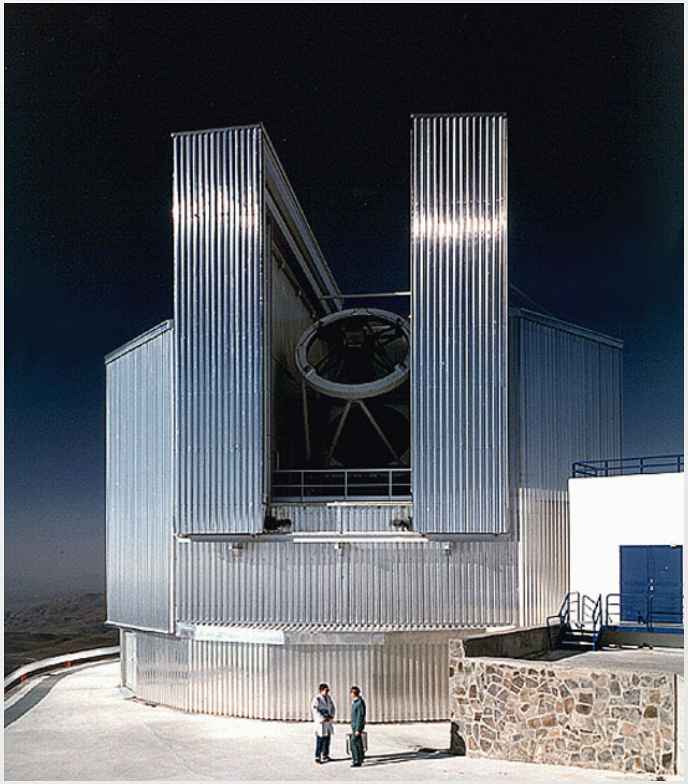
- Provides hundreds of SNe of further follow-up with PESSTO

- Will provide a new SN Ia sample for the local Hubble Diagram



PESSTO

(Public ESO Spectroscopic Survey for Transient Objects)



PESSTO has 25% of the NTT for 4 years

(1/3 of the time during 10 lunations a year)

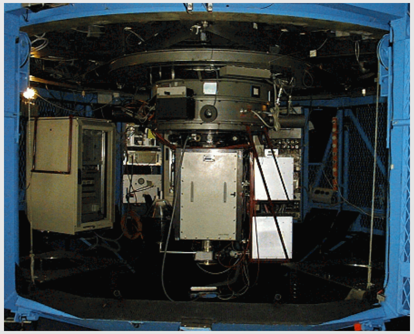
Studying all explosive transients, with an emphasis on the "exotic"

Making detailed studies of thermonuclear Sne

2000 classifications; ~75% of classifications are SNe Ia

Now in month 3

All data public!



Summary

- This is a boom time for studying supernovae
- ESO has played a role in supernova cosmology since the very beginnings of the field
- SN cosmology entering a new area, with
  - DES at high redshift
  - LSQ at low redshift
  - PESSTO for detailed studies
- ESO is well placed to make defining contributions to the field

Systematics

- 170 systematic terms
  - "Calibration"
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