The Nearby Supernova Factory

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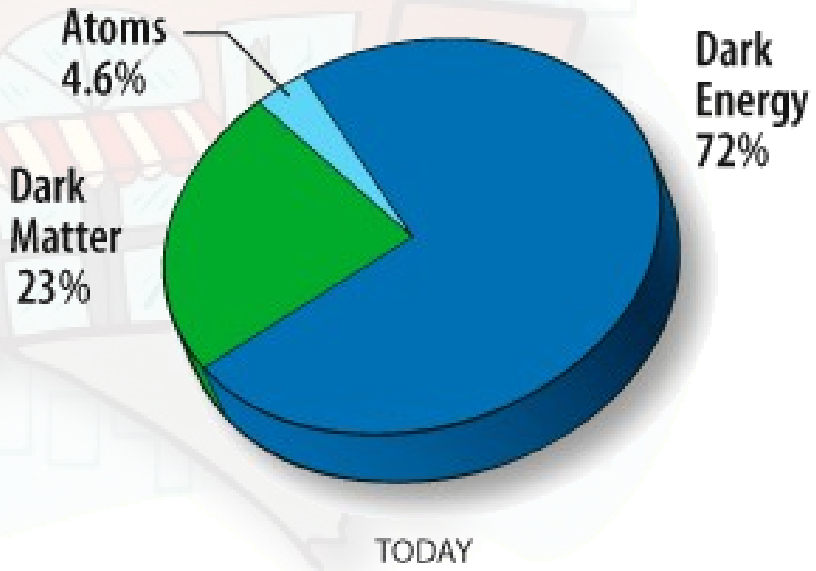
Cosmology for dummies (or instrumentalists)

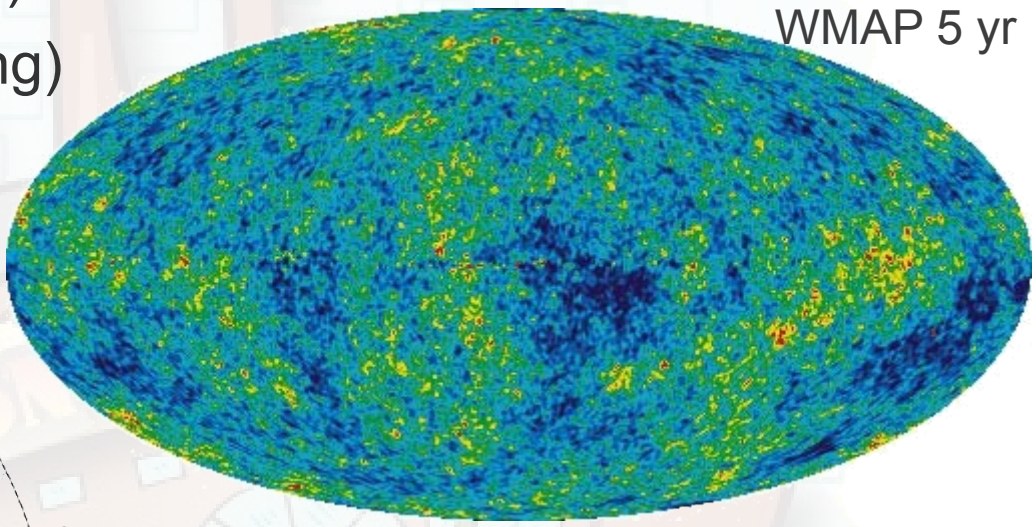
$$\Omega_{\text{total}} \hat{=} \sum_{\substack{\text{components } i \\ (M, \Lambda, \gamma, \nu, \ldots)}} \Omega_i = 1 + \frac{k c^2}{H_0^2} \hat{=} 1 - \Omega_k$$

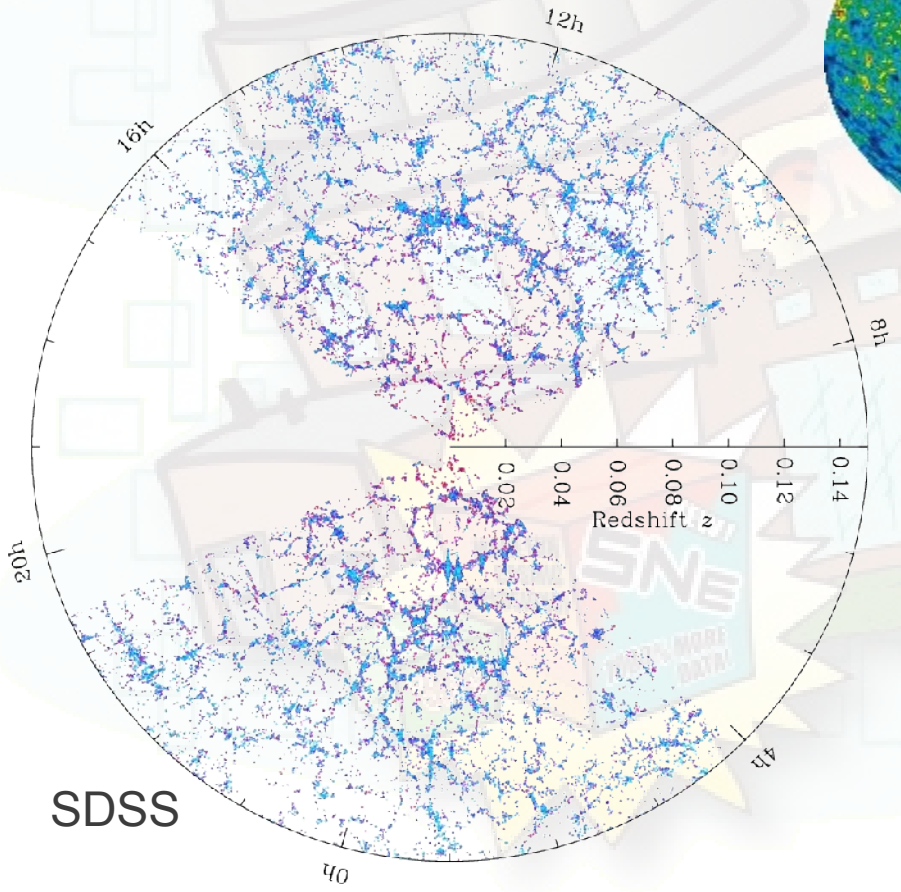
- Friedmann equations relate Universe expansion to energy content
- Cosmological parameters
  - Energy density Ω_i and equation of state $w_i = P/\rho$ of different components
    - Hot/cold matter, cosmological constant/vacuum energy, radiations, etc.
  - Univers curvature *k*
    - $k = 0 : \rho = \rho_c = 3H^2/8\pi G$, euclidian universe
    - $k = \pm 1 : \rho \gtrless \rho_c$, closed/open universe



Observational cosmology

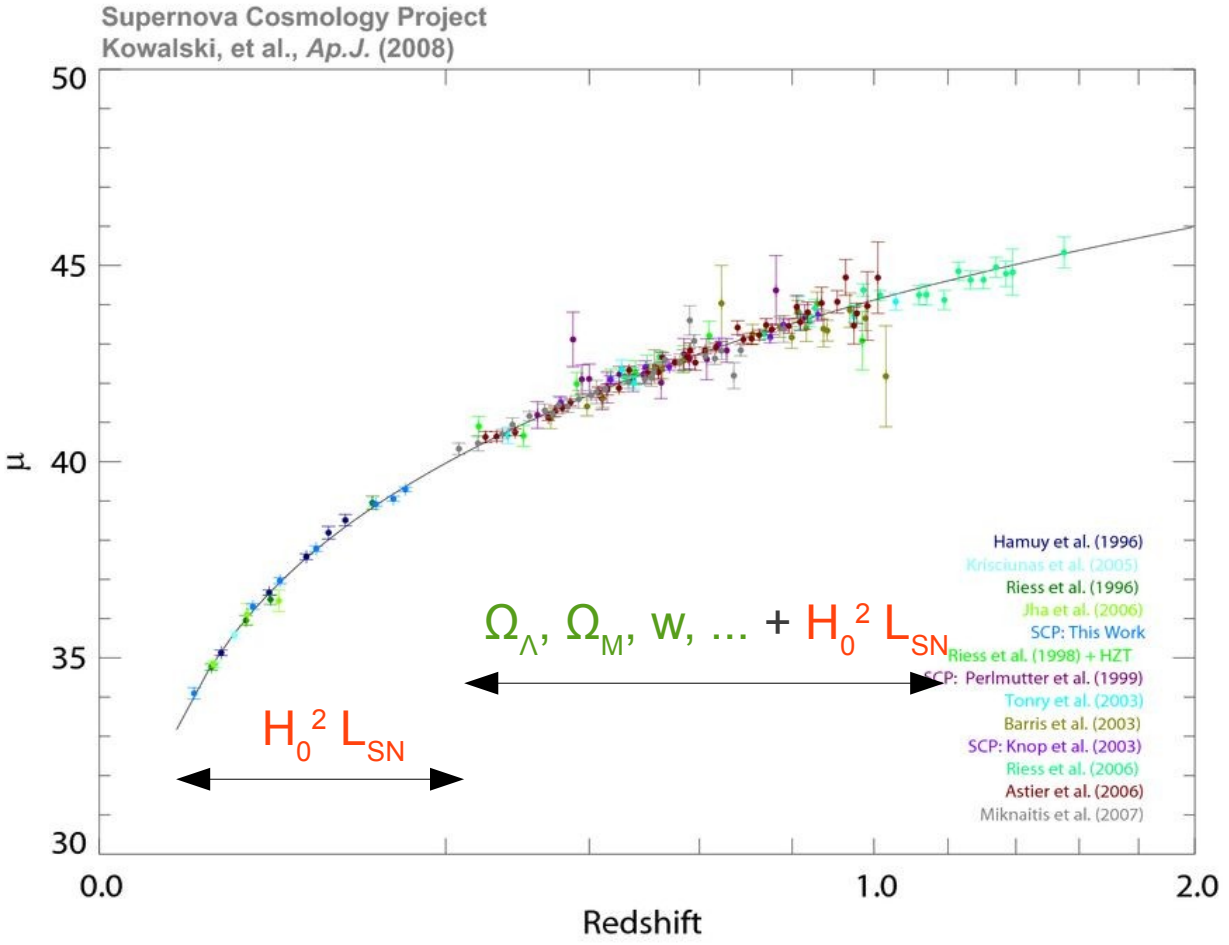
- Three major cosmological probes
  - Angular correlations (CMB, BAO)
  - Large structures (clusters, lensing)
  - Standard candles (**SNe Ia**)





SDSS

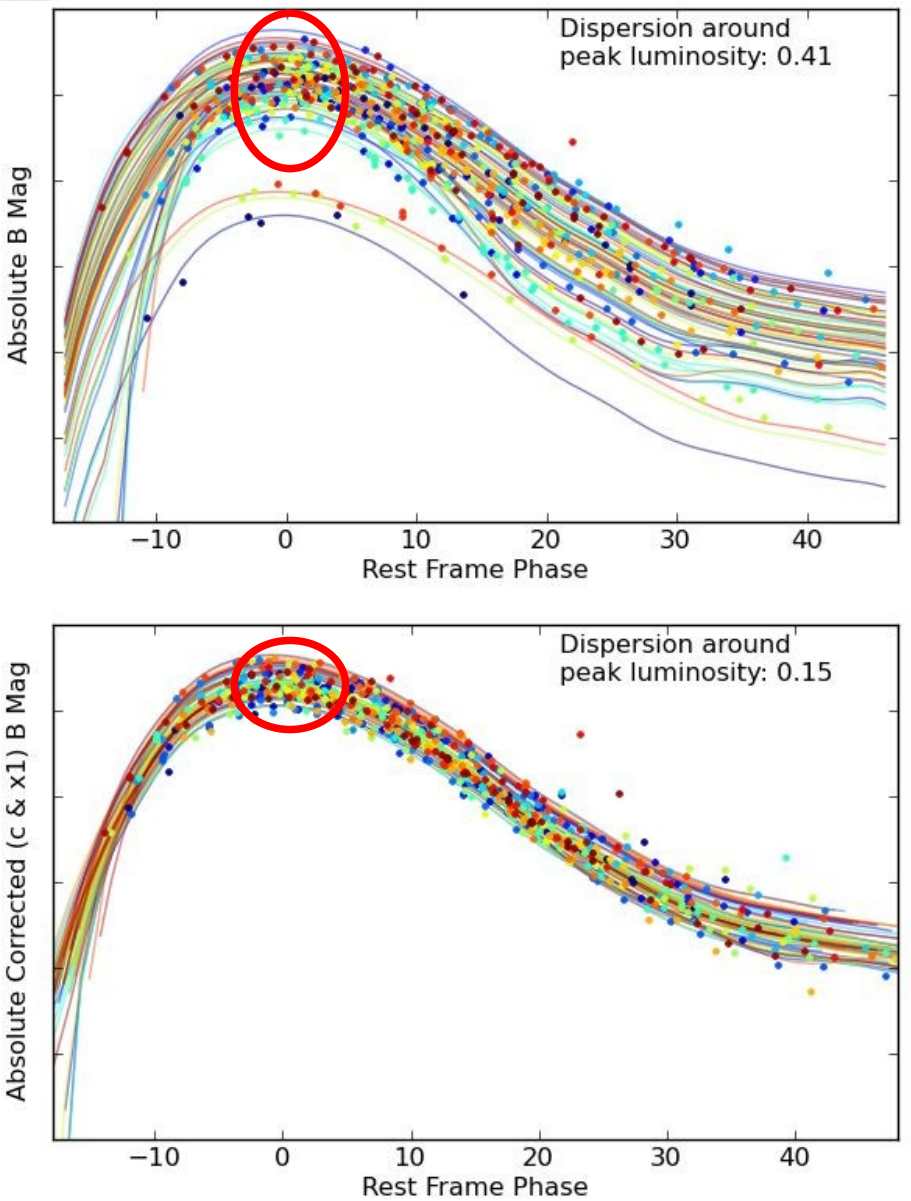
SN Ia Hubble diagram (μ vs. z)



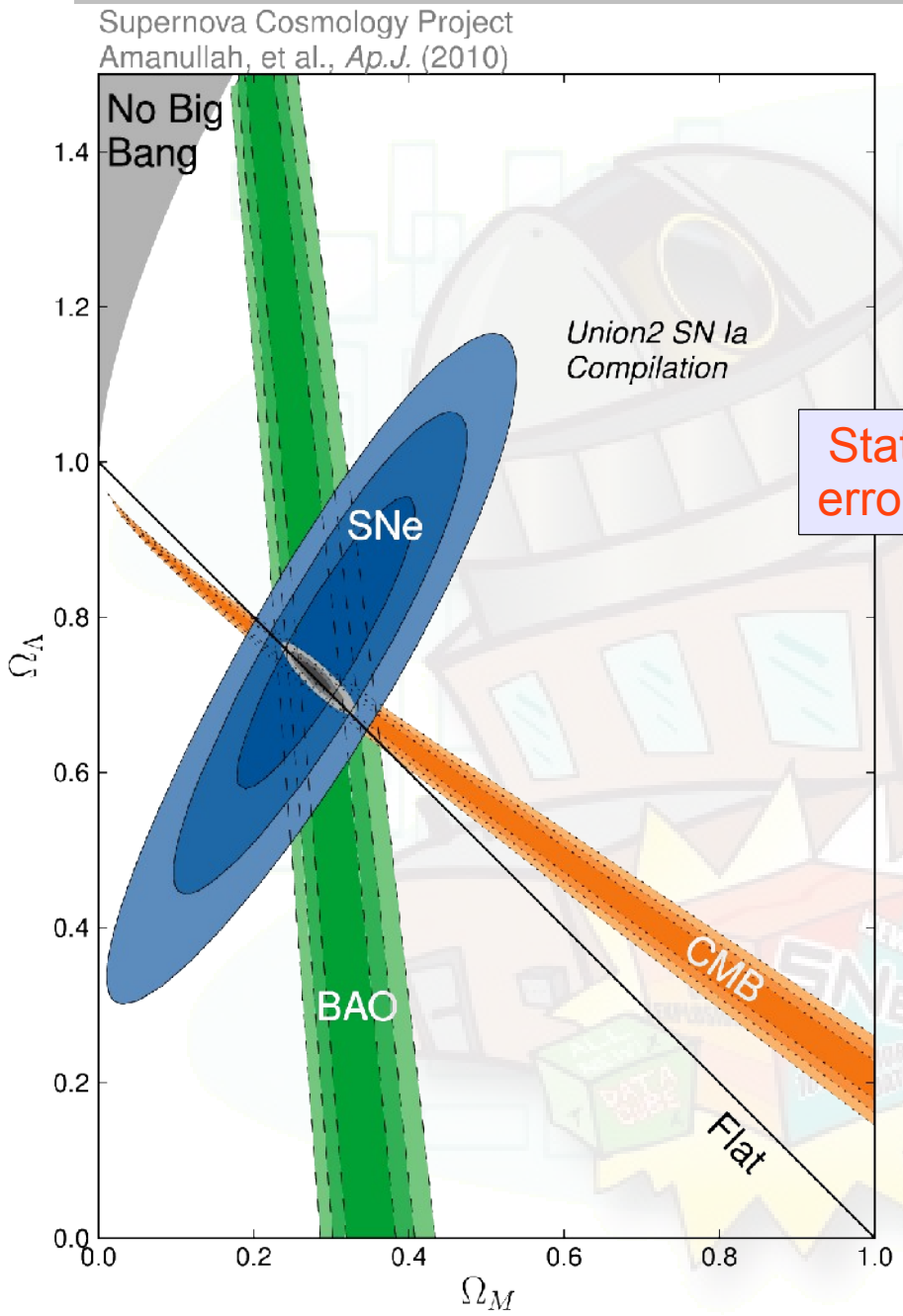
- Redshift $z \equiv (\lambda - \lambda_0)/\lambda_0$
  - Spectroscopic measurement
- $\mu_B \equiv m_B - M_B = 5 \log(d_L/10pc)$
  - m_B : photometric measurement
  - $d_L(z$; cosmological parameters)
  - M_B(SN parameters)
- High redshift SNe
  - Adjust cosmological parameters
  - *Hypothesis : SNe **are** standard candles*
    - Adjust M_B(SN parameters)
    - *Nuisance parameters*
- Low redshift SNe
  - $d_L(z\sim0)$ independent of cosmology
  - *Are SNe good standard candles ?*
    - Standardization process
    - Derive M_B(SN parameters)

SNe Ia, standard candles

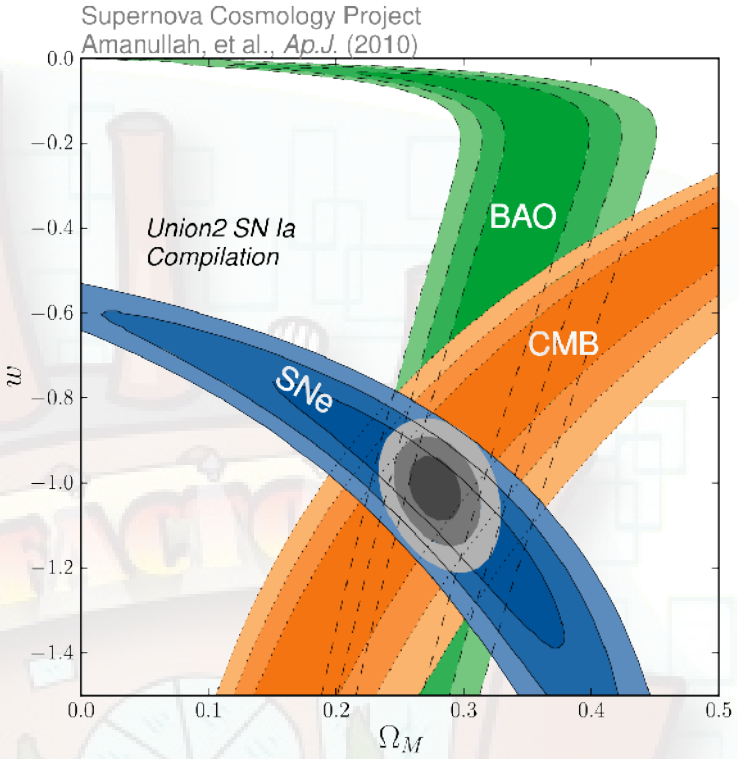
- Almost standard candles...
  - Raw dispersion at max ~40%
  - Intrinsic variability
    - Progenitor composition
    - Ignition conditions
  - Extrinsic variability
    - Host galaxy extinction
    - Circum-stellar envelop ?
- Empirical calibration
  - Color (extinction+intrinsic)
    - ***"Brighter – bluer"***
  - *Stretch* (Ni mass)
    - ***"Brighter – slower"***
  - $M_B(x_1,c) = M_B^0 - \alpha\, x_1 + \beta\, c$
  - Dispersion reduced to ~15%



Cosmic concordance

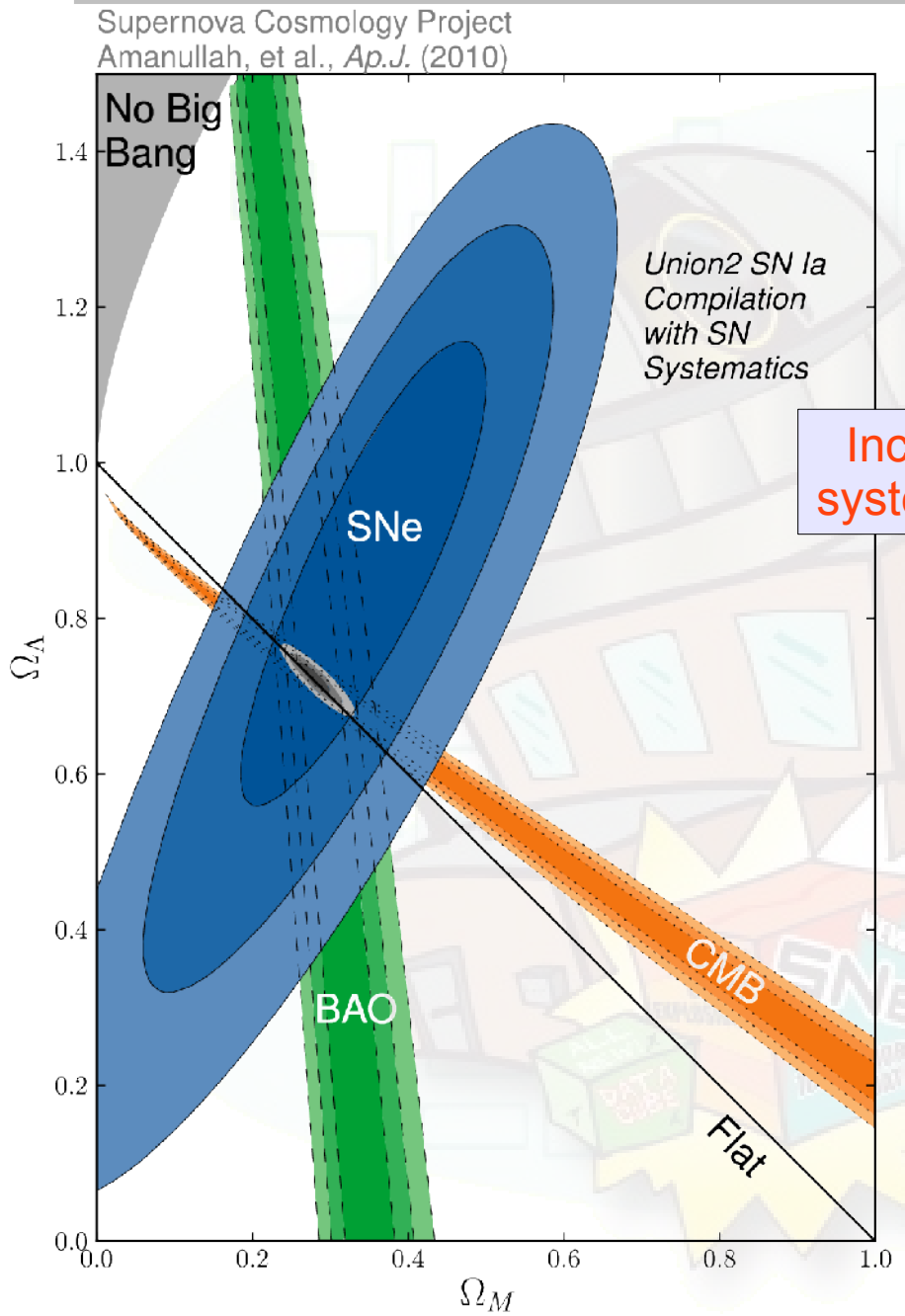


Statistical errors only

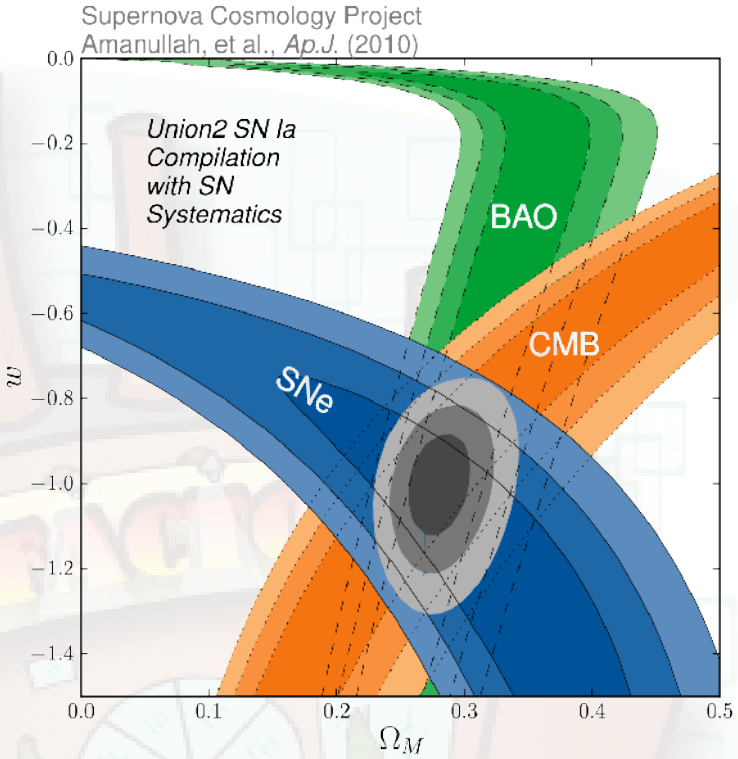


- $\Omega_T \sim 1.0 \pm 0.02$
  - Euclidian universe
- $\Omega_\Lambda \sim 0.73 \pm 0.01$, $\Omega_M \sim 0.27 \pm 0.01$
  - Dominated by dark energy
- $w \sim -1.0 \pm 0.1$
  - Cosmological constant

Cosmic concordance



Including systematics



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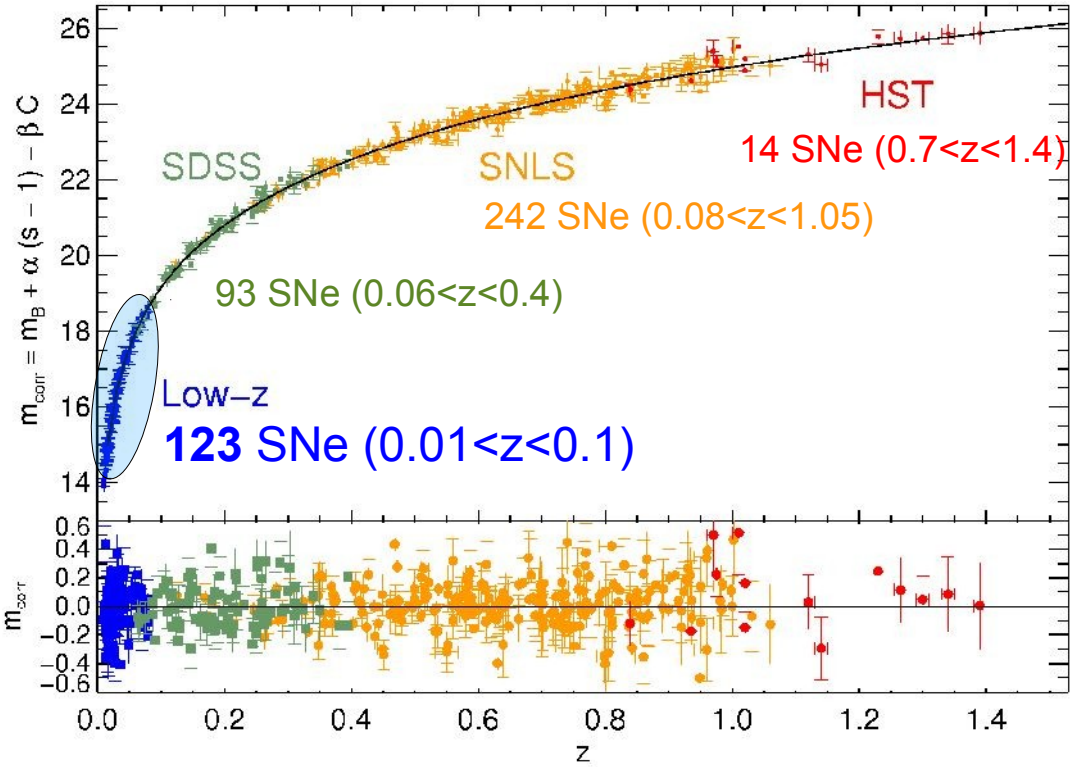
Need for nearby SNe Ia

- Nearby SNe are still *required* for cosmology
  - Lever arm low *z*/high *z*
  - Systematic errors are sensitive to nearby sample
- Importance of spectro-photometry
  - Production of spectral templates
  - Sub-classification
  - Intrinsic colors
  - Spectral indicators
  - Physics of SNe

SNLS 3 yr (Conley et al. 2011)



"We don't need more SNe, we need better SNe"

The Nearby Supernova Factory

The Nearby Supernova Factory

- SNfactory key dates
  - 2000: project kick off
  - 2001: France-Berkeley MoU
  - 2004: SNIFS on the sky
  - 2005-2008: SNf search program
  - 12/2009 : end of SNf follow-up
  - 2011 : start of SNf-II

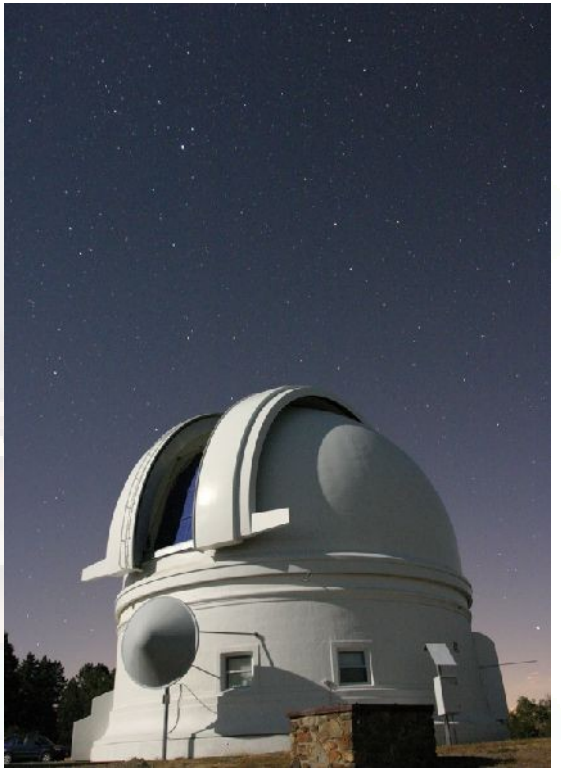
The Nearby Supernova Factory

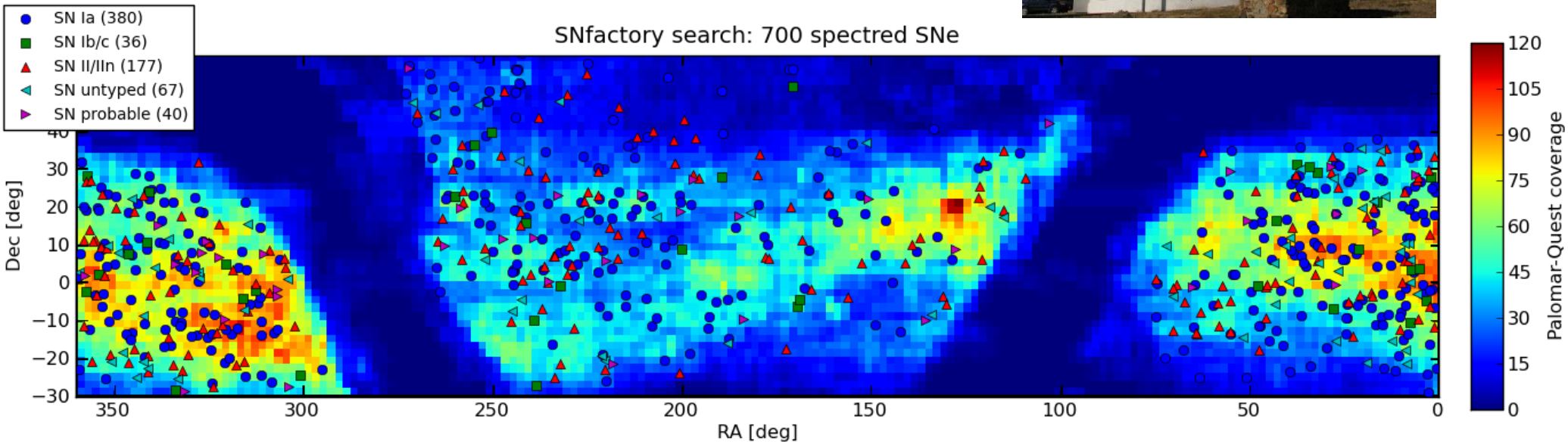
- Increase the local SN Ia sample in the Hubble flow
  - $0.03 < z < 0.08$
  - Unbiased wide field survey
- Acquire spectro-photometric time-series
  - 3D spectrography
  - Highly automated observations
    - From -15 to +45 d
    - Every 2-3 days
  - Extended optical domain
    - 320 – 1000 nm
    - Resolution $\lambda/\Delta\lambda \sim 2000$
  - Effective atmospheric extinction

1. SN search 
   - Palomar 1,2 m + Quest II
   - *Unbiased*
2. Spectro-photometric follow-up 
   - UH 2,2 m + SNIFS (3D)
   - Typing and selection
   - Time tracking
3. Analysis
   - Time-series
   - Broad-band photometry
   - Spectral indicators
   - Host galaxies, etc.

QUEST search program

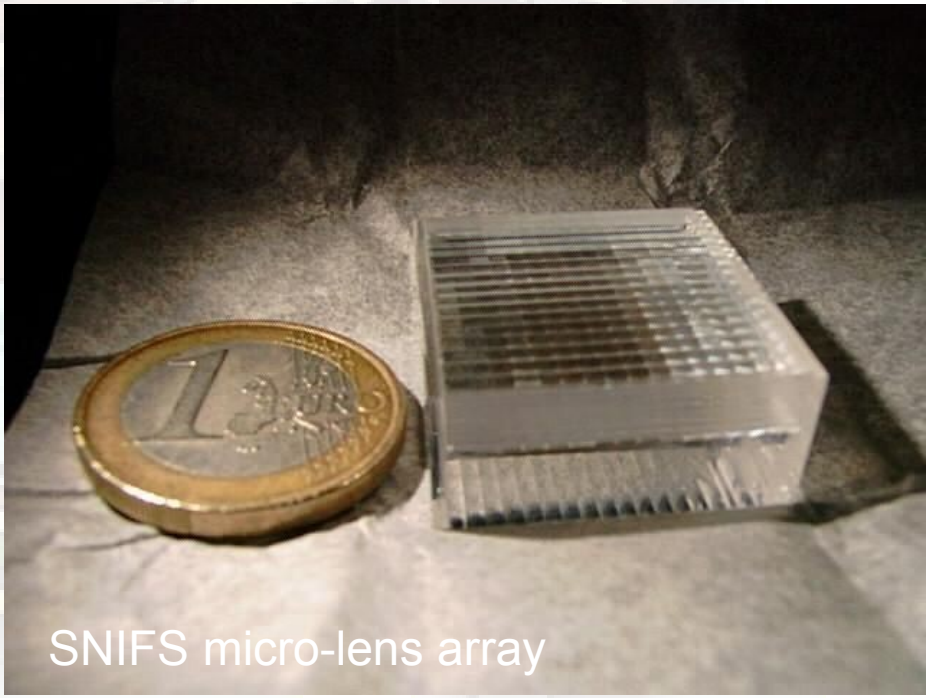
- Palomar-QUEST survey (2004-08)
  - Palomar Oschin 1.2 m telescope
  - 112 CCD (161 Mpx), 9.4 deg^2
  - 350-850 deg^2/night, 20.5 mag. depth
  - 30 000 images, ~50 Gb/night
  - 2π coverage
- +1000 candidates in 28 months





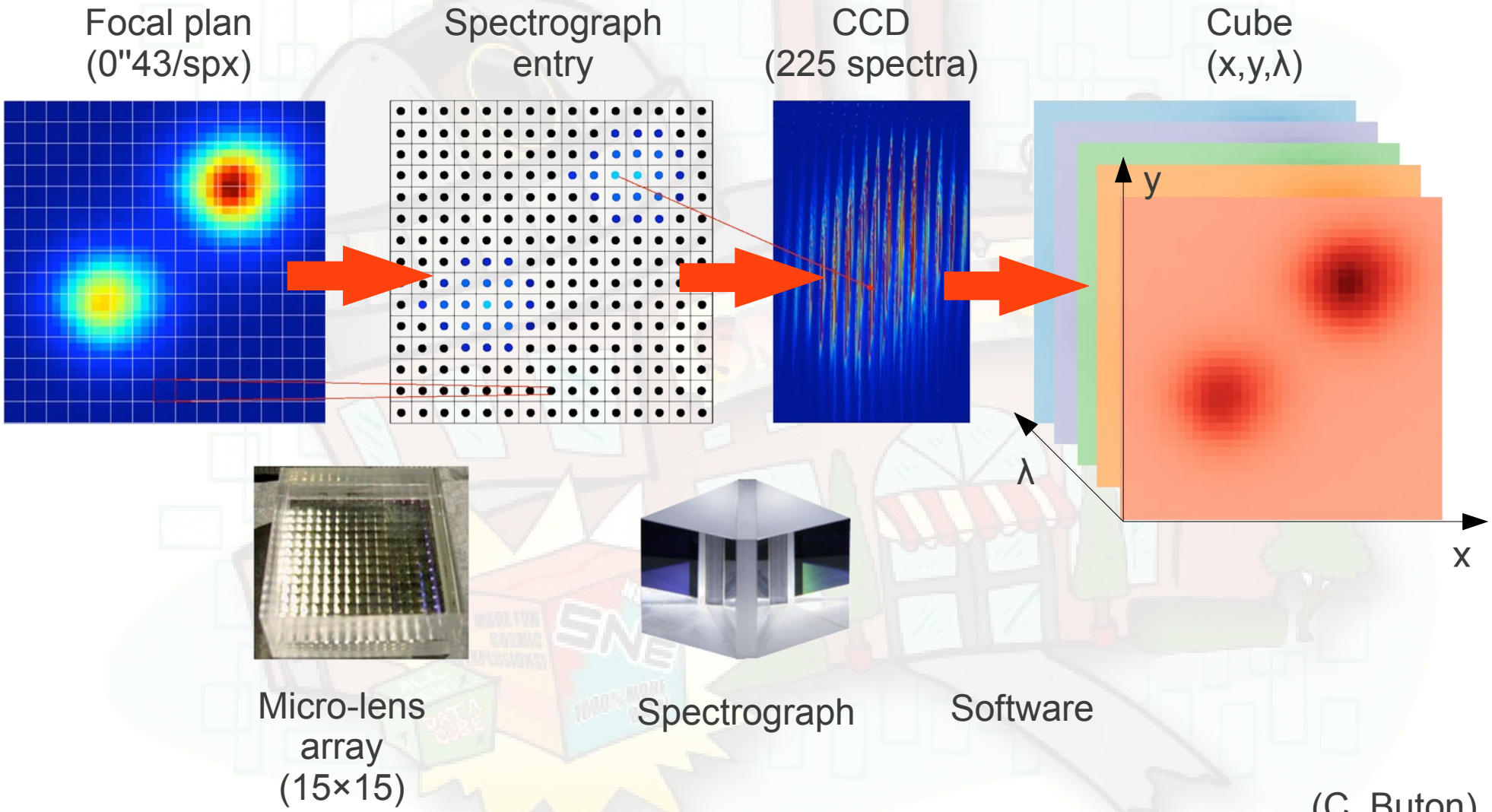
SuperNova Integral Field Spectrograph

- Micro-lens array IFS
  - Tiger-like (Oasis, Sauron)
    - Designed and built in Lyon
    - Spectro-photometric goals
- Spatial stage
  - 15×15 spx of 0"43
  - 6"5×6"5 field of view
- Spectral stage
  - 2 spectroscopic channels
    - B: 320–520 nm @2.4 A
    - R: 510–1000 nm @2.9 A
  - 2 2k×4k CCDs
- High efficiency
  - Throughput from scope to CCD
    - B: 15% and R: 25%
  - Low operational overhead



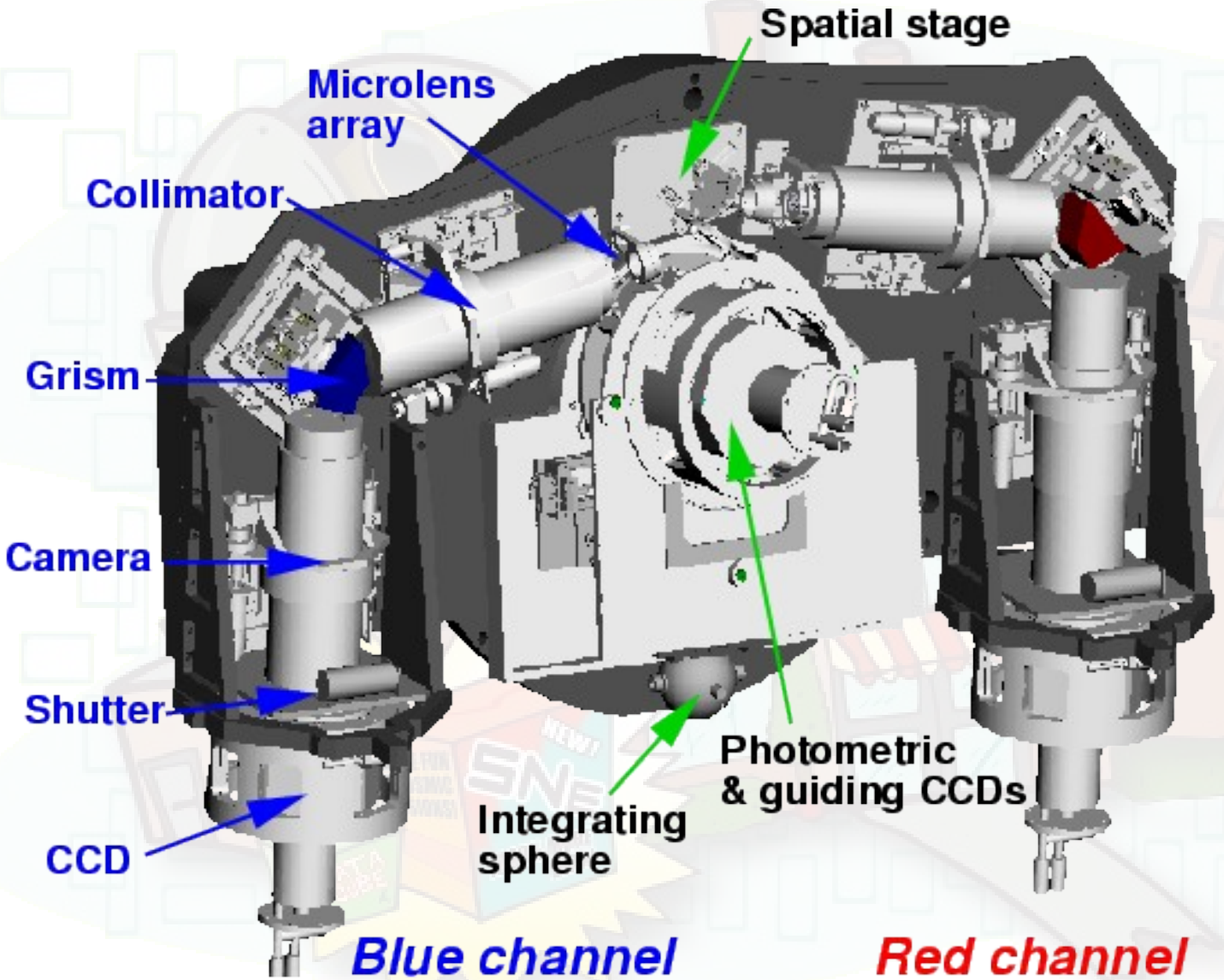
SNIFS micro-lens array

Optical design of a Tiger-like IFS



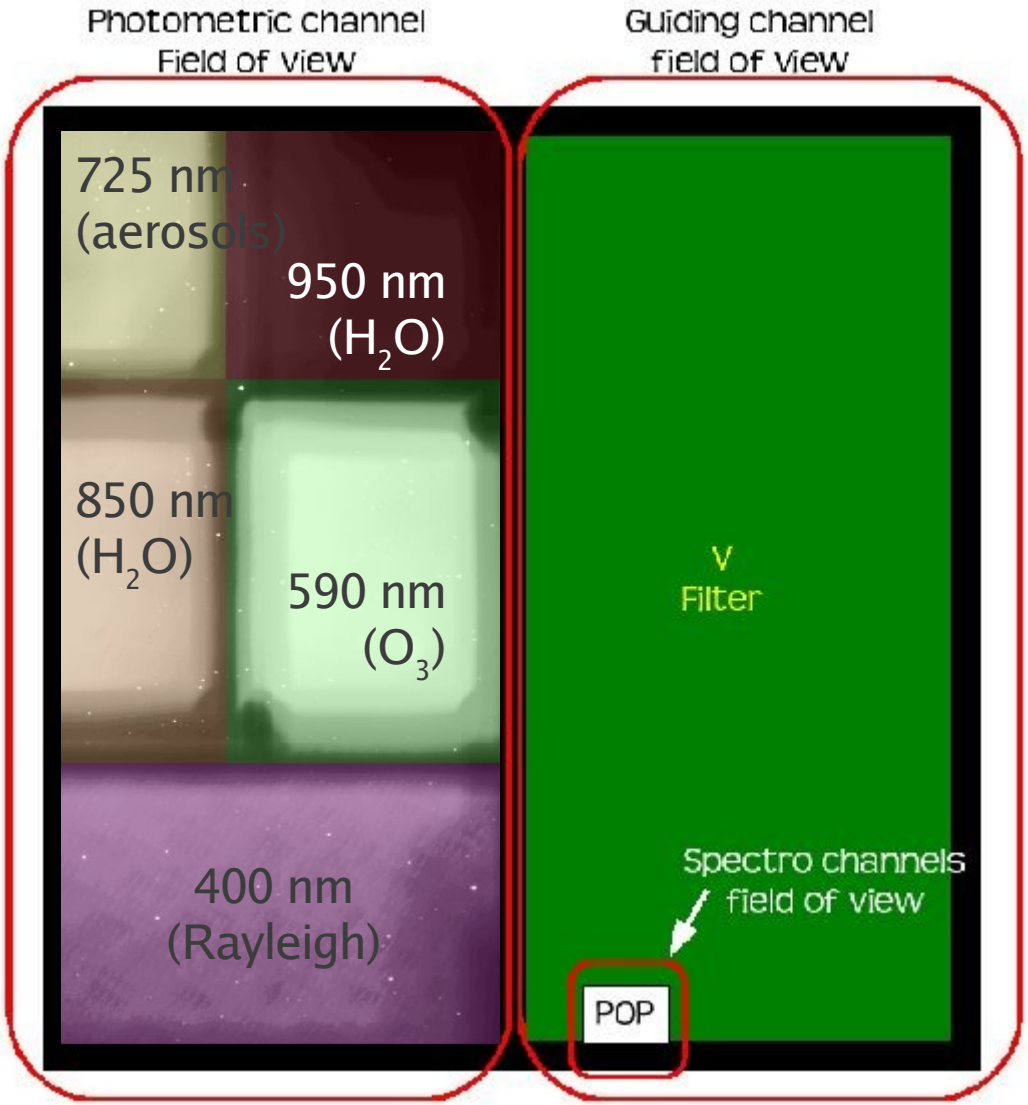
(C. Buton)

SNIFS mechanical design



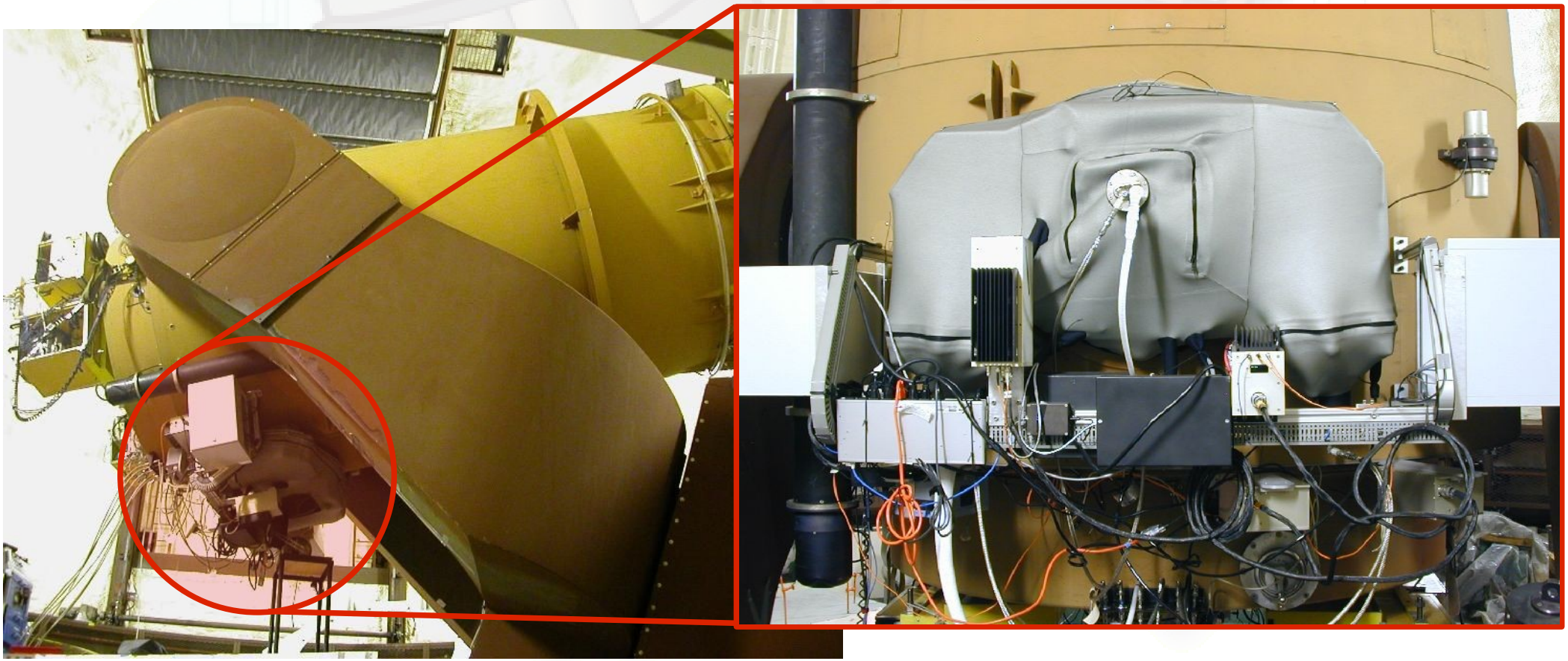
Guiding and photometric channel

- 2 × 4'8×9'6
- Target acquisition
- [UBVRIZ photometry]
- During the spectro exposure:
  - Right : guiding CCD
  - Left : multi-filter for effective atmospheric extinction



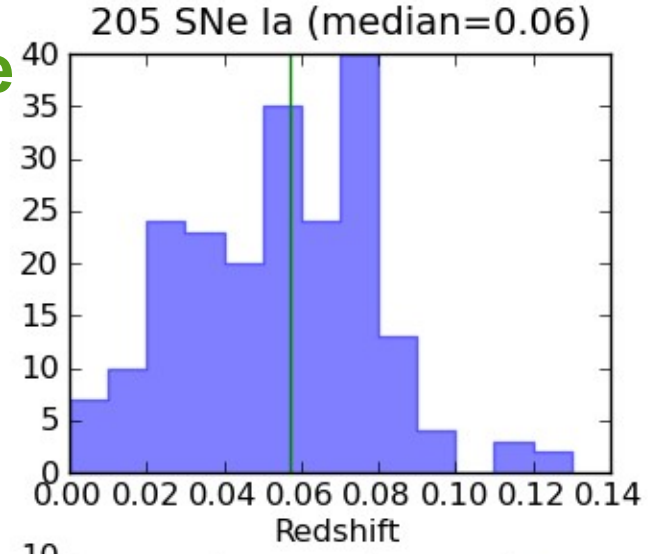
SNIFS on UH 2.2 m telescope

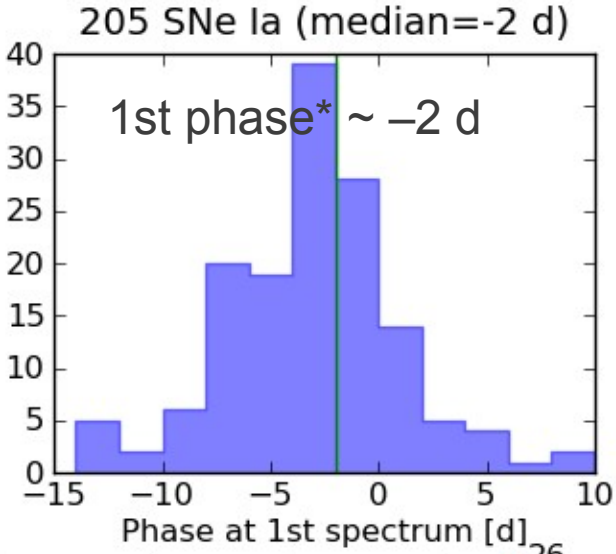
- Permanently mounted on bent Cassegrain port
  - First ~3×½-nights/week, then complete nights since may 2006
- Remotely semi-automatically operated
  - Queue scheduling, virtual control room, AI support

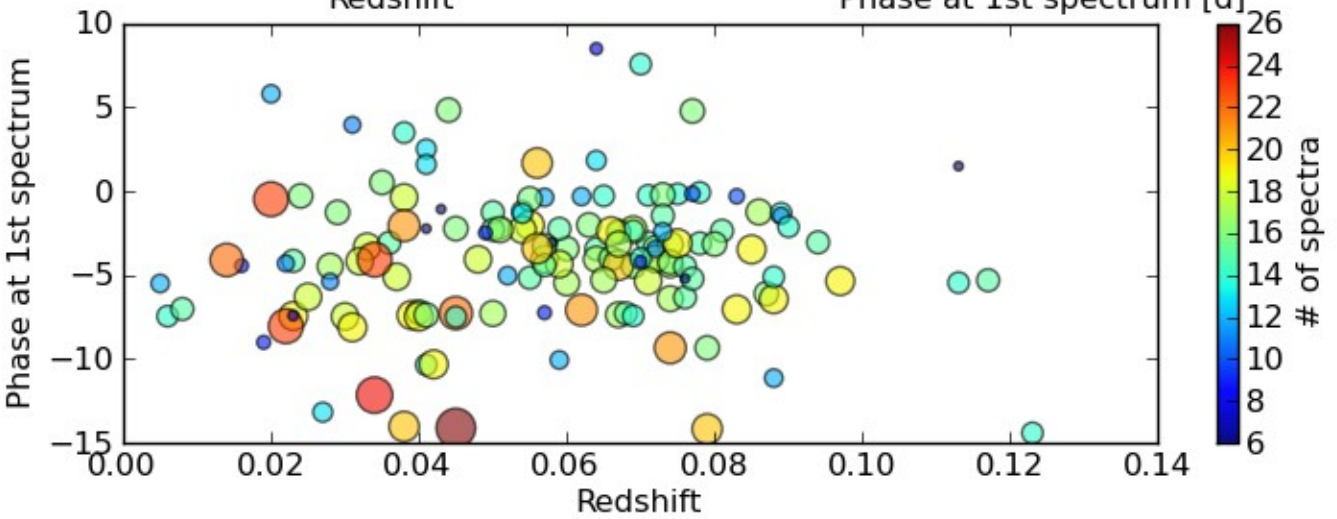


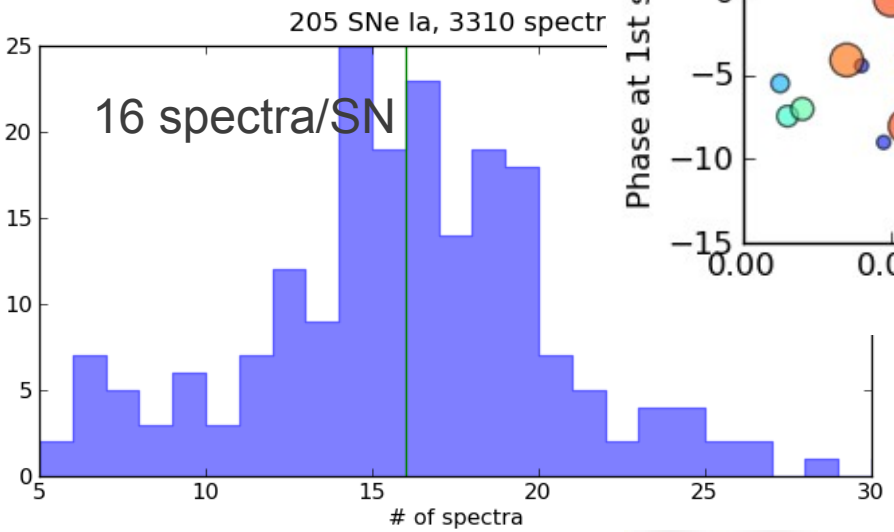
SNfactory final sample

- **205 SNe with more than 5 spectra**
  - 3310 spectra
  - 16 spectra/SN (median)
  - 181 SNe with >10 spectra



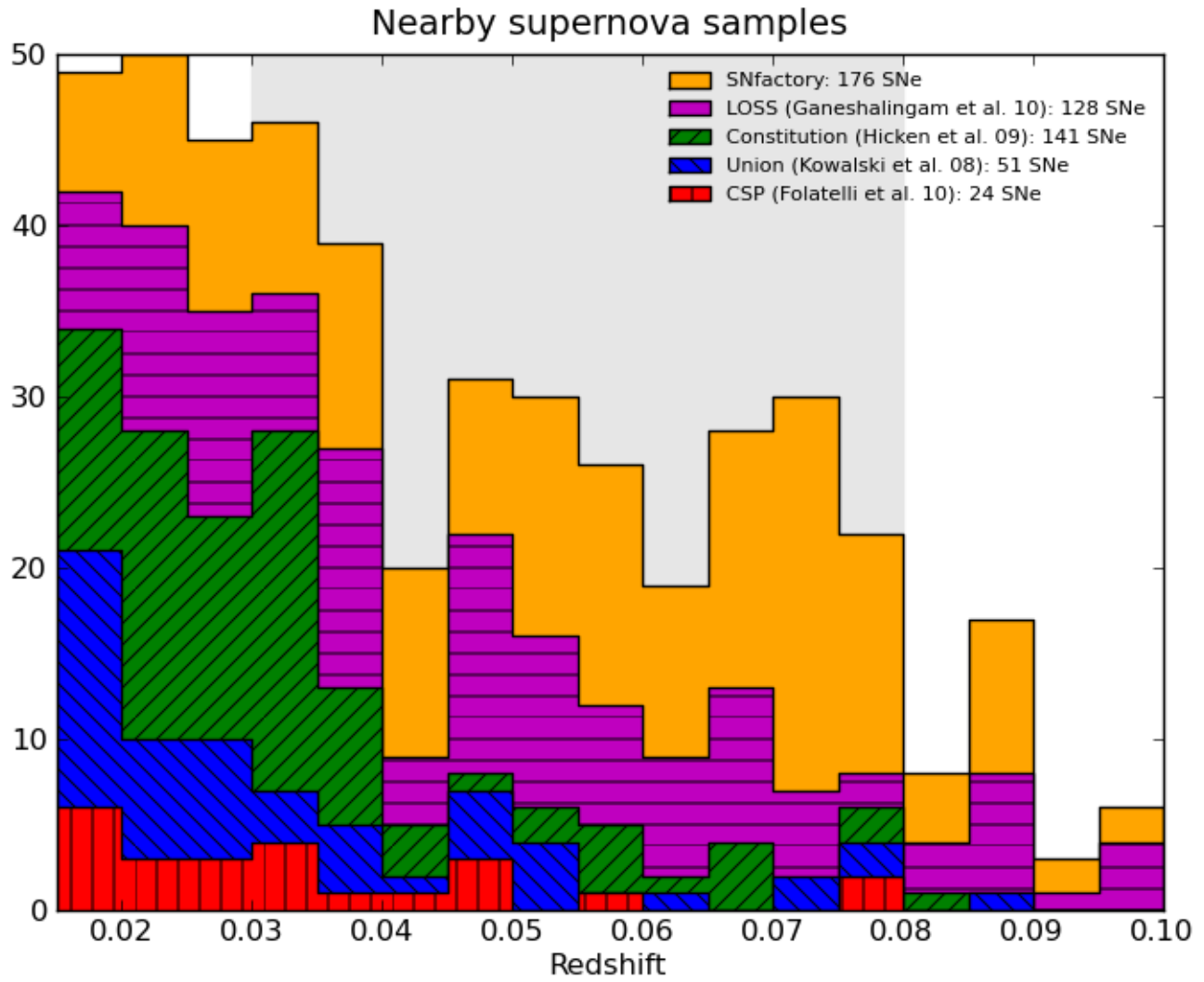




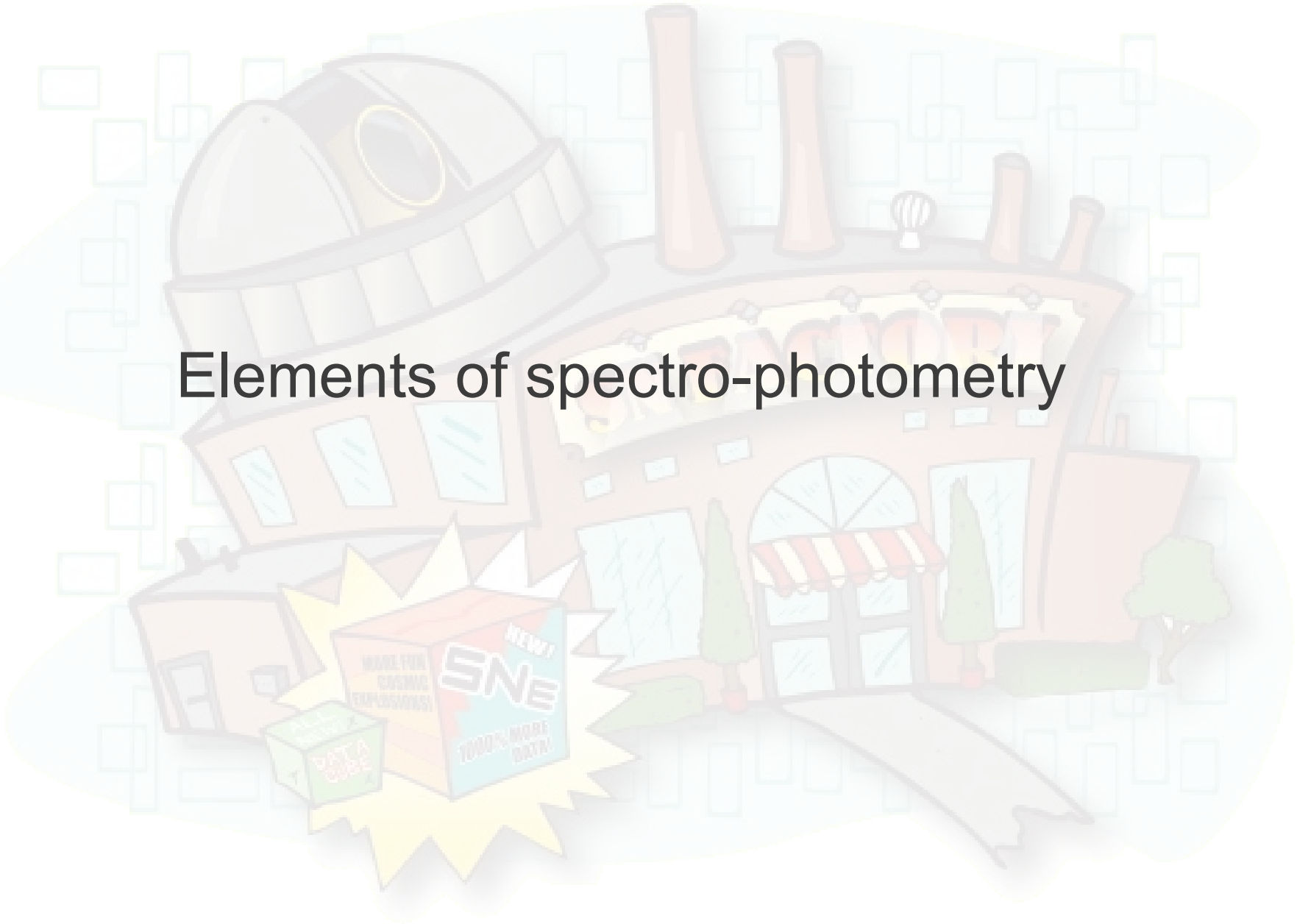


* SNID phase of 1st spectrum

Nearby SN samples



Elements of spectro-photometry

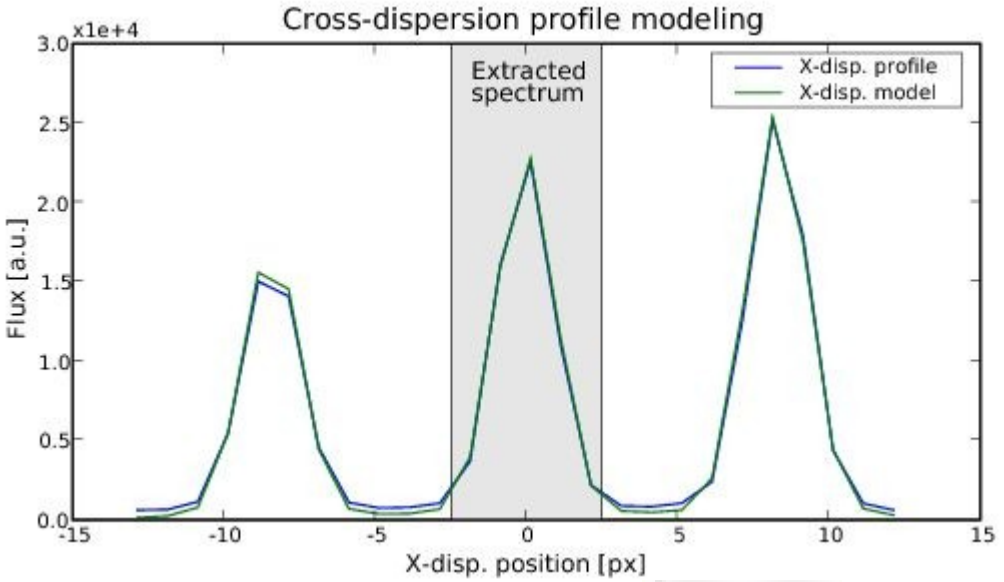


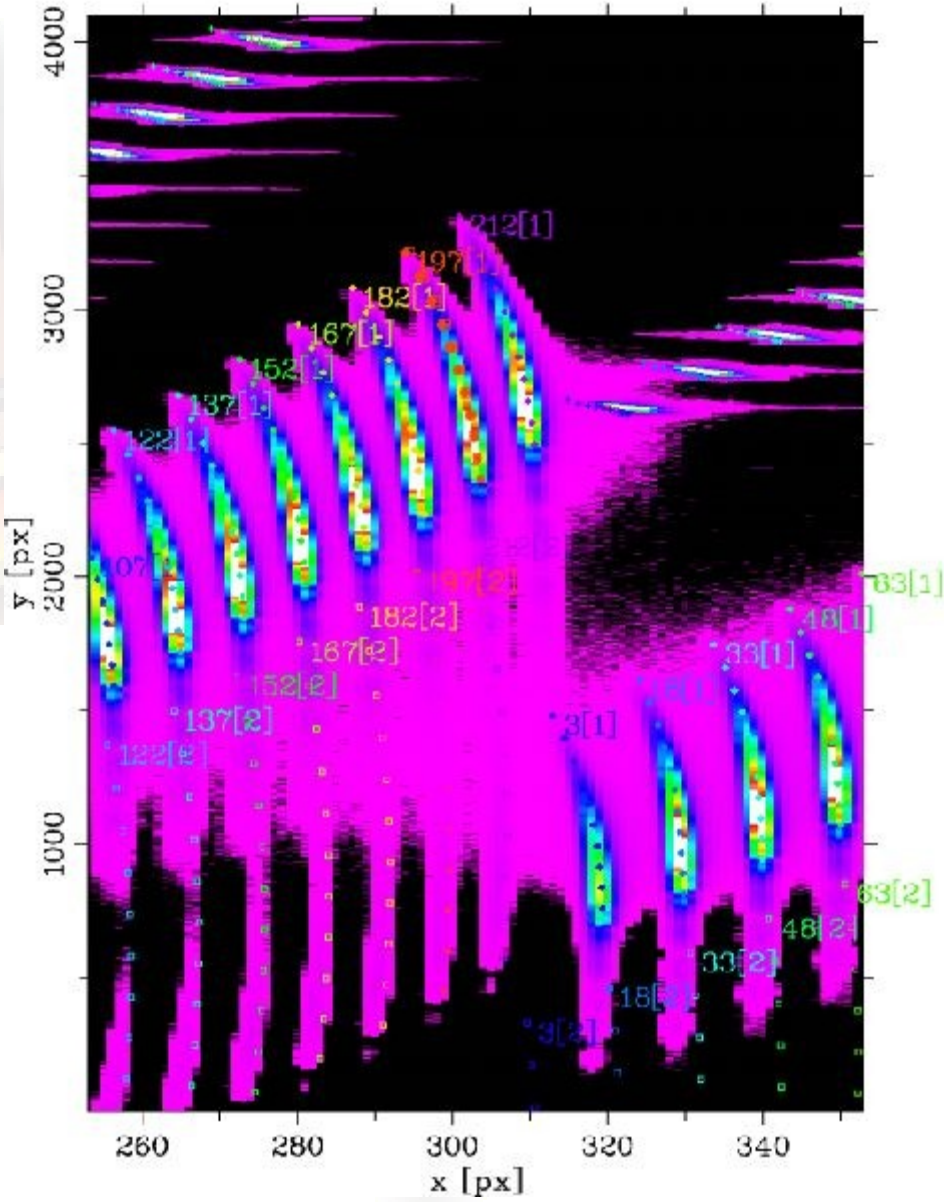
Spectro-photometric accuracy

- The goal is to reach percent-level accuracy on the whole SN timeseries
  - ...notwithstanding a complex instrument and data-reduction flow
  - ...despite the moon, clouds, atmosphere, etc.
- Rather common in photometry, but still new in SN spectroscopy
  - Cube extraction
  - Point source extraction
    - Only IFS allows spectro-photometric accuracy
  - Modeling of the effective atmospheric transmission
    - Beyond 1st-order color corrections
    - Including in non-photometric conditions

Cube extraction

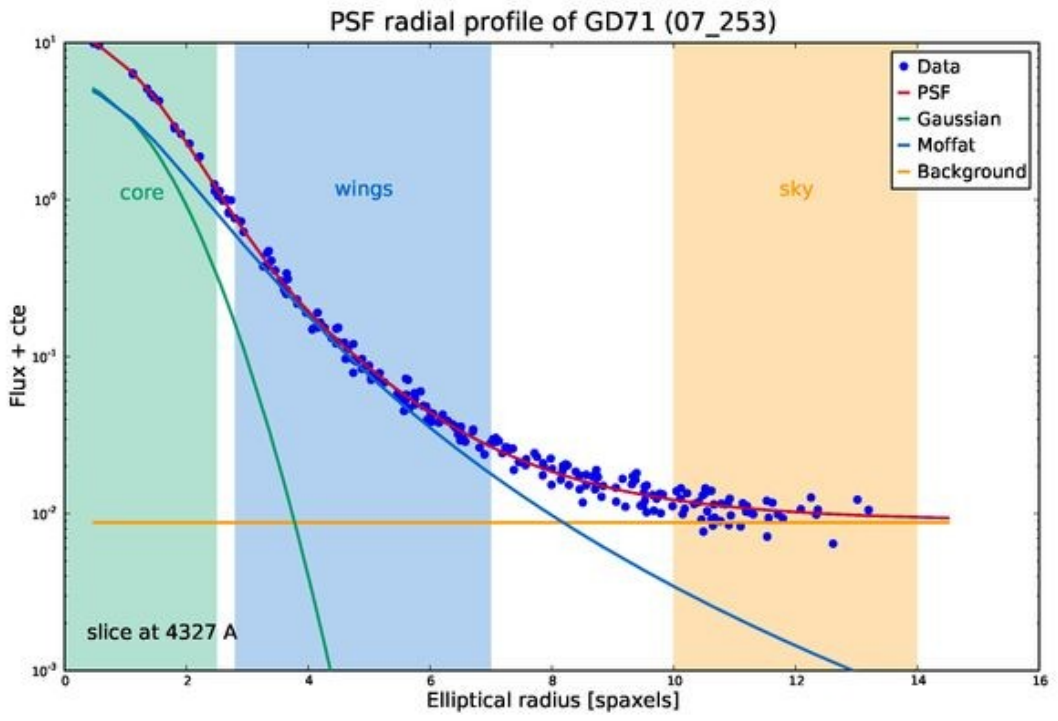
- Ad-hoc ray-tracing optical model
  - Spectrum positions
  - Cross-dispersion profiles
    - Optimal extraction
    - 1st-order cross-talk correction
    - Wavelength pre-calibration





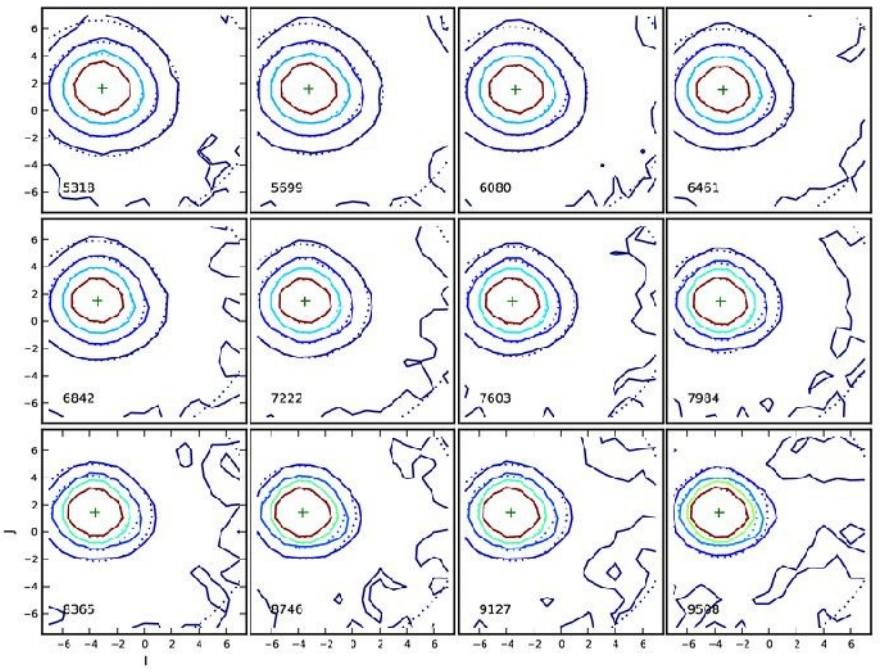
Point-source extraction

- PSF photometry
  - The FoV (6"5×6"5) is too small for accurate aperture photometry and accurate sky subtraction



C. Buton (PhD 2009)

- Semi-empirical model
  - Pure Kolmogorov is not enough
  - 2 shape parameters
    - *Seeing* & focus/guiding
  - Chromatic modeling
    - ADR, *seeing*(λ)
- Flux accuracy: 0,7/1,5%



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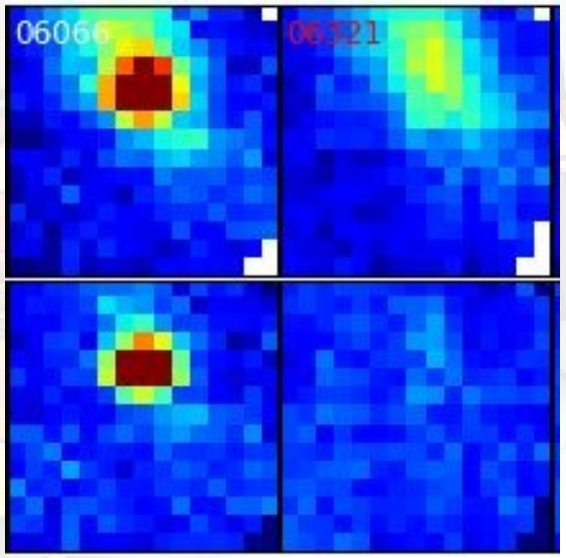
Galaxy background subtraction

- PSF photometry applies to point source *without* structured background: stars, SNe without significant host galaxy
- For SNe with galaxy: background subtraction is required
  - Use of a reference exposure (≥ 1 yr after)
    - Registration and PSF matching (*seeing*)
    - Diffuse background subtraction
  - Structured background-free SN extraction



S. Bongard et al. (in prep.)

Flux calibration – photometric case

- *Photometric night* : atmosphere is **stable** during night
  - "Classical" flux calibration scheme applies
    - Derive atmospheric extinction from standard star observations
    - Joint use of all standard stars of the night (χ^2)

Observed spectrum at airmass z [pseudo-ADU]

Atmospheric extinctions [mag/airmass]

$$\log\left(\frac{S(\lambda)}{S^*(\lambda)}\right) = \log C(\lambda) - 0.4 \times z \times \bar{K}(\lambda) - 0.4 \times \bar{K}_T(\lambda, z)$$

Reference flux [erg/s/cm^2/Å]

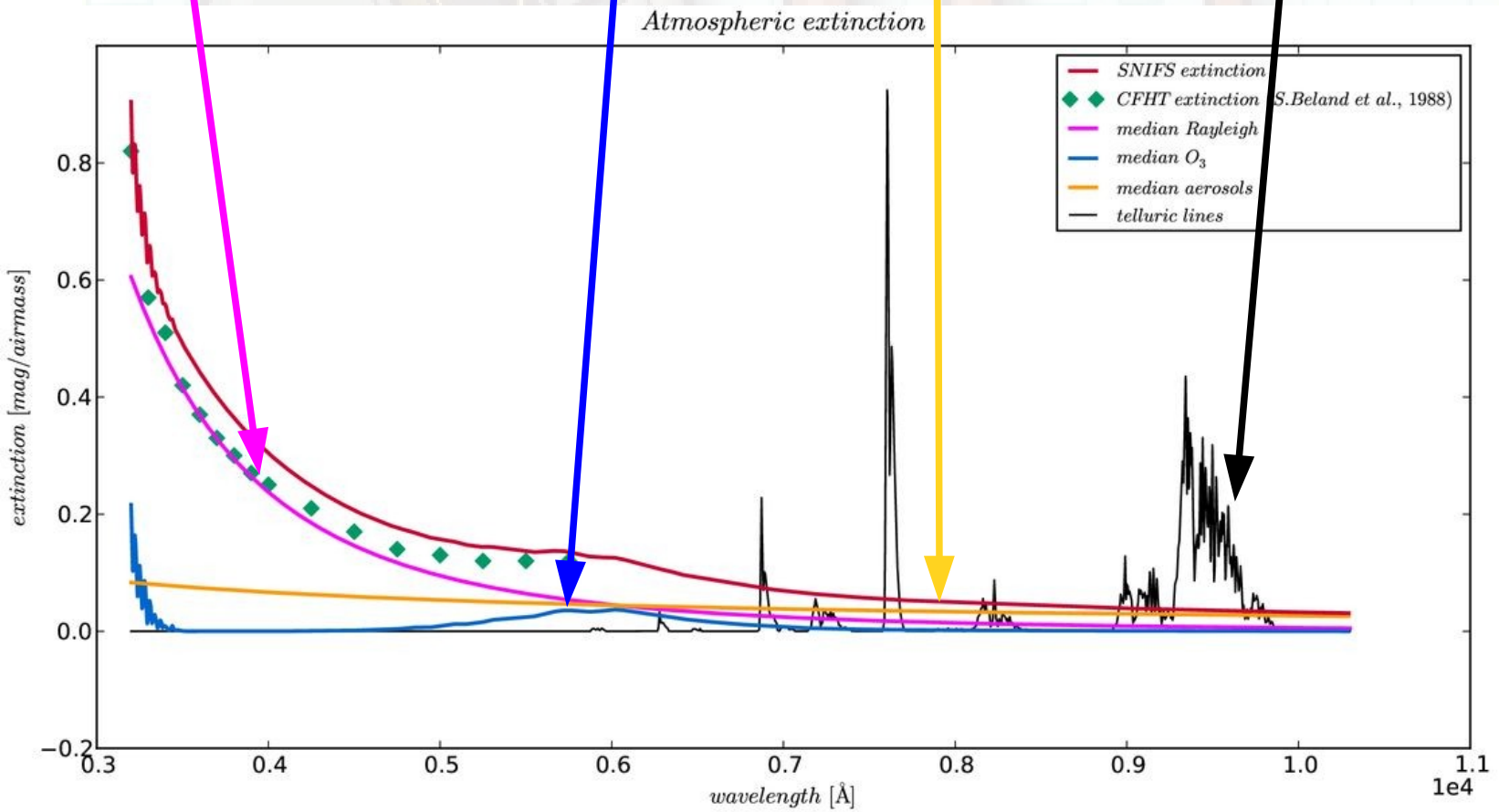
Flux solution [erg/s/cm^2/Å / pseudo-ADU]

C. Buton (PhD 2009)

Atmospheric extinction modeling

- Extinction is split in physical components

$$\bar{K}(\lambda) = K_{\text{Rayleigh}}(P,\lambda) + \alpha_{O_3} k_{O_3}(\lambda) + A K_{\text{Aerosols}}(\lambda,\gamma) + K_{\text{Telluric}}(\lambda,z)$$



C. Buton (PhD 2009), Burke et al. (2010)

Flux calibration – non-photometric case

- *Non-photometric night* : atmospheric extinction **is not constant** during night (clouds)
  - Classical flux calibration scheme does not apply anymore

Observed spectrum at airmass z [pseudo-ADU]

Atmospheric extinction [mag/airmass]

$$\log\left(\frac{S(\lambda)}{S^{*}(\lambda)}\right) = \log C(\lambda) - 0.4 \times z \times K(\lambda, \boldsymbol{t})$$

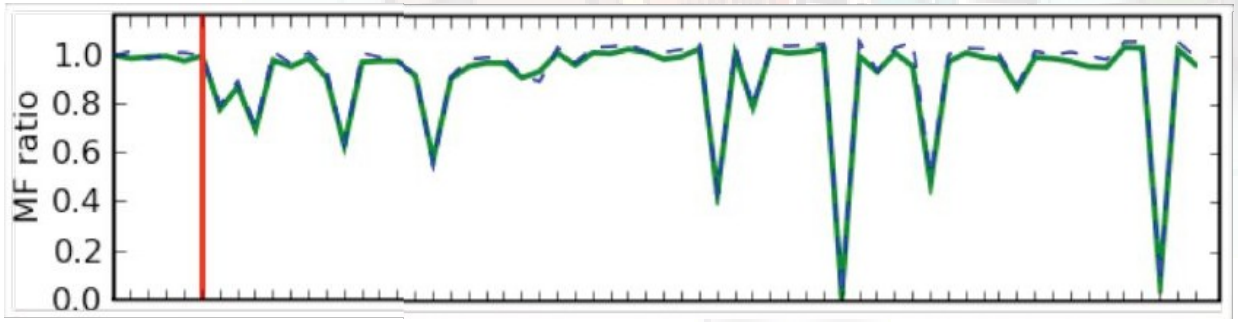
Reference flux [erg/s/cm²/Å]

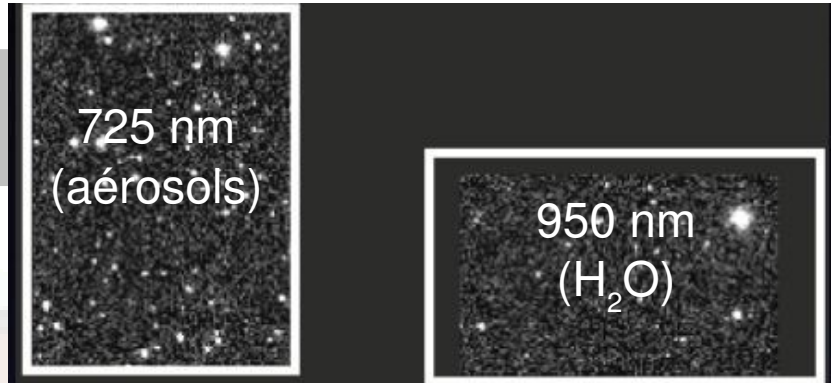
Flux solution [erg/s/cm²/Å / pseudo-ADU]

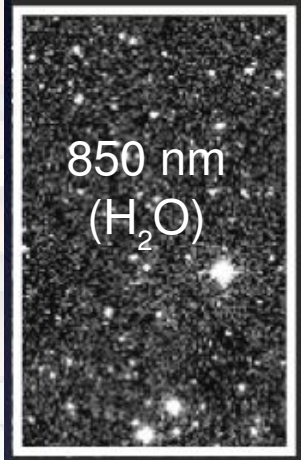
C. Buton (PhD 2009)

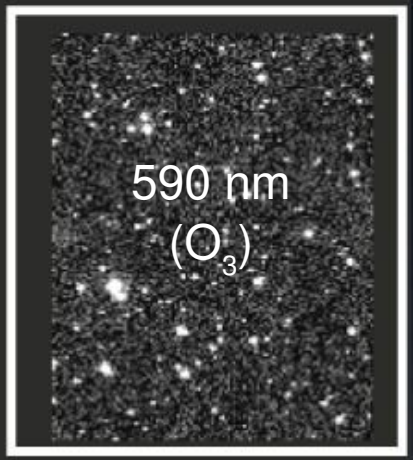
Non-photometric case

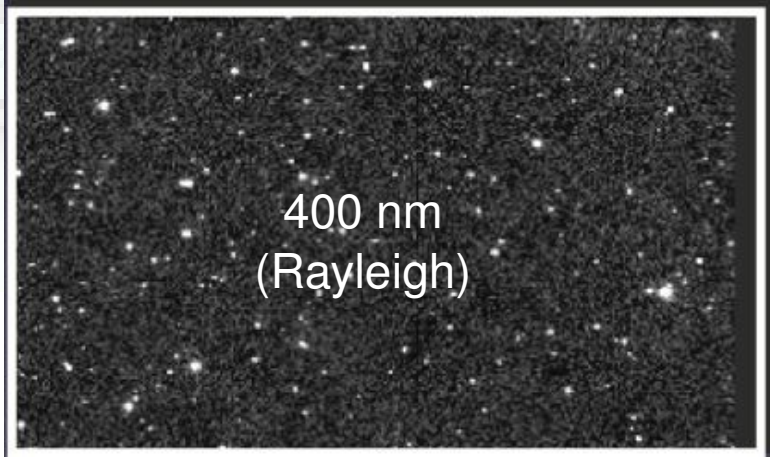
- Effective extinction follow-up during spectroscopic exposure
  - Secondary sources within MF
  - Differential extinction / reference photometric night
    - Self-calibration
- Hypothesis : clouds are “gray”
  - *Achromatic variability* of extinction
    - $K(\lambda,t) = K(\lambda) + \Delta K(t)$
  - Confirmed at the percent-level



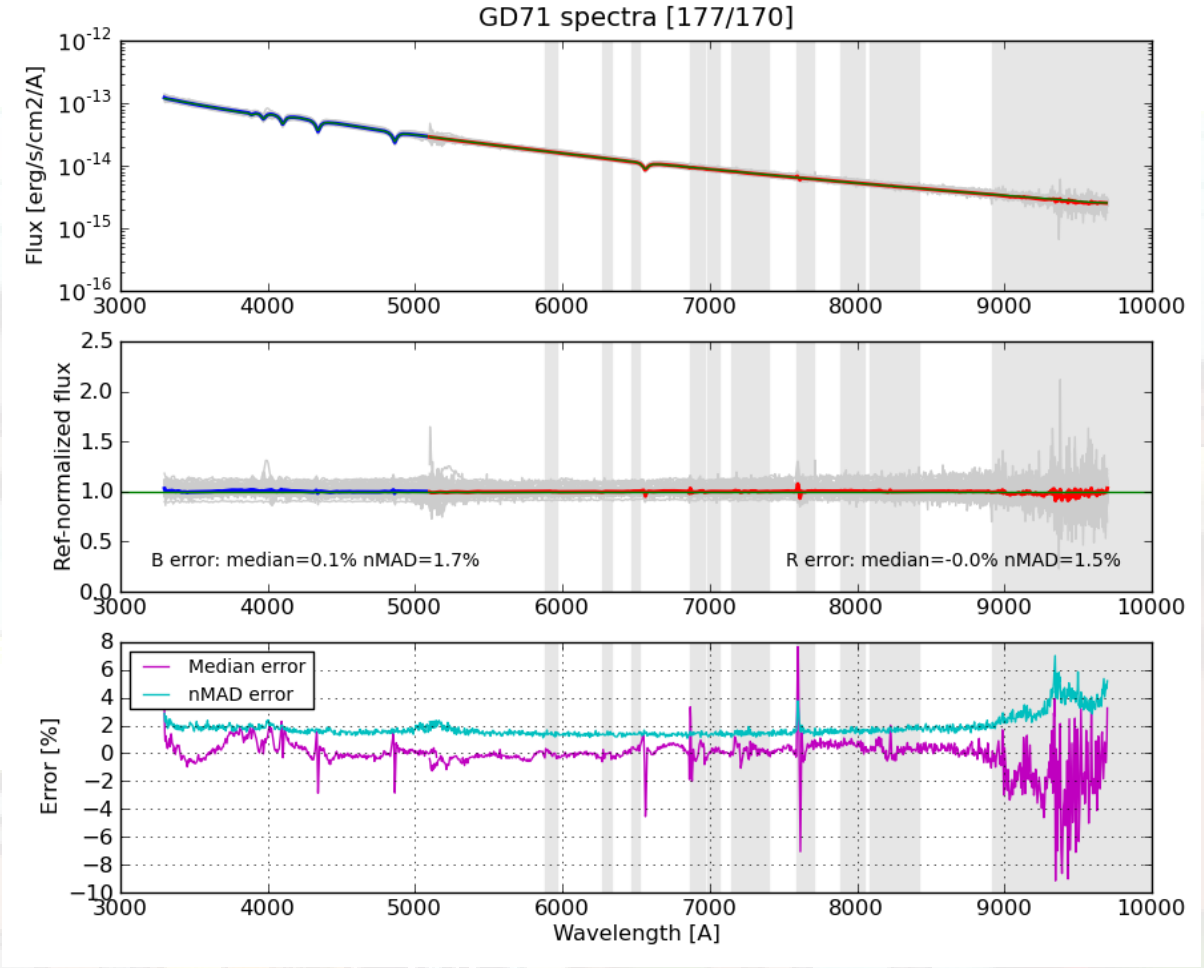








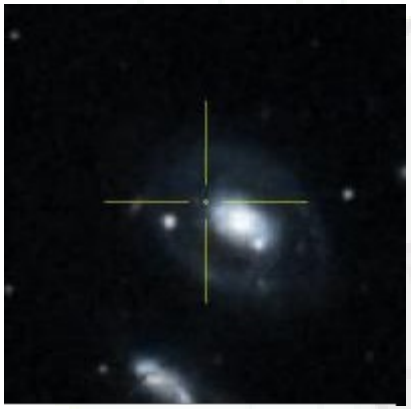
Spectro-photometric accuracy

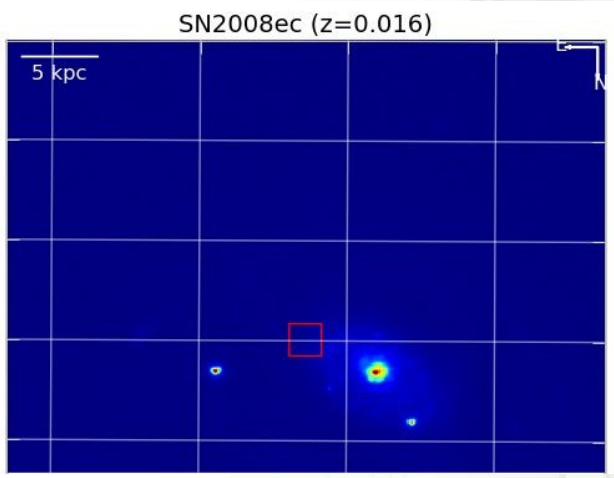


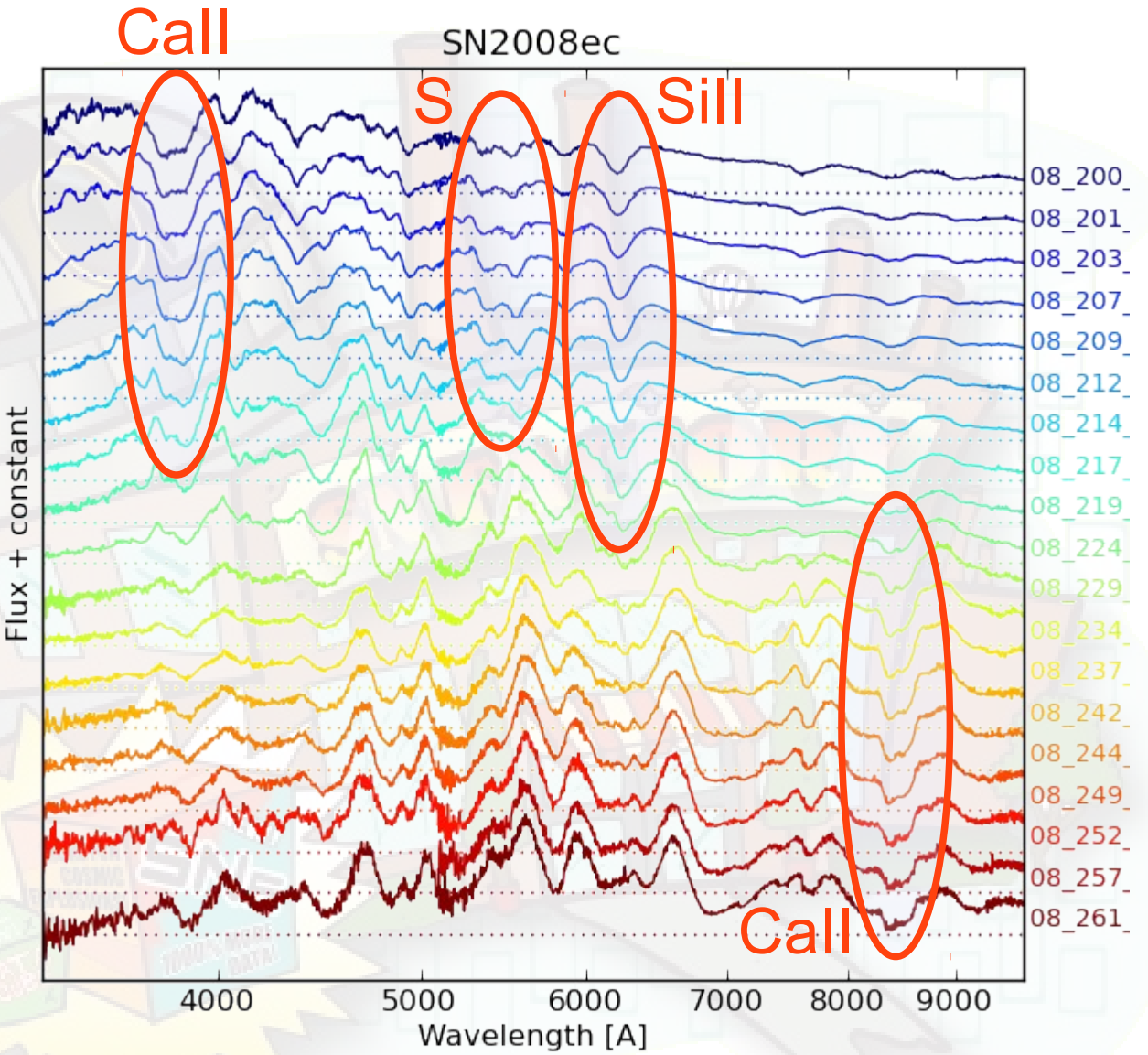
	650 standard stars				
σ (mag)	**U**	**B**	**V**	**R**	**I**
Photo	0.027	0.024	0.023	0.022	0.025
Non-photo	0.034	0.033	0.035	0.034	0.036

Science results

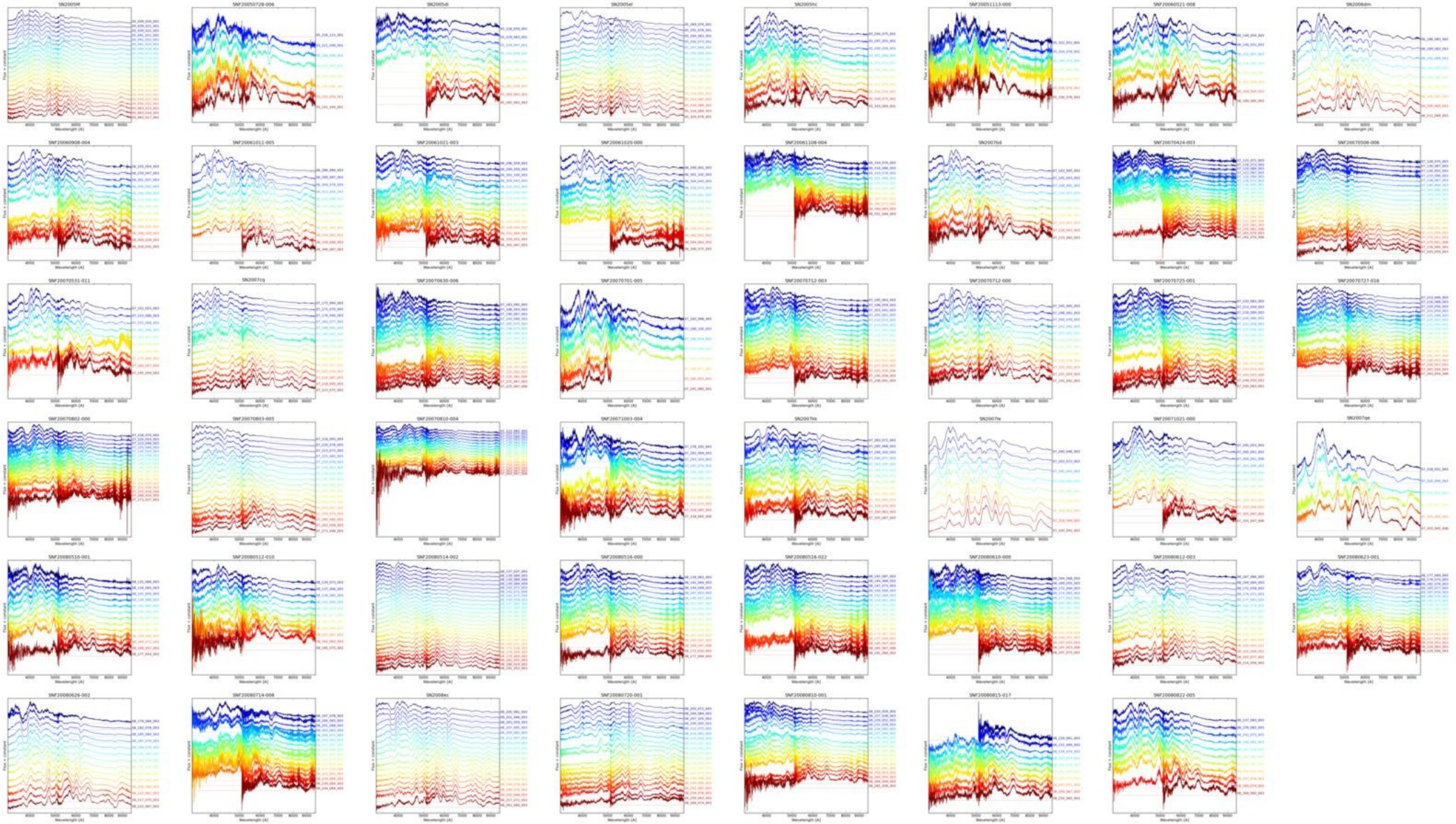
SN2008ec time-series



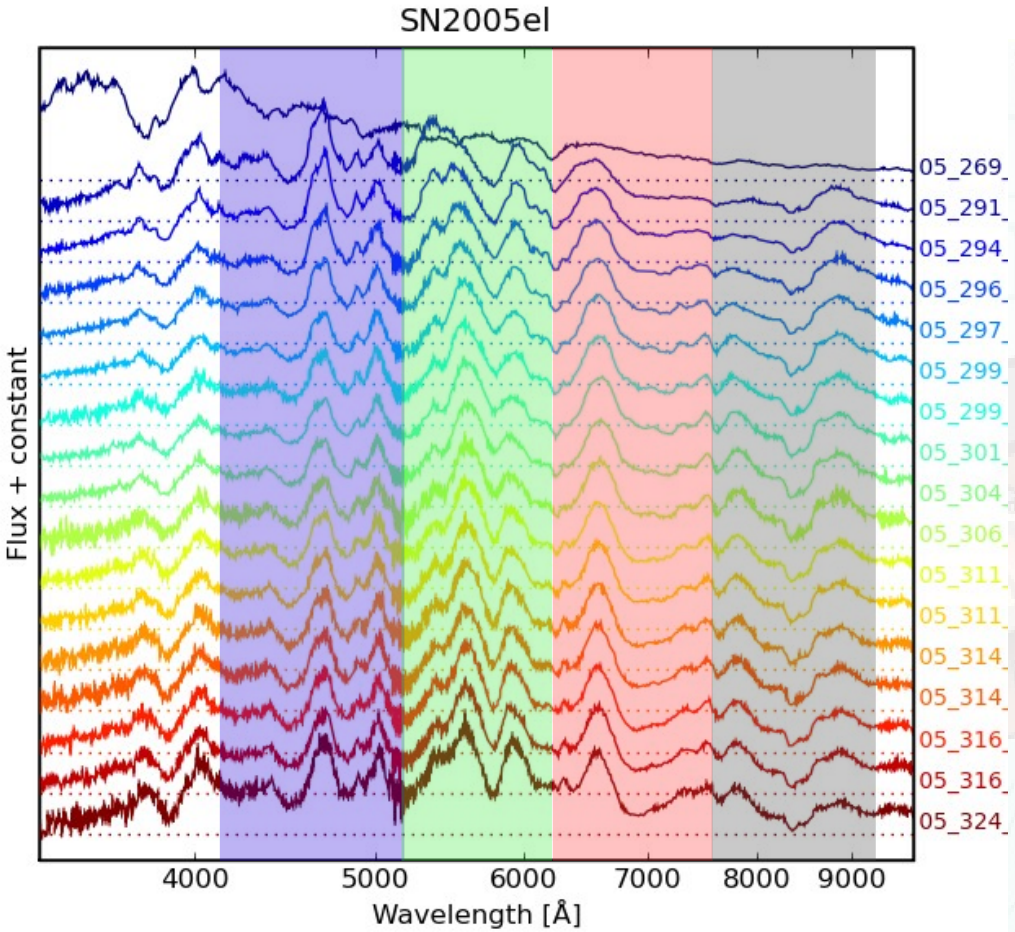




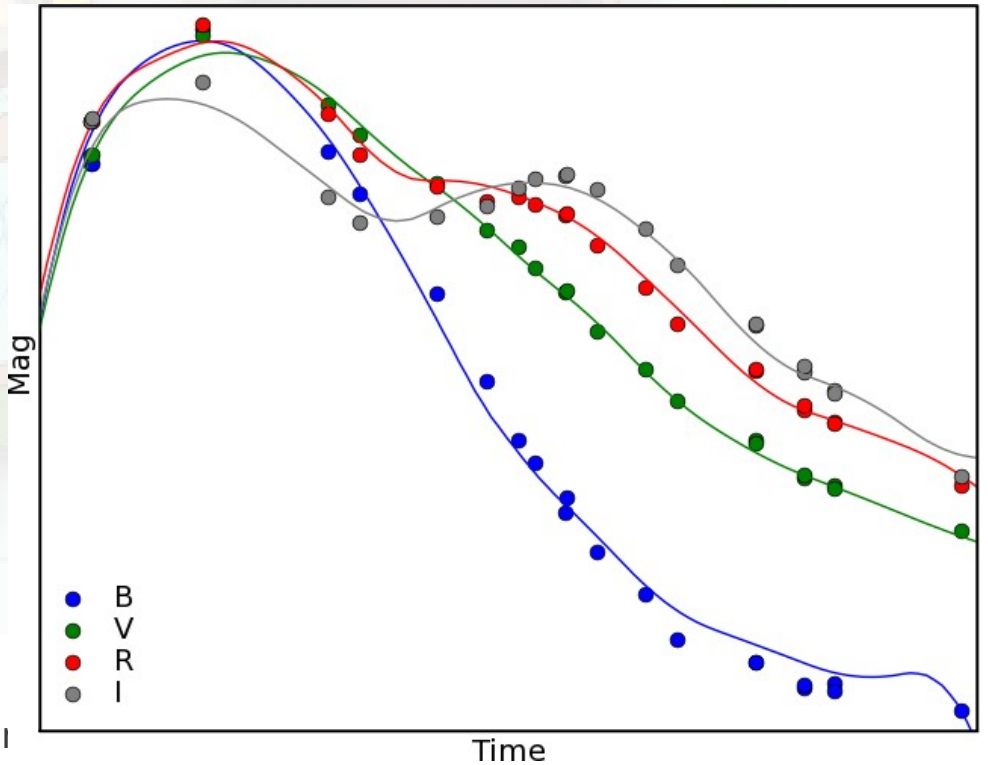
Few timeseries (~1/4)



Broad-band photometry



- Synthetic photometry
  - In any band !
    - Inter-calibration with other experiments
  - Including *rest frame bands*
    - No more need for K corrections



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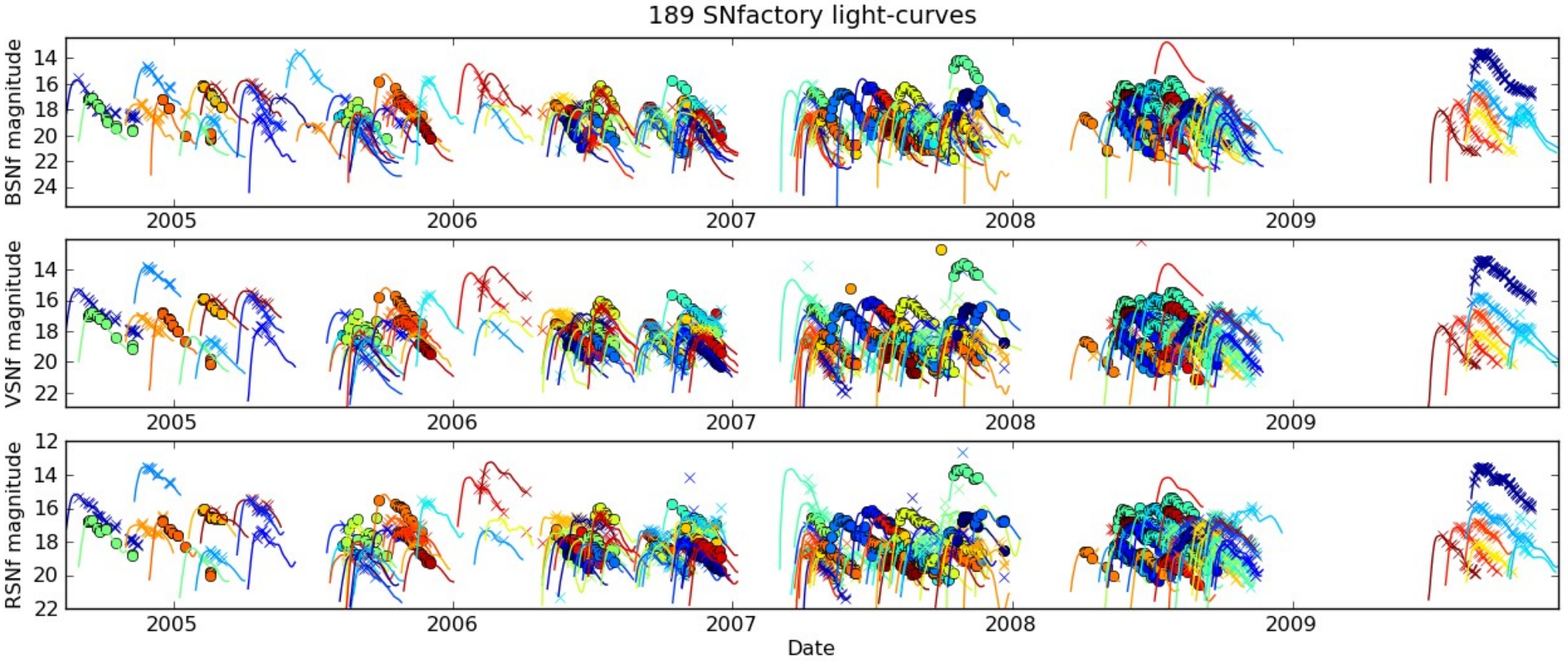
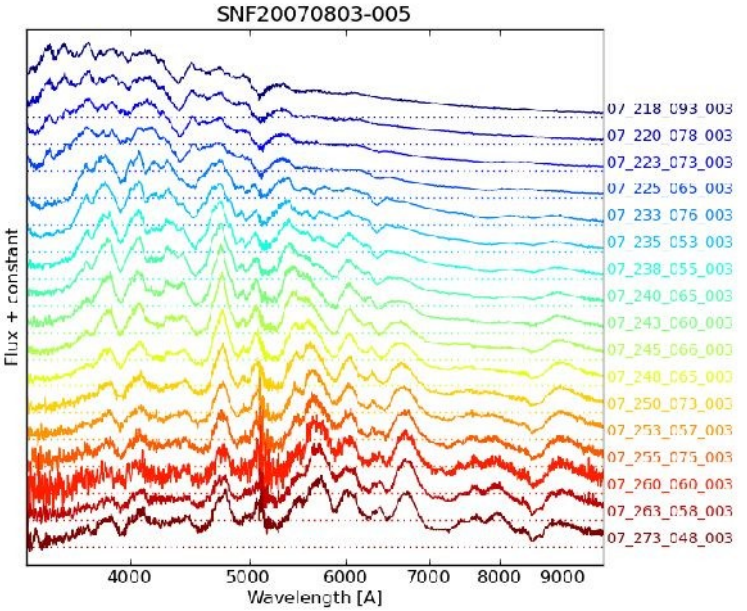
SNfactory sample light-curves

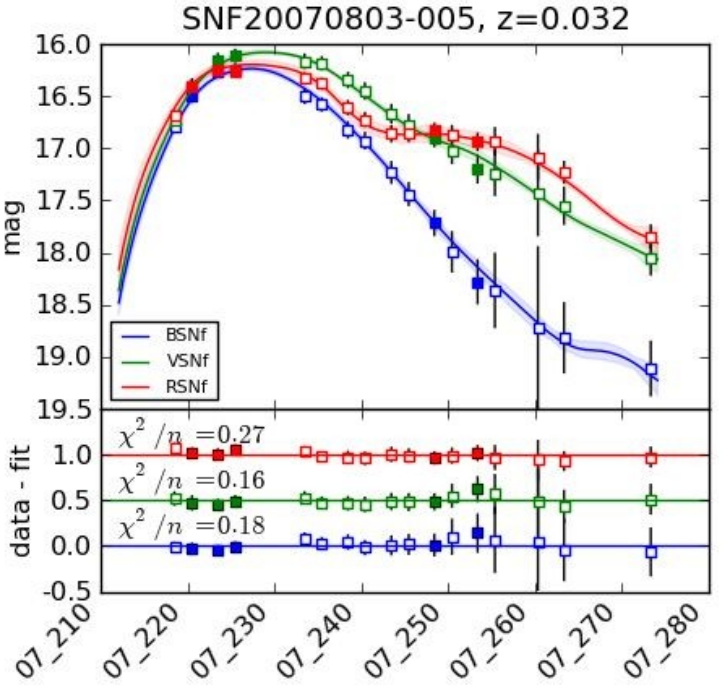


Slow start... SNfactory at full power End of search References

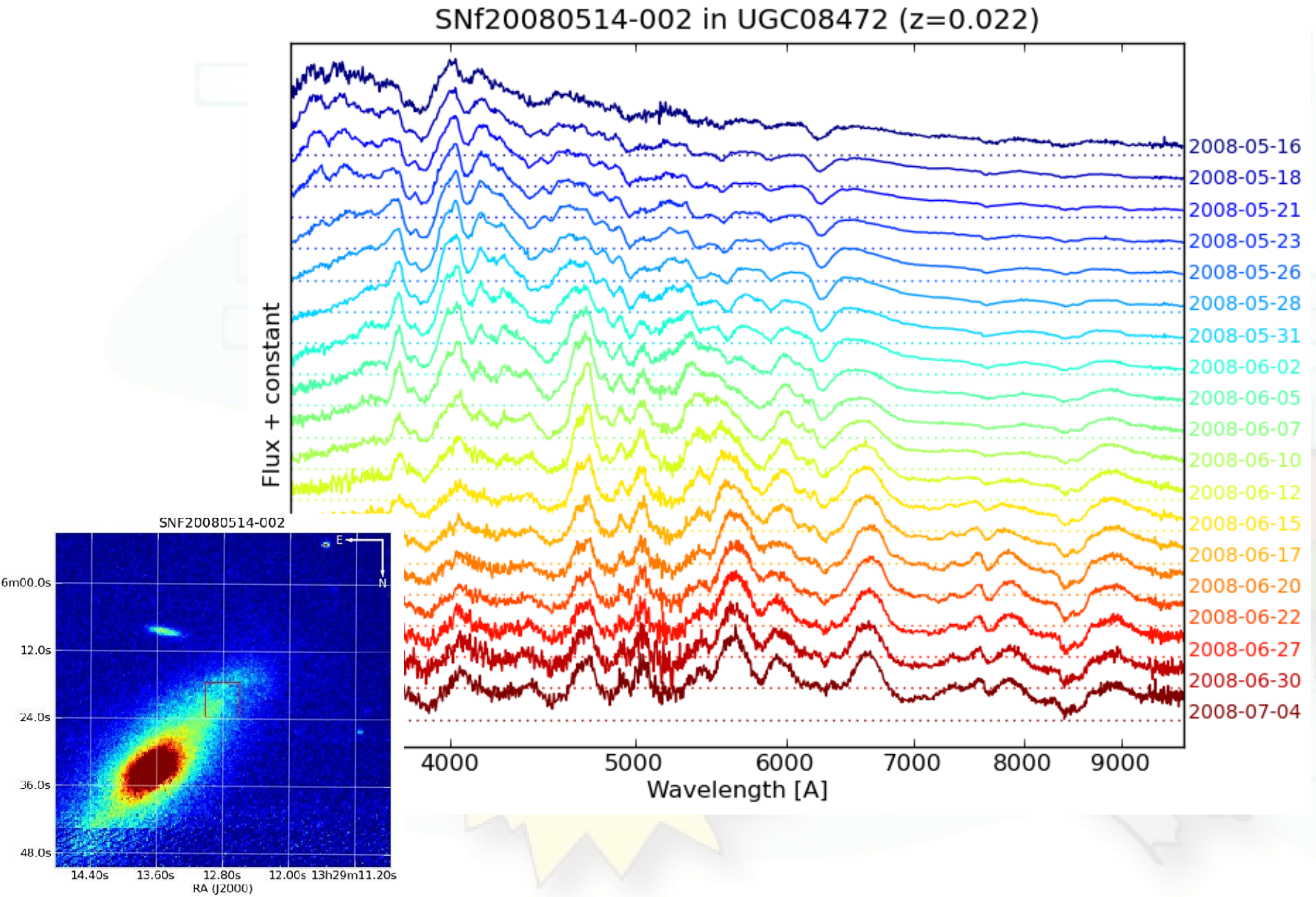
Light-curve fitting

- SALT2 fitter (B,V,R)
  - Minimalist approach to mimic “classical” photometry
- Parameters : M_B^{max}, *stretch* (*x1*), color (*c*)
  - Adjustment : ~10% RMS
    - 7% core + outliers
    - Accuracy ~5% on parameters
- Future developments
  - Rest-frame magnitudes
    - No more K-correction
  - Time-series
    - New spectral templates (SALT3)

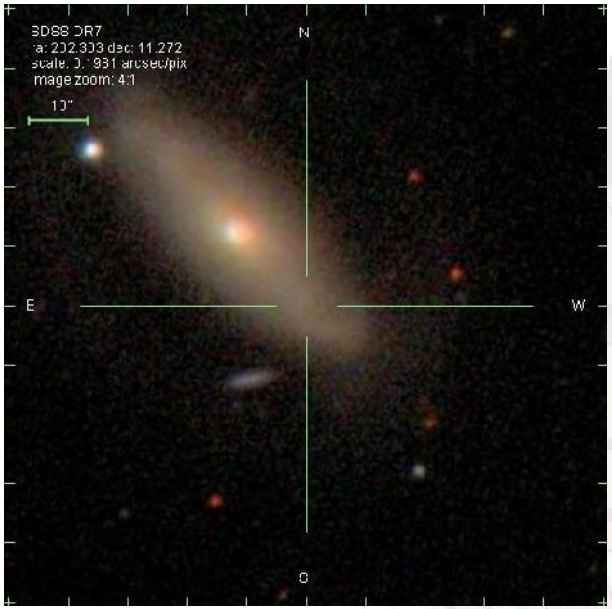


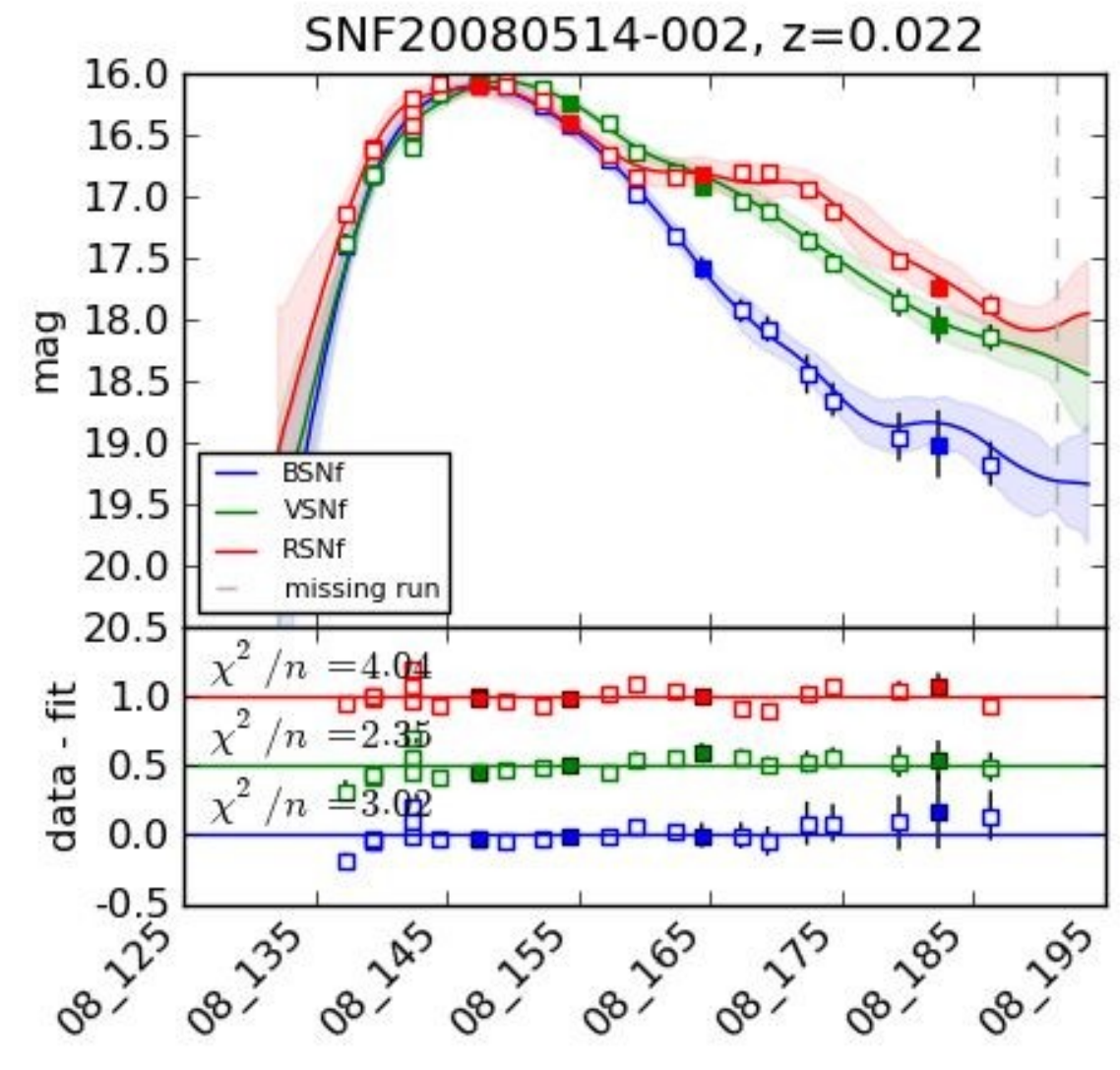


SNF20080514-002 time-series

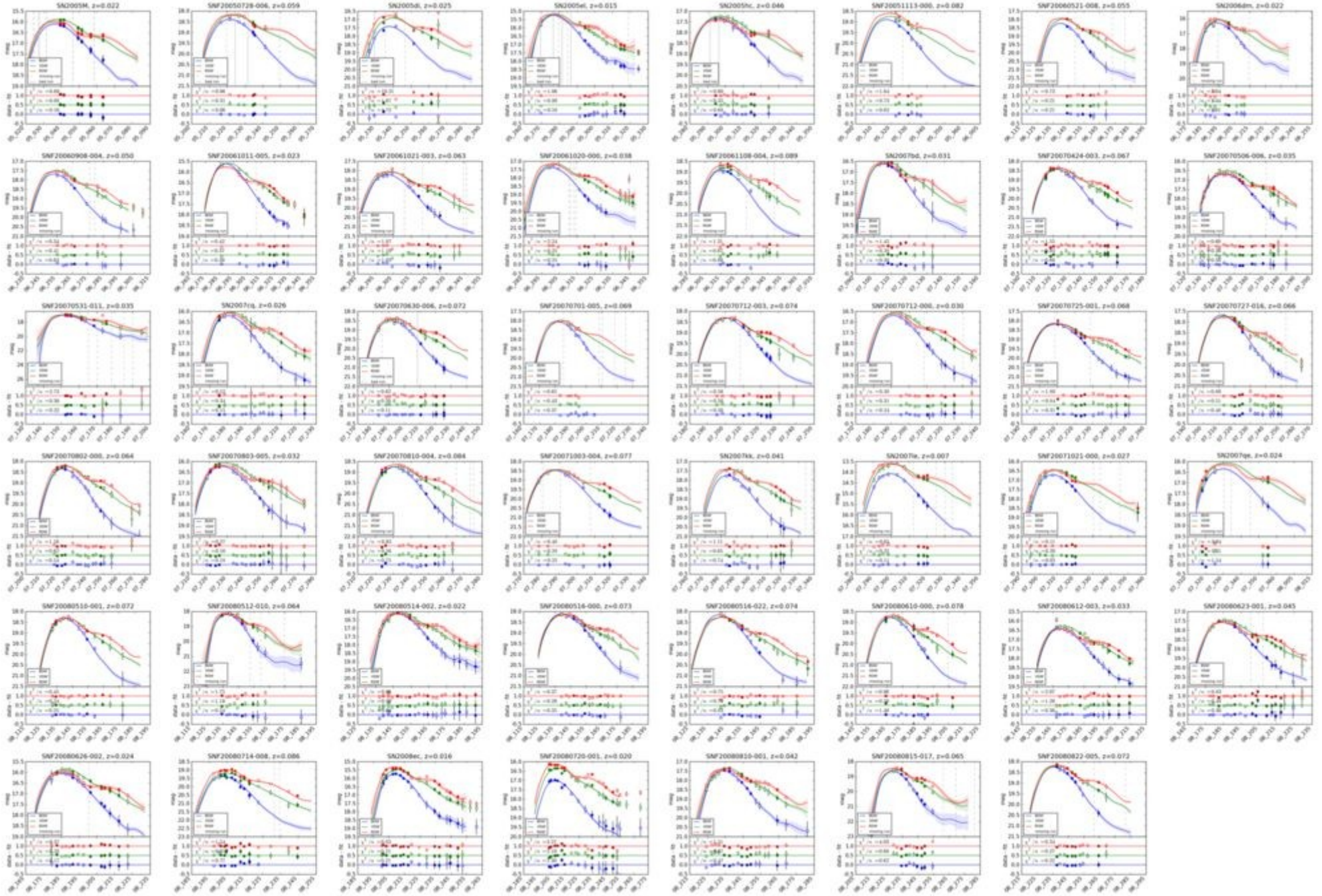


SNF20080514-002 in UGC8472 (z=0.022)



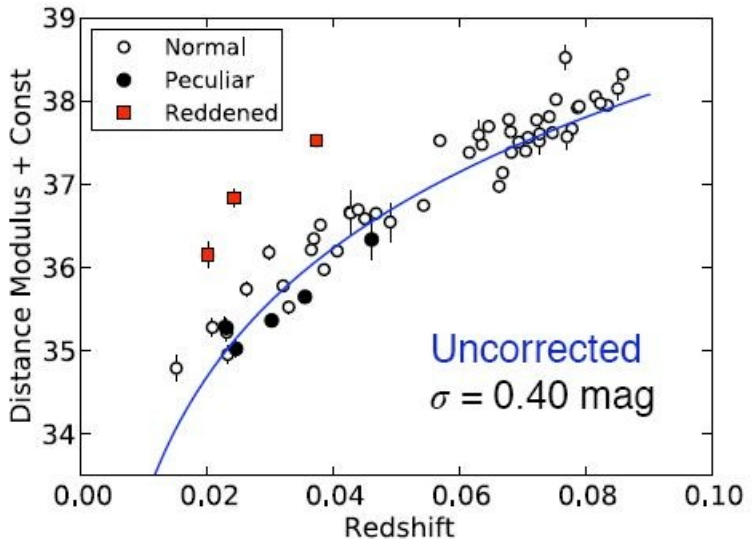


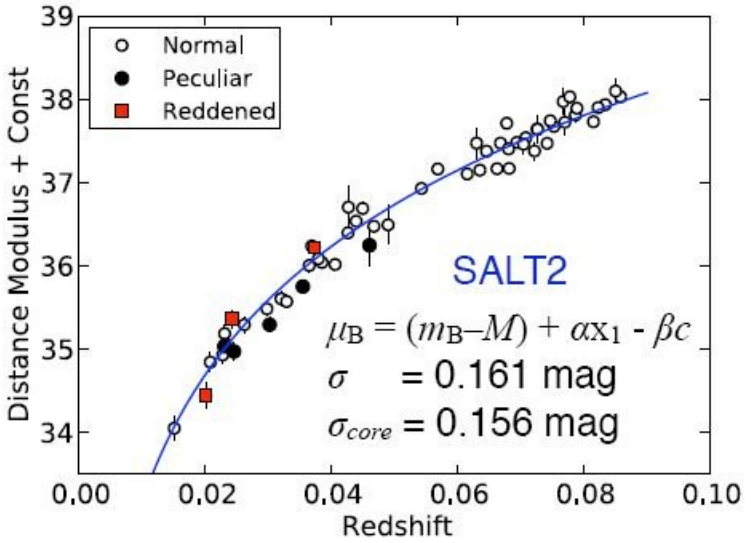
Few light-curves (~1/4)



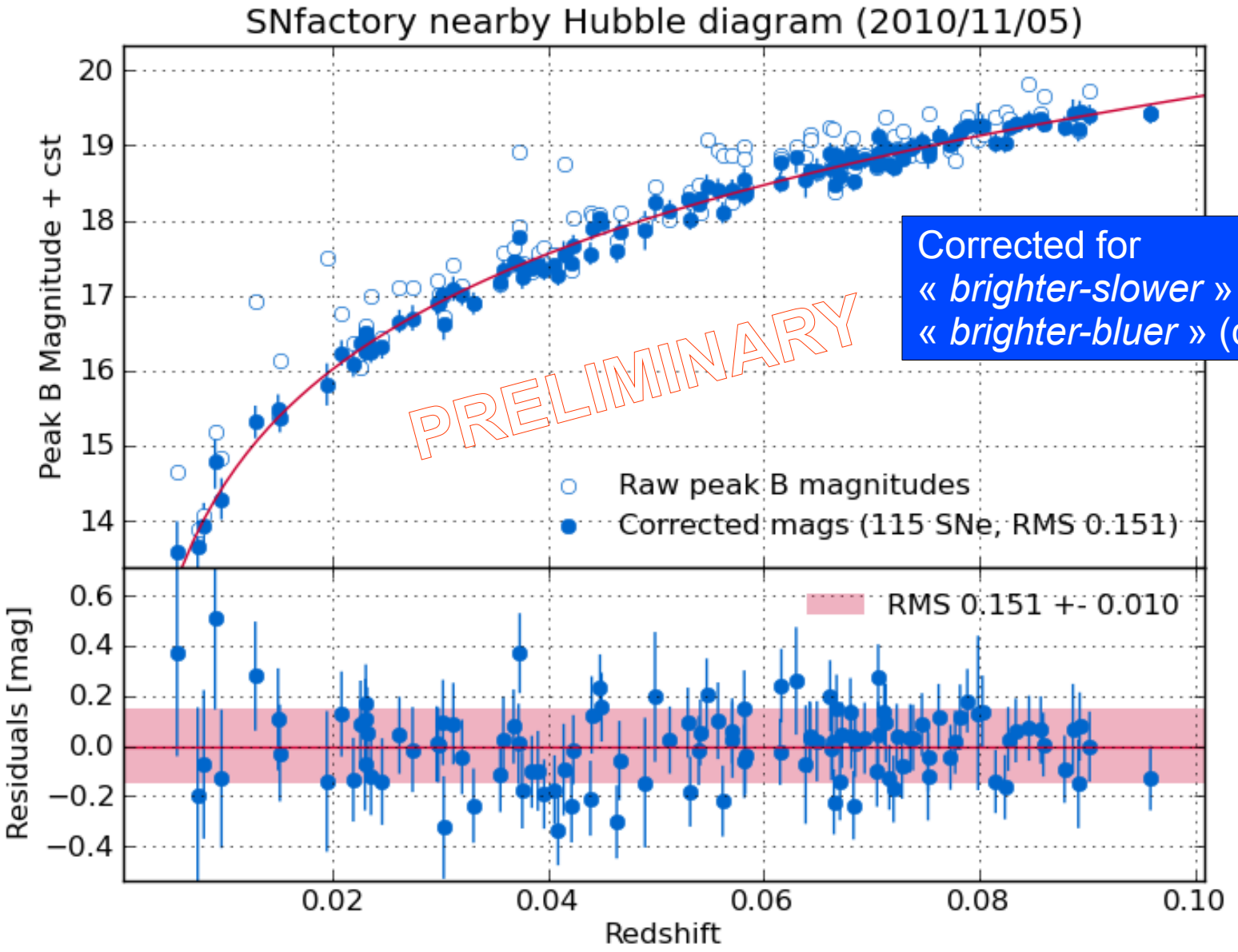
Hubble diagram

- "Traditional" light-curve adjustment
  - « *Brighter–bluer* » & « *Brighter–slower* » (SALT2)
- Synthetic photometry reaches usual precision
  - Sub-sample of 58 Sne (Bailey et al. 09)
    - Spectra at max (± 2.5 d)
    - No or faint uniform host galaxy (no background subtraction)

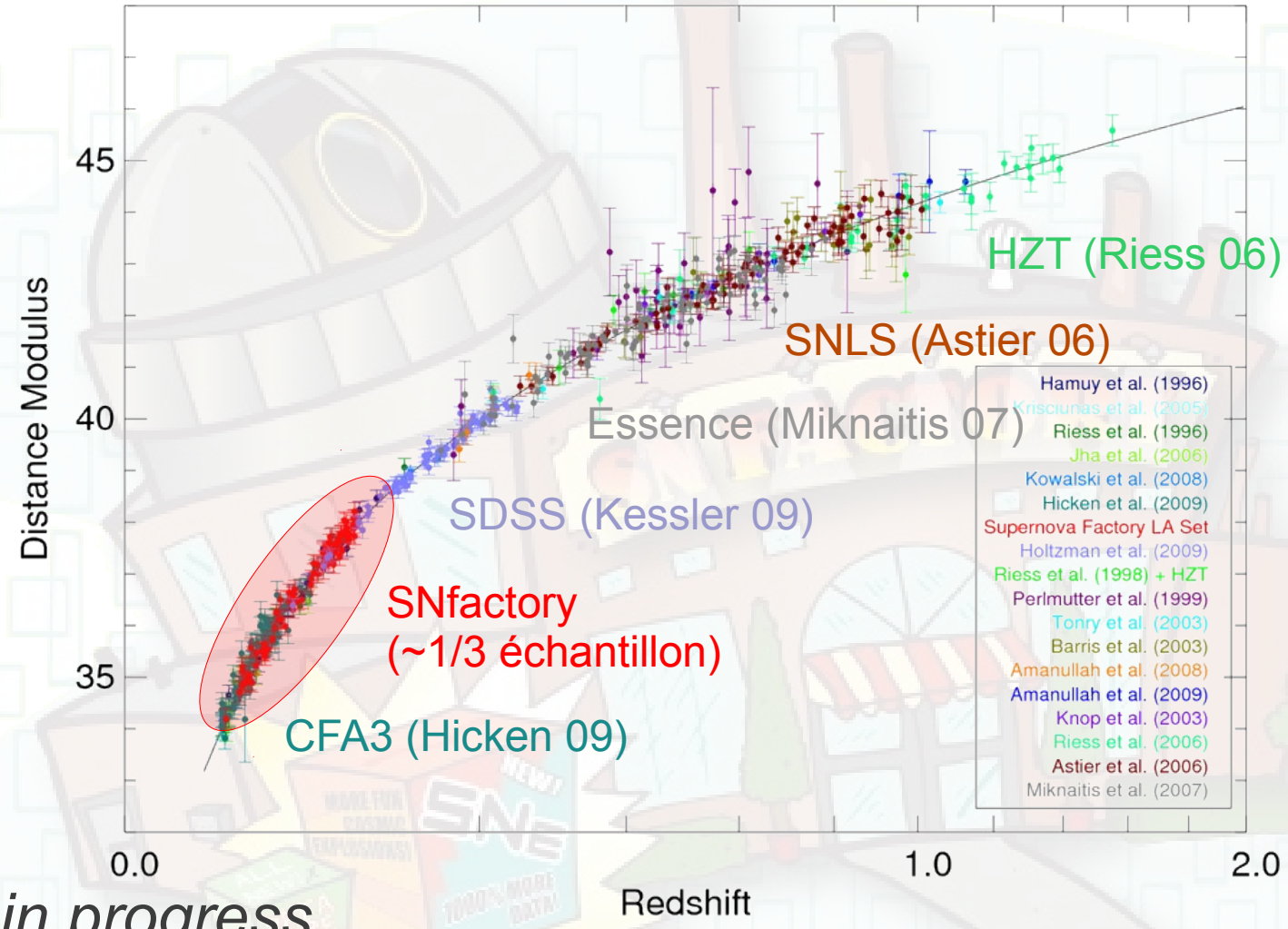




Latest production: Nebraska



SNfactory sample

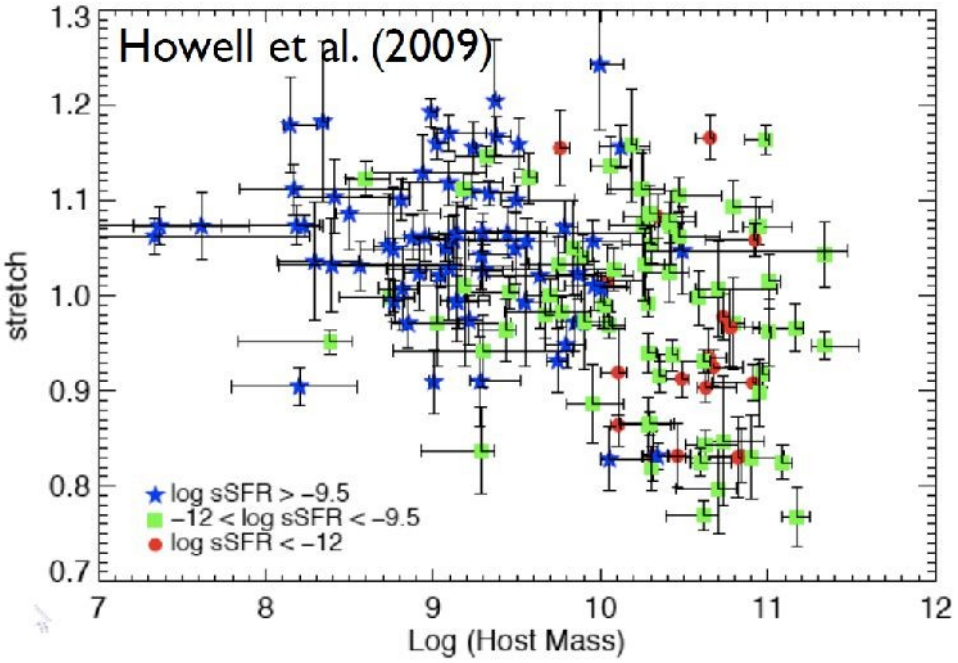


- *Work in progress*
- Blinded cosmology

(D. Rubin)

SN Ia host galaxies

- Light-curve correction
  - Stretch, Δm15 → Ni mass
  - Color → Extinction + color
  - σ(mag) ~ 0.4 → 0.15
  - Can't seem to go lower
- Remaining dispersion?
  - Spectral indicators, standalone or complementary
    - e.g. Bailey et al. 09
  - Disentangle *intrinsic* vs. *extrinsic* colors
    - e.g. Chotard et al. 11
  - Progenitor environment
    - Host galaxy studies

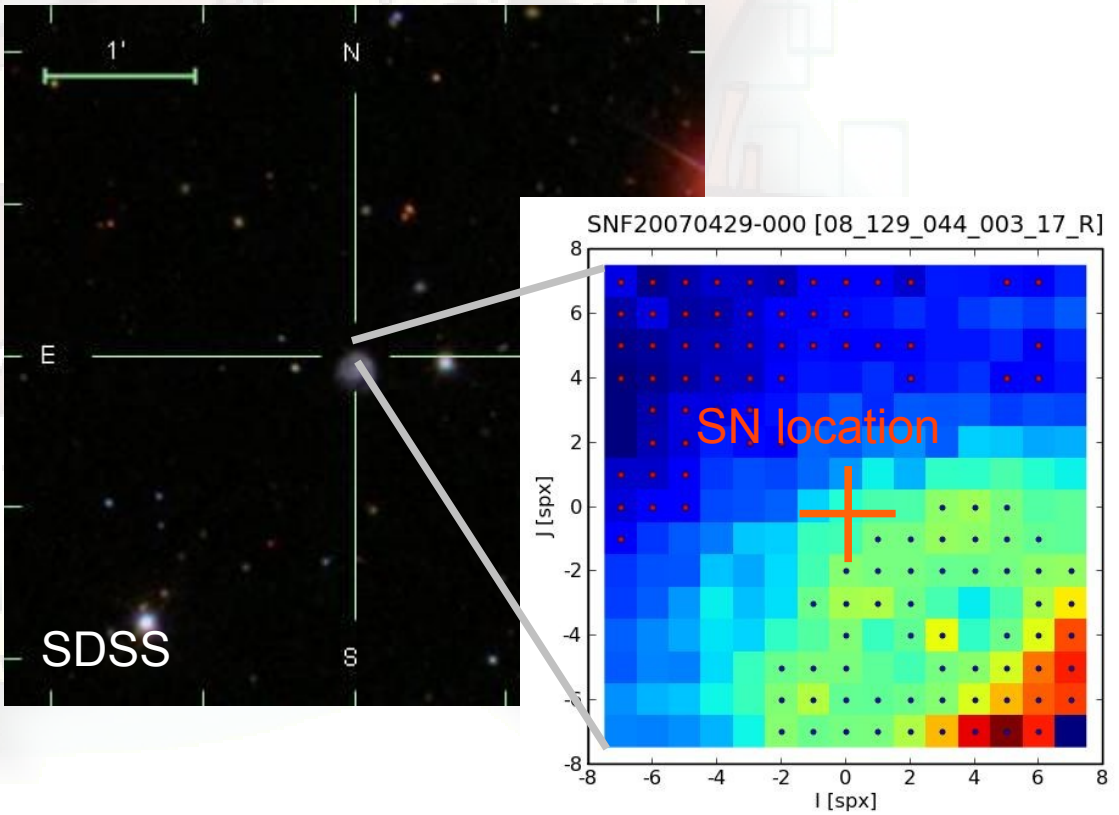


- SNe Ia properties correlate with host galaxy mass
  - "Brighter – bigger"
  - A 0.08 mag effect on Hubble residuals (Sullivan et al. 10)
  - Host mass (presumably) correlates to SFR & metallicity

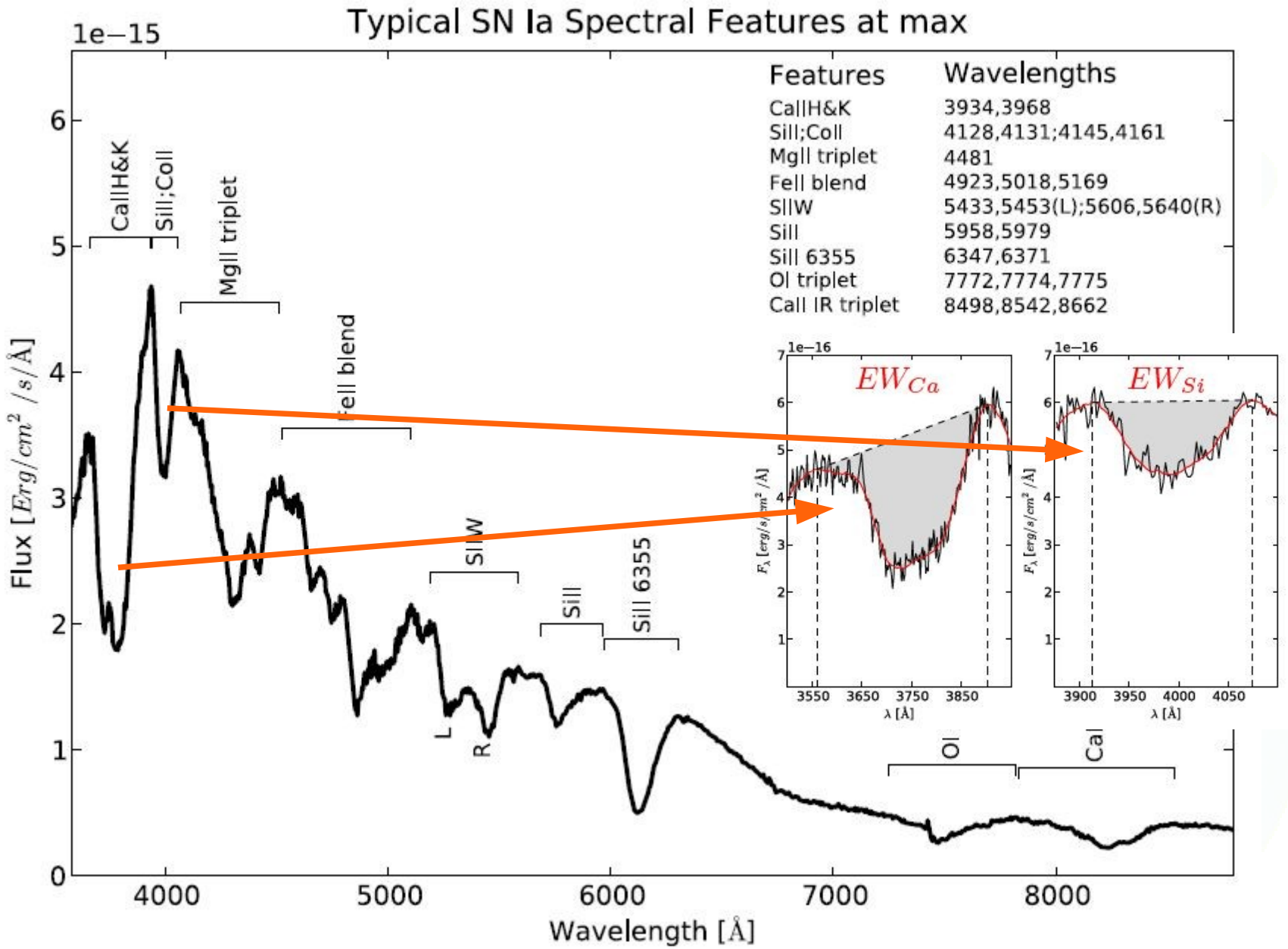
Host galaxy studies in SNfactory

- Core/integrated properties
  - M. Childress et al.
  - Photometry
    - Archives + SNf exposures
    - Host mass
  - Spectroscopy
    - Archives + long-slits **on core**
    - Host metallicity: gas and stars

- Properties *at* SN location
  - M. Rigault
  - Existence of gradients and/or local structures
  - Host spectrum from SNIFS



Spectral analysis at max

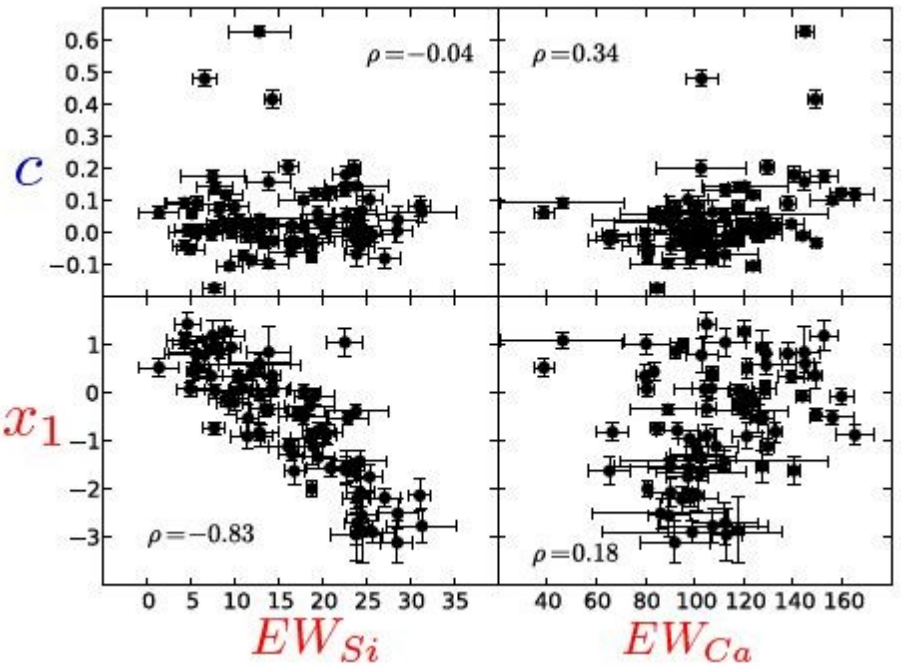


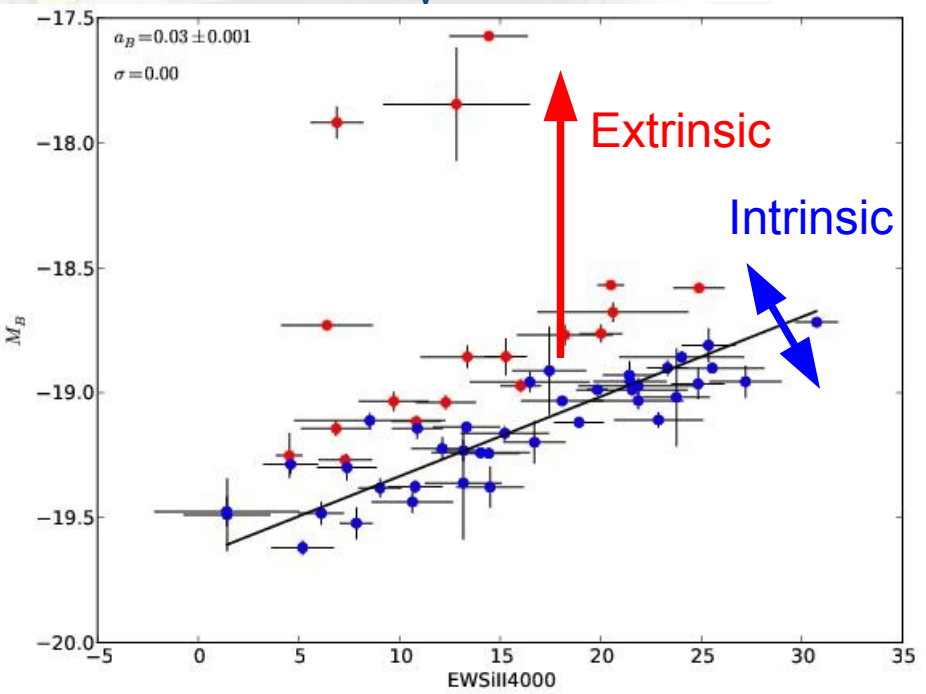
Classical spectral indicators

- EWs competitive with LC quantities (x_1, c)
- Insensitive to reddening
- Objective: disentangle intrinsic vs. extrinsic extinction

- Chotard et al. 2011

Intrinsic correction
+
Dispersion in color
↓
Cardelli-like extinction law
and
$R_V \sim 2.8$

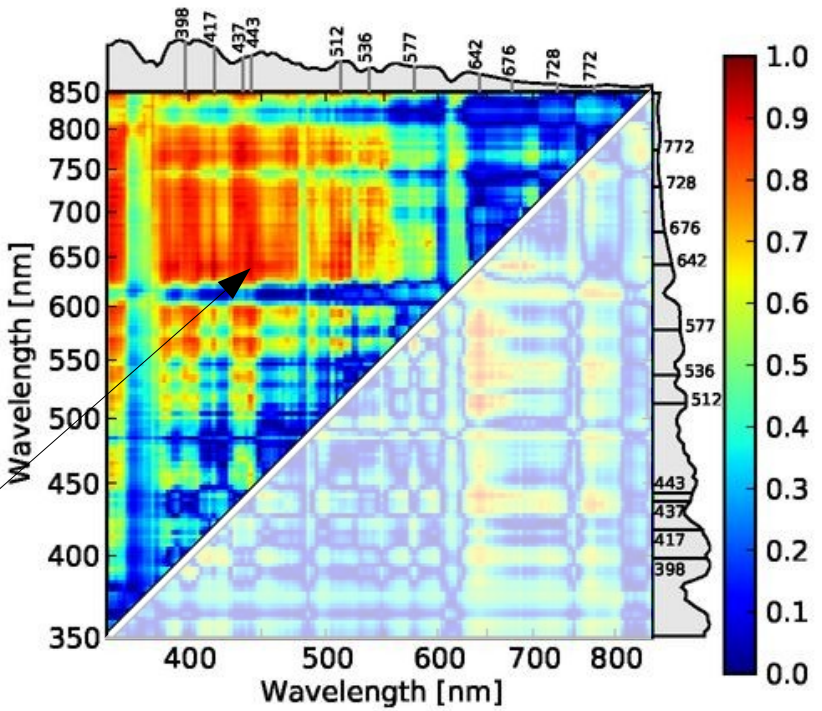


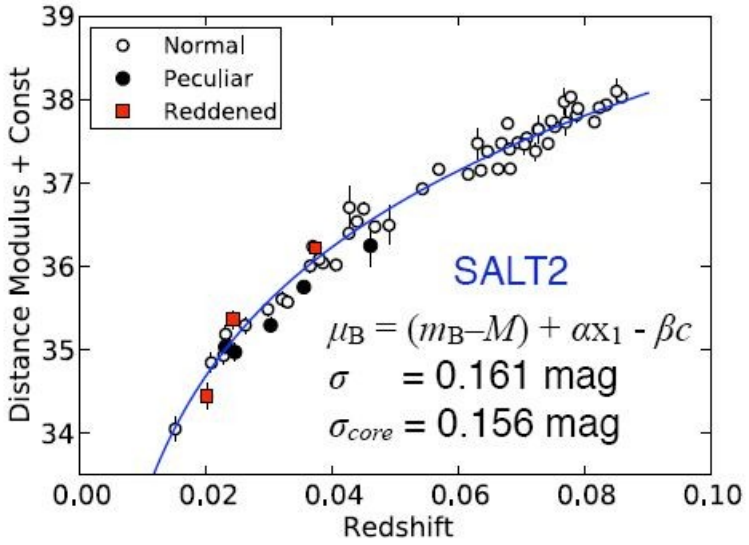


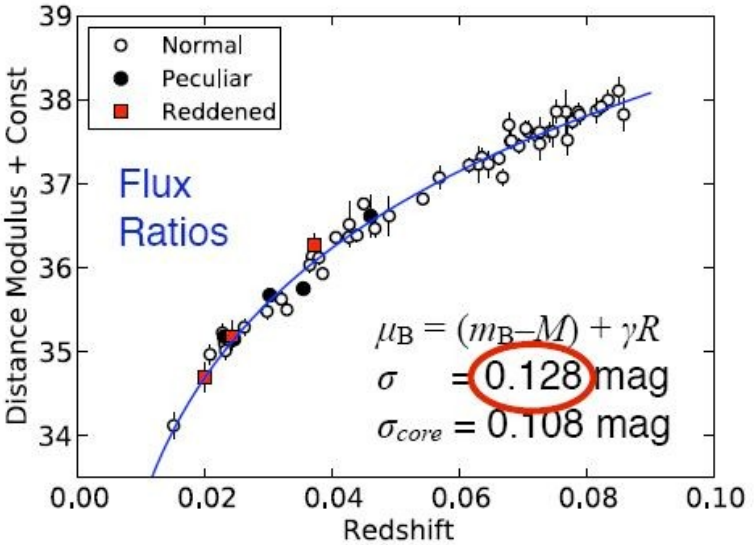
Spectral correlations (Bailey et al. 09)

- Phenomenology
  - Blind search for correlations between $R(\lambda_1/\lambda_2)$ and $\Delta\mu$
  - Sample of 58 SNe
    - ± 2.5 days around max
    - Training / validation split
    - R(642/443): ρ = 0.95

R(642/443)



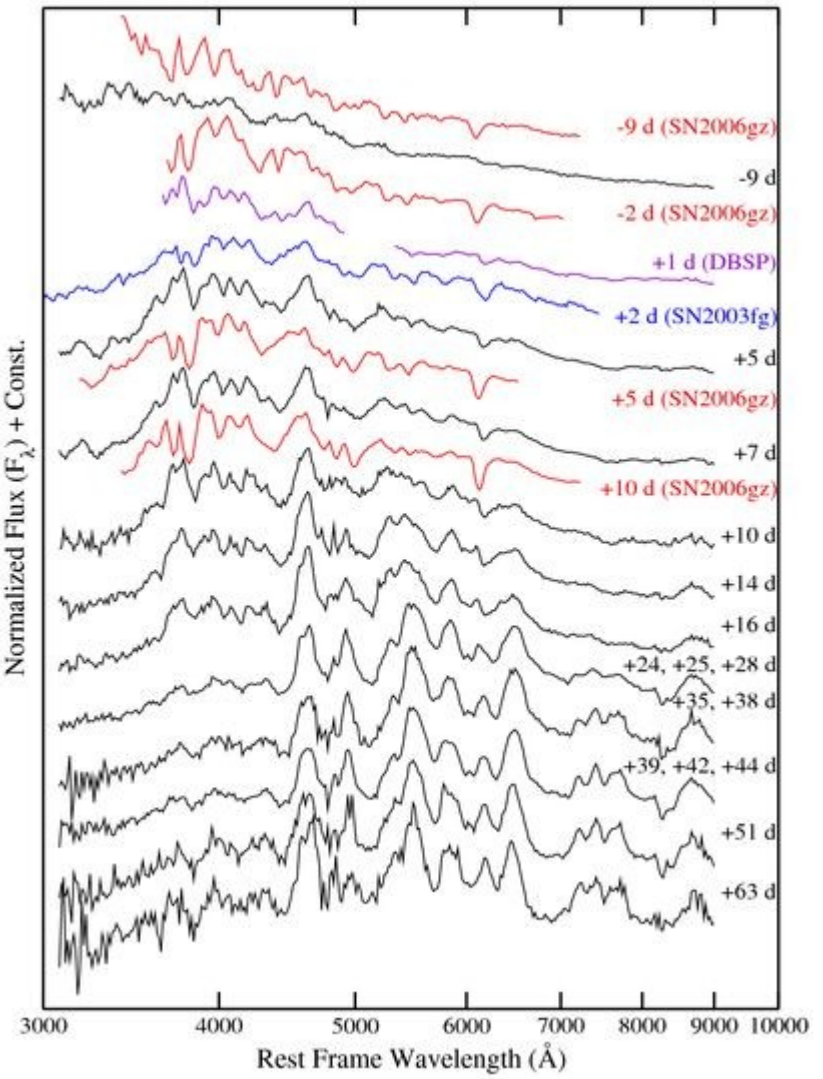




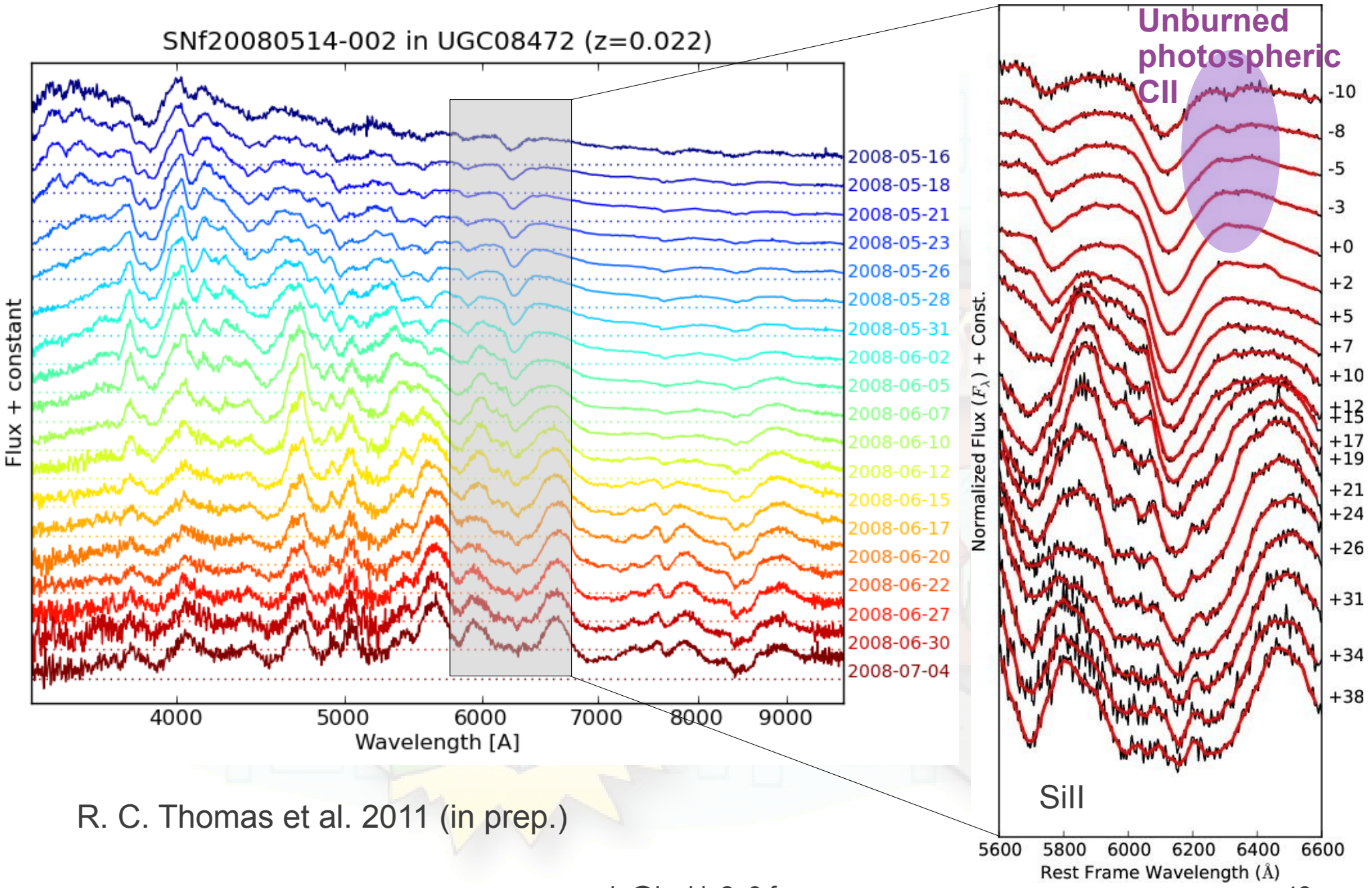
Super-Chandrasekhar SNe Ia

- Ex.: SN 2007if aka SNF20070825-001
  - Scalzo et al. 2010
  - Super-Chandrasekhar SN (with SN03fg, SN06gz, SN09dc)
  - Double degenerate merger
    - 1st total mass measurement :

      $M = 2.4 \pm 0.2\ M_{\odot}$, $M_{Ni} = 1.6 \pm 0.1\ M_{\odot}$
  - Very faint host galaxy
    - Childress et al. 2011
    - Metallicity ~below cutoff for SD SNe (Kobayashi & Nomoto 09)
- Six other DD-WD merger candidates in SNf sample
  - From Si II velocity plateau (→shell in ejecta)



SNF20080514-002 in UGC8472 (z=0.022)



R. C. Thomas et al. 2011 (in prep.)

SNF20080514-002 in UGC8472 (z=0.022)

Conclusions & prospects

- SNfactory (2004-2009)
  - +200 spectro-potometric time-series, 3300 spectra
    - Unmatched sample
    - Last tweaks in data reduction and flux calibration
  - A new era for the SN Ia understanding
    - Greater statistical power, better control of systematics
  - Spectro-photometry
    - 3D spectrography is essential
    - Point source extraction, host galaxy subtraction
    - Atmosphere modeling, self-calibration
    - Host properties at SN location
- Prospects
  - SNfactory-II
    - Extension over 3 years
      - New collaboration (Germany, China)
      - New search(es) (PTF, La Silla)
      - Same follow-up (SNIFS@UH)
    - Enlarged sample, earlier phases
    - Now in progress
  - Need for a spectro-photometric follow-up of photometric surveys
    - PanStarrs, DES, LSST, etc.
    - † Fireball (multi-IFU on VLT)

3D spectro-photometry in few words