The *Nearby Supernova Factory*

Integral field spectrophotometry

(artist's concept)

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Outline of the presentation

- Cosmology with SNe Ia
  - Concordance cosmology
  - SNe Ia as standard candles
  - The SNfactory project
- 3D spectro-photometry
  - Point source extraction
  - Flux calibration
- SNfactory results
  - Photometric accuracy
  - SNf sample
  - Science with SNf
    - Spectral studies
    - Local host studies
- Conclusions

Part I

Observational cosmology using supernovæ of type Ia

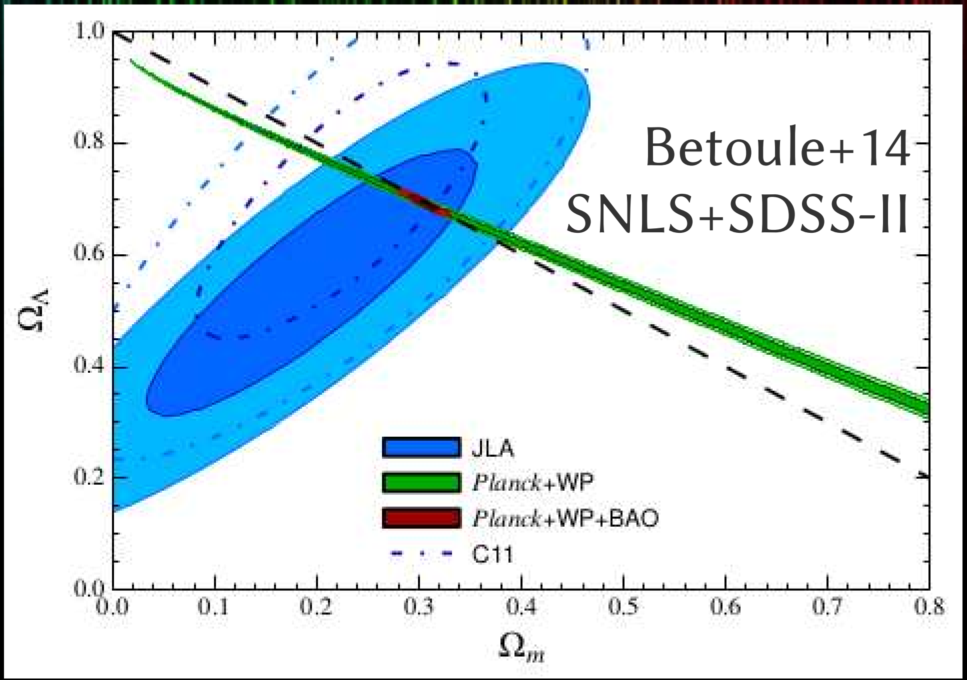
The concordance cosmology

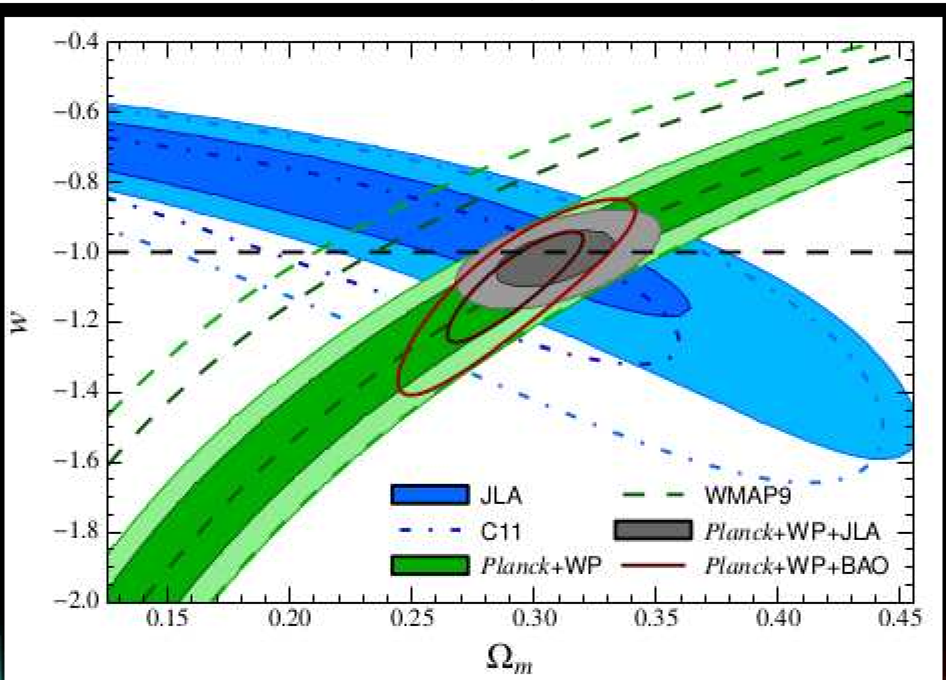
What is the content of the Universe?

- Friedmann equation:

$$\Omega_{tot} = \Sigma_i\, \Omega_i = 1 + kc^2/H_0^2 = 1 - \Omega_k$$

- Cosmological probes
  - Angular correlations: CMB, BAO
  - Large scale structures (clusters, lensing)
  - Expansion history: SNe Ia
- Concordance: ΛCDM
  - $\Omega_{tot} \sim 1.00 \pm 0.02$
    - Euclidian Universe (k=0)
  - $\Omega_\Lambda \sim 0.70 \pm 0.03$ (w = -1.03 ± 0.06)
    - Dark energy dominated
  - $\Omega_M \sim 0.30 \pm 0.03 > \Omega_{baryon} \sim 0.04$
    - Cold Dark Matter

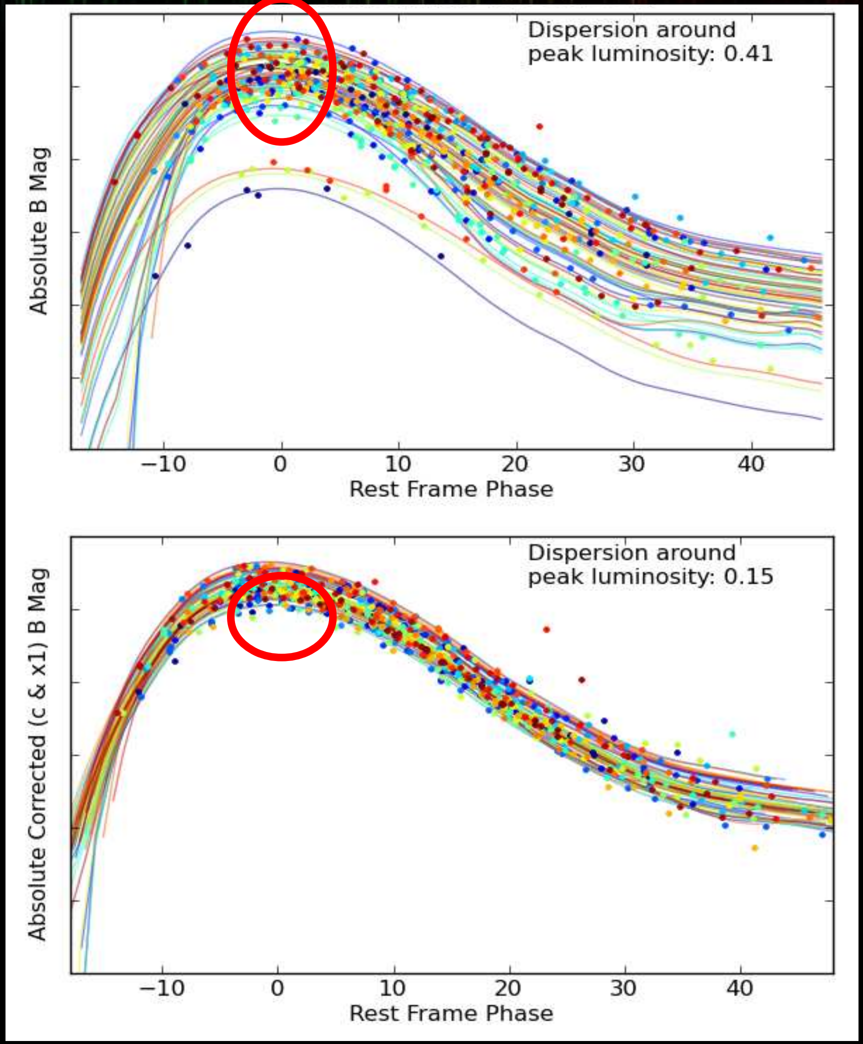




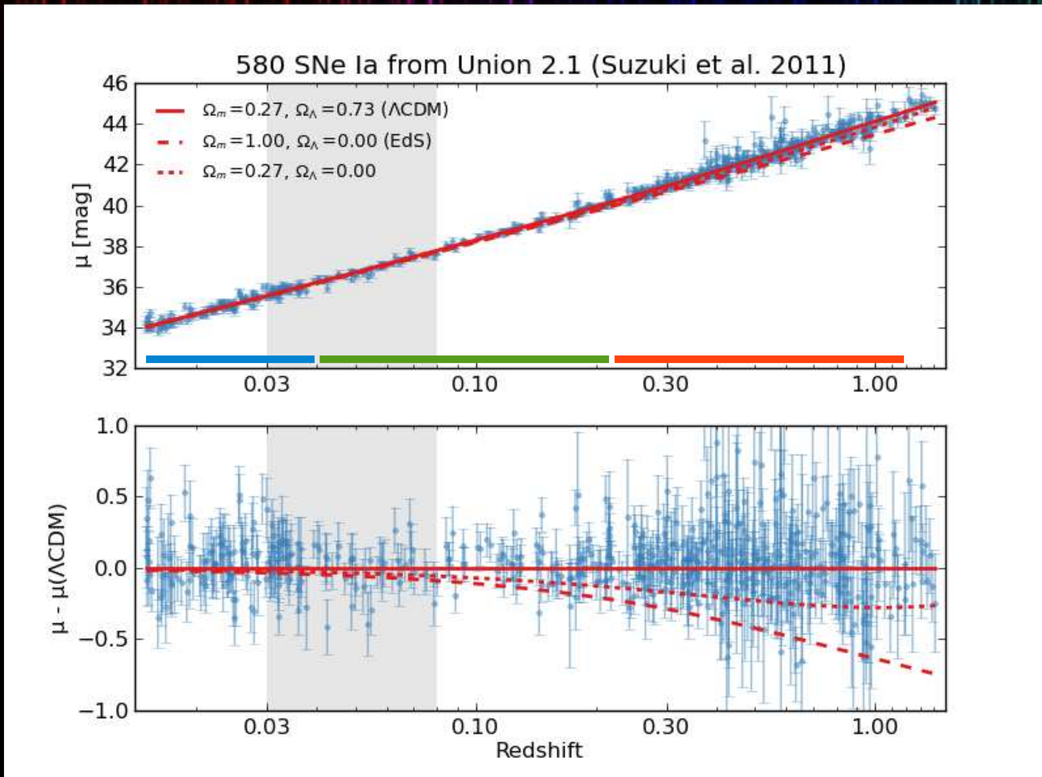
Supernovæ Ia as standard candles

- Thermonuclear SN
  - Explosion of a C+O WD
  - Progenitor still uncertain…
- Cosmological standard candles
  - $M_B^{max} = -19.3 \pm 0.4$
    - Up to z~1.5 (-9 Gyr, 11 Gpc)
    - Intrinsic vs. extrinsic variability
  - Empirical photometric standardization (SALT/MLCS)
    - Fainter – redder (color c)
    - Fainter – faster (stretch ≡ x_1)
    - $M_B = M_B^0 - \alpha x_1 + \beta c$

▶ $\sigma_{std} \sim 0.15$ mag



SN Ia Hubble diagram



- Low-z: $L_0H_0^2$ degeneracy
- High-z: cosmological parameters
  - Ω_Λ, Ω_M, w, etc.
  - $L_0H_0^2$: "nuisance parameter"
- Redshift desert
  - Different search strategies
- Importance of a low-*z* sample
  - Anchor the Hubble diagram: lever arm low vs. high z, best at z ~ 0.05
  - SN Ia standardization: sub-classification, intrinsic colors, spectral properties, environment impact, explosion physics, etc.
  - Control systematic errors: flux calibration, spectral templates, K- and S-corrections, redshift evolution, etc.

The *Nearby Supernova Factory*

- Key dates
  - 1998/99: discovery w/ SNe Ia of the accelerated expansion of the Universe
  - 2000: project kick-off
  - 2001: France-LBL MoU
  - 2004: SNIFS on the sky
  - 2004-2009+: SNf-I
  - 2010-2015: SNf-II

SNIFS on UH88

The *Nearby Supernova Factory*

SN Ia search program

- Untargeted wide-field survey
- Within the Hubble flow
  - $0.03 < z < 0.08$
- Various search programs
  - 05–08: Palomar-QUEST
  - 10–: Palomar Transient Factory
  - 12–: La Silla-QUEST
  - Public sources

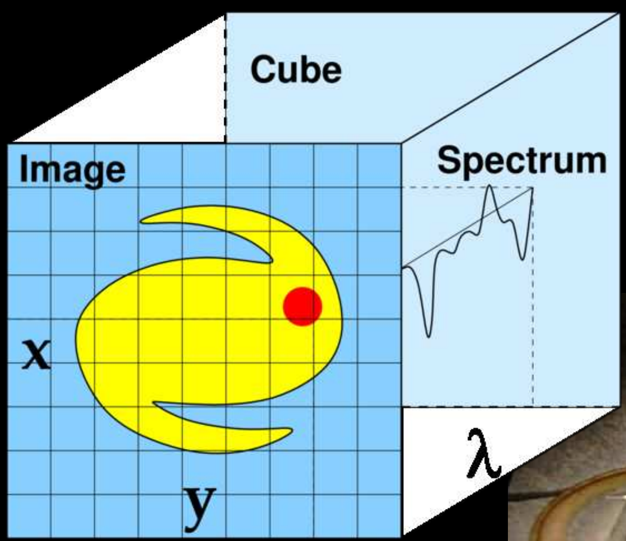
Spectroscopic follow-up

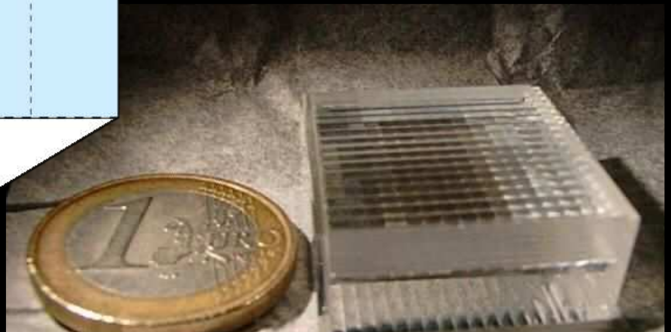
- From -15 to +45 days every 2–3 d.
  - Dedicated & integrated instrument for homogeneous observations
- Mid-resolution optical spectra
- Photometric accuracy
  - **Integral field spectrography**

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"4×6"4 field of view
  - Spectral stage
    - 2 spectroscopic channels
      - B: 320–520 nm @2.4 Å
      - R: 510–1000 nm @2.9 Å
  - Calibration unit

- Photometric channel
  - Target acquisition
  - Guiding
  - Atmospheric extinction
  - *BVugriz* imagery

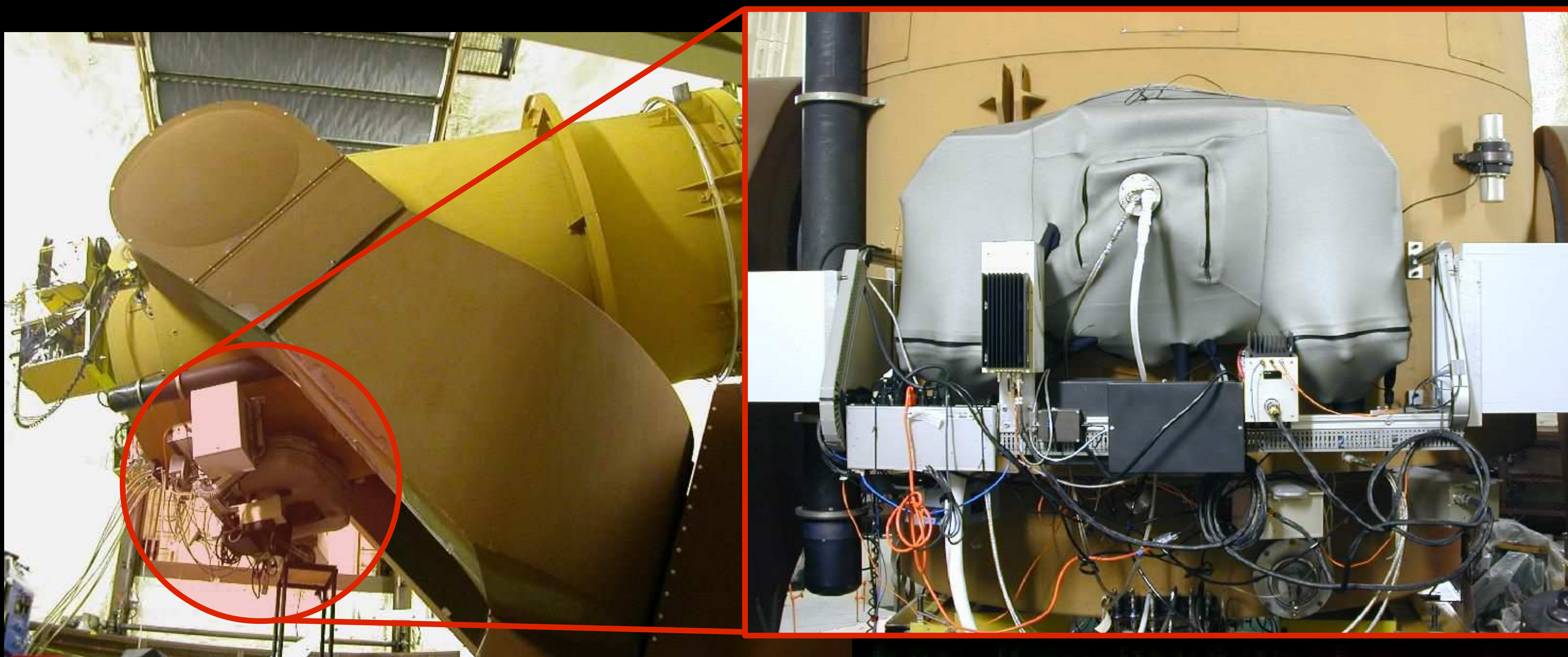




Micro-lens array

SNIFS on UH 2.2 m telescope

- Permanently mounted on UH88 since '04 (900+ nights!)
- Remote semi-automatic operations
  - Queue scheduling, virtual control room, AI support



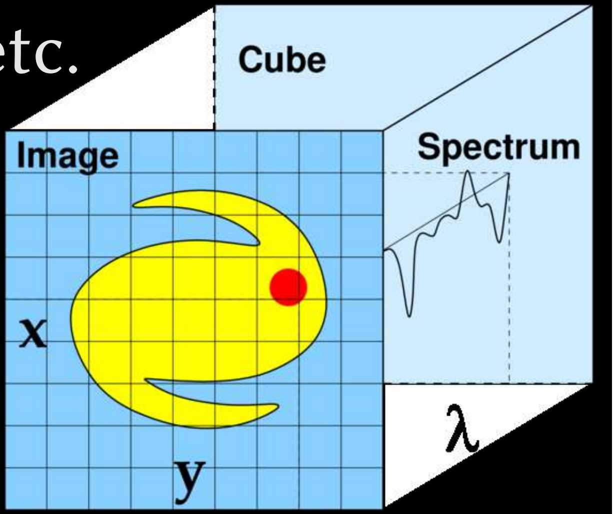
Part II

Integral field spectrophotometry with the *SuperNova Integral Field Spectrograph*

3D spectro-photometry

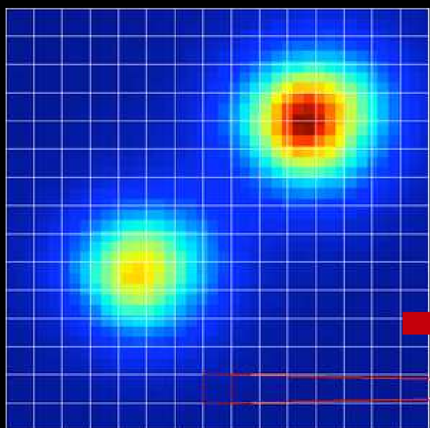
- The goal is to reach high spectro-photometric accuracy on the whole SN time-series
  - …notwithstanding a complex instrument and data-reduction flow
  - …despite the moon, clouds, atmosphere, etc.
- Common in photometry, but

  new in transient spectroscopy
  - Cube reconstruction & calibration
  - Point source extraction: 3D PSF photometry
  - Flux calibration: atmospheric extinction modeling, autocalibration

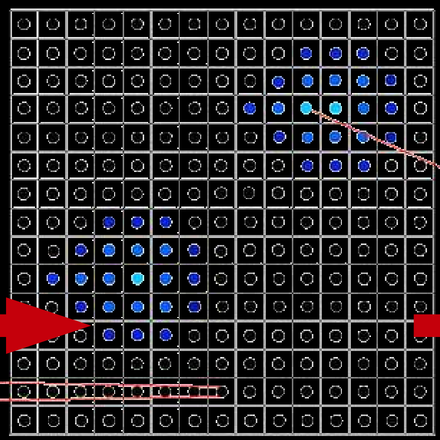


Optical design of SNIFS

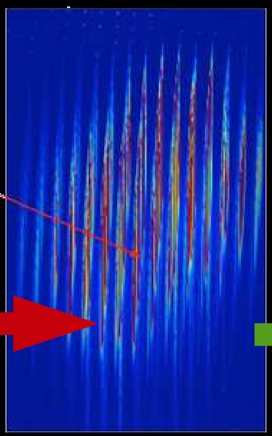
Focal plan
(0''43/spx)



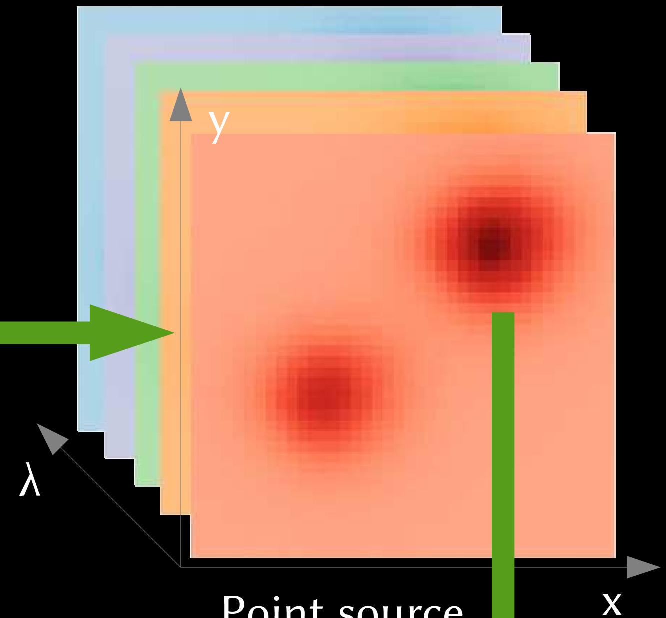
Spectrograph
entry



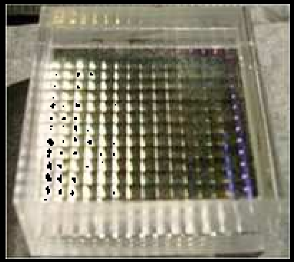
CCD
(225 spectra)



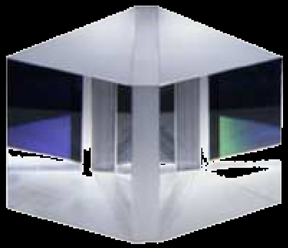
Cube
(x,y,λ)



Point source
extraction

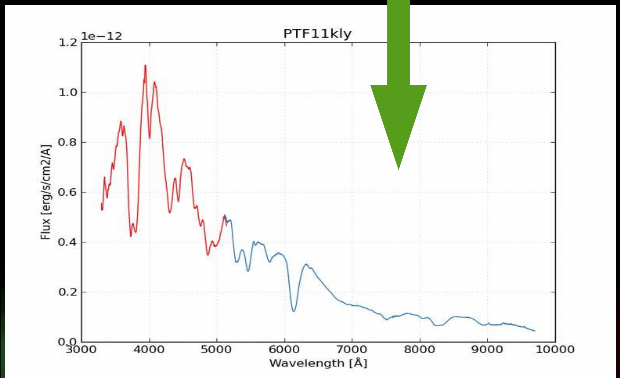


Micro-lens array
(15×15)



Spectrograph

Flux calibration

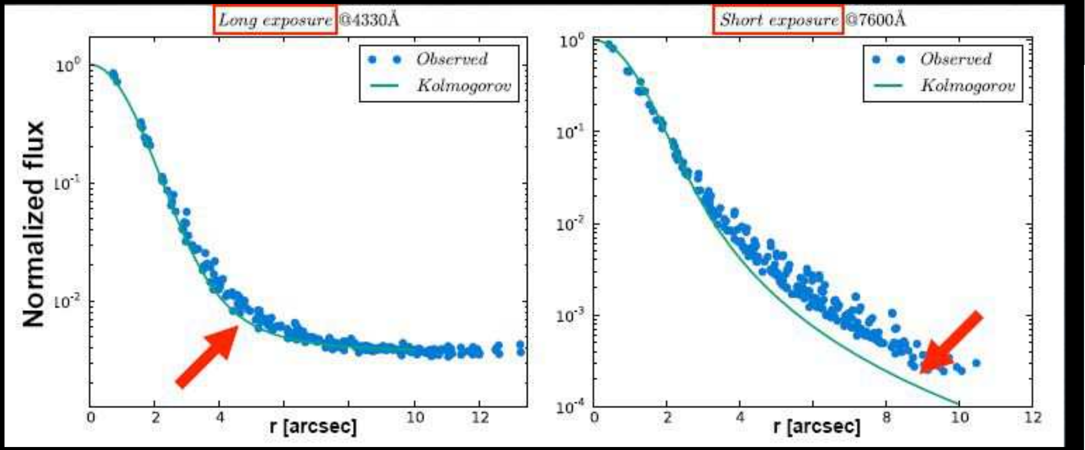


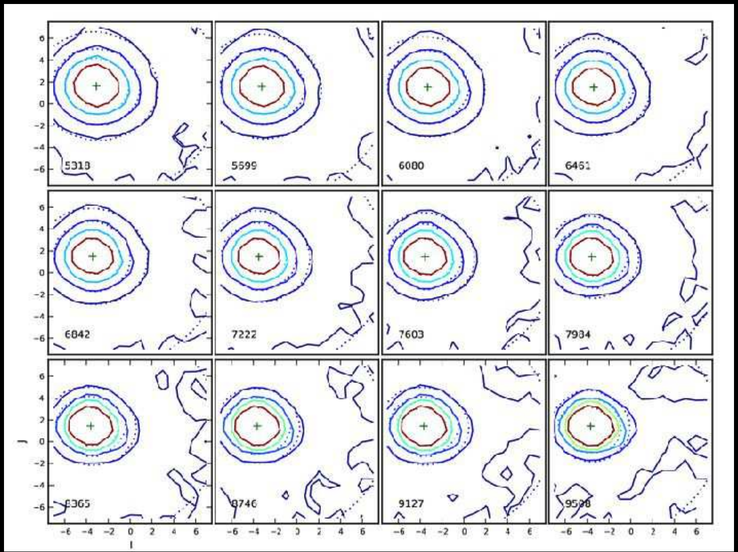
(Fig. C. Buton)

3D PSF photometry

C. Buton (PhD 2009)

- FoV too small for accurate aperture photometry and sky subtraction
- Standard Kolmogorov profile is not adapted
  - Yet, could be adapted ?

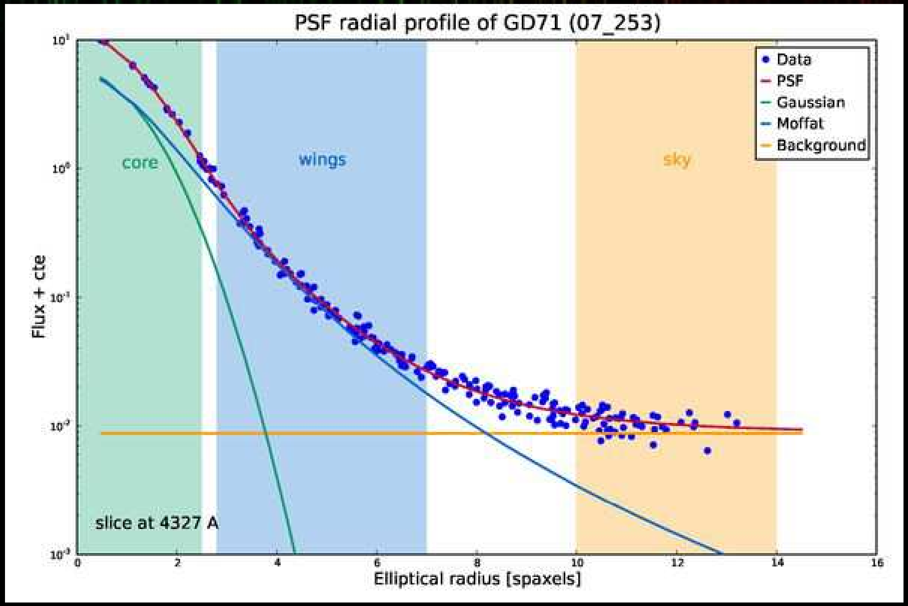


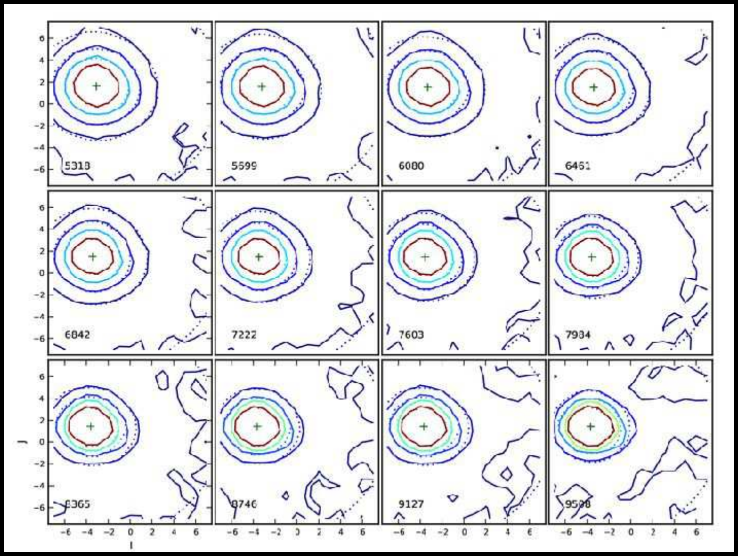


3D PSF photometry

C. Buton (PhD 2009)

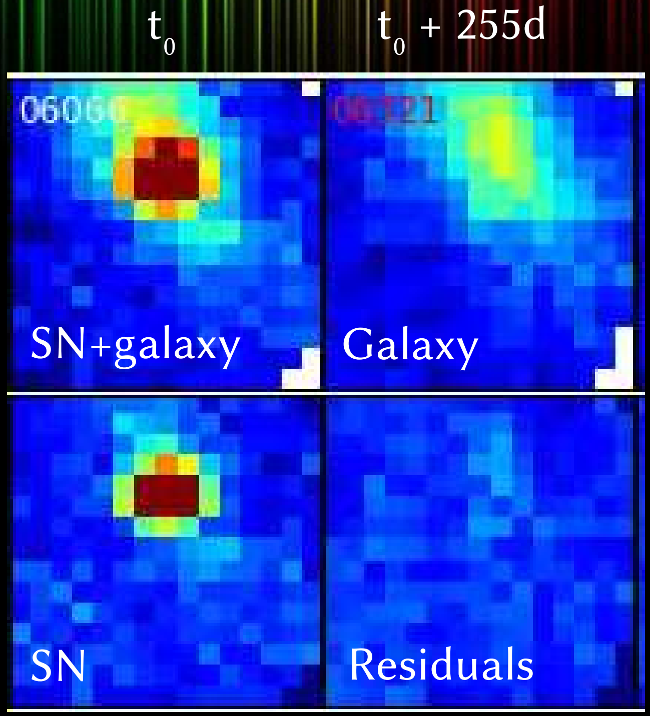
- Empirical constrained Gaussian+Moffat model
  - Radial×azimuthal factorization
  - Trained on high-S/N standard stars
  - 2 shape parameters: "Seeing" & "focus/guiding"
  - Chromatic modeling: ADR, seeing(λ)
  - Bayesian priors
- ▸ Flux accuracy: 0.7–1.5%





Galaxy background subtraction

PSF photometry applies to point sources without structured background: standard stars or SNe without significant host galaxy



For SNe with galaxy: diffuse background subtraction

- Construction of a galaxy model from 3D deconvolution
  - Use of reference exposures (once the SN has vanished)
  - Registration and PSF matching (seeing)
  - Still some regularization issues

Bongard+11

Flux calibration

Buton+13

Observed spectrum at airmass X [ADU]

$$\log\left(\frac{S(\lambda)}{S^{*}(\lambda)}\right) = \log C(\lambda) - 0.4 \times X \times \bar{K}(\lambda) + \cancel{\log \delta T(\lambda, t)}$$

Intrinsic flux [erg/s/cm²/Å]

Flux solution [erg/s/cm²/Å / ADU]

Atmospheric extinction [mag/airmass]

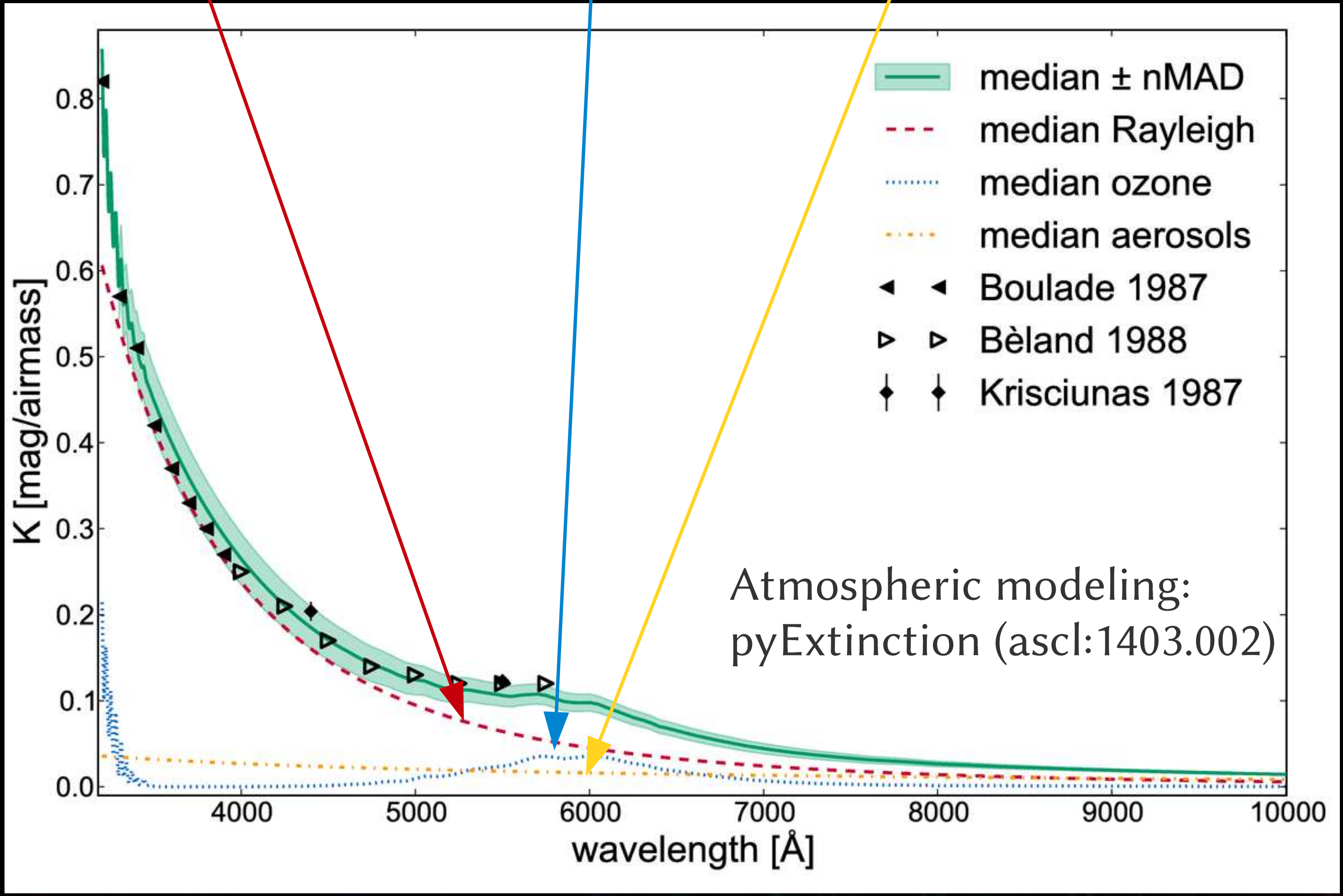
- Photometric night
  - Atmospheric transmission is stable during night: $\delta T \triangleq 1$
  - “Classical” flux calibration scheme applies
    - Derive K(λ) and C(λ) from standard star observations
    - Optimal use of all standard stars of the night (χ^2) + bayesian priors

Atmospheric extinction modeling

Buton+13

Extinction is split into physical components

$$\bar{K}(\lambda) = P\, K_{\mathrm{Rayleigh}}(\lambda) + I_{O_3}\, k_{O_3}(\lambda) + \tau\,(\lambda/1\,\mu m)^{-\mathring{a}} + K_{\oplus}(\lambda, z)$$

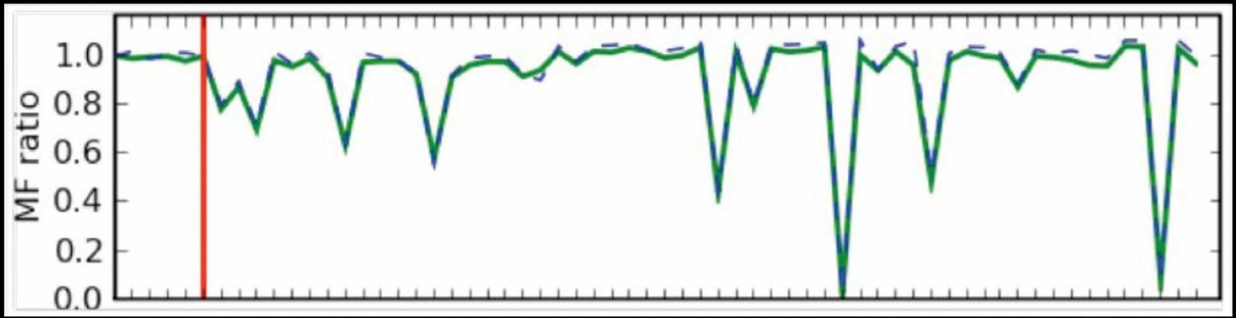


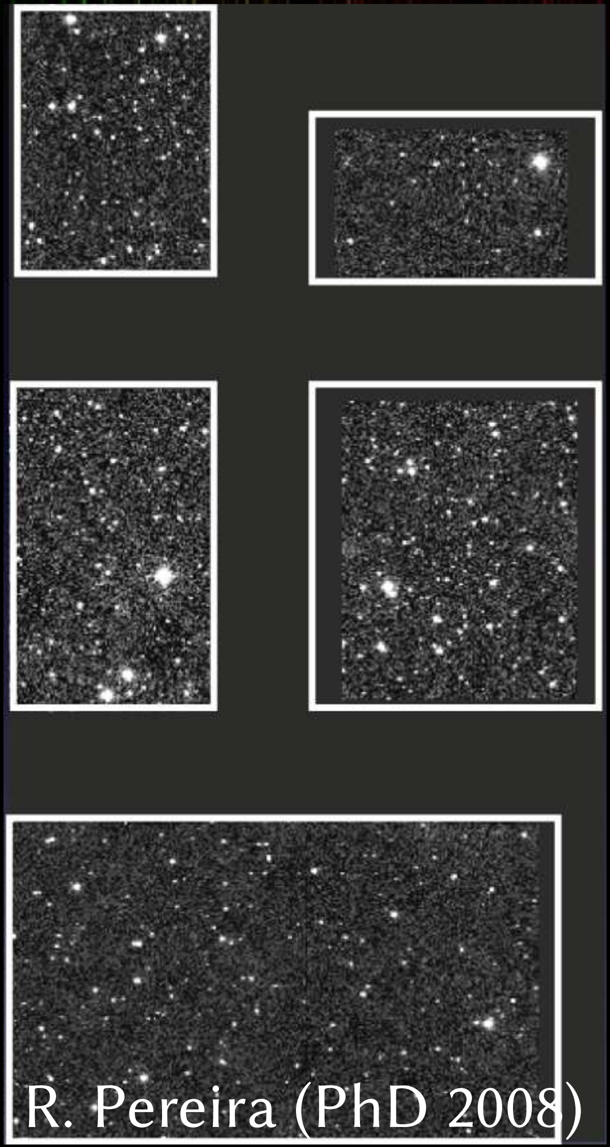
Atmospheric modeling:
pyExtinction (ascl:1403.002)

Non-photometric flux calibration

In non-photometric night, atmospheric extinction is **variable** because of clouds: $\delta T(\lambda, t) \neq 1$

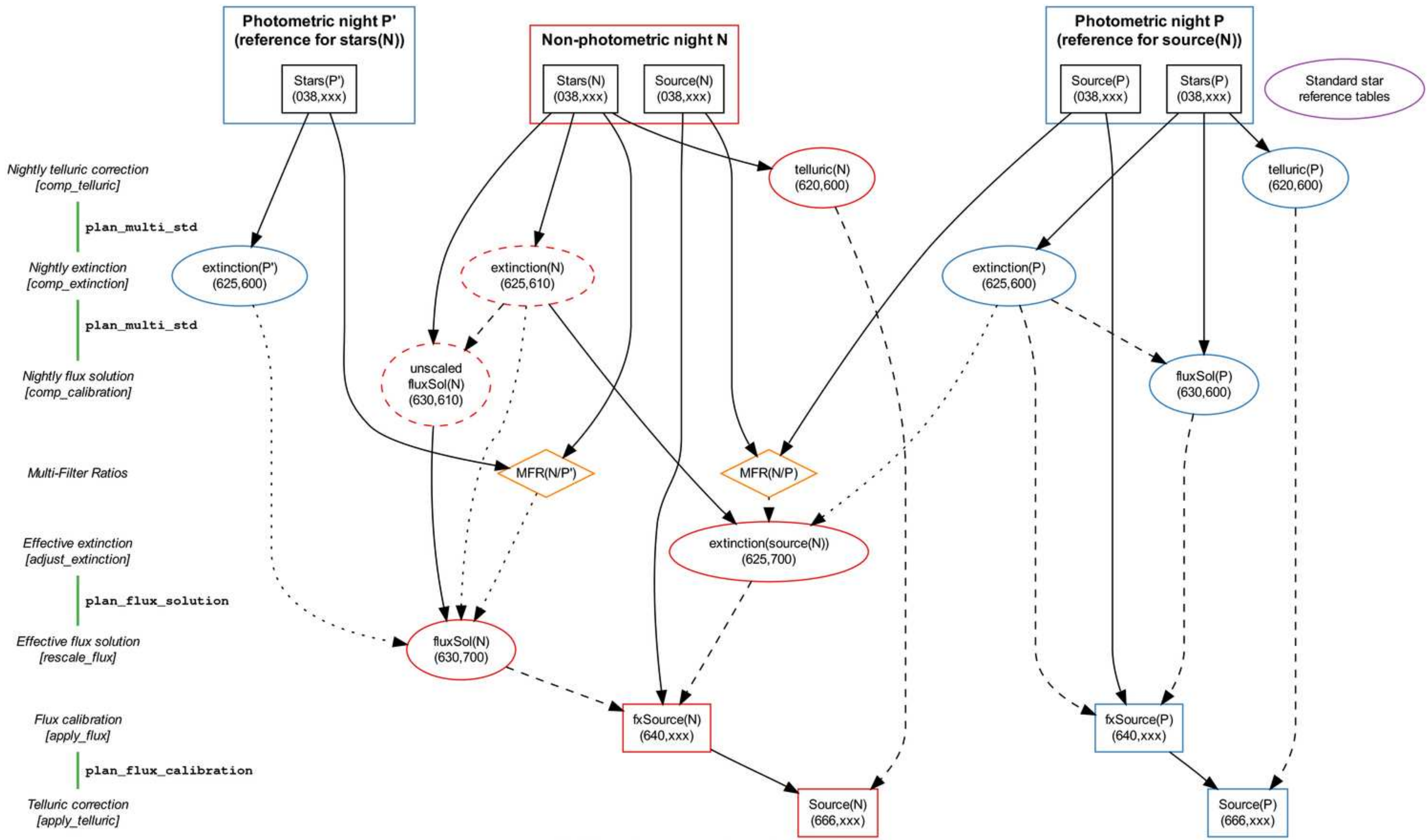
- Auto-calibration using repeated observations of stars in P-channel
  - Clouds are achromatic: $\delta T(\lambda) = \delta T$
- Effective atmospheric transmission
  - Requires at least one photometric observation as reference





R. Pereira (PhD 2008)
Buton+13

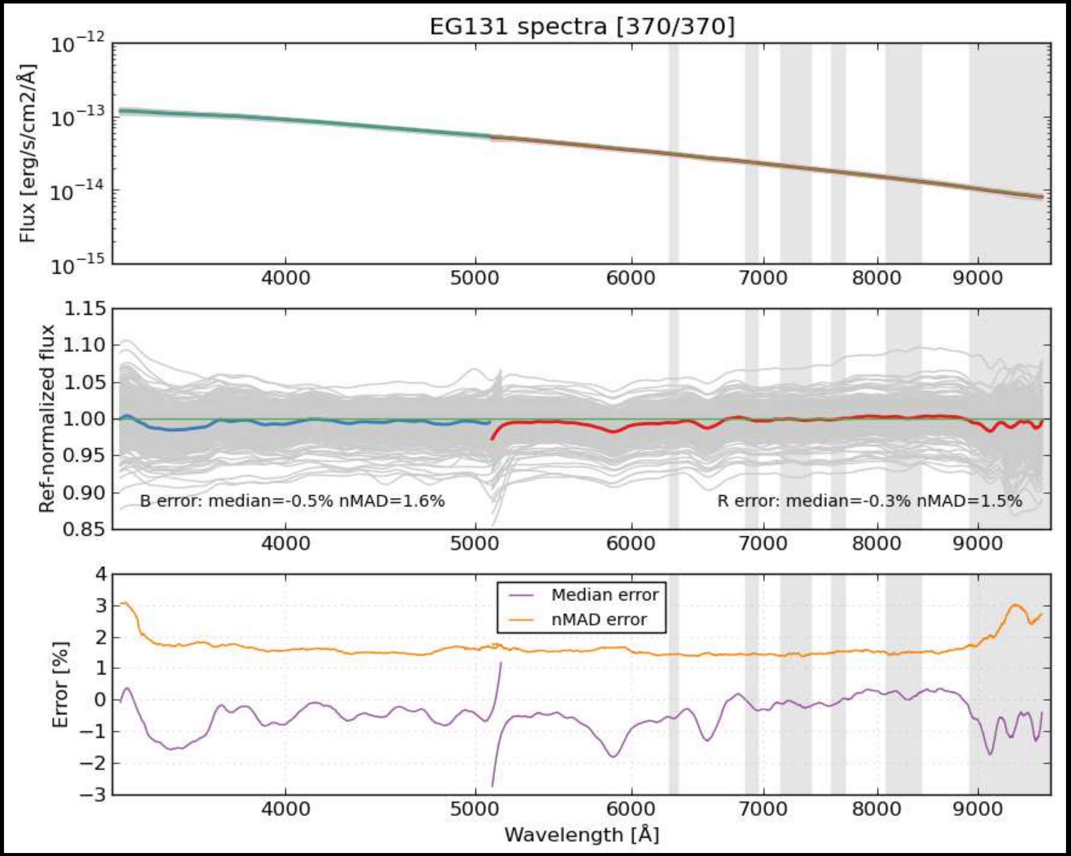
The flux calibration procedure



SNIFS multi-standard flux calibration flow

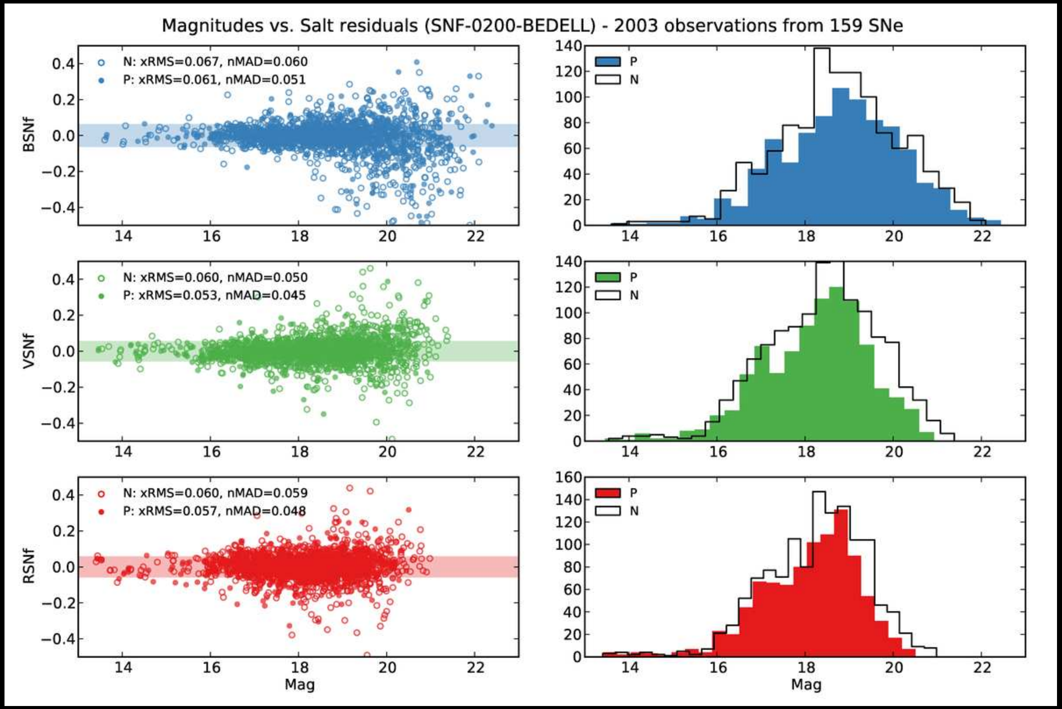
Photometric accuracy: standard stars

- From comparison to reference flux tables
  - *UBVRI*: 25 mmag (RMS)
    - P: 21 mmag, NP: 28 mmag
    - nMAD: 18 mmag
  - *B-V*: 10 mmag (RMS)
- A lower bound
  - High flux regime (*V*<14)
  - No galaxy subtraction
- Heterogeneous references
  - Standard star network
  - SNIFS Calibration Apparatus
    - Work in progress

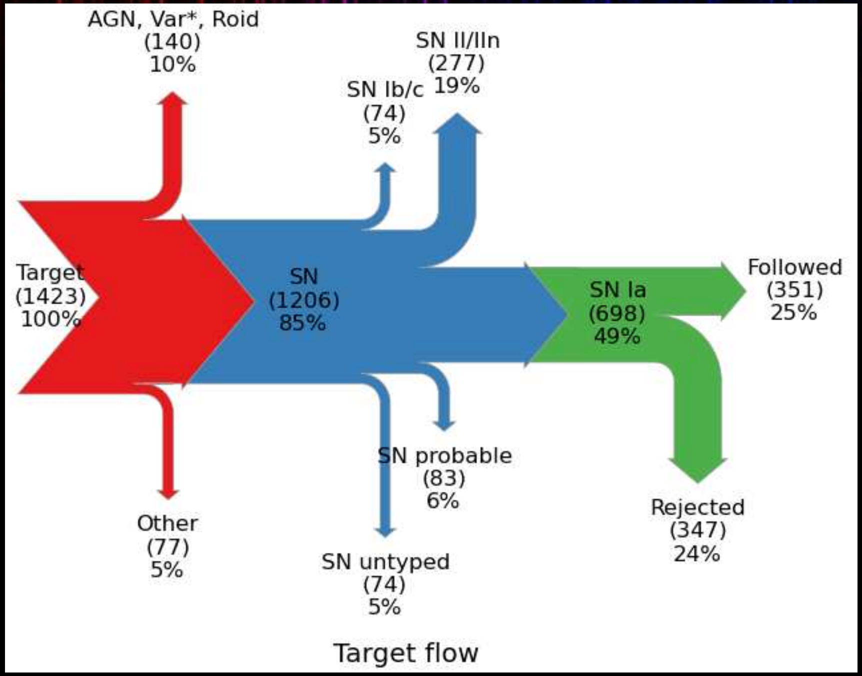


Photometric accuracy: SNe Ia

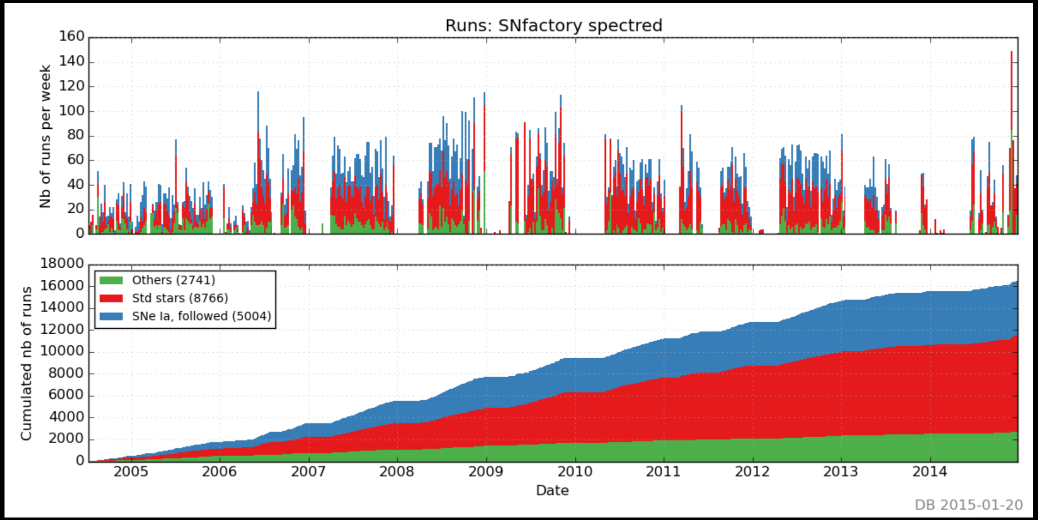
- From multi-color light curve fit (SALT2)
  - Synthetic photometry
  - *BVR*: 60 mmag (xRMS)
  - *B-V*: 43 mmag
  - An upper bound
    - Low flux measurements (V>16), galaxy subtraction
    - But highly sensitive to SALT2 inadequacies

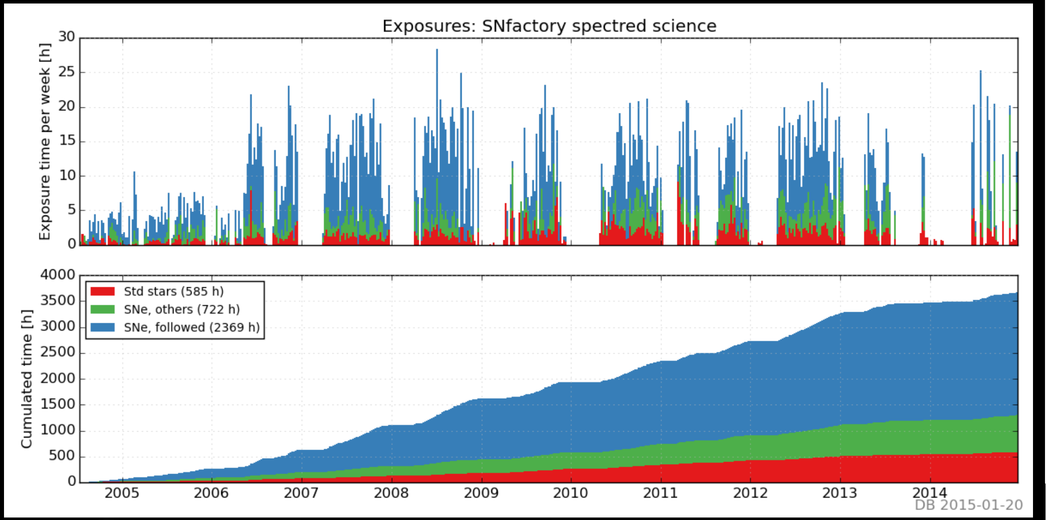


Data acquisition & production



- 16500 spectroscopic pointings
  - 5000 on followed SNe
  - 8800 on std stars
- 3500 h of exposure time
  - 2370 h on followed SNe (others: 600 h)
  - 585 h on std stars
- 750000+ raw files, >10 Tio
  - Total for all productions: >60 Tio





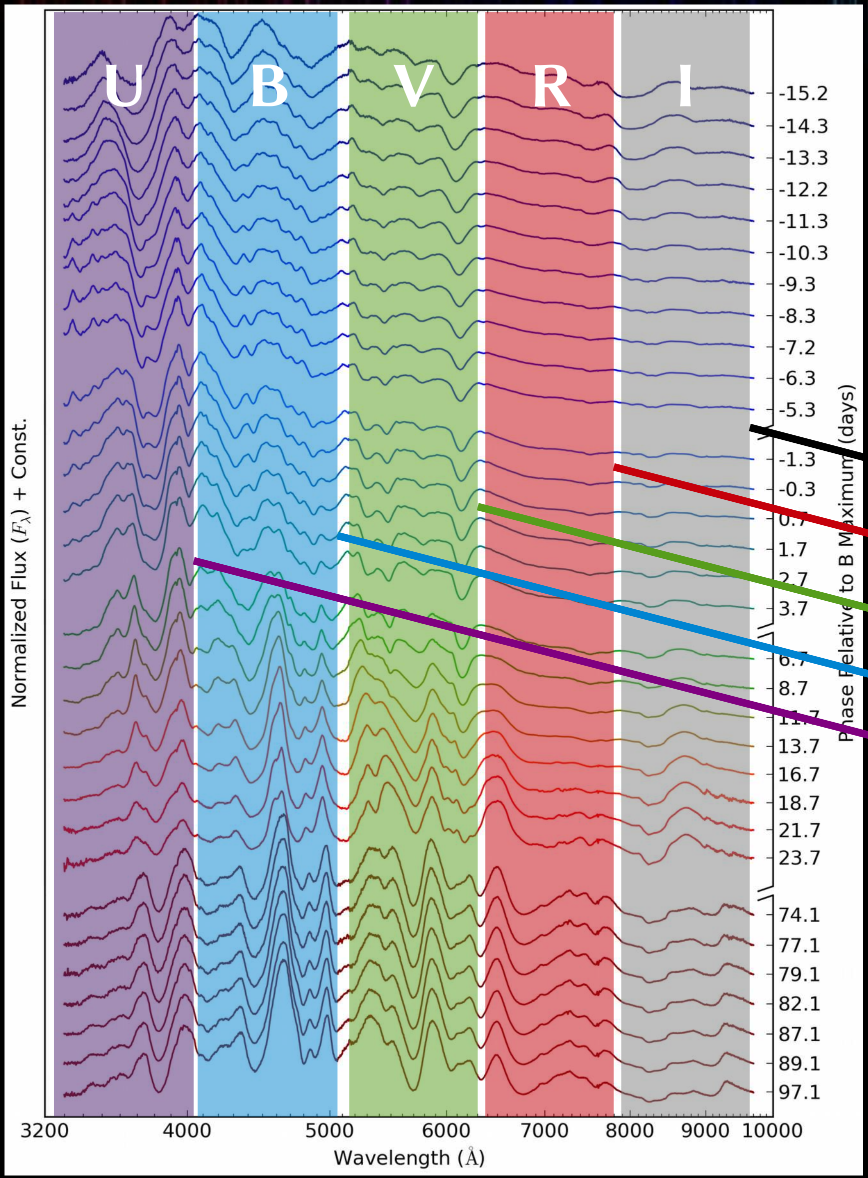
Part III

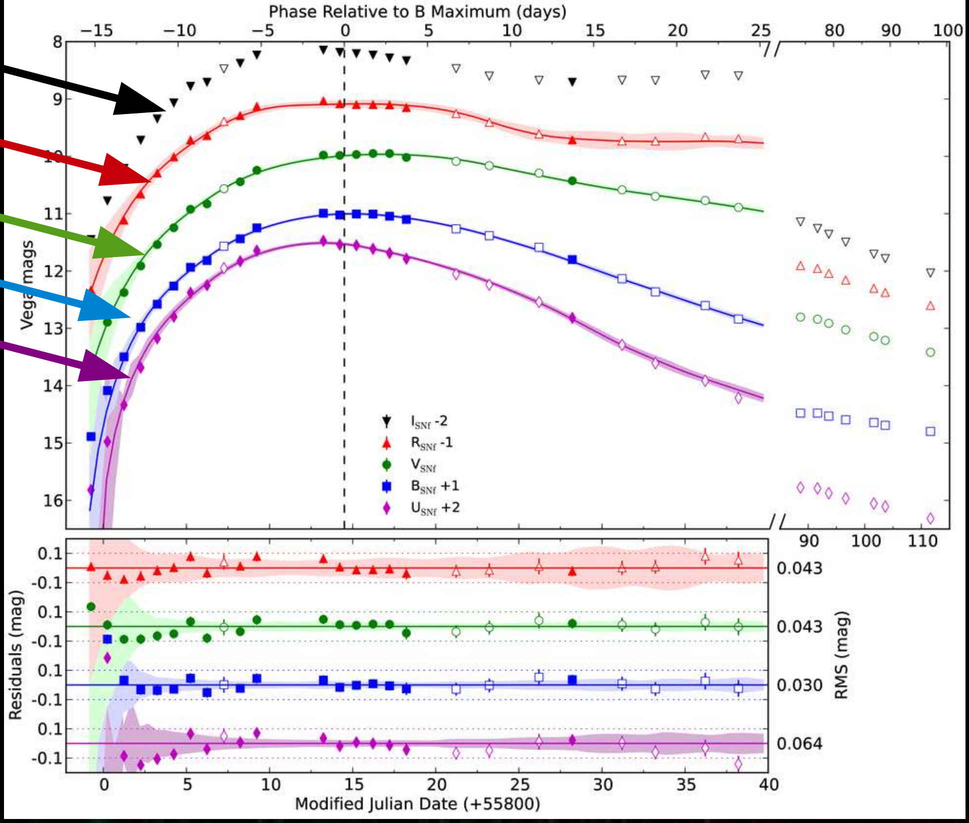
Science from the Nearby Supernova Factory

Time series & synthetic photometry

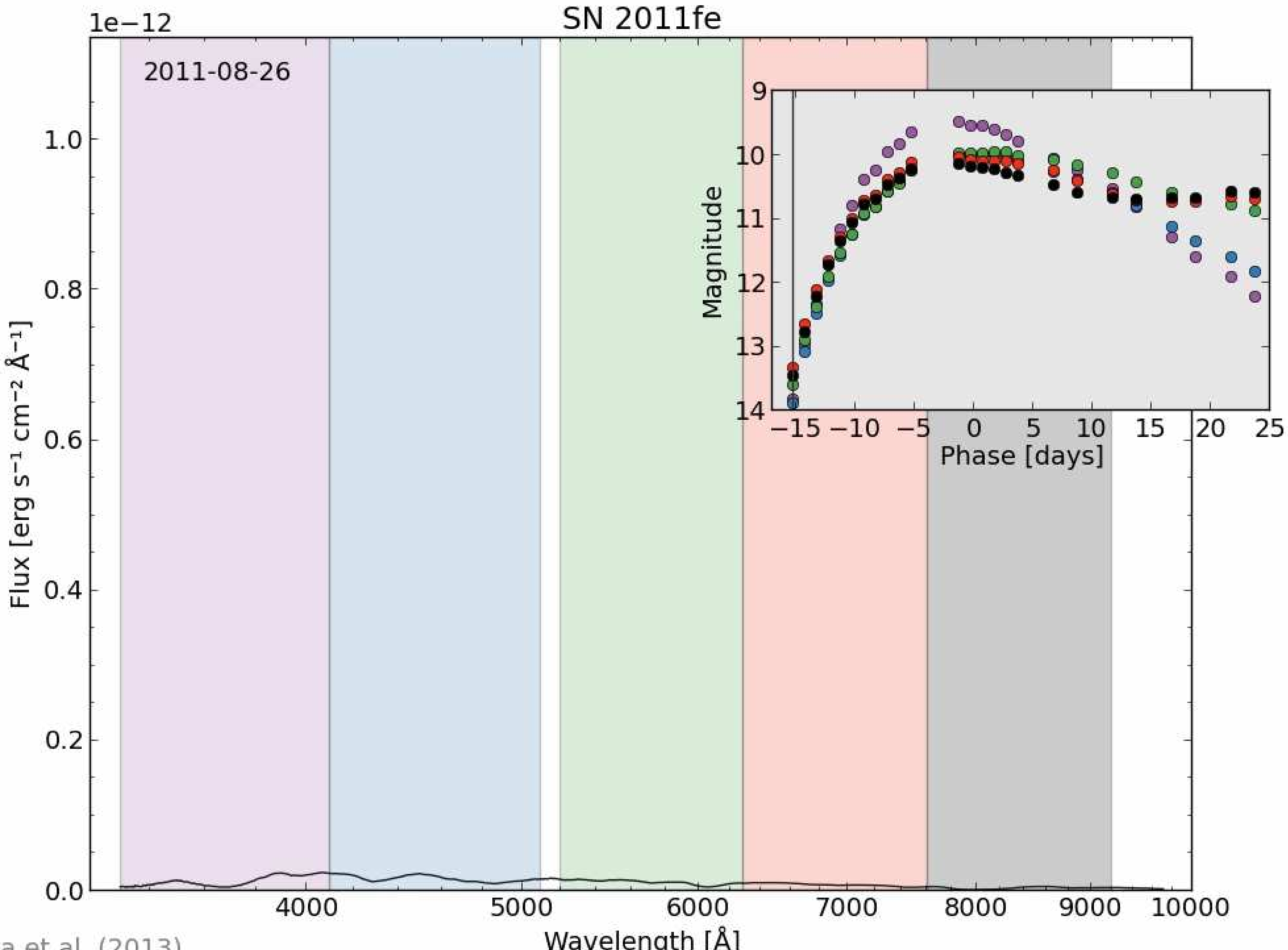
Pereira+13

- SN2011fe
  - The closest SN in the last 25 years (M101, 6.4 Mpc)
  - An archetypal SN Ia



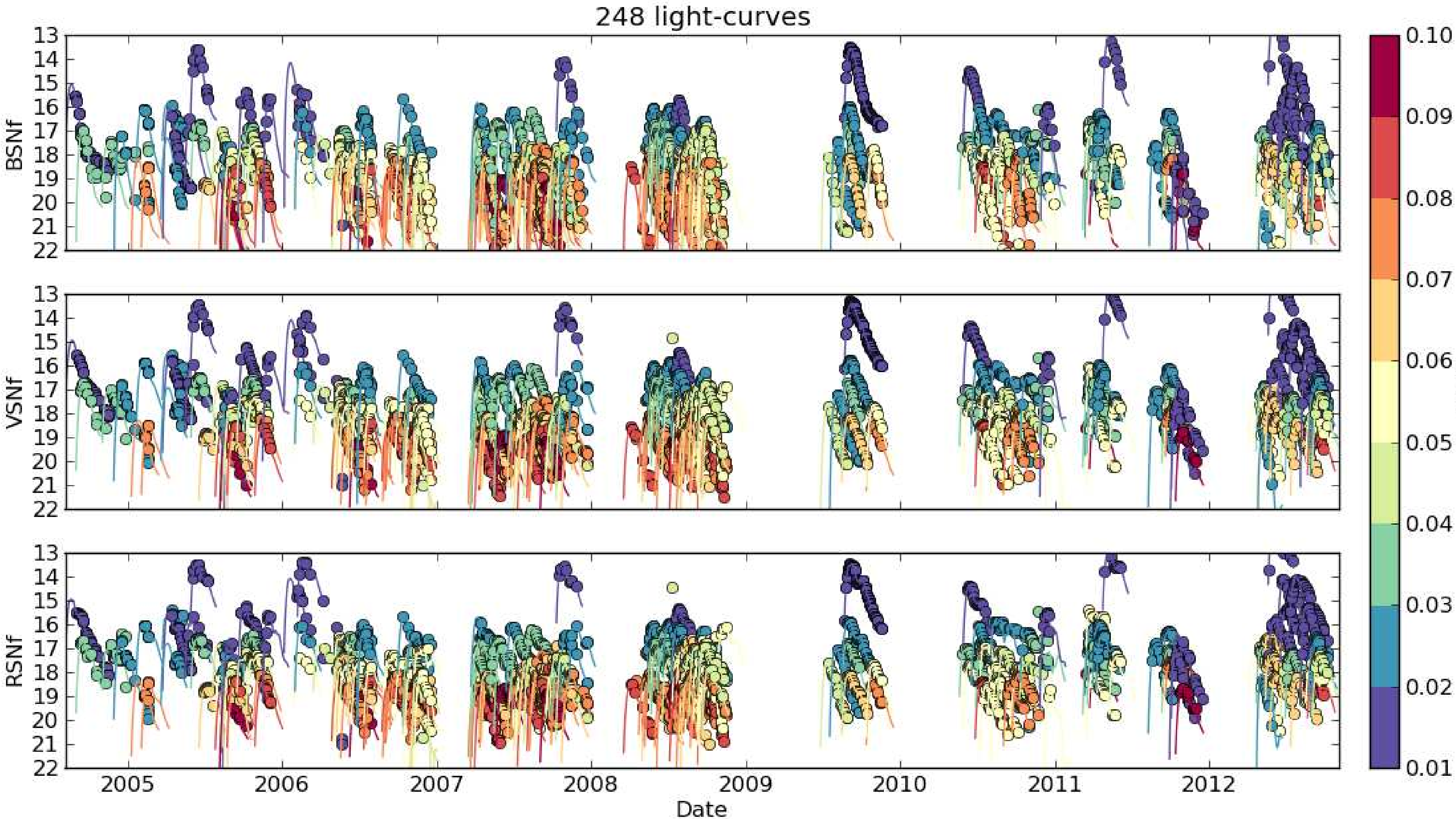


Movie w/ label



Pereira et al. (2013),
The Nearby Supernova Factory

SNfactory SN Ia light curves

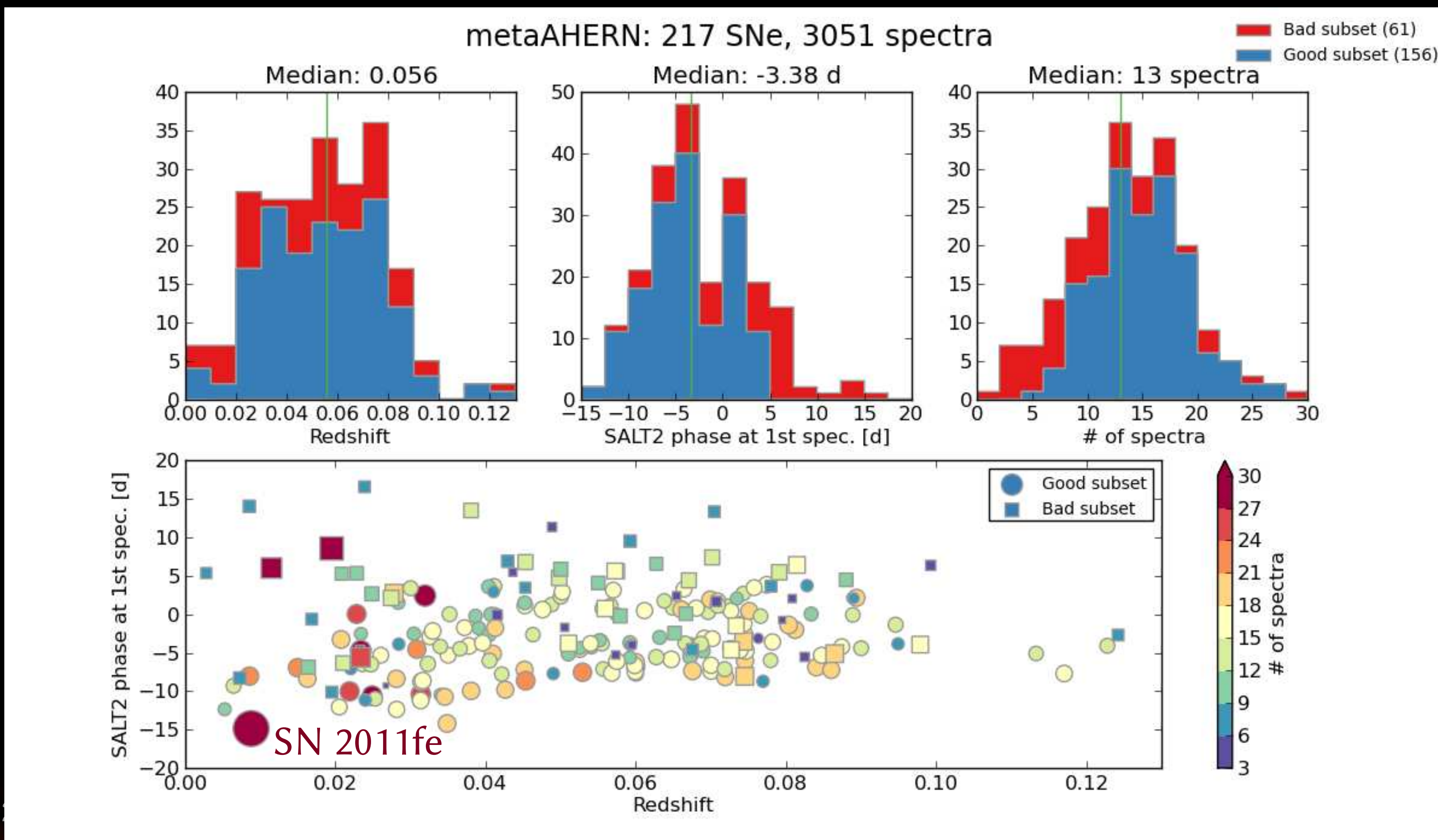


Minimal galaxy subtraction requirements

SNfactory main science sample

217 SNe with more than 5 epochs, 3051 spectra

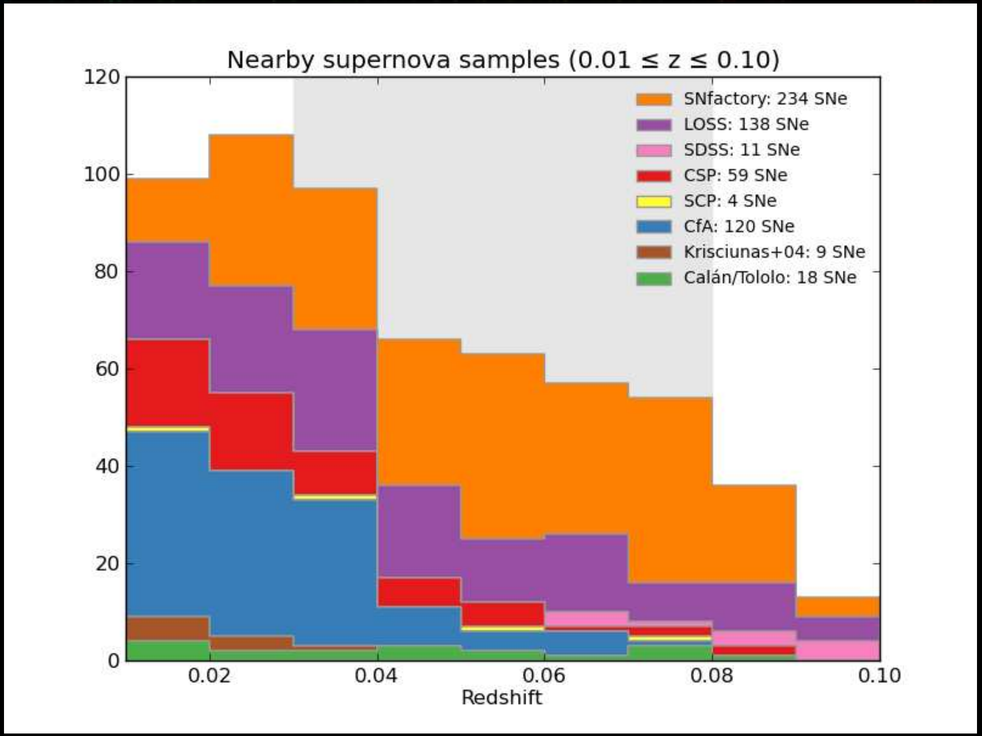
- 156 “good” SNe (2395 spectra)
- 61 “poor” SNe (656), actually *not well described by SALT2*



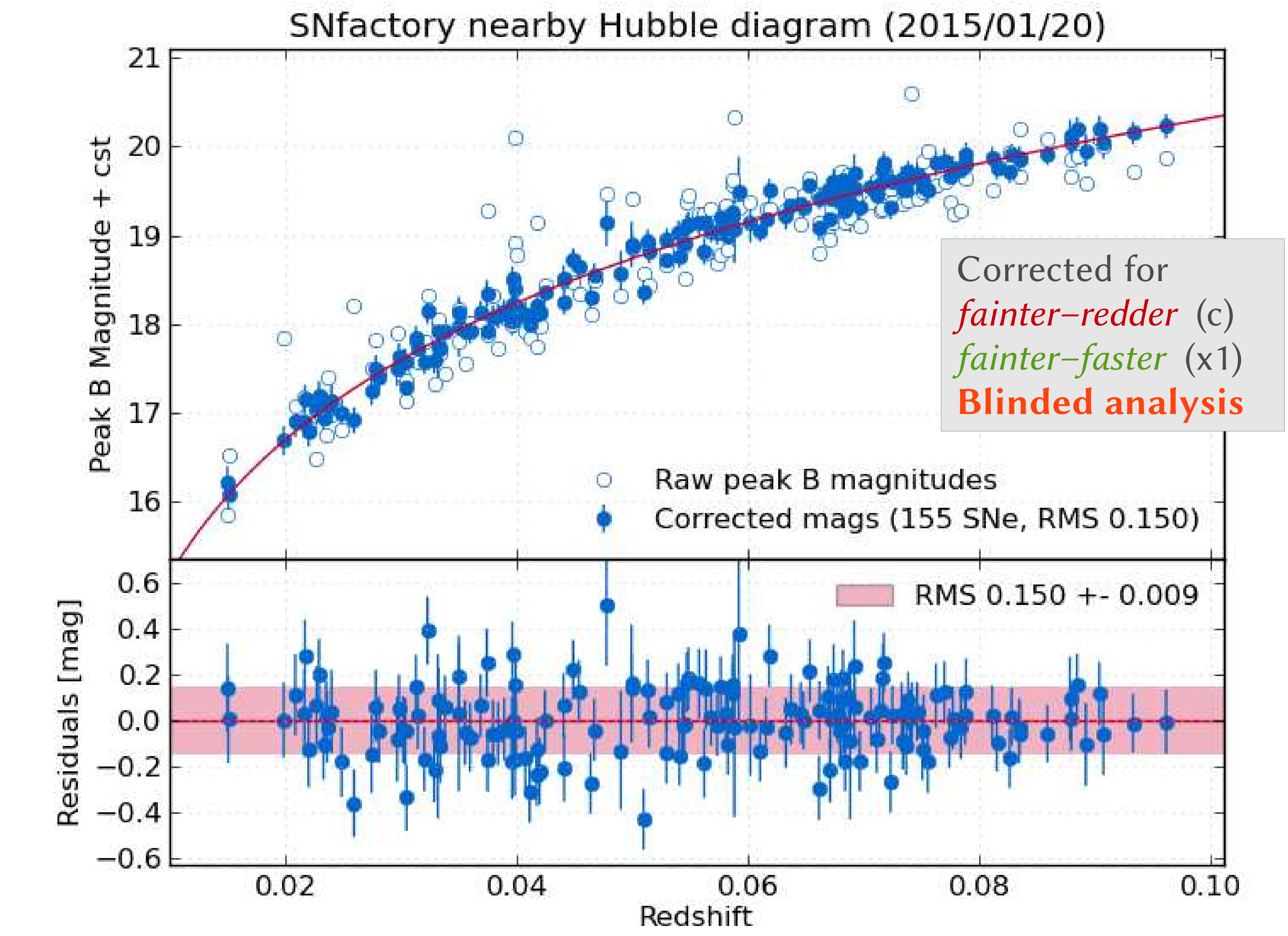
Comparison to other nearby samples

The **largest** homogeneous nearby sample

The **only** spectro-photometric time-series sample

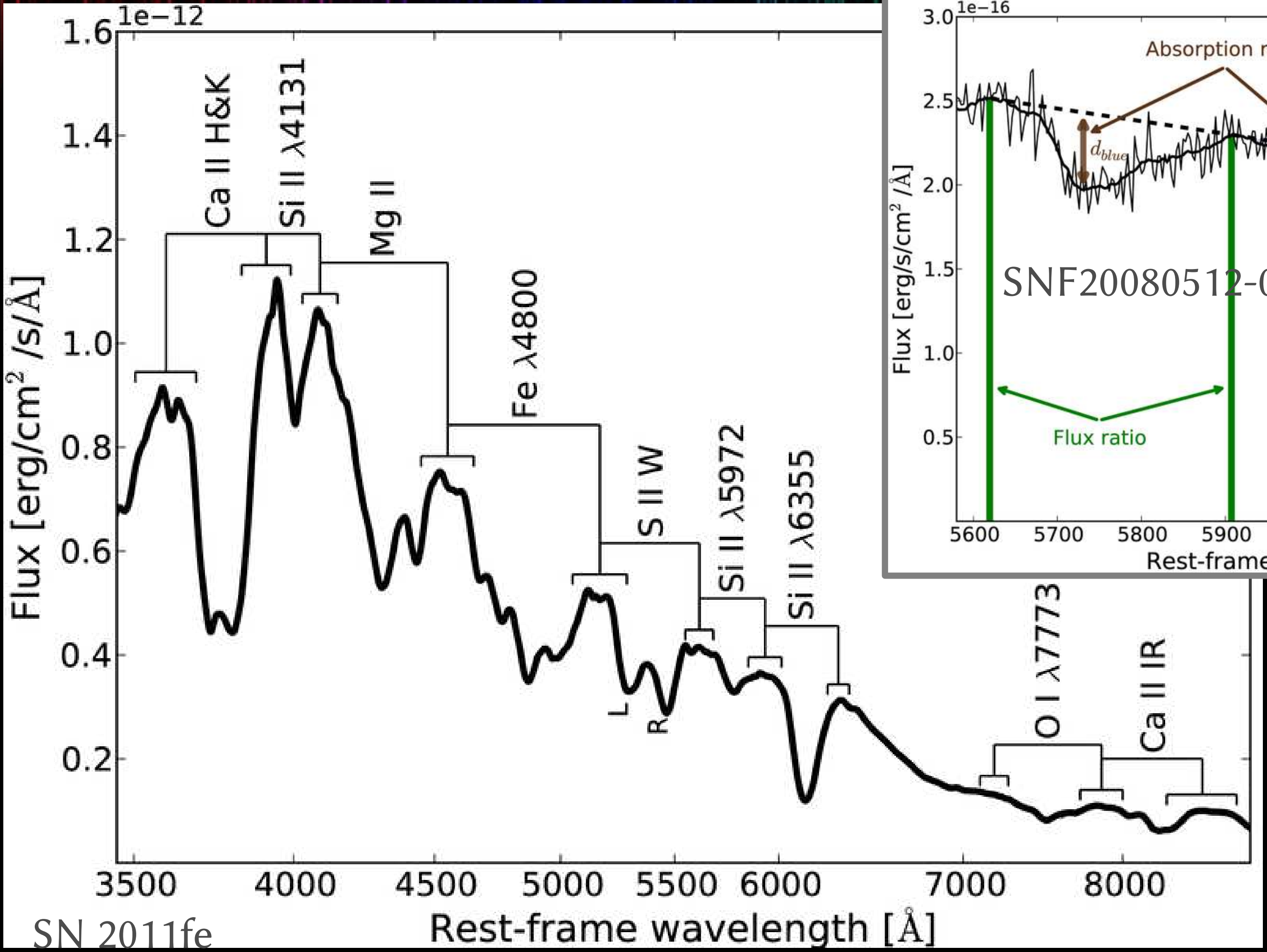


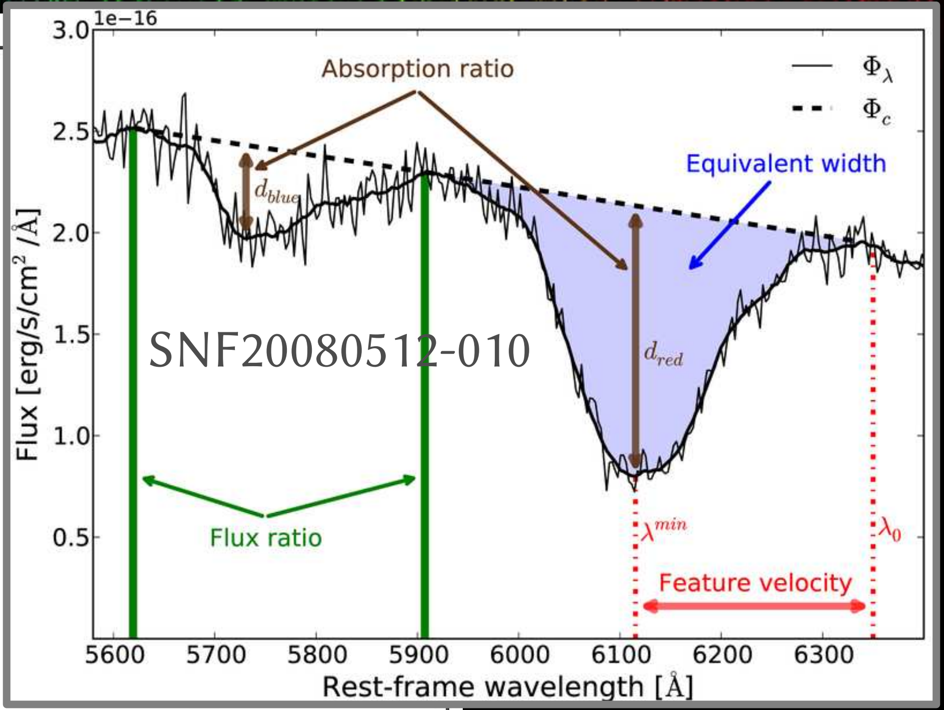
“Traditional” Hubble diagram



Corrected for
fainter–redder (c)
fainter–faster (x1)
Blinded analysis

Spectral analysis at max

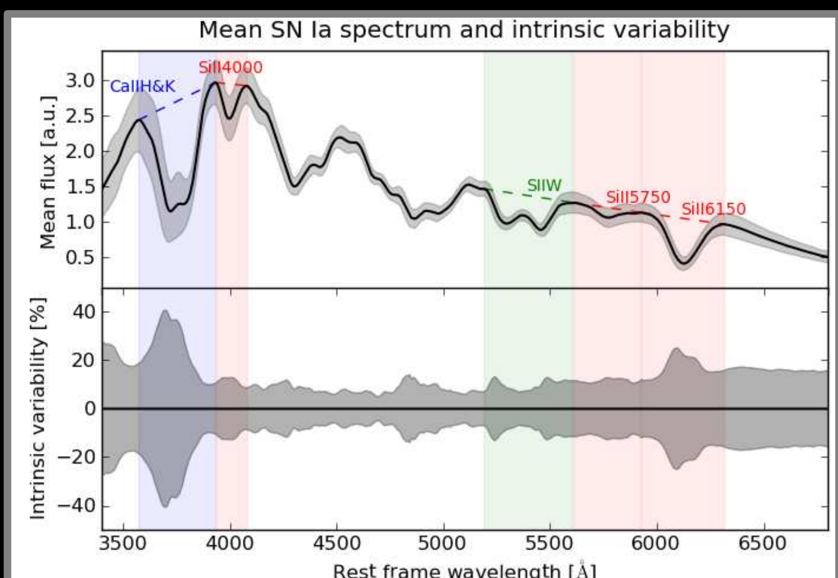




N. Chotard (PhD 2011)
Chotard+15

Spectral indicators & Co.

- SN Ia variabilities
  - Intrinsic: progenitor & explosion physics
  - Extrinsic: host extinction
- Some indicators are insensitive to extinction



- Chotard+11: extinction law and intrinsic color
- Spectral standardization:

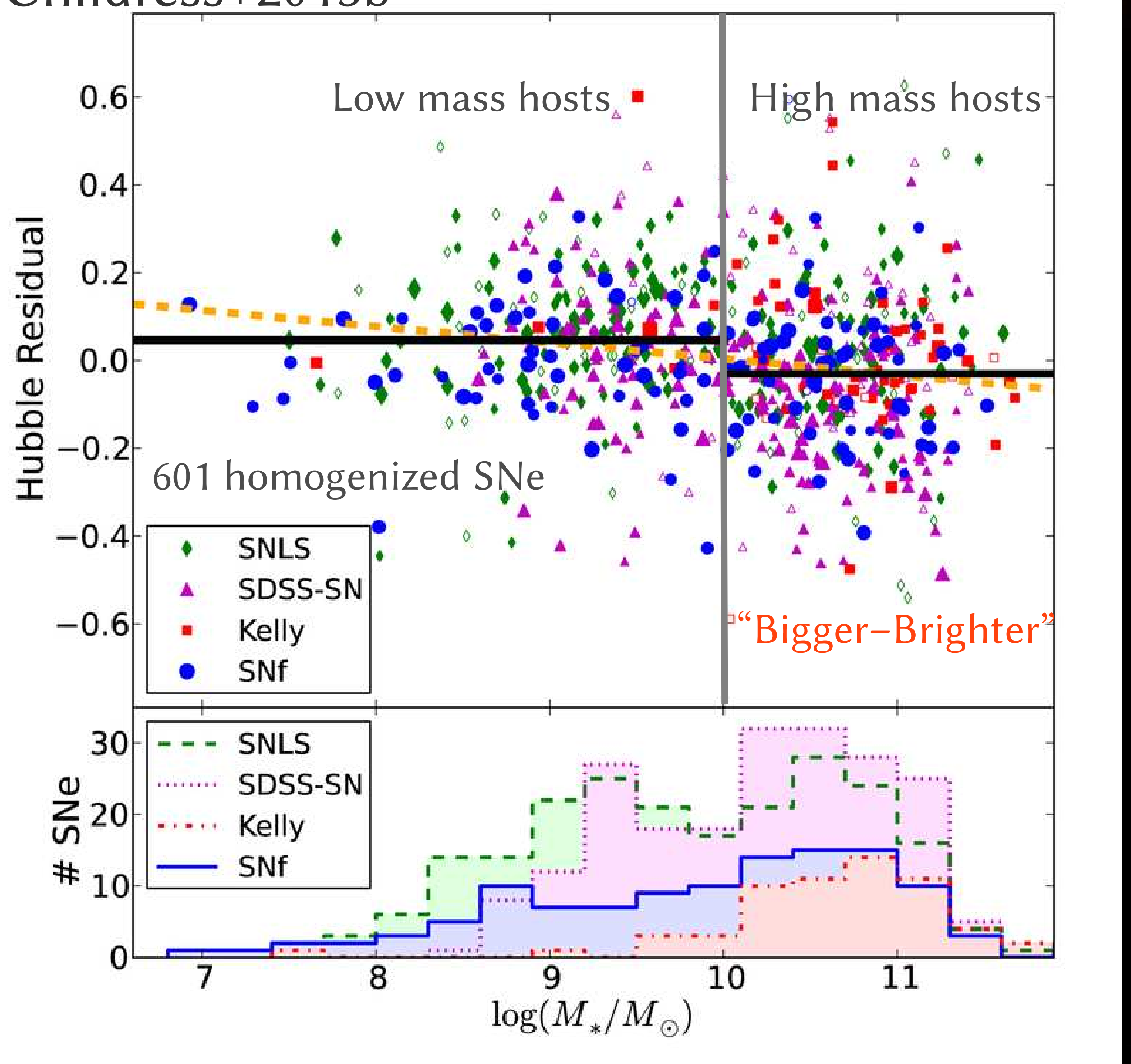
$$M_B = M_B^0 - \alpha\times x_1 + \beta\times c + \gamma\times X + \dots$$

  - Bailey+09: R(λ642/λ443)
  - Chotard+15: "classical" indicators
- Sub-classification
- Other spectral studies
  - Gaussian Processes (Kim+13), derivative space (Sasdelli+15), twin studies, NUV studies, etc.

SN Ia host studies

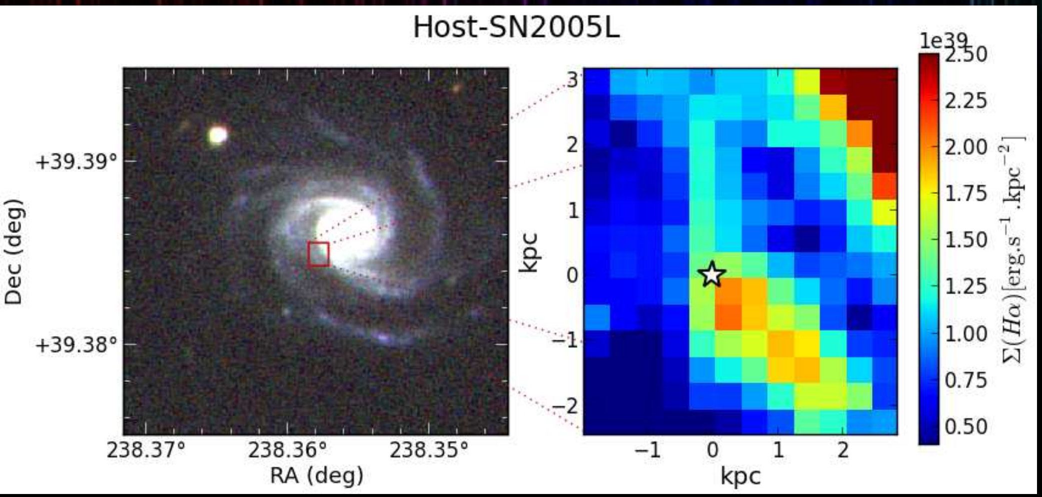
- A probe on the progenitor issue
- Global studies
  - UV+Opt+IR integrated photometry
  - Long-slit spectro. on host core
  - For SNf: Childress+2013a,b
- A 3rd parameter?
  - The "mass step"

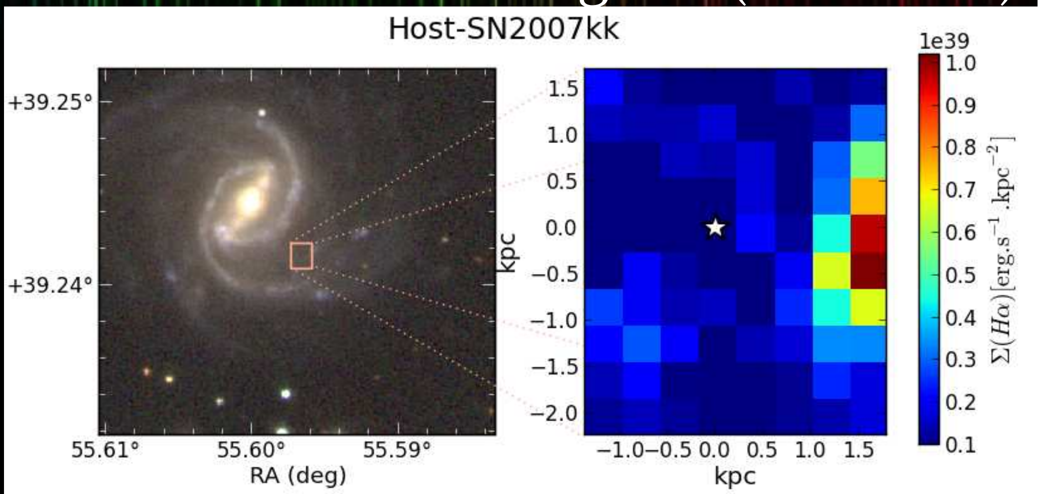
Childress+2013b

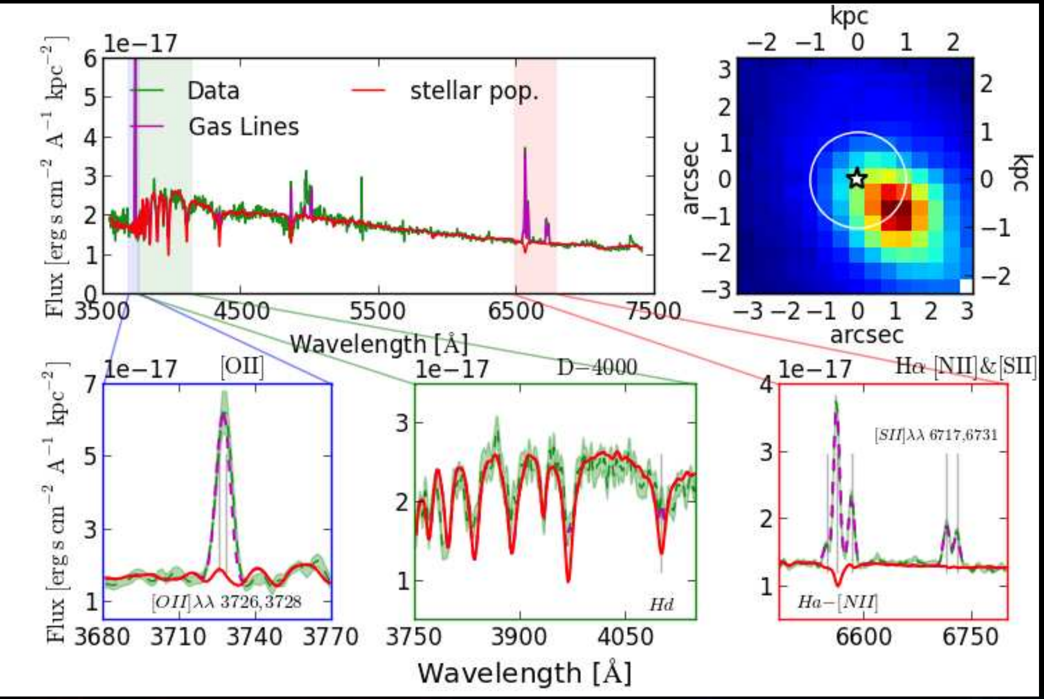


Global vs. local host studies

M. Rigault (PhD 2013)



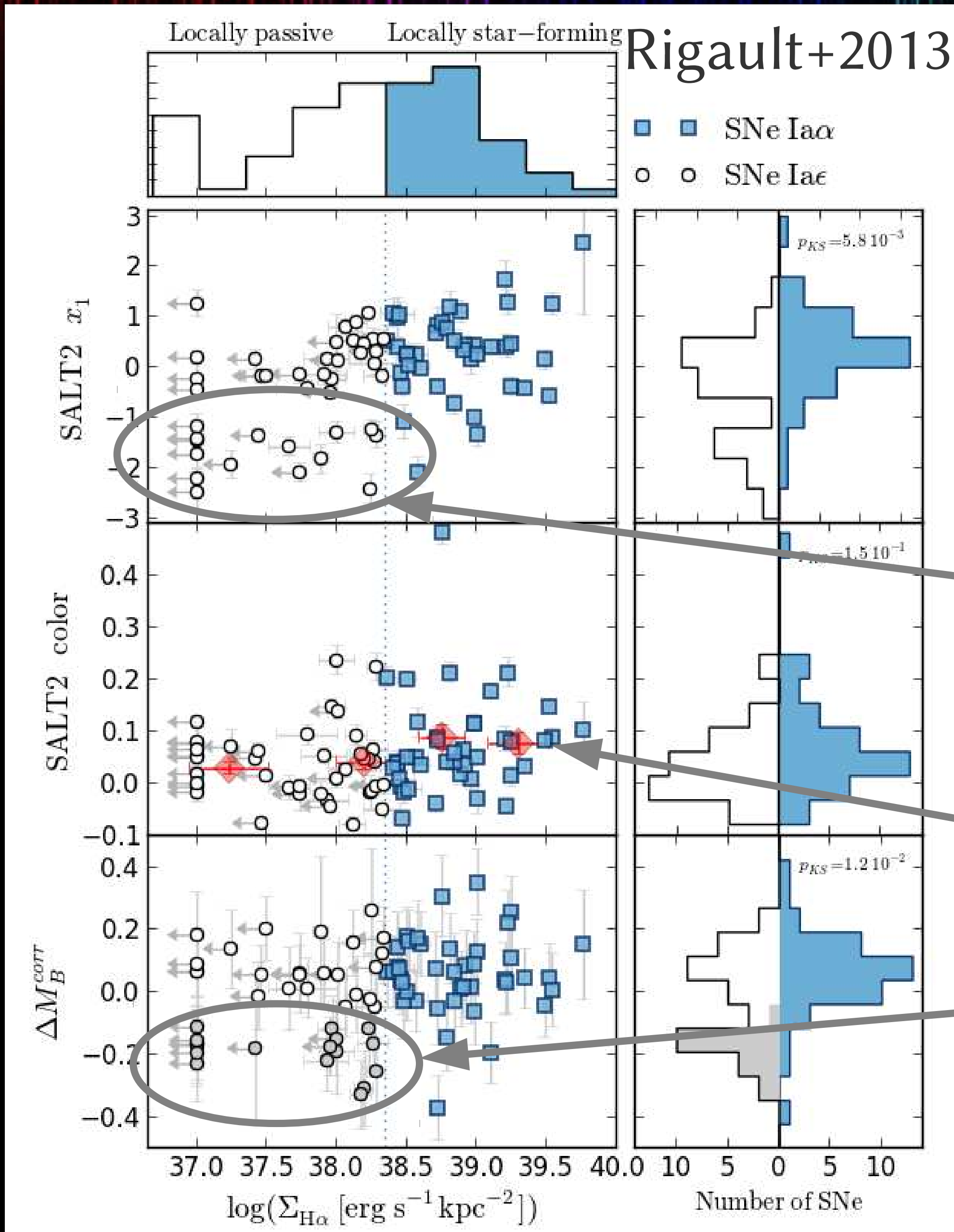




Global ≠ Local

- Use SNIFS FoV to probe local environment of SN (~1 kpc)
  - SN subtraction
  - Full time series cube merging
  - ULySS spectrum modeling
    - Stellar & gas components

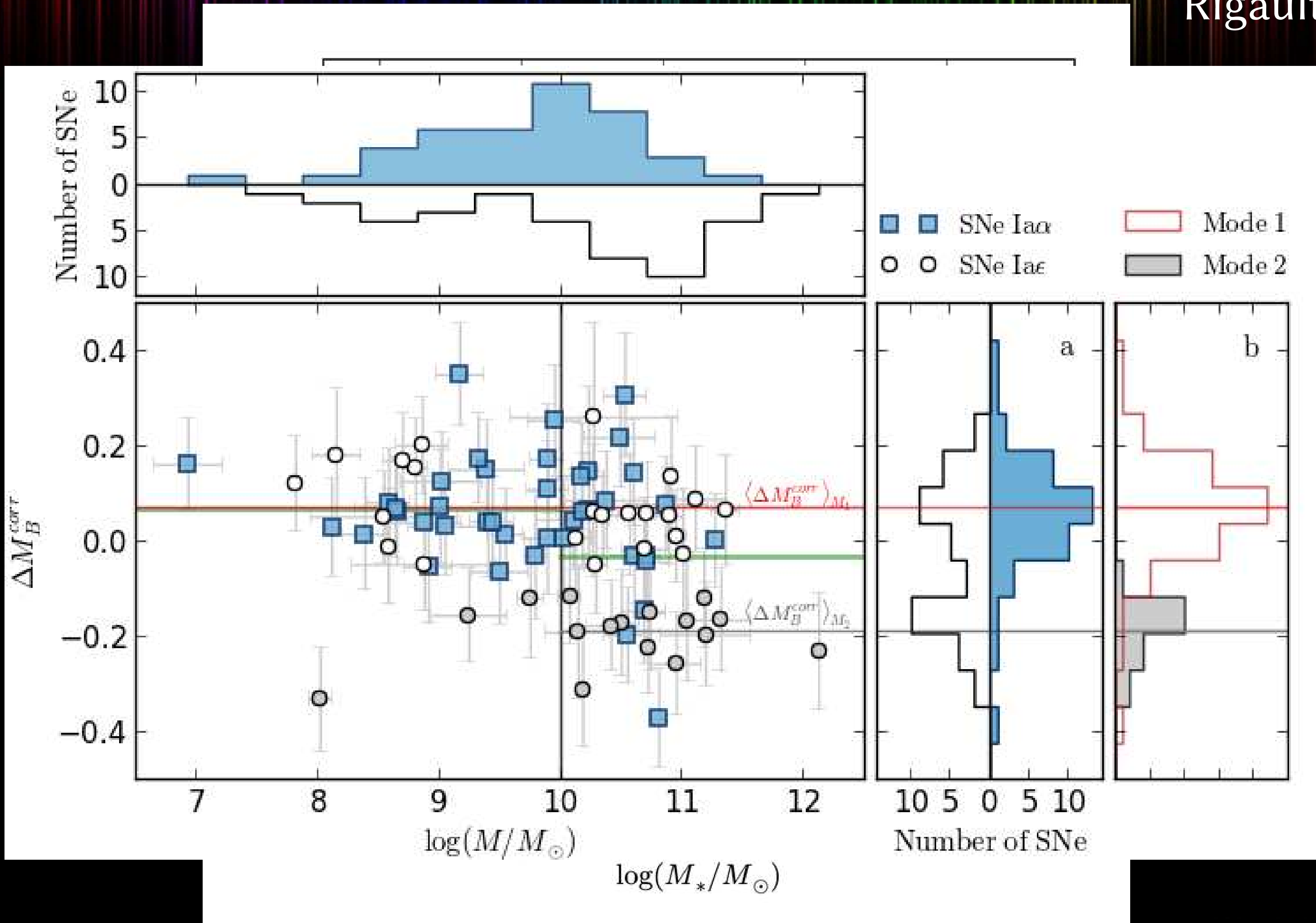
SN properties vs. local environment



- $\Sigma_{H\alpha}$ ≡ current star formation within 1 kpc
  - A proxy for progenitor age
  - SNe Iaε = locally passive
  - SNe Iaα = locally star forming
- Fast SNe are Iaε
  - But the opposite is not true
- Mild color dependency
  - As expected, but not prev. seen
- Over-luminous mode in Iaε after SALT2 correction
  - $\Delta M_B^c = 0.094 \pm 0.031$

The "mass step" from a local perspective

Rigault+2013



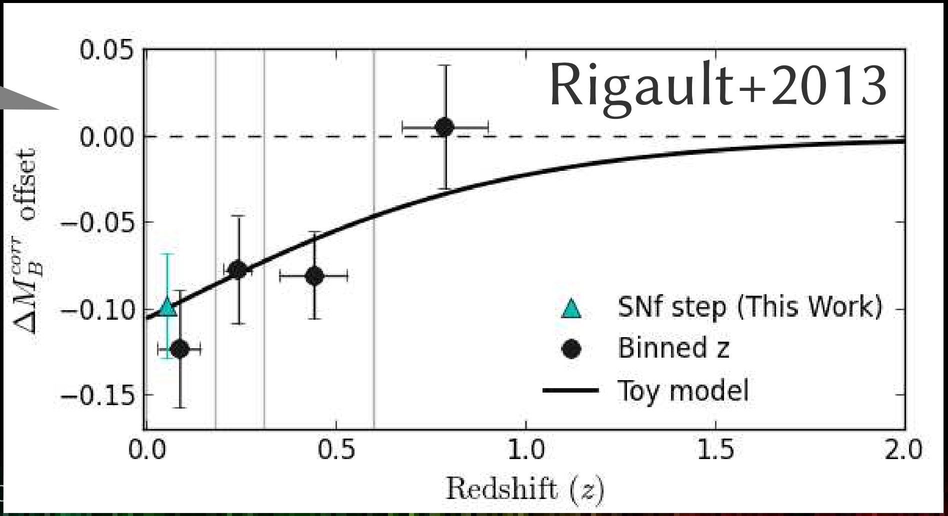
Local studies: SNe Iaε vs. Iaα

SNe Iaε from passive environments

- Heterogeneous population
- Poorly standardized
  - Requires intrinsic dispersion
  - No simple correction!
- Redshift evolution
  - Cosmology bias: $\Delta w \sim 0.06$

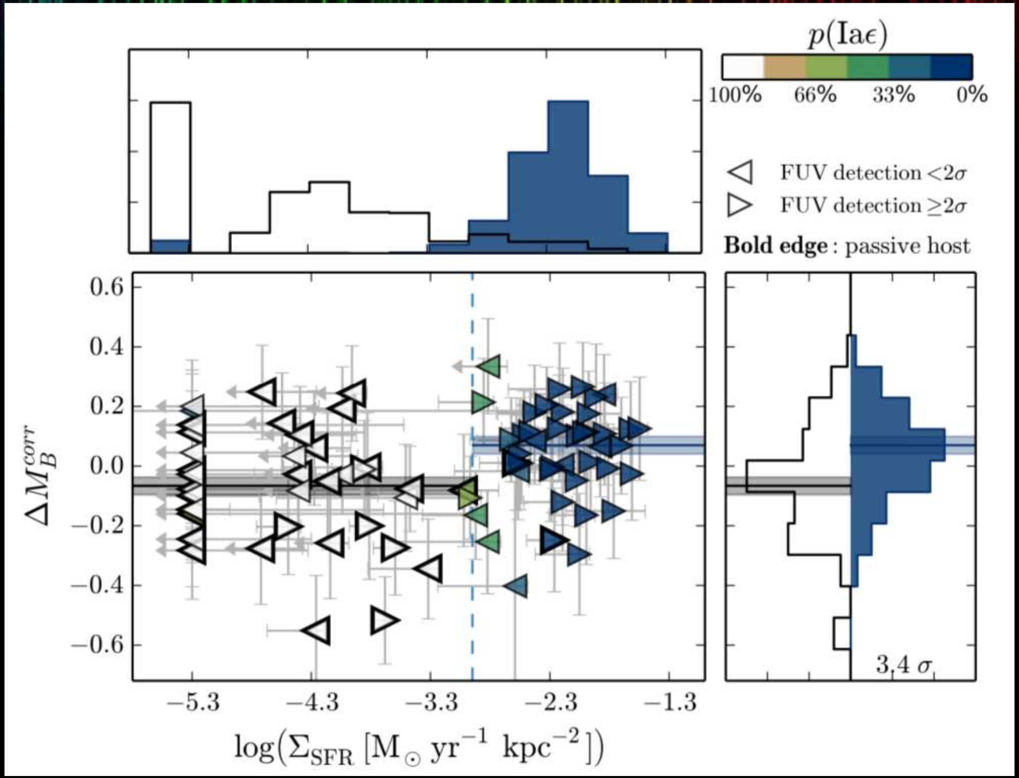
SNe Iaα from star forming environments

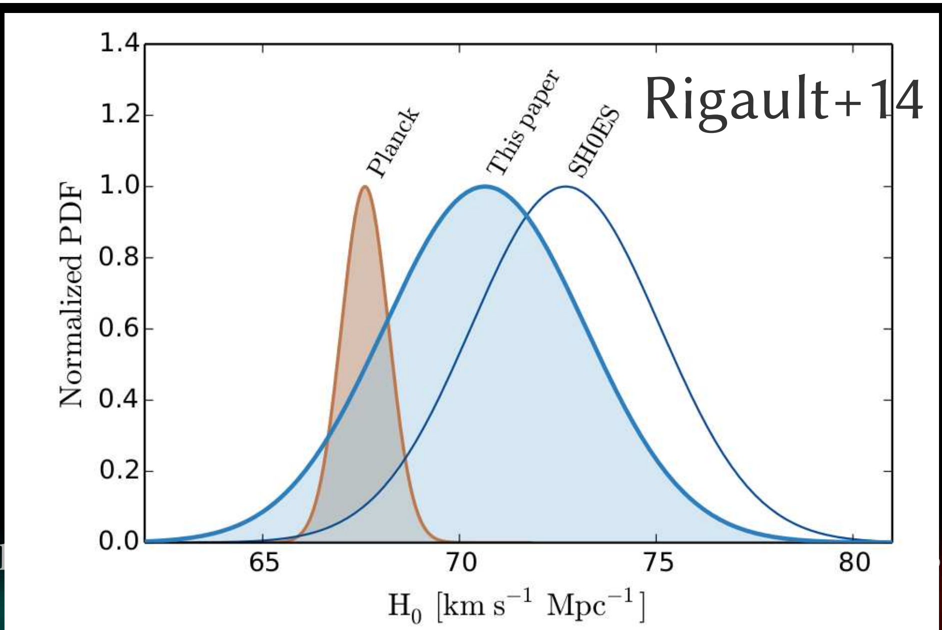
- Homogeneous population
  - No intrinsic dispersion
- Reduced Hubble residuals
  - $\sigma_{SALT2} = 0.15 \longrightarrow 0.11$
  - A better standard candle



SF bias impact on H_0

- FUV flux (GALEX) for local SF
- Confirmation on Constitution sample (Hicken+09)
  - $\Delta M_B^c = 0.094 \pm 0.025$ (combined)
- Confirmation w/ MLCS2k2
  - $\Delta M_B^c = 0.155 \pm 0.041$
- 3.3 ± 0.7% impact on H_0
  - Cepheid-calibrated SNe are in SF-galaxies
  - Hubble-flow SNe are in mixed environments
  - No more tension between Planck and SH0ES (Riess+11)





SNfactory science publications

- Case studies
  - SN2005gj and CSM-SNe (Aldering+06)
  - SN2006D and C-signatures (Thomas+07, 11)
  - SN2007if and super-Chandrasekhar SNe (Scalzo+10, 12, 14, Childress+11)
  - Super-normal SN2011fe (Röpke+12, Pereira+13)
- Sample analyzes
  - Spectral standardization (Bailey+09)
  - Color law (Chotard+11)
  - Gaussian Processes (Kim+13,14)
  - Hosts studies (Childress+13a, b)
  - Anisotropies (Feindt+13)
  - K-correction bias and dispersion (Saunders+14)
  - More to come

Next major publications: 1. photometry release, 2. cosmology analysis, 3. time series publication

Conclusions

- Integrated, robust, science-focused instruments rock
- Nearby SN search is difficult
  - SNIFS was mostly SN-starved
  - A 1000+ SN time series sample will be hard to get
- 3D spectro-photometry, it works!
  - Requires lots of efforts at every reduction steps (there's many)
  - Seems like less precise than standard photometry at 1st…
  - But photometry is "*cheating*": systematic errors are underestimated
- Case for 3D PSF photometry
  - Point-source spectro-photometry, crowded-field IFS, data mining in large IFSs to come (Muse/VLT, eELT, JWST)
- Flux calibration and atmospheric extinction
  - The principal (acknowledged) systematic error in current (SNLS, SDSS) photometric surveys, and future ones (DES, LSST)
  - Auto-calibration, real-time measurement, physical calibration

3D spectro-photometry in few words