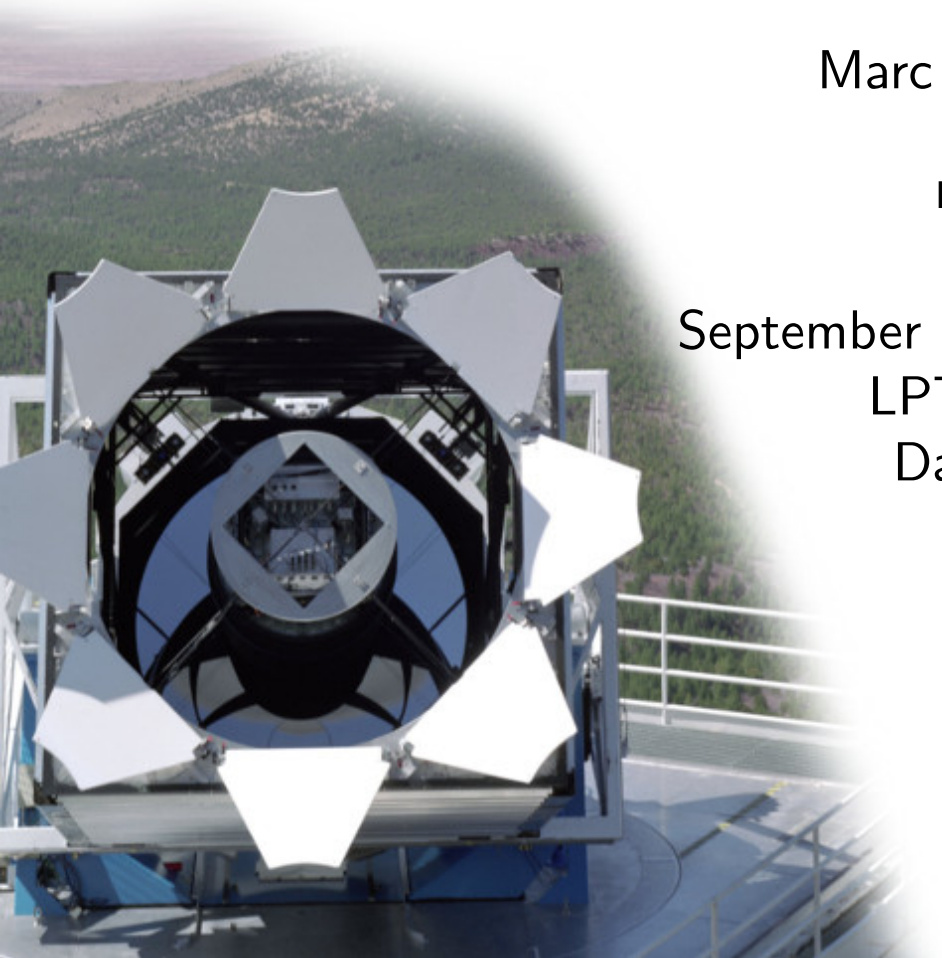
Cosmology with Type Ia Supernovae



Marc Betoule

LPNHE

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LPT Saclay
DarkMod

OUTLINE

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

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Nearly Twenty Years !

1st Part: The Big Picture

1. The Friedmann-Lemaître Universe
2. Type Ia supernovae as standard candles (hygienic version)
3. Constraints from current data
4. Summary

2nd Part: State of the Art

5. Measurement principles
6. Origin of Limitations and Improvement Prospects in Forthcoming Survey
7. Summary

Distances in the Friedman-Lemaître Universe

Cosmology principle

The universe is isotropic and homogeneous

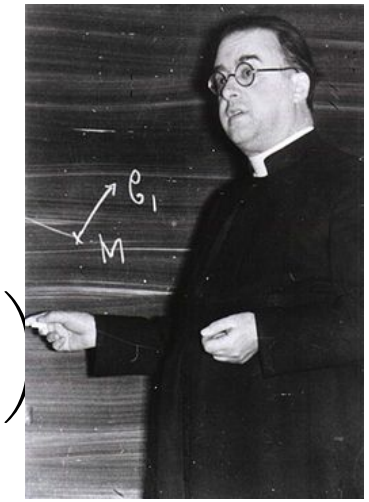
Alexander Friedmann

Encoded in the Friedman-Lemaître -Robertson-Walker (FLRW) metric

$$ds^2 = c^2dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + sin^2\theta d\phi^2)\right)$$

with $k = -1, 0, 1$. Introducing ($a = R/R_0$) and coordinate change $r = S\left(\frac{\chi}{R_0}\right)$ with $S = sin, Id, sinh$ for $k = 1, 0, -1$:

$$ds^2 = -c^2dt^2 + a^2(t)\left(d\chi^2 + R_0^2 S^2\left(\frac{\chi}{R_0}\right)d\Omega^2\right)$$



Monseigneur Georges Lemaître

Kinematics of test masses

We are an observer at rest in $(t_0, 0, 0, 0)$

Observing light emitted by a test mass in $(t_e, \chi, 0, 0)$

Redshift

$$\frac{\lambda_o}{\lambda_e} = \frac{R(t_o)}{R(t_e)} = 1 + z = \frac{1}{a(t_e)}$$

Distances

- $\chi = c \int_{t_0}^{t_e} \frac{dt}{a(t)} = c \int_0^z \frac{dz}{H(z)} = \frac{c}{H_0} \int_0^z \frac{dz}{E(z)}$ with $H = \frac{\dot{a}}{a}$ and $E = \frac{H}{H_0}$
- transverse comoving: $d_M^2 = \frac{dS_{comoving}}{d\Omega^2} = R_0^2 S^2 \left(\frac{\chi}{R_0}\right)$
- angular diameter: $d_A = \left(\frac{dS_{physical}}{d\Omega^2}\right)^{-1/2} = d_M/(1+z)$
- luminosity: $f_{obs} = \frac{L_{source}}{4\pi d_L^2} \rightarrow d_L = (1+z)^2 d_A$ (Etherington law)

The distance-redshift relation traces the evolution of the expansion rate H

to probe the dynamic

Friedman equations

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3c^2}\rho - \frac{kc^2}{R^2(t)} \quad (1)$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left(\frac{\rho + 3p}{c^2}\right) \quad (2)$$

(1) In dimension of ρ_c:

$\rho_c = \frac{3c^2 H_0^2}{8\pi G} \rightarrow \Omega_0 = \frac{\rho_0}{\rho_c}$ and $\Omega_k = -\frac{kc^2}{R^2(t_0)H_0^2}$

$E^2(z) = \Omega_0 \frac{\rho(z)}{\rho_0} + \Omega_k (1+z)^2$

(2) − (1) = $\dot{H}$ with $p/\rho = w$

$\frac{\dot{\rho}}{\rho} = -3(1+w)\frac{\dot{a}}{a} \rightarrow \log\frac{\rho(z)}{\rho_0} = 3\int_0^z \frac{1+w(z)}{1+z}dz$

Splitting Ω into species

$$\log \frac{\rho(z)}{\rho_0} = 3 \int_0^z \frac{1 + w(z)}{1 + z} dz$$

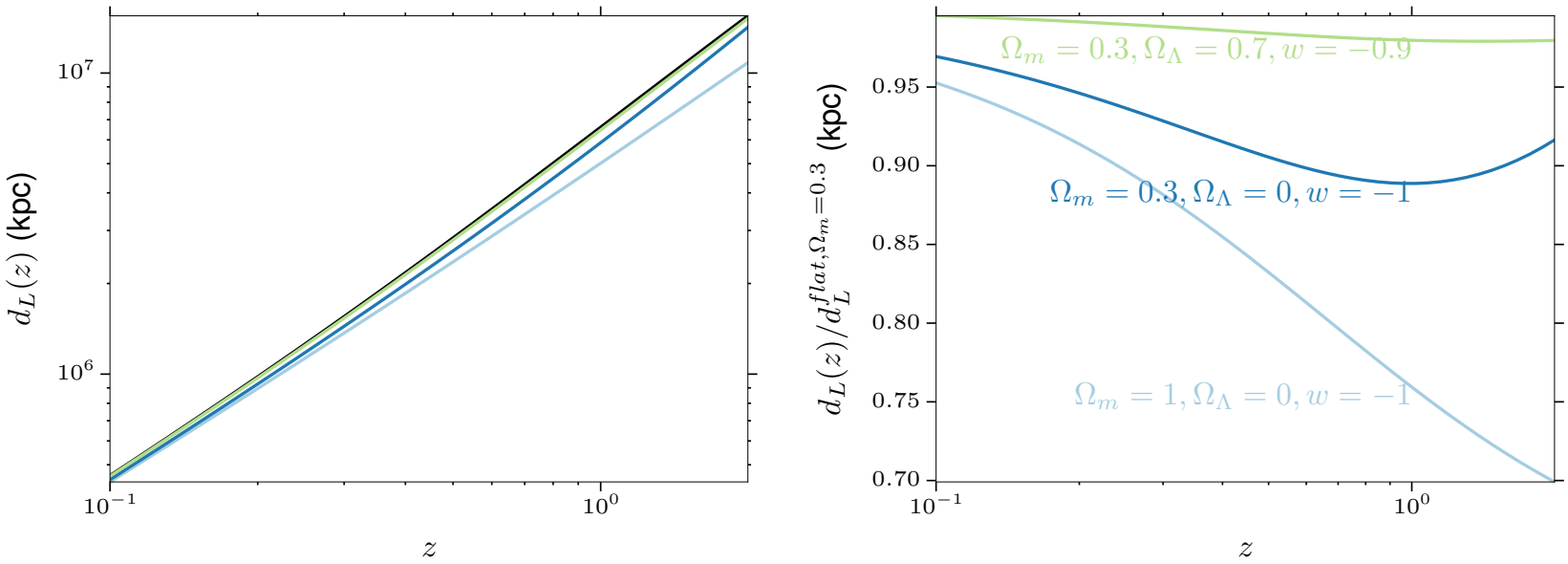
- Non relativistic matter ($w = 0$): $\Omega_m = \Omega_{m0}(1 + z)^3$
- Radiation ($w = 1/3$): $\Omega_r = \Omega_{r0}(1 + z)^4$
- Cosmological constant ($w = -1$): $\Omega_\lambda = cte$
- Dark energy with constant w: $\Omega_X = \Omega_{X0}(1 + z)^{3(1+w)}$

$$E(z) = \left(\Omega_m(1 + z)^3 + \Omega_r(1 + z^4) + \Omega_k(1 + z)^2 + \Omega_X(1 + z)^{3(1+w)}\right)^{1/2}$$

Measuring cosmological distances probes the dynamic

$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{\left(\Omega_m(1+z)^3+\Omega_r(1+z^4)+\Omega_k(1+z)^2+\Omega_X(1+z)^{3(1+w)}\right)^{1/2}}$$

Numerical integration



- All curves are for $H_0 = 70 km/s/Mpc$
- Black curve is a flat Λ-CDM model with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$

Probing a perturbed universe ?

The effect of density perturbation on the mean luminosity distance has been controversial for years

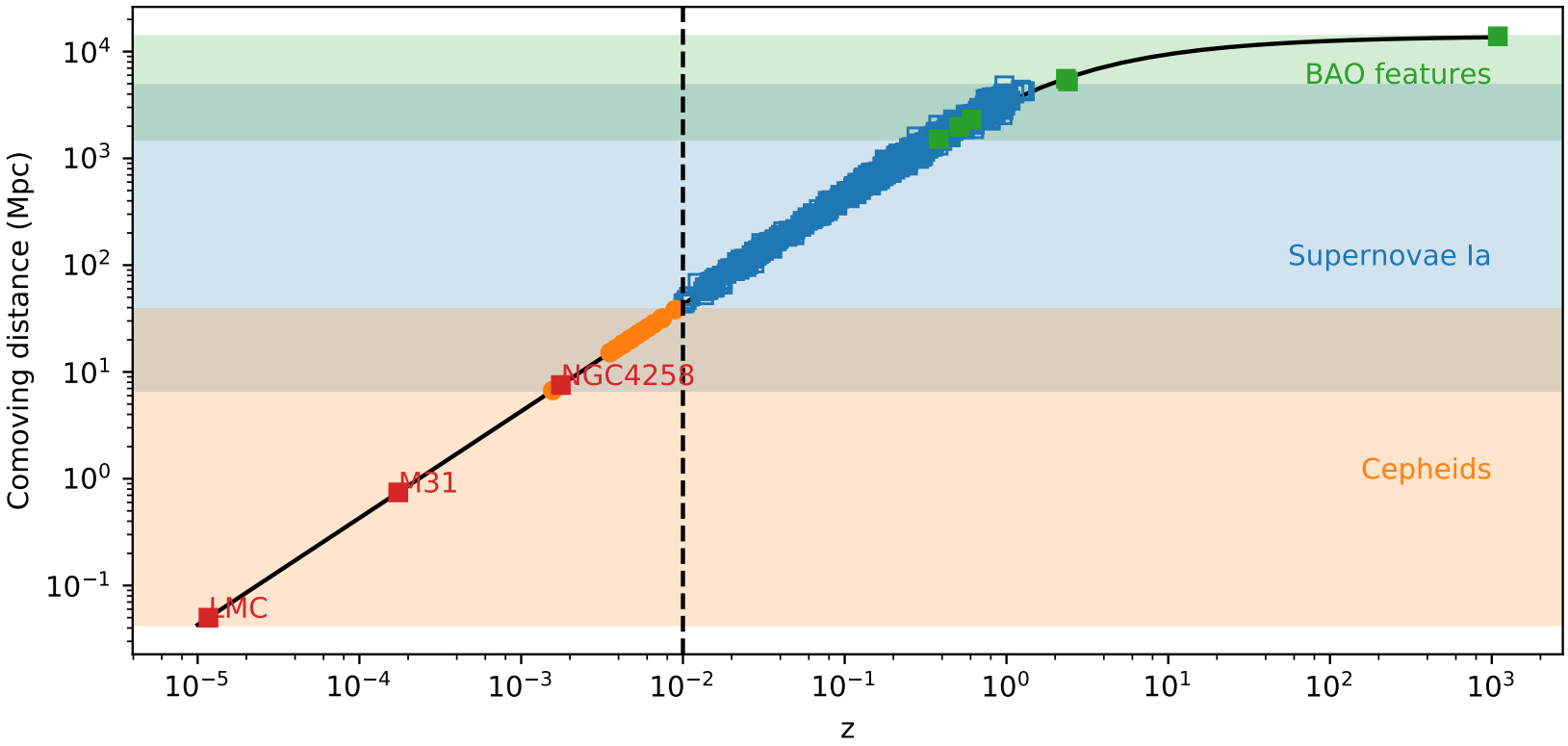
- Coined as "back-reaction"
- Could cause apparent acceleration ?

We'll come to that in the second lecture. For now let us assume that this introduce 3 main effects

- Peculiar motion of the observer $\rightarrow$ correction to the CMB frame
- Peculiar motion of nearby events $\rightarrow$ bias at some level, extra noise
- Lensing of high-redshift sources $\rightarrow$ an extra noise

LPNHE PARIS

Practical ways of measuring distances



- Geometrical Anchors
- Standard candles such as Cepheids and SNe Ia
- The absolute standard ruler provided by acoustic oscillation features in the CMB anisotropies and matter distribution

Standard candles

Find classes of astrophysical objects whose intrinsic luminosity can be estimated

Standard convention is to use magnitudes

- Intrinsic magnitude: $M = -2.5 \log_{10} L + cte$
- apparent magnitude: $m = -2.5 \log_{10} f + cte$

Definition of the distance modulus

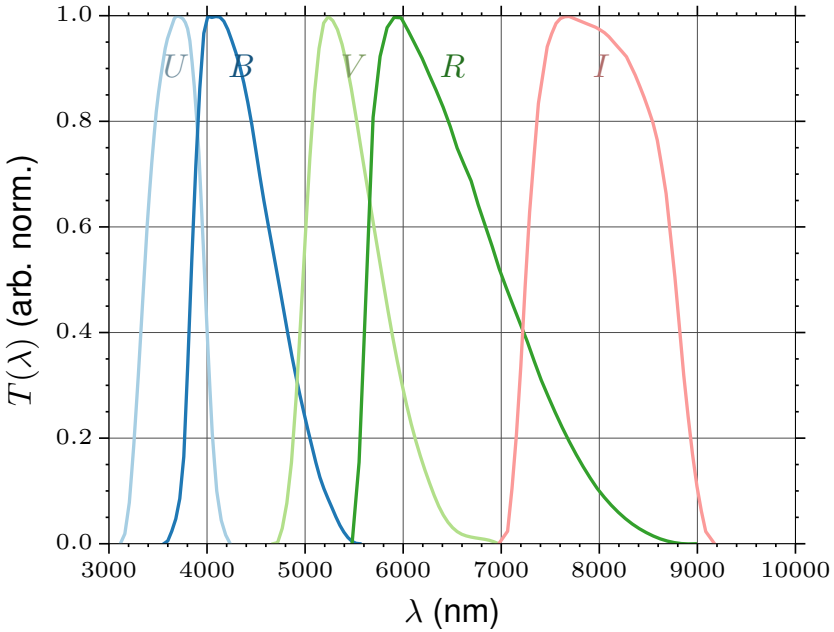
$$f = \frac{L}{4\pi d_l^2} \rightarrow m = M - 5 \log_{10} d_l + cte \quad (3)$$

$$= M + \mu \quad (4)$$

The constant are chosen such that $M = m$ for an object at $10pc$

$$\rightarrow \mu = -5 \log_{10} \left(\frac{d_l}{1Mpc} \right) + 25$$

In practice, flux measurements are performed in finite, well-defined, passbands



$$f = \int \lambda T(\lambda) S(\lambda) d\lambda$$

$$B = -2.5 \log_{10} \int \lambda T_B(\lambda) S(\lambda) d\lambda$$

$$V = -2.5 \log_{10} \int \lambda T_V(\lambda) S(\lambda) d\lambda$$

Colors are differences in broadband magnitudes

E.g.: B-V

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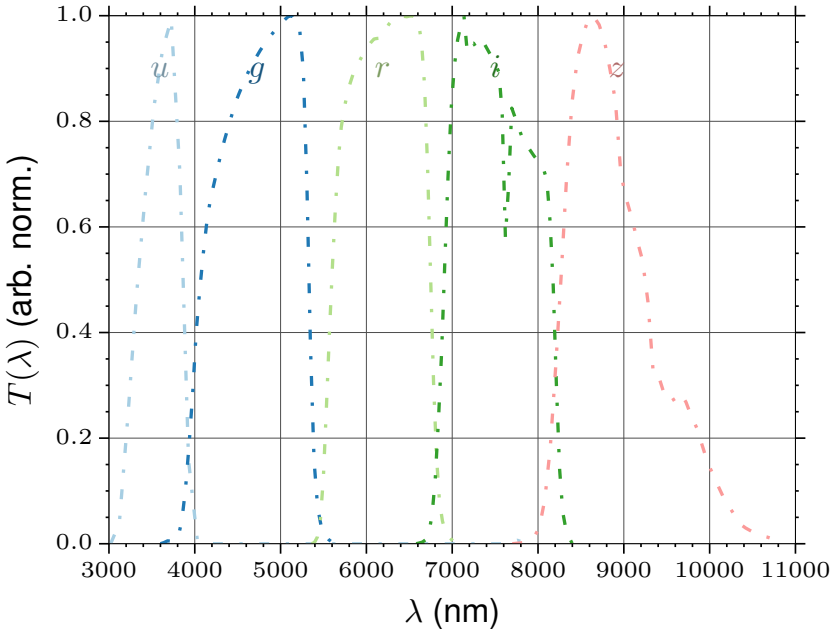

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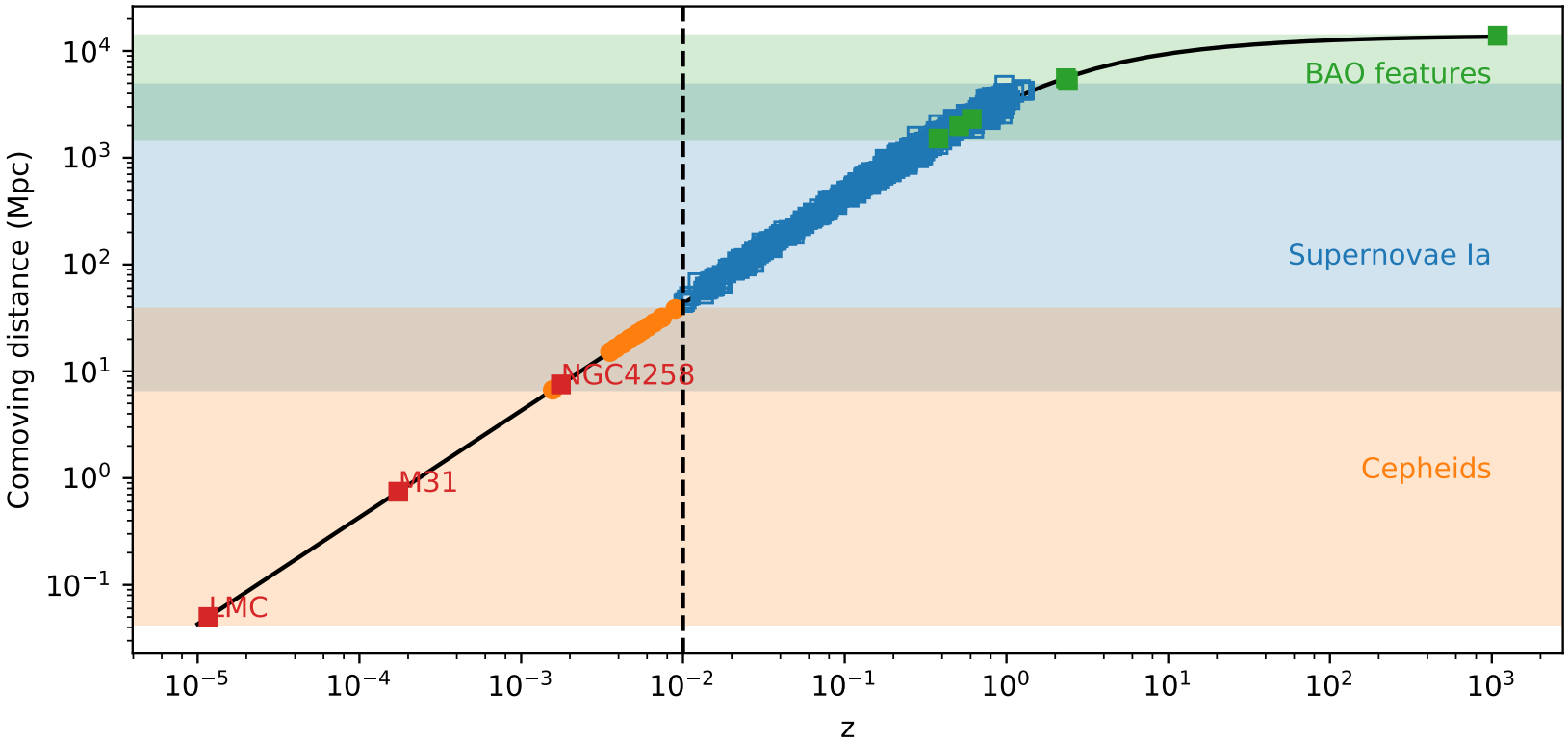
Cepheids



- Big pulsating stars
- Brightness linked to pulsation period $m_H = M_H + b_w \log(P) + \mu$
- $10 < P < 80$ days, $M_H \sim -2.9$, $b_w \sim -1.4 \rightarrow -4 < M < -9$
- Decreasing SNR and increasing confusion limits accessible distance

The Hubble diagram of cepheids (Hubble 1929)

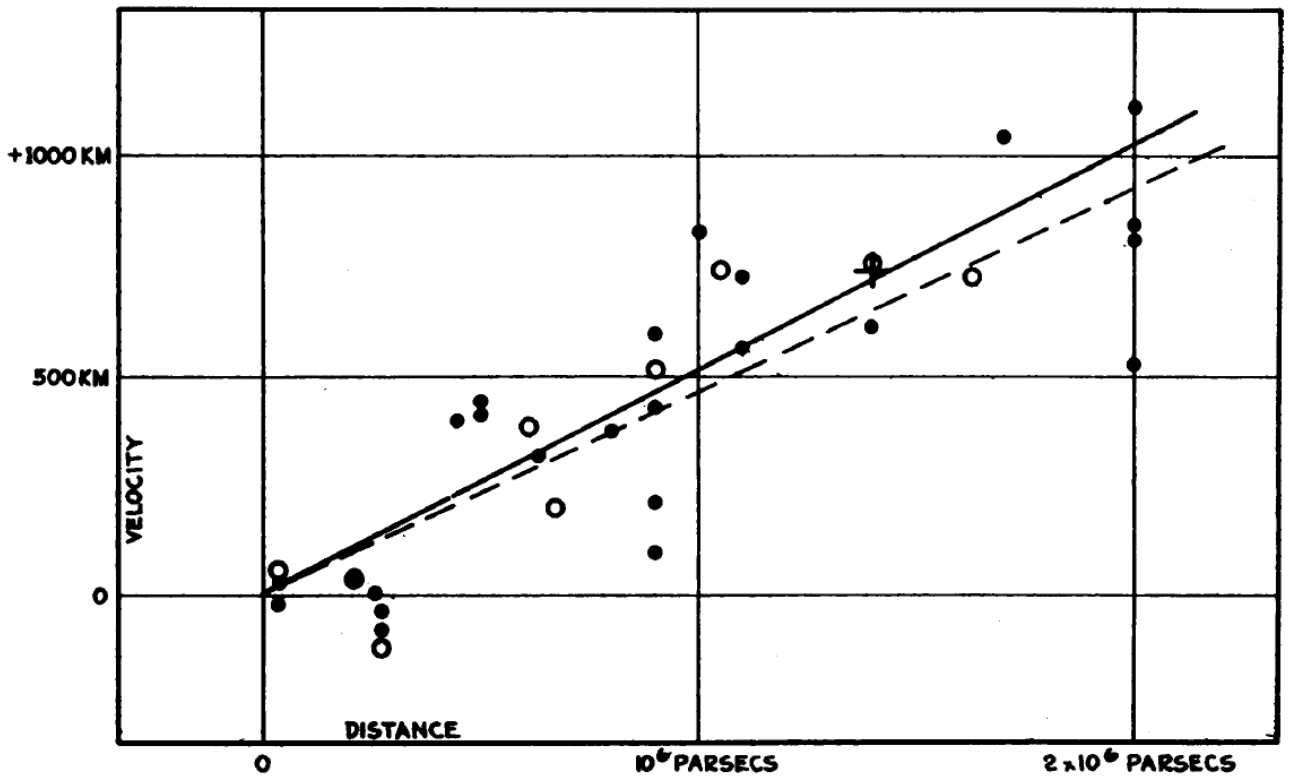
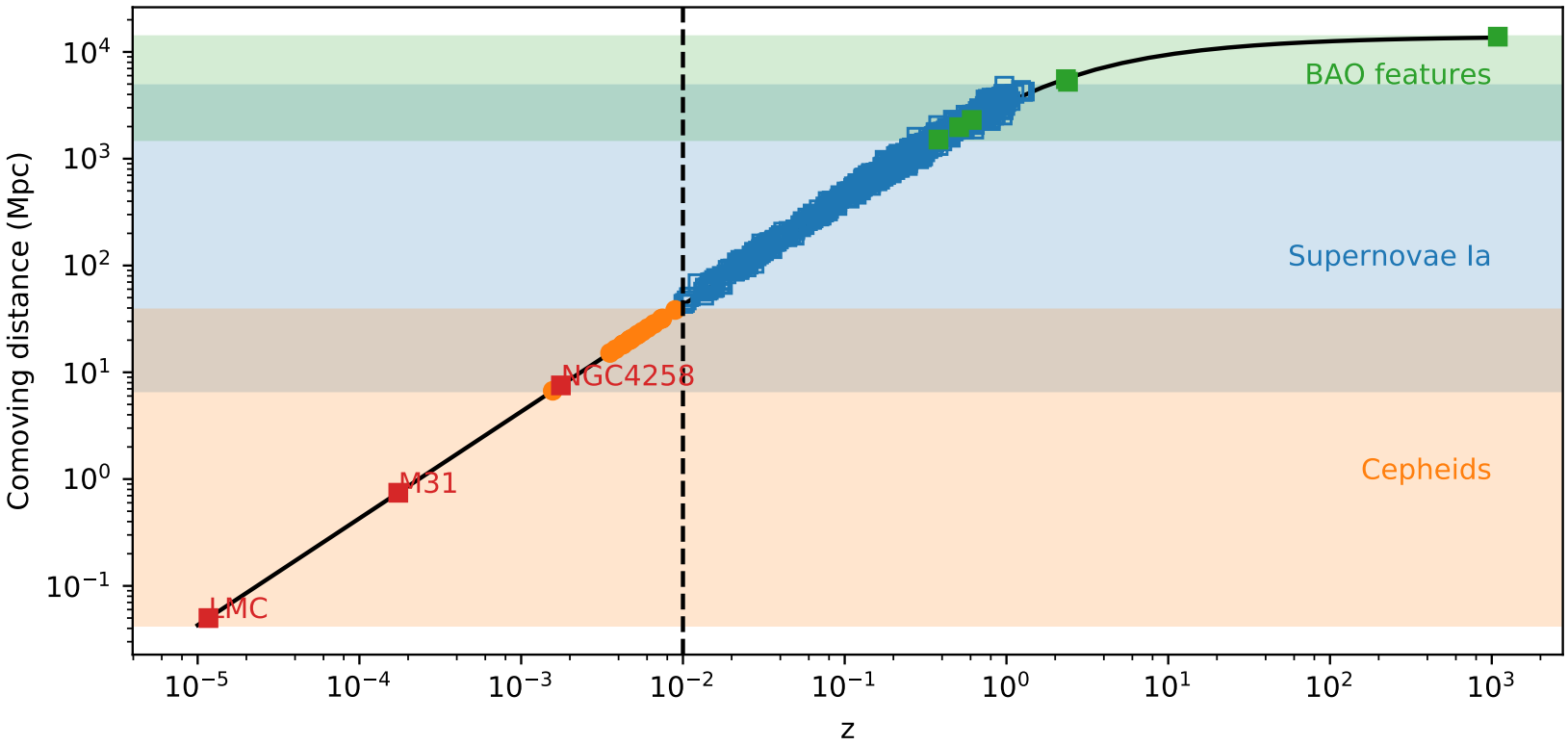


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

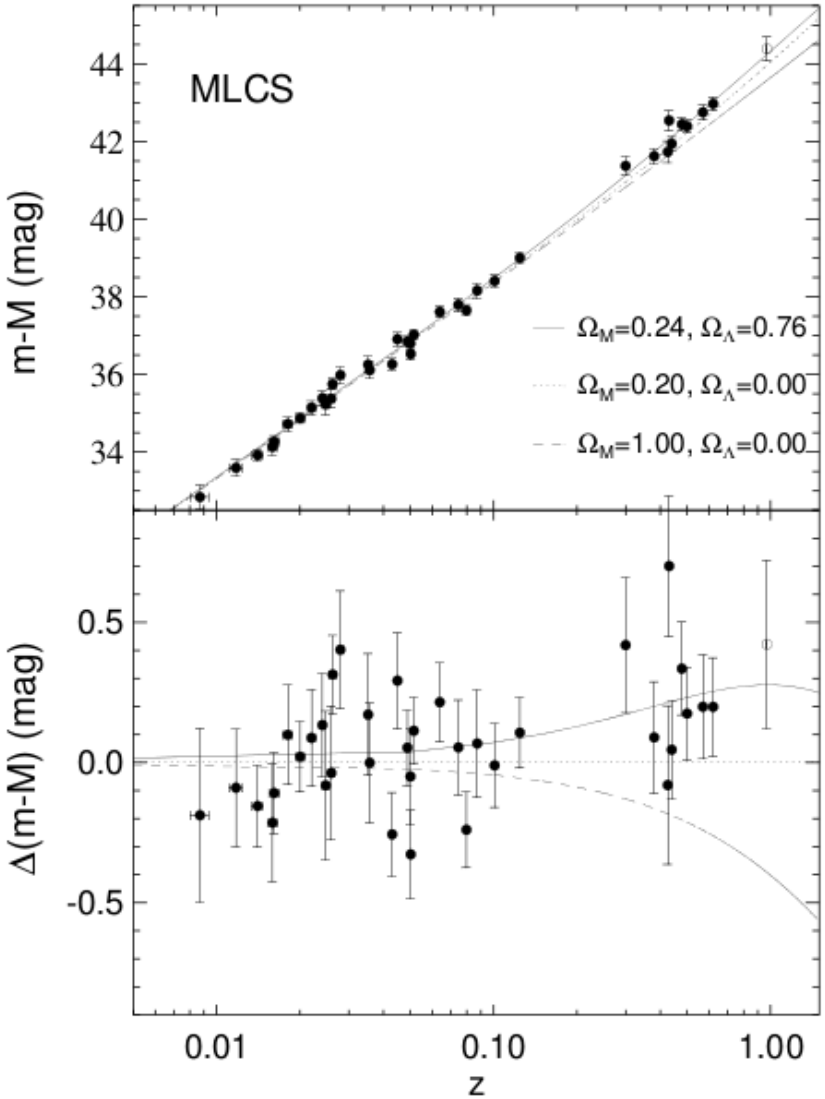
- Discovery of expansion
- Already proposed by Lemaître in 1927
- Nowadays Cepheids are succesfully measured up to $m_H \sim 26$, $\mu \sim 40 Mpc$ with HST (see Riess et al. 2016)

Supernovae



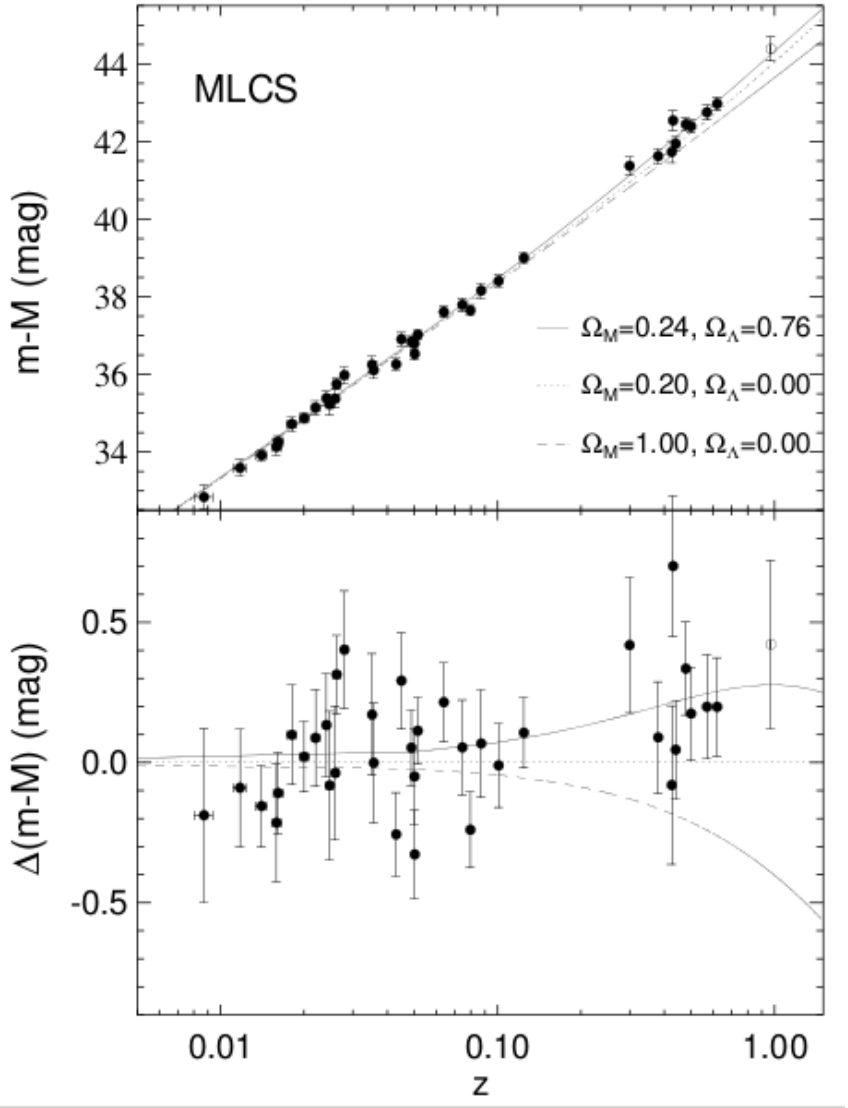
- Rare events. Today the rate is $R \sim 0.25 event/10^4 years/Mpc^3$
- Extremely bright transitory events $M \sim -19$ in the blue band
- Subject of this lecture

The Hubble diagram of SNe Ia (Riess et al. 1998, Perlmutter et al. 1999)



- Compares brightness of distant and nearby SNe
- Rules out the flat matter-dominated Universe
- Disfavor the empty universe
- $\Omega_\lambda > 0$

The Hubble diagram of SNe Ia (Riess et al. 1998, Perlmutter et al. 1999)



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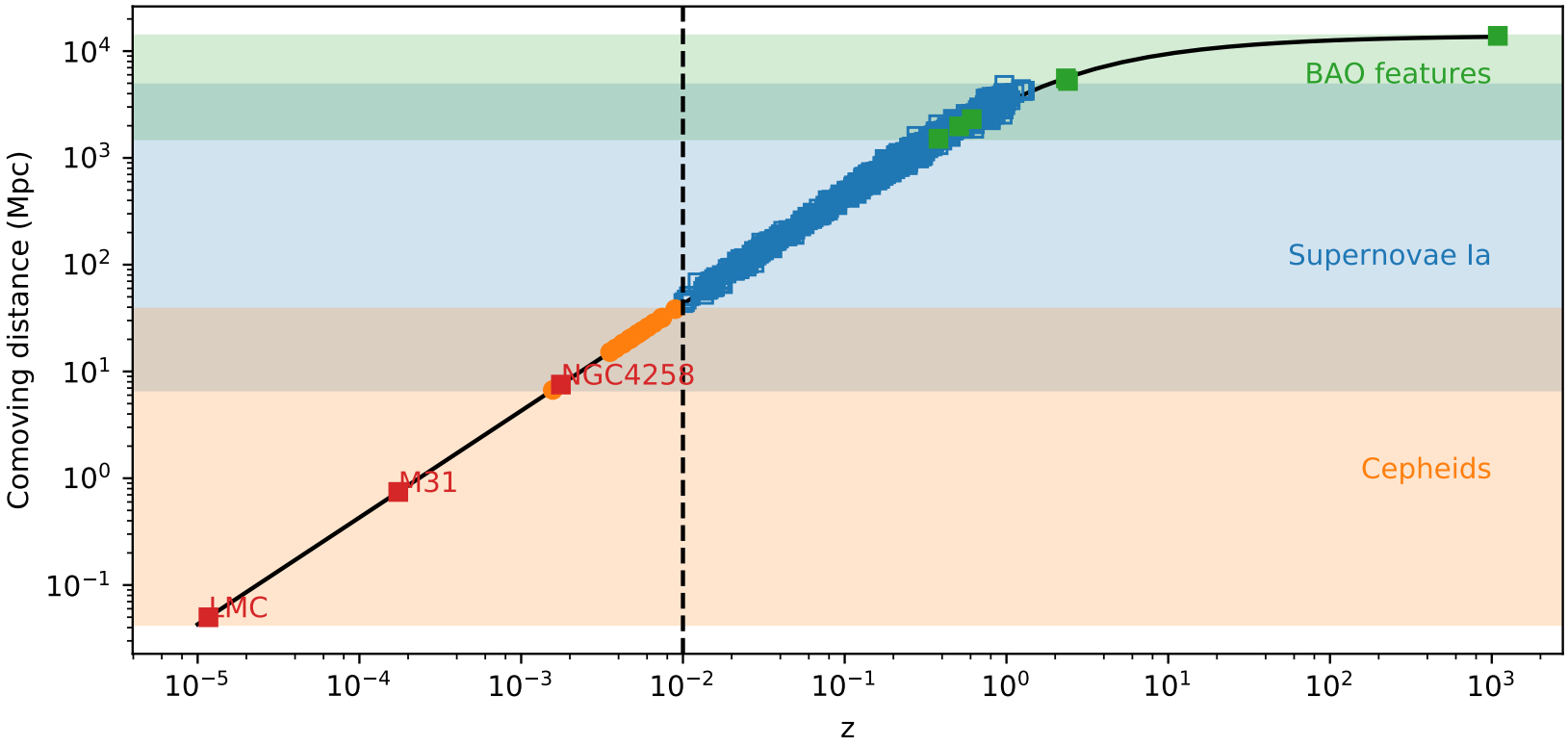
Anchoring the distance scale: 3 kinds in use



- Parallaxes of cepheids: for now limited to the milky way. See Casertano et al. 2016 for recent parallaxes measurement from Gaia
- Self eclipsing binaries up to M31 ($\sim$ 0.7 Mpc)
- Very long baseline interfometry of maser lines in massive galactic black holes accretion disks. NGC4258 distance comparable to supernova hosts.

The water masers

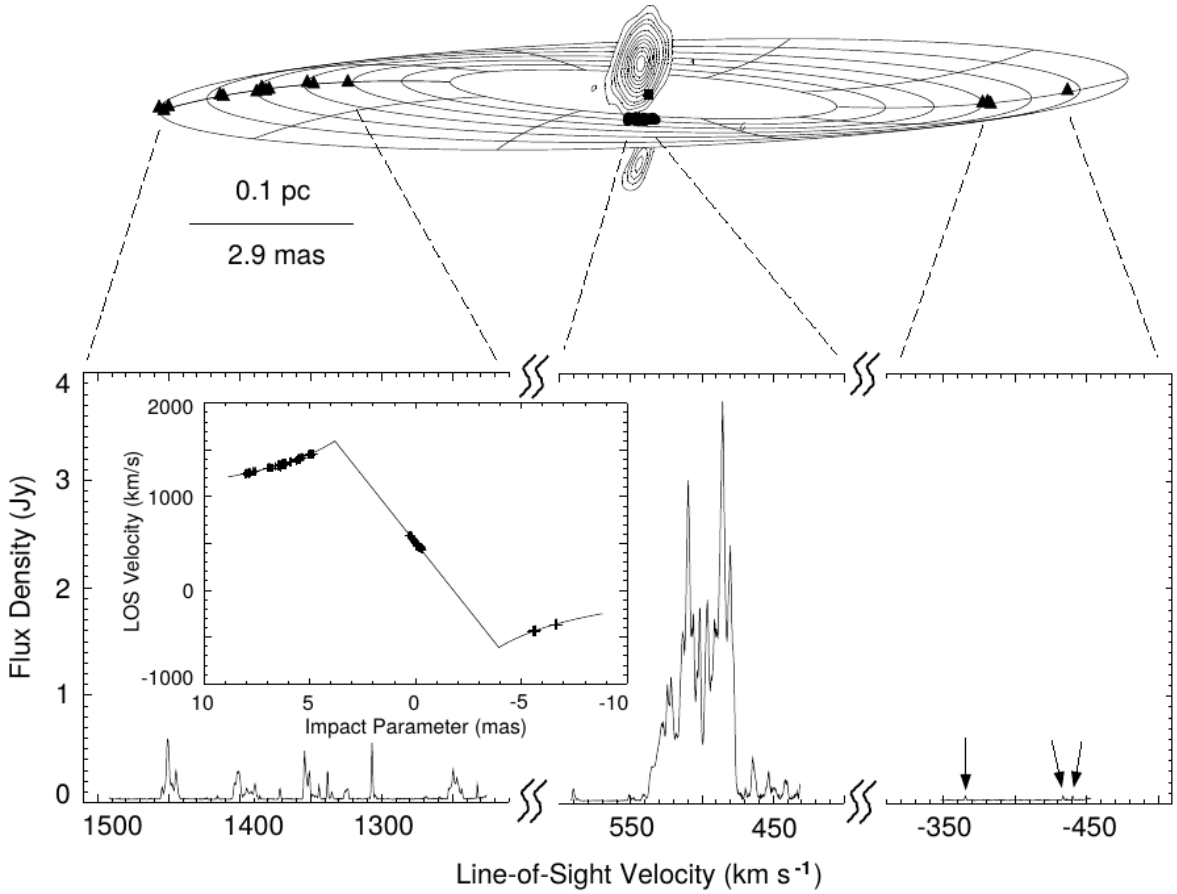
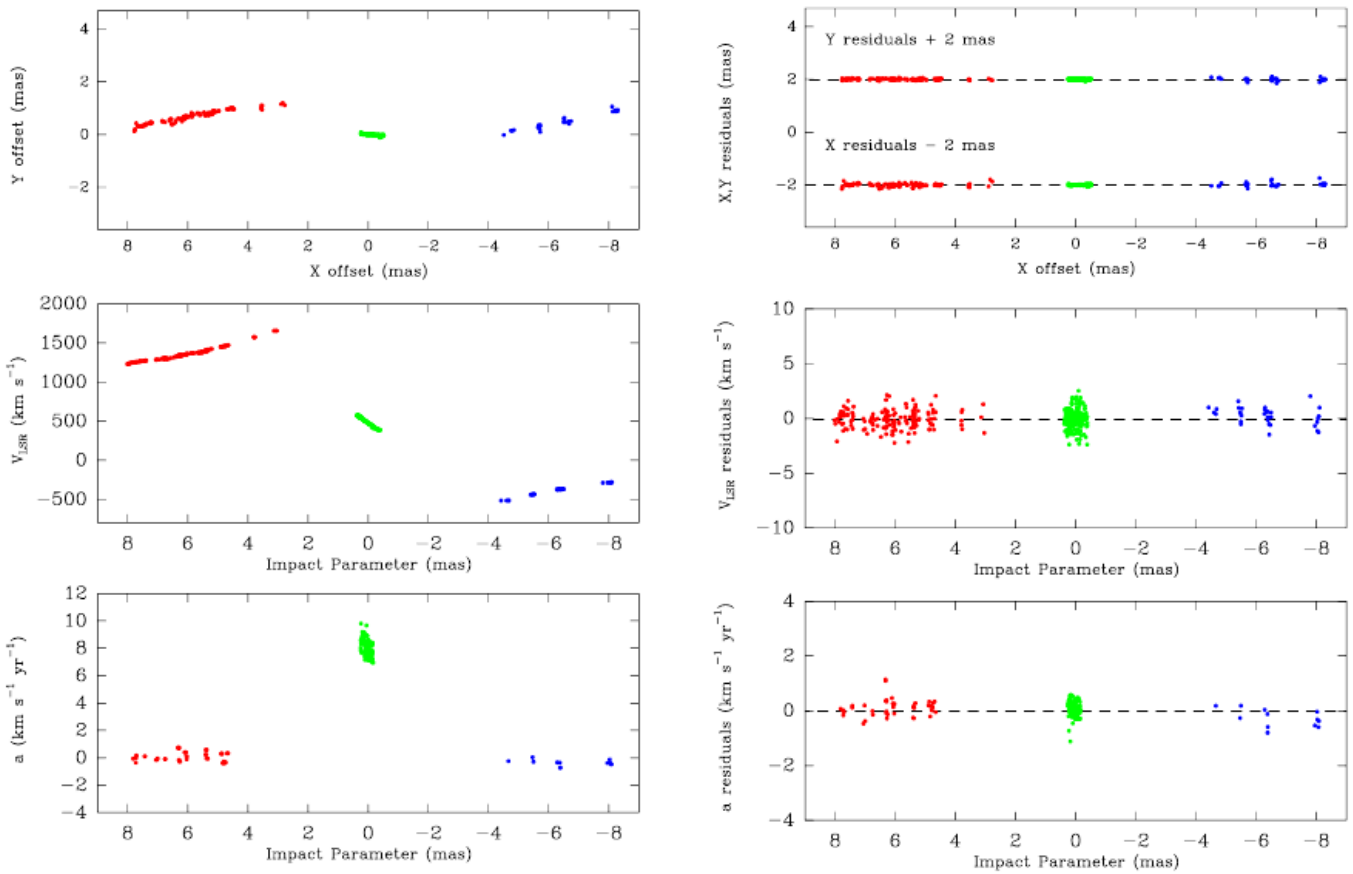


Figure from Herrnstein et al. 1999

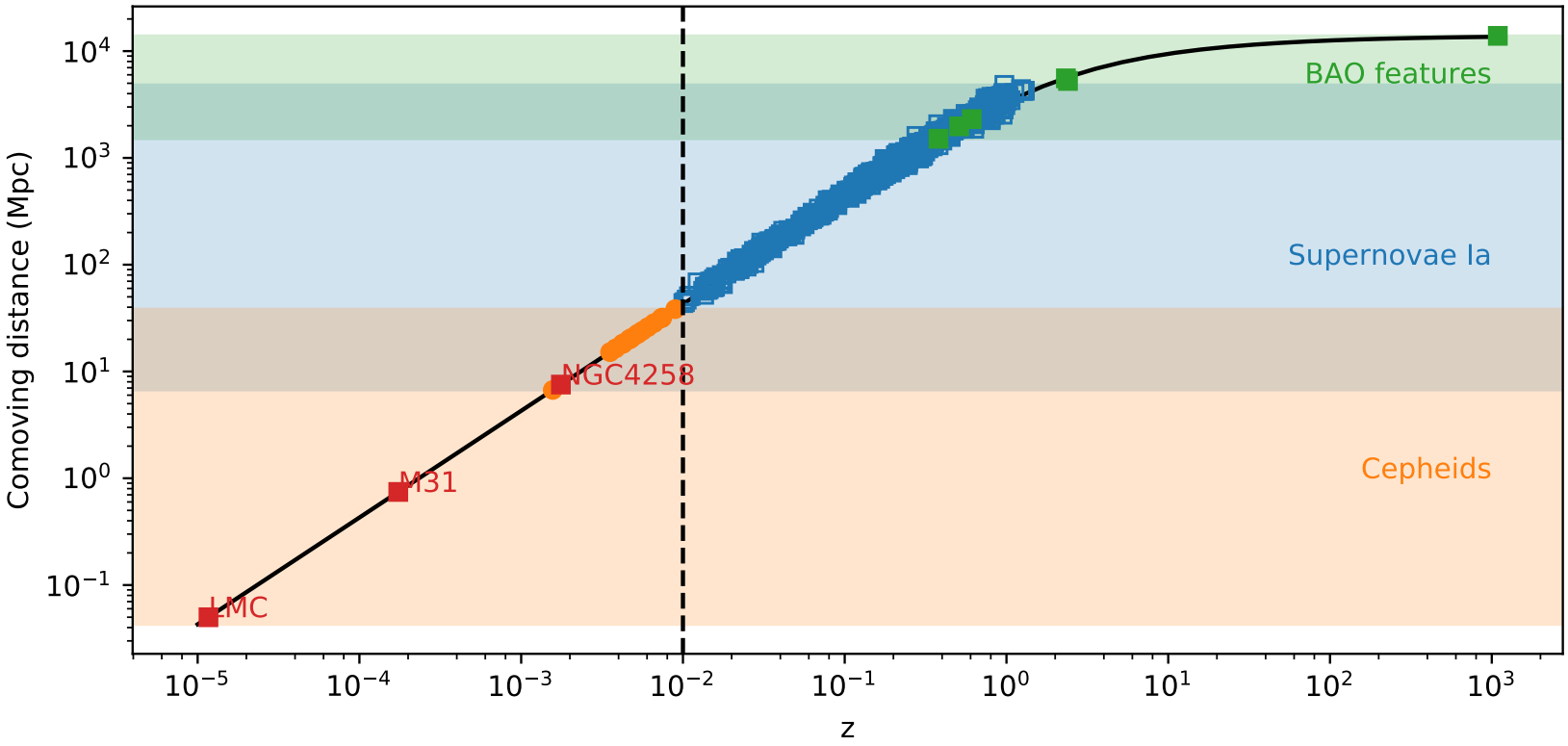
- Clumps of molecular gas in the accretion disk of an AGN
- Powerful and thin emission lines
- LOS velocity and position follow-up

Fit of the disk rotation model to available data (Humphreys et al. 2013)



- Gives distance to NGC4258 7.54 ± 0.20 Mpc or 2.6% (Riess et al. 2016)
- NGC4258 similar to SNe Hosts in term of distance and metallicity

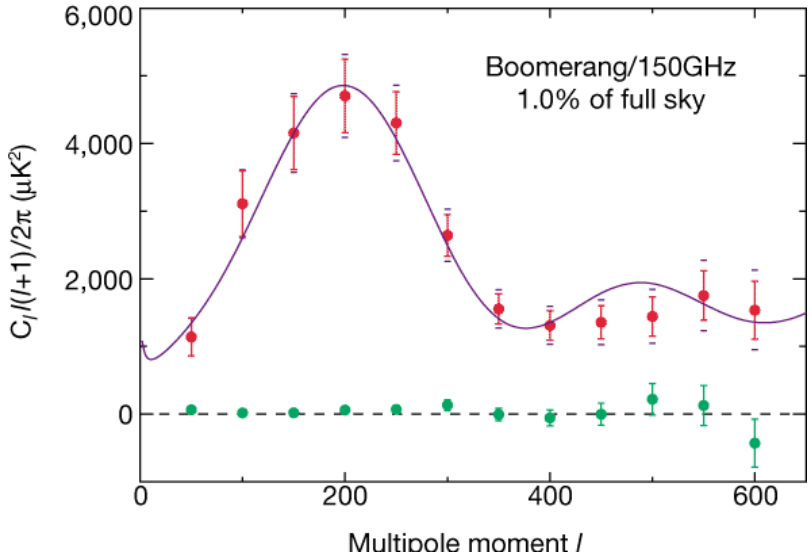
The BAO scale



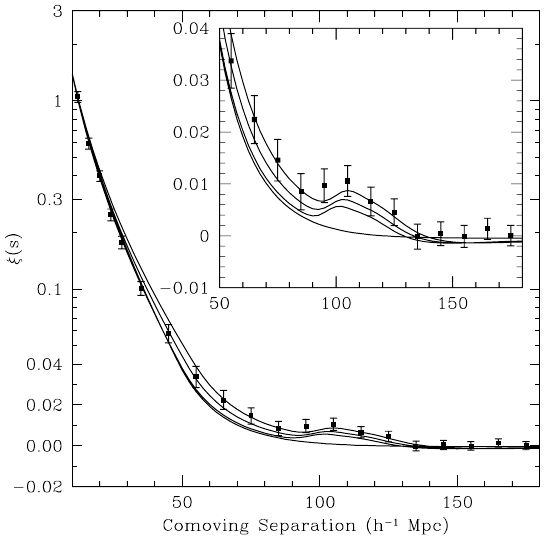
- Absolute scale: sound horizon at drag epoch, very clean measurement
- Once the feature is detected at a given redshift, its apparent angular size constrains the angular distance at that redshift (among other things)
- Dedicated lecture (J. Rich)

Detection of the accoustic oscillation features

In the power spectrum of the CMB temperatur fluctuations (de Bernardis et al. 2000)



In the distribution of galaxies (Eisenstein et al. 2005)



- Requires sufficient statistics (volume) for a precise determination of the 2-point correlation function to see the feature
- Once the feature is detectable precision of its position gives precise distance measurements (5% for the first SDSS measurement)

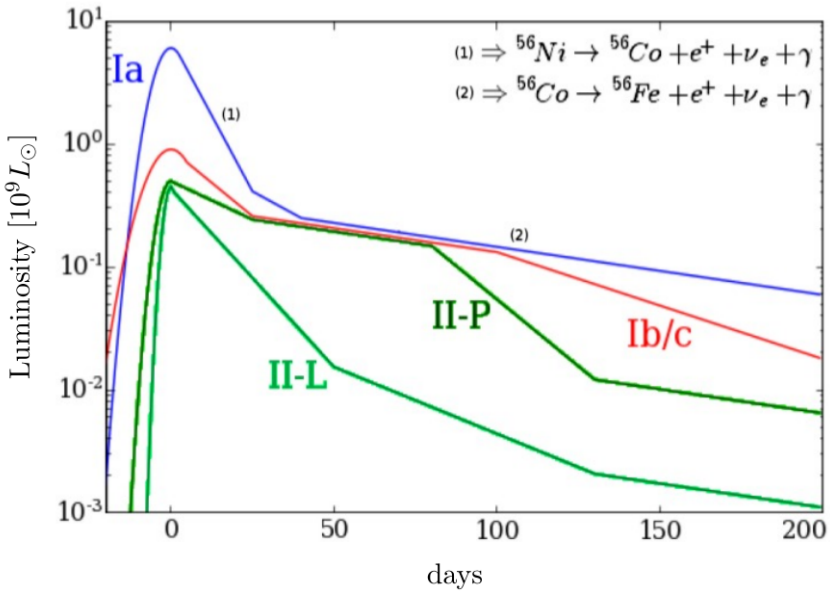
SN 2011fe

Supernovae have excellent standard candles properties

- Bright enough to be seen at cosmological distances
- Eventually fade away at some point so that they can be disantangled from the background
- Standard enough to produce meaningful d_L measurements

Good. But what are they ?

Clear facts

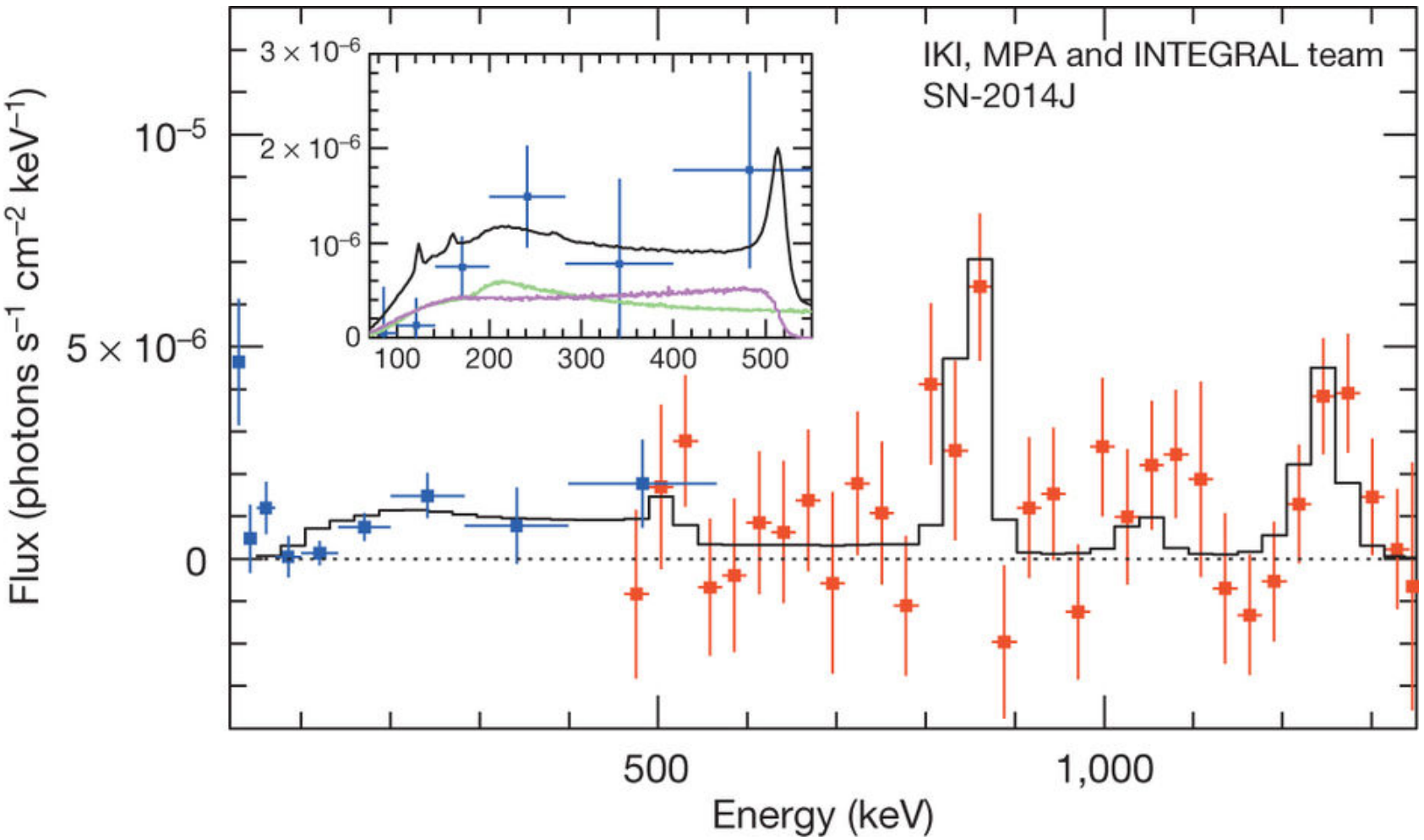


- Brightness is powered by the radioactive decay of $Ni^{56} \rightarrow^{\tau=6d} Co^{56} \rightarrow^{\tau=77d} Fe^{56}$
- Absence of H and He lines $\rightarrow$ degenerated stars
- Thermonuclear explosion of a $C + O$ white dwarf $M \sim 1.4 M_\odot$

Physics underlying explosion is still poorly understood

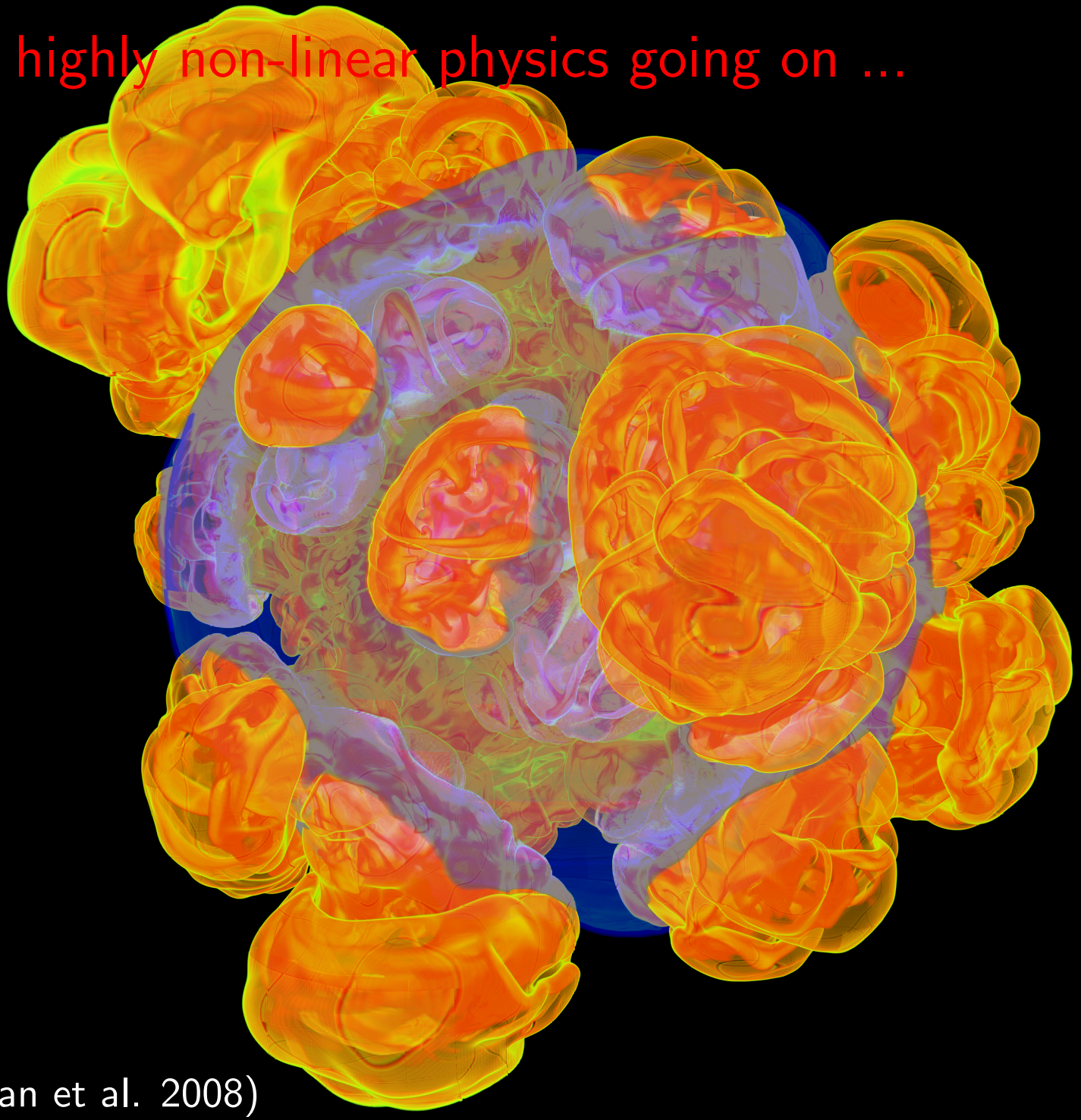
- Progenitor system ?
- Ignition mechanism ?
- Numerical modeling of the nuclear explosion of a whole star is a though job

Direct detection of cobalt lines by *integral* for SN2014J



Churazov et al. 2014

Lots of highly non-linear physics going on ...



(Jordan et al. 2008)

A working definition of Type-Ia Sne for the cosmologist

- A transient event
- Reach a maximum in band B about 10 days after explosion
- Has a B-V color at maximum comprised between -0.3 and 0.3
- Spectrum around maximum without H or He lines, but distinctive Si lines

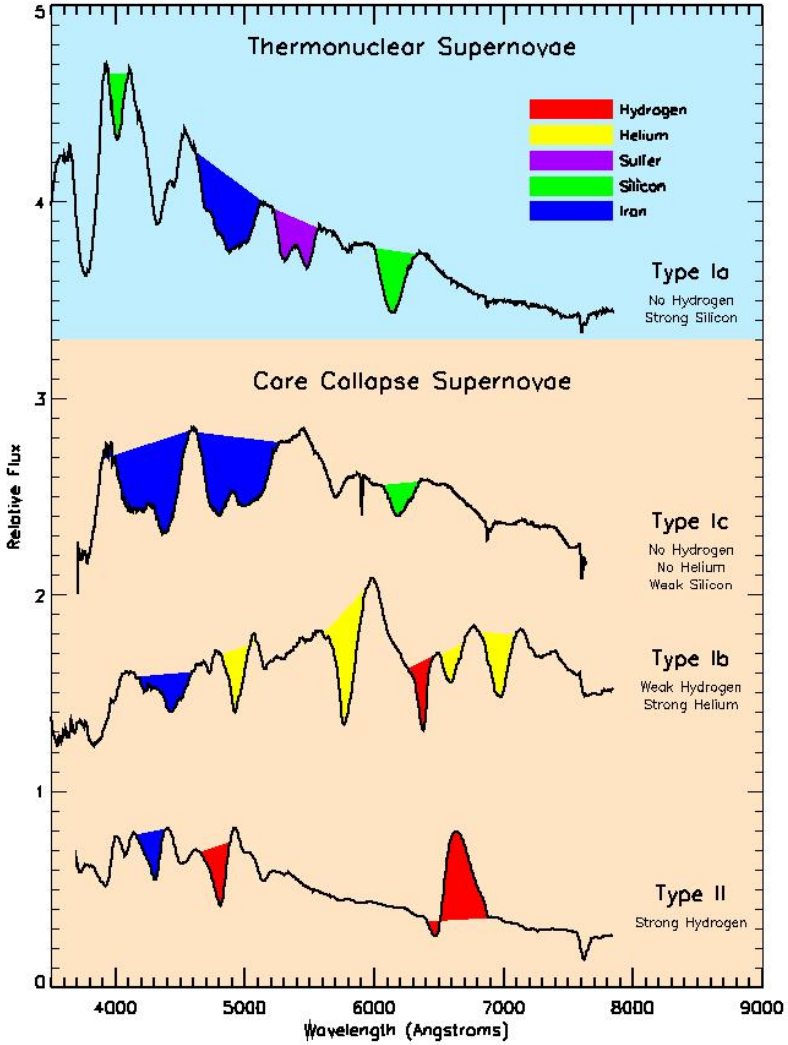
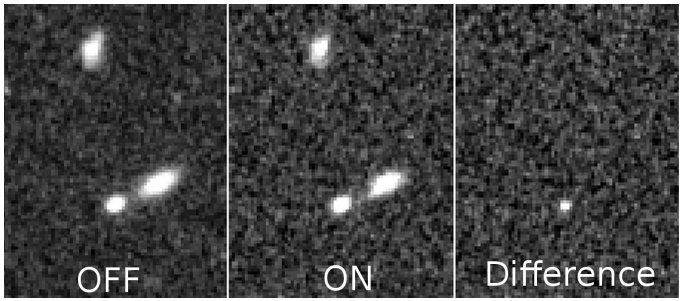


Fig. from Dan Kasen tutorial

Detecting SNe



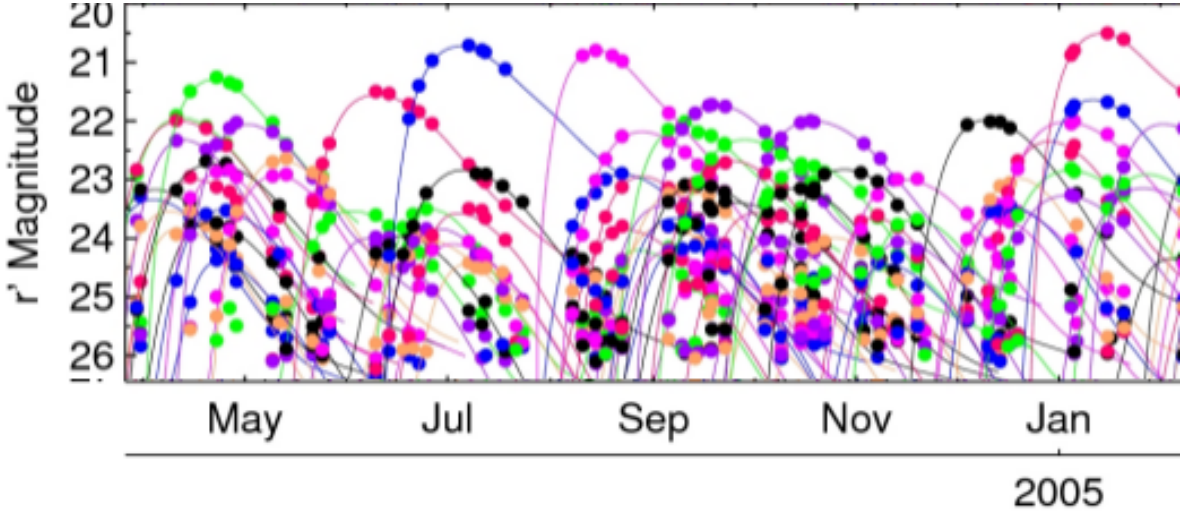
Take images of the same sky region at different epochs

- Transient pops out in the difference

But those events are rare

- $\sim 0.510^{-4} yr^{-1} Mpc^{-3}$

The rise of the rolling-search approach...

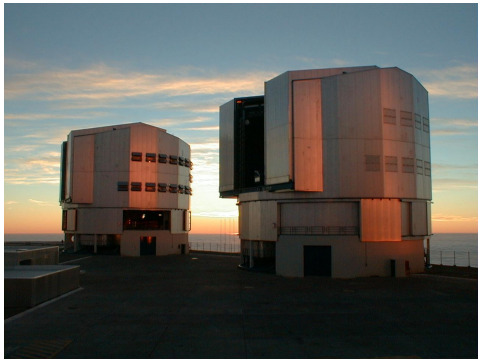


with large CCD matrices

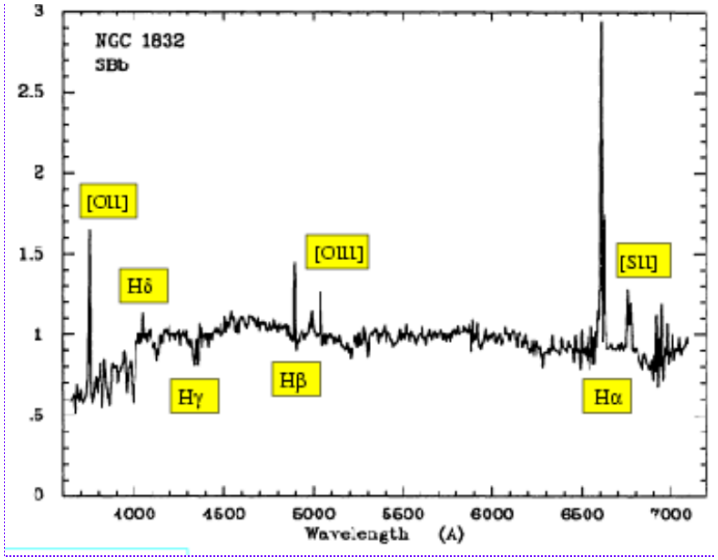
Redshift measurements

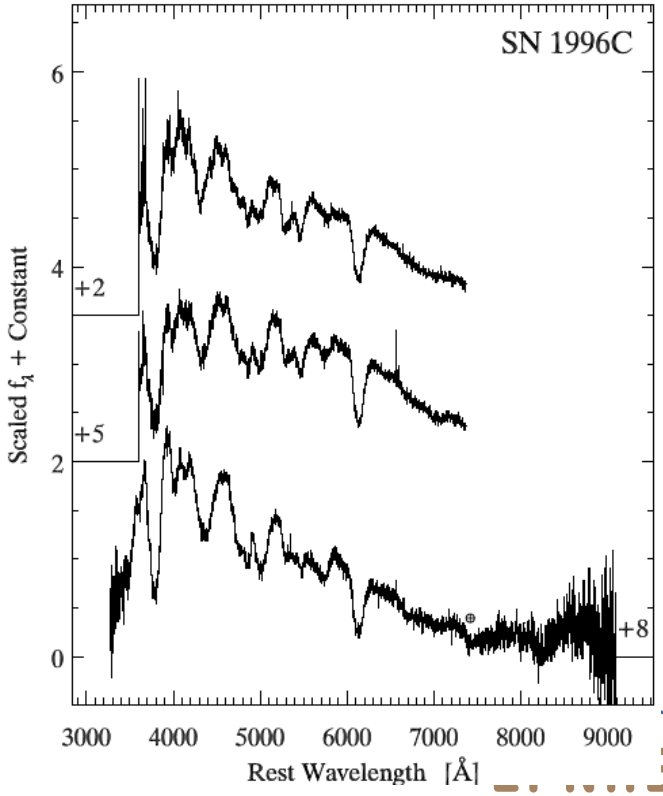
Live spectroscopy

- Host galaxy lines: $\rightarrow \delta z \sim 0.001$
- Supernova spectrum: Identification + $\delta z \sim 0.005$



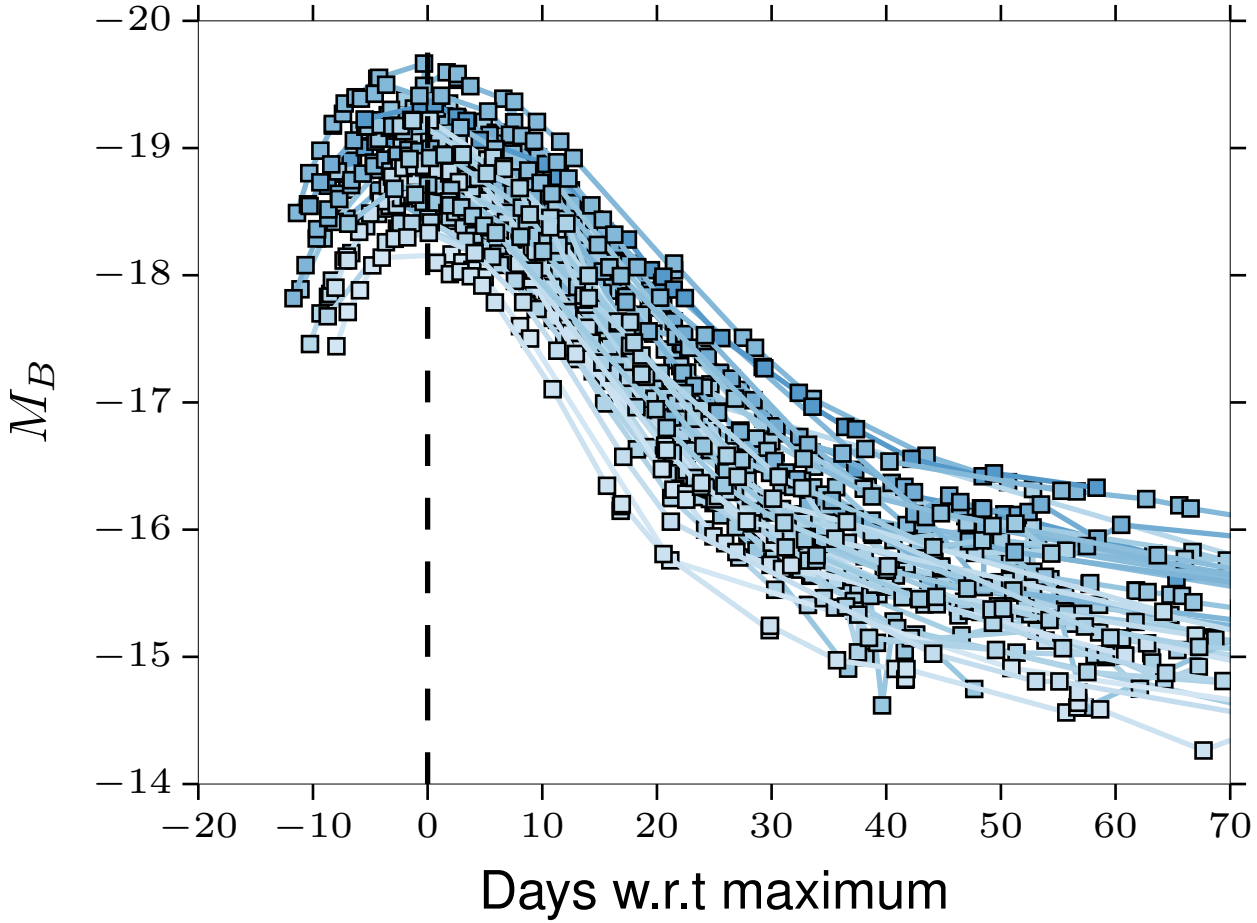
Measuring redshifts from galaxy spectra is precise





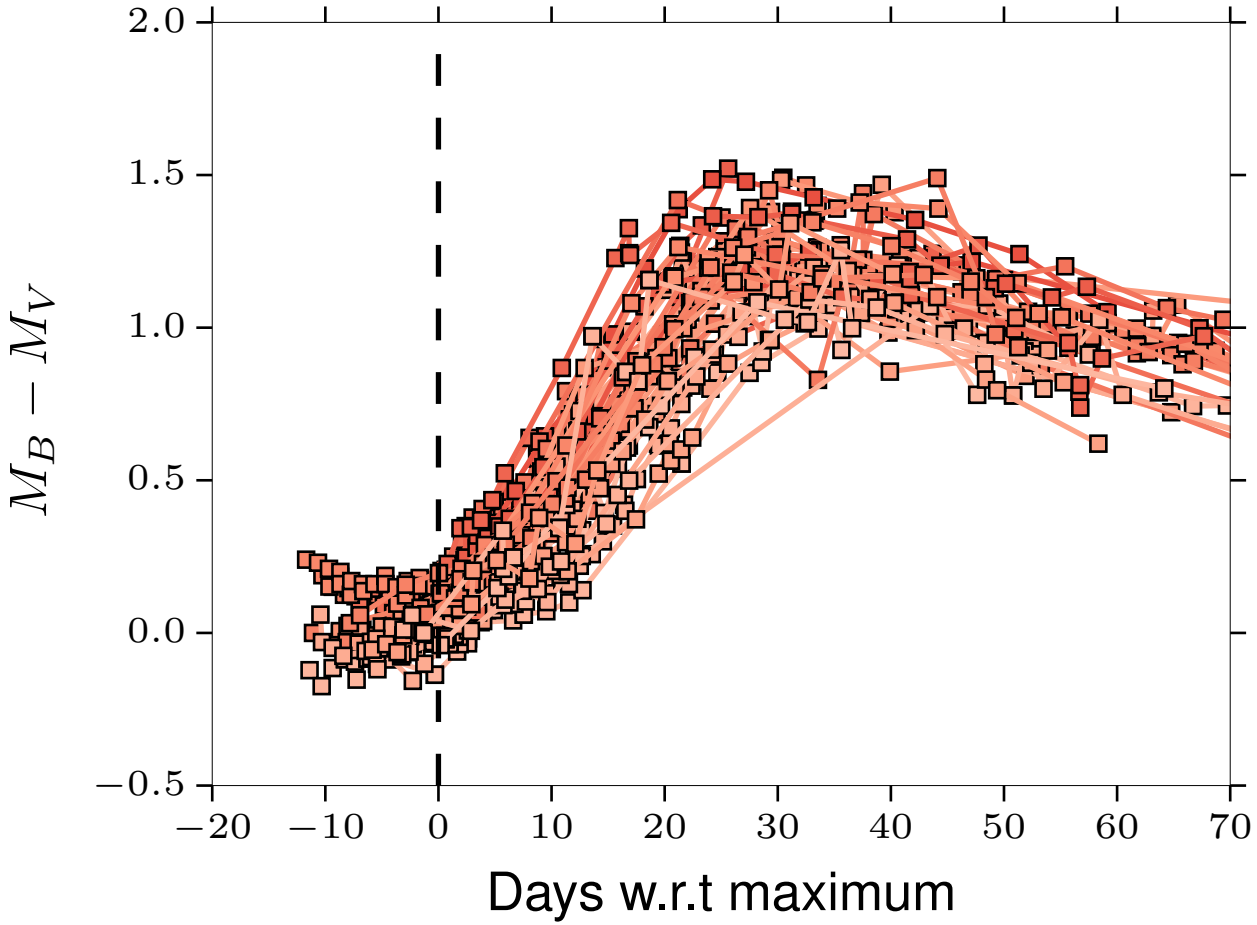
Spectrum from Blondin et al. 2011

Ligth-curves of low redshift supernovae



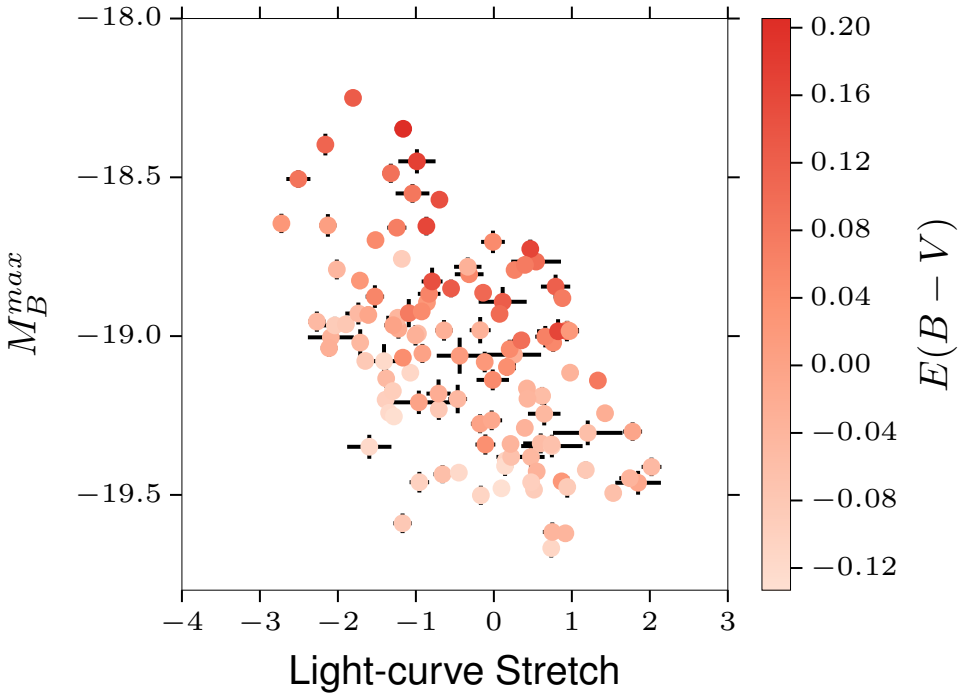
- Scaled and "stretched" versions of a single template
- A smooth interpolation enables the measurement of Peak brightness and light-curve "stretch"

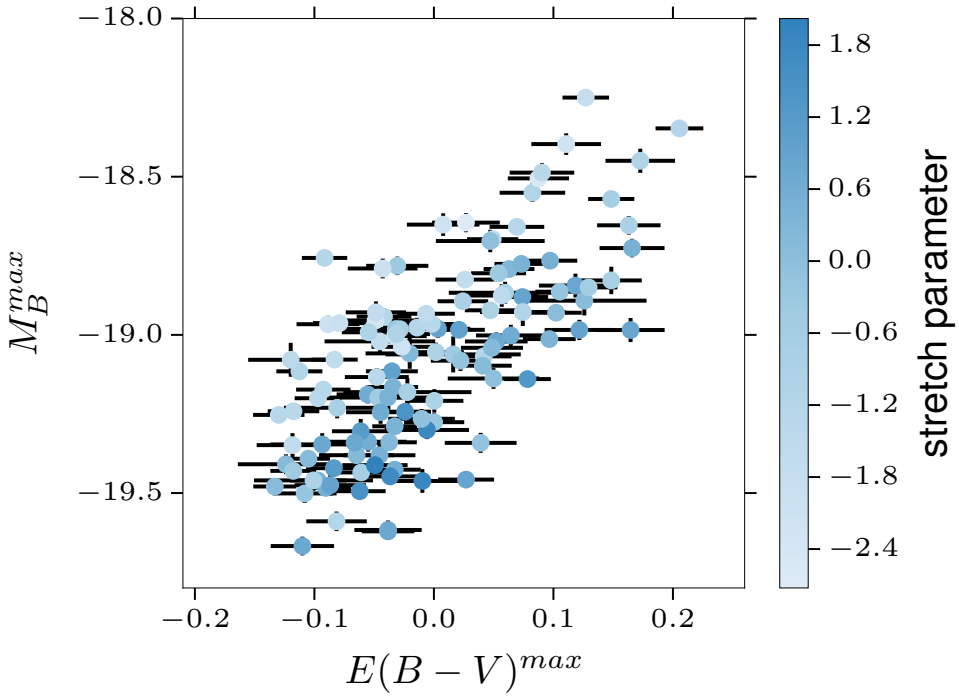
Colors



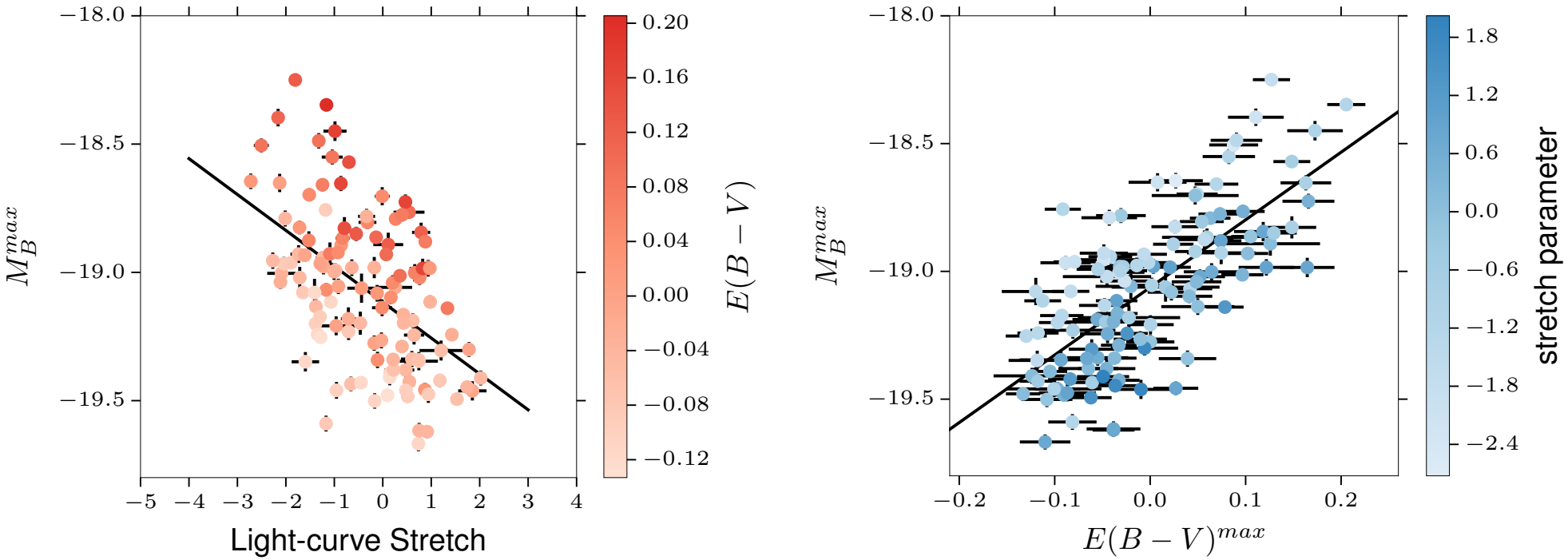
"scaled" version of a single template

Brighter-slower and Brighter-Bluer





Brighter-slower and Brighter-Bluer

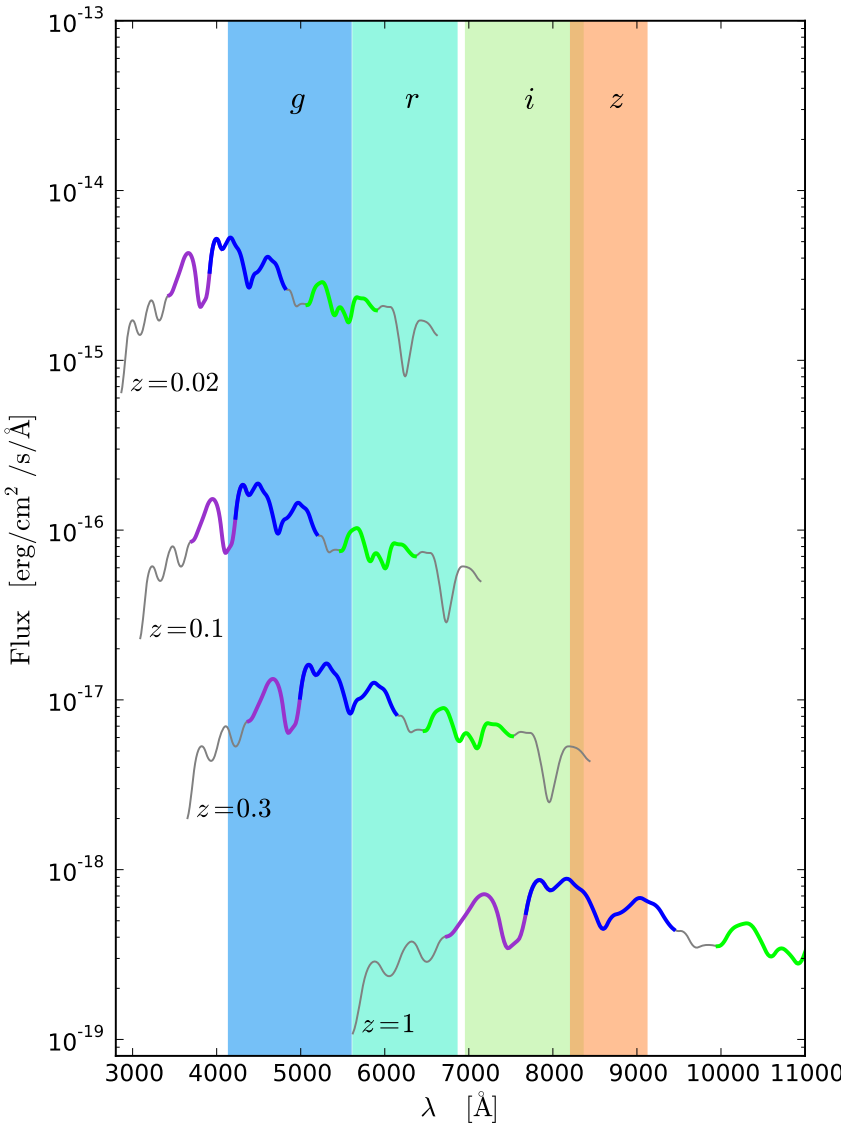


Fit linear relations (simultaneously) and construct:

$$M = M_B^{max} - \alpha s + \beta (B-V)^{max} \quad \rightarrow \quad \sigma(M_B) \sim 0.12$$

(Philips 1993, Tripp 1998)

How to do the same at higher redshift ?



- B at maximum, stretch, B-V are readily available at low redshift
- Different quantities are measured in fixed observer-frame passbands

That's where things get a bit technical, we need:

- A parametric model of $flux(t, \lambda)$ to interpret broadband measurements at random phases and z
- Precise intercalibration between bands

We'll come to that in the second lecture. Let's assume it is feasible.

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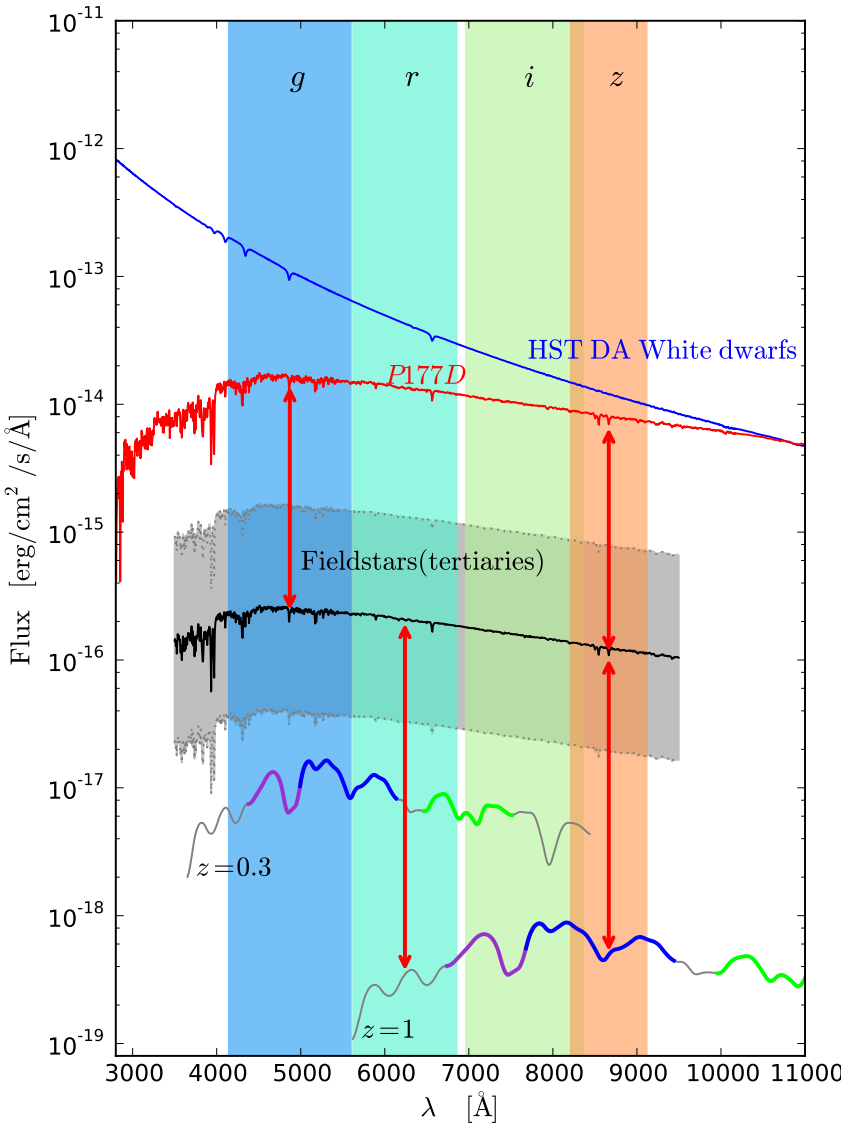

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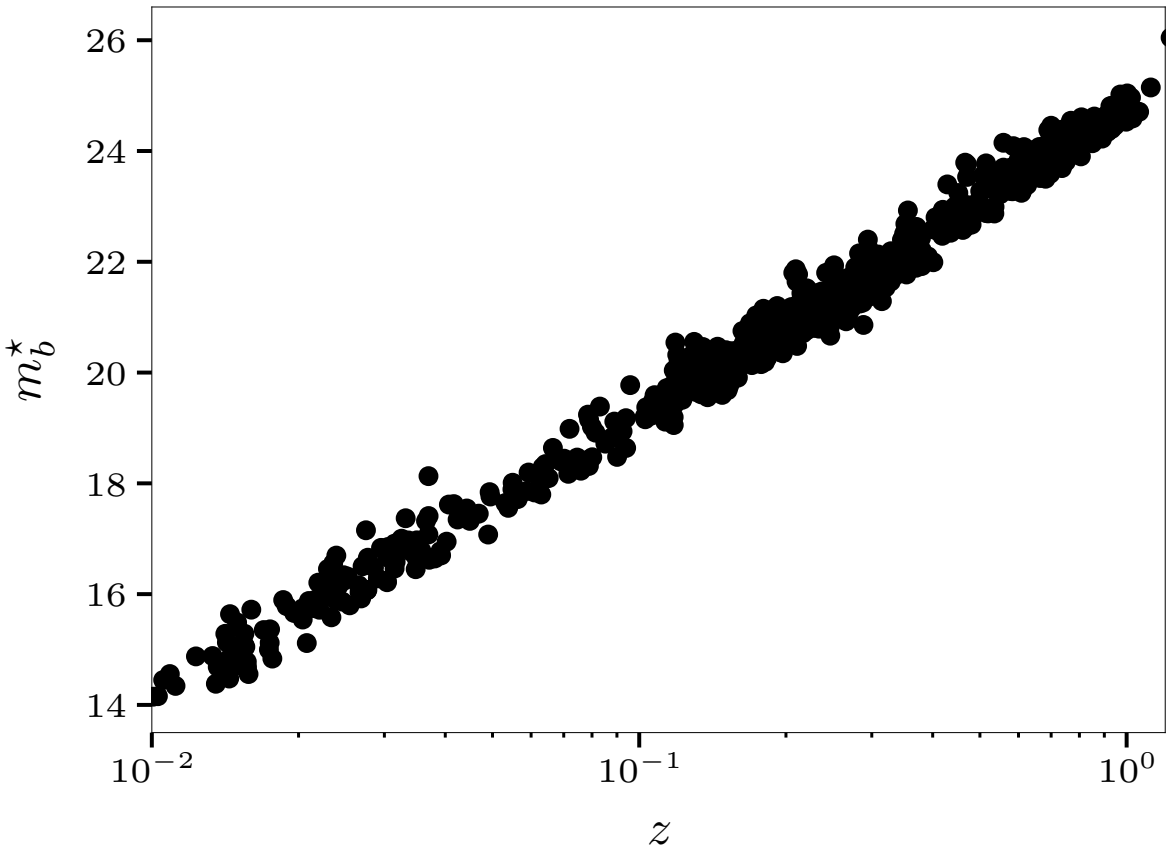
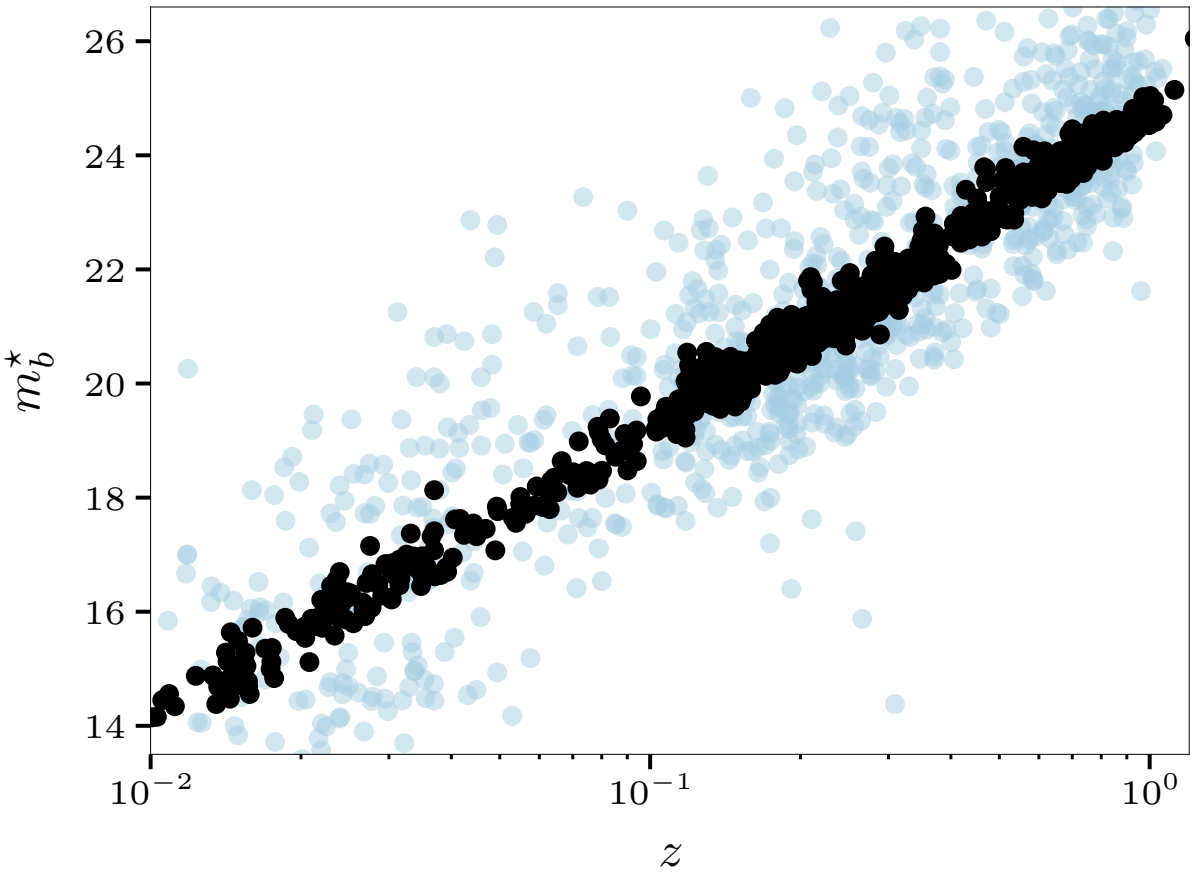
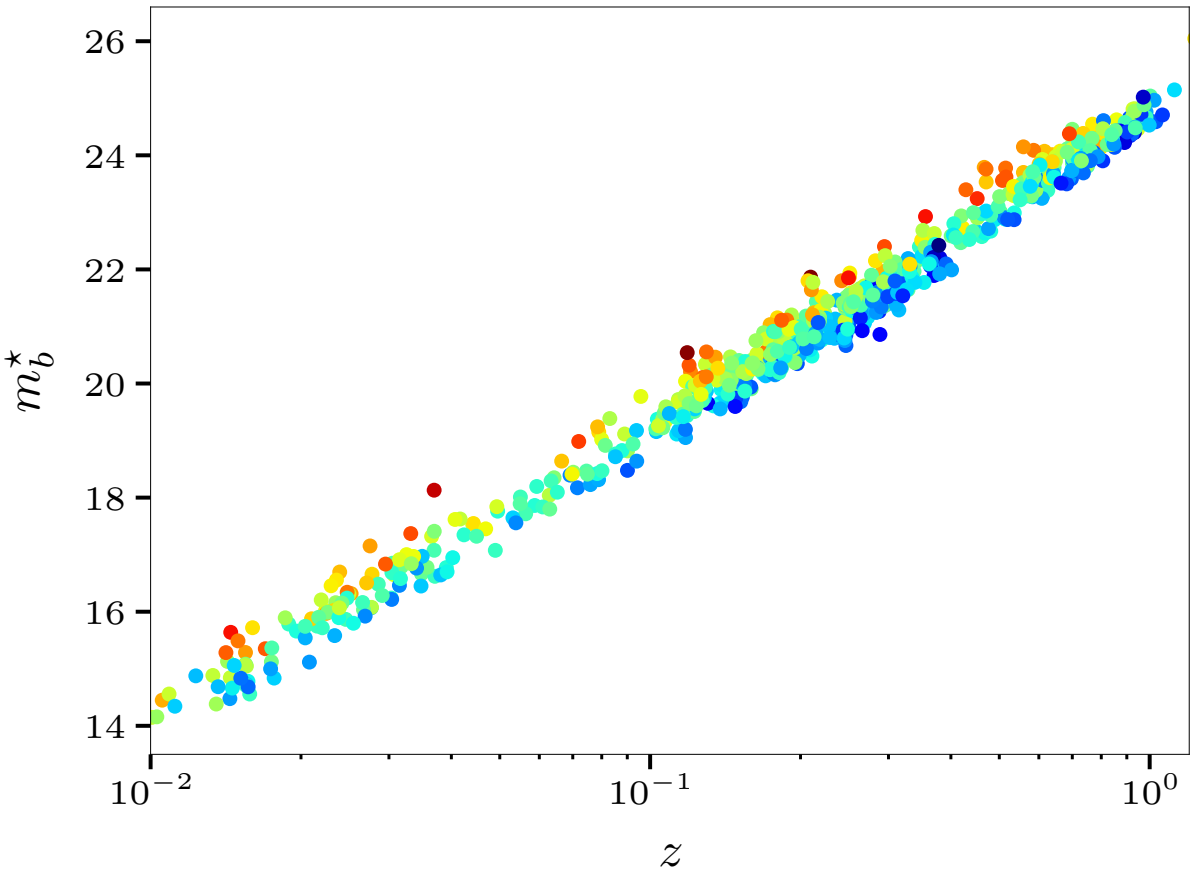
The raw Hubble diagram



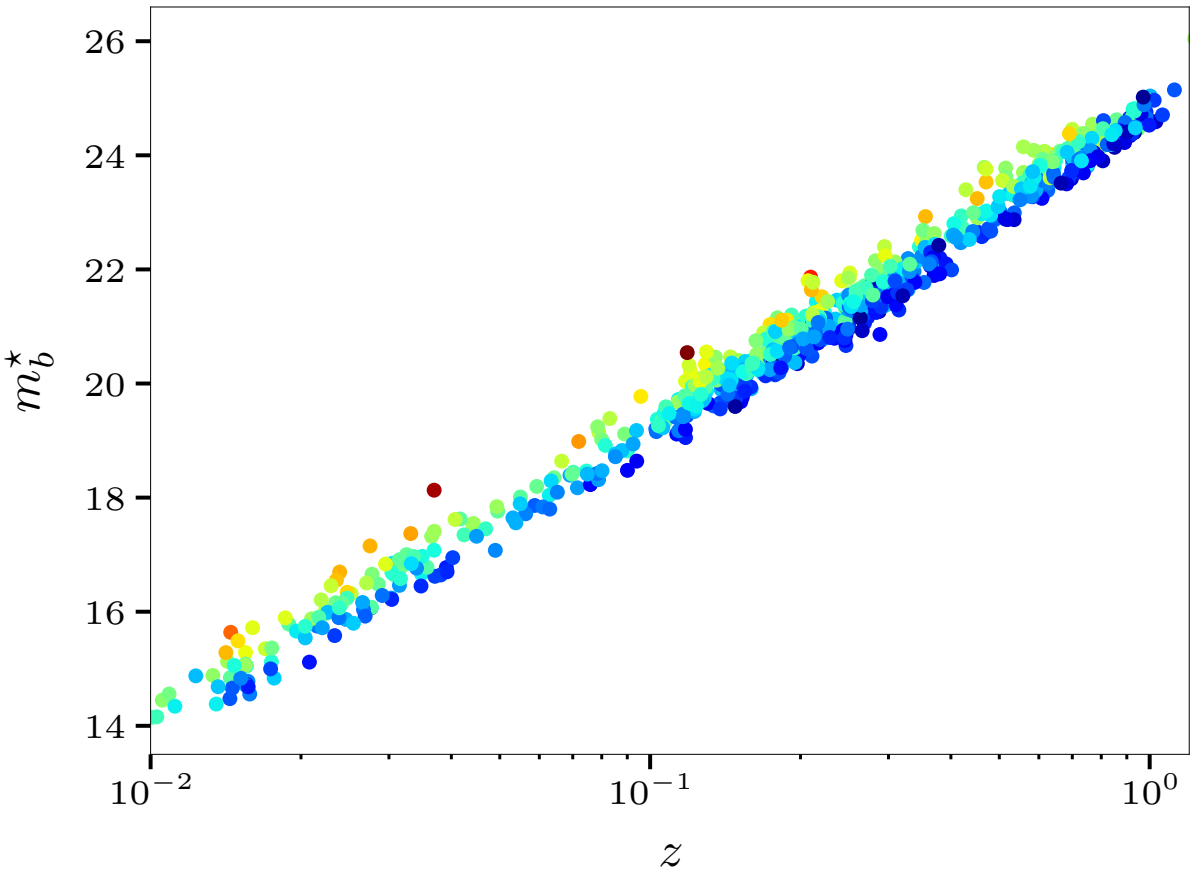
The raw Hubble diagram, compared to host luminosity



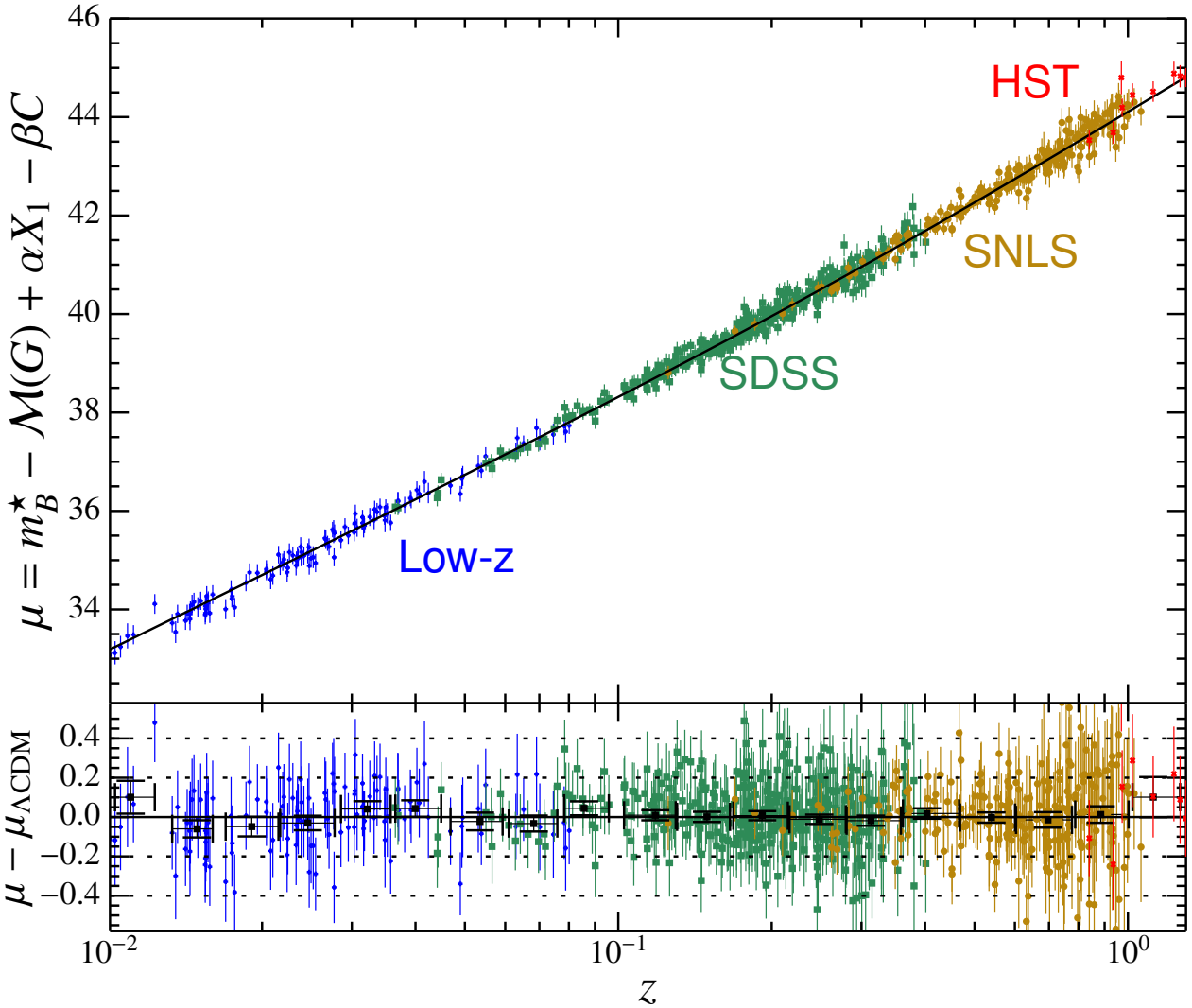
Color sorts this



Color and stretch combined do even better



The result



$$\mu(z) = 5\log_{10}(d_l) \approx m(z) - M = m(z) - (\mathcal{M}(G) - \alpha x_1 + \beta C)$$

Different surveys and instruments involved

What can we do with this measurement alone ?

$$d_L = \frac{(1+z)}{H_0\sqrt{|\Omega_k|}} \mathrm{Sin}\left(c\sqrt{|\Omega_k|} \int_0^z \frac{dz}{\sqrt{\Omega_m(1+z)^3+\Omega_k(1+z)^2+\Omega_X(1+z)^{3(1+w)}}} \right)$$

Keep in Mind that this is a relative measurement

- The brightness is not known a priori. We just assume it is constant.
- $$\frac{d_L(z_1)}{d_L(z_2)} = \frac{(1+z_1)\,\mathrm{Sin}\left(c\sqrt{|\Omega_k|} \int_0^{z_1} \frac{dz}{\sqrt{\Omega_m(1+z_1)^3+\Omega_k(1+z_1)^2+\Omega_X(1+z_1)^{3(1+w)}}} \right)}{(1+z_2)\,\mathrm{Sin}\left(c\sqrt{|\Omega_k|} \int_0^{z_2} \frac{dz}{\sqrt{\Omega_m(1+z_2)^3+\Omega_k(1+z_2)^2+\Omega_X(1+z_2)^{3(1+w)}}} \right)}$$
- No constraints on H_0 at all.
- It constrains the dynamical parameters through the expansion rate history.
- The parameter space probed depends on the redshift lever arm.

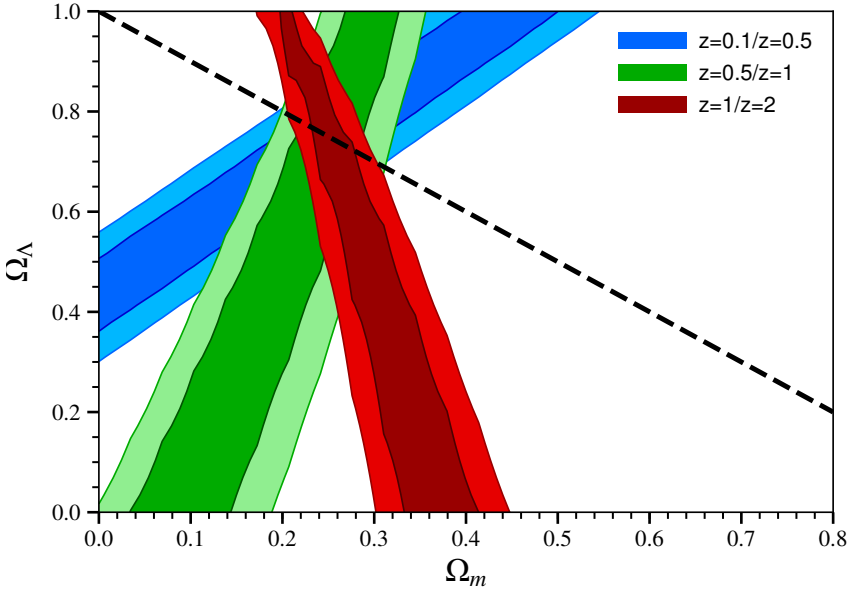
The parameter space probed depends on the probed z

$$\frac{d_L(z_1)}{d_L(z_2)} = \frac{(1+z_1)\,\mathrm{Sin}\left(c\sqrt{|\Omega_k|}\int_0^{z_1}\frac{dz}{\sqrt{\Omega_m(1+z_1)^3+\Omega_k(1+z_1)^2+\Omega_\Lambda}}\right)}{(1+z_2)\,\mathrm{Sin}\left(c\sqrt{|\Omega_k|}\int_0^{z_2}\frac{dz}{\sqrt{\Omega_m(1+z_2)^3+\Omega_k(1+z_2)^2+\Omega_\Lambda}}\right)}$$

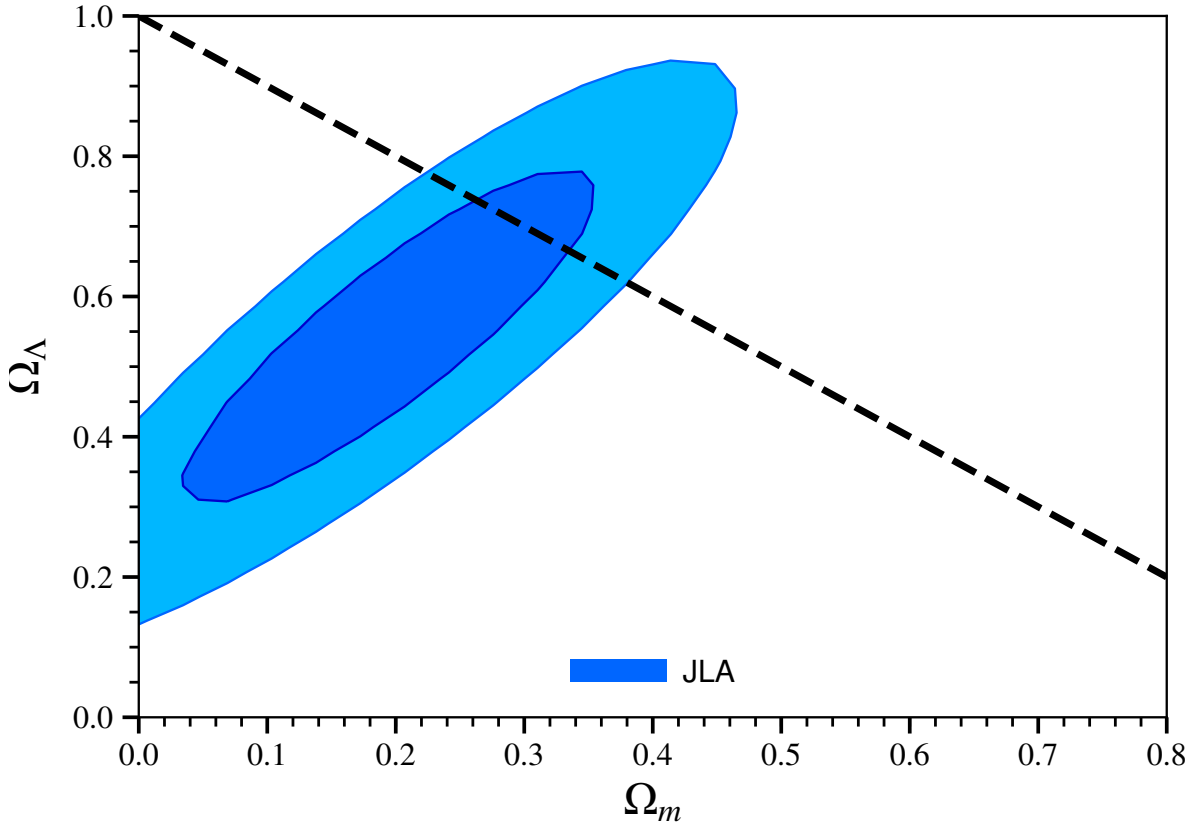
To illustrate that let us consider measurements of 3 distance ratios with equal precision (1.4%)

- $d_L(z=0.1)/d_L(z=0.5)$
- $d_L(z=0.5)/d_L(z=1)$
- $d_L(z=1)/d_L(z=2)$

And see how confidence contours evolves in the $\Omega_M - \Omega_\Lambda$ plane

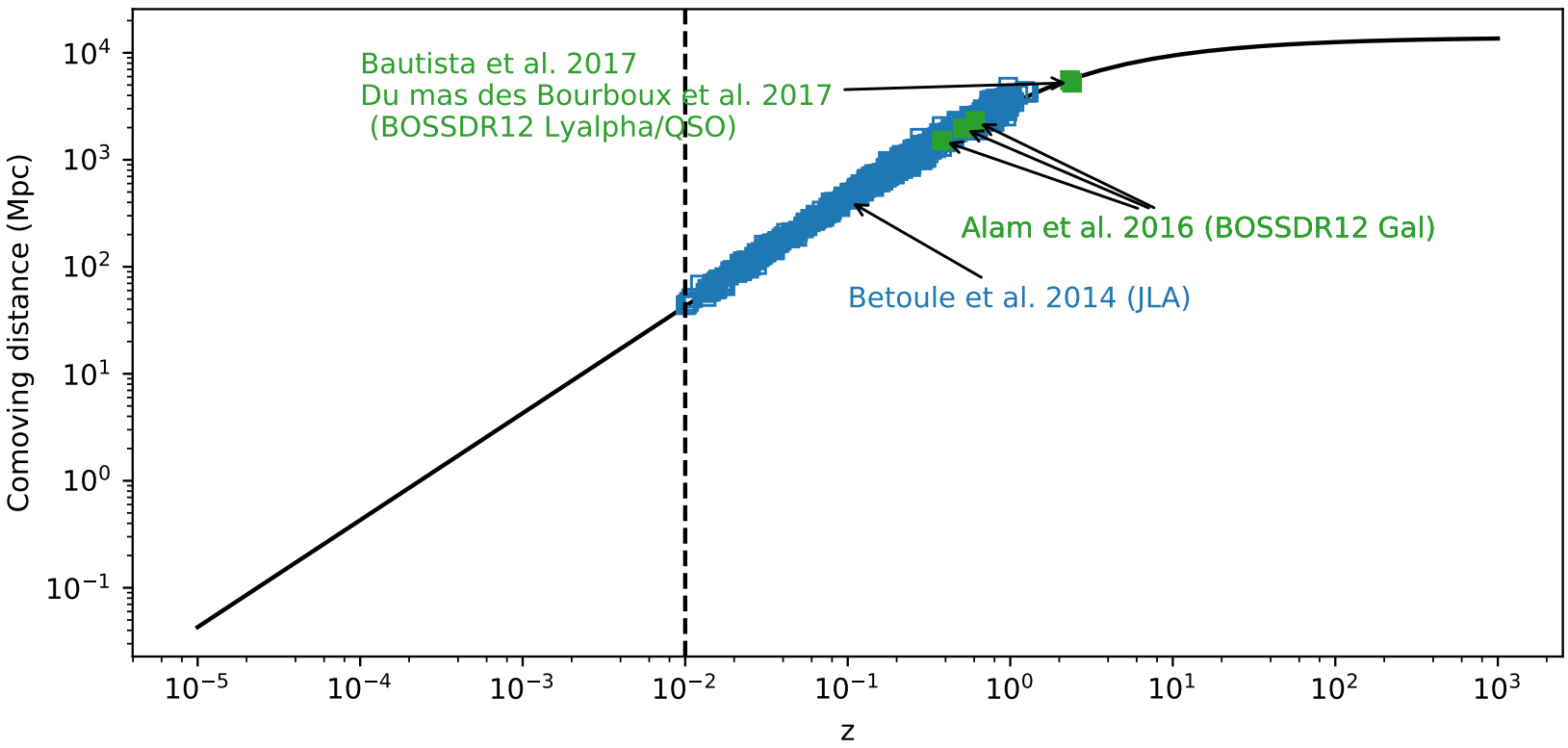


The synthetic view of constraints in the parameter space



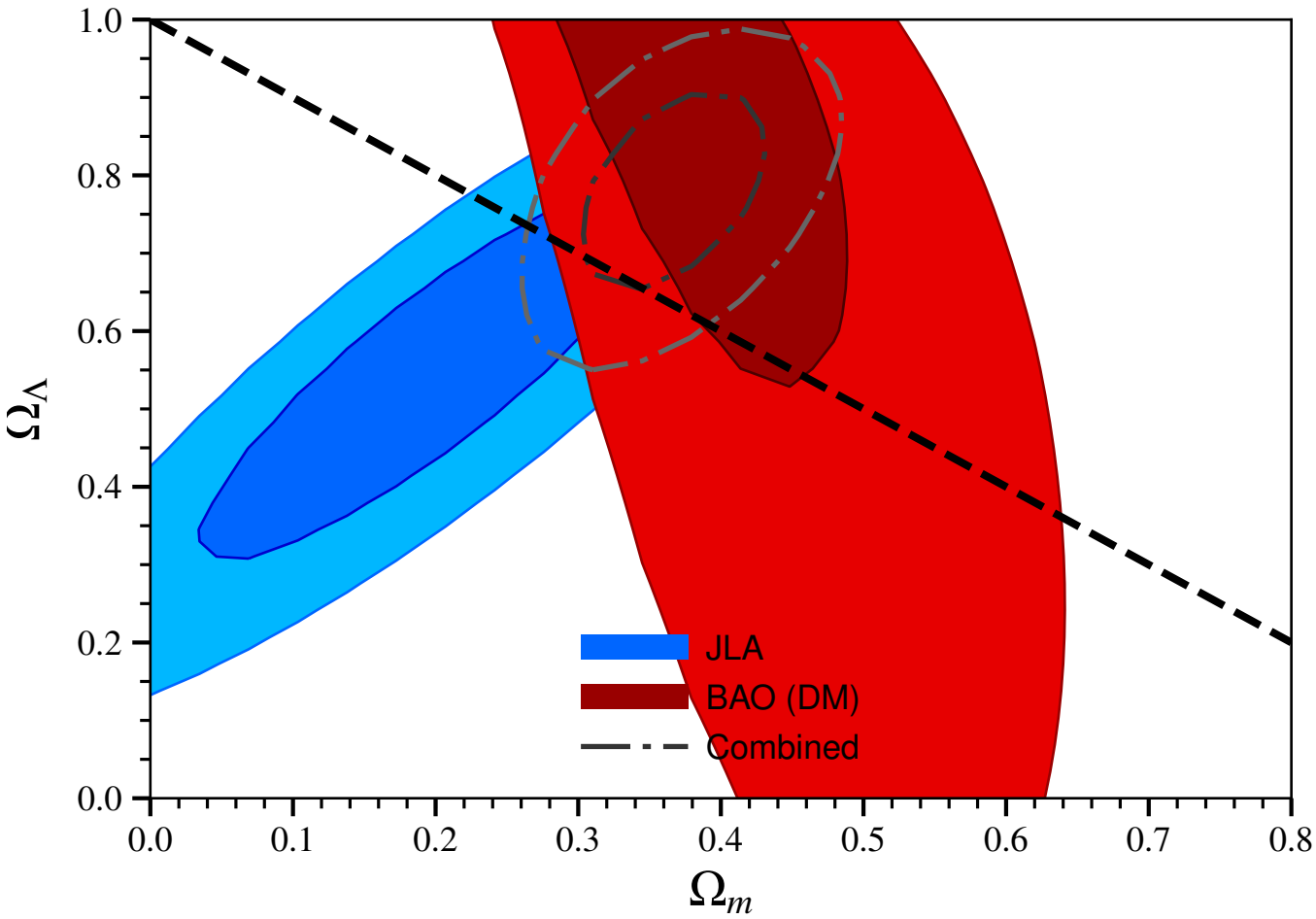
- Current supernova surveys efficiently probe the redshift range $0.05 < z < 0.7$. (For reasons detailed in next lecture)
- Therefore a large degeneracy remains
- $\Omega_M = \Omega_T = 1$ is very effectively ruled out.
- Assuming flatness calls for $\Omega_\Lambda \sim 0.7$.

Increasing the redshift lever-arm: The uncalibrated Hubble diagram SN+high-redshift BAOs distance measurement



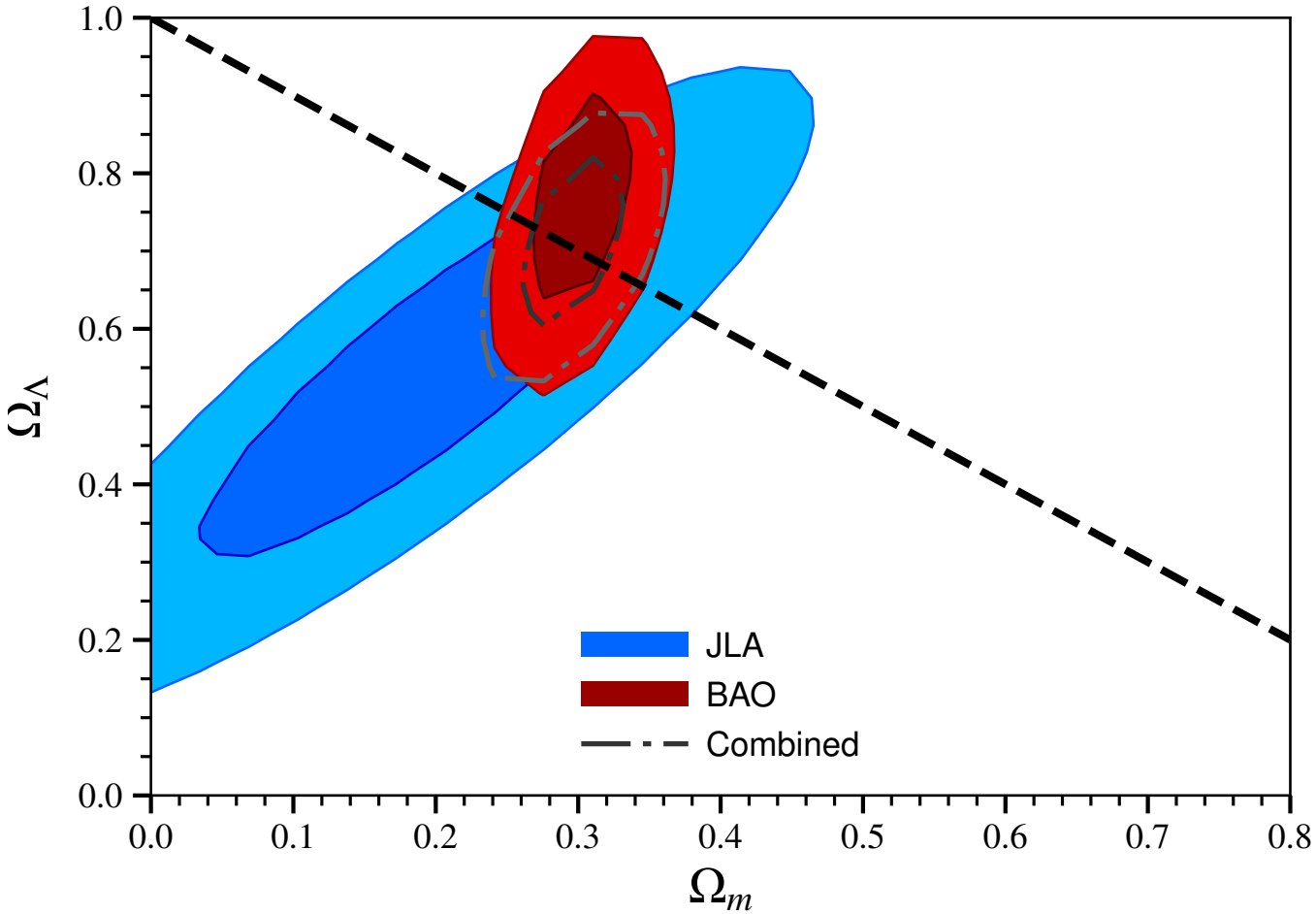
- Detection of the BAO in the Lyman-alpha forest (Busca et al. 2013) as extended the Hubble diagram up to $z > 2$

Considering only the BAOs angular distance measurement



- A purely geometric claim for dark energy

But BAO also probes directly H at different redshift



- Nowadays, observations of the BAO peak in different matter tracers alone very effectively constrains $\Omega_\lambda > 0$ (See Bautista et al. 2017)

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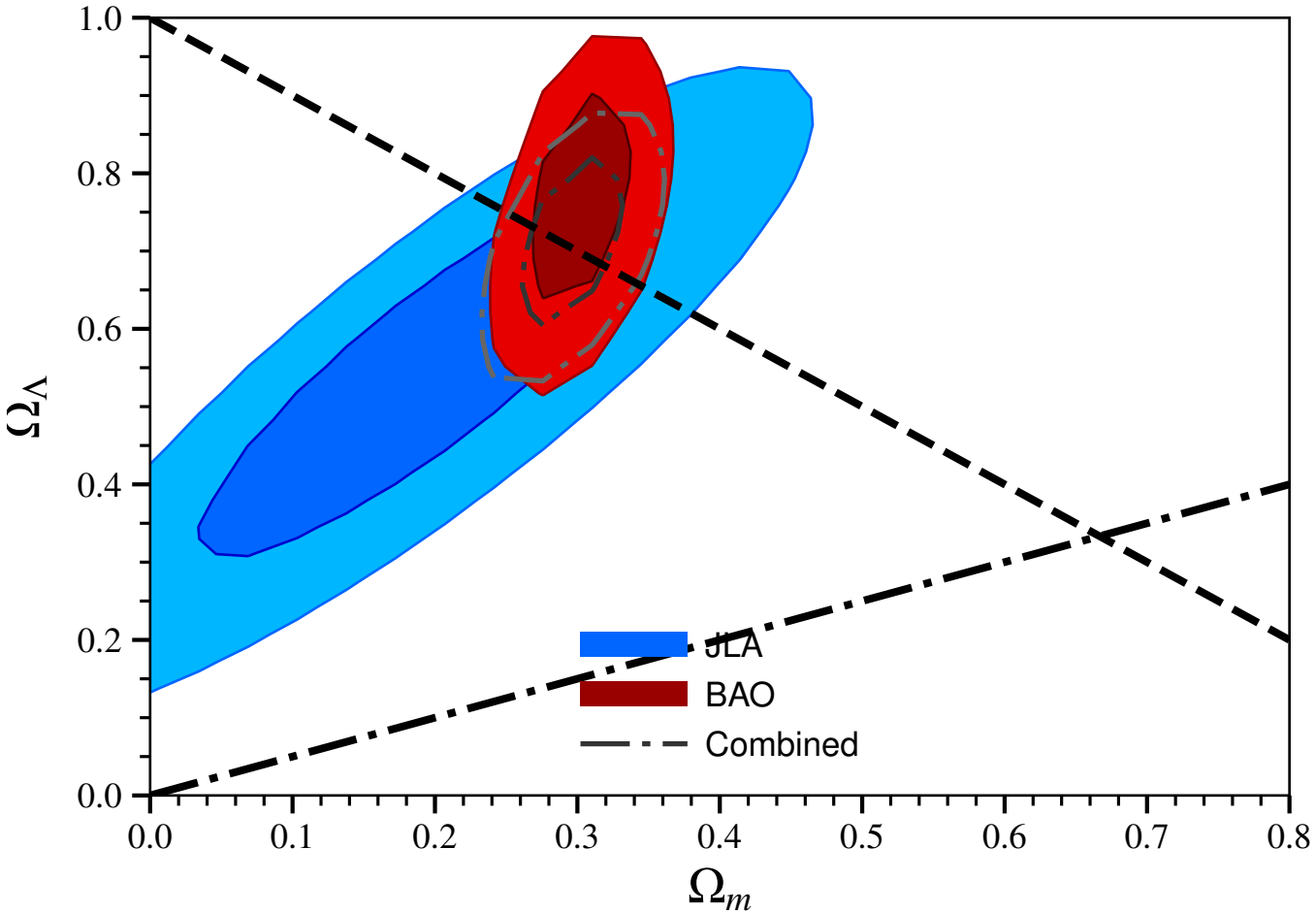
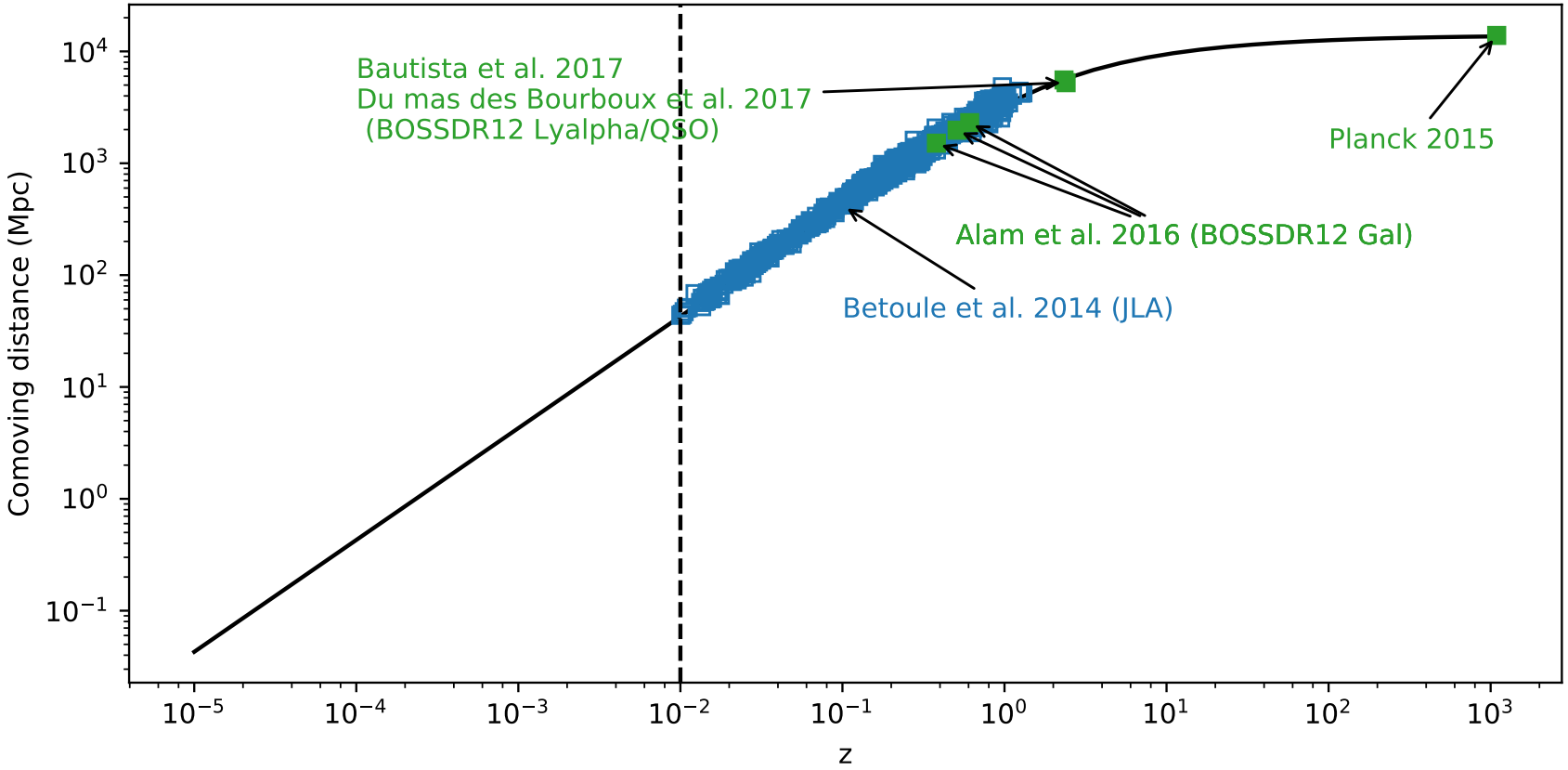


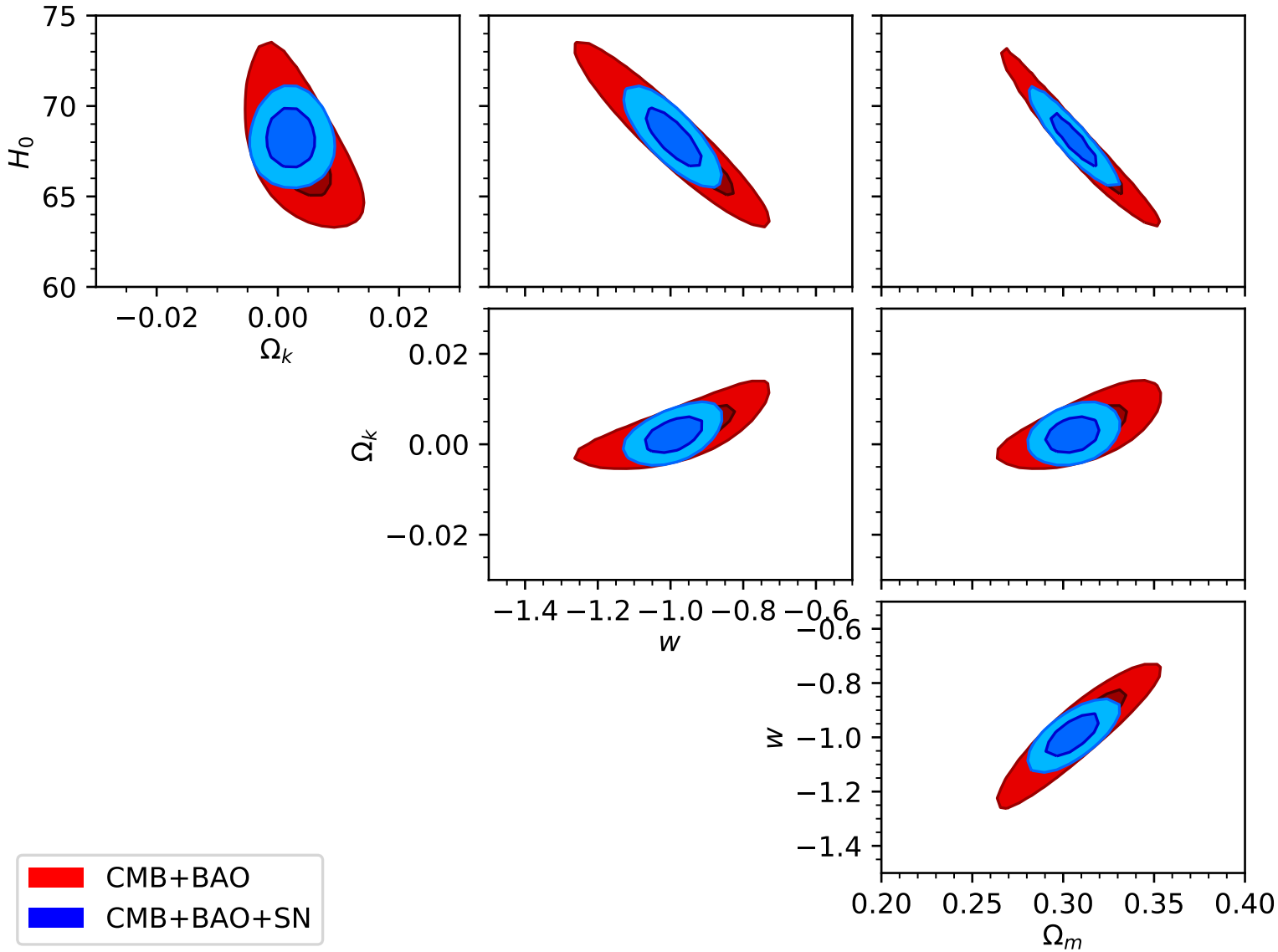
- Nowadays, observations of the BAO peak in different matter tracers alone very effectively constrains $\Omega_\lambda > 0$ (See Bautista et al. 2017)
- What about acceleration ($q_0 < 0$) ? See discussion on systematics in next lecture.

Combining probes to constrain the Dark Energy EoS

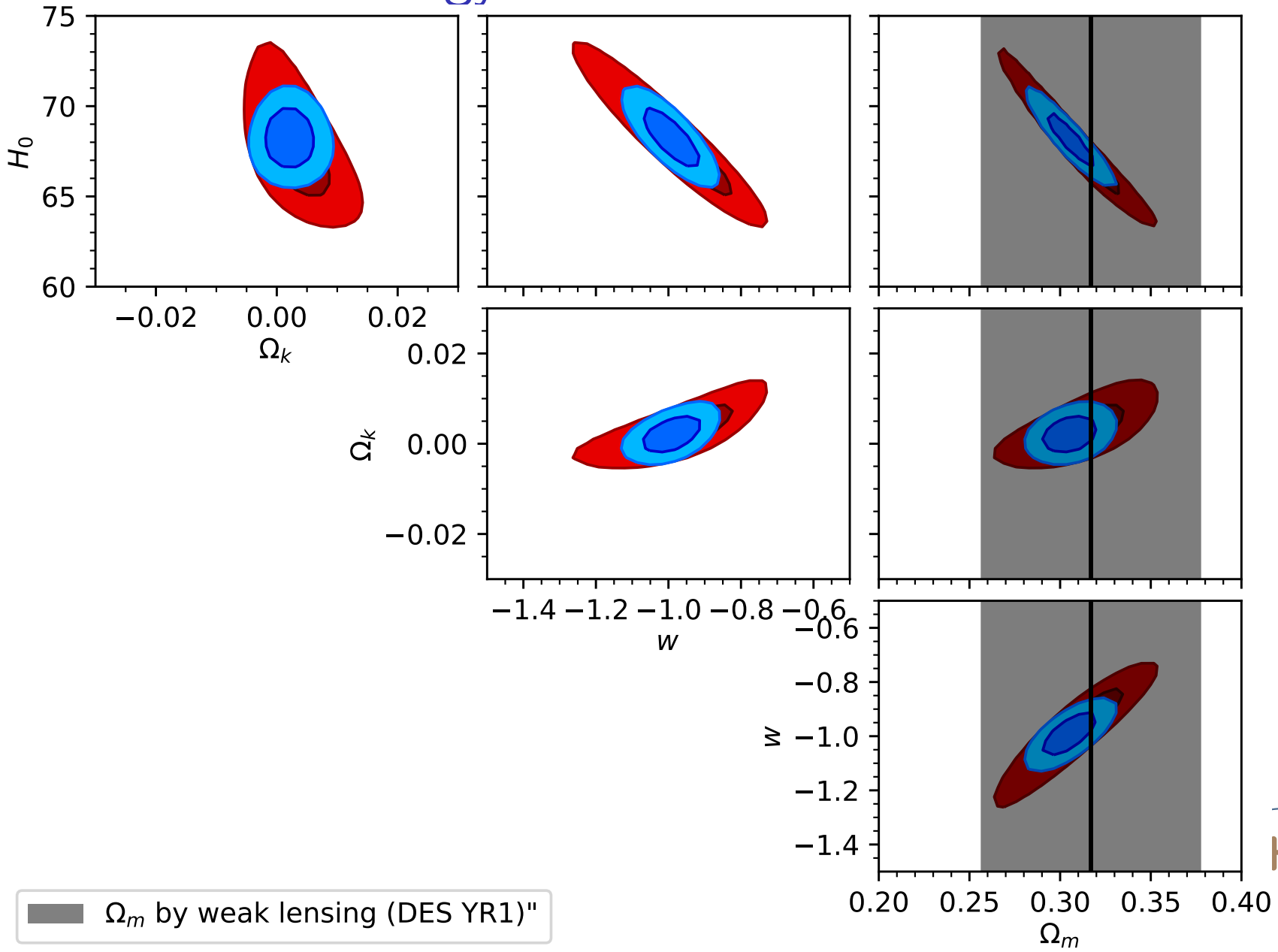


- The CMB measures r_d and $d_A(z \sim 1000)$
- Combination with BAOs extends distance measurement down to $z \sim 0.4$, locks Ω_M and curvature.
- Addition of supernovae to the above probes background evolution further in the dark energy dominated regime and provide model independant measurement of H_0.

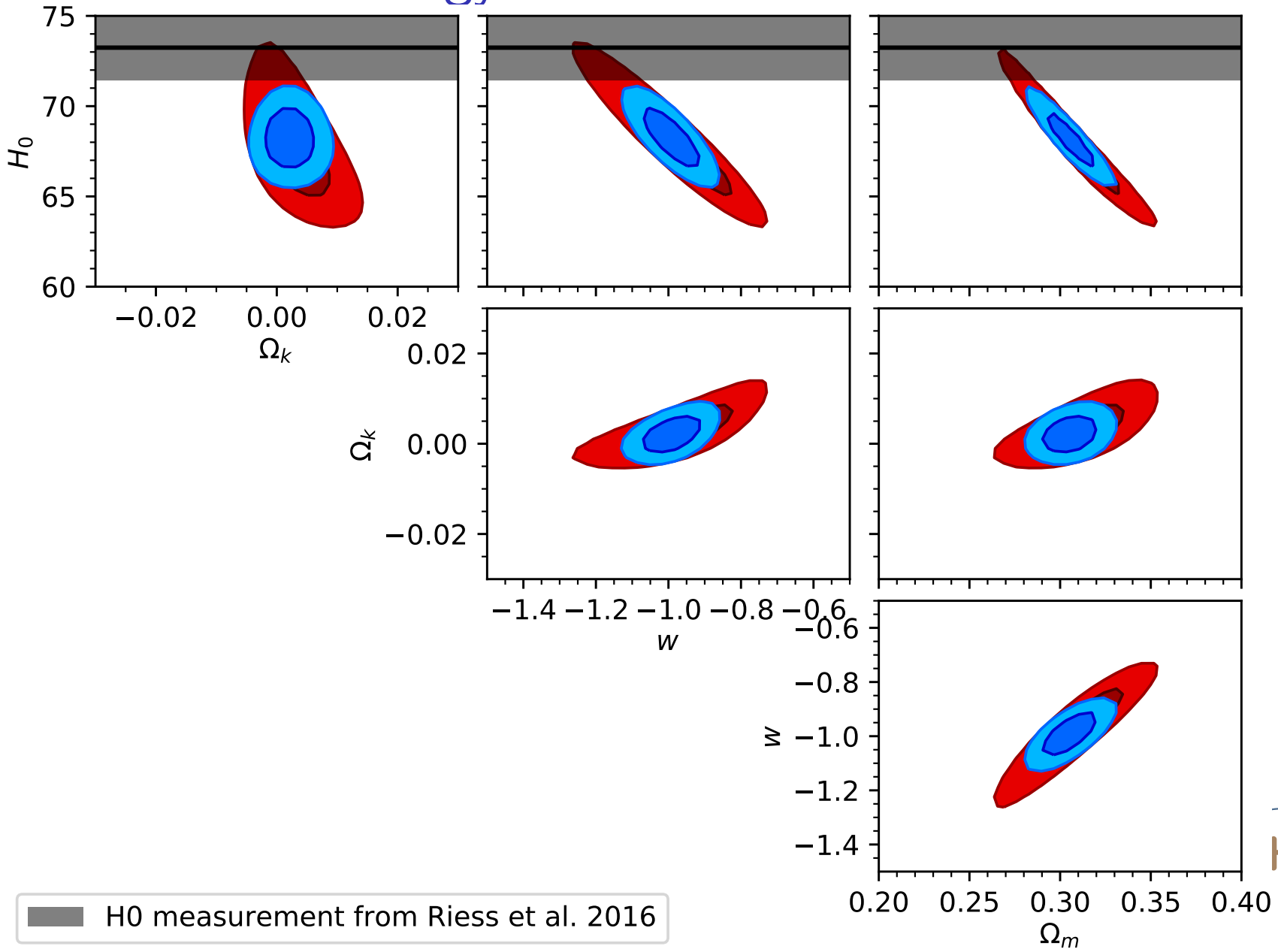
Combined constraints on Dark Energy Equation of states from the inverse distance ladder



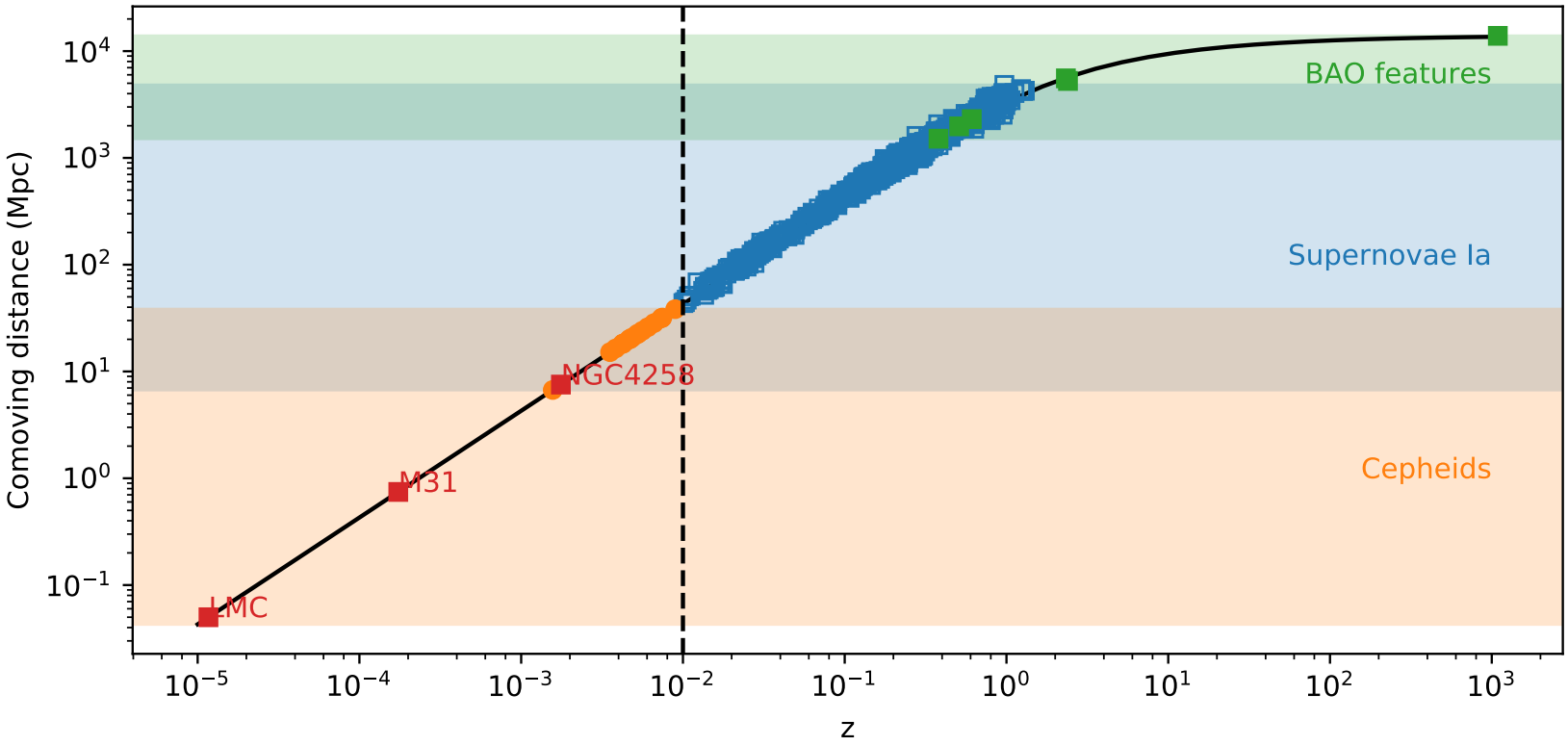
Concordance cosmology



Concordance cosmology ?



The Direct and inverse Distance Ladder



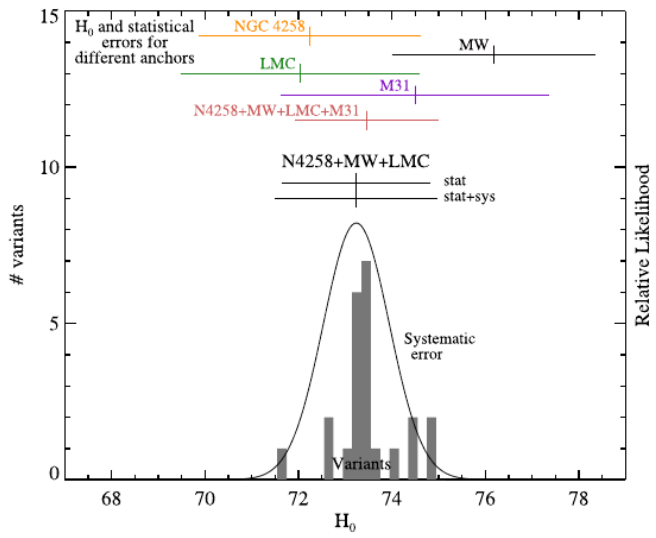
- The Cepheid+SNe+BAO distance measurements link together 2 competing scale references independently of a DE model:
  - The geometrical measurements leading to absolute distance for cepheids
  - The CMB constrained early universe physics leading to a value for sound horizon at the drag epoch $r_d = \int_{z_d}^{\infty} dz \frac{c/\sqrt{3(1+3\rho_b/4\rho_\gamma)}}{H(z)}$

The competing scales

The "discrepancy" to get from $H_0 = 73.24$km/s/Mpc to ~ 68km/s/Mpc represents:

- a 7.7% increase in the cepheid distance or
- a 7.7% decrease in r_d or
- a .16 mag jump/slope in the luminosity scale

Geometrical anchors



Riess et al. 2016

Sound horizon

CMB independent (beside T_{cmb}) determination of r_d from BAO plus deuterium abundance

Parameter	BAO+D/H (theoretical)	BAO+D/H (empirical)	*WMAP* 9-year	*Planck* 2016
$100\Omega_b h^2$	2.156 ± 0.020	2.257 ± 0.034	2.265 ± 0.049	2.215 ± 0.021
$100\Omega_c h^2$	10.94 ± 1.20	11.19 ± 1.29	11.37 ± 0.46	12.07 ± 0.21
$100\theta_{\rm MC}$	1.0292 ± 0.0168	1.0320 ± 0.0173	1.04025 ± 0.00223	1.04076 ± 0.00047
H_0 [km s^{-1} Mpc^{-1}]	66.98 ± 1.18	67.81 ± 1.25	69.68 ± 2.17	66.89 ± 0.90
Ω_m	0.293 ± 0.019	0.293 ± 0.020	0.283 ± 0.026	0.321 ± 0.013
r_d [Mpc]	151.6 ± 3.4	149.2 ± 3.6	148.49 ± 1.23	147.16 ± 0.48

see Adisson et al. 2017

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Scrutinizing the luminosity scale

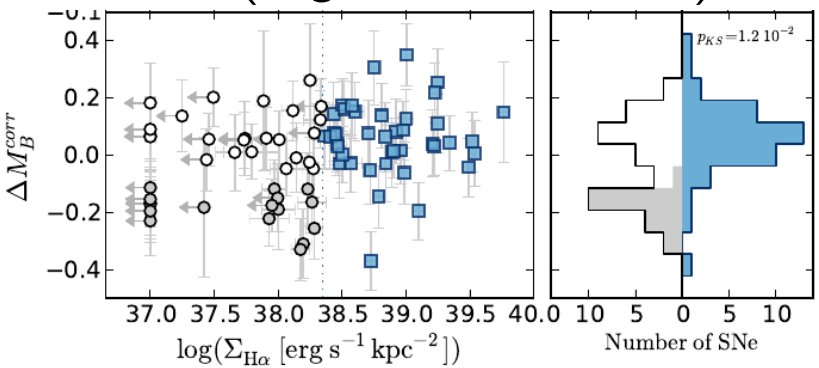
.16 mag is a lot but what about transforming $\sim 3\sigma$ discrepancy into a $\sim 2\sigma$ agreement ?

Selection bias in the SNe Ia calibration sample:

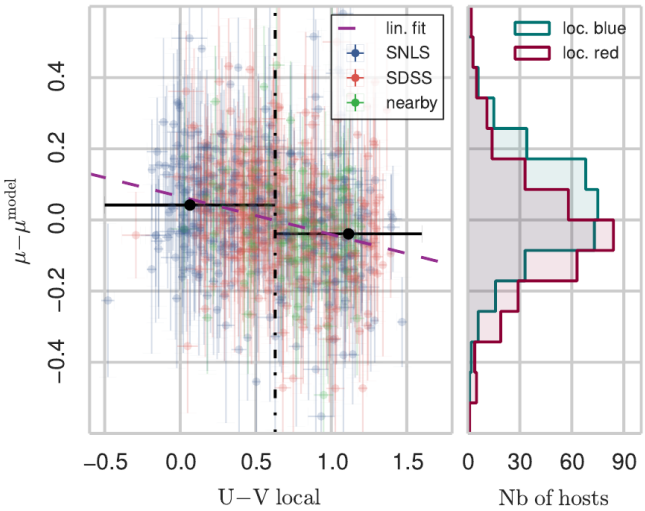
- The calibration sample is biased because of cepheid requirement
- Having cepheids implies young active galaxy
- SNe more likely to originate from a young environment

Supernovae in young active env. are .09mag fainter than mean

3σ in SNF (Rigault et al. 2014)



7σ in SNLS (Roman et al. 2017)



The impact of this effect on H_0 measurement is still controversial

- Rigault et al. 2015 claims that it solves the discrepancy
- Riess et al. 2016 see no relevant effect in his sample
- Discarding SNe from passive galaxies to make the Hubble flow and calibration sample similar makes no difference
- An independant check is waited

Summary

Probing the Friedmann background dynamical parameters

- The Hubble diagram (relation between distance and redshift) is a primary probe of the Background evolution
- Type Ia supernovae are:
  - frequent enough to efficiently probe redshifts above 0.01
  - bright enough to go as far as $z \sim 1$ with current instruments (see next lecture for prospects)
- They cover more than 2 orders of magnitude in distance and overlap with both cepheids and BAO

Standard candle properties are mostly empirical constatations

- Modelisation provides rough understanding of observed properties
- Precise standardisation is obtained from the data themselves
- Feasability of this relies on diversity in redshift slices
- The standardisation is excellent ($\sigma \sim 0.12$ mag)
- But not perfect (leaves room for evolution systematics)

Summary

Concordance cosmology

- Current supernovae data are in agreement with the flat ΛCDM model from Planck
- Despite the historical importance of the SNe+Flatness measurement strongest support for Dark Energy comes from Planck+BAO
- Supernovae remain the main probe of the dark-energy dominated area
- In combination with CMB and BAO data they provide a 5% measurement of the Dark Energy Equation of state parameter (without assuming flatness)
- The combination also provide a relatively model independant "reverse" measurement of H_0
- That can be compared to the "direct" measurement obtained by calibrating the SNe luminosity

OUTLINE

I^{st} Part: The Big Picture

1. The Friedmann-Lemaître Universe
2. Type Ia supernovae as standard candles (hygienic version)
3. Constraints from current data
4. Summary

2nd Part: State of the Art

5. Measurement principles
6. Origin of Limitations and Improvement Prospects in Forthcoming Survey
7. Summary

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Reminder

We need to be able to:

1. Detect SNe Ia
2. Measure their redshift
3. Measure their apparent flux
   - As a function of time to get a good measurement of "maximum" brightness and "stretch"
   - In several bands to get a color

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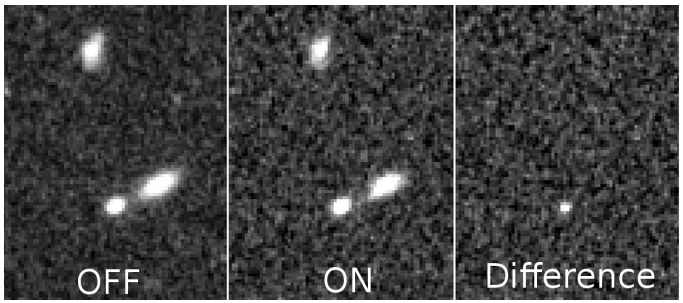
Reminder: Detecting SNe



Take images of the same sky region at different epochs

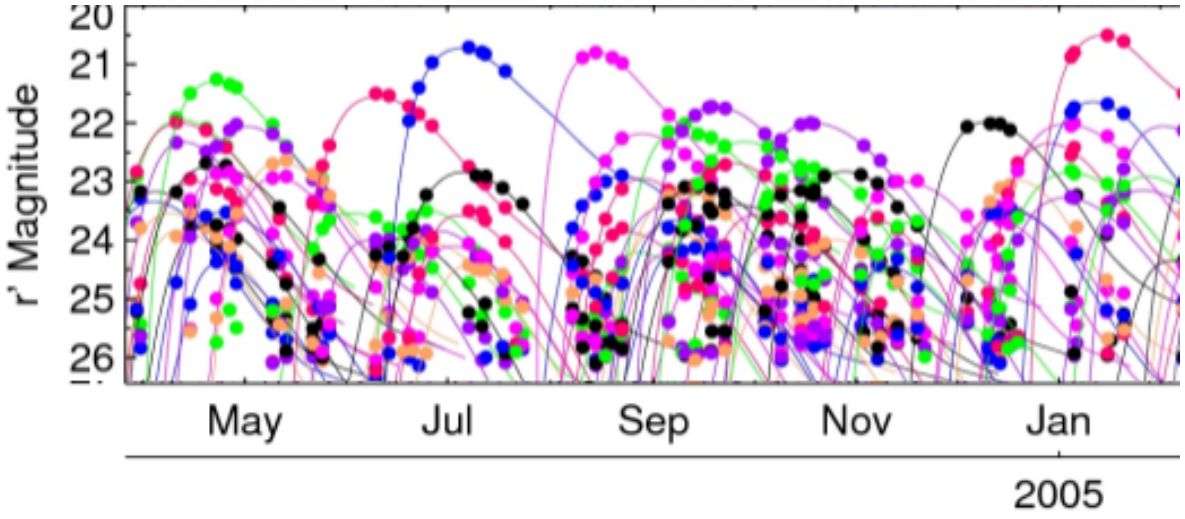
- Transient pops out in the difference

But those events are rare

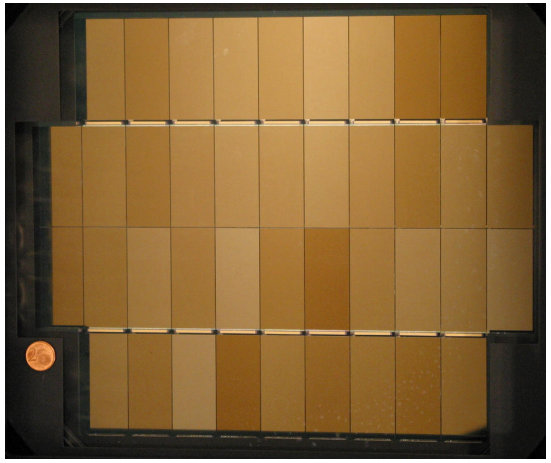
- $\sim 0.510^{-4} yr^{-1} Mpc^{-3}$
- Probing a large volume is mandatory

Finding SNe Ia efficiently: A key technology

The rise of the rolling-search approach...



with large CCD matrices



Requirements

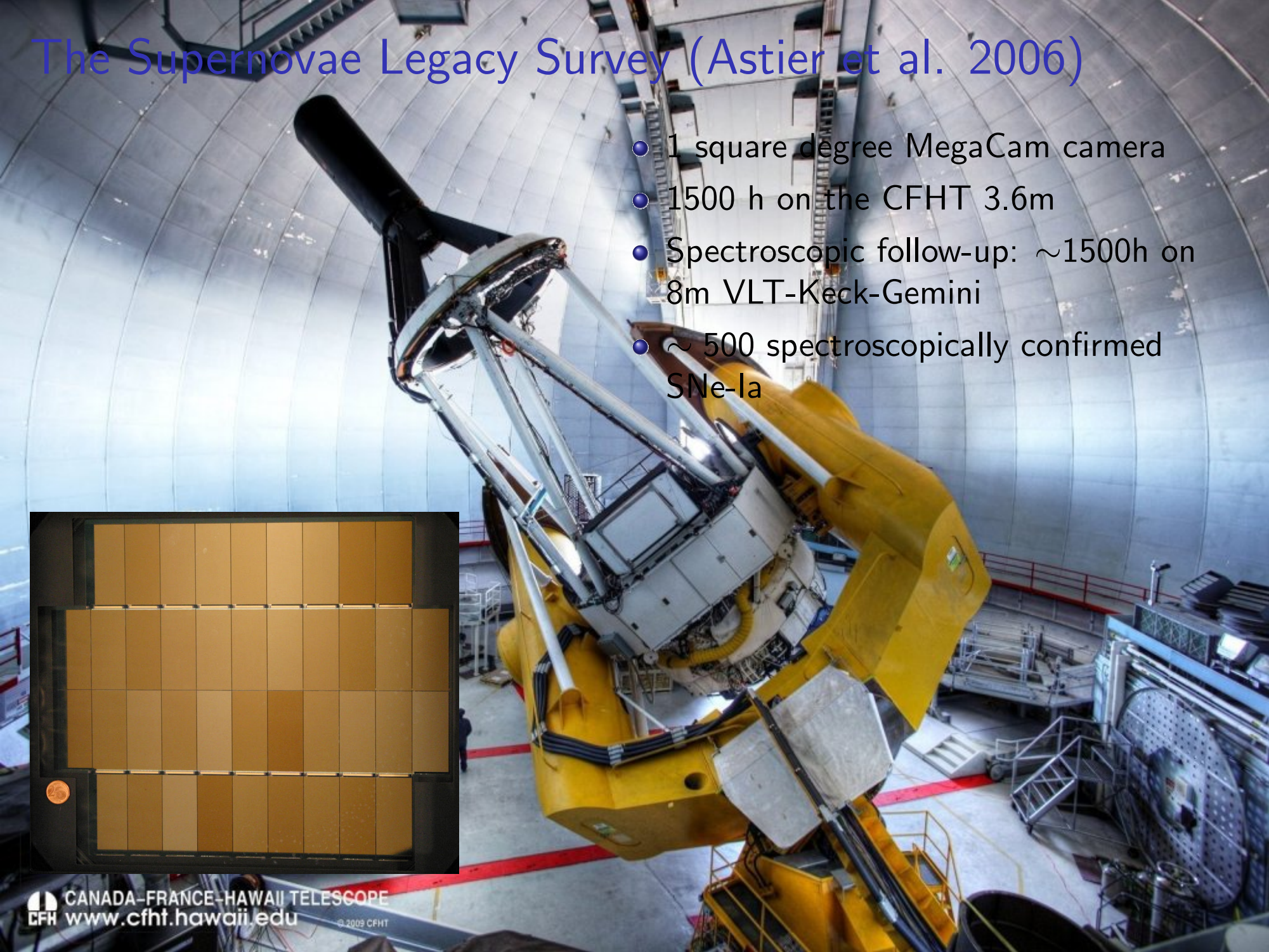
1. Discovery in images subtraction
2. Flux evolution measurement
3. Host galactic flux model
4. Spectroscopic follow-up: identification and redshift measurement

Multiplex step 1-3 for several SNe-Ia in the same image

- Repeated imaging of the same sky portion
- Implemented in 3 major survey
- Classical spectroscopic follow-up

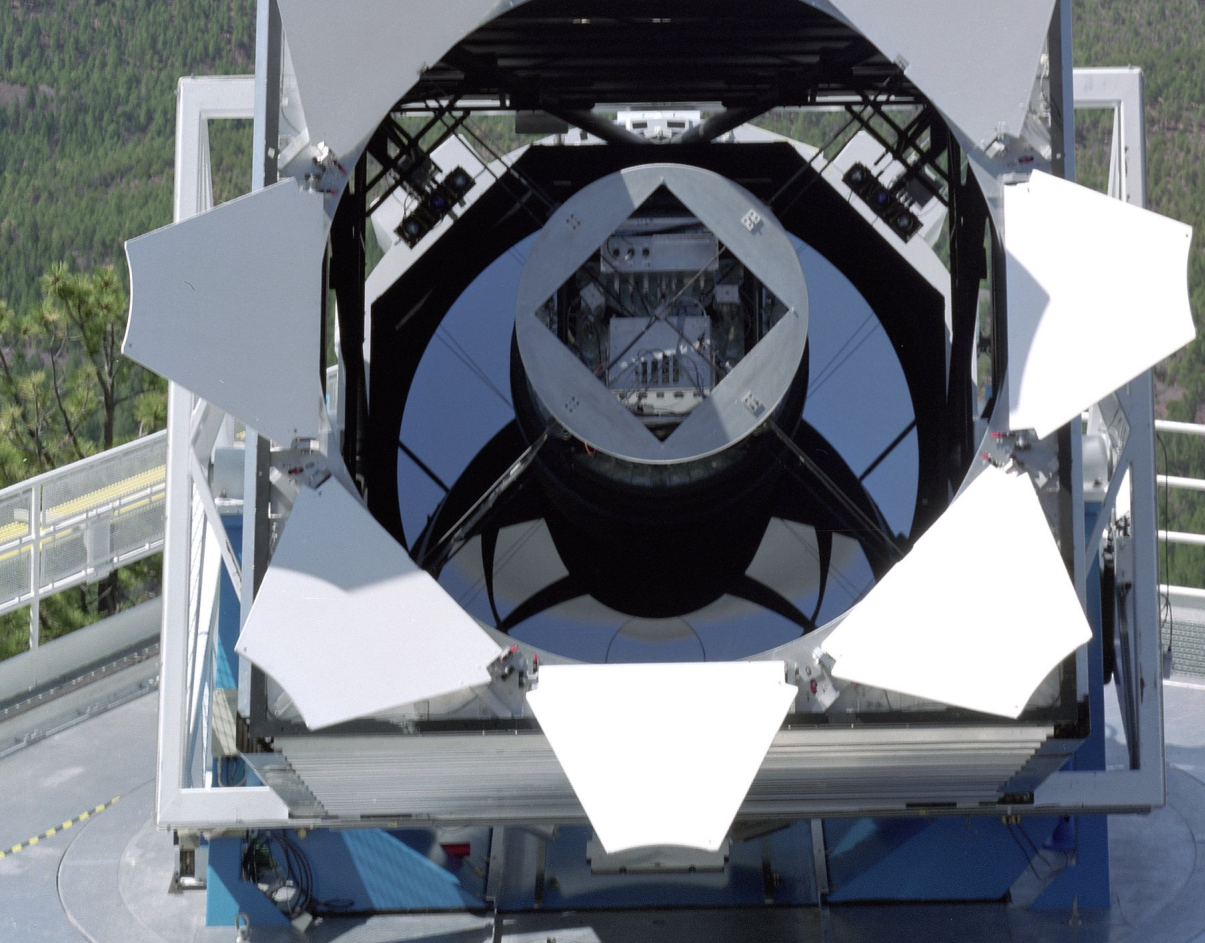
The Supernovae Legacy Survey (Astier et al. 2006)

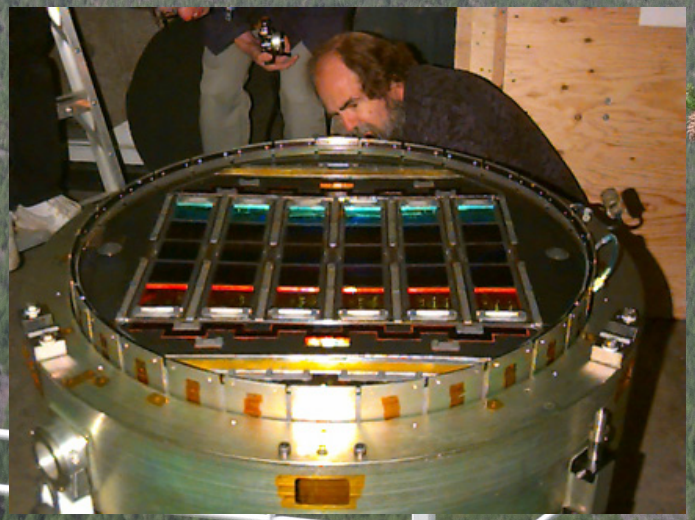
- 1 square degree MegaCam camera
- 1500 h on the CFHT 3.6m
- Spectroscopic follow-up: $\sim$1500h on 8m VLT-Keck-Gemini
- $\sim$ 500 spectroscopically confirmed SNe-Ia



The SDSS-II Supernovae Survey (Kessler et al. 2009)

- 1.5 degree-wide fast-scanning SDSS Camera
- $\sim$ 2000 hours on the 2.5m SDSS telescope
- $\sim$ 500 spectroscopically confirmed SNe-Ia





Low redshift

- No trully rolling survey yet
- Regular follow-up of known galaxies
- By several experiments (CSP, CfA ...)

Because of the instrumental cost of spectroscopy at high redshift

They provide the vast majority of the spectroscopic information about Ia

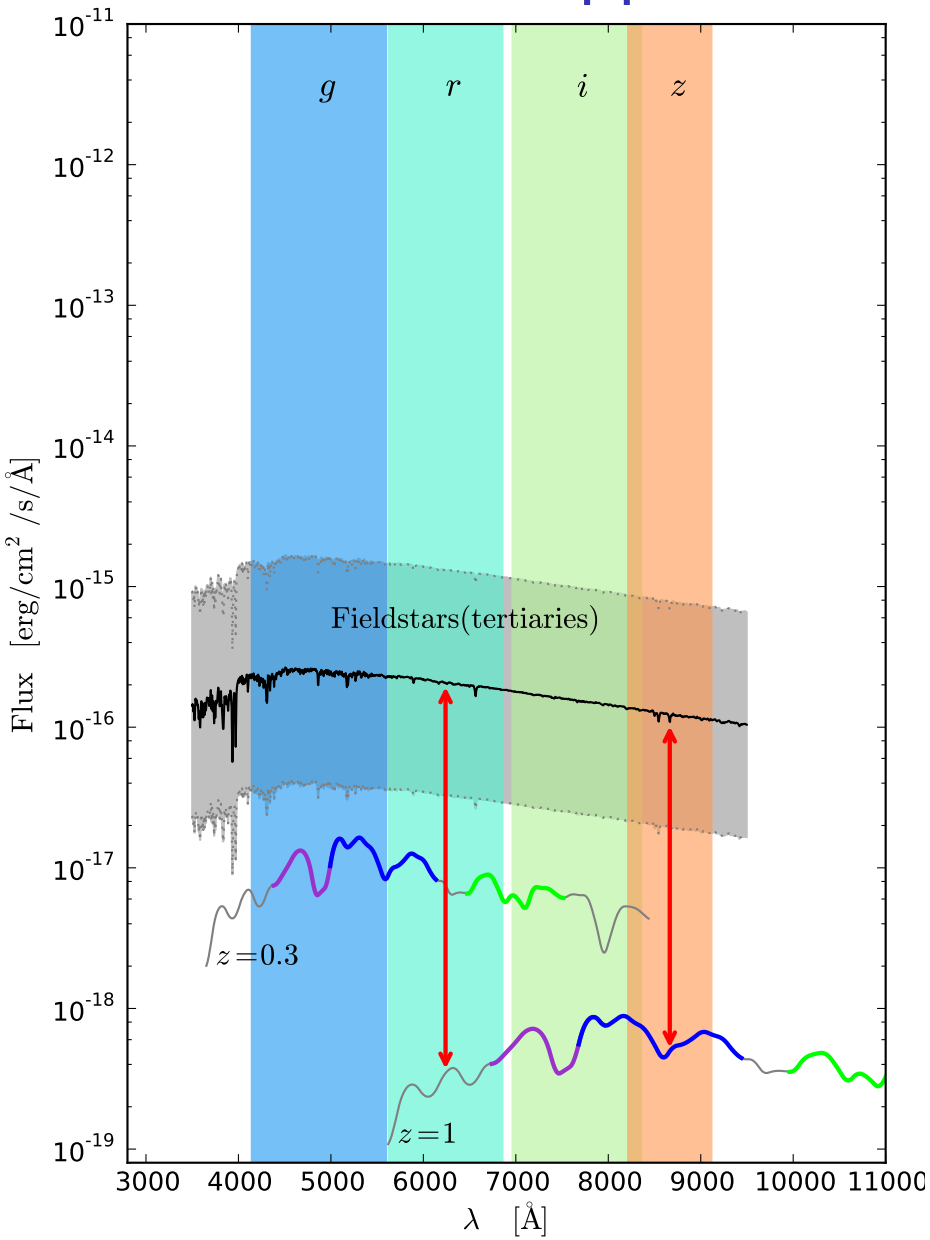
Image differences

You need to match

- Astrometry
- Photometric response
- Point spread function

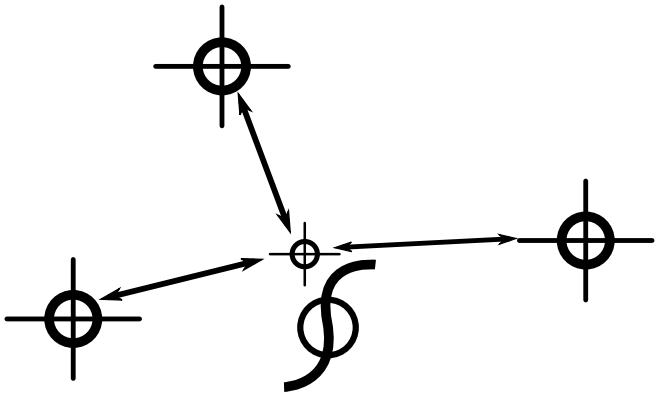
Everything varies at the size of the focal plane

Measurement of apparent fluxes

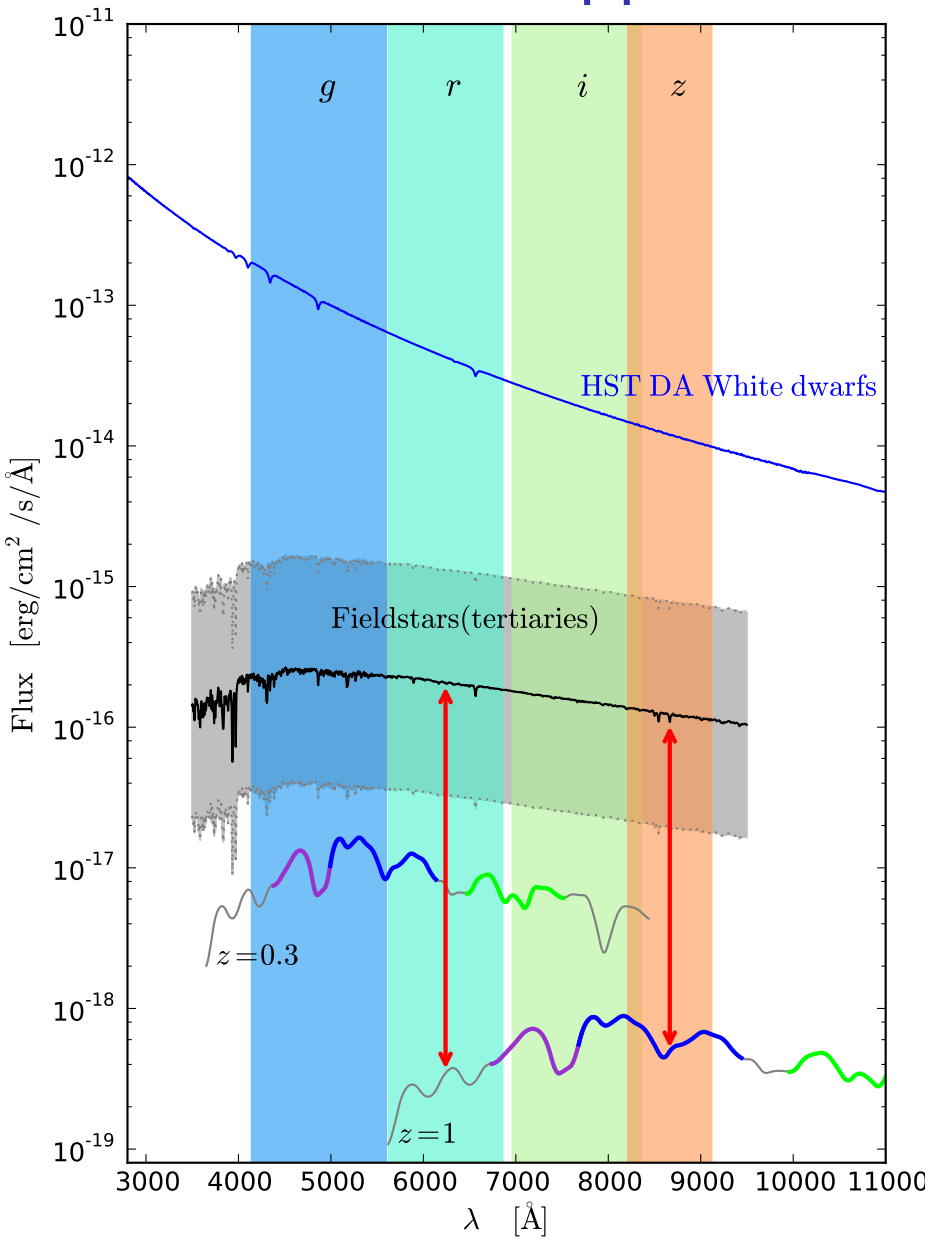


I) Differential photometry

- measurement of SN/stars **flux ratios** in a single image



Measurement of apparent fluxes



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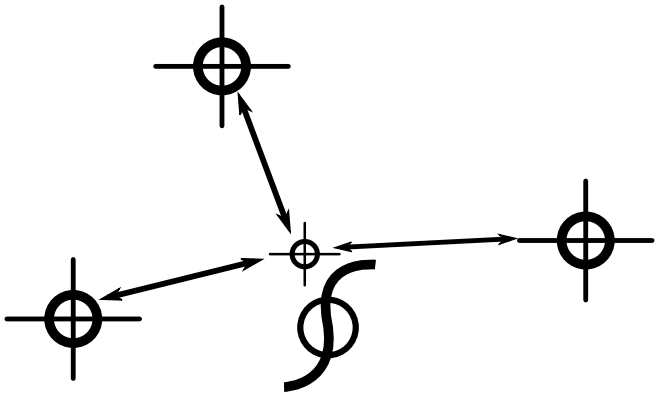
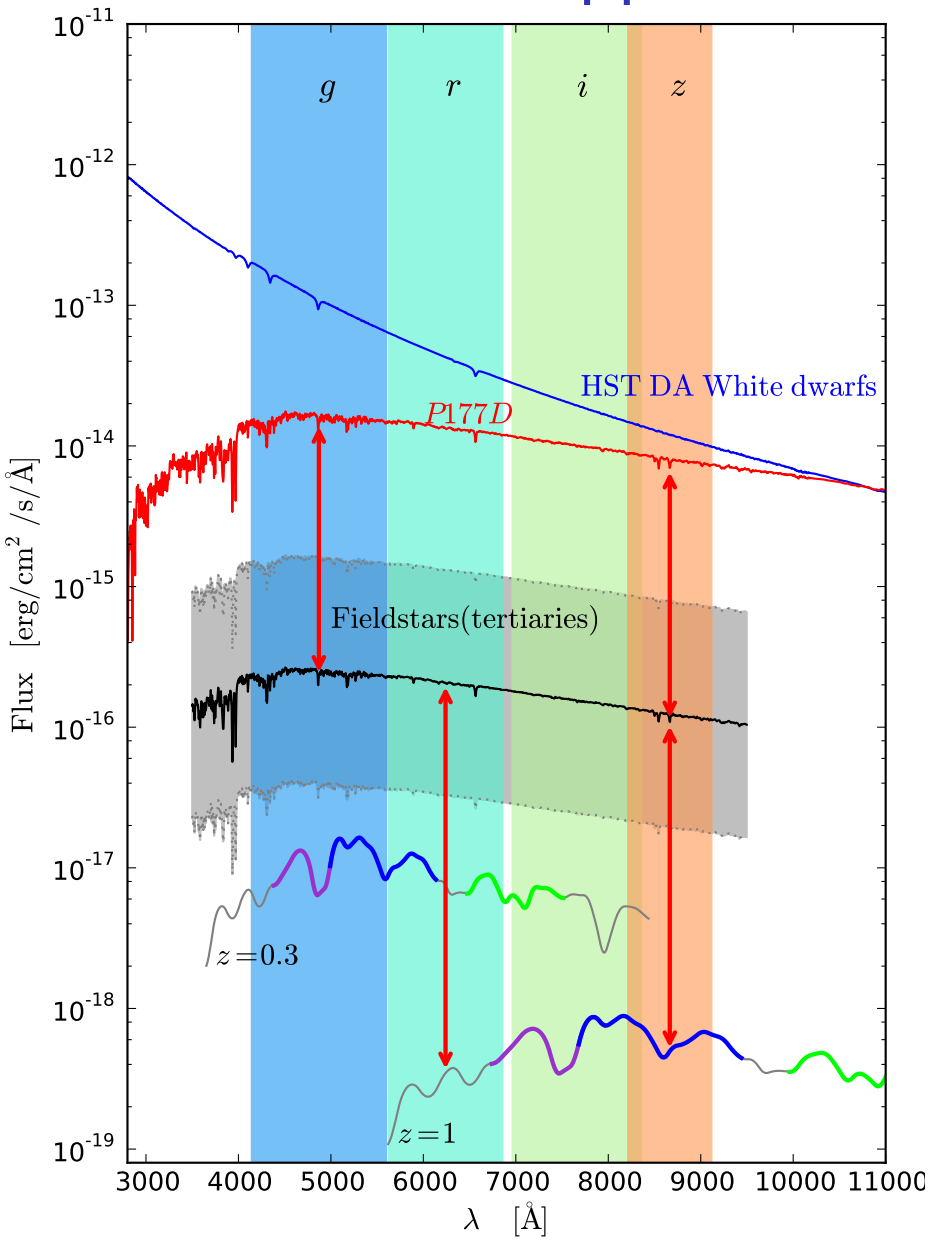


II) Calibration transfer

- HST standard stars as primary calibration source
- Enable comparison of flux in different bands/instruments

Measurement of apparent fluxes



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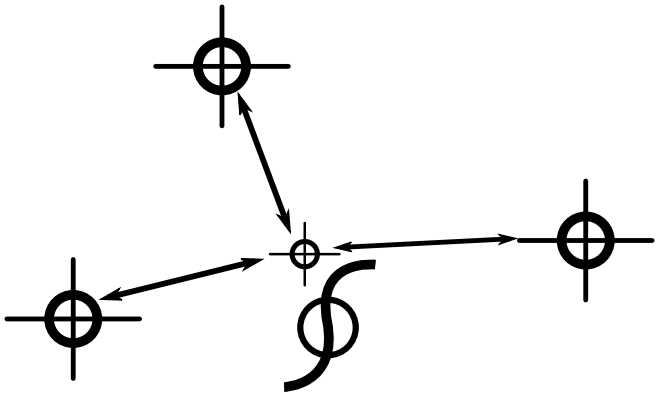

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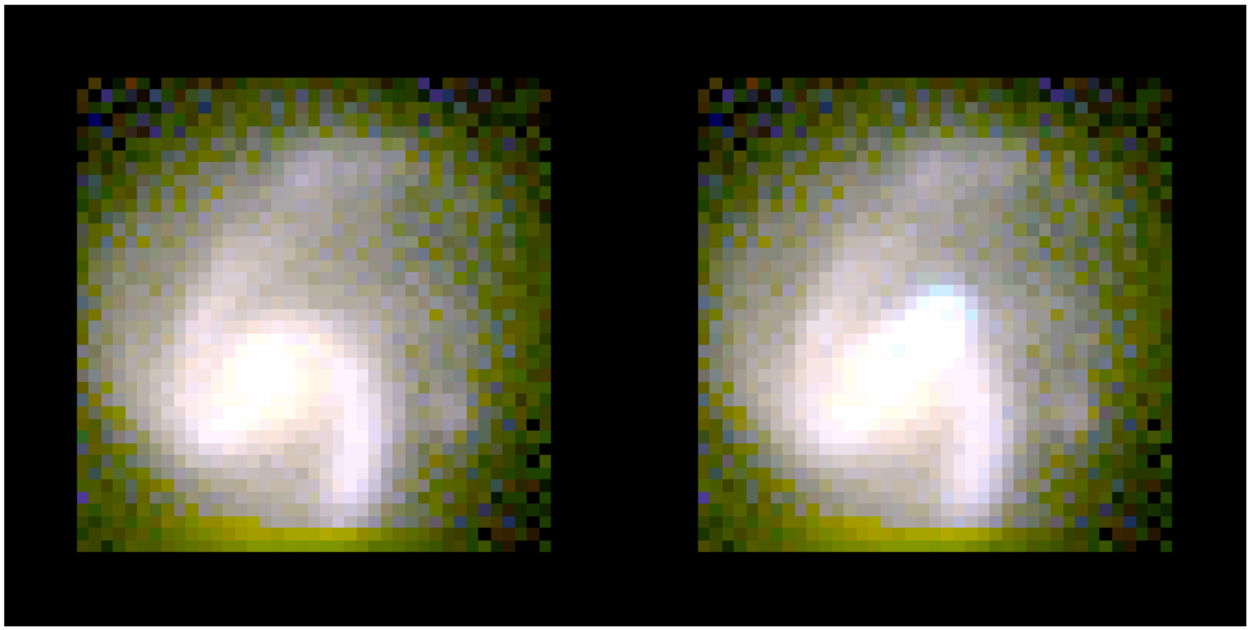
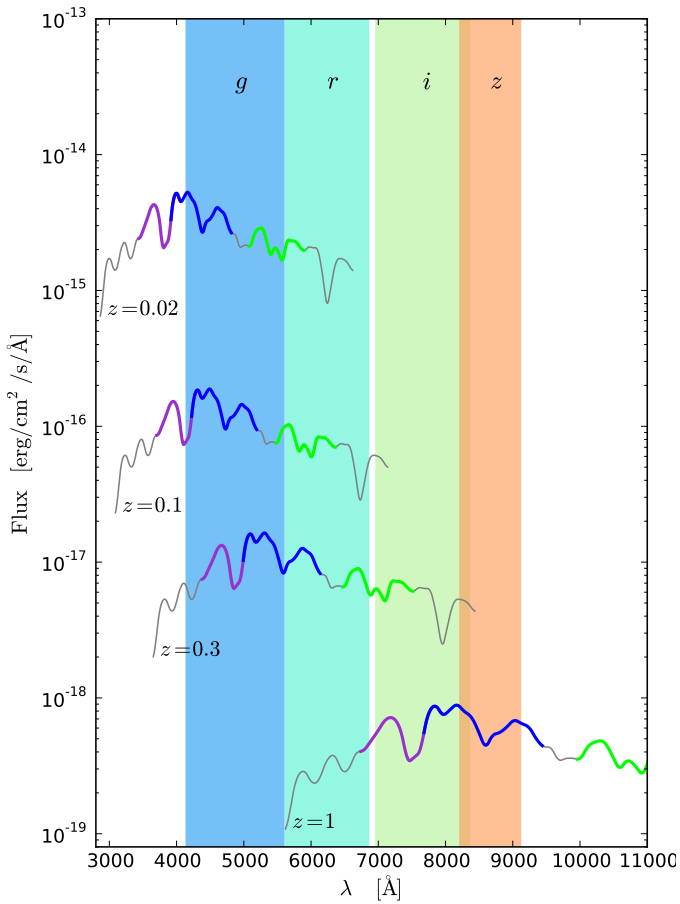
PSF photometry with scene modeling

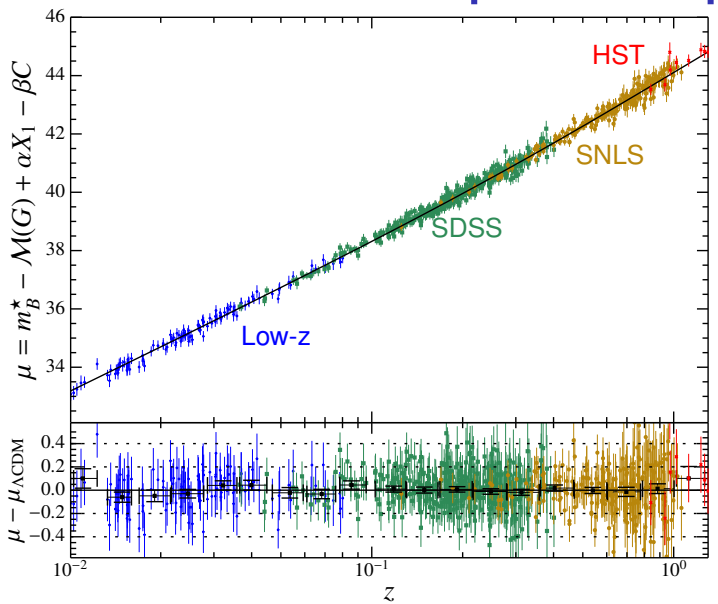


$$M_{i,p} = \{[f_i \times \phi_{ref}(\vec{x}_p - \vec{x}_{SN}) + gal_{ref}] \otimes K_i\}_p + s_i$$

- The rolling search provide a collection of images (before, during, and after the supernova)
- The astrometry and the PSF for each image patch is known from surrounding stars
- Global fit for a constant background + a time varying point source
- Shown to be accurate at the permil level (Astier et al. 2013)

Calibration accuracy: back of the envelope computation





Let us divide the HD in 2 bins

- $\sigma^{stat} \sim 0.008$ mag $\rightarrow \sigma(\Delta_\mu) \sim 0.011$

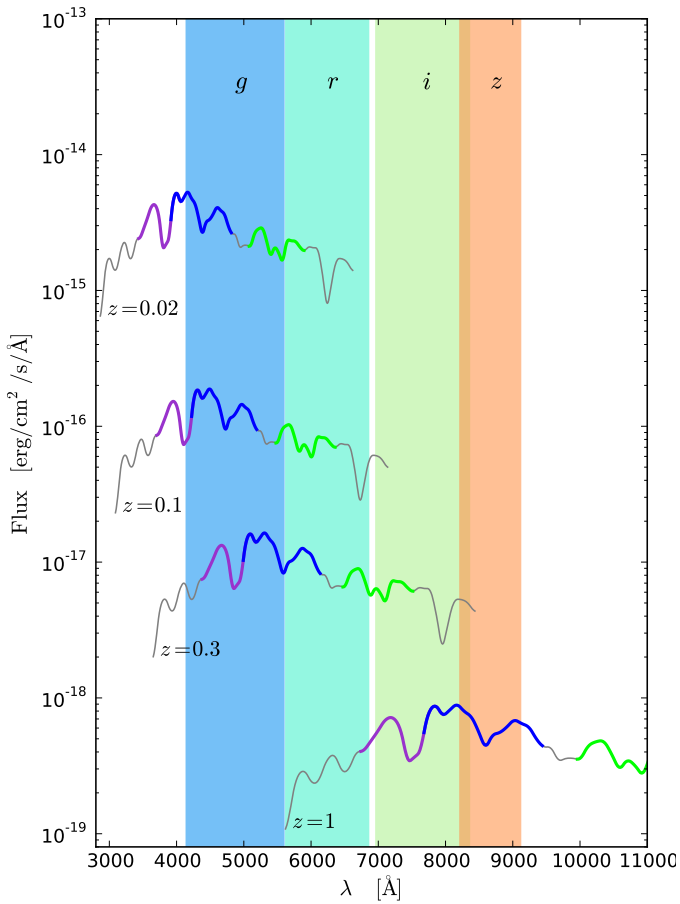
and assume that

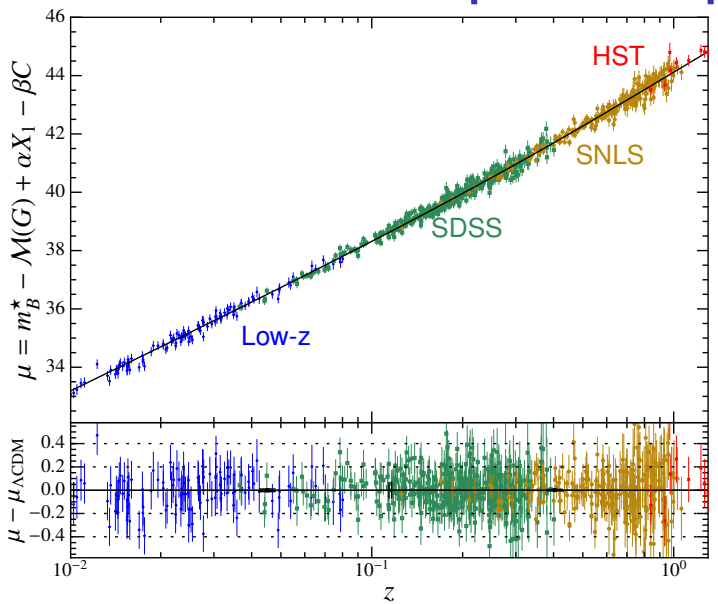
- $m_1 \sim \langle g \rangle$ and $c_1 \sim \langle g \rangle - \langle r \rangle$
- $m_2 \sim \langle i \rangle$ and $c_2 \sim \langle i \rangle - \langle z \rangle$

$$\begin{aligned} \Delta\mu &\sim m_1 - m_2 - \beta(c_1 - c_2) \\ &\sim 2\langle g \rangle - 2\langle i \rangle + 3\langle r \rangle - 3\langle z \rangle \end{aligned}$$

$$\Rightarrow \sigma(\Delta\mu)_{cal} \sim \sqrt{10}\sigma(cal)$$

Calibration accuracy: back of the envelope computation





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$$\Rightarrow \sigma(\Delta\mu)_{cal} \sim \sqrt{10}\sigma(cal)$$

Spectrophotometric standards

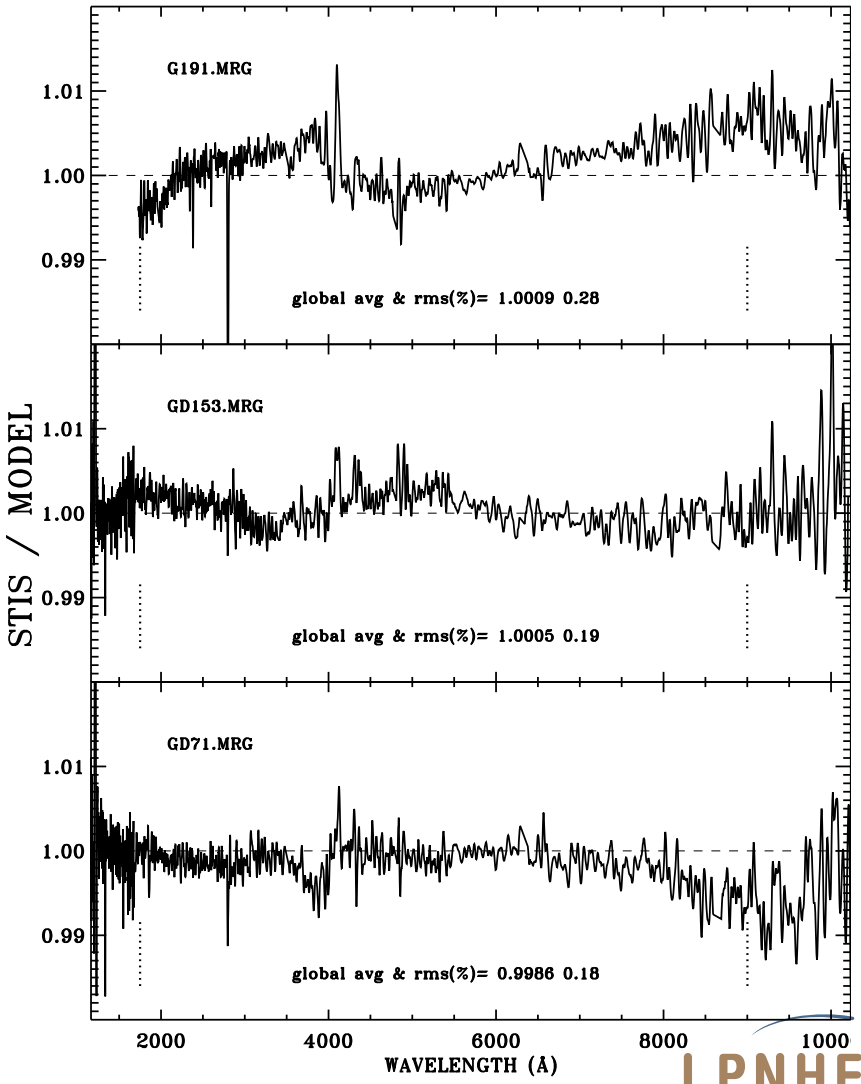
Numerical model of the spectra of pure hydrogen white dwarfs

Bohlin, Gordon & Tremblay 2014

- Solve for the radiative transfer in the pure H atmosphere
- Model parameters (T, $\log g$) provided by high-resolution spectro of H lines
- Rauch et al 2013 NLTE model
- 3 DA WD: G191B2B, GD153, GD71

The average defines the HST/STIS calibration

- Residuals below the percent level in the visible range



(Bohlin et al. 2014)

Calibration transfer

1. The HST STIS spectrograph provides calibrated spectra of a small set (~ 50) of secondary standards
2. If the transmission T of a photometric instrument is known up to constant ($T = \kappa \hat{T}$) observation of a standard of known spectrum S sets the calibration constant

$$m = \kappa \int \hat{T}(\lambda) S(\lambda) d\lambda$$

3. The calibrated instrument can now observe the field stars to provide the calibrated fluxes we need

But in practice:

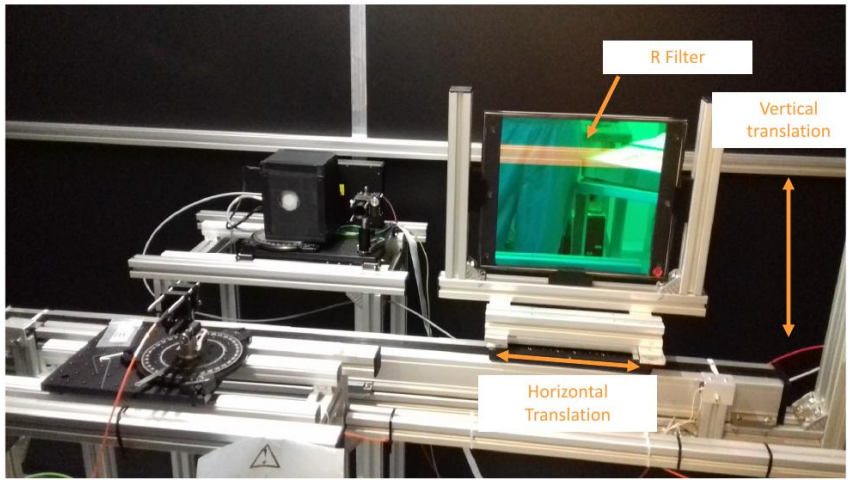
- Everything varies (at some level) between the two images
- Especially the atmosphere transmission (typically $\sim 1\%$)
- Repeat the measurement many times
- In clever ways so that all effects average out
- A good transfer dataset for SNLS was taken in 2011-2014
- The JLA paper was based on the first round of this program

Measuring the filters

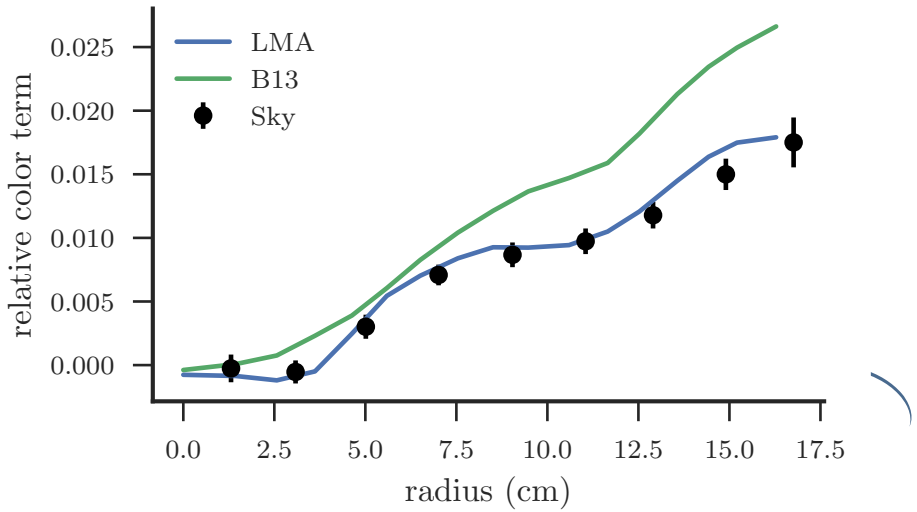
All the above holds only if the passband shapes are precisely known

- Interference filters are complex
- Their transmission is not uniform (Regnault et al. 2009)
- The manufacturer transmission measurements were not accurate (Betoule et al. 2013)

Ongoing survey of the MegaCam filter transmission



Encouraging results



Building an empirical model

Now that we have calibrated flux measurements at many epochs and in several bands we need a model to interpret them

What can we suppose ?

- The spectrum is smooth at all phases
- The spectrum evolve smoothly
- Continuous differences in color and decline rate between events

SALT2 (Guy et al. 2010): An exemple of empirical description

$$\Phi_{sn}(p, \lambda; x_0, x_1, c) = x_0[M_0(p, \lambda) + x_1 M_1(p, \lambda)]exp(c\,CL(\lambda))$$

The SNe family is characterized by:

- A mean spectrum M_0, expandable in a low-resolution spline basis
- A smooth wrapping of the spectrum in wavelength (the color law) $CL(\lambda)$
- A first-order variation around the mean spectrum: M_1, expended in splines

A given SN is characterized:

- x_0 the scaling of the total luminosity
- x_1 the amount of time stretching
- c the color of the event

Training SALT2 on data

M_0, M_1 and CL can be developped on function bases

- e.g. B-splines for M_0 and M_1 and polynomial for CL
- Coordinates in the basis are fitted to best describes the data

Fitting the model to photometric and spectrometric data

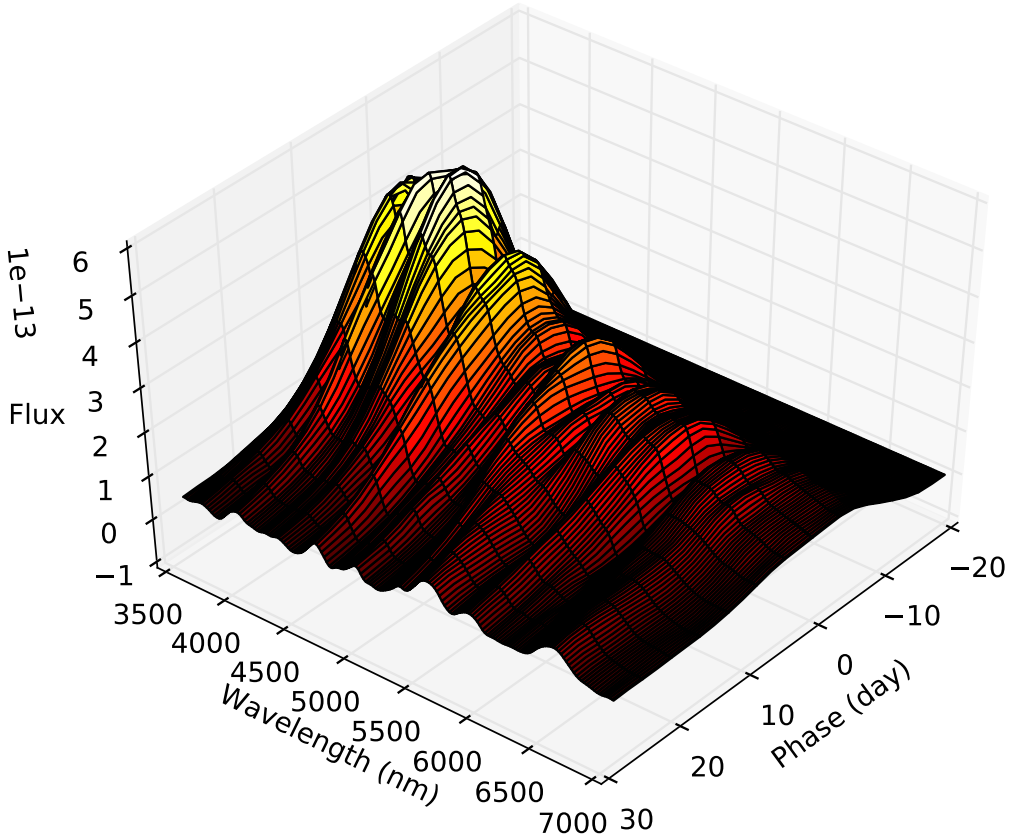
- Given a SNe Spectrum S_i at phase p_i the residual to the model is: $r_i(\lambda) = S_i(\lambda) - \Phi_{sn}(p_i, \lambda; x_0, x_1, c)$
- Given a photometric measurement m_i in band T at phase p_i: $r_i = m_i + 2.5 log_{10} \int_\lambda T(\lambda)\Phi_{sn}(p_i, \lambda; x_0, x_1, c)$

Adjust parameters to minimize:

$$\chi^2 = \sum_i \frac{r_i^2}{\sigma_i^2 + \sigma_{sn}^2}$$

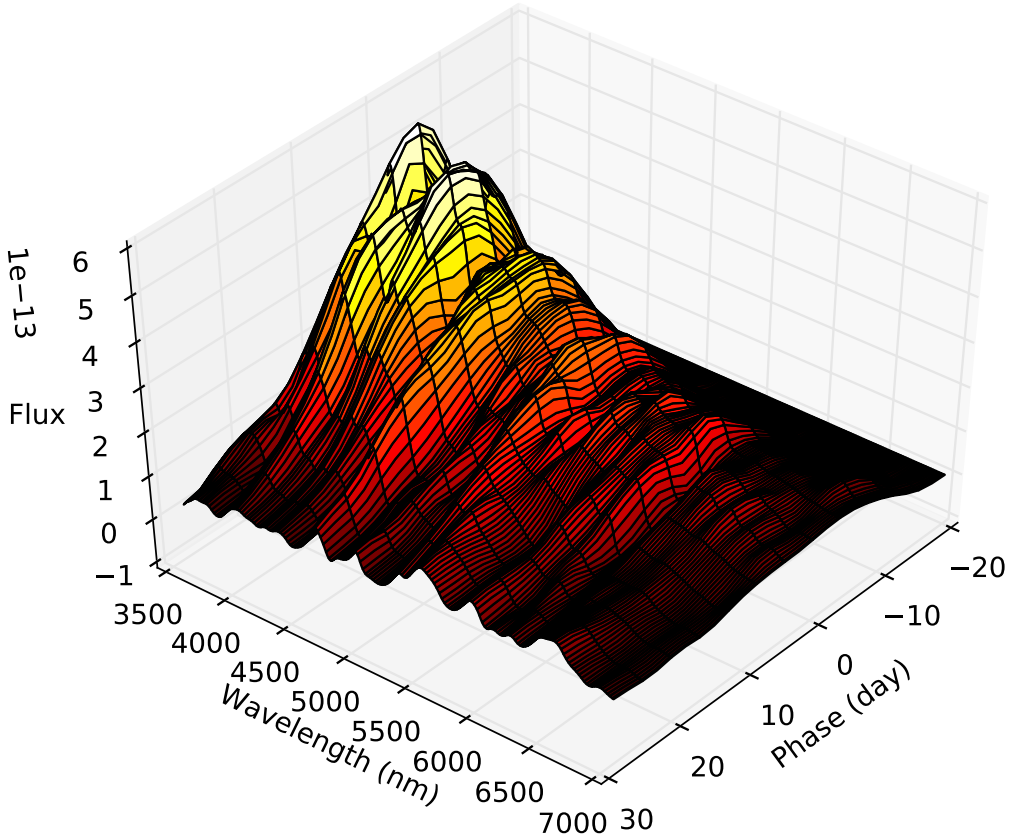
σ_{sn} is needed because the model is not a perfect description of the data.

Playing with the Model



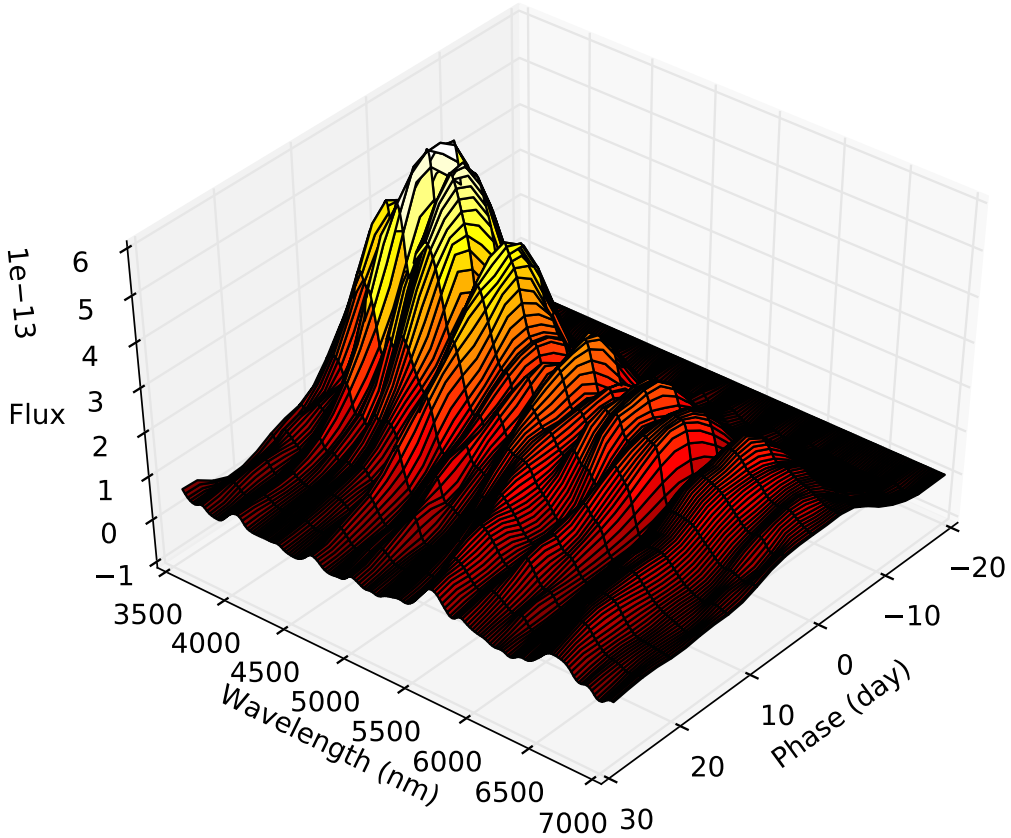
$$x_1 = 0, c = 0$$

Playing with the Model



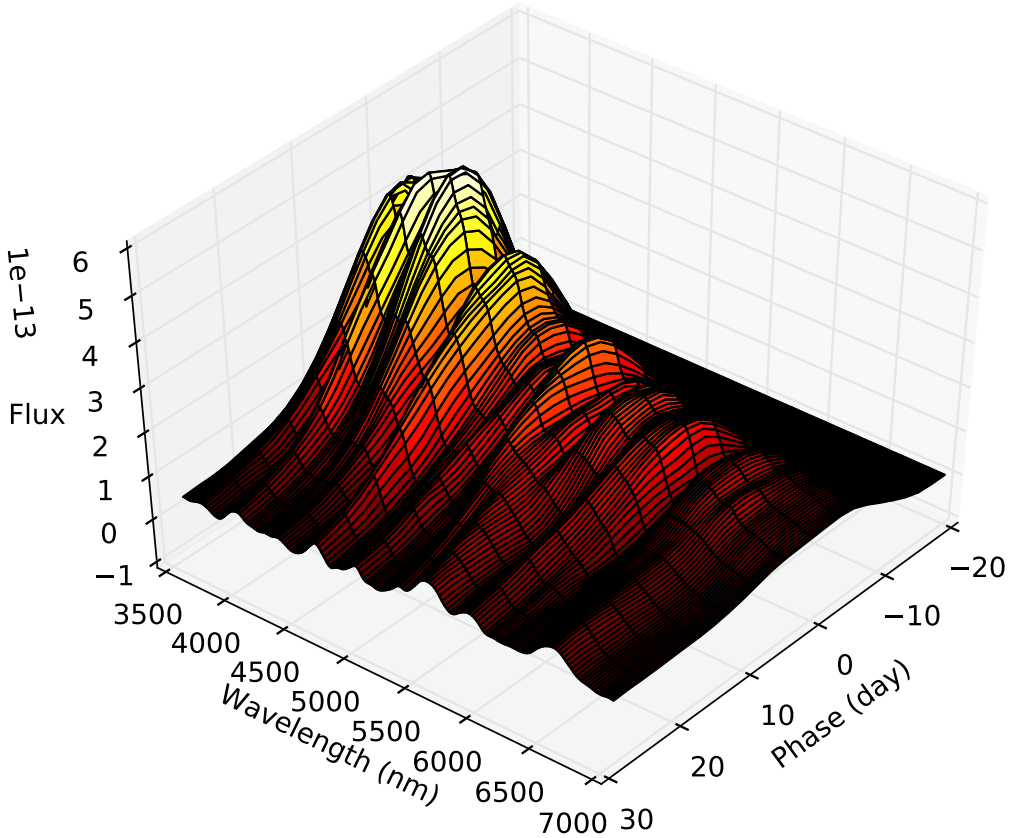
$x_1 = 2, c = 0$

Playing with the Model



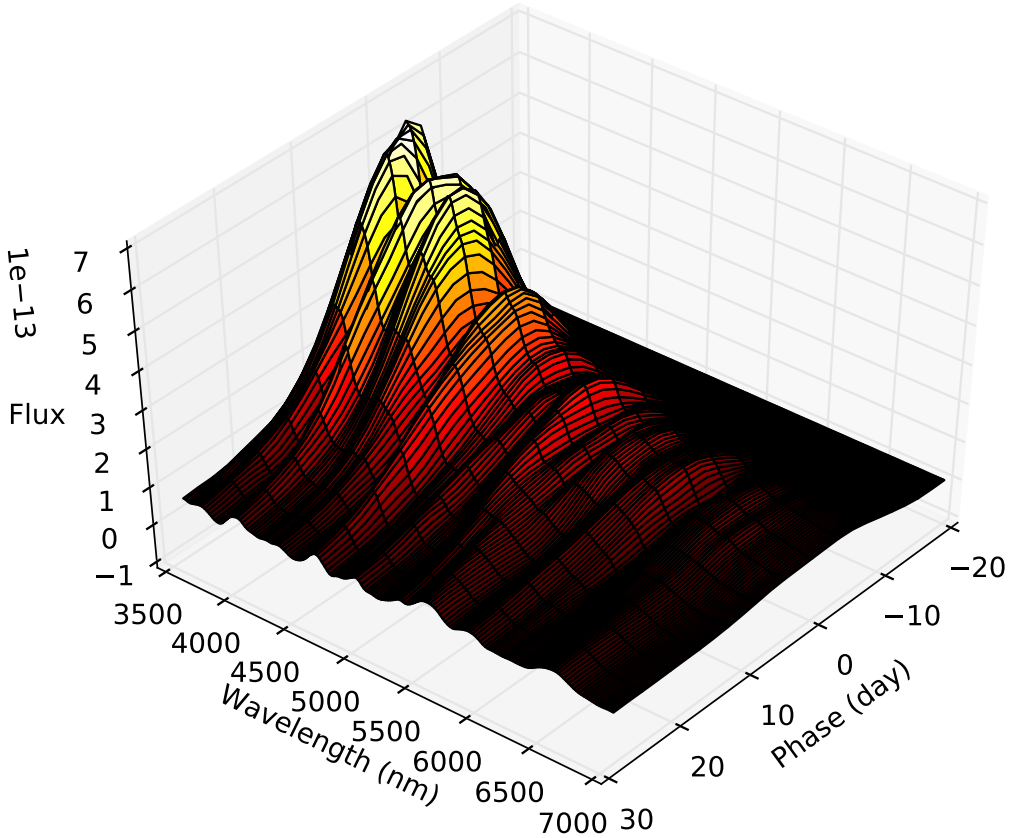
$$x_1 = -2, c = 0$$

Playing with the Model



$$x_1 = 0, c = 0$$

Playing with the Model



$x_1 = 0, c = -0.3$

Accuracy ?

Residual scatter around the model

$$\chi^2 = \sum_i \frac{r_i^2}{\sigma_i^2 + {\sigma_{sn}}^2}$$

- $\sigma_{sn} \sim 4\%$ in the wavelength range $400\mathrm{nm} < \lambda < 700\mathrm{nm}$

Trained on both high and low-z SNe

- Fitting x_0 along the rest enable the use of high-z SNe without prior knowledge of cosmology
- Ensure that the mean is representative of the SNe that populate the Hubble Diagram
- Improves the modeling of the UV part which is hard to observe from the ground

Good but incomplete description of the data

Other approaches

- MLCS2k2 (Jha, Riess & Kirshner 2007): Physical assumption about the color variation (attributed to extinction by dust on the light path)
- SiFTO (Conley et al. 2007): Assume that the time variability is a pure stretch effect
- SNooPy (Burns et al. 2011): Focus on the infrared part of the spectrum
- Kim et al. 2013: Pushes the PCA to 4 components
- Sugar (Gangler et al. 2016)

Cosmology fit

We minimize the following likelihood

$$\chi^2 = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu}_{\Lambda CDM}(z;\Omega_m))^{\dagger} \mathsf{C}^{-1} (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu}_{\Lambda CDM}(z;\Omega_m))$$

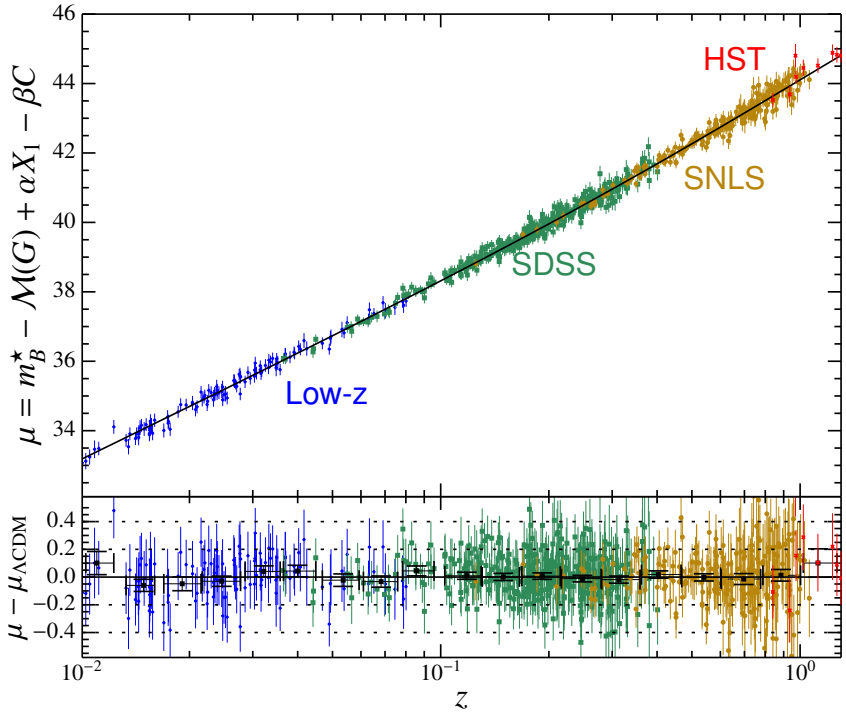
- $\hat{\mu}$ depends on nuisance parameters, C also
- It is possible to marginalize over nuisance parameters assuming only that distance is a smooth function of redshift (provide an accurate but largely simplified description of the dataset)
- Everything is available from here: `http://supernovae.in2p3.fr/sdss_snls_jla/ReadMe.html`

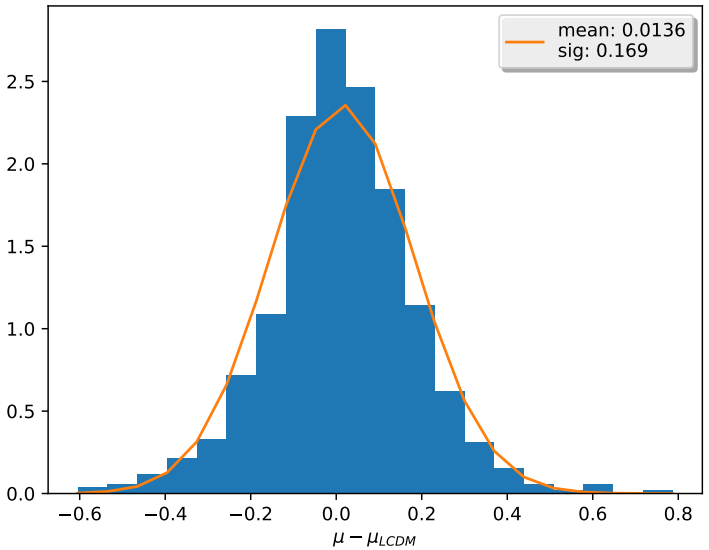
You can do more sophisticated things but please don't do that (because that is wrong):

$$p(x_1|\theta) = (2\pi\sigma_{x_0}^2)^{-1/2} \exp\left\{-\left[(x_1 - x_0)/\sigma_{x_0}\right]^2/2\right\},$$
$$p(c|\theta) = (2\pi\sigma_{c_0}^2)^{-1/2} \exp\left\{-\left[(c - c_0)/\sigma_{c_0}\right]^2/2\right\}.$$

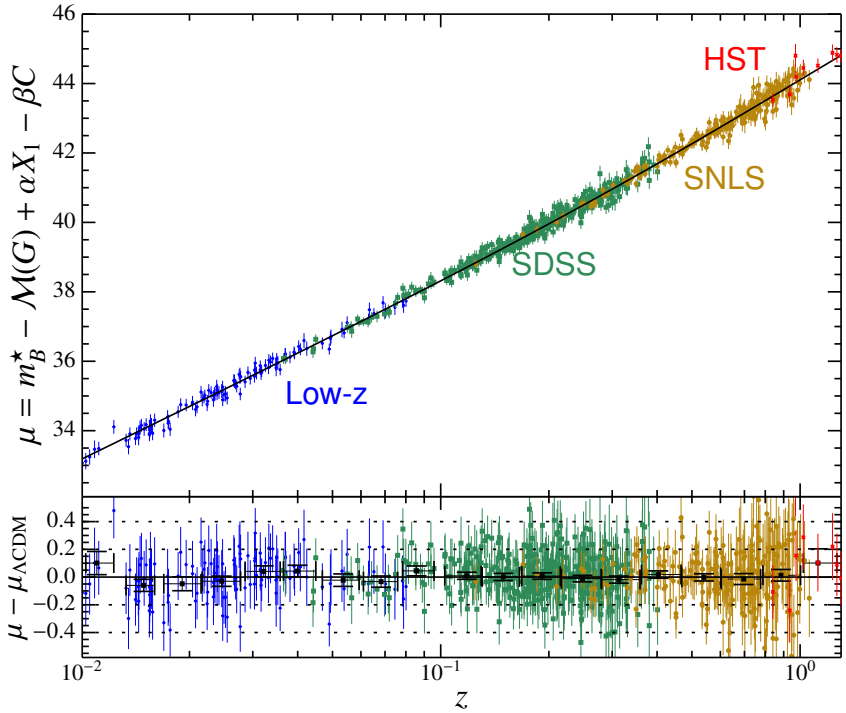
Have a look at arXiv:1507.01602 for correct Bayesian inference from SN data

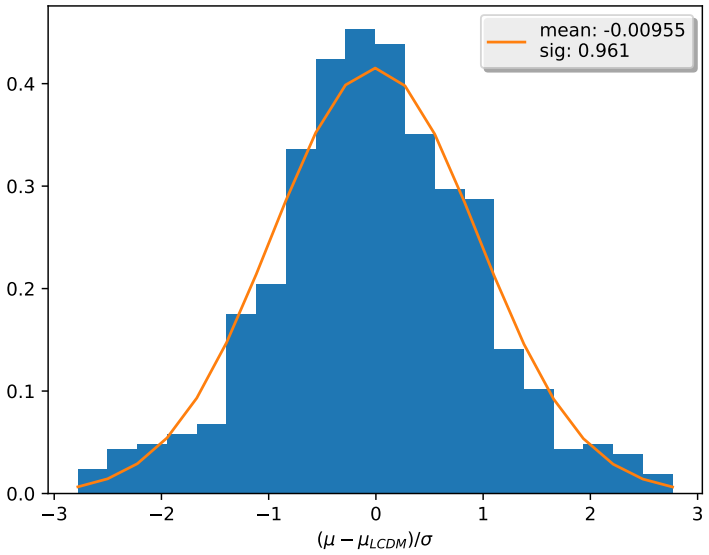
A look at fit results





A look at fit results





Current limitations to the precision

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

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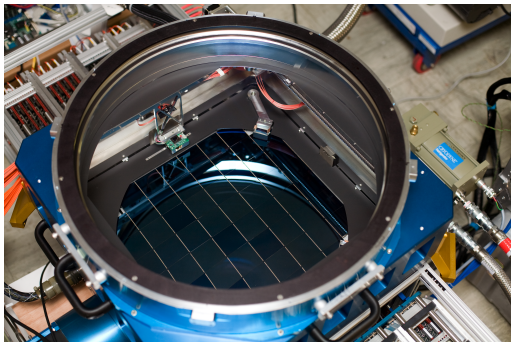
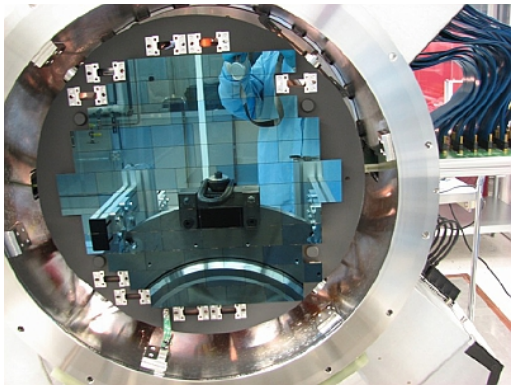
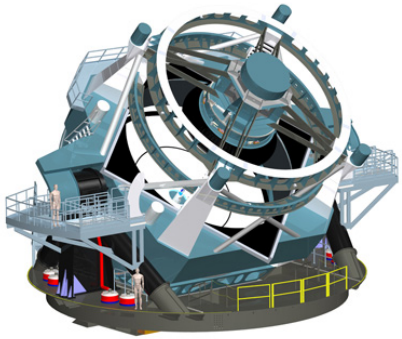
Increasing the statistics to > 10000 SNe







Ongoing surveys

- CfA and CSP continuing $z < 0.1$
- SN factory (Aldering 2002) $z < 0.1$
- Pan-STARRS (Kaiser 2004) $z < 0.7$
- DES (Bernstein 2011) $z < 0.8.$
- Subaru Supernovae Project $0.8 < z < 1.4$

Starting soon

- ZTF $z < 0.1$

Around 2020

- LSST able to rolling-search in the full redshift range
- EUCLID/WFIRST would allow infrared follow-up of high-z SNe-Ia

Detection and photometric follow-up of SNe

Not what currently limits the statistics

Spectroscopic follow-up does (see next slide), at least at high redshift

- Correct multiplexing in the rolling-search approach

Unlikely to be the limitation in the future

Just going from CFHT to LSST

$$\left.\begin{array}{r} 3.6m \rightarrow 6.4m \\ 1deg^2 \rightarrow 9deg^2 \end{array}\right\} \text{provides a factor 30 in the statistics}$$

Spectroscopic follow-up

what limits the statistics today

- $\sim$ 500 hundred high redshift SNe
- 500 hours on 8m telescopes
- No obvious way to improve the efficiency

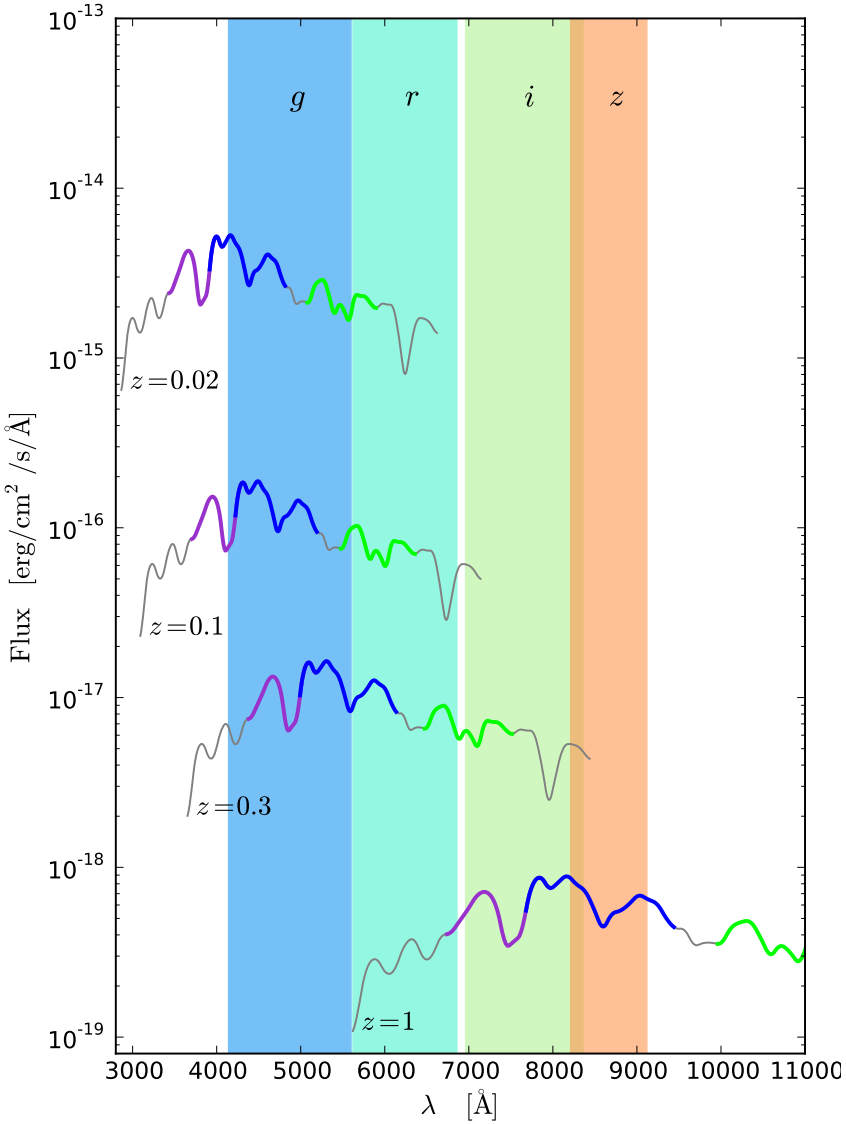
Can we live without live spectroscopy ?

- Supernovae Ia actually are standard, we can already tell from the LC
- Efficiently get redshifts after the facts from host spectra

The answer will be given soon by the ongoing DES survey

LPNHE PARIS

What about extending the redshift range ?

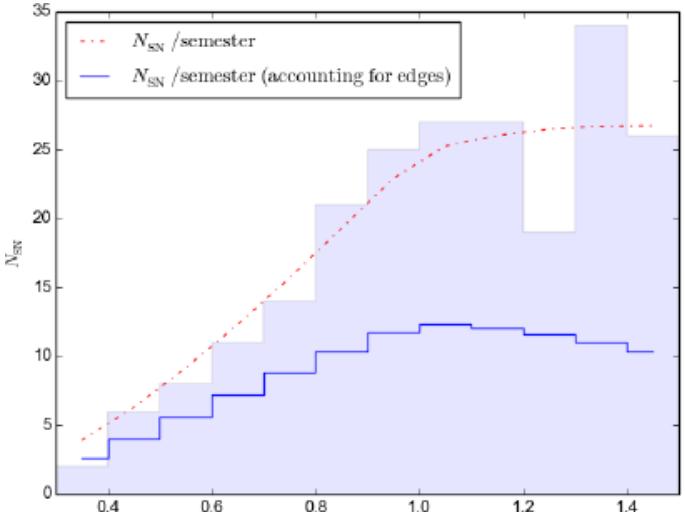


Both ends are hard for different reasons

- The low redshift part requires huge field of view, but apparently we are building those instruments, nevertheless the weight is likely to shift slighty (toward $0.1 \lesssim z$) just because of volume.
- The high redhift end requires infrared

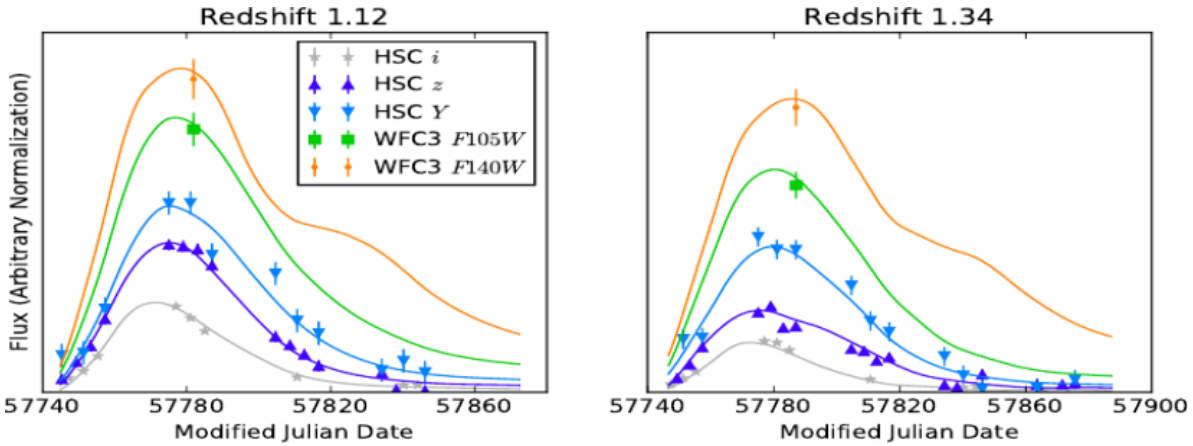
SSP: unique opportunity to extend the HD up to $z \sim 1.4$

By complementing discoveries in the Ultra Deep Subaru Survey



- A two semester rolling-search
- with the 8m Subaru telescope
- and 1.7deg^2 HSC camera
- Redshift complementary to DES
- The combination improves the JLA FoM $\times 5$

With single epoch infrared photometry with Hubble

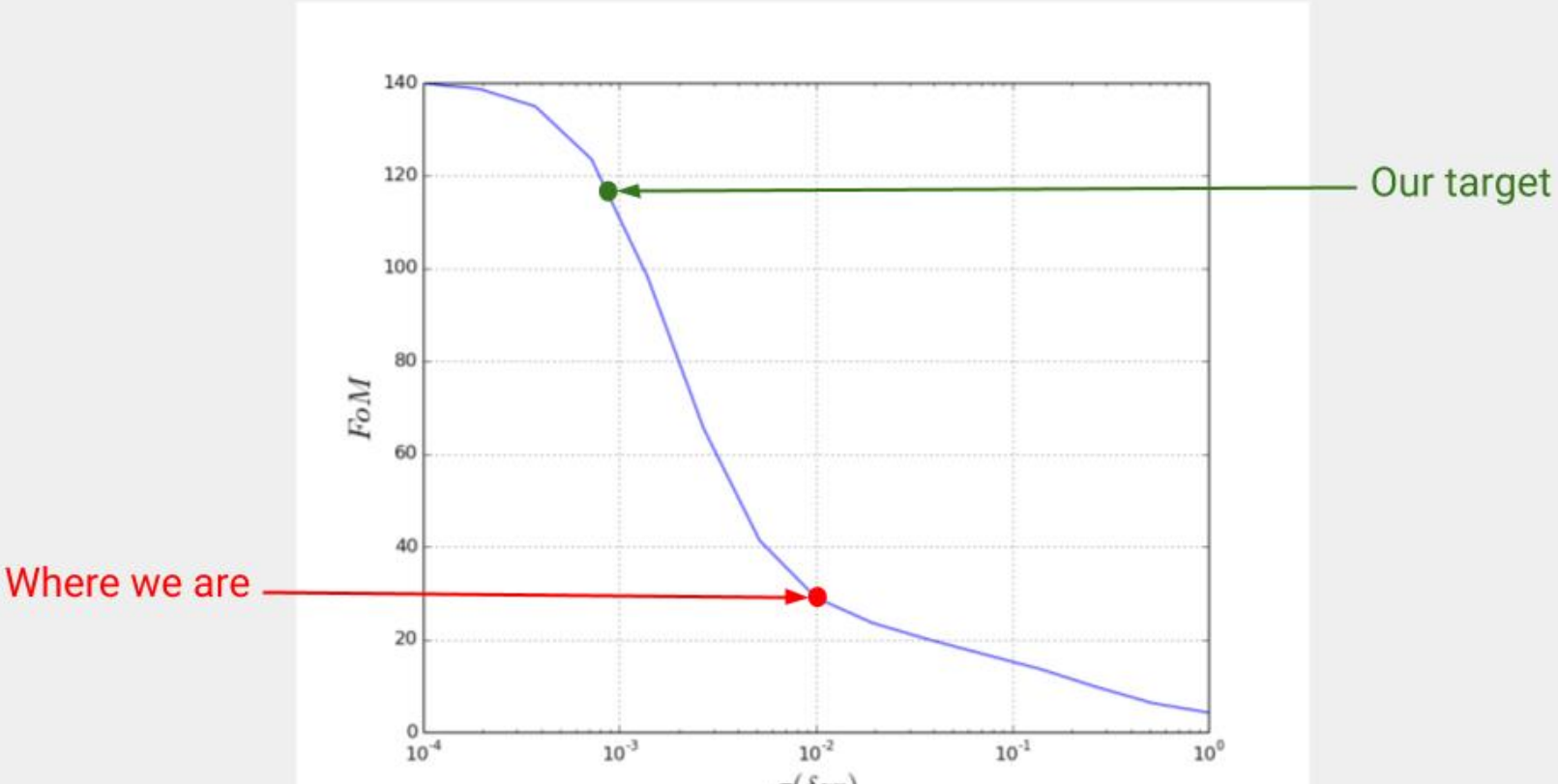


Calibration. How bad is it ?

Forecast for LSST (F. Hazenberg)

FoM

We compute the FoM from the covariance matrix for 5k SNe Ia :



Motivate hard work to break the calibration barrier

Transfer may actually comes for free

- Gaia is currently paving the sky with a homogeneous grid of low-resolution spectroscopic standards
- can be used to ensure uniformity of any survey

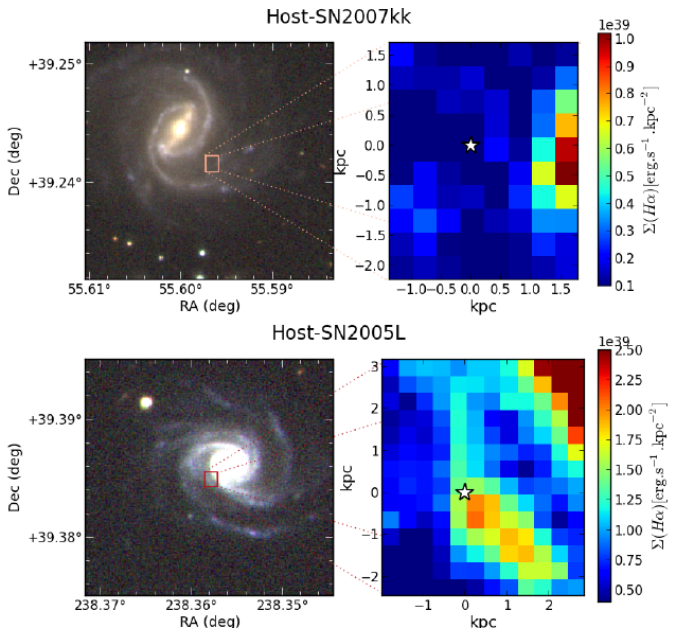
The hard part is to replace the WD with laboratory standards

- Effort coordinated within the LSST DESC collaboration
- 2 starting instrumental projects

Milky-way dust

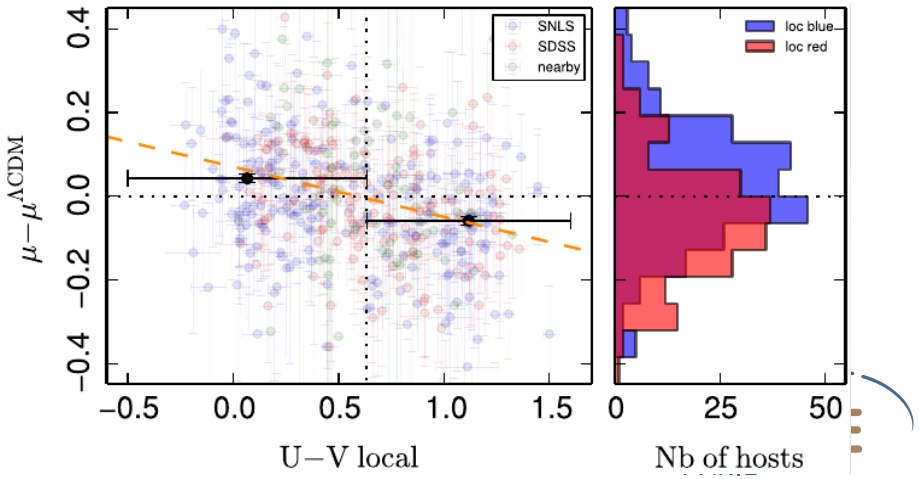
- Importance of the effect arises from the fact that we are comparing high-z SNe from clean parts of the sky to low-z SNe exploding preferentially everywhere
- The effect will drastically decrease for a rolling-search limited to low-extinction region (but a slightly higher minimum redshift)
- We were using a 20 years-old dust map, we have been conservative.
- The knowledge of milky-way dust improves a lot thanks to Planck and stellar surveys (go there http://argonaut.skymaps.info/)

Improving the evolution proxy



Look at the local environment of the supernovae

- Using data from the SNFactory IFU
- Characterize local stellar formation thanks to Halpha emission
- Correlation detected at 3σ in a small low redshift sample (Rigault et al. 2013)



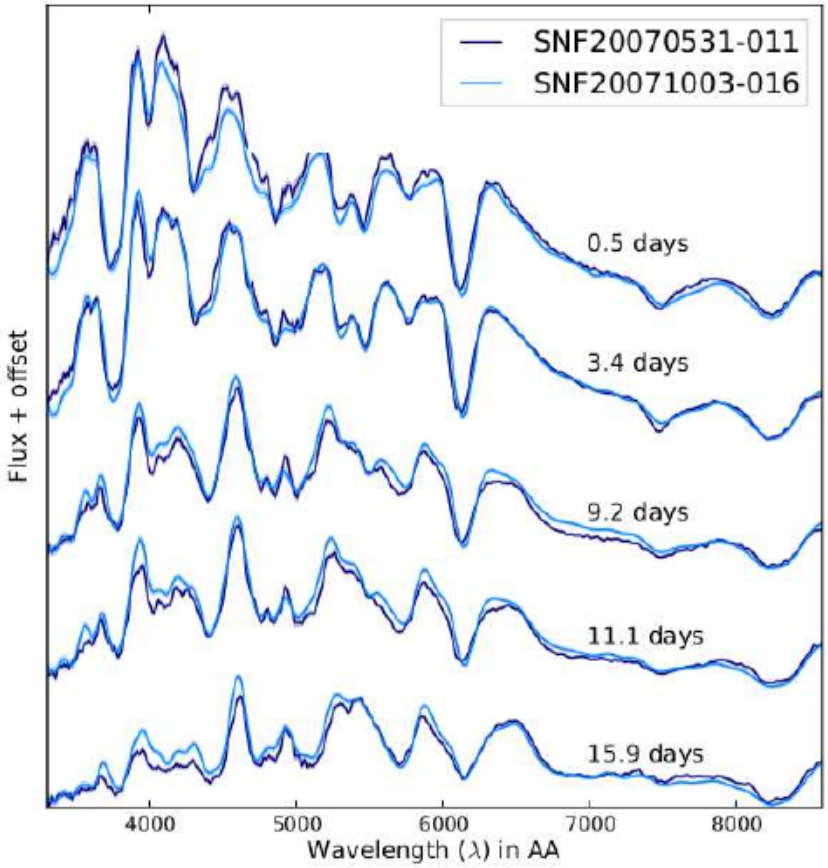
Confirmed in SNLS5

- > 700 SNe at all z
- local color measurements
- 7σ significance
- *Roman et al. 2017.*

Improving the standardization scheme

Increasing hints it is possible from publications by the SNFactory collaboration

- Bailey et al. 2012 (0.12)
- Fakhouri et al. 2015 (0.08 for twins)
- Leget et al. in prep. (~ 0.12 with LC + spectrum at max)



Proof on Hubble diagram and evolution cross-check still to be done

A solution from the UV ?

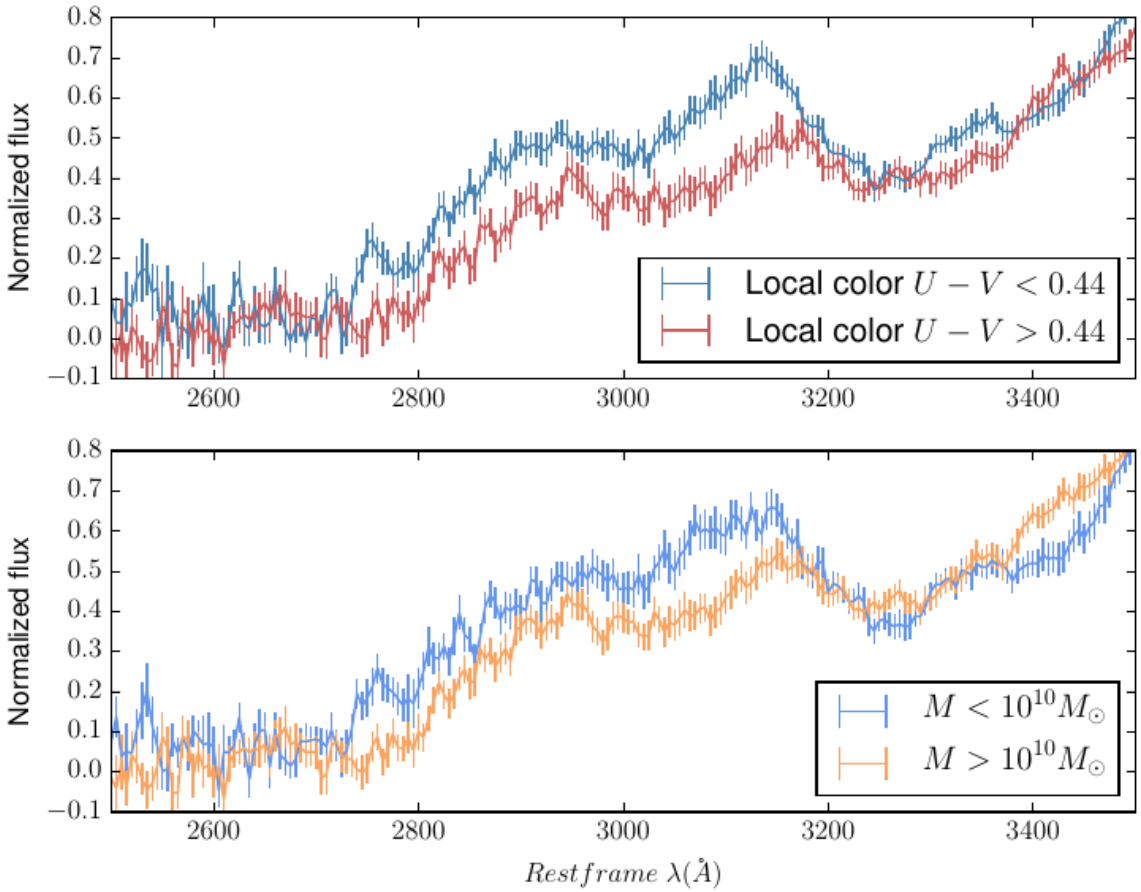


Fig. 18. Comparision of composite spectra obtained when spliting the sample according to local color (top panel) or mass (bottom panel). The cut are made at the sample average value.

Is the distance average valid in a perturbed universe

Perturbative computations (Ben-Dayan, Gasperini, Marozzi, Nugier and Veneziano 2013)

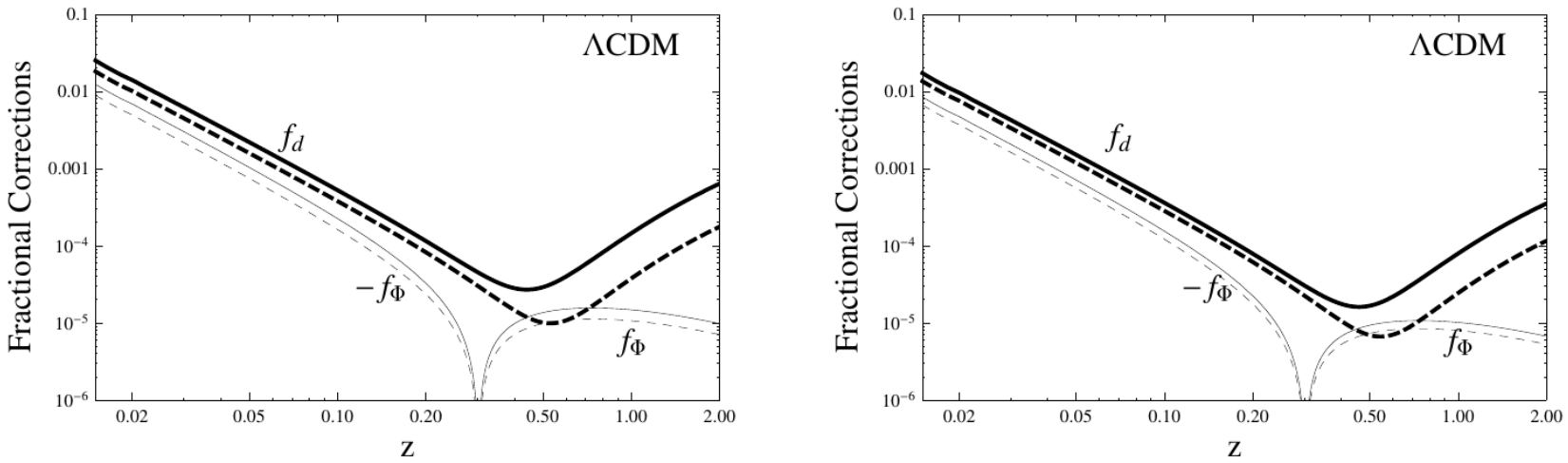


FIG. 3: The fractional correction to the flux f_Φ of Eq. (3.3) (thin curves) is plotted together with the fractional correction to the luminosity distance f_d of Eq. (3.5) (thick curves), for a ΛCDM model with $\Omega_{\Lambda 0} = 0.73$. We have used two different cutoff values: $k_{UV} = 0.1\mathrm{Mpc}^{-1}$ (dashed curves) and $k_{UV} = 1\mathrm{Mpc}^{-1}$ (solid curves). The left panel shows the results obtained with a linear spectrum without baryon contributions. The right panel illustrates the effects of including baryons (we have used, in particular, $\Omega_{b0} = 0.046$).

Numerical investigations

Summary

- Cosmology with SNe involves a flux measurement which is not as difficult as the shape measurement for cosmic shear
- Large increase in the statistics is granted in the coming years
- Two challenges
  - Improving the standardisation scheme
  - Replacing the stellar flux references with laboratory standards
- One open question: sample contamination in absence of live spectroscopy
- Even if the open challenges are not met, SNe are going to be interesting for isotropy

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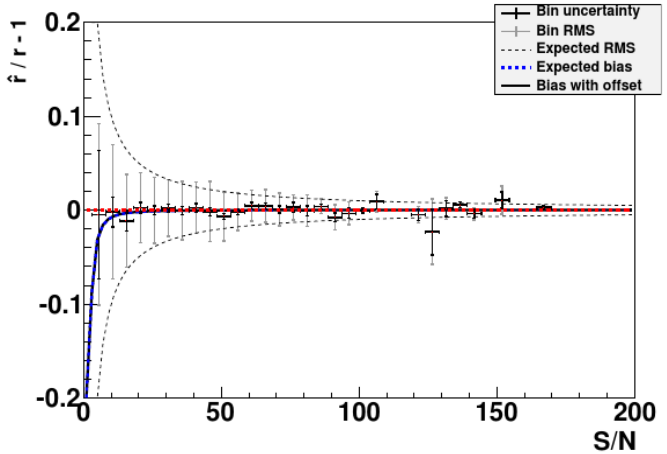
Accuracy of the SN photometry (relative to stars)

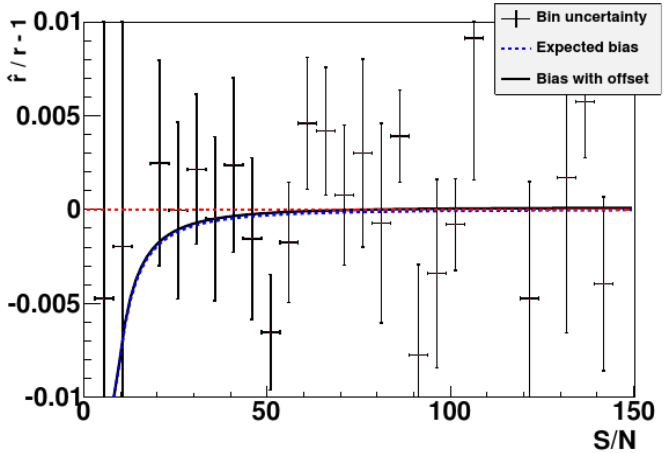
- Star and SN photometry differ in gal flux modeling
- Tested on realistic simulation
- No bias measured 0.00012 ± 0.0009

Although it takes quite a lot to reach that results

(Astier et al. 2013)



(a) For a wide range of S/N ratios



(b) Zoom on low S/N region