Latest constraints on Dark Energy from the Supernova Cosmology Project and Self Calibration

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Outline

- Latest cosmological results from Union2
- Zero-point uncertainties are important !
- Kim & Miquel (2006, hereafter KM) introduce a better way to treat them, used by Union2
- Idea: treat Zero-point uncertainties as nuisance parameters
- Introduce the method
- Example of future experiment: SNAP/JDEM/WFIRST
- Main take away message:

The method is general and can be used in future experiments

A Quick Introduction to Dark Energy

- Usually parametrized by an equation of state parameter:

$$P = w(z)\rho$$

- In principle w is time dependent; a cosmological constant is equal to -1 at all times
- w(z) often parametrized as $w(z)=w_0+w_a z/(1+z)$
- The data so far favor a Lambda Cold Dark Matter Model (LCDM), (i.e a cosmological constant)
- **But it is by no means firmly established that a cosmological constant is the correct explanation for the observed cosmic acceleration**

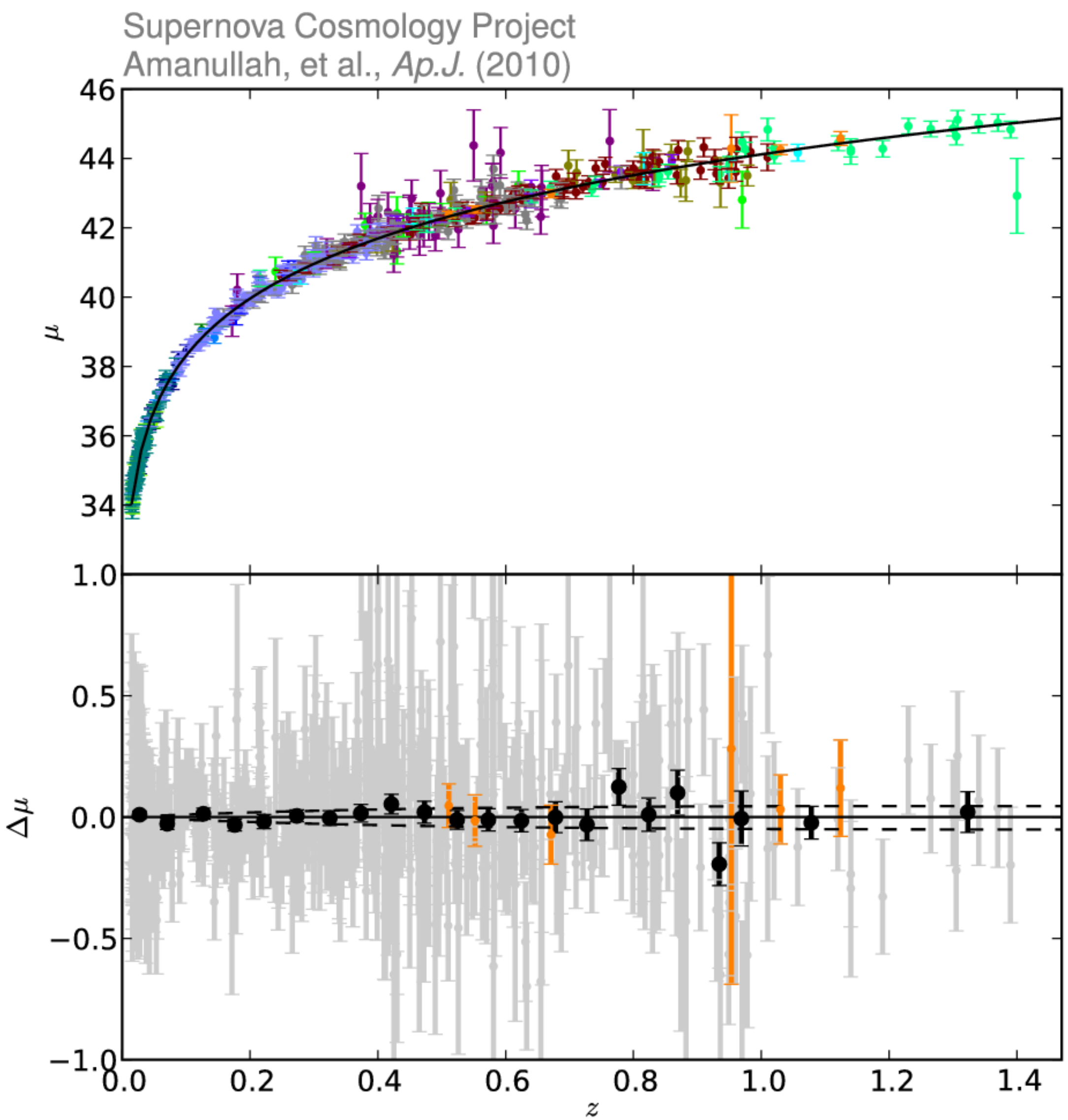
The (Union2) Compilation of the World SNe

- Compilation of 557 SNe uniformly analyzed
- Provides the best constraints to date on dark energy
  - —LCDM still a good fit to the data

$$w = -0.997^{+0.050}_{-0.054}(\mathrm{Stat})^{+0.077}_{-0.082}(\mathrm{Stat+Sys})(\mathrm{FlatUniverse})$$
$$w = -1.038^{+0.056}_{-0.059}(\mathrm{Stat})^{+0.093}_{-0.097}(\mathrm{Stat+Sys})(\mathrm{WithCurvature})$$

  - —The data however do not constrain well dark energy at *z>1*
  - —Systematic errors are approaching the size of statistical errors
  - —Zero-point uncertainties among the most important systematics
  - —KM used to reduce systematic uncertainty
- Results published in Amanullah et al 2010, ApJ, 716, 712
- Check out the website at: http://supernova.lbl.gov/Union/

The Union2 Hubble Diagram



551 SNe selected from several surveys

6 new SNe at mid and high z

Uniform analysis of all SNe

Blind analysis to avoid biases

Largest Hubble diagram to date: 557 SNe

Tightest constraints on dark energy to date

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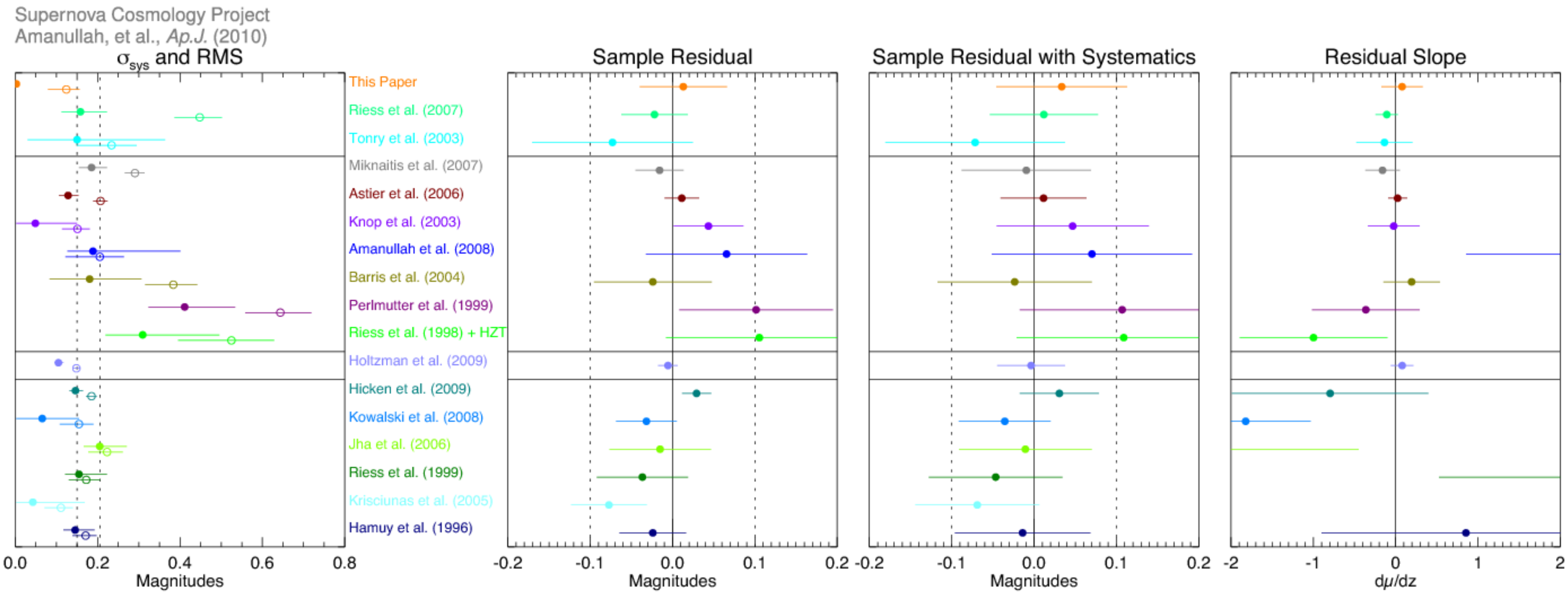
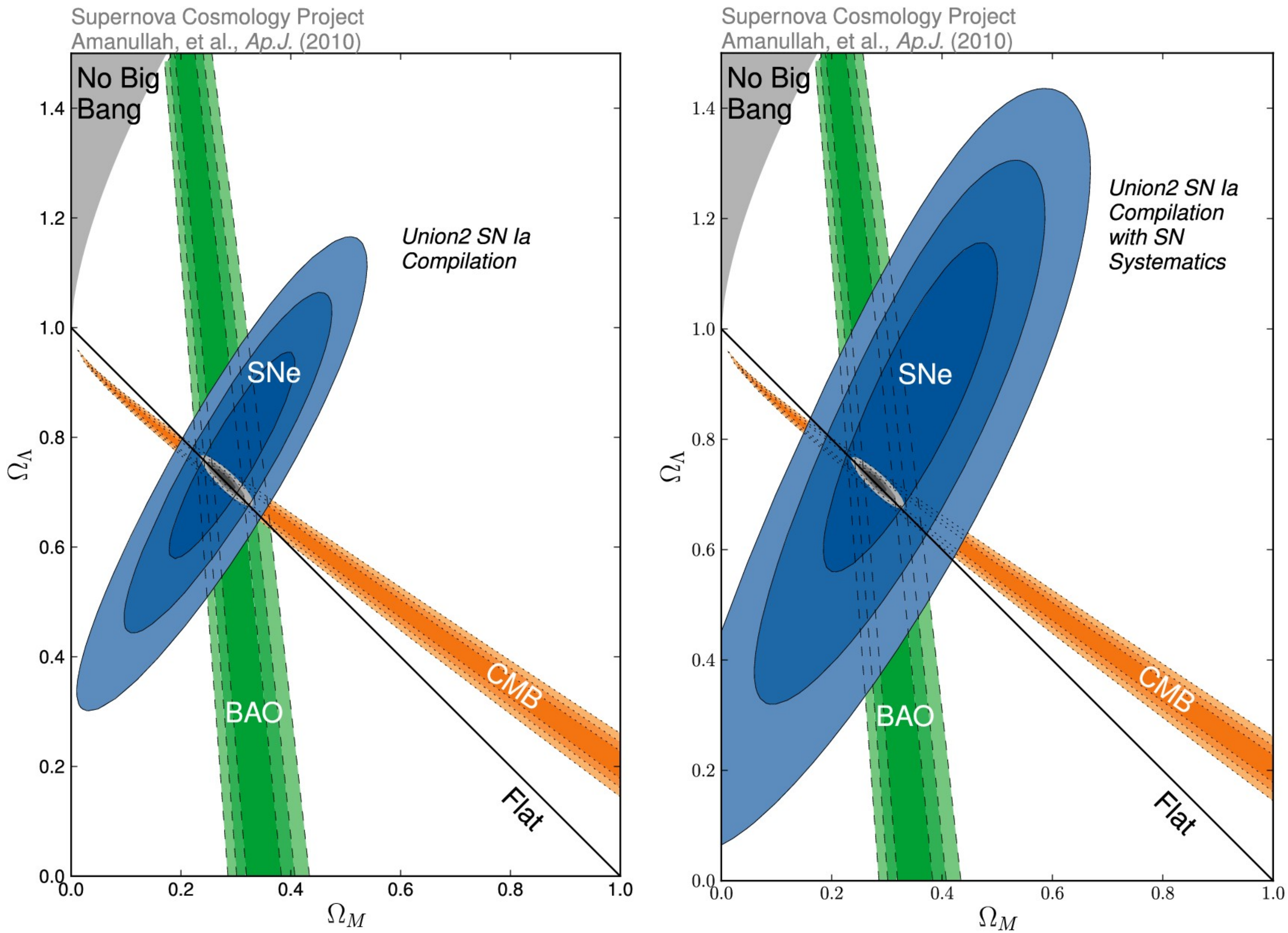
Diagnostic Tests



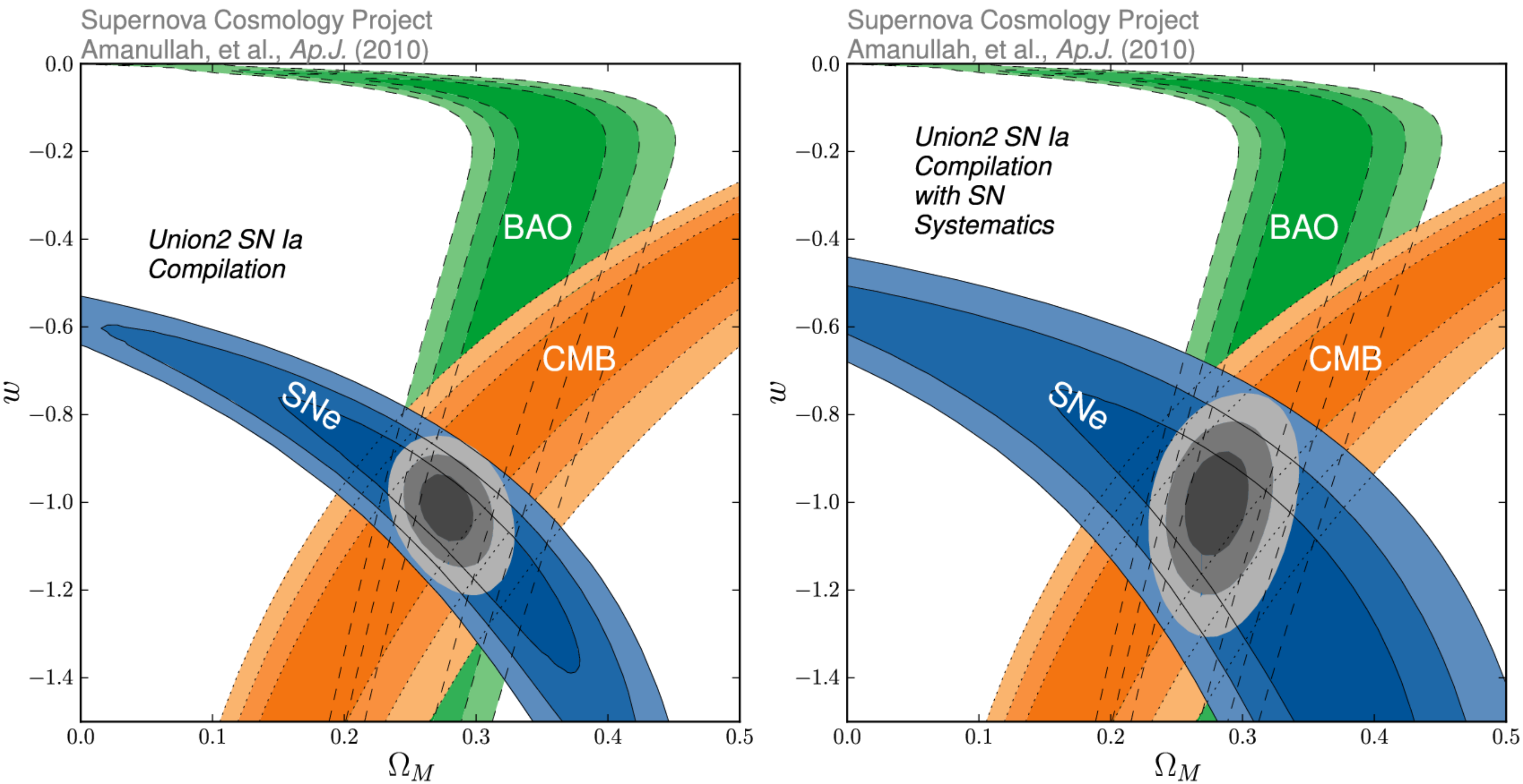
The large number of SNe allows us to run diagnostic tests and see tensions between samples

Constraints on Ω_M and Ω_Λ



68.3%, 95.4%, and 99.7% confidence regions without and with systematics with CMB and BAO
w=-1 assumed

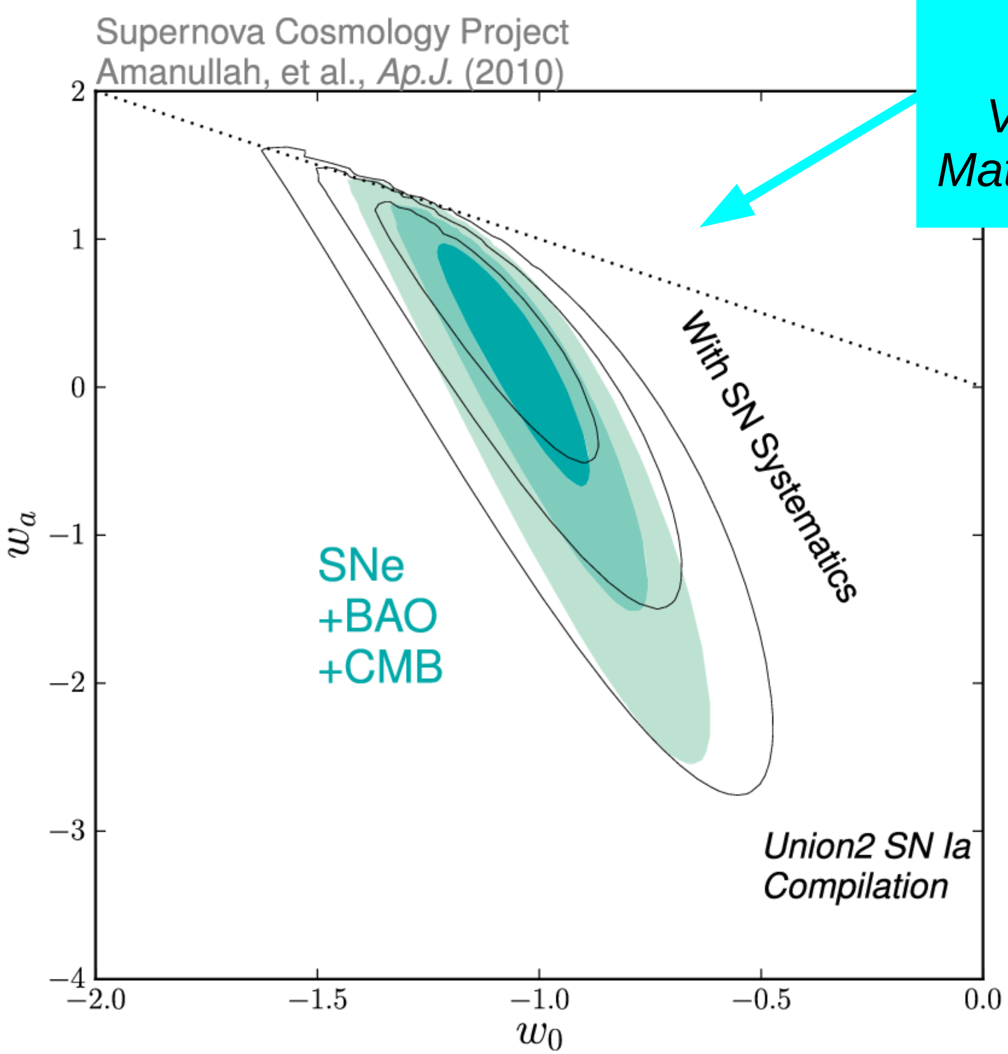
Constraints on Ω_M and w



68.3%, 95.4%, and 99.7% confidence regions without and with systematics with CMB and BAO
zero curvature and constant *w* assumed

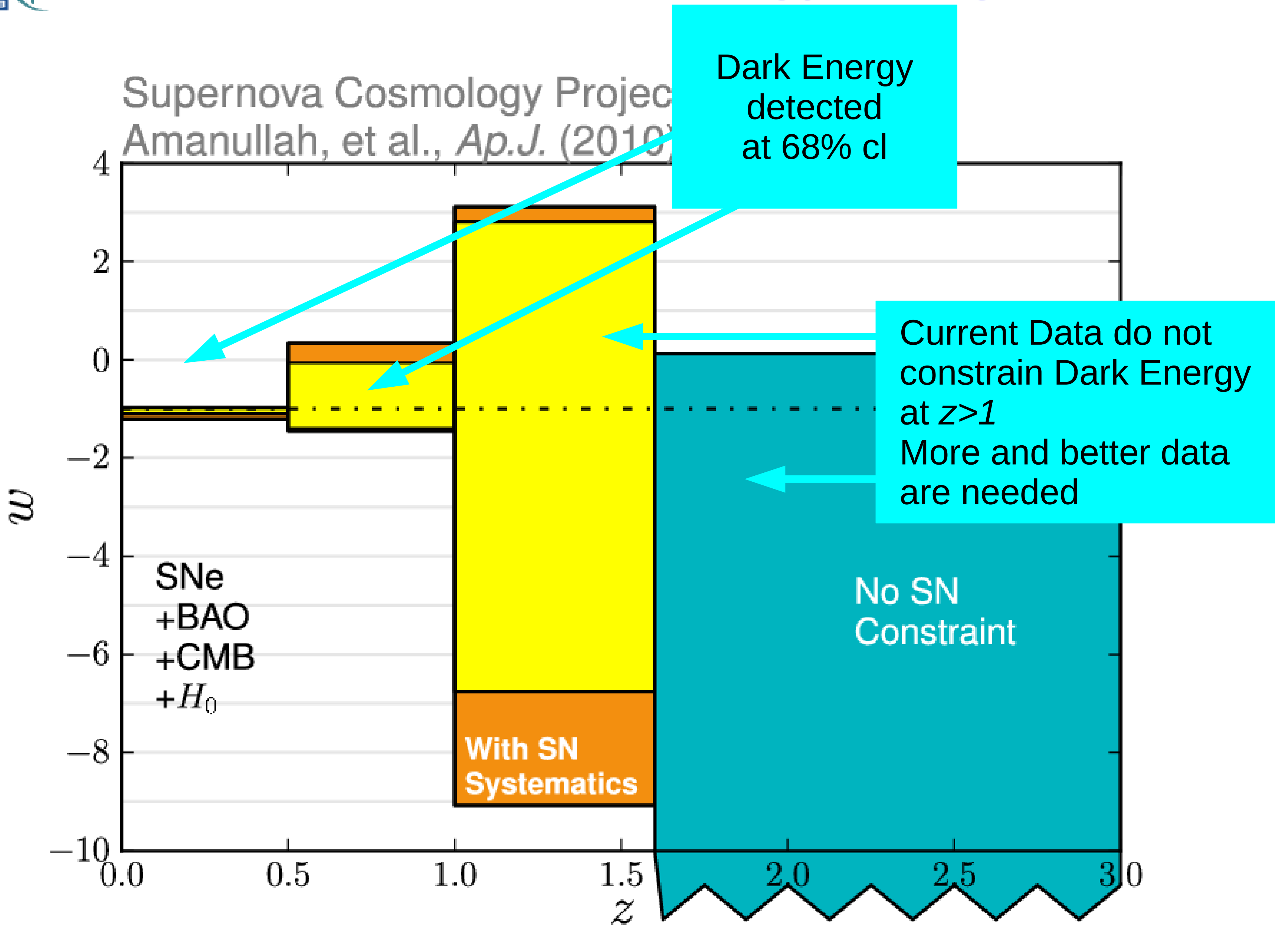
Constraints on w_0 and w_a

$w_a+w_0>0$
Violates Early Matter Domination



68.3%, 95.4%, and 99.7% confidence regions without (shaded) and with (solid) systematics with CMB and BAO, zero curvature assumed; above the line early matter domination is violated

Do We See Dark Energy at High *z* ?



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Summary of Union2 Systematics

Source	Error on *w*
Zero point	0.037
Vega	0.042
Galactic extinction normalization	0.012
Rest-frame *U* band	0.010
Contamination	0.021
Malmquist bias	0.026
Intergalactic extinction	0.012
Light-curve shape	0.009
Color correction	0.026
Quadrature sum (not used)	0.073
Summed in covariance matrix	0.063

Table from Amanullah et al 2010, ApJ, 716, 712

Important Lessons from the Union2 Compilation

- Main conclusion: current data **do not constrain dark energy at *z*>1**
- Need more and better data: **JDEM**
- Other important lessons:
  - —Zero-point uncertainties among the most important source of systematic
  - —Idea: treat them as nuisance parameters to be fitted (this can be applied to other systematics as well, as done by Union2)

The Joint Dark Energy Mission (aka JDEM)

- Proposed space-based, stage IV dark energy experiment to study dark energy with multiple probes, including type Ia supernovae
  - The Union2 results show the need for JDEM
- JDEM will be systematics limited
  - For Union2 statistical and systematic errors are about the same already
- Calibration uncertainties will be among the most important systematics
  - Imperative to treat them properly: KM introduce a better way

A Better Treatment of Systematics (1)

- Key observation: type Ia supernovae are standardizable candles
  - This means that after stretch and color correction their absolute magnitudes in a band are the same.
- Zero-point uncertainties will affect all the supernovae in the same way
  - Supernovae observed in the same filter will be equally affected: their observed magnitude will depend on their distance, their absolute magnitude (same after standardization) and the same filter Zero-point uncertainty.

A Better Treatment of Systematics (2)

- Here's the algorithm:
  - —Treat filter Zero-point uncertainties as nuisance fit parameters
  - —Fit for all SNe at once with these additional fit parameters and derive distance moduli for all SNe with their covariance matrix (we will call this approach simultaneous fit)
  - —Do the cosmology fit
  - —w_0,w_a uncertainties are reduced because of self calibration
- Faccioli et al, 2010, (hereafter F10, submitted to Astroparticle Physics, arXiv:1004.3511) use this approach to investigate Zero-point uncertainties in future experiments
  - —Focus on JDEM, but method is general

Comparison with the Usual Approach

- The usual approach in treating Zero-point uncertainties is:
  - —Consider each SN in the survey separately and derive its distance modulus with an uncertainty (we will call this approach the SN by SN fit)
  - —Derive the cosmology
    - Compute a covariance matrix for each systematic separately, including Zero-point uncertainties
    - Add them to the covariance matrix of the distance moduli computed above
    - Do the cosmology fit.

Investigating Zero-point Uncertainties in JDEM

- We study a large set of mission configurations
  - —Different number of SNe and maximum survey redshifts
  - —Inclusion of color uncertainties
    - Important note: **by color uncertainties we mean in the following a residual, band dependent uncertainty that is left after the supernova color had been determined**
  - —Inclusion of other systematic error models, such as the Linder & Huterer (LH) systematic.
- F10 incorporate all this in the SNAP/JDEM simulation tool, SNAPsim
  - —Originally developed for SNAP, now part of JDEM/WFIRST

Mathematical Model of Simultaneous Fit

$$
\begin{aligned}
m_k^1 &= \mu^1 + \alpha(S^1 - 1) + M(z_1)_k + {A_V}^1 a(z_1)_k + (\frac{A_V}{R_V})^1 b(z_1)_k + \mathcal{Z}_k \\
{s^1}_k &= S^1 \\
&\vdots \\
m_k^N &= \mu^N + \alpha(S^N - 1) + M(z_N)_k + {A_V}^N a(z_N)_k + (\frac{A_V}{R_V})^N b(z_N)_k + \mathcal{Z}_k \\
{s^N}_k &= S^N \\
{\mathcal{Z}^{\mathrm{obs}}}_k &= \mathcal{Z}_k
\end{aligned}
$$

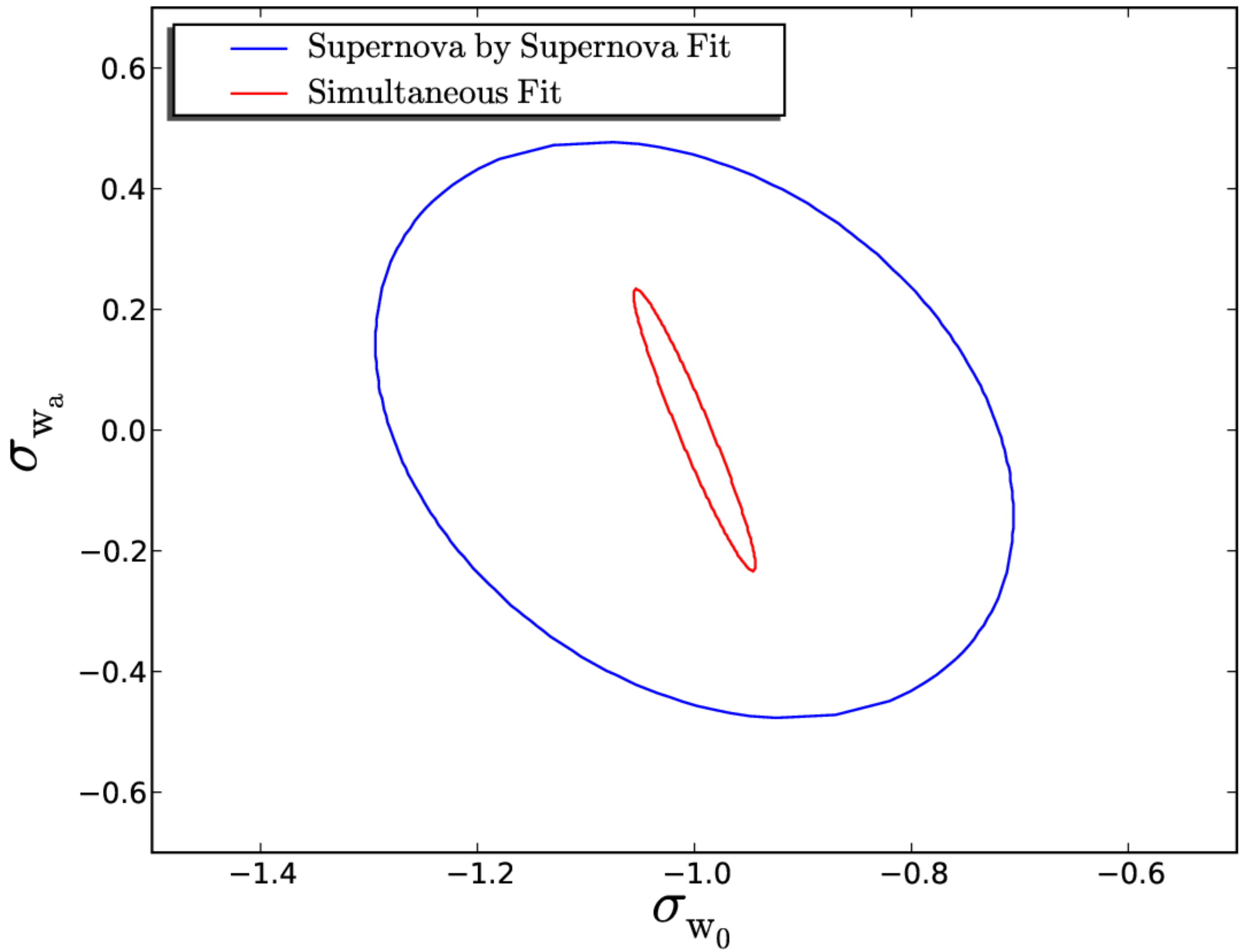
Running the Simulations

- We first compare simultaneous fit vs SN by SN fit; then we explore the survey parameter space
  - —We are interested in the best we can do for given number of observed SNe, *N*, or maximum redshift *z*, therefore we vary them independently of each other
  - —We do not consider joint constraints on *N* and *z* imposed by survey duration (important, but is is not the focus of our study)
- Baseline survey configuration:
  - —Aperture 1.5 m
  - —8 Filters, 5 visible, 3 NIR
  - —2000 SNe with flat z distribution + 316 nearby (0.03<z<0.08).
  - —Maximum survey redshift 1.5

Simulating the SN by SN fit with MC

- We simulate a Zero-point covariance matrix via MC
  - —create SN models at specific *z*s, add random shifts, find μ
  - —Build a μ covariance matrix for the SNe from all MC runs
  - —Store this matrix for future use
- For each SN pair in the real dataset (or in the dataset that simulates future real datasets such as JDEM's)
  - —Spline interpolate the Zero-point covariance matrix to obtain the Zero-point covariances of the two SNe
  - —Obtain a Zero-point covariance matrix for the dataset
- Add this covariance matrix to the other matrices and do the cosmology fit

Supernova by Supernova Fit vs Simultaneous Fit: Error Ellipses



N_{sn}=2000

Z_{max}=1.5

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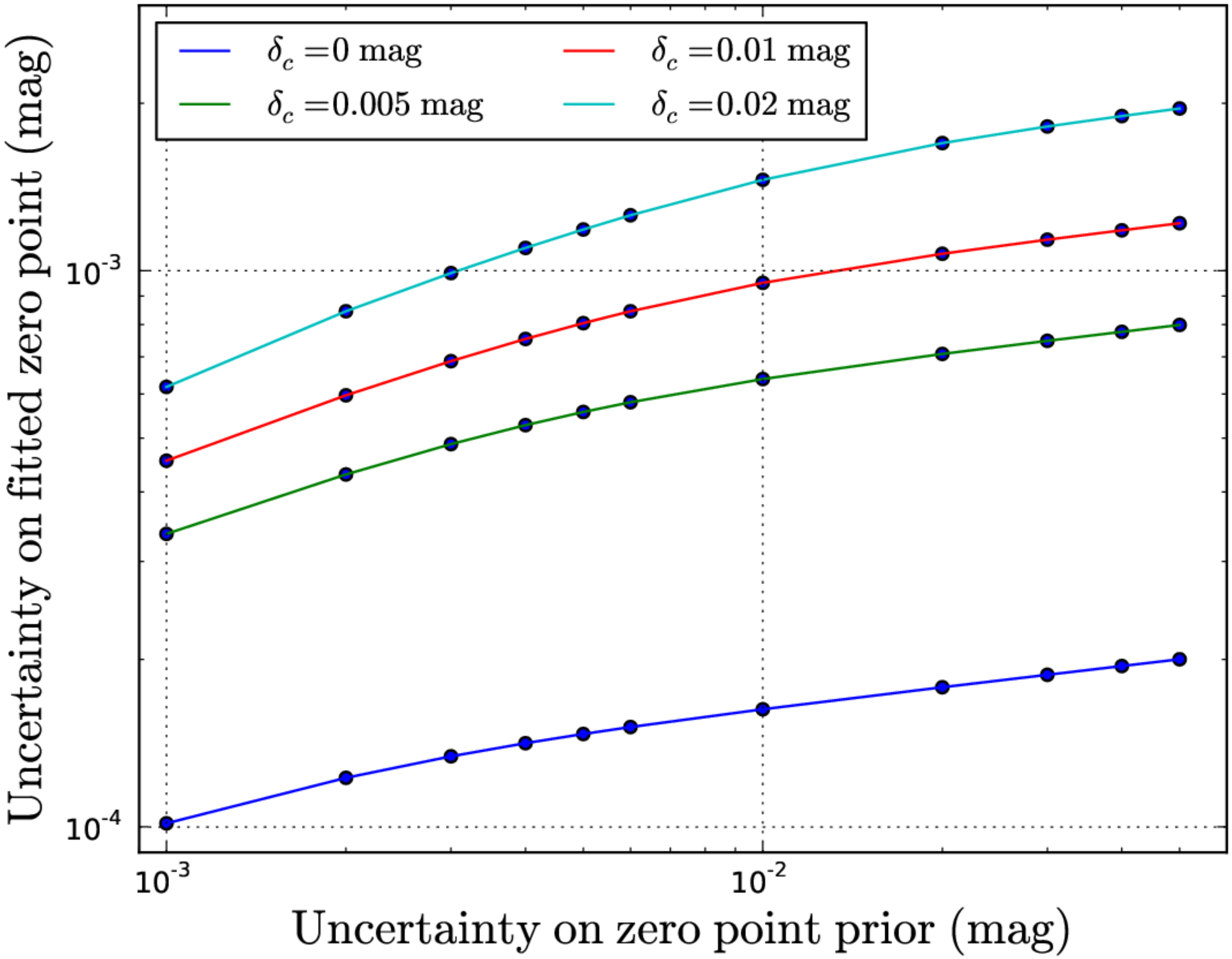
Supernova by Supernova Fit vs Simultaneous Fit: Results

Zero-point prior	Figure Of Merit							
	Color uncertainty 0		Color uncertainty 0.005		Color uncertainty 0.01		Color uncertainty 0.02	
	SN by SN	Sim Fit	SN by SN	Sim Fit	SN by SN	Sim Fit	SN by SN	Sim Fit
0	311	311	306	306	295	295	262	262
0.001	246	309	244	302	238	288	217	252
0.002	167	309	166	298	163	283	153	246
0.003	122	308	121	295	120	278	113	239
0.004	95	308	94	292	93	273	88	232
0.005	76	308	76	291	75	268	71	226
0.006	63	308	62	290	61	265	58	219
0.01	35	308	35	288	35	257	33	202
0.02	17	308	17	287	17	252	16	186
0.03	11	308	11	286	10	251	10	181
0.04	7	308	7	286	7	251	7	179
0.05	NC	308	NC	286	NC	250	NC	179

Zero-point prior and color uncertainties in mag
Figure of Merit (FoM): inverse of the error ellipse area in the $w_{0,}\ w_a$ plane

The simultaneous fit outperforms the SN by SN fit, both without and with color uncertainty

Self Calibration in Action

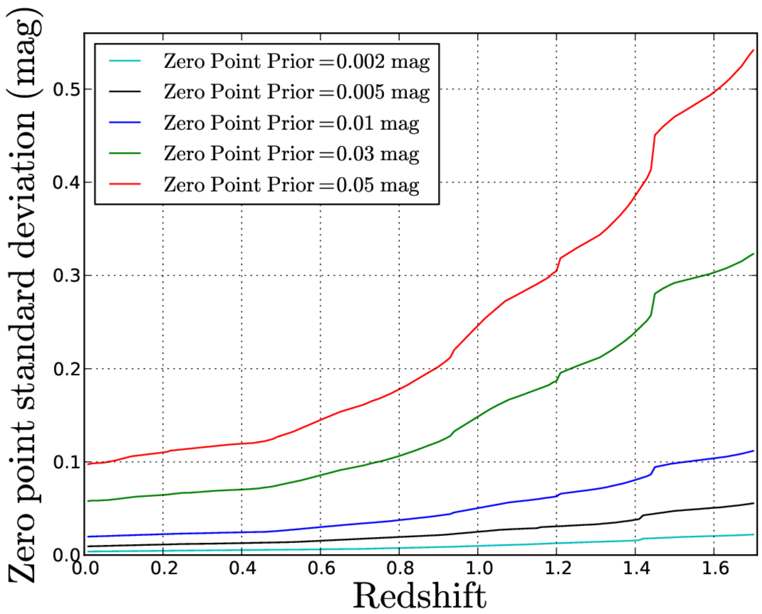


The uncertainty on the filter parameters after the fit is at least one order of magnitude smaller than the prior uncertainty

N_{sn}=2000
Z_{max}=1.5

Why is the SN by SN fit so bad?

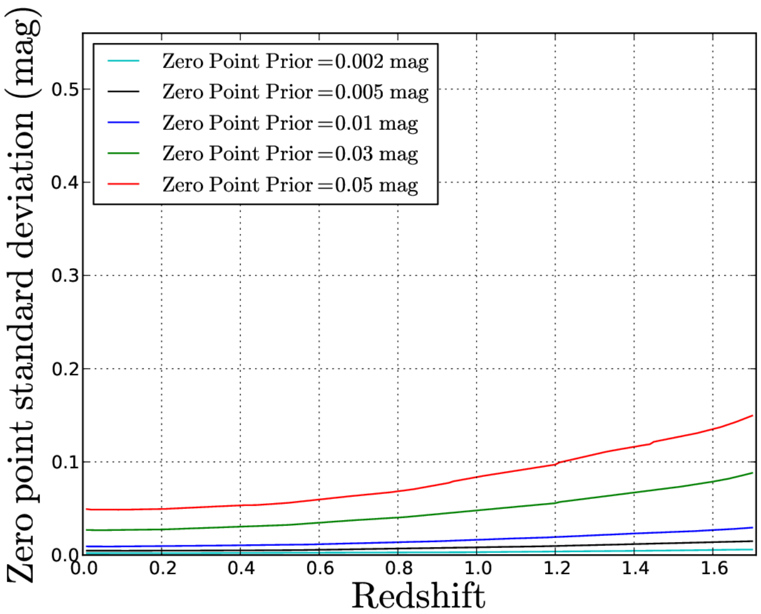
Zero-point standard deviations estimated from Monte Carlo vs *z*



Fitting for dust parameter

$\boldsymbol{B_v = A_v / R_v}$

(Used in the simulations)



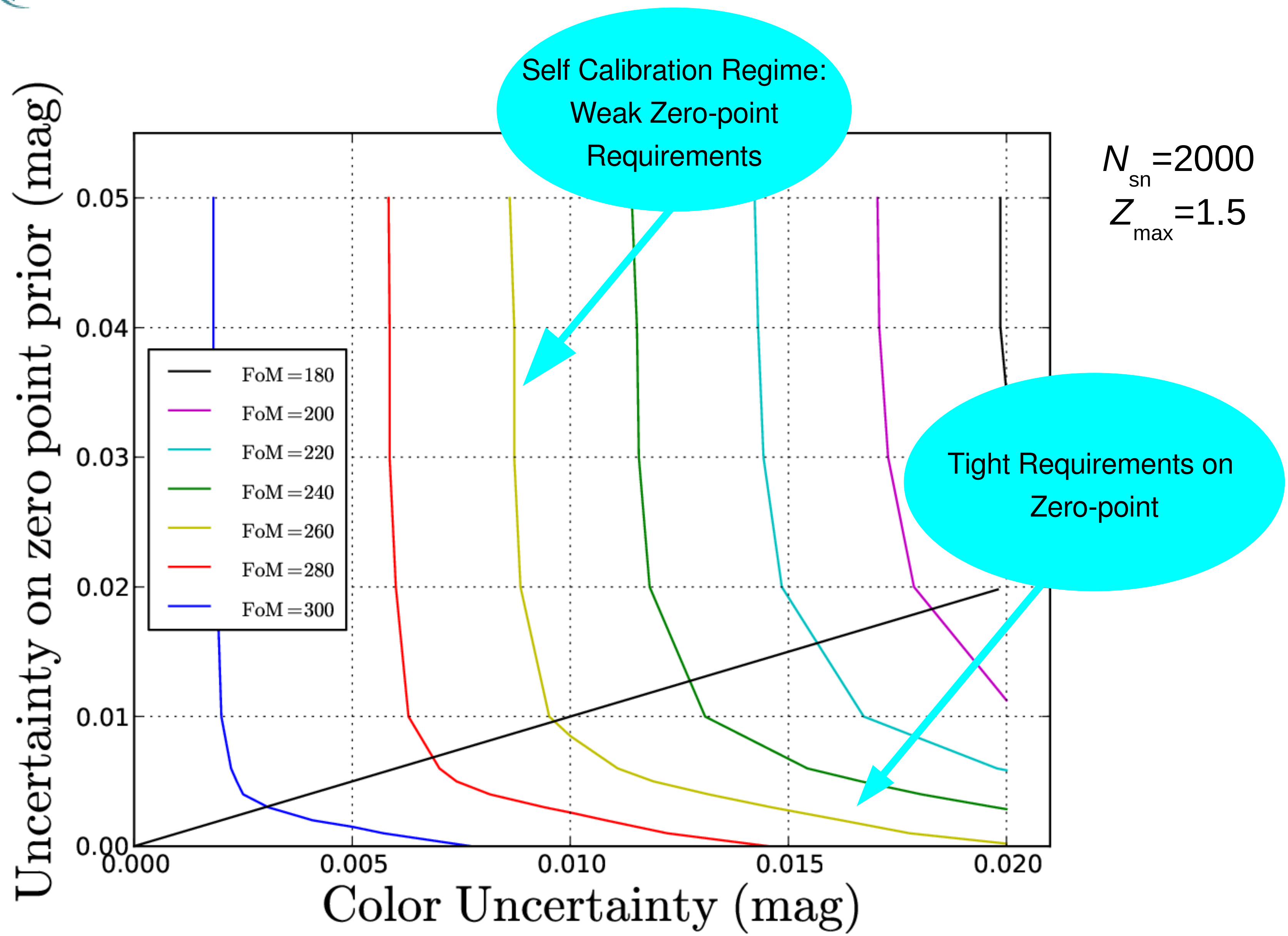
Dust parameter $\boldsymbol{B_v = A_v / R_v}$

fixed to 3.1

(Not used in the simulations)

- Fitting for B_v increases the Zero-point standard deviations by factor of ~3, degrading the fit performance in the SN by SN fit
- We cannot assume a Milky Way extinction law: need to fit for B_v

Zero-point vs Color Uncertainty



N_{sn}=2000
Z_{max}=1.5

Varying the Baseline Survey

- Starting from the baseline survey we varied independently
  - —The number of observed SNe.
  - —The maximum survey redshift.
  - —The maximum allowed prior zero-point uncertainties.
- Results shown as contours of constant FoM with two of the above parameters varying and the third fixed
- We include the LH systematic to describe other sources of systematic uncertainty
- In the following we assume a color uncertainty 0.01 mag.

The Linder Huterer Systematic

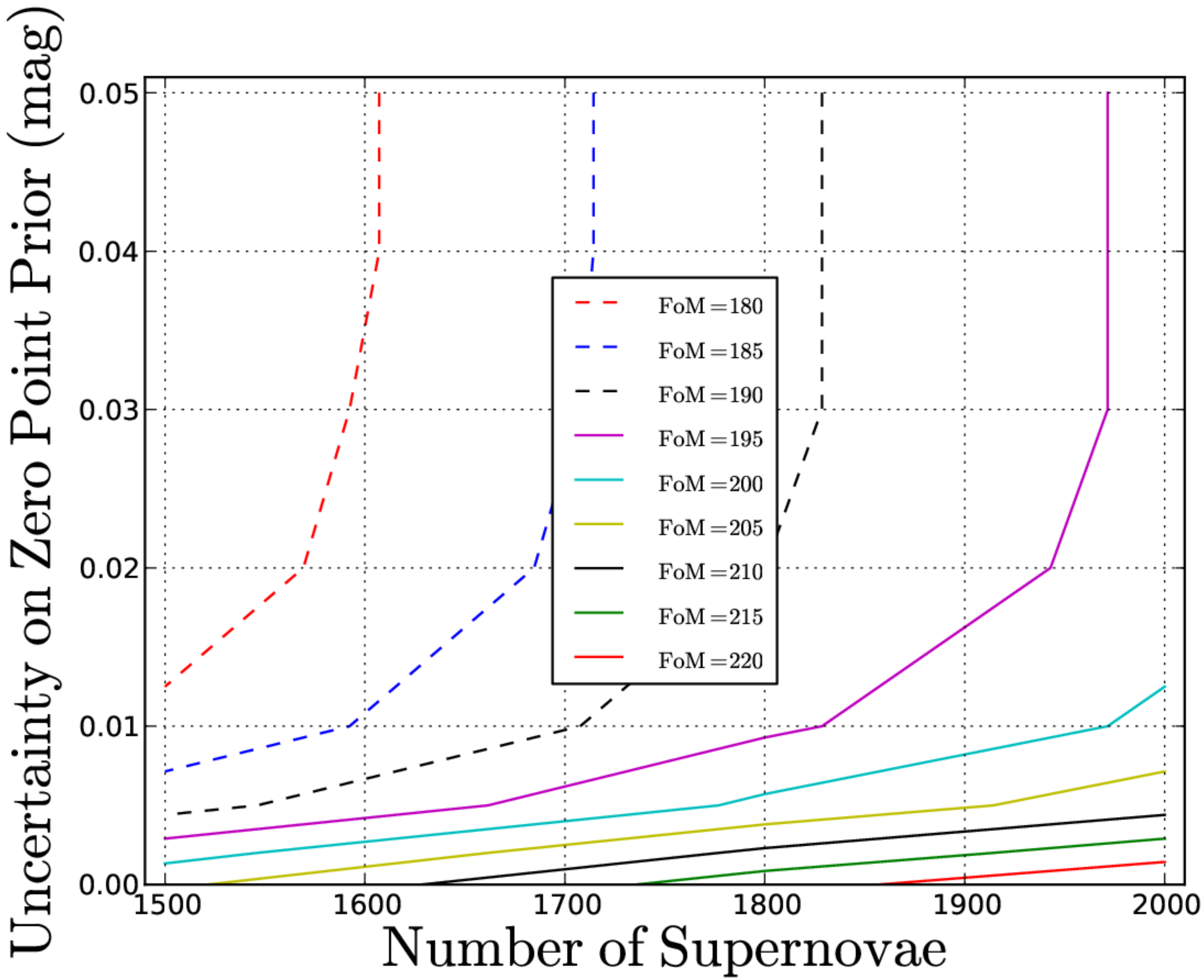
Linder & Huterer (2003) introduce a systematic error model:

$$\Delta\mu = 0.02\frac{1+z}{1+z_{\rm max}}$$

We include one half of this systematic to model other systematics:

—LH covariance matrix added to the distance modulus covariance matrix before doing the cosmology fit.

Zero-point Prior vs Number of SNe



Z_{max}=1.5
Color Uncertainty=0.01

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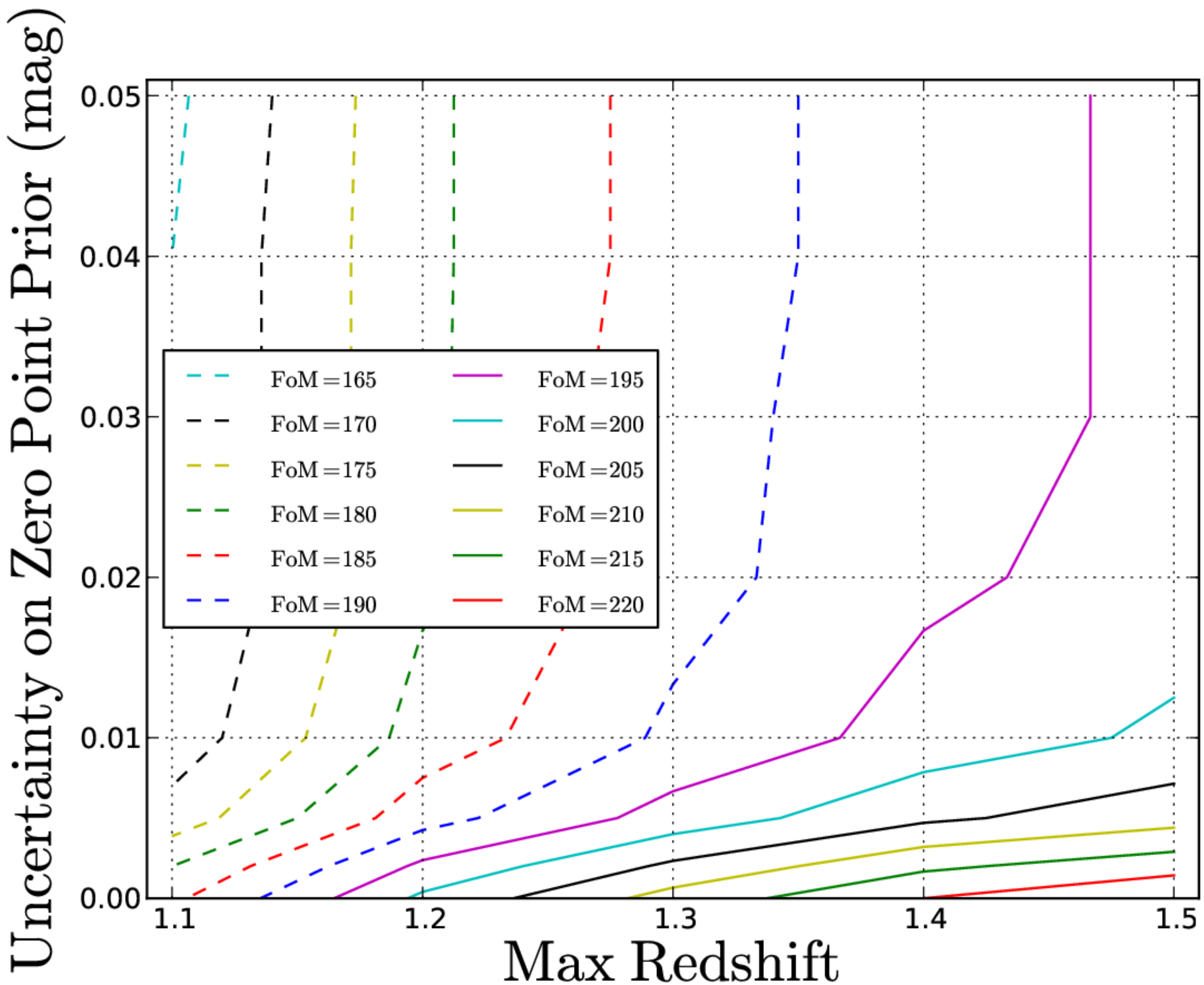
Zero-point Prior vs Maximum Redshift



N_{sn}=2000

Color Uncertainty=0.01

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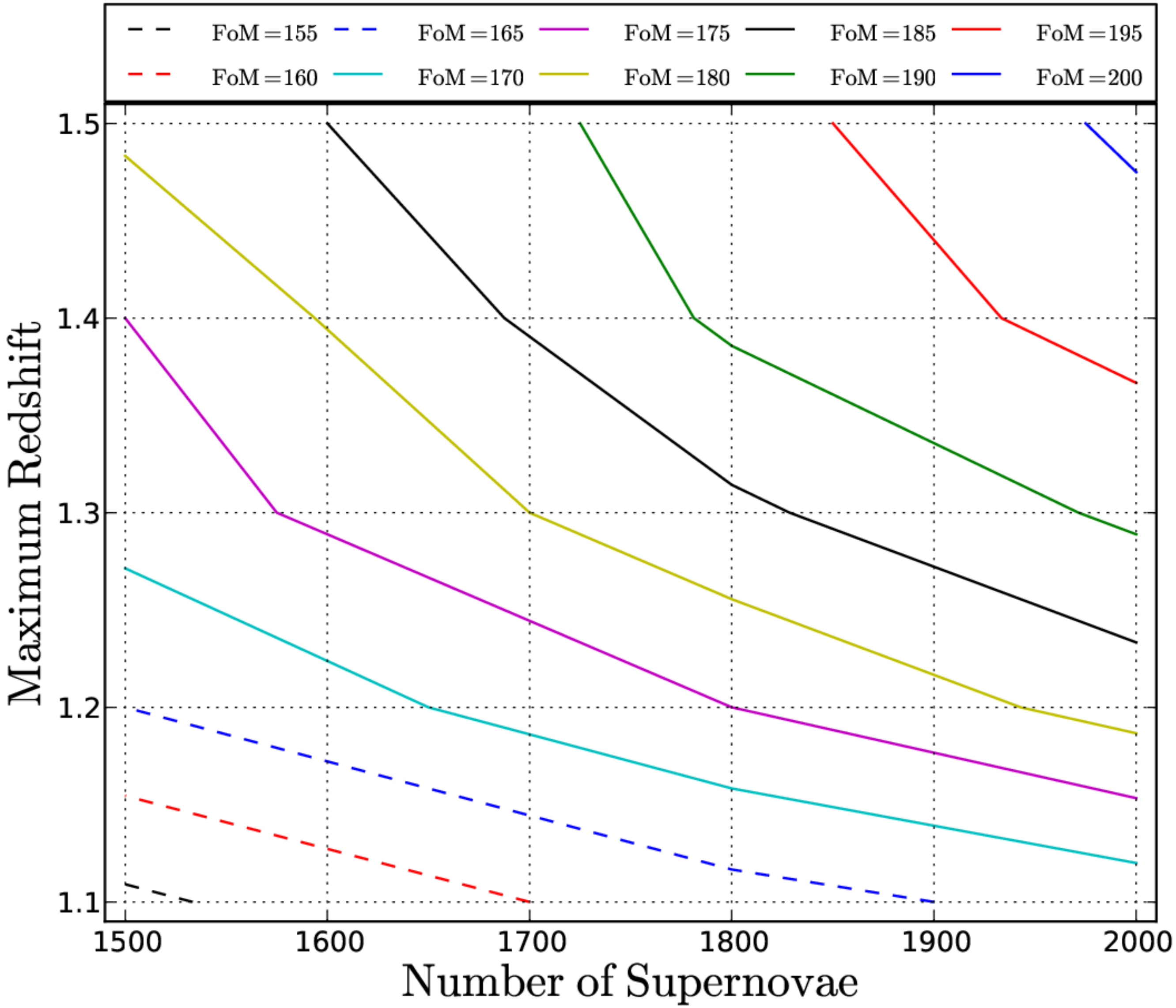
Maximum Redshift vs Number of SNe



Zero-point prior=0.01
Color Uncertainty=0.01

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Conclusions

- Current data do not constrain dark energy at $z>1$
  - —**JDEM needed to do better**
- Zero-point uncertainties are among the most important systematic in supernova dark energy experiments
- KM introduce a better and general way of dealing with them
- Union2 use KM to reduce their overall systematic and achieve the tightest constraints on dark energy to date
- F10 apply the approach to study future experiments, taking as example JDEM/SNAP; more studies can be done
- Our simulation tool allows for much more comprehensive studies of future missions

The Future

- F10 consider SNAP/JDEM but the method is general and recommended for future experiments (DES, JDEM, LSST)
- The parameters space to explore is vast and F10 only consider a part of it; however our simulation tool can easily sample the whole space and produce comprehensive studies of future experiments
- Other sources of systematics (e.g. LH) are important; crucial to better study them before stage III and IV experiments get under way
- More work to be done: e.g. better treatment of host galaxy extinction (so far we assumed CCM)