Probing Dark Energy: combining SNe and the CMB

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Dark Energy from SNe Ia: Toward the realistic assumptions...

- dark energy remains important out to $z \approx 2$

- possibility that w is time-varying.

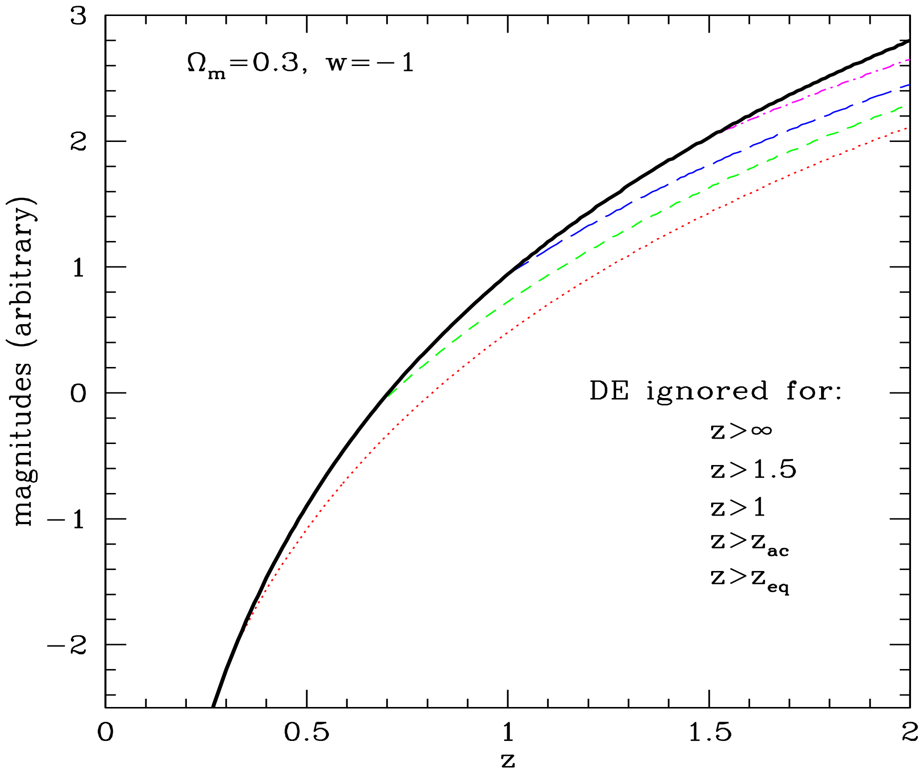
  E.g., $w(z) = w_0 + w_1 z$

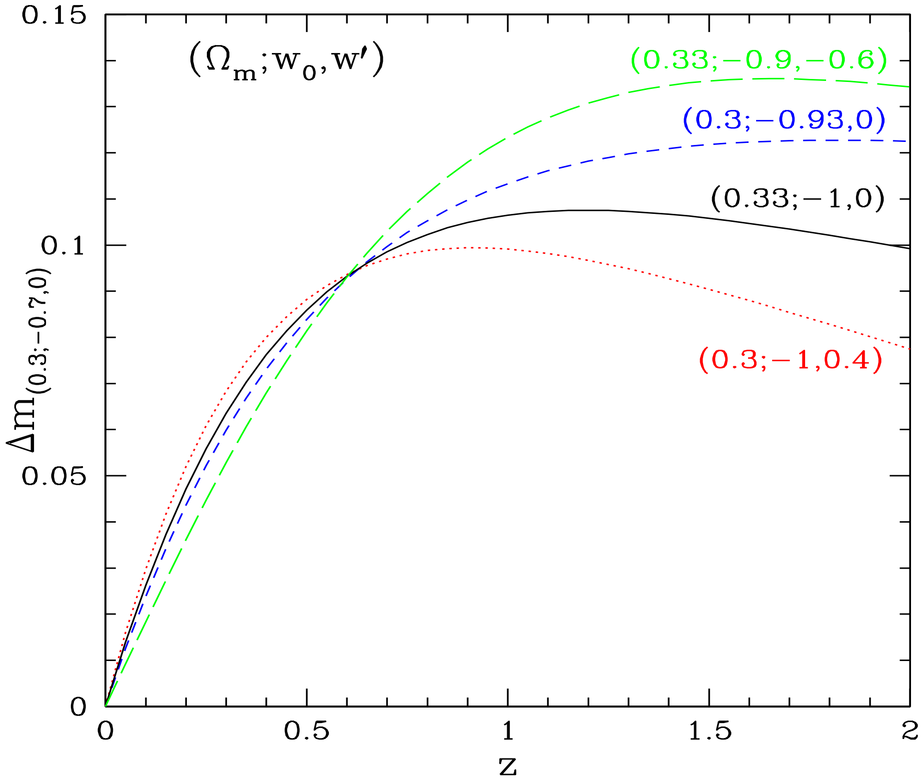
- presence of a systematic error:

$$\sigma = \sqrt{0.02^2 + \frac{0.15^2}{N_i}} \text{ magnitudes}$$

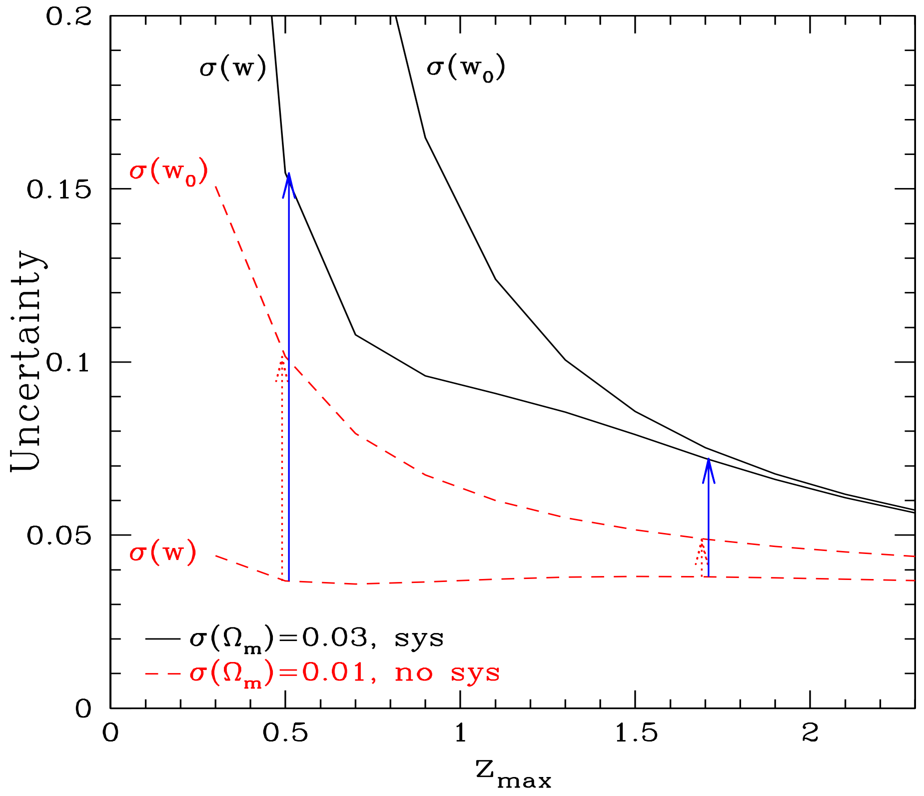
- realistic CMB/LSS priors

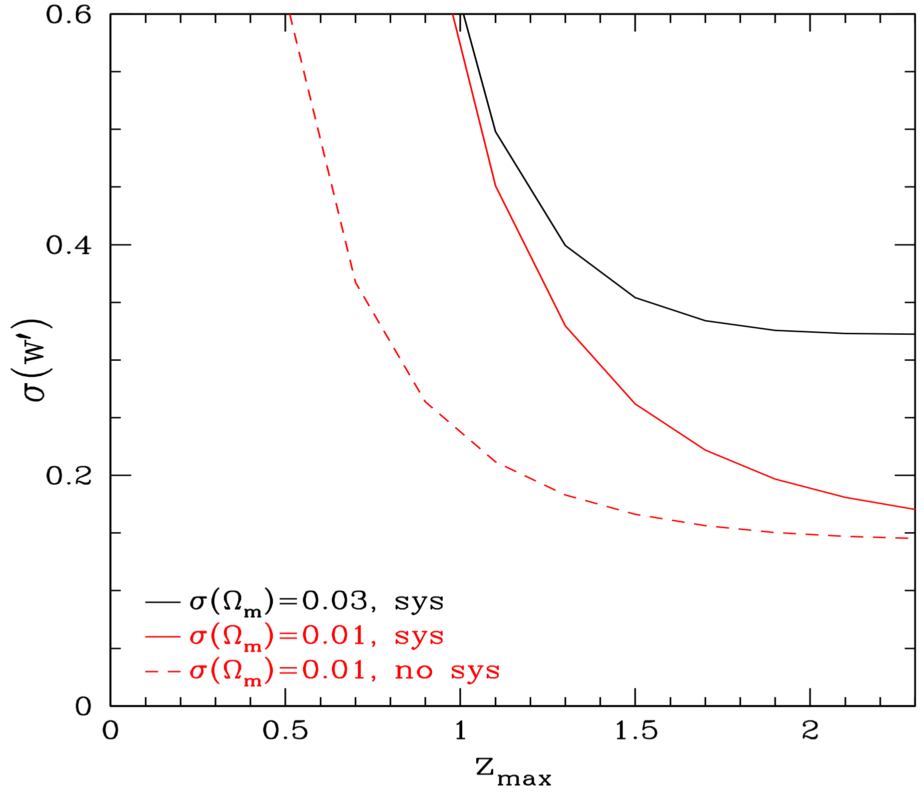
Importance of SNe at high redshift



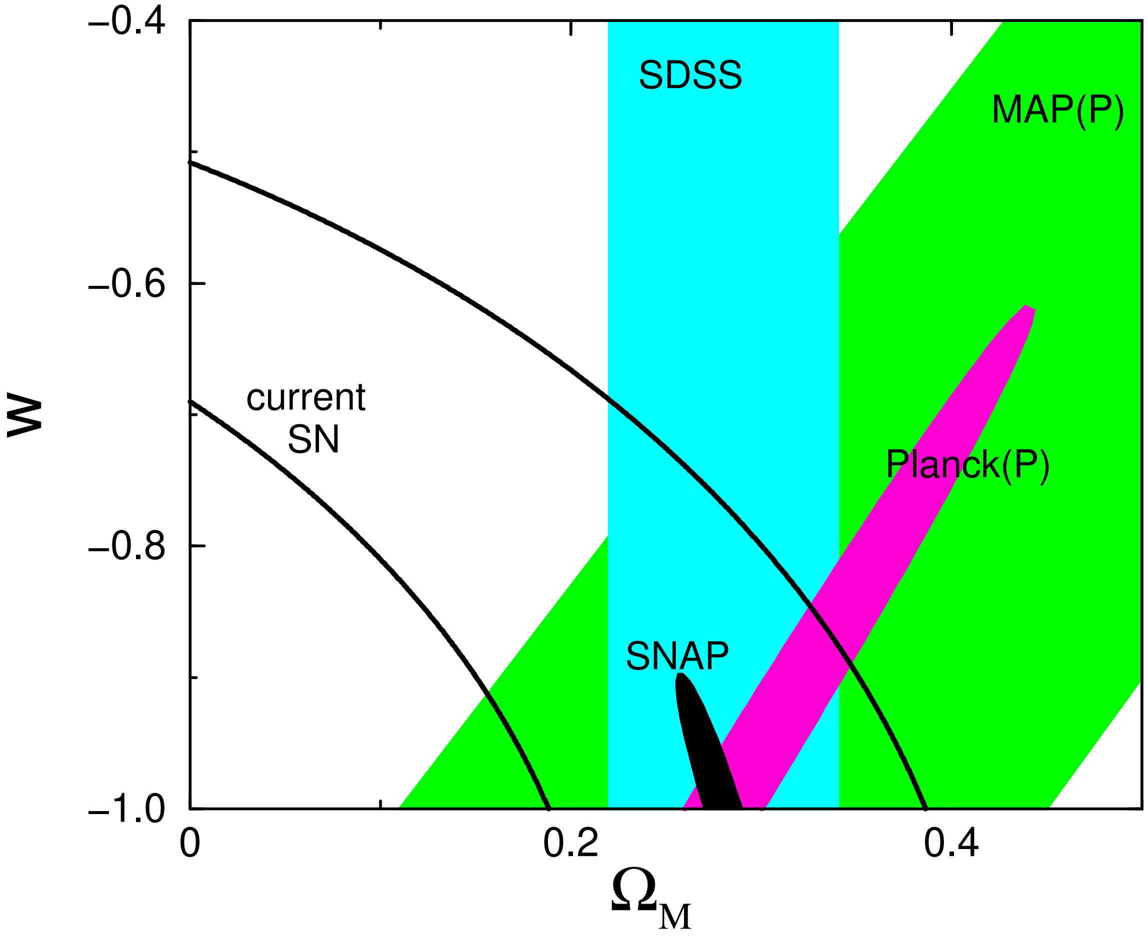


Including the systematics and evolving w





SNe+CMB Complementarity



CMB

- measure $\theta = \eta_{SH}/\eta_{LSS}$

- angular power spectrum peak locations ($l \propto 1/\theta$) depend on Ω_M, w, $\Omega_M h^2$, $\Omega_B h^2$:

$$\frac{\Delta l_1}{l_1} = -0.084\Delta w - 0.23\frac{\Delta\Omega_M h^2}{\Omega_M h^2} + 0.09\frac{\Delta\Omega_B h^2}{\Omega_B h^2} + 0.089\frac{\Delta\Omega_M}{\Omega_M} - 1.25\frac{\Delta\Omega_{\rm TOT}}{\Omega_{\rm TOT}}$$

- $\Omega_M h^2$, $\Omega_B h^2$ to be determined to a high (percent) accuracy from morphology of the peaks

- remaining dependence on Ω_M, w:
  a measurement of $\eta(z = 1100)$ *with* $\Omega_M h^2$ *fixed*

$$\eta = \frac{1}{\sqrt{\Omega_M H_0^2}} \int_0^z \frac{dz}{\sqrt{(1+z)^3 + \frac{1-\Omega_M}{\Omega_M}(1+z)^{3(1+w)}}}$$

- end up constraining: $\mathcal{D} \equiv \Omega_M - 0.28(1+w) \approx 0.3$
  (Planck: $\mathcal{D}$ to $\sim 10\%$)

- sensitive only to $\langle w \rangle$

SNe

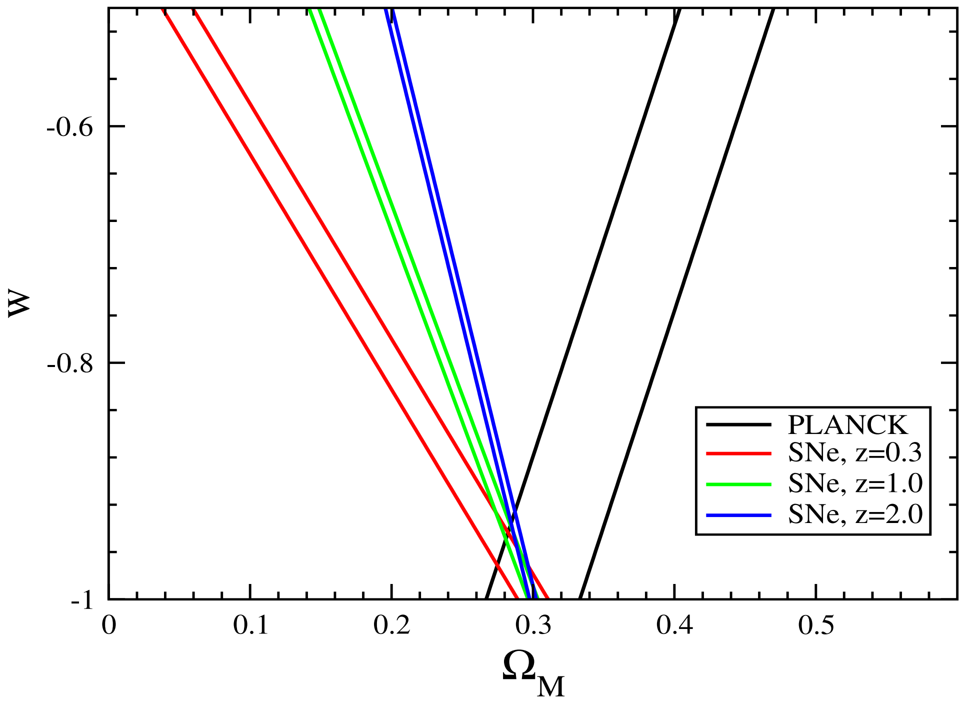
$$F(z) = \frac{\mathcal{C}10^{-0.4M}}{4\pi d_L^2} = \frac{(10^{10}\mathcal{C}/4\pi)10^{-0.4\mathcal{M}}}{H_0^2 d_L^2}$$

$$\mathcal{M} = M - 5\log(H_0) + 25$$

- Measurements depend on Ω_M, w, and $\mathcal{M}$
- The CMB prior on $\Omega_M h^2$ does not help, *unless* we have independent info on the Hubble parameter:
  1) from direct measurements, or
  2) from measurements of $\mathcal{M}$ *and* M
- $\mathcal{M}$ can be determined from a low-z sample of SNe
  (to $\pm(0.01 - 0.02)$ from the Nearby Supernova Factory)
- sensitive to $w(z)$

Varying the redshift of SNe

Assume for a moment all SNe are at a single redshift:

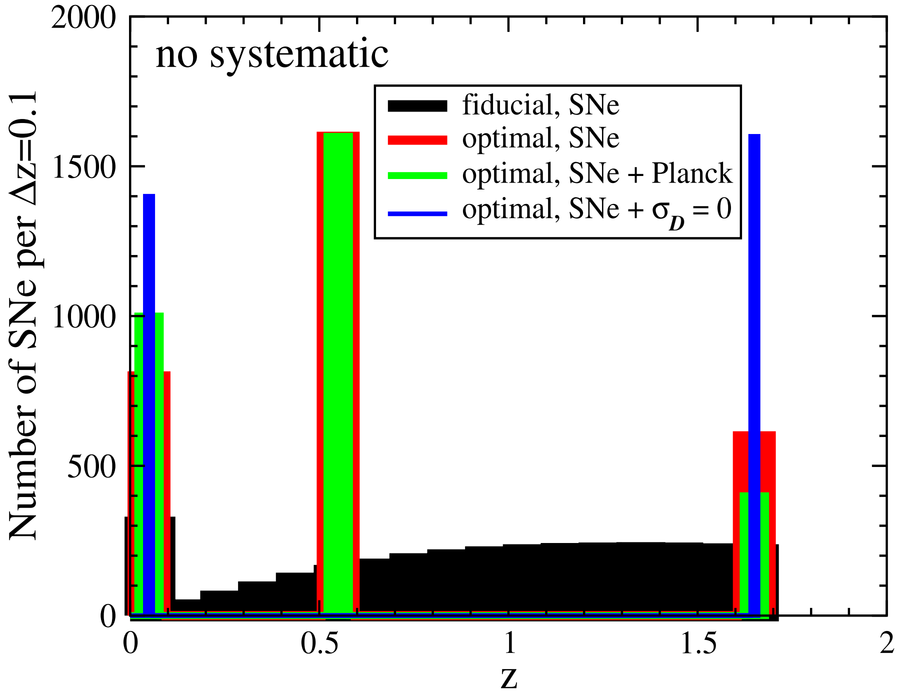


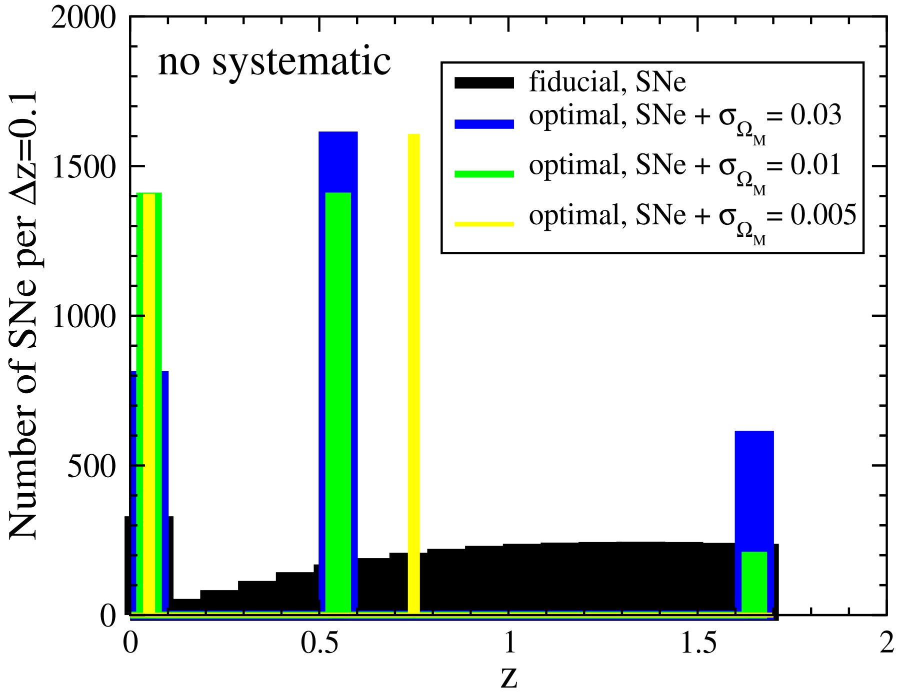
But really, we want :

- SNe distributed out to some $z = z_{\rm max}$.
- in the presence of systematic error
- realistic CMB/LSS prior

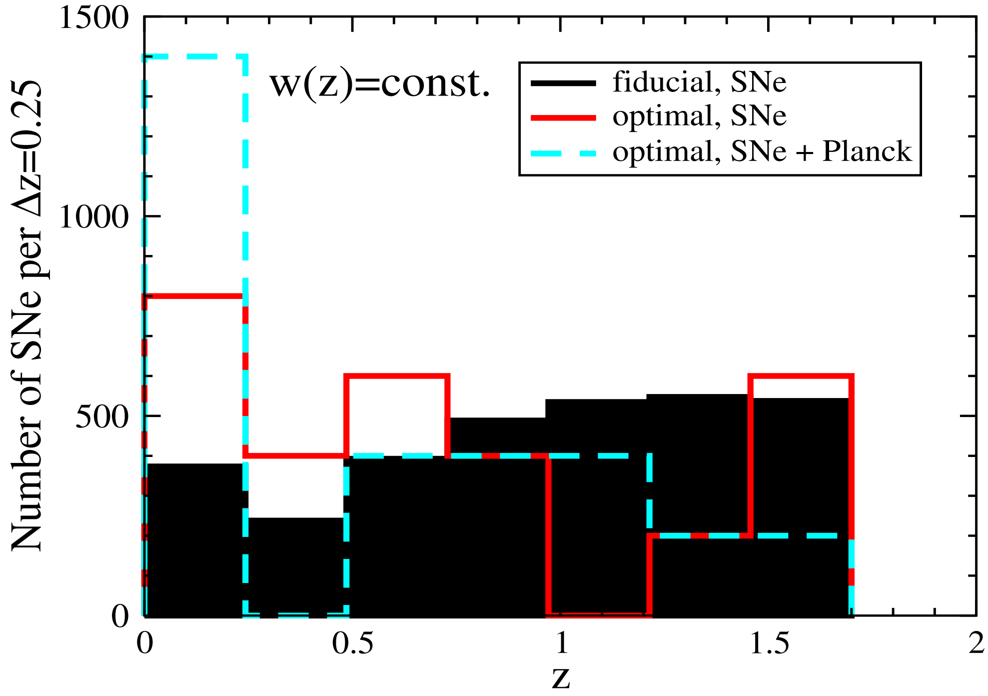
$$\mathcal{L}(\Omega_M, w, \mathcal{M}) \propto \exp\left(\frac{(\mathcal{D}-\mathcal{D}_0)^2}{2\sigma_{\mathcal{D}}^2}\right) \times \prod_i \exp\left(-\frac{[F_i - F(z_i)]^2}{2\sigma_i^2}\right)$$

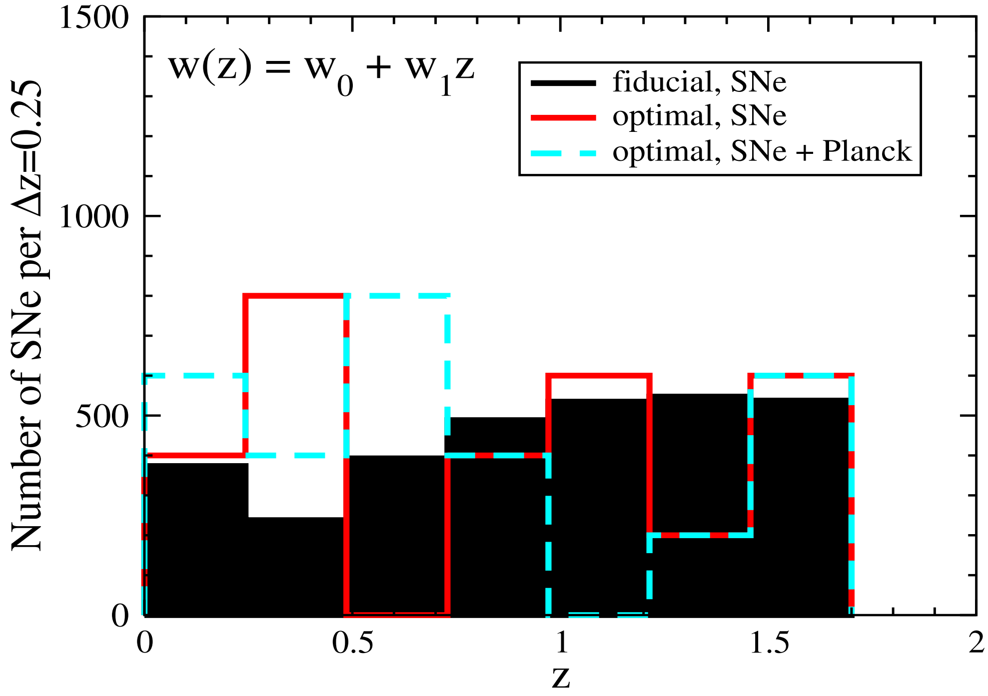
Optimal, no systematics



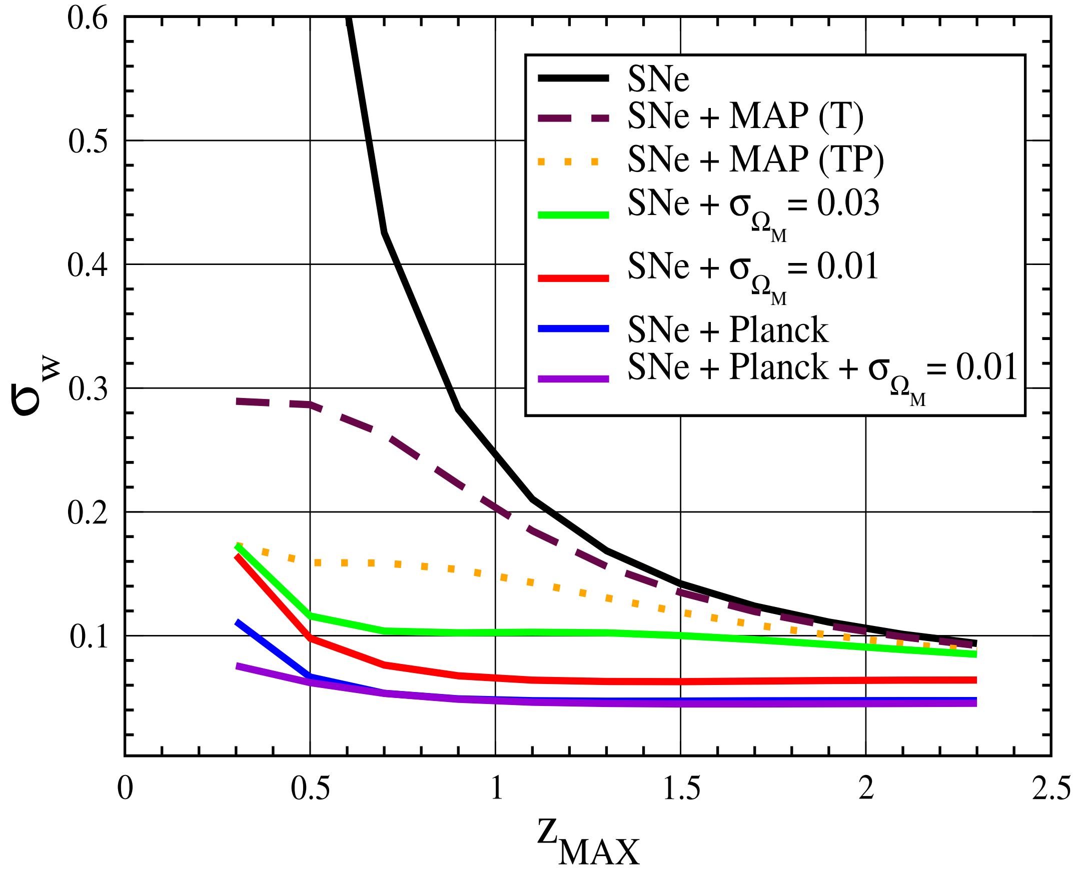


Optimal, with systematics



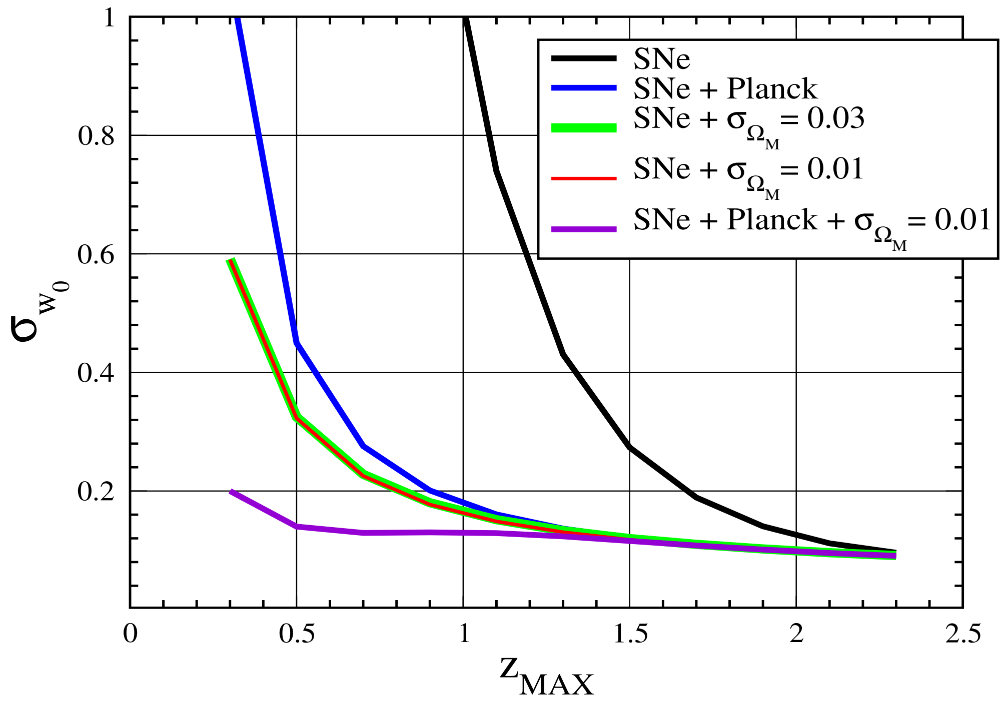


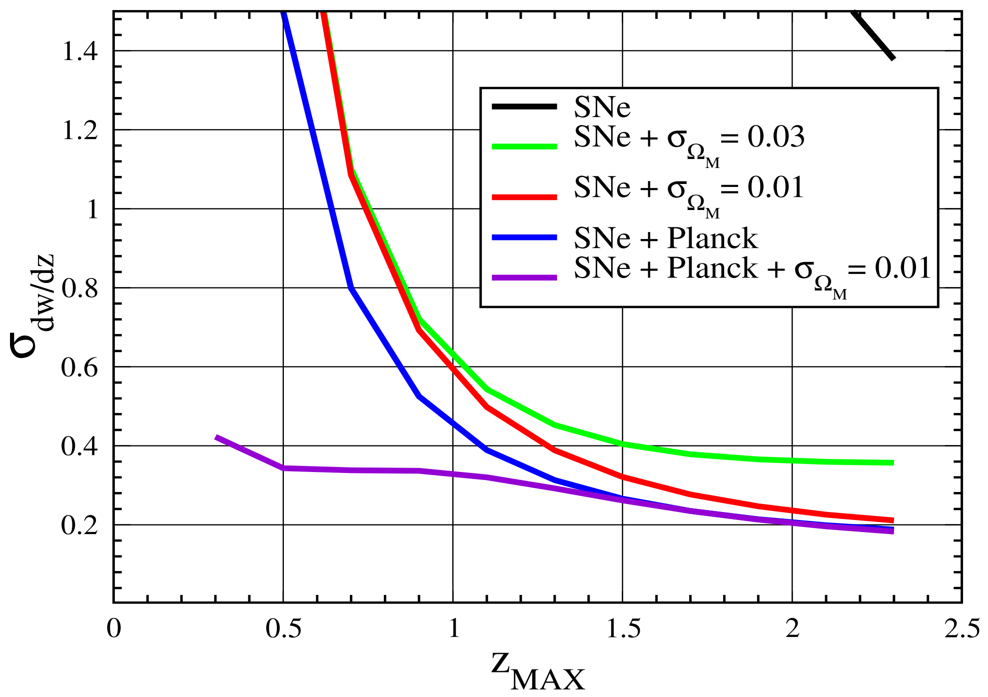
Measuring w



SNe
SNe + MAP (T)
SNe + MAP (TP)
SNe + σ_{Ω_M} = 0.03
SNe + σ_{Ω_M} = 0.01
SNe + Planck
SNe + Planck + σ_{Ω_M} = 0.01
σ_w
z_{MAX}
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
1
1.5
2
2.5

Measuring $w(z) = w_0 + w_1\, z$





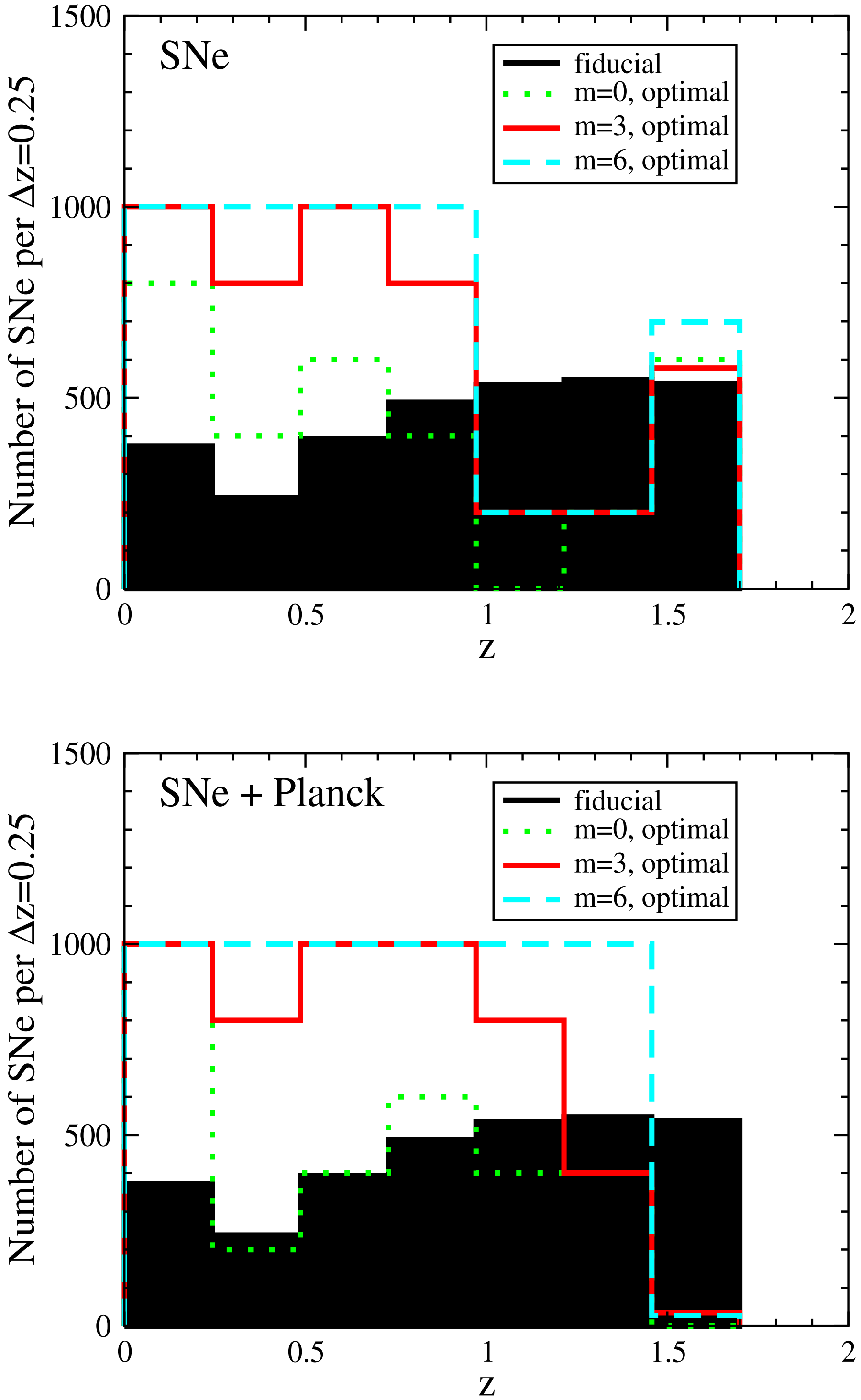
Resource-limited SN survey

A crude model:

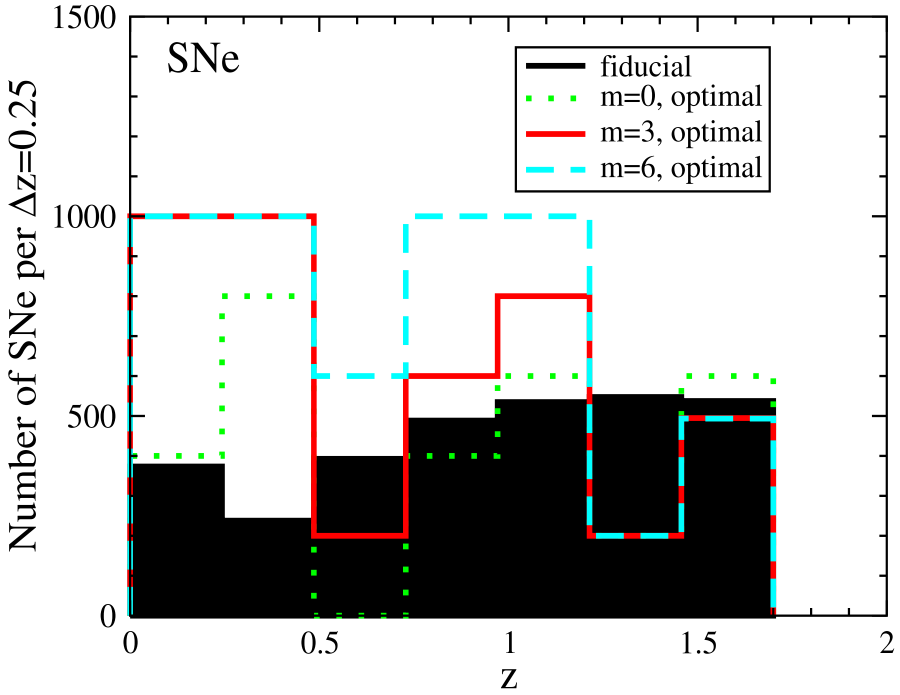
- cost of SN at redshift $z \quad \propto (1+z)^m$
- assume total resources R
- fix R: sufficient resources to carry out a survey of 3000 SNe (SNAP + SN Factory)
- minimize uncertainty in w under the resource constraint $\sum_{i=1}^{N}(1+z_i)^m \leq R$
- include systematics; try with/without the Planck constraint

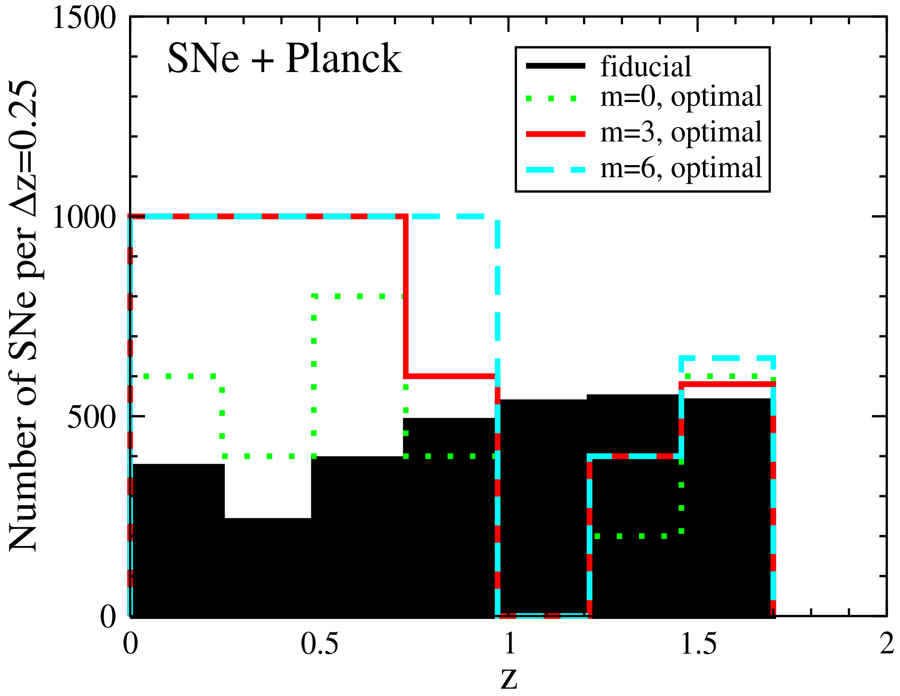
Try $m = 0, 3, 6$ (spans the range of possible values).

Resource-limited: $w(z) = \text{const}$



Resource-limited: $w(z) = w_0 + w_1\, z$





Conclusions

- CMB can significantly improve the ability of SNe to probe dark energy

- Planck + SNAP determines w two times better than SNAP alone; for evolving w CMB info is even more important

- Strong CMB prior is better than strong Ω_M prior

- For constant w without Planck prior, or for evolving w regardless of prior, SNe at $z > 1$ are crucial (a factor of two improvement in σ_w)

- The conclusions do not change with the resource-limited SN survey

- Realistic strategies are obtained from realistic assumptions (same to be done for number counts, weak lensing, CMB...)