

**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.

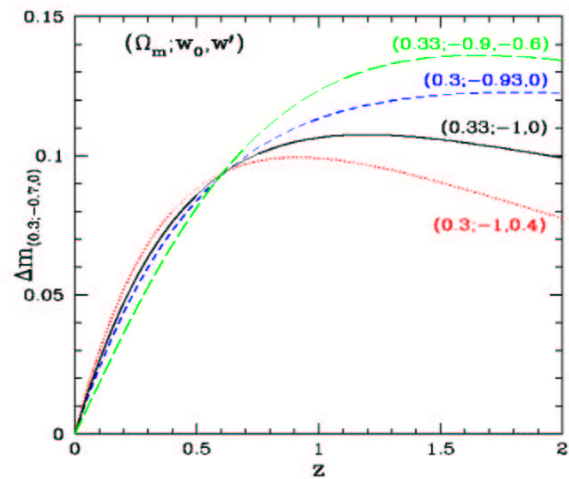
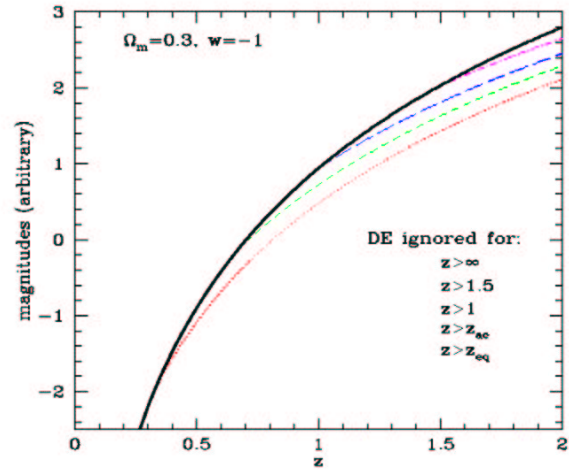
E.g., $w(z) = w_0 + w_1 z$

- presence of a systematic error:

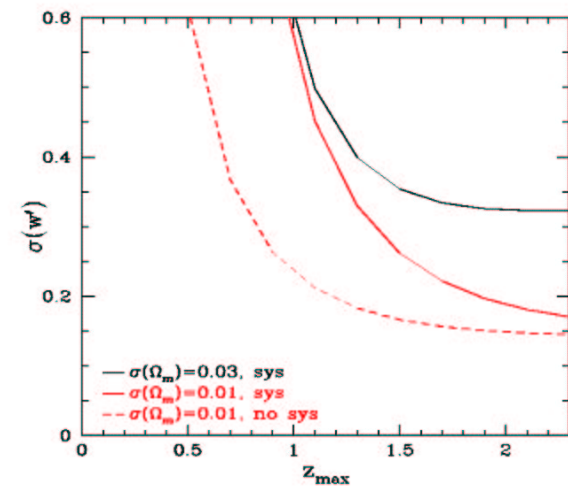
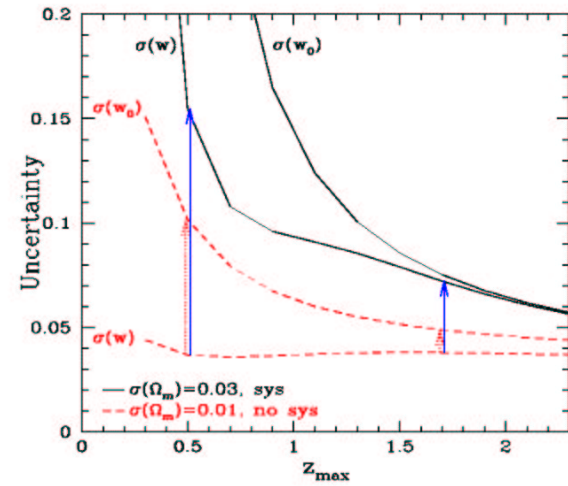
$$\sigma = \sqrt{0.02^2 + \frac{0.15^2}{N_i}} \text{ magnitudes}$$

- realistic CMB/LSS priors

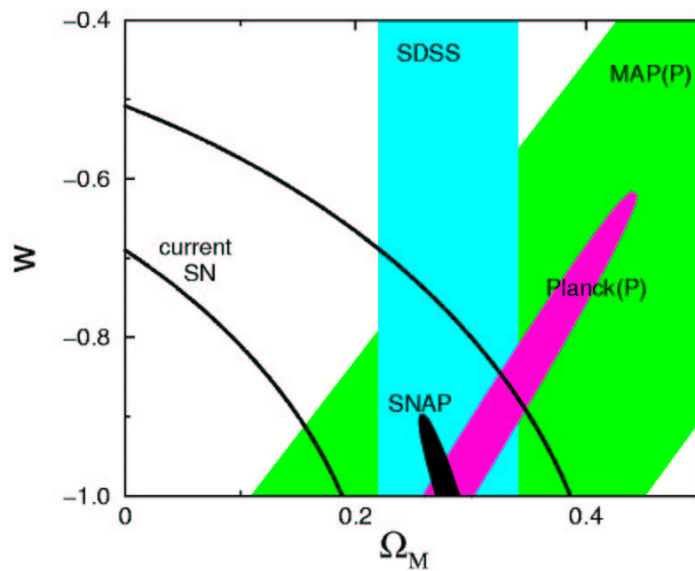
Importance of SNe at high redshift



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 , $\Omega_M h^2$, $\Omega_B h^2$:

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

- $\Omega_M h^2$, $\Omega_B h^2$ 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

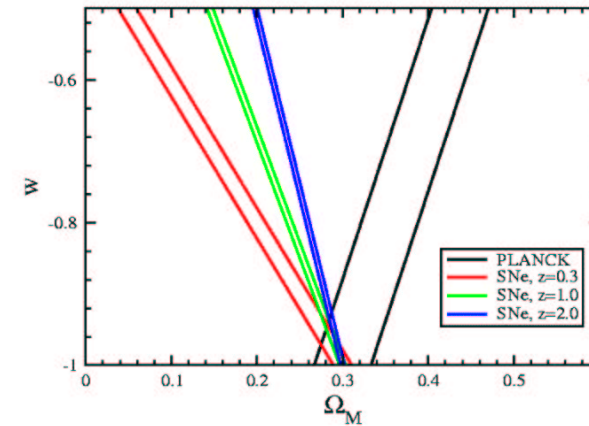
$$F(z) = \frac{C10^{-0.4M}}{4\pi d_L^2} = \frac{(10^{10}C/4\pi)10^{-0.4M}}{H_0^2 d_L^2}$$

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

- 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:

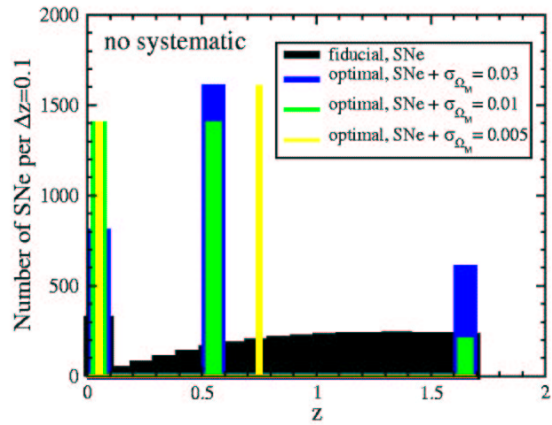
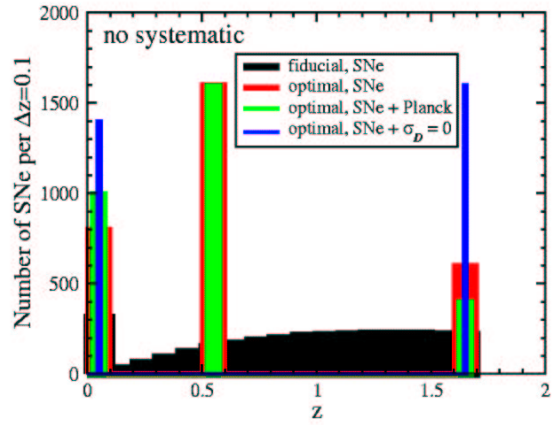


But really, we want :

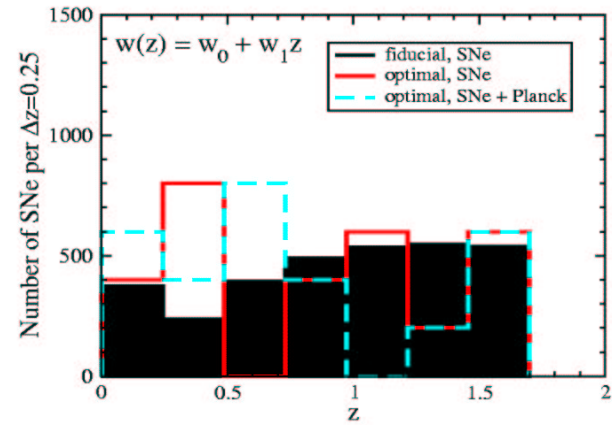
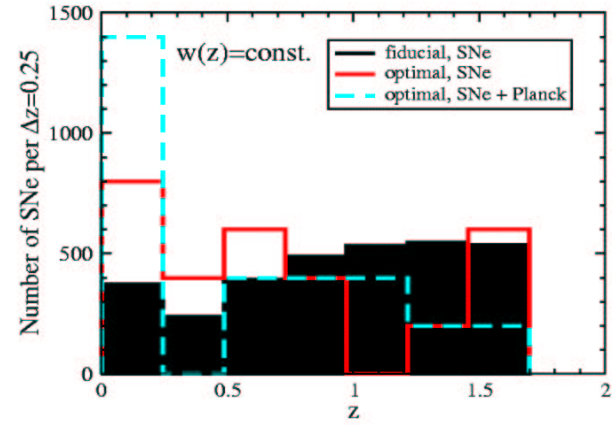
- SNe distributed out to some $z = z_{\max}$.
- in the presence of systematic error
- realistic CMB/LSS prior

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

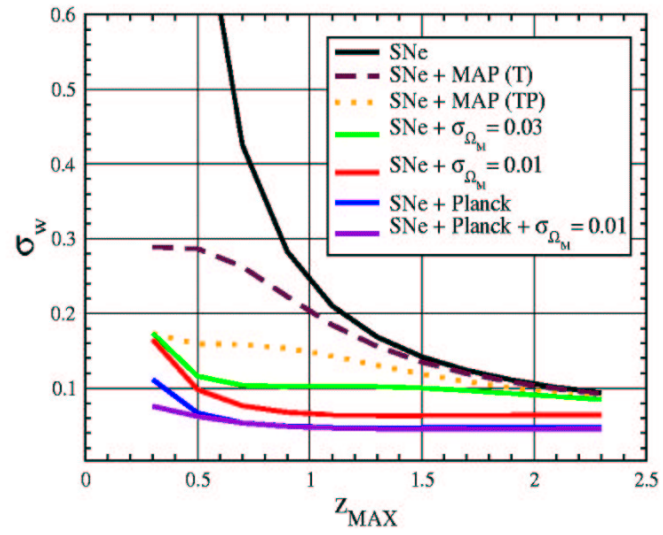
Optimal, no systematics



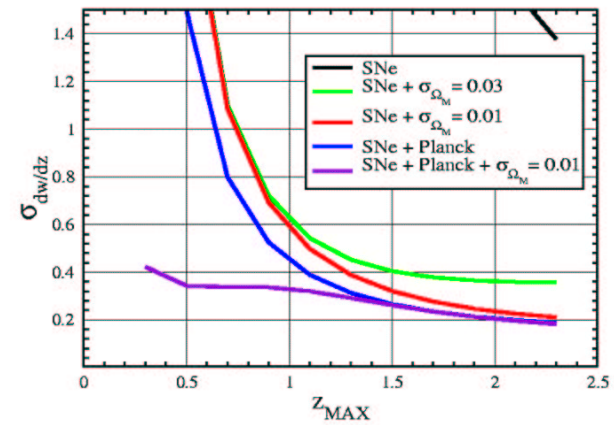
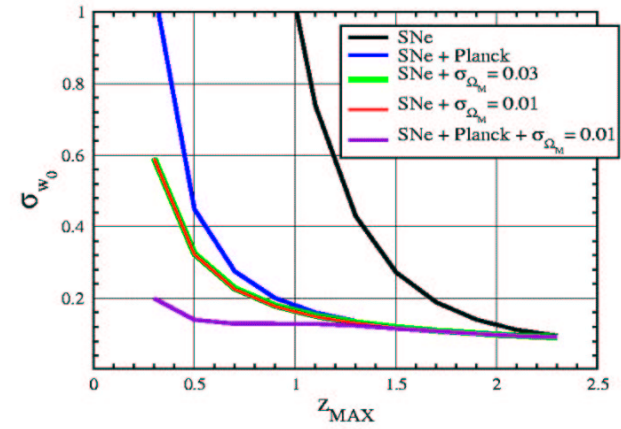
Optimal, with systematics



Measuring w



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



Resource-limited SN survey

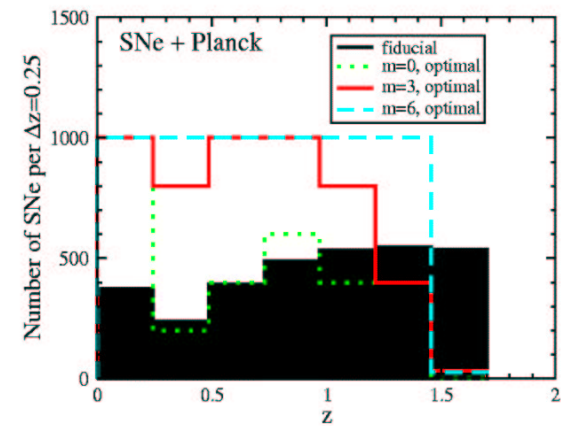
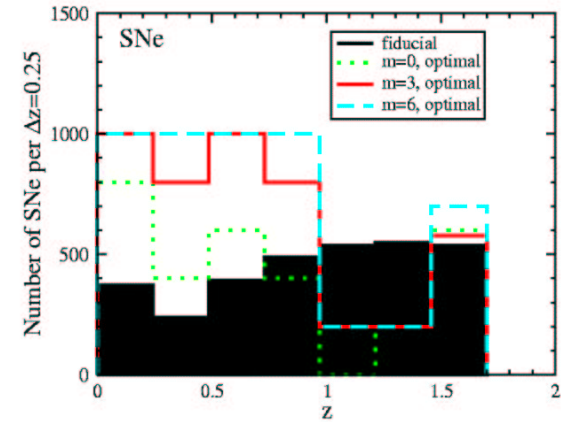
A crude model:

- cost of SN at redshift $z \propto (1+z)^m$
- 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

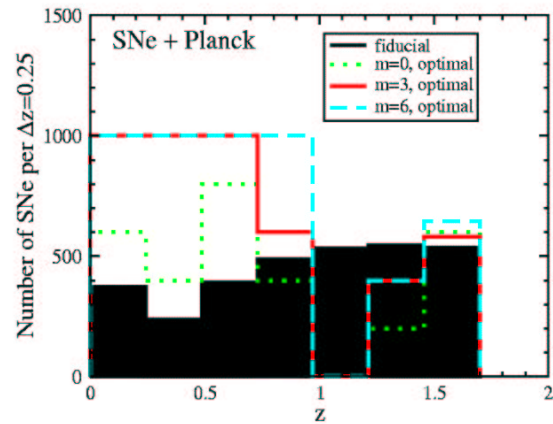
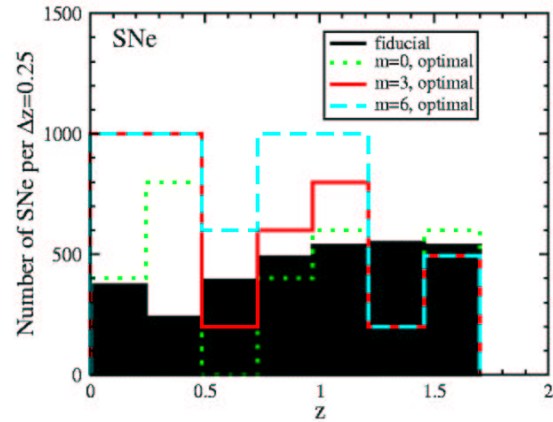
$$\sum_{i=1}^N (1+z_i)^m \leq R$$
- include systematics; try with/without the Planck constraint

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...)