# Luminosity distance tests of an inhomogeneous cosmological model

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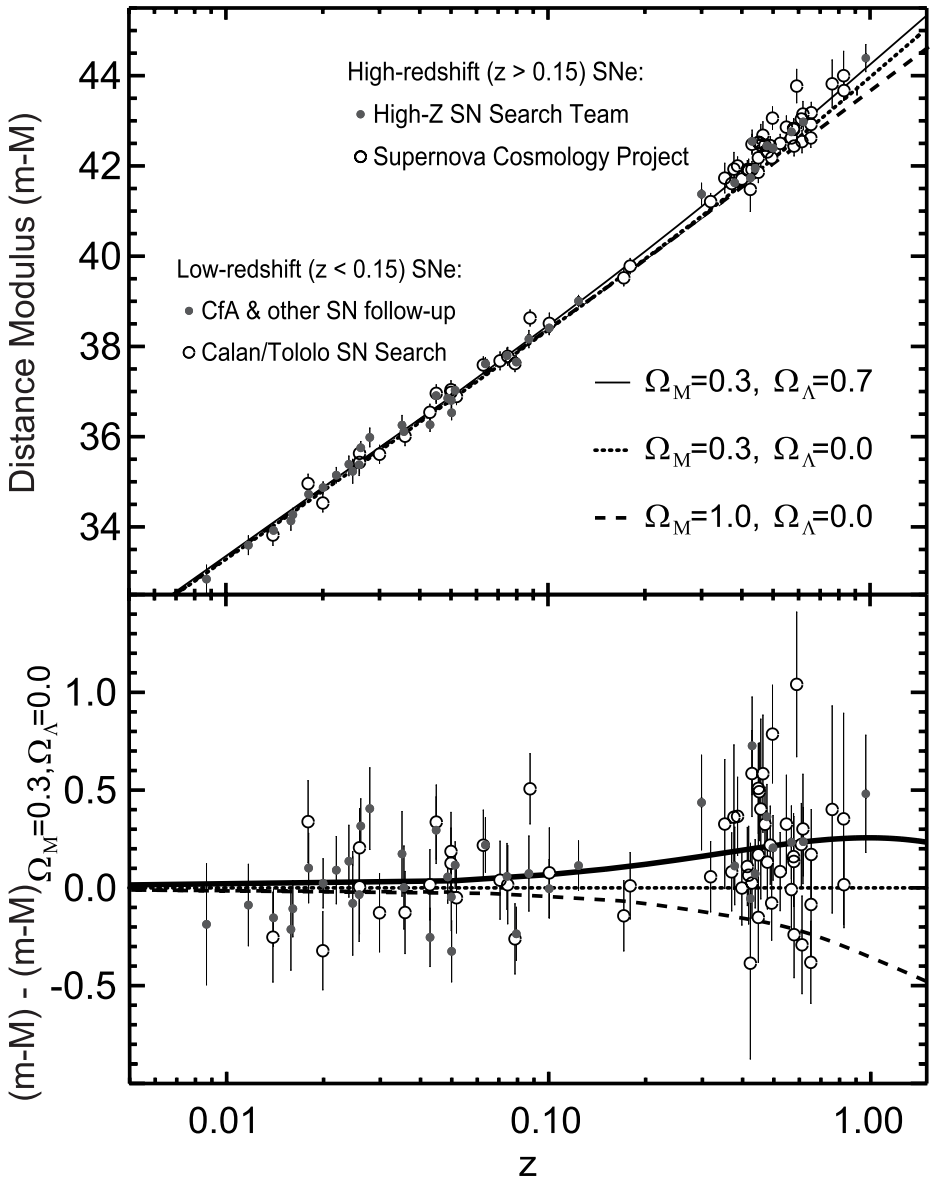
# Outline

# The original observations.

High-Z[1] & SCP[2]




Deviation from EdS expansion: How?

1. Dark energy
2. Std GR invalid at large scales
3. Universe is not homogeneous and isotropic
4. Combination?

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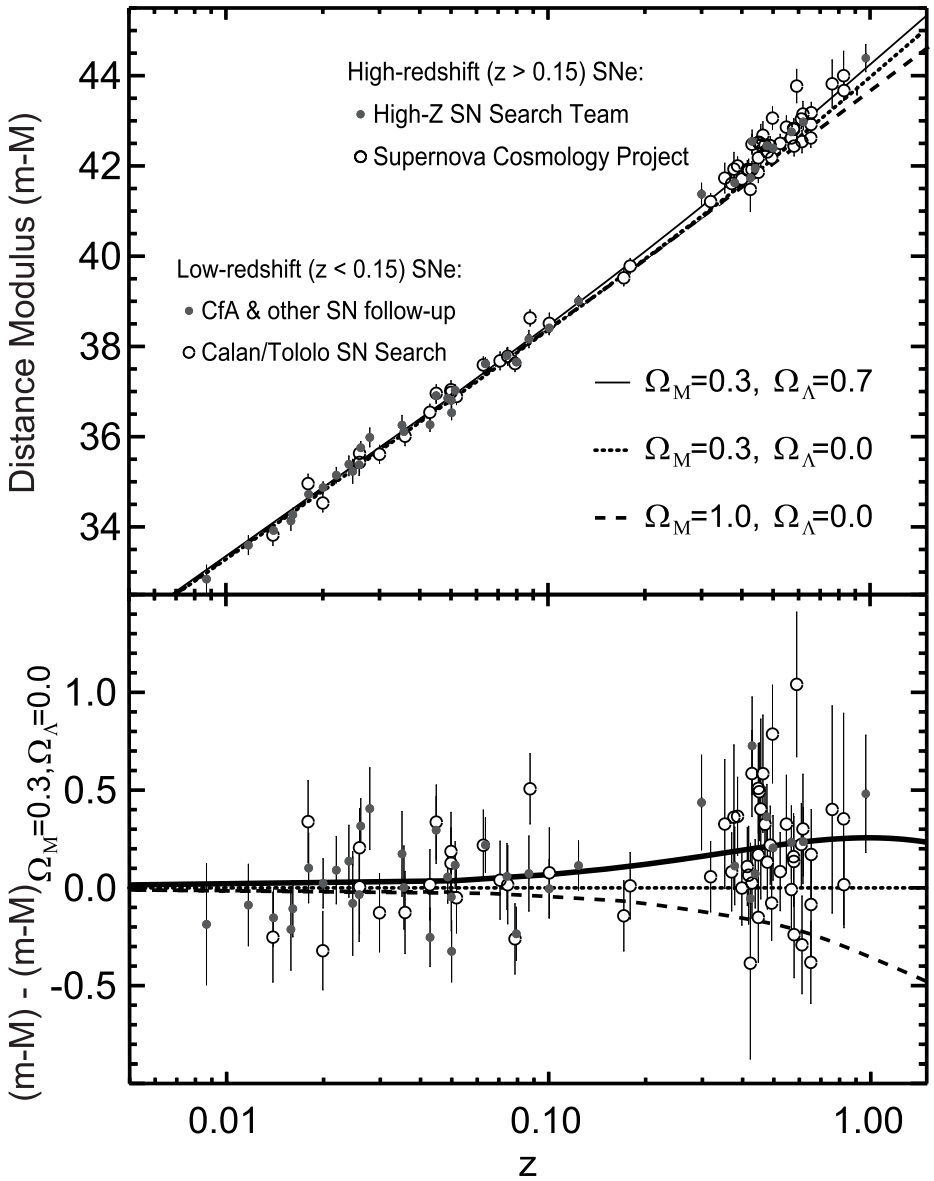


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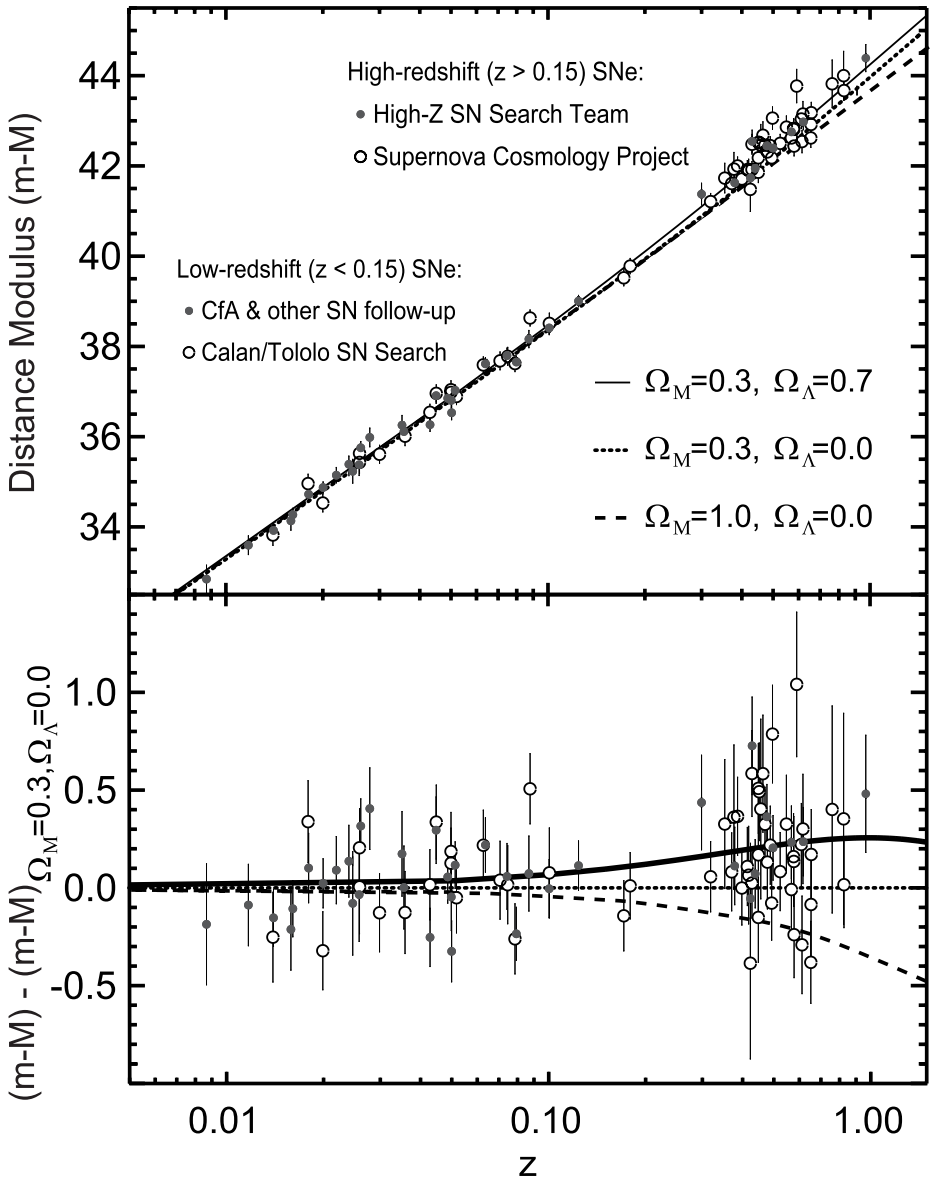


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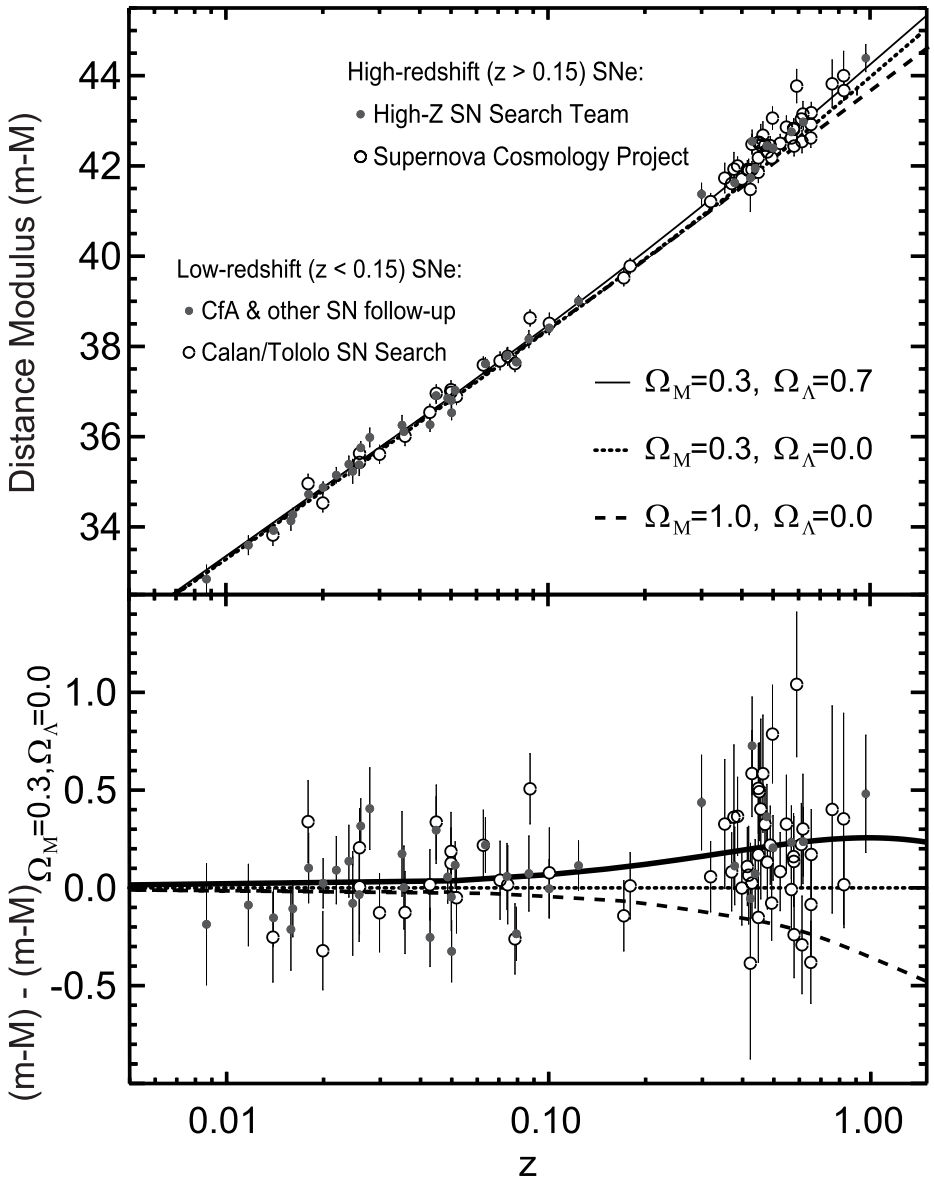


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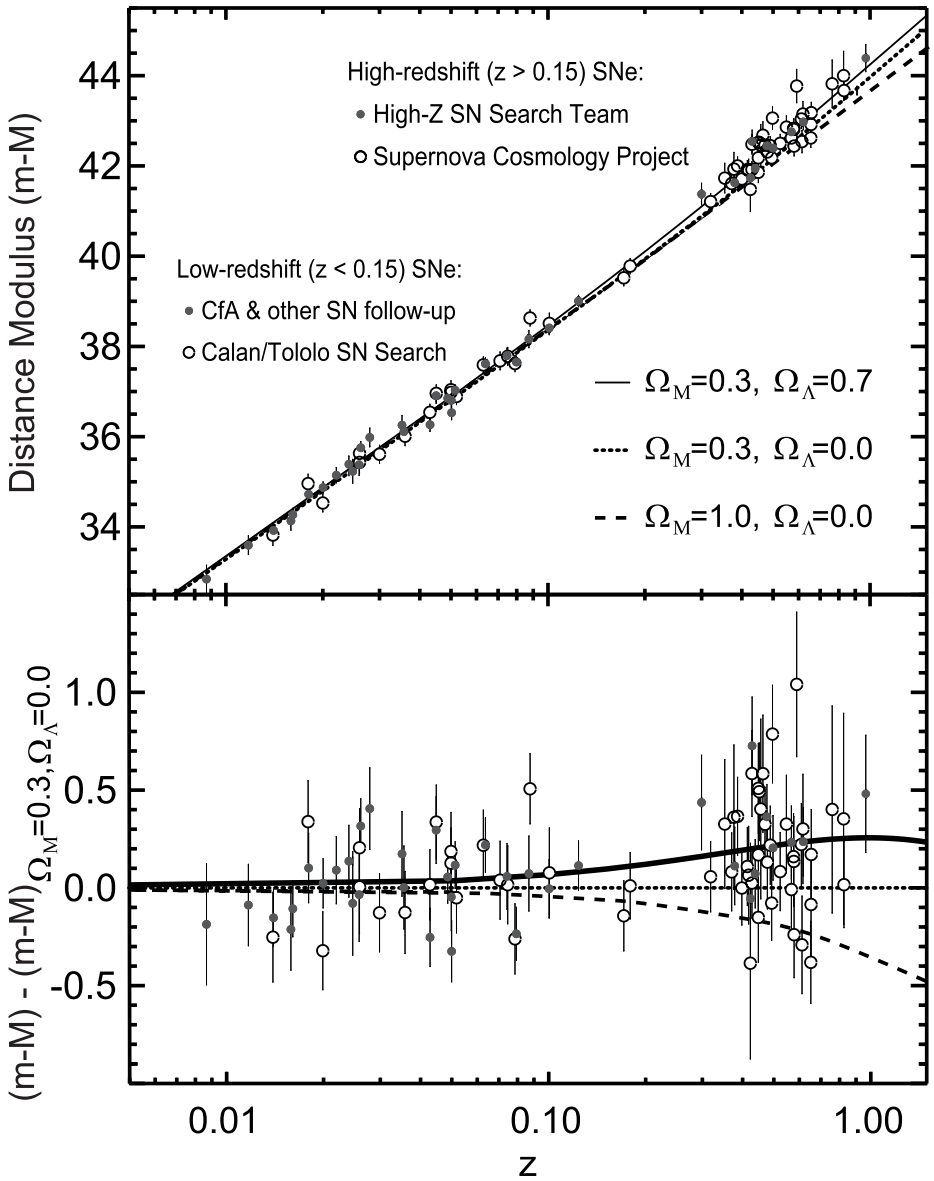


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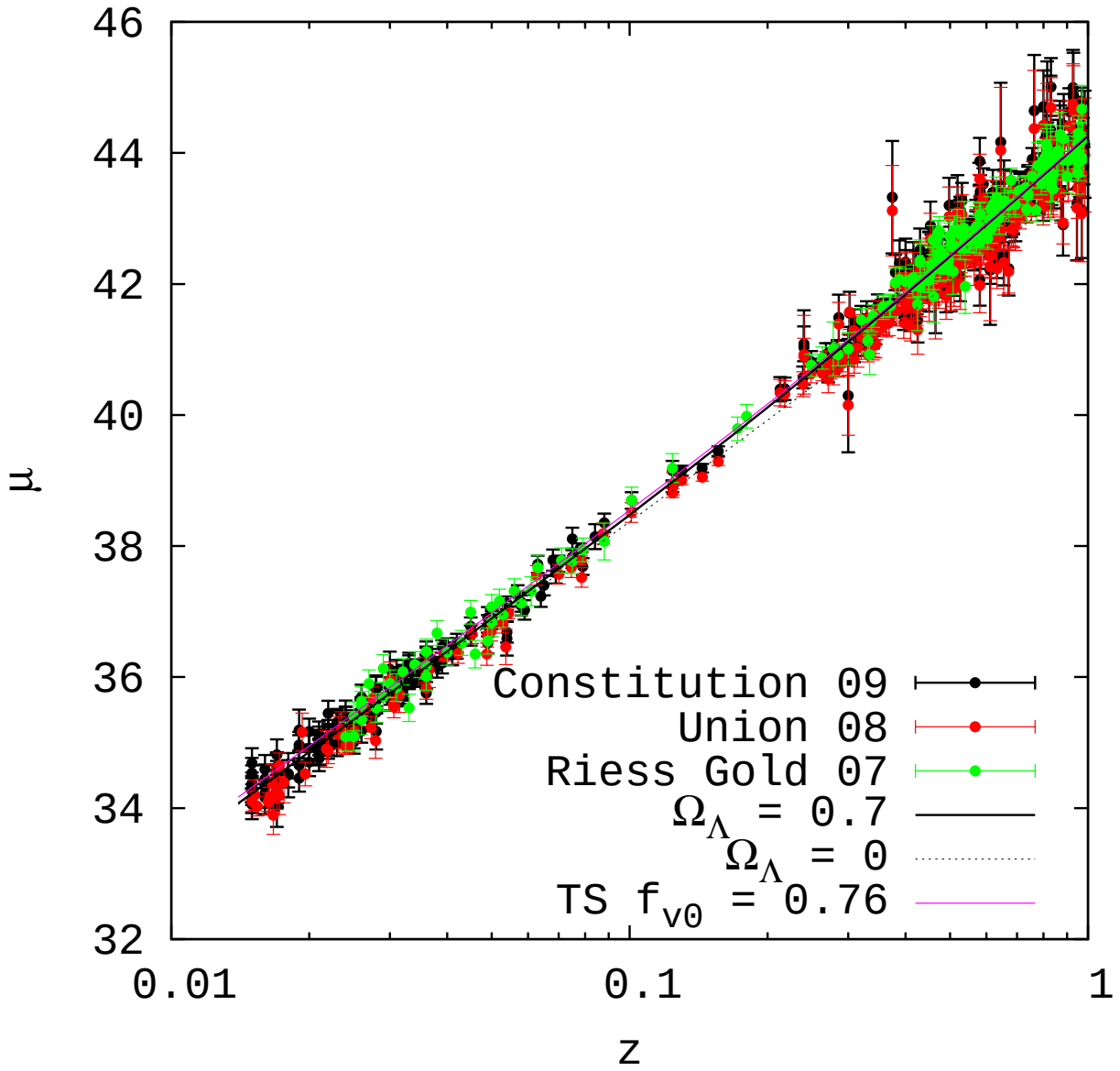
# The timescape.

## An inhomogeneous cosmological model (Wiltshire, 2007)[3]

- Statistical homogeneity on scales $\gg 100h^{-1}$ Mpc
- *Back-reaction* (variance of the expansion rate) $\leq 5\%$ during structure formation
- A two-scale average of the resulting inhomogeneous structure in the universe
  - Walls : spatially flat, gravitationally bound regions
  - Voids : expanding underdense regions
- The variation in clock rates between walls and voids gives rise to apparent cosmic acceleration ("Timescape")
- Luminosity distance $d_L$ is function of present void fraction $f_{v0}$ and the (dressed) Hubble constant $H_0$.

# SNe Ia Hubble diagram.



# SNe Ia data reduction methods

Brighter-broader, brighter-bluer

**MLCS** (High-Z)

Use nearby well-observed SNe to create light curve templates.

$$\mathbf{m}_X(t - t_0) = \mathbf{M}_X^0 + \mu_0 + \zeta_X\left(\alpha_X + \frac{\beta_X}{R_V}\right)A_V^0 + \mathbf{P_X}\Delta + \mathbf{Q_X}\Delta^2.$$

Fit observed light curves to redshifted templates to get

$\Delta$ (light curve shape variation),

$A_V$ (host-galaxy extinction parameter),

$\mu_0$ (distance modulus).

Milky Way-like reddening law: $R_V = 3.1$

**SALT** (SCP)

Find $s$ and $c$ for *each* SN by fitting to synthetic fiducial template.

Marginalize over $\mathcal{M}(h, M)$, $\alpha$ and $\beta$ for *all* SN to obtain distance estimator:

$$\mu_B = m_B^* - \mathcal{M} + \alpha(s - 1) - \beta c$$

assumes cosmological model

# Comparison with given distance moduli "out of the box".

*Timescape*

| Dataset | $N$ | $\chi^2$ | $\Omega_{M0}$ | $f_{v0}$ | Method |
|---|---|---|---|---|---|
| [4]Riess Gold 07 | 182 | 162.7 | $0.33^{+0.11}_{-0.16}$ | $0.77^{+0.12}_{-0.09}$ | MLCS2k2 |
| [5]Union | 307 | 319.6 | $0.09^{+0.16}_{-0.09}$ | $0.94^{+0.06}_{-0.12}$ | SALT |
| Constitution | 397 | 470.8 | $0.01^{+0.18}_{-0.01}$ | $0.99^{+0.01}_{-0.12}$ | SALT |
| MLCS17 | 372 | 403.1 | $0.20^{+0.11}_{-0.17}$ | $0.86^{+0.12}_{-0.08}$ | MLCS2k2 |
| MLCS31 | 366 | 432.8 | $0.03^{+0.12}_{-0.00}$ | $1.00^{+0.00}_{-0.08}$ | MLCS2k2 |
| SALT2 | 352 | 346.8 | $0.04^{+0.18}_{-0.04}$ | $0.97^{+0.03}_{-0.13}$ | SALT2 |

*$\Lambda$CDM*

| Dataset | $N$ | $\chi^2$ | $\Omega_{M0}$ | Method |
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| Union* | 307 | 310.8 | $0.29^{+0.05}_{-0.04}$ | SALT |
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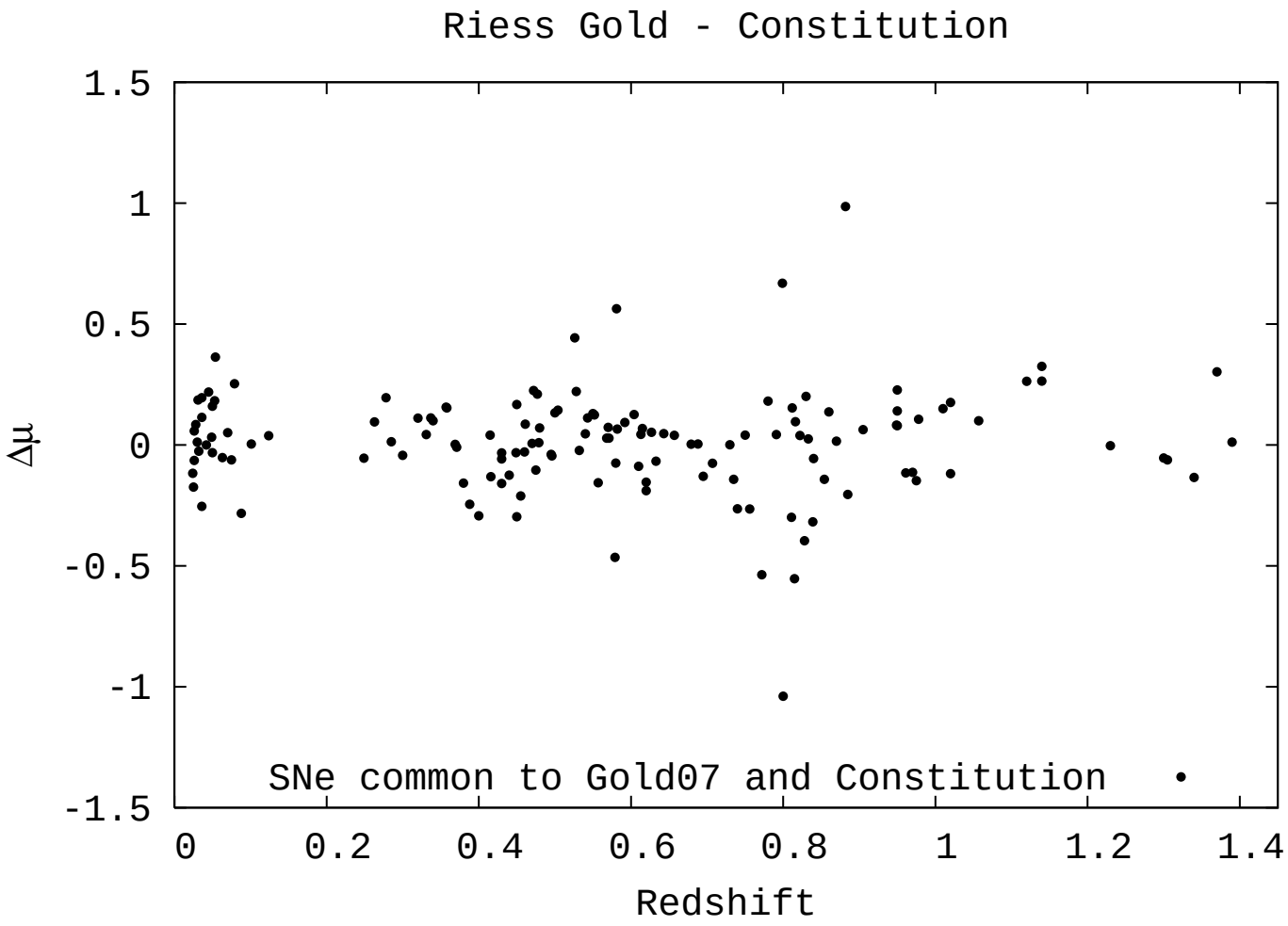
# Why the deviations?

...depending on which methods are used, the derived distances can change, sometimes in a systematic way [8]




- Need to recalibrate: $\mu_{\Lambda\mathrm{CDM}} \longrightarrow \mu_{\mathrm{TS}}$

# Recalibrating the distances.

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# Systematic uncertainties.

Increasing the number of SNe in the Hubble diagram may not be as important as reducing the systematic uncertainties[10]

- Photometry
- Distance estimation
  - $K$-corrections
  - Extinction/reddening
- SN evolution?
- Gravitational lensing
- Malmquist bias
- Cuts (Hubble bubble?)
- Method-dependent systematics: e.g. SALT has greater scatter at high z than MLCS[7]

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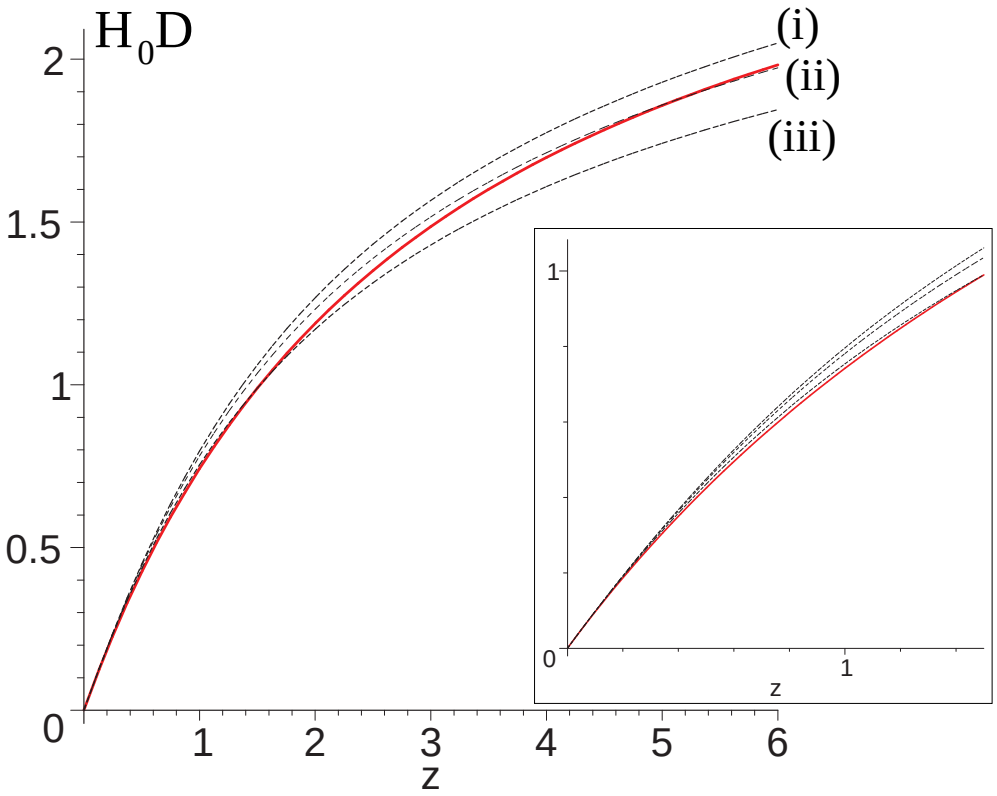
# A Gamma ray burst Hubble Diagram?

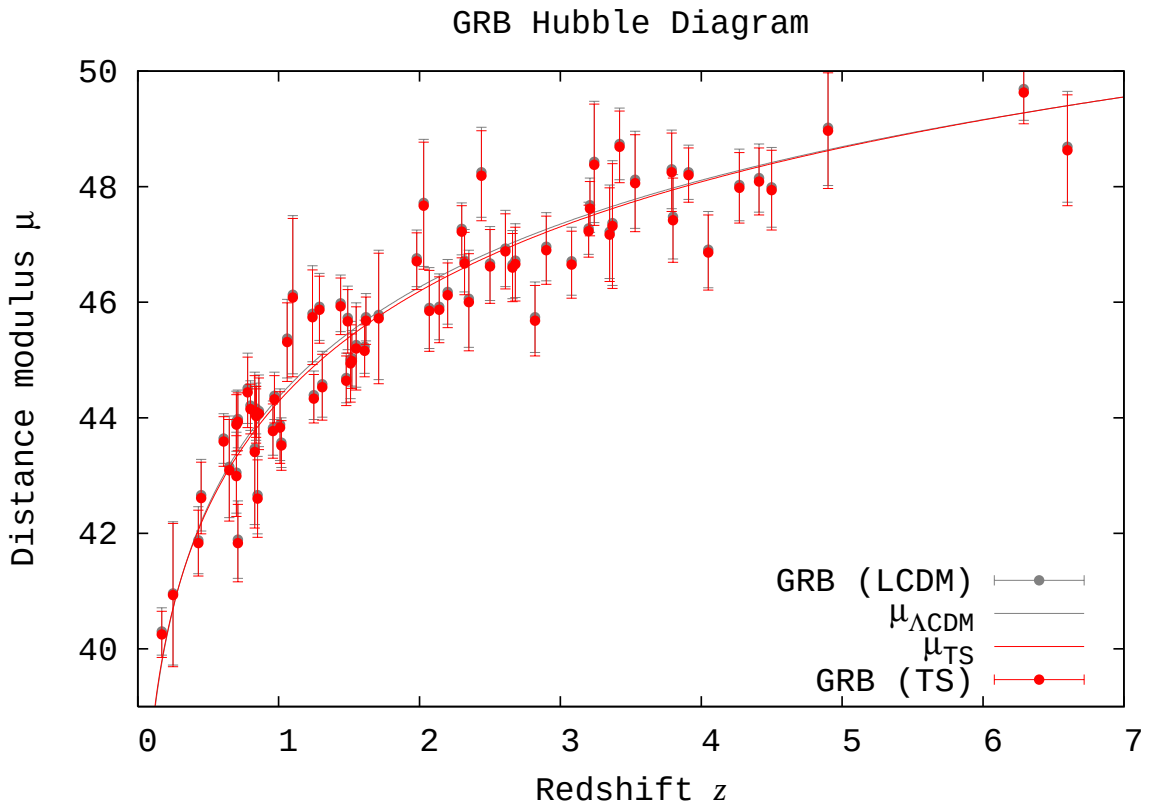
## GRBs are standardizable candles too! (Well, maybe)

- GRBs could extend HD range out to matter-dominated regime
  (GRB 090423: $z = 8.2$)



# A Gamma ray burst Hubble Diagram

After Schaefer (2007)[11]




| Dataset | $N$ | $\chi^2$ | $\Omega_{M0}$ | $f_{v0}$ |
|---|---|---|---|---|
| ΛCDM | 69 | 72.3 | 0.27 | |
| TS | 69 | 70.5 | $0.27^{+0.11}_{-0.16}$ | $0.81^{+0.19}_{-0.29}$ |

# Summary

- SNe Ia: Different results depending on reduction method.
- Although in principle we have sufficient SNe Ia data to distinguish between models, systematic uncertainties have to be understood before conclusions can be drawn.
- GRB “lever arm” could distinguish between models with better data....

# References and acknowledgements

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