Confronting Out-of-Equilibrium Dark Energy Models with Supernova Data

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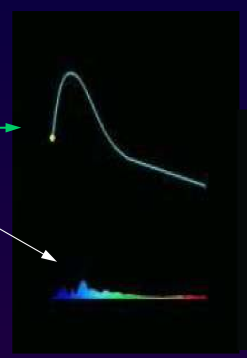
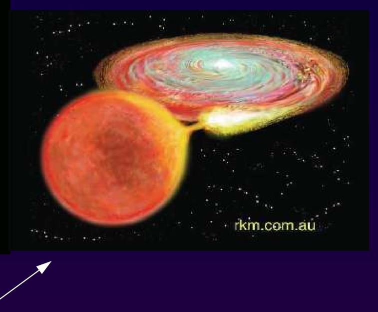
Abstract

We discuss fits of cosmological dark energy models to the available data on high-redshift supernovae. We consider a conventional model with Cold Dark Matter and a cosmological constant (ΛCDM), a model invoking super-horizon perturbations (SHCDM) and models based on Liouville strings in which dark energy is provided by a rolling dilaton field (Q-cosmology). The two main high-redshift supernova data sets give compatible constraints on these models. We find that both ΛCDM and the super-horizon model fit very well the combined supernova data sets. These are also compatible with the data on baryon acoustic oscillations, yielding together a determination of the matter density in the ΛCDM (assuming a flat Universe) which is comparable with that provided by the three-year WMAP data. A simple parametrisation of the full version of the Q-cosmology model that includes off-shell effects fits the supernova data very well [Ellis, Mavromatos, Mitsou, Nanopoulos, astro-ph/0604272].

Type Ia supernovae

- Exploding white dwarf star, briefly as bright as an entire galaxy
- Can measure both intensity and spectra as the supernova brightens and fades over many days



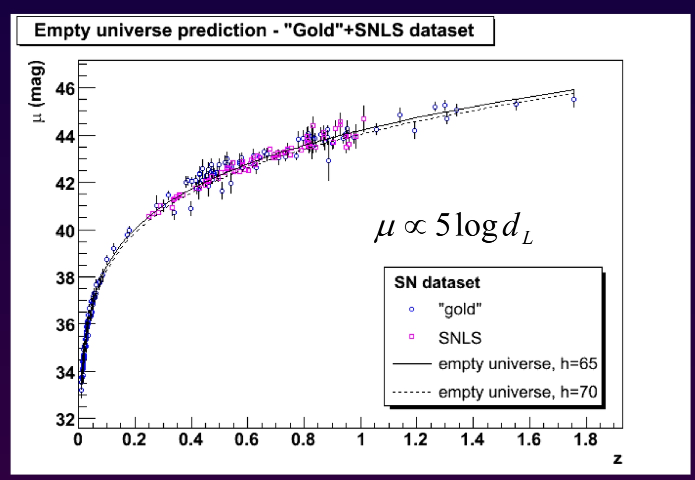


- Accretion of mass from companion increases the central pressure leading to thermo-nuclear detonation
- Similar explosion with nearly the same peak intensity → 'Standard' Candles

Distance-redshift relation

- Defines luminosity distance d_L → $F = \frac{L}{4\pi d_L^2}$
  "know" L, measure F
  ↓ Standard candles ↓ Intensity

$$d_L \propto (1+z)\int_0^z \frac{dz'}{H(z')}$$



Comparison of SN Ia redshifts and magnitudes provides straightforward measurement of the changing rate of expansion of the universe

Available data on high-z SNe

- **'Gold' dataset**
  - 16 type Ia SNe discovered by the Hubble Space Telescope (HST) at $z > 1.25$
  - plus ground-based SNe discoveries = 157 SNe Ia in total
  - 29 additional SNe tagged as 'silver' due to lower quality of photometric and spectroscopic record
  - **Reiss et al, Astrophys. J. 607, 665 (2004) [arXiv:astro-ph/0402512]**
- **SNLS dataset (Supernova Legasy Survey)**
  - 71 high-redshift SNe discovered during the first year of SNLS
  - + 44 nearby SNe = 115 SNe
  - **Astier et al, Astron. Astrophys. 447, 31 (2006) [arXiv:astro-ph/0510447]**

ΛCDM model

- ΛCDM: assumes a constant dark energy density Ω_Λ

$$d_L \propto (1+z)|\Omega_k|^{-1/2}\,\mathrm{sinn}\left\{|\Omega_k|^{1/2}\int_0^z dz'\left[(1+z')^2(1+\Omega_M z') - z'(2+z')\Omega_\Lambda\right]^{-1/2}\right\}$$

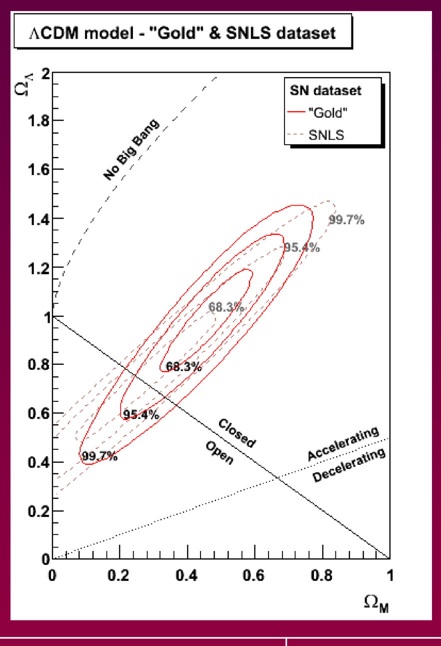
$$\Omega_k = 1-\Omega_M-\Omega_\Lambda,\quad \mathrm{sinn}=\sinh,\ \text{for } \Omega_k>0\ \text{(closed)};\quad \sin,\ \text{for } \Omega_k<0\ \text{(open)}$$

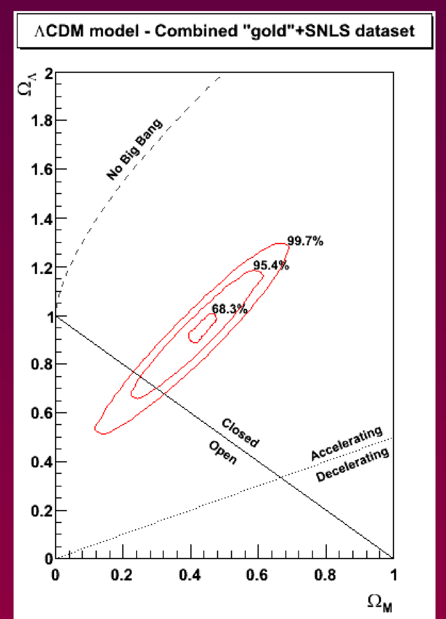
- Scale factor of universe $\alpha(t)=\alpha_0/(1+z)$
- ΛCDM for a flat universe:

$$d_L \propto (1+z)\int_0^z dz'\left[\Omega_M(1+z')^3 + (1-\Omega_M)\right]^{-1/2},\quad \Omega_\Lambda = 1-\Omega_M$$

- Method: Minimise ⟶ $\chi^2 = \sum_i \frac{(\mu_{ob,i}-\mu_{th}(z_i))^2}{\sigma^2_{ob,i}+\sigma^2_{int}}$ $\quad(\mu \propto 5\log d_L)$

- Results compatible with
  - Riess et al
  - Astier et al
- Combined = 157 gold + 71 SNLS
- χ^2 values for flat universe





Dataset	Ω_M	χ^2	χ^2/dof
'Gold'	0.287±0.026	178	1.14
SNLS	0.265±0.022	114	1.00
Combined	0.274±0.017	239	1.05

Super-Hubble CDM model (SHCDM)

- No dark energy assumed **[Kolb, Matarrese, Notari, Riotto, Mod. Phys. Lett. A 20, 2705 (2005) [arXiv:astro-ph/0410541]; arXiv:hep-th/0503117]**
- Observed effects (CMB, SNe, etc) induced by cosmological perturbations larger than the present Hubble radius $1/H_0$ (super-horizon)

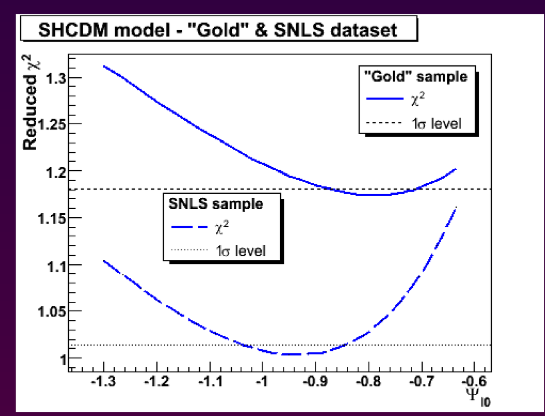
$$ds^2 = -dt^2 + a^2(t)e^{-2\Psi(\vec{x},t)}\delta_{ij}dx^i dx^j$$

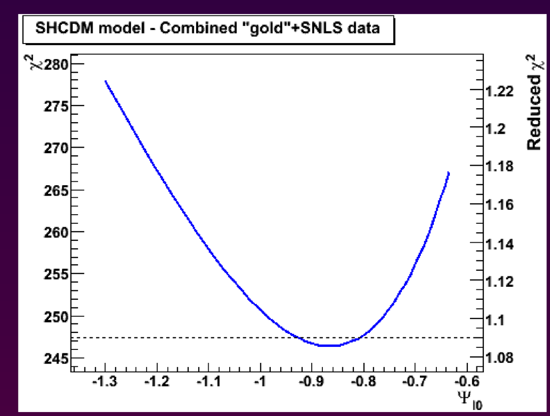
$$H(t) = \frac{\bar{H}_0}{1-\Psi_{\ell 0}}\left(a^{-3/2} - a^{-1/2}\Psi_{\ell 0}\right)$$

- $\Psi(\vec{x},t)$ gravitational potential
- Depends on one parameter $\Psi_{\ell 0}$: $\quad \Psi_\ell(t) \cong a(t)\Psi_{\ell 0}$
  - Specified by primordial inflation physics: $\quad 1+z = a^{-1}e^{(a-1)\Psi_{\ell 0}}$

$$d_L \propto (1+z)\int_0^z \frac{dz'}{H(z')}$$

- Slightly inferior goodness of fit than ΛCDM





Dataset	$\Psi_{\ell 0}$	χ^2	χ^2/dof
'Gold'	-0.79±0.08	183	1.17
SNLS	-0.94±0.09	114	1.00
Combined	-0.87±0.06	245	1.09

Off-Equilibrium String Q-Cosmology [1-2]

- Relaxing-to-zero (dilaton) dark energy density, non-critical string contributions ⇒ off-shell equations of motion for dilaton, graviton
- No cosmological constant ⇒ asymptotic states/S-matrix may be well defined (strings)

$$H(z) = H_0\left[\Omega_3(1+z)^3 + \Omega_\delta(1+z)^\delta + \Omega_2(1+z)^2\right]^{1/2},$$
$$\Omega_2 = 1-\Omega_3-\Omega_\delta,\quad \delta = 4$$

- In certain models could be more complicated [3]
- Mixed-origin contributions to Ω_i from dark matter and dark energy ⇒ Important: Ω_3 could be negative!
- $(1+z)^2$ scaling distinct from curvature!
- Exotic scaling of dark matter different from $(1+z)^3$ ⇒ non-trivial equation of state, $w_e \neq 0$ $\quad (p_{DM} = w_e \rho_{DM})$
- Exponent δ=4 (fixed)

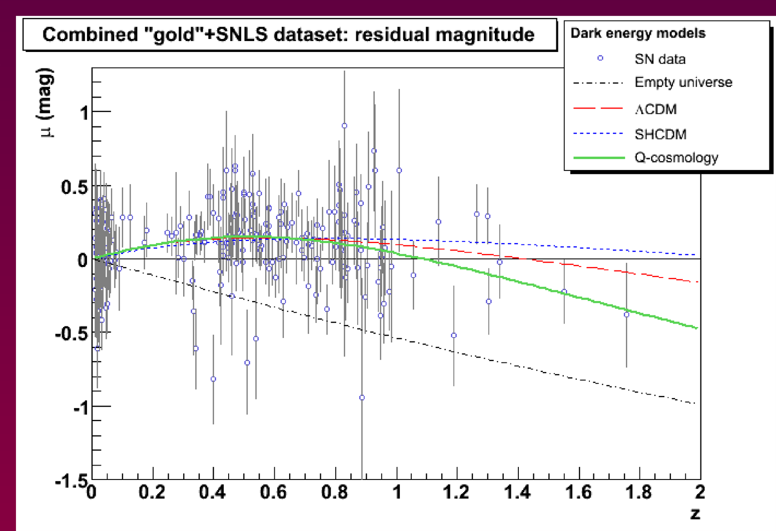
Dataset	Ω_3	Ω_δ	Ω_2 (*)	χ^2	χ^2/dof
'Gold'	-3.6±0.8	1.2±0.3	3.4±0.9	177	1.14
SNLS	-3.0±0.9	1.0±0.4	3.0±1.0	113	1.00
Combined	-3.3±0.6	1.11±0.25	3.2±0.7	237	1.05

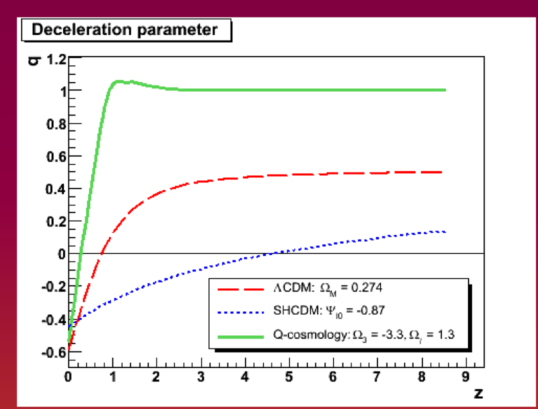
(*) determined as $1-\Omega_3-\Omega_\delta$

- Quality of fit comparable to ΛCDM !!
- Similar results obtained when δ is a free parameter
- Note negative Ω_3 ! (e.g. string loop corrections in Liouville strings, negative dust compactified graviton modes in brane models, etc)

Comparison between models

- Future searches for high-z SNe (SNAP) decisive for picking up best model
- Further analyses from CMB data, measurements of equations of state, etc needed





Model	χ^2	χ^2/dof	z_0
ΛCDM	239	1.05	~0.7
SHCDM	245	1.09	~4.5
Q-cosmology	237	1.05	~0.3

Conclusions

- ΛCDM may not be the only model to fit the SN data
- Super-horizon model (SHCDM) fits very well the combined supernova data sets
- Off-equilibrium (Liouville) string Q-Cosmology fits data equally good with negative dust-like energy densities and exotic dark-matter scaling
- Comparison with CMB (WMAP3) data in progress
- Large Scale Structures (e.g. Baryon Acoustic Oscillations, etc) might give important new constraints – in progress
- Encouraging results so far prompt further studies (theoretical & observational)

Further reading

[1] Ellis, Mavromatos and Nanopoulos, Phys. Lett. B 619, 17 (2005) [arXiv:hep-th/0412240]; Ellis, Mavromatos, Nanopoulos and Westmuckett, Int. J. Mod. Phys. A 21, 1379 (2005) [arXiv:gr-qc/0508105]

[2] Diamandis, Georgalas, Mavromatos and Papantonopoulos, Int. J. Mod. Phys. A 17, 4567 (2002) [arXiv:hep-th/0203241]; Diamandis, Georgalas, Mavromatos, Papantonopoulos and Pappa, Int. J. Mod. Phys. A 17, 2241 (2002) [arXiv:hep-th/0107124]

[3] Diamandis, Georgalas, Lahanas, Mavromatos and Nanopoulos, arXiv:hep-th/0605181 (numerical solutions)

[4] Ellis, Mavromatos, Mitsou and Nanopoulos, arXiv:astro-ph/0604272 (work presented here)

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