Confronting Braneworld Models of Dark Energy with Supernova and other Datasets

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(International Centre for Theoretical Physics)

Based on **Phys. Rev. D 73 084024 (2006)**;
Ujjaini Alam(ICTP) & Varun Sahni (IUCAA)

Plan of Talk :

- Introduction : Dark Energy
- Braneworld Models of Dark Energy
- Observations & Methodology
- Current Results
  - Results from SNe
  - Results from complementary data
- Conclusion

Observations of Dark Energy :

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SNe Observations– Universe Acceleration

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$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \sum (\rho + 3p)$$

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Theoretical explanation–

Zero point vacuum fluctuation $< T_{\mu\nu} >= \Lambda g_{\mu\nu}$

– Zeldovich (1968)

Problems :

- Cosmological Constant Problem–

Divergence problem– $\Lambda/8\pi G =< T_{00} >_{\rm vac} \propto \int_0^\infty k^2\sqrt{k^2+m^2}dk$

Planck scale cut-off– $< T_{00} >_{\rm vac} \simeq 10^{76}{\rm Gev}^4$

QCD scale cut-off– $< T_{00} >_{\rm vac} \simeq 10^{-3}{\rm Gev}^4$

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- **Fine-tuning Problem–**

  DE density today– $\rho_\Lambda \simeq 10^{-47}{\rm Gev}^4$

  Slightly smaller density– $\rho_\Lambda \simeq 10^{-50}{\rm Gev}^4$– Recollapse

  Slightly larger density– $\rho_\Lambda \simeq 10^{-43}{\rm Gev}^4$– Inhibits structure formation

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- Braneworld models $\Rightarrow$ Modifying the left-hand side of Einstein's equations !

Brane Models of Dark Energy :

$$S = M^3 \left[\int_{\rm bulk} (R_5 - 2\Lambda_{\rm b}) - 2 \int_{\rm brane} K \right] + \int_{\rm brane} \left[m^2 R_4 - 2\sigma + L\left(h_{\alpha\beta}, \phi\right) \right] .$$

(Sahni & Shtanov, 2003)

$l = \frac{2m^2}{M^3}$: $r << l \Rightarrow$ General relativity

$r >> l \Rightarrow$ Brane-specific effects

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$$H^2(a) = \frac{A}{a^3} + B + \frac{2}{l^2}\left[1 \mp \sqrt{1 + l^2\left(\frac{A}{a^3} + B - \frac{\Lambda_b}{6} - \frac{C}{a^4}\right)}\right] .$$

$$A = \frac{\rho_0 a_0^3}{3m^2} , B = \frac{\sigma}{3m^2} .$$

Brane Models of Dark Energy :

- $m = 0 \Rightarrow$ FRW generalization of Randall Sundrum :

$$H^2 = \frac{\Lambda_b}{6} + \frac{C}{a^4} + \frac{(\rho + \sigma)^2}{9M^6} \ .$$

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- $\sigma = \Lambda_b = 0 \Rightarrow$ Dvali Gabagadze Porratti (DGP) model :

$$H^2 = \frac{A}{a^3} + \frac{2}{l^2} \mp \frac{2}{l}\sqrt{\frac{1}{l} + \frac{A}{a^3}} \ .$$

$(+)$ sign leads to self-accelerating braneworld model.

Brane Models of Dark Energy :

$$H^2 = \frac{A}{a^3} + \Lambda_{\rm eff}$$

$$\Lambda_{\rm eff} = \underbrace{\left(B + \frac{2}{l^2}\right)}_{\Downarrow\ \Lambda} \mp \underbrace{\frac{2}{l^2}\sqrt{1 + l^2\left(\frac{A}{a^3} + B - \frac{\Lambda_b}{6}\right)}}_{\Downarrow\ \text{Screening term}} .$$

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$\Downarrow$ Λ

$\Downarrow$ Screening term

$$w_{\rm eff}(a = a_0) = -1 \mp \frac{1}{\left(H_0^2 - \frac{A}{a_0^3}\right)\sqrt{1 + l^2\left(\frac{A}{a_0^3} + B - \frac{\Lambda_b}{6}\right)}} \ .$$

Brane Models of Dark Energy :

Brane1 :

$$\frac{H^2(z)}{H_0^2} = \Omega_{0\mathrm{m}}(1+z)^3 + \Omega_\sigma$$

$$+2\Omega_l - 2\sqrt{\Omega_l}\sqrt{\Omega_{0\mathrm{m}}(1+z)^3 + \Omega_\sigma + \Omega_l + \Omega_{\Lambda_\mathrm{b}}}\,,$$

$$\Omega_{0\mathrm{m}} = \frac{\rho_0}{3m^2 H_0^2},\ \Omega_\sigma = \frac{\sigma}{3m^2 H_0^2},\ \Omega_l = \frac{1}{l^2 H_0^2},\ \Omega_{\Lambda_\mathrm{b}} = \frac{\Lambda_b}{6H_0^2}$$

$$\text{Flat universe} \Rightarrow \Omega_\sigma = 1 - \Omega_{0\mathrm{m}} + \sqrt{\Omega_l}\sqrt{1+\Omega_{\Lambda_\mathrm{b}}}$$

$$w_0 = -1 - \frac{\Omega_{0\mathrm{m}}}{1-\Omega_{0\mathrm{m}}}\sqrt{\frac{\Omega_l}{\Omega_{0\mathrm{m}} + \Omega_\sigma + \Omega_l + \Omega_{\Lambda_\mathrm{b}}}} \leq -1\ .$$

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Current SNe data :

SNe Ia $\Rightarrow$ Thermonuclear explosion in C+O white dwarf

Strong correlation between peak magnitude & light curve shape $\longrightarrow$ calibrated candles

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High-z SNe $\longrightarrow$ Accelerating Universe $\longrightarrow$ Dark Energy

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High-z SNe $\rightarrow$ Accelerating Universe $\rightarrow$ Dark Energy

1. Calan Tololo low z data + Supernova Cosmology Project (SCP) + High-z SNe Search Team (HZT) + Hubble Space Telescope (HST)–

   Gold Sample $\Rightarrow$ 157 SNe between $z = 0 - 1.7$

2. Calan Tololo + SuperNova Legacy Survey 2 yr data

   SNLS sample $\Rightarrow$ 115 SNe between $z = 0 - 1.0$

Complementary Datsets :

- Baryon Acoustic Oscillations (BAO) :

For SDSS data at $z_{ob} = 0.35$

$$A = \frac{\sqrt{\Omega_{0\rm m}}}{h(z_{ob})^{1/3}} \left[\frac{1}{z_{ob}} \int_0^{z_{ob}} \frac{dz}{h(z)} \right]^{2/3} = 0.469 \pm 0.017 \, ,$$

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Cosmic Microwave Background (CMB) :

For WMAP3 data with $\Omega_{0\mathrm{m}} h^2 = 0.127^{0.007}_{0.013}$

$$R = \sqrt{\Omega_{0\mathrm{m}}} \int_0^{z_{\mathrm{ls}}} \frac{dz}{h(z)} = 1.70 \pm 0.03$$

Model Fitting :

Observations ⇒

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Observations $\Rightarrow$ SNe $\rightarrow \{y = 5\log(d_L), z, \sigma_y, \sigma_z\}$

BAO $\rightarrow \{A(z_{ob}), z_{ob}, \sigma_A\}$

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χ^2 Minimisation

Model parameters $\{\Omega_{0\mathrm{m}}, \Omega_l, \Omega_{\Lambda_{\mathrm{b}}}\}$

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Likelihood in $\{\Omega_{0\mathrm{m}}, \Omega_l, \Omega_{\Lambda_\mathrm{b}}\}$

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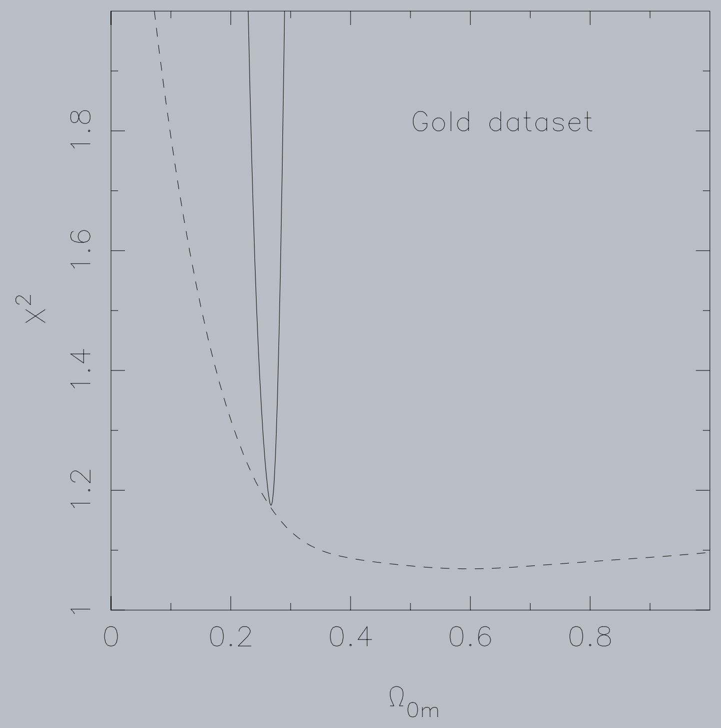
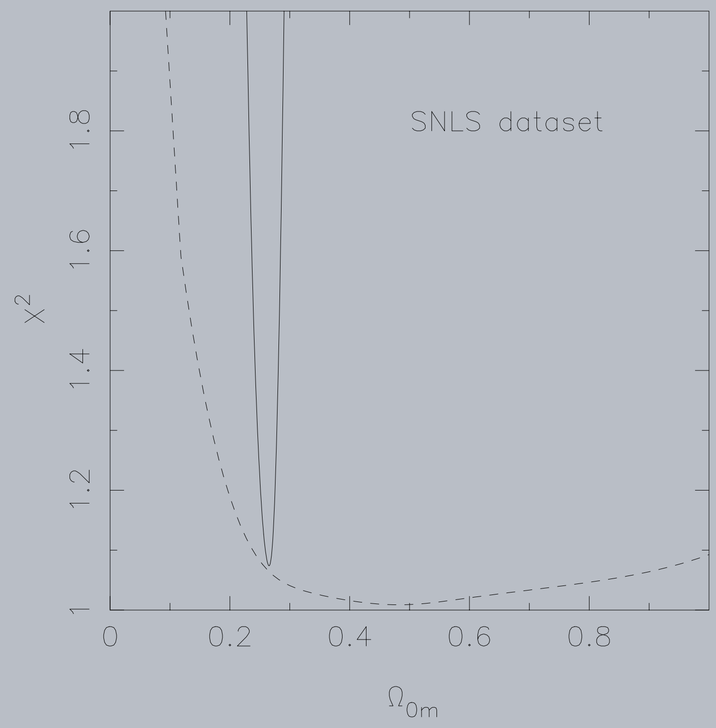
Likelihood in $\{\Omega_{0\mathrm{m}}, \Omega_l\}$

Results for B1 :



Gold



SNLS

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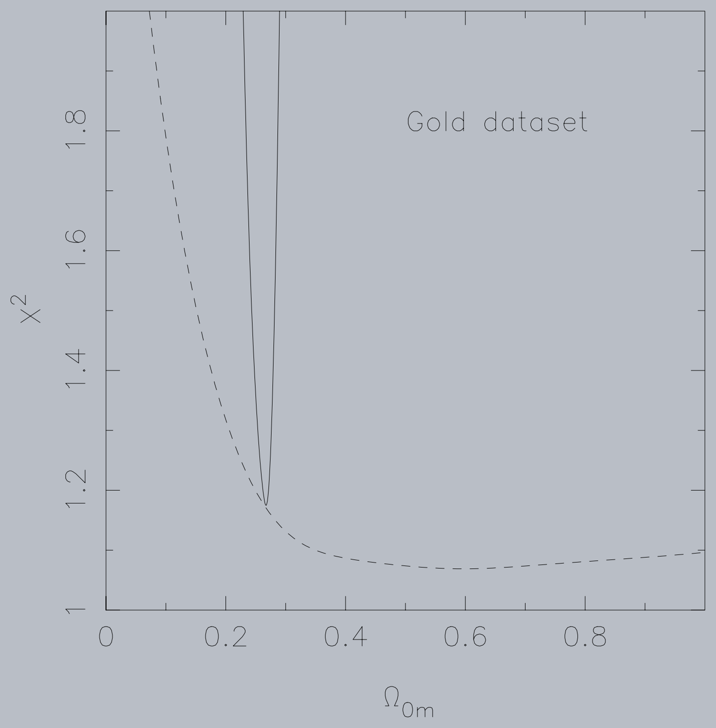

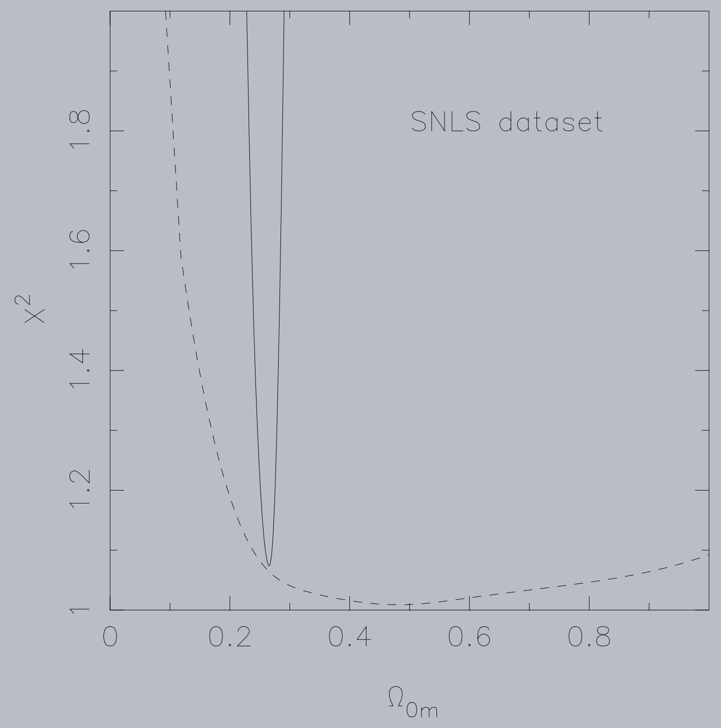

Gold *SNLS*

$$
\begin{aligned}
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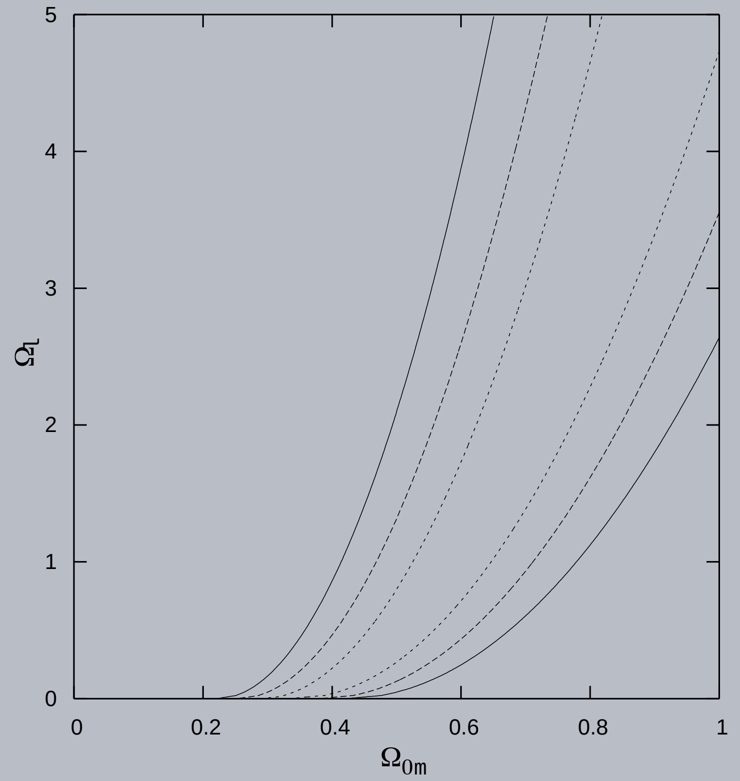

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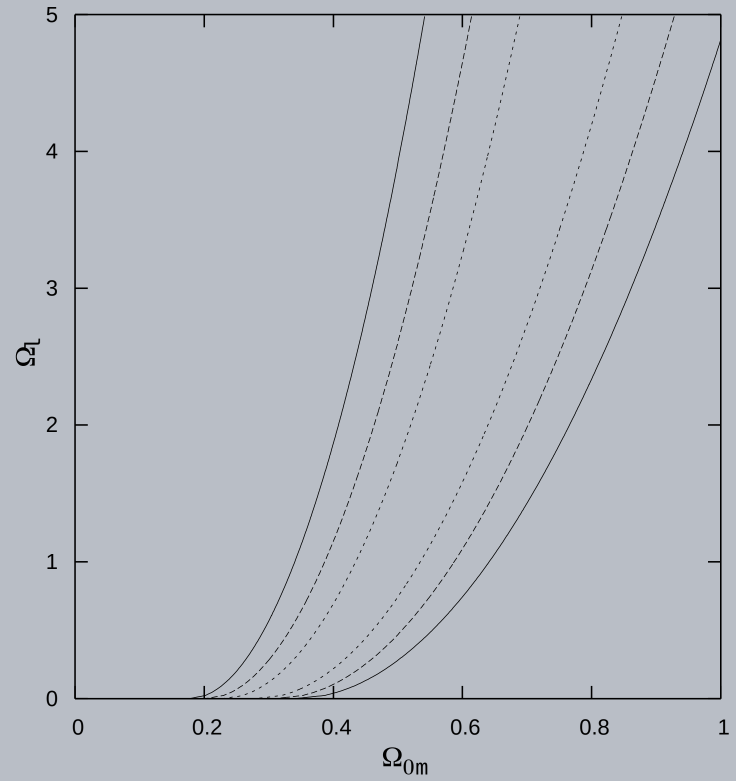
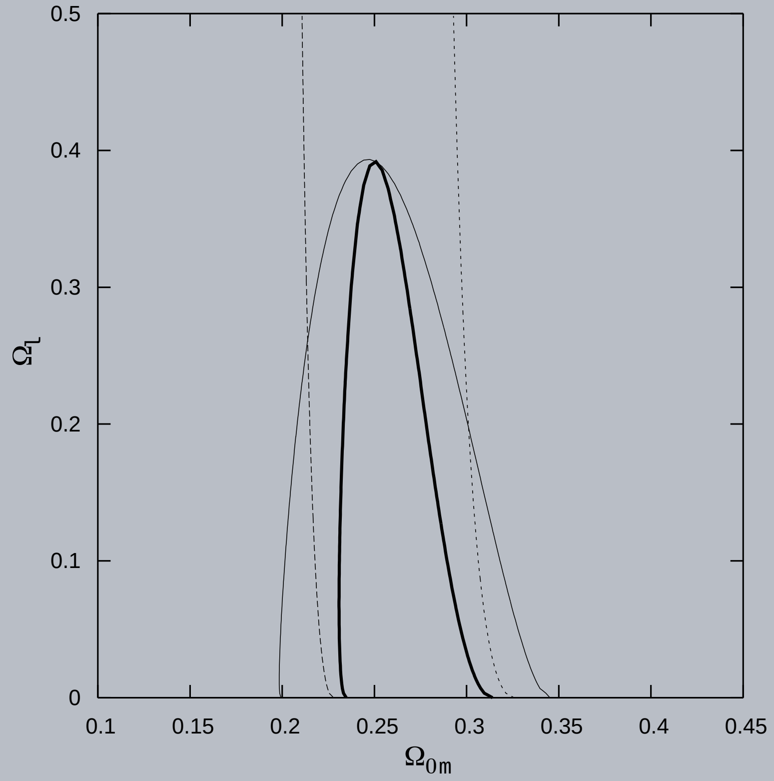
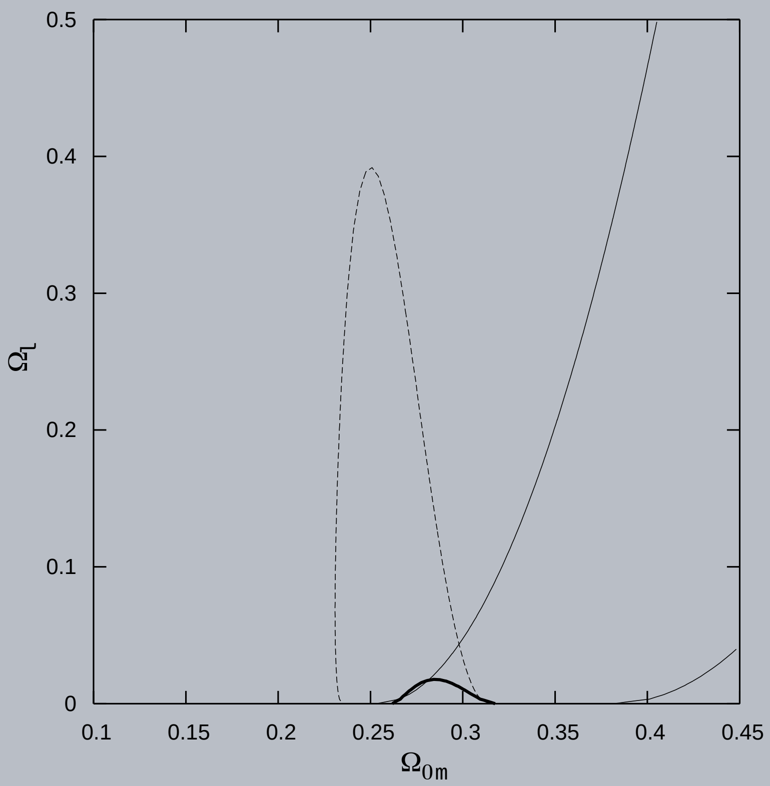


SNLS

CMB+BAO Results for B1 :



CMB+BAO+SNe Results for B1 :



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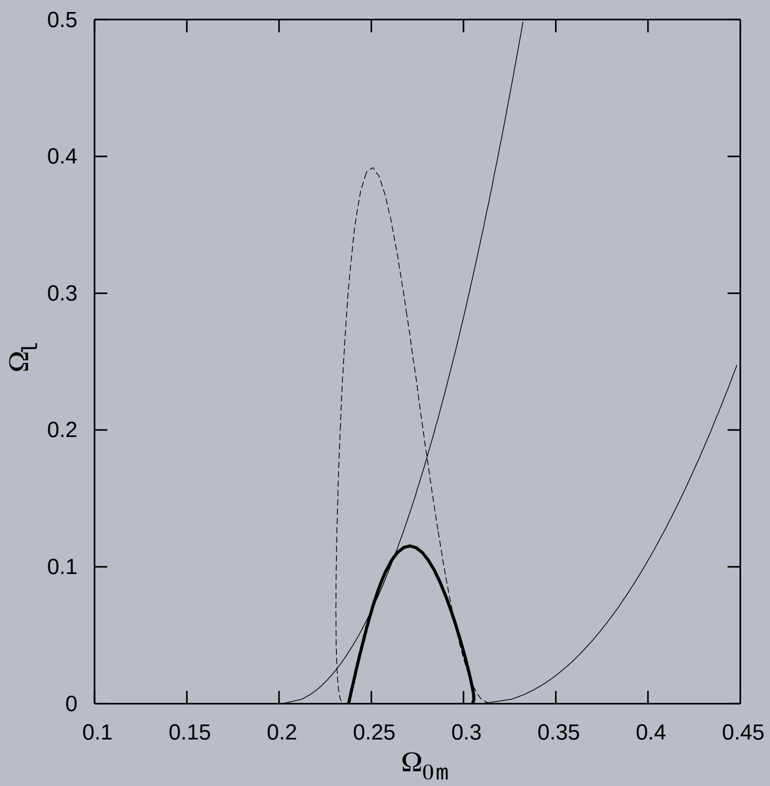
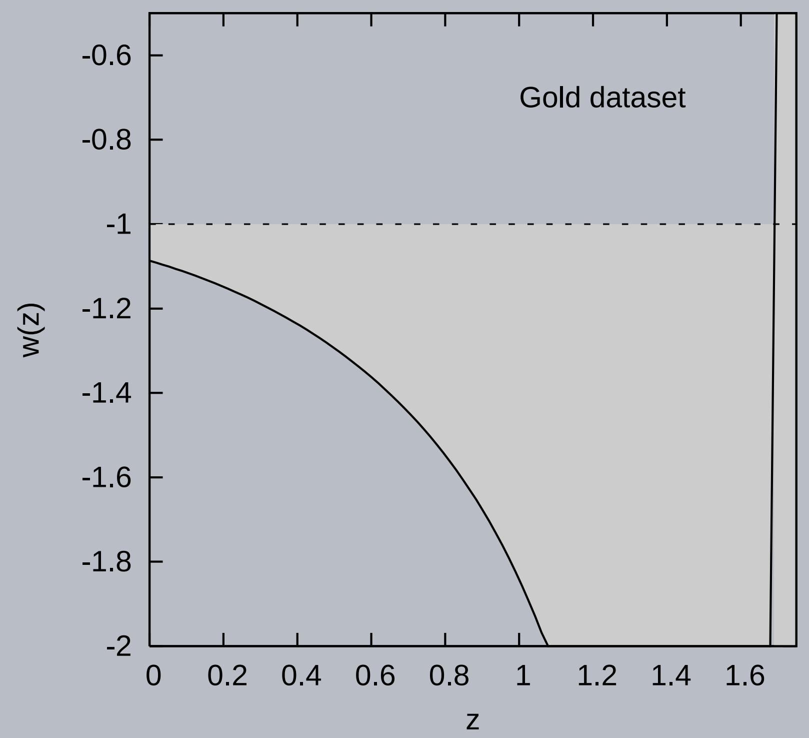


SNLS

$w_{\rm eff}$ for B1 :



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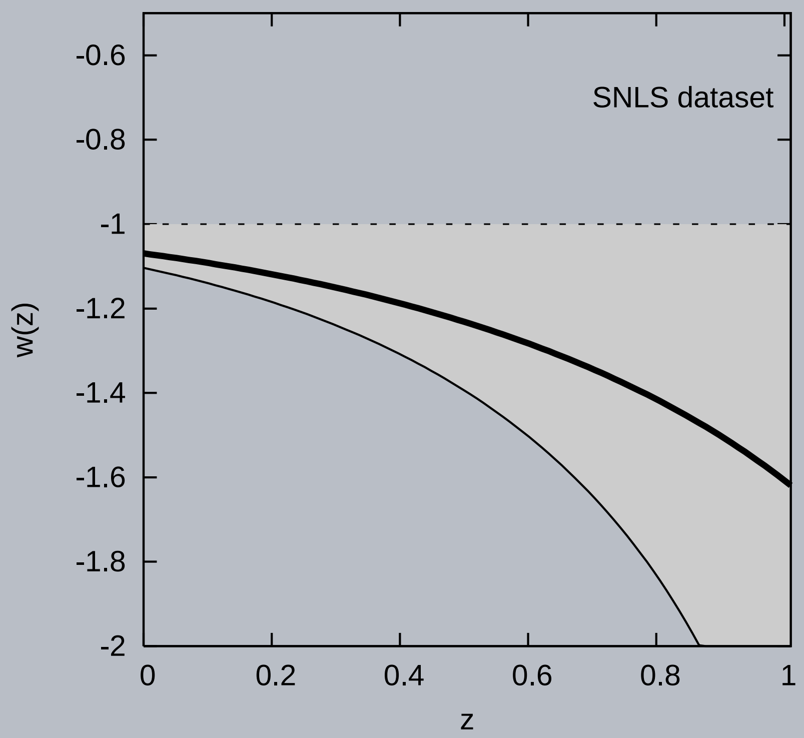
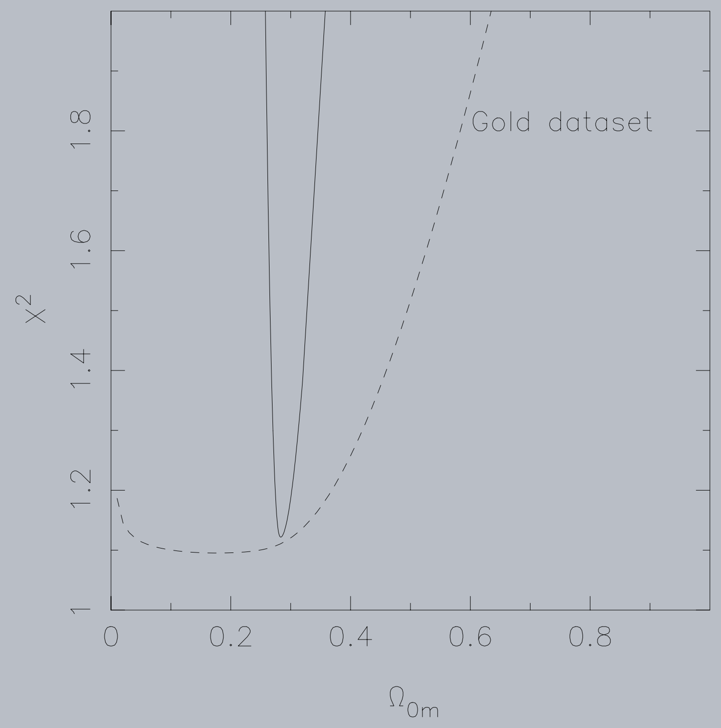


SNLS

Results for B2 :



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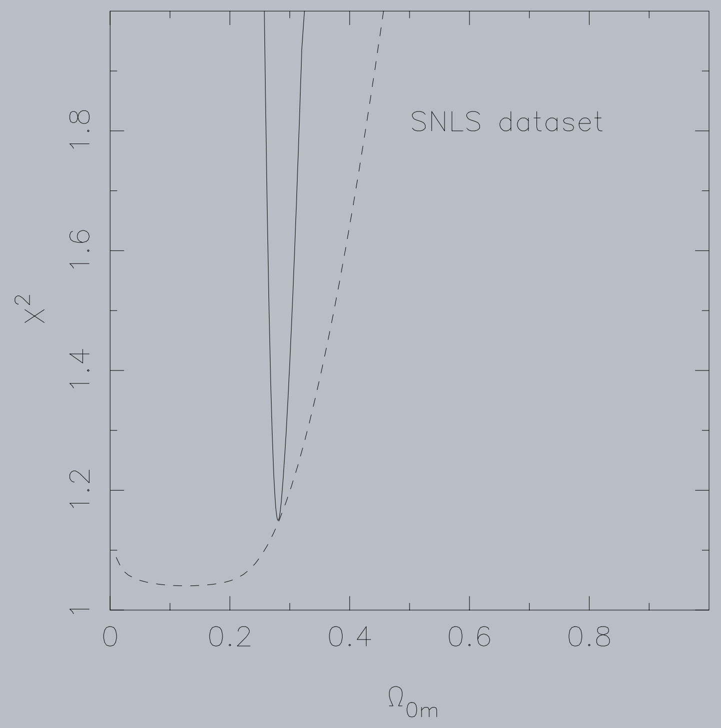

SNLS

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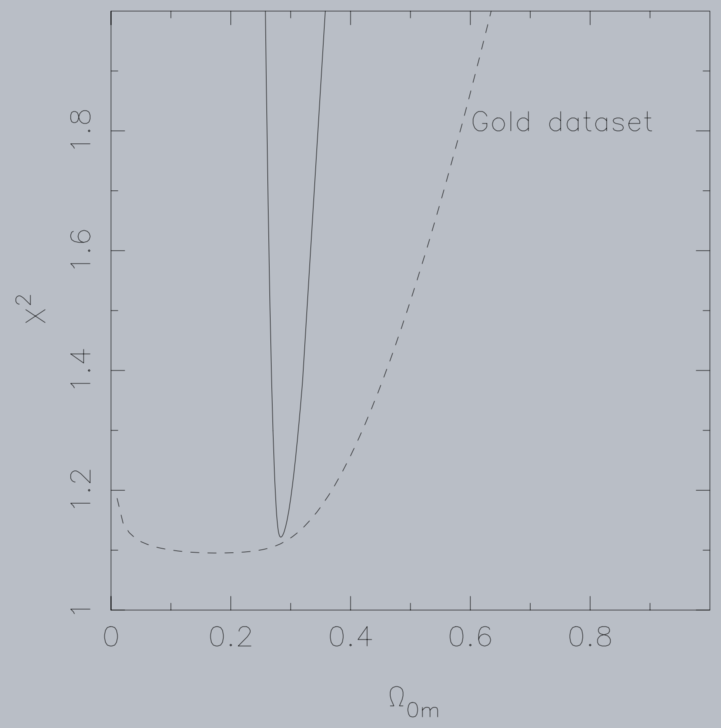

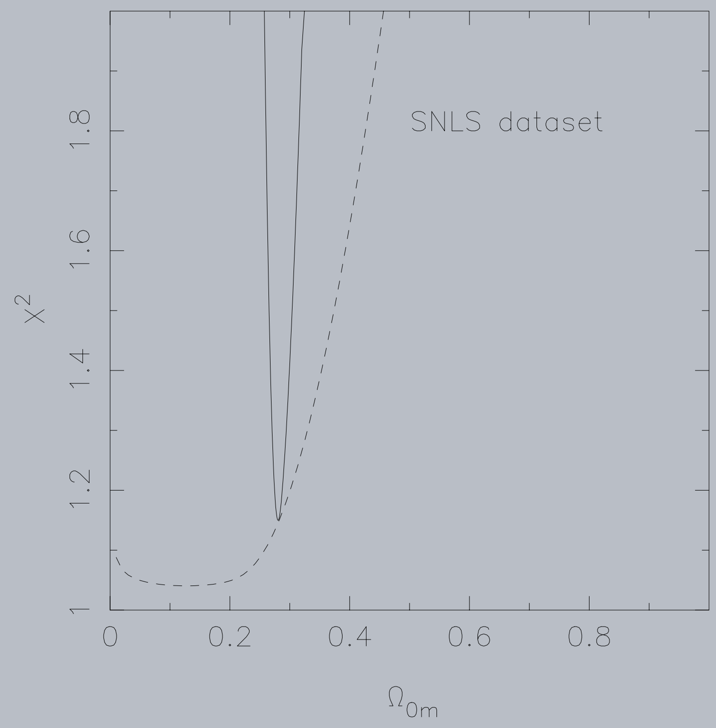

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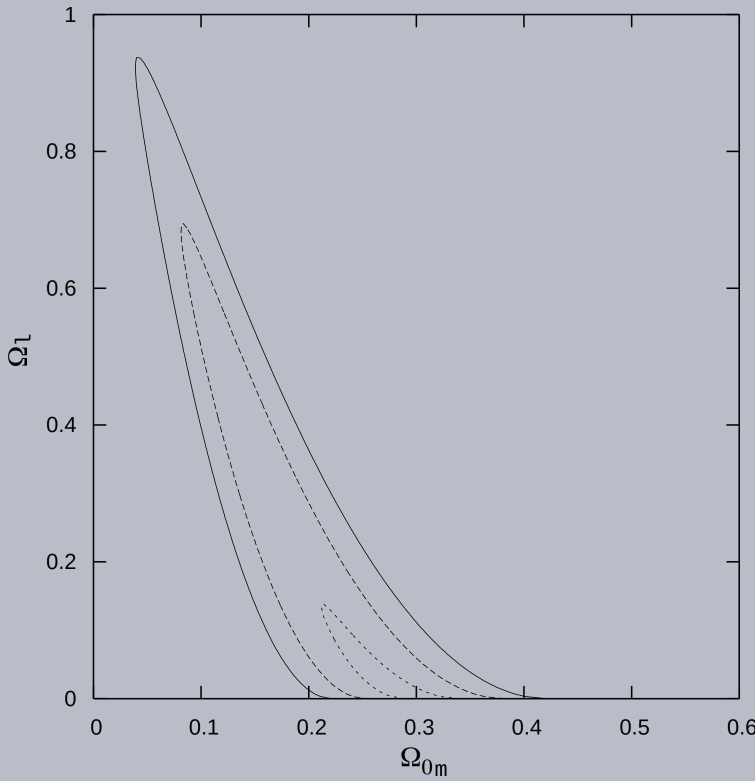

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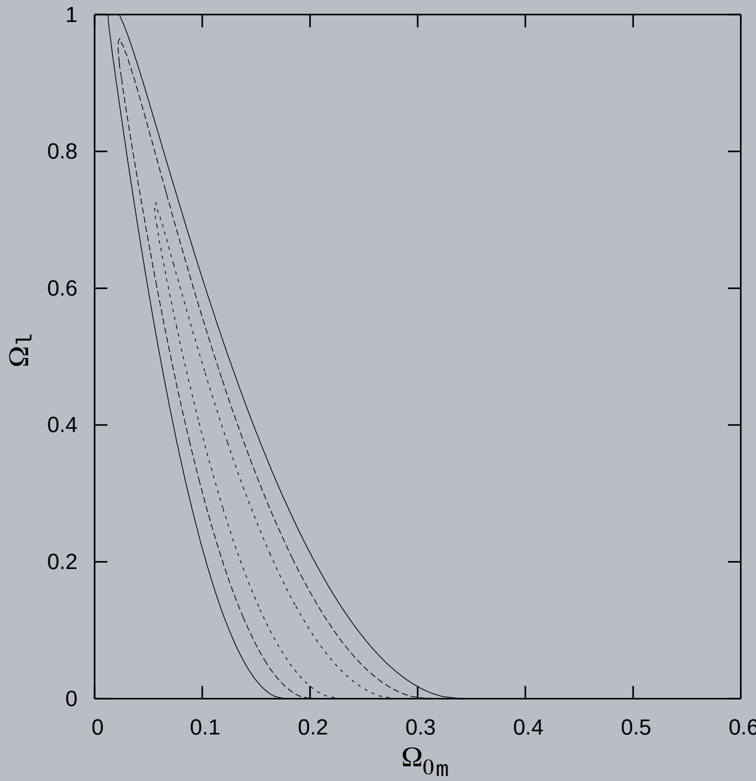

SNLS

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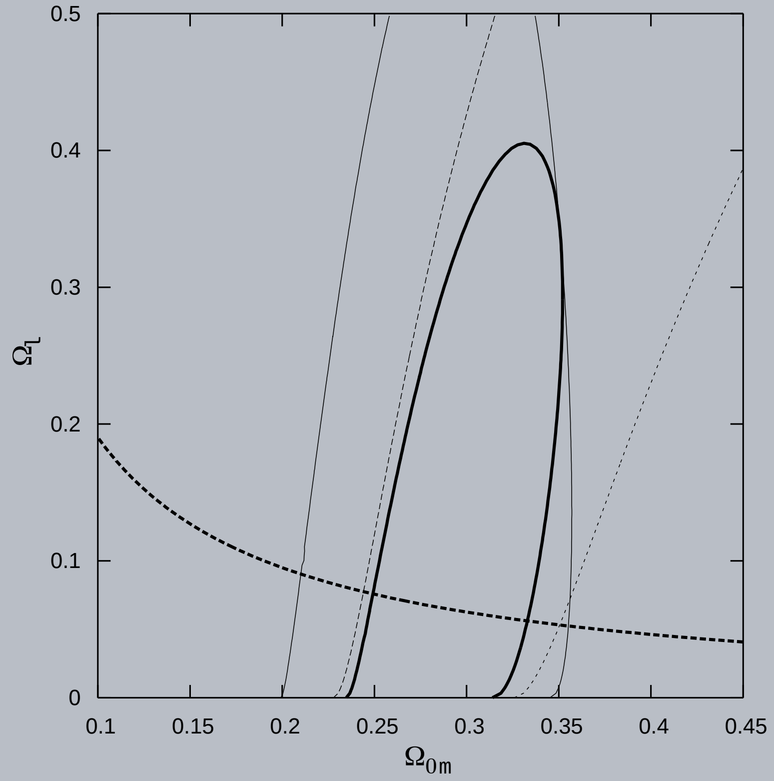
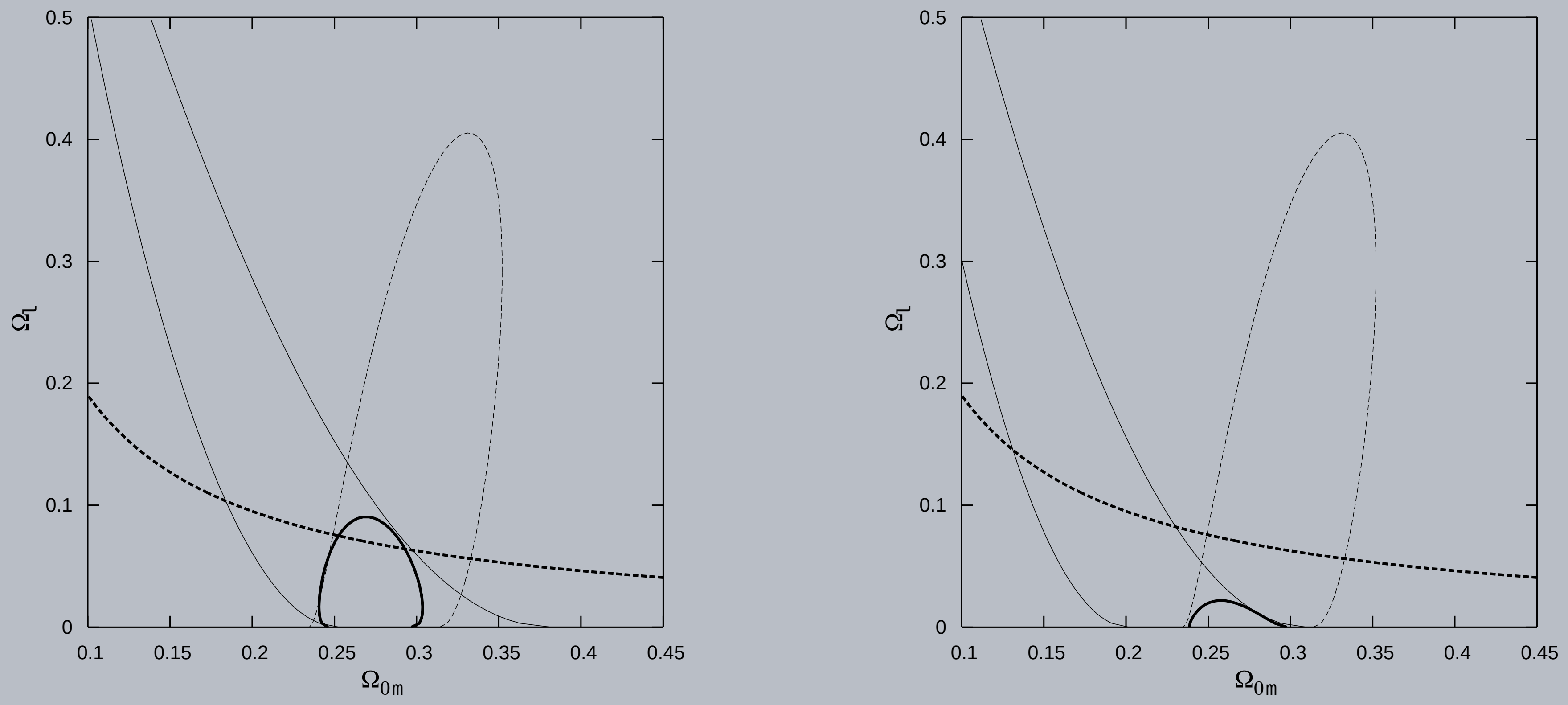


CMB+BAO+SNe Results for B2 :



Gold *SNLS*

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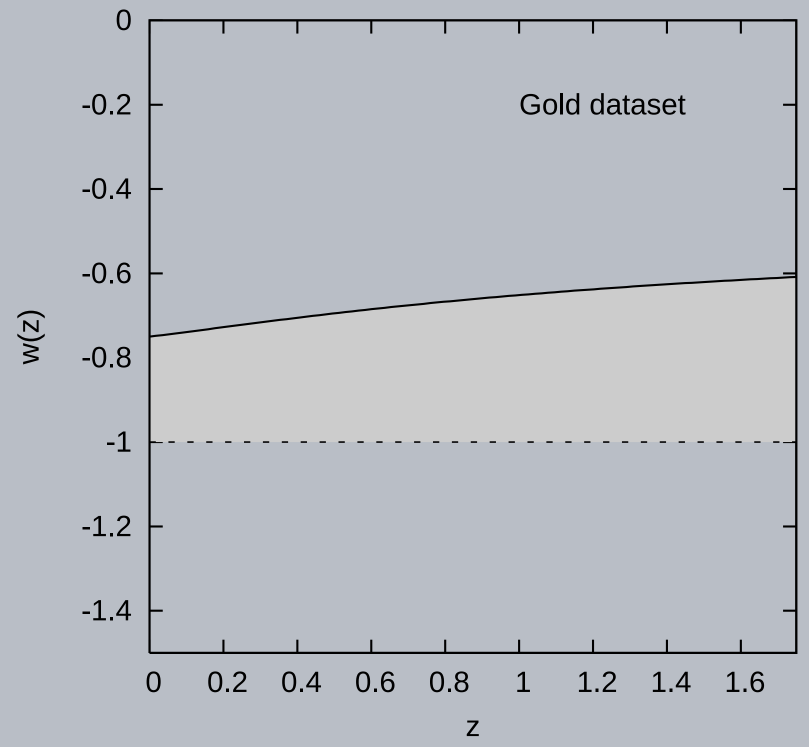

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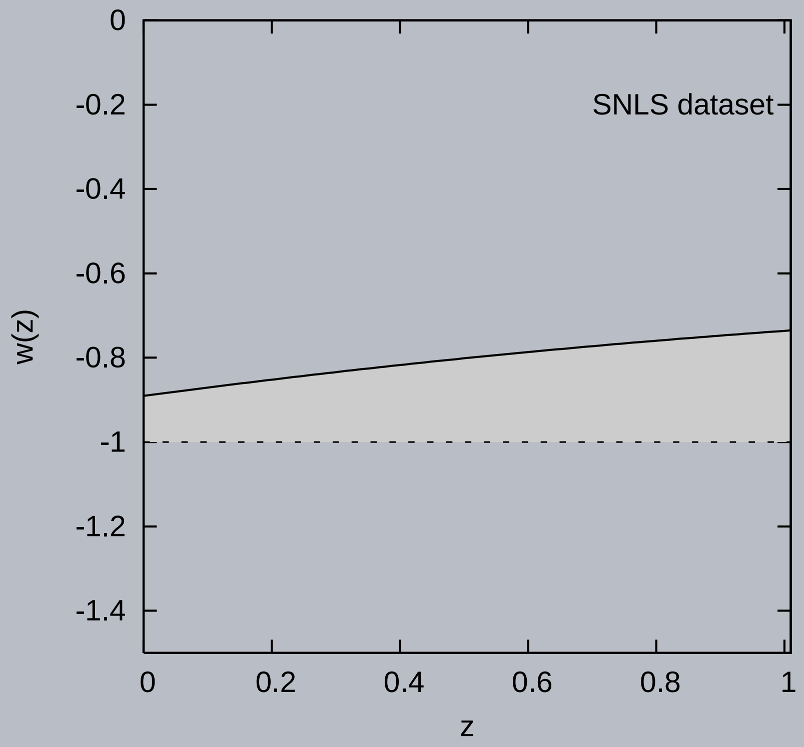

SNLS

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- SNe data– Slight discrepancy between results from two datasets–

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