Constraining Accelerating Cosmologies with Distance Measures

astro-ph/0611775, updated with ESSENCE data

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Our universe is…

- Expanding: $$H(a) = \frac{\dot{a}}{a} > 0$$

$$\mathrm{H}_0 = 72 \pm 8$$ (Friedman 2001)

$$\mathrm{H}_0 = 62.3 \pm 6.3$$ (Sandage 2006)

- Accelerating:

Decelerating parameter $$q(a) = -\frac{\ddot{a}}{H^2 a} < 0$$

Luminosity distance

- Probe for cosmological expansion history $E(z)$
- Theoretical: $D_L(z) = (1+z)\sqrt{|\Omega_k|}\, f[\frac{1}{\sqrt{|\Omega_k|}}\int_0^z \frac{dx}{E(x)}]$
    - f: *sinh* if $\Omega_k > 0$ or *sin* if $\Omega_k < 0$
- Experimental:

  $5\log_{10}(D_L/10) \sim M_{(\text{absolute luminosity})} - m_{(\text{apparent luminosity})}$

Distance Modulus $m = M - m$ + correction

from SN light curve

Standard Candle

- Type-Ia supernovae

  Explosion at 1.44 solar mass, Energy ~10^{46} J

  $\Rightarrow$ consistent absolute luminosity

  $\Rightarrow$ measurable D_L

- Available datasets

  HST Key Project (Riess et.al. 2006)
  SNLS (Astier et. al. 2005)
  ESSENCE (Wood-Vasey et. al. 2007)
  "Nearby SN" at low redshift z < 0.015 (Guy et.al. 2005)

Data compilations

Gold set (Riess 2006) http://braeburn.pha.jhu.edu/~ariess/R06/

182 Type-Ia SN, $z < 1.7$, 16 SN $z > 1$

Combined with initial ESSENCE release (Davis 2007)

Available at: http://www.ctio.noao.edu/essence

192 SN with 15 $z > 1$,

Improved SN selection and uncertainty analysis

Other Constraints

CMB shift parameter (WMAP)

$$R = \sqrt{\Omega_m}\,\frac{D_L(z_{CMB})}{1+z_{CMB}} = 1.70 \pm 0.03$$

(Wang & Mukherjee 2006)

Insensitive to DE models

Baryonic acoustic oscillation (SDSS)

$$A = \sqrt{\Omega_m}\left[\frac{1}{E(z_{BAO})}\left(\frac{D_L(z_{BAO})}{z_{BAO}(1+z_{BAO})}\right)^2\right]^{1/3} = 0.469 \pm 0.017$$

suitable for stationary DE models

Statistical Analysis

- Likelihood function $c^2 = c^2_{SN} + c^2_{R} + c^2_{BAO}$

$$c^2_{SN} = \sum_i \frac{(m_i^{obs} - m_i^{th})^2}{s_i^2} = \sum_i \frac{(m_i^{obs} - 5\log_{10} D_{L,i} - M)^2}{s_i^2}$$

$$c^2_{R} = \frac{(R^{obs} - R^{th})^2}{s_R^2} \qquad c^2_{BAO} = \frac{(A^{obs} - A^{th})^2}{s_{BAO}^2}$$

- Marginalization over SN nuisance parameter M

(E.Pietro, J. Claeskens, 2002)

$$A = \sum_i \frac{(m_i^{obs} - 5\log_{10} D_{L,i})^2}{s_i^2}$$

$$B = \sum_i \frac{(m_i^{obs} - 5\log_{10} D_{L,i})}{s_i^2} \quad \Longrightarrow \quad c^2_{SN} = A - \frac{B^2}{C}$$

$$C = \sum_i \frac{1}{s_i^2}$$

Cosmological models

- ΛCDM

  Einstein's cosmological constant Λ with non-evolutionary dark energy equation of state

$$w \equiv p/r = -1$$

Dimensionless Friedman equation

$$\frac{H^2(z)}{H_0^2} \equiv E^2(z) = \Omega_m (1+z)^3 + \Omega_K (1+z)^2 + \Omega_\Lambda$$

$$E^2(z=0) = 1 \Rightarrow \sum_i \Omega_i = 1$$

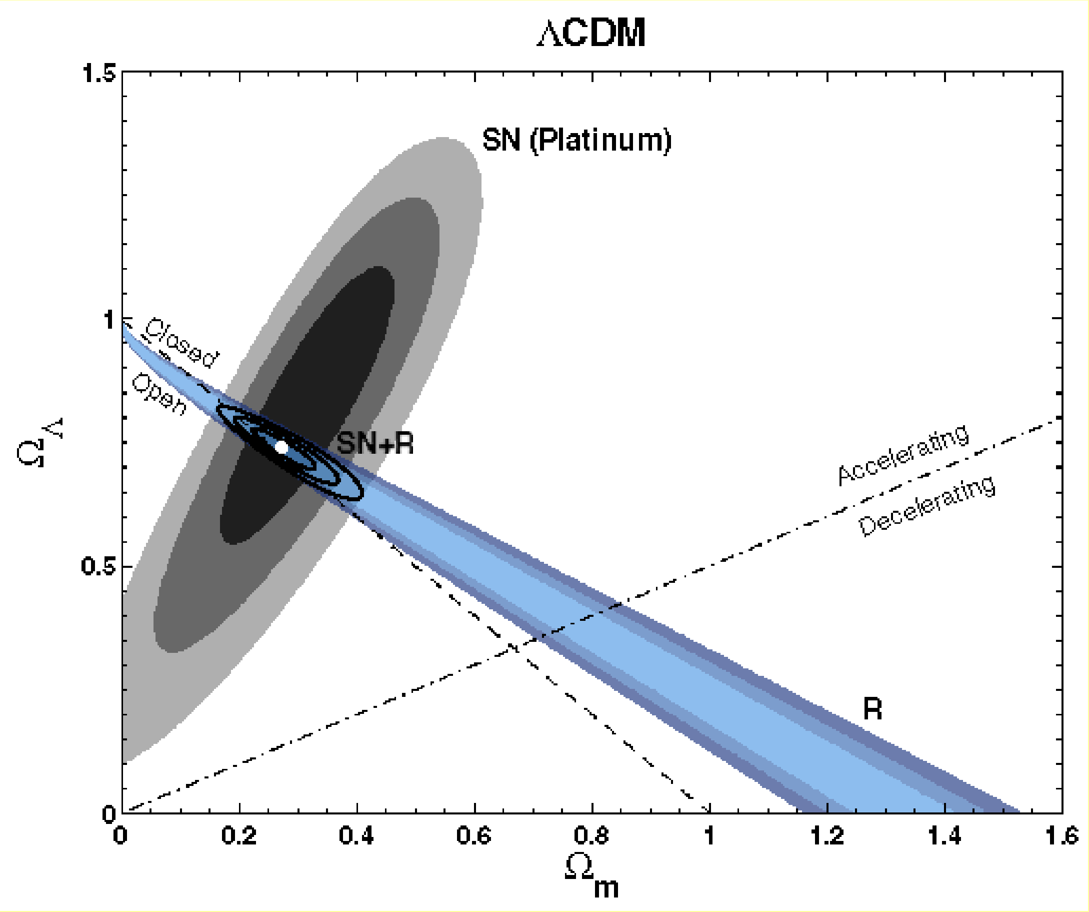
Ω_m: Total matter density

Ω_K: Curvature density, universe is **OPEN** if Ω_K<0 or **CLOSED** if Ω_K>0

Ω_Λ: Dark energy density

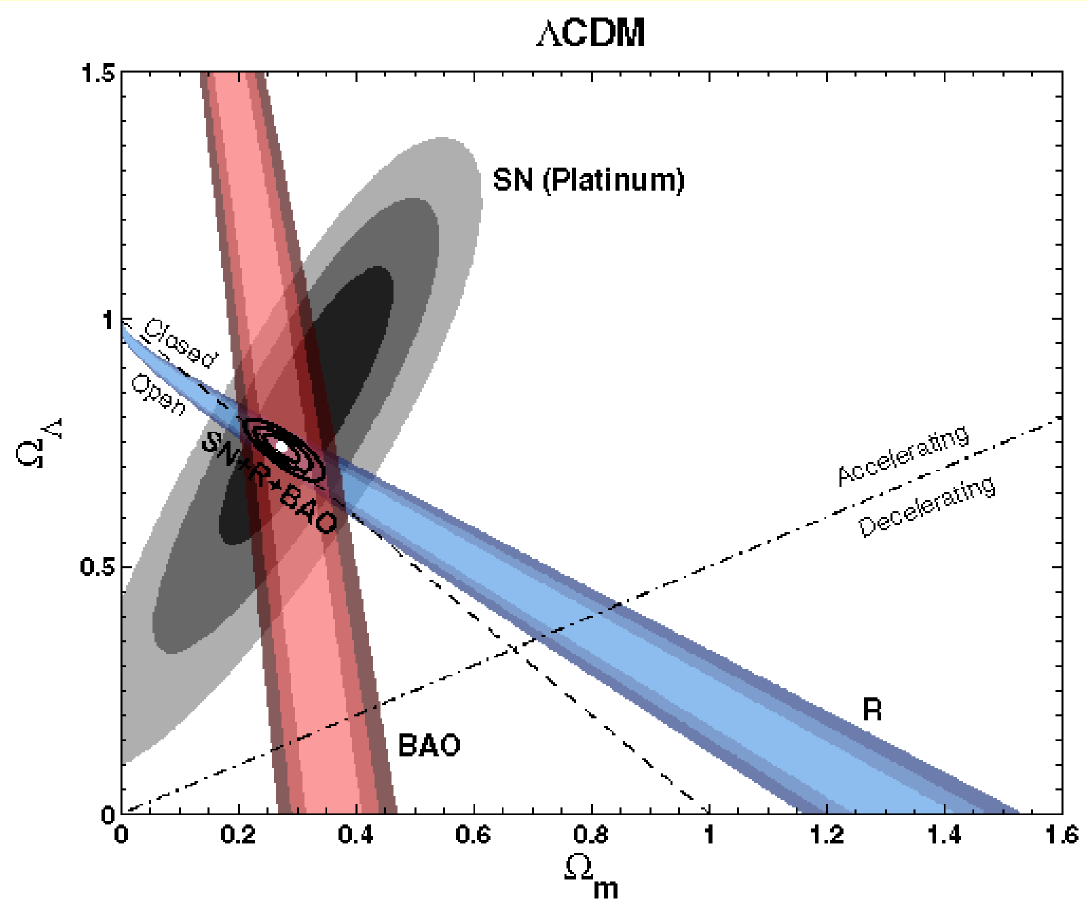
ΛCDM, SN+shift parameter(R)

Davis 07 data



ΛCDM, SN+BAO+shift parameter(R)

Davis 07 data



Davis 07	χ^2	Ω_Λ	Ω_k	Ω_m
SN	195.2	$0.85^{+0.25}_{-0.30}$	$-0.17^{+0.43}_{-0.37}$	$0.33^{+0.13}_{-0.16}$
SN+R	195.6	0.74 ± 0.04	$-0.01^{+0.02}_{-0.03}$	$0.27^{+0.06}_{-0.05}$
SN+R+BAO	195.6	0.74 ± 0.03	-0.01 ± 0.02	0.27 ± 0.03

- *w*CDM

Dark energy equation of state $\frac{\dot{\rho}}{\rho} = -3(1+w)H$ evolves according to

$$w = w_0 + w_a \frac{z}{1+z}$$ (M. Chevallier, D Polarski, 2000)

*w*CDM Friedman equation

$$E^2(z) = \Omega_m (1+z)^3 + \Omega_K (1+z)^2 + \Omega_\Lambda (1+z)^{3(1+w_0+w_a)} e^{-3w_a \frac{z}{1+z}}$$

$\Rightarrow$ * Spatially flat models: $\Omega_K = 0$

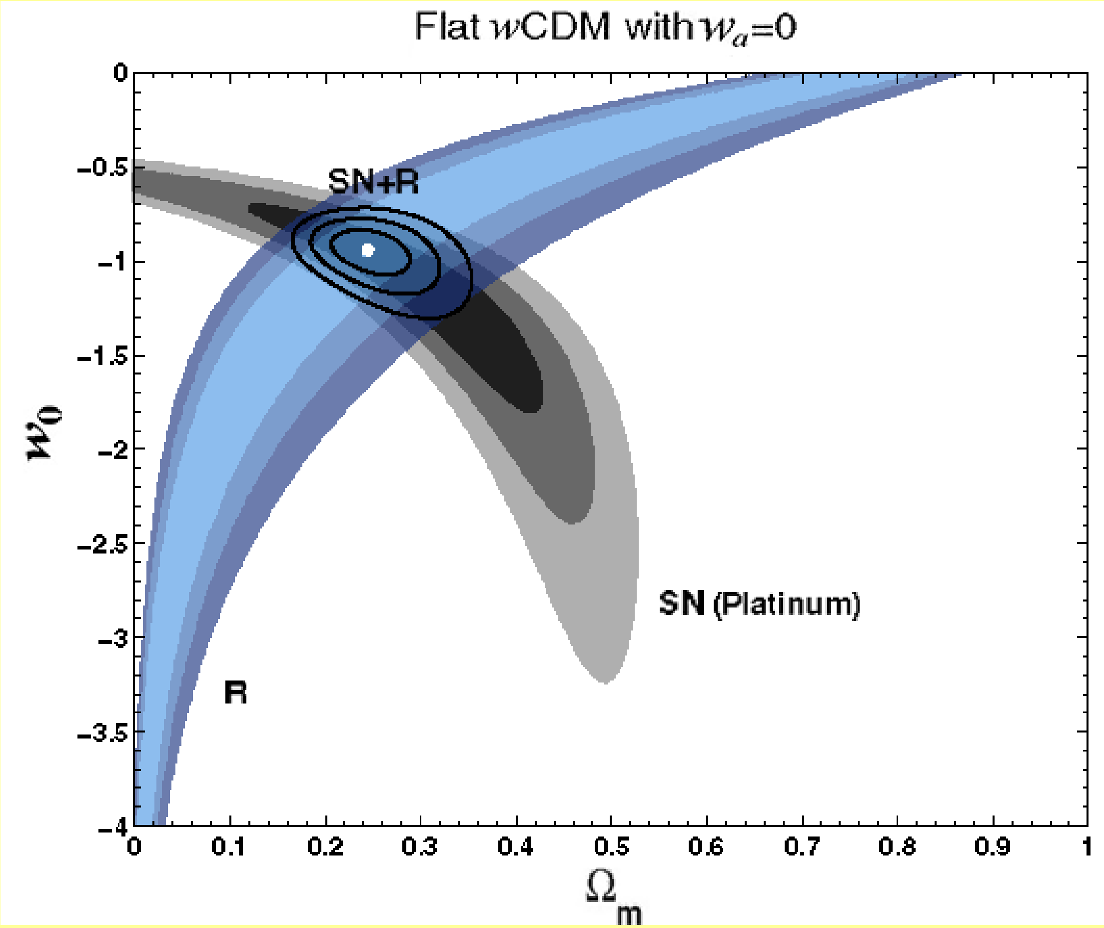
* ΛCDM: $w_a = 0$, $w_0 = -1$

* "Weak prior", assumes $w(z>1.8) = -1$ (Riess 06)

i.e. outside red-shift range probed by supernovae

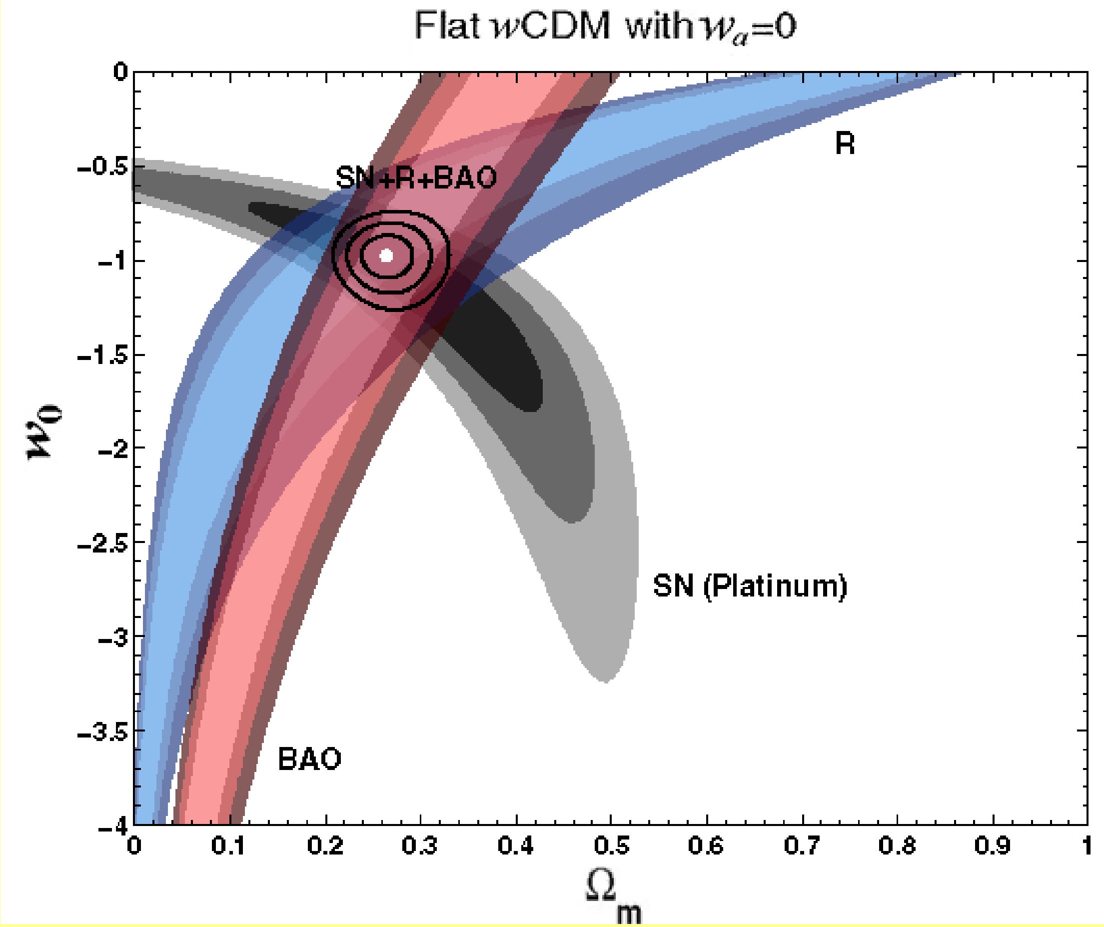
Flat wCDM w_a=0, SN+shift parameter(R)

Davis 07 data



Flat wCDM w_a=0, SN+BAO+shift parameter(R)

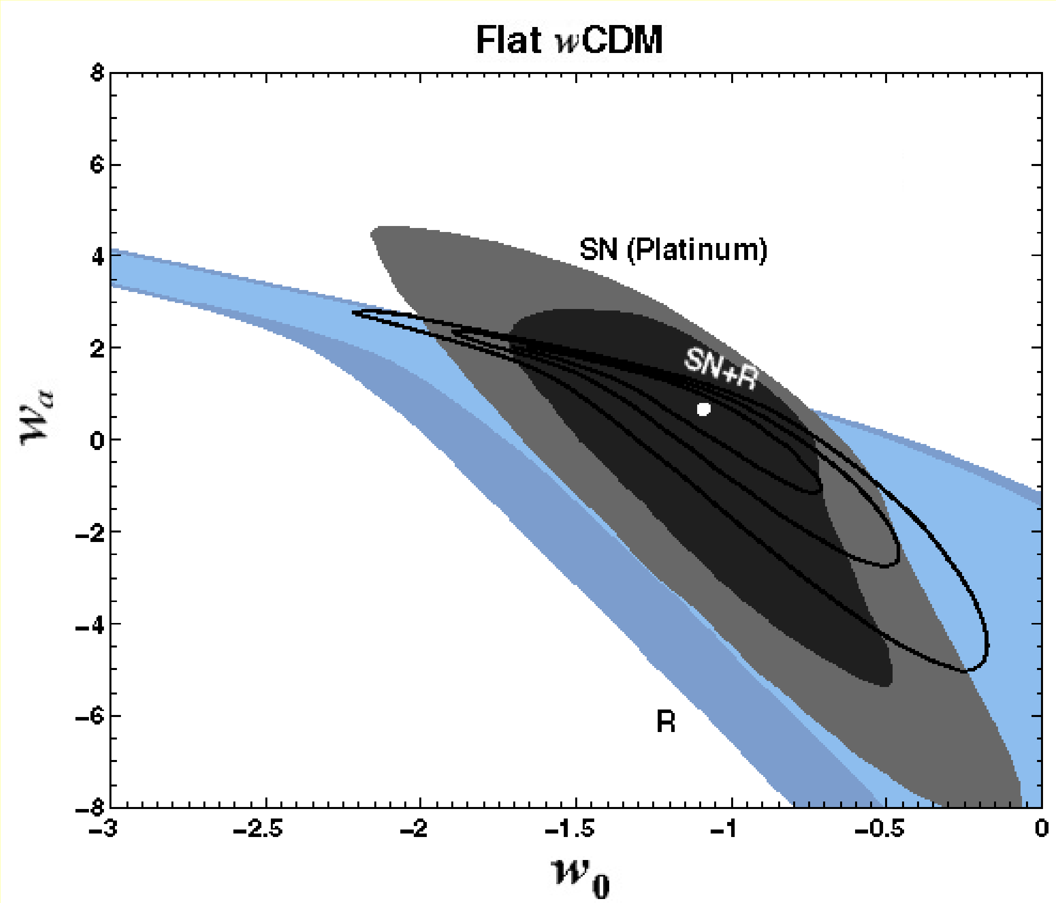
Davis 07 data



	χ^2	w_0	Ω_m
SN	195.4	$-1.16^{+0.46}_{-0.62}$	$0.31^{+0.12}_{-0.19}$
SN+R	195.9	$-0.94^{+0.11}_{-0.13}$	$0.24^{+0.05}_{-0.03}$
SN+R+BAO	196.6	$-0.98^{+0.11}_{-0.12}$	$0.26^{+0.03}_{-0.02}$

Flat *w*CDM, 0.15< Ω_m<0.35, SN+shift parameter(R)

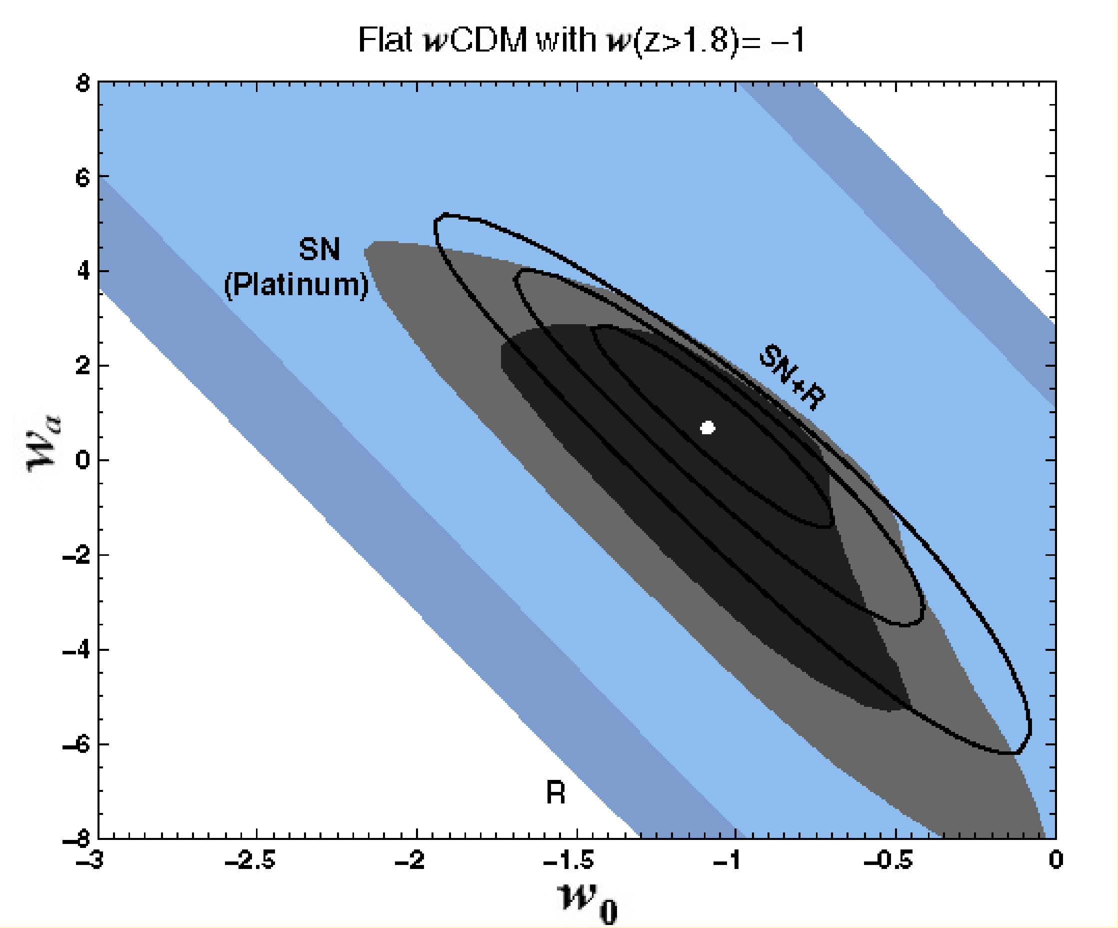
Davis 07 data



	χ^2	w_0	w_a
SN	195.3	-1.1 **±0.6**	-1.2 $^{+4.0}_{-4.1}$
SN+R	195.5	-1.1 **±0.6**	0.7 $^{+2.2}_{-6.0}$

Flat *w*CDM,*w*(z>1.8) = -1, SN+shift parameter(R)

Davis 07 data



	χ^2	w_0	w_a
SN	195.3	-1.1 ±0.6	$-1.2^{+4.0}_{-4.1}$
SN+R	195.5	-1.1 ±0.4	$-0.8^{+3.6}_{-0.6}$

Modified gravity?

- Braneworld model (Randall & Sundrum 1999)

  Gravitation with Extra dimension

  Generically, $$E^2(z) = \Omega_m(1+z)^3 + \Omega_K(1+z)^2 + \Omega_s + 2\Omega_l \mp 2\sqrt{\Omega_l}\sqrt{\Omega_m(1+z)^3 + \Omega_s + \Omega_l + \Omega_{\Lambda b}}$$

  (Sahni, Shtanov 2002)

  Problem: Too many free parameters for SN data.

- **A specific case**: DGP (Dvali, Gabadadze & Porrati 2000)

  Gravitational leakage into 5th bulk dimension over long distance

$$r > r_0 = \frac{M_4^2}{2M_5^3}$$

Hubble expansion in DGP

A braneworld case with $\Omega_s, \Omega_{\Lambda b} \to 0$

Solution on the self-accelerating branch:

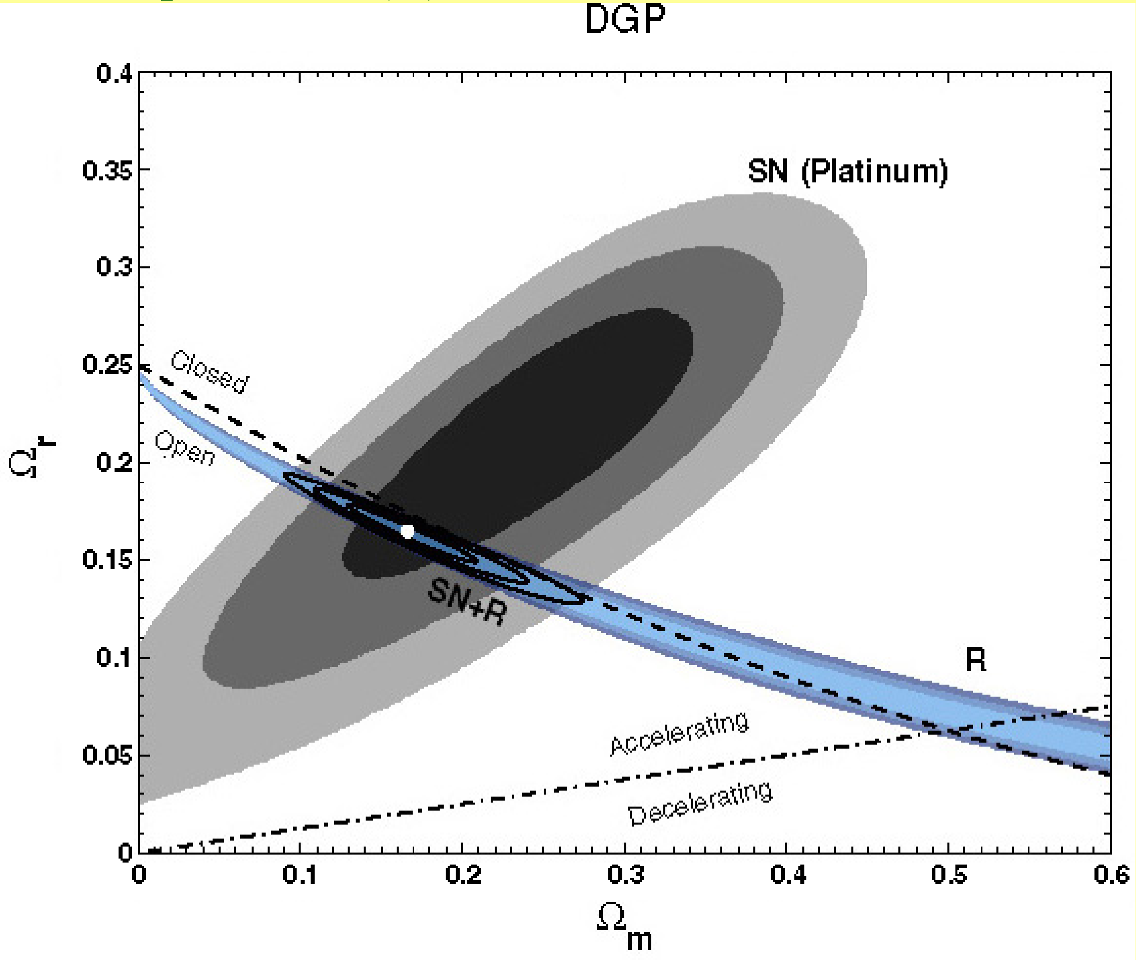
$$E^2(z) = \Omega_m(1+z)^3 + \Omega_K(1+z)^2 + 2\Omega_r + 2\sqrt{\Omega_r}\sqrt{\Omega_r + \Omega_m(1+z)^3}$$

$$E(z=0) = 1 \qquad \Rightarrow \qquad \Omega_K = 1 - [\sqrt{\Omega_r} + \sqrt{\Omega_r + \Omega_m}]^2$$

Where $\Omega_r \equiv \dfrac{1}{4H_0^2 r_0^2}$

DGP, SN+shift parameter(R)

Davis 07 data



	χ^2	Ω_r	Ω_k	Ω_m
SN	195.1	$0.22^{+0.06}_{-0.08}$	$-0.30^{+0.48}_{-0.39}$	$0.24^{+0.10}_{-0.11}$
SN+R	196.4	$0.16^{+0.02}_{-0.01}$	0.04 ± 0.02	0.17 ± 0.04

Summary: Models, constraints and best-fit parameters

Model	Gold+SNLS+ESSENCE (Davis 07)		
ΛCDM	χ^2	Ω_Λ	Ω_m
SN	195.2	$0.85^{+0.25}_{-0.30}$	$0.33^{+0.13}_{-0.16}$
SN+R	195.6	0.74 ± 0.04	$0.27^{+0.06}_{-0.05}$
SN+R+BAO	195.6	0.74 ± 0.03	0.27 ± 0.03
Flat ΛCDM	χ^2	Ω_Λ	Ω_m
SN	195.6	0.73 ± 0.03	0.27 ± 0.03
SN+R+BAO	196.6	$0.74^{+0.01}_{-0.02}$	$0.26^{+0.02}_{-0.01}$
wCDM, w_a=0 *	χ^2	w_0	Ω_m
SN	195.4	$-1.16^{+0.46}_{-0.62}$	$0.31^{+0.12}_{-0.19}$
SN+R	195.9	$-0.94^{+0.11}_{-0.13}$	$0.24^{+0.05}_{-0.03}$
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* Spatially flat models

Model	Gold+ESSENCE (Davis 07)		
*w*CDM, $0.15 < \Omega_m < 0.35$ *	χ^2	w_0	w_a
SN	195.3	-1.1 ±0.6	$-1.2^{+4.0}_{-4.1}$
SN+R	195.5	-1.1 ±0.6	$0.7^{+2.2}_{-6.0}$
*w*CDM, *w*(z>1.8)= -1*	χ^2	w_0	w_a
SN	195.3	-1.1 ±0.6	$-1.2^{+4.0}_{-4.1}$
SN+R	195.5	-1.1 ±0.4	$-0.8^{+3.6}_{-0.6}$
DGP	χ^2	Ω_r	Ω_m
SN	195.1	$0.22^{+0.06}_{-0.08}$	$0.24^{+0.10}_{-0.11}$
SN+R	196.4	$0.16^{+0.02}_{-0.01}$	0.17 ±0.04

* Spatially flat models

BAO not included for DGP and $w_a \neq 0$ models

Conclusion

- ΛCDM fits data very well;
  All models produces close minimal χ^2

- Combined analysis prefers **(almost)** flat universe.

What could be more effective probes?

Higher redshift objects (GRB) ?

CMB spectrum for braneworld models ?

… …