Constraining Accelerating Cosmologies with Distance Measures

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Our universe is…

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

$$H_0 = 72 \pm 8$$ (Friedman 2001)

$$H_0 = 62.3 \pm 6.3$$ (Sandage 2006)

- Accelerating:

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

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 $\Omega_K<0$ or **CLOSED** if $\Omega_K>0$

Ω_Λ: Dark energy density

- wCDM

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

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

wCDM Friedman equation

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

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

* ΛCDM: $w_a = 0$

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

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

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 $\Omega_s, \Omega_{\Lambda b} \to 0$

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

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

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

DGP is self-accelerating when $\Omega_r >> \Omega_m$:

(Deffayet, Dvali, Gabadadze, 2001)

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \cdot \left(\frac{\Omega_K}{a^2} + 4\Omega_r\right)$$

$$\Rightarrow \quad \frac{\dot{a}}{a} \sim \frac{1}{r_0}$$

Luminosity distance

- Probe for cosmological expansion history $E(z)$

- Theoretical: $$D_L(z) = (1+z)\sqrt{|\Omega_k|}\, f\left[\frac{1}{\sqrt{|\Omega_k|}}\int_0^z \frac{dx}{E(x)}\right]$$
    - *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,

Reduced uncertainty in distance modulus

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 models where z_{CMB}=1089

Baryonic acoustic oscillation (SDSS)

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

where z_{BAO}=0.35
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)

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

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

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

Models, constraints and best-fit parameters

Model	Gold set (Riess06)			Gold+ESSENCE (Davis 07)		
ΛCDM	χ^2	Ω_Λ	Ω_m	χ^2	Ω_Λ	Ω_m
SN	156.4	0.95	0.48	195.2	0.85	0.33
SN+R	158.4	0.68	0.36	195.6	0.74	0.27
SN+R+BAO	161.4	0.72	0.30	195.6	0.74	0.27
Flat ΛCDM	χ^2	Ω_Λ	Ω_m	χ^2	Ω_Λ	Ω_m
SN	158.7	0.66	0.34	195.6	0.73	0.27
SN+R+BAO	163.2	0.72	0.28	196.6	0.74	0.26
wCDM, w_a=0 *	χ^2	w_0	Ω_m	χ^2	w_0	Ω_m
SN	156.6	-1.75	0.46	195.4	-1.16	0.31
SN+R	160.2	-0.85	0.28	195.9	-0.94	0.24
SN+R+BAO	160.3	-0.86	0.29	196.6	-0.98	0.26

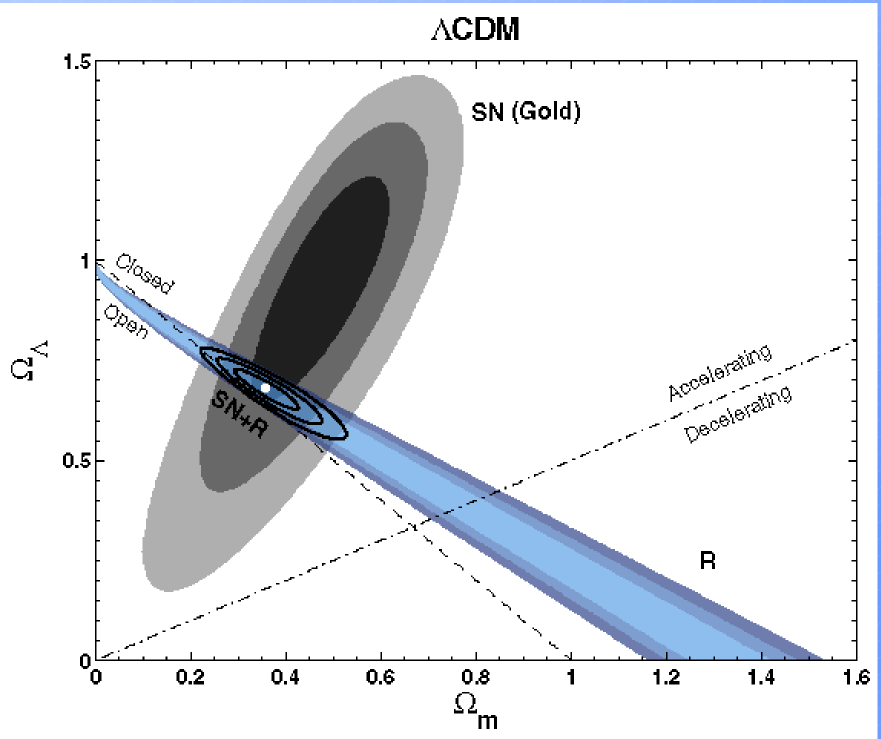
* Spatially flat models

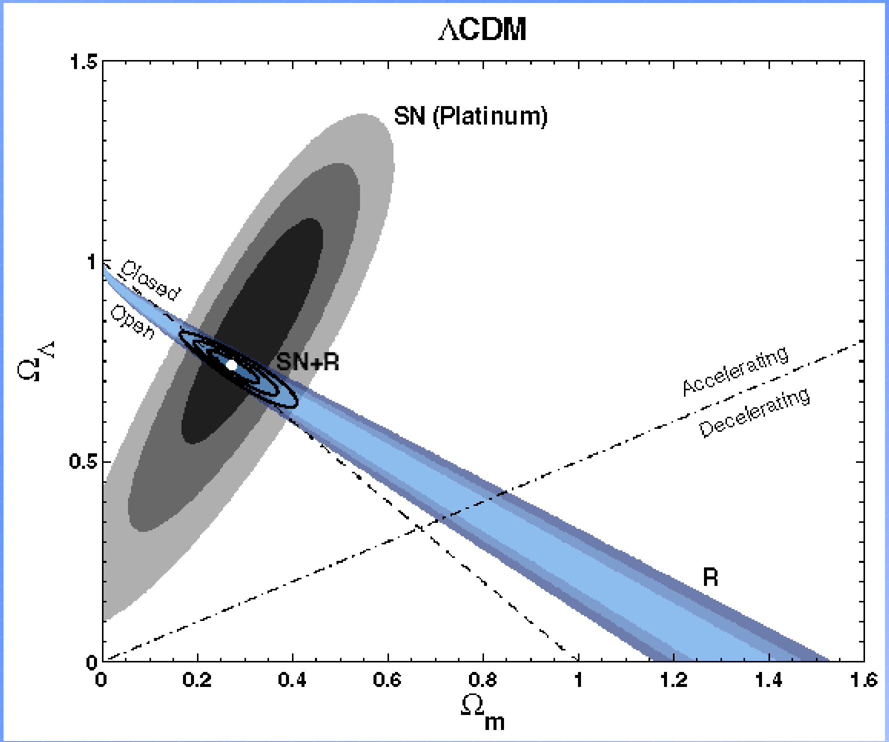
Model	Gold set (Riess06)			Gold+ESSENCE (Davis 07)		
*w*CDM, *w*(z>1.8)= -1*	χ^2	w_0	w_a	χ^2	w_0	w_a
SN	156.5	-1.11	2.39	195.3	-1.11	-1.16
SN+R	156.5	-1.28	2.69	195.5	-1.06	-0.81
*w*CDM, $0.15 < \Omega_m < 0.35$ *	χ^2	w_0	w_a	χ^2	w_0	w_a
SN	156.5	-1.11	2.39	195.3	-1.11	-1.16
SN+R	157.1	-1.37	1.56	195.5	-1.09	0.67
DGP	χ^2	Ω_r	Ω_m	χ^2	Ω_r	Ω_m
SN	156.4	0.24	0.36	195.1	0.22	0.24
SN+R	160.3	0.14	0.23	196.4	0.16	0.17

* Spatially flat models

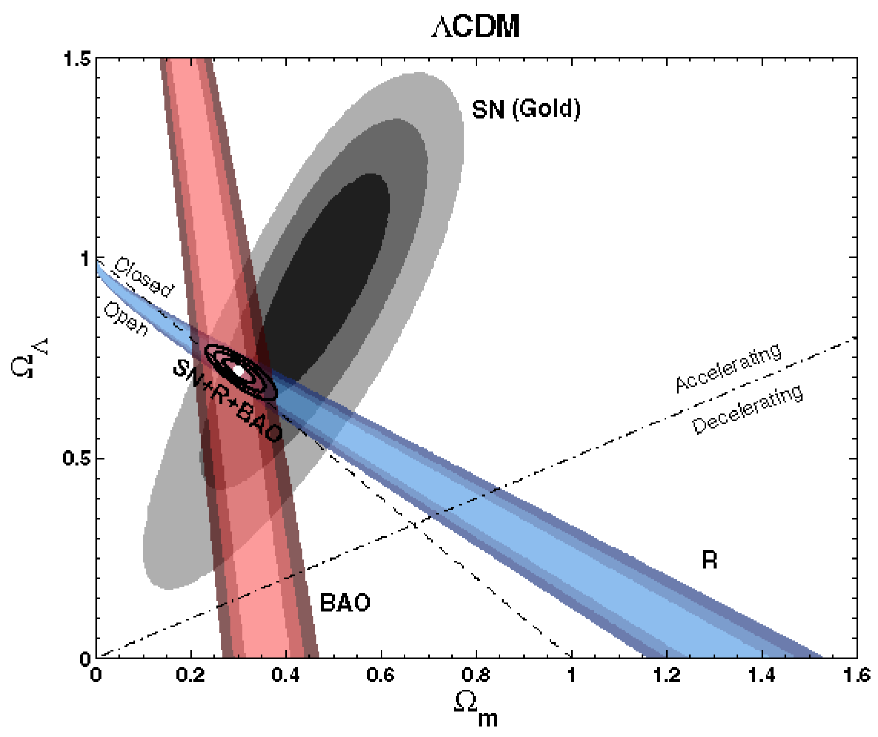
BAO not included for DGP and $w_a \neq 0$ models

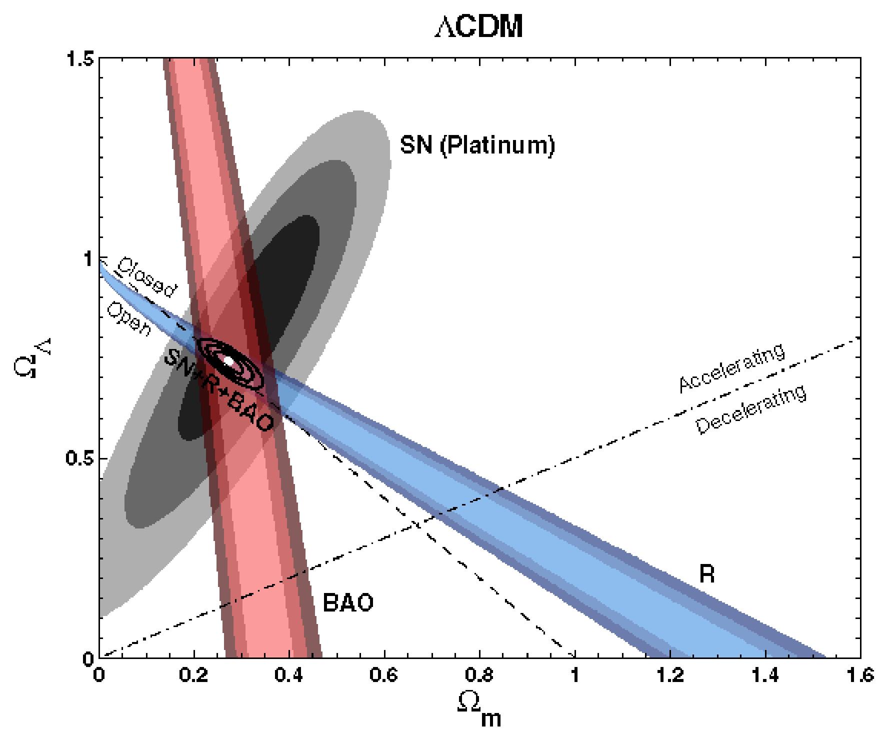
ΛCDM, SN+shift parameter(R)





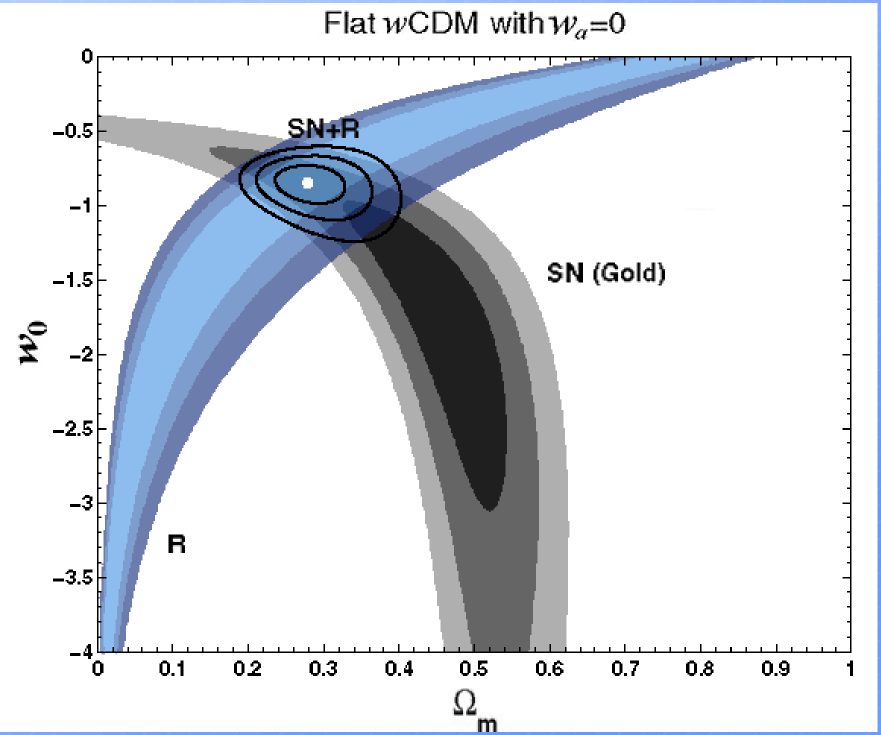
ΛCDM, SN+BAO+shift parameter(R)

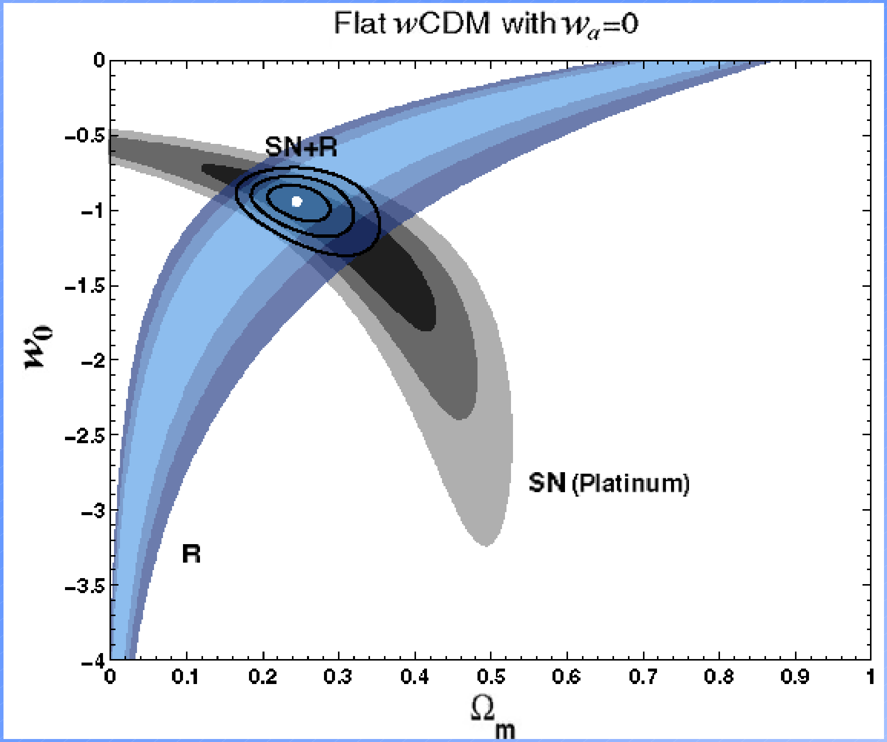




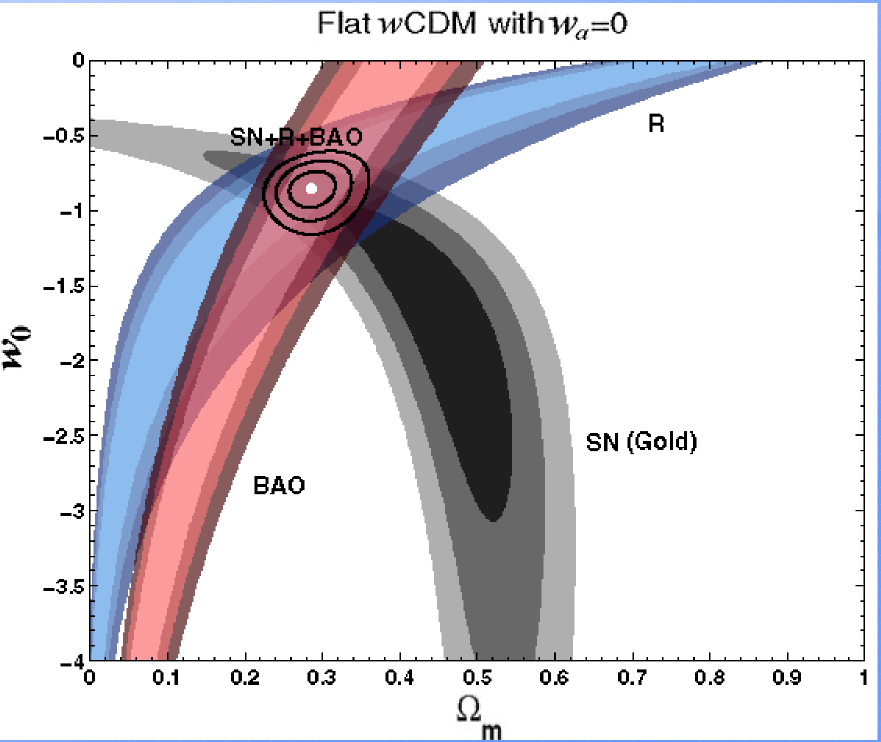
	χ^2	Ω_Λ	Ω_k	Ω_m	χ^2	Ω_Λ	Ω_k	Ω_m
SN	156.4	0.95	-0.43	0.48	195.2	0.85	-0.17	0.33
SN+R	158.4	0.68	-0.04	0.36	195.6	0.74	-0.01	0.27
SN+R+BAO	161.4	0.72	-0.02	0.30	195.6	0.74	-0.01	0.27

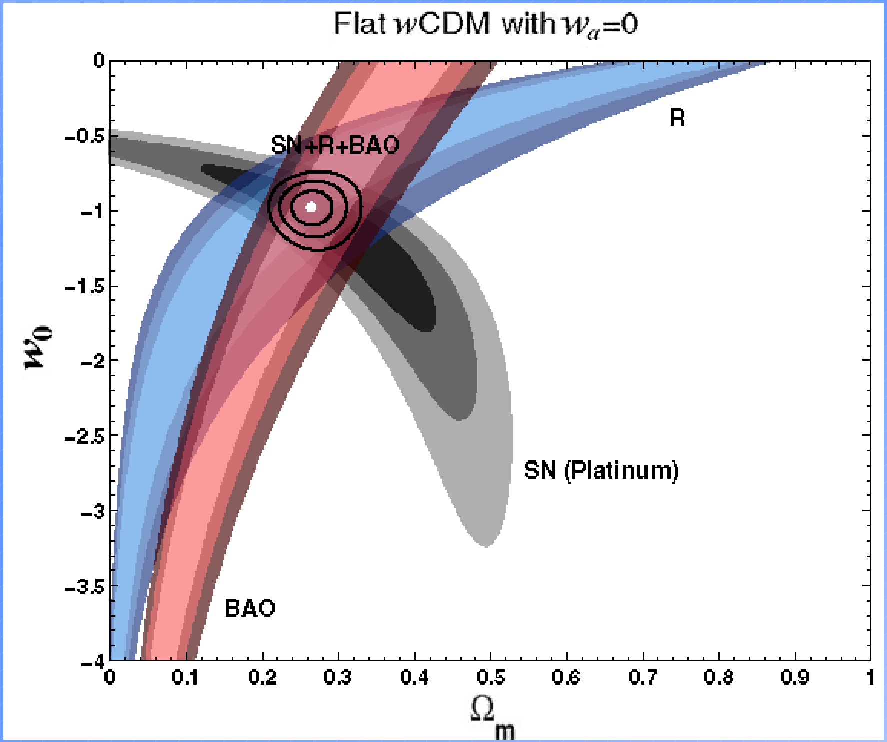
Flat wCDM w_a=0, SN+shift parameter(R)





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





	χ^2	w_0	Ω_m	χ^2	w_0	Ω_m
SN	156.6	-1.75	0.46	195.4	-1.16	0.31
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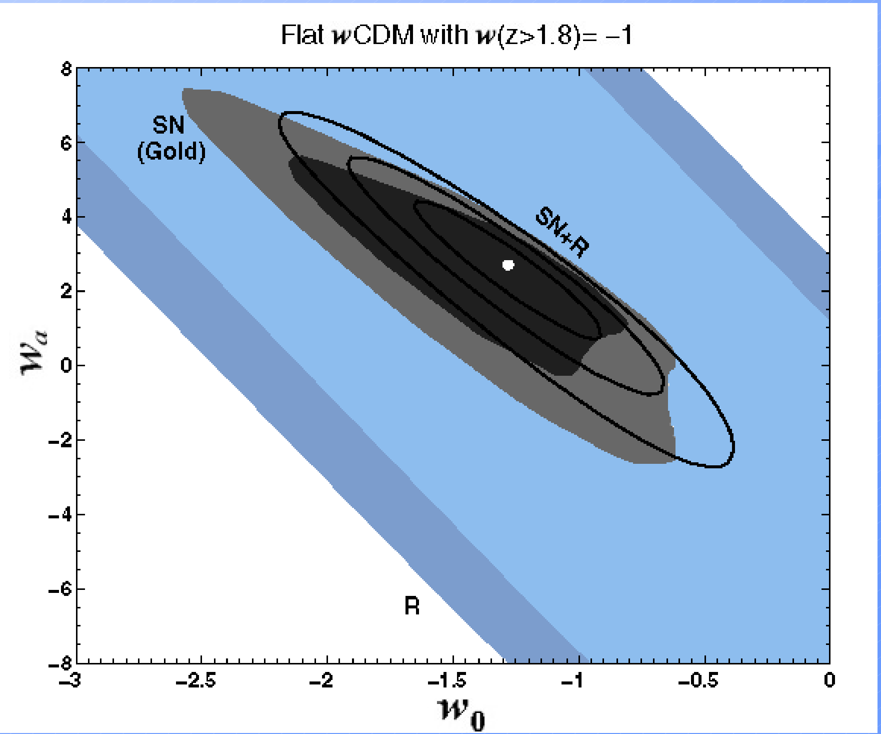
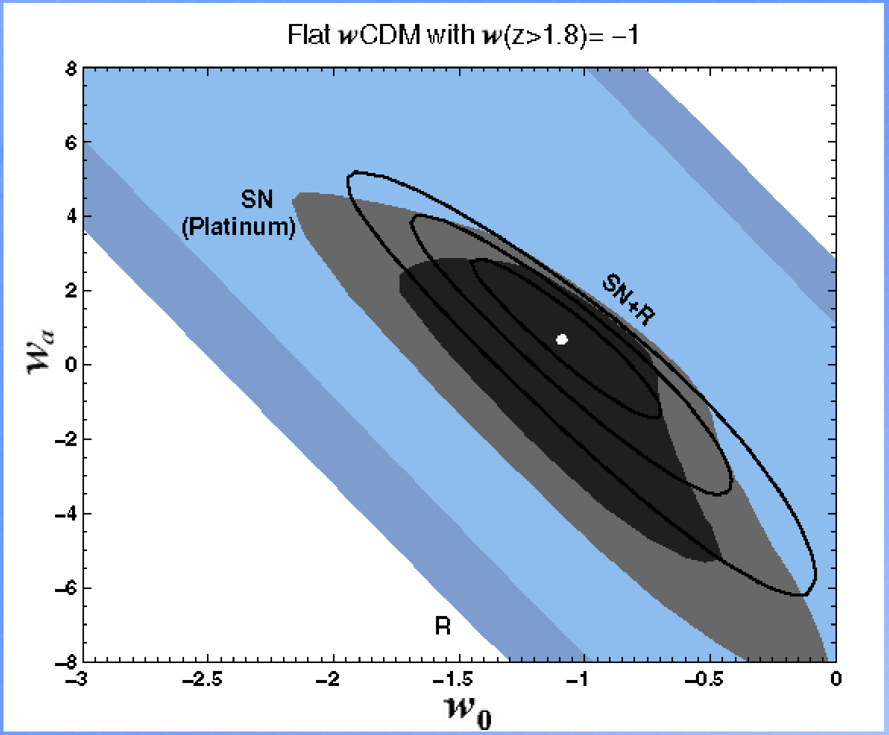
Flat *w*CDM, *w*(z>1.8) = -1, SN+shift parameter(R)





	χ^2	w_0	w_a	χ^2	w_0	w_a
SN	156.5	-1.11	2.39	195.3	-1.11	-1.16
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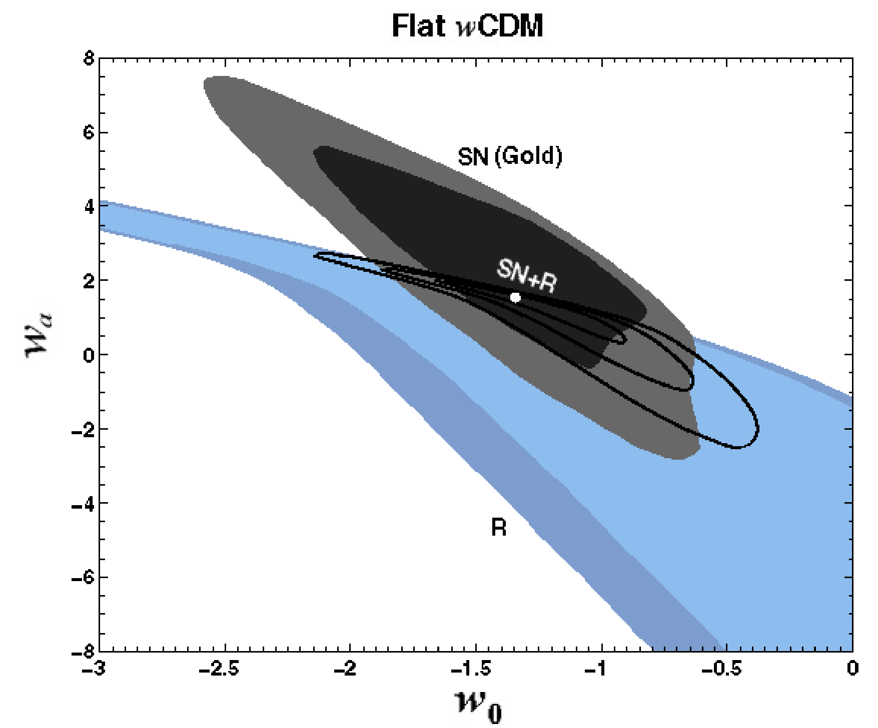
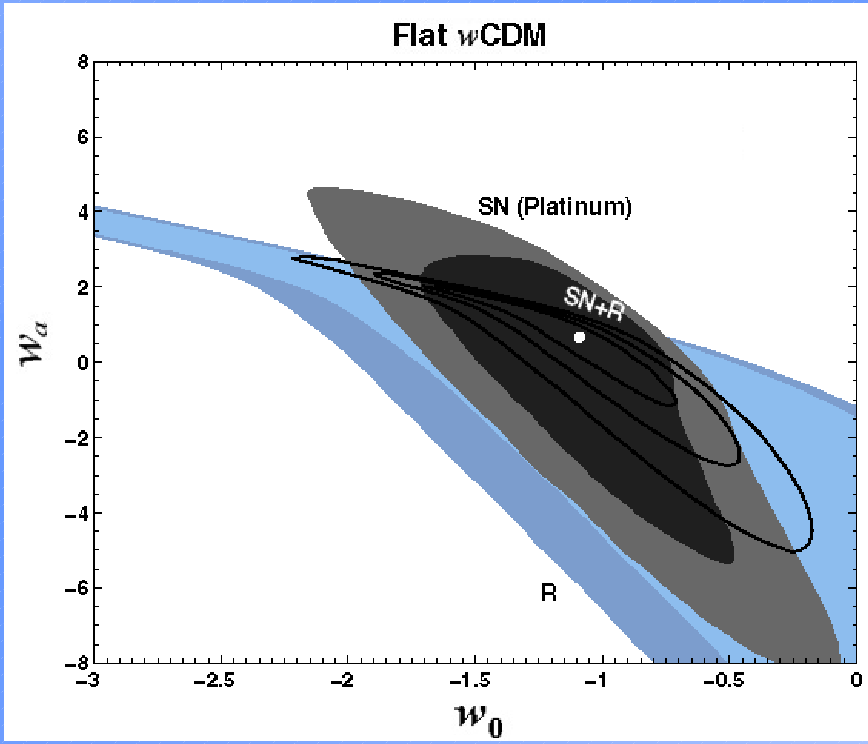
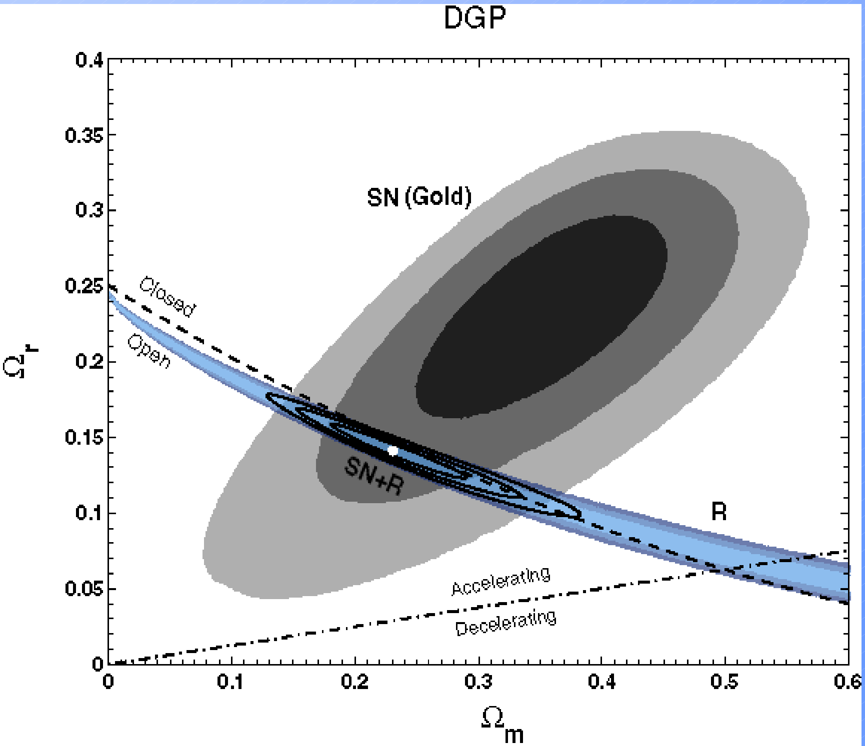
Flat *w*CDM, $0.15 < \Omega_m < 0.35$, SN+shift parameter(R)

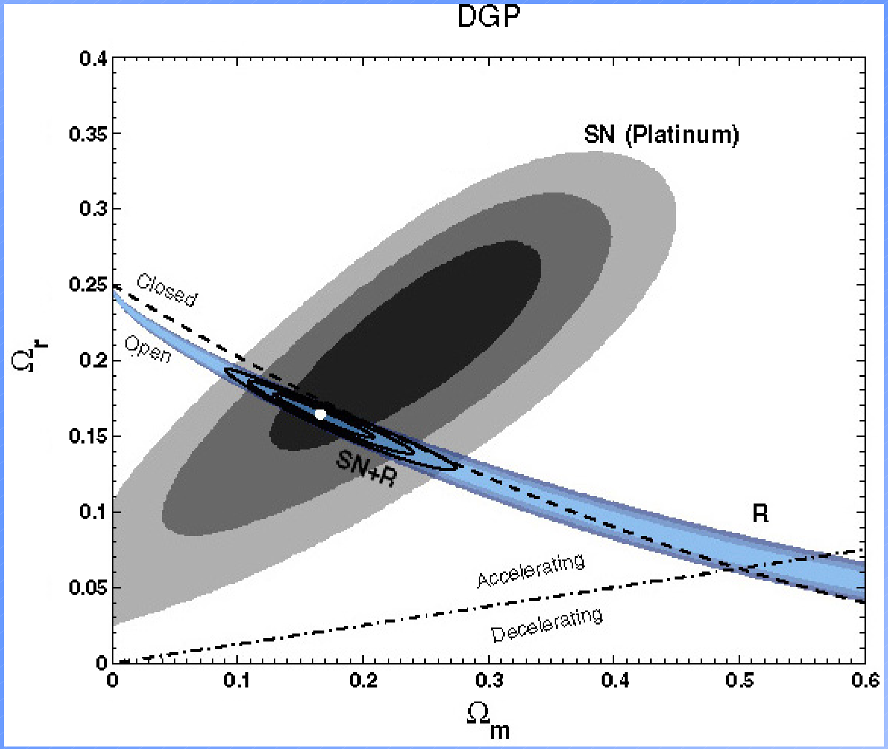




	χ^2	w_0	w_a	χ^2	w_0	w_a
SN	156.5	-1.11	2.39	195.3	-1.11	-1.16
SN+R	157.1	-1.37	1.56	195.5	-1.09	0.67

DGP, SN+shift parameter(R)





	χ^2	Ω_r	Ω_k	Ω_m	χ^2	Ω_r	Ω_k	Ω_m
SN	156.4	0.24	-0.59	0.36	195.1	0.22	-0.30	0.24
SN+R	160.3	0.14	0.03	0.23	196.4	0.16	0.04	0.17

Conclusion

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

- Combined analysis prefers flat universe,
  with very slightly positive curvature.

What could be more effective probes?

Bayesian analysis ?

Higher redshift objects (GRB) ?

CMB spectrum for braneworld models ?

… …