Dark Energy Models and Constraints

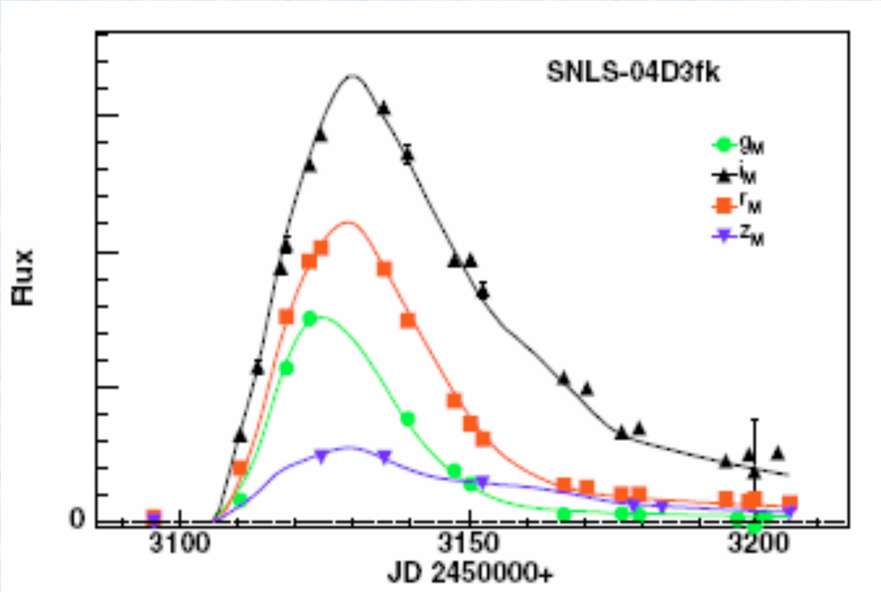
Supernova Legacy Survey

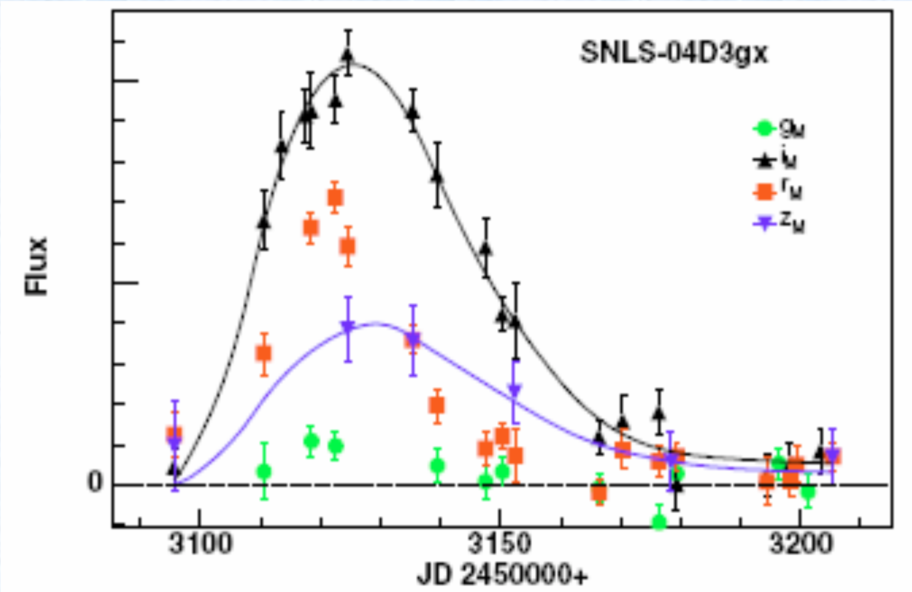
Astier, et al

Supernova Legacy Survey

- Use photometry to obtain light curves and detect possible SNe
  - Compare light curve to "past" image to find events
- Follow up with spectroscopy to find redshifts and natures of SNe
  - Classify events as SN Ia or SN Ia*
- 91 SN Ia or SN Ia* detected

Sample Light Curves





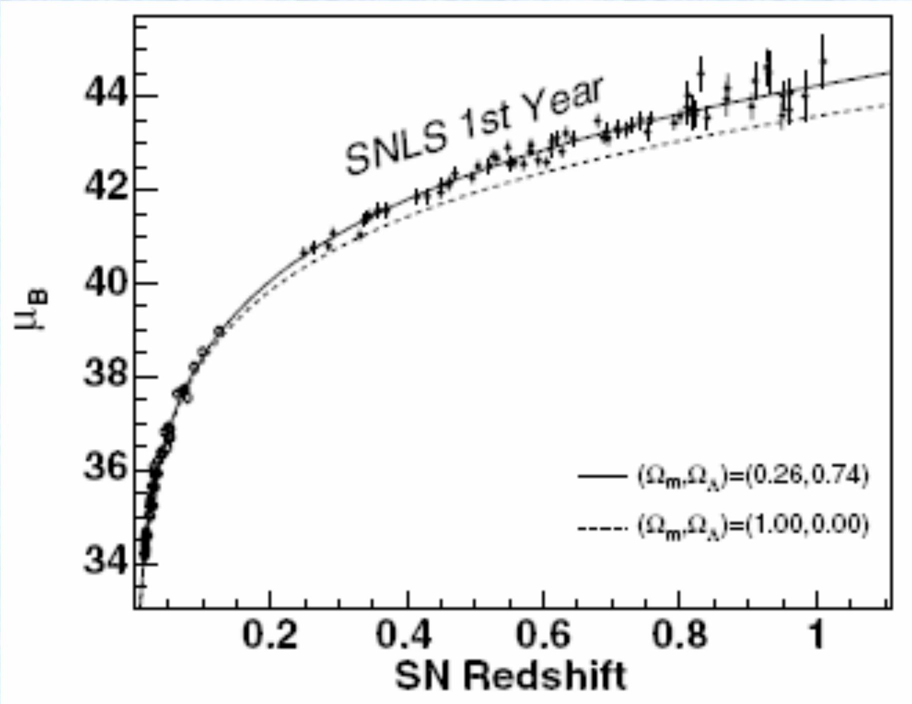
z=0.358 **z=0.91**

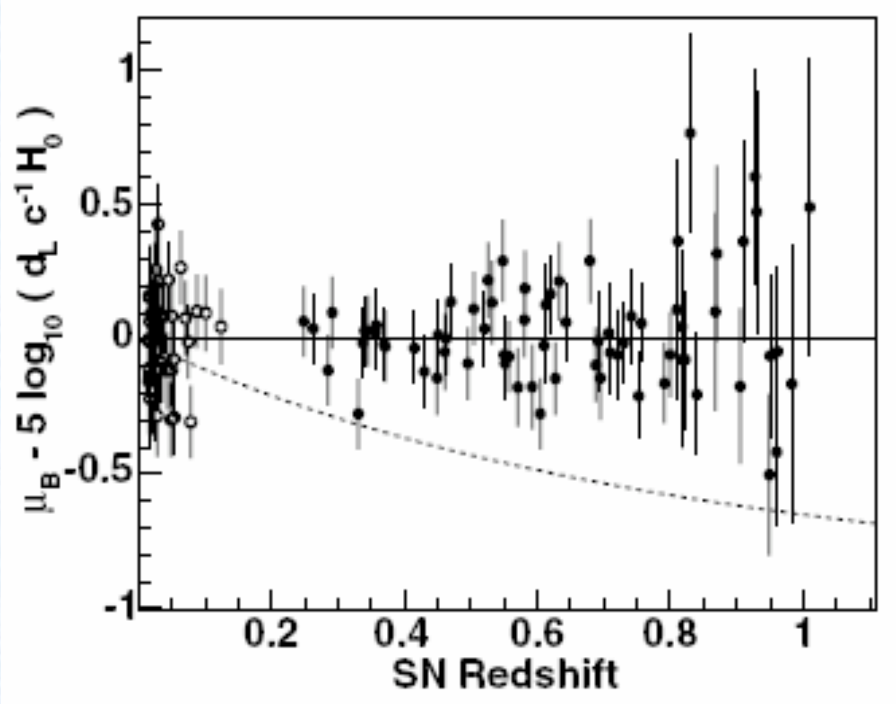
Calibration

- Compare flux of SNe to "tertiary standards" → field stars in the image
- Use Vega as reference star to calibrate flux levels in bandpasses

- Survey done in SDSS bandpasses
  - u, g, r, i, z

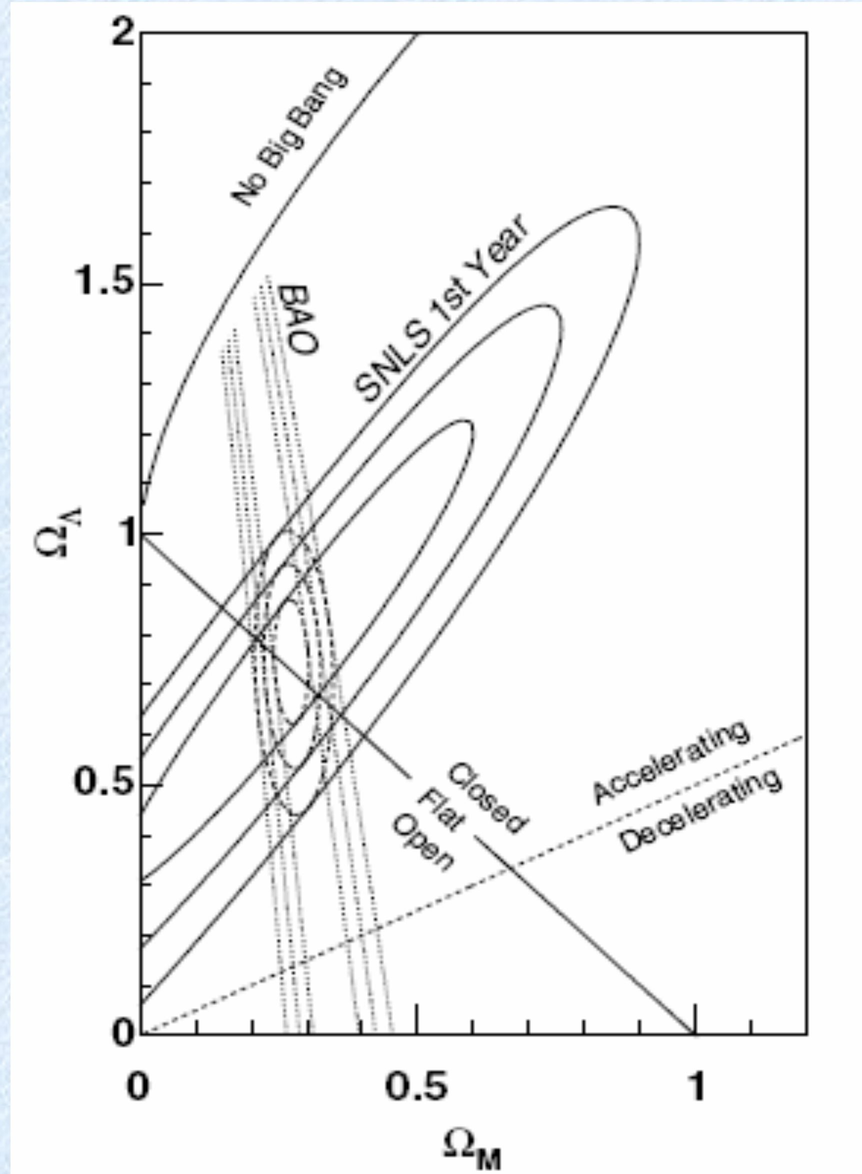
Cosmological Fits



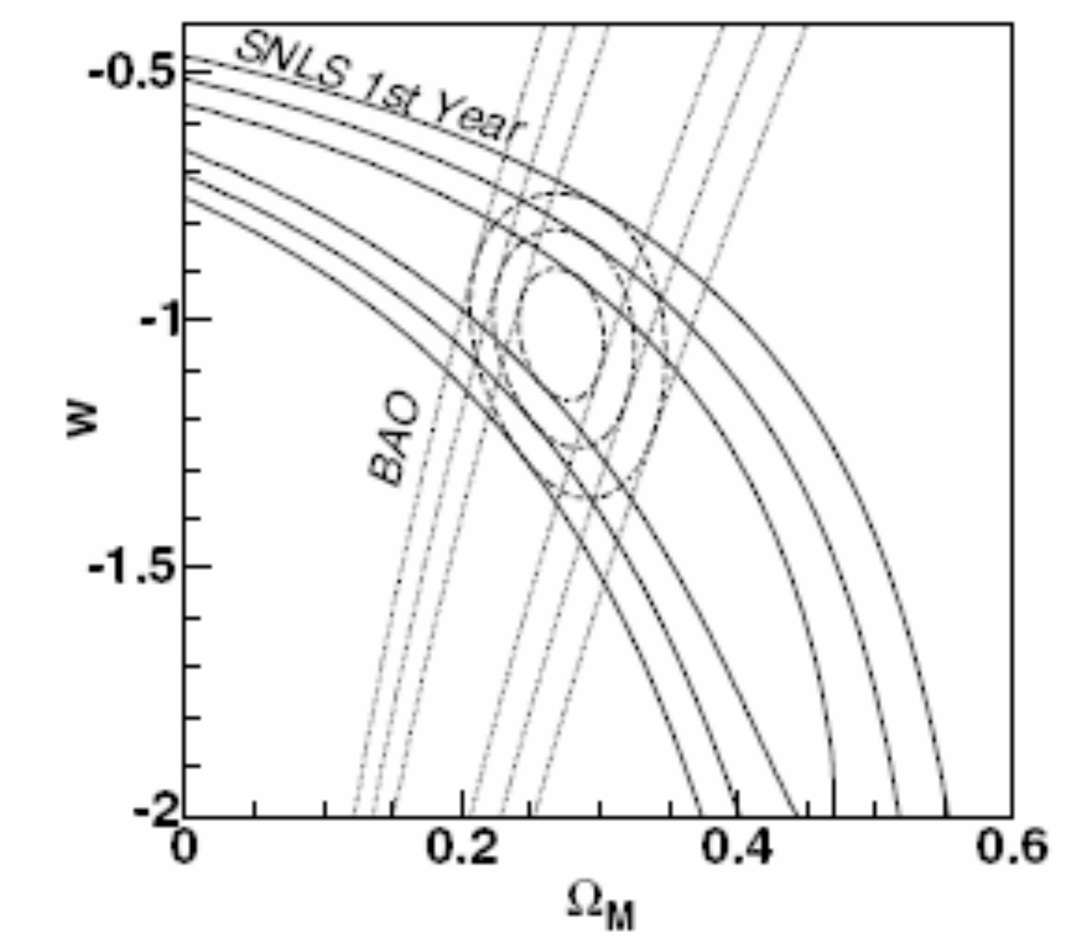


- Contours of 68.3%, 95.5%, and 99.7% CL

- Ω_M and Ω_Λ are free parameters
  - Not necessarily $\Omega_{Tot} = 1$



- Flat cosmology, with Ω_M and w as free parameters



Uncertainties

Source	$\sigma(\Omega_M)$ (flat)	$\sigma(\Omega_{tot})$	$\sigma(w)$	$\sigma(\Omega_M)$ (with BAO)	$\sigma(w)$
Zero-points	0.024	0.51	0.05	0.004	0.040
Vega spectrum	0.012	0.02	0.03	0.003	0.024
Filter bandpasses	0.007	0.01	0.02	0.002	0.013
Malmquist bias	0.016	0.22	0.03	0.004	0.025
Sum (*sys*)	0.032	0.55	0.07	0.007	0.054
Meas. errors	0.037	0.52	0.09	0.020	0.087
$U-B$ color (*stat*)	0.020	0.10	0.05	0.003	0.021
Sum (*stat*)	0.042	0.53	0.10	0.021	0.090

“Survey Says…”

Flat Λ cosmology

$$\Omega_M = 0.263 \pm 0.042(stat) \pm 0.032(sys)$$

Constant w cosmology

$$\Omega_M = 0.271 \pm 0.021(stat) \pm 0.007(sys)$$

$$w = -1.013 \pm 0.090(stat) \pm 0.054(sys)$$

Exotic Cosmological Models

Davis, et al.

Data

- Use supernova searches
  - ESSENCE
  - SNLS
  - HST
- Baryon acoustic oscillations

Selection Methods

- χ^2 analysis is not a good indicator of which model is the best
- Goodness-of-fit tests do not take into account the differences between models

- So what can we use?

Information Criteria

- Bayesian Information Criterion

$$\mathrm{BIC} = -2\ln L + k\ln N$$

- Akaike Information Criterion

$$\mathrm{AIC} = -2\ln L + 2k$$

L = Maximum likelihood

k = Number of parameters

N = Number of data points

Let's Meet Our Contestants

TABLE 1
SUMMARY OF MODELS

Model	Abbreviation[a]	Parameters[b]	Section
Flat cosmological constant	FΛ	Ω_m	4.1.1
Cosmological constant	Λ	Ω_m, Ω_Λ	4.1.2
Flat constant w	Fw	Ω_m, w	4.1.3
Constant w	w	Ω_m, Ω_k, w	4.1.4
Flat $w(a)$	Fwa	Ω_m, w_0, w_a	4.2.1
DGP	DGP	Ω_k, Ω_{r_c}	4.3.1
Flat DGP	FDGP	Ω_{r_c}	4.3.2
Cardassian	Ca	Ω_m, q, n	4.4
Flat general Chaplygin	FGCh	A, α	4.5.1
General Chaplygin	GCh	Ω_k, A, α	4.5.1
Flat Chaplygin	FCh	A	4.5.2
Chaplygin	Ch	Ω_k, A	4.5.2

Dark Energy with Constant w

$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \frac{\Omega_x}{a^{3(1+w)}}$$

with $H \equiv \frac{\dot{a}}{a}$

Flat, ΛCDM

$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + (1 - \Omega_m)$$

$$\Omega_m = 0.27 \pm 0.04$$

ΛCDM

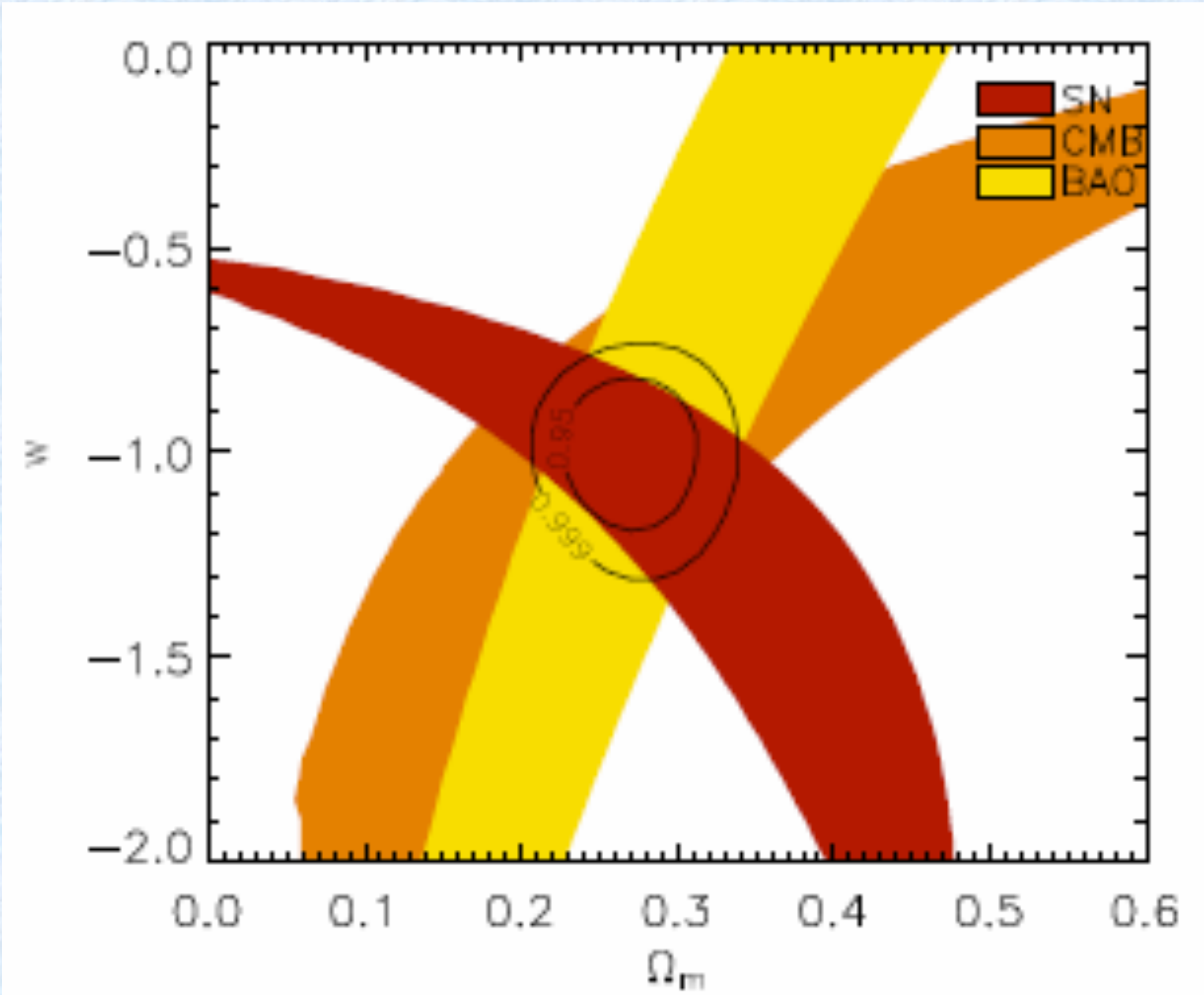
$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \Omega_\Lambda$$

Flat, constant w

$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \frac{\Omega_x}{a^{3(1+w)}}$$

$$\Omega_m = 0.27 \pm 0.04, \quad w = -1.01 \pm 0.15$$

Dark Energy with Constant w



Dark Energy With Changing w

$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \frac{\Omega_x}{a^{3(1+w)}}$$

with

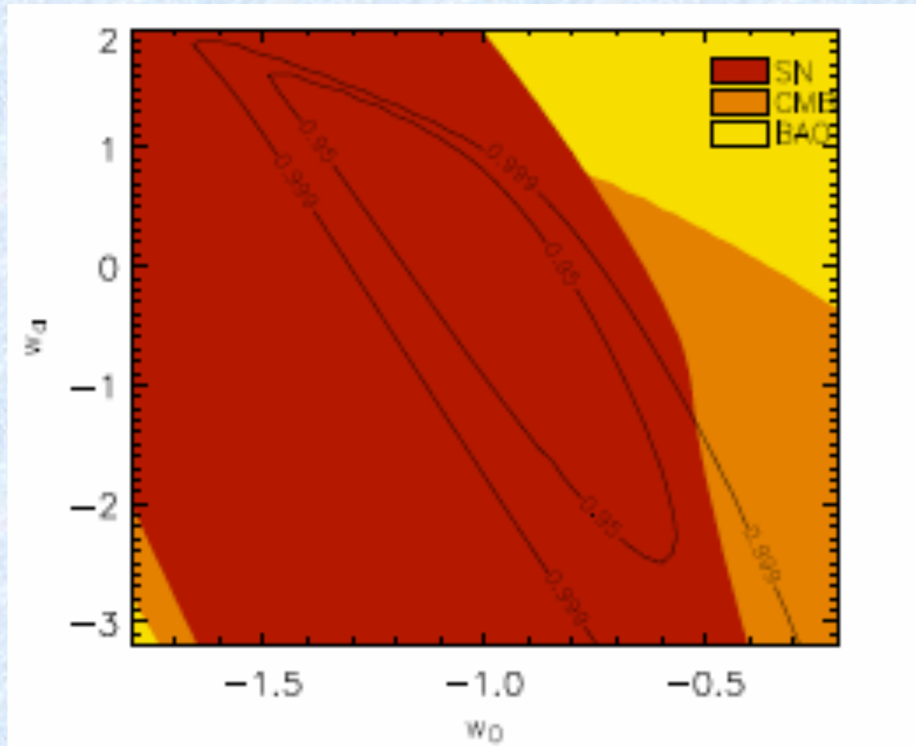
$$a^{3(1+w)} \rightarrow \exp\left[3\int_a^1 \frac{1+w(a')}{a'}\,da'\right]$$

Using parametrization

$$w(a) = w_0 + w_a(1-a)$$

we get

$$a^{3(1+w_0)} \longrightarrow a^{3(1+w_0+w_a)} e^{3w_a(1-a)}$$

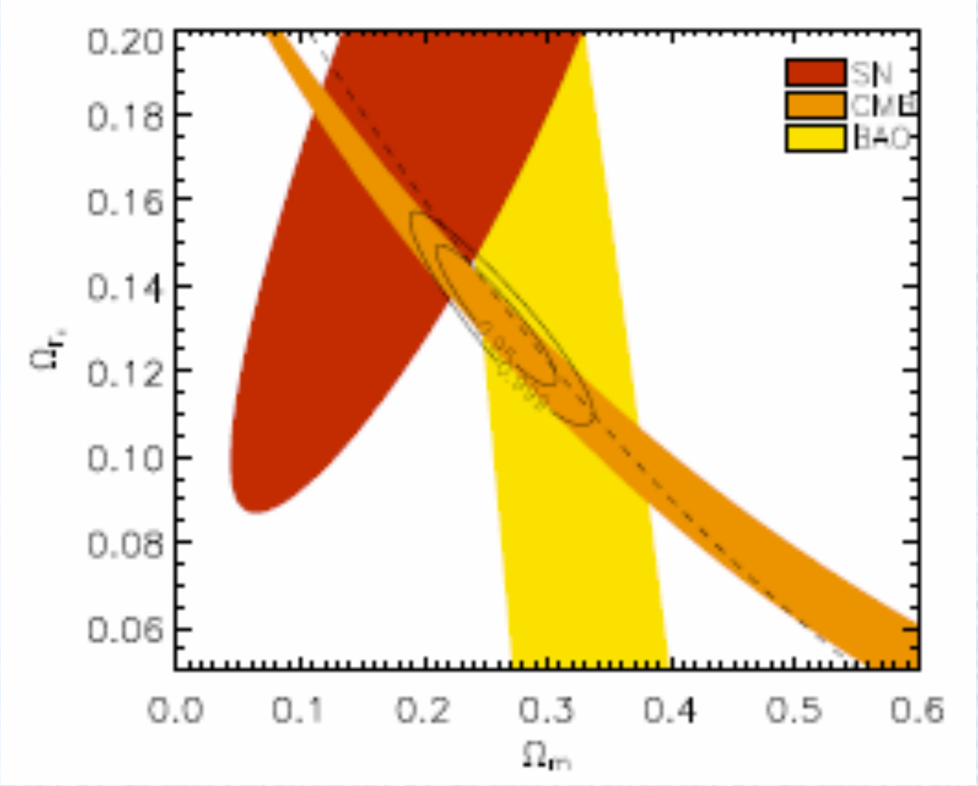


DGP Models

$$\frac{H^2}{H_0^2} = \frac{\Omega_k}{a^2} + \left(\sqrt{\frac{\Omega_M}{a^3} + \Omega_{r_c}} + \sqrt{\Omega_{r_c}} \right)^2$$

$$\Omega_M = 1 - \Omega_k - 2\sqrt{\Omega_{r_c}}\sqrt{1 - \Omega_k}$$

$$\Omega_{r_c} = \frac{1}{4 r_c^2 H_0^2}$$



Cardassian Expansion

Freese and Lewis 2002

- Introduce new terms to account for self-interaction of dark matter, brane nature of the Universe, etc.

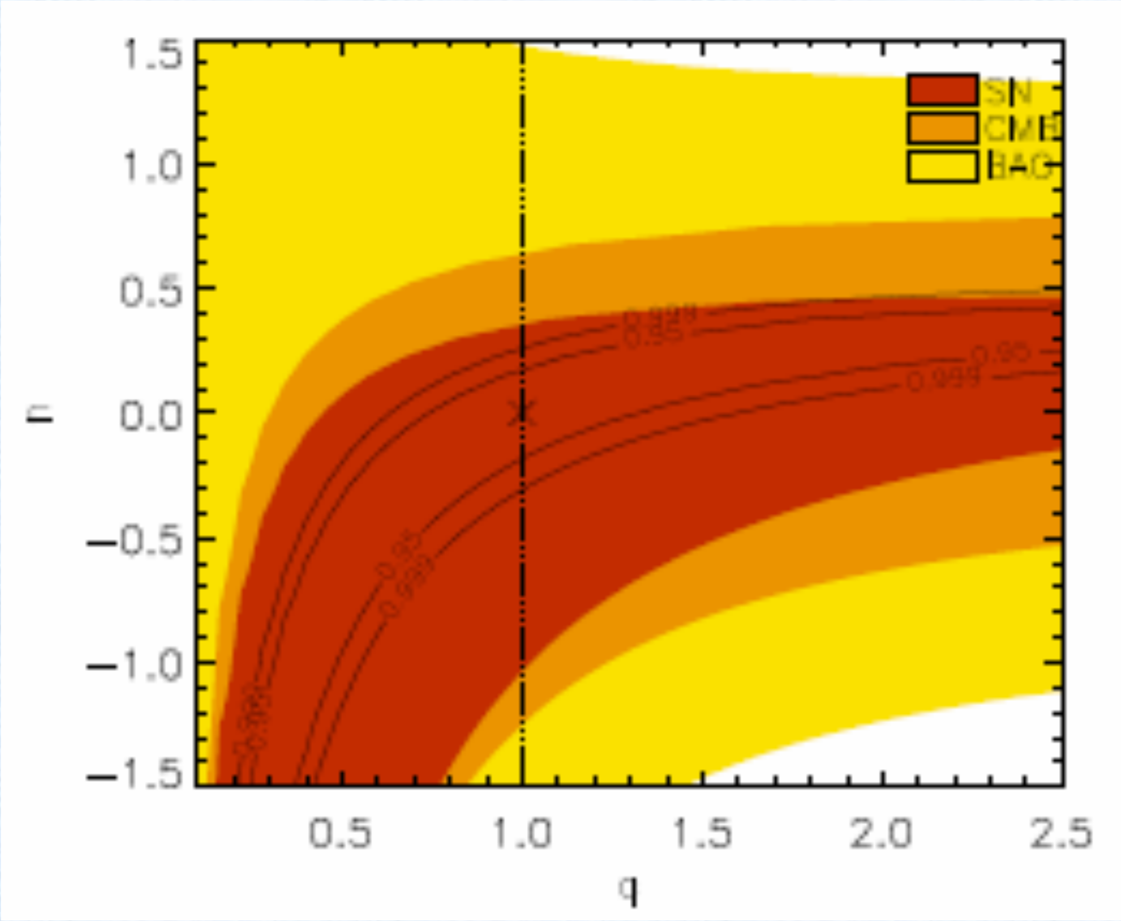
$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3}\left[1 + \frac{\left(\Omega_m^{-q} - 1\right)}{a^{3q(n-1)}}\right]^{1/q}$$

with n (dimensionless) related to w

- Suffers under IC analysis since it has 3 parameters

Cardassian Expansion

Poorly constrained



Chaplygin Gas

$$p = -A/\rho^{\alpha} \qquad \rho > 0 \qquad A > 0\,(\mathrm{const})$$

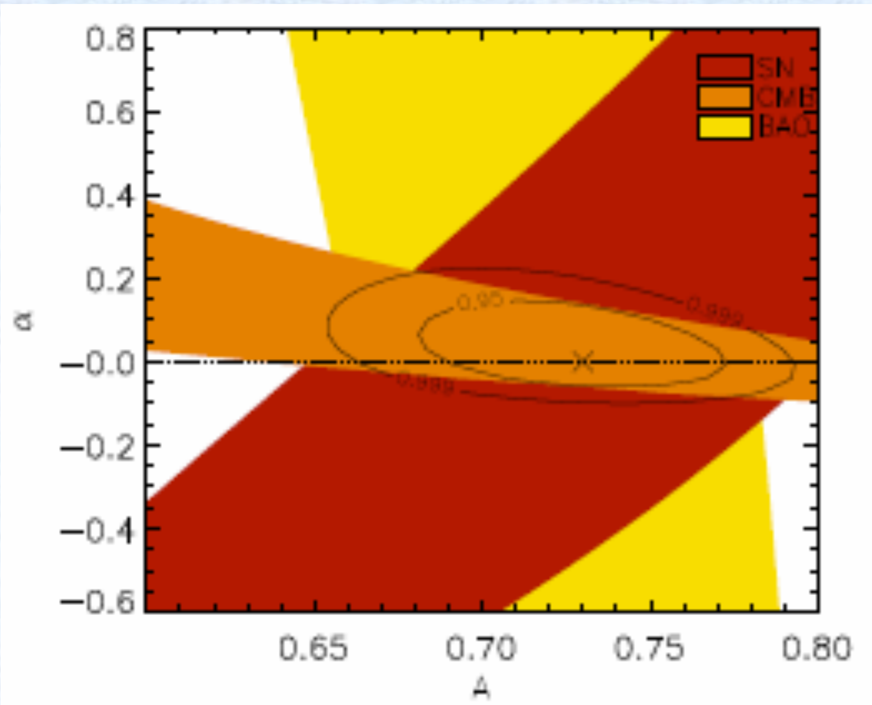
As opposed to conventional $p = w\rho$

General
$$\frac{H^2}{H_0^2} = \frac{\Omega_k}{a^2} + (1-\Omega_k)\left[A + \frac{(1-A)}{a^{3(1+\alpha)}}\right]^{1/(1+\alpha)}$$

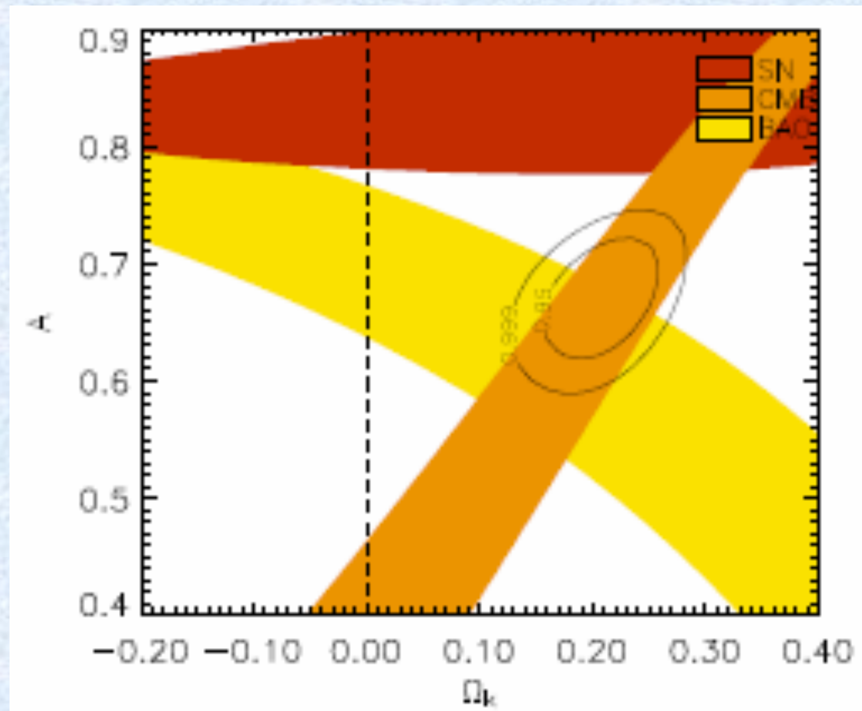
Standard (α=1)
$$\frac{H^2}{H_0^2} = \frac{\Omega_k}{a^2} + (1-\Omega_k)\sqrt{A + \frac{(1-A)}{a^6}}$$

Chaplygin Gas

Flat Generalized



Standard



EWWW

Conclusions

TABLE 2

SUMMARY OF THE INFORMATION CRITERIA RESULTS

Model	χ^2/dof	GoF (%)	ΔAIC	ΔBIC
Flat cosmological constant	194.5/192	43.7	0	0
Flat general Chaplygin	193.9/191	42.7	1	5
Cosmological constant	194.3/191	42.0	2	5
Flat constant w	194.5/191	41.7	2	5
Flat $w(a)$	193.8/190	41.0	3	10
Constant w	193.9/190	40.8	3	10
General Chaplygin	193.9/190	40.7	3	10
Cardassian	194.1/190	40.4	4	10
DGP	207.4/191	19.8	15	18
Flat DGP	210.1/192	17.6	16	16
Chaplygin	220.4/191	7.1	28	30
Flat Chaplygin	301.0/192	0.0	30	30

- Best fits include the standard concordance model and those that can reduce to it
- Models which cannot reduce to ΛCDM model do poorly

Conclusions