

# Dark Energy: constant or time variable? (... and other open questions)

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LBNL Physics    Thursday May 12, 2016

# By no means is cosmology “solved”

...while not perfect, I do not think we are fooling ourselves about the gross validity of the “standard” model of cosmology, as has sometimes happened in the past ...



The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote ... Future discoveries must be looked for in the sixth place of decimals.

A. A. Michelson (1894)



There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

William Thomson,  
Baron Kelvin (1900)

(... meanwhile, Planck and Einstein were laying the foundations of quantum mechanics and relativity ...)

# Main contributors to the present cosmological energy budget :

about 5% baryonic matter (mostly atoms in gas clouds, stars, planets, dust , ... ), first clearly measured in the 1960's (Gamow, Alpher, Herman, Penzias & Wilson, Dicke et al.)

about 20% non-baryonic non-relativistic cold dark matter (probably a WIMP), first seen in the 1930's (Zwicky, Smith, Babcock,...) and first clearly measured in the 1970's (Rubin & Ford, Ostriker & Peebles, Einasto et al., Ostriker et al.)

about 70% non-baryonic relativistic dark energy (not clear what this is), first real suggestion in the 1980's (Peebles, Peebles & Ratra) and first clearly measured in the 1990's (Riess et al., Perlmutter et al.)

We do not understand 95% of the current cosmological energy budget, but we do have a “standard” model of cosmology!

# Outline

motivate dark energy

two dark energy models ( $\Lambda$ CDM,  $\phi$ CDM), one popular but incomplete parameterization (XCDM)

(parameterizations are somewhat arbitrary, usually have more free parameters than models)

compare to observations (neoclassical cosmological tests), derive model-parameter constraints, test consistency of different data

show preliminary observational evidence for deceleration-acceleration transition

include spatial curvature

open questions

# The general motivation

Cosmological data not yet good enough to allow tight model-independent conclusions.

Analyzing observational data in the context of a model allows for tighter, but model-dependent, constraints.

Comparing observational constraints for various models gives an indication of the generality of the conclusions.

Comparing different observational constraints on a model might help uncover hidden systematic errors.

Models also allow us to combine constraints from different data sets.

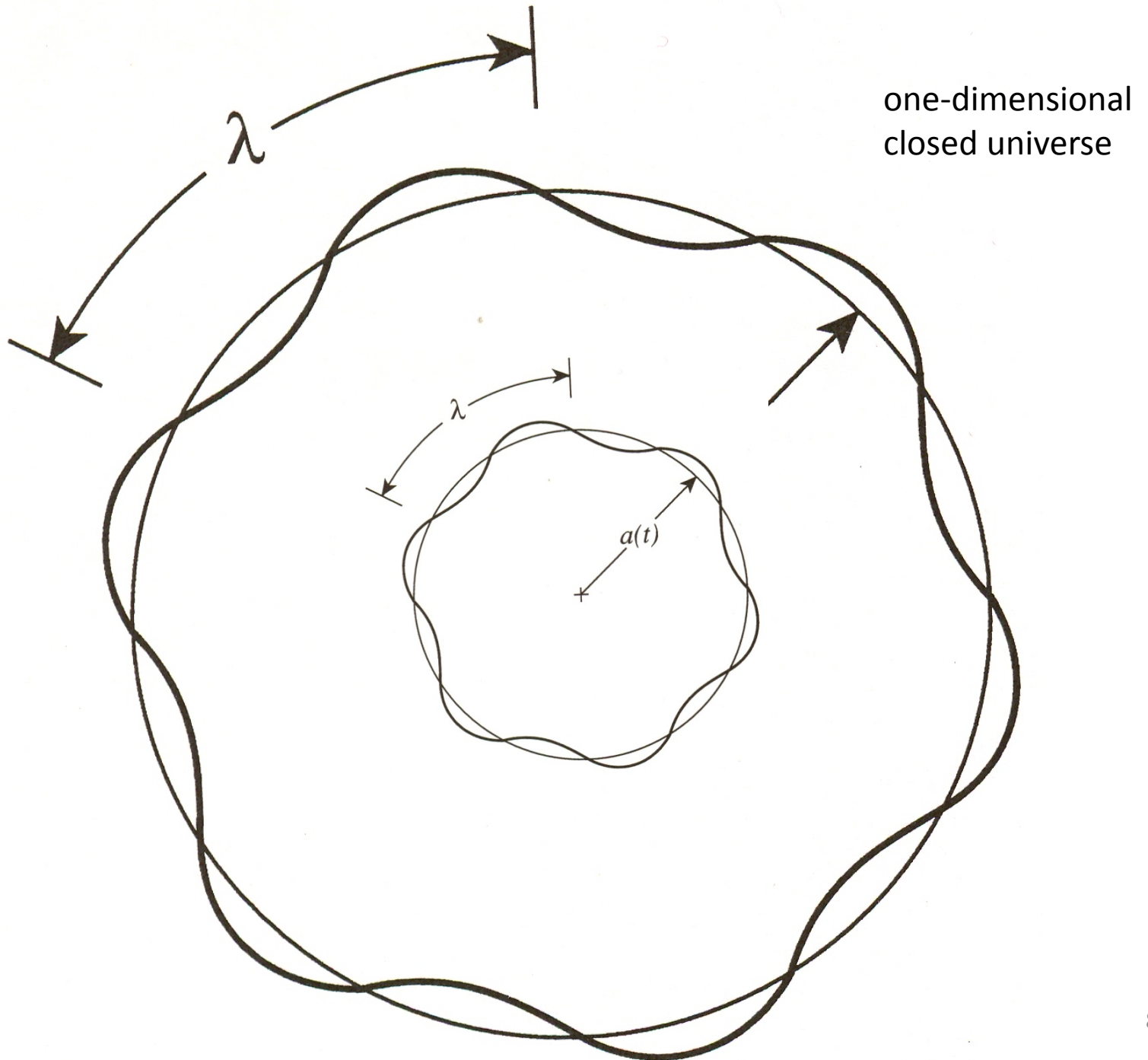
# Fact: the universe expands.

Consider a wave propagating in a one-dimensional expanding universe. For adiabatic expansion the wavelength must expand with scalefactor,  $\lambda \sim a(t)$  (redshifting).

There is no preferred center. **Galaxies separate and the light from them redshifts.**

Slipher\* discovered the redshifting in 1912.

\*Indirectly motivated by the idea of a Martian civilization!





Fact: farther apart the galaxies, the greater the redshift, and the faster the separation.

$$v = H_0 r$$

$v$  = recession speed of galaxy,  $r$  = distance to galaxy

$H_0$  = Hubble constant =  $(68 \pm 2.8) \text{ km s}^{-1} \text{ Mpc}^{-1}$

=  $100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$

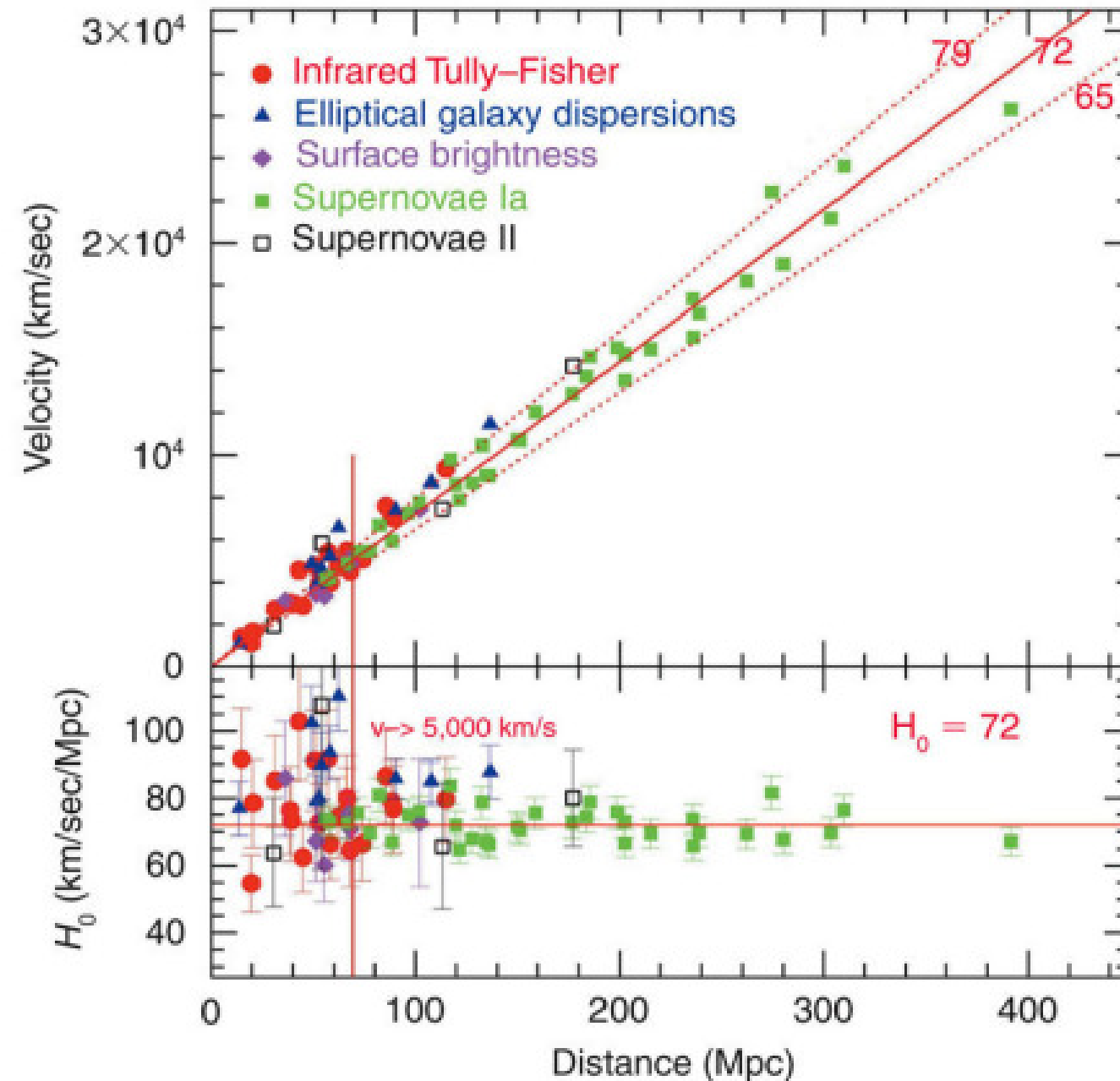
Chen & Ratra PASP123,1127 (2011)

$H_0$  is the present value of the Hubble parameter.

This is the Hubble (1929) law, discovered by Hubble and Humason.\*

\*Middle school dropout and one time muleskinner and janitor.

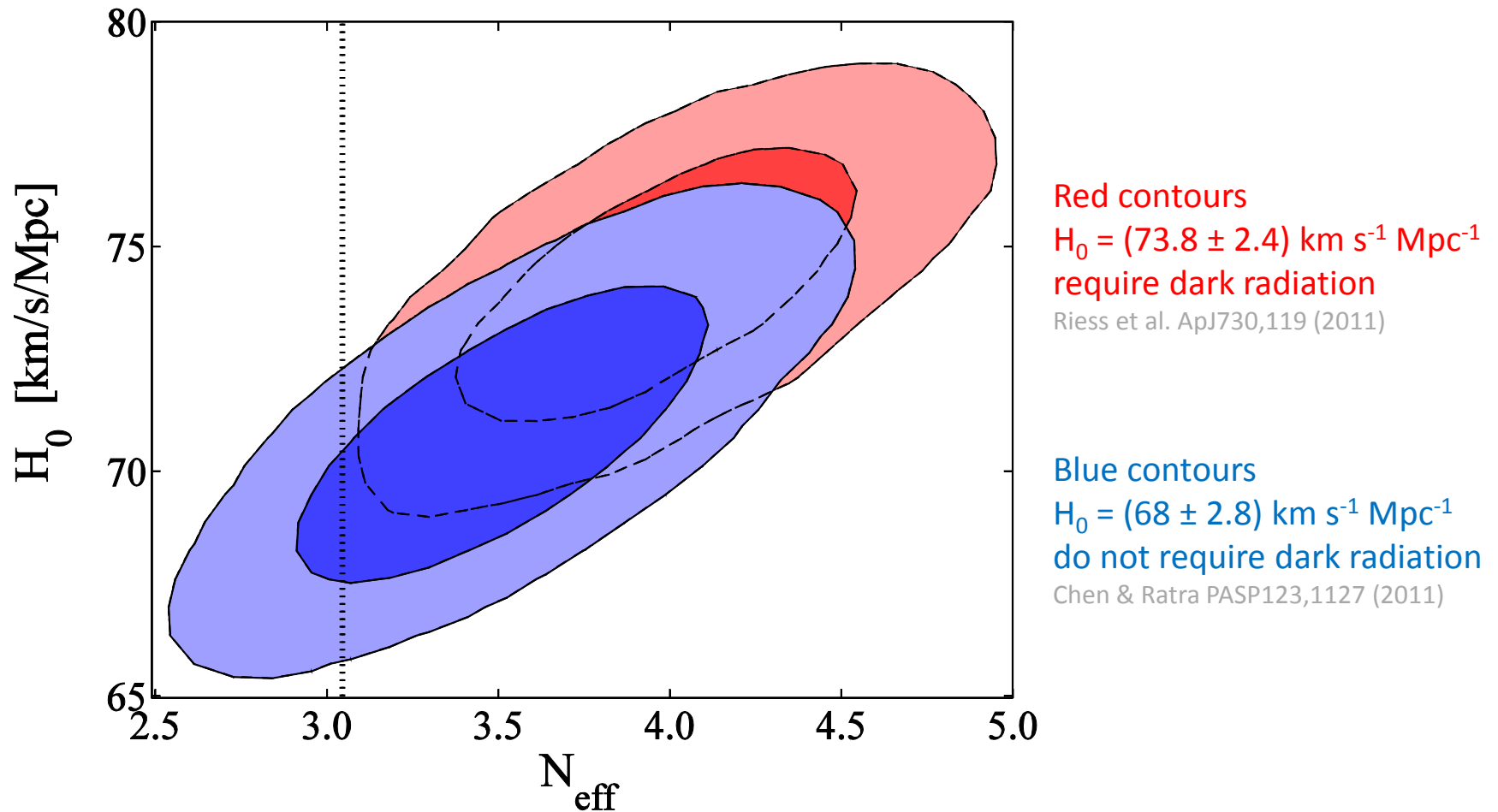
# Hubble law



$H_0$  = Hubble constant  
 $= (68 \pm 2.8) \text{ km s}^{-1} \text{ Mpc}^{-1}$   
 $= 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$

Chen & Ratra PASP123,1127 (2011)

## An aside: Large $H_0$ value forces consideration of dark radiation



From WMAP7, ACBAR, ACT, SPT & SDSS-DR7

Calabrese et al. PRD86, 043520 (2012)

Cosmology thus re-introduces preferred observers, cosmological observers, locally at rest w.r.t. the expansion.

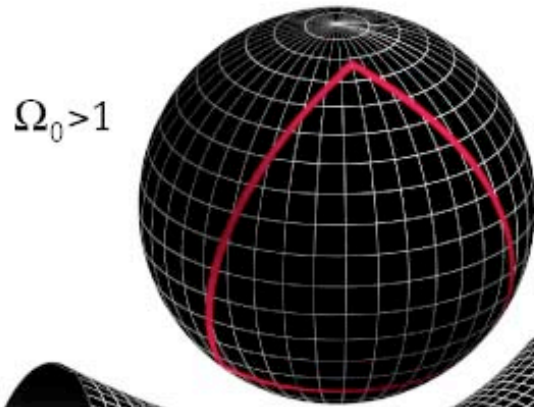
**Cosmological Principle** (assumption): the universe is (statistically) spatially isotropic for all cosmological observers.

This implies (statistical) spatial homogeneity.

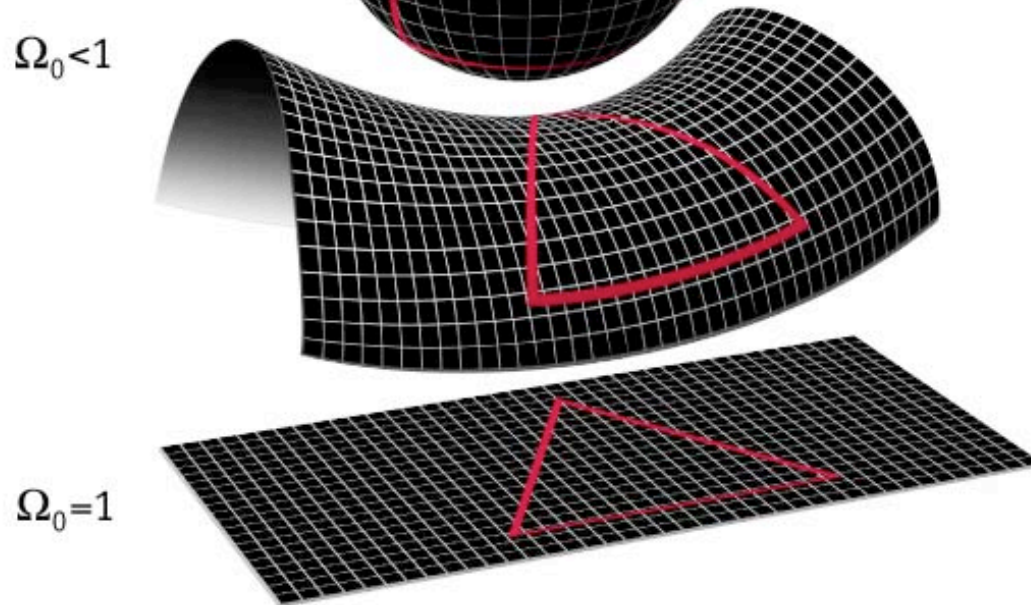
Ignoring global topology, there are then only three possible spatial geometries: the flat, open and closed Friedmann-Lemaître-Robertson-Walker models.

$$ds^2 = dt^2 - a^2(t) [dr^2 + S_K^2(r) \{d\theta^2 + \sin^2(\theta)d\phi^2\}]$$

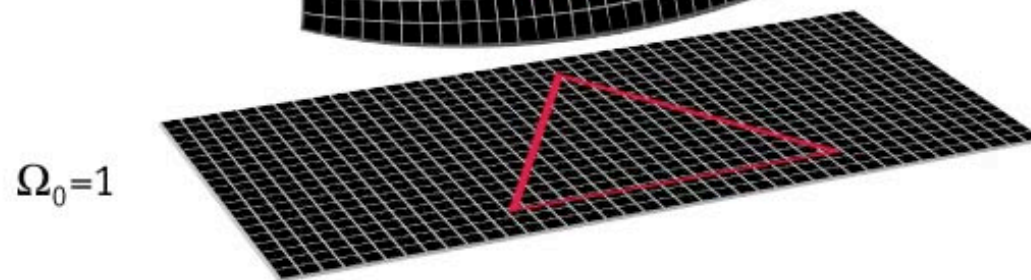
(2 dimensional analogs)



|        |           |       |
|--------|-----------|-------|
|        | $S_K(r)$  | $K^2$ |
| closed | $\sin(r)$ | $>0$  |



|      |            |      |
|------|------------|------|
| open | $\sinh(r)$ | $<0$ |
|------|------------|------|



|      |     |      |
|------|-----|------|
| flat | $r$ | $=0$ |
|------|-----|------|

equations of motion (ideal fluid matter):

$$H^2 = (\dot{a}/a)^2 = 8\pi G\rho/3 - K^2/a^2 + \Lambda/3 \quad \text{Einstein-Friedmann}$$

$$\dot{\rho} = -3 (\dot{a}/a) (\rho + p) \quad \text{stress-energy conservation}$$

$$p = p(\rho) \quad \text{equation of state}$$

$H(t) = \dot{a}/a$  is the expansion rate

Is this increasing or decreasing with time?

$$\text{also, } \ddot{a}/a = -(4\pi G/3)(\rho + 3p) \quad (\rho \text{ includes } \Lambda)$$

matter and radiation with  $p > 0$

$\Rightarrow \ddot{a} < 0$  decelerated expansion

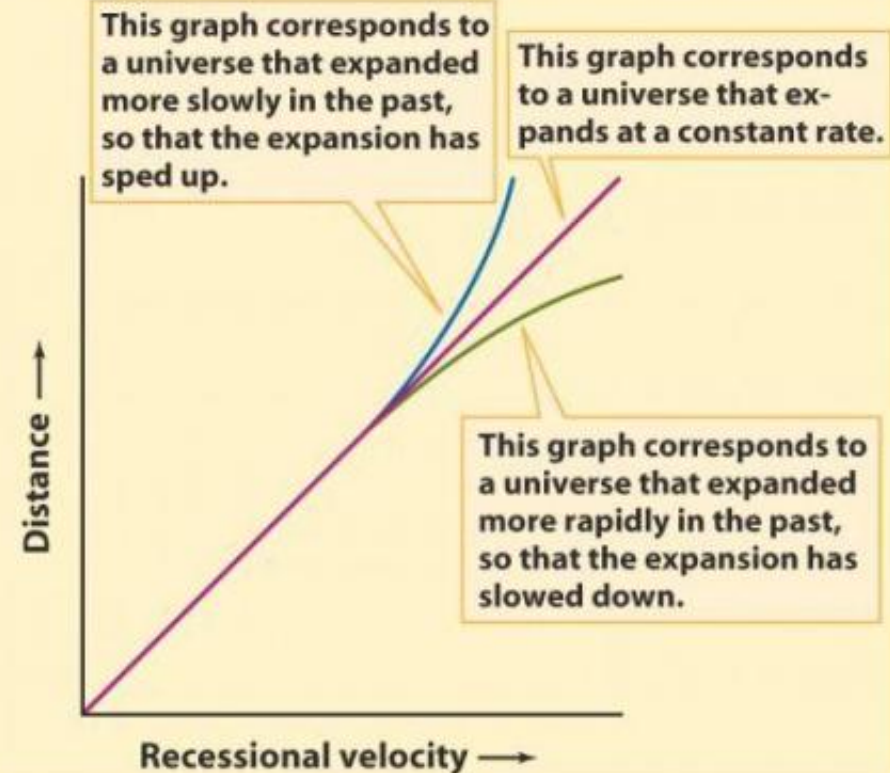
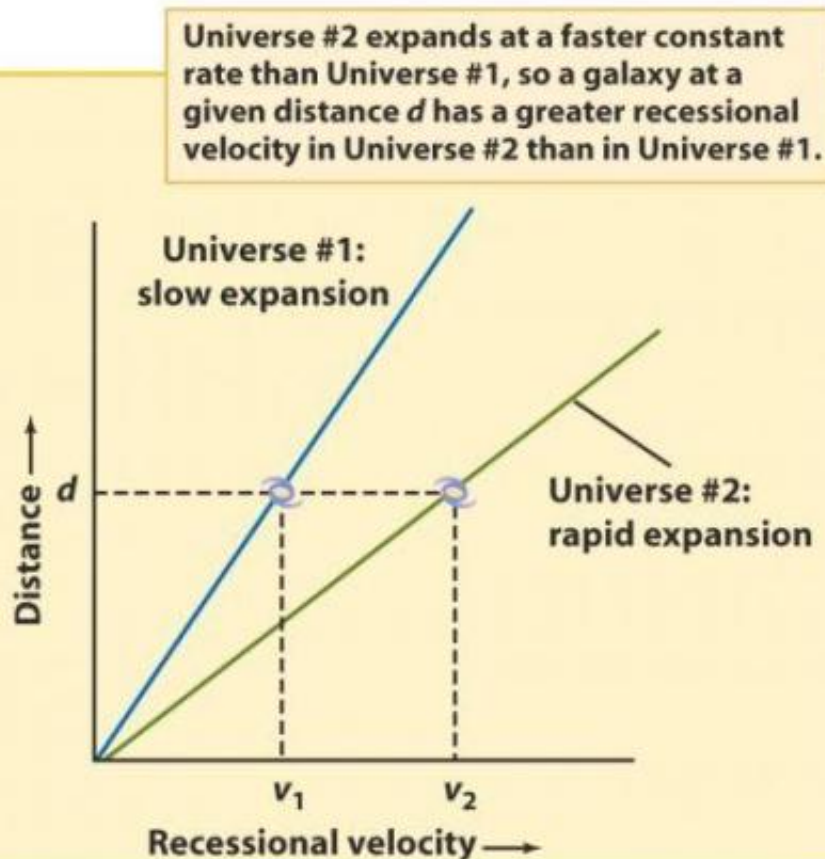
Einstein-de Sitter mass density

$$\rho_c = 3H^2/8\pi G = 1.9 \times 10^{-29} \text{ h}^2 \text{ g cm}^{-3}$$

Density parameter  $\Omega = \rho/\rho_c$

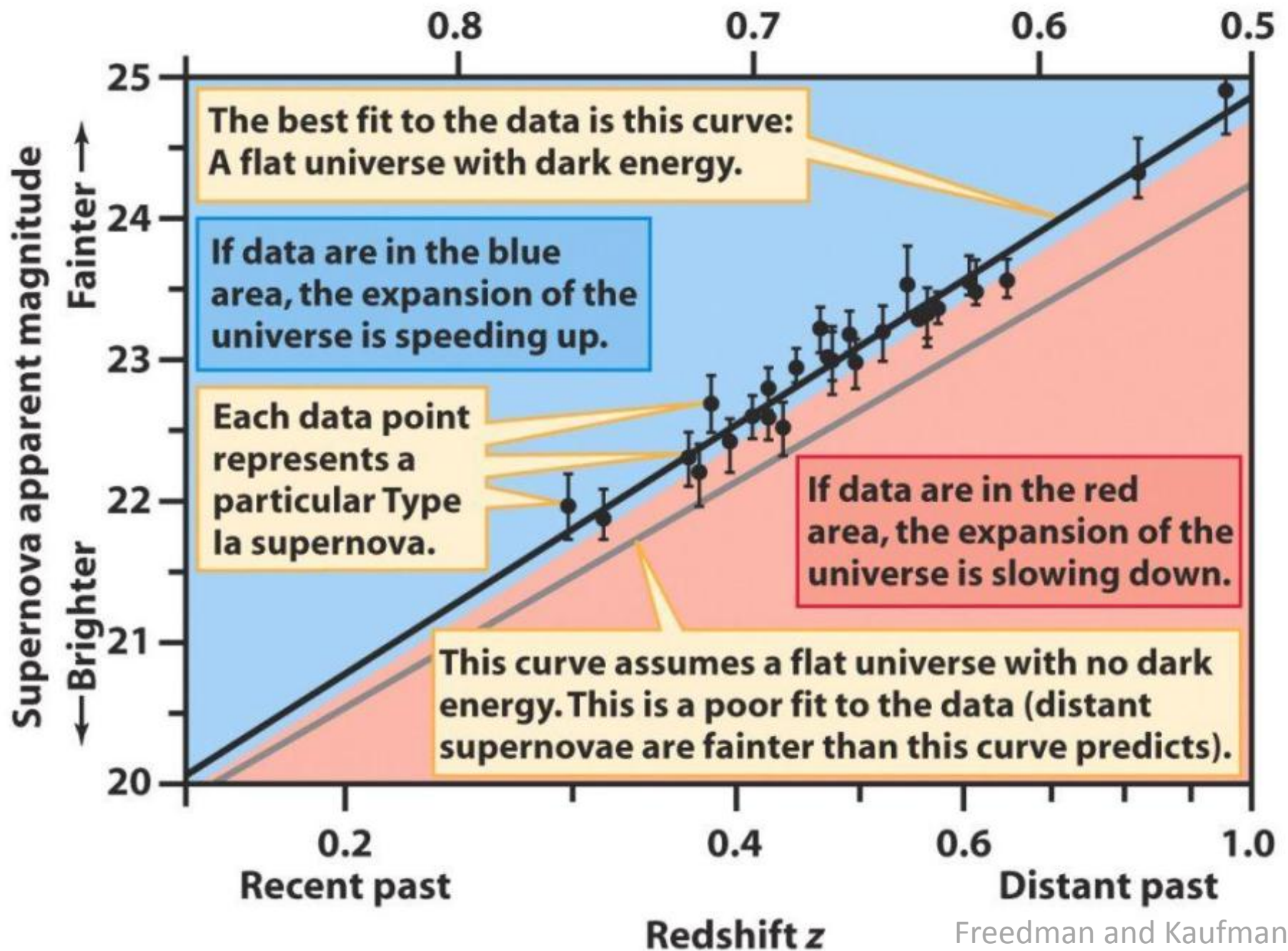
# Dark Energy

The general idea (more correctly discussed in terms of the  $m$ - $z$  diagram).



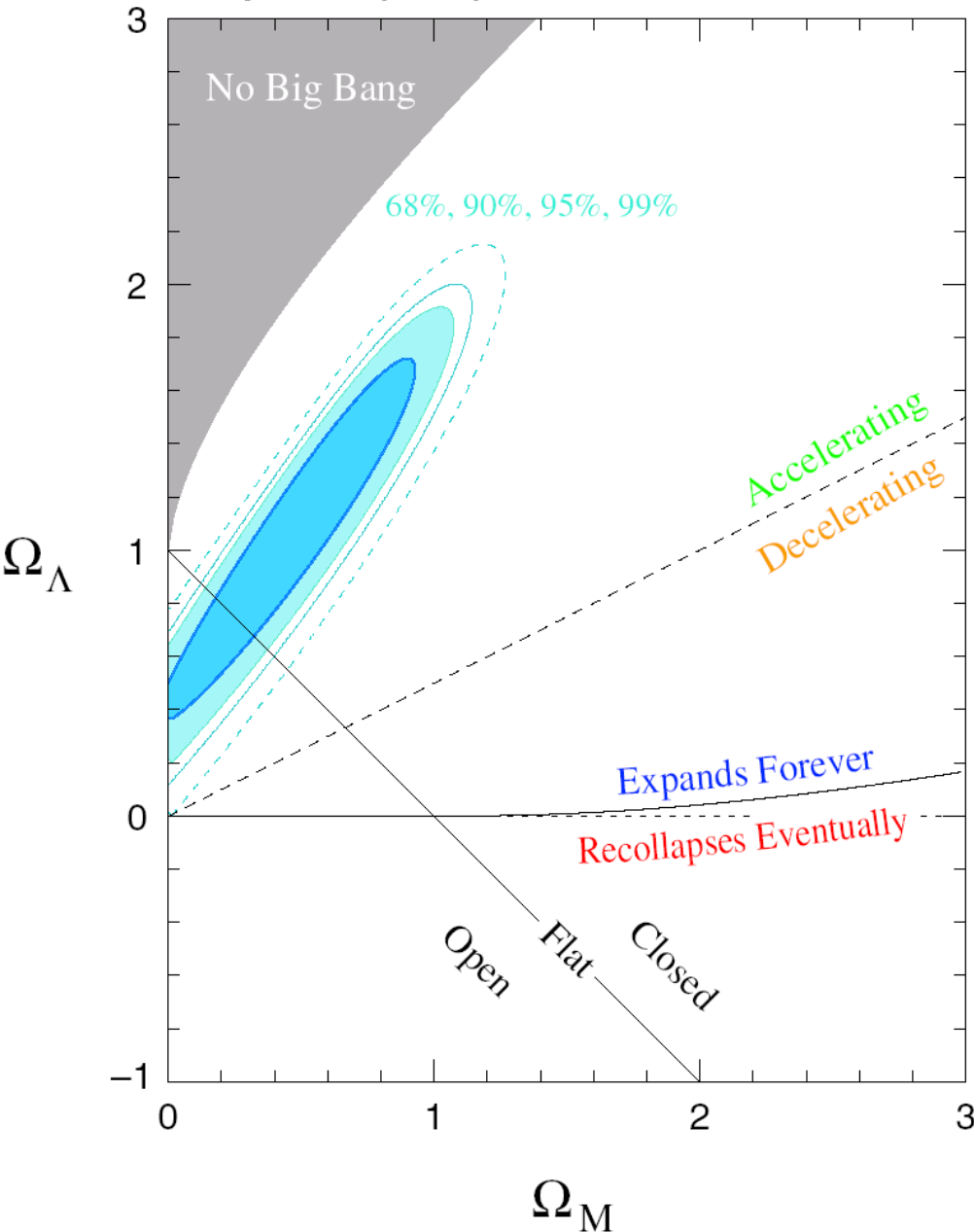


# Scale of the universe relative to today





Supernova Cosmology Project  
Knop et al. (2003)



accelerated expansion

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

$$p \leq -\rho/3$$

dark energy

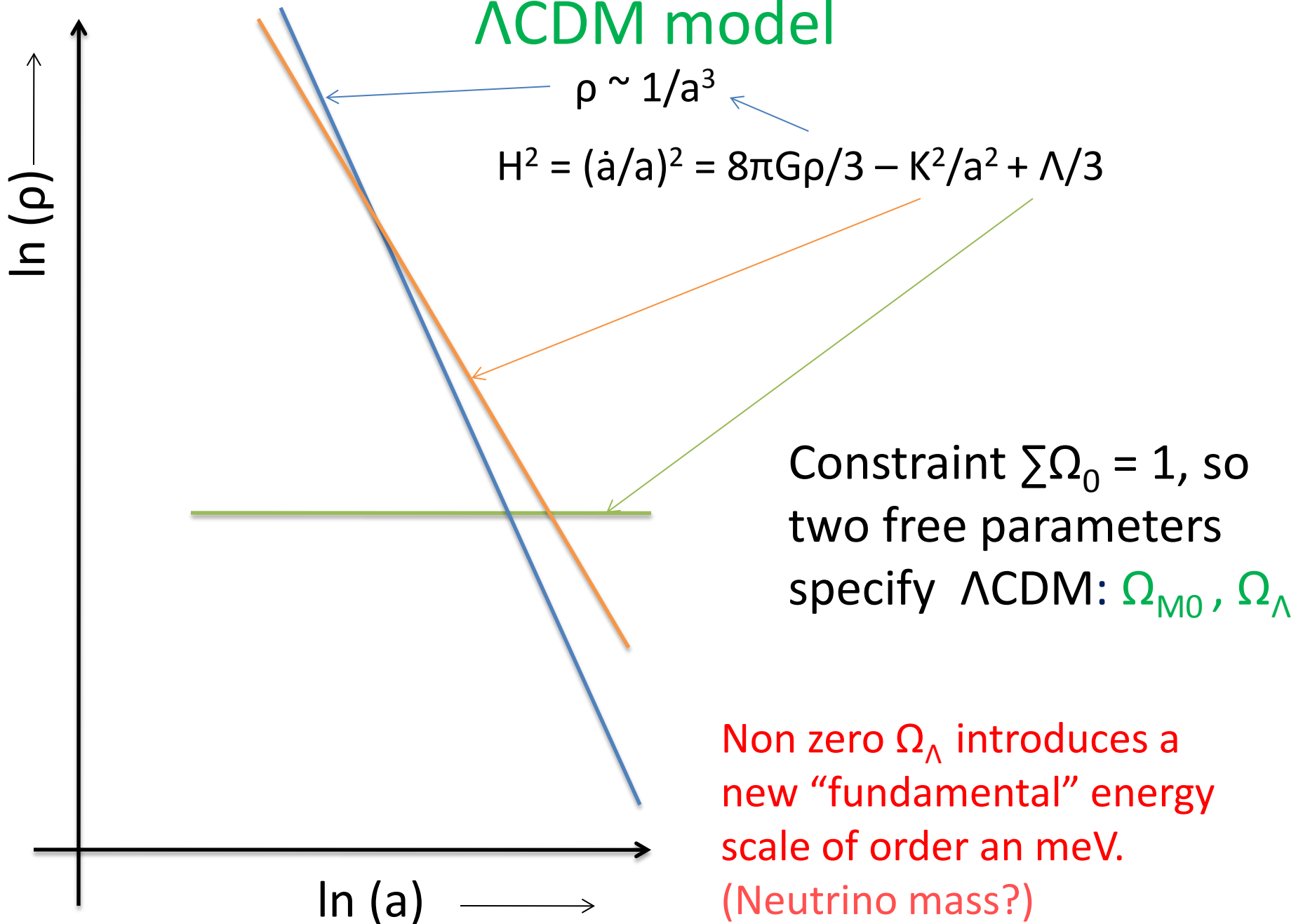
What do we know about dark energy, the major contributor to the energy budget?

E.g., is it a cosmological constant, or does it vary with space and in time?

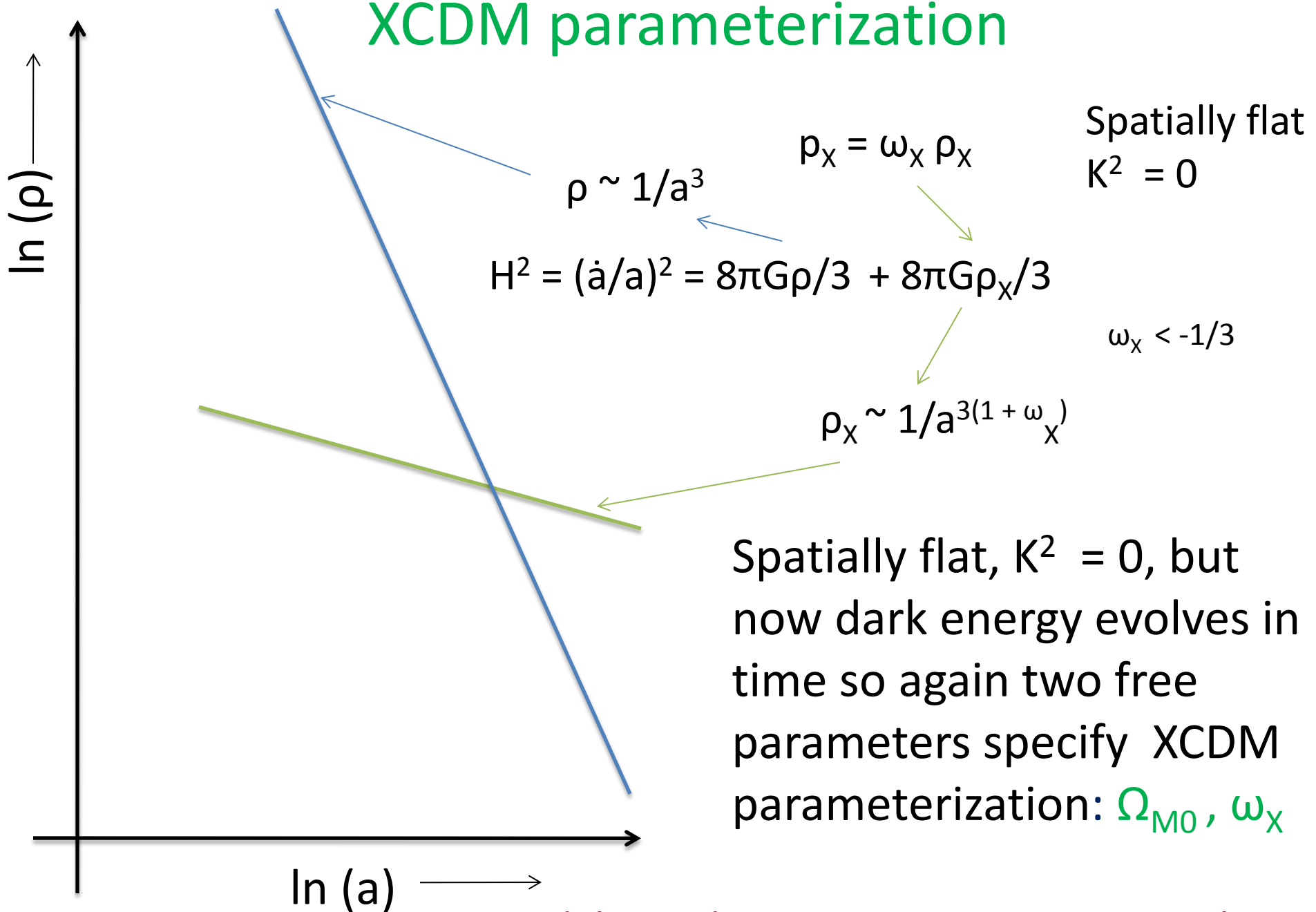
The fine print: The general theory of relativity is valid on cosmological length scales and astronomical evidence for dark energy is secure.

Simplest way to approach such questions is to compare predictions of different dark energy models to observational data.      First look at models...

# $\Lambda$ CDM model



# XCDM parameterization



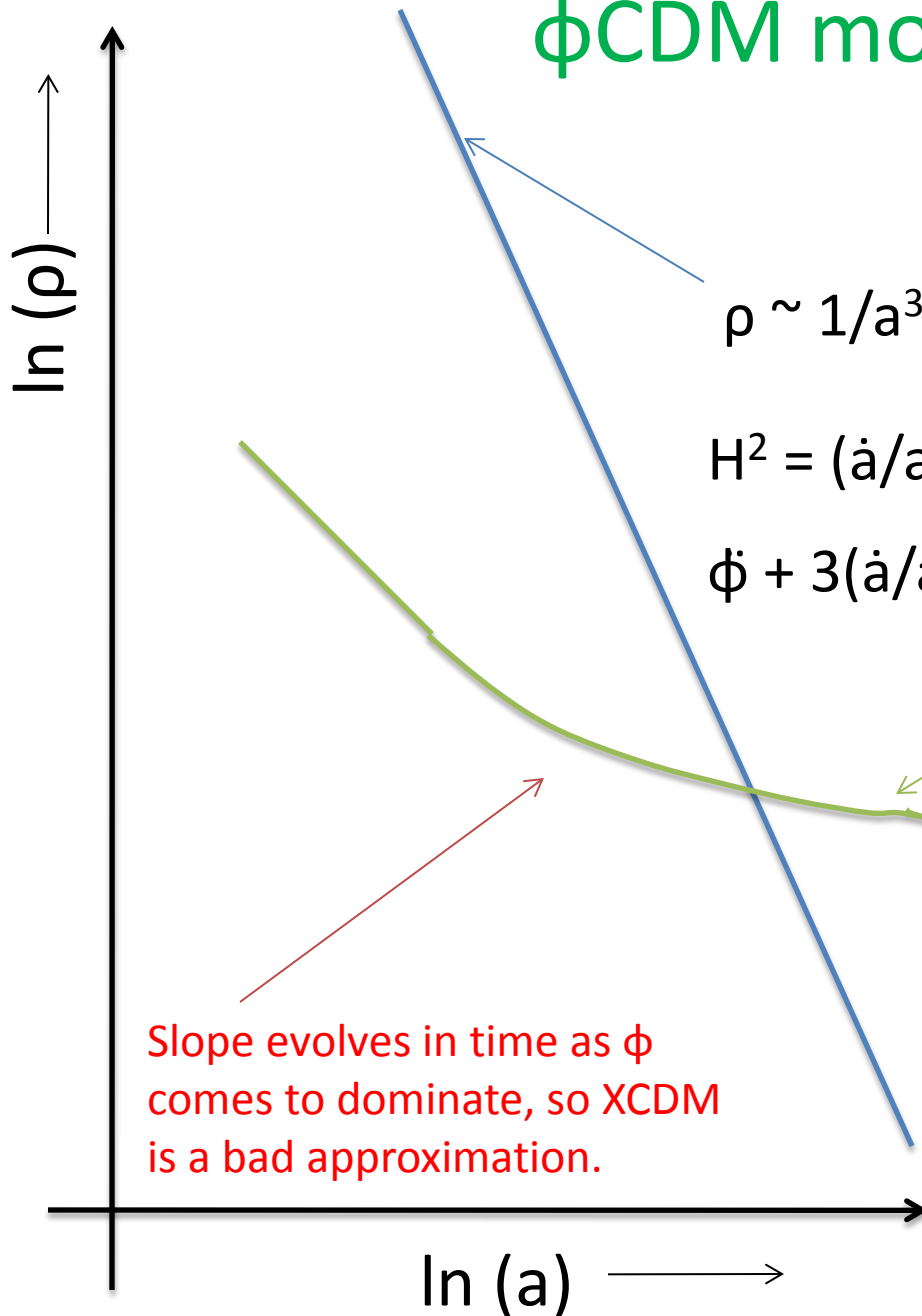
Spatially flat,  $K^2 = 0$ , but now dark energy evolves in time so again two free parameters specify XCDM parameterization:  $\Omega_{M0}$ ,  $\omega_X$

Widely used parameterization is incomplete.

# $\phi$ CDM model

(Peebles and Ratra 1988)

Spatially flat  
 $K^2 = 0$



$$\rho \sim 1/a^3$$

$$\rho_\phi = (\dot{\phi}^2 + \kappa\phi^{-\alpha}/G)/2$$

$$H^2 = (\dot{a}/a)^2 = 8\pi G\rho/3 + 8\pi G\rho_\phi/3$$

$$\ddot{\phi} + 3(\dot{a}/a)\dot{\phi} - \kappa\alpha\phi^{-(\alpha+1)}/(2G) = 0$$

numerically  
integrate

Spatially flat,  $K^2 = 0$ , but now dark energy evolves in time so again two free parameters specify  $\phi$ CDM:  $\Omega_{M0}, \alpha$

$\phi$ CDM model is special for some  $V(\phi)$ : the  $\phi$  solution is an attractor,  $\rho_\phi$  decreases less rapidly than  $\rho_M$  and comes to dominate. This helps to partially resolve the coincidence problem and makes  $\Lambda$  small because the universe is old.

Slope evolves in time as  $\phi$  comes to dominate, so XCDM is a bad approximation.

# Cosmological Tests

Type Ia supernova apparent magnitude vs. redshift

Baryon acoustic peak

Hubble parameter vs. redshift

Growth factor vs. redshift

There are many others but these 4 suffice for illustrative purposes.

# Procedure

Compute model-parameter-dependent predictions for the lookback time, the luminosity distance, etc., as functions of redshift  $z$ :  $1+z = \lambda_{\text{obs}}/\lambda_{\text{em}} = a(t_0)/a(t)$

$$H^2 = (\dot{a}/a)^2 = H_0^2 [\Omega_{M0}(1+z)^3 + \Omega_{K0}(1+z)^2 + \Omega_{\Lambda}] = H_0^2 E^2(z, p)$$

(Einstein-Friedmann equation for  $\Lambda$ CDM model)

at  $z = 0$ :  $\Omega_{M0} + \Omega_{K0} + \Omega_{\Lambda} = 1$  so  $p = (\Omega_{M0}, \Omega_{\Lambda})$

E.g., Hubble parameter vs. redshift:

$$H(z, p, H_0) = H_0 E(z, p)$$

Use such **model-parameter-dependent predictions** and **observational data** on these quantities and a technique such as least squares or maximum likelihood to constrain the cosmological parameters of these models.

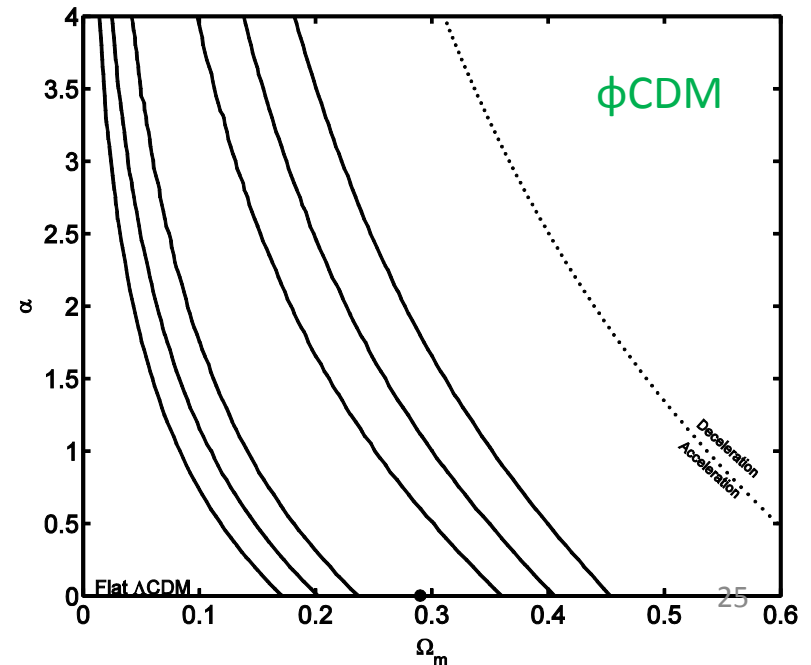
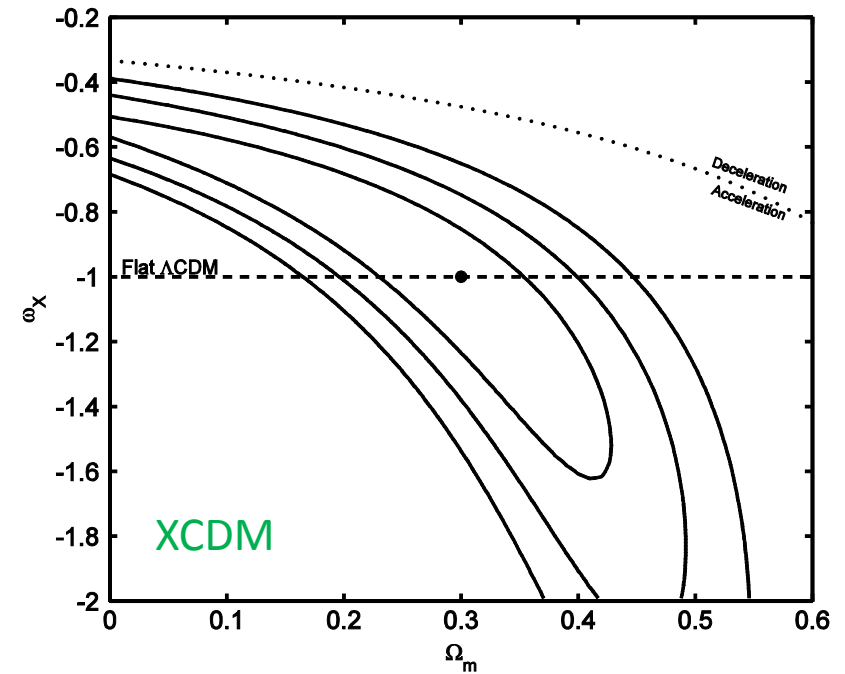
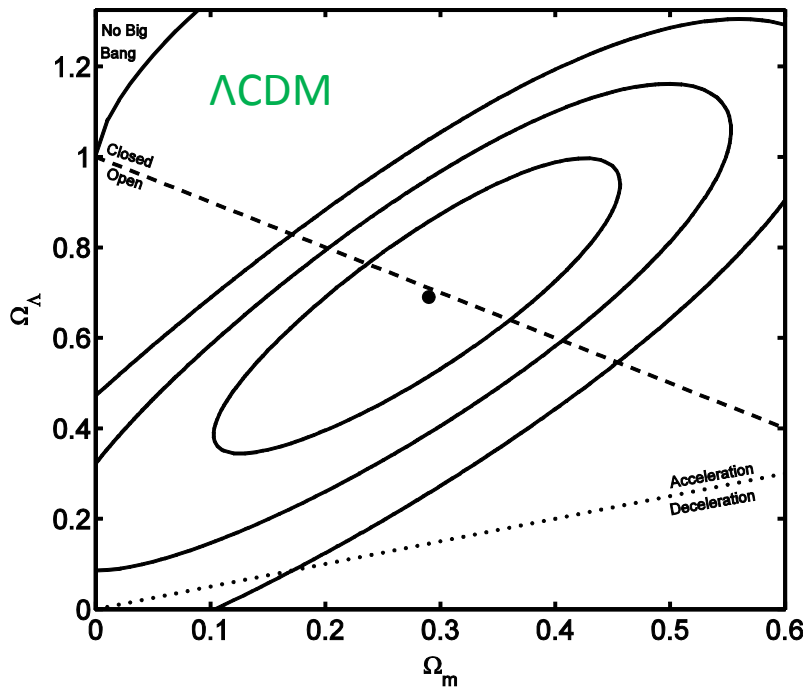
For nice reviews see the Ph.D. theses of Samushia 0908.4597 and Farooq 1309.3710.

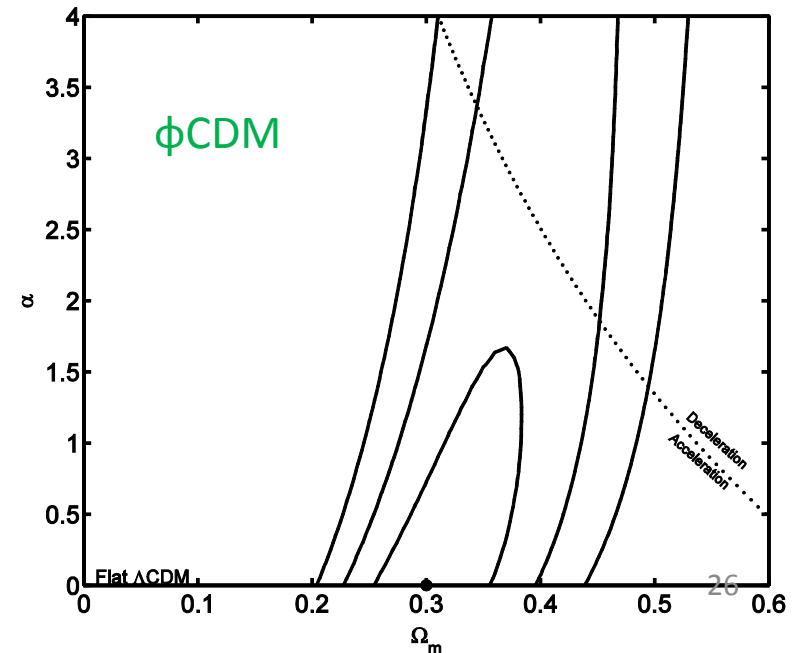
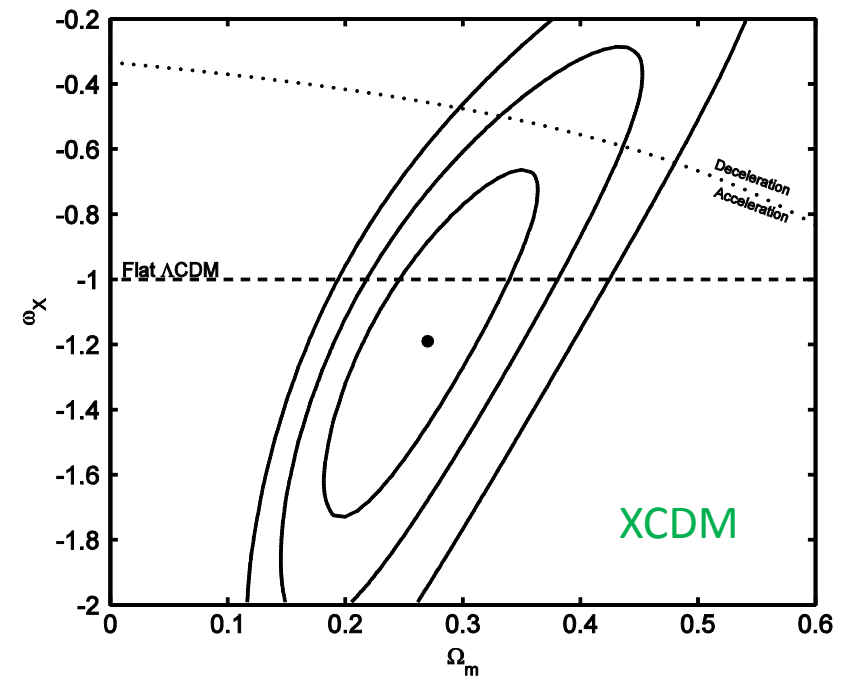
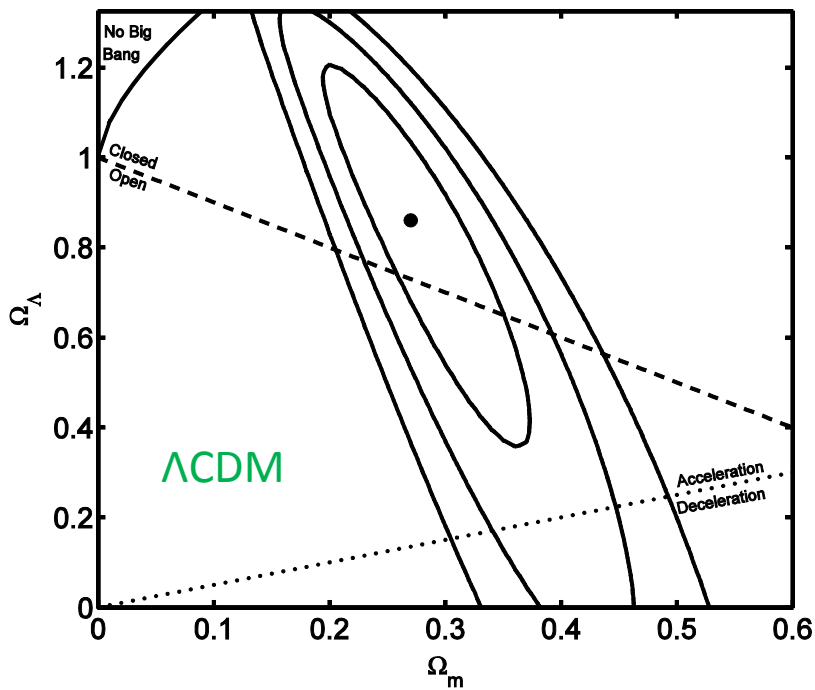


# Type Ia SN magnitude-redshift test. Union2.1, with systematic errors.

Suzuki et al. *ApJ*746, 85 (2012) 580 SNe.  
Marginalize over  $h$  with flat prior.

Farooq et al *ApJ*764,139 (2013)

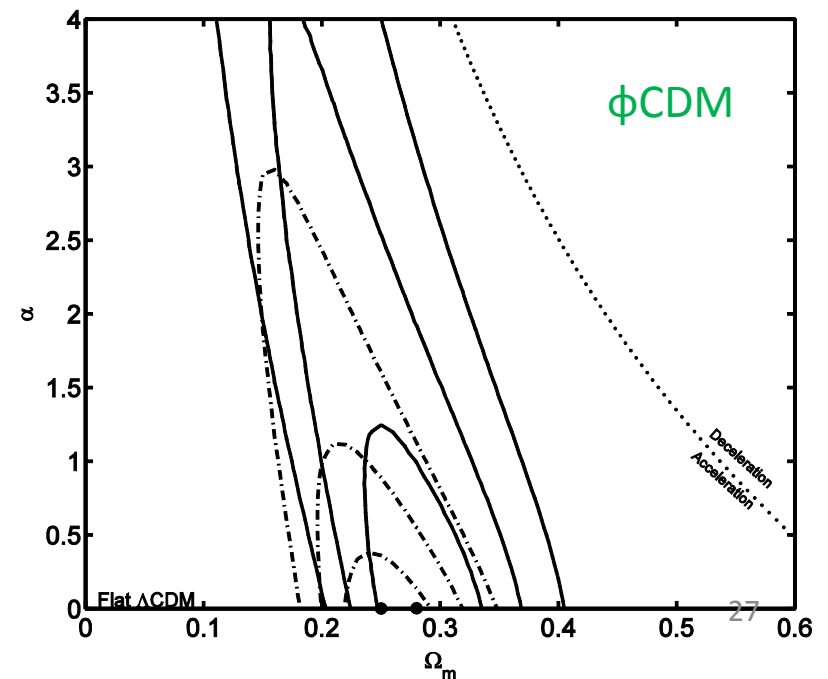
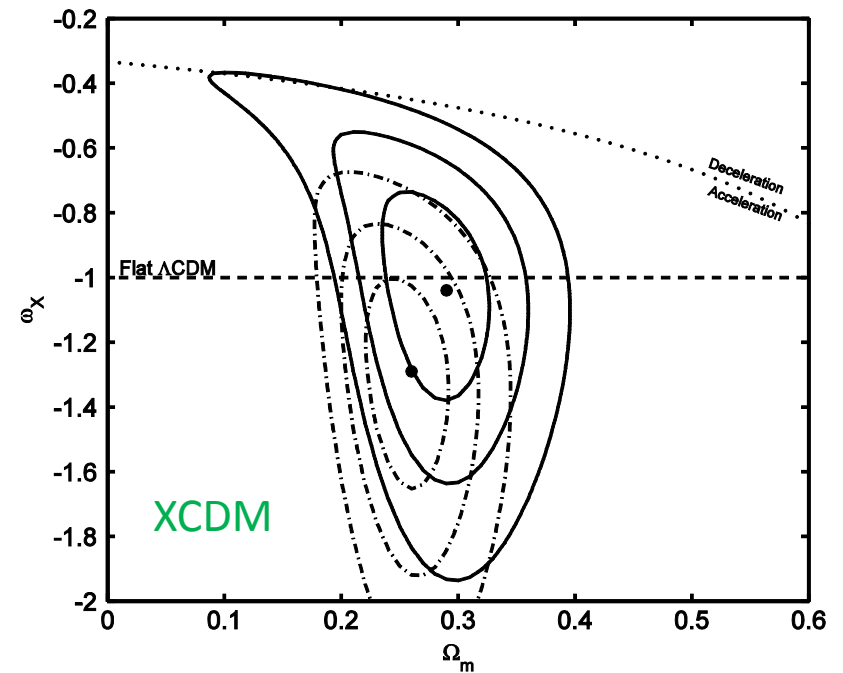
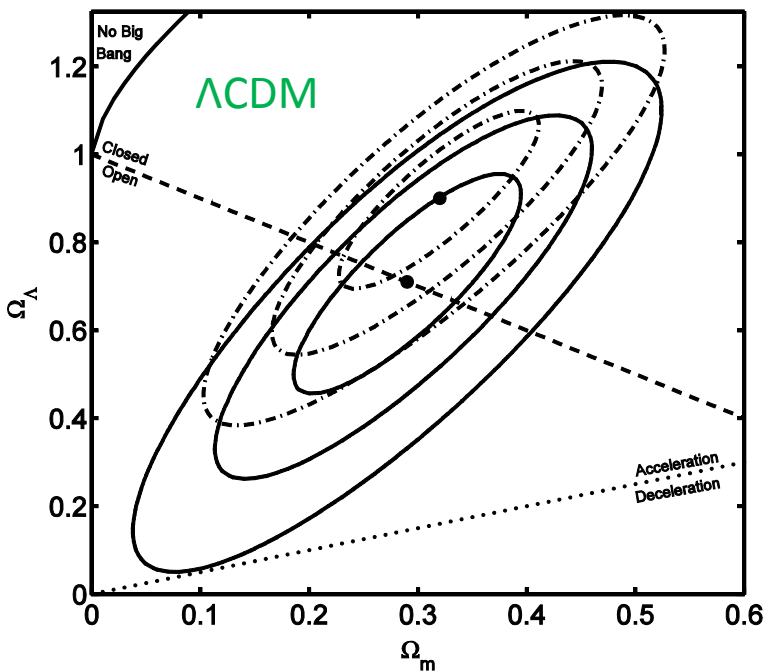




## Baryon acoustic peak test.

- 3 WiggleZ Blake et al MNRAS418, 1707 (2011)
- 1 6dFGS Beutler et al MNRAS416, 3017 (2011)
- 2 SDSS Percival et al MNRAS410, 2148 (2010)

Farooq et al ApJ764,139 (2013)

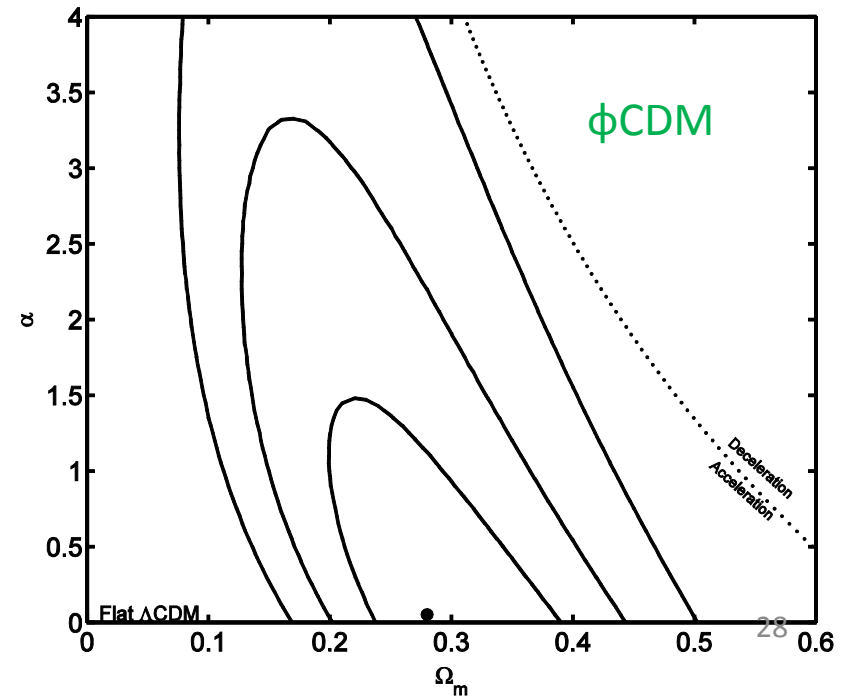
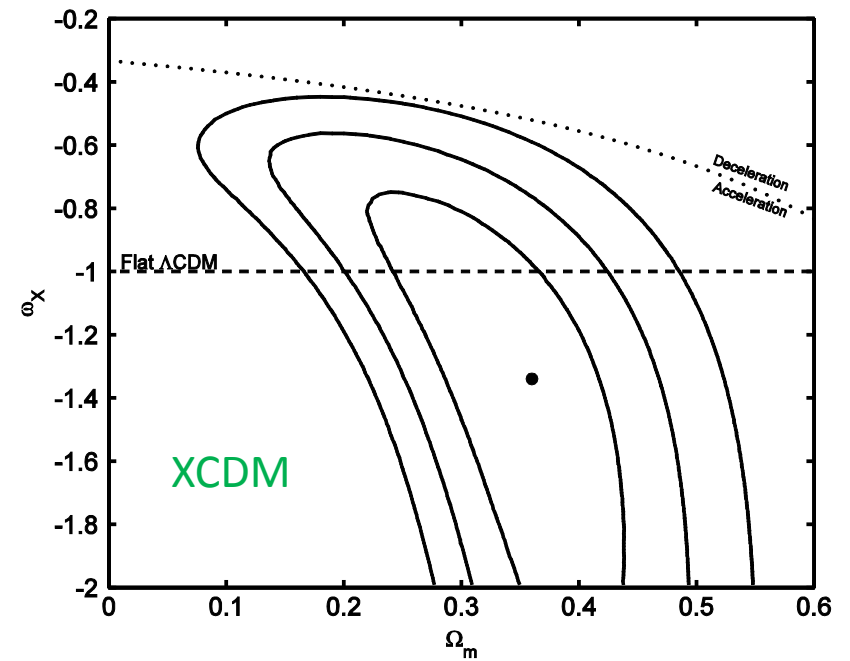
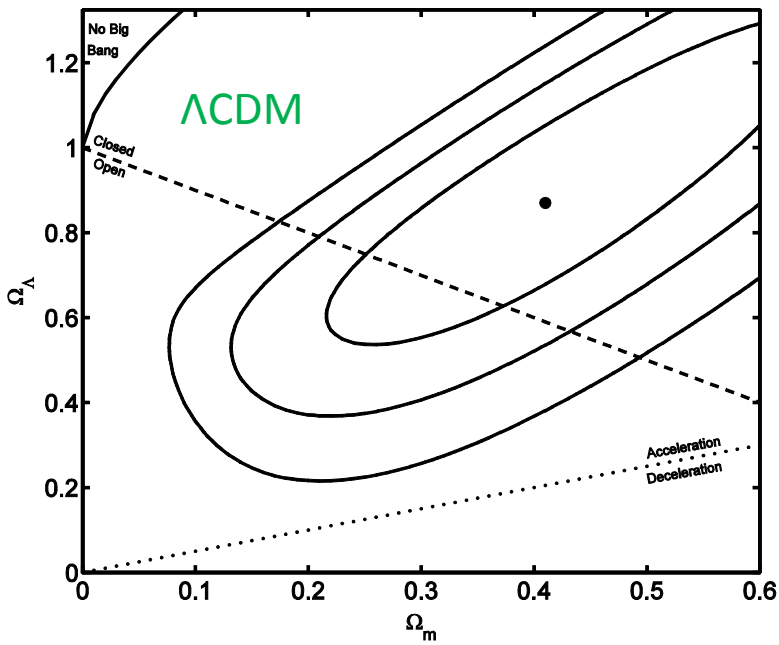


## Hubble parameter vs. redshift test.

Farooq & Ratra ApJ766, L7 (2013) 28 points.

Marginalize over:

- 1)  $h = 0.68 \pm 0.028$  solid lines
- 2)  $h = 0.738 \pm 0.024$  dash-dotted lines



Growth rate vs. redshift test.

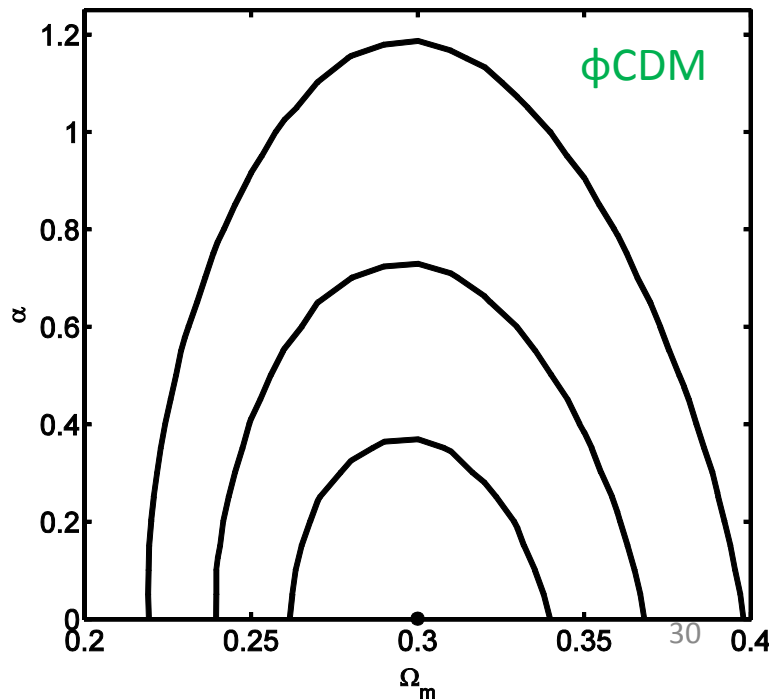
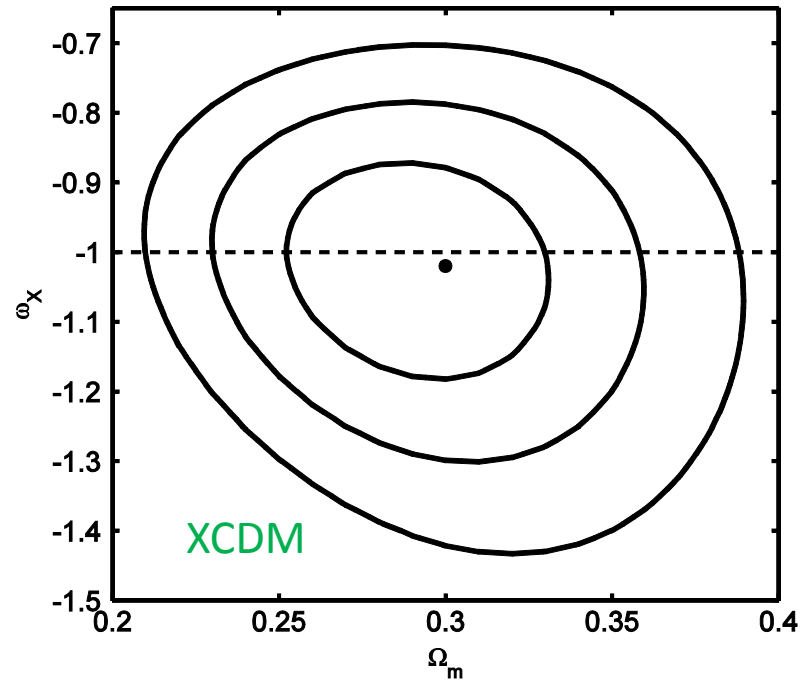
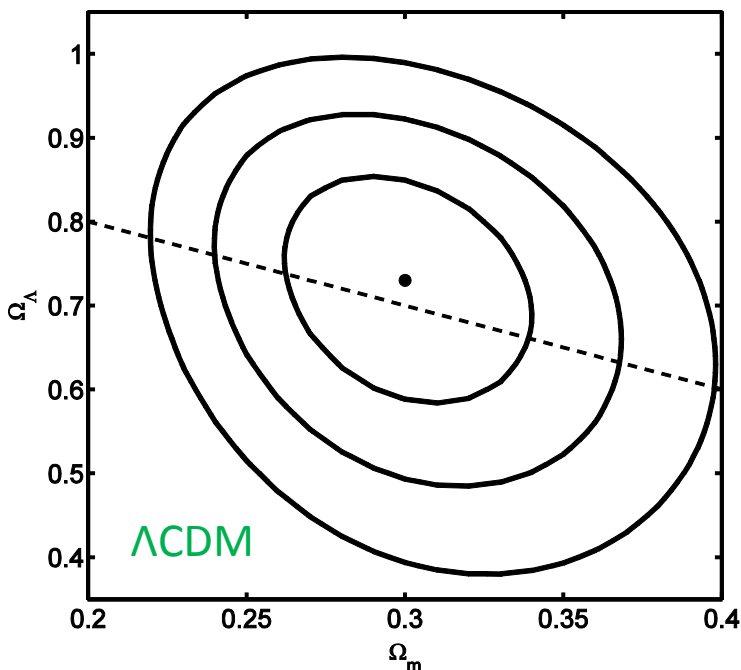
Pavlov et al PRD90, 023006 (2014)  
14 measurements

Constraints from different data are not inconsistent.

Individual data sets are consistent with a spatially-flat  $\Lambda$ CDM model with  $\Omega_\Lambda$  of order 0.7 and  $\Omega_{\text{matter}}$  of order 0.3, but do not yet rule out time-evolving dark energy.

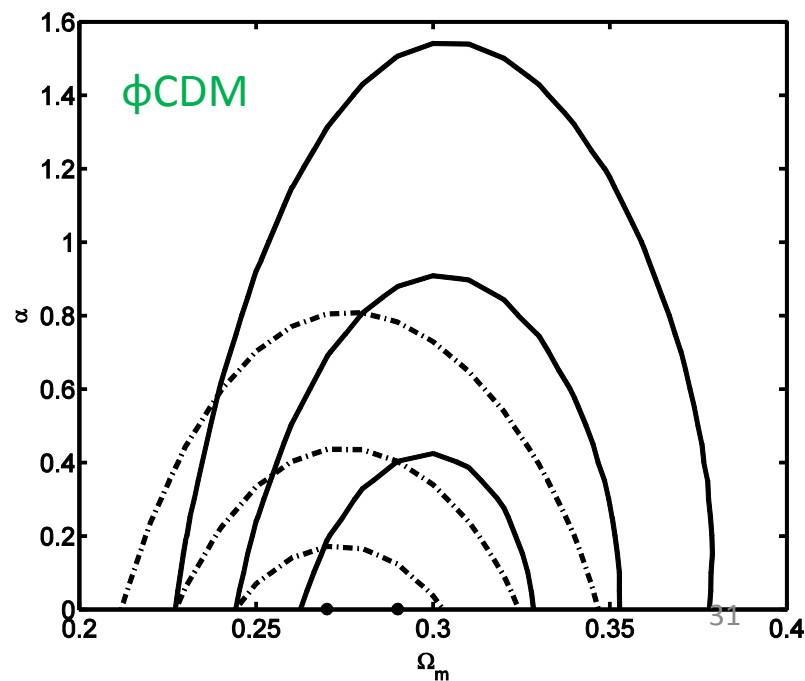
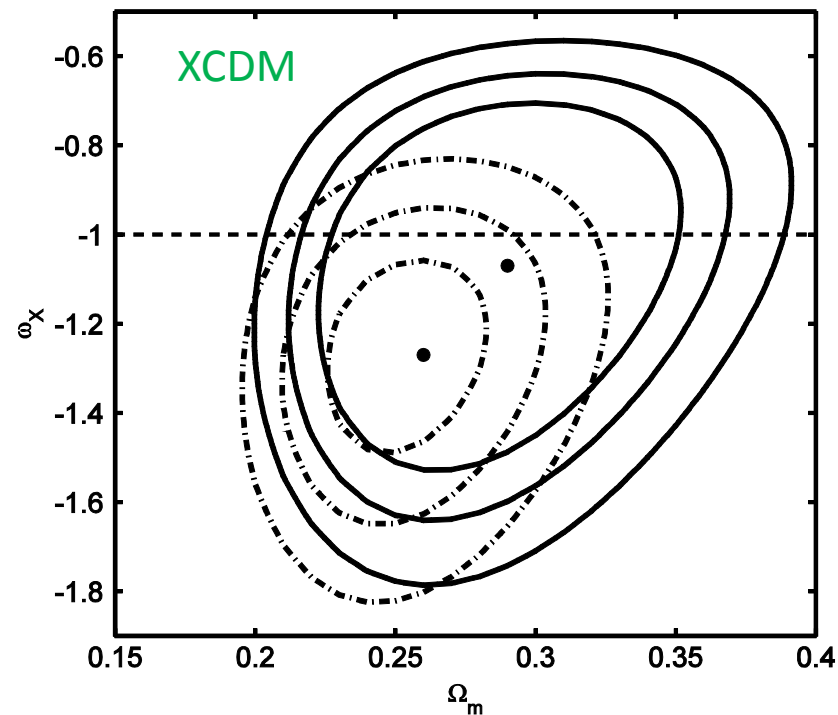
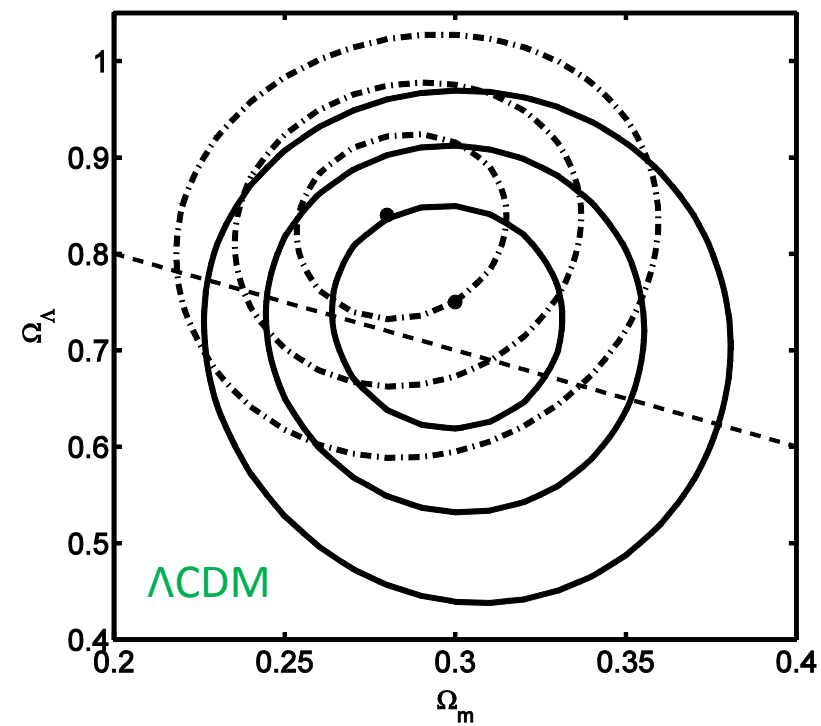
What about combinations of data sets?

Two data sets at a time, except for growth + Hubble parameter, since there is some correlation.



Supernovae and BAO.

A. Pavlov

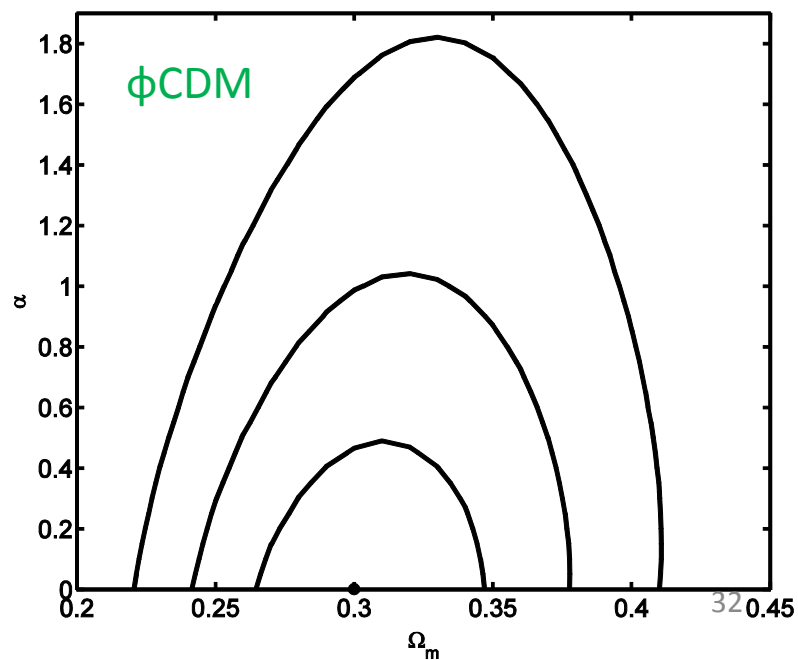
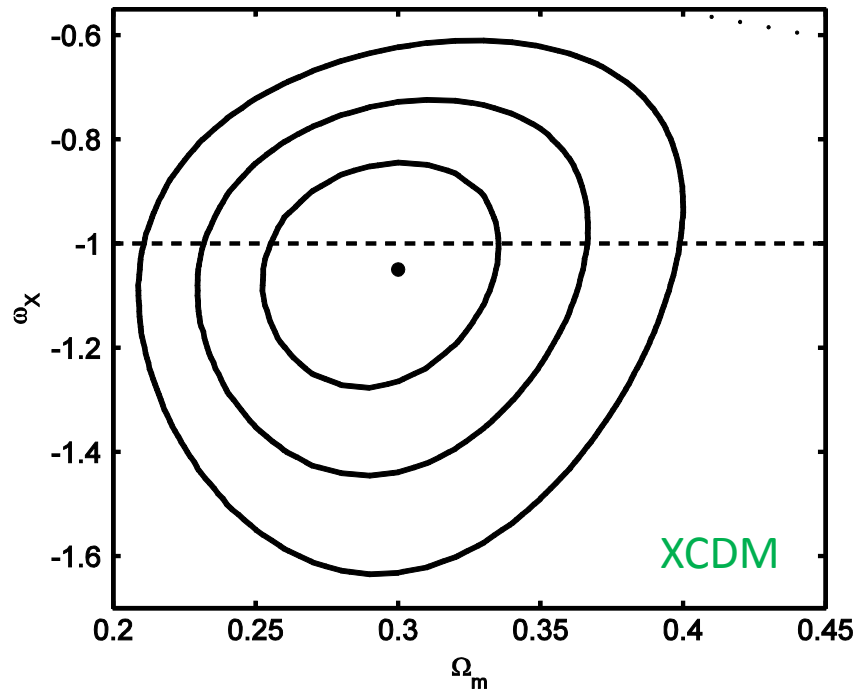
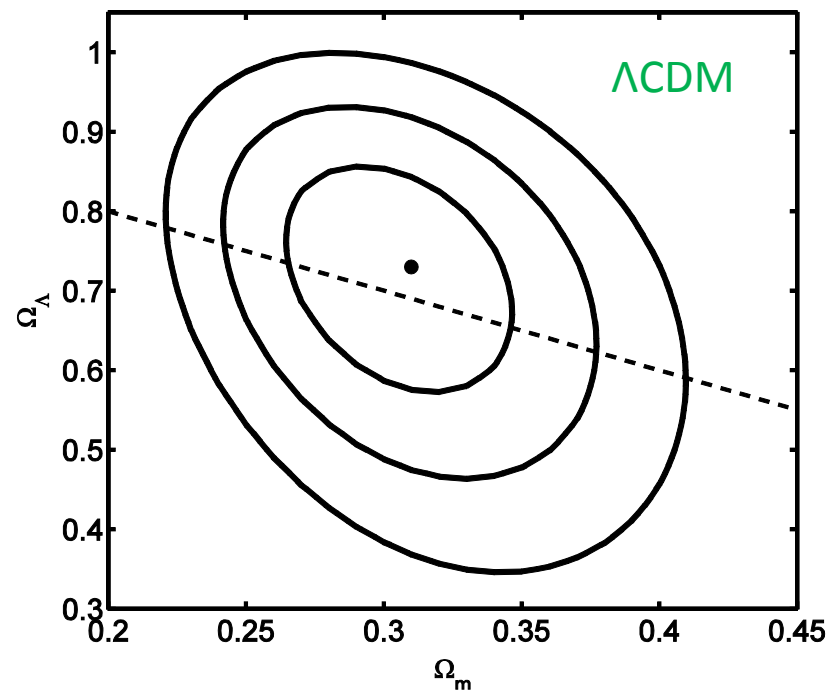


## Hubble parameter and BAO.

Marginalize over:

- 1)  $h = 0.68 \pm 0.028$  solid lines
- 2)  $h = 0.738 \pm 0.024$  dash-dotted lines

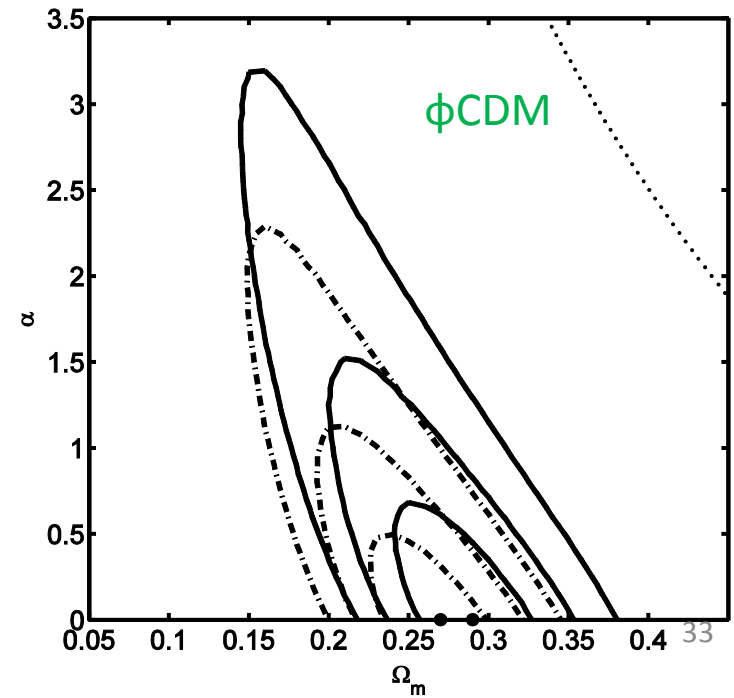
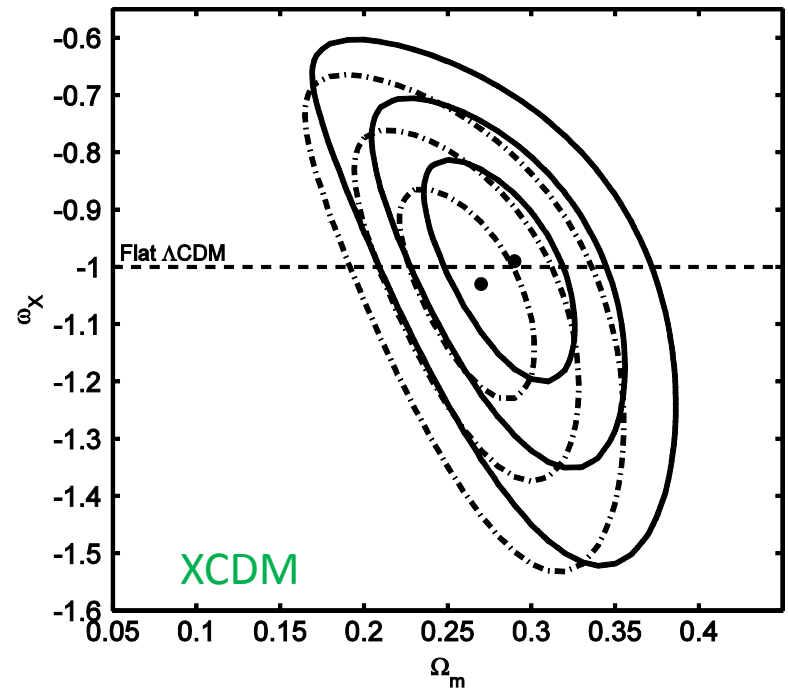
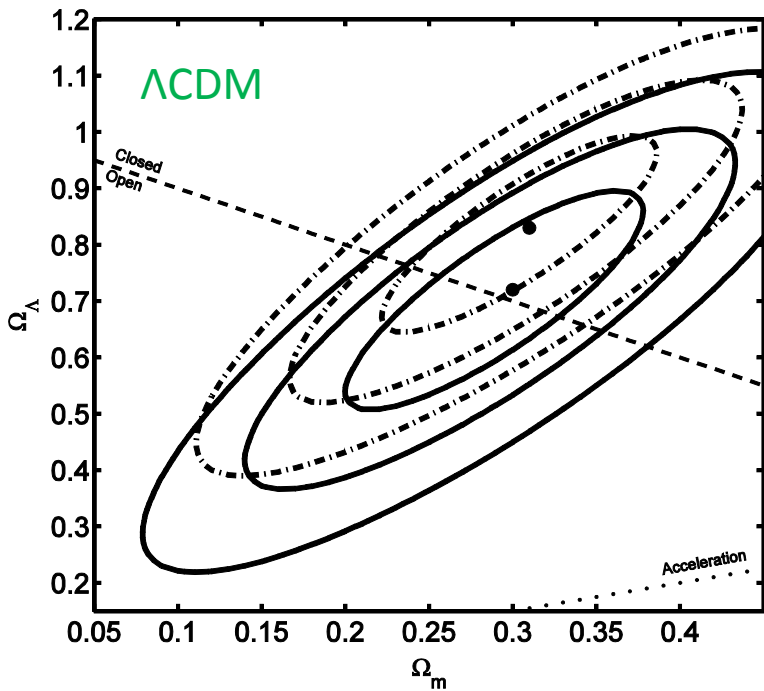
A. Pavlov



BAO and growth factor.

A. Pavlov





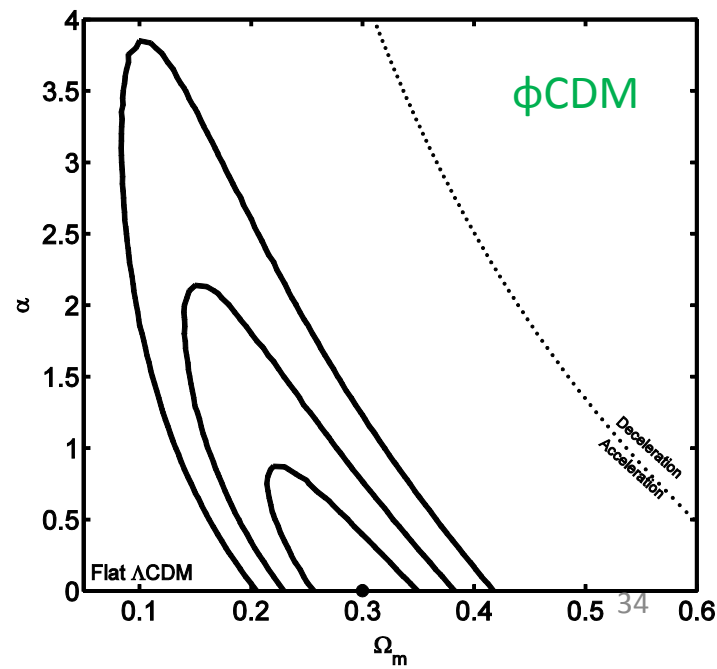
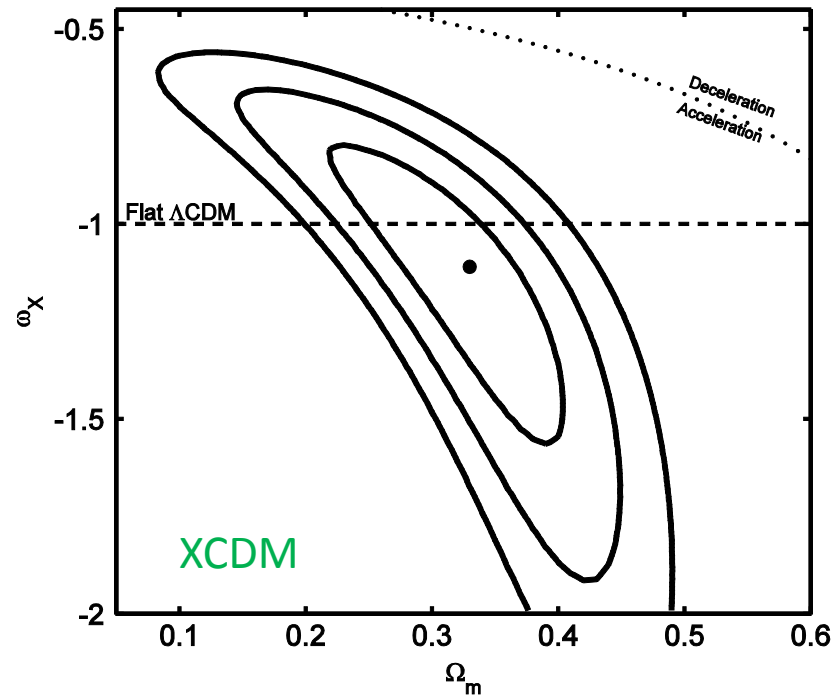
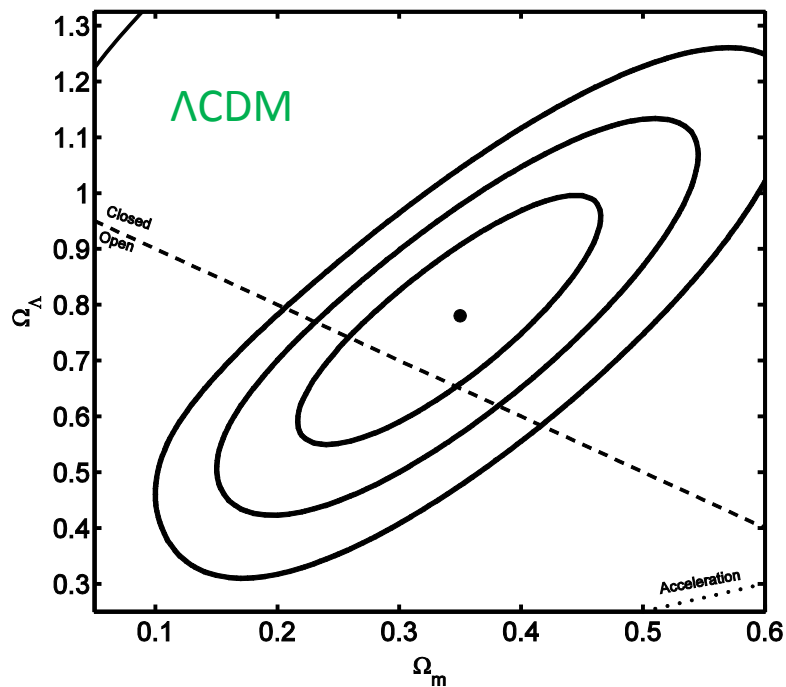
# Hubble parameter and supernovae.

- Marginalize over:
- 1)  $h = 0.68 \pm 0.028$  solid lines
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A. Pavlov

# Supernovae and growth factor.

A. Pavlov



Data sets combined two at a time result in tighter constraints which are consistent with a spatially-flat  $\Lambda$ CDM model with  $\Omega_\Lambda$  of order 0.7 and  $\Omega_{\text{matter}}$  of order 0.3, but do not yet strongly rule out time-evolving dark energy.

Some data issues: different SNeIa data result in different constraints (systematics?); different GRB data analysis techniques result in different constraints (not yet standard candles?), improve  $h$  determination, improve  $\Omega_b h^2$  determination (is simplest BBN model adequate?), ...

We need more and better-quality data before we can draw stronger conclusions.

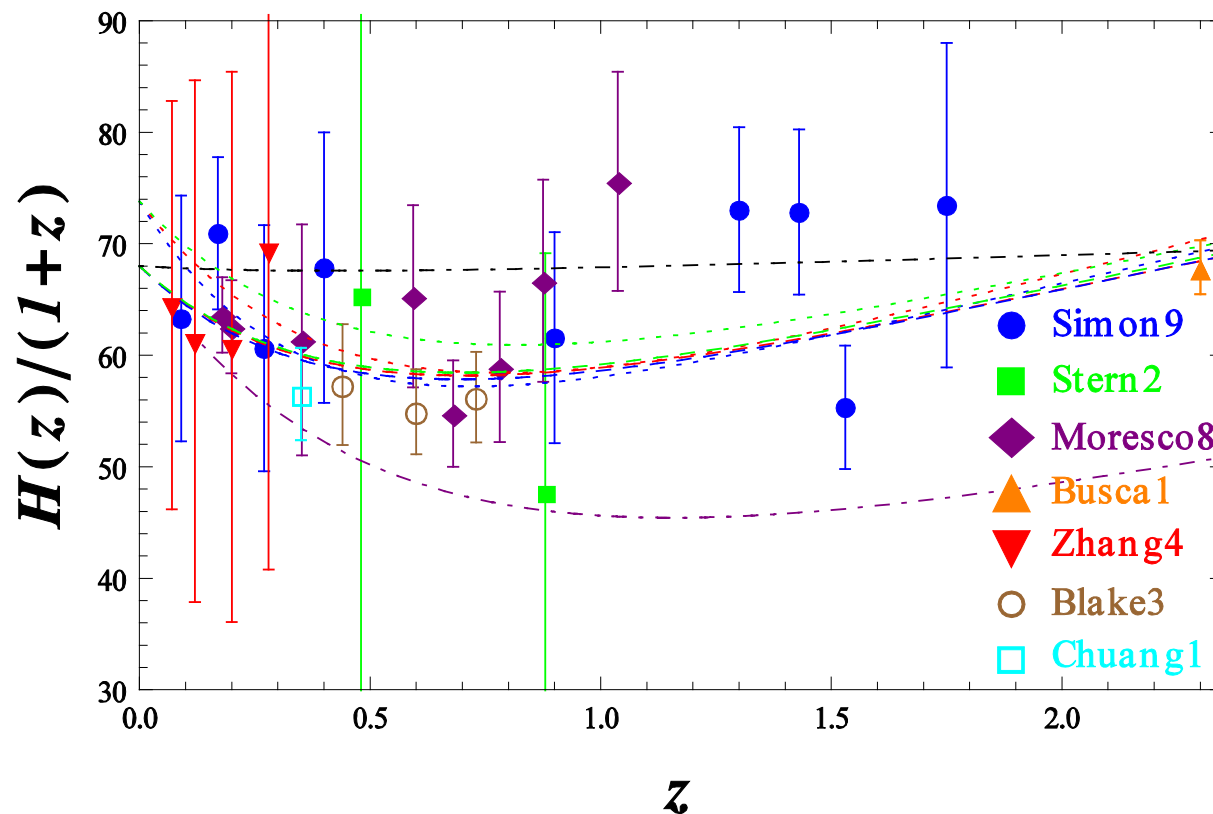
This will be possible soon.

# H(z) data & deceleration-acceleration transition

It is now possible to measure  $H(z)$  by using cosmic chronometers or radial BAO data (e.g., Moresco JCAP1208, 006; Busca A&A552, A96 (2013))

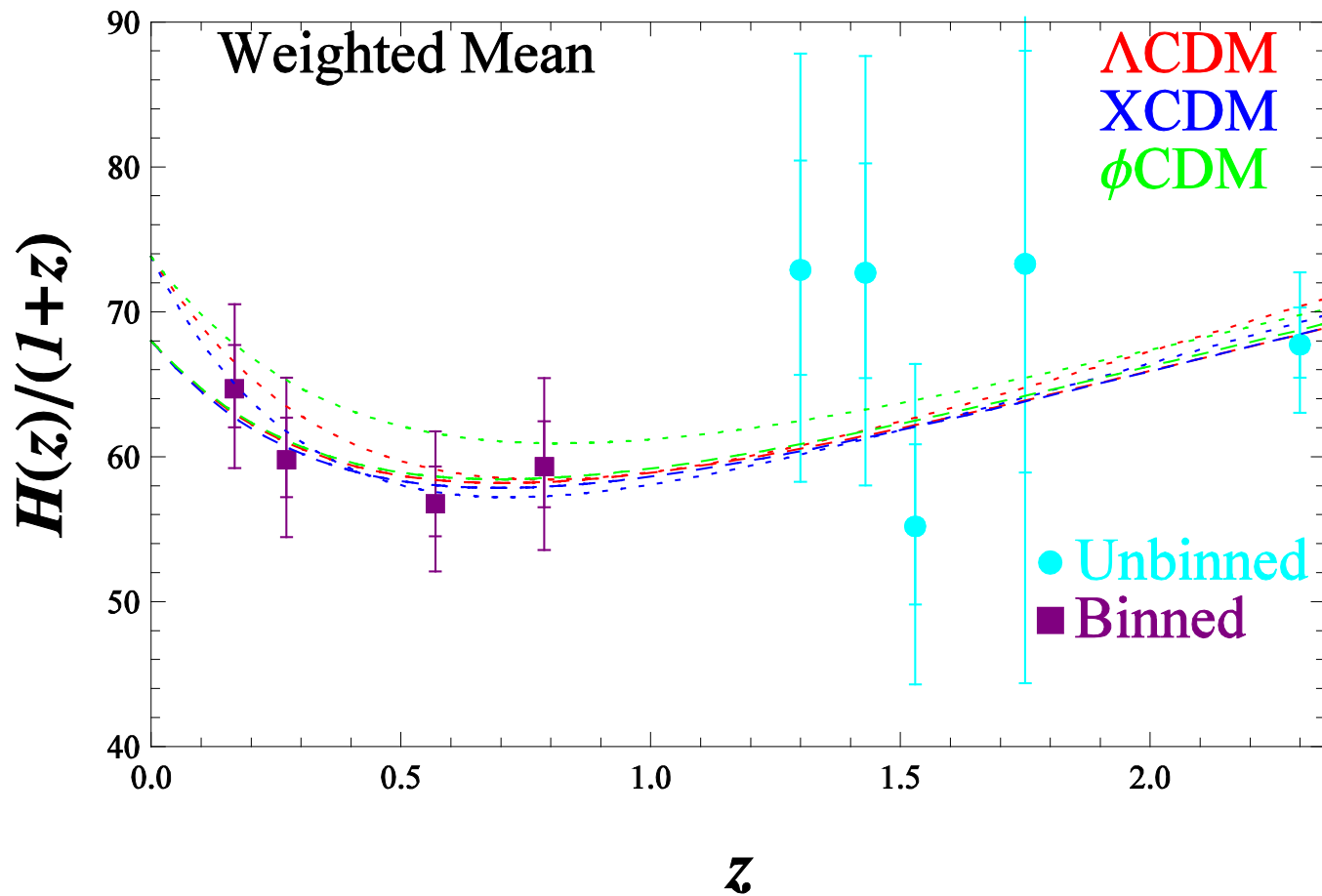
Combining 28 independent measurements over  $0.07 < z < 2.3$

(Farooq & BR ApJ766, L7 (2013); Farooq, Crandall & BR PLB726, 72 (2013)) shows a transition:



Six best-fit models and two  $3\sigma$  deviant models

Data are noisy, so let's bin them



For  $\Lambda$ CDM:  $H/(1+z) = H_0[\Omega_{M0}(1+z) + \Omega_{K0} + \Omega_{\Lambda}/(1+z)]^{1/2}$

Averaging over models and  $H_0$  priors, transition redshift  $z = 0.74 \pm 0.04$

(This is the first real measurement of the deceleration-acceleration transition redshift.)

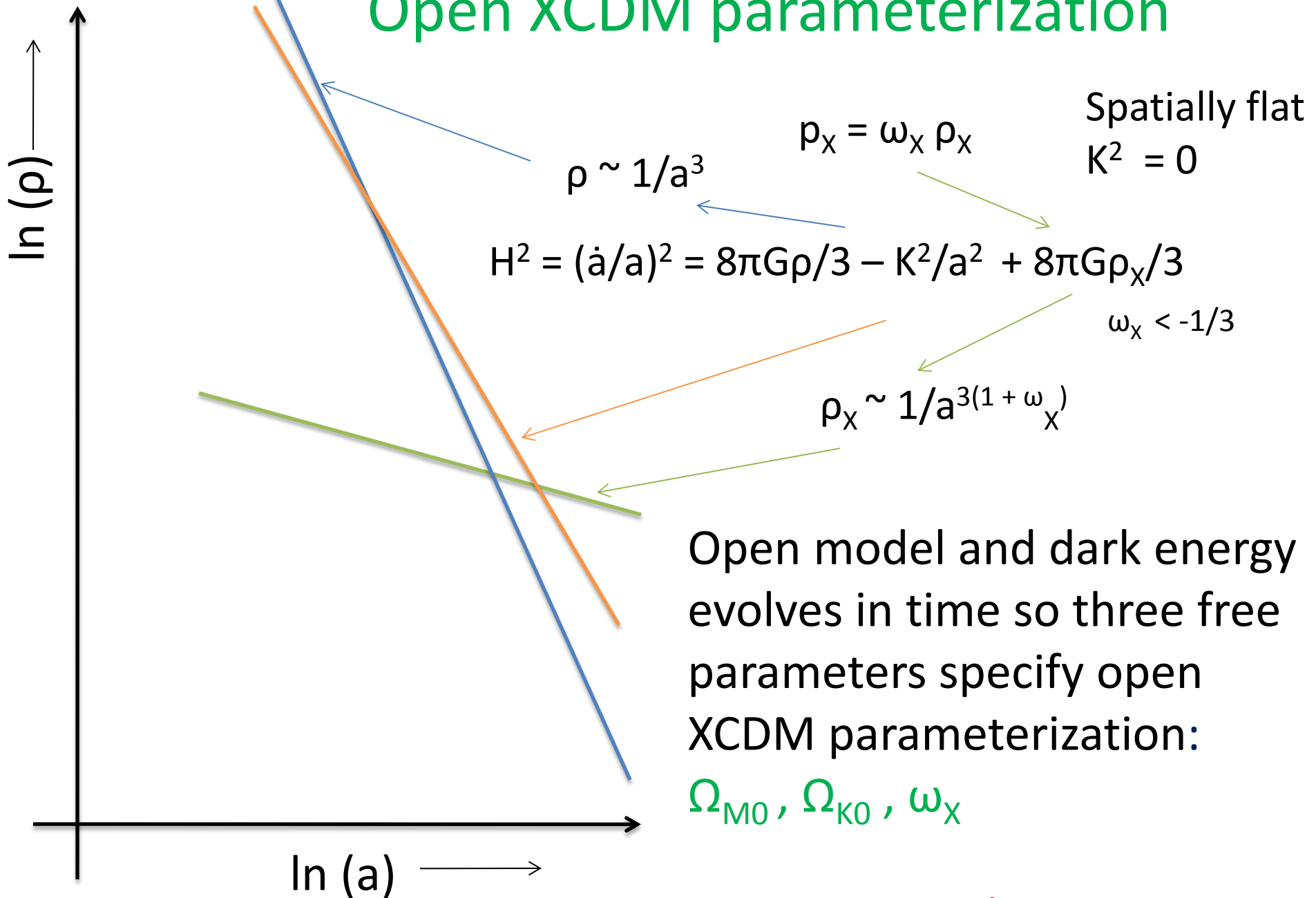
Do observations really require close to zero space curvature?

YES, CMB anisotropy data requires a flat geometry, IF dark energy density is time-independent as in  $\Lambda$ CDM, but **NOT IF** the dark energy density varies in time as in the XCDM parameterization and or the  $\phi$ CDM model.

**AND** in non-flat models the data do not as strongly demand time-independent dark energy density.

Consider 2 options, non-flat XCDM parameterization and non-flat  $\phi$ CDM.

# Open XCDM parameterization



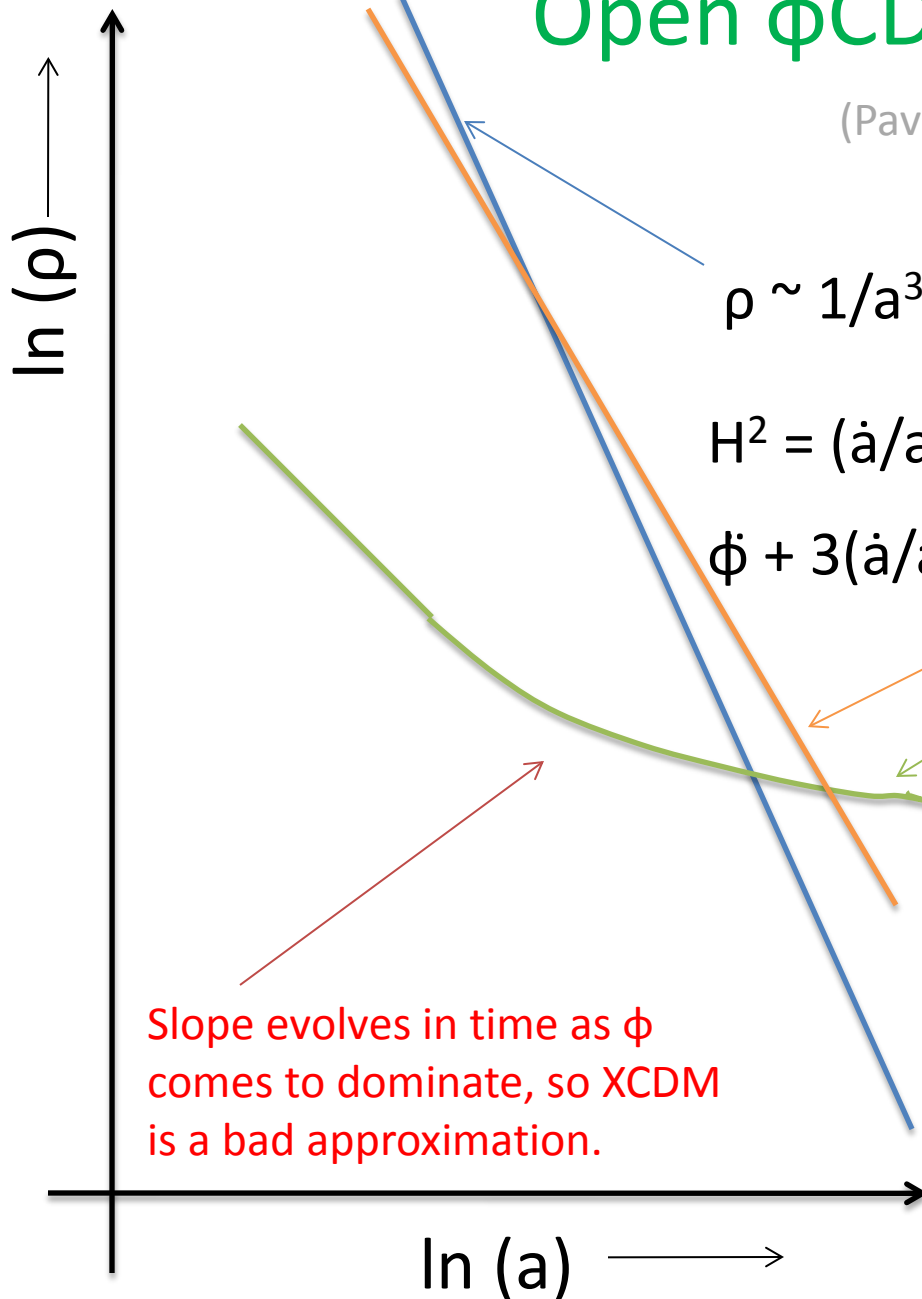
Parameterization is incomplete.

# Open $\phi$ CDM model

Spatially flat

$$K^2 = 0$$

(Pavlov et al. PRD88, 123513 (2013))



$$\rho \sim 1/a^3$$

$$\rho_\phi = (\dot{\phi}^2 + \kappa\phi^{-\alpha}/G)/2$$

$$H^2 = (\dot{a}/a)^2 = 8\pi G\rho/3 - K^2/a^2 + 8\pi G\rho_\phi/3$$

$$\ddot{\phi} + 3(\dot{a}/a)\dot{\phi} - \kappa\alpha\phi^{-(\alpha+1)}/(2G) = 0$$

← numerically integrate

Open and dark energy evolves in time so three free parameters specify open  $\phi$ CDM:  $\Omega_{M0}$ ,  $\Omega_{K0}$ ,  $\alpha$

Slope evolves in time as  $\phi$  comes to dominate, so XCDM is a bad approximation.

$\phi$ CDM model is special for some  $V(\phi)$ : the  $\phi$  solution is an attractor,  $\rho_\phi$  decreases less rapidly than  $\rho_M$  and comes to dominate. This helps to partially resolve the coincidence problem and makes  $\Lambda$  small because the universe is old.

The new energy scale can be much higher; time evolution decreases it to of order an meV now.

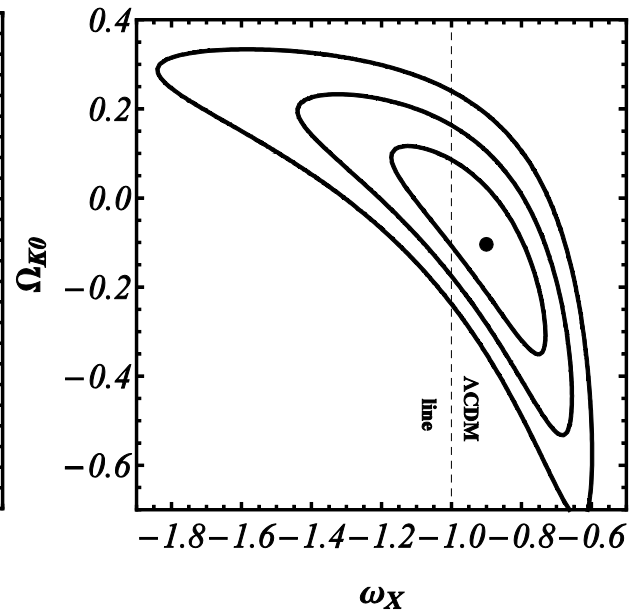
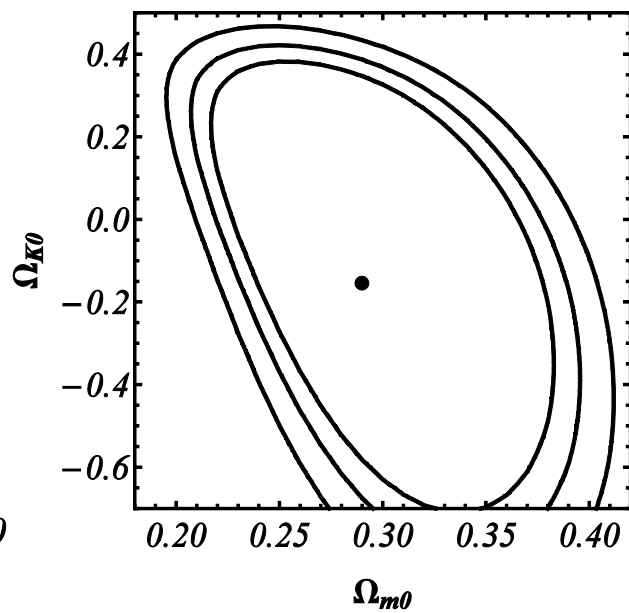
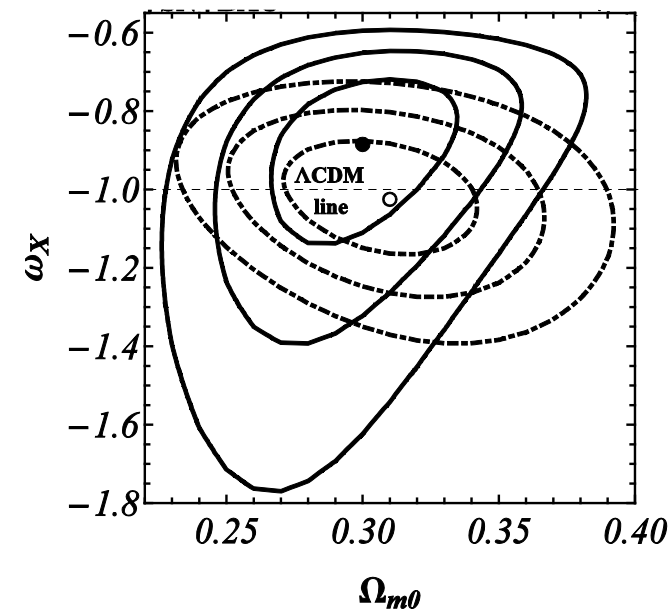


Constrain parameters of these two open models  
using recent SNIa, BAO, and  $H(z)$  data

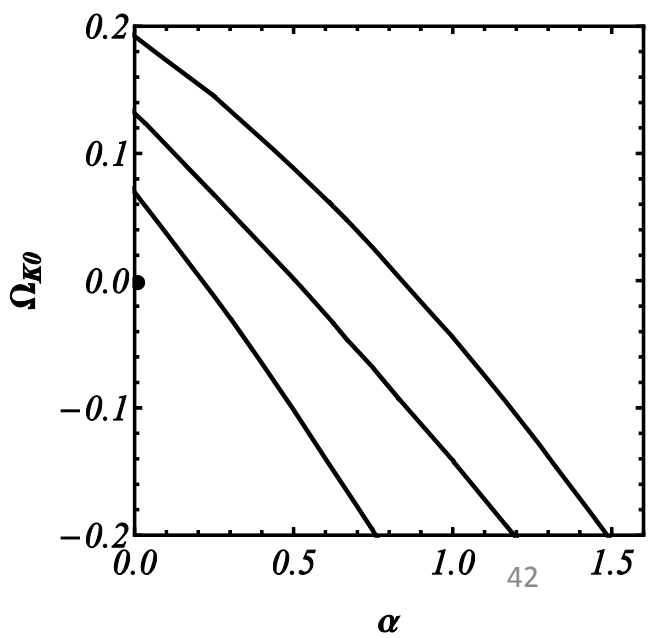
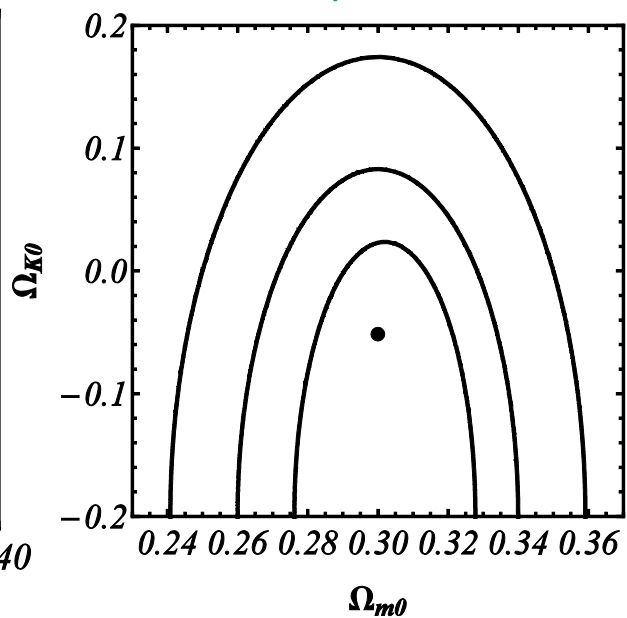
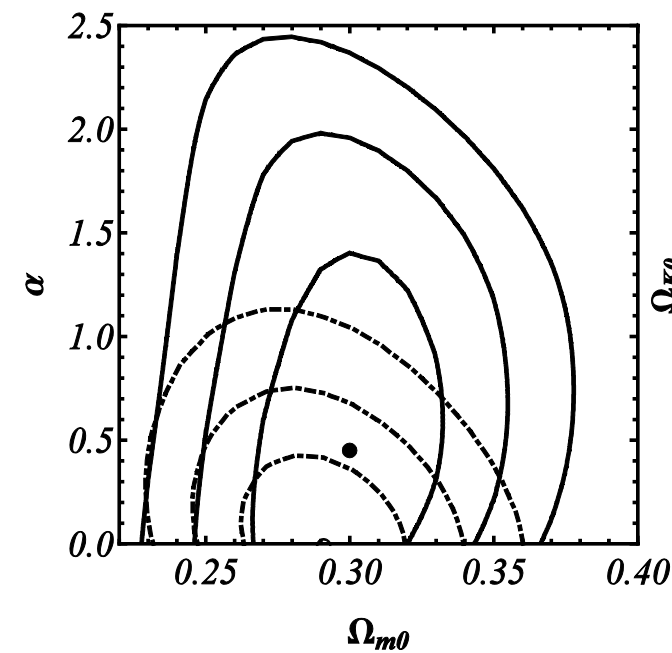
(Farooq et al ApSS357, 11 (2015))

Will eventually need to include CMB anisotropy data,  
but this requires figuring out how to deal with  
spatial inhomogeneities.

# Non-flat XCDM



# Non-flat $\phi$ CDM



# Open Questions, Missing Links

B.R. & M. Vogele, PASP120,235 (2008)

## What is dark energy?

Is it a cosmological constant, or does it vary with space and in time?

Is the general theory of relativity correct on large scales?

Are the astronomy observations for dark energy secure?

Is it really decoupled (except gravitationally) from everything else?

## What is dark matter?

Supersymmetry? Axions?

Will the Large Hadron Collider at CERN tell us?

Laboratory searches for dark matter.

Dwarf galaxy abundances, galactic nuclear profiles might be problems for “pure” CDM.

What are the masses of neutrinos?

Are the constraints on baryon density consistent?

When and how was the baryon excess generated?

What is the topology of space?

What are the initial seeds for structure formation?

Did the early universe inflate and reheat?

When, how, and what were the first structures formed?

How do baryons light up galaxies and what is their connection to mass?

How do galaxies and black holes co-evolve?

Does the Gaussian, adiabatic CDM structure formation model have a real flaw?

Is the low quadrupole moment of the CMB anisotropy a problem for flat  $\Lambda$ CDM?

Are the largest observed structures a problem for flat  $\Lambda$ CDM?

Is there a cosmological magnetic field and what effects does it have?

...when you have eliminated the impossible,  
whatever remains, however improbable, must  
be the truth.



Sherlock Holmes (Arthur Conan Ignatius Doyle)