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

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Abstract: <p>Experiments and observations over the last decade and a half have persuaded cosmologists that (as yet undetected) dark energy is by far the main component of the energy budget of the universe. I review a few simple dark energy models and compare their predictions to observational data, to derive dark energy model-parameter constraints and to test consistency of different data sets. I conclude with a list of open cosmological questions.</p>

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

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Perimeter Institute Wednesday September 23, 2015

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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)

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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!

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Outline

motivate dark energy

two dark energy models (ΛCDM, ϕCDM), 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

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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.

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Fact: the universe expands.

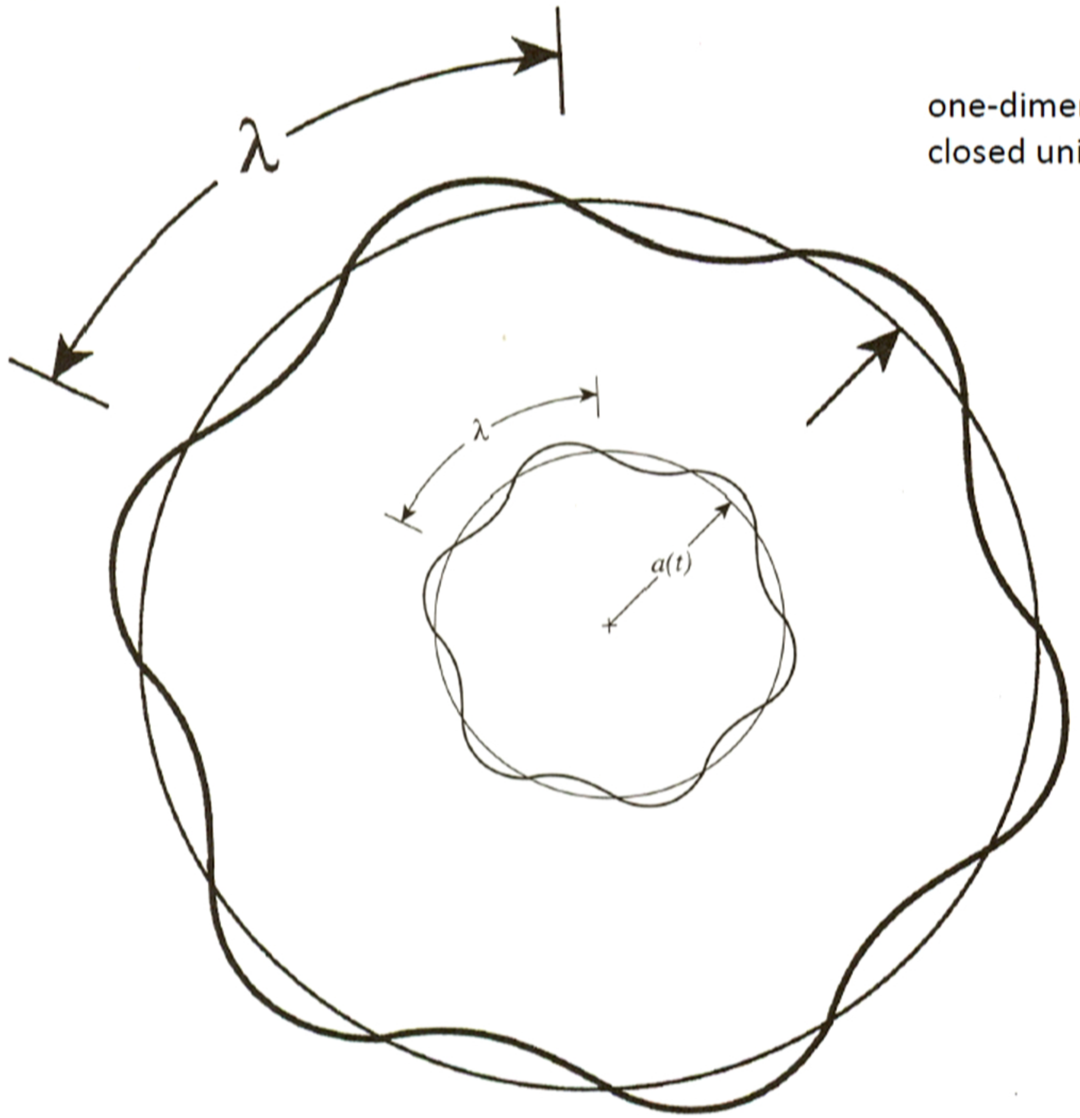
Consider a wave propagating in a one-dimensional expanding universe. For adiabatic expansion the wavelength must expand with scalefactor, $\lambda \sim a(t)$ (redshifting).

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!

one-dimensional
closed universe



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

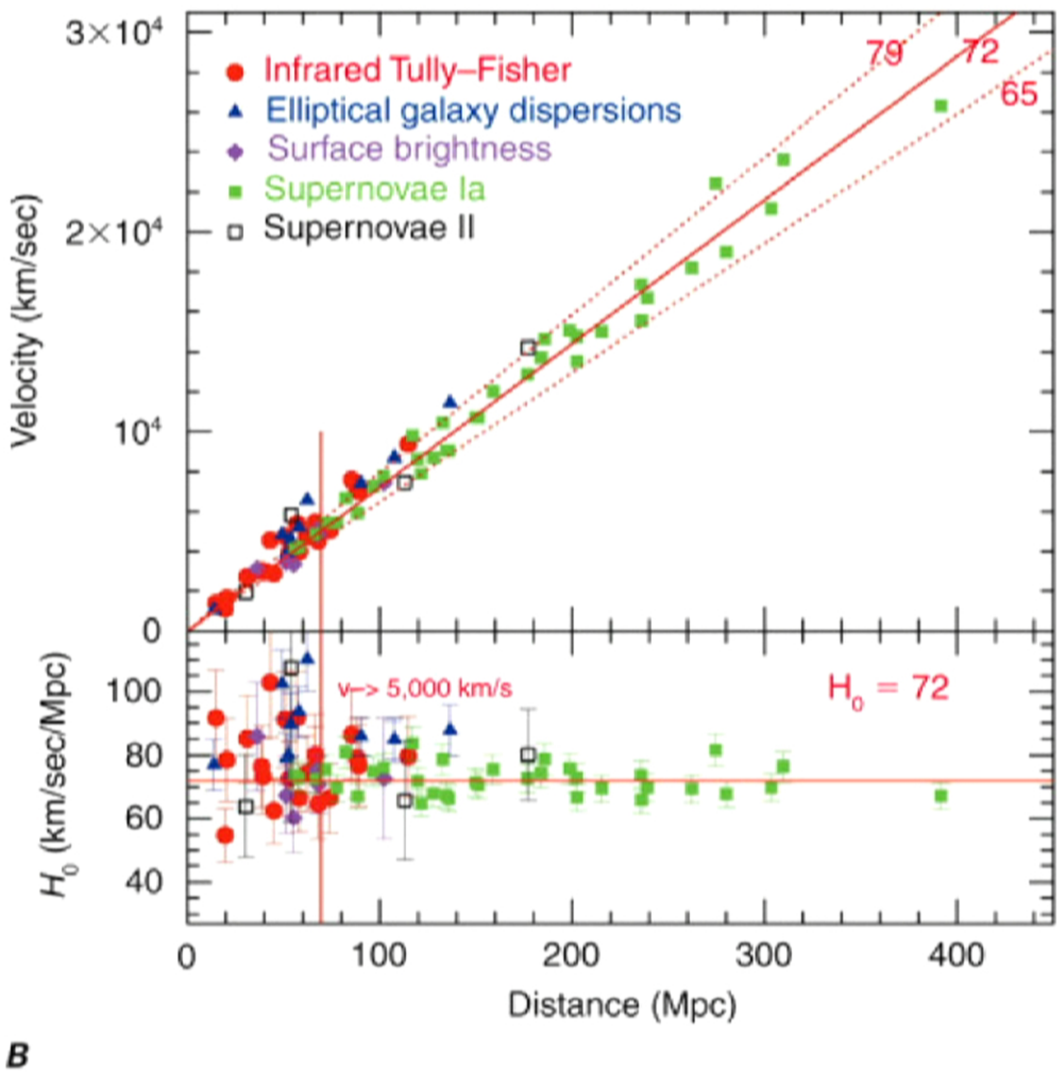
H_0 = Hubble constant = (68 ± 2.8) km s^{-1} Mpc^{-1}

= 100 h km s^{-1} 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.



(Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA)

Hubble law

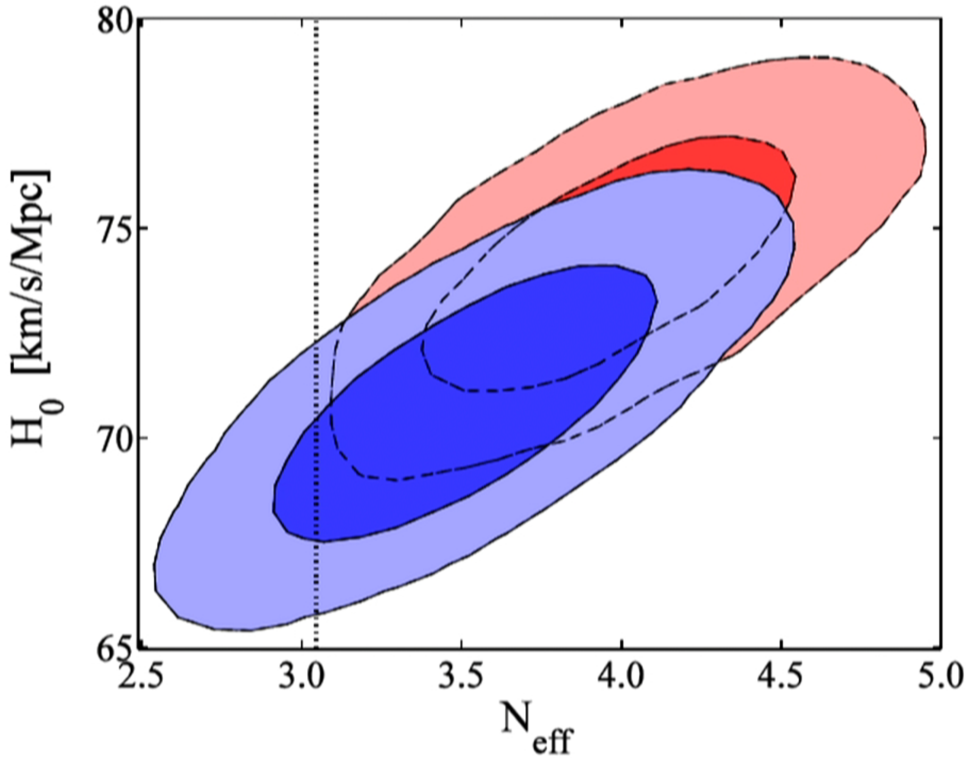
H_0 = Hubble constant

= (68 ± 2.8) km s^{-1} Mpc^{-1}

= 100 h km s^{-1} Mpc^{-1}

Chen & Ratra PASP123,1127 (2011)

An aside: Large H_0 value forces consideration of dark radiation



Red contours
H_0 = (73.8 ± 2.4) km s^{-1} Mpc^{-1}
require dark radiation
Riess et al. ApJ730,119 (2011)

Blue contours
H_0 = (68 ± 2.8) km s^{-1} Mpc^{-1}
do not require dark radiation
Chen & Ratra PASP123,1127 (2011)

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.

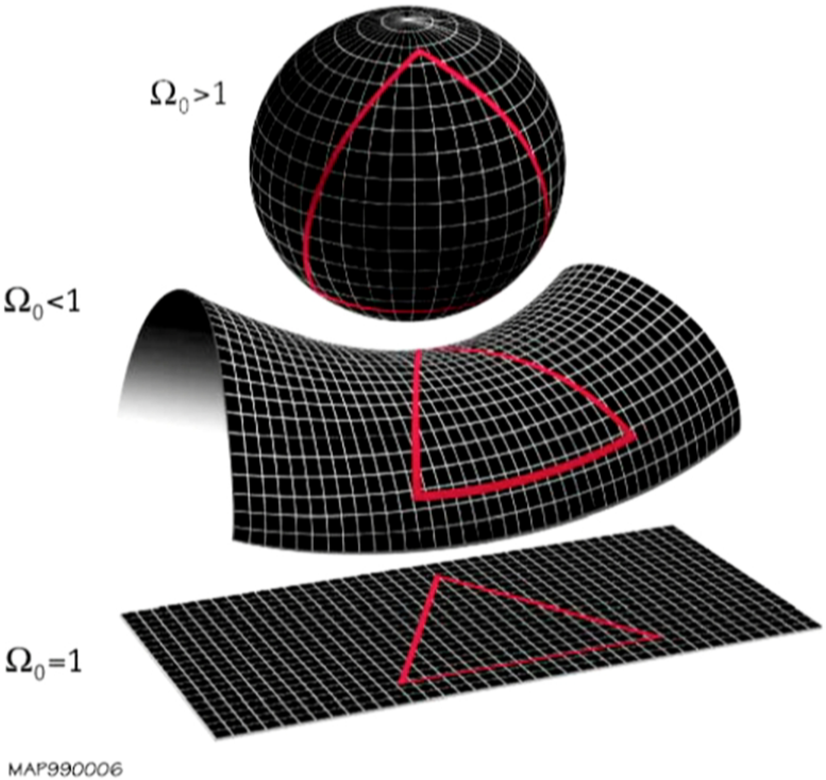
Cosmological Principle (assumption): the universe is (statistically) spatially isotropic for all cosmological observers.

This implies (statistical) spatial homogeneity.

Ignoring global topology, there are then only three possible spatial geometries: the flat, open and closed Friedmann-Lemaitre-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

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equations of motion (ideal fluid matter):

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

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

$p = p(\rho)$ equation of state

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

Is this increasing or decreasing with time?

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

matter and radiation with $p > 0$

=> $\ddot{a} < 0$ decelerated expansion

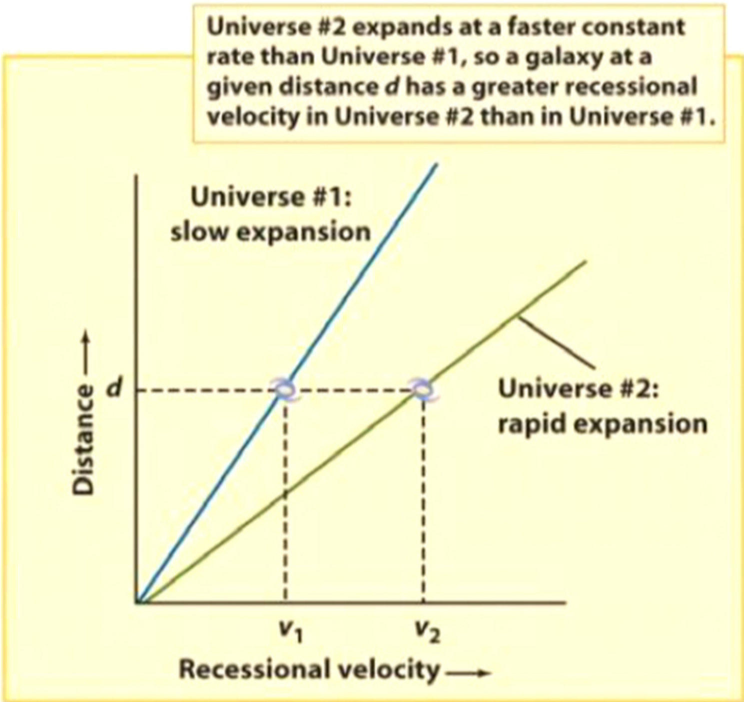
Einstein-de Sitter mass density

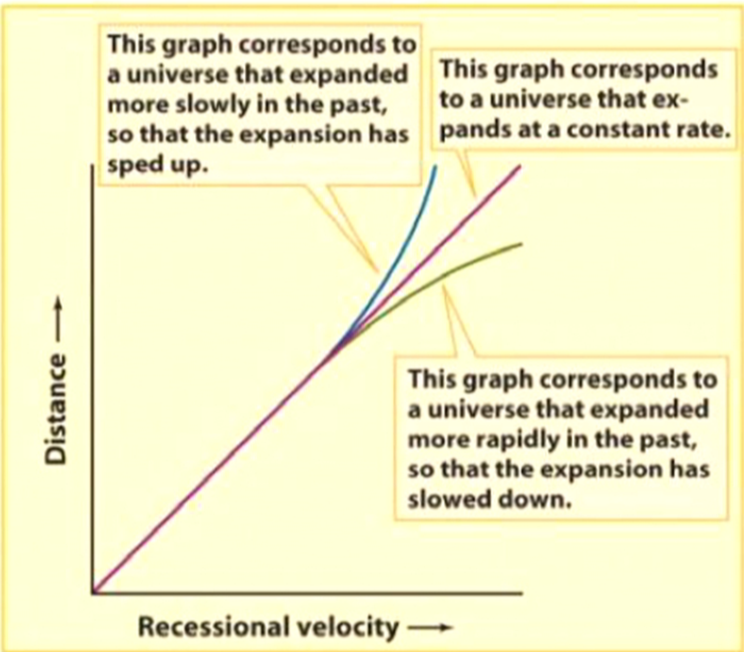
$\rho_c = 3H^2/8\pi G = 1.9 \times 10^{-29}\, h^2$ g cm^{-3}

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

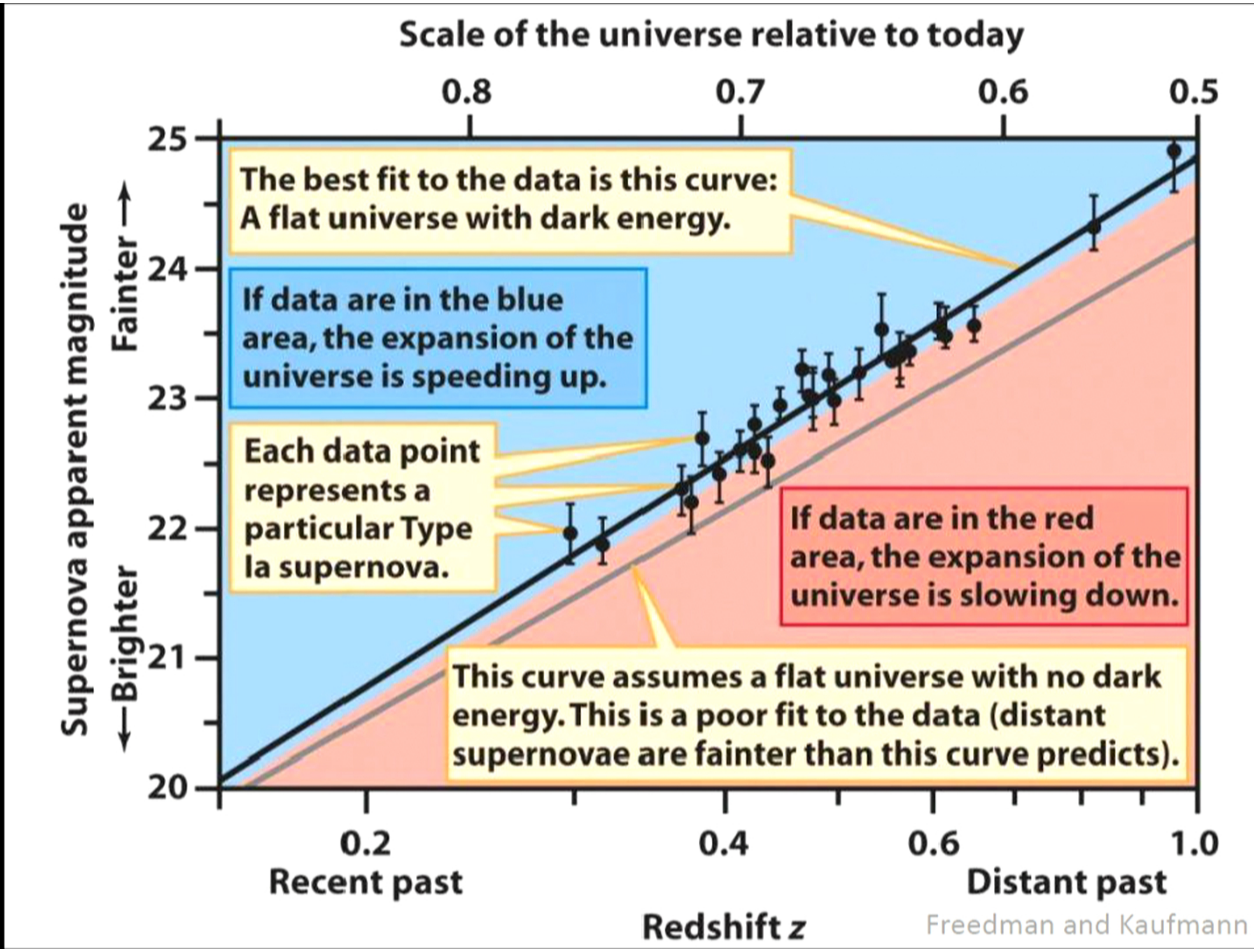
Dark Energy

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



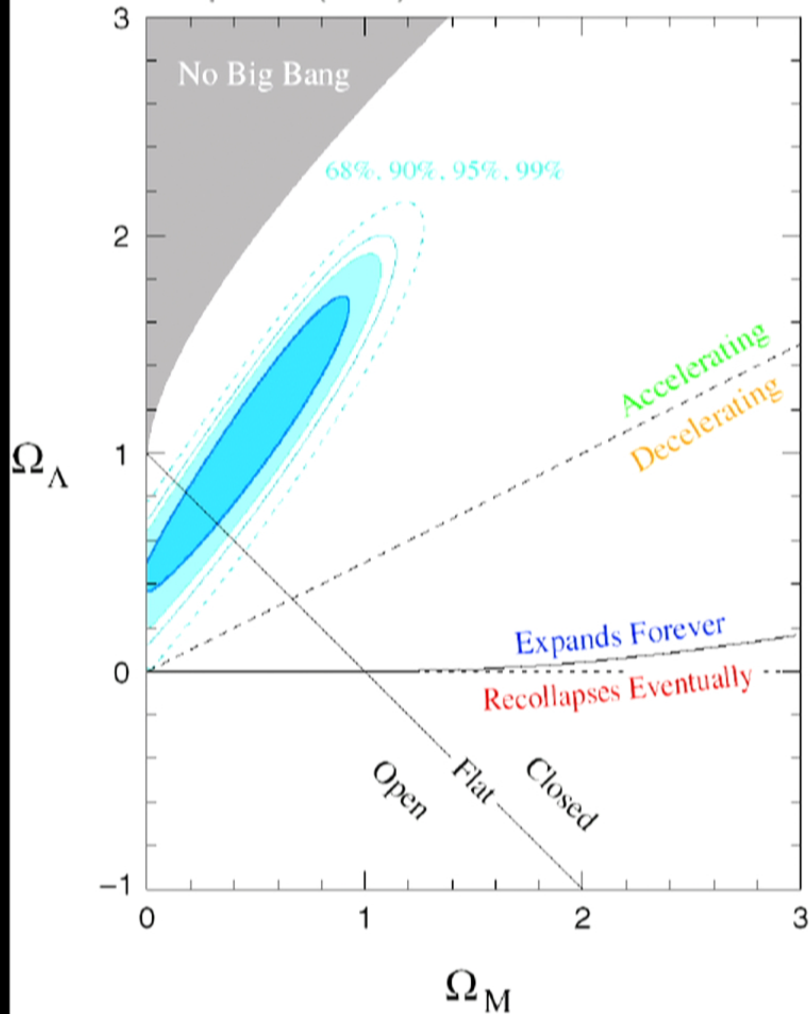


Freedman and Kaufmann



Scale of the universe relative to today
0.8
0.7
0.6
0.5
25
24
23
22
21
20
Supernova apparent magnitude
Fainter →
← Brighter
The best fit to the data is this curve: A flat universe with dark energy.
If data are in the blue area, the expansion of the universe is speeding up.
Each data point represents a particular Type Ia supernova.
If data are in the red area, the expansion of the universe is slowing down.
This curve assumes a flat universe with no dark energy. This is a poor fit to the data (distant supernovae are fainter than this curve predicts).
0.2
0.4
0.6
1.0
Recent past
Distant past
Redshift z
Freedman and Kaufmann

Supernova Cosmology Project
Knop et al. (2003)



accelerated expansion

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

$p \leq -\rho/3$

dark energy

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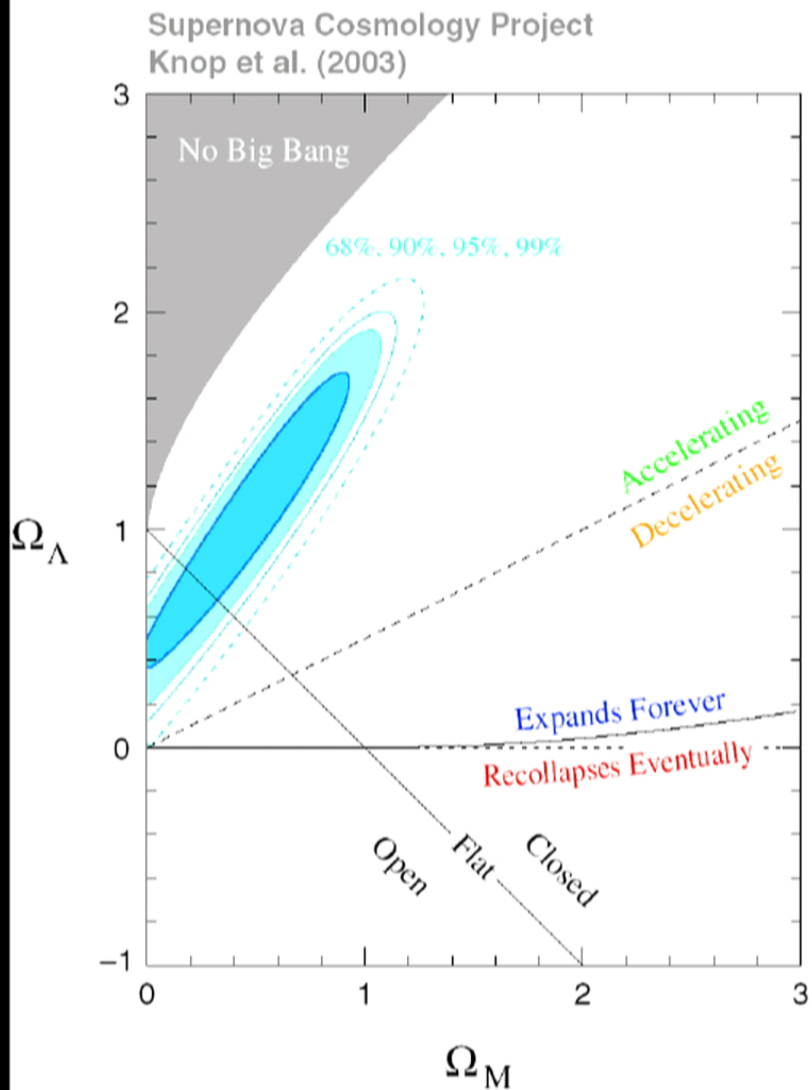

accelerated expansion

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

$p \leq -\rho/3$

dark energy

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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...

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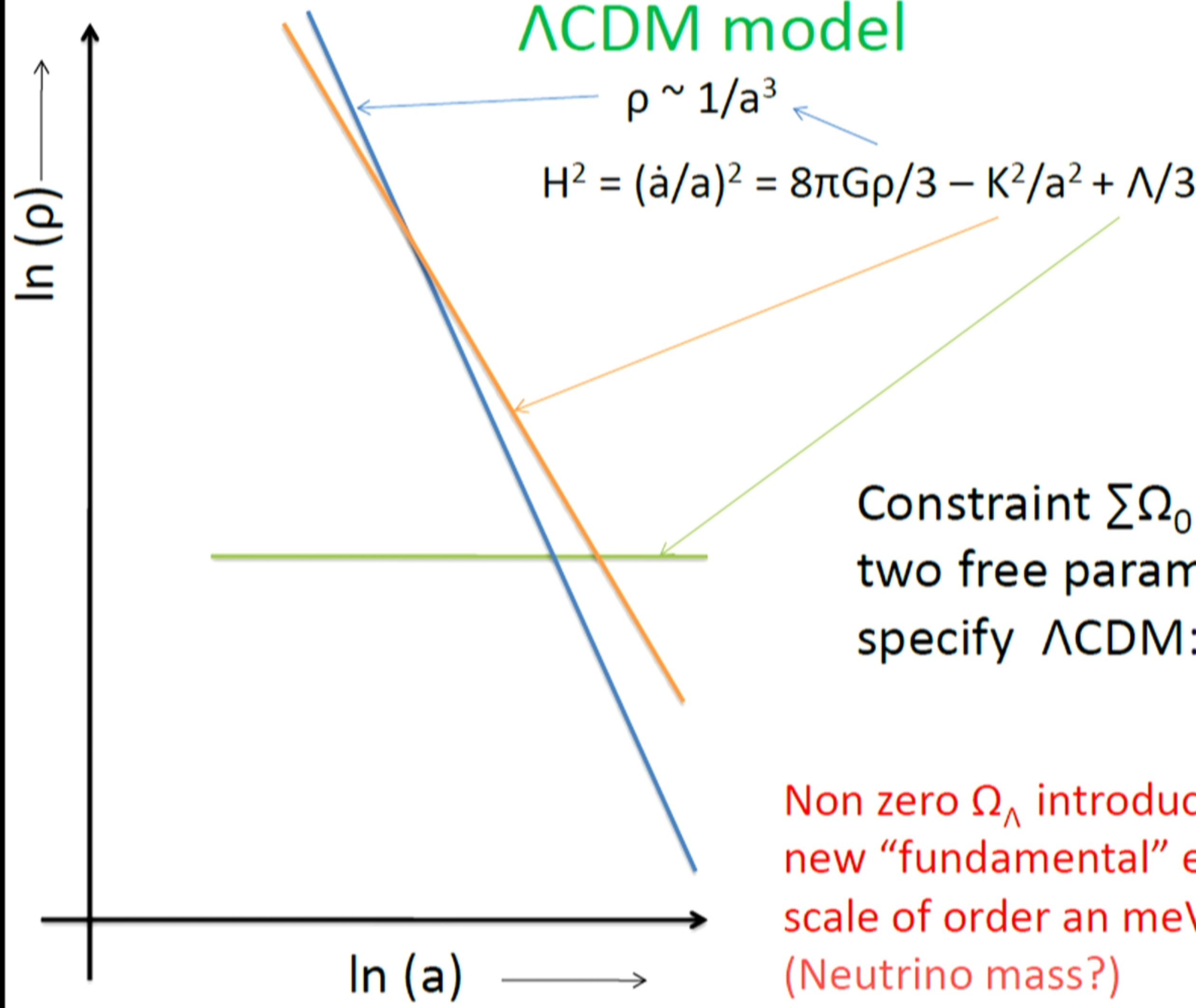
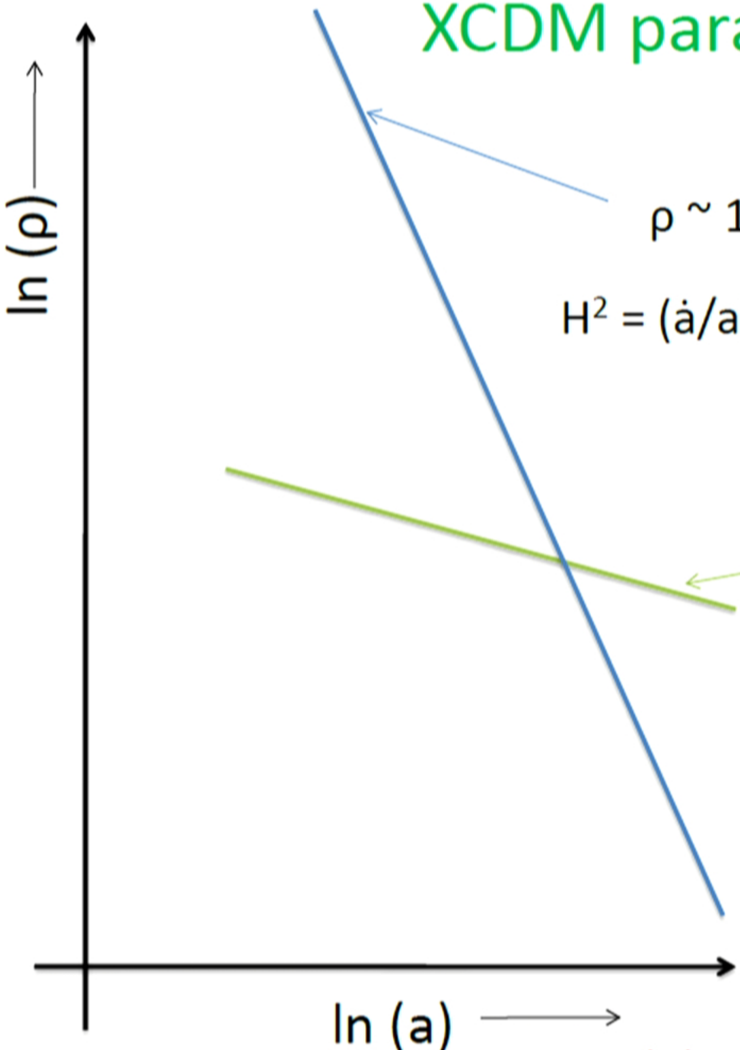
ΛCDM model



Constraint $\sum\Omega_0 = 1$, so two free parameters specify ΛCDM: Ω_{M0}, Ω_Λ

Non zero Ω_Λ introduces a new "fundamental" energy scale of order an meV. (Neutrino mass?)

XCDM parameterization



$\rho \sim 1/a^3$

$p_X = \omega_X \rho_X$

Spatially flat
$K^2 = 0$

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

$\omega_X < -1/3$

$\rho_X \sim 1/a^{3(1+\omega_X)}$

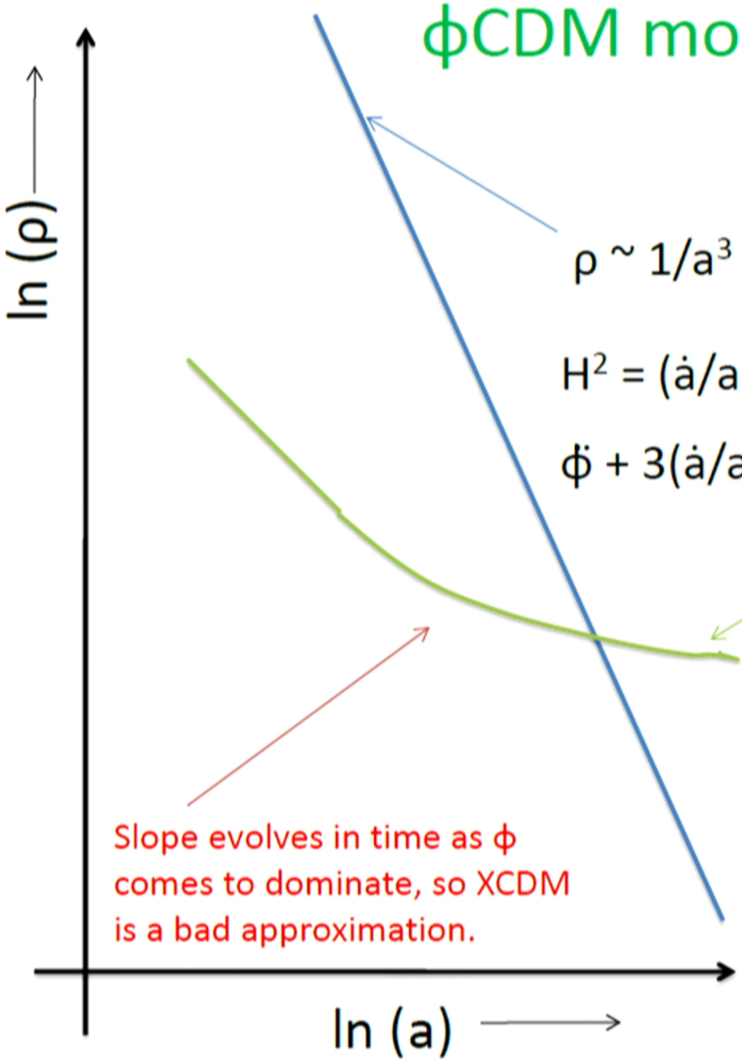
Spatially flat, $K^2 = 0$, but now dark energy evolves in time so again two free parameters specify XCDM parameterization: Ω_{M0}, ω_X

Widely used parameterization is incomplete.

ϕCDM 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 ϕCDM: Ω_{M0}, α

ϕCDM model is special for some V(ϕ): the ϕ solution is an attractor, ρ_ϕ decreases less rapidly than ρ_M and comes to dominate. This helps to partially resolve the coincidence problem and makes Λ small because the universe is old.

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

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: $1+z = \lambda_{obs}/\lambda_{em} = a(t_0)/a(t)$

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

(Einstein-Friedmann equation for ΛCDM model)

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

E.g., Hubble parameter vs. redshift:

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

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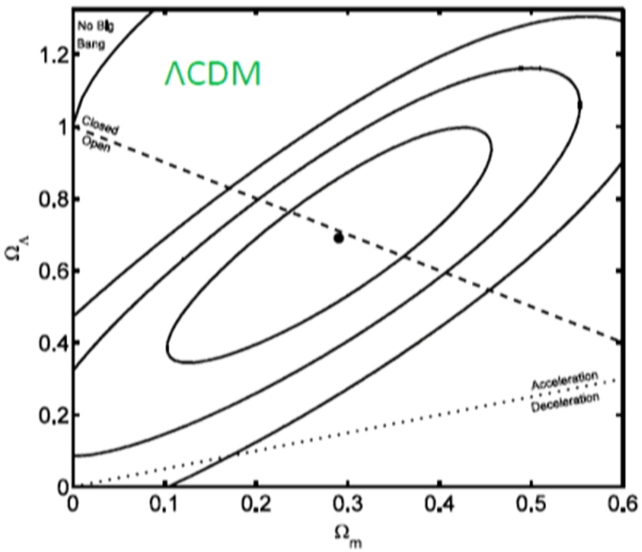
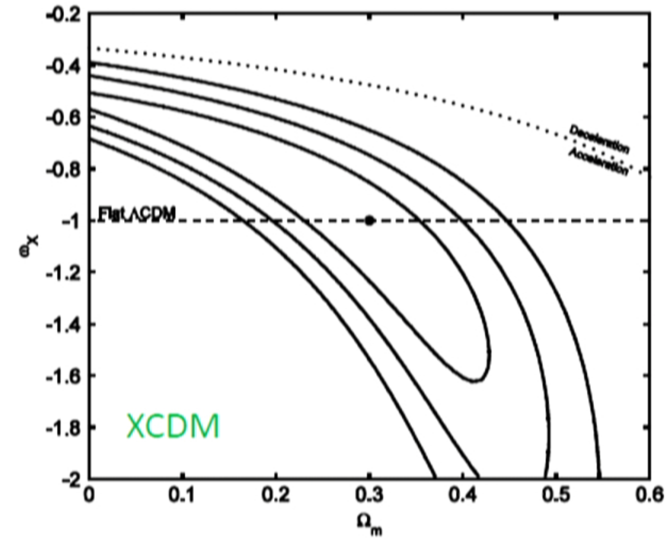
Use such model-parameter-dependent predictions and observational data on these quantities and a technique such as least squares or maximum likelihood to constrain the cosmological parameters of these models.

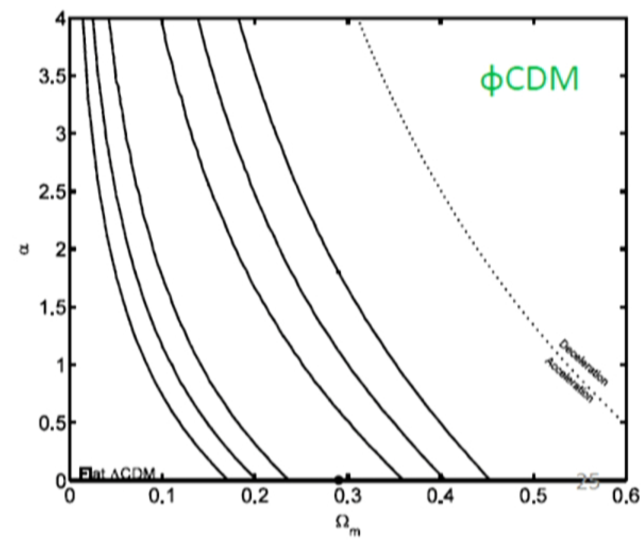
For nice reviews see the Ph.D. theses of Samushia 0908.4597 and Farooq 1309.3710.



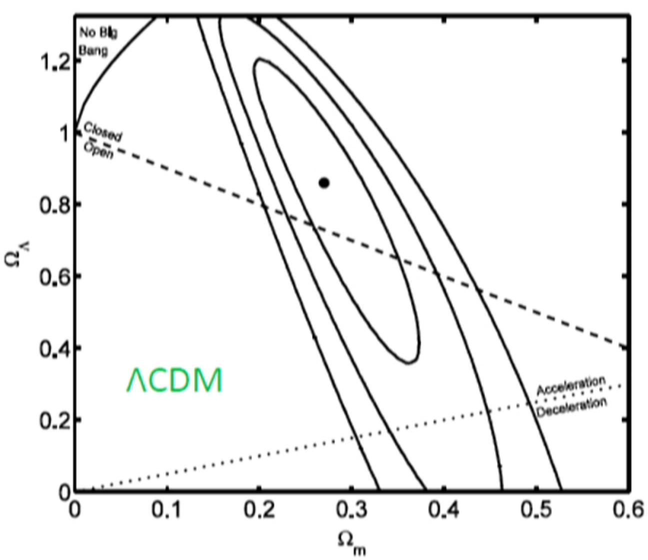


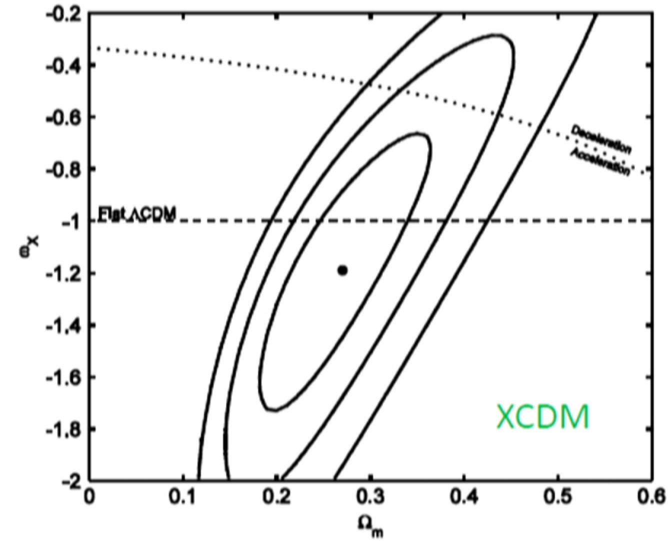
Type Ia SN magnitude-redshift test.
Union2.1, with systematic errors.

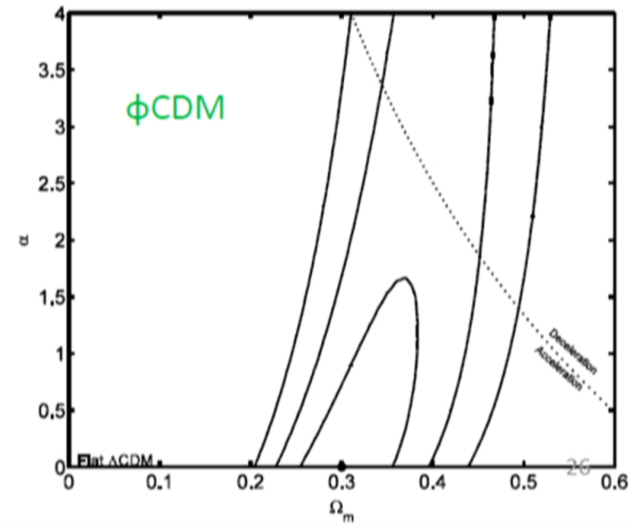
Suzuki et al. ApJ746, 85 (2012) 580 SNe.
Marginalize over h with flat prior.



Farooq et al ApJ764,139 (2013)







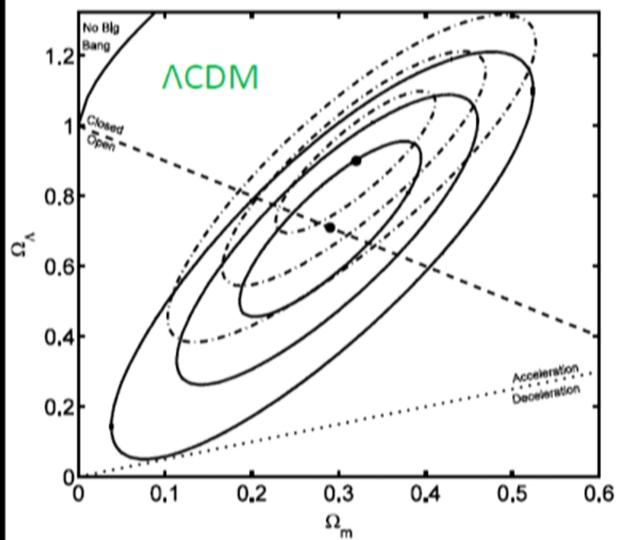
Baryon acoustic peak test.

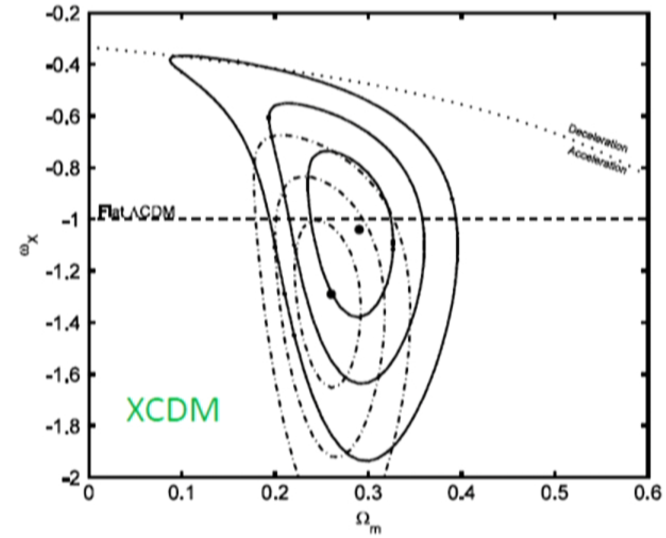
3 WiggleZ Blake et al MNRAS418, 1707 (2011)

1 6dFGS Beutler et al MNRAS416, 3017 (2011)

2 SDSS Percival et al MNRAS410, 2148 (2010)

Farooq et al ApJ764,139 (2013)





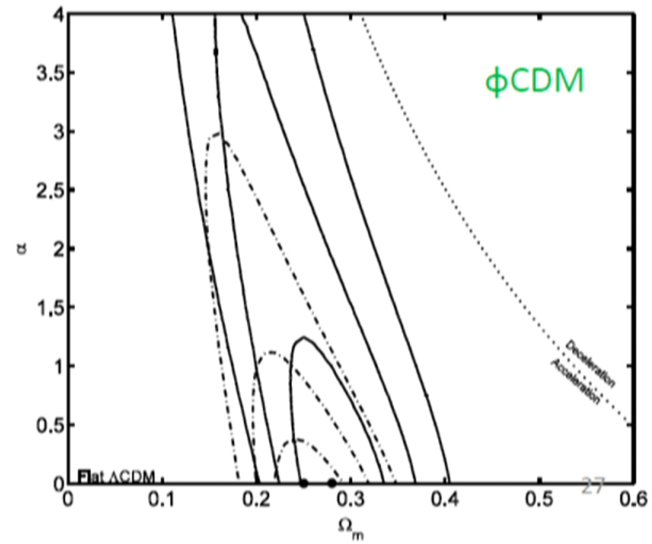
Hubble parameter vs. redshift test.

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

Marginalize over:

1) h = 0.68 +/- 0.028 solid lines

2) h = 0.738 +/- 0.024 dash-dotted lines



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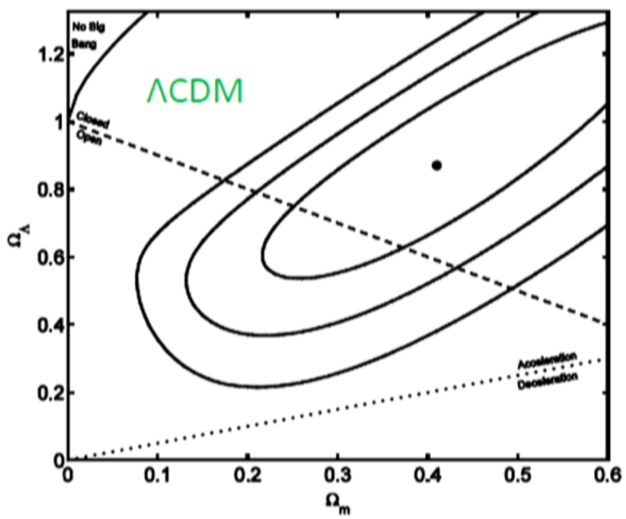
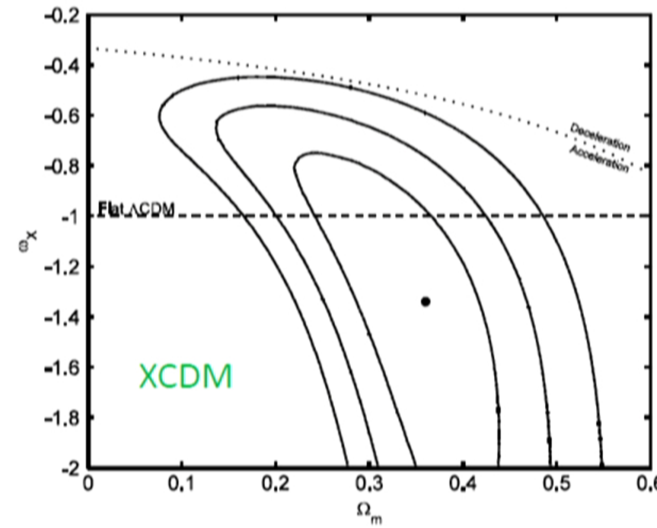
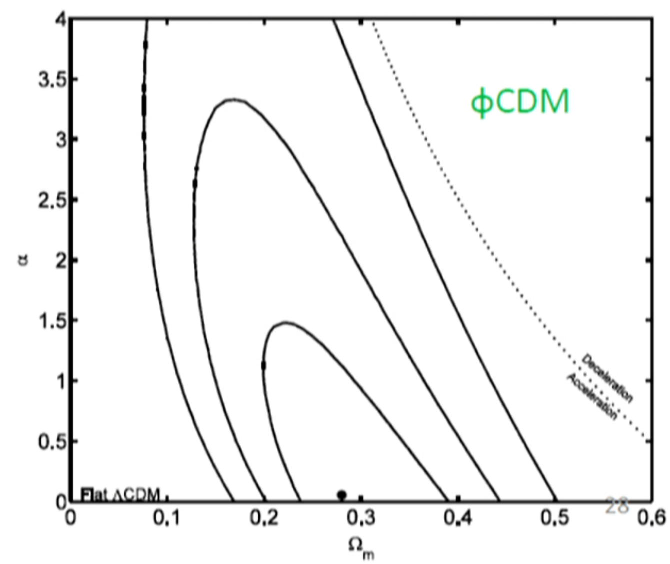




Growth rate vs. redshift test.

Pavlov et al PRD90, 023006 (2014)

14 measurements



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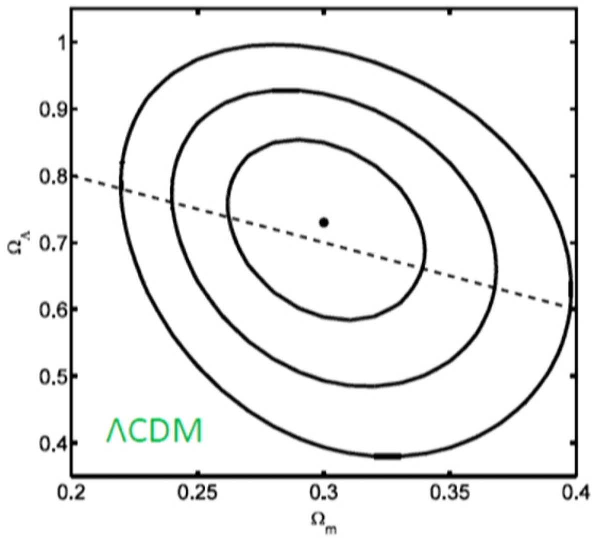
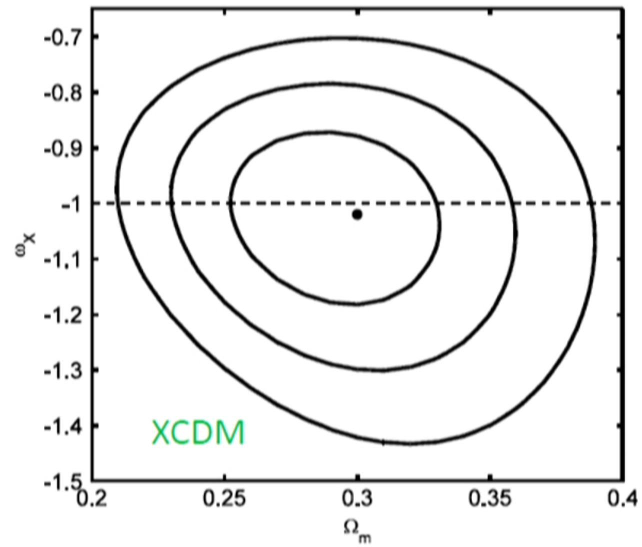
Constraints from different data are not inconsistent.

Individual data sets are consistent with a spatially-flat ΛCDM model with Ω_Λ of order 0.7 and Ω_{matter} of order 0.3, but do not yet rule out time-evolving dark energy.

What about combinations of data sets?

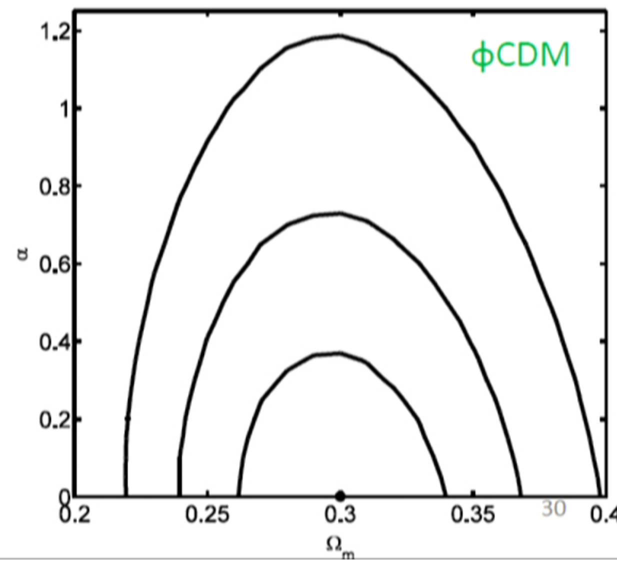
Two data sets at a time, except for growth + Hubble parameter, since there is some correlation.

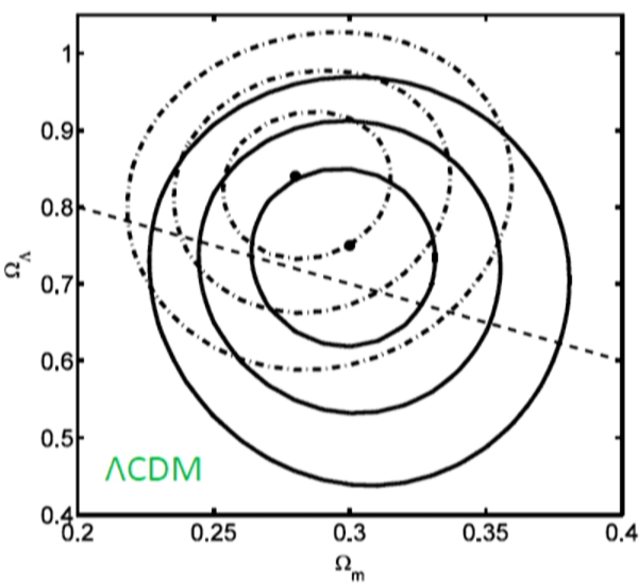


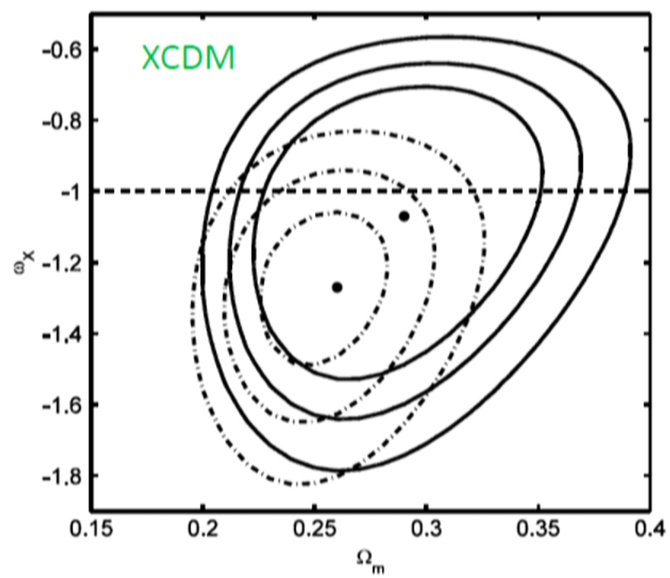


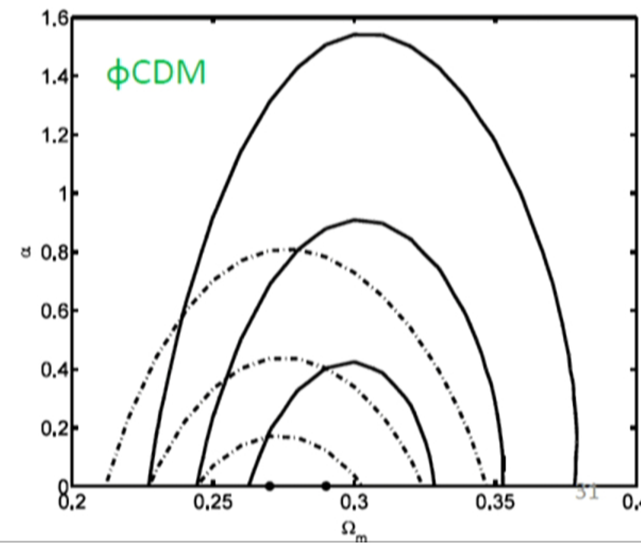
Supernovae and BAO.

A. Pavlov







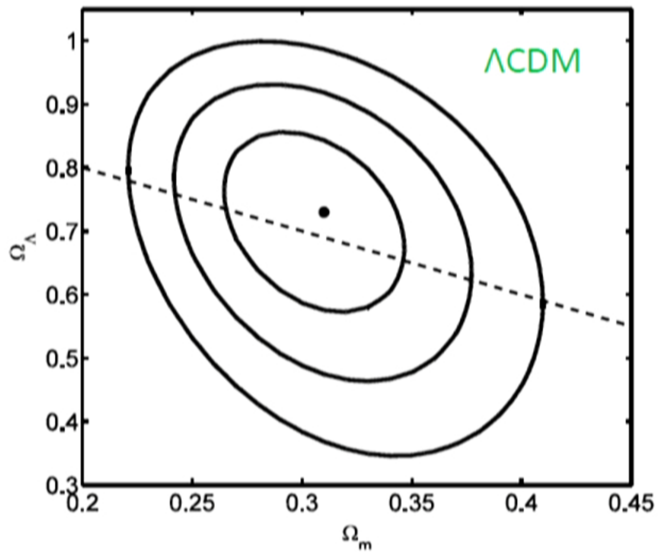


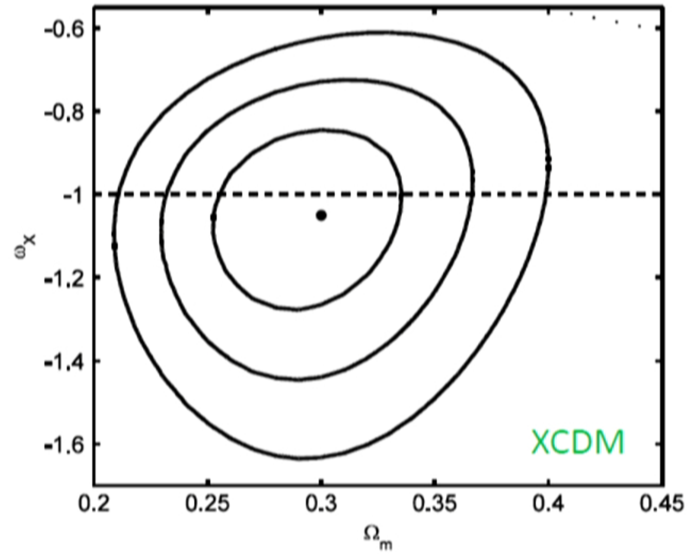
Hubble parameter and BAO.

Marginalize over:

1) h = 0.68 +/- 0.028 solid lines
2) h = 0.738 +/- 0.024 dash-dotted lines

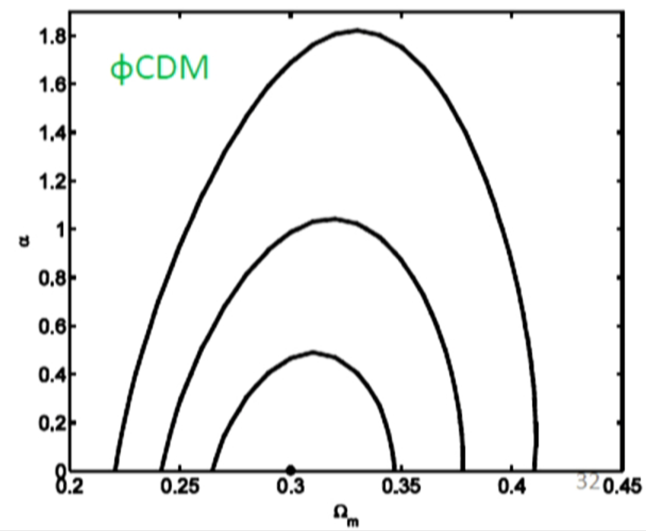
A. Pavlov





BAO and growth factor.

A. Pavlov



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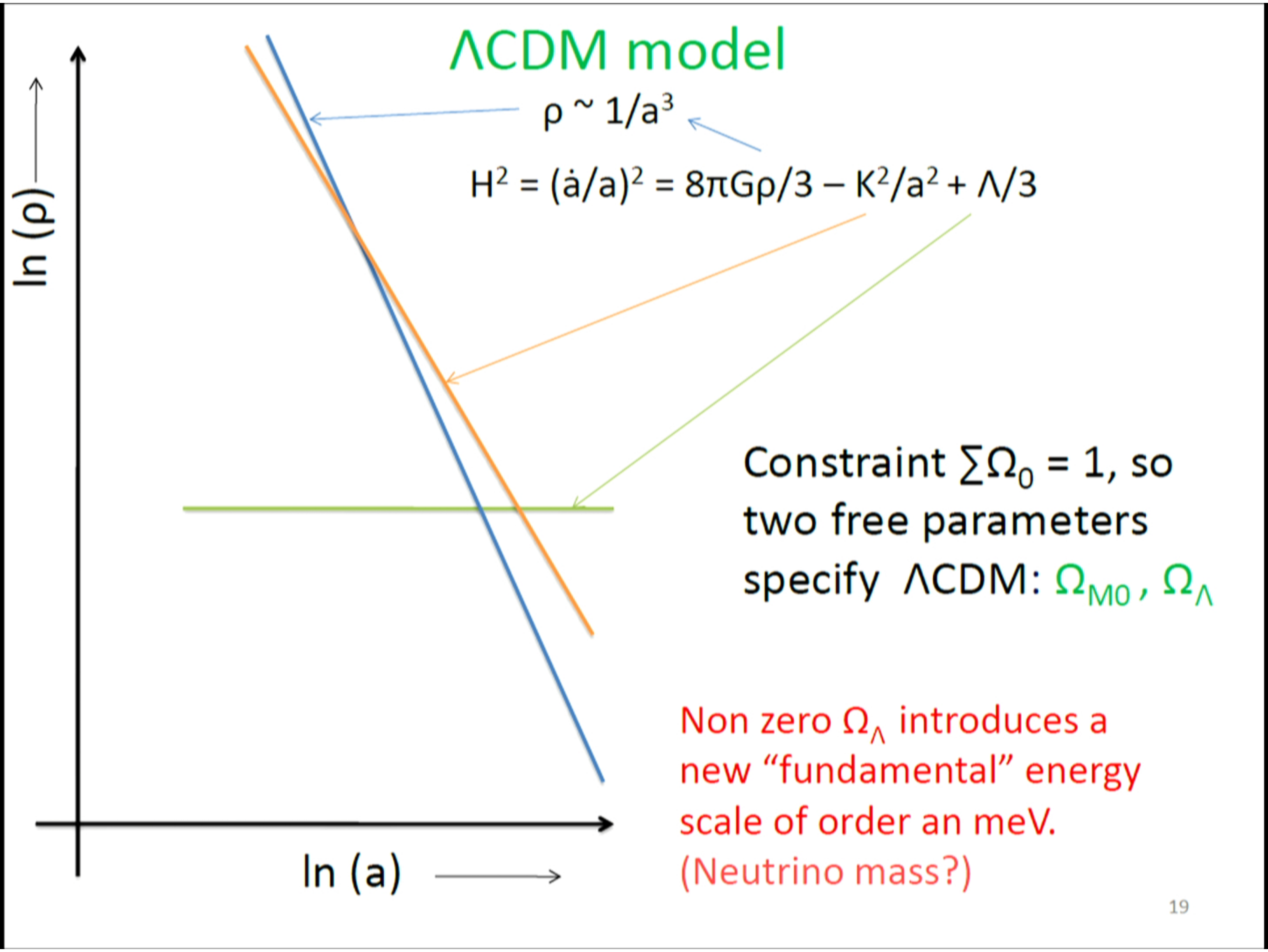
Data sets combined two at a time result in tighter constraints which are consistent with a spatially-flat ΛCDM model with Ω_Λ of order 0.7 and Ω_{matter} of order 0.3, but do not yet strongly rule out time-evolving dark energy.

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.


ΛCDM model
ρ ~ 1/a³
H² = (ȧ/a)² = 8πGρ/3 – K²/a² + Λ/3
ln (ρ)
ln (a)
Constraint ∑Ω₀ = 1, so two free parameters specify ΛCDM: Ω_M0 , Ω_Λ
Non zero Ω_Λ introduces a new "fundamental" energy scale of order an meV.
(Neutrino mass?)
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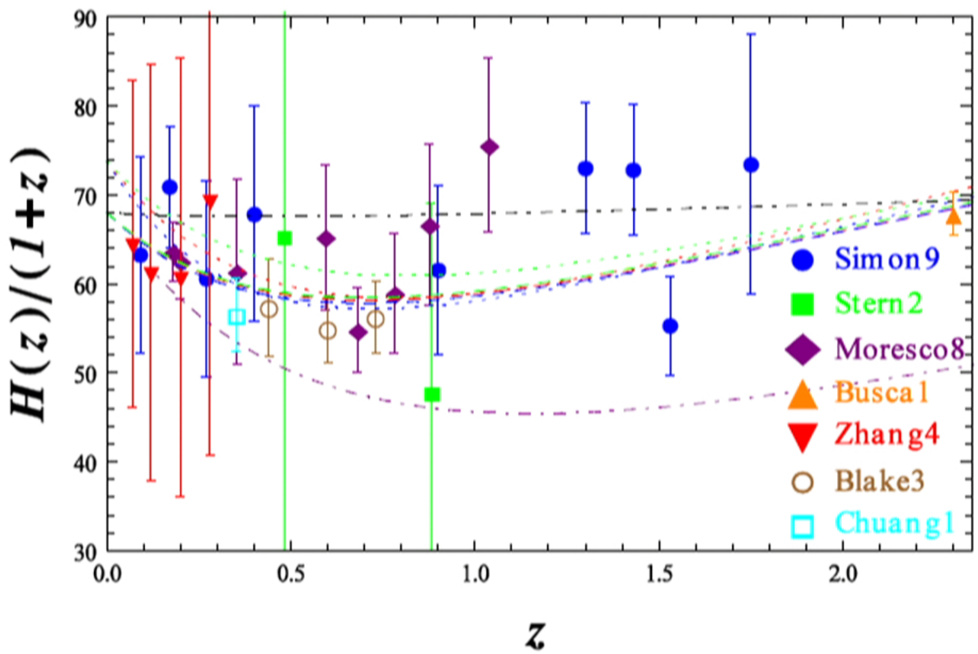
H(z) data & deceleration-acceleration transition

It is now possible to measure H(z) by using cosmic chronometers or radial BAO data (e.g., Moresco JCAP1208, 006; Busca 1211.2616)

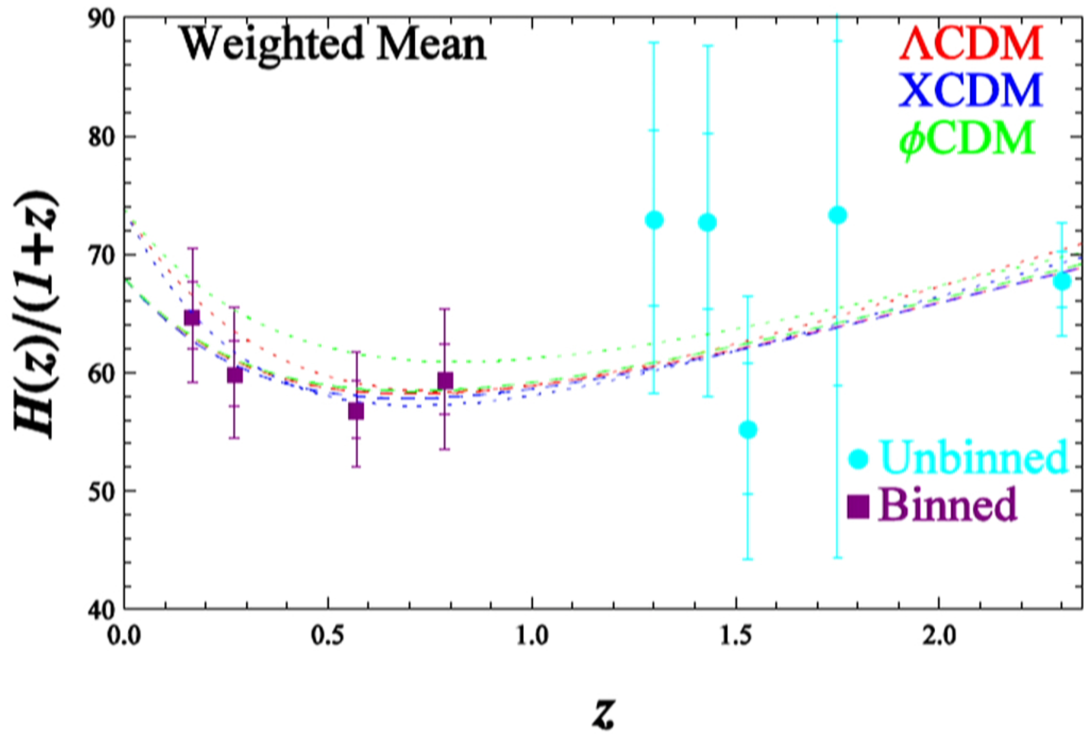
Combining 28 independent measurements over $0.07 < z < 2.3$

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



Six best-fit models and two 3σ deviant models

Data are noisy, so lets bin them



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

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.)

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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 ΛCDM, but NOT IF the dark energy density varies in time as in the XCDM parameterization and or the φCDM 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 φCDM.

Open Questions, Missing Links

B.R. & M. Vogeley, 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 ΛCDM?

Are the largest observed structures a problem for flat ΛCDM?

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)