Dark Energy

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Overview

- LCDM and its problems
- possible explanations
- evolving dark energy and constraints on w
- short look at supernova data
- modified gravity
- general parametrisation up to first order in perturbation theory
- outlook

What's in the Universe?

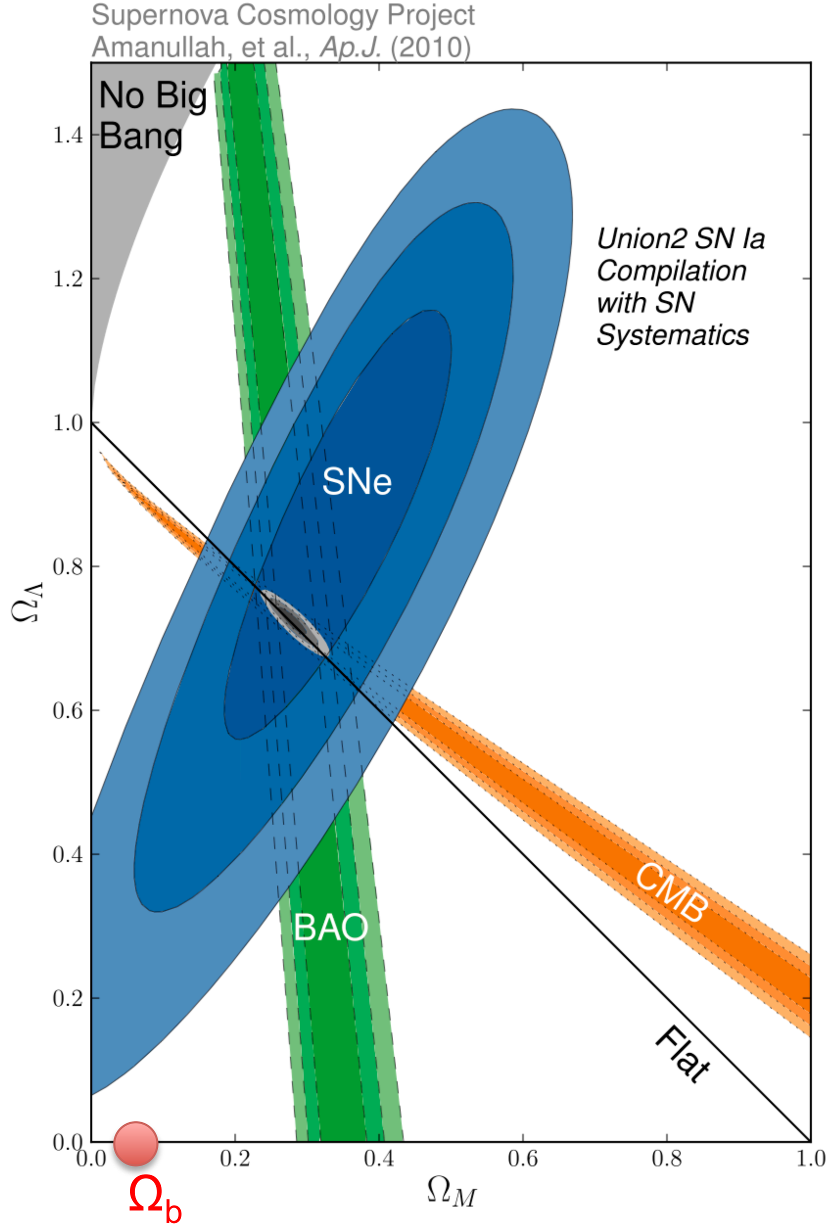
Innocent exercise:
take FLRW metric with cosmological constant and constrain contents of Universe

Naïve expectation:
$\Omega_r << 1$, $\Omega_m = \Omega_b \sim 0.05$, $\Omega_\Lambda = 0$

Result:
$\Omega_r << 1$, $\Omega_m \sim 0.25$ ($\Omega_b \sim 0.05$), $\Omega_\Lambda \sim 0.75$

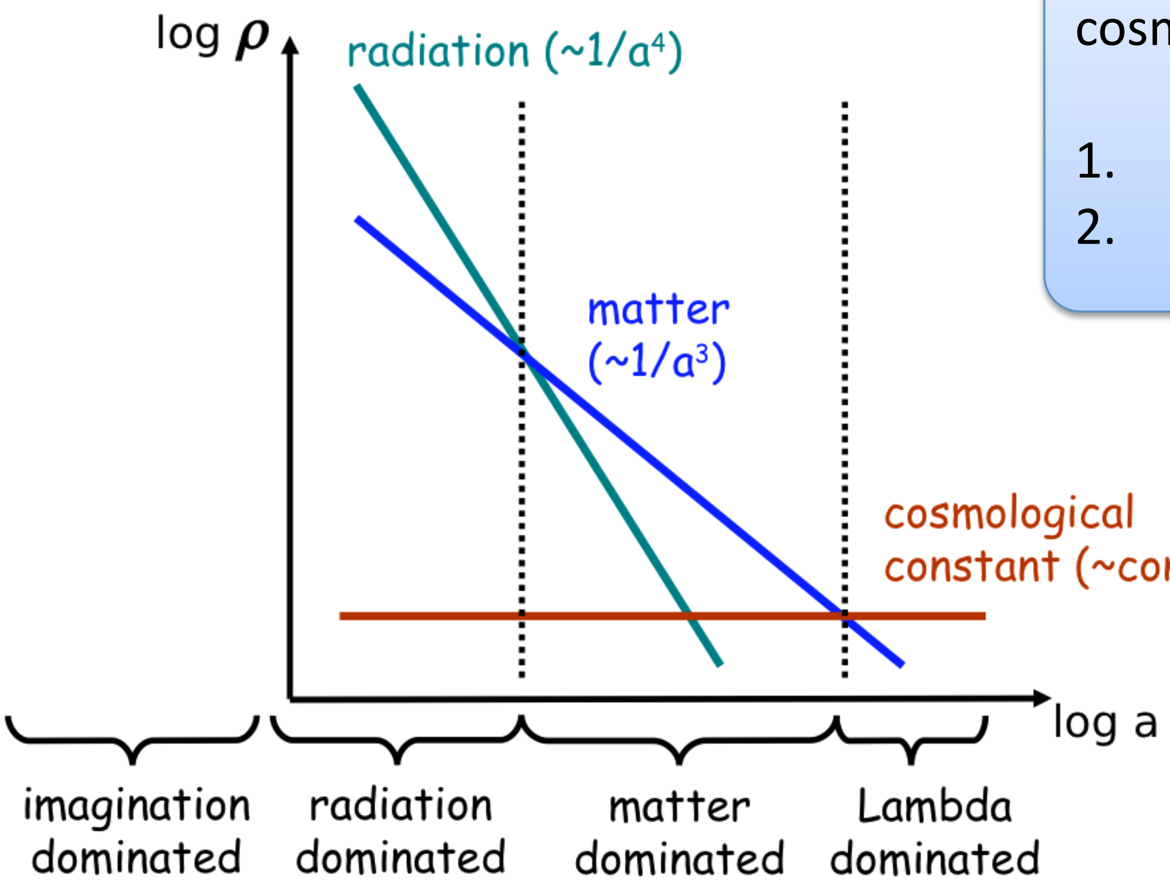
Oops.

But is it really a problem?
• matter: could be lightest SUSY particle, playing role of WIMP dark matter
• cosmological constant: could be a cosmological constant…



What's the problem with Λ?

Evolution of the Universe:



Classical problems of the cosmological constant:

1. Value: why so small?
2. Coincidence: Why now?

Naïve value of Λ

Free field ~ harmonic oscillator everywhere in space

$$\rho_{\rm vac} = \sum_x \hbar \frac{\omega}{2} \rightarrow \frac{\hbar}{4\pi^2} \int_{k_{\rm min}}^{k_{\rm max}} dk k^2 \sqrt{k^2 + m^2} \propto k_{\rm max}^4$$

cut-off at Planck scale: ρ_{vac} ~ $\boxed{10^{74}}$ $(\mathrm{GeV})^4$

SUSY cancels vacuum energy when unbroken:
cut-off at SUSY breaking: ρ_{vac} ~ $(\mathrm{TeV})^4$

experimental value:

$$\rho_\Lambda = \Omega_\Lambda \rho_c = \Omega_\Lambda \frac{3H_0^2}{8\pi G} \approx \Omega_\Lambda h^2 10^{-5} \mathrm{GeV/cm}^3 \approx \Omega_\Lambda h^2 \boxed{10^{-46}} (\mathrm{GeV})^4$$

Possible explanations

1. The (supernova) data is wrong
2. It is a cosmological constant, and there is no problem (‘anthropic principle’, ‘string landscape’)
3. We are making a mistake with GR (aka ‘backreaction’) or the Copernican principle is violated (‘LTB’)
4. It is something evolving, e.g. a scalar field (‘dark energy’)
5. GR is wrong and needs to be modified (‘modified gravity’)

1. Data wrong?

Difficult to get to work:

1. CMB needs h~0.3 to allow $\Lambda=0$ (and then the universe is not flat) vs HKP: $H_0 = 72\pm8$ km/s/Mpc
2. If $\Omega_m \sim 1$, $\Omega_\Lambda = 0$, the age of the Universe is

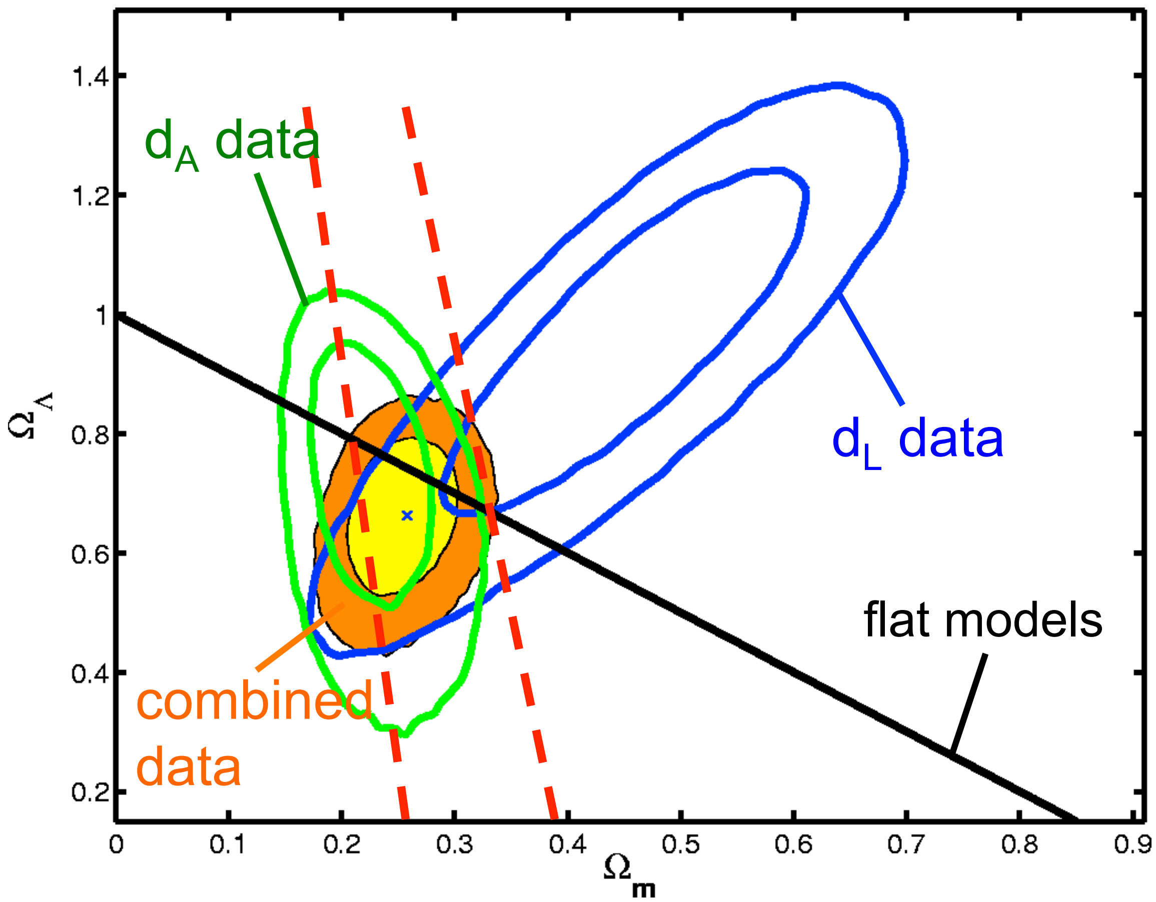
   $$t_0 = \int_0^t dt = \int_0^1 \frac{da}{aH} \rightarrow^{\Omega_m=1} = \frac{2}{3H_0} \approx 6.5h^{-1}\mathrm{Gyr}$$

   Oldest stars ~ 11 Gyr
3. ISW effect is absent in matter-dominated universe since ϕ=const.
4. Other data also problematic
   - shape of P(k)
   - cluster counts
5. Other distance data:

Distance Duality

The relation $d_L = (1+z)^2 \, d_A$ is very general and holds in all metric theories

=> we can check the supernova data with angular diameter distance data!



- constrain photon loss, grey dust, etc
- very different systematics

-> no evidence of SN-Ia results being wrong!

(yes, there is newer data)

2. anthropic principle

$$P(\Lambda | \text{we exist}) \sim P(\text{we exist} | \Lambda)\, P(\Lambda)$$

example: why is the Earth just the right distance from the sun that life can exist? Are we surprised about this?

Probably not: there are many solar systems, and planets are not especially unlikely to exist in the habitable zone.

- $P(\text{we exist}|\Lambda)$: maybe lower bound on age of Universe when Λ starts to dominate?
- $P(\Lambda)$: Does it have support for small Λ? We would need 'many Λ' for this to apply. Recent interest from 'string landscape' where many different vacuum states exist.

Overall, a bit unsatisfactory, but could be the answer…

3. LTB and Backreaction

Two large classes of models:

- Inhomogeneous cosmology: Copernican Principle is wrong, Universe is not homogeneous (and we live in a special place).
- Backreaction: GR is a nonlinear theory, so averaging is non-trivial. The evolution of the 'averaged' FLRW case may not be the same as the average of the true Universe.

Lemaitre-Tolman-Bondi

We live in the center of the world!

LTB metric: generalisation of FLRW to spherical symmetry, with new degrees of freedom

-> can choose a radial density profile, e.g. a huge void, to match one chosen quantity

☺ can mimic distance data (need to go out very far)

☺ demonstrates large effect from inhomogeneities

☹ unclear if all data can be mimicked (esp. ISW)

☹ mechanism to create such huge voids?

☹ fine-tuning to live in centre, ca $1:(1000)^3$ iirc

testing the geometry directly

Is it possible to test the geometry directly?

Yes! Clarkson et al (2008) -> in FLRW (integrate along ds=0):

$$H_0 D(z) = \frac{1}{\sqrt{-\Omega_k}} \sin\left(\sqrt{-\Omega_k}\int_0^z \frac{H_0}{H(u)} du\right)$$

$$\Rightarrow H_0 D'(z) = \frac{H_0}{H(z)} \cos\left(\sqrt{-\Omega_k}\int_0^z \frac{H_0}{H(u)} du\right)$$

$$\to \left(HD'\right)^2 - 1 = \sin^2(\cdots) = -\Omega_k \left(H_0 D\right)^2$$

It is possible to reconstruct the curvature by comparing a distance measurement (which depends on the geometry) with a radial measurement of H(z) without dependence on the geometry.

Backreaction

normal approach: separation into "background" and "perturbations"

$$g_{\mu\nu}(t,x) = \bar{g}_{\mu\nu}(t) + h_{\mu\nu}(t,x)$$

$$\rho(t,x) = \bar{\rho}(t) + \delta\rho(t,x)$$

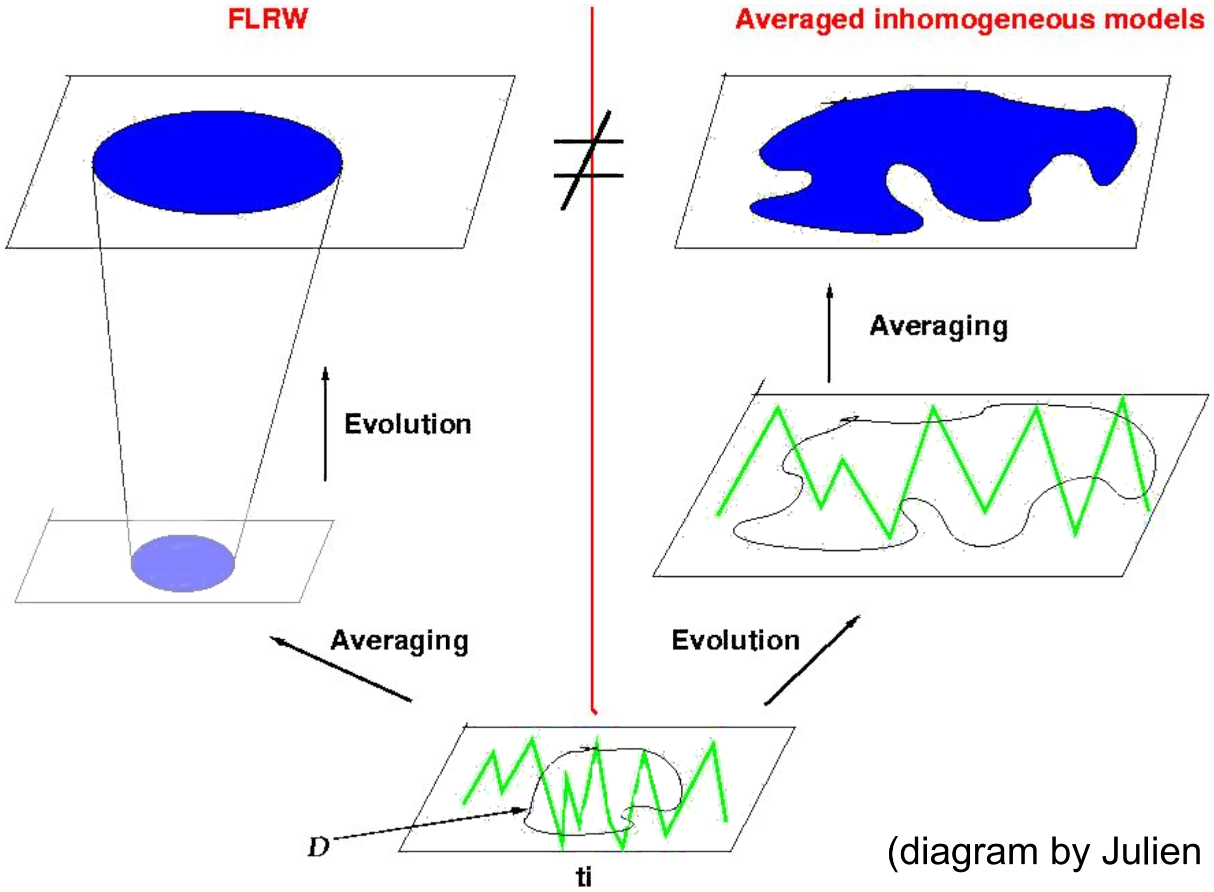
but which is the "correct" background, and why should it evolve as if it was a solution of Einsteins equations? The averaging required for the background does not commute with derivatives or quadratic expressions,

$$\partial_t \langle \phi \rangle \neq \langle \partial_t \phi \rangle \qquad \langle \theta^2 \rangle \neq \langle \theta \rangle^2$$

-> can derive set of averaged equations, taking into account that some operations not not commute: "Buchert equations"

average and evolution

the average of the evolved universe is in general not the evolution of the averaged universe!



(diagram by Julien Larena)

Buchert equations

- Einstein eqs, irrotational dust, 3+1 split (as defined by freely-falling observers)
- averaging over spatial domain D
- $a_D \sim V_D^{1/3}$ [<-> enforce isotropic & homogen. coord. sys.]
- set of effective, averaged, local eqs.:

$$\frac{\dot{a}_D}{a_D} = \frac{8\pi G}{3}\langle\rho\rangle_D - \frac{1}{6}\left(\mathscr{Q} + \langle\mathscr{R}\rangle_D\right) \quad 3\frac{\ddot{a}_D}{a_D} = -4\pi G\langle\rho\rangle_D + \mathscr{Q}$$

$$\mathscr{Q} = \frac{2}{3}\left\langle(\theta - \langle\theta\rangle_D)^2\right\rangle_D - \langle\sigma_{ij}\sigma^{ij}\rangle_D$$

if this is positive then
it looks like dark energy!

(θ expansion rate, σ shear, from expansion tensor Θ)

- looks like Friedmann eqs., but with extra contribution!
- $<\rho> \sim a^{-3}$

Backreaction

- ☺ is certainly present at some level
- ☺ could possibly explain (apparent) acceleration without dark energy or modifications of gravity
- ☺ then also solves coincidence problem

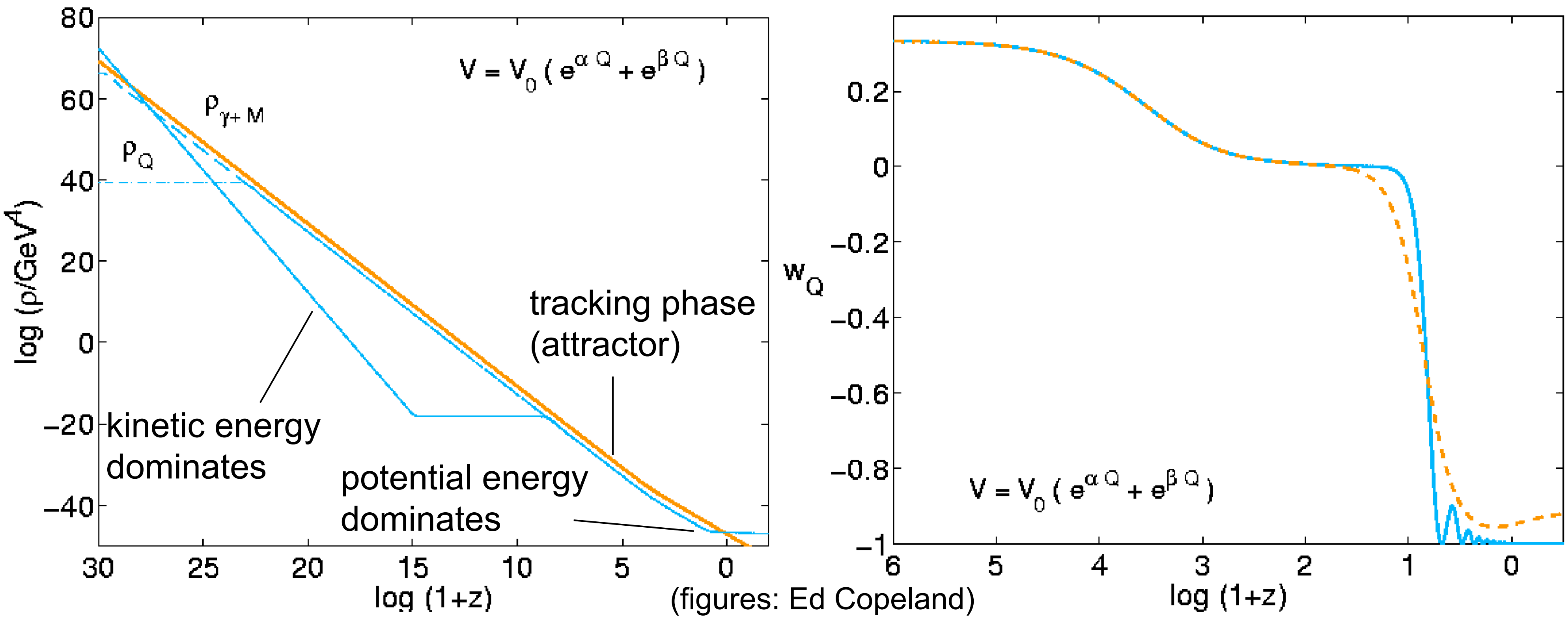
- ☹ amplitude unknown (too small? [*])
- ☹ scaling unknown (shear vs variance of expansion)
- ☹ link with observations difficult

[*] Poisson eq: $-\left(\frac{k}{Ha}\right)^2 \phi = \frac{3}{2}\delta$ (k = aH : horizon size)

=> Φ never becomes large, only δ ! (but this is not a sufficient argument)

4. evolving dark energy

- Inflation: accelerated expansion with help of scalar field
- If w=p/ρ can change, then initial dark energy density can be much higher -> solves one problem of Λ
- extra bonus: tracking behaviour



(figures: Ed Copeland)

quick reminder on actions, etc

GR + scalar field: $$S = S_g + S_\phi = \int d^4x\sqrt{-g}\left(\frac{R}{16\pi G} + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + V(\phi)\right)$$

gravity e.o.m. (Einstein eq.): $$\frac{\delta S[g_{\mu\nu},\phi]}{\delta g^{\mu\nu}} = 0 \qquad G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

entries in scalar field EM tensor (FLRW metric)

$$\left\{\begin{aligned} \rho_\phi &= \frac{1}{2}\dot{\phi}^2 + V(\phi) \\ p_\phi &= \frac{1}{2}\dot{\phi}^2 - V(\phi) \end{aligned}\right.$$

scalar field e.o.m. : $$\frac{\delta S[g_{\mu\nu},\phi]}{\delta \phi} = 0 \qquad \ddot{\phi} + 3H\dot{\phi} + dV(\phi)/d\phi = 0$$

- this is the general method to compute Einstein eq., EM tensor and field e.o.m. from any action
- w=p/ρ for scalar fields can vary, as a function of V(ϕ)

dynamical systems & tracking

Can write scalar field + ‘matter’ fluid as dynamical system

-> example for $V(\phi) \propto \exp(-\kappa\lambda\phi) \qquad (\kappa^2 = 8\pi G)$

use new variables & write Friedmann and field equations as

$$x = \frac{\kappa\dot{\phi}}{\sqrt{6}H} \quad y = \frac{\kappa\sqrt{V}}{\sqrt{3}H} \quad N = \ln a \qquad x^2 + y^2 + \frac{\kappa^2\rho_m}{3H^2} = 1$$

$$\frac{dx}{dN} = -3x + \frac{\sqrt{6}}{2}\lambda y^2 + \frac{3}{2}x\left[(1-w_m)x^2 + (1+w_m)(1-y^2)\right]$$

$$\frac{dy}{dN} = -\frac{\sqrt{6}}{2}\lambda xy + \frac{3}{2}y\left[(1-w_m)x^2 + (1+w_m)(1-y^2)\right]$$

fixed points (for details see e.g. hep-th/0603057)

1. {x=0,y=0} -> $\Omega_\phi=0$ (fluid dominated phase)
2. {x=+/-1,y=0} -> $\Omega_\phi=1$, $w_\phi=1$ (kinetic phase)
3. {x=1/sqrt(6),y=$[1-\lambda^2/6]^{1/2}$} -> $\Omega_\phi=1$, $1+w_\phi = \lambda^2/3$ (dark energy phase)
4. {…} -> $\Omega_\phi = 3(1+w_m)/\lambda^2$, $w_\phi = w_m$ (tracking phase)

Quintessential problems

- no solution to coincidence problem (need to e.g. put a bump into the potential at the right place)
- potential needs to be very flat
- need to avoid corrections to potential
- need to avoid couplings to baryons
- no obvious candidates for scalar field

- but nonetheless the ‘standard evolving dark energy model’

(there are many other scalar field models)

observational interlude

No obvious scalar field candidates

-> we can ask reverse question: what model do we need to agree with data?

-> relationship $V(\phi(t))$ <-> $w(t)$ <-> $H(t)$

-> we can always reconstruct a potential that would give us a certain $w(z)$! Actually, we don't even need to do this explicitly, as we can directly compute the behaviour of the perturbations (later)

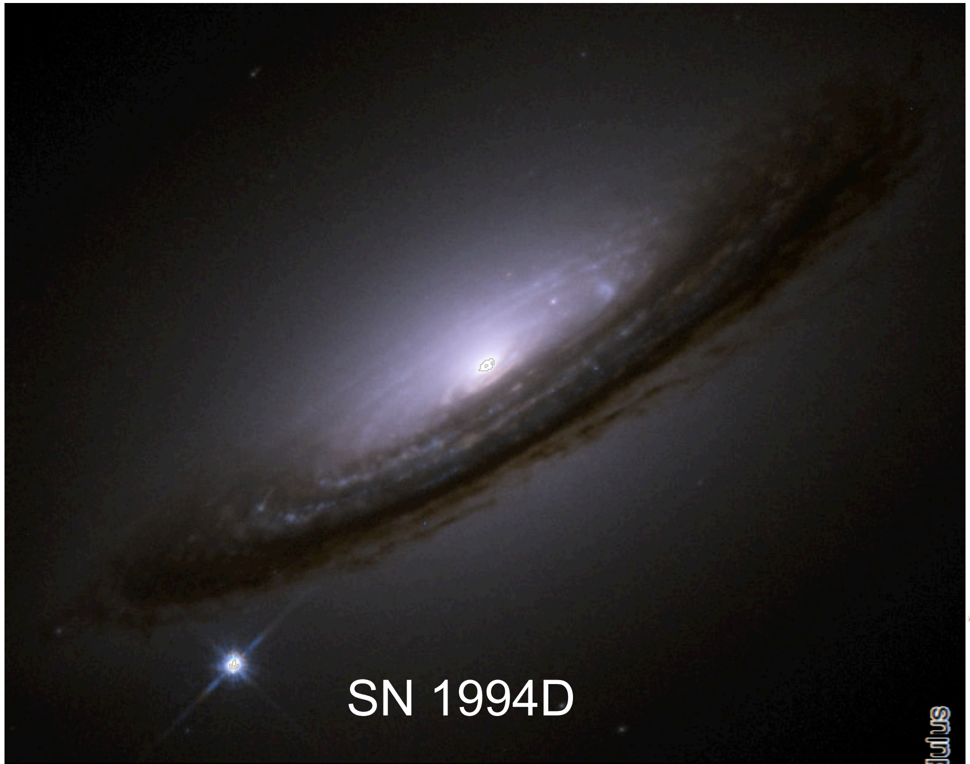
-> 'MCMC' method: pick a $w(z)$, compute observables, compare to data (does it fit?), repeat

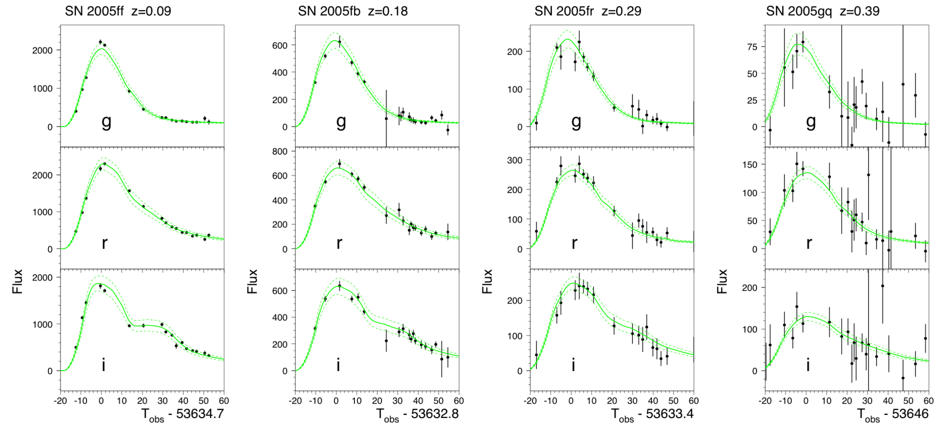
overview of cosmological data

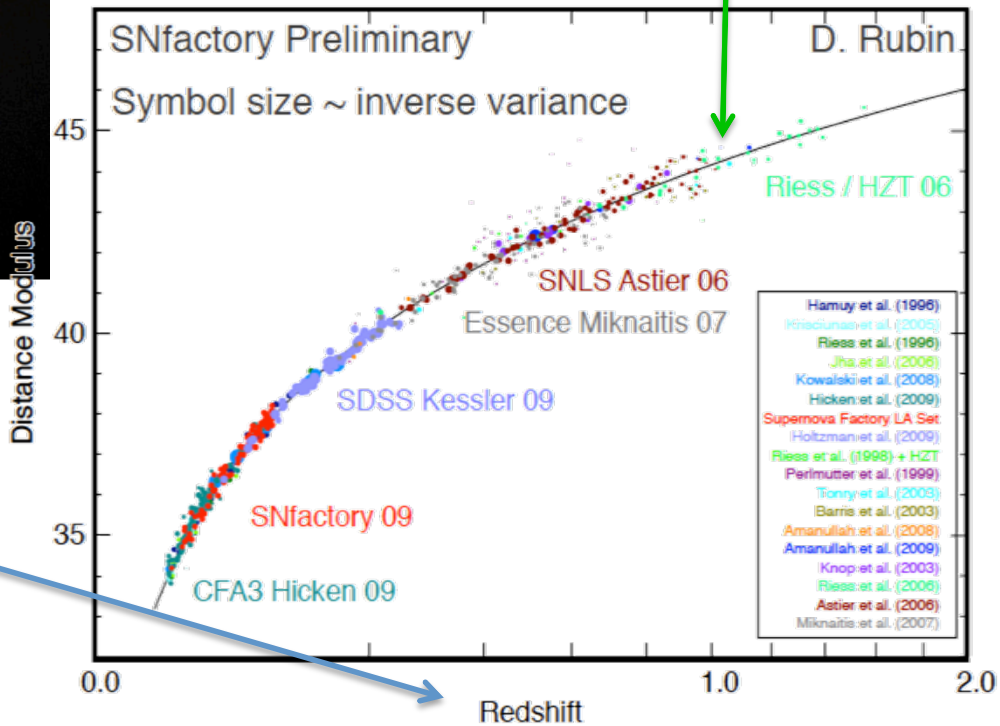
- distances (‘pure background’)
  - CMB peak locations: ~ angular diameter distance
  - supernovae: luminosity distance
  - Baryonic Acoustic Oscillations: angular diameter distance, H
  - change in redshift of distant objects: H
- perturbations:
  - full CMB spectrum (acoustic peaks, ISW)
  - full shape galaxy power spectrum P(k) [but: bias]
  - redshift space distortions & peculiar velocities
  - growth rate of matter perturbations [P(k,z)]
  - gravitational lensing
  - galaxy clusters
  - perturbations in background measurements

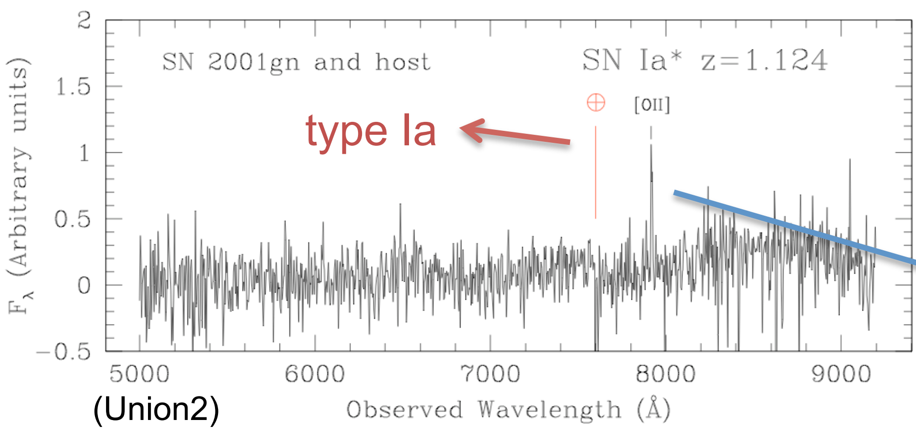
SN-Ia and luminosity distance

(SDSS)









(Union2)

supernova status / outlook

- used for cosmology since 1998 (SCP, High-z)
- today ca 1000 SN-Ia, $z \sim 0$ to 1.5
- need spectra and well-sampled lightcurves
- start to be dominated by systematics
  - calibration
  - understanding of survey (selection biases, etc)
  - light-curve fitter / templates [e.g. SDSS paper]
  - perturbations (e.g. peculiar velocities, lensing)
  - evolution with redshift / environment effects
- still: maybe best understood technique after CMB
- outlook: $O(10^4)$ SNe in a few years, $O(10^5)$ with LSST -> problems: spectra & systematics

luminosity-redshift diagram

spectra: redshift & type
light curves: different 'fitters'

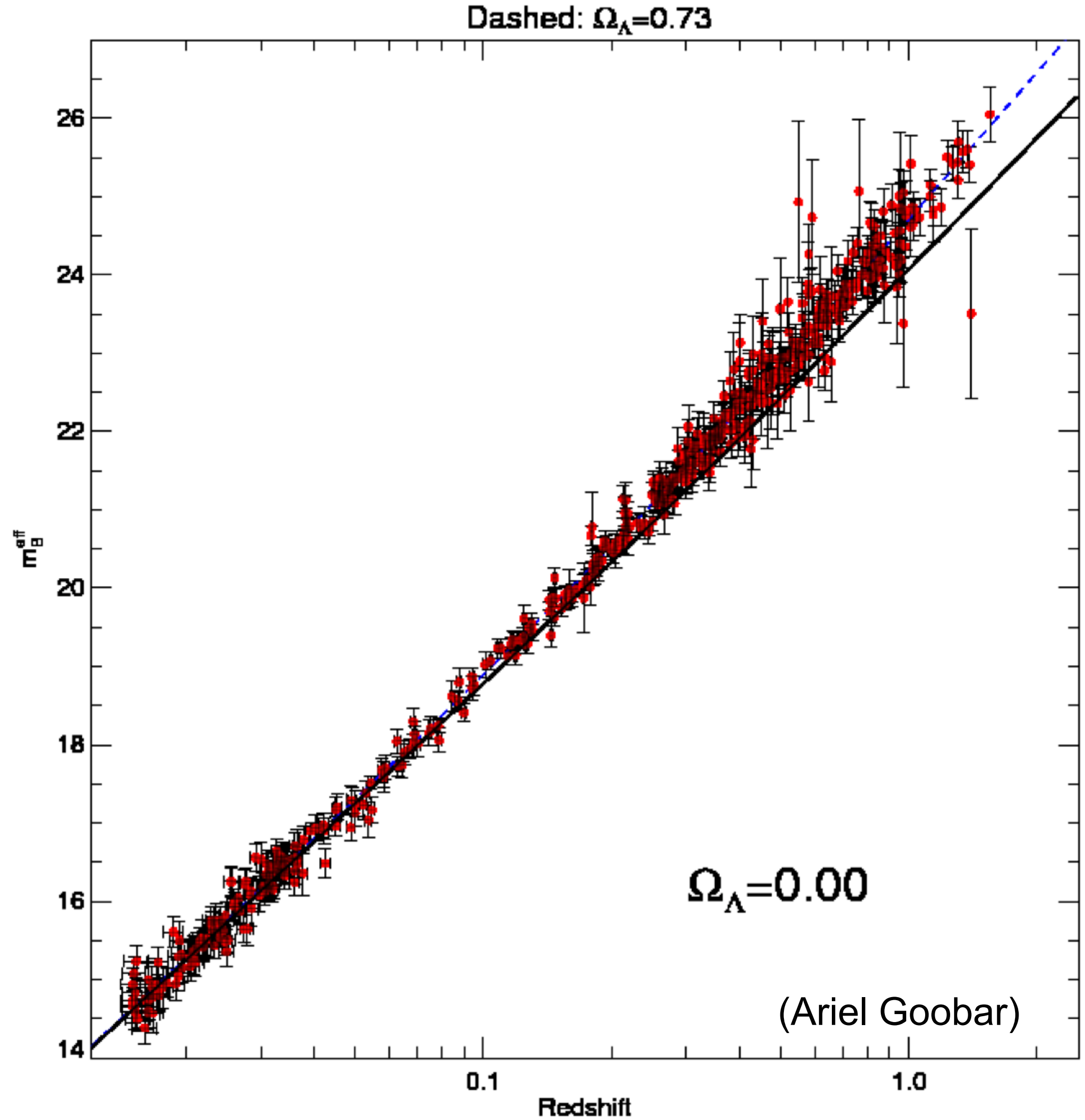
- SALT(2)
- MLCS2k2
- others

example: **SALT2**
-> SED templates F(time,λ)
returns 3 parameters:

1. m_B ~ -2.5 $\log_{10}$(flux at max)
2. x_1 ~ decline rate
3. c ~ colour variation

$$\mu_B = m_B + \alpha x_1 - \beta c - M_B$$

should fit α, β, M_B together with cosmology



constraining cosmology

Analysis then assumes Gaussian errors in μ and uses something like

$$\chi^2 = \sum_{\mathrm{SNe}} \frac{[\mu_B(\alpha,\beta,M) - \mu(z;\Omega_m,\Omega_{\mathrm{DE}},w,H_0)]^2}{\sigma^2_{\mathrm{ext}} + \sigma^2_{\mathrm{sys}} + \sigma^2_{\mathrm{lc}}}$$

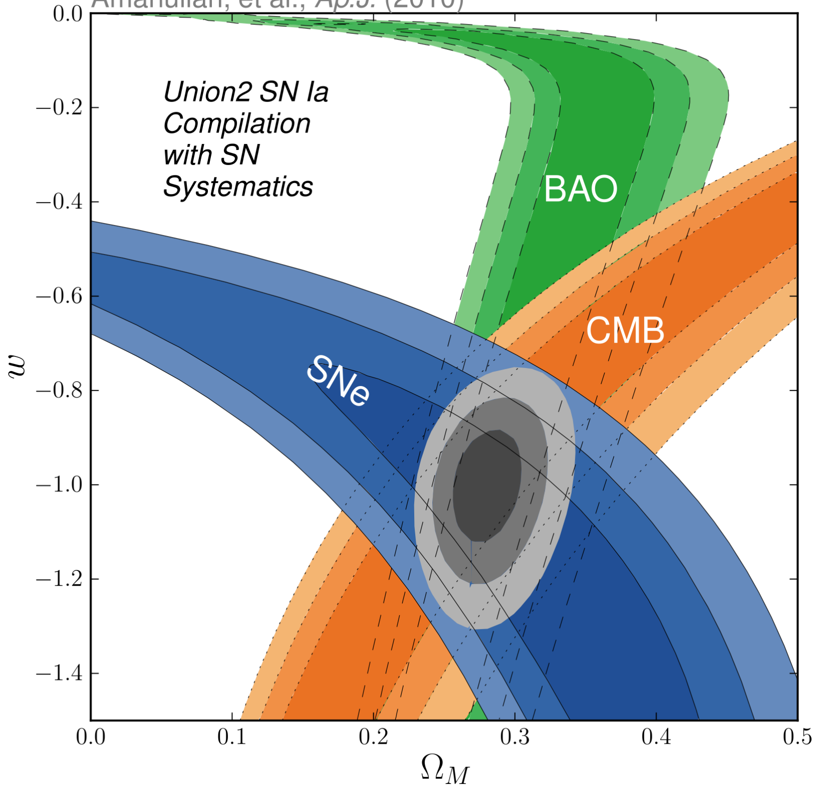
errors (example: SCP Union 2):

- σ_{lc}: propagated from light-curve fits
- σ_{ext}: various contributions (e.g. v_{pec})
- σ_{sys}: unknown intrinsic dispersion, used to make reduced χ^2=1 (size ~ 0.1 – 0.15mag)

comments:

1. should really use covariance matrix
2. normally okay (but not great) to just use errors and fixed α, β from ΛCDM case
3. H_0 vs M:
   - M and log(H_0) enter in the same way
   - must marginalise over H_0
   - can be done analytically

Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)



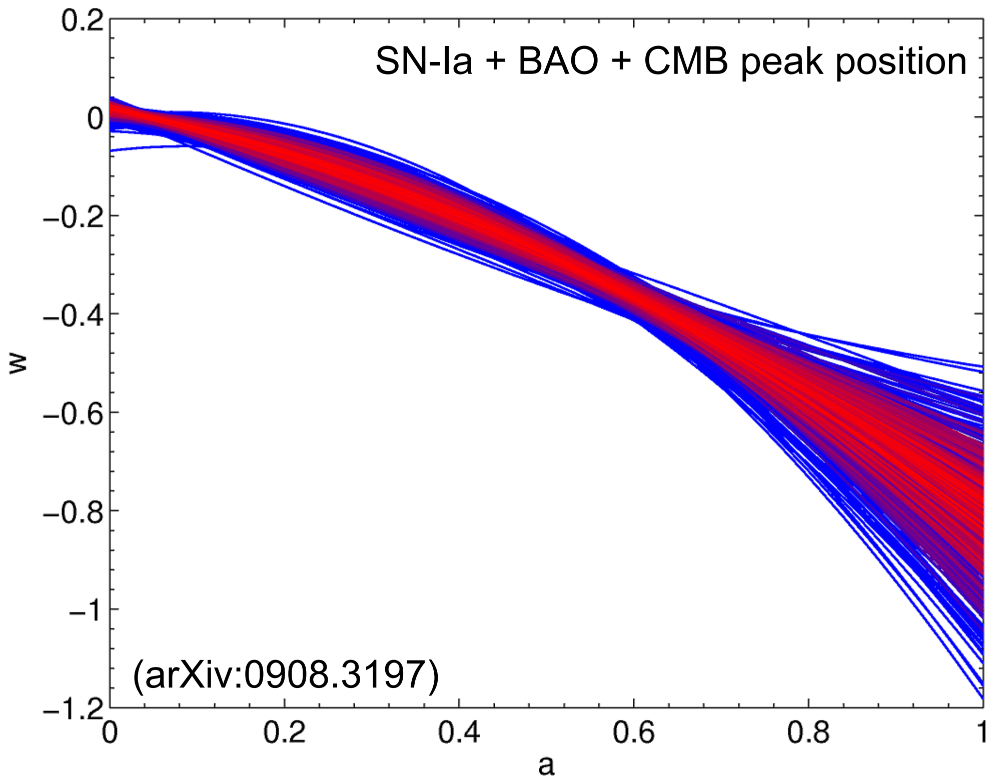
$$w = -0.997^{+0.077}_{-0.082}(\mathrm{stat}+\mathrm{sys})$$

evolving w(z)

flat universe: $H^2 = \frac{8\pi G}{3}\rho \qquad \dot{\rho} + 3H(\rho + p) = 0 \qquad p = w\rho$

$$\int \frac{d\rho}{\rho} = 3\int (1+w)\frac{da}{a}$$

$$H^2 = H_0^2 \exp\left\{\int_0^z \frac{3(1+w)}{(1+z')}dz'\right\} \qquad d_L = (1+z)\int_0^z \frac{du}{H(u)}$$



example:
$w(a) = w_0 + w_1\, a + w_2\, a^2$

best $\chi^2 = 309.8$
ΛCDM: $\chi^2 = 311.9$
w const: $\chi^2 = 391.3$

What is w_{DE}? Beware:
- MUST leave Ω_m free
- need DE model (split not unique in general), e.g. scalar field

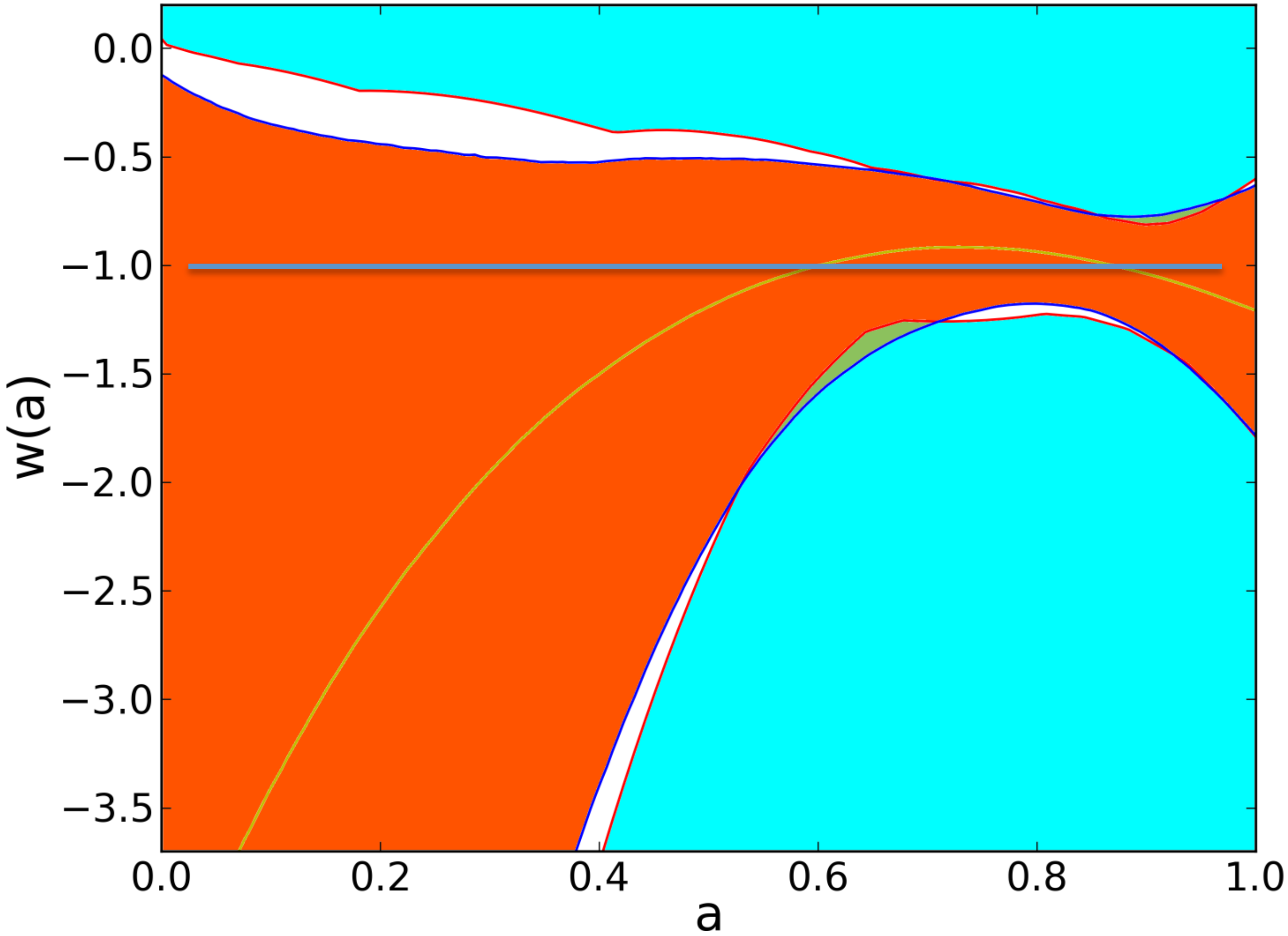
parametrisations of w

- vast literature
- generally, inverse methods difficult and noisy
- forward methods better: parametrise w(a)
  - $w = w_0$ constant
  - $w = w_0 + (1-a)\, w_a$ (especially forecasts, DETF FoM)
  - general series expansions in a or z
  - w = f(a), with f(a) e.g. a transition
  - w in bins
  - w as expansion in some other functional basis
- balance between stiffness of expansion and size of error bars -> regularisations, PCA, …

w of quintessence models

Play same game, but now using effective quintessence model (with some tricks to cross w=-1) including perturbations, and CMB+SN-Ia data.

Parameters: $\{\Omega_m, \Omega_b h^2, H_0, \tau, n_s, A_s, w_0, w_1, w_2, w_3\}$ (cubic expansion of w(a))



- 95% limits
- w=-1 is a good fit
- best constraints at low z
- ca 10%-15% error on w at ‘best’ redshift
- not very strong dependence on parametrisation

Is it just Λ?
- remember the problems
- also: inflation

5. modified gravity models

4D generalisation of GR:

⇨ Scalar/(V)/Tensor : natural generalisation, strong limits from solar system, effects can be screened

⇨ f(R) : modify action: R + f(R) (e.g. R-μ^4/R), consistency constraints and problems with matter dominated era

⇨ massive gravitons / degravitation (~ related to DGP)

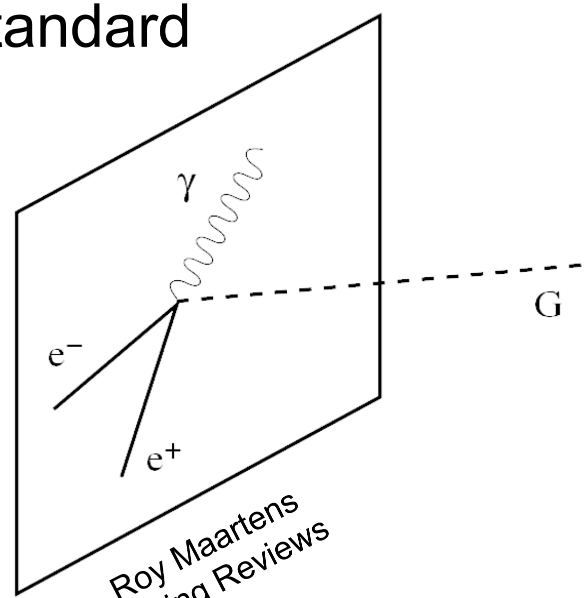
Higher-dimensional gravity (aka "braneworlds")

gravity (closed strings) propagates freely, standard model (open strings) fixed to branes

⇨ DGP : sum of 5D and 4D gravity action

- instabilities, ghosts, finetuning
- solar-system tests
- dependence on background

very difficult to construct viable models!



Roy Maartens
Living Reviews

non-cosmological probes

a few things to look out for:

- fifth force (weak, long-range) from couplings of standard model to new fields
- new particles with strange couplings and/or mass hierarchies (KK)
- varying “fundamental constants” and other violations of the equivalence principle
- perihelion shifts / solar system constraints (including double pulsar timings, etc)
- modifications to stellar structure models
- short-distance gravity modified (now well below 0.1mm)

cosmological probes of MG

- our world has 3 space dimensions
- cosmology is governed by an effective 3+1 D metric: two functions ϕ and ψ in metric
- assume DM exists, behaves as 3D matter (i.e. conserved)
- but Einstein equations are now different

- background example
- perturbation theory
- general argument
- examples
- observational constraints / outlook

‘dark’ phenomenology

What can we actually measure?

two kinds of equations:

$$\boxed{G_{\mu\nu} = -8\pi G T_{\mu\nu} \quad T^{\nu}_{\mu;\nu} = 0}$$

$g_{\mu\nu}$

$$G_{\mu\nu} = -8\pi G T_{\mu\nu}$$

determine metric coeffs from $T_{\mu\nu}$

$$\nabla_\nu T^{\nu}_{\mu} = 0$$

determine evolution of $T_{\mu\nu}$ from metric and “physics”

the background case

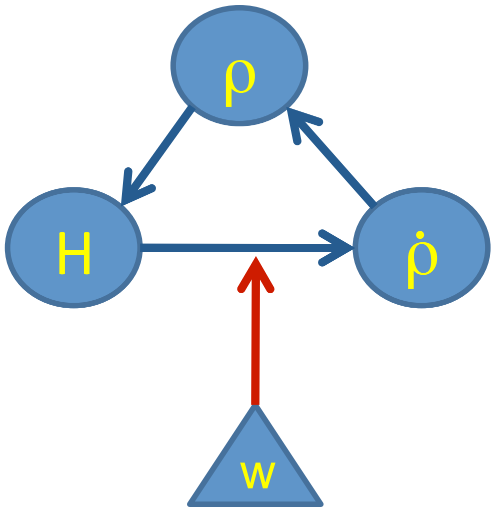
$$ds^2 = -dt^2 + a(t)^2 dx^2$$ metric "template"

Einstein eq'n $$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_1 + \rho_2 + \ldots + \rho_n)$$

conservation $$\dot{\rho}_i = -3H(\rho_i + p_i) = -3H(1 + w_i)\rho_i \qquad i = 1, \ldots, n$$

- w_i describe the fluids
- normally all but one known

- H|a describe observables (distances, ages, etc)



MG at the background level

- modified gravity can change Friedmann eq'n:

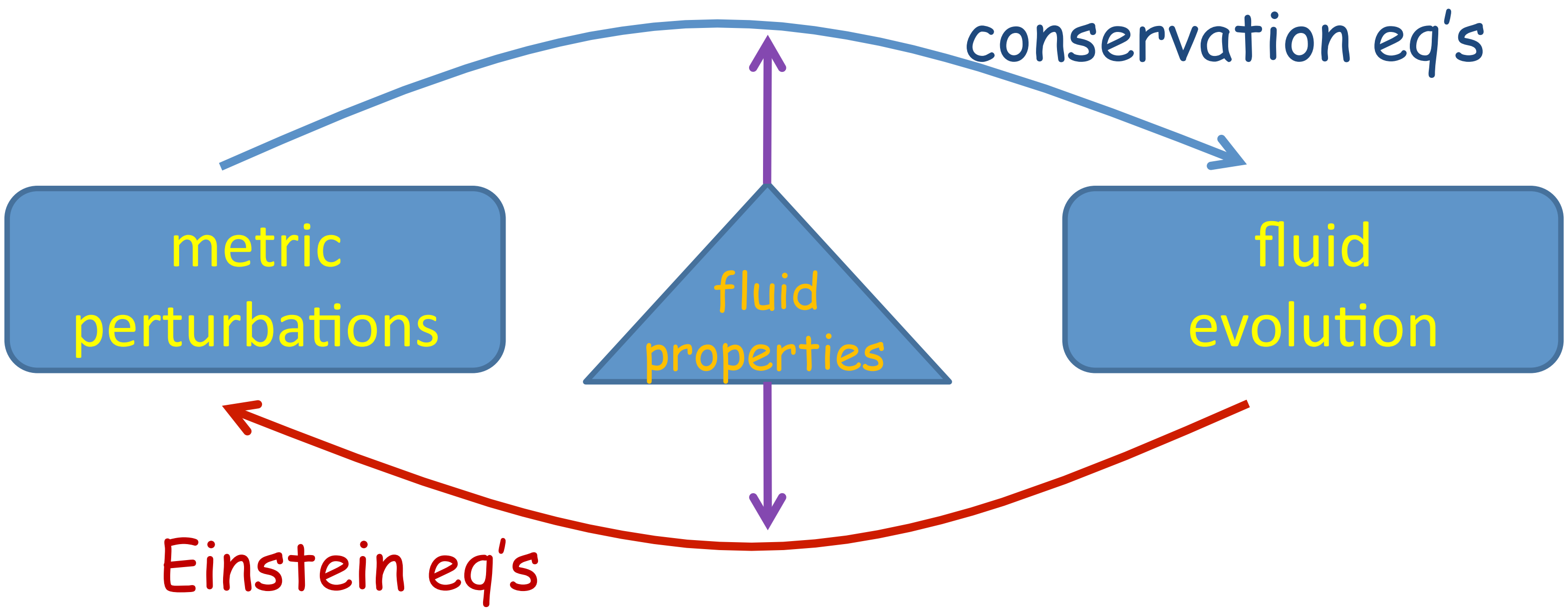
$$H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}\rho_m \qquad H^2 = \frac{8\pi G}{3}\rho_m\left(1 + \frac{\rho_m}{2\lambda}\right)$$

- no DE, but DM still conserved
- since a DE model with free w(z) can give any H(z), we can construct a w that gives the same expansion history (and observations):

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

perturbations

$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$$ metric (gauge fixed, scalar dof)



$$k^2\phi = -4\pi G a^2 \sum_i \rho_i \left(\delta_i + 3Ha\frac{V_i}{k^2}\right), k^2(\phi - \psi) = 12\pi G a^2 \sum_i (1+w_i)\rho_i \sigma_i$$

$$\delta_i' = 3(1+w_i)\phi' - \frac{V_i}{Ha^2} - \frac{3}{a}\left(\frac{\delta p_i}{\rho_i} - w_i\delta_i\right)$$

$$V_i' = -(1-3w_i)\frac{V_i}{a} + \frac{k^2}{Ha}\left(\frac{\delta p_i}{\rho_i} + (1+w_i)(\psi - \sigma_i)\right)$$

General Argument

modified "Einstein" eq:
(projection to 3+1D)

$$X_{\mu\nu} = -8\pi G T_{\mu\nu}$$

$$\boxed{G_{\mu\nu} = -8\pi G T_{\mu\nu} - Y_{\mu\nu} \quad Y_{\mu\nu} \equiv X_{\mu\nu} - G_{\mu\nu}}$$

$Y_{\mu\nu}$ can be seen as an effective DE energy-momentum tensor.

Is it conserved?

Yes, since $T_{\mu\nu}$ is conserved, and since $G_{\mu\nu}$ obeys the Bianchi identities!

There is also no place "to hide", since $T_{\mu\nu}$ is also derived from a general symmetric tensor.

parametrisations

- could parametrise (effective) dark energy with anisotropic stress σ and pressure perturbation δp
- or directly deviations in metric potentials, e.g.

$$-k^2\phi = 4\pi G a^2 Q \rho_m \Delta_m \qquad \psi = (1+\eta)\phi$$

- in both cases two new functions of space and time -> much worse than w(z)!
- can either restrict form (e.g. just sub- and super-horizon behaviour) or course binning and PCA
- BUT: at least in principle we know what to look for! (And results can then be compared with theoretical predictions)

some model predictions

scalar field: $$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} \partial_\mu \phi \partial^\mu \phi + V(\phi) \right)$$

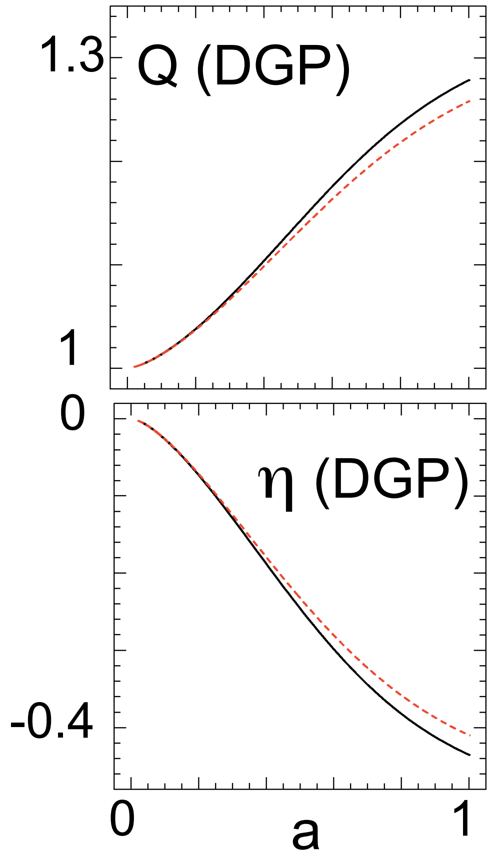
One degree of freedom: V(ϕ) <-> w(z) therefore
other variables fixed: $c_s^2 = 1$, $\sigma = 0$
-> $\eta = 0$, $Q(k \gg H_0) = 1$, $Q(k \sim H_0) \sim 1.1$

(naïve) DGP: compute in 5D, project result to 4D

Lue, Starkmann 04
Koyama, Maartens 06

$$\eta = \frac{2}{3\beta - 1} \qquad Q = 1 - \frac{1}{3\beta}$$

implies large DE perturb.



Scalar-Tensor: Boisseau, Esposito-Farese, Polarski, Starobinski 2000, Acquaviva, Baccigalupi, Perrotta 04

$$\mathcal{L} = F(\varphi)R - \partial_\mu \varphi \partial^\mu \varphi - 2V(\phi) + 16\pi G^* \mathcal{L}_{\text{matter}}$$

$$\eta = \frac{F'^2}{F + F'^2} \qquad Q = \frac{G^*}{F G_0} \frac{2(F + F'^2)}{2F + 3F'^2}$$

f(R): $S_g = \int d^4x \sqrt{-g} f(R)$ similar to scalar-tensor

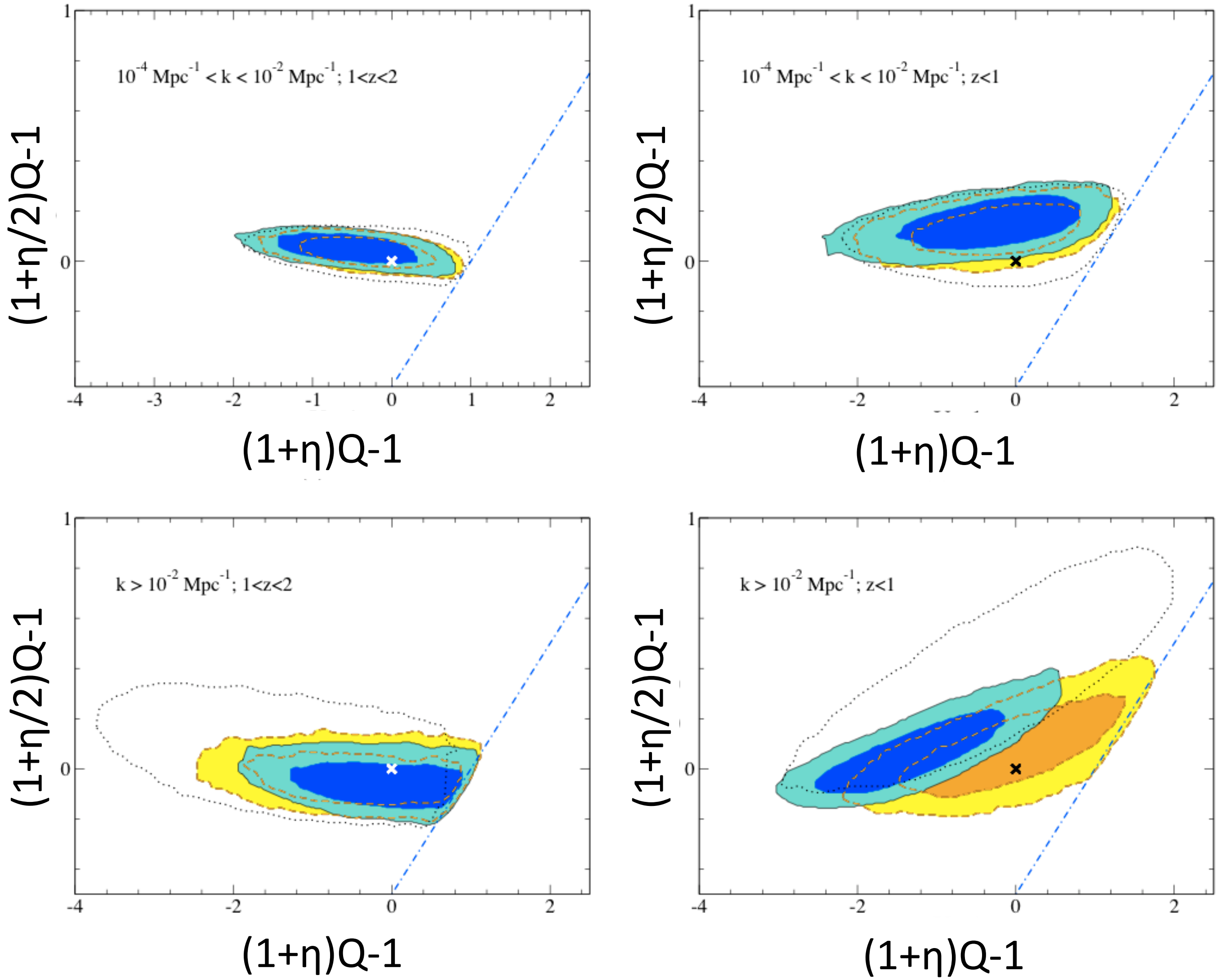
current constraints

- 2x2 grid in k and z
- CMB + SN-Ia + WL + P(k)

- weak constraints
- WL data not very reliable (blue vs yellow)
- no deviation from GR

- future data will improve constraints by at least one order of magnitude

(arxiv:1003:0001)



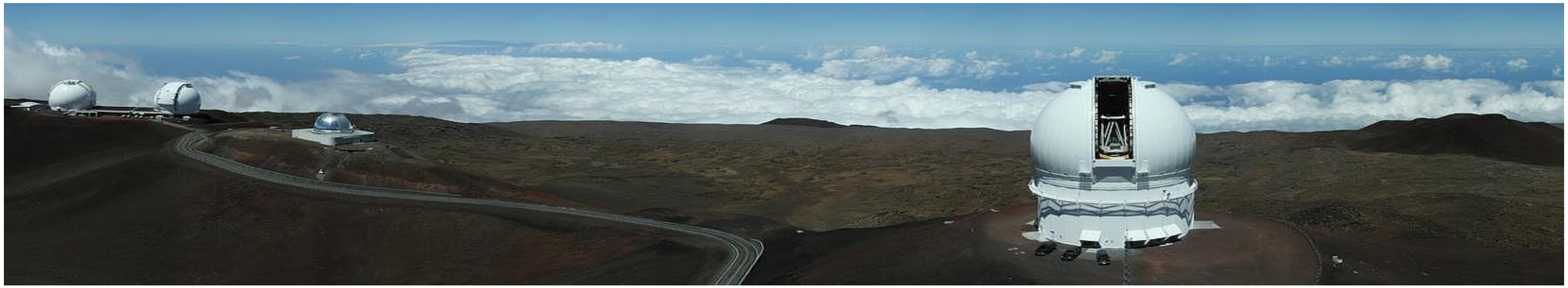
observational aspects

How to measure DE properties?

- w(z) from SN-Ia, BAO directly (and contained in most other probes)
- Curvature from radial & transverse BAO
- In addition 5 quantities, e.g. φ, ψ, bias, δ_m, V_m
- Need 3 probes (since 2 cons eq for DM)
- e.g. 3 power spectra: lensing, galaxy, velocity
- Lensing probes $\varphi + \psi$ (geodesics of *massless* particles -> not $\delta\rho_m$ in general!)
- Velocity (of *massive* test particles) probes ψ (z-space distortions?)
- And galaxy P(k) then gives bias

Observational postlude

Survey	diameter (m)	FOV (deg2)	Area (deg2)	start
CFHTLS	3.6	1	172	2003
KIDS (VST)	2.6	1	1700	2010
DES (NOAO)	4	2	5000	2011
HSC (Subaru)	8	2	5000(?)	2011
Pan-STARRS	1.8(x4)	4(x4)	20000	2009(2014)
LSST	8	7	20000	2014
Euclid	1.2 space	2x0.5	20000	2018
JDEM/WFIRST	1.5? space	0.5?	20000?	2020?



(slide by A. Refregier)

The Euclid Mission

Mapping the Geometry of the Dark Universe

Primary surveys:

all-sky Vis+NIR imaging

NIR spectroscopy

Primary probes:

Weak Lensing

Galaxy P(k) / BAO

Additional probes:

Clusters Counts, Galaxy clustering, Redshift space distortions, Integrated Sachs-Wolfe Effect

(slide partially by A. Refregier)

Euclid mission baseline:

L2 Orbit

4-5 year mission

Launch of first M-class mission: 2018

Telescope:

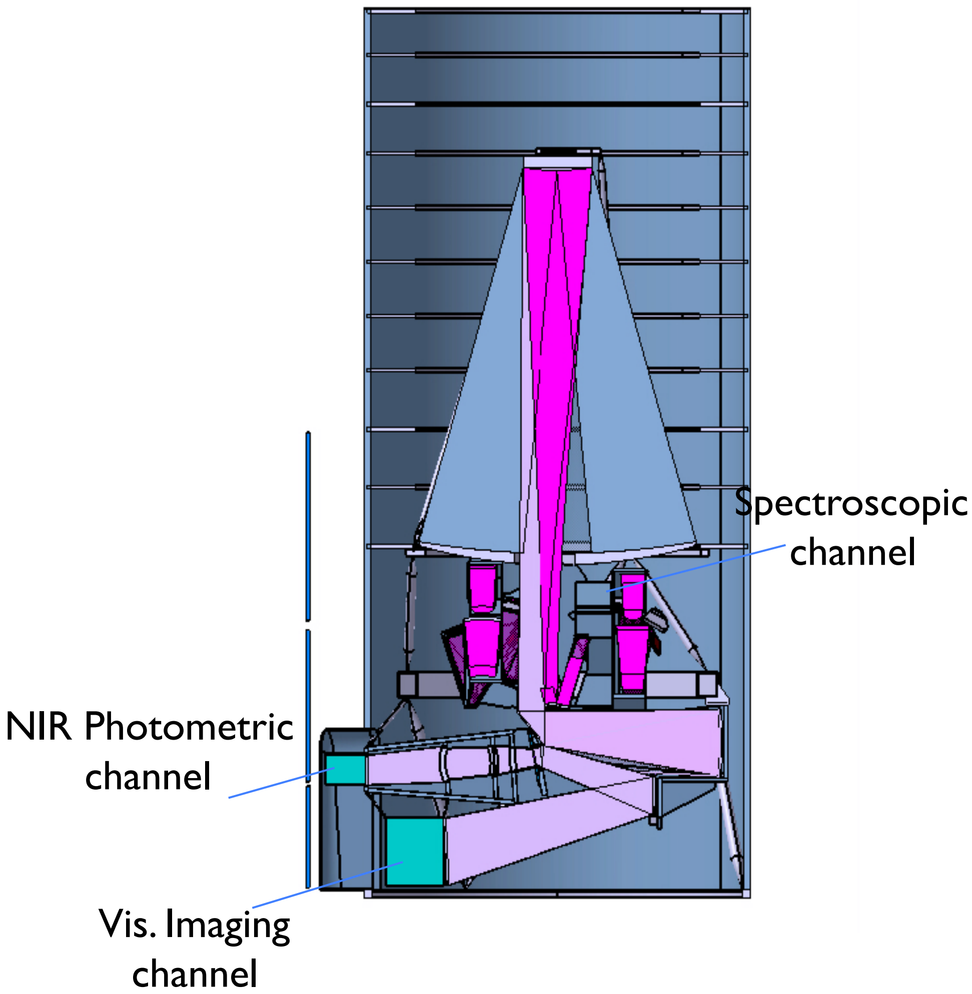
three mirrors with 1.2 m primary

Instruments:

Visible imaging channel: 0.5 deg^2, 0.10” pixels, 0.18” PSF FWHM, broad band R+I+Z (0.55-0.92mu), CCD detectors, galaxy shapes

NIR photometry channel: 0.5 deg^2, 0.3” pixels, 3 bands Y,J,H (1.0-1.7mu), HgCdTe detectors, Photo-z’s

NIR Slitless Spectroscopic channel: 0.5 deg^2, R=500, 0.9-2.0mu, redshifts



(slide by A. Refregier)

Euclid Surveys

Wide Survey: entire extra-galactic sky (20 000 deg^2)

Imaging for Weak lensing: 2 billion galaxies

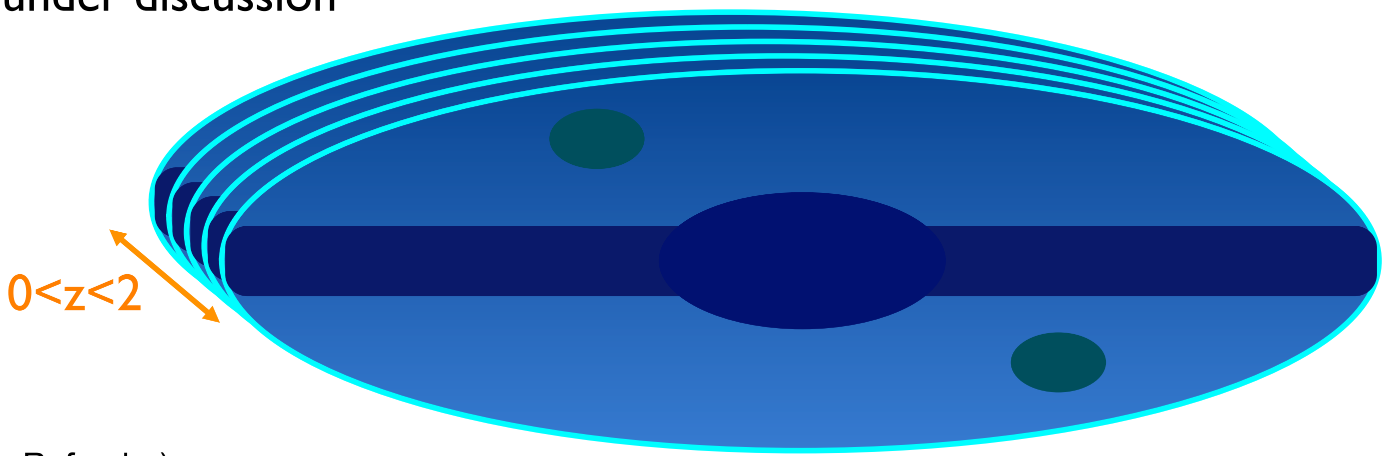
Visible: Galaxy shape measurements in R+I+Z<24.5 (AB,10σ), 40 resolved galaxies/amin^2, median redshift of 0.9

NIR photometry: Y,J,H<24 (AB, 5σ PS), photometric redshifts rms 0.03-0.05 (1+z) with ground based complement

Spectroscopic redshifts: 70 million galaxies with emission line fluxes >4.10^{-16} ergs/cm^2/s (slitless), σ_z~0.001

Deep Survey: ~30 deg^2, visible/infrared imaging to H(AB)=26 mag and spectroscopy to H(AB)=24 mag

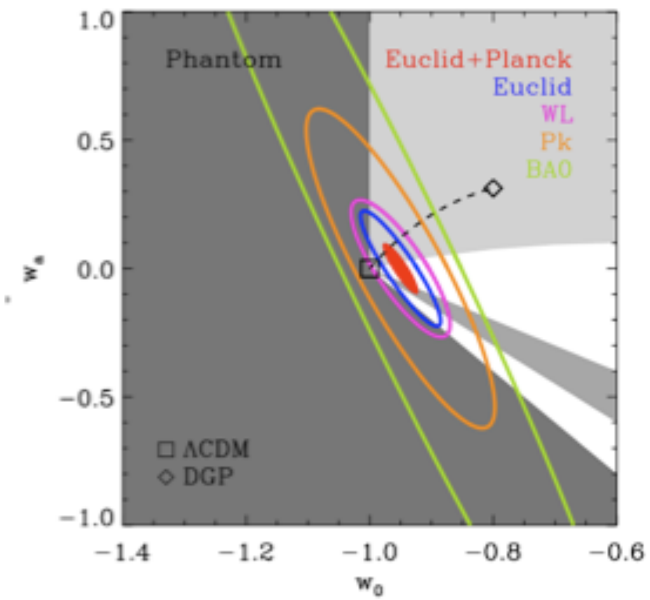
Galactic surveys: Galactic plane and microlensing extra-solar planet surveys under discussion



(slide by A. Refregier)

Euclid and cosmology

	Δw_p	ΔW_a	$\Delta\Omega_m$	$\Delta\Omega_\Lambda$	$\Delta\Omega_b$	$\Delta\sigma_8$	Δn_s	Δh	DE FoM
Current+WMAP	0.13	-	0.01	0.015	0.0015	0.026	0.013	0.013	~10
Planck	-	-	0.008	-	0.0007	0.05	0.005	0.007	-
Weak Lensing	0.03	0.17	0.006	0.04	0.012	0.013	0.02	0.1	180
Imaging Probes	0.018	0.15	0.004	0.02	0.007	0.0009	0.014	0.07	400
Euclid	0.016	0.13	0.003	0.012	0.005	0.003	0.006	0.020	500
Euclid +Planck	0.01	0.066	0.0008	0.003	0.0004	0.0015	0.003	0.002	1500
Factor Gain	13	>15	13	5	4	17	4	7	150



Dark Energy: w_p and w_a with an error of 2% and 13% respectively (no prior)

Dark Matter: test of CDM paradigm, precision of 0.04eV on sum of neutrino masses (with Planck)

Initial Conditions: constrain shape of primordial power spectrum, primordial non-gaussianity

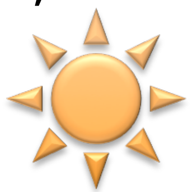
Gravity: test GR by reaching a precision of 2% on the growth exponent $(d\ln_m / d\ln a_m)$

→ Uncover new physics and map LSS at 0<z<2: Low redshift counterpart to CMB surveys

(slide by A. Refregier)

Summary

- data wrong

  data consistent, difficult to still achieve within standard model
- anthropic principle
- LTB/Backreaction
  - can be tested
  - needs predictions for precision cosmology
- dark energy / modified gravity
  - current observations: consistent with LCDM
  - general parametrisations now in place: w(z) + 2 functions of k and z
  - need: predictions for models, generic differences
  - need: data analysis methods, non-linear evolution
- outlook: generally sunny 

Ze final words

There are known knowns.

These are things we know that we know.

There are known unknowns.

That is to say, there are things that we know we don't know.

But there are also unknown unknowns.

There are things we don't know we don't know.

(Don, famous poet of early 21st century)

CMB and Ω_Λ (WMAP 5yr)