# dark energy

Martin Kunz

University of Geneva

see also:

- Supernovae ➜ Ariel Goobar
- Braneworld models ➜ Kazuya Koyama
- Strings & Cosmo ➜ Cliff Burgess
- Scalar fields (very early DE) ➜ Lev Kofman
- Tests of Gravity ➜ Clive Speake

# why am I giving this talk?

- FLRW metric + data: $\ddot{a} > 0$
- expansion of universe accelerating
- but Einstein eqs: $\ddot{a} \sim -(\rho + 3p)$
- so need $p < -\rho/3$
- but normal matter has $p \geq 0$
- we also know vacuum energy with $p=-\rho$
  (Casimir, phase transitions, SUSY, etc)

# how much vacuum energy?

Let us count the energy density in the universe:

$(\Omega_X = \rho_X / \rho_c = 8\pi G \rho_X / (3H_0^2))$

- radiation: CMB-temp $\Rightarrow \Omega_\gamma \approx 5\times10^{-5}$

too small to matter…

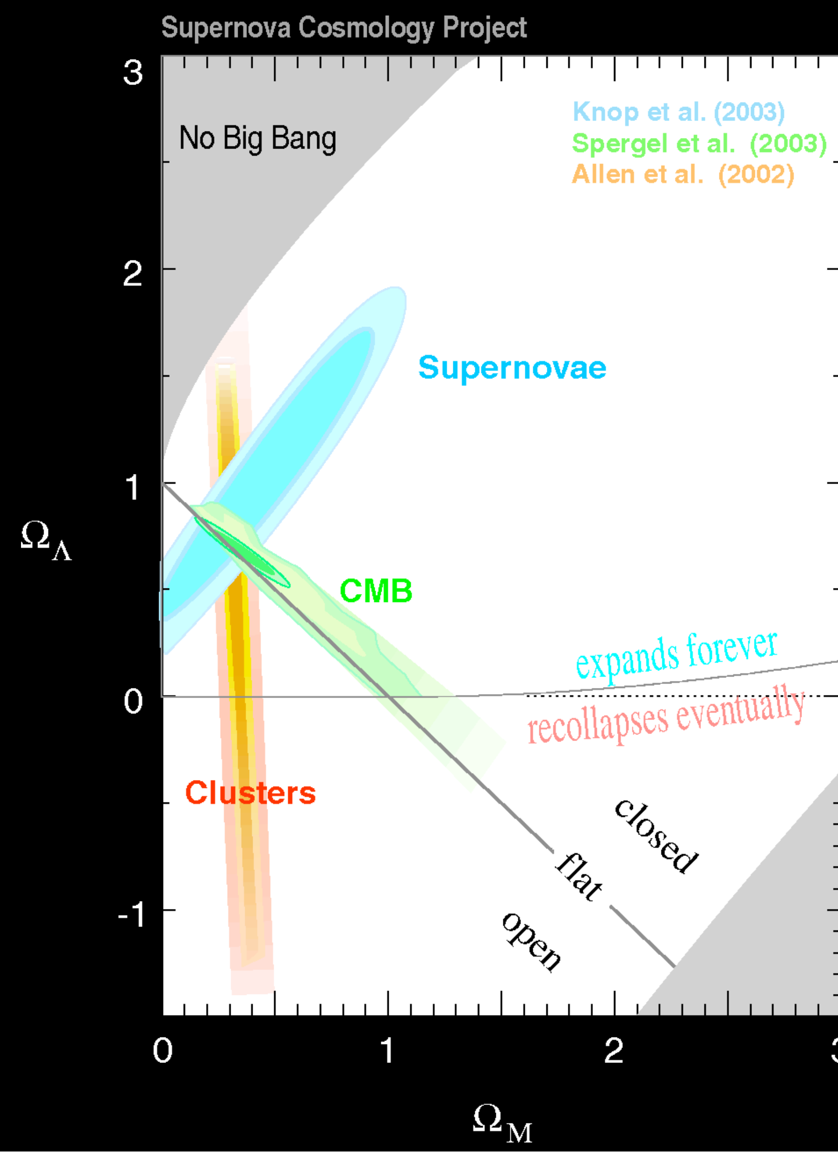
combine SN-Ia and CMB distance measurements:

- matter: $\Omega_m \approx 0.3$

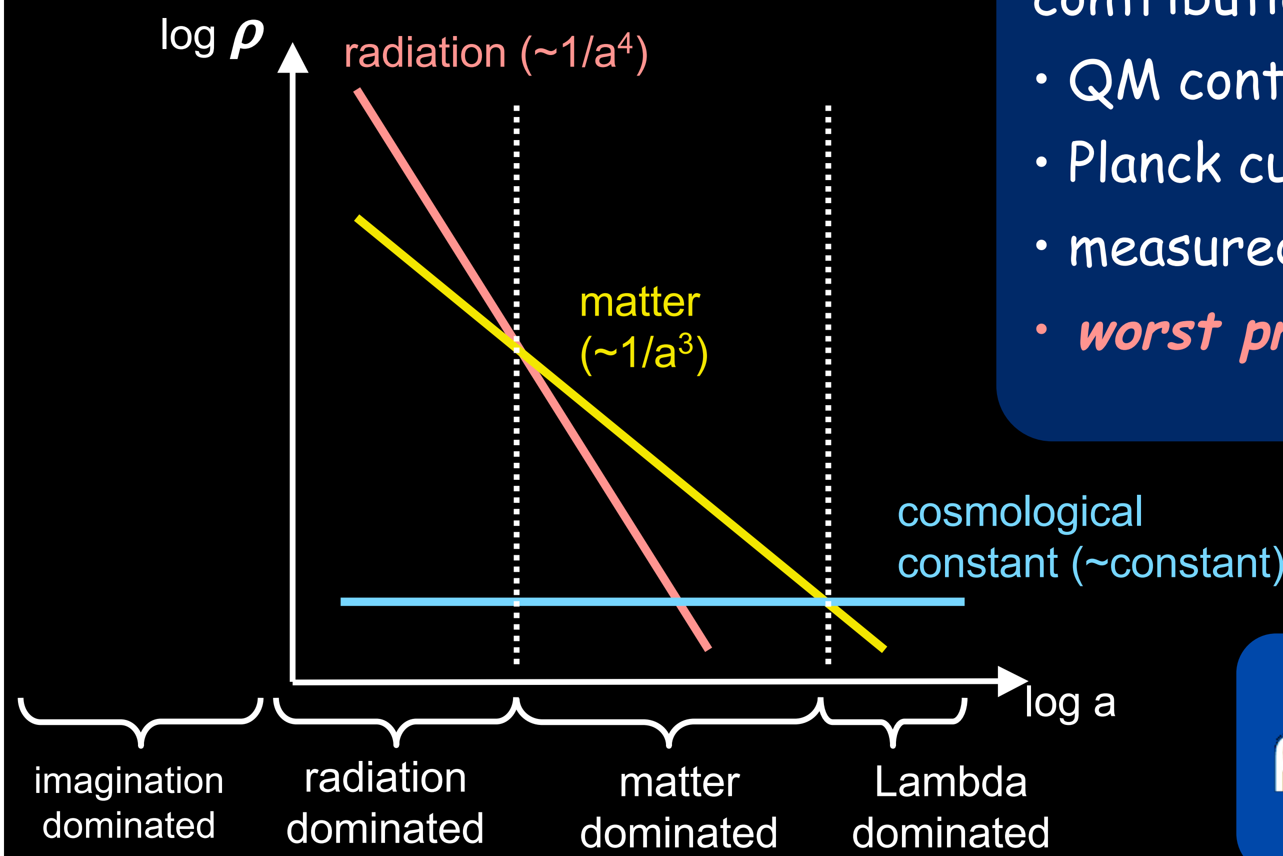
(whereof baryons ≈ 0.05! [BBN/CMB])

-cosmological const.: $\Omega_\Lambda \approx 0.7$

(and space is close to flat)



# what is the problem with Λ?




Let's guess the size of the contribution by Λ:

- QM contribution ~ $k^4$.
- Planck cutoff: $\Lambda \approx 10^{76}$ GeV$^4$
- measured: $\Lambda \approx 10^{-47}$ GeV$^4$
- ***worst prediction*** ever?

$$\dot{\rho} = -3\frac{\dot{a}}{a}(\rho + p)$$

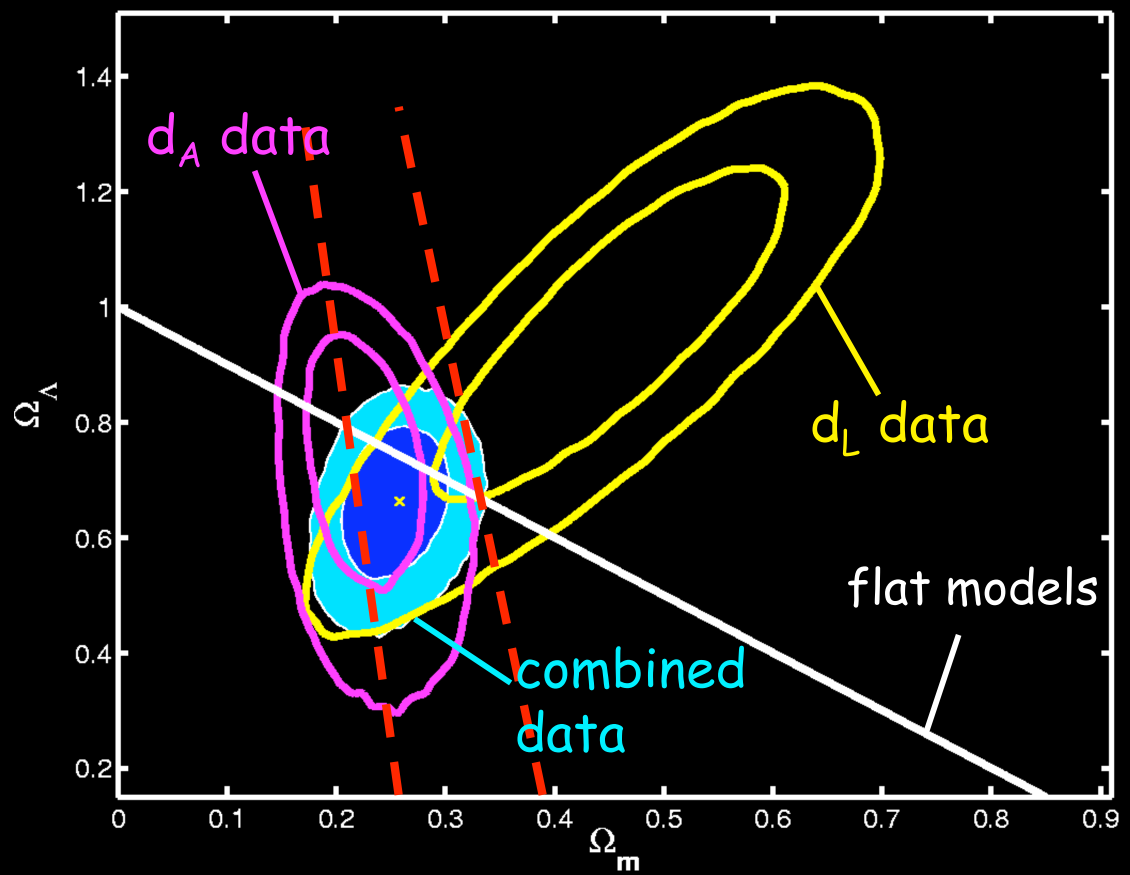
$$p = w\rho \rightarrow \rho(a) \propto a^{-3(1+w)}$$

# if not $\Lambda$, what else?

- a problem with the data
  - *data is wrong*
  - physicists are wrong (e.g. backreaction)
- anthropic principle (the landscape)
- modification of GR
- dynamical dark energy
  - quintessence / Chaplygin gas / K-essence / …
  - *general fluid (measure DE parameters)*
- too many English breakfasts

# should we believe the data?

angular diameters and luminosities measure the same distances
➜ they cannot vary independently




- constrains photon-loss (dust, some axions)
- very different systematics
- models without dark energy are ruled out at high confidence
- newer data (baryon oscillations) arriving, much more reliable

# is the acceleration apparent?

maybe the expansion of the universe is not accelerating, but the light-path is affected by the growth of inhomogeneities?

➜ solves size problem (effect expected to be small)

➜ solves coincidence problem (we appear after structure forms)

Working toy models exist (e.g. with Lemaitre-Tolman-Bondi metric) and exact smoothed dust solutions ("Buchert equations") contain an apparent acceleration term.

However, the CMB is very isotropic, 1st order perturbation theory is very successful and the gravitational potentials appear to be small. Also some theoretical arguments say that the backreaction effect is expected to be present, but too small without finetuning.

(and it still needs $\Lambda$=0)

(talk by I. Brown)

# "real" dark energy

General Relativity:

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R + S_{matter}$$

equation of motion: (non-linear partial differential equations)

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

geometry ➜ modified gravity

matter ➜ dark energy

# the scalar field

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

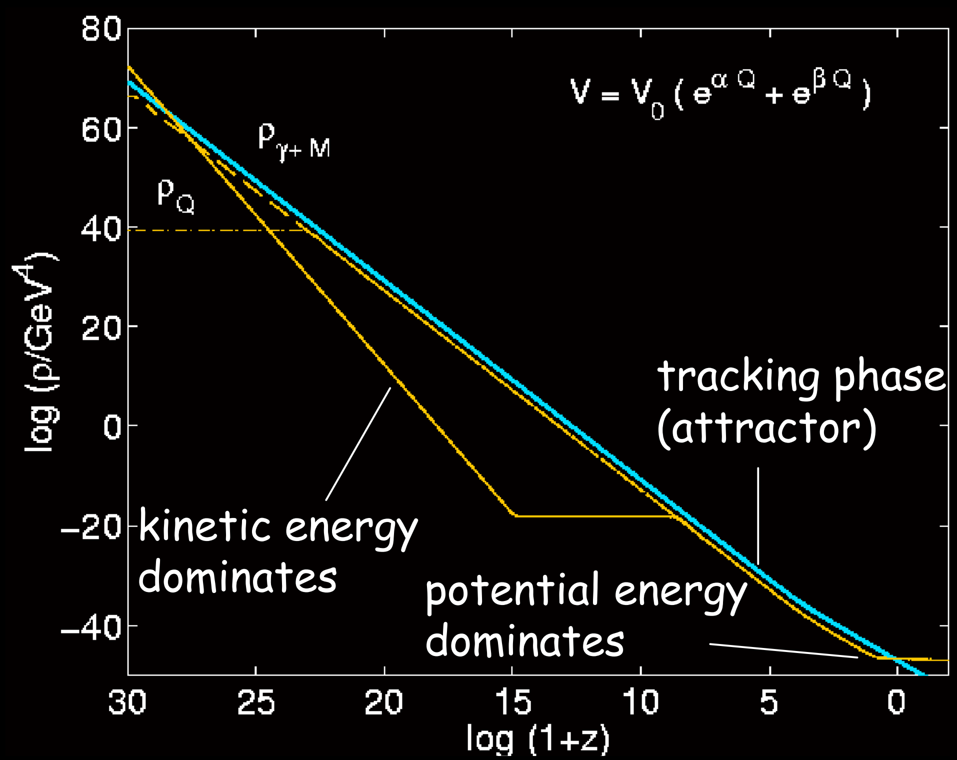
$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV(\phi)}{d\phi} = 0$$

$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

only free parameter: $V(\varphi)$,
linked with $w(z)$.

(talks by O. Bjaelde, S. Winitzki)




Quintessence DE requires fine-tuning ***and*** Λ=0. Other scalar fields improve some aspects but fail in others (e.g. superluminal motion)

# modified gravity models

4D generalisation of GR:

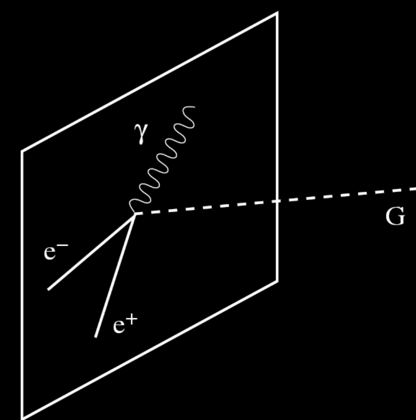
➜ Scalar/(V)/Tensor : natural generalisation, strong limits from solar system, effects can be screened

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

S. Tsujikawa
S. Appleby
A. de Felice
T. Multamaki
D. Sunhede
C. van de Bruck
S. Davis
P. Frampton

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
- sensitivity to background (“chameleon”)
- unknown non-linear evolution

Ph. Brax
D. Shaw
D. Litim
A. Padilla
M. Roos

these models rarely fail because of cosmological data

# non-cosmological probes

a few things to look out for:

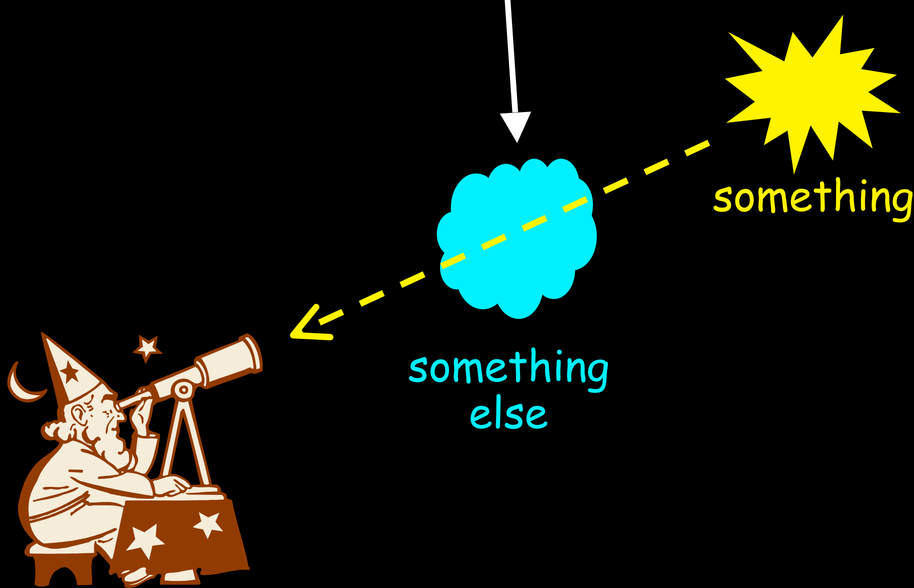
- fifth force (weak, long-range) from couplings of standard model to new fields
- new particles with strange couplings and/or mass hierarchies (KK)
- varying “fundamental constants” and other violations of the equivalence principle
- perihelion shifts / solar system constraints
- short-distance gravity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

# measuring dark things
## (in cosmology)

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

(determined by the metric) → geometry

stuff (what is it?) ↕ your favourite theory




Cosmologists observe the geometry of space time

This depends on the total energy momentum tensor

What can we learn?

# homogeneous dark energy

Assume that the universe is perfectly homogeneous and isotropic (and flat): FLRW metric

$$ds^2 = dt^2 - a(t)^2 \, dr^2$$

$T_{\mu\nu}$ must be:

$$T_\mu^\nu = diag(\rho(t), -p(t), -p(t), -p(t))$$

Einstein: $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$

probed by distance measurements

$$\dot{\rho} = -3\frac{\dot{a}}{a}(\rho + p)$$

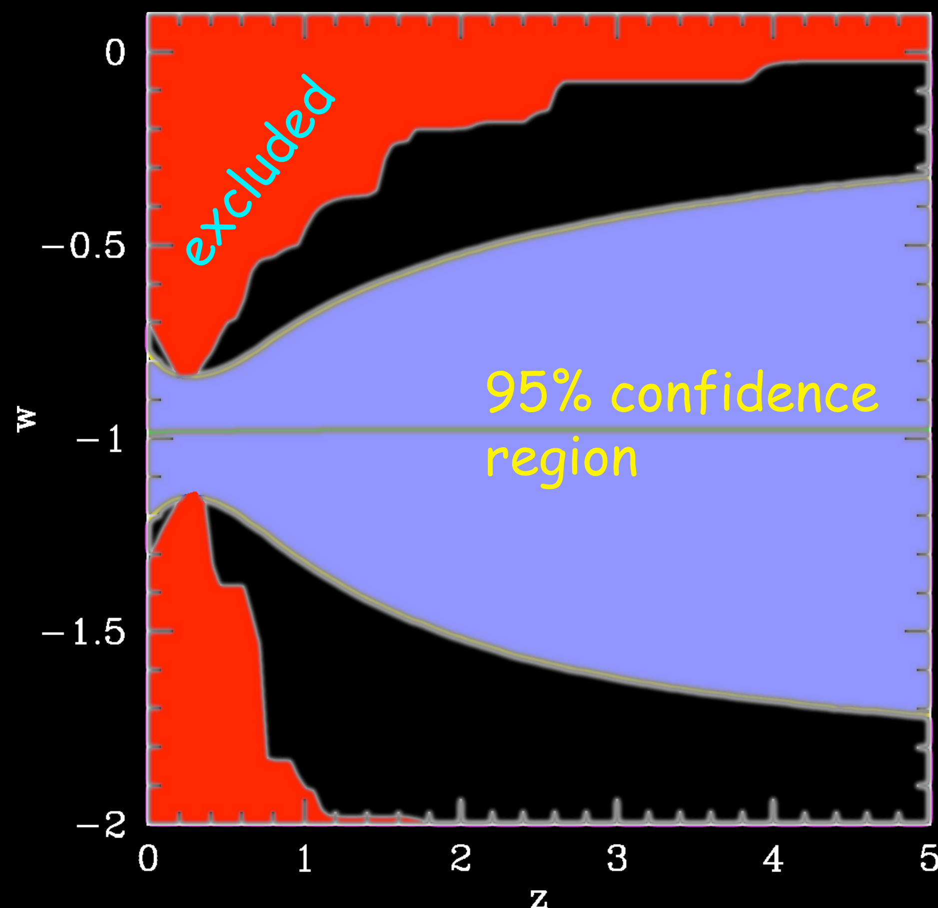
matter: $p = 0$ -> $\rho \sim a^{-3}$
radiation: $p = \rho/3$ -> $\rho \sim a^{-4}$
dark energy: $p = ?$ ($< -\rho/3$)
(define $w = p/\rho$)
-> the only thing to measure is $w(z)$

# limits on scalar field DE

WMAP-3yr + SNLS-1yr limits:

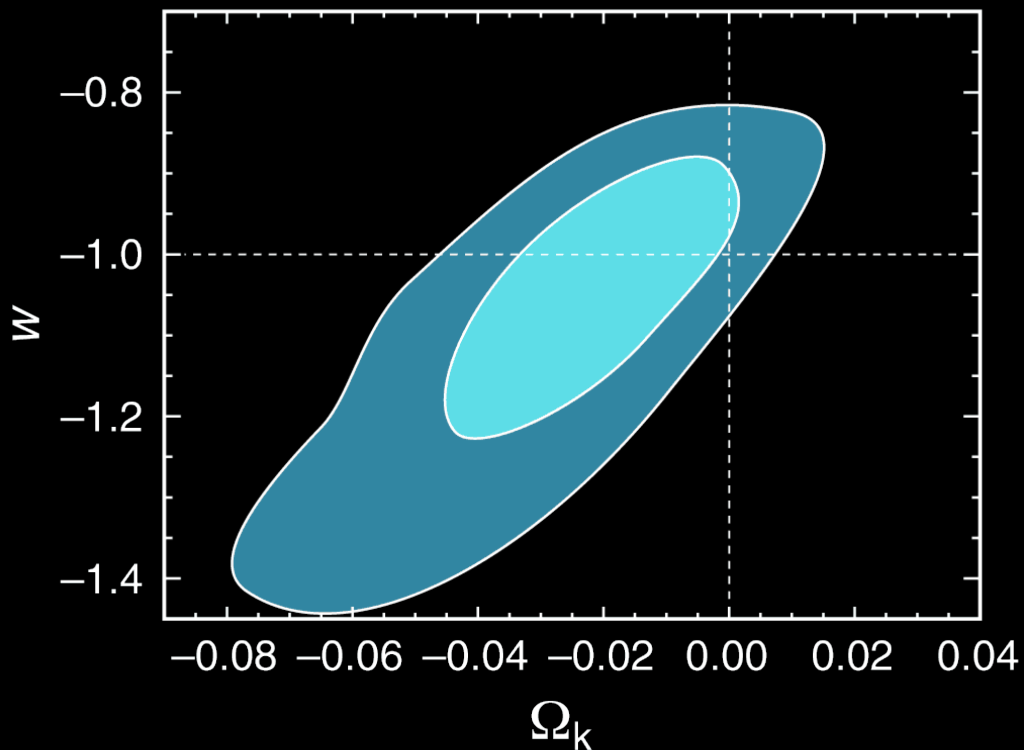
- flat universe only
- $c_s^2=1$, $\sigma=0$ [<-> scalar field model]
- regularised transition of w=-1
- uses "kink" model for w(z)
- strong constraints only at low-z
- dark energy becomes sub-dominant in the past
- several subtleties have been hidden

(→ talks by Z. Huang, R. Crittenden, D. Parkinson, A. Cardoso)




DGP: $w_{eff}(z) \approx -0.78+0.32*(1-a)$ disfavoured by CMB+SN-Ia data
(but need to allow curvature, and CMB sensitive to perturbations)

# adding curvature




constant w scalar field:

$\Omega_k = 0$ ➜ w = -0.92 ± 0.05

$\Omega_k$ free ➜ w = -1.08 ± 0.12

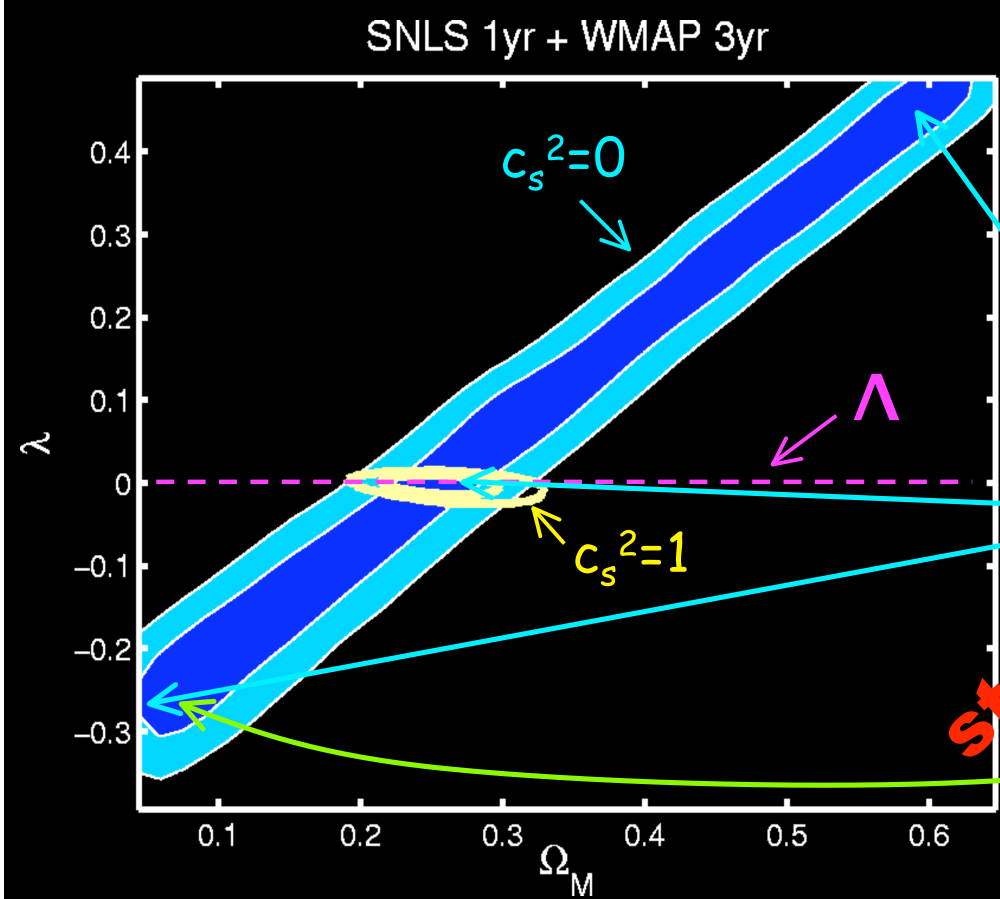
(CMB+LSS+SNIa)

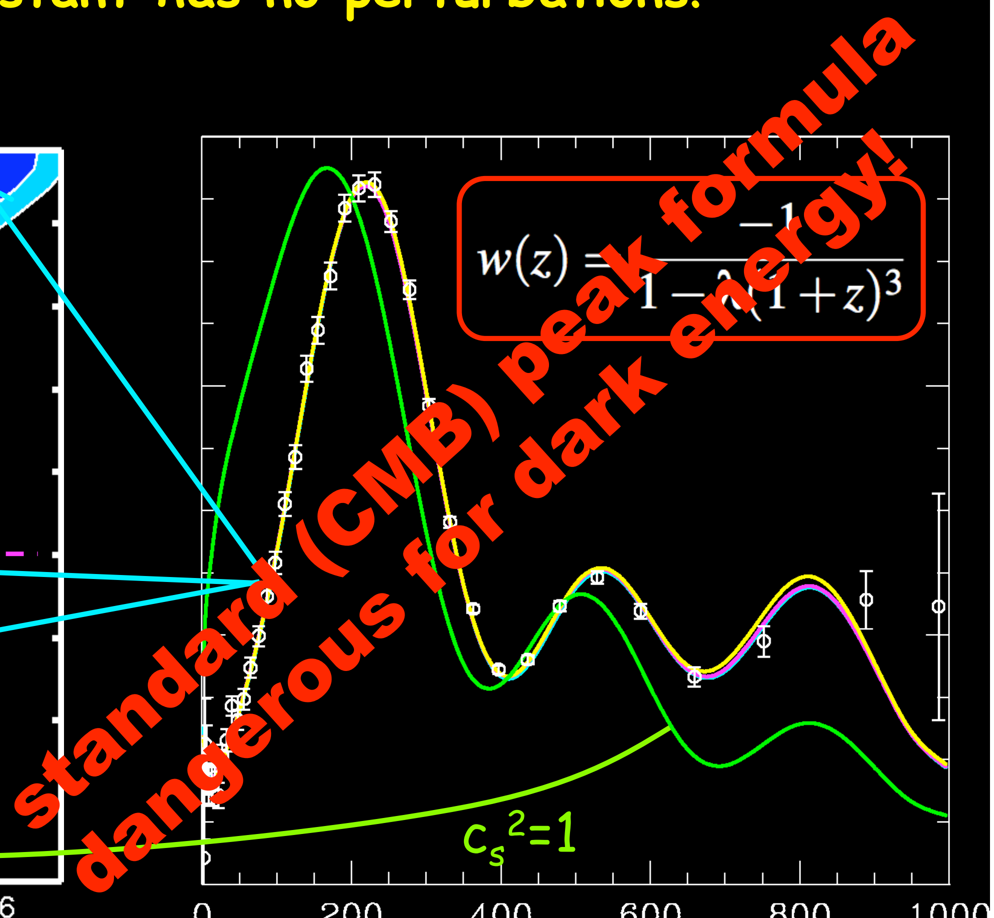
from WMAP3, Spergel et al, ApJS 2007

will become worse if w(z) follows curvature degeneracy,
(cf talk by M. Cortes yesterday)

# why w is not everything

**Only a cosmological constant has no perturbations!**




(cf talk yesterday by M. Bruni)

# measuring the dark side

small perturbations: extended metric

$$ds^2 = -(1+2\psi)dt^2 + a(t)^2(1-2\phi)dx^2$$

$\varphi$ $\psi$ gravitational potentials <-> $\delta\rho$ and $V$ perturbations of $T^{\mu\nu}$

Einstein eqs.

fluid properties

$\delta p = c_s^2\, \delta\rho$ in DE rest frame

$\sigma$ (anisotropic stress, $\varphi = \psi$ for $\sigma = 0$)

***measure*** $w$, $\delta p$, $\sigma$ !

alternative parametrisation:

$$k^2\phi = -4\pi G a^2 Q \rho_m \Delta_m$$

$$\psi = (1+\eta)\phi$$

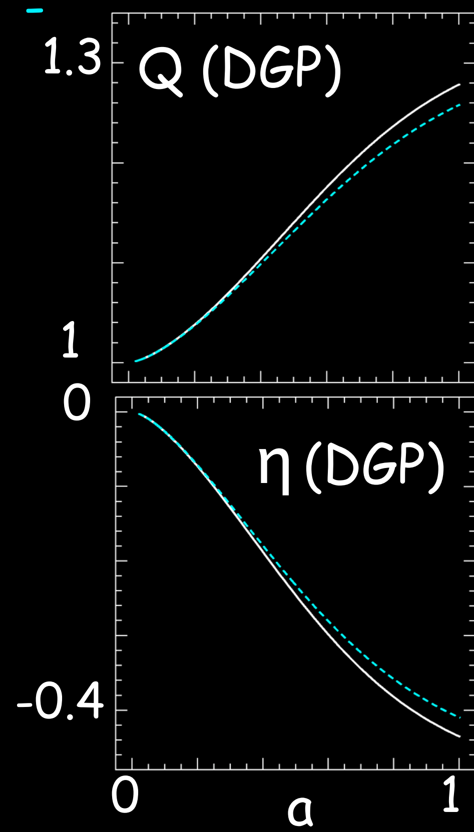
matter only!

unifies mod. grav. and DE description

# 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: $V(\varphi)$ <-> $w(z)$
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

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

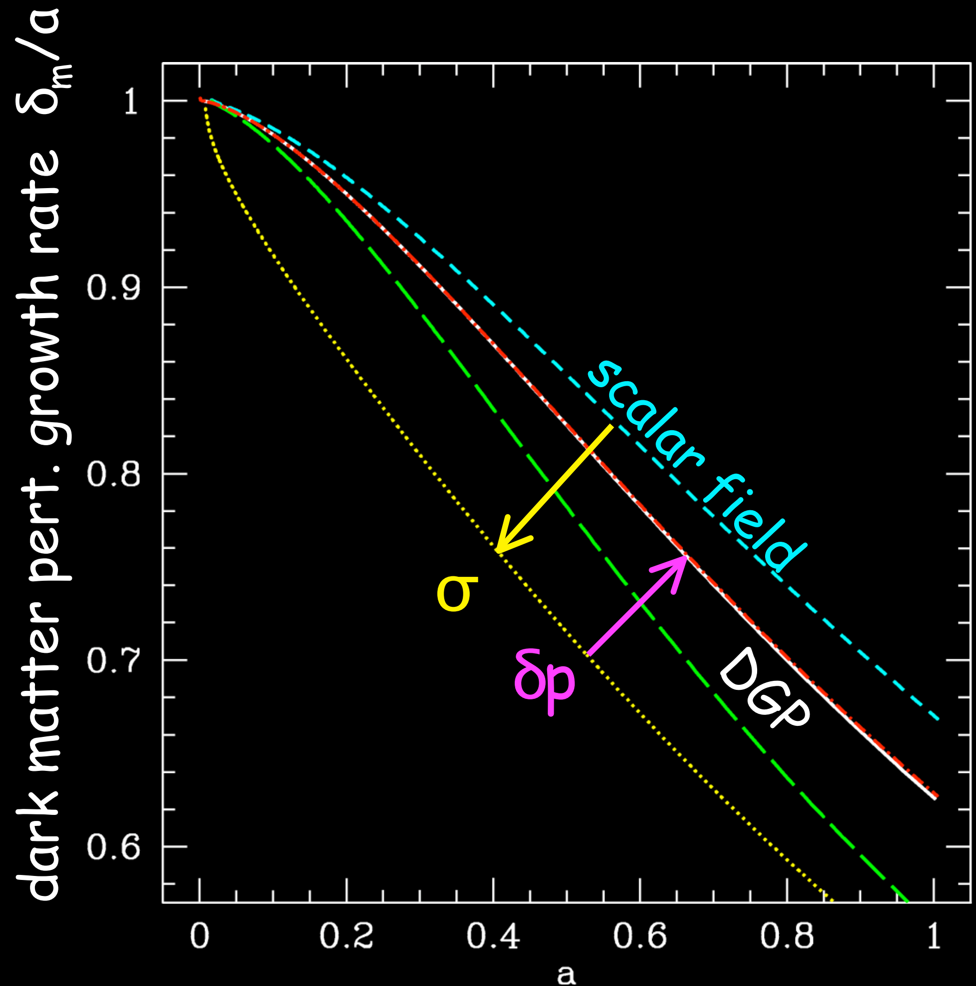
$$\eta = \frac{F'^2}{F + F'^2} \qquad Q = \frac{G^*}{F G_0}\frac{2(F + F'^2)}{2F + 3F'^2}$$

f(R) : talk by A. Silvestri

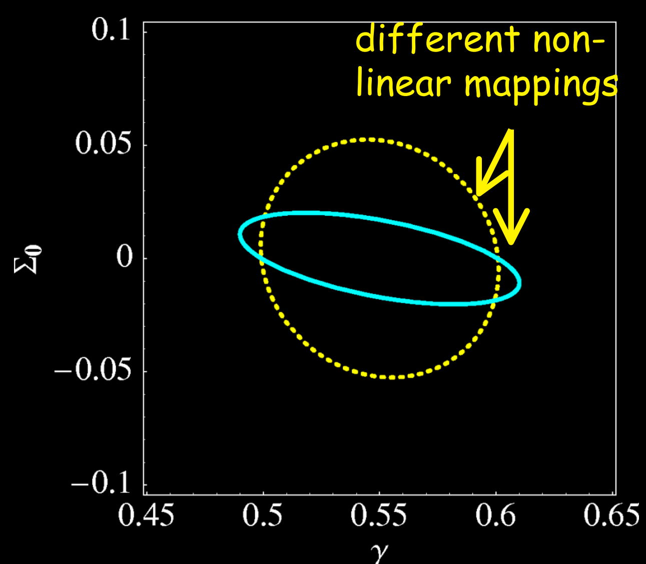
# example: naïve DGP

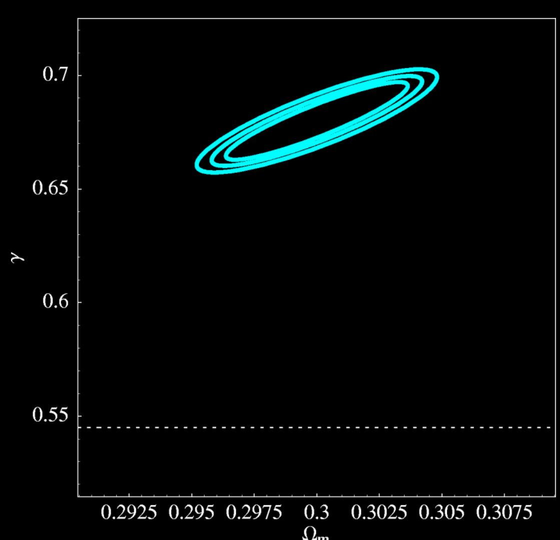
- DGP: brane-world model without dark energy
- scalar field: high sound speed prevents DE clustering
- the perturbations in the dark energy can perturb the dark matter
- and mimic models of modified gravity
- $\sigma = 0$ kills DGP, S/T, f(R)
- $\sigma \neq 0$ kills scalar field DE

-> we can test such models!



# weak lensing forecasts [DUNE]




lensing potential:

$$k^2(\phi+\psi) = Q(2+\eta)\frac{3H_0^2\Omega_m}{2a}\Delta_m$$

not just $\phi$ — don't forget! — $4\pi G a^2 \rho_m \Delta_m$

but $\Delta_m$ is also affected directly!

$$g \equiv \frac{\Delta_m}{a} = \exp\left\{\int_0^a d\ln a\,(\Omega_m(a)^\gamma - 1)\right\}$$

$\Sigma = Q\,(1+\eta/2) \sim 1+O(0.1)$ [except DGP (?)]

- these are very optimistic plots
- weak lensing has uncertain systematics
- and requires linear -> non-linear mapping
- very powerful if it works!

(talk by F. Silva)

# future experiments

- CMB: parameters, ISW; Planck, Bpol, ground (SZ/B)
- SN-Ia: w(z); lots (JDEM/SNAP, DUNE, ground†)
  - low-z : normalisation, probe of local universe
  - perturbations (→ C. Gordon), "luminosity tomography"
  - theoretical & statistical advances (reduce dispersion)
- BAO: w(z); SDSS, WFMOS, photometric†, Ly-$\alpha$ ($z \lesssim 3$)
  - complementary to SN-Ia (mostly linear physics, different)
- weak lensing: $\varphi+\psi$ [not DM!]; DUNE, JDEM, ground†
- galaxy surveys: growth rate, $\varphi$; SDSS, WFMOS
- (peculiar velocities: $\psi$; ?)
- LHC / dark matter searches: pin down DM, theory

†e.g. FMOS, DES, darkCAM, Pan-STARRS [~2009] / LSST, SKA [2014+]

→ talk by J. Weller yesterday

# conclusions

- the cosmological constant is still unbeaten
- we are still lacking a well-motivated and working model for either dark energy or modified gravity

- we know very little so far, for non-clustering DE and a flat universe: $-1.3 < w_{eff}(z \sim 0.3) < -0.7$ (at 3-4 σ)
- perturbations are next: $\{Q,\eta\} \leftrightarrow \{\varphi,\psi\} \leftrightarrow \{\sigma,\delta p\}$
  ➜ rule out modified gravity or scalar field DE?

- non-linear aspects badly understood but important