fingerprinting dark energy

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Outline

I) dark energy phenomenology

- what can we measure?
- what should we be looking for?

II) perturbations in scalar field DE

- what are they?
- (how) can we see them?

problem solving strategies

- forward: known model, predict observations
  - need to test lots of models
  - need to know correct model a priori
- backward: get model from observations
  - not all models are equivalent (e.g. 4D vs 5D)
- backward/forward: use intermediate, effective parametrisation
  - can be made general
  - can exclude/favour whole model classes

measuring dark things
(in cosmology)

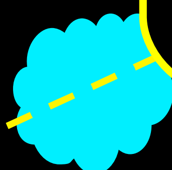
Einstein: $G_{\mu\nu} = 8\pi G T_{\mu\nu}$

(determined by the metric) → geomet

stuff (what is it?) ↕ your favourite theory

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

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



something else

smologists observe the geometry of space time

This depends on the ***total*** energy momentum tensor

That is what we measure!

measuring dark things
(in cosmology)

Einstein eq. (possibly effective):

$$G_{\mu\nu} - 8\pi G T_{\mu\nu}^{(bright)} = 8\pi G T_{\mu\nu}^{(dark)}$$

directly measured

given by metric:
- $H(z)$
- $\Phi(z,k)$, $\Psi(z,k)$

- inferred from lhs
- obeys conservation laws
- can be characterised by
  - $p = w(z)\,\rho$
  - $\delta p = c_s^2(z,k)\,\delta\rho$, $\pi(z,k)$

what can be measured?

only the total dark $T_{\mu\nu}$!

→ any further separation is arbitrary !

- 1 or 10 kinds of DE? We can't know!
- Interactions? Can test but not measure!
- Dark matter vs dark energy? Not unique!

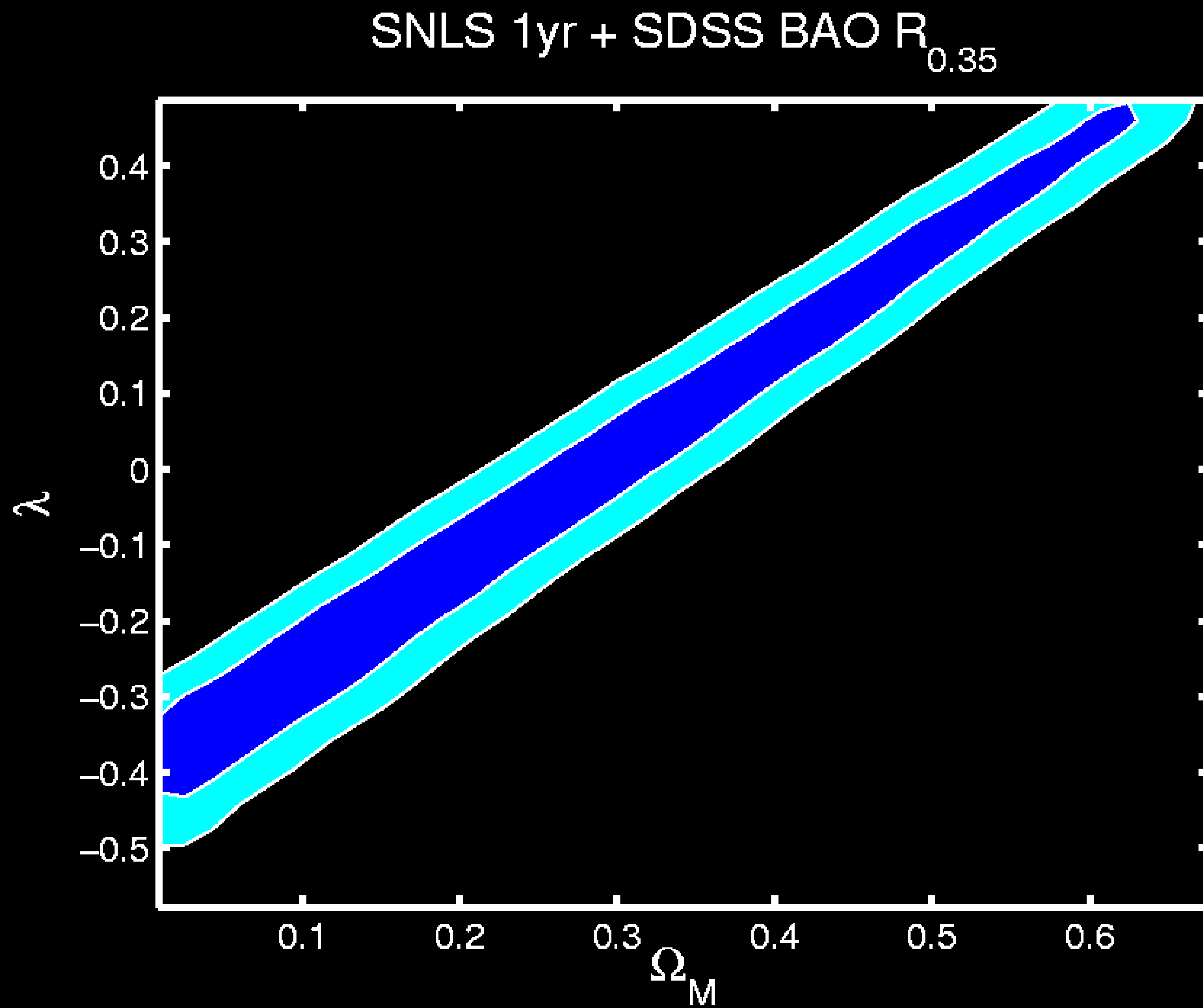
  (hey, wait, don't we know that Ω_m=0.3?)

In our minds, dark matter and dark energy are neatly separated concepts.

But in reality we can only observe their combined effect.

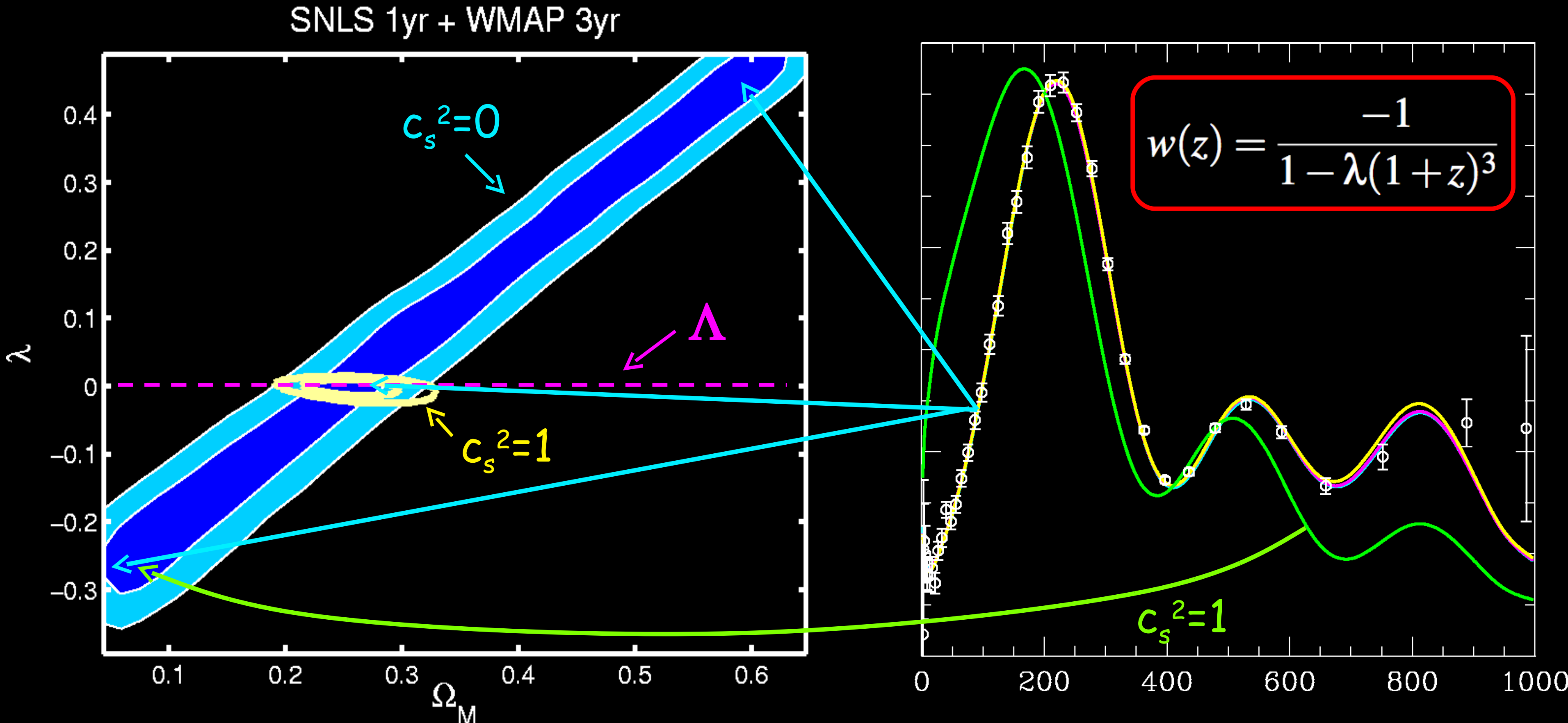
If we can adjust the temperature and flow of the hot water, we can vary the flow of the cold water without changing the total flow or the total temperature.

The true value of Ω_m is…



do we see DE perturbations?

Whenever you run CAMB, you make more choices than you think!
Only a cosmological constant has no perturbations.

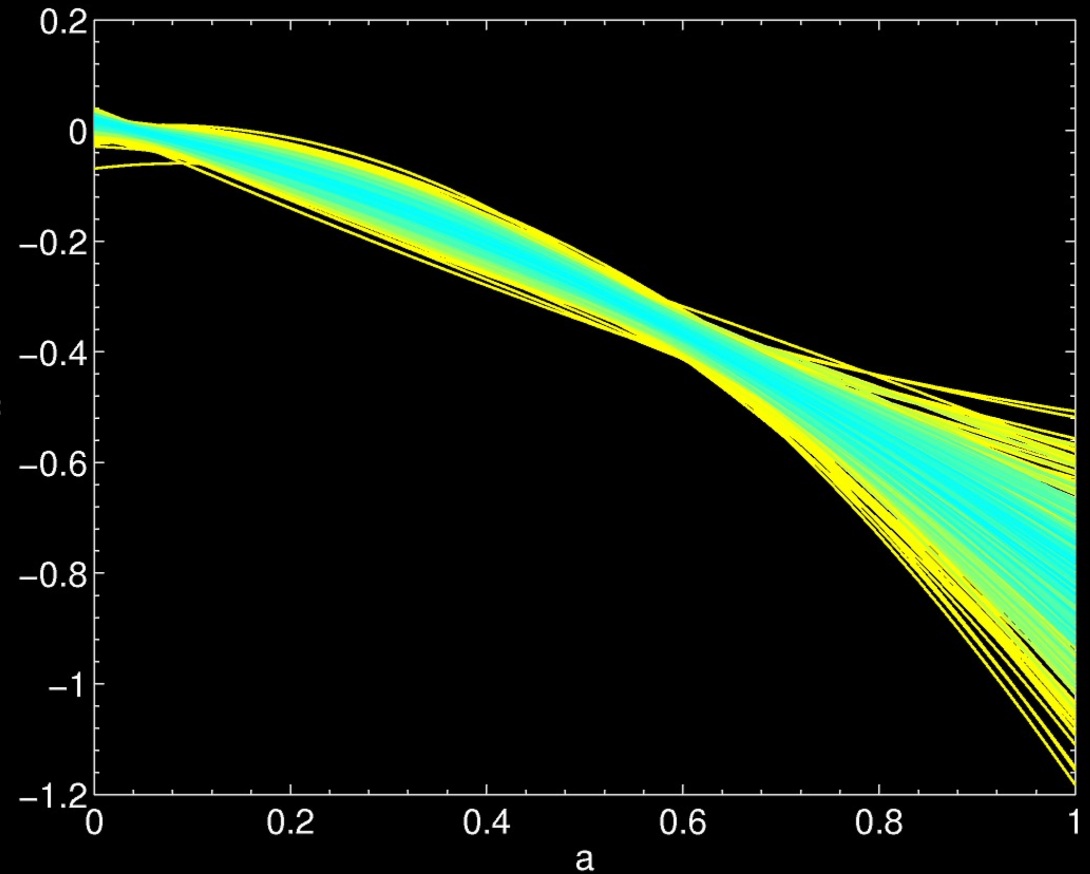


(c_s^2 << 1 can be achieved with $L \sim X^\alpha + V$, α >> 1 , $X = (\nabla\phi)^2$, also DBI, f(R)?)

MK, astro-ph/0702615, arXiv:0710.5712, PRD 80, 123001 (2009)

constraints on total dark w

- Union SNe, BAO and CMB peak location
- just distances, no perturbations
- quadratic expansion of w(a)
- best: χ^2 = 309.8
- LCDM: χ^2 = 311.9



MK, A. Liddle, D. Parkinson & C. Gao, PRD 80, 083533 (2009)

measuring the dark side

small perturbations: extended metric

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

ϕ, ψ gravitational potentials <-> δp and V perturbations of $T^{\mu\nu}$

Einstein eqs.

fluid properties

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

π (anisotropic stress, $\phi = \psi$ for $\pi=0$)

***measure* total** w, δp, π !

(and compare with predictions)

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

How to measure this?

- 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
- Could even skip DM, we cannot see it (yet)
- Need 3 probes (since 2 cons eq for DM)
- e.g. 3 power spectra: lensing, galaxy, velocity
- Lensing probes $\phi + \psi$
- Velocity probes ψ (z-space distortions?)
- And galaxy P(k) then gives bias (reqd for z-dist)

some model predictions

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

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: $V(\phi)$ <-> $w(z)$

therefore other variables fixed: $c_s^2 = 1$, $\pi = 0$

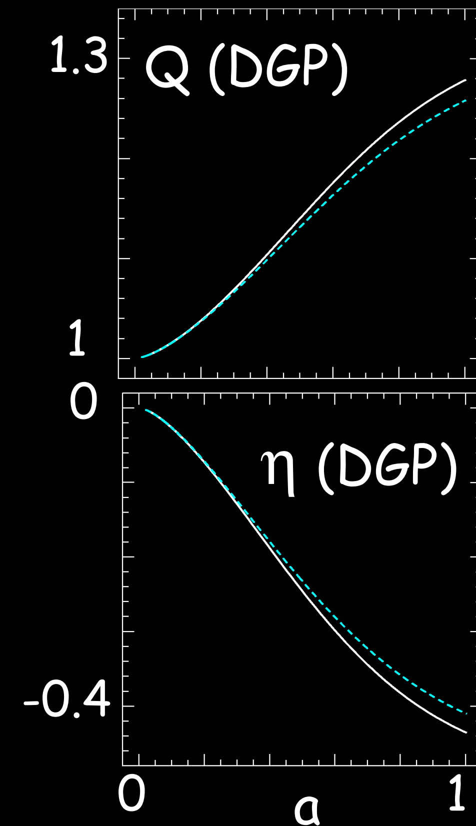
-> $\eta = 0$, $Q(k \gg H_0) = 1$, $Q(k \sim H_0) \sim 1.1$

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

Lue, Starkmann 04
Koyama, Maartens 06
Hu, Sawicki 07

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

implies large DE perturb.



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

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

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

Short summary

- We can always reconstruct an effective, phenomenological dark sector model.
- At first order perturbation level, we need always 2 new functions (plus w or H).

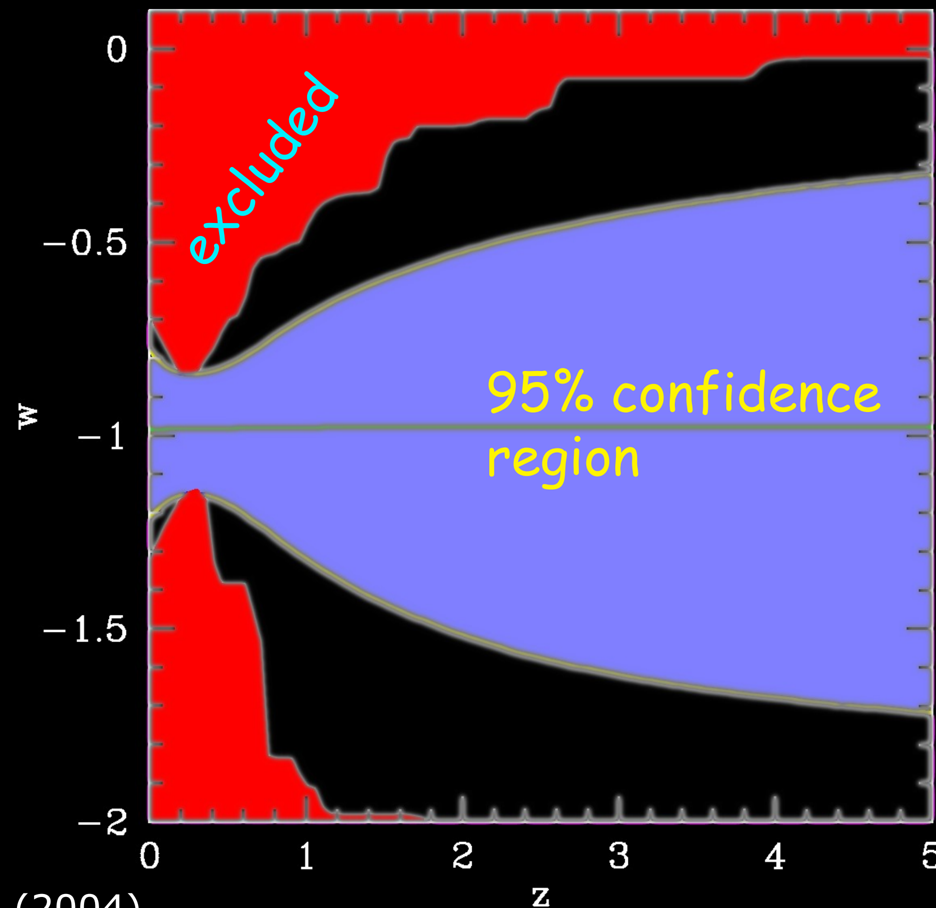
  → fingerprint of DE / MG model
- You DO specify these 2 functions as soon as perturbations are relevant!
- Also beware priors from parametrisations and other assumptions (FRW, ...)

scalar field dark energy

WMAP-3yr + SNLS-1yr limits:

- canonical scalar field model [<-> $c_s^2=1$, $\pi=0$]
- regularised transition of w=-1
- uses "kink" model for w(z)

- cosmological constant fits well
- w < -0.8 at z ~ 0.4
- can we detect the dark energy perturbations to confirm the nature of the DE? And how?



MK & D. Sapone, PRD **74**, 123503 (2006)
B.A. Bassett, P.S. Corasaniti & MK, ApJL 617, L1 (2004)
P.S. Corasaniti, MK, D. Parkinson, E.J. Copeland & B.A. Bassett, PRD **70**, 083006 (2004);
MK, P.S. Corasaniti, D. Parkinson & E.J. Copeland, PRD **70**, 041301R (2004);
B.A. Bassett, MK, D. Parkinson & C. Ungarelli, PRD **68**, 043504 (2003);
B.A. Bassett, MK, J. Silk & C. Ungarelli, MNRAS **336**, 1217 (2002)
& lots of others, some in the audience!

'analytical' scalar field DE

(D. Sapone & MK PRD80, 083519 (2009) ,
D. Sapone, MK and L. Amendola, arXiv:1007.2188)

scalar field 'fingerprint': w ~ arbitrary, $c_s=1$, $\pi=0$

generalisation: c_s arbitrary constant

(but we take w constant as well)

→ two scales:

1) horizon scale $k = aH$
2) sound horizon scale $c_s k = aH$

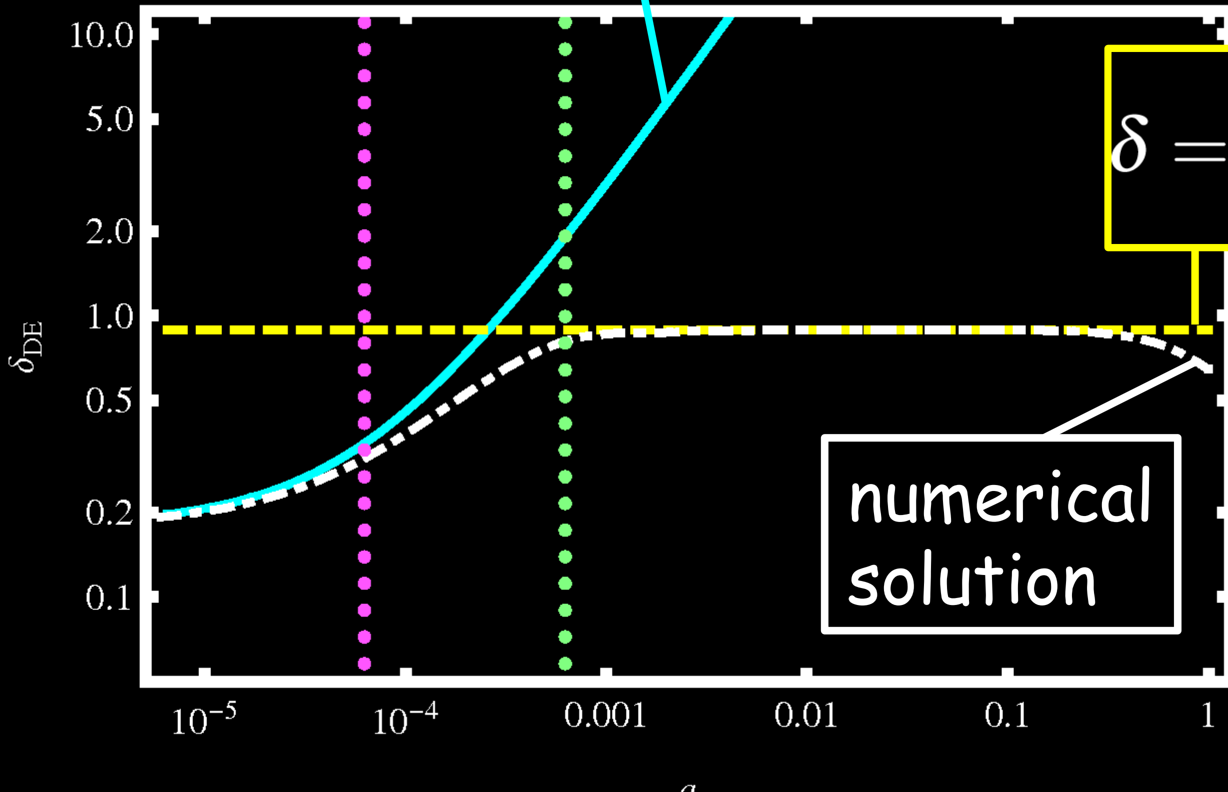
matter domination

Φ = constant, $\delta_m \sim a$

$$\delta = \delta_0 (1+w)\left(\frac{a}{1-3w} + \frac{3H_0^2\Omega_m}{k^2}\right)$$

→ $\delta(w=-0.8) \lesssim 1/20\ \delta(w=0)$ on subhorizon scales

$$\delta = \delta_0 \frac{3}{2}(1+w)\frac{H_0^2\Omega_m}{c_s^2 k^2}$$



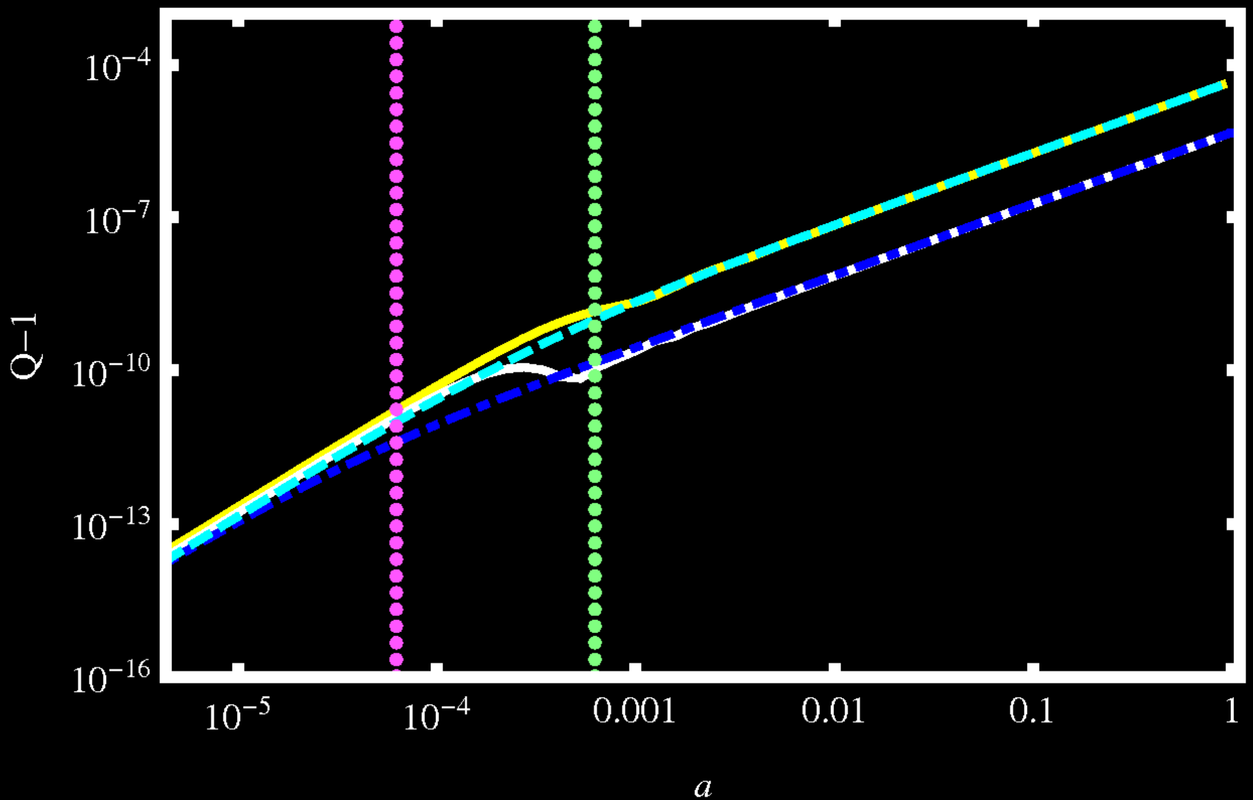
- $w = -0.8$
- $c_s = 0.1$
- $k = 200\ H_0$

beyond m.d. → Q(k,z)

$$k^2\phi = -4\pi G a^2 \left(\rho_m \Delta_m + \rho_{\mathrm{DE}} \Delta_{\mathrm{DE}}\right) = -4\pi G a^2 Q \rho_m \Delta_m$$

$$Q - 1 = \left(\frac{1-\Omega_m}{\Omega_m}\right)\left(\frac{1+w}{1-3w}\right) a^{-3w} \lesssim 0.2 a^{-3w}$$

super-sound-horizon



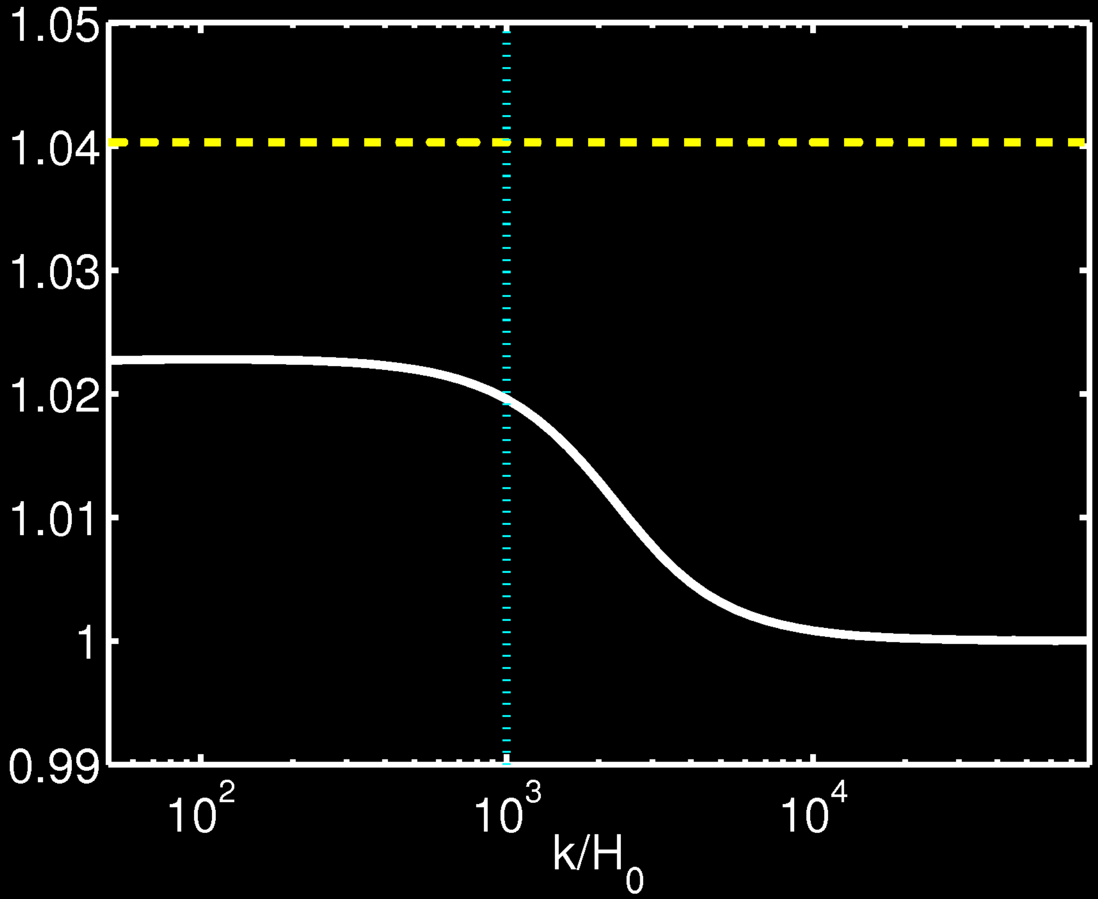
Q-1 suppressed by one power of a inside the sound horizon.

→ scale dependence

a^{-3w} from scaling of ρ → early DE can be more important.

impact on matter power spect.

The additional contribution to Φ from Q changes the matter growth → both P(k) and γ are changed.



P(k) is enhanced by a few % outside sound horizon.

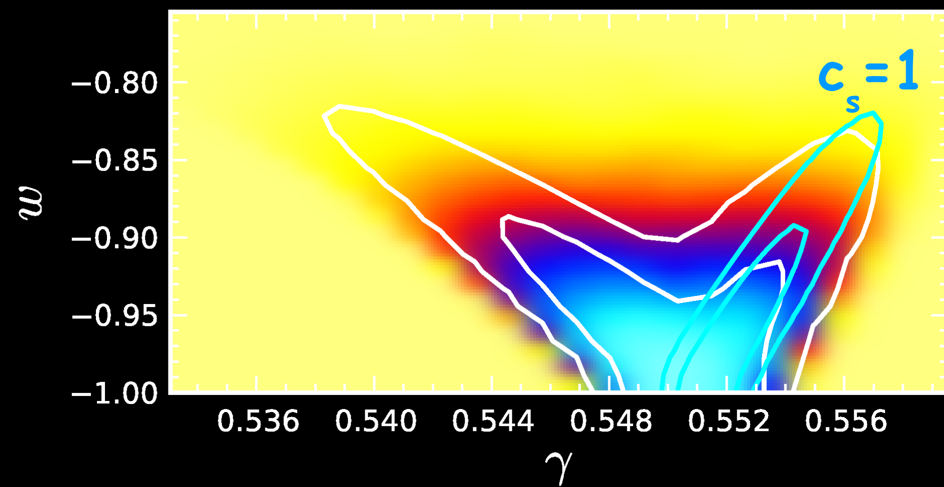
Everything is now scale dependent!

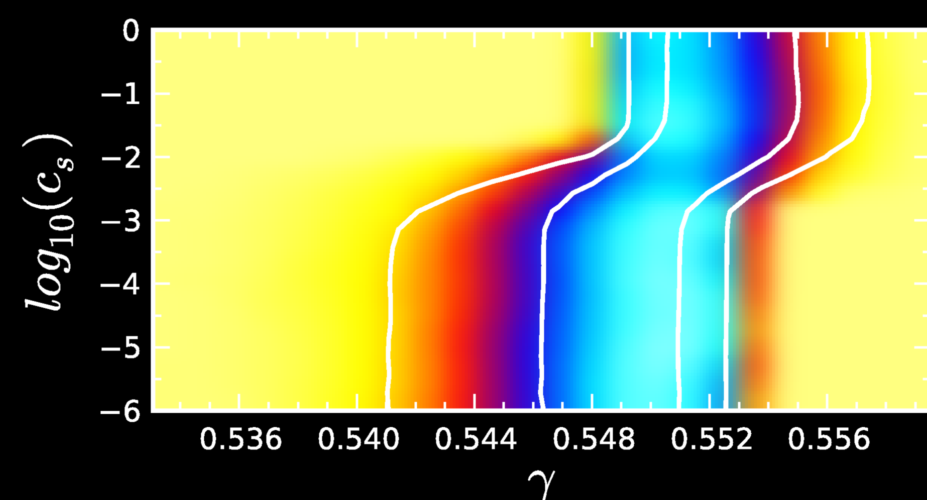
gamma (matter growth)

$$\frac{d\log\Delta_m}{d\log a} = \Omega(a)^\gamma$$

$$\gamma \approx \frac{3(1-w)}{5-6w} + f(Q,\eta)$$

E.V. Linder & R.N. Cahn 2007
L. Amendola, MK & D. Sapone 2008





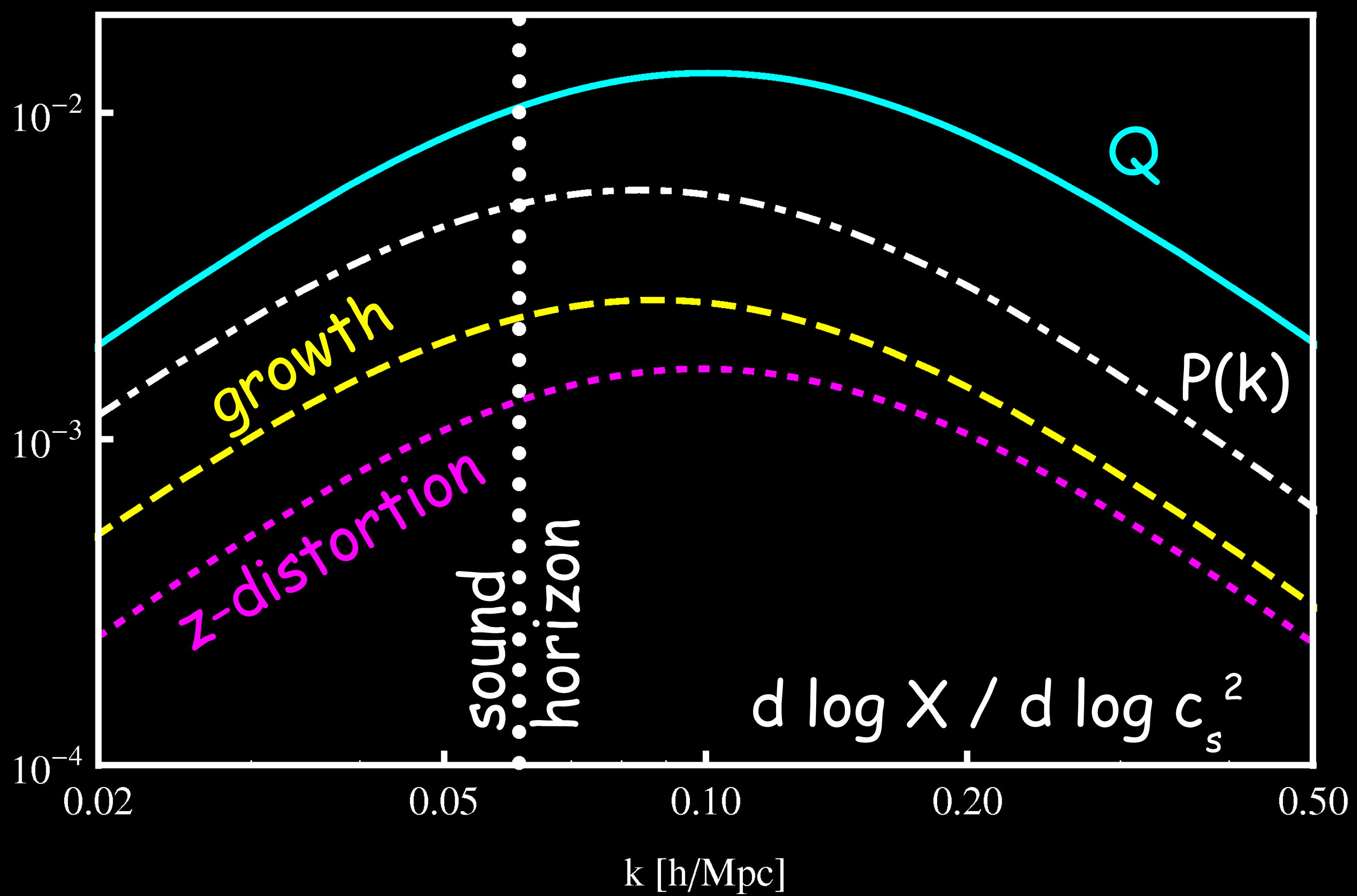
- γ picks up scale dependence
- perturbation corrections 'turn on' as sound horizon passes scale on which γ computed
- γ always decreased by DE perturbations for w>-1, η = 0

(Lukas Hollenstein, priv. comm.)

sensitivity to sound horizon

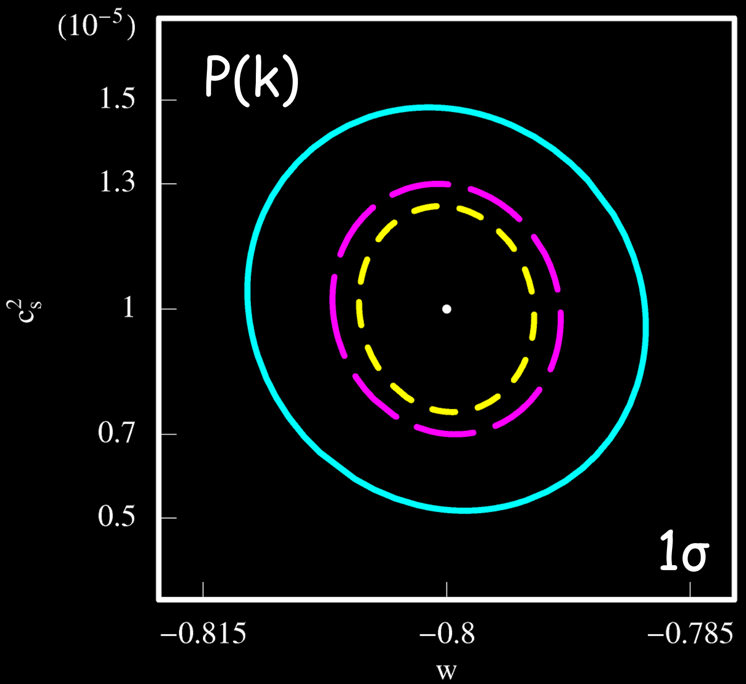
lensing: $2\Phi \rightarrow Q\,\Delta_m \rightarrow$ Q, growth, shape

galaxy survey: $P(k,a) \rightarrow$ growth, shape, RSD



redshift dependence differs: RSD stronger at low redshift

can we see the DE sound horizon?

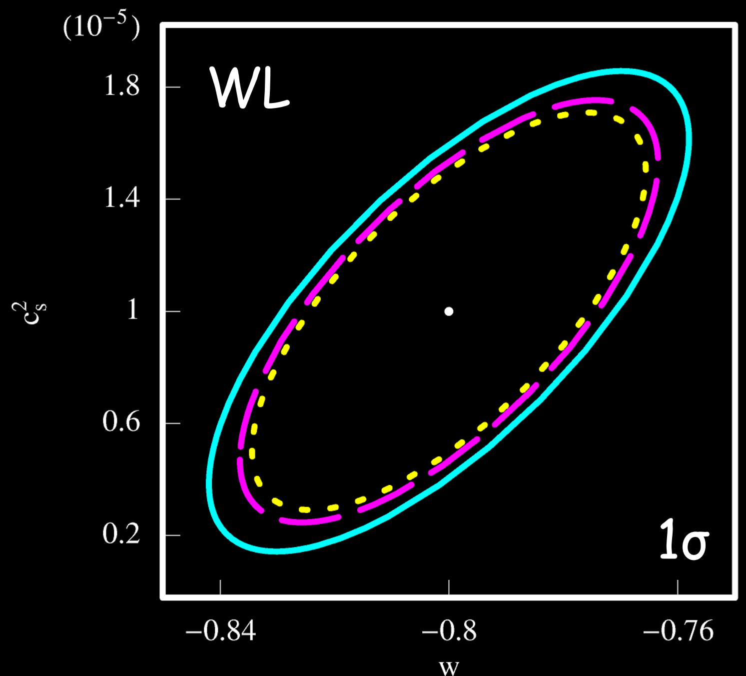


two large surveys to z_{max} = 2, 3, 4

fiducial model has w=-0.8

→ only if c_s<0.01 can we measure it!

(for w=-0.9 we need c_s<0.001)



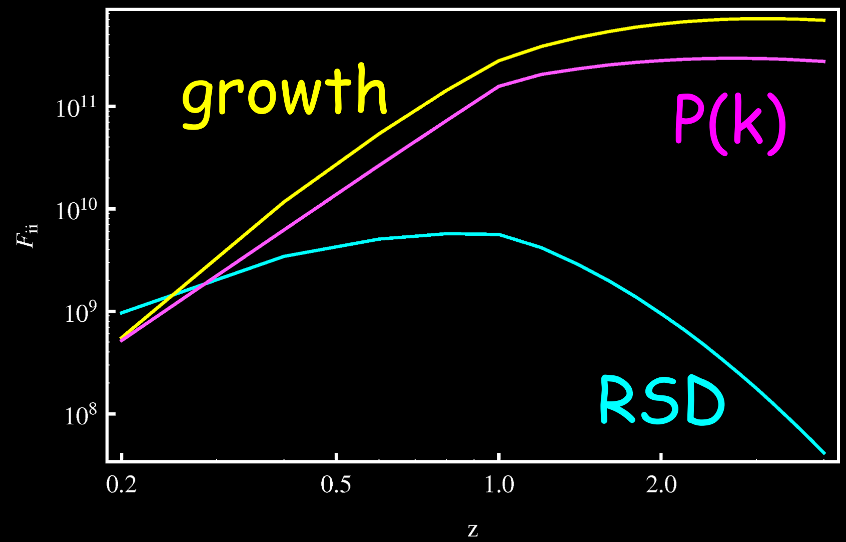
$P(k)$+WL			
c_s^2	σ_{w_0}	$\sigma_{c_s^2}/c_s^2$	σ_W/W
10^{-5}	0.00639	0.15	0.11
10^{-4}	0.00581	0.41	0.36
10^{-3}	0.00547	0.87	1.02
10^{-2}	0.00531	2.48	2.39
10^{-1}	0.00528	14.79	13.14
1	0.00524	22.05	21.29

what do we see?

We can turn off certain contributions and check how the errors change:

- ISW: driven by Q (direct DE contribution to Φ)
- WL: driven by Q (direct DE contribution to Φ)
- P(k): high cs → shape of P(k) [but not enough]
  low cs → mostly RSD and growth

Fisher matrix elements for galaxy survey, $c_s^2 = 1e\text{-}5$, $w = -0.8$



conclusions

- linear perturbations: w + 2 new functions
- provide a fingerprint for DE / MG
- need to be included correctly in data analysis (as soon as you go beyond ΛCDM)
- will be difficult to measure! E.g. we can only see perturbations in 'cold dark energy'
- how to best parametrise extra d.o.f.?
- what do we expect from theory?
- how to deal with non-linear scales?
- discussion meeting Monday 5pm