UNIVERSITÉ DE GENÈVE

(cosmological) tests of acceleration: why and what

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testing acceleration...

Outline

- quantifying the acceleration
- does inflation look like dark energy?
- beyond w
  - formalism
  - examples
  - what can we learn
- outlook + summary

measuring dark things
(in cosmology)

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

(determined by the metric) → geomet

stuff (what is it?)

↕

ur favourite theory

something else

assuming FLRW:

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

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

nologists observe the
metry of space time

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

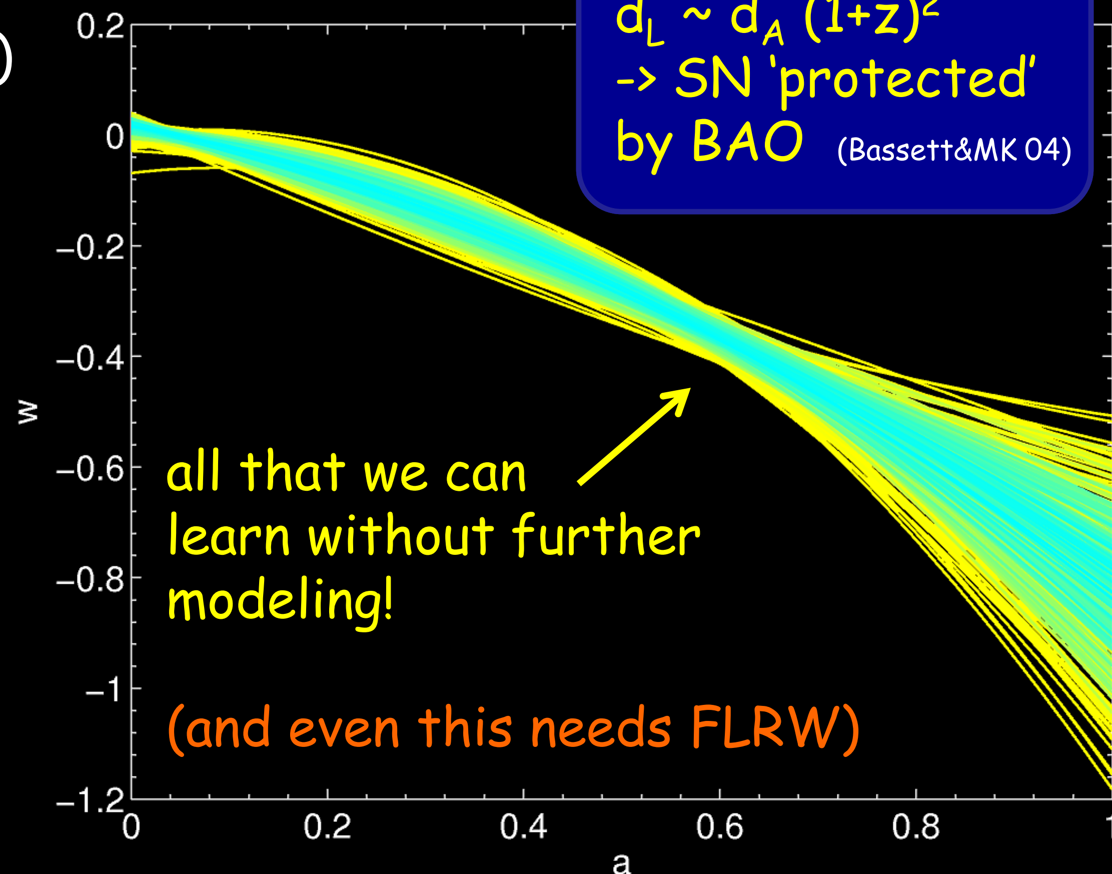
That is what we measure!

constraints on the total w

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

→ rewrite $p = w\,\rho$

- quadratic expansion of w(a)
- fit to Union SNe, BAO and CMB peak location
  → just distances, no perturbations



$d_L \sim d_A\,(1+z)^2$
-> SN 'protected' by BAO (Bassett&MK 04)

all that we can learn without further modeling!

(and even this needs FLRW)

- best: χ^2 = 309.8
- ΛCDM: χ^2 = 311.9
- w const.: χ^2 = 391.3

definitely not w=0!

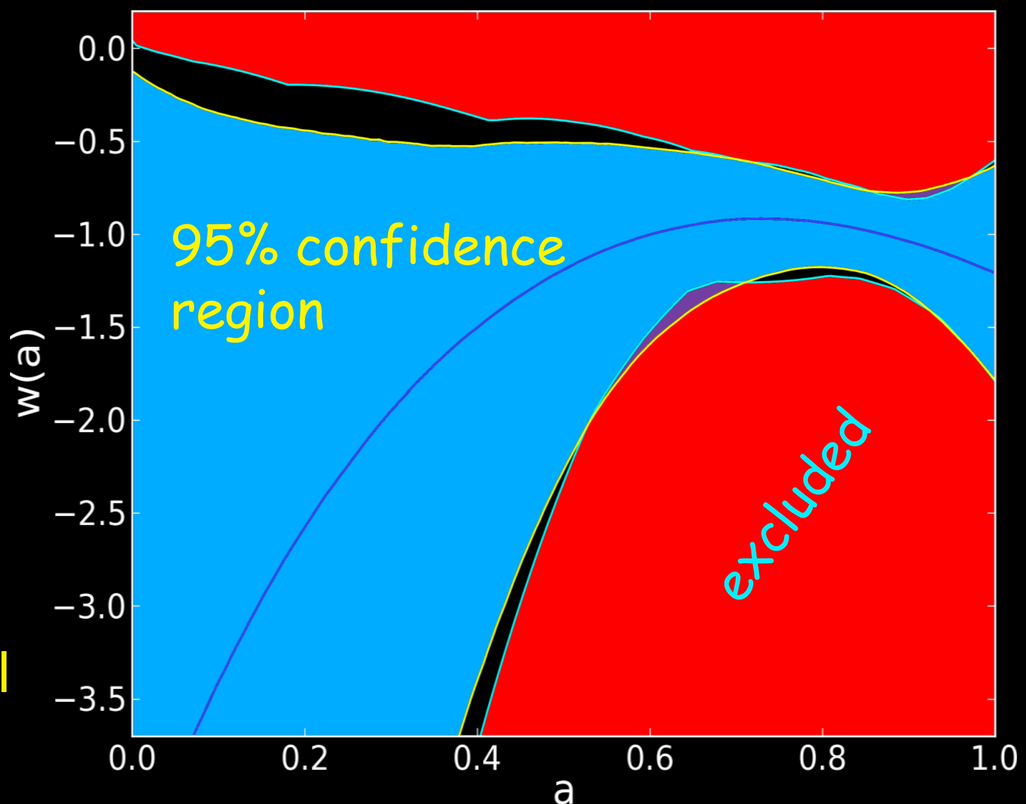
MK, A. Liddle, D. Parkinson & C. Gao, PRD 80, 083533 (2009)

dark energy w(a)

total w : weighted combination of w_{DE} and $w_{DM}(=0)$

→ what is what?

→ need specific model for DE!



- canonical scalar field model [↔ $c_s^2=1$, $\sigma=0$]
- WMAP-7yr + SN-Ia compilation
- regularised transition of w=-1
- cubic expansion of w(a)

- cosmological constant fits well
- $|1+w| < 0.2$ at $a \sim 0.8$ @ 2σ

To make this figure, we needed to fix the perturbations – but what can/should be fixed?

very early dark energy?

The cosmological constant (w=-1, no perturbations) fits the data very well. Why look further?

Because we don't like it!

Inflation is usually modeled as a period of accelerated expansion, just like dark energy

- Is this unavoidable?
- Was inflation due to a cosmological constant?
- What would we have observed during inflation?

causal sources after COBE?

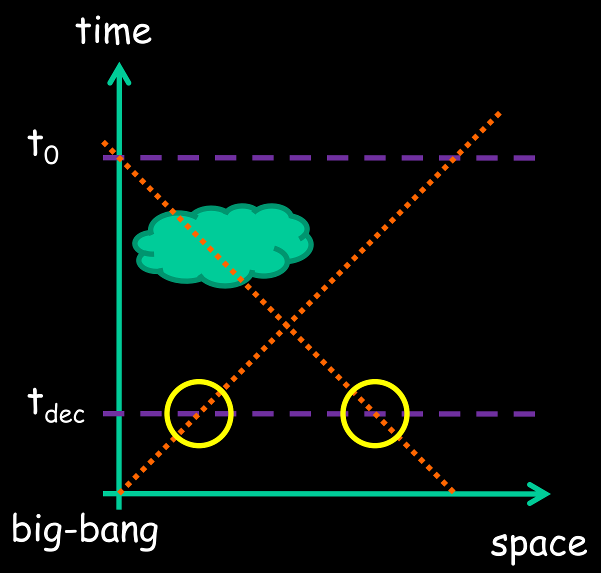
COBE observed fluctuations correlated on scales much larger than the horizon at last scattering!

-> Horizon problem

-> is this not proof of "acausal" physics?

NO!

Can create them at late times with time-dependent potentials (ISW).



(a)causality constraints

(Scodeller, MK & Durrer, 2009)

outgoing spherical shells of energy with velocity v

accepted points in MCMC chain

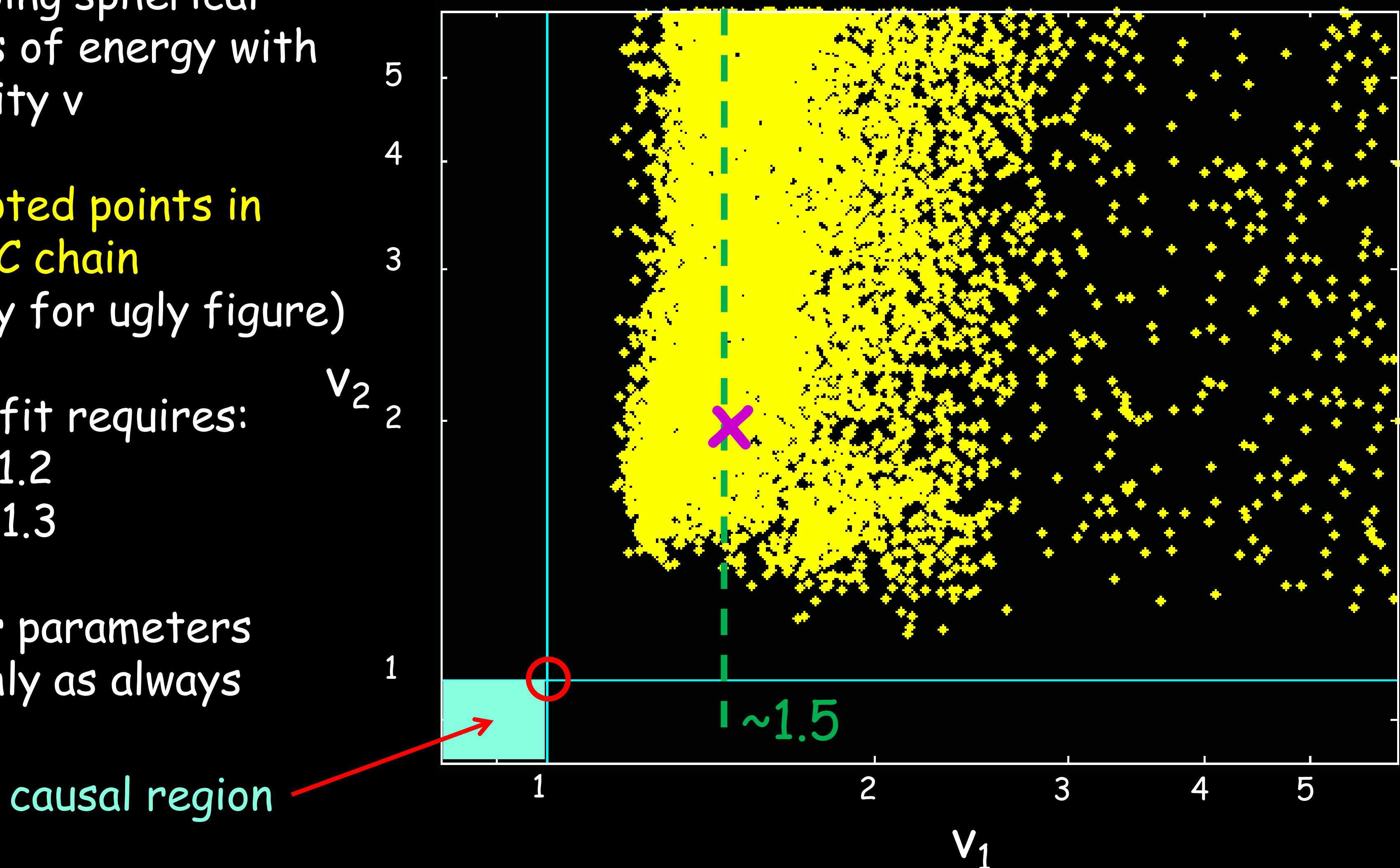
(sorry for ugly figure)

good fit requires:

$v_1 > 1.2$

$v_2 > 1.3$

other parameters roughly as always



TE cross-polarisation

Polarisation induced at last scattering and reionisation [Spergel & Zaldarriaga, 1997] -- TE shows a dip around l ~ 100 :

adiabatic density mode ~ $\cos(kc_s t_{dec})$

velocity mode: derivative ~ $\sin(kc_s t_{dec})$

TE: $\sin(2kc_s t_{dec})$

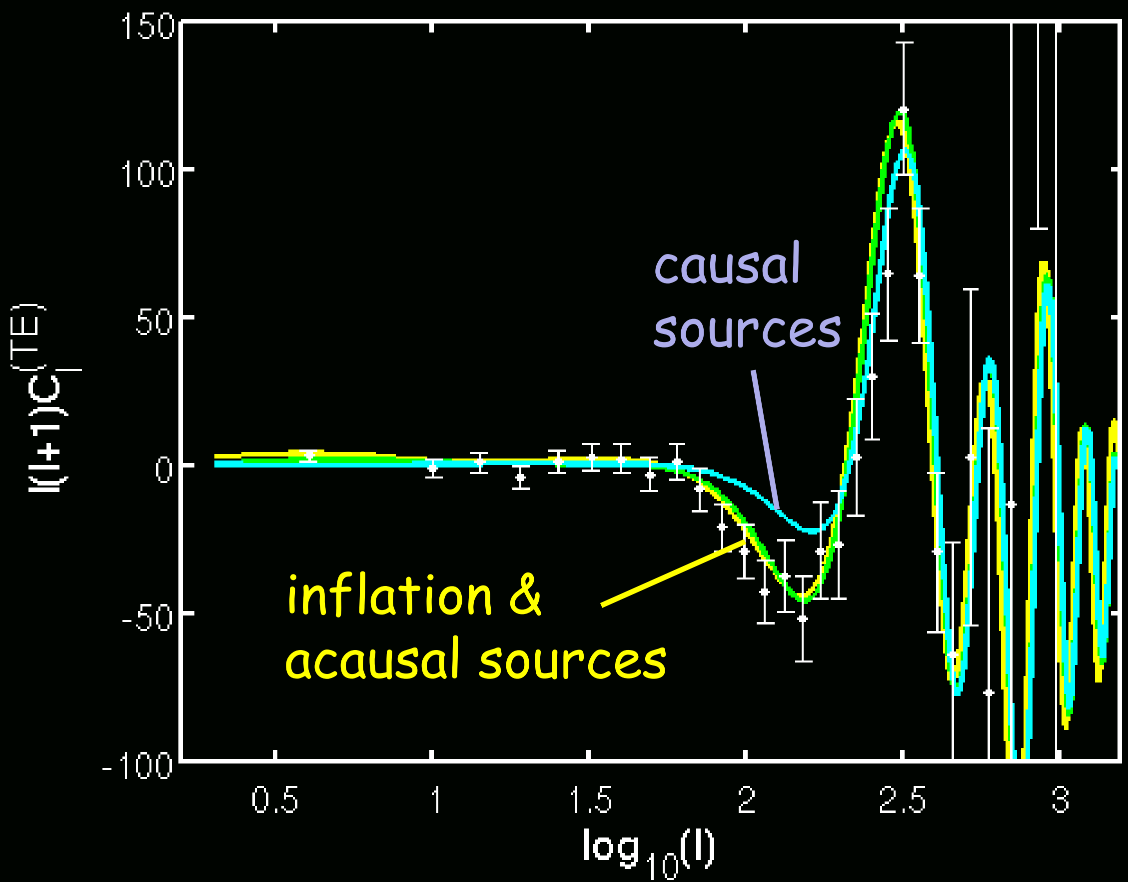
peak: $kt_{dec} \approx 0.66$

horizon: $kt_{dec} \sim 1/v$

-> $v \sim 1.5$

possibilities:

- inflation
- acausal physics
- huge reionisation fine-tuning (?)

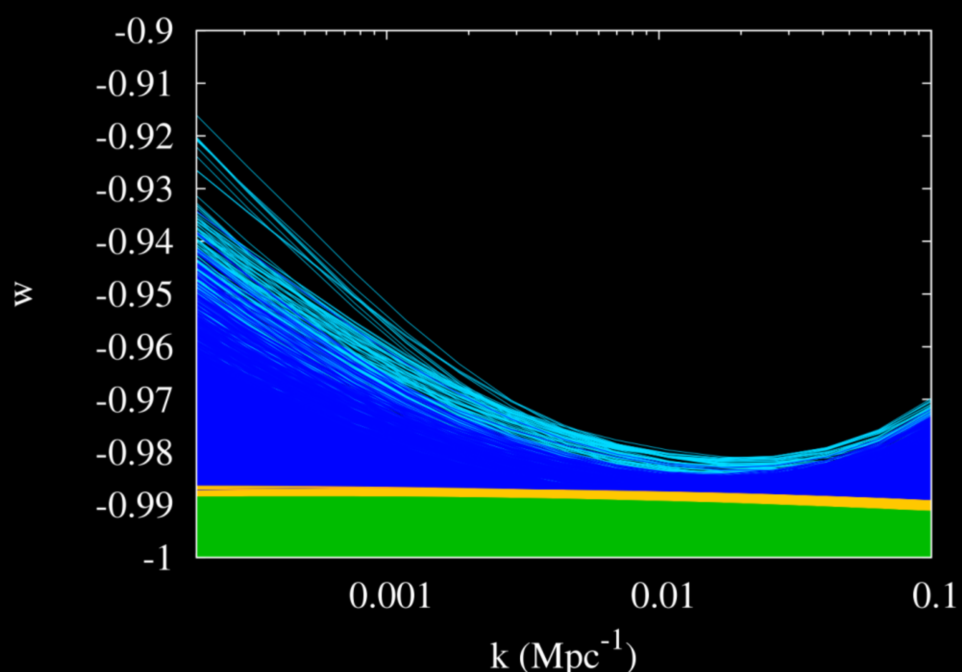


w during inflation

(Ilic, MK, Liddle & Frieman, 2010)

- Scalar field inflaton: $1+w = -\frac{2}{3}\frac{\dot{H}}{H^2} = \frac{2}{3}\epsilon_H$ and r = T/S ~ 24 (1+w)
- Link to dw/da: $\frac{d\ln(1+w)}{dN} = 2(\eta_H - \epsilon_H)$ $2\eta_H = (n_s - 1) + 4\epsilon_H$

$n_s \neq 1 \Rightarrow \epsilon \neq 0$ or $\eta \neq 0$
=> $w \neq -1$ and/or w not constant



WMAP 5yr constraints on w:
- (1+w) < 0.02
- No deviation from w=-1 necessary

(but in the middle of long slow-roll period, not clear if representative of dark energy)

→ w ~ -1 appears natural during observable period of inflation
→ but it was not an (even effective) cosmological constant!

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
  - $p = w(z)\,\rho$
  - $\delta p = c_s^2(z,k)\,\delta\rho$, $\pi(z,k)$

(MK & Sapone 2007;
Hu & Sawicki 2007)

linear perturbation equations

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

conservation equations (in principle for full dark sector)

$$\delta_i' = 3(1+w_i)\phi' - \frac{V_i}{Ha^2} - \frac{3}{a}\left(\frac{\delta p_i}{\rho_i} - w_i\delta_i\right) \qquad \delta p = c_s^2\delta\rho + 3Ha(c_s^2 - c_a^2)\rho\frac{V}{k^2}$$

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

(vars: $\delta=\delta\rho/\rho$, V ~ divergence of velocity field, δp , σ anisotropic stress)

Einstein equations (common, may be modified if not GR)

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

$$k^2(\phi - \psi) = 12\pi G a^2 \sum_i (1+w_i)\rho_i\sigma_i$$

(Bardeen 1980)

simplified observations

- Curvature from radial & transverse BAO
- w(z) from SN-Ia, BAO directly (and contained in most other probes)
- 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 $\phi + \psi$
- Velocity probes ψ (z-space distortions?)
- And galaxy P(k) then gives bias

$\rightarrow$ what do we learn if we do this?

some model predictions

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

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

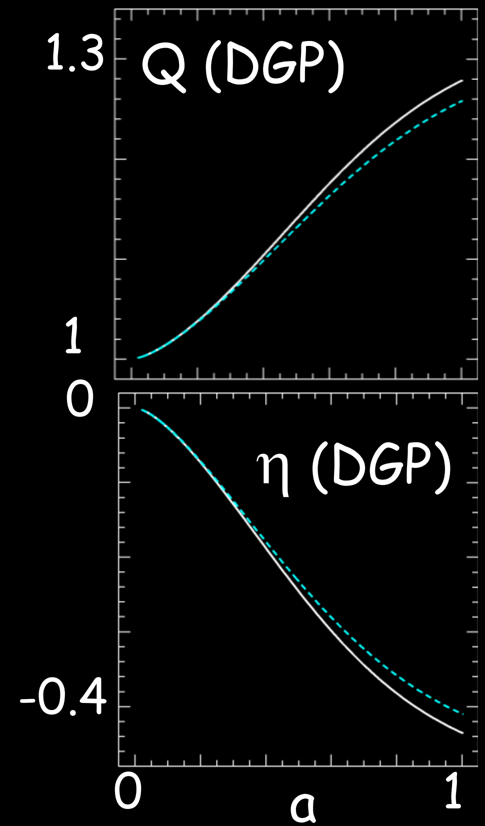
One degree of freedom: $V(\phi)$ <-> $w(z)$
therefore other variables fixed: $c_s^2 = 1$, $\sigma = 0$
-> $\eta = 0$, $Q(k \gg H_0) = 1$, $Q(k \sim H_0) \sim 1.1$

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

Lue, Starkmann 04
Koyama, Maartens 06
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

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

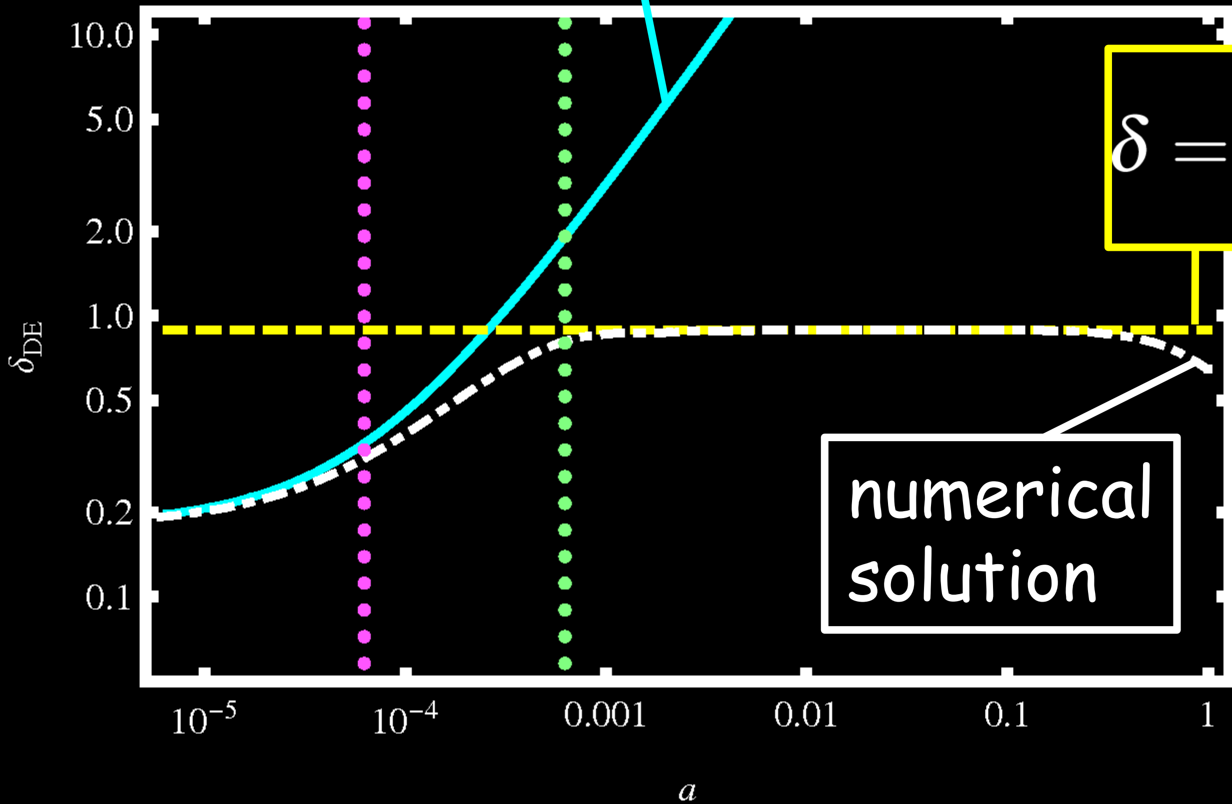
$$\eta = \frac{F'^2}{F + F'^2} \qquad Q = \frac{G^*}{F G_0}\frac{2(F + F'^2)}{2F + 3F'^2}$$

behaviour of scalar field δ

model $\{w, c_s, \sigma=0\}$;   matter dom.: Φ = constant, $\delta_m \sim a$

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

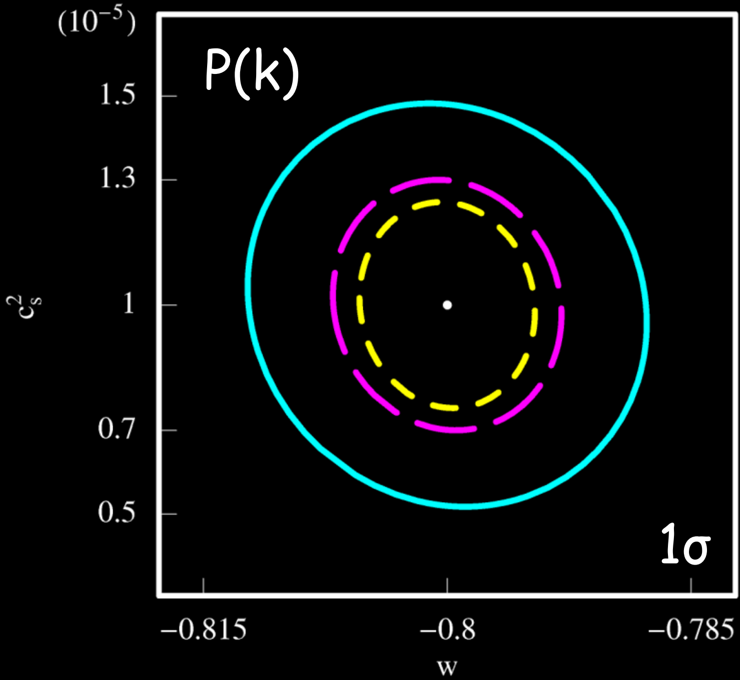
→ δ(w=-0.8) ≤ 1/20 δ(w=0) on subhorizon scales



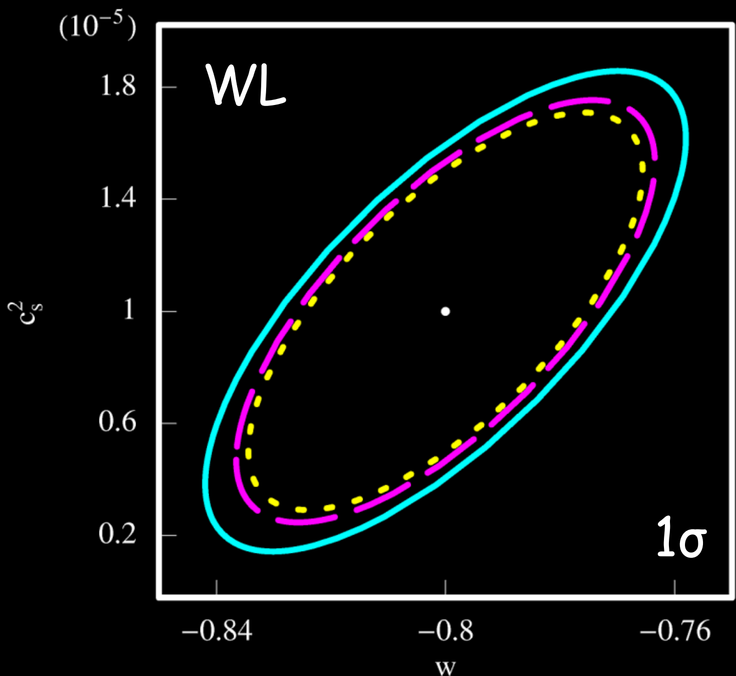
$$\delta = \delta_0 \frac{3}{2} (1+w) \frac{H_0^2 \Omega_m}{c_s^2 k^2}$$

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

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

(Sapone & MK 2009; Sapone, MK & Amendola 2010)

the importance of η / σ

(Saltas & MK 2011, cf talk yesterday afternoon)

scalar-tensor theories: $\eta = \frac{F'^2}{F + F'^2}$

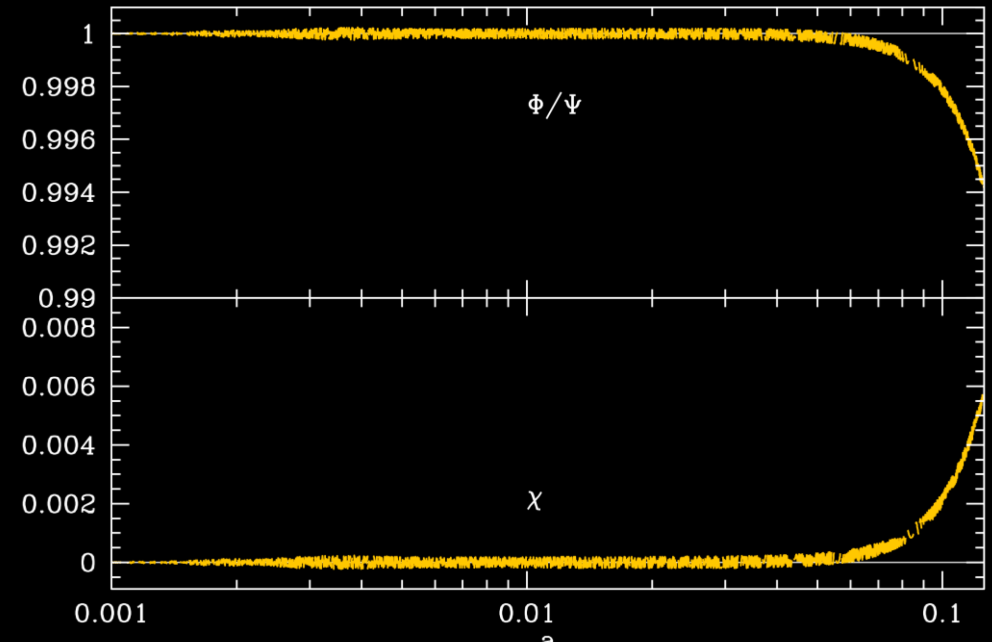
f(R) theories: η = 0 ↔ f''(R) = 0; R+f(G): η = 0 ↔ f''(G) = 0

f(R,G): in de Sitter background requires mass of effective scalar to diverge → instabilities, dS cannot be reached dynamically

also in DGP η ≠ 0!

canonical scalar field: η = 0
→ standard 'GR' model: at late times only very small anisotropic stress from relativistic particles

→ η can rule out whole classes of models!



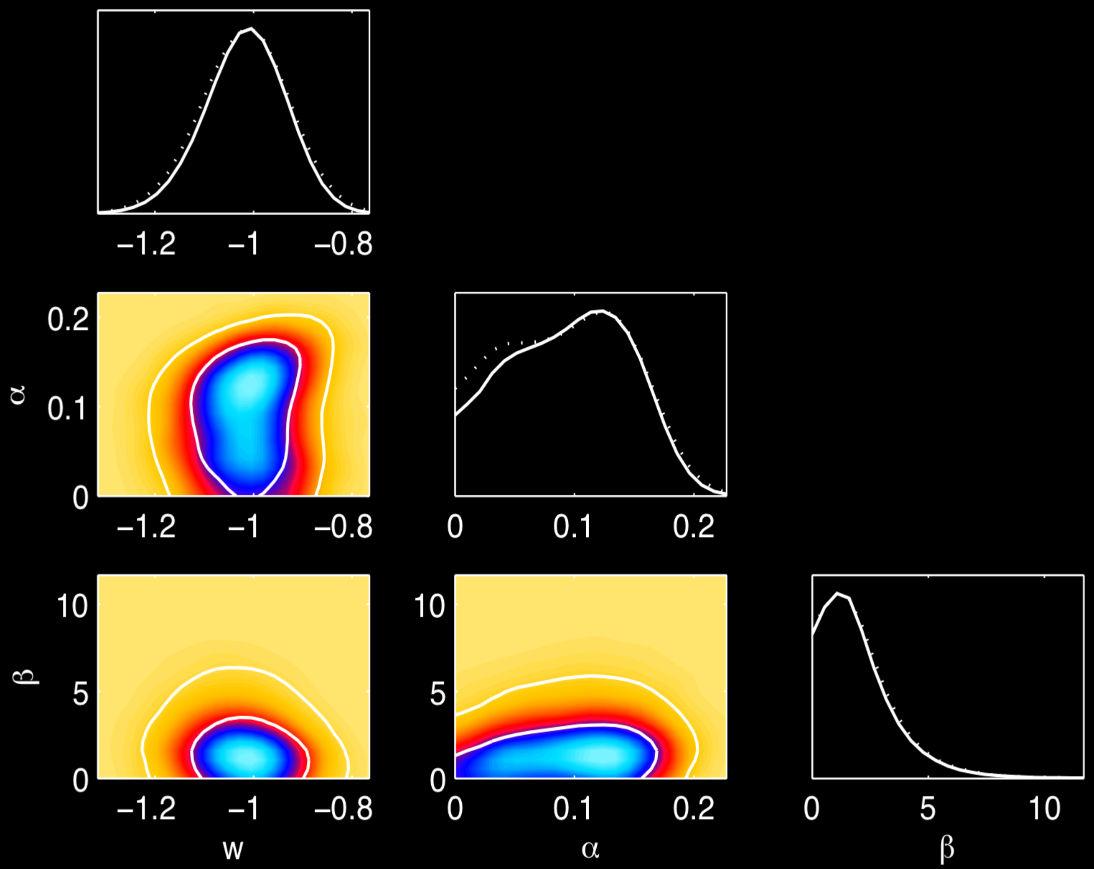
(Pogosian & Silvestri 2008)

current constraints on σ~(ϕ-ψ)

(from Lukas Hollenstein, private communication)

Inspired by modified gravity models: $\sigma \sim \alpha\, \Delta_m + \beta\, \psi$

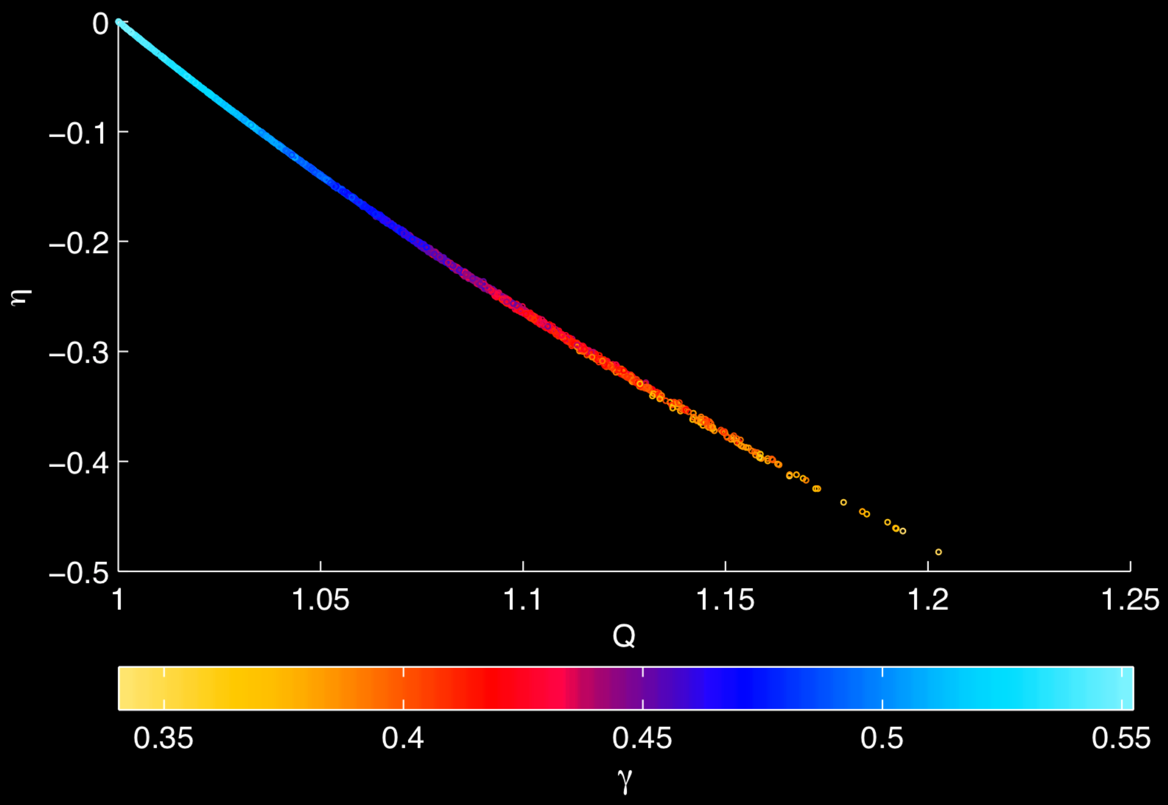
- WMAP-7yr & SN-Ia data compilation
- w, α, β constant
- $c_s = 1$ ($\rightarrow Q \approx 1$ for $\sigma = 0$)
- w consistent with -1
- α, β consistent with 0
- no signs of anything strange going on



expressed as Q and eta

(again Lukas Hollenstein)

- Projection on Q and η (on small scales)
- Need to vary also c_s^2 (δp) to access more of parameter space
- really need 2 extra parameters!
- again consistent with standard model



→ current constraints are weak, O(1) in Q and η!
→ no deviation from standard cosmology ('GR')

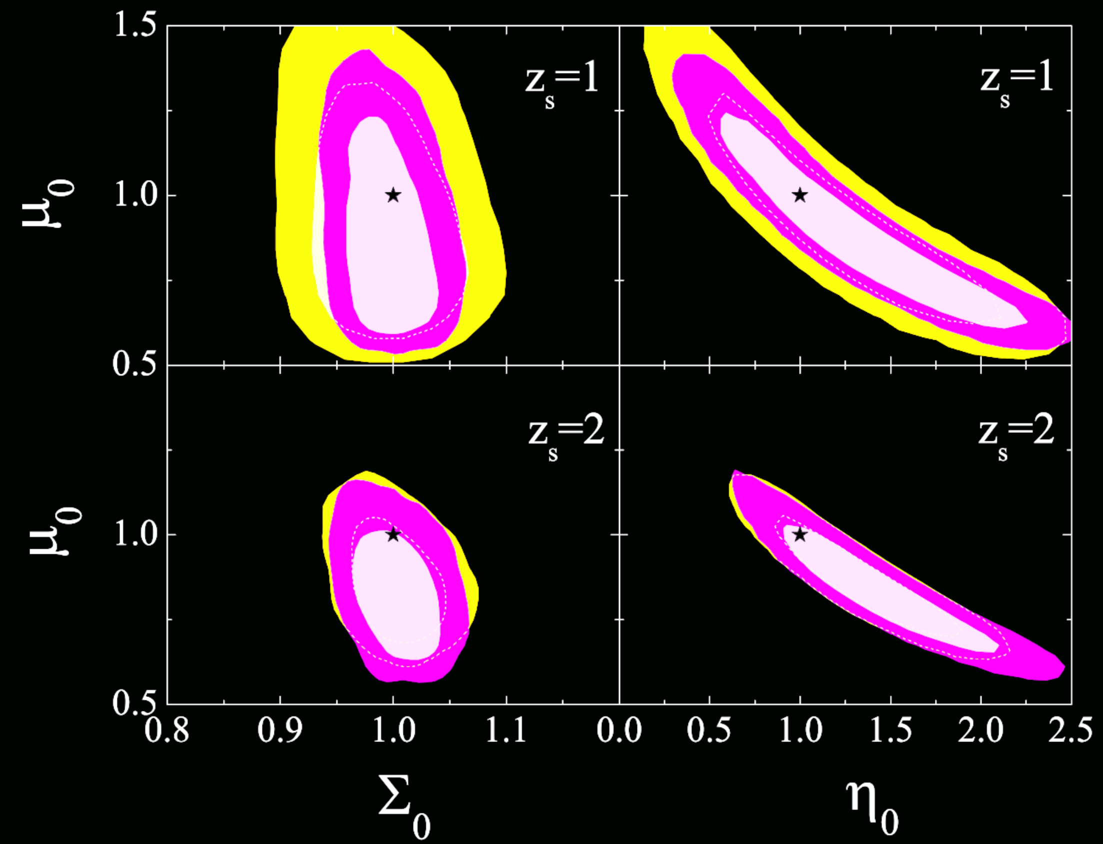
current state of constraints

methodology:
'just' stick a model into a likelihood for as much data as you believe

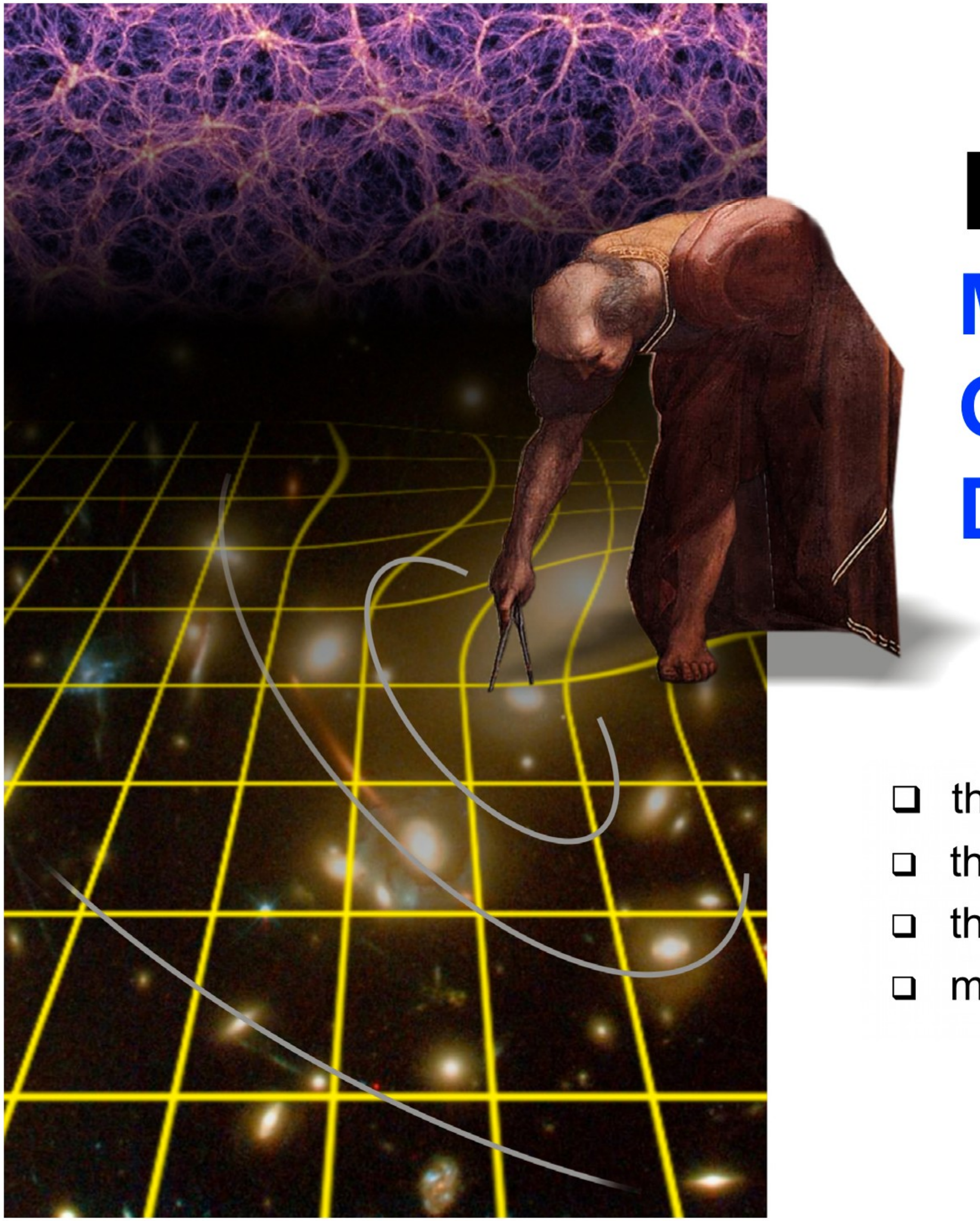
model:
binned or parametrised variables, e.g. {w, Q, η}

data:
SN-Ia & BAO: constrain w
CMB: other params + ISW
WL: beware systematics

result:
weak constraints, no deviations from LCDM



(Zhao et al 2010)
WL+CMB+ISW, model w/ transition
μ: modified Poisson eqn. in ψ ~ Q
Σ: lensing (ϕ+ψ), η ~ ϕ/ψ



Euclid

Mapping the Geometry of the Dark Universe

- the nature of the Dark Energy
- the nature of the Dark Matter
- the initial conditions (Inflation Physics)
- modifications to Gravity

esa

The Euclid Mission

Primary probes:
all-sky Vis+NIR imaging and spectroscopic survey
• Weak Lensing
• Galaxy Clustering, BAO

Additional Probes: cluster counts, redshift space distortions, integrated Sachs-Wolfe effect

huge legacy data set!

other science: strong lensing, galaxy evolution, star formation, supernovae, extrasolar planets (even Earth-sized planets in habitable zone!)

conclusions

- ✓ if metric is close to FLRW, then acceleration is detected at very high significance
- ✓ behaviour is compatible with cosmological constant
- ✓ even when taking into account perturbations
- ✓ but same would have been true during inflation

- ✓ we need to improve measurements of perturbations as they are a good model discriminator
- ✓ example: anisotropic stress and modifications of GR
- ✓ first goal should be: Kill ~~Bill~~ Lambda

- ✓ need to combine probes, e.g. lensing and velocities
- ✓ Euclid would be a great mission for this purpose