Fingerprinting dark energy: observational tests

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Outline

I) dark energy phenomenology

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

II) perturbations in de

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

measuring dark things (in cosmology)

Einstein:

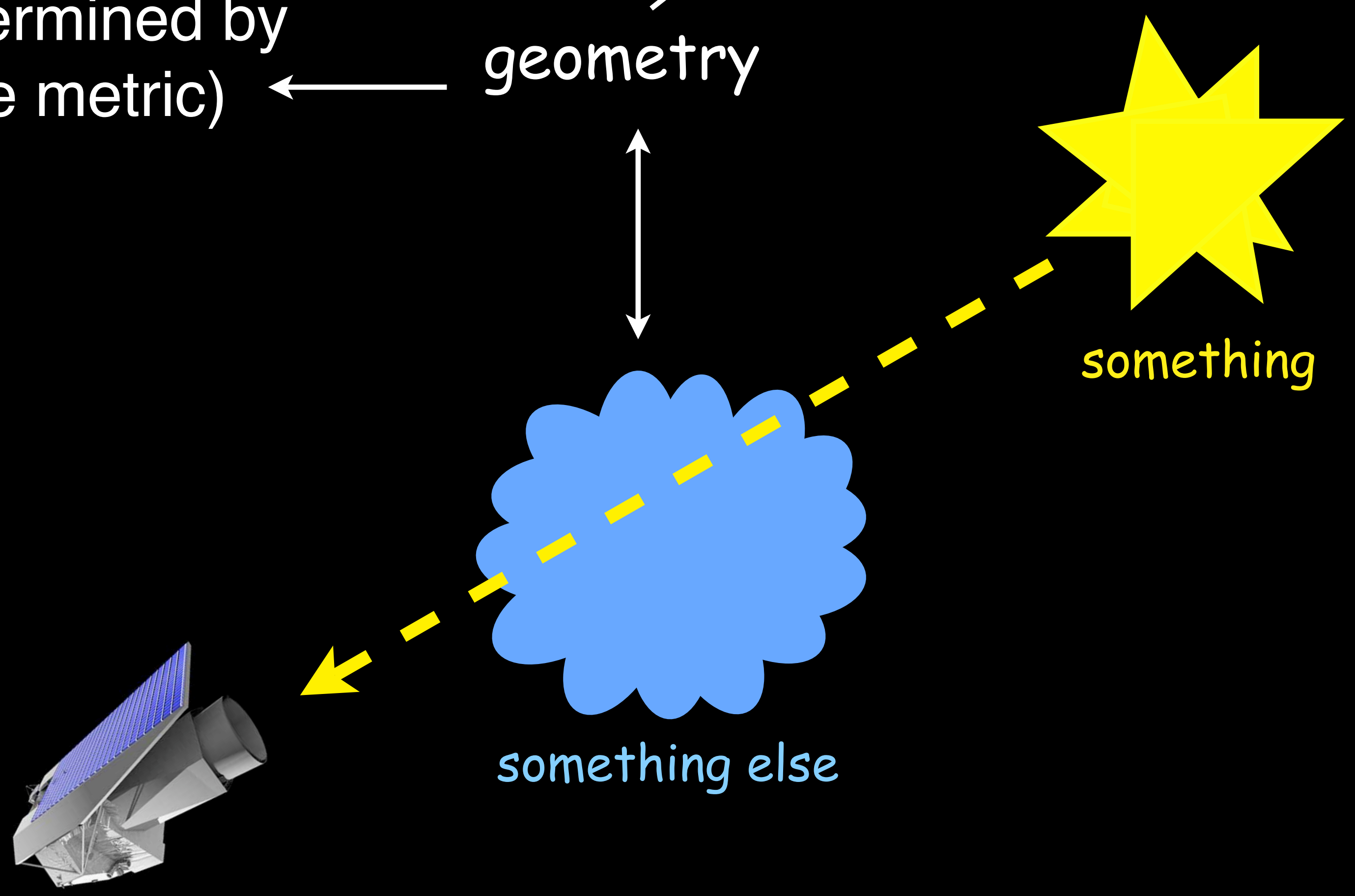
$$G_{\mu\nu} = 8\pi \, G \, T_{\mu\nu}$$

geometry

(determined by the metric)

stuff (what is it?)

your favourite theory



Cosmologists observe the geometry of space time

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

That is what we measure

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(determined by the metric) ← geome

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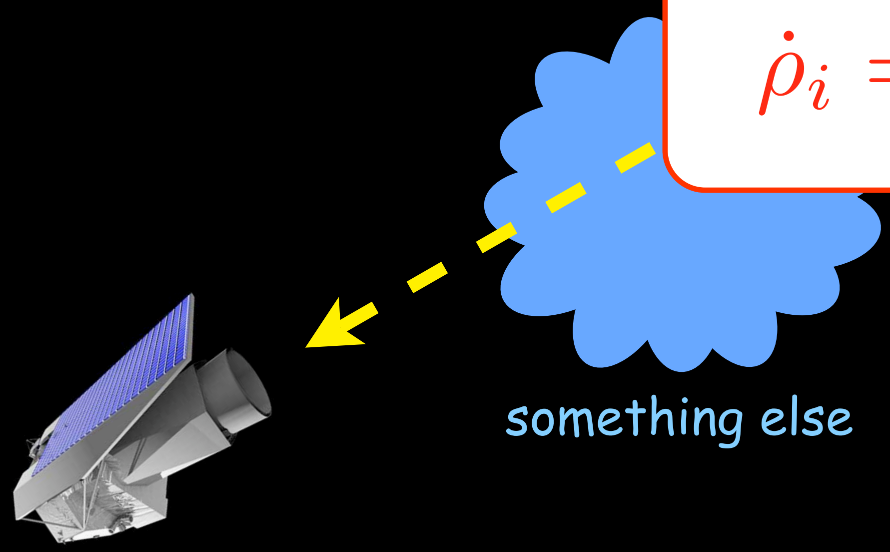
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{K}{a^2}$$

$$\dot{\rho}_i = -3\frac{\dot{a}}{a}(\rho_i + p_i)$$



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measuring dark things (in cosmology)

Einstein eq. (possibly effective):

$$\mathrm{G}_{\mu\nu} = 8\pi\, G\, T_{\mu\nu}^{(bright)} + 8\pi\, G\, T_{\mu\nu}^{(dark)}$$

directly measured

given by metric:

- $H(z)$
- $\Phi(z,k)$, $\Psi(z,k)$

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

cosmic degeneracies

cosmic degeneracies

CD1:

there are infinite models which can give the same expansion history

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

cosmic degeneracies

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CD2:
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$$X_{\mu\nu} = -8\pi G T_{\mu\nu}$$

cosmic degeneracies

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CD2:
modified matter can always mimic modified gravity

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

Martin Kunz and DS, PRL.98:121391 (2007)

measuring dark side

small perturbations: extend metric

$$\boxed{\mathrm{d}s^2 = -(1+2\psi)\,\mathrm{d}t^2 + a^2(1-2\phi)\,\mathrm{d}x^2}$$

ϕ, ψ gravitational potentials ⟷ $\delta\rho$ and V perturbations of $T_{\mu\nu}$

Einstein eqs

fluid properties

$$\delta p = c_s^2\,\delta\rho$$

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

measure total w, δp, π!

(and compare with predictions)

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

Luca Amendola, Martin Kunz & DS, JCAP 0804:013 (2008)

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some model predictions

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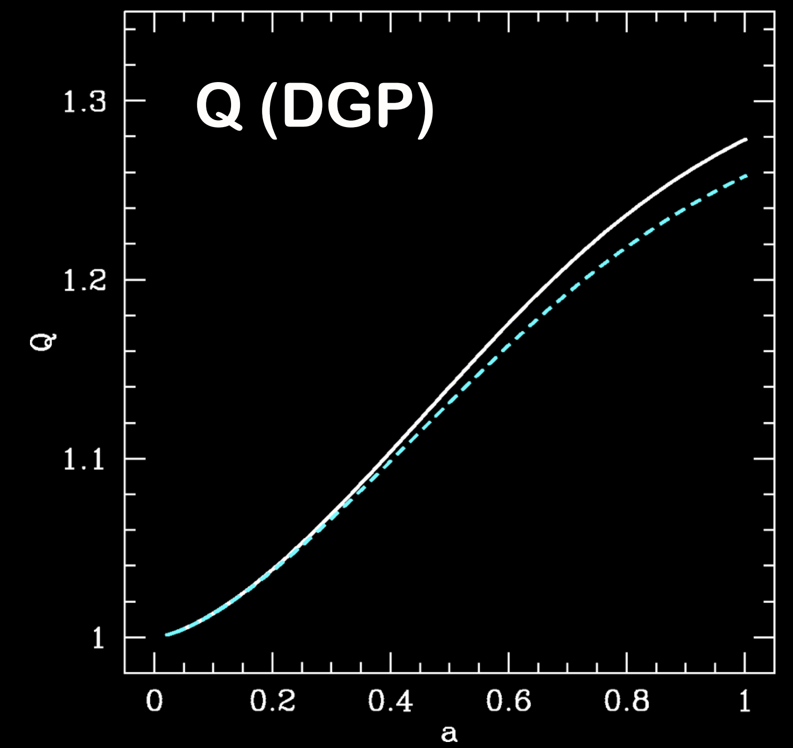


scalar field:

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

one degree of freedom: $V(\phi)$ <-> $w(z)$

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

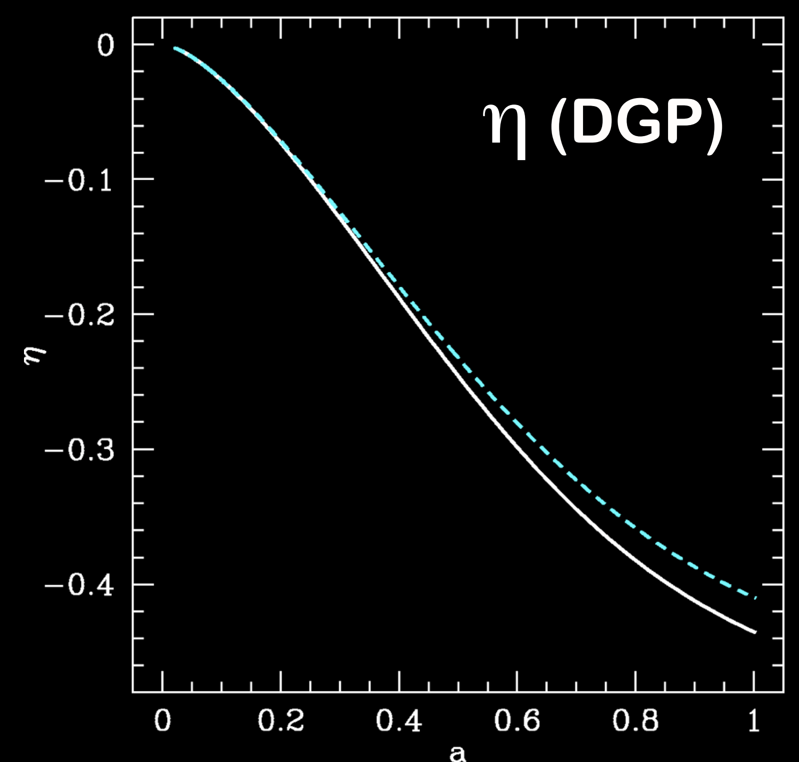
-> $\eta = 0$, $Q(k \gg H_0) = 1$, $Q(k \sim H_0) \sim 1.1$

(naïve) DGP: compute in 5D, project result in 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 perts.



scalar-tensor:

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

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

$$\eta = \frac{F'^2}{F+F'^2} \qquad Q = \frac{G^*}{FG_0}\frac{2(F+F'^2)}{2F+3F'^2}$$

Luca Amendola, Martin Kunz & DS, JCAP 0804:013 (2008)

First short summery

- 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!

‘analytic’ dark energy

(DS & M. Kunz PRD80, 083519 (2009) ,
DS, M. Kunz and L. Amendola, arXiv:1007.2188)

Fingerprinting scalar field: w $\sim$ arbitrary, $c_s^2 = 1$ and $\pi = 0$

-> generalization $c_s \sim$ arbitrary const

but also -> w $\sim$ const

Whenever we are dealing with de perts:

-> two scales:

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

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$H^2 = H_0\,\Omega_m\,a^{-3}$, Φ = constant, $\delta_m \sim a$

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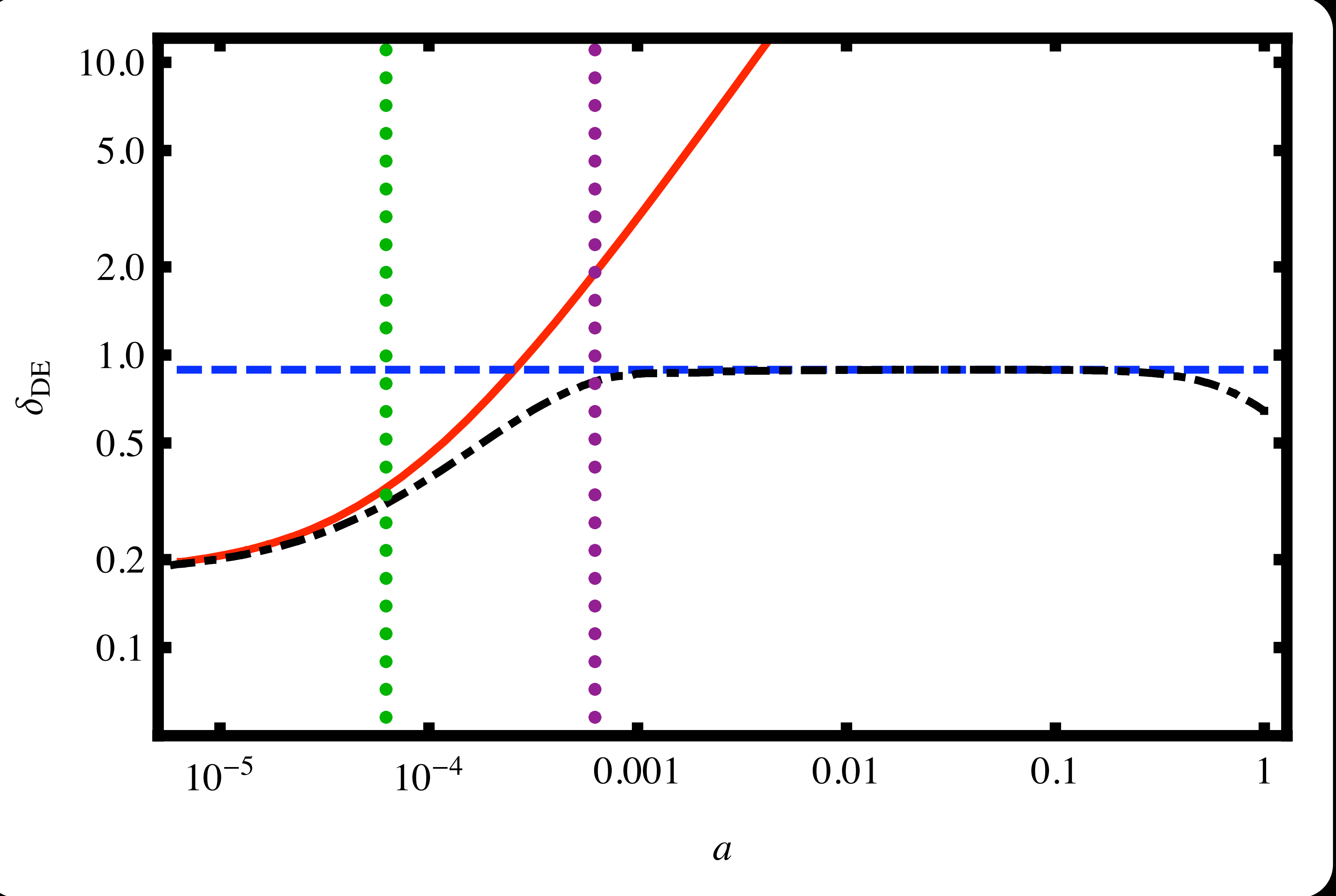

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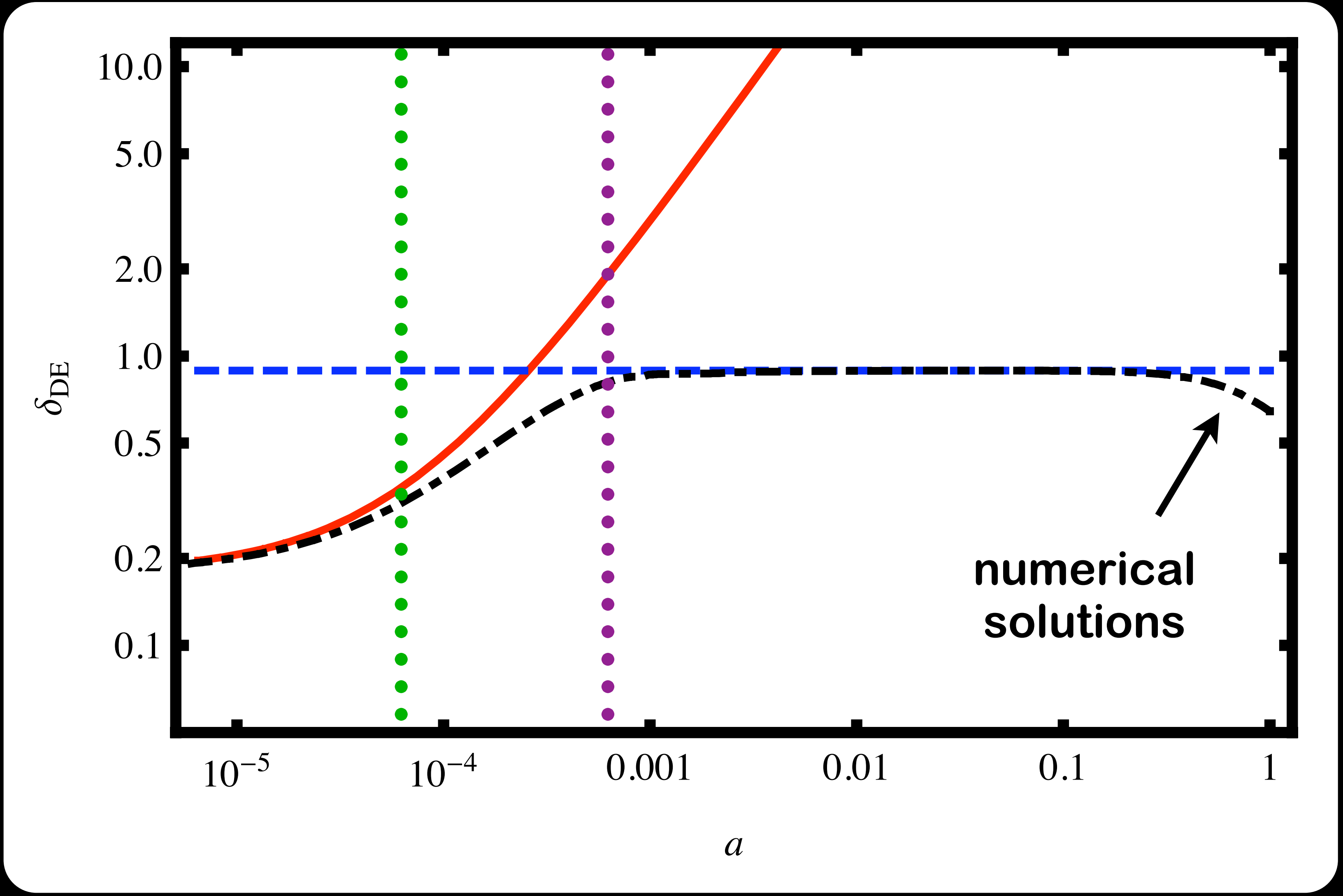

w = -0.8

c = 0.1

k = 200H

causal horizon

sound horizon

radiation omitted

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$\longrightarrow$ $\delta(w=-0.8) < 1/20\ \ \delta(w=0)$

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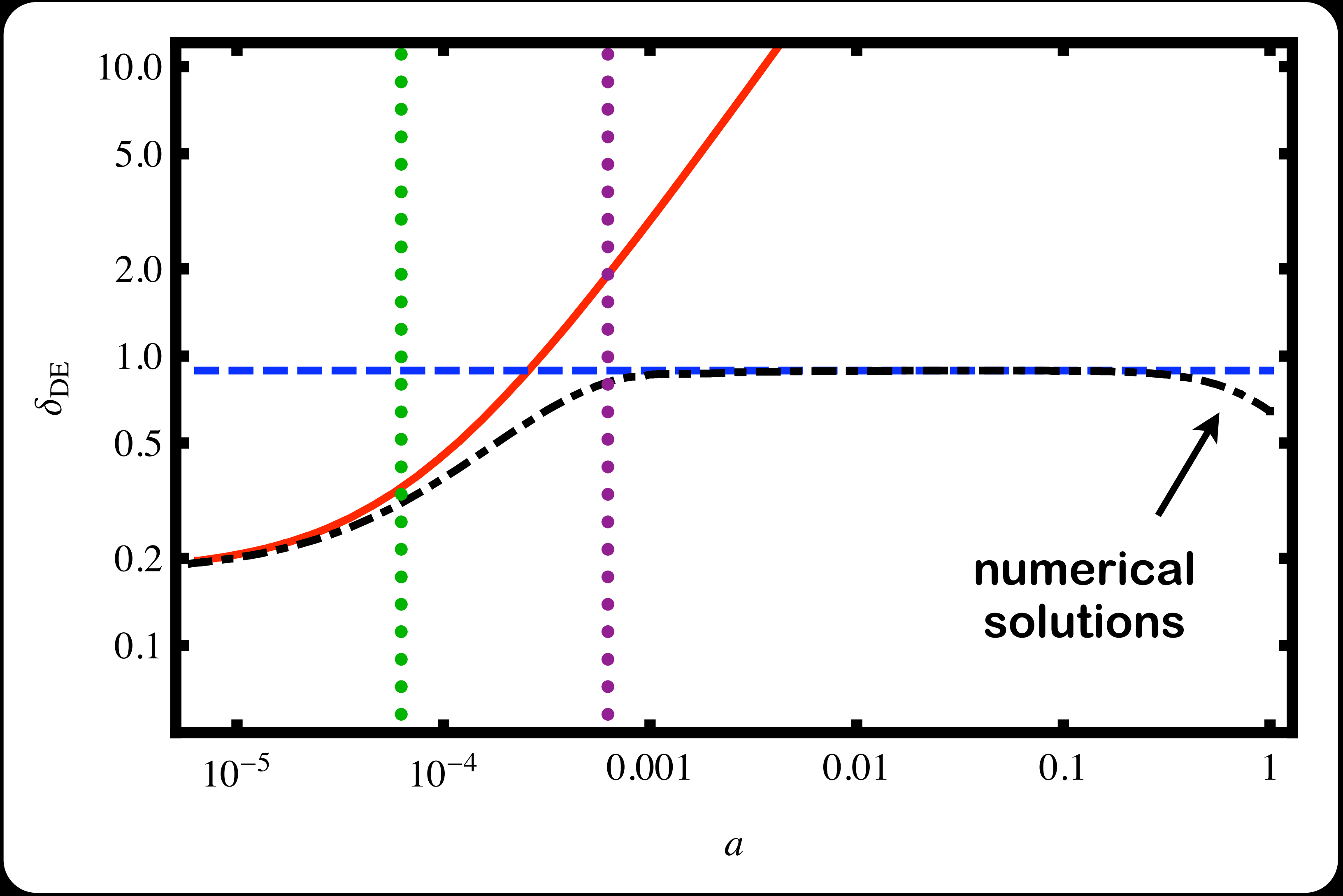

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DE will dominate...eventually!

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

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subhorizon:
Q-1 suppressed
by a power more
-> k dependence

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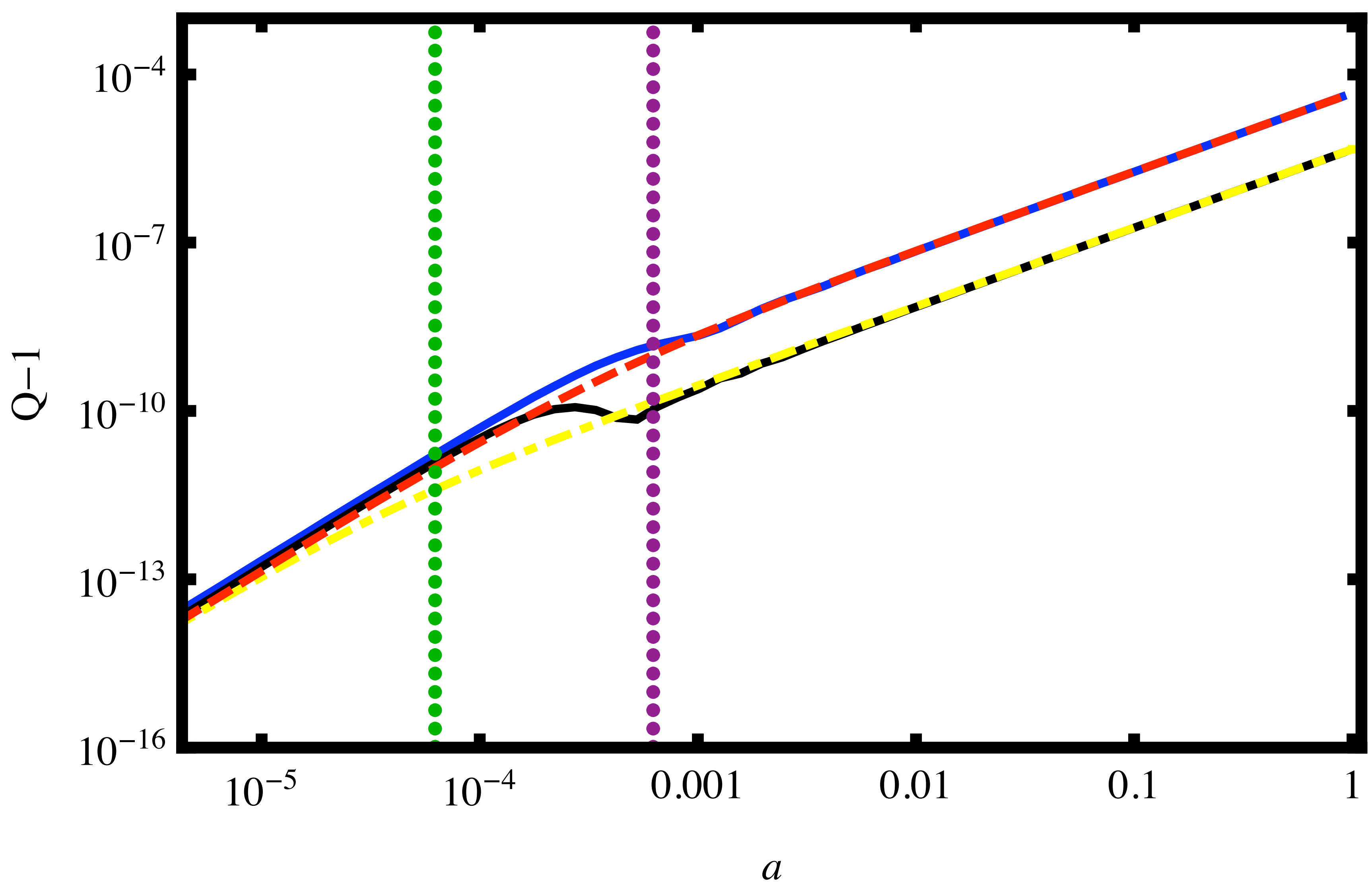
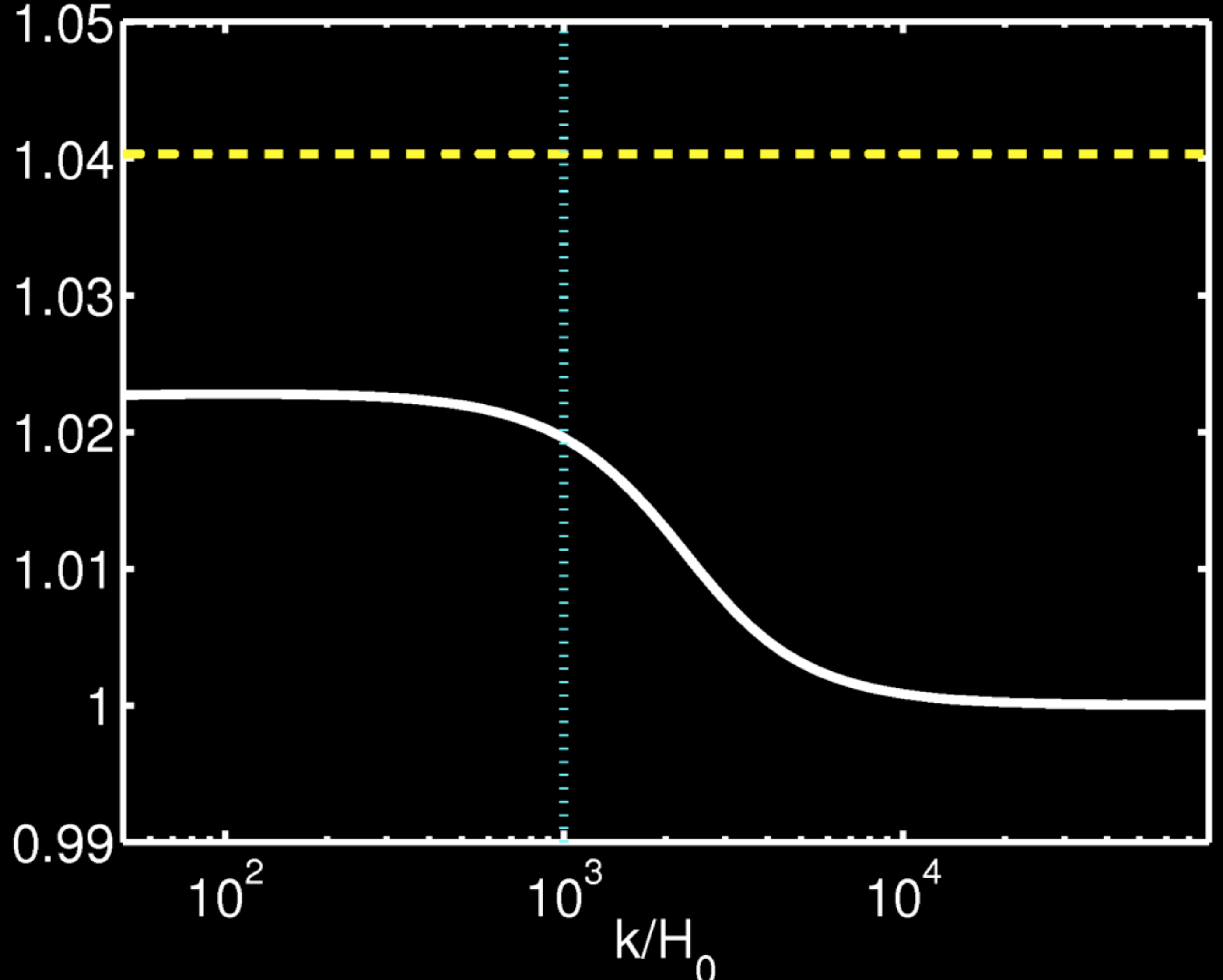


CAMB:
w=-0.8
k = 200H_0
c_s^2 = 0.1
c_s^2 = 1

s.h. c_s^2 = 1
s.h. c_s^2 = 0.1

impact on observational quantities

- with Q we evaluate DM with DE perts -> $\phi \neq$ const but still in MDE
- DM does not have s.h. but now the growth depends on whether or not DE has it just because ϕ depends on it! -> P(k) and γ change



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

Everything is now scale dependent!

More promising land: ISW effect

most affected by DE -> results of late time decay of ϕ and ψ

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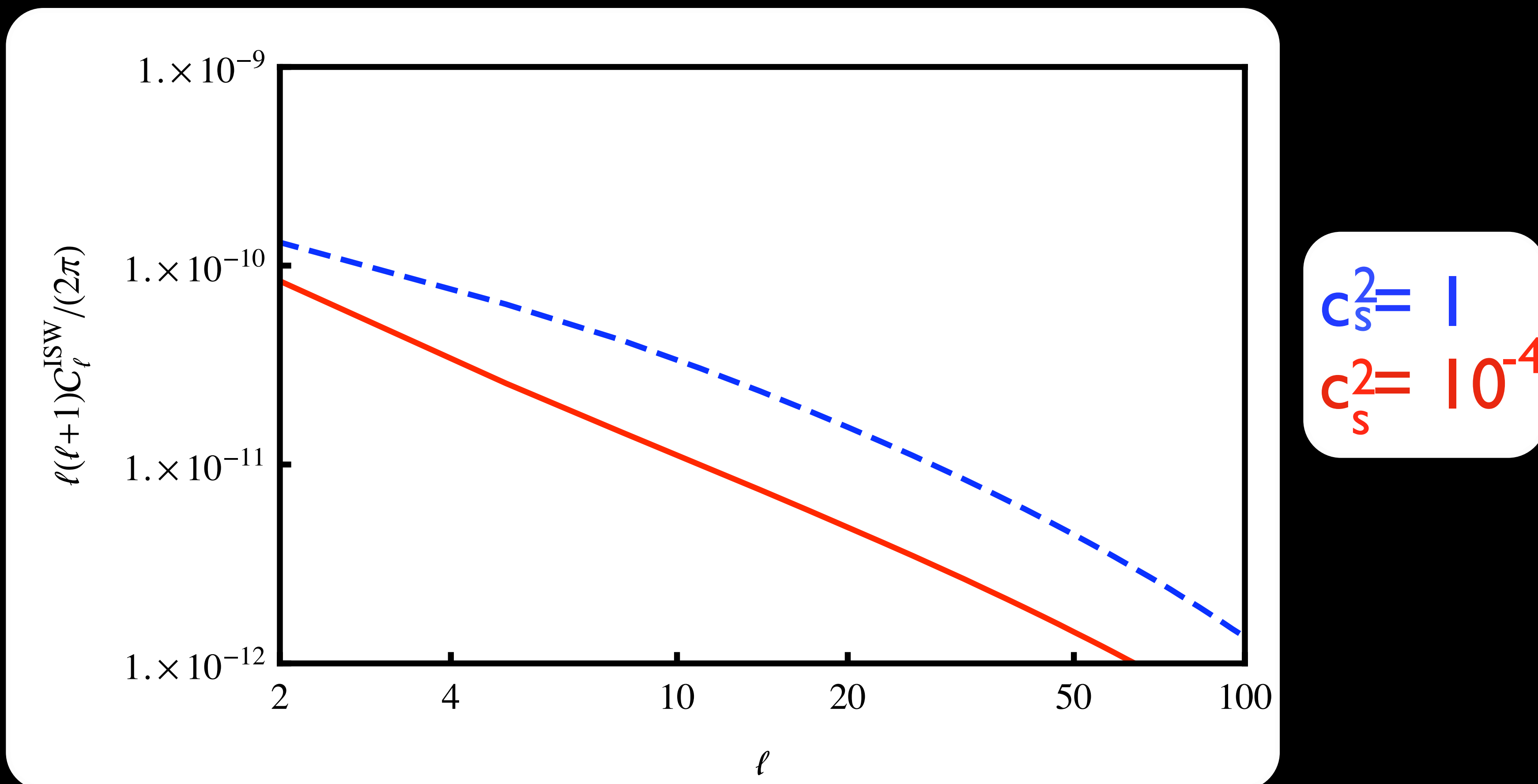

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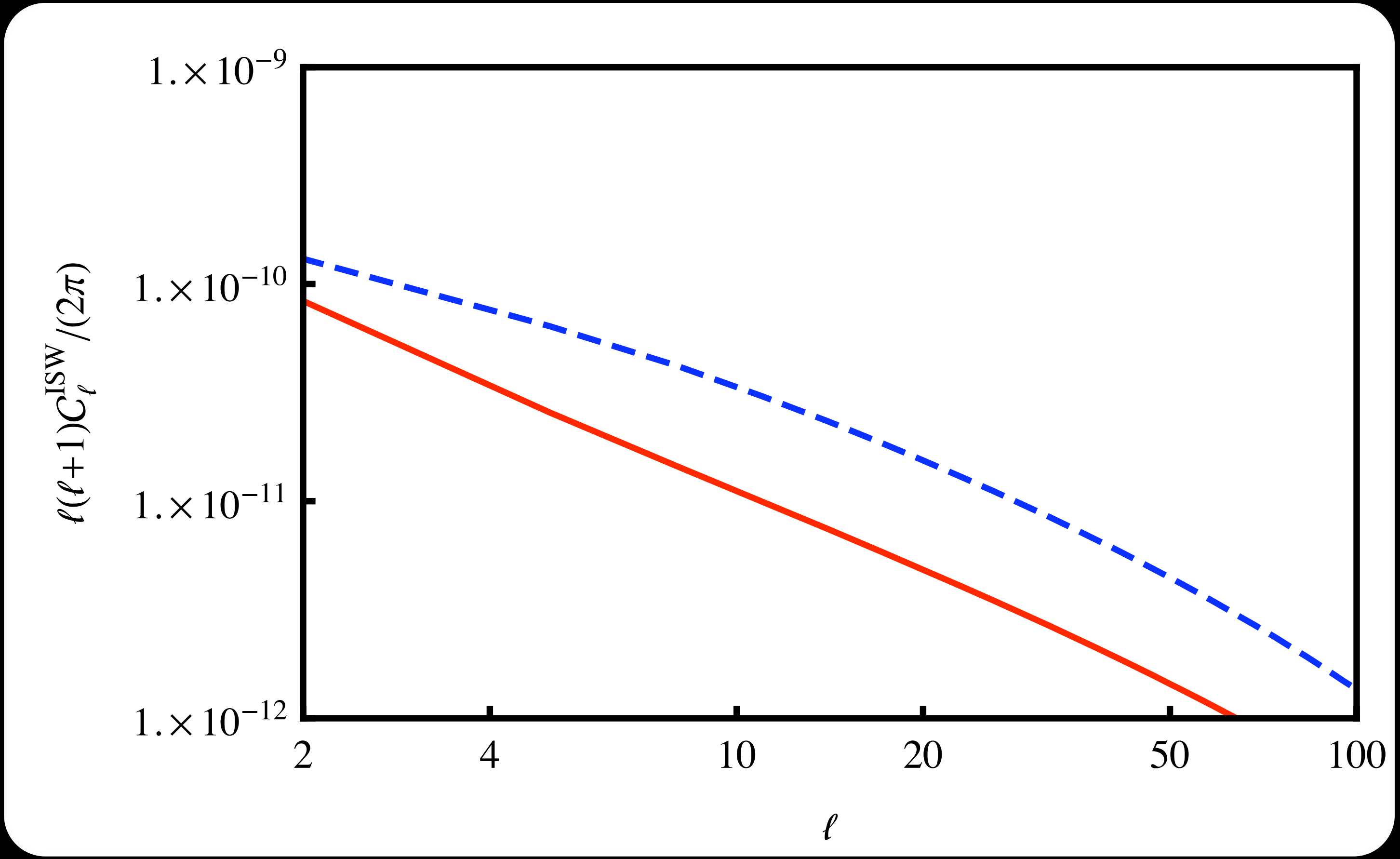

$$(GQ)' = G'\left(Q + \frac{G}{G'}Q'\right)$$

$c_s^2 = 1$

$c_s^2 = 10^{-4}$

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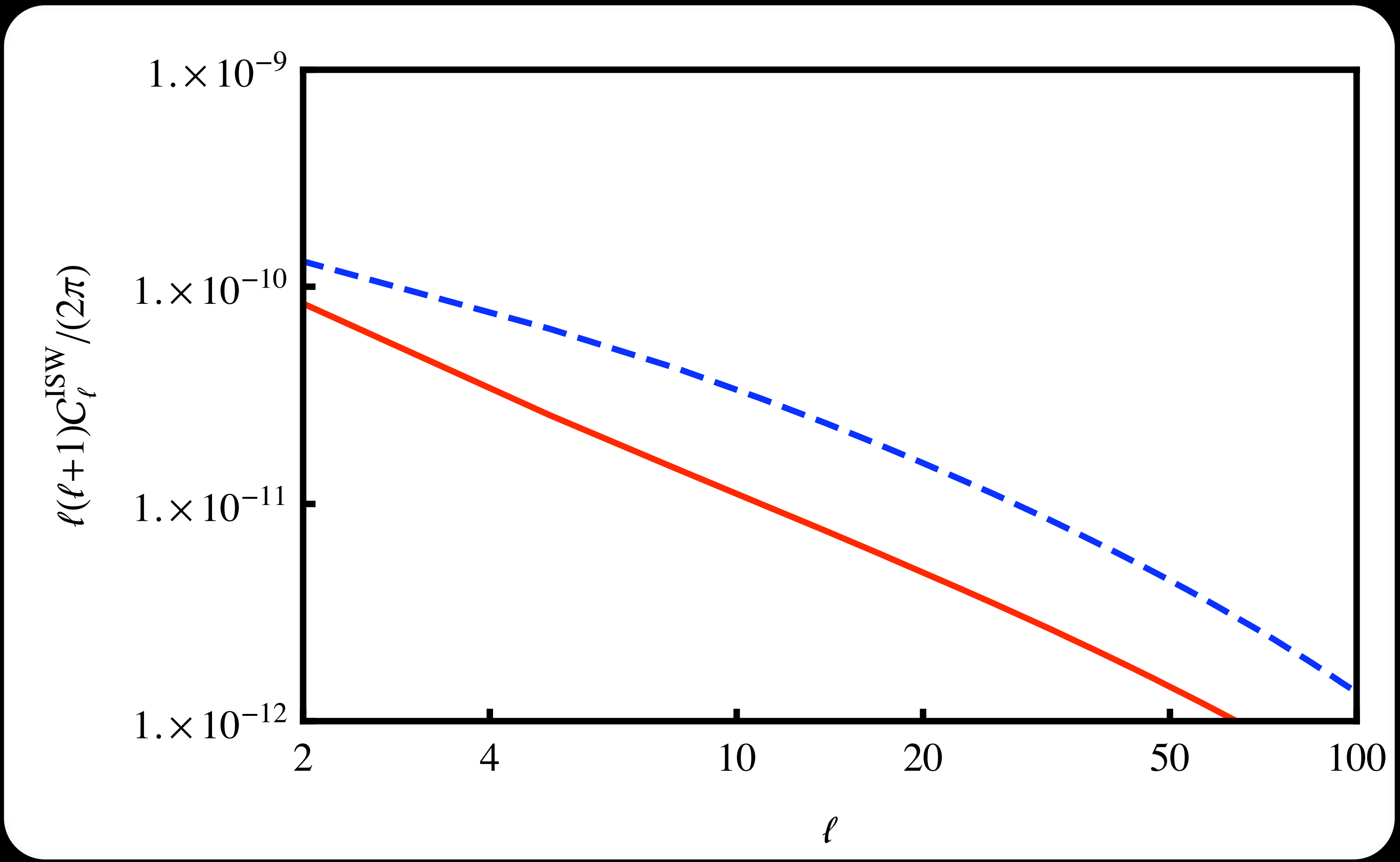

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$aG'/G \approx \Omega^{\gamma} - 1 < 0$

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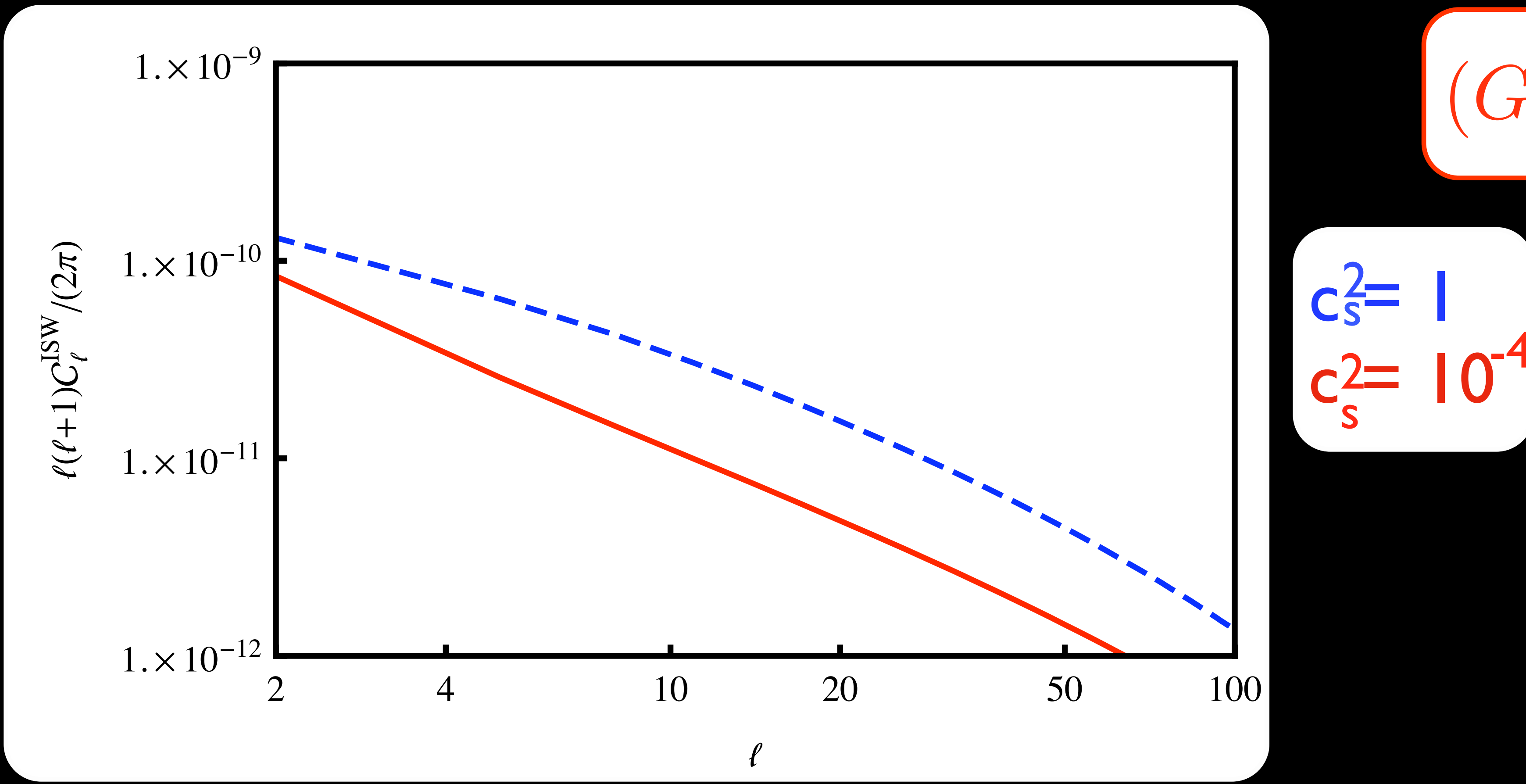

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$$A^2 = \left\{ \frac{d(G(a,k)Q(a,k))/da}{dG(a)/da} \right\}^2 .$$

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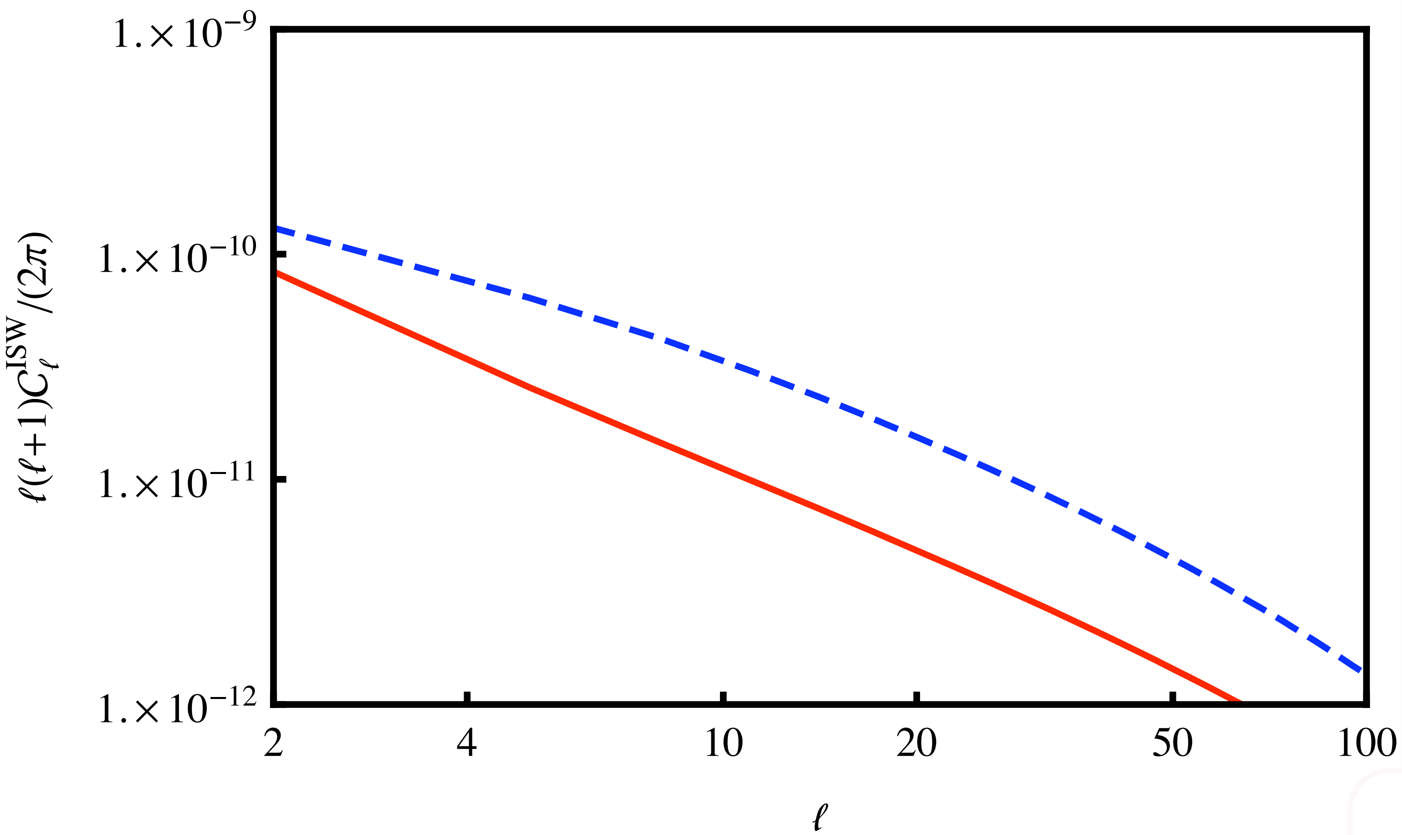

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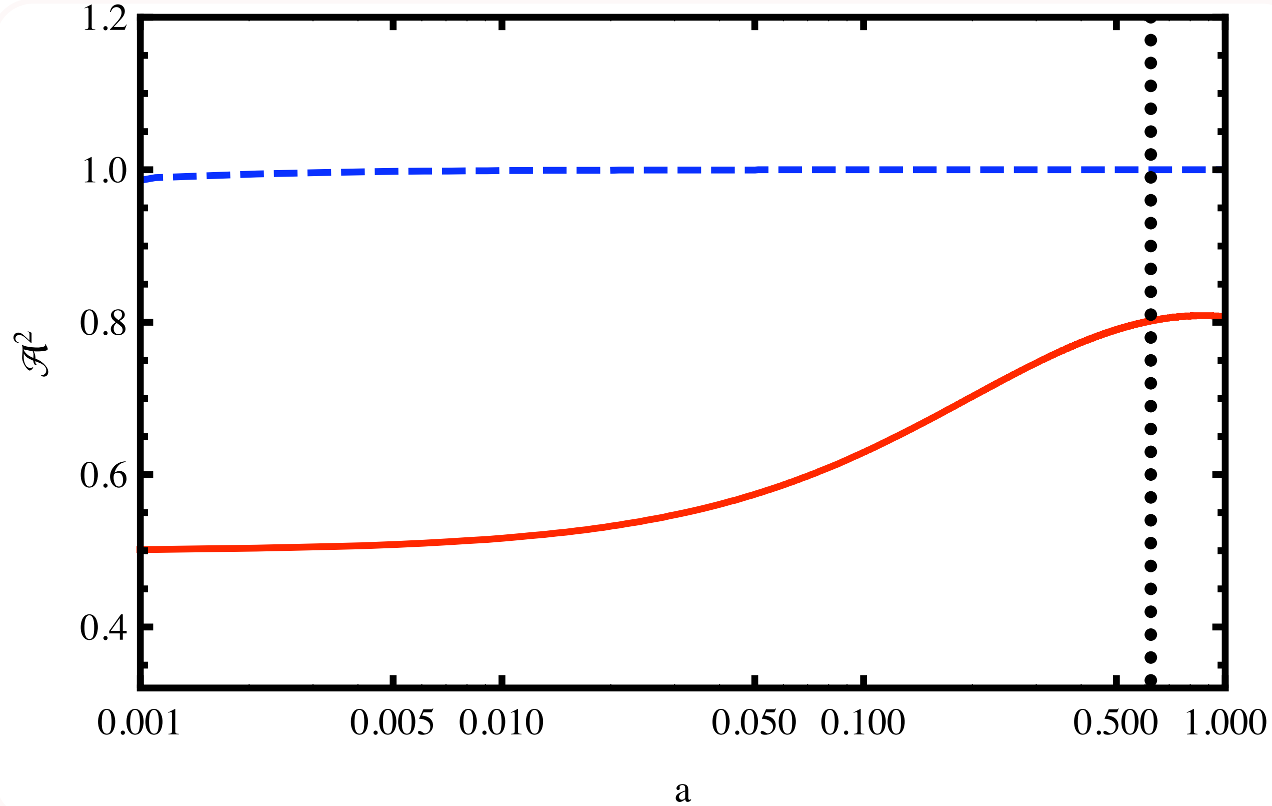
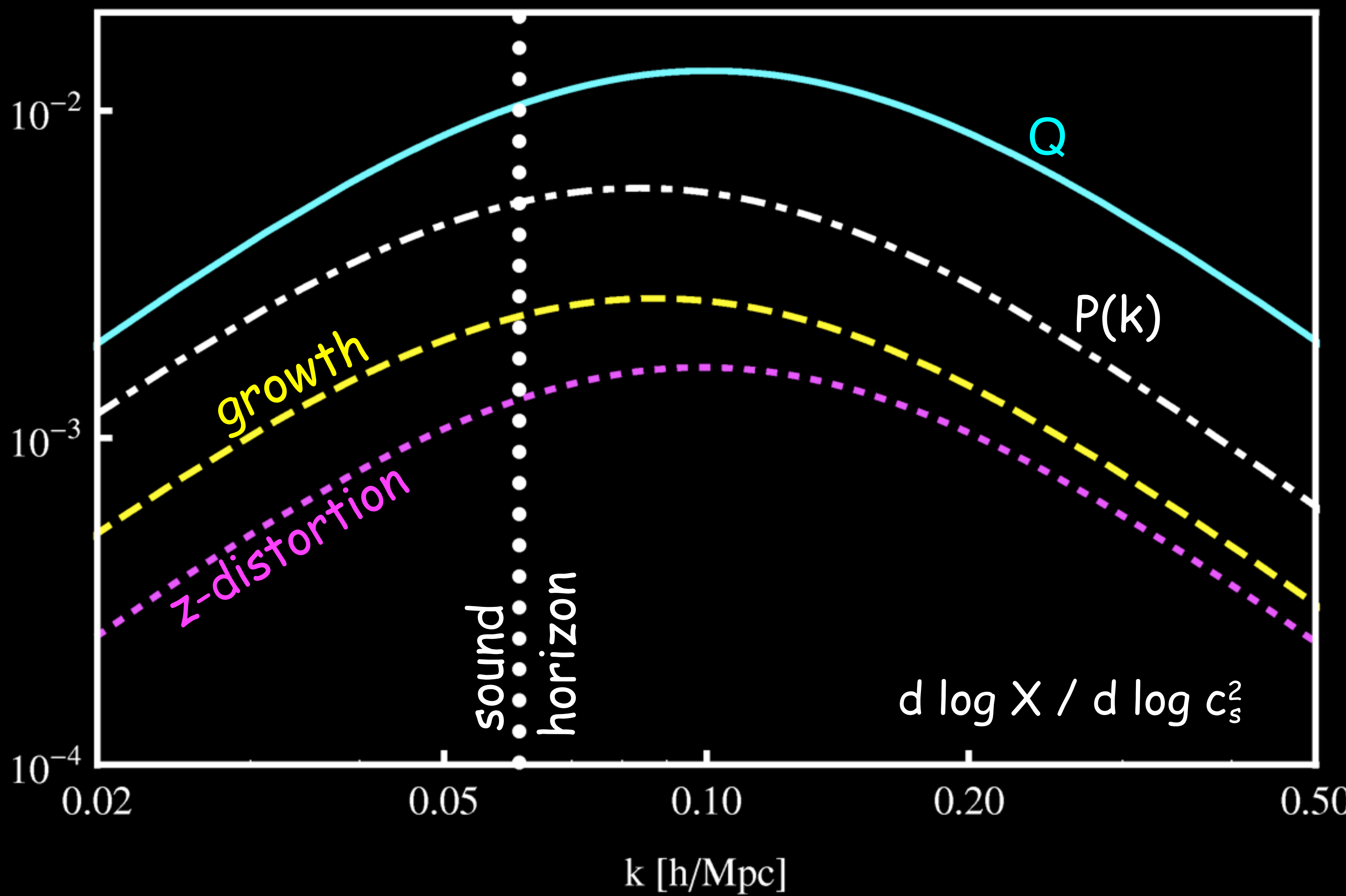


sensitivity to sound speed

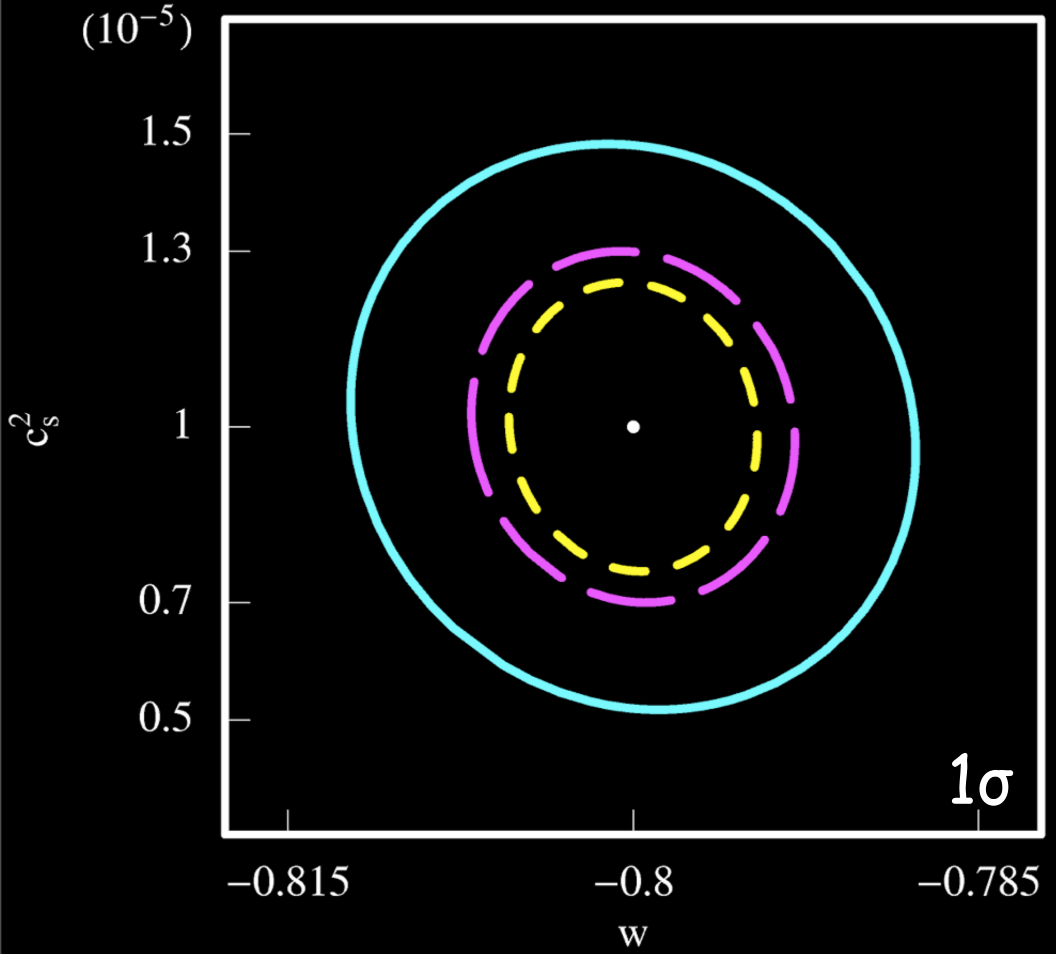
lensing: $2\Phi \to Q\ \Delta_m \to Q$, growth, shape

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



redshift dependence differs: RSD stronger at low redshift

can we see the DE sound horizon?

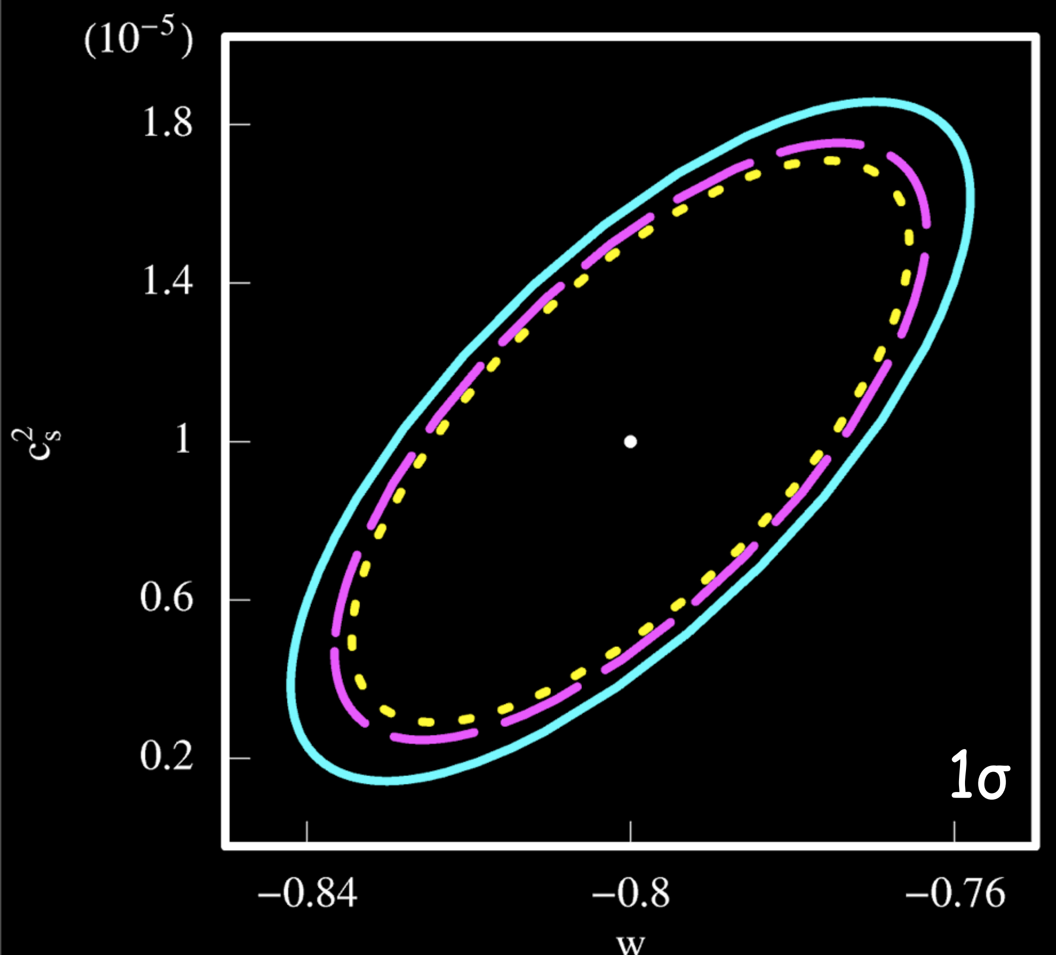


two large surveys to z_{max} = 2, 3, 4

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)



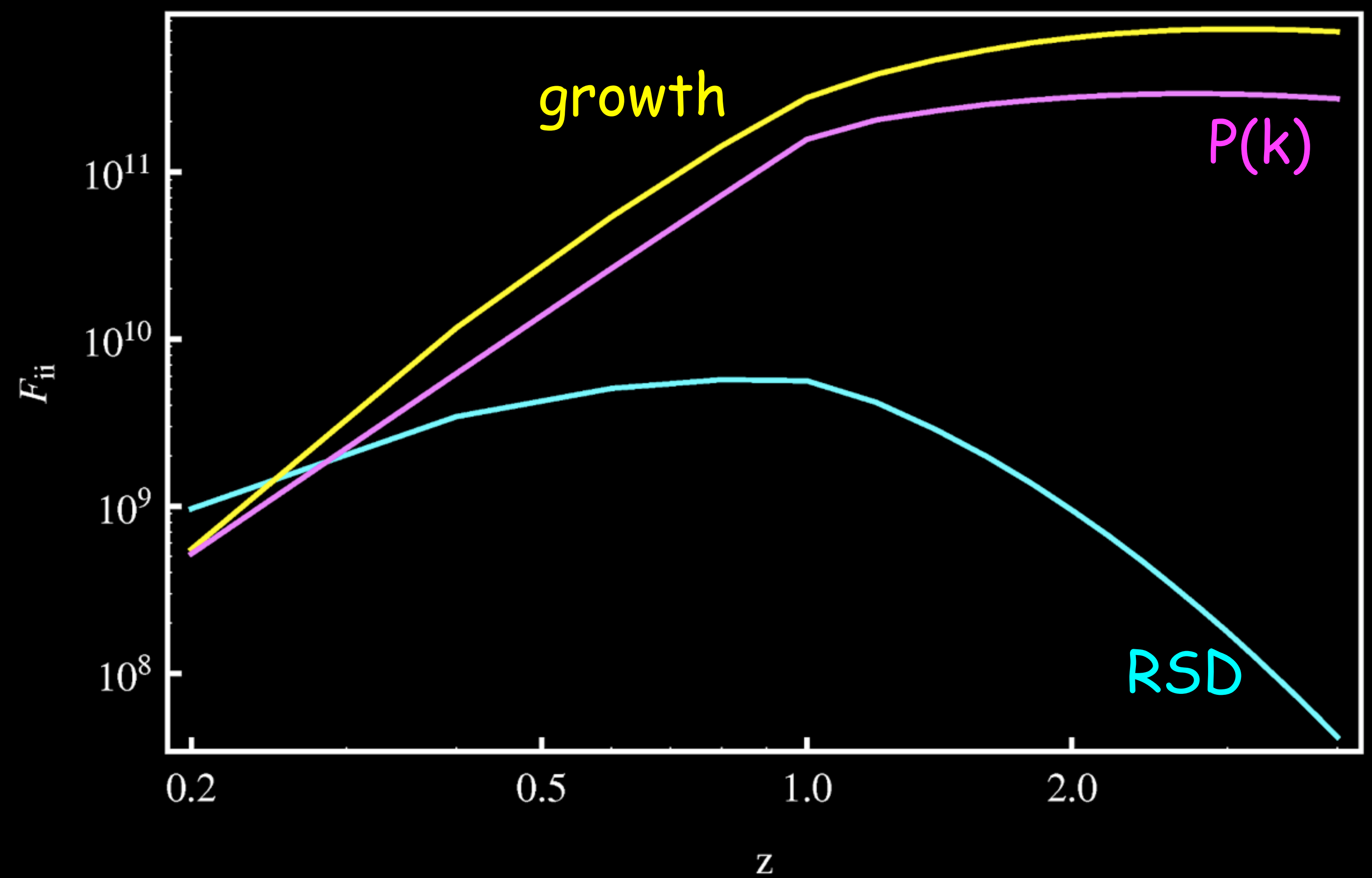
$P(k)$+WL		
c_s^2	σ_{w_0}	$\sigma_{c_s^2}/c_s^2$
10^{-5}	0.00639	0.15
10^{-4}	0.00581	0.41
10^{-3}	0.00547	0.87
10^{-2}	0.00531	2.48
10^{-1}	0.00528	14.79
1	0.00524	22.05

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 contributions shape → of P(k) [but not enough]

  low c_s → mostly RSD and growth



Fisher matrix elements for galaxy survey, c_s^2= 1e-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.?
- how to deal with non-linear scales?
- more discussions on c_s after