Title: Determining dark energy: Observing Lambda or inhomogeneity?

Date: May 18, 2010 02:45 PM

URL: http://pirsa.org/10050016

Abstract: I consider some of the issues we face in trying to understand dark energy. Huge fluctuations in the unknown dark energy equation of state can be hidden in distance data, so I argue that model-independent tests which signal if the cosmological constant is wrong are valuable. These can be constructed to remove degeneracies with the cosmological parameters. Gravitational effects can play an important role. Even small inhomogeneity clouds our ability to say something definite about dark energy. I discuss how the averaging problem confuses our potential understanding of dark energy by considering the backreaction from density perturbations to second-order in the concordance model: this effect leads to at least a 10\% increase in the dynamical value of the deceleration parameter, and could be significantly higher owing to a UV divergence. Large Hubble-scale inhomogeneity has not been investigated in detail, and could conceivably be the cause of apparent cosmic acceleration. I discuss void models which defy the Copernican principle in our Hubble patch can explain acceleration through inhomogeneous cosmic curvature. These can fit the small scale CMB, and can explain the observed primordial lithium abundances - a niggling 4 or 5 sigma discrepancy in the concordance model. I describe how we can potentially rule out these models, and so provide an important test for the existence of dark energy.

determining dark energy

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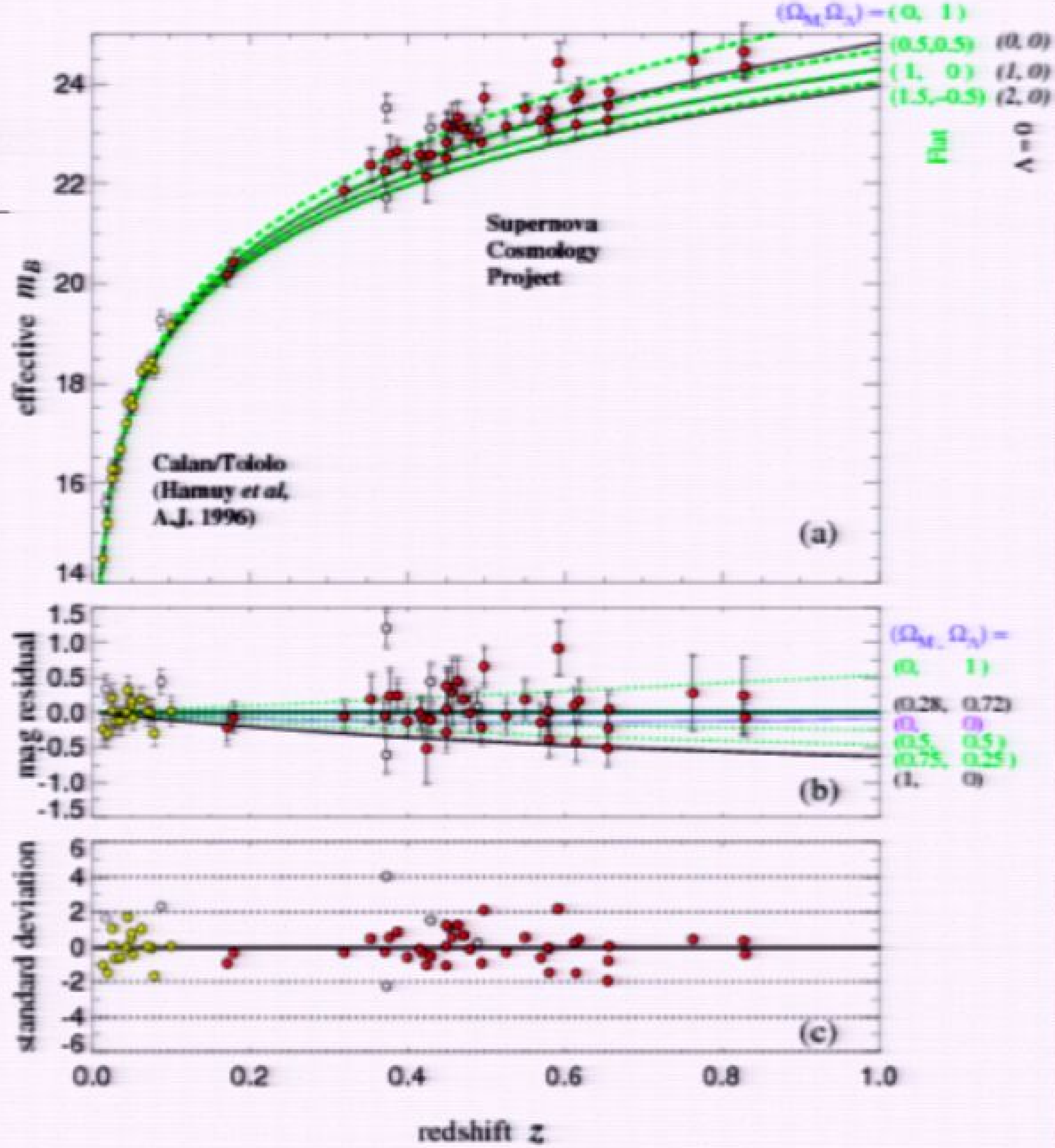
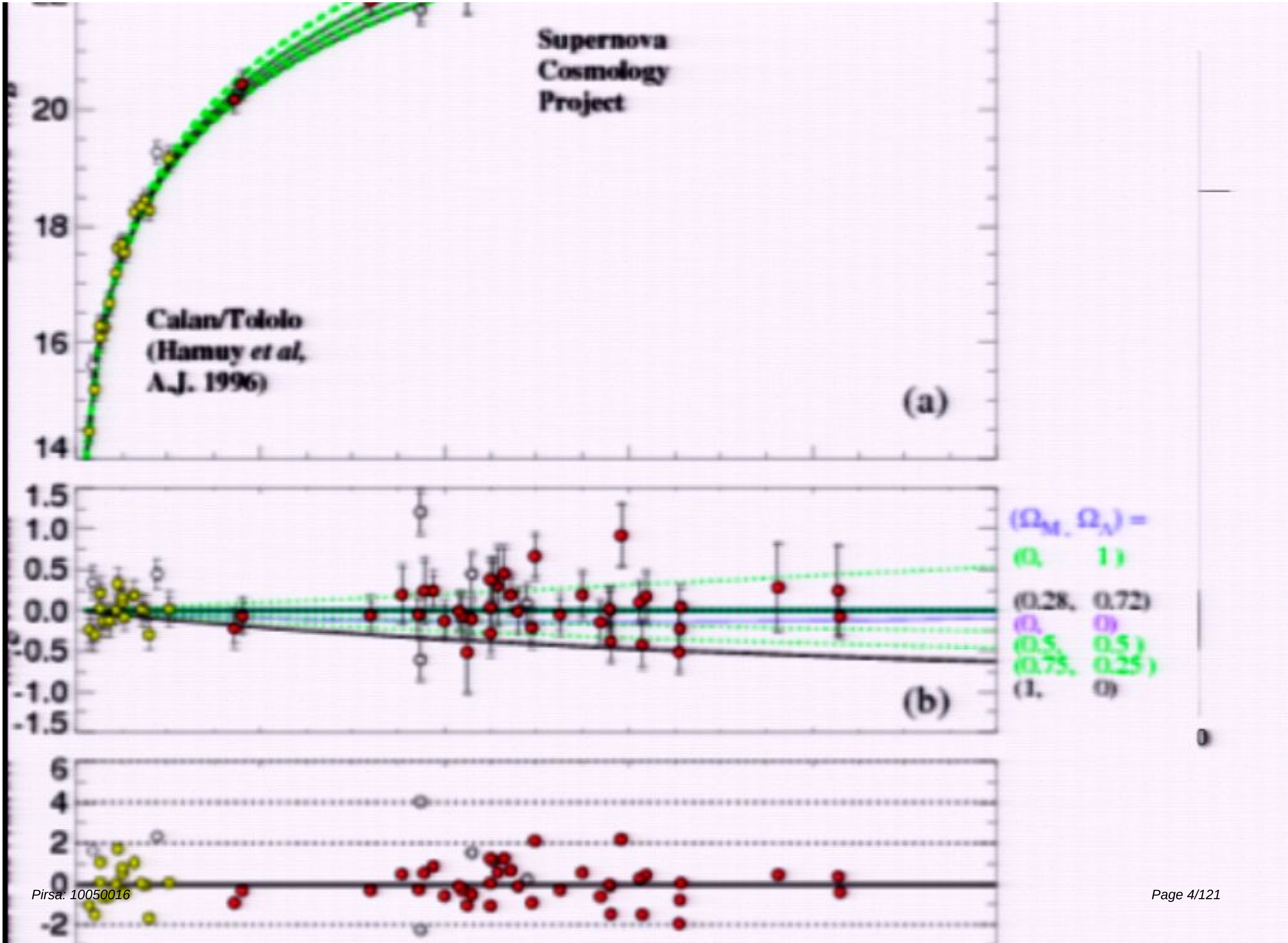
Astrophysics, Cosmology & Gravitation Centre
University of Cape Town

Dark Energy Evidence

- evidence of cosmological constant from COBE + age constraints
- independent confirmation from SNIa
- observations consistent with flat Lambda-CDM
- 'concordance cosmology'

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Cosmology
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Calan/Tololo
(Hamuy et al,
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(b)
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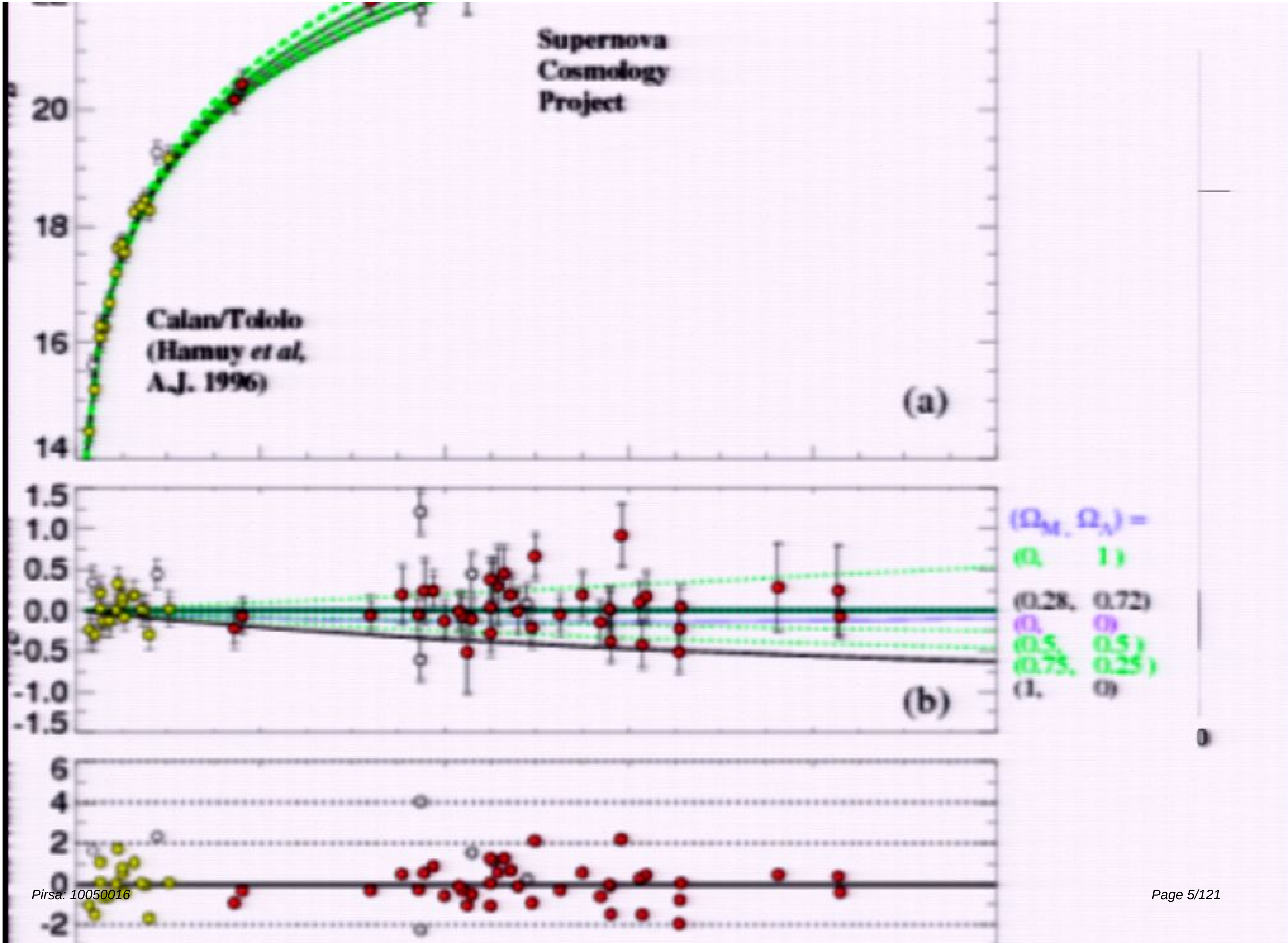
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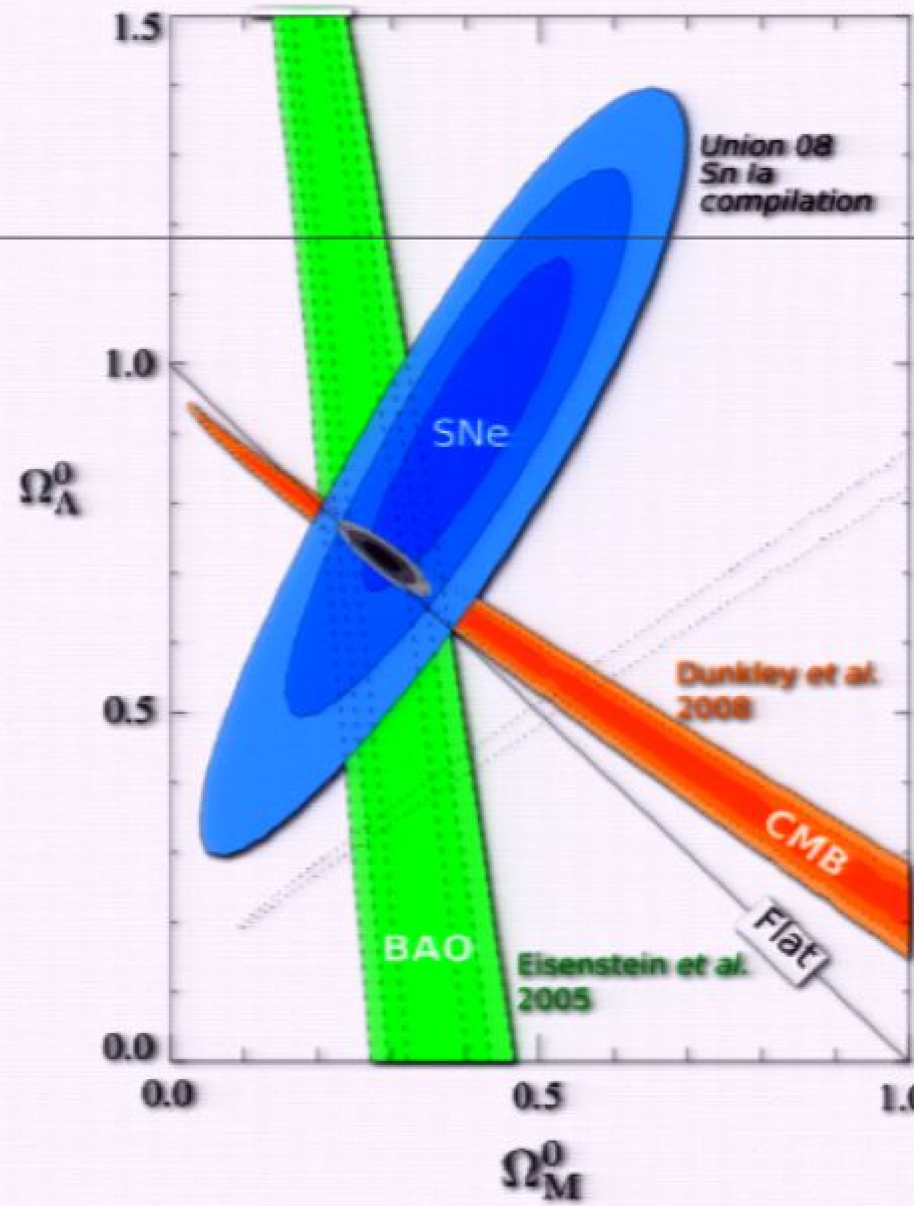

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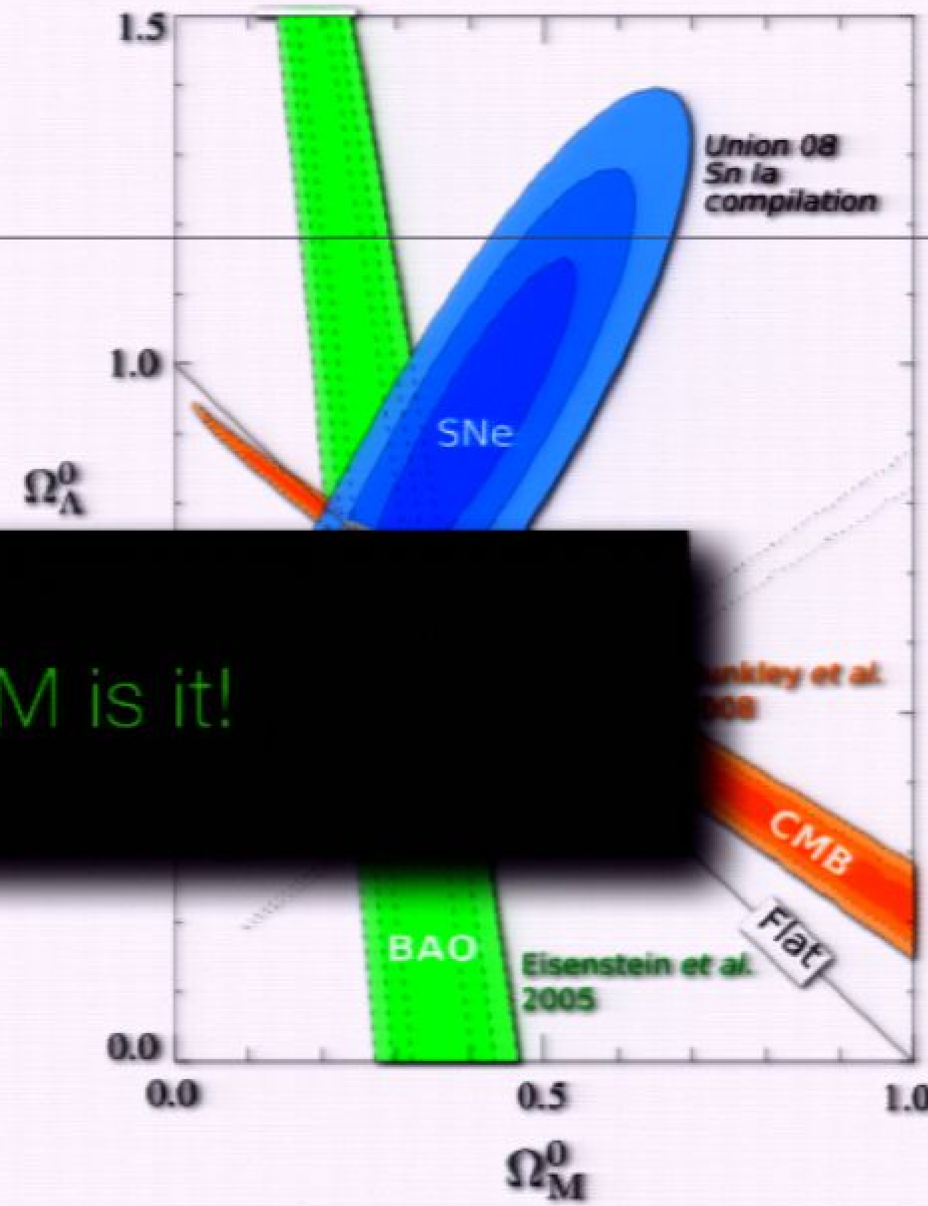

Problems with Λ

- Lambda doesn't make sense as vacuum energy: $\rho_{\rm vac}^{\rm (obs)} \sim 10^{-120} \rho_{\rm vac}^{\rm (theory)}$
- Why do we live at a special time?

$$\frac{\Omega_\Lambda}{\Omega_{\rm M}} = \frac{\rho_\Lambda}{\rho_{\rm M}} \propto a^3$$

- Perhaps Landscape arguments can answer this ... one day ...
- in 10^{500} universes ours must be special - breaks with the Copernican principle...

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s it just LCDM?

if acceleration isn't cosmological constant:

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what's the evidence for these? How can we tell the difference?

overview:

1. Observing Lambda, or not

2. Small inhomogeneity and 'backreaction' of perturbations

3. Large inhomogeneity and the Copernican Principle

dark energy equation of state

Hubble rate

$$H(z)^2 = H_0^2\left\{\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{DE}\exp\left[3\int_0^z \frac{1+w(z')}{1+z'}\mathrm{d}z'\right]\right\},$$

$$(\Omega_{DE} = 1 - \Omega_m - \Omega_k)$$

distances $$d_L(z) = \frac{c(1+z)}{H_0\sqrt{-\Omega_k}}\sin\left(\sqrt{-\Omega_k}\int_0^z \mathrm{d}z'\frac{H_0}{H(z')}\right)$$

i.e.,

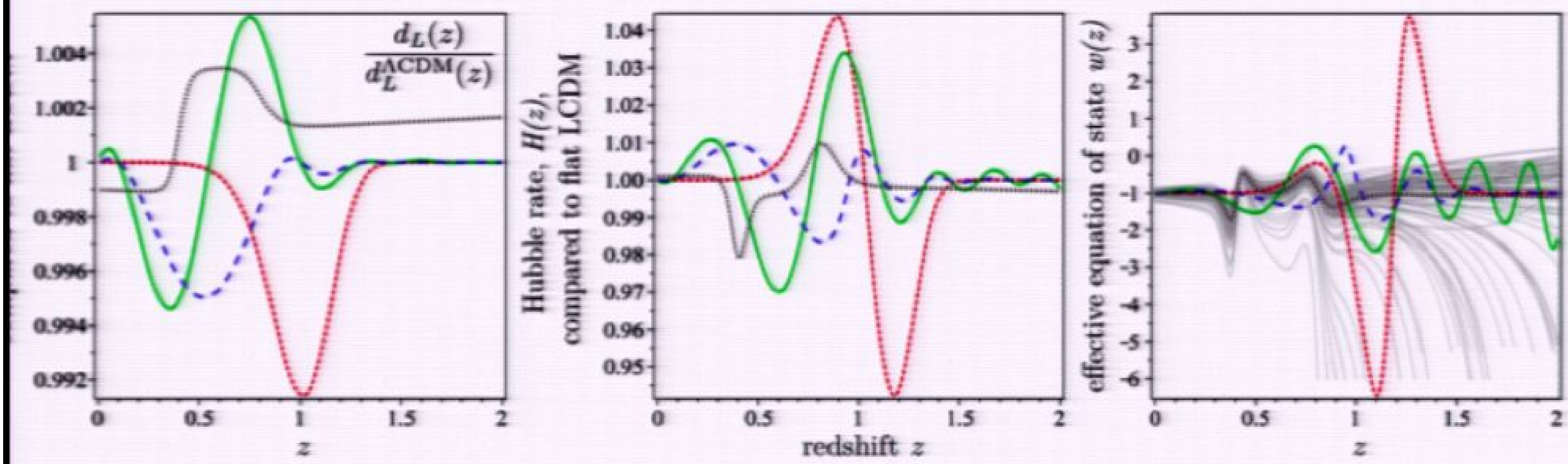
$$= \frac{2}{3}\frac{(1+z)}{[(1+z)D_L' - D_L]}\left\{[\Omega_k D_L^2 + (1+z)^2]D_L'' - \frac{1}{2}(\Omega_k D_L'^2 + 1)[(1+z)D_L' - D_L]\right\}/$$
$$\left\{(1+z)[\Omega_m(1+z) + \Omega_k]D_L'^2 - 2[\Omega_m(1+z) + \Omega_k]D_L D_L' + \Omega_m D_L^2 - (1+z)\right\}$$

$$D_L = (H_0/c)d_L$$

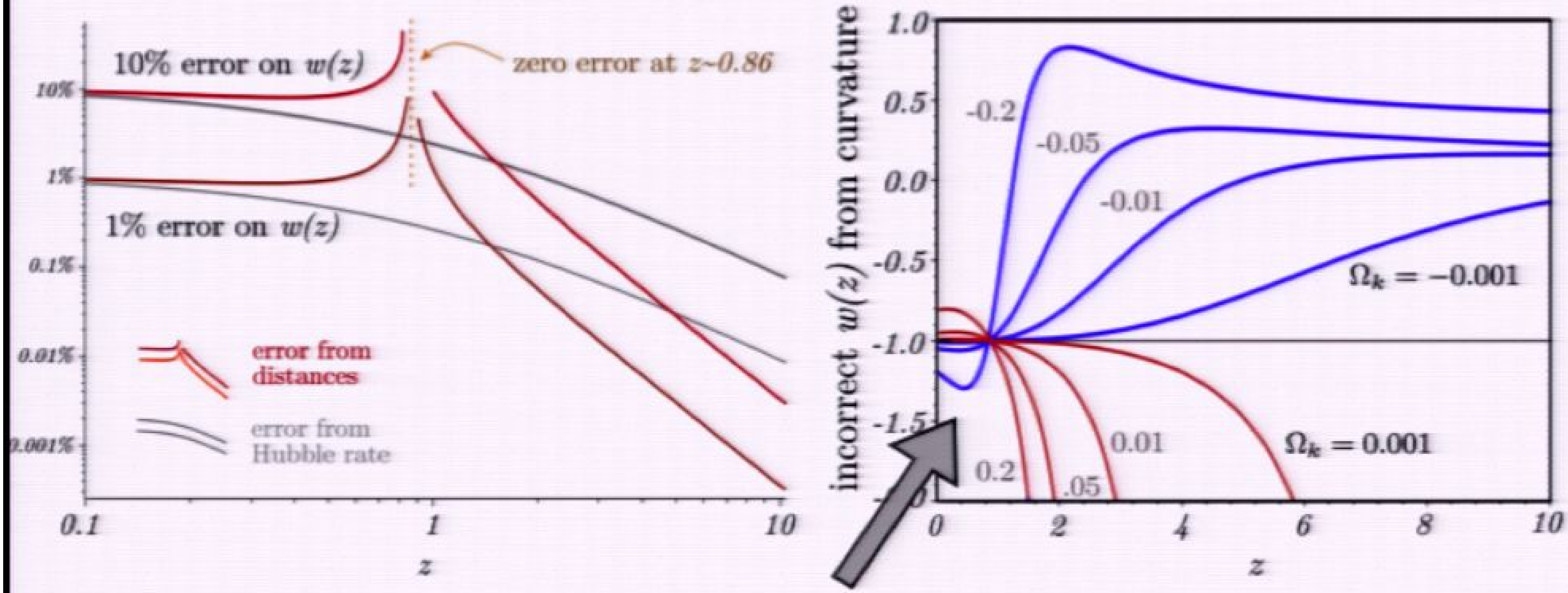
w could be anything ...

trying to observe deviations from *w*=-1

huge fluctuations in $w(z)$ give rise to <1% change in distances from LCDM and ~5% change in the Hubble rate

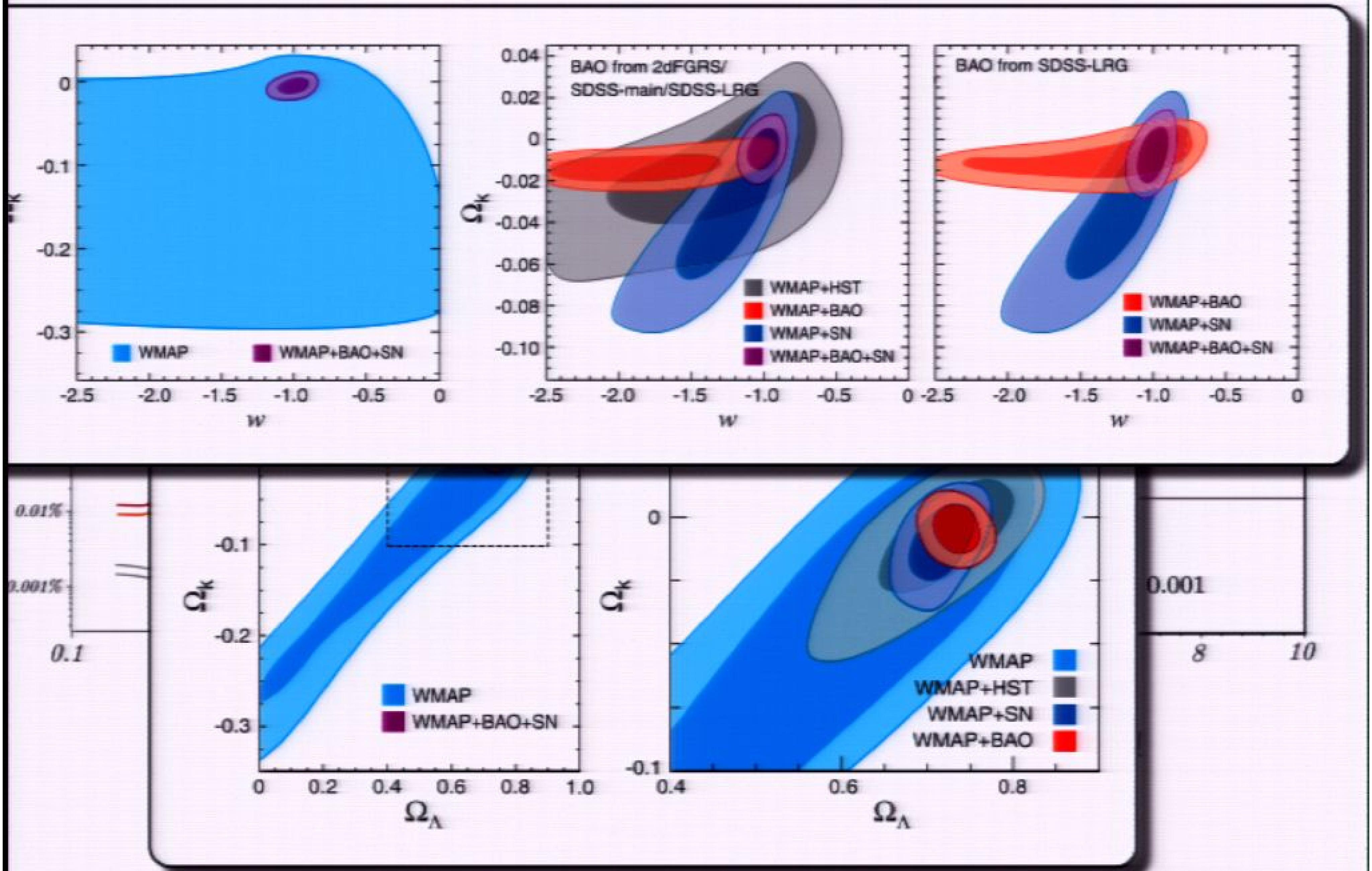


curvature: harder to spot than we thought



these w(z) give same distances as flat LCDM!

arkson, Cortes and Bassett, JCAP08(2007)011



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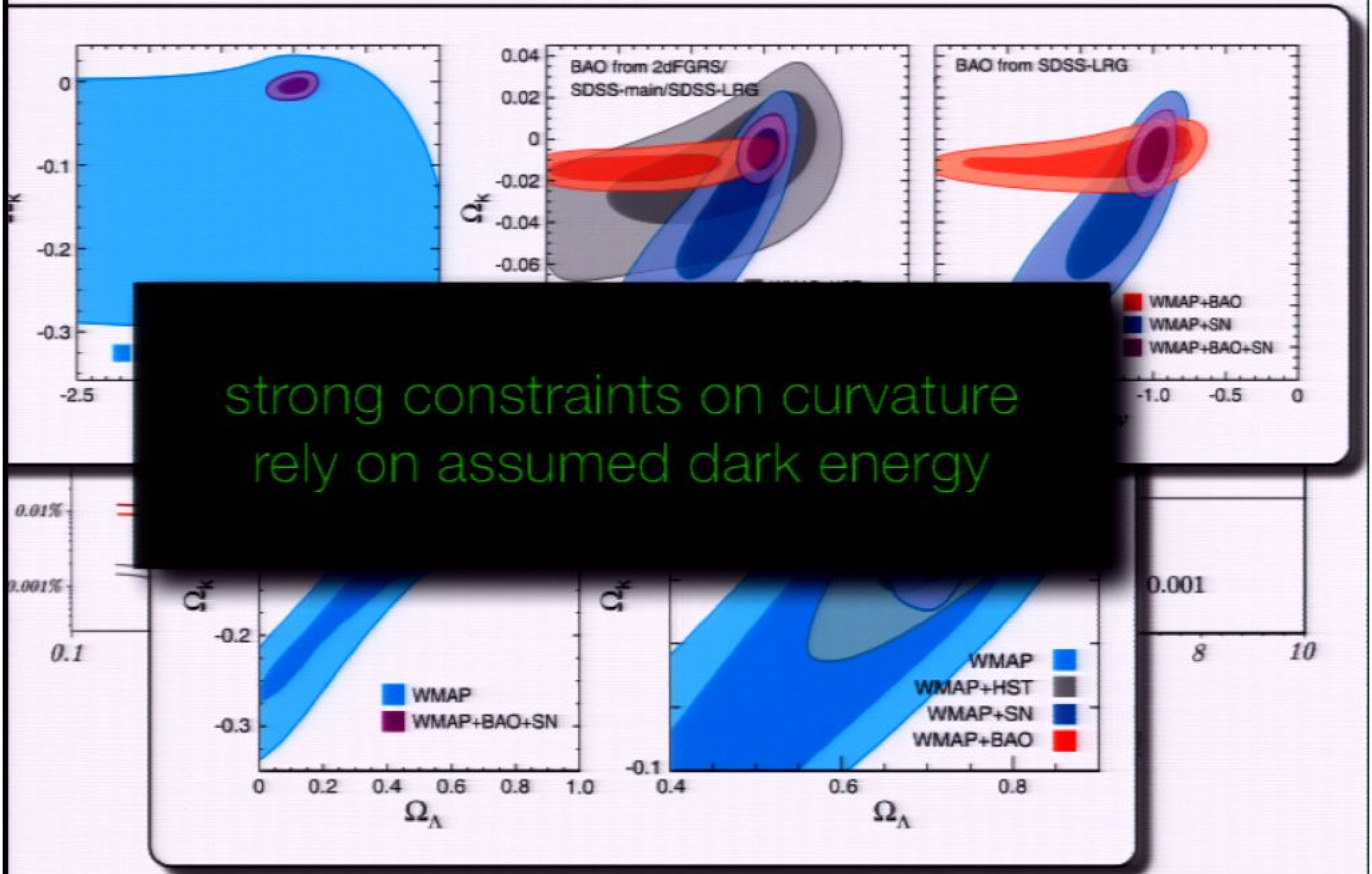

strong constraints on curvature
rely on assumed dark energy

arkson, Cortes and Bassett, JCAP08(2007)011

can we look for *any* deviations from flat LCDM?

... model independent consistency tests ...

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... model independent consistency tests ...

A litmus test for flat ΛCDM

$$\Omega_m = \frac{1 - D'(z)^2}{[(1+z)^3 - 1]D'(z)^2}. \qquad D(z) = (H_0/c)(1+z)^{-1} d_L(z),$$

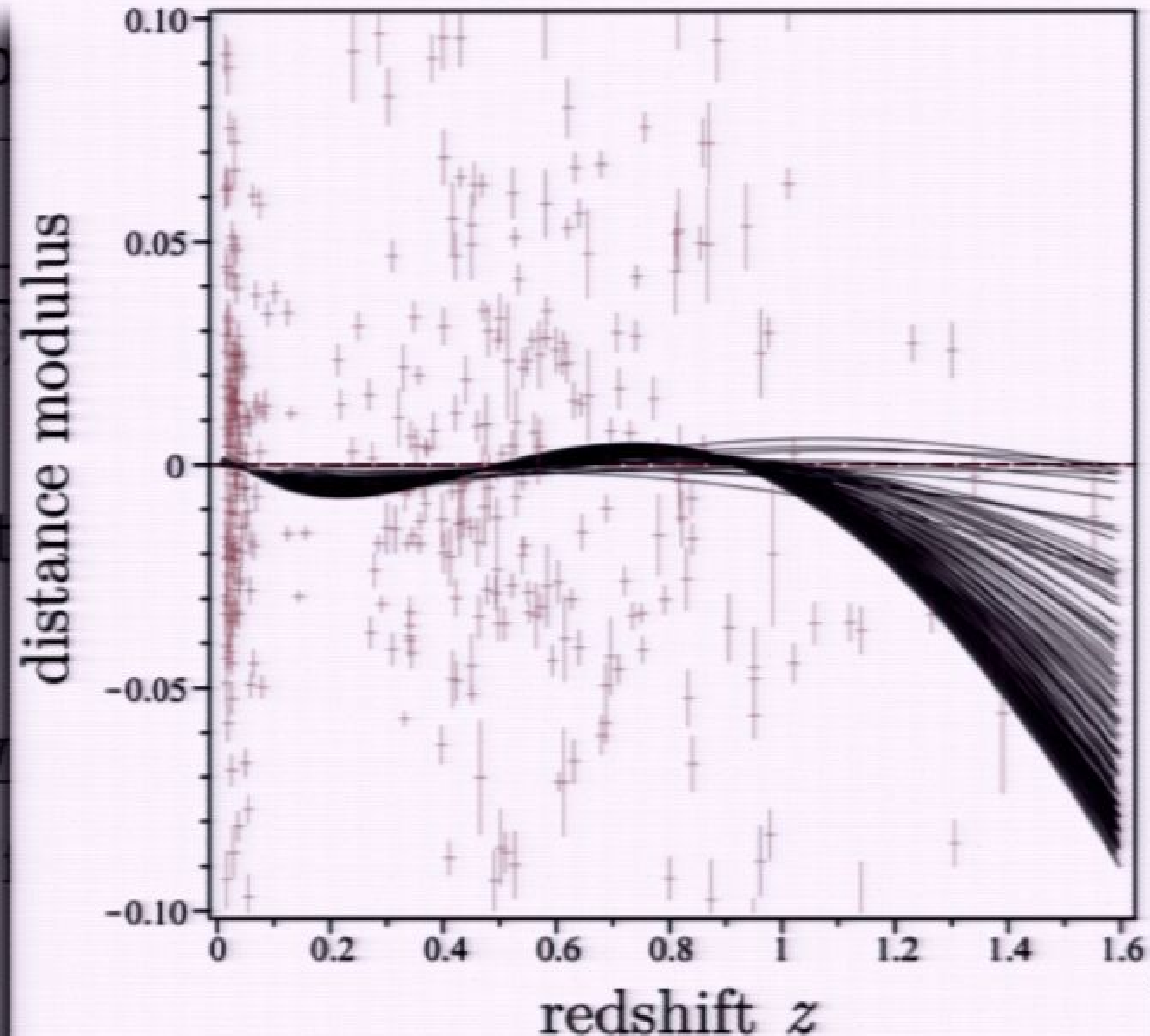
this is *constant* for flat LCDM

$$\mathscr{L}(z) = \zeta D''(z) + 3(1+z)^2 D'(z)[1 - D'(z)^2]$$
$$= 0 \text{ for all flat } \Lambda\text{CDM models.}$$

Zunckel & Clarkson, PRL, arXiv:0807.4304;
see also Sahni etal 0807.3548

A litmus test fo

$$\Omega_m = \frac{1}{[(1+z)}$$



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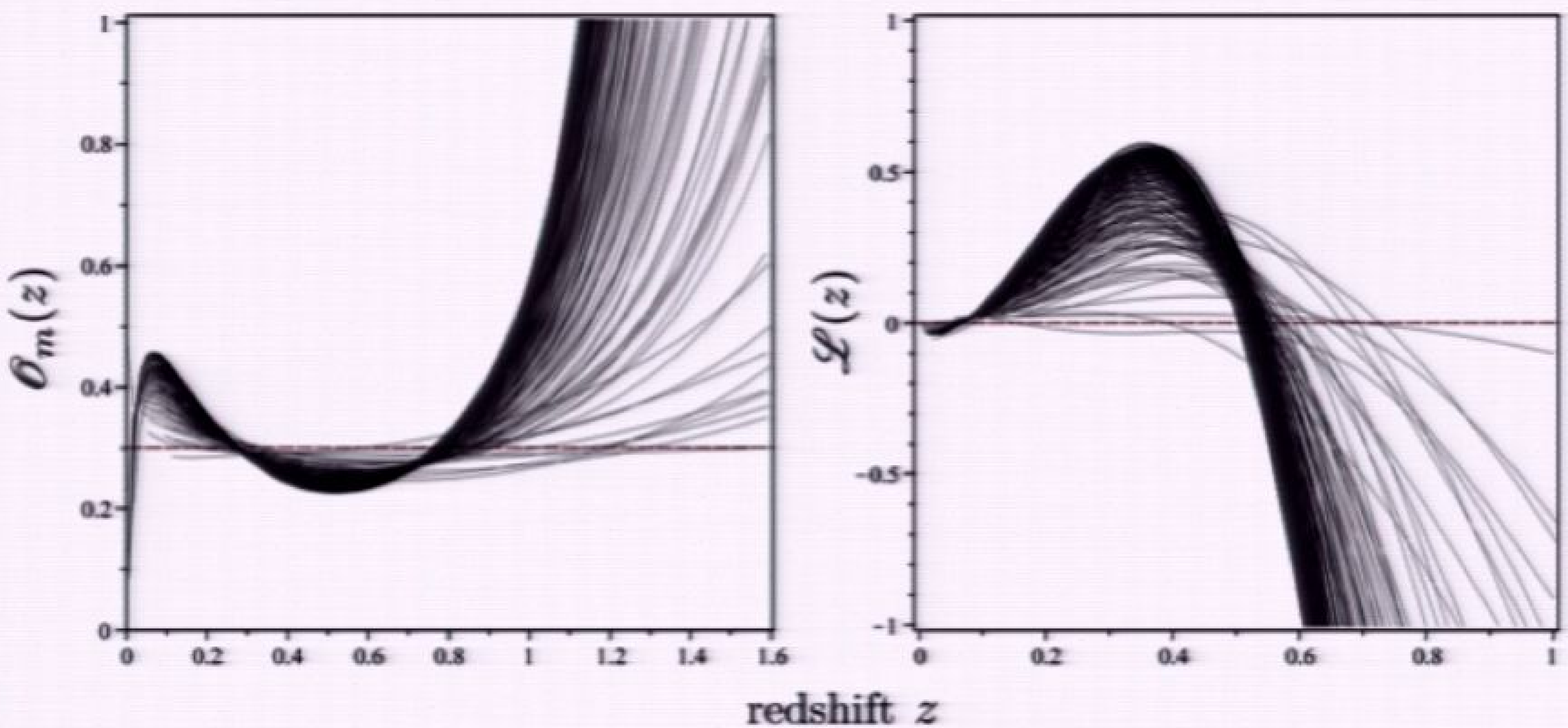
these are better fits to constitution data than LCDM



with Arman Shafieloo

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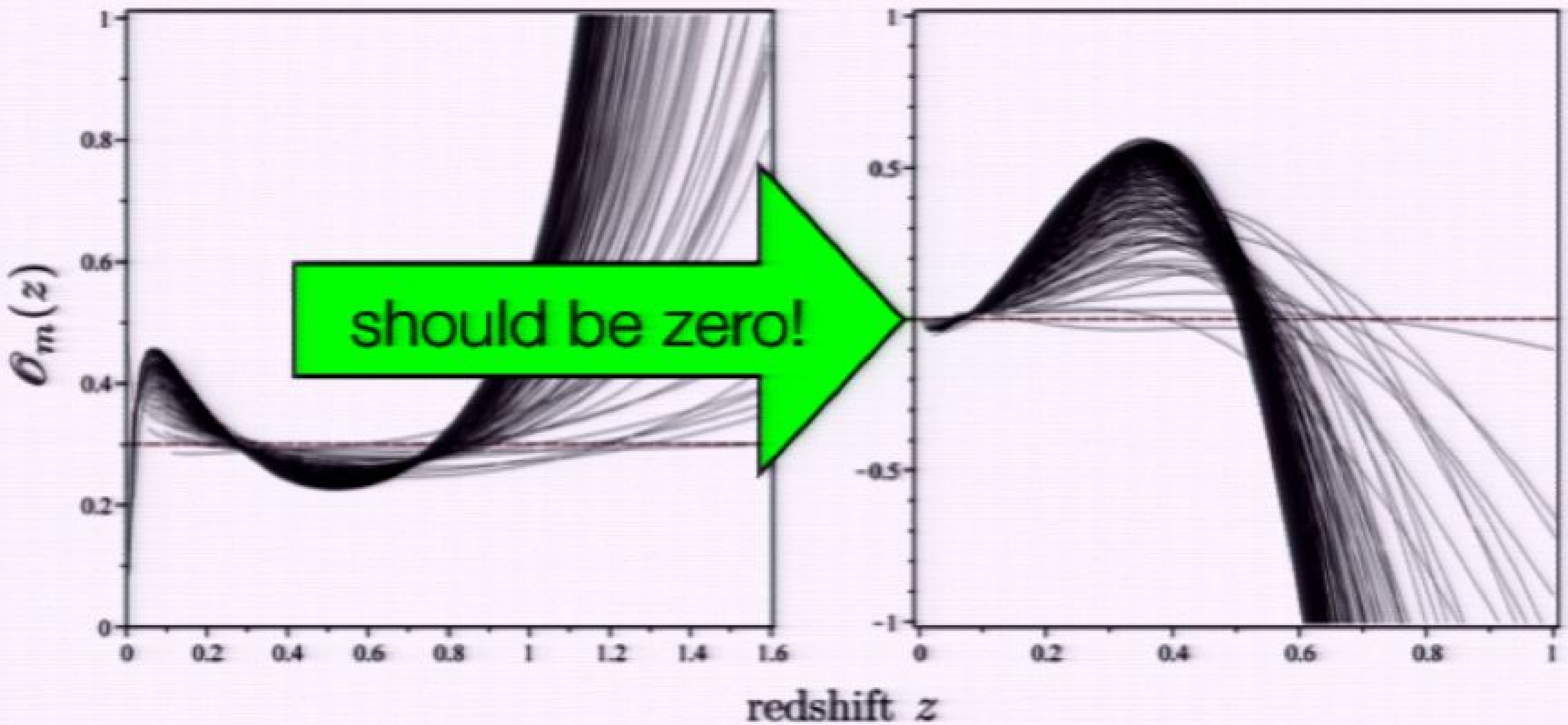

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A litmus tes

no dependence on Omega_m

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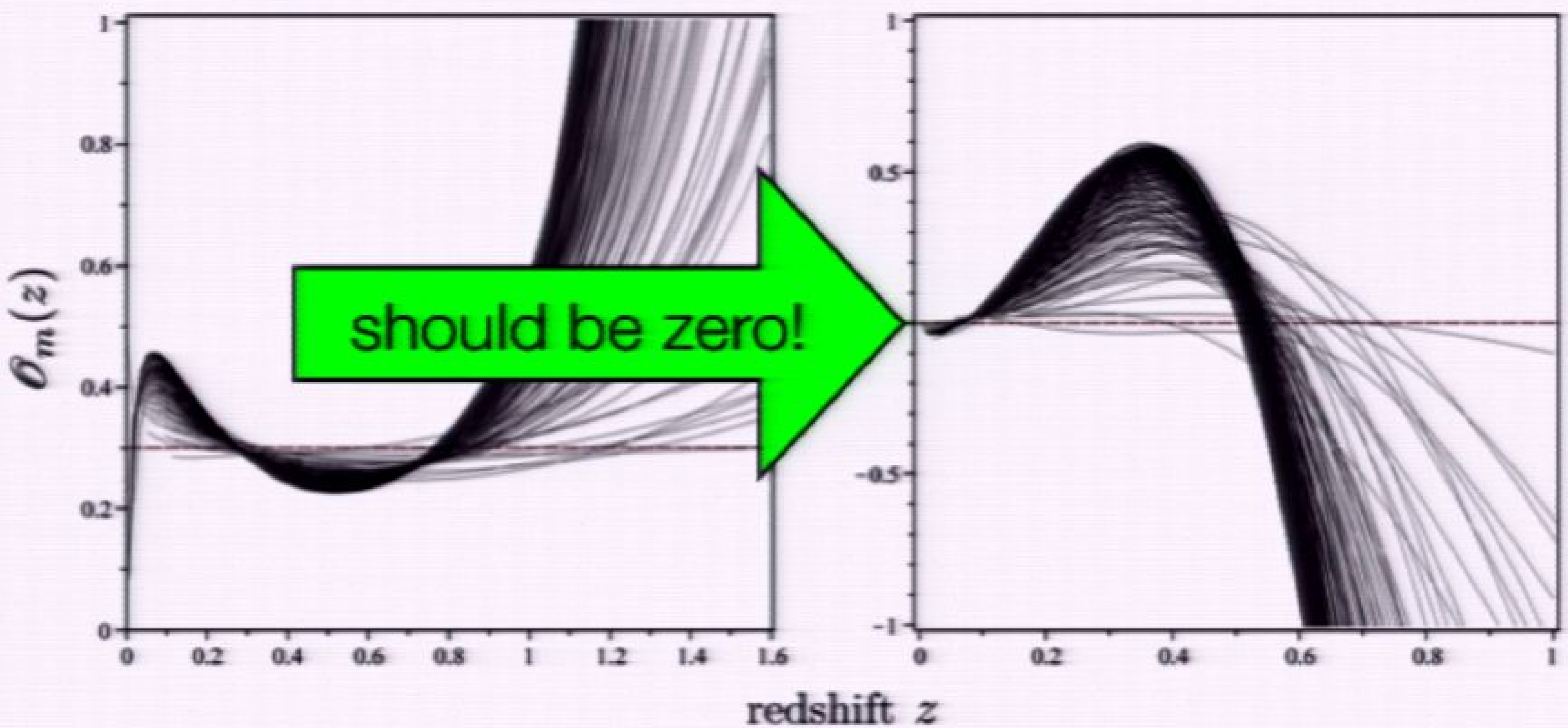

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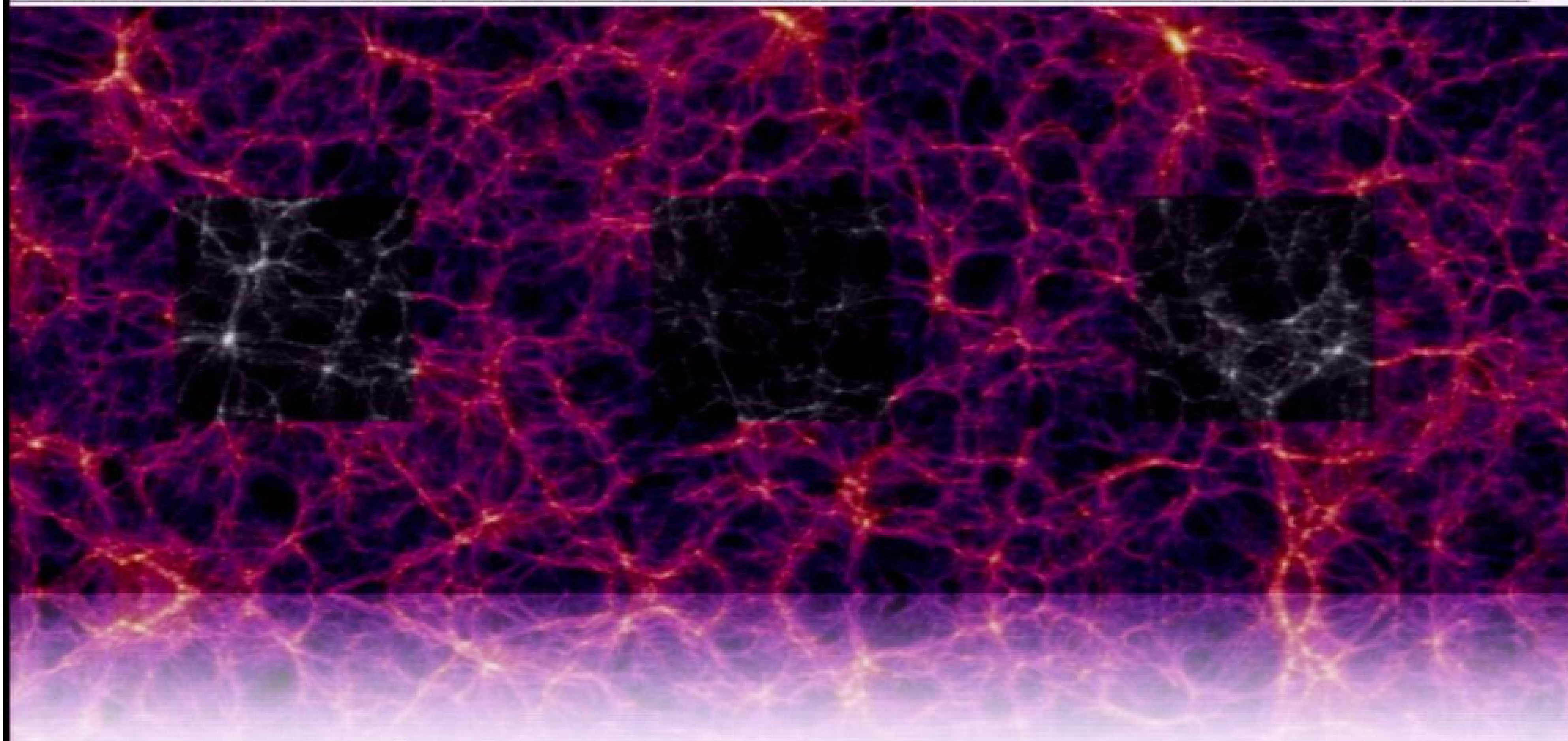
Part 2: how does structure affect the background?



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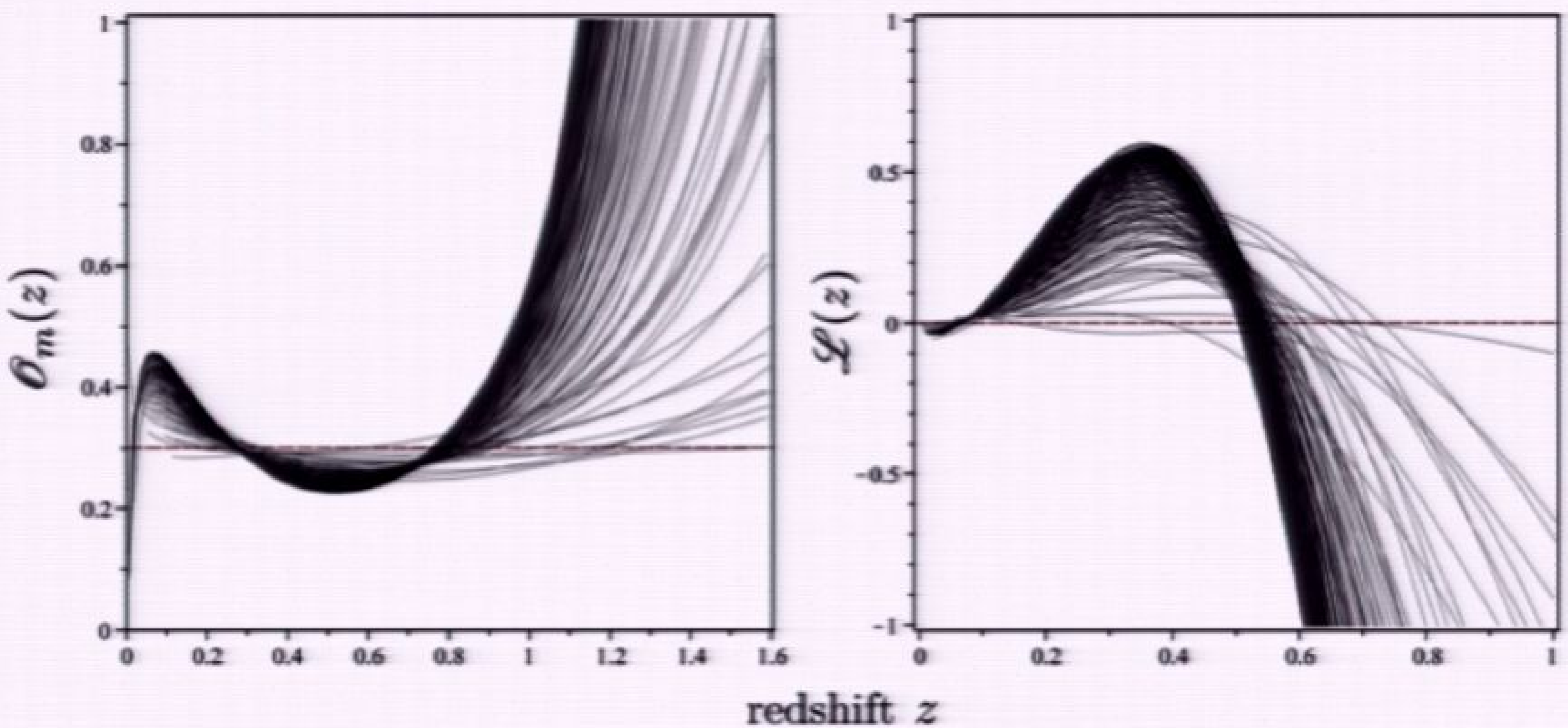

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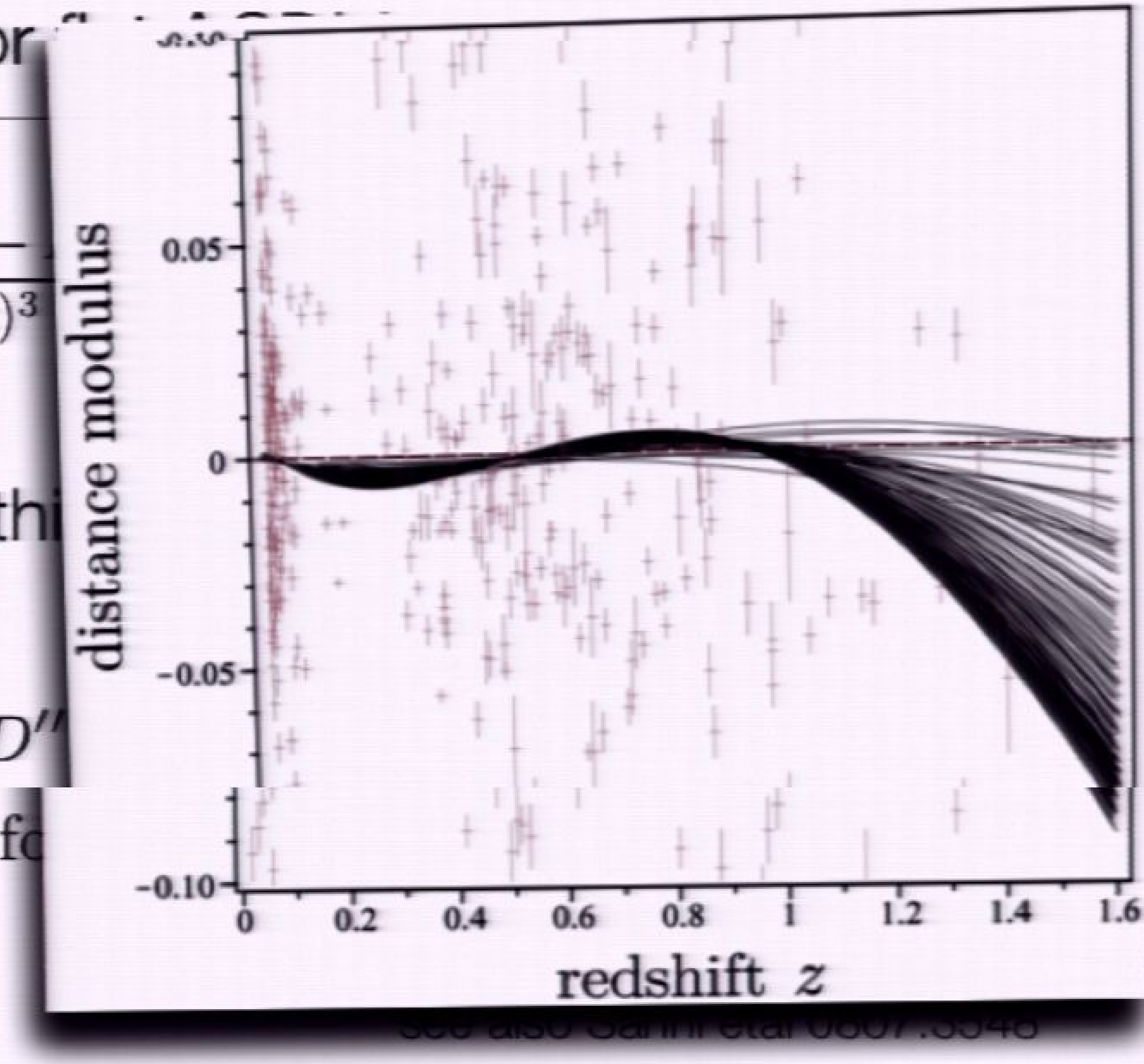
A litmus test for f

$$\Omega_m = \frac{1 - \ldots}{[(1+z)^3 \ldots}$$

thi

$$\mathscr{L}(z) = \zeta D'' \ldots$$

$$= 0 \text{ fo} \ldots$$



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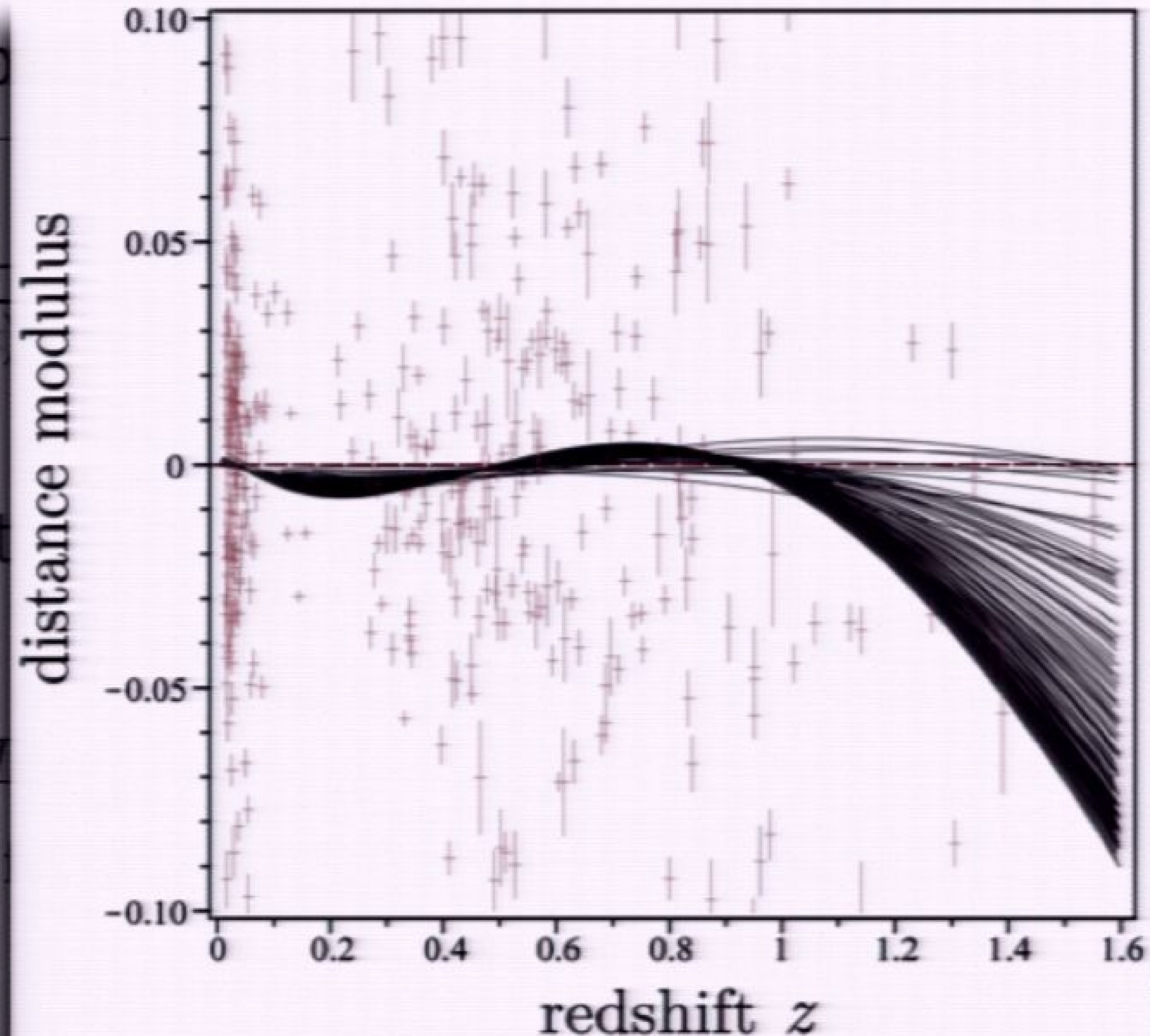

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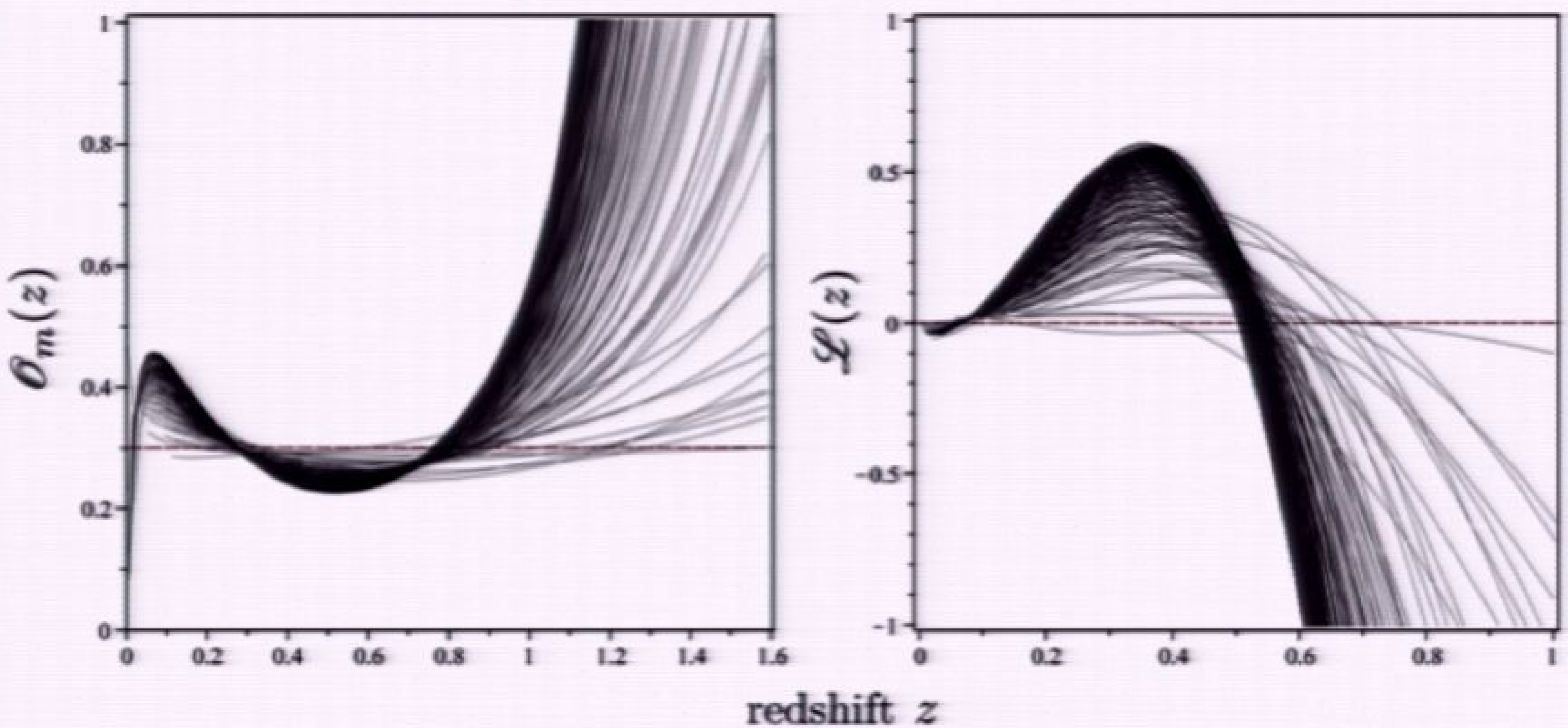

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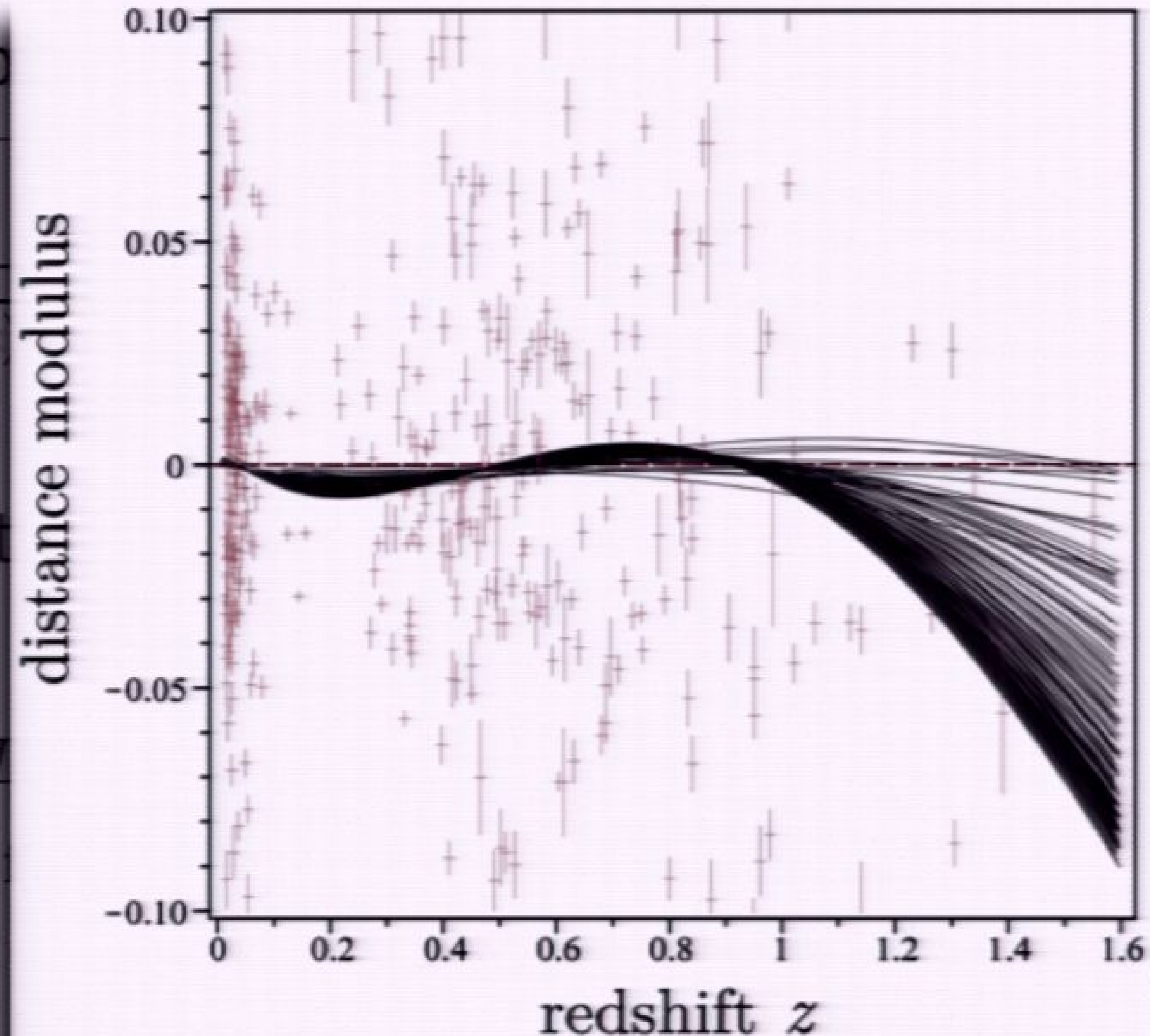

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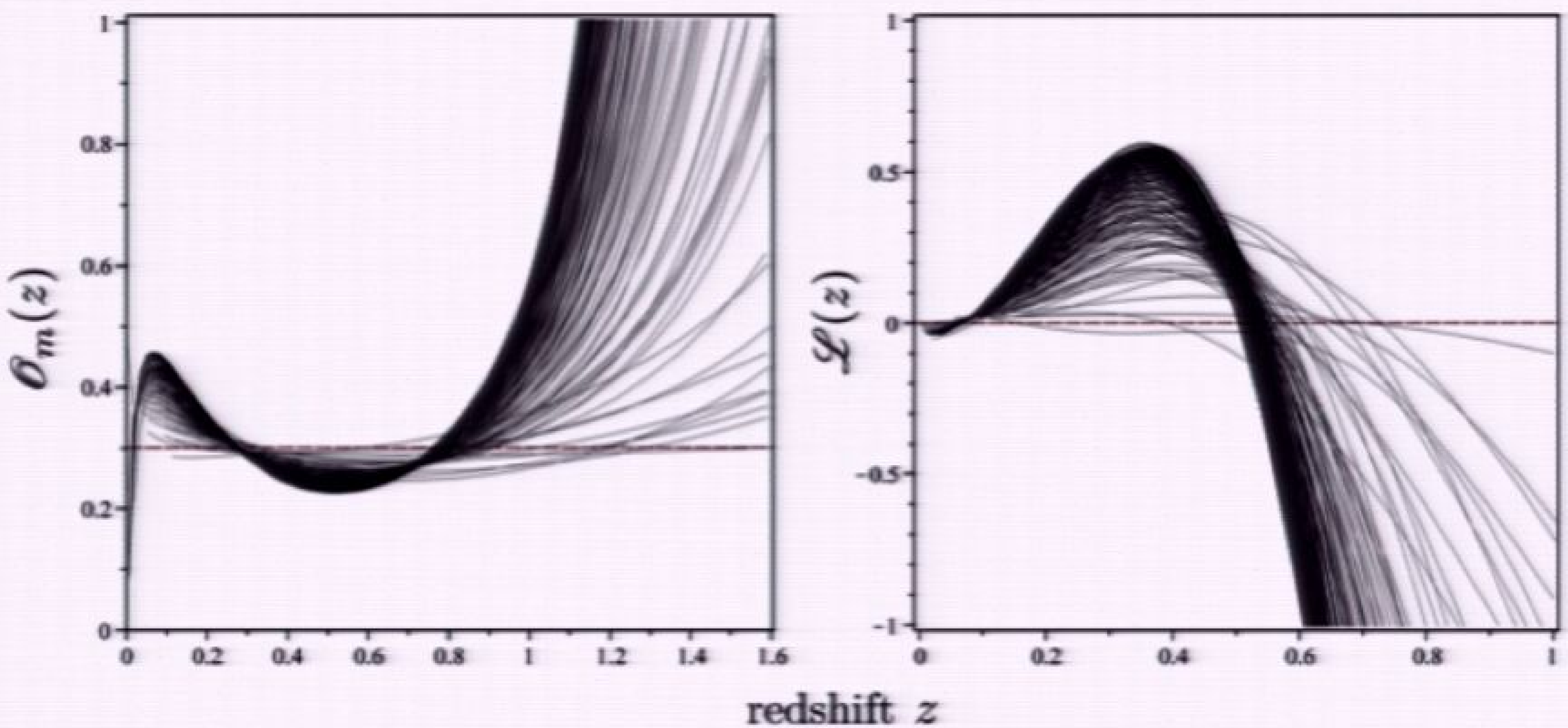

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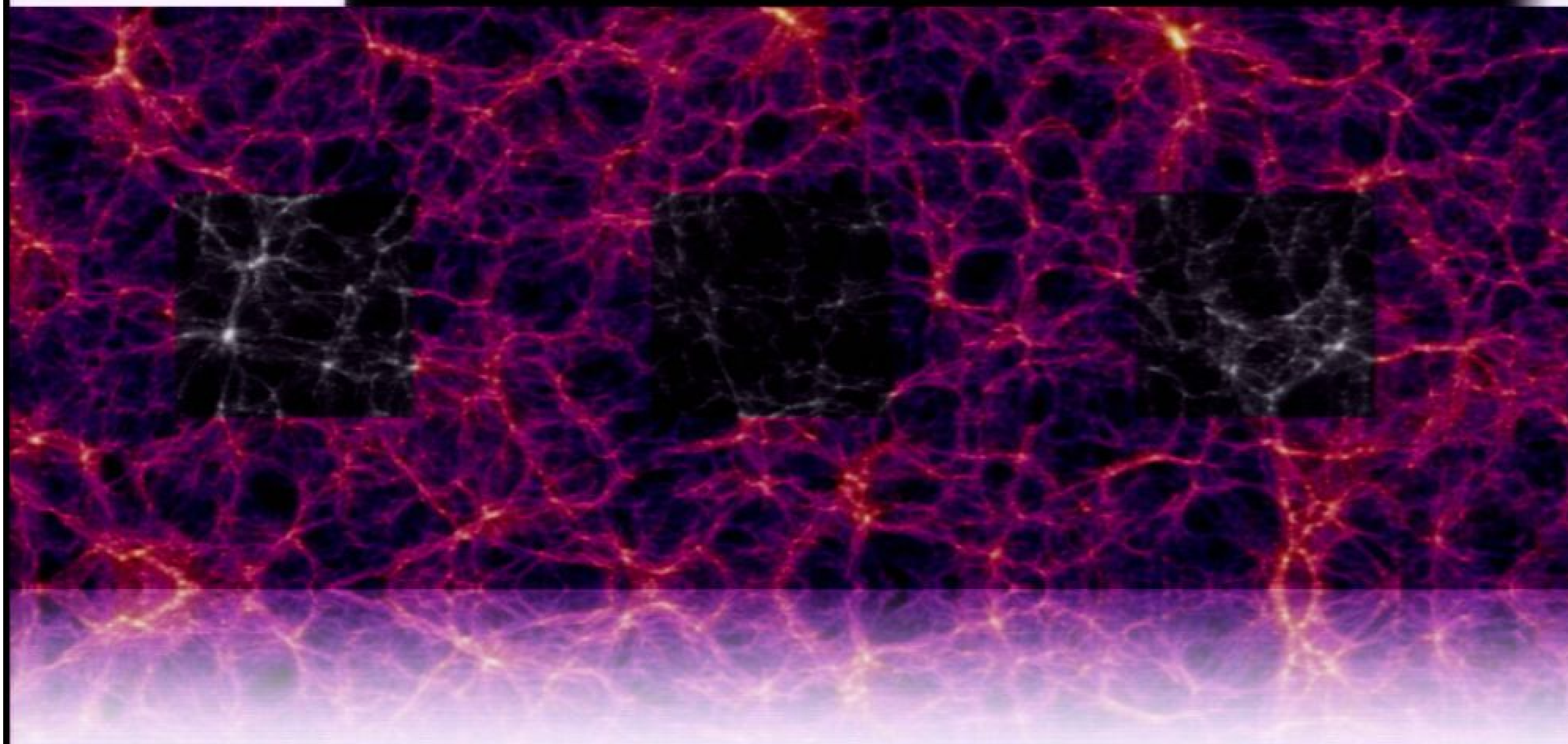
no dependence on Omega_m



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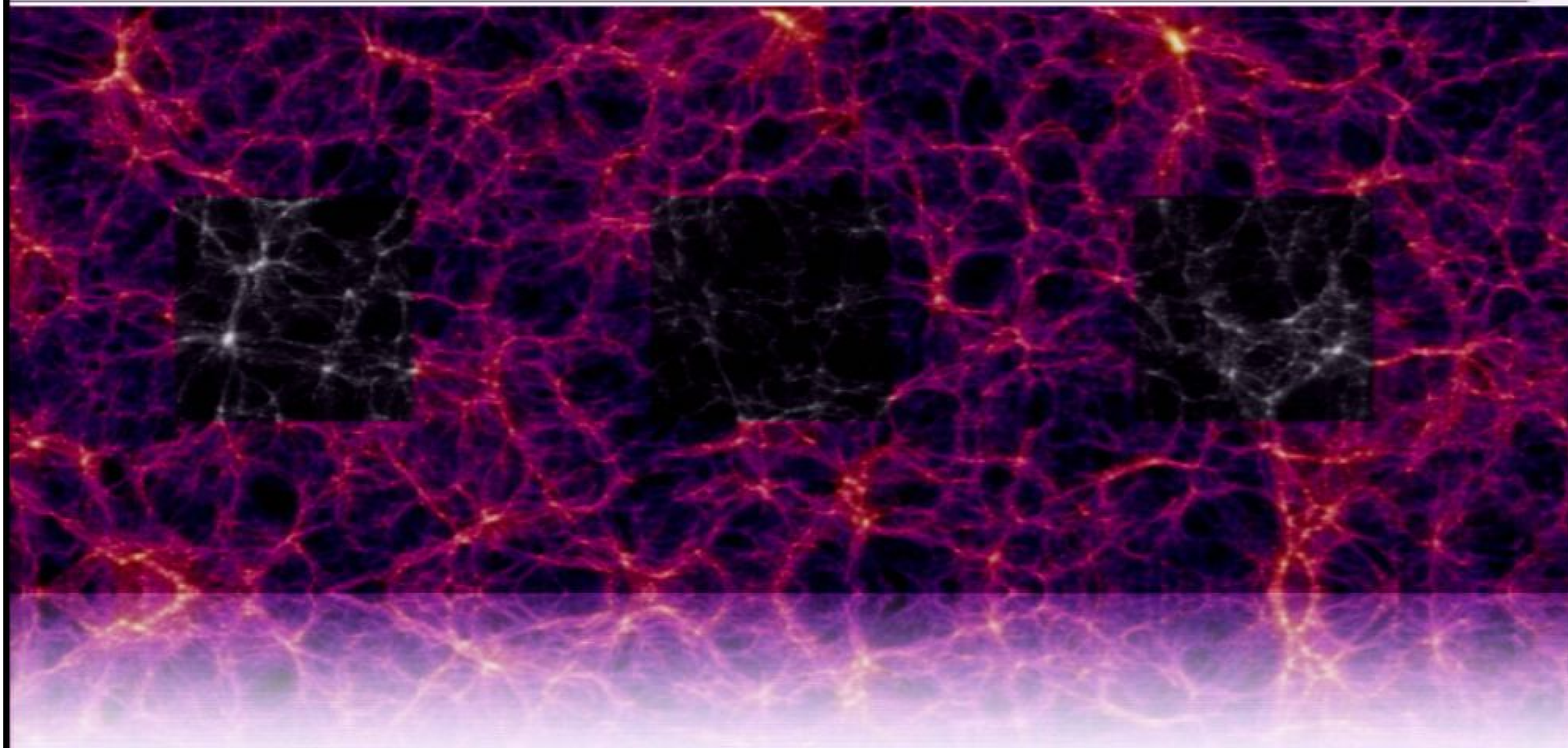

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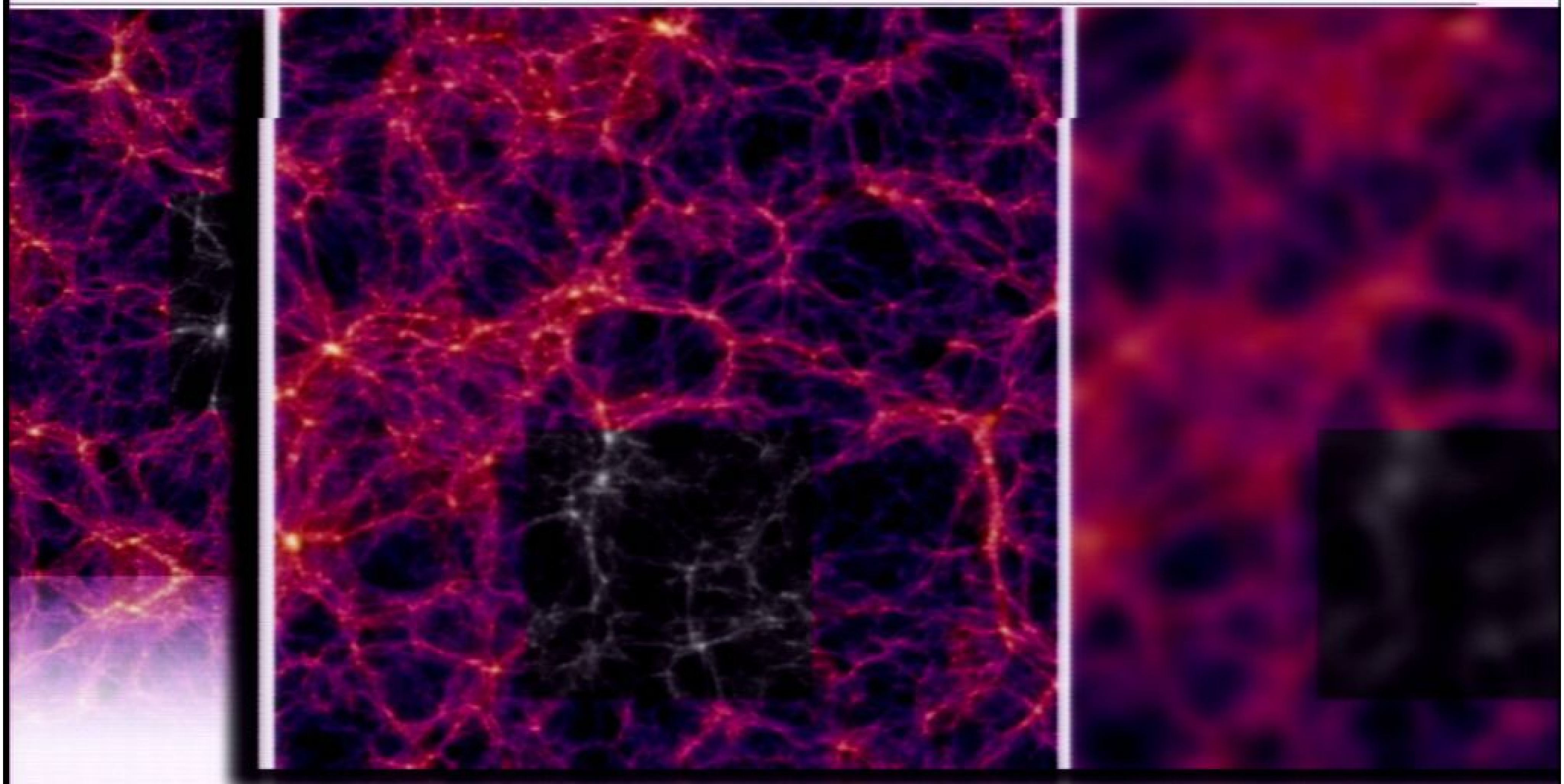

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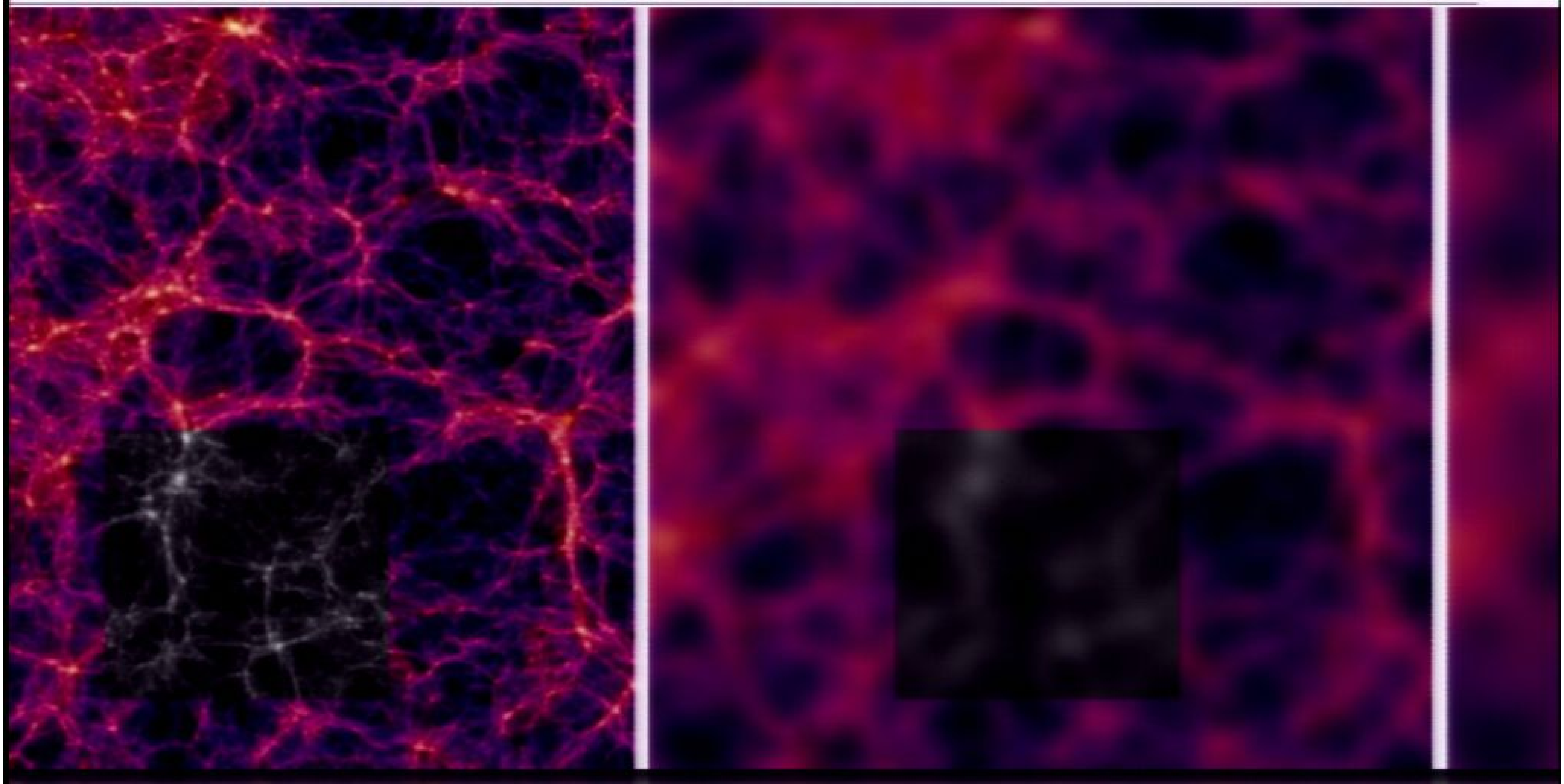

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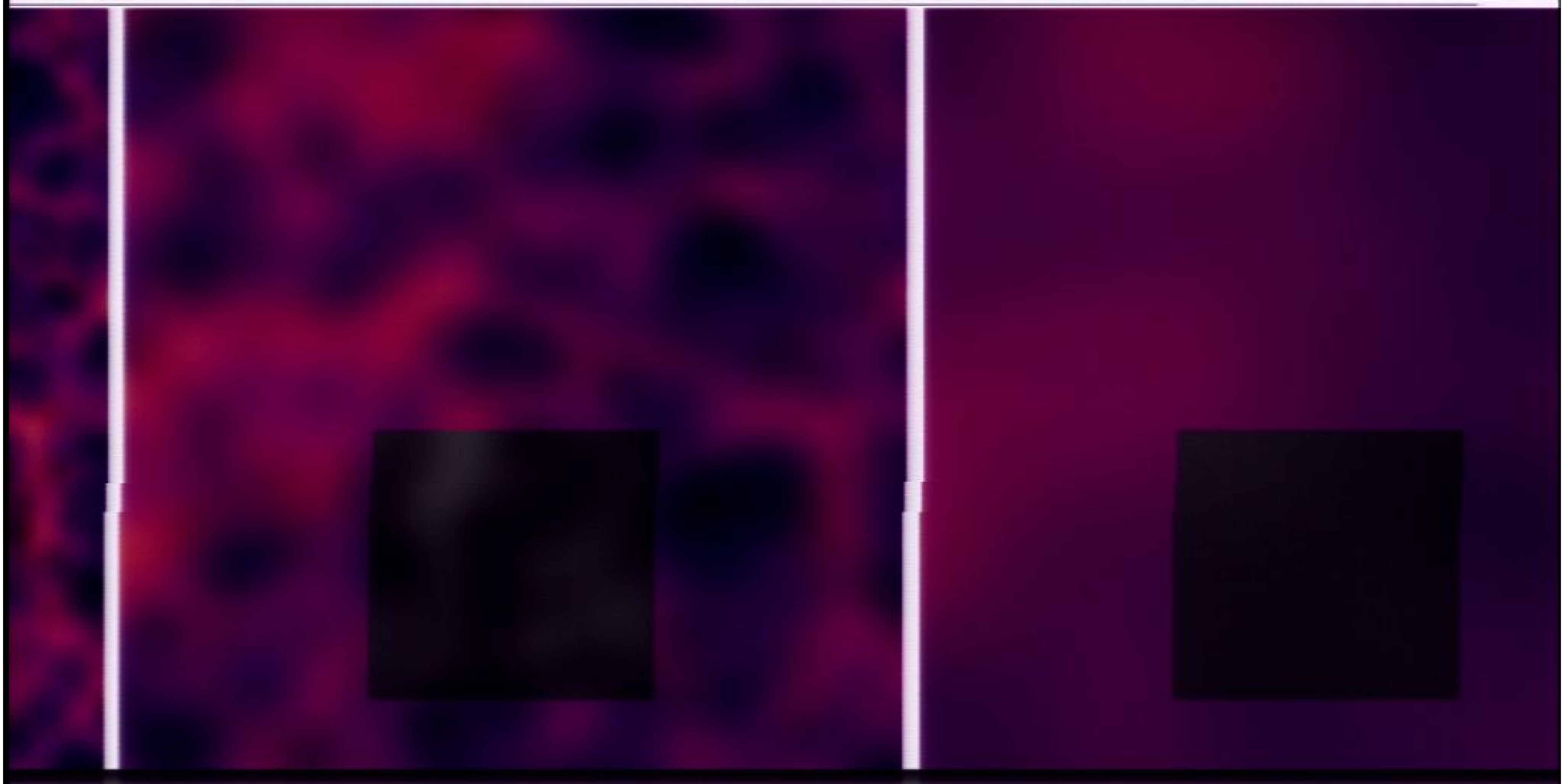

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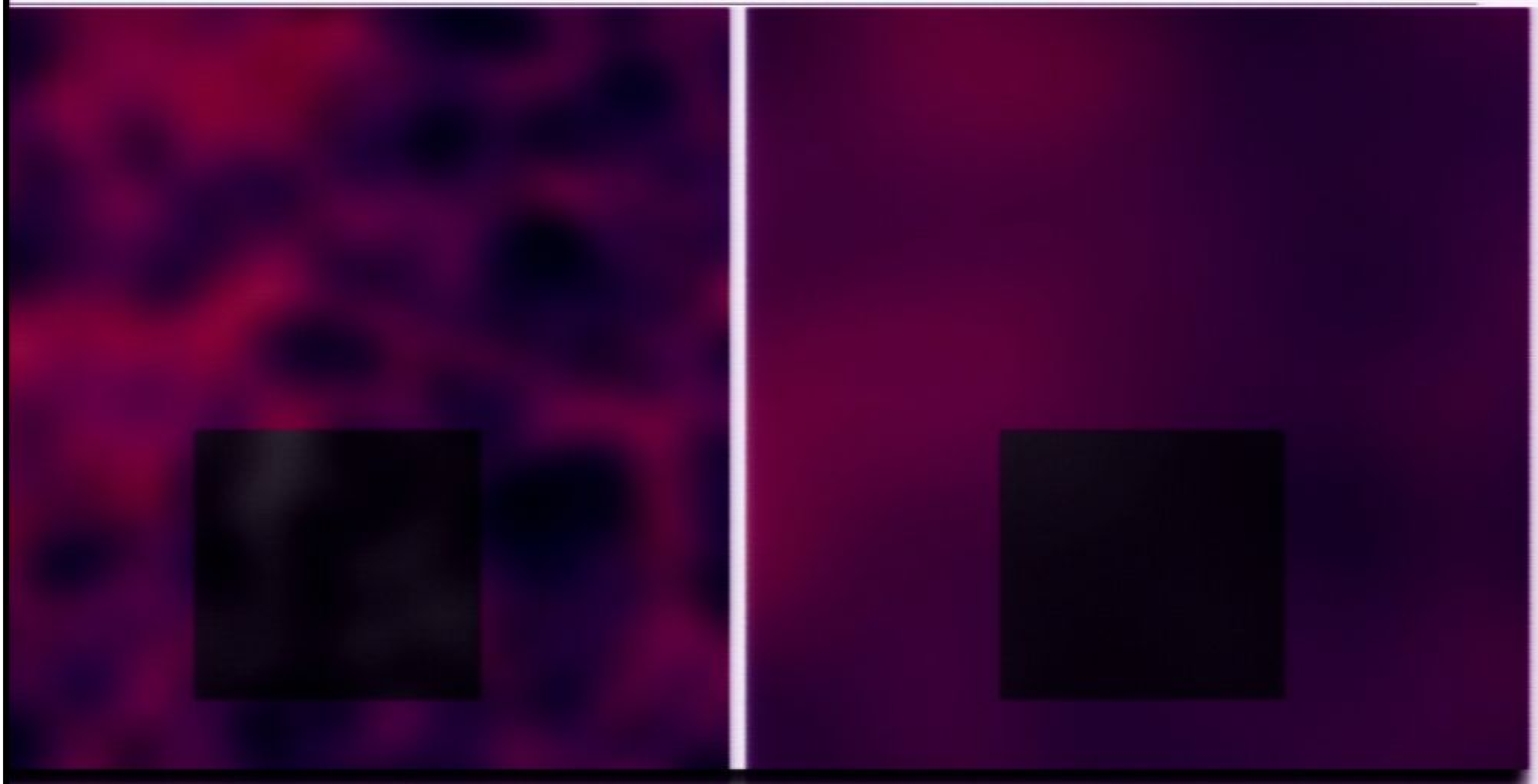


Canonical Cosmology

compute everything as power series in small parameter ε

$$\bar{g}_{\mu\nu} = g_{\mu\nu} + \epsilon\delta^{(1)}g_{\mu\nu} + \epsilon^2\delta^{(2)}g_{\mu\nu} + \cdots$$

‘real’ spacetime

‘background’ spacetime
FLRW

first-order
perturbation

second-order
correction

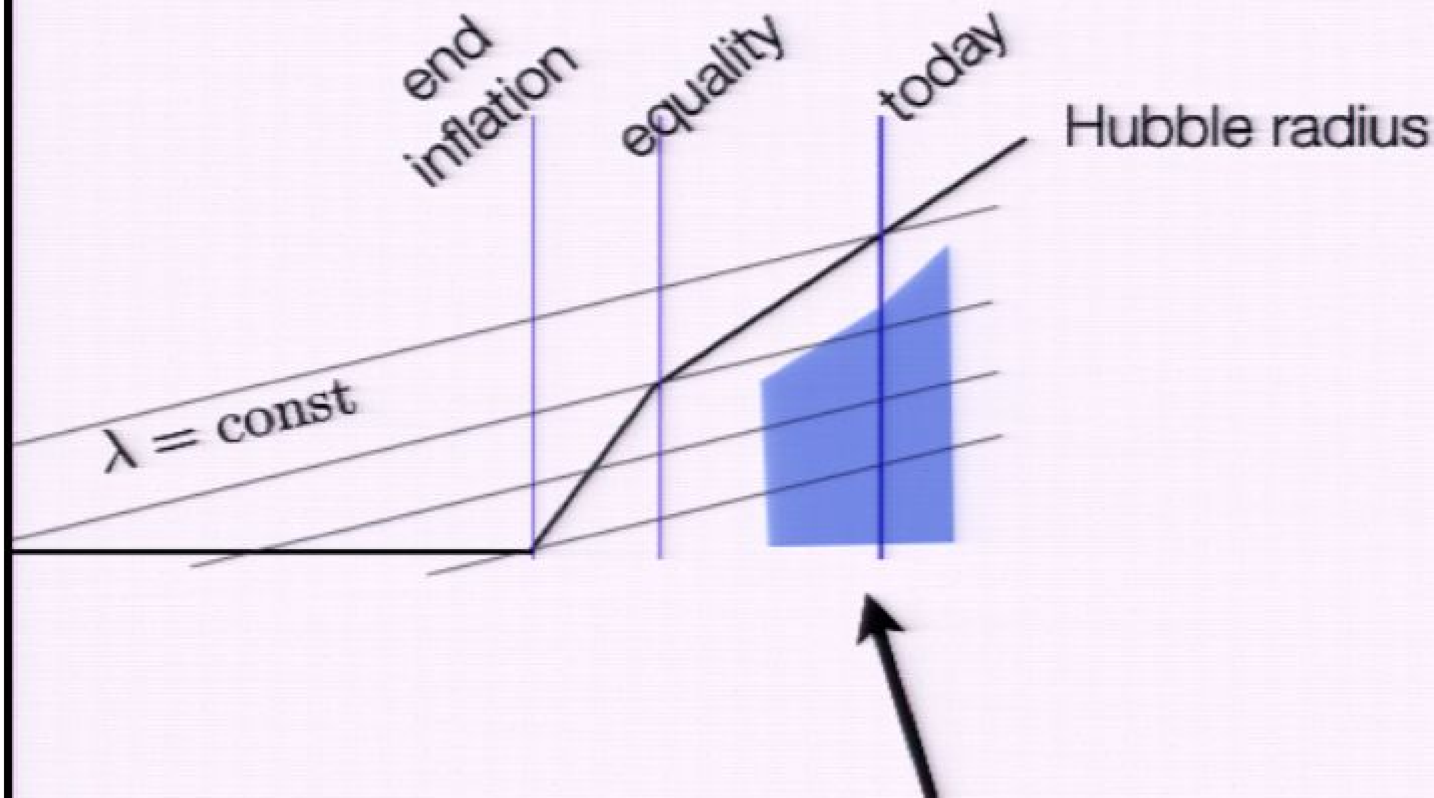
‘background’ observables - SNIa etc

he Averaging Problem

We don't know how to do it!

- We can't average tensors covariantly
- EFE non-linear :
  - an averaged geometry doesn't give 'averaged EFE'
    - averaged EFE don't give averaged geometry
- smoothed geometry doesn't stay close to 'real', modelled, spacetime
  - averaging and evolution don't commute

Another view of the averaging problem



averaging gives corrections here

different *effective* $\dfrac{\rho_{\text{tot}}}{\rho_{\text{critical}}}$ and Λ

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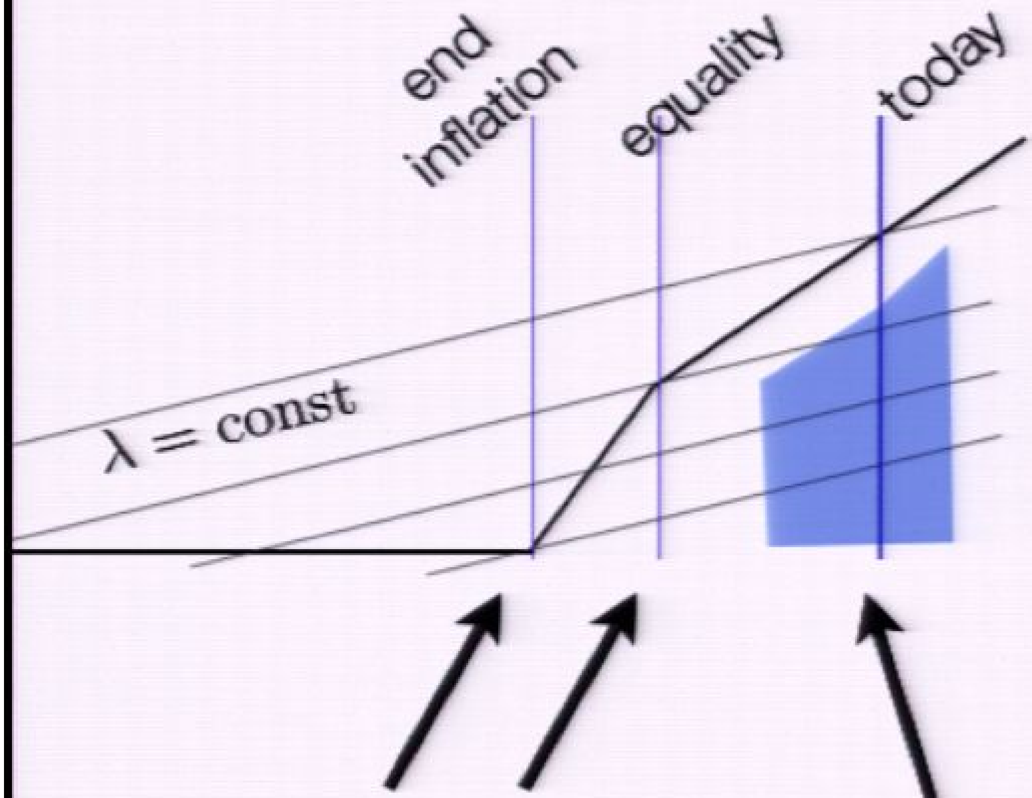

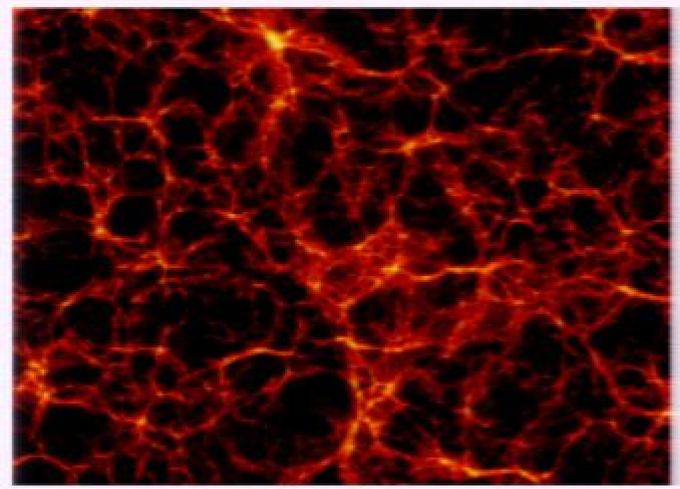

model = flat FLRW +
perturbations

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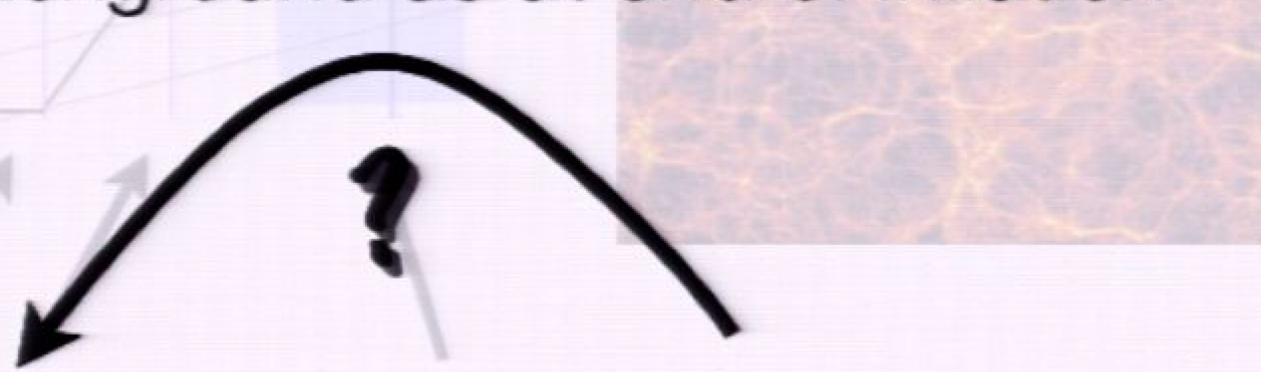
urvature and Λ fixed

Another view of the averaging problem

how do we remove backreaction bits
to get to 'real' background?
smoothed background today is not
same background as at end of inflation



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- Wouldn't it be 10^{-10}?
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- first-order Gaussian perturbations give no direct contribution

Do we care? Isn't cosmology just flat LCDM?

Corrections from averaging enter Friedmann and Raychaudhuri equations

- is this degenerate with 'dark energy'?
- can we separate the effects [if there are any?]

Averaging

Define Riemannian averaging operator on arbitrary domain D

$$\psi_{\mathcal{D}} = \langle \psi \rangle_{\mathcal{D}} \equiv \frac{1}{V_{\mathcal{D}}} \int_{\mathcal{D}} \psi(t, x^i) J d^3 x$$

Riemannian volume element

$$J \equiv \sqrt{\det(h_{ij})}$$

spatial average implies wrt some foliation of spacetime

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if we try to solve averaged field equations how can we also find J?

Perturbations to second-order

In Poisson gauge, second-order in scalars

$$ds^2 = -\left(1 + 2\Phi + \Phi^{(2)}\right) dt^2 + a^2 \left(1 - 2\Psi - \Psi^{(2)}\right) \delta_{ij} dx^i dx^j$$

first-order solution

$$\Psi = \Phi \qquad \Phi'' + 3\mathcal{H}\Phi' + a^2\Lambda\Phi = 0$$

Bardeen eqn at first-order

power spectrum $\mathcal{P}_\Phi(z,k) = \left(\frac{3\Delta_\mathcal{R}}{5g_\infty}\right)^2 g(z)^2 T(k)^2$

T(k) is the transfer function

$$g(z) = \frac{5}{2} g_\infty \Omega_m(z) \left\{ \Omega_m(z)^{4/7} - \Omega_\Lambda(z) + \left[1 + \frac{1}{2}\Omega_m(z)\right]\left[1 + \frac{1}{70}\Omega_\Lambda(z)\right]\right\}^{-1}$$

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Averaging perturbed equations

or the averaged Hubble rate get crazy stuff like

$$H_{\mathcal{D}} = H - \langle\dot{\Phi}\rangle - \frac{2(1+z)^2}{9H^2\Omega_m}\left(H\langle\partial^2\Phi\rangle + \langle\partial^2\dot{\Phi}\rangle\right) + \langle\Phi\,\dot{\Phi}\rangle$$
$$+\frac{2(1+z)^2}{9H^3\Omega_m^2}\left\{2H\Omega_m\left[H\langle\Phi\,\partial^2\Phi\rangle + \langle\Phi\,\partial^2\dot{\Phi}\rangle\right] + H(1+3\Omega_m)\left[H\langle\partial^k\Phi\,\partial_k\Phi\rangle + \langle\partial^k\Phi\,\partial_k\dot{\Phi}\rangle\right] + \langle\partial^k\right.$$
$$-3\langle\Phi\rangle\langle\dot{\Phi}\rangle - \frac{2(1+z)^2}{3H^2\Omega_m}\left[H\langle\Phi\rangle\langle\partial^2\Phi\rangle + \langle\Phi\rangle\langle\partial^2\dot{\Phi}\rangle\right]$$
$$-\frac{1}{2}\langle\dot{\Psi}^{(2)}\rangle + \frac{1}{6}\langle\partial^2 v^{(2)}\rangle.$$

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$$
\begin{aligned}
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& + \frac{2(1+z)^2}{9H^3\Omega_m^2}\Big\{2H\Omega_m\Big[H\langle\Phi\,\partial^2\Phi\rangle + \langle\Phi\,\partial^2\dot\Phi\rangle\Big] + H(1+3\Omega_m)\Big[H\langle\partial^k\Phi\,\partial_k\Phi\rangle + \langle\partial^k\Phi\,\partial_k\dot\Phi\rangle\Big] + \langle\partial^k \\
& - 3\langle\Phi\rangle\langle\dot\Phi\rangle - \frac{2(1+z)^2}{3H^2\Omega_m}\Big[H\langle\Phi\rangle\langle\partial^2\Phi\rangle + \langle\Phi\rangle\langle\partial^2\dot\Phi\rangle\Big] \\
& - \frac{1}{2}\langle\dot\Psi^{(2)}\rangle + \frac{1}{6}\langle\partial^2 v^{(2)}\rangle.
\end{aligned}
$$

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$$
\begin{aligned}
H_{\mathcal{D}} \;=\; & H + \langle\dot\Phi\rangle - \frac{2(1+z)^2}{9H^2\Omega_m}\Big(H\langle\partial^2\Phi\rangle + \langle\partial^2\dot\Phi\rangle\Big) + \langle\Phi\,\dot\Phi\rangle \\
& + \frac{2(1+z)^2}{9H^3\Omega_m^2}\Big\{2H\Omega_m\Big[H\langle\Phi\,\partial^2\Phi\rangle + \langle\Phi\,\partial^2\dot\Phi\rangle\Big] + H(1+3\Omega_m)\Big[H\langle\partial^k\Phi\,\partial_k\Phi\rangle + \langle\partial^k\Phi\,\partial_k\dot\Phi\rangle\Big] + \langle\partial^k \\
& -3\langle\Phi\rangle\langle\dot\Phi\rangle - \frac{2(1+z)^2}{3H^2\Omega_m}\Big[H\langle\Phi\rangle\langle\partial^2\Phi\rangle + \langle\Phi\rangle\langle\partial^2\dot\Phi\rangle\Big] \\
& -\frac{1}{2}\langle\dot\Psi^{(2)}\rangle + \frac{1}{6}\langle\partial^2 v^{(2)}\rangle.
\end{aligned}
$$

first-order contribution

Averaging perturbed equations

or the averaged Hubble rate get crazy stuff like

$$H_{\mathcal{D}} = H - \langle\dot\Phi\rangle - \frac{2(1+z)^2}{9H^2\Omega_m}\Big(H\langle\partial^2\Phi\rangle + \langle\partial^2\dot\Phi\rangle\Big) + \langle\Phi\,\dot\Phi\rangle$$
$$+\frac{2(1+z)^2}{9H^3\Omega_m^2}\Big\{2H\Omega_m\Big[H\langle\Phi\,\partial^2\Phi\rangle + \langle\Phi\,\partial^2\dot\Phi\rangle\Big] + H(1+3\Omega_m)\Big[H\langle\partial^k\Phi\,\partial_k\Phi\rangle + \langle\partial^k\Phi\,\partial_k\dot\Phi\rangle\Big] + \langle\partial^k$$
$$-3\langle\Phi\rangle\langle\dot\Phi\rangle - \frac{2(1+z)^2}{3H^2\Omega_m}\Big[H\langle\Phi\rangle\langle\partial^2\Phi\rangle + \langle\Phi\rangle\langle\partial^2\dot\Phi\rangle\Big]$$
$$-\frac{1}{2}\langle\dot\Psi^{(2)}\rangle + \frac{1}{6}\langle\partial^2 v^{(2)}\rangle.$$

second-order contribution - express ito first-order

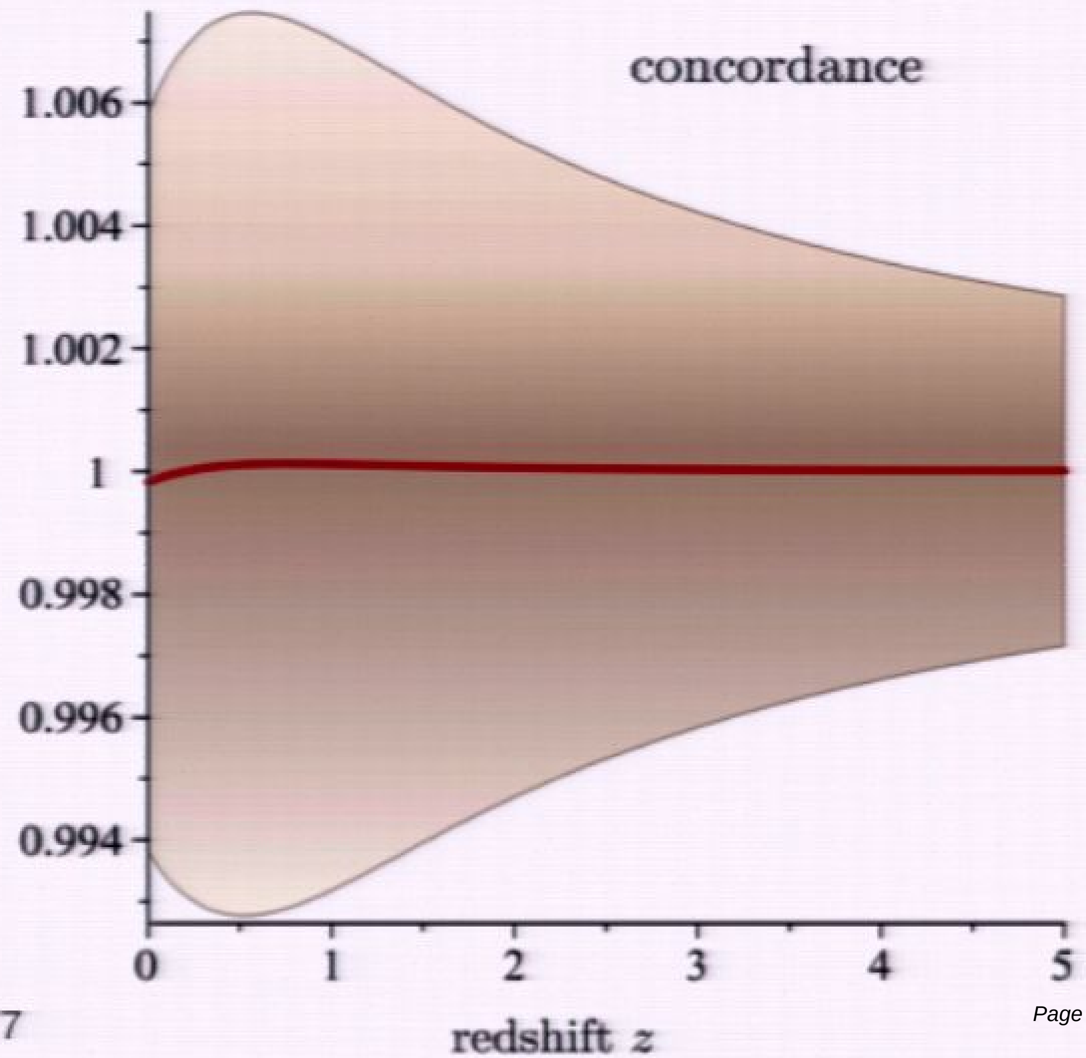
Change to the Hubble rate

lormalised Hubble rate
s function of redshift

om averaging Friedmann
quation

$$\sqrt{\overline{H_{\mathcal{D}}^2}}$$

quality scale domain



arkson, Ananda & Larena, 0907.3377

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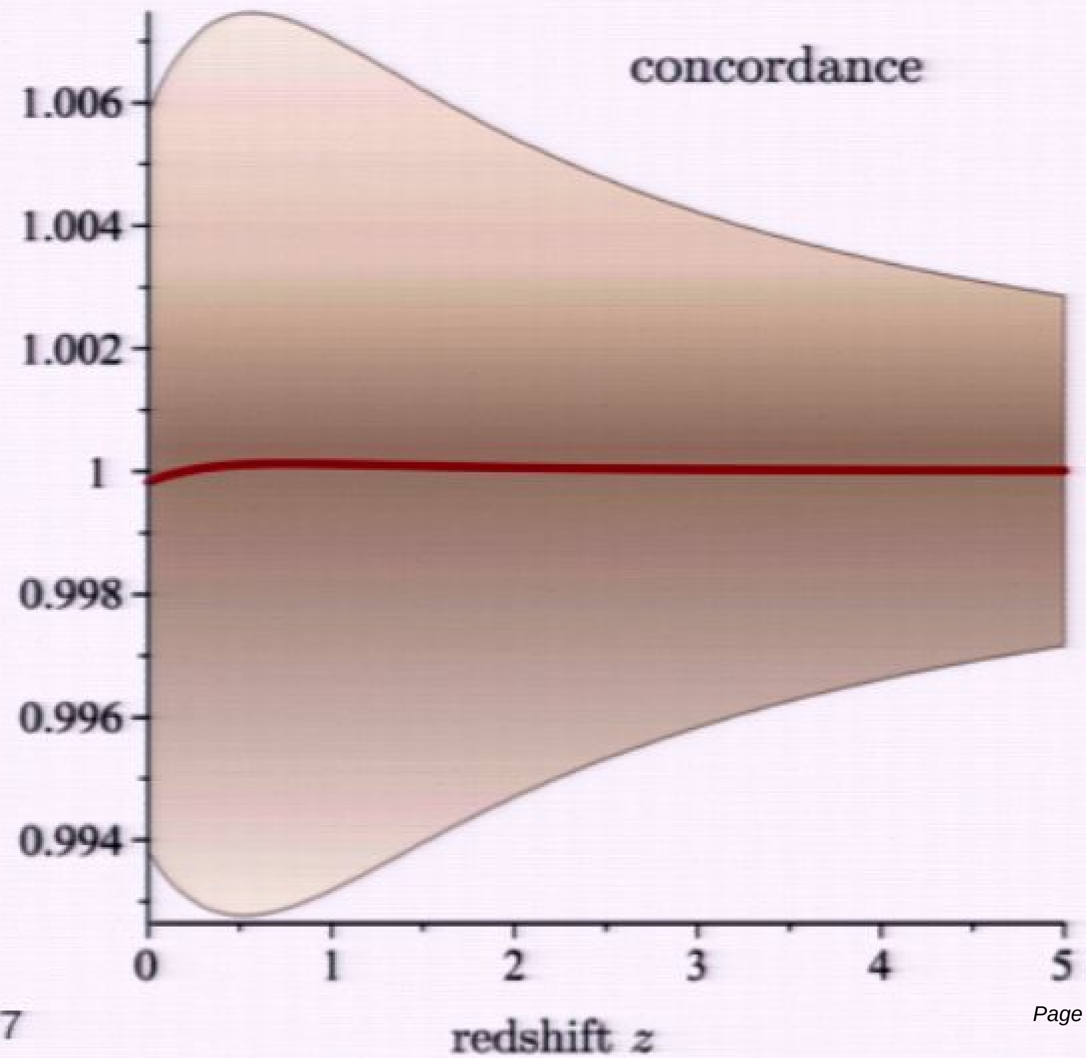

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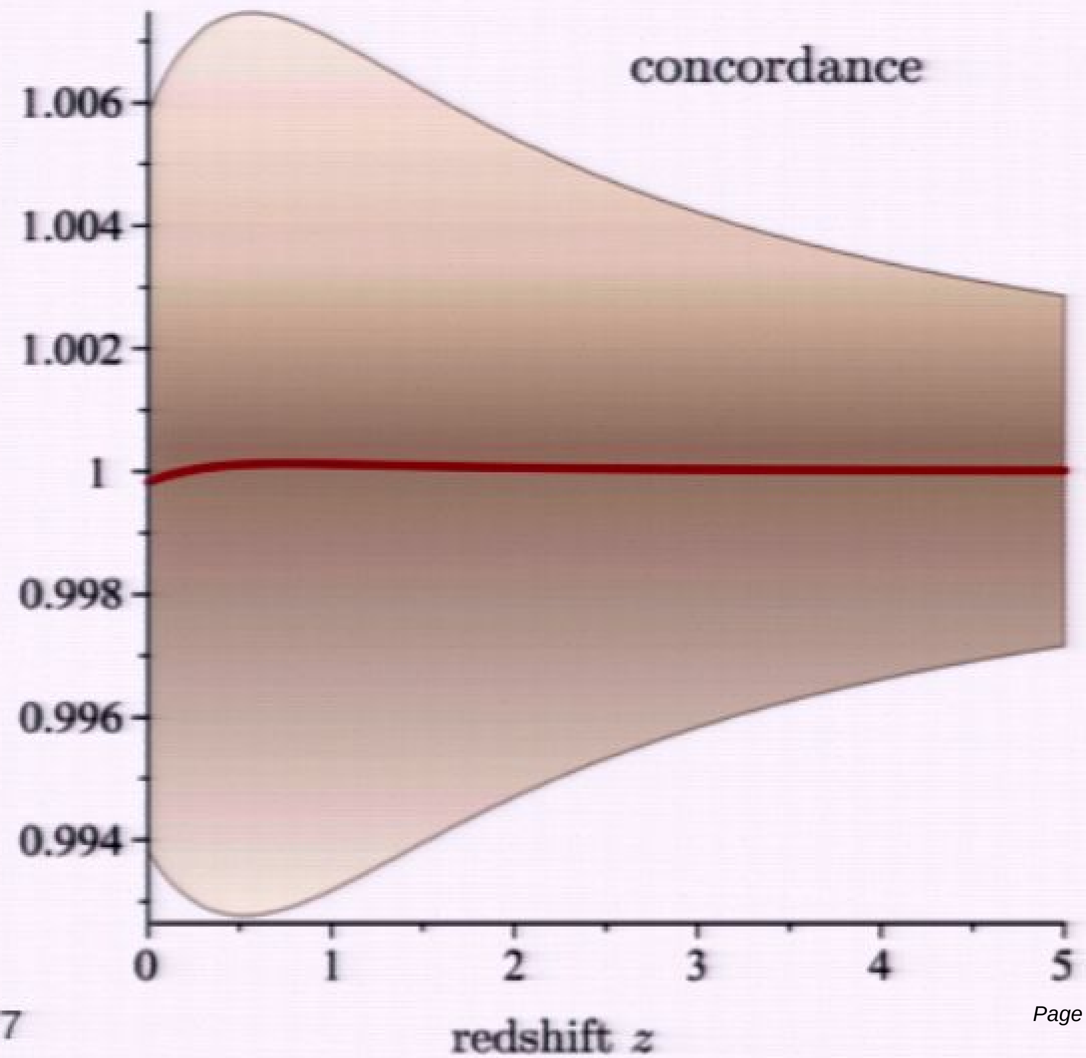

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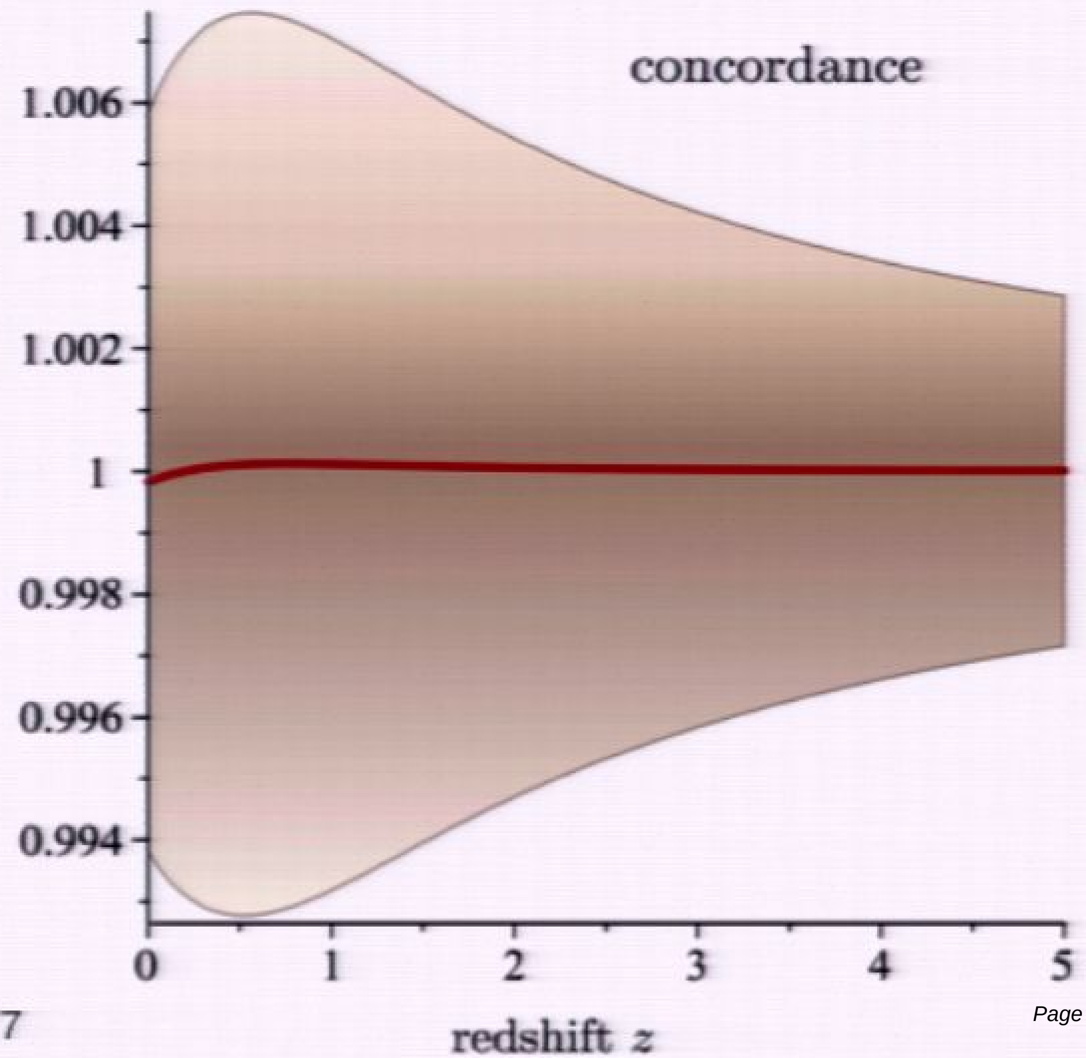

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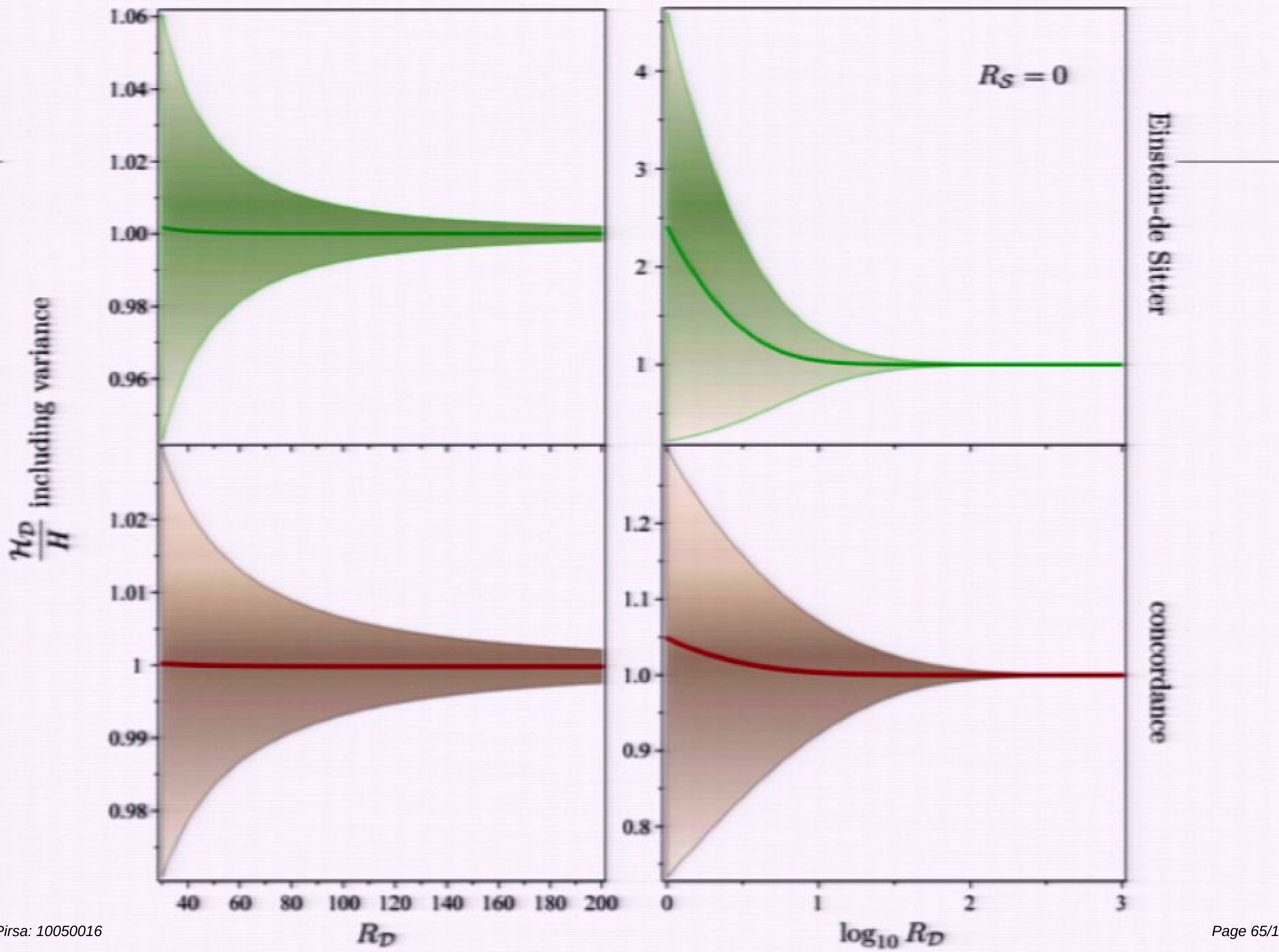
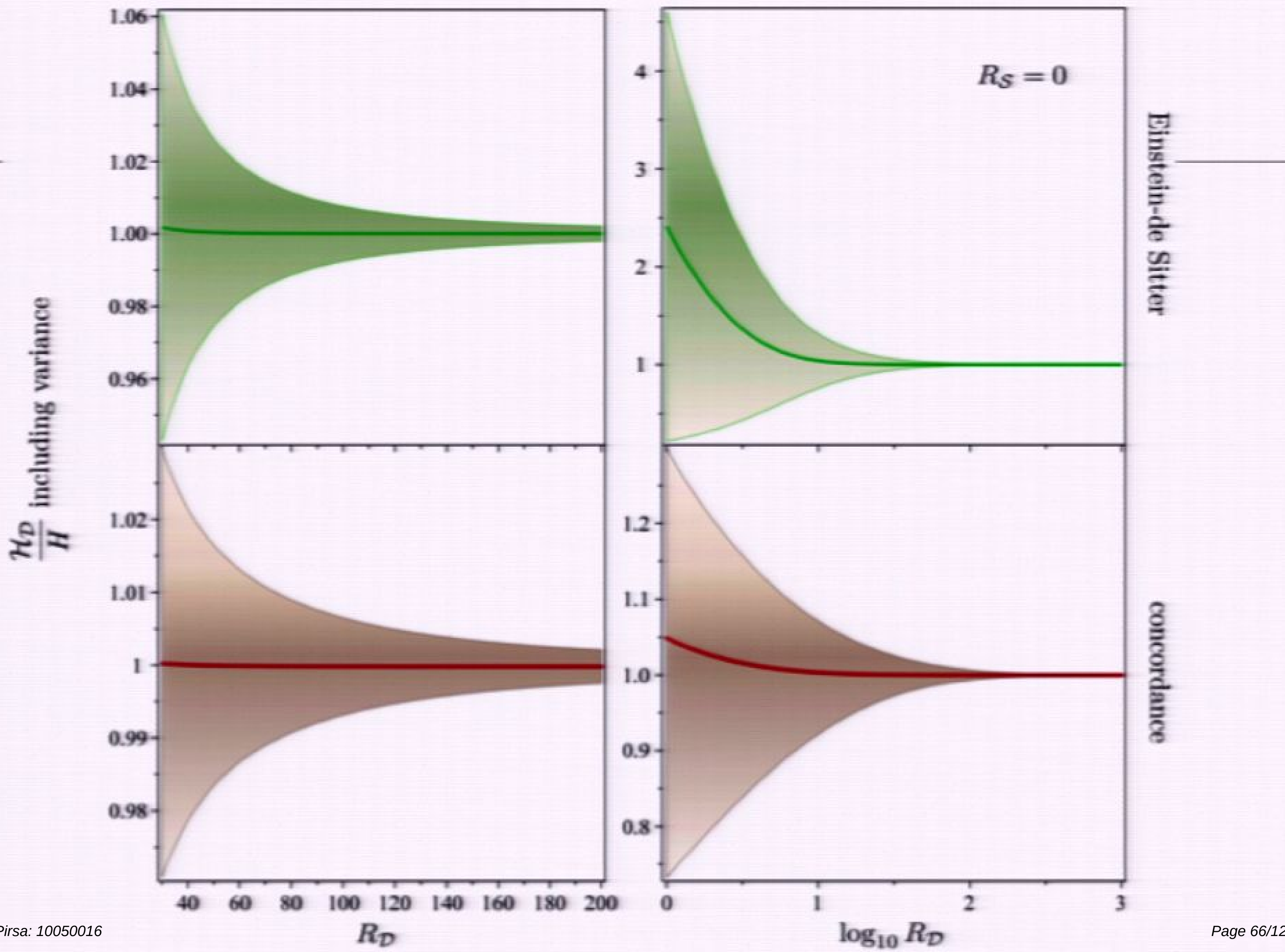


$R_S = 0$
Einstein-de Sitter
concordance
$\frac{\mathcal{H}_\mathcal{D}}{H}$ including variance
$R_\mathcal{D}$
$\log_{10} R_\mathcal{D}$



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ame sort of thing - but much more complicated!

ow includes things like

$$\langle \partial^2\Phi \; \partial^2\Phi \rangle$$

hese have UV divergence - smoothing scale critical

Decelerati… Equation

$q_{\mathcal{D}}(z$

ame sort of th

ow includes t

hese have UV

$$
\begin{aligned}
3\frac{\ddot{a}_{\mathcal{D}}}{a_{\mathcal{D}}} = & -3H^2\left(1-\frac{3}{2}\Omega_m\right) + \mathcal{Q}_{\mathcal{D}} - \mathcal{L}_{\mathcal{D}} + \mathcal{P}_{\mathcal{D}} + \mathcal{F}_{\mathcal{D}} + \mathcal{K}_{\mathcal{D}} \\
& +9H^2(1-\Omega_m)\langle\Phi\rangle + 3H\langle\dot{\Phi}\rangle - (1+z)^2\langle\partial^2\Phi\rangle \\
& +3H^2(9\Omega_m-7)\langle\Phi^2\rangle - 3H\langle\Phi\,\dot{\Phi}\rangle + (1+z)^2\langle\Phi\,\partial^2\Phi\rangle \\
& +\frac{(1+z)^2}{3H^2\Omega_m^2}(4-9\Omega_m)\left[H^2\langle\partial^k\Phi\,\partial_k\Phi\rangle + 2H\langle\partial^k\Phi\,\partial_k\dot{\Phi}\rangle + \langle\partial^k\dot{\Phi}\,\partial_k\dot{\Phi}\rangle\right] \\
& +9H\langle\Phi\rangle\langle\dot{\Phi}\rangle + 27H^2(1-\Omega_m)\langle\Phi\rangle^2 - 3(1+z)^2\langle\Phi\rangle\langle\partial^2\Phi\rangle \\
& +3H^2\left(1-\frac{3}{2}\Omega_m\right)\langle\Phi^{(2)}\rangle - \frac{\kappa^2}{4}\langle\delta^2\rho\rangle.
\end{aligned}
$$

The averaged curvature term is:

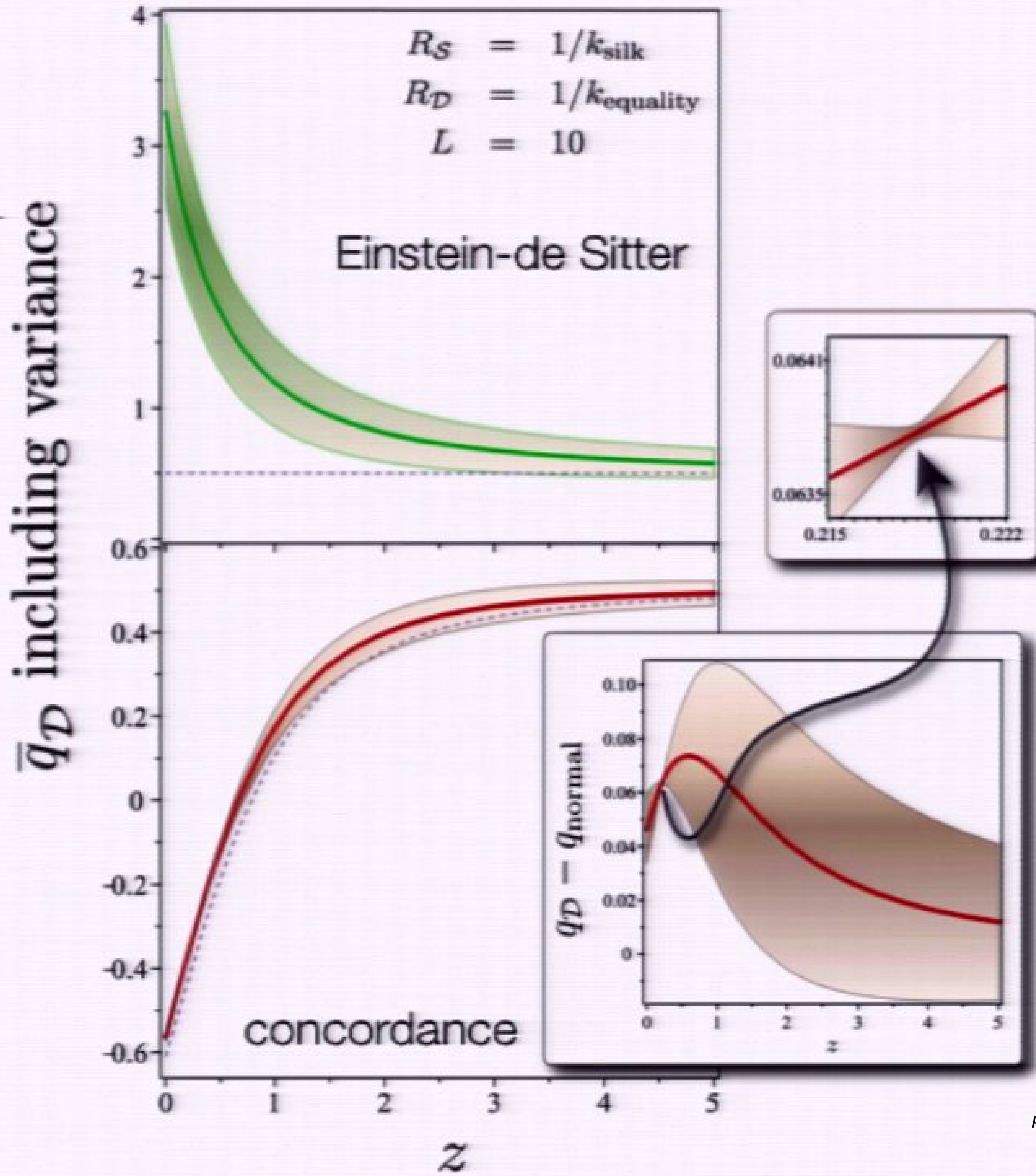
$$
\mathcal{R}_{\mathcal{D}} = 2(1+z)^2\left[2\langle\partial^2\Phi\rangle + 6\langle\Phi\,\partial^2\Phi\rangle + 3\langle\partial^k\Phi\,\partial_k\Phi\rangle + 6\langle\Phi\rangle\langle\partial^2\Phi\rangle + \langle\partial^2\Phi^{(2)}\rangle\right],
$$

and the additional backreaction terms are:

$$
\begin{aligned}
\mathcal{F}_{\mathcal{D}} = & \frac{4(1+z)^2}{3H^2\Omega_m^2}\left[H^2\langle\partial^k\Phi\,\partial_k\Phi\rangle + 2H\langle\partial^k\Phi\,\partial_k\dot{\Phi}\rangle + \langle\partial^k\dot{\Phi}\,\partial_k\dot{\Phi}\rangle\right], \\
\mathcal{P}_{\mathcal{D}} = & \, 3H\langle\dot{\Phi}\rangle + (1+z)^2\langle\partial^2\Phi\rangle - 15H\langle\Phi\,\dot{\Phi}\rangle - 3\langle\dot{\Phi}^2\rangle - (1+z)^2\left[\langle\Phi\,\partial^2\Phi\rangle + 2\langle\partial^k\Phi\,\partial_k\Phi\rangle\right] \\
& -\frac{2(1+z)^2}{3H^2\Omega_m}\left[H\langle\Phi\,\partial^2\Phi\rangle + \langle\dot{\Phi}\,\partial^2\Phi\rangle\right] + 9H\langle\Phi\rangle\langle\dot{\Phi}\rangle + 3(1+z)^2\langle\Phi\rangle\langle\partial^2\Phi\rangle \\
& +\frac{1}{2}(1+z)^2\langle\partial^2\Phi^{(2)}\rangle + \frac{3}{2}H\langle\dot{\Phi}^{(2)}\rangle, \\
\mathcal{Q}_{\mathcal{D}} - \mathcal{L}_{\mathcal{D}} = & \frac{8(1+z)^2}{3H\Omega_m}\left[H\langle\partial^2\Phi\rangle + \langle\partial^2\dot{\Phi}\rangle\right] + 6\langle\dot{\Phi}^2\rangle - 6\langle\dot{\Phi}\rangle^2 \\
& -\frac{8(1+z)^2}{3H\Omega_m}\left[2H\langle\Phi\,\partial^2\Phi\rangle + 2\langle\Phi\,\partial^2\dot{\Phi}\rangle + 3H\langle\partial^k\Phi\,\partial_k\Phi\rangle + 3\langle\partial^k\Phi\,\partial_k\dot{\Phi}\rangle\right] \\
& -\frac{8(1+z)^4}{27H^4\Omega_m^2}\left[H^2\langle\partial^2\Phi\rangle^2 + 2H\langle\partial^2\Phi\rangle\langle\partial^2\dot{\Phi}\rangle + \langle\partial^2\dot{\Phi}\rangle^2\right] \\
& -\frac{8(1+z)^2}{3H^2\Omega_m^2}\left[-3H^2\langle\Phi\rangle\langle\partial^2\Phi\rangle - 3H\langle\Phi\rangle\langle\partial^2\dot{\Phi}\rangle + H\langle\dot{\Phi}\rangle\langle\partial^2\Phi\rangle + \langle\dot{\Phi}\rangle\langle\partial^2\dot{\Phi}\rangle\right] \\
& -2H(1+z)\langle\partial^2 v^{(2)}\rangle, \\
\mathcal{K}_{\mathcal{D}} = & \frac{(1+z)^2}{H^2\Omega_m}\left\{\frac{4H}{3}\left[H\left(1-\frac{3}{4}\Omega_m\right)\langle\partial^2\Phi\rangle + \langle\partial^2\dot{\Phi}\rangle\right]\right. \\
& -\frac{2}{3}\left[H^2(4-3\Omega_m)\langle\Phi\,\partial^2\Phi\rangle + 4H\langle\Phi\,\partial^2\dot{\Phi}\rangle + 3H\langle\dot{\Phi}\,\partial^2\Phi\rangle + 3\langle\dot{\Phi}\,\partial^2\dot{\Phi}\rangle\right] \\
& +\frac{1}{3\Omega_m}\left[3H^2(3\Omega_m^2-2\Omega_m-4)\langle\partial^k\Phi\,\partial_k\Phi\rangle - 8H\langle\partial^k\Phi\,\partial_k\dot{\Phi}\rangle - 2(2-3\Omega_m)\langle\partial^k\dot{\Phi}\,\partial_k\dot{\Phi}\rangle\right] \\
& -\frac{4(1+z)^2}{3H^2\Omega_m}\left[H^2\langle\partial^2\Phi\,\partial^2\Phi\rangle + 2H\langle\partial^2\Phi\,\partial^2\dot{\Phi}\rangle + \langle\partial^2\dot{\Phi}\,\partial^2\dot{\Phi}\rangle\right] \\
& +\left[H^2(4-3\Omega_m)\langle\Phi\rangle\langle\partial^2\Phi\rangle + 2\langle\dot{\Phi}\rangle\langle\partial^2\dot{\Phi}\rangle + 2H\langle\dot{\Phi}\rangle\langle\partial^2\Phi\rangle + 4H\langle\Phi\rangle\langle\partial^2\dot{\Phi}\rangle\right] \\
& \left.+\frac{4(1+z)^2}{9H^2\Omega_m}\left[H^2\langle\partial^2\Phi\rangle^2 + 2H\langle\partial^2\Phi\rangle\langle\partial^2\dot{\Phi}\rangle + \langle\partial^2\dot{\Phi}\rangle^2\right]\right\} \\
& +\frac{1}{2}(1+z)\langle\partial^2\dot{v}^{(2)}\rangle - \frac{1}{2}H(1+z)\langle\partial^2 v^{(2)}\rangle.
\end{aligned}
$$

~10%
change!

UV
vergence



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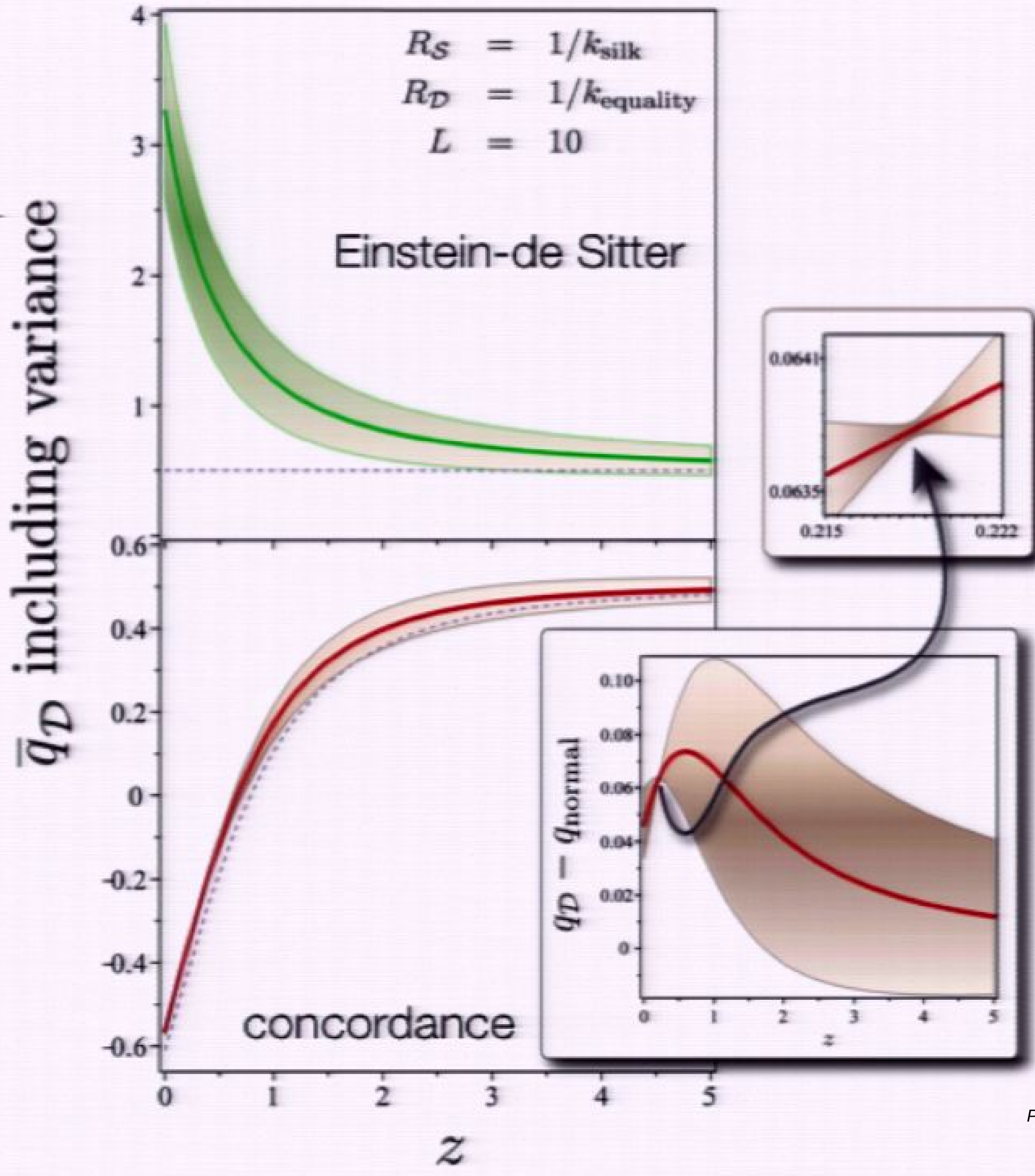

backreaction from structure

- small residual backreaction on large scales
  - background model *is* renormalised
  - this gives *homogeneity scale* in perturbation theory
- large variance could be important for finding ‘correct’ background
- could be 10% or more difference to q(z) and w(z)
  - UV divergence means it’s unquantifiable at second-order?

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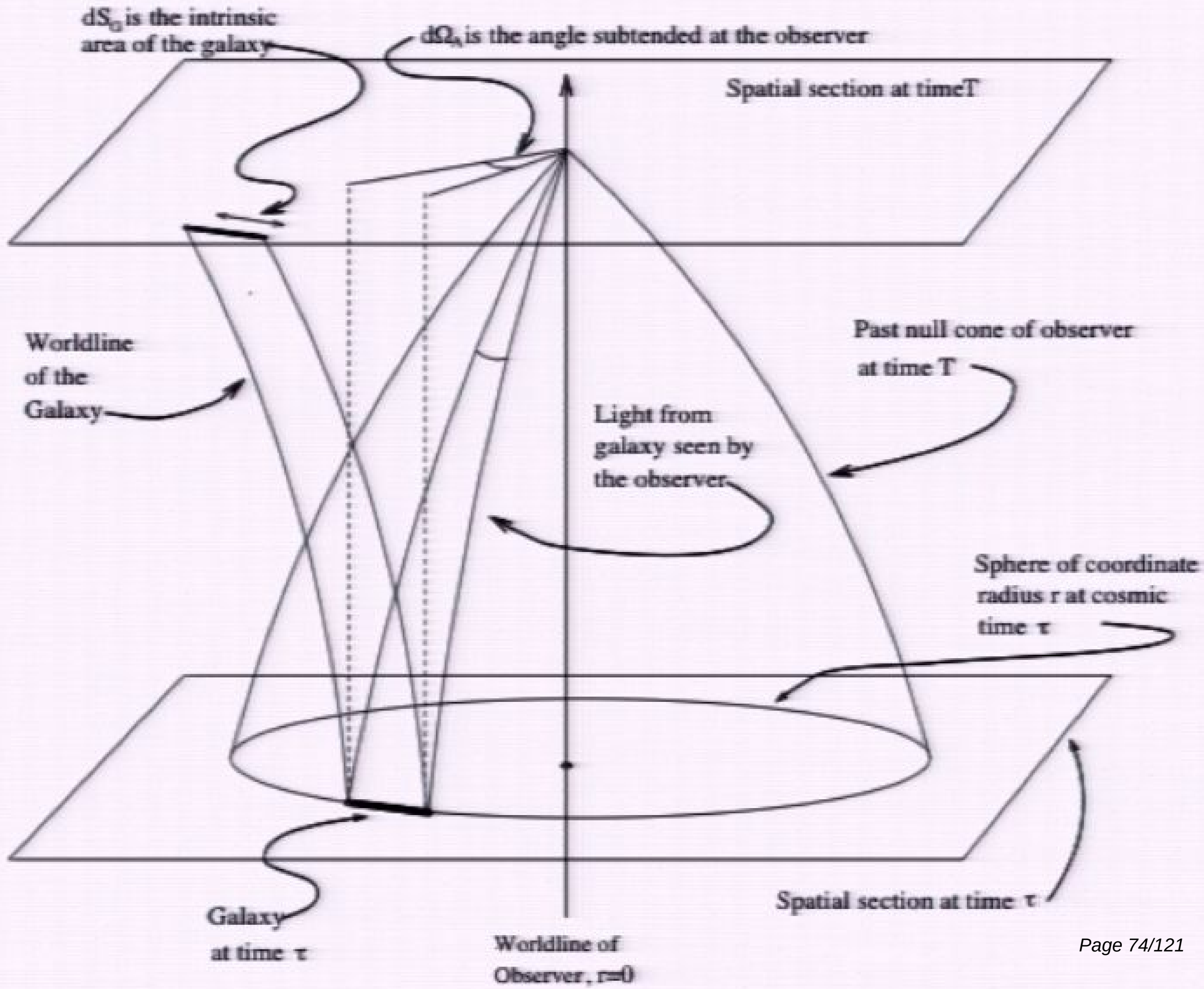
why would large-scale inhomogeneity work?

radial inhomogeneity hard to distinguish from time evolution



Spherical Symmetry

- within dust Lemaitre-Tolman-Bondi models - 2 free radial dof

  - can fit distance-redshift data to *any* FLRW DE model

Mustapha, Hellaby, & Ellis

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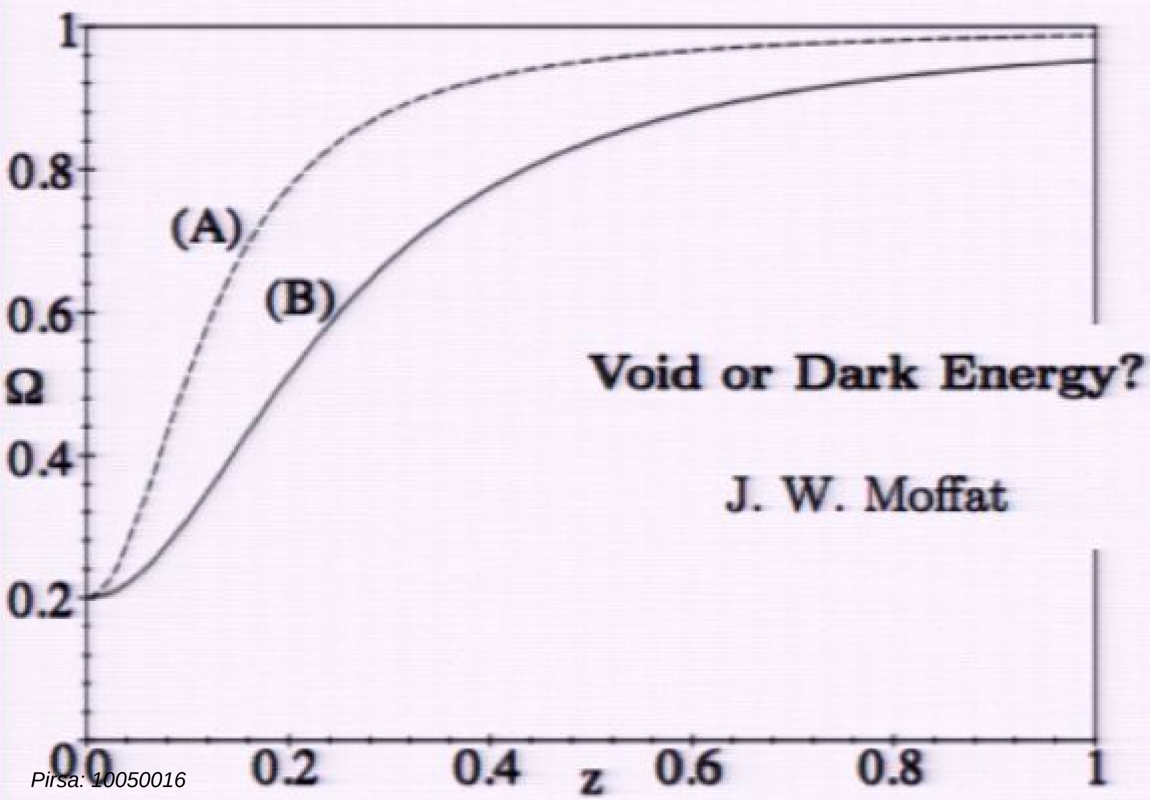

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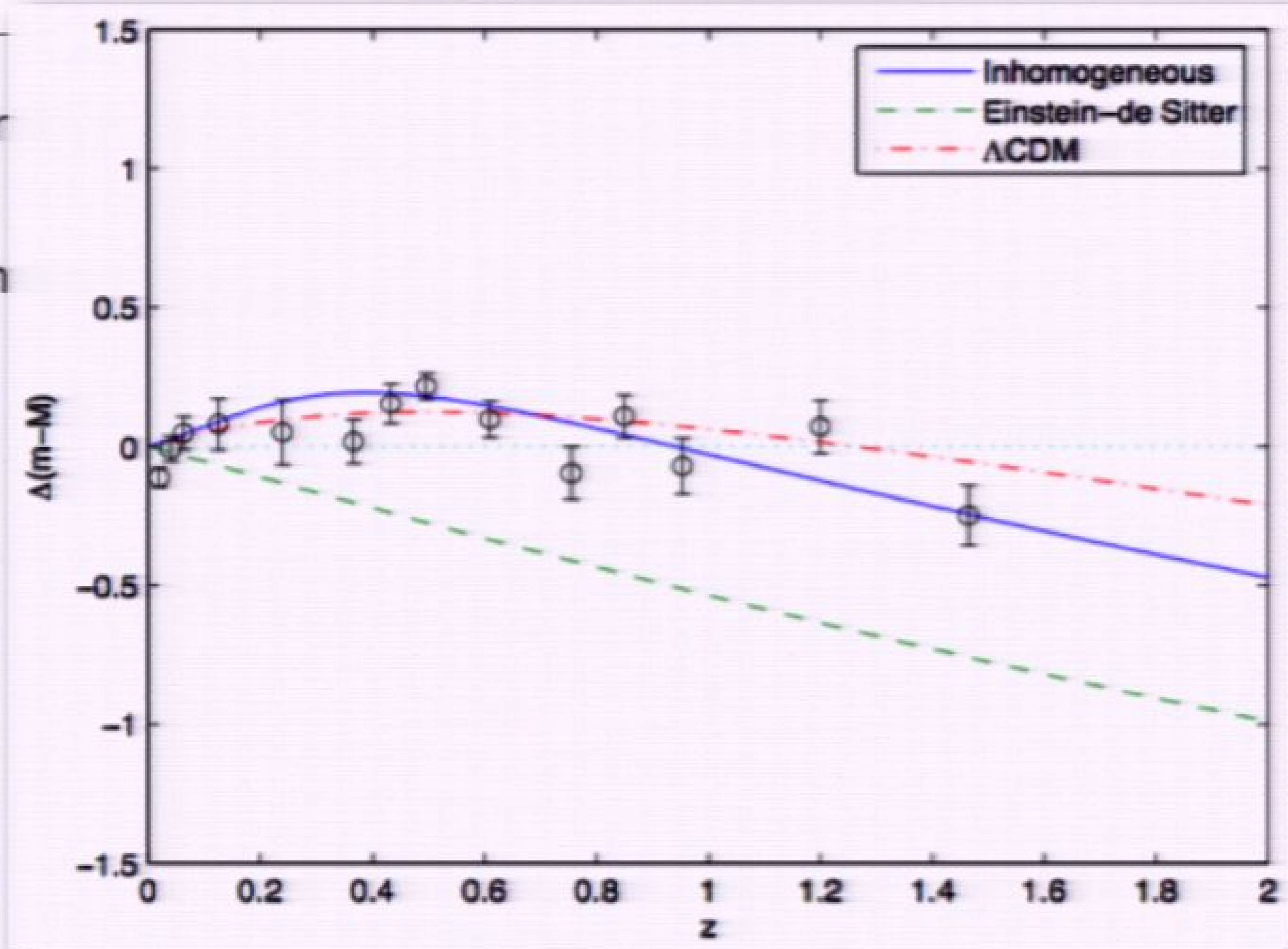
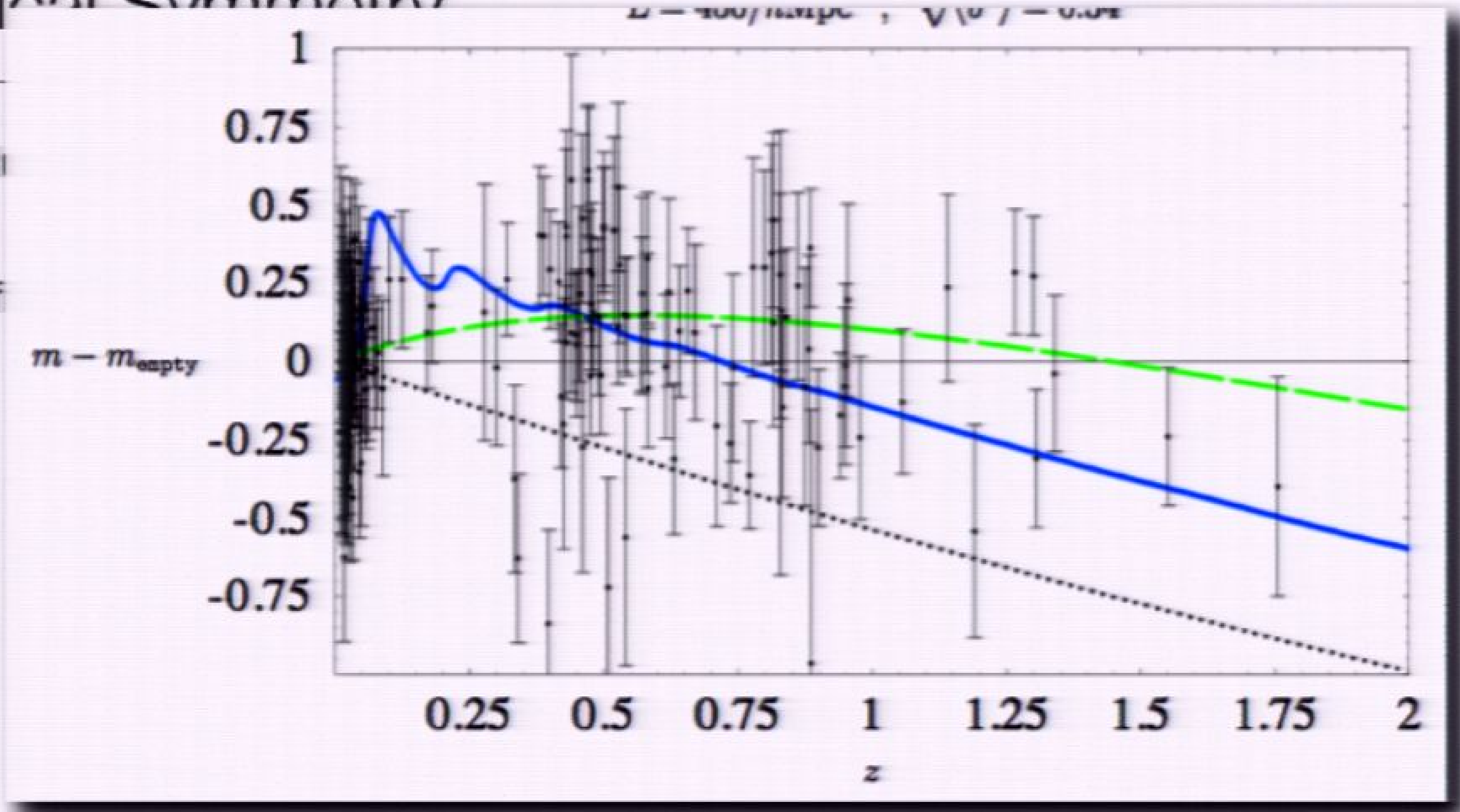


Alnes, Amarzguioui, and Gron astro-ph/0512006

Spherical Symmetry

within d

- can f



Biswas, Monsouri and Notari, astro-ph/0606703

Spherical Symm

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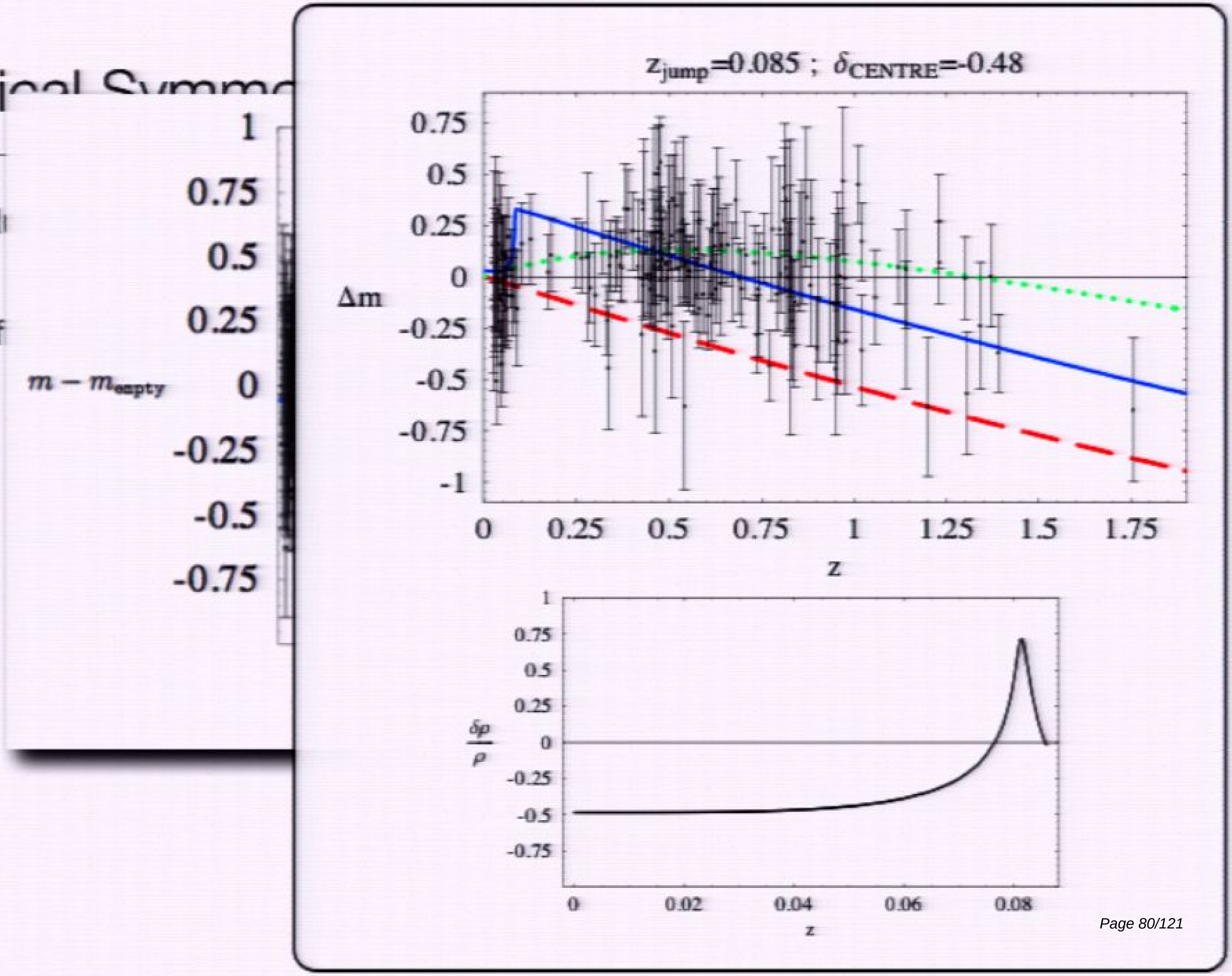
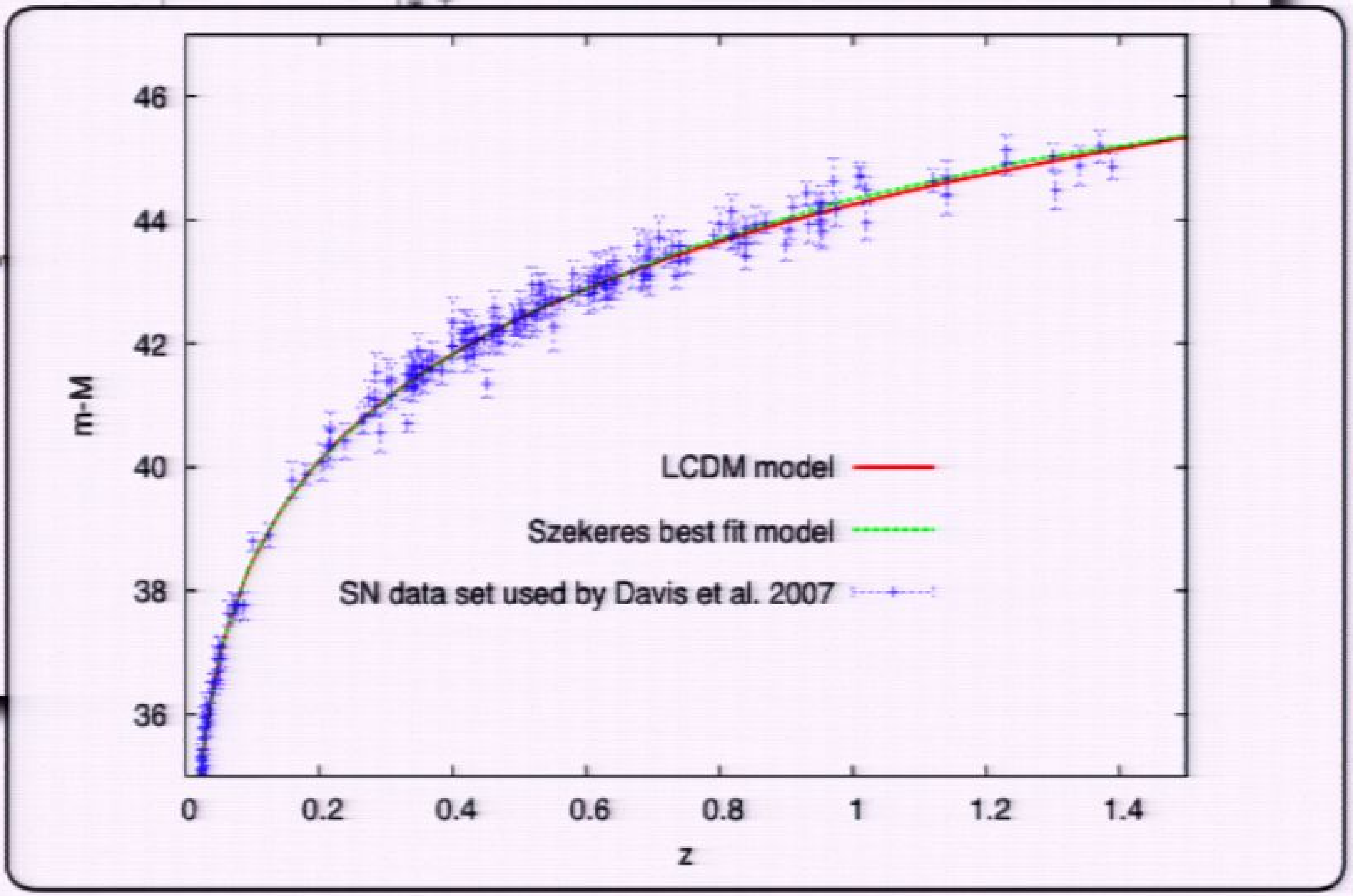


Spherical Symmetry

within d

- can f

$m - m_{exp}$



Ishak et al 0708.2943

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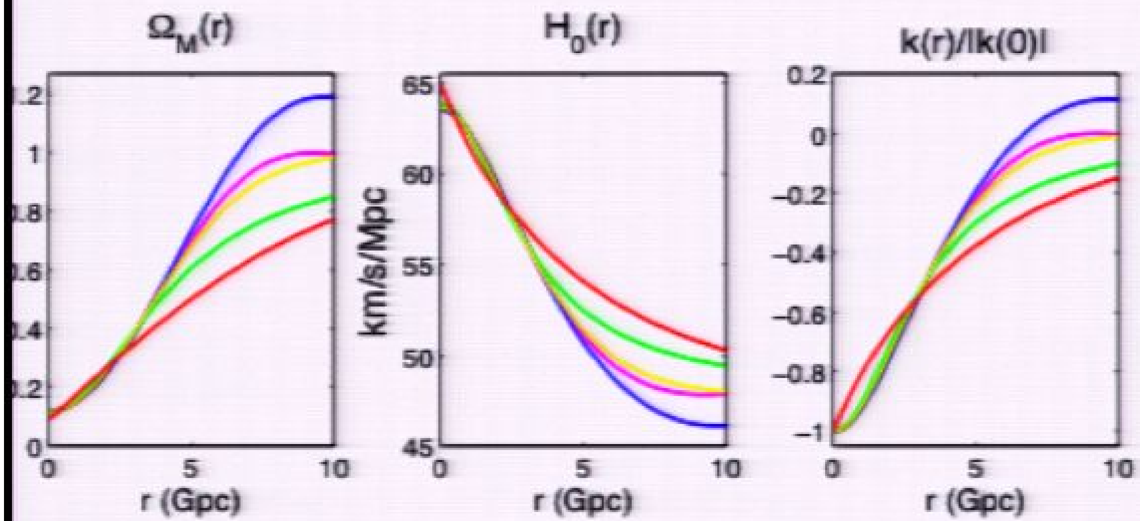
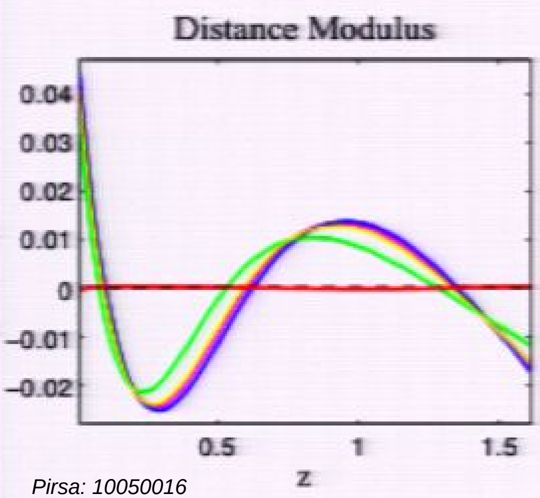
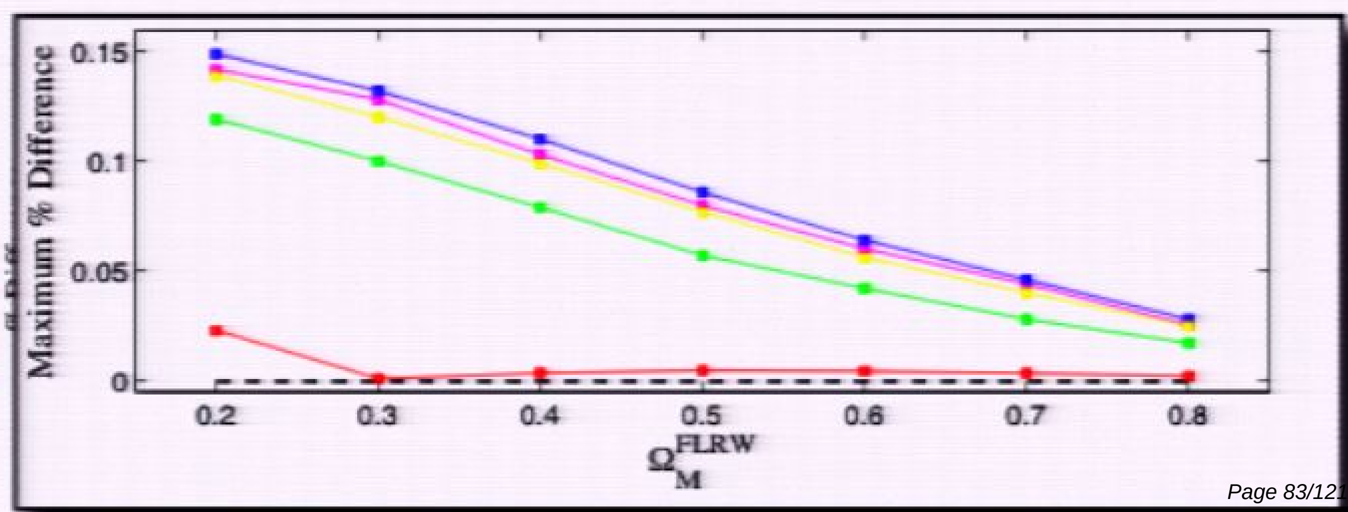
Mustapha, Hellaby, & Ellis

Fitting Voids: to LCDM



indistinguishable
from LCDM
using SNIa



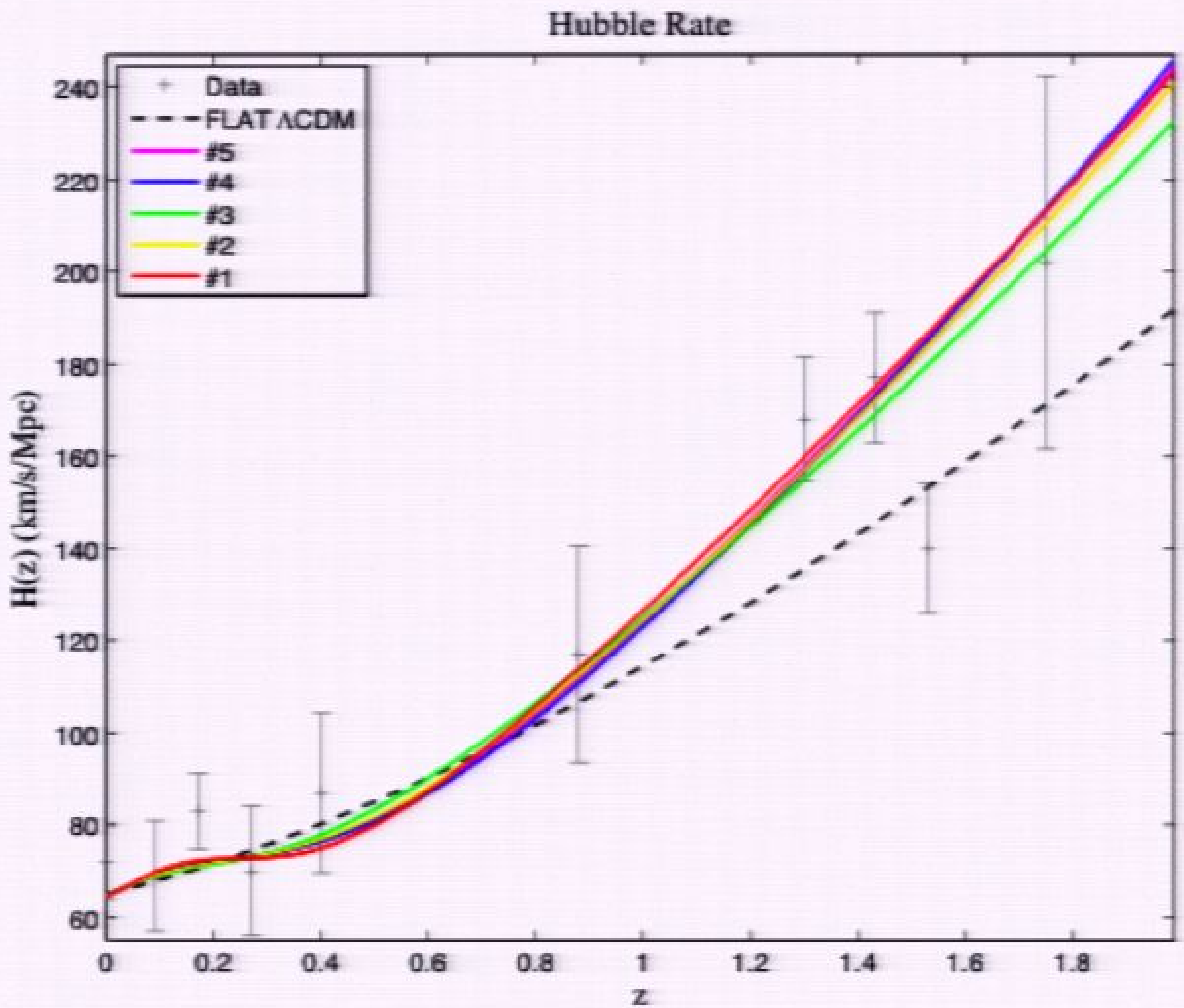


ebruary, Larena, Smith & CC arXiv:0909.1479, MNRAS

Fitting Voids: to SNIa (constitution)

best fit to SNIa fits age data very nicely

$$\frac{dt}{dz} = -\frac{1}{(1+z)H_{\|}}$$



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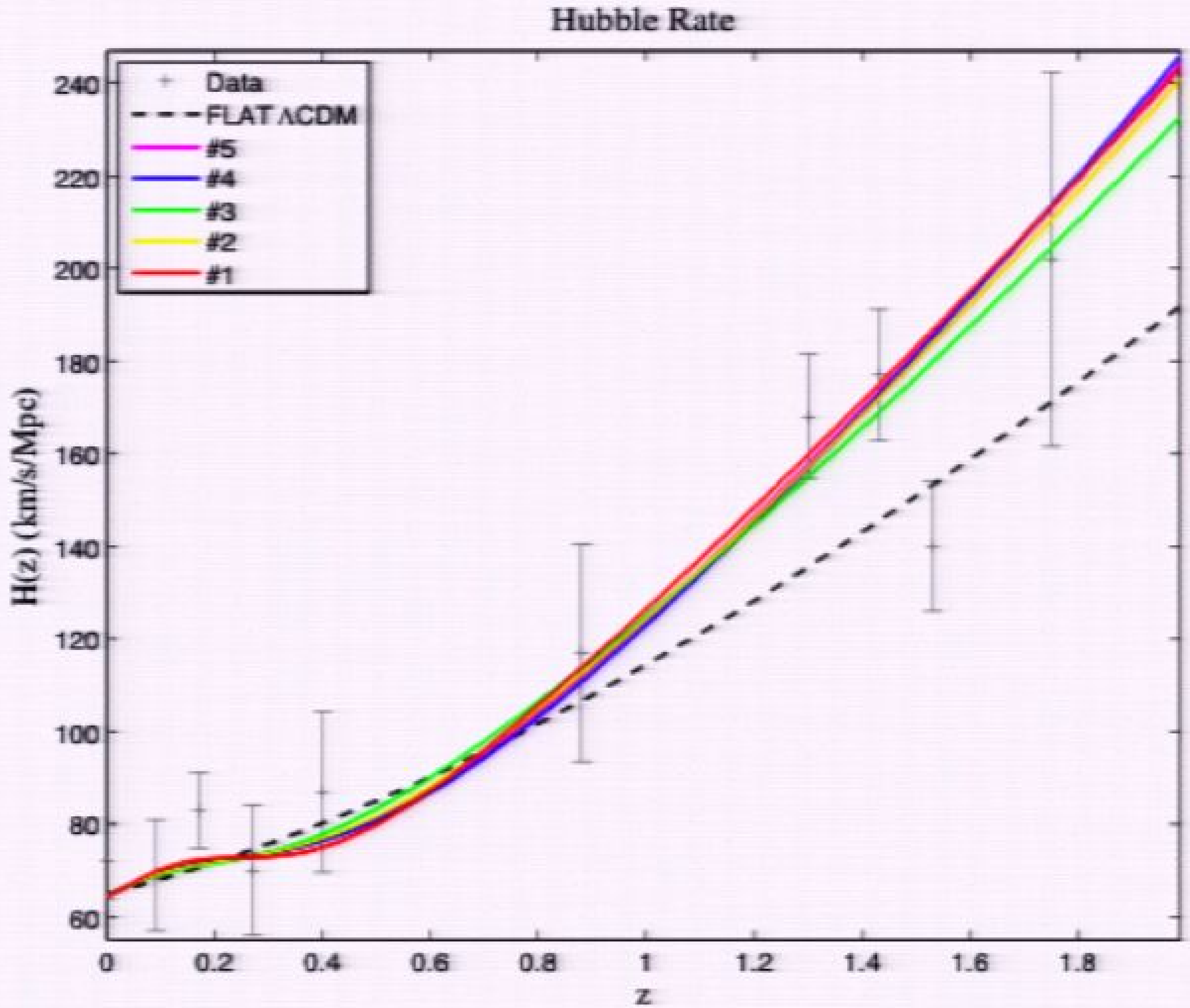

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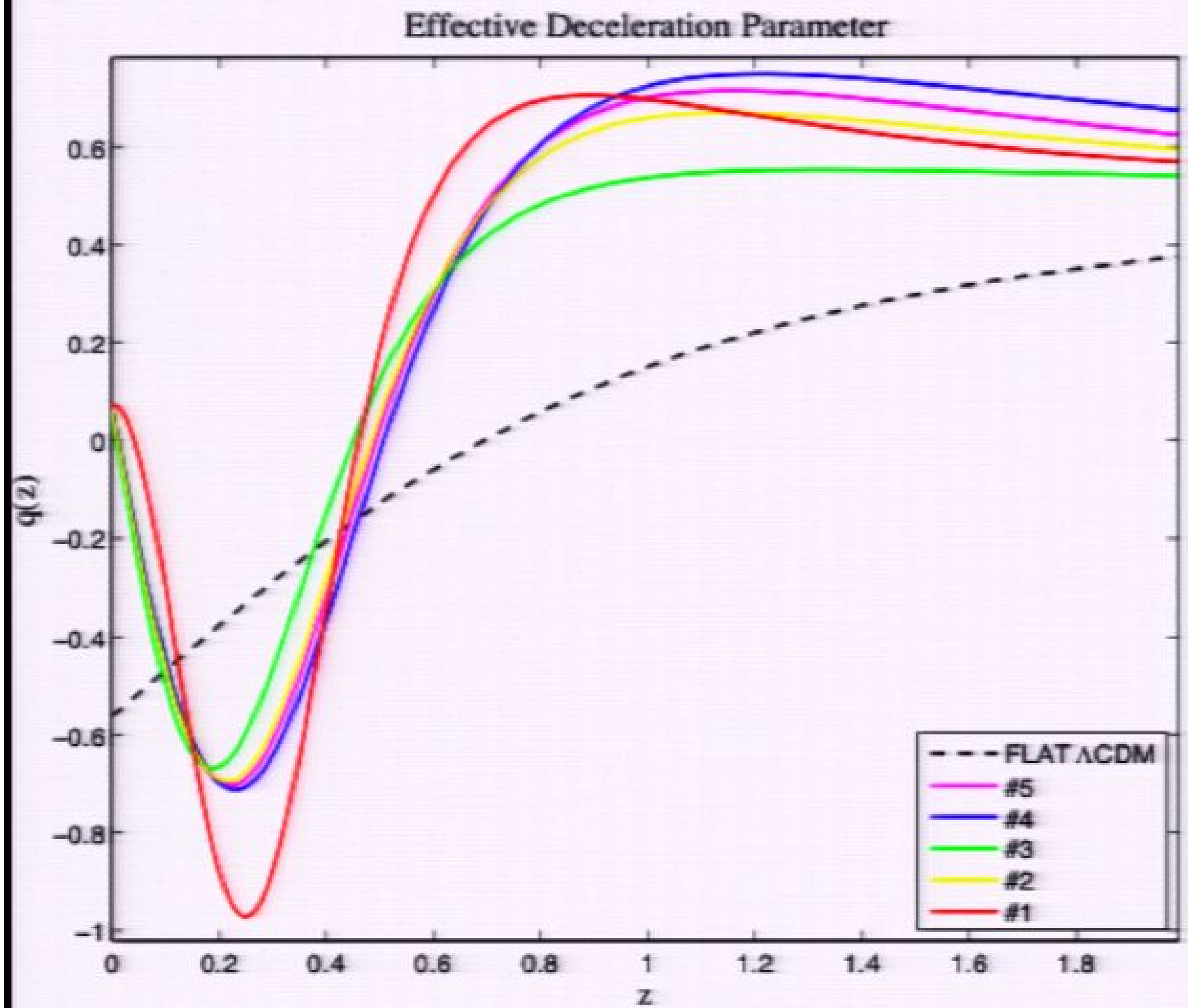
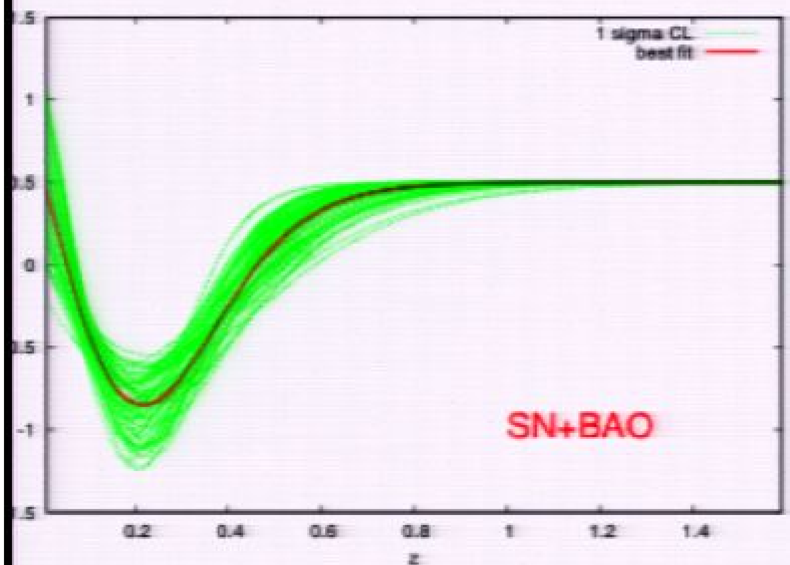


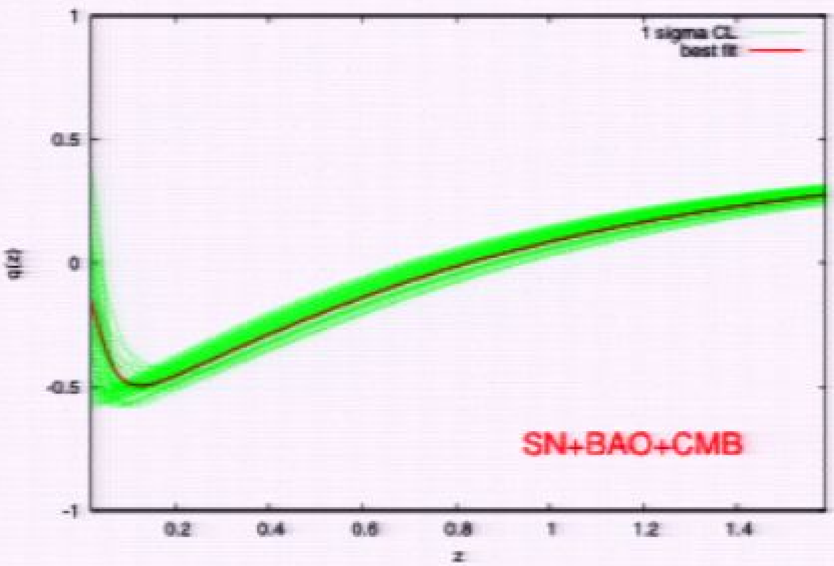
$$q(z) = -1 + (1+z)\frac{H'_{\parallel}}{H_{\parallel}}$$

.. compared to dark energy

$$w(z) = w_0 + w_1 \frac{z}{1+z}$$

$$w(z) = -\frac{1 + \tanh\left[(z - z_t)\Delta\right]}{2}$$





Is cosmic acceleration slowing down?

Arman Shafieloo[a], Varun Sahni[b] and Alexei A. Starobinsky[c]

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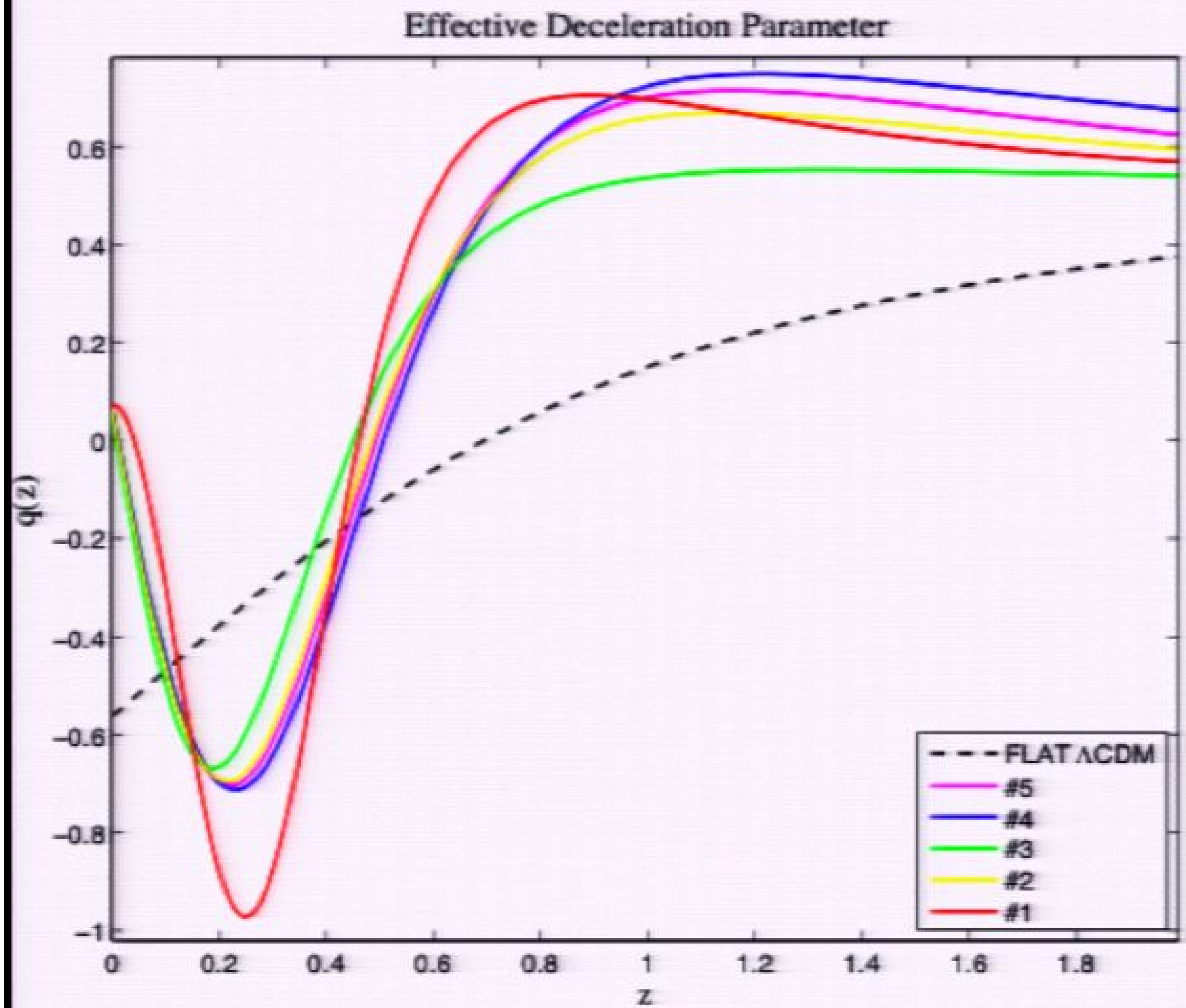

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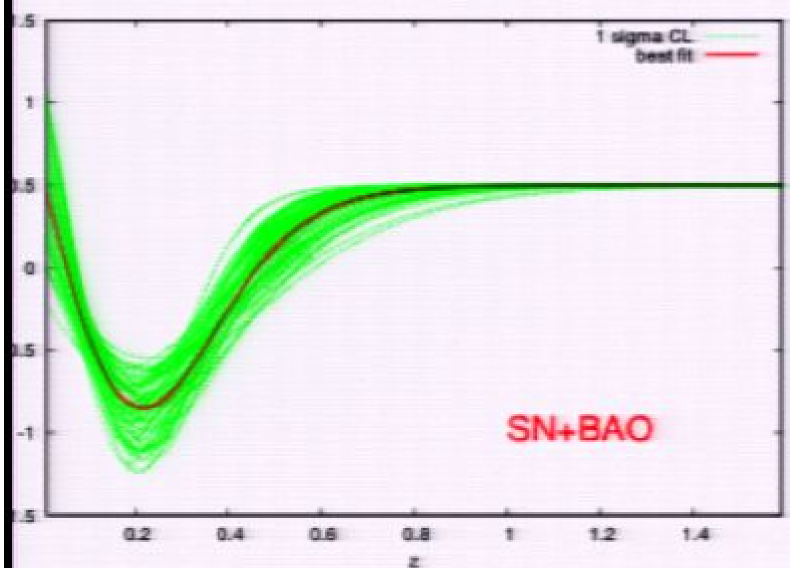

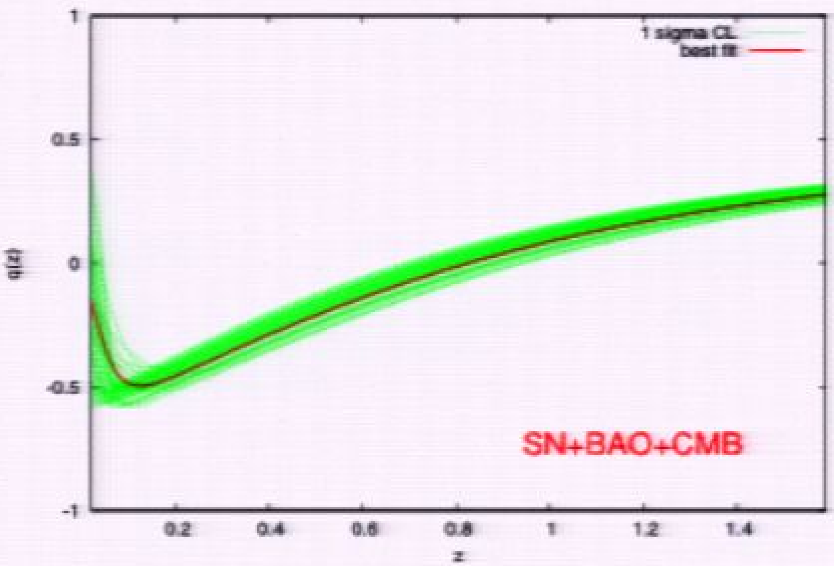

Is cosmic acceleration slowing down?

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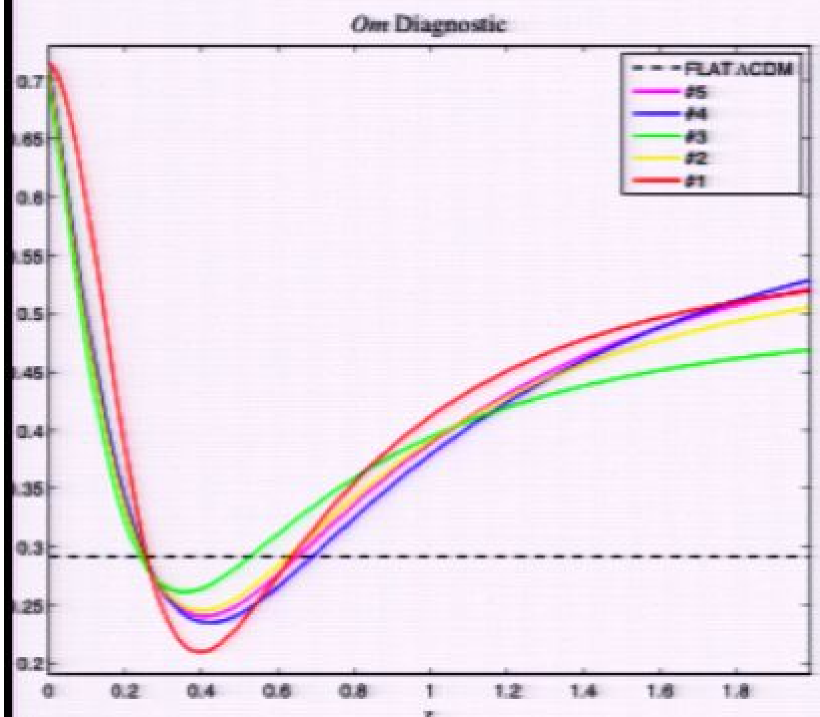
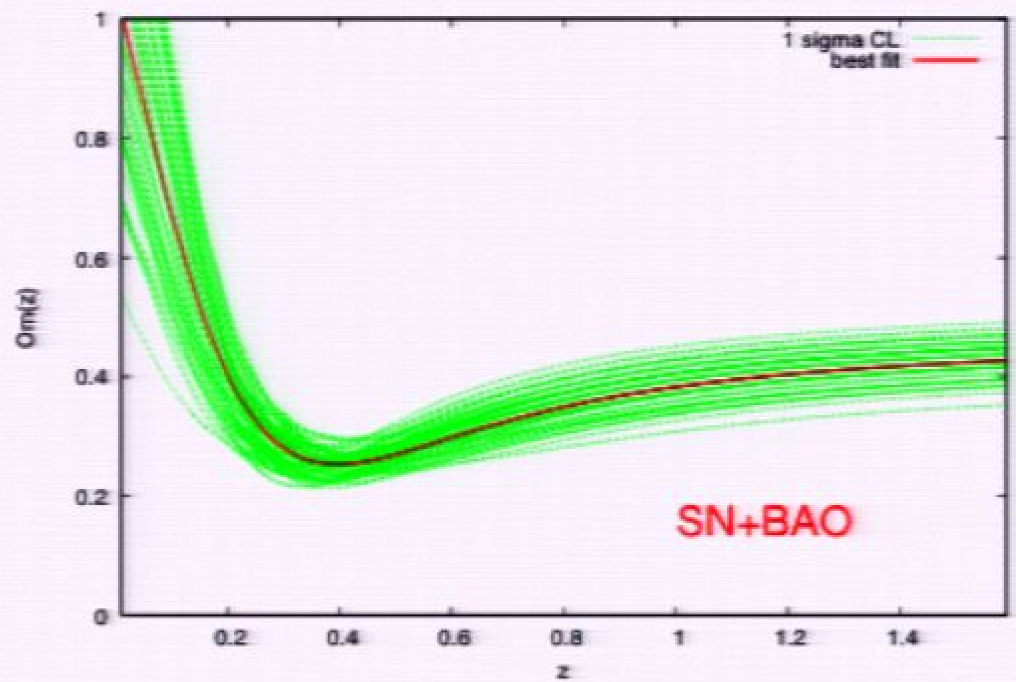
Litmus test for Lambda?

$$\Omega_m = \frac{1 - D'(z)^2}{[(1+z)^3 - 1]D'(z)^2}.$$

best fit voids



fitting evolving DE



Shafieloo, etal arXiv:0903.5141

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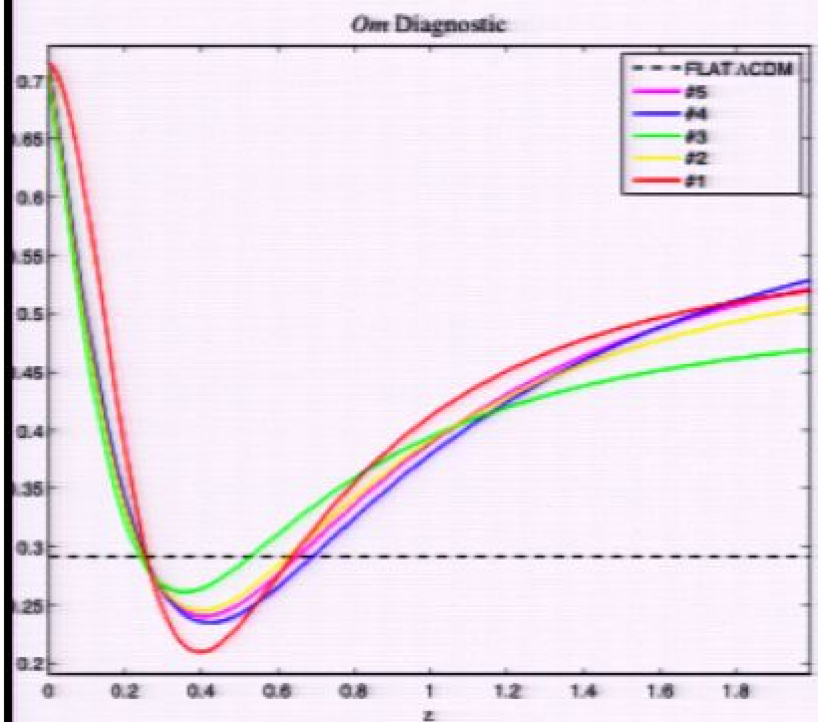
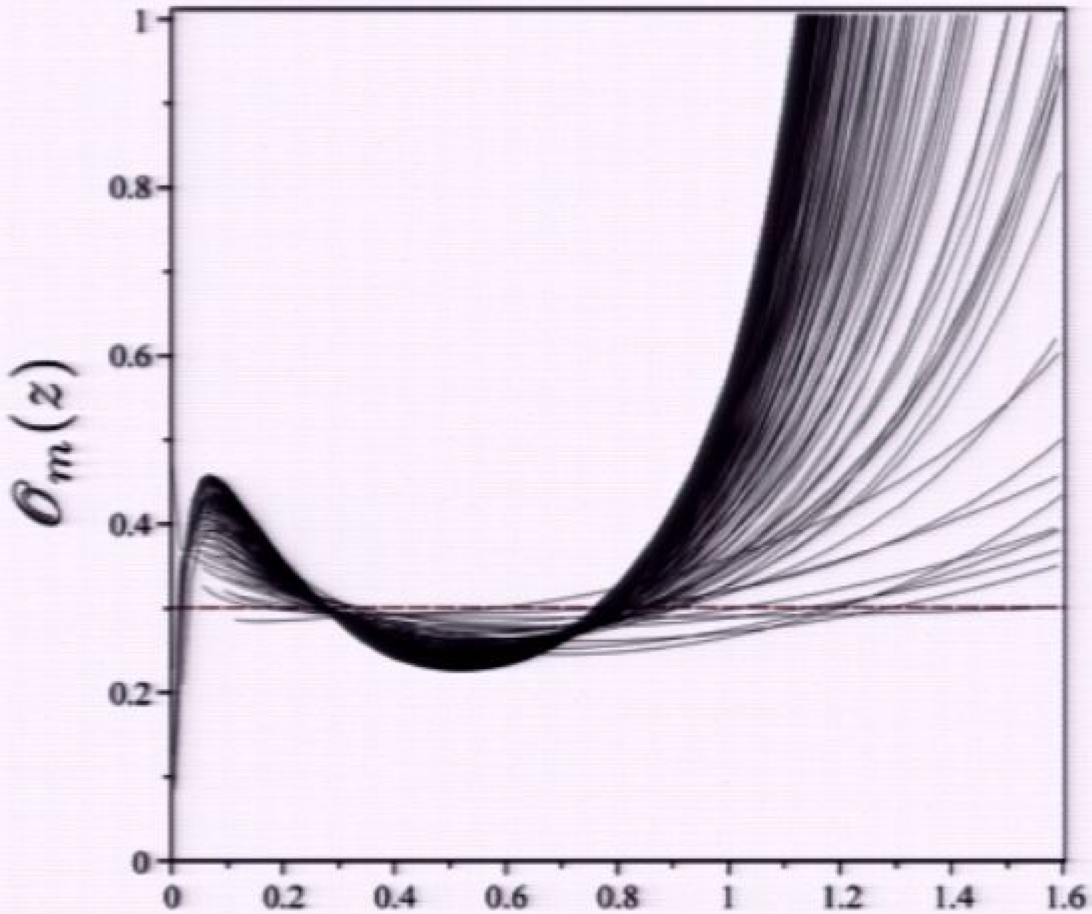
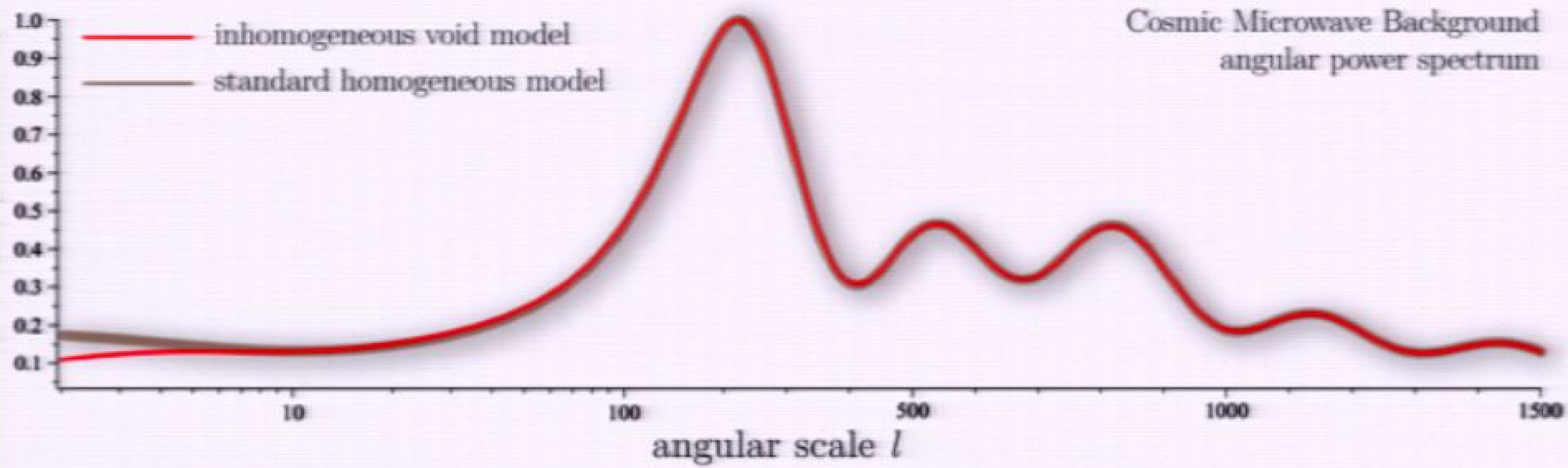




model independent reconstruction

Small scale CMB



Do primordial Lithium abundances imply there's no Dark Energy?

Marco Regis and Chris Clarkson

ithium problem -> inhomogeneity at early times?

Bitter Pill: The Primordial Lithium Problem Worsens

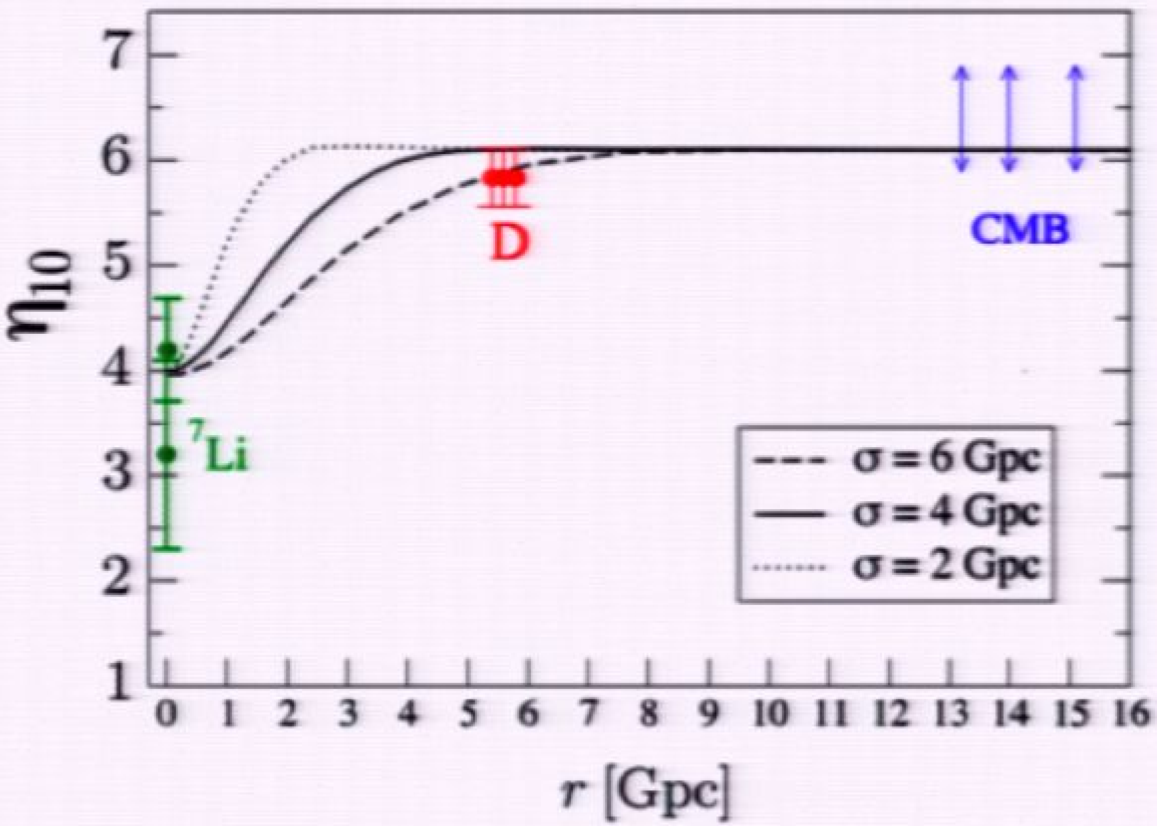
chard H. Cyburt, Brian D. Fields, Keith A. Olive

bmitted on 21 Aug 2008)

The lithium problem arises from the significant discrepancy between the primordial 7Li abundance as predicted by BBN theory and the WMAP baryon density, and the pre-Galactic lithium abundance inferred from observations of metal-poor (Population II) stars. This problem has loomed for the past decade, with a persistent discrepancy of a factor of 2--3 in 7Li/H. Recent developments have sharpened all aspects of the Li problem. Namely: (1) BBN theory predictions have sharpened due to new nuclear data, particularly the uncertainty on 3He(alpha,gamma)7Be, has reduced to 7.4%, and with a central value shift of ~ +0.04 keV barn. (2) The WMAP 5-year data now yields a cosmic baryon density with an uncertainty reduced to 2.7%. (3) Observations of metal-poor stars have tested for systematic effects, and have reaped new lithium isotopic data. With these, we now find that the BBN+WMAP predicts 7Li/H = (5.24+0.71-0.67) 10^{-10}. The Li problem remains and indeed is exacerbated; the discrepancy is now a factor 2.4--4.3 or 4.2sigma (from globular cluster stars) to 5.3sigma (from halo field stars). Possible resolutions to the lithium problem are briefly reviewed, and key nuclear, particle, and astronomical measurements highlighted.

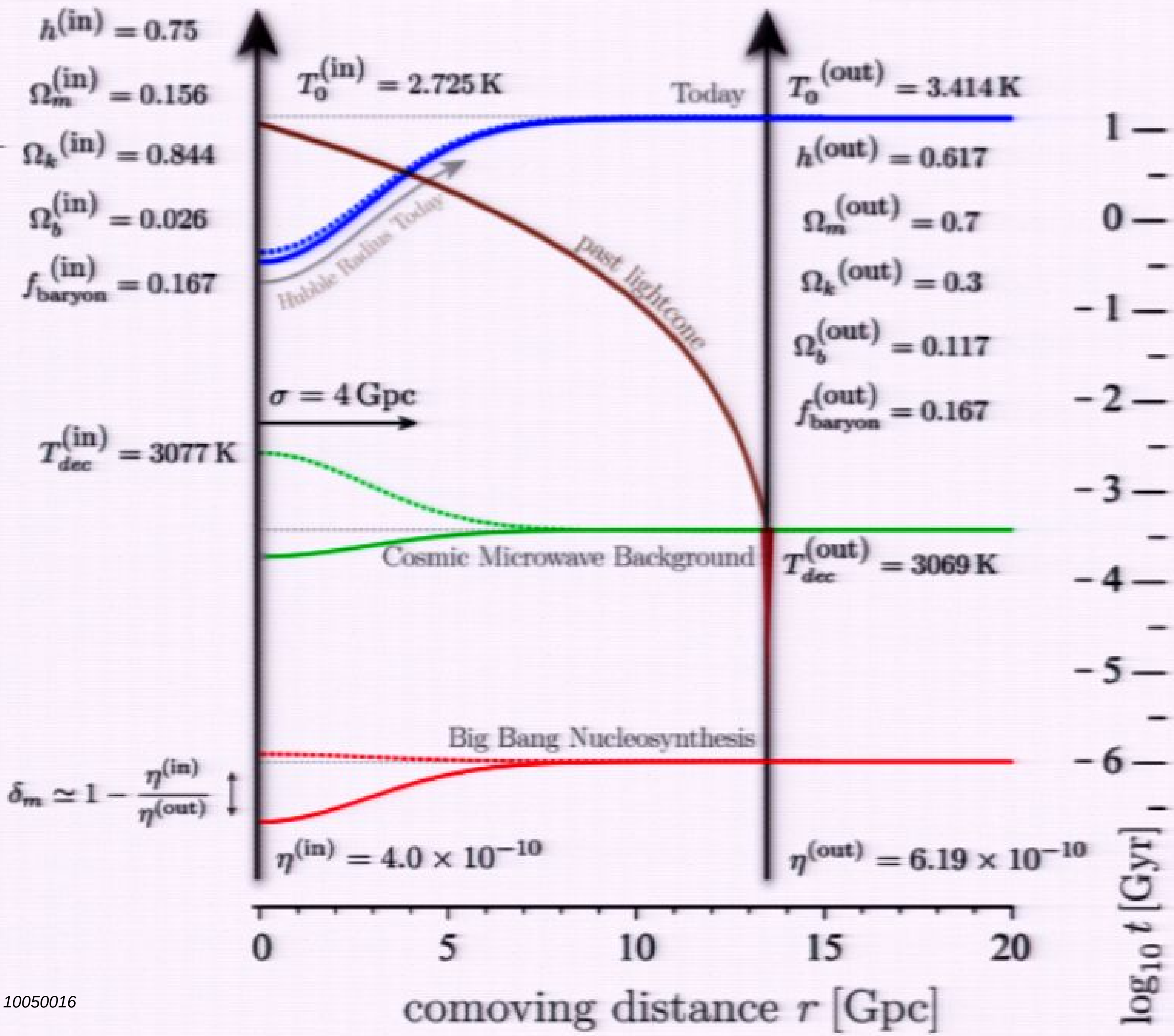
Lithium problem -> inhomogeneity at early times?

a Gpc fluctuation in baryon-photon ratio solves Li problem



Do primordial Lithium abundances imply there's no Dark Energy?

Marco Regis and Chris Clarkson



$h^{(\mathrm{in})} = 0.75$
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$f_{\mathrm{baryon}}^{(\mathrm{in})} = 0.167$
$T_0^{(\mathrm{in})} = 2.725\,\mathrm{K}$
Today
$T_0^{(\mathrm{out})} = 3.414\,\mathrm{K}$
$h^{(\mathrm{out})} = 0.617$
$\Omega_m^{(\mathrm{out})} = 0.7$
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Hubble Radius Today
past lightcone
$\sigma = 4\,\mathrm{Gpc}$
$T_{\mathrm{dec}}^{(\mathrm{in})} = 3077\,\mathrm{K}$
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$T_{\mathrm{dec}}^{(\mathrm{out})} = 3069\,\mathrm{K}$
Big Bang Nucleosynthesis
$\delta_m \simeq 1 - \frac{\eta^{(\mathrm{in})}}{\eta^{(\mathrm{out})}}$
$\eta^{(\mathrm{in})} = 4.0 \times 10^{-10}$
$\eta^{(\mathrm{out})} = 6.19 \times 10^{-10}$
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−1
−2
−3
−4
−5
−6
$\log_{10} t\,[\mathrm{Gyr}]$
0
5
10
15
20
comoving distance r [Gpc]

Lithium problem -> inhomogeneity at early times?

Bitter Pill: The Primordial Lithium Problem Worsens

Richard H. Cyburt, Brian D. Fields, Keith A. Olive

(Submitted on 21 Aug 2008)

The lithium problem arises from the significant discrepancy between the primordial 7Li abundance as predicted by BBN theory and the WMAP baryon density, and the pre-Galactic lithium abundance inferred from observations of metal-poor (Population II) stars. This problem has loomed for the past decade, with a persistent discrepancy of a factor of 2--3 in 7Li/H. Recent developments have sharpened all aspects of the Li problem. Namely: (1) BBN theory predictions have sharpened due to new nuclear data, particularly the uncertainty on 3He(alpha,gamma)7Be, has reduced to 7.4%, and with a central value shift of ~ +0.04 keV barn. (2) The WMAP 5-year data now yields a cosmic baryon density with an uncertainty reduced to 2.7%. (3) Observations of metal-poor stars have tested for systematic effects, and have reaped new lithium isotopic data. With these, we now find that the BBN+WMAP predicts 7Li/H = (5.24+0.71-0.67) 10^{-10}. The Li problem remains and indeed is exacerbated; the discrepancy is now a factor 2.4--4.3 or 4.2sigma (from globular cluster stars) to 5.3sigma (from halo field stars). Possible resolutions to the lithium problem are briefly reviewed, and key nuclear, particle, and astronomical measurements highlighted.

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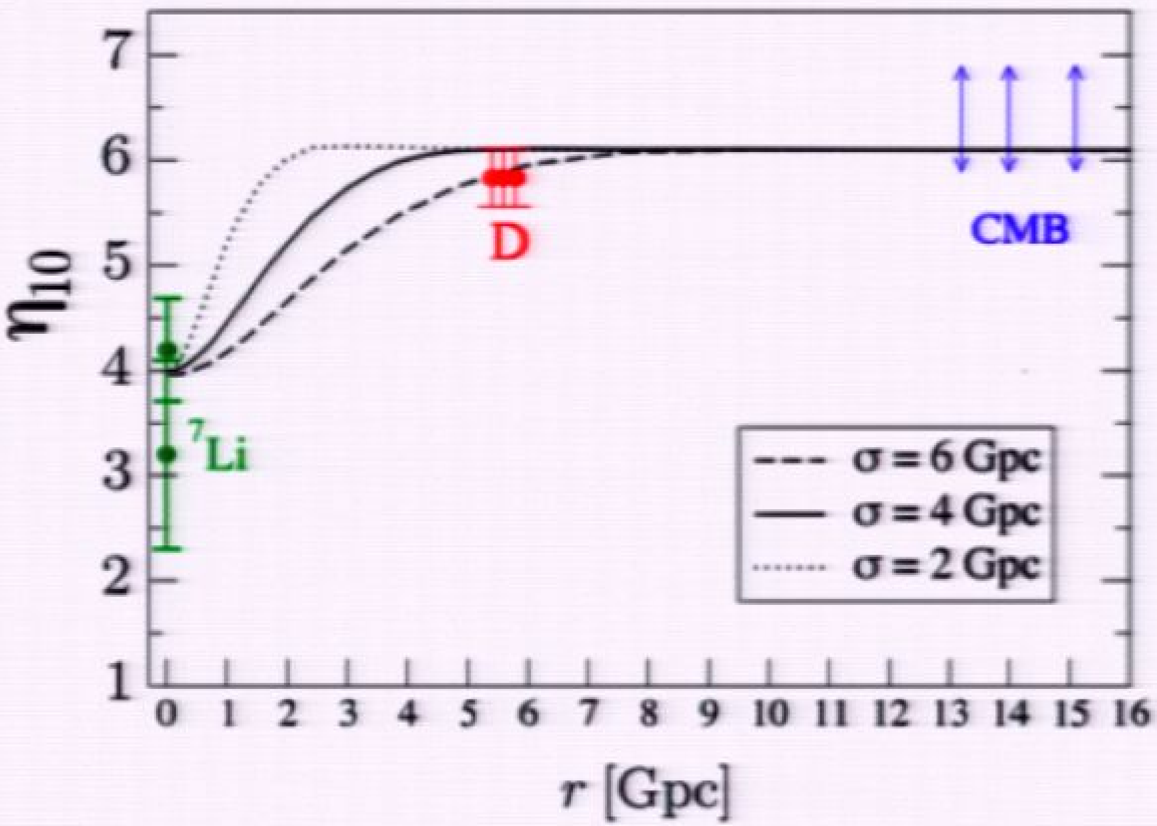

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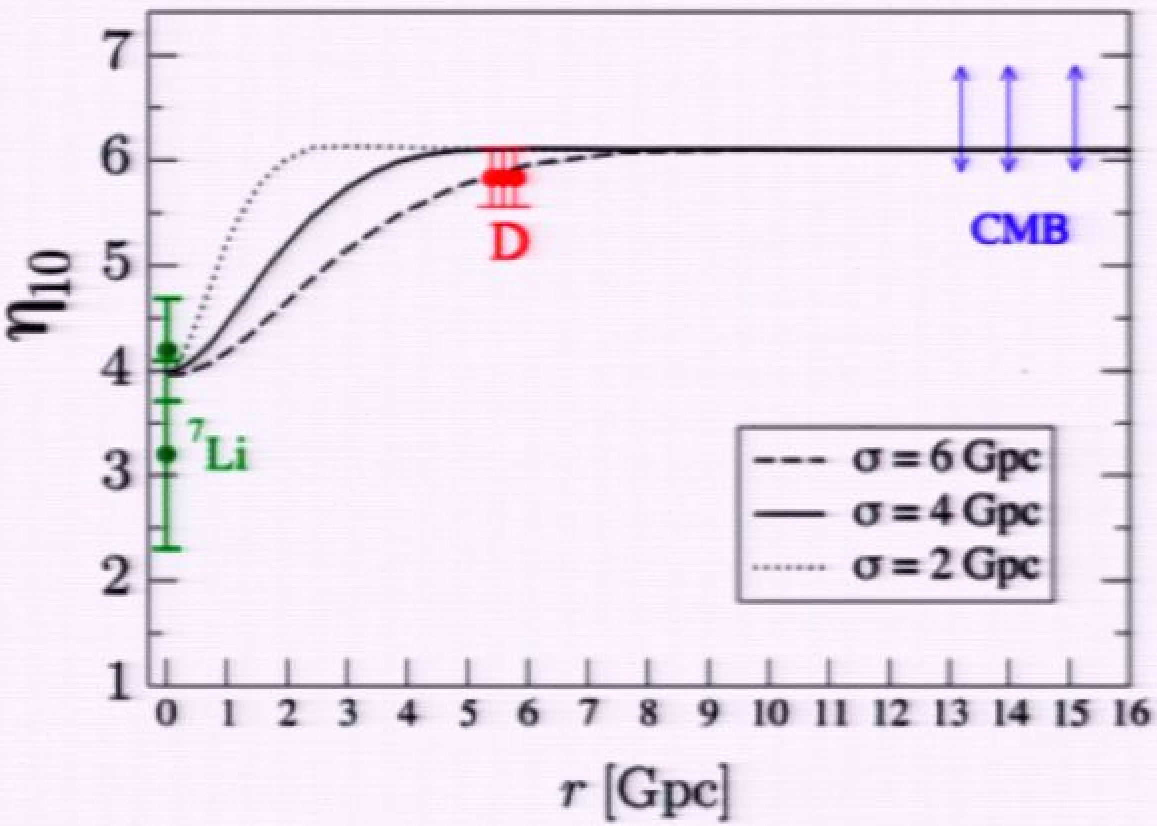

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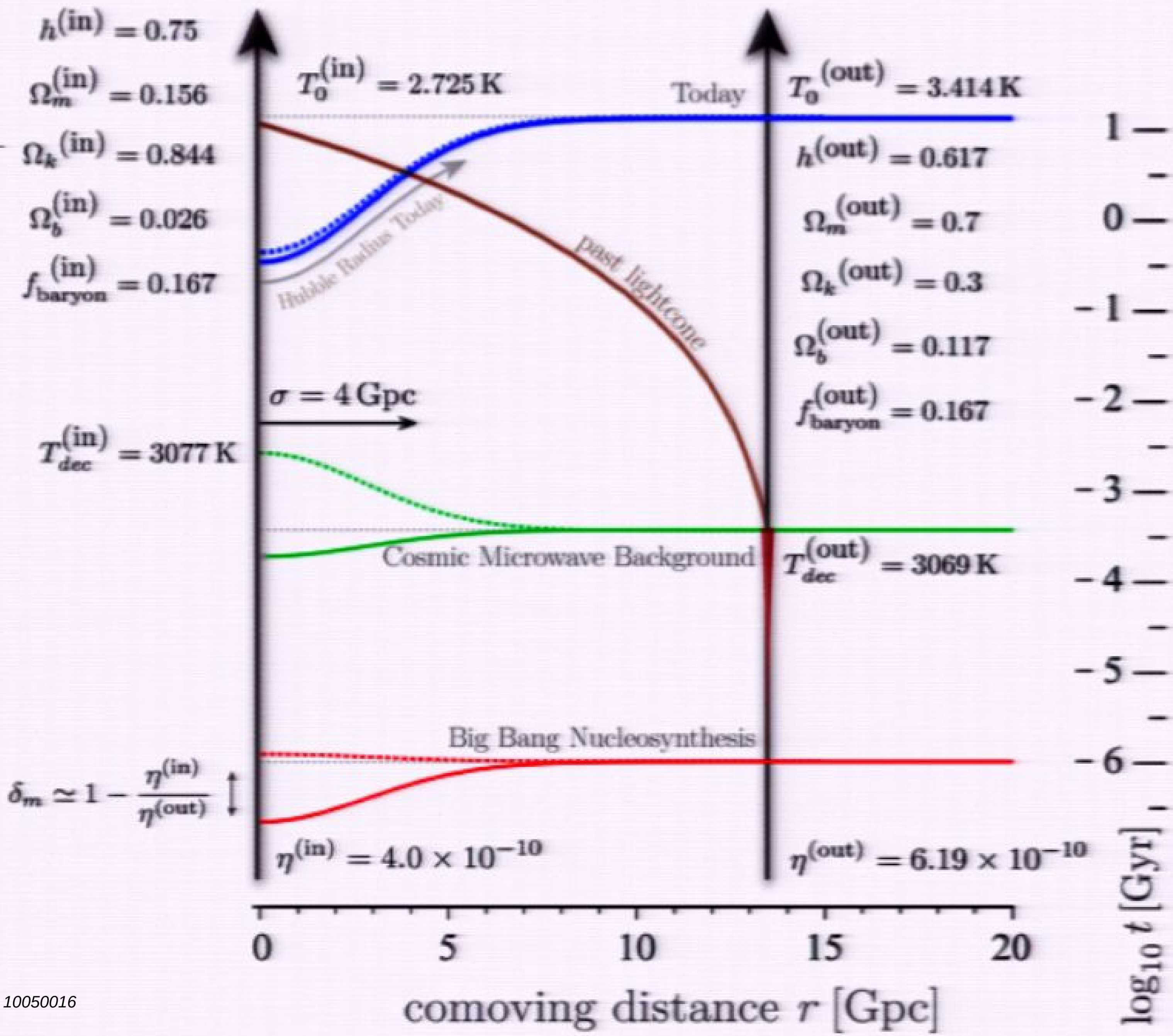

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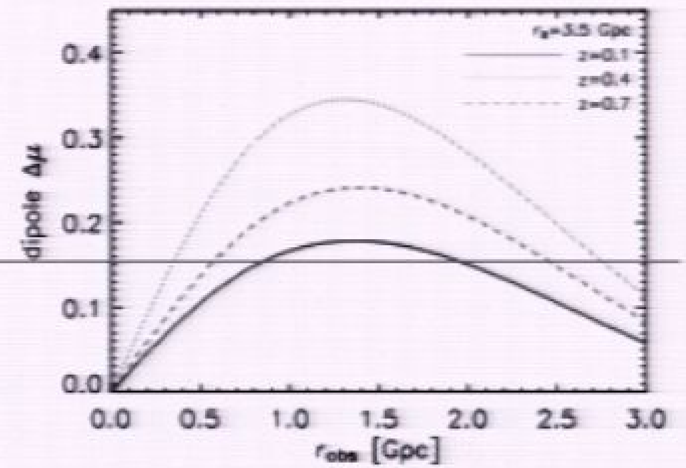
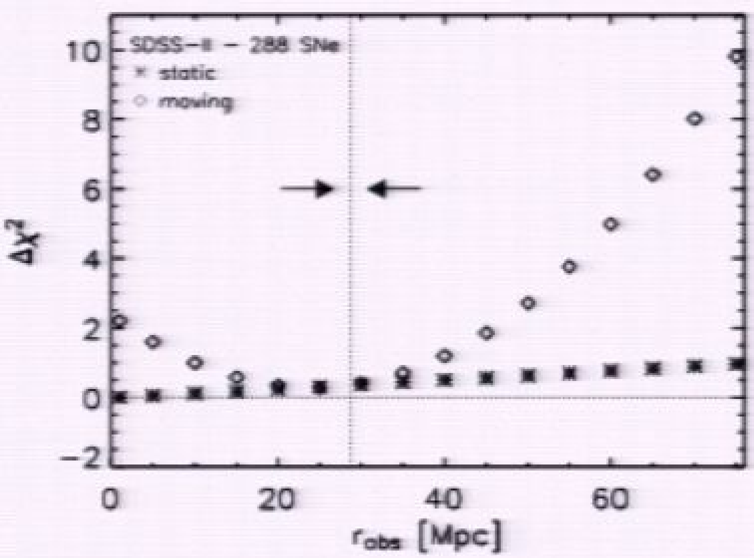
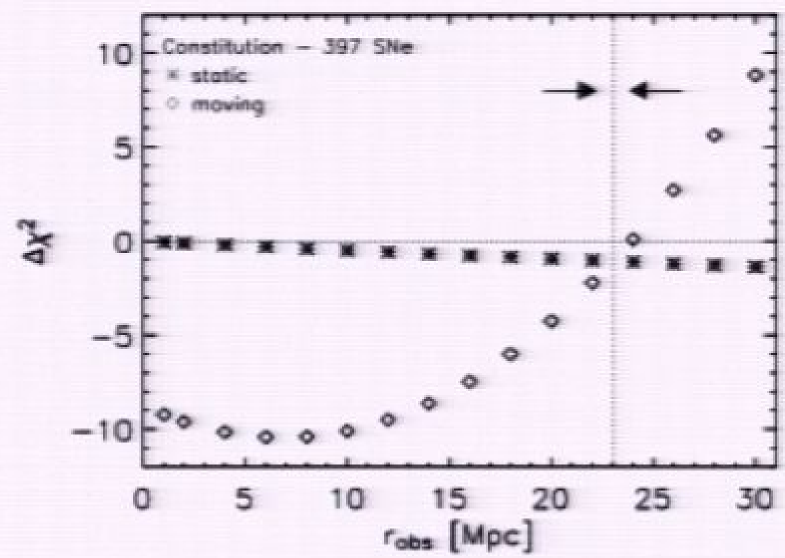
Fine tuned?







Supernovae as seen by off-center observers in a local void

Michael Blomqvist[1] and Edvard Mörtsell[2]

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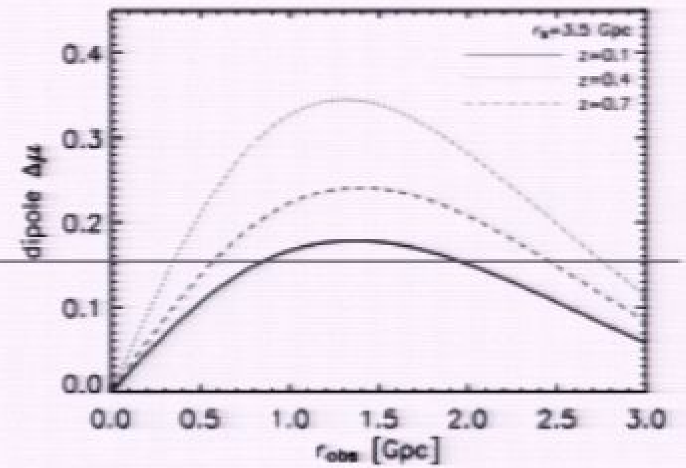

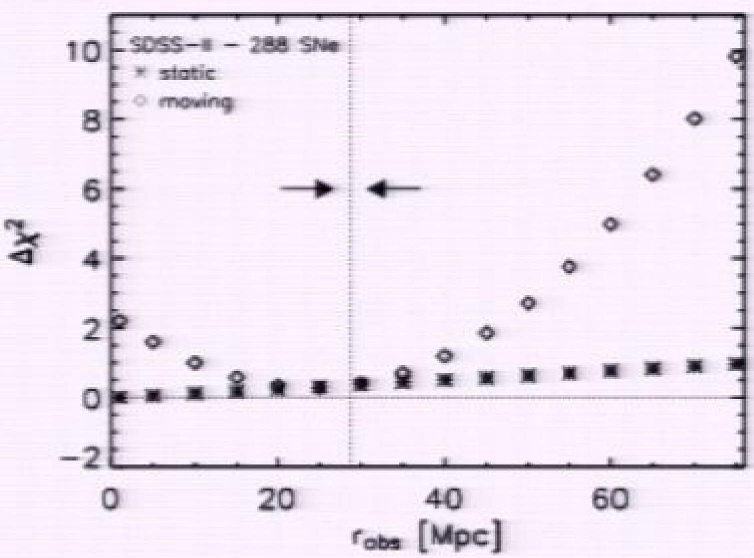

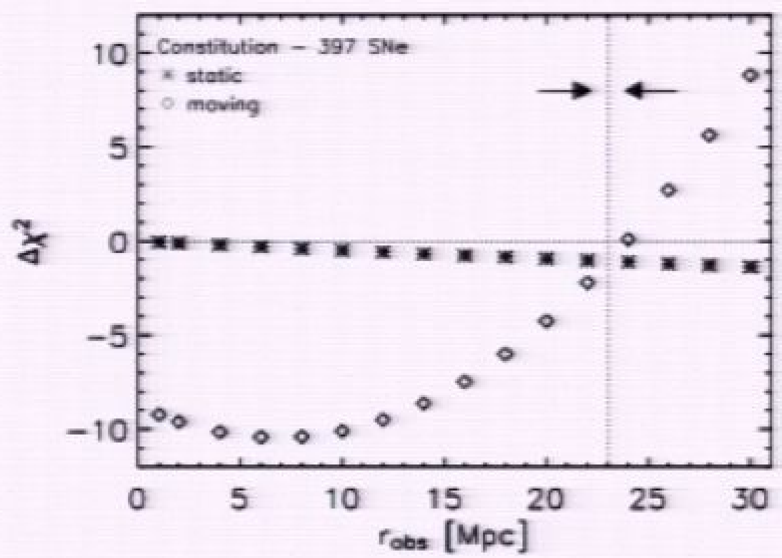

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Could the Copernican Principle be wrong?

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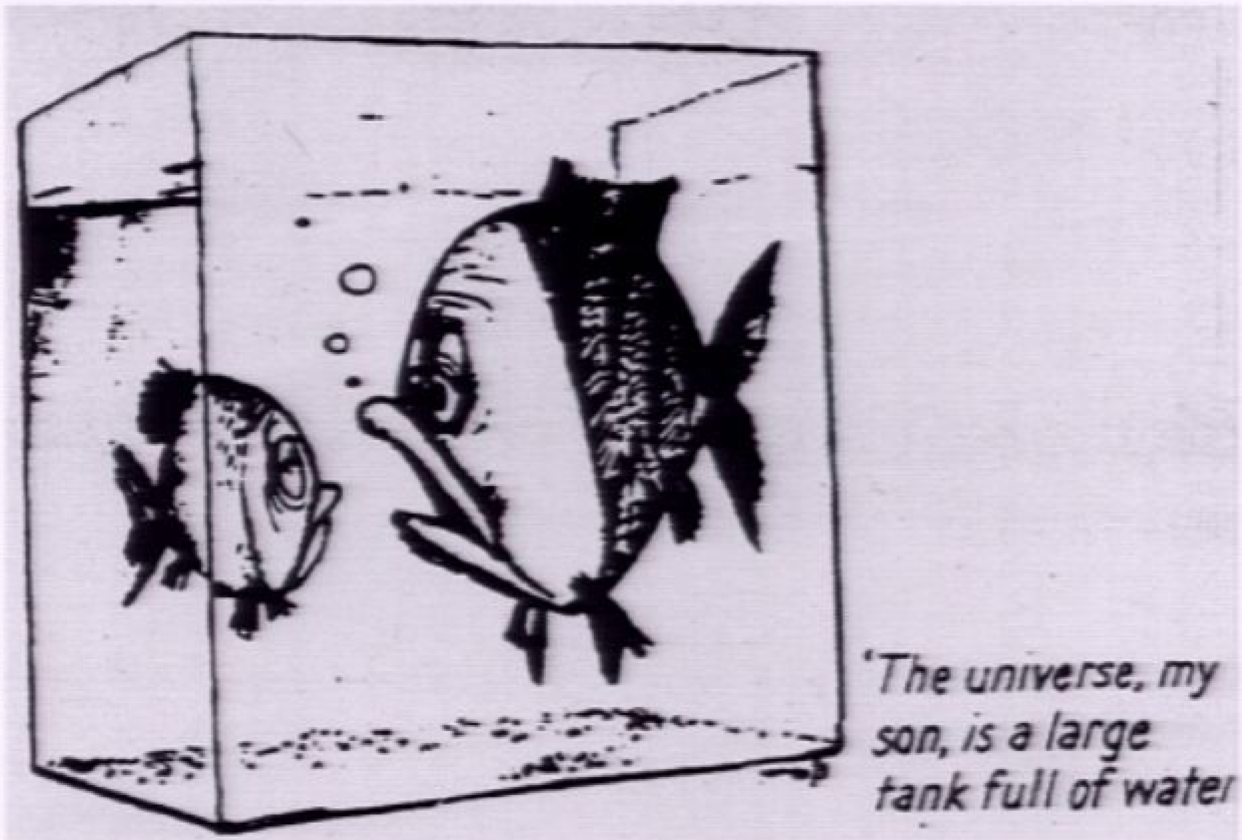


The Cosmological Principle

Could the Copernican Principle be wrong?

Copernican P says we are not at special place in universe

Λ introduced for misguided temporal CP ...

Testing the Copernican Principle directly

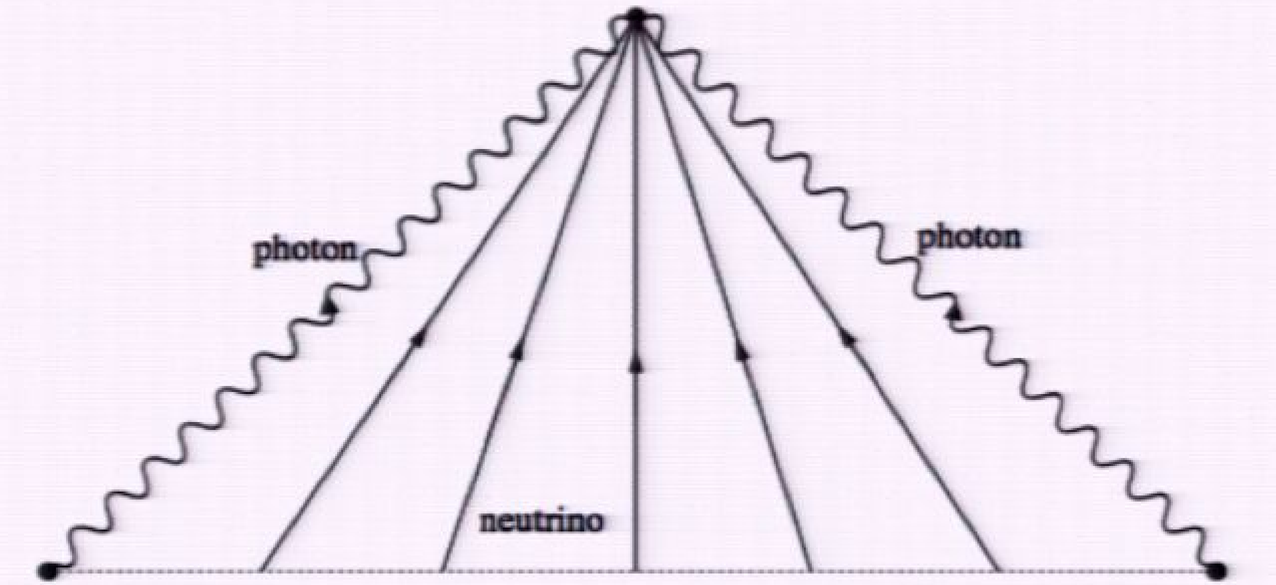


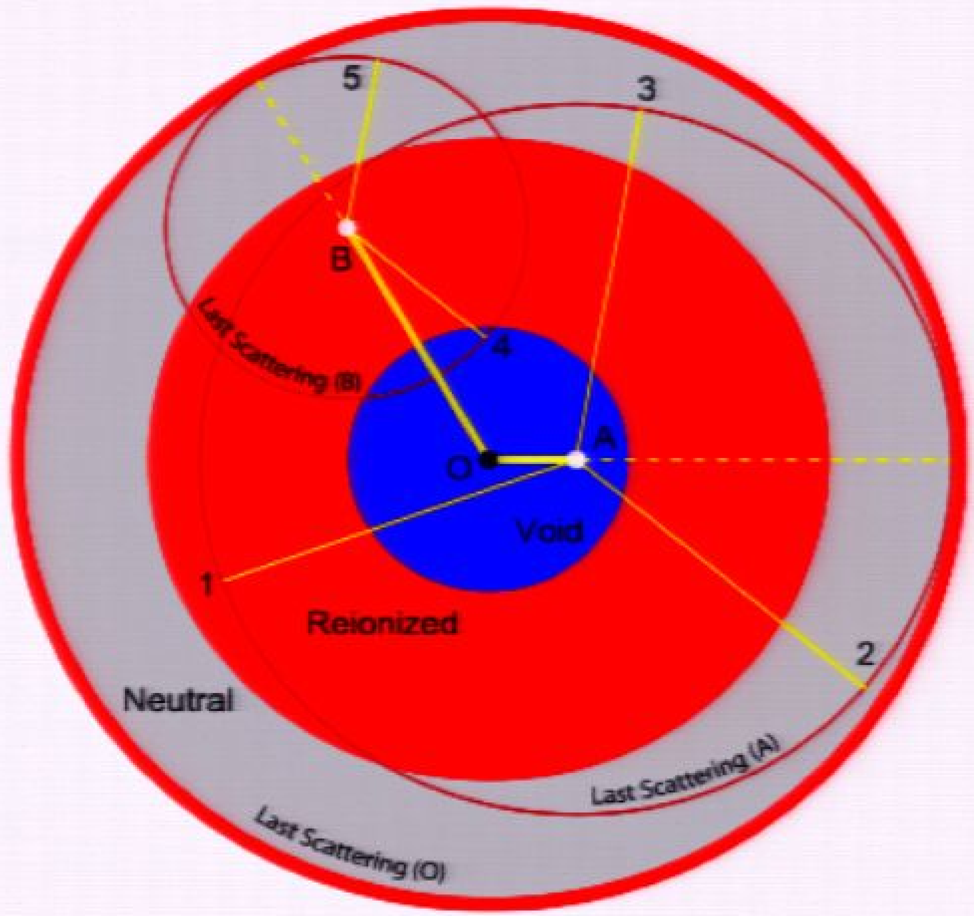
Figure 1: *Different from the cosmic photons, the cosmic neutrinos of different energies come from the different places on the surface of constant t_L and travel to us along the different worldlines.*

an the Copernican principle be tested by cosmic neutrino background?

nji Jia, Hongbao Zhang

Testing the Copernican Principle directly

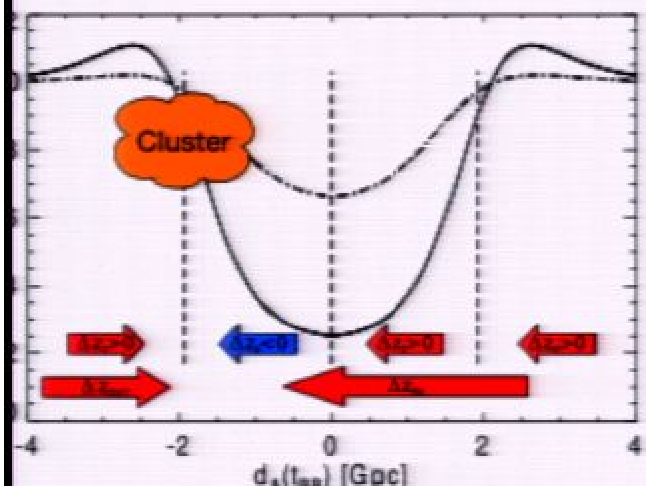
- Fitting voids can rule out void models only
    - doesn't 'test' the Copernican assumption generically
- if we can look inside our past lightcone we get more information
- Goodman-Caldwell-Stebbins test
- relies on void-type models ...

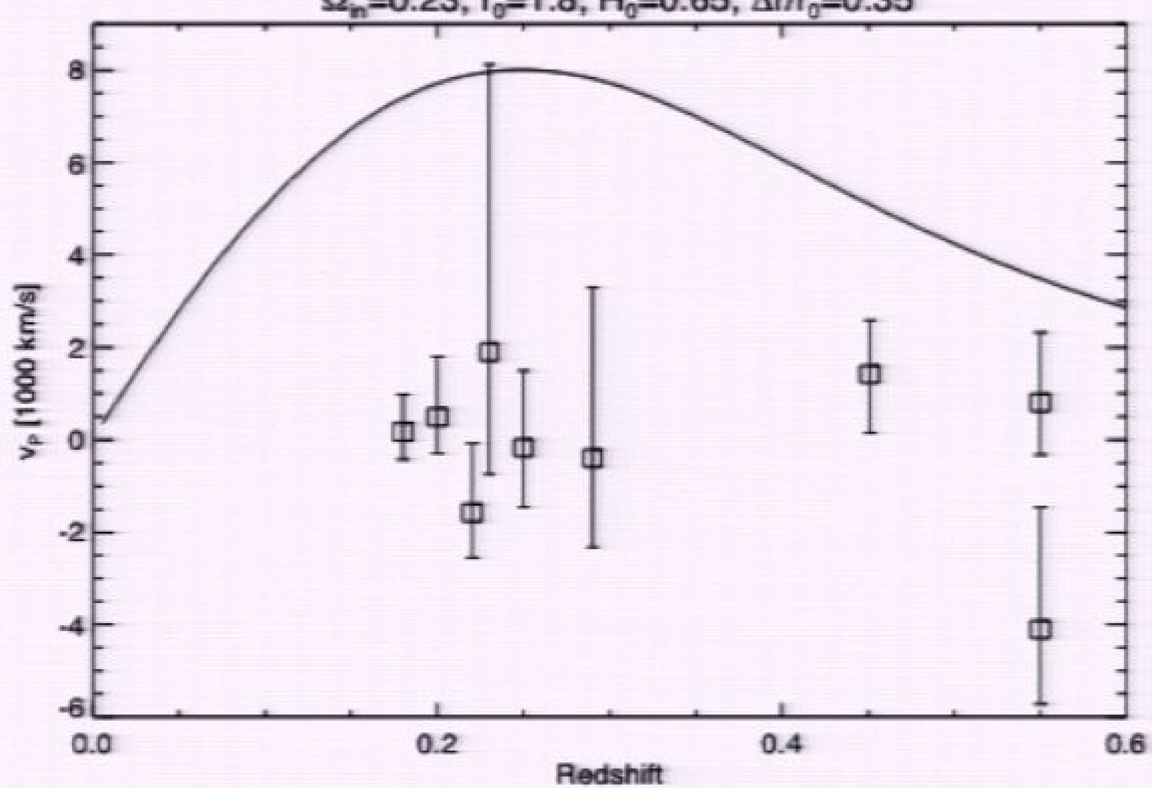


Caldwell & Stebbins 0711.3459

Can they be ruled out?

- kSZ (and SZ) effect can look inside our past lightcone





Looking the void in the eyes - the kSZ effect in LTB models

Juan García-Bellido[1], Troels Haugbølle[1,2]

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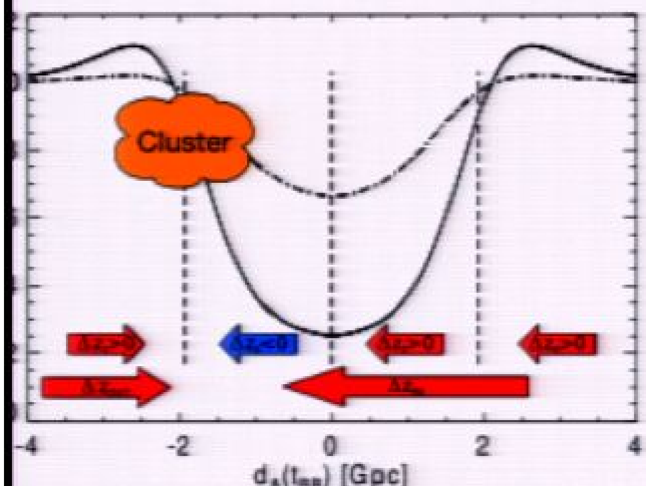

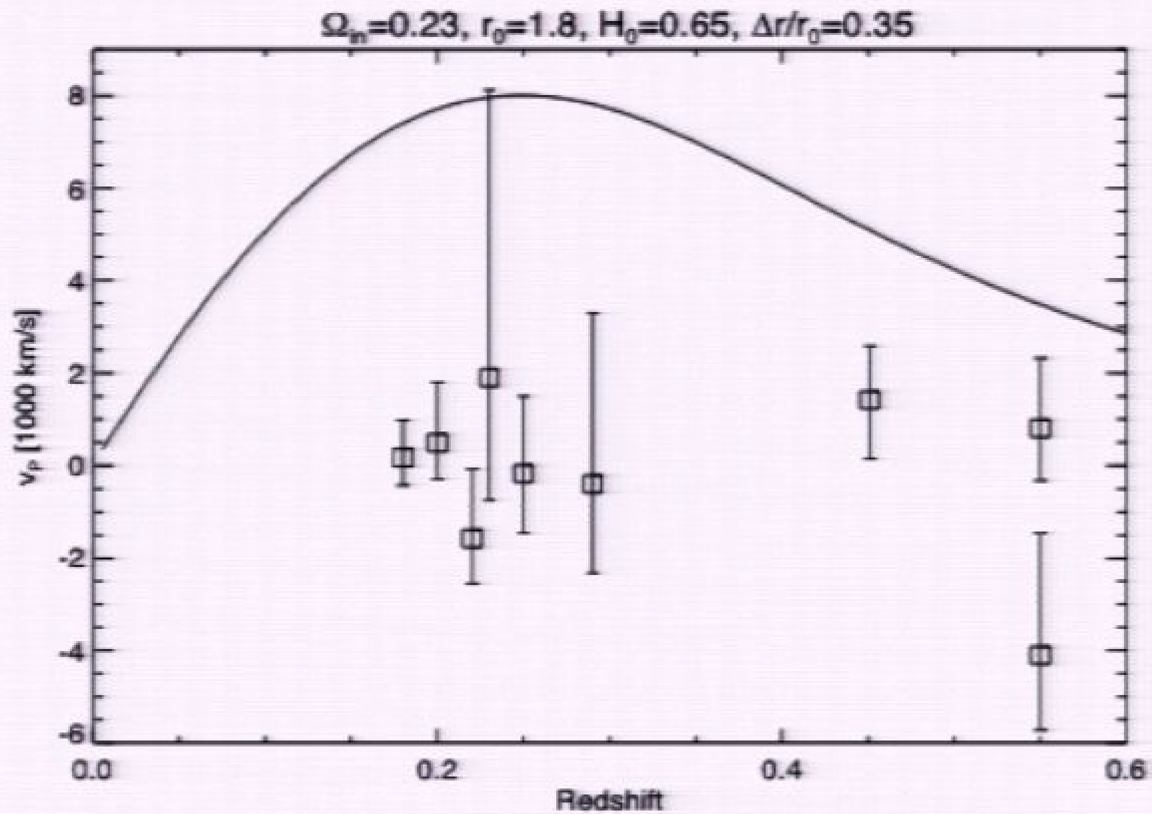

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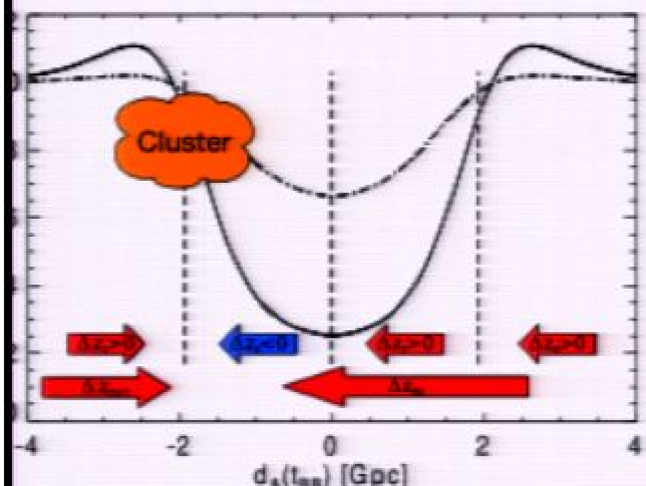

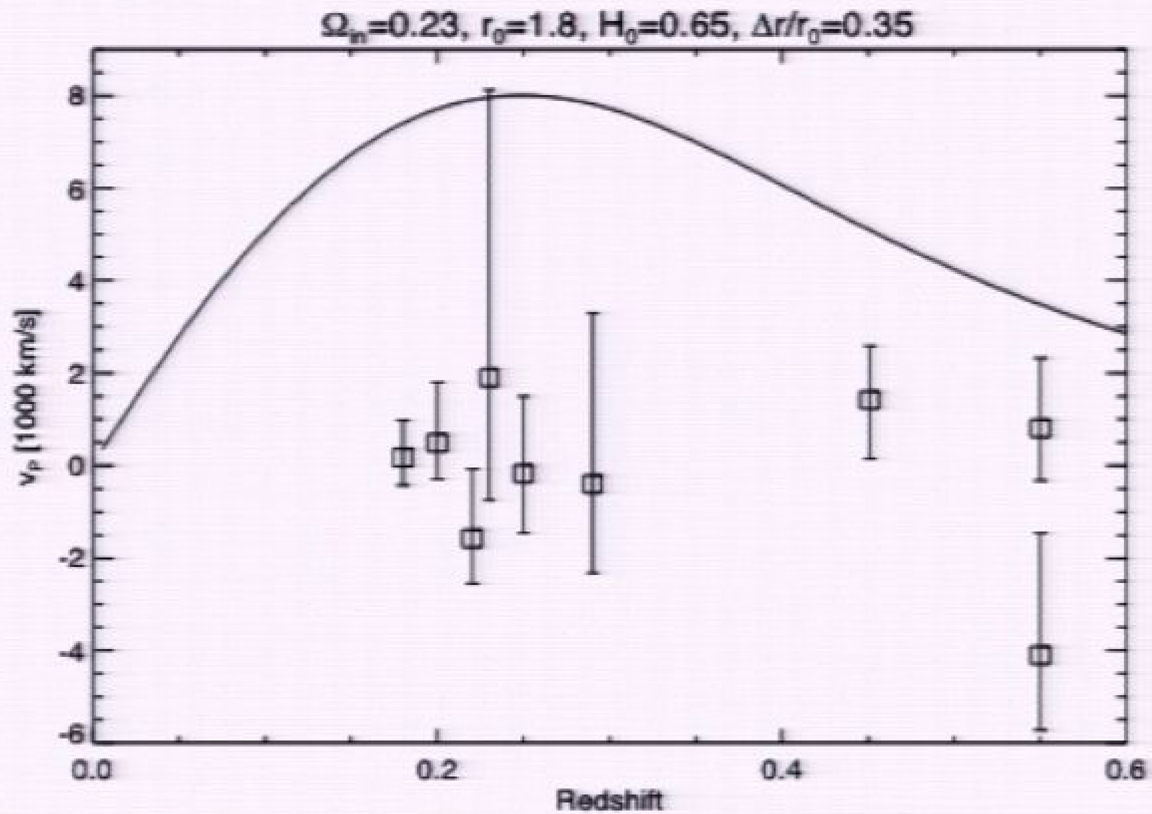

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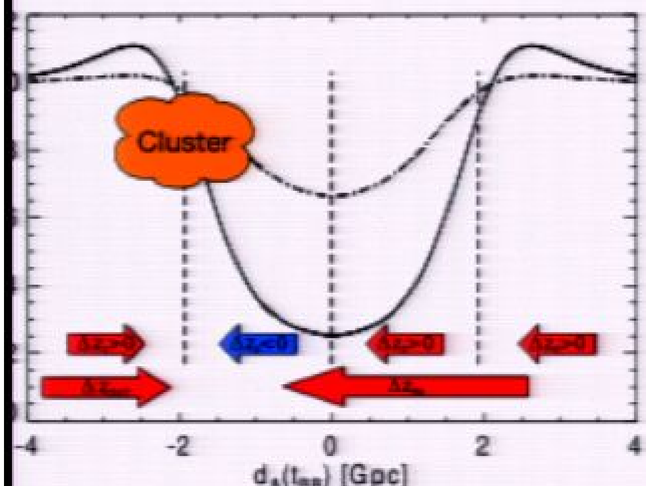

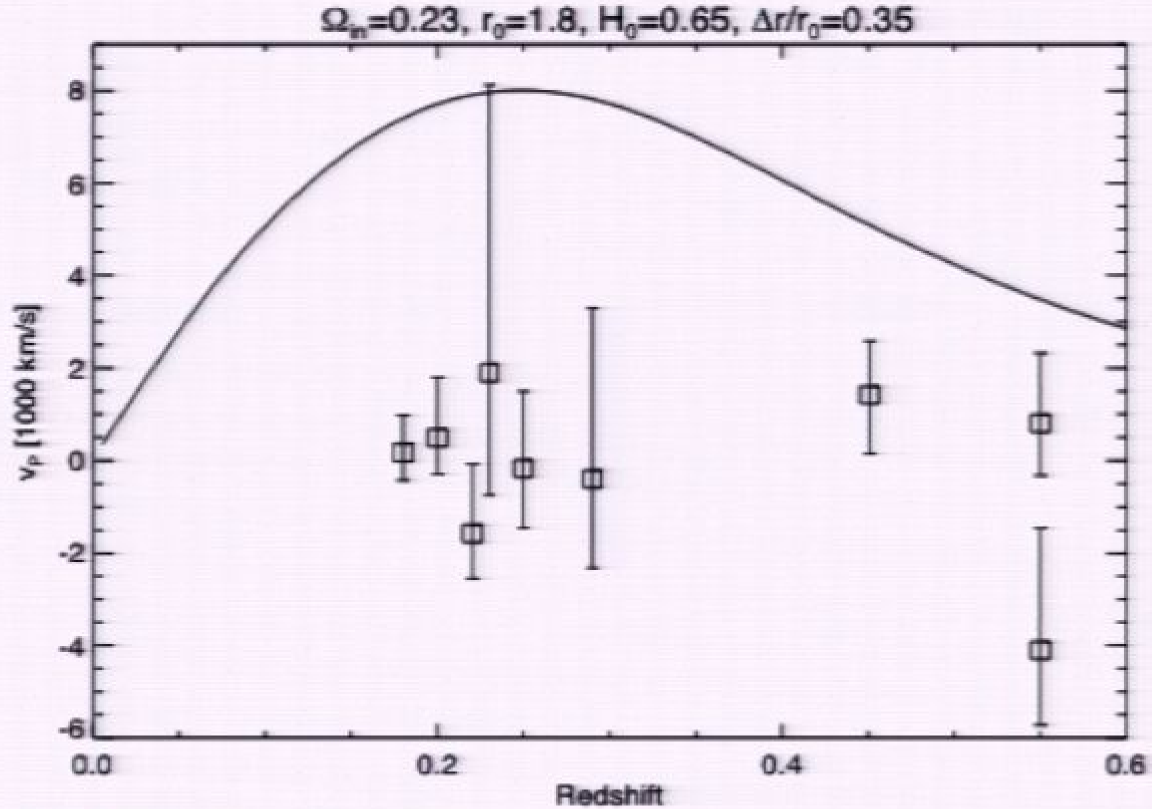

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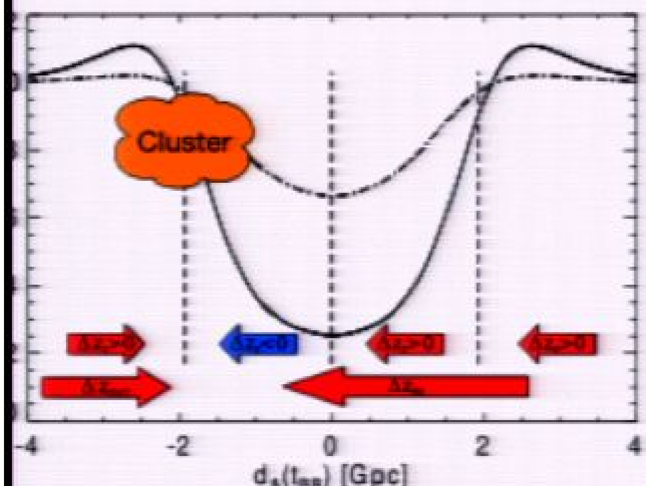

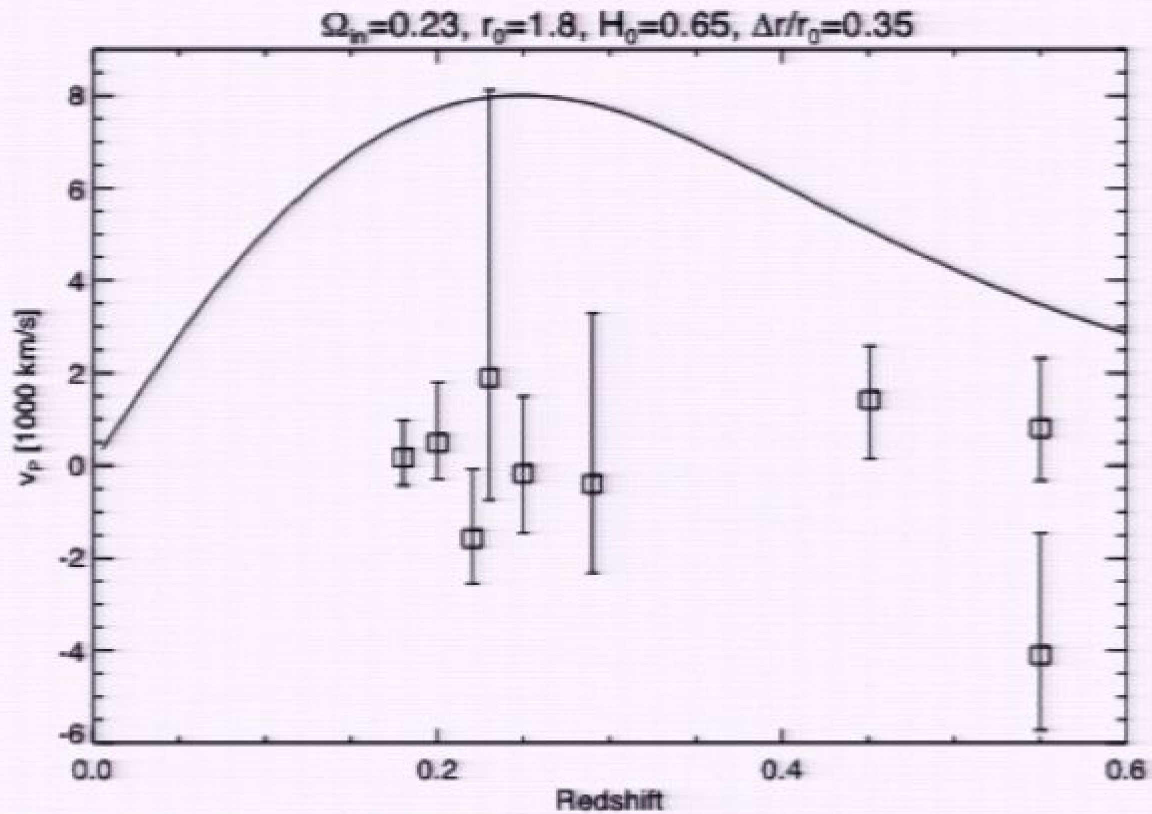

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Curvature test for the Copernican Principle

in FLRW we can combine Hubble rate and distance data to find curvature

$$\Omega_k = \frac{[H(z)D'(z)]^2 - 1}{[H_0 D(z)]^2}$$

$$\left[d_L = (1+z)D = (1+z)^2 d_A\right]$$

independent of *all* other cosmological parameters, including dark energy model, and theory of gravity

tests the Copernican principle and the basis of FLRW ('on-lightcone' test)

$$\mathscr{C}(z) = 1 + H^2\left(DD'' - D'^2\right) + HH'DD' = 0$$

Clarkson, Basset & Lu, PRL 100 191303

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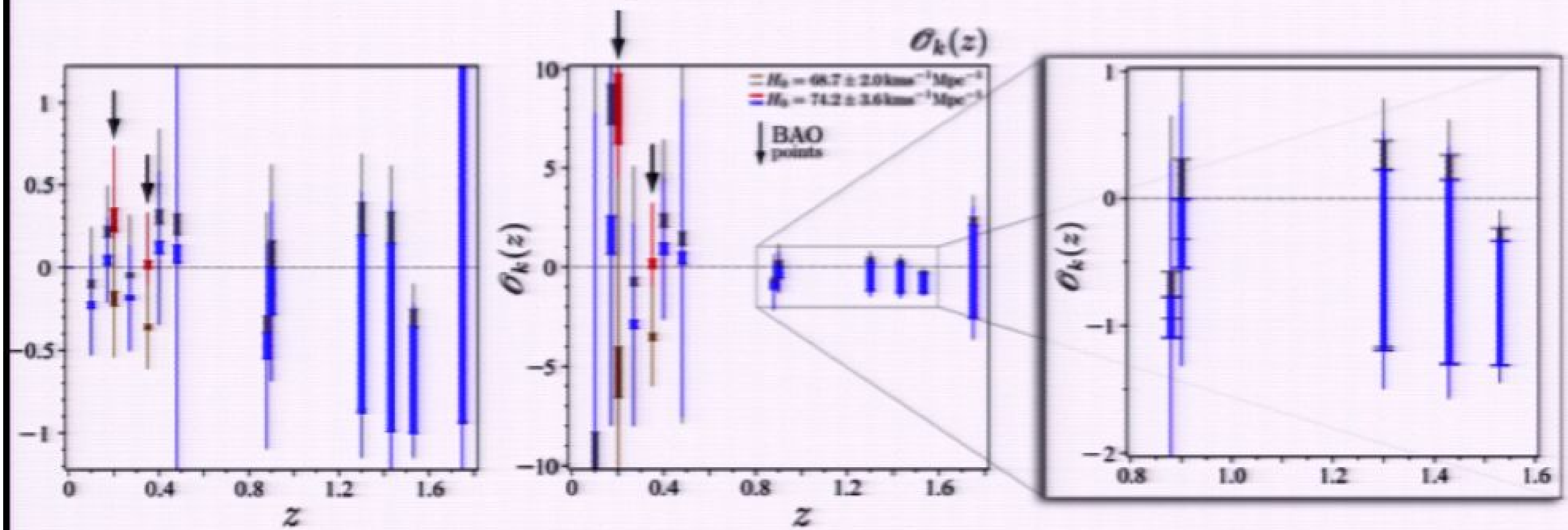
Clarkson, Basset & Lu, PRL 100 191303

Using age data to reconstruct $H(z)$



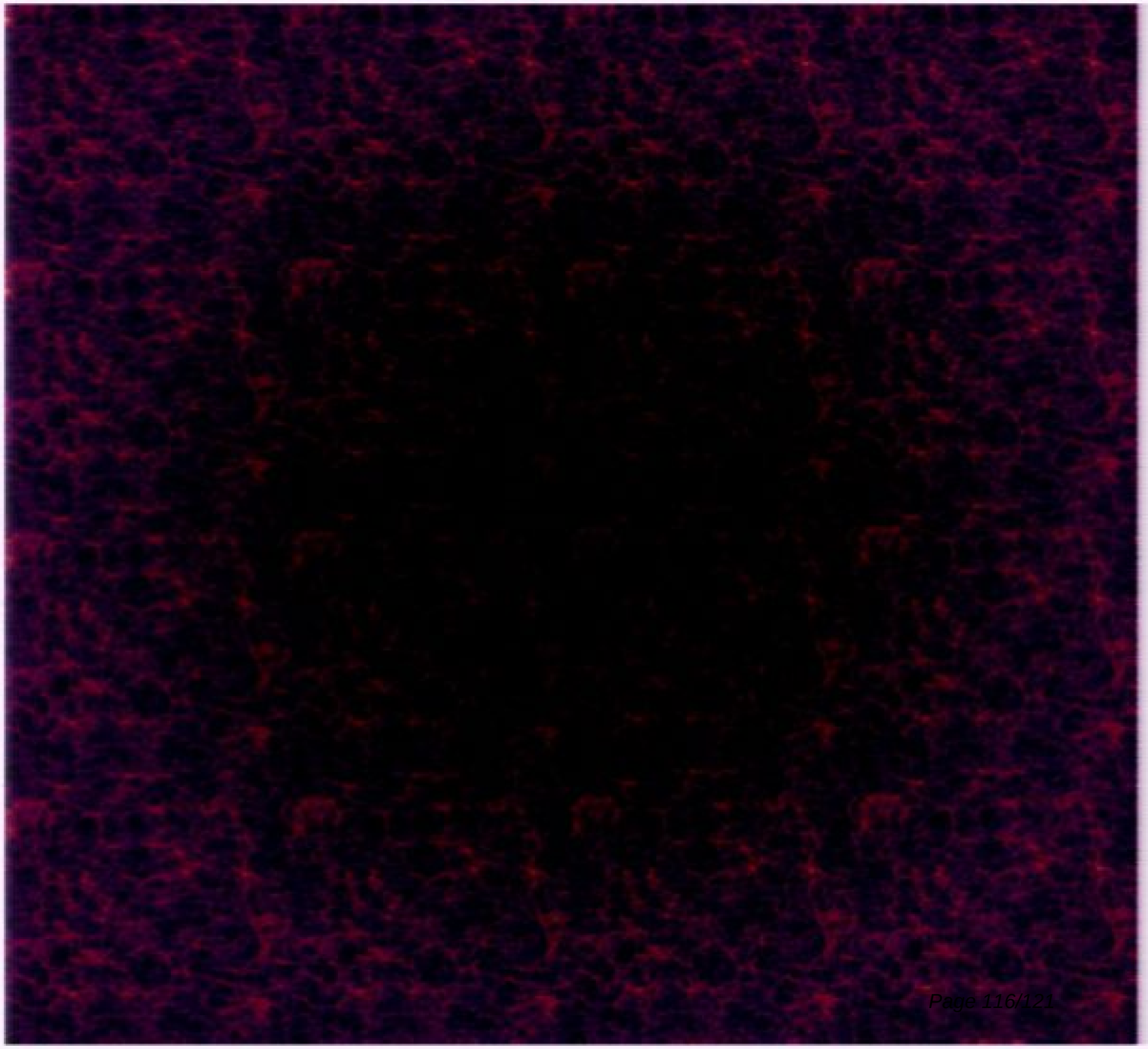
Shafieloo & Clarkson, PRD

Are they ridiculous?

being 'at the centre of the universe' is crazy, but only a coincidence of 1 in 10^9 in our Hubble volume

possible selection effects?

- could dark matter inhibit solar system formation?
- maybe not anti-Copernican



Open issues for voids

void models have many problems:

- perturbations/BAO/large scale CMB not calculated
  - looks like they will be able to fit all observations
- initial conditions: could inflation/something really produce a simple void?
- they're weird: can the Copernican problem be averted?

Conclusions

- Lambda exists by homogeneity assumption!

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model independent consistency tests will be crucial to cement knowledge of Lambda

- quantify lack of understanding better than comparing parameterised models

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Backreaction: how do we formulate the FLRW models in the first place?

- >10% change to dark energy reconstruction? UV divergence?

Conclusions

- Lambda exists by homogeneity assumption!
- *model independent* consistency tests will be crucial to cement knowledge of Lambda
  - quantify lack of understanding better than comparing parameterised models
- Backreaction: how do we formulate the FLRW models in the first place?
  - >10% change to dark energy reconstruction? UV divergence?
- model independent test of the Copernican principle now possible