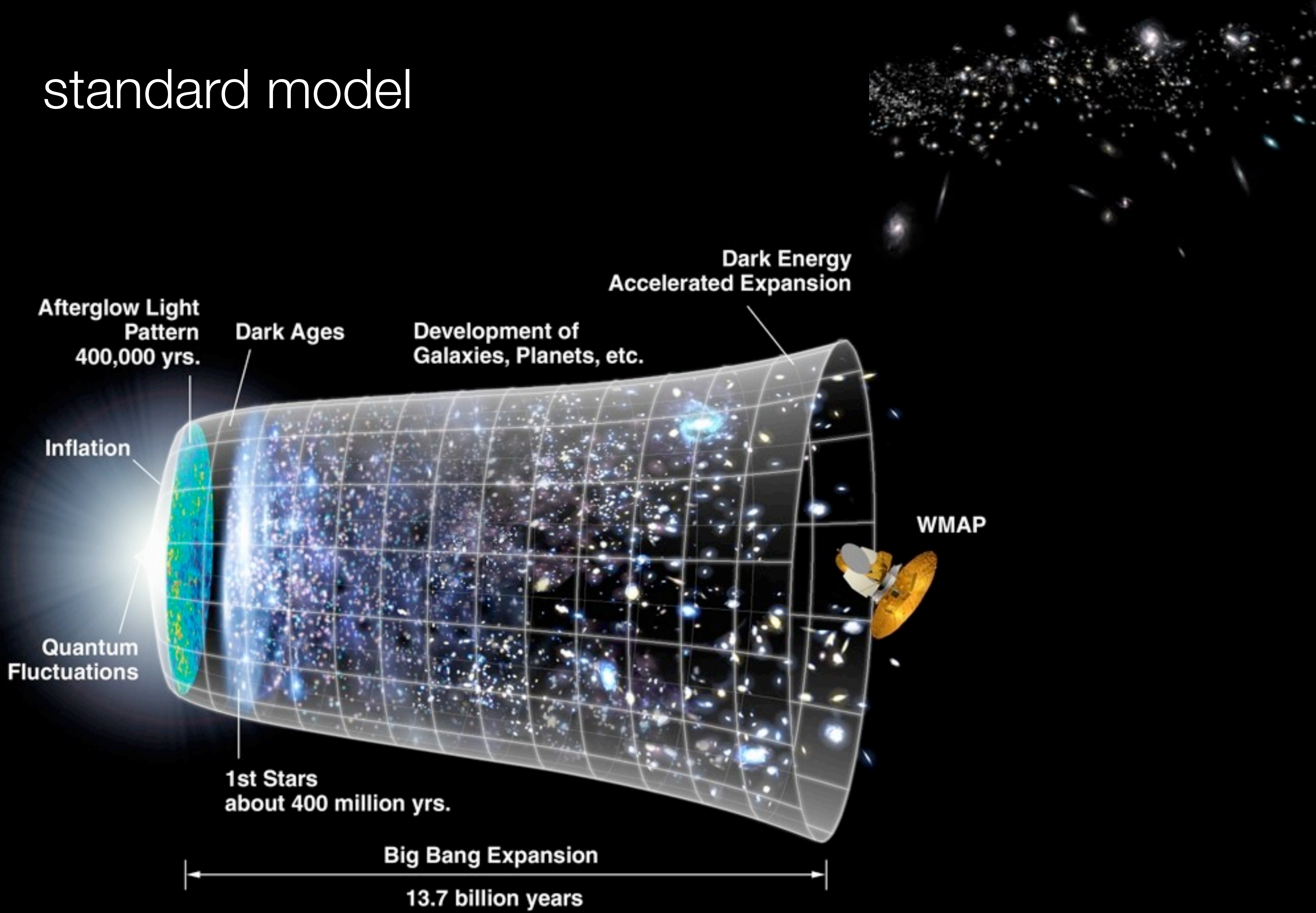
dark energy and inhomogeneity

Chris Clarkson
Astrophysics, Cosmology & Gravitation Centre
University of Cape Town

standard model



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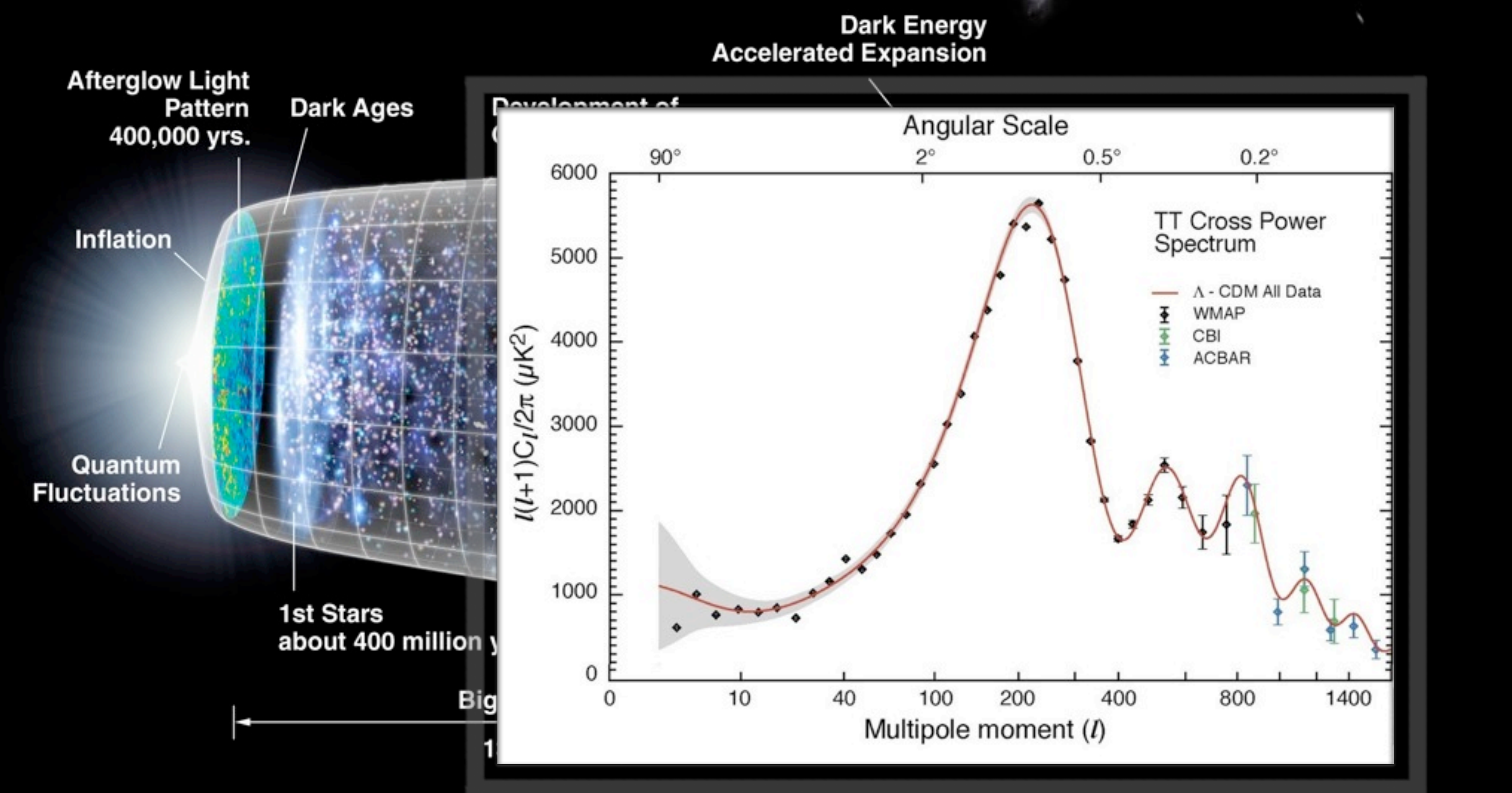

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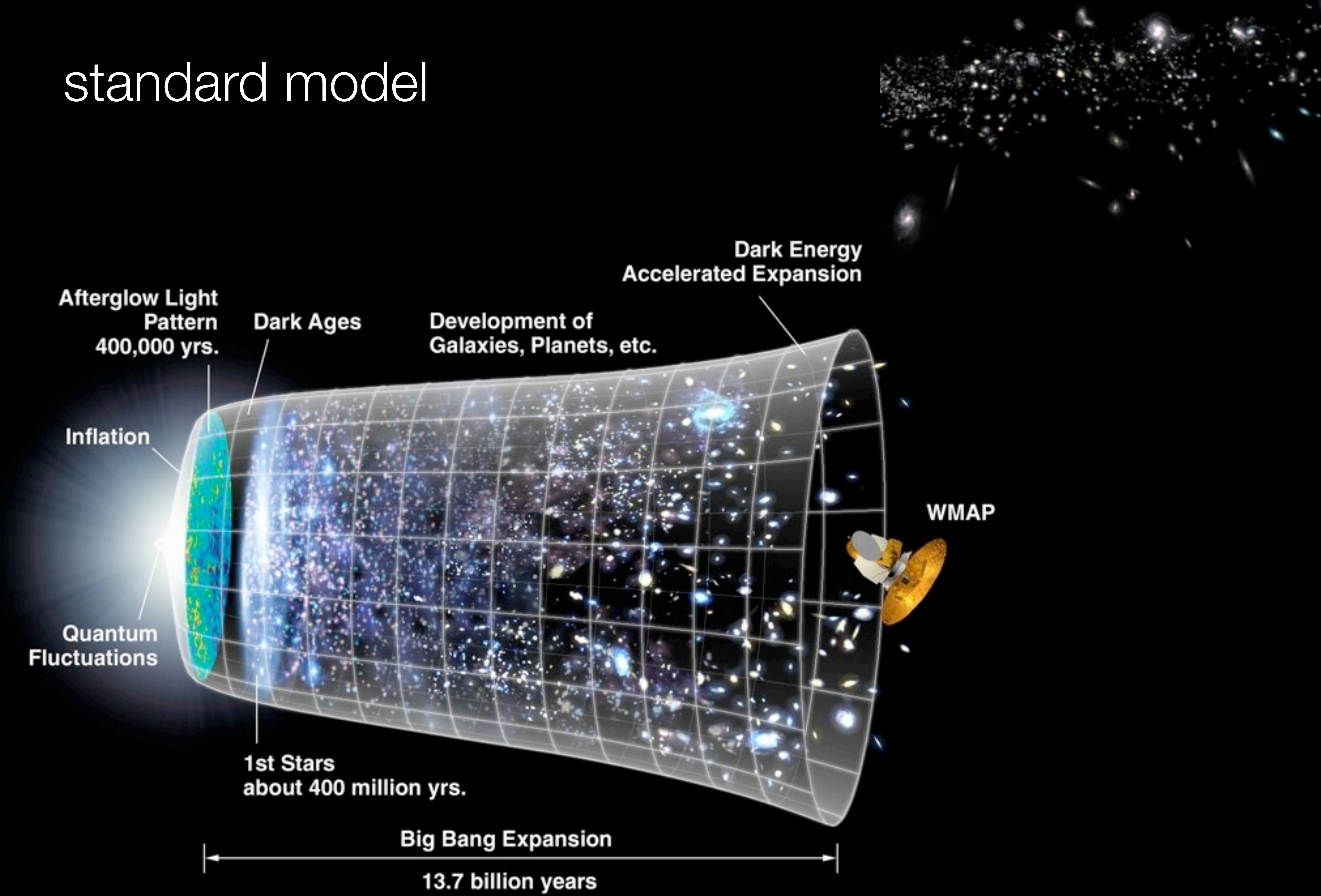
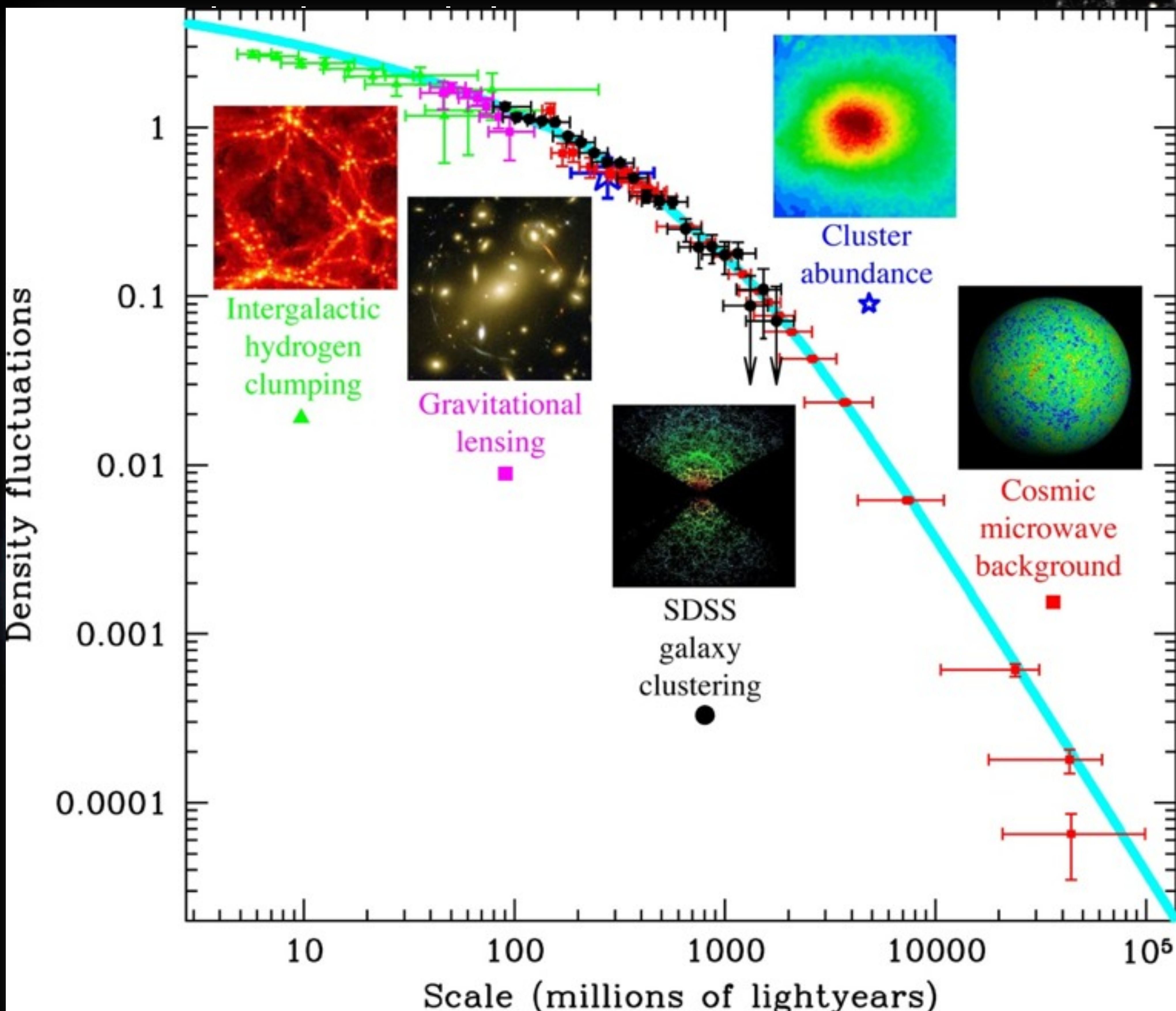
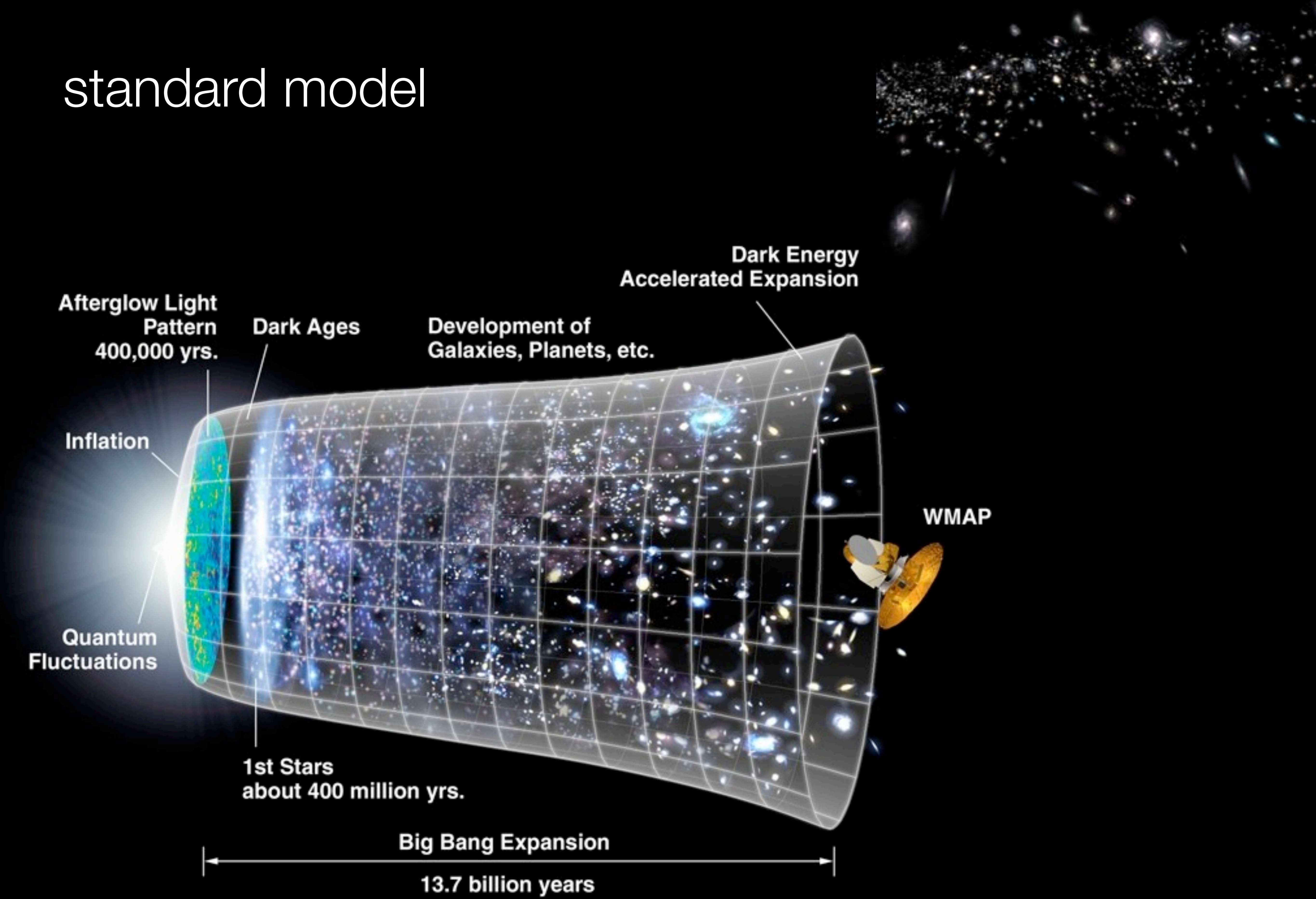




Density fluctuations
1
0.1
0.01
0.001
0.0001
10
100
1000
10000
10⁵
Scale (millions of lightyears)
Intergalactic
hydrogen
clumping
Gravitational
lensing
SDSS
galaxy
clustering
Cluster
abundance
Cosmic
microwave
background

standard model



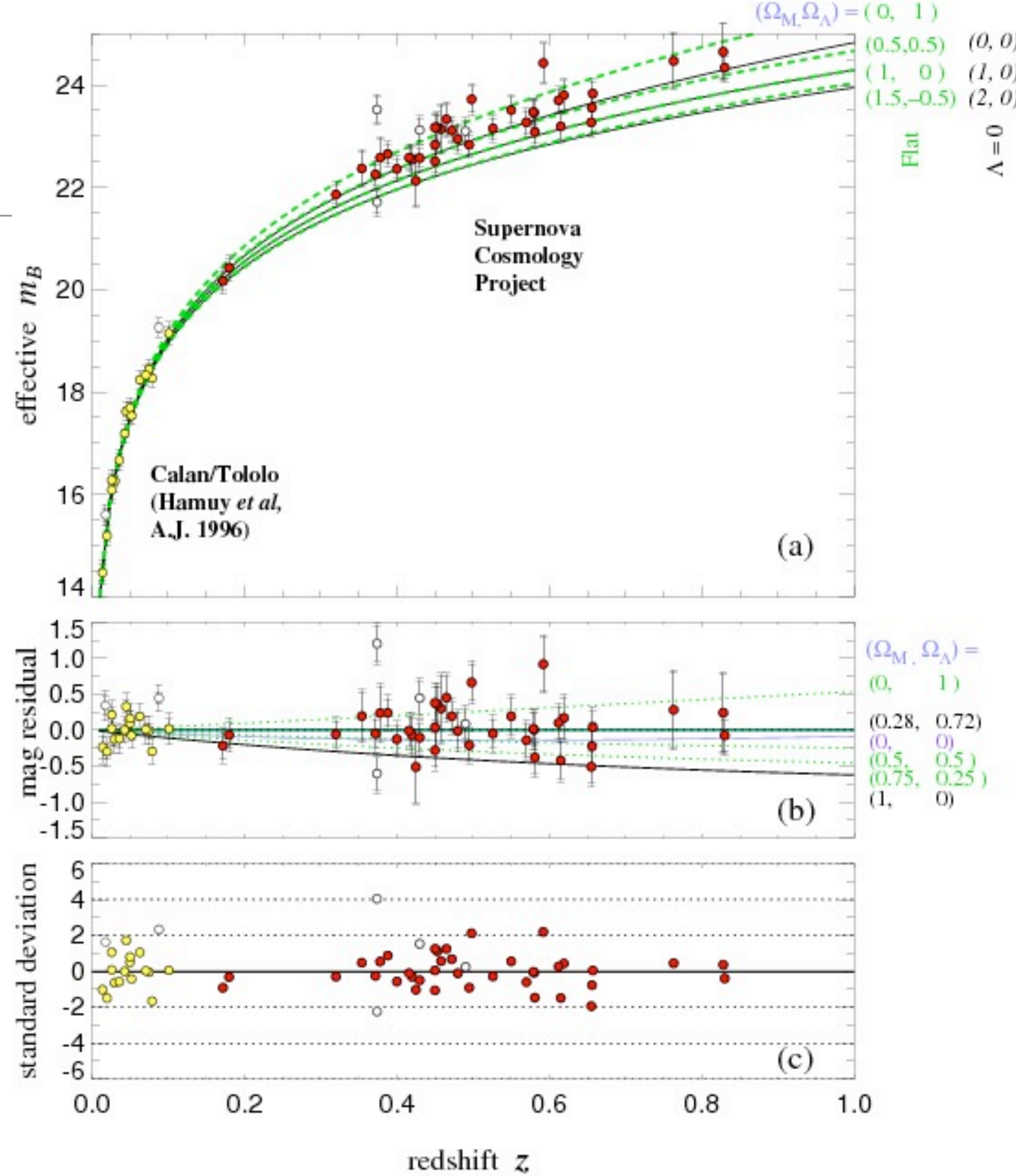
key ingredients for cosmology

- universe homogeneous and isotropic on large scales (>100 Mpc)
- background dynamics determined by amount of matter + curvature present (+ a theory of gravity)
- inflation lays down the seeds for structure formation from quantum fluctuations
  - these grow into galaxies and so on
- works ... if we include a cosmological constant or ‘dark energy’
    - matter + curvature not enough

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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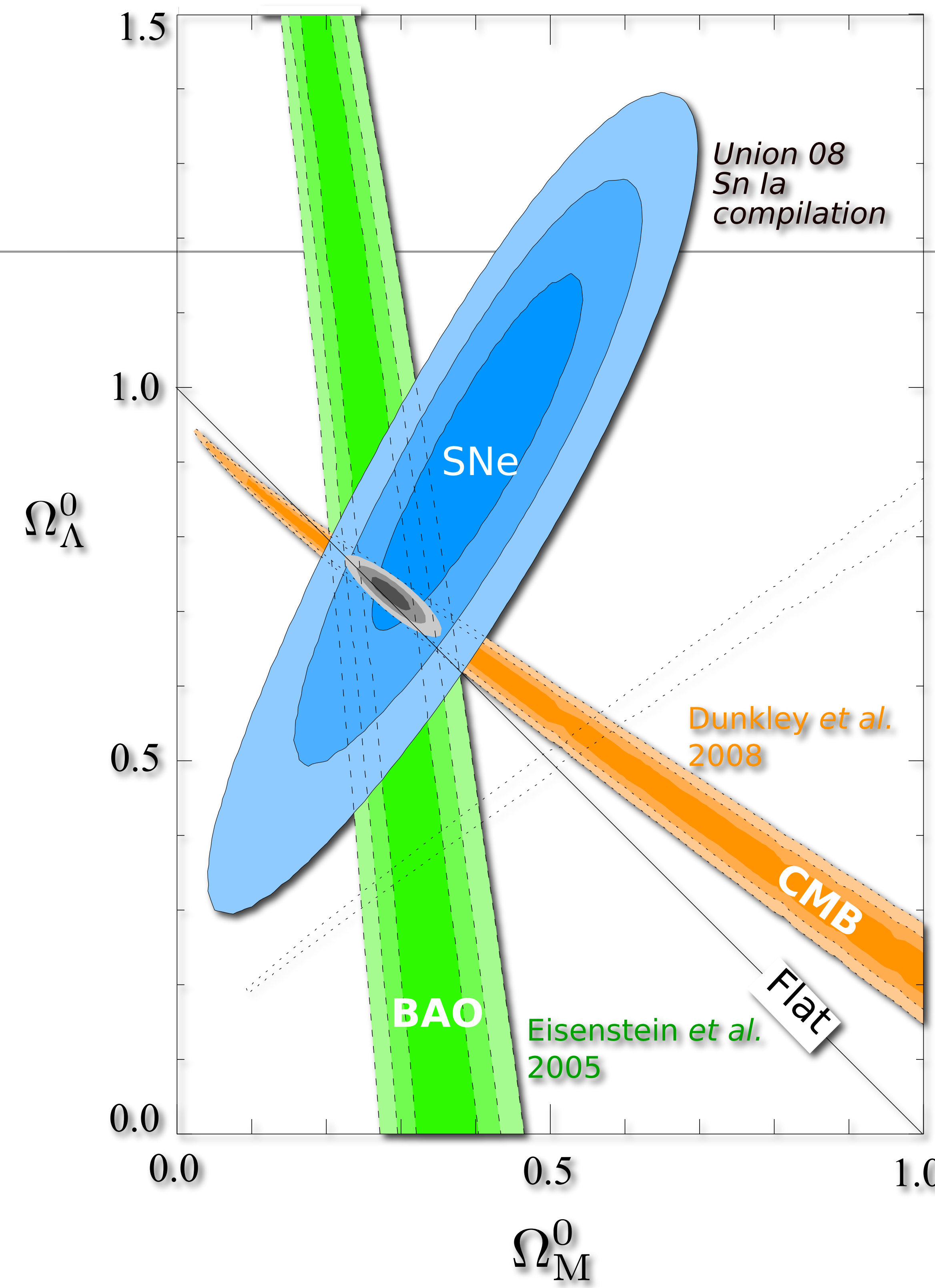

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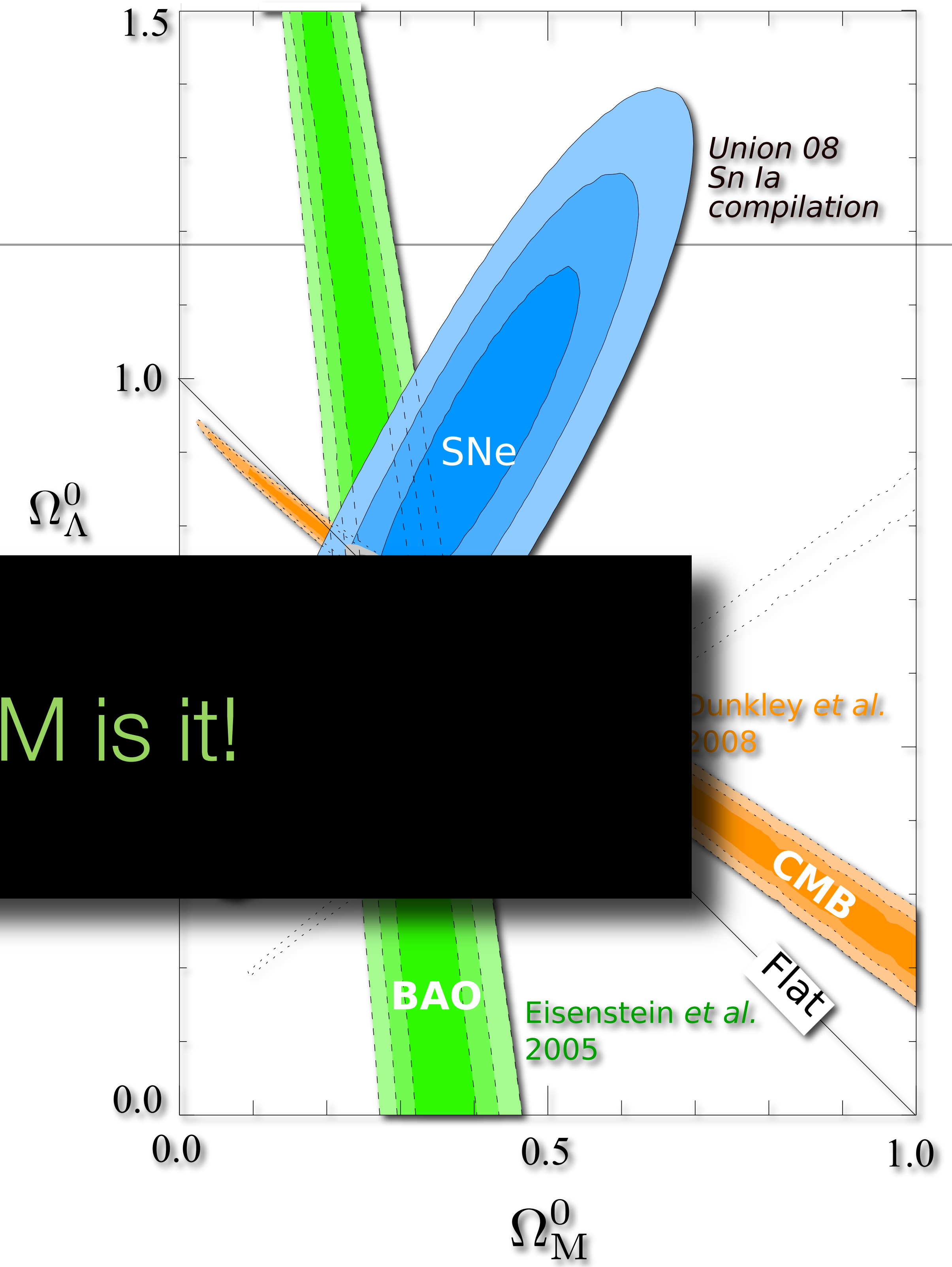


flat LCDM is it!

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?

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

- last modes are entering the Hubble radius ... we coincide with the largest modes which will ever exist

- Perhaps Landscape arguments can answer this ... one day ...

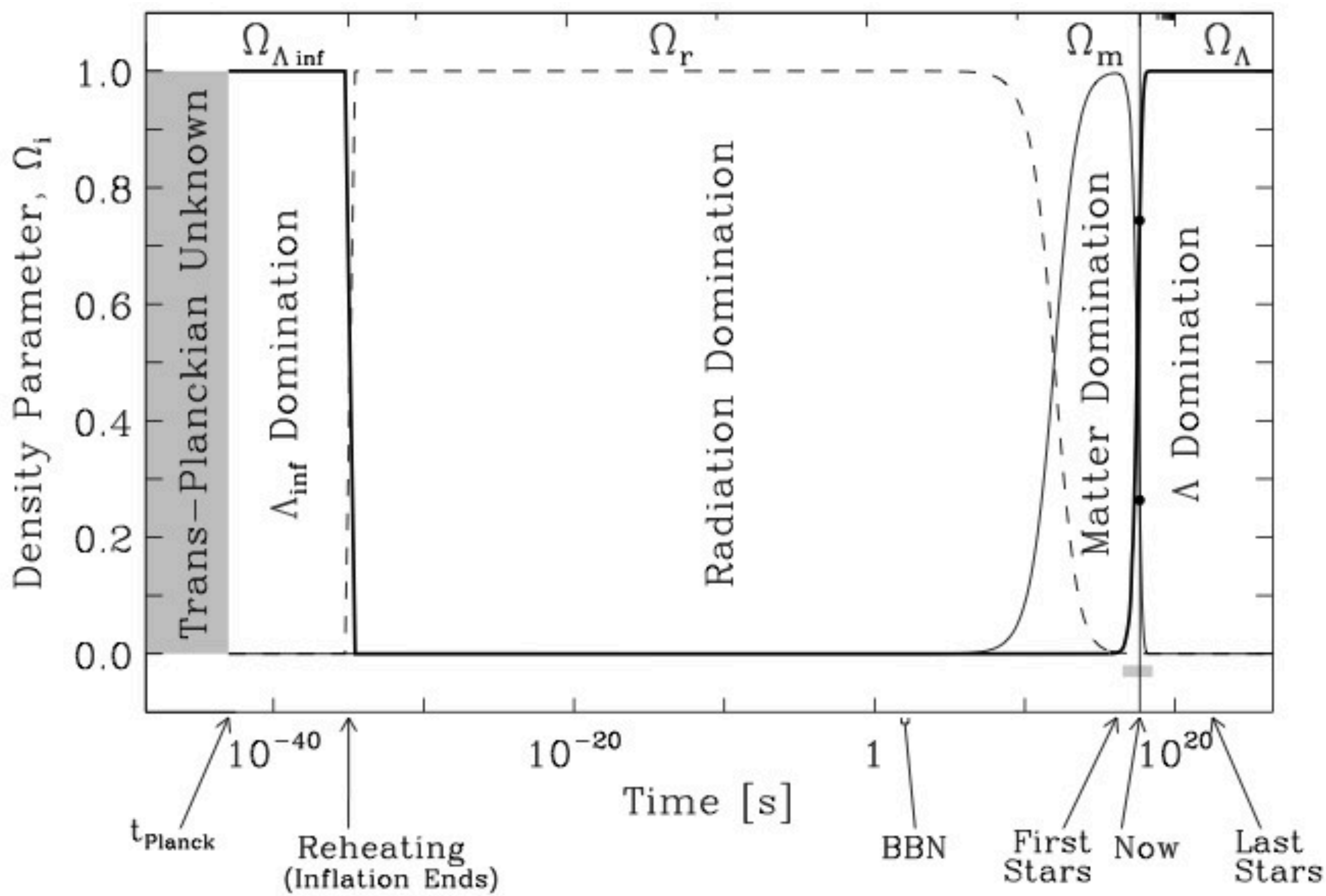
- in 10^{500} universes ours must be special - breaks with the Copernican principle...

Problems with Λ

arXiv:1005.0745 [pdf, other]

Dark Energy, Anthropic Selection Effects, Entropy and Lif

Chas A. Egan



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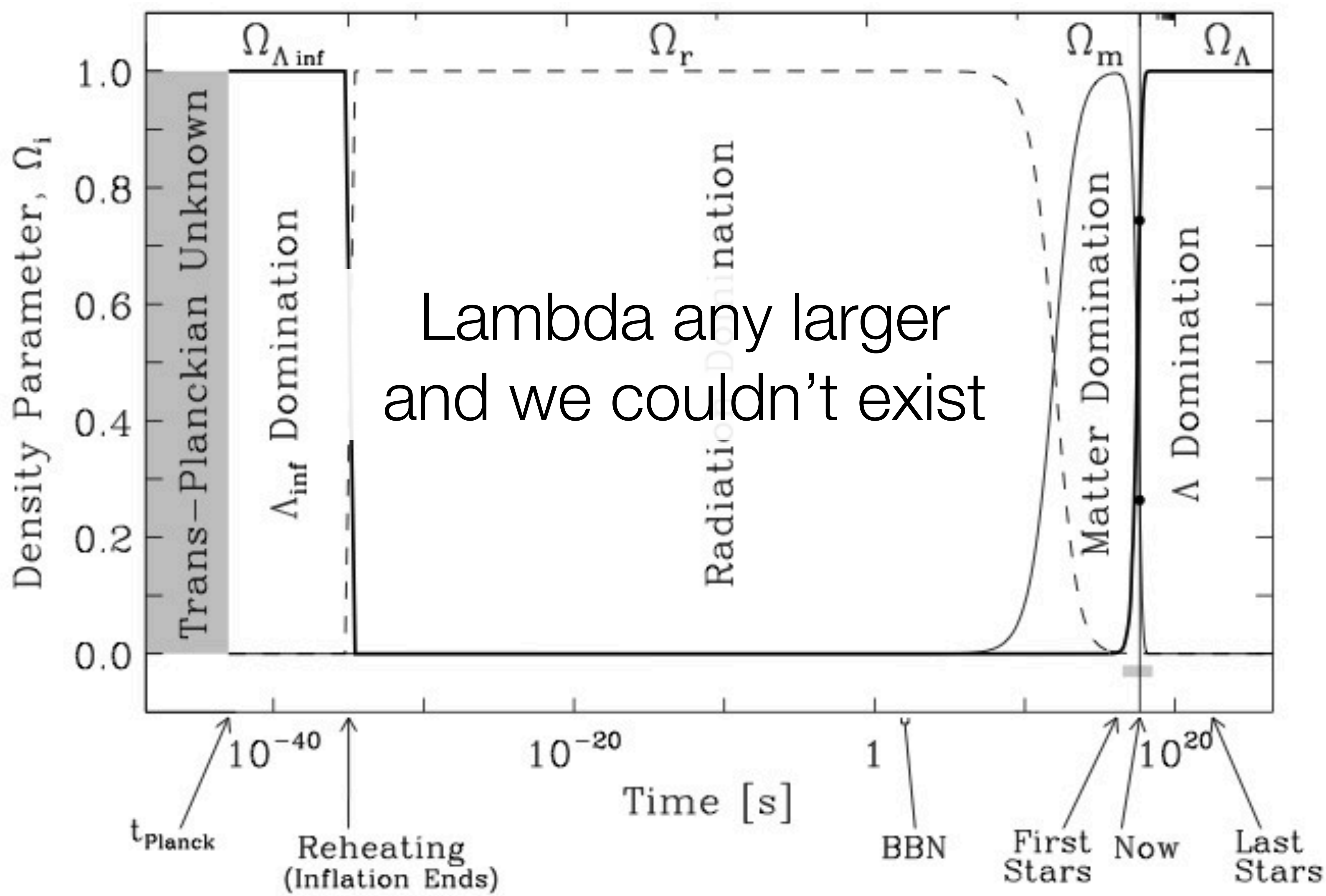


ry)

LCDM Denial

- if acceleration isn't cosmological constant:
  - 'real' dark energy - quintessence, k-essence ...
  - modified gravity - gr wrong on Hubble scales

  make things worse, but help test LCDM

  - inhomogeneous universe - backreaction?
  - do we live at the centre of vast void? - copernican assumption wrong

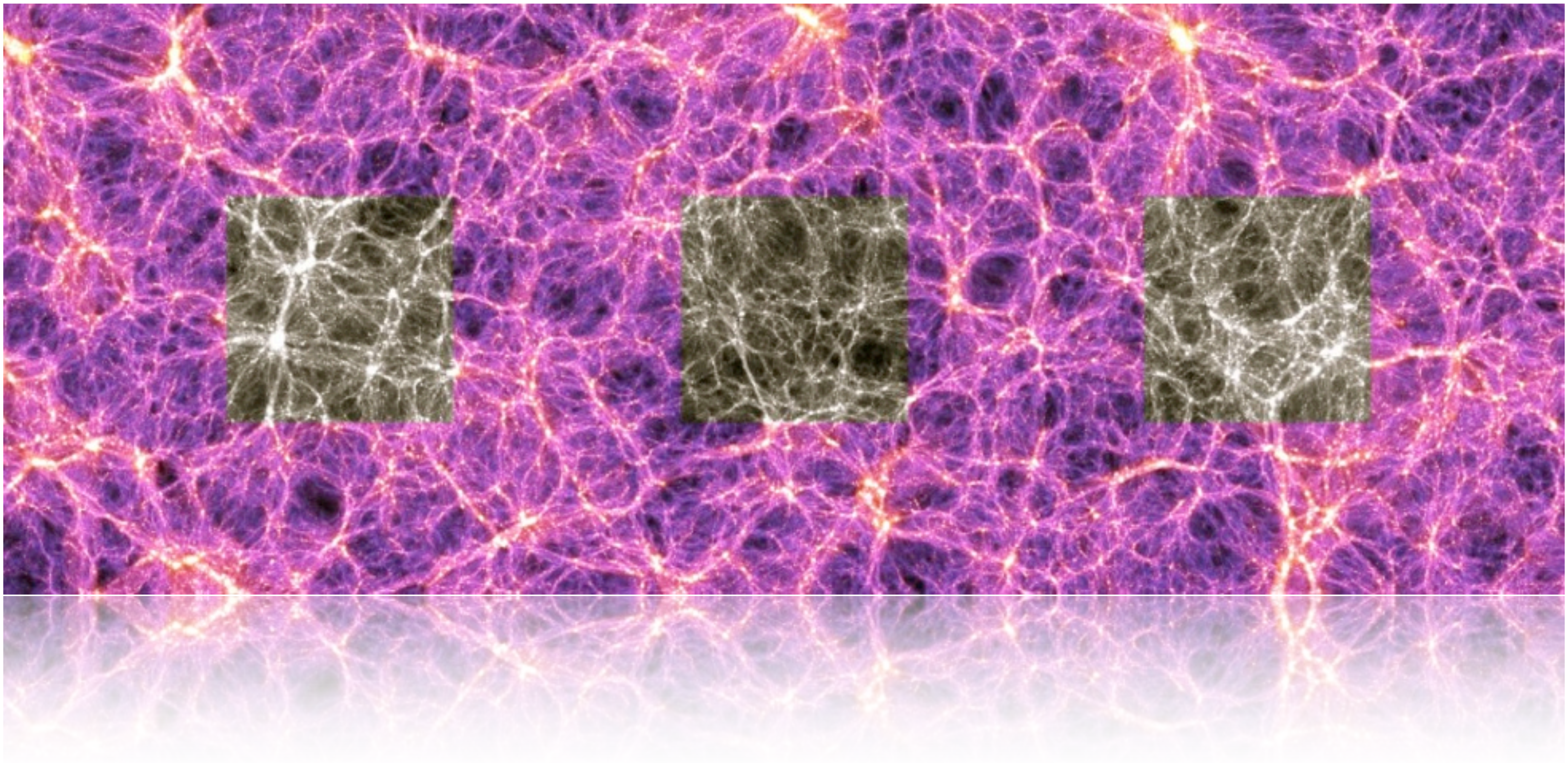
overview:

1. Small inhomogeneity and ‘backreaction’ of perturbations

2. Large inhomogeneity and the Copernican Principle

3. Consistency tests for LCDM

How does structure affect the background?



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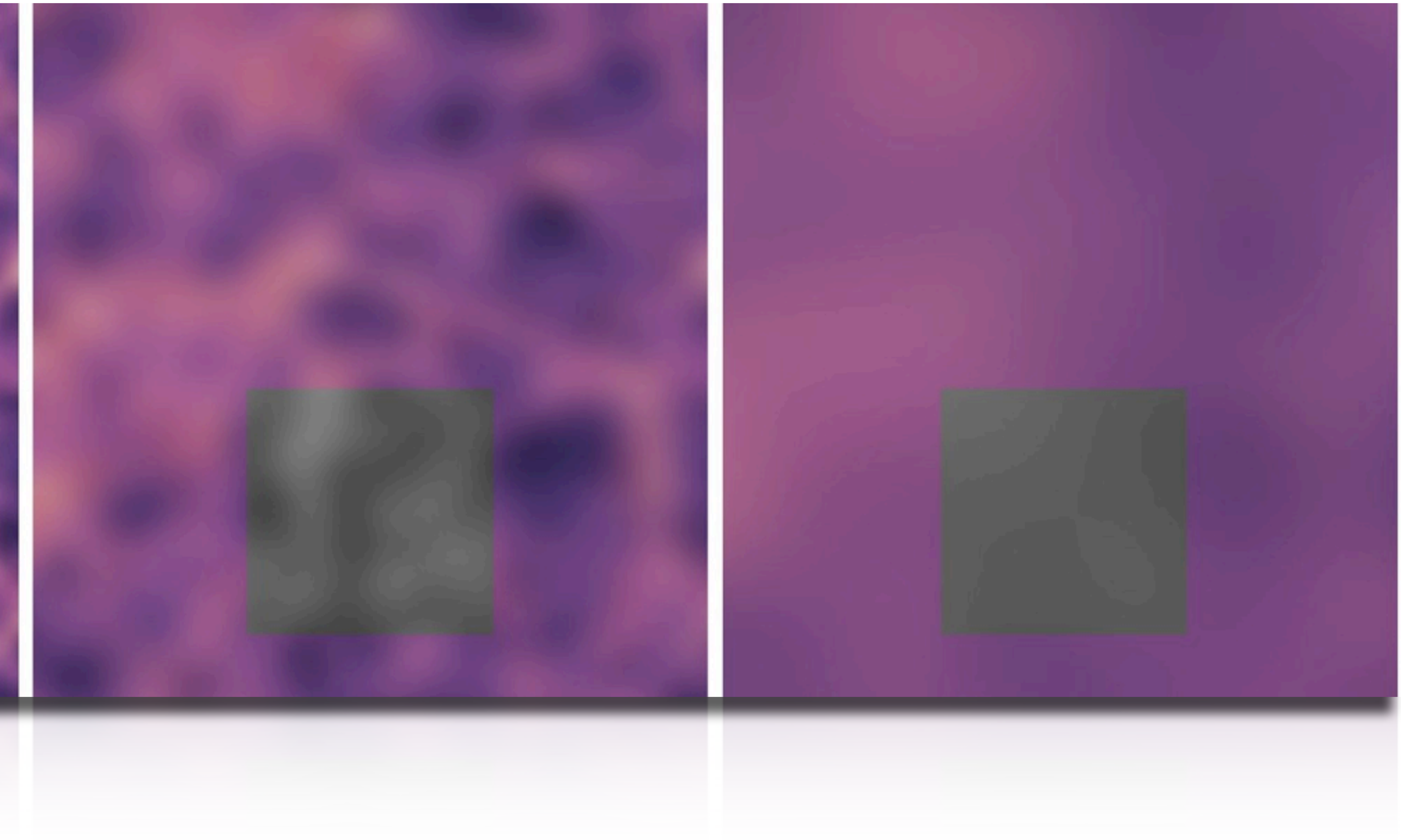

Averaging

- Define Riemannian averaging operator on arbitrary domain D

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

Riemannian volume element

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

spatial average implies wrt some foliation of spacetime

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to specify average energy density need full solution of the field equations

Riemannian volume element

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spatial average implies wrt some foliation of spacetime

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

fit to 'background' observables - SNIa etc

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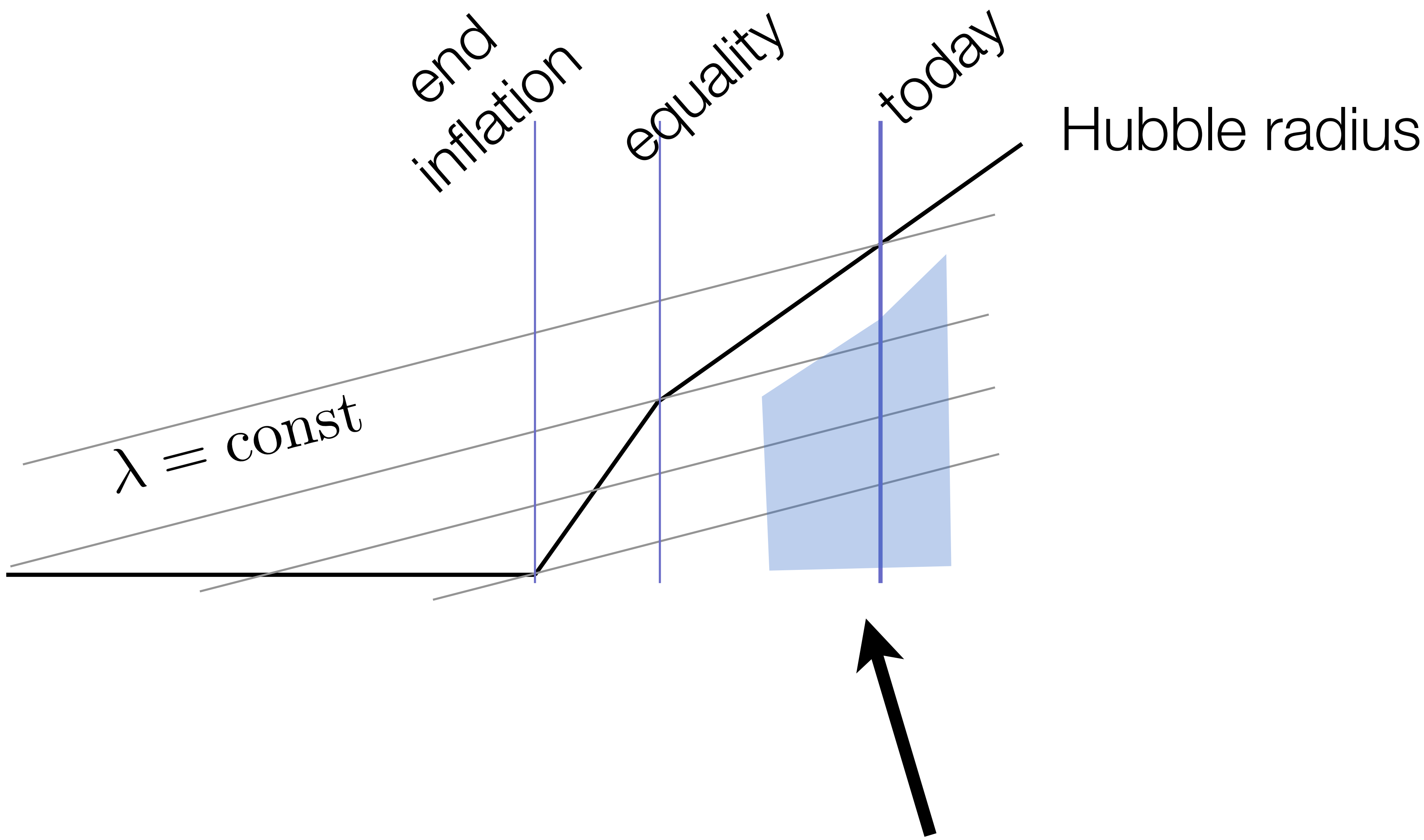
Another view of the averaging problem



averaging gives corrections here

$$\text{different } \textit{effective} \quad \frac{\rho_{\mathrm{tot}}}{\rho_{\mathrm{critical}}} \quad \text{and} \quad \Lambda$$

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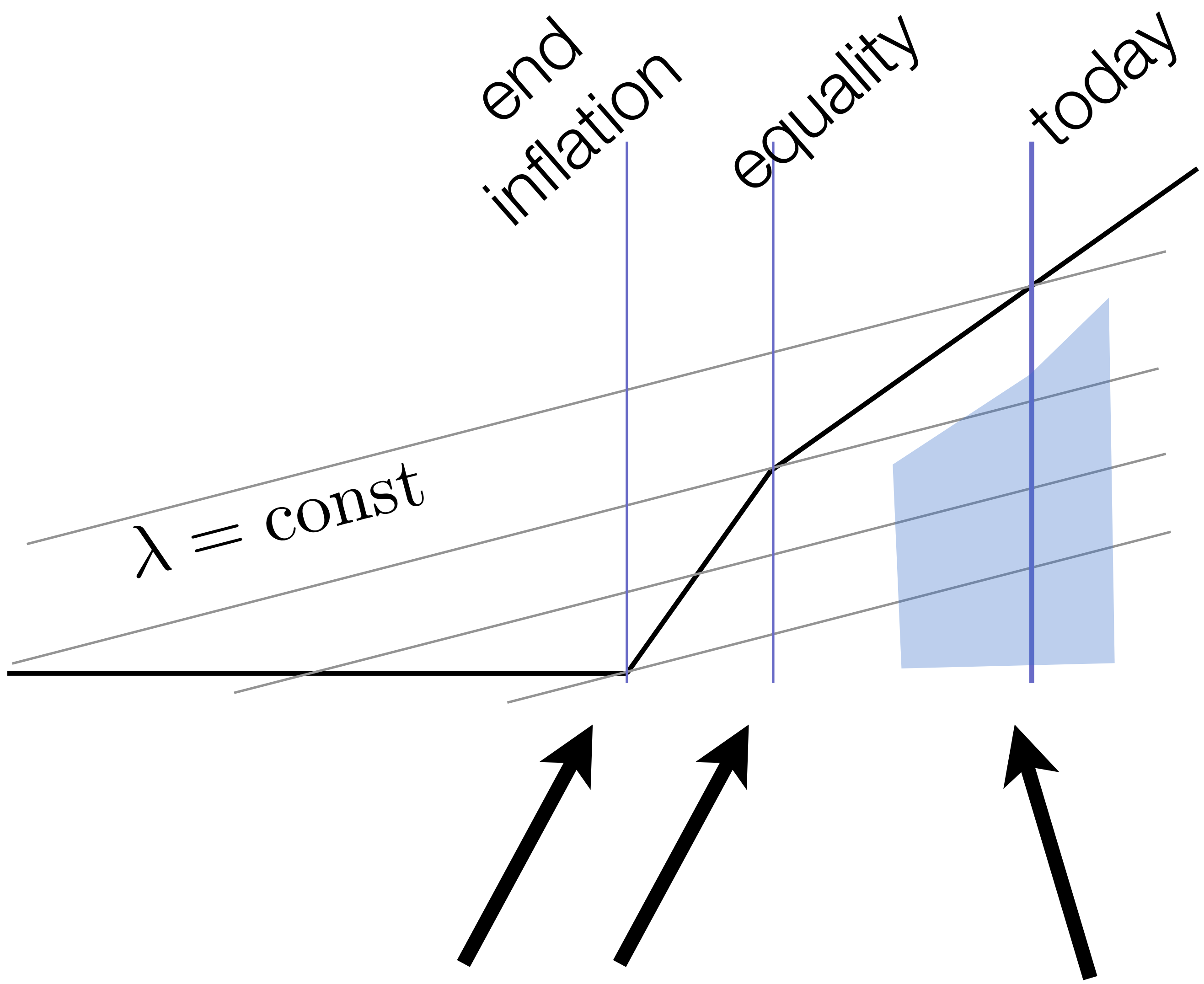
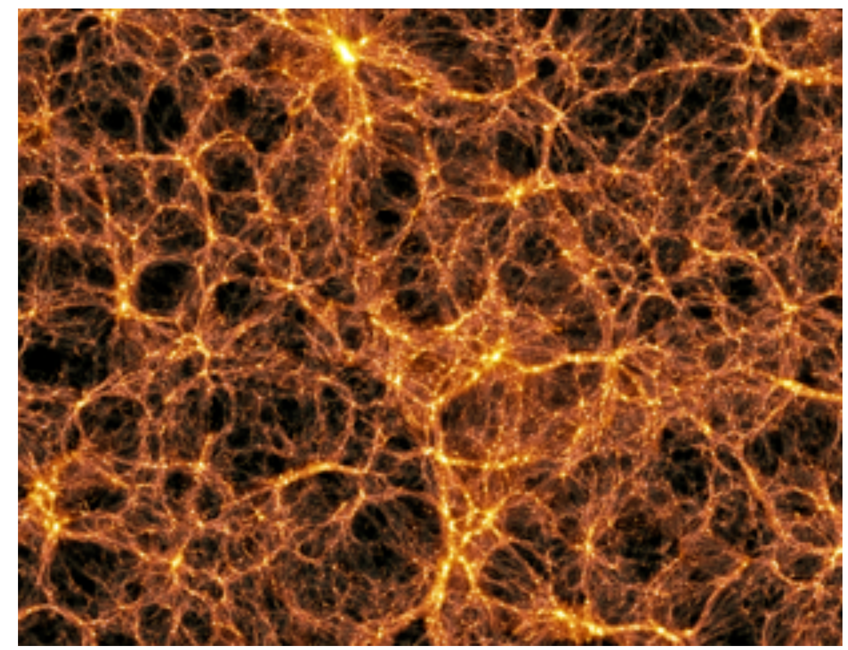




model = flat FLRW +
perturbations

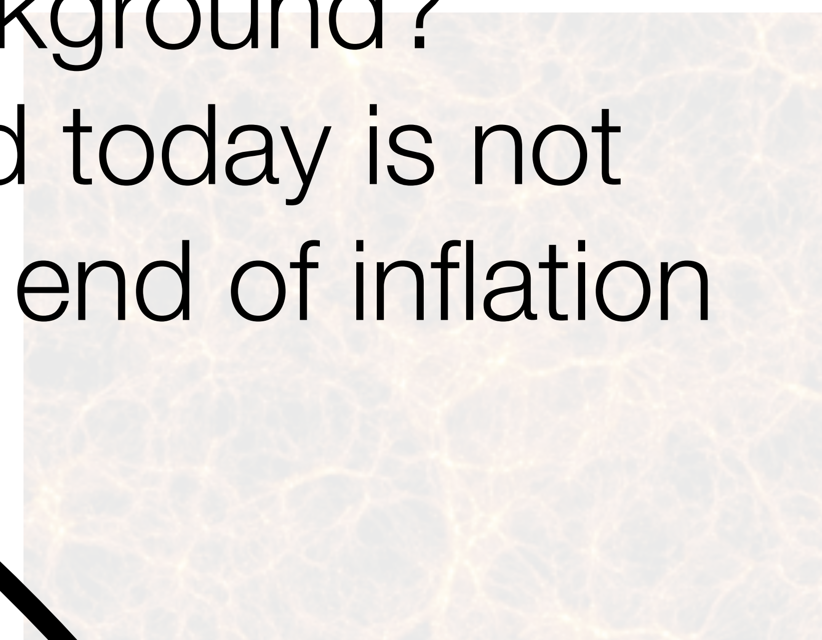
curvature and Λ fixed

averaging gives corrections here

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

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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- Well, maybe. [Rasanen, Li etal, Clarkson etal]
- Corrections from averaging enter Friedmann and Raychaudhuri equations
  - is this degenerate with ‘dark energy’?
  - can we separate the effects [if there are any]?
  - or ... is it dark energy? neat solution to the coincidence problem

Perturbation theory

- metric to second-order

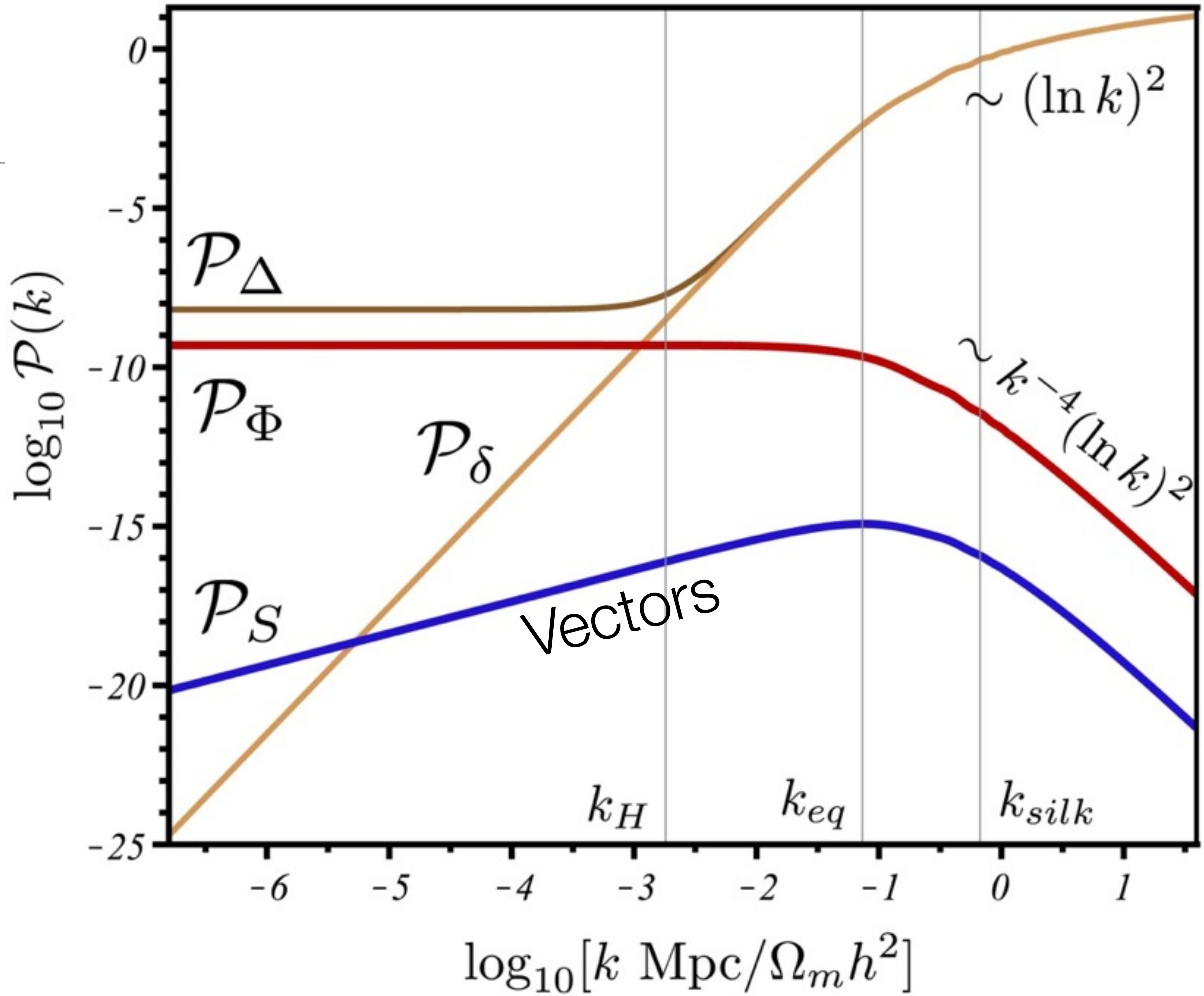
$$ds^2 = -\left[1 + 2\Phi + \Phi^{(2)}\right] dt^2 - aV_i dx^i dt + a^2 \left[(1 - 2\Phi - \Psi^{(2)})\gamma_{ij} + h_{ij}\right] dx^i dx^j$$

- first-order potential: $\ddot{\Phi} + 4H\dot{\Phi} + \Lambda\Phi = 0$

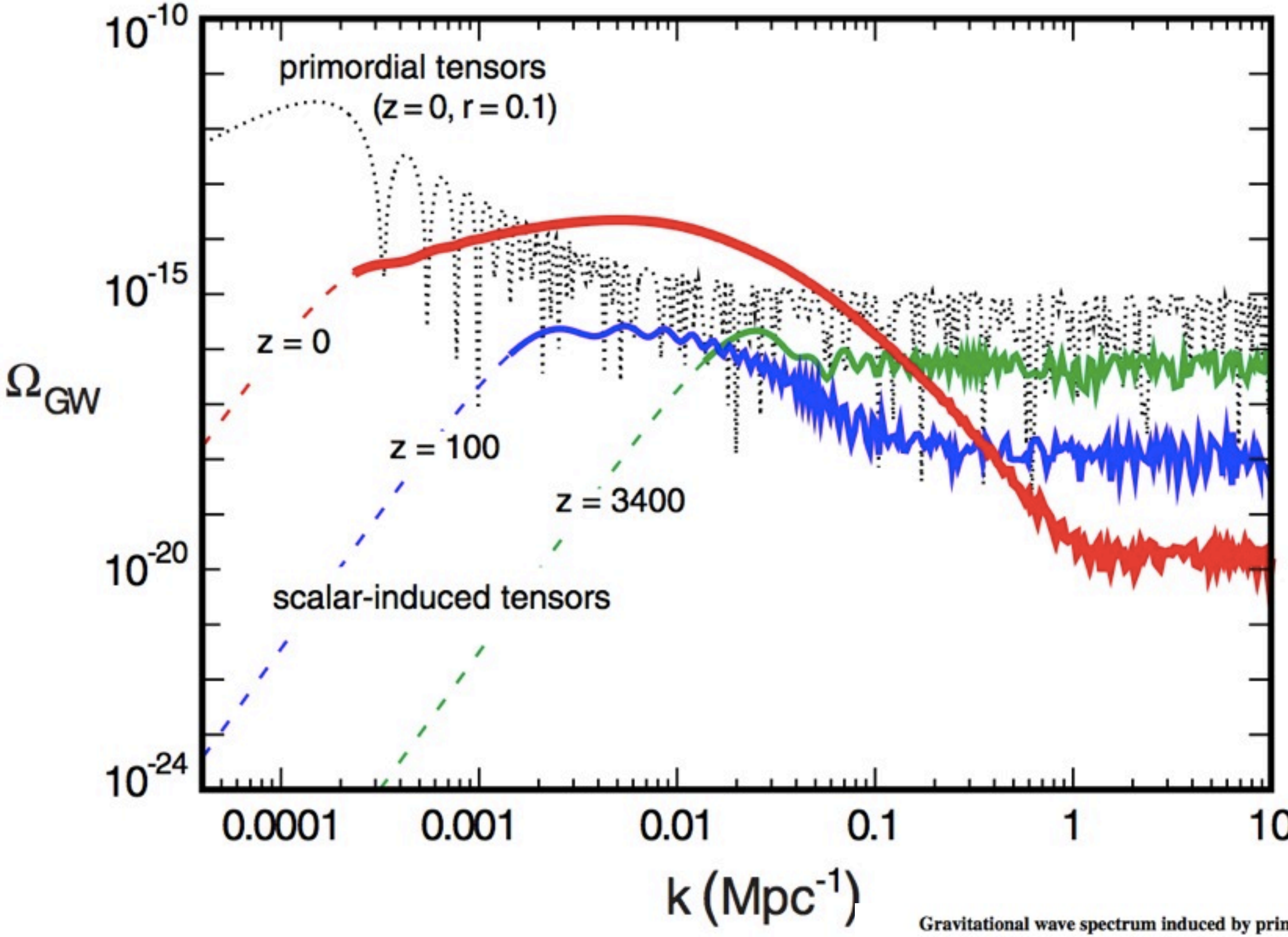
- second-order potentials:

$$\Phi^{(2)} \simeq \Psi^{(2)} \sim (\partial\Phi)^2 \qquad V_i \sim \Phi\partial_i\Phi \qquad h_{ij} \sim \Phi\partial_i\partial_j\Phi$$

- backreaction is concerned with the homogeneous, average contributions



0
-5
-10
-15
-20
-25
-6
-5
-4
-3
-2
-1
0
1
$\log_{10} \mathcal{P}(k)$
$\log_{10}[k \text{ Mpc}/\Omega_m h^2]$
$\mathcal{P}_\Delta$
$\mathcal{P}_\Phi$
$\mathcal{P}_\delta$
$\mathcal{P}_S$
Vectors
$\sim (\ln k)^2$
$\sim k^{-4} (\ln k)^2$
k_H
k_{eq}
k_{silk}



Gravitational wave spectrum induced by primordial scalar perturbations

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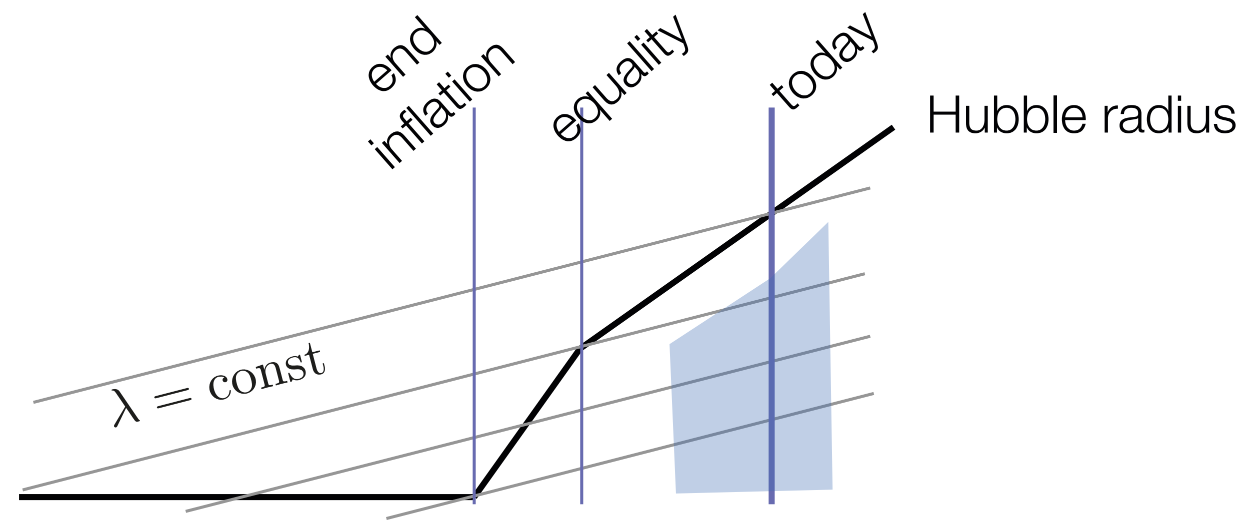
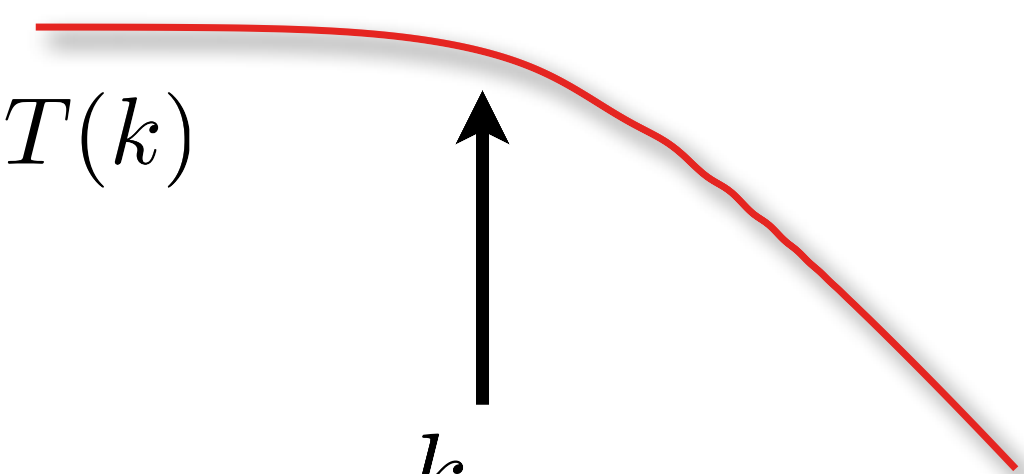
scaling behaviour at first-order



$$\mathcal{P}_\Phi \sim \Delta^2_{\mathcal{R}} T(k)^2$$

$$2.4 \times 10^{-9}$$

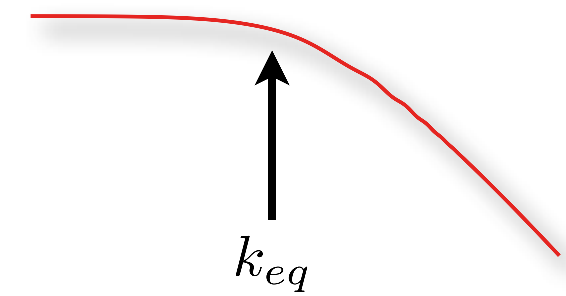
$T(k)$



k_{eq}

scale increasing

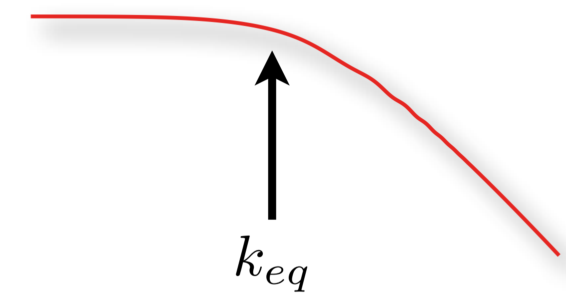
amplitude of second-order contributions



$$\overline{\partial^m \Phi \, \partial^n \Phi} \sim \int_0^\infty \frac{\mathrm{d}k}{k} \, k^{m+n} \mathcal{P}_\Phi(k)$$

$$\sim \Delta_{\mathcal{R}}^2 \left(\frac{k_{eq}}{k_H} \right)^{m+n} \underbrace{\int_0^\infty \mathrm{d}\kappa \, \kappa^{m+n-1} T(\kappa)^2}$$

amplitude of second-order contributions



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$$\approx \begin{array}{cl} -\ln(\kappa_{\mathrm{IR}}) & \text{for} \quad m+n=0 \\ 3.9 & \text{for} \quad m+n=2 \\ 53\ln^3(\kappa_{\mathrm{UV}}) & \text{for} \quad m+n=4 \end{array}$$

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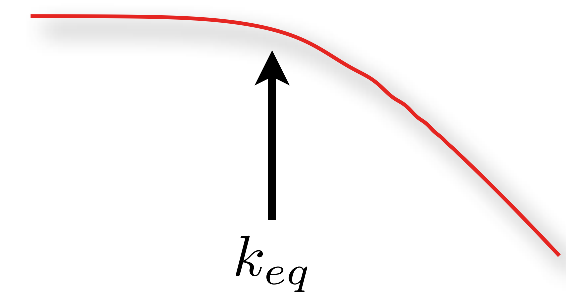

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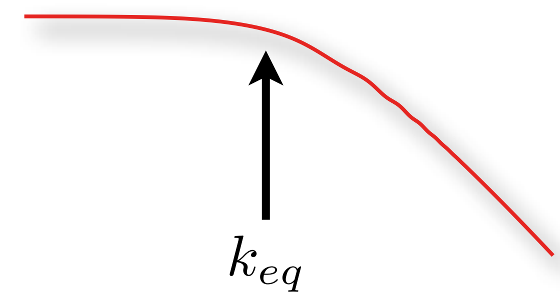

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large equality scale suppresses backreaction - but overcomes factors of Delta

backreaction

- second-order modes give non-trivial backreaction
- Hubble rate depends on

$$\mathrm{H}^{(2)} \sim [\cdots]\Phi^2 + [\cdots](\partial\Phi)^2 + [\cdots]\Phi^{(2)}$$

  - UV divergent terms don’t contribute on average
  - well defined and well behaved backreaction
- this is *only* well behaved because of the long radiation era
  - what would we do if the equality scale were smaller?

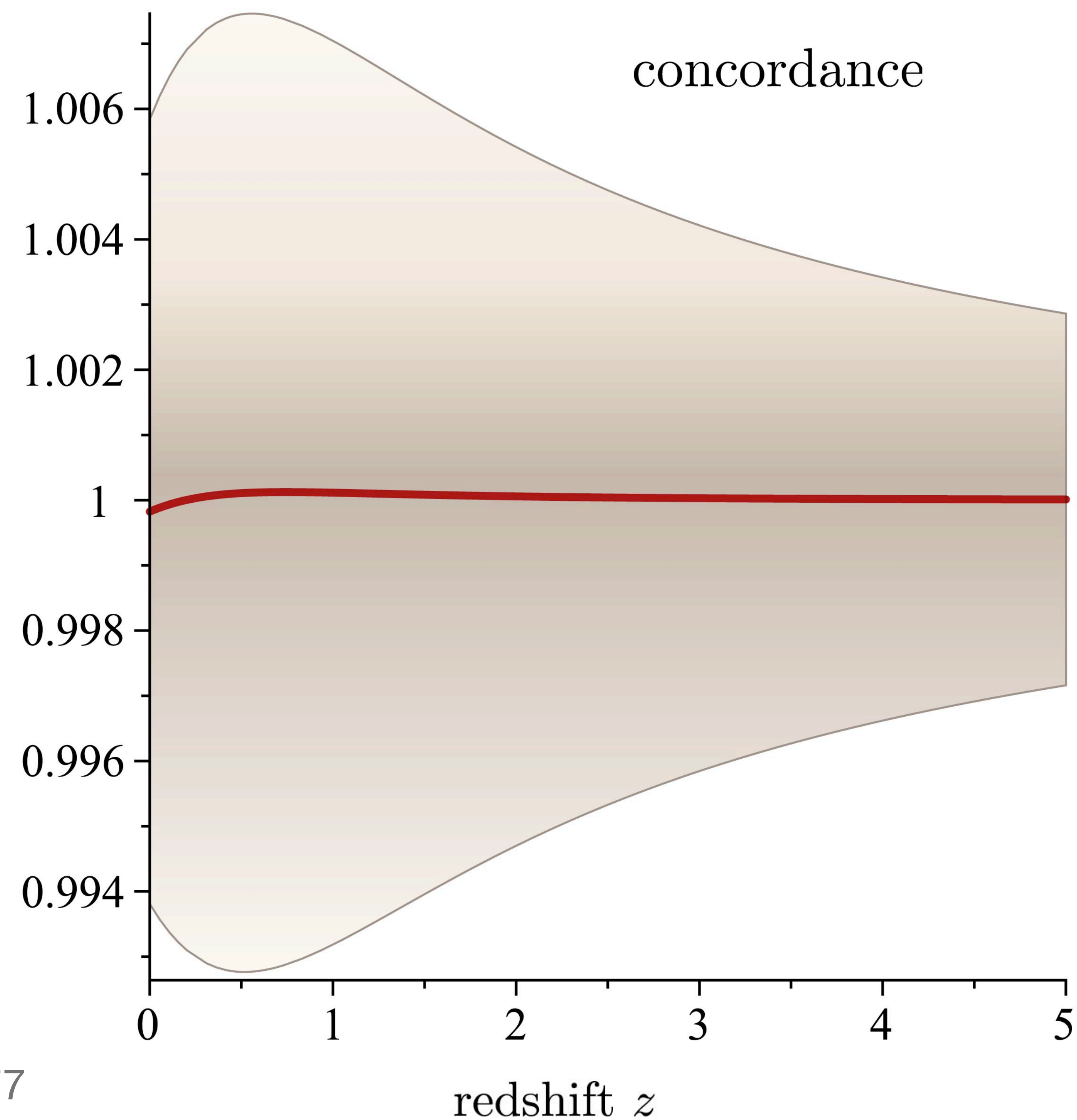
Change to the Hubble rate at second-order

Normalised Hubble rate
as function of redshift

from averaging Friedmann
equation

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

equality scale domain



Clarkson, Ananda & Larena, 0907.3377

backreaction

- other quantities are much stranger
- time derivative of the Hubble rate represented in the deceleration parameter

$$q^{(2)} \sim [\cdots]\Phi^2 + [\cdots](\partial\Phi)^2 + [\cdots]\Phi^{(2)} + \cdots + [\cdots](\partial^2\Phi)^2$$

  - same types of things appear in q defined via distance-redshift relation
  - UV divergent terms do not cancel out

divergent terms

$$\overline{\partial^2\Phi\,\partial^2\Phi} \quad \sim \quad \Delta^2_{\mathcal{R}}\left(\frac{k_{eq}}{k_H}\right)^4 \ln^3\frac{k_{UV}}{k_{eq}}$$

divergent terms

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$$\downarrow$$

$\mathcal{O}(1)$ prefactor

divergent terms

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$\mathcal{O}(1)$ prefactor

k_{UV} should be $< \mathcal{O}(\mathrm{pc})$
from end of inflation
which makes this huge

wtf?

ignore them - probably gauge or unphysical ?

where else could they appear?

fourth-order perturbation theory ... ?

$$(\Phi\partial^2\Phi)^2 \longrightarrow (\partial^2\Phi)^2 \text{ terms}$$

Hubble rate at fourth-order

$$\frac{H^{(4)}}{H} \sim -\frac{16}{729\Omega_m^4}\left(1+3\hat{g}+3\hat{g}^2+\hat{g}^3\right)\tilde{\partial}_k\Phi\tilde{\partial}^k\Phi\tilde{\partial}_j\tilde{\partial}^2\Phi\tilde{\partial}^j\Phi$$

$$+\frac{8}{243\Omega_m^4}\left[3(1-\hat{g}^2-2\hat{g}^3)+\Omega_m(27-67\hat{g}+30\hat{g}^2)\right]\tilde{\partial}_k\Phi\tilde{\partial}^k\Phi\tilde{\partial}^2\Phi\tilde{\partial}^2\Phi$$

$$-\frac{16}{243\Omega_m^4}\left[2(1+3\hat{g}+3\hat{g}^2+\hat{g}^3)+7\Omega_m(1+\hat{g})\right]\tilde{\partial}_k\Phi\tilde{\partial}_k\tilde{\partial}_j\Phi\tilde{\partial}^j\Phi\tilde{\partial}^2\Phi$$

$$+\frac{1}{81\Omega_m^3}\left(\tilde{\partial}_k\tilde{\partial}^2\Psi^{(2)}-\tilde{\partial}_k\tilde{\partial}^2\Phi^{(2)}\right)\left(H\tilde{\partial}^k\Phi^{(2)}+\tilde{\partial}^k\dot{\Psi}^{(2)}\right)$$

$$+\text{ terms of the form: }\ \Phi^{(4)},\ \partial_k v^k_{(4)},\ \partial_k\Phi\partial^k\Phi\partial^2\Phi^{(2)},$$

$$\partial_k\partial^2\Phi^{(3)}\partial^k\Phi,\quad \partial^2\Phi\partial^i\Phi\partial_i\Phi^{(2)},\quad \partial_k\Phi^{(2)}\partial^k\Phi^{(2)},\ldots$$

plus contributions from induced vectors and tensors

Hubble rate at fourth-order

$$
\begin{aligned}
\frac{H^{(4)}}{H} \sim & -\frac{16}{729\Omega_m^4}\left(1+3\hat{g}+3\hat{g}^2+\hat{g}^3\right) \boxed{\tilde{\partial}_k\Phi\tilde{\partial}^k\Phi\tilde{\partial}_j\tilde{\partial}^2\Phi\tilde{\partial}^j\Phi} \\
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& + \text{terms of the form: } \Phi^{(4)},\ \partial_k v^k_{(4)},\ \partial_k\Phi\partial^k\Phi\partial^2\Phi^{(2)}, \\
& \partial_k\partial^2\Phi^{(3)}\partial^k\Phi,\quad \partial^2\Phi\partial^i\Phi\partial_i\Phi^{(2)},\quad \partial_k\Phi^{(2)}\partial^k\Phi^{(2)},\ldots \\
& \text{plus contributions from induced vectors and tensors}
\end{aligned}
$$

Hubble rate at fourth-order

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$$\sim \Delta_{\mathcal{R}}^4 \left(\frac{k_{eq}}{k_H}\right)^6 \times \ln^3 \frac{k_{UV}}{k_{eq}} \, .$$

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overcomes 3 factors of $\Delta_{\mathcal{R}}$

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with $k_{UV} \sim 1\mathrm{pc}^{-1}$ this $\sim 1/\Delta_{\mathcal{R}}$

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fourth-order contribution could give change to background value

~~Conclusions~~ Confusions

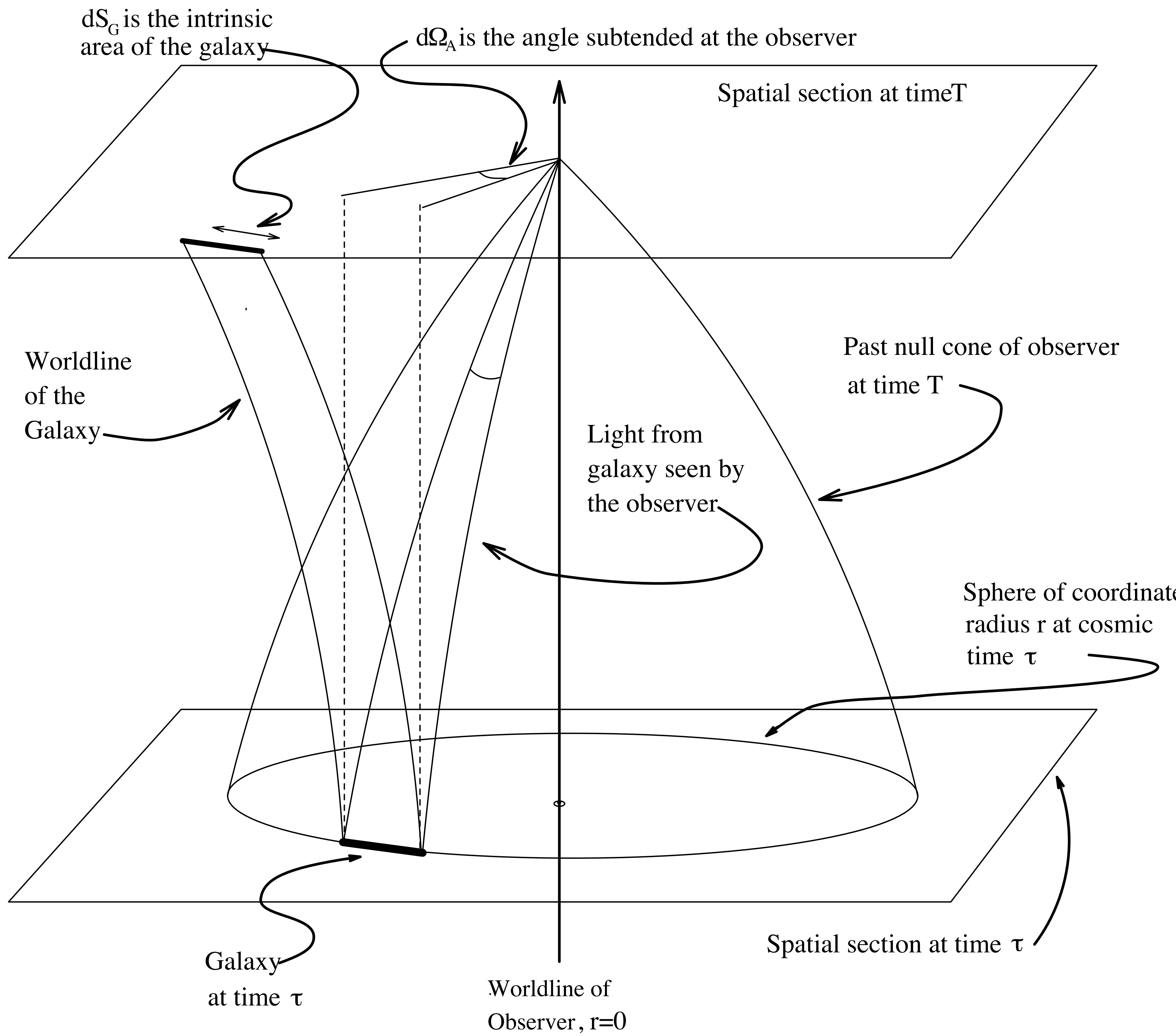
- Why are second-order perturbations so large?
- why is $\Delta_{\mathcal{R}} \left(\frac{k_{eq}}{k_H} \right)^2 \sim 1$?
- tells us that perturbation theory must be relativistic, not Newtonian
- role of UV divergence must be understood to decide whether backreaction is small - higher order or resummation methods needed? must include tensors!
- do we need relativistic N-body replacement?

worse ...

- All this assumes FLRW background spacetime
  - is this obvious?
  - can we demonstrate this observationally [scientifically]?
  - what do we know if we don't assume this?

large-scale inhomogeneity

radial inhomogeneity hard to distinguish from time evolution



Spherical Symmetry → void models

- within dust Lemaitre-Tolman-Bondi models - 2 free radial dof
  - can fit distance-redshift data to *any* FLRW DE model

Mustapha, Hellaby, & Ellis

Spherical Symmetry → void models

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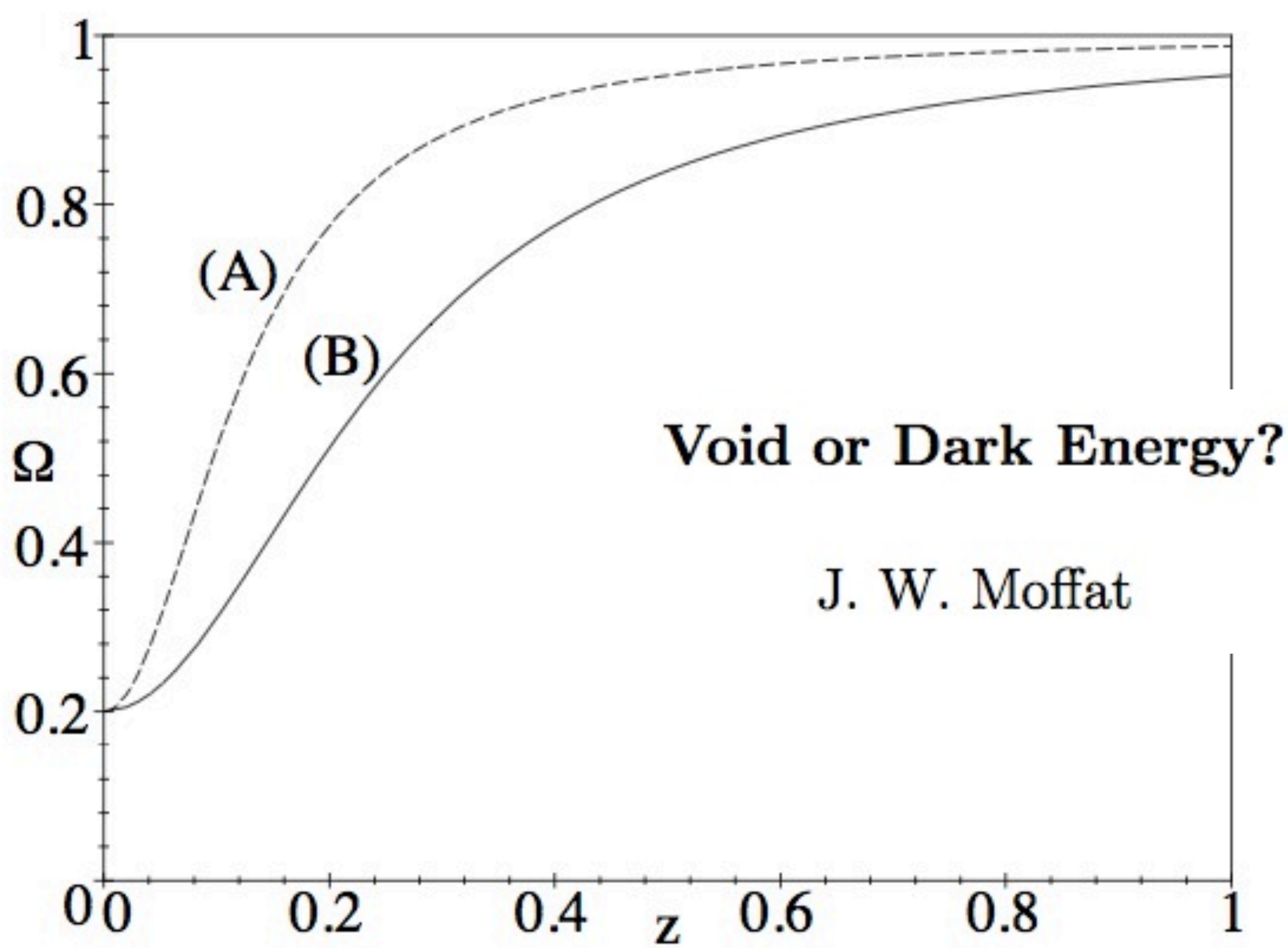

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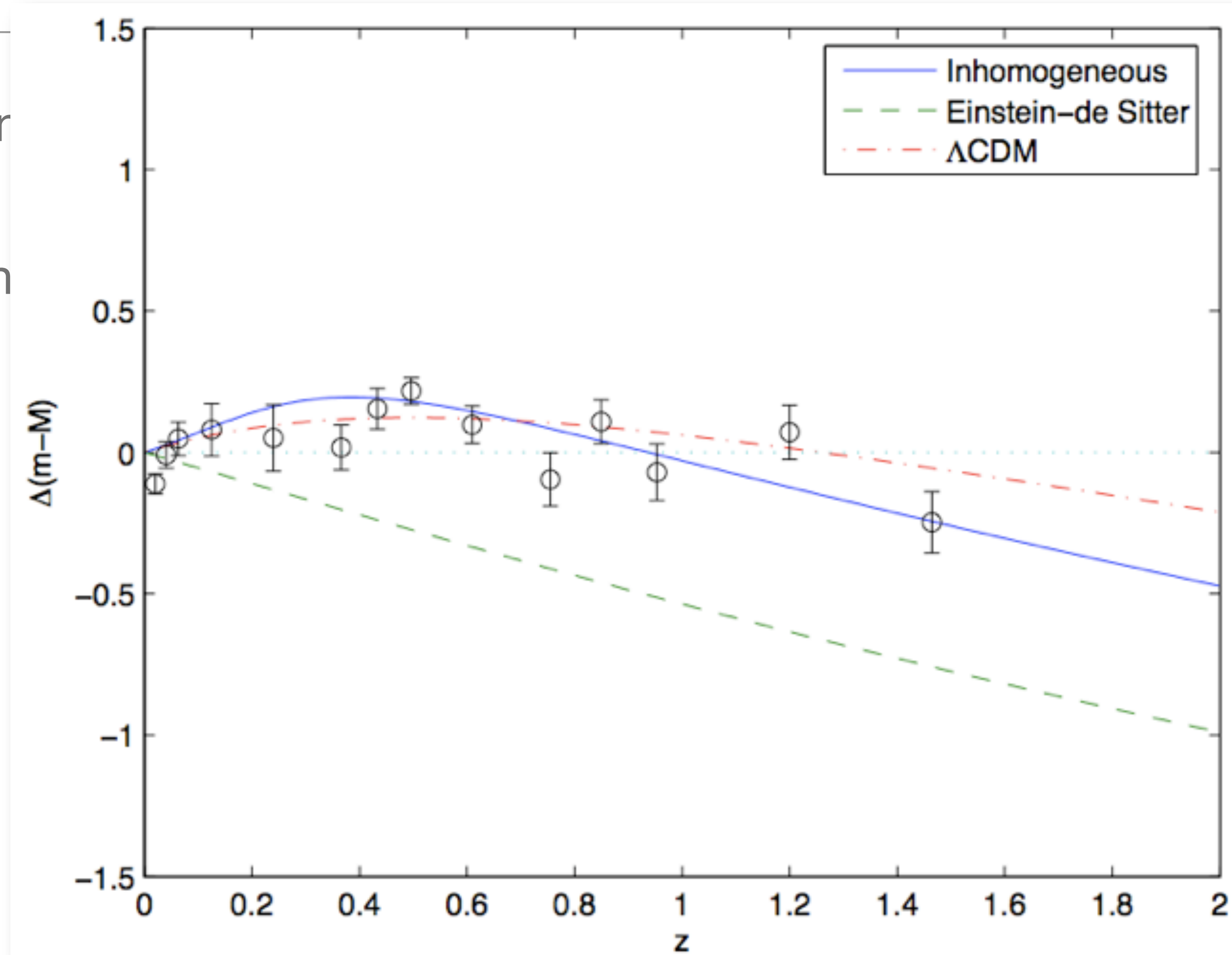
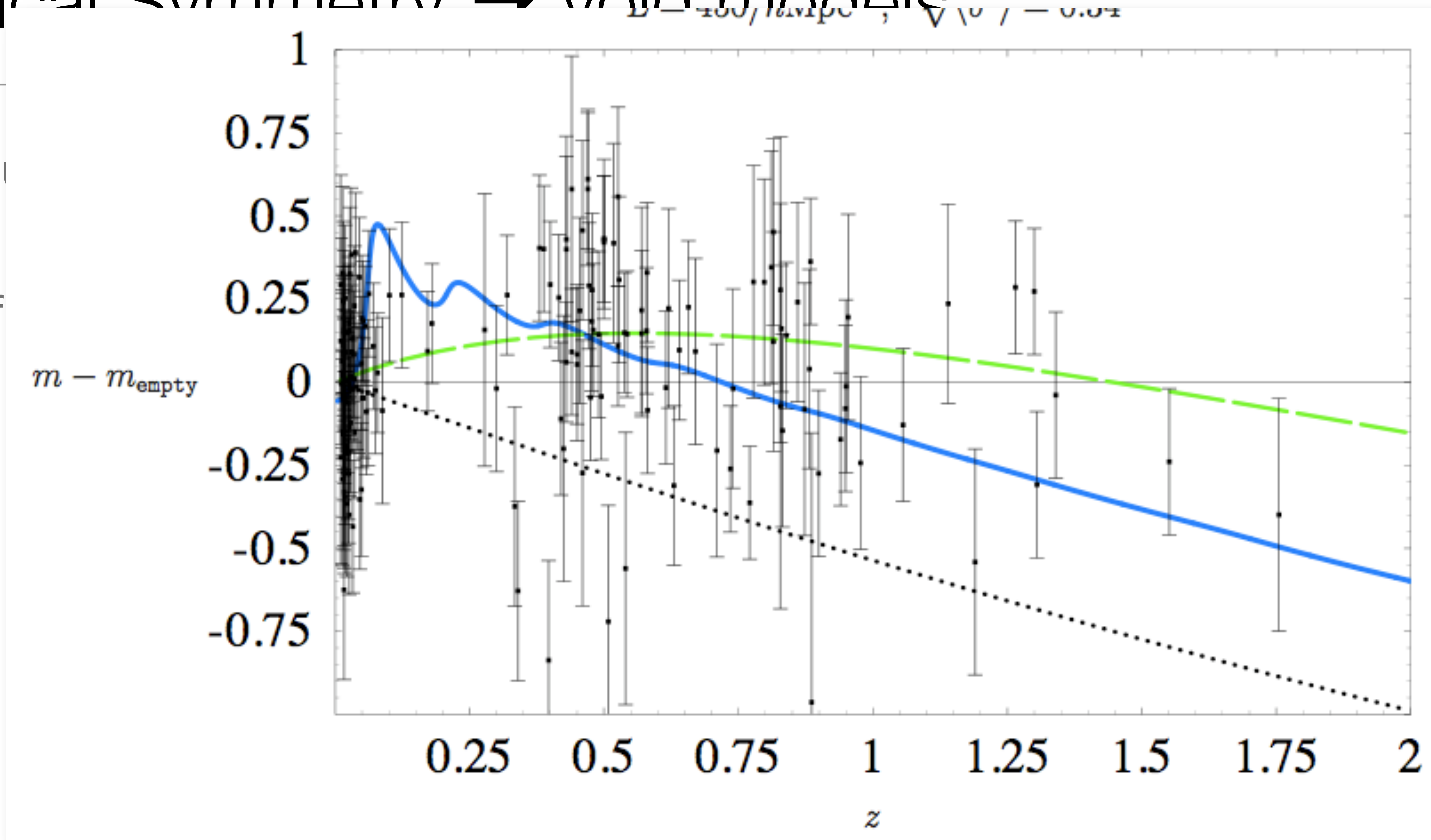


Alnes, Amarzguioui, and Gron astro-ph/0512006

Spherical Symmetry → void models

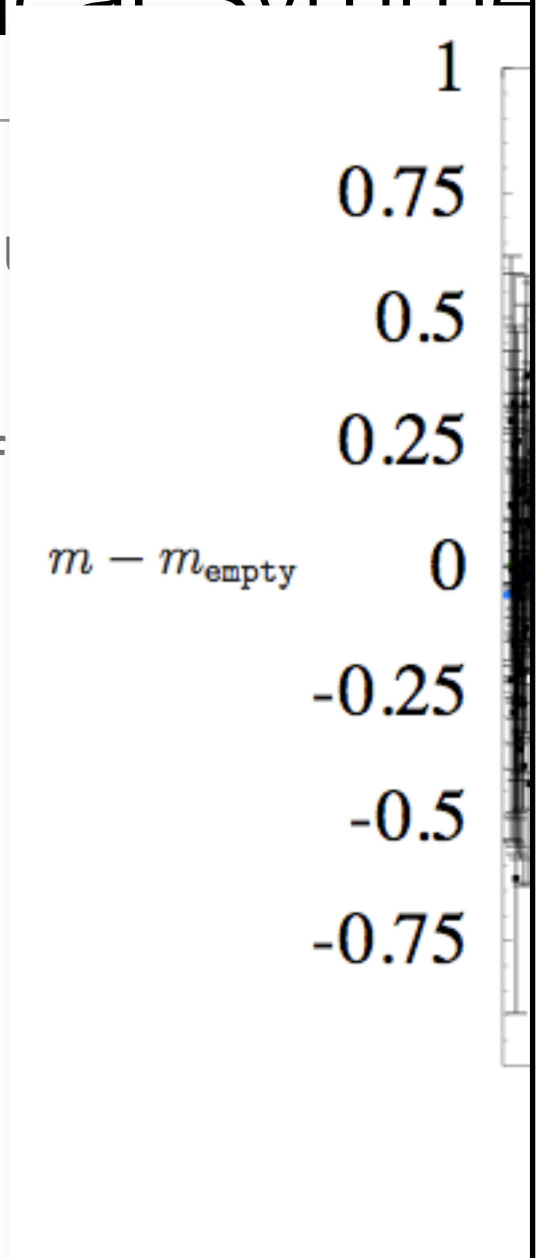
- within d
    - can f

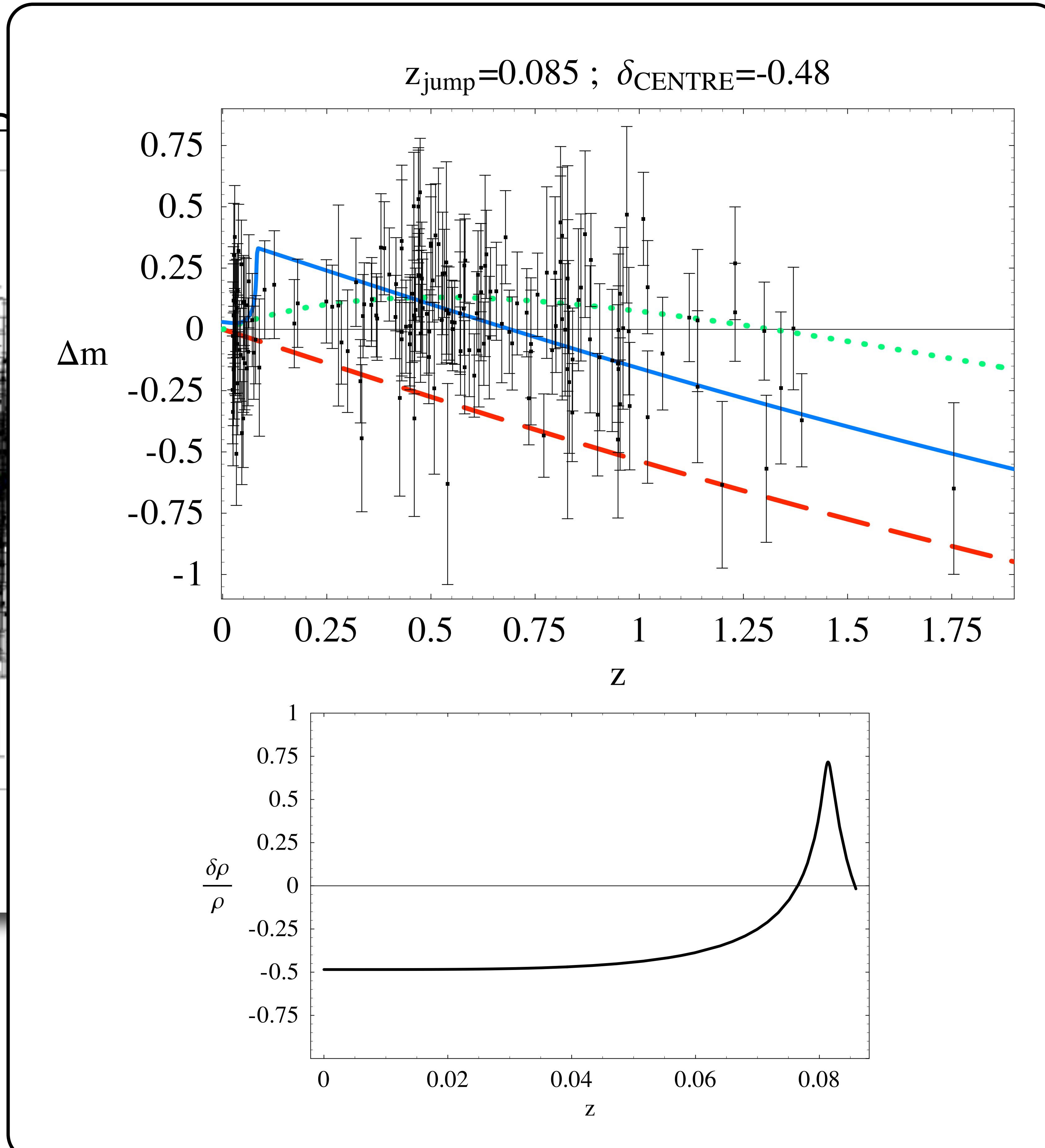


Biswas, Monsouri and Notari, astro-ph/0606703

Spherical Symme

- within d
  - can f





Spherical Symmetry → void models

- within d

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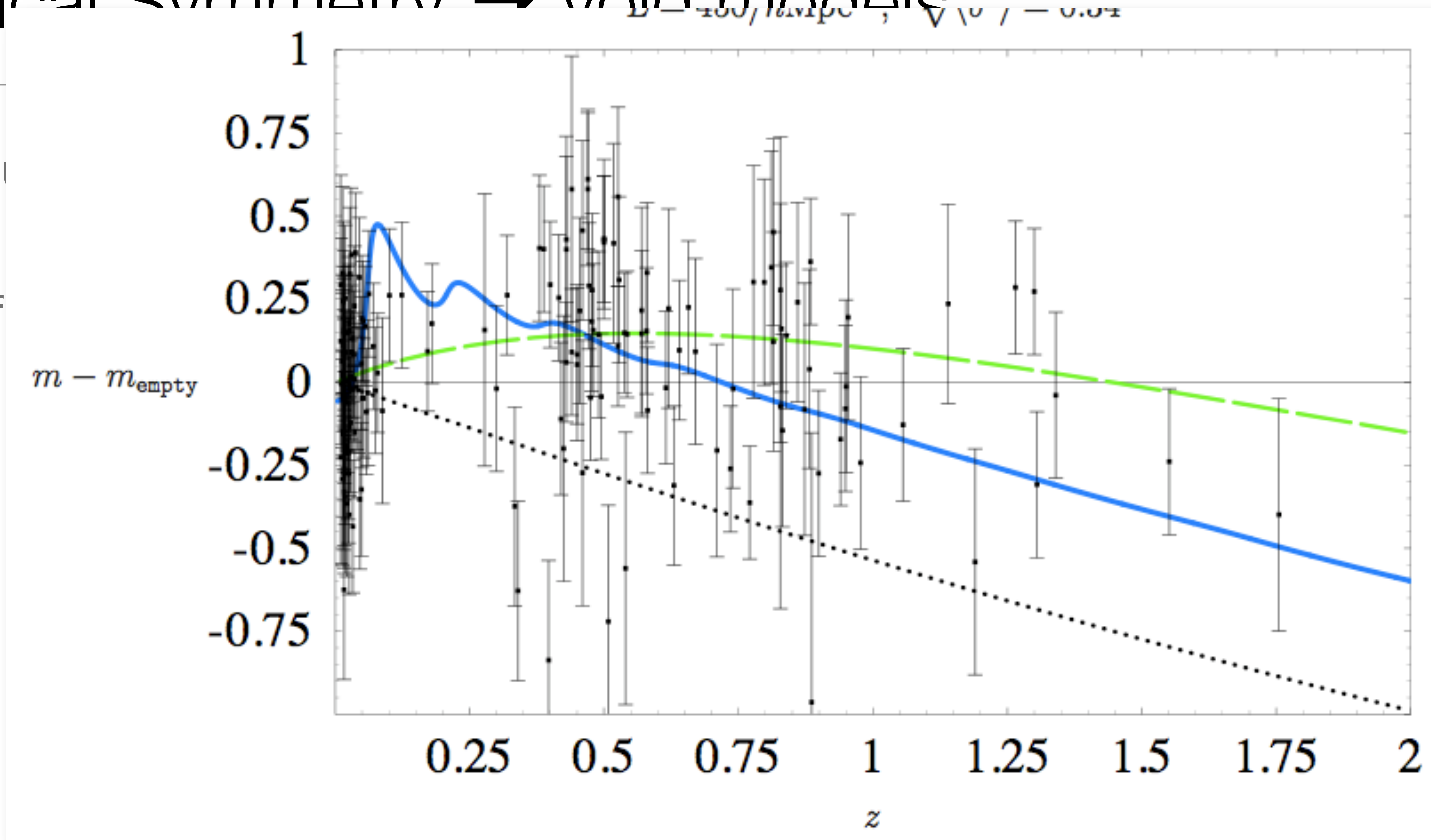

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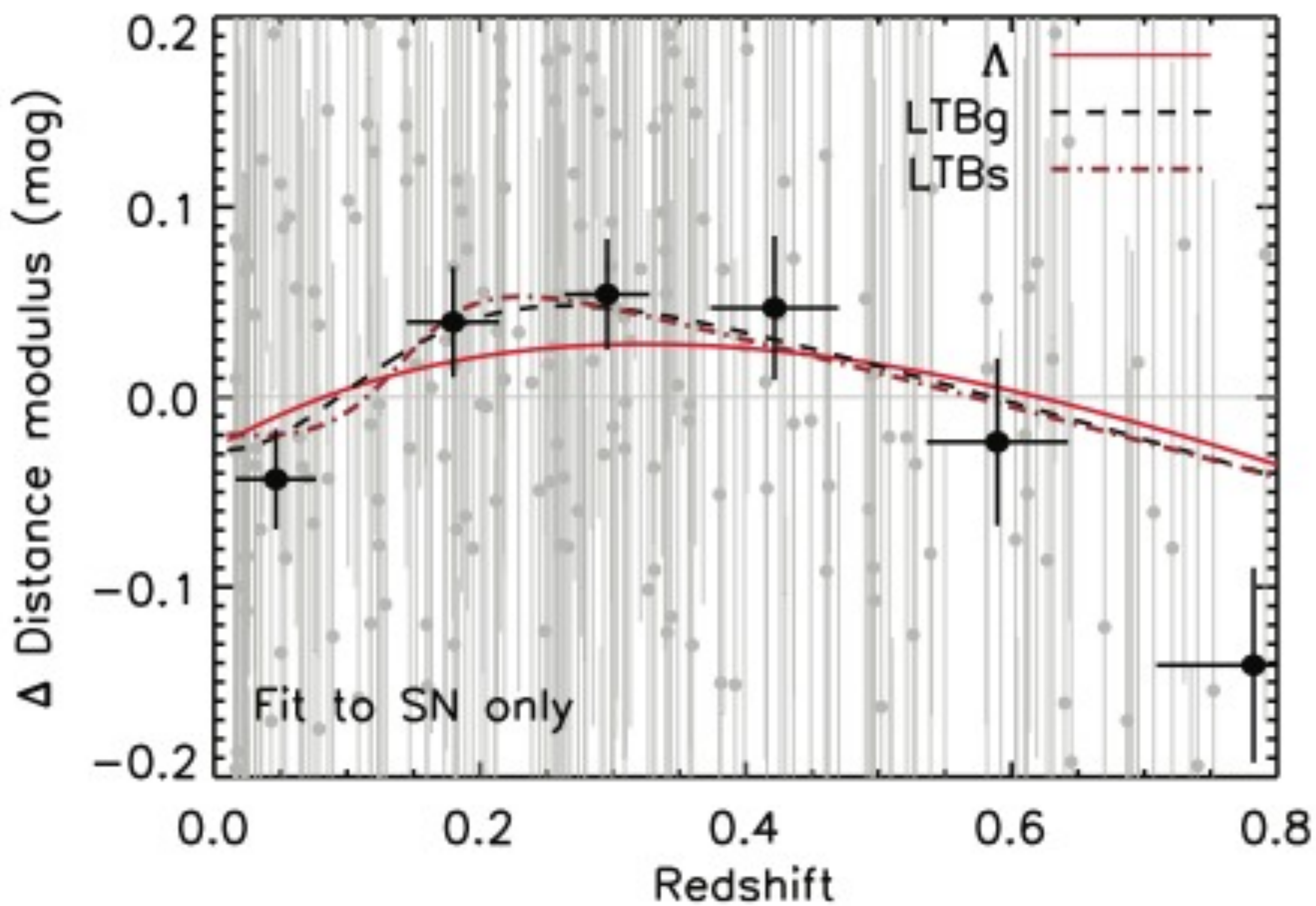
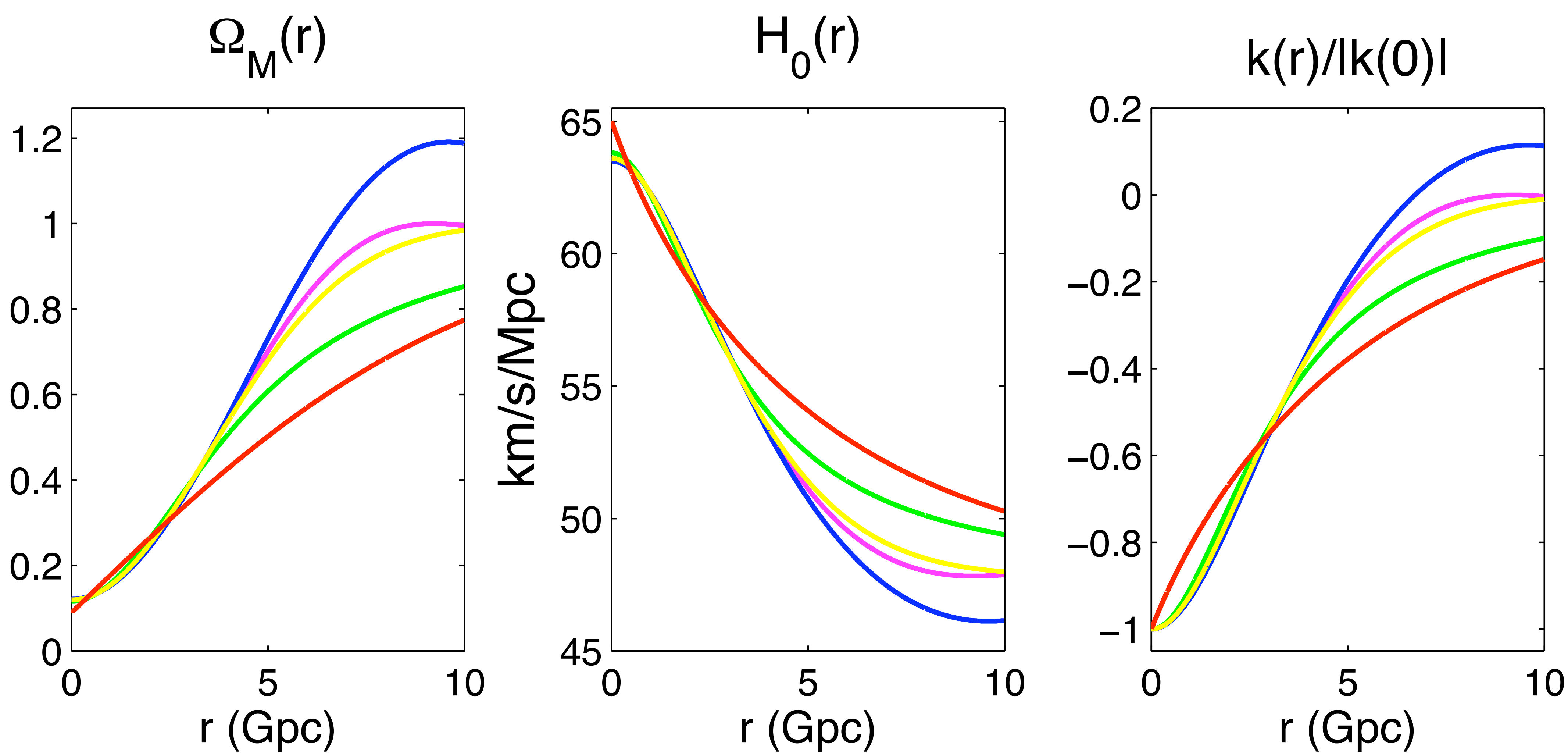
Spherical Symmetry → void models



First-Year Sloan Digital Sky Survey-II (SDSS-II) Supernova Results: Constraints on Non-Standard Cosmological Models

J. Sollerman, E. Mörtsell, T. M. Davis, M. Blomqvist, B. Bassett, A. C. Becker, D. Cinabro, A. V. Filippenko, R. J. Foley, J. Frieman, P. Garnavich, H. Lampeitl, J. Marriner, R. Miquel, R. C. Nichol, M. W. Richmond, M. Sako, D. P. Schneider, M. Smith, J. T. Vanderplas, J. C. Wheeler

Fitting Voids: to LCDM



indistinguishable from LCDM using distance measurements

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

Testing the Void against Cosmological data: fitting CMB, BAO, SN and H0

Tirthabir Biswas, Alessio Notari, Wessel Valkenburg

(Submitted on 19 Jul 2010)

In this paper, instead of invoking Dark Energy, we try and fit various cosmological observations with a large Gpc scale under-dense region (Void) which is modeled by a Lemaitre-Tolman-Bondi metric that at large distances becomes a homogeneous FLRW metric. We improve on previous analyses by allowing for nonzero overall curvature, accurately computing the distance to the last-scattering surface and the observed scale of the Baryon Acoustic peaks, and investigating important effects that could arise from having nontrivial Void density profiles. We mainly focus on the WMAP 7-yr data (TT and TE), Supernova data (SDSS SN), Hubble constant measurements (HST) and Baryon Acoustic Oscillation data (SDSS and LRG). We find that the inclusion of a nonzero overall curvature drastically improves the goodness of fit of the Void model, bringing it very close to that of a homogeneous universe containing Dark Energy, while by varying the profile one can increase the value of the local Hubble parameter which has been a challenge for these models. We also try to gauge how well our model can fit the large-scale-structure data, but a comprehensive analysis will require the knowledge of perturbations on LTB metrics. The model is consistent with the CMB dipole if the observer is about 15 Mpc off the centre of the Void. Remarkably, such an off-center position may be able to account for the recent anomalous measurements of a large bulk flow from kSZ data. Finally we provide several analytical approximations in different regimes for the LTB metric, and a numerical module for CosmoMC, thus allowing for a MCMC exploration of the full parameter space.

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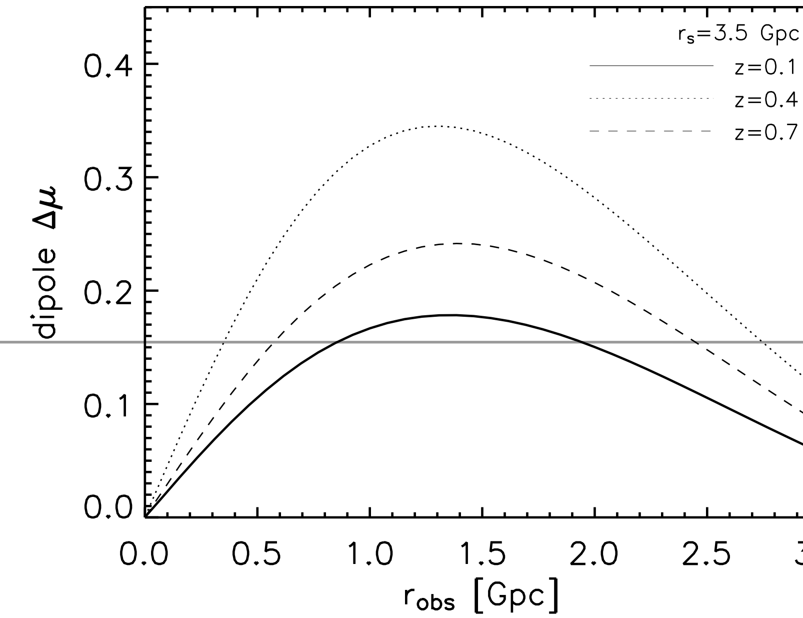
Precision Cosmology Defeats Void Models for Acceleration

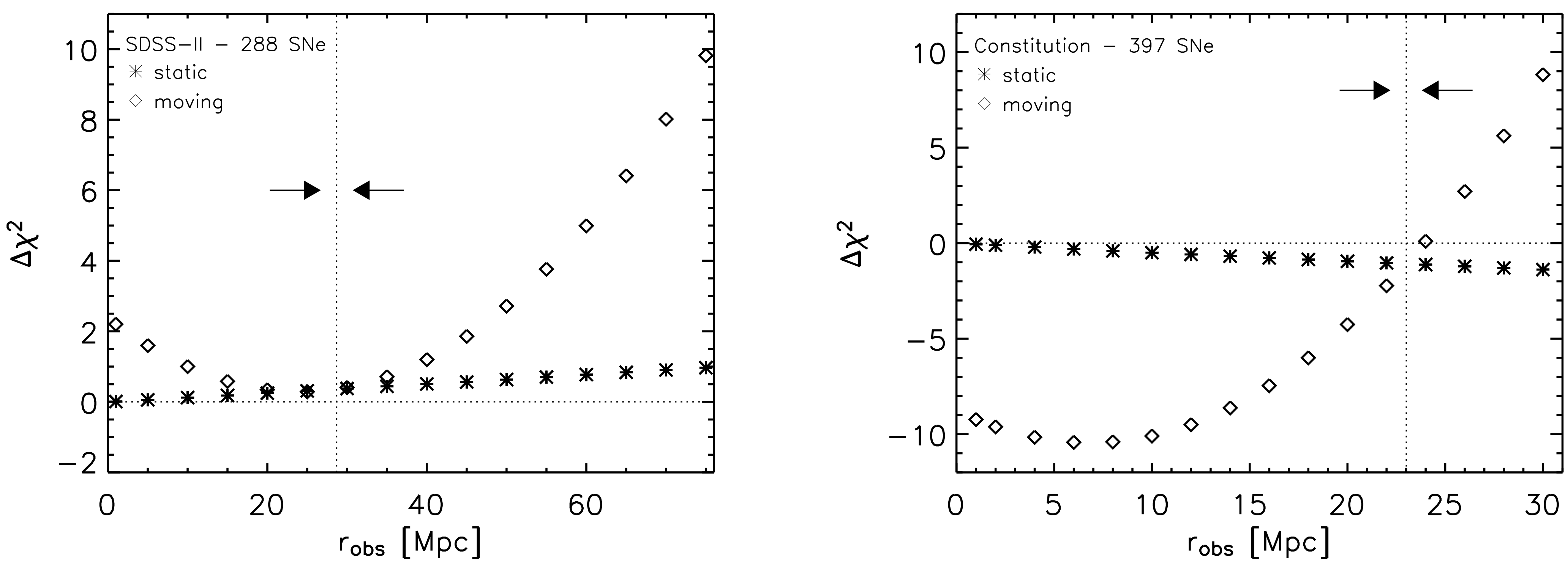
Adam Moss, James P. Zibin, Douglas Scott

(Submitted on 21 Jul 2010)

The suggestion that we occupy a privileged position near the centre of a large, nonlinear, and nearly spherical void has recently attracted much attention as an alternative to dark energy. Putting aside the philosophical problems with this scenario, we perform the most complete and up-to-date comparison with cosmological data. We use supernovae and the full cosmic microwave background spectrum as the basis of our analysis. We also include constraints from radial baryonic acoustic oscillations, the local Hubble rate, age, big bang nucleosynthesis, the Compton y-distortion, and for the first time include the local amplitude of matter fluctuations, \sigma_8. These all paint a consistent picture in which voids are in severe tension with the data. In particular, void models predict a very low local Hubble rate, suffer from an "old age problem", and predict much less local structure than is observed.

Fine tuned?

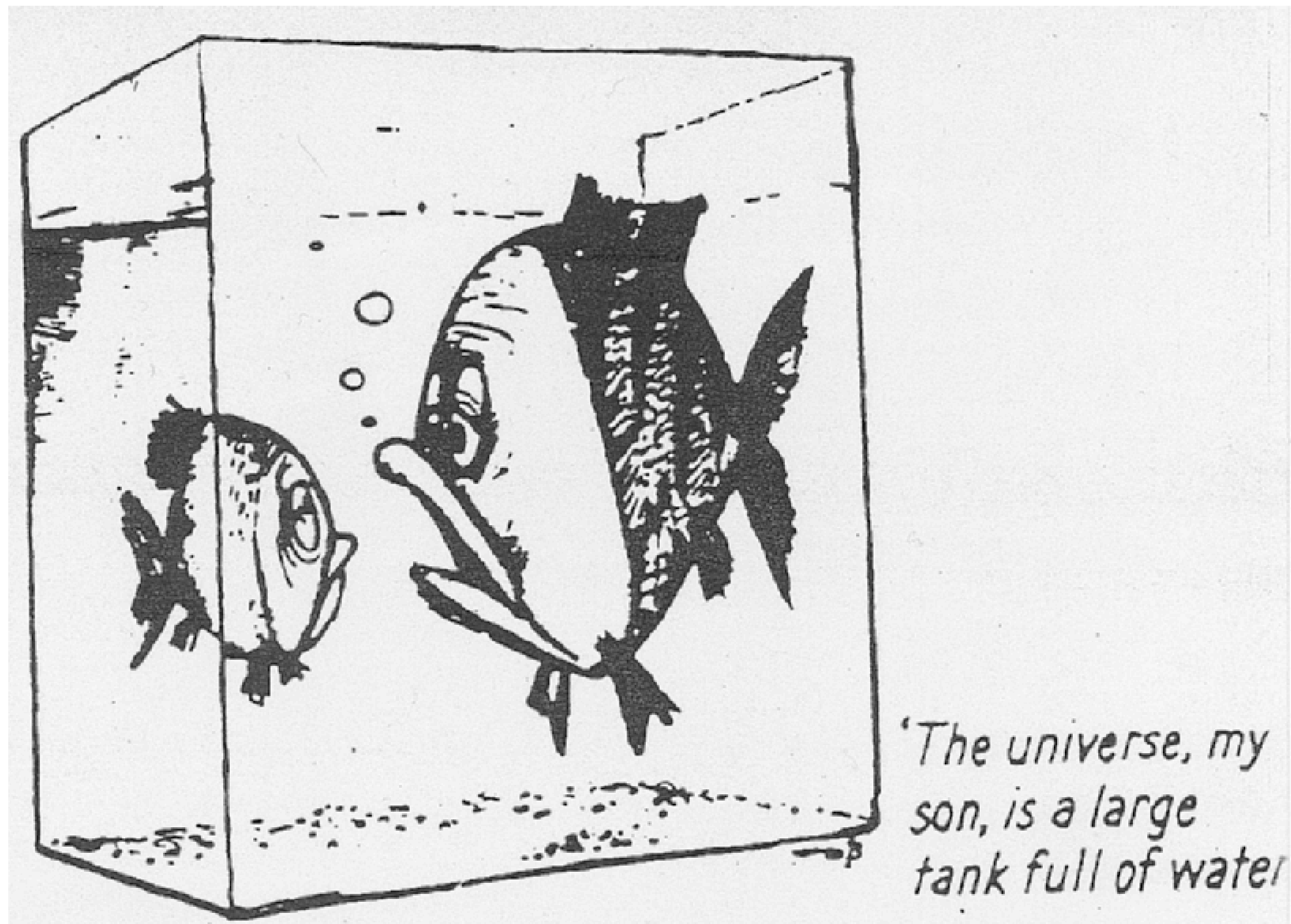




Supernovae as seen by off-center observers in a local void

Michael Blomqvist[1] and Edvard Mörtsell[2]

anti-Copernican



The Cosmological Principle

anti-Copernican

- Copernican P says we are not at special place in universe
- Λ introduced for misguided temporal CP ...
  - we don’t throw out the concordance model because of its coincidence problem - wait for better understanding

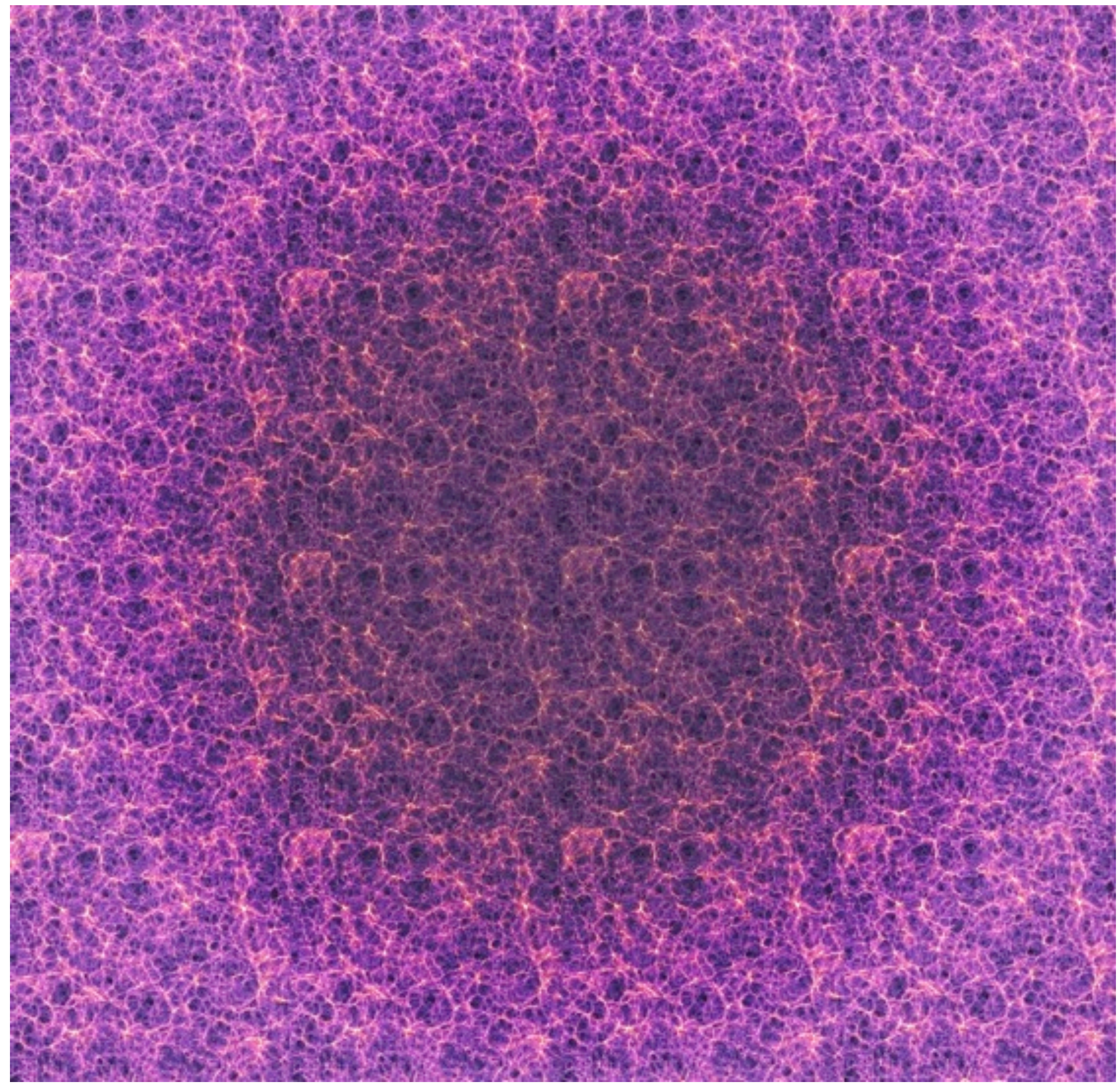
Are void models ridiculous?

- being ‘at the centre of the universe’ is crazy, but actually only a coincidence of
  1 in $10^{\sim 9}$ in our Hubble volume

- possible selection effects?

  - could high dark matter density inhibit solar system formation?
    must be stable for ~5Gyr

  - so, maybe not anti-Copernican ?

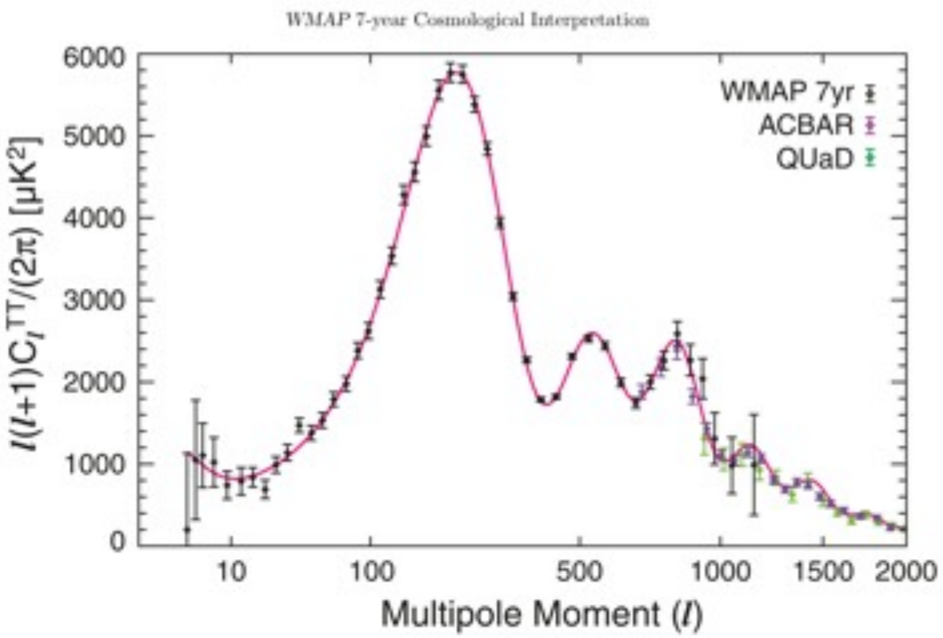


Isn’t this a bit silly?

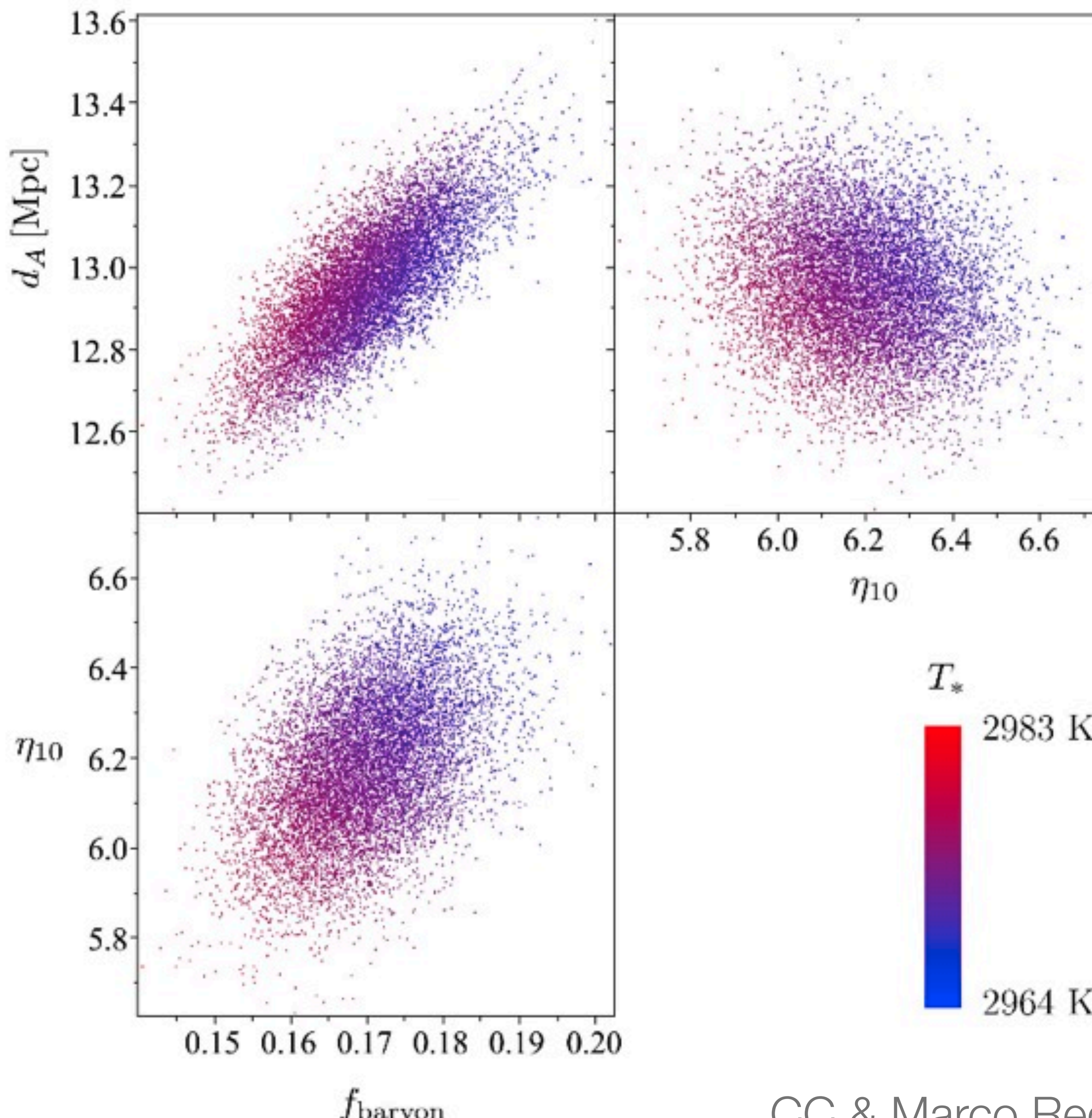
Isn’t this a bit silly?

- Yes
- But:
  - we should be able to rule void models out observationally - tests CP
  - helps make data ‘cosmology independent’ (eg, compare SNIa vs BAO)
  - provides alternative probe of coincidence problem which *can* be tested
    - unusual DE interpretation without LCDM as fixed point - only ‘DE’ model with *known* physics at late times
- can we construct a void which fits *all* observations? fine-tuned?

Small scale CMB



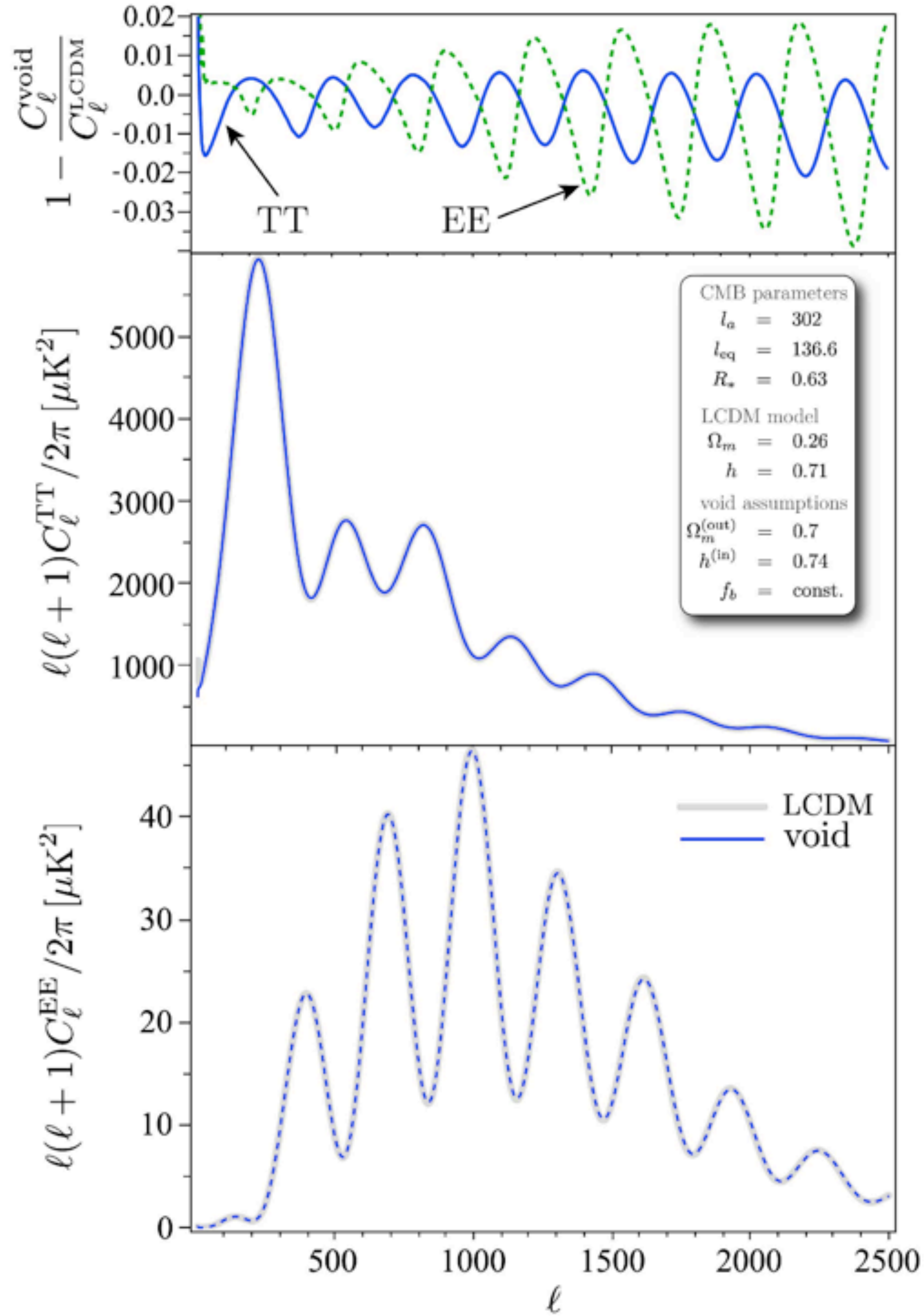
- high-l CMB fixes only:
  - baryon-photon ratio
  - baryon fraction
  - distance to last scattering



CC & Marco Regis

Small scale CMB

indistinguishable from LCDM



large-scale CMB, BAO, structure formation...

- ... all require perturbation theory
- unsolved!
- k-modes not independent - important for BAO

large-scale CMB, BAO, structure formation...

- ... all require perturbation theory

$$-\ddot{\chi} + \chi'' - 3H_{\parallel}\dot{\chi} - 2W\chi' + \left[16\pi\rho - \frac{6M}{a_{\perp}^{3}} - 4H_{\perp}(H_{\parallel} - H_{\perp}) - \frac{(\ell-1)(\ell+2)}{a_{\perp}^{2}r^{2}}\right]\chi$$
$$= -2(H_{\parallel} - H_{\perp})\varsigma' - 2\left[H_{\parallel}' - 2(H_{\parallel} - H_{\perp})W\right]\varsigma + 4(H_{\parallel} - H_{\perp})\dot{\varphi} - 2\left[8\pi\rho - \frac{3M}{a_{\perp}^{3}} - 2H_{\perp}(H_{\parallel} - H_{\perp})\right]\varphi,$$

$$\boxed{\ddot{\varphi} + 4H_{\perp}\dot{\varphi} - 2\left(\frac{1}{a_{\perp}^{2}r^{2}} - W^{2}\right)\varphi} = -H_{\perp}\dot{\chi} + W\chi' - \left[2W^{2} - \frac{\ell(\ell+1)+2}{2a_{\perp}^{2}r^{2}}\right]\chi + 2W(H_{\parallel} - H_{\perp})\varsigma,$$

$$\dot{\varsigma} + 2H_{\parallel}\varsigma = -\chi',$$

- unsolved!

- k-modes not independent - important for BAO

large-scale CMB, BAO, structure formation...

- ... all require perturbation theory

- unsolved!

- k-modes not independent - important for BAO

Looking inside our past lightcone

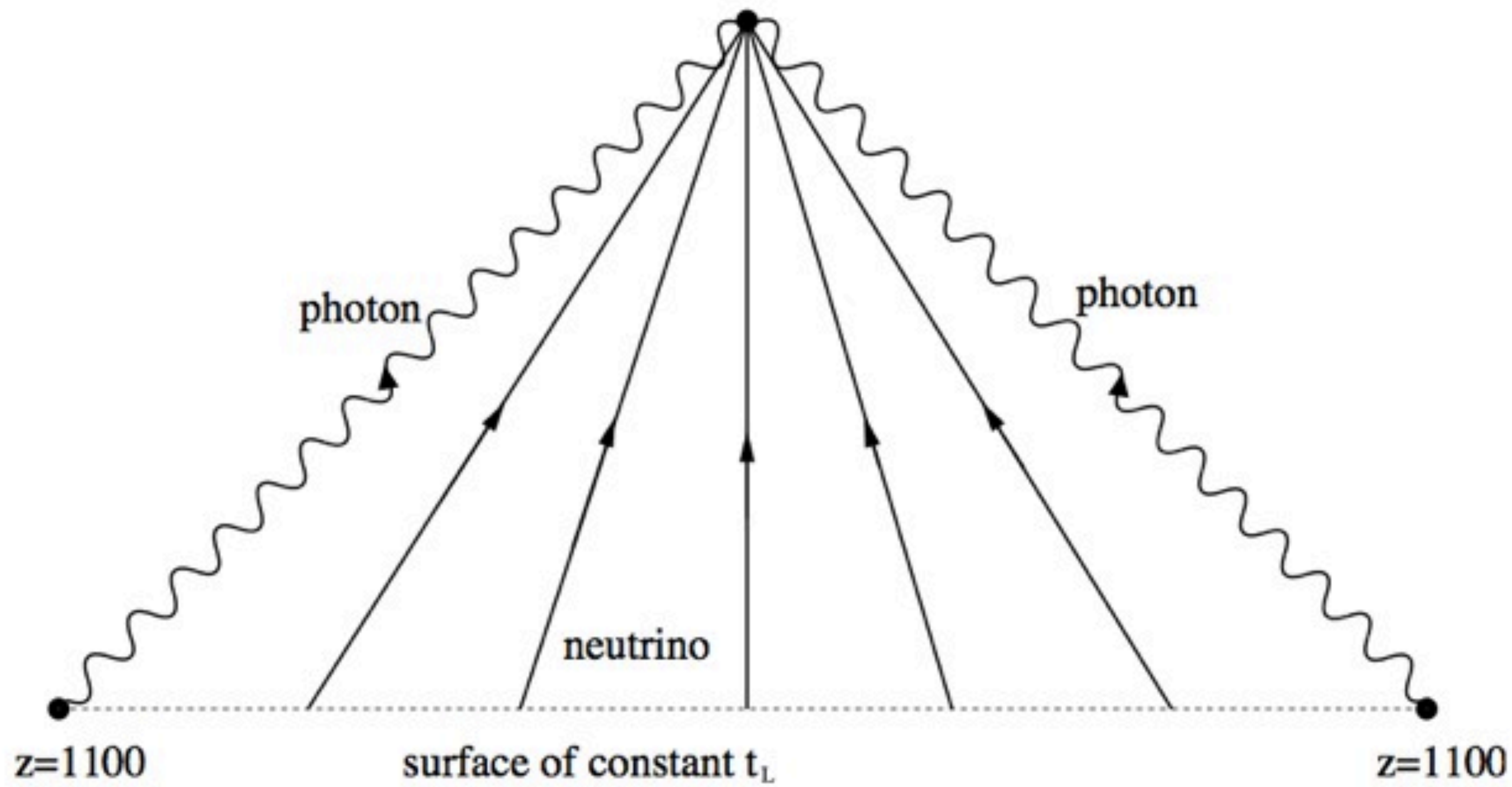


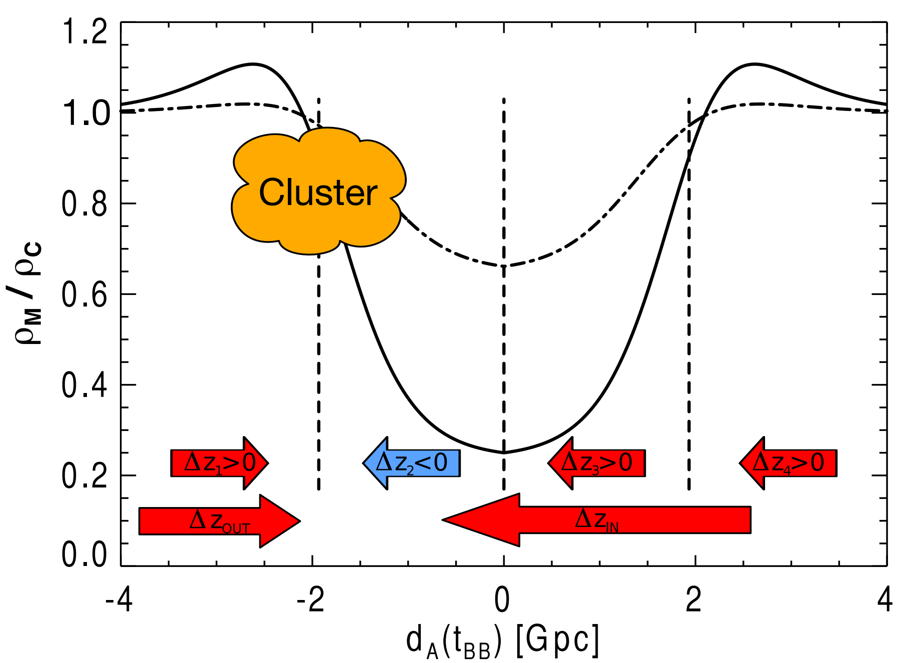
Figure 1: *Different from the cosmic photons, the cosmic neutrinos of different energies come from the different places on the surface of constant t_L and travel to us along the different worldlines.*

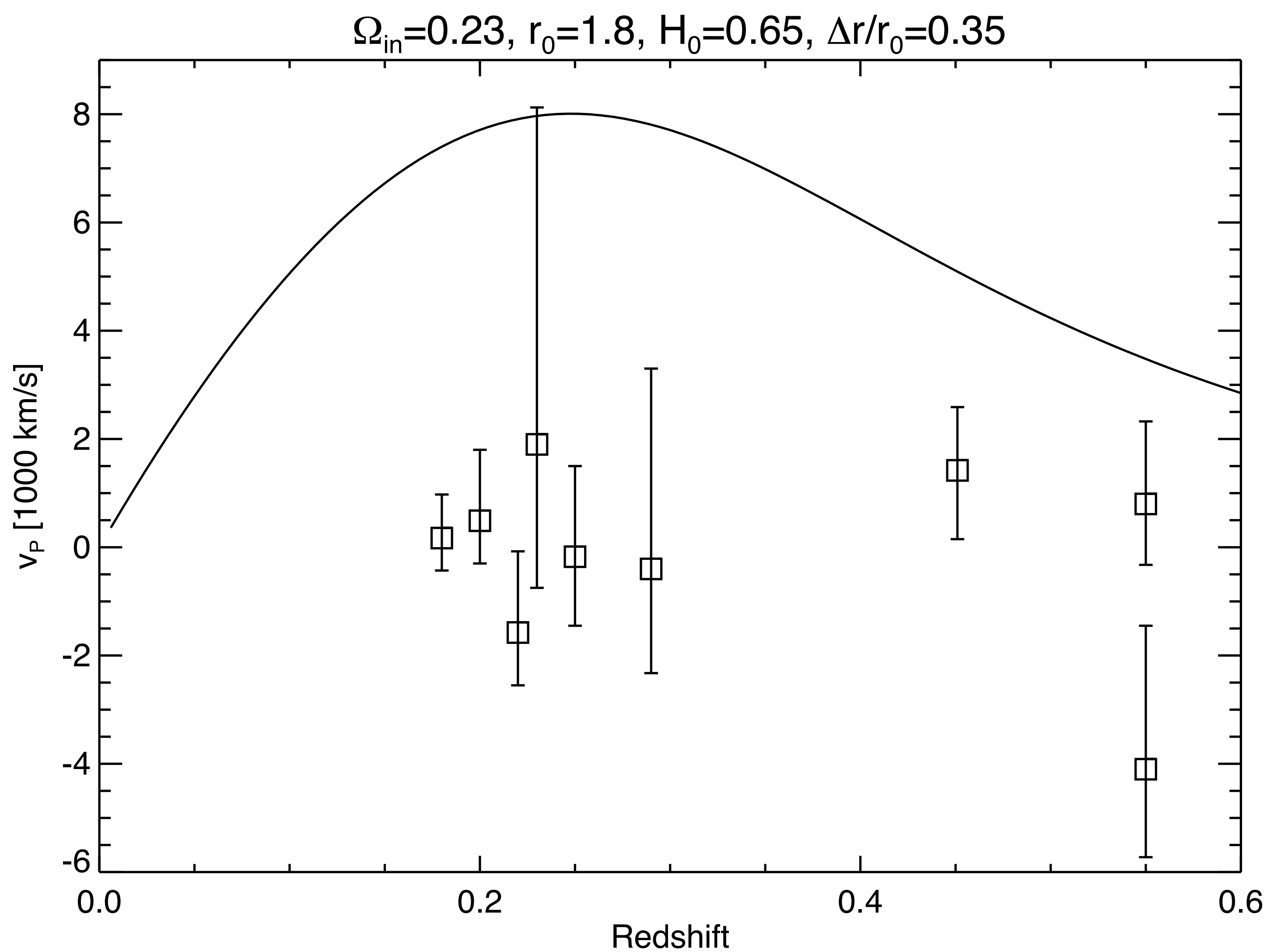
Can the Copernican principle be tested by cosmic neutrino background?

Junji Jia, Hongbao Zhang

Looking inside our past lightcone

- 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]

Looking inside our past lightcone

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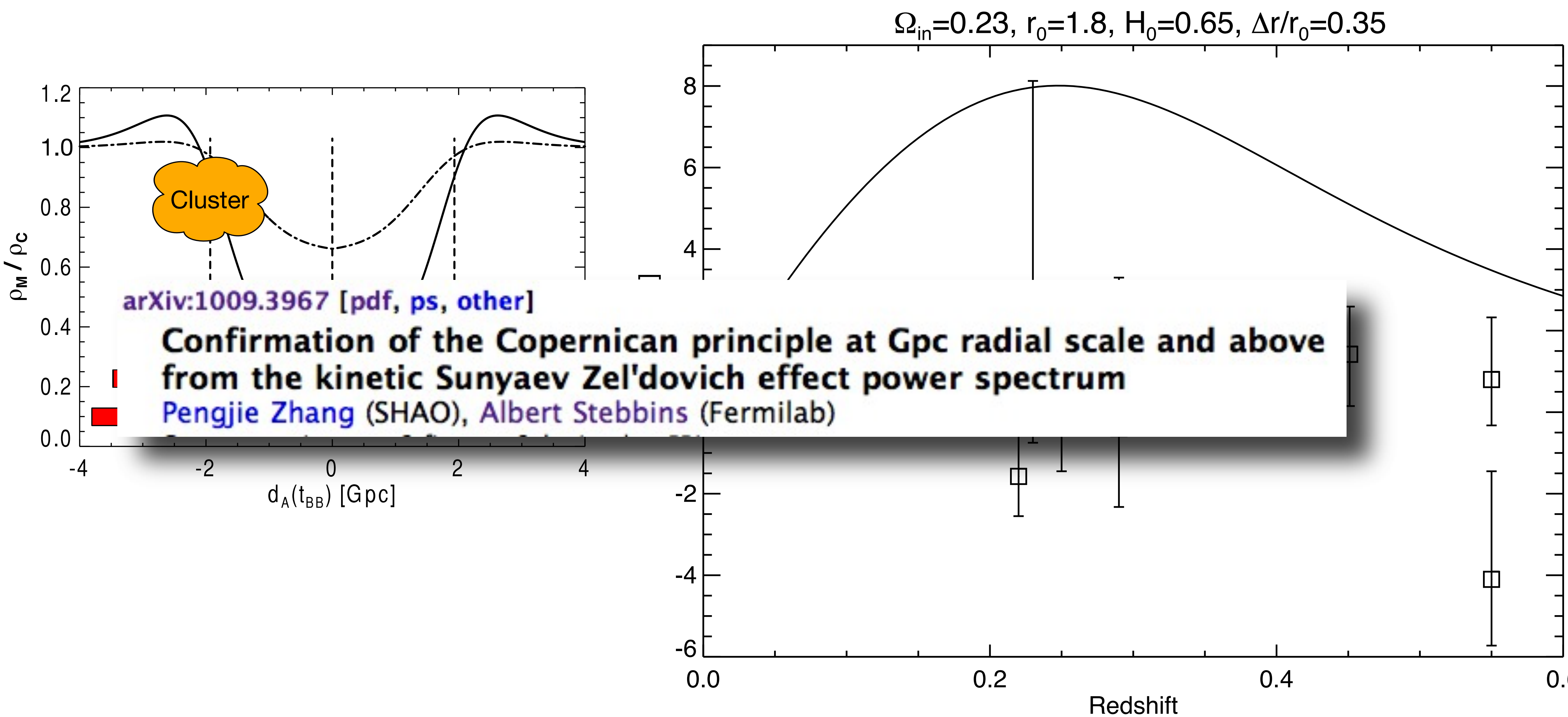

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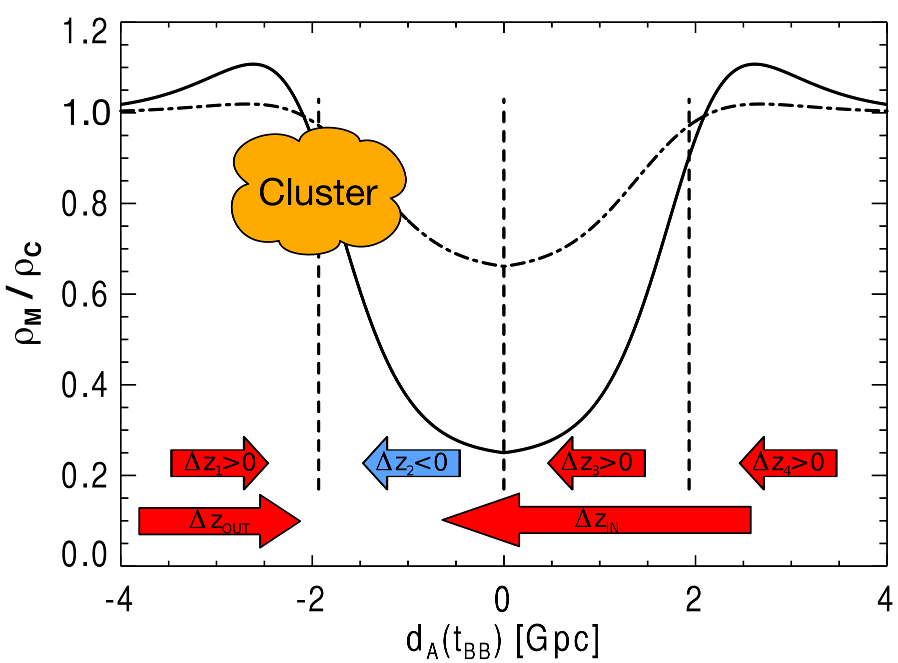

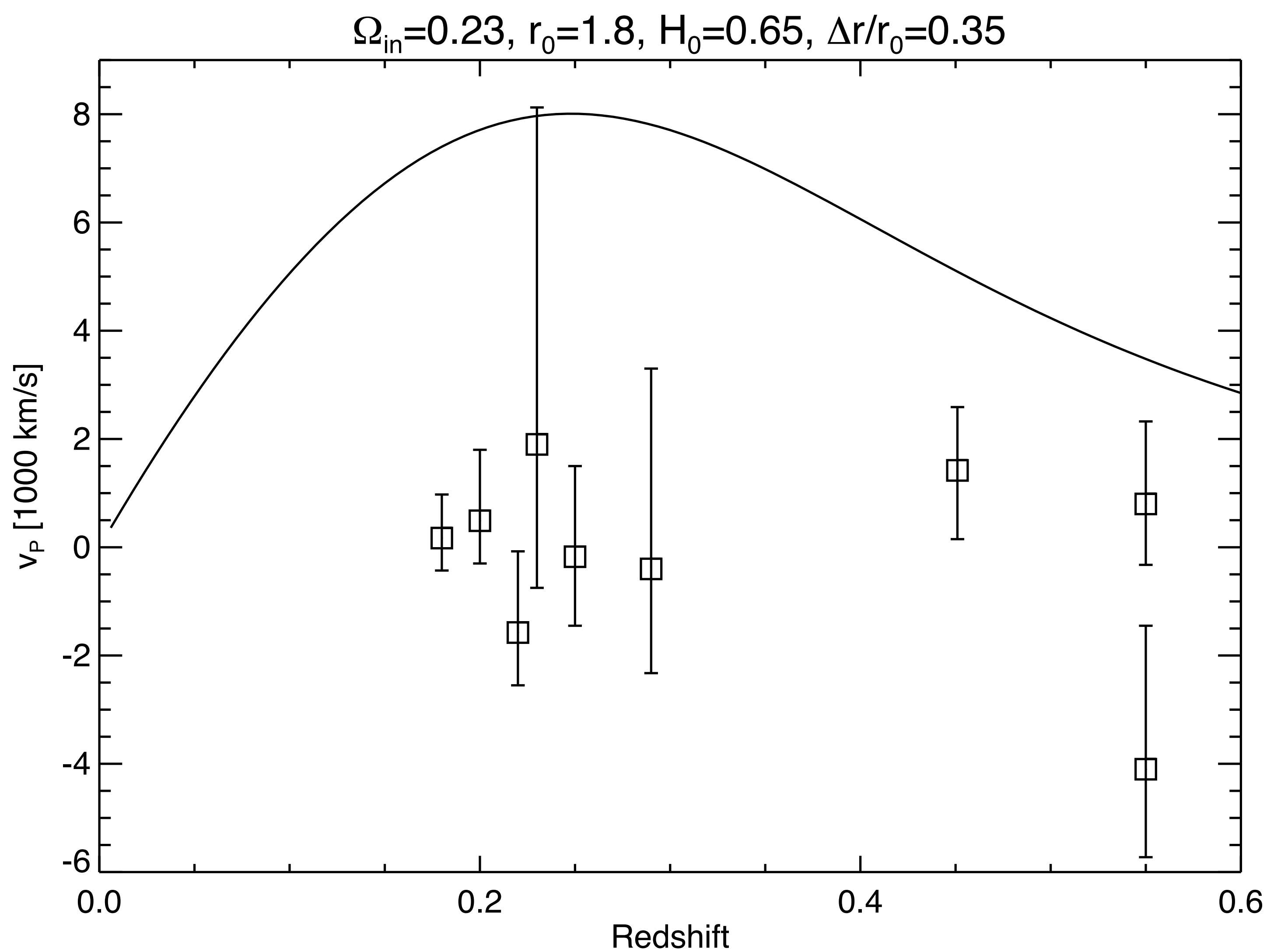

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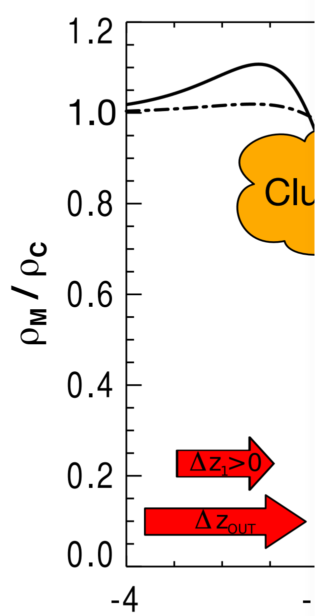
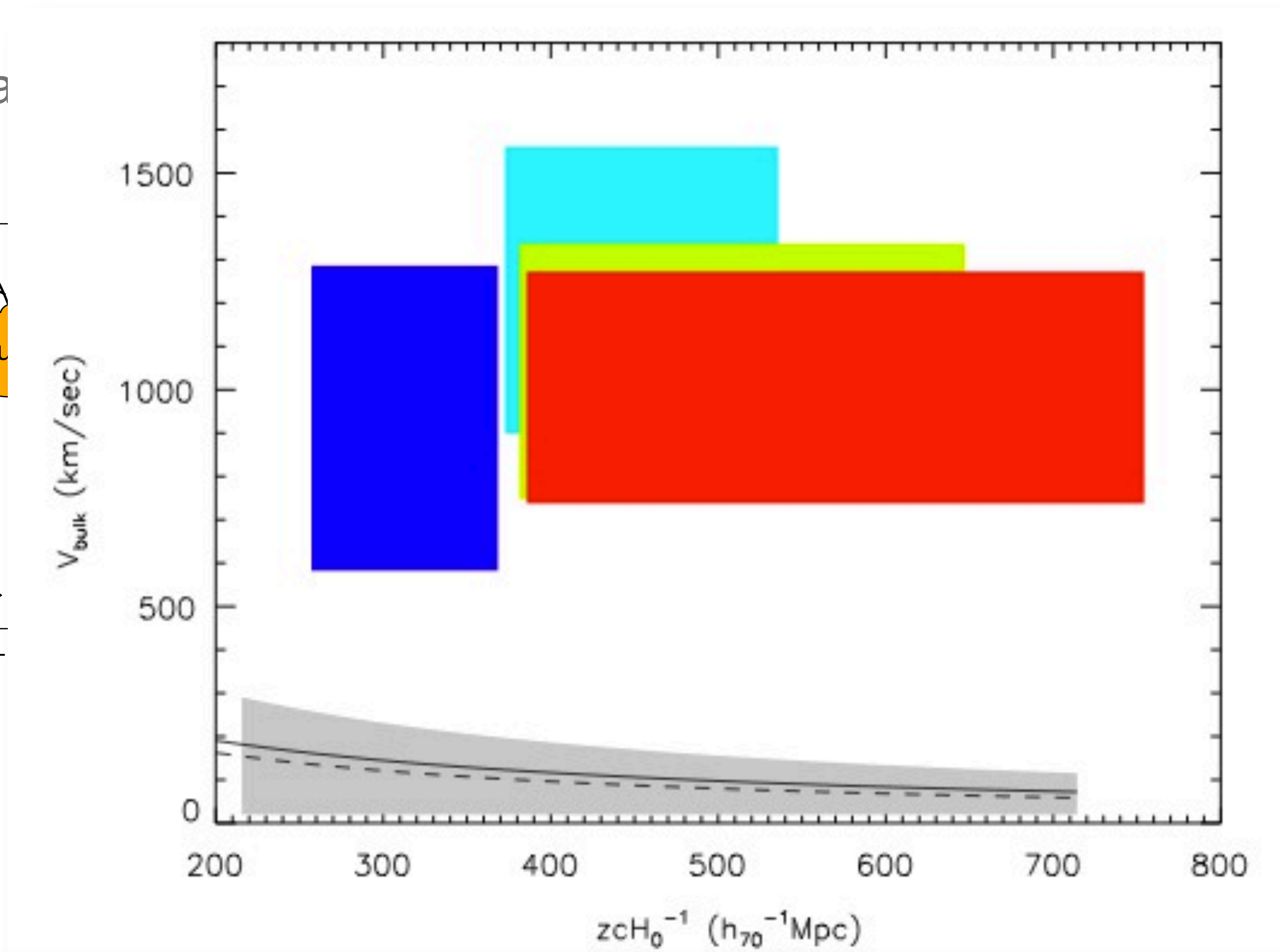
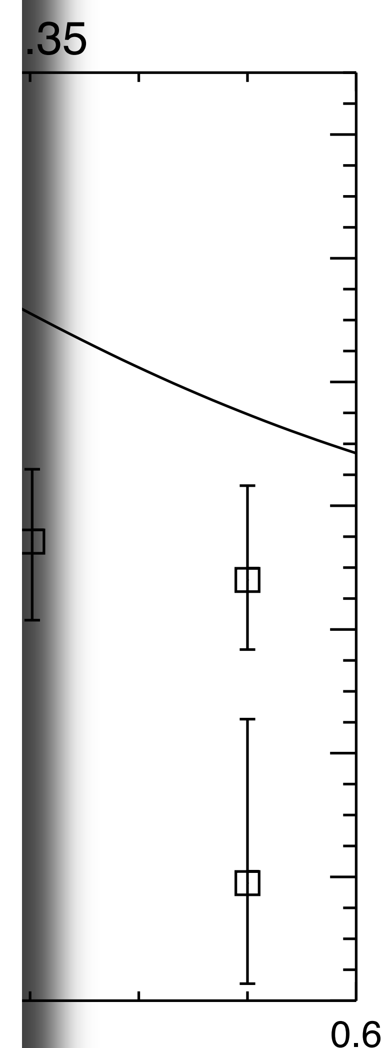
Looking inside our past lightcone

- kSZ (a





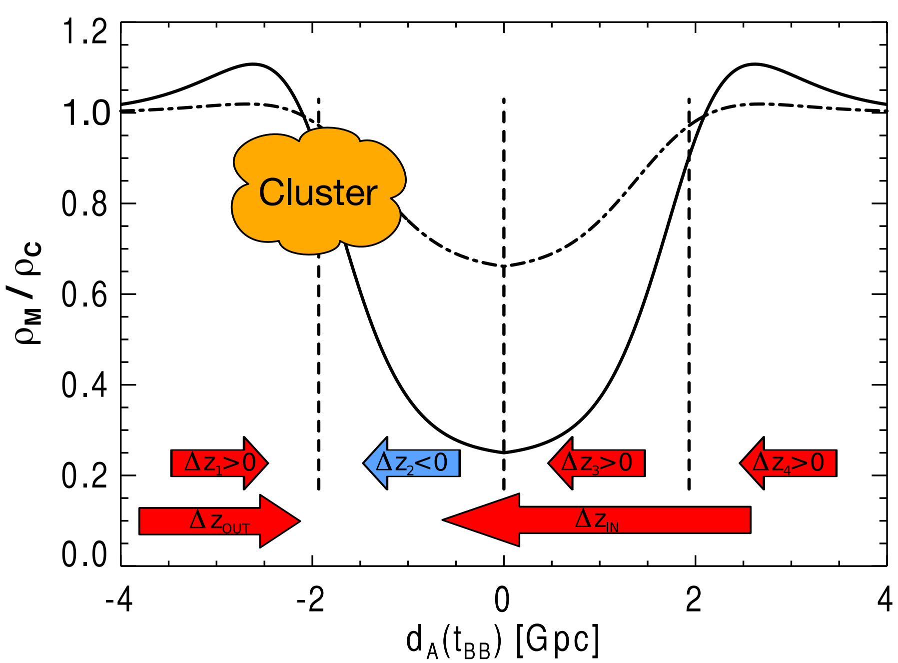


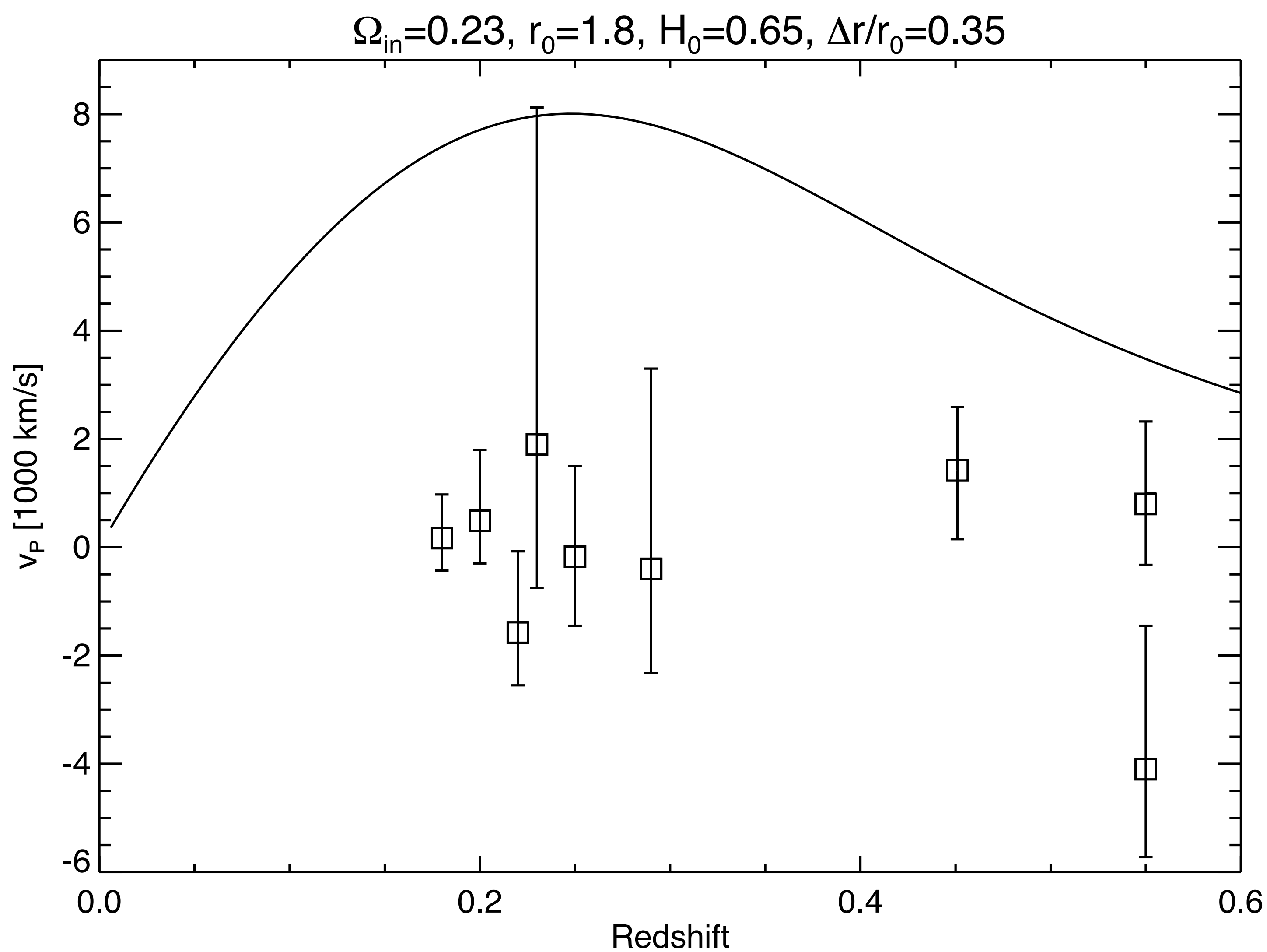
A NEW MEASUREMENT OF THE BULK FLOW OF X-RAY LUMINOUS CLUSTERS OF GALAXIES

A. Kashlinsky[1], F. Atrio-Barandela[2], H. Ebeling[3], A. Edge[4], and D. Kocevski[5]

Looking inside our past lightcone

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





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

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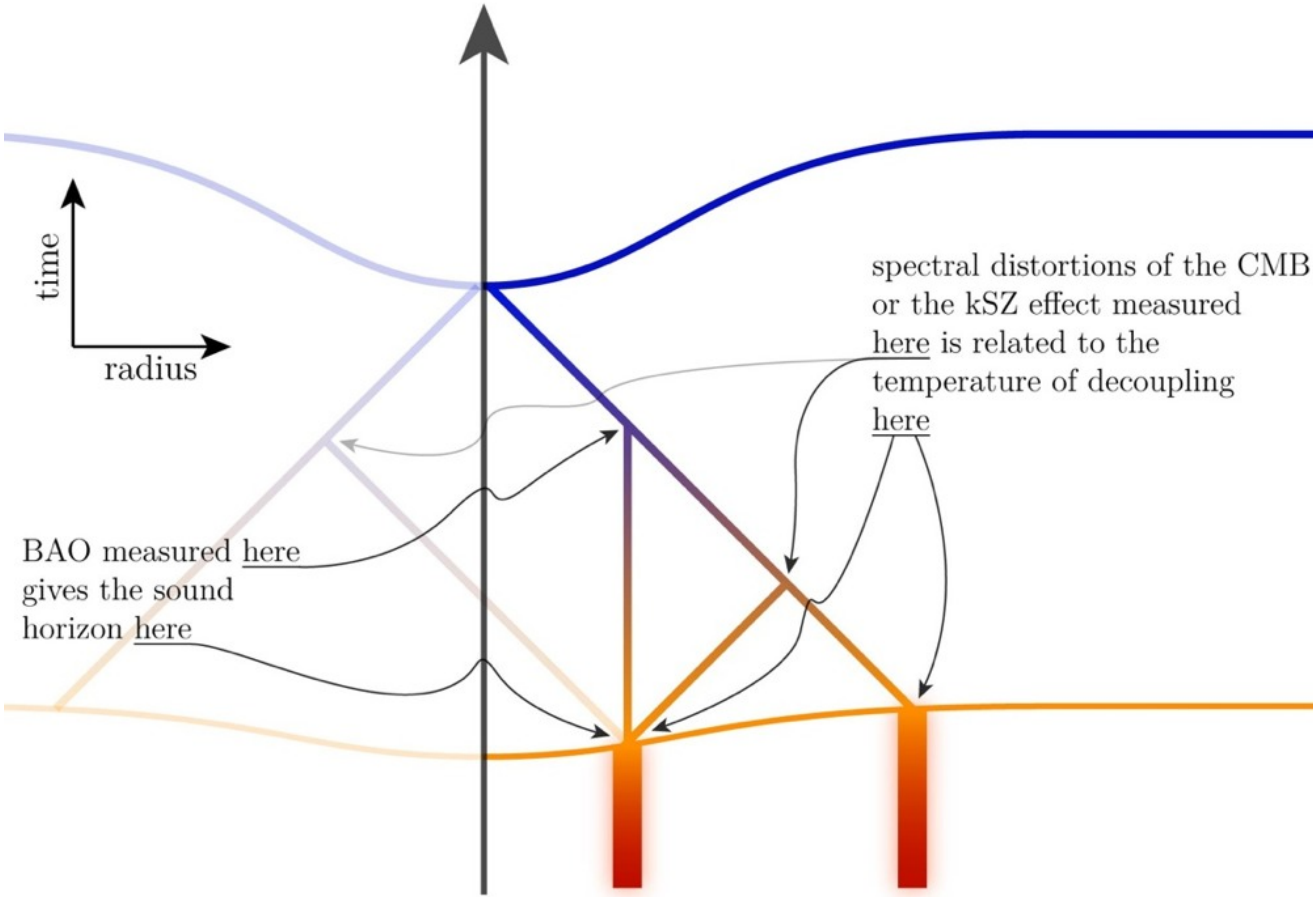
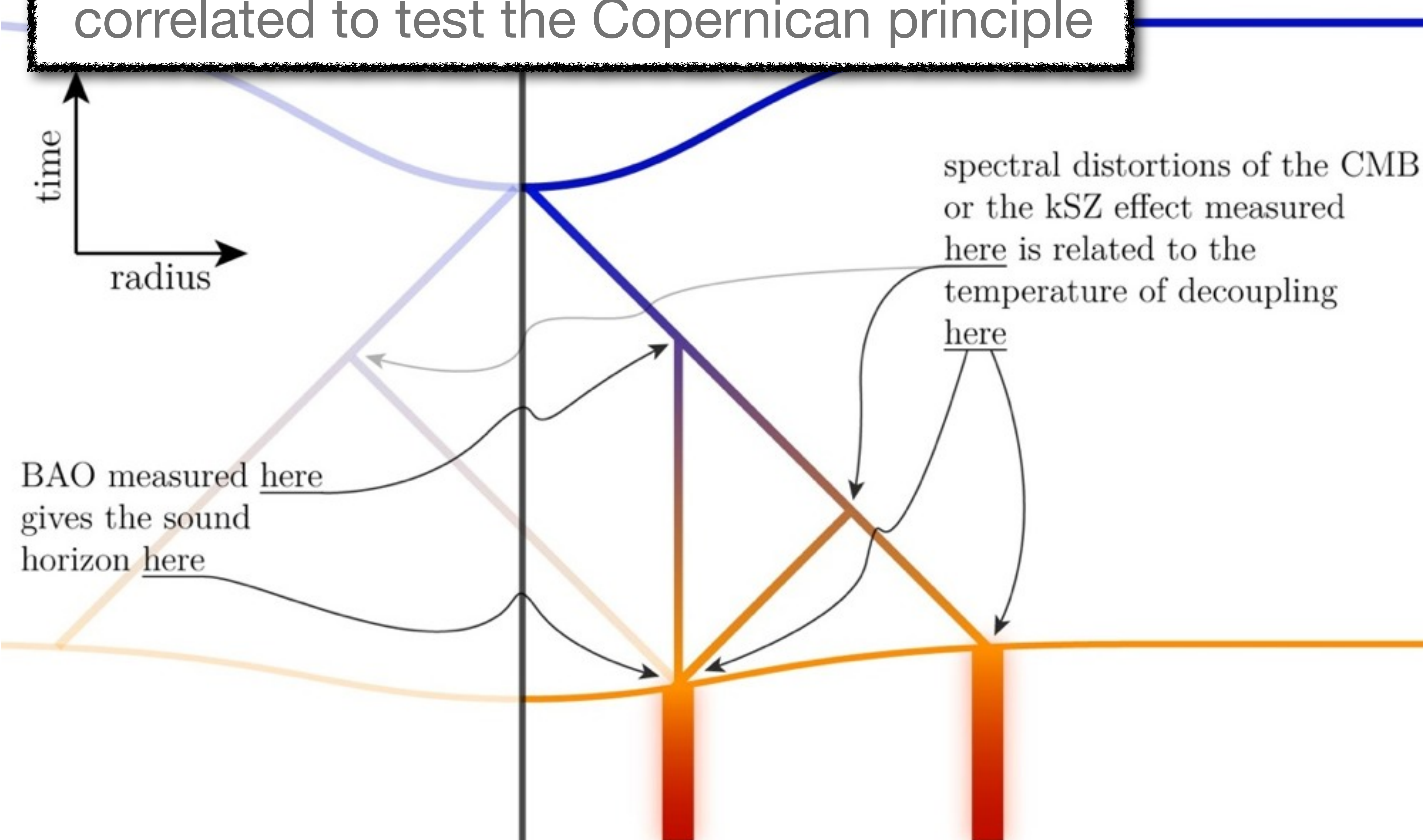

time
radius
spectral distortions of the CMB or the kSZ effect measured here is related to the temperature of decoupling here
BAO measured here gives the sound horizon here

these measurements map out the last scattering surface and must be cross-correlated to test the Copernican principle



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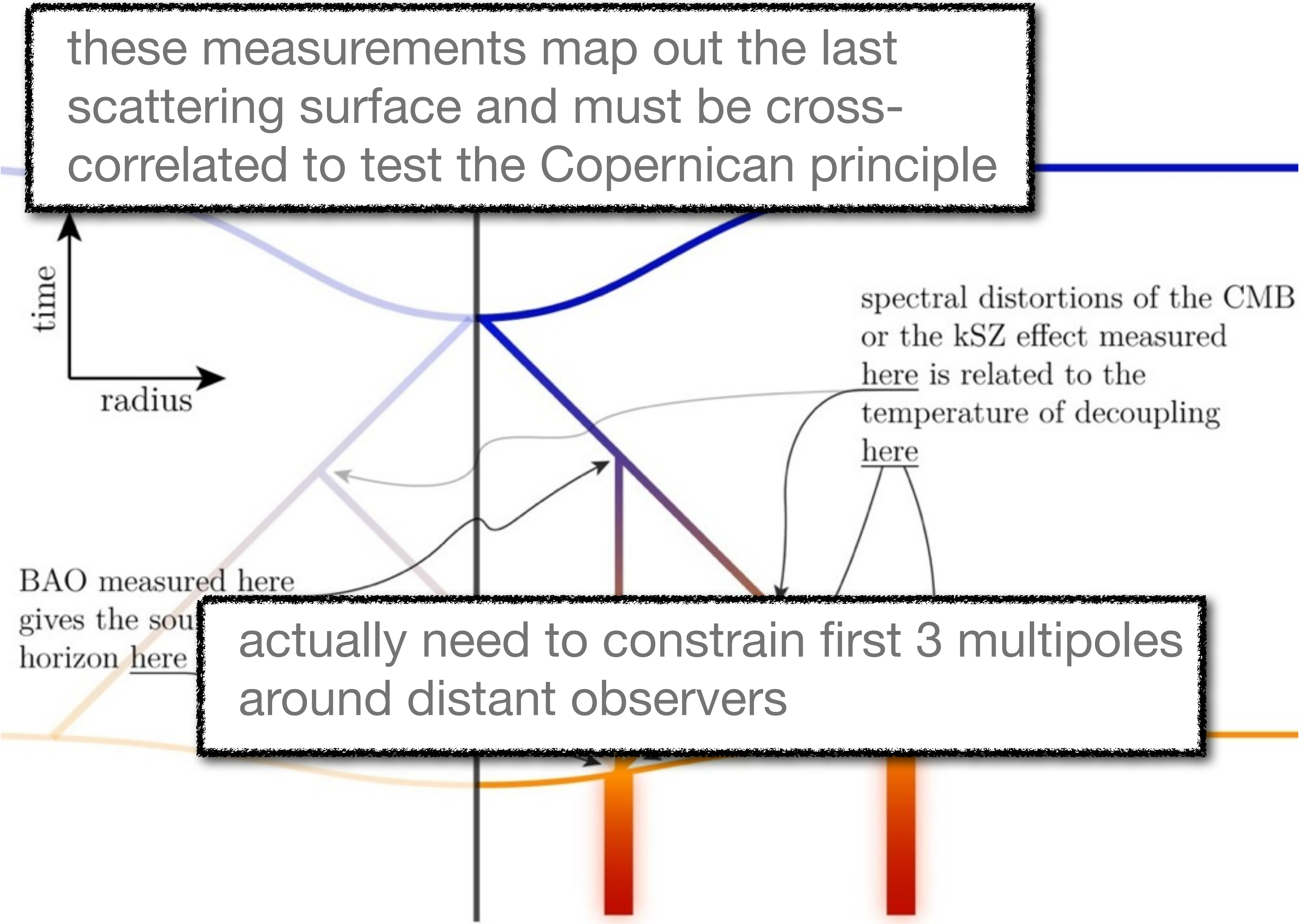


actually need to constrain first 3 multipoles around distant observers

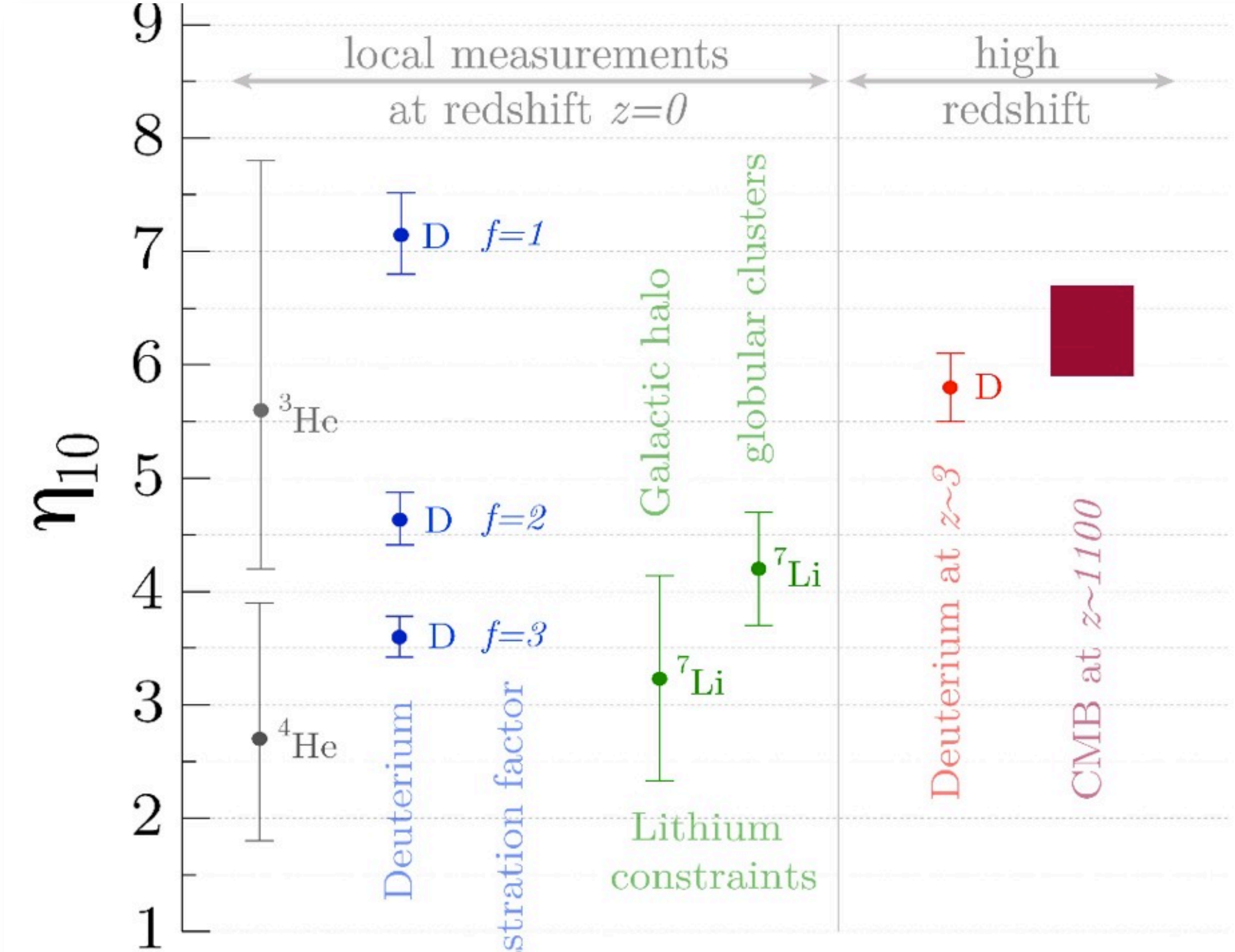
Lithium problem → inhomogeneity at early times?

A 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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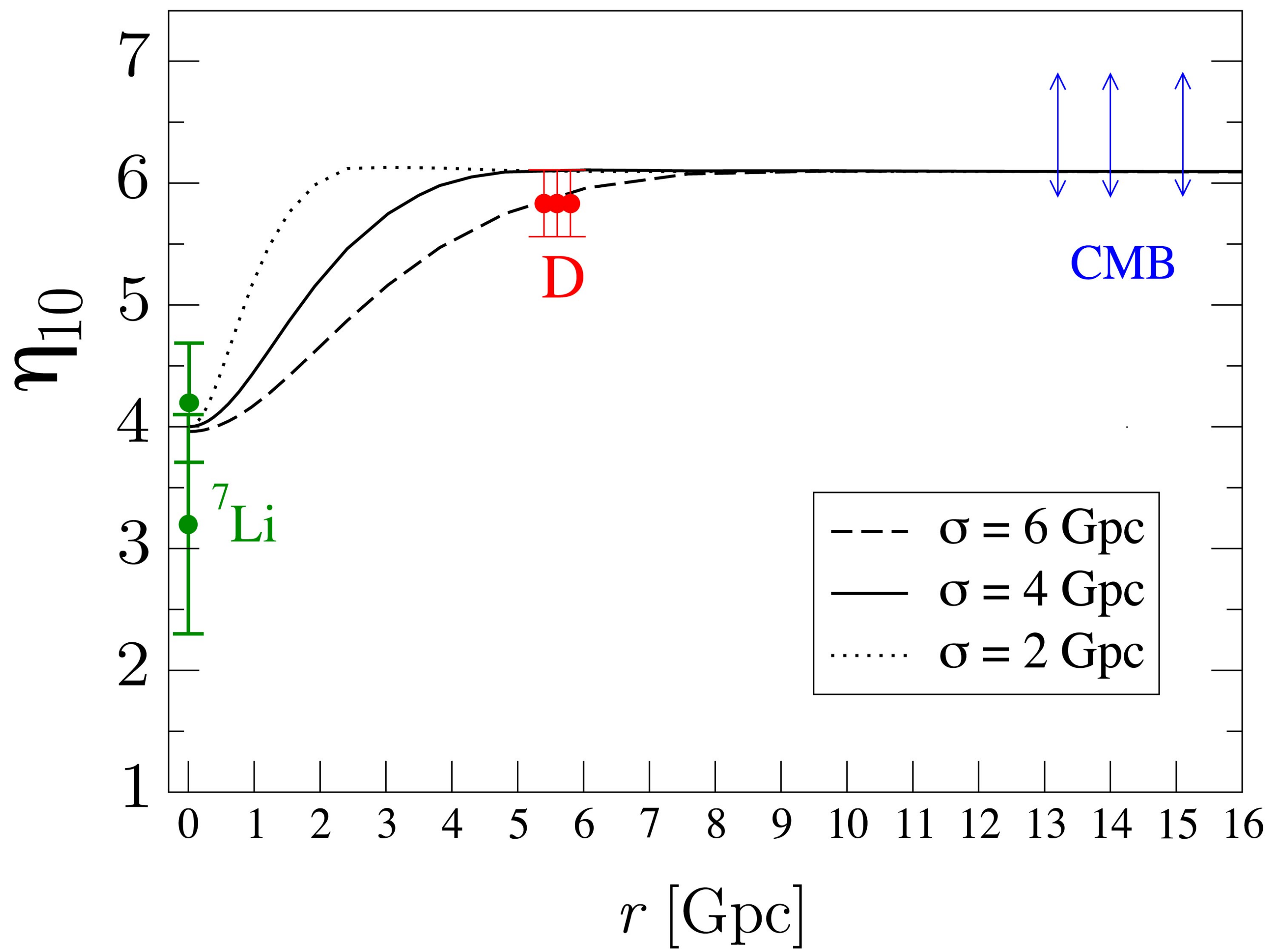
Lithium problem → inhomogeneity at early times?

- a Gpc fluctuation in baryon-photon ratio solves Li problem

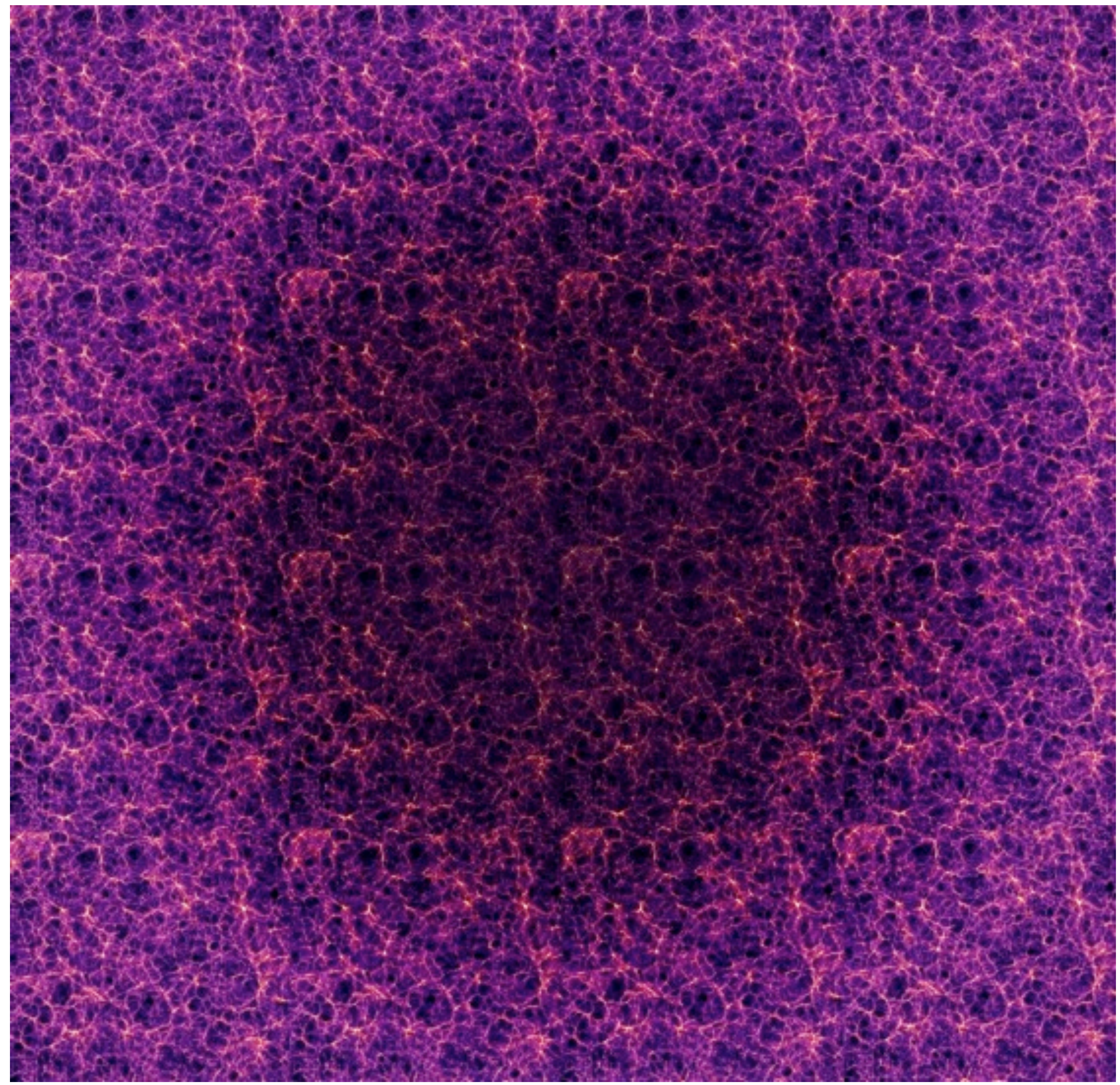


Do primordial Lithium abundances imply there's no Dark Energy?

Marco Regis and Chris Clarkson

Are void models ridiculous?

- what if the universe is huge, with voids all over the place? [like galaxies]
- maybe it's a clue to super-Hubble scales?
- then tells us about universe early in inflation era : something is wrong with slow-roll inflation
- **Key conclusion:** *dark energy is consequence of assumed homogeneity*



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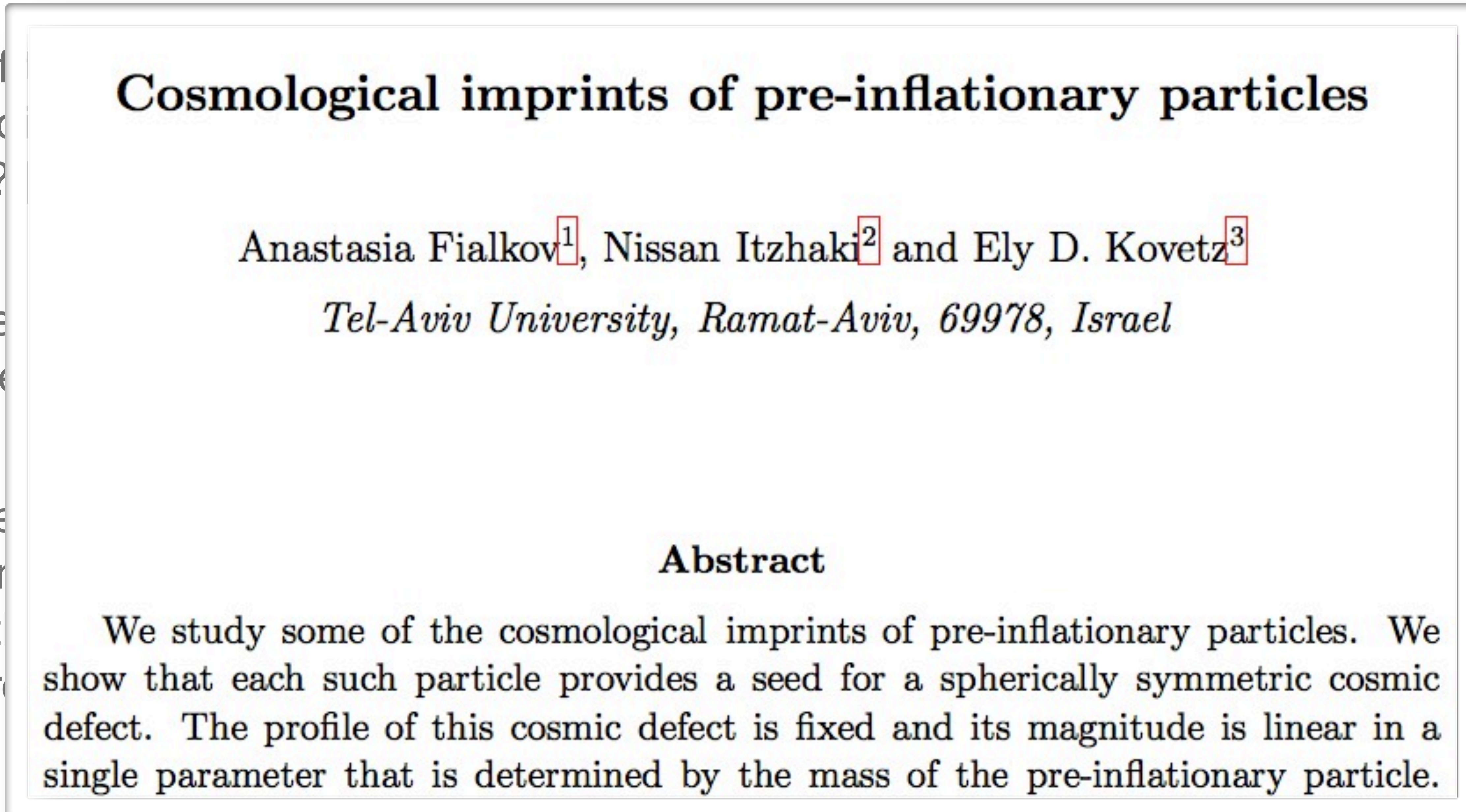


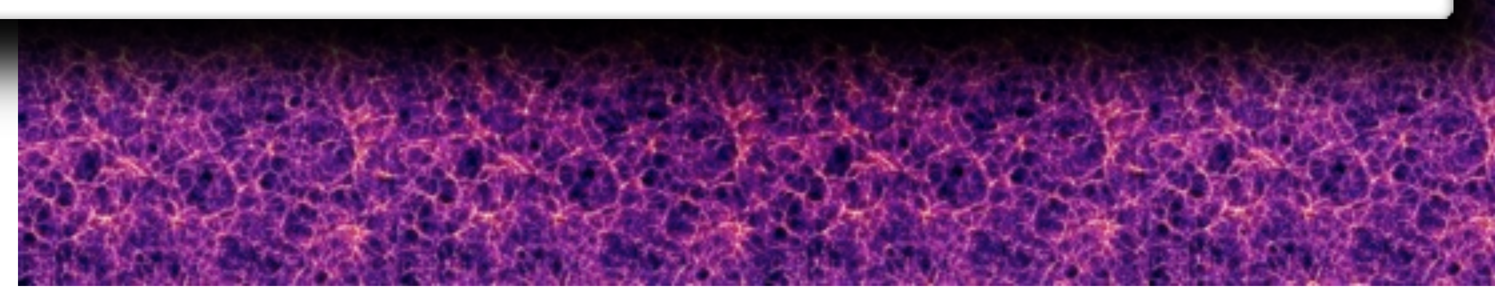
Cosmological imprints of pre-inflationary particles

Anastasia Fialkov[1], Nissan Itzhaki[2] and Ely D. Kovetz[3]

Tel-Aviv University, Ramat-Aviv, 69978, Israel

Abstract

We study some of the cosmological imprints of pre-inflationary particles. We show that each such particle provides a seed for a spherically symmetric cosmic defect. The profile of this cosmic defect is fixed and its magnitude is linear in a single parameter that is determined by the mass of the pre-inflationary particle.



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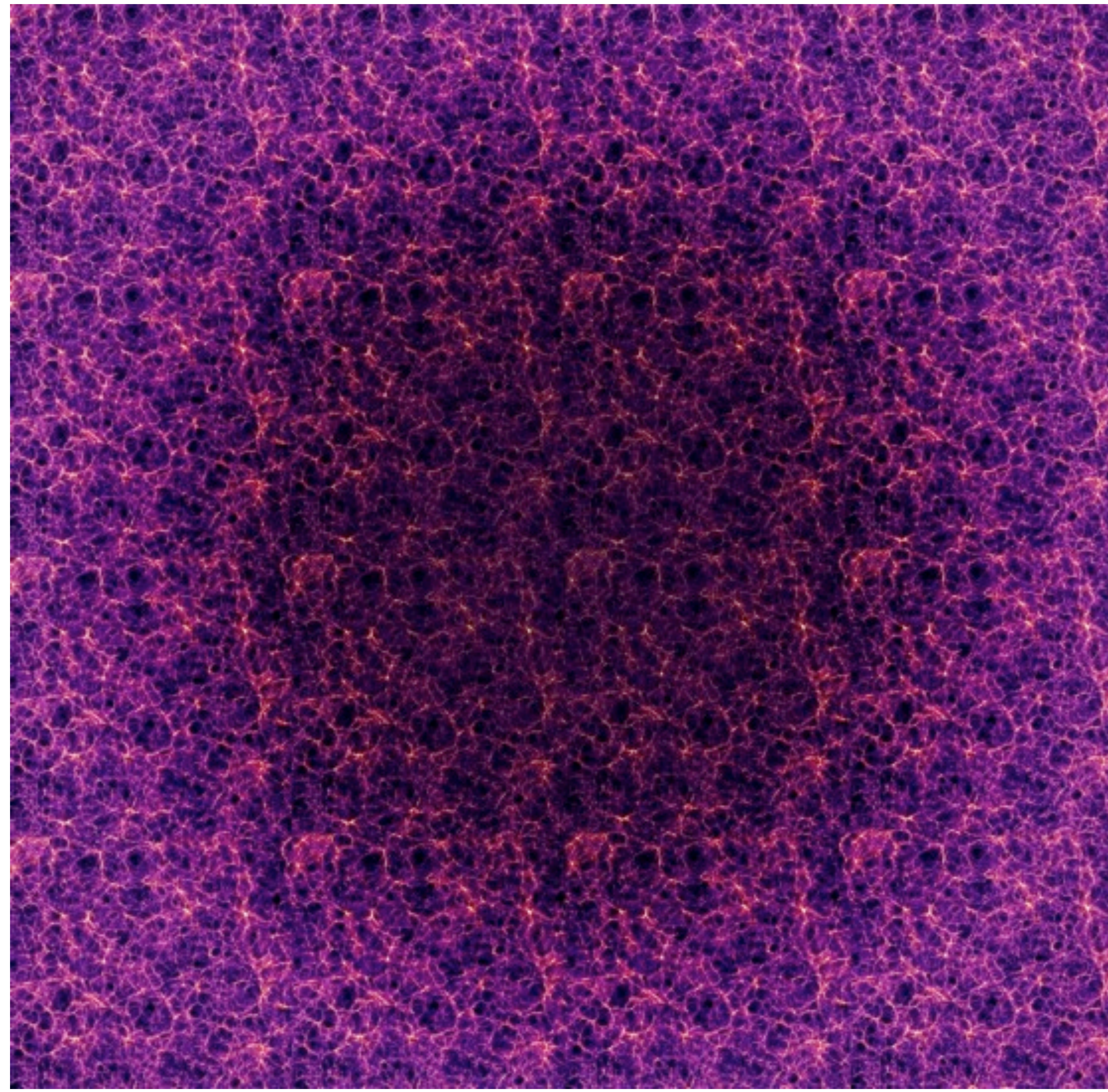

Are void models ridiculous?

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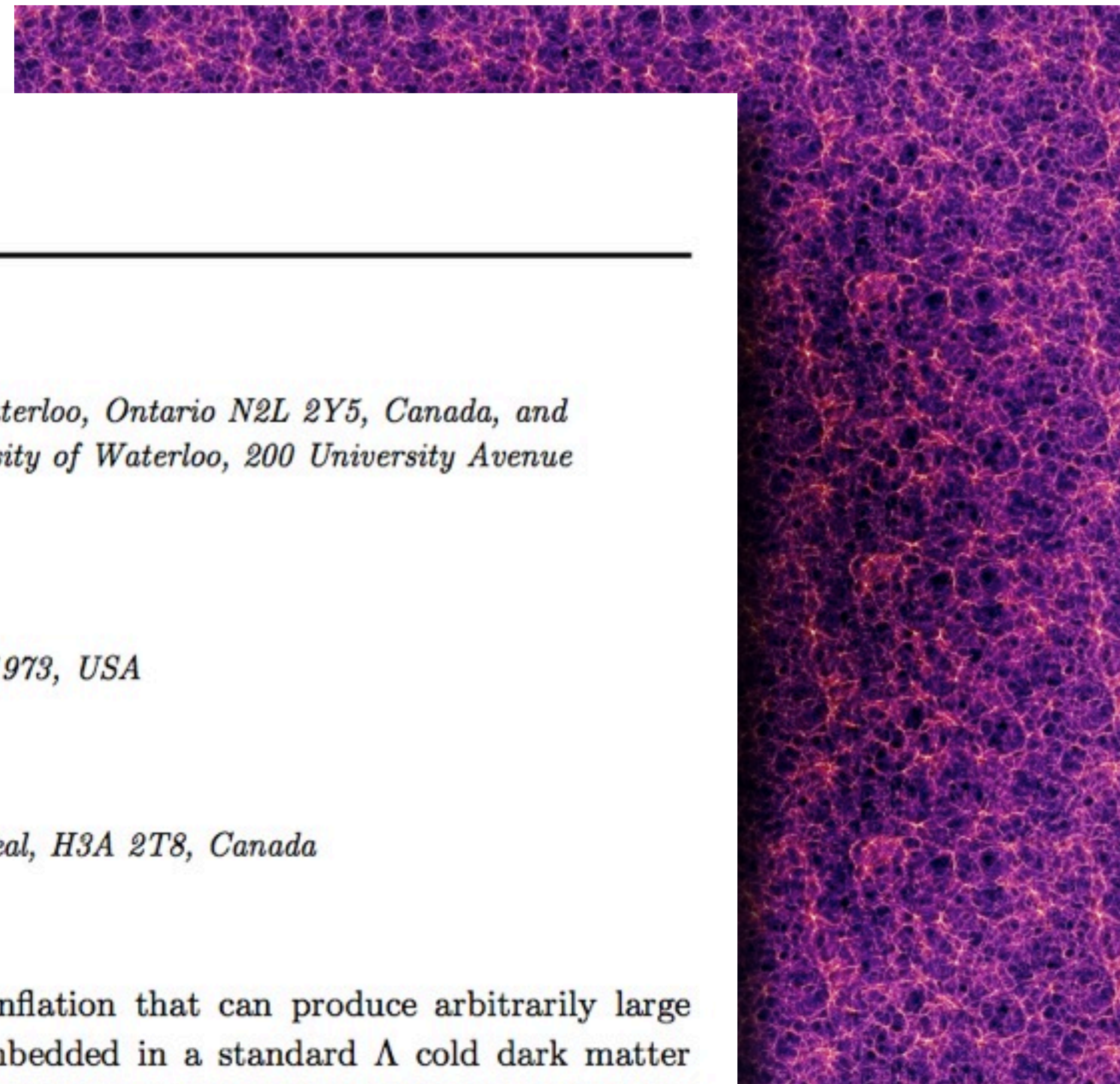

A Theory of a Spot

Niayesh Afshordi

Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada, and Department of Physics and Astronomy, University of Waterloo, 200 University Avenue West, Waterloo, ON, N2L 3G1, Canada
E-mail: nafshordi@perimeterinstitute.ca

Anže Slosar

Brookhaven National Laboratory, Upton, NY 11973, USA
E-mail: anze@bnl.gov

Yi Wang

Physics Department, McGill University, Montreal, H3A 2T8, Canada
E-mail: wangyi@hep.physics.mcgill.ca

Abstract: We present a simple model of inflation that can produce arbitrarily large spherical underdense or overdense regions embedded in a standard Λ cold dark matter paradigm, which we refer to as bubbles. We analyze the effect such bubbles would have on

Are void models ridiculous?

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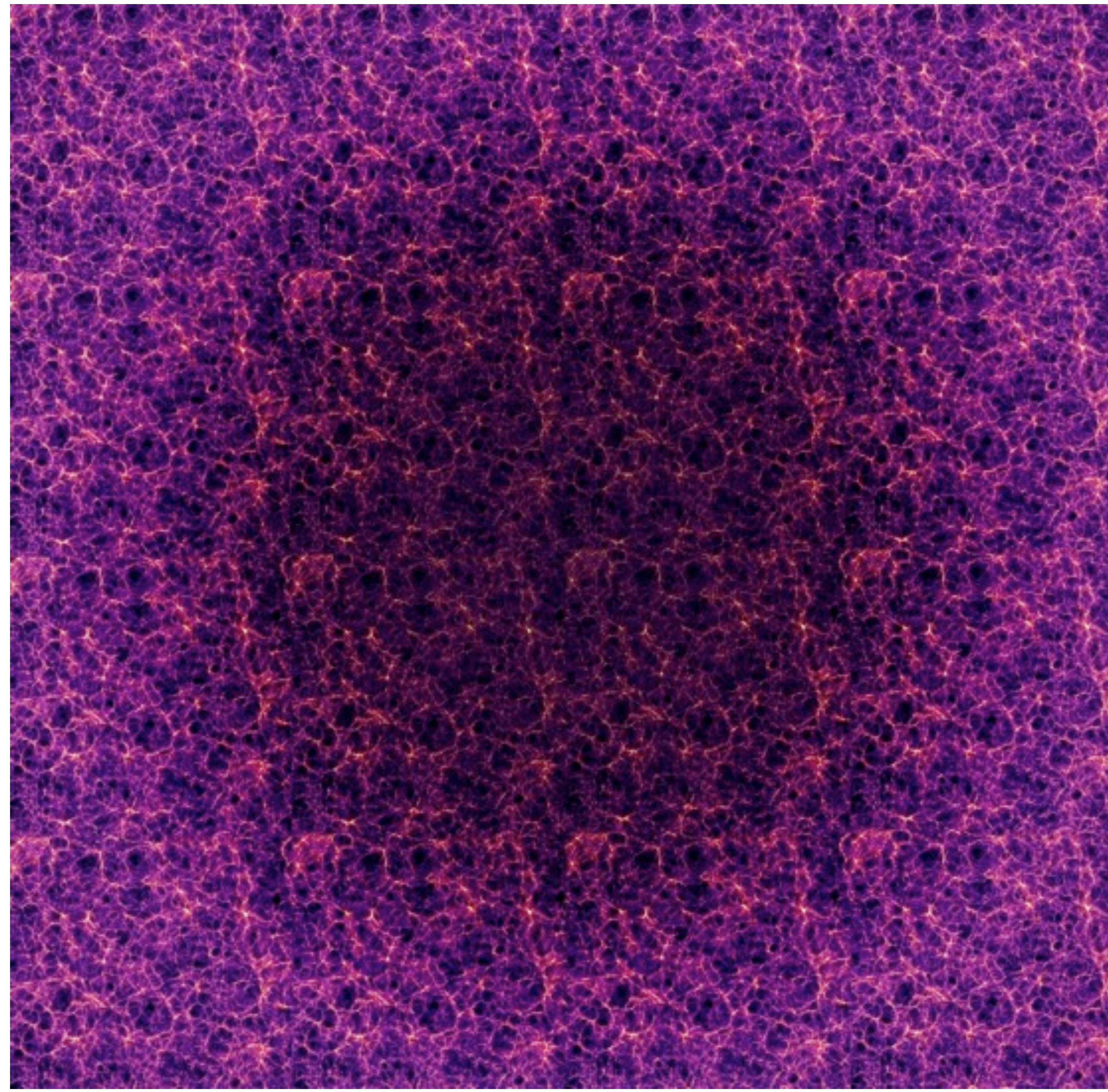


Curvature test for the Copernican Principle

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

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

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

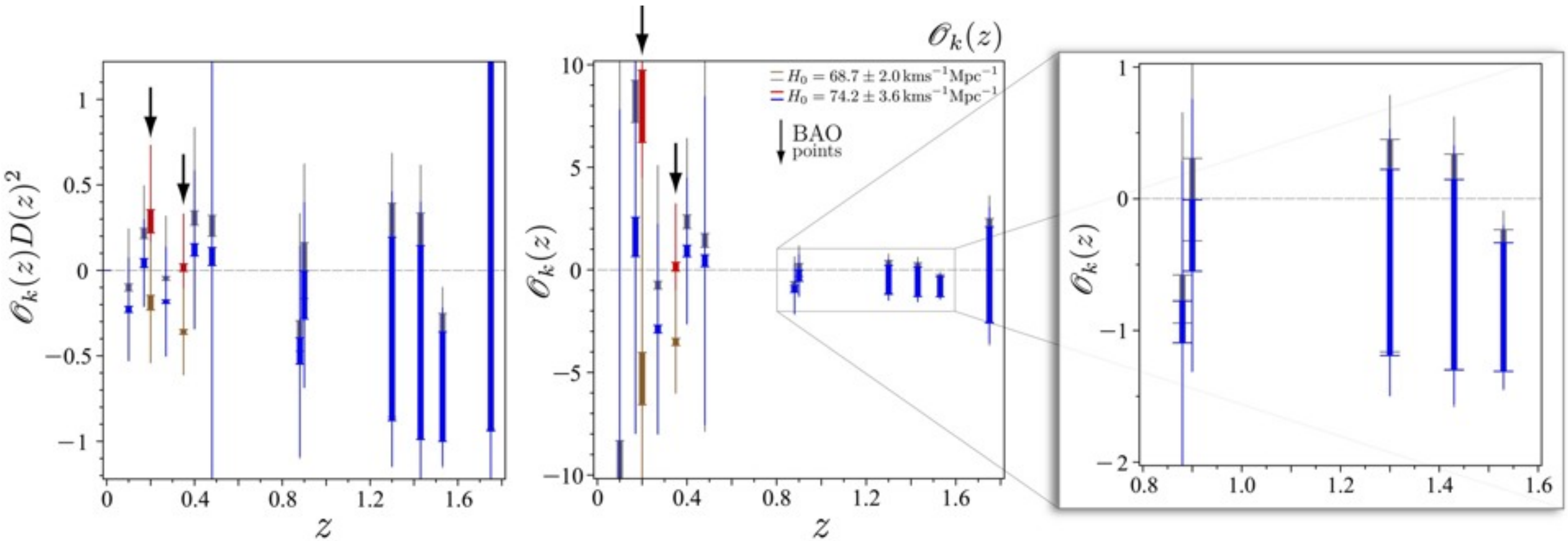
- independent of *all* other cosmological parameters, including dark energy model, and theory of gravity

- 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

Using age data to reconstruct *H(z)*



Shafieloo & Clarkson, PRD

Open issues for voids

- void models have many problems:
  - perturbations/BAO/large scale CMB not calculated, but it looks like they will be able to fit all observations - would this be fine-tuned?
  - initial conditions: could inflation/something produce a simple void?
  - they're weird: can the Copernican problem be averted?
- dark energy, or is slow roll inflation wrong?
- can we test the Copernican principle in general?

can we instead quantify other deviations from flat LCDM?

... 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

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

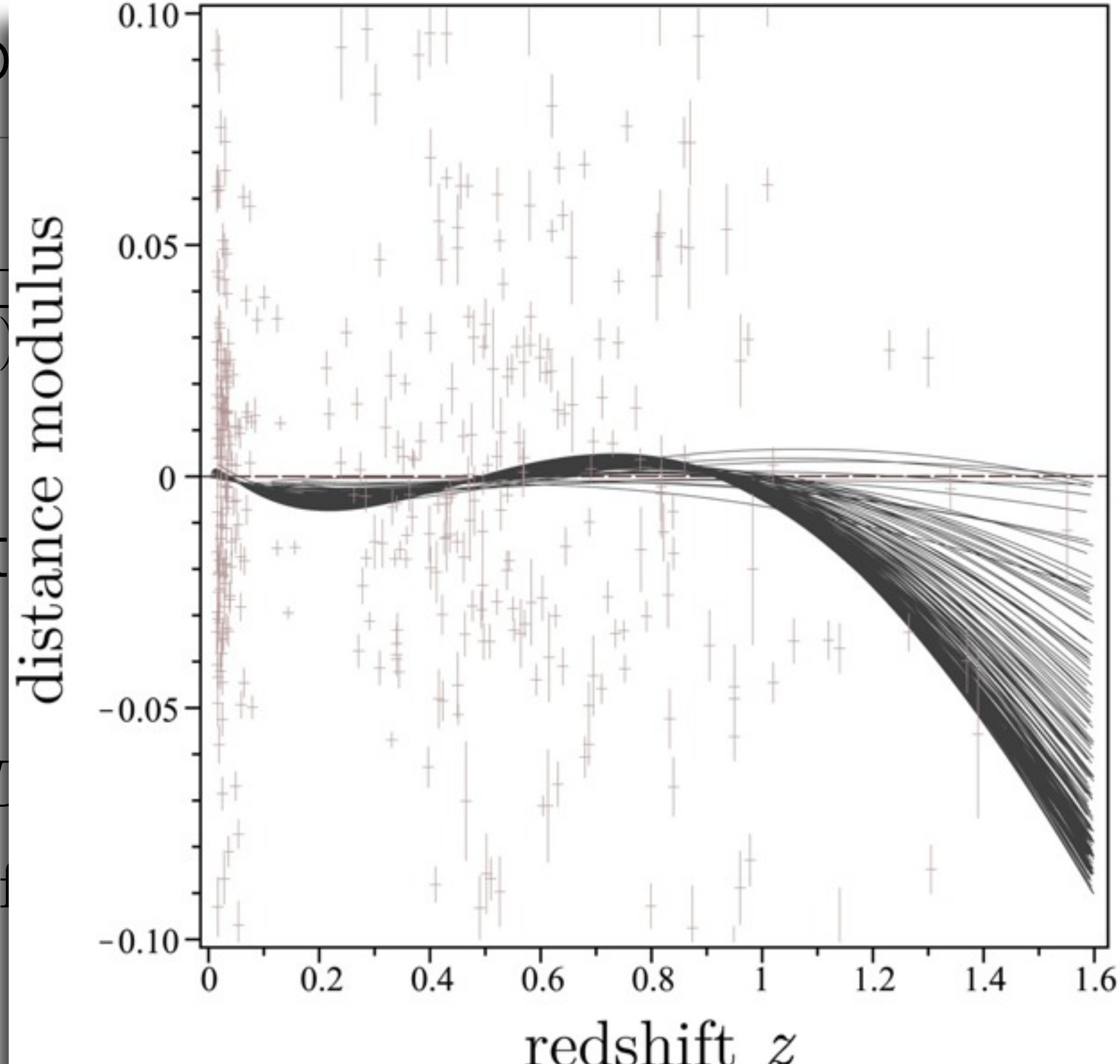
Zunckel & Clarkson, PRL, arXiv:0807.4304;
see also Sahni etal 0807.3548

A litmus test fo

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

t

$$\mathscr{L}(z) = \zeta D$$
$$= 0 \text{ f}$$

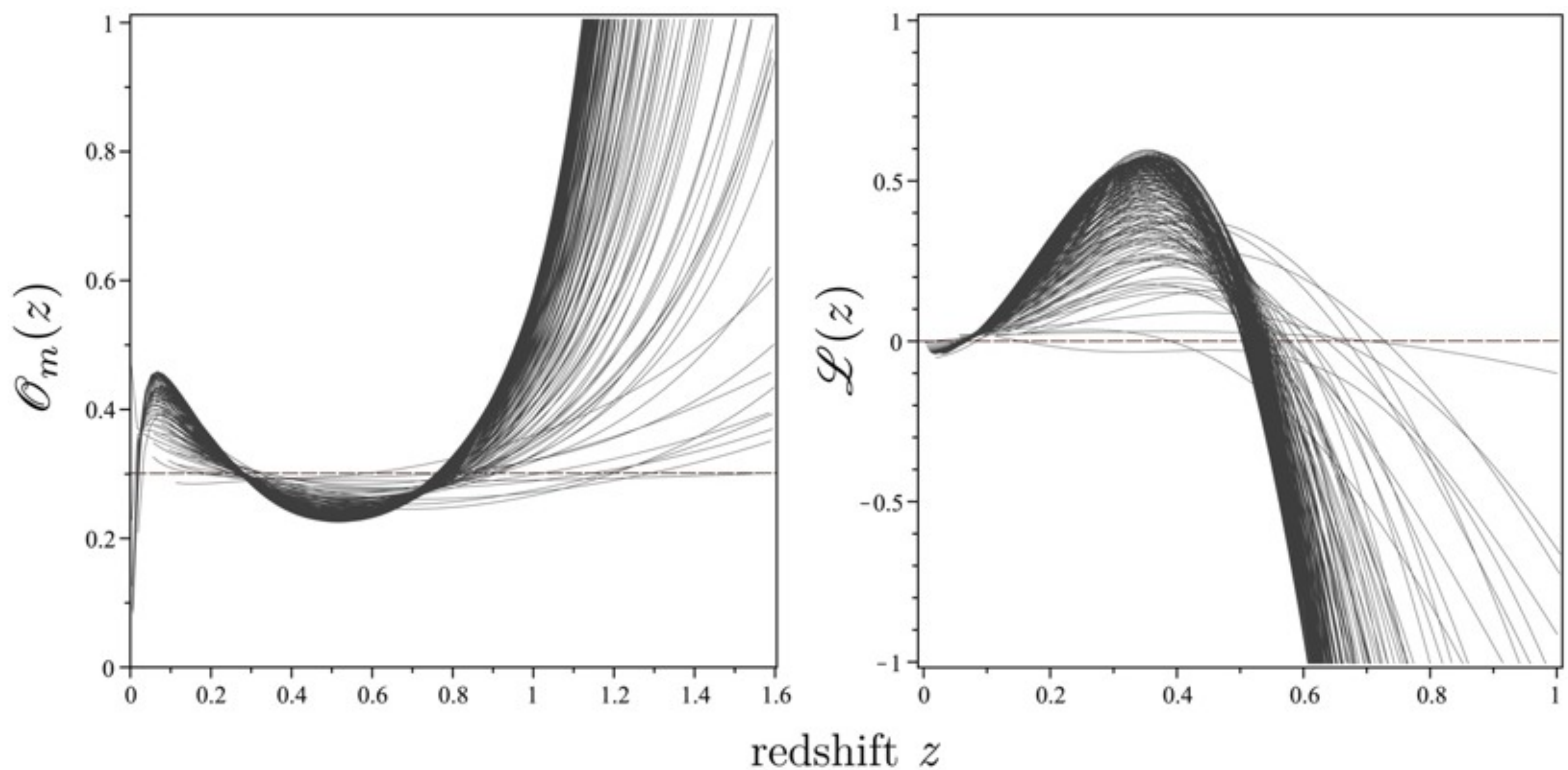


4;

see also Sahni etal 0807.3548

A litmus test for flat ΛCDM

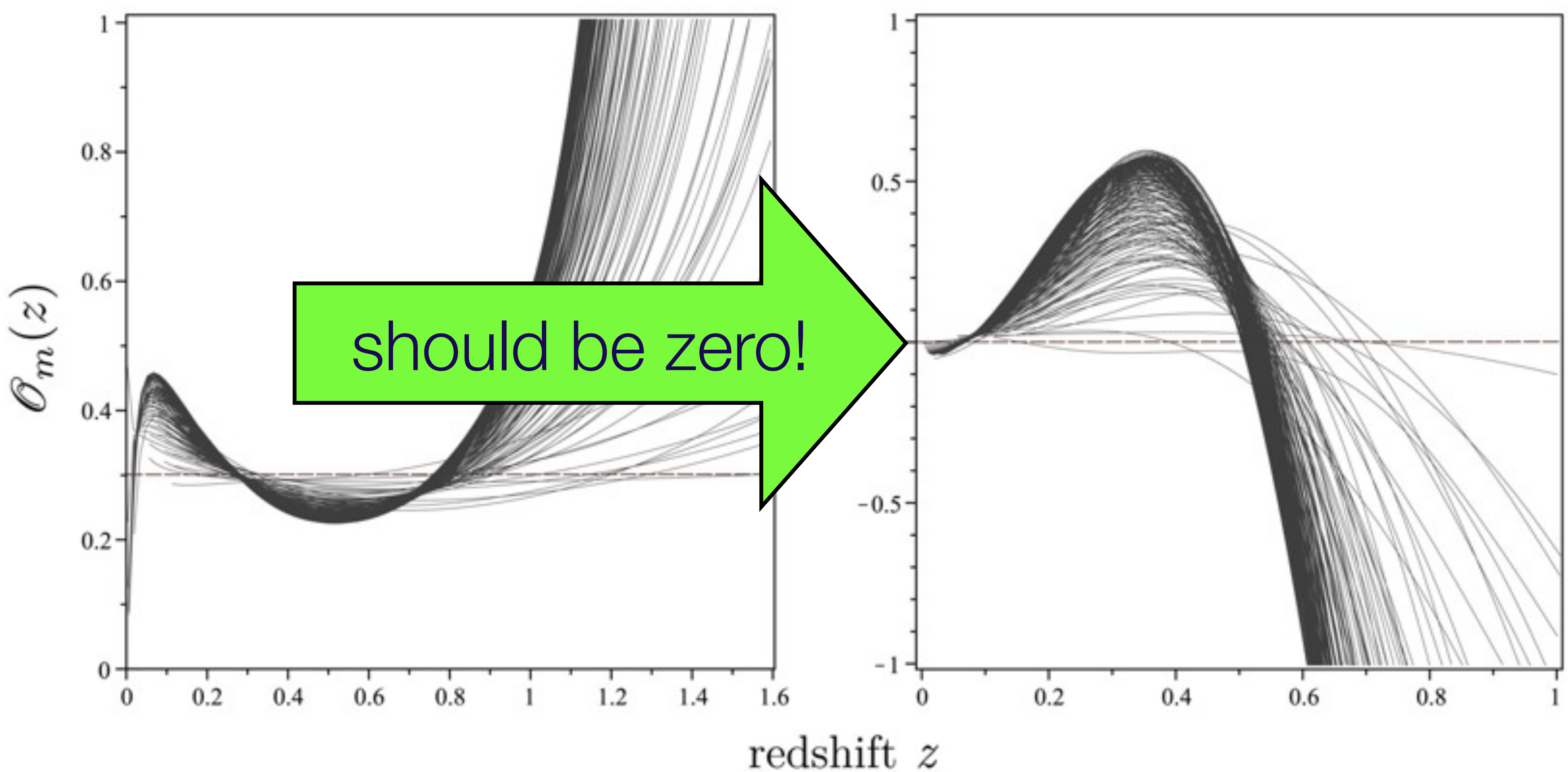
these are better fits to constitution data than LCDM



with Arman Shafieloo, PRD

A litmus test for flat ΛCDM

these are better fits to constitution data than LCDM

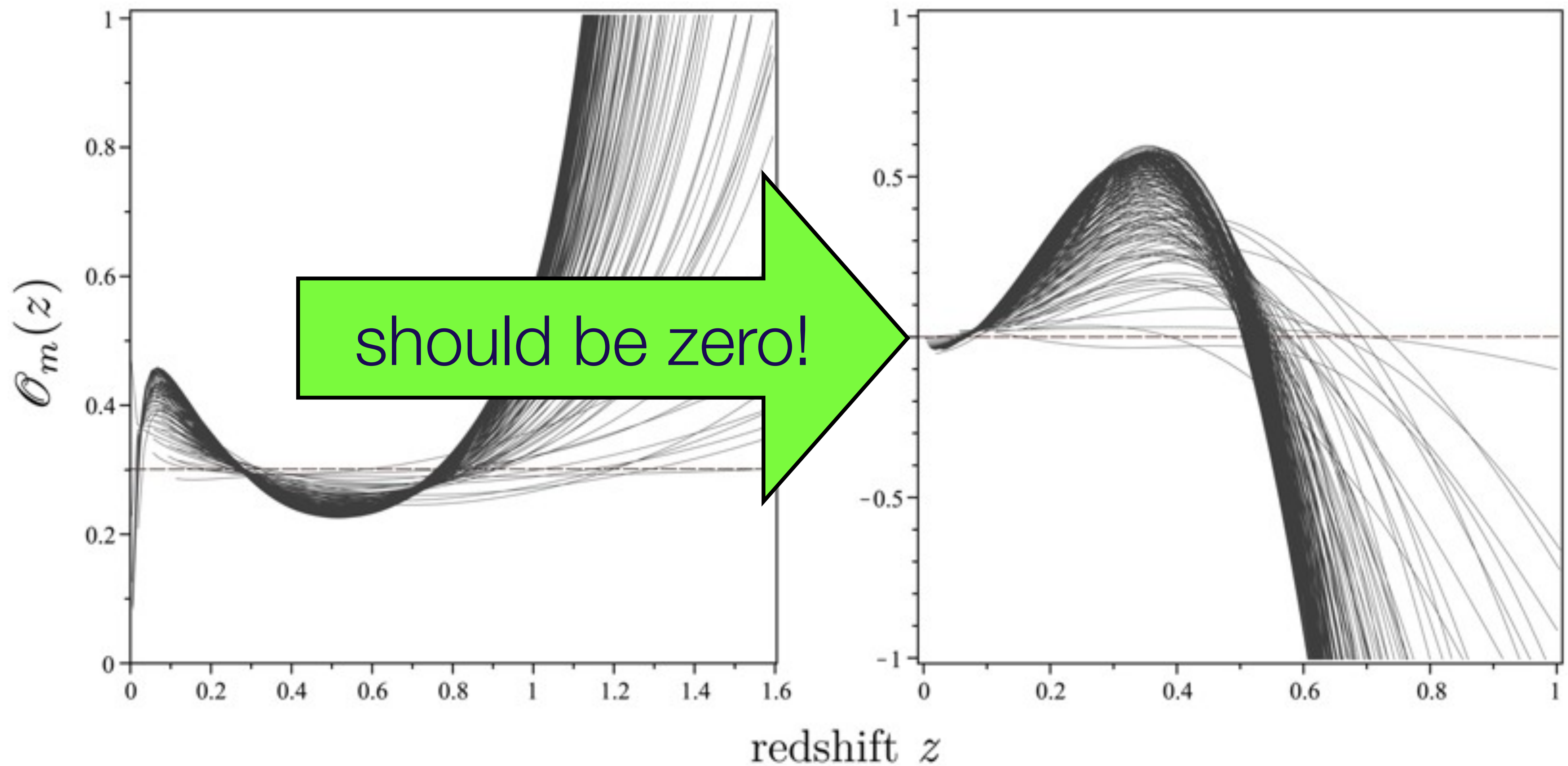


with Arman Shafieloo, PRD

A litmus test

no dependence on Omega_m

these are better fits to constitution data than LCDM



with Arman Shafieloo, PRD

other tests

$$
\begin{aligned}
\Omega_k &= \Upsilon(z)\left\{2\left(1-(1+z)^3\right)D'' + 3D'^3(D'^2-1)(1+z)^2\right\} \equiv \mathscr{O}_k^{(2)}(z) \\
\Omega_m &= 2\Upsilon(z)\left\{\left[(1+z)^2 - D^2 - 1\right]D'' - \left(D'^2-1\right)\left[(1+z)D' - D\right]\right\} \equiv \mathscr{O}_m^{(2)}(z) \\
\Upsilon(z)^{-1} &= 2\left[1-(1+z)^3\right]D^2D'' \\
&\quad -\left\{(1+z)\left[(1+z)^3 - 3(1+z) + 2\right]D'^2 - 2\left[1-(1+z)^3\right]DD' - 3(1+z
\end{aligned}
$$

other tests

$$
\begin{aligned}
\Omega_k &= \Upsilon(z)\left\{2\left(1-(1+z)^3\right)D'' + 3D'^3(D'^2-1)(1+z)^2\right\} \equiv \mathscr{O}_k^{(2)}(z) \\
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\end{aligned}
$$

$$
\begin{aligned}
w(z) &= -\frac{1}{3}\frac{\Omega_k(1+z)^2 + 2(1+z)hh' - 3h^2}{(1+z)^2[\Omega_m(1+z)+\Omega_k] - h^2} \\
&= \frac{2(1+z)(1+\Omega_k D^2)D'' - \left[(1+z)^2\Omega_k D'^2 + 2(1+z)\Omega_k DD' - 3(1+\Omega_k D^2)\right]D'}{3\left\{(1+z)^2\left[\Omega_k + (1+z)\Omega_m\right]D'^2 - (1+\Omega_k D^2)\right\}D'}
\end{aligned}
$$