Inhomogeneous cosmologies

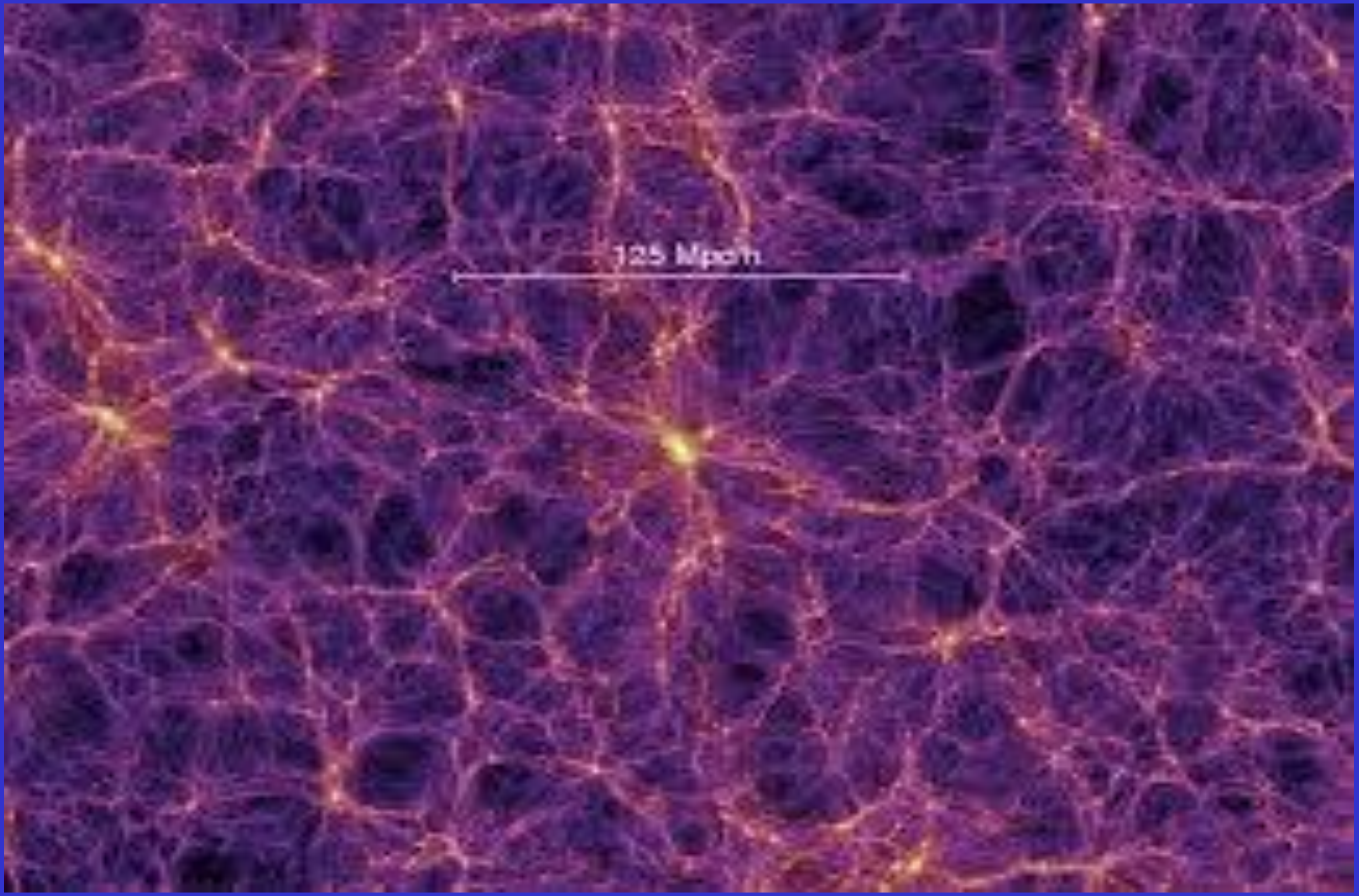
George Ellis,

University of Cape Town

27th Texas Symposium on Relativistic Astrophyiscs

Dallas, Texas

Thursday 12th December 9h00-9h45



- The universe is inhomogeneous on all scales except the largest
- This conclusion has often been resisted by theorists who have said it could not be so (e.g. walls and large scale motions)

- Most of the universe is almost empty space, punctuated by very small very high density objects (e.g. solar system)
- Very non-linear: ☠♉/♉ = 10^{30} in this room.

Models in cosmology

- Static: Einstein (1917), de Sitter (1917)
- Spatially homogeneous and isotropic, evolving:
  - Friedmann (1922), Lemaitre (1927), Robertson-Walker, Tolman, Guth
- Spatially homogeneous anisotropic (Bianchi/ Kantowski-Sachs) models:
  - Gödel, Schücking, Thorne, Misner, Collins and Hawking,Wainwright, …

- Perturbed FLRW: Lifschitz, Hawking, Sachs and Wolfe, Peebles, Bardeen, Ellis and Bruni: structure formation (linear), CMB anisotropies, lensing

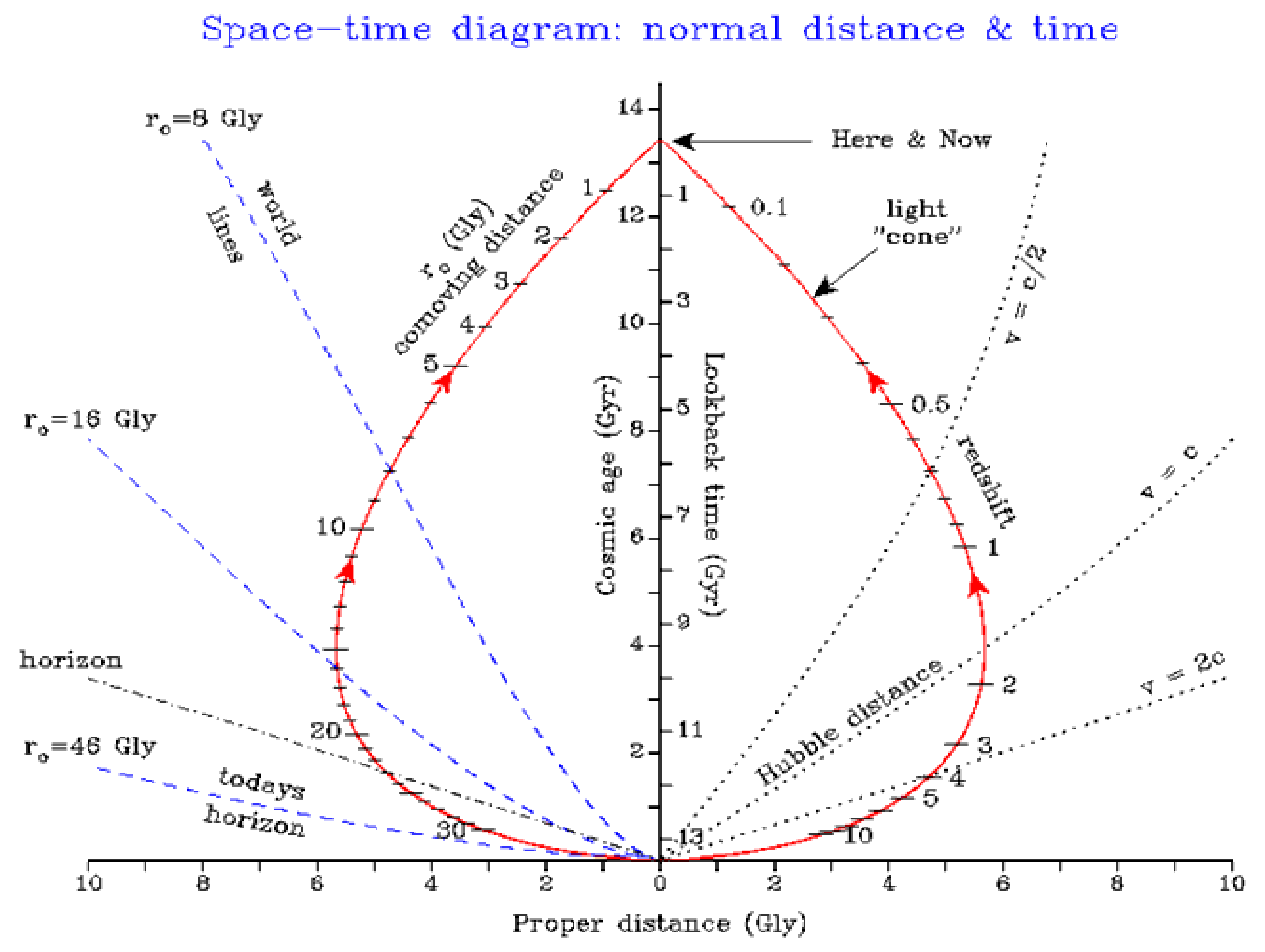
- Spherically symmetric inhomogeneous:
  LTB: Lemaître, Tolman, Bondi, Silk, Krasinski, Celerier , Bolejko,…,
- Szekeres (no symmetries): Sussman, Hellaby, Ishak, …

- Swiss cheese: Einstein and Strauss, Schücking, Kantowski, Dyer,…
- Lindquist and Wheeler: Perreira, Clifton, …

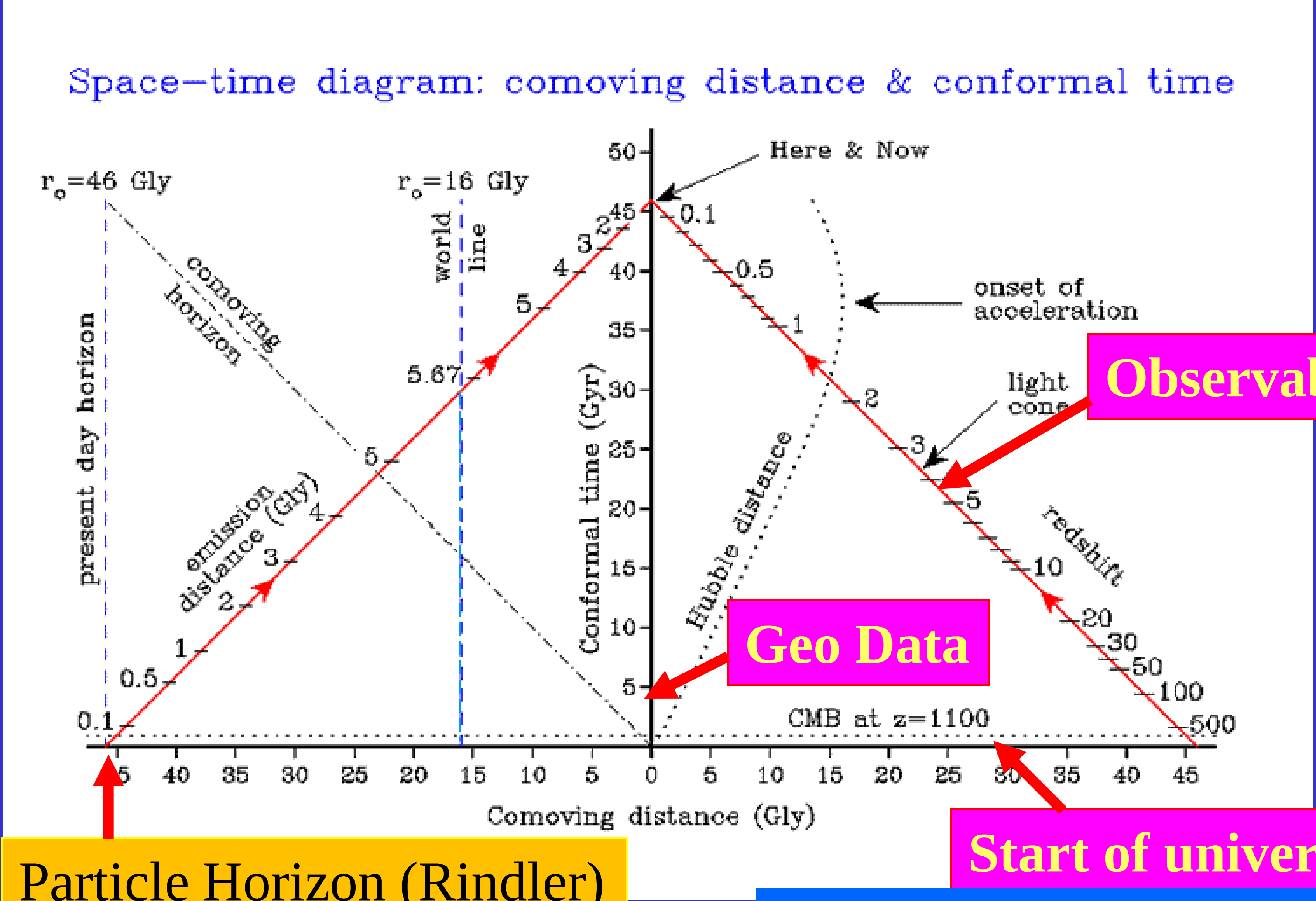
- Black holes: Schwarzschild, Kerr

The key observational point is that we can only observe on the past light cone (Hoyle, Schücking, Sachs)

See the diagrams of our past light cone by Mark Whittle (Virginia)



Expand the spatial distances to see the causal structure: light cones at ±45°.



Observable

Geo Data

Start of universe

Particle Horizon (Rindler)

Spacelike singularity (Penrose).

The cosmological principle

The CP is the foundational assumption that the Universe obeys a cosmological law:

It is necessarily spatially homogeneous and isotropic

(Milne 1935, Bondi 1960)

Thus *a priori*: geometry is Robertson-Walker

Weaker form: the Copernican Principle:

We do not live in a special place (Weinberg 1973).

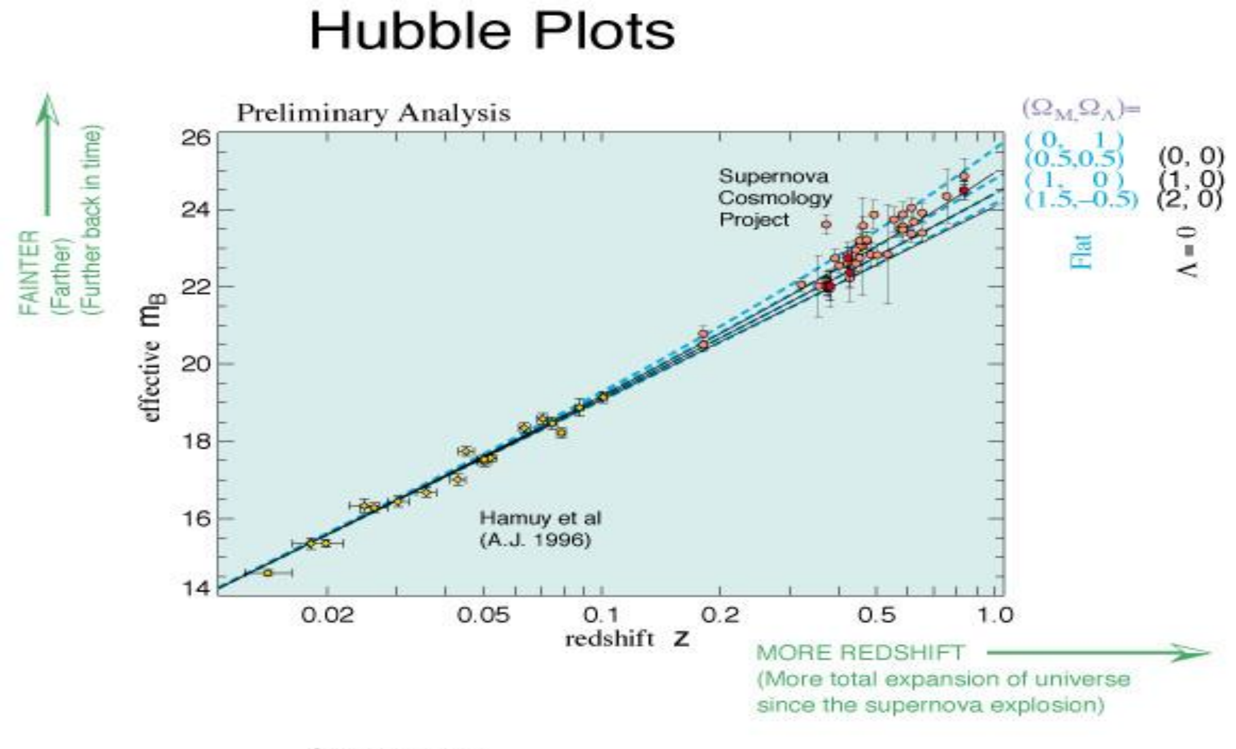
With observed isotropy, implies Robertson-Walker.

Philosophical Principle at Foundation

of Standard Cosmology

On this basis: dark energy exists

Dark Energy Discovery

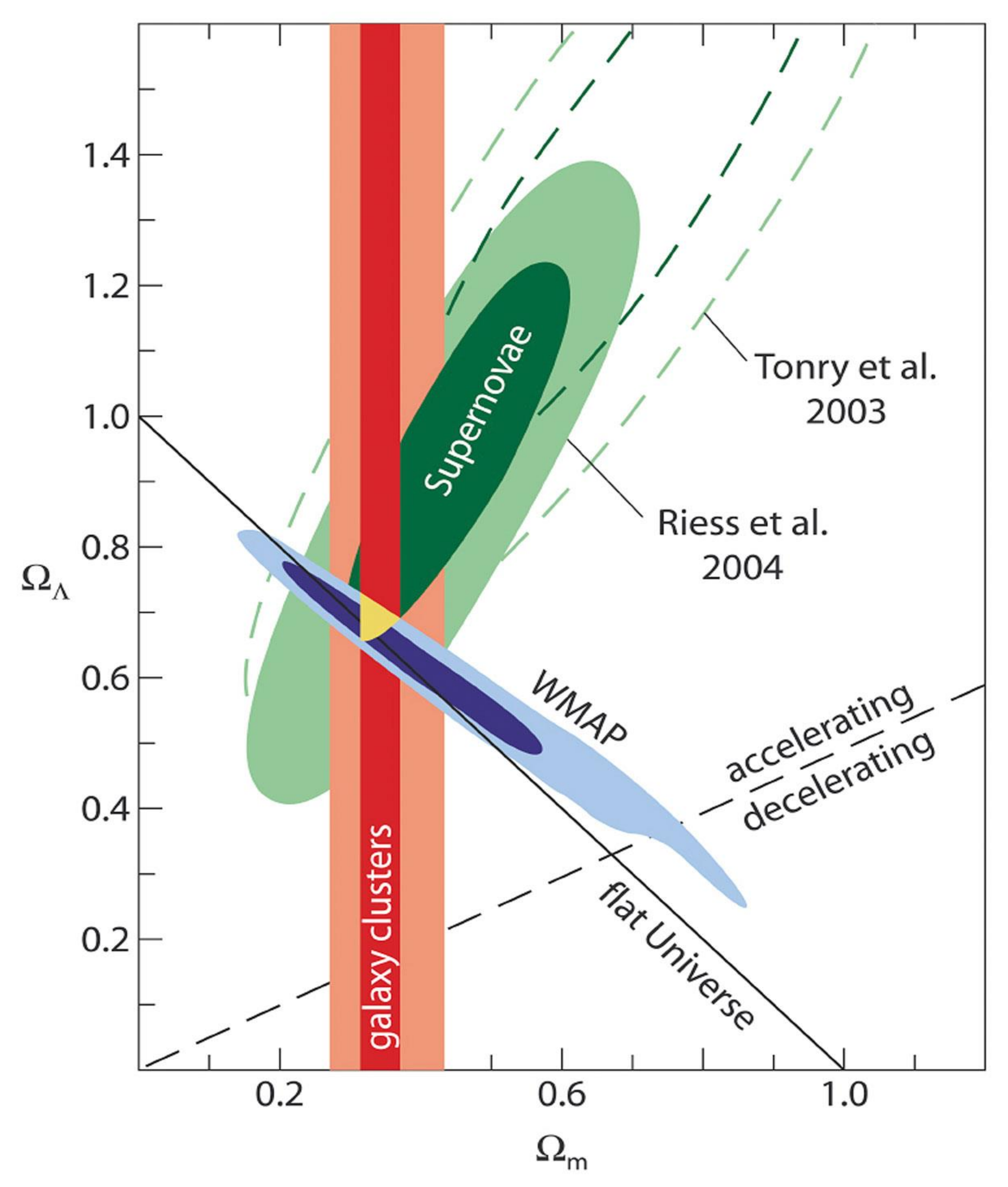


Decay of supernovae in distant galaxies provides a usable standard candle (maximum brightness is correlated to decay rate)

With redshifts, gives the first reliable detection of non-linearity

- the assumed FLRW universe is *presently accelerating*

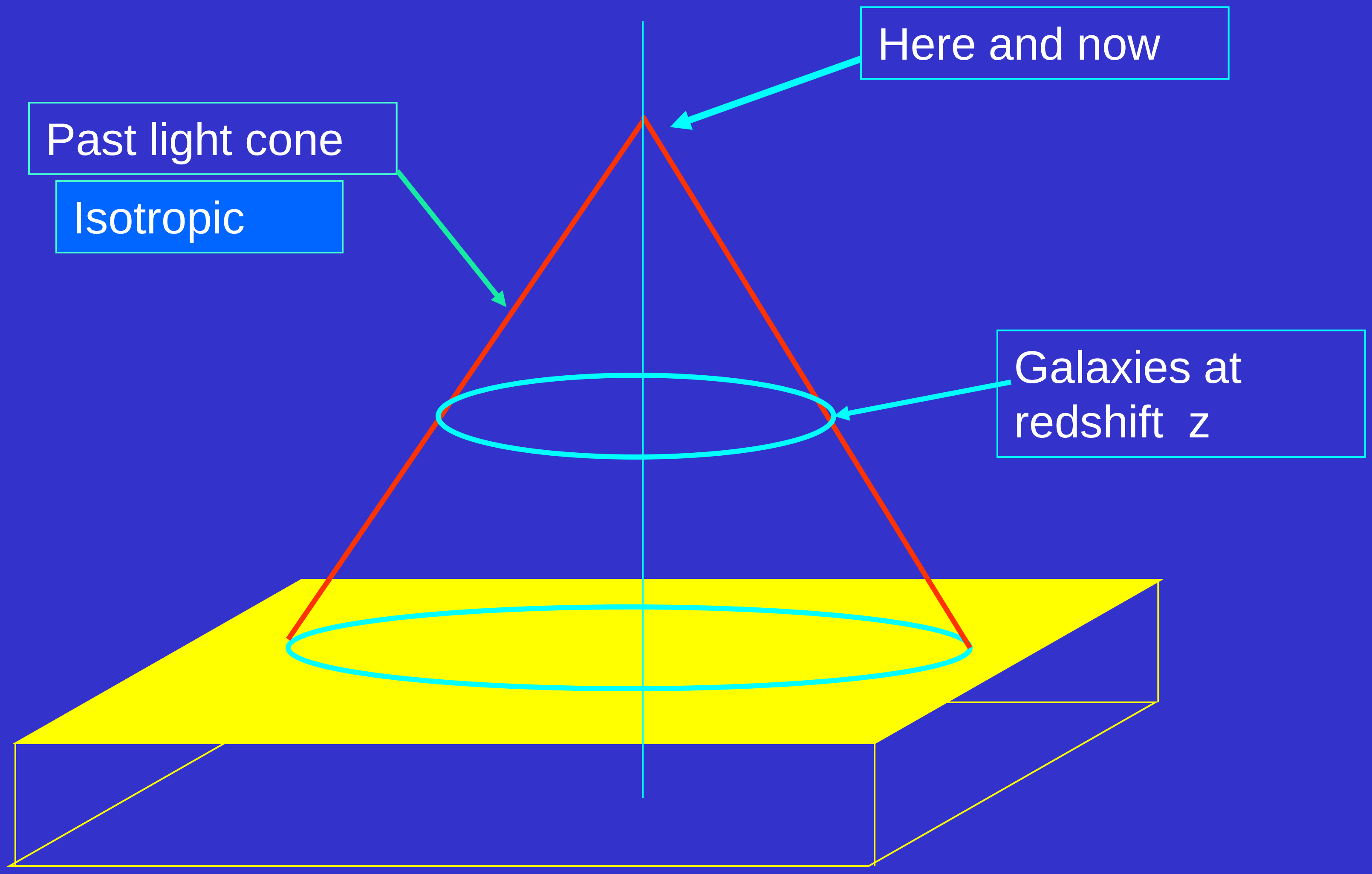
Consequently there is presently an effective positive cosmological constant with $\Omega_\Lambda \sim 0.7$: Nature unknown!



Concordance
FLRW
model:

Dark energy
and
dark matter
with an
almost
flat universe

BUT: We can’t see spatial homogeneity! What we can see is isotropy :



Here and now

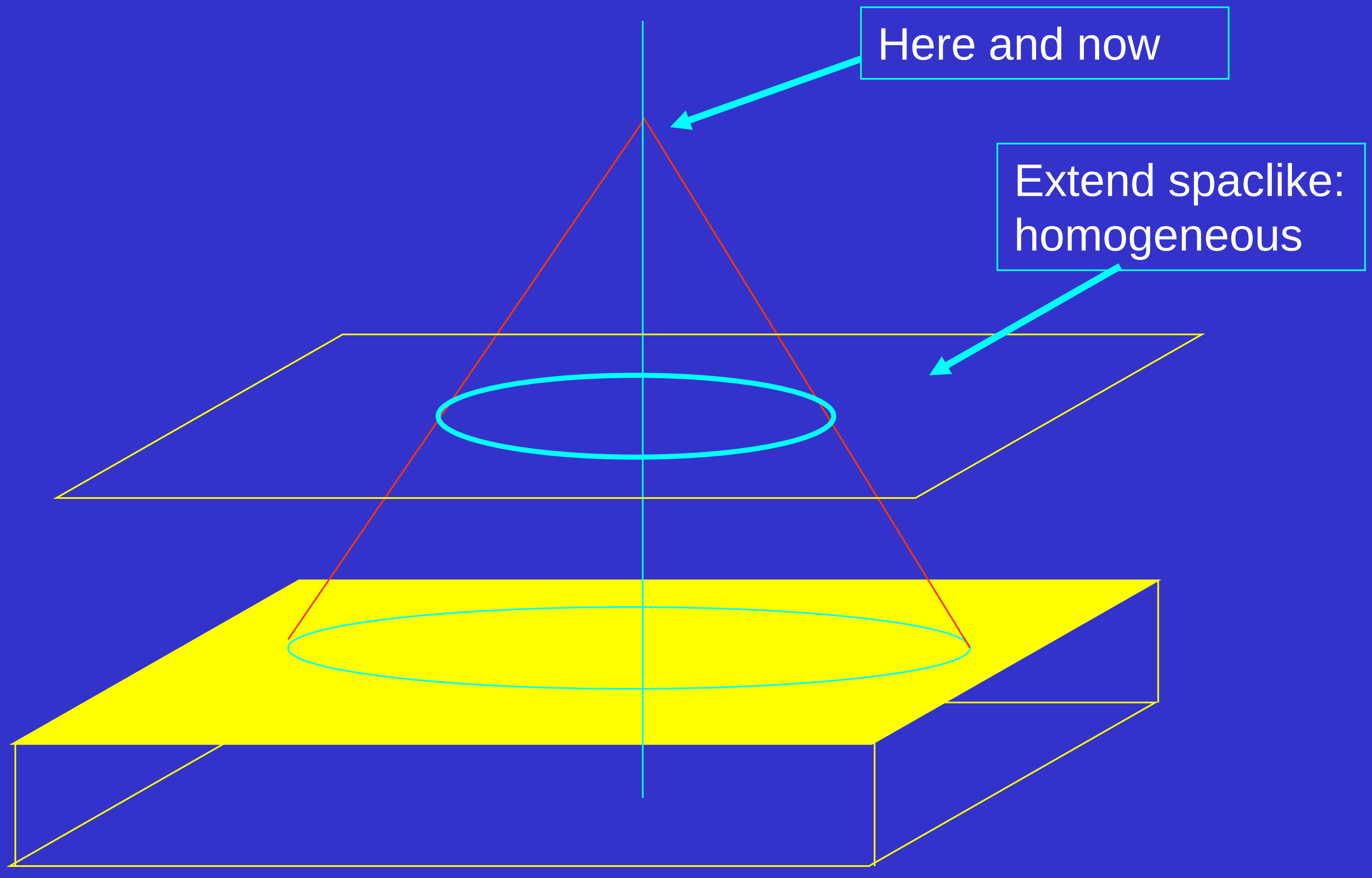
Past light cone

Isotropic

Galaxies at redshift z

G F R Ellis: ``Limits to verification in cosmology''.
9th Texas Symposium on Relativistic Astrophysics, 1978. Munich.

Spatially homogeneous extension:

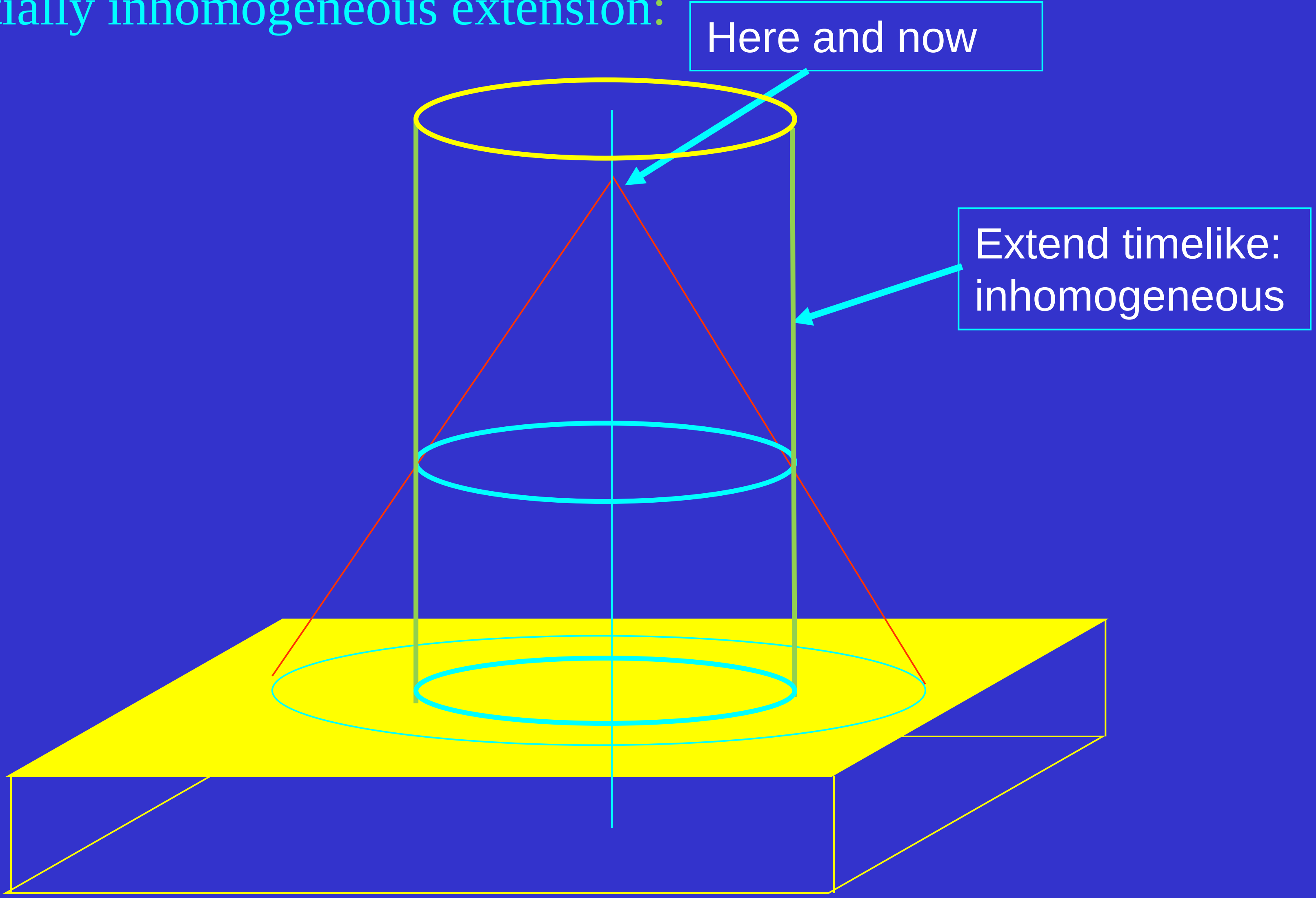


Here and now

Extend spaclike: homogeneous

➔ FLRW model: Standard cosmology

Spatially inhomogeneous extension:


Here and now

Extend timelike: inhomogeneous

➔ LTB model, in pressure-free case.

Is the CP True? Two major theorems

1. Isotropy everywhere in an open set U implies spatial homogeneity in U → FLRW in U

(Walker 1944, Ehlers 1961)

2: Isotropy of freely moving CMB everywhere about a geodesic congruence in an open set U implies spatial homogeneity in U

→ FLRW in U

(Elhers, Geren and Sachs 1967)

Stability of EGS: “Almost EGS” theorem

(Stoeger, Maartens, Ellis 1995)

But those conditions are not directly observable

(G F R Ellis: Qu Journ Roy Ast Soc 16, 245-264: 1975).

Is dark energy inevitable? Large scale inhomogeneity?

Perhaps there is a large scale inhomogeneity of the observable universe

such as that described by the Lemaitre-Tolman-Bondi pressure-free spherically symmetric models:

- With no dark energy or CC.

We are near the centre of a void

M-N. Célérier: "The Accelerated Expansion of the Universe Challenged by an Effect of the Inhomogeneities. A Review" *New Advances in Physics* 1, 29 (2007)

[astro ph/0702416].

LTB (Lemaitre-Tolman Bondi) models

Metric: In comoving coordinates,

$$ds^2 = -dt^2 + B^2(r,t) + A^2(r,t)(d\Theta^2+\sin^2\Theta\, d\Phi^2)$$

where

$$B^2(r,t) = A'(r,t)^2\,(1-k(r))^{-1}$$

and the evolution equation is

$$(\mathring{A}/A)^2 = F(r)/A^3 + 8\pi G\rho_\Lambda/3 - k(r)/A^2$$

with $F'(A'A^2)^{-1} = 8\pi G\rho_{M.}$

Two arbitrary functions: k(r) (curvature) and F(r) (matter).

Large scale inhomogeneity: observational properties

Theorem: LTB model scan provide any m(z) and $r_0(z)$ relations with or without any dark energy,

N Mustapha, C Hellaby and G F R Ellis:

Large Scale Inhomogeneity vs Source Evolution: Can we Distinguish Them?

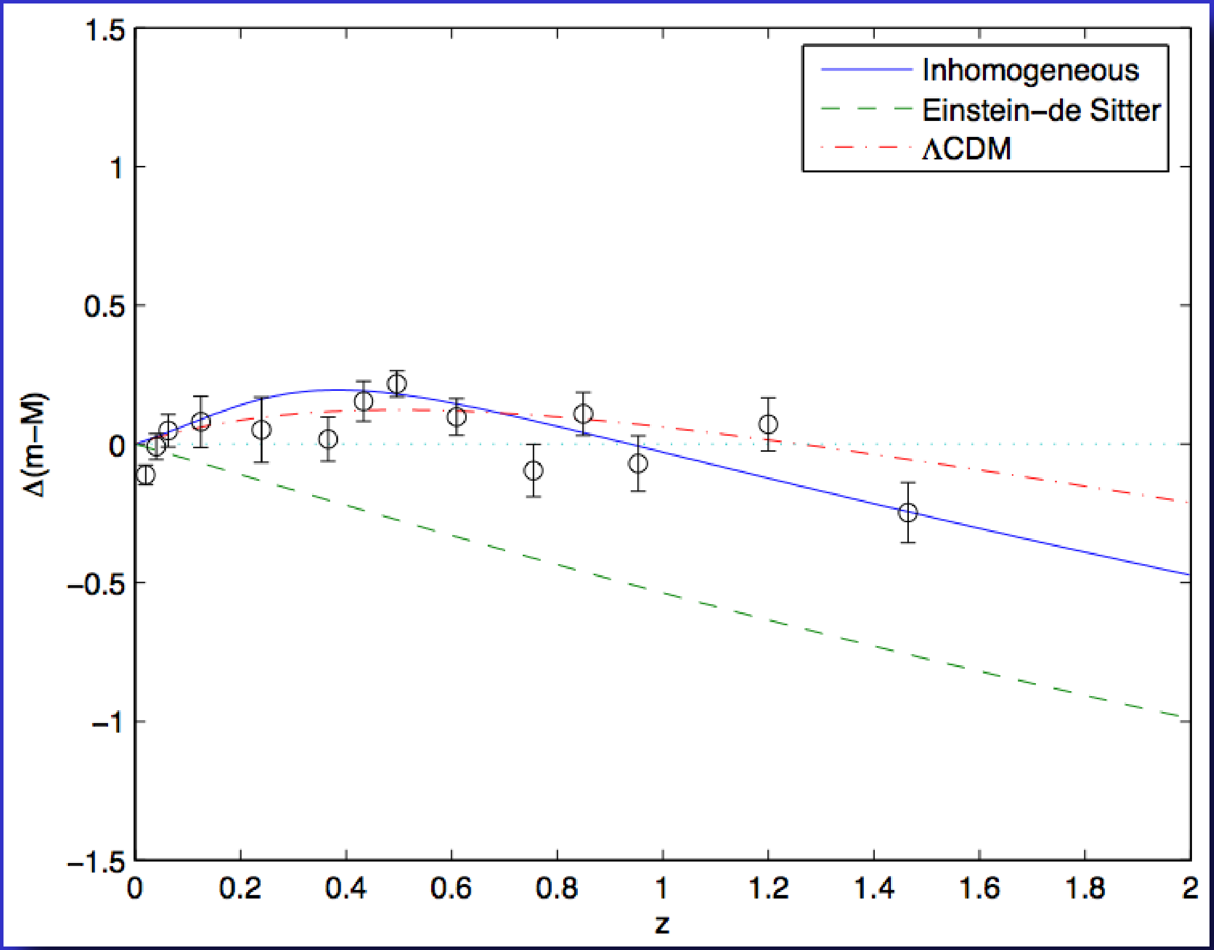
***Mon Not Roy Ast Soc* 292: 817-830 (1999)**

Two arbitrary functions can match any data

Number counts don't prove spatial homogeneity because of source evolution

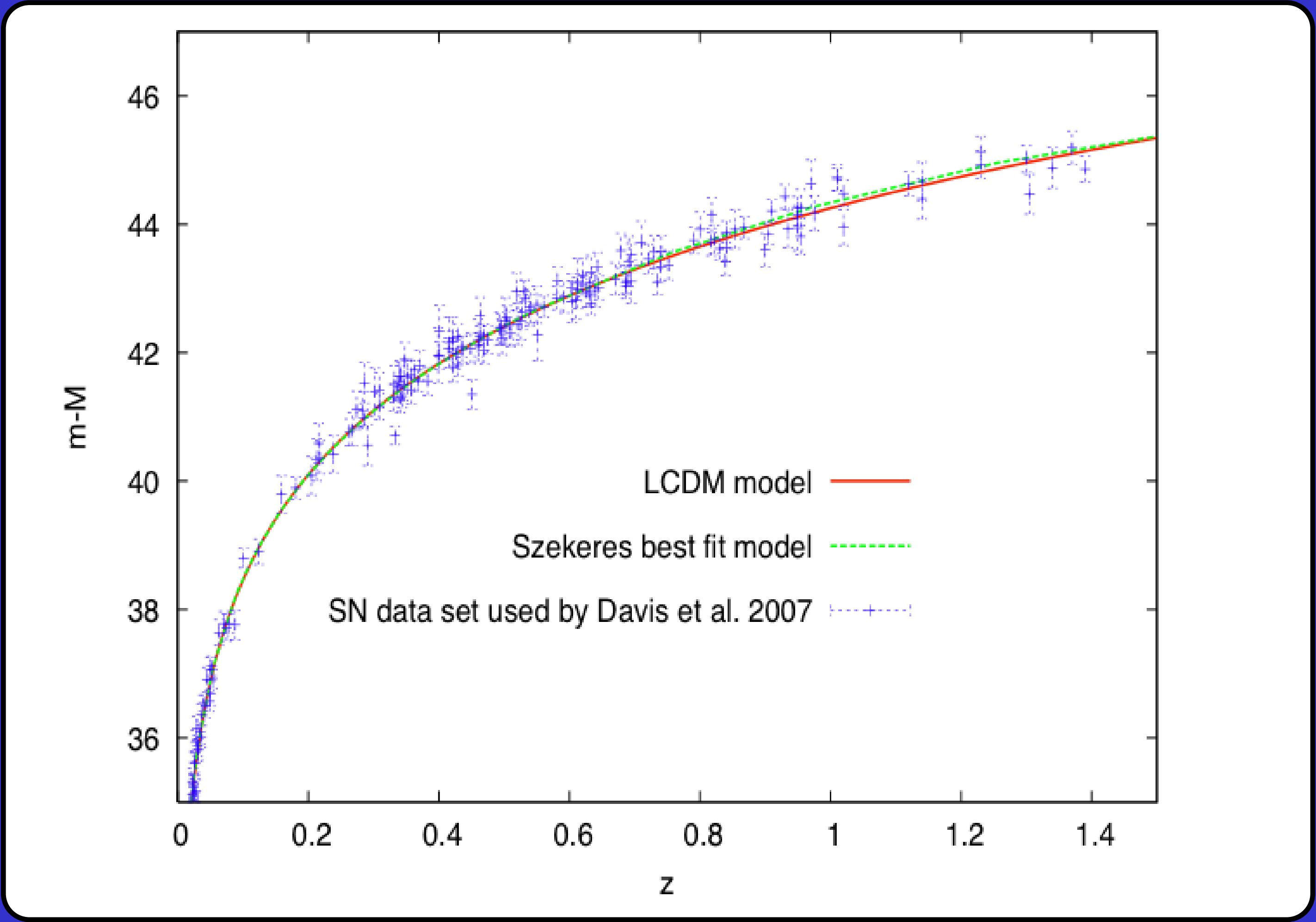
Can't fit radio source number count data by FRW model without source evolution.

We run models backwards to find source evolution!



Alnes, Amarzguioui, and Gron astro-ph/0512006

We can fit any area distance and number count observations with no dark energy in an inhomogeneous model



Szekeres model: “We find that such a model can easily explain the observed luminosity distance-redshift relation of supernovae without the need for dark energy, when the inhomogeneity is in the form of an underdense bubble centered near the observer. We find that the position of the first CMB peak can be made to match the WMAP observations.” Ishak et al 0708.2943

Typical observationally viable model:

We live roughly centrally (within 10% of the central position) in a large void:

a compensated underdense region stretching to $z \approx 0.08$ with $\delta \approx -0.4$ and size 160/h Mpc to 250/h Mpc, a jump in the Hubble constant of about 1.20, and no dark energy or quintessence field

Other observations??

Can also fit CBR observations: Larger values of r

"Local void vs dark energy: confrontation with WMAP and Type IA supernovae" (2007)

S. Alexander, T. Biswas, A. Notari, D. Vaid [arXiv:0712.0370]

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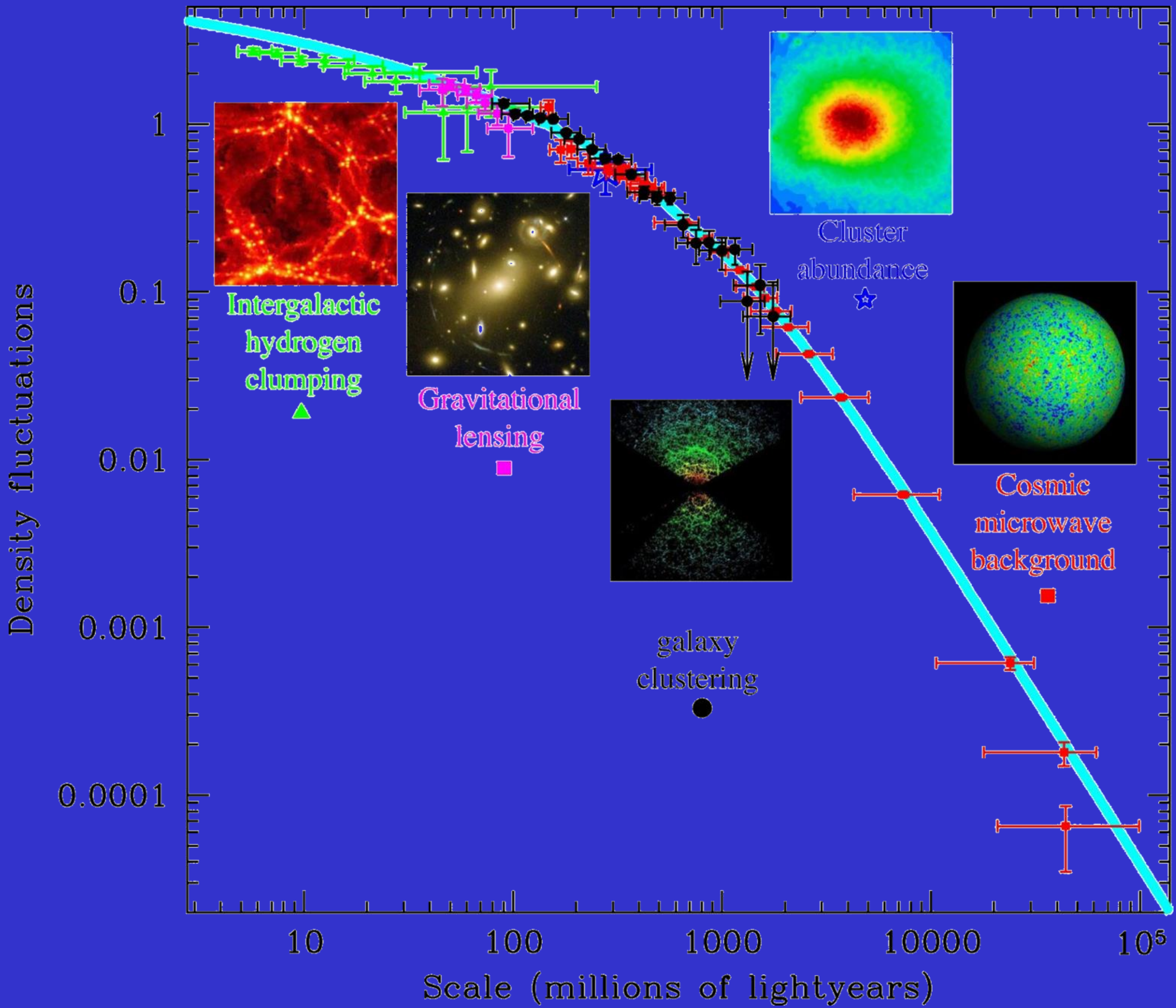
"Testing the Void against Cosmological data: fitting CMB, BAO, SN and H0"

Biswas, Notari, Valkenburg [arXiv:1007.3065]

Quadrupole? Perhaps also (and alignment)
Baryon acoustic oscillations? Maybe – more tricky

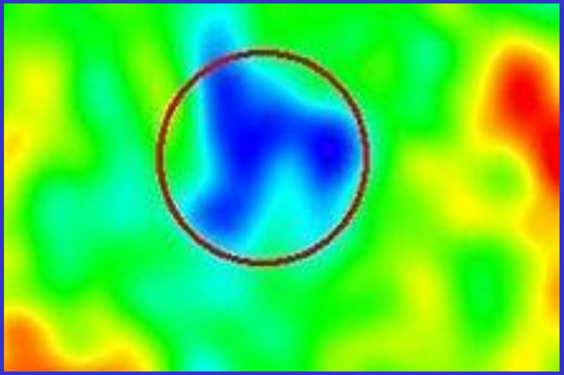
Nucleosynthesis: OK indeed better

scales probed by different observations: different distances



Do large voids occur?

Perhaps- CMB cold spot:



Might indicate large void.

If so: your inflationary model had better allow this to happen! – Indeed inflation can allow almost anything to happen (Steinhardt)

Stop press: Pan-STARRS preliminary figures that appear to tell a story of a fairly large, (up to 100 Mpc radius) void at around redshift 0.1-0.11, and front of it a filament at a slightly lower redshift.

From I.Szapudi, A.Kovacs, B. Granett, and Z. Frei with the Pan-STARRS1 Collaboration:

I.Szapudi, A.Kovacs, B. Granett, and Z. Frei with the Pan-STARRS1 Collaboration

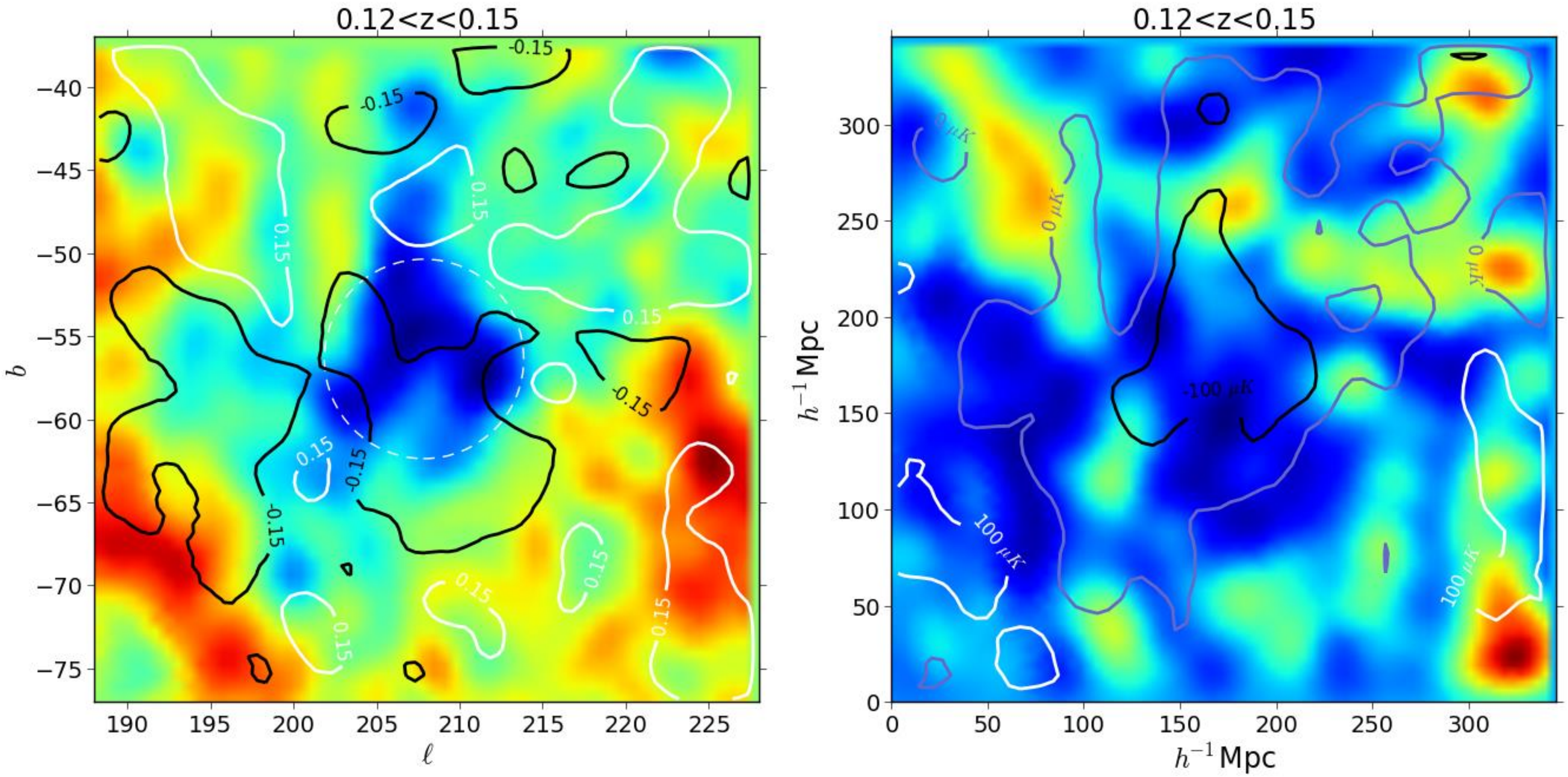
Photo-metric redshift slices showing LSS=Large Scale Structure, i.e. galaxies.

They are centered on the ``infamous" CMB Coldspot, and the main void appears to be centered slightly in the lower left from that.

The photometric redshift error is estimated to be 0.033 from GAMA, so the slices are clearly not independent.

Our main problem is that we are still worried about systematic errors, in particular another method gives us about 20% stretched photo-z (although qualitatively similar images), and while we tried to figure out the reason, so far we could not get them to be consistent. Therefore all of this is *very* preliminary, should be taken with a grain of salt.

I.Szapudi, A.Kovacs, B. Granett, and Z. Frei with the Pan-STARRS1 Collaboration



A photo-metric redshift slice (0.12<z<0.15). The left figure shows the CMB in colors with LSS in contours, while the right figure shows LSS in colors, and CMB in contours.

Fairly large void (up to 100 Mpc radius) at z ~ 0.1-0.11

Improbability

“It is improbable we are near the centre”

But there is always improbability in cosmology

Can shift it:

FRW geometry
Inflationary potential
Inflationary initial conditions
Position in inhomogeneous universe
Which universe in multiverse

Competing with probability 10^{-120} for Λ in a FRW universe.

Also: there is no proof universe is probable.
May be improbable!! Indeed, it is!!
- Test idea by making inhomogeneous models

Can We Avoid Dark Energy?

James P. Zibin, Adam Moss, and Douglas Scott

The idea that we live near the center of a large, nonlinear void has attracted attention recently as an alternative to dark energy or modified gravity. We show that an appropriate void profile can fit both the latest cosmic microwave background and supernova data. However, this requires either a fine-tuned primordial spectrum or a Hubble rate so low as to rule these models out. We also show that measurements of the *radial* baryon acoustic scale can provide very strong constraints.

Our results present a serious challenge to void models of acceleration.

Phys. Rev. Lett. 101, 251303 (2008)

- **“First-Year Sloan Digital Sky Survey-II (SDSS-II) Supernova Results: Constraints on Non-Standard Cosmological Models”** J. Sollerman, et al Astrophysical Journal 703 (2009) 1374-1385 [**arXiv:0908.4276**]
  - We use the new SNe Ia discovered by the SDSS-II Supernova Survey together with additional supernova datasets as well as observations of the cosmic microwave background and baryon acoustic oscillations to constrain cosmological models. This complements the analysis presented by Kessler et al. in that we discuss and rank a number of the most popular non-standard cosmology scenarios.
  - Our investigation also includes inhomogeneous Lemaitre-Tolman-Bondi (LTB) models. While our LTB models can be made to fit the supernova data as well as any other model, the extra parameters they require are not supported by our information criteria analysis.

Testing the void against cosmological data: fitting CMB, BAO, SN and H_0

Tirthabir Biswas, Alessio Notari and Wessel Valkenburg

JCAP November 2010

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). [➔]

Tirthabir Biswas, Alessio Notari and Wessel Valkenburg

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,

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.

Precision cosmology defeats void models for acceleration

Adam Moss, James P. Zibin, and Douglas Scott

Phys. Rev. D 83, 103515 (2011)

The suggestion that we occupy a privileged position near the center of a large, nonlinear, and nearly spherical void has recently attracted much attention as an alternative to dark energy.

We use supernovae and the *full* cosmic microwave background spectrum. We also include constraints from radial baryonic acoustic oscillations, the local Hubble rate, age, big bang nucleosynthesis, the Compton *y* distortion, and 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

Galaxy correlations and the BAO in a void universe: structure formation as a test of the Copernican Principle

Sean February, Chris Clarkson, and Roy Maartens

arXiv1206.1602

Large scale inhomogeneity distorts the spherical Baryon Acoustic Oscillation feature into an ellipsoid which implies that the bump in the galaxy correlation function occurs at different scales in the radial and transverse correlation functions. The radial and transverse correlation functions are very different from those of the concordance model, even when the models have the same average BAO scale.

This implies that if the models are fine-tuned to satisfy average BAO data, there is enough extra information in the correlation functions to distinguish a void model from LCDM.

We expect these new features to remain when the full perturbation equations are solved, which means that the radial and transverse galaxy correlation functions can be used as a powerful test of the Copernican principle.

Direct Observational tests

We have two different models – standard ΛCDM and inhomogeneous LTB – that can both explain the observations. How to distinguish them?

What we need are direct observational tests of the Copernican (spatial homogeneity) assumption;

These crucially test the geometric foundations of the standard model;

This is now the subject of much investigation .

Particularly important are such tests that are independent of field equations and matter content rather than being highly model dependent

A general test of the Copernican Principle

Chris Clarkson, Bruce A. Bassett, Teresa Hui-Ching Lu

To date, there has not been a general way of determining the validity if the Copernican Principle -- that we live at a typical position in the universe -- significantly weakening the foundations of cosmology as a scientific endeavour.

Here we present an observational test for the Copernican assumption which can be automatically implemented while we search for dark energy in the coming decade.

Our test is entirely independent of any model for dark energy or theory of gravity and thereby represents a model-independent test of the Copernican Principle.

[PhysRevLett.101.011301: arXiv:0712.3457v2]

Measuring Curvature in FLRW

- in FLRW we can combine Hubble rate and distance data to find curvature at present time from null cone data

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

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

- independent of *all* other cosmological parameters, including dark energy model, and theory of gravity
- can be used at single redshift
- what else can we learn from this?

- FLRW: must be same for all z!

Clarkson Bassett Lu arXiv:0712.3457

Generic Consistency Test of FLRW

- since Ω_k independent of *z* we can differentiate to get consistency relation

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

- depends *only* on FLRW geometry:
  - **independent of curvature, dark energy, theory of gravity**

- should expect $\mathscr{C}(z) \approx 10^{-5}$ in FLRW
- In non-FLRW case this will not be true. $\mathscr{C}(z) \neq 0$

Copernican Test!

- Errors may be estimated from a series expansion

$$\mathscr{C}(z) = \left[q_0^{(D)} - q_0^{(H)}\right] z + \mathcal{O}(z^2)$$

deceleration parameter measured from *area distance* measurements

deceleration parameter measured from *Hubble* measurements

- simplest to measure *area distance* from BAO

[Percival et al]

- In FLRW they have to be the same
- In LTB they can be different

It’s only as difficult as dark energy...

- measuring *w(z)* from Hubble uses

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

  – requires *H’(z)*

[see Clarkson Cortes & Bassett JCAP08(2007)011; arXiv:astro-ph/0702670

- and from distances requires second derivatives *D’’(z)*

$D_L = (H_0/c)d_L$

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

- simplest to begin with $\Delta\Omega_k = \Omega_k(z_1) - \Omega_k(z_2)$ via $\Omega_k = \frac{[H(z)D'(z)]^2 - 1}{[H_0 D(z)]^2}$

Time drift of cosmological redshifts as a test of the Copernican principle

Jean-Philippe Uzan, Chris Clarkson, George F.R. Ellis

We present the time drift of the cosmological redshift in a general spherically symmetric spacetime.

We demonstrate that its observation would allow us to test the Copernican principle and so determine if our universe is radially inhomogeneous, an important issue in our understanding of dark energy. In particular, when combined with distance data, this extra observable allows one to fully reconstruct the geometry of a spacetime describing a spherically symmetric under-dense region around us, purely from background observations.

[arXiv:0801.0068]

Postulate of Uniform Thermal Histories

Why do we think universe is homogeneous?

Different initial conditions and/or physics out there would lead to different objects forming: but we see similar everywhere

Hence require the same thermal histories:

- Identical function T(t)

Hypothesis: this requires spatially homogeneous geometry

But: counterexample! Bonnor and Ellis

``Observational homogeneity of the universe".

Mon Not Roy Ast Soc 218: 605-614 (1986).

Presumption: this is exceptional:

the result is almost always true!

Testing Homogeneity with Galaxy Star Formation Histories

Ben Hoyle, Rita Tojeiro, Raul Jimenez, Alan Heavens, Chris Clarkson, Roy Maartens arXiv:1209.6181

Homogeneity must be probed inside our past lightcone, while observations take place on the lightcone. The star formation history (SFH) in the galaxy fossil record provides a novel way to do this.

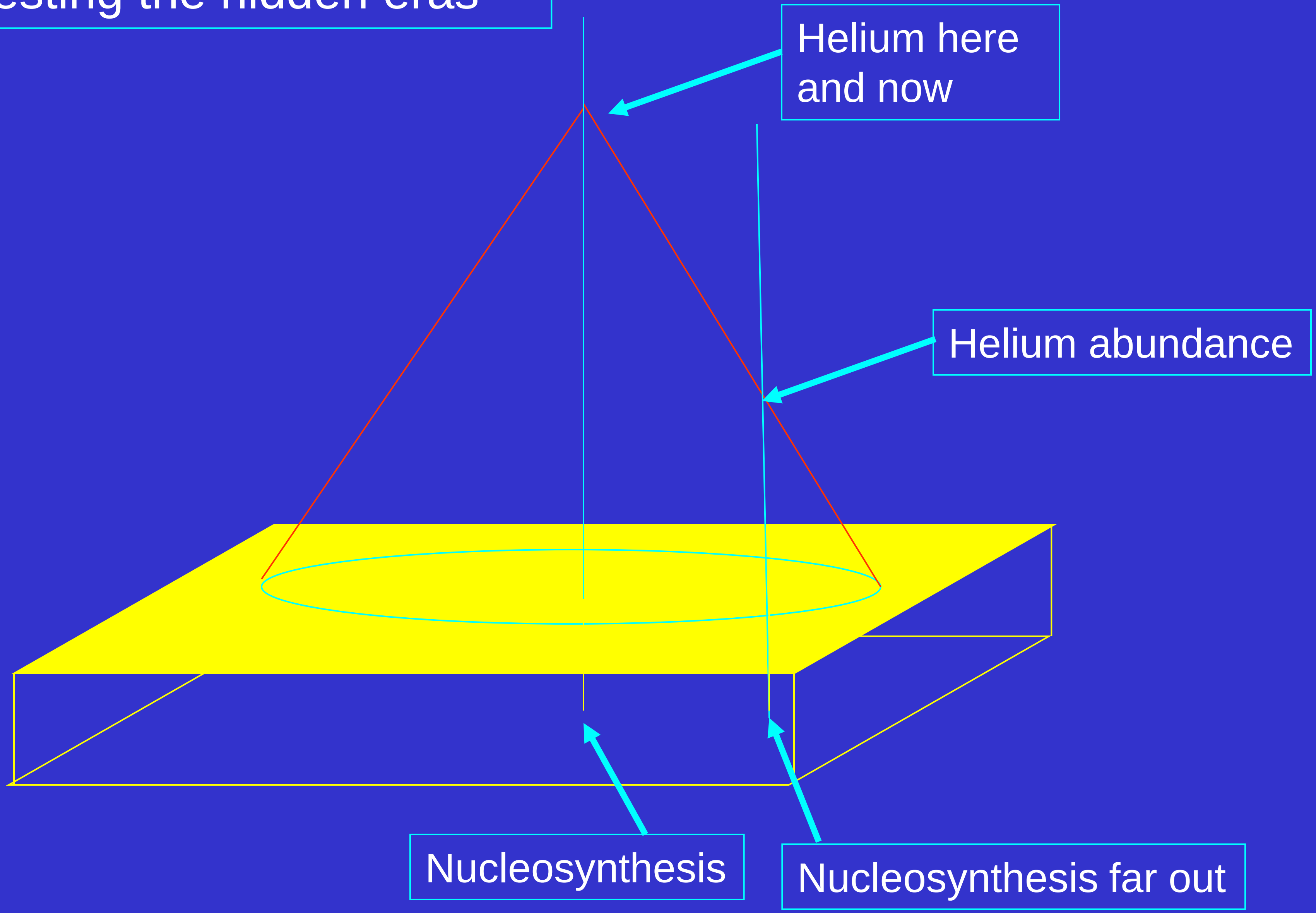
We calculate the SFH of stacked Luminous Red Galaxy (LRG) spectra obtained from the Sloan Digital Sky Survey.

Using the SFH in a time period which samples the history of the Universe between look-back times 11.5 to 13.4 Gyrs as a proxy for homogeneity, we calculate the posterior distribution for the excess large-scale variance due to inhomogeneity, and find that the most likely solution is no extra variance at all.

At 95% credibility, there is no evidence of deviations larger than 5.8%.

Key test: variation of ages with redshift. Are high z ages discordant?

Elements with distance:
Testing the hidden eras



Helium here and now

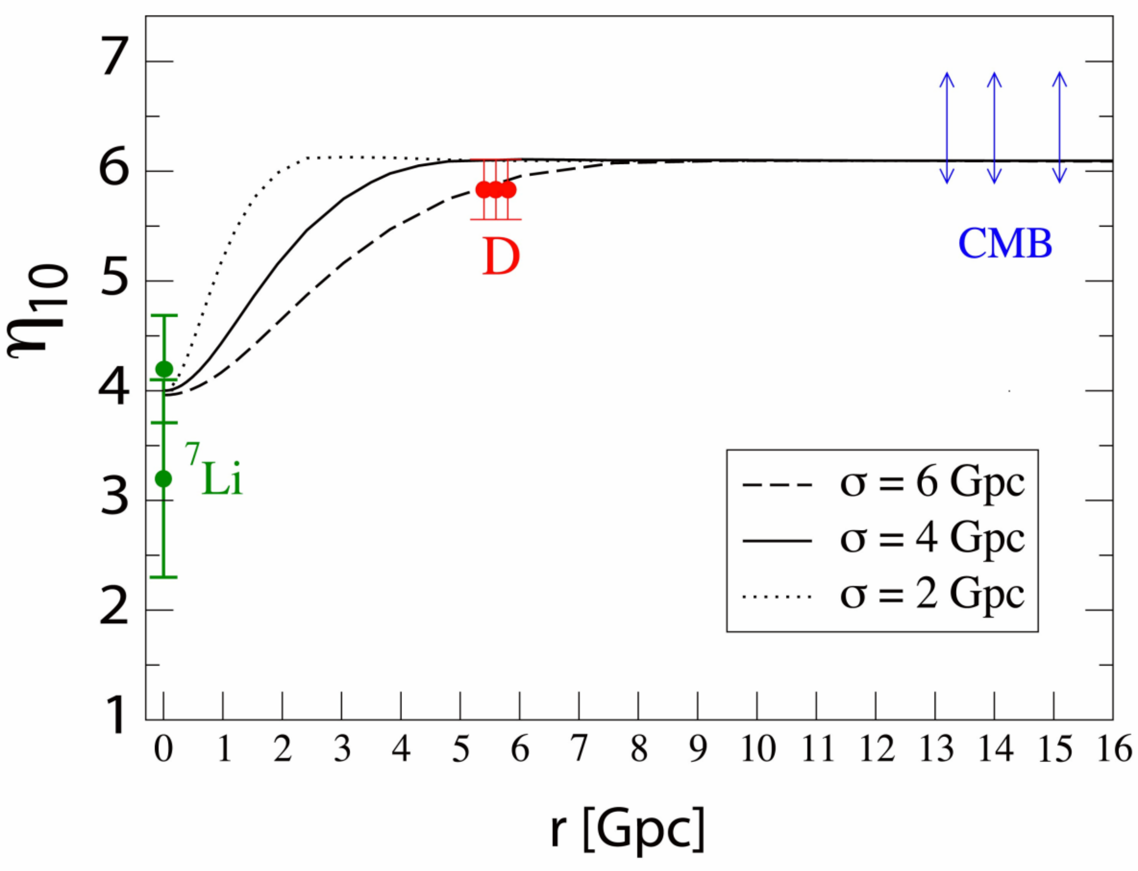
Helium abundance

Nucleosynthesis

Nucleosynthesis far out

Element abundances

arXiv:1003.1043 “Do primordial Lithium abundances imply there's no Dark Energy? : Regis, Clarkson



CMB Observational Tests

- Almost EGS Theorem: If CMB is almost isotropic everywhere on U, universe is almost FLRW in U

WR Stoeger, R Maartens, GFR Ellis 1995/4 Astrophysical Journal 443: 1-5

Test via scattered CMB photons - looking inside past null cone [Goodman 1995; Caldwell & Stebbins 2007]

  - if CMB very anisotropic around distant observers, SZ scattered photons have distorted spectrum

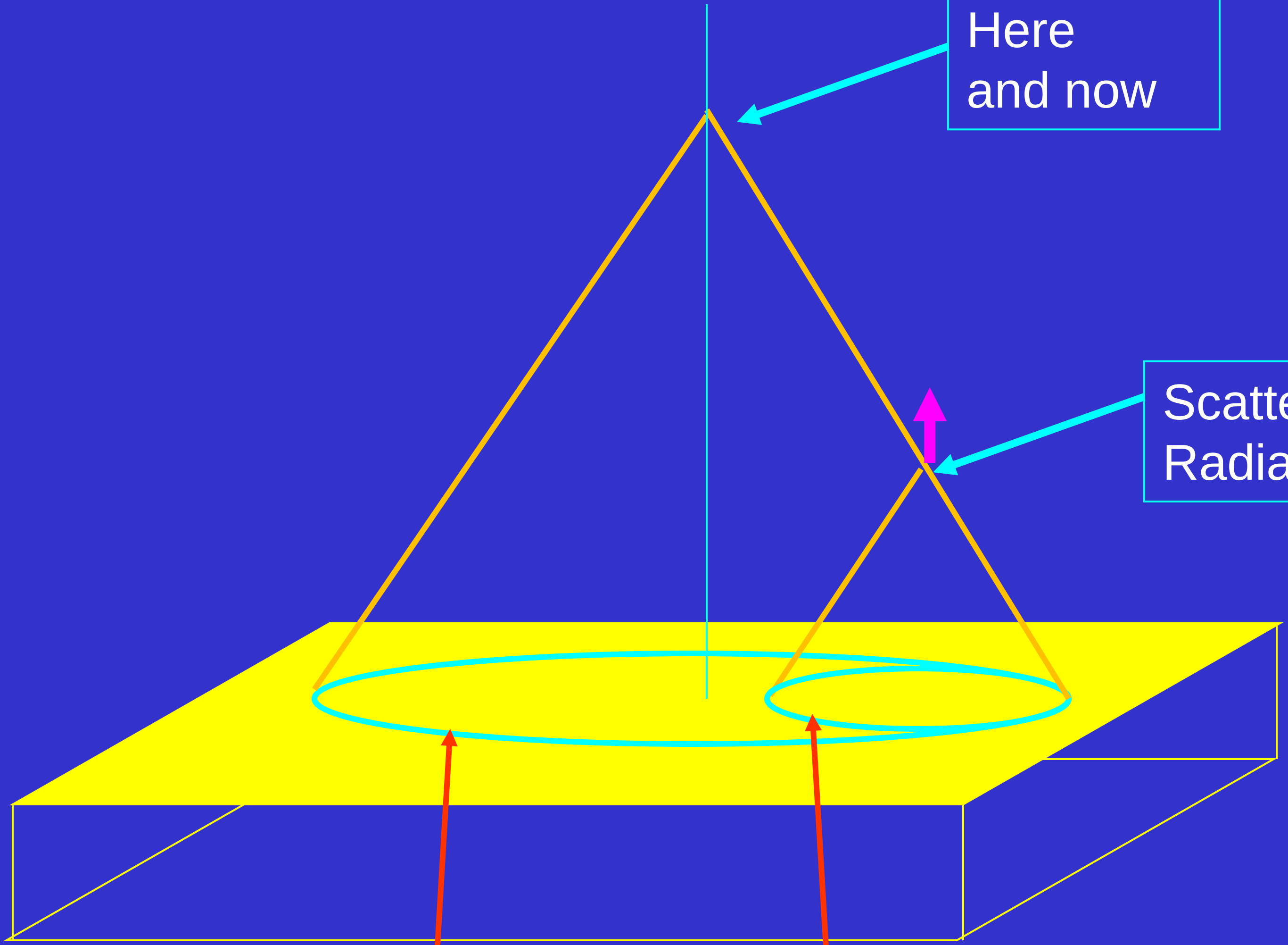
The isotropic blackbody CMB as evidence for a homogeneous universe Timothy Clifton, Chris Clarkson, Philip Bull
arXiv:1011.4920v1 [gr-qc]

Neither an isotropic primary CMB nor combined observations of luminosity distances and galaxy number counts are sufficient to establish whether the Universe is spatially homogeneous and isotropic on the largest scales

The inclusion of the Sunyaev-Zel'dovich effect in CMB observations, however, dramatically improves this situation. We show that even a solitary observer who sees an isotropic blackbody CMB can conclude that the universe is homogeneous and isotropic in their causal past when the Sunyaev-Zel'dovich effect is present.

Critically, however, the CMB must either be viewed for an extended period of time, or CMB photons that have scattered more than once must be detected.

KSZ test of Copernican Principle:



Here
and now

Scattering event:
Radiation isotropic?

CMB 2-sphere

COBE, WMAP, Planck

Probes Interior

Confirmation of the Copernican Principle at Gpc Radial Scale and above from the Kinetic Sunyaev-Zel’dovich Effect Power Spectrum

Pengjie Zhang and Albert Stebbins

Phys. Rev. Lett. 107, 041301 (2011)

The Copernican principle, a cornerstone of modern cosmology, remains largely unproven at the Gpc radial scale and above. Here will show that violations of this type will inevitably cause a first order anisotropic kinetic Sunyaev-Zel’dovich effect. If large scale radial inhomogeneities have an amplitude large enough to explain the “dark energy” phenomena, the induced kinetic Sunyaev-Zel’dovich power spectrum will be much larger than the Atacama Cosmology Telescope and/or South Pole Telescope upper limit. This single test confirms the Copernican principle and rules out the adiabatic void model as a viable alternative to dark energy.

Linear kinetic Sunyaev–Zel'dovich effect and void models for acceleration J P Zibin and A Moss *CQG.* **28** 164005 (2011)

We examine a new proposal constrain inhomogeneous models using the linear kinetic Sunyaev–Zel'dovich (kSZ) effect due to the structure within the void. The simplified 'Hubble bubble' models previously studied appeared to predict far more kSZ power than is actually observed, independently of the details of the initial conditions and evolution of perturbations in such models.

We show that the constraining power of the kSZ effect is considerably weakened (though still impressive) under a fully relativistic treatment of the problem and point out several theoretical ambiguities and observational shortcomings which further qualify the results. Nevertheless, we conclude that a very large class of void models is ruled out by the combination of kSZ and other methods.

Kinematic Sunyaev-Zel’dovich effect as a test of general radial inhomogeneity in Lemaître-Tolman-Bondi cosmology

P Bull T Clifton and P G. Ferreira **Phys. Rev. D 85, 024002 (2012)**

Most of these previous studies explicitly set the LTB “bang time” function to be constant, neglecting an important freedom of the general solutions. Here we examine these models in full generality by relaxing this assumption. We find that although the extra freedom allowed by varying the bang time is sufficient to account for some observables individually, it is not enough to simultaneously explain the supernovae observations, the small-angle CMB, the local Hubble rate, and the kinematic Sunyaev-Zel’dovich effect.

This set of observables is strongly constraining, and effectively rules out simple LTB models as an explanation of dark energy

A key result

- The tests seem to be confirming the Copernican principle
- That is an important result. If we could do away with dark energy a lot of current cosmology would change
- It requires precision tests for this exclusion
- It is good science: it generates a variety observational tests which can be carried out
- It changes a philosophical assumption into a tested scientific hypothesis
- UNLESS …

EVIDENCE FOR A ~300 MEGAPARSEC SCALE UNDER-DENSITY IN THE LOCAL GALAXY DISTRIBUTION

R. C. Keenan, A. J. Barger, and L. L. Cowie

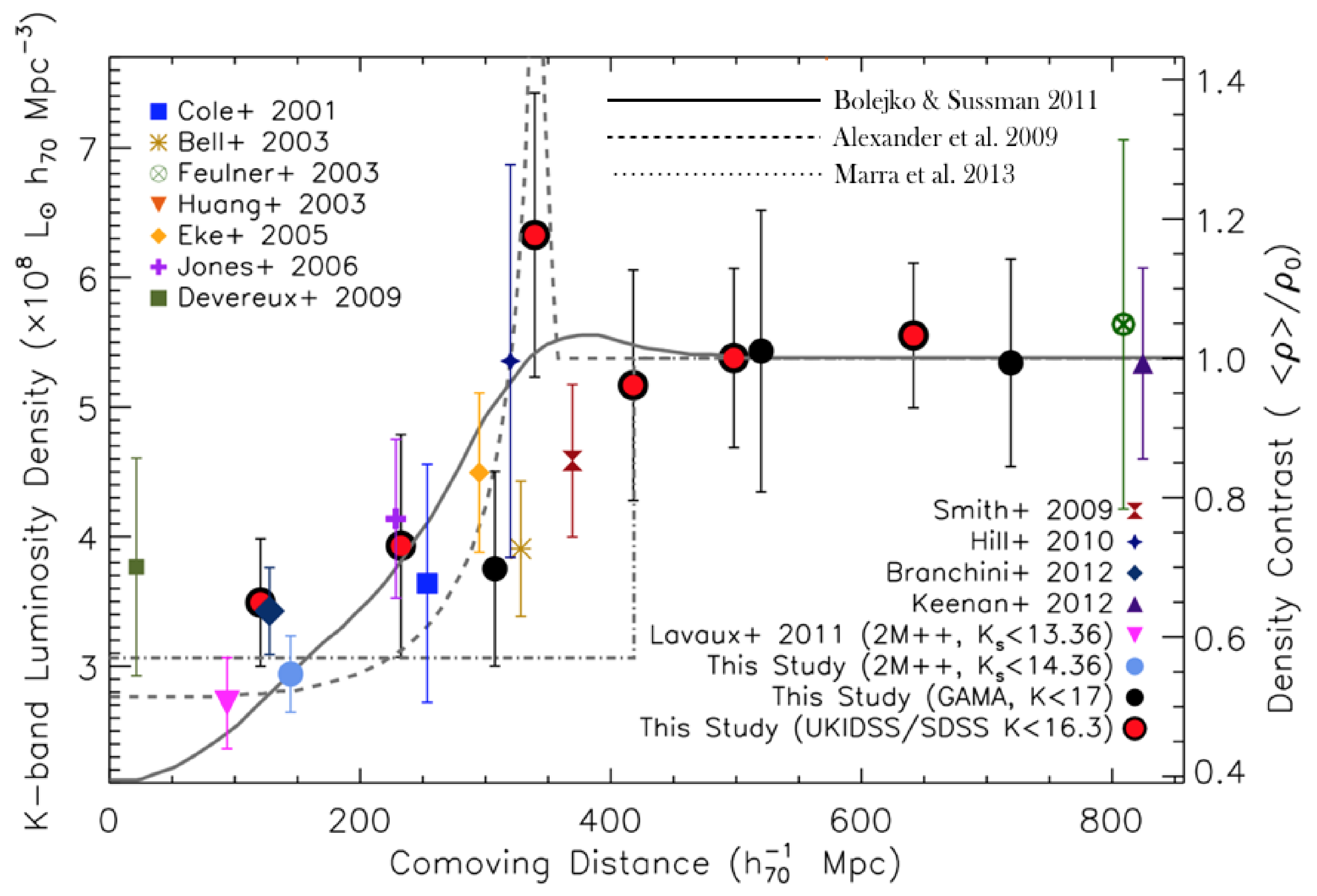
The Astrophysical Journal, 775:62, 2013 September 20

We measure the *K*-band luminosity density as a function of redshift to test for a local under-density. We select galaxies from the UKIDSS Large Area Survey and use spectroscopy from the Sloan Digital Sky Survey (SDSS), the Two-degree Field Galaxy Redshift Survey, the Galaxy And Mass Assembly Survey (GAMA), and other redshift surveys to generate a *K*-selected catalog of ~35,000 galaxies that is ~95% spectroscopically complete at *K*AB < 16.3 (*K*AB < 17 in the GAMA fields).

To complement this sample at low redshifts, we also analyze a *K*-selected sample from the 2M++ catalog, which combines Two Micron All Sky Survey (2MASS) photometry with redshifts from the 2MASS redshift survey, the Six-degree Field Galaxy Redshift Survey, and the SDSS.

The combination of these samples allows for a detailed measurement of the *K*-band luminosity density as a function of distance over the redshift range $0.01 < z < 0.2$ (radial distances $D \sim 50\text{–}800\ h^{-1}{}_{70}$ Mpc).

Luminosity Density vs. Distance



Keenan, Barger, & Cowie 2013, ApJ 775, 62

Must use the right perturbation theory:

Evolution of linear perturbations in spherically symmetric dust models
Sean February, Julien Larena, Chris Clarkson, Denis Pollney arXiv:1311.5241

We present a new numerical code to solve the master equations describing the evolution of linear perturbations in a spherically symmetric but inhomogeneous background.

This is considerably more complicated than linear perturbations of a homogeneous and isotropic background because the inhomogeneous background leads to coupling between density perturbations and rotational modes of the spacetime geometry, as well as gravitational waves.

Previous analyses of this problem ignored this coupling in the hope that the approximation does not affect the overall dynamics of structure formation in such models. The evolution of the gravitational potentials within the void is inaccurate at more than the 10% level, and is even worse on small scales.

2: Consistency over Scales

1. Backreaction effects on dynamics?

Non commutation of averaging and deriving the field equations
Averaging leads to extra terms in effective higher level equations

G. F. R. Ellis in *General Relativity and Gravitation,*
Ed B Bertotti et al (Reidel, 1984), 215.

Cosmology: contribution to dark energy??

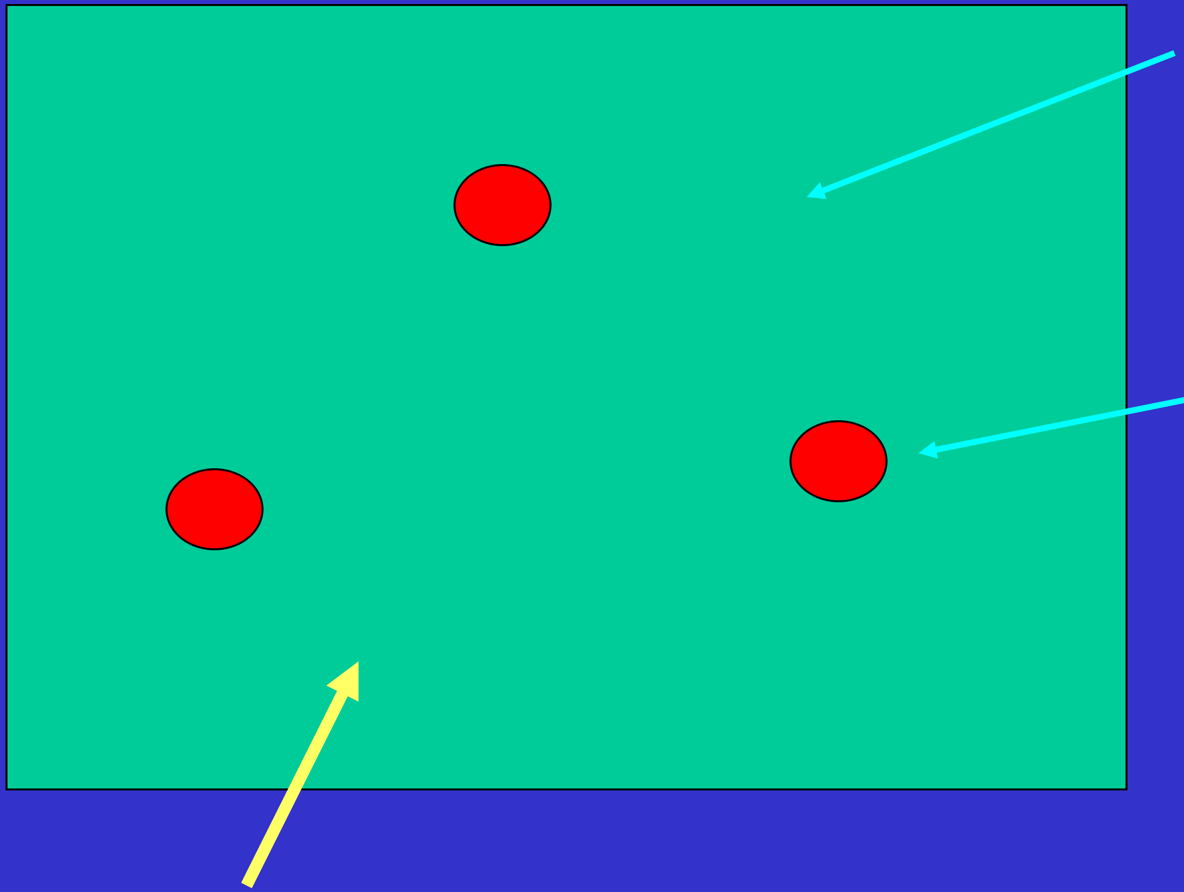
- Very interesting effect, certainly there
- Probably not significant in cosmological context
- But Buchert, Wiltshire, Kolb, Ishak disagree.

2. Observations in the lumpy real universe:

Most light rays travel in vacuum, not FLRW geometry!
- Affects observations in an era of precision cosmology

Standard perturbed FLRW

FLRW with inhomogeneities imbedded



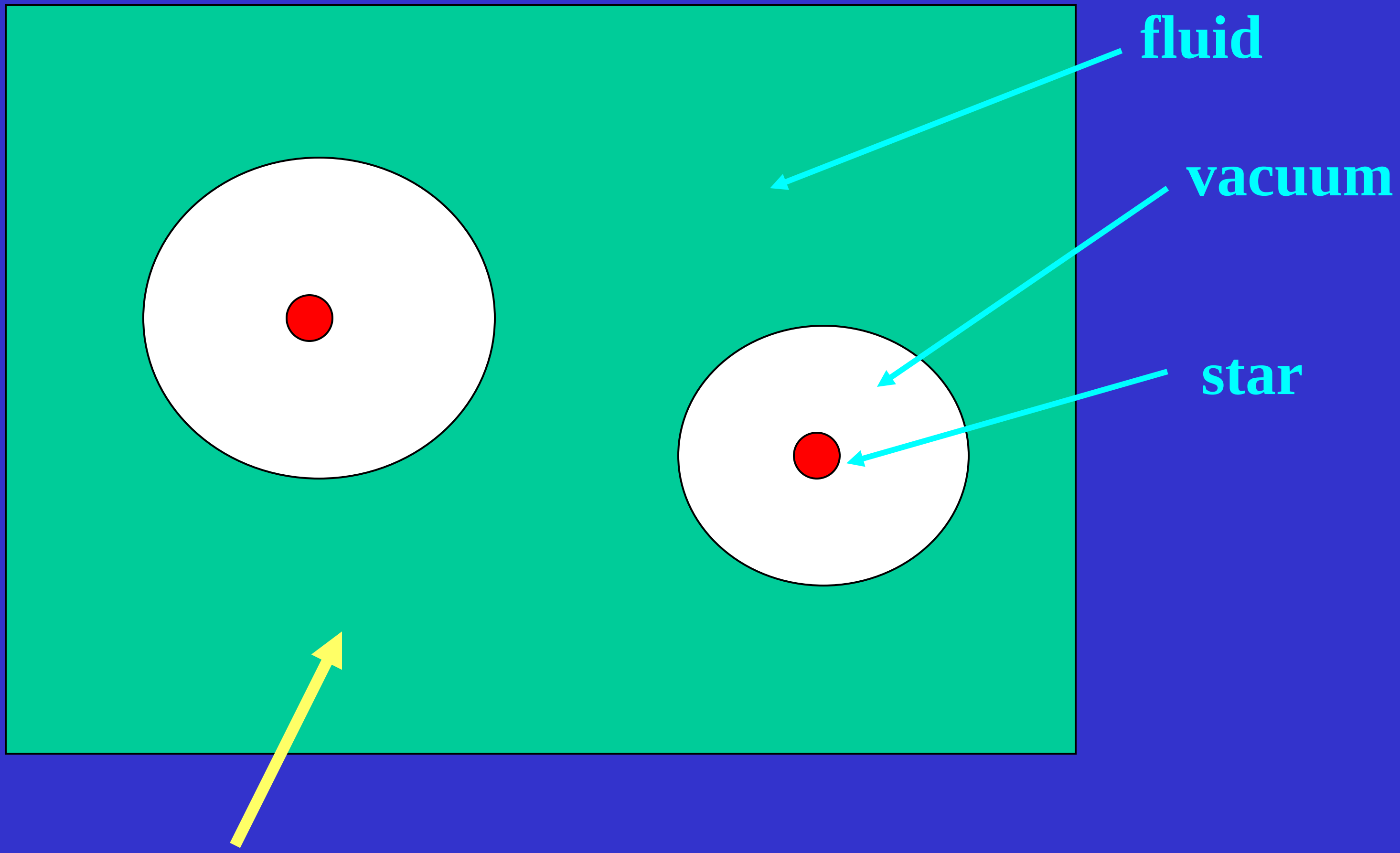
fluid

Galaxy cluster:
Virialized;
Solar system??

FLRW regions expand and carry galaxies with them
BUT no local static domains (can measure Ho in Solar System?)

Swiss cheese model

(Einstein-Strauss)

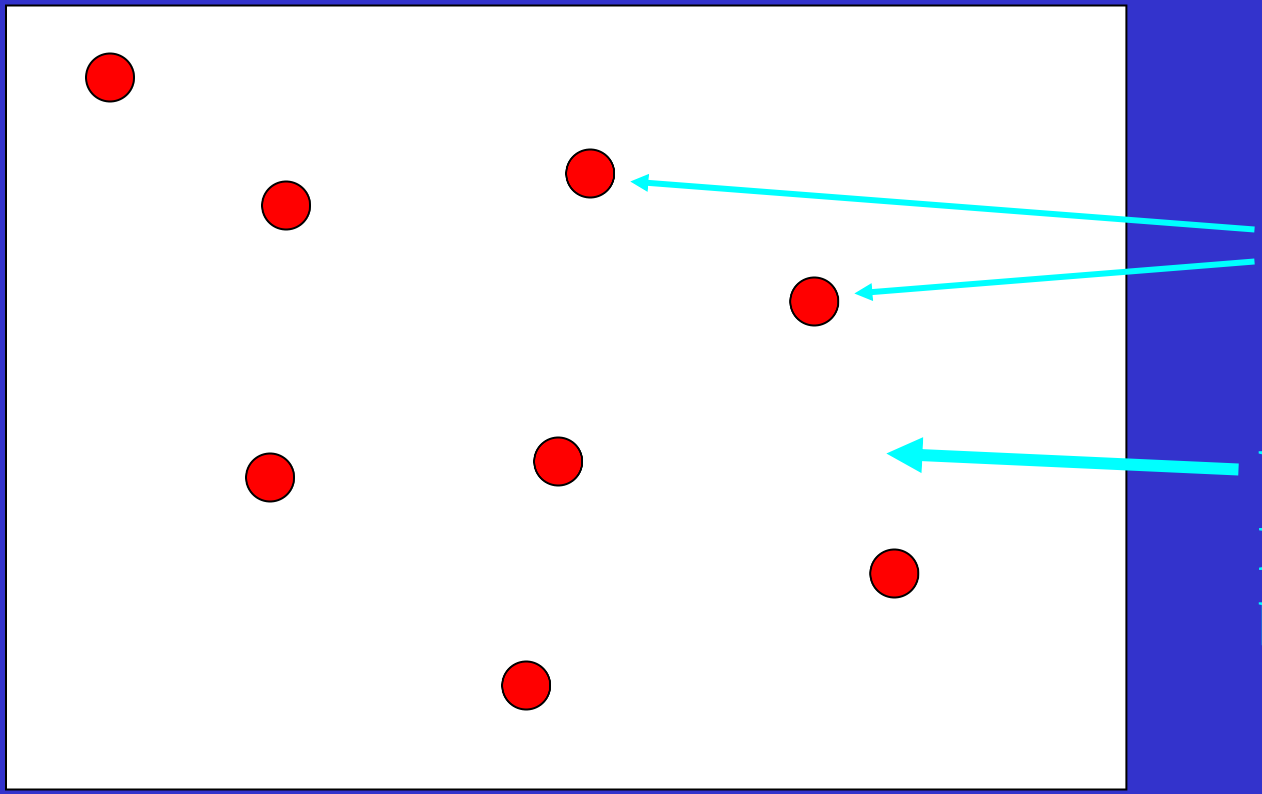


FLRW regions expand and carry static vacuoles with them
Cannot measure Ho in Solar System

Lindquist-Wheeler

NO background FLRW spacetime

No connected fluid that expands



stars

Vacuum:
Locally Static,
by Birkhoff

Averages to FLRW spacetime

The expanding universe and local vacuum solutions

- The issue:

Locally the universe is made of spherically symmetric vacuum regions (such as the Solar System)

Static, because of Birkhoff's theorem

Somehow joined together to give a globally expanding approximately spatially homogeneous spacetime

How is it done? – Lindquist and Wheeler, *Rev Mod Phys* **29**: 423 (1957) Schwarzschild vacuum cells joined together

Ferreira, Clifton et al: arXiv:1005.0788 , arXiv:1203.6478

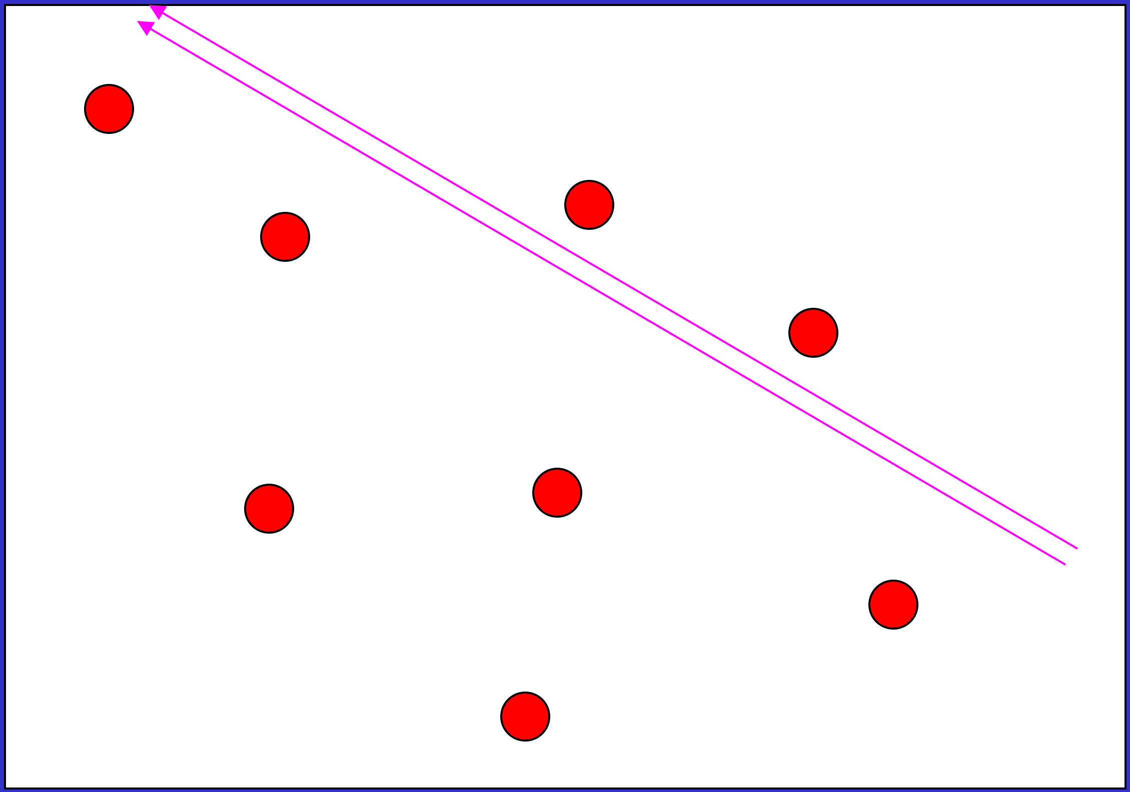
Nice models: But not exact solutions. Are there any?

Observations in the real universe:

Most light rays travel in vacuum!

NOT the same as FLRW:

Area distance,shear, and affine parameter effects



Clustering of matter?

Halos?

SN and Gravitational wave cases – integrated effects

Real Observations

Most of the Universe is empty, with matter concentrated in isolated clumps separated by vast regions of empty space; the homogeneity of the FL models is only a realistic representation when we average on large averaging scales

- Light rays travel in empty space (Weyl focusing) rather than uniform matter (Ricci focusing) as in FL models

-The FL description is likely to be misleading along the narrow bundles of rays whereby we observe distant supernovae

- Use Dyer Roeder distances ? Do not accurately represent this: no shear C. C Dyer. & R C Roeder, “Observations in Locally Inhomogeneous Cosmological Models” ApJ 189: 167 (1974)

- Better use non-linear inhomogeneous models

Ricci focusing and Weyl focusing

Null geodesics $x^a(\lambda)$, tangent vector $k^a = dx^a/d\lambda$

- Expansion equation for null geodesics

$$d\theta/d\lambda + (1/2)\theta^2 + \sigma^2 = - R_{ab}k^a k^b$$

Shear equation for null geodesics

$$d\sigma_{ab}/d\lambda + \theta\sigma_{ab} = - C_{abcd}k^c k^d$$

Robertson-Walker case: $C_{abcd}=0$, $R_{ab} \neq 0$

- *pure Ricci focusing caused by smooth matter on path*

Real Observations: $C_{abcd} \neq 0$, $R_{ab=}0$

- *pure Weyl focusing caused by lumpy matter elsewhere*

(Feynman 1964, Bertotti, Dashevskii and Slysh, Gunn, Weinberg)

B. Bertotti "The Luminosity of Distant Galaxies" *Proc Royal Soc London.* A294, 195 (1966).

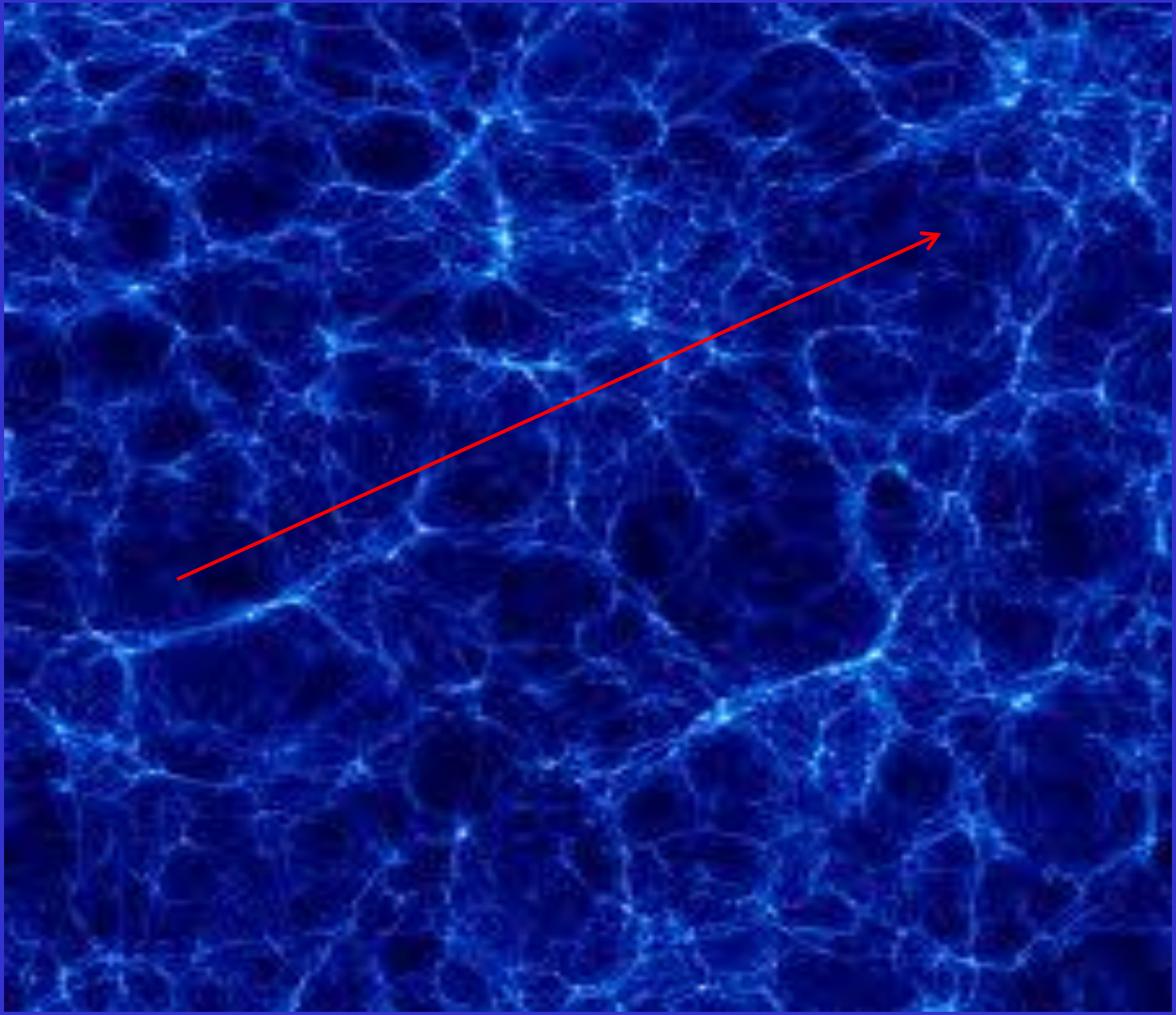
On the scale at which we see SN: Extremely small angular scale .Most directions intersect almost no matter.

The typical observational aperture is of order 1 *arcsec*, whereas the relevant beam is actually much thinner: ~ AU for a source at redshift $z \sim 1$, i.e. an aperture of 10^{-7} *arcsec*.

This is typically smaller than the mean distance between any massive objects (galaxies, stars, H clouds, small dark matter halos) and on a scale where the fluid continuum model may not be suitable any more.

Thus the beam propagates in preferentially low density regions with rare encounters of gravitationally collapsed, high density patches (halos) resulting in highly inhomogeneous geometry.

Compensated by a few directions that intersect a very high density of matter The all sky average giving the same as FLRW models (Weinberg)



The very small ray tube may avoid the walls and filaments

Interpreting supernovae observations in a lumpy universe

Chris Clarkson, George F.R. Ellis, Andreas Faltenbacher, Roy Maartens, Obinna Umeh, Jean-Philippe Uzan [arXiv:1109.2484]

Light from ‘point sources’ such as supernovae typically travels through unclustered dark matter and hydrogen with a mean density much less than the cosmic mean, and through dark matter halos and hydrogen clouds. Using N-body simulations, as well as a Press-Schechter approach, we quantify the density probability distribution as a function of beam width and show that, even for Gpc-length beams of 500 kpc diameter, most lines of sight are significantly under-dense.

The cumulative probability for a mean density below the cosmic mean for the 100, 250, 500 and 1000 h^{-1}Mpc beams is 75%, 71%, 68% and 65%, respectively. Based on our results, we estimate that significantly more than 75% of beams experience less than the mean density

Local inhomogeneity: observational effects

Swiss-Cheese models: FRW regions joined to vacuum regions
Exact inhomogeneous solutions

R. Kantowski “The Effects of Inhomogeneities on Evaluating the mass parameter Ω_m and the cosmological constant Λ” (1998) [astro-ph/9802208]

“Determination of Ω_m made by applying the homogeneous distance-redshift relation to SN 1997ap at z=0.83 could be as much as 50% lower than its true value”

V. Marra, E. W. Kolb, S. Matarrese “Light-cone averages in a Swiss-Cheese universe” (2007) [arXiv:0710.5505].

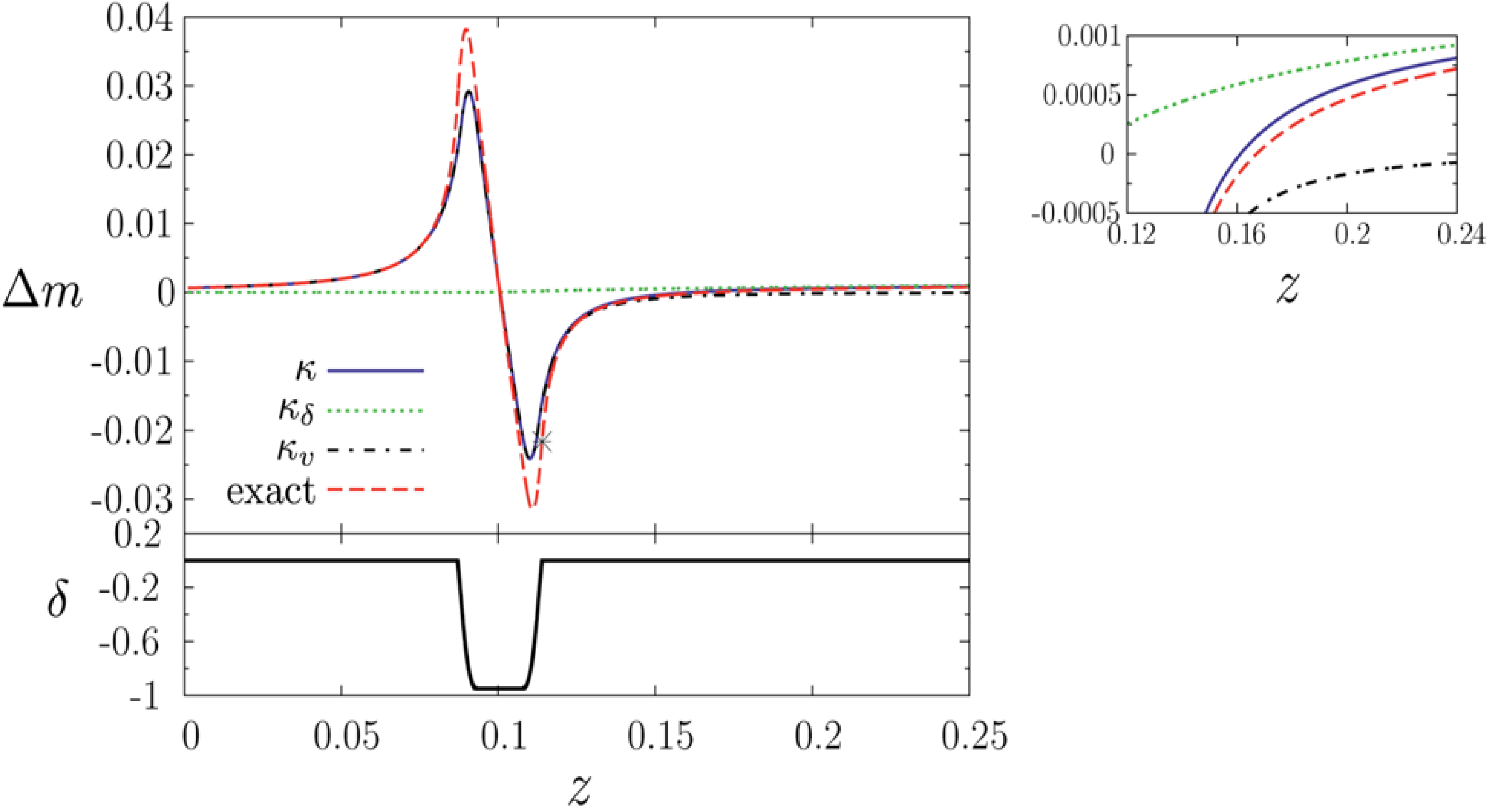
Probably enough to significantly influence concordance model values

Anti-lensing: the bright side of voids

Krzysztof Bolejko, Chris Clarkson, Roy Maartens, David Bacon, Nikolai Meures, Emma Beynon [arXiv:1209.3142]

More than half of the volume of our Universe is occupied by cosmic voids. The lensing magnification effect from those under-dense regions is generally thought to give a small dimming contribution: objects on the far side of a void are supposed to be observed as slightly smaller than if the void were not there, which together with conservation of surface brightness implies net reduction in photons received. This is predicted by the usual weak lensing integral of the density contrast along the line of sight.

We show that this standard effect is swamped at low redshifts by a relativistic Doppler term that is typically neglected. Contrary to the usual expectation, objects on the far side of a void are brighter than they would be otherwise. Thus the local dynamics of matter in and near the void is crucial and is only captured by the full relativistic lensing convergence. There are also significant nonlinear corrections to the relativistic linear theory, which we show actually under-predicts the effect. We use exact solutions to estimate that these can be more than 20% for deep voids.



very deep voids - GR effects linear theory doesn’t capture full effect

CONCLUSION

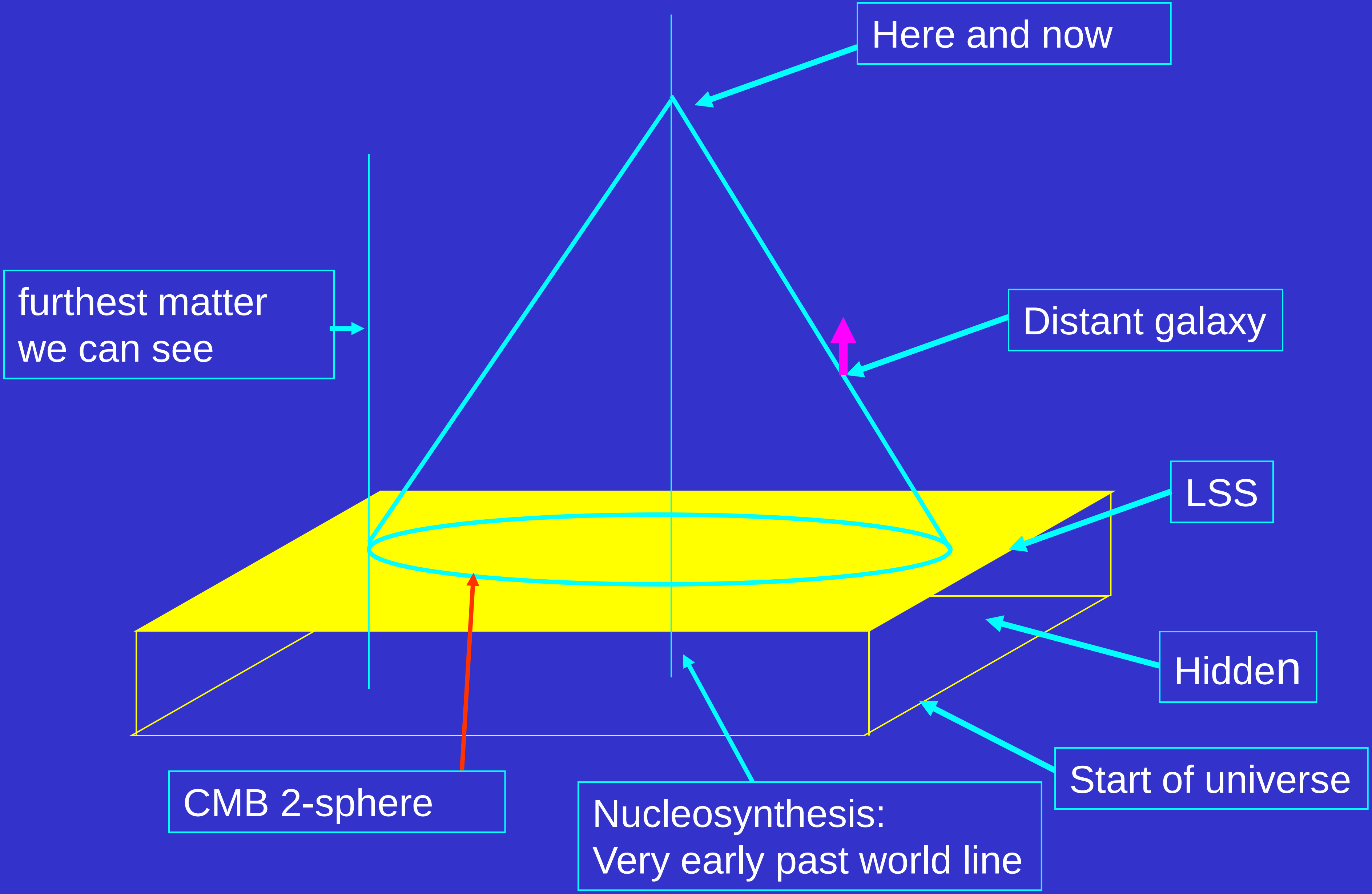
1. Could be inhomogeneity violating Copernican Principle
- with no need for DE: Lemaitre-Tolman-Bondi models

Able to explain SN observations easily: Theorem
Can it explain precision cosmology? - maybe not.
A variety of tests have been developed:
- SN observations
- CBR observations

* good science! Testable alternatives
Important to do that test: CP is foundation of standard model
and it can possibly do away with need for Dark Energy

2. Need to take small scale effects on observations in doing precision cosmology: non-linear effects of empty space and voids on observations. Depends on clustering, dark matter halos.

The observational context: Can only observe on past light cone



Here and now

furthest matter
we can see

Distant galaxy

LSS

Hidden

Start of universe

CMB 2-sphere

Nucleosynthesis:
Very early past world line

Inhomogeneity in cosmology

- First: Does the Universe averaged on a large scale obey the Copernican principle? Recent studies have changed this question from an a priori philosophical assumption, taken for granted as the foundation of our cosmological models, to a scientifically testable hypothesis about the geometry of the universe. This is a major step forward in cosmological theory, and has led to proposals for various ways of testing the Copernican hypothesis. This provides a scientific justification for use of Robertson-Walker geometries as the background models of cosmology.

Inhomogeneity in cosmology

- Secondly, assuming the Copernican principle holds on large scales, there exist fluctuations on all smaller scales. There may then be dynamical interactions between structures at different scales, and additionally observational relations on various angular scales are affected differently by structures on different scales.
- It is important to take the latter effects into account in an era of precision cosmology; they depend crucially on the details of matter clustering.
- Finally dynamical back reaction effects can occur.

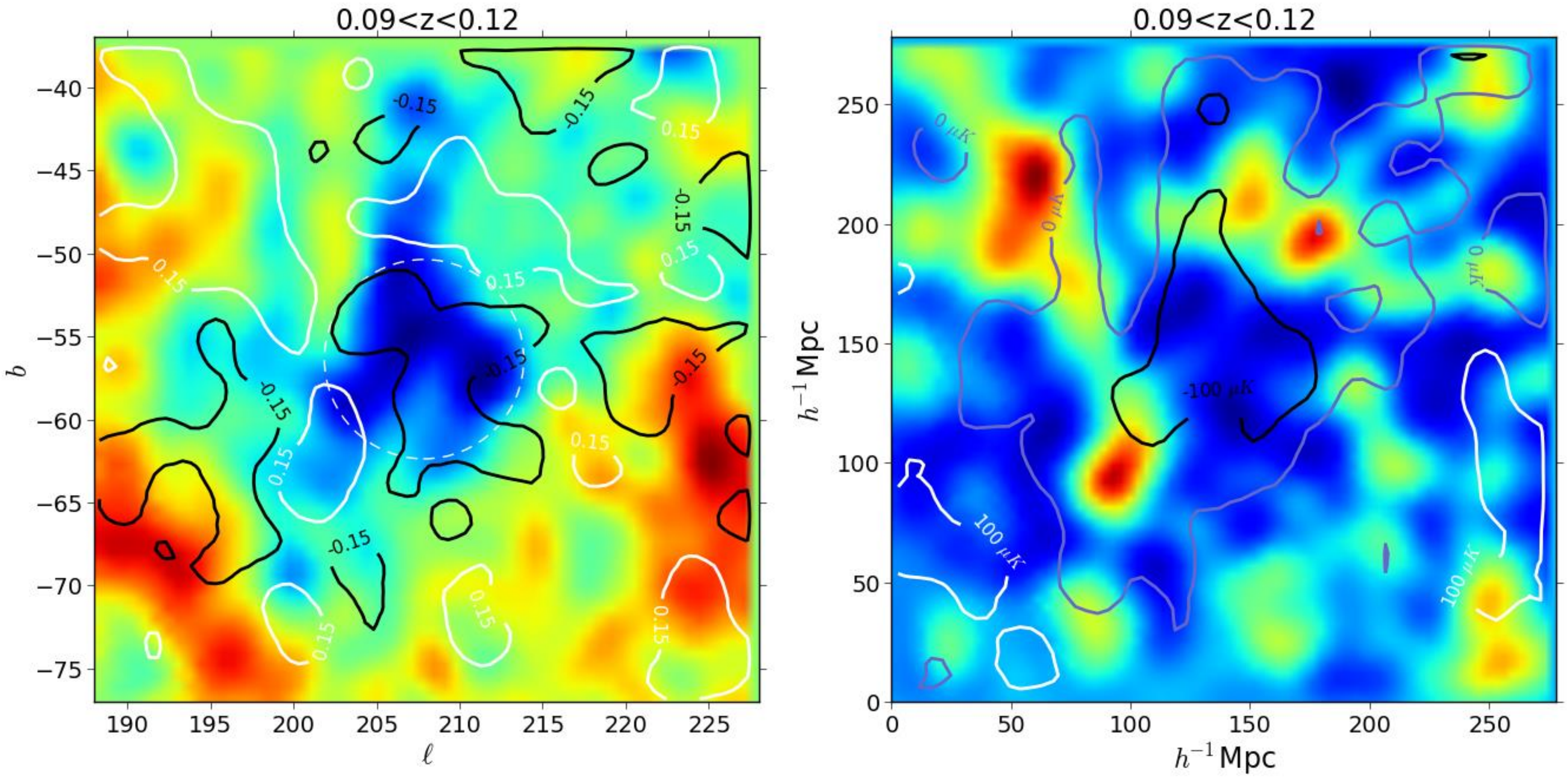
However they may not be important in cosmology.

Keenan et al: We find that the overall shape of the $z = 0$ rest-frame K-band luminosity function ($M*–5 \log(h70) = −22.15 \pm 0.04$ and $\alpha = −1.02 \pm 0.03$) appears to be relatively constant as a function of environment and distance from us. We find a local ($z < 0.07, D < 300$ $h^{-1}70$ Mpc) luminosity density that is in good agreement with previous studies.

Beyond $z \sim 0.07$, we detect a rising luminosity density that reaches a value of roughly ∼1.5 times higher than that measured locally at $z > 0.1$. This suggests that the stellar mass density as a function of distance follows a similar trend.

Assuming that luminous matter traces the underlying dark matter distribution, this implies that the local mass density of the universe may be lower than the global mass density on a scale and amplitude sufficient to introduce significant biases into the determination of basic cosmological observables

I.Szapudi, A.Kovacs, B. Granett, and Z. Frei with the Pan-STARRS1 Collaboration



A photo-metric redshift slice (0.09<z<0,12)
The left figures show the CMB in colors with LSS in contours, while the right figures show LSS in colors, and CMB in contours. This slice is the foreground one.

- Local Voids As The Origin Of Large-Angle Cosmic Microwave Background Anomalies
- K T Inoue and J Silk [arXiv:astro-ph/0602478]

We explore the large angular scale temperature anisotropies in the cosmic microwave background due to expanding homogeneous local voids at redshift $z \sim 1$. A compensated spherically symmetric homogeneous dust-filled void with radius ~ 3×102*h*-1Mpc, and density contrast δ ~ -0.3 can be observed as a cold spot with a temperature anisotropy *T*/*T* ~ -1×10-5 surrounded by a slightly hotter ring.

- We find that a pair of these circular cold spots separated by~50◦ can account both for the planarity of the octopole and the alignment between the quadrupole and the octopole in the cosmic microwave background (CMB) anisotropy. The cold spot in the Galactic southern hemisphere which is anomalous at the ~ 3σ level can be explained by such a large void at $z \sim 1$. The observed north-south asymmetry in the large-angle CMB power can be attributed to the asymmetric distribution of these local voids between the two hemispheres.

Indirect Observational tests

If the standard inverse analysis of the supernova data to determine the required equation of state shows

there is any redshift range where

$w := p/\rho < -1$,

this may well be a strong indication that one of these geometric explanations is preferable to the Copernican (Robertson-Walker) assumption,

for otherwise the matter model indicated by these observations is non-physical (it has a negative k.e.)

M.P. Lima, S. Vitenti, M.J. Reboucas "Energy conditions bounds and their confrontation with supernovae data" (2008) [arXiv:0802.0706].

Local inhomogeneity: dynamic effects

Averaging and calculating the field equations do not commute

G. F. R. Ellis: ``Relativistic cosmology: its nature, aims and problems". In *General Relativity and Gravitation*, Ed B Bertotti et al (Reidel, 1984), 215.

Averaging leads to extra terms in effective higher level equations

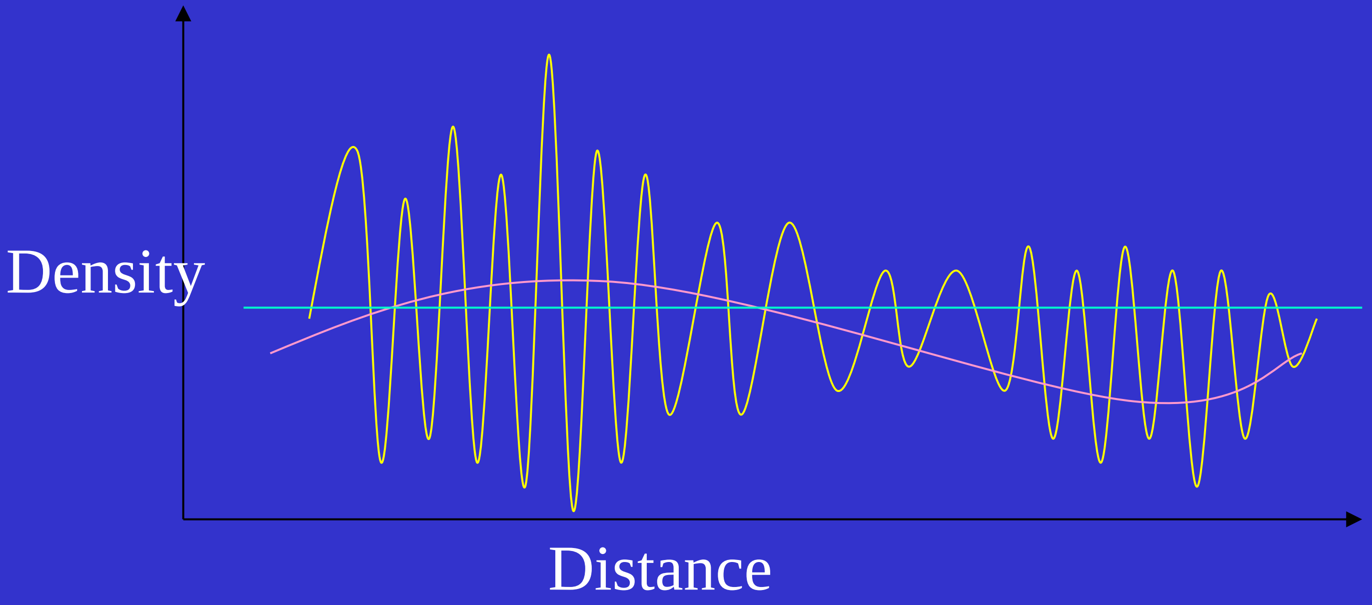
Cosmology: contribution to dark energy??

(Kolb, Mataresse, Buchert, Wiltshire, et al.)

Local inhomogeneity: description

Multiple scales of representation of ***same*** system

Implicit averaging scale



Stars, clusters, galaxies, universe

In **electromagnetic theory**,

polarization effects result from a large--scale field being applied to a medium with many microscopic charges. The macroscopic field E differs from the point--to—point microscopic field which acts on the individual charges, because of a fluctuating internal field E_i , the total internal field at each point being $D = E + E_i$

Spatially averaging, one regains the average field because the internal field cancels out: $E = \langle D \rangle$, indeed this is how the macroscopic field is defined (implying invariance of the background field under averaging: $E = \langle E \rangle$).

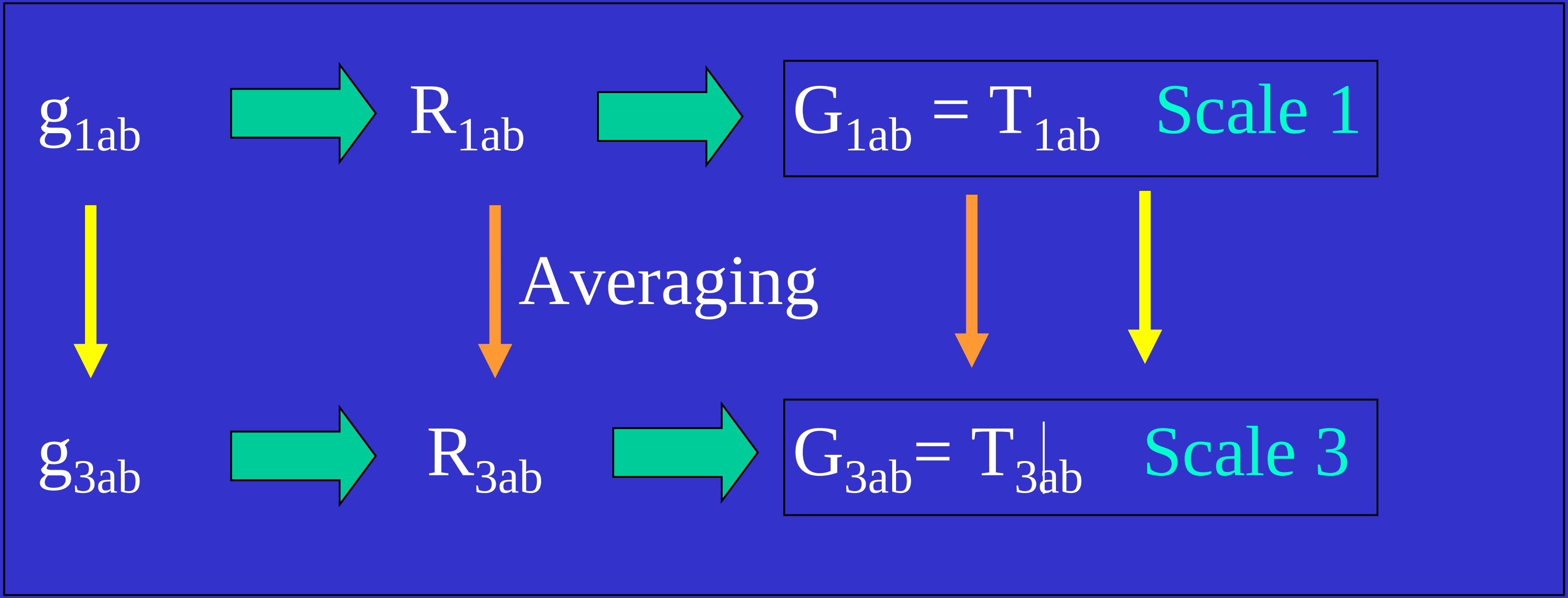
On a microscopic scale, however, the detailed field D is the effective physical quantity, and so is the field ``measured" by electrons and protons at that scale. Thus, the way different test objects respond to the field crucially depends on their scale. A macroscopic device will measure the averaged field.

Exactly the same issue arises with regard to the gravitational field. The solar system tests of general relativity theory are at solar system scales. We apply gravitational theory, however, at many other scales: to star clusters, galaxies, clusters of galaxies, and cosmology.

Cosmology utilizes the largest scale averaging envisaged in astrophysics: a representative scale is assumed that is a significant fraction of the Hubble scale, and the cosmological velocity and density functions are defined by averaging on such scales.

Local inhomogeneity: dynamic effects

Averaging and calculating the field equations do not commute



$$\begin{tikzcd}
g_{1ab} \arrow[r] \arrow[d, yellow] & R_{1ab} \arrow[r] \arrow[d, orange, "\text{Averaging}"] & G_{1ab} = T_{1ab} \arrow[d, orange] & \text{Scale 1} \arrow[d, yellow] \\
g_{3ab} \arrow[r] & R_{3ab} \arrow[r] & G_{3ab} = T_{3ab} & \text{Scale 3}
\end{tikzcd}$$

→ averaging process

→ averaging gives different answer

Averaging effects

Metric tensor: $g_{ab} \longrightarrow \hat{g}_{ab} = \langle g_{ab} \rangle$

Inverse Metric tensor: $g^{ab} \longrightarrow \hat{g}^{ab} = \langle g^{ab} \rangle$

but not necessarily inverse …

need correction terms to make it the inverse

Connection: $\Gamma^a{}_{bc} \longrightarrow \langle \Gamma^a{}_{bc} \rangle + C^a{}_{bc}$

new is average plus correction terms

Curvature tensor plus correction terms

Ricci tensor plus correction terms

Field equations $G_{ab} = T_{ab} + P_{ab}$

Problem of covariant averaging

The problem with such averaging procedures is that they are not covariant. Can’t average tensor fields in covariant way (coordinate dependent results).

They can be defined in terms of the background unperturbed space, usually either flat spacetime or a Robertson--Walker geometry, and so will be adequate for linearized calculations where the perturbed quantities can be averaged in the background spacetime.

But the procedure is inadequate for non--linear cases, where the integral needs to be done over a generic lumpy (non--linearly perturbed) spacetime that are not ``perturbations" of a high--symmetry background. However, it is precisely in these cases that the most interesting effects will occur.

Problem of covariant averaging

Can't average tensor fields in covariant way (coordinate dependent results)

Can use bitensors (Synge) for curvature and matter, but not for metric itself: and leads to complex equations

- R Zalaletdinov "The Averaging Problem in Cosmology and Macroscopic Gravity" *Int. J. Mod. Phys*. **A 23:** 1173 (2008) [arXiv:0801.3256]

Scalars: can be done (Buchert),
But: usually incomplete, so hides effects

Polarisation Form (flat background)

Peter Szekeres developed a polarization formulation for a gravitational field acting in a medium, in analogy to electromagnetic polarization. He showed that the linearized Bianchi identities for an almost flat spacetime may be expressed in a form that is suggestive of Maxwell's equations with magnetic monopoles.

Assuming the medium to be molecular in structure, it is shown how, on performing an averaging process on the field quantities, the Bianchi identities must be modified by the inclusion of polarization terms resulting from the induction of quadrupole moments on the individual ``molecules". A model of a medium whose molecules are harmonic oscillators is discussed and constitutive equations are derived.

This results in the form:

$$G_{ab} = T_{ab} + P_{ab\,.\,,} \qquad P^{ab} = Q^{abcd}{}_{;cd}$$

that is P_{ab} is expressed as the double divergence of an effective quadrupole gravitational polarization tensor with suitable symmetries:

$$Q^{abcd} = Q^{[ab][cd]} = Q^{cdab}$$

Gravitational waves are demonstrated to slow down in such a medium. Thus the large scale effective equations include polarisation terms, as in the case of electromagnetism

P Szekeres: "Linearised gravitational theory in macroscopic media" Ann Phys 64: 599 (1971)

The averaging problem in cosmology

Buchert equations for scalars gives modified Friedmann equation

T Buchert "Dark energy from structure: a status report". *GRG Journal* **40:** 467 **(2008) [arXiv:0707.2153].**

Keypoint:

Expansion and averaging do not commute:

in any domain D, for any field Ψ

$$\partial_t \langle \Psi \rangle - \langle \partial_t \Psi \rangle = \langle \theta \Psi \rangle - \langle \theta \rangle \langle \Psi \rangle$$

The averaging problem in cosmology

Buchert equations for scalars gives modified Friedmann and Raychaudhuri equations: e.g.

$$\partial t\langle\Theta\rangle_D = \Lambda - 4\pi G\rho_D + 2\,\langle II\rangle_D - \langle I\rangle_D{}^2$$

where $II = \Theta^2/3 - \sigma^2$ and $I = \Theta$.

This in principle allows acceleration terms to arise from the averaging process

Local inhomogeneity: dynamic effects

Claim: weak field approximation is adequate and shows effect is negligible (Peebles)

Counter claim: it certainly matters

-Kolb, Mattarrese, others

NB one can check if it can explain dark energy issue fully

But if not it might still upset the cosmic concordance: it might show spatial sections are not actually flat

Improbability

There is only one universe

Concept of probability does not apply to a single object, even though we can make many measurements of that single object

There is no physically realised ensemble to apply that probability to, unless a multiverse exists

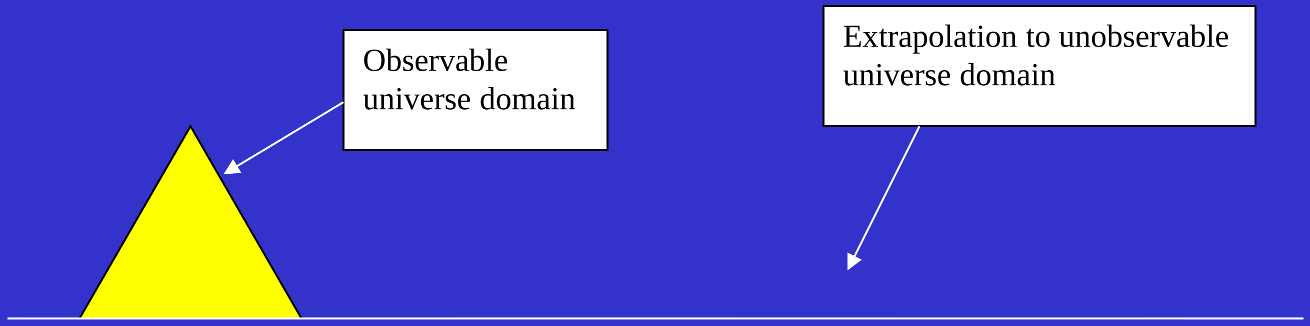
– which is not proven: it’s a philosophical assumption

and in any case there is no well-justified measure for any such probability proposal

Can we observationally test the inhomogeneity possibility?

Whatever theory may say, it must give way to such tests

Largest scale inhomogeneity??

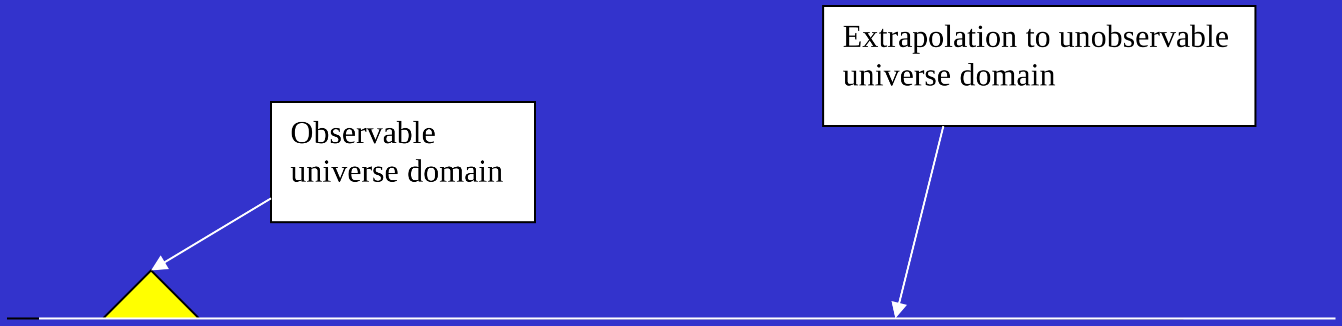


Observable universe domain

Extrapolation to unobservable universe domain

No observational data whatever are available!

Better scale:



Extrapolation to unobservable universe domain

Observable universe domain

Homogeneous or inhomogeneous? Copernican or chaotic? Isolated island universe?