From Quantum to Statistical Cosmology

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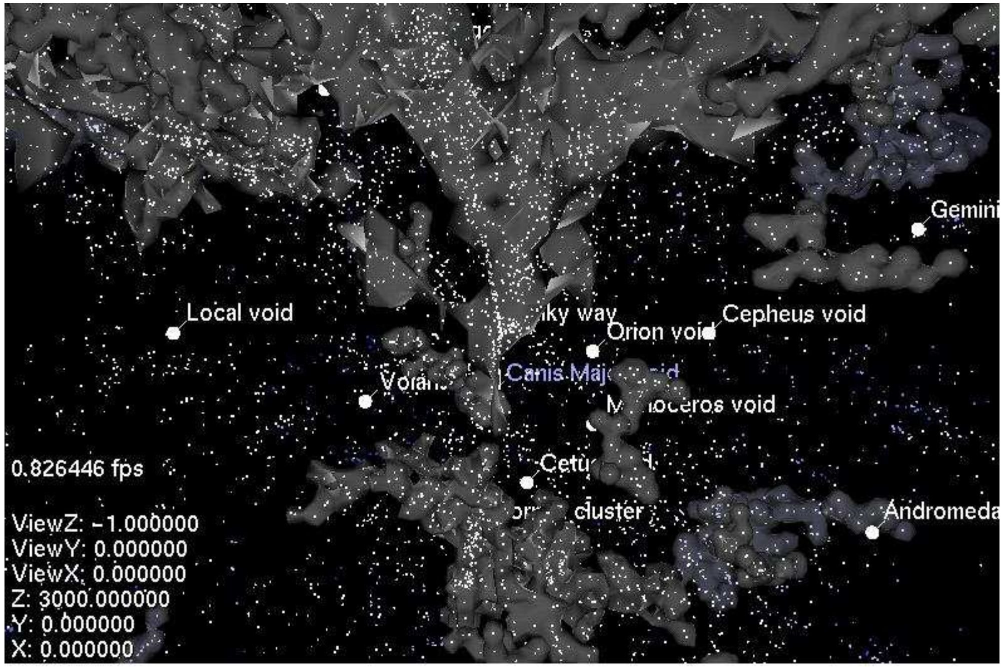


DLW: **New J. Phys. 9 (2007) 377**

Phys. Rev. Lett. 99 (2007) 251101

Phys. Rev. D78 (2008) 084032

Phys. Rev. D80 (2009) 123512

Class. Quan. Grav. 28 (2011) 164006

B.M. Leith, S.C.C. Ng & DLW:

ApJ 672 (2008) L91

P.R. Smale & DLW, **MNRAS 413 (2011) 367**

P.R. Smale, **MNRAS 418 (2011) 2779**

J.A.G. Duley, M.A. Nazer & DLW: **Class. Quan. Grav. 30 (2013) 175006**

Cosmology school lectures: **arXiv:1311.3787**

Outline of talk

- What is dark energy?:

  Dark energy is a misidentification of gradients in quasilocal dilatational kinetic energy

  (in presence of density and spatial curvature gradients on scales $\lesssim 100\, h^{-1}$Mpc – *statistical homogeneity scale (SHS)* – which also alter average cosmic expansion).

- Overview of ideas/principles/results/tests of Timescape Cosmology

- Merging Shape Dynamics and Timescape
  - 2 + (1 + 1) formulation required
  - Light propagation in a statistical geometry

Averaging and backreaction

- *Fitting problem* (Ellis 1984):
  On what scale are Einstein's field equations valid?

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- In general $\langle G^{\mu}{}_{\nu}(g_{\alpha\beta})\rangle \neq G^{\mu}{}_{\nu}(\langle g_{\alpha\beta}\rangle)$
- Inhomogeneity in expansion (on $\lesssim 100\,h^{-1}$Mpc scales) may make average non–Friedmann as structure grows
- *Weak backreaction*: Perturb about a given background
- *Strong backreaction*: fully nonlinear
  - Spacetime averages (R. Zalaletdinov 1992, 1993);
  - Spatial averages on hypersurfaces based on a $1+3$ foliation (T. Buchert 2000, 2001).

Buchert equations

For irrotational dust cosmologies, with energy density, $\rho(t,\mathbf{x})$, expansion scalar, $\vartheta(t,\mathbf{x})$, and shear scalar, $\sigma(t,\mathbf{x})$, where $\sigma^2 = \frac{1}{2}\sigma_{\mu\nu}\sigma^{\mu\nu}$, **defining** $3\dot{\bar{a}}/\bar{a} \equiv \langle\vartheta\rangle$, we find average cosmic evolution described by exact Buchert equations

$$
\begin{aligned}
&(1) \qquad & 3\frac{\dot{\bar{a}}^2}{\bar{a}^2} &= 8\pi G\langle\rho\rangle - \tfrac{1}{2}\langle\mathcal{R}\rangle - \tfrac{1}{2}\mathcal{Q} \\
&(2) \qquad & 3\frac{\ddot{\bar{a}}}{\bar{a}} &= -4\pi G\langle\rho\rangle + \mathcal{Q} \\
&(3) \qquad & \partial_t\langle\rho\rangle &+ 3\frac{\dot{\bar{a}}}{\bar{a}}\langle\rho\rangle = 0 \\
&(4) \qquad & \partial_t\left(\bar{a}^6\mathcal{Q}\right) &+ \bar{a}^4\partial_t\left(\bar{a}^2\langle\mathcal{R}\rangle\right) = 0 \\
& & \mathcal{Q} &\equiv \frac{2}{3}\left(\langle\vartheta^2\rangle - \langle\vartheta\rangle^2\right) - 2\langle\sigma^2\rangle
\end{aligned}
$$

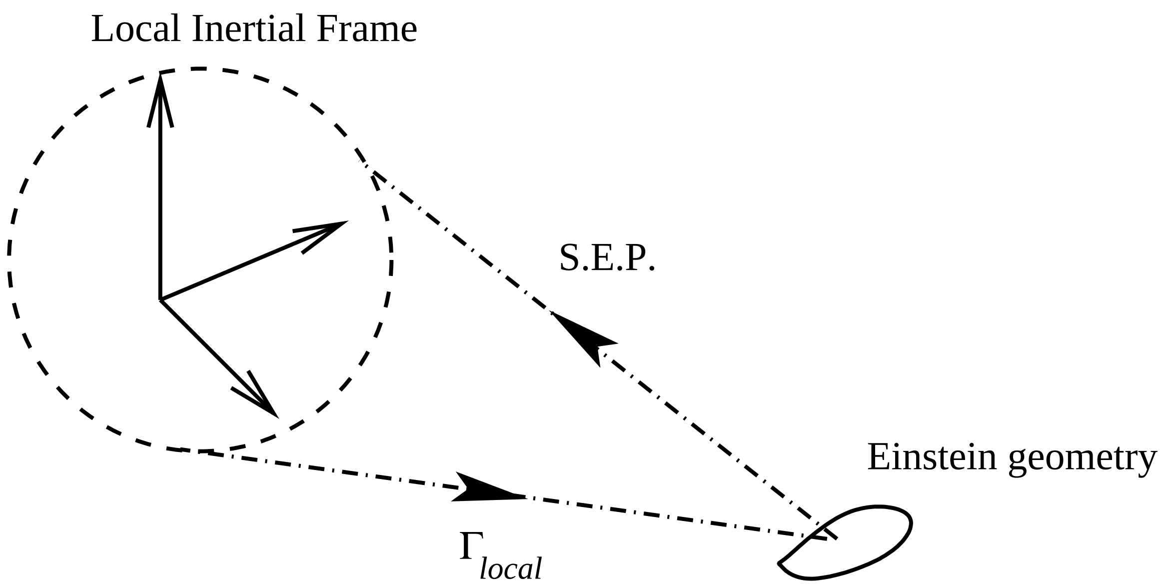
Backreaction in Buchert averaging

- *Kinematic backreaction* term can also be written

$$\mathcal{Q} = \tfrac{2}{3}\langle(\delta\vartheta)^2\rangle - 2\langle\sigma^2\rangle$$

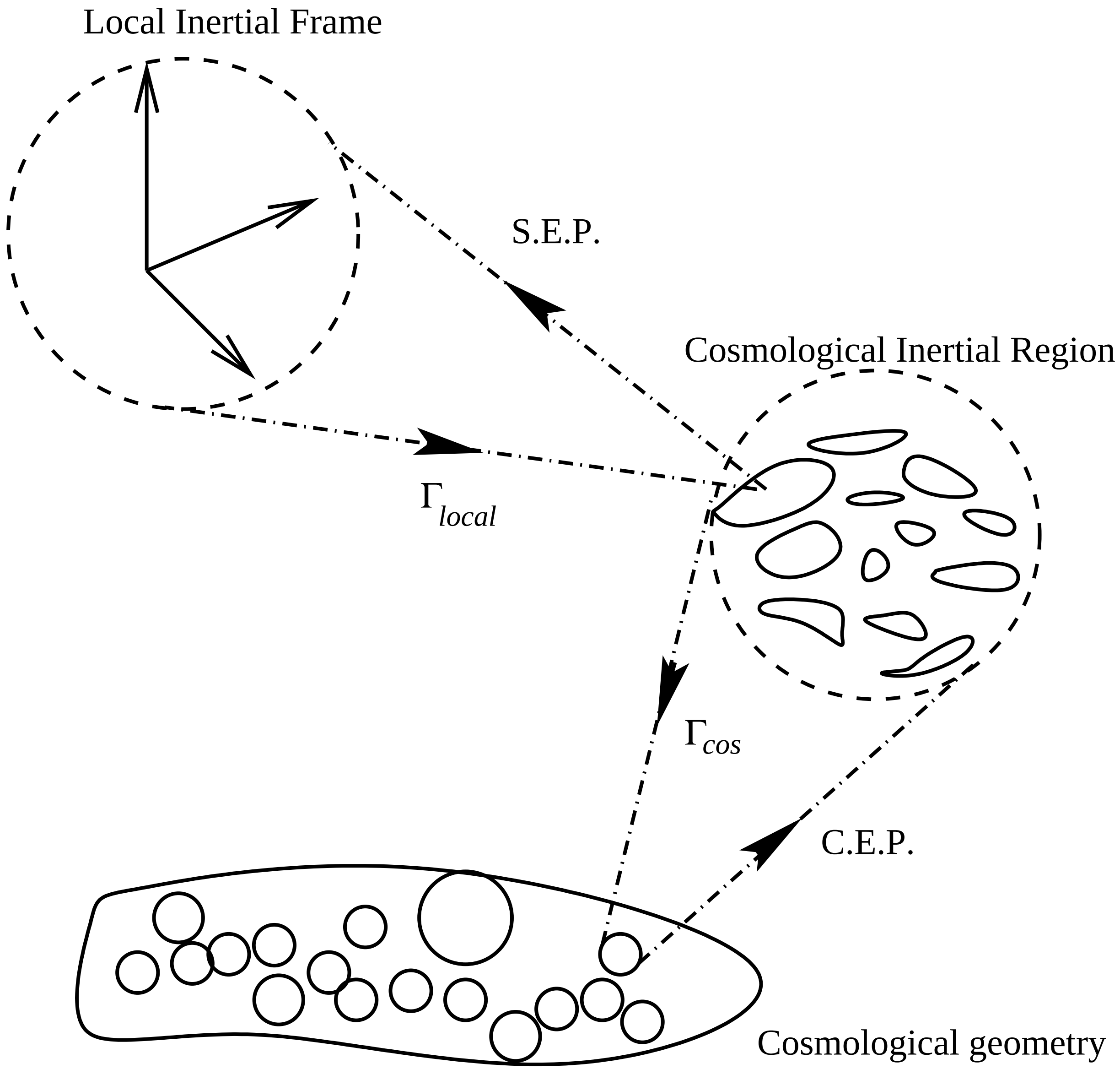
  i.e., combines variance of expansion, and shear.
- Eq. (6) is required to ensure (3) is an integral of (4).
- Buchert equations look deceptively like Friedmann equations, but deal with *statistical* quantities
- The extent to which the back–reaction, $\mathcal{Q}$, can lead to apparent cosmic acceleration or not has been the subject of much debate (e.g., Ishibashi & Wald 2006):
  - How do statistical quantities relate to observables?
  - What about the time slicing?
  - How big is $\mathcal{Q}$ given reasonable initial conditions?

Back to first principles. . .



- Need to address Mach's principle: *"Local inertial frames are determined through the distributions of energy and momentum in the universe by some weighted average of the apparent motions"*
- Need to separate non-propagating d.o.f., in particular regional density, from propagating modes: shape d.o.f.
- Need to specify relevant asymptotic scale of "fixed stars" for local/regional mass definitions

Statistical geometry. . .



Cosmic web: typical structures

- Galaxy clusters, 2 – 10 h^{-1}Mpc, form filaments and sheets or “walls” that thread and surround voids
- Universe is void dominated (60–80%) by volume, with distribution peaked at a particular scale (40% of total volume):

Survey	Void diameter	Density contrast
PSCz	$(29.8 \pm 3.5)h^{-1}$Mpc	$\delta_\rho = -0.92 \pm 0.03$
UZC	$(29.2 \pm 2.7)h^{-1}$Mpc	$\delta_\rho = -0.96 \pm 0.01$
2dF NGP	$(29.8 \pm 5.3)h^{-1}$Mpc	$\delta_\rho = -0.94 \pm 0.02$
2dF SGP	$(31.2 \pm 5.3)h^{-1}$Mpc	$\delta_\rho = -0.94 \pm 0.02$

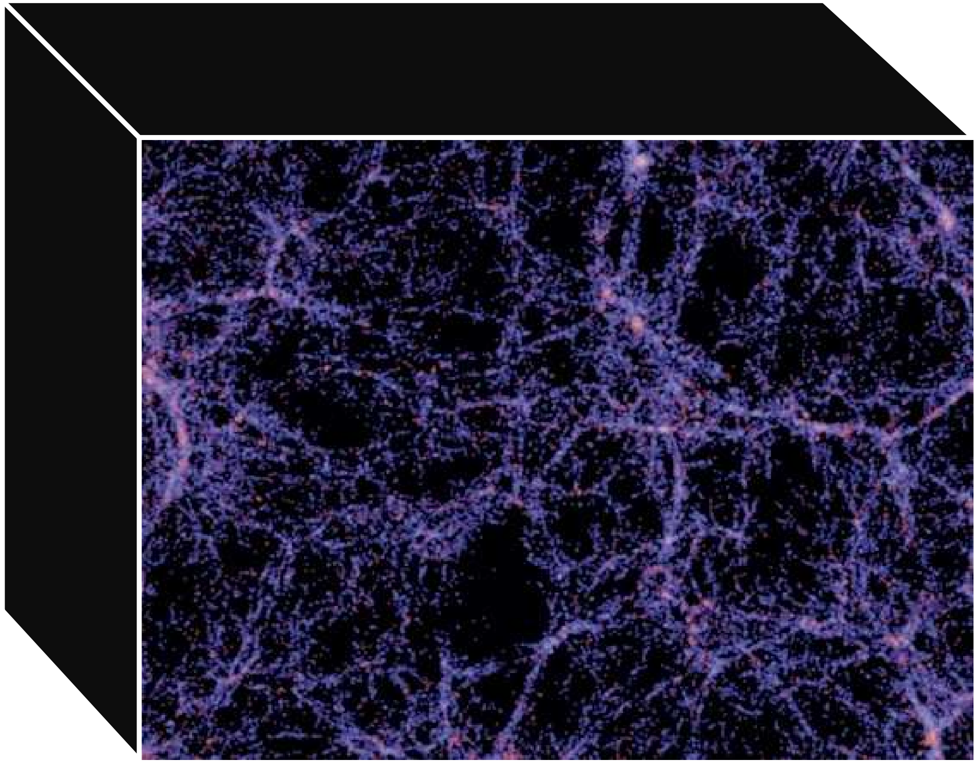
Dominant void statistics in the Point Source Catalogue Survey (PSCz), the Updated Zwicky Catalogue (UZC), and the 2 degree Field Survey (2dF) North Galactic Pole (NGP) and South Galactic Pole (SGP), (Hoyle and Vogeley 2002,2004). More recent results of Pan et al. (2011) using SDSS Data Release 7 similar.

What is a cosmological particle (dust)?

- In FLRW one takes observers "comoving with the dust"
- Traditionally galaxies were regarded as dust. However,
  - Neither galaxies nor galaxy clusters are homogeneously distributed today
  - Dust particles should have (on average) invariant masses over the timescale of the problem
- Must coarse-grain over expanding fluid elements larger than the largest typical structures [voids of diameter $30\,h^{-1}$Mpc with $\delta_\rho \sim -0.95$ are $\gtrsim 40\%$ of $z = 0$ universe]

$$\left.\begin{array}{l} g^{\rm stellar}_{\mu\nu} \longrightarrow g^{\rm galaxy}_{\mu\nu} \longrightarrow g^{\rm cluster}_{\mu\nu} \longrightarrow g^{\rm wall}_{\mu\nu} \\ \hphantom{g^{\rm stellar}_{\mu\nu} \longrightarrow g^{\rm galaxy}_{\mu\nu} \longrightarrow g^{\rm cluster}_{\mu\nu} \longrightarrow\ } \vdots \\ \hphantom{g^{\rm stellar}_{\mu\nu} \longrightarrow g^{\rm galaxy}_{\mu\nu} \longrightarrow g^{\rm cluster}_{\mu\nu} \longrightarrow\ } g^{\rm void}_{\mu\nu} \end{array}\right\} \longrightarrow g^{\rm universe}_{\mu\nu}$$

Within a coarse-grained cell



- Need to consider relative position of observers over scales of tens of Mpc over which $\delta\rho/\rho \sim -1$.
- GR is a local theory: gradients in spatial curvature and gravitational energy can lead to calibration differences between our rulers & clocks and volume average ones

Dilemma of gravitational energy...

- In GR spacetime carries *energy* & *angular momentum*

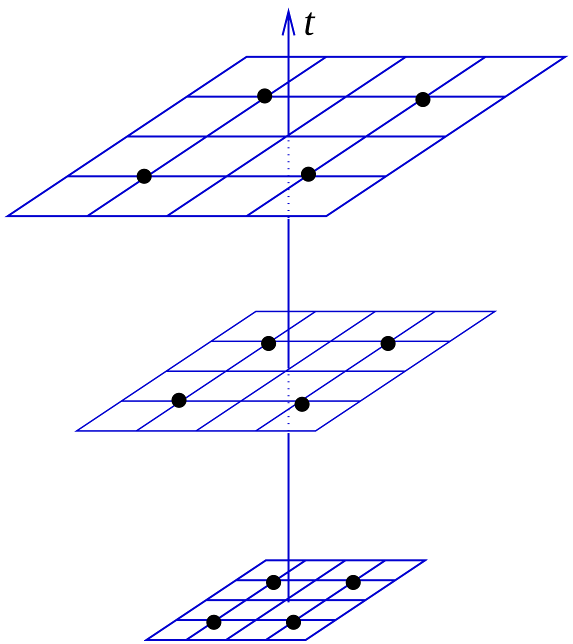
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- On account of the strong equivalence principle, $T_{\mu\nu}$ contains localizable energy–momentum only
- Kinetic energy and energy associated with spatial curvature are in $G_{\mu\nu}$: variations are “quasilocal”!
- Newtonian version, $T - U = -V$, of Friedmann equation

$$\frac{\dot{a}^2}{a^2} + \frac{kc^2}{a^2} = \frac{8\pi G\rho}{3}$$

where $T = \frac{1}{2}m\dot{a}^2x^2$, $U = -\frac{1}{2}kmc^2x^2$, $V = -\frac{4}{3}\pi G\rho a^2x^2m$; $\mathbf{r} = a(t)\mathbf{x}$.

What expands? Can't tell locally!

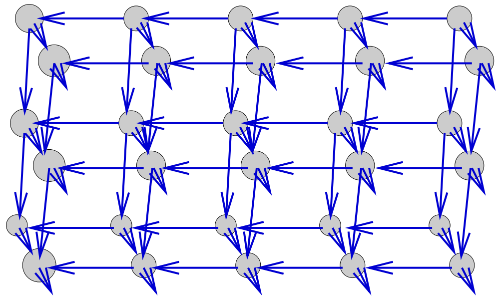


- Homogeneous isotropic volume expansion is locally indistinguishable from equivalent motion in static Minkowski space; on local scales

$$z \simeq \frac{v}{c} \simeq \frac{H_0 \ell_r}{c}, \qquad H_0 = \left.\frac{\dot{a}}{a}\right|_{t_0}$$

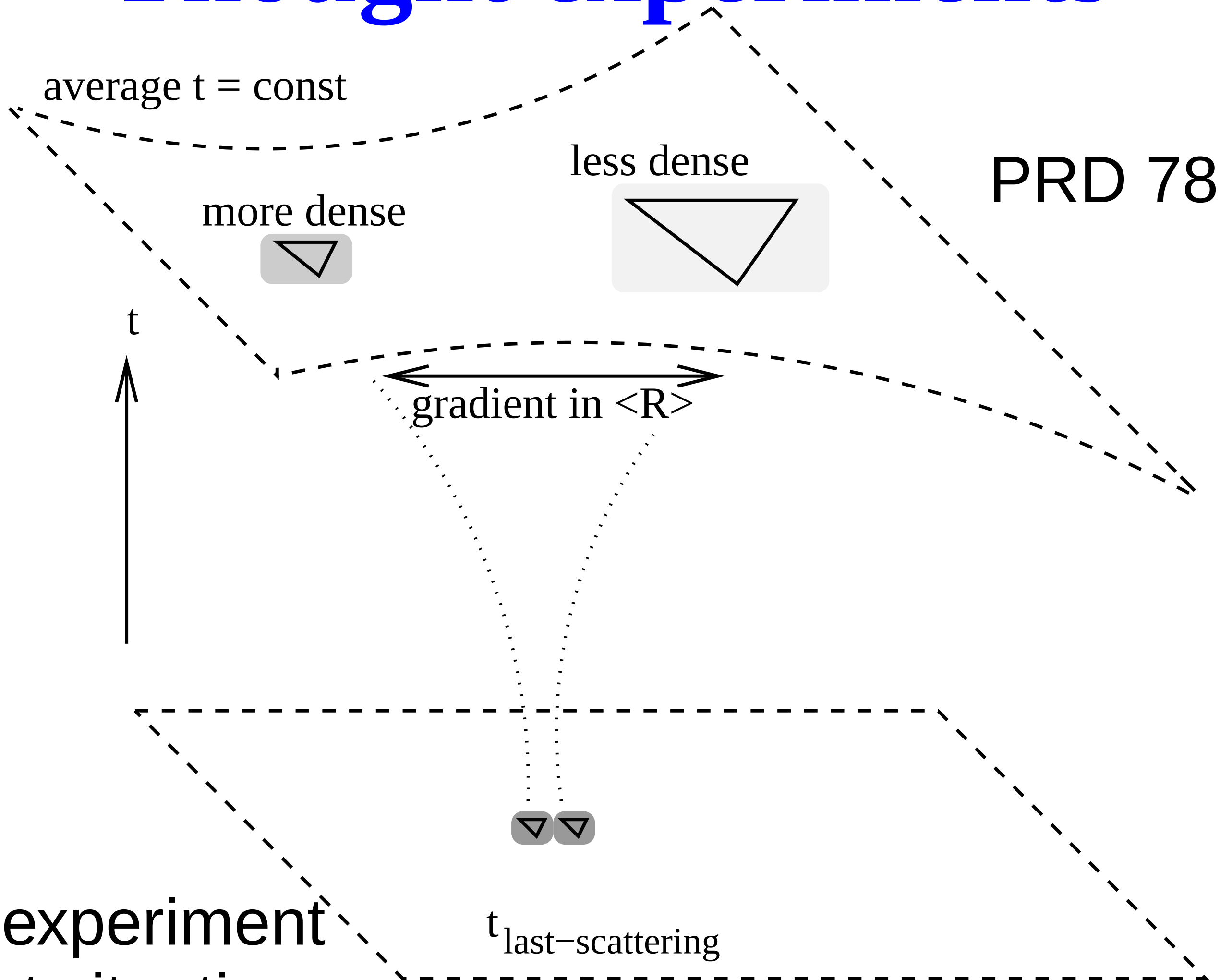
whether $z + 1 = a_0/a$ or $z + 1 = \sqrt{(c+v)/(c-v)}$.

Thought experiment: Semi-tethered lattice



- Extend to decelerating motion over long time intervals by Minkowski space analogue (semi-tethered lattice - indefinitely long tethers with one end fixed, one free end on spool, apply brakes syncronously at each site)
- Brakes convert kinetic energy of expansion to heat and so to other forms
- Brake impulse can be arbitrary pre-determined function of local proper time; but provided it is synchronous deceleration remains homogeneous and isotropic: *no net force on any lattice observer*.
- Deceleration preserves inertia, by symmetry

Thought experiments



PRD 78, 084032 (2008)

Thought experiment equivalent situations:

- GR: regions of different density have different volume deceleration (for same initial conditions)
- Those in denser *expanding* region age less

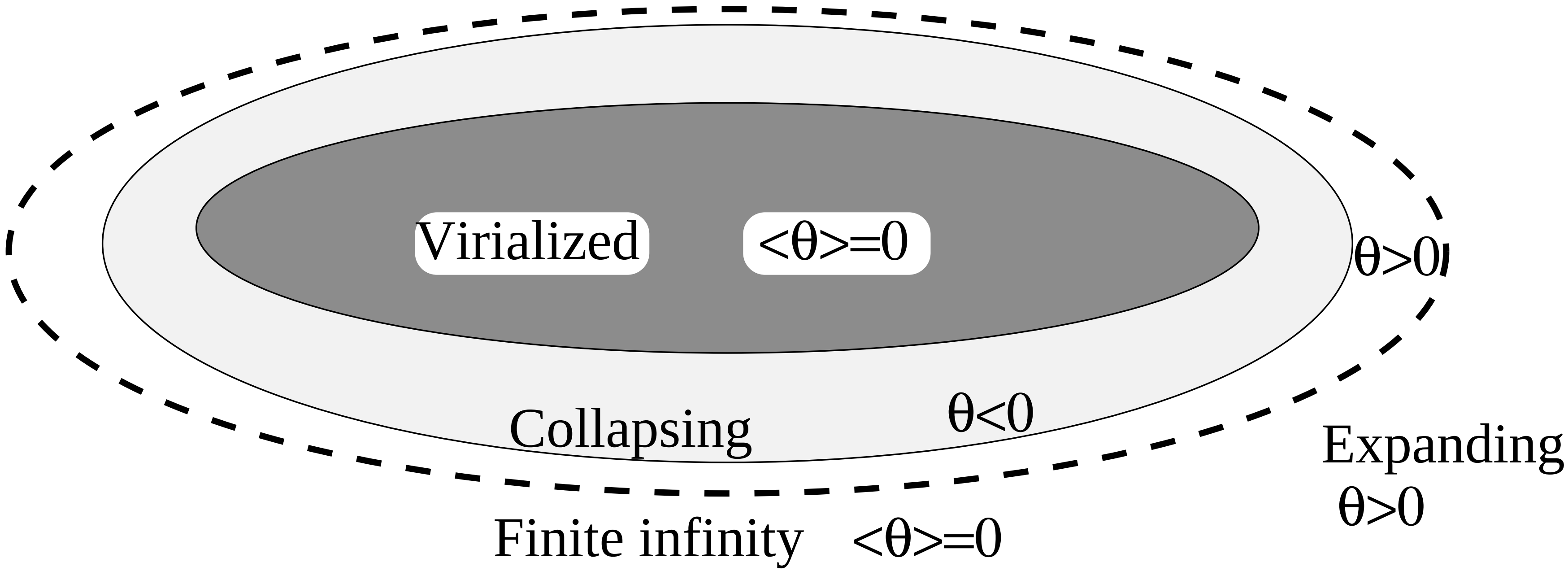
Cosmological Equivalence Principle

- *In cosmological averages it is always possible to choose a suitably defined spacetime region, the cosmological inertial region, on whose boundary average motions (timelike and null) can be described by geodesics in a geometry which is Minkowski up to some time-dependent conformal transformation*,

$$\mathrm{d}s^2_{\mathrm{CIR}} = a^2(\eta)\left[-\mathrm{d}\eta^2 + \mathrm{d}r^2 + r^2\mathrm{d}\Omega^2\right],$$

- Defines Cosmological Inertial Region (CIR) in which *regionally isotropic* volume expansion is equivalent to a velocity in special relativity
- Such velocities integrated on a bounding 2-sphere define *"kinetic energy of expansion"*: globally it has gradients

Finite infinity



- Define *finite infinity*, "*fi*" as boundary to *connected* region within which *average expansion* vanishes $\langle\vartheta\rangle = 0$ and expansion is positive outside.
- Shape of *fi* boundary irrelevant (minimal surface generally): could typically contain a galaxy cluster.

Why is ΛCDM so successful?

- The early Universe was extremely close to homogeneous and isotropic
- Finite infinity geometry (2 – $15\,h^{-1}$Mpc) is close to spatially flat (Einstein–de Sitter at late times) – N–body simulations successful *for bound structure*
- At late epochs there is a simplifying principle – Cosmological Equivalence Principle
- Hubble parameter (first derivative of statistical metric; i.e., connection) is to some extent a “gauge choice”
  - Affects ‘local’/global H_0 issue
  - Has contributed to fights (e.g., Sandage vs de Vaucouleurs) H_0 depends on measurement scale
- *Even on small scales there is a notion of uniform Hubble flow at expense of calibration of rulers AND CLOCKS*

Timescape phenomenology

$$\mathrm{d}s^2 = -(1+2\Phi)c^2\mathrm{d}t^2 + a^2(1-2\Psi)g_{ij}\mathrm{d}x^i\mathrm{d}x^j$$

- Global statistical metric not a solution of Einstein equations
- Relative regional volume deceleration integrates to a substantial difference in clock calibration of bound system observers relative to volume average over age of universe
- All actual observers in overdensities have a mass-biased view of the Universe
- Retain Copernican principle but recognize differences between *bare* (statistical or volume–average) and *dressed* (regional or finite–infinity) parameters

Model details

- Split spatial volume $\mathcal{V} = \mathcal{V}_i \bar{a}^3$ as disjoint union of negatively curved void fraction with scale factor $a_{\rm v}$ and spatially flat "wall" fraction with scale factor $a_{\rm w}$.

$$
\begin{aligned}
\bar{a}^3 &= f_{\rm wi} a_{\rm w}{}^3 + f_{\rm vi} a_{\rm v}{}^3 \equiv \bar{a}^3 (f_{\rm w} + f_{\rm v}) \\
f_{\rm w} &\equiv f_{\rm wi} a_{\rm w}{}^3 / \bar{a}^3, \qquad f_{\rm v} \equiv f_{\rm vi} a_{\rm v}{}^3 / \bar{a}^3
\end{aligned}
$$

- $f_{\rm vi} = 1 - f_{\rm wi}$ is the fraction of present epoch horizon volume which was in uncompensated underdense perturbations at last scattering.

$$
\bar{H}(t) = \frac{\dot{\bar{a}}}{\bar{a}} = f_{\rm w} H_{\rm w} + f_{\rm v} H_{\rm v}; \qquad H_{\rm w} \equiv \frac{1}{a_{\rm w}} \frac{{\rm d}a_{\rm w}}{{\rm d}t}, \quad H_{\rm v} \equiv \frac{1}{a_{\rm v}} \frac{{\rm d}a_{\rm v}}{{\rm d}t}
$$

- Here t is the Buchert time parameter, considered as a collective coordinate of dust cell coarse-grained at SHS.

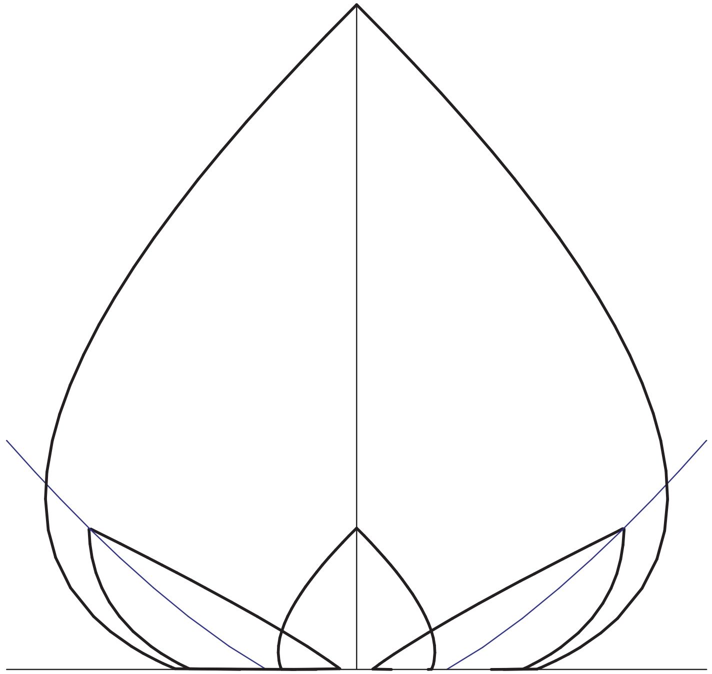
Phenomenological lapse functions

- According to Buchert average variance of ϑ will include internal variance of H_{w} relative to H_{v}.
  Note $h_r \equiv H_{\mathrm{w}}/H_{\mathrm{v}} < 1$.
- Buchert time, t, is measured at the *volume average* position: locations where the local Ricci curvature scalar is the same as horizon volume average
- In timescape model, rates of wall and void centre observers who measure an isotropic CMB are fixed by the uniform quasilocal Hubble flow condition, i.e.,

$$\frac{1}{\bar{a}}\frac{\mathrm{d}\bar{a}}{\mathrm{d}t} = \frac{1}{a_{\mathrm{w}}}\frac{\mathrm{d}a_{\mathrm{w}}}{\mathrm{d}\tau_{\mathrm{w}}} = \frac{1}{a_{\mathrm{v}}}\frac{\mathrm{d}a_{\mathrm{v}}}{\mathrm{d}\tau_{\mathrm{v}}}; \qquad \text{or} \qquad \bar{H}(t) = \bar{\gamma}_{\mathrm{w}} H_{\mathrm{w}} = \bar{\gamma}_{\mathrm{v}} H_{\mathrm{v}}$$

where $\bar{\gamma}_{\mathrm{v}} = \frac{\mathrm{d}t}{\mathrm{d}\tau_{\mathrm{v}}}$, $\bar{\gamma}_{\mathrm{w}} = \frac{\mathrm{d}t}{\mathrm{d}\tau_{\mathrm{w}}} = 1 + (1 - h_r) f_v / h_r$, are *phenomenological lapse functions* (NOT ADM lapse).

Past light cone average



- Interpret solution of Buchert equations by radial null cone average

$$ds^2 = -dt^2 + \bar{a}^2(t)\, d\bar{\eta}^2 + A(\bar{\eta}, t)\, d\Omega^2,$$

where $\int_0^{\bar{\eta}_{\mathcal{H}}} d\bar{\eta}\, A(\bar{\eta}, t) = \bar{a}^2(t)\mathcal{V}_{\rm i}(\bar{\eta}_{\mathcal{H}})/(4\pi)$.

- LTB metric but NOT an LTB solution

Physical interpretation

- Conformally match radial null geodesics of spherical Buchert geometry to those of finite infinity geometry with uniform local Hubble flow condition $\mathrm{d}t = \bar{a}\,\mathrm{d}\bar{\eta}$ and $\mathrm{d}\tau_{\mathrm{w}} = a_{\mathrm{w}}\mathrm{d}\eta_{\mathrm{w}}$. But $\mathrm{d}t = \bar{\gamma}\mathrm{d}\tau_{\mathrm{w}}$ and $a_{\mathrm{w}} = {f_{\mathrm{wi}}}^{-1/3}(1 - f_{\mathrm{v}})\,\bar{a}$. Hence *on radial null geodesics*

$$\mathrm{d}\eta_{\mathrm{w}} = \frac{{f_{\mathrm{wi}}}^{1/3}\mathrm{d}\bar{\eta}}{\bar{\gamma}\,(1 - f_{\mathrm{v}})^{1/3}}$$

  Define η_{w} by integral of above on radial null-geodesics.
- Extend spatially flat wall geometry to dressed geometry

$$\mathrm{d}s^2 = -\mathrm{d}\tau_{\mathrm{w}}^2 + a^2(\tau_{\mathrm{w}})\left[\mathrm{d}\bar{\eta}^2 + r_{\mathrm{w}}^2(\bar{\eta},\tau_{\mathrm{w}})\,\mathrm{d}\Omega^2\right]$$

  where $r_{\mathrm{w}} \equiv \bar{\gamma}\,(1 - f_{\mathrm{v}})^{1/3}\,{f_{\mathrm{wi}}}^{-1/3}\eta_{\mathrm{w}}(\bar{\eta},\tau_{\mathrm{w}})$, $a = \bar{a}/\bar{\gamma}$.

Dressed cosmological parameters

- N.B. The extension is NOT an isometry

$$\text{N.B.}\qquad \begin{aligned} \mathrm{d}s^2_{\mathcal{F}_I} &= -\mathrm{d}\tau_{\mathrm{w}}^2 + {a_{\mathrm{w}}}^2(\tau_{\mathrm{w}})\left[\mathrm{d}\eta_{\mathrm{w}}^2 + \eta_{\mathrm{w}}^2 \mathrm{d}\Omega^2\right] \\ \to \mathrm{d}s^2 &= -\mathrm{d}\tau_{\mathrm{w}}^2 + a^2\left[\mathrm{d}\bar\eta^2 + r_{\mathrm{w}}^2(\bar\eta,\tau_{\mathrm{w}})\,\mathrm{d}\Omega^2\right] \end{aligned}$$

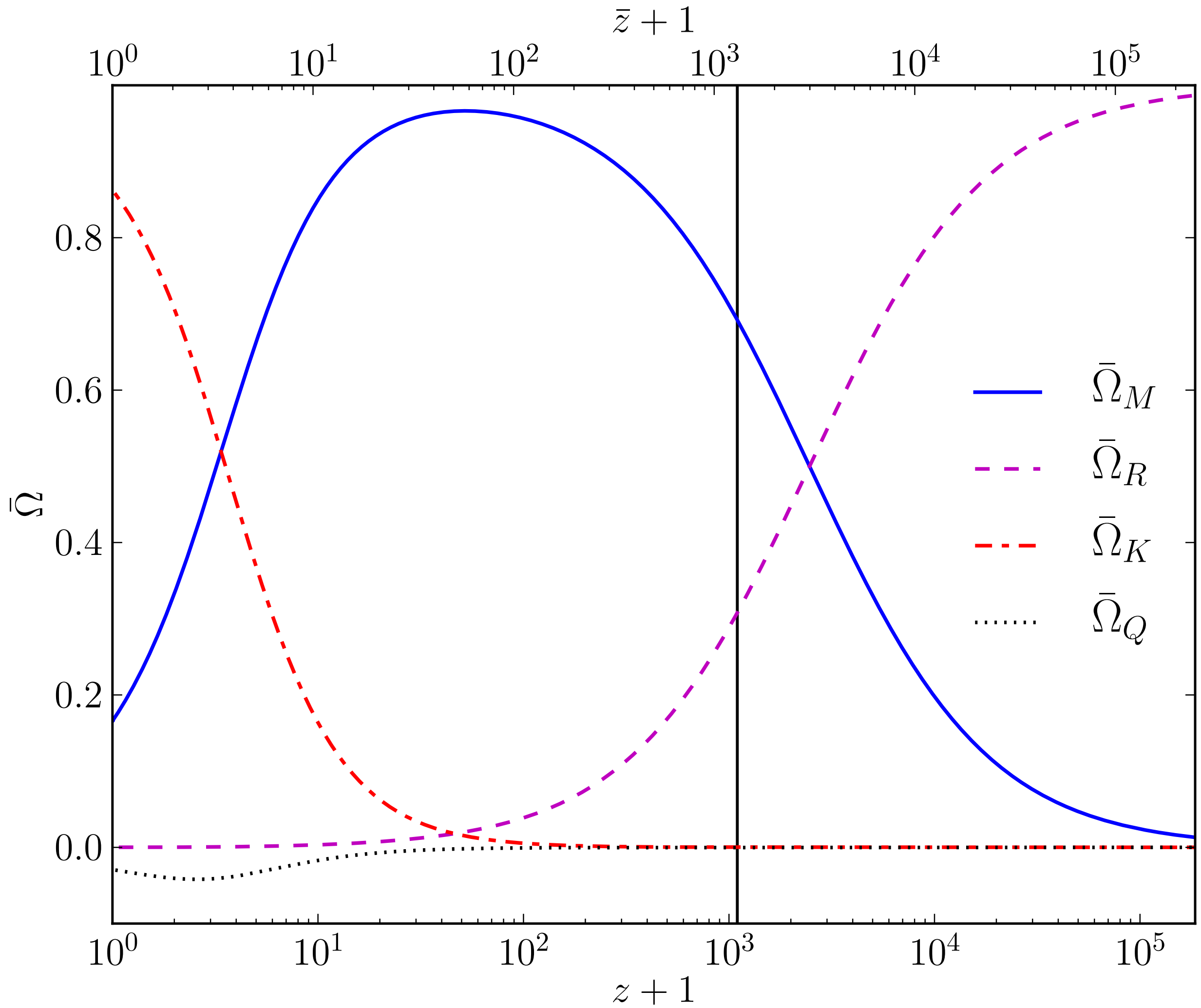
- Extended metric is an effective “spherical Buchert geometry” adapted to wall rulers and clocks.
- Since $\mathrm{d}\bar\eta = \mathrm{d}t/\bar a = \bar\gamma\,\mathrm{d}\tau_{\mathrm{w}}/\bar a = \mathrm{d}\tau_{\mathrm{w}}/a$, this leads to *dressed parameters* which do not sum to 1, e.g.,

$$\Omega_M = \bar\gamma^3 \bar\Omega_M\,.$$

- Dressed average Hubble parameter

$$H = \frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}\tau_{\mathrm{w}}} = \frac{1}{\bar a}\frac{\mathrm{d}\bar a}{\mathrm{d}\tau_{\mathrm{w}}} - \frac{1}{\bar\gamma}\frac{\mathrm{d}\bar\gamma}{\mathrm{d}\tau_{\mathrm{w}}}$$

Bare cosmological parameters



J.A.G. Duley, M.A. Nazer & DLW, CQG 30 (2013) 175006: full numerical solution with matter, radiation

Apparent cosmic acceleration

- Volume average observer sees no apparent cosmic acceleration

$$\bar{q} = \frac{2\left(1 - f_{\mathrm{v}}\right)^2}{(2 + f_{\mathrm{v}})^2}\,.$$

  As $t \to \infty$, $f_{\mathrm{v}} \to 1$ and $\bar{q} \to 0^+$.

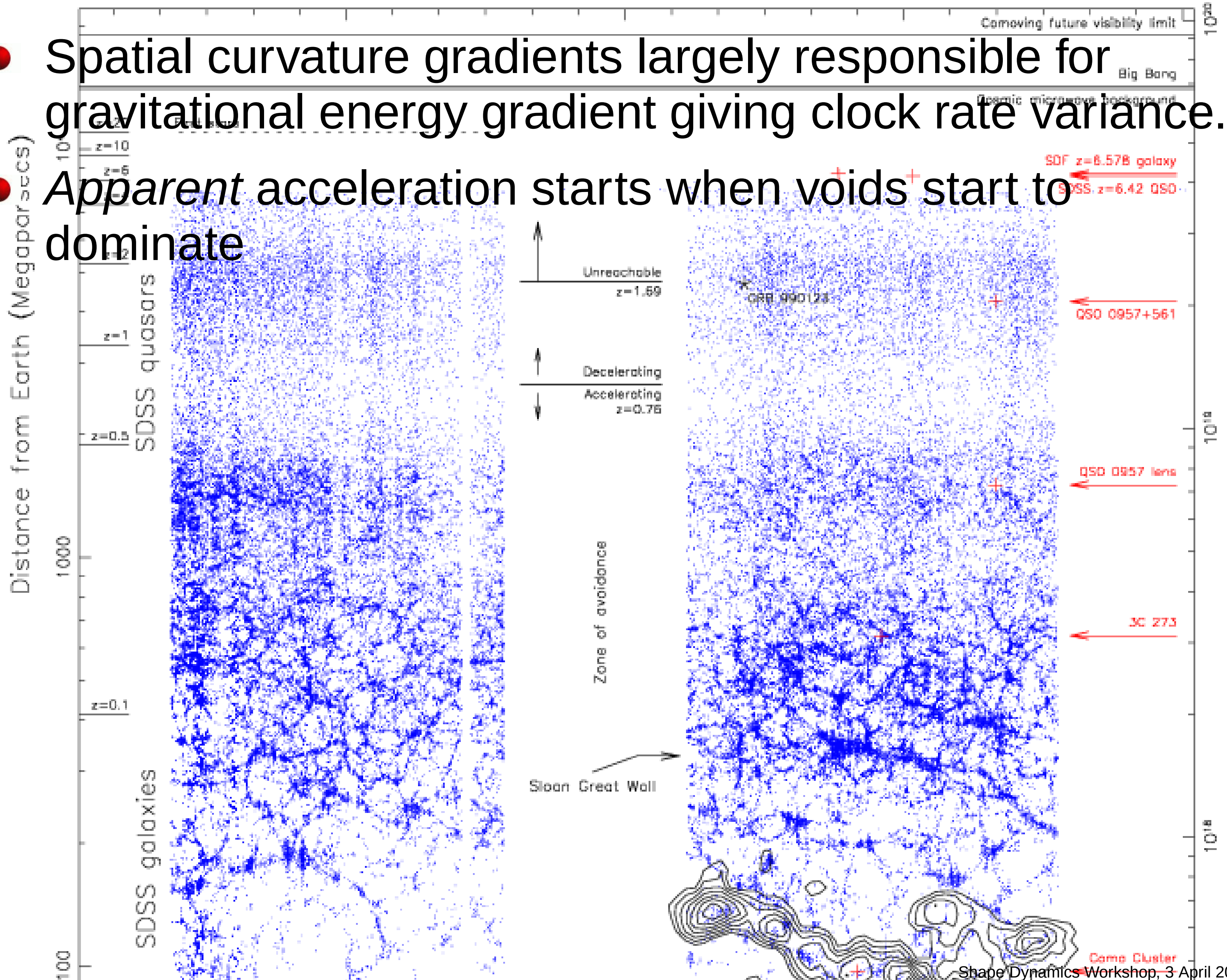
- A wall observer registers apparent cosmic acceleration

$$q = \frac{-\left(1 - f_{\mathrm{v}}\right)\left(8{f_{\mathrm{v}}}^3 + 39{f_{\mathrm{v}}}^2 - 12f_{\mathrm{v}} - 8\right)}{\left(4 + f_{\mathrm{v}} + 4{f_{\mathrm{v}}}^2\right)^2}\,,$$

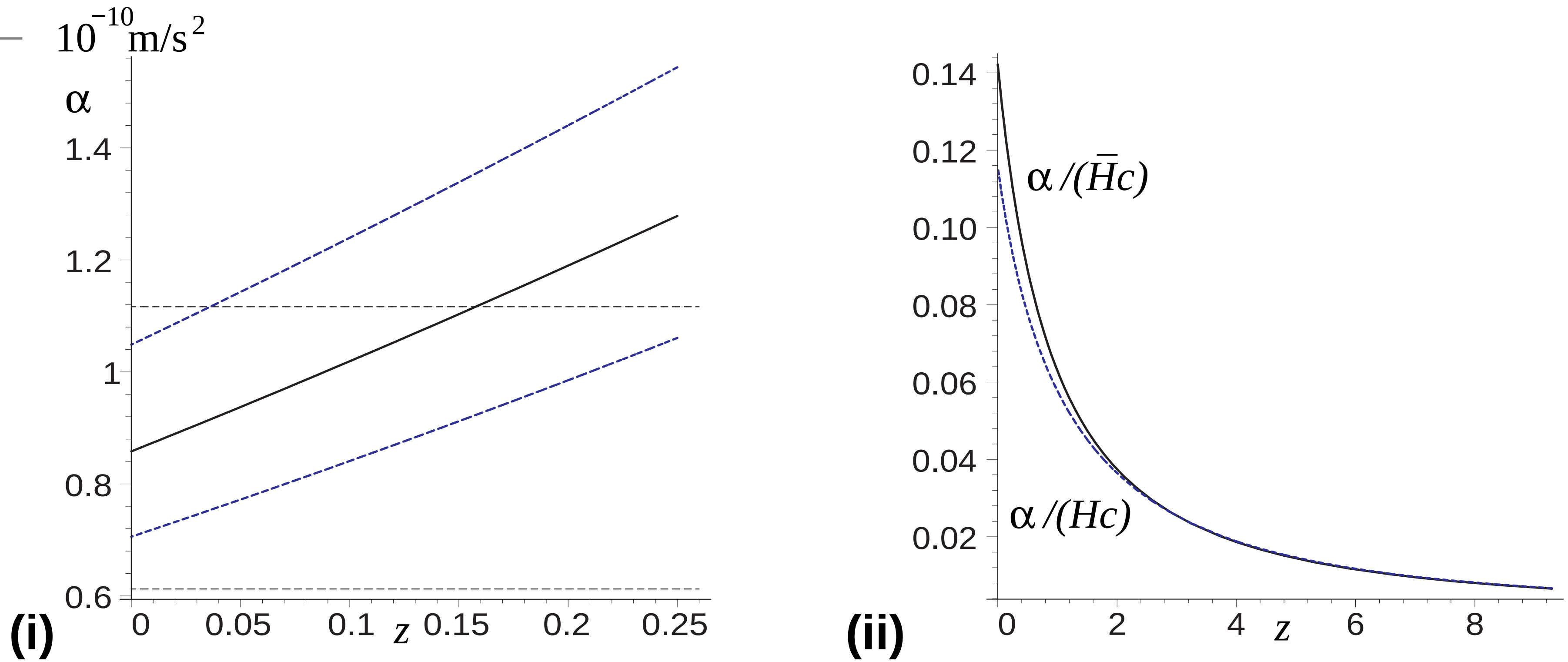
  Effective deceleration parameter starts at $q \sim \frac{1}{2}$, for small f_{v}; changes sign when $f_{\mathrm{v}} = 0.5867\ldots$, and approaches $q \to 0^-$ at late times.

Cosmic coincidence problem solved

- Spatial curvature gradients largely responsible for gravitational energy gradient giving clock rate variance.
- *Apparent* acceleration starts when voids start to dominate



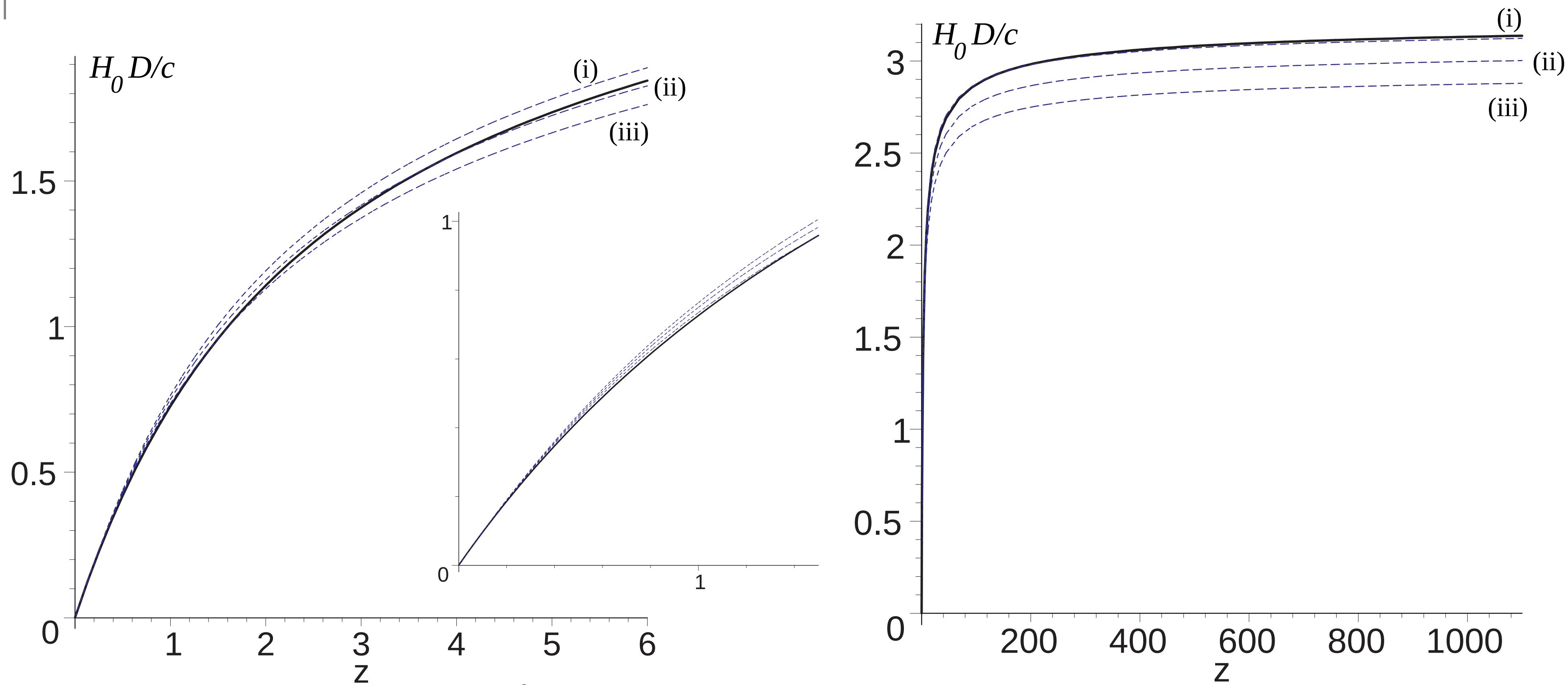
Relative deceleration scale



By cosmological equivalence principle the instantaneous relative deceleration of backgrounds gives an instantaneous 4-acceleration of magnitude $\alpha = H_0 c\bar{\gamma}\dot{\bar{\gamma}}/(\sqrt{\bar{\gamma}^2 - 1})$ beyond which *weak field cosmological general relativity* will be changed from Newtonian expectations: **(i)** as absolute scale nearby; **(ii)** divided by Hubble parameter to large z.

- Relative *volume* deceleration of expanding regions of different local density/curvature, leads cumulatively to canonical clocks differing by $\mathrm{d}t = \bar{\gamma}_{\mathrm{w}}\, \mathrm{d}\tau_{\mathrm{w}}$ ($\rightarrow \sim 35\%$)

Dressed "comoving distance" $D(z)$

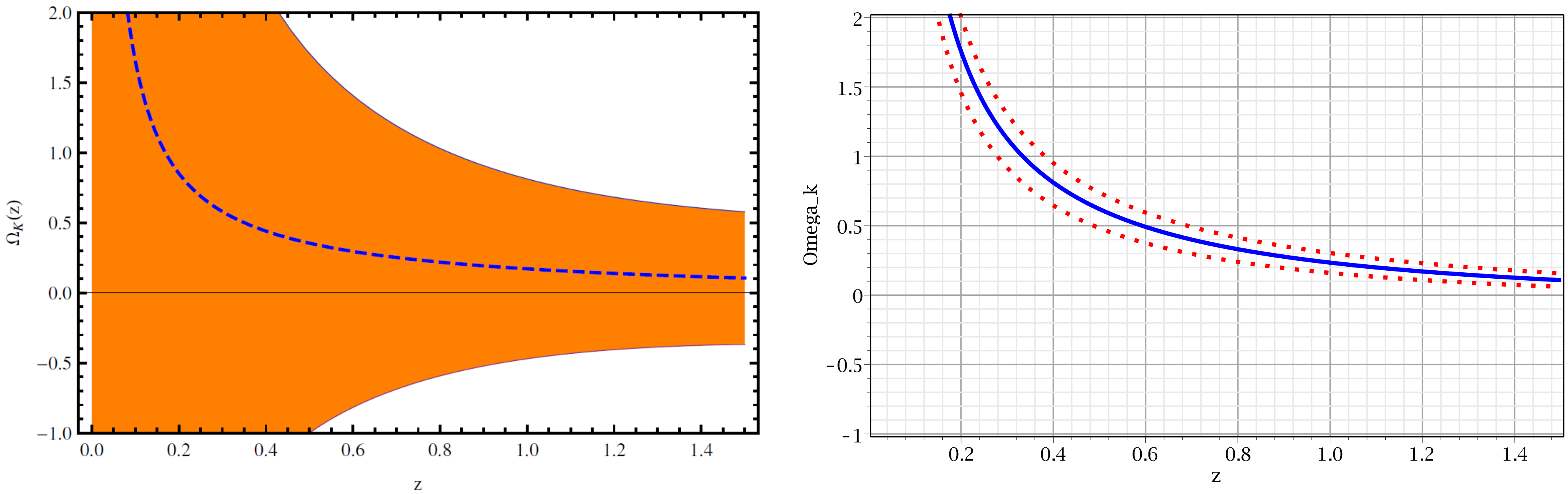


TS model, with $f_{\rm v0} = 0.695$, **(black)** compared to 3 spatially flat ΛCDM models (blue): **(i)** $\Omega_{M0} = 0.3175$ (best-fit ΛCDM model to Planck); (ii) $\Omega_{M0} = 0.35$; **(iii)** $\Omega_{M0} = 0.388$.

Clarkson Bassett Lu test $\Omega_k(z)$

- For Friedmann equation a statistic constant for all z

$$\Omega_{k0} = \Omega_k(z) = \frac{[c^{-1}H(z)D'(z)]^2 - 1}{[c^{-1}H_0 D(z)]^2}$$

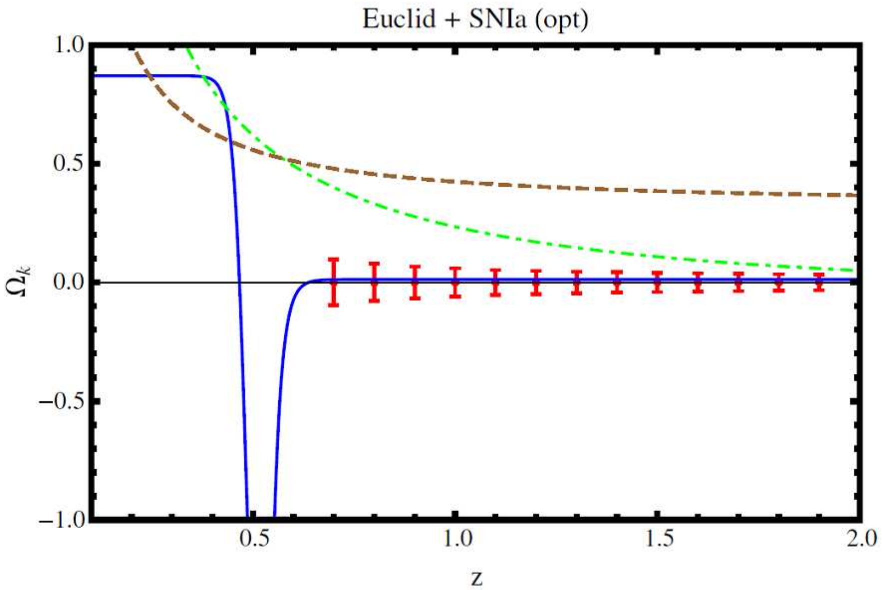


Left panel: CBL statistic from Sapone, Majerotto and Nesseris, PRD 90, 023012 (2015) Fig 8,

using existing data from SneIa (Union2) and passively evolving galaxies for $H(z)$.

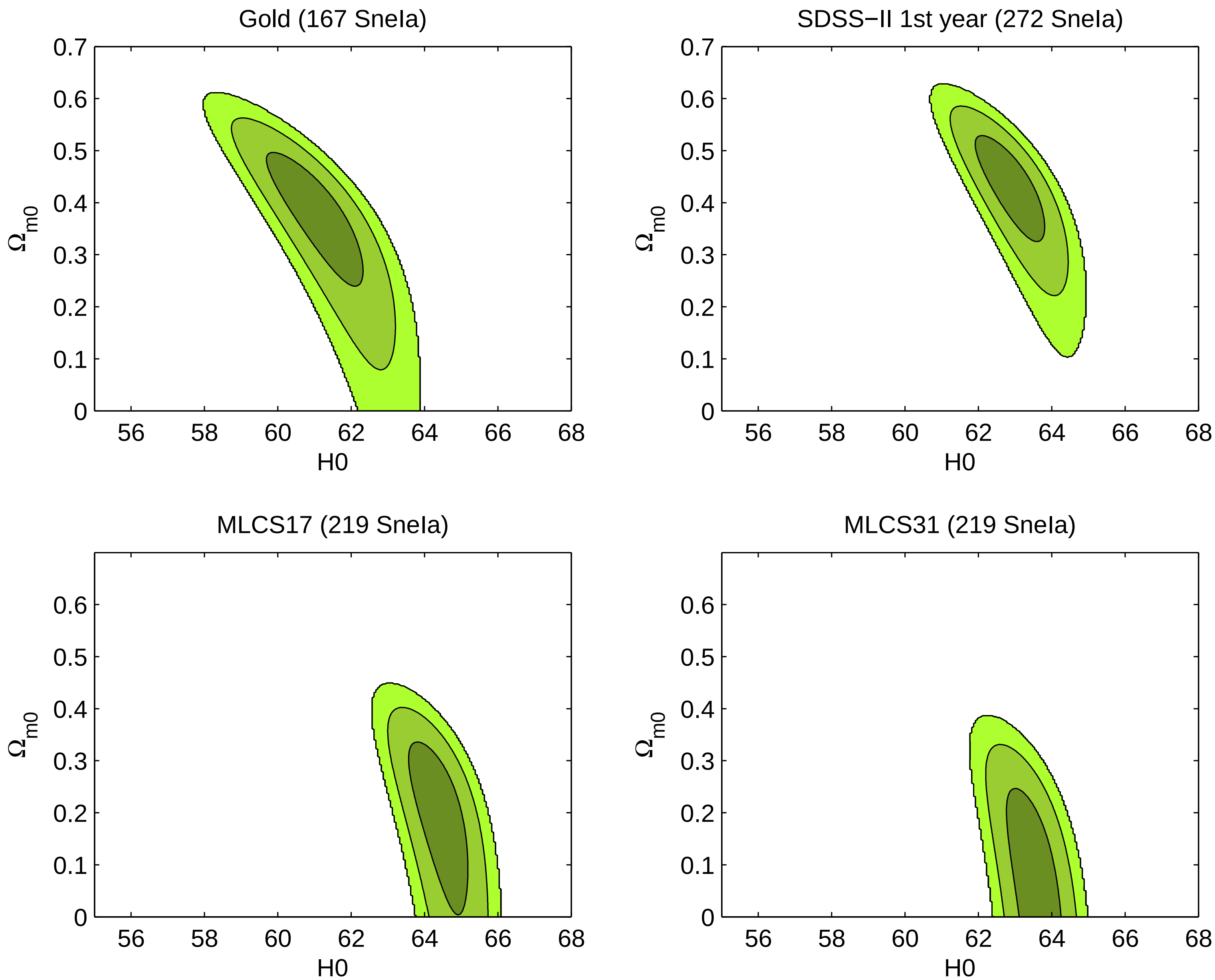
Right panel: TS prediction, with $f_{v0} = 0.695^{+0.041}_{-0.051}$.

Clarkson Bassett Lu test with *Euclid*

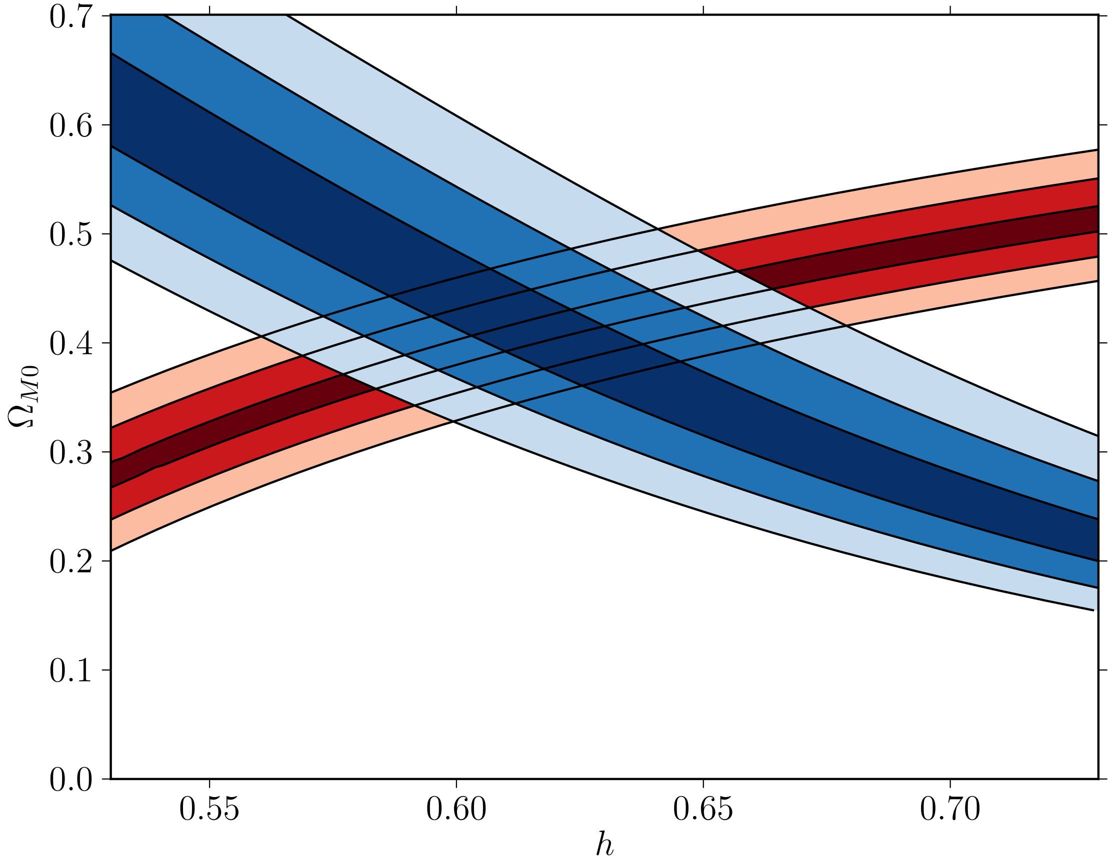


- Projected uncertainties for ΛCDM model with *Euclid* $+$ 1000 SneIa, Sapone *et al*, arXiv:1402.2236v2 Fig 10
- Timescape prediction (green), compared to non-Copernican Gpc void model (blue), and *tardis* cosmology, Lavinto *et al* arXiv:1308.6731 (brown).
- Timescape prediction becomes greater than uncertainties for $z \lesssim 1.5$. (Falsfiable.)

Supernovae systematics



CMB: sound horizon + baryon drag

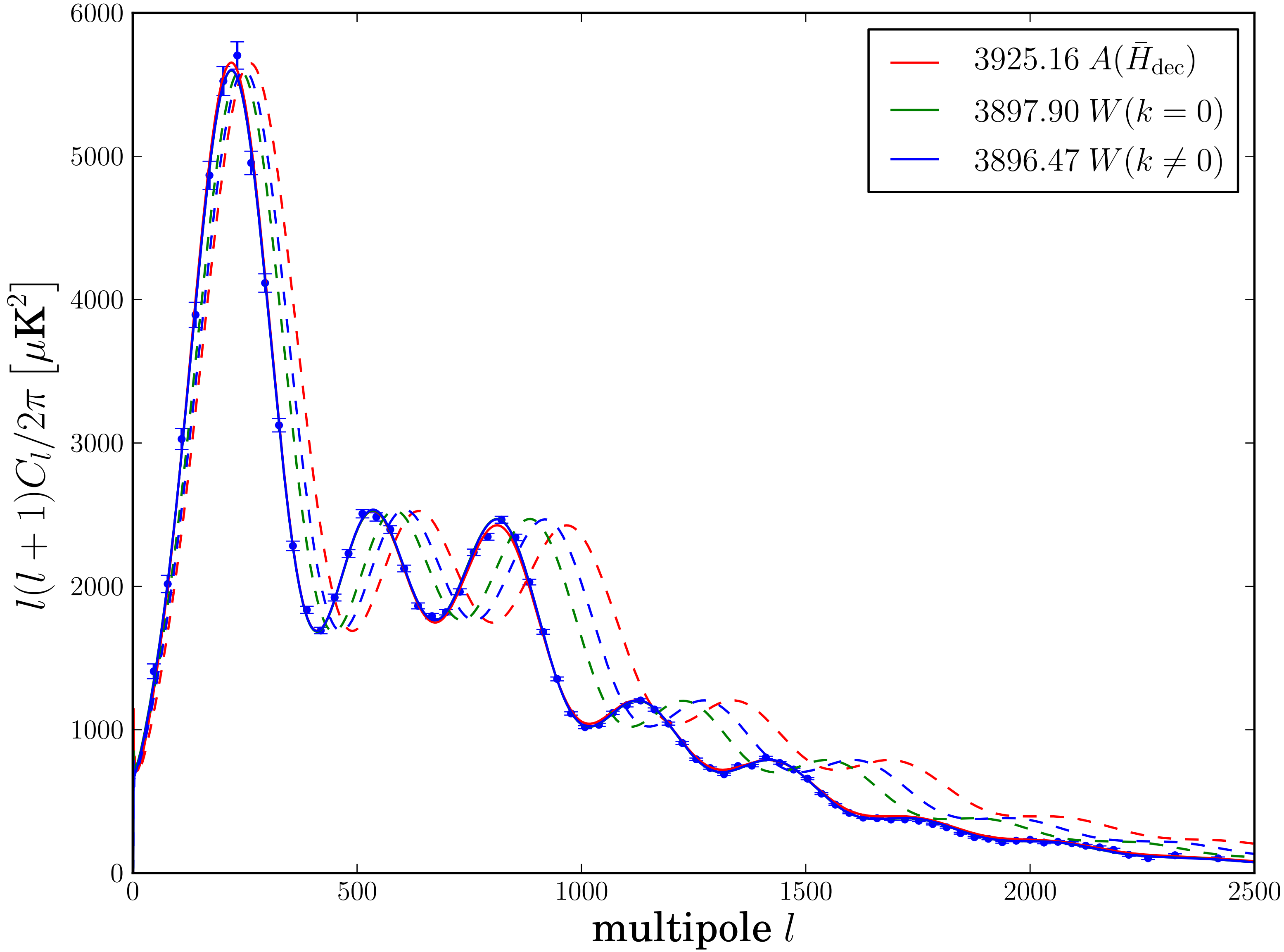


Parameters within the (Ω_{M0},H_0) plane which fit the angular scale of the sound horizon $\theta_* = 0.0104139$ (blue), and its comoving scale at the baryon drag epoch as compared to Planck value $98.88\,h^{-1}$Mpc (red) to within 2%, 4% and 6%, with photon-baryon ratio $\eta_{B\gamma} = 4.6$–5.6×10^{-10} within 2σ of all observed light element abundances (including lithium-7). J.A.G. Duley, M.A. Nazer + DLW, Class. Qu. Grav. **30** (2013) 175006

Planck constraints $D_A + r_{drag}$

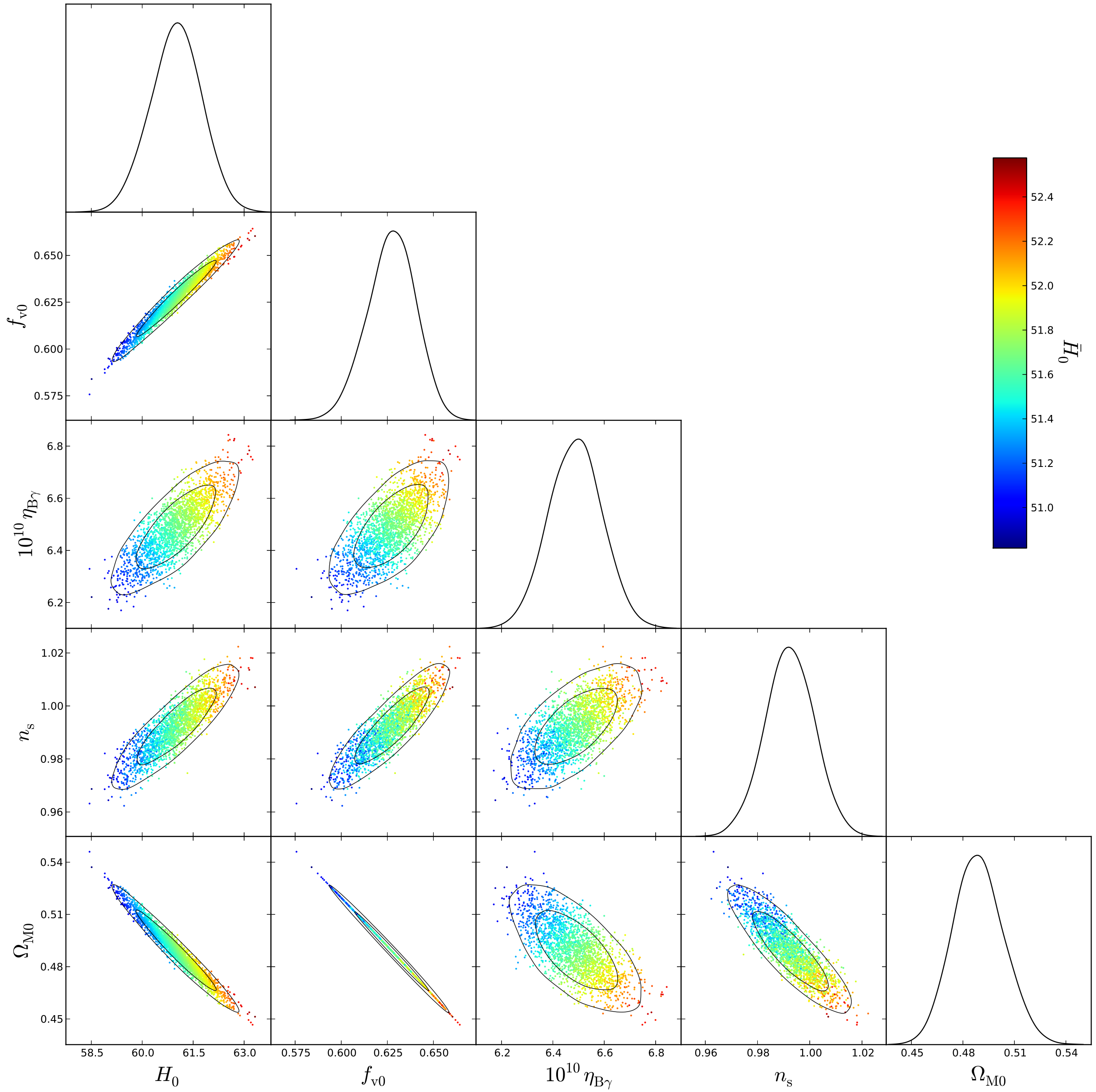
- Dressed Hubble constant $H_0 = 61.7 \pm 3.0$ km/s/Mpc
- Bare Hubble constant $H_{\rm w0} = \bar{H}_0 = 50.1 \pm 1.7$ km/s/Mpc
- Local max Hubble constant $H_{\rm v0} = 75.2^{+2.0}_{-2.6}$ km/s/Mpc
- Present void fraction $f_{\rm v0} = 0.695^{+0.041}_{-0.051}$
- Bare matter density parameter $\bar{\Omega}_{M0} = 0.167^{+0.036}_{-0.037}$
- Dressed matter density parameter $\Omega_{M0} = 0.41^{+0.06}_{-0.05}$
- Dressed baryon density parameter $\Omega_{B0} = 0.074^{+0.013}_{-0.011}$
- Nonbaryonic/baryonic matter ratio $\Omega_{\rm C0}/\Omega_{B0} = 4.6^{+2.5}_{-2.1}$
- Age of universe (galaxy/wall) $\tau_{\rm w0} = 14.2 \pm 0.5$ Gyr
- Age of universe (volume-average) $t_0 = 17.5 \pm 0.6$ Gyr
- Apparent acceleration onset $z_{\rm acc} = 0.46^{+0.26}_{-0.25}$

CMB acoustic peaks, full Planck fit



MCMC coding by M.A. Nazer, adapting *CLASS*

M.A. Nazer + DLW, arXiv:1410.3470

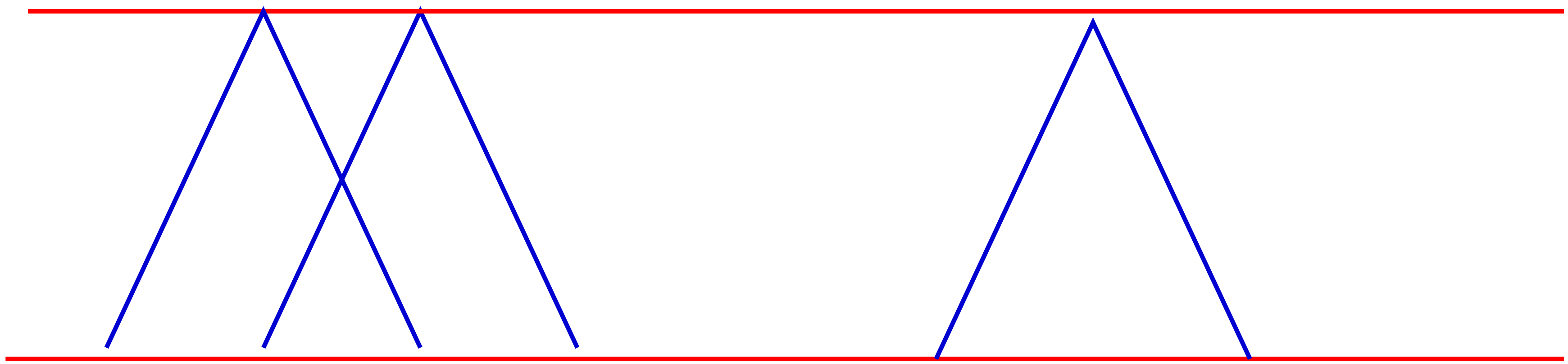


CMB acoustic peaks: arXiv:1410.3470

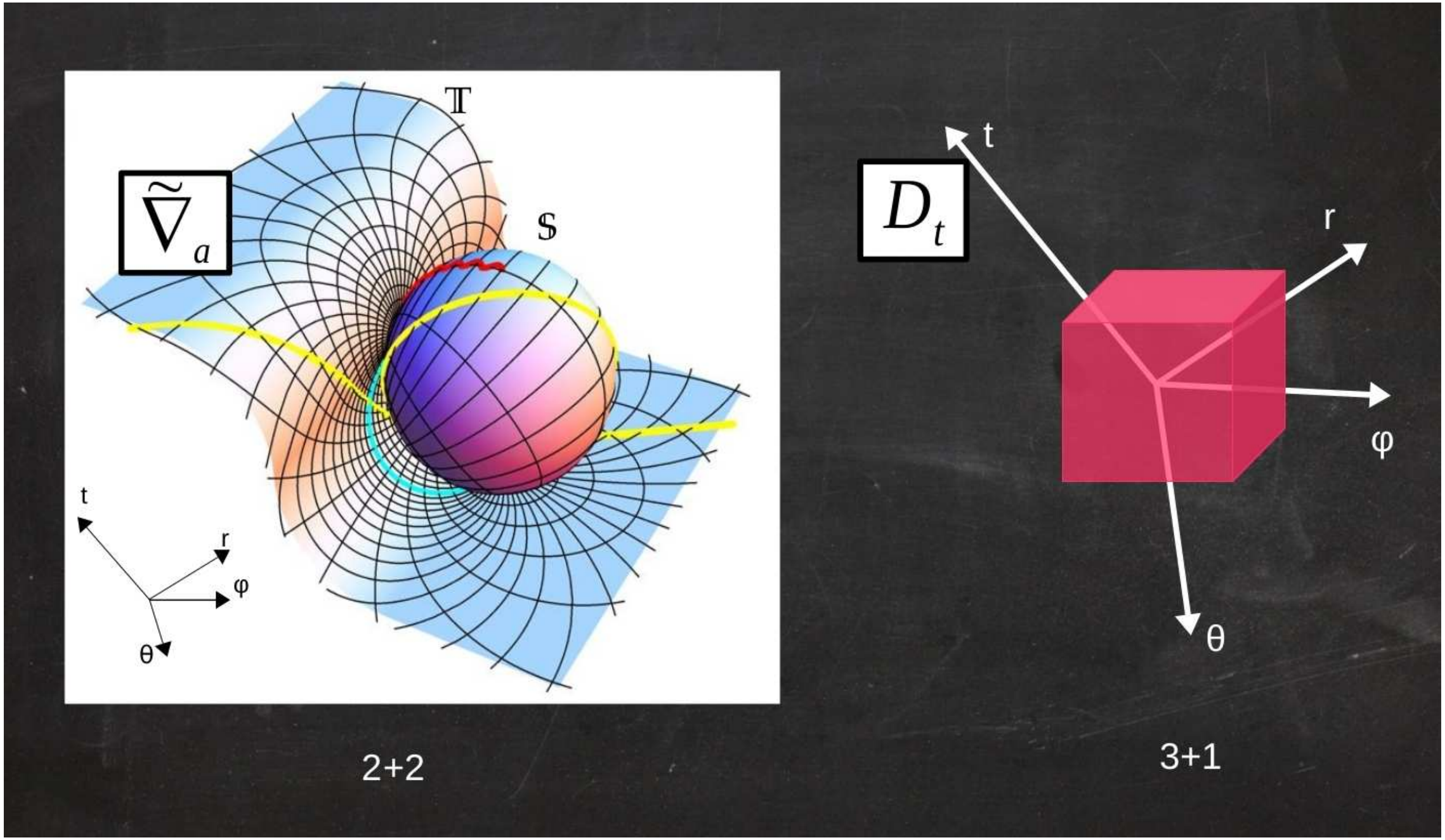
- Likelihood $-\ln\mathcal{L} = 3925.16$, 3897.90 and 3896.47 for A($\bar{H}_{\rm dec}$), W($k=0$) and W($k\neq 0$) methods respectively on $50 \le \ell \le 2500$, c.f., ΛCDM: 3895.5 using `MINUIT` or 3896.9 using `CosmoMC`.
- $H_0 = 61.0$ km/s/Mpc (± 1.3% stat) (± 8% sys); $f_{\rm v0} = 0.627$ (± 2.33% stat) (± 13% sys).
- Previous D_A + r_{drag} constraints give concordance for baryon–to–photon ratio $10^{10}\eta_{B\gamma} = 5.1 \pm 0.5$ with no primordial ^{7}Li anomaly, $\Omega_{\rm C0}/\Omega_{B0}$ possibly 30% lower.
- Full fit – driven by 2nd/3rd peak heights, $\Omega_{\rm C0}/\Omega_{B0}$, ratio – gives $10^{10}\eta_{B\gamma} = 6.08$ (± 1.5% stat) (± 8.5% sys).
- With bestfit values, primordial ^{7}Li anomalous and BOSS $z = 2.34$ result in tension at level similar to ΛCDM

All roads lead to 2 dimensions

- Dimensional reduction to 2 dimensions in QG defines initial conditions
- Relational structure: When all relations lightlike spacetime melts
- Idea: effective CMC slice of statistical geometry, and emergent small scale spacetime geometry is a 3+1 view on initial conditions

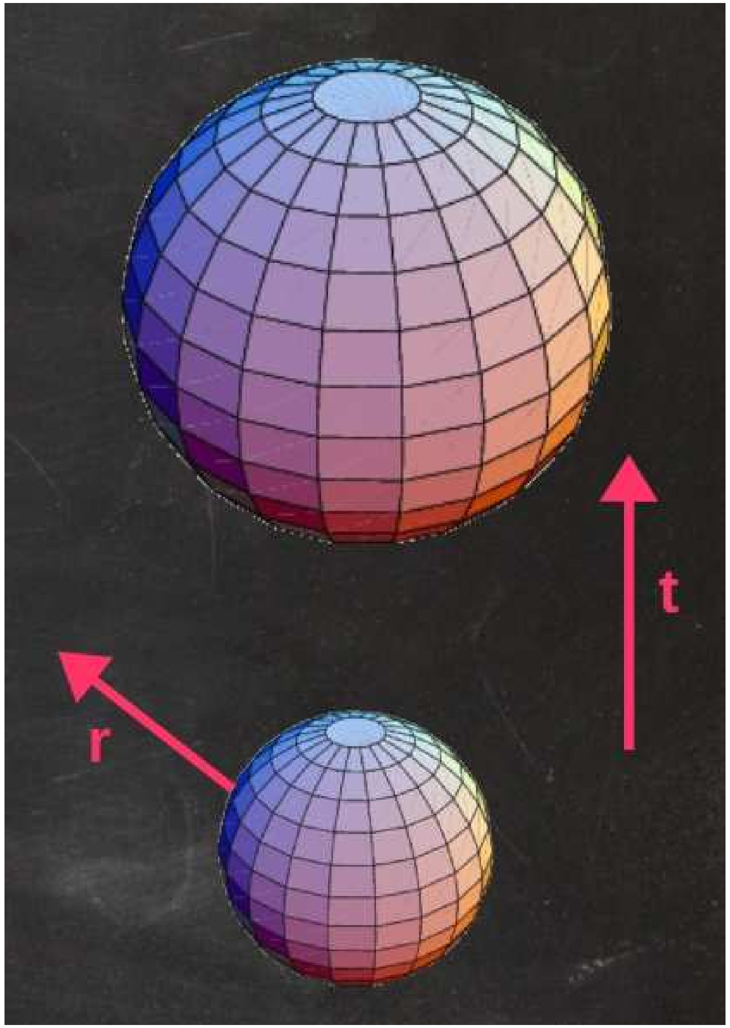


Evolution – Change $\longrightarrow$ 2 + 2 formalism



N. Uzun + DLW, Class. Quan. Grav. 32 (2015) 165011
Nezihe Uzun, arXiv:1602.07861

Quasilocal energy



$$E_{\mathrm{BY}} = -\frac{1}{8\pi}\int_{\mathbb{S}}\sqrt{\sigma}\,(k - k_0)$$

$$E_K = -\frac{1}{16\pi}\int_{\mathbb{S}}\sqrt{\sigma}\left(\frac{k^2 - l^2 - k_0^2}{k_0}\right)$$

$$E_{\mathrm{E}} = -\frac{1}{8\pi}\int_{\mathbb{S}}\sqrt{\sigma}\sqrt{k^2 - l^2} - E_{ref}$$

$$E_{KLY} = -\frac{1}{8\pi}\int_{\mathbb{S}}\sqrt{\sigma}\left(\sqrt{k^2 - l^2} - k_0\right)$$

$$k^2 - l^2$$

$$\downarrow$$

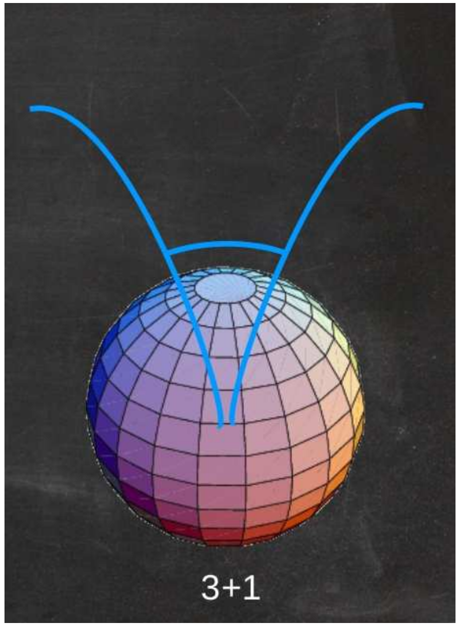
Mean extrinsic curvature

$$\downarrow$$

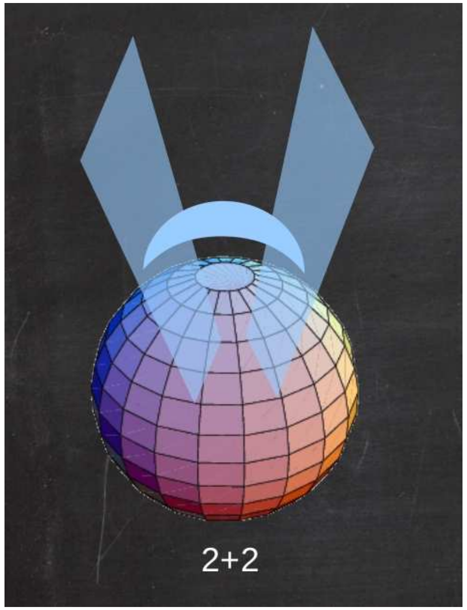
Quasilocal Energy!

Raychaudhuri eqn for worldsheet $\mathcal{T}$

Extrinsic geometry: how worldlines/worldsheets expand



Θ^2



$f\left(k^2 - l^2\right)$

Minimize $f\left(k^2 - l^2\right) \rightarrow$ Equilibrium (arXiv:1506.05801)
General case $\rightarrow$ Energy exchange (arXiv:1602.07861, Nezihe Uzun)

Marrying with shape dynamics

- Kijowski modifies the ADM symplectic 2-form with a boundary term invariant w.r.t. gauge transformations that do not move 2-D boundary

$$\omega = \frac{-1}{16\pi} \int_{\mathcal{V}} \delta g_{ij} \wedge \delta P^{ij} + \frac{1}{8\pi} \int_{\delta\mathcal{V}} \delta\lambda \wedge \delta\alpha$$

$\lambda \equiv \sqrt{\det g_{A,B}}$, $A, B = 2, 3$ volume density on $\mathcal{S}$; $\sinh\alpha = g^{01}/\sqrt{g^{00}g^{11}}$ gives tilt between 3-D spacelike hypersurface and $2+1$ worldtube of $\mathcal{S}$

- Using E_{K-L-Y} as boundary charge

$$\mathcal{H} = \frac{1}{16\pi} \int_{\mathcal{V}} \sqrt{g} \left(NH + N^k H_k \right) - \frac{1}{8\pi} \int_{\partial\mathcal{V}} \sqrt{\sigma} \left(\sqrt{k^2 - l^2} - k_0 \right)$$

- Need $2+1+1$ version of Shape Dynamics

Conclusion and Challenges

Einstein: *“In a consistent theory of relativity there can be no inertia relatively to ‘space’, but only an inertia of masses relatively to one another.”*

- I propose the CEP as a step towards realizing Mach’s principle in general relativity, as a limiting principle which outlaws Gödel’s universe and other craziness
- Spacetime does not exist separately from matter but is a causal relational structure between things
- The Universe started 2-dimensional when all particles were massless and all relationships lightlike
- 3-dimensional spatial conformal invariance of a statistical geometry under quasilocal dimensions should emerge, as well as Einstein geometries