Perhaps

There Is No Dark Energy and the Universe Is Not Accelerating

in the Usual Sense

Origins of Dark Energy   May 2007

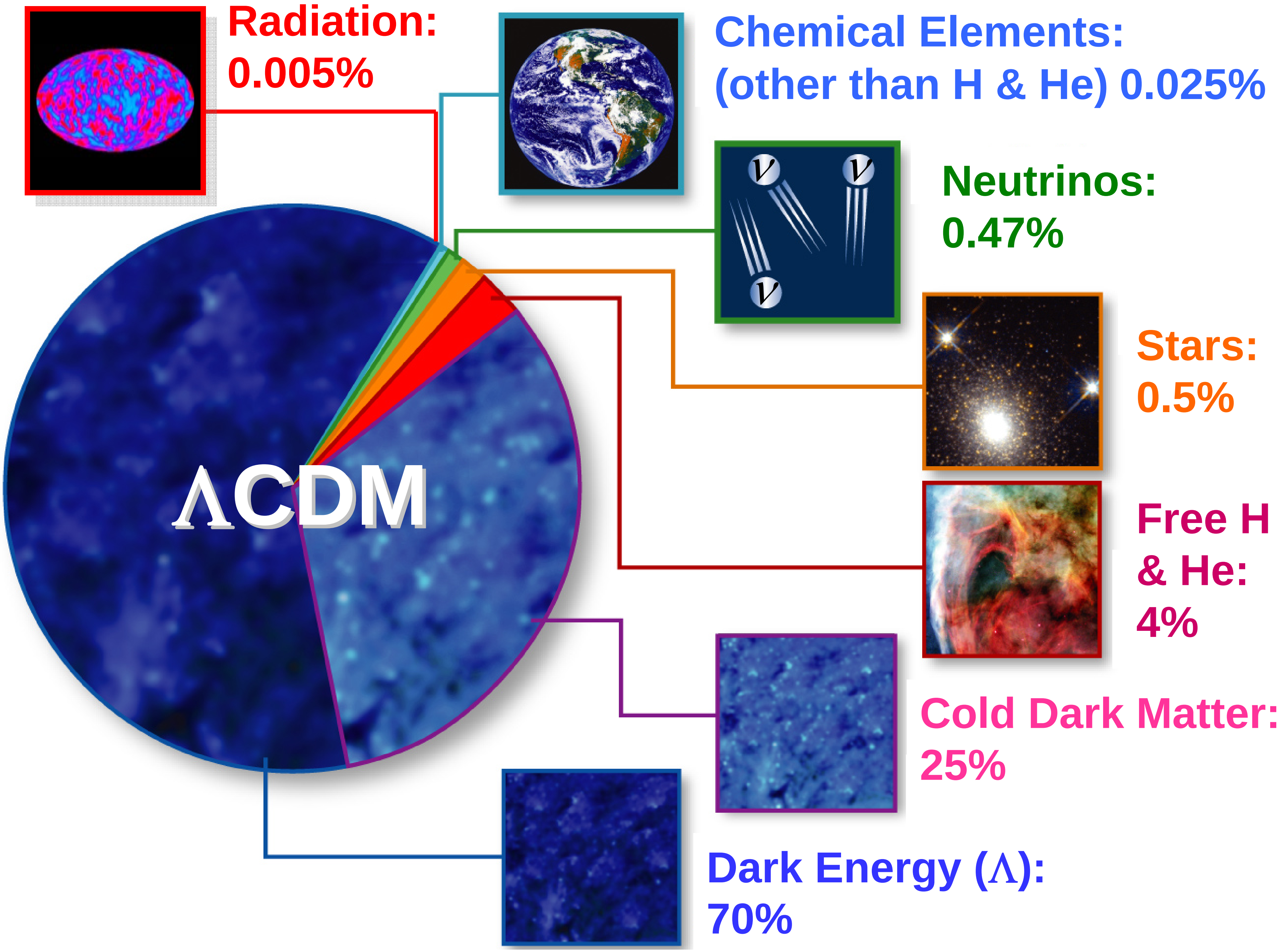
Rocky Kolb   *University of Chicago*

Published work from collaborations with Sabino Matarrese and Antonio Riotto (Padova) [and occasionally Alessio Notari (McGill)]

Kolb, Matarrese, and Riotto, *New Journal of Physics* **8**, 322 (2006)

Ongoing collaborations with Valentin Kostov and Valerio Marra (Chicago)

No Dark Energy, No Acceleration!!!!!


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.47%
Stars:
0.5%
Free H
& He:
4%
Cold Dark Matter:
25%
Dark Energy (Λ):
70%
ΛCDM

ΛCDM: Reality Or Substitute for It?

The construction of a model … consists of snatching from the enormous and complex mass of facts called reality a few simple, easily managed key points which, when put together in some cunning way, becomes for certain purposes a substitute for reality itself.

Evsey Domar
Essays on the Theory of Economic Growth

It hardly matters to me whether he [Copernicus] claims that Earth moves or that it is immobile, so long as we get an absolutely exact knowledge of the movements of the stars and the periods of their movements, so long as both are reduced to altogether exact calculation.

Gemma Frisius
16th century Dutch astronomer

Evolution of $H(z)$ Is a Key Quantity

Robertson–Walker metric

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

Many observables based on $H(z)$ through coordinate distance $r(z)$

$$r(z) = \left.\begin{matrix}\sin\\ 1\\ \sinh\end{matrix}\right\}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

- Luminosity distance

  Flux = (Luminosity / $4\pi d_L^2$)

$$d_L(z) \propto r(z)(1+z)$$

- Angular diameter distance

  $\alpha =$ Physical size / d_A

$$d_A(z) \propto \frac{r(z)}{(1+z)}$$

- Volume (number counts)

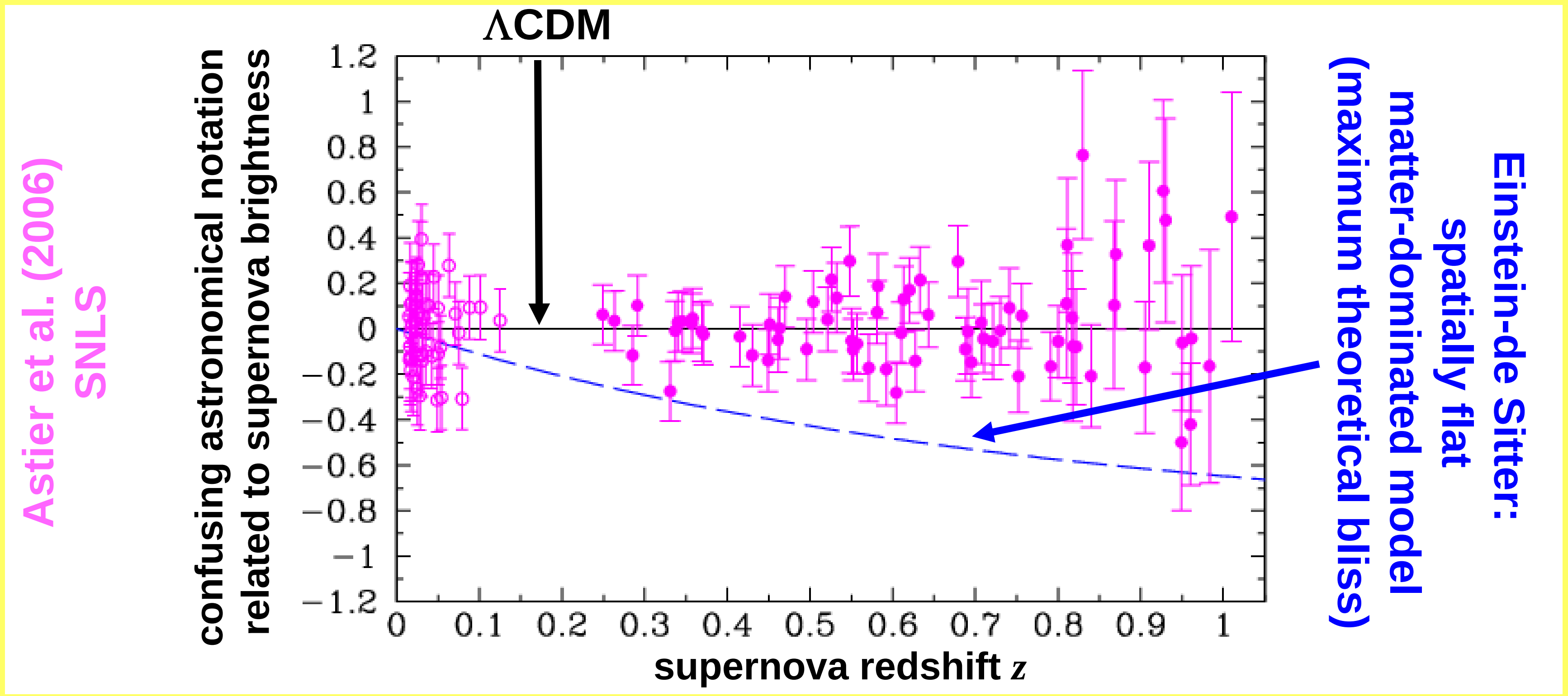
  $N \propto V^{-1}(z)$

$$dV = \frac{r^2(z)}{\sqrt{1-kr^2(z)}}\, dr\, d\Omega$$

- Age of the universe

$$t(z) \propto \int_0^z \frac{dz'}{(1+z')H(z')}$$

Evidence for Dark Energy



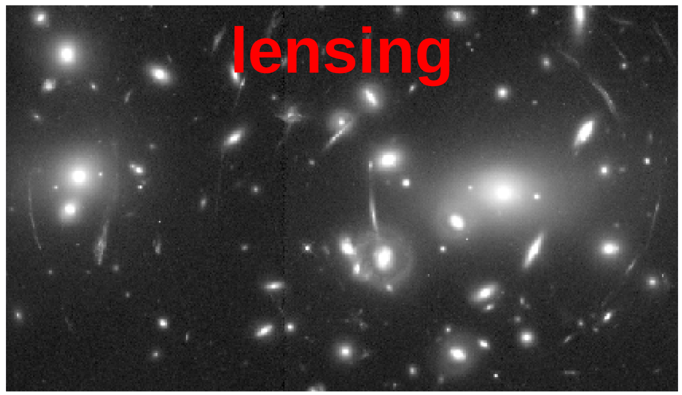
High-z SNe are fainter than expected in the Einstein-deSitter model

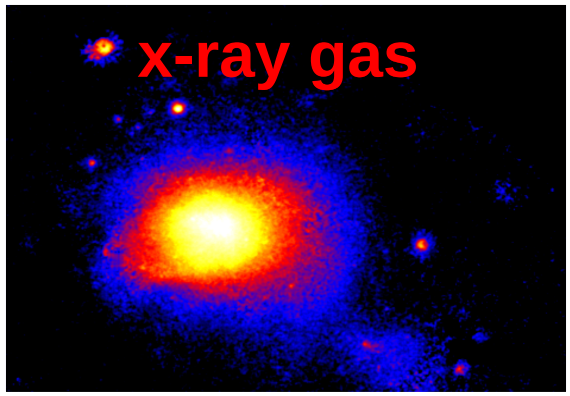
The case for Λ:

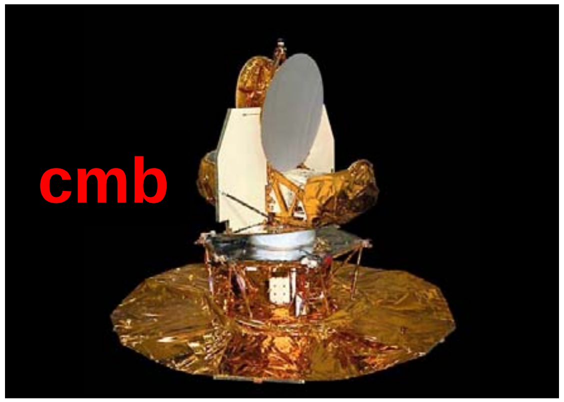
1) Hubble diagram (SNe)
2) subtraction
3) age of the universe
4) structure formation
5) baryon acoustic oscillations
6) weak lensing
7) galaxy clusters

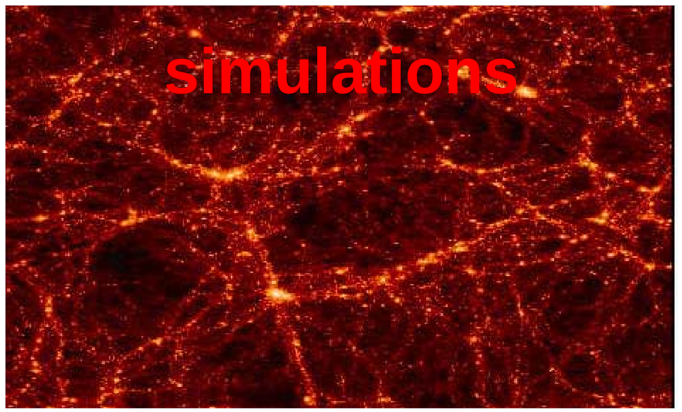
Subtraction

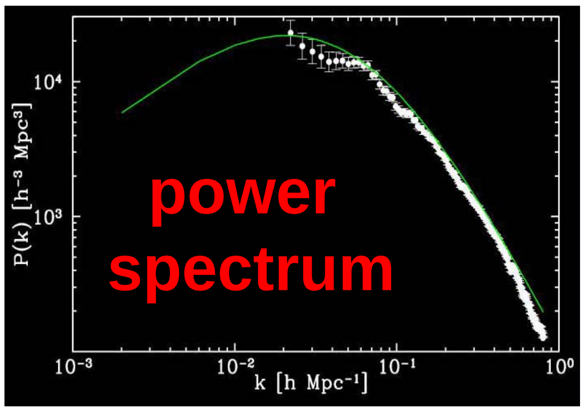
$\Omega_i \equiv \rho_i / \rho_C \qquad \rho_C \equiv 3H_0^2 / 8\pi G$











$\Omega_{\mathrm{TOTAL}} = 1$ (CMB) $\qquad \Omega_M = 0.3$

$1 - 0.3 = 0.7$

$\Omega_{\mathrm{TOTAL}} - \Omega_M = \Omega_\Lambda$

How Do We "Know" Dark Energy Exists?

- Assume model cosmology:
  - Friedmann-Lemaître-Robertson-Walker (FLRW) model
    Friedmann equation: $H^2 = 8\pi G\rho / 3 - k/a^2$
  - Energy (and pressure) content: $\rho = \rho_M + \rho_R + \rho_\Lambda + \ldots$
  - Input or integrate over cosmological parameters: H_0, Ω_M, *etc*.
- Calculate observables $d_L(z)$, $d_A(z)$, $H(z)$, …
- Compare to observations
- Model cosmology fits with ρ_Λ, but not without ρ_Λ
- All evidence for dark energy is *indirect* : observed $H(z)$ is *not* described by $H(z)$ calculated from the Einstein-de Sitter model [spatially flat ($k = 0$) from CMB ; matter dominated ($\rho = \rho_M$)]

Take Sides!

- Can't hide from the data – ΛCDM too good to ignore
  - SNIa
  - Subtraction: $1.0 - 0.3 = 0.7$
  - Age
  - Large-scale structure
  - …

  } $H(z)$ not given by Einstein–de Sitter

$$G_{00}\,\text{(FLRW)} \neq 8\pi G\, T_{00}\text{(matter)}$$

- Modify <u>right-hand side</u> of Einstein equations (ΔT_{00})
  1. Constant ("just" Λ)
  2. Not constant (dynamics driven by scalar field: $M \sim 10^{-33}$ eV)
- Modify <u>left-hand side</u> of Einstein equations (ΔG_{00})
  3. Beyond Einstein (non-GR: $f(R)$, branes, *etc*.)
  4. (Just) Einstein (back reaction of inhomogeneities)

Tools for the Right-Hand Side

scalar fields
(quintessence)

anthropic principle
(the landscape)

Modifying the left-hand side

- Braneworld modifies Friedmann equation — Binetruy, Deffayet, Langlois
- Gravitational force law modified at large distance — Deffayet, Dvali & Gabadadze
  Five-dimensional at cosmic distances
- Tired gravitons — Gregory, Rubakov & Sibiryakov; Dvali, Gabadadze & Porrati
  Gravitons metastable - leak into bulk
- Gravity repulsive at distance $R \approx \mathrm{Gpc}$ — Csaki, Erlich, Hollowood & Terning
- $n = 1$ KK graviton mode very light, $m \approx (\mathrm{Gpc})^{-1}$ — Kogan, Mouslopoulos, Papazoglou, Ross & Santiago
- Einstein & Hilbert got it wrong $f(R)$ — Carroll, Duvvuri, Turner, Trodden

$$S = \left(16\pi G\right)^{-1} \int d^4x \sqrt{-g} \left(R - \mu^4 / R\right)$$

- Backreaction of inhomogeneities — Räsänen; Kolb, Matarrese, Notari & Riotto; Notari; Kolb, Matarrese & Riotto

"Acceleration" from Inhomogeneities

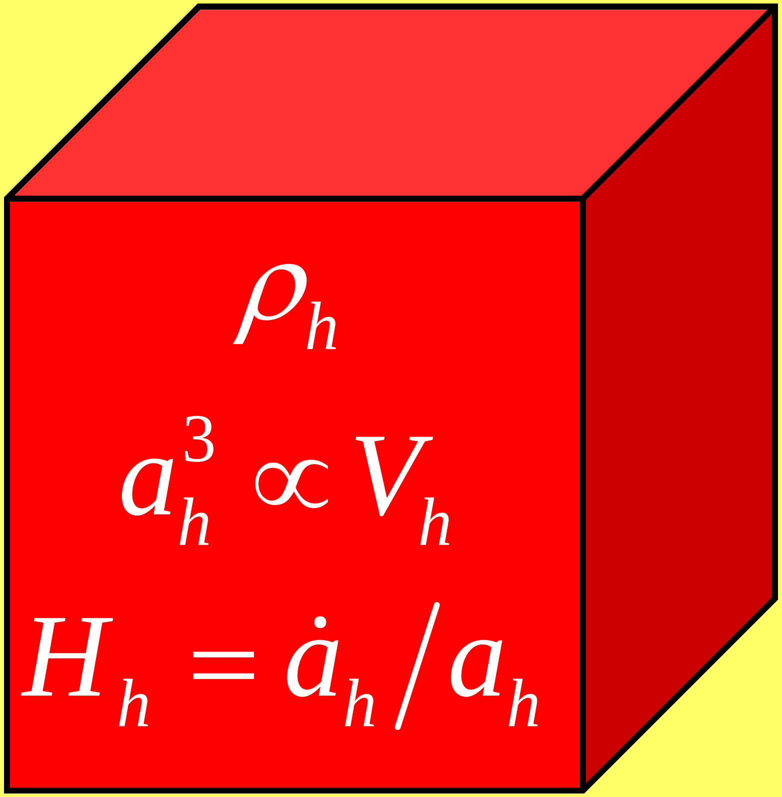
- Most conservative approach — nothing new
  - no new fields (like $10^{-33}\,\mathrm{eV}$ mass scalars)
  - no extra long-range forces
  - no modification of general relativity
  - no modification of gravity at large distances
  - no Lorentz violation
  - no extra dimensions, bulks, branes, etc.
  - no anthropic/landscape or similar faith-based reasoning

- Magnitude?: calculable from observables related to $\delta\rho/\rho$

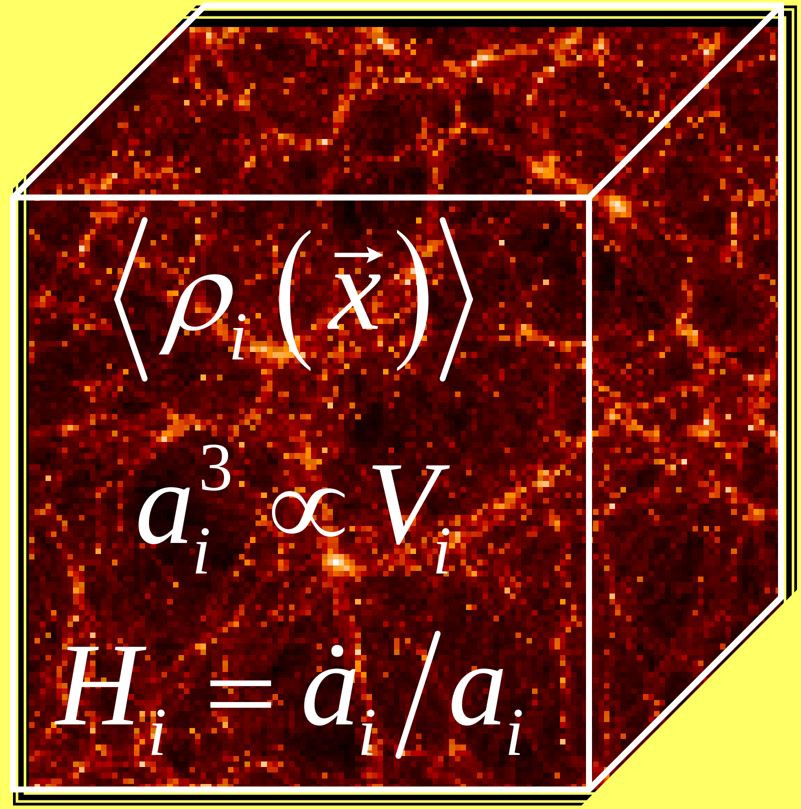
- Why now?: acceleration triggered by era of non-linear structure

Acceleration from Inhomogeneities

Homogeneous model

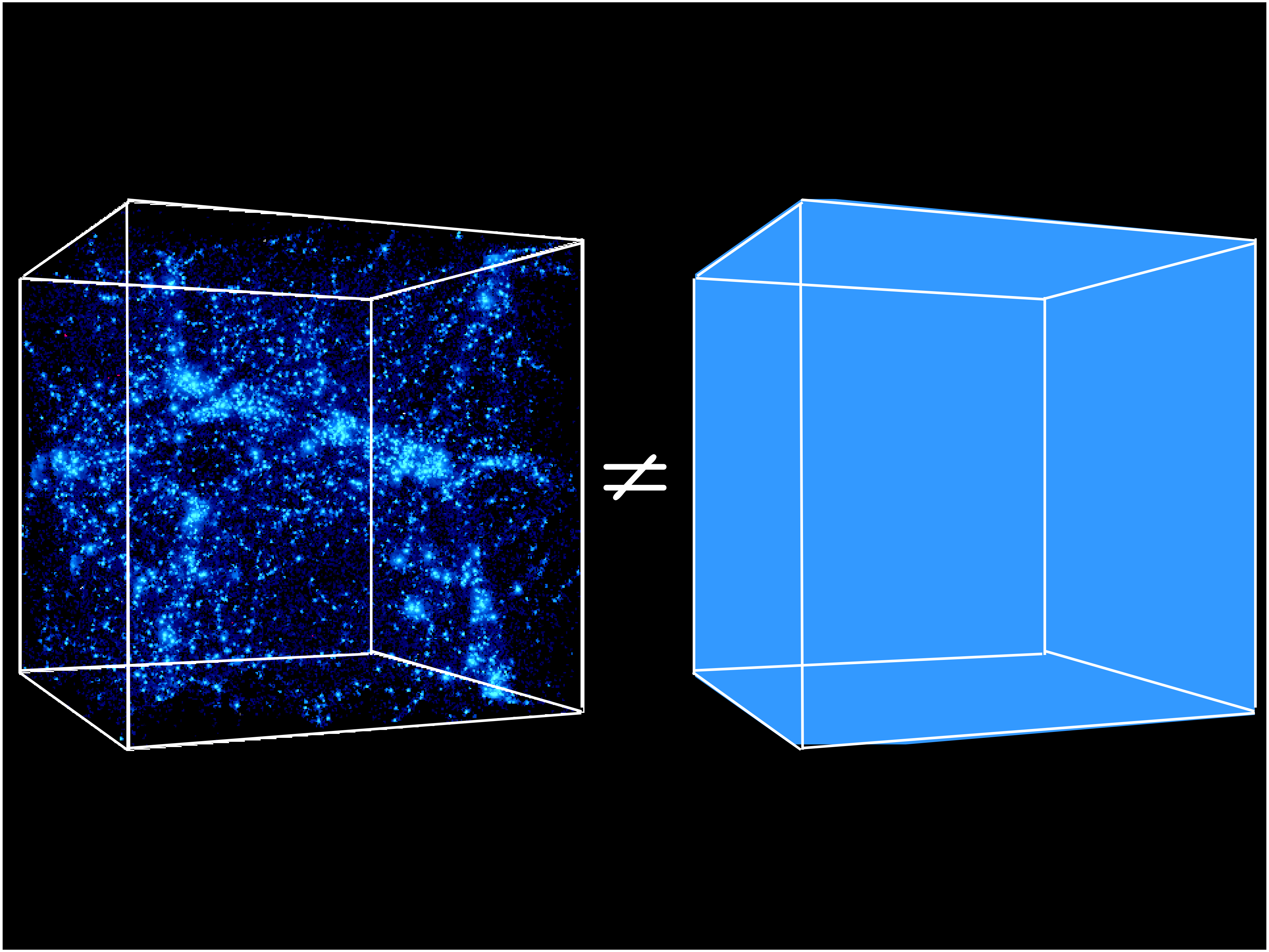


Inhomogeneous model



$$\rho_h = \langle \rho_i(\vec{x}) \rangle \Rightarrow H_h = H_i \ \& \ d_L^h(z) = d_L^i(z) \ ?$$

We think not!



Acceleration from Inhomogeneities

- View scale factor as zero-momentum mode of gravitational field
- In homogeneous/isotropic model it is the only degree of freedom
- Inhomogeneities: non-zero modes of gravitational field
- Non-zero modes interact with and modify zero-momentum mode

Cosmology $\leftrightarrow$ scalar field theory analogue

	cosmology	scalar-field theory
zero-mode	a	$\langle\phi\rangle$(vev of a scalar field)
non-zero modes	inhomogeneities	thermal/finite-density bkgd.
physical effect	modify $a(t)$ *e.g.,* acceleration	modify $\langle\phi(t)\rangle$ *e.g.,* phase transitions

Different Approaches

Standard approach	Our approach
• Model an inhomogeneous Universe as a homogeneous Universe model with $\rho = \langle \rho \rangle$	• Expansion rate of an inhomogeneous Universe $\neq$ expansion rate of homogeneous Universe with $\rho = \langle \rho \rangle$
• Zero-mode [$a(t) \propto V^{1/3}$] is zero-mode of homogeneous model with $\rho = \langle \rho \rangle$	• Inhomogeneities modify zero-mode [effective scale factor is $a_D \equiv V_D^{1/3}$]
• Inhomogeneities only have a local effect on observables	• Effective scale factor has a (global) effect on observables
• Cannot account for observed acceleration	• Potentially can account for acceleration without dark energy or modified GR

Acceleration from Inhomogeneities

- We *do not* use super-Hubble modes for acceleration.

  (If it works the first time, it's over-designed.)
- We *do not* depend on large gravitational potentials such as black holes and neutron stars.
- We assert that the back reaction should be calculated in a frame comoving with the matter—other frames can give spurious results.
- We demonstrate large corrections in the gradient expansion, but the gradient expansion technique can not be used for the final answer—so we have indications (not proof) of a large effect.
- The basic idea is that small-scale inhomogeneities "renormalize" the large-scale properties.

Inhomogeneities–Cosmology

- The expansion rate of an *inhomogeneous* universe of average density $\langle\rho\rangle$ is ***NOT!*** the same as the expansion rate of a *homogeneous* universe of density $\rho = \langle\rho\rangle$!

Ellis, Barausse, Buchert

- Difference is a new term that enters an effective Friedmann equation — the new term need not satisfy energy conditions!
- We deduce dark energy because we are comparing to the wrong model universe (*i.e.,* a homogeneous/isotropic model)

Räsänen, Kolb, Matarrese, Notari, Riotto, Schwarz

Inhomogeneities–Example

Kolb, Matarrese, Notari & Riotto

- Perturbed Friedmann–Lemaître–Robertson–Walker model:

$$G_{\mu\nu}\left(\vec{x},t\right) = G_{\mu\nu}^{\text{FLRW}}\left(t\right) + \delta G_{\mu\nu}\left(\vec{x},t\right)$$

$$G_{00}^{\text{FLRW}}\left(t\right) + \delta G_{00}\left(\vec{x},t\right) = 8\pi G T_{00}\left(\vec{x},t\right)$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left[\left\langle \rho \right\rangle - \frac{3}{8\pi G}\left\langle \delta G_{00} \right\rangle\right]$$

- $(\dot{a}/a)^2$ *is not* $8\pi G\,\langle\rho\rangle/3$
- ($\dot{a}/a$ *is not even the expansion rate*)
- Could $\langle \delta G_{00} \rangle$ be large, or is it 10^{-10}?
- Could $\langle \delta G_{00} \rangle$ play the role of dark energy?

Inhomogeneities–Cosmology

- For a general fluid, four velocity $u^{\mu} = (1, \vec{0})$
  (local observer comoving with energy flow)

- For irrotational dust, work in synchronous and comoving gauge

$$ds^2 = -dt^2 + h_{ij}(\vec{x}, t) dx^i dx^j$$

- Velocity gradient tensor

$$\Theta^i{}_j = u^i{}_{;j} = \tfrac{1}{2} h^{ik} \dot{h}_{kj} = \Theta \delta^i{}_j + \sigma^i{}_j \qquad (\sigma^i{}_j \text{ is traceless})$$

- Θ is the volume-expansion factor and $\sigma^i{}_j$ is the shear tensor
  (shear will have to be small)

- For flat FLRW, $h_{ij}(t) = a^2(t) \delta_{ij}$

  $\Theta = 3H$ and $\sigma^i{}_j = 0$

What Accelerates?

- No-go theorem: Local deceleration parameter positive:

$$q = -\frac{\left(3\dot{\Theta} + \Theta^2\right)}{\Theta^2} = 6\left(\sigma^2 + 2\pi G\rho\right) \geq 0$$

Hirata & Seljak;
Flanagan;
Giovannini;
Ishibashi & Wald

- However must coarse-grain over some finite domain:

$$\langle\Theta\rangle_D = \frac{\int_D \sqrt{h}\,\Theta\, d^3x}{\int_D \sqrt{h}\; d^3x}$$

- Evolution and smoothing do not commute: $\langle\Theta\rangle_D^{\bullet} \neq \langle\Theta^{\bullet}\rangle_D$

$$\langle\Theta\rangle_D^{\bullet} = \langle\Theta^{\bullet}\rangle_D + \langle\Theta^2\rangle_D - \langle\Theta\rangle_D^2 \geq \langle\Theta^{\bullet}\rangle_D$$

Buchert & Ellis;
Kolb, Matarrese & Riotto

- $\langle\Theta\rangle_D^{\bullet} \neq \langle\Theta^{\bullet}\rangle_D$ Can have $q \geqslant 0$ but $\langle q\rangle_D \leqslant 0$ ("no-go" goes)

Inhomogeneities and Smoothing

Kolb, Matarrese & Riotto astro-ph/0506534; Buchert & Ellis

- Define a coarse-grained scale factor:

$$a_D \equiv \left(V_D / V_{D0}\right)^{1/3} \qquad V_D = \int_D d^3x\sqrt{h}$$

- Coarse-grained Hubble rate:

$$H_D = \frac{\dot{a}_D}{a_D} = \tfrac{1}{3}\langle\Theta\rangle_D$$

- Effective evolution equations:

$$\frac{\ddot{a}_D}{a_D} = -\frac{4\pi G}{3}\left(\rho_{\rm eff} + 3p_{\rm eff}\right) \qquad \rho_{\rm eff} = \langle\rho\rangle_D - \frac{Q_D}{16\pi G} - \frac{\langle R\rangle_D}{16\pi G}$$

$$\left(\frac{\dot{a}_D}{a_D}\right)^2 = \frac{8\pi G}{3}\rho_{\rm eff} \qquad 3p_{\rm eff} = -\frac{3Q_D}{16\pi G} + \frac{\langle R\rangle_D}{16\pi G}$$

not described by a simple $p = w\,\rho$

- Kinematical back reaction: $Q_D = \tfrac{2}{3}\left(\langle\Theta^2\rangle_D - \langle\Theta\rangle_D^2\right) - 2\langle\sigma^2\rangle_D$

Inhomogeneities and Smoothing

- Kinematical back reaction: $$Q_D = \tfrac{2}{3}\left(\left\langle\Theta^2\right\rangle_D - \left\langle\Theta\right\rangle_D^2\right) - 2\left\langle\sigma^2\right\rangle_D$$
- For acceleration: $$\rho_{\text{eff}} + 3p_{\text{eff}} = \left\langle\rho\right\rangle_D - \frac{Q_D}{4\pi G} < 0$$
- Integrability condition (GR): $$\left(a_D^6 Q_D\right)^{\bullet} + a_D^4\left(a_D^2\left\langle {}^3R\right\rangle_D\right)^{\bullet} = 0$$
- Acceleration is a pure GR effect:
  - curvature vanishes in Newtonian limit
  - Q_D will be exactly a pure boundary term, and small
- Particular solution: $3Q_D = -\langle {}^3R\rangle_D =$ const.
  - *i.e.*, $\Lambda_{\text{eff}} = Q_D$ (so Q_D acts as a cosmological constant)

Can We See It in Perturbation Theory?

Kolb, Notari, Matarrese & Riotto

- 2nd-order perturbation theory in $\phi(x)$ (Newtonian potential):

$$\frac{\langle \Theta - H \rangle}{H} = -\frac{20\tau^2}{9}\langle \nabla^2\phi \rangle - \frac{23\tau^4}{54}\langle \nabla^2\phi \rangle\langle \nabla^2\phi \rangle$$

mean of $\nabla^2\phi = 0$

$$+\frac{130\tau^2}{27}\langle \phi^{,i}\phi_{,i} \rangle + \frac{4\tau^4}{27}\left(\langle \nabla^2\phi\nabla^2\phi \rangle - \langle \phi^{,ij}\phi_{,ij} \rangle\right)$$

Post-Newtonian **Newtonian**

- Each derivative accompanied by conformal time $\tau = 2/aH$
- Each factor of τ accompanied by factor of c.
- Highest derivative is highest power of $\tau \propto c$: "Newtonian"
- Lower derivative terms $\propto c^{-n}$: "Post-Newtonian"
- ϕ and its derivatives can be expressed in terms of $\delta\rho/\rho$

Some Examples

- $$\tau^2 \left\langle \nabla\phi \cdot \nabla\phi \right\rangle = -\frac{4}{a^2 H^2} \int_{V(R)} \frac{d^3x}{V(R)} \int \frac{d^3k_1}{(2\pi)^3} \int \frac{d^3k_2}{(2\pi)^3} k_1 \cdot k_2 \; \overline{\phi_{\vec{k}_1} \phi_{\vec{k}_2}} \; e^{i\left(\vec{k}_1+\vec{k}_2\right)\cdot\vec{x}}$$

$$\simeq A^2 \frac{1}{a^2 H^2} \int_0^{k_H} dk\, k\, T^2(k) \sim 10^{-5} \frac{a}{a_0}$$

- $$\tau^4 \left\langle \nabla^2\phi \nabla^2\phi \right\rangle = -\frac{1}{a^4 H^4} \int_{V(R)} \frac{d^3x}{V(R)} \int \frac{d^3k_1}{(2\pi)^3} \int \frac{d^3k_2}{(2\pi)^3} k_1^2 k_2^2 \; \overline{\phi_{\vec{k}_1} \phi_{\vec{k}_2}} \; e^{i\left(\vec{k}_1+\vec{k}_2\right)\cdot\vec{x}}$$

$$\simeq A^2 \frac{1}{a^4 H^4} \int_0^{k_H} dk\, k^3\, T^2(k) \sim 10^0 \left(\frac{a}{a_0}\right)^2$$

Räsänen

– Individual Newtonian terms large, *i.e.*, $\langle \nabla^2\phi \nabla^2\phi \rangle = \mathcal{O}(1)$

– <u>*But*</u> total Newtonian term vanishes $\langle \nabla^2\phi \nabla^2\phi \rangle = \langle \phi^{,ij} \phi_{,ij} \rangle$

– Post-Newtonian: $\langle \nabla\phi \cdot \nabla\phi \rangle = \mathcal{O}(10^{-5})$ ***huge!*** (large k^2/a^2H^2)

Sub-Hubble Instabilities

- Gradient expansion:

$$\langle R\rangle_D = \sum_{n=1}^{\infty} r_n a^{n-3} \qquad \left(r_n = \sum_{m=n}^{2n} \left(2n \text{ derivatives}\right) \phi^m \right)$$

$$Q_D = \sum_{n=2}^{\infty} q_n a^{n-3} \qquad \left(q_n = \sum_{m=n}^{2n} \left(2n \text{ derivatives}\right) \phi^m \right)$$

- Lowest-order term to make big contribution is $n = 3$ (6 derivatives)
- Disconnected fourth-order moment of ϕ : $\left\langle \frac{\left(\nabla^2 \phi\right)^2}{H_0^4} \right\rangle \left\langle \frac{\left(\nabla \phi\right)^2}{H_0^2} \right\rangle$
- Notice $n = 3$ contributes to Q_D and $\langle R\rangle_D$ terms $\propto a^0$, *i.e.*,

  expansion as if driven by a cosmological constant !!!
- But why stop at $n = 3$?????
- We have developed a RG-improved calculation (still inadequate)

Many issues:

- non-perturbative nature
- shell crossing
- comparison to observed LSS
- gauge/frame choices
- physical meaning of coarse graining

Program:

- can inhomogeneities change effective zero mode?
- how does (does it?) affect observables?
- can one design an inhomogeneous universe that accelerates?
- could it lead to an apparent dark energy?
- can it be reached via evolution from usual initial conditions?
- does it at all resemble our universe?
- large perturbative terms resum to something harmless?
- is perturbation theory relevant?

Inhomogeneities

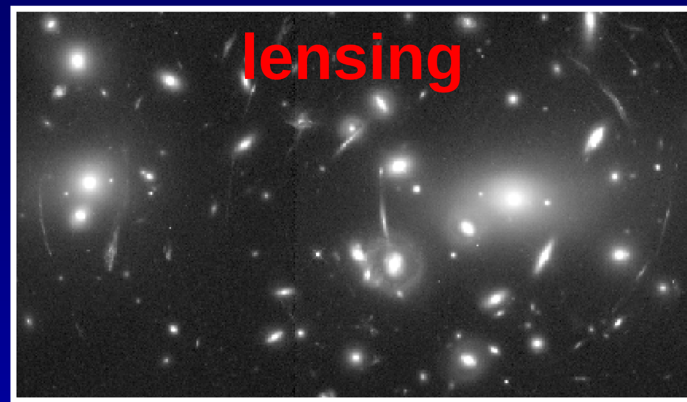
- Does this have anything to do with our universe?
- Have to go to non-perturbative limit!
- Shell crossing?
- How to relate observables ($d_L(z)$, $d_A(z)$, $H(z)$, …) to Q_D & $\langle {}^3R \rangle_D$?
- Can one have large effect and isotropic expansion/acceleration? (related to small shear?)
- What about gravitational instability?
- Scalar field correspondence (Buchert, Larena, Alimi)
- Toy model proof of principle: Lemaître-Tolman-Bondi dust model

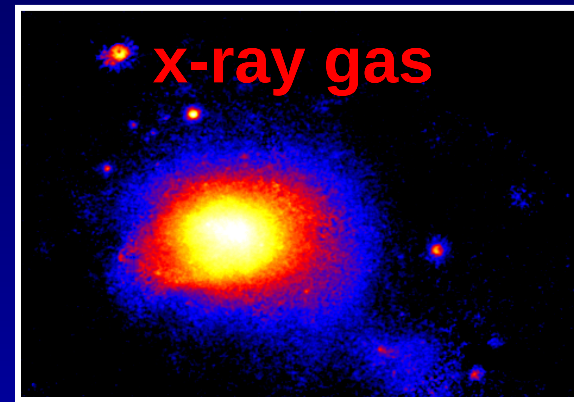
Comments

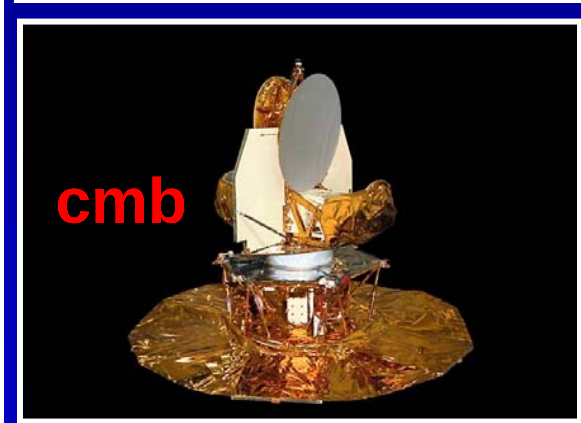
- *"Do you believe?"* is not the relevant question
- Acceleration of the Universe is important; this must be explored
- How it could go badly wrong:
  - Backreaction should not be calculated in frame comoving with matter flow
  - Series re-sums to something harmless
  - No reason to stop at first large term
  - Synchronous gauge is tricky
    - ☹ Residual gauge artifacts
    - ☹ Synchronous gauge develops coordinate singularities at late time (shell crossings)
    - ☺ Problem could be done in Poisson gauge

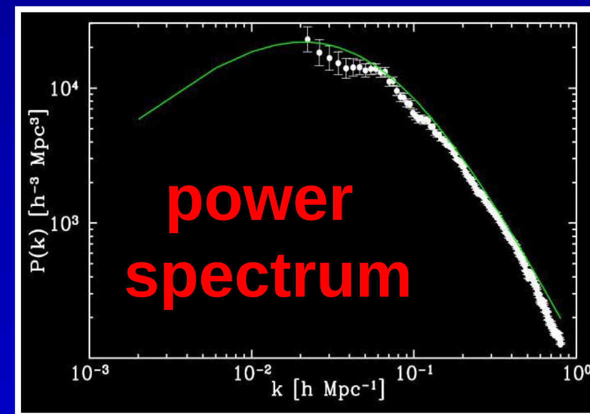
Subtraction

$$\Omega_i \equiv \rho_i / \rho_C \qquad \rho_C \equiv 3H_0^2 / 8\pi G$$









$\Omega_{\mathrm{TOTAL}} = 1$ (CMB) $\qquad \Omega_M = 0.3$

$$1 - 0.3 = 0.7$$

$$\Omega_{\mathrm{TOTAL}} - \Omega_M = \Omega_\Lambda$$

Subtraction

How can $1.0 = 0.3$?

For a spatially flat FLRW universe $H^2 = 8\pi G\rho/3$

This is another way of stating $\Omega = 1$.

This expression is not valid if FLRW is not valid

e.g., $H^2 = \frac{8\pi G}{3}\left[\langle\rho\rangle - \frac{3}{8\pi G}\langle\delta G_{00}\rangle\right]$

The Morphon Field

Buchert, Larena, Alimi

- Dynamics of the of inhomogeneities on the smoothed scale factor can be modeled by a scalar field, the morphon.
- Can lead to quintessence-like potentials, even phantom quintessence-like potentials. (k-essence?).
- Easier to study dynamics (phase diagrams, *etc*.).
- Suggests solutions not obtainable from perturbations of FLRW

Can be arbitrarily close to FLRW,
but not obtainable from perturbation of FLRW
NEW DYNAMICS!

Lemaître–Tolman–Bondi

Celerier 1999 astro-ph/9907206
Iguchi, Nakamura, Nakao 2002 *Prog. of Theo. Phys.* 809
Moffat 2005 astro-ph/0505326
Nambu and Tanimoto 2005 gr-qc/0507057
Mansouri 2005 astro-ph/0512605
Chang, Gu, Hwang 2005 astro-ph/0512651
Alnes, Amarzguioui, Grøn 2006 *Phys. Rev.* D73 083519
Mansouri 2006 astro-ph/0601699
Apostolopoulos, Brouzakis, Tetradis, Tzavara 2006 astro-ph/0603234
Garfinkle 2006 gr-qc/0605088
Kai, Kozaki, Nakao, Nambu, Yoo 2006 gr-qc/0605120

- We regard LTB models as toy models

Lemaître–Tolman–Bondi

Spherically symmetric metric
$$ds^2 = -dt^2 + \frac{R'^2(r,t)}{1+\beta(r)}dr^2 + R^2(r,t)\,d\Omega^2$$

$\dot{} \equiv d/dt \qquad ' \equiv d/dr$

Expansion rates
$$H_\perp^2 = \dot{R}/R \qquad H_r^2 = \dot{R}'^2/R'^2$$

Spherically symmetric density
$$8\pi G\rho(r,t) = \frac{\alpha'(r,t)}{R^2(r,t)R'(r,t)}$$

FRW
$$\begin{cases} R(r,t) \to r a(t) \\ R'(r,t) \to a(t) \\ \beta(r) \to H_0^2\Omega_k r^2 \\ \alpha(r) \to H_0^2\Omega_M r^3 \end{cases}$$

Lemaître–Tolman–Bondi

Alnes, Amarzguioui, Grøn

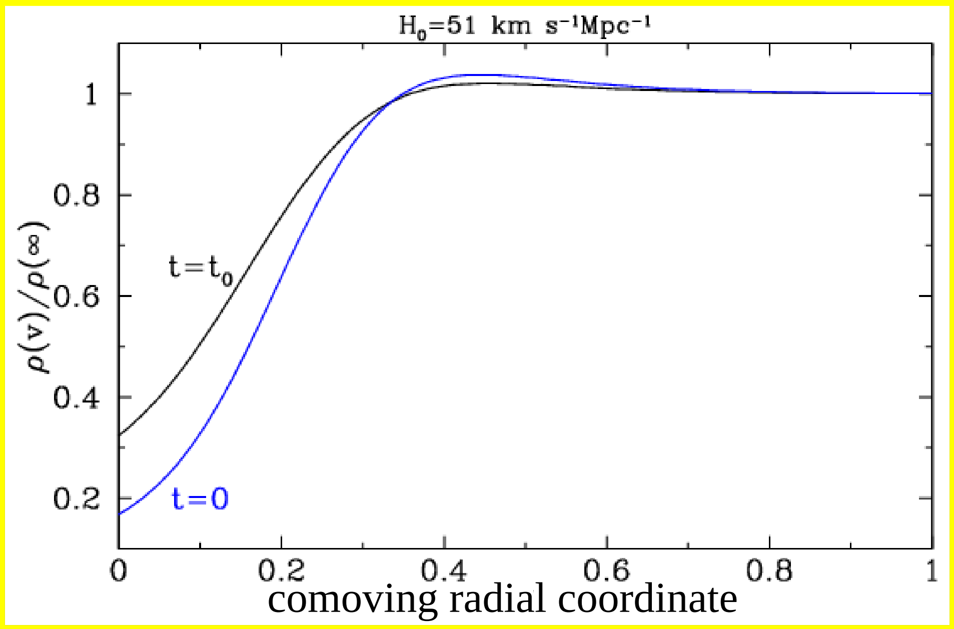
Specify $\alpha(r)$ and $\beta(r)$:

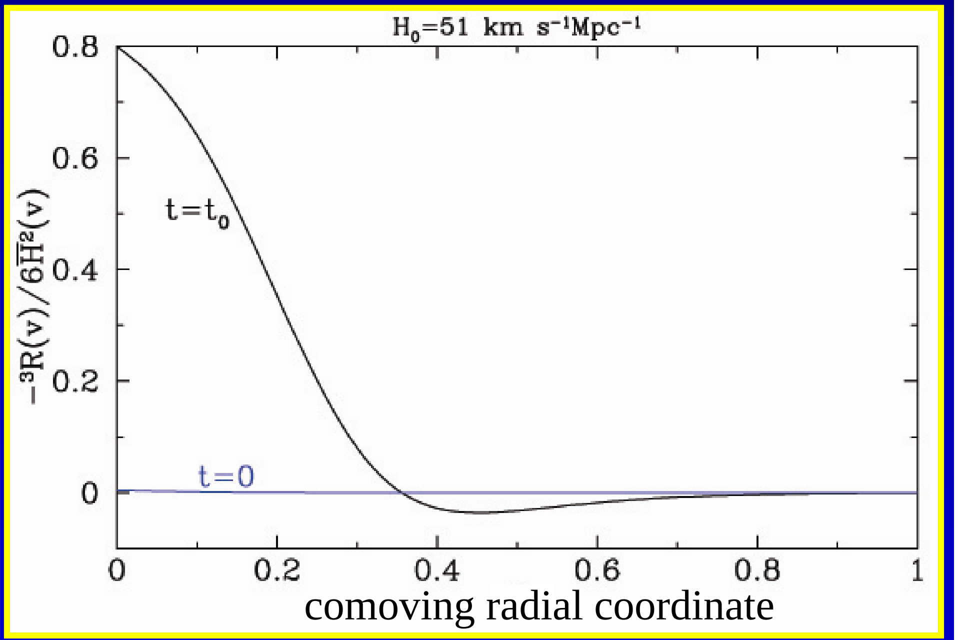
$$\alpha(r) \propto r^3 \left\{ \alpha_0 - \frac{\Delta_\alpha}{2} \left[1 - \tanh\left(\frac{r - r_0}{2\Delta_r} \right) \right] \right\}$$

$$\Delta\alpha = 0.90 \quad r_0 = 1.35 \text{ Gpc}$$

$$\Delta_r = 0.4\, r_0$$

$$\beta(r) \propto -r^2 \frac{\Delta_\alpha}{2} \left[1 - \tanh\left(\frac{r - r_0}{2\Delta_r} \right) \right]$$

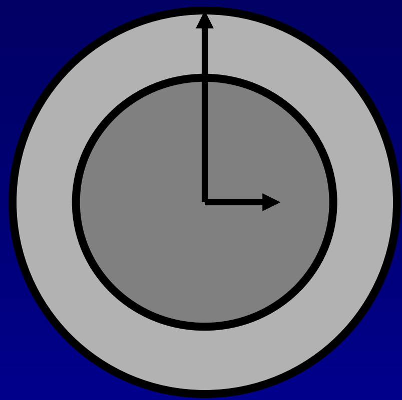


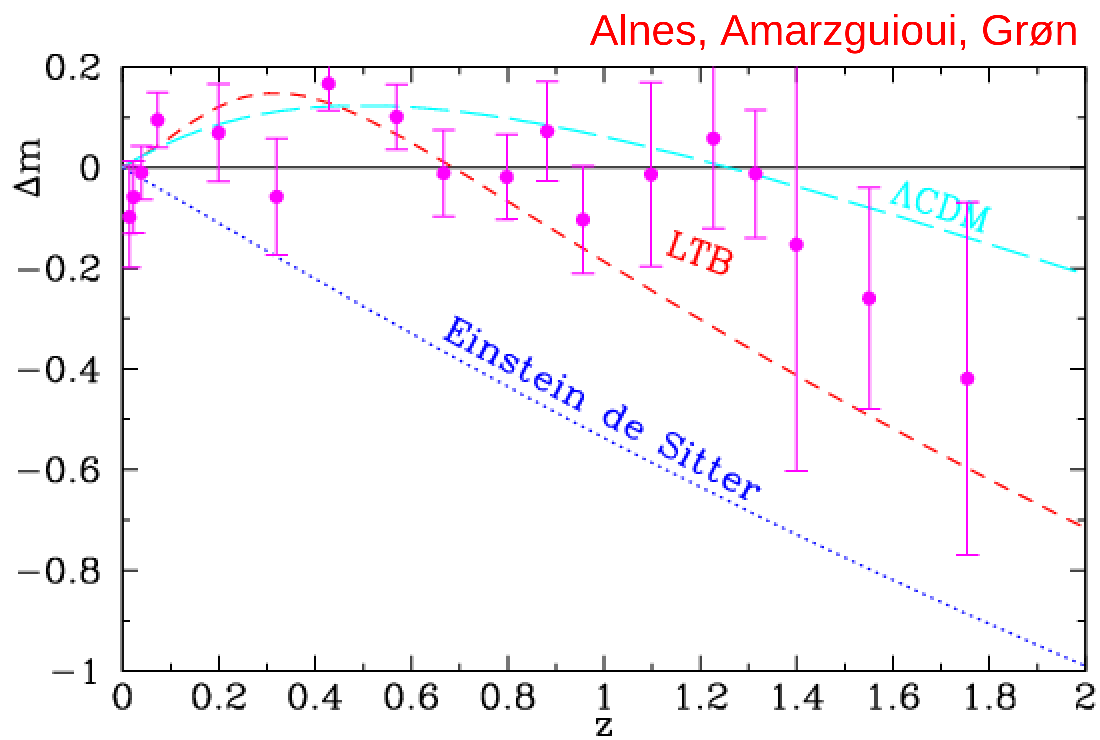


$$\Omega_{M,inner} = 0.2 \quad \Omega_{M,outer} = 1.0 \quad h_{in} = 0.65 \quad h_{out} = 0.51$$

Lemaître–Tolman–Bondi

- Spherical model
- Asymptotically Einstein–de Sitter
- Inner underdense Gpc region
- Calculate $d_L(z)$
- Compare to SNIa data
- Fit with $\Lambda = 0$!

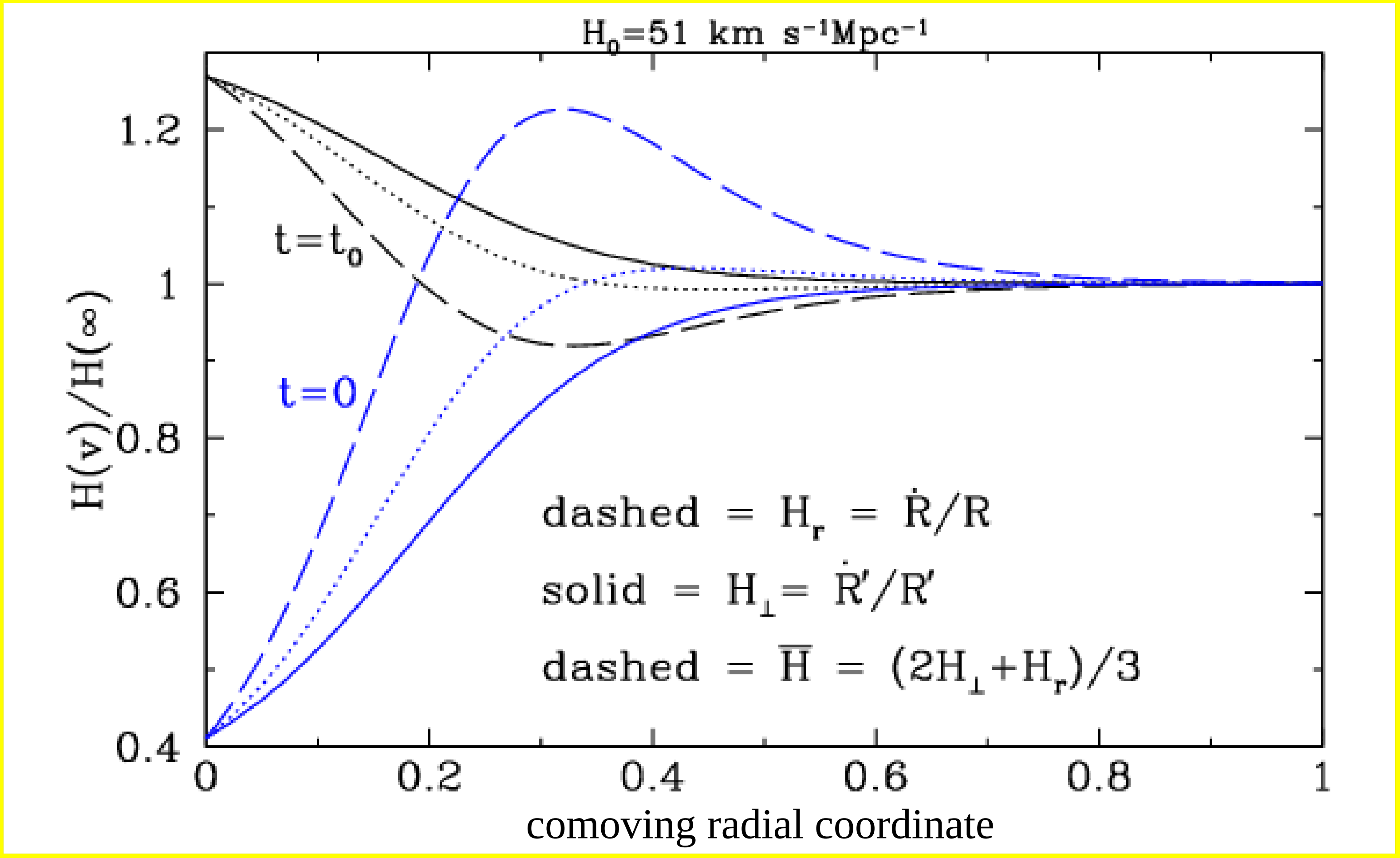




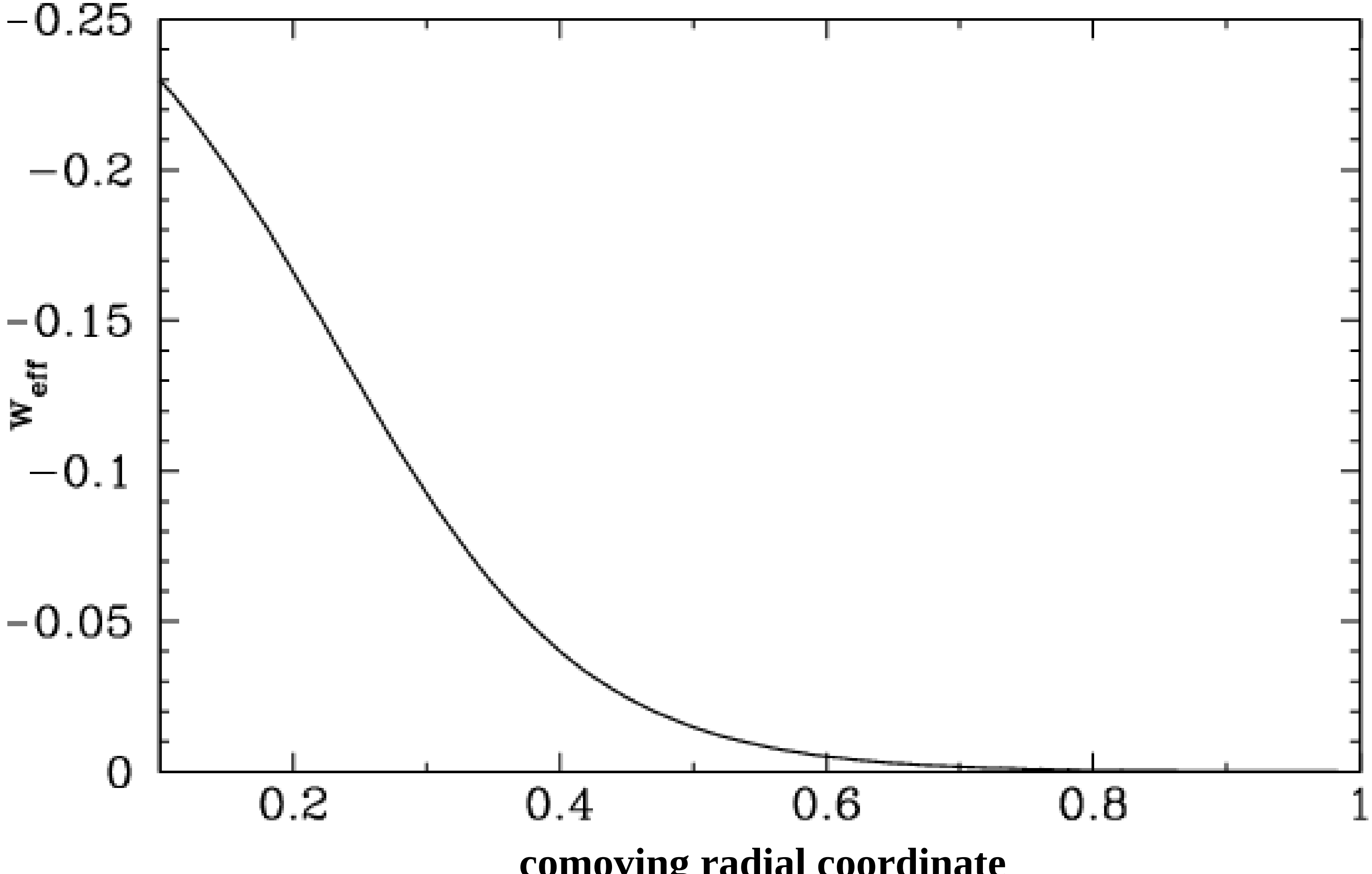
(counterexample to no-go theorems)

- regular everywhere
- no shell crossing
- It's not a gauge artifact
- Newtonian: $\phi < 1$
- Is there acceleration?

Lemaître–Tolman–Bondi

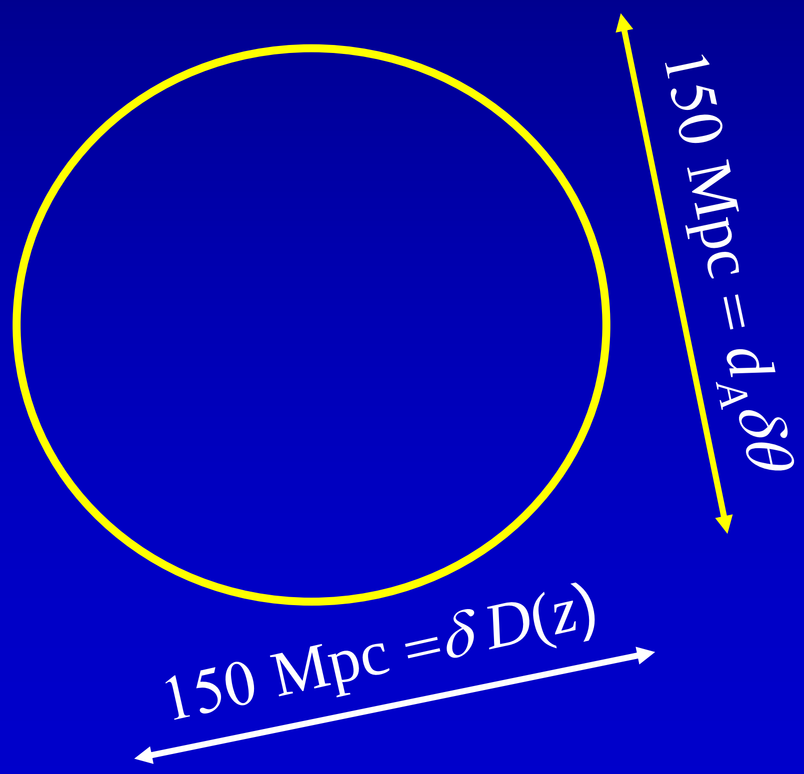


Lemaître–Tolman–Bondi



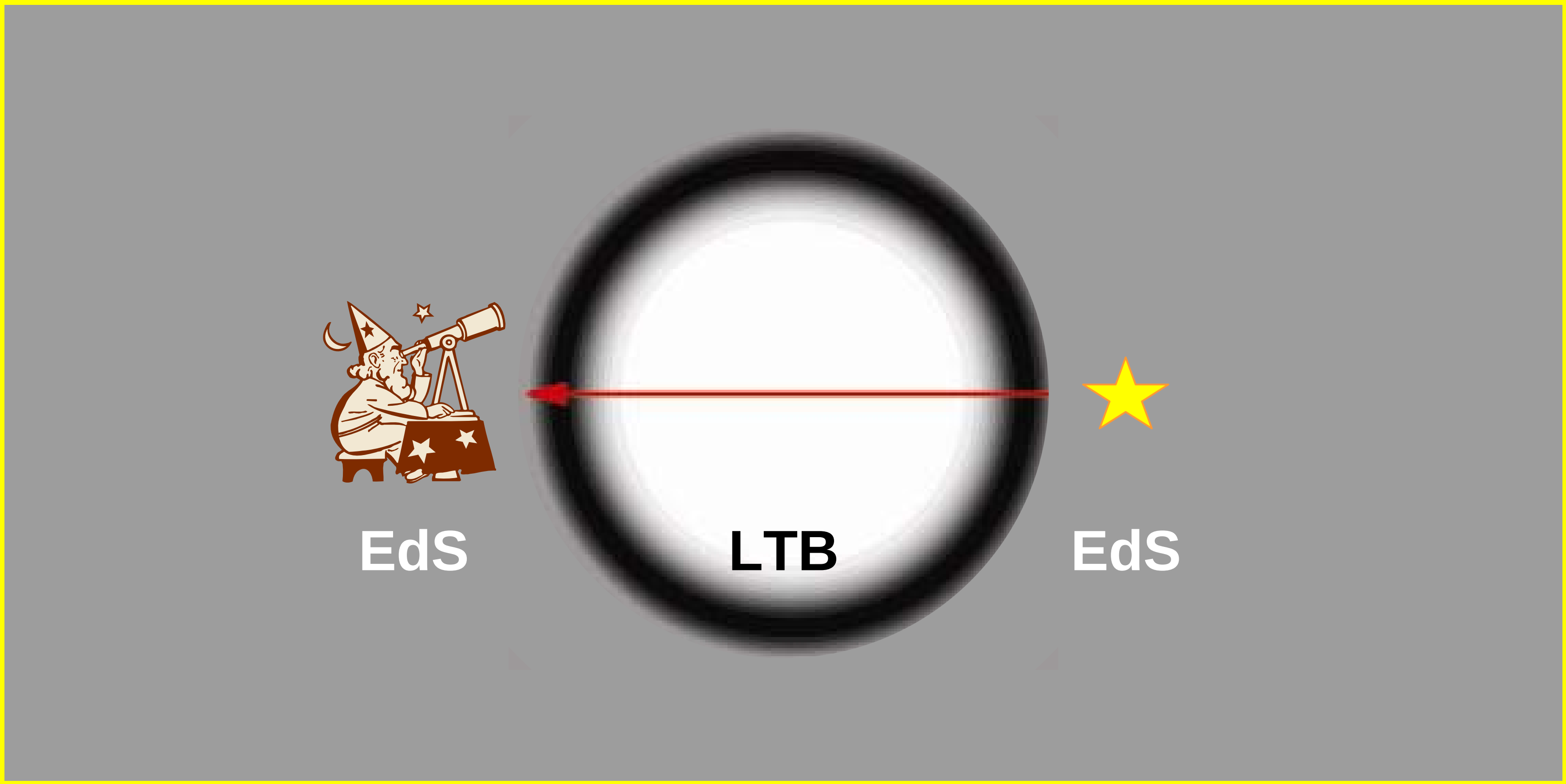
Baryon Acoustic Oscillations

- LTB models have different radial and transverse expansions
- Standard rulers will have different radial and transverse behavior
- BAO experiments are sensitive to both! (Kolb & Kostov)



Lemaître–Tolman–Bondi

- The large effect in $d_L(z)$ when observer near center
- What happens if observer and source outside hole?
- Many smaller voids rather than one large one?



Lemaître–Tolman–Bondi

- Cosmology 101 derivation of $d_L(z)$

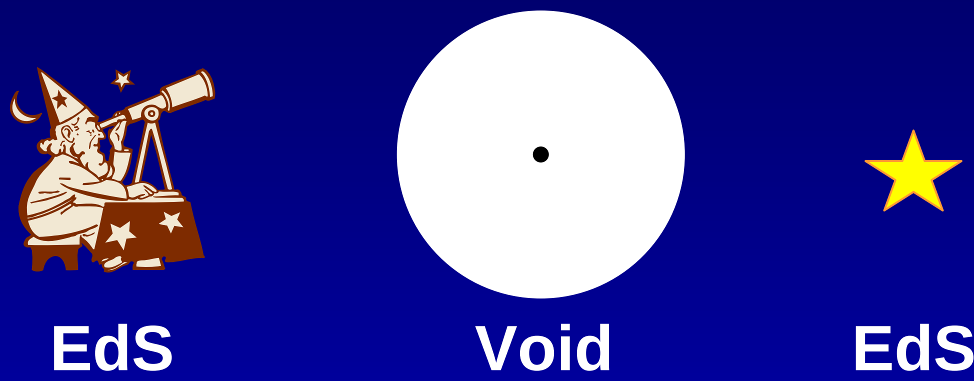
$$d_L^2(z) = \mathrm{Area}\left({}^2S\right)\times(1+z)^2$$

$(1+z)^2$ → not directly related to a_D

$\mathrm{Area}\left({}^2S\right)$ → directly related to a_D

Lemaître–Tolman–Bondi

- Einstein—Strauss: embed Schwarzschild in FRW



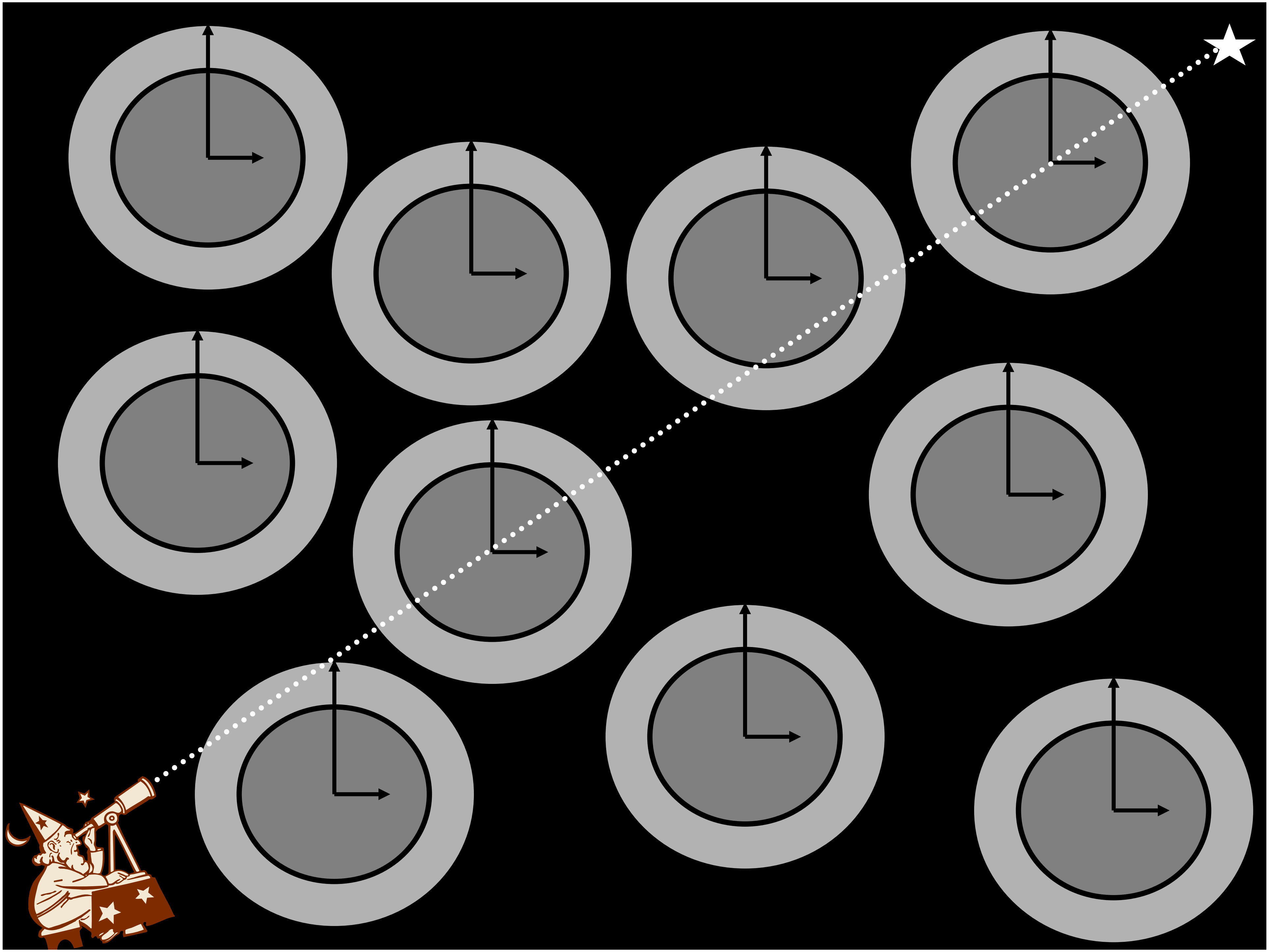
- FRW observer evolves as in FRW universe

- $Q_D = 0$ for volume encompassing observer/source

- In *spherically symmetric* model

  $\mathrm{Area}\left({}^2S\right)$ unaffected if source & observer in FRW region

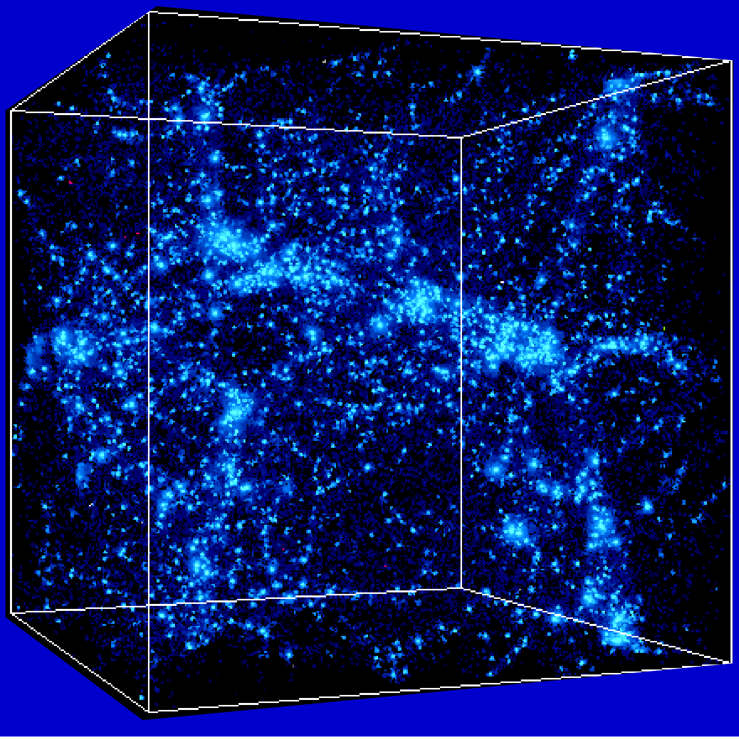
  $\left(1+z\right)$ changes only if evolution in $\rho\left(r\right)$ in interior region

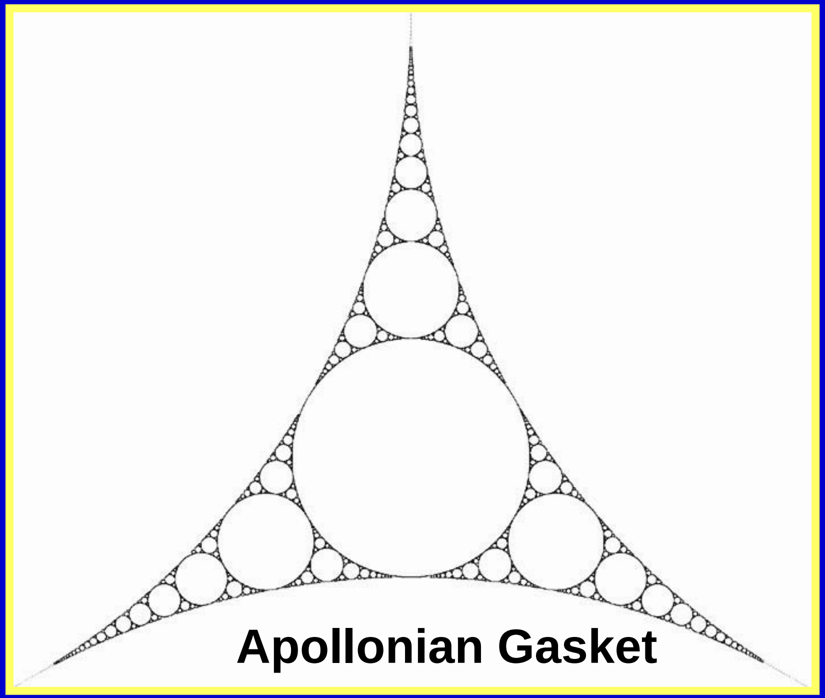


The Swiss Cheese Universe

Khosravi, Kourkchi, Mansouri & Arkami; Biswas & Notari; Marra & Kolb

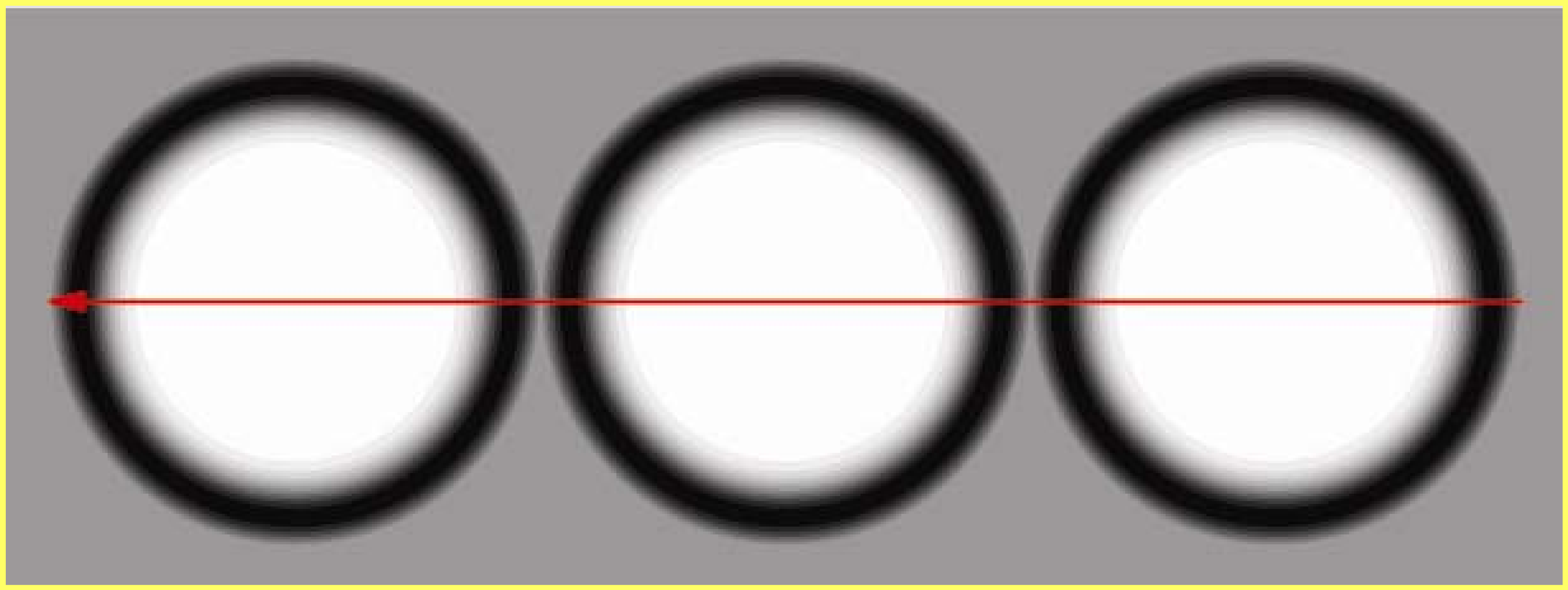
- start with Einstein—de Sitter model (the cheese)
- carve out ***spherical*** underdense regions (the holes)
- place extra matter density in shells (the crust)
- evolution of cheese unaffected by holes (Birkhoff)
- evolution of spherical hole/crust (LTB)





The Swiss Cheese Universe

Marra & Kolb



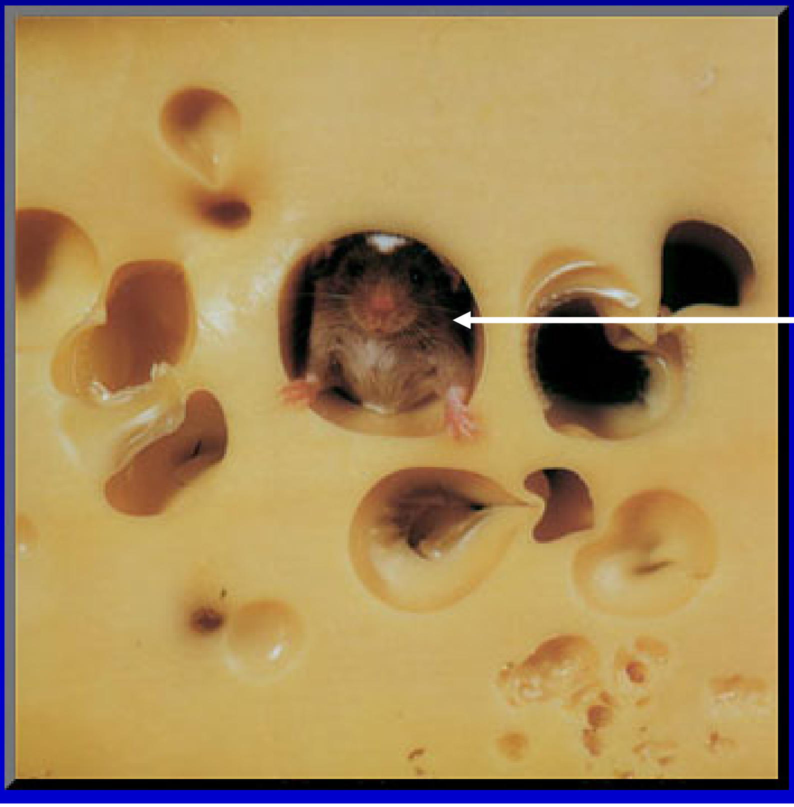
- observer in void
- observer in crust
- observer in cheese

- one hole
- three holes
- five holes

- $z\,(r)$
- $d_L(z)$

The Swiss Cheese Universe

- Where to put the observer/source?
- Is Swiss the best cheese?
- Can we explore perturbations of sphericity?
- Do results depend on particular LTB model?
- See Notari's talk on Saturday



Observer in a Swiss Cheese Universe

Conclusions

- Must properly smooth inhomogeneous Universe
- In principle, acceleration possible even if "locally" $\rho + 3p > 0$
- Super-Hubble modes, of and by themselves, cannot accelerate
- Sub-Hubble modes have large terms in gradient expansion
  - Newtonian terms can be large but combine as surface terms
  - Post-Newtonian terms are not surface terms, but small
  - Mixed Newtonian $\times$ Post-Newtonian terms can be large
  - Effect from "mildly" non-linear scales
- The first large term yields effective cosmological constant
- No reason to stop at first large term
- Can have $w < -1$?
- Advantages to scenario:
  - No new physics
  - "Why now" due to onset of non-linear era

Perhaps

There Is No Dark Energy and the Universe Is Not Accelerating

in the Usual Sense

Origins of Dark Energy May 2007

Rocky Kolb *University of Chicago*

Published work from collaborations with Sabino Matarrese and Antonio Riotto (Padova) [and occasionally Alessio Notari (McGill)]

Kolb, Matarrese, and Riotto, *New Journal of Physics* **8**, 322 (2006)

Ongoing collaborations with Valentin Kostov and Valerio Marra (Chicago)