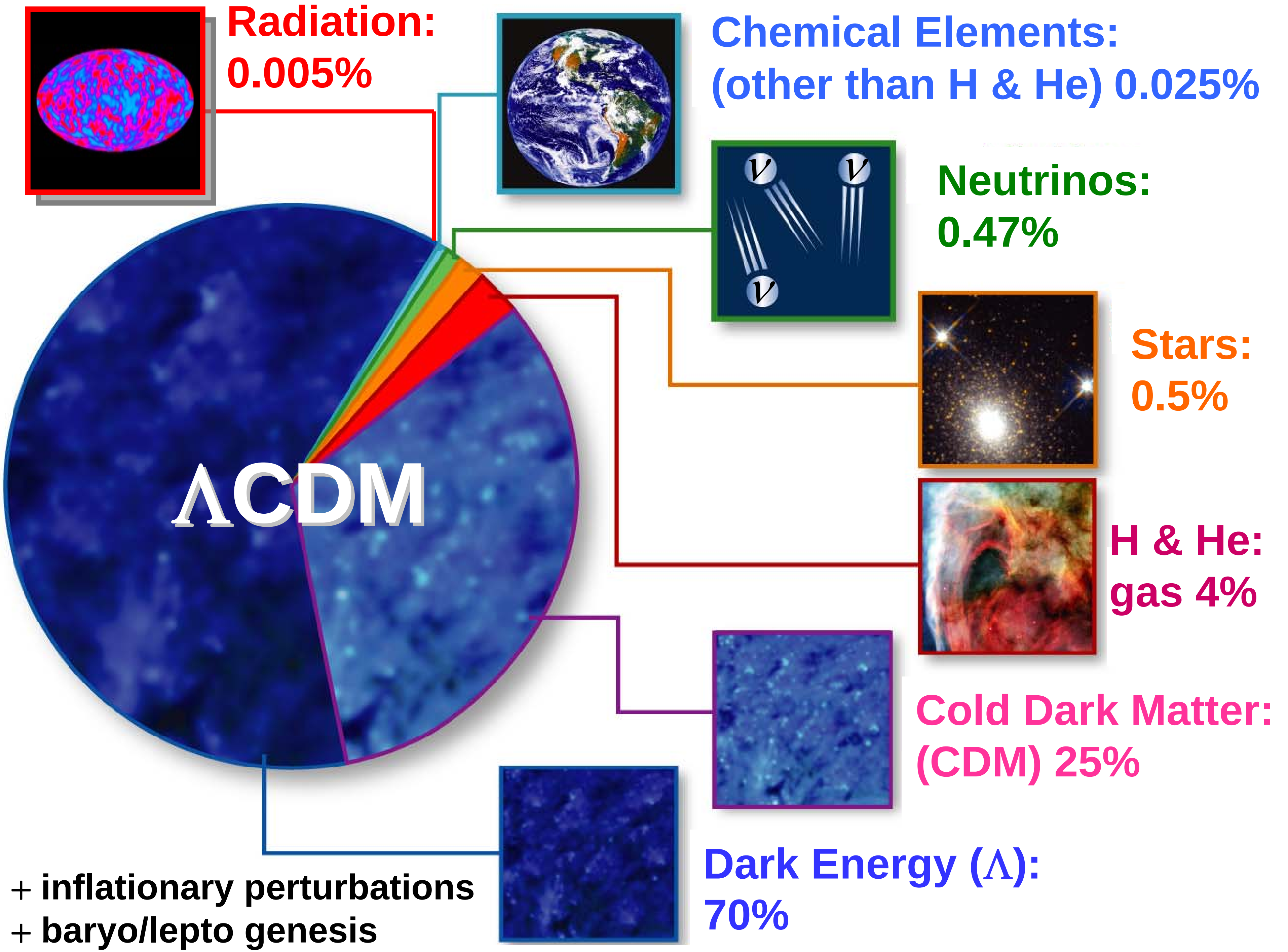
Dark Energy: Taking Sides

Barocky

Rocky Kolb

The University of Chicago


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.47%
Stars:
0.5%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
ΛCDM
+ inflationary perturbations
+ baryo/lepto genesis

ΛCDM: Reality Or A Substitute?

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

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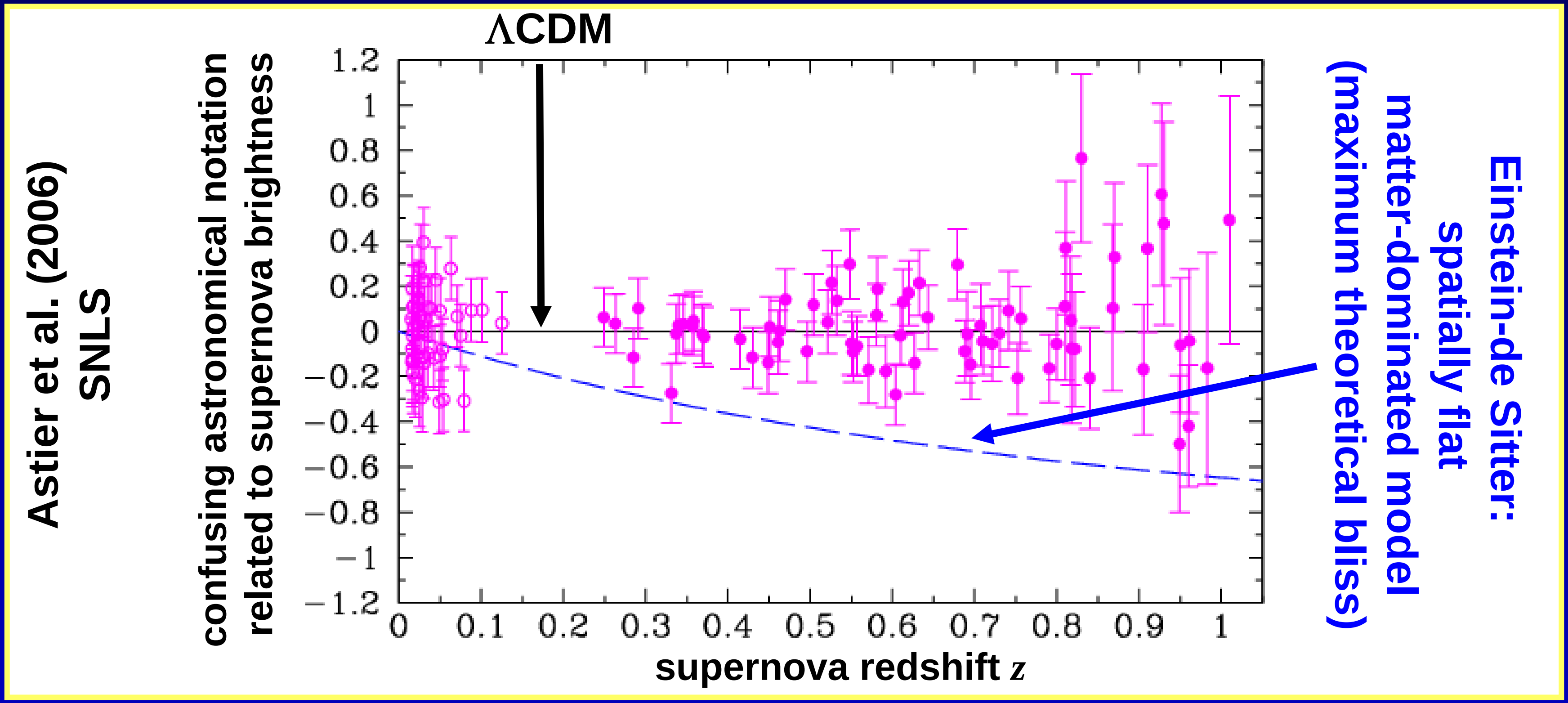
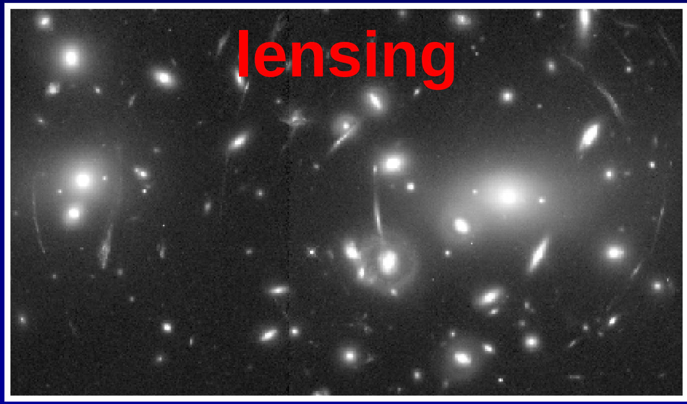
Evidence For Dark Energy

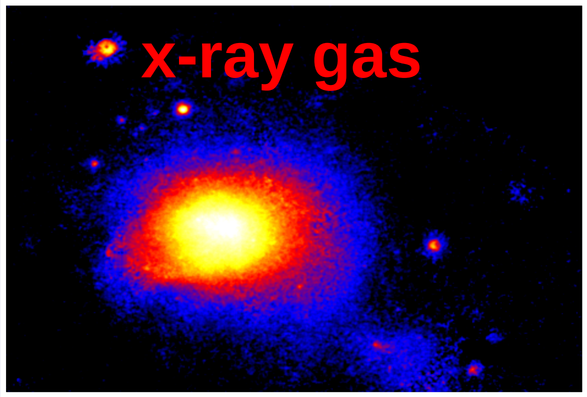


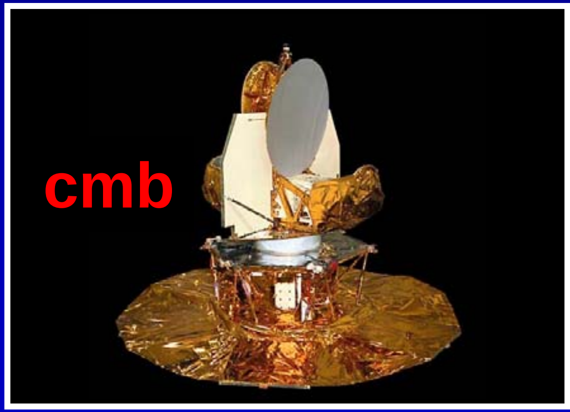
<u>The case for Λ:</u>

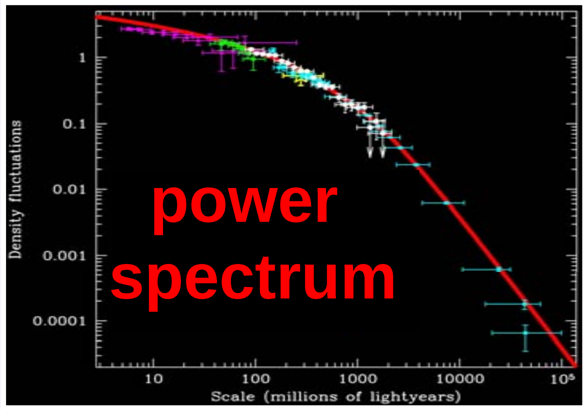
1) Hubble diagram (SNe)
2) Cosmic Subtraction
3) Baryon acoustic oscillations
4) Weak lensing
5) Galaxy clusters
6) Age of the universe
7) Structure formation

Cosmic Subtraction









$\Omega_{\mathrm{TOTAL}} = 1$

CMB

$\Omega_M \sim 0.3$

many methods

$$1.0 - 0.3 = 0.7 \neq 0$$

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

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

Taking Sides on the Dark Energy Issue

- Can't hide from the data – ΛCDM too good to ignore
  - SNe
  - Subtraction: $1.0 - 0.3 = 0.7$
  - Baryon acoustic oscillations
  - Galaxy clusters
  - Weak lensing
  - …

} $H(z)$ 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" a cosmoillogical constant Λ)
  2. Not constant (dynamics driven by scalar field)

- Modify <u>left-hand side</u> of Einstein equations (ΔG_{00})
  3. Beyond Einstein (non-GR: $f\,(R)$, extra dimensions, *etc*.)
  4. (Just) Einstein (back reaction of inhomogeneities)

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

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

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

"Backreaction" Causes Allergic Reaction

- No compelling argument that backreactions are the answer
  - We don't know necessary or sufficient conditions
  - Just because some unrealistic model seems to give SNe $d_L(z)$ doesn't mean that backreactions are the answer

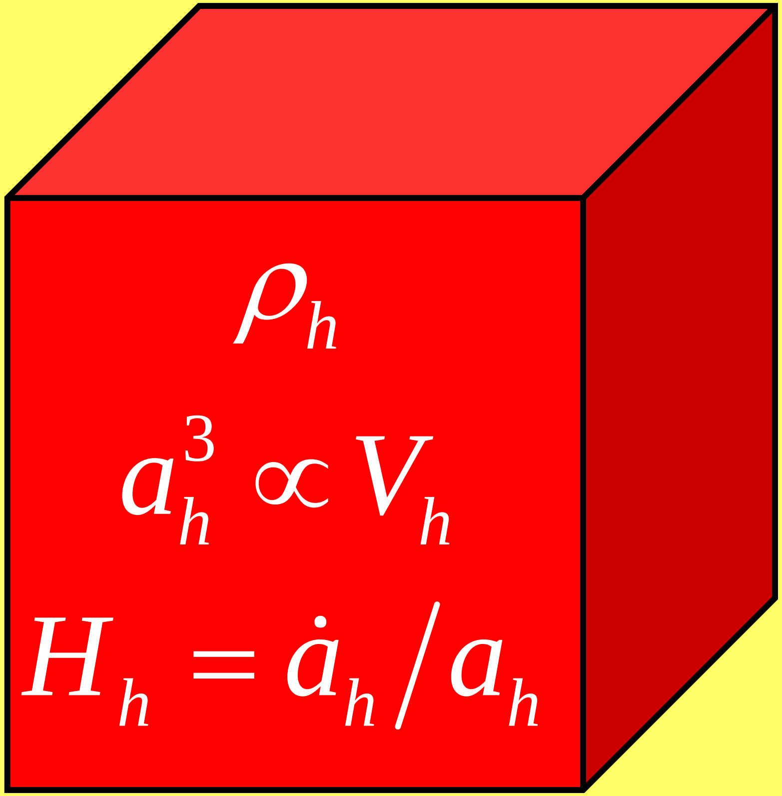
- No proof that backreactions are not the answer
  - Physics is littered with discarded *no-go* theorems
  - Just because some unrealistic model doesn't give SNe $d_L(z)$ doesn't mean that backreactions are *not* the answer

Acceleration from Inhomogeneities

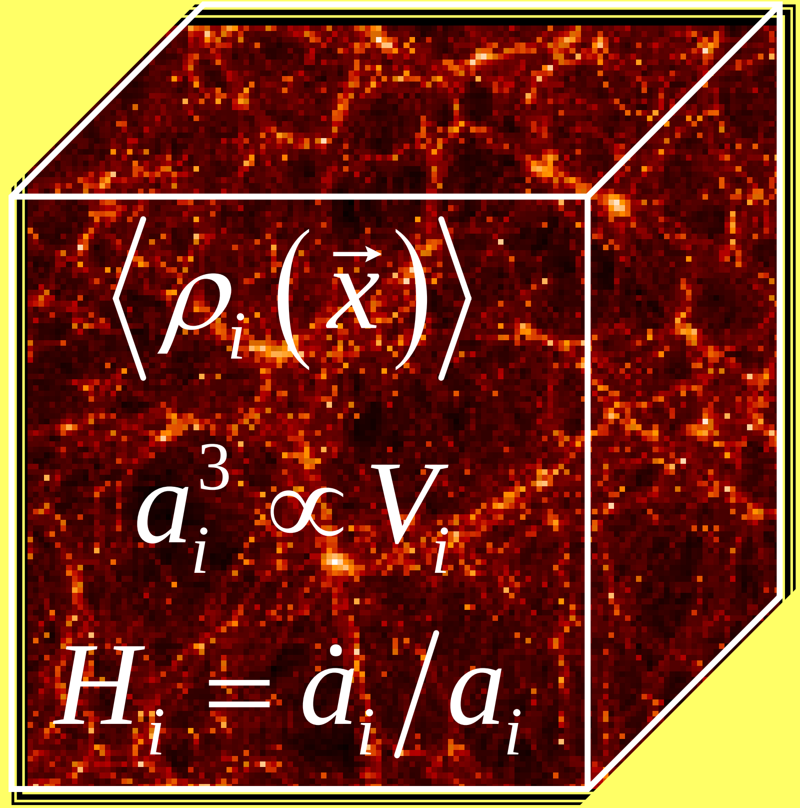
(Buchert & Ellis)

Strong Backreaction

Homogeneous model



Inhomogeneous model



$$\rho_h = \langle \rho_i(\vec{x}) \rangle \Rightarrow H_h = H_i ?$$

We think not!

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 average density $\langle \rho \rangle$!

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

- 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?

Kolb, Matarrese, Notari & Riotto

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

- 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 □ 0 but $\langle q \rangle_D$ □ 0 (“no-go” goes)

Inhomogeneities and Smoothing

Kolb, Matarrese & Riotto
New J.Phys.8:322,2006;
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:

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

- Effective evolution equations:

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

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

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

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

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: $$\rho_{\mathrm{eff}} + 3p_{\mathrm{eff}} = \left\langle \rho \right\rangle_D - \frac{Q_D}{4\pi G} < 0$$
- 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: $3Q_D = -\langle {}^3R \rangle_D = \mathrm{const.}$
  - *i.e.*, $\Lambda_{\mathrm{eff}} = Q_D$ (so Q_D acts as a cosmological constant)

Inhomogeneities and Smoothing

- What does volume evolution have to do with observables?

- Why take spatial average at fixed time?
  (e.g., why not light-cone average?)

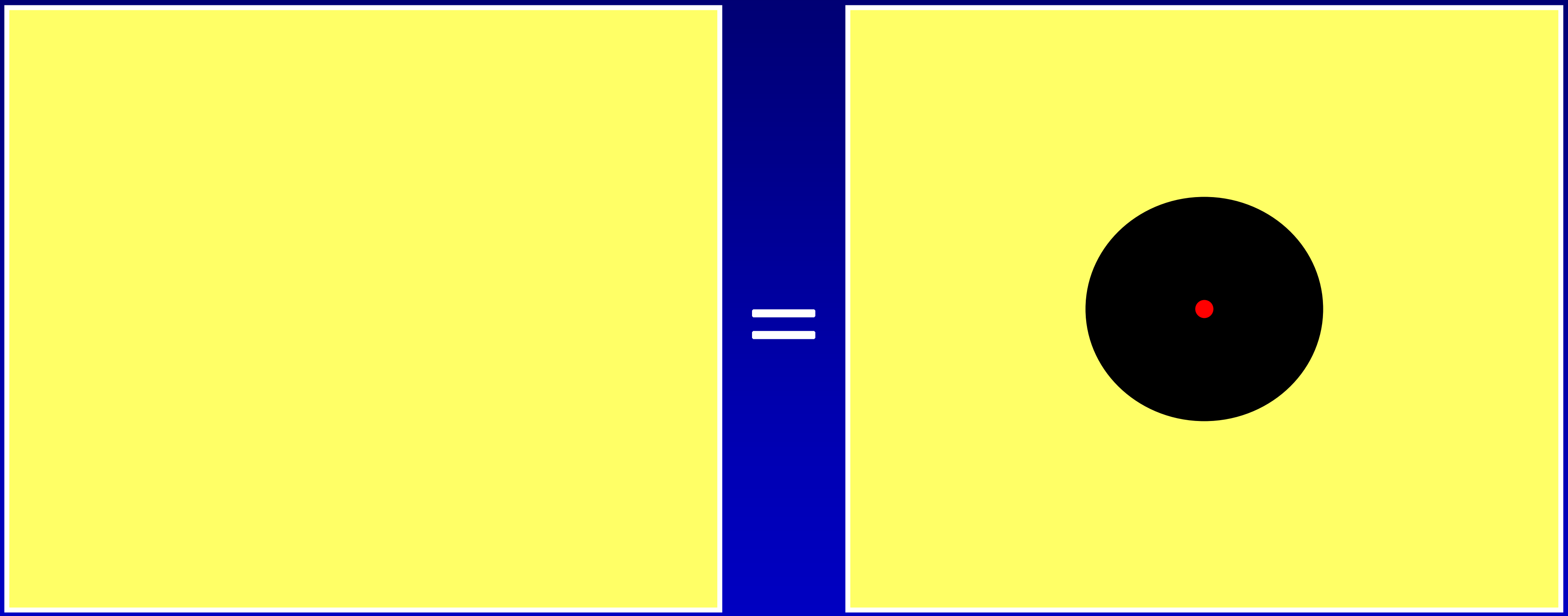
- Explore some toy models.

Lemaître–Tolman–Bondi

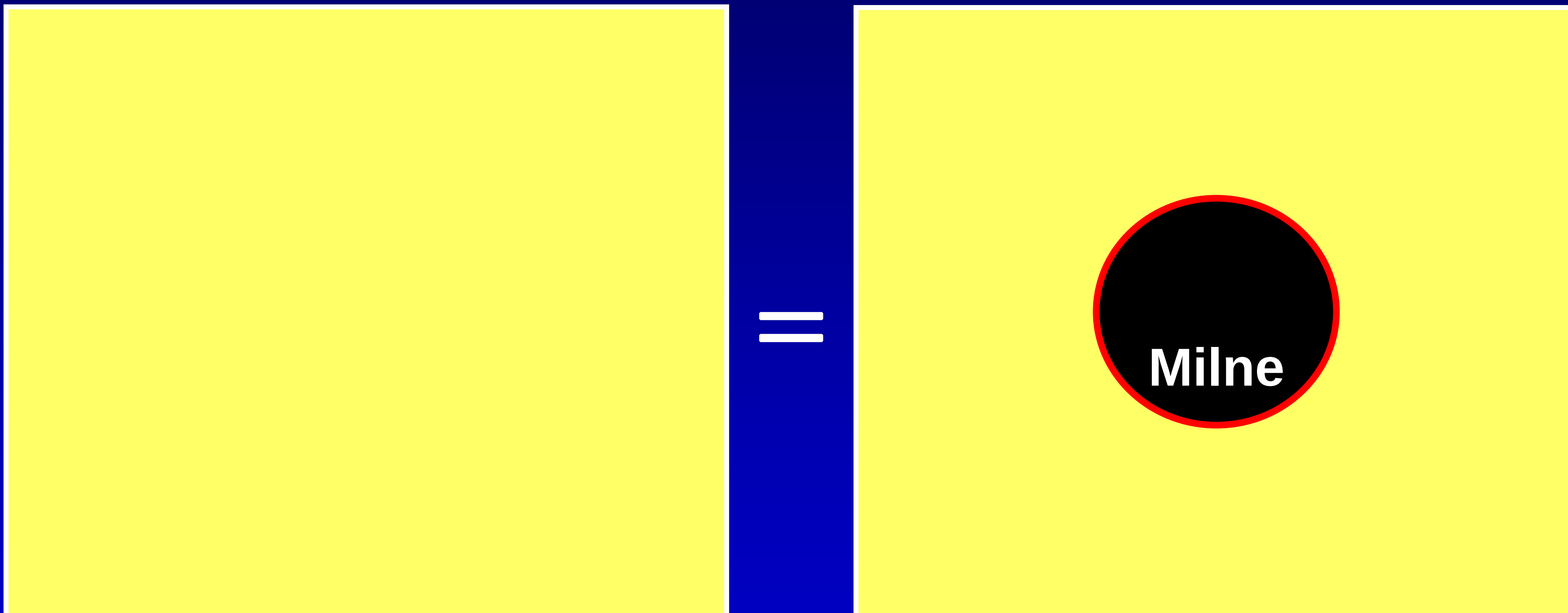
Celerier
Iguchi, Nakamura, Nakao
Moffat
Nambu and Tanimoto
Mansouri
Chang, Gu, Hwang
Alnes, Amarzguioui, Grøn
Mansouri
Apostolopoulos, Brouzakis, Tetradis, Tzavara
Garfinkle
Kai, Kozaki, Nakao, Nambu, Yoo
Marra, Kolb, Matarrese, Riotto
Mustapha, Hellaby, Ellis
Iguchi, Nakamura, Nakao
Vanderveld, Flanagan, Wasserman
Enqvist and Mattsson
Biswas, Mansouri, Notari
Marra, Kolb, Matarrese
Marra
Brouzakis, Tetradis, Tzavara
Biswas and Notari
Brouzakis and Tetradis
Alnes and Amarzguioui
Garcia-Bellido and Haugboelle

- Advantages:
  - Solvable inhomogeneous model
  - Can describe wide variety of dynamics
- Disadvantages:
  - Can't encompass strong (volume) backreaction (spherical symmetry)
  - Generically have small dynamical range before shell crossing

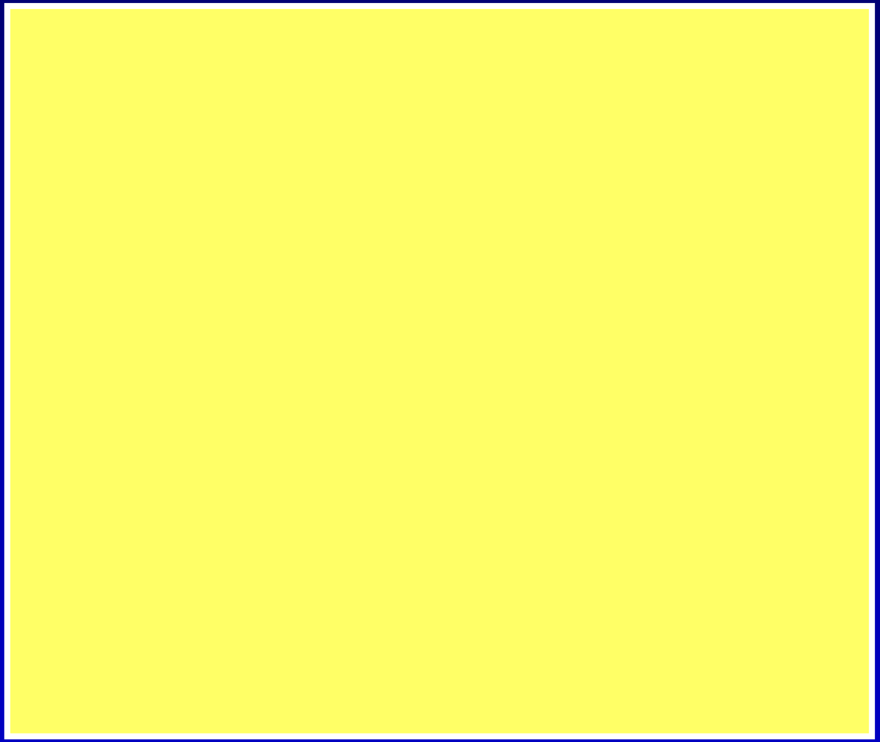
Spherical Symmetry



Spherical Symmetry



Spherical Symmetry



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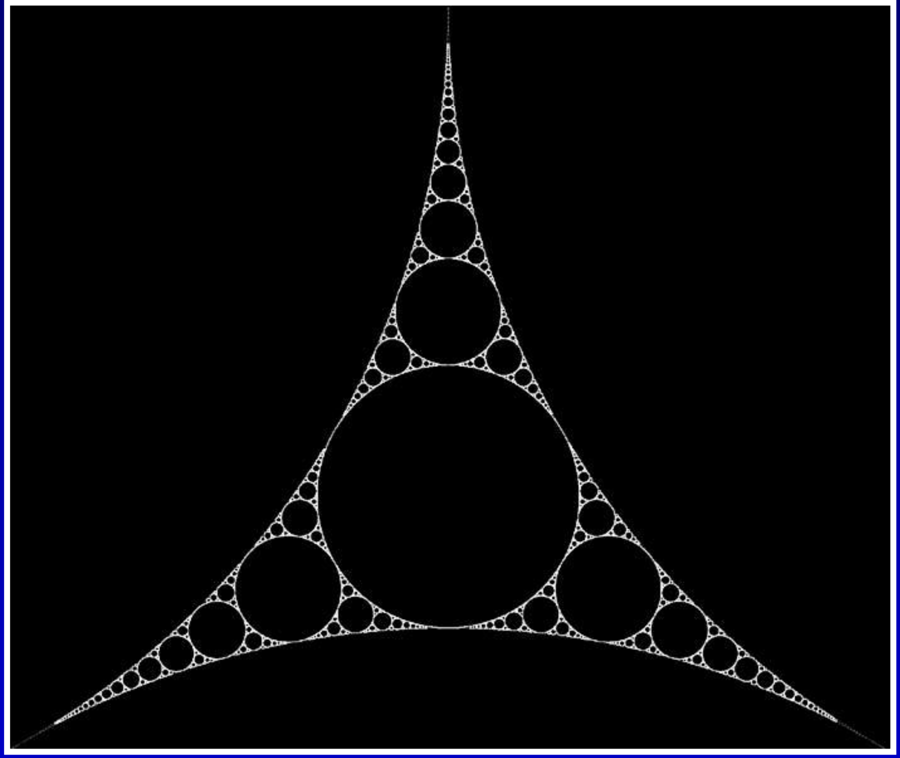
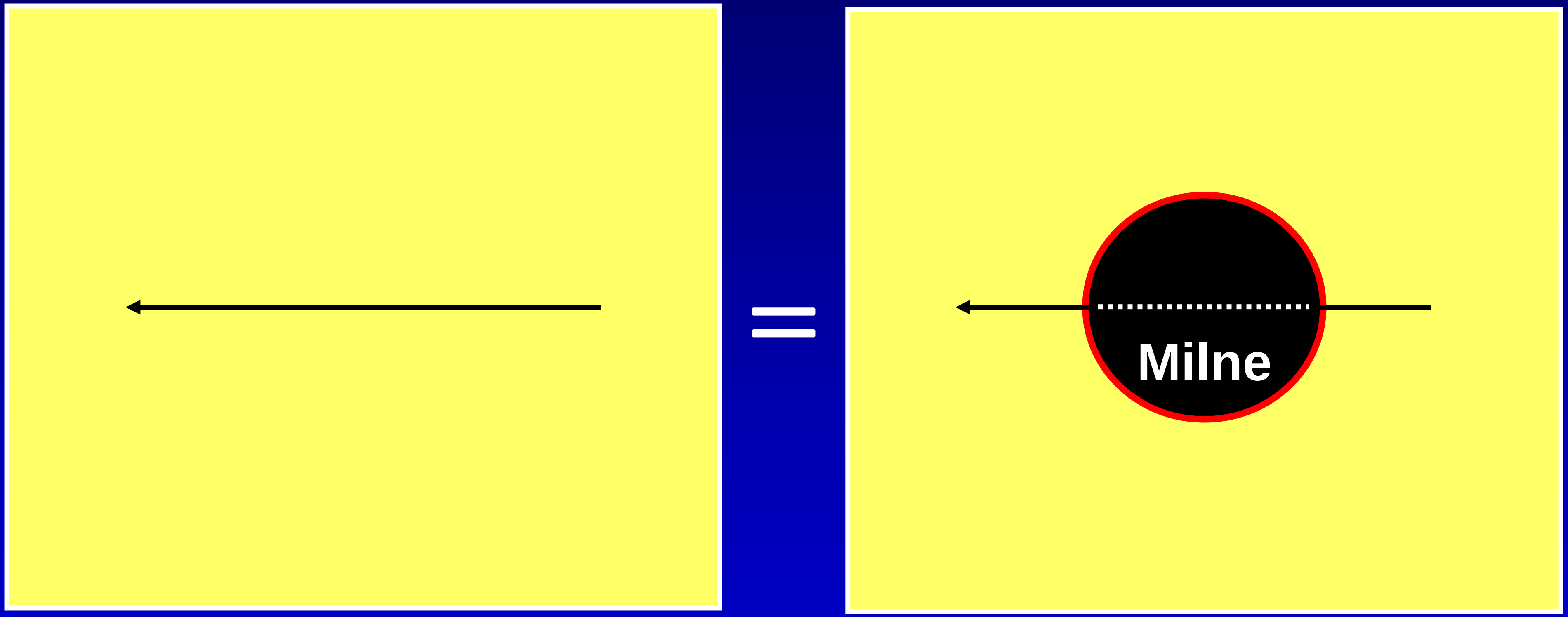


Spherical Symmetry



Large effects on redshift cancelled by spherical symmetry

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

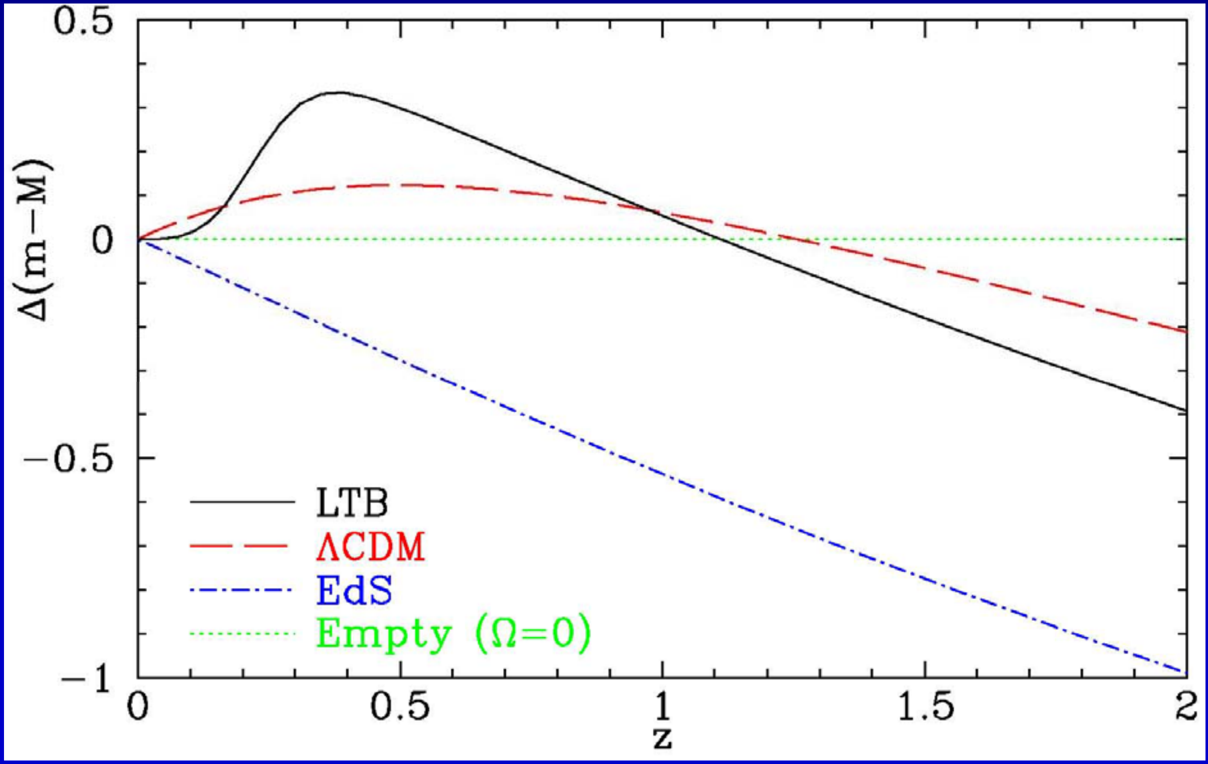
$$8\pi G\rho(r,t) = \frac{\alpha'(r,t)}{R^2(r,t)\,R'(r,t)}$$

FRW

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

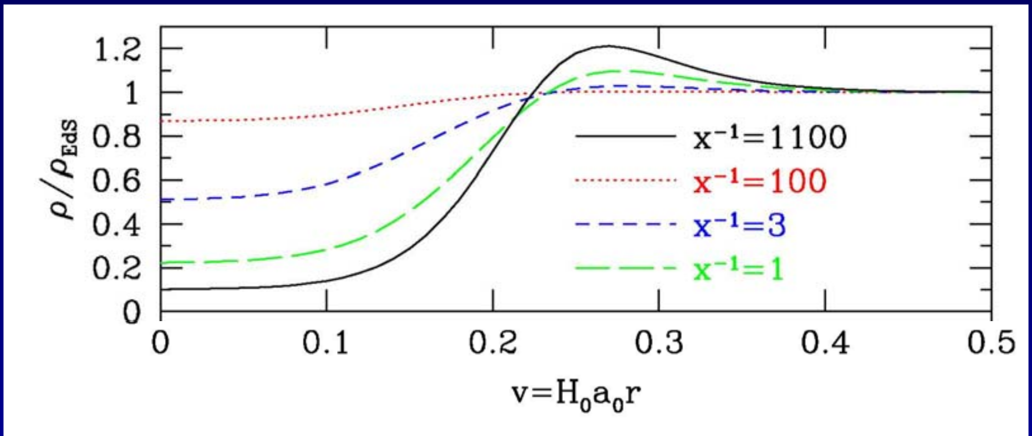
Lemaître–Tolman–Bondi

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



(counterexample to no-go theorems)

Lemaître–Tolman–Bondi

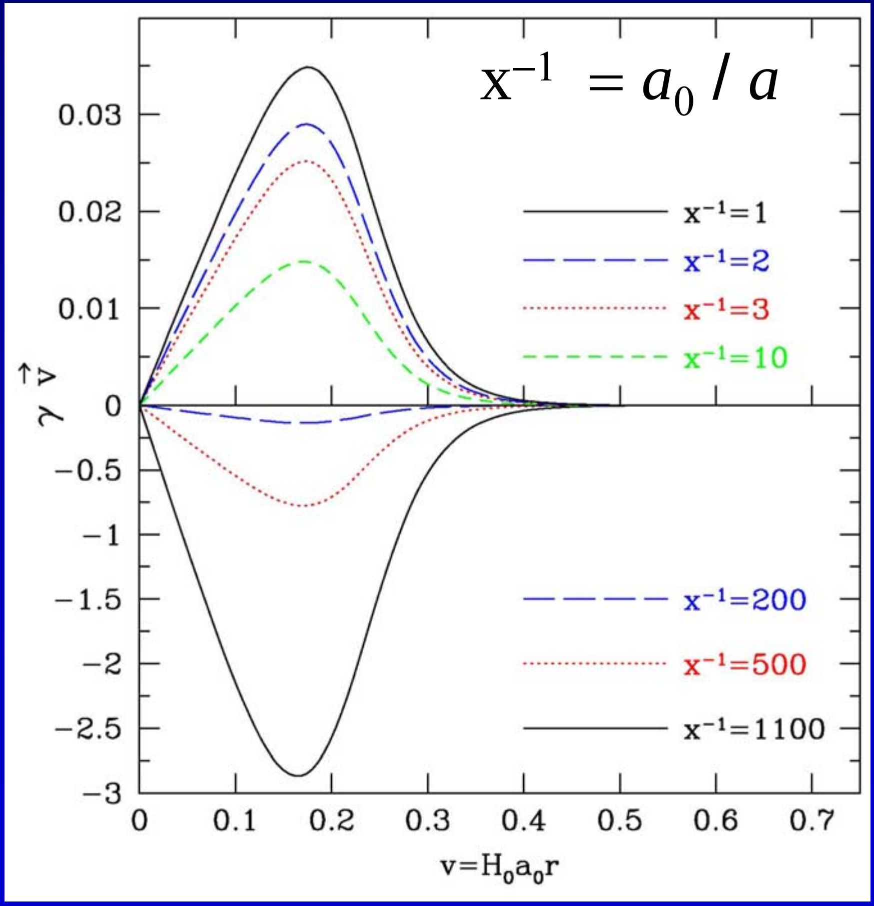


Inner underdense region prevented from overtaking denser regions (leading to shell crossing) by large initial infall velocity.

Large initial infall velocity means metric can not be written in the conformal Newtonian form:

$$ds^2 = -(1+2\psi)\, dt^2 + a^2(t)\,(1-2\psi)\, dx^2$$

with $a(t)$ from underlying EdS model.



Kolb, Marra, Matarrese

Backgrounds and Backreactions

Can write $ds^2 = -(1+2\psi)\,dt^2 + a^2(t)\,(1-2\psi)\,dx^2$, but not with $a(t)$ from the underlying EdS model, but $a(t)$ from a ΛCDM model.

How?

Give some thought to what is meant by a background solution.

Backgrounds and Backreactions

Some thoughts on cosmological background solutions

Global Background Solution**:** FLRW solution generated using $\rho = \langle \rho \rangle_H$, ${}^3\mathrm{P} = \langle {}^3\mathrm{P} \rangle_H$ (sub-$H \rightarrow$ Hubble volume average), and the local equation of state (e.o.s.).

Average Background Solution**:** FLRW solution that describes volume expansion of our past light cone. Energy content, curvature, and e.o.s. that generates the *ABS* need not be $\langle \rho \rangle$, $\langle {}^3\mathrm{P} \rangle$, and local e.o.s. (Buchert formalism)

Phenomenological Background Solution**:** FLRW model that best describes the observations on our light cone. Energy content, curvature, and e.o.s. that generates the *PBS* need not be $\langle \rho \rangle$, $\langle {}^3\mathrm{P} \rangle$, and local e.o.s. (Swiss-cheese example)

Kolb, Marra, Matarrese

Backgrounds and Backreactions

***Backreaction*:** the three backgrounds do not coincide

***Strong Backreaction*:**

Global Background Solution does not describe global expansion (hence does not describe observations) (Buchert)

***Weak Backreaction*:**

Global Background Solution describes global expansion, but *Phenomenological Background Solution* differs (Swiss Cheese)

Kolb, Marra, Matarrese

Backgrounds and Backreactions

***FLRW Assumption*: a global background solution follows from the cosmological principle**

Specify $\langle {}^3\mathrm{P} \rangle_H$, $\langle \rho \rangle_H$, & local e.o.s. $\rightarrow$ Global Background Solution
describes $a(t)$, $H(t)$,
and all other observables

GBS $\neq$ if large peculiar velocities

Kolb, Marra, Matarrese

Backgrounds and Backreactions

***Background Peculiar Velocities*:** obtained after subtracting the Global Background Solution

***Local Peculiar Velocities*:** obtained after subtracting the Phenomenological Background Solution

Background peculiar velocity $\neq$ Local peculiar velocity

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Backgrounds and Backreactions

***Bare Cosmological Principle*:** universe is homo/iso on sufficiently large scales → can describe universe by a mean-field approach → *Average Background Solution* exists.

***Bare Copernican Principle*:** every observer can describe the universe by a mean-field approach → a *Phenomenological Background Solution* exists for every observer (but not necessarily unique).

Kolb, Marra, Matarrese

Backgrounds and Backreactions

- ***Global Background Solution*** follows from the *FLRW assumption*.

- ***Average Background Solution*** follows from the *Bare Cosmological Principle.*

- ***Phenomenological Background Solution*** follows from the *Bare Copernican Principle* (the success of ΛCDM).

- ***Backreaction*** is the non-coincidence of the three backgrounds.

Kolb, Marra, Matarrese

“Backreaction” Causes Allergic Reaction

- “Dark Energy” may herald something really revolutionary
- We have considered some remarkable new things
  - 10^{500} ground states in the landscape
  - Modification of GR in the infrared
  - Lorentz violation
  - 10^{-33} eV scalar fields
  - Extra dimensions
- There should be some effort in rethinking some basic old things
  - Is the global background solution relevant?
  - Is the FLRW assumption invalid?
  - Is ΛCDM just a *phenomenological background solution*?
  - Could it revolutionize something in the early universe (requiring a new book)?

Dark Energy: Taking Sides

Rocky Kolb **The University of Chicago**

Backgrounds and Backreactions

<u>Phenomenological Background Solution</u>**:** FLRW model that best describes the observations on our light cone. Energy content, curvature, and e.o.s. that generates the *PBS* need not be $\langle \rho \rangle$, $\langle ^3\mathrm{P} \rangle$, and local e.o.s. (Swiss-cheese example)

$$H^2(z) = H_0^2\left[\left(1-\Omega_{\mathrm{TOTAL}}\right)\left(1+z\right)^2 + \Omega_M\left(1+z\right)^3 + \Omega_R\left(1+z\right)^4 + \Omega_w\left(1+z\right)^{3(1+w)}\right]$$