Breaking the symmetry

Cosmological structure formation and accelerated expansion

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Physics Nobel prize 2011

HELSINKI INSTITUTE OF PHYSICS

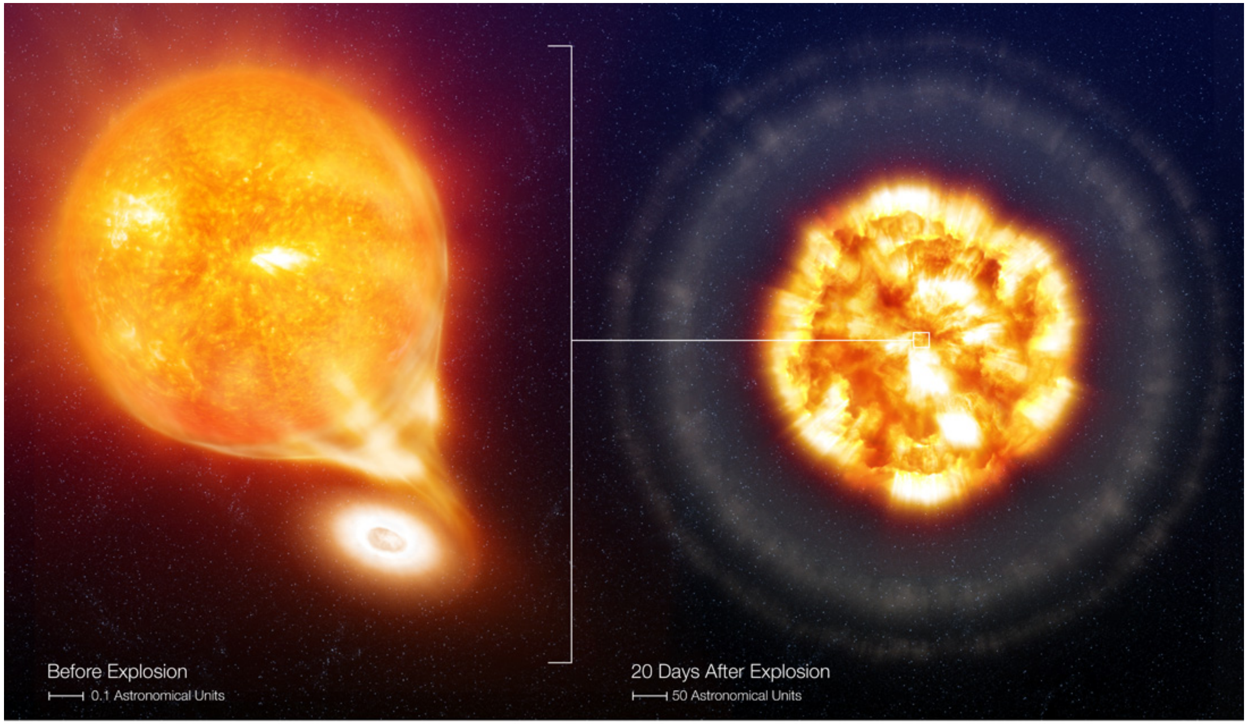
- *“for the discovery of the accelerating expansion of the Universe through observations of distant supernovae”*

Saul Perlmutter

Brian P. Schmidt

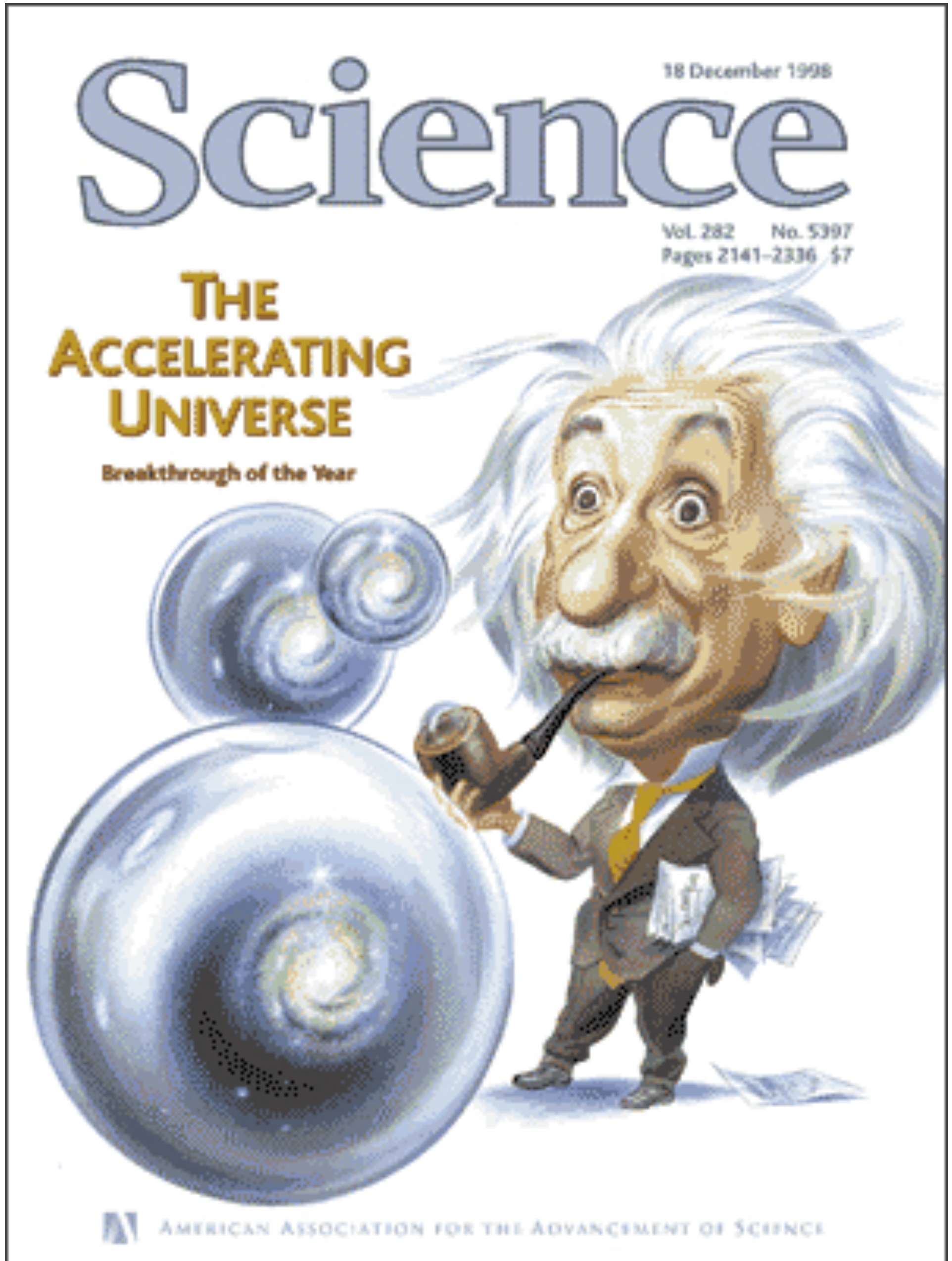
Adam G. Riess

Type Ia supernova



SN 2006X, before and after the Type Ia Supernova Explosion
(Artist Impression)

ESO Press Photo 31b/07 (12 July 2007)


Science
18 December 1998
Vol. 282 No. 5397
Pages 2141–2336 $7
THE ACCELERATING UNIVERSE
Breakthrough of the Year
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

From brightness to darkness

- Observation: Distances are longer than expected. ✓
- Kinematical interpretation: Expansion of the universe has accelerated. ?
- Dynamical cause: Dark energy. ??

"dark energy [...] is an enigma, perhaps the greatest in physics today"

The Friedmann-Robertson-Walker model

- It is usually assumed that the universe is exactly homogeneous and isotropic.
- Such a model with ordinary matter and ordinary gravity works in the early universe.
- However, it underpredicts distances and expansion rates at late times by a factor of 2.

A factor of 2

- Three alternatives:

  1) There is matter with negative pressure.

  2) General relativity does not hold.

  3) The universe is not homogeneous and isotropic.

Dark energy

- Dark energy is a form of matter which has negative pressure, does not absorb or emit light and is evenly spread in the universe.

- Not to be confused with *dark matter,* which has positive pressure and is clumped.

Vacuum energy

- Best candidate for dark energy.
- In quantum field theory, there is energy associated with empty space.
- Also known as the cosmological constant.
- Fits observations well. (Some issues with galaxy distribution remain.)

Problems with vacuum energy

1. Why is the vacuum energy density so small?

2. Why is the vacuum energy density so close to the matter energy density today?

The smallness problem

- Naive theoretical estimate:

$$\rho \sim (10^{18}\,\mathrm{GeV})^4 \ \text{or}\ (10^{3}\,\mathrm{GeV})^4$$

- Value which fits observations: $\rho \approx (2\ m\mathrm{eV})^4$

- A mismatch of 10^{-120}.

"The worst prediction in all of theoretical physics."

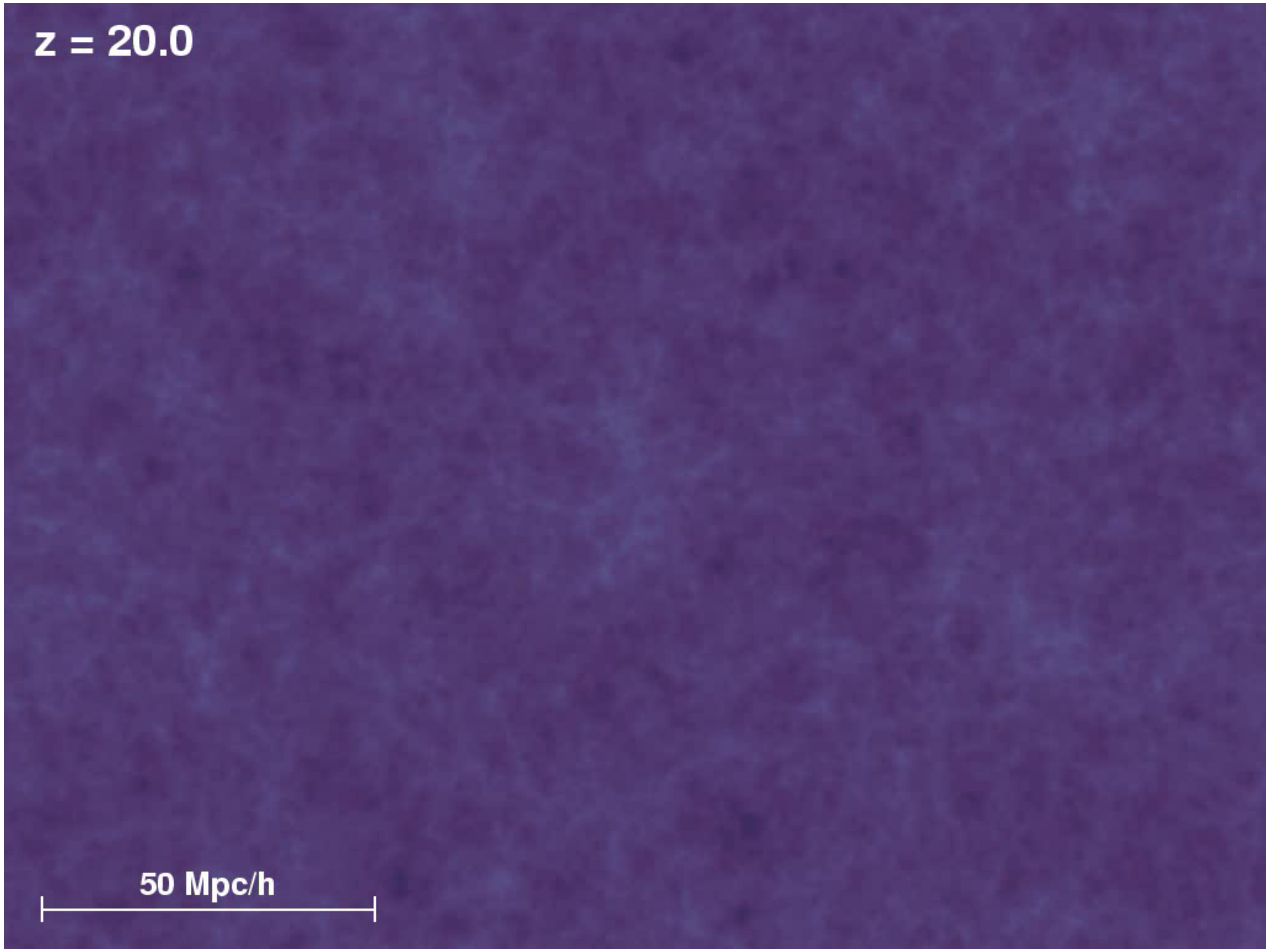
The coincidence problem

- Vacuum energy density stays constant.
- In contrast, as the universe expands, the energy density of matter drops inversely to the volume.
- Today, $\rho_{\text{vacuum}} \approx 3\rho_{\text{matter}}$.
- Why are we living in a special era? Why 10 billion years?

The effect of structures

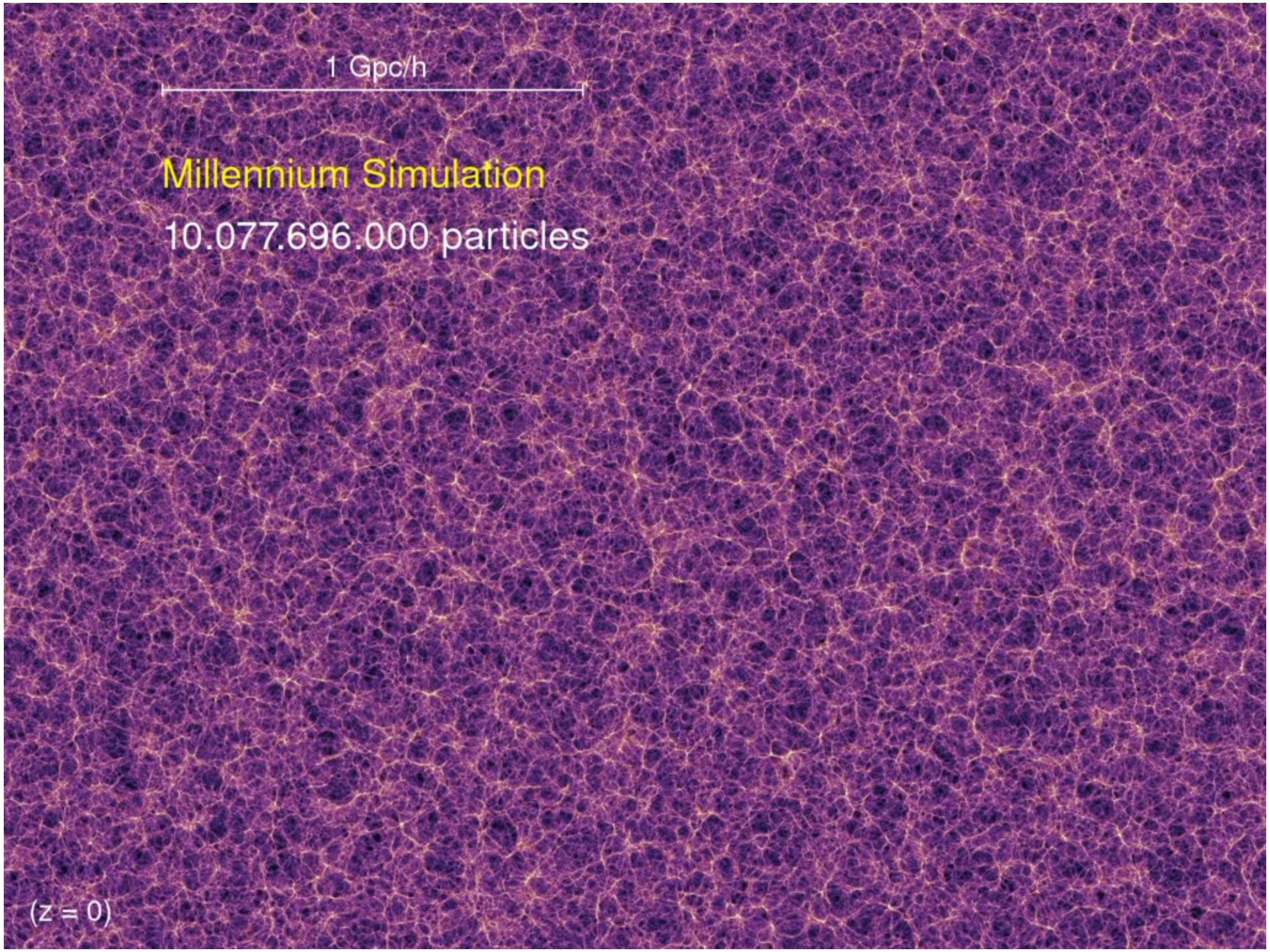
- At late times, non-linear structures form, so the universe is no longer close to homogeneous and isotropic.
- Structure formation has a preferred time of 10 billion years.
- This affects the expansion rate, the distance and their relation.
  - Distances can be longer without acceleration.
  - Expansion can accelerate without negative pressure.

Evolution of structures



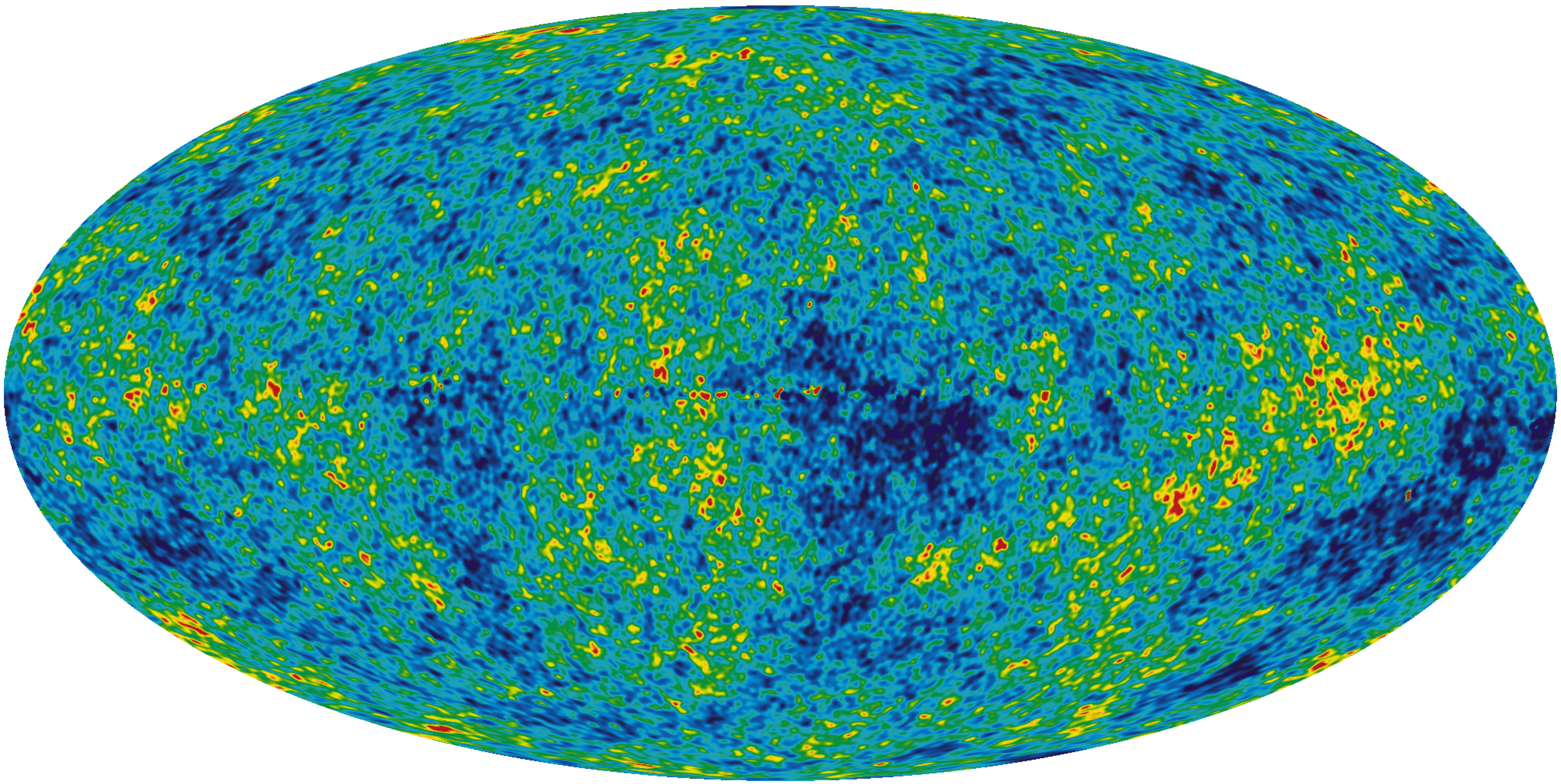
http://www.mpa-garching.mpg.de/galform/data_vis/index.shtml

Homogeneity



http://www.mpa-garching.mpg.de/galform/virgo/millennium/

Isotropy



http://map.gsfc.nasa.gov/

Backreaction

- At late times, the universe is only *statistically* homogeneous and isotropic, on scales >100 Mpc.
- The average evolution of a clumpy spacetime is not the same as the evolution of a smooth spacetime, a feature known as **backreaction**.
- Describing the average behaviour of a clumpy universe was termed **the fitting problem** by George Ellis in 1983.
- The average expansion rate of a clumpy spacetime can accelerate, even though the expansion decelerates locally.

Understanding acceleration

- The average expansion rate can increase, because the fraction of volume taken by faster regions grows.
- Structure formation involves overdense regions decelerating more and underdense regions decelerating less.
- Acceleration can be demonstrated with a toy model which has one overdense and one underdense region.

$$H \equiv \frac{\dot{a}}{a} = \frac{a_1^{\,3}}{a_1^{\,3} + a_2^{\,3}} H_1 + \frac{a_2^{\,3}}{a_1^{\,3} + a_2^{\,3}} H_2 = v_1 H_1 + v_2 H_2$$

$$\frac{\ddot{a}}{a} = v_1 \frac{\ddot{a}_1}{a_1} + v_2 \frac{\ddot{a}_2}{a_2} + 2 v_1 v_2 (H_1 - H_2)^2$$

Towards reality

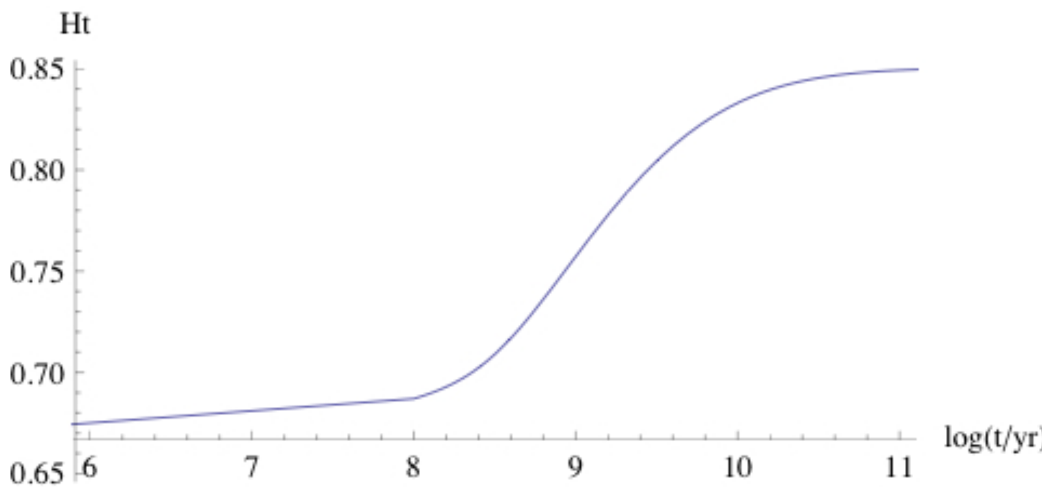
- Acceleration due to structures is possible: is it realised in the universe?
- The non-linear evolution is too complex to follow exactly.
- Because the universe is statistically homogeneous and isotropic, a statistical treatment is sufficient.
- We can evaluate the expansion rate with an evolving ensemble of regions.

The peak model

- Start from the a smooth background with an initial Gaussian linear density field.
- Identify structures with spherical isolated peaks of the smoothed density field.
- Each peak evolves separately.
- The peak number density as a function of time is determined by the power spectrum.

Ensemble evolution

- The expansion rate is $H(t) = \int_{-1}^{\infty} d\delta\, v_\delta(t) H_\delta(t).$



Ht as a function of time

Beyond Newton

- Non-linear evolution in cosmology is studied with N-body simulations.
- Simulations use Newtonian gravity with periodic boundary conditions.
- In Newtonian gravity, backreaction reduces to a boundary term. (Buchert and Ehlers 1995)
- In general relativity, this is not the case. (Buchert 1999)
- Newtonian cosmology is not the small-velocity, weak field limit of general relativity.

Questions remain

- Observations of the late universe are inconsistent with homogeneous and isotropic models with ordinary matter and gravity.
- Vacuum energy fits observations, but makes people uneasy.
- Structure formation has a preferred timescale of 10 billion years.
- If backreaction is important, this is due to non-Newtonian, non-perturbative aspects of gravity.
- More work is necessary to quantify the effect before it could be concluded that new physics is needed.