Cody Astronomical Society

7th December 2011

Inflation

and the origin of structure

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outline of my talk:

- large-structure in the universe
- inflation in the very early universe
- ...and the origin of structure

What is the ICG?

Research institute at University of Portsmouth

- established in 2002
- deliver undergraduate units and projects in maths, engineering and physics
- approx 50 academic staff, postdoctoral researchers, phd students and visiting researchers

Professor Martin Rees opens the new Dennis Sciama Building

Big questions:

about our Universe:

- What is it made of?
  - Dark matter? Dark energy?
- How does structure emerge?
- Do the laws of physics change with time or scale?
  - String theory? Quantum gravity? Extra dimensions?

about galaxies:

- How were they made and how do they evolve?
- Why are there different types and shapes of galaxies?
- When and how do stars form in them?
- What are the important processes?
  - Mergers? Massive black holes? SN explosions?

Facilities:

NATIONAL COSMOLOGY GRID sgi

Sloa

DES news 7/12/11: "the first dark images with the cooled imager in the dome at CTIO have been taken and so far look good, i.e., so far it appears that the imager survived shipping. They have verified that cosmic rays exist in the Southern hemisphere as well. The alignment work on the optical corrector at UCL has been completed, the corrector is being packed up, and it will ship to Chile next week." http://www.facebook.com/darkenergysurvey

DARK ENERGY Survey

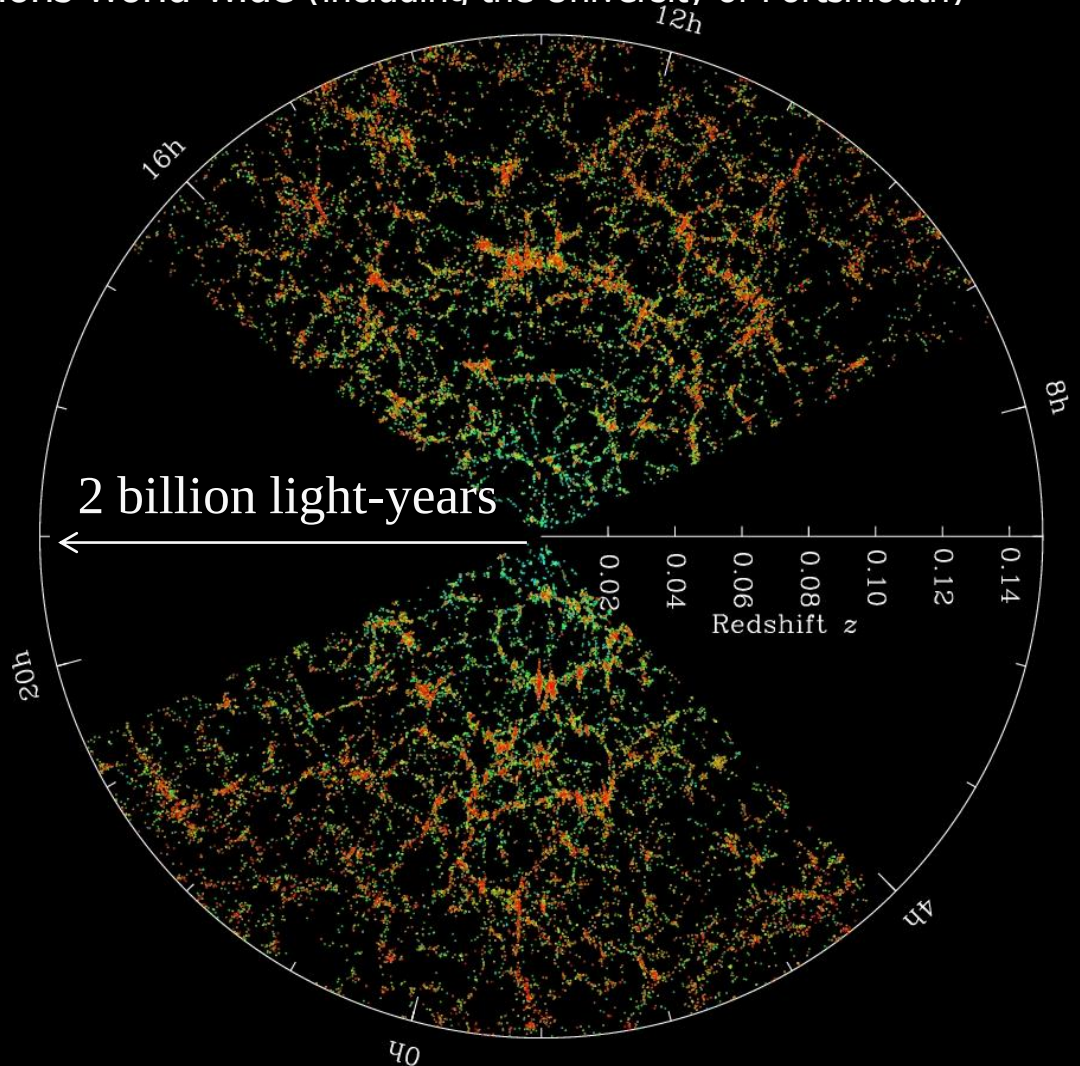
Sloan Digital Sky Survey

the largest galaxy survey to date

about 200 scientists from 25 institutions world-wide (including the University of Portsmouth)

it has mapped one million galaxies

see *www.galaxyzoo.org*



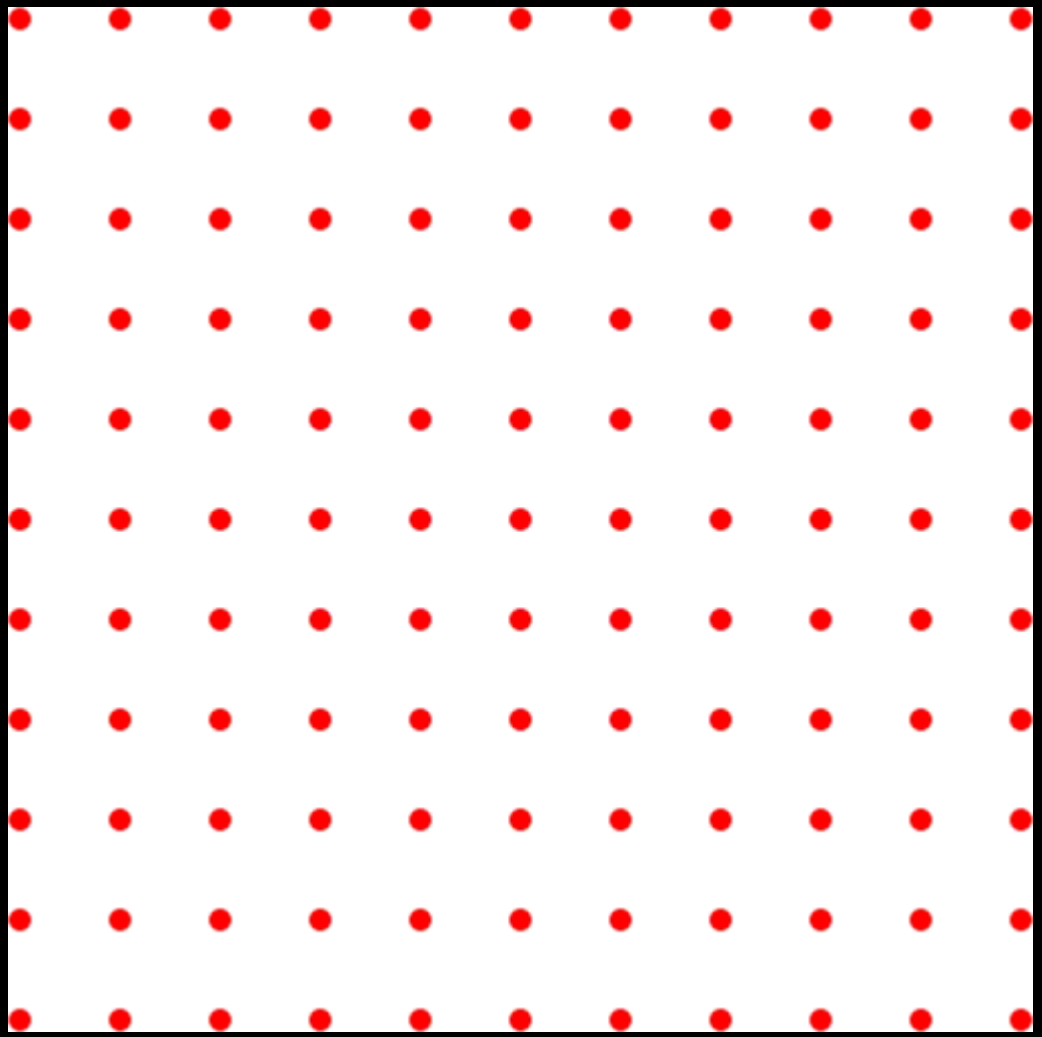
Hubble's law

Edwin Hubble made the most remarkable scientific discovery of the 20th century

Distant galaxies are moving away from us

and their speed is proportional to their distance: $v = H d$

the amazing, expanding universe!

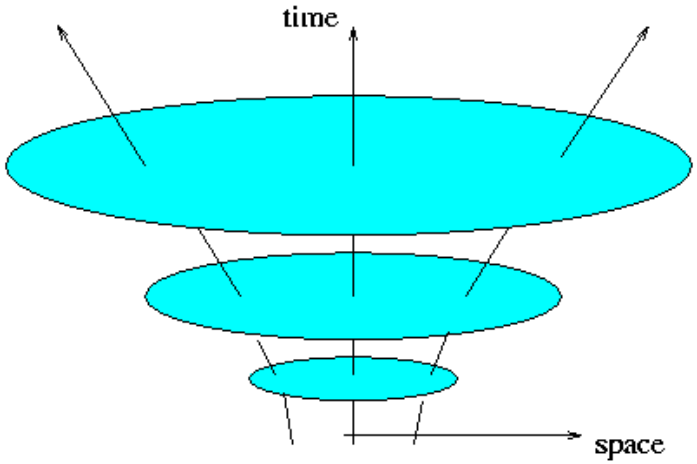


Robert Knop, Vanderbilt University

no centre, no edge!

Friedmann's dynamic cosmology

- slice up 4D spacetime into expanding 3D space
  with uniform matter density and spatial curvature



- Friedmann equation from Einstein's general relativity:

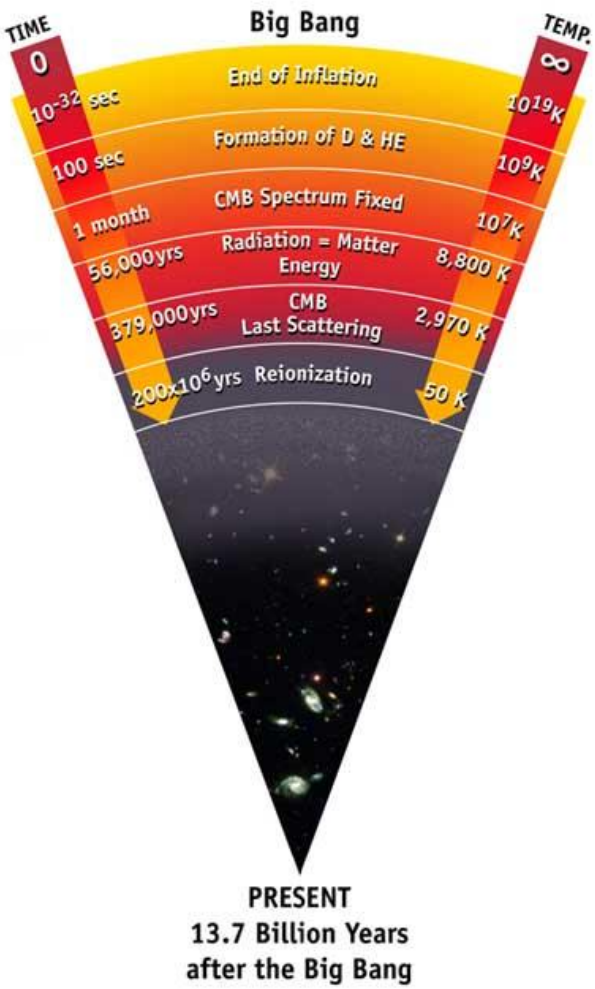
  Hubble expansion rate:

$$H^2 = (8\pi G/3)\rho c^2 - (k/R^2) + \Lambda/3$$

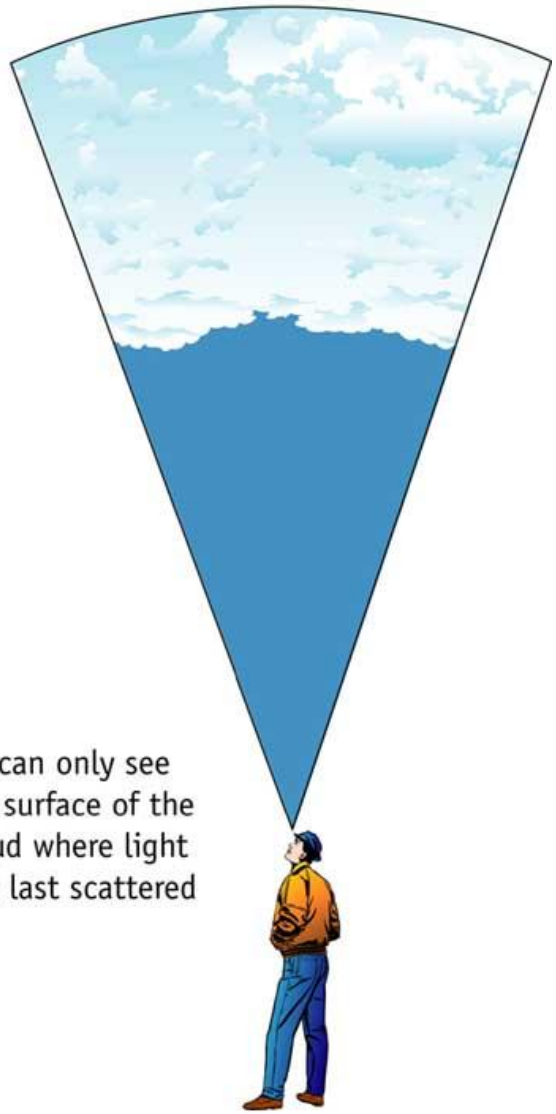
density + curvature + cosmological constant

how far can we look back?

can we see the Big Bang?



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



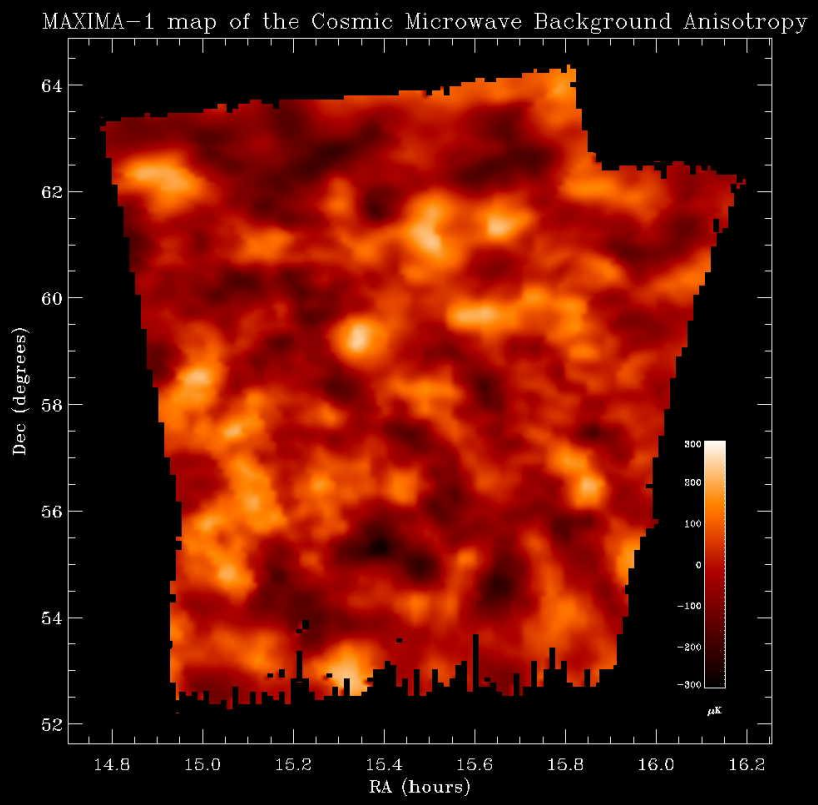
Cosmic Microwave Background radiation

- discovered in 1965 by
  Arno Penzias and Robert Wilson

- relic thermal radiation
  from the hot big bang

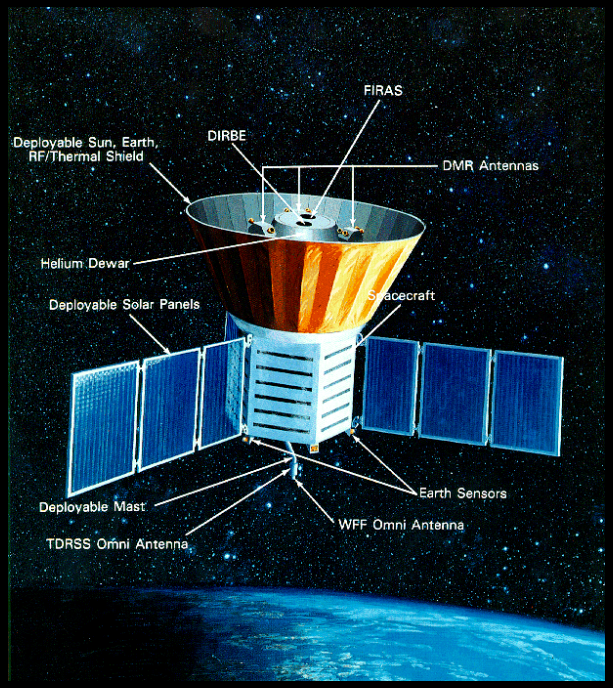
- 3 Kelvin, just three degrees
  above absolute zero

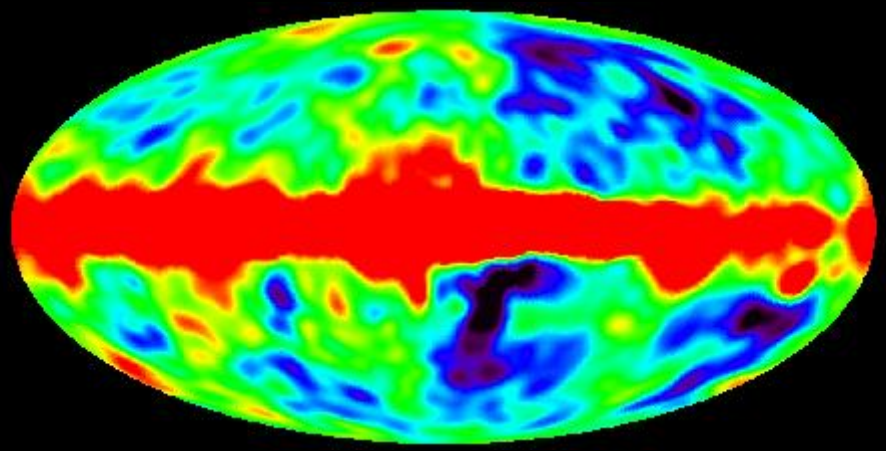
- more than 10 thousand million
  light years away



CoBE satellite

launched by NASA in 1990





2.7 K everywhere

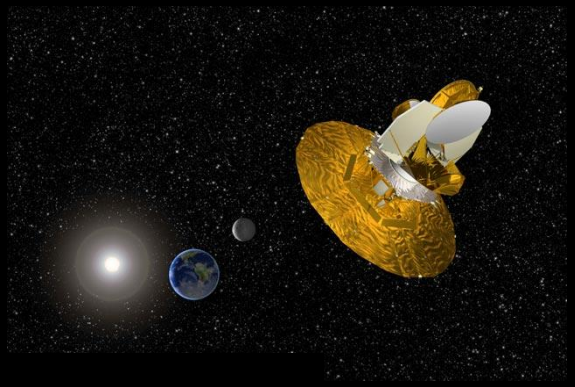
+/- 3.3 mK redshift due local motion

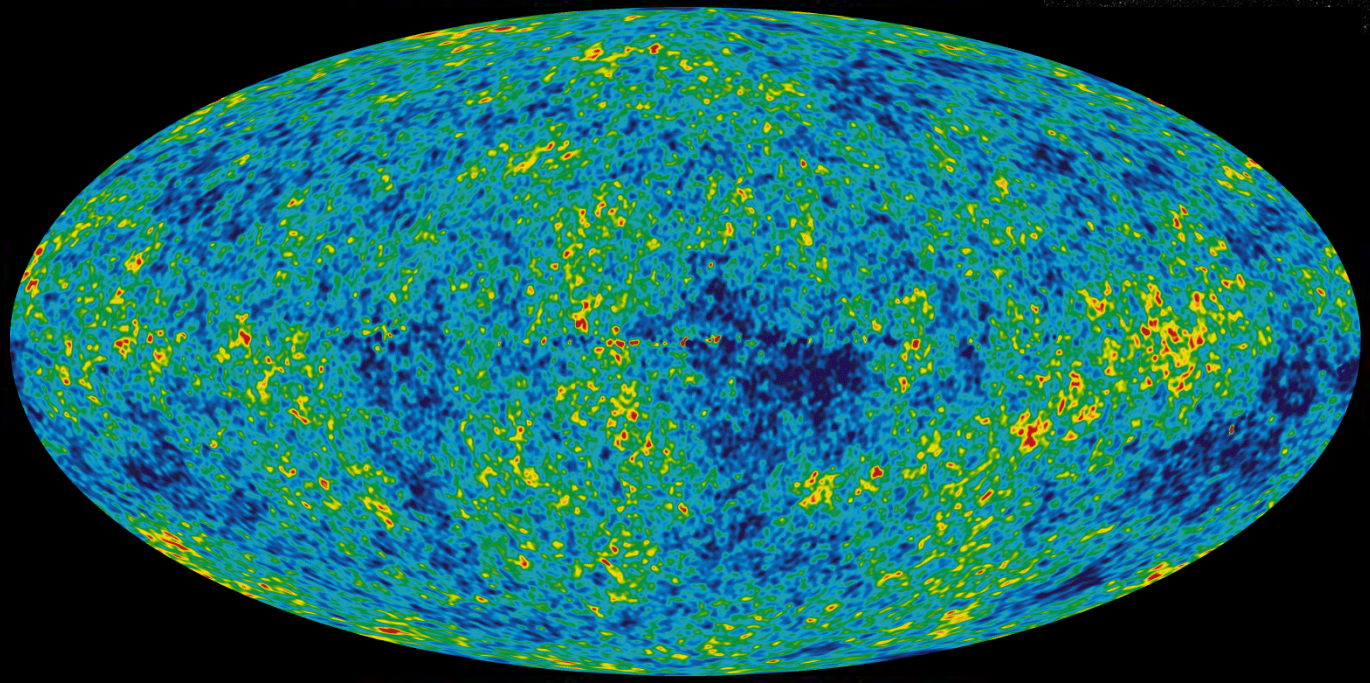
(at 1 million miles per hour)

+/- 18 μK intrinsic anisotropies

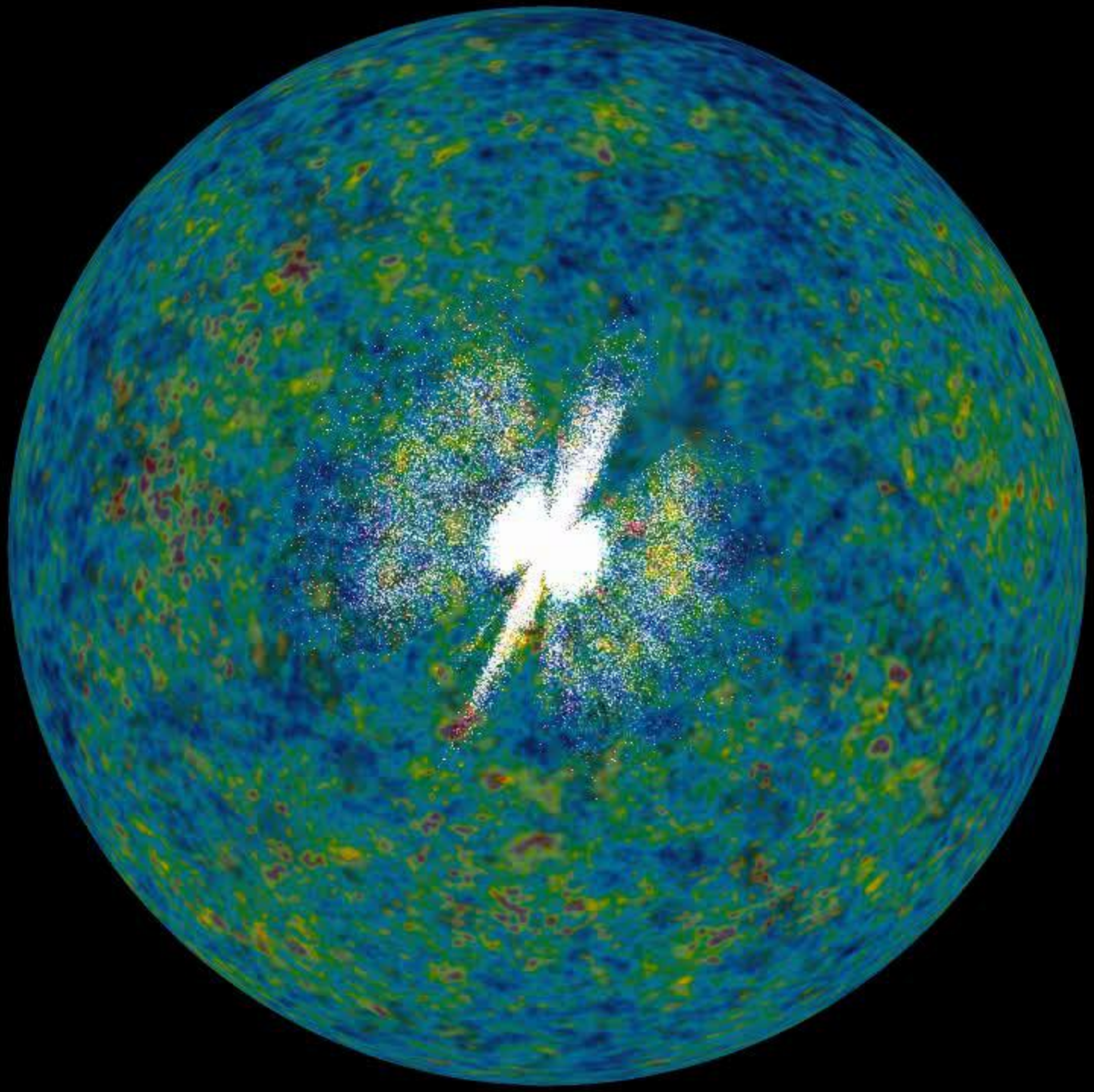
COBE launched 1990

WMAP launched 2001, latest data 2010





the surface of last scattering



leaves one question…

where do the primordial ripples in the CMB come from?

Inflation:

Starobinsky (1980)

Guth (1981)

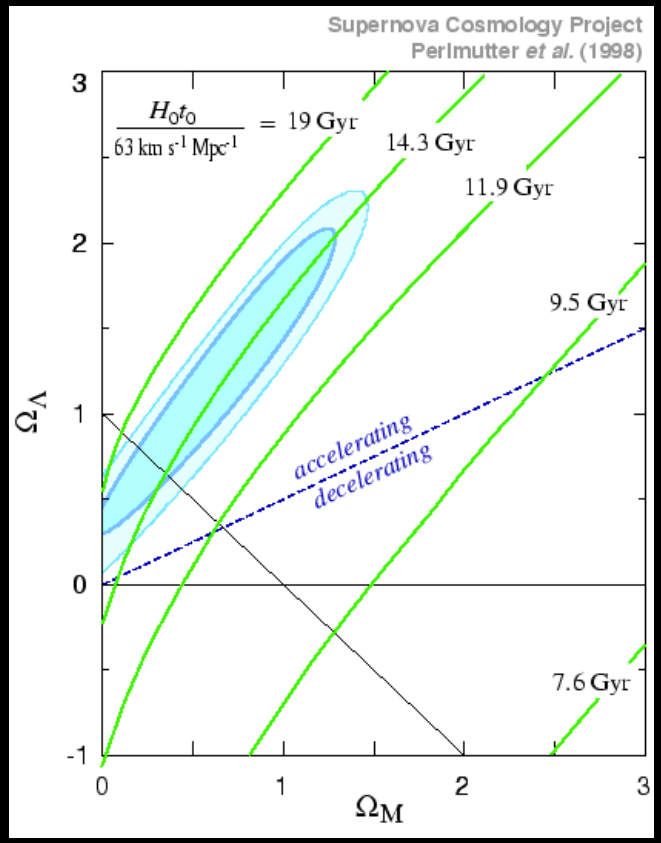
- period of accelerated expansion in the very early universe

- requires exotic matter

  (negative pressure!)

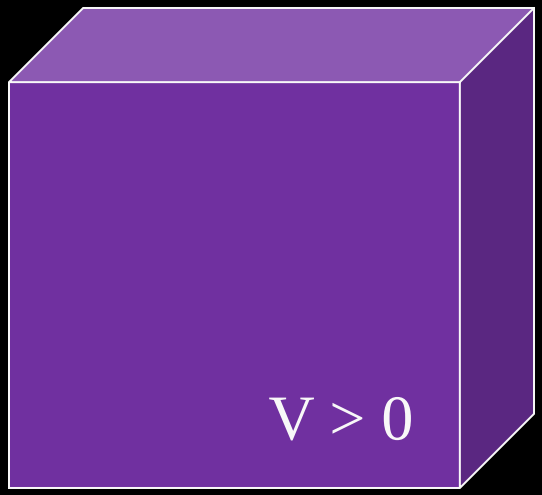
- speculative and uncertain physics

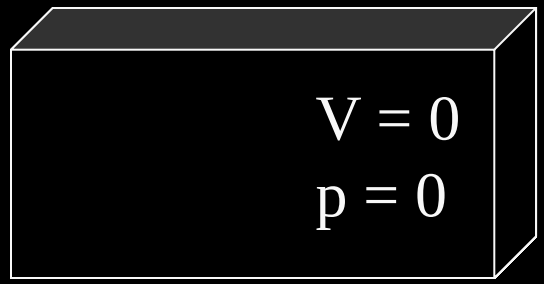
- just the kind of peculiar (Nobel prize 2011 winning!) expansion we observe today

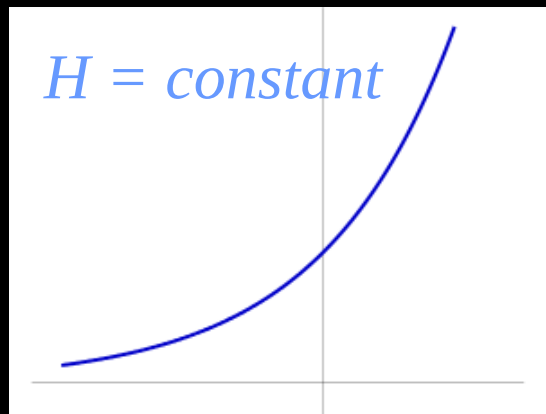


Everything from nothing

- "empty" space can have vacuum energy, V, (what is left once all the particles are gone)
- vacuum energy has odd properties, like negative pressure (p=-V)
- *false vacuum* (V>0) is unstable to decay into *true vacuum* with V=0
- only the relative energy matters in physics – *except for gravity:*
  - $H^2 = (8\pi G/3)V - (k/R^2) + \Lambda/3$
- "work done" as the universe expands is negative , so total energy grows (the ultimate free lunch!)

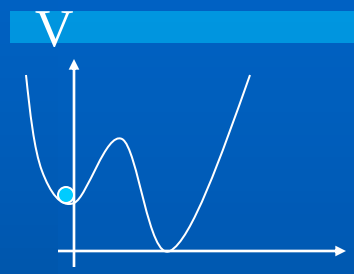


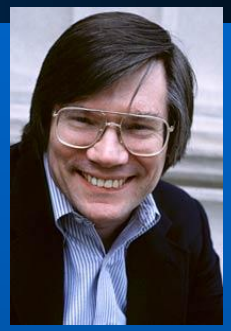




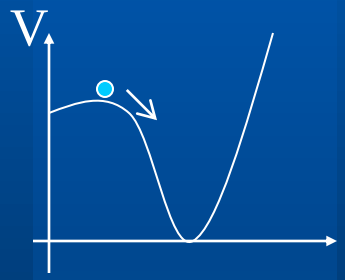
Models of inflation

- **Starobinsky inflation** 1980
  - **gravitational energy in vacuum (also slow-roll)**

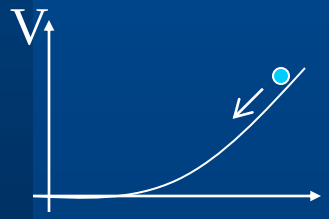




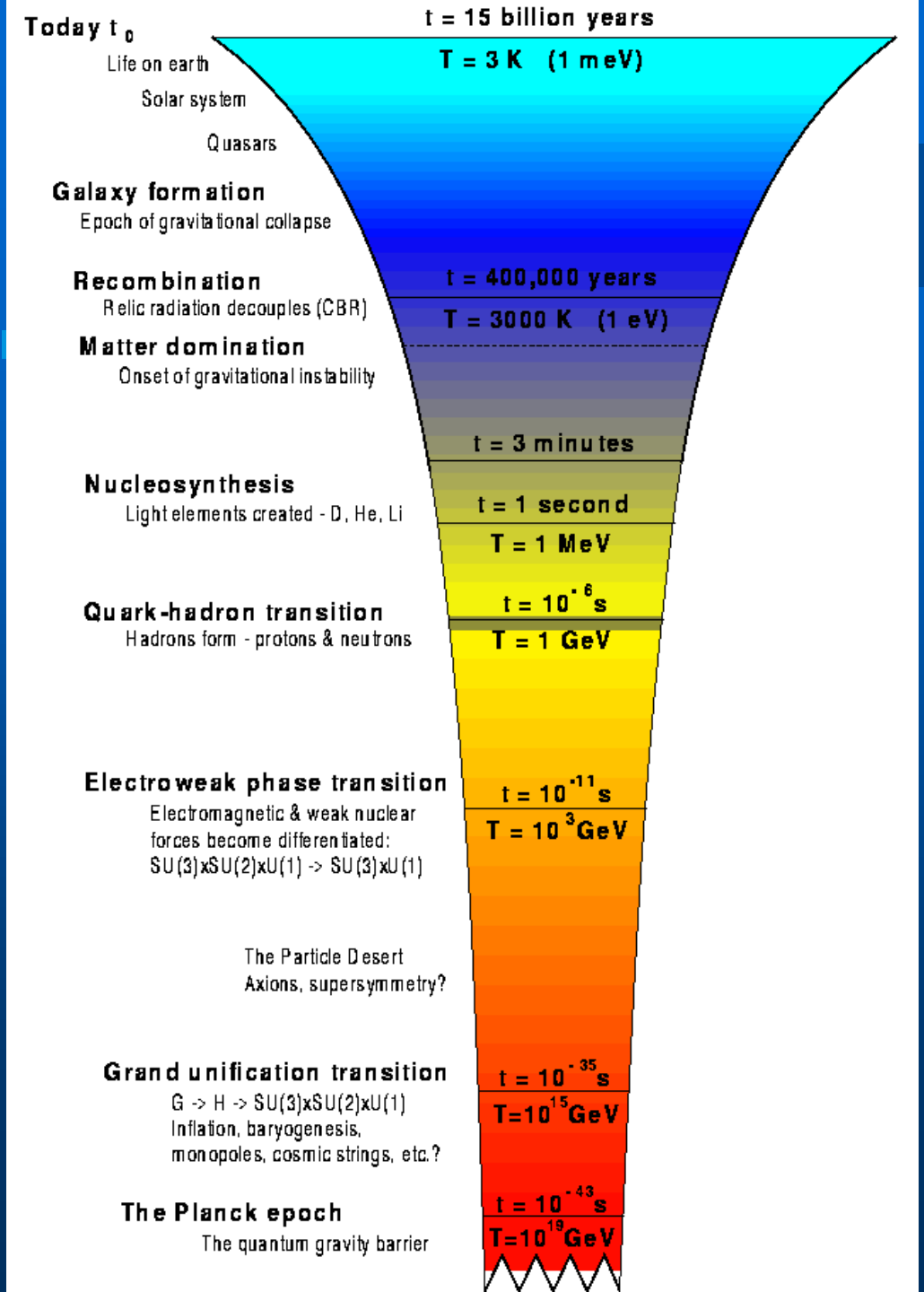
- **old inflation** Guth 1981
  - **de Sitter inflation in Grand Unified Theory**
  - **first-order phase transition to true vacuum**
  - **exit problem - need some classical dynamics...**



- **new inflation** Linde and Albrecht & Steinhardt ’82
  - **slow-roll inflation**
  - **second-order phase transition to true vacuum**
  - **fine-tuning problem to spend enough time in false vacuum in “realistic” (c.1982) GUT model**



- **chaotic inflation** Linde 1985
  - **inflation as slow-roll from high energy regime to true vacuum (not necessarily GUT)**



Inflationary scale:

- $10^3 – 10^{16}$ GeV
  > LHC
  < Planck scale
- redshift $10^{15} – 10^{28}$
- size of our presently observable universe was 10^{11} m – 1 cm
- density $10^{30} – 10^{82}$ gcm^{-3}

many more models of inflation...

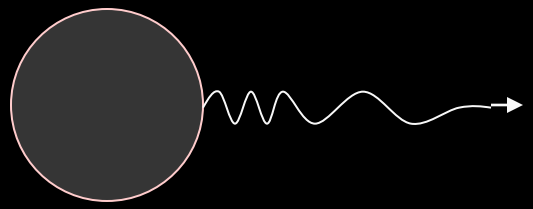
natural, hybrid, extended, hyper-extended, super-natural, assisted, GUT, SUSY, tribrid, brane, steep, DBI, quintessential, open, power-law, intermediate, mutated, thermal, double, single-field, multi-field, multi-brane, multi-brid, roulette, racetrack Nflation...

models of inflation are testable against observations through their predicted primordial perturbations

Hawking radiation

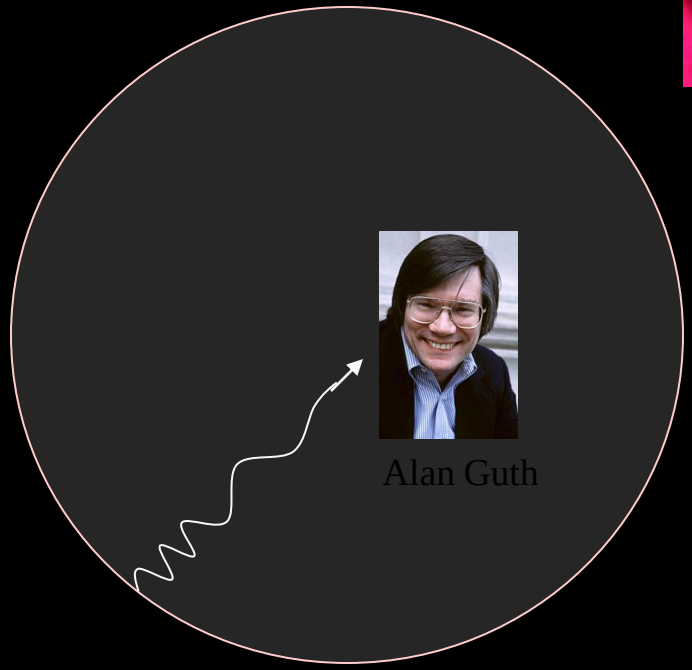
quantum vacuum in curved spacetime (semi-classical gravity)

radiation from a black-hole event horizon



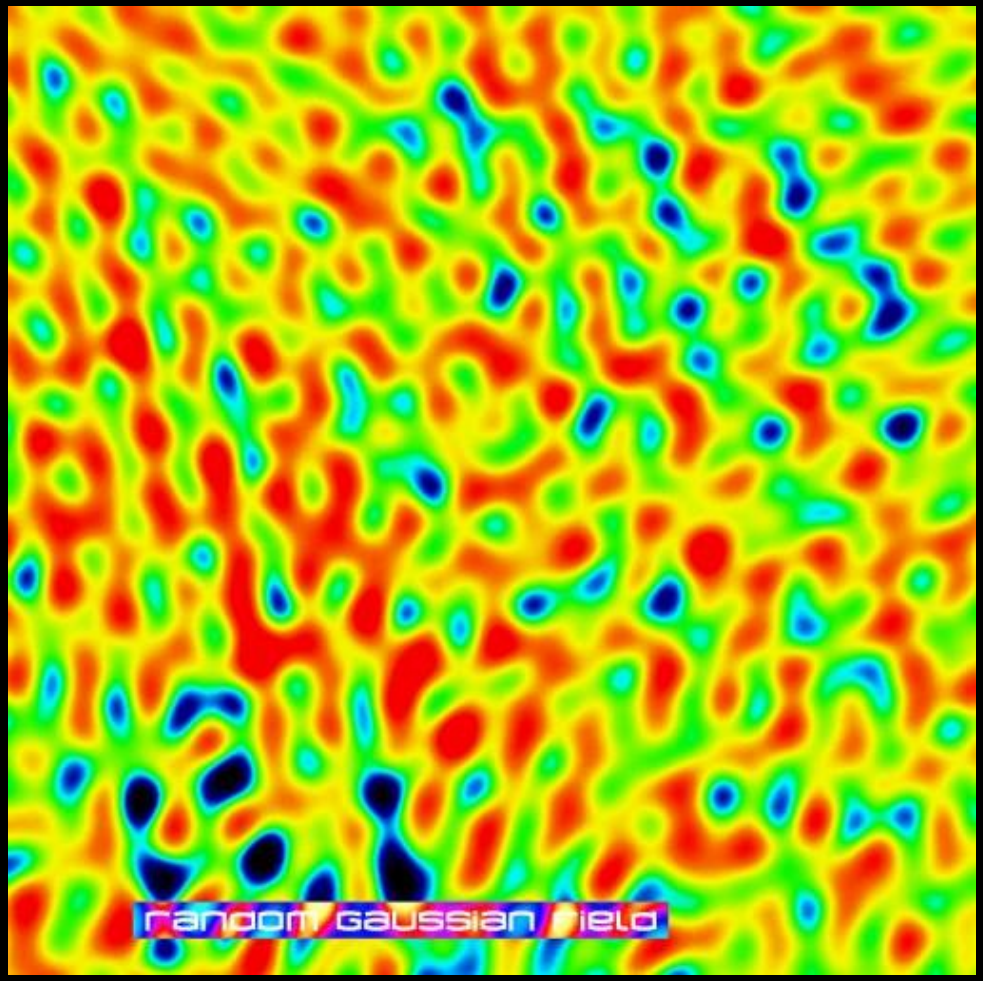
Hawking ‘73

or from a cosmological event horizon during a period of inflation in the very early universe



Hawking ‘82
Starobinsky ‘82
Guth and Pi ’82
Mukhanov and Chibisov ‘81

Microscopic fluctuations of free quantum field stretched by inflation to astrophysical scales



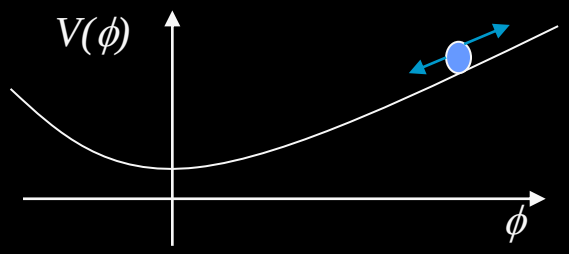
http://robertwcorkery.wordpress.com/

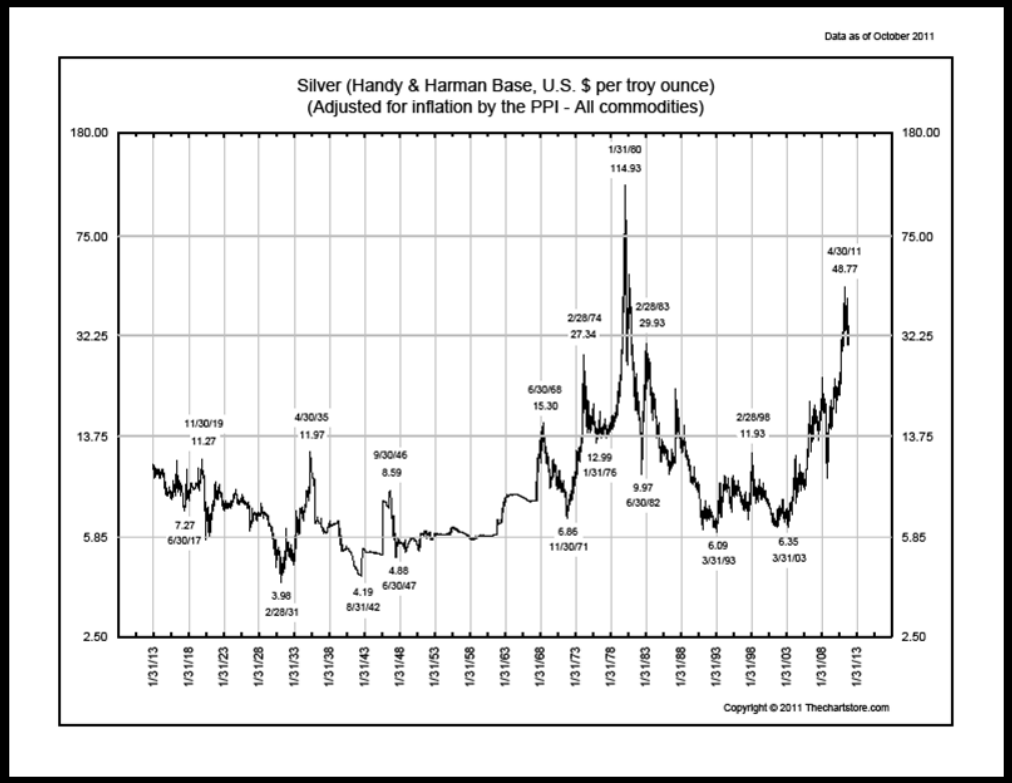
- **density fluctuations**
- **gravitational waves**

seen in the CMB could reveal the Hawking temperature of the inflationary universe

Stochastic inflation:

Starobinsky (1982); Vilenkin & Ford (1982)





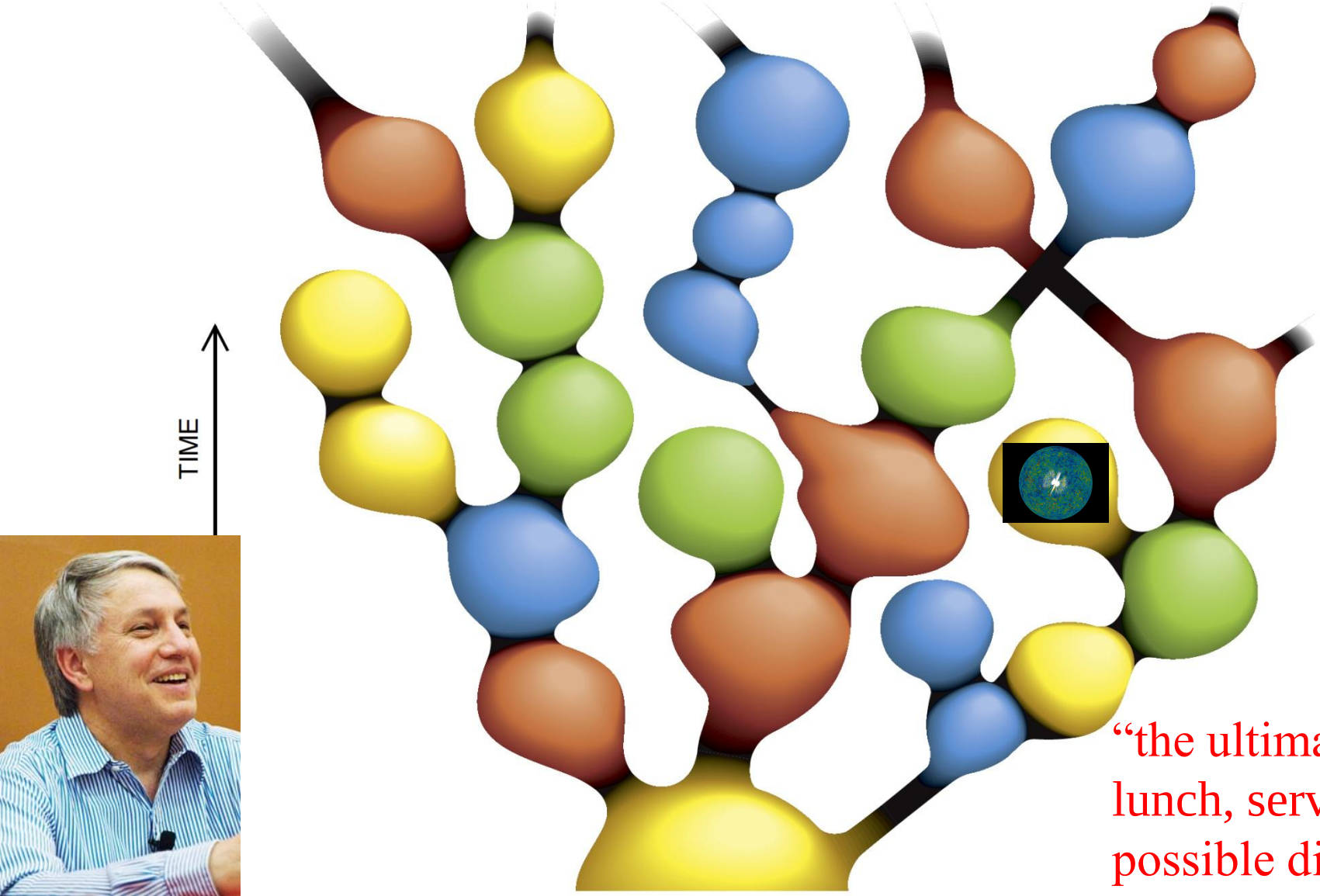
competition between smooth classical evolution and quantum noise

diffusion $\propto H^2 \propto V$

can lead to the field jumping up to higher energies

Eternal inflation and the multiverse

Linde (1986)



"the ultimate free lunch, serving all possible dishes"

in our *observable* universe...

models of inflation are testable against observations through their predicted primordial perturbations

such tests provide supporting evidence for models, not a proof

but specific models ***are*** falsifiable

outlook

NASA WMAP satellite has already detected slight scale-dependence of density perturbations

(interpreted as evolution of inflaton field)

ESA Planck satellite is next all-sky CMB survey, data release early 2013

looking for gravitational waves

+ non-linear evolution in the fluctuations

+ future high redshift galaxy surveys

summary:

solid evidence for the standard Big Bang model from galaxy surveys and the cosmic microwave background

- the geometry of the universe is relatively simple - expanding, flat space
- the universe is (about) 14 billion years old

plenty of scope for speculation and discoveries

- Vacuum energy could inflate the very early universe
- primordial ripples may emerge from quantum fluctuations
- could test high energy physics with astronomical surveys
- there could be a vast "multiverse" beyond our CMB sky

online resources:

- Institute of Cosmology and Gravitation
  - University of Portsmouth
  - http://www.icg.port.ac.uk/
- WMAP, the Universe 101 tutorial
  - http://wmap.gsfc.nasa.gov/universe/
- Ned Wright's cosmology tutorial
  - UCLA
  - http://www.astro.ucla.edu/~wright/cosmolog.htm
- Robert Knop movies for introductory astronomy
  - http://brahms.phy.vanderbilt.edu/~rknop/astromovies/
- Sloan Digital Sky Survey
  - http://www.sdss.org/
- Galaxy Zoo
  - http://galaxyzoo.org/
- COSMUS animations
  - University of Chicago
  - http://astro.uchicago.edu/cosmus/

THE END

what we might learn by looking at the sky!

THE END