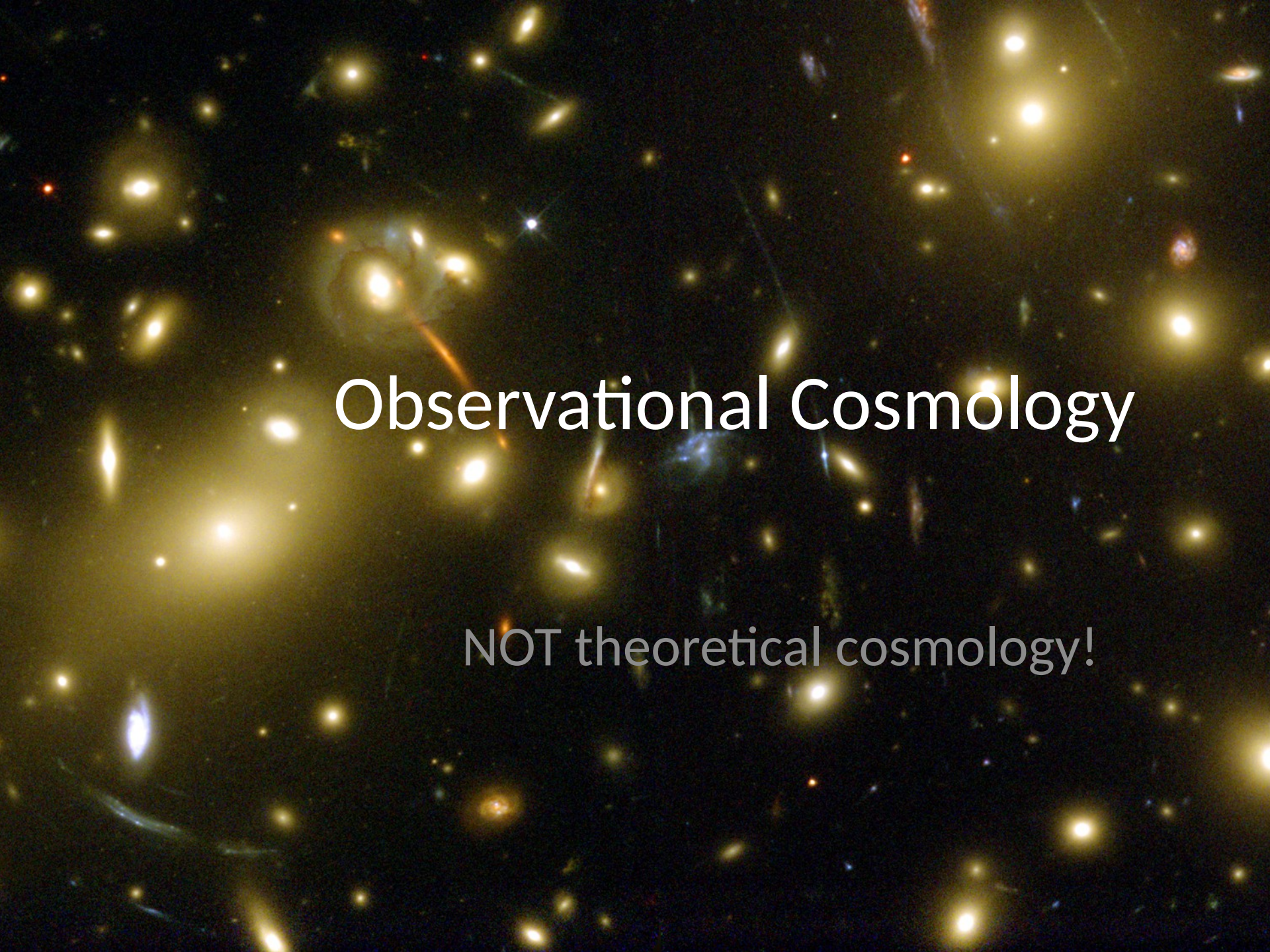


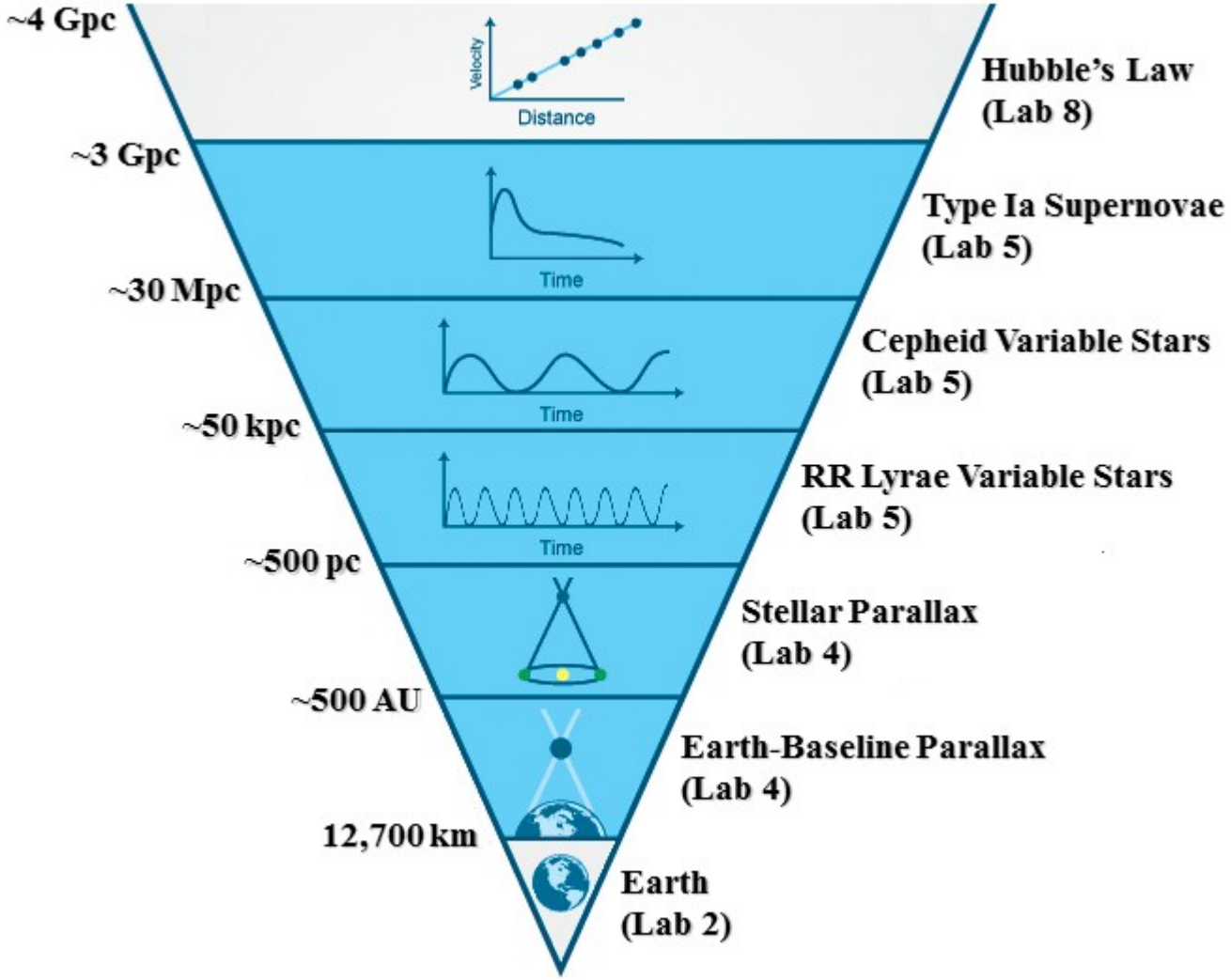
Observational Cosmology

NOT theoretical cosmology!

Topics

- Measuring cosmic distances
- Hubble constant and age of universe
- Big Bang models of the Universe
- Problems with simple picture
- Inflation
- History of the Universe – standard model
- Nucleosynthesis in early universe
- Cosmic Microwave Background
- Cosmological parameters
- Anthropic cosmological principle
- Beyond the standard model – the multiverse,etc?

Cosmic distance ladder



http://skynet.unc.edu/introastro/ourplaceinspace/ourplaceinspacelabs/

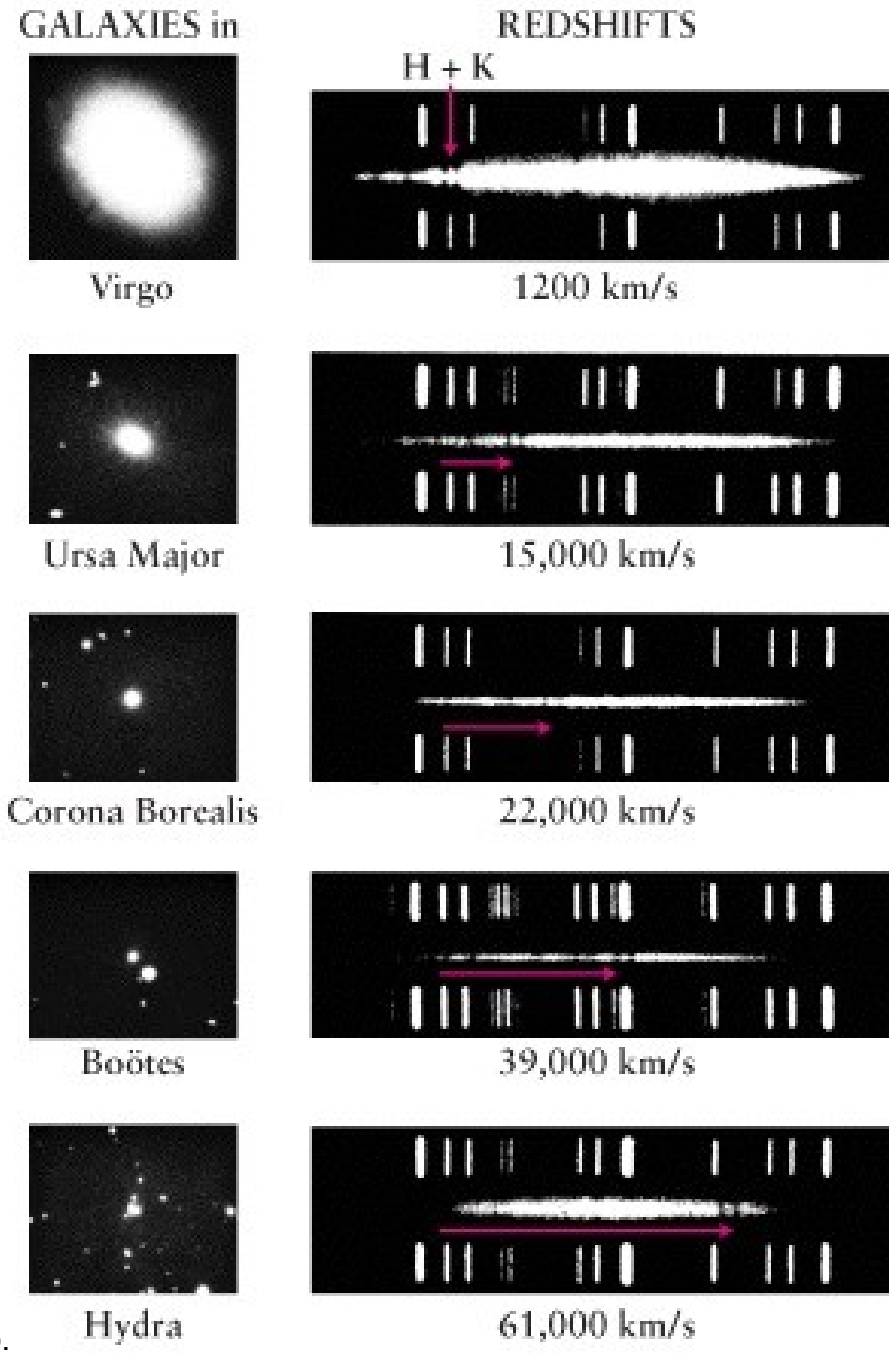
Redshift

- The expansion of the universe is measured by the redshifts of galaxies
- Redshift, z, is defined by

$$z = \frac{\lambda_{obs} - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0}$$

λ_{obs} - observed wavelength of spectral features in galaxy spectrum, λ_0 is rest or emitted wavelength

- $$1 + z = \frac{\lambda_{obs}}{\lambda_0}$$



Slipher's redshift measure-ments

- Hubble interpreted redshift as radial velocity
- The radial velocity (apparent velocity of recession) is related to redshift by

$$v = \frac{\Delta\lambda}{\lambda_0} c = cz$$

- (Note as velocities become comparable to the speed of light a different relativistic formula must be used)

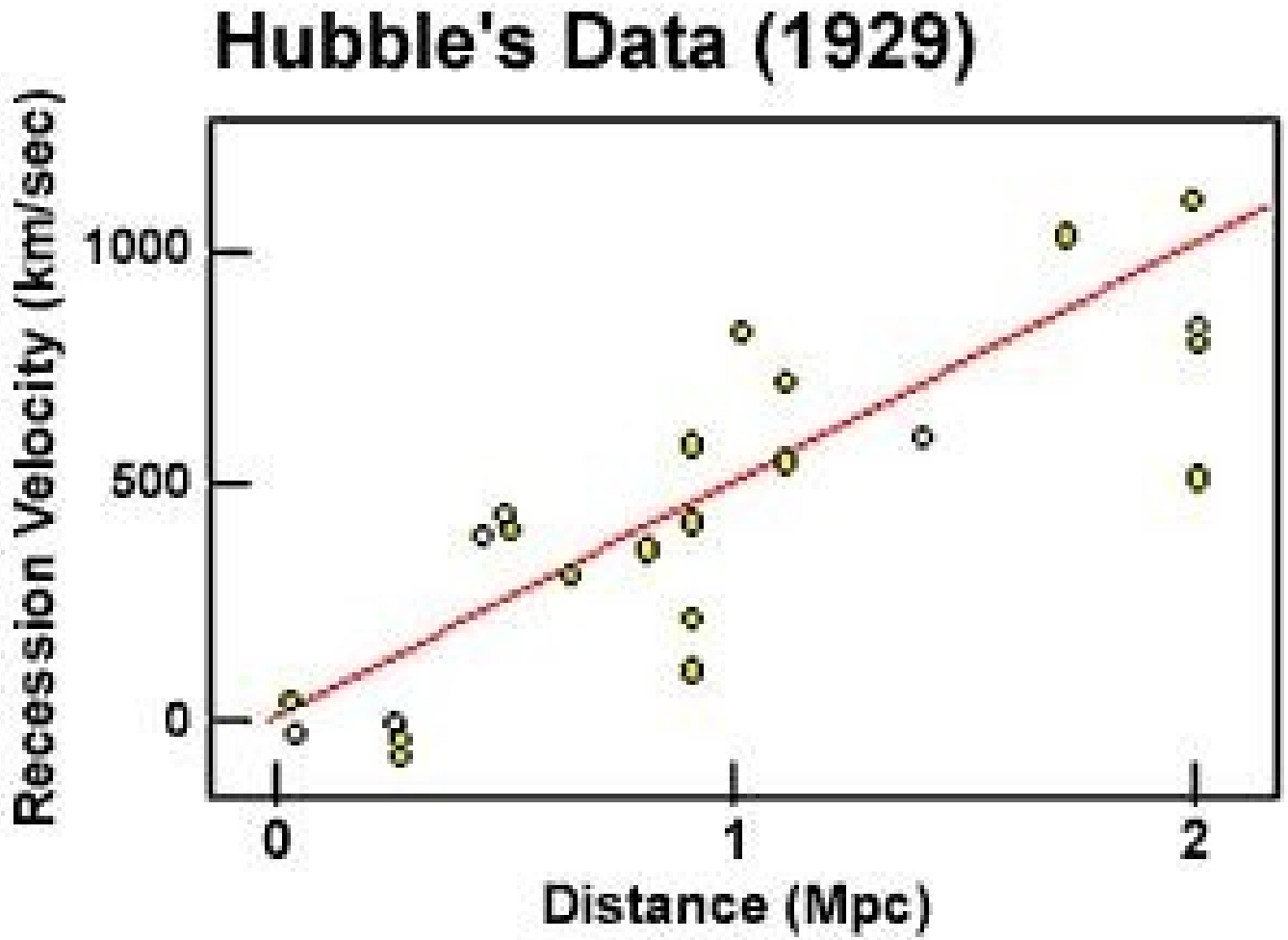
Hubble's Law

- Hubble found that the majority of galaxies have redshifted lines
- He also found that the further away the galaxy the higher the redshift (and apparent radial velocity), i.e.

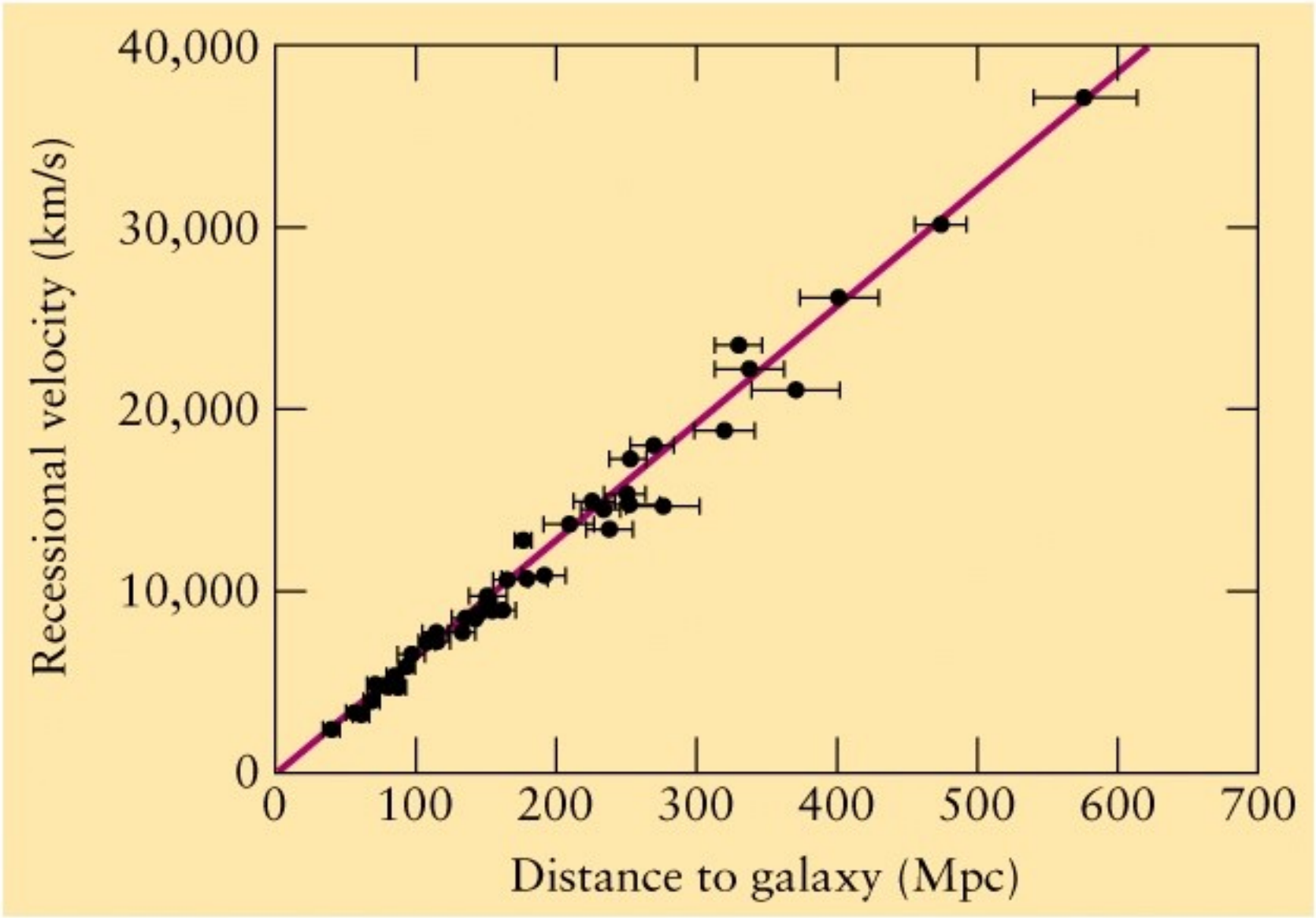
$$v = Hd$$

where H is Hubble's constant

Recession of galaxies



http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit5/expand.html

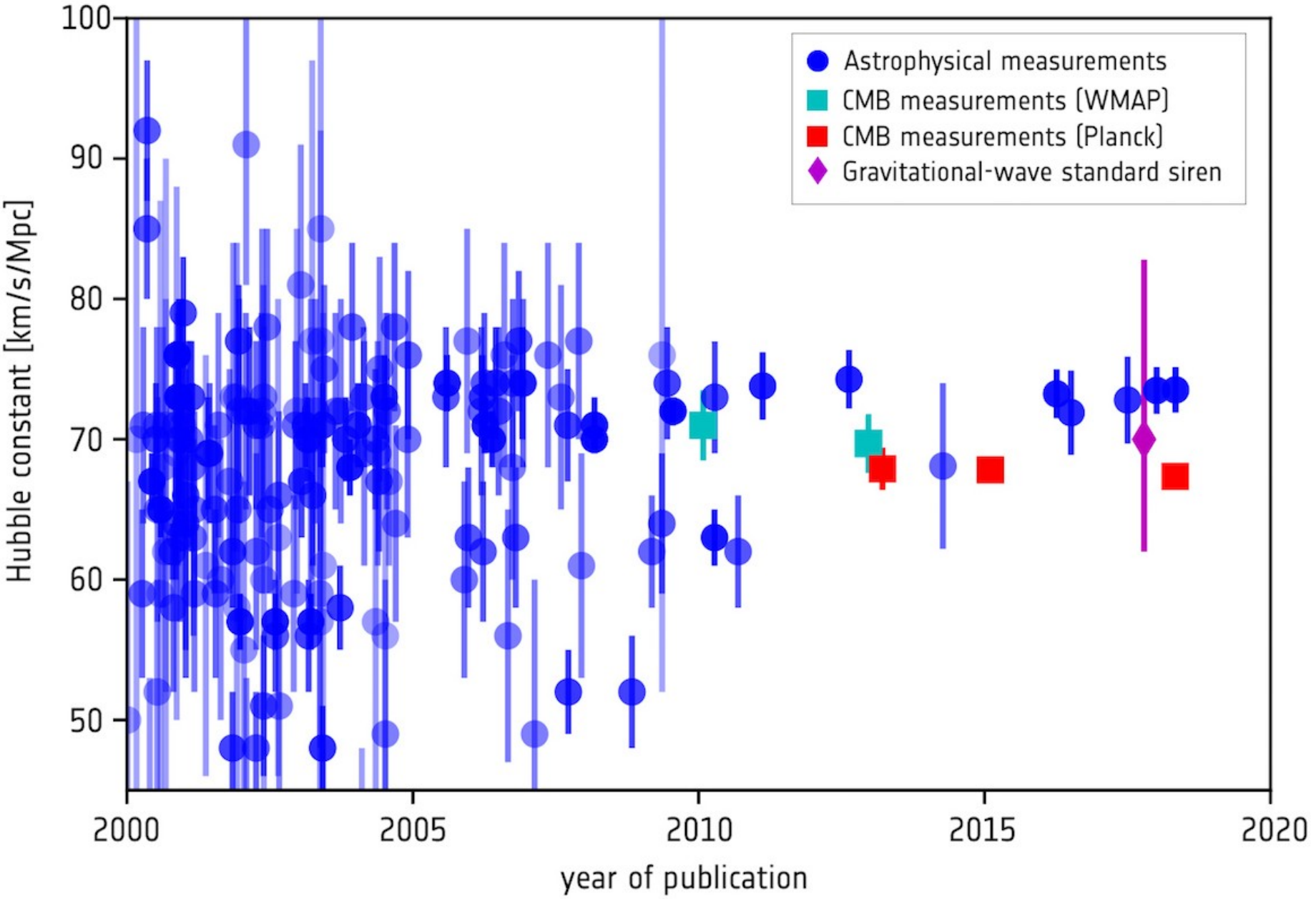


Hubble's Constant (Parameter?)

- The current best value is
- HST key program $H_0 = 74.3 \pm 2.1 \,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

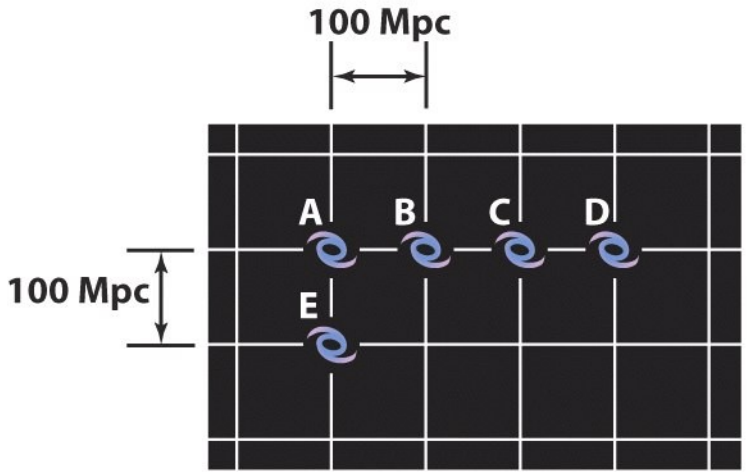
  But H_0=67.36+/-0.54 km s^{-1} Mpc^{-1} (Planck)

  (The subscript 0 indicates the value of *H* at the current age of the Universe)
- Published by Hubble and Hummason
- Currently some tension between Planck (CMB) data and HST (Cepheids) values of H_0

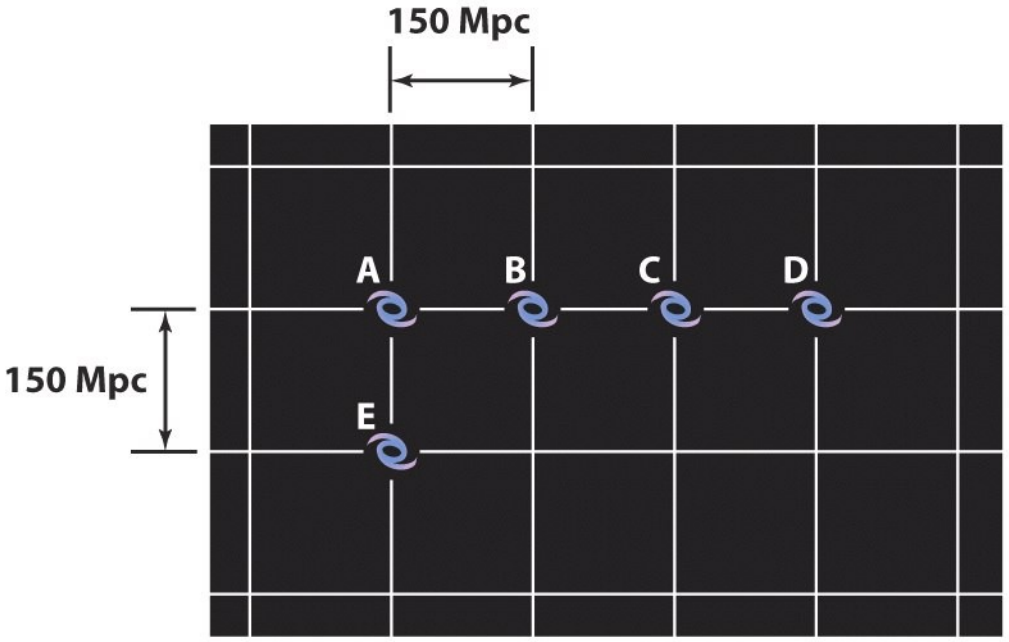

Astrophysical measurements
CMB measurements (WMAP)
CMB measurements (Planck)
Gravitational-wave standard siren
Hubble constant [km/s/Mpc]
100
90
80
70
60
50
2000
2005
2010
2015
2020
year of publication

Expansion of the Universe

- The simplest explanation for Hubble's law is that the Universe is uniformly expanding
- The galaxies are not rushing through space but space itself is expanding
- We are not at a special location



(a) Five galaxies spaced 100 Mpc apart



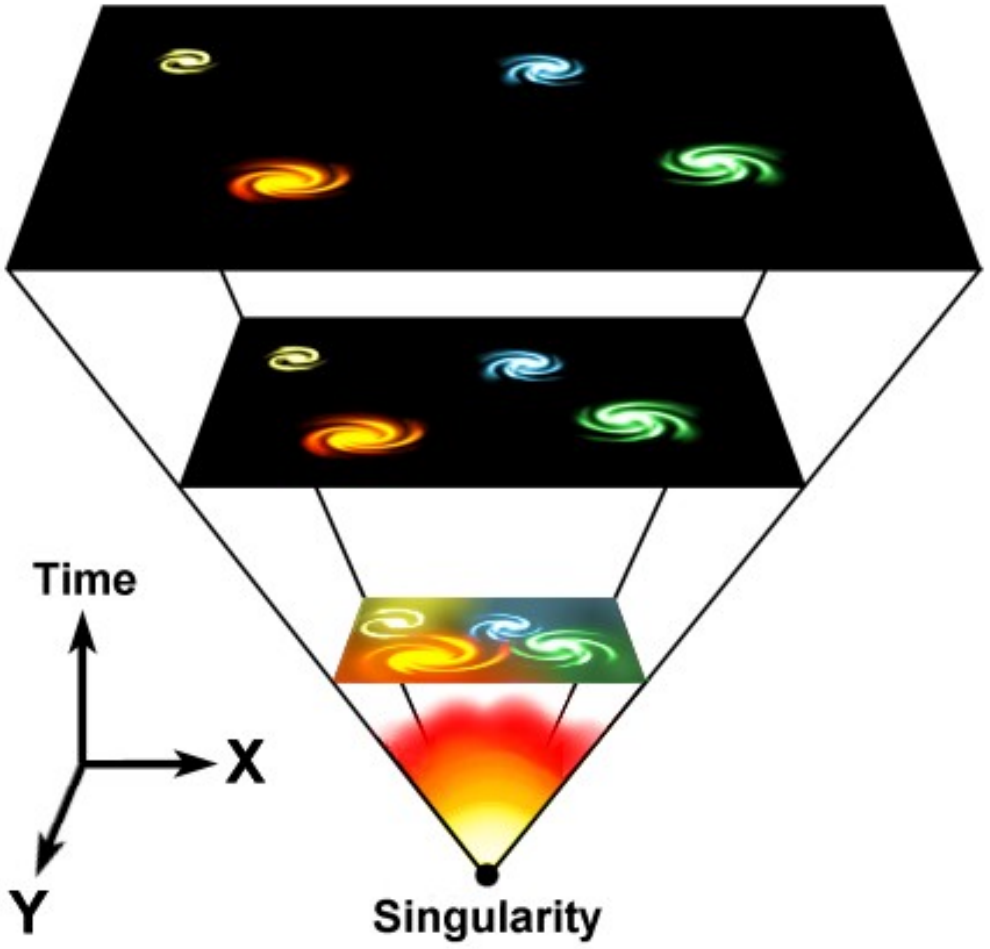
(b) The expansion of the universe spreads the galaxies apart

Running the expansion backwards…

The “Big Bang” (Fred Hoyle)

- As we go back in time all galaxies (all matter) will get closer and closer together
- Matter will get denser and hotter (very much!)
- Eventually all of space will occupy a very small volume – in fact a singularity (like a black hole)

Reverse the expansion



http://www.universetoday.com/122161/will-the-big-bang-go-backwards/

Theoretical background

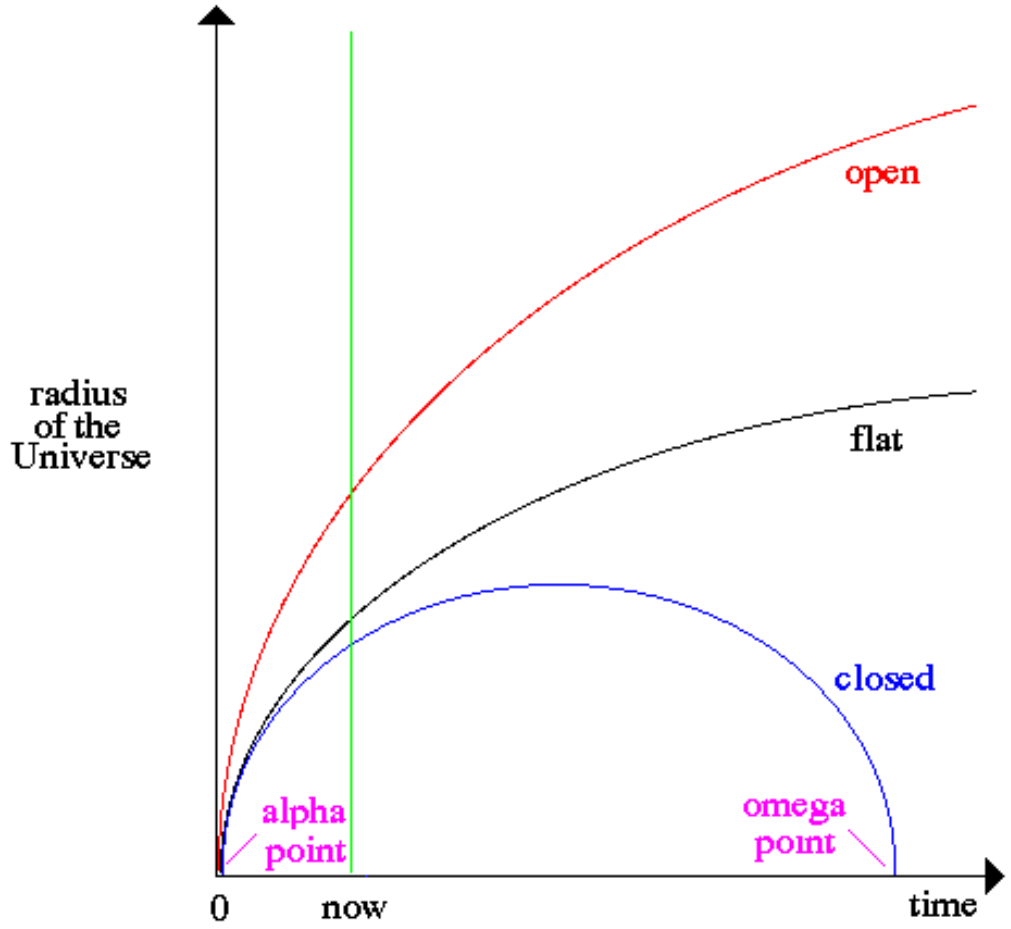
- Cosmological principle – we do not have special location in the universe
- Universe is isotropic, homogeneous and expanding on the large scale
- General relativity – relates energy/momentum tensor (matter moves like perfect fluid – Weyl's postulate) to geometrical properties of space time
- Theory developed **before** observations (LeMaître, de Sitter etc.)

Theoretical background

Whole lecture course in here!

- Basis of standard models are Einstein field equations
- $\ddot{a} = -\frac{4\pi G}{3} a\left(\rho + \frac{3p}{c^2}\right) + \frac{1}{3}\Lambda a$ (1)
  - De- or acc-celeration under competing influences of gravity and dark energy
- $\dot{a}^2 = \frac{8\pi G\rho}{3} a^2 - \frac{kc^2}{R^2} + \frac{1}{3}\Lambda a^2$ (Friedman's equation) (2)
  - How space curvature determined by total mass-energy density at any epoch

Density parameter for open, closed and flat universes



$\rho < \rho_{crit}$

$\rho = \rho_{crit}$

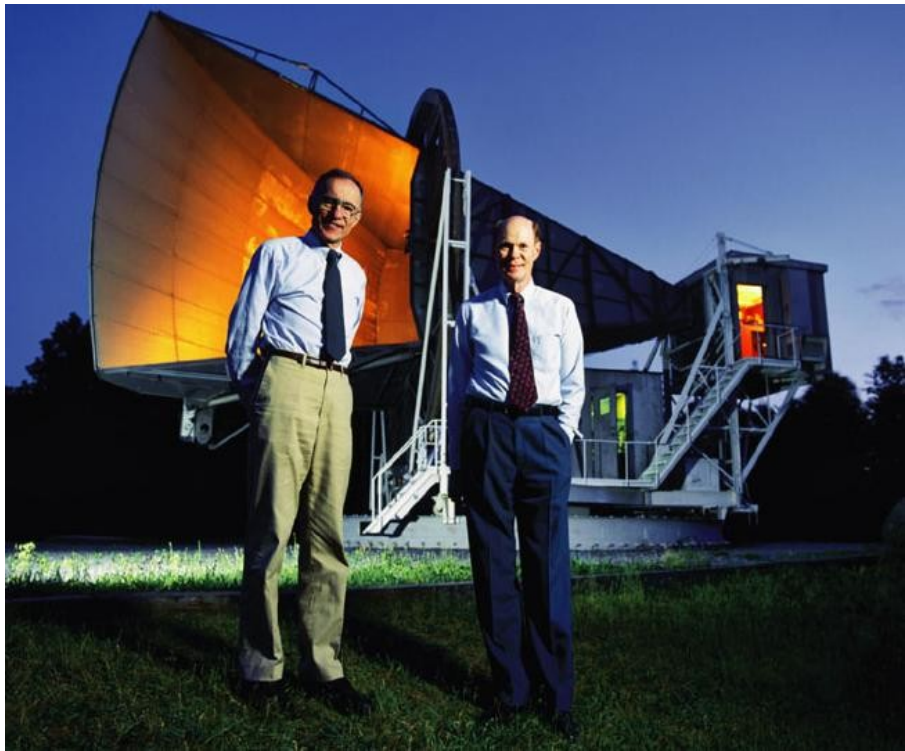
$\rho > \rho_{crit}$

Cosmological parameters

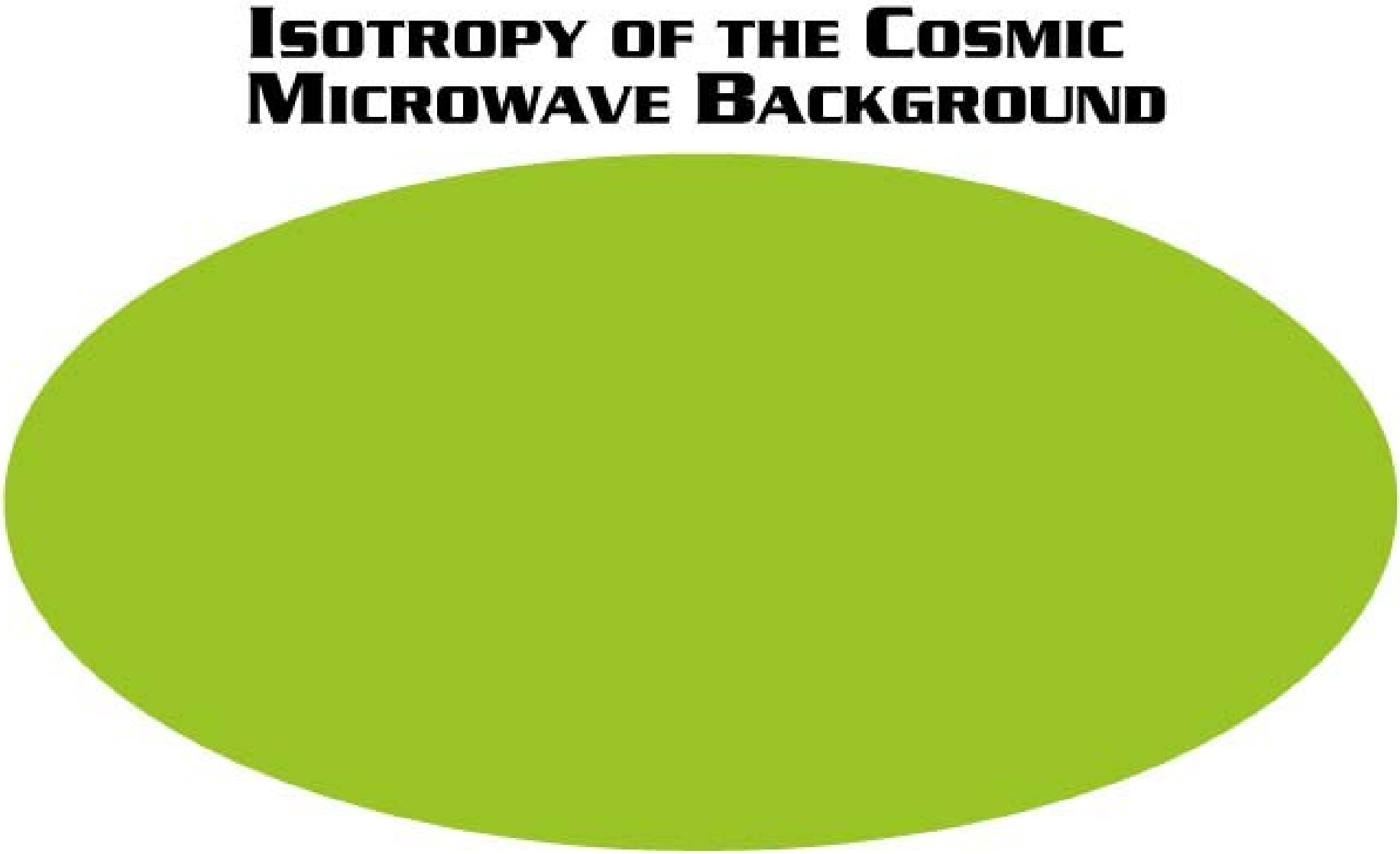
- Hubble constant (parameter, $H(t)$) H_0 present rate of expansion of Universe
- Deceleration parameter q_0 – present dimensionless de- (acc)celeration of Universe
- Density parameter Ω_0 - ratio of present mass-energy density ρ_0 to the critical density ρ_{crit}
  - Ω_B density in baryonic matter
  - Ω_{DM} density in dark matter
  - Ω_Λ dark energy (vacuum field) energy density
- Age of Universe T_0
- Curvature of space κ

What would such a universe look like?

- Predictions in 1940s (Gamow, Alpher and Herman, primordial nucleosynthesis) predicted hot early stage, cool radiation now.
- Accidental discovery 1964 by Arno Penzias and Robert Wilson
- Dicke and Peebles recognised
- 1978 Nobel Prize
- Very smooth, apparently featureless radiation



CMB at 2.7K, uniform to 1:1000



http://map.gsfc.nasa.gov/universe/bb_tests_cmb.html

Cosmic microwave background radiation

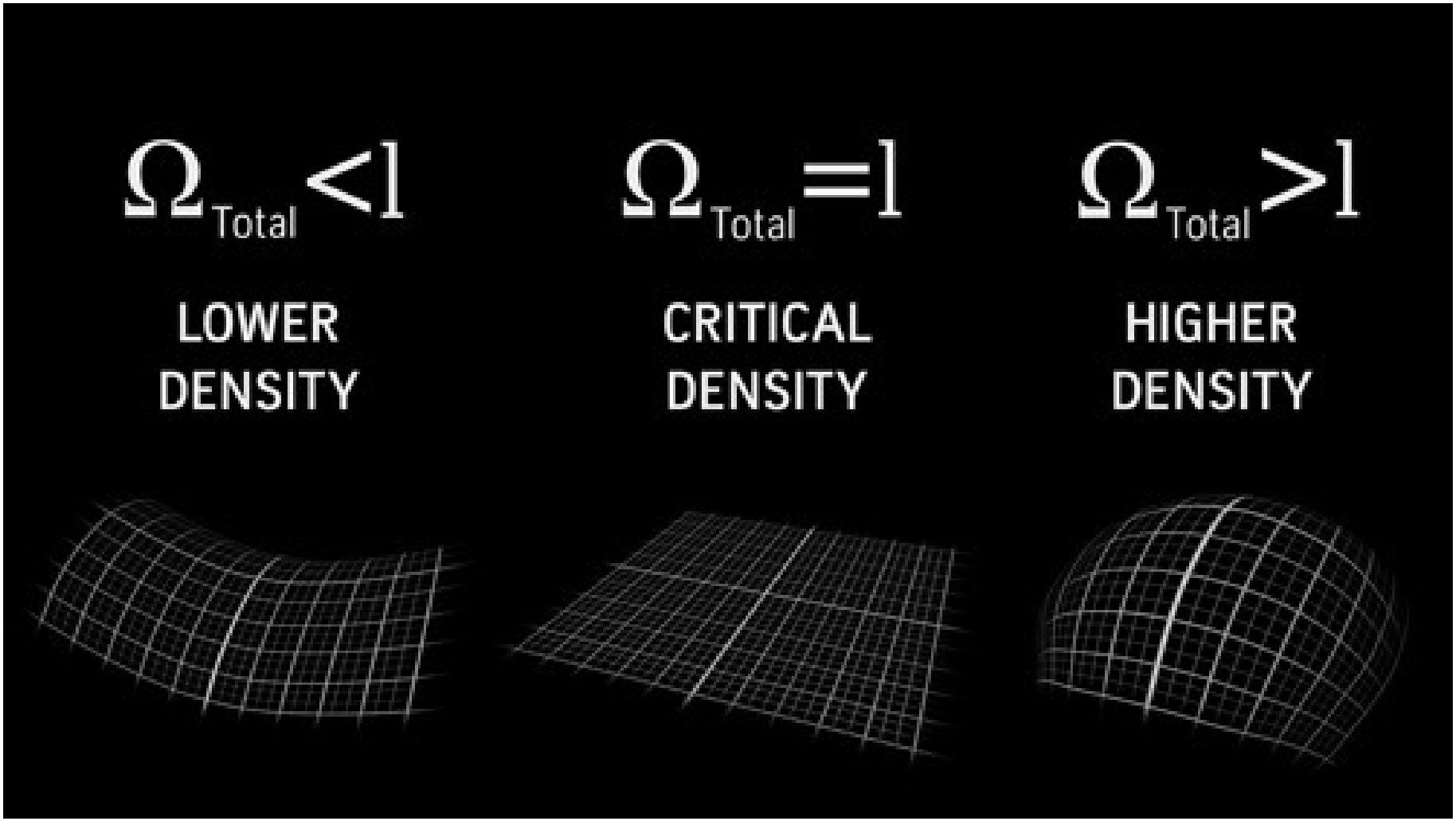
- Thermal radiation left over from the time of recombination in Big Bang cosmology.
- Oldest visible electromagnetic radiation
- But should contain structure – seeds which develop into structure we see today? How do density perturbations evolve?
- How could structure be generated?

Problems with the simple picture

- Horizon problem – homogeneity and isotropy
  - Different regions all same temperature, but have not had time to communicate (no causal contact)
- Flatness problem
  - Density of Energy and matter in the universe, curvature of spacetime exactly that

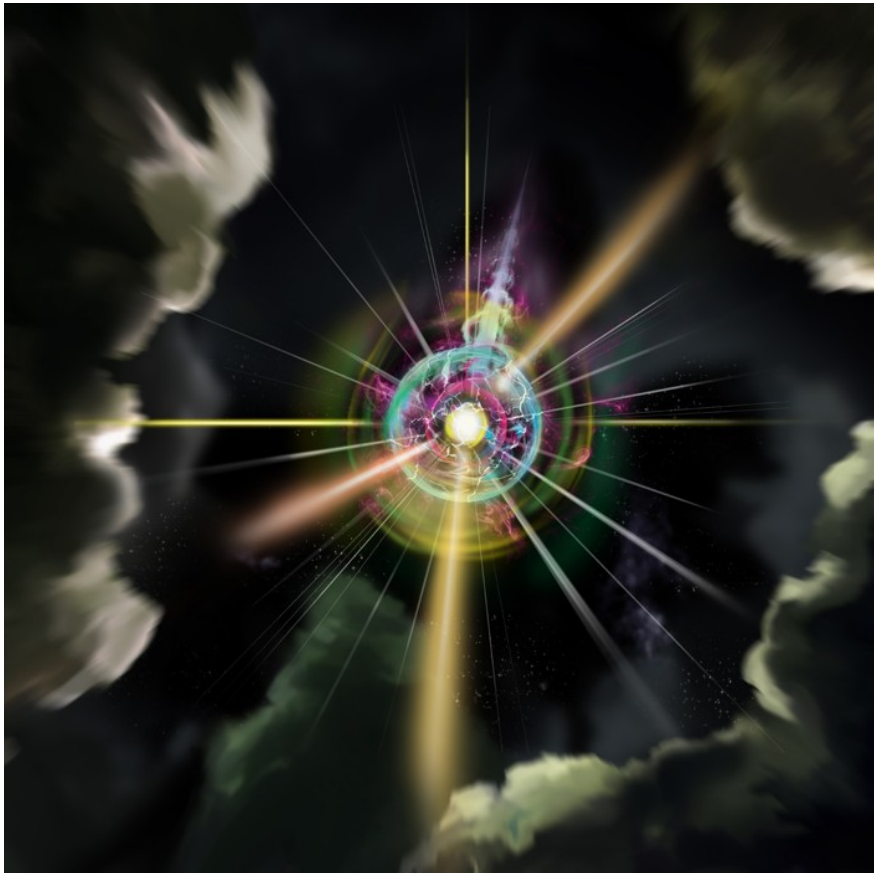
    required for a flat universe
  - Very finely tuned
- Magnetic monopole problem

Flatness problem



Magnetic monopole problem

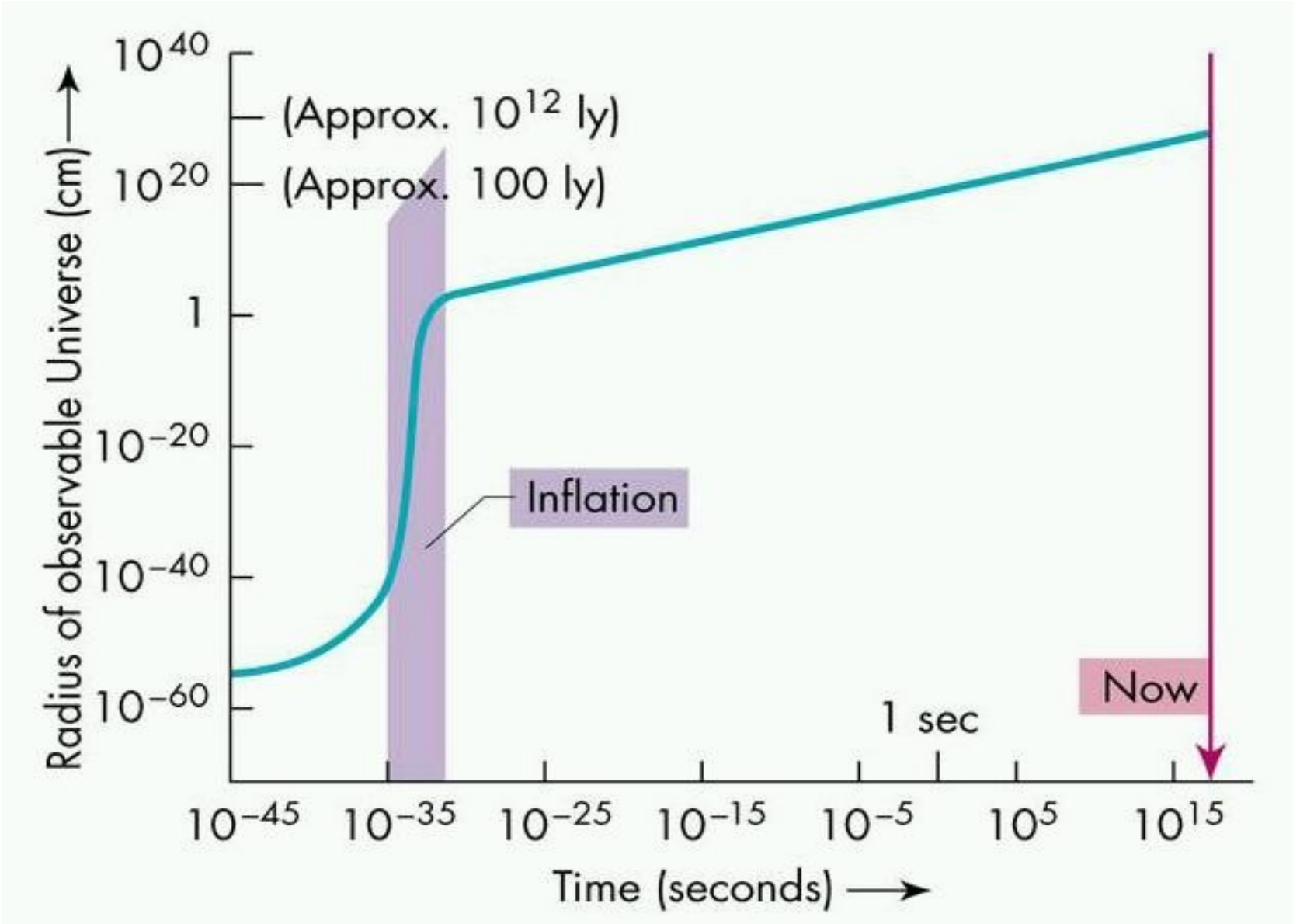
- **Magnetic monopole -** isolated **magnet** with only one **magnetic** pole (a north pole without a south pole or vice versa).
- Net magnetic charge – never observed or created
- GUT and superstring theories predict they should exist



Solution - inflation

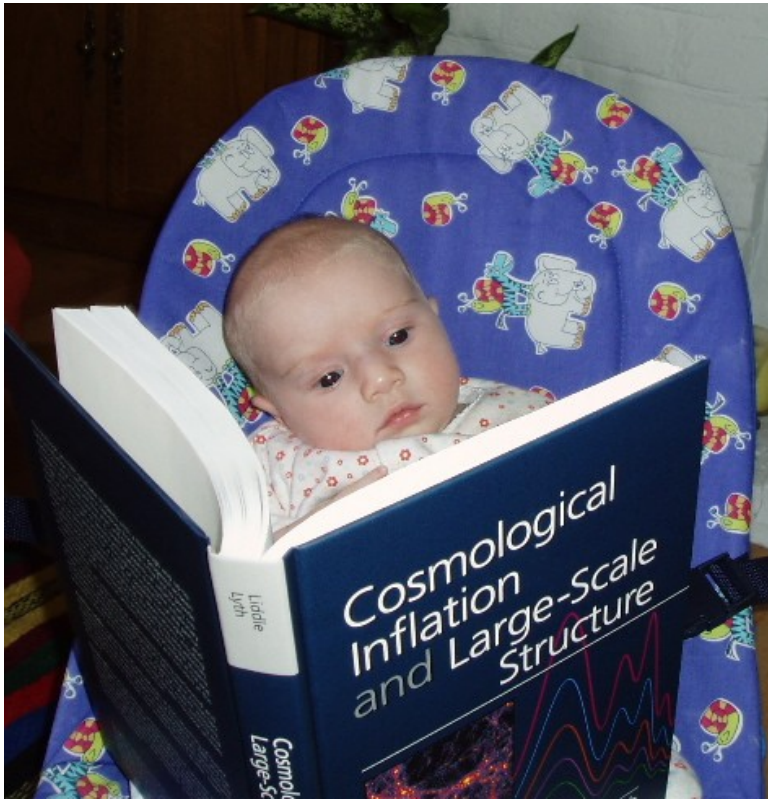
- Alan Guth proposed **inflation** in January 1980 to explain the nonexistence of magnetic monopoles.
- Starobinsky - quantum corrections to gravity replace initial singularity with exponentially expanding de Sitter phase.
- Problem – not enough radiation and matter once inflation stopped, cured by choosing different initial potential

Inflation


Radius of observable Universe (cm)
10^40
(Approx. 10^12 ly)
10^20
(Approx. 100 ly)
1
10^-20
10^-40
10^-60
Inflation
Now
1 sec
10^-45
10^-35
10^-25
10^-15
10^-5
10^5
10^15
Time (seconds)

What inflation does for us

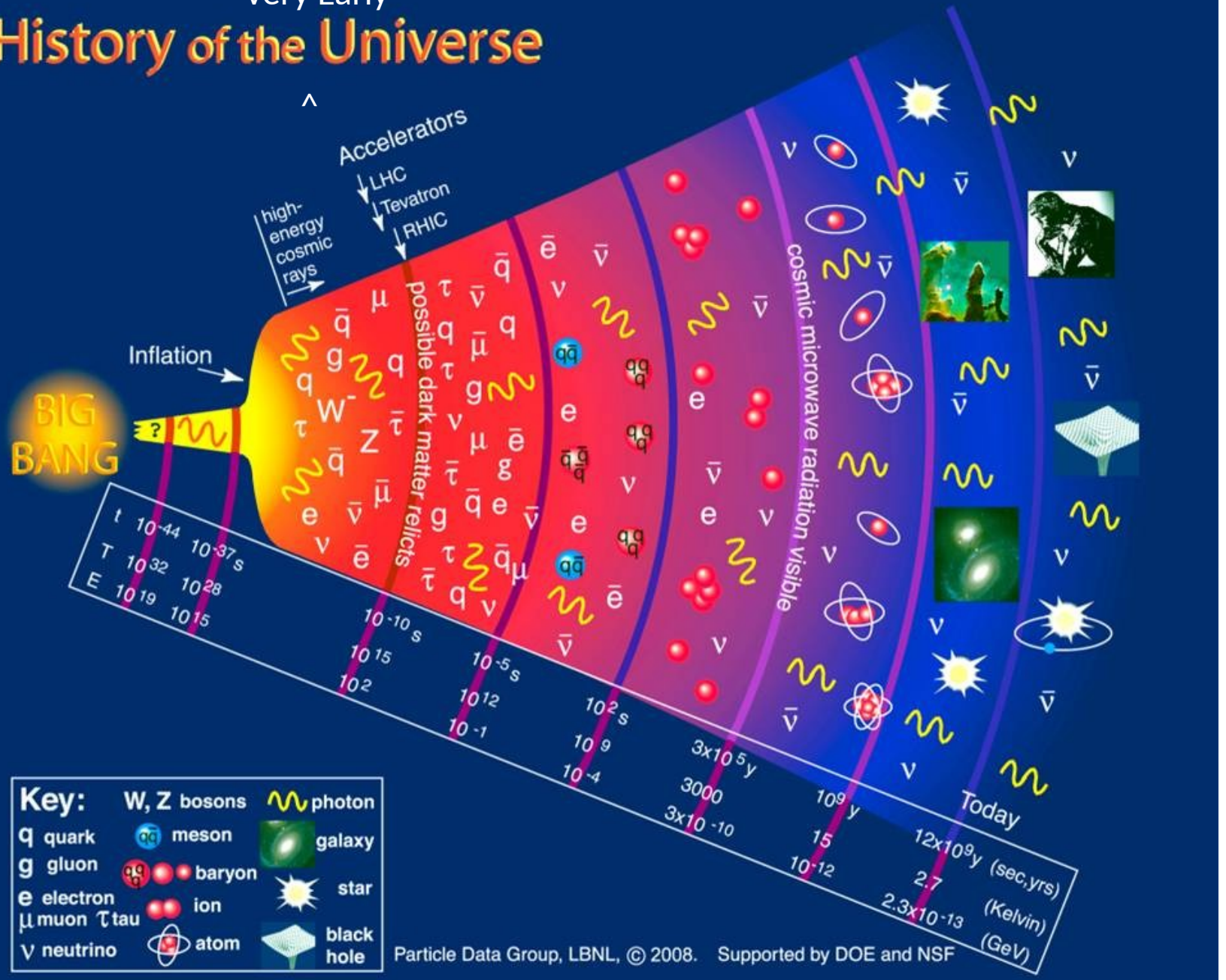
- Exponential acceleration from 10^{-36} to 10^{-32} sec
- Solves “horizon problem”
- Solves “flatness problem”
- Expands structures $<10^{-30}$m to human scales



Very Early

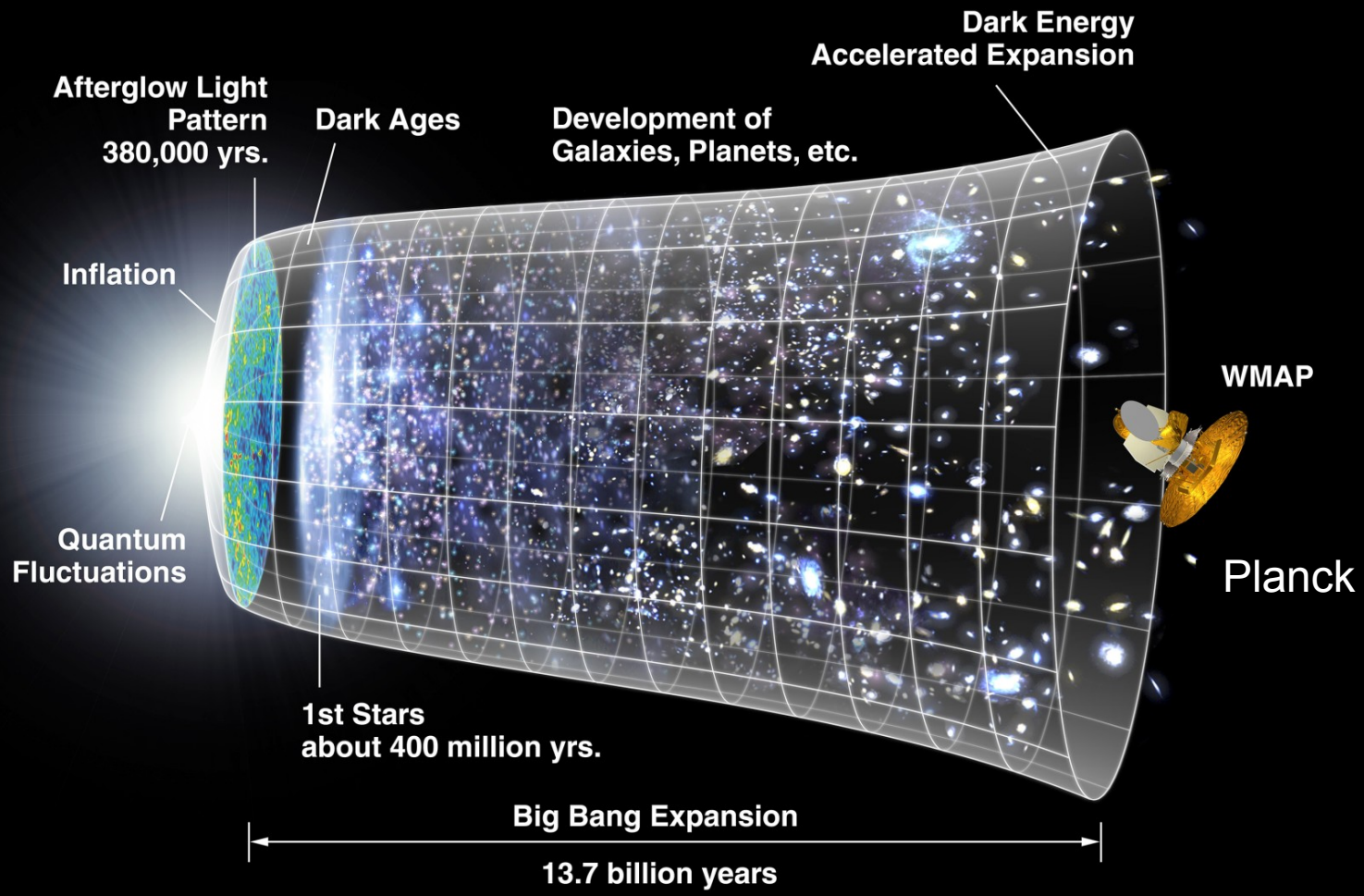
History of the Universe

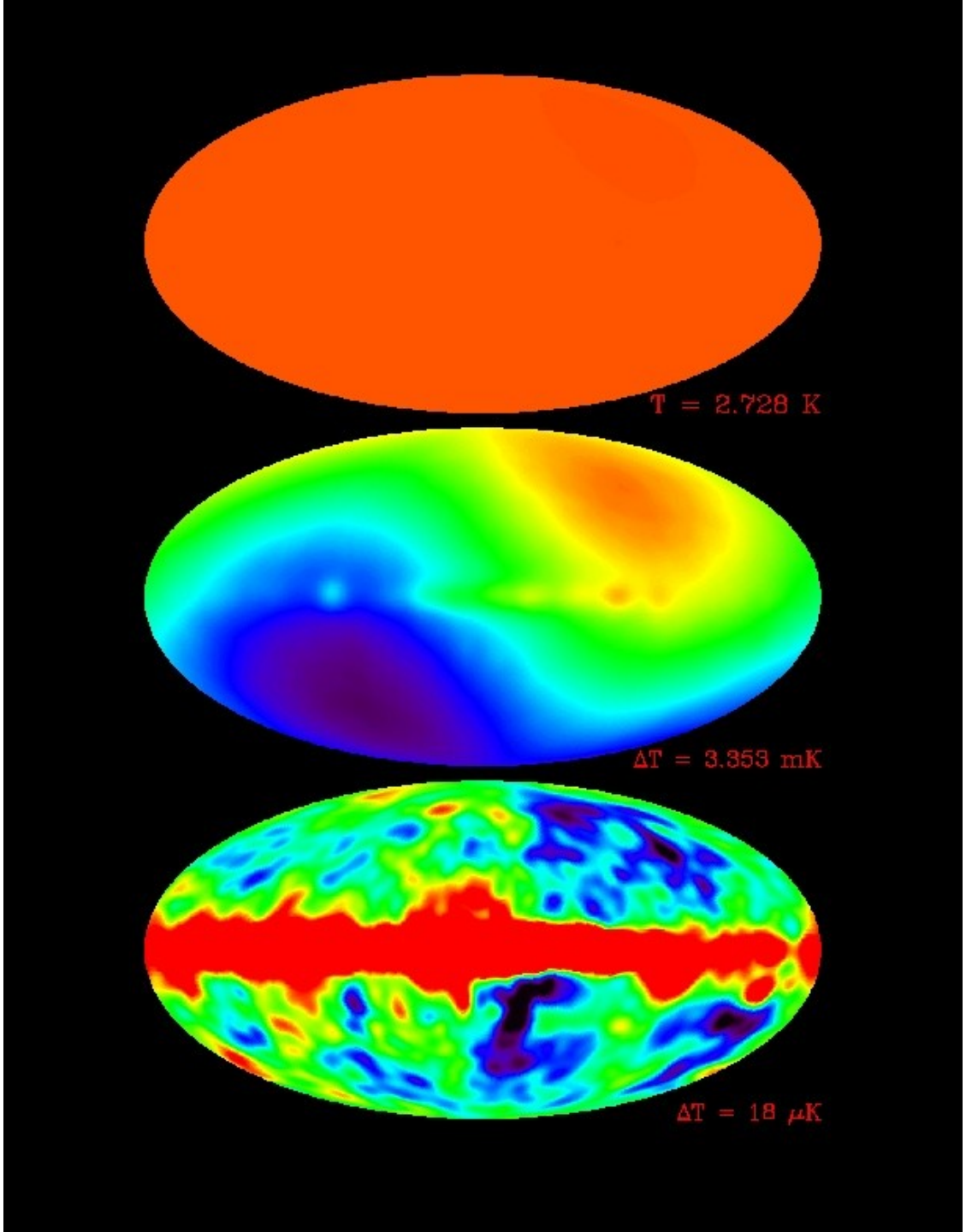
^



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Standard model of History of the Universe





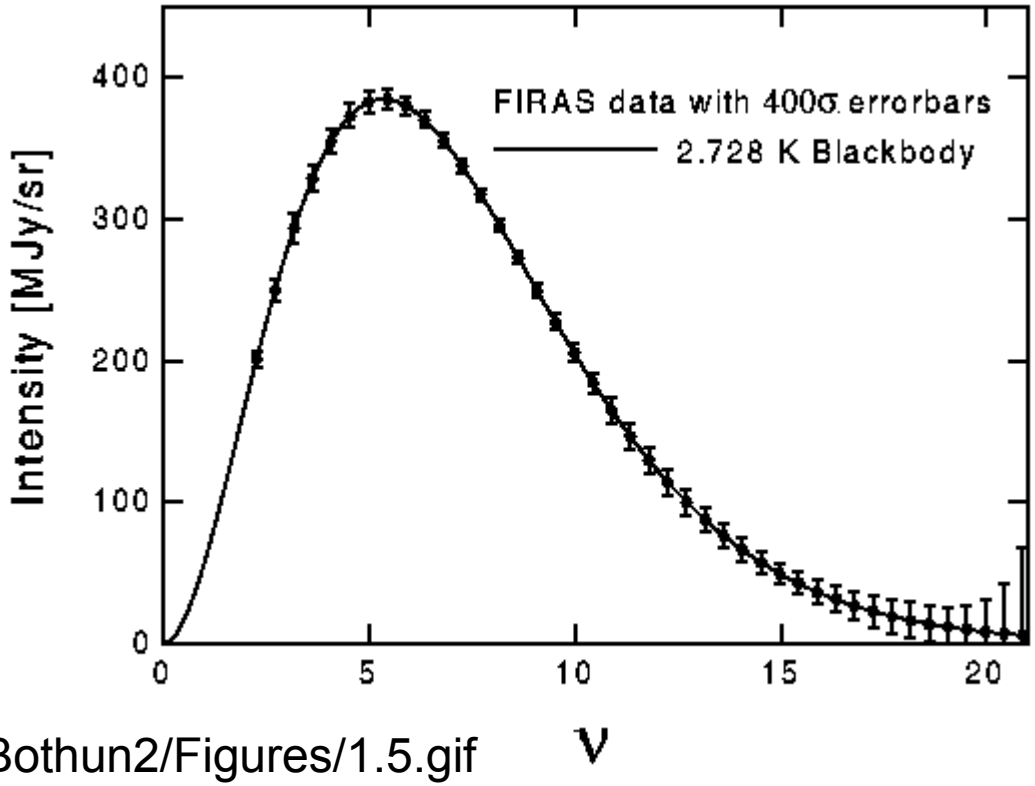
How faint the ripples are

CMB missions

- >70 Ground based, balloon and spacecraft experiments
  https://en.wikipedia.org/wiki/List_of_cosmic_microwave_background_experiments
- Satellites
  - Planck, WMAP, COBE, future polarisation missions
- Balloons
  - Boomerang ++
- South pole ground based
  - BICEP, SPT ++

Results (1)

- Thermal black body spectrum at a temperature of 2.72548±0.00057 K (COBE)
  (peak wavelength is 1.063 mm, $\nu = 2\pi/\lambda$)

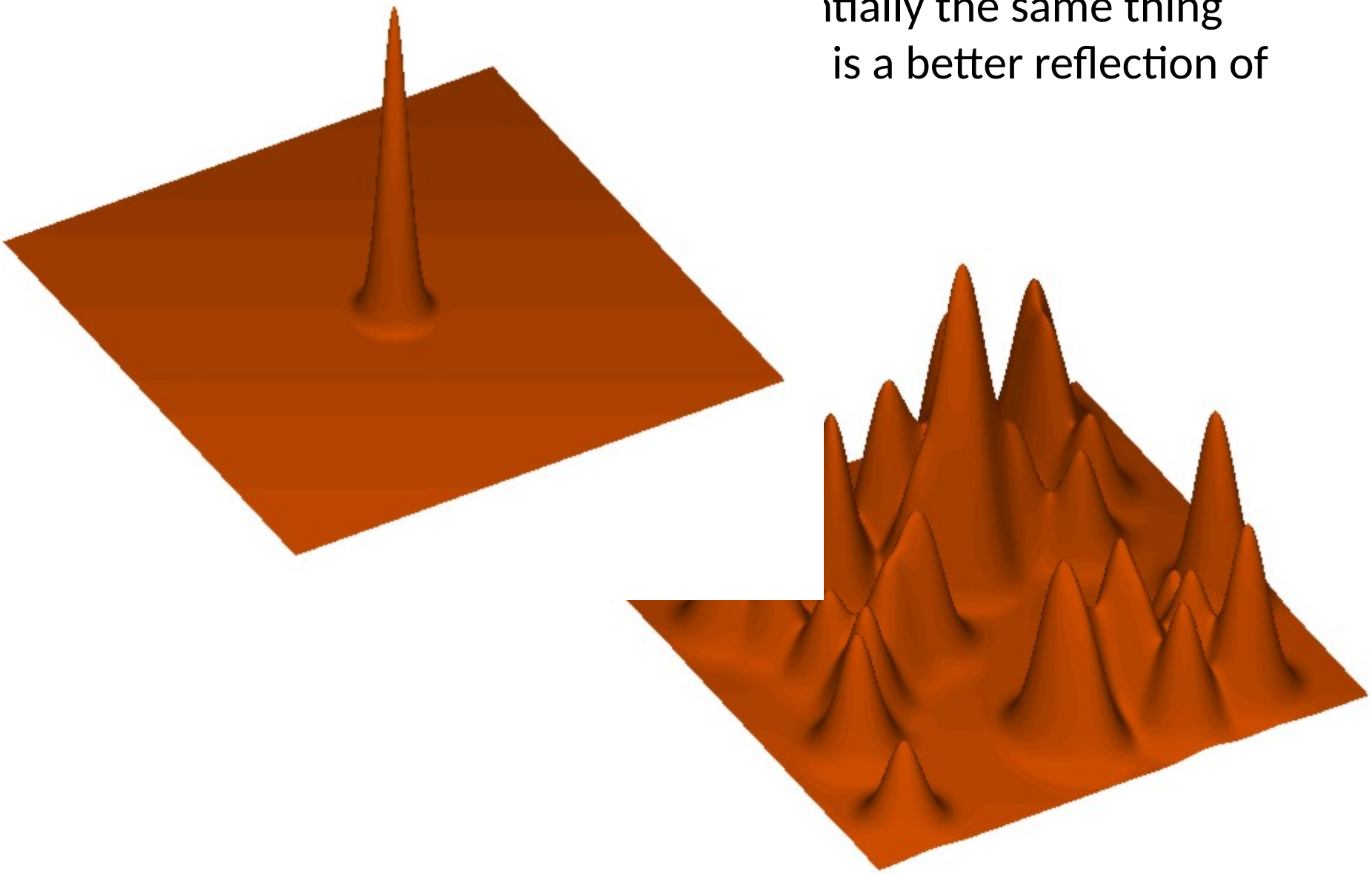


https://ned.ipac.caltech.edu/level5/Bothun2/Figures/1.5.gif

What about the structure?

- We see lots of structure in the Universe now
- Where did that come from?
- Universe initially very tiny, size where quantum effects dominated – created over and under densities
- Structure seen is overdensities expanded by inflation

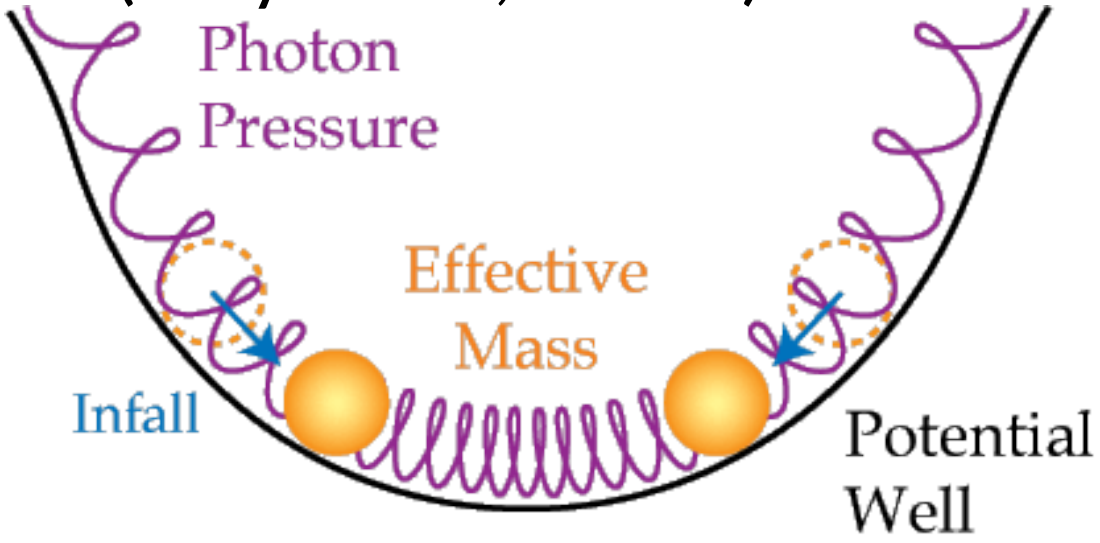
2D animations of density perturbations evolving. On the left is a
nd then freezing in place
ıtially the same thing
is a better reflection of

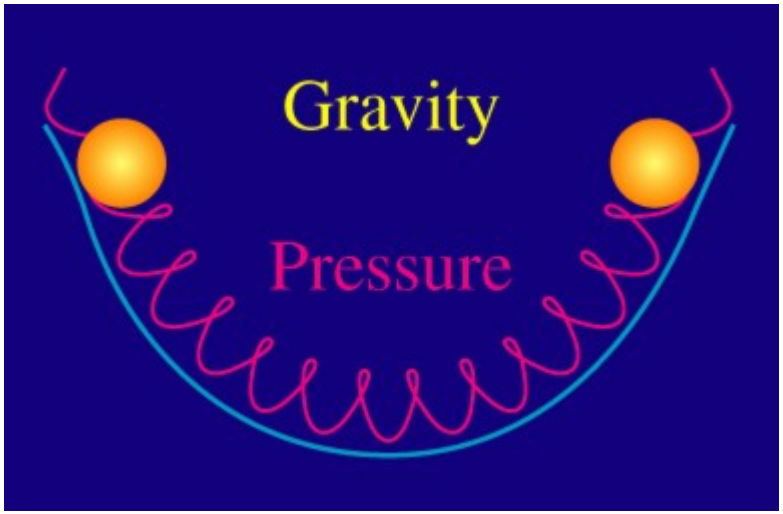


http://galaxies-cosmology-2015.wikidot.com/baryon-acoustic-oscillations

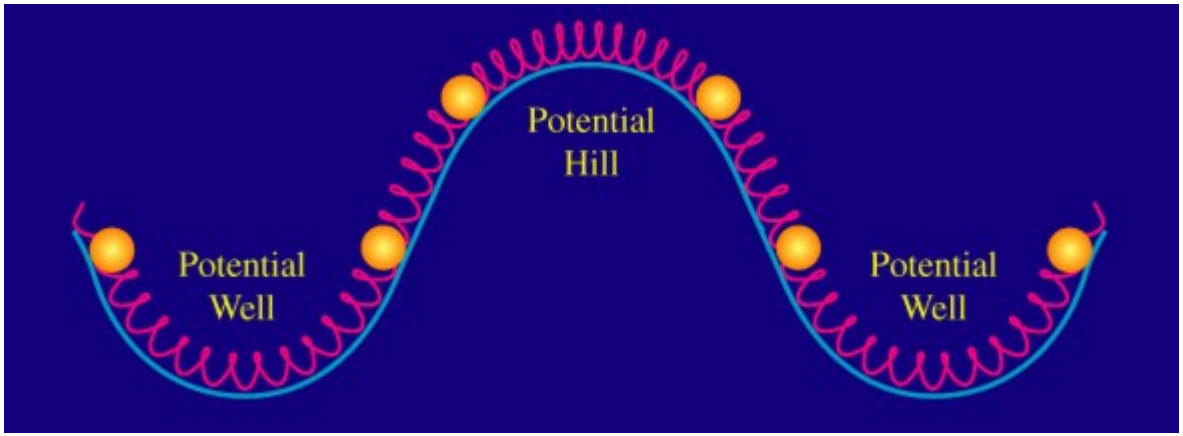
Cosmic Microwave Background Anisotopies - generation

- Perturbations in baryon density travel as acoustic oscillations in plasma before recombination
- Caused by gravity in over-densities and radiation pressure fighting each other
- Forced damped SHM (Wayne Hu, Liddle)



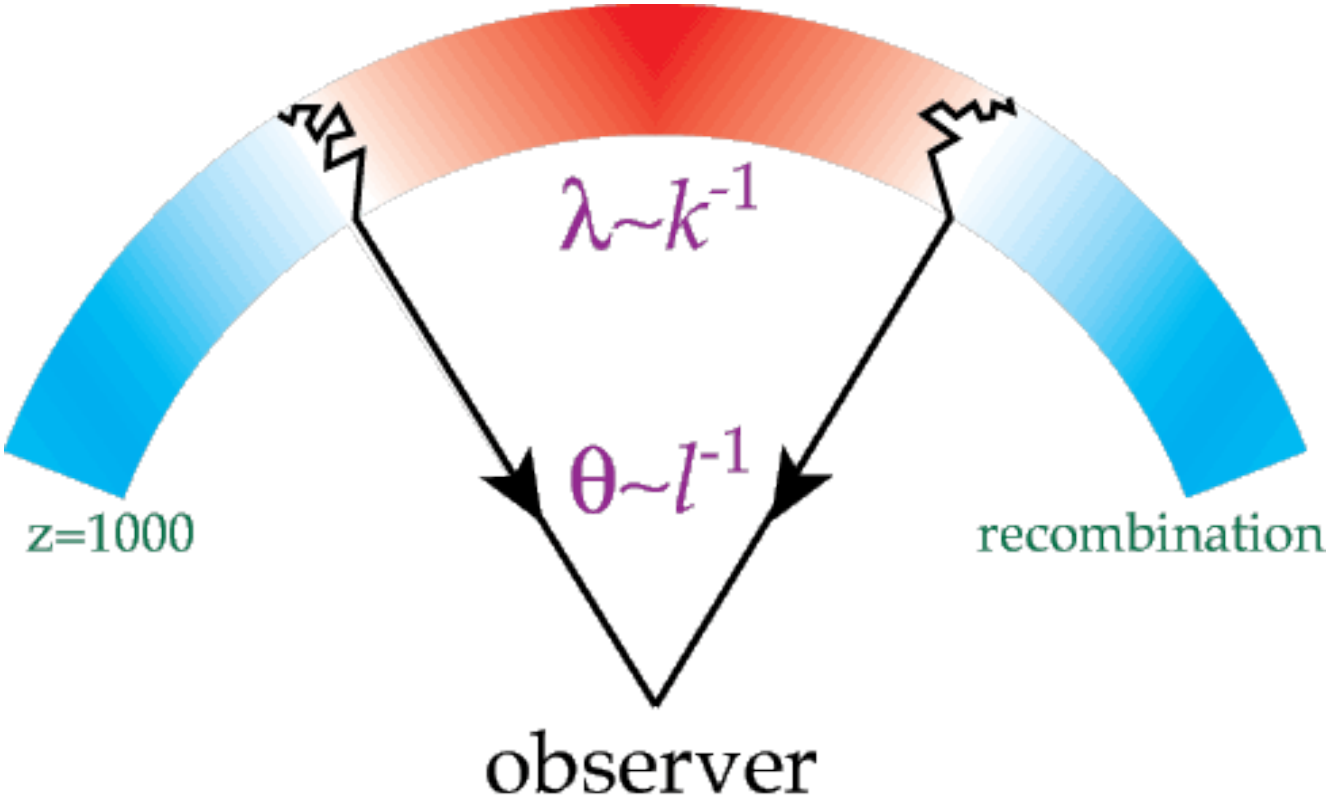


- Potential hills appear in under-density regions. Compression into the wells corresponds to rarefaction in the hills.

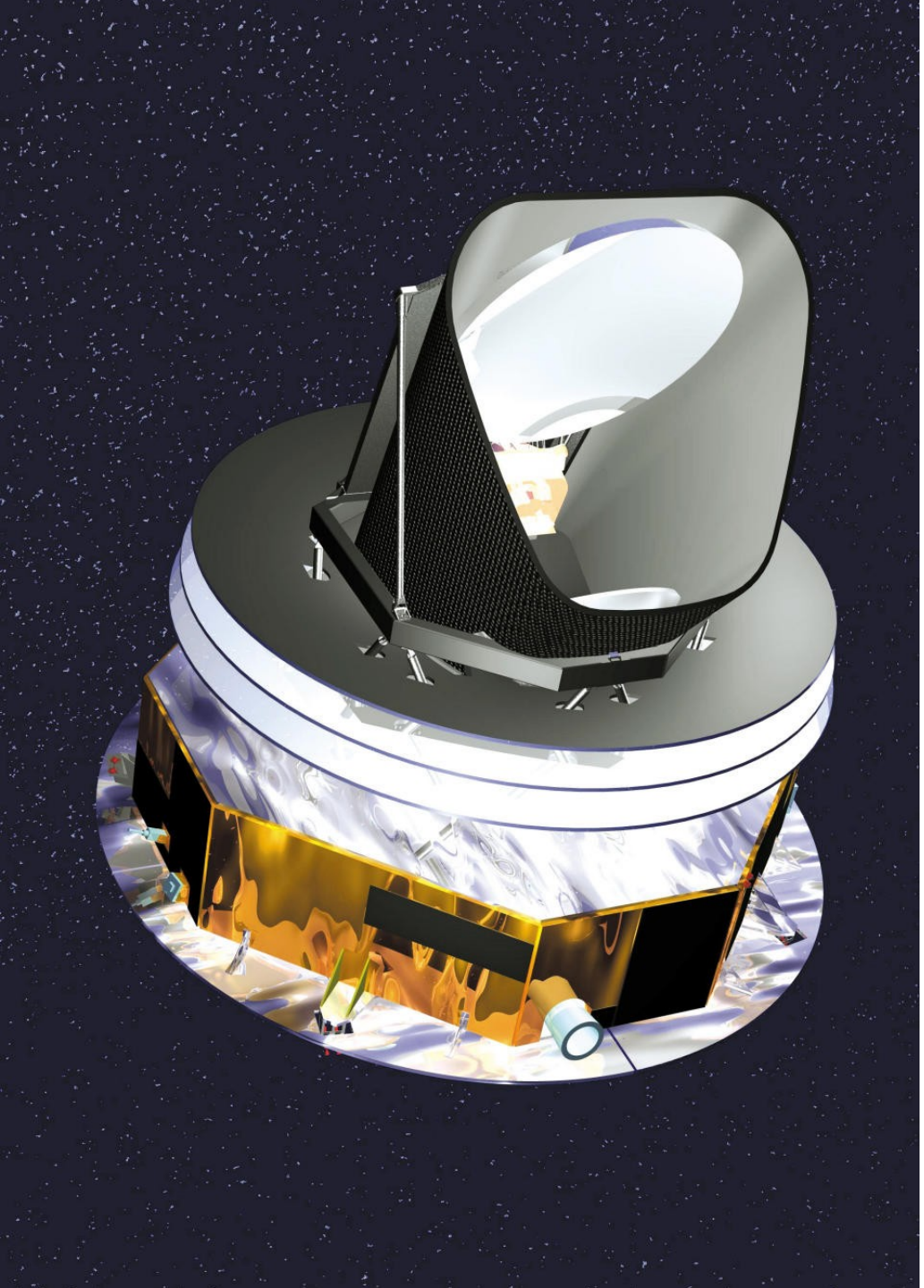


http://galaxies-cosmology-2015.wikidot.com/baryon-acoustic-oscillations,courtesy Wayne Hu

Last scattering surface



Wavelengths of acoustic oscillations ≤ horizon scale
“get through” Recombination



Planck Satellite

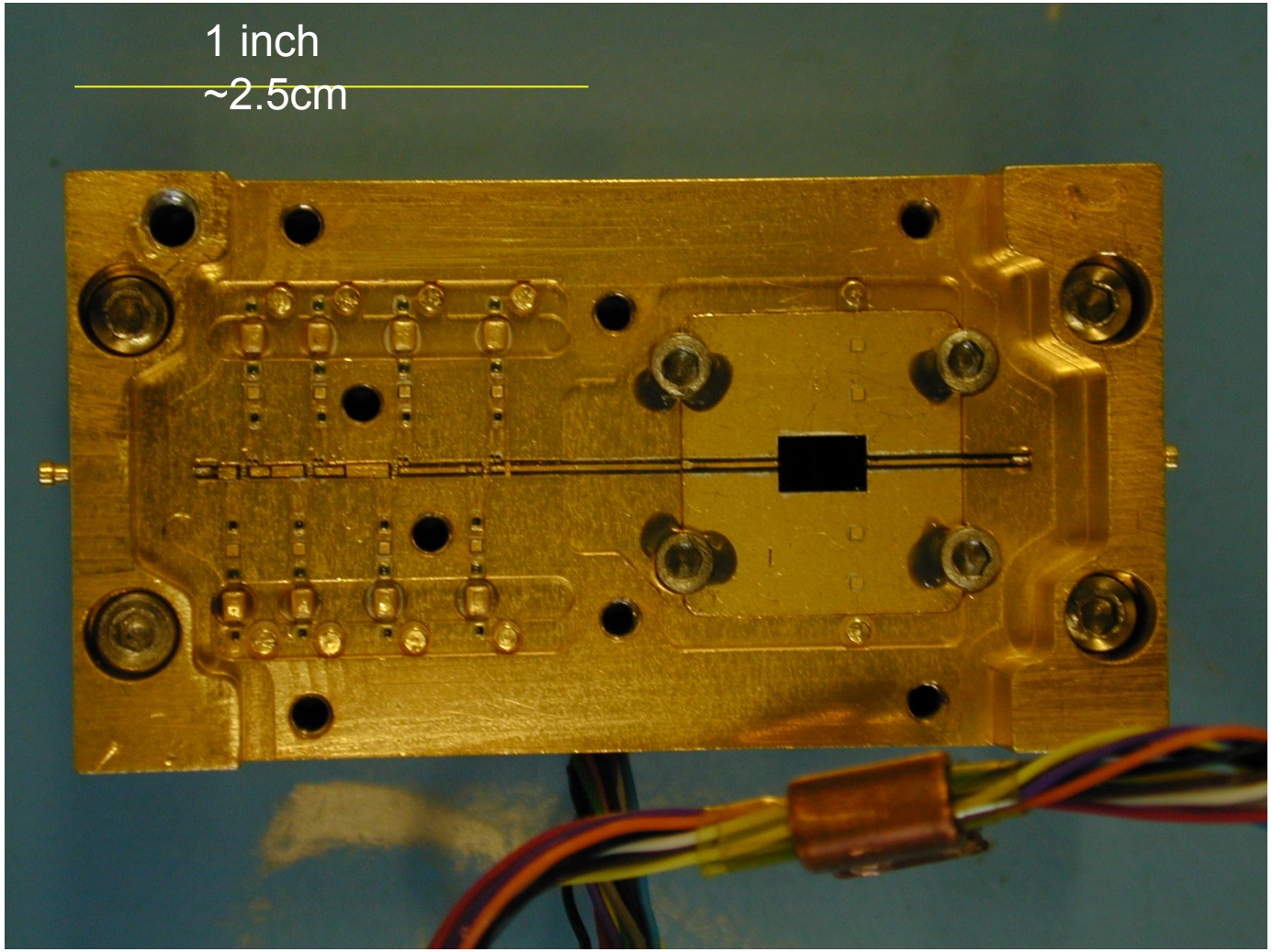
ESA Mission

Instruments built by Italy, France, UK, Spain, Finland, USA, Canada

Jodrell Bank (University of Manchester) built the lowest frequency channels

What we built

30 GHz cryogenic low noise amplifier



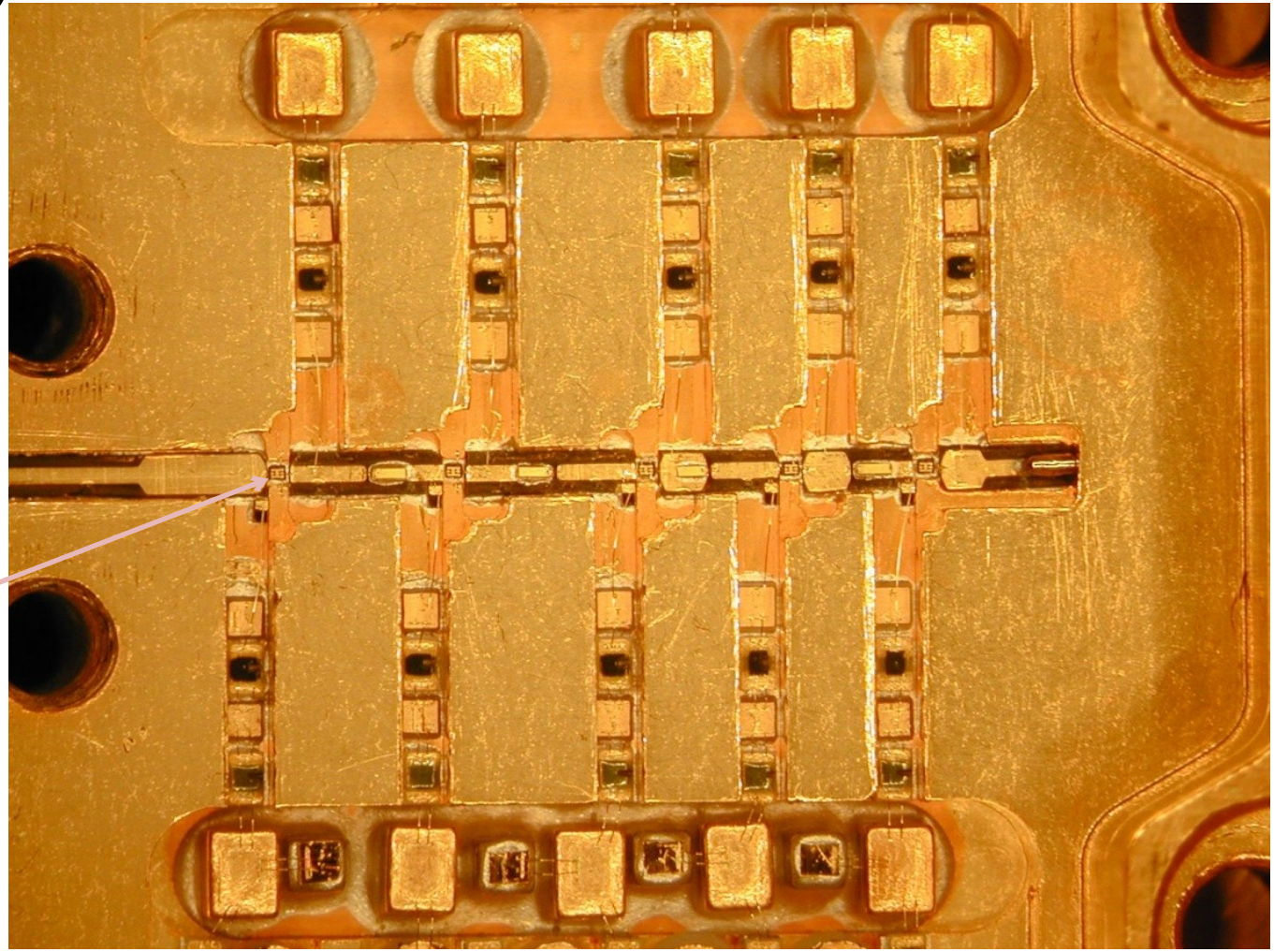
JBO speciality

Had to operate at 20K (HFI at 4K)

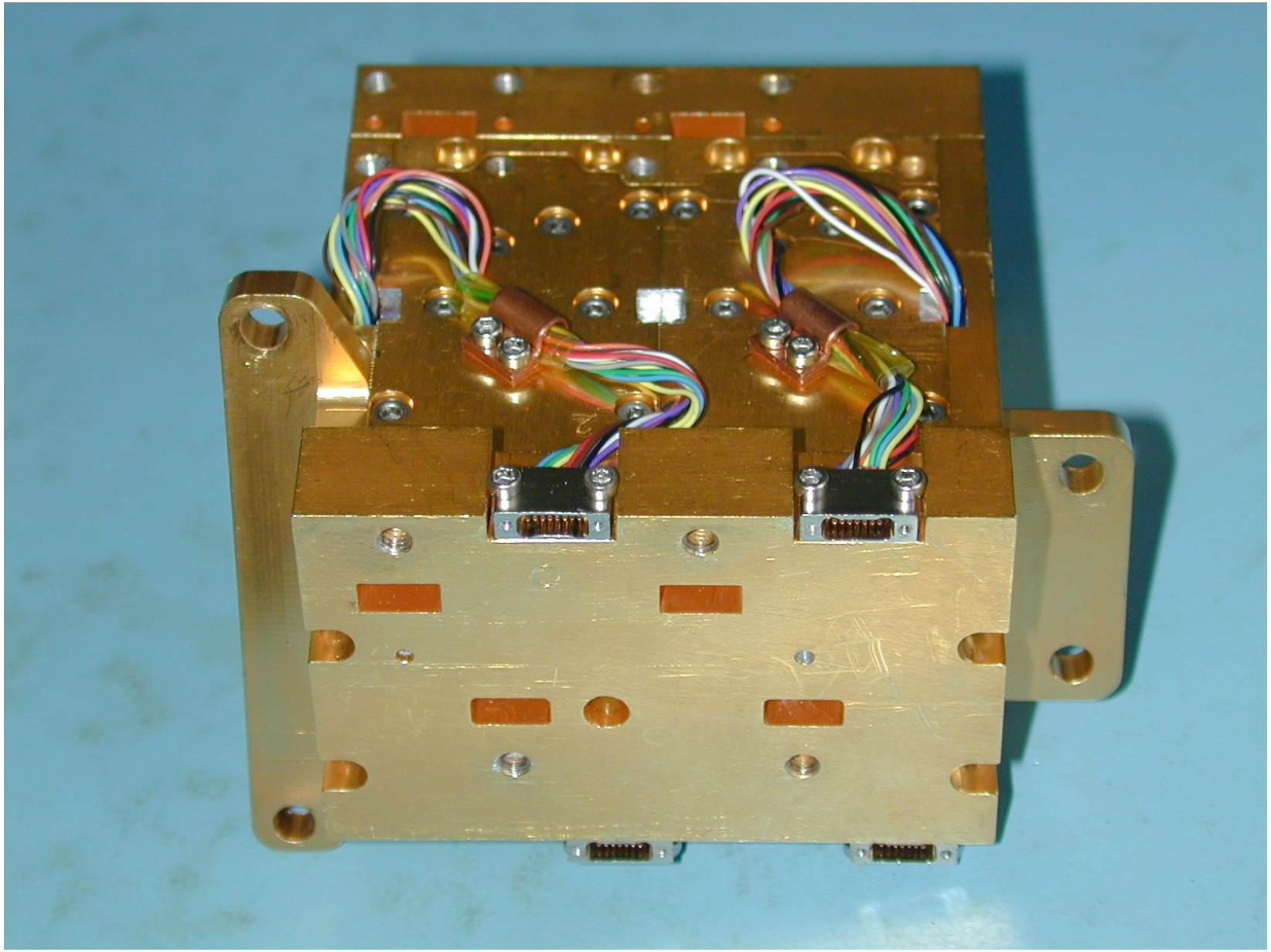
Had to be state-of-the-art low noise

A peak of JBO engineering achievement

44 GHz 5-stage amplifier,
showing HEMTs and bias chains (note bonds)

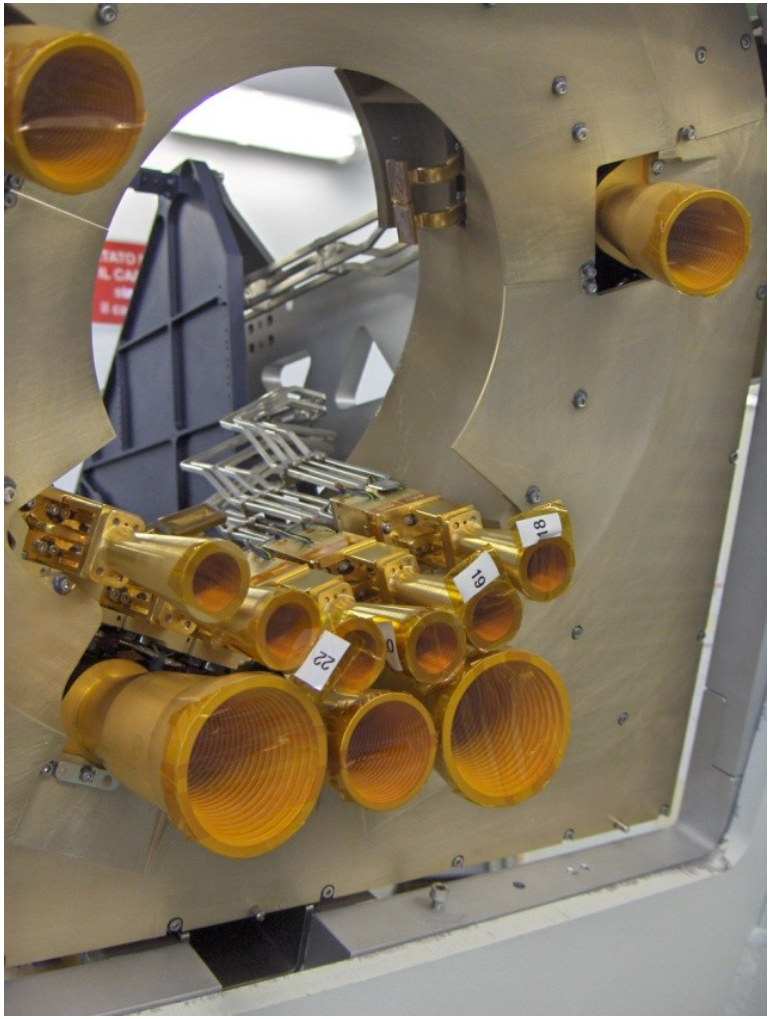


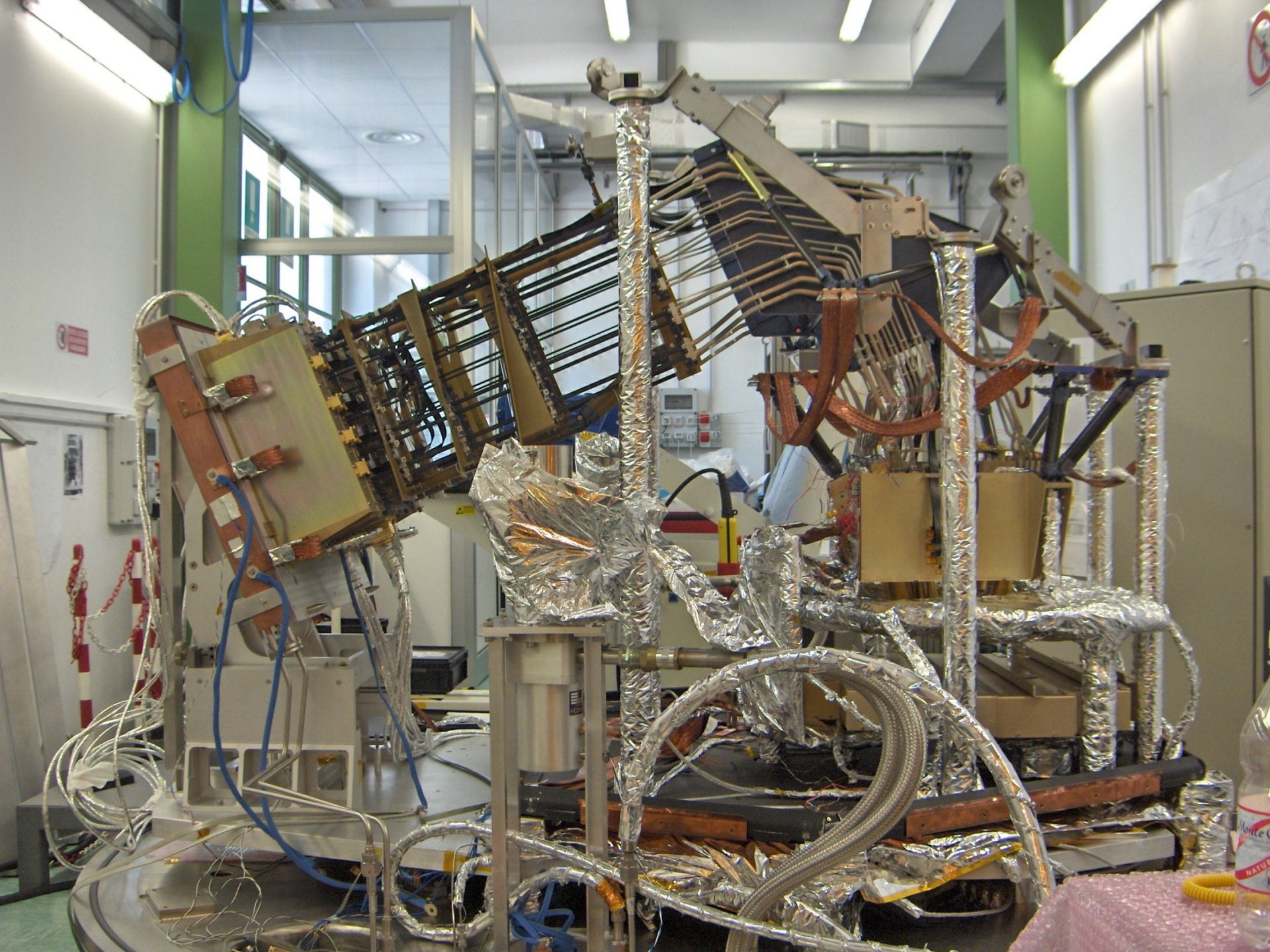
Front end modules (FEMs) – 4 LNAs in each




1 2 3 4
5 6 7 8

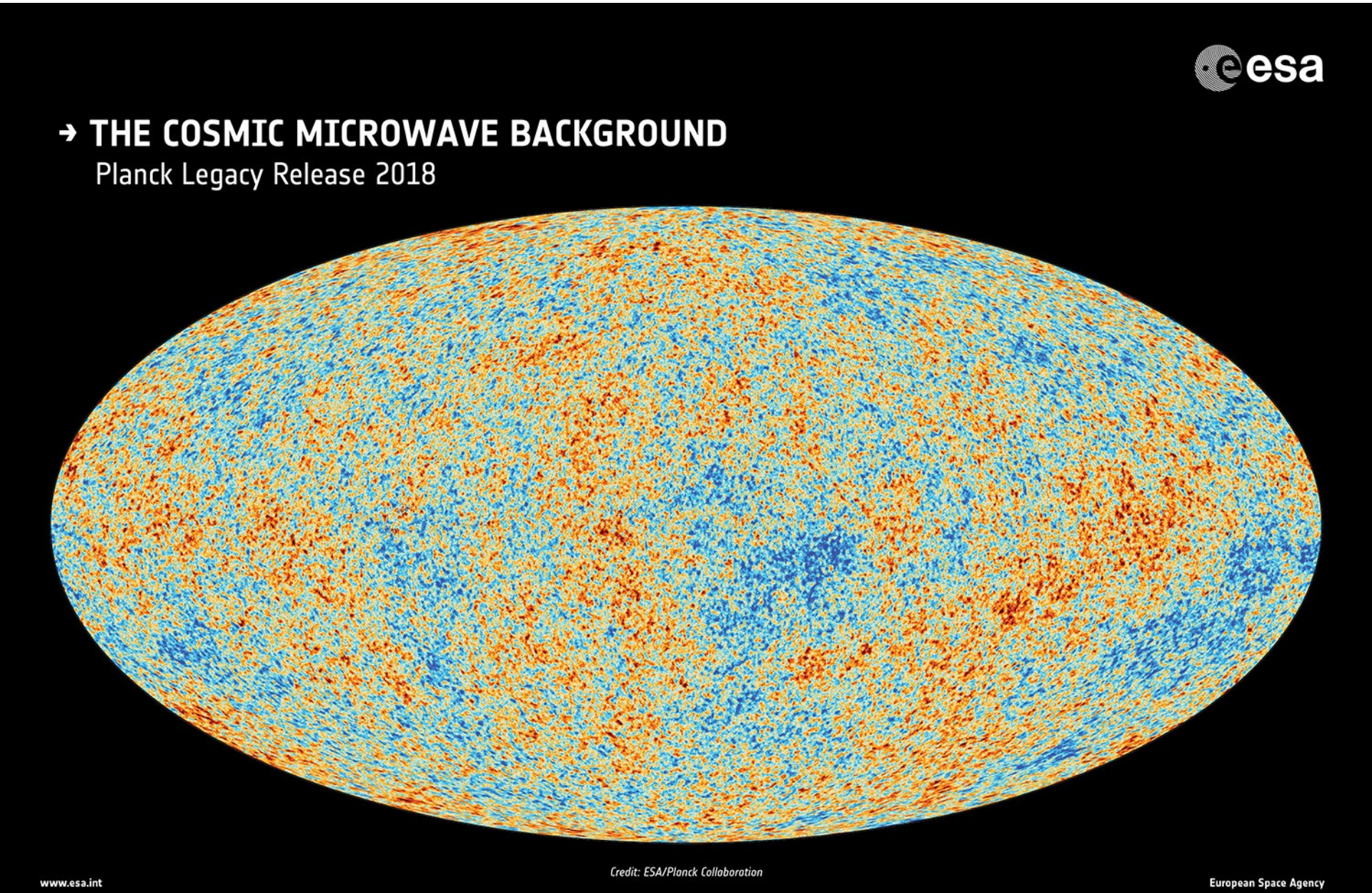
Planck LFI focal plane





Launch of Planck and Herschel
Ariane V rocket,
May 14th 2009 from Kourou,
French Guyana

Planck 2018 CMB map

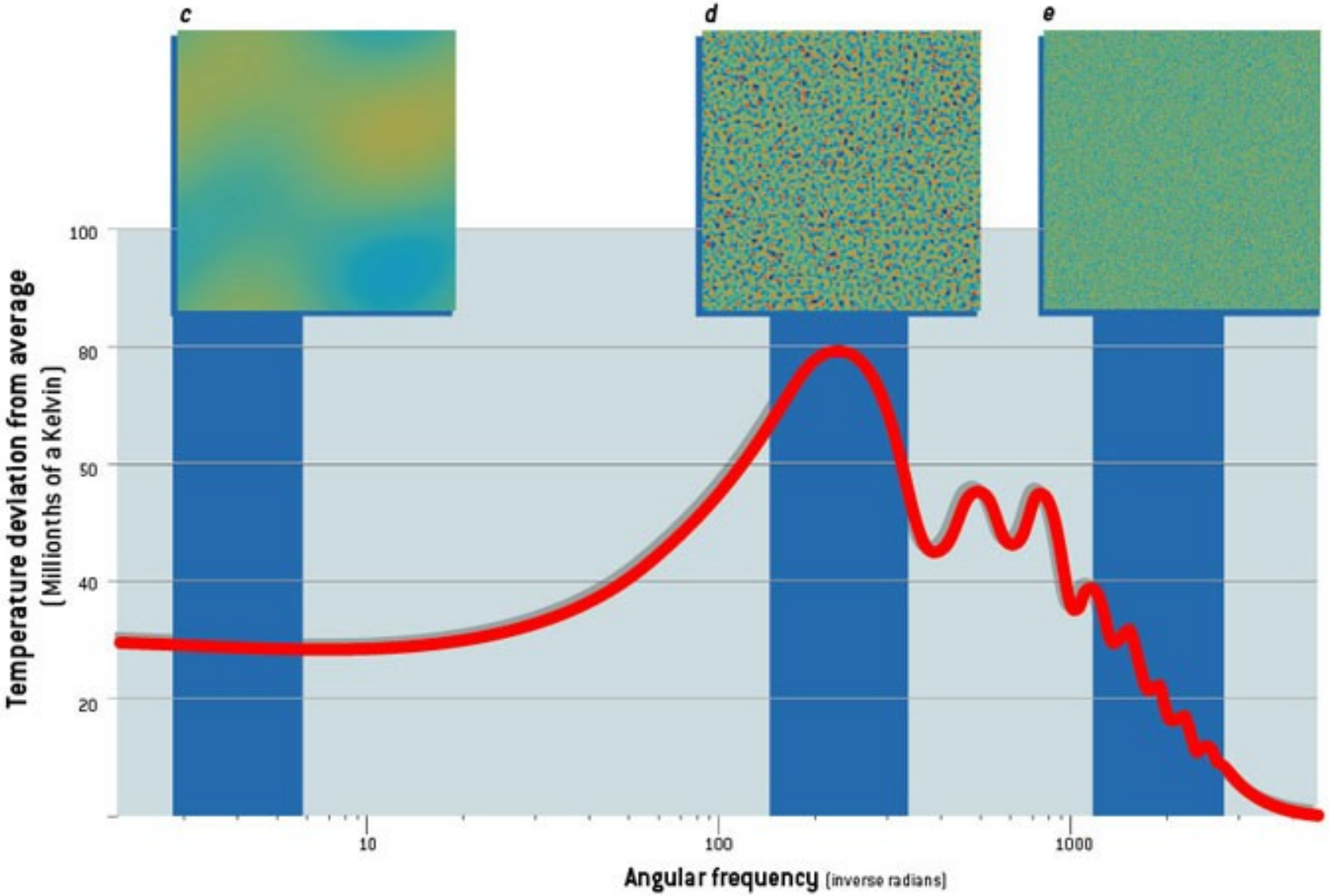


Analysis of CMB anisotropies

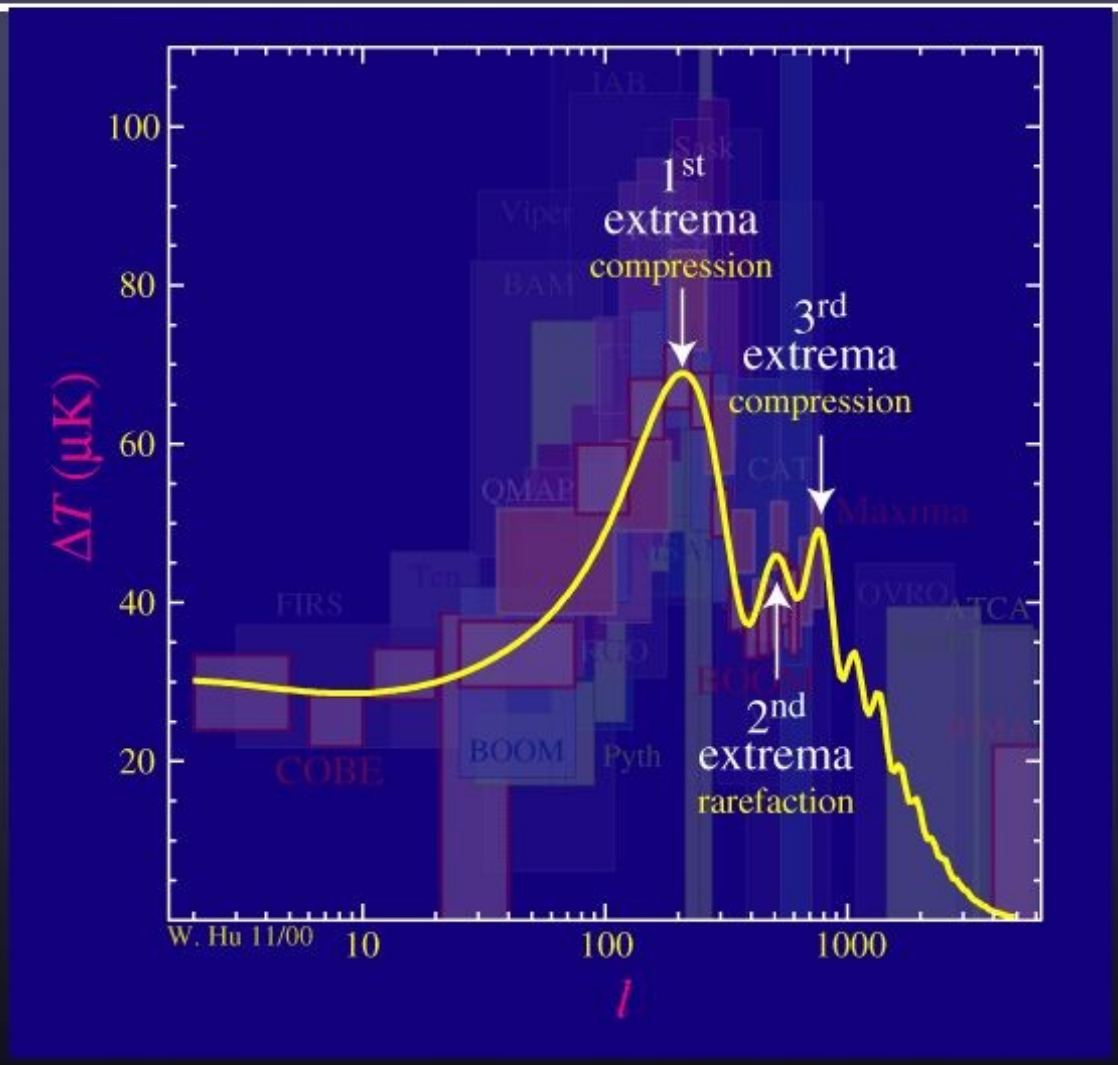
- Analyse fluctuations in terms of spherical harmonics
- Very characteristic anisotropy power spectrum predicted
- Depends very sensitively on cosmological parameters in model
- Exquisitely accurate observations help refine our models of the Universe

CMB anisotropy power spectrum

Wayne Hu



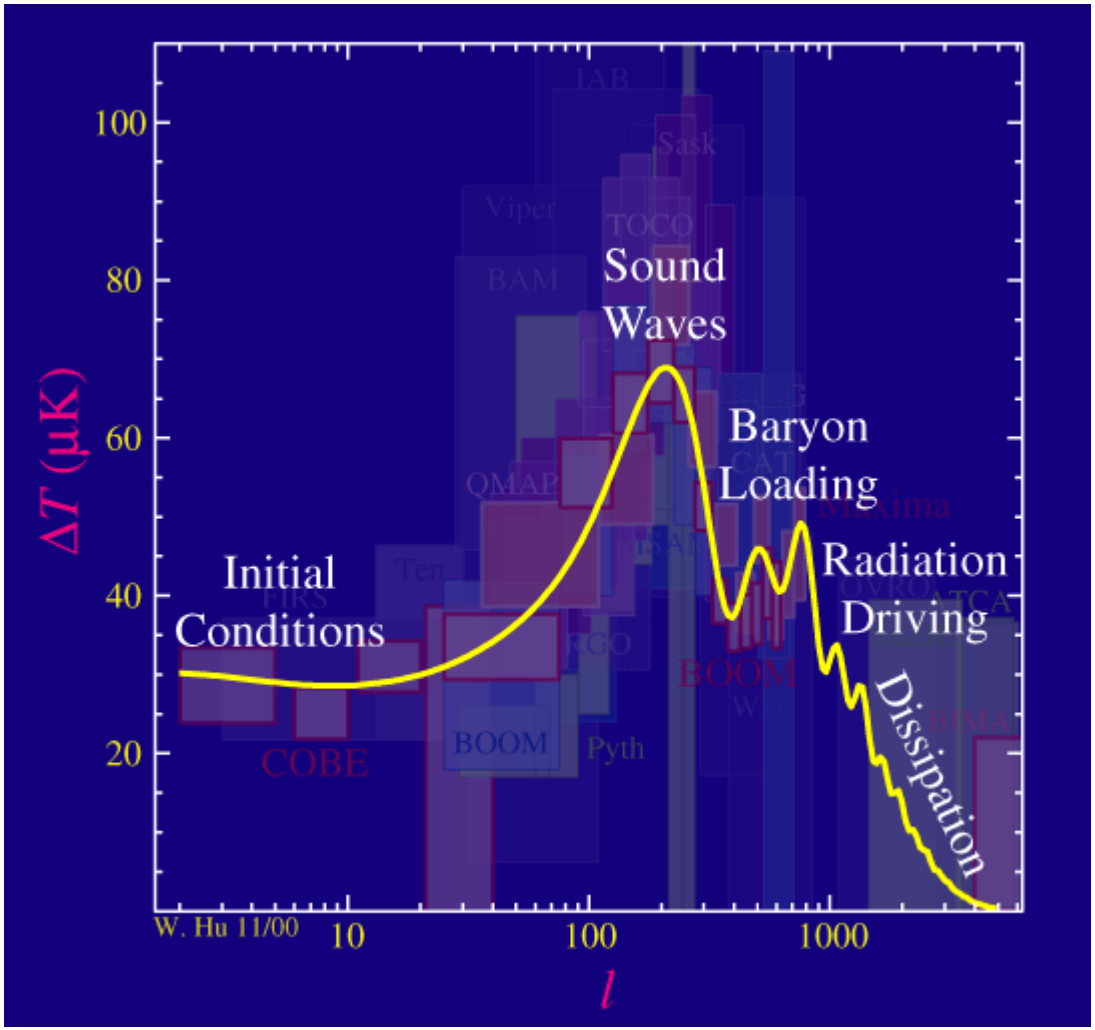
CMB Acoustic Overtones



- If we choose to follow a crest (overdensity) after horizon entry, the first acoustic peak is its first compression…

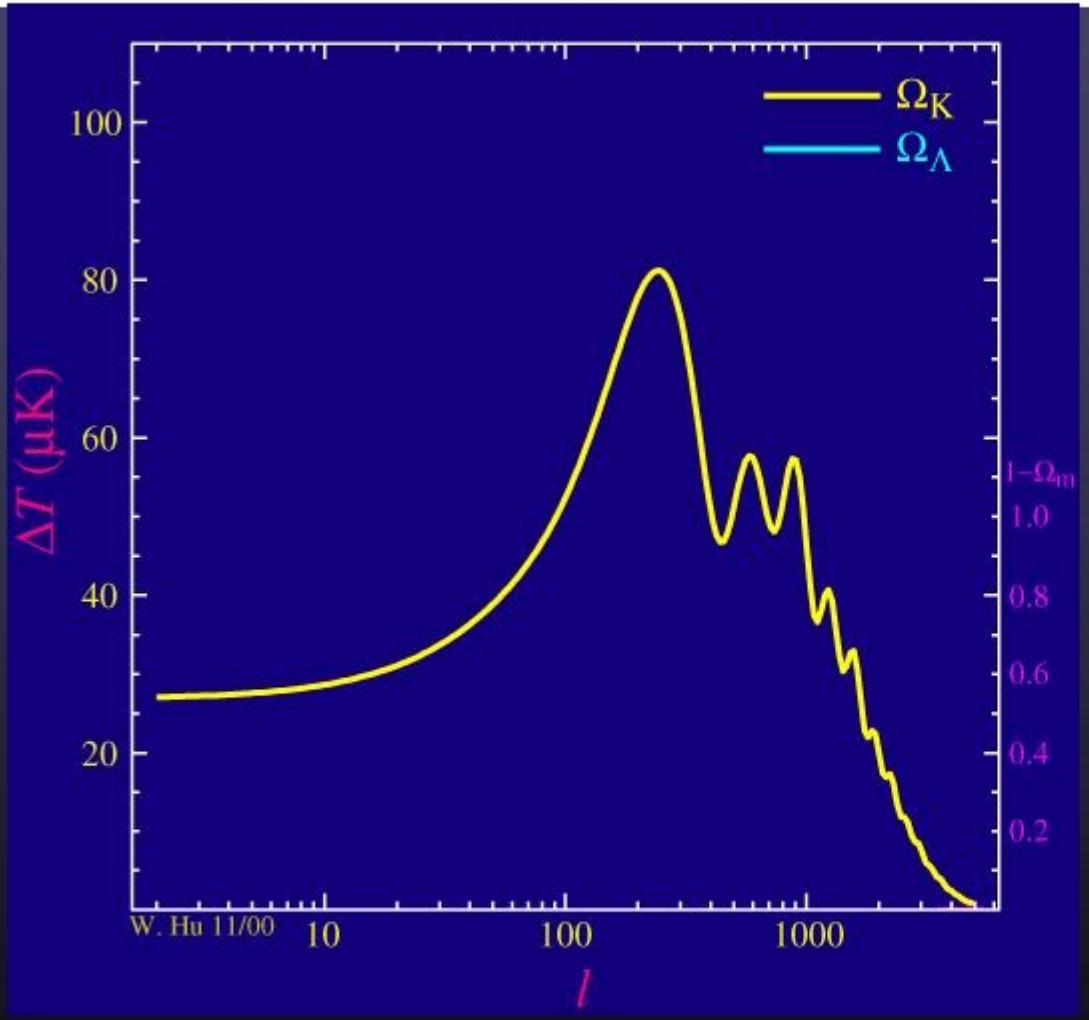
Wayne Hu

The physics behind the anisotropy power spectrum



Wayne Hu

Peaks and Curvature

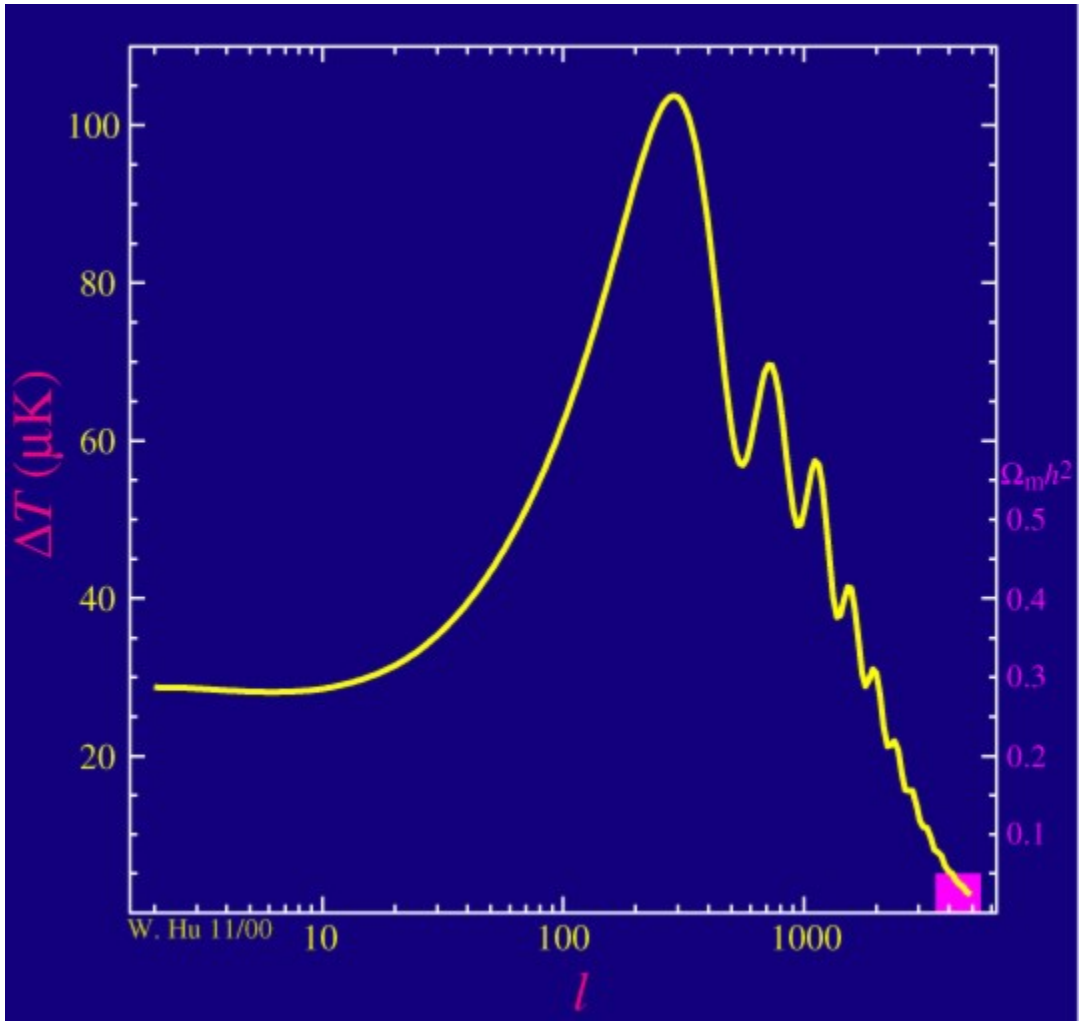


Cosmological parameter dependence

- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

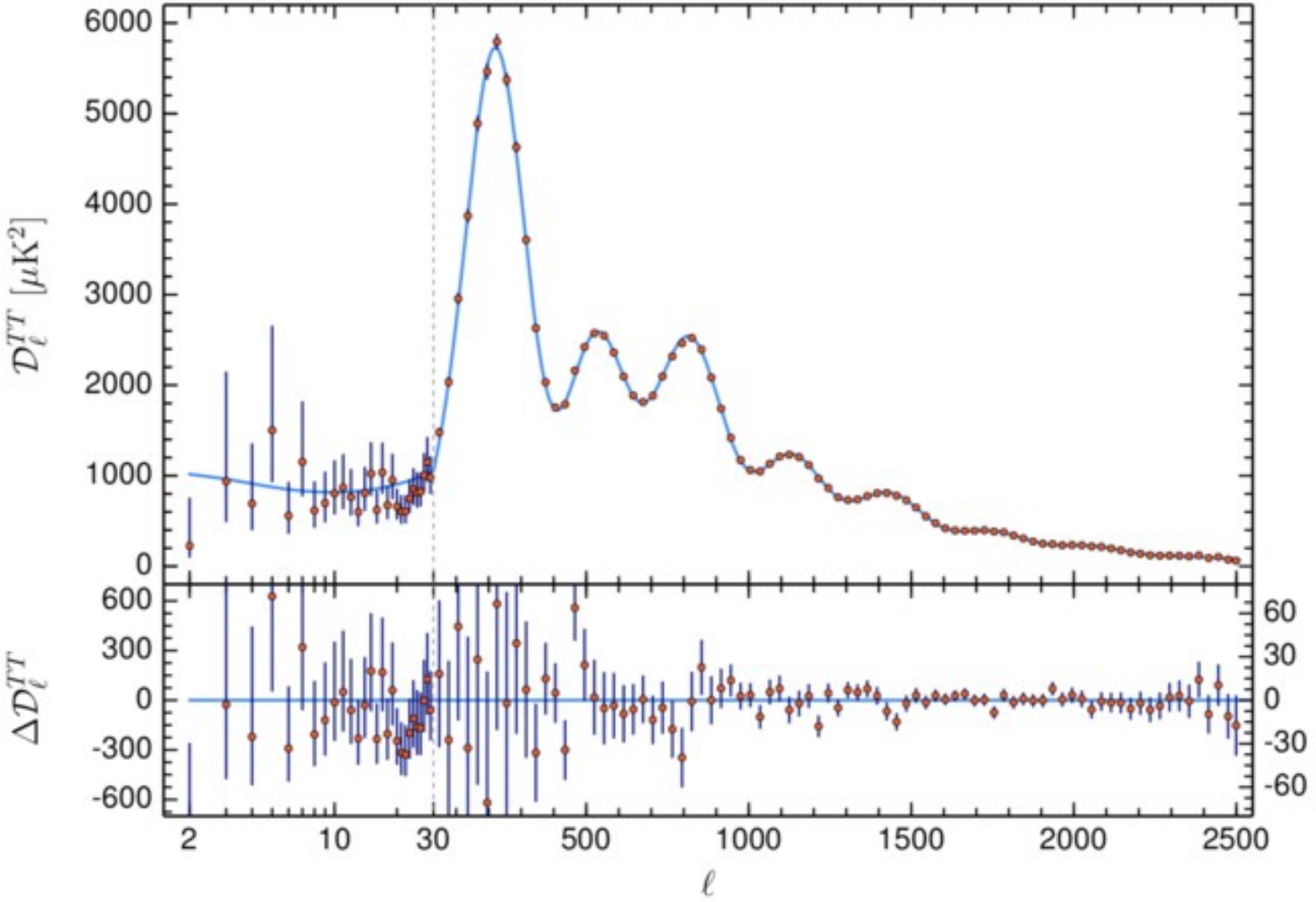
Courtesy Wayne Hu – *http://background.uchicago.edu*

How total density affects this plot



Percentages of H, He, Li formed in Big Bang also very sensitive to baryon/photon ratio – limit about 4%

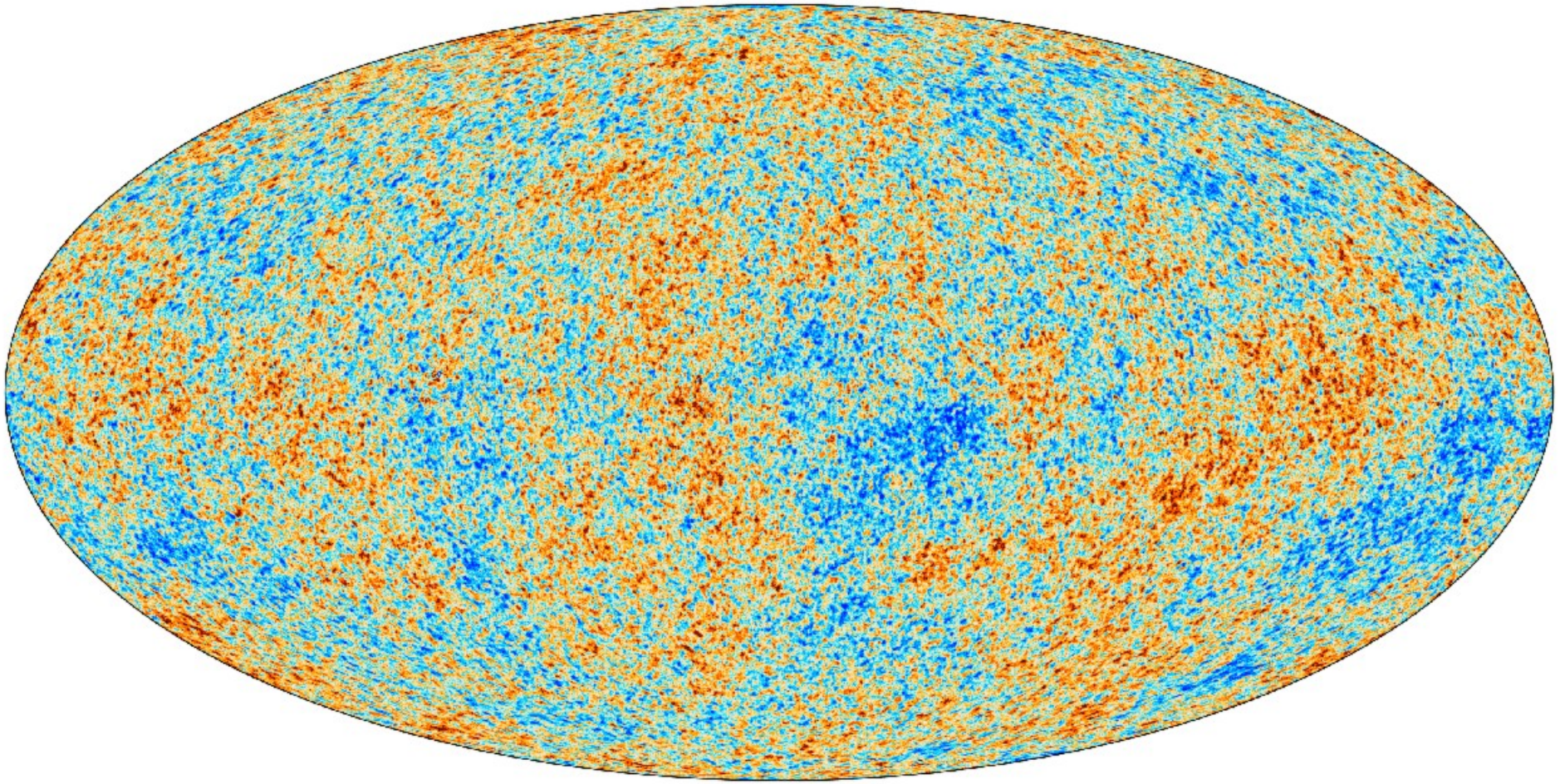
Planck power spectrum 2018



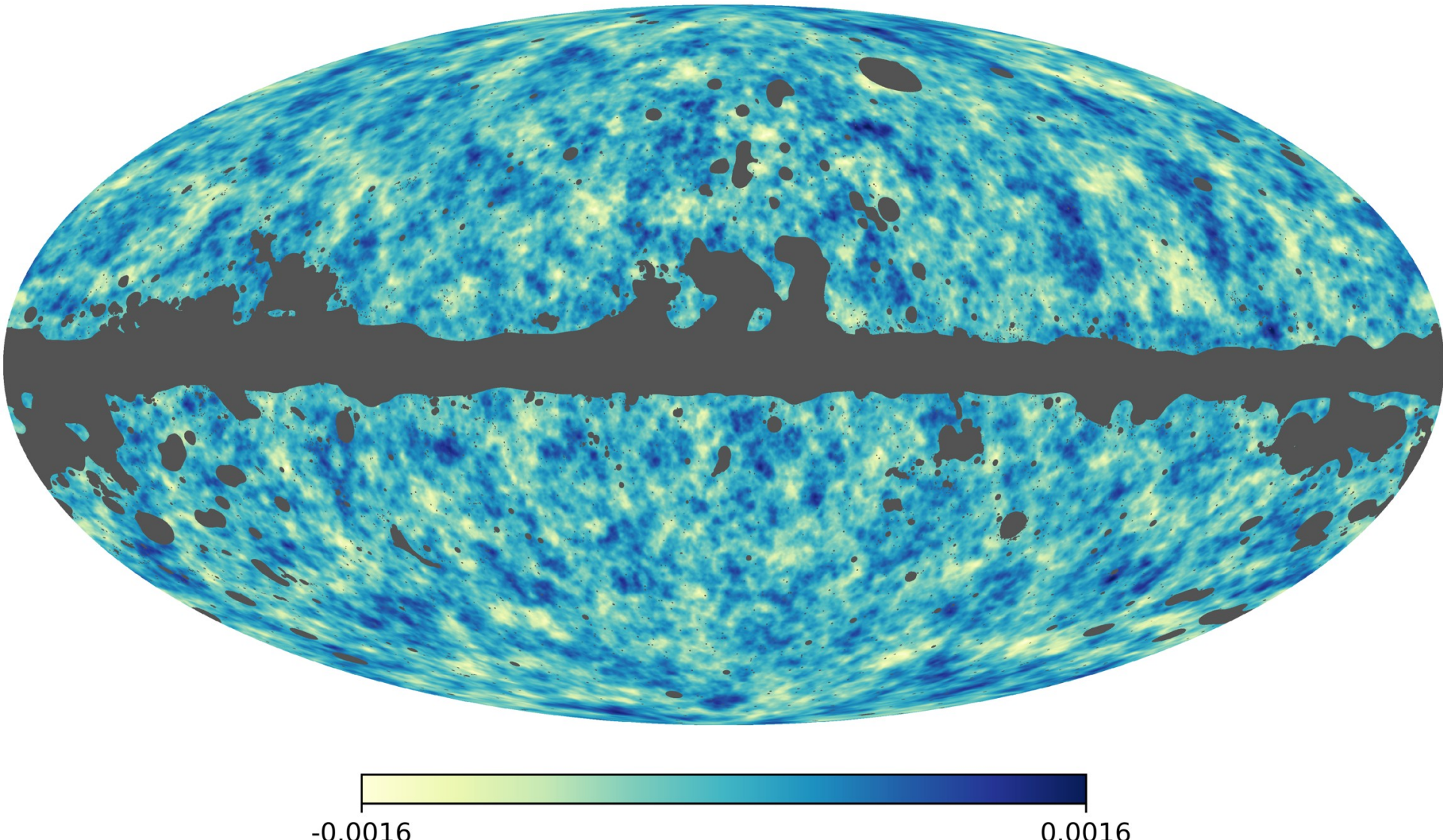
Planck 2018 results

- Map of the CMB
- Map the thermal SZ effect
- Map of thermal dust
- Map of cosmic infrared background
- Map of Galactic carbon monoxide
- Map of Synchrotron radiation
- Map of free-free emission
- Map of anomalous microwave emission
- Catalogues of compact Galactic and extragalactic sources, including polarization information.

Planck intensity and polarisation 2018



Planck map of Dark Matter 2018



Comments

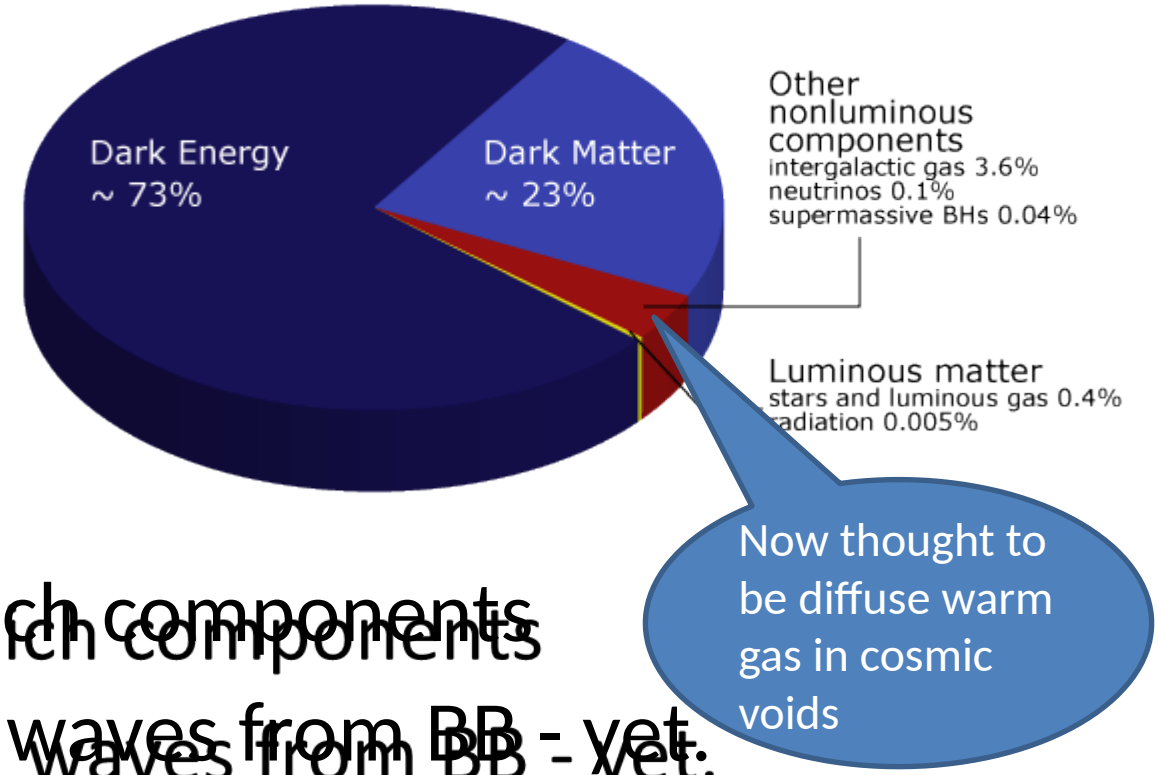
- Incredibly good fit
- At recombination, fluctuations of the same size as the horizon scale dominate
- Physics behind shape of power spectrum is complex but relatively well understood
- Inflation after hot big bang is only model that predicts the anisotropies seen

Planck legacy

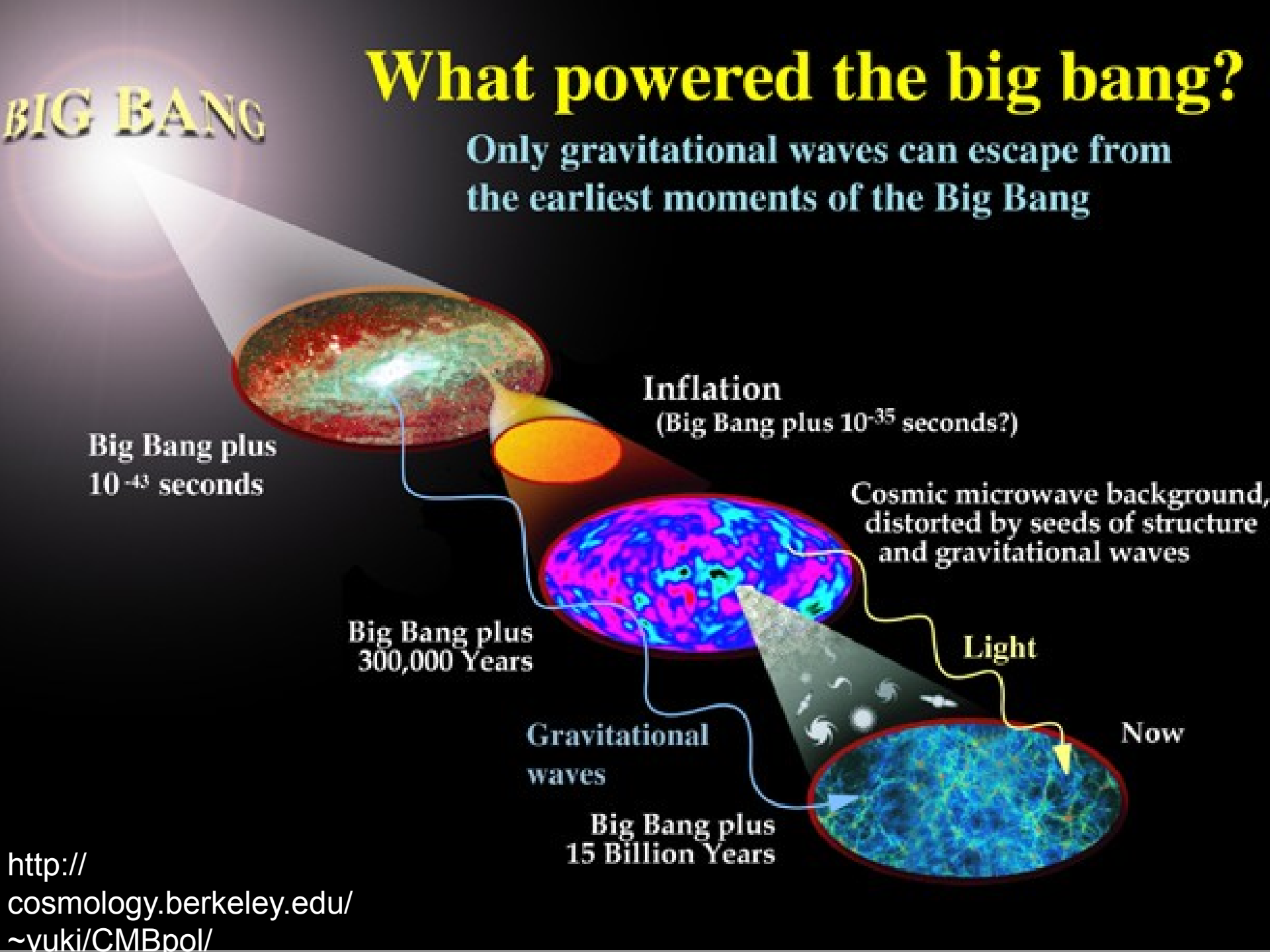
- Confirms ΛCDM, cold dark matter plus cosmological constant. Not modified gravity or additional component of gravitational fields (alternatives to “dark energy”)
- Tight constraints on inflationary models
- Cosmological parameters mostly known to few % or better.

Current Understanding of Universe

- New values of cosmological parameters, to ~1%
- H_0 67.8 +/- 0.9 km s^{-1} Mpc^{-1}
- Age 13.813 ±0.026 GYr
- Flatness
- Densities, in which components
- No gravitational waves from BB - yet.



What powered the big bang?

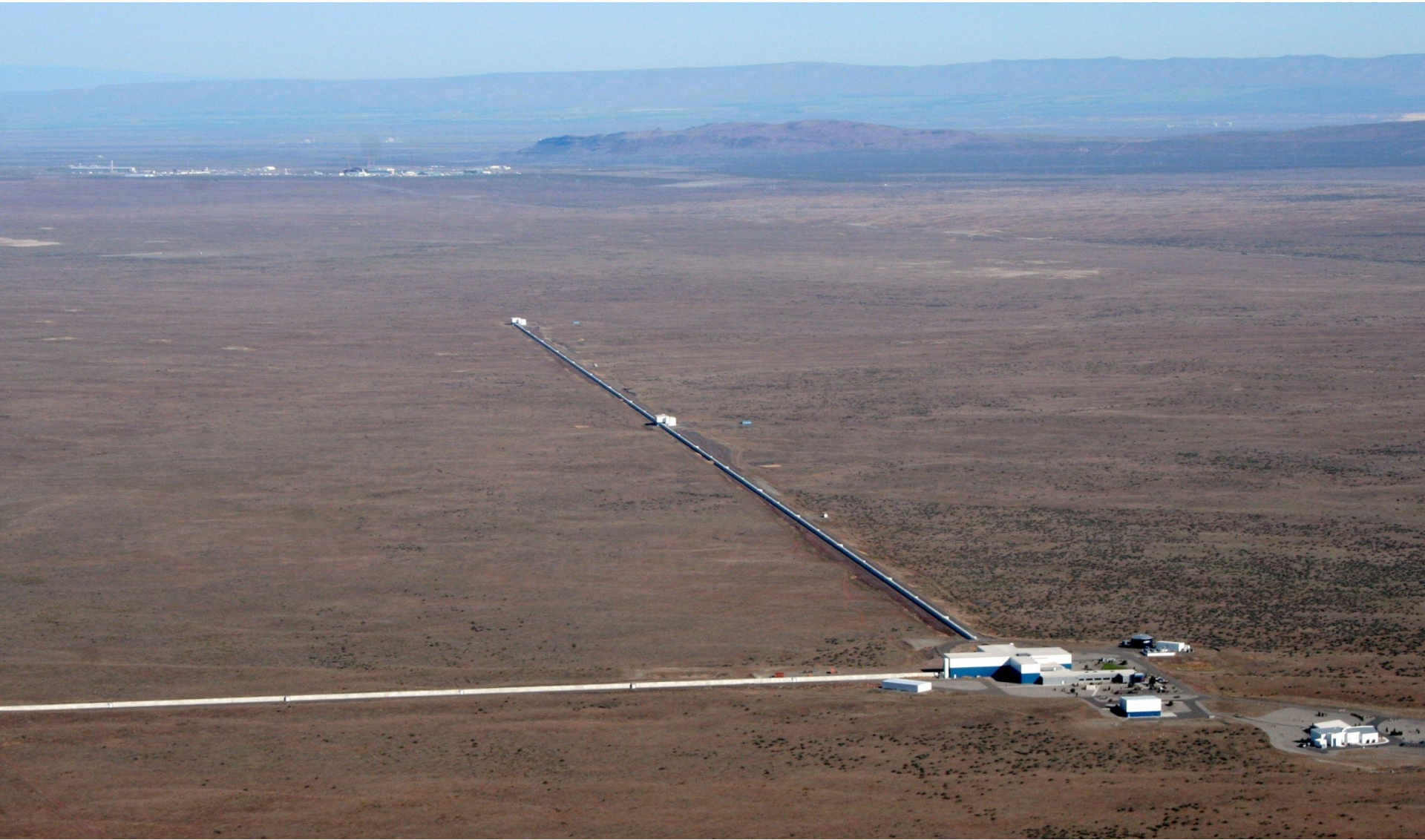


http://cosmology.berkeley.edu/~yuki/CMBpol/

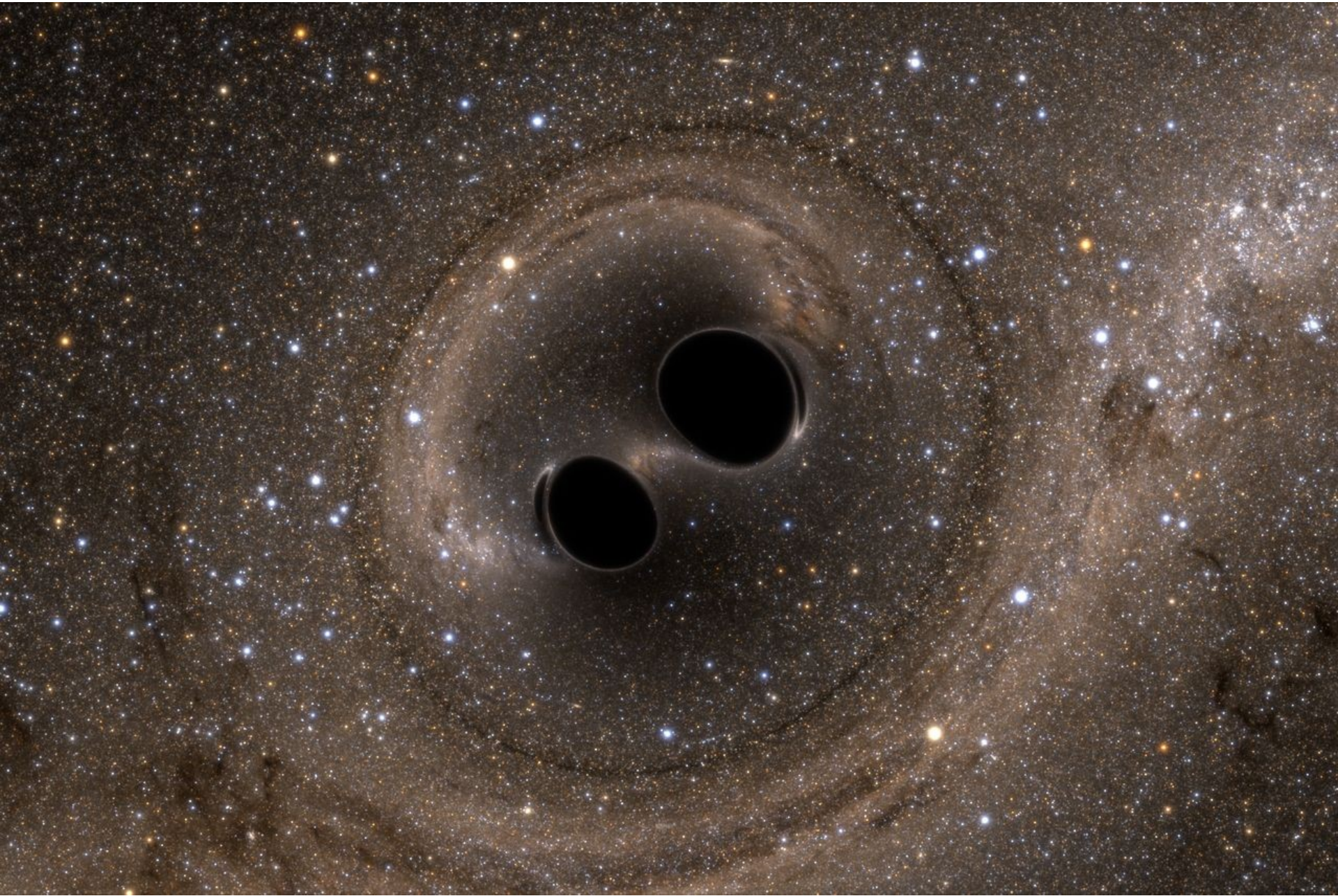
How can we measure Gravitational waves?

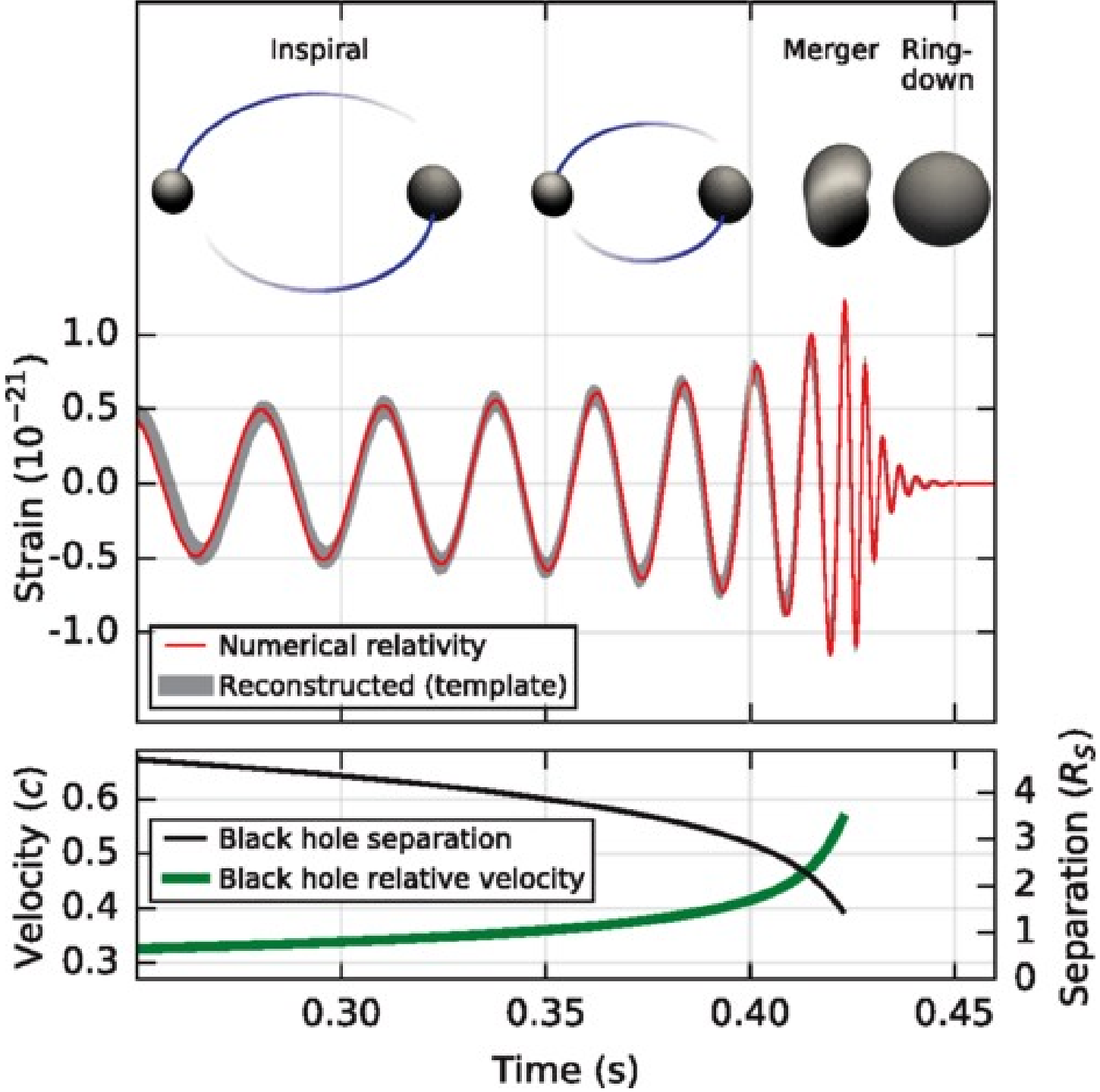
- LIGO and VIRGO!
- Direct measurement for merging black holes and neutron stars at few M_{SUN}
- Expect many more detections
- Should be gravitational waves from the Big Bang
  - Much longer wavelength
  - Need much bigger detectors

LIGO - Laser Interferometer Gravitational-Wave Observatory



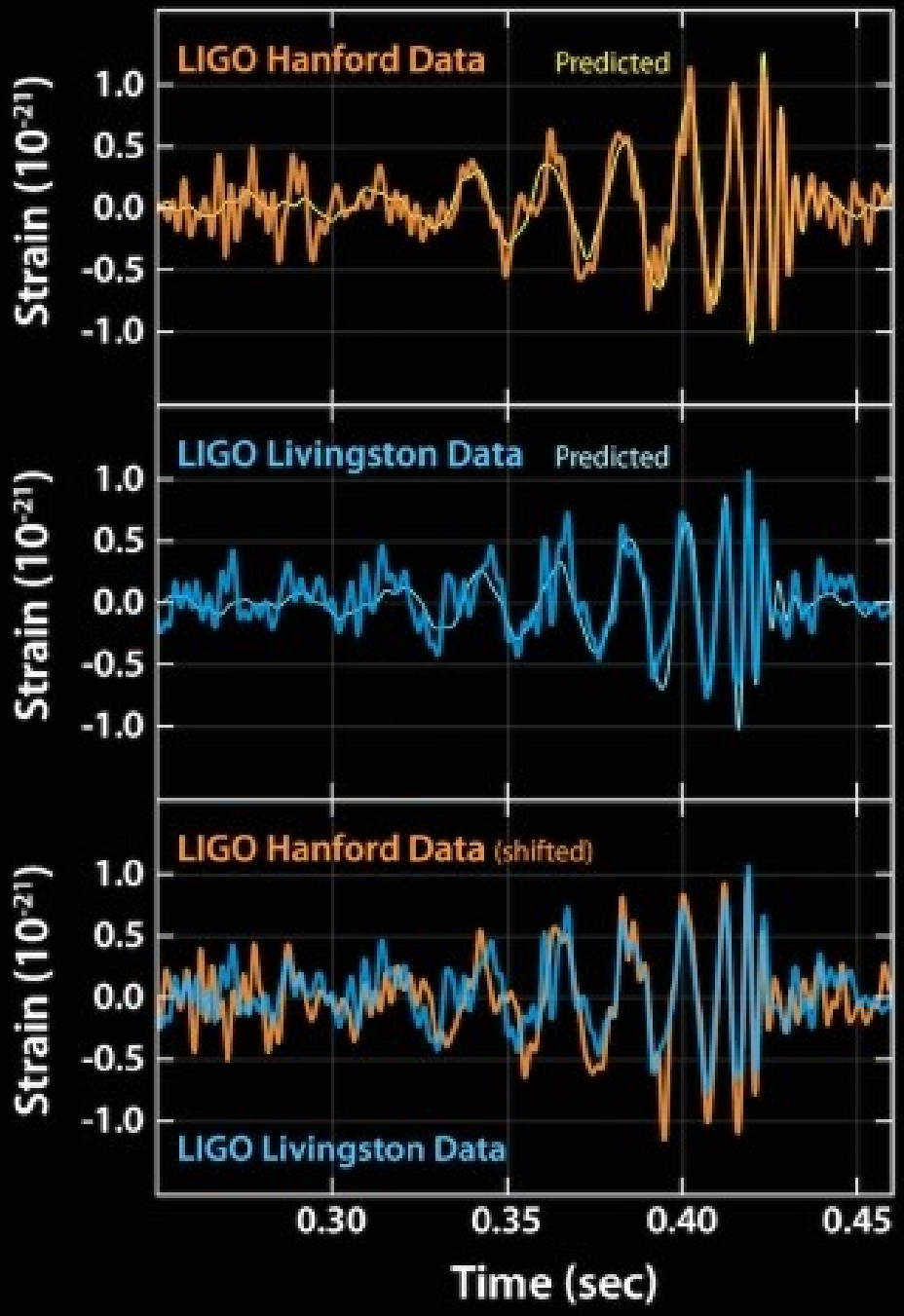
Simulation of GW150914





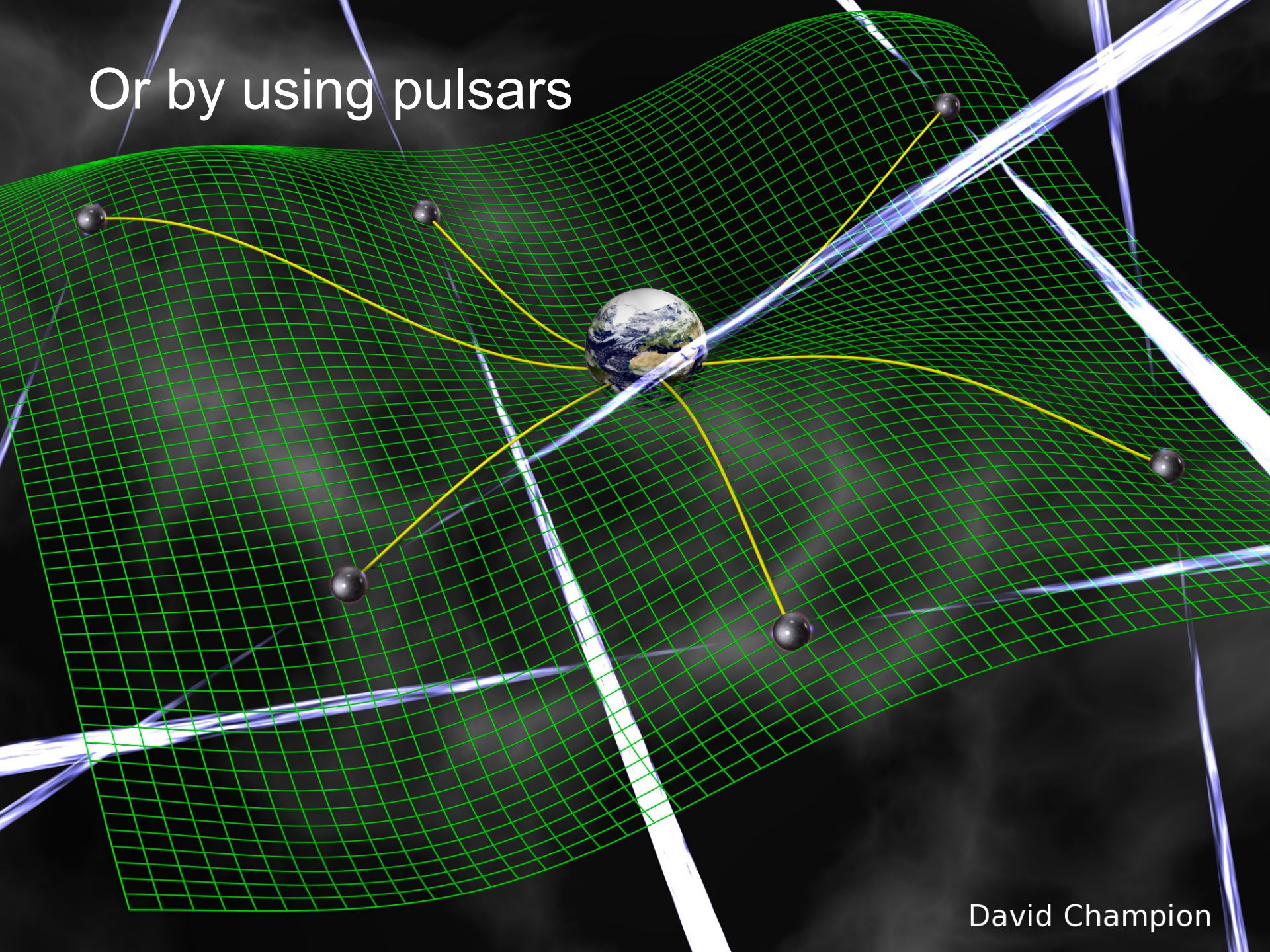
LIGO

What they expected to see



LIGO results

Separate and superposed from the two stations 2000 km apart


Or by using pulsars
David Champion

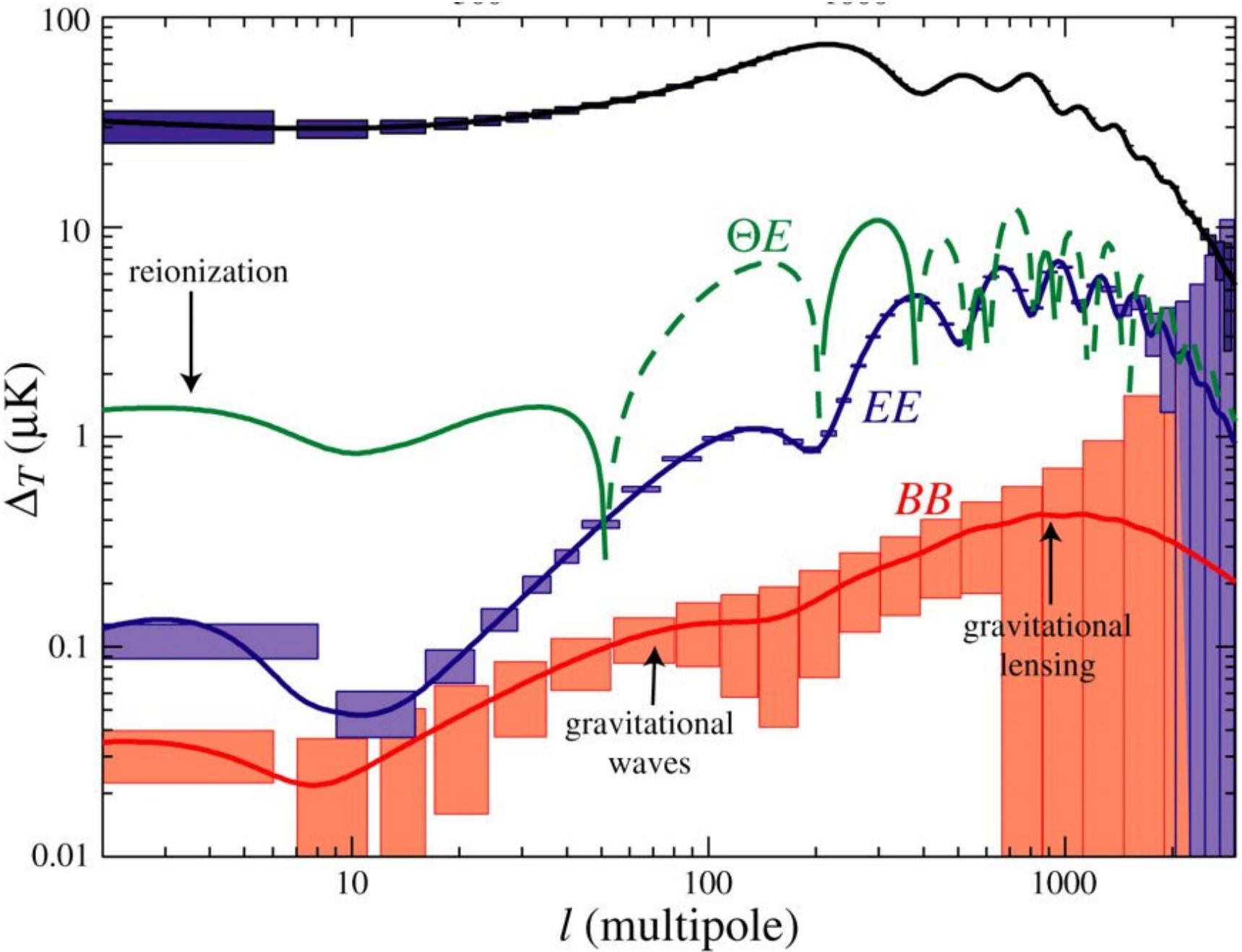
Gravitational Waves from the Big Bang (primordial gravitational waves)

- From polarised CMB
- Polarised radiation can be split into curl-less (E) and divergence-less (B) components (analogous to but not actual electric and magnetic fields)
- Scalar (density) perturbations produce only E modes
- Tensor (gravitational) perturbations produce B modes

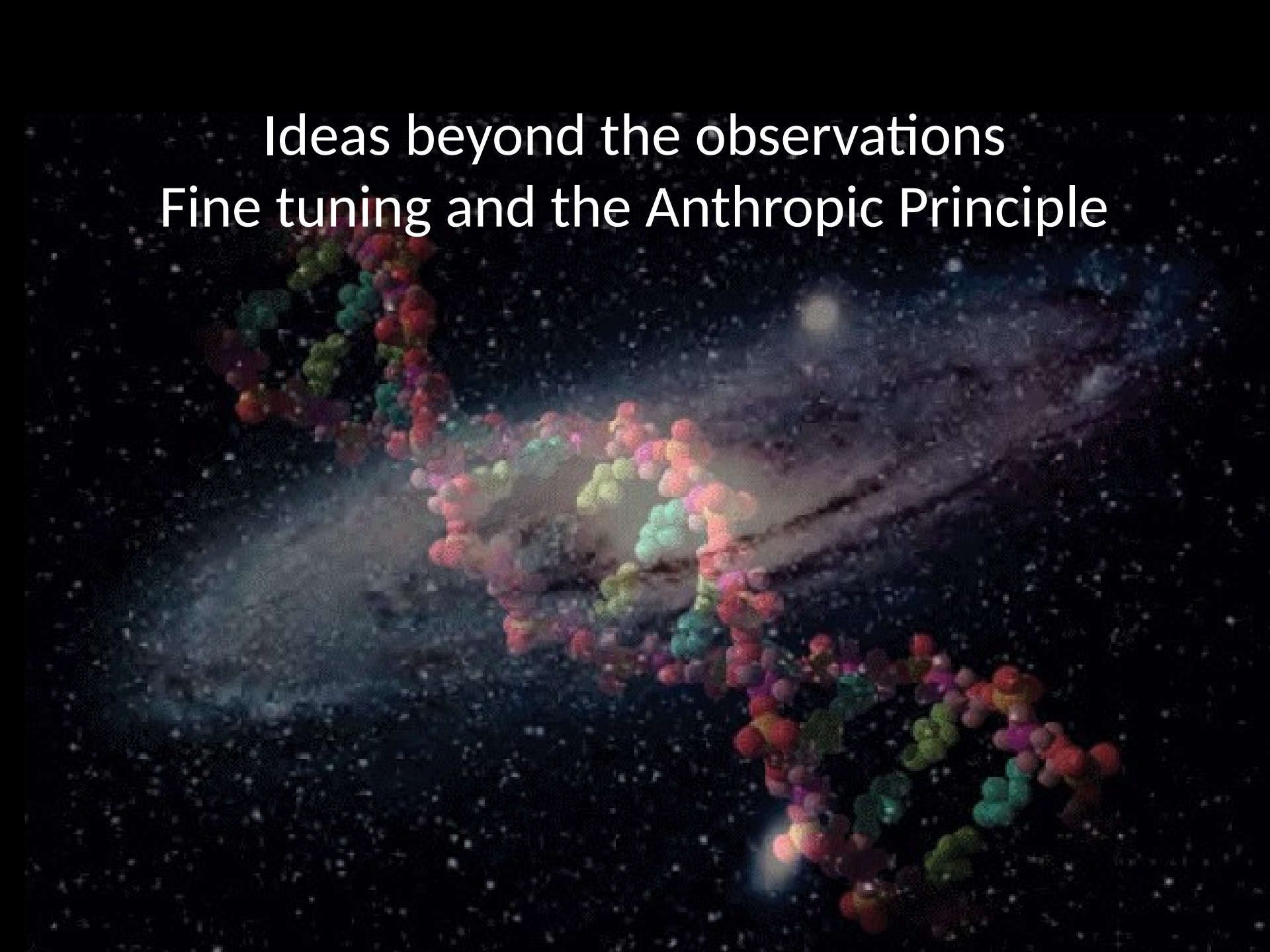
Reference for E and B modes

- See Wayne Hu's tutorials for good visualisation
- http://background.uchicago.edu/~whu/polar/webversion/node8.html
- And "Statistics of Cosmic Microwave Background Polarization"
- By Marc Kamionkowski, Arthur Kosowsky, Albert Stebbins
- https://arxiv.org/abs/astro-ph/9611125

http://cosmology.berkeley.edu/~yuki/CMBpol/CMBpol.htm



Ideas beyond the observations
Fine tuning and the Anthropic Principle



Main fine tuned parameters

- **Cosmic constants** – four fundamental force constants and the cosmological constant
- **Initial conditions** – distribution of mass energy, velocity of light, ratio of masses for protons and neutrons, matter-antimatter asymmetry.
- **Local planetary conditions** – within galactic habitable zone, within circumstellar habitable zone, right planetary mass, presence of liquid water, plate tectonics steady, during cosmic habitable age, etc.

(Rees: “Just Six Numbers”)

Anthropic principle

- **Strong Anthropic Principle (SAP)**: Universe **must** have properties which make it inevitable that conscious life will develop (Barrow and Tipler).
- **Weak Anthropic Principle (WAP)**– only get sentient beings in universe which can support them
- Interpretations:
  - one possible Universe 'designed' for 'observers'.
  - observers needed to bring Universe into being
  - ensemble of other universes needed for existence of our Universe.

Beyond the Big Bang

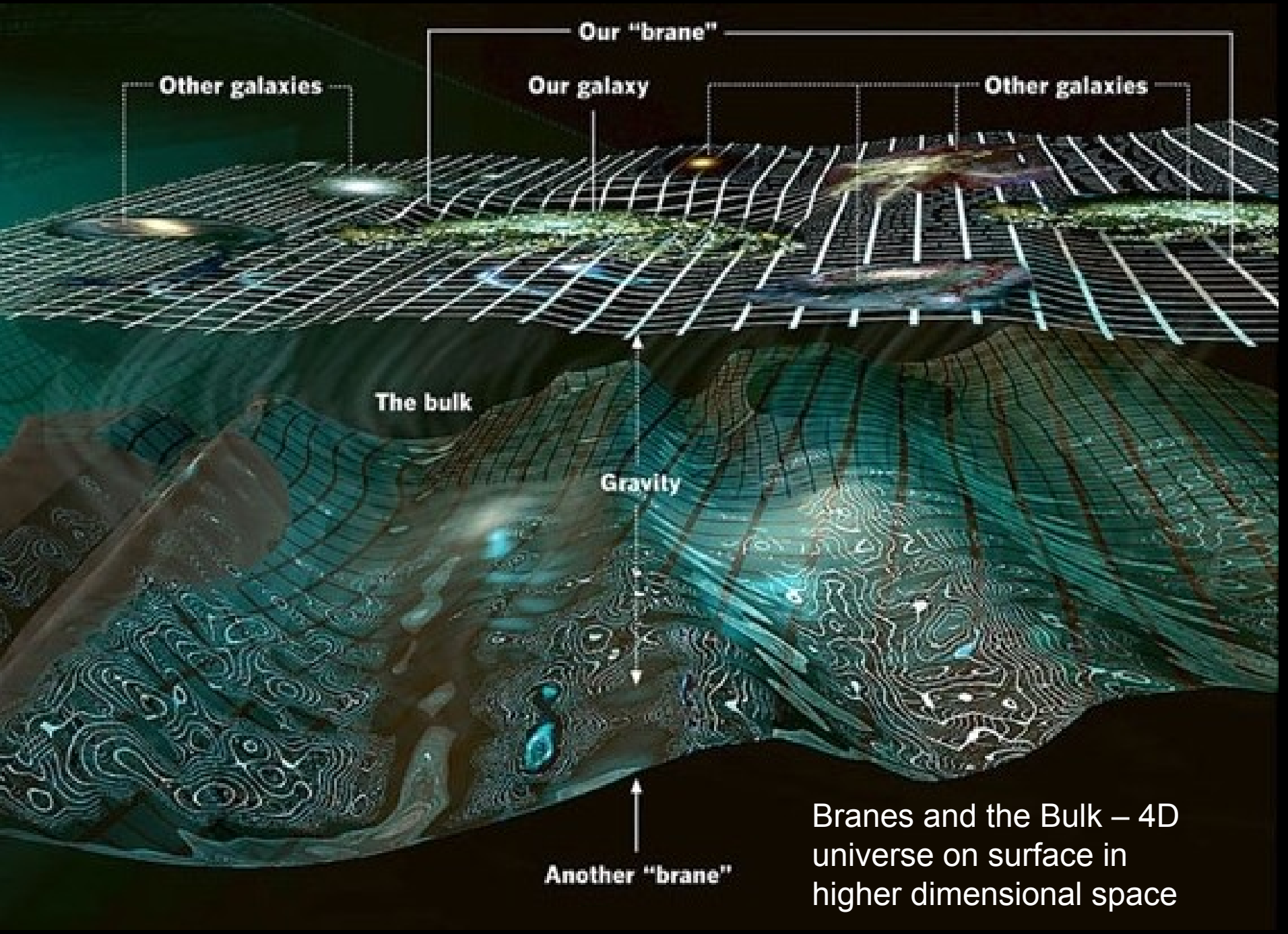
- Only by mathematics, no observational proof possible
  - A computer simulation
  - Theory of everything (TOE)
  - Quantum "Many Worlds"
  - Eternal inflation - The Multiverse
  - String Theory, M-Theory = multiverse (10^{500} universes!), and ~11 dimensions
  - Conformal Cyclic Cosmology

All completely speculative!

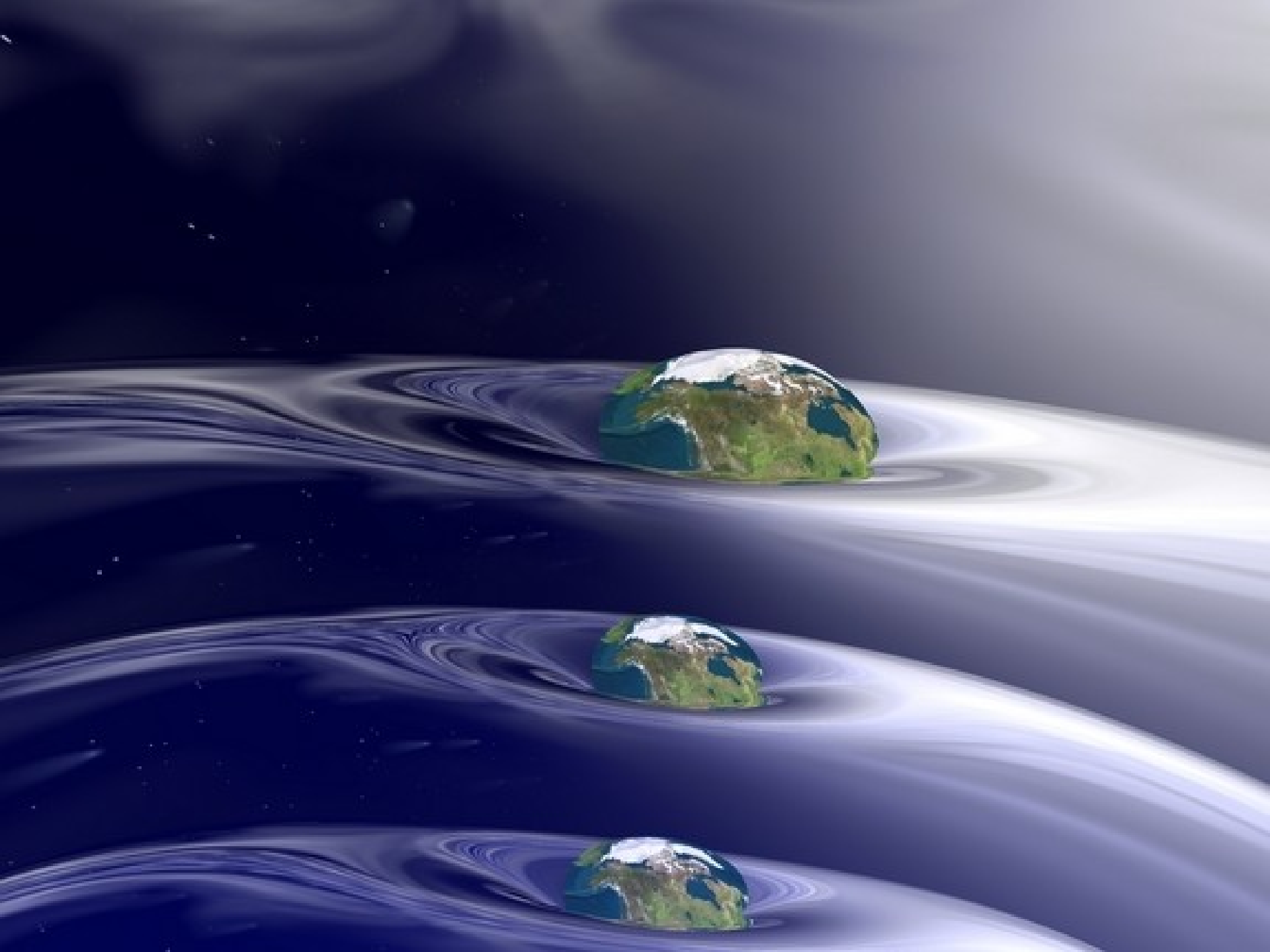
Never – ending repro-duction of inflated regions.

Multi-verse

String Theory



Branes and the Bulk – 4D universe on surface in higher dimensional space

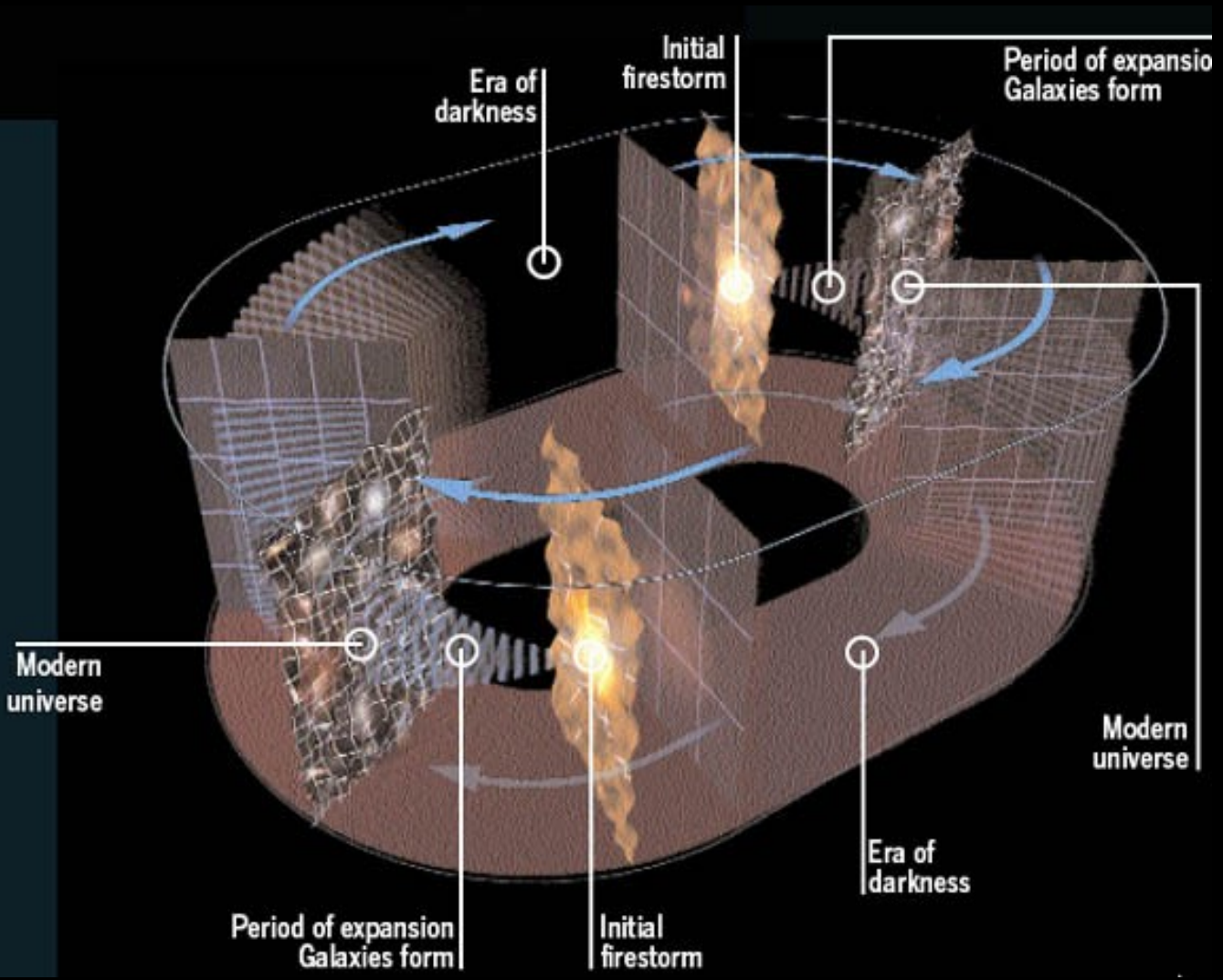


Ekpyrotic universe

Steinhardt and Turok

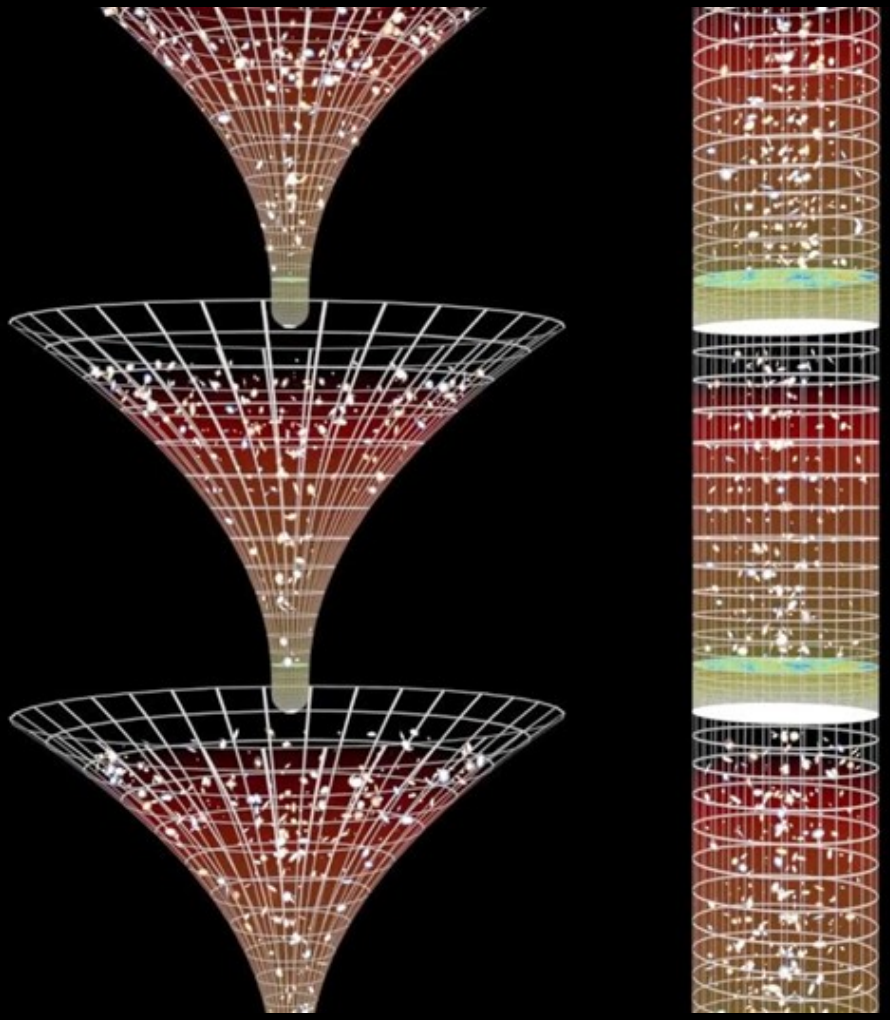
Cyclic Model

To address some of the limitations and paradoxes of the Big Bang model, cosmologists Paul Steinhardt and Neil Turok have developed a new cosmology that views the visible universe as one small part of a much larger reality, most of which exists in other dimensions that we cannot perceive. Our universe exists on a three-dimensional membrane (represented by the flat panels at right) that lies right next to another membrane. Every trillion years or so, the two membranes collide, unleashing a firestorm of energy analogous to the Big Bang. As in the earlier model, the universe cools, gives rise to galaxies, and eventually expands to near emptiness. In this version, however, another collision between membranes then restarts the whole cycle of creation. Thus, time and space are both infinite.



Conformal Cyclic Cosmology (CCC)

Penrose and Gurzadyan




Simulated Universes
Maths - the true reality
*
Quantum Many Worlds
TOEs
Quantum Cosmology
Eternal Inflation
String Theory
Ekpyriotic Universe
The Multiverse
Plausibility, Falsifiability?
CCC

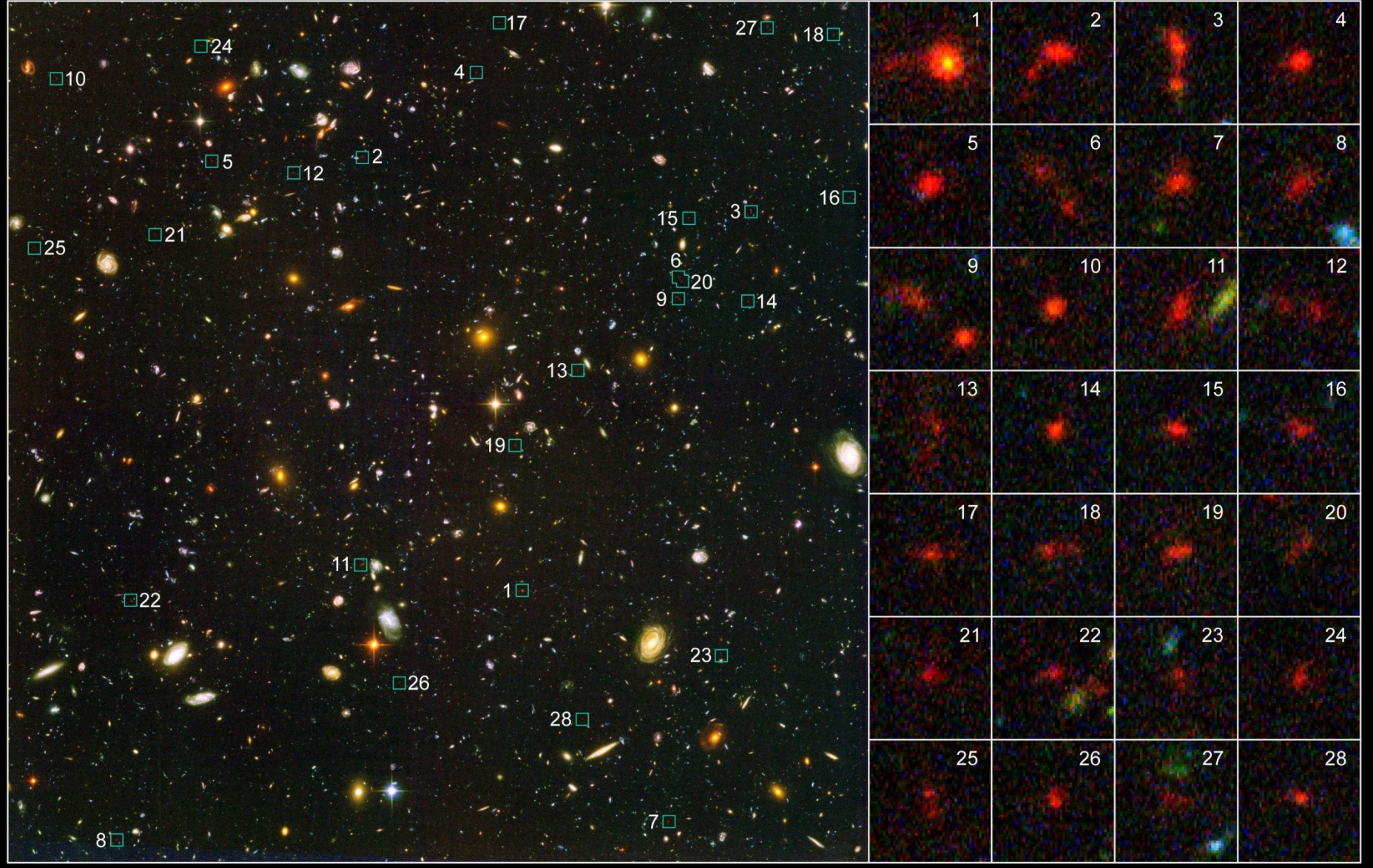
Where is cosmology going now?

- All these cosmologies non-verifiable
- Doubts because predicted fundamental particles not being seen by LHC
- Physics standard models are NOT secure
- Ready for new paradigm? Yes!
- Also need to understand dark matter and dark energy
- And to measure primordial gravitational waves


The End

http://hubblesite.org/newscenter/archive/releases/2004/07/image/a/format/large_web/

Hubble Ultra Deep Field



Distant Galaxies in the Hubble Ultra Deep Field

Hubble Space Telescope • Advanced Camera for Surveys

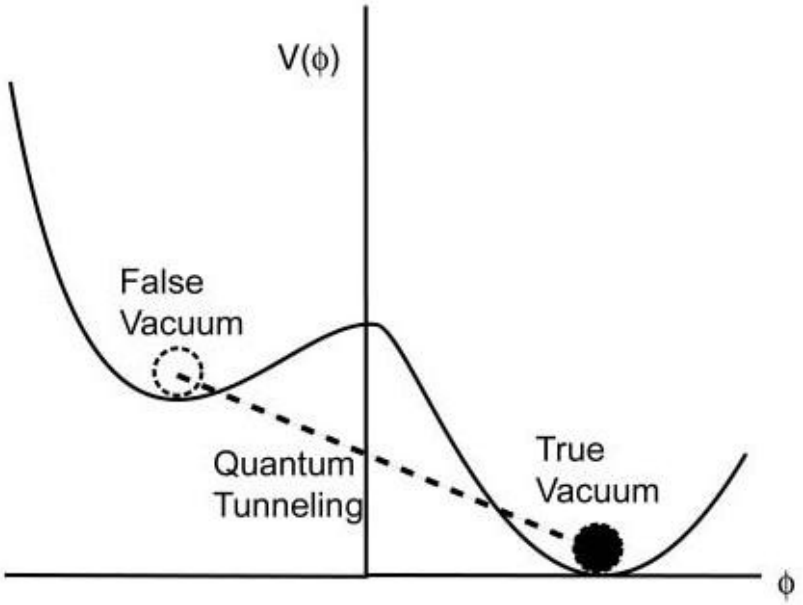
NASA, ESA, R. Bouwens and G. Illingworth (University of California, Santa Cruz)

Hubble deep field South

http://www.dailygalaxy.com/my_weblog/2015/02/beyond-hubble-a-new-3-d-view-of-the-earliest-galaxies-in-the-universe.html

“Old” inflation

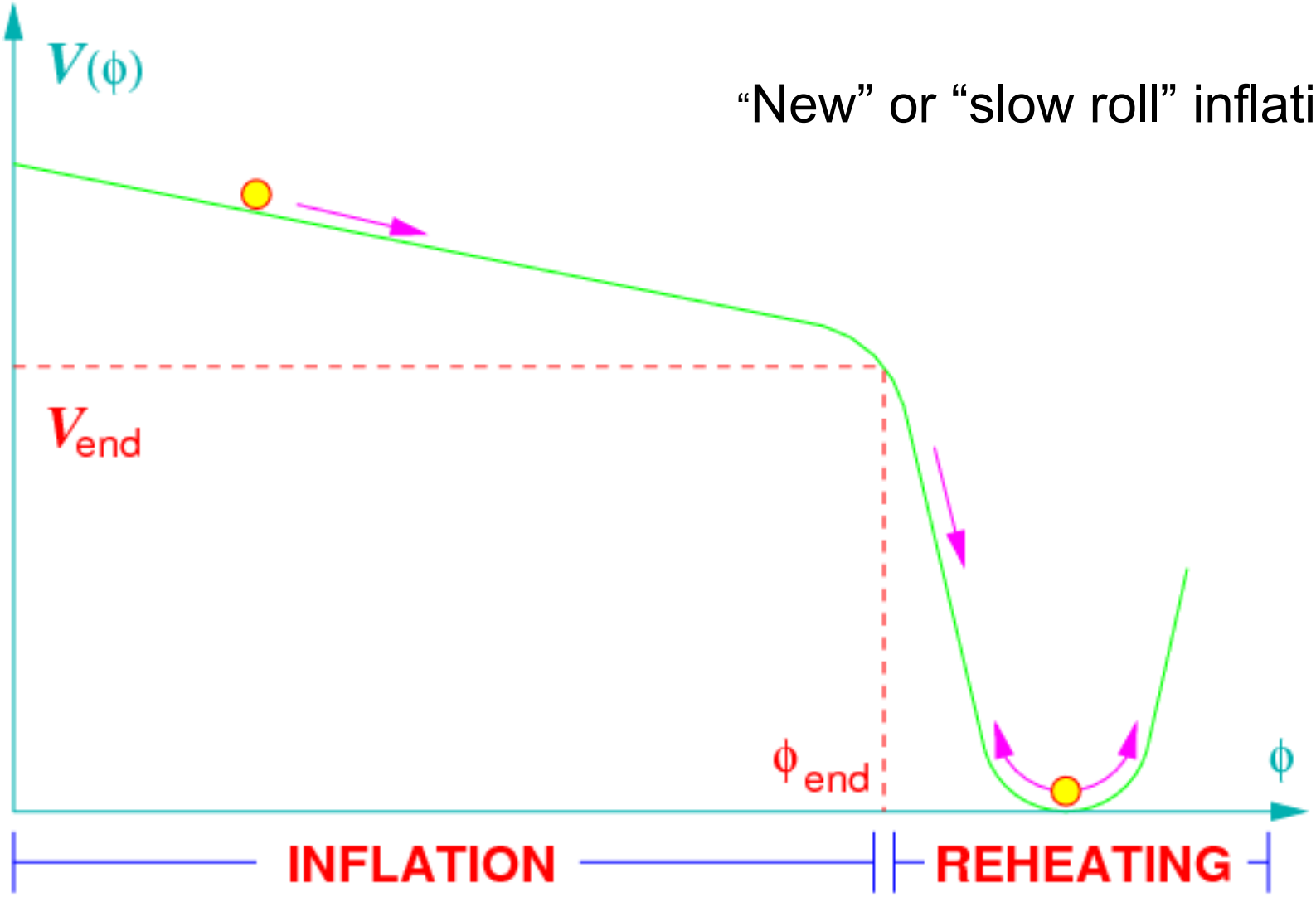
- Universe tunnelling out of a false vacuum state
- Did not allow end of inflation (reheating) to happen



“Slow Roll inflation”

- Linde, independently Albrecht and Steinhardt - **new inflation** or **slow-roll inflation**
- Scalar field rolling down a potential energy hill. When field rolls very slowly compared to expansion of Universe, inflation occurs.
- When hill becomes steeper, inflation ends and reheating can occur.
- Inflationary epoch - 10^{-36} seconds after Big Bang singularity to between 10^{-33} and 10^{-32} seconds

Picture of inflaton potential

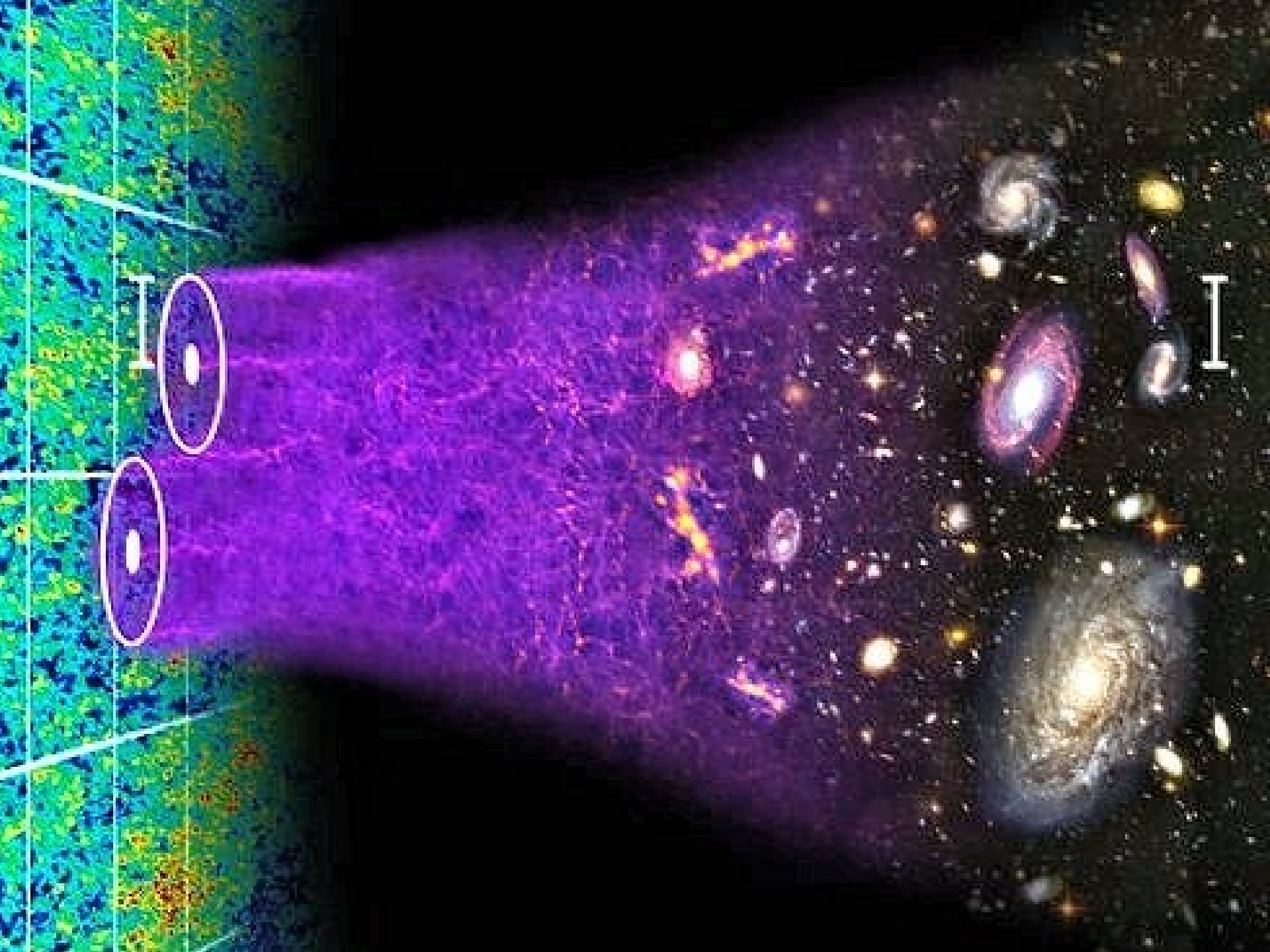


- non-linear development – evolve to bound structures – star formation
- for galaxies, clusters and superclusters – now , 1000 and a few
- ρ – now 10^6, 1000 and a few
- $a \propto (1+z)^{-1}$ respectively
- Galaxy formation started long after CMB emitted (recombination) at
- Perturbations **linear** before $z \approx 100$, so can do theory confidently

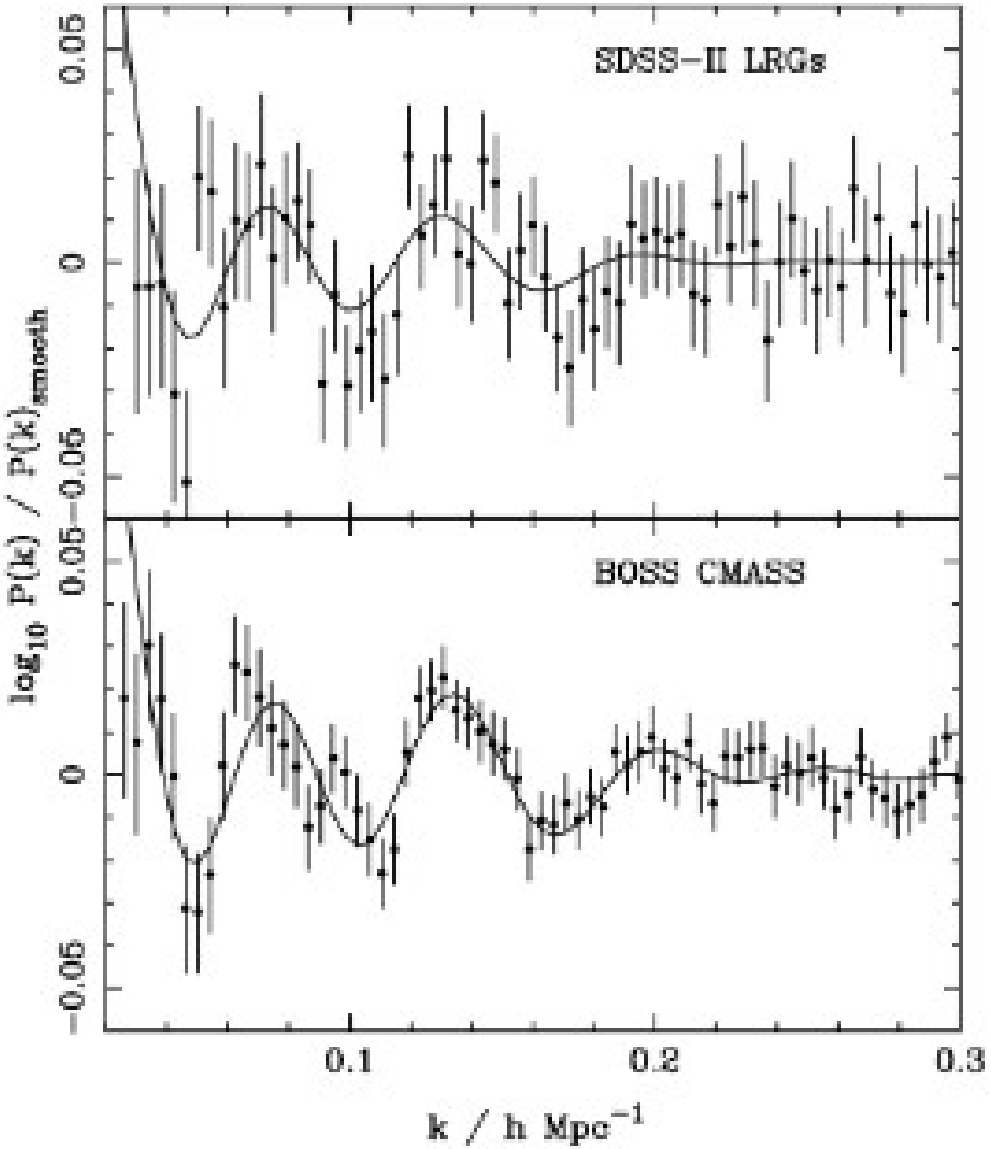
"Galaxy Formation", M.Longair, 2008

Baryon Acoustic Oscillations

- Sound waves propagate in the early universe, like spreading ripples in a pond,
- Waves imprint characteristic scale on cosmic microwave background (CMB) fluctuations.
- These fluctuations have evolved into today's walls and voids of galaxies, meaning this baryon acoustic oscillation (BAO) scale (about 150 Mpc) is visible among galaxies today.



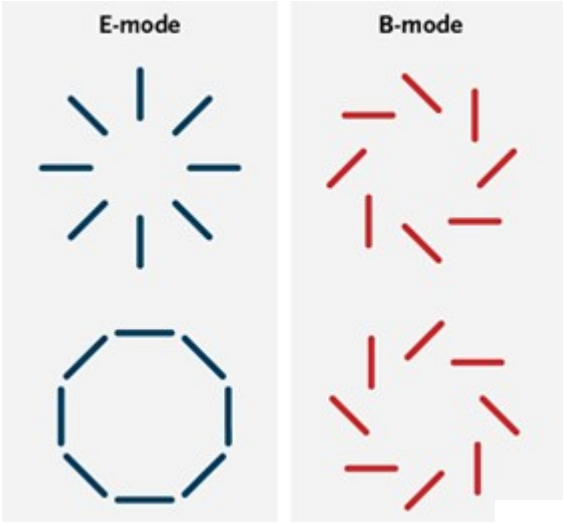
Baryon Acoustic Oscillations



What BAOs can tell us from distribution of galaxies

- Acoustic scale is physically calibrated ruler
- Measure angular diameter distance with a precision of 1% at redshifts z = 0.3 and z = 0.55
- Measure distribution of quasar absorption lines at z = 2.5 (angular diameter distance) to accuracy of 1.5%.
- Measure cosmic expansion rate H(z) with 1-2% precision at same redshifts. Tests theories of dark energy and origin of cosmic acceleration.

ESA/Hubble & NASA, ESO/Lutz Wisotzki et al.

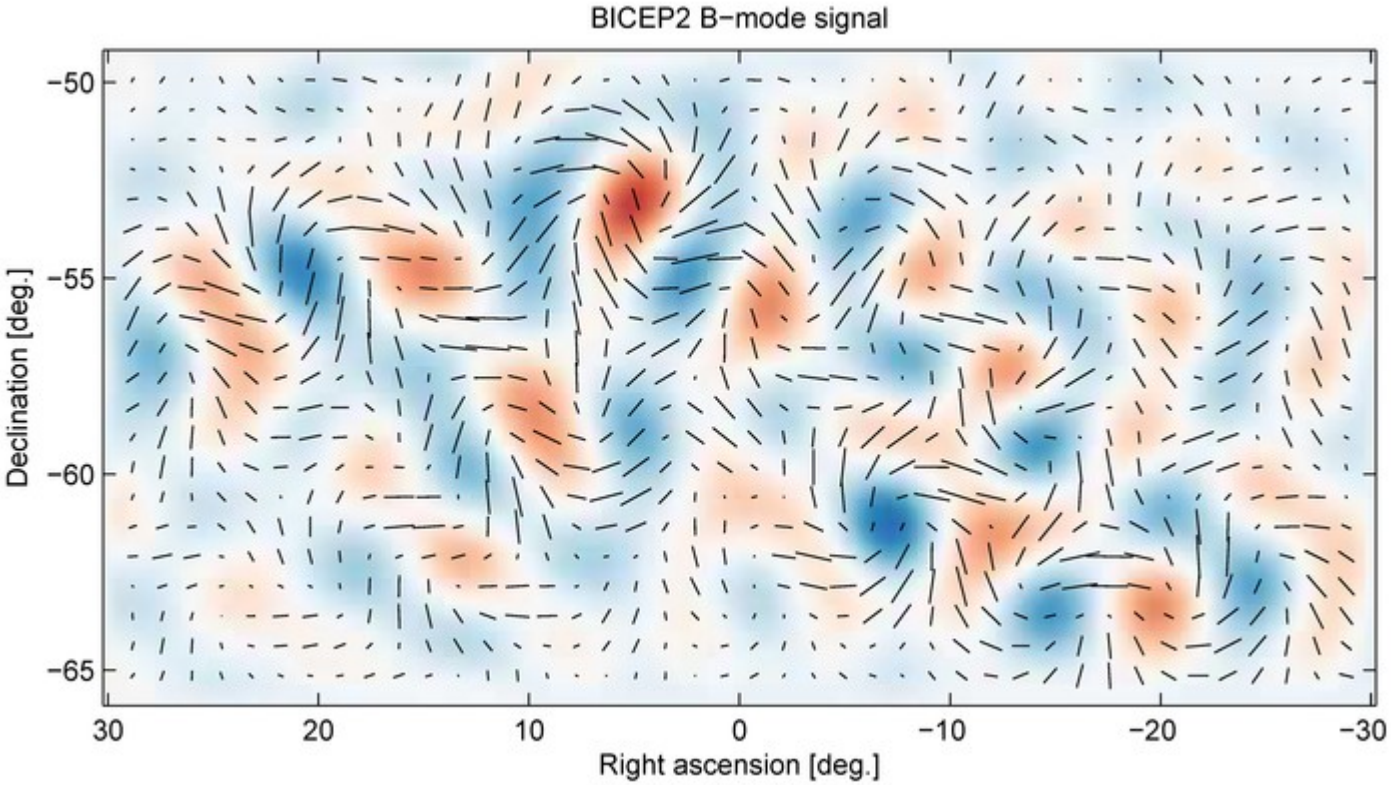


Polarization of CMB

Sean carroll - http://www.preposterousuniverse.com/blog/2014/03/16/gravitational-waves-in-the-cosmic-microwave-background/

Scalar, density

Tensor, gravity



https://www.cfa.harvard.edu/~cbischoff/img/B2_Bmodes.png