Special Lecture

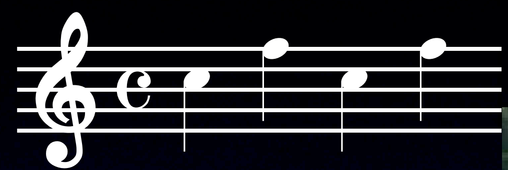
Cosmology

Hitoshi Murayama

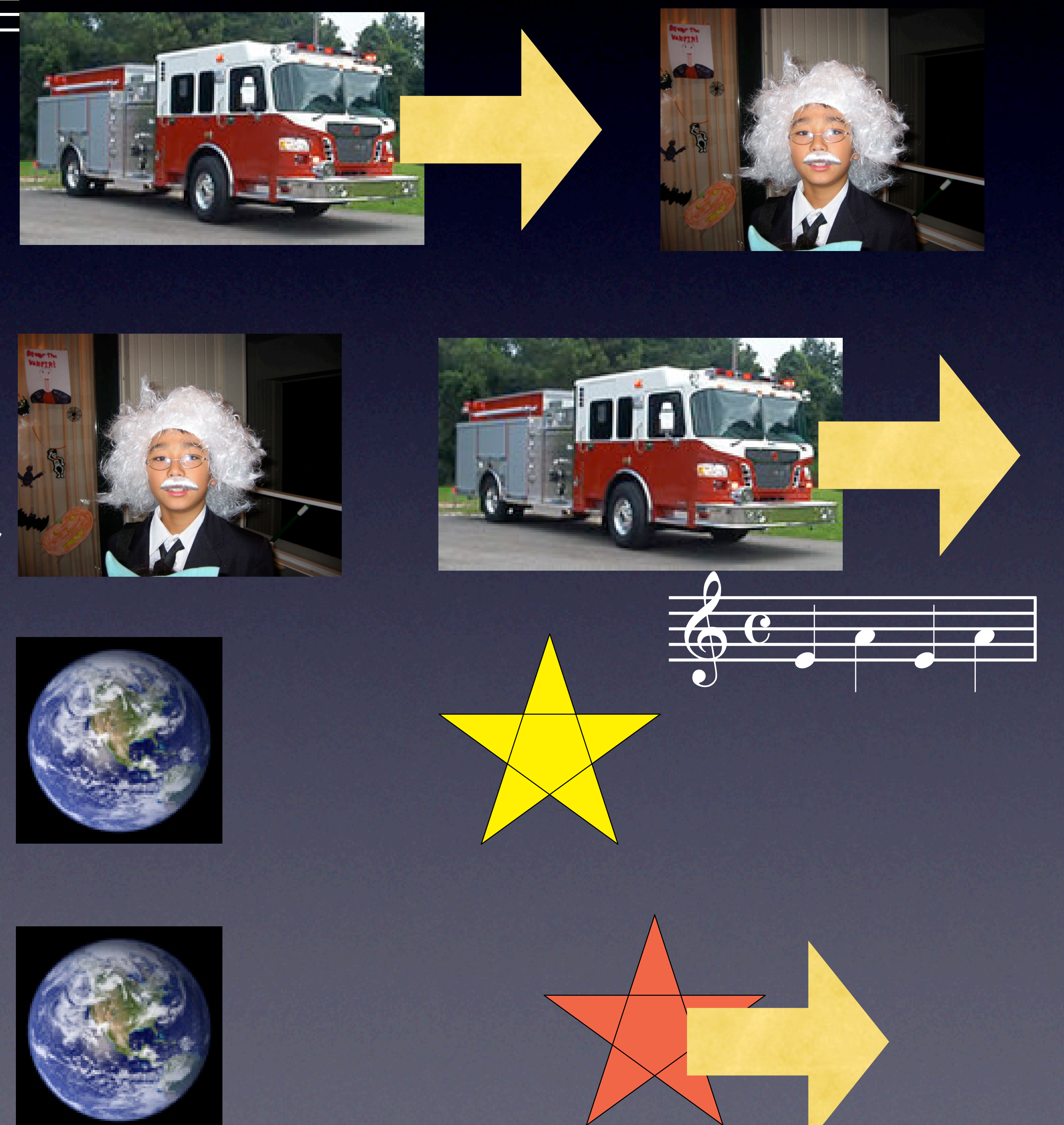
Physics 221A, Oct 4, 2006

Big-Bang

Universe is expanding

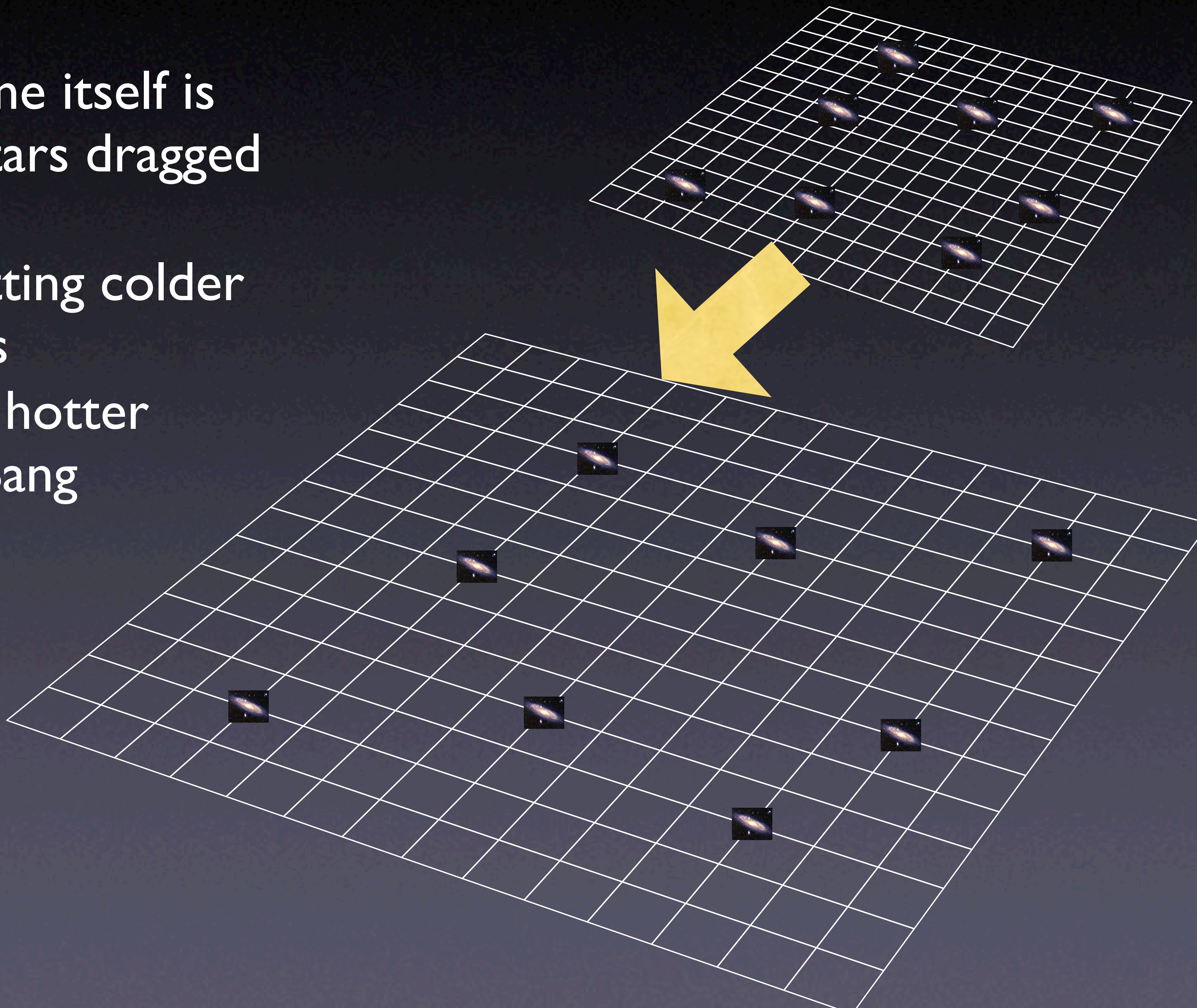


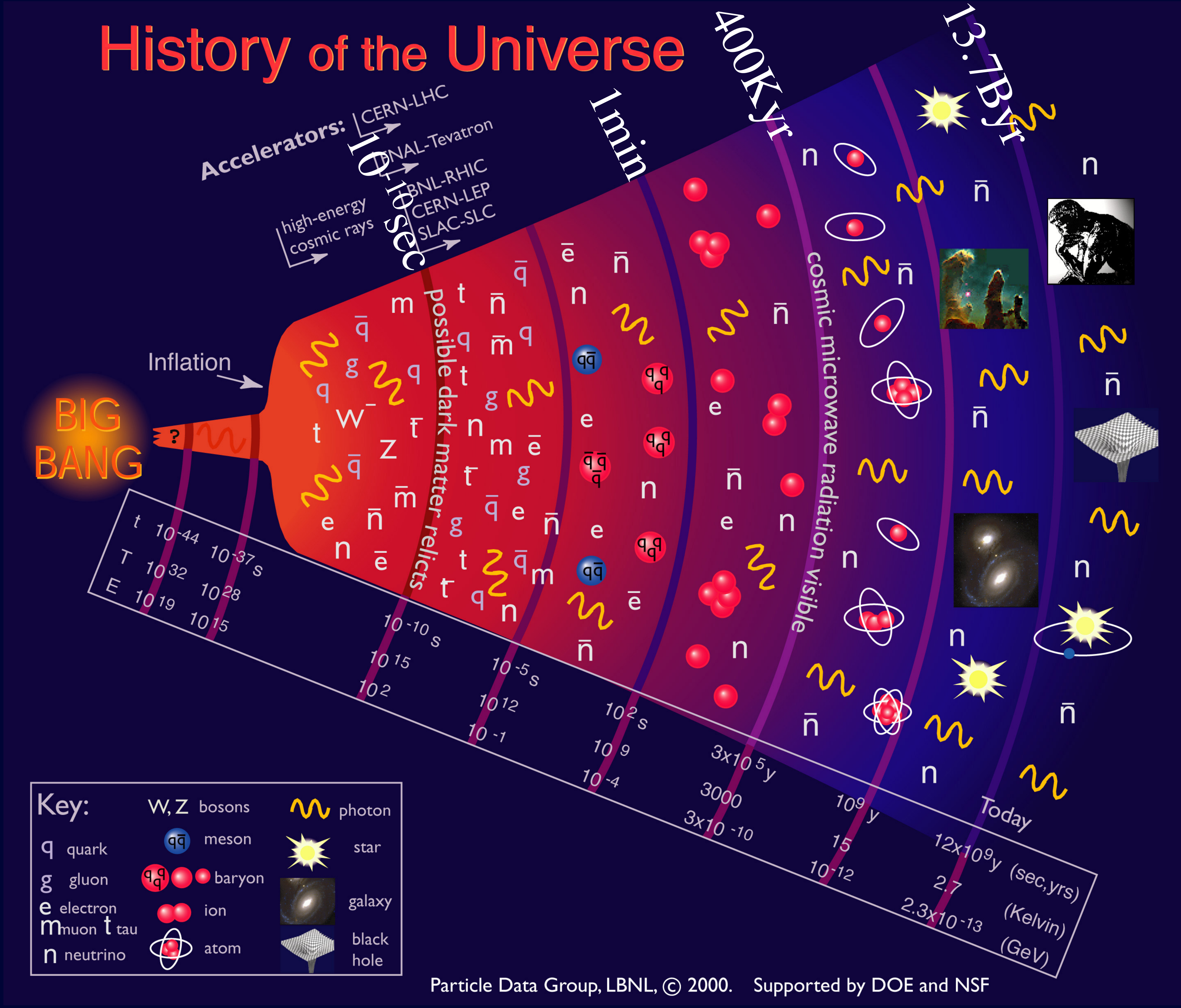
- Approaching ambulance: higher key
- Moving-away ambulance: lower key
- Much the same way, moving-away stars: lower key (redder) in spectrum of light
- We see distant stars/ galaxies are redder



Expansion of Space

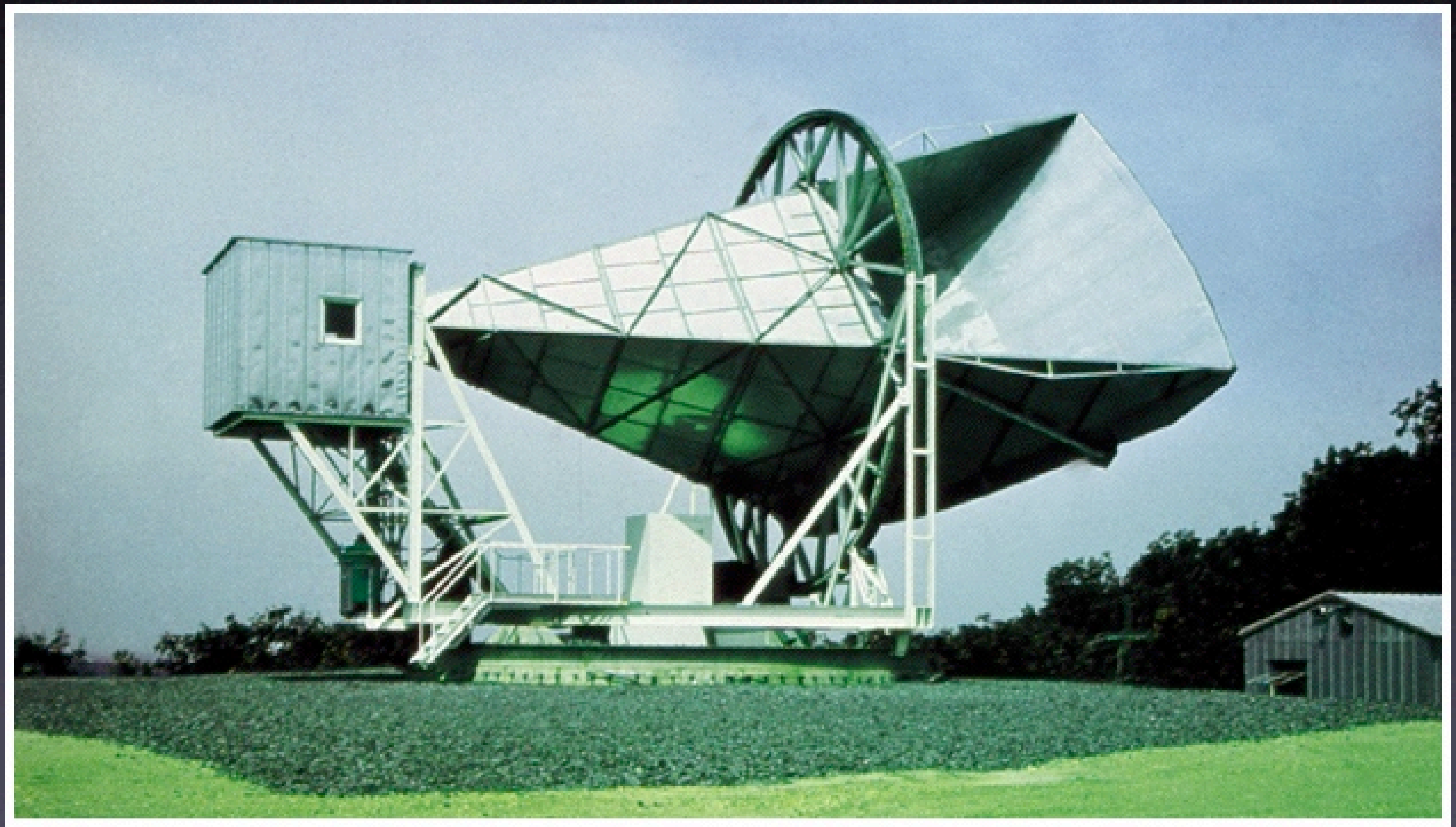
- The spacetime itself is stretching, stars dragged away
- Universe getting colder as it expands
- It was much hotter earlier: Big Bang



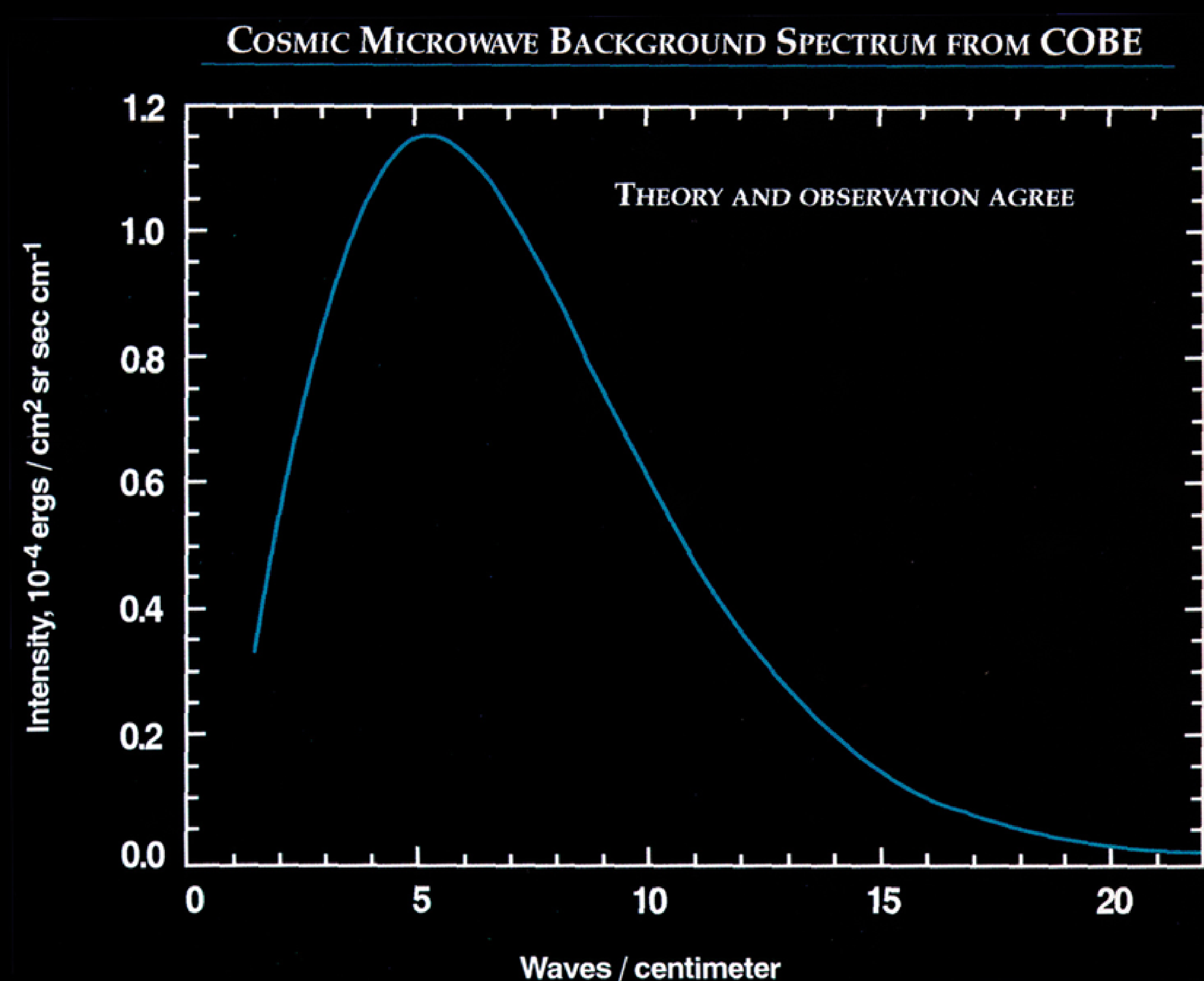

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
10-10 sec
1 min
400Kyr
13.7Byr
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 102 s 3x105 y 109 y 12x109 y (sec,yrs)
T 1032 1028 1015 1012 109 3000 15 2.7 (Kelvin)
E 1019 1015 102 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

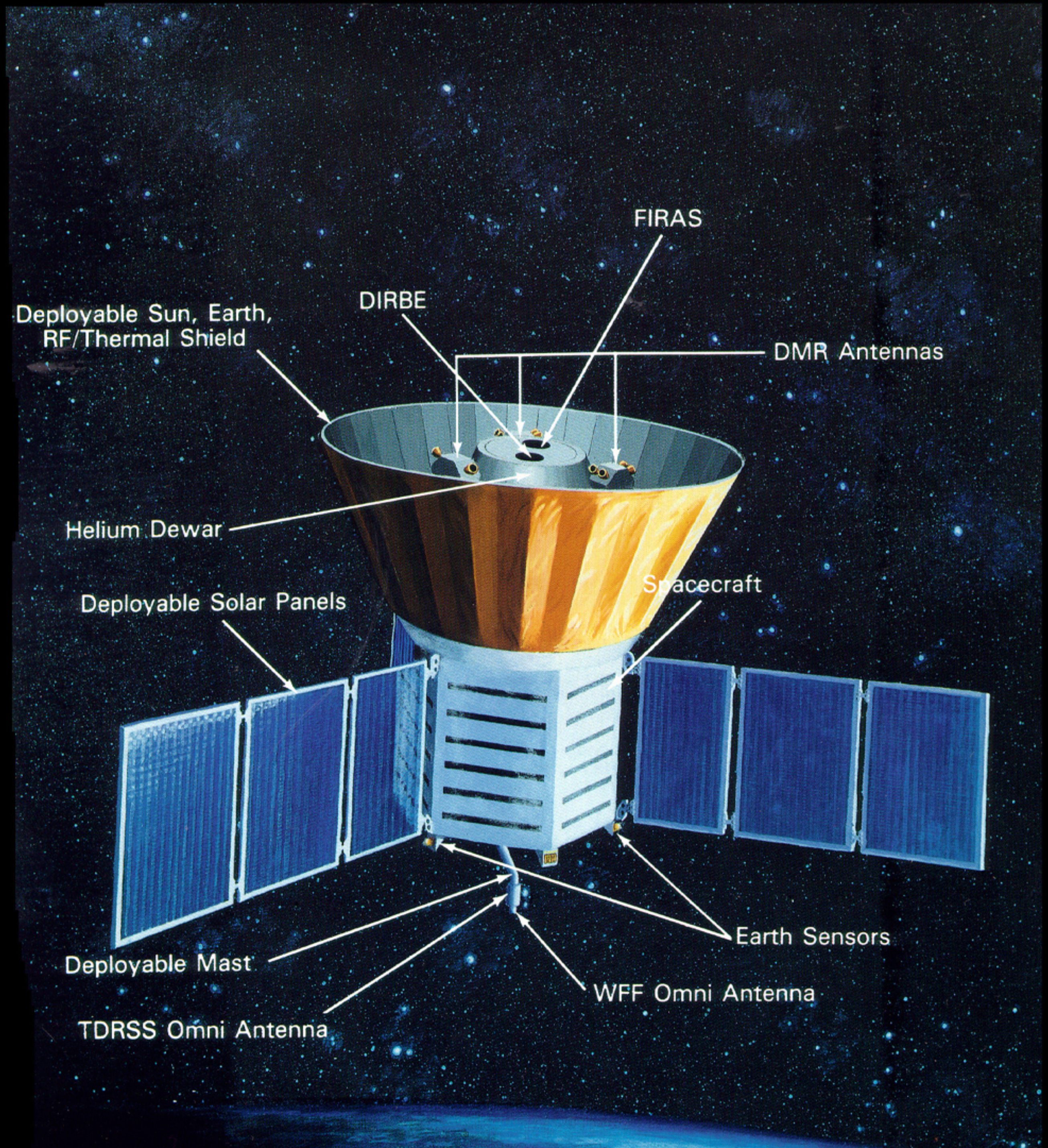
Cosmic Microwave Background

Afterglow of Big Bang



Afterglow of Big Bang





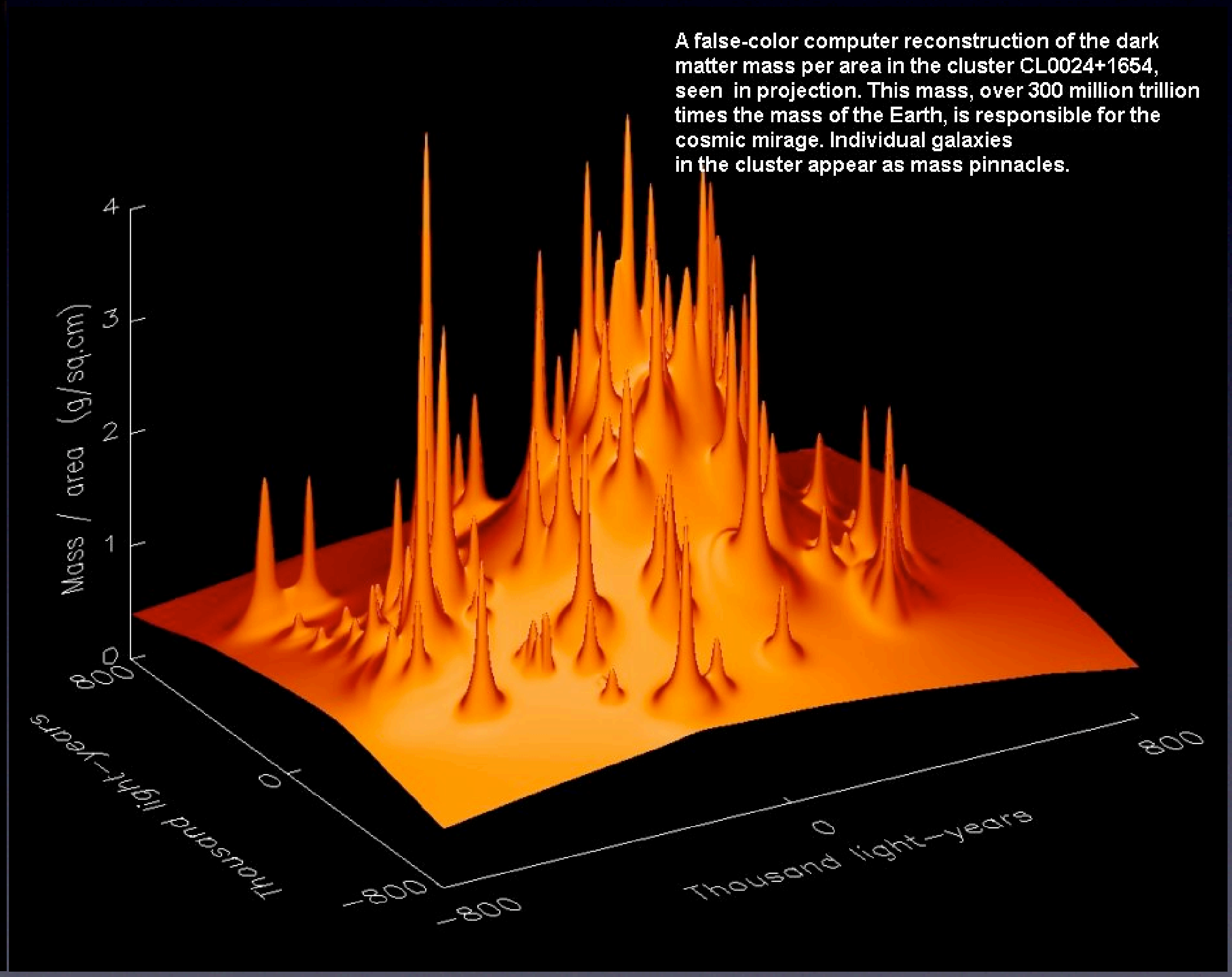
Isotropy of CMB

- The CMB has the temperature no matter which direction you look at the level of 10^{-5}
- Maybe we are at the center of the universe?
- More likely the CMB is almost completely homogeneous
- universe at T~4000K was extremely homogeneous
- How come the current universe isn't homogeneous?

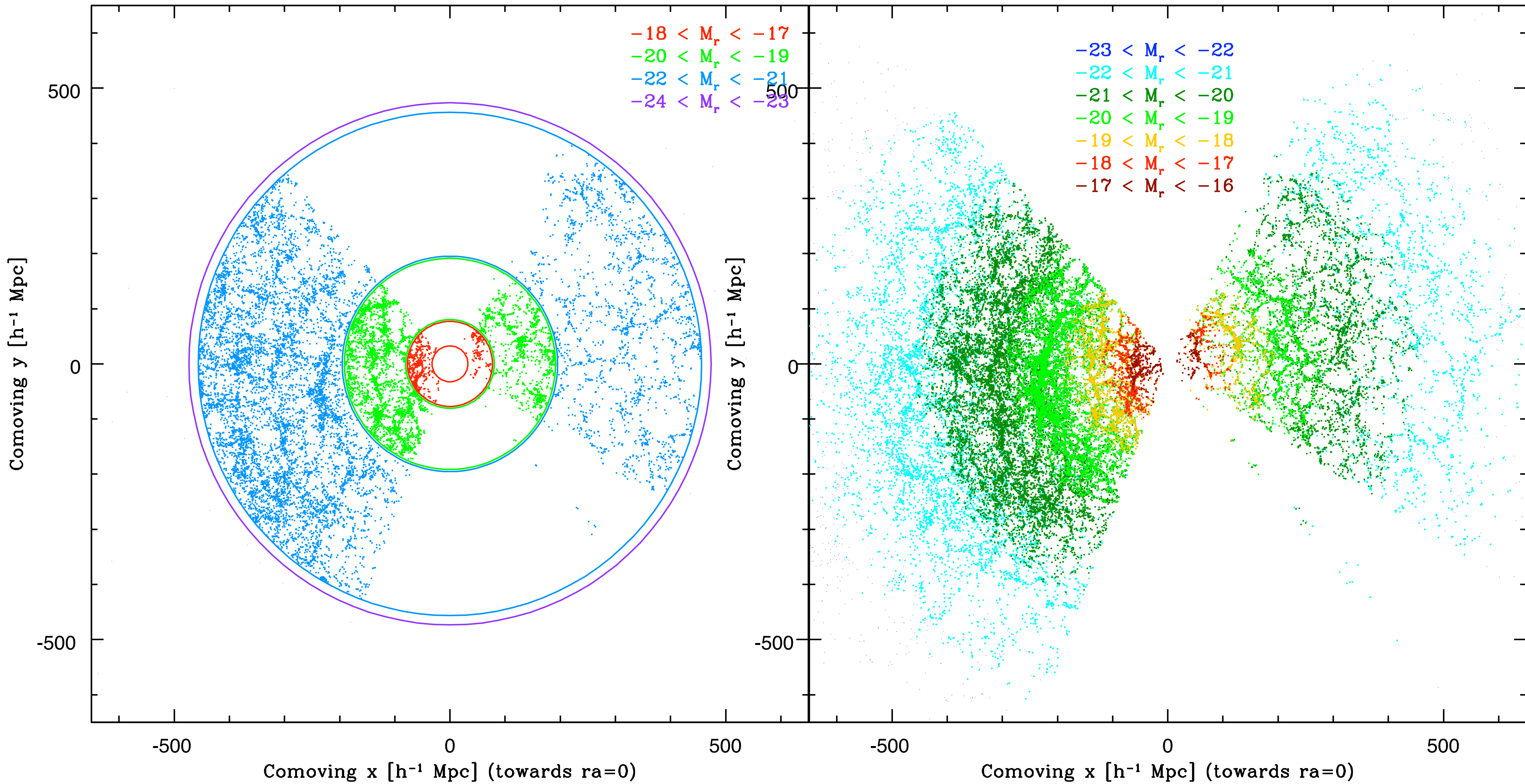
bumpy universe

COMA cluster

Cluster of galaxies



galaxy map



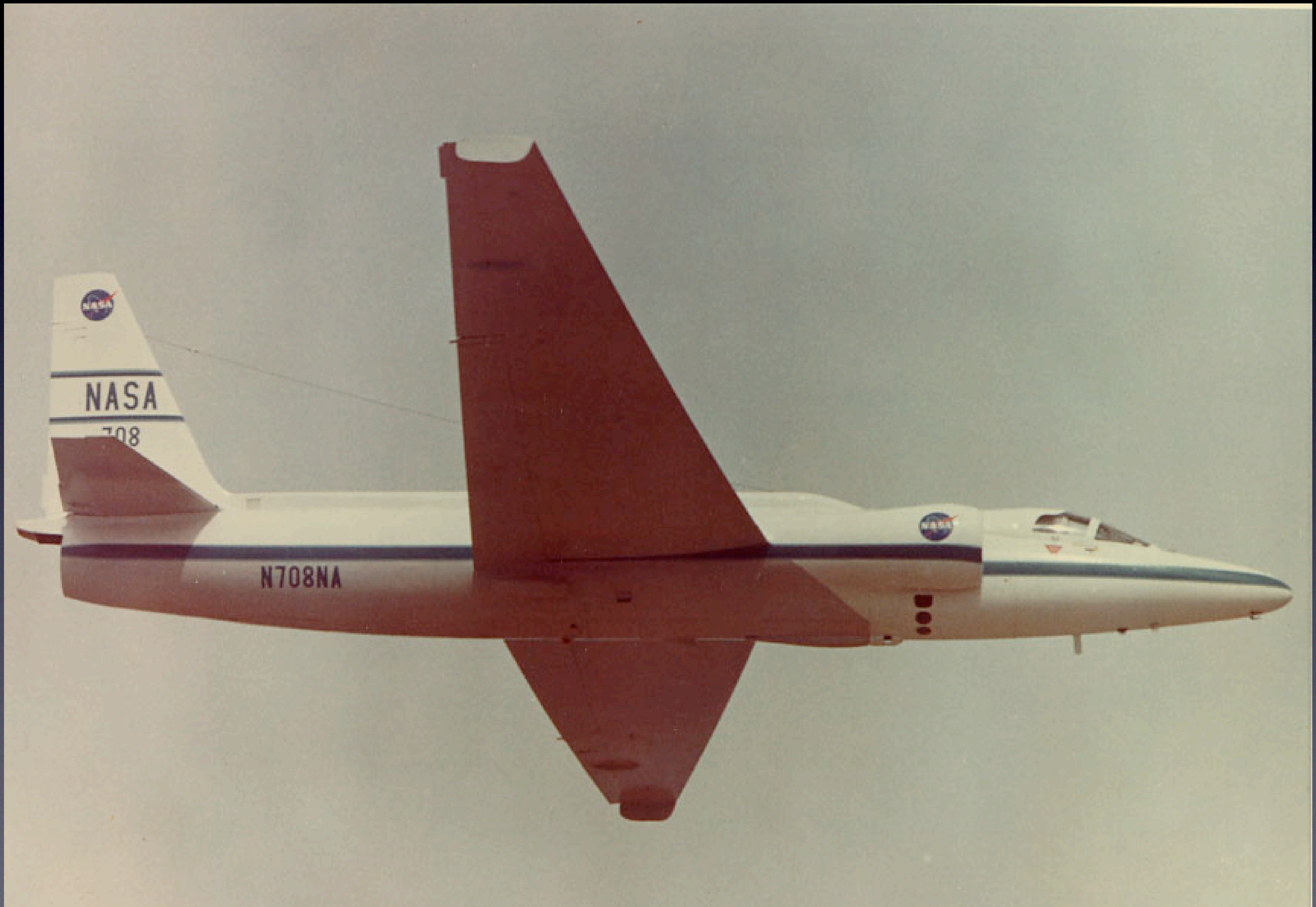
−18 < Mr < −17
−20 < Mr < −19
−22 < Mr < −21
−24 < Mr < −23
500
0
-500
Comoving y [h⁻¹ Mpc]
-500
0
500
Comoving x [h⁻¹ Mpc] (towards ra=0)
−23 < Mr < −22
−22 < Mr < −21
−21 < Mr < −20
−20 < Mr < −19
−19 < Mr < −18
−18 < Mr < −17
−17 < Mr < −16
500
0
-500
Comoving y [h⁻¹ Mpc]
-500
0
500
Comoving x [h⁻¹ Mpc] (towards ra=0)

Structure Formation

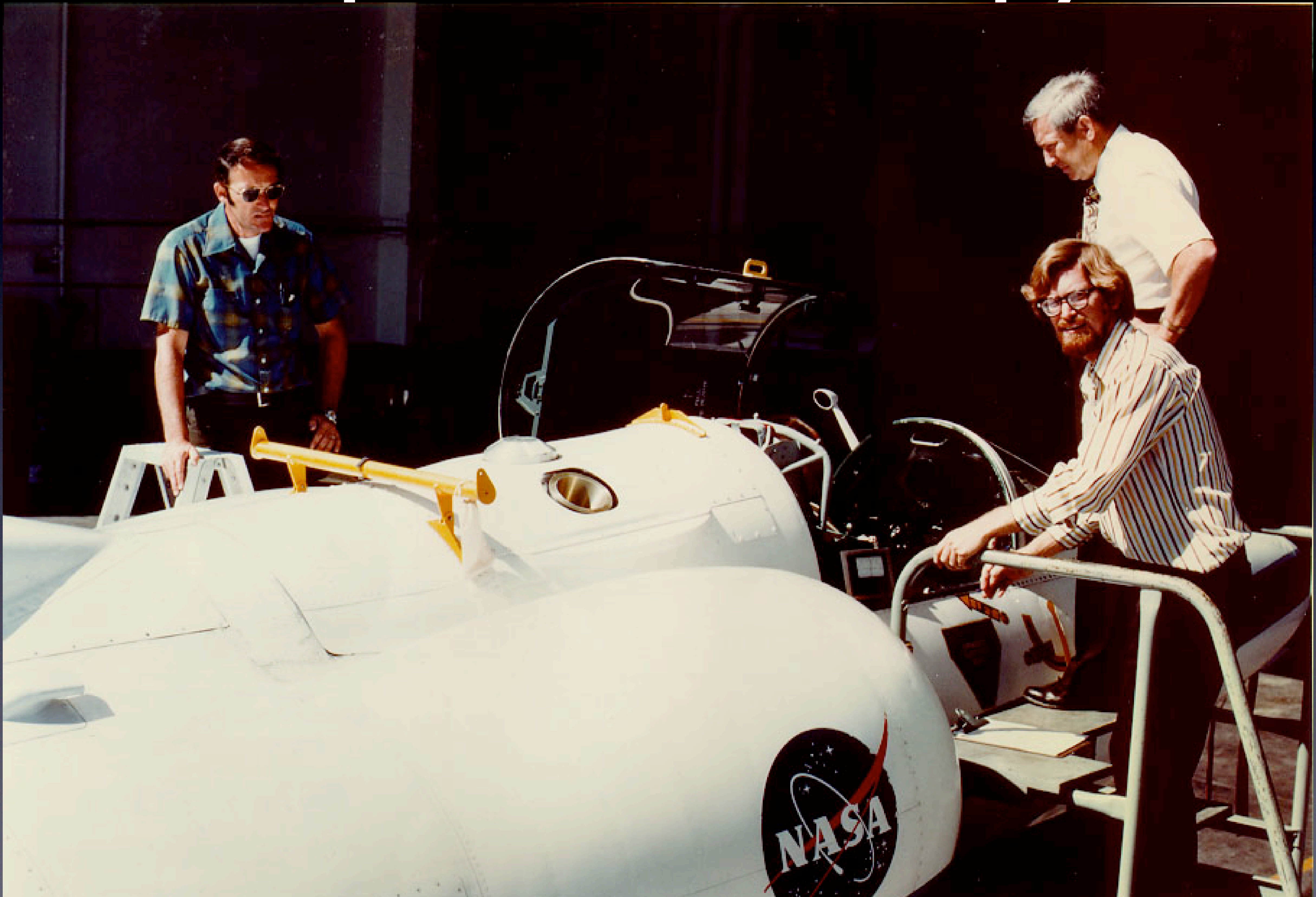
- Somehow extremely homogeneous universe eventually became bumpy
- Gravitational instability!
- gravity only pulls, doesn't push
- small ripples eventually grew, collapsed, formed galaxies, clusters, etc
- then there must be small ripples in CMB
- Holy Grail: CMB Anisotropy

CMB Anisotropy

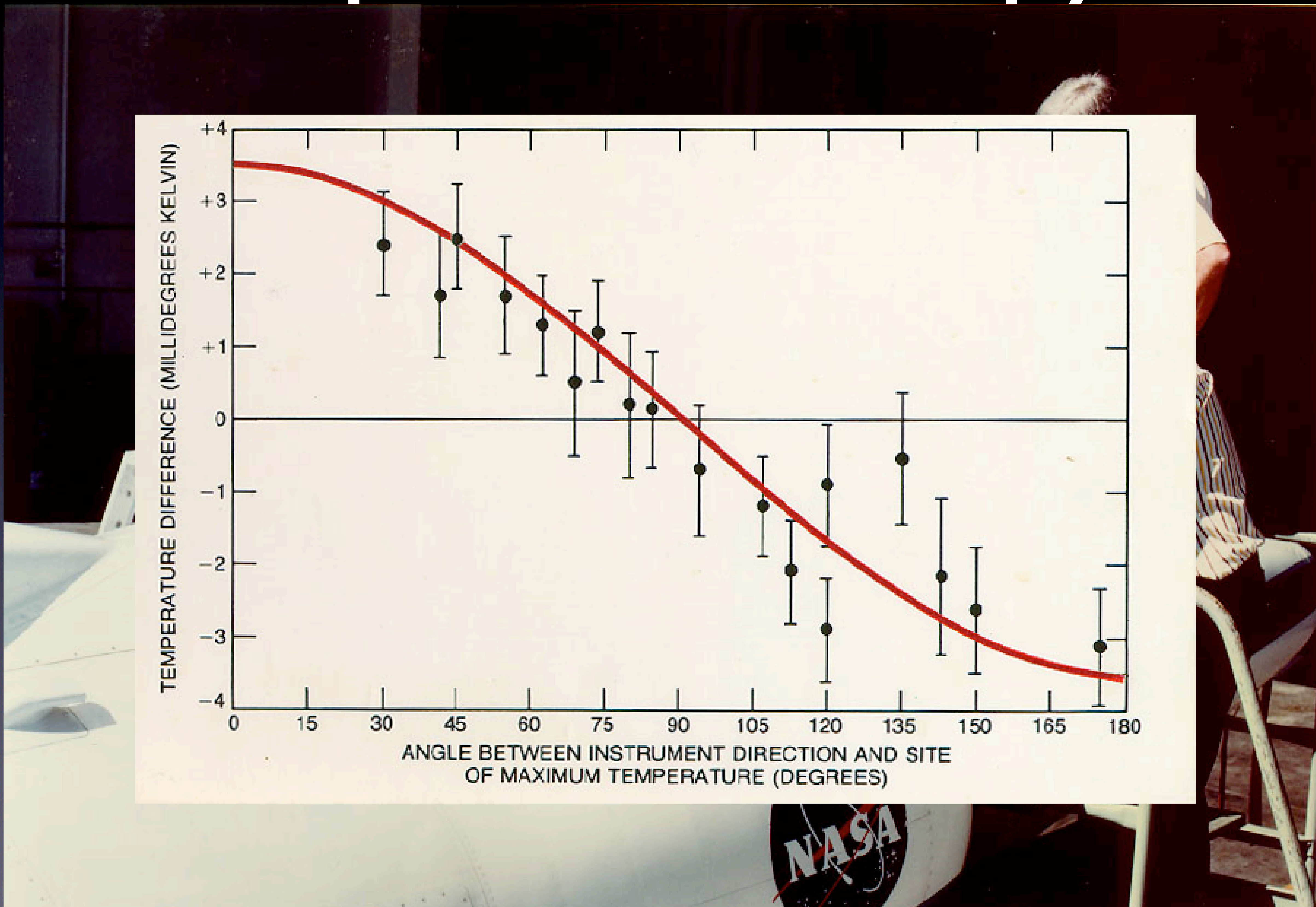
Dipole anisotropy



Dipole anisotropy



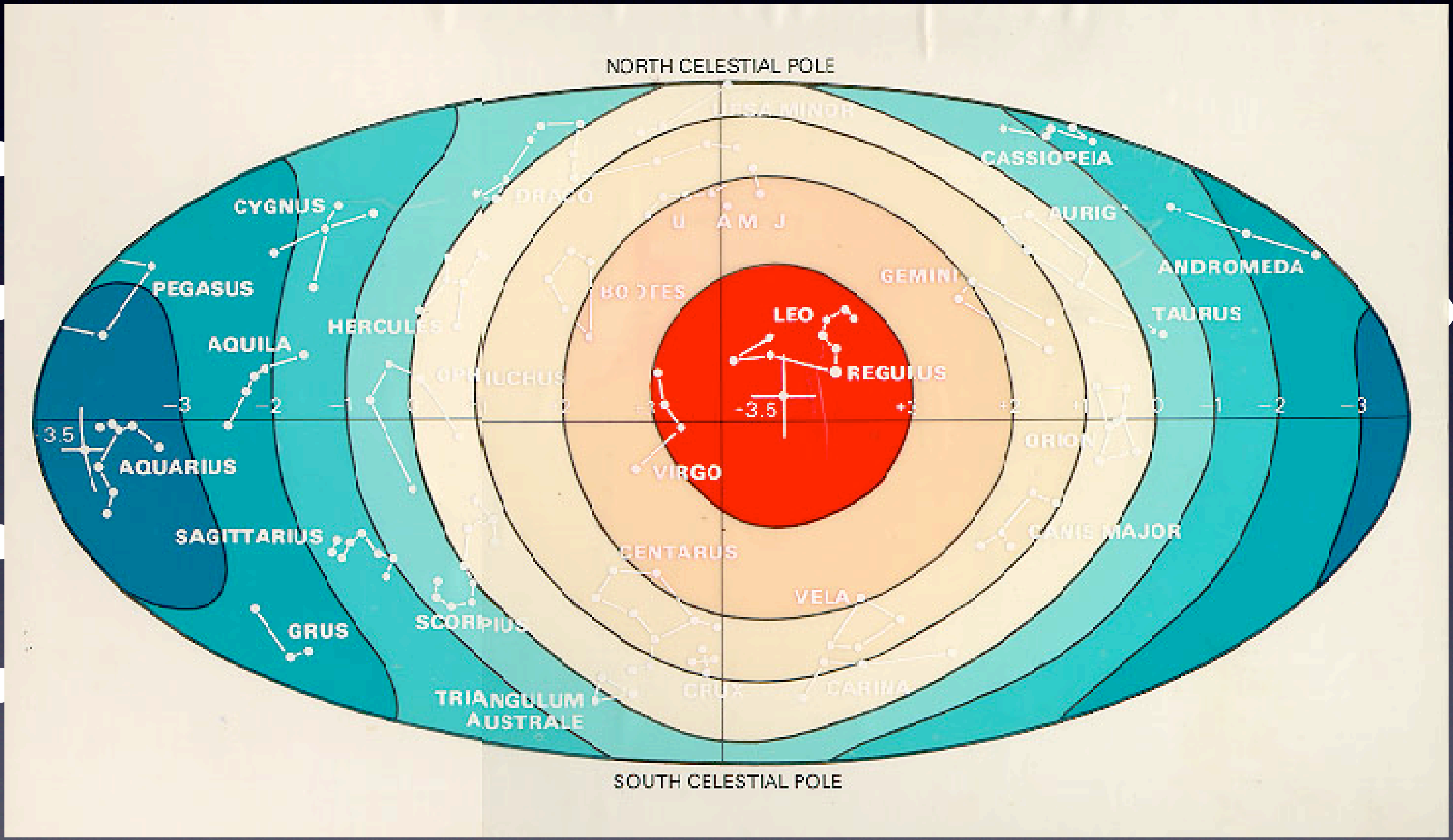
Dipole anisotropy



Dipole anisotropy

- We are not in the reference frame of CMB
- Milky Way galaxy moves at a speed of about 10^{-2} c towards Virgo cluster
- “Virgo infall”
- We are falling!

Dipole anisotropy



growing uneasiness

- Before COBE, upper limit on CMB anisotropy kept getting better and better
- Before 1998, the universe appeared younger than oldest stars
- cosmologists got antsy
- “crisis in standard cosmology”
- settled by COBE and dark energy

“Big Bang not yet dead but in decline”
Nature 377, 14 (1995)

“Bang! A Big Theory May Be Shot”
A new study of the stars could rewrite the history of the universe
Times, Jan 14 (1991)

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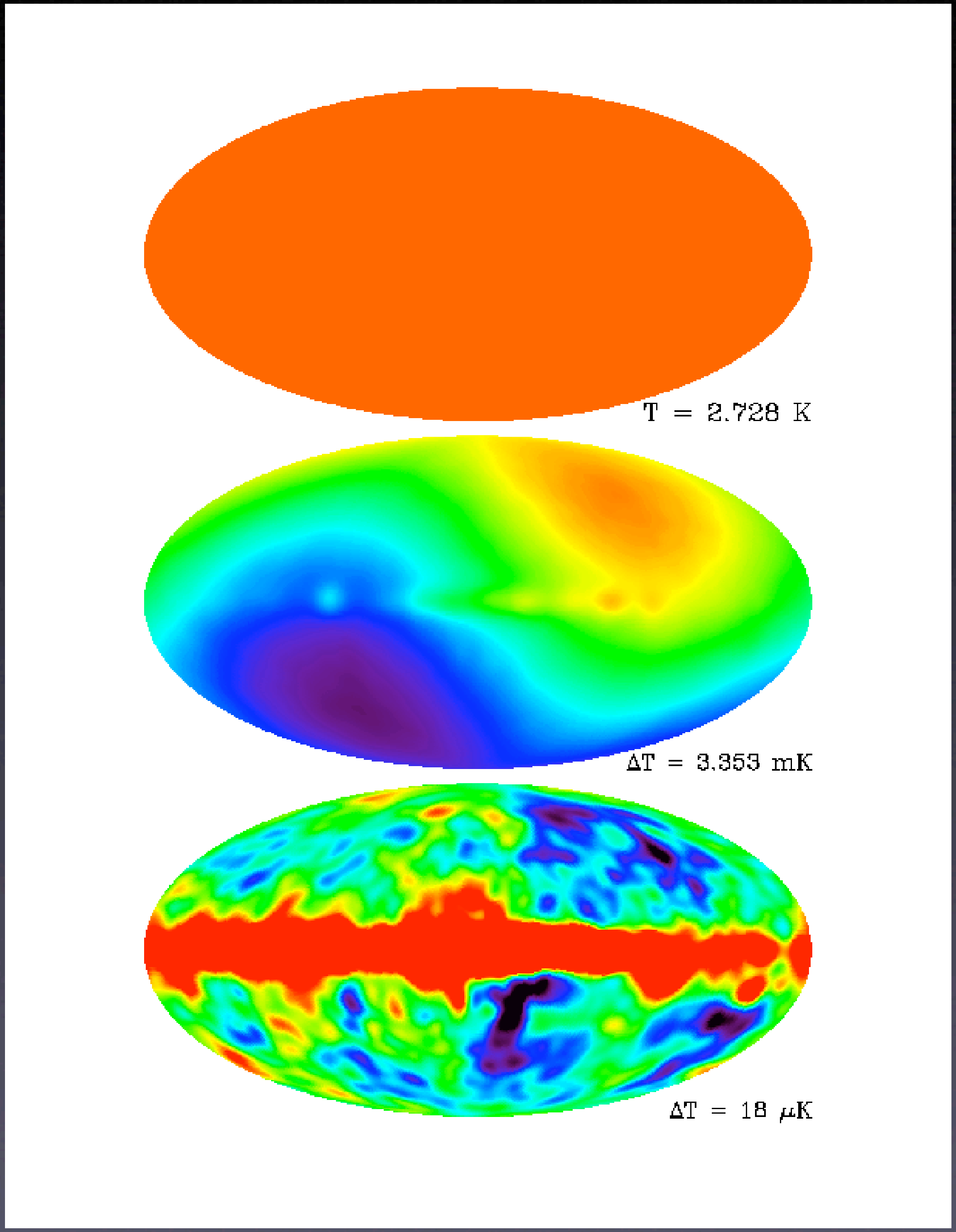
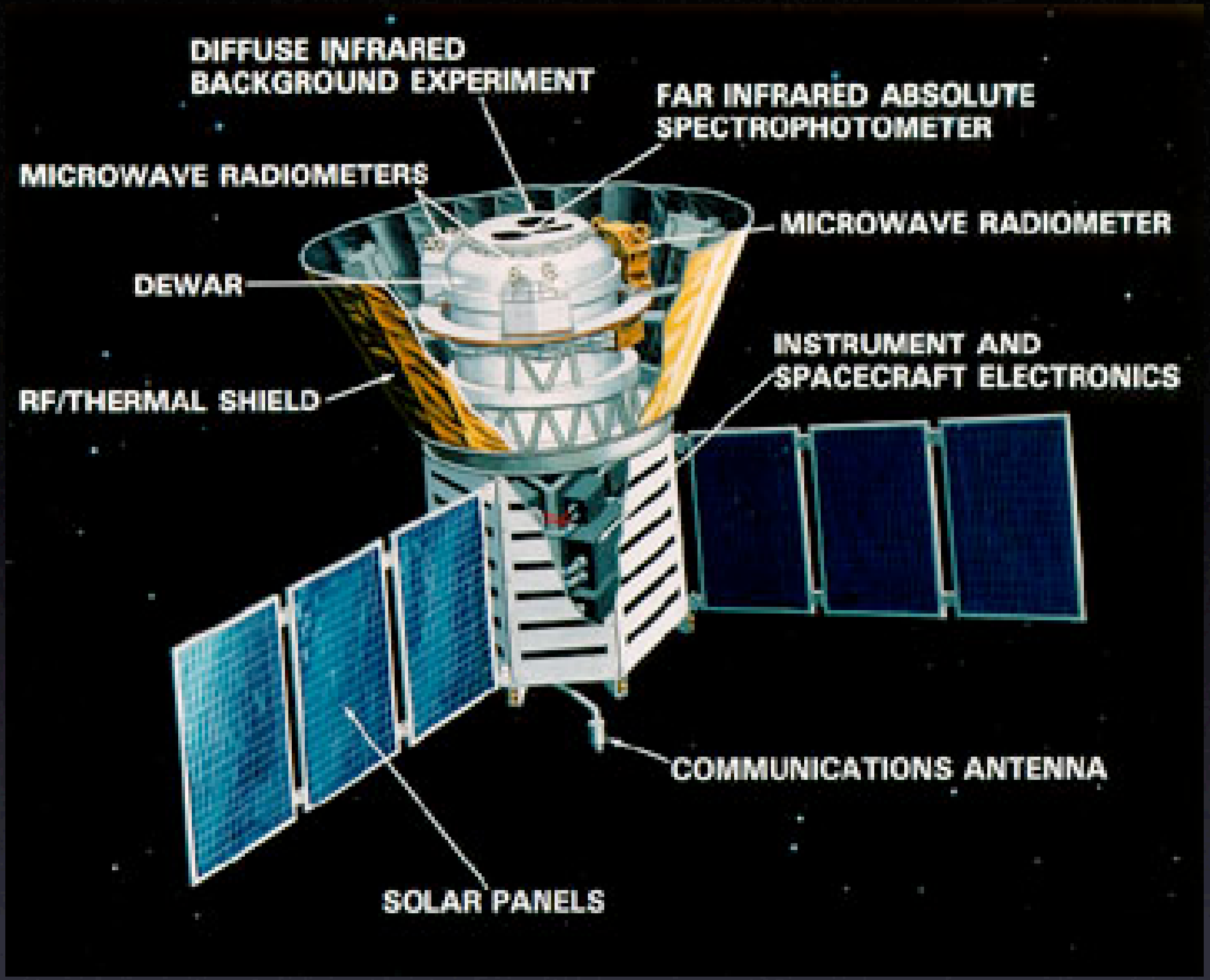
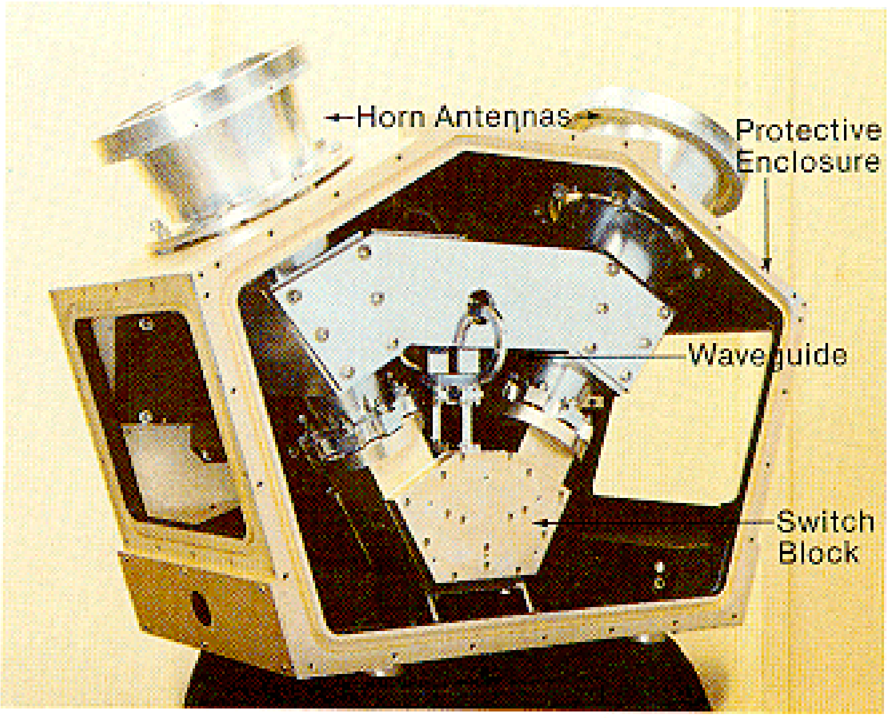
Tim

The galaxy M100, as seen by the Hubble Space Telescope. Images like this and other new discoveries are turning theories of the cosmos upside down.

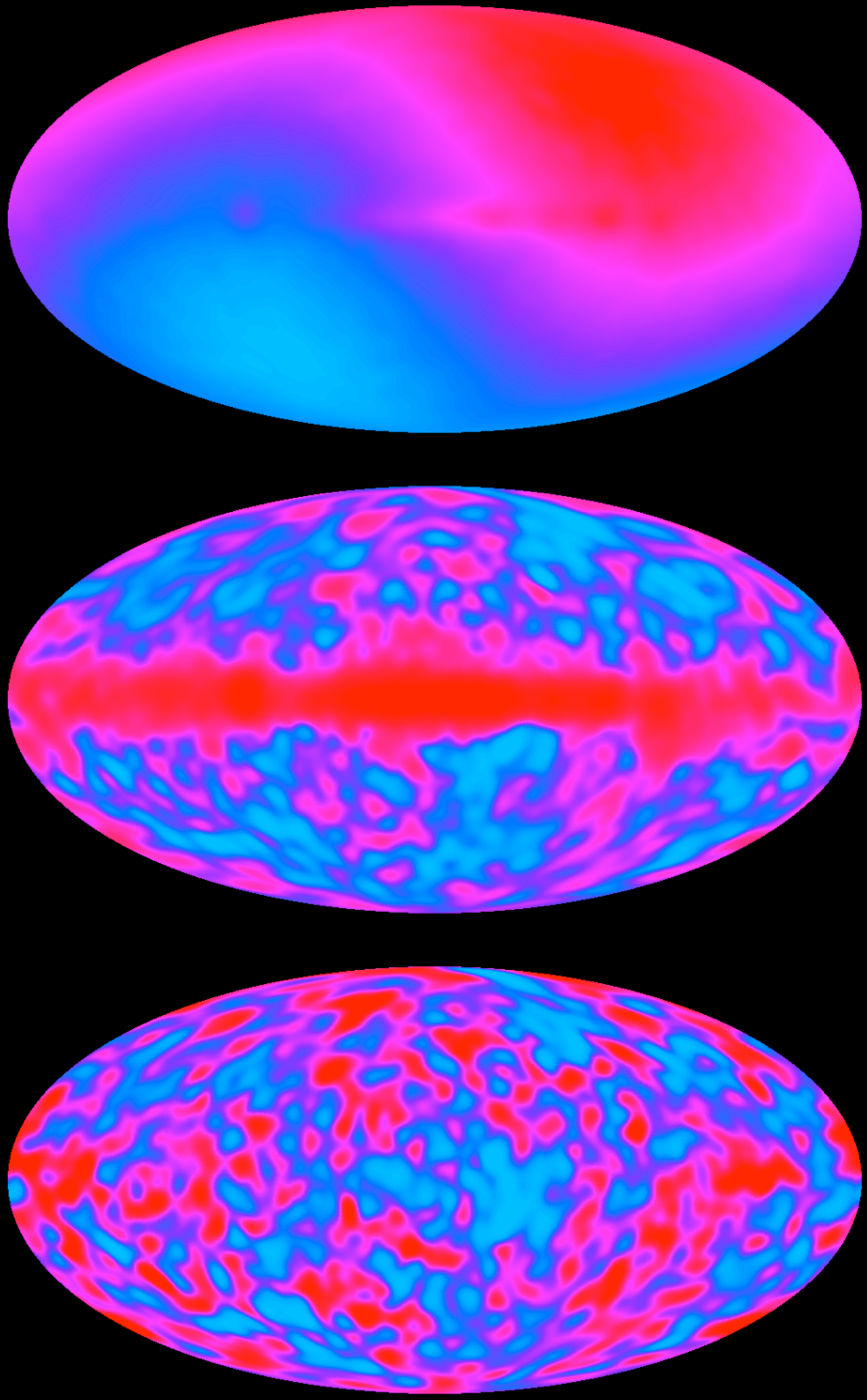
DMR



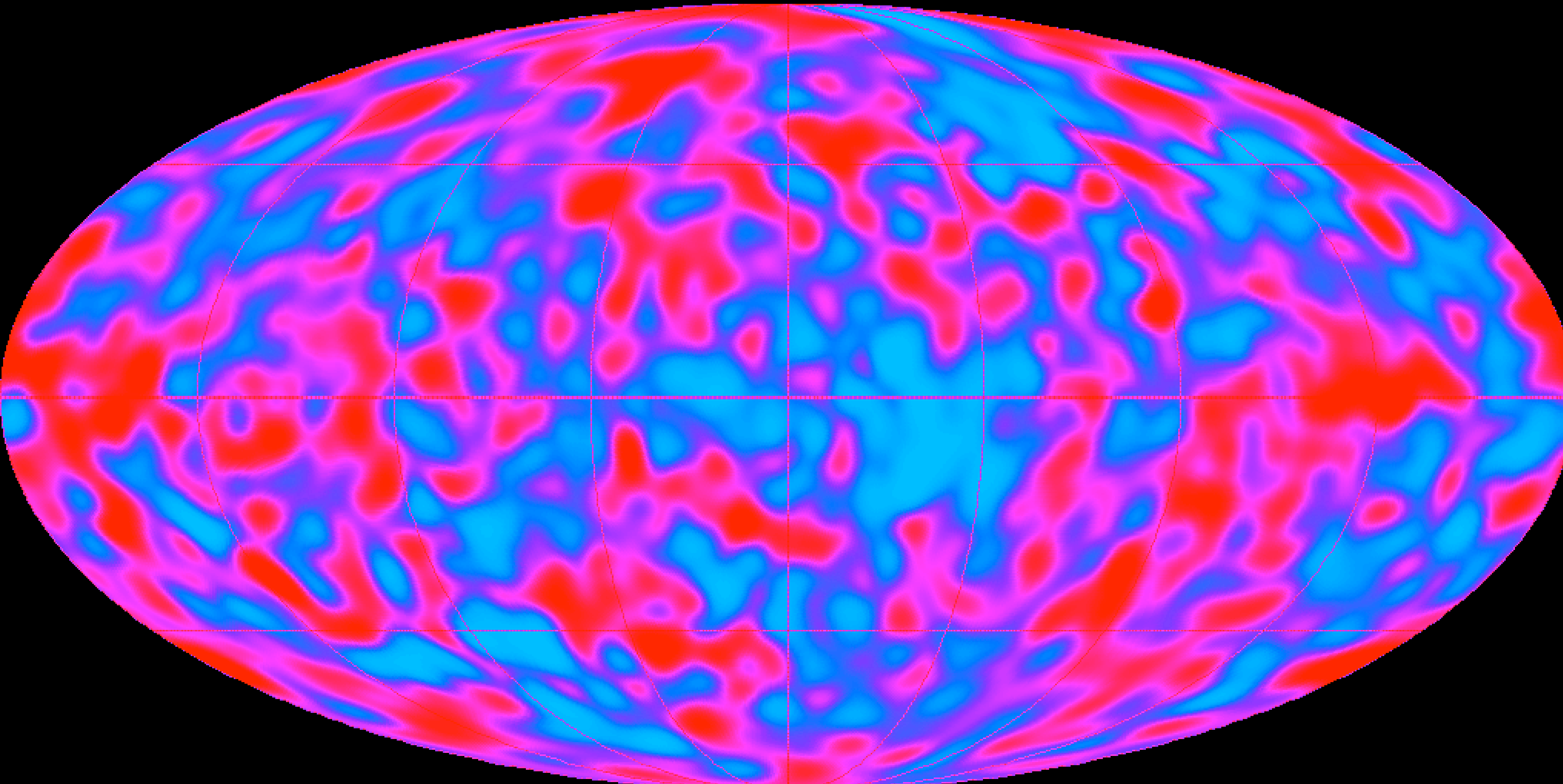


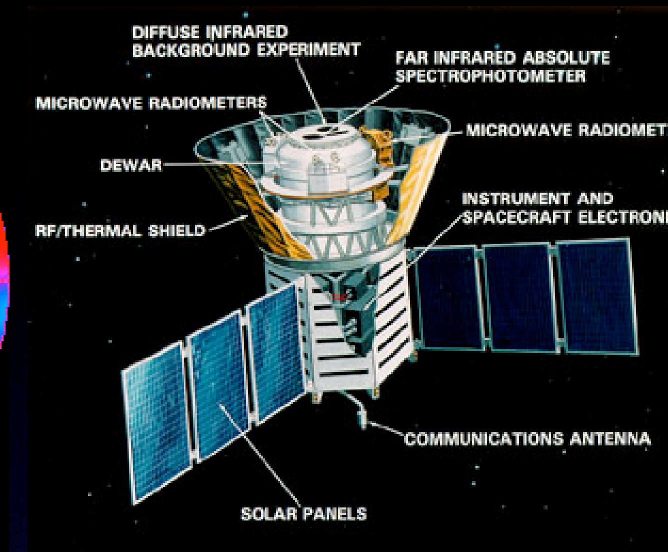


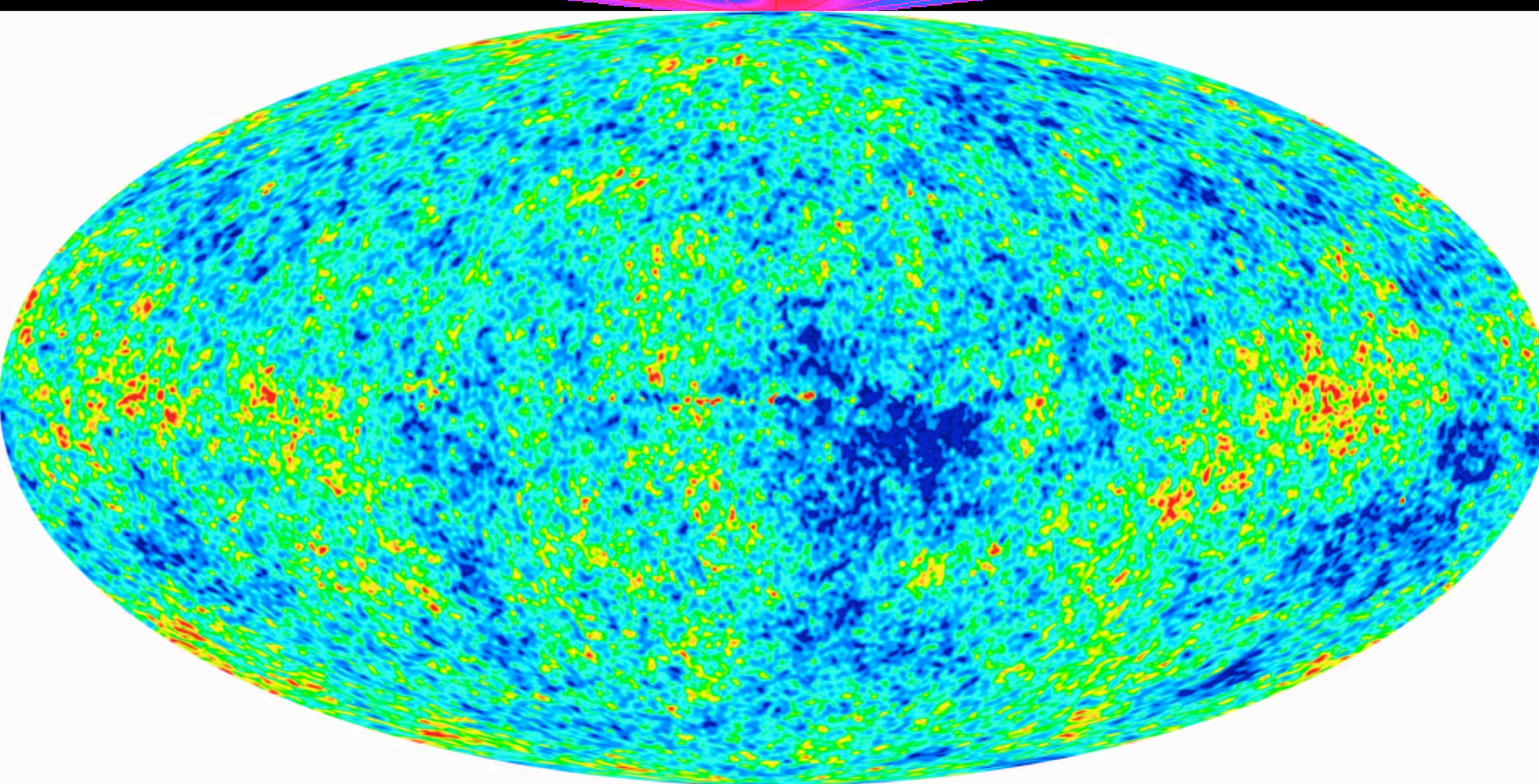
The 9.6 mm DMR receiver partially assembled. Corrugated cones are antennas.

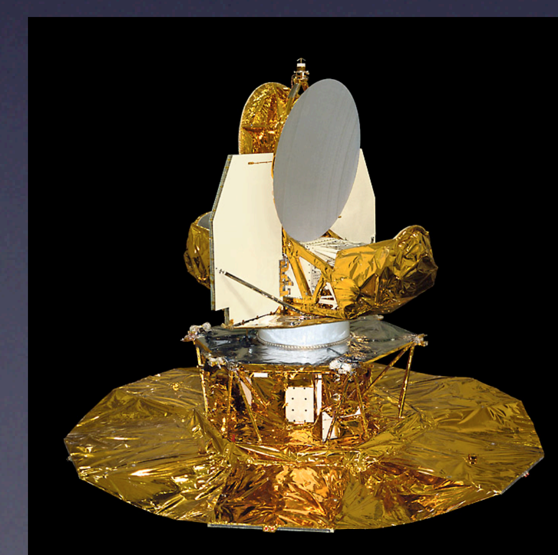


“If you are a religious person it's like seeing the face of God.”



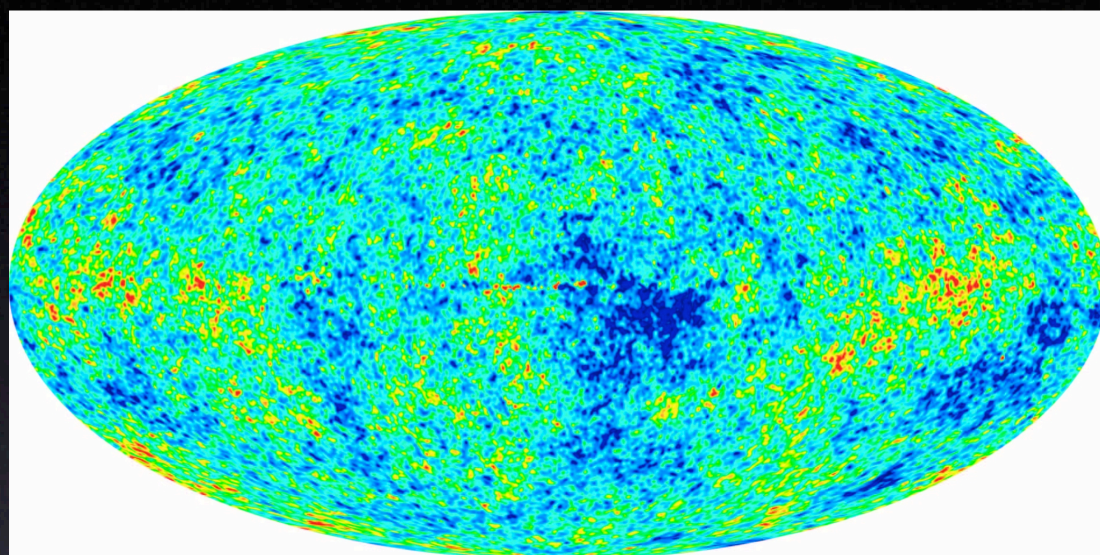

DIFFUSE INFRARED
BACKGROUND EXPERIMENT
FAR INFRARED ABSOLUTE
SPECTROPHOTOMETER
MICROWAVE RADIOMETERS
MICROWAVE RADIOMETER
DEWAR
INSTRUMENT AND
SPACECRAFT ELECTRONICS
RF/THERMAL SHIELD
COMMUNICATIONS ANTENNA
SOLAR PANELS

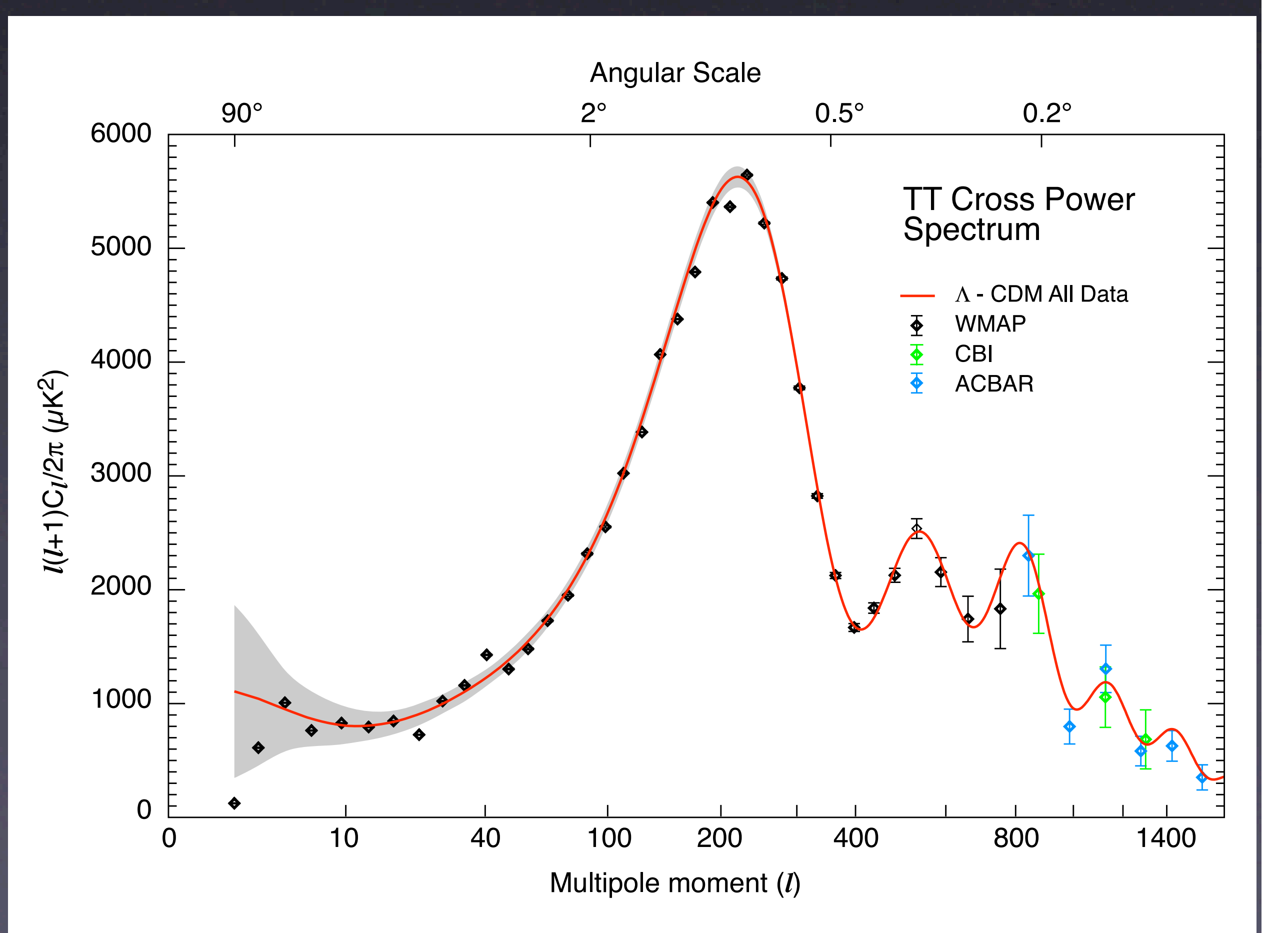


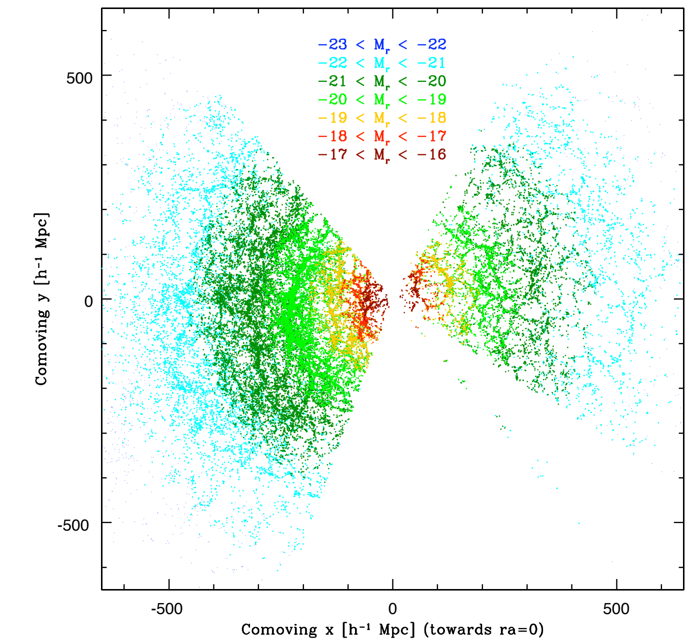


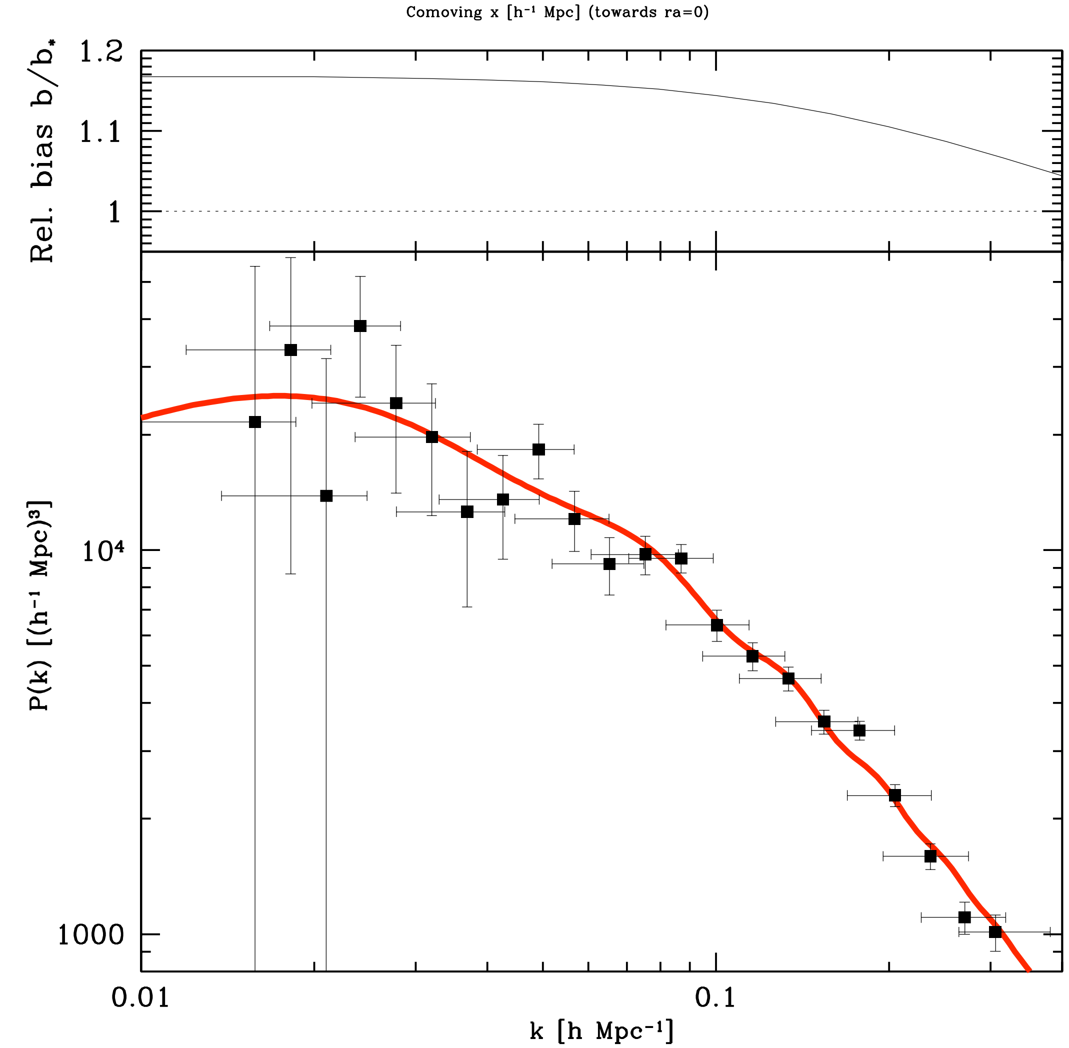
Present

Precision Cosmology









Cosmological Parameters

- One can extract cosmological parameters from linear perturbation theory

$$\rho(\vec{x},t) = \rho_0(t)(1+\delta(\vec{x},t))$$

- Use CMB anisotropy, galaxy power spectrum

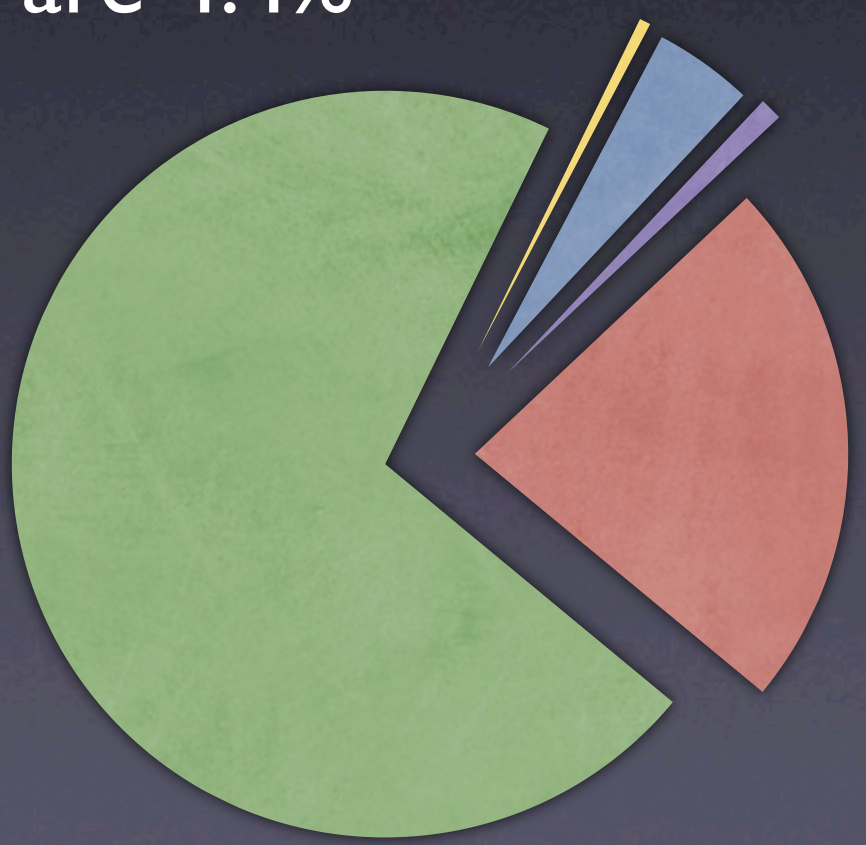
http://space.mit.edu/home/tegmark/movies_60dpi/OI_movie.html

- more recently, weak lensing, baryon oscillation
- rely on simulation once $\delta \simeq O(1)$


There are many
things we don’t see

Energy Budget of the Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.1–1.5%
- Rest of ordinary matter (electrons, protons & neutrons) are 4.4%
- Dark Matter 23%
- Dark Energy 73%
- Anti-Matter 0%
- Dark Field $\sim 10^{62}\%$??



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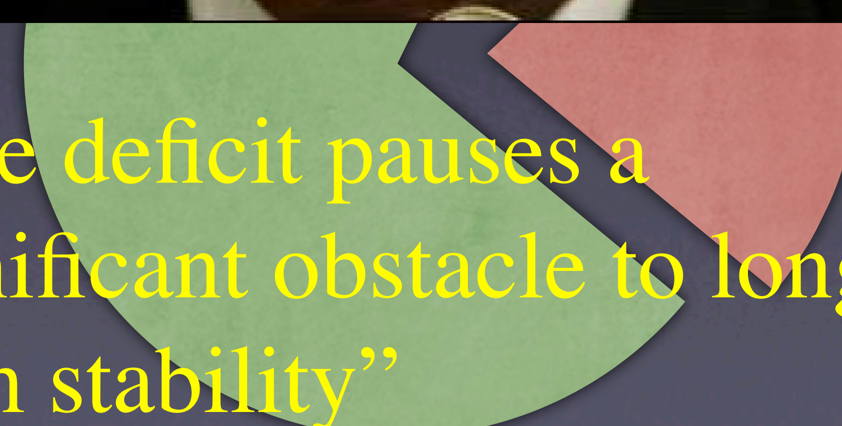
- Dark Field ~10^{62}%??

not accounted for

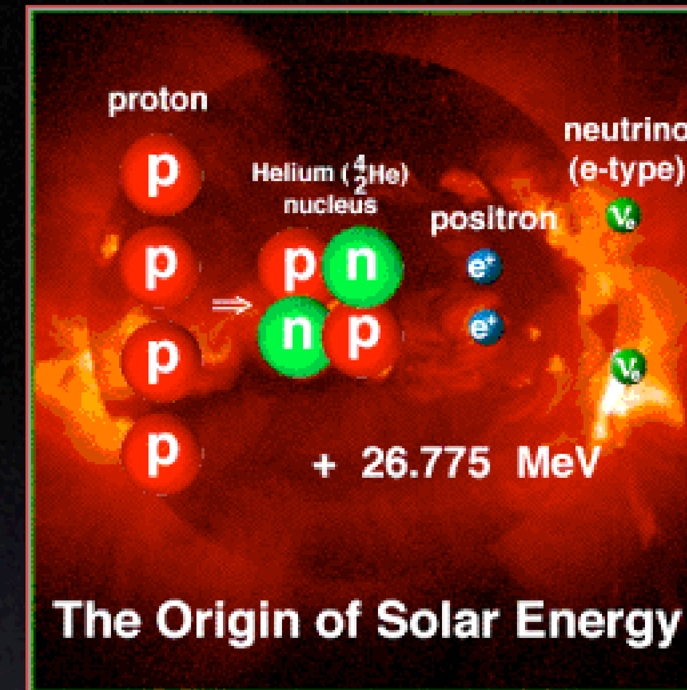


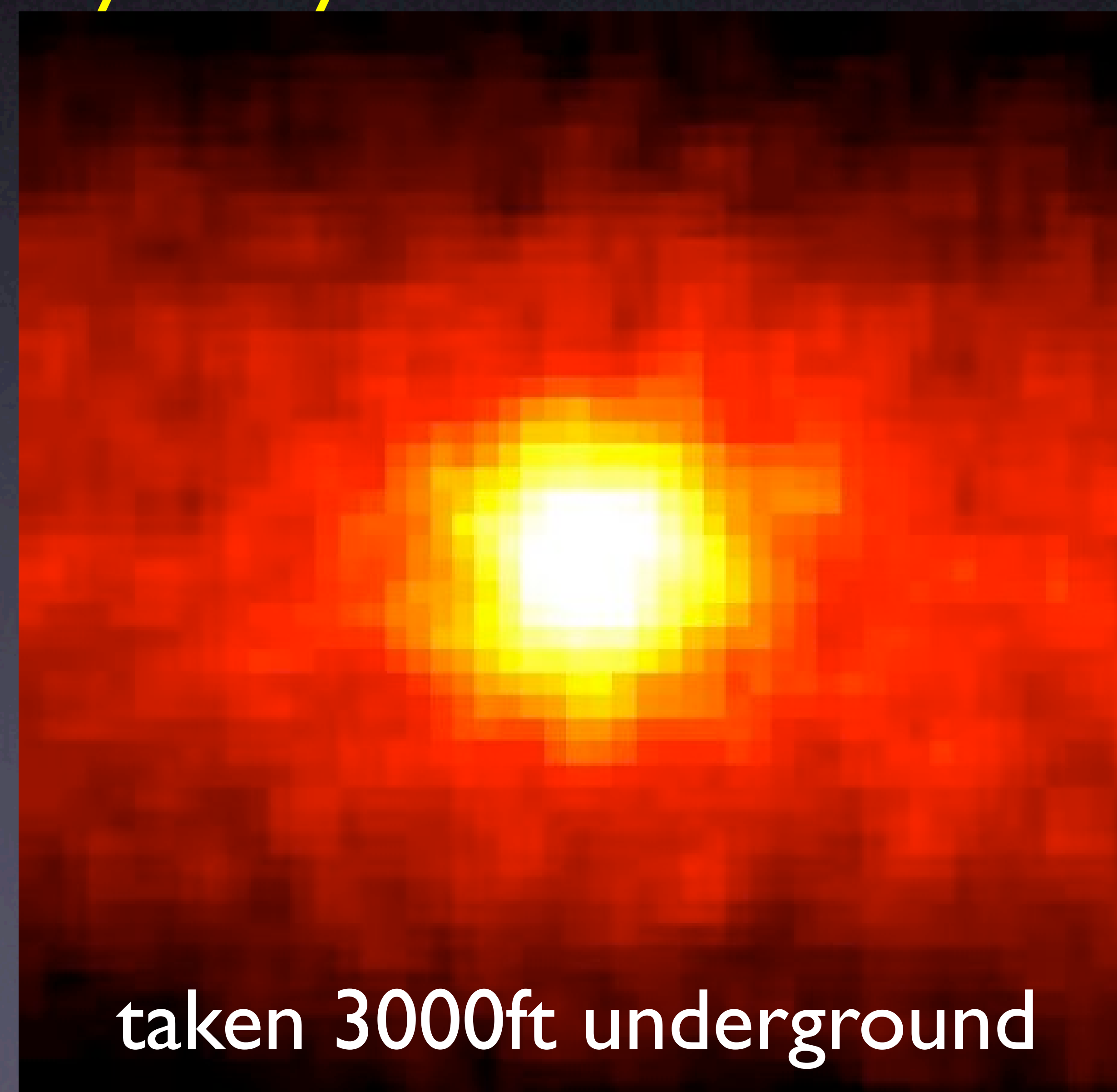
"The deficit pauses a significant obstacle to long-term stability"

Don’t be afraid of invisibles

Pauli regretted to have predicted neutrinos nobody can detect

Trillions of them go through our body every second





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DISNEY PRESENTS A PIXAR FILM
THE INCREDIBLES
NOW PLAYING
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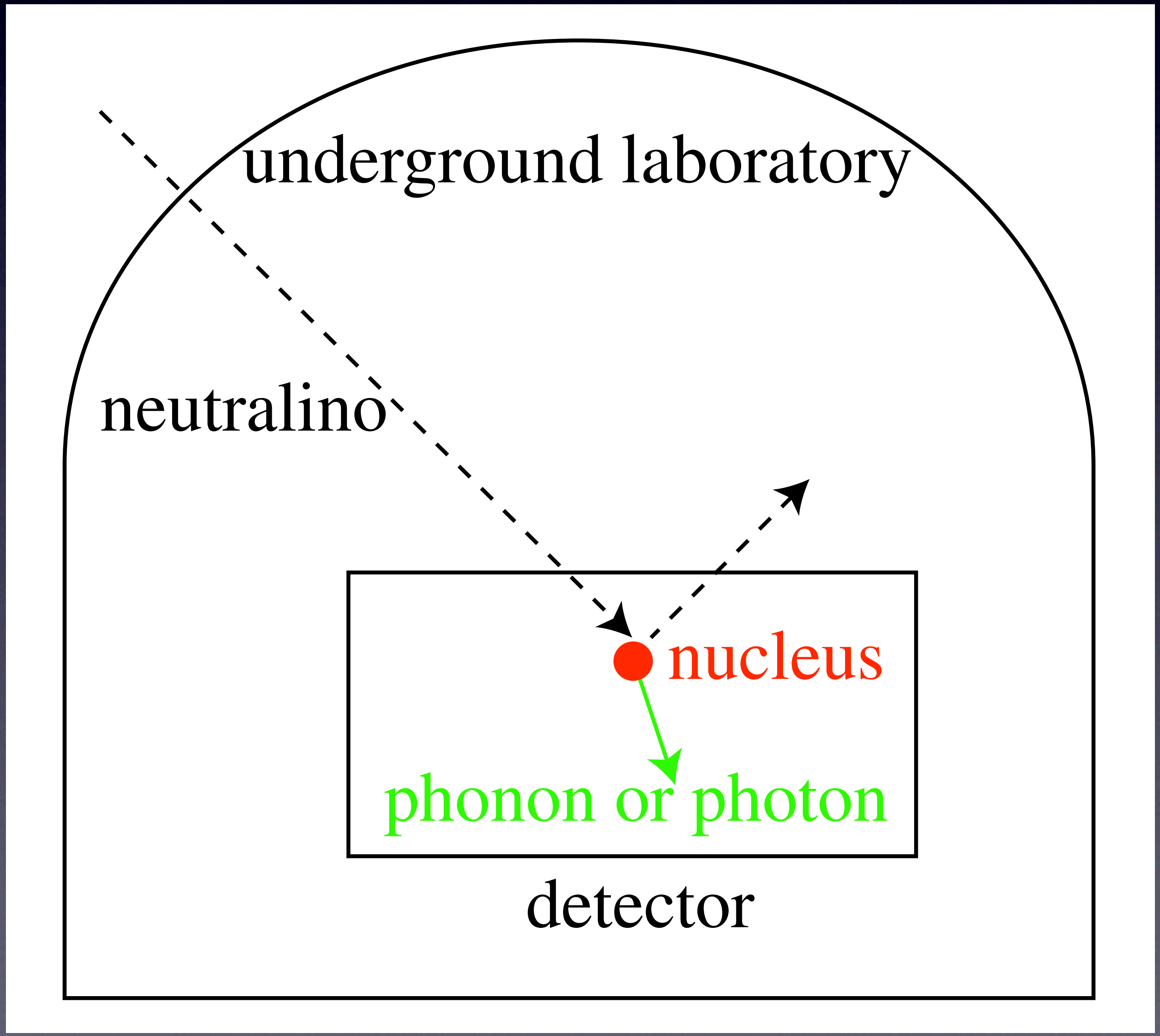
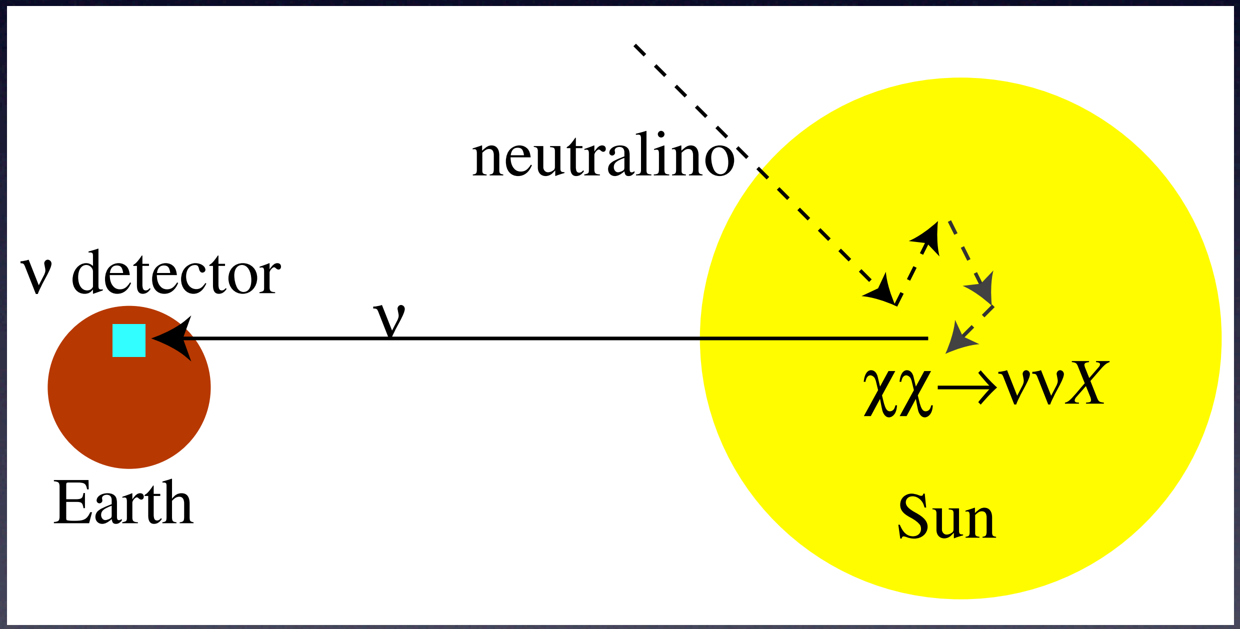
Finding Dark Matter

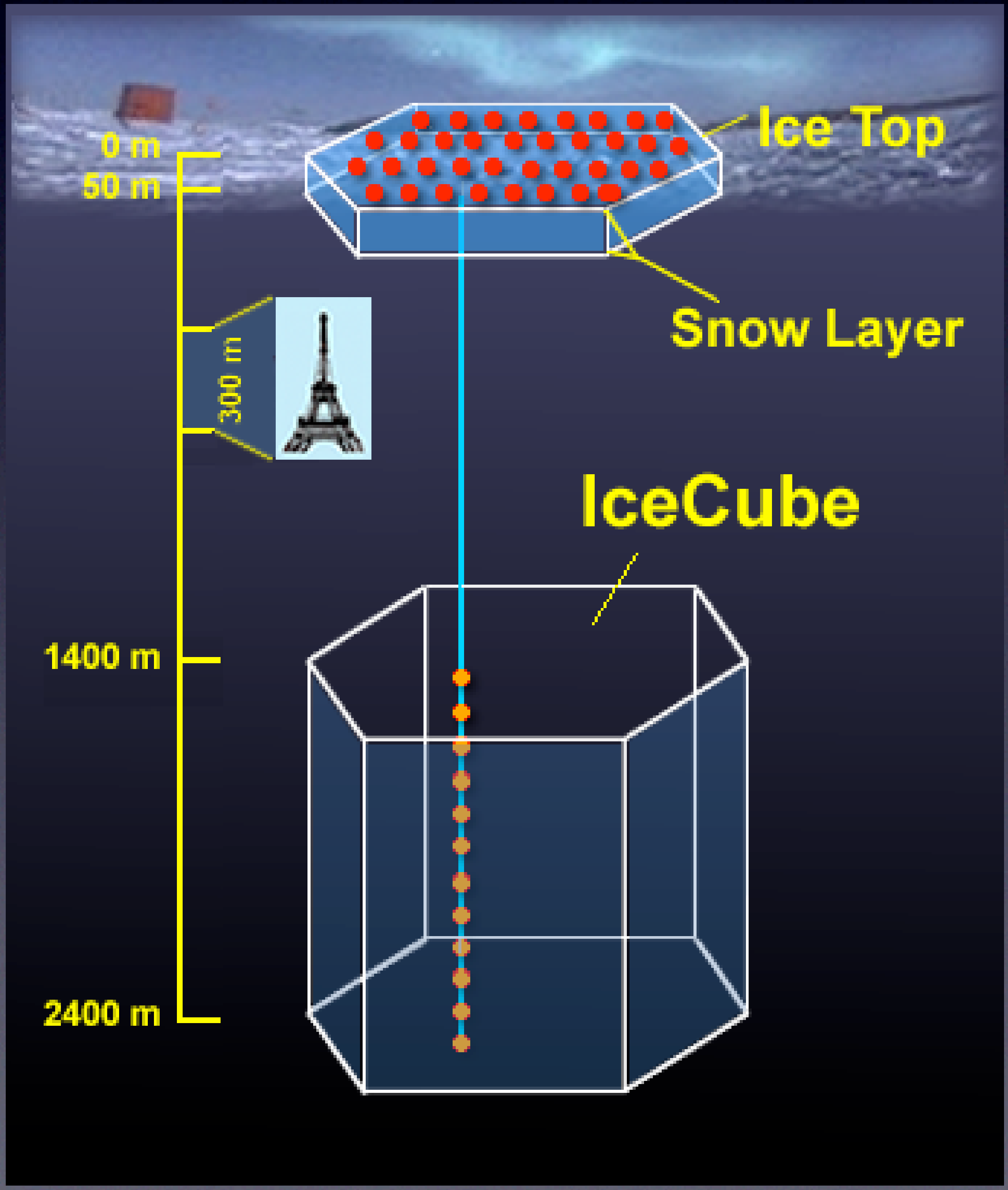
Direct method



Finding Dark Matter

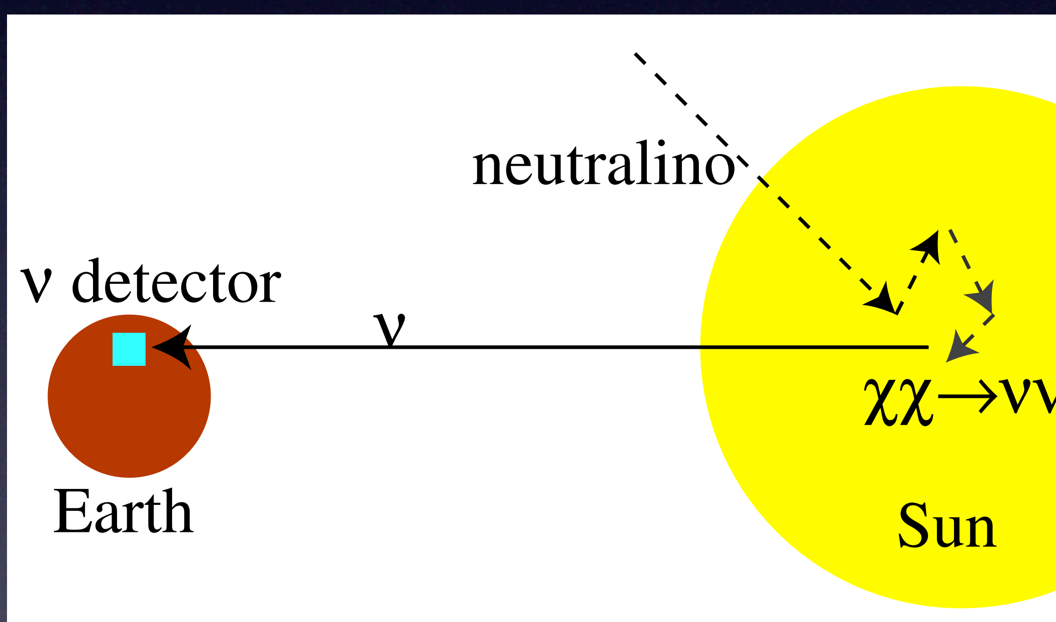
Indirect method





Finding Dark Matter

Indirect method



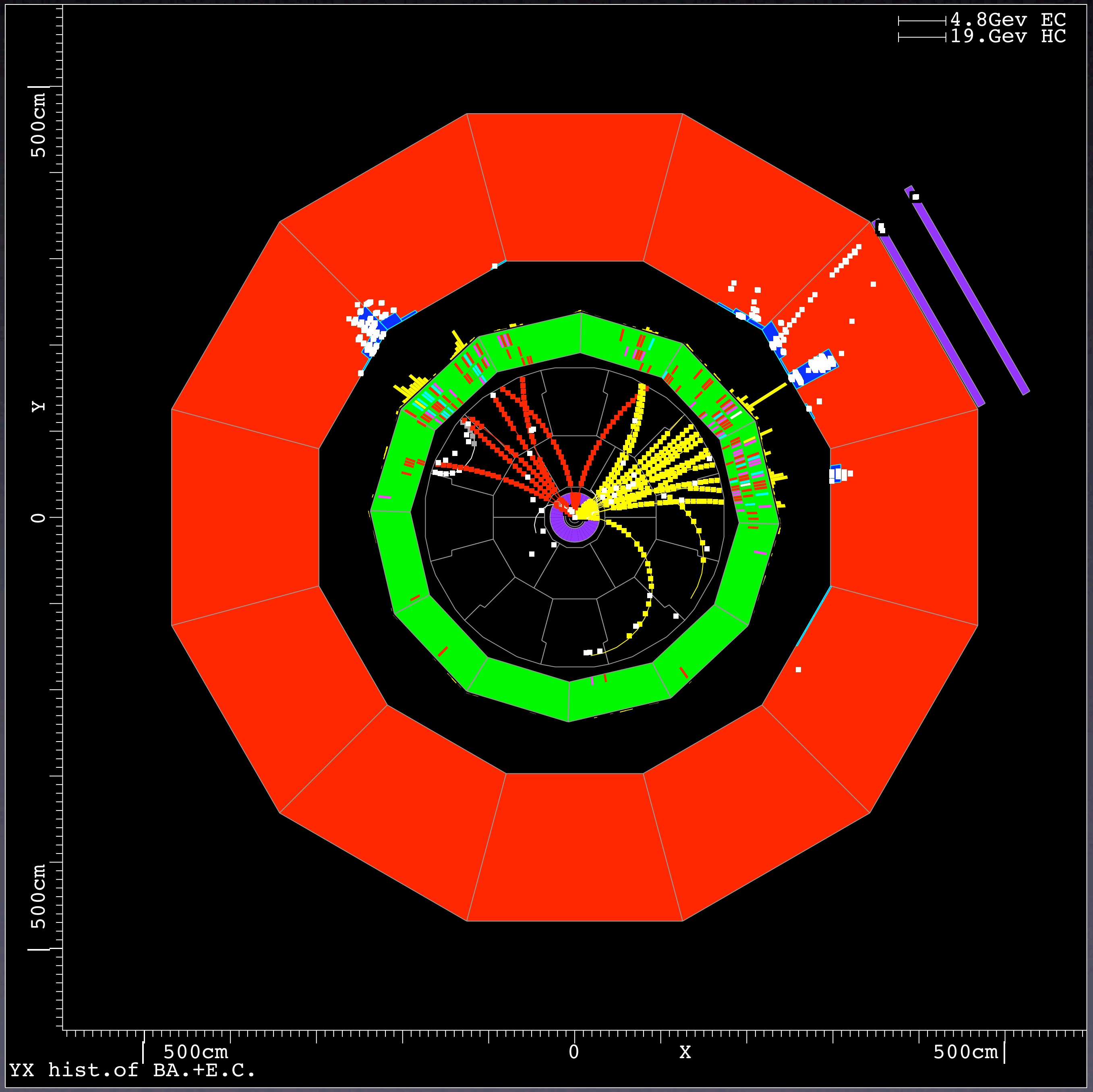
Producing Dark Matter in the laboratory

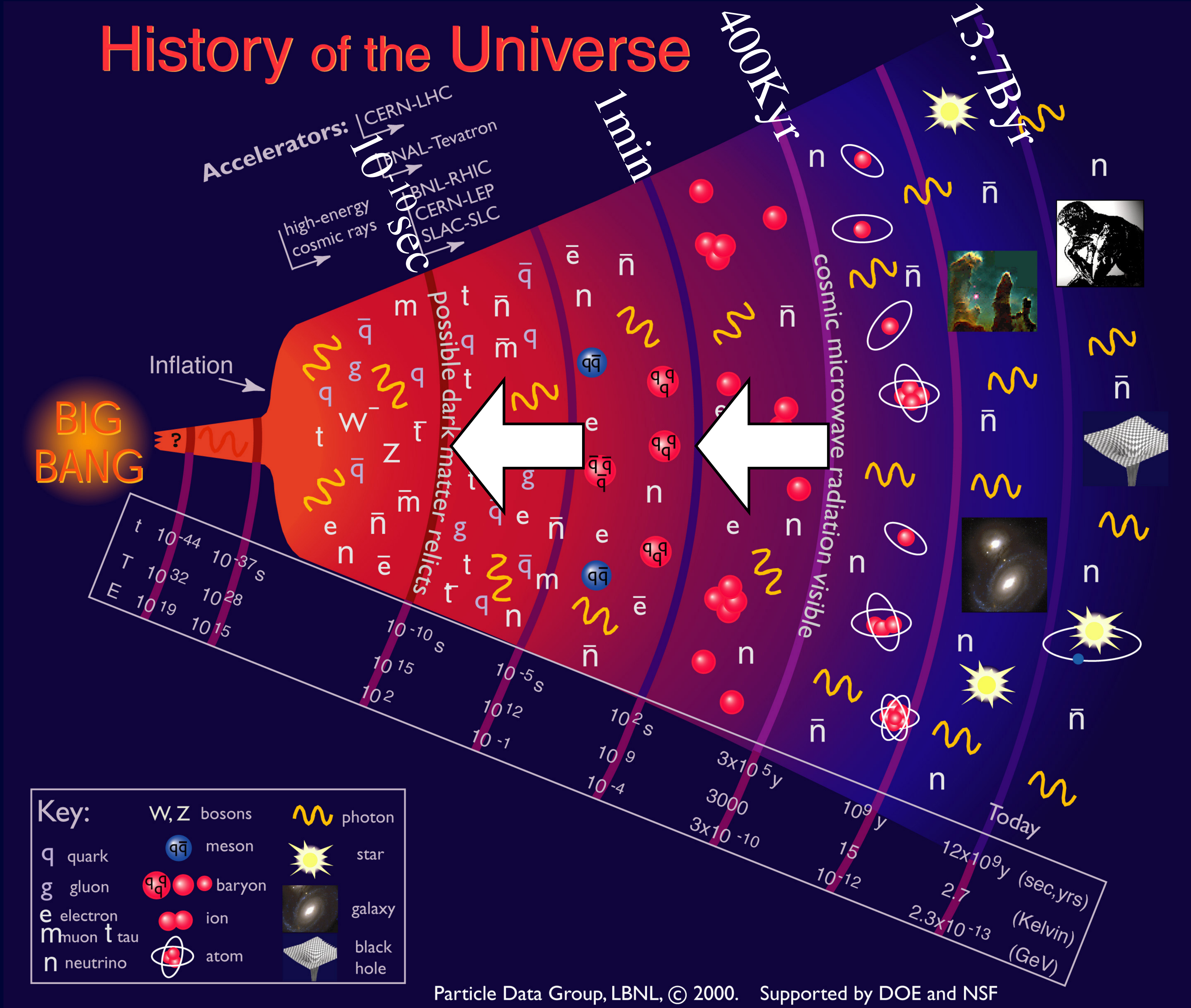
- Collision of high-energy particles mimic Big Bang
- We hope to create Dark Matter particles in the laboratory
- Look for events where energy and momenta are unbalanced

"missing energy" E_{miss}

- Something is escaping the detector
- electrically neutral, weakly interacting

⇒Dark Matter!?

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t 10⁻⁴⁴ 10⁻³⁷ s
T 10³² 10²⁸
E 10¹⁹ 10¹⁵
10⁻¹⁰ s
10¹⁵
10²
10⁻⁵ s
10¹²
10⁻¹
10² s
10⁹
10⁻⁴
3x10⁵ y
3000
3x10⁻¹⁰
10⁹ y
15
10⁻¹²
Today
12x10⁹ y (sec,yrs)
2.7 (Kelvin)
2.3x10⁻¹³ (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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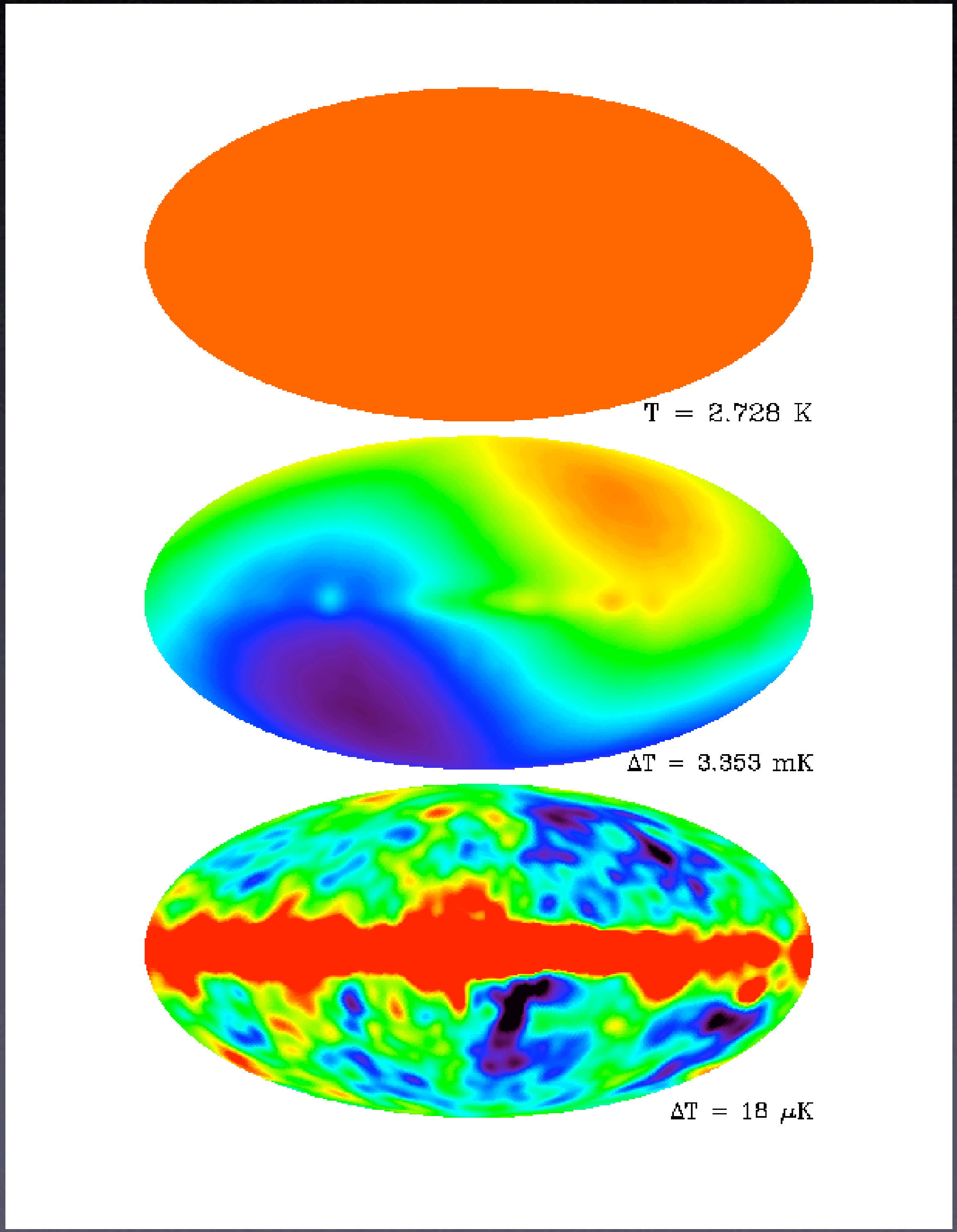
Inflation

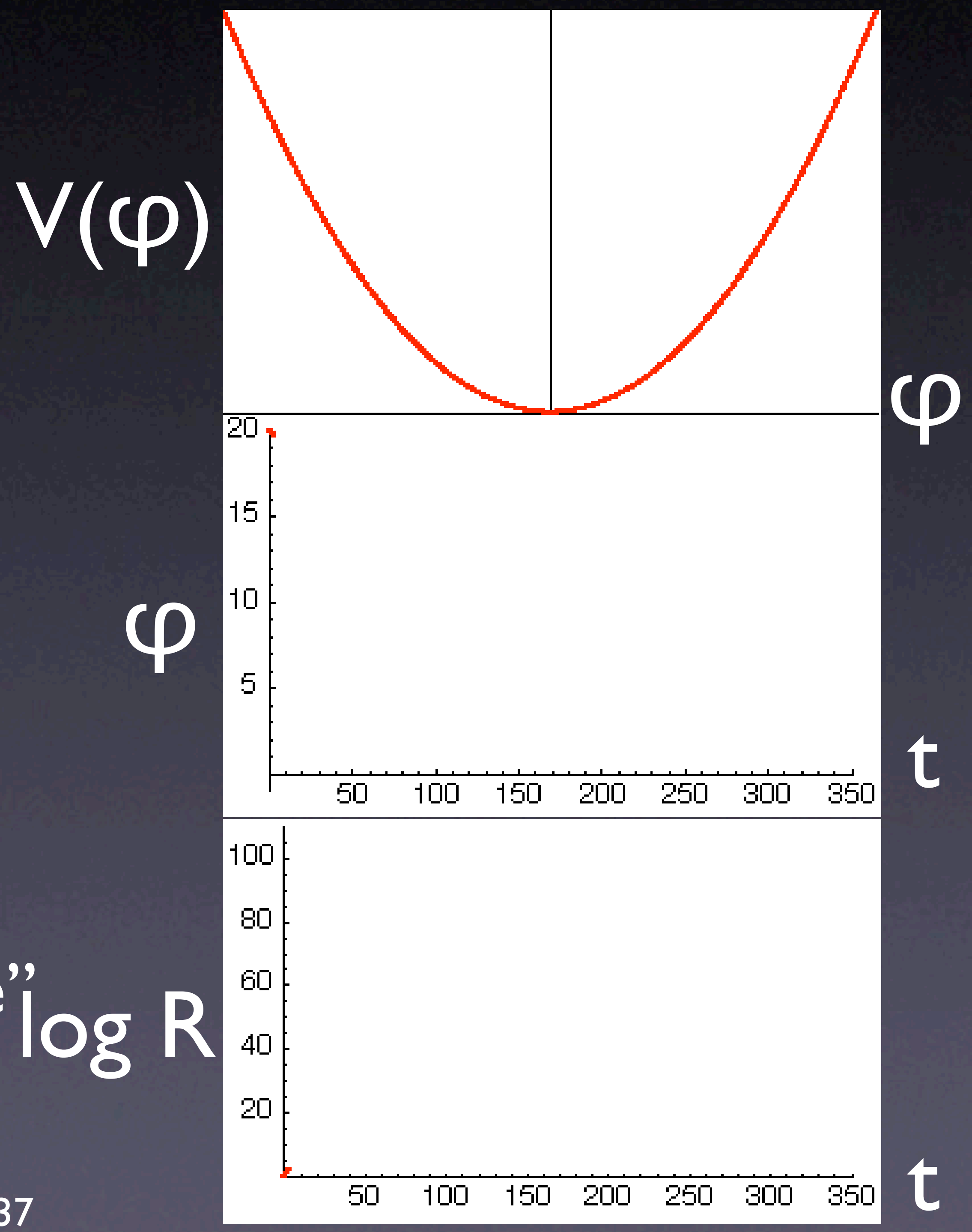
Why do they all look the same?



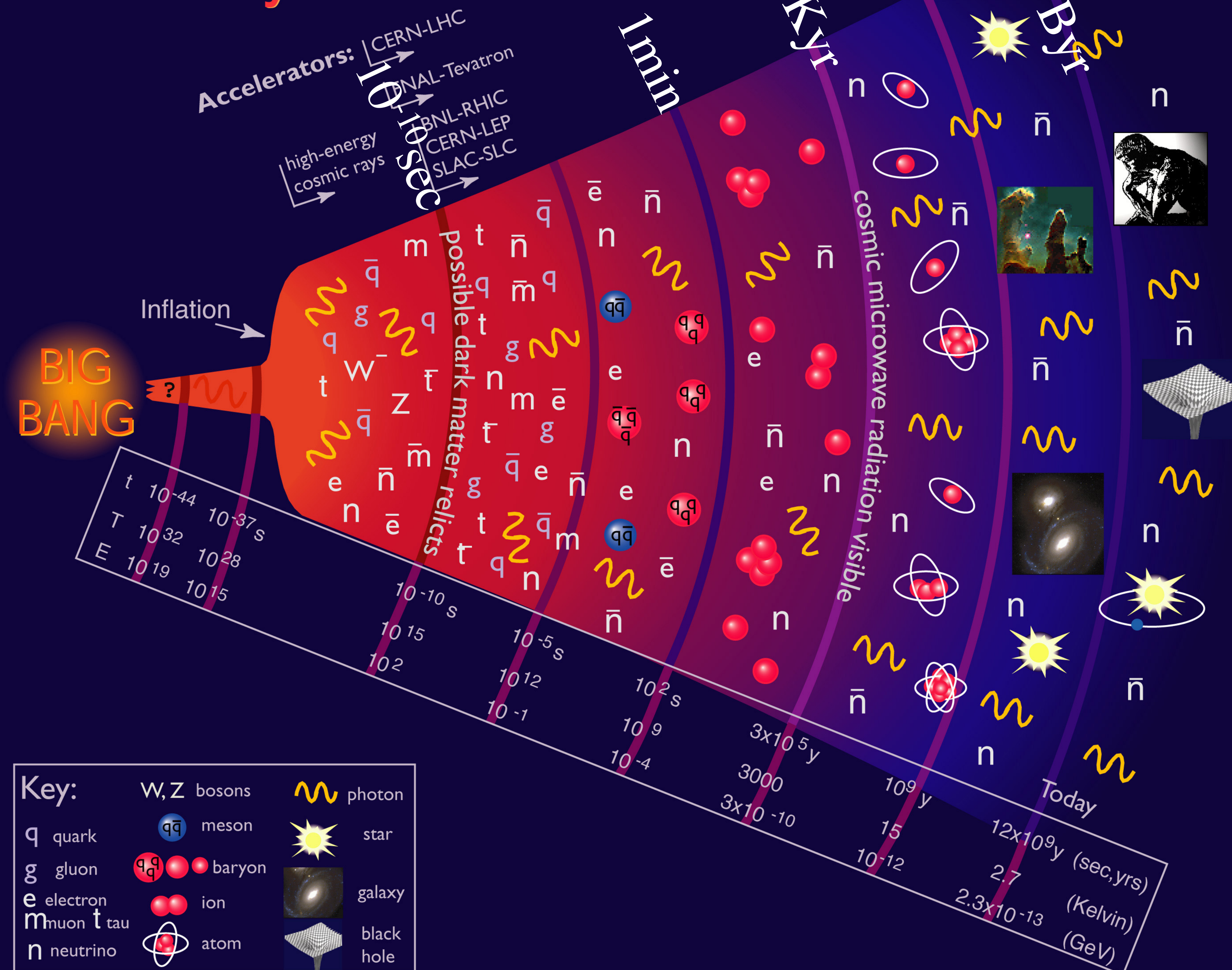
- Like having discovered two remote islands in very different parts of the world, speaking the same language
- even the accents are nearly the same: one part in 100,000
- we suspect they had communication

Stretching the universe

- A spinless field with relatively flat potential
- displaced from the minimum at the beginning
- rolls down slowly
- universe expands exponentially: inflation
- the entire visible universe emerged from a small causally connected patch
- no wonder everybody "speaks the same language"



History of the Universe



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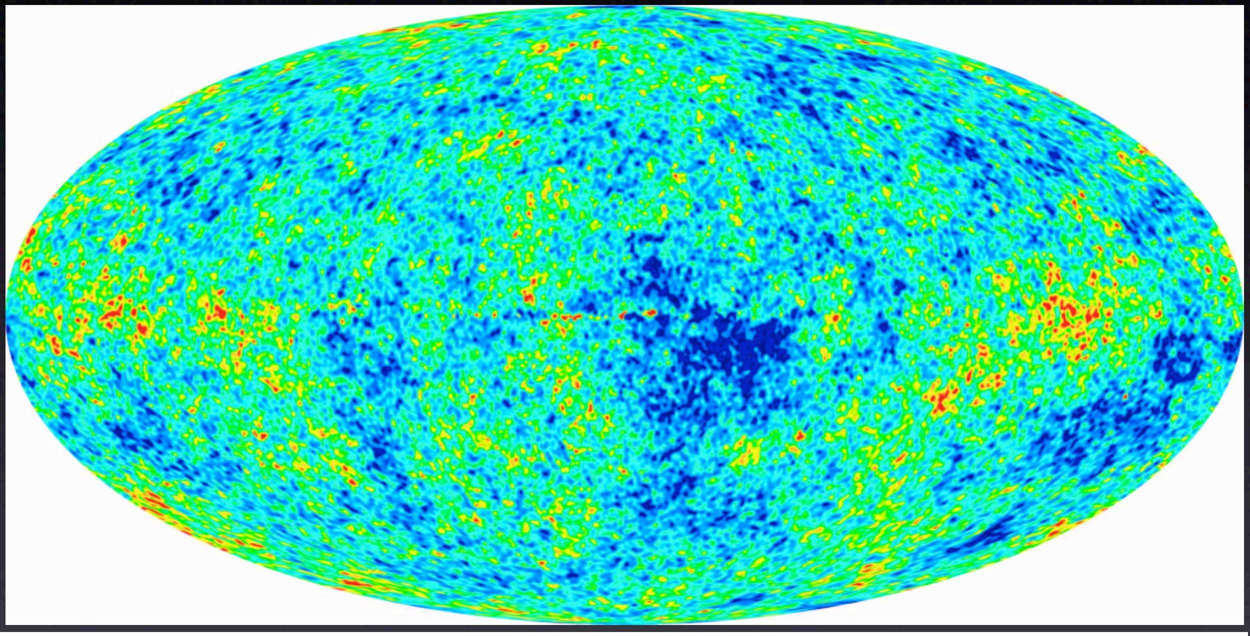
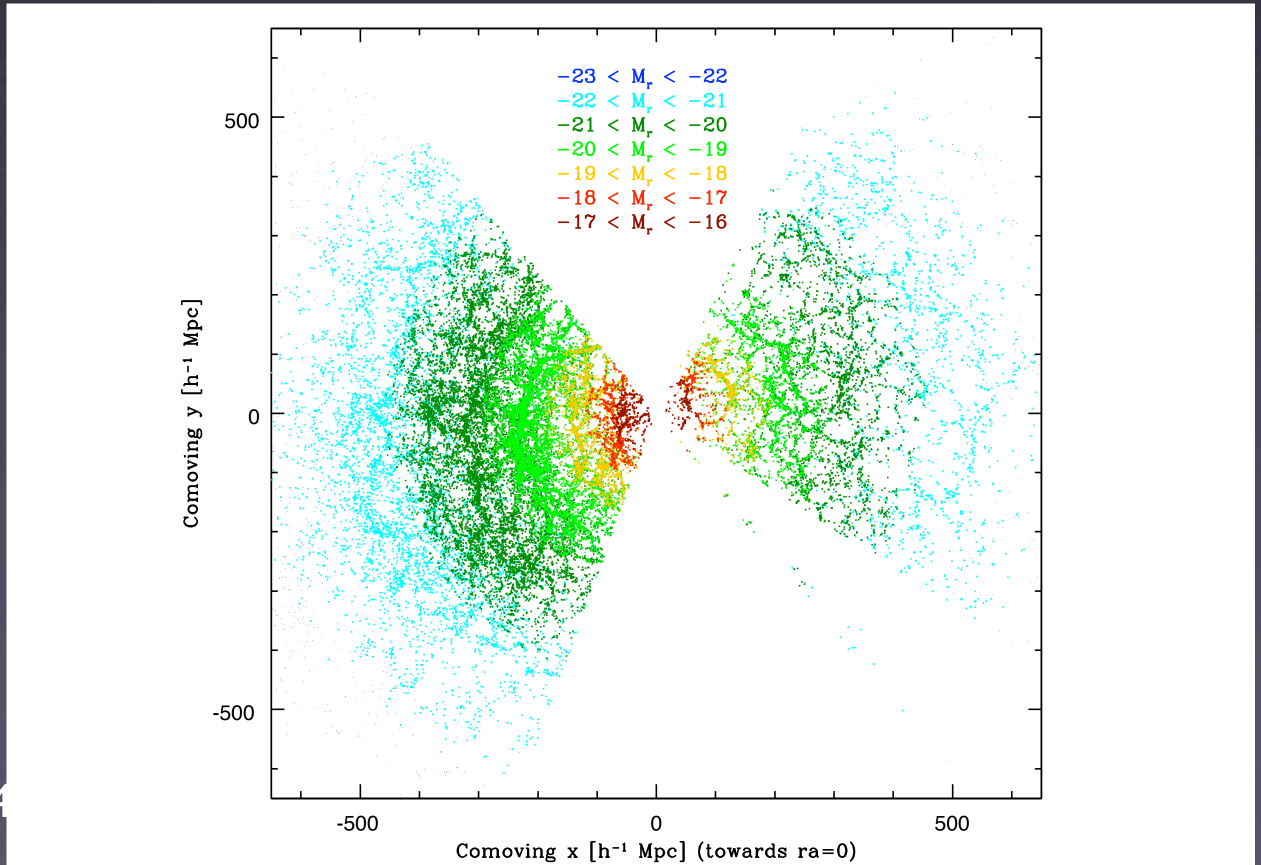
"I suspect that it was inevitable in those conditions of low inflation, rapid growth"

Before the Joint Economic Committee, U.S. Congress, October 29, 1997

Seeds for structure

- Cosmic Inflation stretched the new-born microscopic space to our entire visible universe
- OK, that explains why the temperature is the same. What about the difference?
- Observed density perturbation is due to quantum fluctuation of inflaton





Quantum Fluctuation

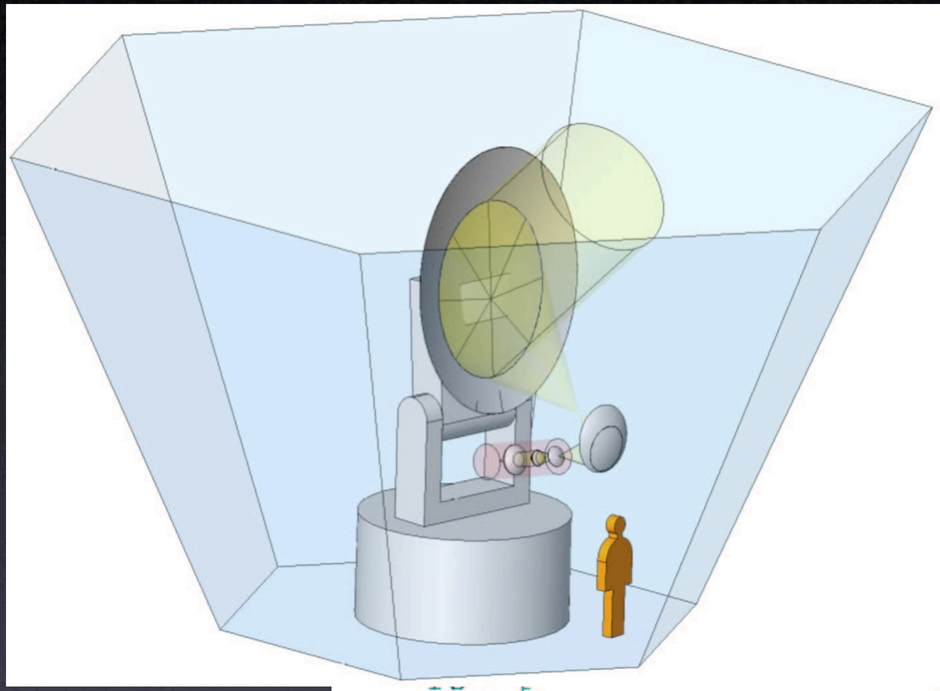
- Inflation is an exponential expansion $a(t) = a(0)e^{Ht}$
- During the inflation, the expansion rate of the universe is more or less constant $H = \frac{\dot{a}}{a}$
- only a fixed size of the space remains in causal contact: "horizon" $d_H = \frac{c}{H}$
- it is like living in a box
- quantum fluctuations $\Delta p \sim \frac{\hbar}{\Delta x} = \frac{\hbar}{d_H}$

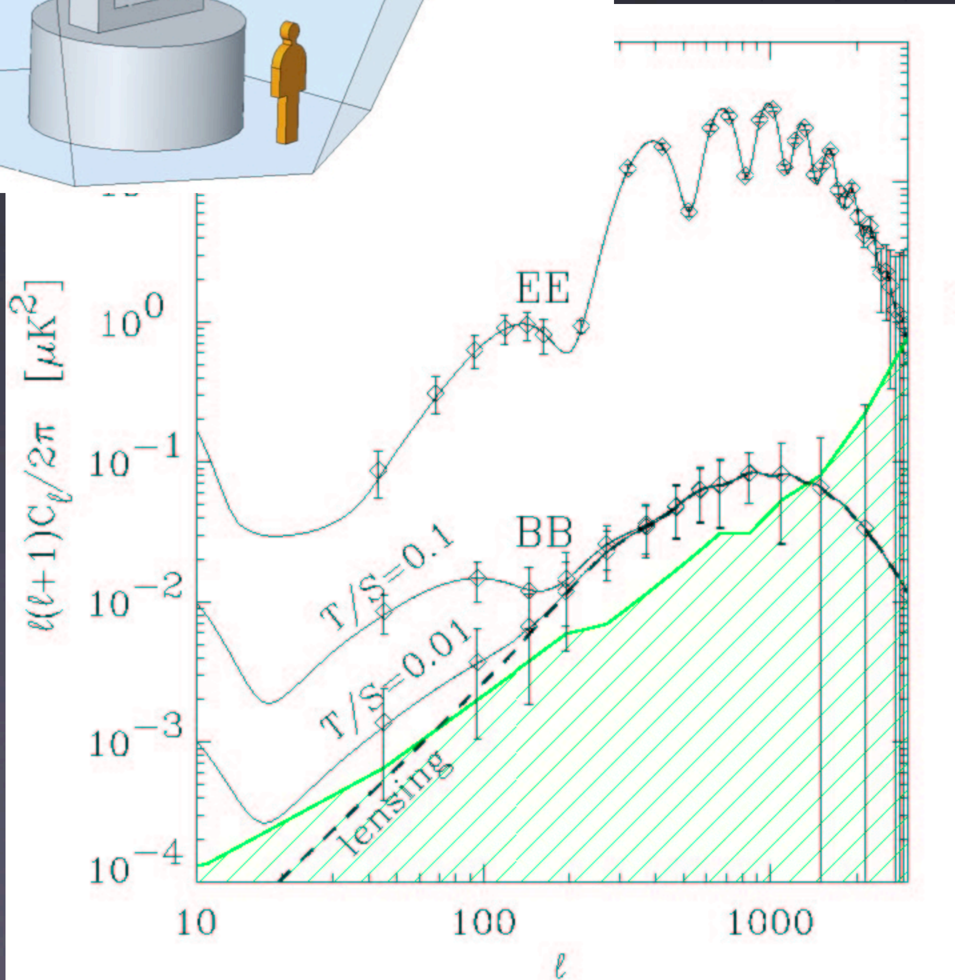
Classical Fluctuation

- quantum fluctuation in energy density with wave lengths $\lambda < d_H$
- Inflation stretches the wave length, goes beyond the horizon $\lambda e^{Ht} \gg d_H$
- Once beyond horizon, no longer causally connected
- quantum fluctuation becomes classical
- frozen in as the density fluctuation
- nearly scale-invariant Gaussian fluctuation

How do we know it really happened?

- everything gets quantum fluctuation, including gravitons
- Gravitons from quantum fluctuation gives B-mode polarization in CMB
- The size is directly proportional to the inflationary energy scale
  ⇒POLARBEAR

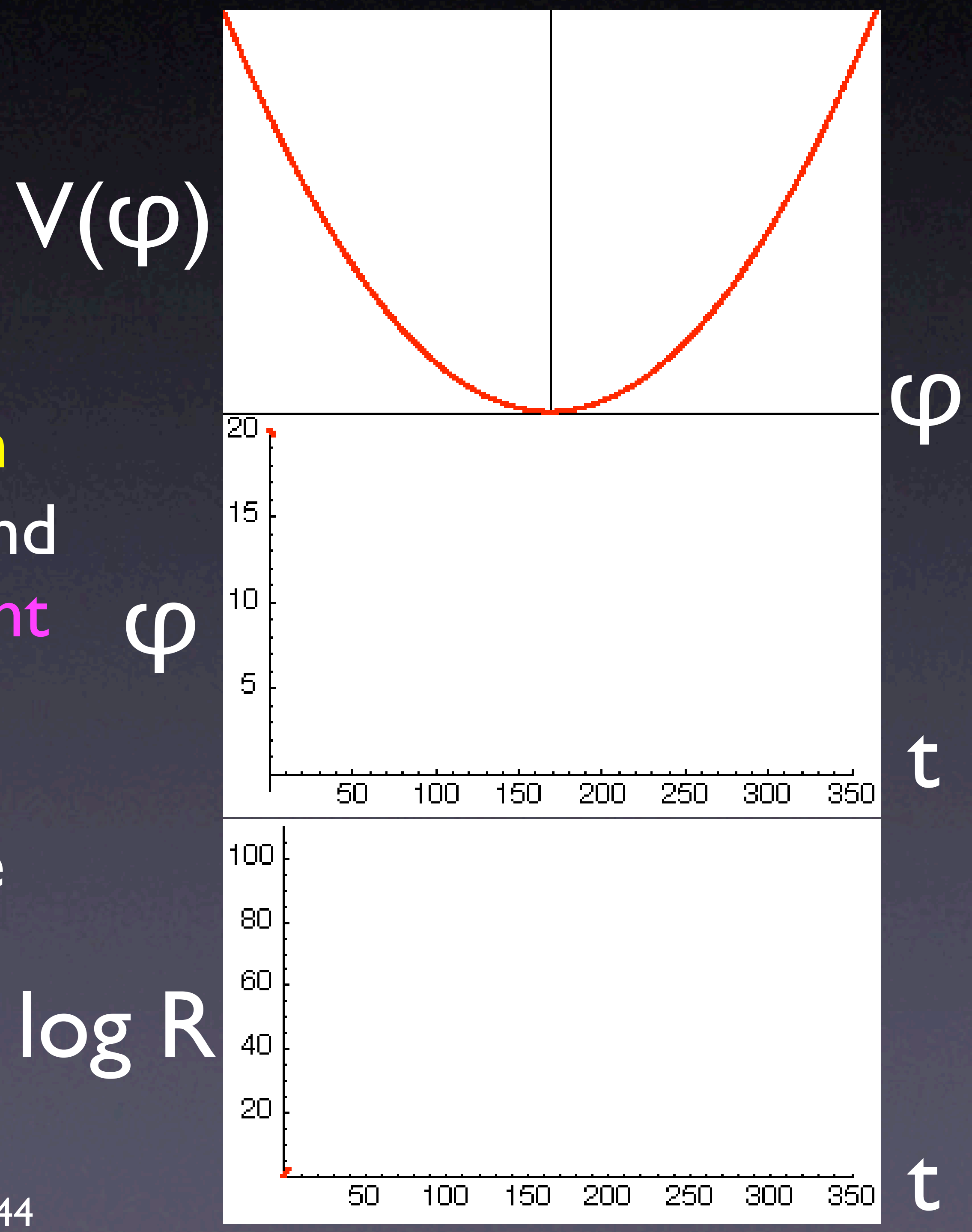




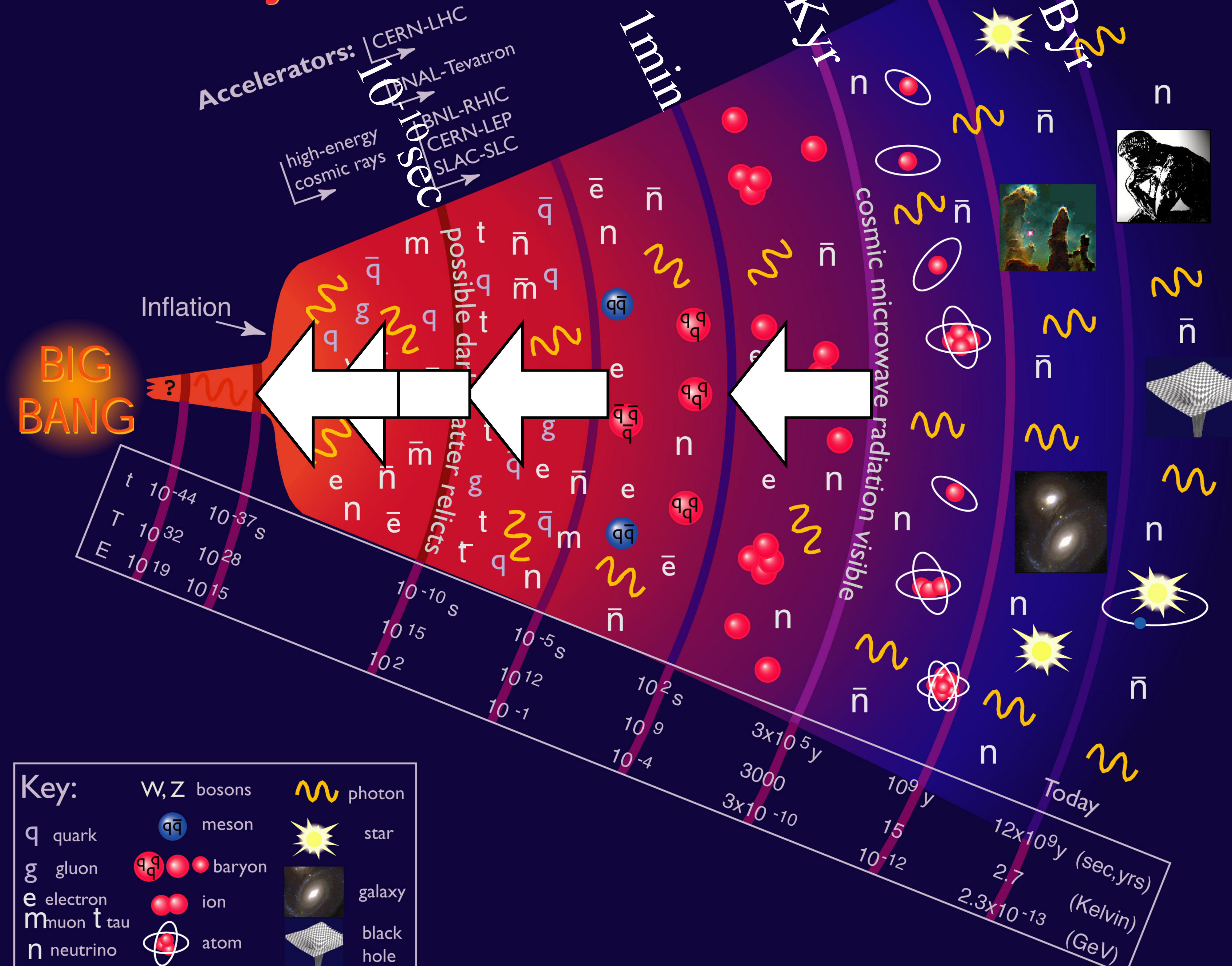
Who caused inflation?

- Superpartner of a heavy neutrino
- displaced from the minimum at the beginning
- rolls down slowly: inflation
- decays into both matter and anti-matter, but with a slight preference to matter
- decay products contain supersymmetry and hence Dark Matter

H. Murayama et al, PRL 70, 1912



History of the Universe



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Conclusion

- COBE's discovery of CMB anisotropy settled a critical issue with Big-Bang cosmology
- why is there structure in universe now, so that we can live?
- it grew from tiny $\sim 10^{-5}$ density fluctuations
- best source is quantum fluctuations during inflationary expansion of universe
- we are born from quantum noise