Particles in the Early Universe

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TRIUMF

Saturday Morning Physics, October 16, 2010

Using Little Stuff to Explain Big Stuff

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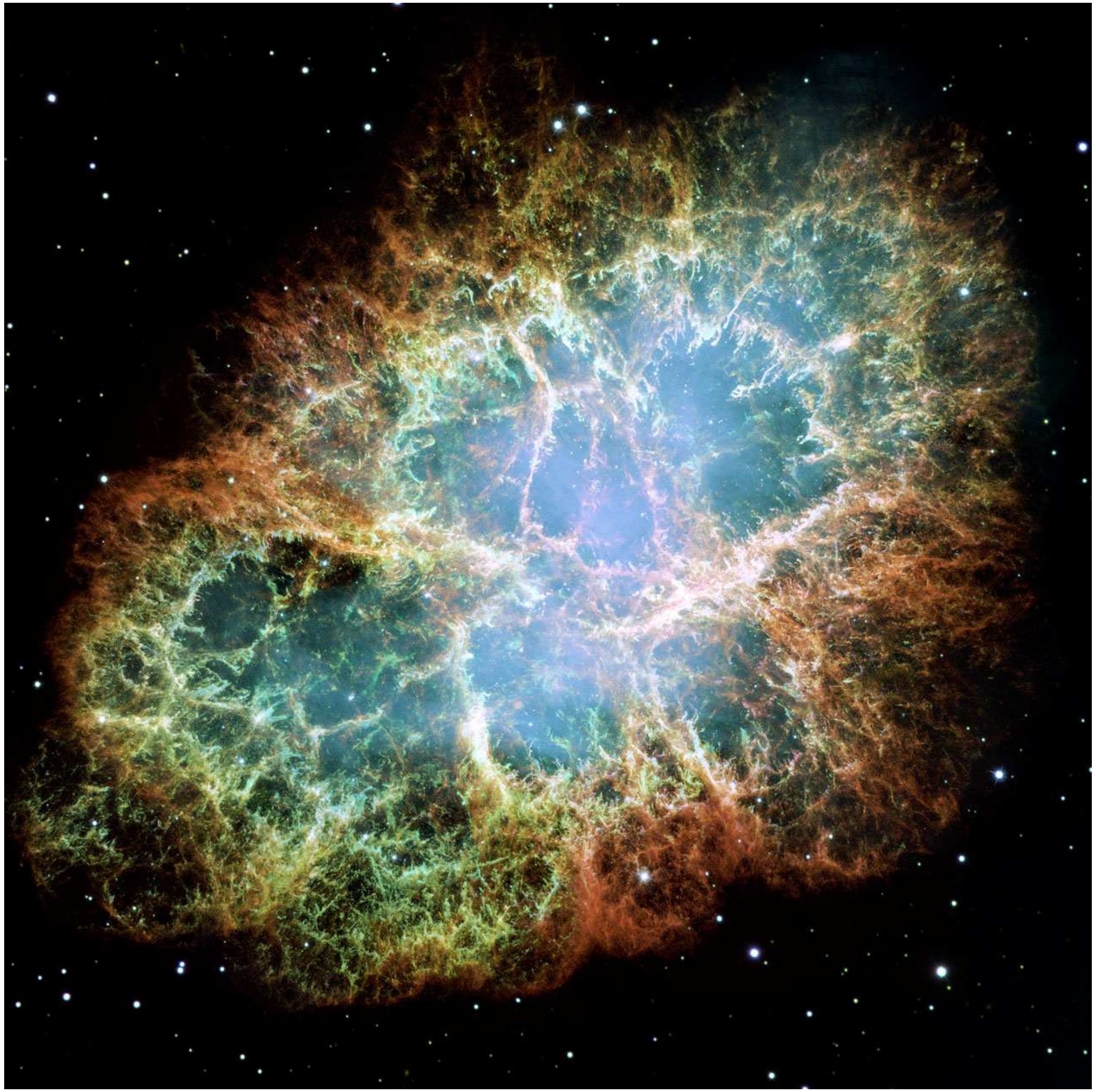
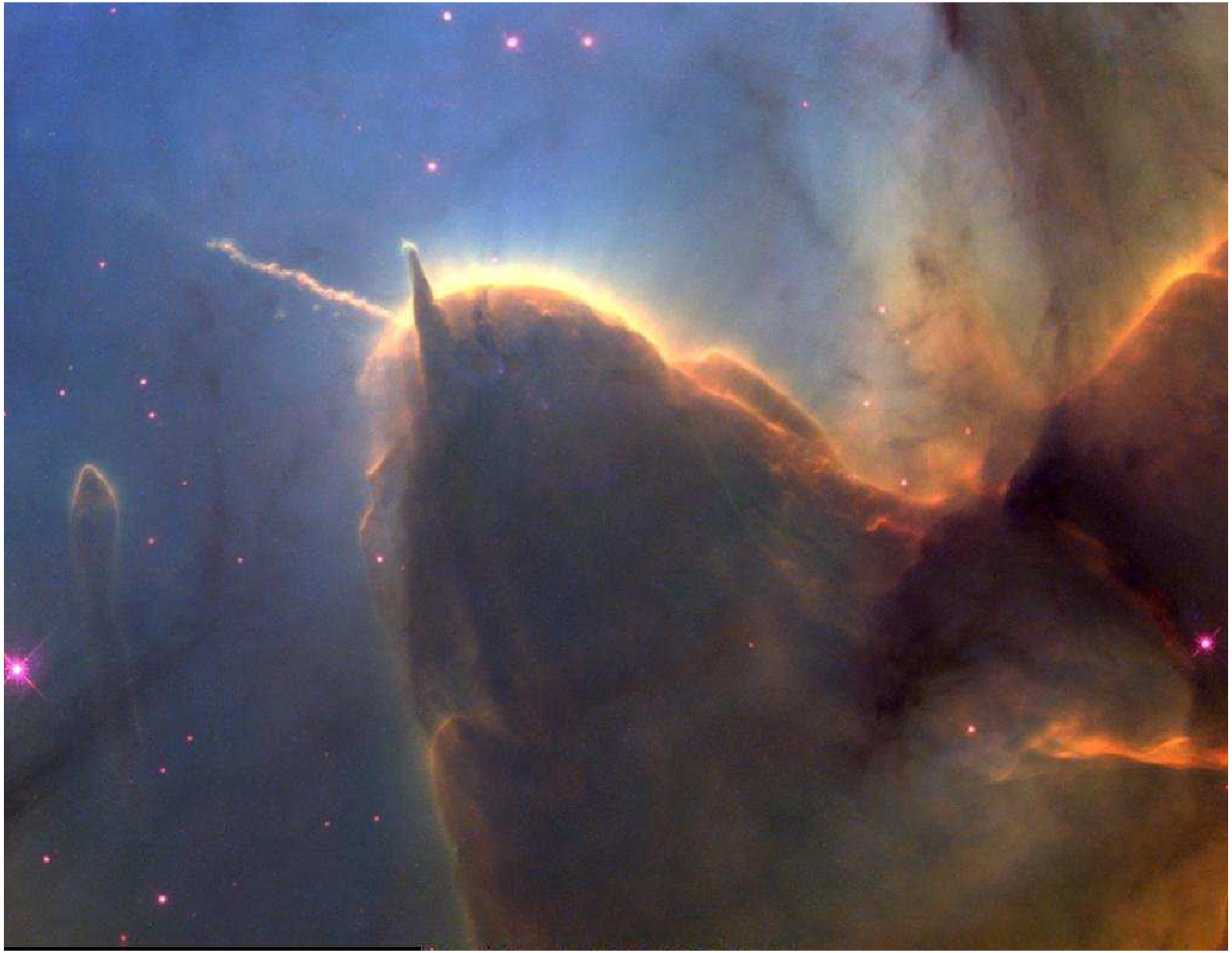
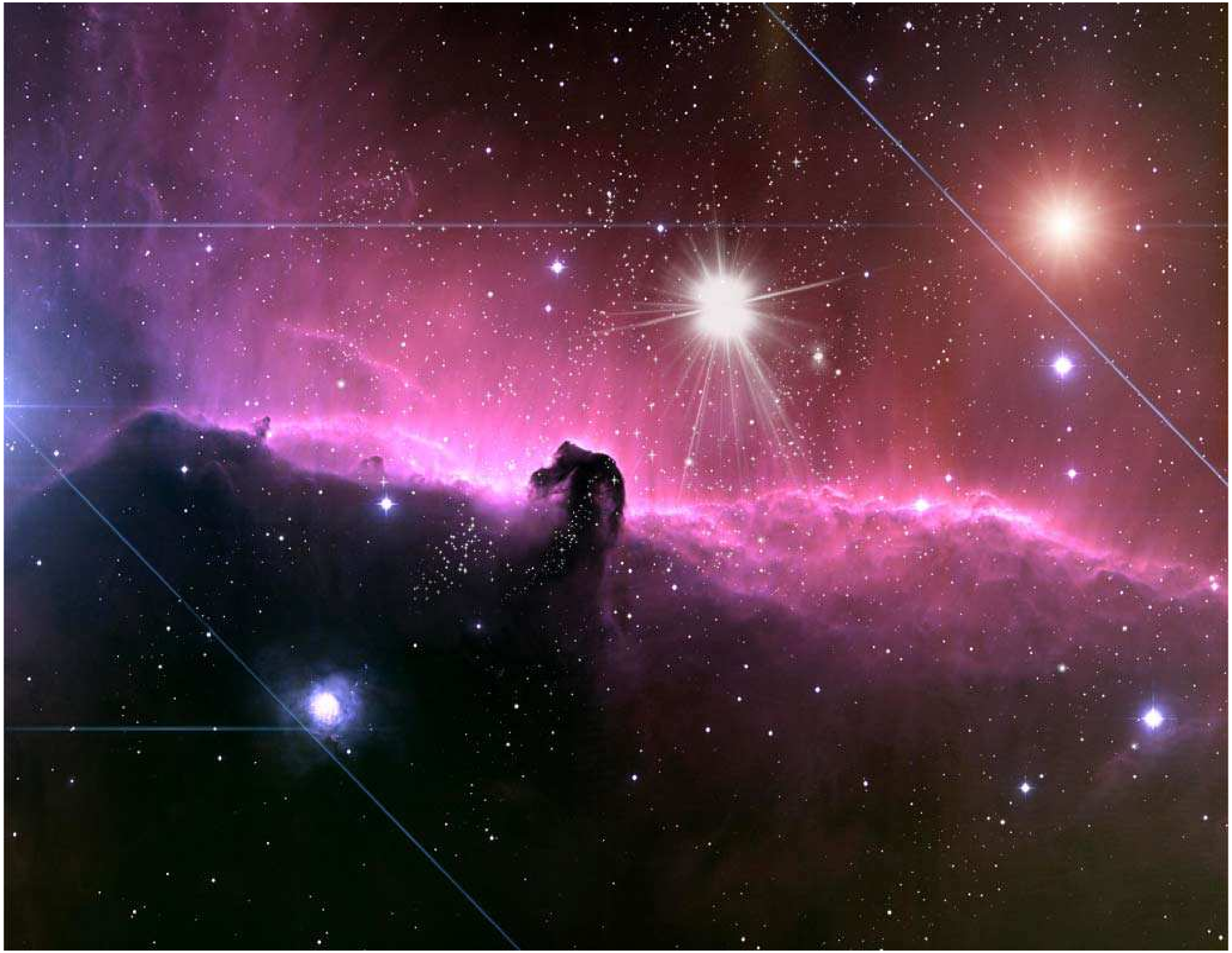
Can we explain this?



Or this?



Or this?



Or this?

The Really Big Question

- Can we explain the Universe using the physics we know?

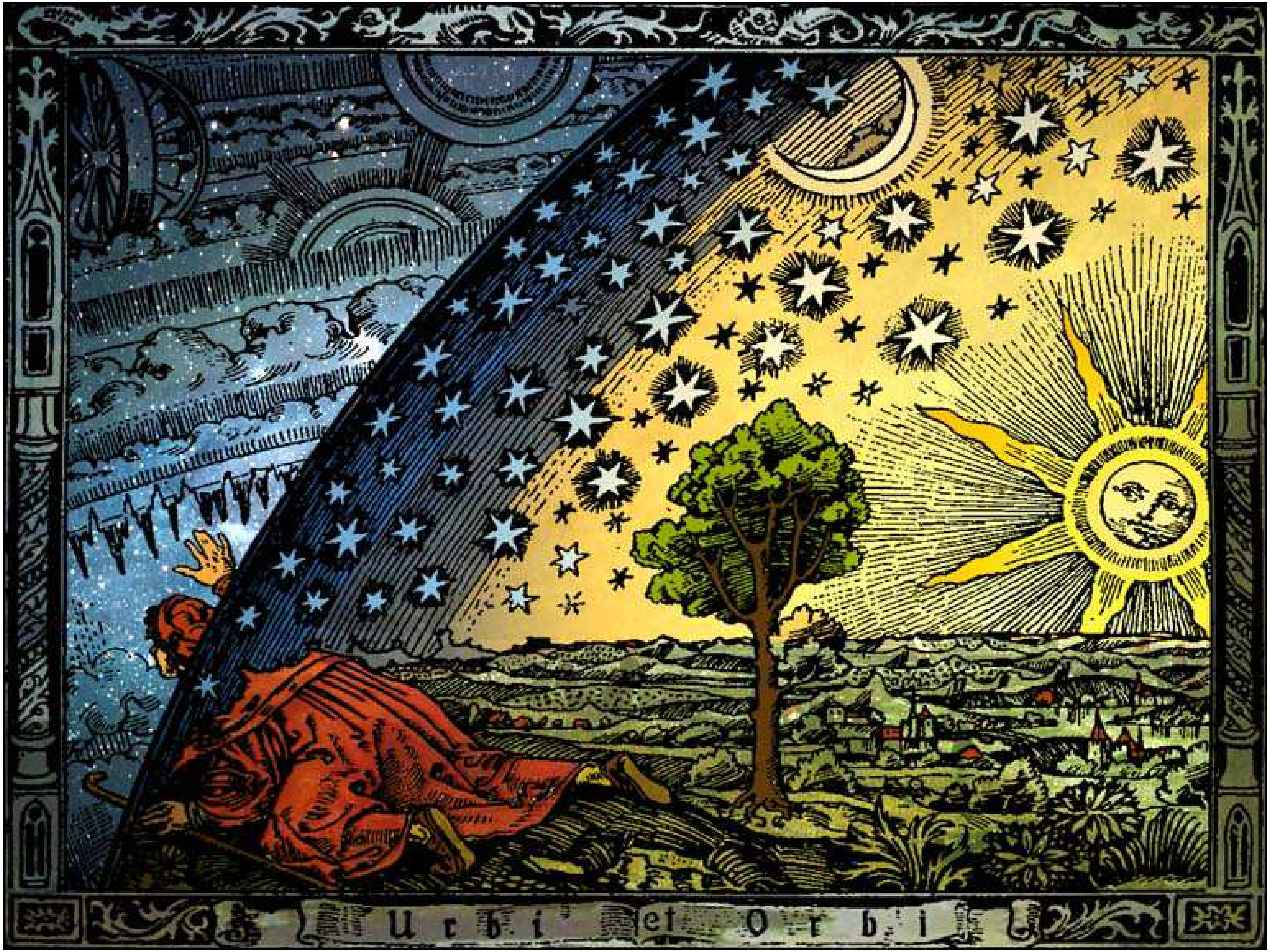
  What is its large scale structure?

  How did it evolve over time?

- Really Ambitious!

  "Physics we know" comes from experiments on Earth.

  Will it still work over much larger astronomical distances?

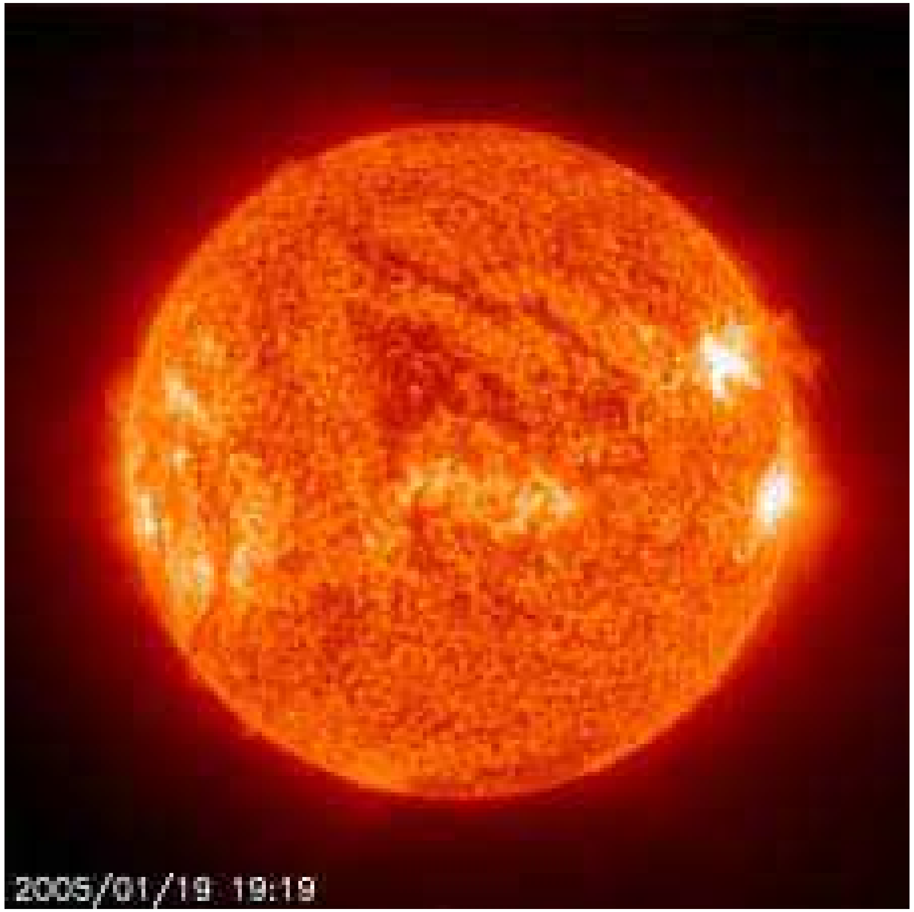

Urbi et Orbi

Looking Around, from Near to Far

Stars

- There are lots of stars out there.

  (Ours is the sun.)



Galaxies

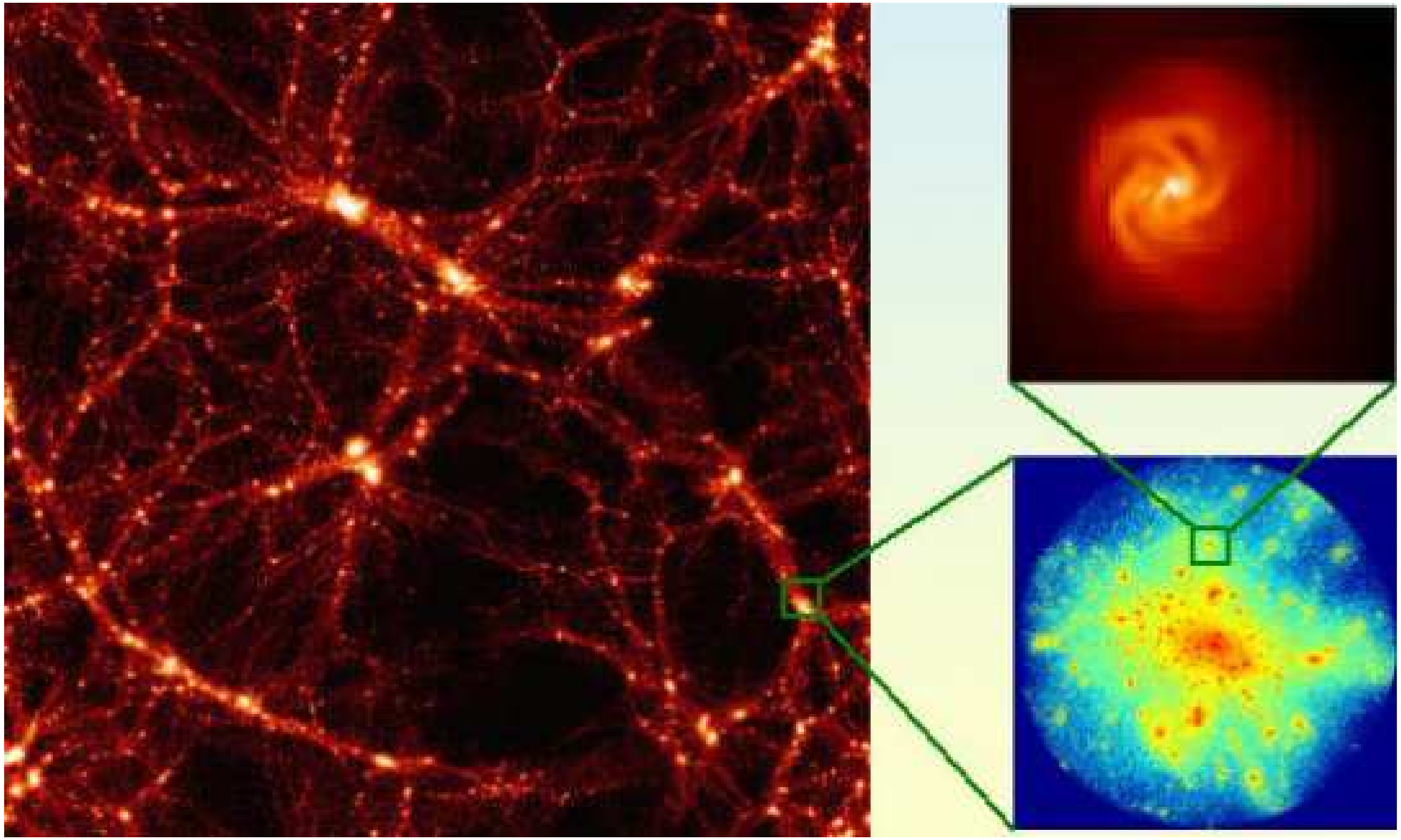
- Stars bunch together into galaxies.

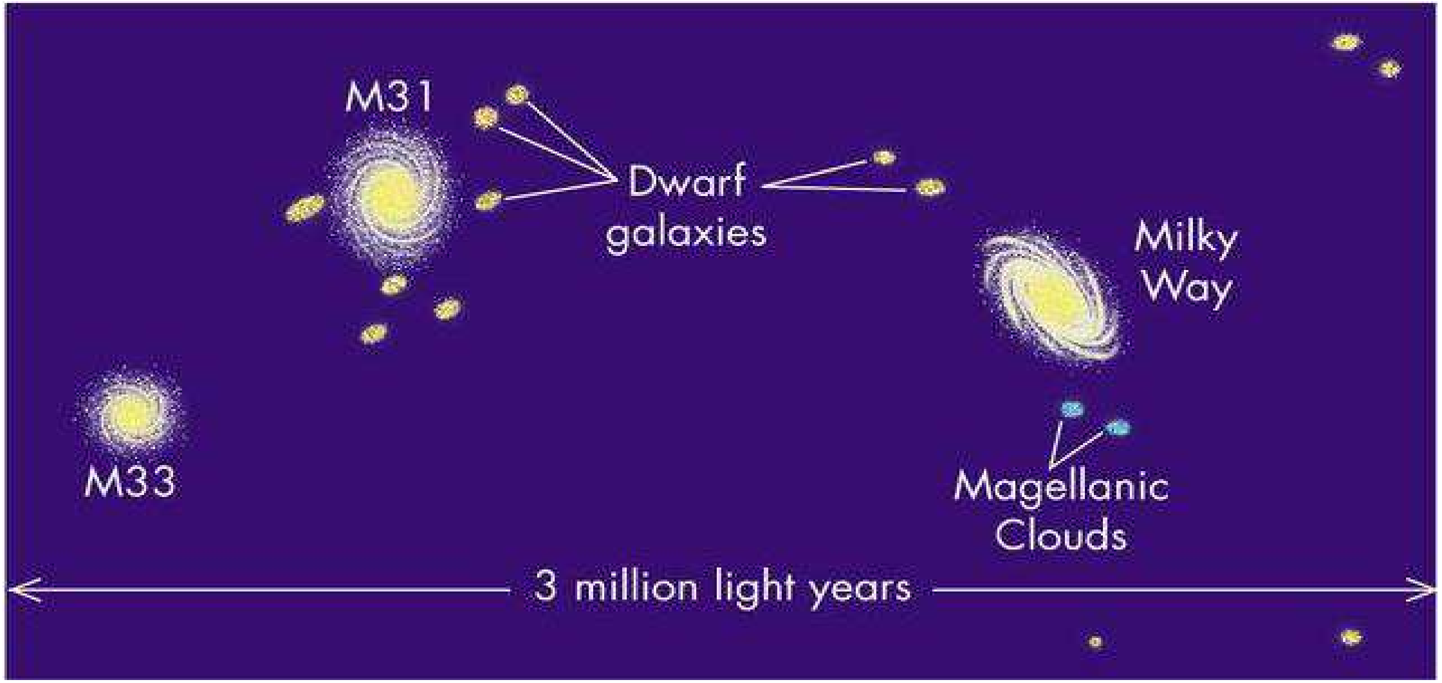
  (Ours is the Milky Way.)

Galaxy Clusters

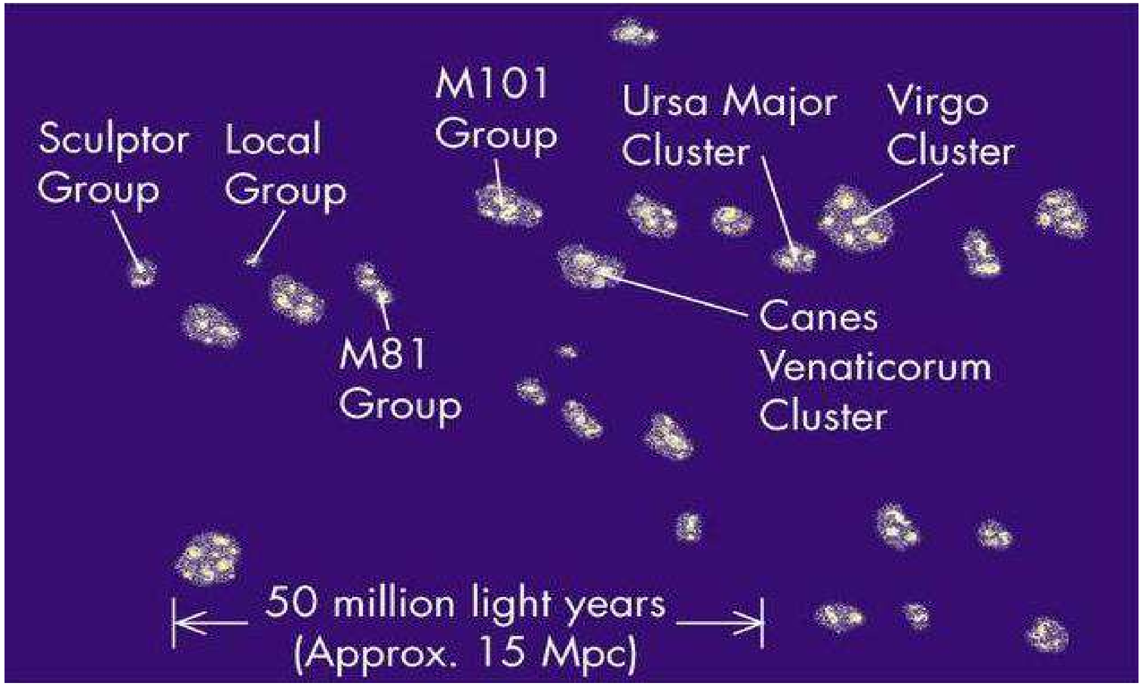
- Galaxies bunch together into galaxy clusters.

  (Ours is the local cluster.)





M31
Dwarf galaxies
Milky Way
M33
Magellanic Clouds
3 million light years



M101 Group
Ursa Major Cluster
Virgo Cluster
Sculptor Group
Local Group
Canes Venaticorum Cluster
M81 Group
50 million light years
(Approx. 15 Mpc)

Even Bigger Distances – Cosmology

- Astronomy over bigger distances is called cosmology.
  (Not to be confused with cosmetology.)

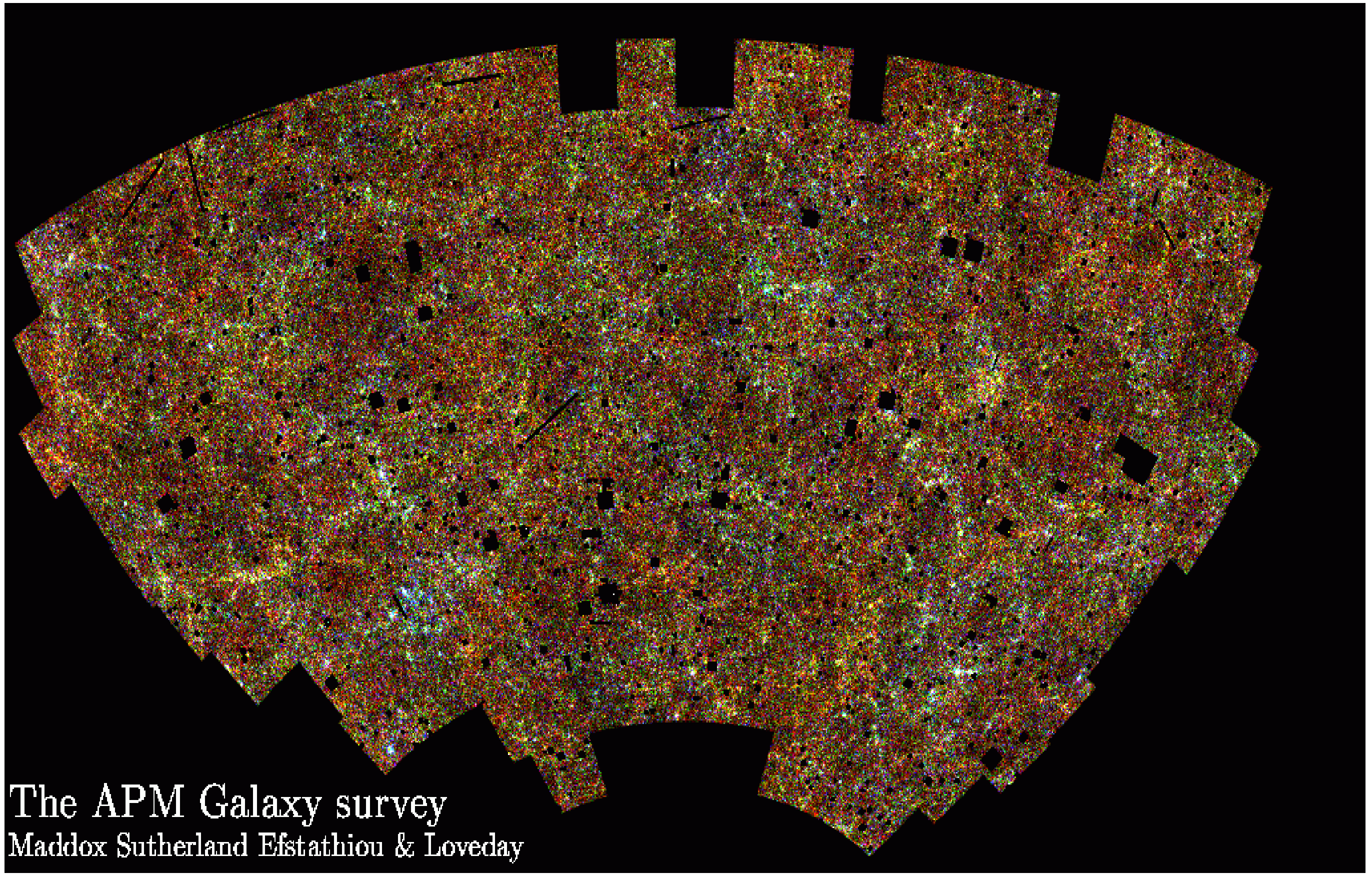
- Three Main Observations:

  1. Everything is the same (on average) everywhere.
  2. Distant galaxies are moving away from us.
  3. Outer space isn't empty – it has a faint amount of light.

- We can use these facts, together with particle physics, to reconstruct the history of the Universe!

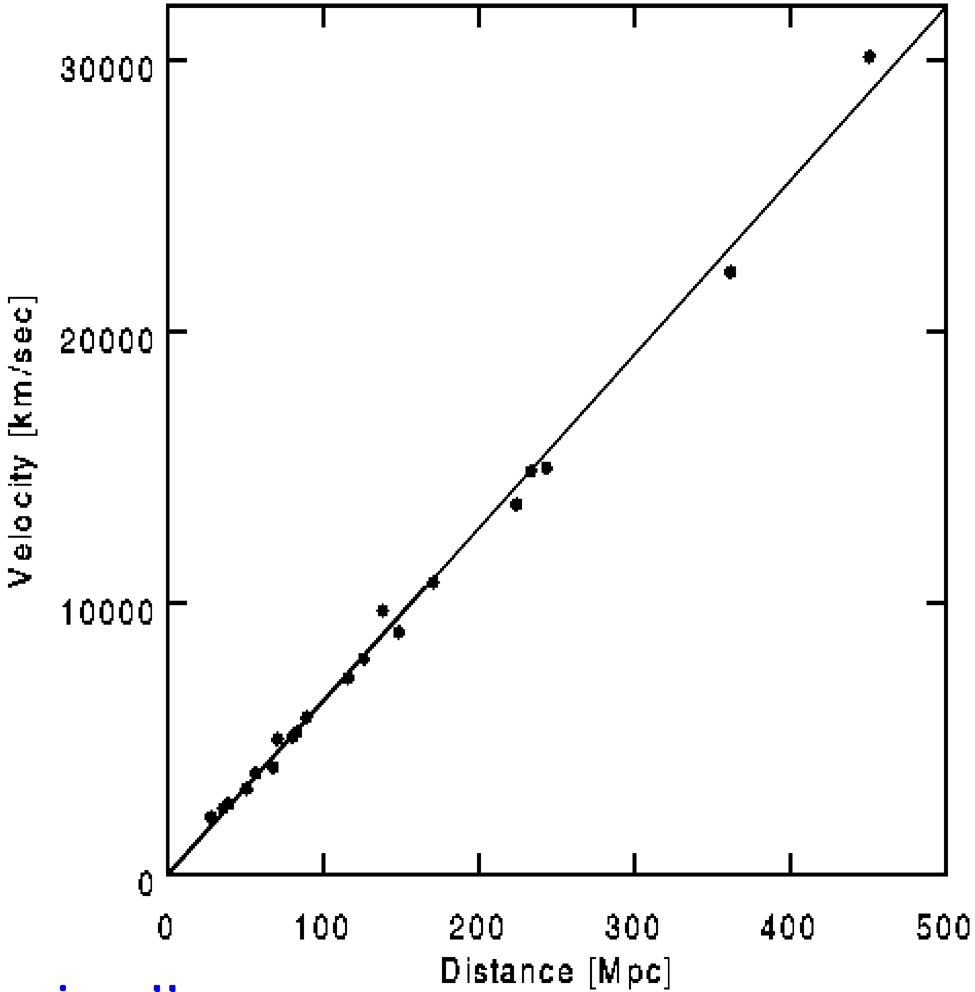
Important Observation #1

- The universe is the same in all directions, on average:



Important Observation #2

- All the stuff out there is moving away from us:



“Hubble Expansion”

Important Observation #3

- Empty "space" is not quite empty.

  Outer space is filled a very faint glow of light.

- This Cosmic Microwave Background (CMB)

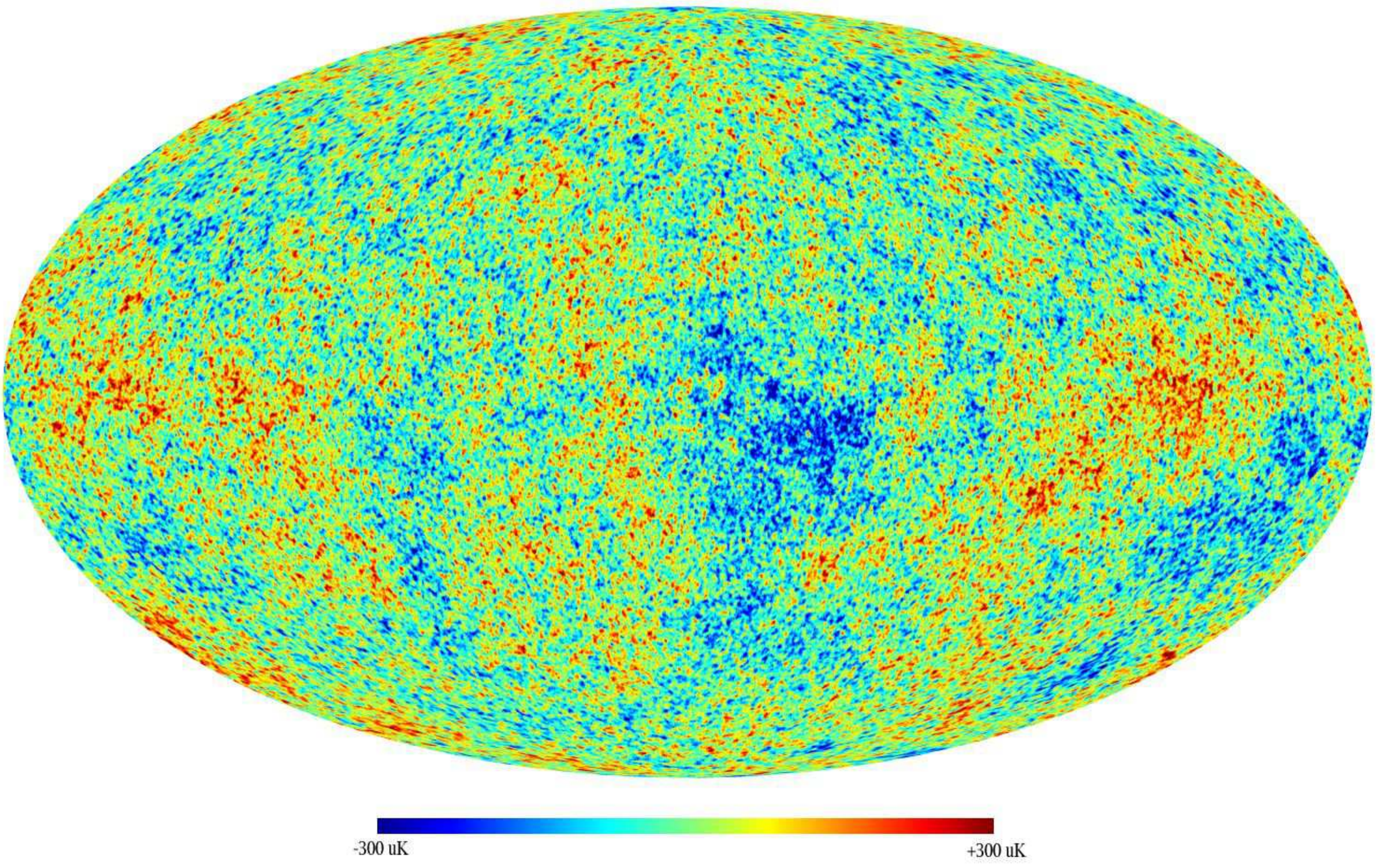
  has a temperature of $T \simeq 2.73\,K$.

  (Room temperature is about $293\,K$, freezing is $273\,K$.)

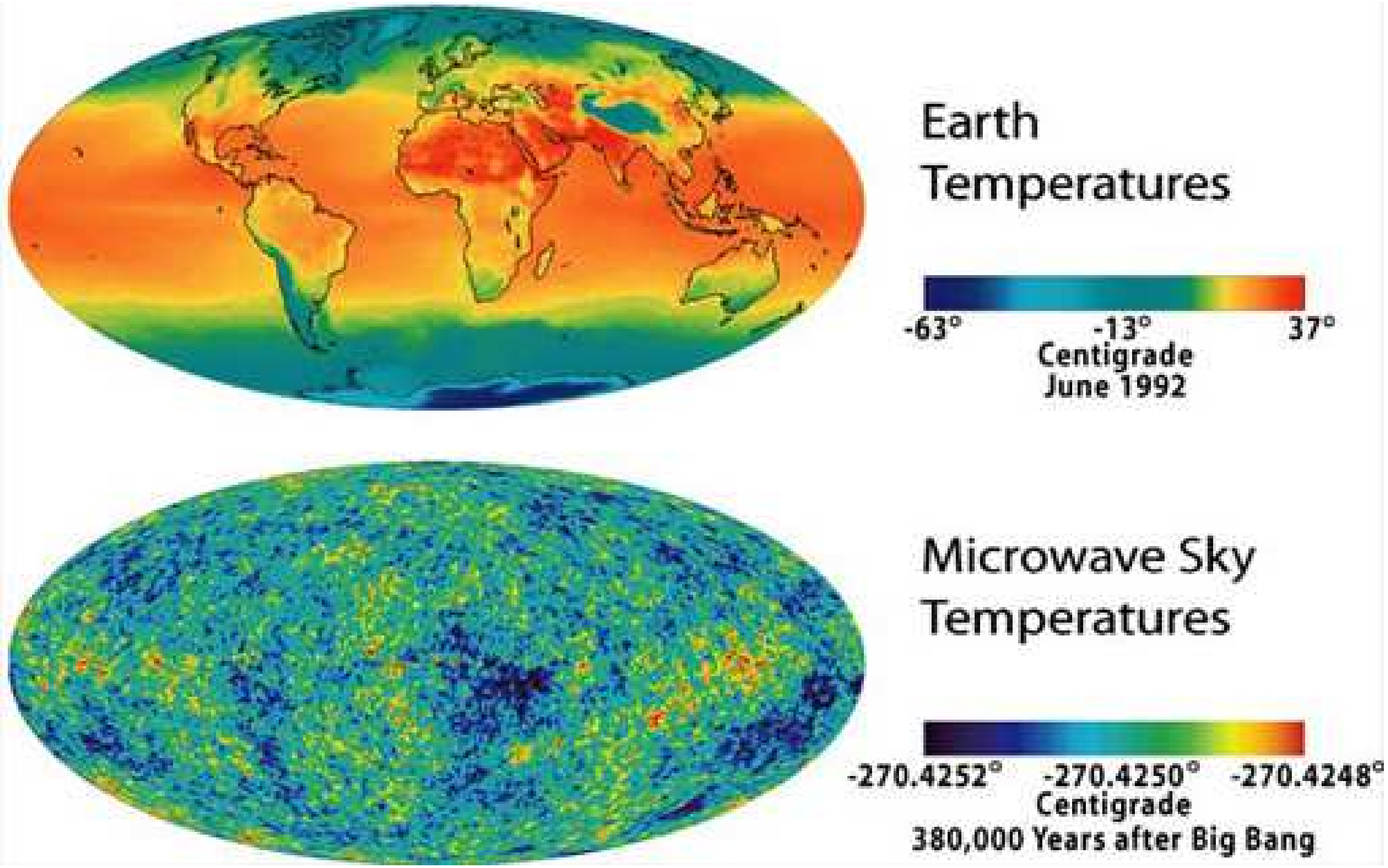
- It is extremely uniform: $\Delta T/T \simeq 1/10000$.

  These variations contain a lot of information.

- Cosmic Microwave Background (CMB).



• Temperature Fluctuations

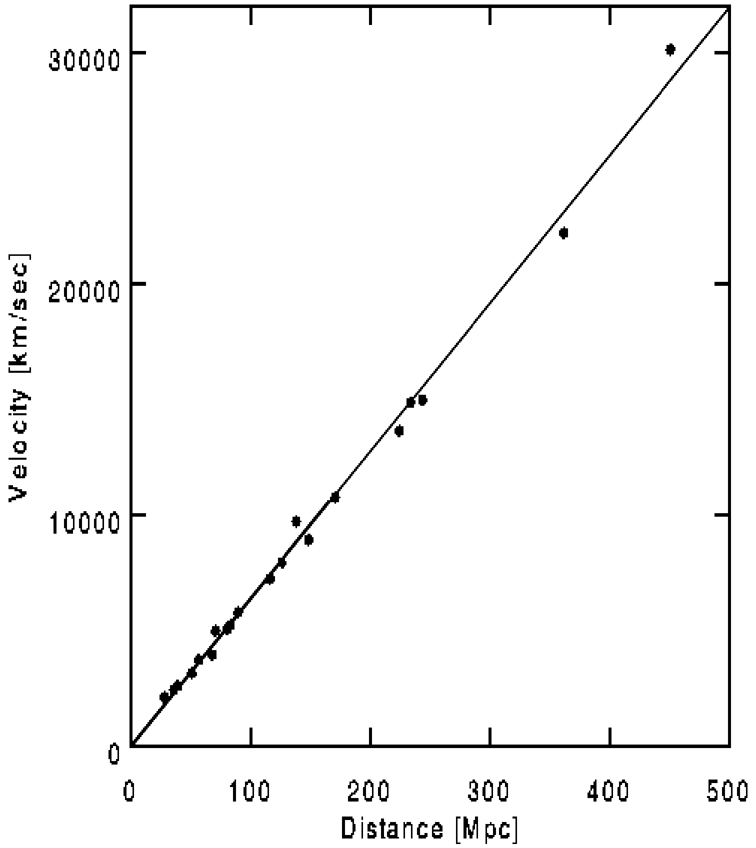


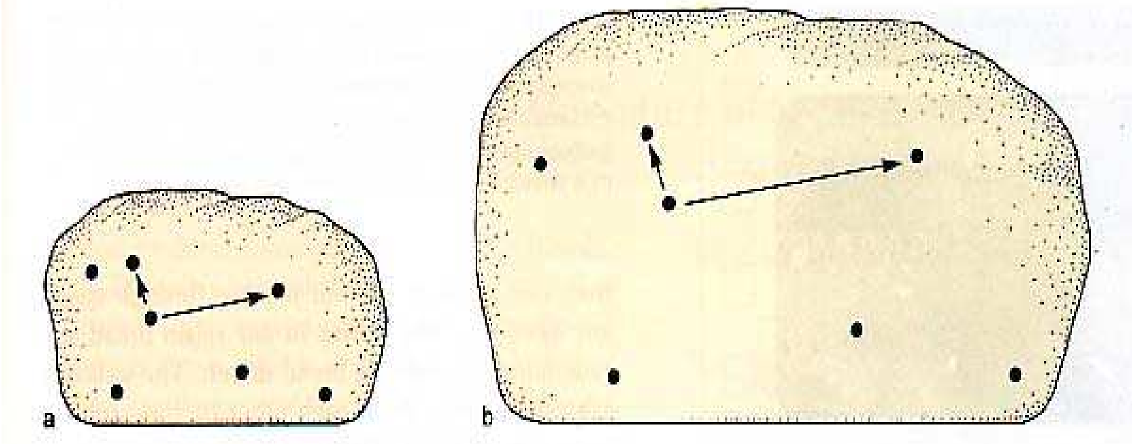
What Gravity has to Say About This

- Gravity is this only force that matters over astronomical and cosmological length scales.
- Equations for Gravity $\leftrightarrow$ General Relativity [Einstein 1915]
- Look for gravity solutions that have:
  - spacetime that is the same everywhere (= "homogeneous and isotropic")
  - contains a smooth density of matter and energy (*e.g.* background CMB light, dust, stars, galaxies, . . .)

- Result: spacetime is expanding.

- This is precisely what we see – Hubble Expansion.





The Big Bang [Alpher,Bethe,Gamow '1947]

- Remember all that $T = 2.73\,K$ CMB light?

  As the universe expands it cools off.

- Going back in time, the universe must have been much hotter in the past.

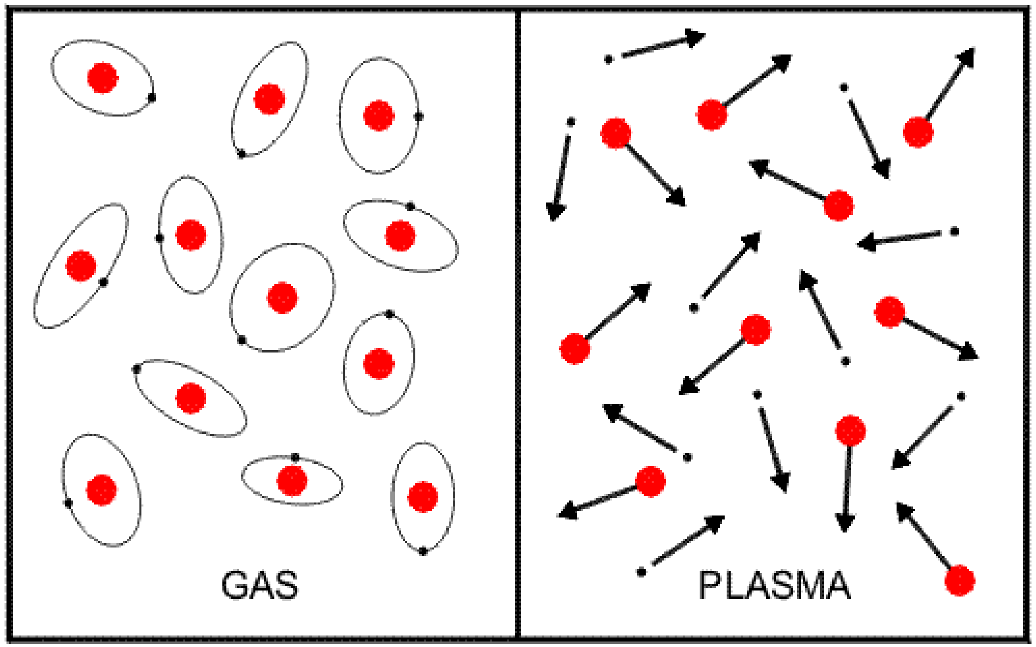
- $T \to \infty$ as $t \to 0$!

Big Bang!

Looking Inside, Elementary Particles

Elementary Particles at High Temperatures

- The early Universe was very very hot.
- At high temperatures, matter gets ripped apart into its basic building blocks.



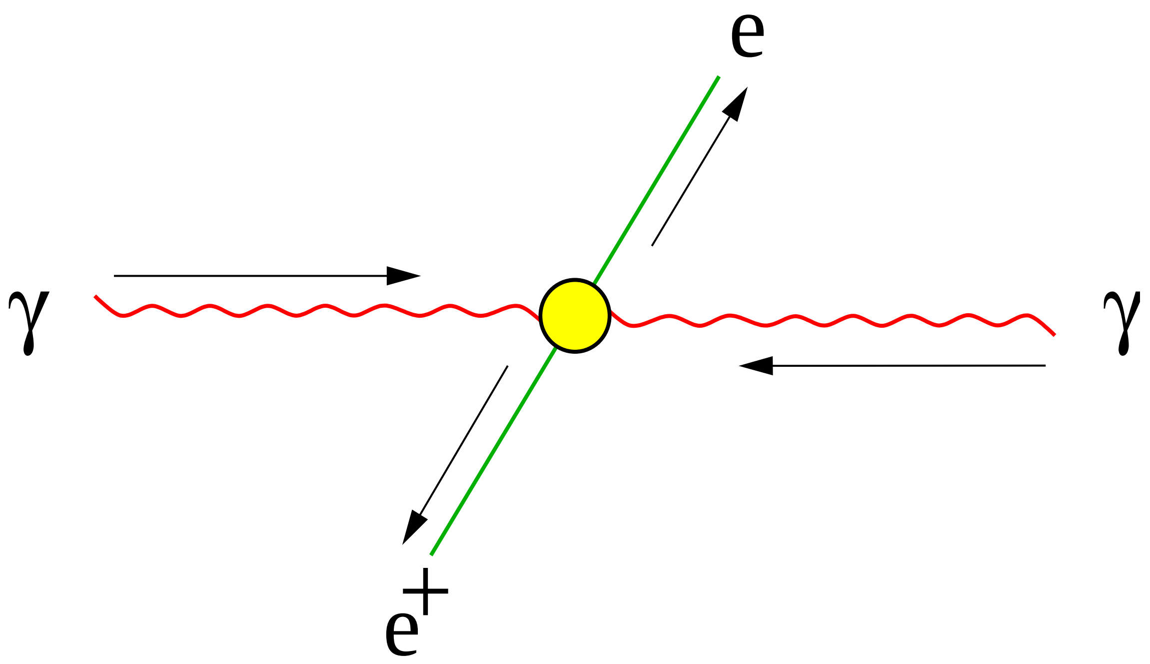
- Temperature corresponds to the average particle energy:

$$T \sim E_{avg}$$

- Relativity tells us that

$$E = mc^2$$

- Particles can be created spontaneously when $T > 2mc^2$!



Elementary Particles

Fermions

u	c	t
d	s	b
ν_e	ν_μ	ν_τ
e	μ	τ

Bosons

γ
g
W^{+-}
Z^0
h

In Stuffed Toy Form

Four Fundamental Forces

1. Gravity – mediated by the graviton.

   Very weak, always attractive, infinite range.

2. Electromagnetism – mediated by the photon.

   Medium strength, attractive or repulsive, infinite range.

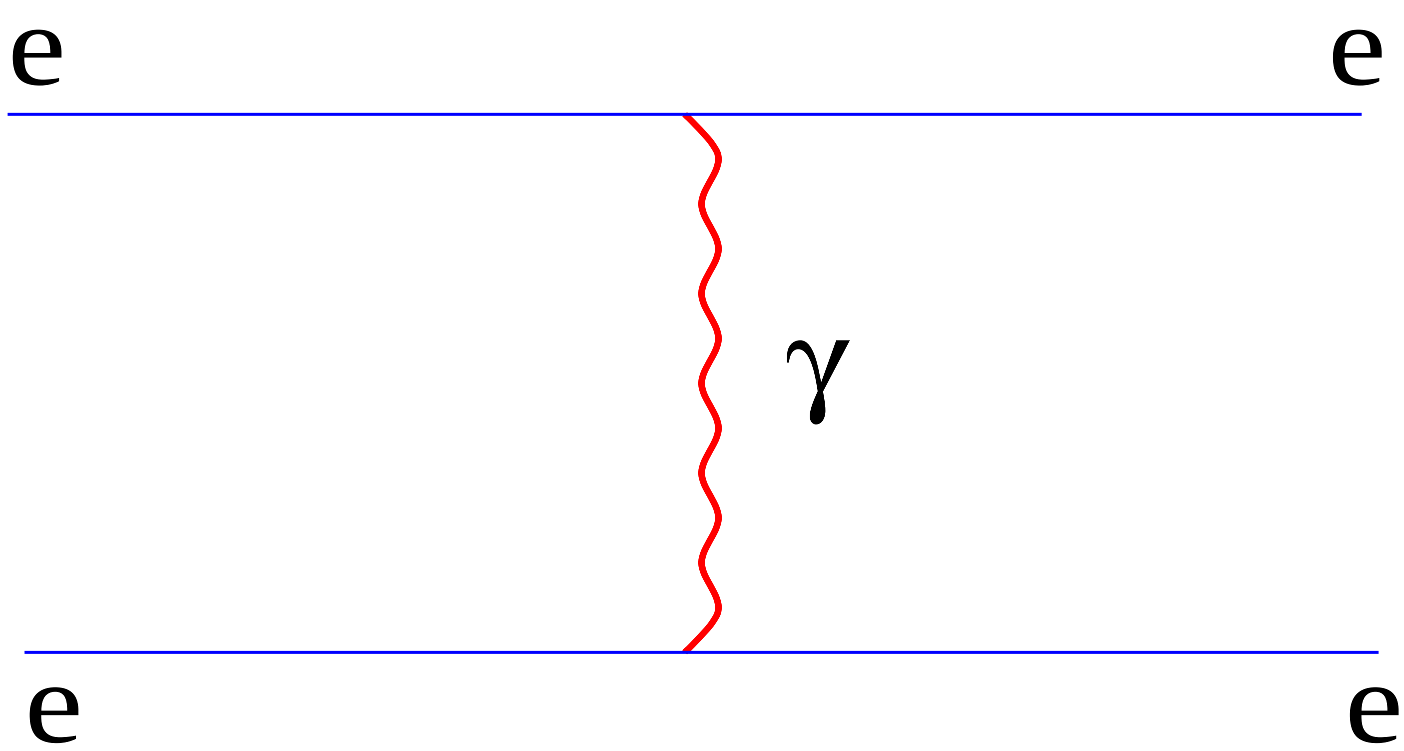
3. Strong – mediated by the gluon.

   Strong, holds nuclei together, binds quarks into nucleons.

4. Weak – mediated by the $W^{\pm}$ and Z^0 vector bosons.

   Weak, leads to radioactive nuclear decays.

e.g. Electromagnetic Scattering of Two Electrons



Cosmology:

Storytelling about our Universe

In the Beginning . . .

. . . we don't really know. (42?)

- Elementary particles and forces have been tested only up to energies near 200 GeV.
- Start with a soup of elementary particles at $T \sim 100$ GeV.

- Aside: we measure energy in units of eV = electronvolts.

  1 eV = energy of an electron through a 1 Volt potential

  1 MeV = 10^6 eV = 1 million electronvolts

  1 GeV = 10^9 eV = 1 billion electronvolts

  Room Temperature $\sim 300\,\mathrm{K} \sim \frac{1}{40}\,\mathrm{eV}$

Hot Soup: $t \sim 10^{-10}\, s$

- Start with a hot soup of elementary particles at $T \sim 100$ GeV.

  - free quarks and gluons
  - electrons and photons
  - muons, taus, neutrinos
  - $W^{\pm}$, Z^0, Higgs, . . .

- The soup cools as the Universe expands.

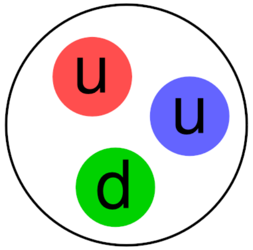
  Unstable particles disappear when T falls below mc^2.

(Rate of Production) < (Rate of Decay)

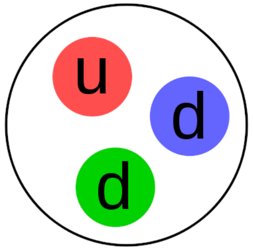
Protons and Neutrons: $t \simeq 10^{-6}\,s$

- Protons and neutrons form when T falls below 1 GeV.

Proton = p = $u + u + d$



Neutron = n = $u + d + d$



- Why? Binding Strength $\sim m_p \sim m_n \sim$ 1 GeV.

  $T >$ 1 GeV: plasma collisions rip nucleons apart

  $T <$ 1 GeV: plasma collisions don't have enough energy

Light Nuclei: $t \simeq 1\,s - 1\,min$

- At $T > 1\,\text{MeV}$ $(t < 1\,s)$ we have:

$$p + e^- \leftrightarrow n + \nu_e, \qquad (m_n - m_p = 1.2\,\text{MeV})$$

- For $T < 1\,\text{MeV}$ the reverse reaction is more likely.

  The reaction "turns off" when $T \simeq 0.3\,\text{MeV}$ with

$$\frac{N_n}{N_p} \simeq \frac{1}{7}.$$

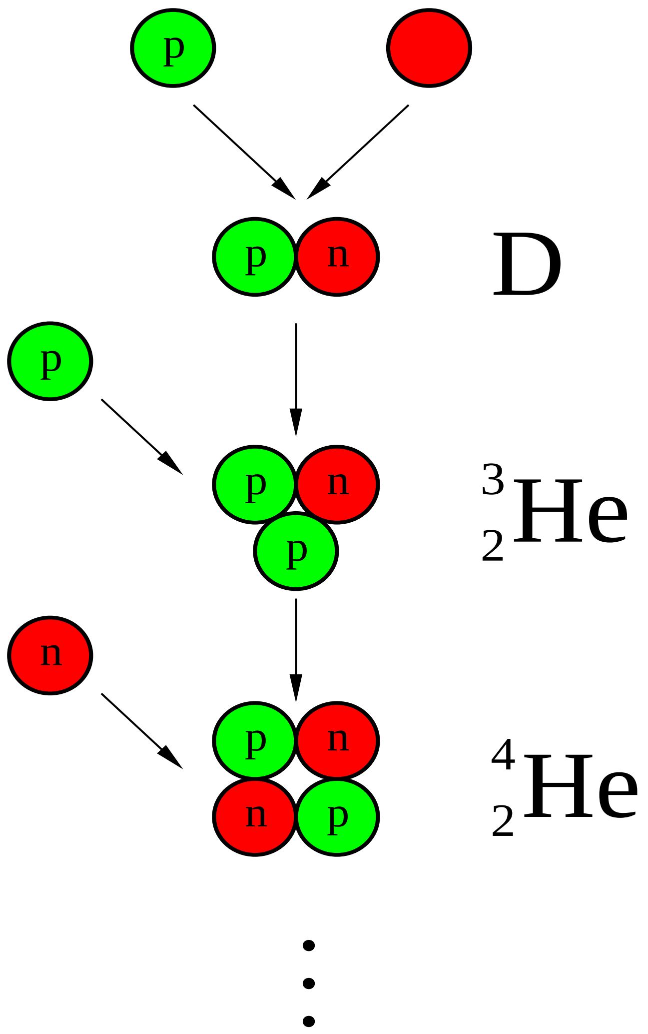
- At $T < 0.1\,\mathrm{MeV}$, some light nuclei start to form:

$$p + n \to D + \gamma$$

$$p + D \to {}^3_2He + \gamma$$

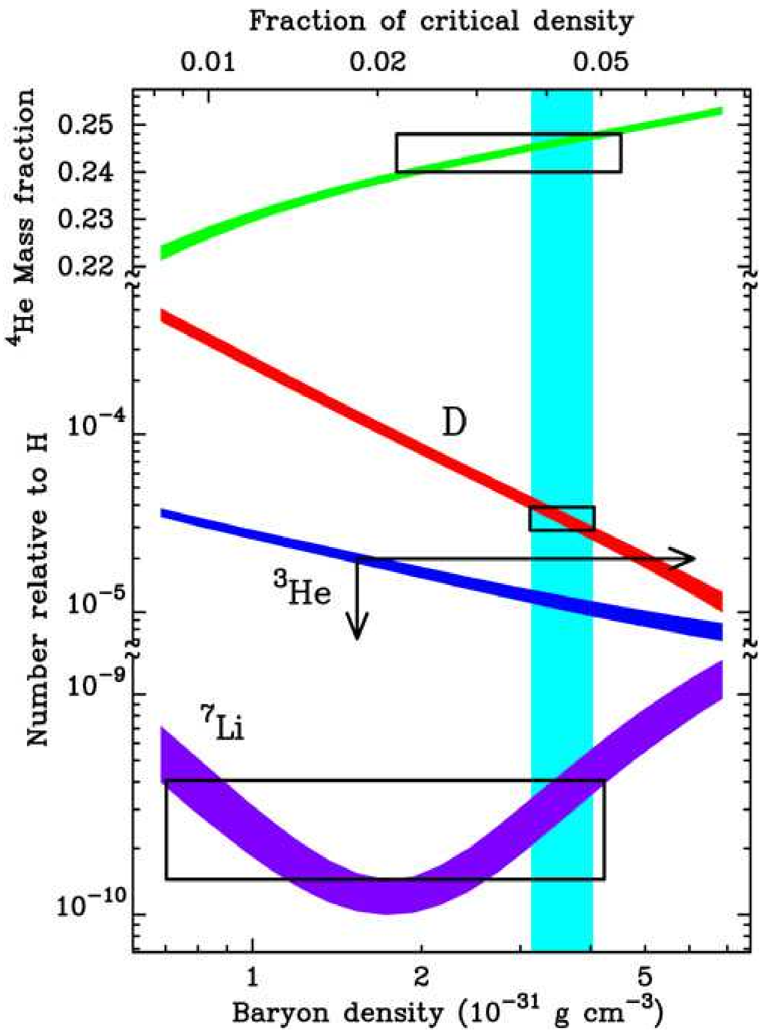
$$n + {}^3_2He \to {}^4_2He + \gamma$$

$$\ldots$$



- We can predict element abundances from particle physics!

- Calculations agree well with observations:

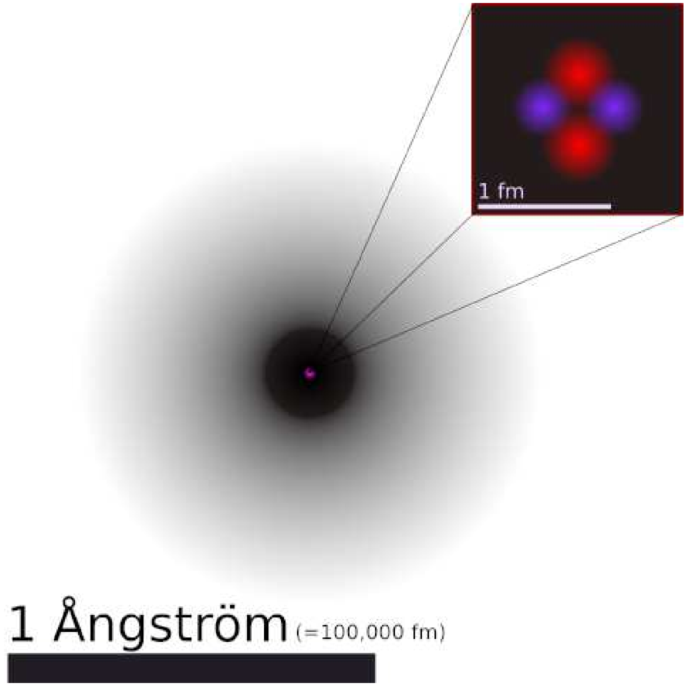


- Only light ($A \lesssim 7$) nuclei are produced this way due to small temperatures and densities.

Atoms: $t \simeq 10^{10} s \simeq 1000\, yr$

- Hydrogen atom:

  Binding Strength $= 13.6\,\mathrm{eV}$



$\Rightarrow$ for $T > 13.6\,\mathrm{eV}$ we only have ions and free electrons.

- For $T < 13.6\,\mathrm{eV}$, electrons and nuclei bind into atoms:

$$p + e^- \rightarrow H + \gamma$$

- Nearly all free charges are bound by $T \simeq 0.3\,\mathrm{eV}$ $\;(t \simeq 10^{12}\, s)$.

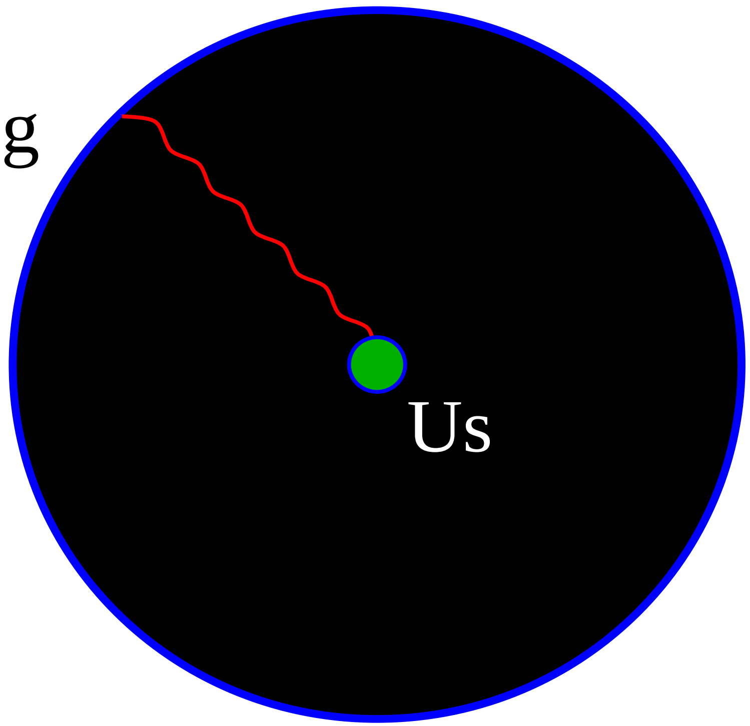
- With no free charges, photons nothing to scatter with.

  $\Rightarrow$ light travels unimpeded

  $\Rightarrow$ universe becomes transparent

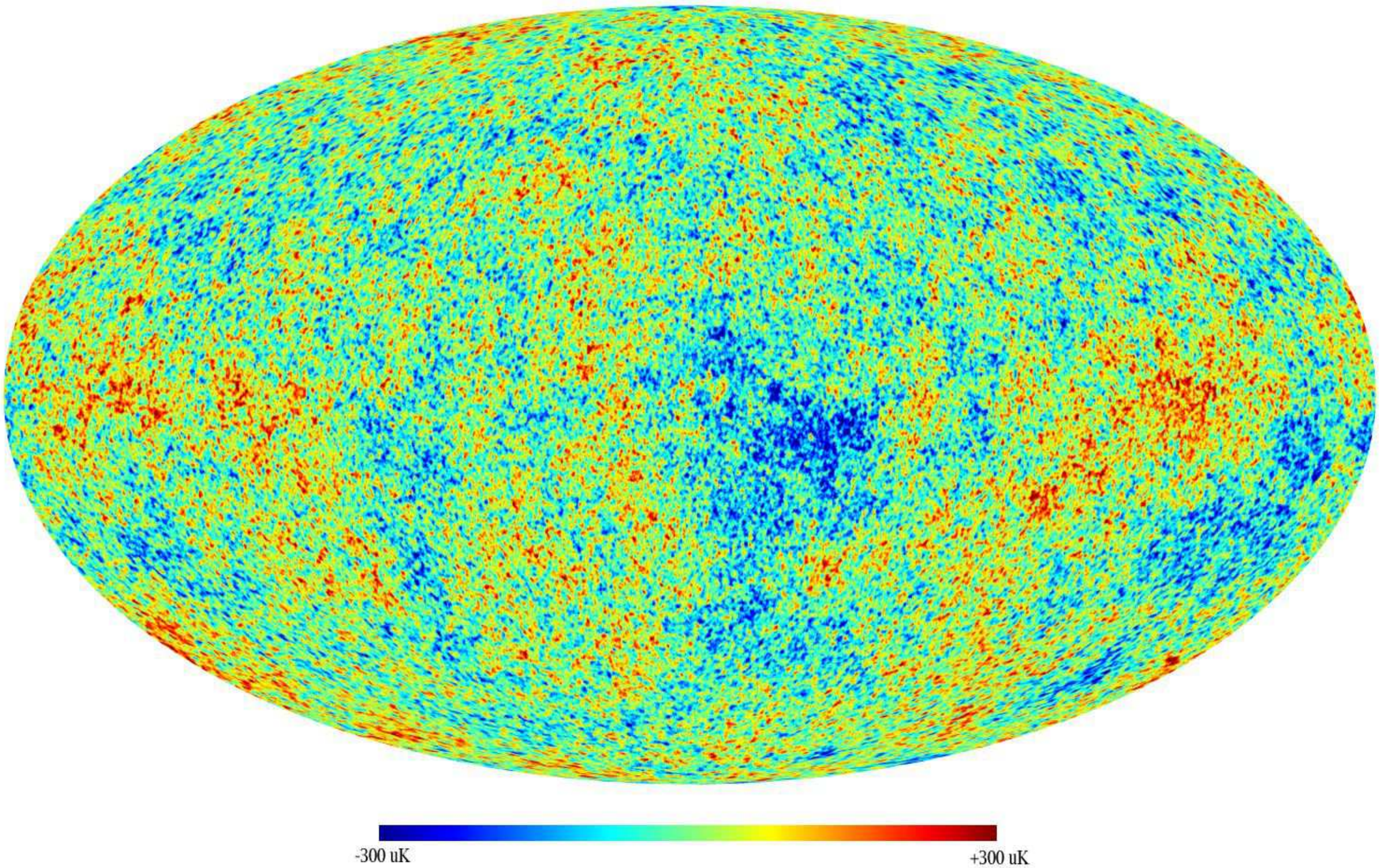
- These photons are what we see today as the $T \simeq 2.73\,K$ cosmic microwave background (CMB) light.

Surface of Last Scattering



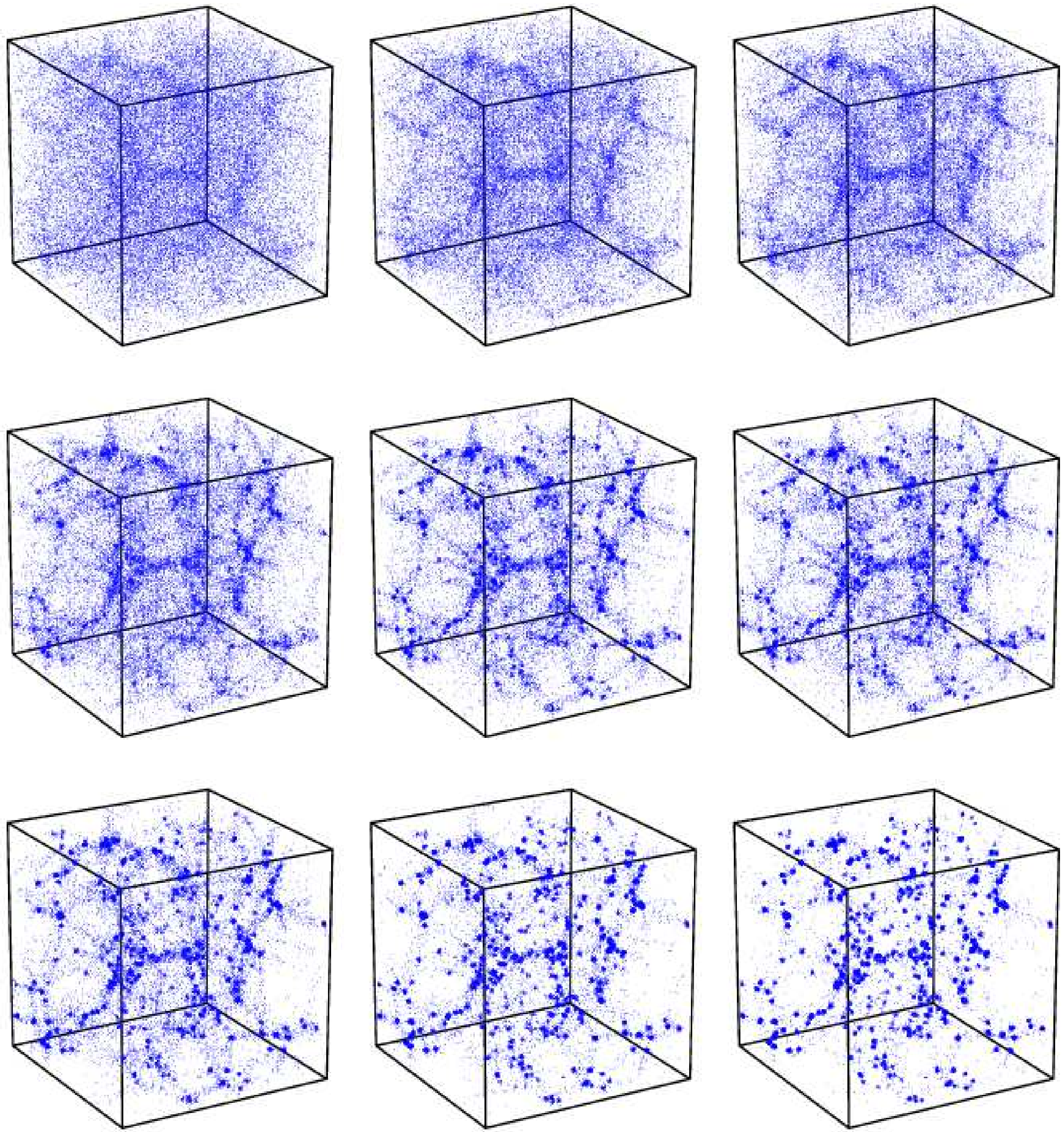
The Cosmic Microwave Background (CMB)

- The CMB is a snapshot of the universe at recombination.
- It is almost completely uniform: $\Delta T/T \simeq 10^{-4}$



Structure Formation: $t > 10^{10}\, s \simeq 1000\, yrs$

- CMB spots represent local density variations.
- These grow with time, and eventually become unstable to gravitational collapse at $t \simeq 10^{10} s$.
- Gravity pulls matter together into clumps of dust that eventually become galaxies, stars, planets, . . .



Star Formation: $t > 10^{15} s \simeq 100$ million yrs

- Clumps of dust get pulled together by gravity at $t \simeq 10^{15}\, s$. As they condense, they heat up.

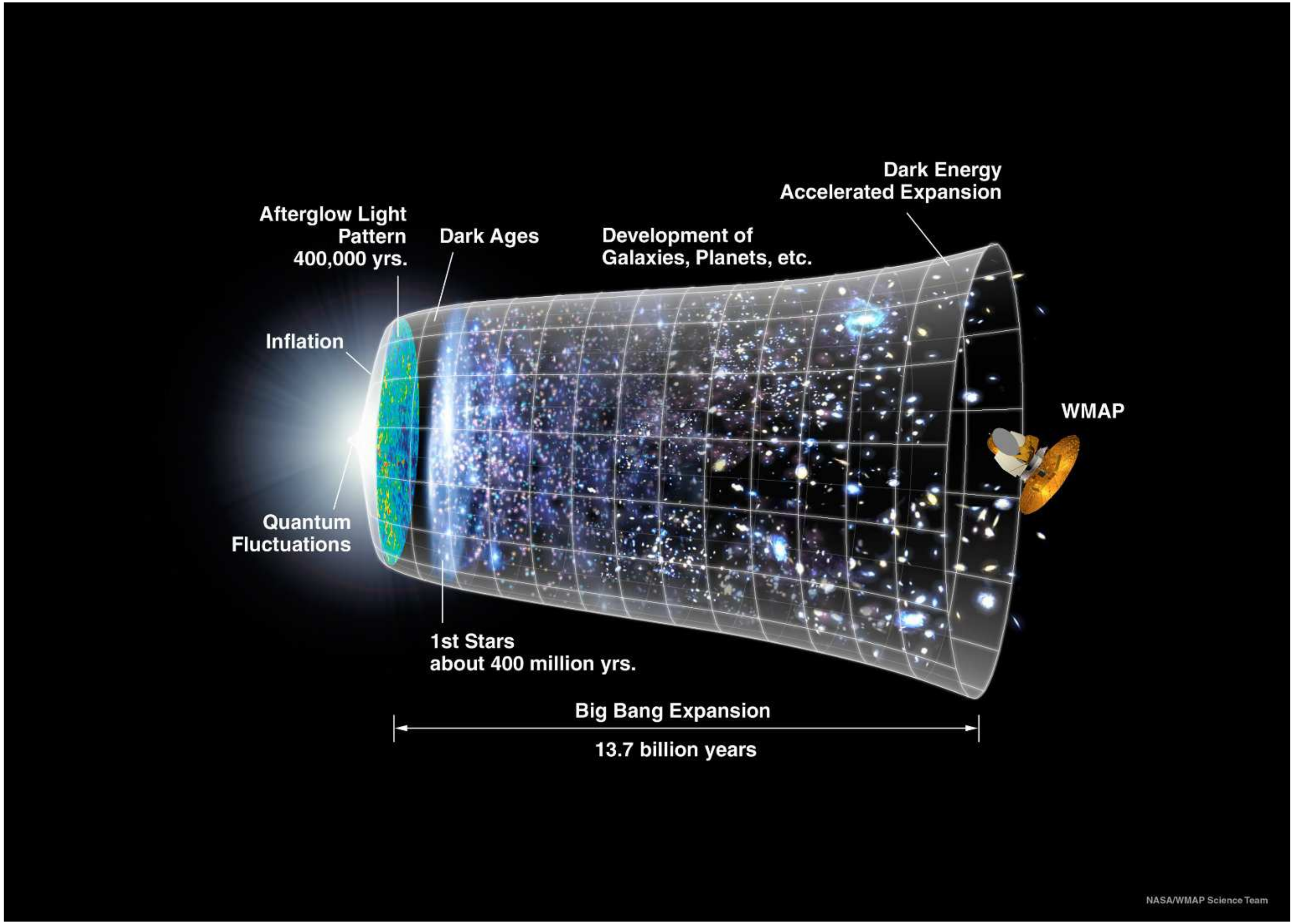
- Thermal pressure eventually balances out gravity when

$$T_{dust} \simeq 10^8\, K \simeq 0.01\,\text{MeV},$$

hot enough to ignite nuclear fusion and make a star!

- Stars evolve over their lifetime to make heavier elements. We can predict their abundances as well!

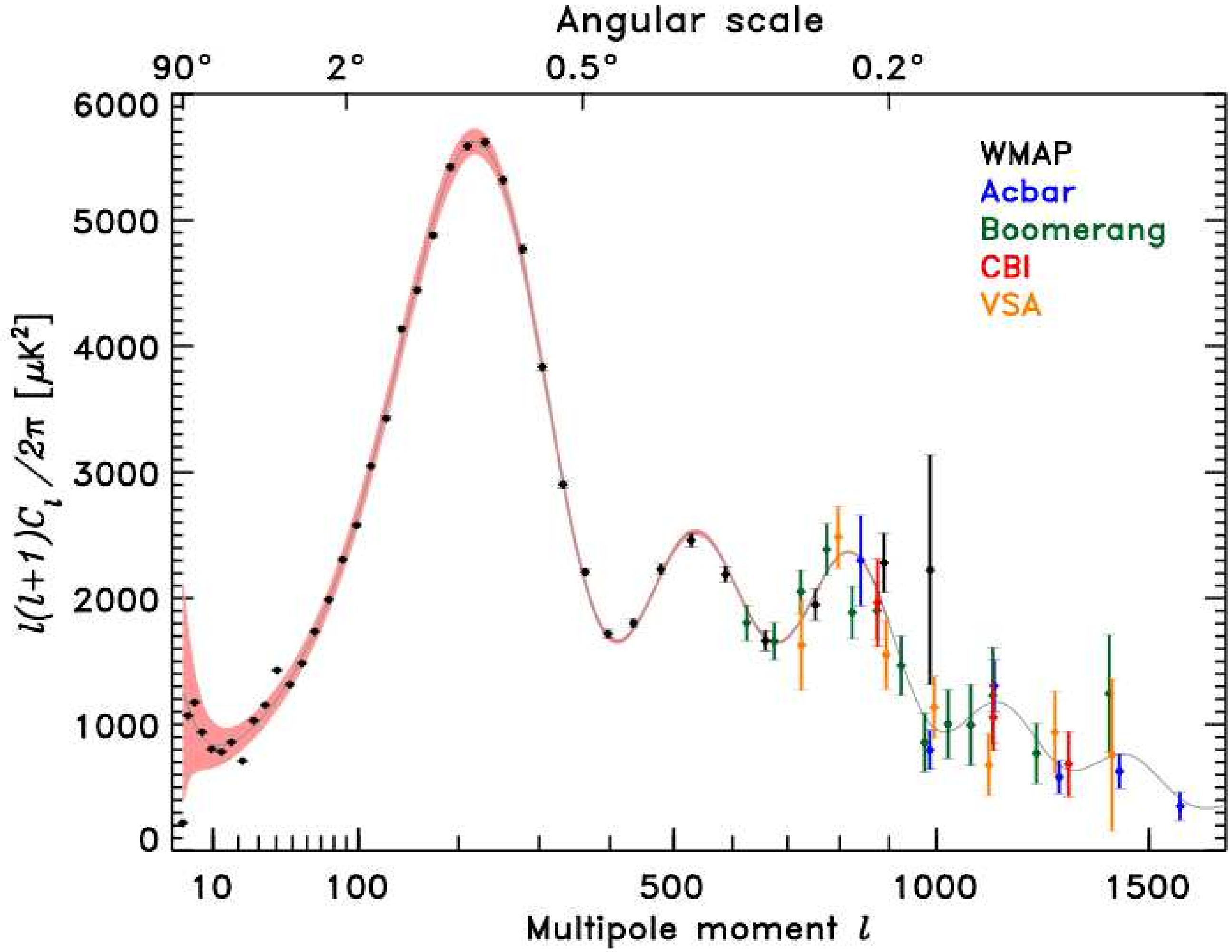
- $t_{today} \simeq 13.7$ billion yrs



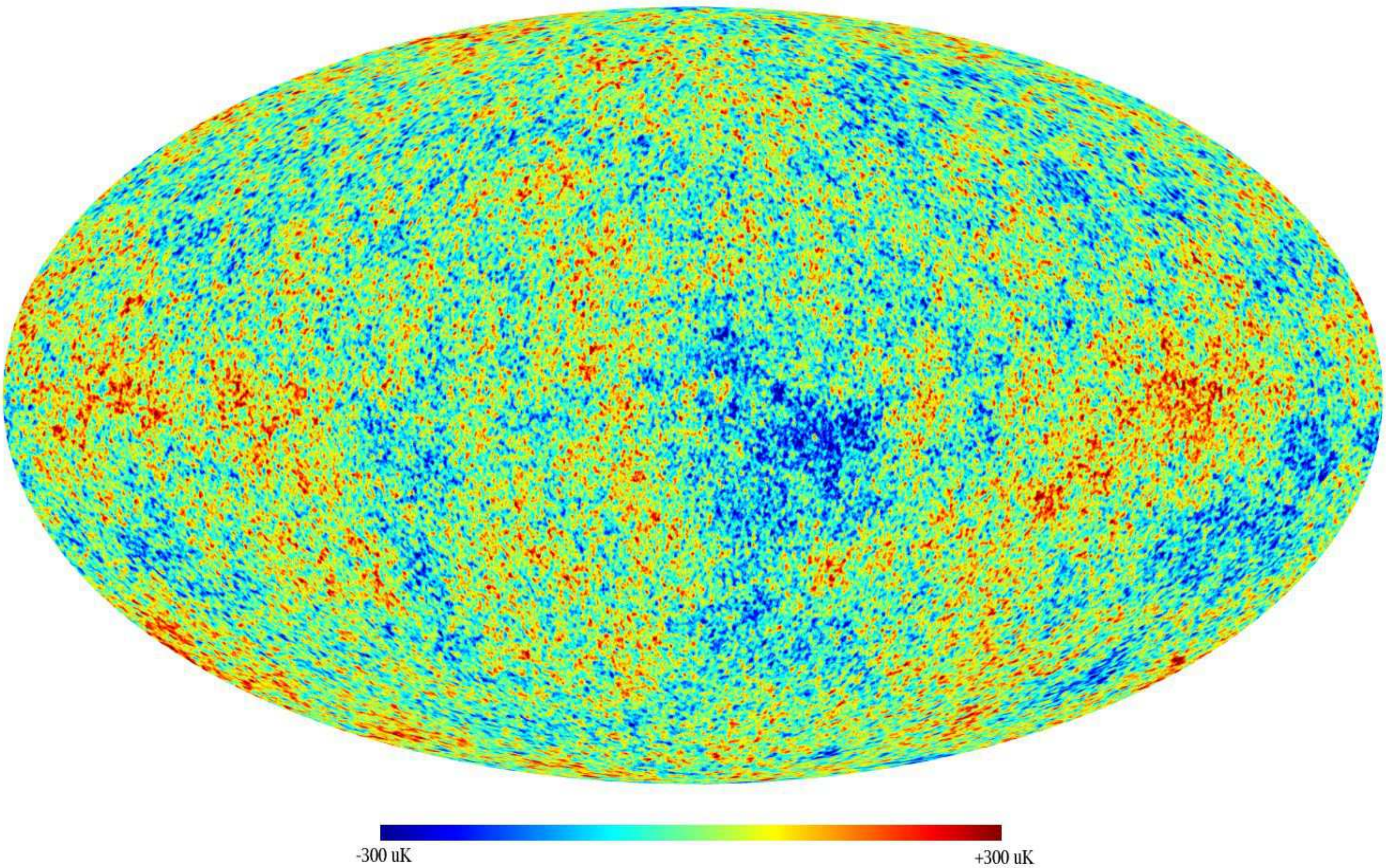
The Dark Side

Missing Matter: CMB

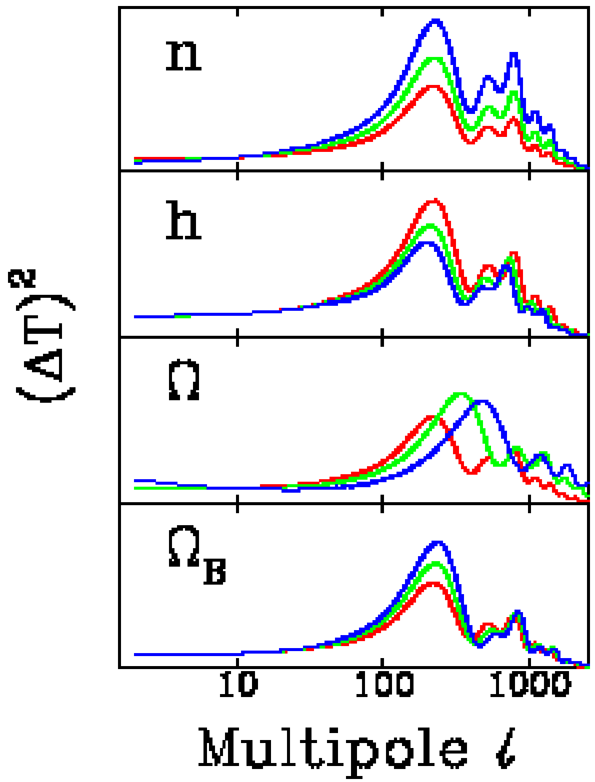
- Variations in the Cosmic Microwave Background (CMB) temperature contain a lot of information.

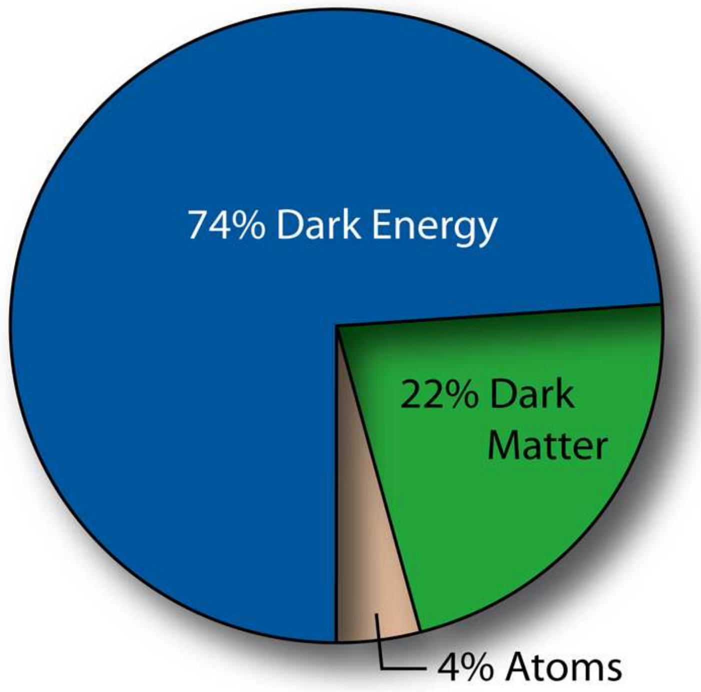


- Cosmic Microwave Background (CMB).



- The heights and locations of the peaks depends on the amount of matter in the Universe.





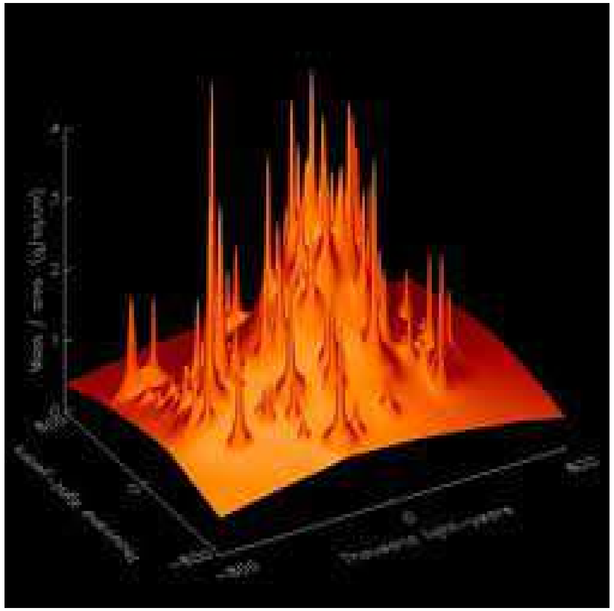
- (Total Matter) $\simeq 5 \times$ (Visible Matter)

  Where's the missing matter!?

Missing Matter: Gravitational Lensing

- Gravitational Lensing: light is bent by gravity.

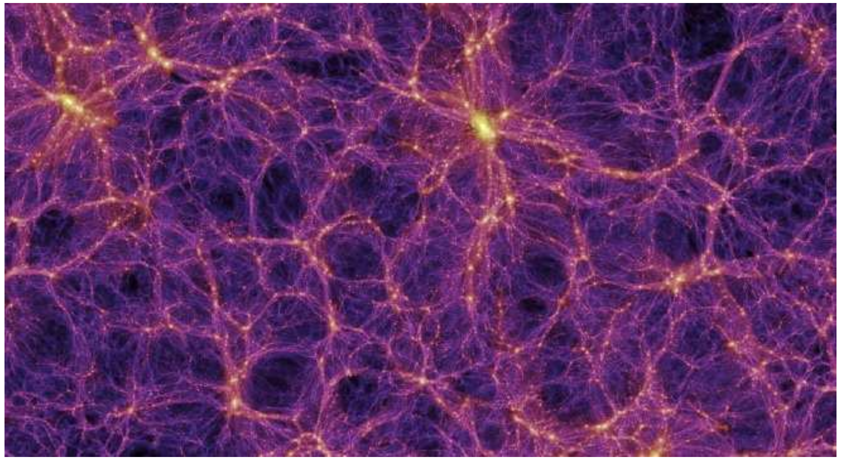
(Amount of Bending) $\sim$ (Amount of Matter)

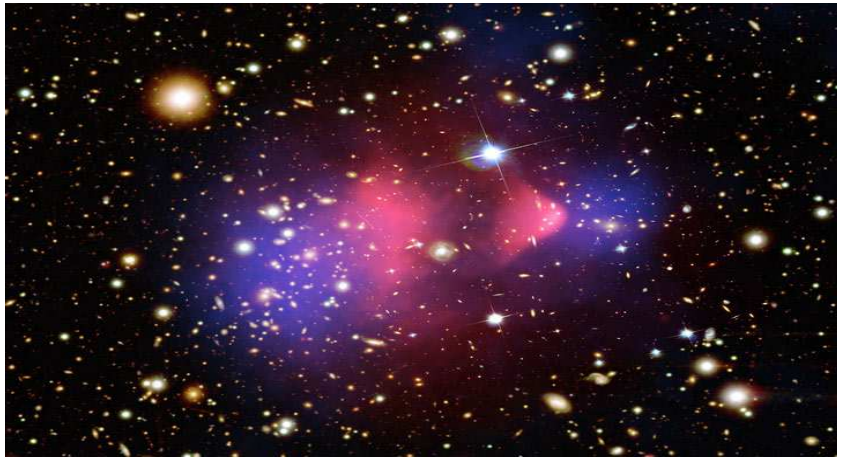


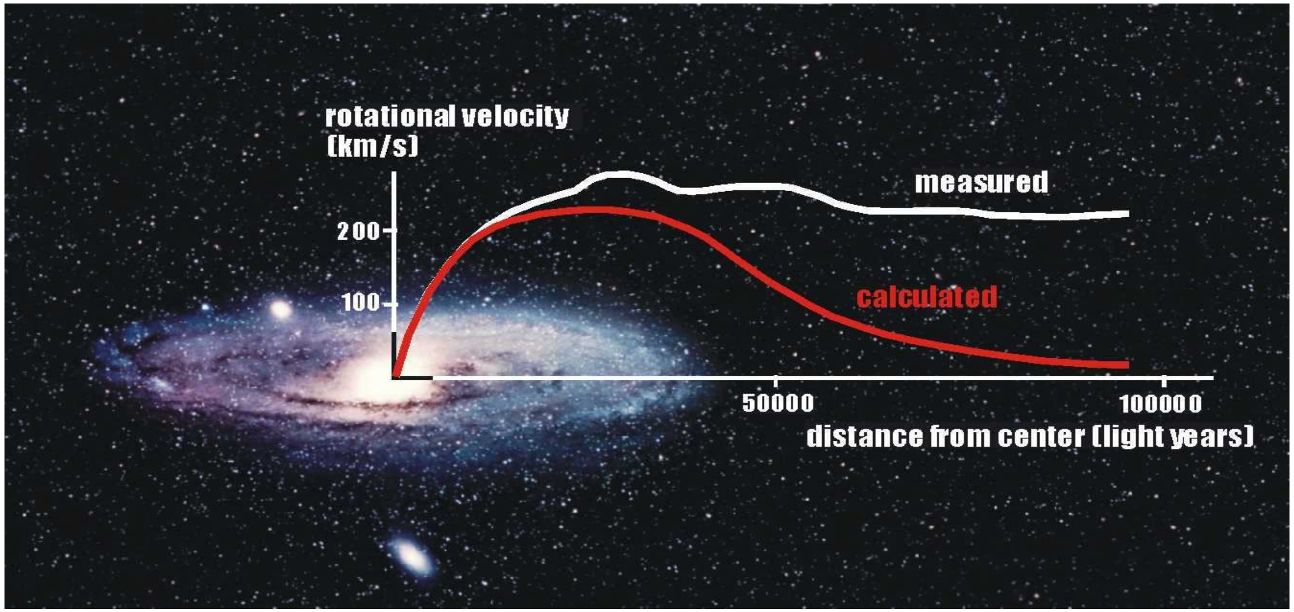
- Much more matter than is visible!

Missing Matter: Galaxies

- We need hidden matter to explain the structure of galaxies.





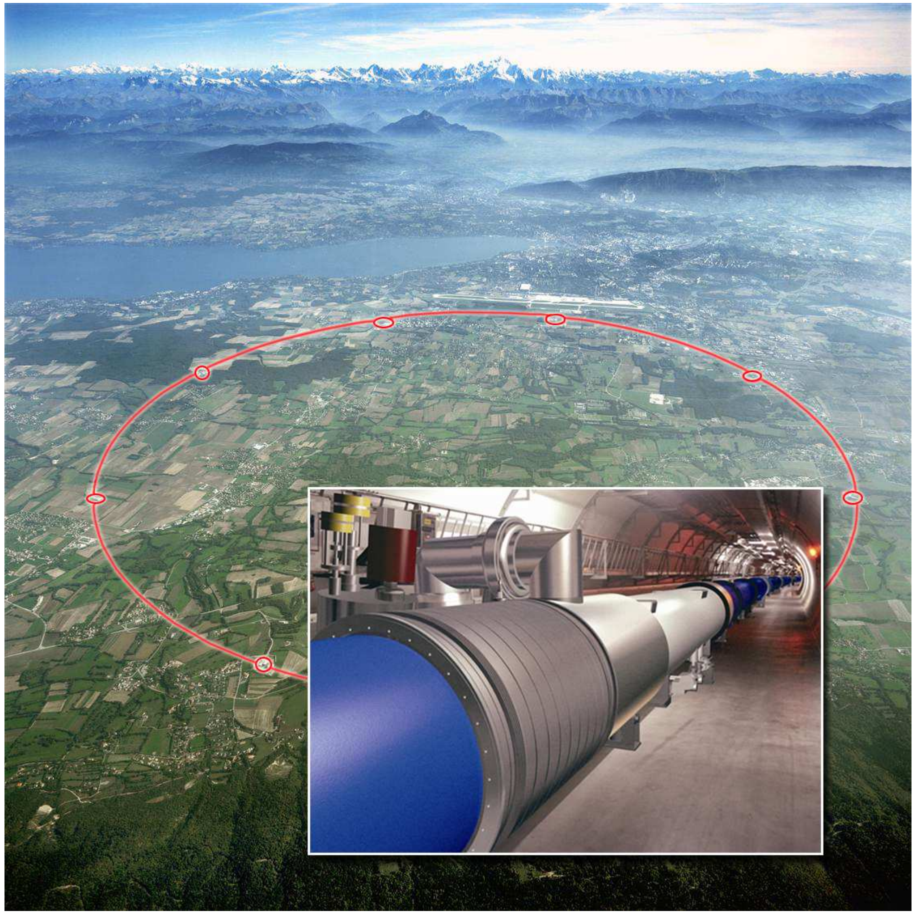


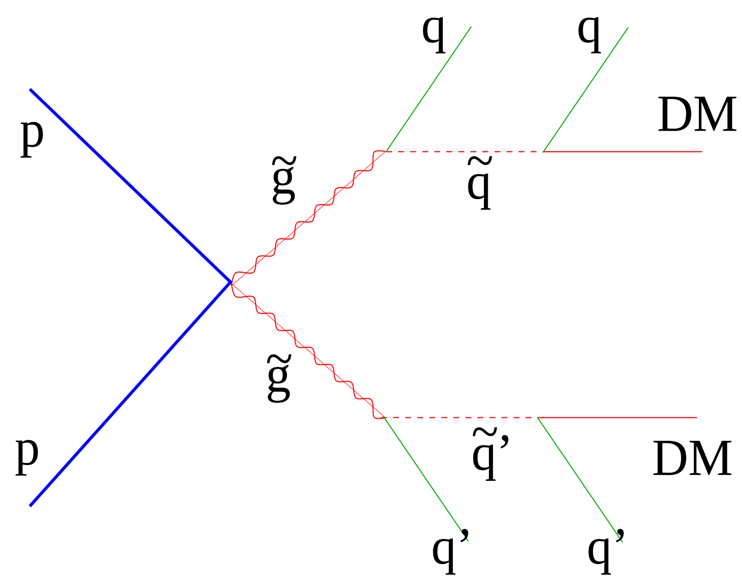
Dark Matter

- Missing cosmological matter is called Dark Matter (DM).
- None of the known particles can be the DM.
- A DM particle needs to be heavy, stable, and neutral.
- DM Hunting:
  - Create DM in particle colliders (LHC).
  - Look for DM scattering off sensitive detectors.
  - Search for DM effects in the galaxy.

- DM can be created in energetic particle collisions.

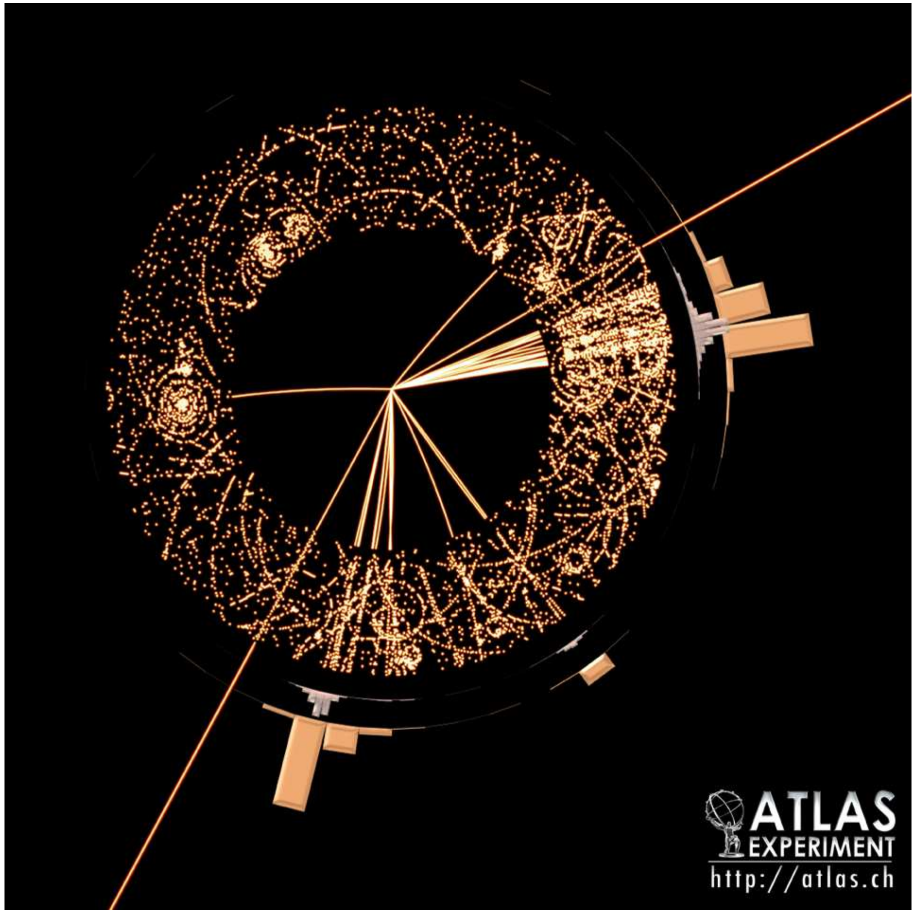
  e.g. CERN LHC: proton–proton with $E = 14000\,\mathrm{GeV}$.





* DM leaves no trace in particle detectors.

No trace is still a signal: missing momentum.



Summary

- Science Works . . .

  Physics on the Earth seems to work in the Cosmos!

- Cosmology = Storytelling
  - Start with a hot plasma of elementary particles
  - Expand and cool
  - Form nucleons, nuclei, atoms, stars, galaxies, . . .

- But what is the Dark Matter?

Extra Slides: Stars

H Burning: Main Sequence Stars

- H burning is the first process to take place:

$$
\begin{aligned}
p + p &\rightarrow D + e^{+} + \nu_e \\
p + D &\rightarrow {}^{3}_{2}He + \gamma \\
{}^{3}_{2}He + {}^{3}_{2}He &\rightarrow {}^{4}_{2}He + p + p
\end{aligned}
$$

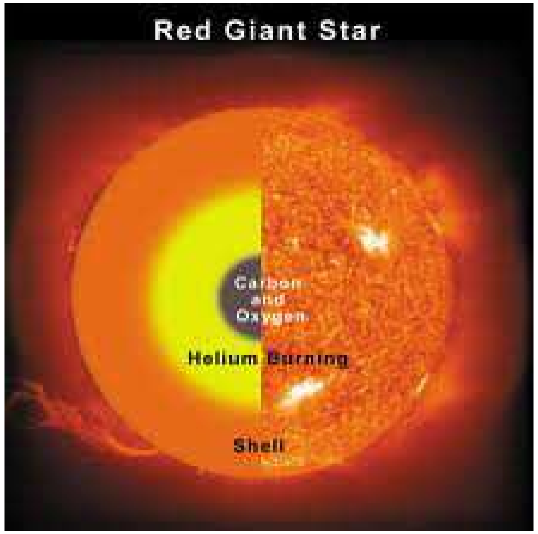
- Net result: $6p \rightarrow {}^{4}_{2}He + 2p$. (Other processes too.)

- Energy released by H burning provides thermal pressure that supports the start from gravitational collapse.

- Star supported only by H burning = "main sequence". The sun is a familiar example of this.

He Burning and Beyond: Giants

- When H is used up: – gravity compresses the core more
  – the core heats up
  – He burning starts
- He burning: ${}^4_2He + {}^4_2He + {}^4_2He \rightarrow {}^{12}_6C$, ${}^4_2He + {}^{12}_6C \rightarrow {}^{16}_8O$
- When ${}^4_2He$ is used up, C and O burning kicks in.

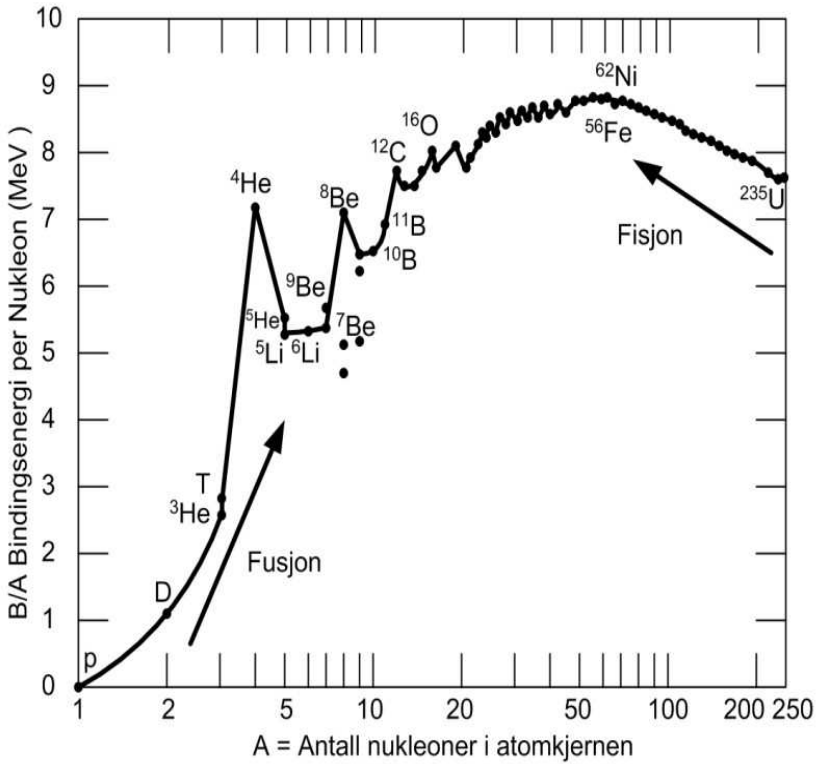


- (Red) Giant Star

- $^{20}_{10}Ne$, $^{24}_{11}Na$, $^{24}_{12}Mg$ burning next.
- $^{28}_{14}Si$ burning next
- This chain stops when the core becomes $^{56}_{28}Fe$.

  $^{56}_{28}Fe$ is the lowest energy nuclear state.

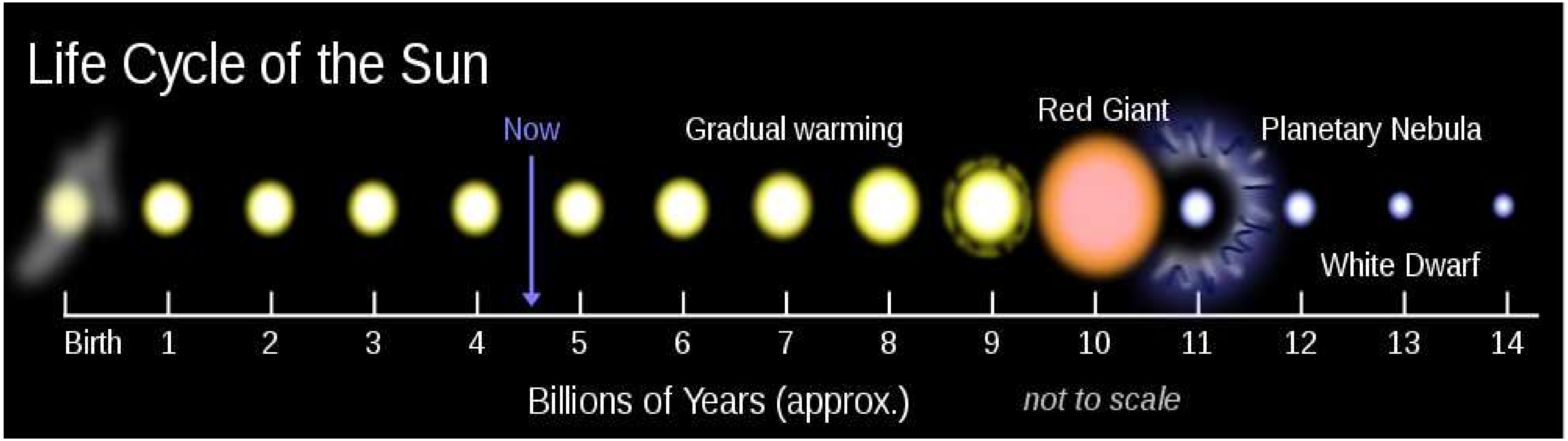
  $\Rightarrow$ no more energy can be obtained from nuclear fusion



- So what next?

- Big stars with $M \gtrsim 10\, M_\odot$ blow up – supernova!

- Smaller stars might never get to the $^{56}_{28}Fe$ core stage.



- White dwarf = star supported by electron degeneracy.

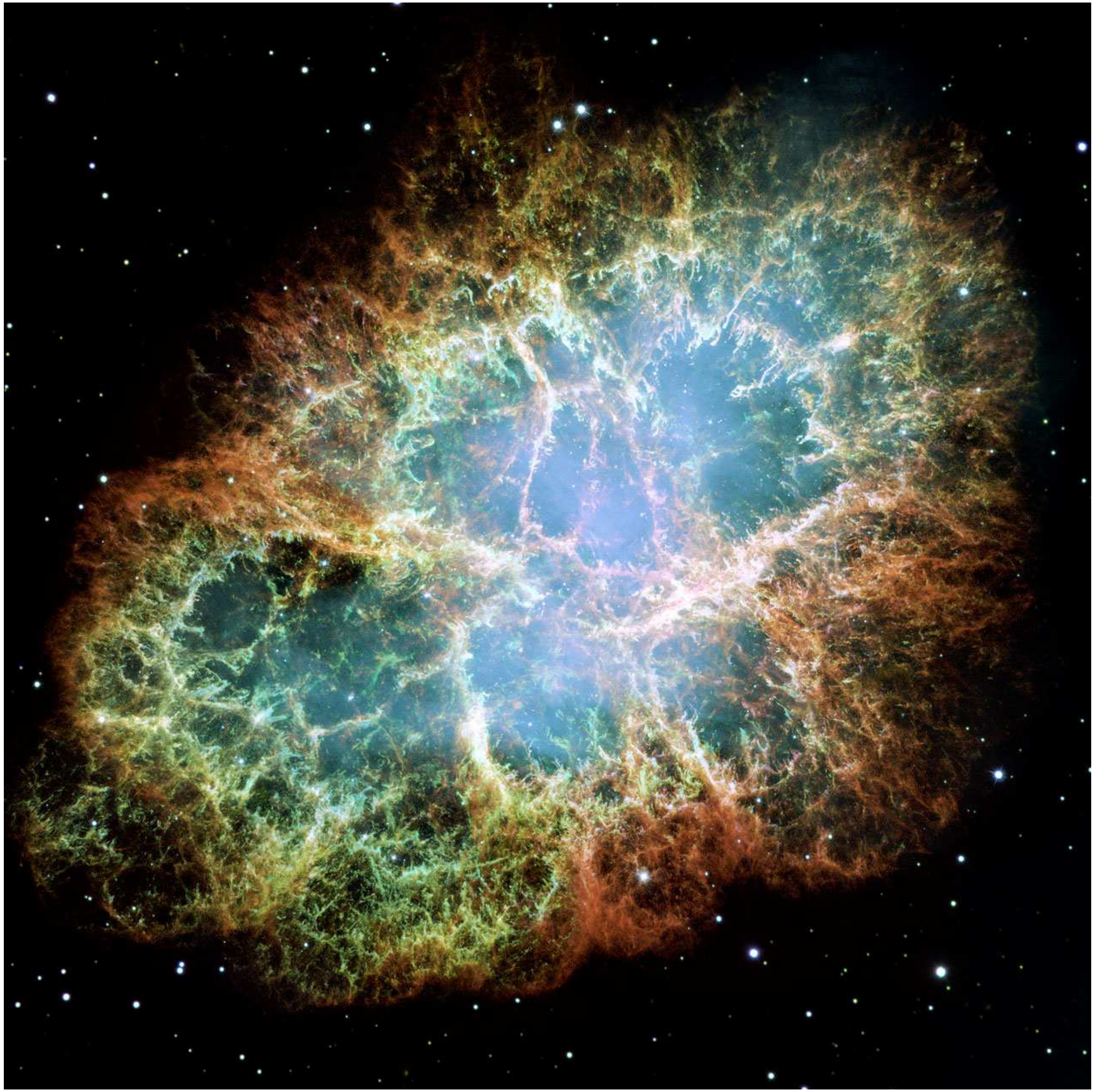
Supernova!

- Big stars with a $^{56}_{28}Fe$ core can no longer support themselves against gravity.
- The core collapses creating a huge pressure.
  Pure neutron matter then becomes energetically favourable.

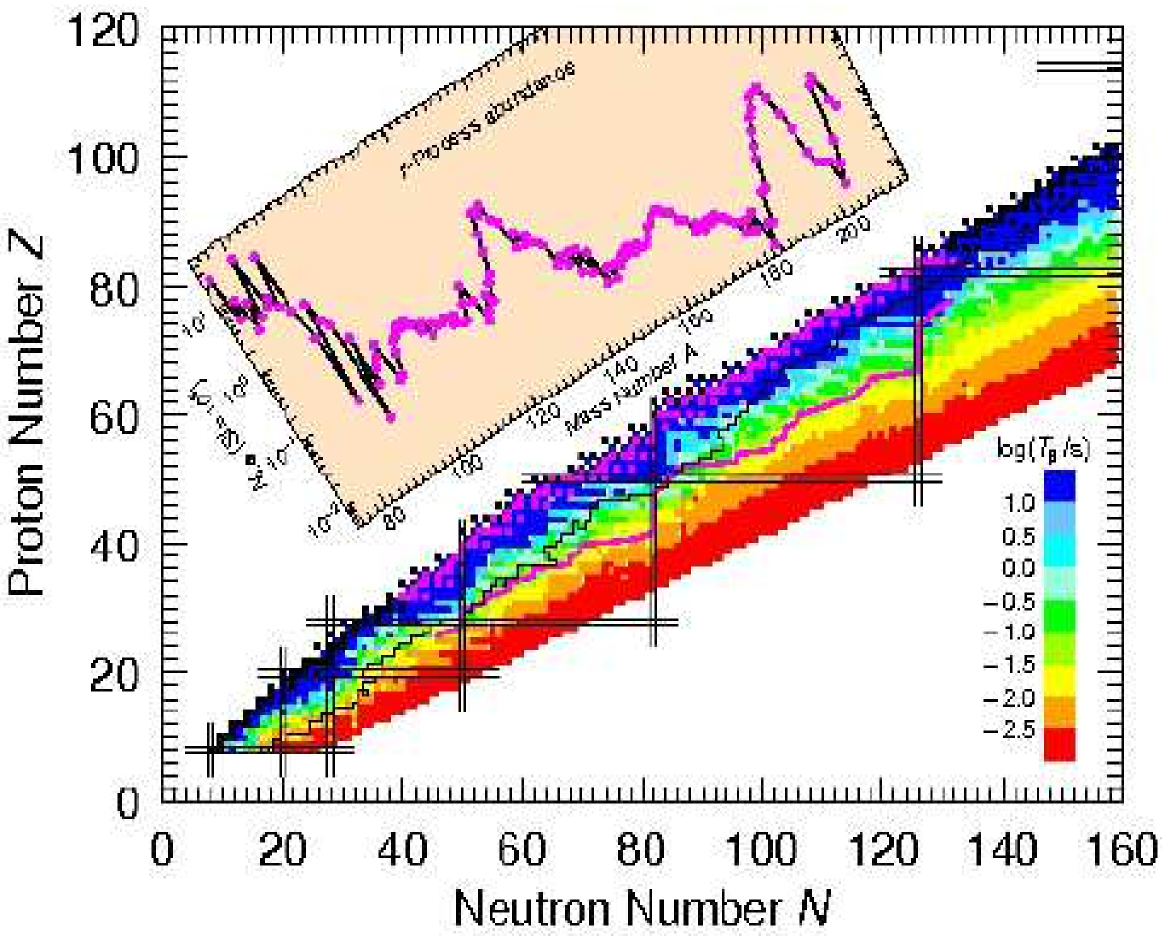
$$p \rightarrow n + e^{+}\nu_e$$

- Neutron degeneracy pressure stops the core collapse.
- The core "bounces" sending off a shock wave and that blows away the outer layers of the star.

$\rightarrow$ Supernova!!!



- Heavy elements are produced in the outgoing neutron-rich shock wave via the r-process.



- These drift off, and are incorporated into new stars.