Nature's Design

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April 20 2004, Designing Matter, #13

Designing Matter Lecture Series:

Topics 1 - 12 span: atoms → humans → earth's surface
Topic 13 (this one): the rest of the Universe…….

In terms of size :

Topics 1-12

Atomic nucleus

Topic 13

Outline

1) Design in Nature: the stage, actors and play.
2) Quick tour: from nuclei to distant galaxies.
3) Universe as a laboratory of extremes:
   size/mass/time/power/density/temperature.
4) Constituents, and their construction/creation:
   nuclei & atoms, particles, matter,forces.
5) Emergence of structure:
   stars, galaxies, clusters/voids.
6) Origin of energy.

Shakespeare : "As You Like It"
Reflections on human life

"All the world's a stage,
And all the men and women merely players.
They have their exits and their entrances,
And one man in his time plays many parts,
His acts being in seven ages."

Deep Contents

- Space & Time (space-time)
- Matter (particles)
- Forces (act between particles)
  4(5) : strong, electromagnetic, weak, gravity, (QM)
- Rules (quantum/classical physics)
  (e.g. conservation laws, QED, QCD, GR)

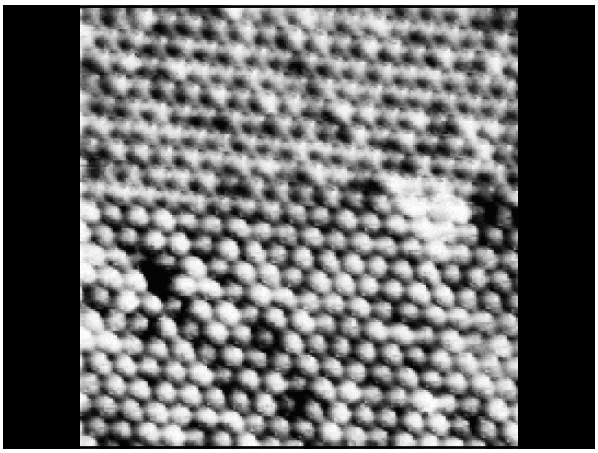
Together, these make four basic structures

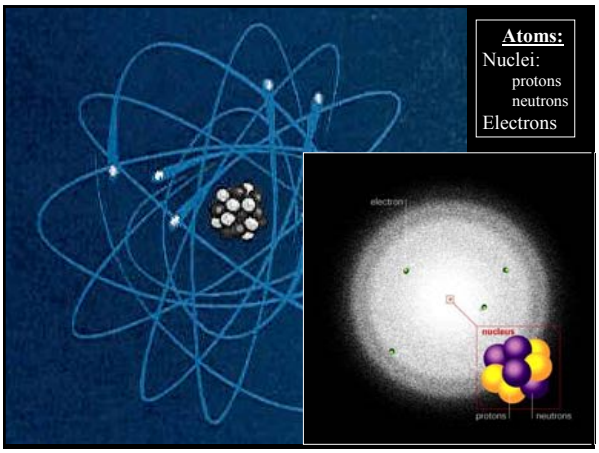
Four Basic Structures

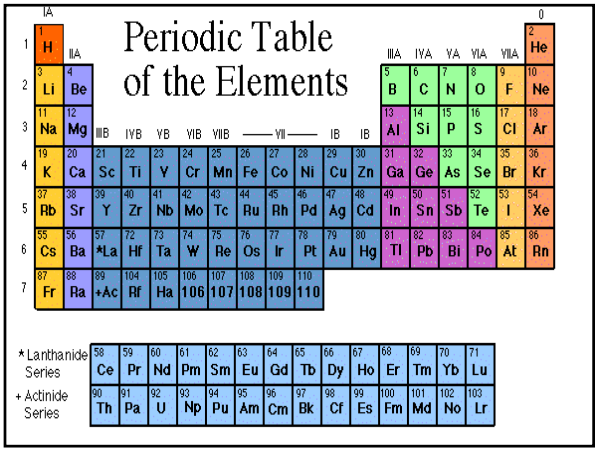
- Nuclei
- Atoms
- Stars/Planets
- Galaxies

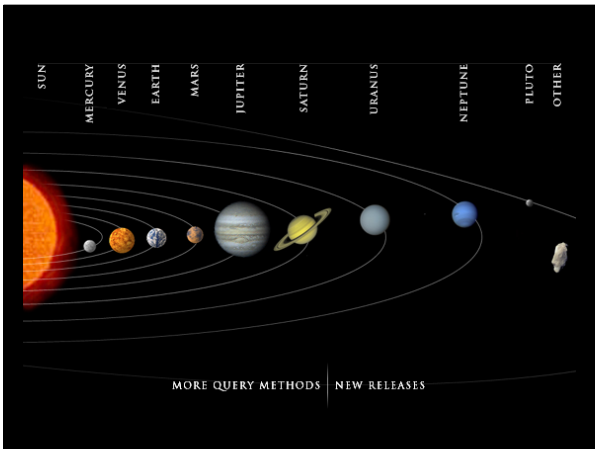
FORCES
strong, **EM, QM**
EM, QM
gravity, **EM, QM**
gravity

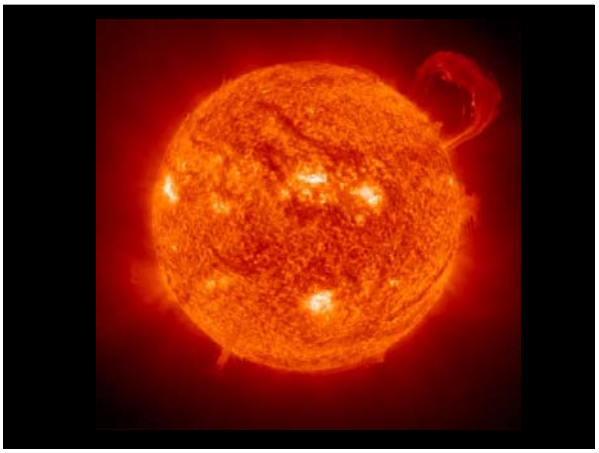
Lets begin our brief tour of these basic structures

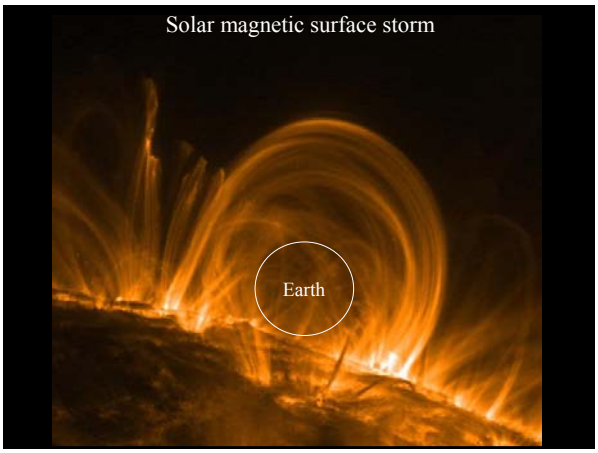



Atoms:
Nuclei:
protons
neutrons
Electrons
electron
nucleus
protons
neutrons


Periodic Table of the Elements
IA
0
IIA
IIIA
IVA
VA
VIA
VIIA
IIIB
IVB
VB
VIB
VIIB
VII
IB
IB
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
57 *La
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
89 +Ac
104 Rf
105 Ha
106 106
107 107
108 108
109 109
110 110
* Lanthanide Series
+ Actinide Series
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
90 Th
91 Pa
92 U
93 Np
94 Pu
95 Am
96 Cm
97 Bk
98 Cf
99 Es
100 Fm
101 Md
102 No
103 Lr


SUN
MERCURY
VENUS
EARTH
MARS
JUPITER
SATURN
URANUS
NEPTUNE
PLUTO
OTHER
MORE QUERY METHODS
NEW RELEASES




Solar magnetic surface storm
Earth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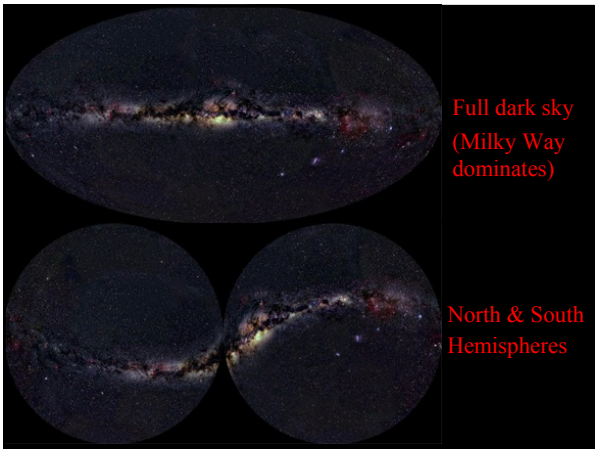
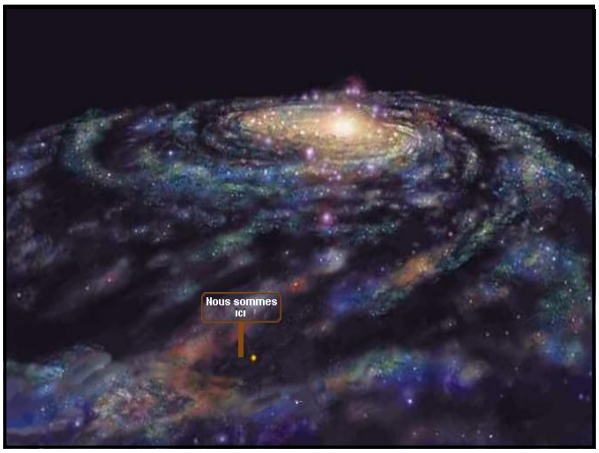

Full dark sky (Milky Way dominates)
North & South Hemispheres


Nous sommes ICI


NGC 891 edge on Spiral Galaxy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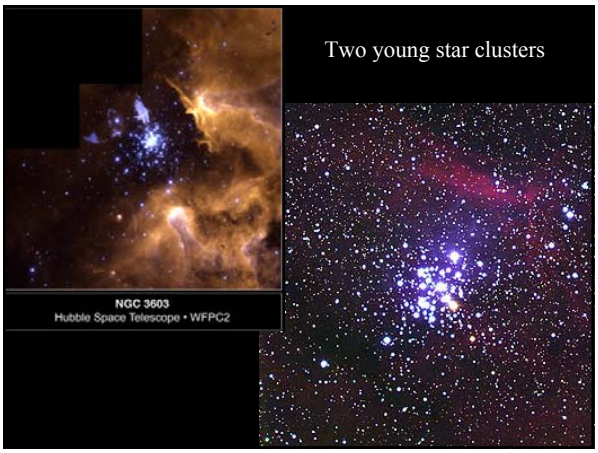
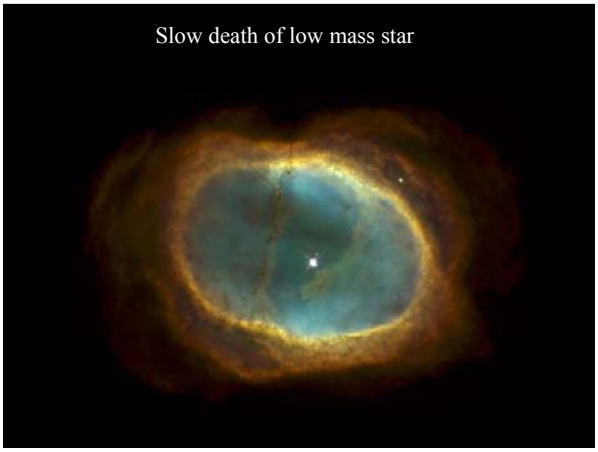
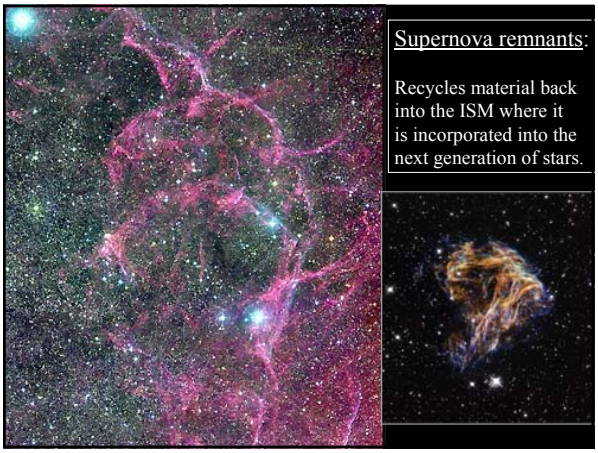
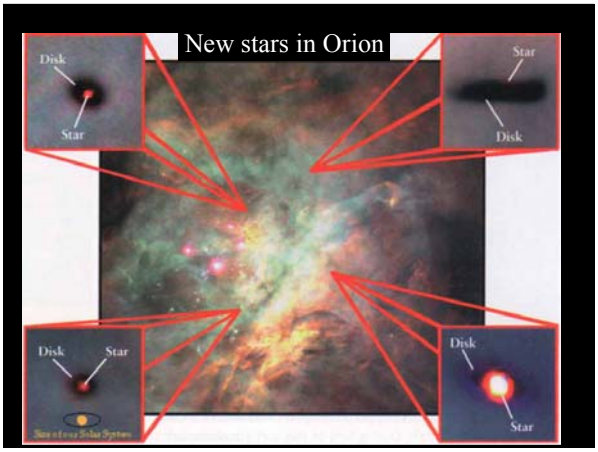

Two young star clusters
NGC 3603
Hubble Space Telescope • WFPC2


Slow death of low mass star

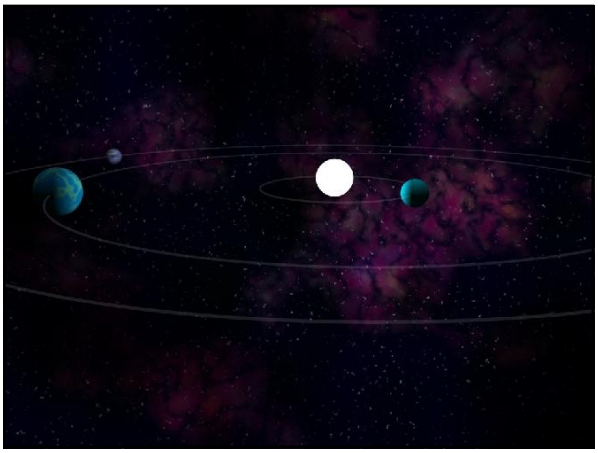

Explosive death of high mass star

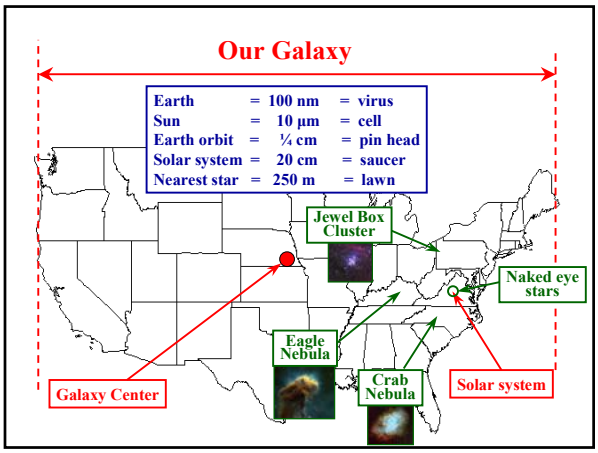

Supernova remnants:
Recycles material back into the ISM where it is incorporated into the next generation of stars.

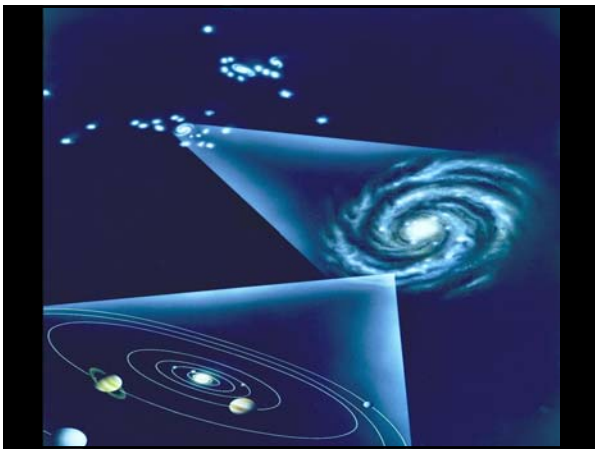
New star-formation region

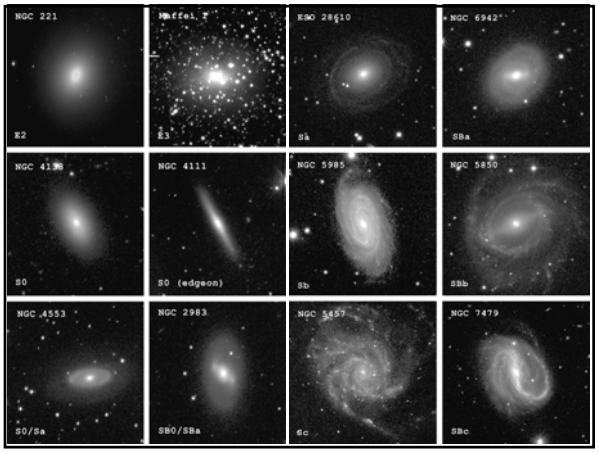


Early stage of star/planet formation




Our Galaxy
Earth = 100 nm = virus
Sun = 10 µm = cell
Earth orbit = ¼ cm = pin head
Solar system = 20 cm = saucer
Nearest star = 250 m = lawn
Jewel Box Cluster
Naked eye stars
Eagle Nebula
Crab Nebula
Solar system
Galaxy Center

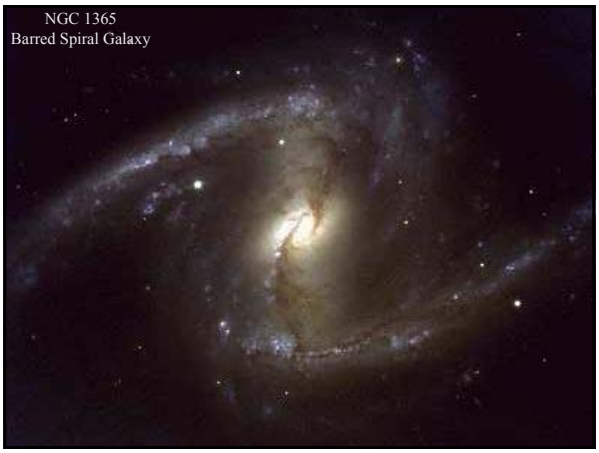


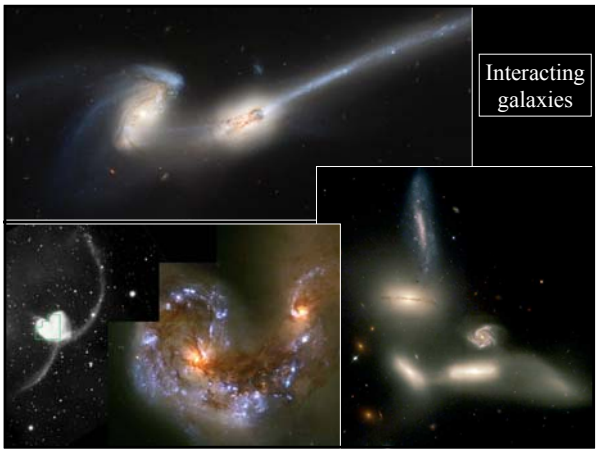

NGC 221
E2
NGC 4111
S0 (edgeon)
NGC 5985
Sb
NGC 5850
SBb
NGC 2983
SB0/SBa
NGC 7479
SBc

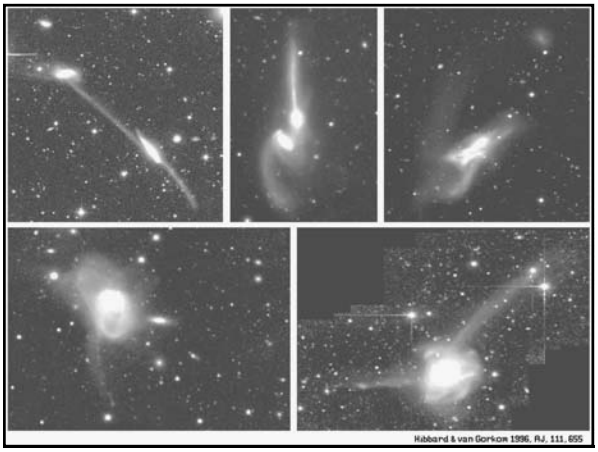

Sombrero Galaxy • M104
Hubble Heritage

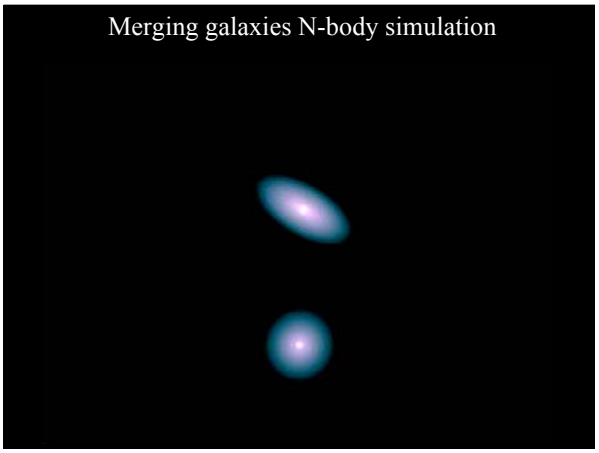

NGC 3310
Spiral Galaxy


NGC 5194
Spiral Galaxy

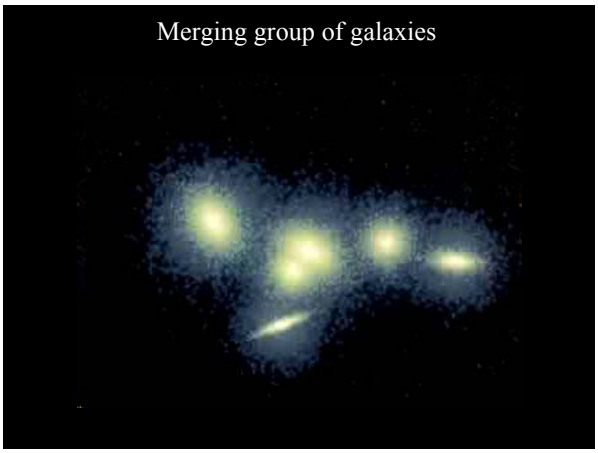

NGC 1365
Barred Spiral Galaxy


Interacting
galaxies

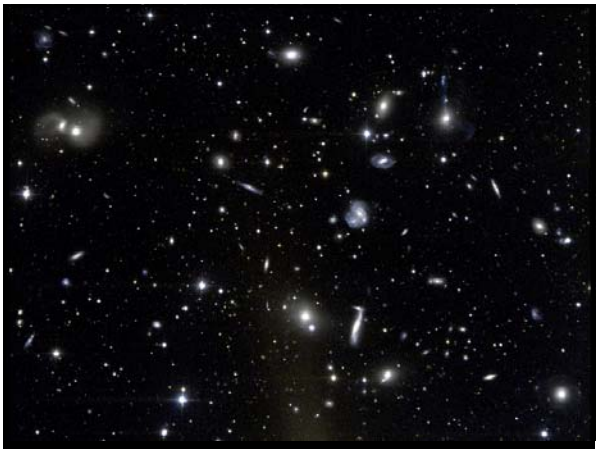

Hibbard & van Gorkom 1996, AJ, 111, 655

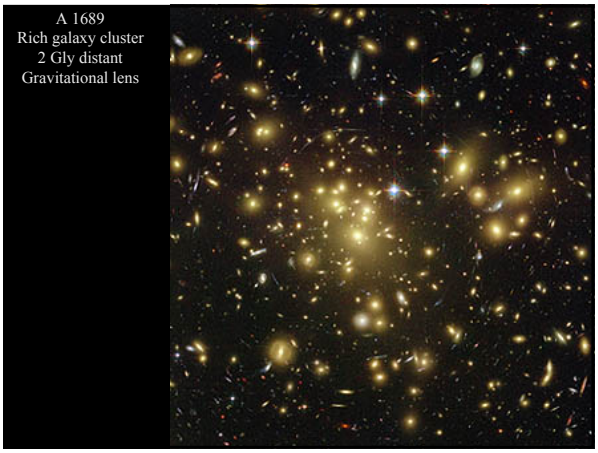

Merging galaxies N-body simulation

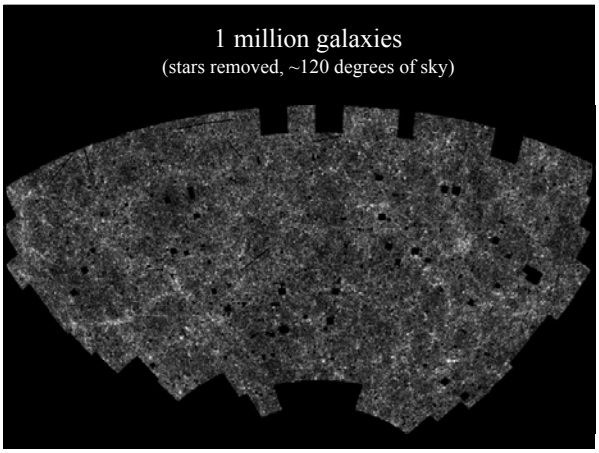

NGC 6240 post merger galaxy

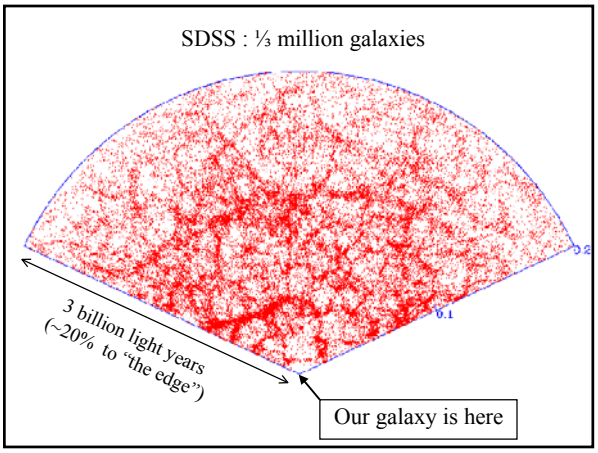

Merging group of galaxies

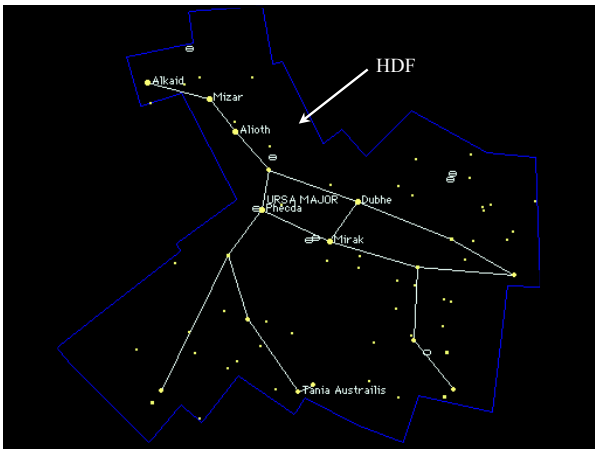

NGC 4686
Giant Elliptical Galaxy

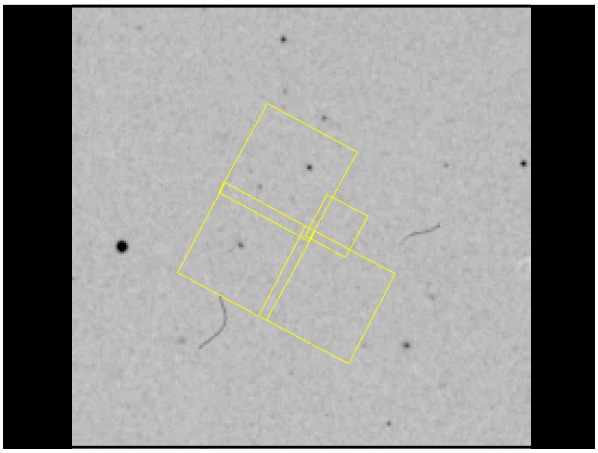


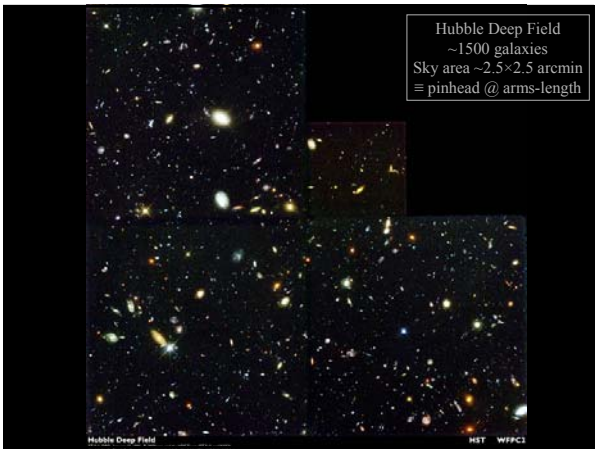

A 1689
Rich galaxy cluster
2 Gly distant
Gravitational lens

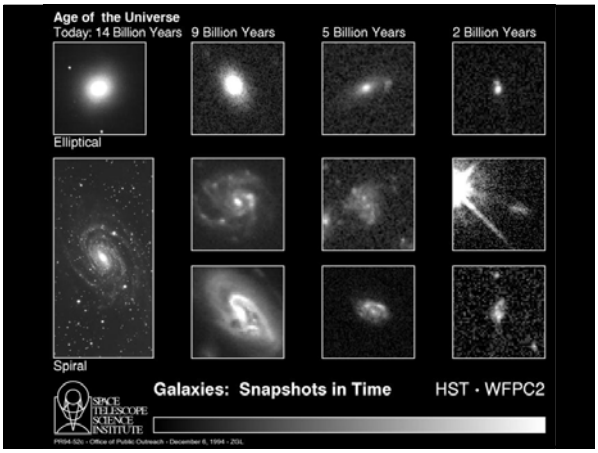

1 million galaxies
(stars removed, ~120 degrees of sky)

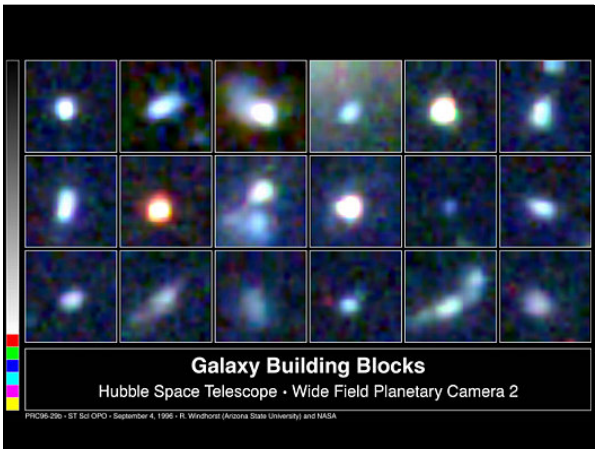

SDSS : ⅓ million galaxies
3 billion light years
(~20% to "the edge")
Our galaxy is here

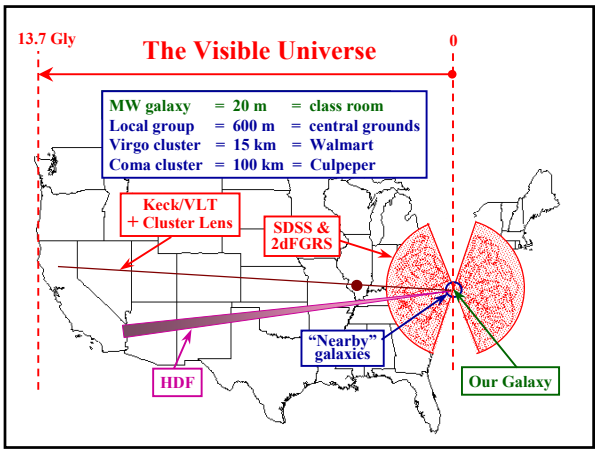

HDF
Alkaid
Mizar
Alioth
URSA MAJOR
Phecda
Dubhe
Mirak
Tania Australis




Hubble Deep Field
~1500 galaxies
Sky area ~2.5×2.5 arcmin
≡ pinhead @ arms-length


Age of the Universe
Today: 14 Billion Years
9 Billion Years
5 Billion Years
2 Billion Years
Elliptical
Spiral
Galaxies: Snapshots in Time
HST · WFPC2


Galaxy Building Blocks
Hubble Space Telescope · Wide Field Planetary Camera 2



3. Universe as a creative laboratory

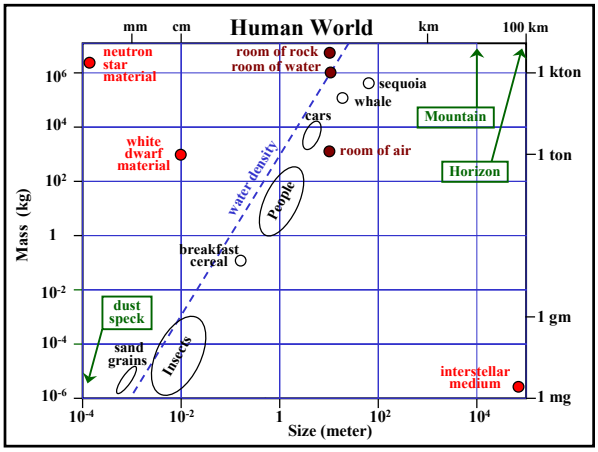
The Universe is a wild and wonderful place !

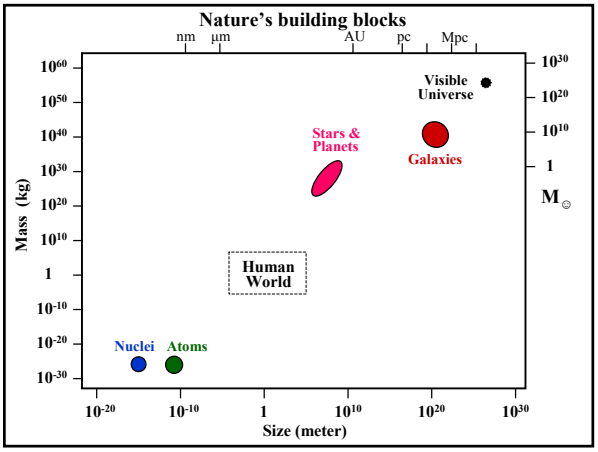
- it is vast, beyond imagination
- its building blocks are minute, beyond imagination
- Almost all of it is:
  - hotter or colder
  - denser or more rarified
  - more powerful or more delicate
  - evolves faster or more slowly

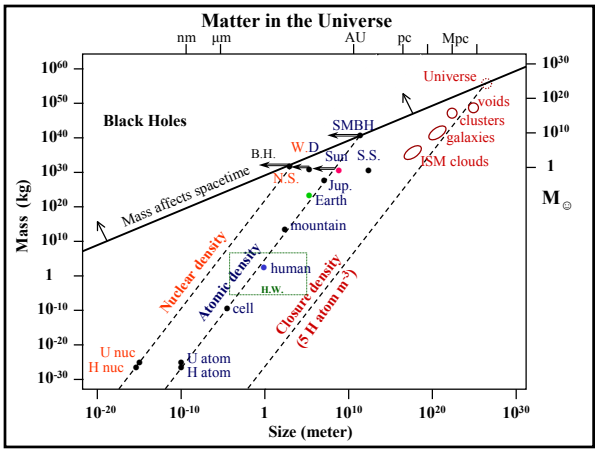
} than we can possibly imagine

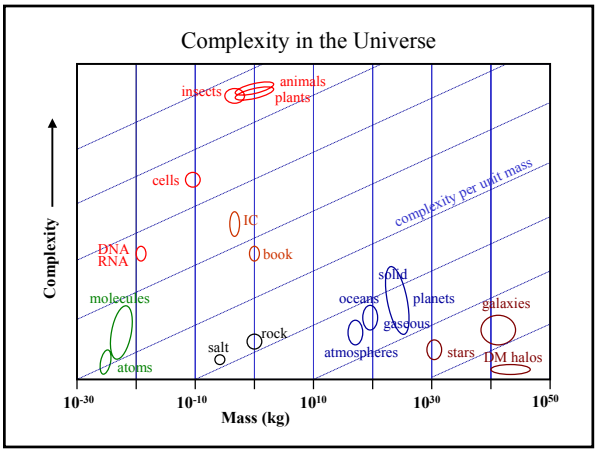
Within such extremes, the Universe is highly creative

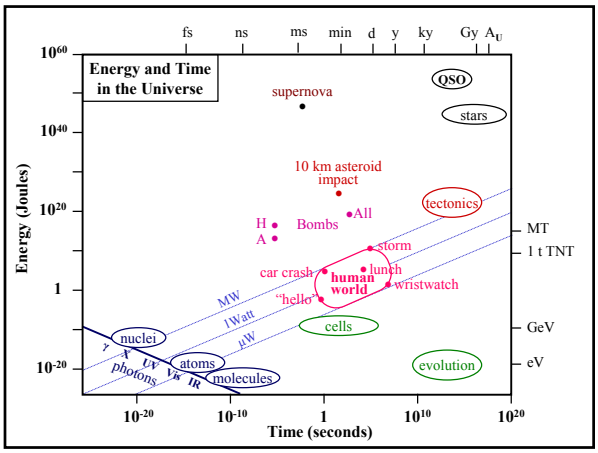
Lets try to locate our world amongst these properties, and identify where creativity arises, and why…….

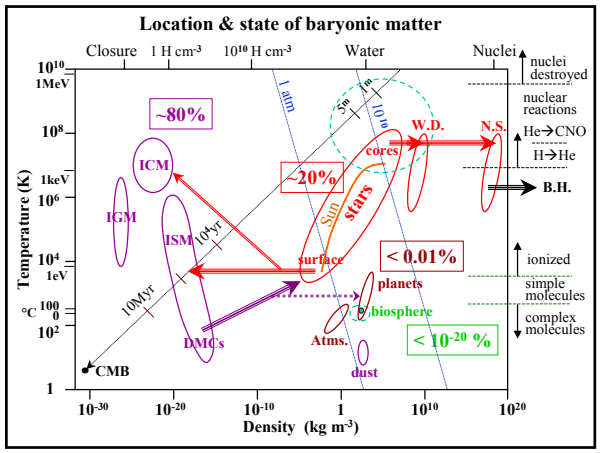


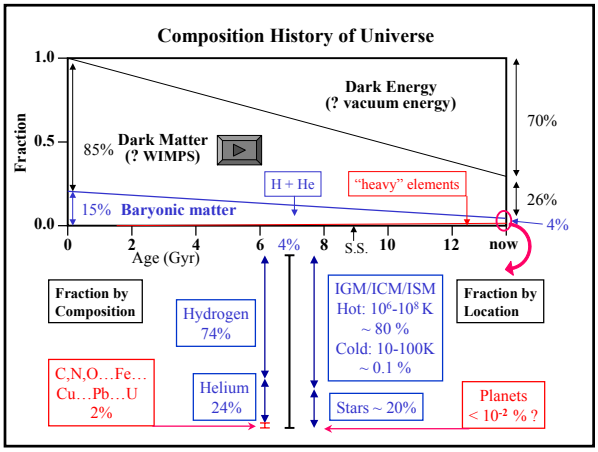










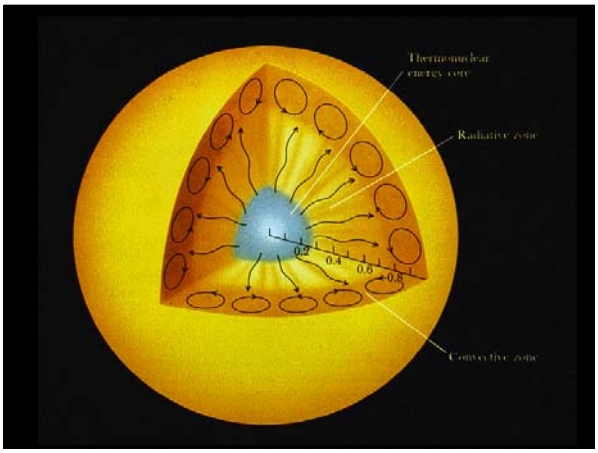


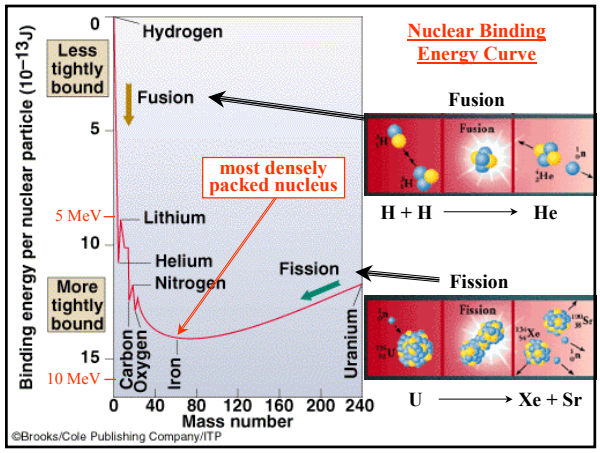
4. Creation of elements & particles

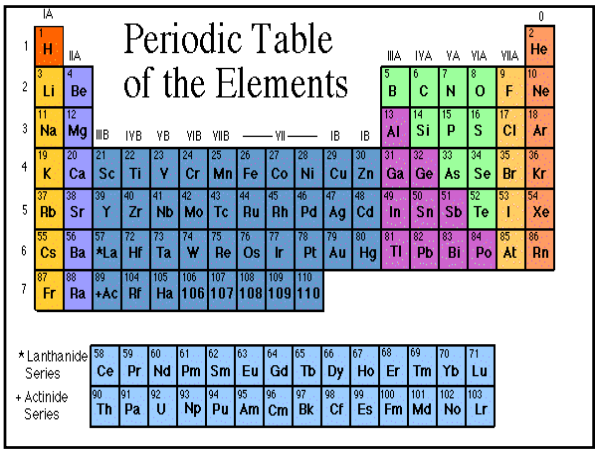
We must go inside stars and back to the Big bang.

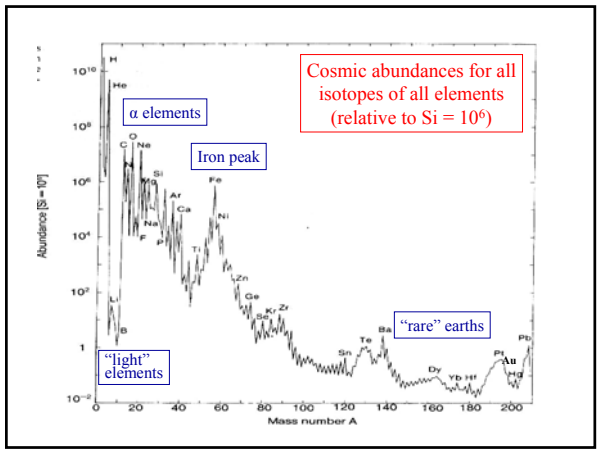
We consider the creation of three things:

1) heavy elements (nuclei) in stars
2) helium in the Big Bang (1-5 mins).
3) protons/electrons in the Big Bang (< 1sec)









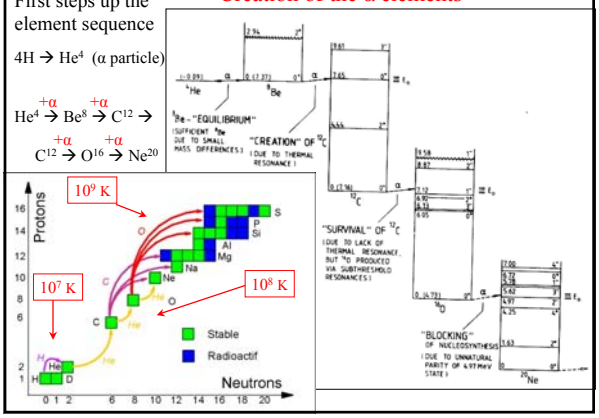
First steps up the element sequence

$4H \rightarrow He^4$ (α particle)

$He^4 \xrightarrow{+\alpha} Be^8 \xrightarrow{+\alpha} C^{12} \rightarrow$

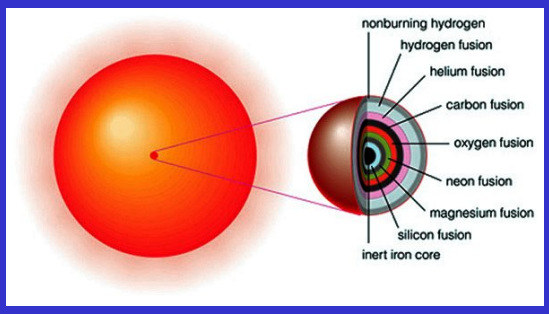
$C^{12} \xrightarrow{+\alpha} O^{16} \xrightarrow{+\alpha} Ne^{20}$

Creation of the α elements



Heavier elements come from High Mass stars

Pre-supernova red supergiant star: onion shell core

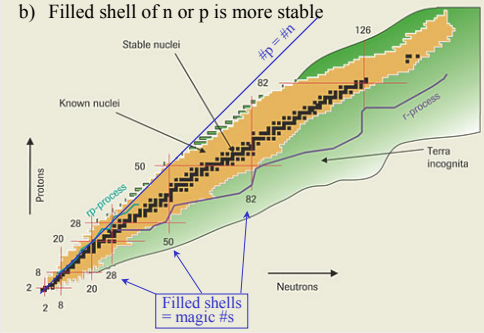


Valley of Stability

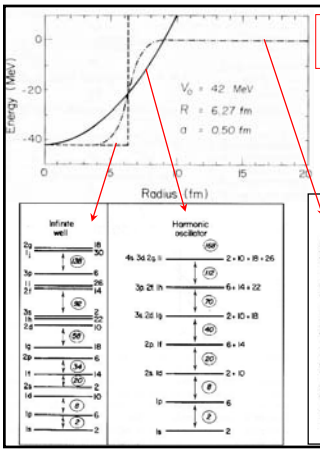
Not all nuclei are stable

a) Need ~correct ratio of #protons / #neutrons

b) Filled shell of n or p is more stable



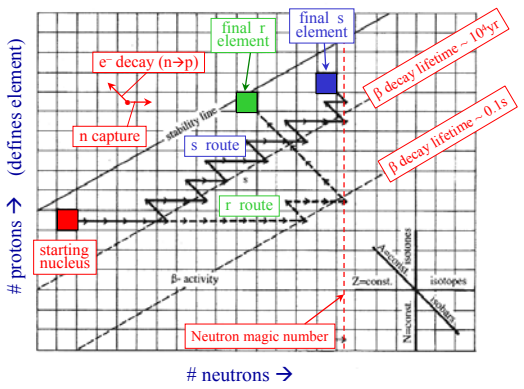
The origin of shells & magic numbers in atomic nuclei



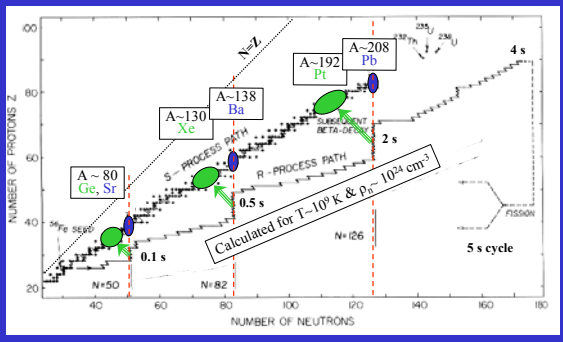
As in atoms, nuclear force field creates nucleon energy levels

Significant gaps create "filled shells" similar to noble gases.

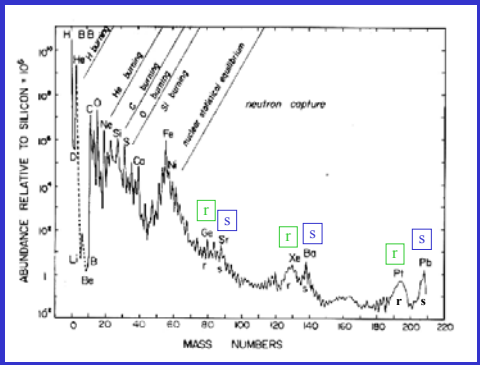
Slow & rapid neutron capture → trans iron-peak elements



Full element sequence from s & r process



Abundances with sources



What about helium ??

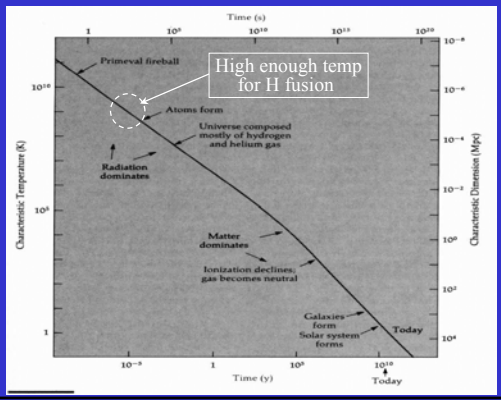
- He^4 is extremely common: ~25% everywhere
- far too much to come from stars
- even oldest stars have ~24% …..

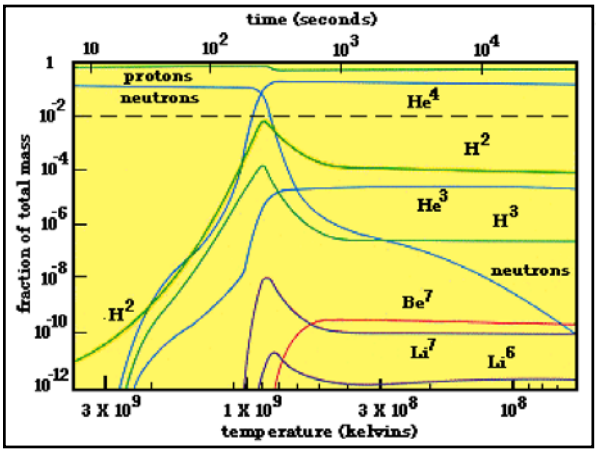
→ It was made before all stars, in the big bang

- We see the Universe expanding (with $v \propto d$) suggests all together 14Gyr ago

→began with "Big Bang"
High temp & density → lower temp & density

Temperature history of the Universe





What about protons & electrons ??

- were p, n, e^- made at some earlier time ?
- if so, how ?
- what about other particles (μ, υ, q…) ?
- what about anti-matter, was it also created ?

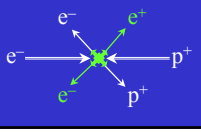
- must consider energy ↔ matter interchange
- must visit much earlier times
  - well-known physics: back to ~1μs
  - ~known physics : back to ~10^{-12} sec
  - ~rough guesses : back to ~10^{-35} sec
  - profound ignorance : before ~10^{-43} sec

Energy / Matter Interchange

Matter is very concentrated energy : $E = mc^2$
1kg ≡ 10^{17} Joules = 100 megatons (big H bomb)

Examples of matter into energy:
In general: particle + anti-particle → energy
$e^- + e^+ \rightarrow 2\gamma$ (½ MeV photons created)

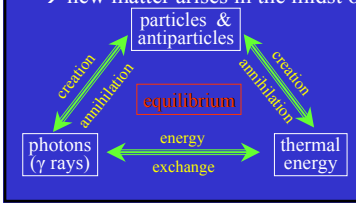
Examples of energy into matter:
In general: energy → particle + anti-particle
$2\gamma \rightarrow p + \bar{p}$ (need >1 GeV γs)
KE can also create matter:
(need KE > $2m_ec^2$
= threshold energy)

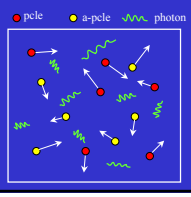


Energy / Matter Interchange

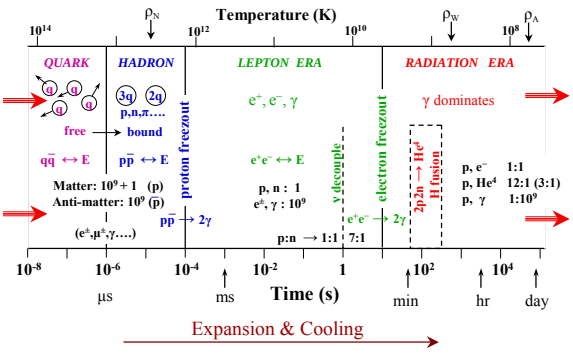
Consider extremes of temperature:
temperature = KE / particle ($E_{pcle} = k \times T$)
what happens when E_{pcle} > threshold energy ?
eg: 6×10^9 K (electron); 1.1×10^{13} K (proton)

→ matter/anti-matter created out of thermal energy
→ new matter arises in the midst of existing matter

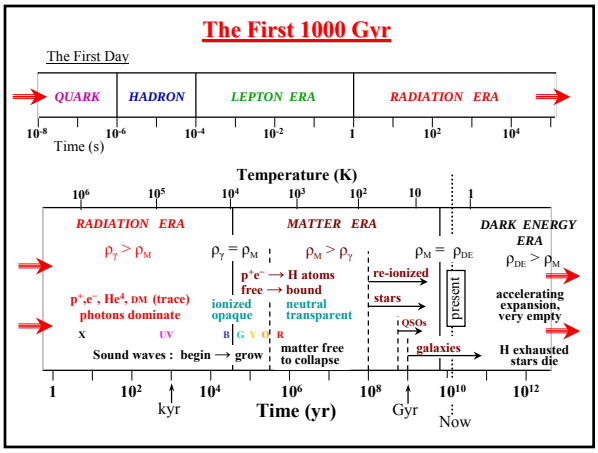




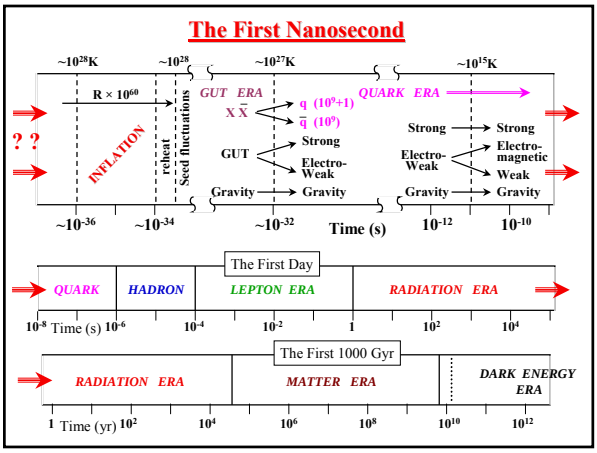
The First Day



The First 1000 Gyr



The First Nanosecond

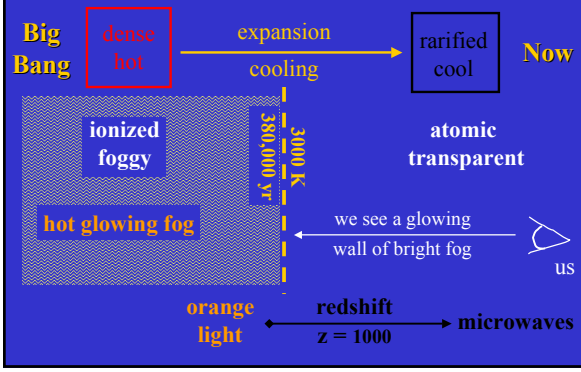


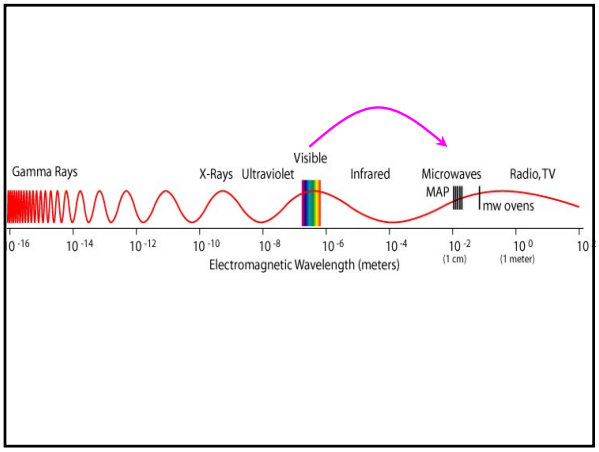
5. Origin of cosmic structures

- Today's Universe is extremely lumpy
  - clusters, galaxies, stars, planets, people…..
  - with very very little in between
- But, the Universe started out smooth
- How did the structure arise ?
  - there must be initial variation/ripples
  - which are amplified (by gravity?)
- Observe the early Universe by looking far away

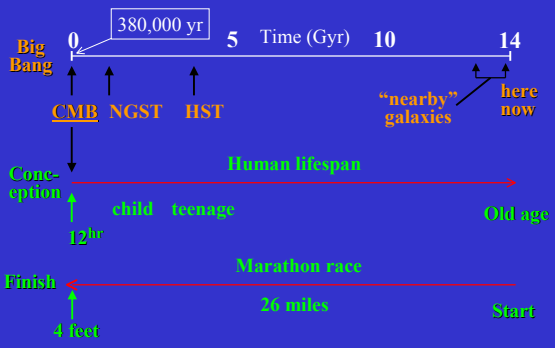
→ the Cosmic Microwave Background (CMB)

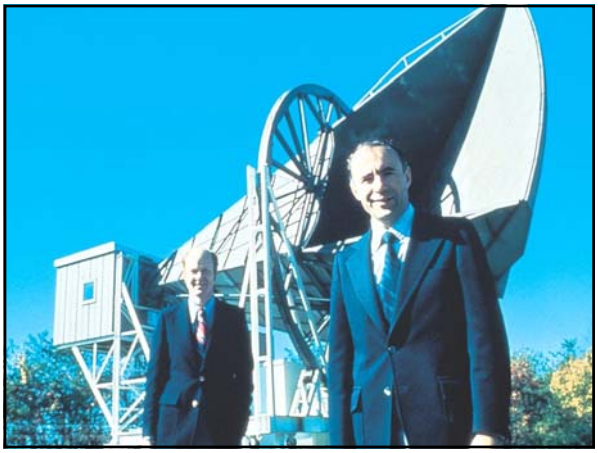
The Microwave Background

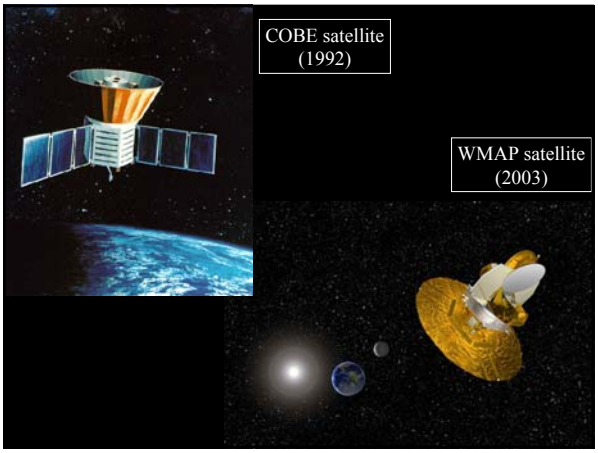


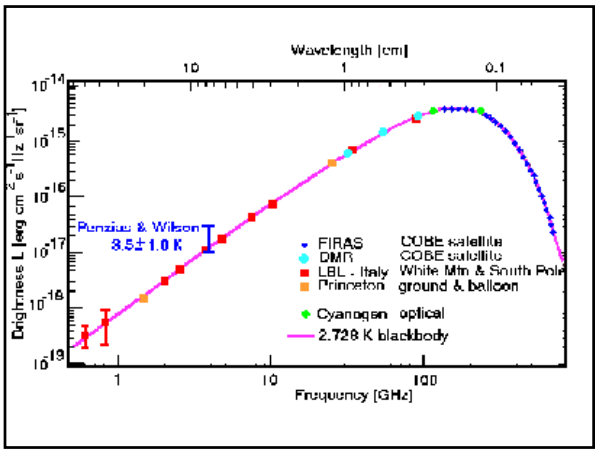


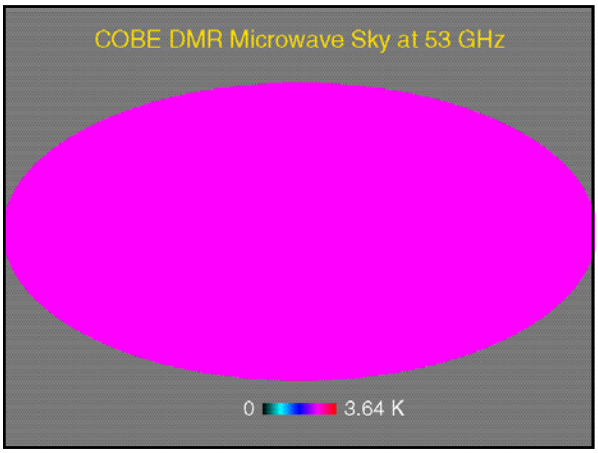
CMB is Young and Far

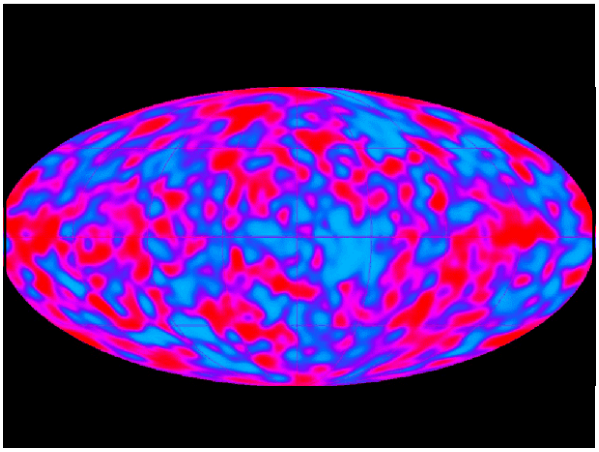


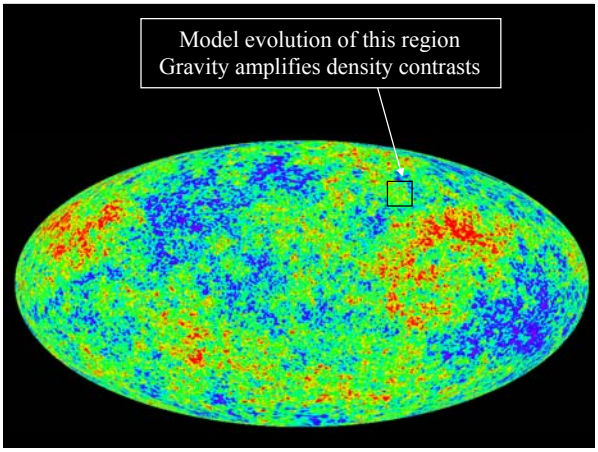


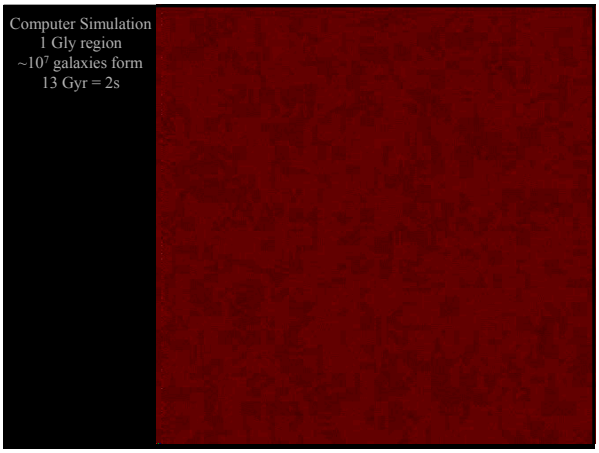


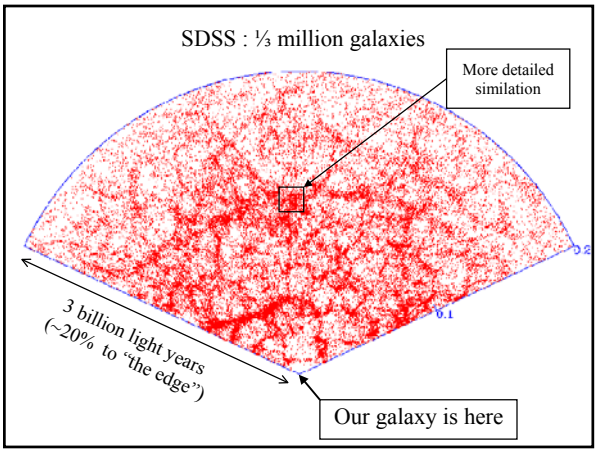

Wavelength [cm]
10
1
0.1
Penzias & Wilson
3.5± 1.0 K
FIRAS COBE satellite
DMR COBE satellite
LBL - Italy White Mtn & South Pole
Princeton ground & balloon
Cyanogen optical
2.728 K blackbody
Frequency [GHz]

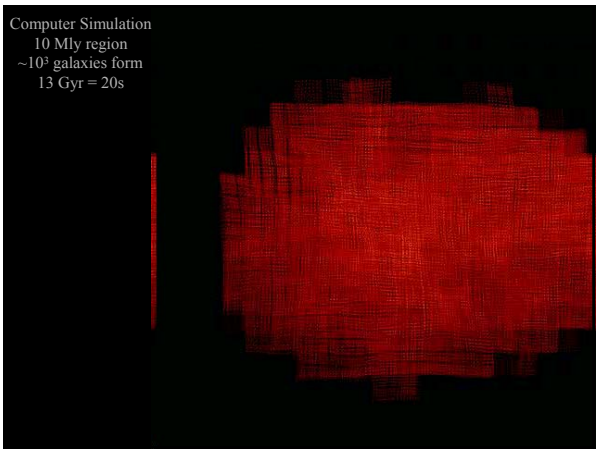

COBE DMR Microwave Sky at 53 GHz
0
3.64 K

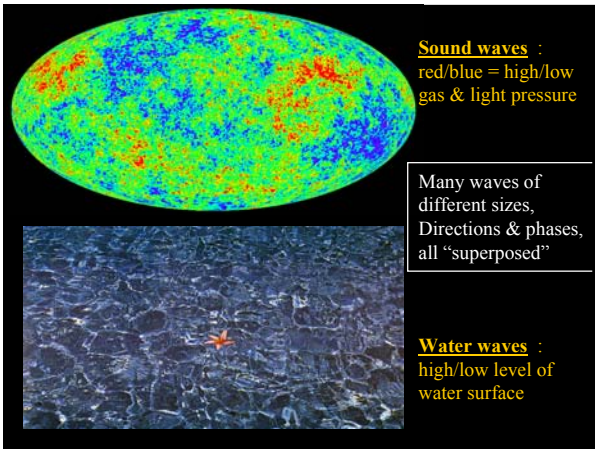



Model evolution of this region
Gravity amplifies density contrasts


Computer Simulation
1 Gly region
~10^7 galaxies form
13 Gyr = 2s


SDSS : ⅓ million galaxies
More detailed simulation
3 billion light years (~20% to "the edge")
Our galaxy is here





Generating cosmic sound

a) gas falls into valleys to make first compression

b) it then rebounds out to make first rarefaction

c) then back in again to make second compression

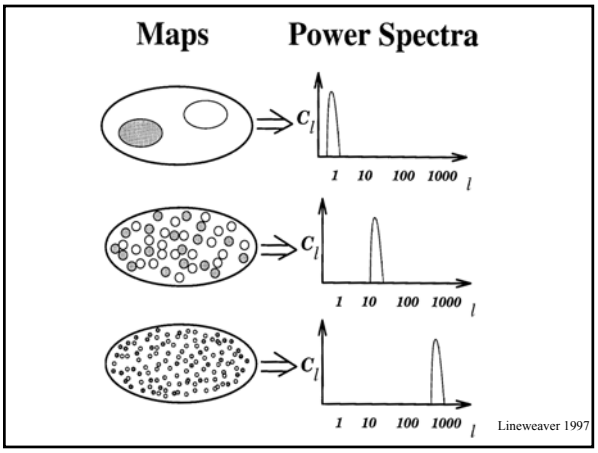
→ **the oscillation continues → sound wave created**

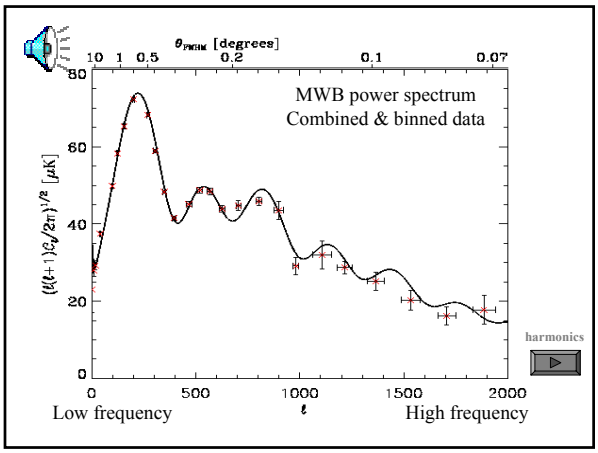
Nature of Cosmic Sound

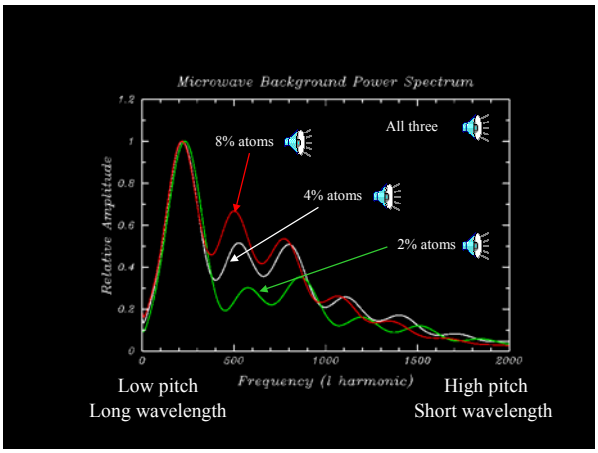
1. **Volume** :
   pressure variations ~ 1/100,000
   corresponds to about 90 dB
   → Loud but not cacophonous

2. **Pitch** :
   measured wavelengths 20,000 – 200,000 lyr
   pitch 10^{-12} – 10^{-13} Hz (v ~ 0.6c)
   → 48 – 52 octaves below concert A (440 Hz)

3. **Quality** :
   need to construct the "power spectrum"







Properties from the CMB

• Age of Universe	13.7 Byr	(2%)
• Flatness	1.02	(2%)
• Atoms	4.4%	(9%)
• Dark matter	23%	(15%)
• Dark energy	73%	(5%)
• Hubble constant (km/s/Mpc)	71	(6%)
• Photon/proton ratio	1.6×10^9	(5%)
• Time of first stars	180 Myr	(50%)
• Time of CMB	380,000yr	(2%)

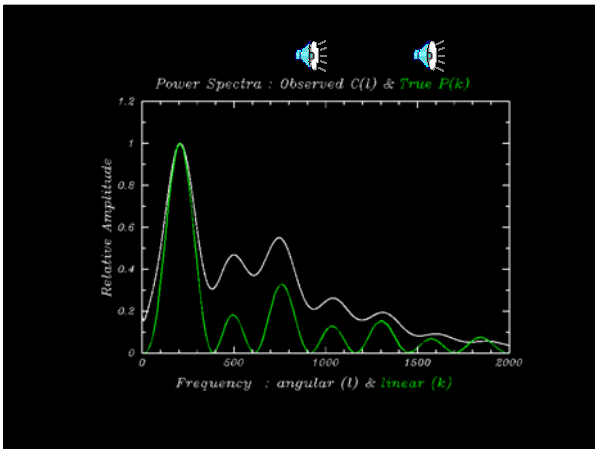
The cosmic concert hall

The universe is **not** a perfect concert hall
There is distortion en-route and local noise.

Similar to carpet+drapes in a concert hall plus a noisy audience adding distractions.

Correct for these problems using detailed computer calculations of the early Universe.

Observed : C(l) → Pure : P(k)



Into the fog : yet earlier times

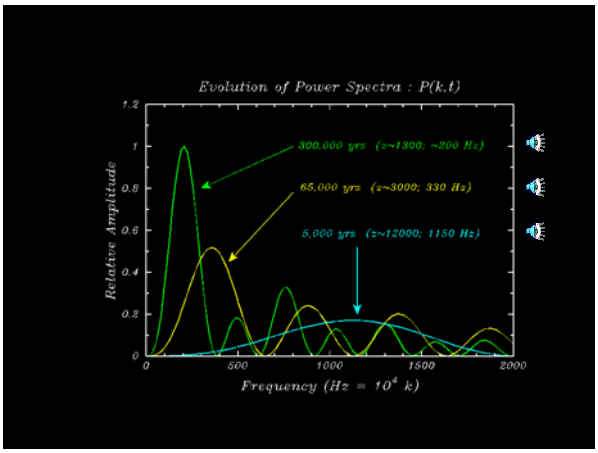
The CMB shows the sound at 380,000 yrs
What was the sound like **before** then ?

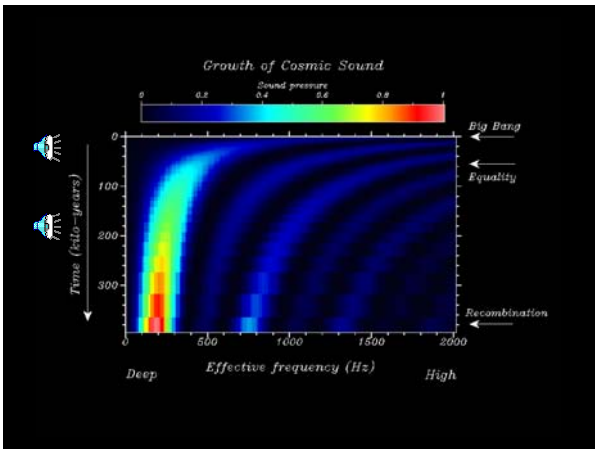
We can't see beyond the CMB foggy wall !
But computer models can take us there

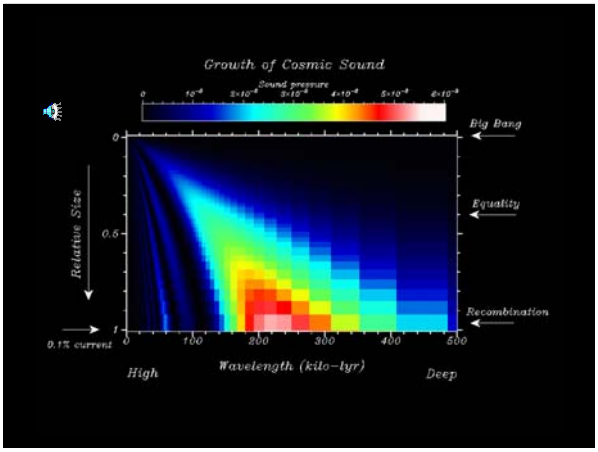
Earlier times :

- → Gas only had time to fall into **smaller** "valleys"
- → Wavelengths are shorter, **frequencies higher**
- → Amplitudes lower, sound is **quieter**

Examples :







The first sound : striking the bell

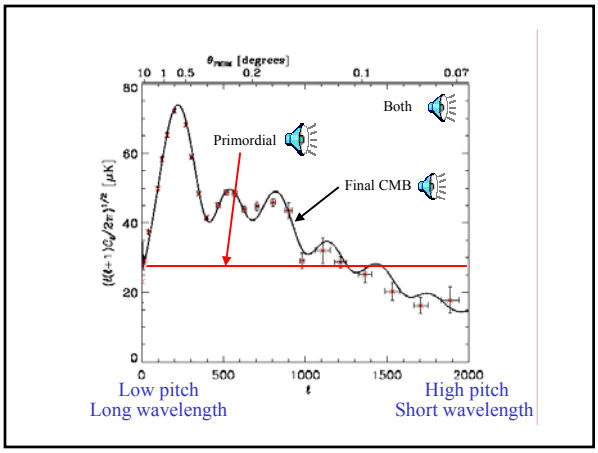
Although gravity amplifies sound, there must be initial irregularities, what caused these ?

Deep mystery, but recent progress :

- → Quantum roughness in early universe
- → Amplified by ~10^{50} during inflation at ~10^{-35} sec
- → Inaudible quantum hiss made audible by inflation
- → All structure in the universe due to quantum effects !

What did the quantum hiss sound like ?

- → Its power spectrum is **flat** → "white noise"
- → Gravity's amplifier then distorts the sound to make the final power spectrum with its harmonics



From sound to structure

Gravity amplifies sound into structure, right?

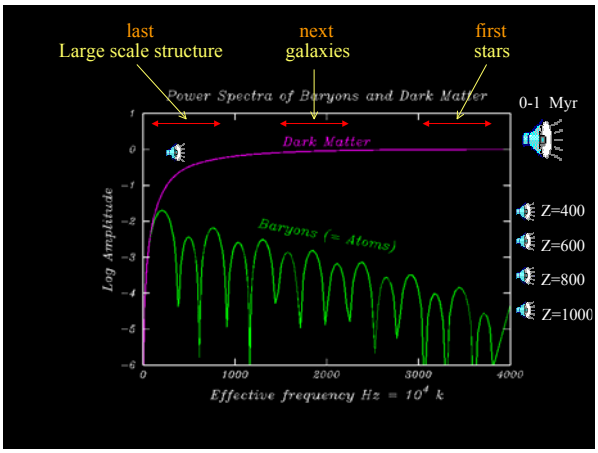
Wrong !! ….. it is too **quiet**

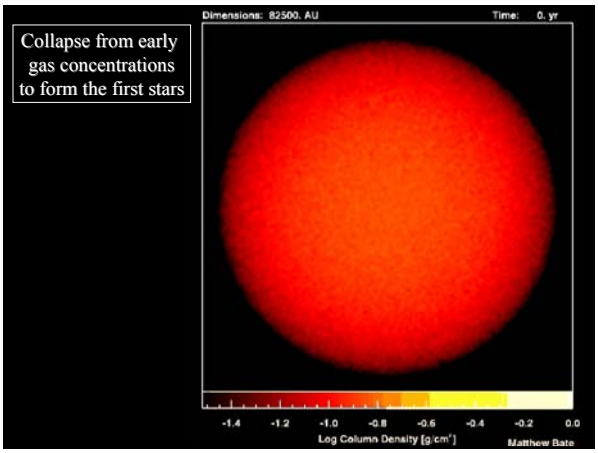
at the CMB, the maximum fluctuations are ~10^{-5} at the 1st peak (size ~2 x 10^5 lyr), all others are weaker. This is too small to grow quickly into stars & galaxies.

- → We need something else with greater variation ??

Dark matter comes to the rescue

- → it feels no pressure
- → it keeps collapsing from early times (no rebound)
- → At CMB, fluctuations are large (~10^{-2})
- → P.S. shows no harmonics, power at high frequencies





6. Origin of Energy

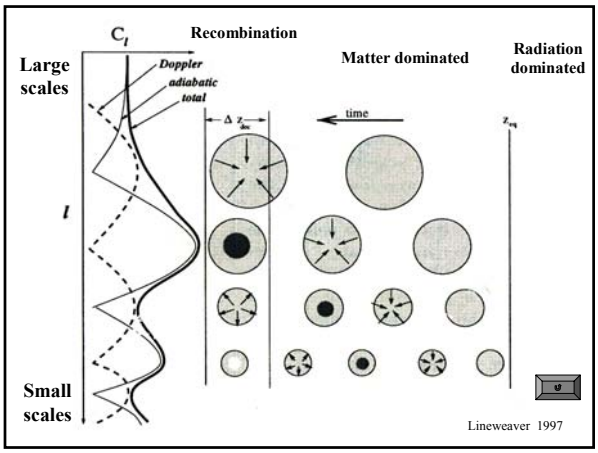
- In high school we learn:
  - many types of energy (heat/light/KE/chemical,nuclear..)
  - conversion from one type to another is possible
  - such conversions always conserve energy
  - energy can facilitate transformations: eg
    - sunlight drives/creates the biosphere
    - energy needed to purify and fabricate material things
- Where does all this energy ultimately come from ?

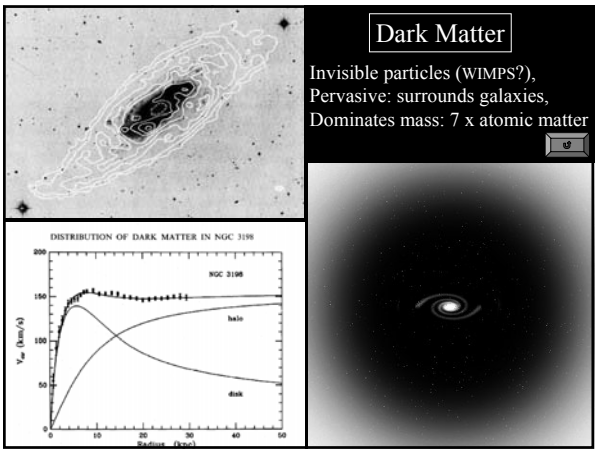
Origin of Energy (ii)

- All energy arises when particles "drop" down the potential associated with one of the four forces
- Examples:
  - chemical energy: electrons closer to nucleus
  - nuclear energy: protons/neutrons packed tighter
  - gravitational energy: released when objects fall
- Sometimes need one to enable another
  eg : starlight (sunshine)
  collapsing star (gravity) heats core (particle KE) enabling protons to overcome repulsion and combine, dropping down the (short range) nuclear potential

Origin of Energy (iii)

- Ultimately, then, energy arises because things are initially far apart, and then come closer.
- What separated everything initially ?
  - → The Big Bang !!
  - → specifically, inflation which drove expansion
  - → inflation stored energy in all the force fields
  - → to be released later, when circumstances allow
- Without fluctuations, gravity could never have begun the process, energy production would have ceased following He^4 production & recombination


C_l
Recombination
Large scales
Doppler
adiabatic
total
Matter dominated
Radiation dominated
time
Δz_{dec}
z_{eq}
l
Small scales
Lineweaver 1997


Dark Matter
Invisible particles (WIMPS?),
Pervasive: surrounds galaxies,
Dominates mass: 7 x atomic matter
DISTRIBUTION OF DARK MATTER IN NGC 3198
NGC 3198
halo
disk
200
150
100
50
0
0
10
20
30
40
50