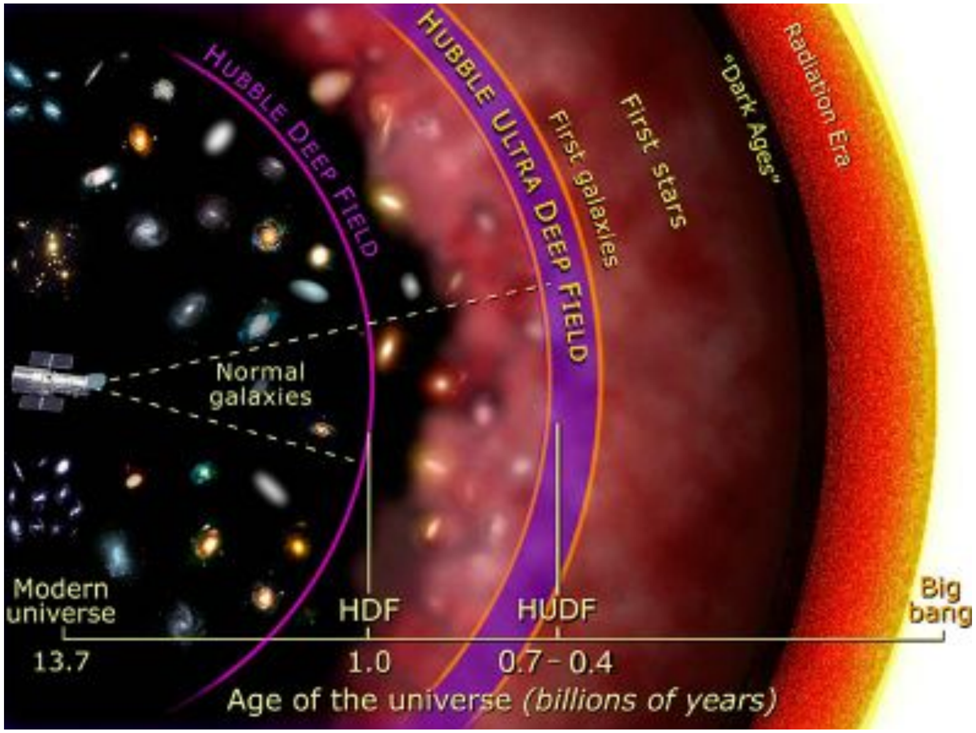
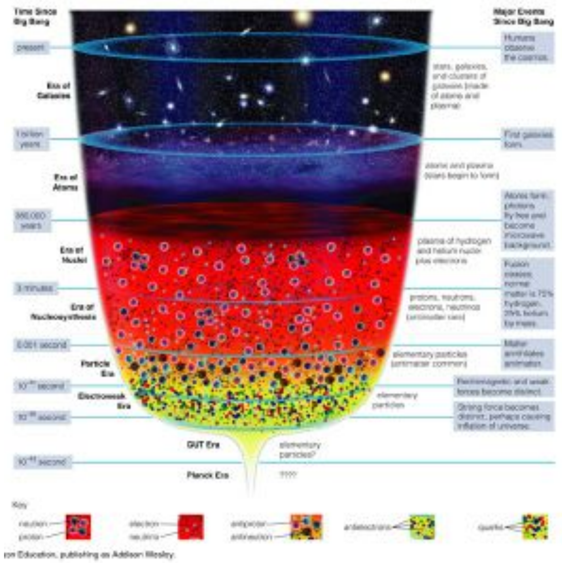
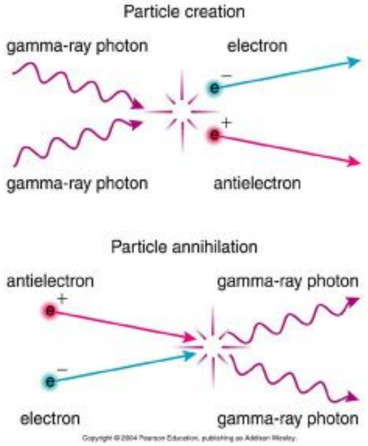
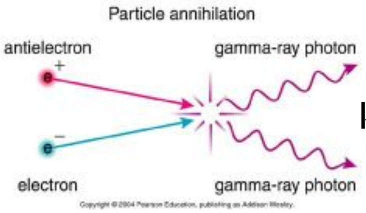


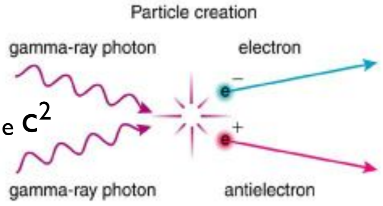


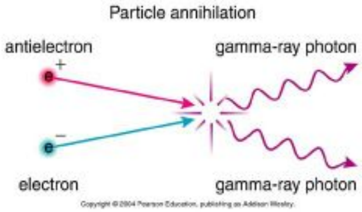


kT ~ $m_{particle} c^2$



kT > $m_{particle} c^2$





kT < $m_{particle} c^2$

“Freeze-out” temperatures

T (K)	particle / antiparticle	time since BB
6x10	e	20 sec
1.2x10	μ	1 sec
1x10	p	10

NOTE: after freeze-out, must have been an excess of matter over antimatter

---

neutrinos (ν)

- $\bar{\nu}$ + **p**roton ↔ **e**$^+$ + **n**eutron
- **e**$^-$ + **p**roton ↔ **n**eutron + **ν**

} **ν** energy ~ 10^{10} K

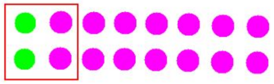
- n, p, in equilibrium when T > 10^{10} K
- ν + n → p^+ + e^- favored for T < 10^{10} K
  - neutrinos “decouple”
  - T < 10^{10} K - **p** preferred over **n**
  - **still hot enough for p + n** ↔ deuterium

The First Three Minutes

time	Temp [K]	Z (redshift)	Radius (?)	Density [g/cc]	Stuff
0:00:00.01	10^{11}	3×10^{10}	10 ly	4×10^{9}	• e+ , e- • photons, neutrinos • protons(p+) = neutrons(n) (1)
0:00:00.1	3×10^{10}	10^{10}	30 ly	3×10^{7}	• e+ , e- • photons, neutrinos • 62% p+ , 38% n
0:00:01	10^{10}	3×10^{9}	100 ly	4×10^{5}	• e+ , e- • photons • neutrinos -- decoupled! • 76% p+ , 24% n

Big Bang Nucleosynthesis

- final result as T ~ 3×10^9 K: **87% p, 13% n**
  - **10 seconds after BB!**
- 2 out of 16 baryons are neutrons



- make 1 Helium for every 12 Hydrogens
- mass fraction of Helium = 4/16 = 25%
- **Big Bang Nucleosynthesis should produce a universe that is 25% helium, by mass**
- predicted by G. Gamow in the 1940s - verified by observations of 1st stars

The First Three Minutes

time	Temp [K]	Z (redshift)	Radius (?)	Density [g/cc]	Stuff
0:00:00.01	10^{11}	3×10^{10}	10 ly	4×10^{9}	• e+ , e- • photons, neutrinos • protons(p+) = neutrons(n) (1)
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0:00:01	10^{10}	3×10^{9}	100 ly	4×10^{5}	• e+ , e- • photons • neutrinos -- decoupled! • 76% p+ , 24% n
0:00:13.8	3×10^{9}	10^{9}	300 ly	3×10^{3}	• e- frozen out • photons, neutrinos • 83% p+, 17% n

a complication - the "deuterium bottleneck"

- deuterium (d) = ^{2}H = n+p
- essential step to go from H → ^{4}He:
  - $p + p \rightarrow d + e^+ + \gamma$
  - $p + d \rightarrow {}^3He + p \rightarrow {}^4He$
- **BUT:** $d + \gamma \leftrightarrow p + n$ *easily* destroys when T > 10^9 K
- can't finish the chain to ^{4}He
  - deuterium doesn't hang around long enough
- T < 10^9 K:
  - d is stable, $d+p \rightarrow {}^3He$ $(+ p \rightarrow {}^4He)$ can proceed
  - **3 minutes 52 seconds after Big Bang**

0:00:13.8	3x10^9	10^9	300 ly	3x10^3	• e- frozen out • photons, neutrinos • 83% p+, 17% n
0:03:02	10^9	3x10^8	1000 ly	40	• photons, neutrinos • 86% p+, 14% n • deuterium bottleneck (2)
0:03:42	9x10^8	~3x10^8	~1000 ly	26	• photons, neutrinos • 87% p+ , 13% n (in He) • deuterium now stable • -> 26% Helium (3)
0:34:40	3x10^8	10^8	3000 ly	0.10	• e+ , e- • photons, neutrinos • 87% p+ , 13% n (in He) • trace ^{3}He, ^{7}Li, deuterium

Adapted from *The First Three Minutes*, by Steven Weinberg

1) antineutrino + proton <--> e+ + neutron
   e- + proton <--> neutron + neutrino

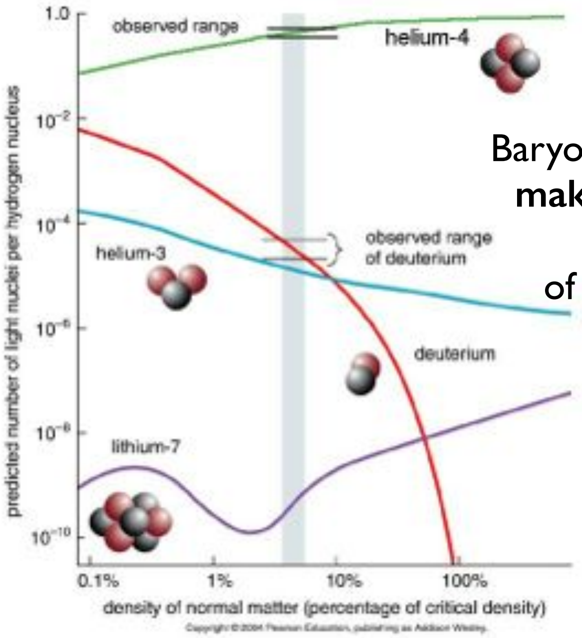
2) proton + neutron <--> deuterium + photon

3) deuterium + proton --> ^{3}He

---

more nucleosynthesis

- residual d, ^{3}He sensitive to baryon **density**
- d ↑, ^{3}He↓ in high density Universe
- d and ^{3}He probe baryonic density of early Universe
- measure cosmic d, ^{3}He to determine Universe density independent of other “local” measures
- ^{7}Li is another probe



BBN Result:
Baryonic (ordinary) matter
makes up at most a few percent
of the critical density of
the Universe

---

revisiting the critical density

$$v_{\rm esc}^2 = \frac{2GM}{R} = c^2 \quad \text{and} \quad \rho = \frac{M}{R}\frac{3}{4\pi R^2}$$

so we can write: $c^2 = 2G \times \dfrac{4\pi R^2 \rho}{3}$

Hubble Law: v = H$_o$ x R = c - so - $\boxed{R = c/H_o}$

$$\cancel{c}^2 = 2G \times \frac{4\pi \cancel{c}^2 \rho}{3H_o^2} c \qquad \text{rearrange:} \qquad \rho_{\rm crit,today} = \frac{3H_o^2}{8\pi G}$$

$$\boxed{\rho_{\rm crit} = 3H^2/8\pi G \sim 9.1\times10^{-30}\ \text{g/cc} \times (H_o/70)^2}$$

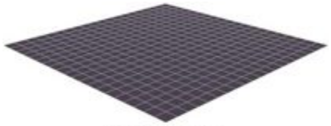
Is the Universe a black hole?

- define ‘horizon’ using age of Universe from H_o
- **critical density:**

  $\rho_{crit} = 3H^2/8\pi G \sim 9.1\times10^{-30}$ g/cc x $(H_o/70)^2$
- **measured density:** ρ
- recast as $\Omega_o \equiv \rho/\rho_{crit}$
  - **if $\Omega < 1$:** expansion continues forever: universe is “open”
  - **if $\Omega > 1$**: expansion reverses: universe is “closed”
- **Open (infinite) Universe:**
  - infinite volume no true edge
- **Closed (finite) Universe:**
  - finite volume no true edge
- **Flat Universe**: density = critical density $\Omega = 1$

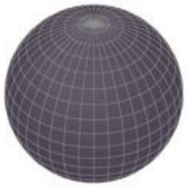
Three possible geometries

- Flat: $\Omega = 1$



flat (critical) geometry

- Closed: $\Omega > 1$



spherical (closed) geometry

- Open: $\Omega < 1$

saddle-shaped (open) geometry

The need for dark matter

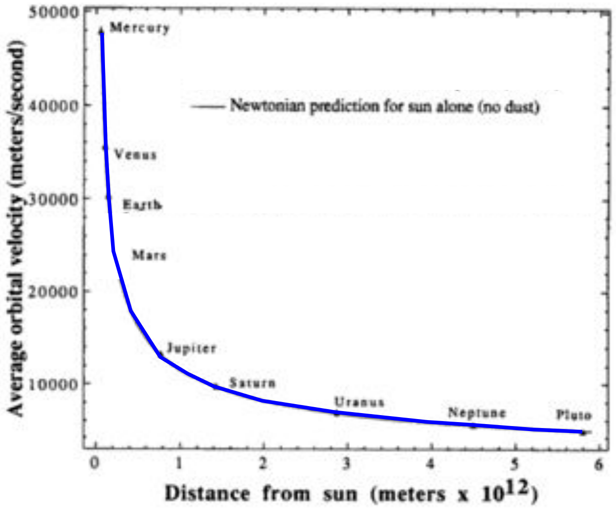
- Big Bang Nucleosynthesis:
  - constrained by ^{3}He and deuterium
  - $\Omega_{baryon} < 0.1$
- There MUST be some gravitating stuff made of exotic, NON-BARYONIC matter
  - see the web links...

Probing matter via dynamics

- Kepler’s 3rd law gives orbital period in terms of orbital distance and mass within the orbit:
  - $P^2_{orb} \propto \dfrac{d^3}{M_{\rm within}}$
- the orbital speed is simply
  - $v_{orb} = 2\pi d / P_{orb}$ -so-
  - $v_{orb} \propto \sqrt{M_{within}/d}$

Probing matter via dynamics

$$v_{orb} \propto \sqrt{M_{\rm within}/d}$$



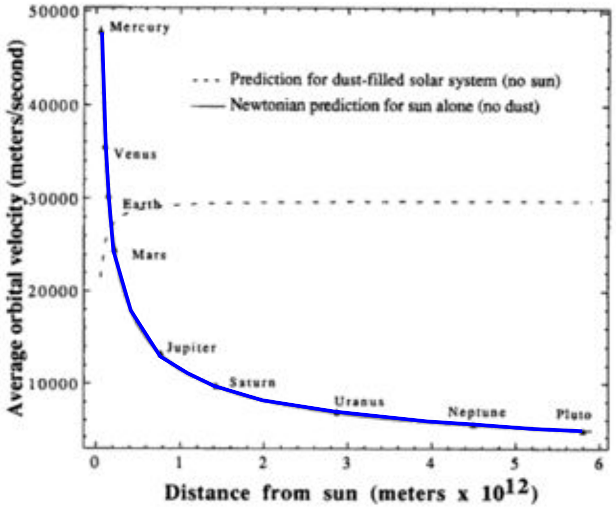
from ‘Qunitessence’ by Lawrence Krauss

Probing matter via dynamics

- *what if... solar system was filled with invisible dust?*
- can put ~ $1M_\odot$ of dust within the Earth’s orbit at very low density (10^{-4} x air)
- if evenly distributed
  - M within orbits would *increase* as d increases
  - expect higher V than Keplerian
  - faster orbital speed than without dust:

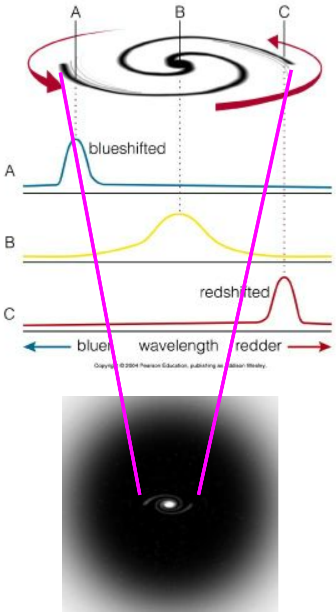
Probing matter via dynamics

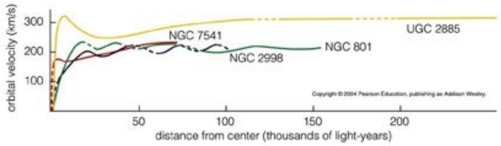
$$v_{orb} \propto \sqrt{M_{\rm within}/d}$$



from ‘Qunitessence’ by Lawrence Krauss

Dark Matter (within galaxies)





- “Rotation curve” gives rotation speed via spectroscopy
- Rotation rate of stars/clouds gives mass within the orbit
- **Spiral Galaxies** - matter extends well beyond visible disks
- **Elliptical Galaxies**
  - big M/L ratio
- **90% of mass in galaxies is dark**

mass-density of the Universe (in galaxies)

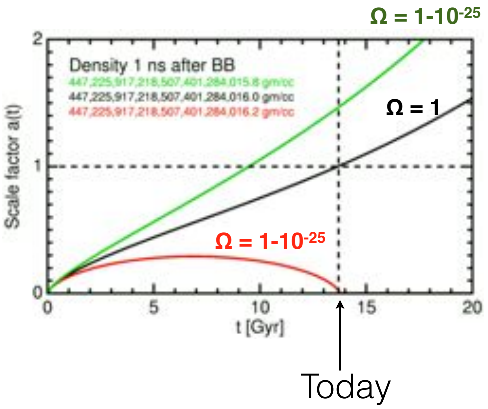
- measure "average" mass of a galaxy via rotation curve
- count the number of galaxies
- determine **mass** (in galaxies) of the universe
- divide by **volume** of the galaxy sample to get $\boldsymbol{\Omega}$

so what if $\Omega_o < 1$?

- if $\Omega_o > 0.1$, then the dark matter in galaxies must be **non-baryonic (?!)**
- the “flatness problem” looms:
  - if $\Omega_o = 1.0$ now, then Ω has *always* been 1.0
  - if $\Omega_o < 1.0$ now, it was much closer to 1.0 in the distant past, but still less than 1.0
  - if $\Omega_o > 1.0$ now, it was much closer to 1.0 in the distant past, but still greater than 1.0

the flatness problem

- if not *exactly* 1.000... at the Big Bang, then Ω diverges very rapidly away from it as the universe expands.
- If Ω was only slightly *smaller* than 1.000... at the Big Bang, then Ω_o should be *nearly zero* today.
- If Ω was only slightly *bigger* than 1.000... at the Big Bang, the Universe should have collapsed long ago.



(From Ned Wright’s cosmology tutorial)