Physical Cosmology I

6th Egyptian School for HEP

Thermal History

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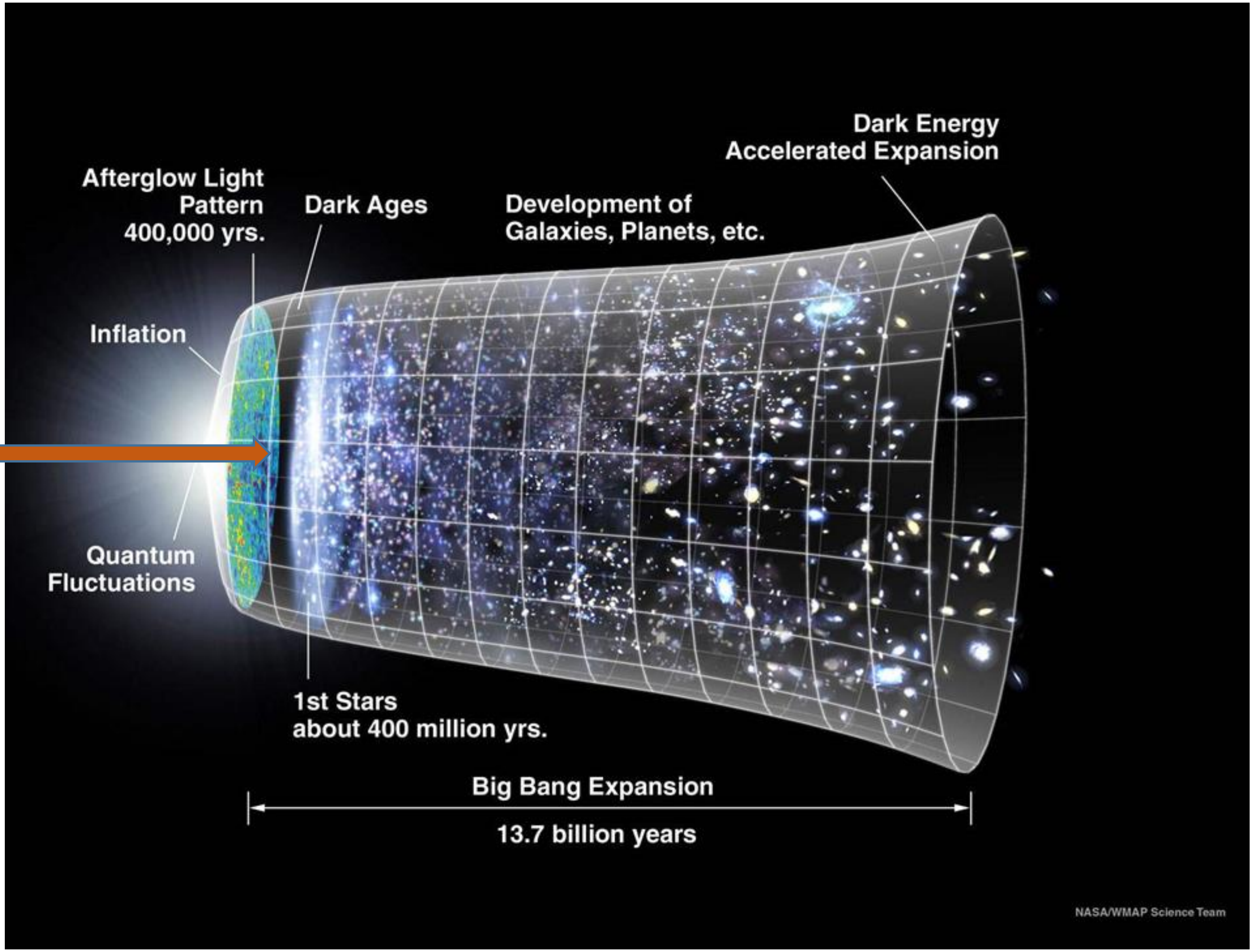
Google 'Cosmic History' → Images: Things Like

This talk



Subject Matter

- Our universe is expanding → Should have been 'hot' in the past

→ As T rises:

- Atoms ionize

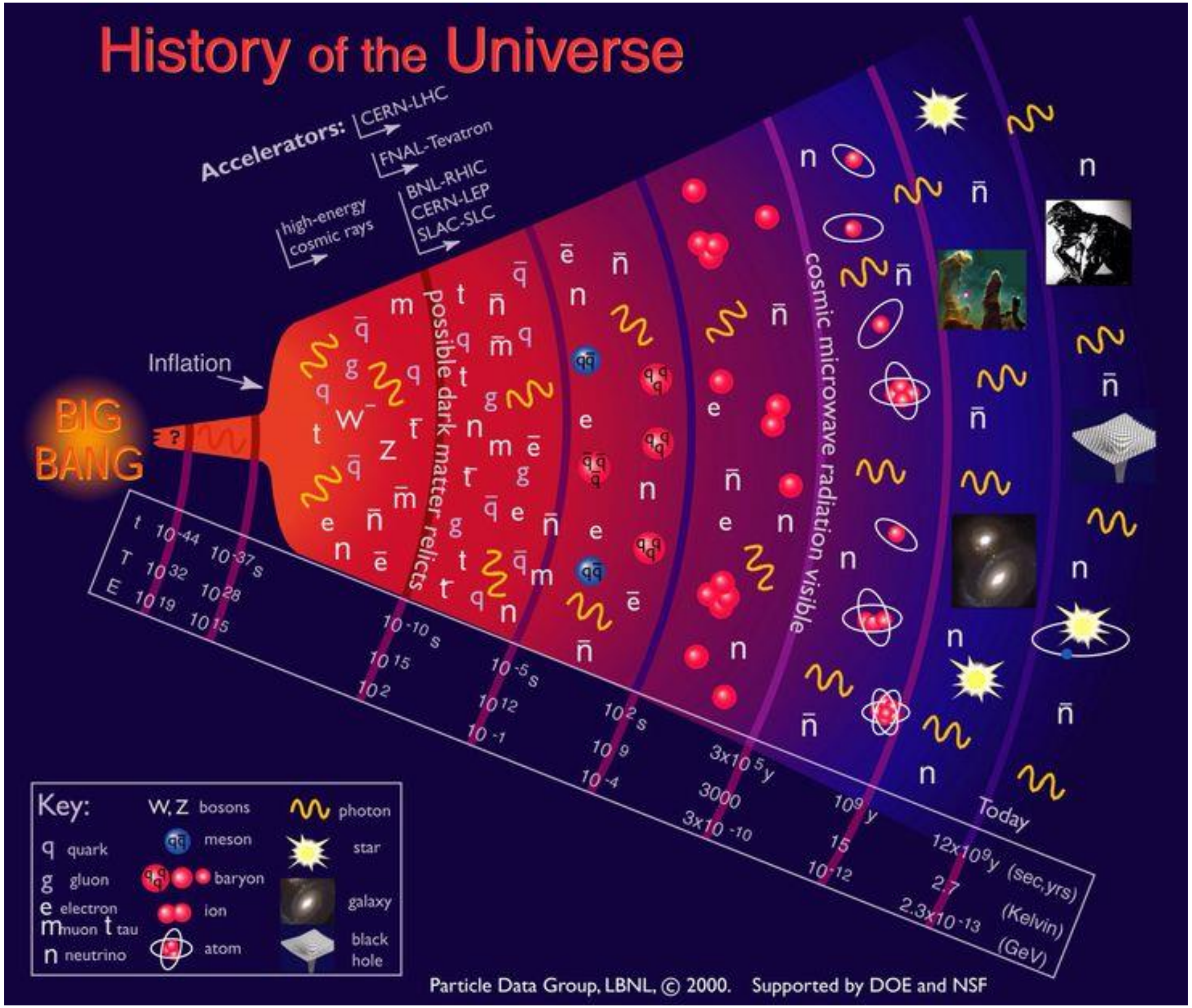
- Nuclei disassociate → individual protons neutrons → quarks-gluons

- SM phase transitions (electroweak, QCD) expected. Others (GUT) predicted

mass nuclei

→ At some level universe is testing ground for HEP

Google some more: A Thermal Bath of Particles and Antiparticles that Leaves Relics



Tightly coupled, highly interacting, system

Couple of proper refs

Kolb & Turner: The Early Universe (standard text)

Daniel Baumann Tripos lectures Chapter 3
www.damtp.cam.ac.uk/user/db275/Cosmology.pdf
(which I follow to some extent)

The Cosmic Microwave Background

- Tells us of prior **thermal equilibrium**
- Current temperature of spectrum: **2.728 Kelvin**
- Current energy density of CMB:

$$(4\sigma/c)T^4 = 4.19 \times 10^{-14}\ \mathrm{J\ m^{-3}}$$

- The average energy per photon

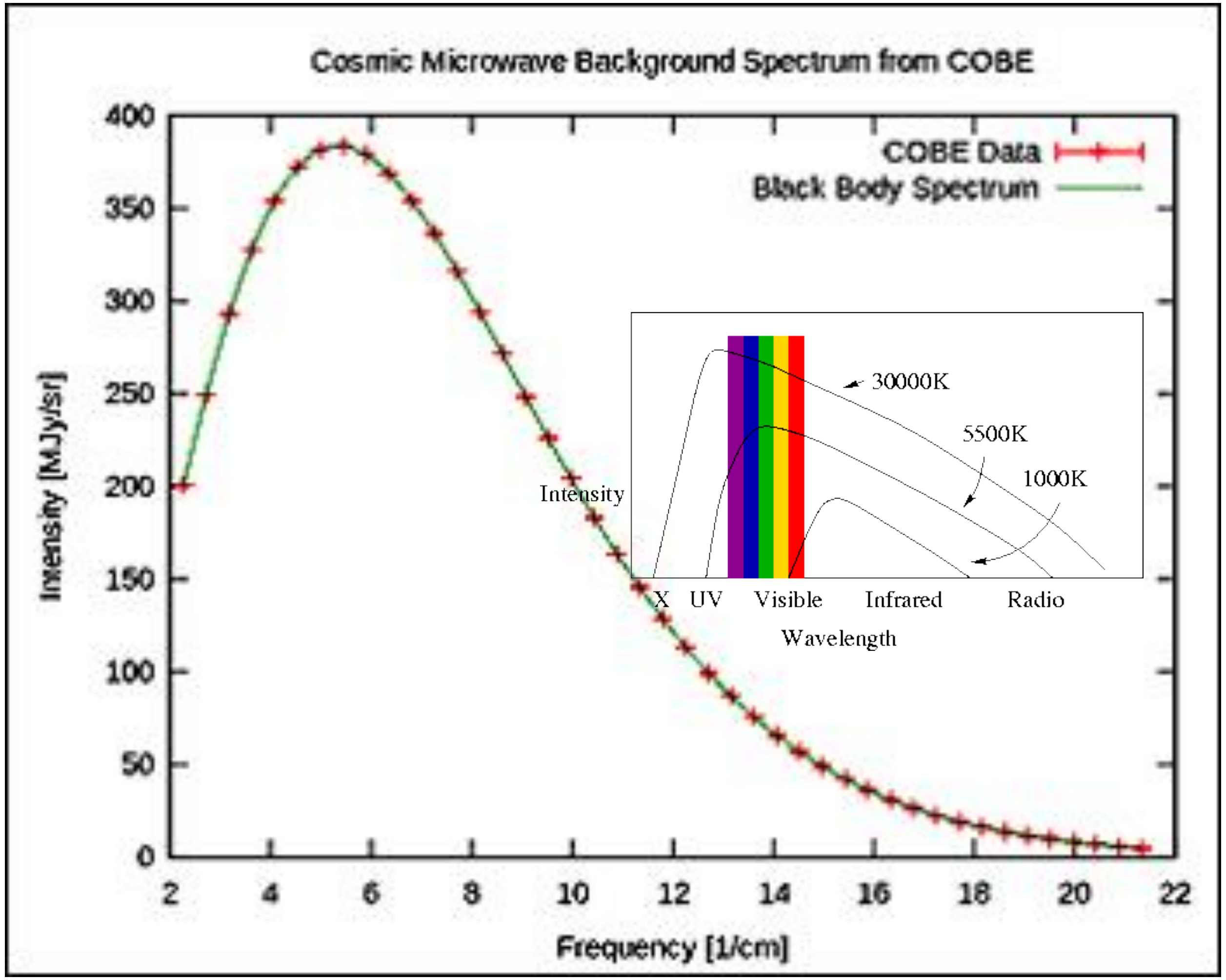
~ k T ~ h ν (since distn ~ $e^{-\frac{E}{kT}}$)

→ photon number density ~ $10^8\ \mathrm{m^{-3}}$

Compare with < one proton per cubic meter!

Entropy ~ large ratio; well conserved

in comoving vol



Units, rates (and '~convention'!)

- Using **'natural units': $c = \hbar = G = k_B = 1$**

- Temperature, energy, momentum and mass are in electron volts
- Length and time are in inverse electron volts
- In these units, during radiation era gives

Expansion rate

$$H \sim T^2/M_{\rm pl}$$

Using Stefan-Boltzmann and $H \sim \sqrt{\rho}/M_{\rm pl}.$ law Natural units

The reduced Planck mass $M_{Pl} = \sqrt{\hbar/8\pi G}$

- Already twiddle '~' sign reappearing!

→ we will be making mainly order of magnitude (factor ten) estimates

Relativistic Degrees of Freedom g_*

$$\frac{T}{1\,\mathrm{MeV}} \simeq 1.5 g_\star^{-1/4} \left(\frac{1\,\mathrm{sec}}{t}\right)^{1/2}$$

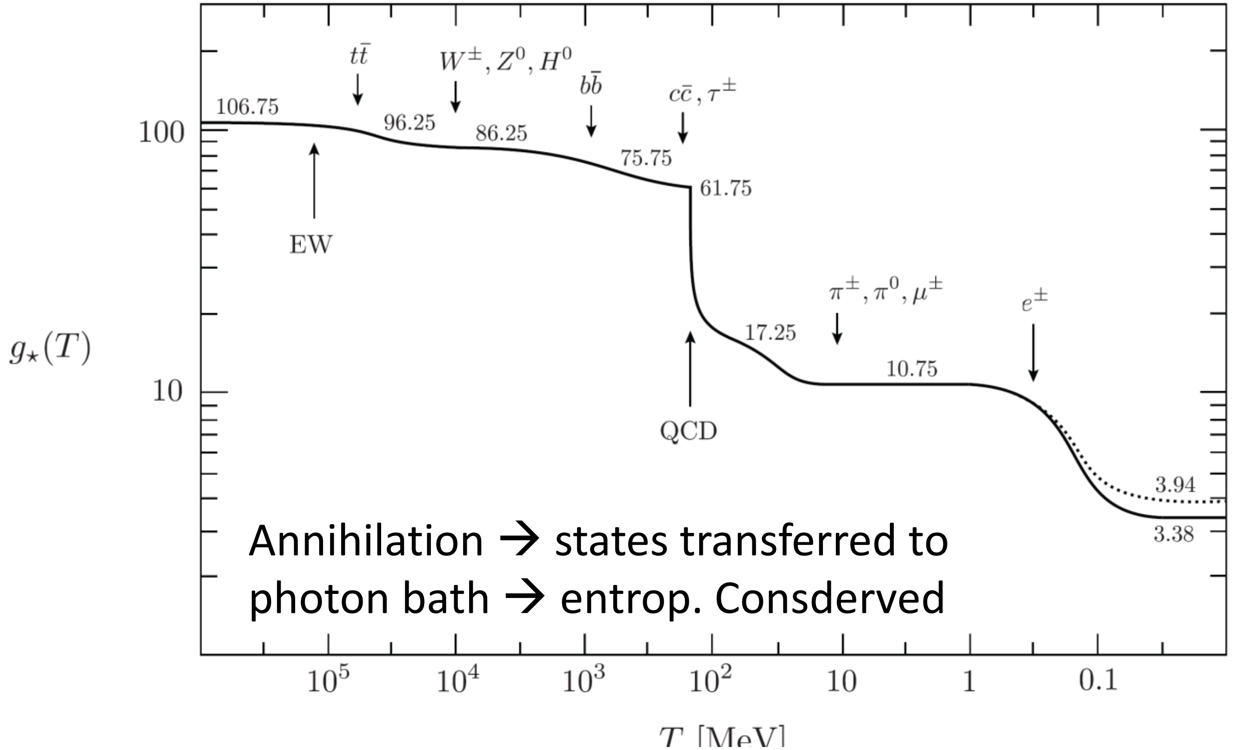
Expansion influenced by number of relativistic degrees of freedom (essentially number of species and their internal degrees of freedom; e.g. spin)

The total **energy density of relativistic species** is (using Stefan-Boltzmann again in natural units)

$$\rho_r = \sum_i \rho_i = \frac{\pi^2}{30} g_\star(T) T^4$$

(similar relation for entropy *s~ ρ/T*)

These act as 'radiation' with pressure 1/3 ρ



A thermal particle is **relativistic if** $(m \ll T)$

A particle is in the thermal equilibrium if: **interaction rate** with thermal bath **> expansion rate**

Number densities in Thermal Equilibrium

- Spatially homogeneous system with phase space density *f(p)* →

$$\mathrm{d}\, n = g\, f(p) dp_x dp_y dp_z \;\rightarrow\; n = 4\,\pi\, g \int f(p) p^2 dp$$

(isotropic momenta and number of internal deg. freed., e,.g. spin, *g*)

$$f(p) \sim \frac{1}{e^{\frac{E(p)}{T}} \pm 1}$$

$$n = 4\,\pi\, g \int_0^\infty \mathrm{d}p \frac{p^2}{\exp\left[\sqrt{p^2 + m^2}/T\right] \pm 1}$$

Chemical equilib. → particles are created – annihilated so as to keep these distn
→
Non-relativistic parts → more difficult to make → lose out and suppressed

Relativistic $(m \ll T)$ $$n \sim g\, T^3$$

Non-relativistic $(m \gg T)$ $$n \sim g\, (mT)^{\frac{3}{2}}\, e^{-\frac{m}{T}}$$

→ As T → 0 a massive particles should vanish… !

'Normal matter'; should vanish; it's existence suggests violations of baryon number and charge parity conservation
→ ***Baryogenesis*** through particle antipart asymmetry (probably BSM)

Era of Tightly Coupled Plasma

- Currently interaction rate of CMB photons with matter negligible, but
- As universe changes scale *a* →

Number density of photons $n \sim \frac{1}{a^3} \sim T^3$

$\rightarrow T \sim \frac{1}{a}$ $\qquad (\sim h\,\nu \sim 1/\lambda)$

Back in time → higher density and temperature → universe ionised

Number of neutral atoms (~Hydrogen) suppressed by

factor Boltzmann factor $e^{-\frac{B_H}{T}}$ ($B_H = 13.6$ eV is Hydrogen's binding energy)

There are ~ *10^9 photons per proton* → $T_{\mathrm{rec}} \sim 14/\ln 10^9 = 0.7$ eV (proper calc gives 0.3)

3600 Kelvin → ***a (rec) =1/1300*** → *z (rec.) = 1300* → t (rec) ~ 300 000 yr for $a(t) = (t/t_0)^{2/3}$

Cosmic Plasma Coupling

- **Gas fully ionized** → strongly interacts with photons by **Thompson scattering**:

- Electron placed in EM field → $m_e \frac{d^2 z}{dt^2} = -e\, E_0 \sin(\omega\, t)$, → oscillates
- radiates back $\frac{dP}{d\Omega} = \frac{e^4\, E_0^2}{32\pi^2\, \epsilon_0\, c^3\, m_e^2} \sin^2\theta.$

Crossection ~ power radiated / mean incident energy flux

~ Square of classical electron radius $r_e = \frac{e^2}{4\pi\, \epsilon_0\, m_e\, c^2} = 2.82 \times 10^{-15}\,\mathrm{m}$

$$\sigma_T \approx 2 \times 10^{-3}\,\mathrm{MeV}^{-2}$$

$e^- + \gamma \leftrightarrow e^- + \gamma$ interaction rate $\Gamma_\gamma \approx n_e \sigma_T$ (note relative vely ~ *c = 1* here!)

Interaction Rate of Coupled Plasma

- Electron dens. ~ Baryon dens ~ 10^{-9} photon dens ~ 0.1 T^3

→

Photon electron Interaction rate at decoupling~ $\sigma_T \, T_{dec}^3$

$\sim 10^{-10} \,.\, 0.3^3 \;\; 10^{-18} \,.\;\; 2 \;\; 10^{-3}$ MeV $= \; 10^{-10} \,.\, 0.3^3 \;\; 10^{-18} \,.\;\; 2 \;\; 10^{-15}$ eV

n $\qquad\qquad\qquad$ σ

Interaction Time ~ 2 10^{26} eV^{-1} ~ 1.4 10^{11} s ~ 4400 years **(<< age of uni at recom.)**

→ 6.582119×10^{-16} s

→Timescale for interaction much smaller than age of universe

→ Plasma tightly coupled in (kinetic) equilib. Before recom.

Similar process of binding in QCD phase trans. And BBN

Rough rule of thumb for equilibrium:

Interaction rate > expansion rate (interaction time < age of universe)

Neutrino Decoupling

- Neutrinos are coupled to electrons through weak interactions

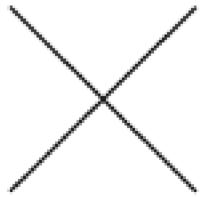
→Much looser than Thompson coupling → early decoupling

Below electroweak scale (~100 GeV) but

In relativistic limit → crossection

('four Fermion' interaction)

$\sigma \sim \left| \quad \right|^2 \sim G_F^2 T^2$



$$G_F \sim \alpha / M_W^2 \sim 1.17 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

Neutrinos thus decouple at $\frac{\Gamma}{H} \sim \frac{\alpha^2 M_{\rm pl} T^3}{M_W^4} \sim \left(\frac{T}{1\ \mathrm{MeV}}\right)^3$ (recall H ~ T^2 in rad era)

→ When scales ~ 3 million times smaller than recombination ~ 1 s after start of expansion

Cosmological Element Production (BBN)

- Elements beyond hydrogen need neutrons, these are in equilibrium with protons before weak scale freeze out

Post QCD

$$n + \nu_e \leftrightarrow p^+ + e^-$$
$$n + e^+ \leftrightarrow p^+ + \bar{\nu}_e$$

→

$$\left(\frac{n_n}{n_p}\right)_{\mathrm{eq}} = e^{-Q/T}$$

$$Q \equiv m_n - m_p = 1.30 \text{ MeV}.$$

At Freeze out (1 MeV) neutron fraction ~ 1/6 ++ decay ~ 1/8

Elements cannot form until Boltzmann suppression ~ $10^{-9} e^{\frac{B_E}{T}}$ overcome

Virtually all neutrons go to Helium → abundance ~ 1/16 → by mass 1/4

Heavier elements absent due to low densities (process ends after three min…)

Of BBN and BSM

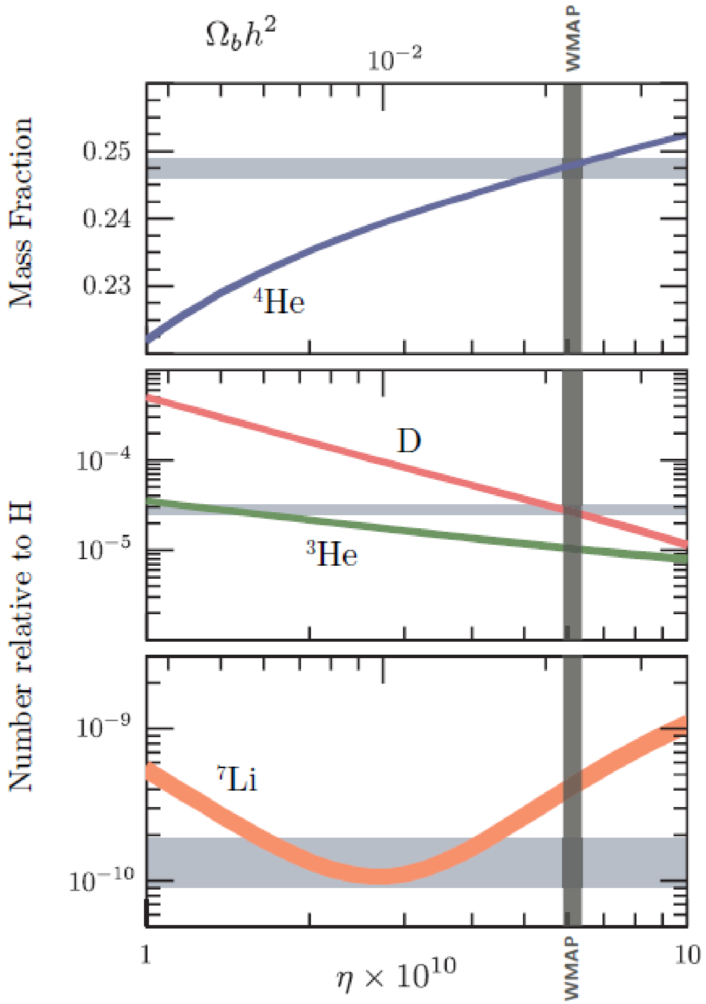
**Dependence on baryon dens. →

Non-Baryonic Dark Matter dominant

** **Dependence on expansion rate →**
number of relativistic species (with m << T)
(Recall the expansion rate $H^2 \sim \rho \sim g_*$)

→puts bounds on neutrino species
(and any other relativistic species prior to T~MeV)

****Places constraints on G and G_F at early times**
++ Constraints on non-standard cosmology



Vertical line Baryon fraction ~ 5 %

What Then is the DM: A WIMP Miracle?

- **Assume DM is composed of weakly interacting massive particles**
- **Mass of order 100 proton mass ~ 1 GeV, consistent with BSM models**

Rough feasibility estimate

Freeze out at interaction rate ~ expansion rate

Recall for neutrinos this gave $\frac{\Gamma}{H} \sim \frac{\alpha^2 M_{\rm pl} T^3}{M_W^4} \sim \left(\frac{T}{1\ \rm MeV}\right)^3$

Density of DM ~ 1/20 baryon density for ~100 GeV particle

++ baryons less dense than neutrinos by a factor 10^{-9}

And in non relativistic lim σ → const

→T of non-relativistic relic $n\,\sigma \sim 10^{-10}\,T^3\sigma \sim \frac{T^2}{M_{pl}}$ →

$T_{dec} \sim 10^{10}\,\sigma^{-1} M_{Pl}^{-1}$ ~ **few GeV for** $\sigma \sim 10^{-8}\ \mathrm{GeV}^{-2}$ → **characteristic of weak interaction…**

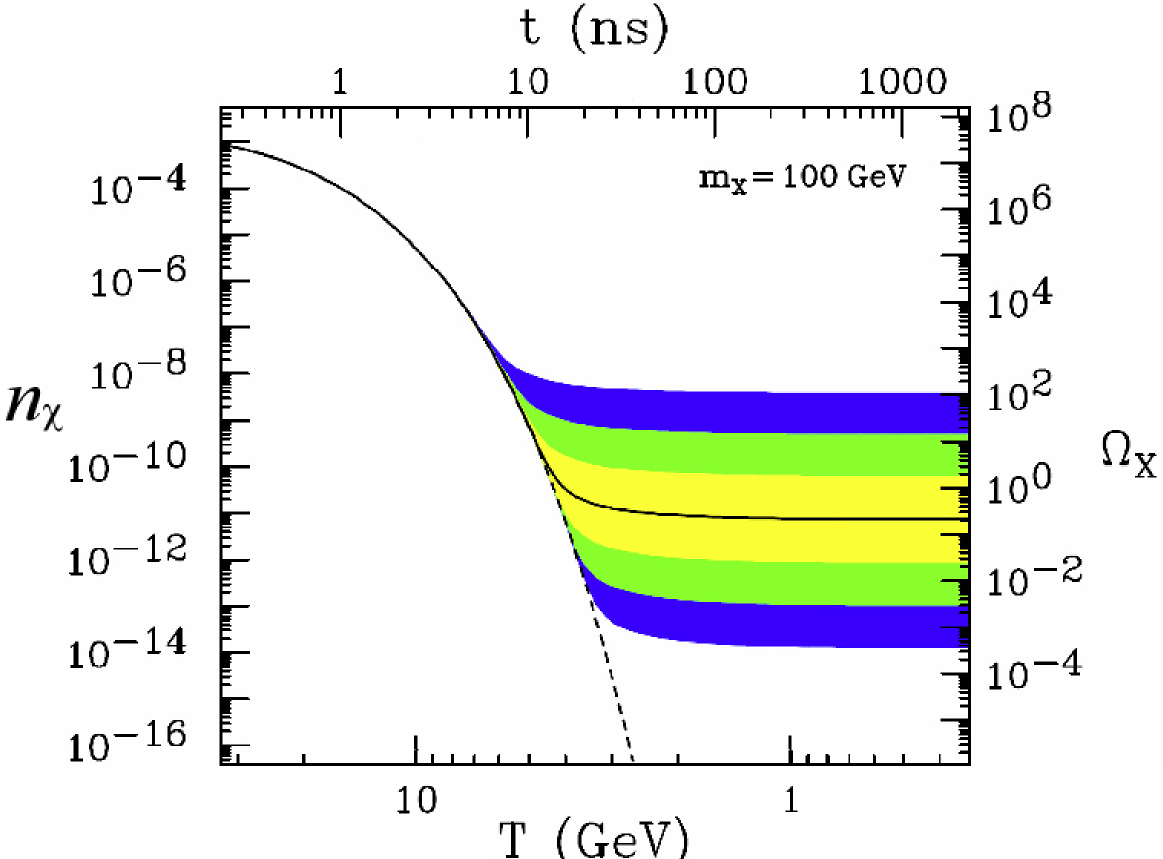
The Miracle **more precisely**

- Use Boltzmann equation for *comoving* number density

$$\frac{dN_X}{dt} = -s\langle\sigma v\rangle\left[N_X^2 - (N_X^{\rm eq})^2\right]$$

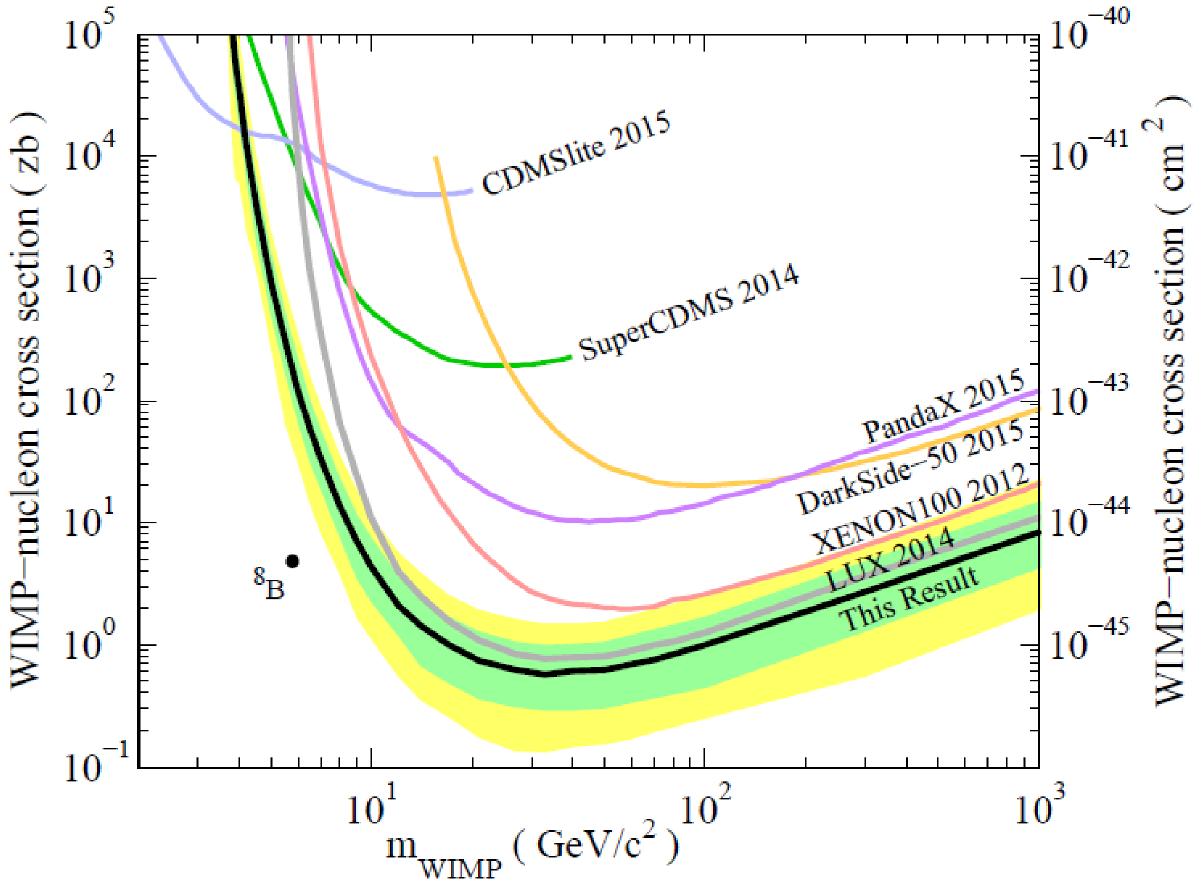
- The equilibrium abundance is Boltzmann suppressed

(Recall non-relativistic $n \sim g\,(mT)^{\frac{3}{2}}\, e^{-\frac{m}{T}}$)



- **It is suppressed in the right way** → proper abundance for weak decoupling

Nevertheless…



Direct detection constraints from Akerib et. al. (2016)

$Cm^2 \sim 4 * 10^{-28}\ GeV^{-2}$

Experimental constraints → WIMP miracle wither away?

(Also appears withering at LHC…)

Some Alternatives

- Sterile neutrinos (can be produced from oscillations with regular ones)

→'Warm dark matter' in keV range

- Axions (introduced to solve CP violation problem in QCD re neutron's electric dipole moment)

→Tiny mass but dynamical friction effect leads to similar behavior as cold dark matter

- Non-thermal production of WIMPS or WDM

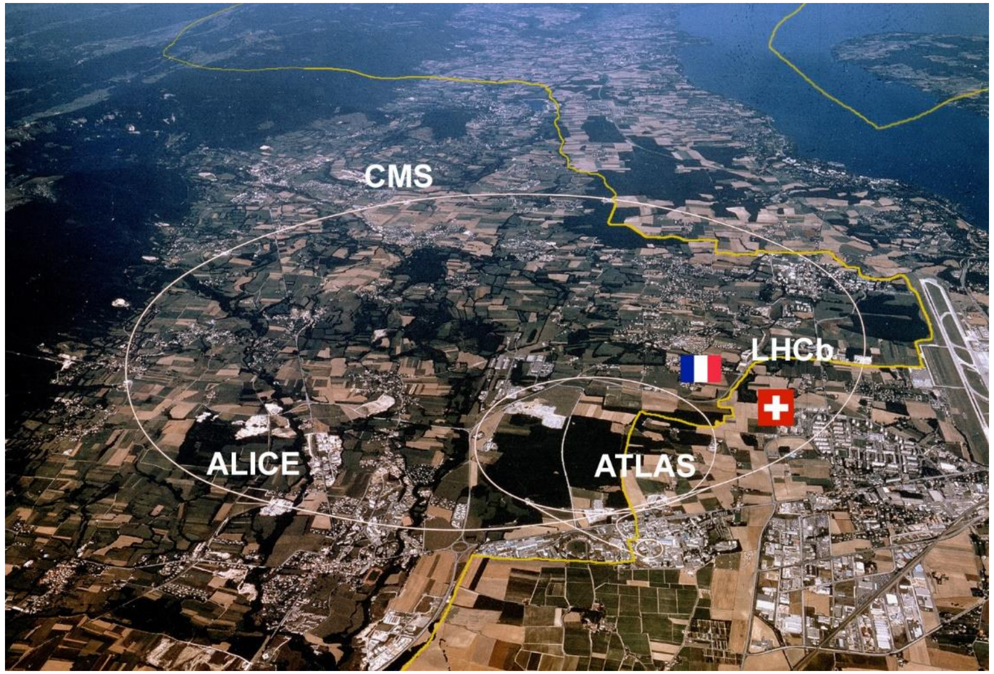
e.g., from direct decay of Inflaton like field → escapes thermal constrains if equilibrium is not established (e.g., produced after T_decoup.)

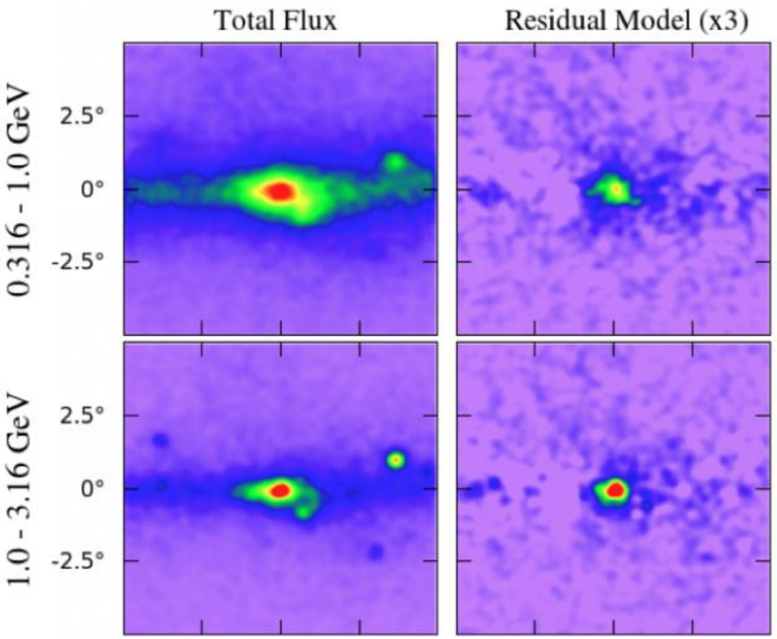
This is normally accompanied by 'entropy production' (decay of field into relativistic particles) which can adjust expansion rate and thus the DM abundance (diluting it)

→ Constrained by BBN and CMB

Searching for Dark Matter

- Detection experiments (DM in the room!)
- LHC (at CERN)
- Annihilation Signals (in the sky)

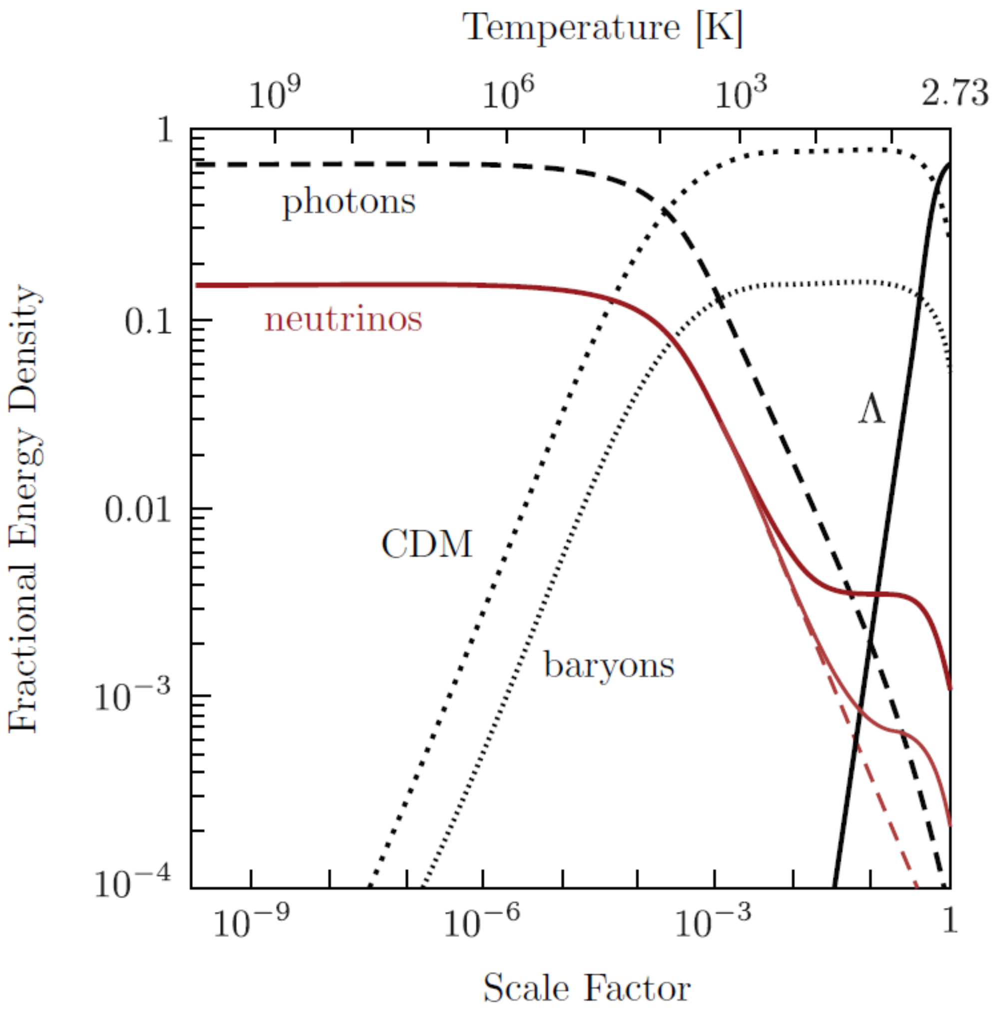


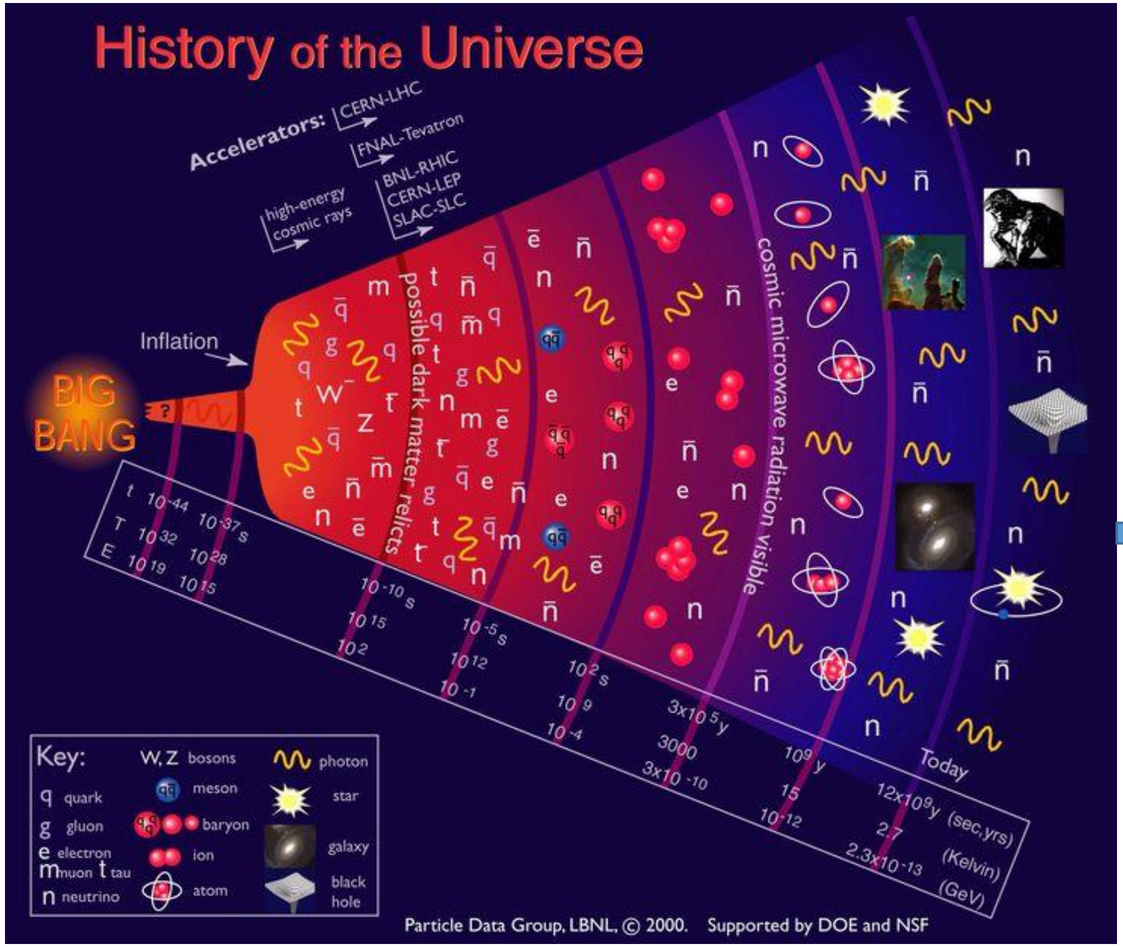


Overview of Evolution

Event	time t	redshift z	temperature T
Inflation	10^{-34} s (?)	–	–
Baryogenesis	?	?	?
EW phase transition	20 ps	10^{15}	100 GeV
QCD phase transition	20 μs	10^{12}	150 MeV
Dark matter freeze-out	?	?	?
Neutrino decoupling	1 s	6×10^{9}	1 MeV
Electron-positron annihilation	6 s	2×10^{9}	500 keV
Big Bang nucleosynthesis	3 min	4×10^{8}	100 keV
Matter-radiation equality	60 kyr	3400	0.75 eV
Recombination	260–380 kyr	1100–1400	0.26–0.33 eV
Photon decoupling	380 kyr	1000–1200	0.23–0.28 eV
Reionization	100–400 Myr	11–30	2.6–7.0 meV
Dark energy-matter equality	9 Gyr	0.4	0.33 meV
Present	13.8 Gyr	0	0.24 meV

From lecture notes by Daniel Baumann




History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
Today
Key:
W, Z bosons
q quark
g gluon
e electron
m muon t tau
n neutrino
meson
baryon
ion
atom
photon
star
galaxy
black hole
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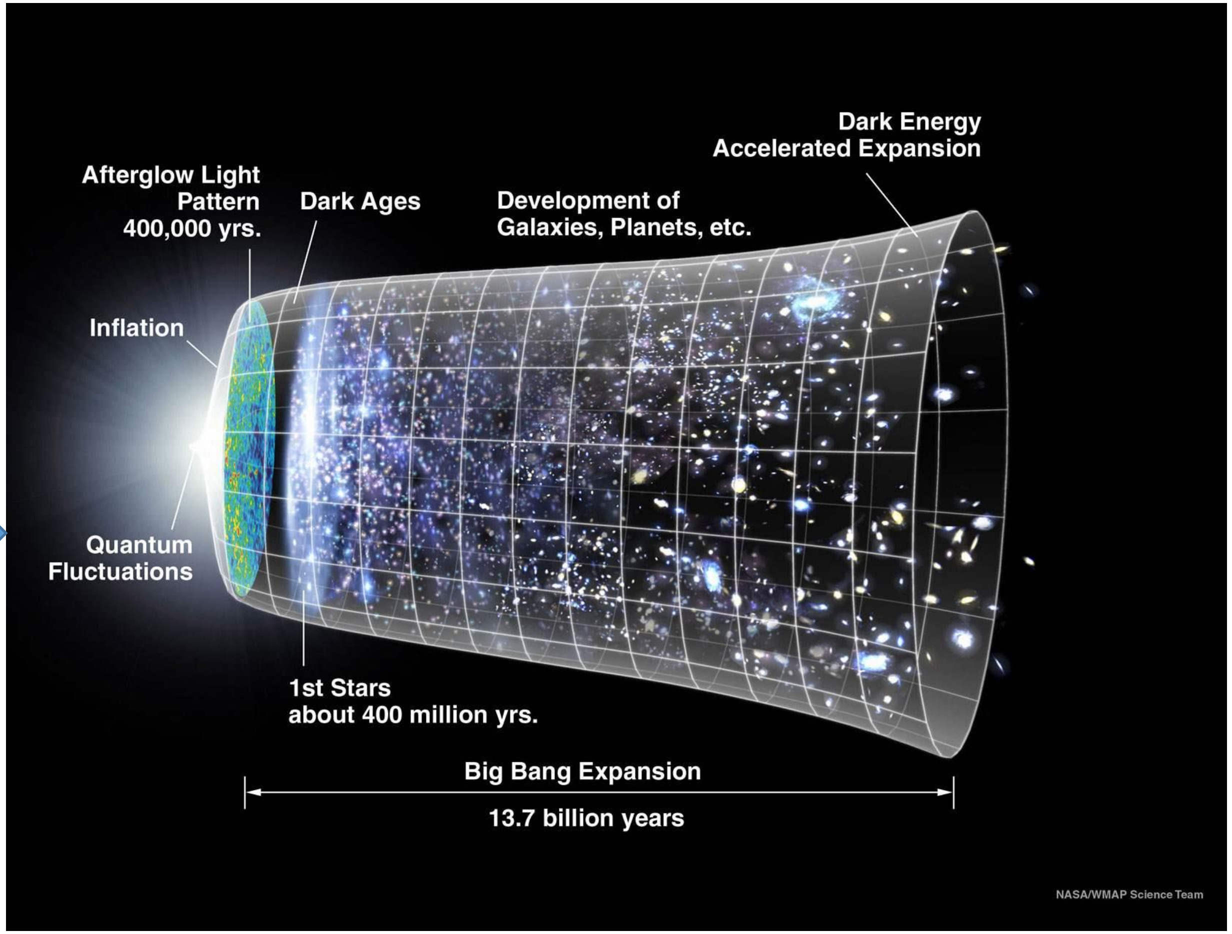
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team