COSMOLOGY 101
2

Chris Pearson : RAL Space

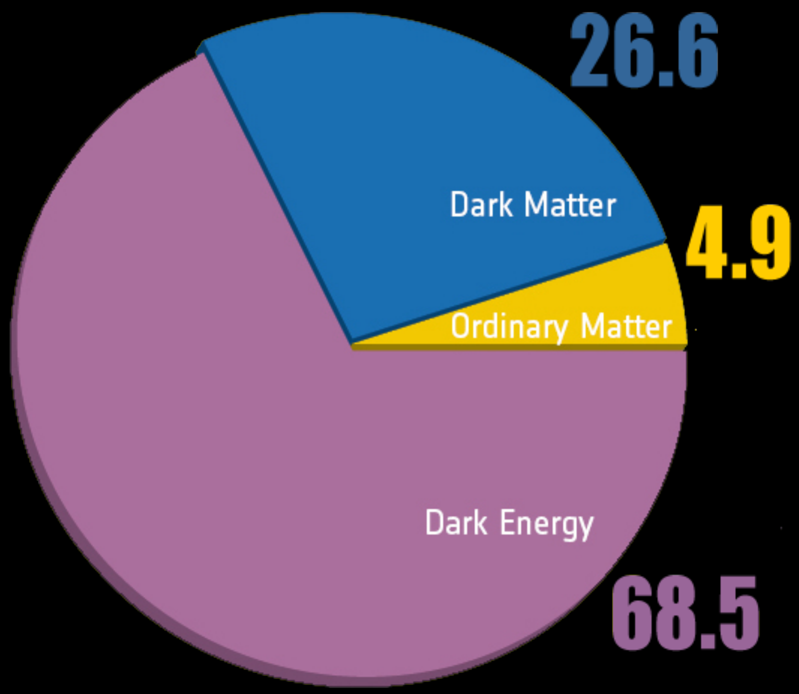
July 2015

COSMOLOGY

- How did the Universe Begin ?
- How old is the Universe ?
- How big is the Universe ?
- Where are we in the Universe ?
- What is the Universe made of ?
- Will the Universe end ?

COSMOLOGY

- Our Universe is flat and infinite
- The expansion of the Universe is expanding
- The Universe began in a hot Big Bang



H_o = 67.3 ± 0.012 km/s/Mpc

τ_{age} = 13.81 ± 0.05 Gyr

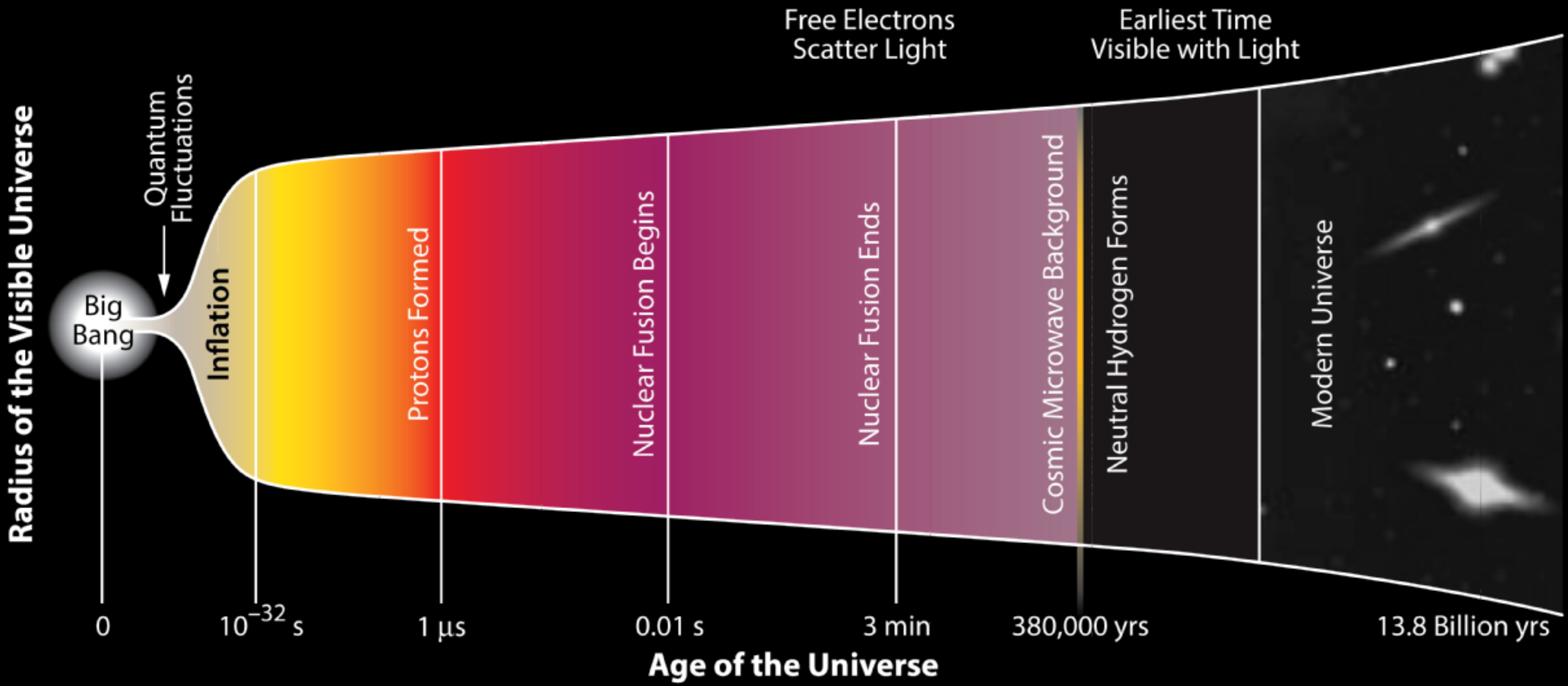
$\Omega_{\Lambda,o}$ = 0.685 ± 0.017

$\Omega_{m,o}$ = 0.315 ± 0.016

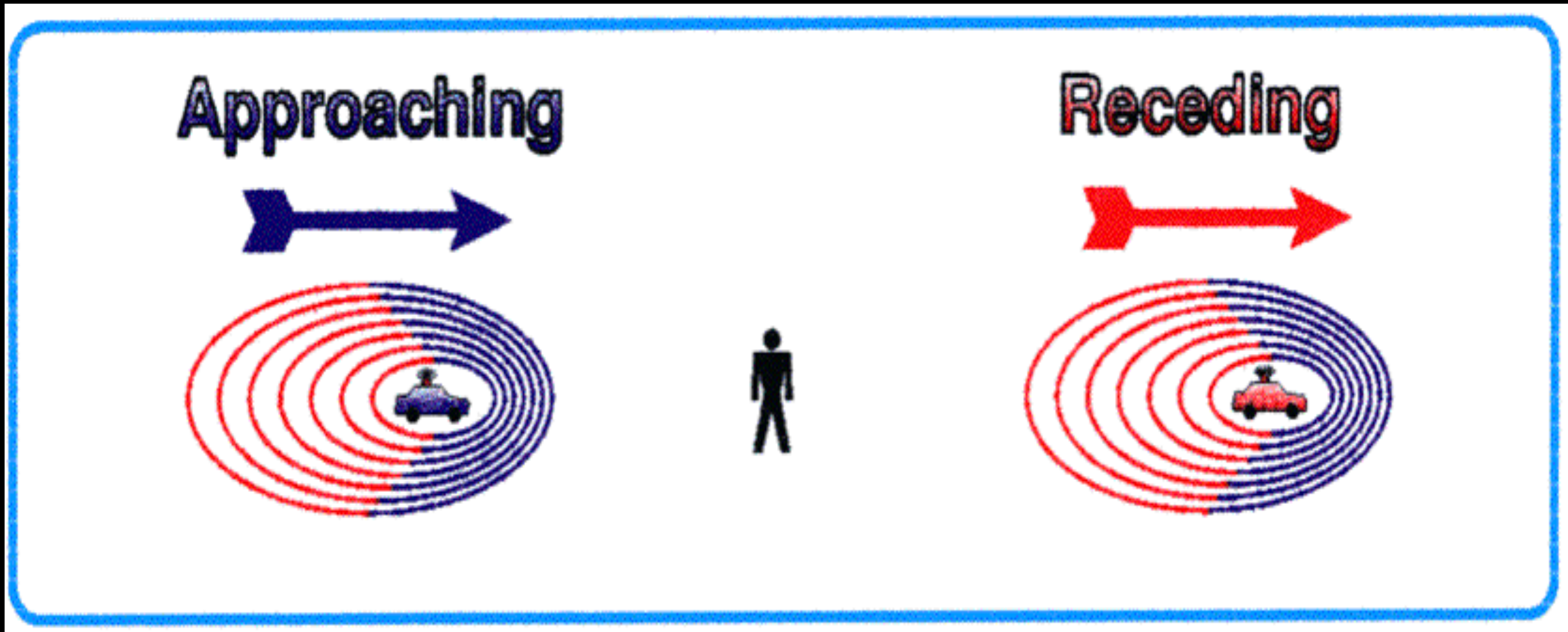
$\Omega_{DM,o}$ = 0.2662 ± 0.016

$\Omega_{b,o}$ = 0.0487 ± 0.00027

A Very Brief History of Time



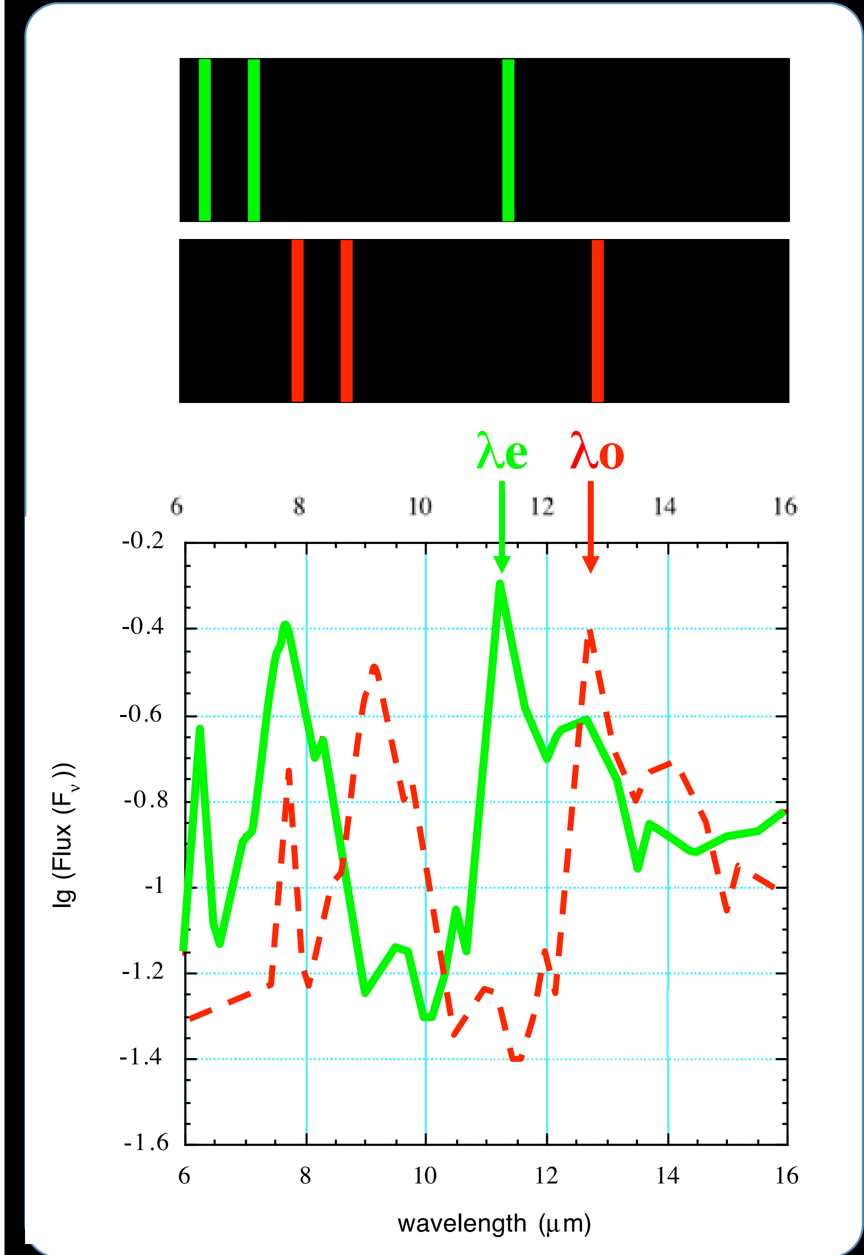
The Redshift



Frequency increasing
Wavelength decreasing
Wave crests get closer together
Colour gets BLUER = BLUESHIFT

Frequency decreasing
Wavelength increasing
Wave crests get further apart
Colour gets REDDER = REDSHIFT

The Redshift



$$z = \frac{\Delta\nu}{\nu_o} = \frac{\Delta\lambda}{\lambda_e} = \frac{\nu_e - \nu_o}{\nu_o} = \frac{\lambda_o - \lambda_e}{\lambda_e} \approx \frac{\vec{v}}{c} \quad \text{for } \upsilon << c$$

$$1 + z = \frac{\nu_e}{\nu_o} \equiv \frac{\lambda_o}{\lambda_e}$$

The Redshift

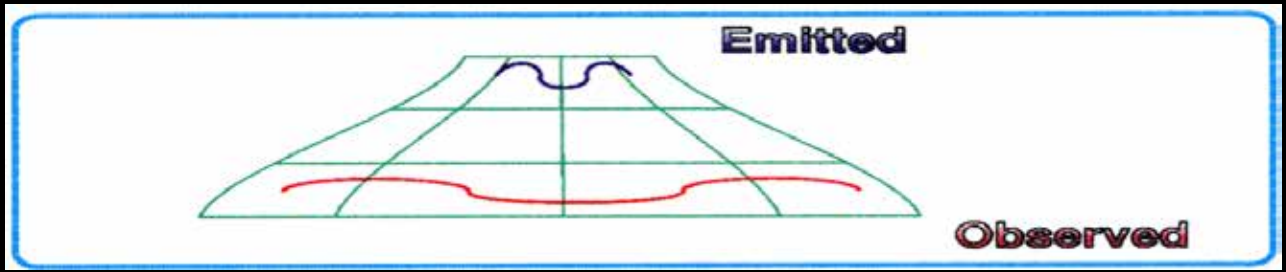
The Redshift

- **Doppler Redshift** $$z = \frac{\Delta \nu}{\nu_o} = \frac{\Delta \lambda}{\lambda_e} = \frac{\nu_e}{\nu_o} - 1$$

- **Special Relativistic Redshift** $$1 + z = \frac{\nu_e}{\nu_o} = \sqrt{\frac{1 + \vec{v}/c}{1 - \vec{v}/c}} = \sqrt{\frac{c + \vec{v}}{c - \vec{v}}} \approx \frac{\vec{v}}{c} \qquad \text{for } \upsilon << c$$

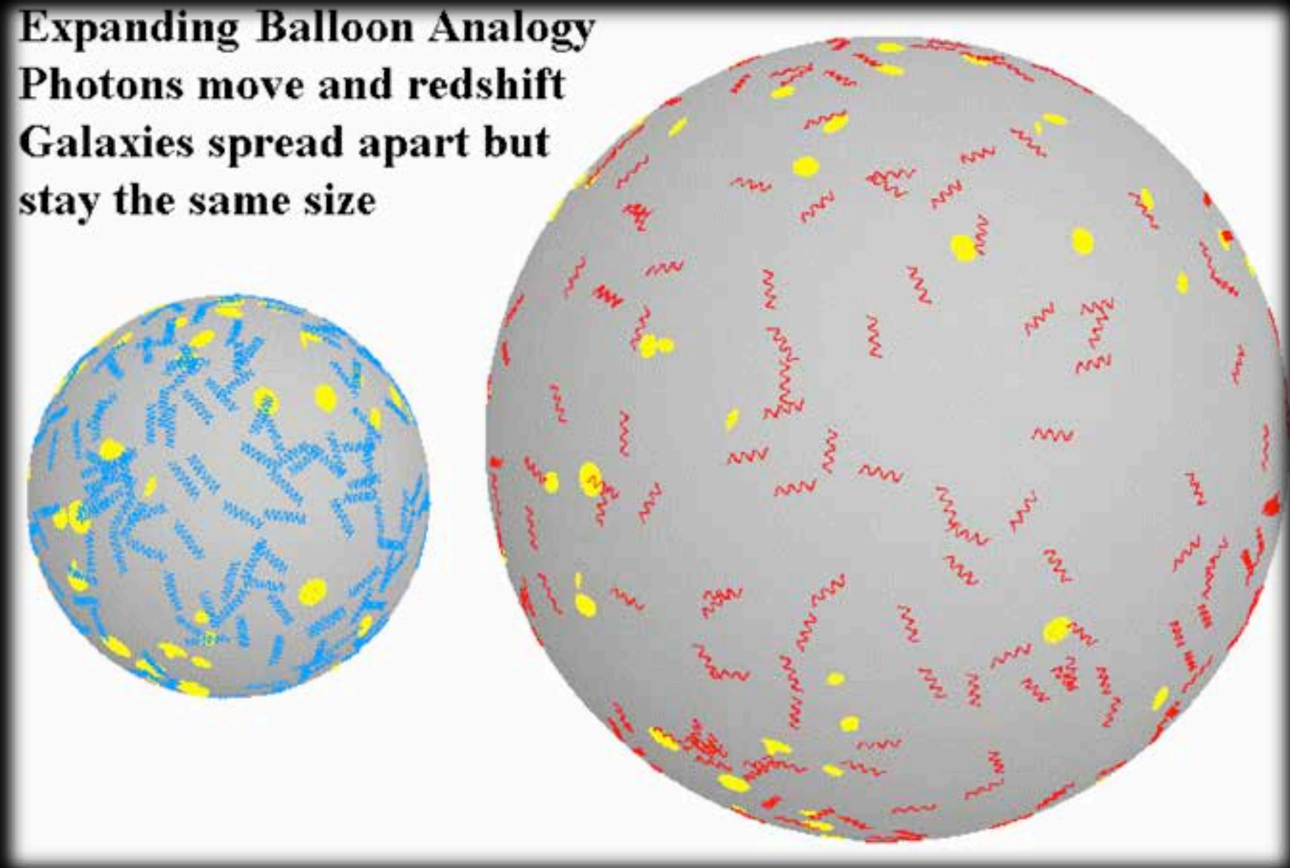
- **Cosmological Redshift** $\vec{v} = cz = H_o d$ **Hubble's Law**

  - **Correct interpretation of Cosmological Redshift of galaxies is NOT a Doppler shift.**
  - **Wave fronts expand with the expanding Universe, stretching the photon wavelength.**



The Redshift

Cosmological Redshift



$$1 + z \equiv \frac{\lambda_0}{\lambda_e} = \frac{R(t_o)}{R(t_e)}$$

Cosmological explanation:
Redshift - natural consequence since R(t) is an increasing function of time
Wavefronts expand with the expanding Universe, stretching the photon wavelength.

A Very Brief History of Time

THE HOT BIG BANG: How does the temperature of the early Universe evolve ?

Redshift **Wiens Law**

$$\frac{\lambda_0}{\lambda} = \frac{R_0}{R} = (1+z) \quad + \quad \lambda_{max} T = \text{constant} \quad \rightarrow \quad R_0 T_0 = RT$$

Energy density of radiation $\varepsilon = aT^4 = \rho c^2$

Friedmann Equation

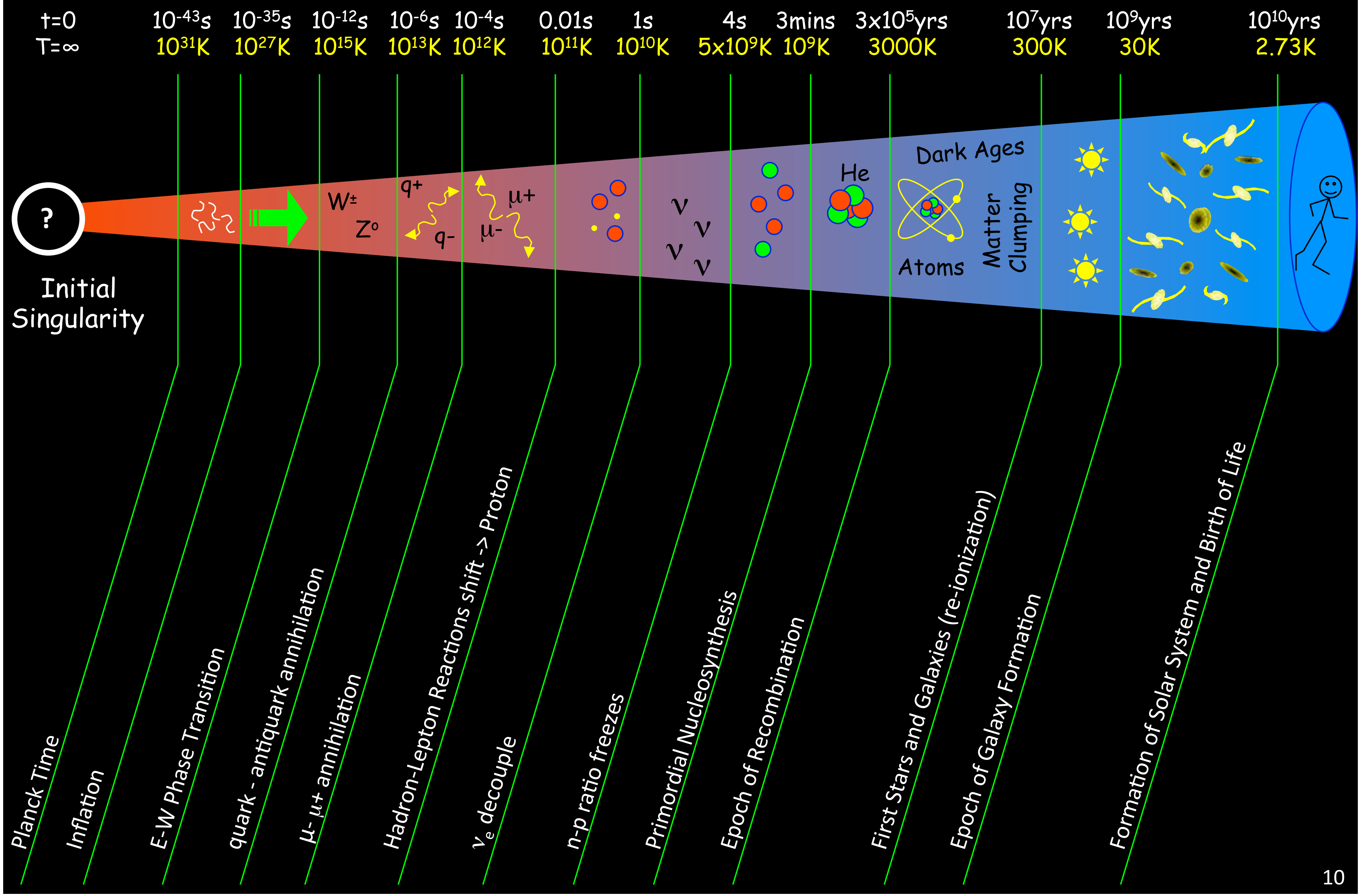
$$\frac{\dot{R}^2}{R^2} = \frac{8\pi G \rho}{3}$$

$$T = \left(\frac{32\pi G a}{3c^2} \right)^{-1/4} t^{-1/2} \approx 1.5 \times 10^{10} t^{-1/2}$$

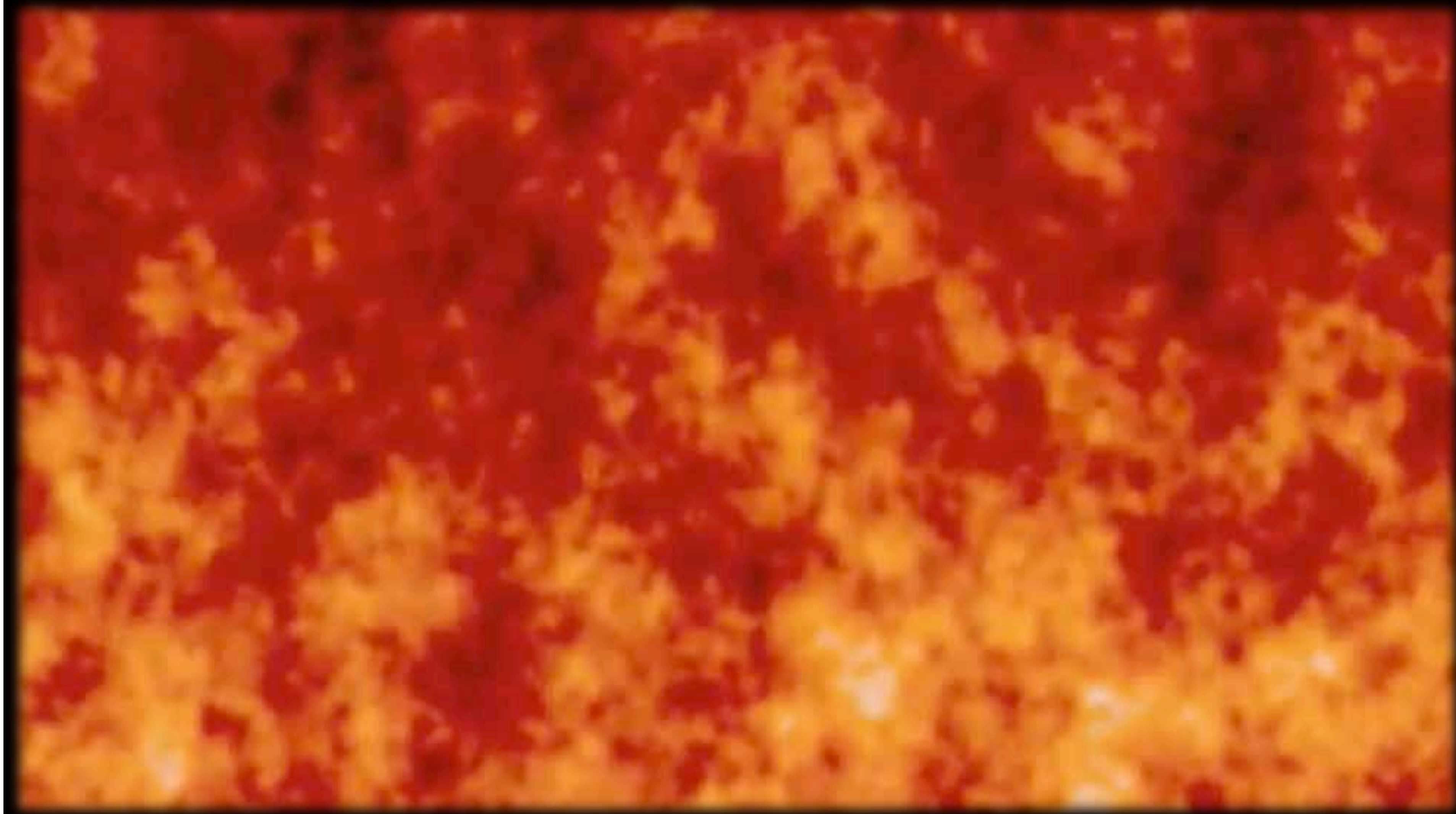
a = Radiation constant
G = Newton's Gravitational Constant
c = speed of light

Temperature evolution in early Universe depends ONLY on Nature's fundamental constants!

A Very Brief History of Time

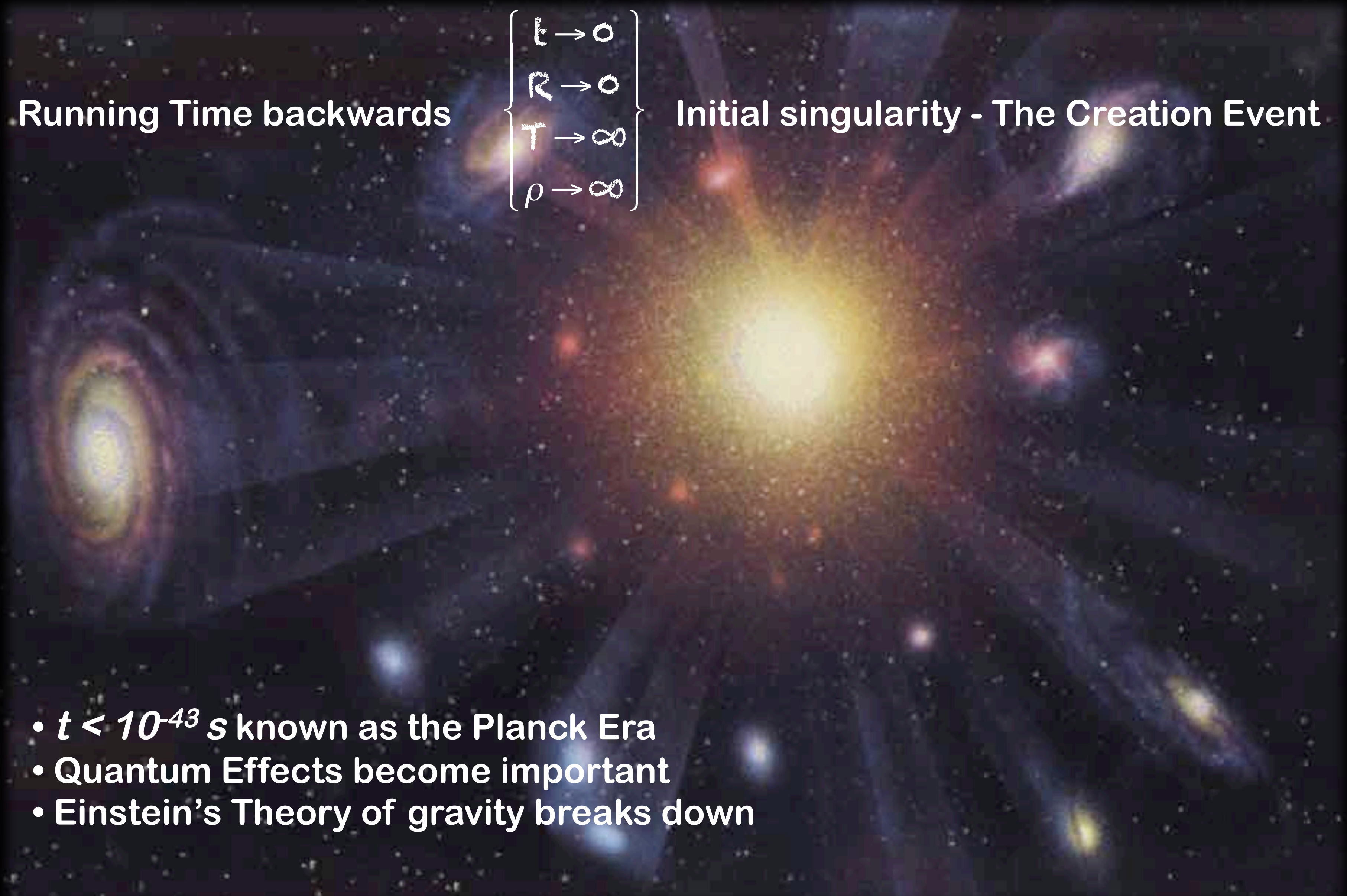


It All Started with a Big Bang



It All Started with a Big Bang

In the Beginning…… Planck Era = 10^{-43} s 10^{31} K



Running Time backwards

$$\left\{\begin{array}{l} t \to 0 \\ R \to 0 \\ T \to \infty \\ \rho \to \infty \end{array}\right\}$$

Initial singularity - The Creation Event

- $t < 10^{-43}$ *s* known as the Planck Era
- Quantum Effects become important
- Einstein's Theory of gravity breaks down

It All Started with a Big Bang

In the Beginning…… Planck Era = 10^{-43} s 10^{31} K

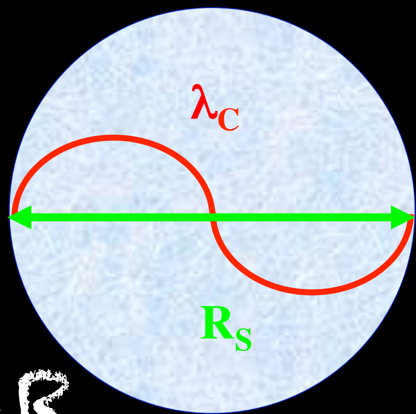
Quantum fluctuations of spacetime ~ Planck length, are of cosmic magnitude

For a particle of mass, m,
Scale at which quantum effects become important : Compton Wavelength

$$\lambda_c = \frac{h}{mc}$$

Scale at which self gravity becomes important : Schwarzchild Radius

$$R_s = \frac{2Gm}{c^2}$$



For a particle of mass, m_P = the Planck mass

$$\lambda_c \approx R_s$$

Compton Wavelength & Schwarzchild Radius are comparable

It All Started with a Big Bang

In the Beginning...... Planck Era = 10^{-43} s 10^{31} K

Did the Big Bang .... Bang?!?

Or was it a Quantum Theory of Gravity ?

1. Quantum Gravity
2. Super Gravity
3. Superstrings
4. M-Theory

Problems with the Big Bang ?

The Inflationary Era = 10^{-35} s 10^{27} K

1. **THE HORIZON PROBLEM**

   the isotropy of apparent causally disconnected regions of the CMB

2. **THE FLATNESS PROBLEM**

   the apparent remarkable closeness of Omega to 1

3. **THE RELIC PROBLEM**

   the apparent absence of relics from the Big Bang in our Universe

Problems with the Big Bang ?

The Inflationary Era = 10^{-35} s 10^{27} K

1. **THE HORIZON PROBLEM**

   the isotropy of apparent causally disconnected regions of the CMB

2. **THE FLATNESS PROBLEM**

   the apparent remarkable closeness of Omega to 1

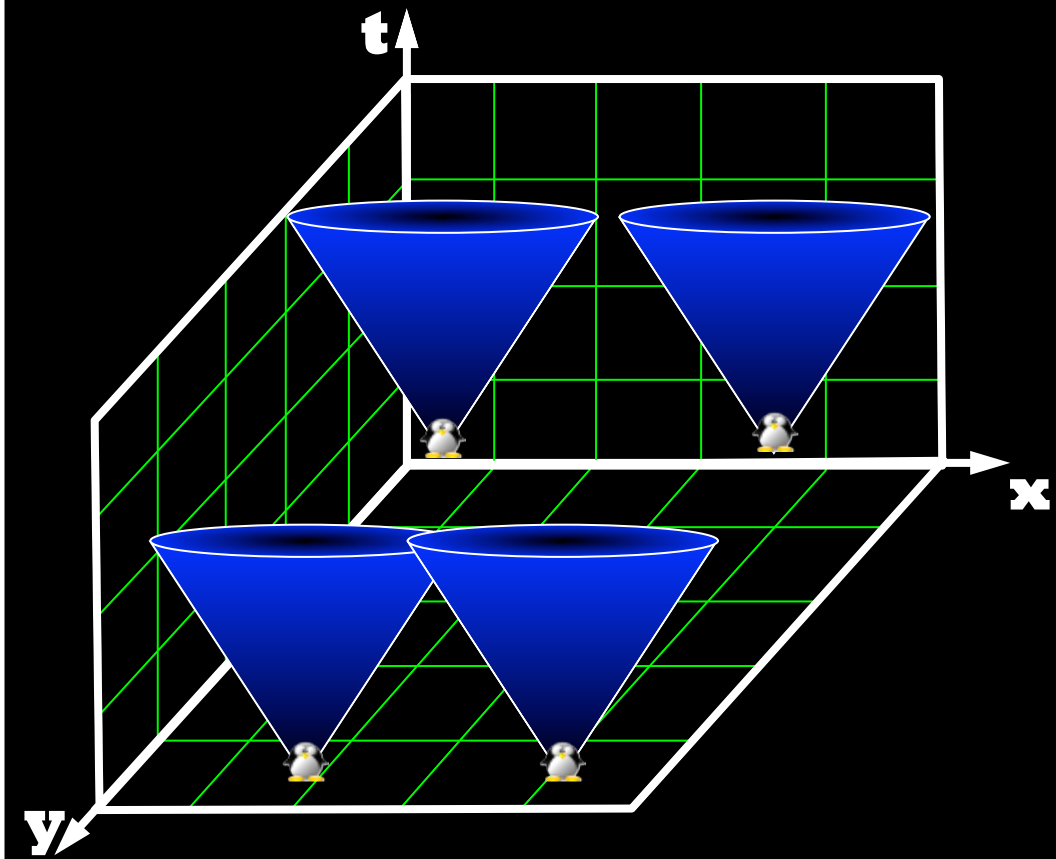
3. **THE RELIC PROBLEM**

   the apparent absence of relics from the Big Bang in our Universe

The Horizon Problem

The Inflationary Era = 10^{-35} s 10^{27} K

Cosmological Horizon:
measure of distance at a given time from which information can be retrieved into the past: Defines the Observable Universe.



The Horizon Problem

The Inflationary Era = 10^{-35} s 10^{27} K

Cosmological Horizon:
measure of distance at a given time from which information can be retrieved into the past: Defines the Observable Universe.

Cosmic distance from Robertson Walker metric

$$ds^2 = c^2dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right)$$

The Horizon Scale:

$$d_H = R(t_H)r = R(t_H)\int_0^{t_H}\frac{c}{R(t)}dt \quad \approx 3ct_H$$

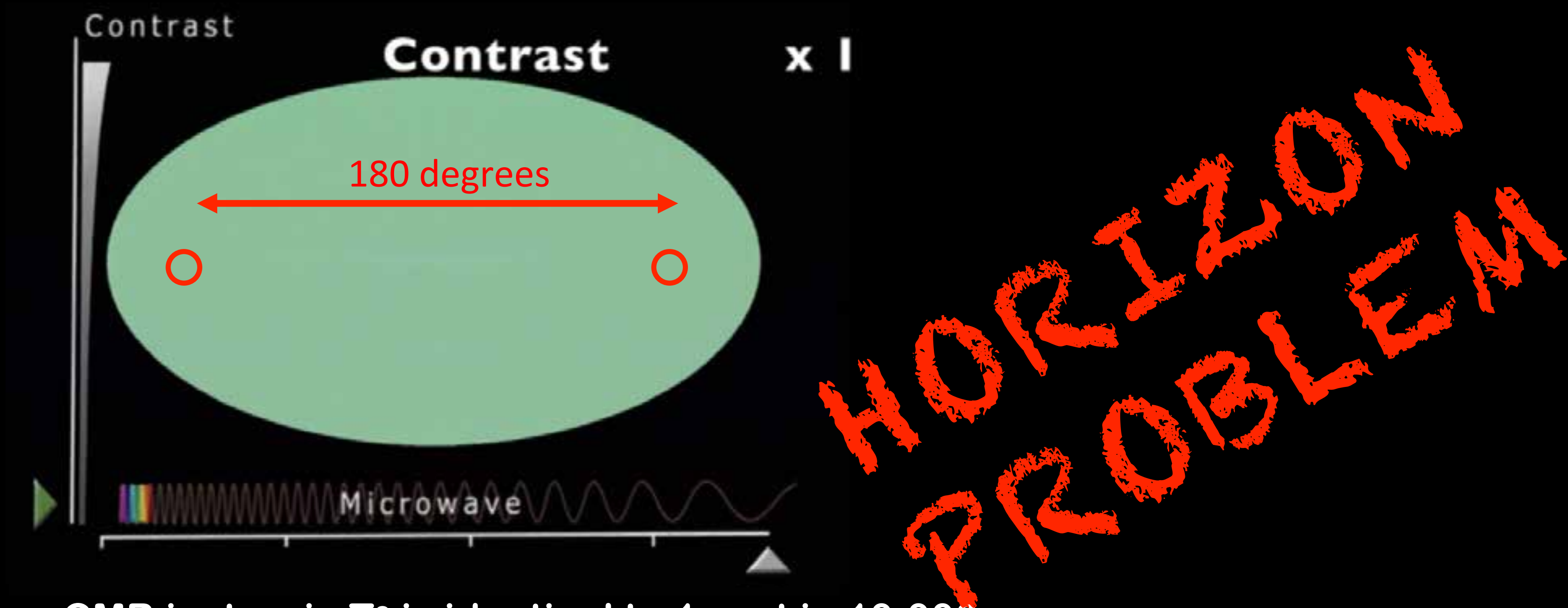
Horizon size today: ~ 46 Billion light years

The Horizon Problem

The Inflationary Era = 10^{-35} s 10^{27} K

Horizon size today: ~ 46 Billion light years

Horizon on microwave background: *t ~ 3x10⁵yrs 10¹³s* : 1 million light years
~ 1.3 degrees on the sky



- CMB isotropic T° is identical to 1 part in 10,000
- Opposite regions appear never to have been in causal contact
- But opposite points in CMB are ~ 90 horizon distances apart !!
- So how do they know that they should be at the same temperature??

Problems with the Big Bang ?

The Inflationary Era = 10^{-35} s 10^{27} K

1. **THE HORIZON PROBLEM**

   the isotropy of apparent causally disconnected regions of the CMB

2. **THE FLATNESS PROBLEM**

   the apparent remarkable closeness of Omega to 1

3. **THE RELIC PROBLEM**

   the apparent absence of relics from the Big Bang in our Universe

The Flatness Problem

The Inflationary Era = 10^{-35} s 10^{27} K

Planck satellite Observations: The Universe is almost flat today: $\Omega_o \sim 1 \pm 0.02$
How about in the past ?

$$\frac{\dot{R}^2}{R^2} = H^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2} = \Omega H^2 - \frac{kc^2}{R^2}$$

$$\left|\Omega - 1\right| = \frac{|k|c^2}{R^2 H^2}$$

$$\frac{\left|\Omega - 1\right|_t}{\left|\Omega - 1\right|_{t_o}} = \frac{\left(R^2H^2\right)_{t_o}}{\left(R^2H^2\right)_t}$$

Evolution of Ω with time

Matter dominated Era:

$$R \propto t^{2/3} \Rightarrow R^2H^2 = \dot{R}^2 \propto t^{-2/3}$$

Radiation dominated Era:

$$R \propto t^{1/2} \Rightarrow R^2H^2 = \dot{R}^2 \propto t^{-1}$$

$$\frac{\left|\Omega - 1\right|_t}{\left|\Omega - 1\right|_{t_o}} = \left(\frac{t}{t_o}\right)^{2/3}_{matter} = \left(\frac{t}{t_o}\right)_{radiation}$$

The Flatness Problem

The Inflationary Era = 10^{-35} s 10^{27} K

Planck satellite Observations: The Universe is almost flat today: $\Omega_o \sim 1 \pm 0.02$
How about in the past ?

$$\frac{|\Omega - 1|_t}{|\Omega - 1|_{t_o}} = \left(\frac{t}{t_o}\right)^{2/3}_{matter} = \left(\frac{t}{t_o}\right)_{radiation}$$

Evolution of Ω with time

Matter Radiation Equality	$t_{eq} \sim 10^{6}\,yr = 10^{13} s$	➠ $\lvert 1-\Omega \rvert < 10^{-7}$
Big Bang Nucleosynthesis	$t_{BBN} \sim 3mins = 180s$	➠ $\lvert 1-\Omega \rvert < 10^{-18}$
Planck Time	$t_P \sim 10^{-43} s$	➠ $\lvert 1-\Omega \rvert < 10^{-63}$

FLATNESS PROBLEM

- **Why is the Universe so FLAT ….. fine Tuning to > 1 part in 10^{60}**
- **Why did the Universe not expand - contract back to a big crunch very quickly**
- **Why did the Universe not expand so quickly that galaxies and life were unable to form**

Problems with the Big Bang ?

The Inflationary Era = 10^{-35} s 10^{27} K

1. **THE HORIZON PROBLEM**

   the isotropy of apparent causally disconnected regions of the CMB

2. **THE FLATNESS PROBLEM**

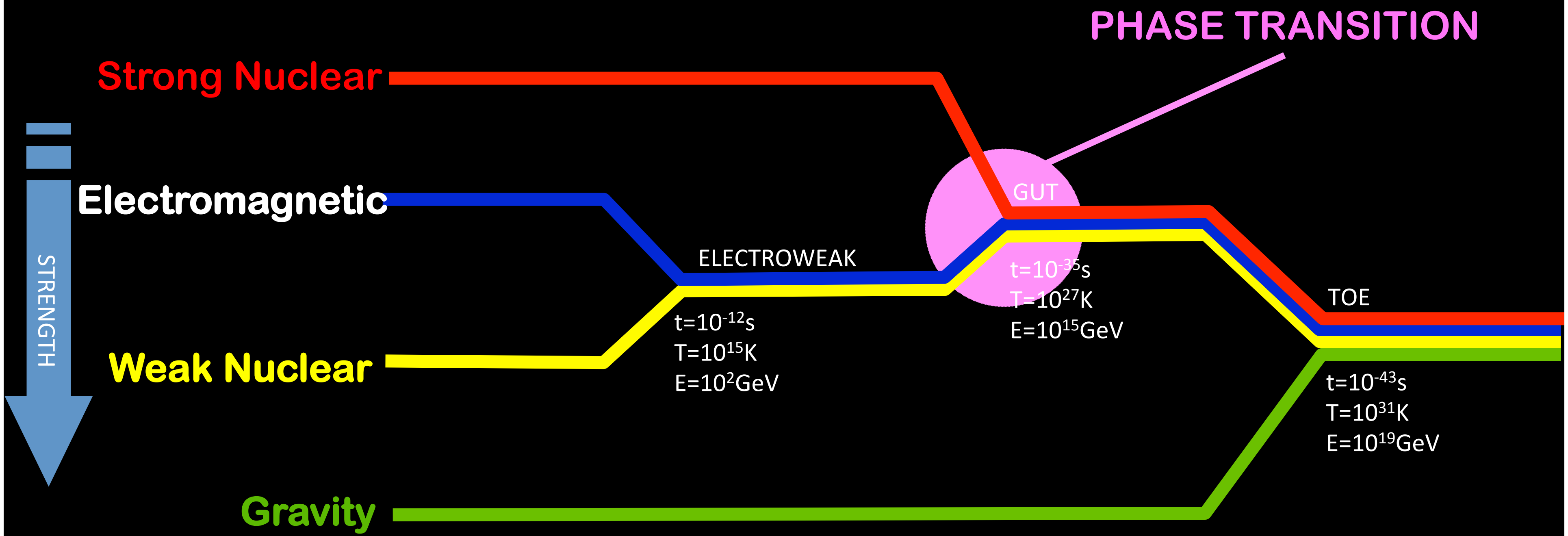
   the apparent remarkable closeness of Omega to 1

3. **THE RELIC PROBLEM**

   the apparent absence of relics from the Big Bang in our Universe

The Relic Problem

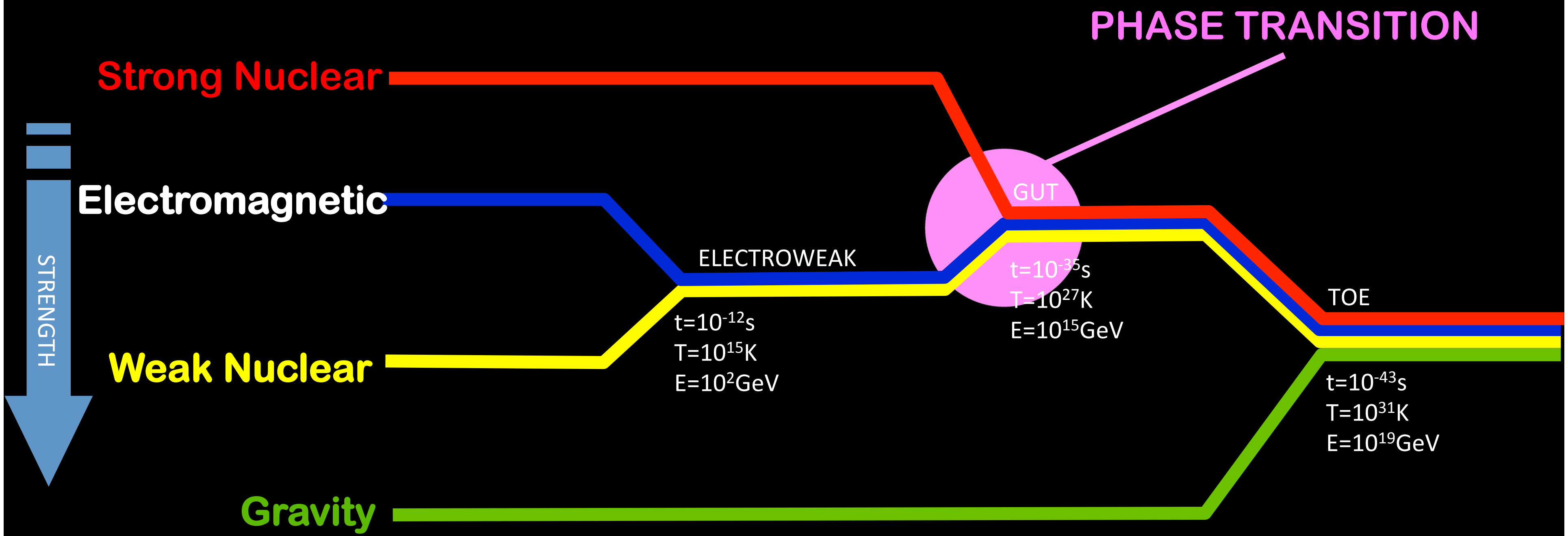
The Inflationary Era = 10^{-35} s 10^{27} K



- At high energies the forces of nature unify
- Symmetry ➡ Forces become indistinguishable from each other
- Universe cools ➡ temperature drops ➡ symmetry breaks ➡ phase transition
- Like water freezing into ice ➡ defects appear on cooling

The Relic Problem

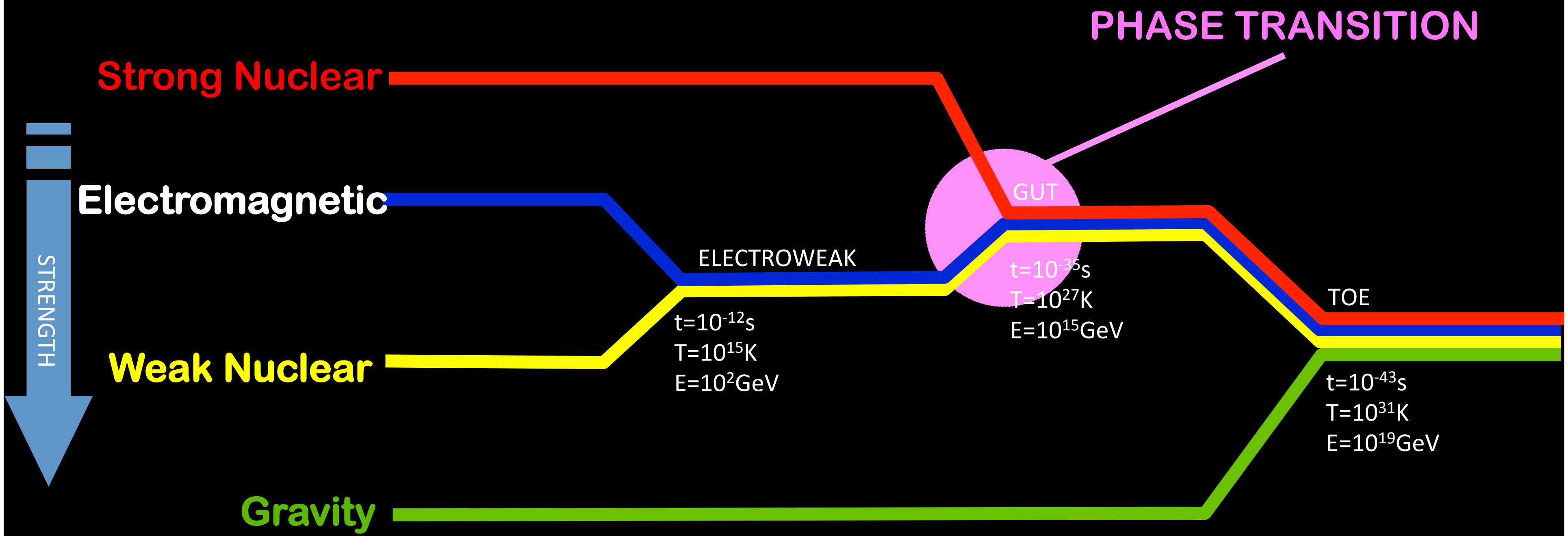
The Inflationary Era = 10^{-35} s 10^{27} K



- Phase transition ➡ loss of symmetry ➡ topological defects
- Predicted for GUT (strong/electroweak unification) *$t=10^{-35}$s, $T=10^{27}$K, $E=10^{15}$GeV*
- Compare with freezing water
    - different ice nucleation sites
    - different axes (domains) of symmetry ➡ topological defects

The Relic Problem

The Inflationary Era = 10^{-35} s 10^{27} K



- 0D point like defects = Magnetic Monopoles (isolated North/South poles)
- 1D linear defects = Cosmic Strings
- 2D sheet like defects = Textures

The Relic Problem

The Inflationary Era = 10^{-35} s 10^{27} K

Magnetic Monopole rest energy ~ *10^{15}GeV* ➡ E=mc^2 ➡ mass ≡ bacterium

- **Phase Transition ➡ symmetry breaking ➡ topological defects**
- **Expect one topological defect / horizon distance**

Horizon distance at t_{GUT} $$d_H = 2ct_{GUT}$$

Number density of Monopoles $$\frac{1}{d_H^3} \approx 10^{146}\ \mathrm{Mpc}^{-3}$$

with energy density $$\frac{mc^2}{d_H^3} \approx 10^{161}\ \mathrm{GeV\,Mpc}^{-3}$$

RELIC PROBLEM

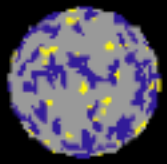
Monopoles would dominate the energy density and close the Universe by 10^{-12} s

However…… we are here …… so where are the monopoles ????

Problems with the Big Bang ?

The Inflationary Era = 10^{-35} s 10^{27} K

1. THE HORIZON PROBLEM
2. THE FLATNESS PROBLEM
3. THE RELIC PROBLEM



Solution ? :   Inflation

Inflationary Epoch

- 1980s, Alan Guth - Inflation Theory -
- Period between 10^{-36} and 10^{-34} s
- Small portion of Universe balloons to become today's visible Universe.
- Can solve horizon, flatness, relic problems !!

Inflation

The Inflationary Era = 10^{-35} s 10^{27} K

During inflation the Universe accelerates

Negative pressure, or large, positive Λ

Friedmann Equations become

$$\ddot{R} = -\frac{4\pi G\rho}{3}R + \frac{\Lambda R}{3} \Rightarrow \frac{\Lambda R}{3}$$

$$\frac{\dot{R}^2}{R^2} = H^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2} + \frac{\Lambda}{3} \Rightarrow \frac{\Lambda}{3}$$

$$R \propto e^{\frac{\Lambda^{1/2}}{\sqrt{3}}t} = e^{Ht}$$

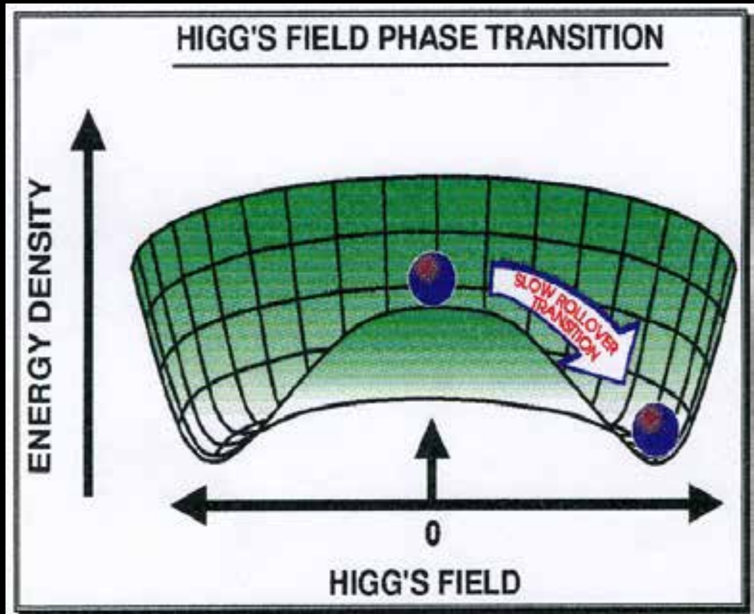
Hubble Parameter during inflation is constant $= (\Lambda / 3)^{1/2}$

Universe expands exponentially

Inflation

The Inflationary Era = 10^{-35} s 10^{27} K

Inflation mechanism: symmetry breaking



- Ordinary vacuum, Higgs field is non-zero known as TRUE VACUUM
- Phase transition is slow compared to cooling of Universe
- Regions of Universe supercool without breaking symmetry
- Like water super cooling 253K without turning to ice
- Supercooled regions in a state known as FALSE VACUUM
- False Vacuum acts like a Cosmological Constant Λ
- Higgs field finally reaches lowest state- symmetry breaks.
- Latent heat stored in Higgs Field released and re-heats the Universe - inflation ends

Inflation can provide the BANG in the Big Bang ?

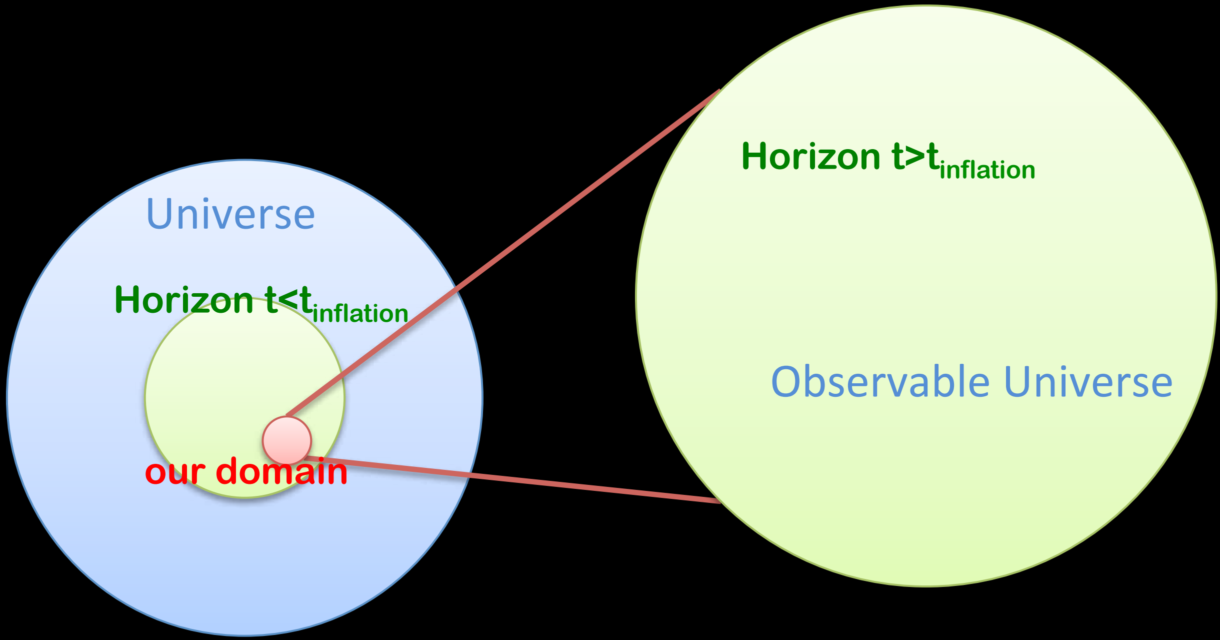
Inflation

The Inflationary Era = 10^{-35} s 10^{27} K

1. THE HORIZON PROBLEM

The isotropy of apparent causally disconnected regions of the CMB

- Inflate from a small sub horizon region
- Seemingly causally disconnected points today were in causal contact before inflation
- Inflation creates bubble Universes separated by domain walls of order of Horizon



Inflation

The Inflationary Era = 10^{-35} s 10^{27} K

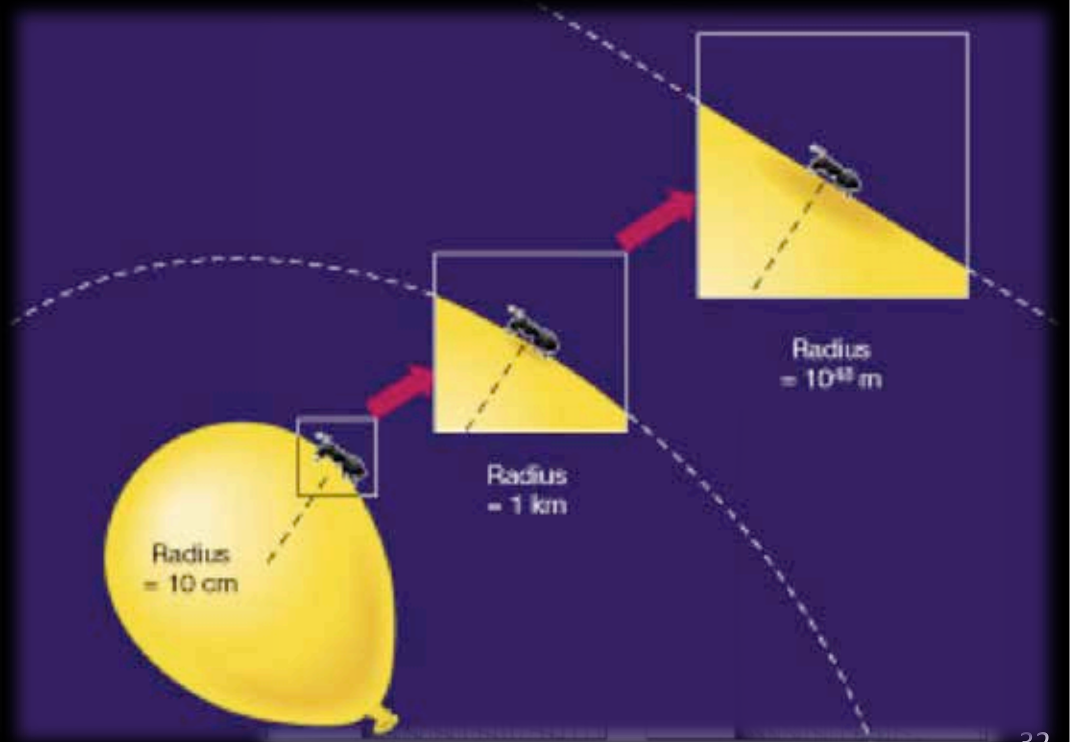
2. THE FLATNESS PROBLEM

the apparent remarkable closeness of Omega to 1

Inflation can make Universe arbitrarily flat

During inflation, H is constant: Ω is driven relentlessly towards unity

$$|\Omega - 1| = \frac{|k|c^2}{R^2H^2} \rightarrow 0$$



- Require flatness to $\sim 10^{-63}$
- ➠ need $>10^{31}$ inflation folds

Inflation

The Inflationary Era = 10^{-35} s 10^{27} K

3. THE RELIC PROBLEM

the apparent absence of relics from the Big Bang in our Universe

Inflation pushes domain boundaries beyond our horizon distance

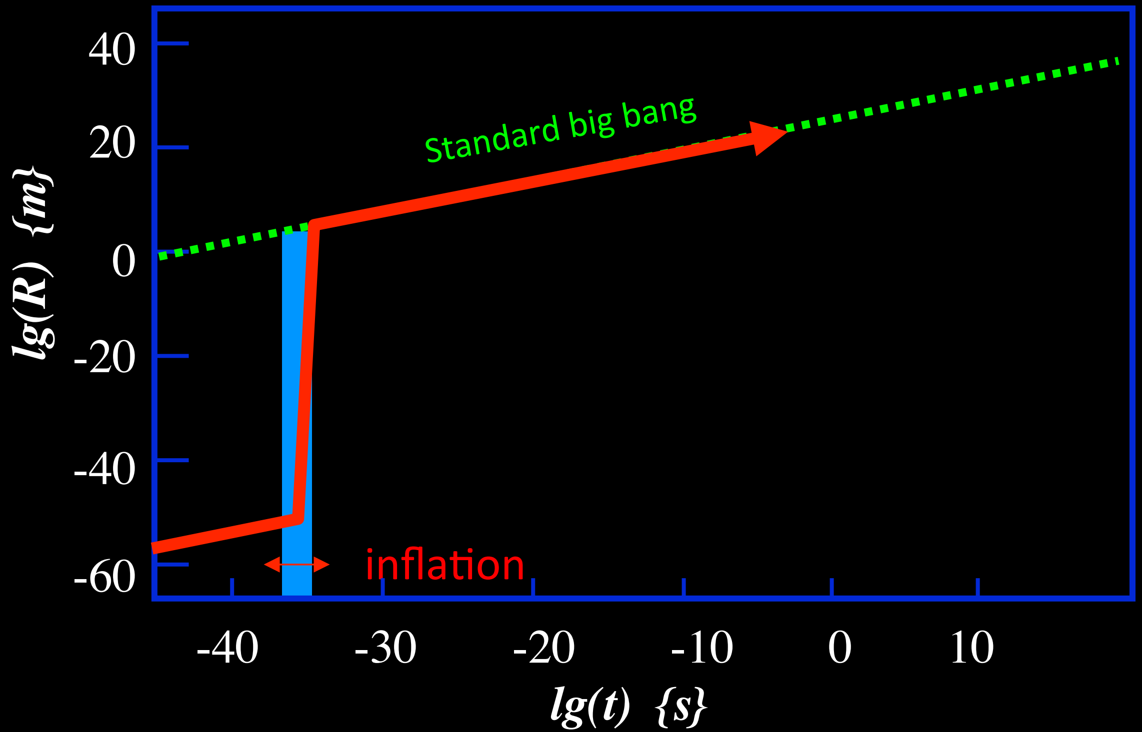
The density of relics is diluted

Inflation

The Inflationary Era = 10^{-35} s 10^{27} K

$$R \propto e^{\frac{\Lambda^{1/2}}{\sqrt{3}}t} = e^{Ht}$$

- Require Flatness 10^{31}
- Require Horizon ~100
- For Relics depends on details of the physics
- For inflation from $t_1=10^{-36}$ $(1/H_1)$ to $t_2=10^{-34}$ s ➡ 100 e foldings !



During the inflationary era

$$R_2/R_1 = e^{\frac{t_2-t_1}{t_1}} = e^{99} = 10^{43}$$

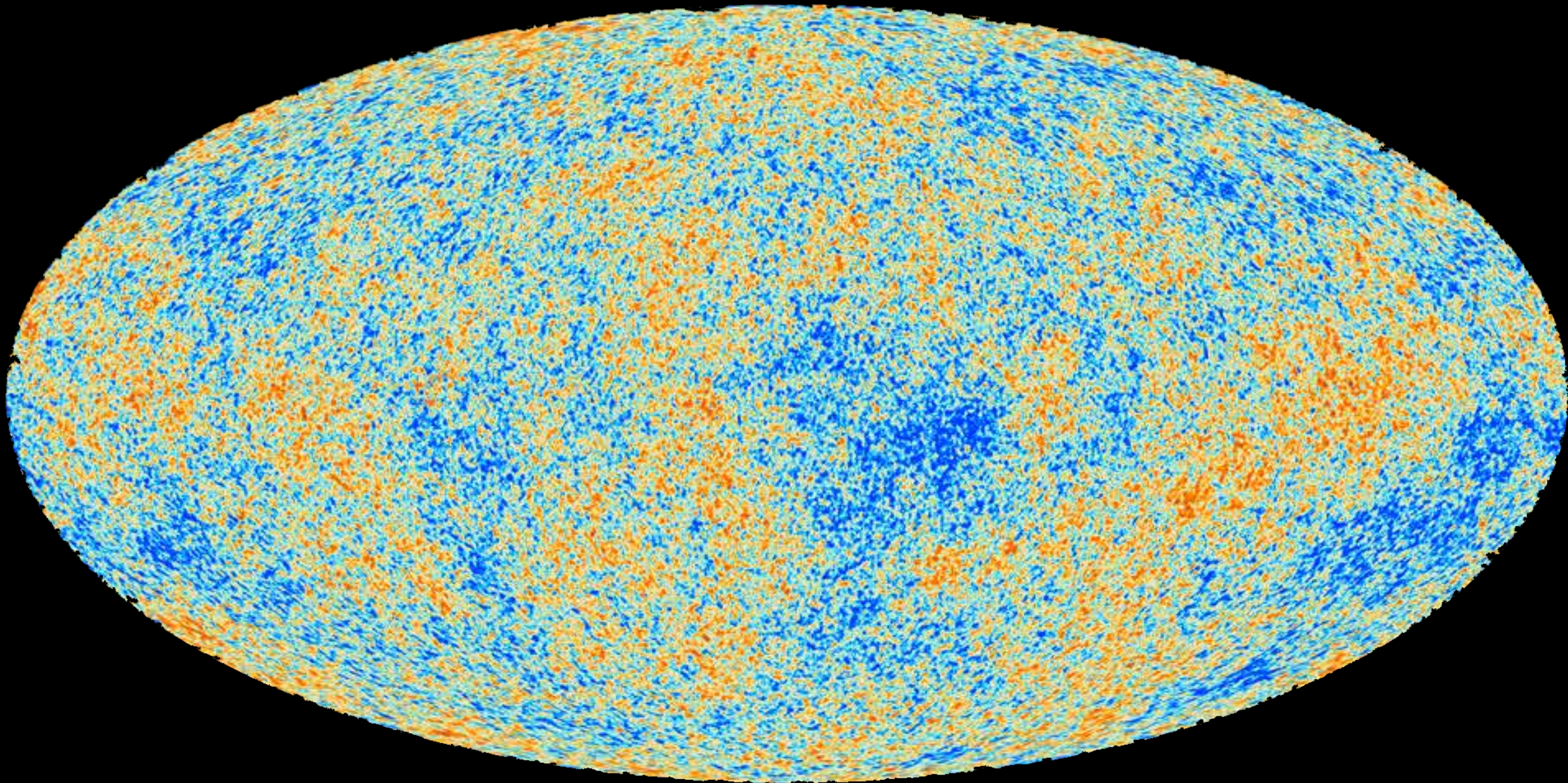
$$T_2/T_1 = 10^{-43}$$

But energy in Higgs Field reheats

Inflation of quantum fluctuations ➡ macroscopic scales ➡ seeds of **Structure Formation**

Inflation

The Inflationary Era = 10^{-35} s 10^{27} K



Inflation of quantum fluctuations ➡ macroscopic scales ➡ seeds of **Structure Formation**

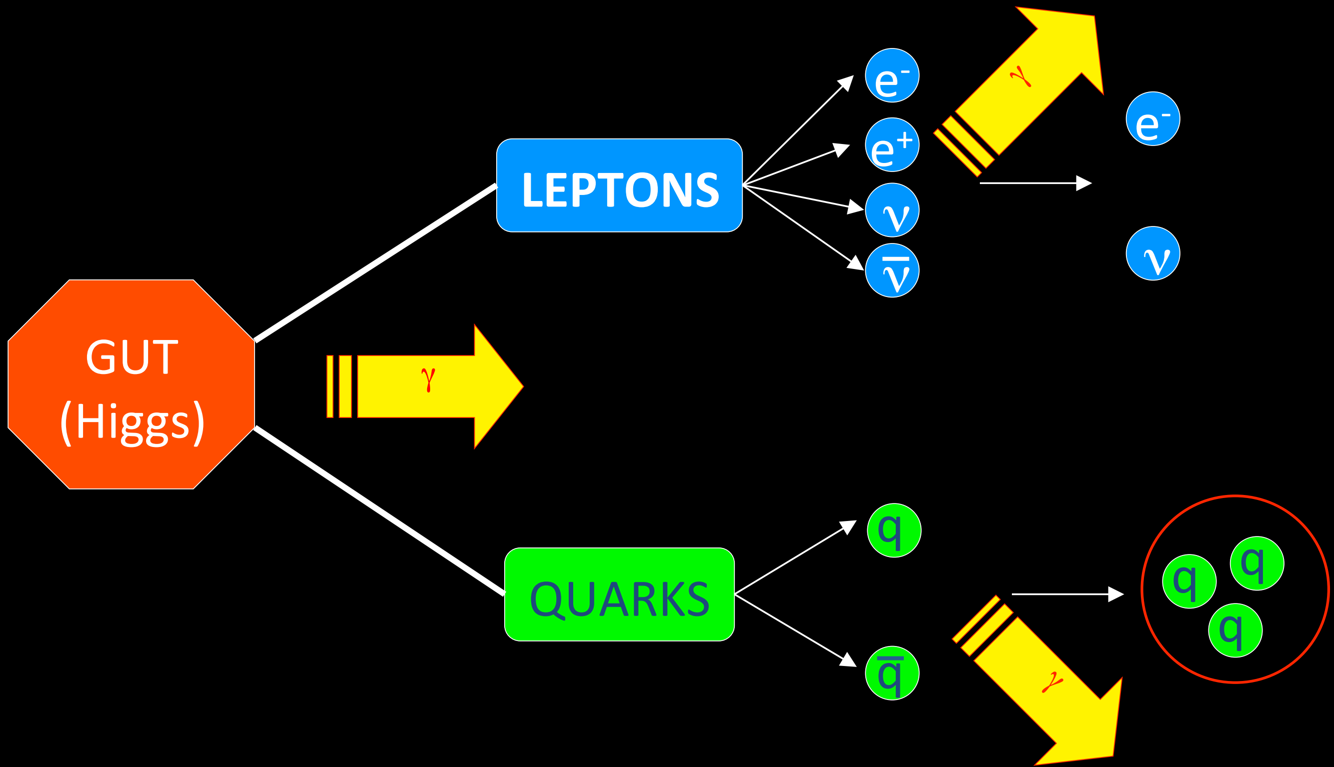
Structure of the Cosmic Microwave Background can constrain inflation

Post Inflation Universe

Post Inflationary Era = 10^{-34} s

Thermal Equilibrium in the Early Universe

- For any particle *X* of mass, *m*, there will be an epoch where $kT \sim mc^2$
- Creation of particle anti-particle pair creation becomes favourable
- For $kT > mc^2$: number of particles ~ number of photons
- For $kT < mc^2$: pairs can no longer be created ➜ annihilation & freeze out



The Quark Era

The Quark Era = 10^{-34} – 10^{-23} s 10^{22} K

- 10^{-34}s inflationary period ends
- Energy in inflation field released
- Universe reheats to 10^{22} K

The **primordial soup** in thermal equilibrium

- photons + free quarks, antiquarks, exchange particles

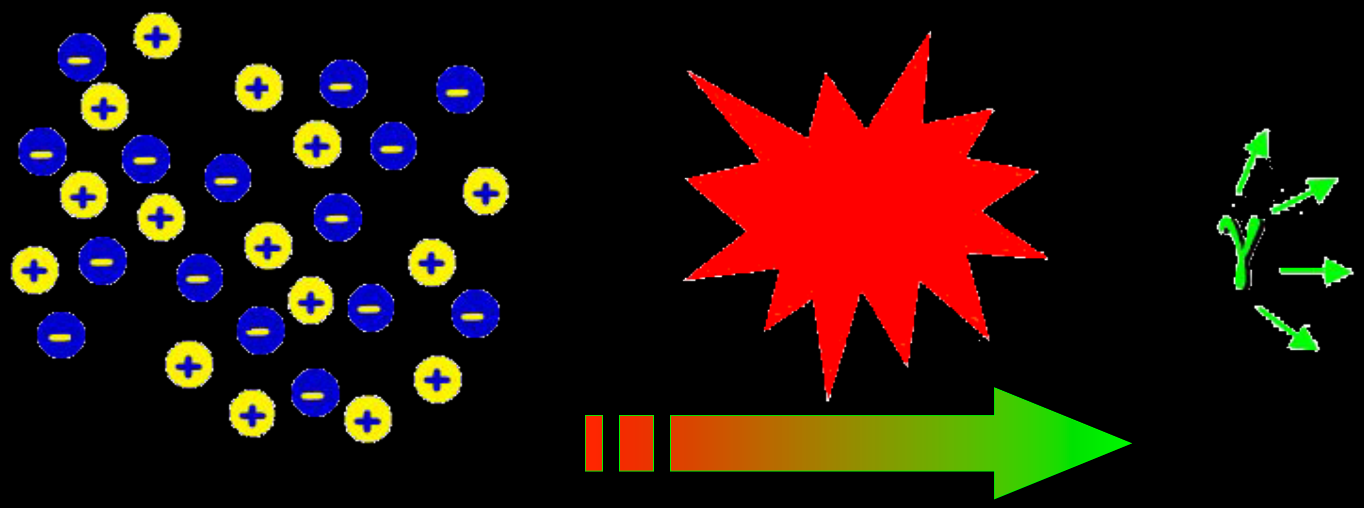
$$q + \overline{q} \leftrightarrow \gamma + \gamma$$

The Hadron Era

Electroweak symmetry breaking= 10^{-12} s 10^{15} K

- 10^{-12} s ElectroWeak Symmetry breaking (g, $W^{\pm}$, Z^0) ➡ E-M and Weak Nuclear Force
- 4 fundamental forces of nature now distinct
- Expansion of Universe cools Big Bang Fireball ~10^{13}K (10^{-6}s) ≡ 1GeV
- Quarks bond to form individual Baryons ➡ **Quark Confinement ➡ Baryogenesis**

1) Why are there so many photons in the Universe ?
2) Why is there no antimatter in the Universe ?



1) Photon Background produced from matter/antimatter annihilation

The Hadron Era

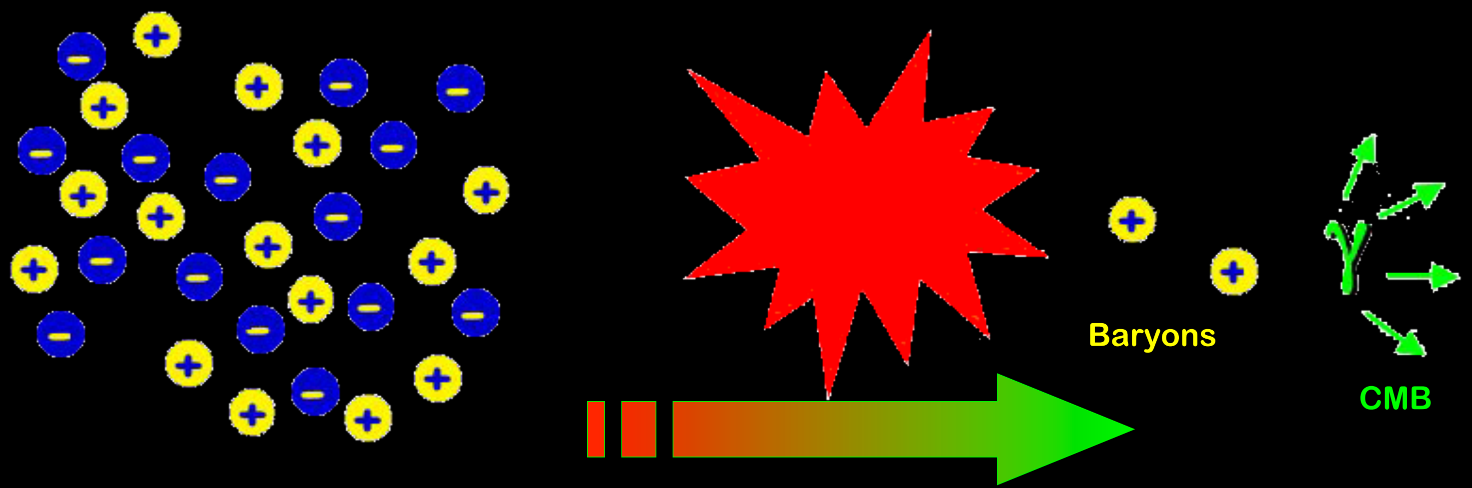
Matter Antimatter Asymmetry = 10^{-4} s 10^{12} K

Assume some tiny tiny asymmetry between quarks & anti quarks (matter & antimatter)

$$\delta_q = \frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}}$$

After matter & antimatter anihilation:
small excess of quarks remain

$$\delta_q \approx \frac{n_q}{n_g}$$



- How large is δ_q?
- From CMB and Ω_{baryon} estimate Baryon to photon ratio = *~10^{-10}*

The Lepton Era

Neutrino Decoupling = 1s 10^{10} K

- ~ equal numbers of γ, e, *n* in thermal equilibrium
- For every 10^9 photons, electrons, or neutrinos, ~ 1 proton or neutron exists
- T<~10^{10}K neutrinos decouple forming their own 'ghost Universe'
- T~10^9K electrons and positrons annihilate

•Universe gets extra source of photons (heating) which neutrinos never "see"

➠ neutrino background colder

Neutrino background ~ 1.4 Photon background

Big Bang Nucleosynthesis

The Neutron Proton ratio = 1-4 s 10^{10} K

- **After Hadron era - Neutrons & Protons (nucleons) present in equal numbers**
- $T \sim 9 \times 10^9 K >> m_e c^2 \Rightarrow e^- + e^+ \leftrightharpoons \gamma + \gamma$
- **Nucleons in thermal equilibrium with electrons and photons**

$$(1) \quad n \leftrightarrow p + e^- + \bar{\nu}_e$$

$$(2) \quad n + \nu_e \leftrightarrow p + e^-$$

$$(3) \quad n + e^+ \leftrightarrow p + \bar{\nu}_e$$

Neutron Decay Mode

Number densities of nucleons given by Maxwell-Boltzmann Distribution

$$\frac{N_n}{N_p} = e^{-\frac{Q}{kT}} = e^{-\frac{1.5 \times 10^{10}}{T}}$$

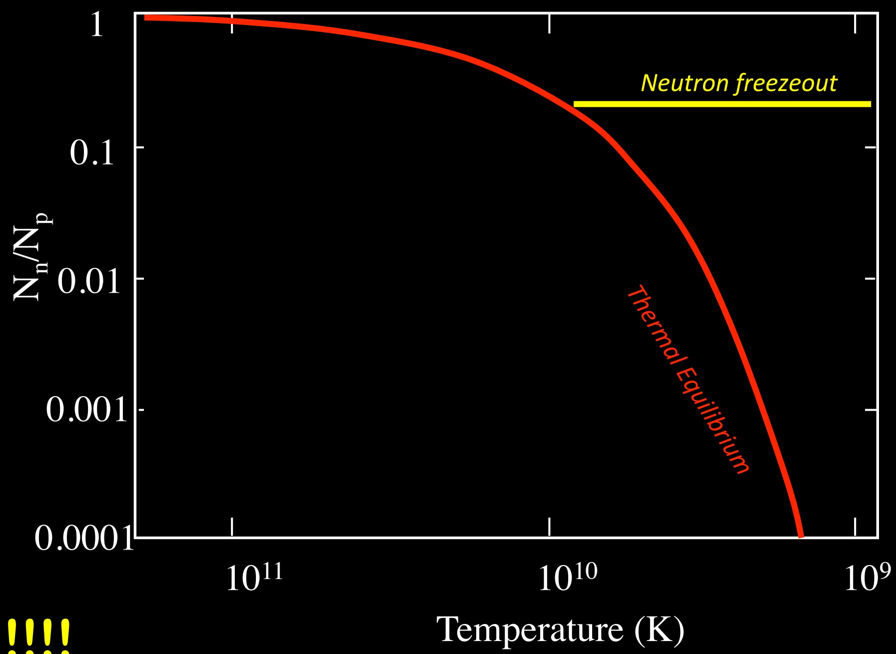
Neutron - Proton ratio is decided by the temperature

Big Bang Nucleosynthesis

The Neutron Proton ratio = 1-4 s 10^{10} K

- After Hadron era - Neutrons & Protons (nucleons) present in equal numbers
- T~10^{10}K neutrinos decouple from nucleons
- T~9×10^9K electrons and positrons annihilate $e^- + e^+ \rightarrow \gamma + \gamma$
- Small neutron mass difference ➡ reactions shift in favour of lighter Proton

$$\frac{N_n}{N_p} = e^{-\frac{1.5\times10^{10}}{9\times10^9}} \approx 0.2$$



Only neutron decay mode remains

$$N_n(t) = N_{no}e^{-t/\tau}$$

t ~16mins decay time of free neutron

Neutrons disappearing quickly !!!!

Big Bang Nucleosynthesis

Nucleosynthesis = 3 minutes 10^9 K

Onset of nucleosynthesis locks up all free neutrons in nuclei, halting the neutron decay

- Nucleosynthesis of the elements begins with Deuterium and ends with Helium (+ a little Lithium, Beryllium, Boron)
- Number densities too low to directly make $2p + 2n \rightarrow {}^4He$
- Sequence of 2 body reactions

FIRST STEP: Deuterium ^2H = D

$$n + p \Leftrightarrow D + \gamma$$

Deuterium binding energy low = $m_n+m_p+m_D$=2.22MeV → Immediately destroyed

Stability when $N_D \sim N_n$ → Temperature drops ~ *kT~0.07 = 7x10^{8}K*   *(t~200s)*

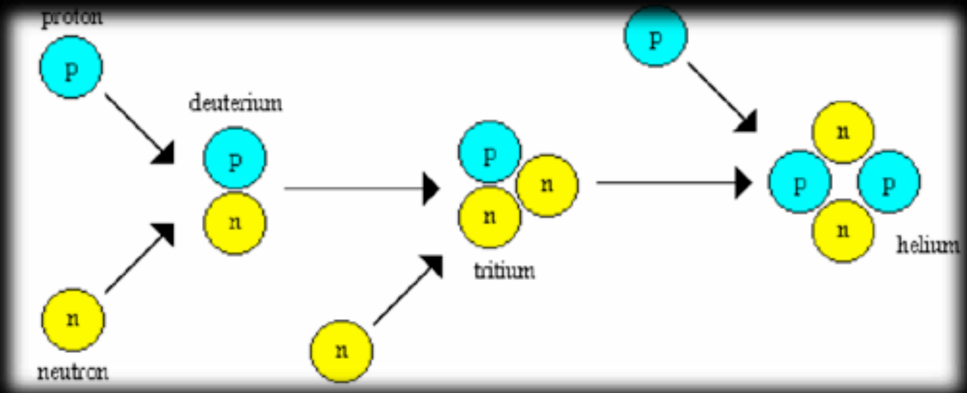
Neutron decay mode →N_n/N_p~0.16 (nucleosynthesis will be quite an inefficient process)

Big Bang Nucleosynthesis

Nucleosynthesis = 3 minutes 10^9 K

Onset of nucleosynthesis locks up all free neutrons in nuclei, halting the neutron decay

- Once significant Deuterium formed the heavier elements form very fast
- Reactions proceed quickly to Helium



Formation of Nuclei

$$n + p \rightarrow D + \gamma$$

$$D + n \rightarrow {}^3H + \gamma$$

$$D + p \rightarrow {}^3He + \gamma$$

$$D + D \rightarrow {}^3H + p$$

$$D + D \rightarrow {}^3He + n$$

$$D + D \rightarrow {}^4He + \gamma$$

$$^3H + p \rightarrow {}^4He + \gamma$$

$$^3He + n \rightarrow {}^4He + \gamma$$

$$^3H + D \rightarrow {}^4He + n$$

$$^3He + D \rightarrow {}^4He + p$$

Big Bang Nucleosynthesis

Nucleosynthesis = 3 minutes 10^9 K

Most of ^{3}H, ^{3}He gets locked up in ^{4}He - how about heavier elements ?

$$^4He + D \rightarrow {}^6Li + \gamma$$

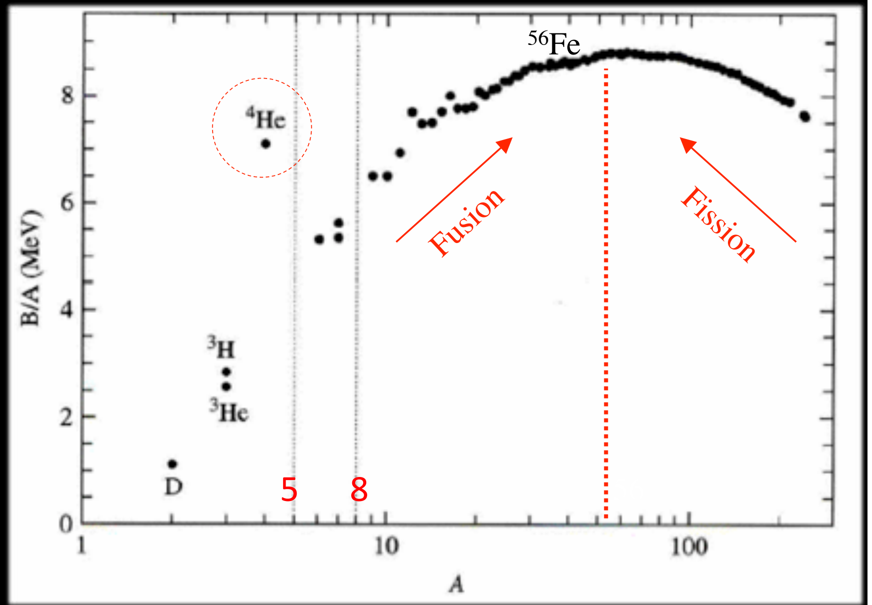
$$^4He + {}^3H \rightarrow {}^7Li + \gamma$$

$$^4He + {}^3He \rightarrow {}^7Be + \gamma$$

$$^4He + {}^4He \rightarrow {}^8Be$$

$$^8Be \rightarrow \text{(unstable)}$$

$$\rightarrow {}^4He + {}^4He \quad (t \sim 3\times10^{-16}\,s)$$



- Decrease in binding energy beyond Iron as the nucleus gets bigger, strong force loses to electrostatic force.
- Maximum binding energy at iron ➠ means that elements lighter than Iron release energy when fused.
- Elements heavier than iron only release energy when split
- Peaks in binding energy at 4,16 & 24 nucleons from the stability of ^{4}He combination of 2 protons/neutrons

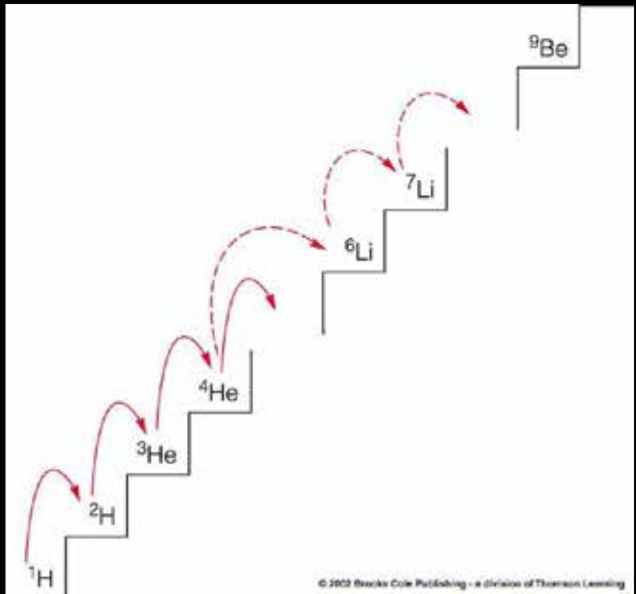
• No stable nuclei with atomic number 5 or 8

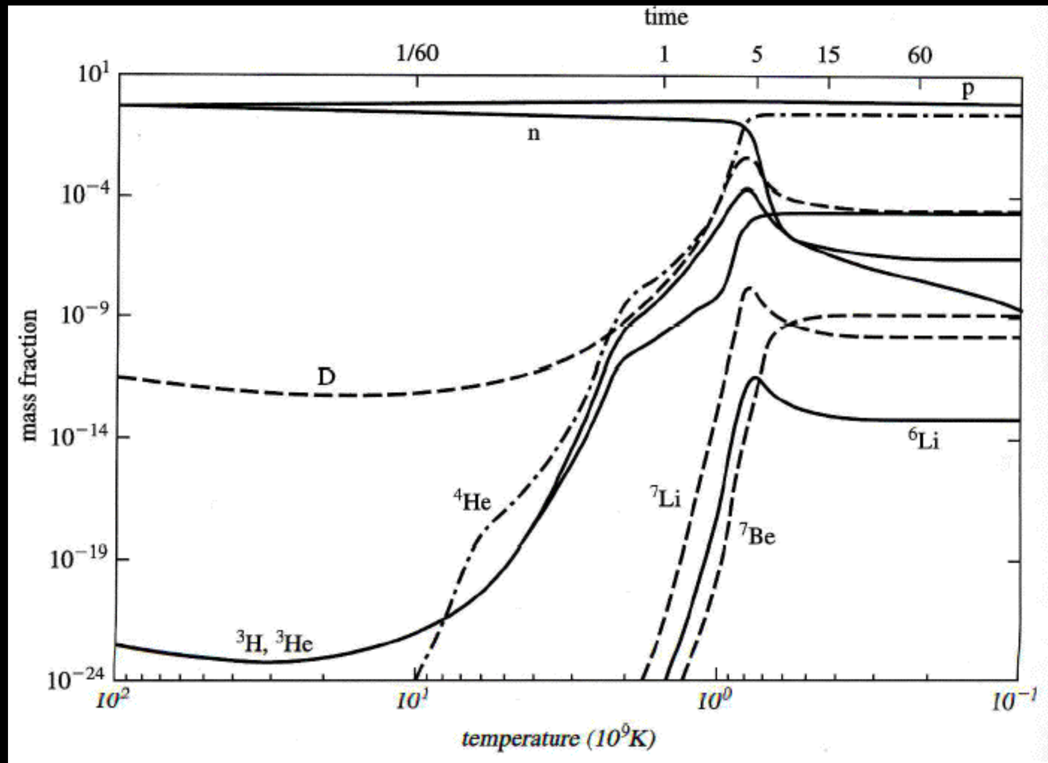
• Unusually large binding energy of Helium

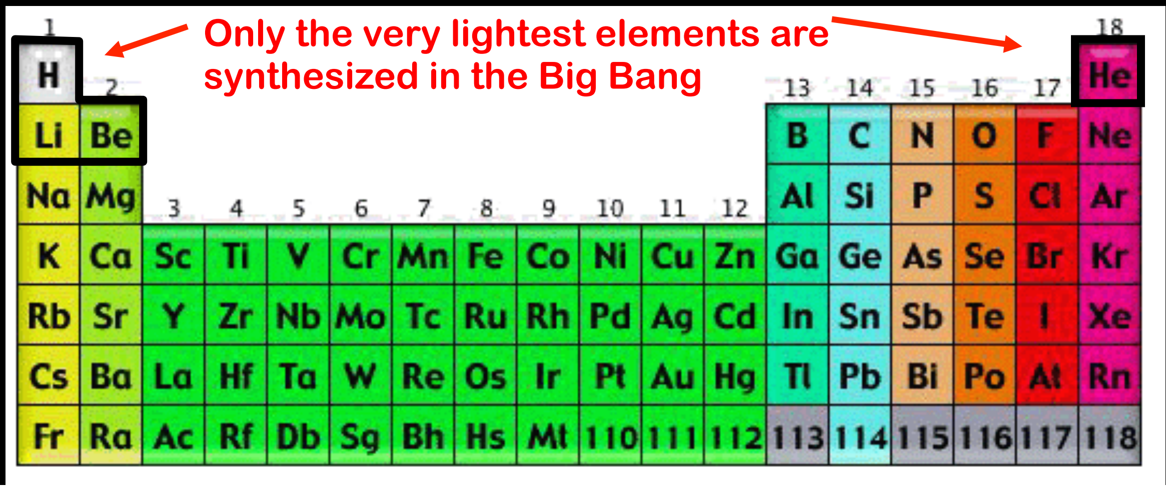
Universe runs out of steam production *ceases* with Helium

Big Bang Nucleosynthesis

Nucleosynthesis = 3 minutes 10^9 K







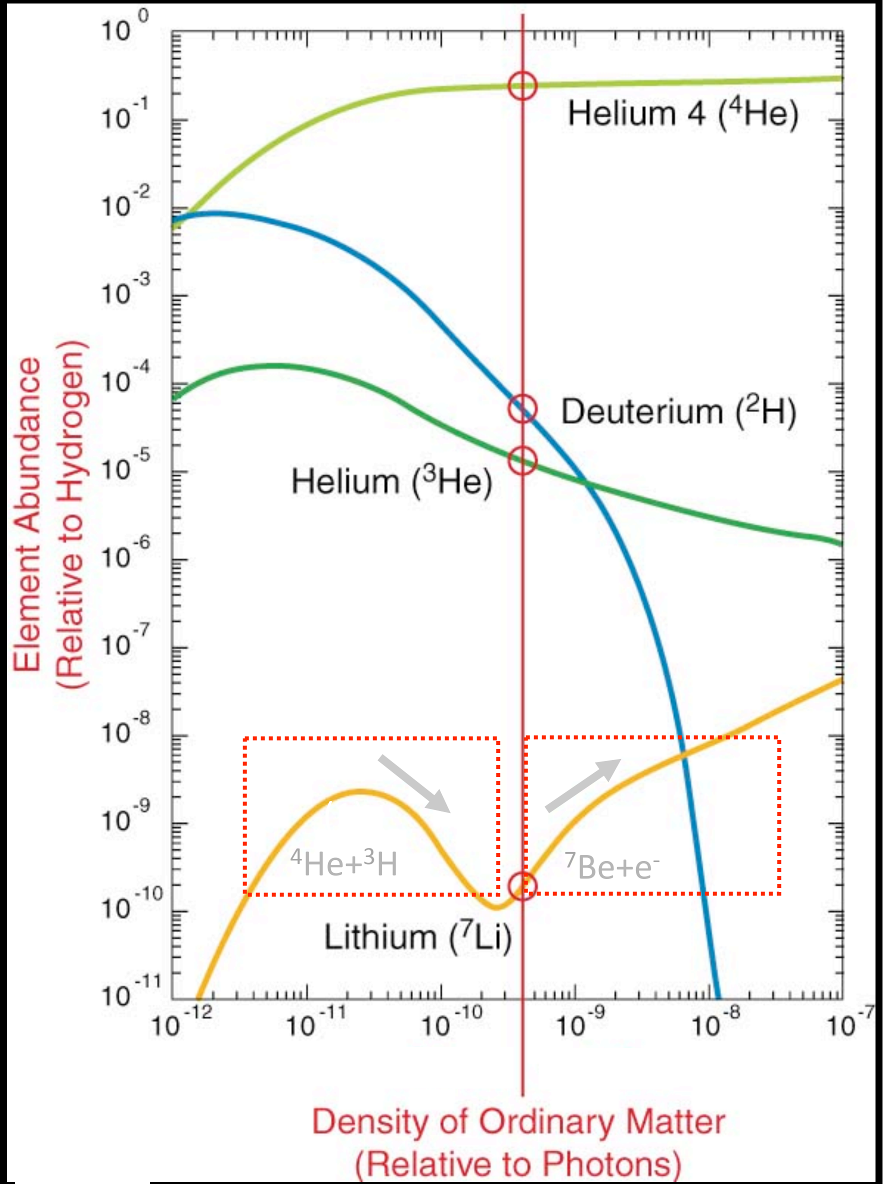
Everything Else is made in Stars 10^7-10^8 yrs later

Big Bang Nucleosynthesis

Nucleosynthesis = 3 minutes 10^9 K

Abundance depends on Baryon photon ratio (η)

- High η ➟ higher density
- ➟ nucleosynthesis starts earlier (higher T)
- Helium production more efficient
- Less D & ^{3}He leftover



Mass fraction of He
~ N_n/N_p~0.16 ➟ ~6 protons for every neutron

So for 2n + 2p ➟ ^{4}He ➟ 10 protons leftover ➟ H

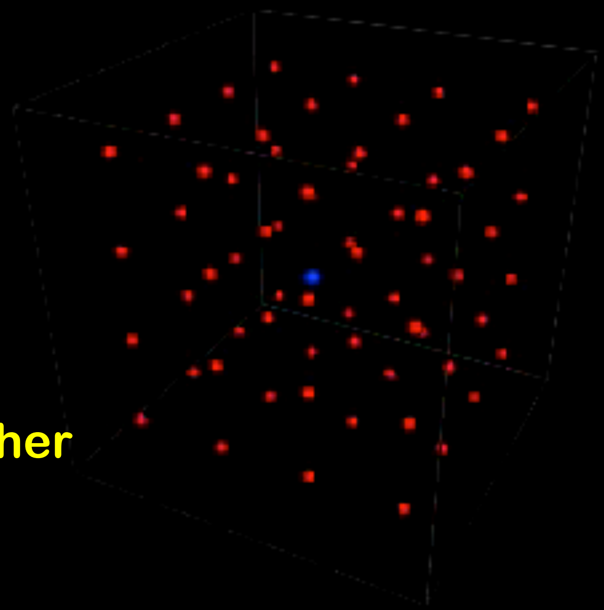
Maximum allowed mass fraction He

$$\frac{4x(\text{number He nuclei})}{4x(\text{number He nuclei})+(\text{number H nuclei})}=\frac{4}{4+10}= \mathbf{28\%}$$

The Radiation Era

Recombination = 380,000 years 3000 K

- Temperature 3000° K, electrons captured by protons to form hydrogen atoms
- Electrons no longer scatter photons
- Radiation decouples from matter
- Universe becomes transparent to radiation
- Fireball that flooded expanding universe for first 10^6 years appears as CBR

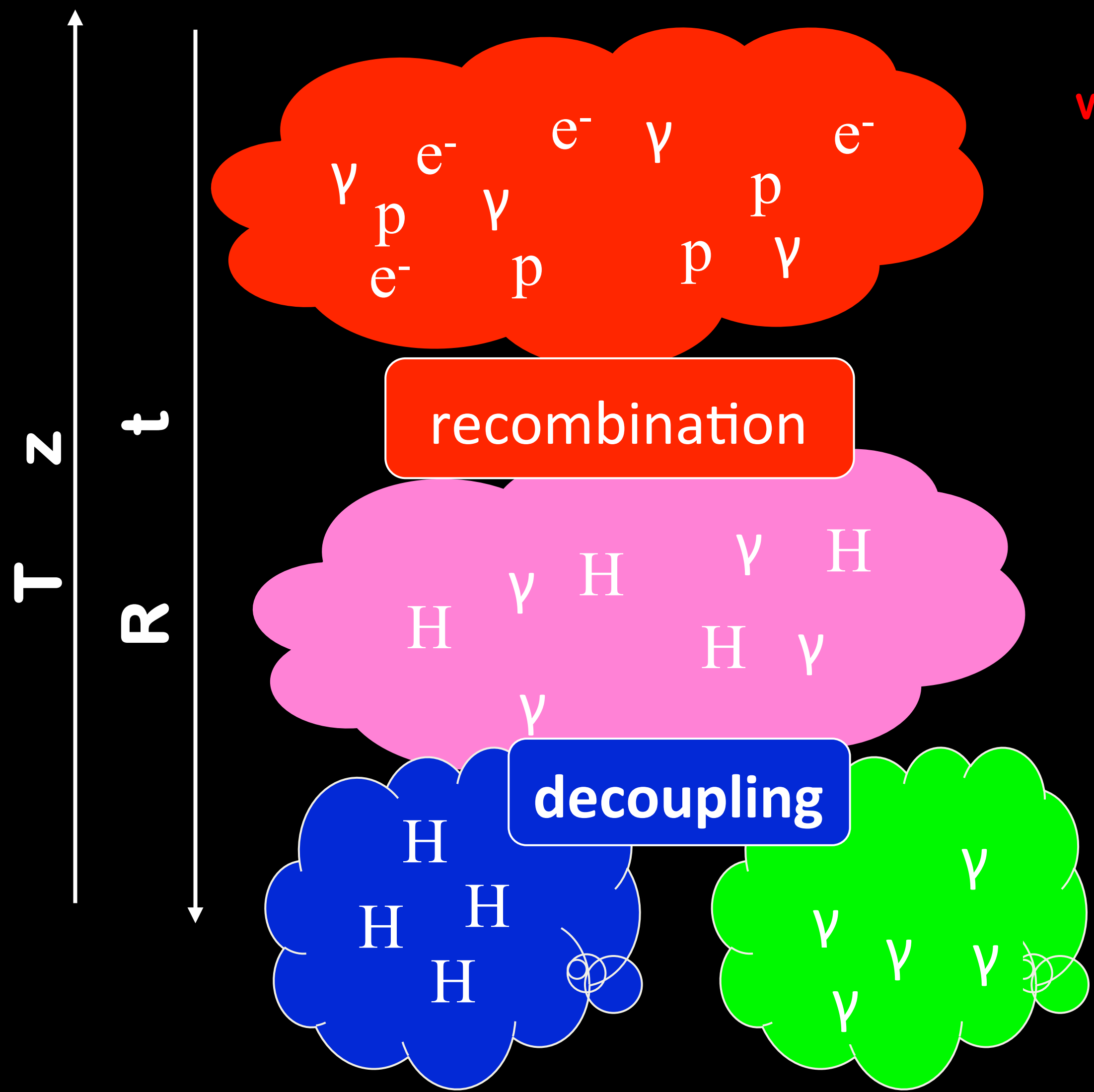


Before Recombination photon mean free path is very short

Radiation and matter are thermally bound together

The Radiation Era

Decoupling and Recombination = 380,000 years 3000 K



matter in thermal equilibrium with the radiation. photons and electrons to interact via Thompson scattering

Temperature drops
$p+e^- \Longrightarrow H$ ➠ *recombination*

Eventually interactions stop, allowing the photons to flow freely on scales of the horizon ➠ *de-coupling*

The Radiation Era

Decoupling and Recombination = 380,000 years 3000 K

Redshift of Recombination / Decoupling

~ z=1089 over redshift shell dz=195

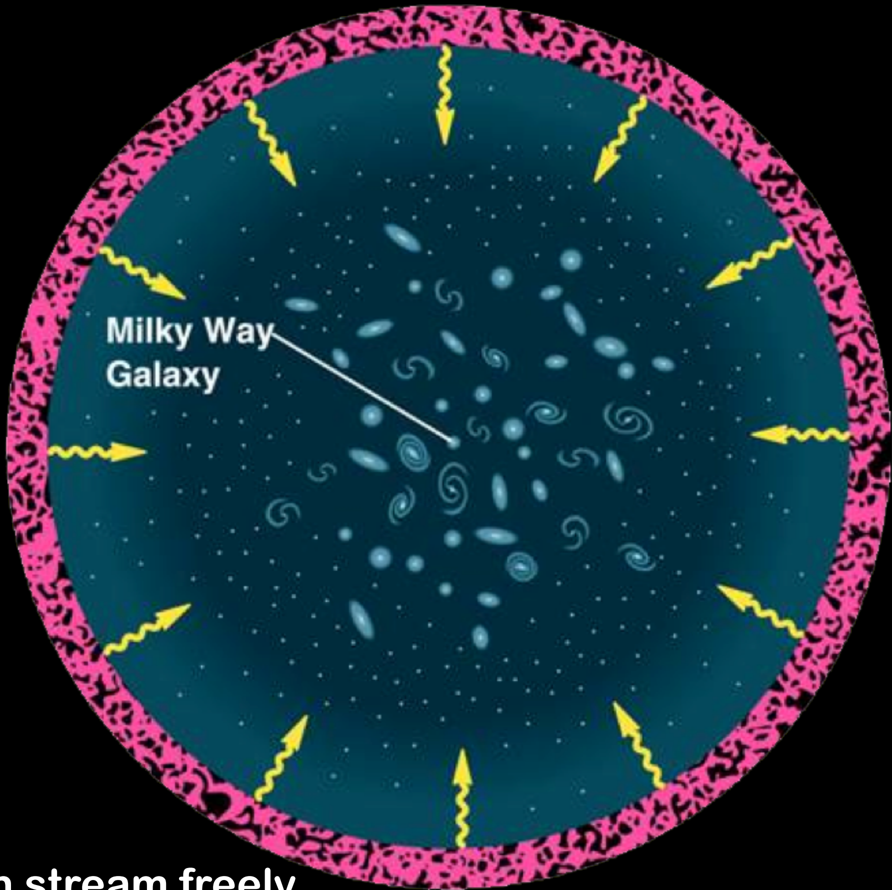
380,000 years after Big Bang over a time scale of ~ 118,000yr

After Recombination and Decoupling

- Photons no longer bound to matter and can stream freely
- Photons from Big Bang fill the universe observed as the 2.7K microwave background.
- The redshifted relic or ashes of the Big Bang
- Last time photons interacted ➠ ***SURFACE OF LAST SCATTERING***
- Means that we can not observe the Universe when it was younger than ~400,000 years

The Radiation Era

Decoupling and Recombination = 380,000 years 3000 K



After Recombination and Decoupling

- **Photons no longer bound to matter and can stream freely**
- **Photons from Big Bang fill the universe observed as the 2.7K microwave background.**
- **The redshifted relic or ashes of the Big Bang**
- **Last time photons interacted ➟ *SURFACE OF LAST SCATTERING***
- **Means that we can not observe the Universe when it was younger than ~400,000 years**

The Matter Era

The Dark Ages = < 10^6 years 300 K

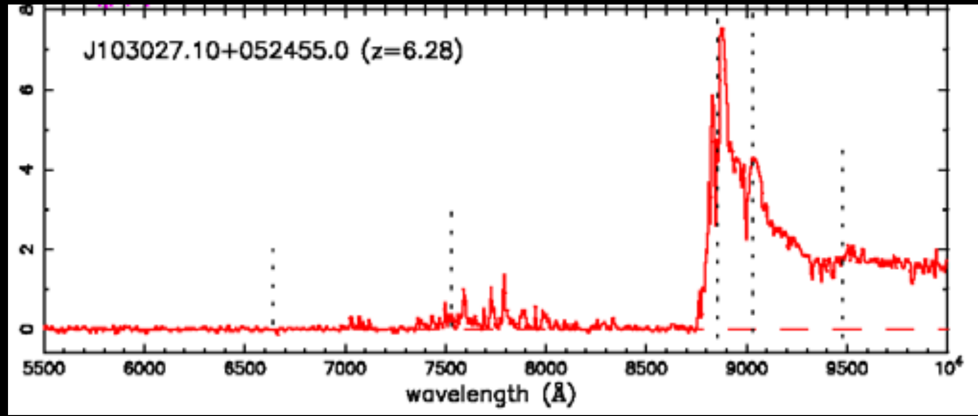
• Before Recombination - Radiation coupled to matter ➠ Matter cannot cluster
• After recombination, radiation no longer influences the distribution of matter.
• Matter can cluster and collapse around density enhancements
• Form the structures of galaxies and clusters of galaxies we observe today

•Universe <10^6 years old
- Universe filled with neutral Hydrogen with density 1 H-atom/cm^3
- No galaxies existed prior to 10^6 years …….. The Dark Ages

The Matter Era

Reionization = 150 million years 300 K

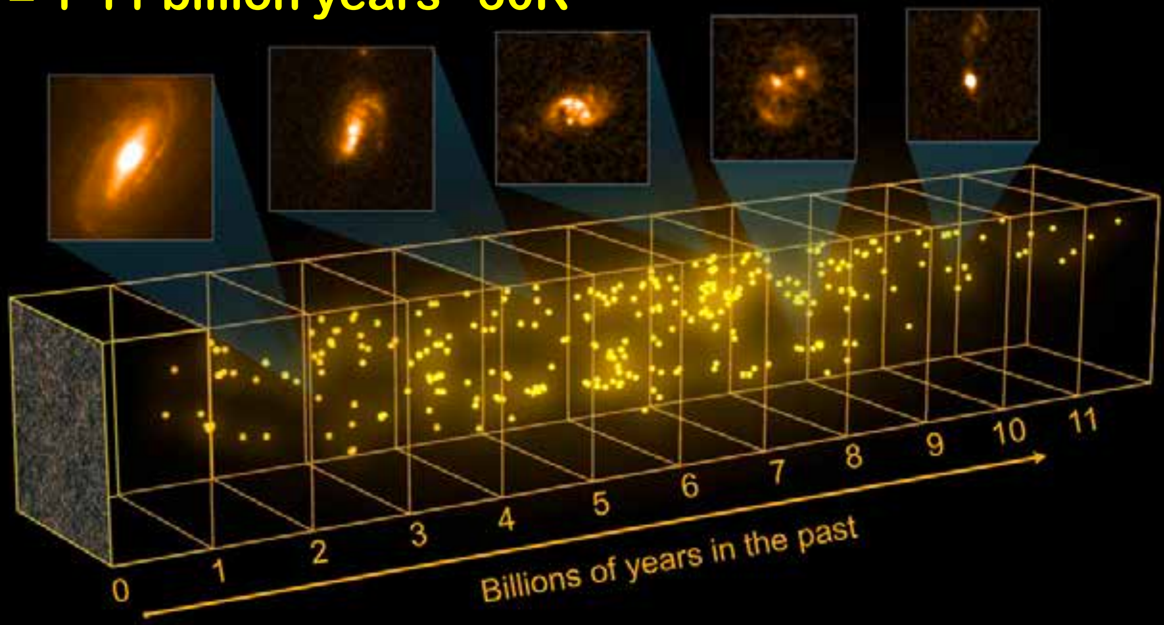
- First light in the Universe
- The first stars and quasars turn on
- Reionize the neutral Hydrogen
- Redshifts 10 ~ 6

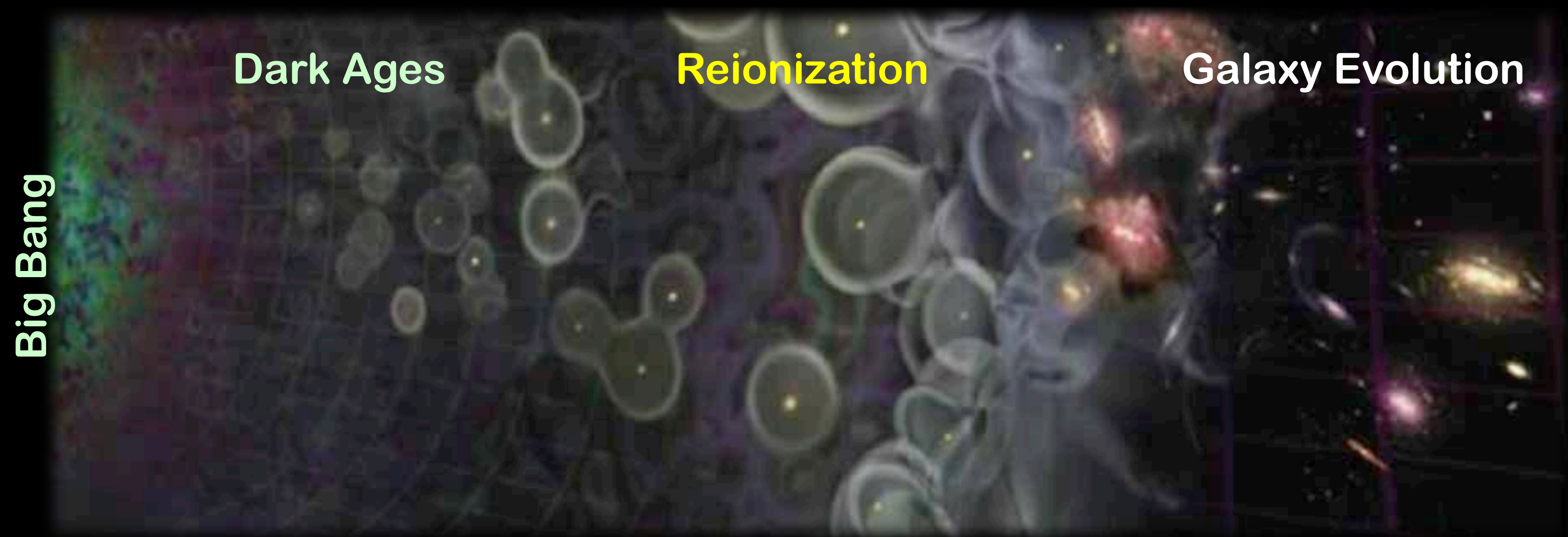


The Matter Era

The formation of structure = 1-11 billion years 30K

- Galaxies evolving
- Stars forming

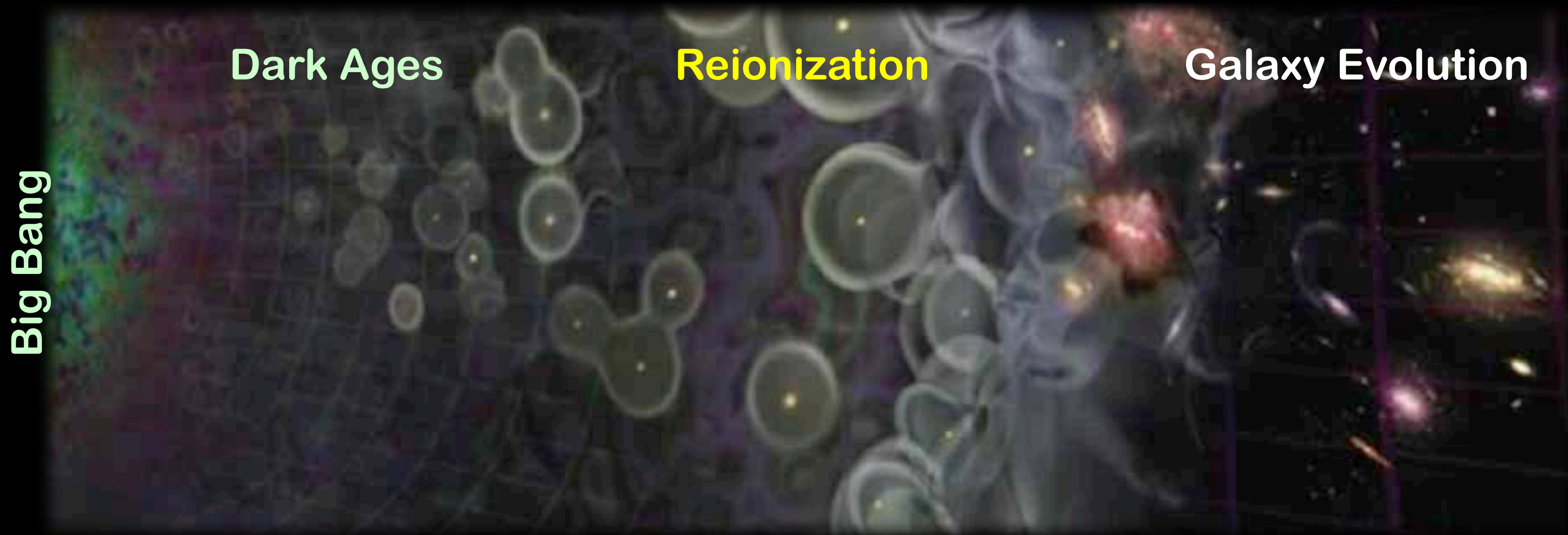




The Matter Era

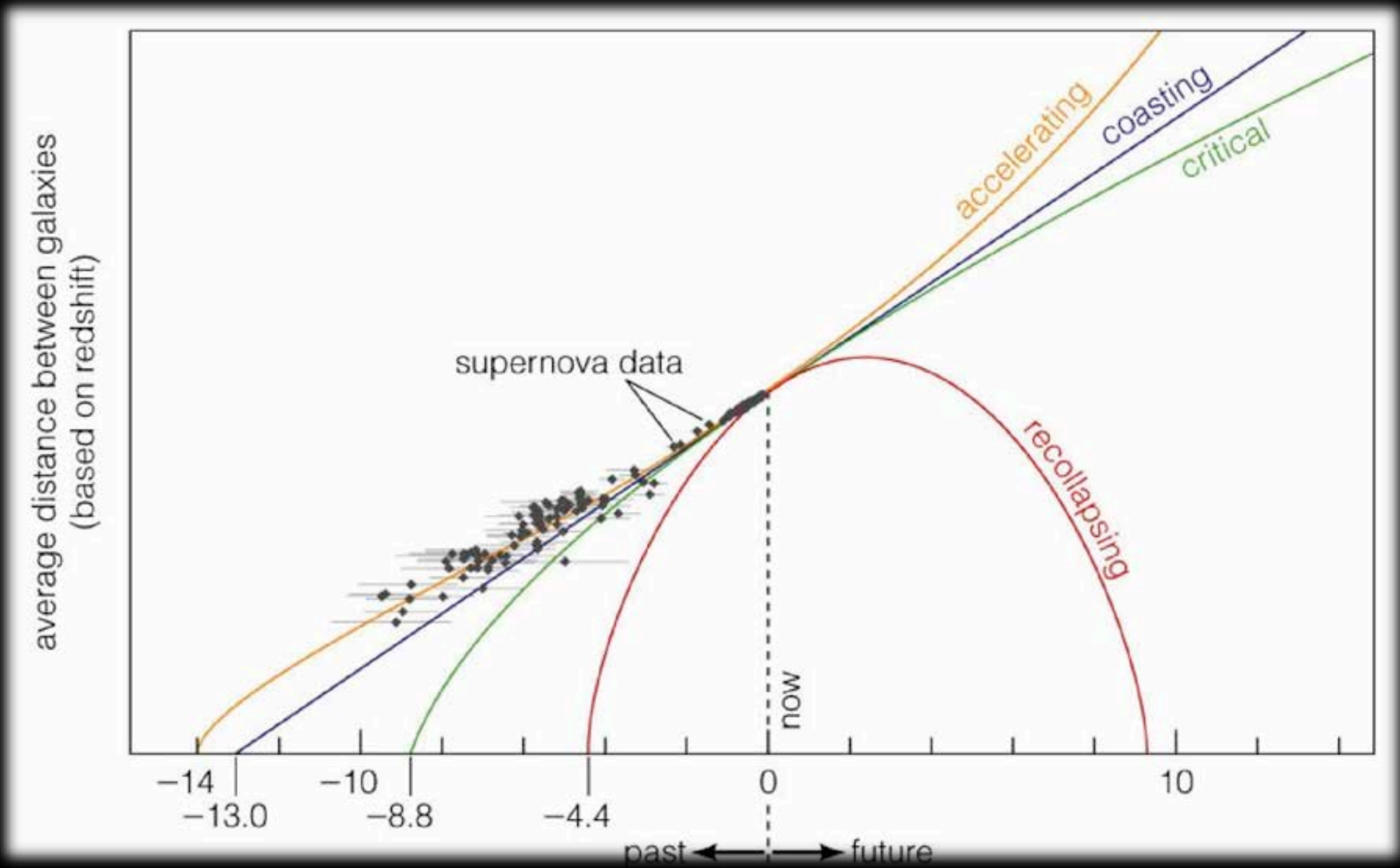
The Present era = 13.8 billion years   2.7K

- 13.8 billion years after big bang
- Density 1 H-atom/m^3
- ~10^{80} particles in observable universe
- 10^9 photons and neutrinos for each baryon
- Galaxies exist in billions; stars forming everywhere
- CBR has redshift of 1000 and temperature of 2.7 K



The Acceleration Era

The Universe starts to accelerate = 10 billion years (redshift ~4)



The Undiscovered Country

The The Fate of the Universe

- **STELLAR ERA:**
  - Energy of the Universe from thermonuclear fusion in Stars.
  - Stellar era lasts until the last stars have used up their fuel.
  - ~10^{14}yrs for 0.1M_o Red Dwarf

- **DEGENERATE ERA:**
  - All stars in the form of stellar remnants
  - white dwarfs / neutron stars / black holes.
  - Eventually all stars become black dwarves. Galaxies dissolve

- **BLACK HOLE ERA:**
  - Proton decays with lifetime of 10^{30}yrs.
  - Only organized units are black holes.
  - Black Holes evaporate via Hawking Radiation over 10^{100} yr for galactic sized systems.
  - Universe becomes a cold photon sea Heat Death

- **DARK ERA:**
  - Universe consists of leptons + photons - ultimate disorder.
  - Cools to vacuum energy state

The End ?

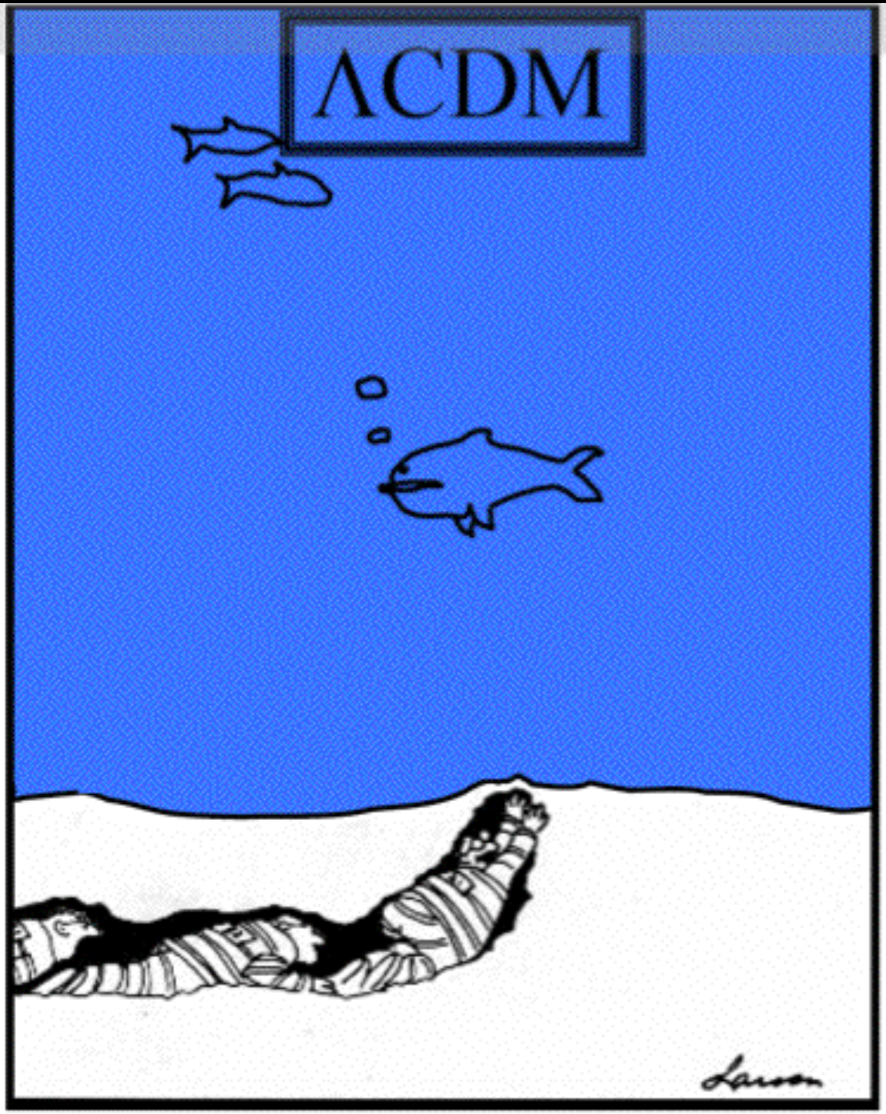
Followed the evolution of the Universe from the Big Bang to the present and beyond
The farthest back we can observe is the surface of last scattering

At times prior to this our evidence is indirect
- Early Universe must consider Particle Physics
- $T \rightarrow 0$ a Quantum Theory of Gravity

- However the Big Bang Theory has had great success in predicting fine details of
    - The expanding Universe
    - Primordial Nucleosynthesis and the light element abundances
    - The Relic Radiation from the fireball
    - The beginning of structure formation

- However… there are still many unsolved problems with this Standard Model

Just when you thought it was safe …



We're almost free, I just felt the first drops of rain