# AST 1430
# Cosmology

## VI
## Inflation

"Once, about 13.8 billion years ago, the universe began… It started cranking along and expanding in a fairly ordinary way, except that everywhere you look there [were] insanely high densities and energies. Then, around $10^{-36}$ seconds later something unexpected happened. In a tiny fraction of a second, the universe inflated to something like $10^{100}$ times its original size and then just as suddenly continued with its ordinary expansion as though nothing had happened."

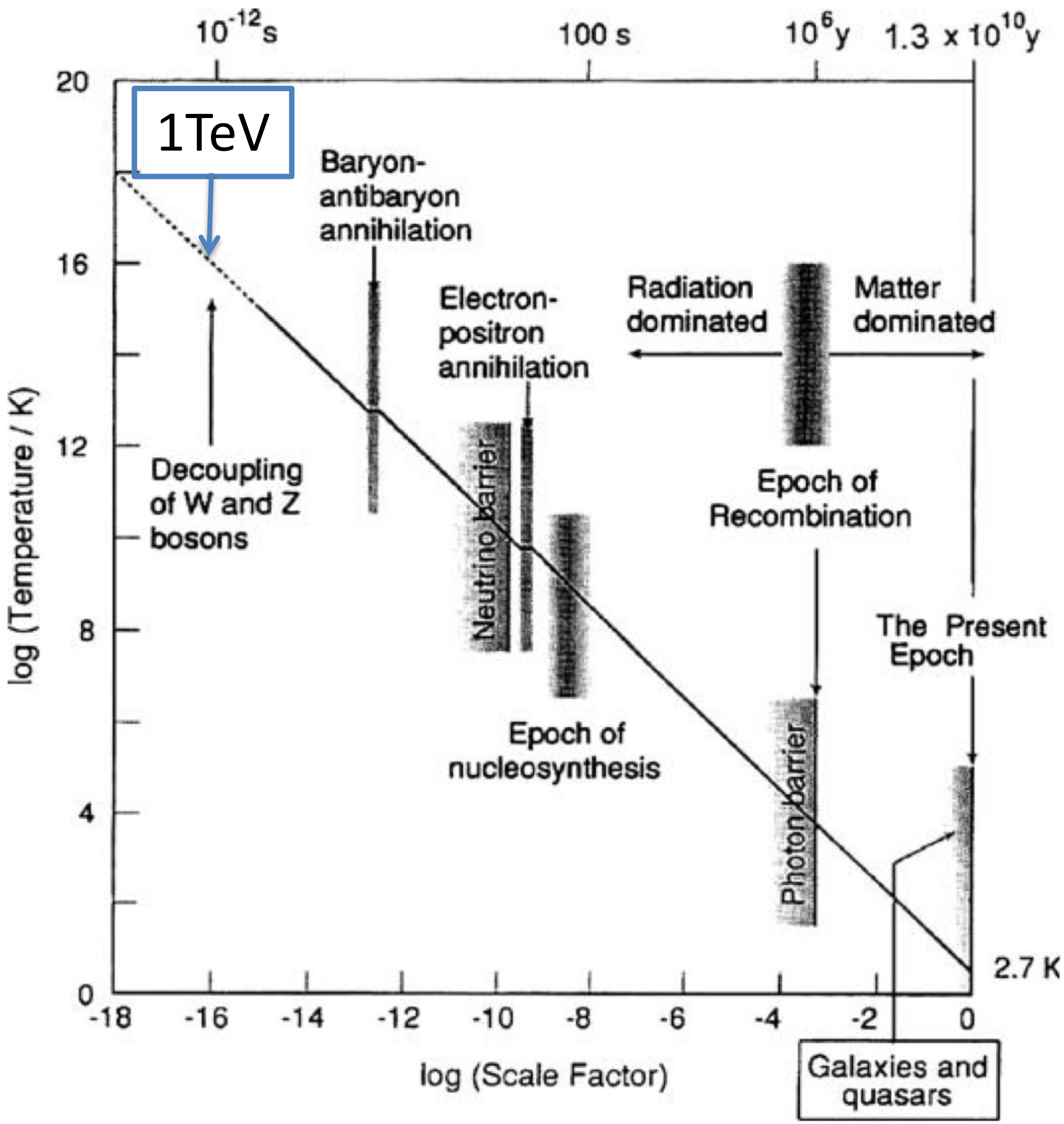
– Dave Goldberg, *Ask a Physicist*

# Announcements

- Venue: back to AB88 for the rest of Feb
- Presentations
  - Feb 15: Anika – Baryogenesis
  - Feb 15: Caleb – CMB B-modes
  - Feb 17: Braden – ??
  - Feb 17: Anna – ??

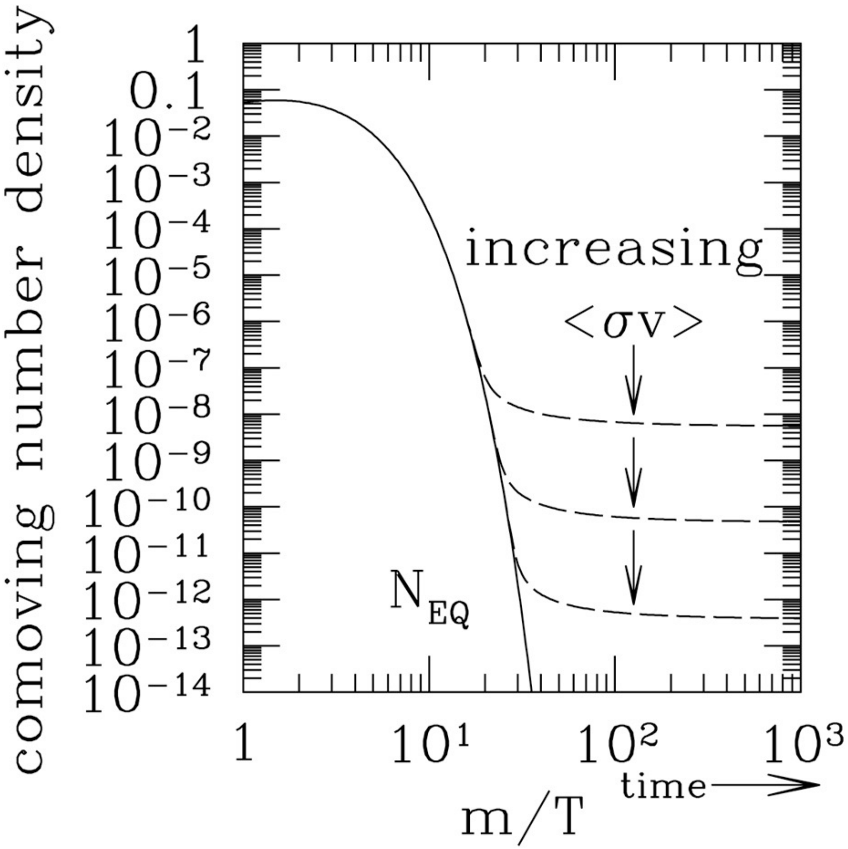
| | Week Index | Dates | Topics | |
|---|---|---|---|---|
| | ~~Week 1~~ | ~~Jan 11, 13~~ | ~~logistics, introduction, basic observations~~ | |
| | ~~Week 2~~ | ~~Jan 18, 20~~ | ~~Basic GR, RW metric, Distances, coordinates, Friedmann equations, cosmological models~~ | |
| | ~~Week 3~~ | ~~Jan 25, 27~~ | ~~Consistency with observations, Early Hot Universe,~~ BBN | asst1 |
| Keith | Week 4 | Feb 1, 3 | Inflation, Perturbations & Structure pre-recombination | |
| | Week 5 | Feb 8, 10 | CMB: basics, polarization, secondaries | |
| | Week 6 | Feb 15, 17 | Early-Universe Presentations + Review | |
| | | | Reading Week – No Class | asst2 |
| | Week 7 | Mar 1, 3 | Post-recombination growth of structure, formation of dark matter halos, halo mass function | |
| | Week 8 | Mar 8, 10 | The relation between dark matter halos and galaxies | |
| | Week 9 | Mar 15, 17 | Probing the cosmic density field / clustering | |
| Jo | Week 10 | Mar 22, 24 | Late-time cosmological observations: BAO, supernovae, weak lensing, etc. | asst3 |
| | Week 11 | Mar 29, 31 | H0 controversy: how fast exactly is the Universe expanding today? | |
| | Week 12 | Apr 5 | Late Universe Presentations + Review | |

# Life in the Early Universe



# Pre-BBN

## Neutron *n*(T)




$n_N$ / $n_P$ frozen when neutrinos decouple @1s

## Deuterium Bottleneck

p + n ⇔ $^2$D + $\gamma$

B ≈ 2.2MeV, so at early times (T > $10^9$K, t < 100s), $^2$D rapidly photo-dissociate.

*(Think: Saha, recombination)*

From freeze-out (1s) to ≈100s, neutrons decay, $\tau$ ≈ 890s.

# BBN Summary

- Neutrons in thermal equilibrium until neutrinos freeze out, t≈1s.
- Nucleosynthesis stalled by Deuterium bottleneck until t≈100s.

    → Timescale set by $\eta = n_b / n_\gamma$
- ~All remaining neutrons get sucked up into $^4He$.
- Small quantities of $^2H$, $^3He$, $^7Li$ remain.
- Nothing heavier has time to fuse.

BBN is a race against time. The conditions are only "right" briefly.
Before 100s, too hot, dense, irradiated. After 15min, too cold, diffuse.

# Y vs Parameters (I)

Fundamental constants

Higher neutron $\Gamma$
→ later freeze-out
→ fewer neutrons
→ smaller Y

Larger $\Delta m = m_n - m_p$
→ fewer neutrons
→ smaller Y

Composition of the Universe

→ Only weak dependence on the various $\Omega_i$.
→ Comes in through $\eta = n_b / n_\gamma$
→ Larger $\eta$ = shorter bottleneck
→ Less neutron decay = larger Y

# $^2H$ and $^3He$

Produced on the path to $^4He$.

$$p + n \Leftrightarrow {}^2D + \gamma$$

$$^2D + {}^2D \Leftrightarrow {}^3He + n$$

Final abundances depend on $\eta$ (i.e., $\Omega_b$)

Larger $\Omega_b$
→ shorter bottleneck
→ higher $^2H$ and $^3He$ reaction rate
→ more $^4He$
→ as a fraction, *less* $^2D$ and $^3He$

# Lithium

$$^{3}T + {}^{4}He \Leftrightarrow {}^{7}Li$$

$$^{3}He + {}^{4}He \Leftrightarrow {}^{7}Be + \gamma \Leftrightarrow {}^{7}Li + e^{+}$$

Small quantity of $^{7}Li$ directly synthesized, mostly destroyed by free p.

Small quantity of unstable $^{7}Be$ is produced, decays later ($\tau \approx 50$ days).

Larger $\Omega_b$
→ shorter bottleneck
→ higher $^{2}H$ and $^{3}He$ reaction rate
→ more $^{4}He$
→ more $^{7}Li$

Smaller $\Omega_b$
→ longer bottleneck
→ less $^{2}H$ and $^{3}He$ reaction
→ higher $^{2}H$ and $^{3}He$ density
→ more $^{7}Li$

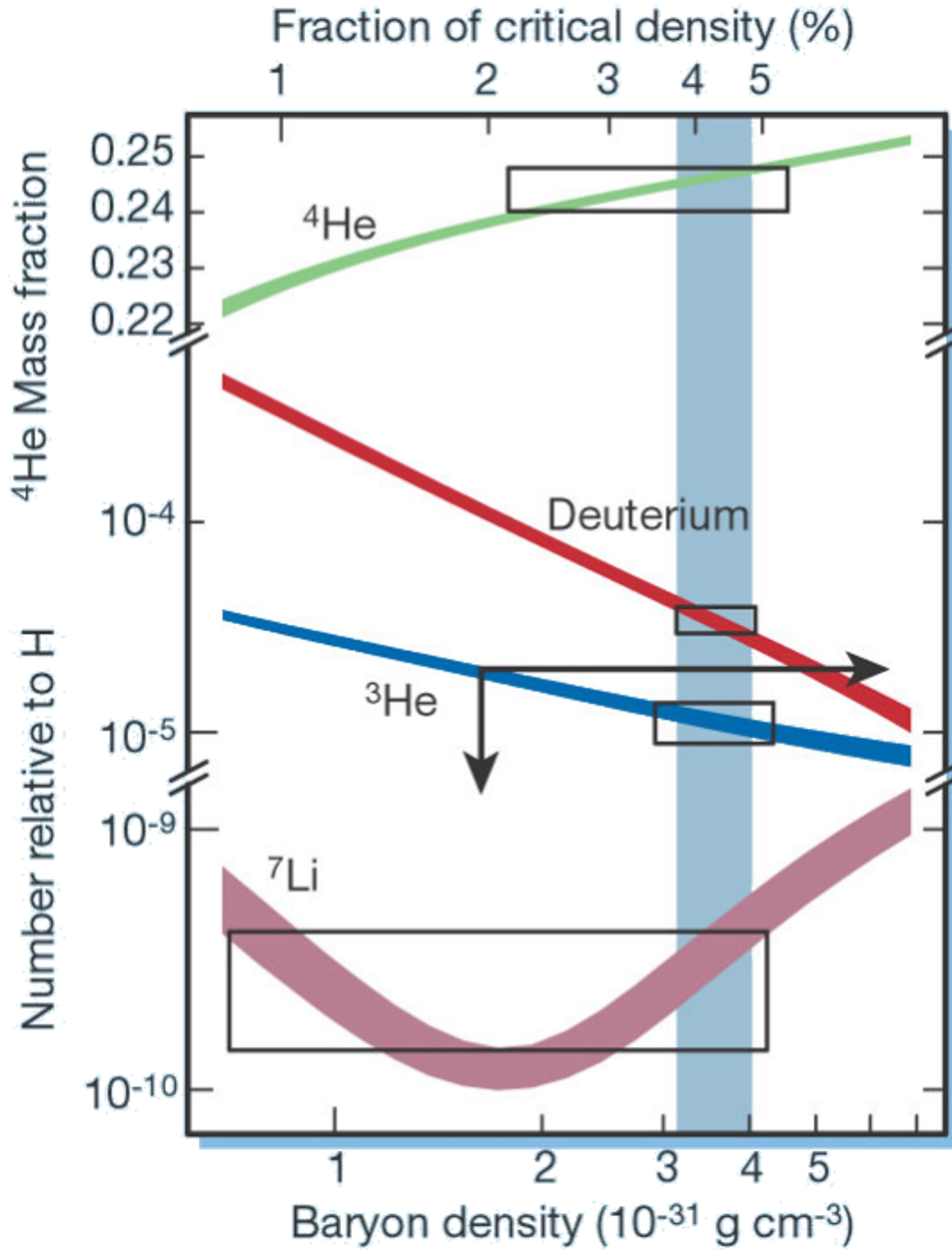
# Final Abundances

Helium is extremely stable compared to other light isotopes.

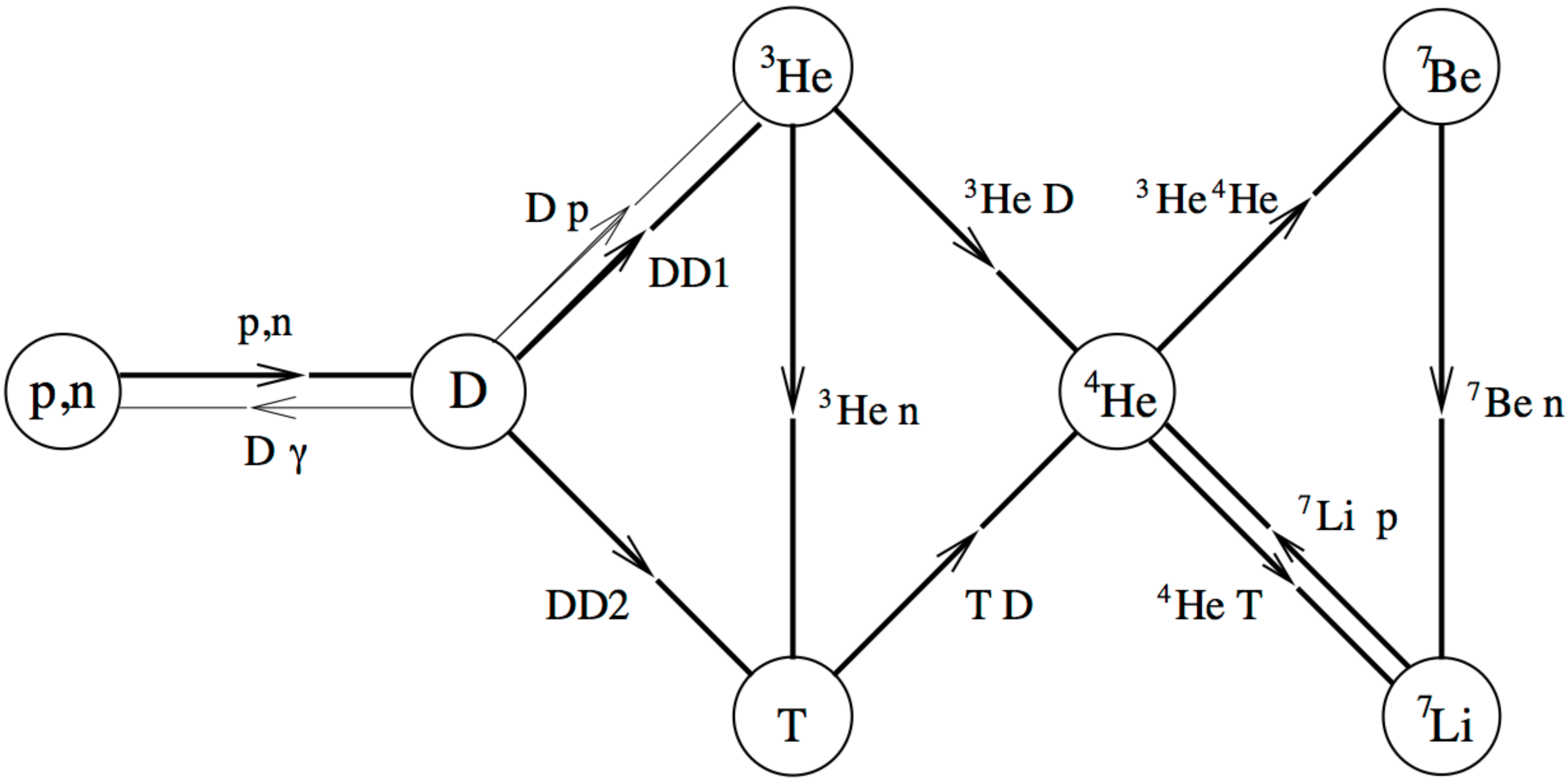
No stable isotopes at A=5, 8.

Triple-alpha rate is too low
$^4He + ^4He + ^4He \Leftrightarrow ^{12}C$

→ Nothing heavy produced before the Universe cools

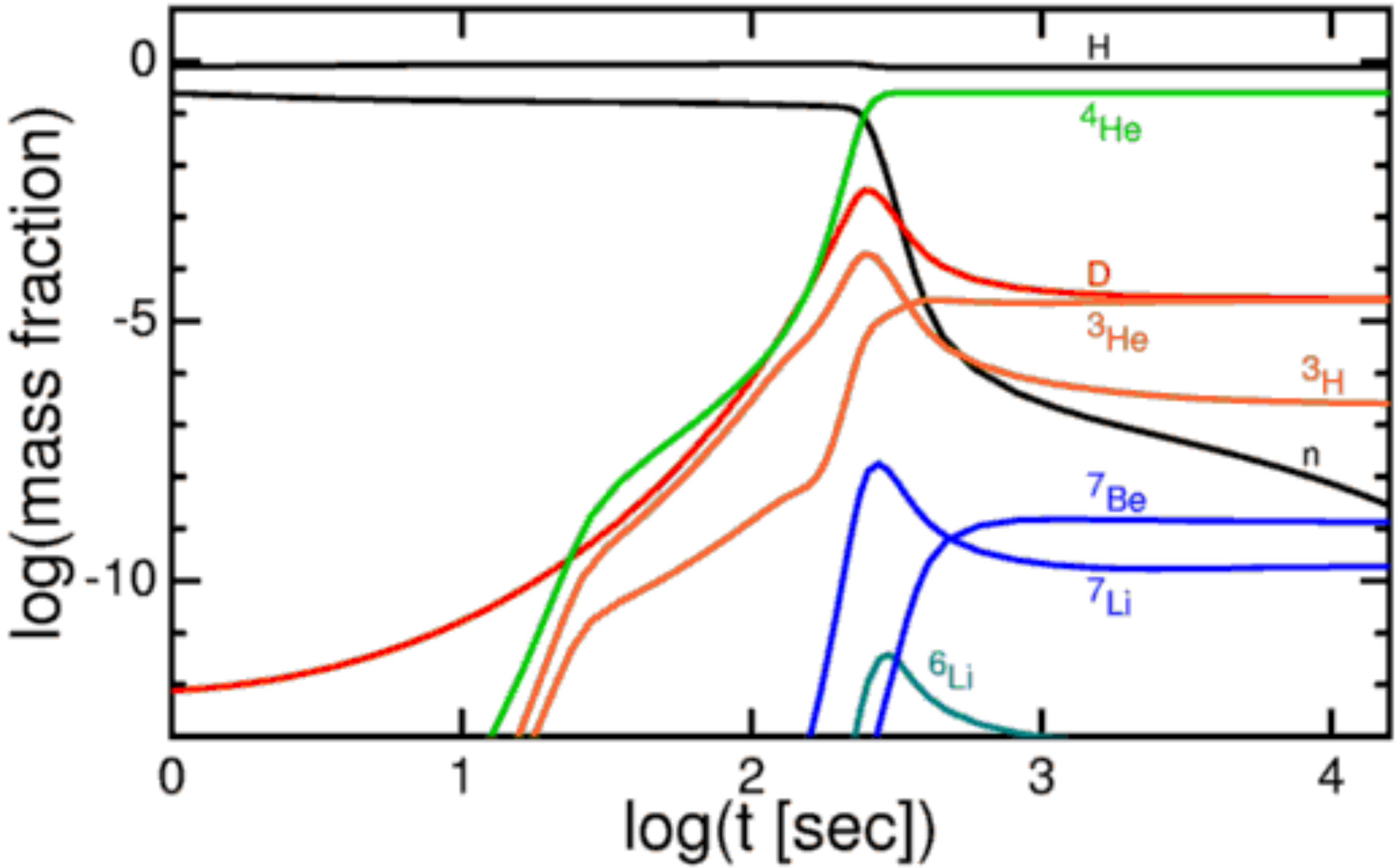


# Pathways

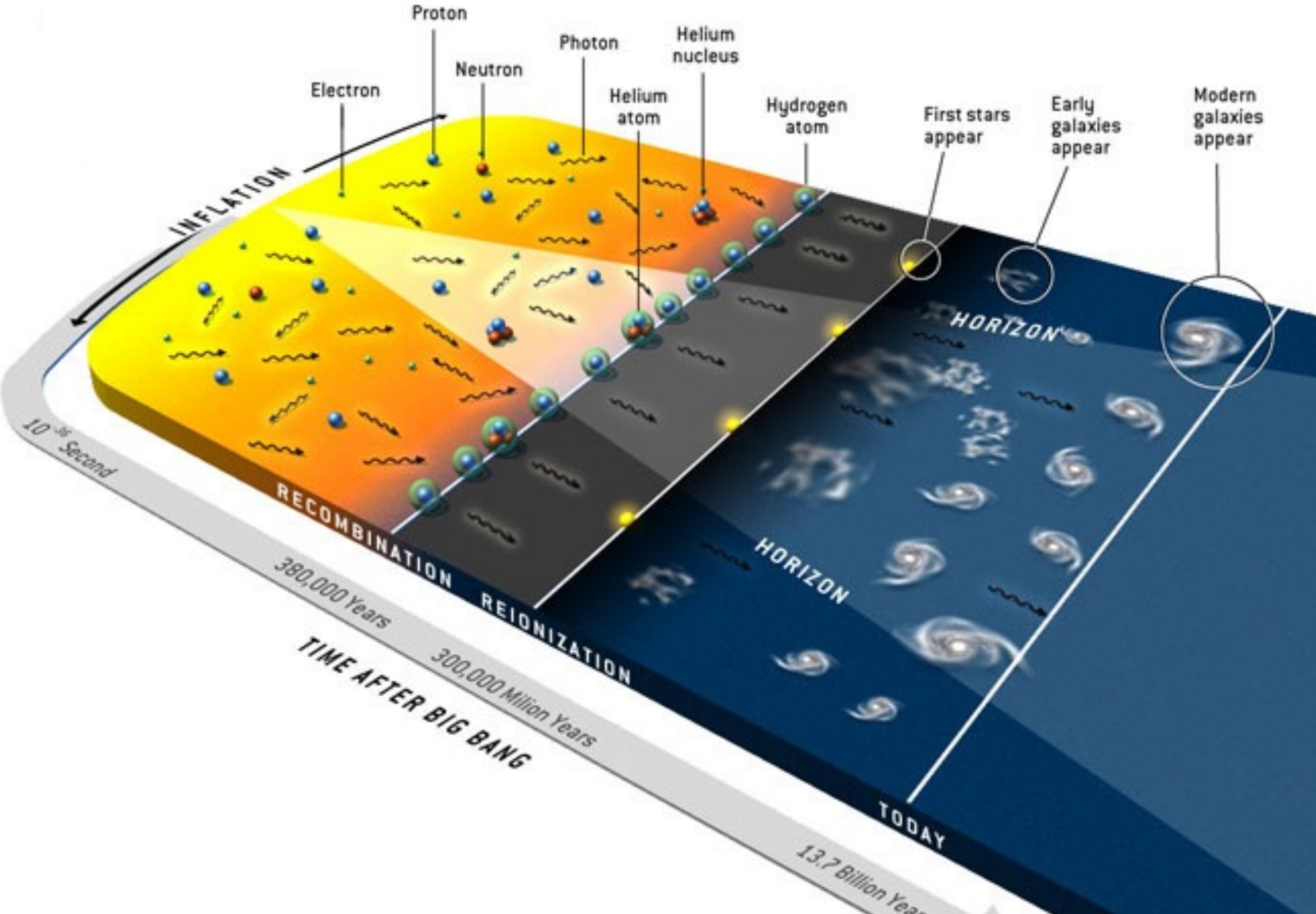


p,n
D
$^3$He
T
$^4$He
$^7$Be
$^7$Li
p,n
D γ
D p
DD1
DD2
$^3$He n
$^3$He D
T D
$^3$He $^4$He
$^4$He T
$^7$Li p
$^7$Be n

# BBN Timeline

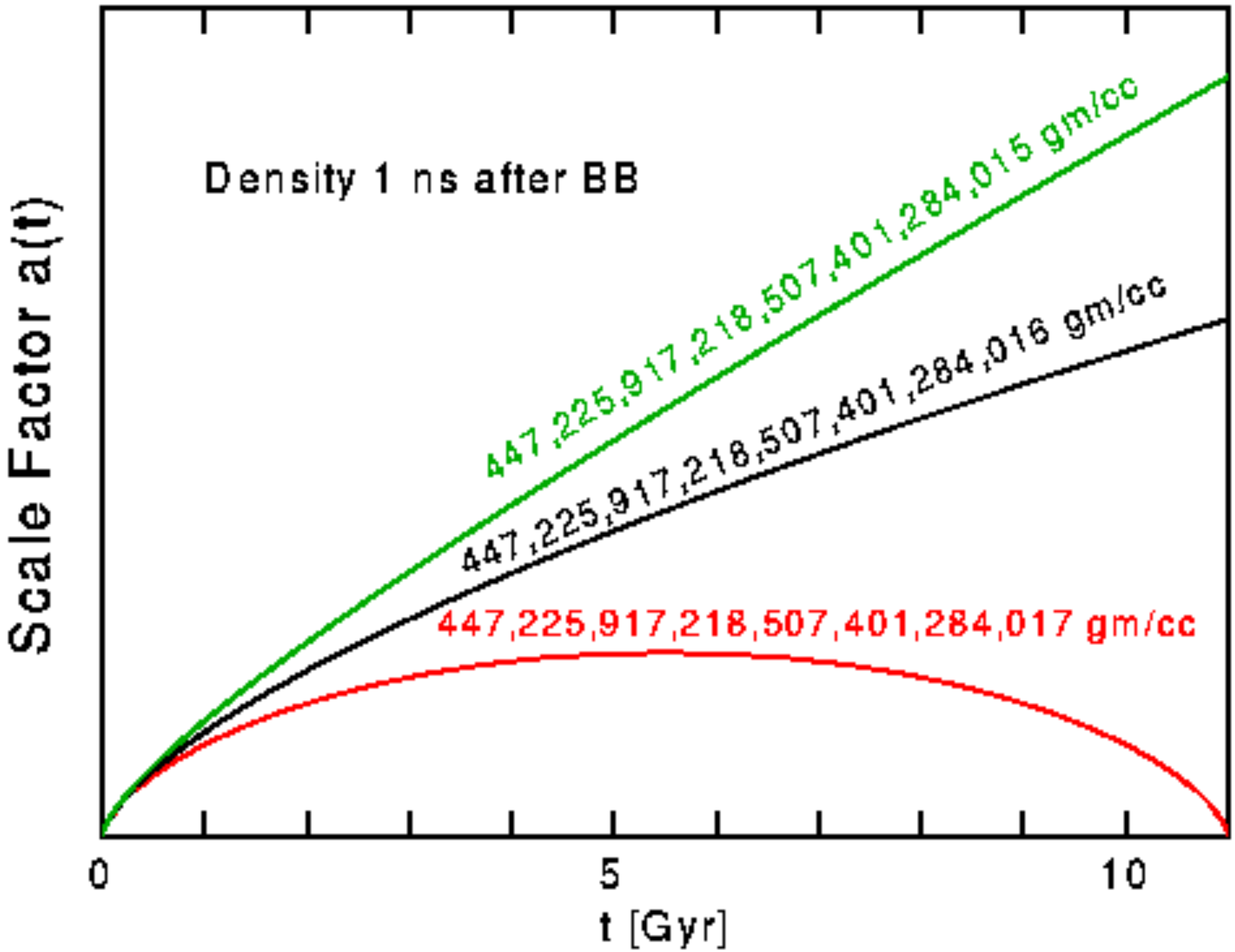


# Context Reminder




Hu & White, Scientific American, 2004

# Problem #1 Flatness



# Flatness

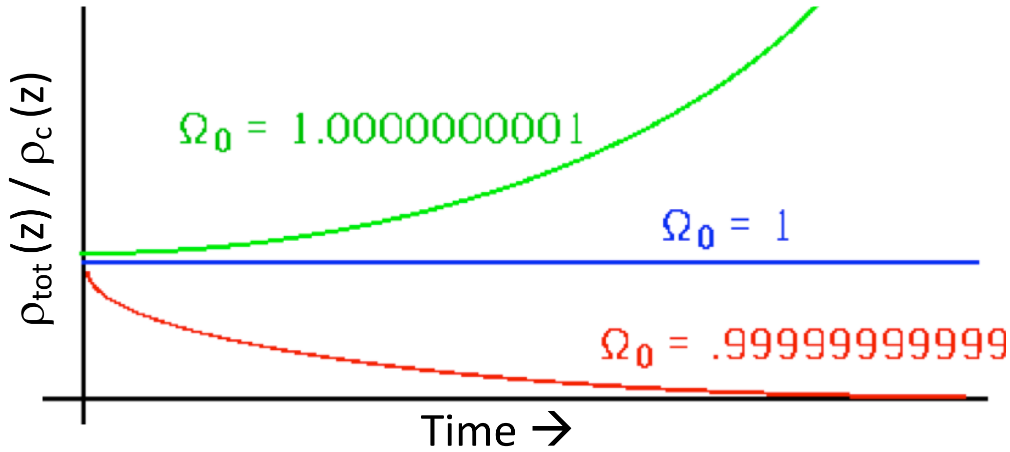
$$H^2 = H_0^2(\Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda)$$

Radiation-dominated:

$\rho_\kappa(t) / \rho_c(t) \propto a^2 \propto t$

Matter-dominated:

$\rho_\kappa(t) / \rho_c(t) \propto a \propto t^{2/3}$




$\Omega_{tot} = \rho / \rho_c \approx 1 \pm 0.2$

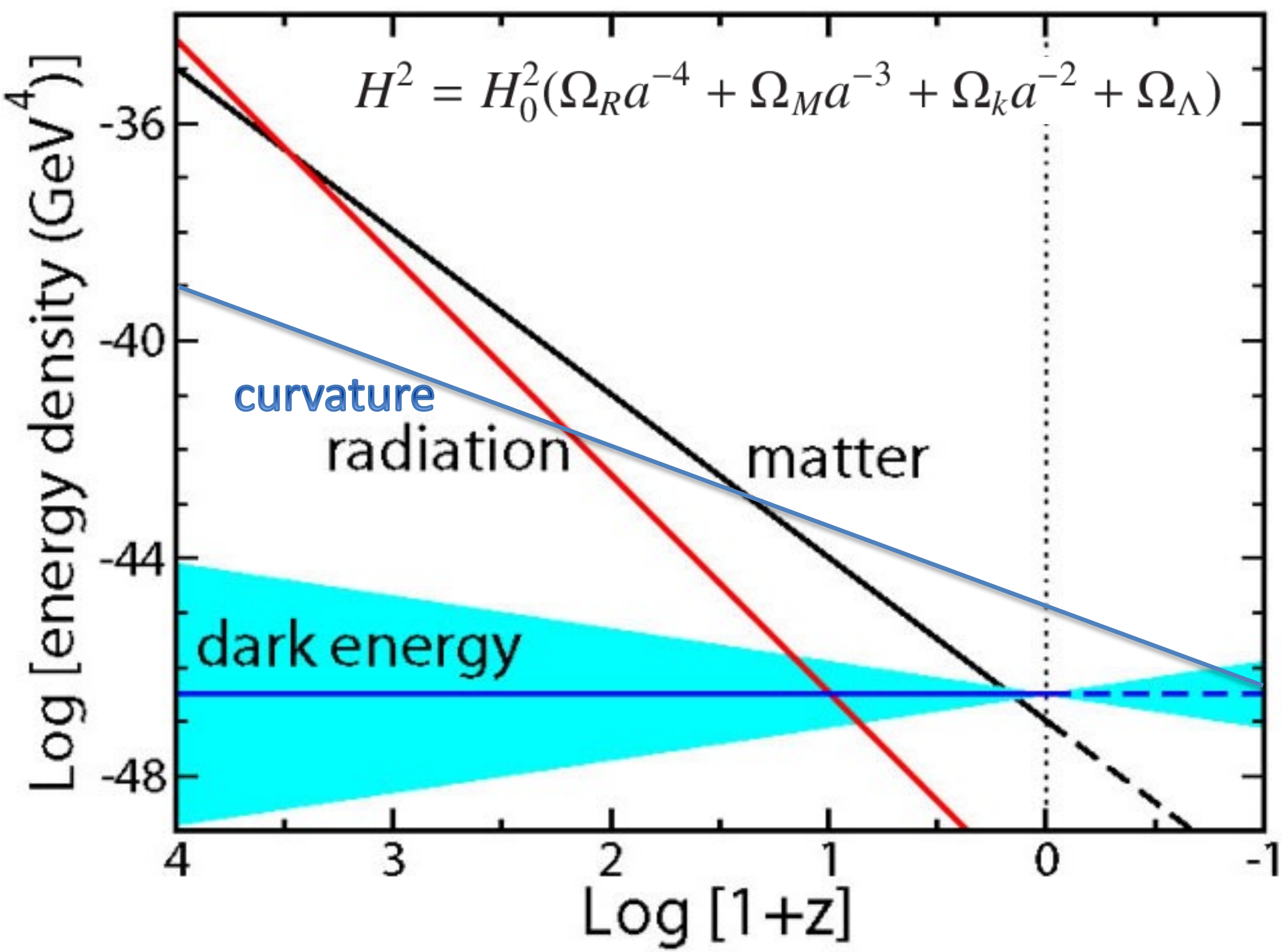
→ During BBN ($t \approx$ 5min)

$\rho / \rho_c \approx 1 \pm 10^{-14}$

→ At a the Planck time, $5 \times 10^{-44}$s

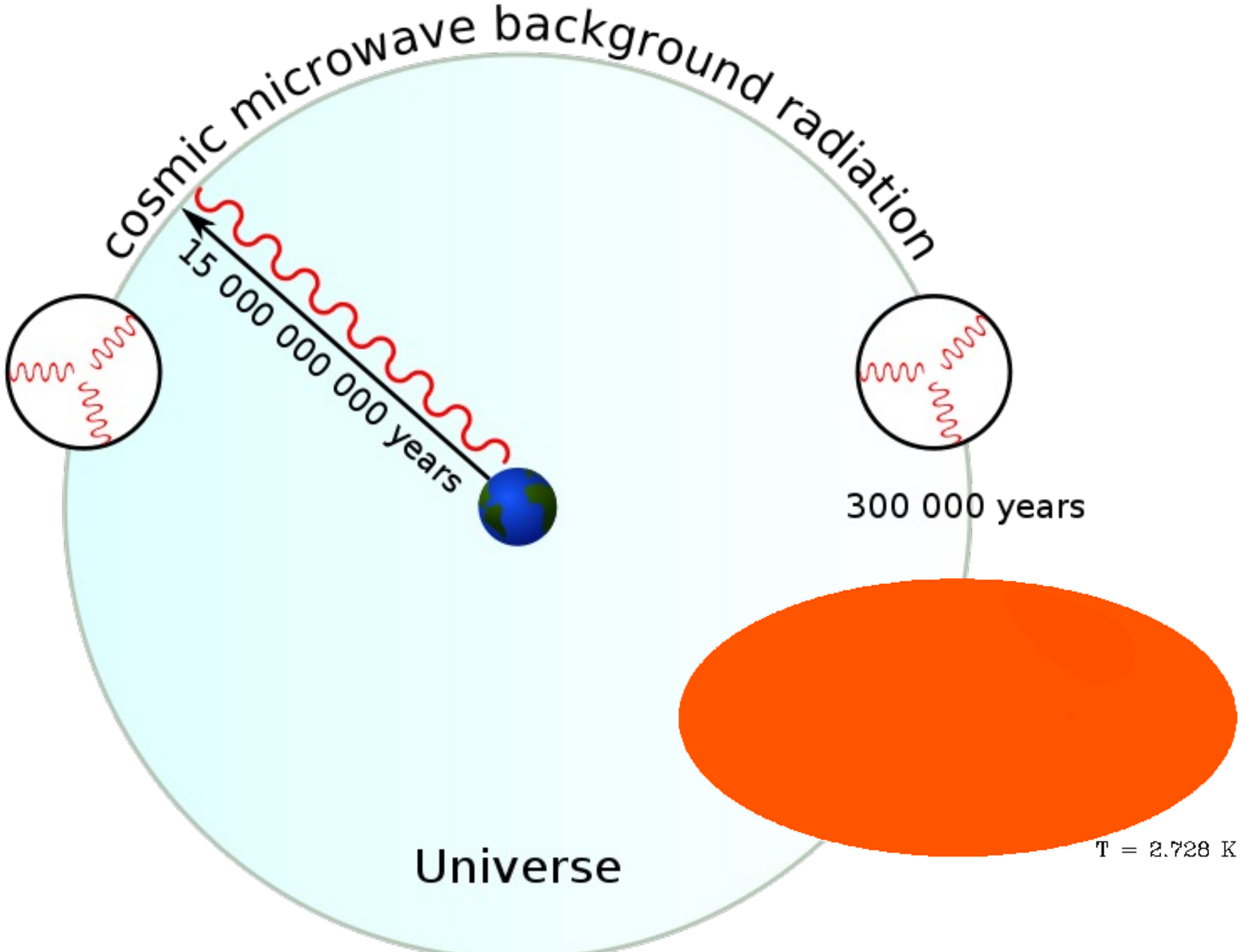
$\rho / \rho_c \approx 1 \pm 10^{-60}$

# Flatness



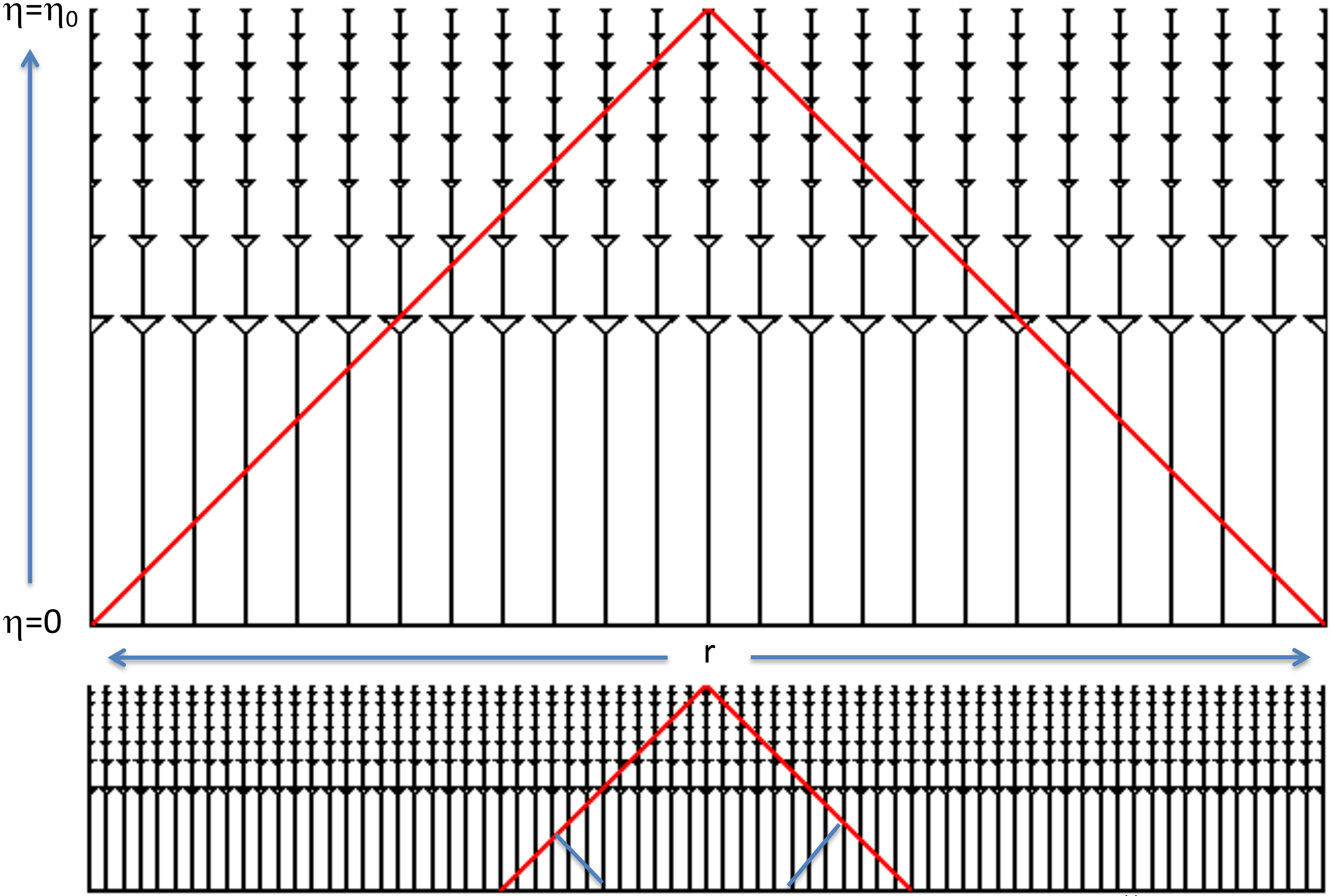
$H^2 = H_0^2(\Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda)$
curvature
radiation
matter
dark energy
Log [energy density (GeV$^4$)]
-36
-40
-44
-48
4
3
2
1
0
-1
Log [1+z]

# Problem #2: Horizon



# Conformal Time

$$\partial\eta = dt \,/\, a(t)$$




Borrowed from Ned Wright's Cosmology Tutorial, http://www.astro.ucla.edu/~wright/

# Horizons

What is the ***maximum*** comoving distance light can travel?

$$d_{hor}(t_0) = \int_0^{t_0} \frac{c}{a(t)} dt$$

Can integrate for any given a(t).

This is called the **particle horizon**.

It's the farthest signals can travel since t=0.
Defines the **observable Universe**.

# Distances in Rad Dom

$a(t) = (t/t_0)^{1/2}$

$$d_p(t_0) = \int_{t_e}^{t_0} \frac{c\,dt}{a(t)}$$

$$= c\int_{t_e}^{t_0} \frac{dt}{(t/t_0)^{1/2}}$$

$$= \frac{c}{H_0}\frac{(1+z)^2 - 1}{(1+z)^2}$$

Horizon at $d_{hor}(t_0) = c/H_0$

# Distances in EdS

$a(t) = (t/t_0)^{2/3}$

$$d_p(t_0) = \int_{t_e}^{t_0} \frac{c\,dt}{a(t)}$$

$$= c \int_{t_e}^{t_0} \frac{dt}{(t/t_0)^{2/3}}$$

$$= \frac{2c}{H_0} \left[ 1 - \frac{1}{\sqrt{1+z}} \right]$$

Horizon at $d_{hor}(t_0) = 2c/H_0$

# Problem #3: Monopoles

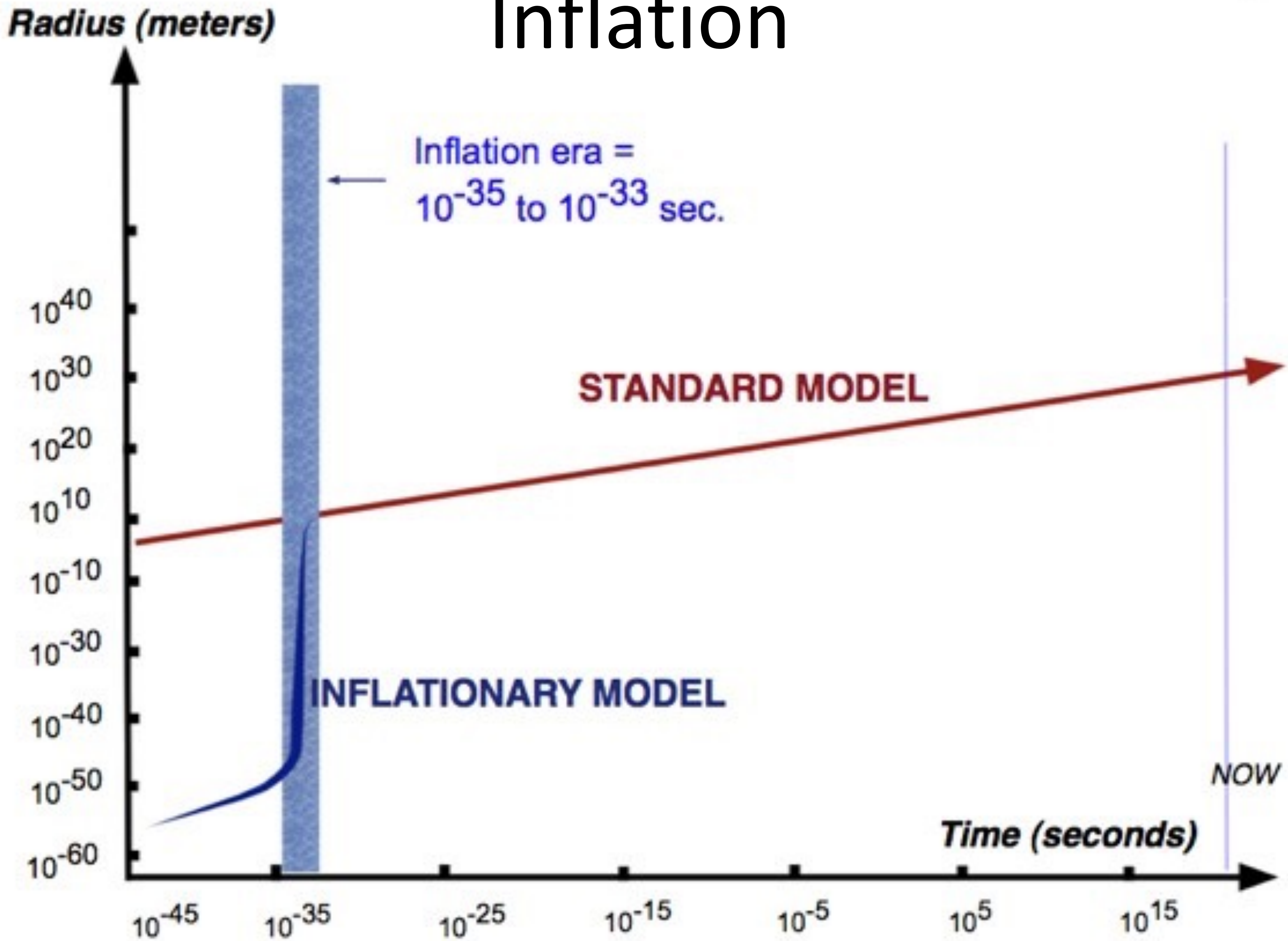
Separation of strong and electro-weak forces requires spontaneous symmetry breaking.

We expect topological defects at borders of causally disconnected regions, $r \approx ct_{GUT}$

Magnetic monopoles and cosmic strings are examples of defects.
$n_{MM} \approx 10^{82}$ $m^{-3}$ at the moment of symmetry breaking.

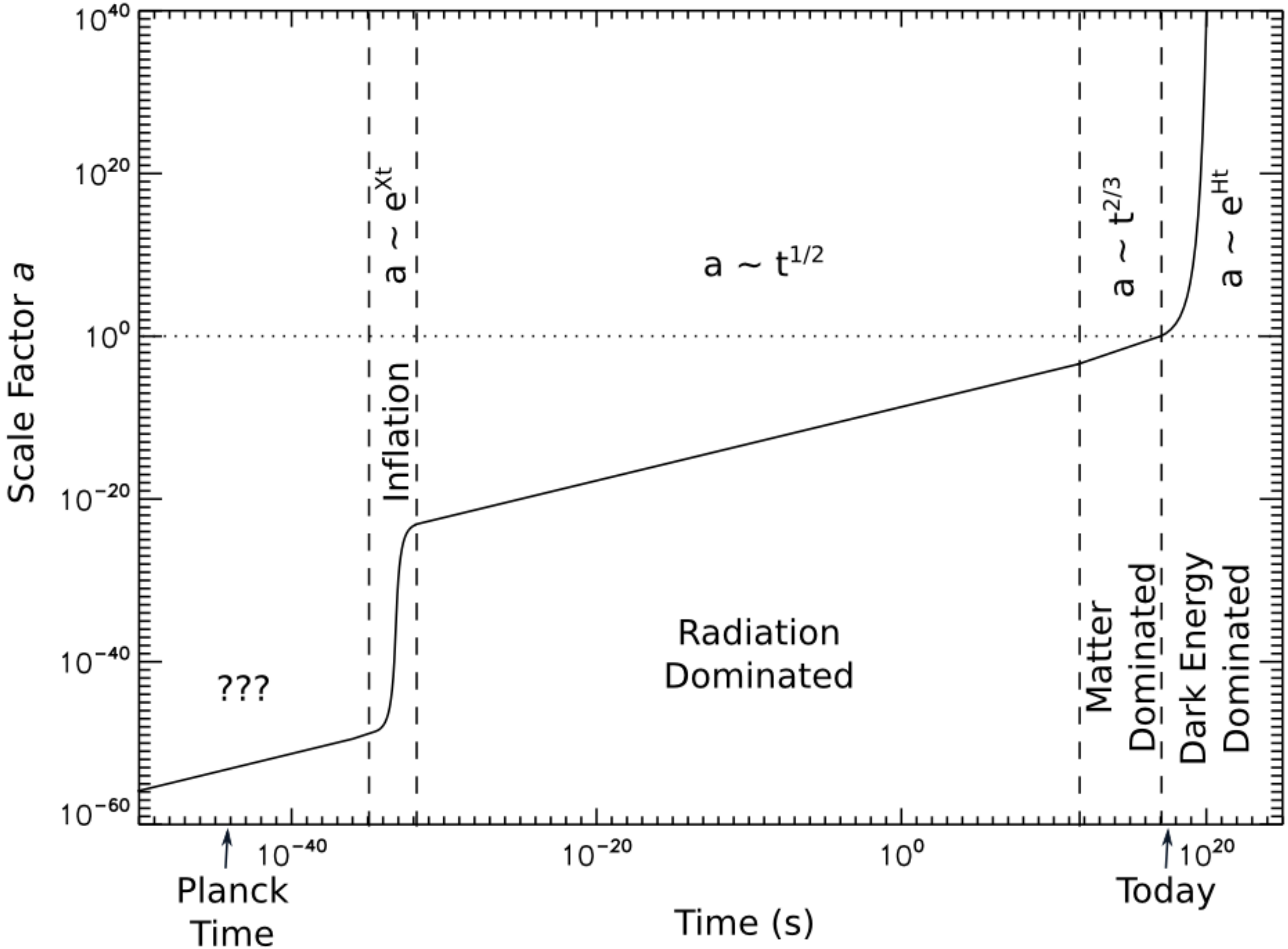
They would quickly dominate the density of the Universe.
(Observation: there aren't any.)

# Inflation




Observed flatness requires expansion by ≈ 60 e-foldings.

# Scale vs Time



# So how do you inflate a Universe?

We've seen one candidate: **Dark Energy**

$$\boxed{\frac{H^2}{H_0^2} = \cancel{\Omega_R a^{-4}} + \cancel{\Omega_M a^{-3}} + \cancel{\Omega_k a^{-2}} + \Omega_\Lambda} \Rightarrow a(t) = C\, e^{H_0 t}$$

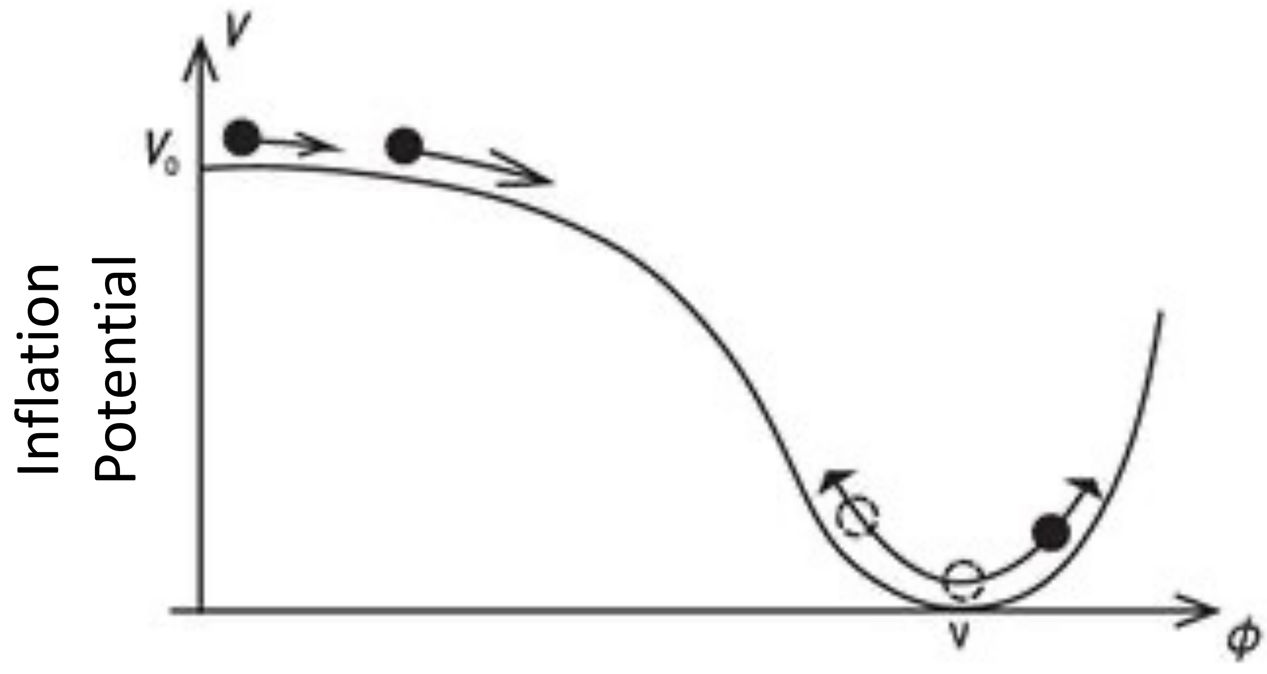
Remember: DE behaves like a vacuum energy density.

To inflate a Universe, we need a vacuum with some energy density built in!

# How do you stop it?

$\Lambda$-driven accelerated expansion will continue indefinitely.
How do we stop inflation from doing the same thing?

Make the energy density of the vacuum move to zero at some point.

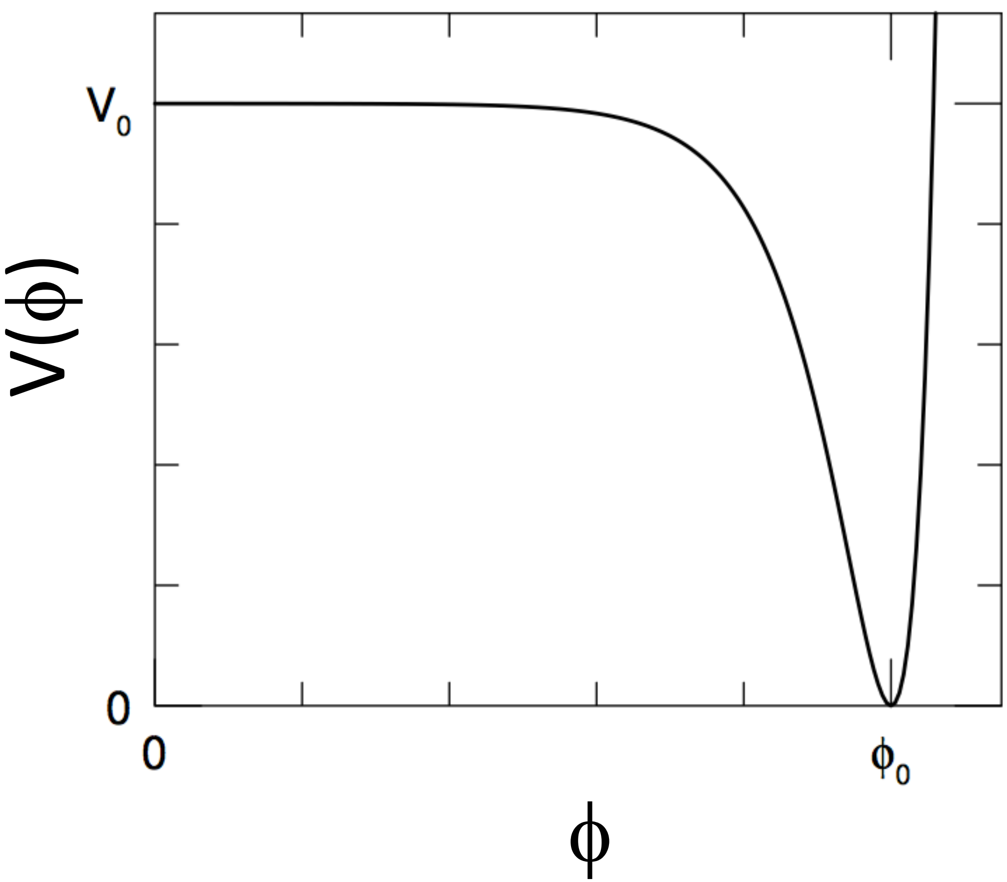



**Single-field slow-roll Inflation**

# How do you Inflate a Universe?

A Time-evolving Scalar field!

$$a(t) \propto \begin{cases} \sinh Ht & (k=-1) \\ \cosh Ht & (k=+1) \\ \exp Ht & (k=0), \end{cases}$$



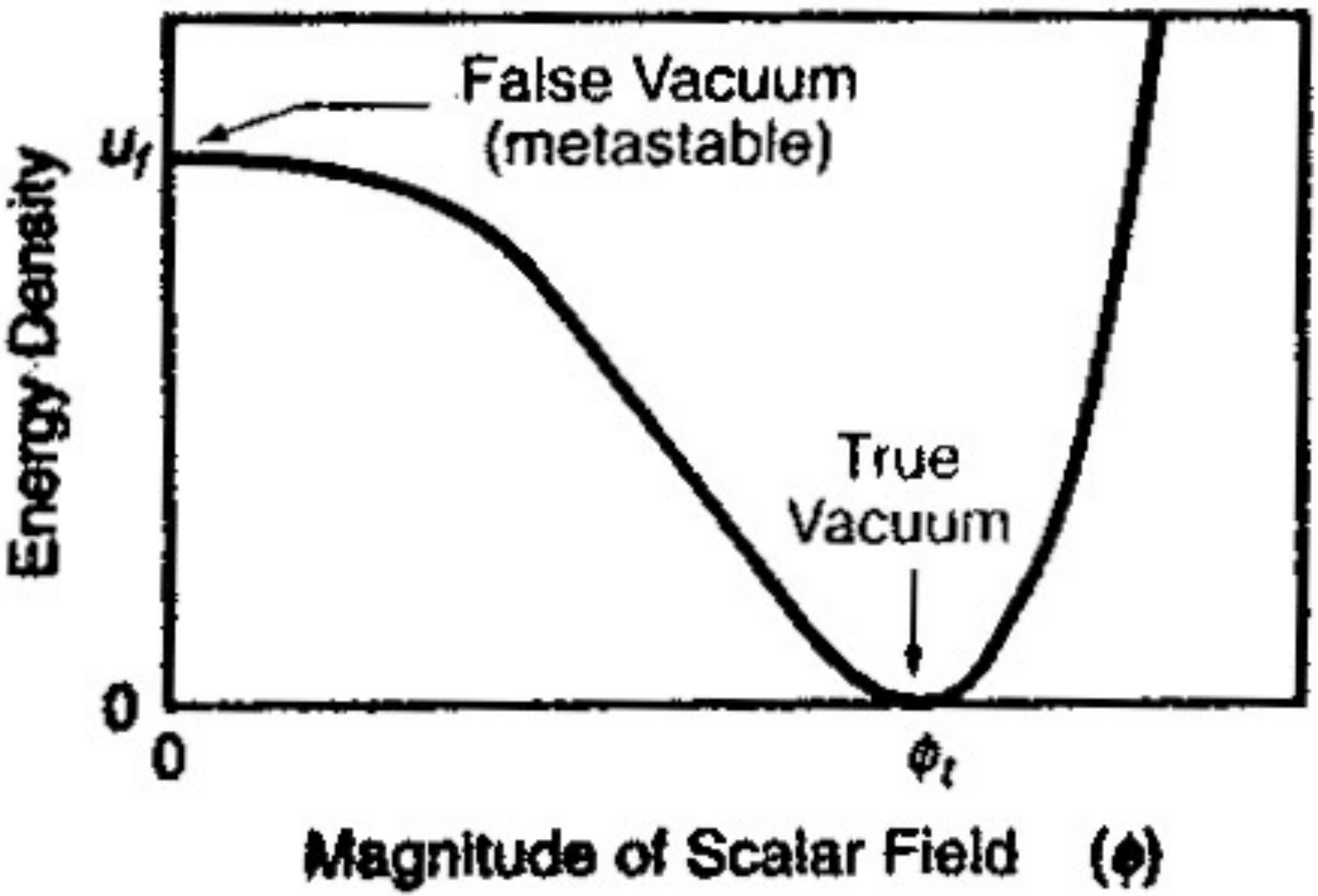

$$\varrho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

2nd Friedmann eq:

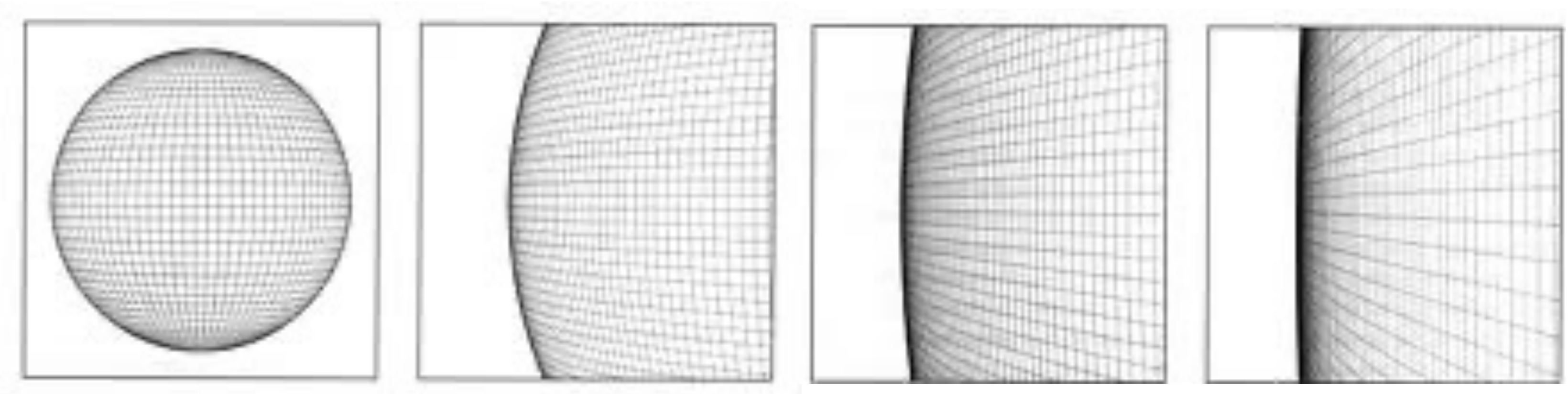
$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV(\phi)}{d\phi} = 0$$

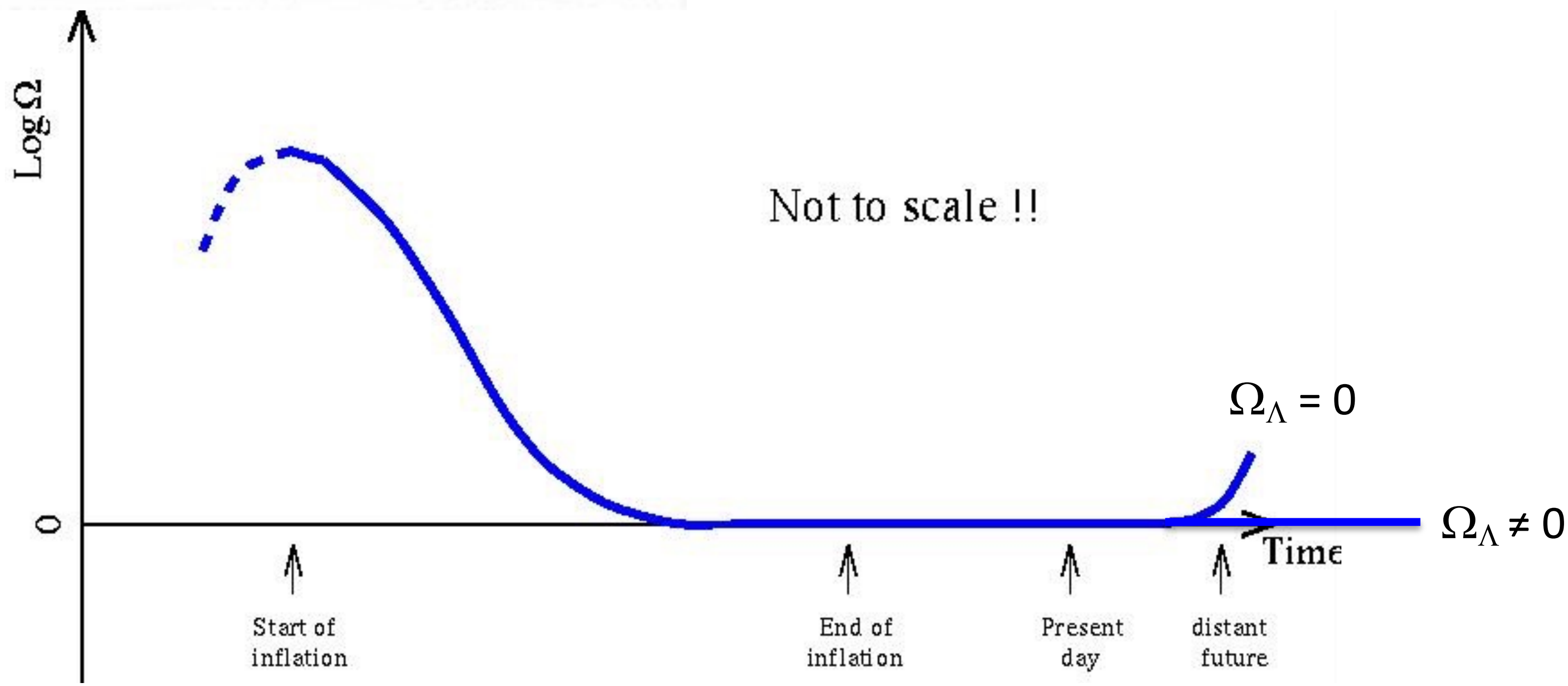
# True and False Vaccua



# Flatness: Fixed

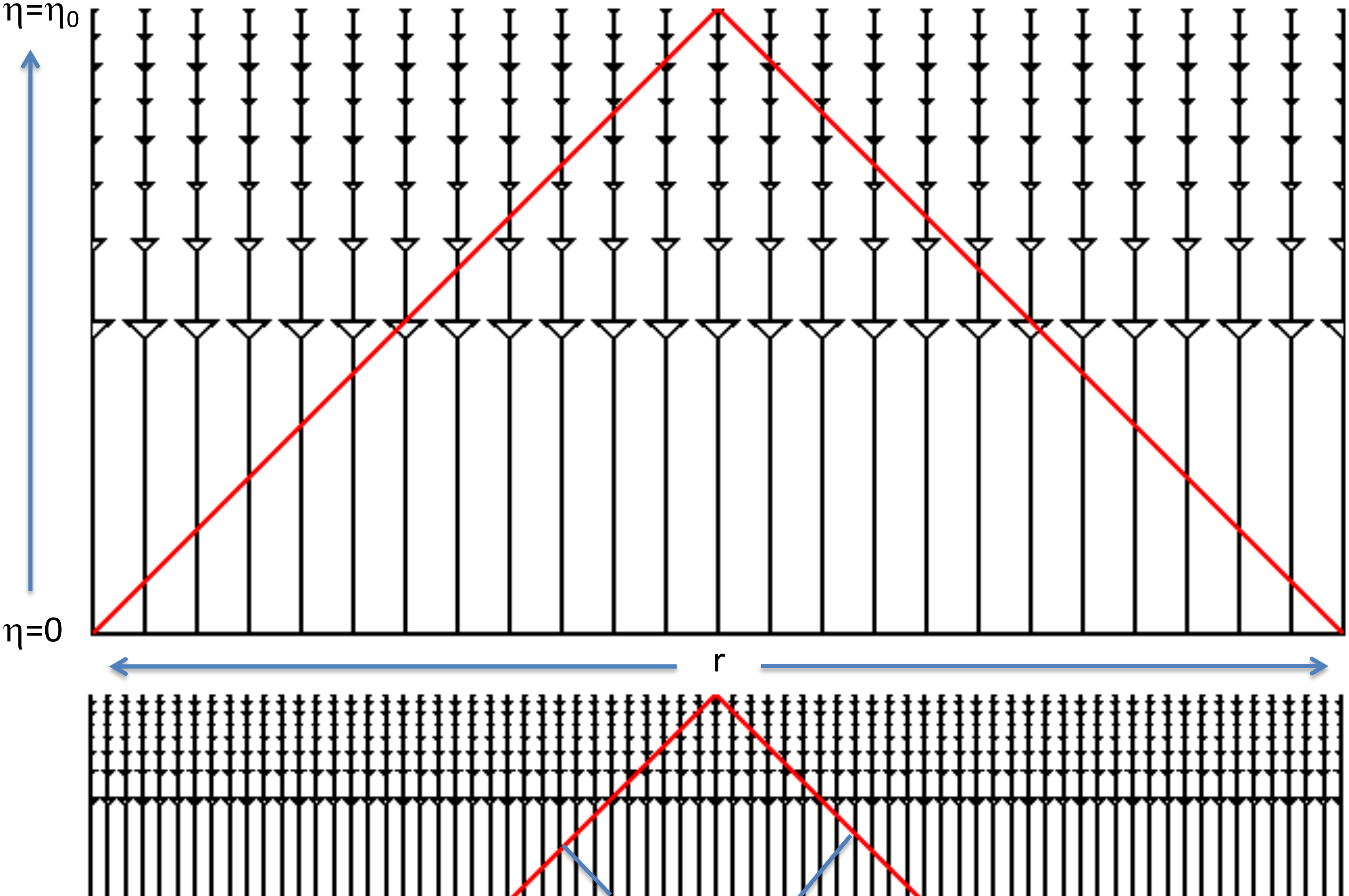
In a cosmological-constant-dominated Universe, $\rho_\kappa / \rho_\Lambda \rightarrow 0$





# Conformal Time

$\partial\eta = dt \,/\, a(t)$




Borrowed from Ned Wright's Cosmology Tutorial, http://www.astro.ucla.edu/~wright/

# Distances in de Sitter

$a(t) = e^{H_0(t-t_0)}$

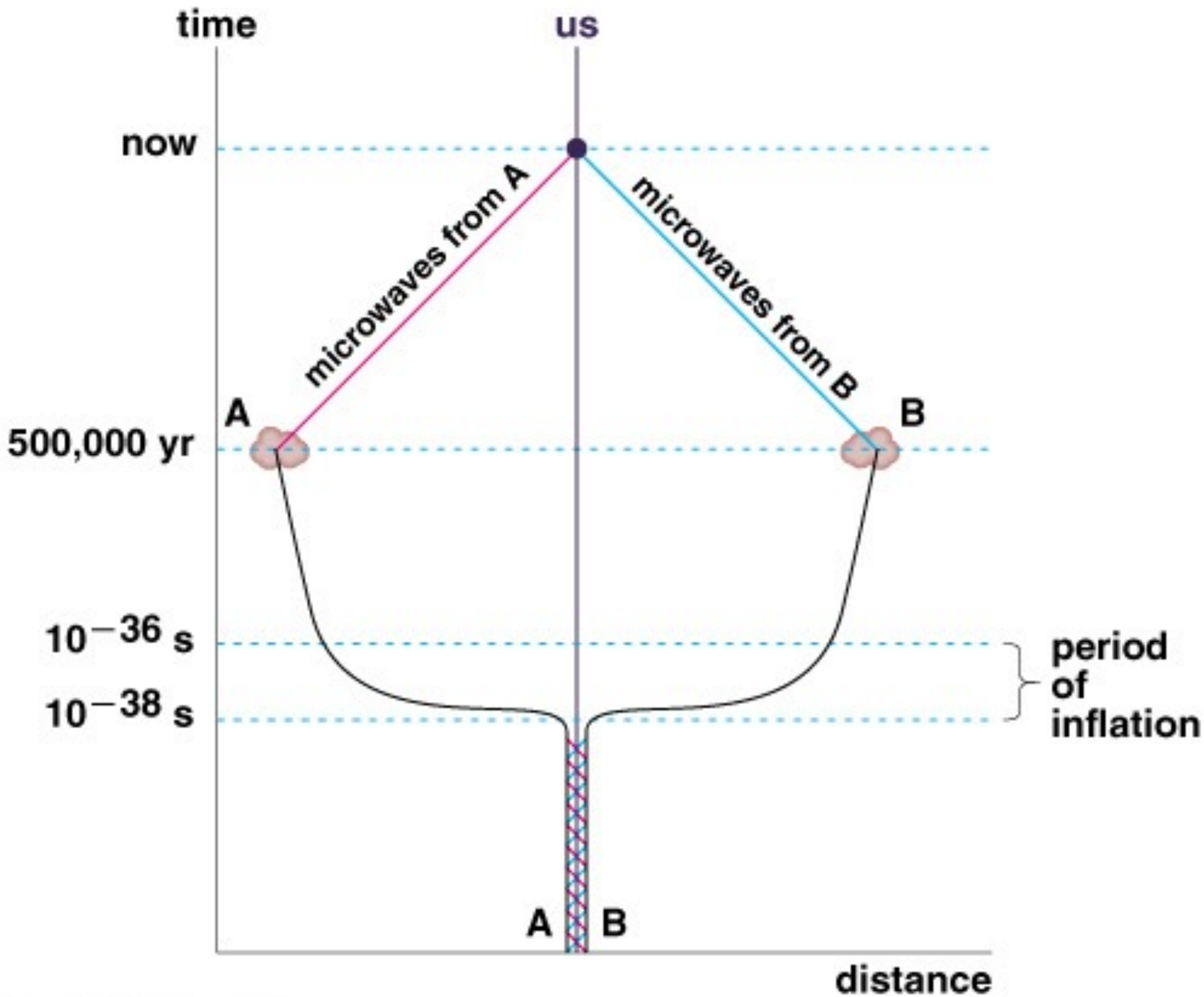
$$d_p(t_0) = \int_{t_e}^{t_0} \frac{c\,dt}{a(t)}$$

$$= \frac{c}{H_0}\left[e^{H_0(t_0-t_e)} - 1\right]$$

$$= cz/H_0$$

No particle horizon!

# Horizon: Fixed



# Monopoles: Fixed

Diluted enormously → expect << 1 in observable Universe

This sets a timing requirement on inflation!
It must be active *after* $T < T_{GUT}$ to get rid of the monopoles.

$t_{inflation} \approx 10^{-34} – 10^{-32}$ seconds

# Why didn’t everything redshift away?

Trick question: It did.

Inflation creates a Universe with **nothing** but the inflation field in it.

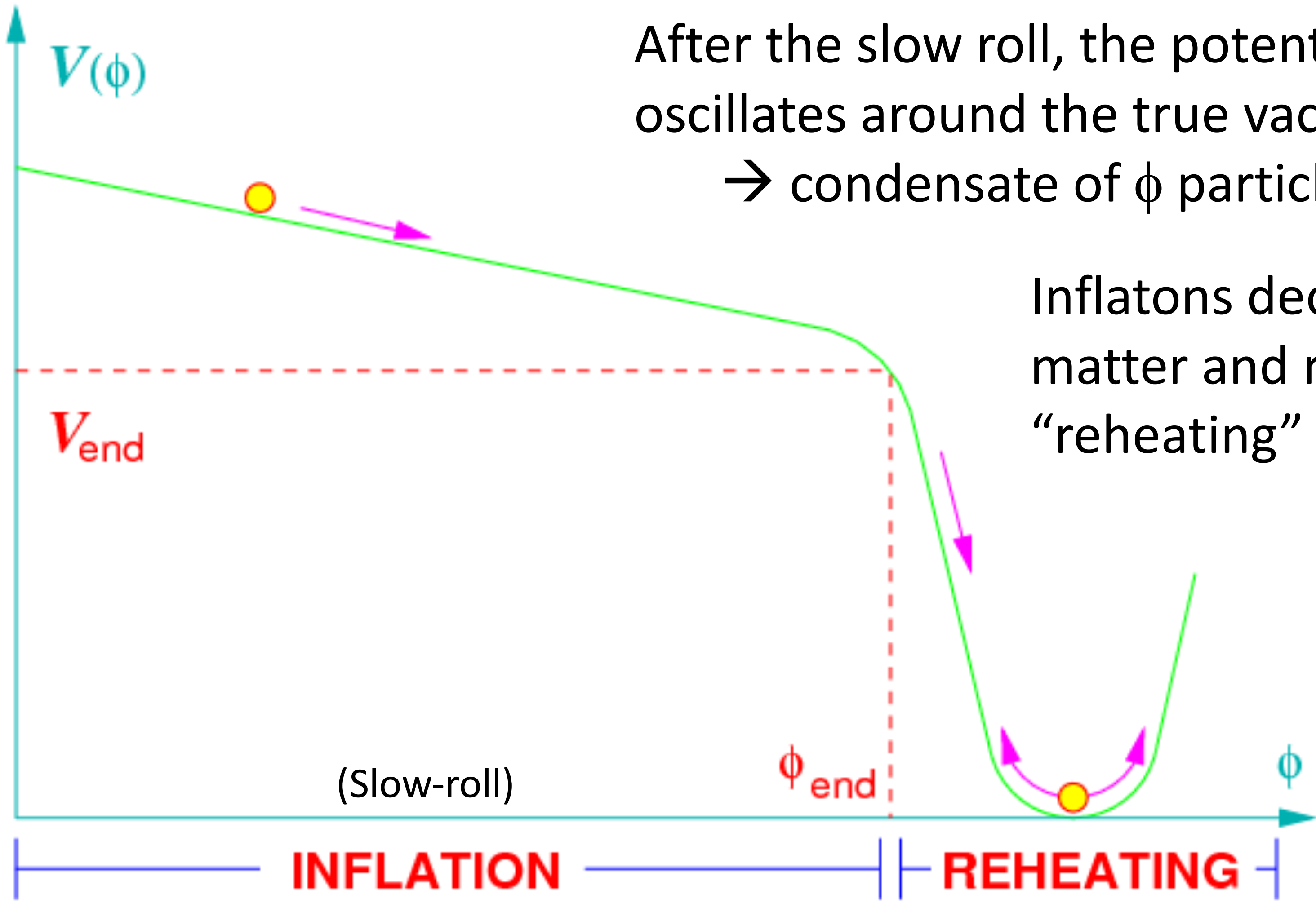
# Reheating

$T_{inflation} \approx 10^{14}$ GeV → 1K

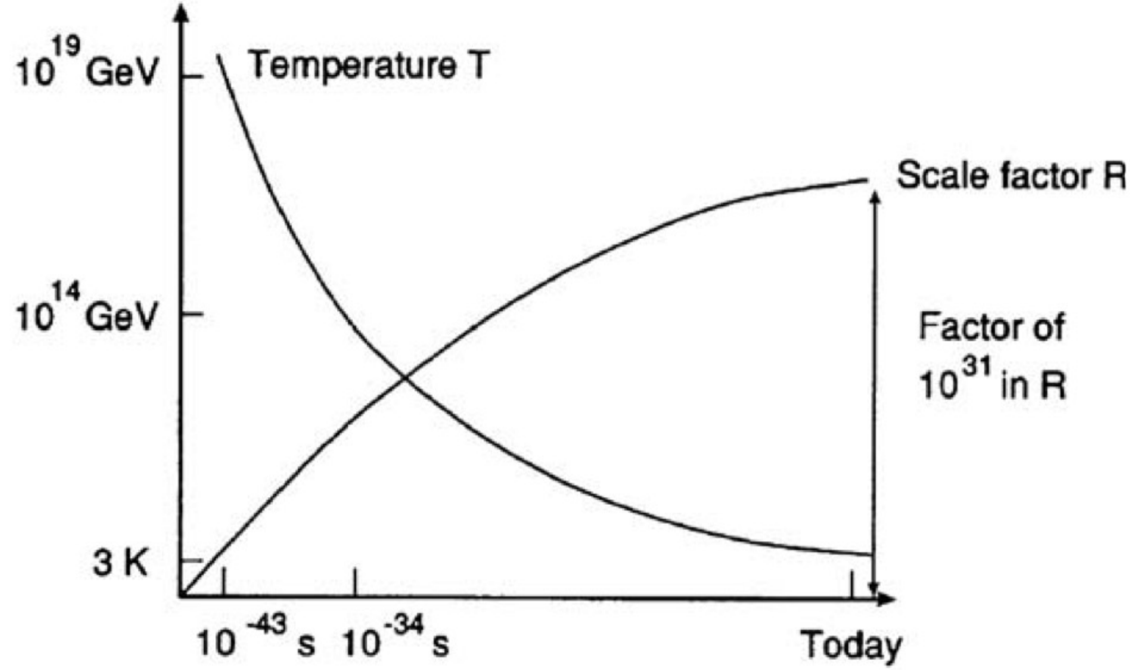
And if everything redshifted away, why is there anything?

After the slow roll, the potential oscillates around the true vacuum state
→ condensate of $\phi$ particles, "inflatons"

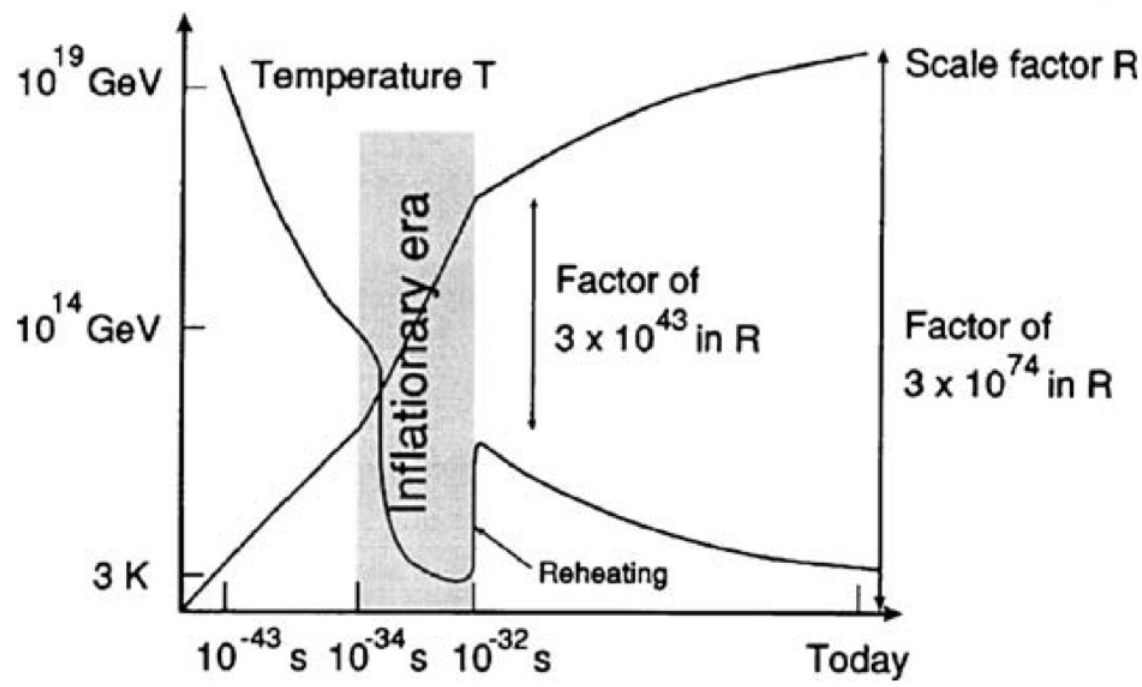
Inflatons decay, producing matter and radiation, "reheating" the Universe.



Without Inflation




With Inflation



# Baryogenesis

Reheating gives a convenient moment to invoke baryogenesis.

Sakharov’s Rules describe the requirements:

- Baryon Number must be violated
- C [charge] and CP [charge/parity] must be violated
- Asymmetry must happen under non-equilibrium conditions

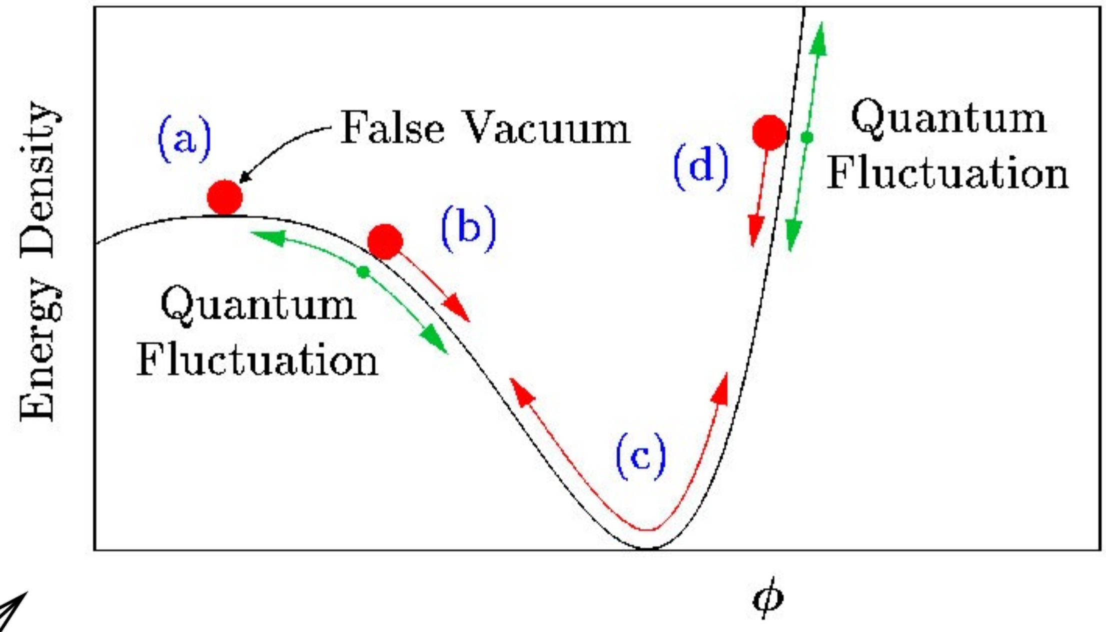
How this actually plays out is still unclear…

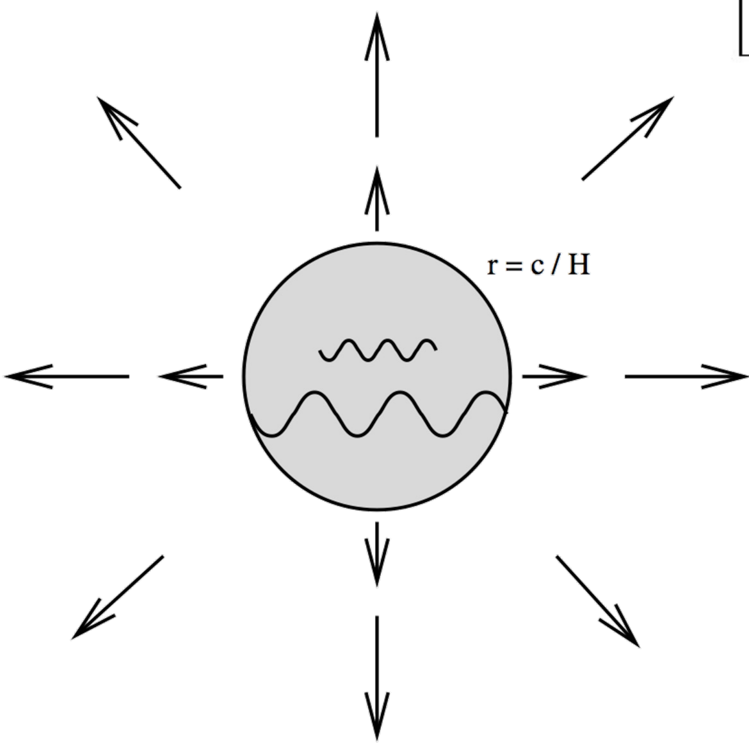
- CP symmetry is violated in electroweak interactions
- B non-conservation has never been observed
- Very short window for non-equilibrium conditions…

# Structure

Heisenberg:

$\Delta E \, \Delta t \geq \hbar/2$




- During inflation, $\phi$ field varies randomly on short timescales.
- These scalar perturbations produce density variations.
- These variations get dragged along with inflating space.
- Once outside causal contact, they become frozen in.

# Other Inflations

We've been discussing only one model,

→ Single-field, slow-roll inflation.

Many others work just as well.

→ multiple field
→ Chaotic inflation
→ etc…

# A Big Reset Button for the Cosmos

Summary:

Inflation takes an arbitrarily messy Universe, and

1) Puts the observable part in causal contact.
2) Empties it of all the junk.
3) Smooths it out nicely.
4) Fills it back up with stuff we know & love.

Good enough to make it widely accepted,
but it's all post-hoc. (For now…)

Warning: Wild Speculation!

# Are we Inflating again?

The energy density of the inflation field is the same as the energy density of the early Universe – very very high!

DE / $\Lambda$ is much much weaker than the inflationary field.
$10^{27}$ = 1,000,000,000,000,000,000,000,000,000 x weaker.

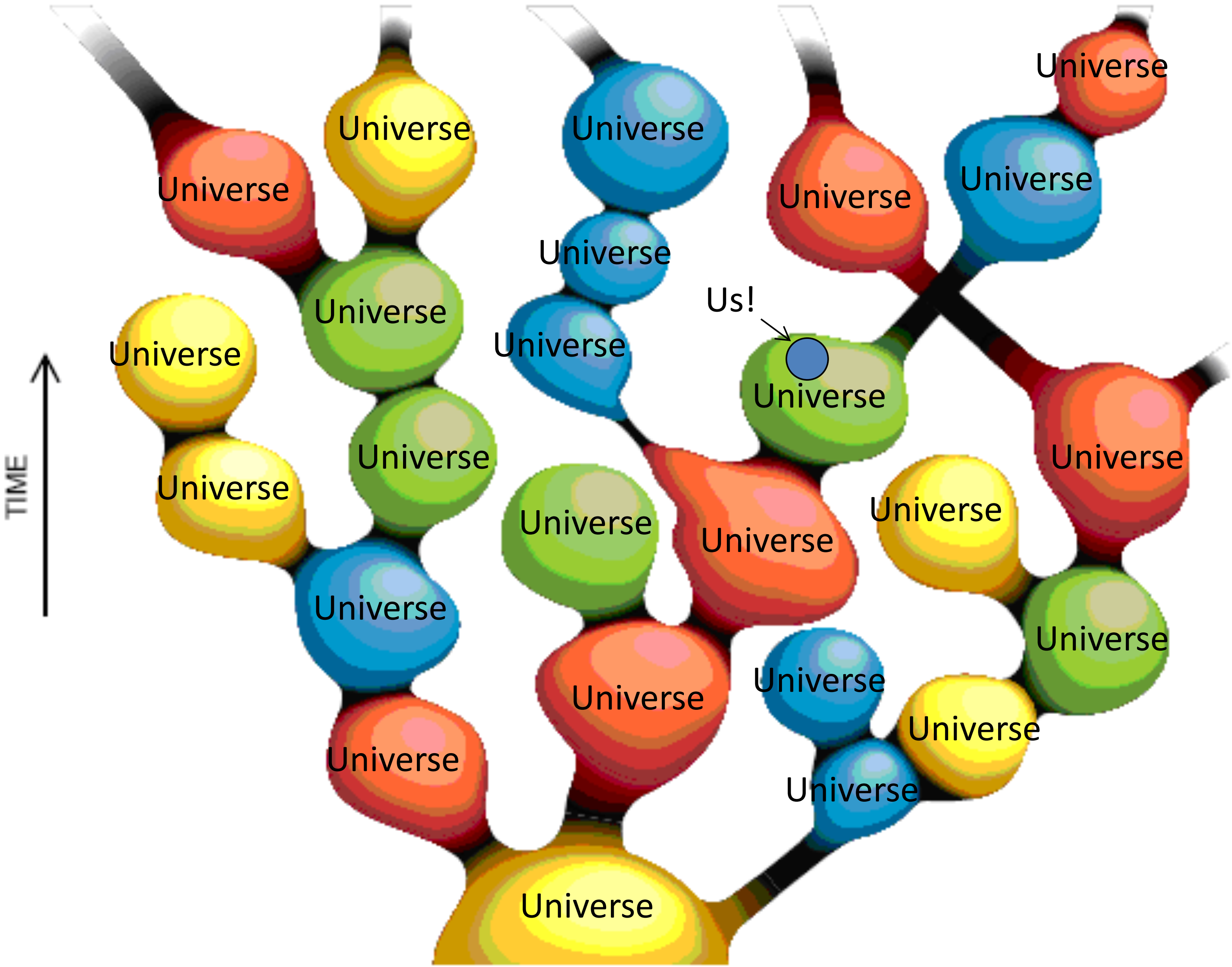
If DE inflates the Universe, redshifts everything away, flattens things out, rips causally connected stuff apart superluminally, then decays, it will only reheat the Universe very weakly.

The post-DE Universe will not contain any of the particles we're familiar with. Probably none of the forces either.

If we're in another inflation, it's to a ***very*** different place.

Warning: Wild Speculation!

# Does this keep happening?



# INTERMISSION

# Perturbations

Consider a small perturbation to the density field,
with Density Contrast $\Delta = \rho(x) / \langle\rho\rangle - 1$.

For example:

Galaxies $\rightarrow$ $\Delta \approx 10^6$

Galaxy Clusters $\rightarrow$ $\Delta \approx 10^3$

Superclusters $\rightarrow$ $\Delta \approx 10^0$

If Virialized / Bound:

$\Delta \approx 1$ at $z \approx (10^6)^{1/3} \approx 100$

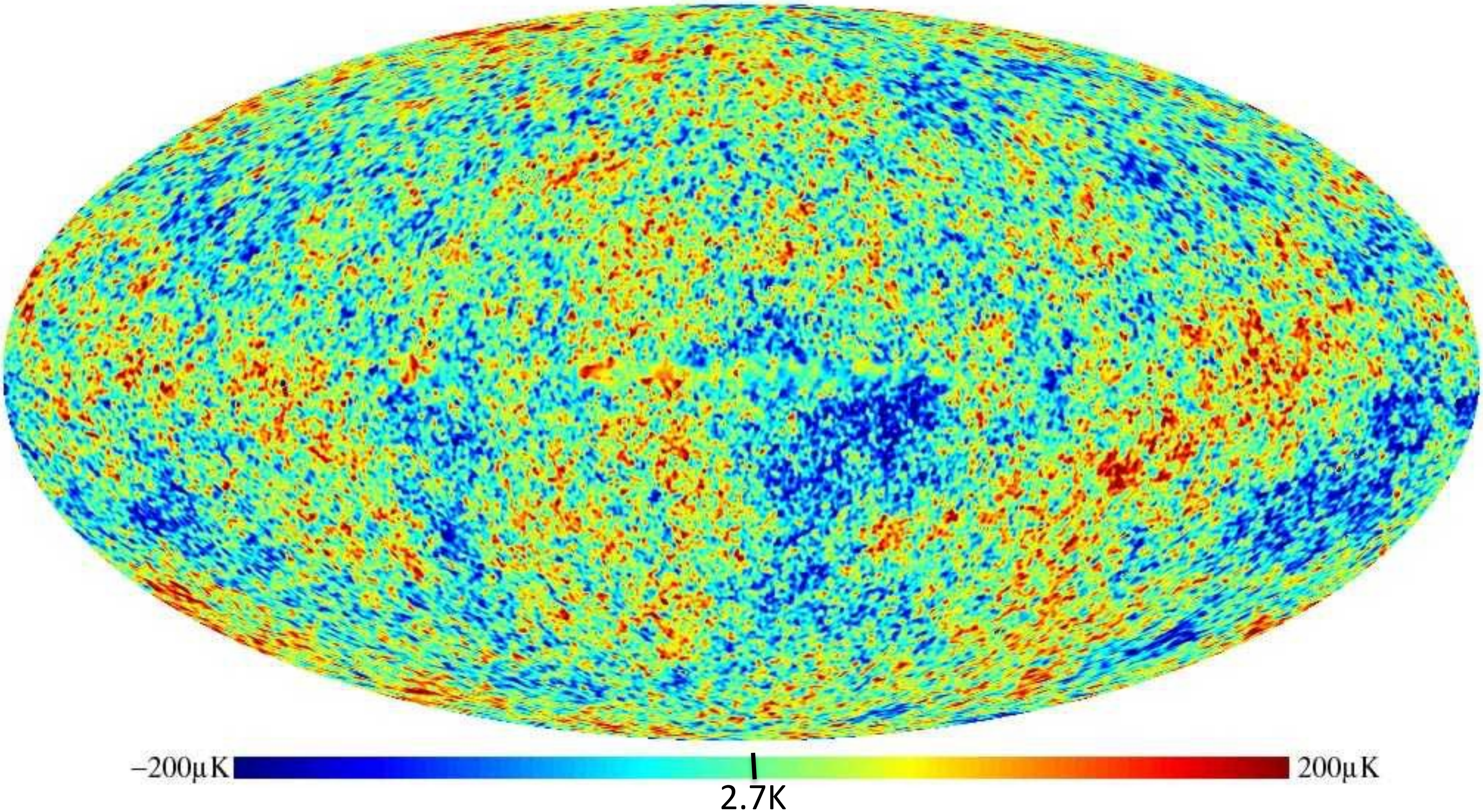
$\Delta \approx 1$ at $z \approx (10^3)^{1/3} \approx 10$

$\Delta \approx 1$ at $z \approx (10^0)^{1/3} \approx 1$

Bound structures cannot have separated before these redshifts.
(Or they would be much more dense today.)

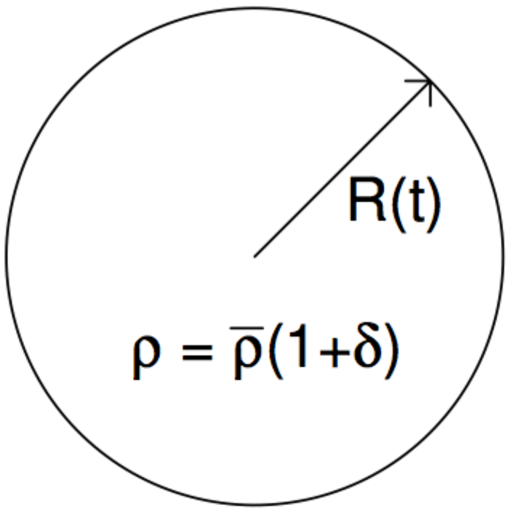
In the early Universe, $\Delta \ll 1$, linear approximations are adequate.

# Looking at $z \approx 1100$




At recombination, $\Delta = \delta\rho / \rho = dT / T \approx 300\mu K / 3K \approx 10^{-4}$

# Gravitational Instability




$$\ddot{R} = -\frac{G(\Delta M)}{R^2} = -\frac{G}{R^2}\left(\frac{4\pi}{3}R^3\bar{\rho}\delta\right)$$

$$\rightarrow \quad \frac{\ddot{R}}{R} = -\frac{4\pi G\bar{\rho}}{3}\delta(t) \underbrace{\approx -\frac{1}{3}\ddot{\delta}}_{\text{mass conservation}}$$

$$\delta(t) = A_1 e^{t/t_{\rm dyn}} + A_2 e^{-t/t_{\rm dyn}}$$

$$t_{\rm dyn} = \frac{1}{(4\pi G\bar{\rho})^{1/2}}$$

More commonly, Δ(t)

# Next Time:

Structure