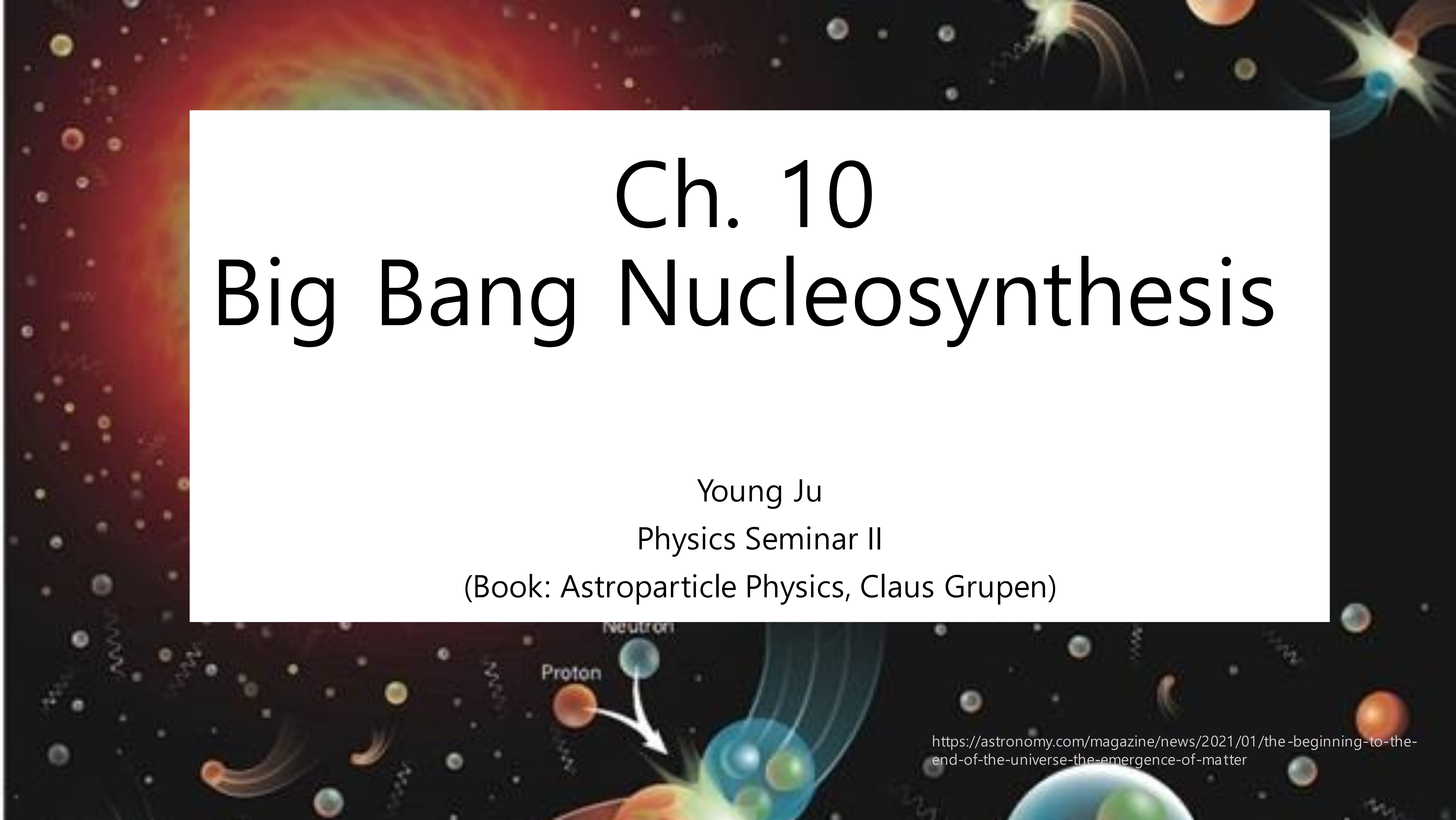



# Ch. 10
# Big Bang Nucleosynthesis

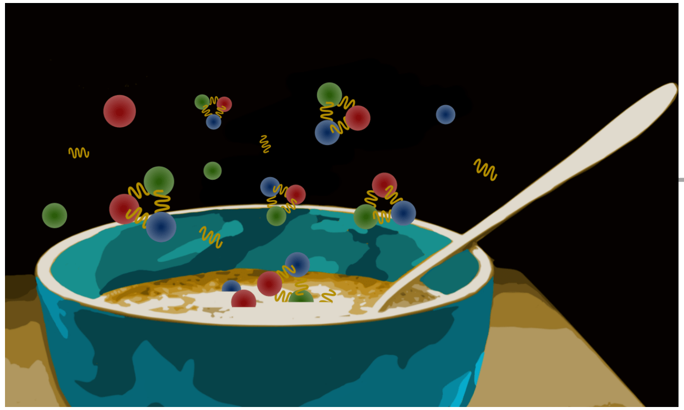
Young Ju

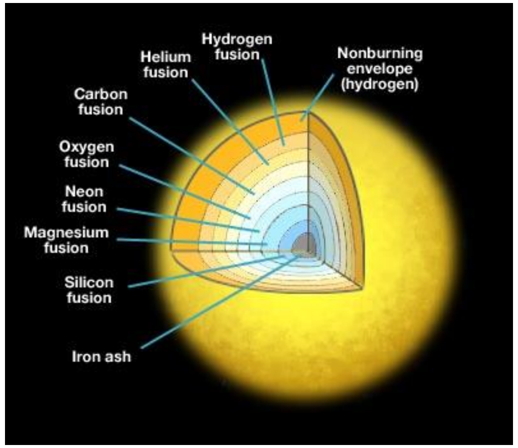
Physics Seminar II

(Book: Astroparticle Physics, Claus Grupen)

https://astronomy.com/magazine/news/2021/01/the-beginning-to-the-end-of-the-universe-the-emergence-of-matter

# Big Bang Nucleosynthesis






- Early universe

Hot soup of quark

- Late universe

Nuclear fusion

?

Where are **Light elements** came from?

1. https://sitn.hms.harvard.edu/flash/2020/the-quark-soup/
2. https://www.e-education.psu.edu/astro801/book/export/html/1829

# Big Bang Nucleosynthesis

- The process that protons and neutrons produce important particles

  Deuterium($^{2}$**H**), Helium-4($^{4}$**He**), lithium-7($^{7}$**Li**), Beryllium-7($^{7}$**Be**)

- Time : 10^-2 sec ~ several minute
- Temperature : 10 ~ 10^-1 MeV

# Start of the BBN era

- *Baryogenesis* : anti-proton and anti-neutron is annihilated at T ~ 20 MeV

- T = 10MeV, t ~ 0.007
- Relativstic particles are in thermal equilibrium

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# Start of the BBN era

- *baryon-number conservation*

- Neutron and proton reaction : $$n\nu_e \leftrightarrow pe^-$$ $$ne^+ \leftrightarrow p\bar{\nu}_e$$

- Question : Is this reaction in the thermal equilibrium as time goes?

# Neutron-proton ratio

- Let's check the reaction rate and expansion rate of the universe

1. Reaction rate : $\Gamma = n\langle\sigma v\rangle \xrightarrow{\text{approximation}} \Gamma(\nu_e n \to e^- p) \approx G_F^2 T^5$

2. Expansion rate :

Density $\varrho = \frac{\pi^2}{30} g_* T^4$

Friedmann eq $\frac{\dot{R}^2}{R^2} = \frac{8\pi}{3} G\varrho$

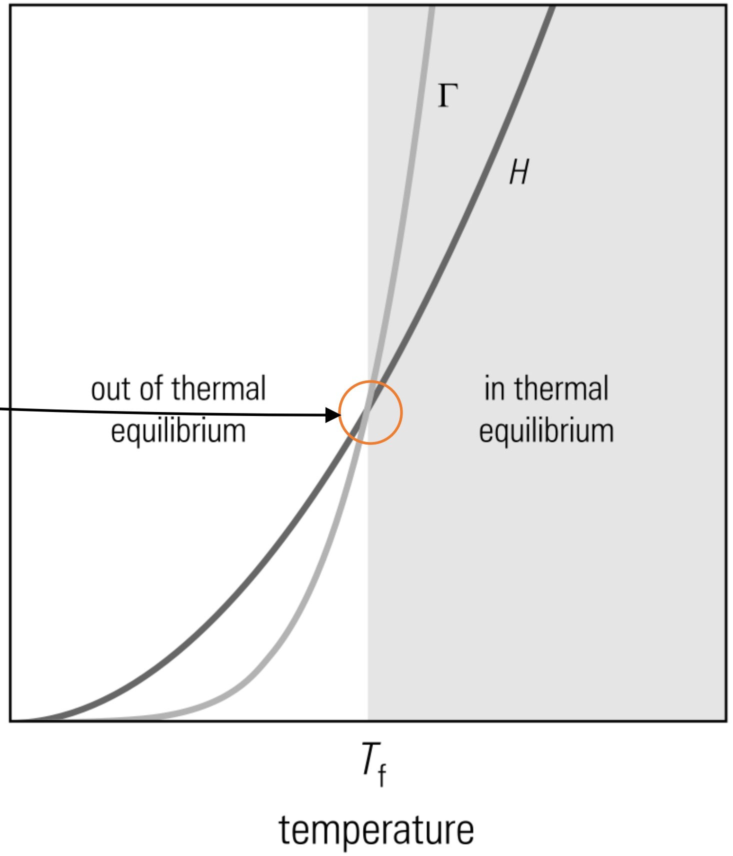
Planck mass $G = 1/m_{\text{Pl}}^2$

$$\Rightarrow \quad H = \sqrt{\frac{8\pi^3 g_*}{90}} \frac{T^2}{m_{\text{Pl}}} \approx 1.66\sqrt{g_*} \frac{T^2}{m_{\text{Pl}}}$$

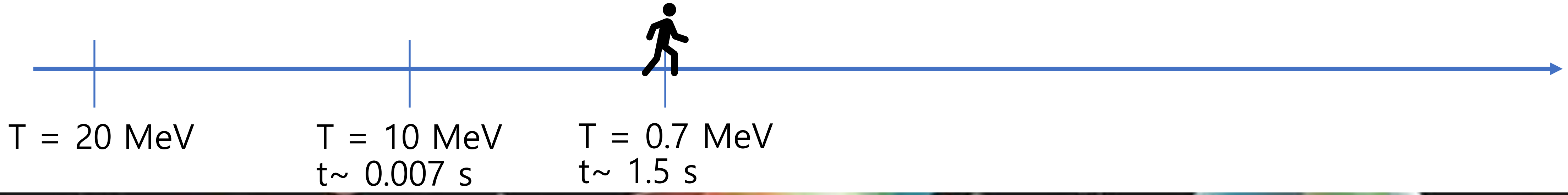
# Neutron-proton ratio

- Decoupling or freeze-out temperature( $T_\mathrm{f}$ )

$$\Gamma = H$$




- $T_\mathrm{f} \approx 0.7\,\mathrm{MeV}$
- t ~ 1.5 sec



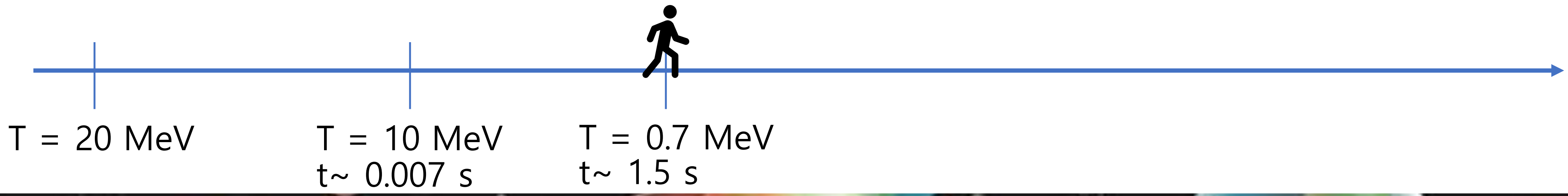
# Neutrino decoupling

- Neutrinos interact with electron and positron

$$e^- + e^+ \longleftrightarrow \nu_e + \bar{\nu}_e$$

- T ~ 0.7MeV : All neutrino flavours are decoupled from other particles

- Cosmic neutrino background radiation ($T_\nu \approx 1.95$ K)

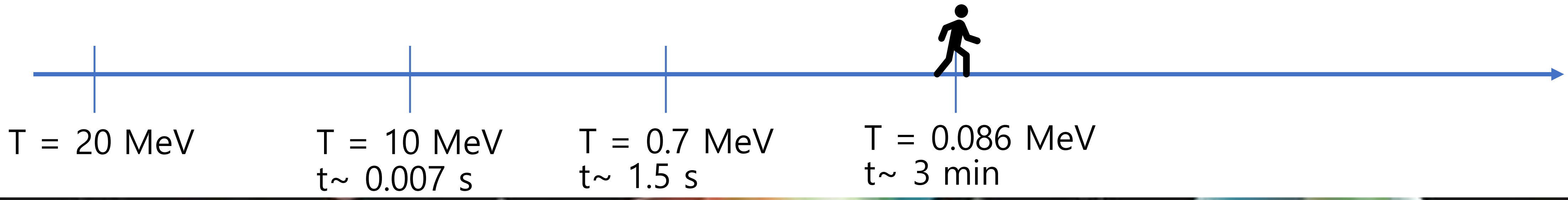


# Synthesis of Light Nuclei (Deuterium)

- Deuterium reaction : $p\, n \rightarrow d\, \gamma$

- *Deuterium bottleneck* : suppressed by photon

- T = 0.086 MeV, t ~ 3 min



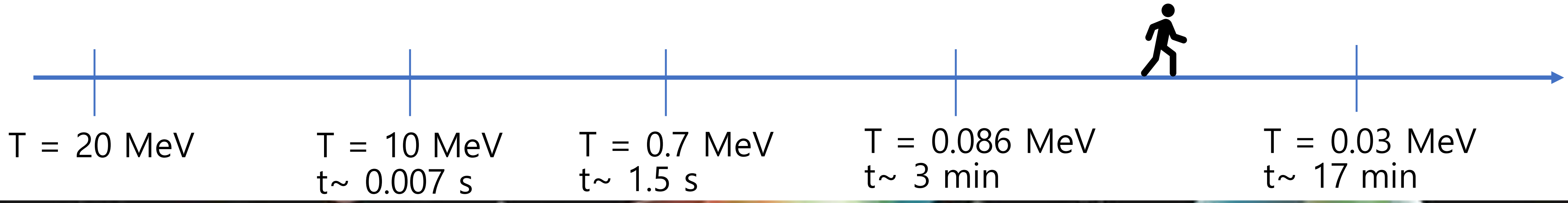
# Synthesis of Light Nuclei ($^4$He)

- The Helium-4 reation :

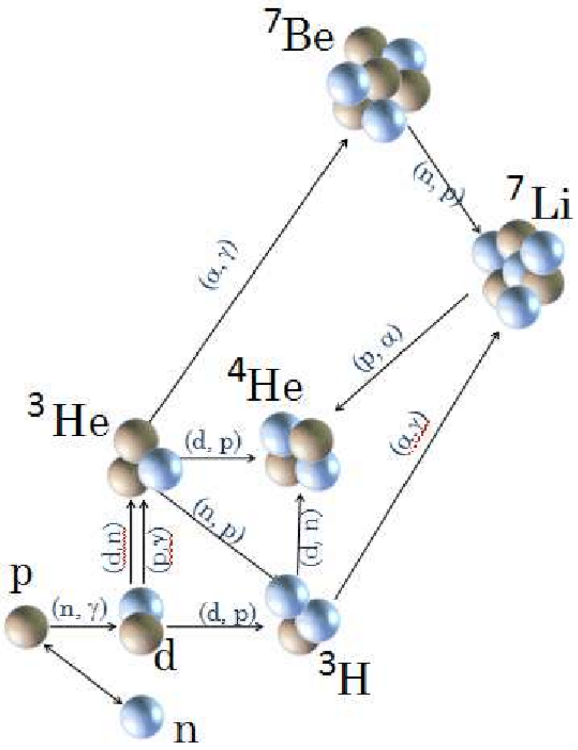
$$d\,p \rightarrow {}^3\mathrm{He}\,\gamma$$
$$d\,{}^3\mathrm{He} \rightarrow {}^4\mathrm{He}\,p$$

- Helium-4 mass function ( $Y_\mathrm{P}$ ) ~ 0.23

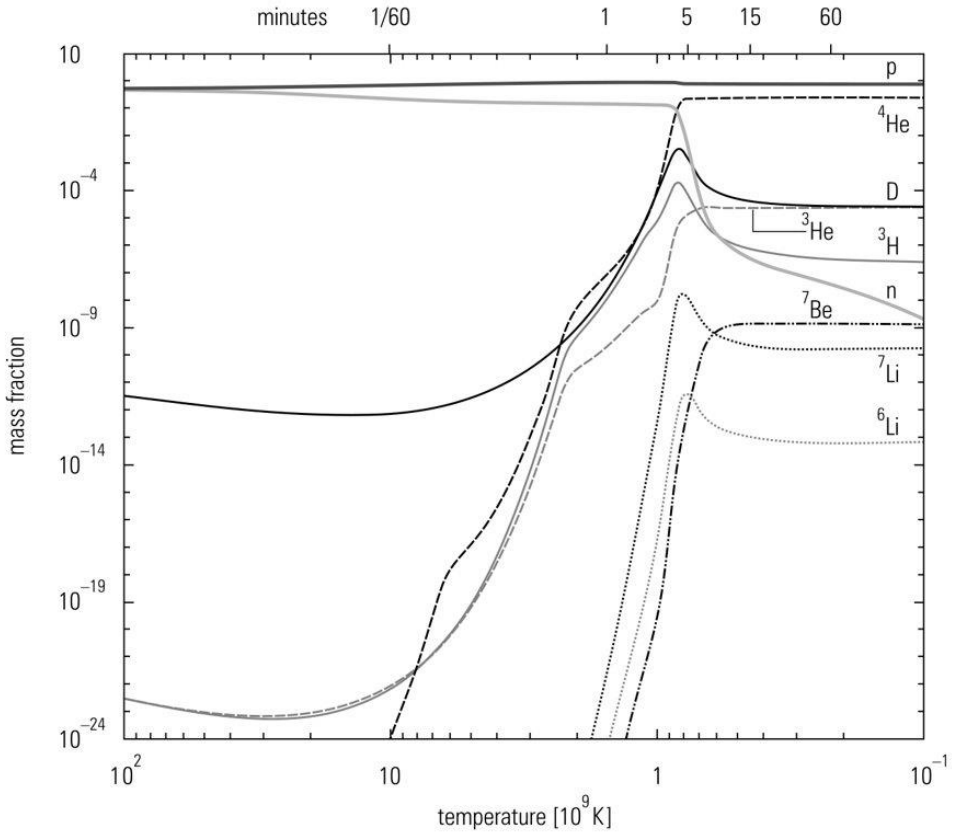
- After BBN the quater of mass is He



# Synthesis of Light Nuclei - Summary




Riou et al., IJMPE, 2017




T = 20 MeV

T = 10 MeV
t~ 0.007 s

T = 0.7 MeV
t~ 1.5 s

T = 0.086 MeV
t~ 3 min

T = 0.03 MeV
t~ 17 min

# Observation evidences of BBN

- Observation of primordial abundances of light elements

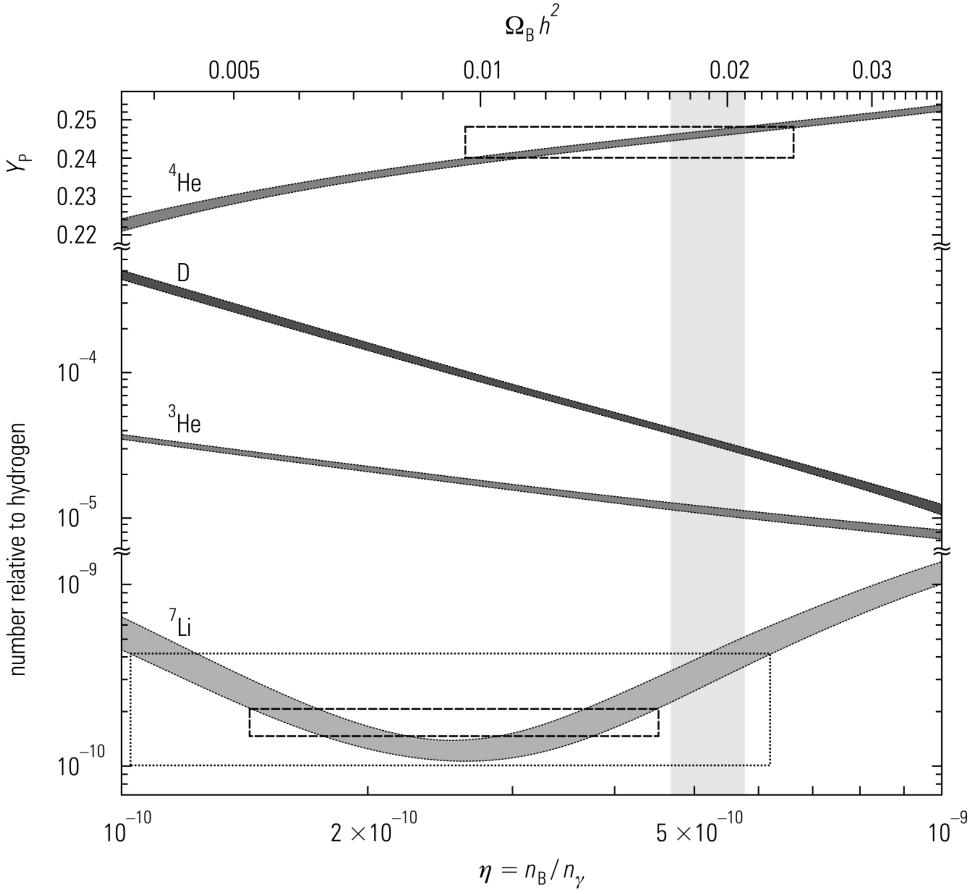
1. **Helium-4** : Find region of hot ionized gas from metal poor galaxies
   $Y_P$ ~ 0.238

2. **Deuterium** : Find gas cloud at high redshift
   $\mathrm{D/H} \quad (3.40 \pm 0.25) \times 10^{-5}$

3. **Lithium-7** : Find hot metal-poor star from galatic halo
   $n_{^7\mathrm{Li}}/n_\mathrm{H} = 1.23 \times 10^{-10}$

4. **Helium-3** is difficult

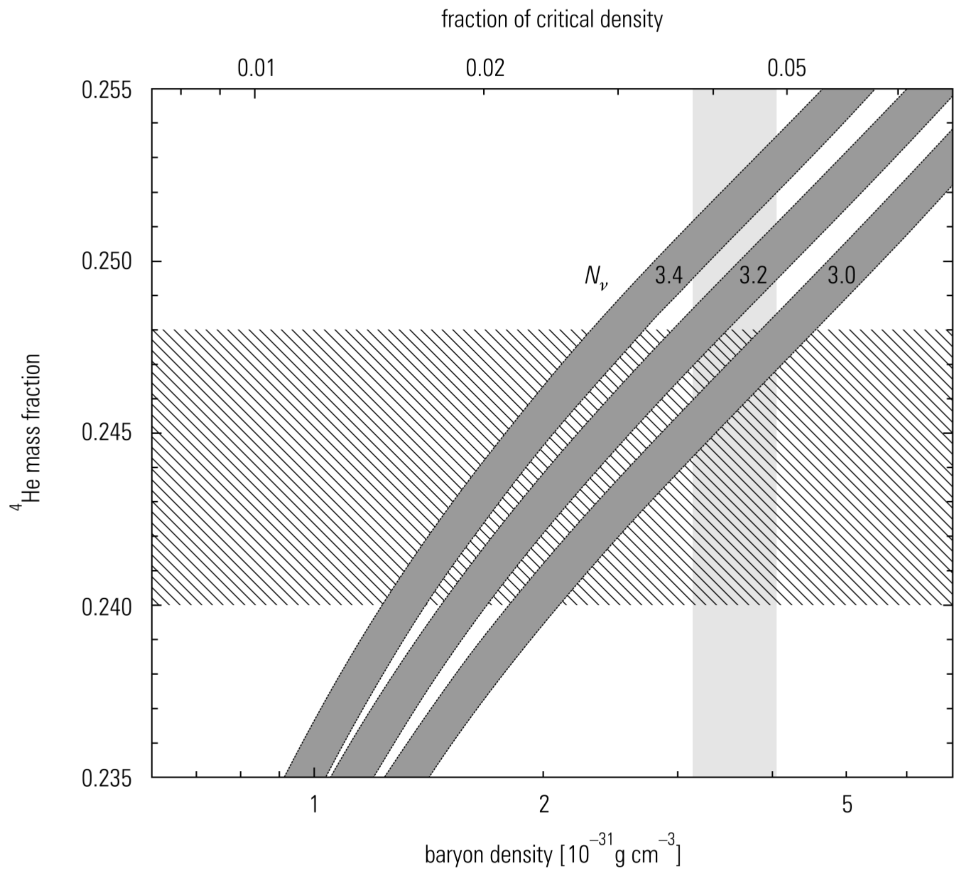
# Observation evidences of BBN




- Baryon-photon ratio : $\eta = (5.1 \pm 0.5) \times 10^{-10}$
- 1. Deuterium : measurement of D/H gives accurate baryon-photon ratio
- Baryon density : $\Omega_b = \dfrac{\varrho_b}{\varrho_c}$

  these value measured by CMB observation
- $\Omega_b = 0.044 \pm 0.004$

# Constraints on the number of neutrino familes




- Is there any other generation of neutrino?
- No…, It is excluded by experiments