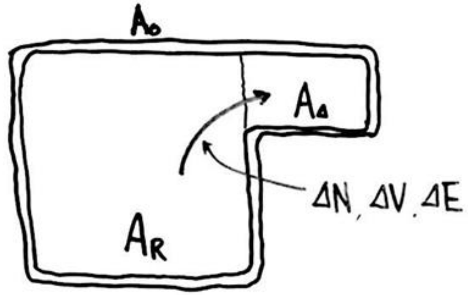
$$P_i \propto \Omega_i \rightarrow \Omega_i = e^{\frac{S_i}{k}} \rightarrow \bar{n} \rightarrow dN \rightarrow dE \rightarrow dU$$

$$S \equiv k \ln \Omega$$



$$\Omega_0 = \Omega_R \Omega_\Delta^{\nearrow 1} = \Omega_R = e^{\frac{S_R}{k}}$$

$$U = Q - W + \mu N$$

$$\Delta U = T\Delta S - p\Delta V + \mu \Delta N$$

$$\Omega_0 = c\, e^{\frac{S_R}{k}} \qquad S_R = S_R^\circ - \Delta S \qquad \Delta S = \frac{1}{T}(\Delta U + p\Delta V - \mu \Delta N)$$

$$\frac{1}{kT} \equiv \beta$$

$$\Omega_0 = c\, e^{\frac{1}{k}\left[S_R^\circ - \frac{1}{T}(\Delta U + p\Delta V - \mu\Delta N)\right]} = c\, e^{-\frac{1}{kT}(\Delta U + p\Delta V - \mu\Delta N)}$$

$$\Delta E = n\varepsilon_s \qquad \Delta N = n$$

$$\Omega_0 = c\, e^{-\beta(\Delta E + p\Delta V - \mu\Delta N)}$$

→ 고전통계

$$P_s = c\, e^{-\beta \varepsilon_s}$$

→ 양자통계

입자수 에너지준위

$$P_n = c\, e^{-\beta n(\varepsilon_s - \mu)}$$

$$P_n = c\, e^{-\beta n(\varepsilon_s - \mu)}$$

$$\bar{n} = \sum_n P_n\, n \qquad \beta(\varepsilon_s - \mu) \equiv x$$

$$\sum_n P_n = 1 \qquad \sum_n c\, e^{-\beta n(\varepsilon_s - \mu)} = 1$$

$$c = \frac{1}{\sum_n e^{-nx}} \qquad P_n = \frac{e^{-nx}}{\sum_n e^{-nx}}$$

$$\bar{n} = \cdot$$

$$\bar{n} = -$$

$E = h\nu$

$$\bar{n} = \frac{\sum_n e^{-nx} \cdot n}{\sum_n e^{-nx}}$$

$dN = (\text{상태수})\,\bar{n}$ $\qquad dE = \varepsilon\, dN$

$$\bar{n} = -\frac{\partial}{\partial x}\left(\ln \sum_n e^{-nx}\right)$$

$\equiv x$

$$dN = \left(\frac{d^3r\, d^3p}{h^3}\right)\bar{n} \qquad dE = \frac{8\pi V \varepsilon^3}{c^3 h^3}\, d\varepsilon \cdot \bar{n} \qquad du = \frac{8\pi}{c^3}$$

$$= \frac{V\, 4\pi p^2 dp}{h^3} \cdot \bar{n} \qquad du = \frac{dE}{V} = \frac{8\pi \varepsilon^3}{c^3 h^3}\, d\varepsilon\, \bar{n} \qquad du = \frac{}{c^3}$$

1

$$\sum_{n=0,1} e^{-nx} = 1 + e^{-x}$$ FD spin $= \frac{1}{2}$ Fermion e^-

$$\frac{e^{-nx}}{\sum_n e^{-nx}}$$

$$\sum_{n=0}^{\infty} e^{-nx} = 1 + e^{-x} + e^{-2x} + \cdots = \frac{1}{1-e^{-x}}$$ BE spin $= 1$ boson γ

$$E^2 = (pc)^2 + (mc^2)^2$$

$E = pc \qquad p = \frac{E}{c}$

$$du = \frac{8\pi \varepsilon^3}{c^3 h^3} \frac{1}{e^{\beta(\varepsilon-\mu)} - 1}\, d\varepsilon$$

$$\bar{n} = -\frac{\partial}{\partial x}\left[\ln(1+e^{-x})\right] = \frac{e^{-x}}{1+e^{-x}} = \frac{1}{e^{x}+1}$$

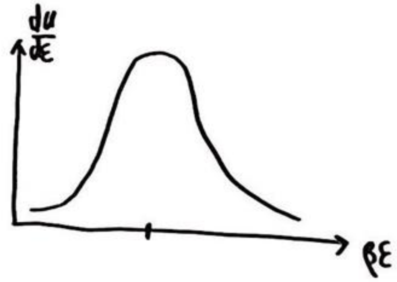
$$dN = \frac{4\pi V p^2 dp}{h^3} \cdot \bar{n}$$

$$\frac{du}{d\varepsilon} = \left(\frac{8\pi}{c^3 h^3}\right)\frac{\varepsilon^3}{e^{\beta\varepsilon} - 1}$$

u

$$\bar{n} = -\frac{\partial}{\partial x}\left[\ln(1-e^{-x})^{-1}\right] = \frac{e^{-x}}{1-e^{-x}} = \frac{1}{e^{x}-1}$$

$$dN = \frac{8\pi V \left(\frac{\varepsilon}{c}\right)^2 \frac{d\varepsilon}{c}}{h^3}\, \bar{n}$$



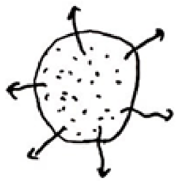
$u =$

$$dN = \frac{8\pi V \varepsilon^2}{c^3 h^3}\, d\varepsilon \cdot \bar{n}$$

$u =$

$$dE = \varepsilon\, dN \qquad E = h\nu$$

$$\varepsilon = \frac{h}{2\pi}\cdot 2\pi\nu = \hbar\omega \qquad \omega = \frac{\varepsilon}{\hbar} \qquad \hbar = \frac{h}{2\pi} \qquad h = 2\pi\hbar$$



$$dE = \frac{8\pi V \varepsilon^3}{c^3 h^3}\, d\varepsilon \cdot \bar{n}$$

$$du = \frac{8\pi\, (\hbar\omega)^3\, \hbar\, d\omega}{c^3 h^3}\, \frac{1}{e^{\beta\hbar\omega}-1}$$

$$\text{선속} = \left(\tfrac{1}{2}u\right)\left(\tfrac{1}{2}c\right) = \frac{c}{4}u$$

$$du = \frac{dE}{V} = \frac{8\pi\varepsilon^3}{c^3 h^3}\, d\varepsilon\, \bar{n}$$

$$du = \frac{8\pi(\hbar\omega)^3\hbar}{c^3(2\pi\hbar)^3}\, \frac{d\omega}{e^{\beta\hbar\omega}-1}$$

$$\beta\hbar\omega \equiv x \qquad \omega = \frac{x}{\beta\hbar} \qquad \beta = \frac{1}{kT}$$

$$\text{선속} = \frac{c}{4}u = \frac{c}{4}\,\frac{8\pi^5 k^4}{15 c^3 h^3}T^4 = \frac{2\pi^5 k^4}{15 c^2 h^3}T^4 = aT^4$$

$)^2$

$$du = \frac{8\pi\varepsilon^3}{c^3 h^3}\, \frac{1}{e^{\beta(\varepsilon-\mu)}-1}\, d\varepsilon$$

$$du = \frac{\hbar}{c^3\pi^2}\, \frac{\omega^3}{e^{\beta\hbar\omega}-1}\, d\omega$$

Stepan's law 1876

$$\frac{du}{d\varepsilon} = \left(\frac{8\pi}{c^3 h^3}\right)\frac{\varepsilon^3}{e^{\beta\varepsilon}-1}$$

$$u = \int du = \frac{\hbar}{\pi^2 c^3}\int \frac{\left(\frac{x}{\beta\hbar}\right)^3 \frac{dx}{\beta\hbar}}{e^x - 1}$$

$$a = 5.67\times 10^{-8}\ \mathrm{J/m^2\cdot s\, K^4}$$

$\bar{n}$

$d\varepsilon\cdot\bar{n}$

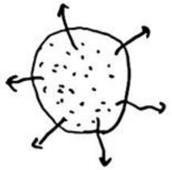
$$u = \frac{\hbar}{\pi^2 c^3}\,\frac{1}{(\beta\hbar)^4}\int_0^\infty \frac{x^3}{e^x - 1}\, dx$$

$\nearrow 7.56\times 10^{-16}\ \mathrm{J/m^3\cdot K^4}$

$$\text{선속}_{SUN} = aT^4 = 5.67\times 10^{-8}\ \mathrm{J/m^2\cdot s\cdot K^4}\ (5800\,\mathrm{K})^4$$

$$u = \frac{(kT)^4}{\pi^2 c^3 \left(\frac{h}{2\pi}\right)^3}\,\frac{\pi^4}{15} = \frac{8\pi^5 k^4}{15 c^3 h^3}T^4 = aT^4$$

$$= 6.2\times 10^7\ \mathrm{J/m^2\cdot s} = 6.2\times 10^4\ \mathrm{kW/m^2}$$



선속 $=\left(\frac{1}{2}u\right)\left(\frac{1}{2}c\right)$

$=\frac{c}{4}u$

$\frac{x}{\beta\hbar}$

선속 $=\frac{c}{4}u=\frac{c}{4}\,\frac{8\pi^5k^4}{15c^3h^3}T^4$

$=\frac{2\pi^5k^4}{15c^2h^3}T^4=aT^4$

Stepan's law 1876

$a=5.67\times10^{-8}\ \mathrm{J/m^2\cdot s\,K^4}$

$6\times10^{-16}\ \mathrm{J/m^3\cdot K^4}$

$^{-4}=aT^4$

$U=Q-W+\mu N$

$\Delta U=T\Delta S-P\Delta V+\mu N$

$du=T\underbrace{ds}_{\to 0}-pdv+\mu\underbrace{dN}_{\to 0}$

$du+pdv=0$

$dE+pdv=0$ $\quad V=\frac{4\pi}{3}r^3$

$E=mc^2=\frac{4\pi}{3}r^3\rho c^2$

$dE=\cancel{\frac{4\pi}{3}}\cancel{3r^2}\dot r\rho c^2+\frac{4\pi}{3}r^3\dot\rho c^2+\cancel{\frac{4\pi}{3}}\cancel{3r^2}\dot r p=0$

$\dot r\rho c^2+\frac{r}{3}\dot\rho c^2+\dot r p=0 \quad \frac{3}{rc^2}\times$

$\dot\rho+3\frac{\dot r}{r}\rho+3\frac{\dot r}{r}\frac{p}{c^2}=0$

선속$_{SUN}=aT^4=5.67\times10^{-8}\ \mathrm{J/m^2\cdot s\cdot K^4}\ (5800k)^4$

$=6.2\times10^{7}\ \mathrm{J/m^2\cdot s}=6.2\times10^{4}\ \mathrm{kW/m^2}$

$T=\left(\frac{3c^2}{32\pi Ga}\right)^{\frac14}\frac{1}{\sqrt t}=1.5\times10^{10}\frac{1}{\sqrt t}$

$\frac{\dot\rho}{\rho}+3\frac{\dot r}{r}+3\frac{\dot r}{r}\frac{p}{\rho c^2}=0$

$\int \frac{dt}{d_4}=t$ $\quad \sum_{k=0}^{\infty}$

$\int dt=$

$\frac{\dot\rho}{\rho}=-3\frac{\dot r}{r}\left(1+\frac{p}{\rho c^2}\right)$

$p=w\rho c^2$ $\quad w=\frac13$ $\quad w=0$ $\quad w=-1$ $\quad \frac{\dot r}{r}=H$ $\quad \dot\rho=\frac{d\rho}{dt}$

$p=\frac13 aT^4$ $\quad H^2=\frac{8\pi G}{3}\rho$

$p=\frac13\rho c^2$

$=\frac13 aT^4$

$\frac{\dot\rho}{\rho}=-3H\left(1+\frac{\frac13\rho c^2}{\rho c^2}\right)=-3H\left(1+\frac13\right)$

$=-4H$

$T^4=\frac{\rho c^2}{a}$

$\dot\rho=-4H\rho=-4\left(\frac{8\pi G}{3}\rho\right)^{\frac12}\rho$ $\quad \rho=\frac{a}{c^2}T^4$

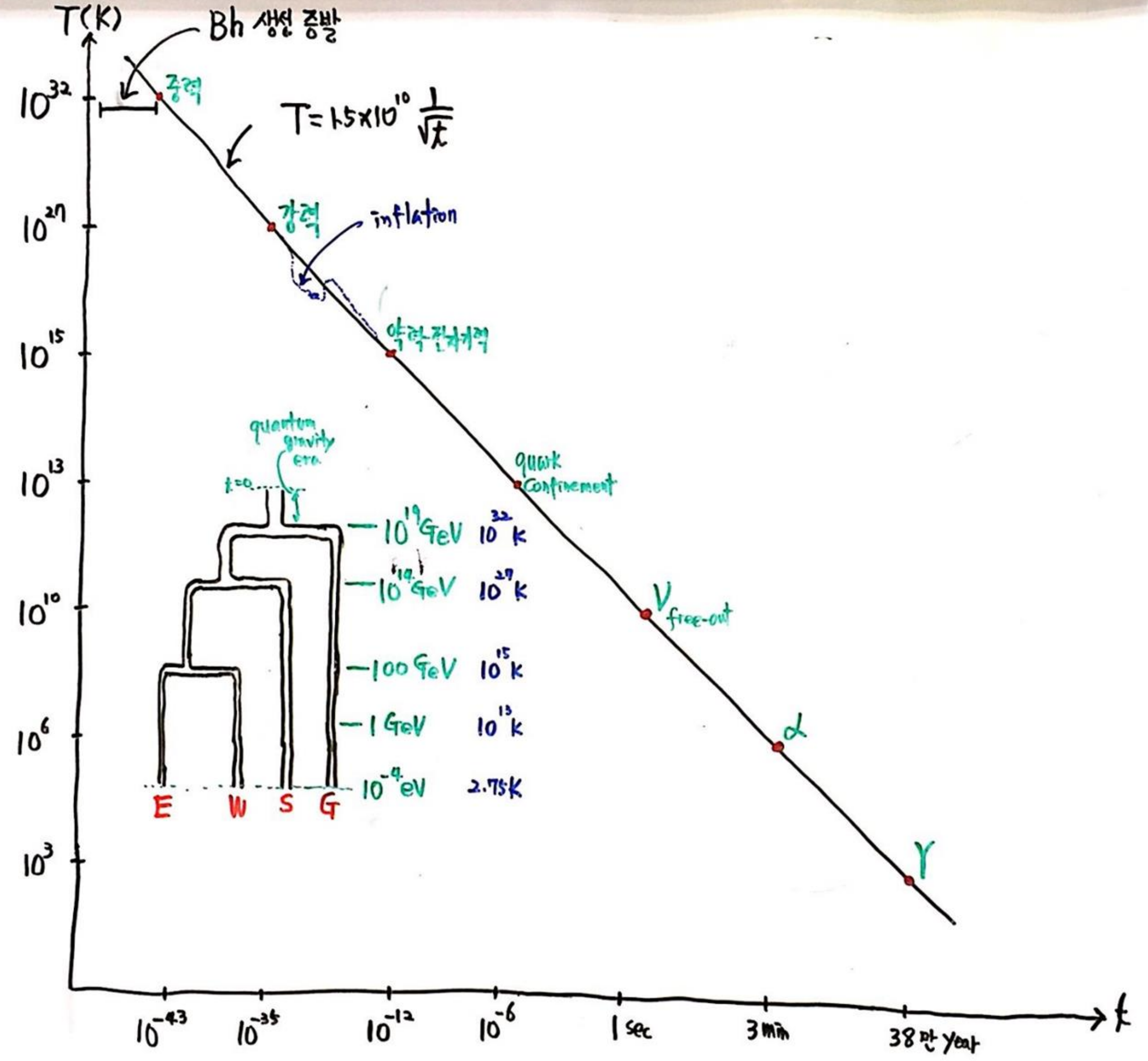
$\dot\rho\rho^{-\frac32}=-\left(\frac{128\pi G}{3}\right)^{\frac12}$

$\int\rho^{-\frac32}d\rho=-\int\left(\frac{128\pi G}{3}\right)^{\frac12}dt$

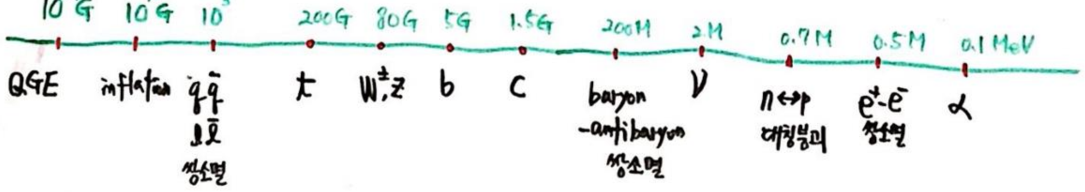
$\frac{\rho^{-\frac12}}{-\frac32+1}=-\left(\frac{128\pi G}{3}\right)^{\frac12}t$ $\quad \rho^{-\frac12}=\left(\frac{32\pi G}{3}\right)^{\frac12}t$

$\rho^{-\frac12}=\frac{1}{\rho^{\frac12}}=\frac{1}{\left(\frac{a}{c}T^4\right)^{\frac12}}=\left(\frac{32\pi G}{3}\right)^{\frac12}t$

$T^2=\frac{1}{\left(\frac{a}{c^2}\right)^{\frac12}\left(\frac{32\pi G}{3}\right)^{\frac12}t}=\left(\frac{3c^2}{32\pi Ga}\right)^{\frac12}\frac1t$



T(K)
Bh 생성 증발
중력
T=1.5×10^10 1/√t
강력
inflation
약력-전자기력
quantum gravity era
t=0
quark confinement
10^19 GeV 10^32 K
10^14 GeV 10^27 K
100 GeV 10^15 K
1 GeV 10^13 K
10^-4 eV 2.75K
E W S G
ν free-out
α
γ
10^32
10^27
10^15
10^13
10^10
10^6
10^3
10^-43
10^-35
10^-12
10^-6
1 sec
3 min
38 만 year
t



10^19 G
10^12 G
10^3
200G
80G
5G
1.5G
200M
2M
0.7M
0.5M
0.1 MeV
QGE
inflation
q q̄ 쌍소멸
t
W±, Z
b
c
baryon -antibaryon 쌍소멸
ν
n↔p 대칭붕괴
e+-e- 쌍소멸
α