Hitchiker's Guide: QGP in the Early Universe

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Contents

- Big Bang Basic Framework
- Nuclear Particles in the Early Universe; Limiting Temperature?
- Thermal Quarks and Gluons; Experimental Evidence

DON'T PANIC

If I can understand it, so can you!

The original Hubble Diagram

"A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae" E.Hubble (1929)

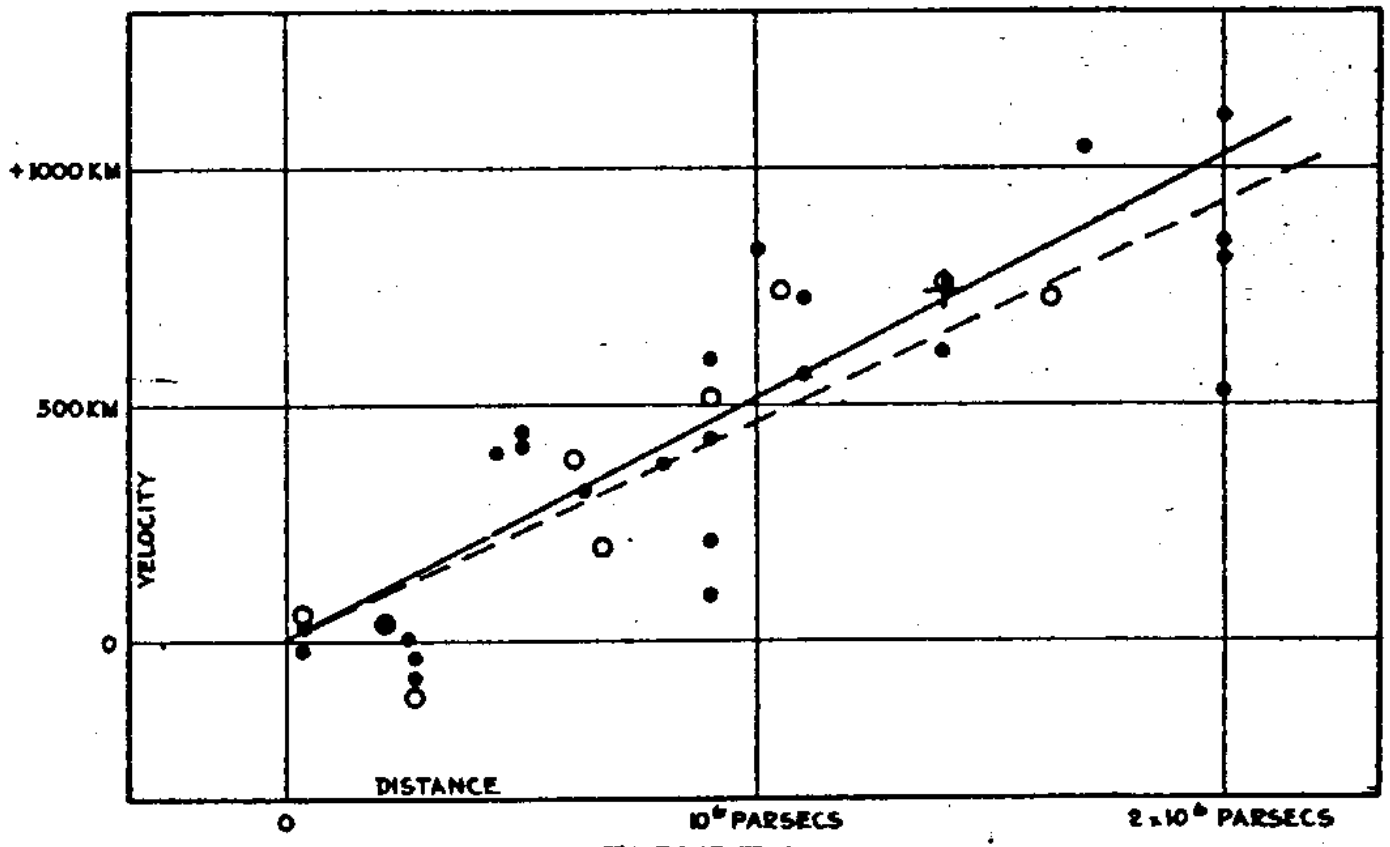


FIGURE 1

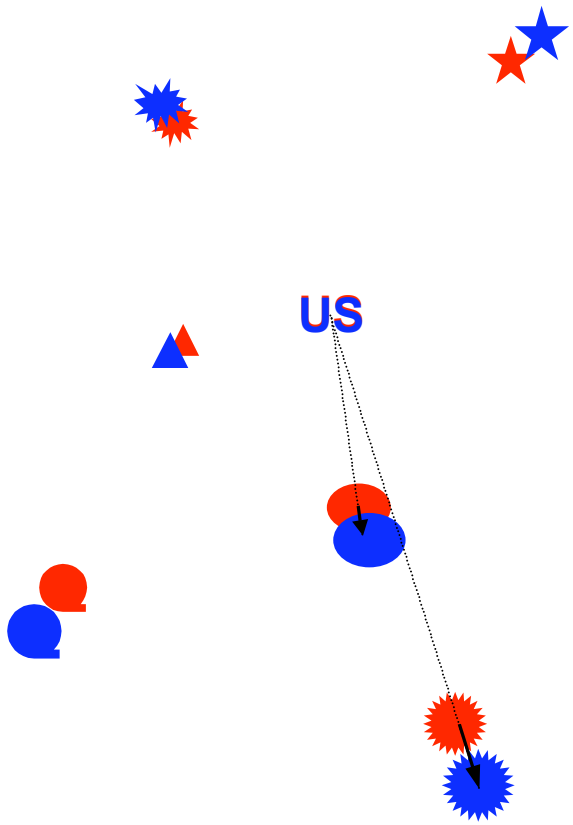
Edwin Hubble
American

Galaxies outside Milky Way

Henrietta Leavitt
American

Distances via variable stars

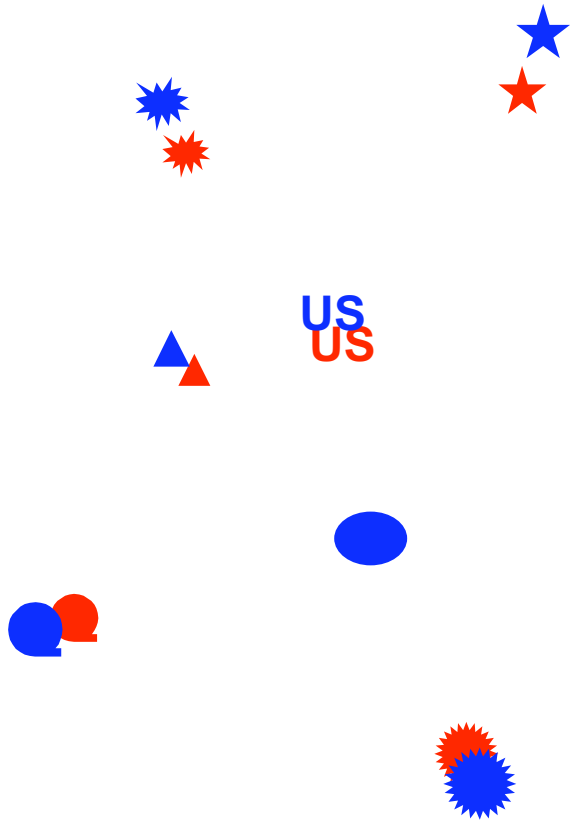
As seen from our position:



Now

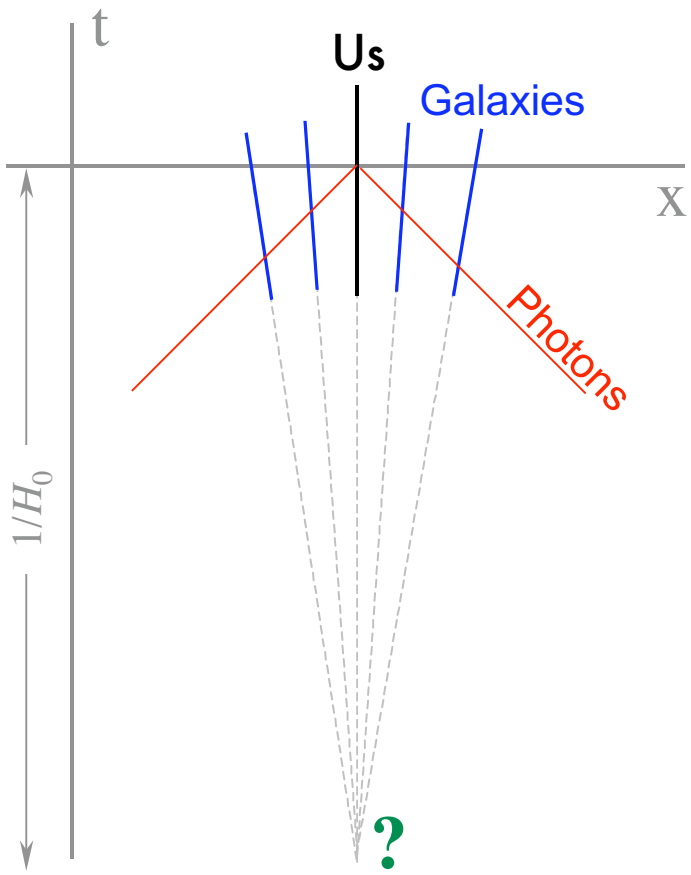
Slightly Earlier

As seen from another position:



Recessional velocity ∝ distance

Same pattern seen by all observers!



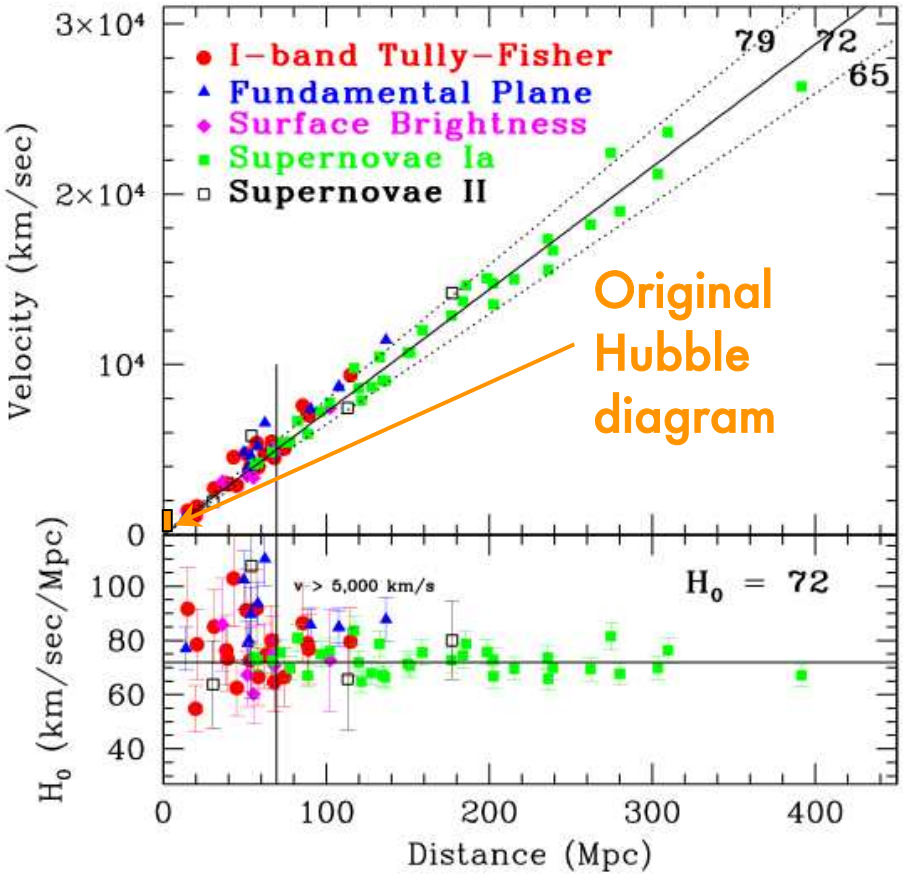
$$v_{\text{Recession}} = H_0\, d$$

$1/H_0 \sim 10^{10}$ year ~ Age of the Universe?

Freedman, et al. Astrophys. J. **553**, 47 (2001)

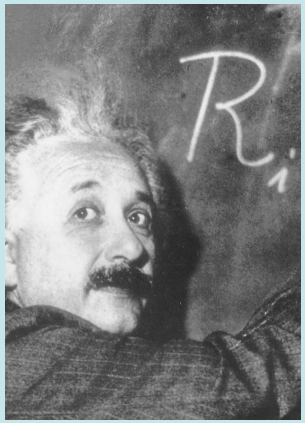
W. Freedman
Canadian

Modern Hubble constant (2001)



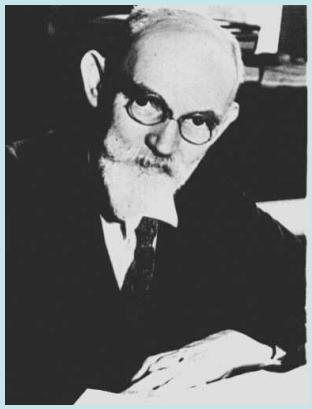
1929: H_0 ~500 km/sec/Mpc

2001: $H_0 = 72 \pm 7$ km/sec/Mpc



Albert Einstein
German

General Theory of Relativity (1915); Static, closed universe (1917)



W. de Sitter
Dutch

Vacuum-energy-filled universes "de Sitter space" (1917)

H.P. Robertson
American

A.G. Walker
British

Formalized most general form of isotropic and homogeneous universe in GR "Robertson-Walker metric" (1935-6)

A. Friedmann
Russian

G. LeMaitre
Belgian

Evolution of homogeneous, non-static (expanding) universes "Friedmann models" (1922, 1927)

Minkowski Metric

$$d\tau^2 = -ds^2 = dt^2 - dx^2$$

H. Minkowski German

"Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality" (1907)

Robertson-Walker Metric

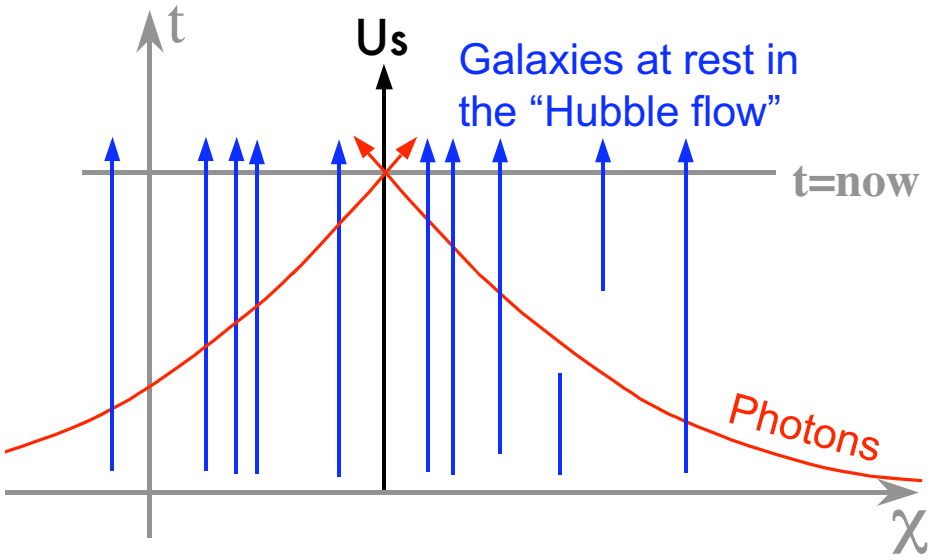
$$d\tau^2 = -ds^2 = dt^2 - \left[a(t)\right]^2 d\chi^2$$

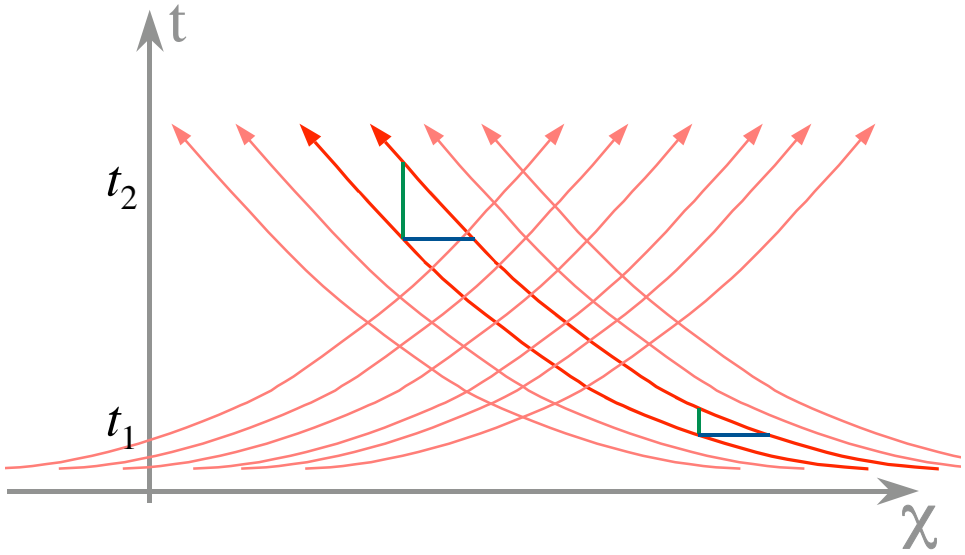
$a(t)$ dimensionless; set $a(\text{now}) = 1$

χ has units of length

$a(t)\Delta\chi =$ physical separation at time t

Robertson-Walker Coordinates





Galaxies

$\chi =$ constant

"At rest in the Hubble flow"

Hubble Constant

$$H(t) = \frac{\text{velocity}}{\text{distance}} = \frac{\frac{d}{dt}[a(t)\Delta\chi]}{a(t)\Delta\chi} = \frac{\dot{a}(t)}{a(t)}$$

Photons

$$d\tau = 0 \;\Rightarrow\; \frac{dt}{d\chi} = \pm a(t)$$

Cosmological Red Shift

A photon's period grows $\propto a(t)$

Its coordinate wavelength $\Delta\chi$ is constant; its physical wavelength $a(t)\Delta\chi$ grows $\propto a(t)$

$\lambda(t_2)/\lambda(t_1) = a(t_2)/a(t_1) \equiv 1+z$

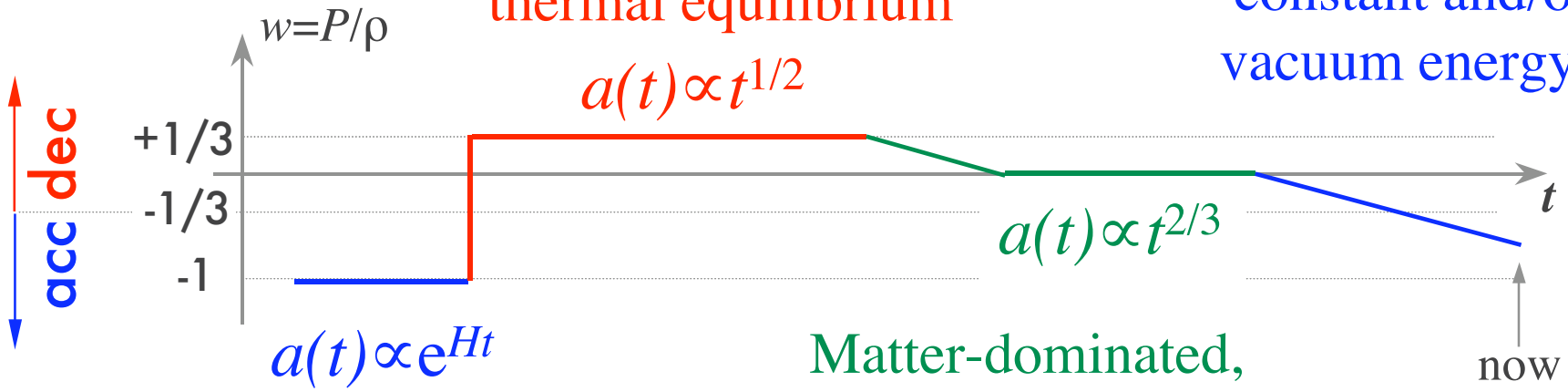
$a(t)$ depends on pressure/energy:

The New Standard Cosmology in Four Easy Steps

Acceleration in $a(t)$, domination by cosmological constant and/or vacuum energy.

Radiation-dominated thermal equilibrium

$a(t) \propto t^{1/2}$



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

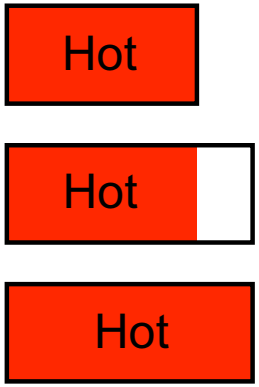
$a(t) \propto e^{Ht}$

Inflation, dominated by "inflaton field" vacuum energy

Matter-dominated, non-uniformities grow (structure)

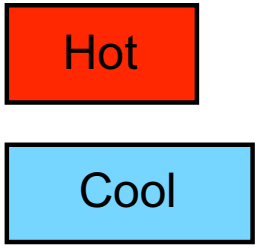
Basic Thermodynamics

$$dE = TdS - PdV$$



Sudden expansion, fluid fills empty space without loss of energy.

$dE = 0 \quad PdV > 0$ **therefore** $dS > 0$



Gradual expansion (equilibrium maintained), fluid loses energy through PdV work.

$dE = -PdV$ **therefore** $dS = 0$ Isentropic Adiabatic

Golden Rule 1: Entropy per co-moving volume is conserved

Golden Rule 2: All entropy is in relativistic species

Expansion covers many decades in T, so typically either T>>m (relativistic) or T<<m (frozen out)

Golden Rule 3: All chemical potentials are negligible

Entropy S in co-moving volume $(\Delta\chi)^3$ preserved

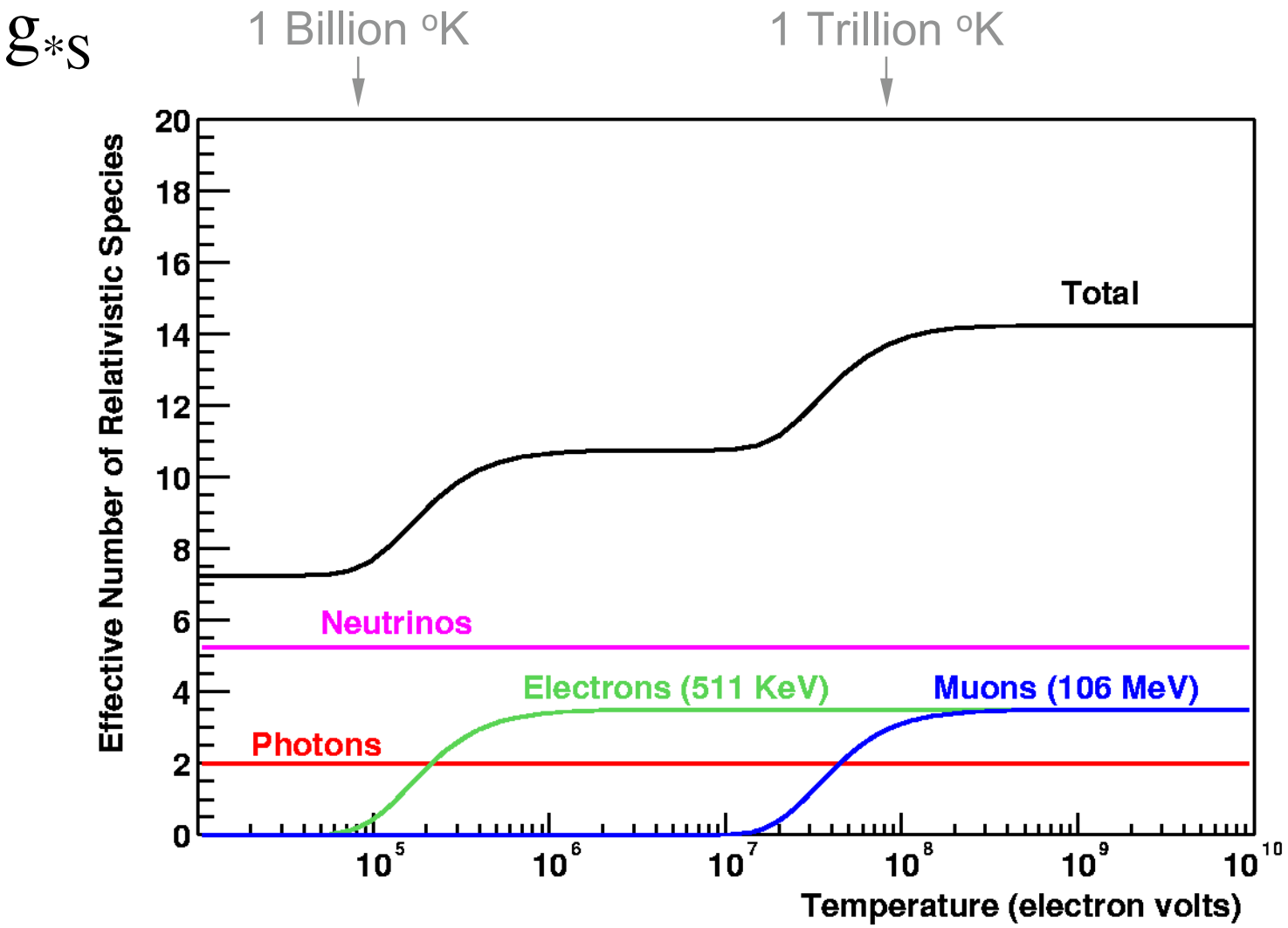
Relativistic gas $$\frac{S}{V} \equiv s = \sum_{\text{Particle Type}} s_{\text{Particle Type}} = \sum_{\text{Particle Type}} \left(\frac{2\pi^2}{45}\right) T^3 = \left(\frac{2\pi^2}{45}\right) g_{*S} T^3$$

$g_{*S} \equiv$ effective number of (Boson) relativistic species

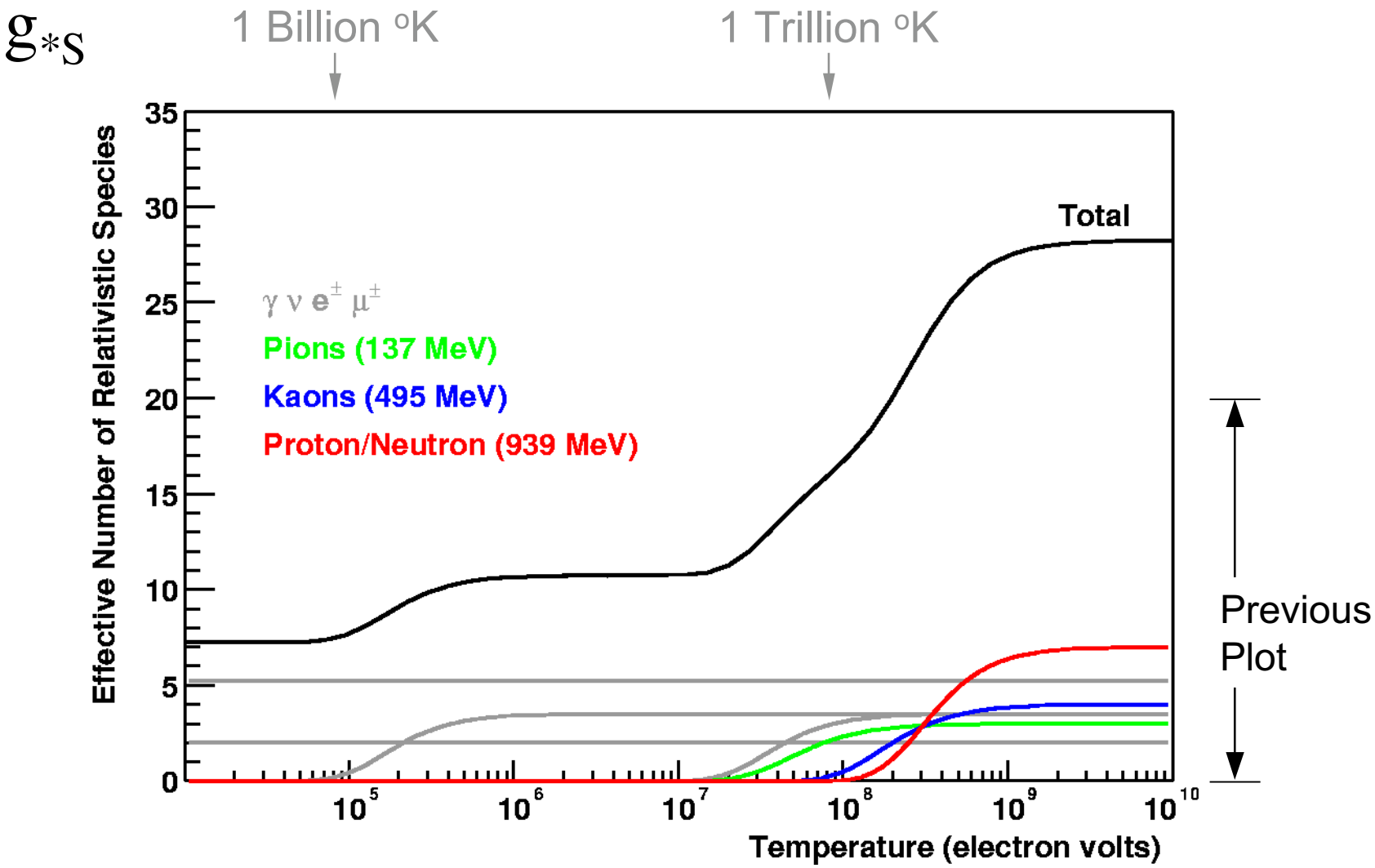
Entropy density $$\frac{S}{V} = \frac{S}{(\Delta\chi)^3}\frac{1}{a^3} = \frac{2\pi^2}{45} g_{*S} T^3$$

Golden Rule 4:

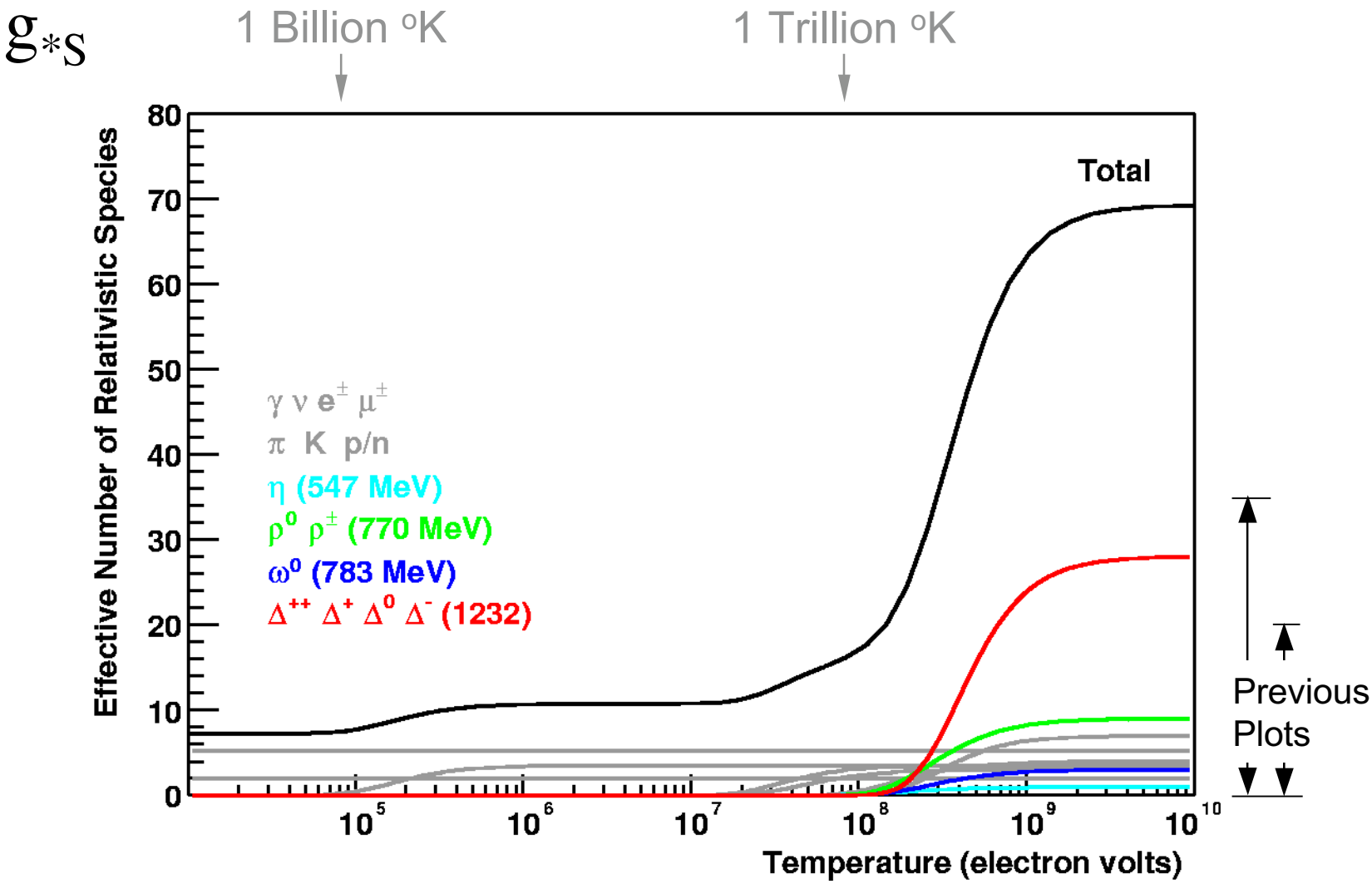
$$T \propto \left(g_{*S}\right)^{-1/3} \frac{1}{a}$$



Start with light particles, no strong nuclear force



Now add *hadrons* = feel strong nuclear force



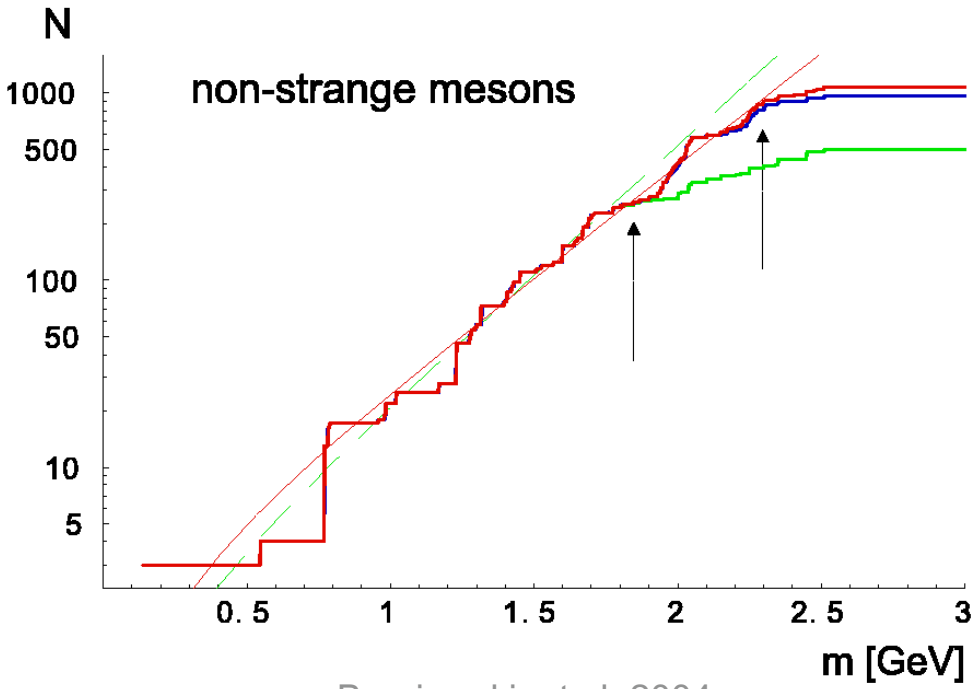
Keep adding more hadrons….

How many hadrons?

Density of hadron mass states dN/dM increases *exponentially* with mass.

$$\frac{dN}{dM} \sim \exp\left(M/T_H\right)$$

$T_H \sim 2\times10^{12}\ ^oK$



Broniowski, et.al. 2004

Prior to the 1970's this was explained in several ways theoretically

Statistical Bootstrap Hadrons made of hadrons made of hadrons…

Regge Trajectories Stretchy rotators, first string theory

Ordinary statistical mechanics:

$$E \sim \sum_{\text{states } i} E_i \, g_i \exp(-E_i/T) \sim \int E \frac{dN}{dE} \exp(-E/T)\, dE$$

For thermal hadron gas (crudely set $E_i = M_i$):

$$E \sim \int M \frac{dN}{dM} \exp(-M/T)\, dM \qquad \text{now add in } \frac{dN}{dM} \sim \exp(M/T_{\mathrm{H}})$$

$$\sim \int M \exp\left(-M\left[\frac{1}{T} - \frac{1}{T_{\mathrm{H}}}\right]\right) dM$$

Energy *diverges* as $T \dashrightarrow T_{\mathrm{H}}$

Maximum achievable temperature?

"…a veil, obscuring our view of the very beginning." Steven Weinberg, *The First Three Minutes* (1977)

Rolf Hagedorn
German

Hadron bootstrap model and limiting temperature (1965)

QCD to the rescue!

Replace Hadrons (messy and numerous)

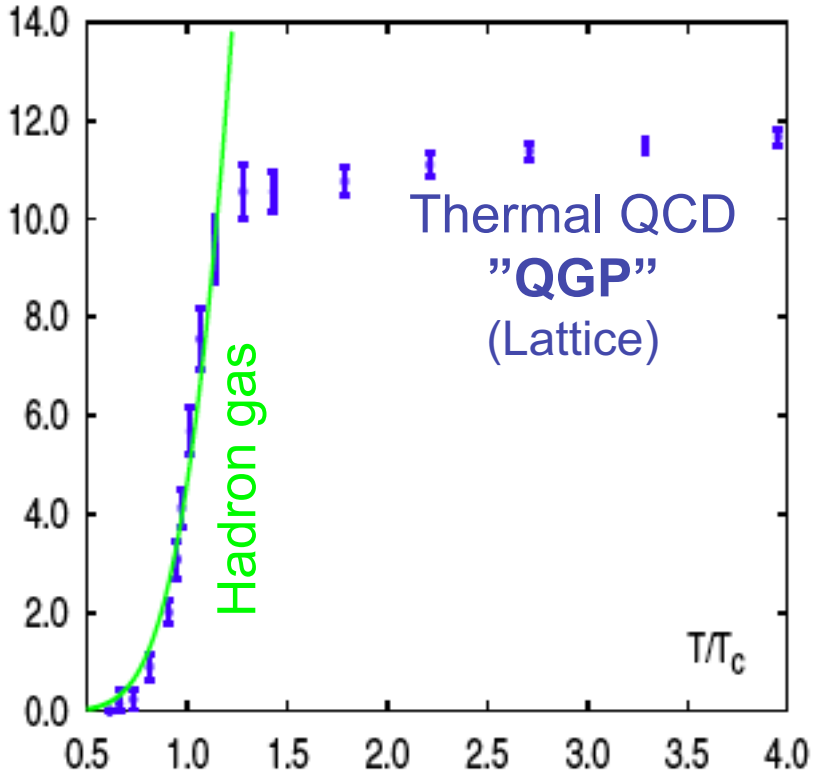
by Quarks and Gluons (simple and few)

"In 1972 the early universe seemed hopelessly opaque…conditions of ultrahigh temperatures…produce a theoretically intractable mess. But asymptotic freedom renders ultrahigh temperatures friendly…"
Frank Wilczek, Nobel Lecture (RMP 05)

D. Gross
H.D. Politzer
F. Wilczek
American

QCD Asymptotic Freedom (1973)

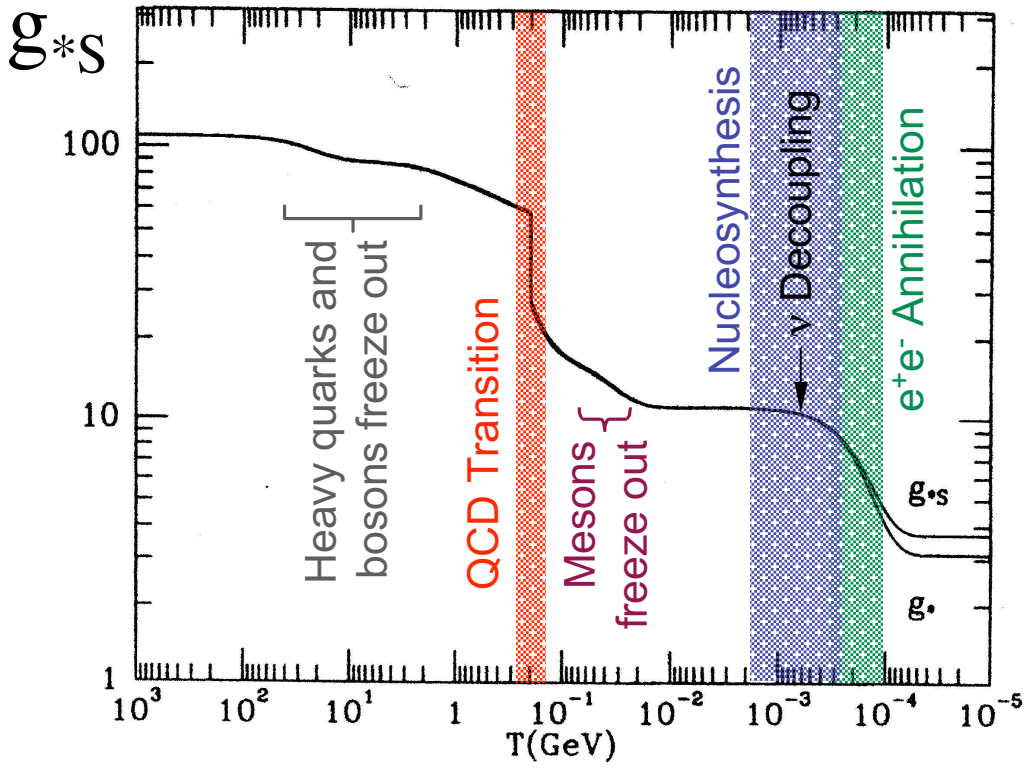
$\varepsilon/T^4 \propto g_{*S}$



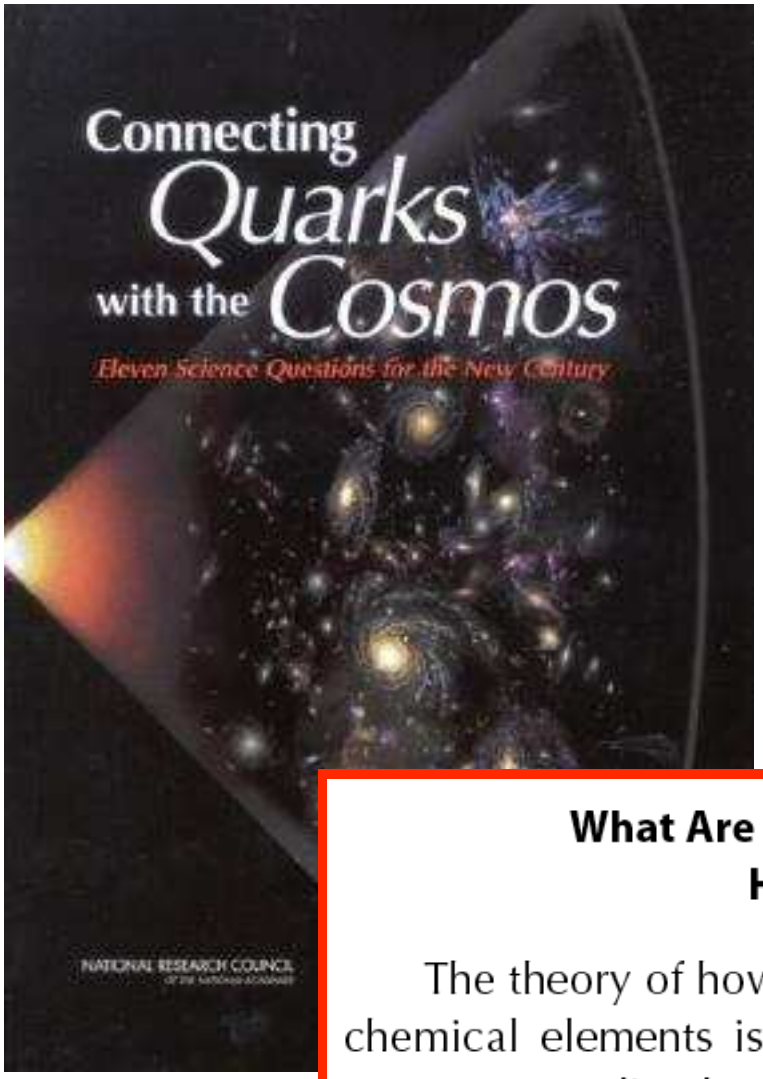
Karsch, Redlich, Tawfik, Eur.Phys.J.**C29**:549-556,2003

"Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today…since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted…to form a quark-gluon plasma."
David Gross, Nobel Lecture (RMP 05)

Thermal QCD – i.e. quarks and gluons – makes the very early universe tractable; but where is the experimental proof?



Kolb & Turner, "The Early Universe"



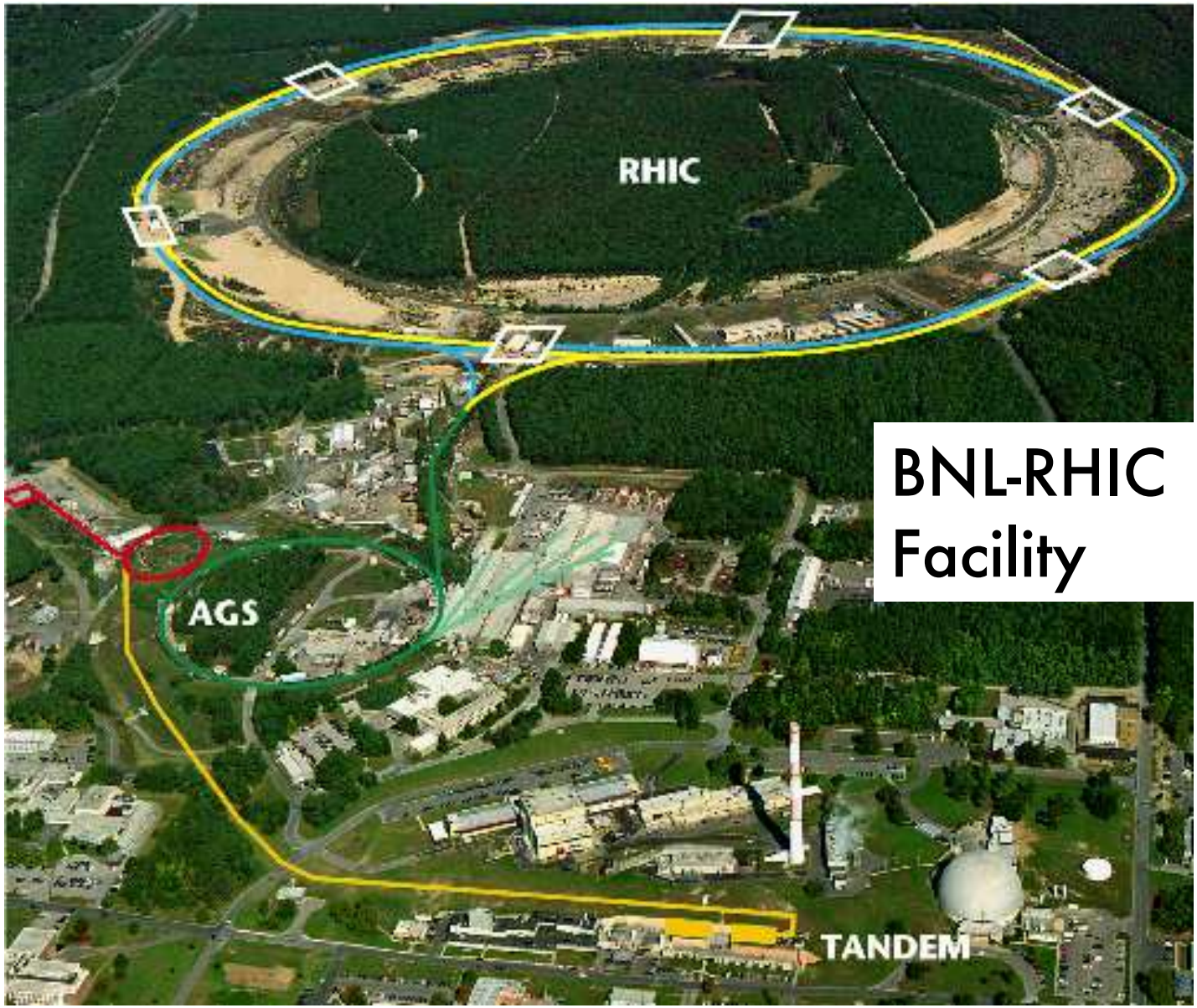
National Research Council Report (2003)

Eleven Science Questions for the New Century

Question 8 is:

What Are the New States of Matter at Exceedingly High Density and Temperature?

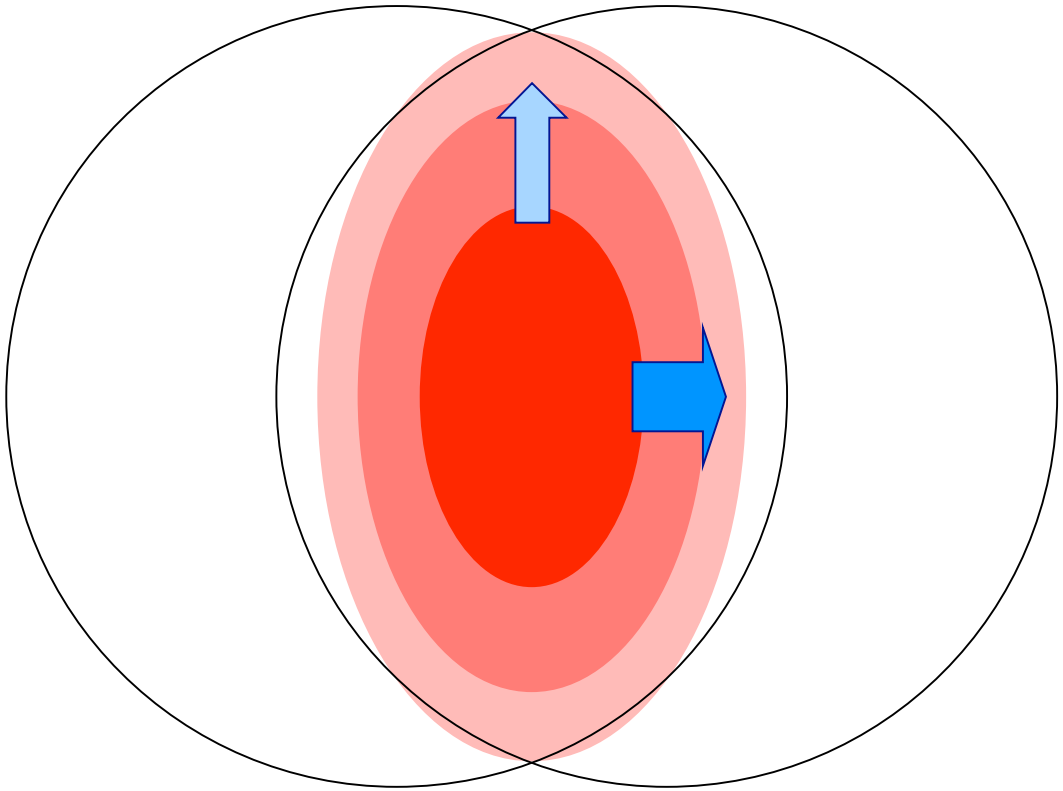
The theory of how protons and neutrons form the atomic nuclei of the chemical elements is well developed. At higher densities, neutrons and protons may dissolve into an undifferentiated soup of quarks and gluons, which can be probed in heavy-ion accelerators. Densities beyond nuclear densities occur and can be probed in neutron stars, and still higher densities and temperatures existed in the early universe.

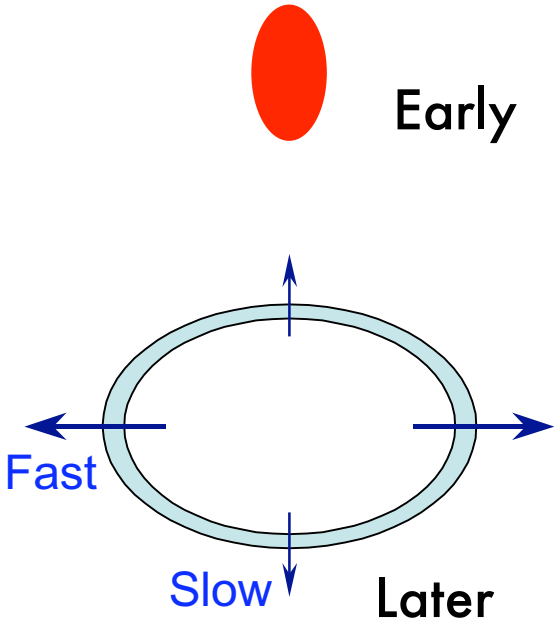


BNL-RHIC Facility

Also: BNL-AGS, CERN-SPS, CERN-LHC

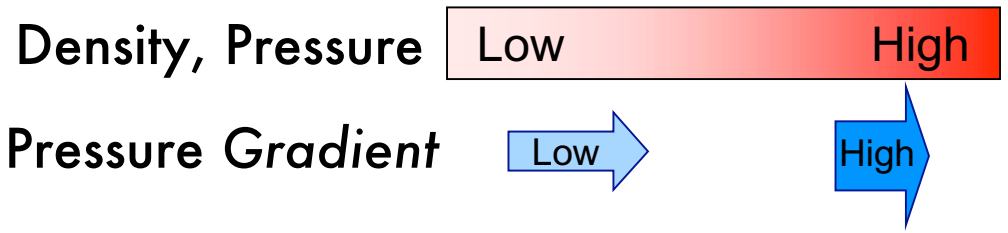
Initial (10^{-24} sec) Thermalized Medium





Elliptic momentum anisotropy

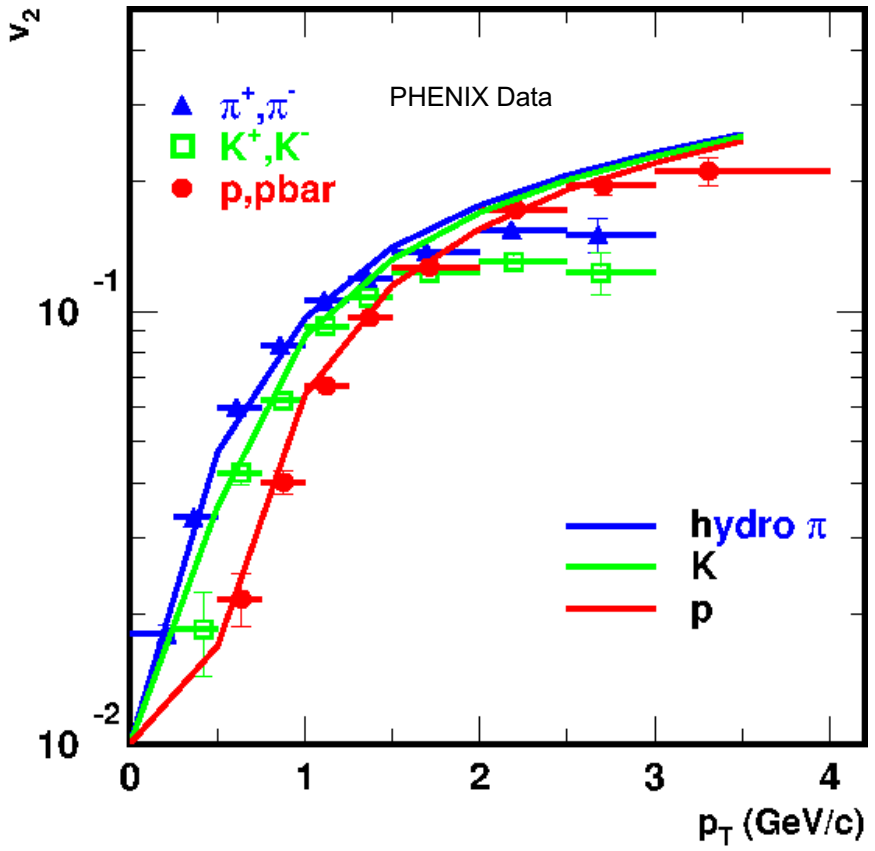
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$



Fluid dynamics predicts momentum anisotropy correctly for 99% of particles produced in Au+Au

What does it mean?

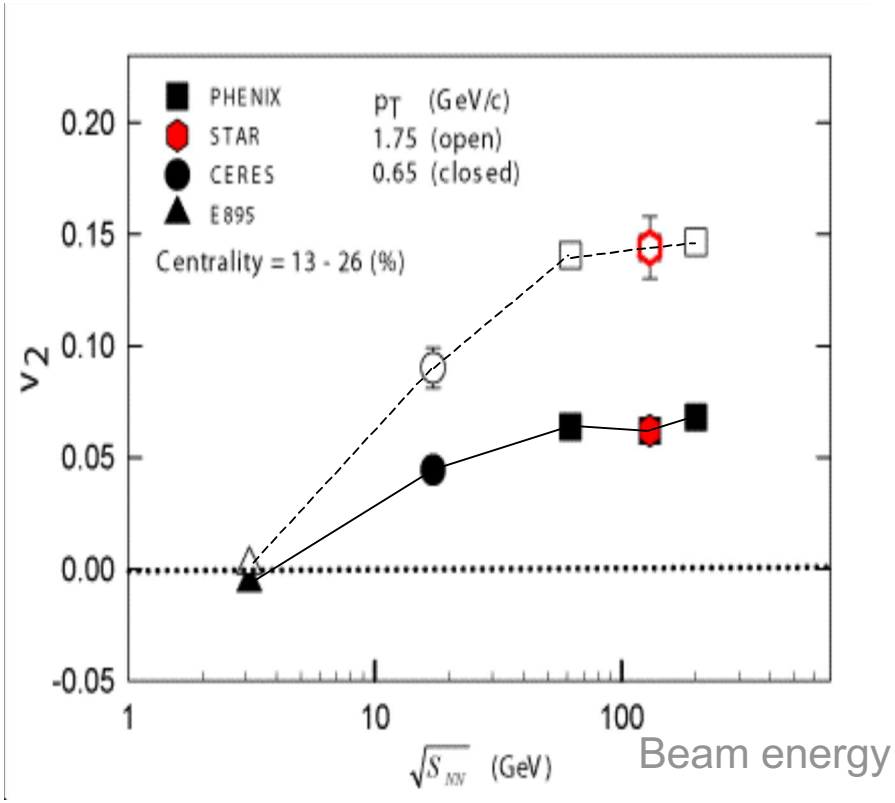
- Strong self-re-interaction
- Early thermalization (10^{-24} sec)
- Low dissipation (viscosity)
- Equation of state P/ρ similar to relativistic gas



Momentum anisotropy increases as we increase beam energy & energy density

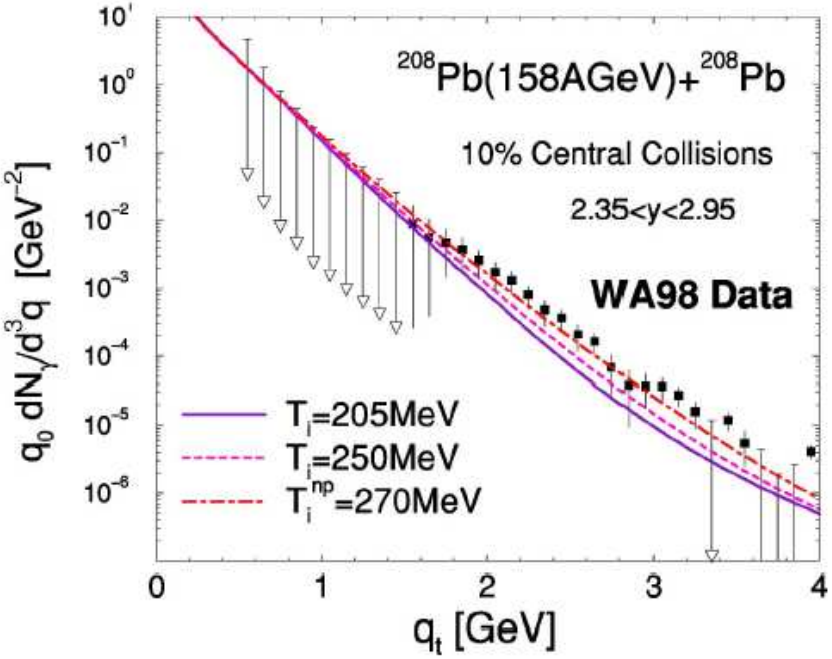
What does it mean?

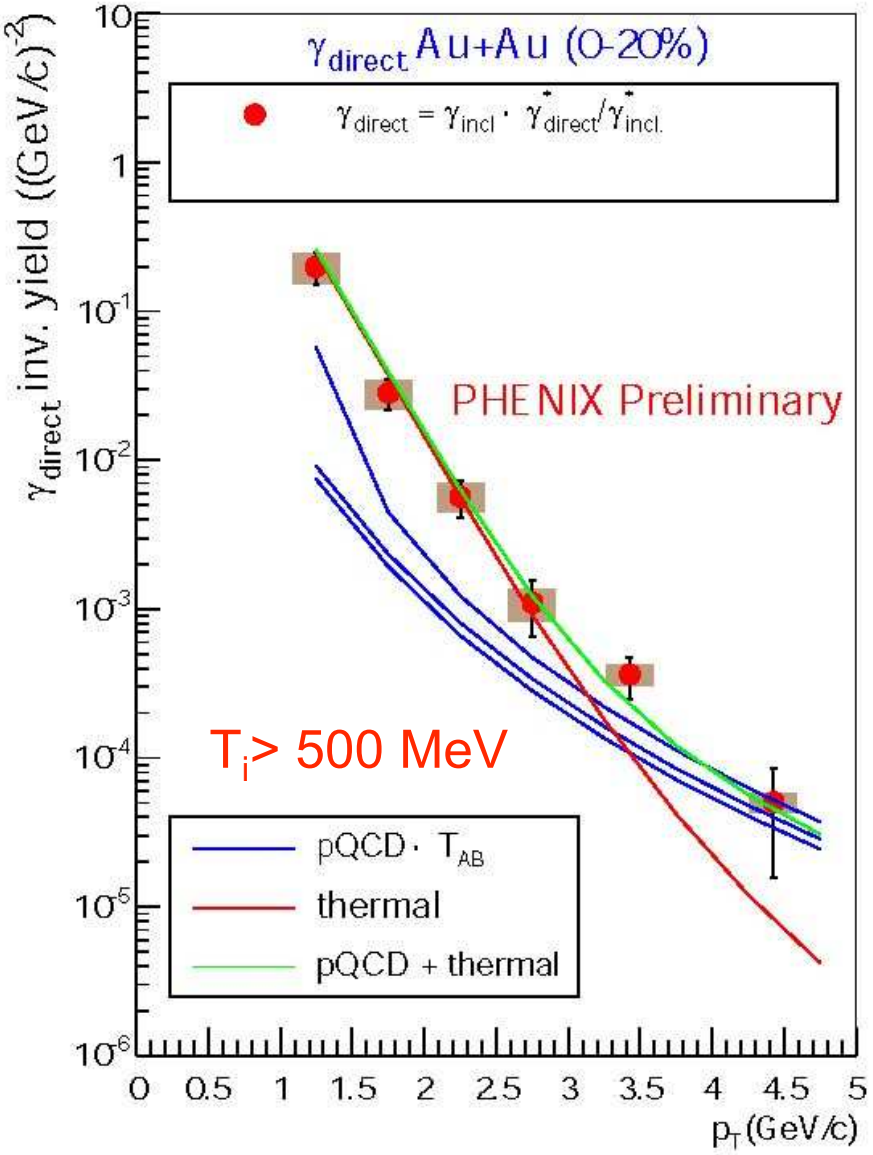
- High acceleration requires high $\boldsymbol{P}/\rho$ pressure/energy density. Hagedorn picture would be softer since massive hadrons are non-relativistic.
- Increase/saturate with higher energy densities. In Hagedorn picture pressure *decreases* with density.



Thermal photon radiation from quarks and gluons?

Direct photons from nuclear collisions *suggest* initial temperatures $> T_H$





Ideal gas ≠ Ideal fluid

Long mfp	Short mfp
High dissipation	Low dissipation

Data imply (D. Teaney, D. Molnar):

$$\frac{\eta \text{ Shear viscosity}}{s \text{ Entropy density}} < \sim 0.1$$

$$\lambda_{\text{Mean Free Path}} \sim \lambda_{\text{de Broglie}}$$

Quantum Limit! "Perfect Fluid"

Sakharov criteria for baryogenesis

1. *B* violation
2. *C*,*CP* violation
3. Out of equilibrium

Most of the early universe is QCD!

Dissipation could be relevant here:

Conclusions

- The early universe is straightforward to describe, given simplifying assumptions of isotropy, homogeneity, and thermal equilibrium.
- Strong interaction/hadron physics made it hard to understand $T > 100$ MeV $\sim 10^{12}$ K.
- Transition to thermal QCD makes high temperatures tractable theoretically; but we are only now delivering on a 30-year-old promise to test it experimentally.

References

Freedman & Turner, "Measuring and understanding the universe", Rev Mod Phys 75, 1433 (2003)

Kolb & Turner, *The Early Universe*, Westview (1990)

Dodelson, *Modern Cosmology*, Academic Press (2003)

Weinberg, *Gravitation and Cosmology*, Wiley (1972)

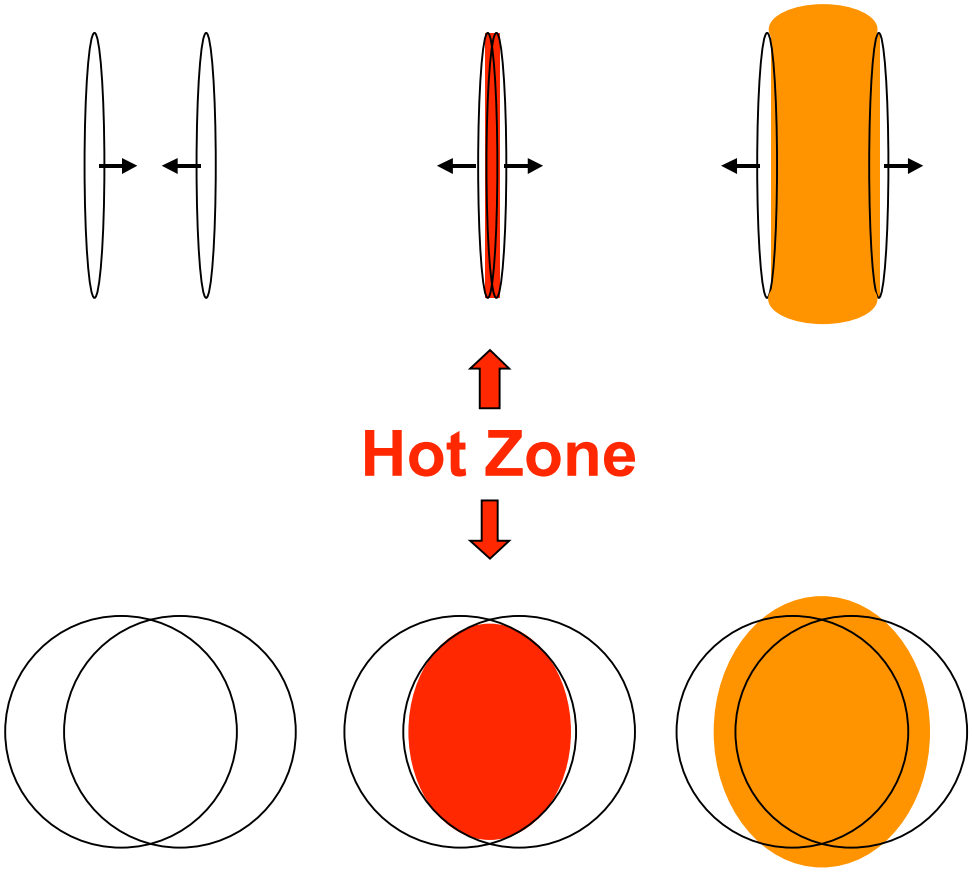
Weinberg, *The First Three Minutes*, Basic (1977, 1993)

Schutz, *A First Course in General Relativity*, Cambridge (1985)

Misner, Thorne, Wheeler, *Gravitation*, W.H.Freeman (1973)

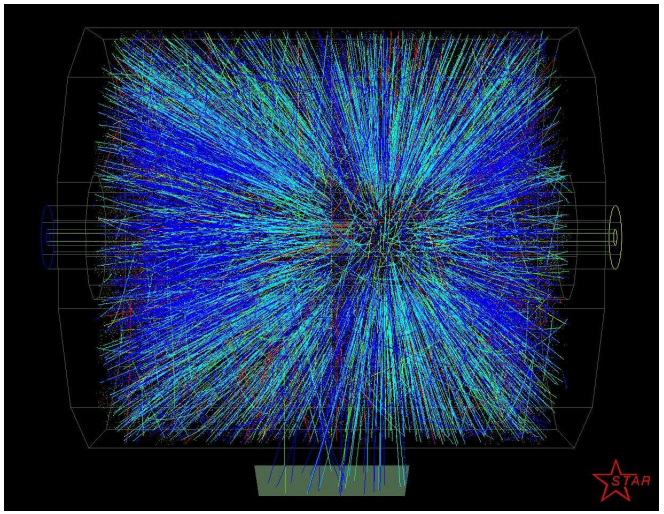
Backup material

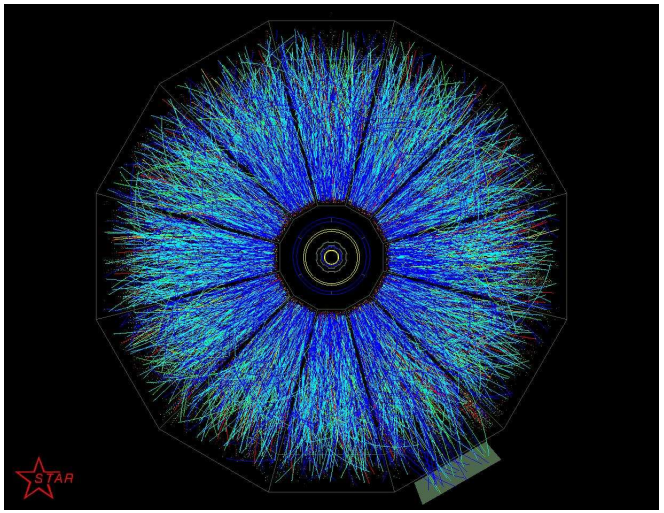
Side-to-beam view



Along-the-beam view

STAR Experiment at RHIC





Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

H. Minkowski German

"Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality" (1907)

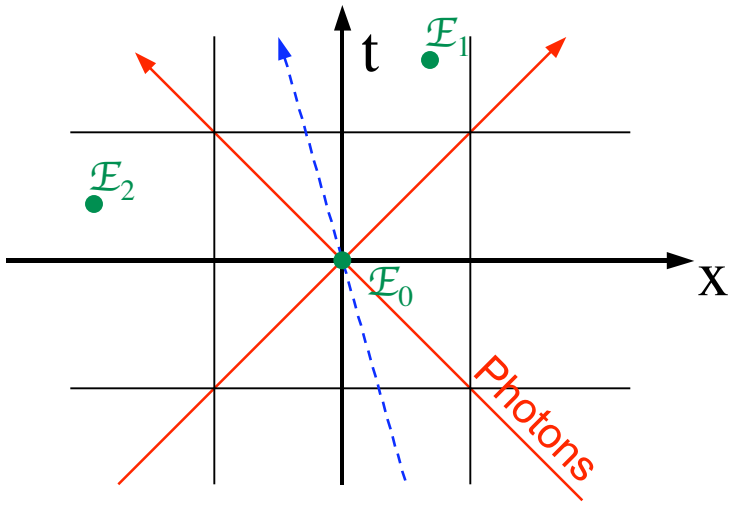
$$d\tau^2 = -ds^2 = (dt)^2 - (dx)^2 - (dy)^2 - (dz)^2$$
$$= (dt')^2 - (dx')^2 - (dy')^2 - (dz')^2$$

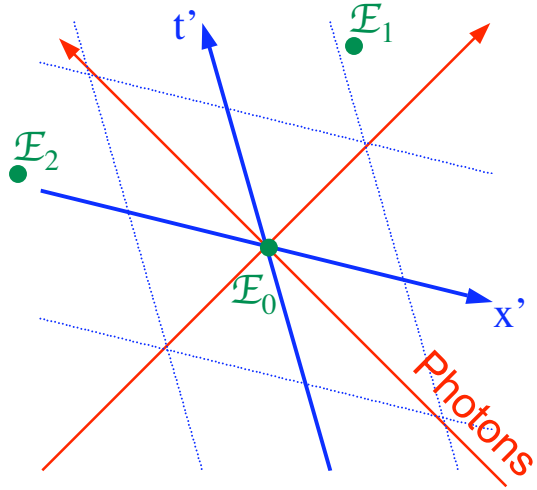
$$dx^0 \equiv dt \quad dx^1 \equiv dx \quad dx^2 \equiv dy \quad dx^3 \equiv dz$$

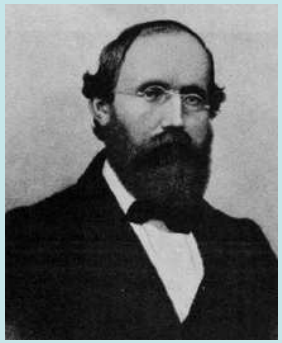
$$d\tau^2 = -ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

$$g_{\mu\nu} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

Metric Tensor







B. Riemann
German

Formalized non-Euclidean geometry (1854)

Complete coordinate freedom!

All physics is in $g_{\mu\nu}(x^0, x^1, x^2, x^3)$

$a(t) \Leftrightarrow$ a Friedmann-Robertson-Walker (FRW) cosmology

Three basic solutions for $a(t)$:

1. Relativistic gas, "radiation dominated"

   $P/\rho = 1/3 \quad \rho \propto a^{-4} \quad a(t) \propto t^{1/2}$

2. Non-relativistic gas, "matter dominated"

   $P/\rho = 0 \quad \rho \propto a^{-3} \quad a(t) \propto t^{2/3}$

3. "Cosmological-constant-dominated" or "vacuum-energy-dominated"

   $P/\rho = -1 \quad \rho \propto \text{constant} \quad a(t) \propto e^{Ht}$ "de Sitter space"

$$T_{00} = \rho$$ Energy density (in local rest frame)

Friedmann Equation 1 (Λ=0 version)

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\pi}{3} G\rho - \frac{1}{r_0^{\,2} a^2}$$

Curvature

$$\rho_{\text{Critical}} \equiv \frac{3H^2}{8\pi G} \qquad \rho / \rho_{\text{Cr}} \equiv \Omega \qquad \Omega = 1 \Rightarrow \text{Flat}$$

Q: How does ρ change during expansion?

Friedmann Equation 2 (Isen/Iso-tropic fluid,Λ=0)

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

Ac/De-celeration of the Universe's expansion

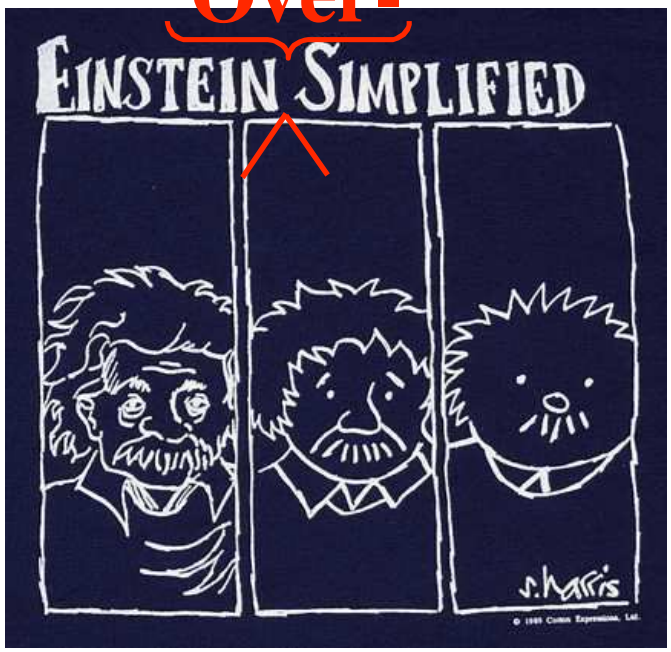
If $\rho(t) \geq 0$ and $P(t) \geq 0$ then

$\dot{a}(t) \geq 0$ and $\ddot{a}(t) \leq 0$, and then

$a(t) = 0$ for some t

Necessity of a Big Bang!

However, this cannot describe a static, non-empty FRW Universe.



$$\begin{pmatrix}\text{Something}\\ \text{about space-time}\\ \text{curvature}\end{pmatrix} = \begin{pmatrix}\text{Something}\\ \text{about}\\ \text{mass-energy}\end{pmatrix}$$

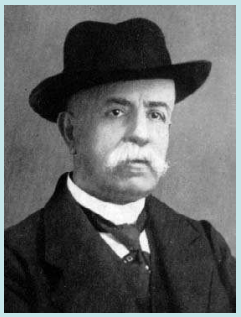
Metric Tensor $g_{\mu\nu}$ Stress-Energy Tensor $T_{\mu\nu}$

Riemann Tensor $R^{\alpha}{}_{\beta\gamma\delta}$

Ricci Tensor $R_{\mu\nu} = R^{\alpha}{}_{\mu\alpha\nu}$

Ricci Scalar $R = R^{\alpha}{}_{\alpha}$

B. Riemann
German
Formalized non-Euclidean geometry (1854)



G. Ricci-Curbastro
Italian
Tensor calculus (1888)

$$\underbrace{R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}}_{\text{For continuity}} - \underbrace{\Lambda}_{\text{Unknown}} g_{\mu\nu} = \underbrace{8\pi G_{\text{Newton}}}_{\text{To match Newton}} T_{\mu\nu}$$

$\equiv G_{\mu\nu}$ Einstein Tensor

$$G_{\mu\nu} = 8\pi T_{\mu\nu} \quad \text{Einstein Field Equation(s)}$$

Friedmann 1 and 2:

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\pi}{3}G\rho - \frac{1}{r_0{}^2 a^2} \qquad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

With freedom to choose $r_0{}^2$ and Λ, we can arrange to have a′=a′′=0 universe with finite matter density

Einstein 1917 "Einstein Closed, Static Universe"

Λ disregarded after Hubble expansion discovered

- but -

"vacuum energy" acts just like Λ

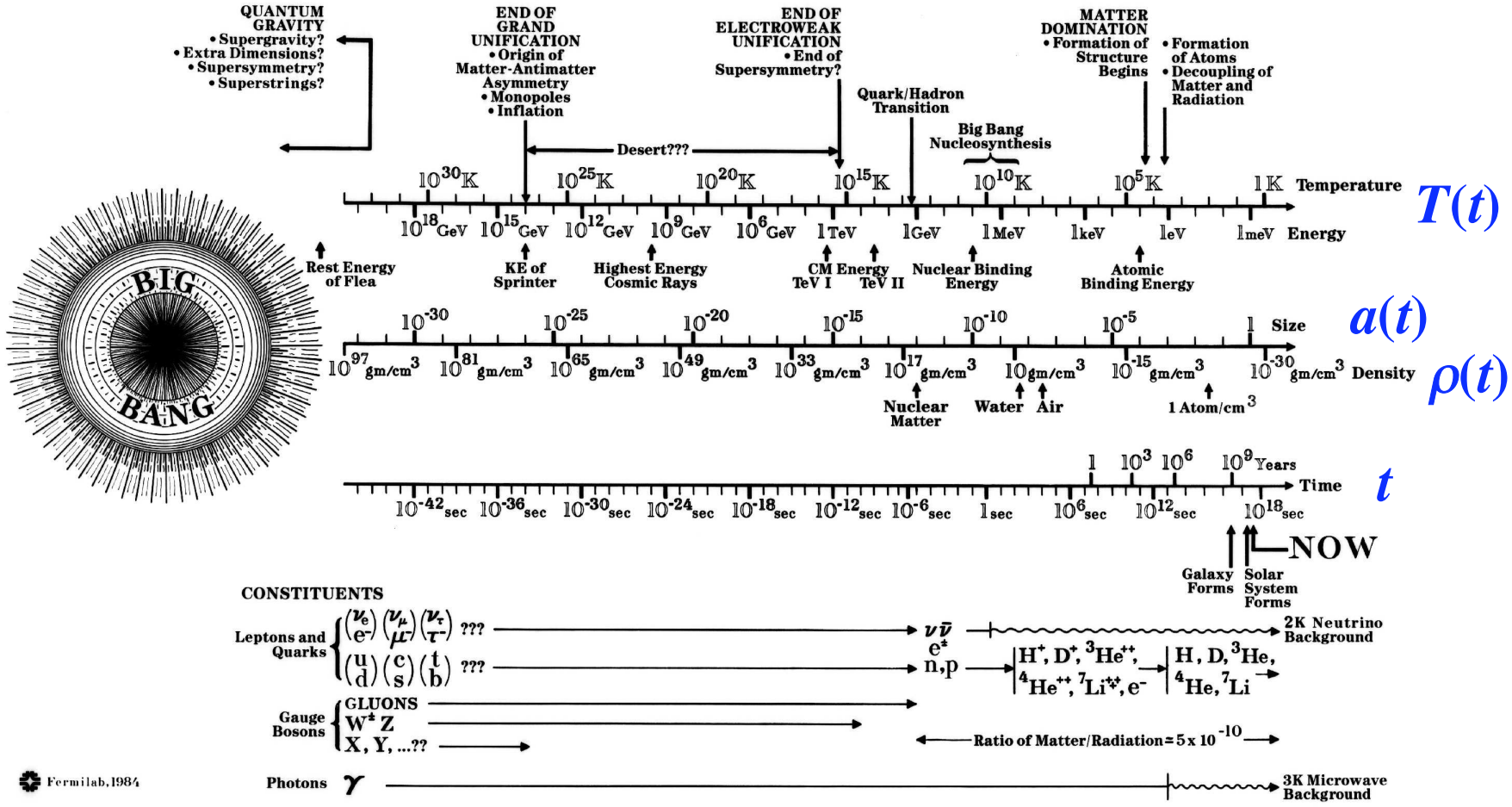
Re-introduce "cosmological constant" Λ

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu} \quad \text{rearrange} \quad G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}$$

$$G_{\mu\nu} = 8\pi \begin{bmatrix} \rho_M + \frac{\Lambda}{8\pi} & 0 & 0 & 0 \\ 0 & P_M - \frac{\Lambda}{8\pi} & 0 & 0 \\ 0 & 0 & P_M - \frac{\Lambda}{8\pi} & 0 \\ 0 & 0 & 0 & P_M - \frac{\Lambda}{8\pi} \end{bmatrix} \equiv 8\pi T^{Eff}{}_{\mu\nu}$$

Generalize $\rho(t)=\rho_{Matter}(t) +\Lambda/8\pi$ $P(t)=P_{Matter}(t) -\Lambda/8\pi$

Cosmological constant acts like constant energy density, constant negative pressure, with EOS $P/\rho = -1$



$T(t)$

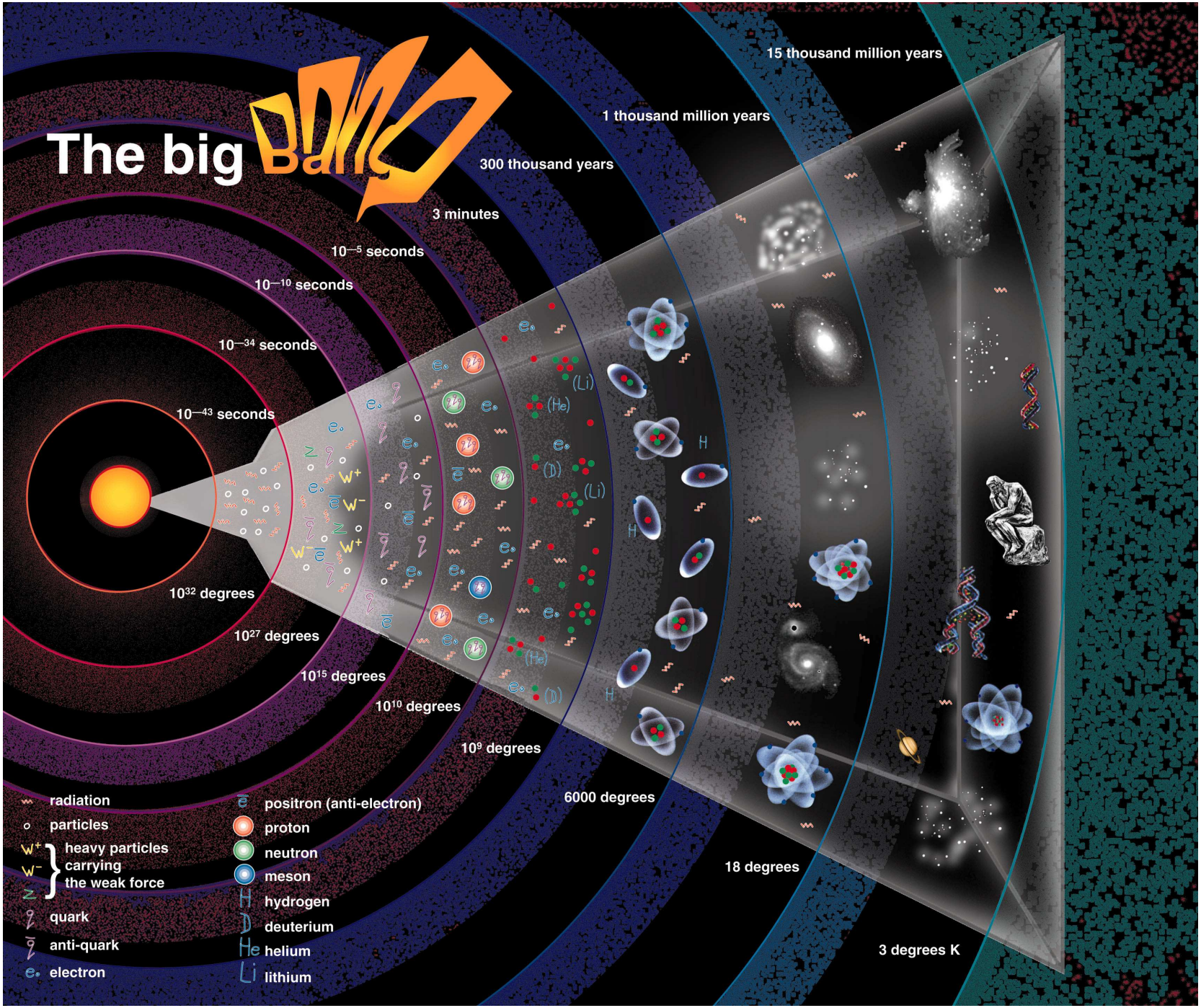
$a(t)$

$\rho(t)$

t

How do we relate T to a,ρ? i.e. thermodynamics

Fermilab Photograph 85-138CN


The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10−5 seconds
10−10 seconds
10−34 seconds
10−43 seconds
10^32 degrees
10^27 degrees
10^15 degrees
10^10 degrees
10^9 degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

The QCD quark-hadron transition is typically ignored by cosmologists as uninteresting

Weinberg (1972): Considers Hagedorn-style limiting-temperature model, leads to $a(t) \propto t^{2/3} |\ln t|^{1/2}$; but concludes "…the present contents…depends only on the entropy per baryon…. In order to learn something about the behavior of the universe before the temperature dropped below 10^{12o}K we need to look for fossils [relics]…."

Kolb & Turner (1990): "While we will not discuss the quark/hadron transition, the details and the nature (1st order, 2nd order, etc.) of this transition are of some cosmological interest, as local inhomogeneities in the baryon number density could possible affect…primordial nucleosythesis…"

Golden Rule 5: Equilibrium is boring!

Would you like to live in thermal equilibrium at 2.75°K?

Example of e^+e^- annihilation transferring entropy to photons, after neutrinos have already decoupled (relics).

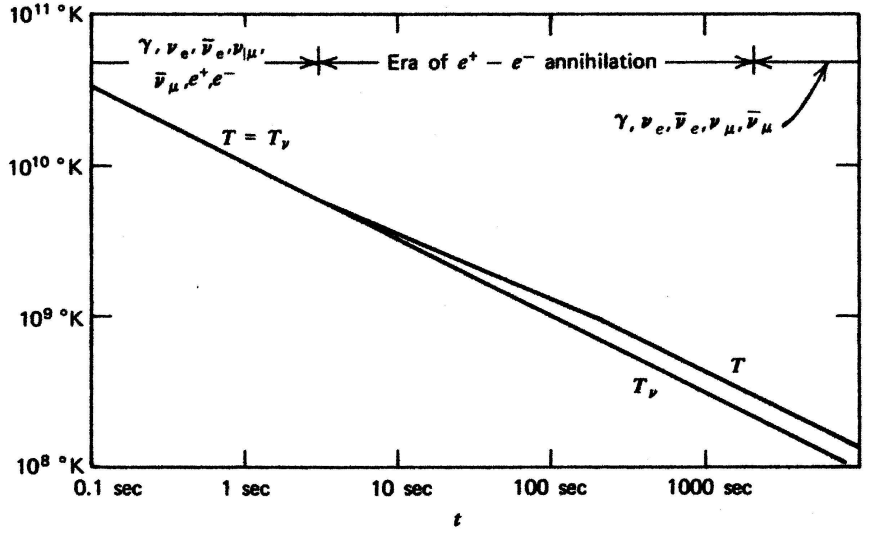


Figure 15.5 Thermal history of the early universe. Here T is the temperature of the $\gamma - e^+ - e^-$ plasma, and T_ν is the temperature of the decoupled ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$.

Weinberg, *Gravitation and Cosmology*, Wiley 1972