QGP: Perfect Fluid and the Early Universe

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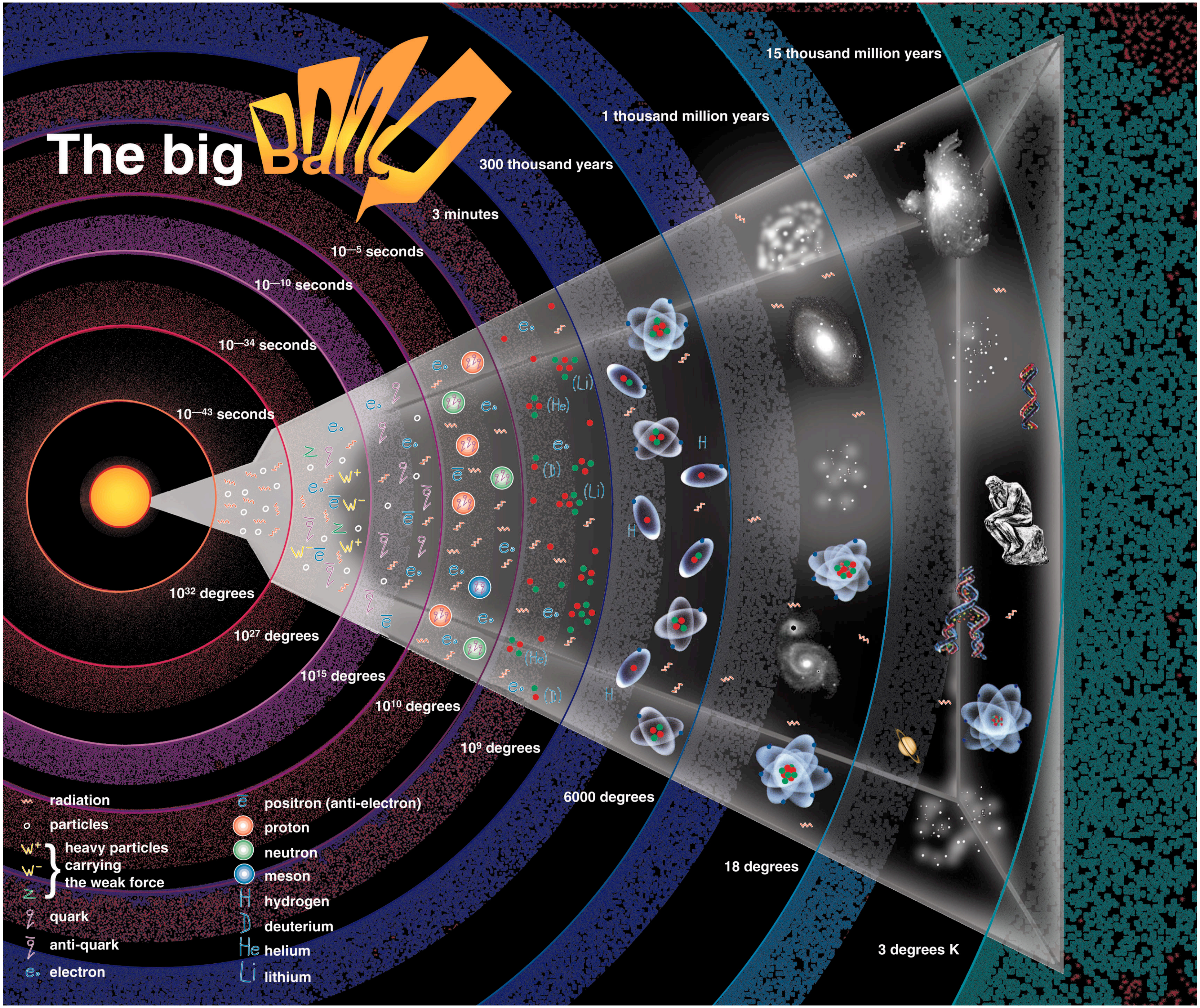
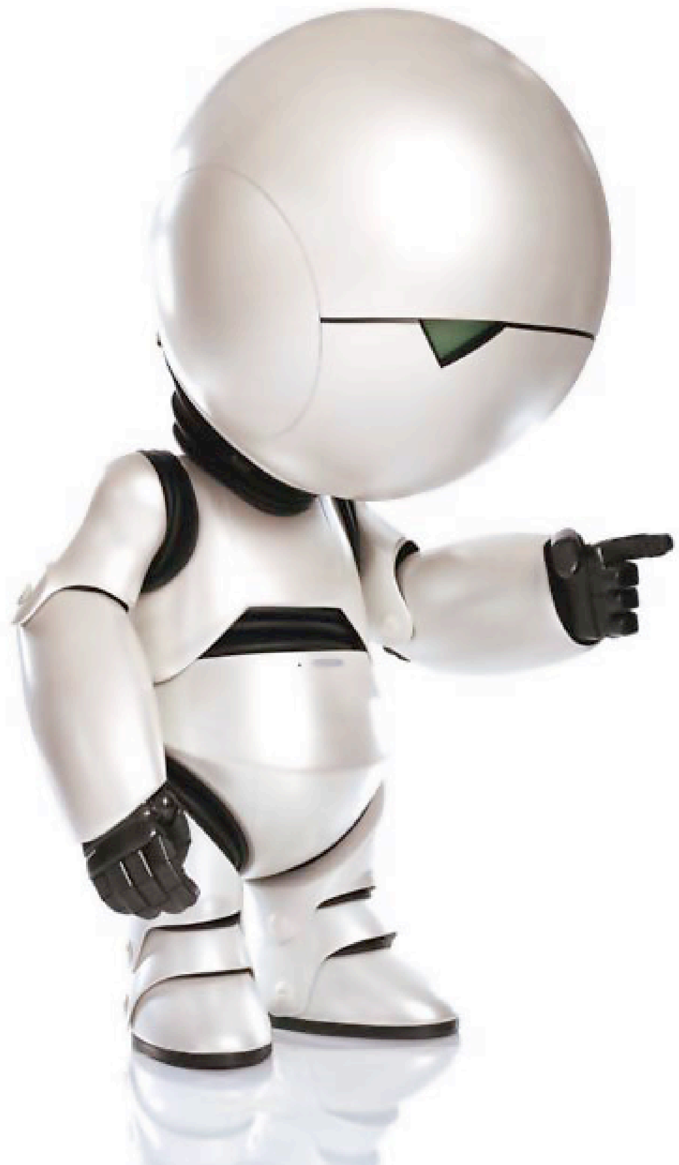
Oak Ridge Nat'l Lab

Ohio APS, Mar/Apr 06



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
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ 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



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)

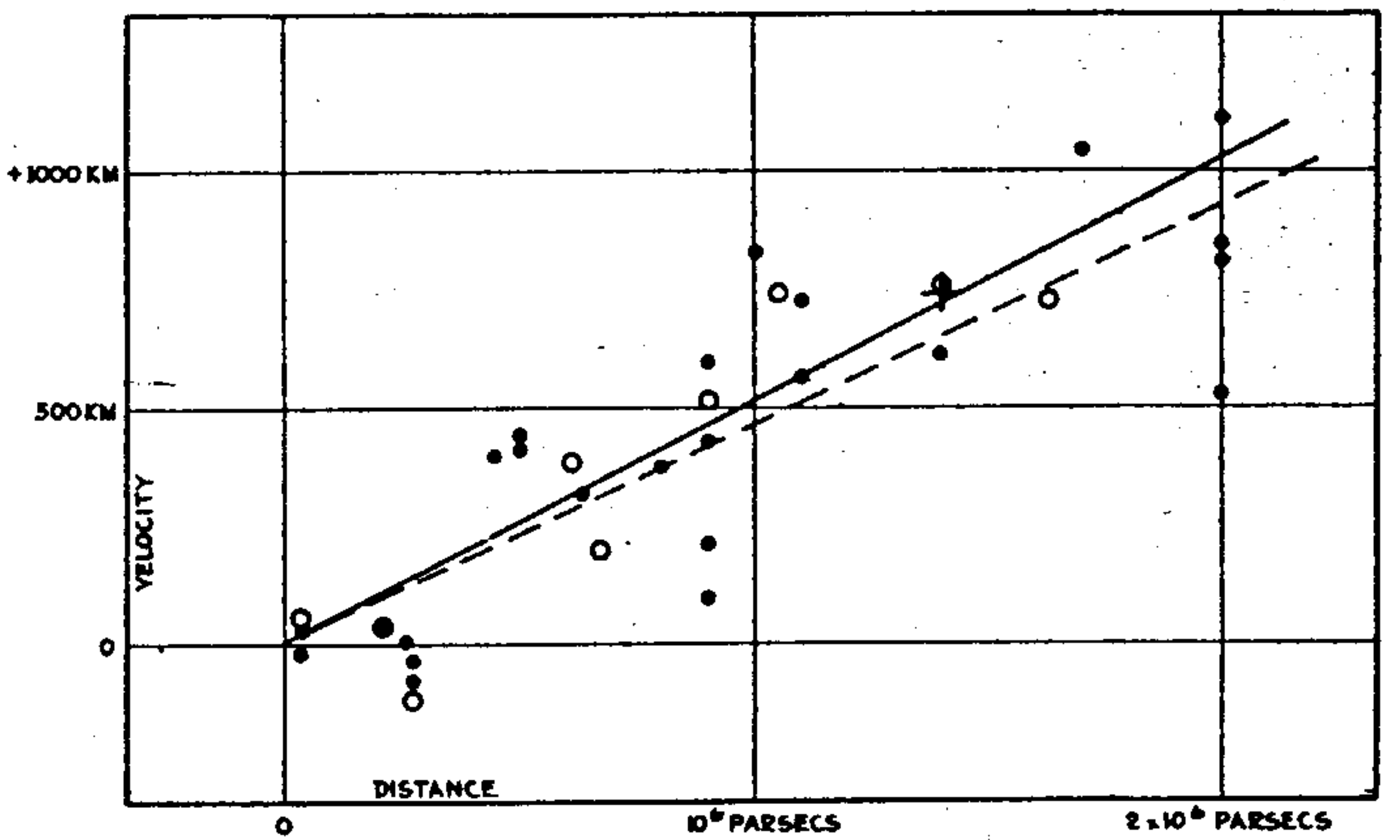


FIGURE 1

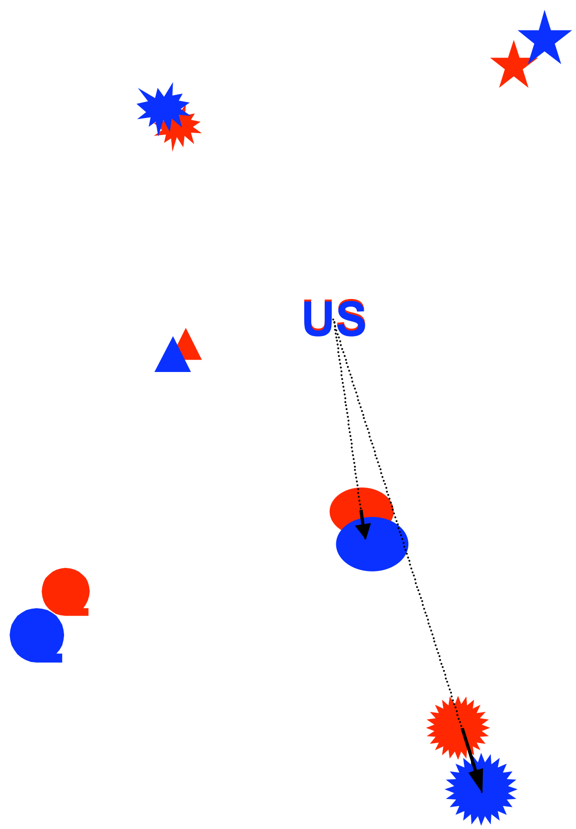
Edwin Hubble
American

Galaxies outside Milky Way

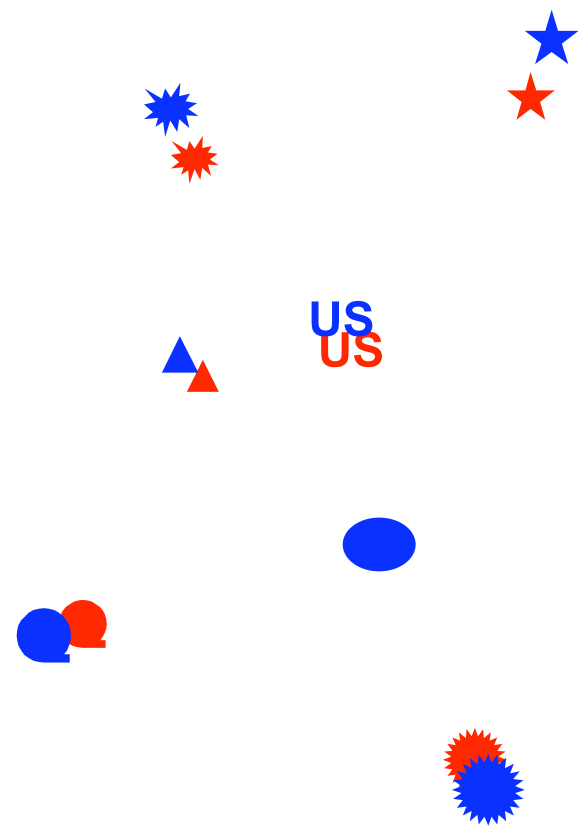
Henrietta Leavitt
American

Distances via variable stars

As seen from our position:



As seen from another position:

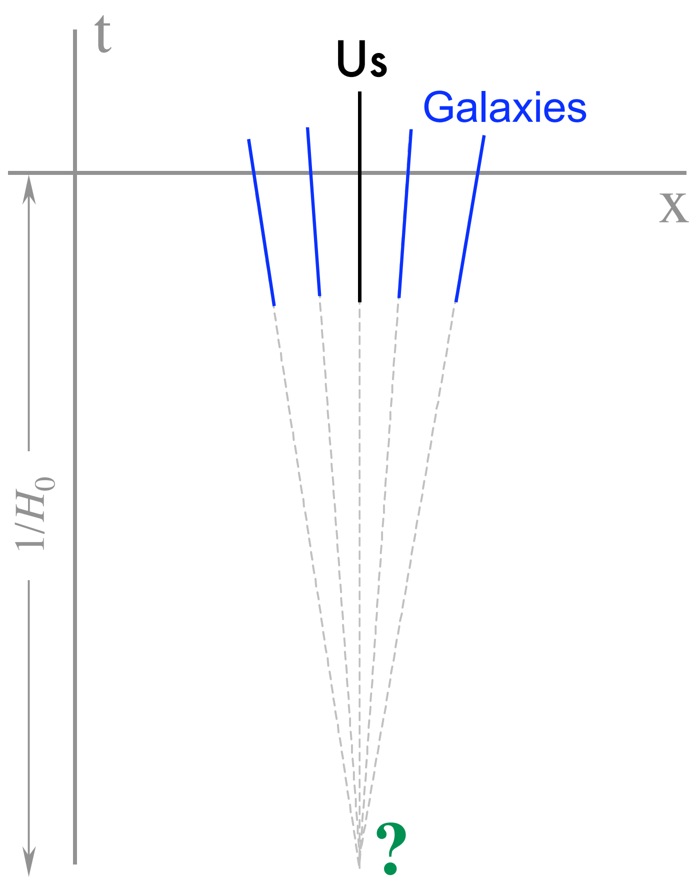


Now

Slightly Earlier

Recessional velocity $\propto$ distance

Same pattern seen by all observers!



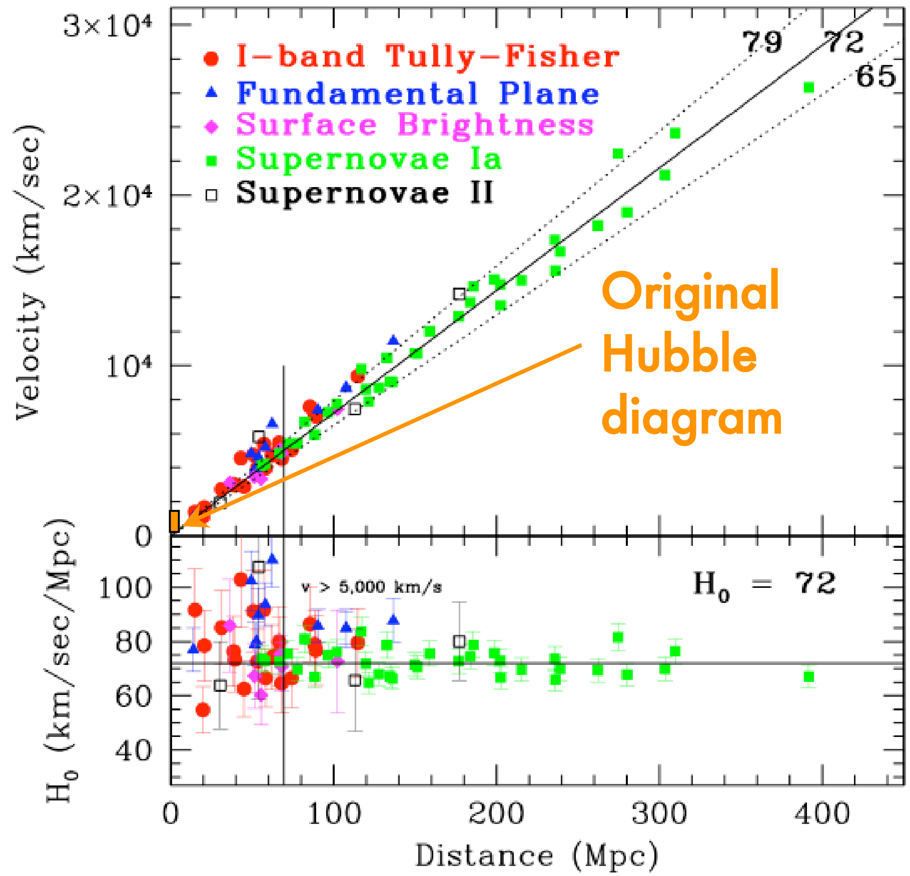
$$v_{\text{Recession}} = H_0\, d$$

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

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

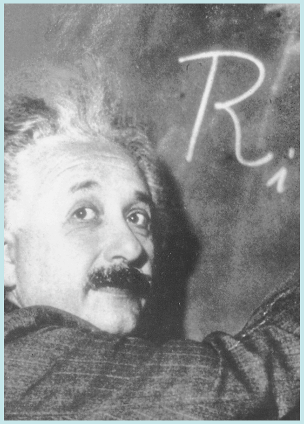
W. Freedman
American

Modern Hubble constant (2001)



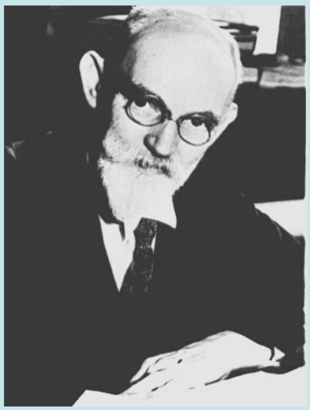
1929: H_0 ~500 km/sec/Mpc

2001: H_0 = 72±7 km/sec/Mpc



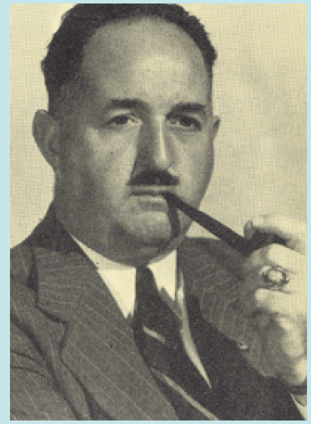
Albert Einstein
German

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

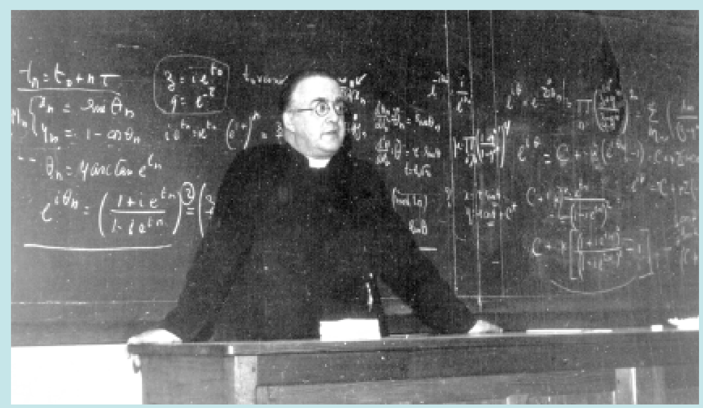
A.G. Walker
British

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

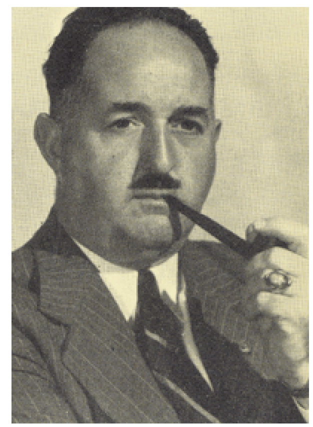
$$d\tau^2 = -ds^2 = dt^2 - dx^2$$

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

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

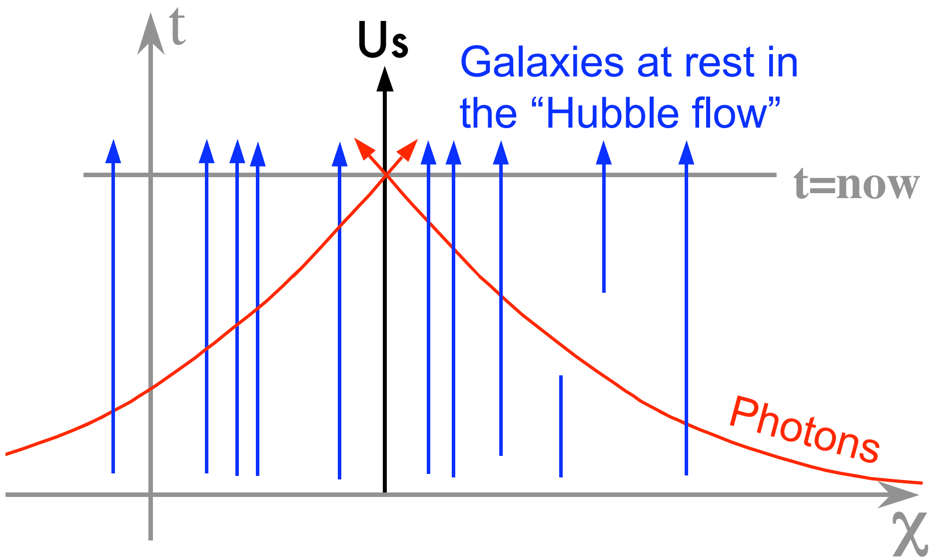


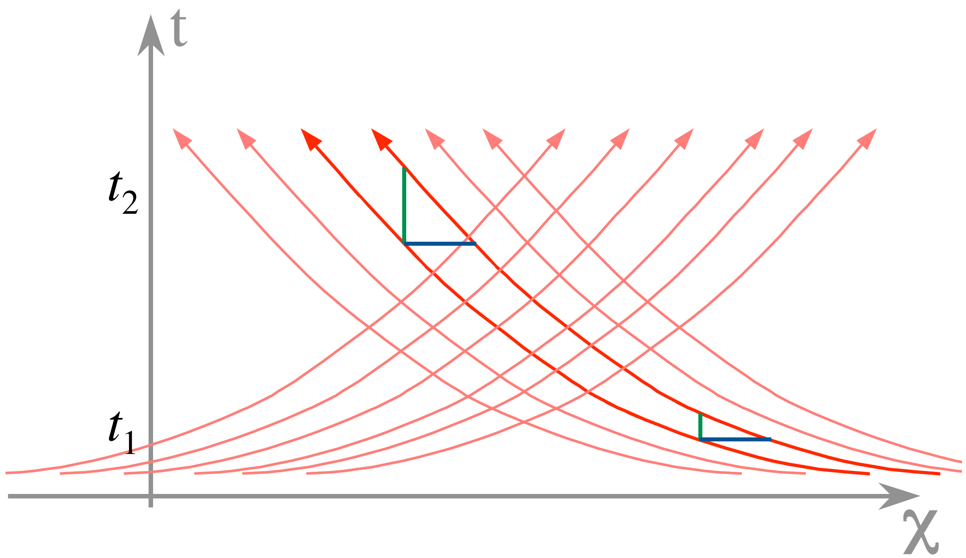
$a(t)$ dimensionless; set $a(\text{now}) = 1$

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 $\propto a(t)$

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

$a(t) \Leftrightarrow$ 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"

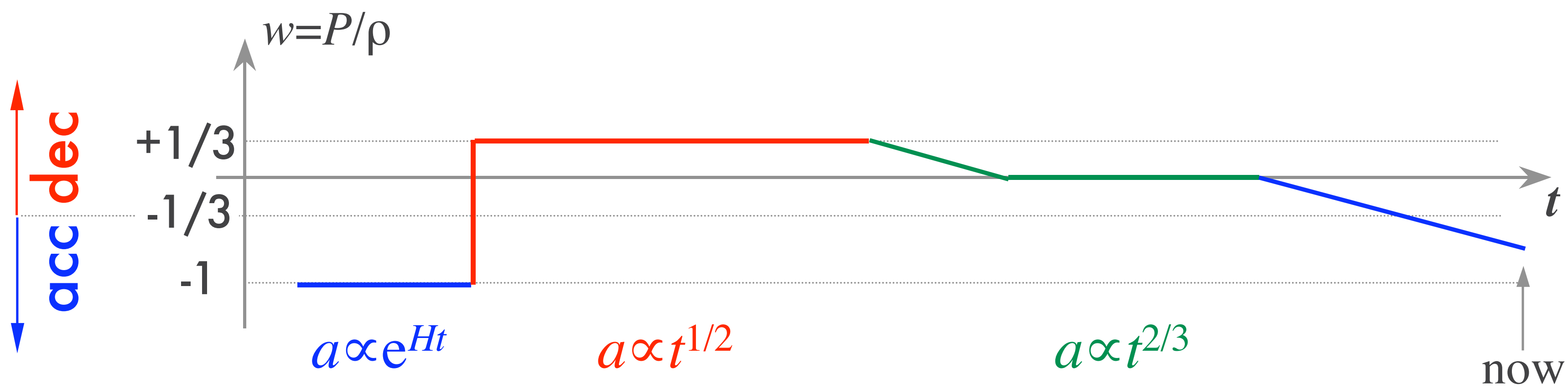
The New Standard Cosmology in Four Easy Steps

Inflation, dominated by "inflaton field" vacuum energy

Radiation-dominated thermal equilibrium

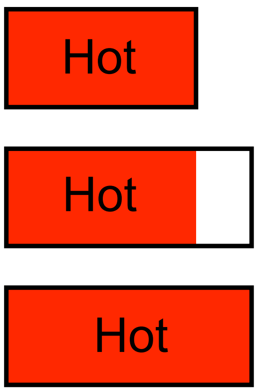
Matter-dominated, non-uniformities grow (structure)

Start of acceleration in $a(t)$, return to domination by cosmological constant and/or vacuum energy.



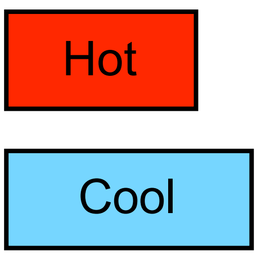
Basic Thermodynamics

$$dE = TdS - PdV$$



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

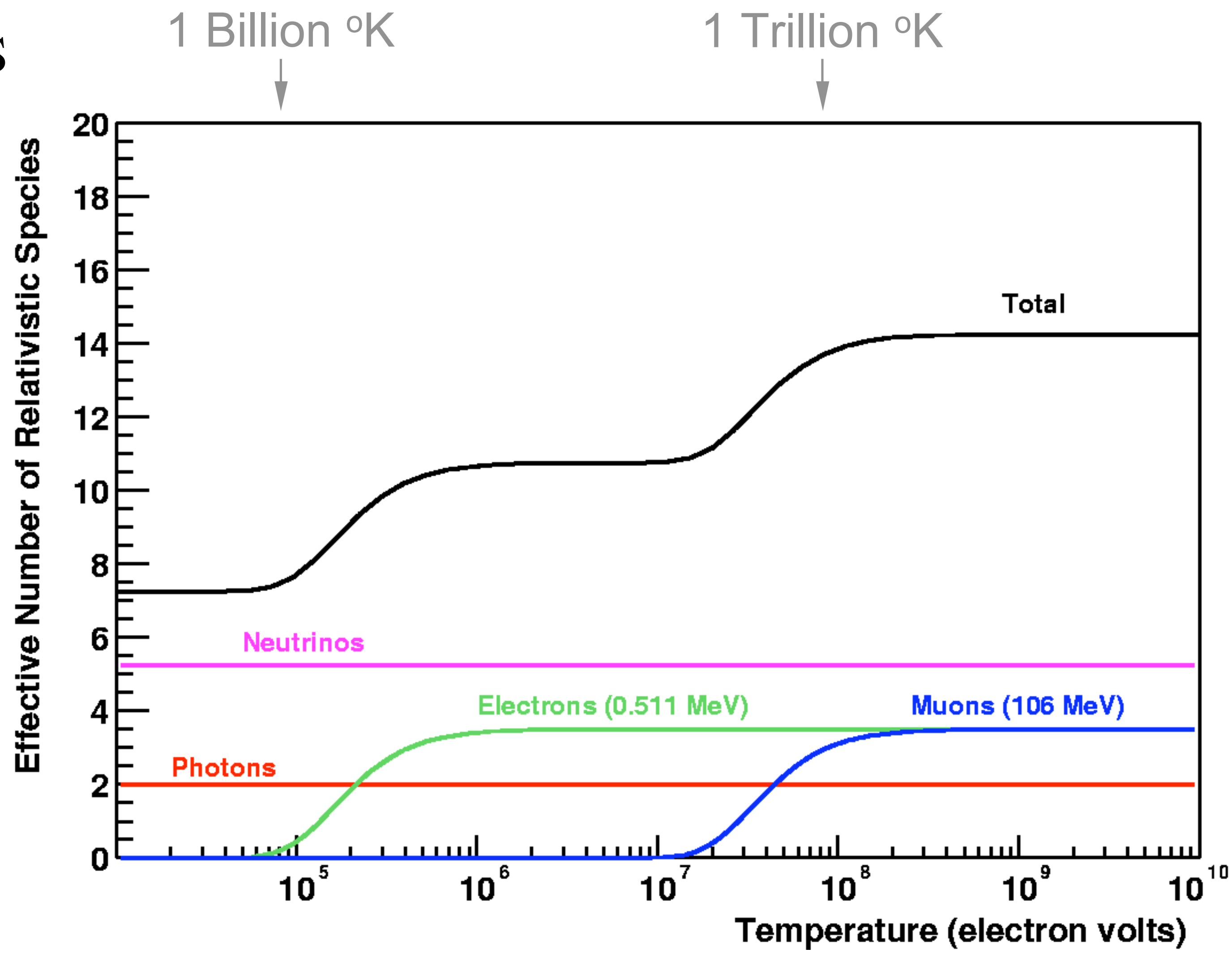
$g_{*S} \equiv$ effective number of relativistic species

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:

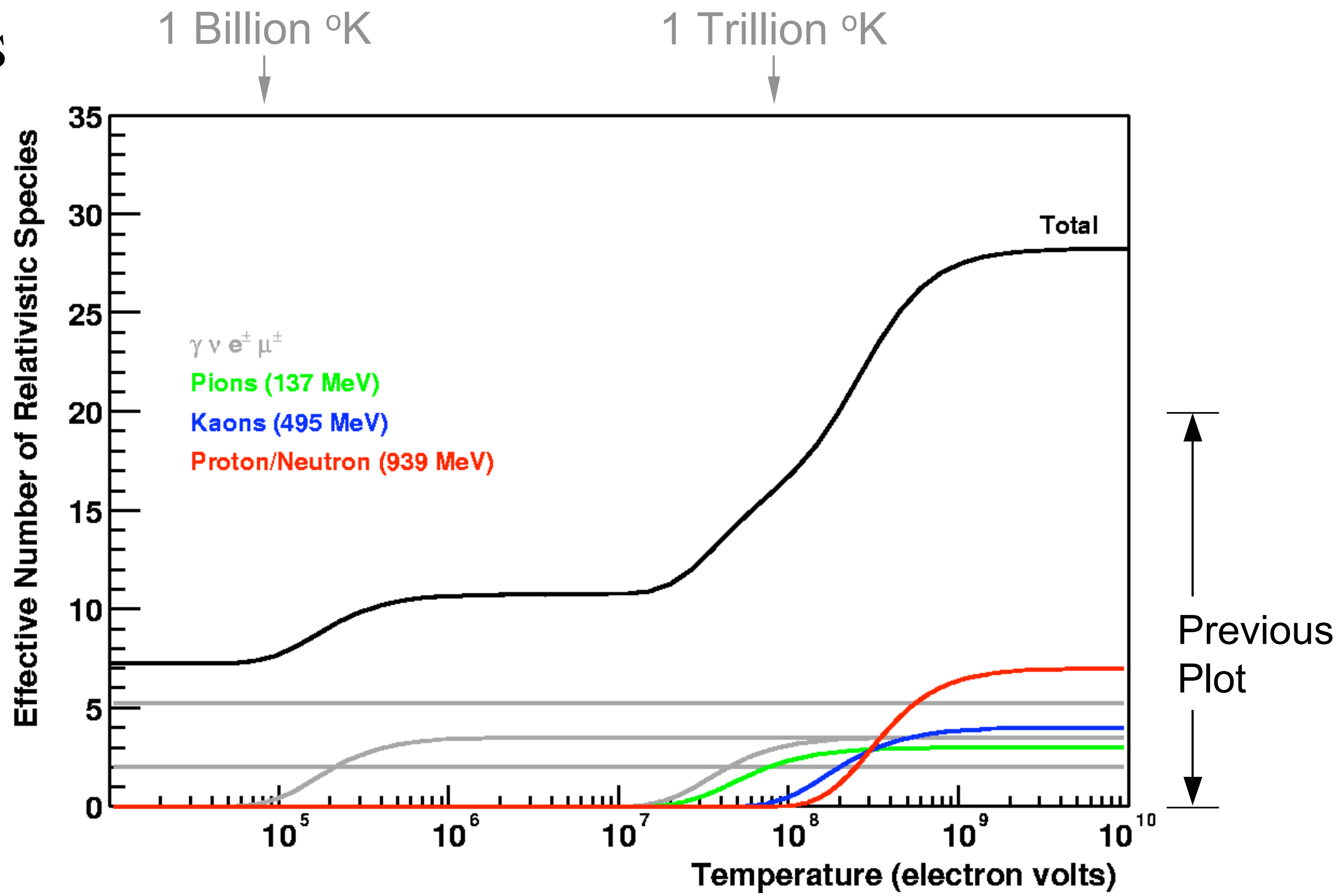
$$T \propto \left(g_{*S}\right)^{-1/3} \frac{1}{a}$$

g_{*S}



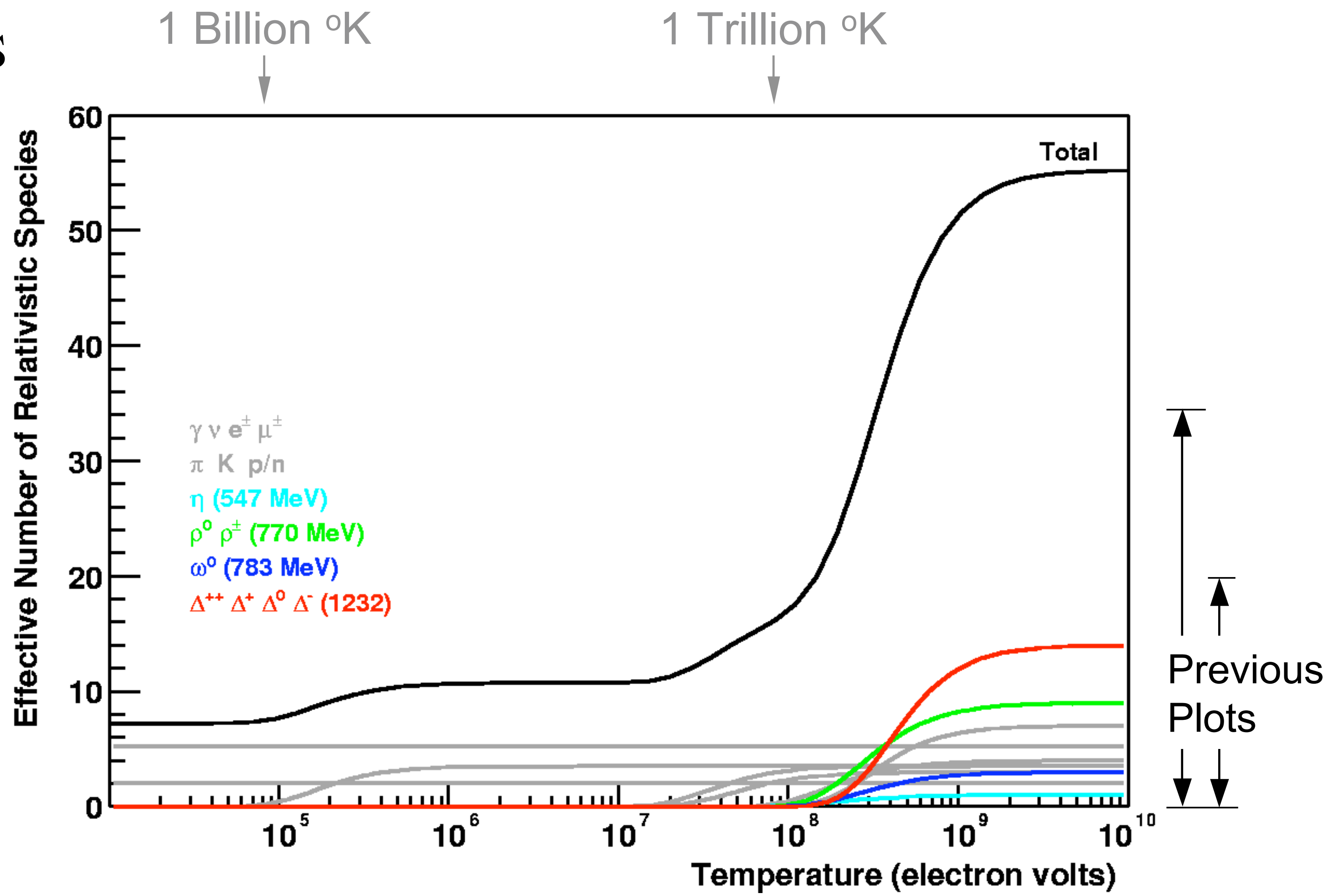
Start with light particles, no strong nuclear force

g_{*S}



Now add *hadrons* = feel strong nuclear force

g_{*S}



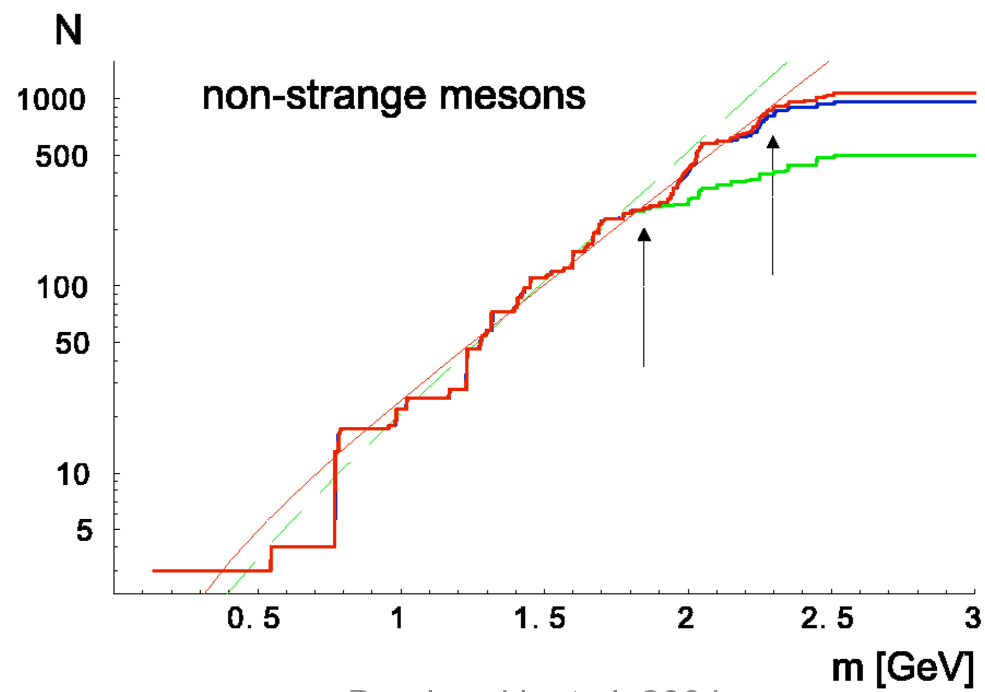
Keep adding more hadrons....

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 (somewhat crudely):

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

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

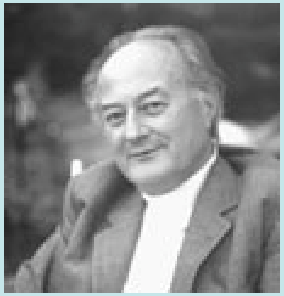
Energy *diverges* as T --> T_{H}

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)



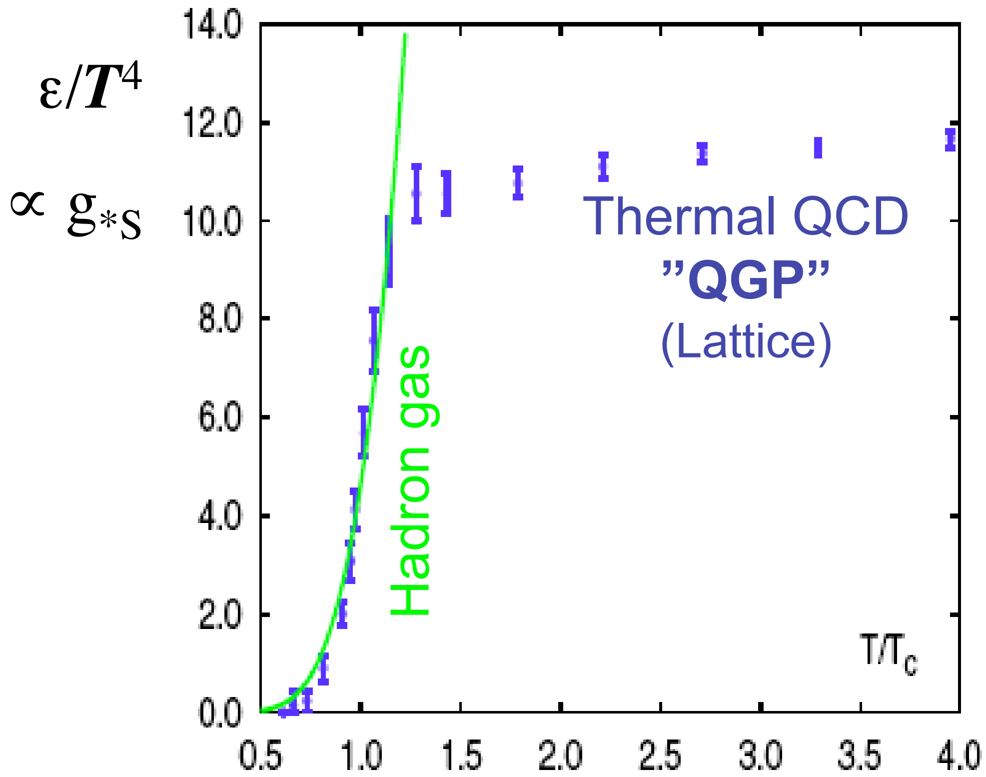
QCD to the rescue!

Replace Hadrons (messy and numerous)

by Quarks and Gluons (simple and few)

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

QCD Asymptotic Freedom (1973)

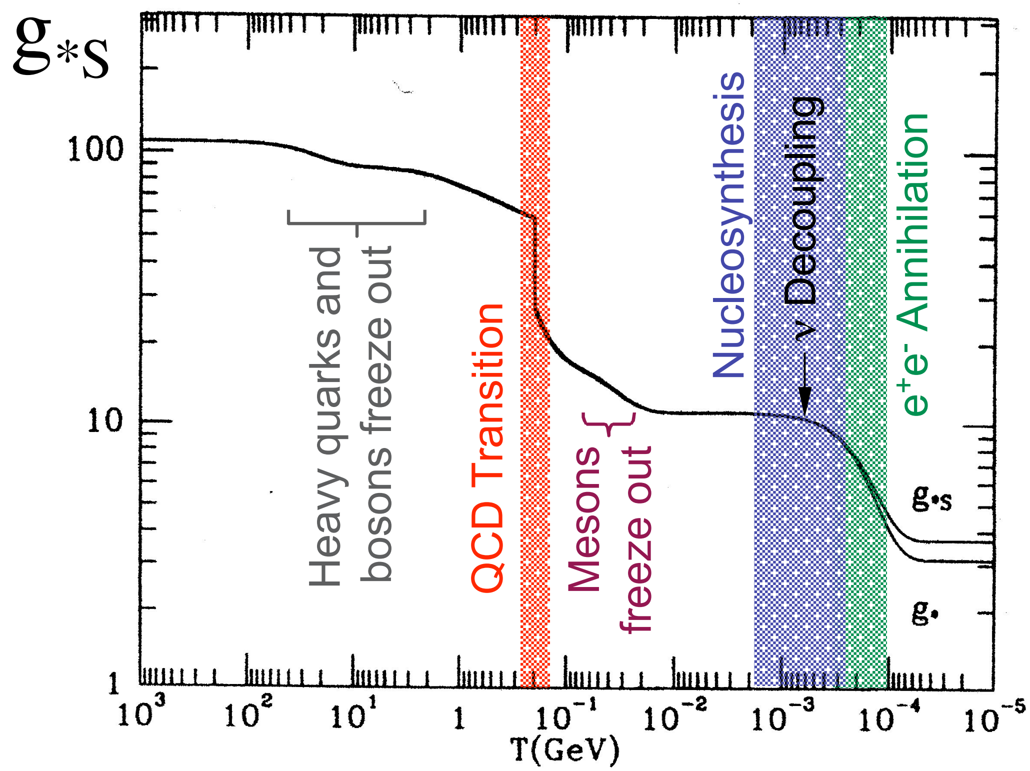


Karsch, Redlich, Tawfik, Eur.Phys.J.**C29**:549-556,2003

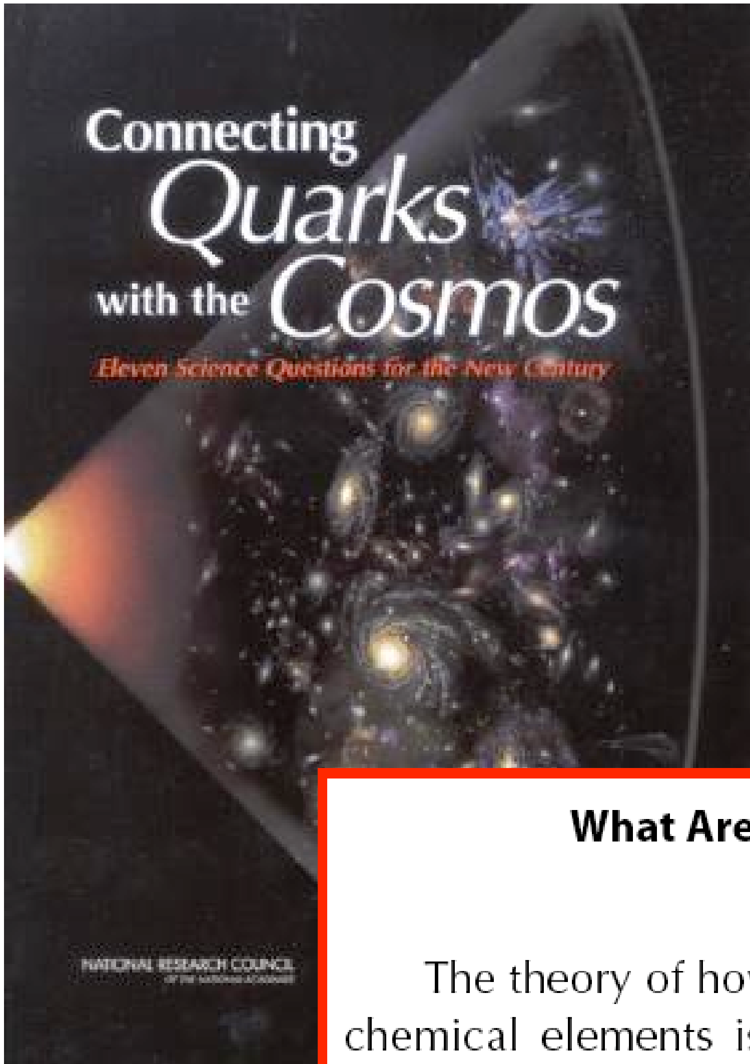
"In 1972 the early universe seemed hopelessly opaque…conditions of ultrahigh temperatures…produce a theoretically intractable mess. But asymptotic freedom renders ultrahigh temperatures friendly…"
Frank Wilczek, Nobel Lecture (RMP 05)

"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"



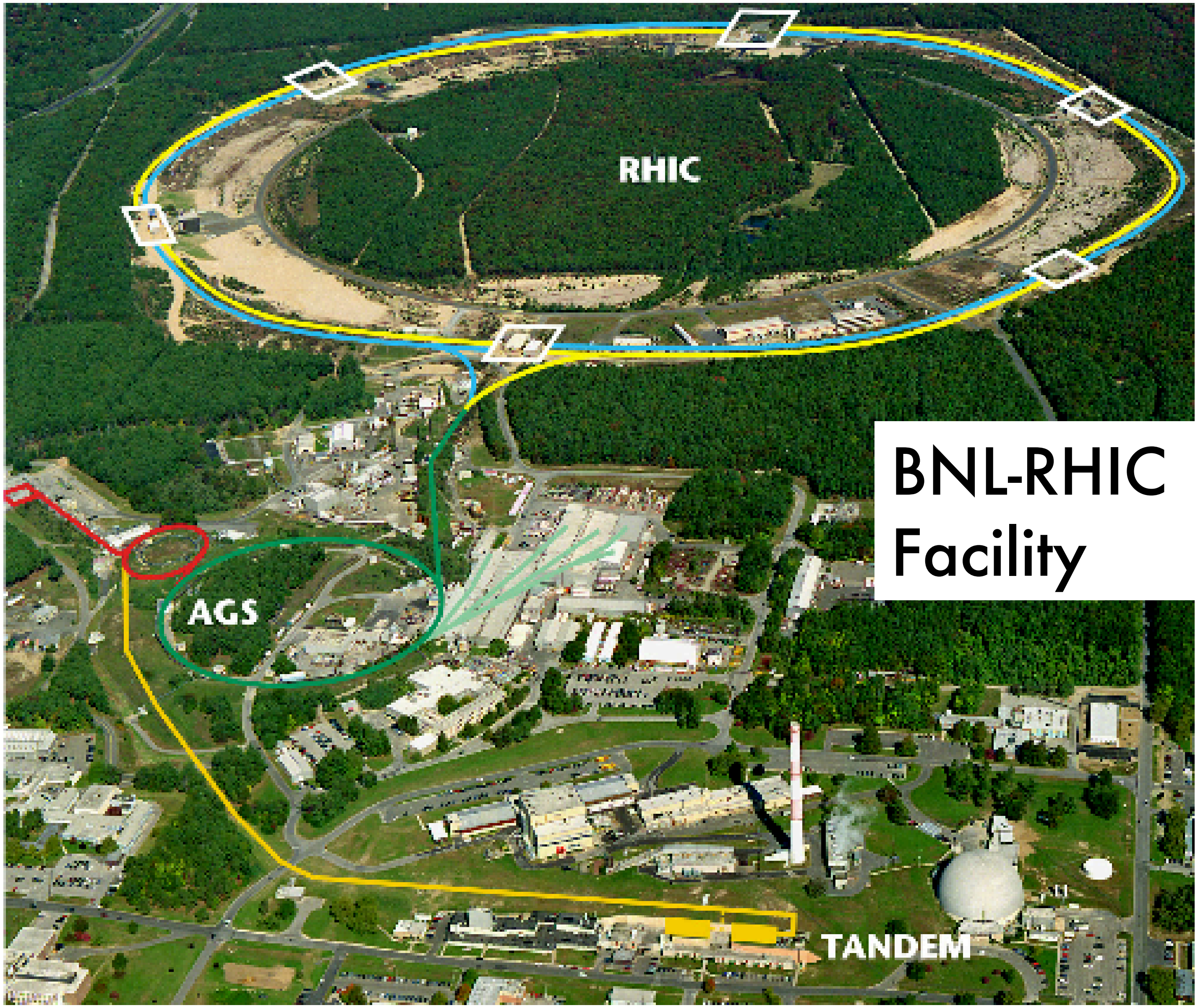
National Research Council Report (2003)

Eleven Science Questions for the New Century

Question 8 is:

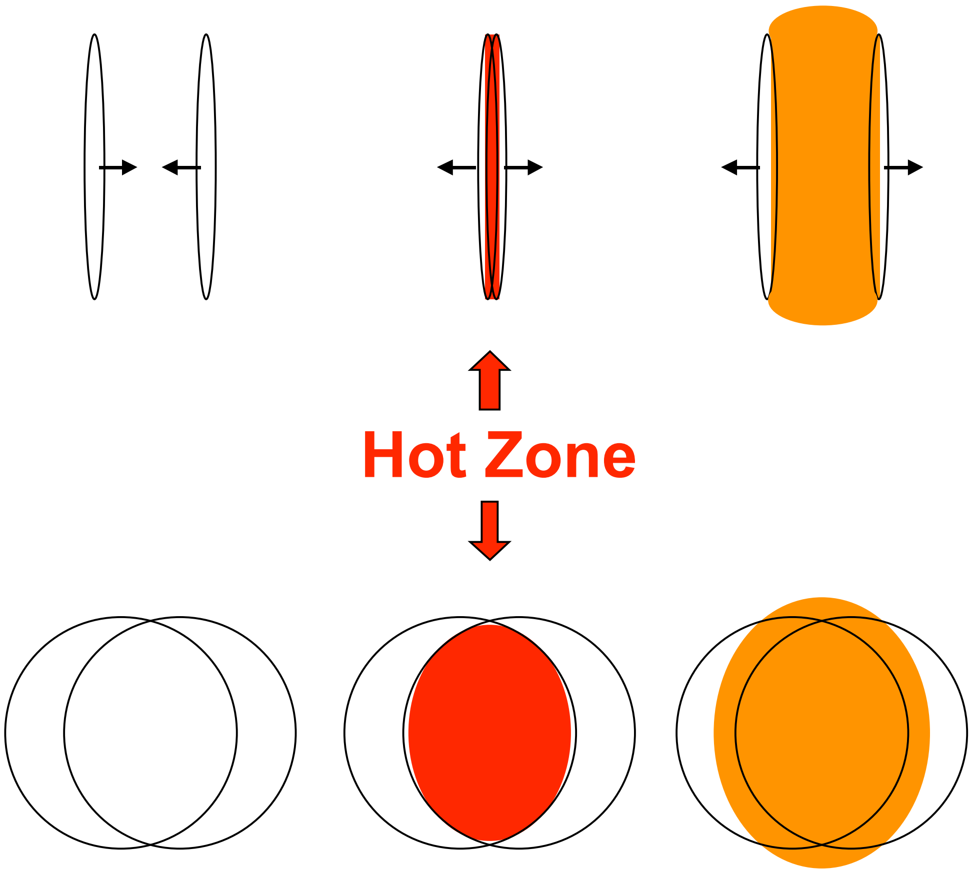
What Are the New States of Matter at Exceedingly High Density and Temperature?

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.



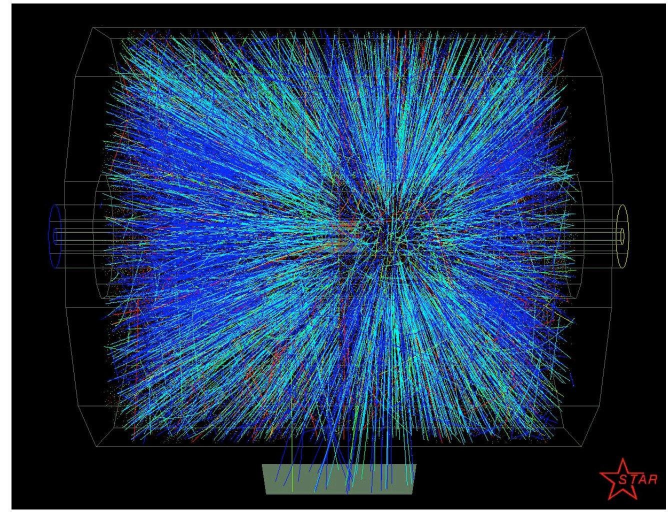
Also: BNL-AGS, CERN-SPS, CERN-LHC

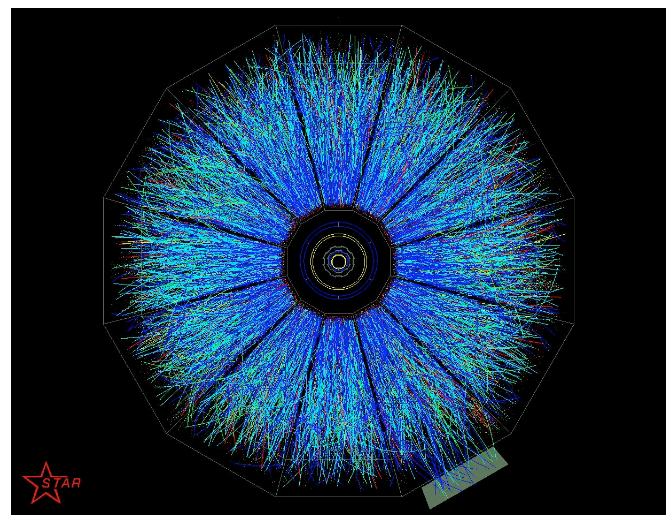
Side-to-beam view



Along-the-beam view

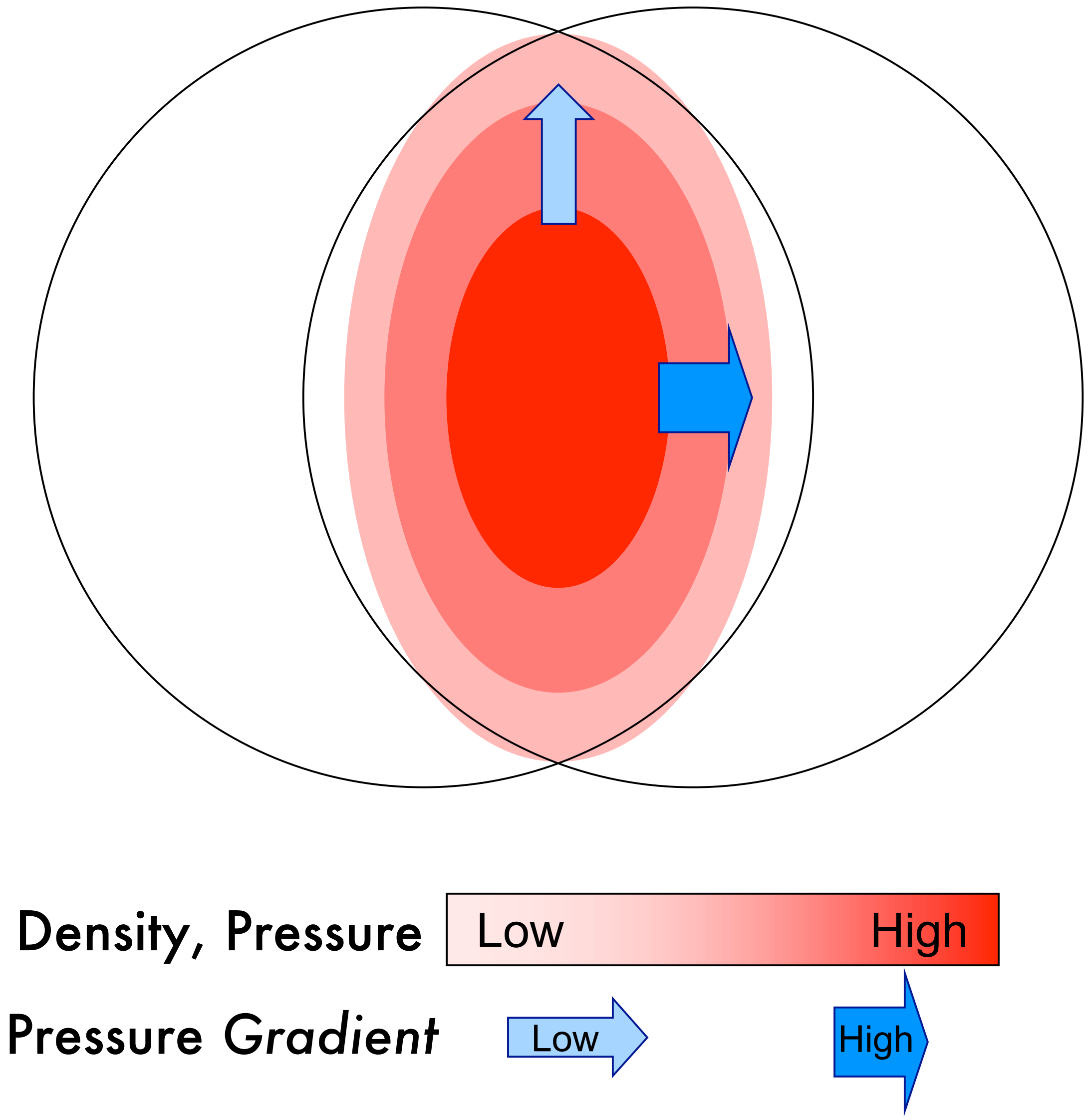
STAR Experiment at RHIC

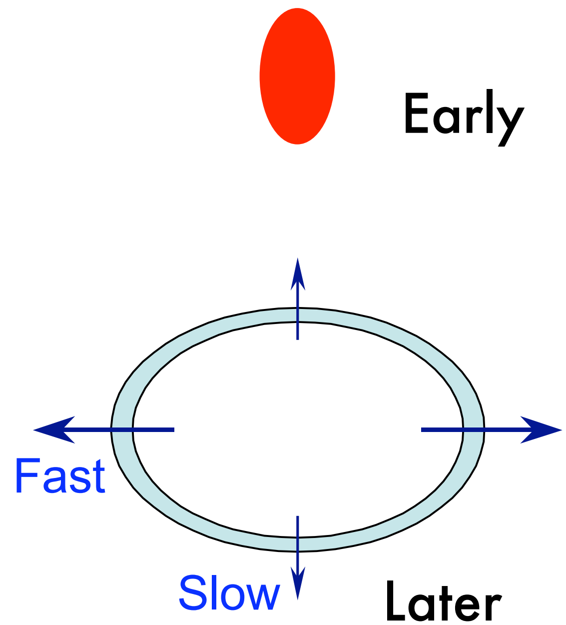




Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

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





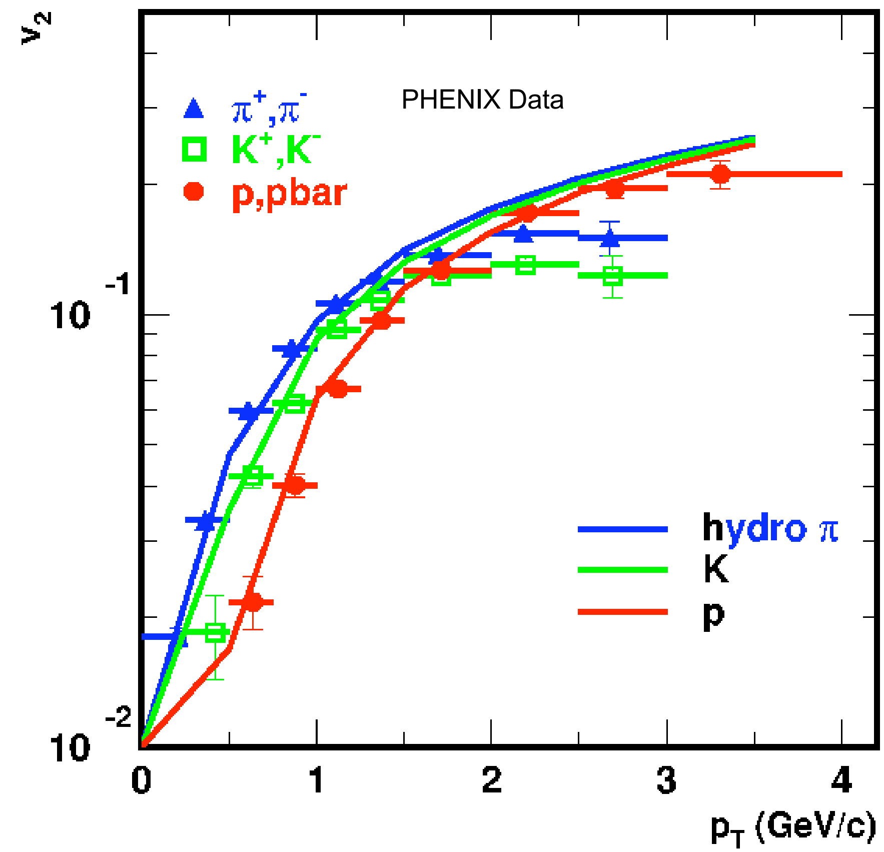
Elliptic momentum anisotropy

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

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

What does it mean?

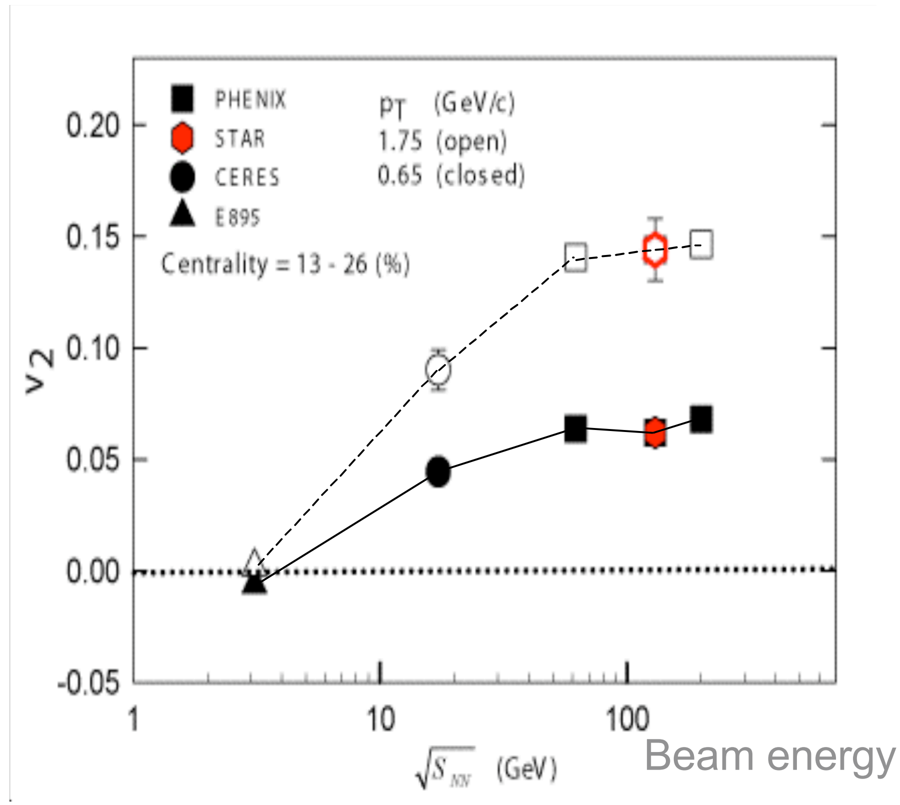
- Strong self-re-interaction
- Early thermalization (10^{-24} sec)
- Low dissipation (viscosity)
- Equation of state P/ρ similar to relativistic gas



Momentum anisotropy increases as we increase beam energy & energy density

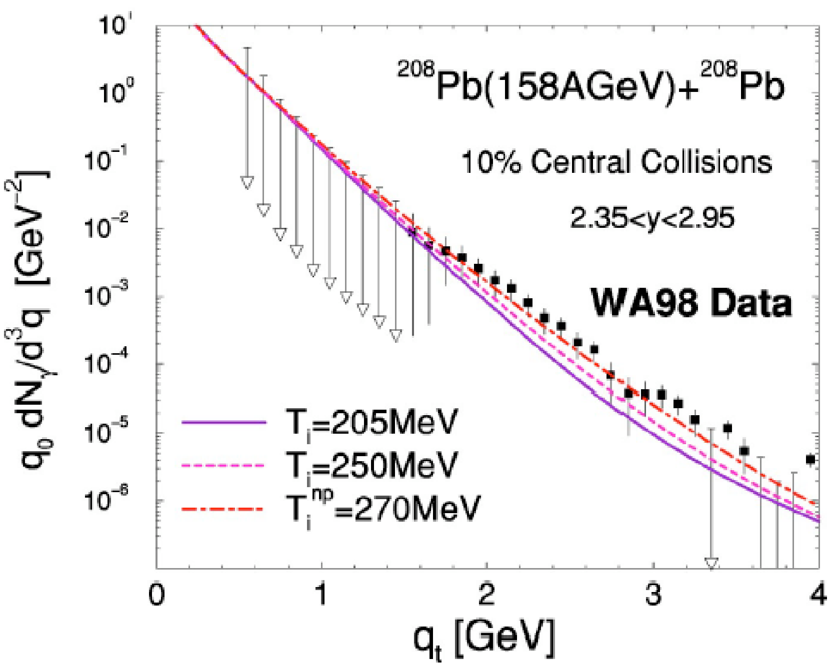
What does it mean?

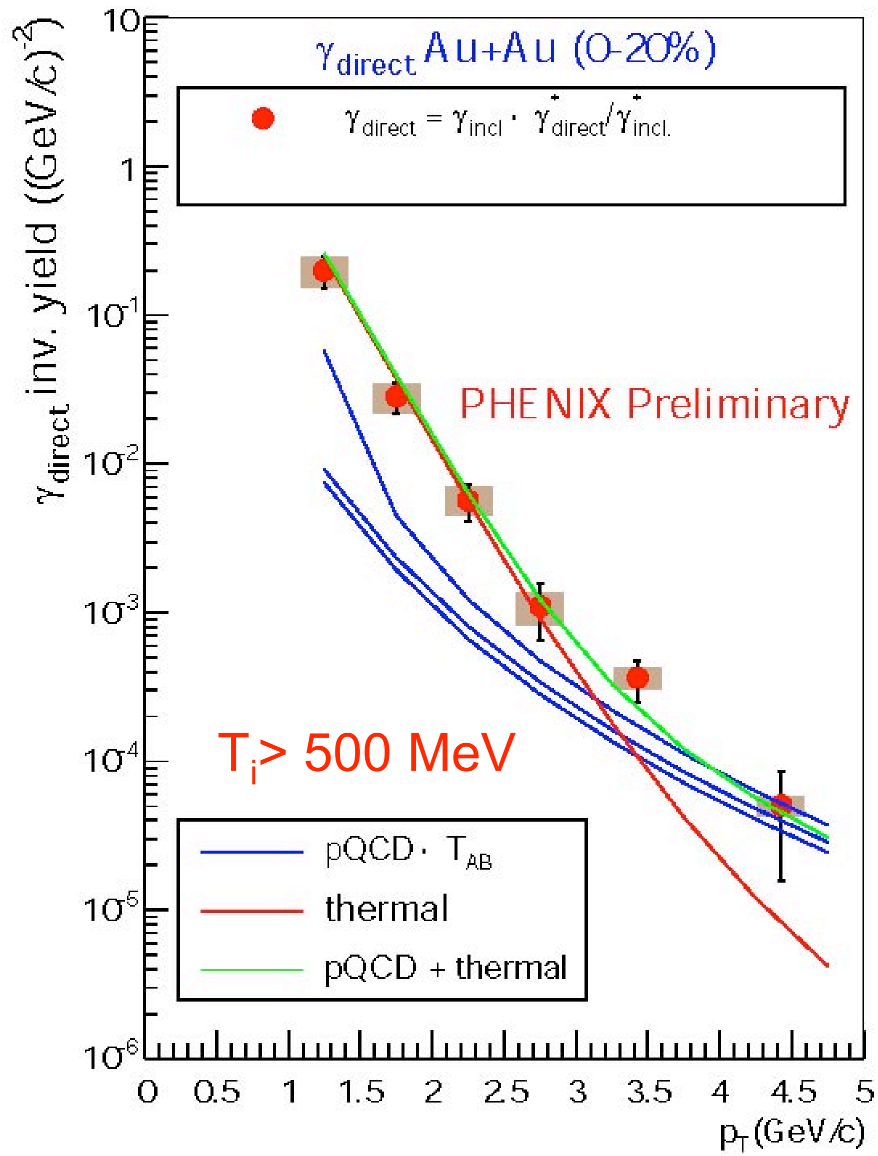
- High acceleration requires high ***P***/ρ pressure/energy density. Hagedorn picture would be softer since massive hadrons are non-relativistic.
- Increase/saturate with higher energy densities. In Hagedorn picture pressure *decreases* with density.



Thermal photon radiation from quarks and gluons?

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





$$\text{Ideal gas} \neq \text{Ideal fluid}$$

Ideal gas	Ideal fluid
Long mfp	Short mfp
High dissipation	Low dissipation

Data imply (D. Teaney):

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

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

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

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