Physics 661

Particle Physics Phenomenology

September 30, 2003

Elementary Particle Phenomenology
Physics 661
Fall 2003

Course Description:

Physics 661 begins a survey of the phenomena of the elementary particles of matter and their interactions. Over the three term sequence (661, 662, and 663) we will include the applications of particle physics to questions of cosmology and astrophysics. For the fall term we will study:

- Introduction to the particles, forces, and the observable universe
- Cosmic Rays
- Quarks and Leptons
- Interactions and Fields
- Invariance Principles and Conservation Laws
- Quarks in Hadrons
- Lepton and Quark Scattering

These topics represent an introduction to the important issues in particle physics research today. Throughout the course, the interplay between theory and experiment will be emphasized. This first quarter course is designed to give an introduction to the field of particle physics, with many of the forefront topics to follow in the second and third terms. During the subsequent terms topics will include the standard model, physics beyond the standard model, cosmological models and inflation, gravitational radiation, and experimental methods of particle physics

Class Hours: TuTh 10:30 - 11:50
(and substitute hours to be determined;
note, the class will start at 10:30 to avoid a
conflict with Advanced Analog Electronics - Phys 610)

Classroom: 318 Willamette Hall

Office Hours: MWF 10-11 am

Texts: Introduction to High Energy Physics, 4th Edition (2000)
Donald H. Perkins
(Required)

Cosmology and Particle Astrophysics (1999)
Lars Bergstrom and Ariel Goobar
(Optional, but not recommended;
this book is now out of print and the bookstore
is having trouble obtaining enough copies.
A second edition is nearly released and should
be available in time for the 2nd and 3rd terms.)

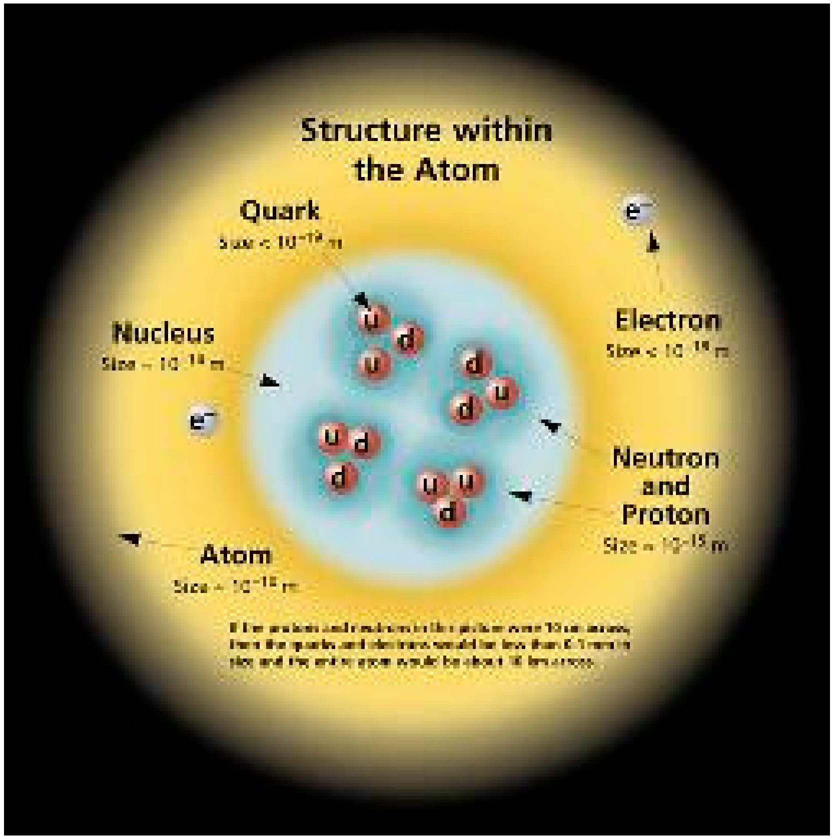
Grading: Grades will be based on homework problem sets, a mid-term exam and a final exam.

Tentative Course Outline and Reading Assignments:

September 30-October 2	**The Observable Universe**
Bergstrom and Goobar, Chapter 1	
Particle Physics and Cosmology, **John Ellis, xxx.lanl.gov/pdf/astro-ph/0305038**	
October 7-9	**Cosmic Rays**
Bergstrom and Goobar, Chapter 13	
Particle Data Group, Cosmic Rays, **http://pdg.lbl.gov/2002/cosmicrayrpp.pdf**	
October 14-16	**Quarks and Leptons**
Perkins, Chapter 1	
October 21-28	**Interactions and Fields**
Perkins, Chapter 2	
October 30-November 11	**Invariance Principles and Conservation Laws**
Perkins, Chapter 3	
November 13-25	**Quarks in Hadrons**
Perkins, Chapter 4	
December 2-4	**Lepton and Quark Scattering**
Perkins, Chapter 5	

http://blueox.uoregon.edu/~jimbrau/ph661-2003

Structure of matter



the atom

the universe

Some fundamental questions

- What is the standard model of elementary particles and their interactions?
- What is the origin of mass and electroweak symmetry breaking?
- What is the role of anti-matter in Nature?
- What is dark matter?
- What are the masses of the neutrinos and how have they shaped the evolution of the universe?
- Are there additional spacetime dimensions?
- What is the nature of the dark energy?
- Are protons unstable?
- How did the universe begin?
- What was the role of gravity in the early universe?
- How do cosmic accelerators work, and what are they accelerating?
- Are there new states of matter at exceedingly high density and temperature?
- Is a new theory of matter and light needed at the highest energies?

The fundamental fermions

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	−1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	−1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	−1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	-1/3
c	charm	1.3	2/3
s	strange	0.1	-1/3
t	top	175	2/3
b	bottom	4.3	-1/3

Baryons and antibaryons

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

The bosons

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- Also the graviton, m=0, q=0, s=2

The Electroweak Lagrangian

$$\mathcal{L}_F = \sum_i \overline{\psi}_i \left(i\,\partial\!\!\!/ - m_i - \frac{g m_i H}{2M_W} \right) \psi_i$$

$$- \frac{g}{2\sqrt{2}} \sum_i \overline{\psi}_i \, \gamma^\mu \, (1-\gamma^5)(T^+ \, W_\mu^+ + T^- \, W_\mu^-) \, \psi_i$$

$$- e \sum_i q_i \, \overline{\psi}_i \, \gamma^\mu \, \psi_i \, A_\mu$$

$$- \frac{g}{2\cos\theta_W} \sum_i \overline{\psi}_i \, \gamma^\mu (g_V^i - g_A^i \gamma^5) \, \psi_i \, Z_\mu \; .$$

- KE and mass
- Charged weak
- Electromag.
- Neutral weak

Fermion lagrangian

Quantity	Value	Standard Model	Pull
m_t [GeV]	174.3 ± 5.1	175.3 ± 4.4	-0.2
M_W [GeV]	80.451 ± 0.061	80.391 ± 0.019	1.0
	80.446 ± 0.040		1.4
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966 ± 0.0016	-0.6
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7429 ± 0.0015	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.76 ± 0.14	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.019 ± 0.027	—
σ_{had} [nb]	41.541 ± 0.037	41.477 ± 0.014	1.7
R_e	20.804 ± 0.050	20.744 ± 0.018	1.2
R_μ	20.785 ± 0.033	20.744 ± 0.018	1.2
R_τ	20.764 ± 0.045	20.790 ± 0.018	-0.6
R_b	0.21664 ± 0.00068	0.21569 ± 0.00016	1.4
R_c	0.1729 ± 0.0032	0.17230 ± 0.00007	0.2
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01637 ± 0.00026	-0.8
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.4
$A_{FB}^{(0,b)}$	0.0982 ± 0.0017	0.1036 ± 0.0008	-3.2
$A_{FB}^{(0,c)}$	0.0689 ± 0.0035	0.0740 ± 0.0006	-1.5
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1037 ± 0.0008	-0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2322 ± 0.0010	0.23143 ± 0.00015	0.8

http://pdg.lbl.gov/2002/stanmodelrpp.pdf

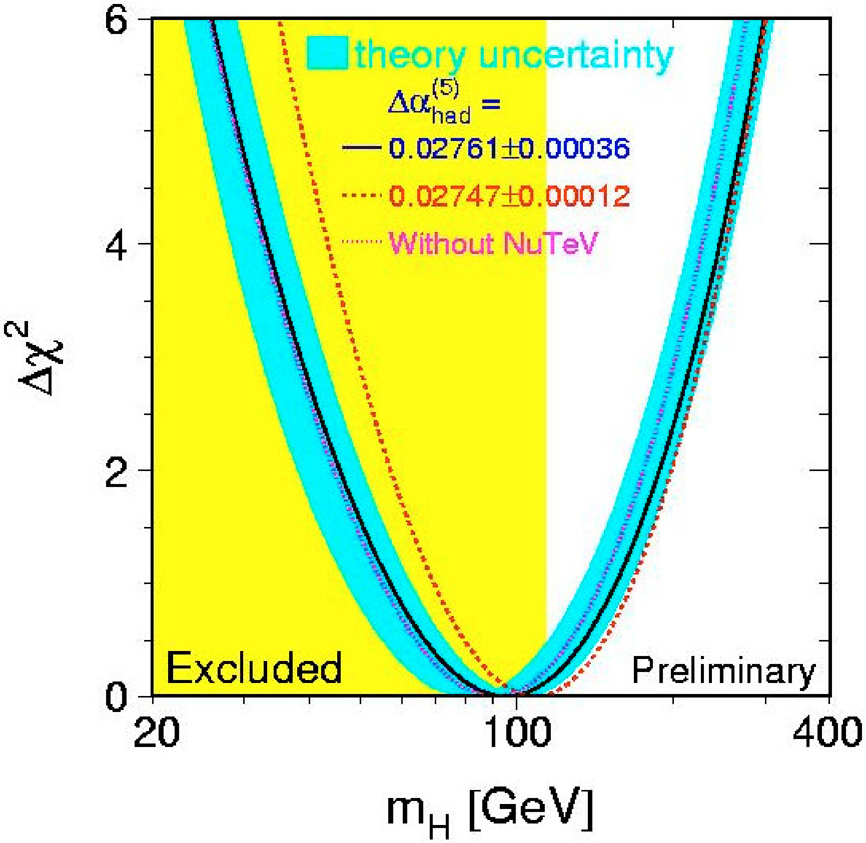
Quantity	Value	Standard Model	Pull
A_e	0.15138 ± 0.00216	0.1478 ± 0.0012	1.7
	0.1544 ± 0.0060		1.1
	0.1498 ± 0.0048		0.4
A_μ	0.142 ± 0.015		-0.4
A_τ	0.136 ± 0.015		-0.8
	0.1439 ± 0.0041		-0.9
A_b	0.921 ± 0.020	0.9347 ± 0.0001	-0.7
A_c	0.667 ± 0.026	0.6681 ± 0.0005	0.0
A_s	0.895 ± 0.091	0.9357 ± 0.0001	-0.4
R^-	$0.2277 \pm 0.0021 \pm 0.0007$	0.2300 ± 0.0002	-1.1
κ^ν	$0.5820 \pm 0.0027 \pm 0.0031$	0.5833 ± 0.0004	-0.3
R^ν	$0.3096 \pm 0.0033 \pm 0.0028$	0.3093 ± 0.0002	0.1
	$0.3021 \pm 0.0031 \pm 0.0026$		-1.7
$g_V^{\nu e}$	-0.035 ± 0.017	-0.0398 ± 0.0003	—
	-0.040 ± 0.015		-0.1
$g_A^{\nu e}$	-0.503 ± 0.017	-0.5065 ± 0.0001	—
	-0.507 ± 0.014		0.0
$Q_W(\mathrm{Cs})$	$-72.65 \pm 0.28 \pm 0.34$	-73.10 ± 0.03	1.0
$Q_W(\mathrm{Tl})$	$-114.8 \pm 1.2 \pm 3.4$	-116.67 ± 0.05	0.5
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to ce\nu)}$	$3.26^{+0.75}_{-0.68} \times 10^{-3}$	$3.14^{+0.17}_{-0.16} \times 10^{-3}$	0.2
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$4510.55 \pm 1.51 \pm 0.51$	4506.55 ± 0.36	2.5

http://pdg.lbl.gov/2002/stanmodelrpp.pdf

Standard Model parameters (derived from EW measurements)

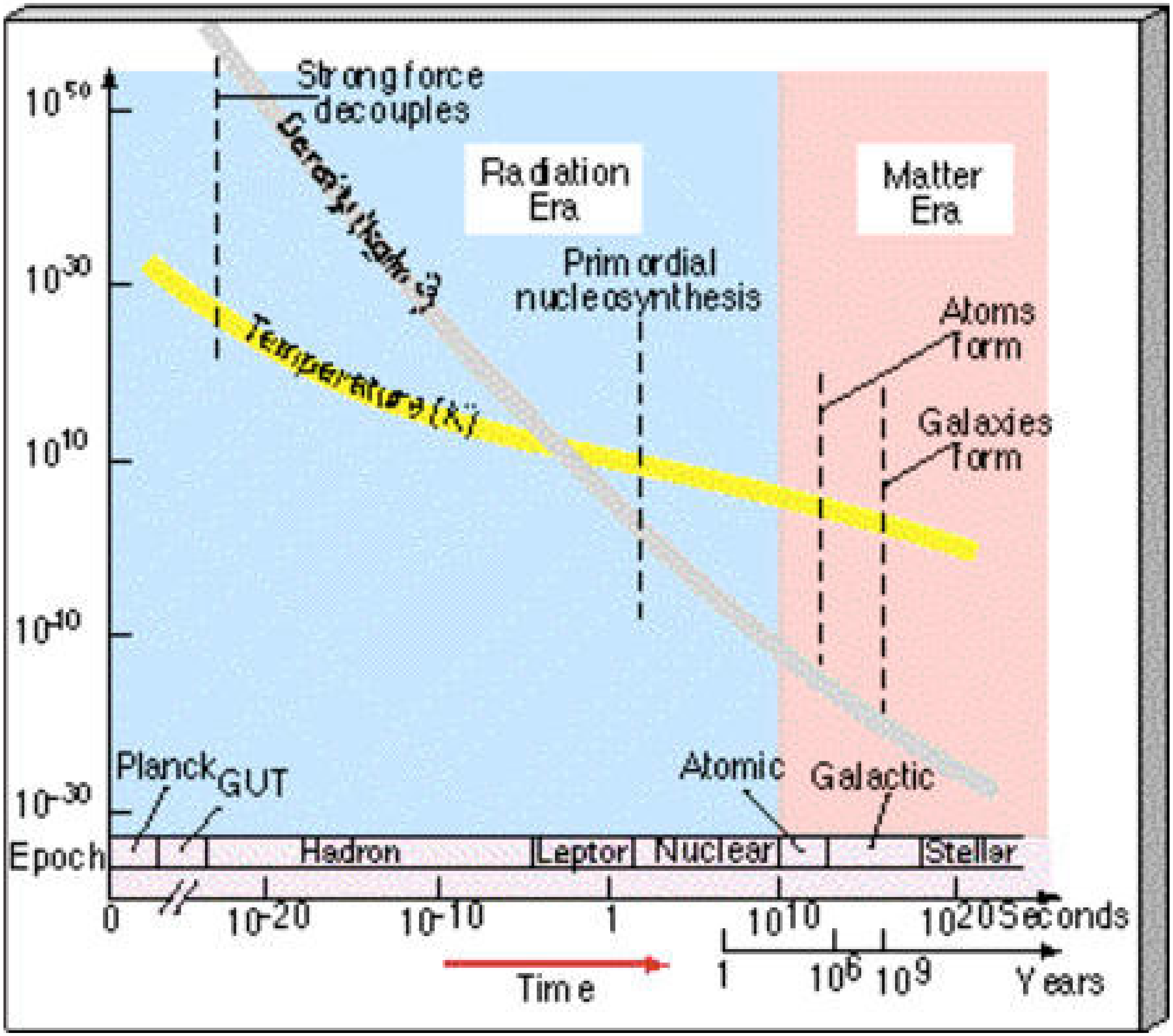
$$M_H = 98^{+51}_{-35}\ \mathrm{GeV}\ ,$$
$$m_t = 175.3 \pm 4.4\ \mathrm{GeV}\ ,$$
$$\hat{s}^2_Z = 0.23113 \pm 0.00015\ ,$$
$$\alpha_s(M_Z) = 0.1200 \pm 0.0028\ .$$

http://pdg.lbl.gov/2002/stanmodelrpp.pdf



http://lepewwg.web.cern.ch/LEPEWWG/plots/summer2003/s03_blueband.eps

Hot Big Bang Model

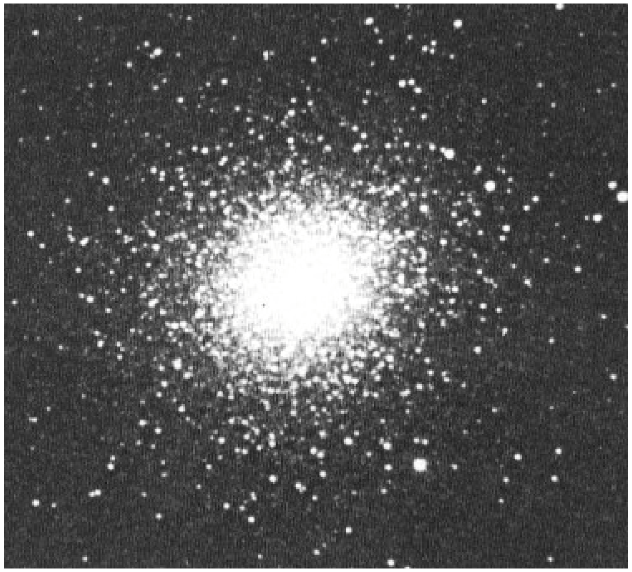


Hot Big Bang Model

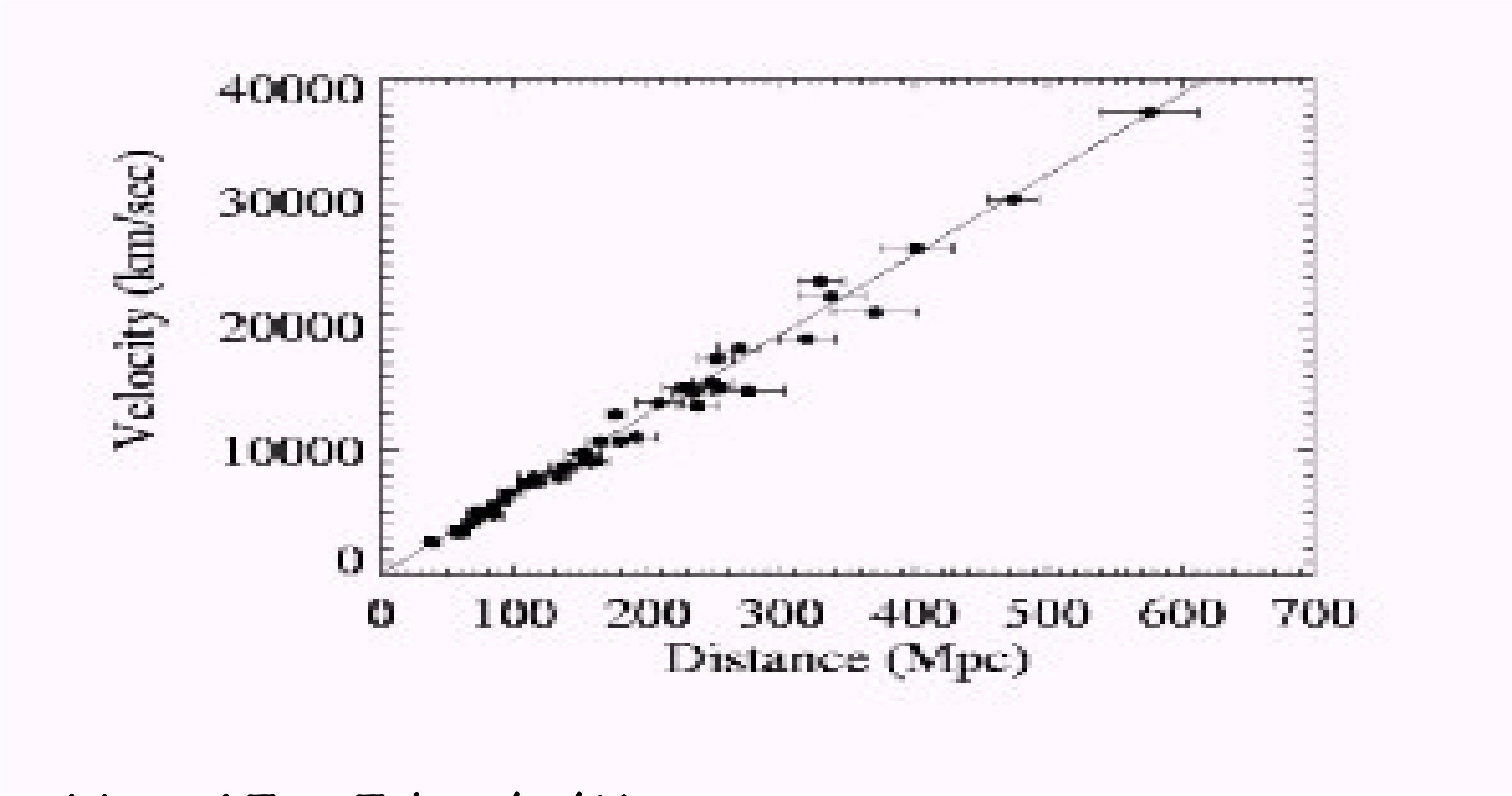
- Initially the Universe was compressed and very hot
  - protons and neutrons could not form due to extreme temperature
- Eventually quarks condense to baryons and baryons to nucleons
- Finally expansion and cooling leads to galaxies and stars

Hot Big Bang Model

- Evidence for theory:
  - Present expansion of the Universe
  - Existence of cosmic microwave background radiation
  - Relative abundance of light elements
- Furthermore, oldest objects (globular clusters) no older than ~15 x 10^9 years



Expansion of the Universe



$H_0 = 65 \pm 5$ km/s/Mpc

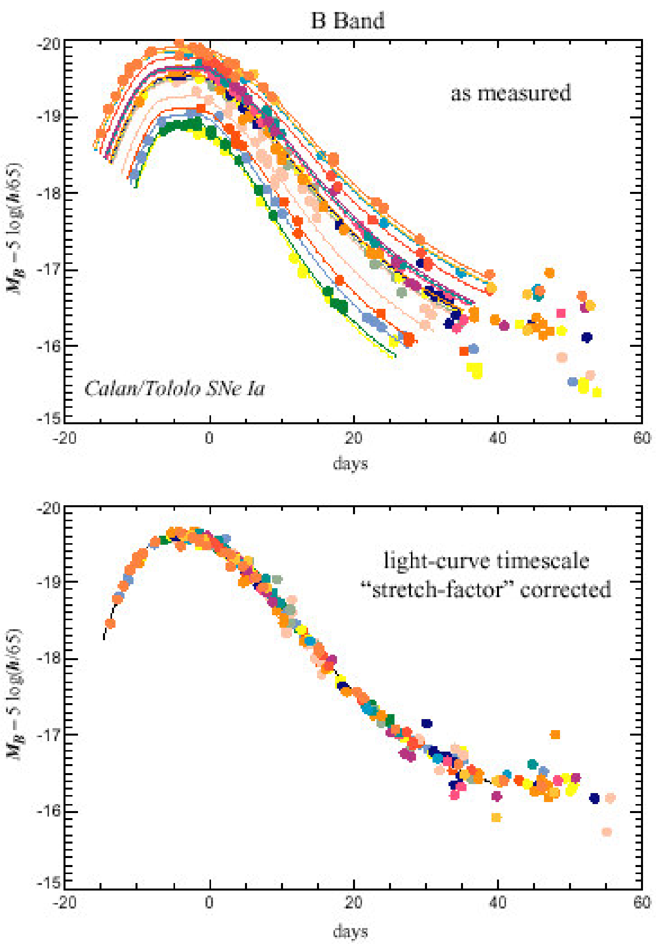
$\equiv h \bullet 100$ km/s/Mpc (1 pc = 3.26 light-years)

Expansion of the Universe

- The expansion of the universe is slowed by matter
  - there is a critical density, ρ_c, the minimum density required to stop the expansion (for $\Lambda=0$)
    - $\Omega_M = \rho / \rho_c$ $(\rho_c = 2 \bullet 10^{-29}\, h^2\ \text{gm/cm}^3)$
  - the existence of a cosmological constant (Λ), complicates this
    - $\Omega_\Lambda = \Lambda / 3H_0$
    - elementary considerations of the vacuum energy would make this at least 55 orders of magnitude larger than the critical density !!
    - See S.M. Carroll and W.H. Press, Annu. Rev. Astron. Astrophys. 1992. 30: 499-542 (http://nedwww.ipac.caltech.edu/level5/Carroll/frames.html)

Expansion of the Universe

Use type Ia Supernovae corrected candles to measure the expansion rate. Ground-based work thus far has uncovered a major surprise:



Kim, *et al.* (1997)