Big-Bang Cosmology

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129A

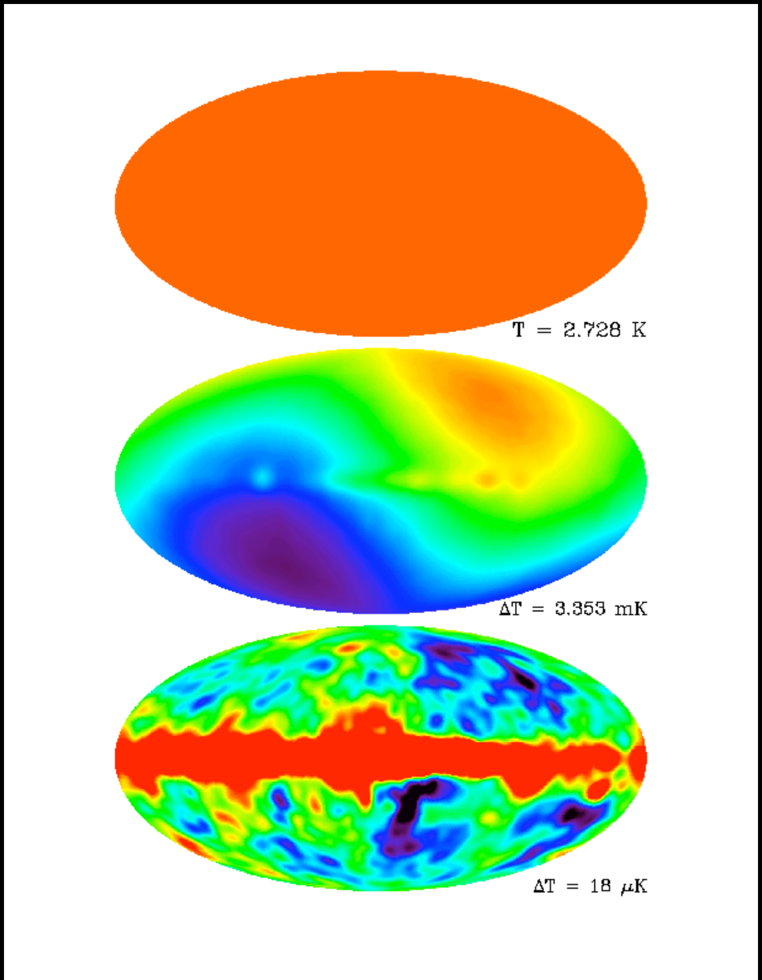
F2002 Semester

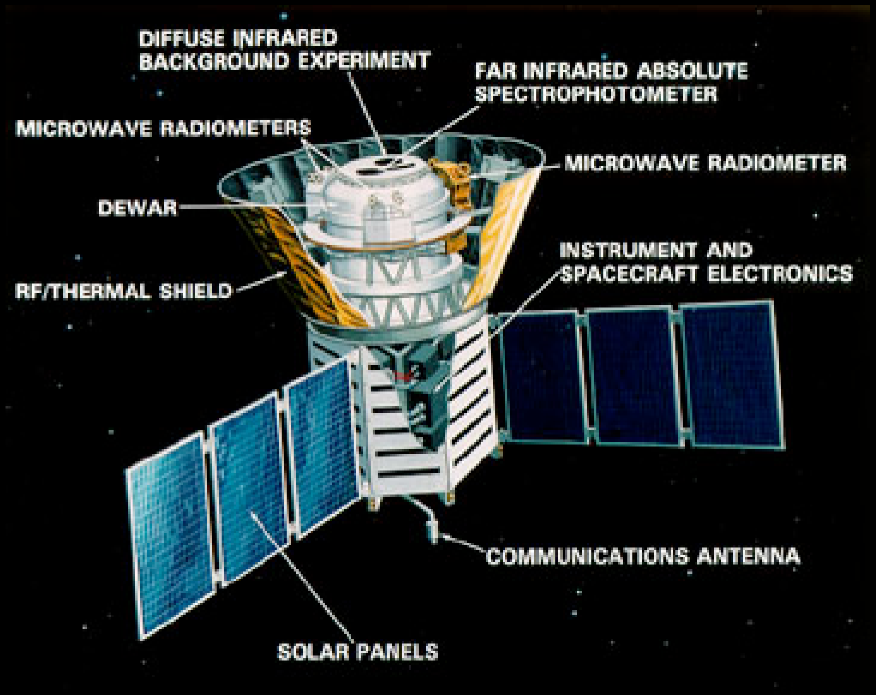
Introduction

- Brief review of standard cosmology
- Big-Bang Nucleosynthesis
- Observational evidence for Dark Matter
- Observational evidence for Dark Energy
- Particle-physics implications
- Baryon Asymmetry

Brief review of standard cosmology

The Isotropic Universe





The Cosmological Principle

- Universe highly isotropic
  - CMBR anisotropy □ $O(10^{-5})$
- Unless we occupy the "center of the Universe," it must also be homogenous
- Isotropy and Homogeneity

  □ maximally symmetric space
  - Flat Euclidean space R^3
  - Closed three-sphere S^3=SO(4)/SO(3) $w^2 + x^2 + y^2 + z^2 = R^2$
  - Open three-hyperbola SO(3,1)/SO(3) $□w^2 + x^2 + y^2 + z^2 = R^2$

Friedman Equation

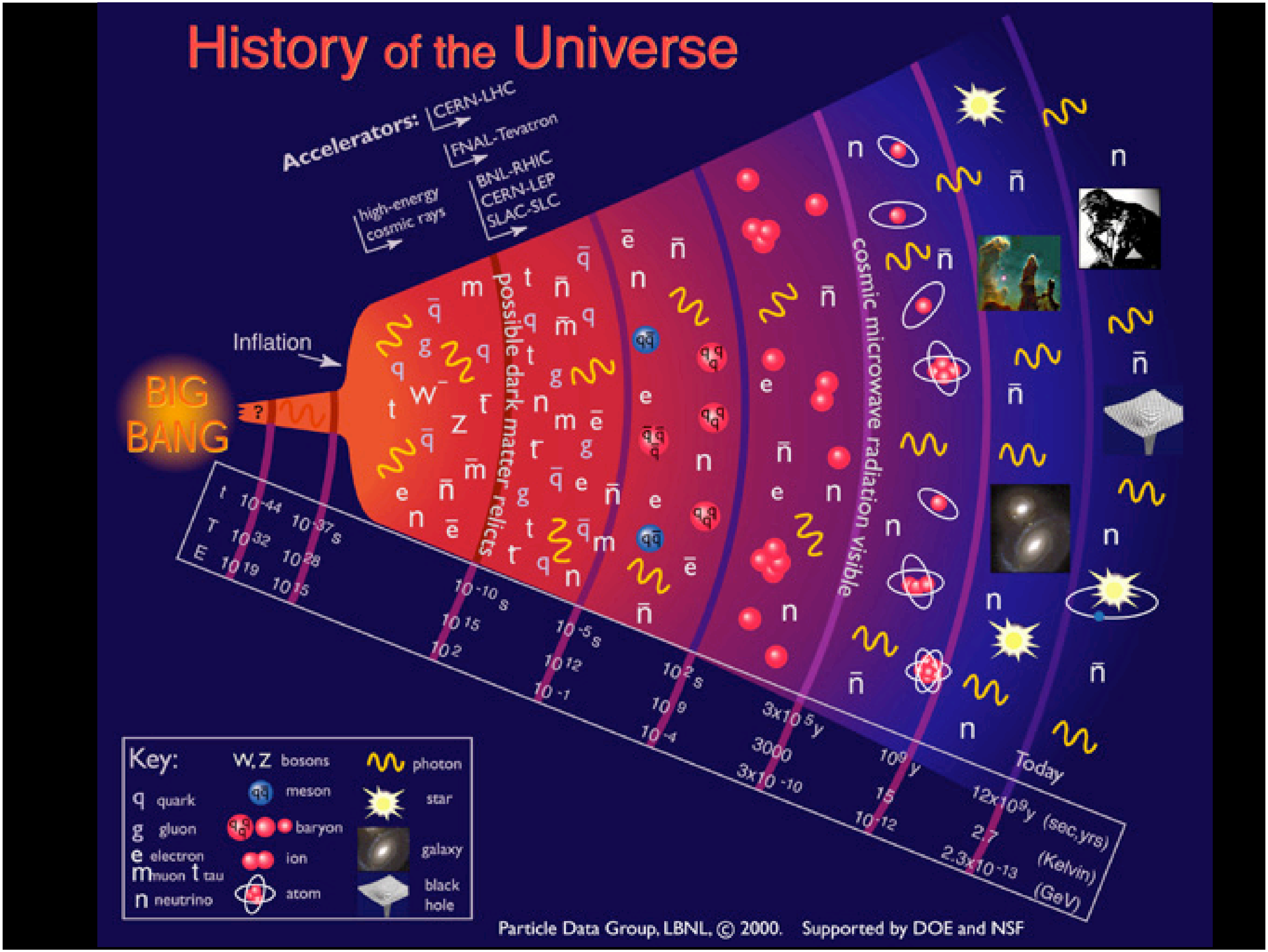
- Equation that governs expansion of the Universe
  - $k=-1$ (closed), $k=1$ (open), $k=0$ (flat)
  - energy density ρ

$$\left(\frac{\dot{R}}{R}\right)^2 - \frac{k}{R^2} = \frac{8\pi}{3} G_N \rho$$

- First law of thermodynamics: $d(\rho R^3) = -p\,d(R^3),\ p = w\rho$

$$\Rightarrow \rho \propto R^{-3(1+w)}$$

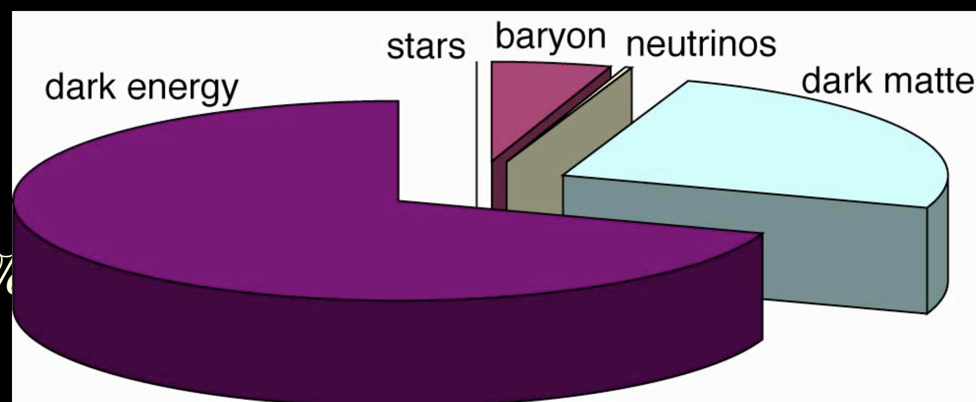
- For flat Universe:
  - Matter-dominated Universe: $\rho \propto R^{-3}, R \propto t^{2/3}$
  - Radiation-dominated Universe: $\rho \propto R^{-4}, R \propto t^{1/2}$
  - Vacuum-dominated Universe: $\rho \propto R^{0}, R \propto e^{Ht}$
- Temperature $T \propto R^{-1}$



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Energy budget of Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.3–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~30%
- Dark Energy ~65%
- Anti-Matter 0%
- Higgs condensate ~10^{62}%



Cosmic Microwave Background

Fossils of Hot Big Bang

- When the temperature of Universe was higher than about 3000K, all atoms (mostly hydrogen and helium) were ionized.
- Photons scatter off unbound electrons and could not stream freely: “opaque Universe.”
- Photons, atoms, electrons in thermal equilibrium.
- Once the temperature drops below 3000K, electrons are bound to atoms and photons travel freely, “recombination.”
- CMBR photons from this era simply stretched by expansion $\lambda \propto R$

Density Fluctuation

- Completely homogeneous Universe would remain homogeneous □ no structure
- Need "seed" density fluctuation
- From observation, it must be nearly scale-invariant (constant in *k* space)
- Atoms also fall into gravitational potential due to the fluctuation and hence affects CMBR
- From COBE, we know □□/□~10^{-5}

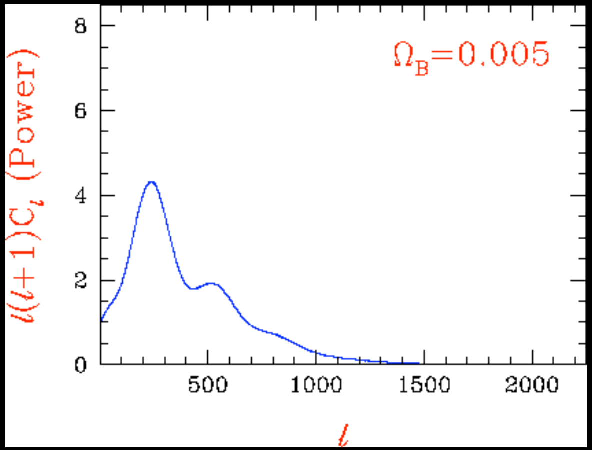
Structure Formation

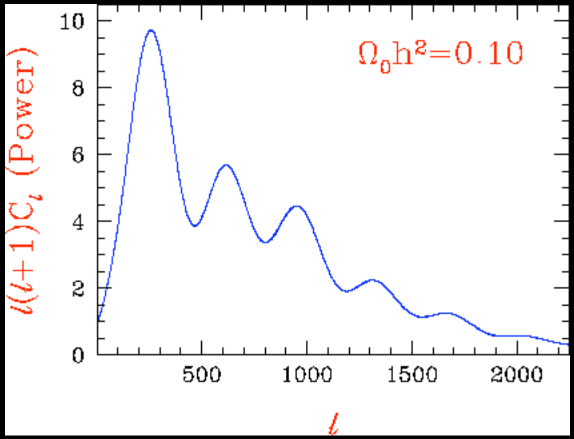
- Jeans instability of self-gravitating system causes structure to form (there is no anti-gravity to stop it!)
- Needs initial seed density fluctuation
- Density fluctuation grows little in radiation- or vacuum-dominated Universe
- Density fluctuation grows linearly in matter-dominated Universe
- If only matter=baryons, had only time for 10^3 growth from 10^{-5}: not enough time by now!

CMBR Anisotropy Probe to Cosmology

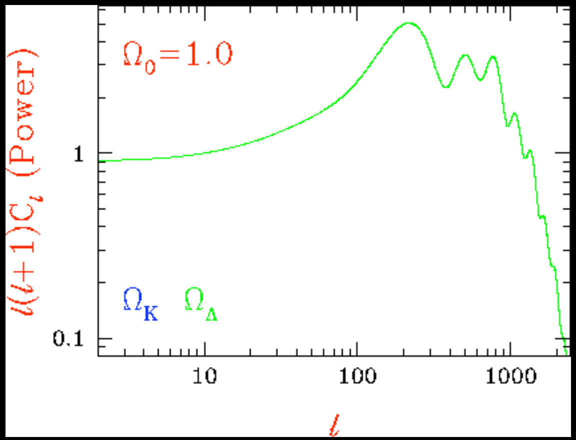
- Evolution of the anisotropy in CMBR depends on the cosmological parameters: Ω_{matter}, Ω_{baryon}, Ω_{Λ}, geometry of Universe
- Evolution: acoustic oscillation between photon and baryon fluid
- Characteristic distance scale due to the causal contact
- Yard stick at the last rescattering surface
- Angular scale determines geometry

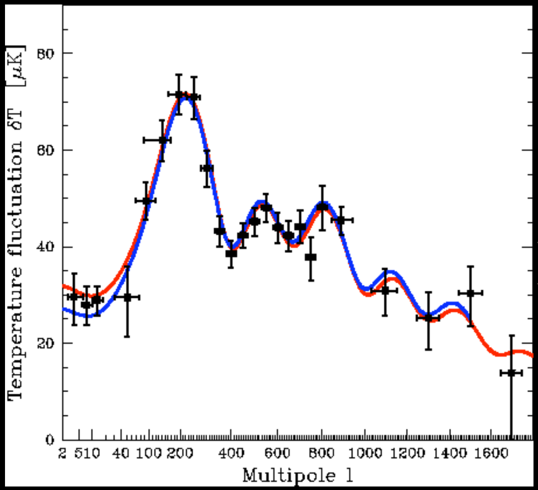
Acoustic Peaks Probe Cosmology





Wayne Hu



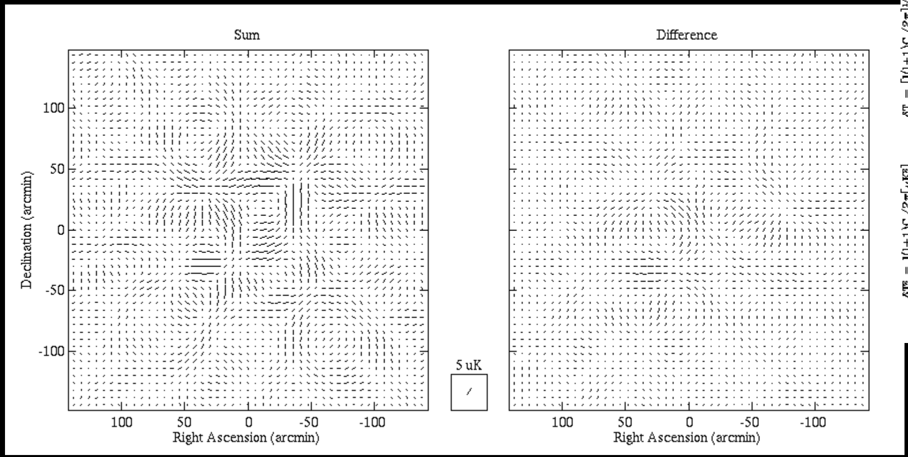


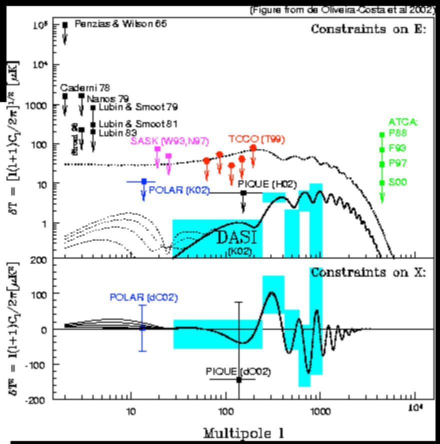
Max Tegmark

Polarization

- Compton scattering polarizes the photon in the polarization plane

$$\left\langle E_i E_j \right\rangle \Box \tfrac{1}{2} \Box_{ij} \left\langle \vec{E}^2 \right\rangle \quad (\Box_i \Box_j \Box \tfrac{1}{2} \Box_{ij} \vec{\Box}^{\,2}) T(x,y)$$





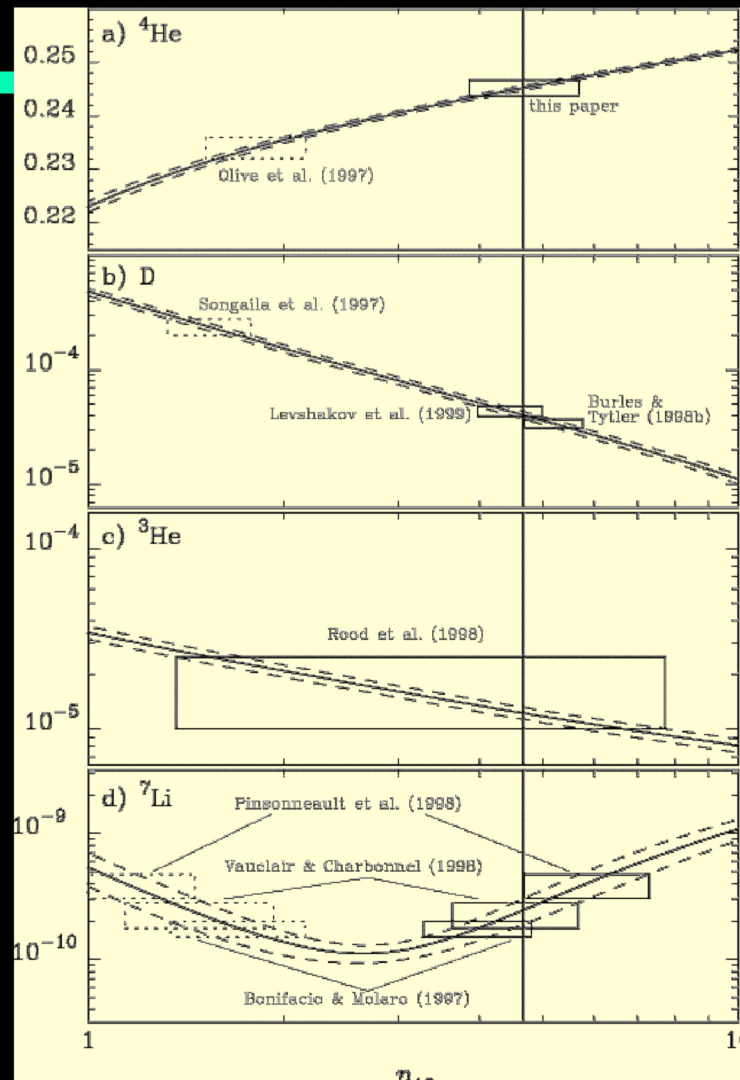
Big-Bang Nucleosynthesis

Thermo-Nuclear Fusion in Early Universe

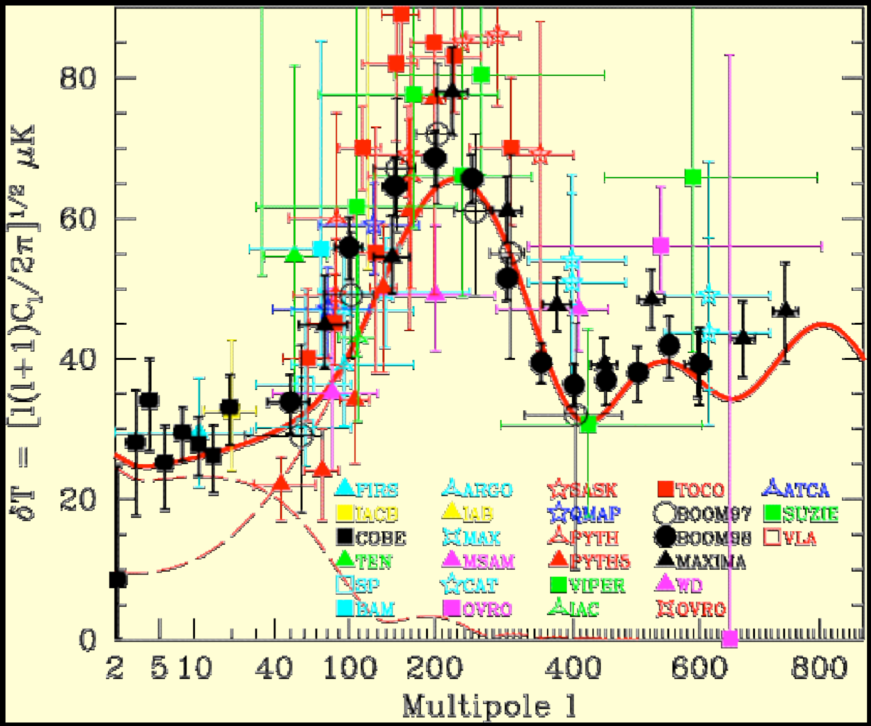
- Best tested theory of Early Universe
- Baryon-to-photon ratio $\eta \equiv n_B/n_\gamma$ only parameter
- Neutron decay-anti-decay equilibrium ends when T~1MeV, they decay until they are captured in deuterium
- Deuterium eventually form ^{3}He, ^{4}He, ^{7}Li, etc
- Most of neutrons end up in ^{4}He
- Astronomical observations may suffer from further chemical processing in stars

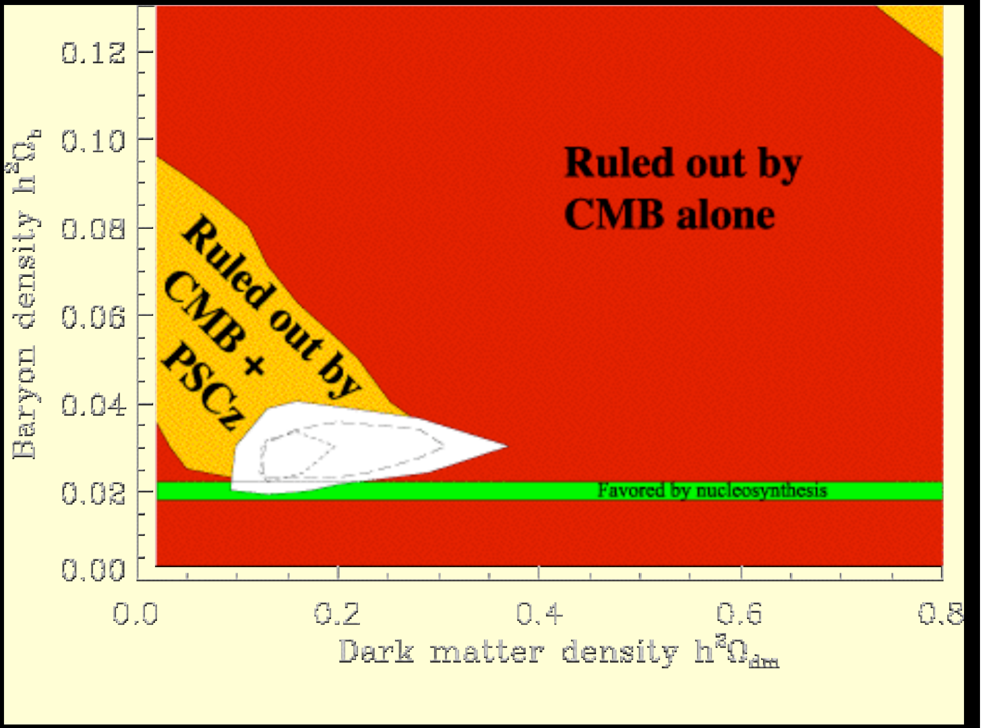
Data

- "Crisis" the past few years
- Thuan-Izotov reevaluation of ^{4}He abundance
- Sangalia D abundance probably false
- Now concordance $\Omega_B h^2=0.017\pm0.004$ (Thuan, Izotov)
- CMB+LSS now consistent $\Omega_B=0.02$–0.037 (Tegmark, Zaldarriaga. Hamilton)



Cosmic Microwave Background





Observational evidence for Dark Matter

Theoretical Arguments for Dark Matter

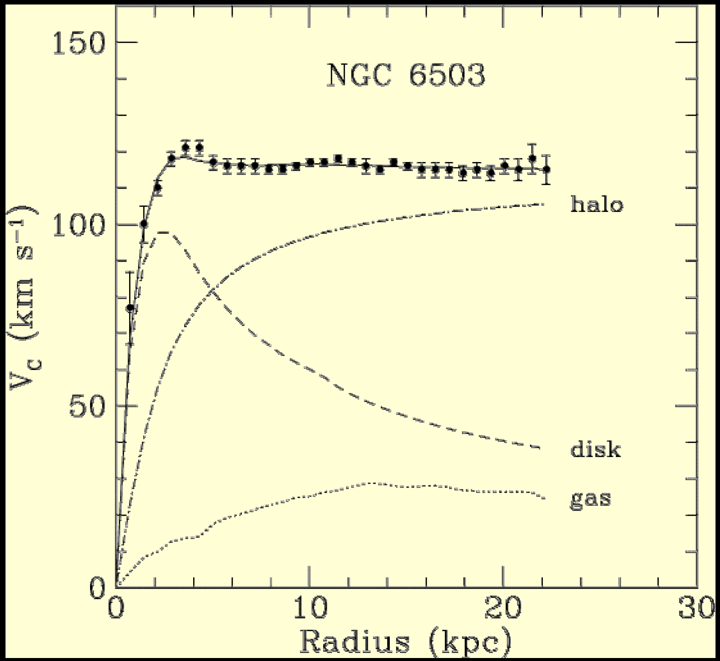
- Spiral galaxies made of bulge+disk: unstable as a self-gravitating system

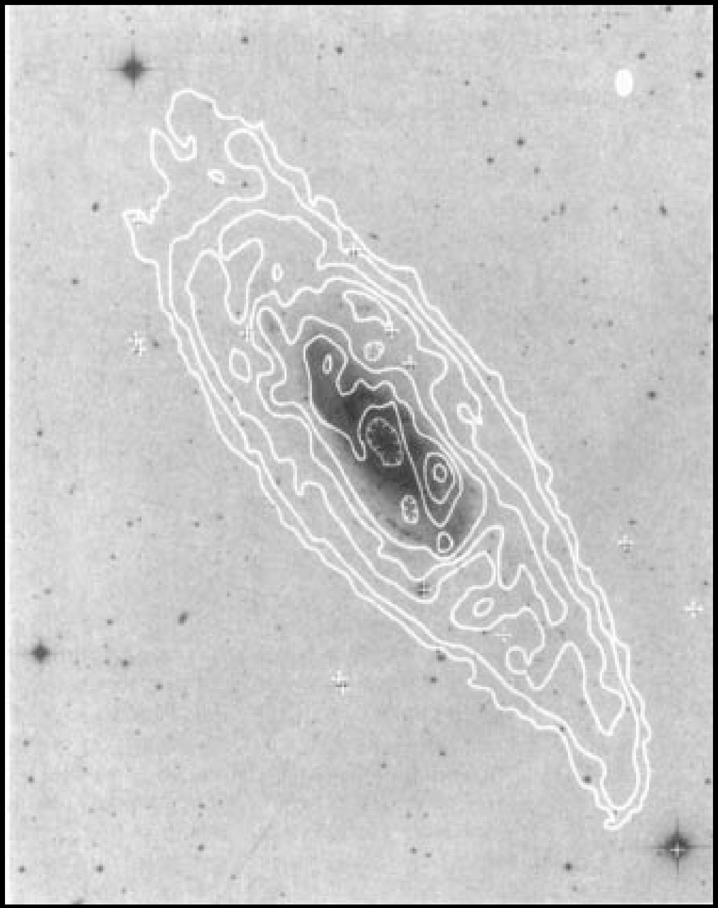
  □ need a (near) spherical halo

- With only baryons as matter, structure starts forming too late: we won’t exist
  - Matter-radiation equality too late
  - Baryon density fluctuation doesn’t grow until decoupling
  - Need electrically neutral component

Galactic Dark Matter

- Observe galaxy rotation curve using Doppler shifts in 21 cm line from hyperfine splitting





Galactic Dark Matter

- Luminous matter (stars)

  $\Omega_{lum}h=0.002–0.006$
- Non-luminous matter

  $\Omega_{gal}>0.02–0.05$
- Only lower bound because we don’t quite know how far the galaxy halos extend
- Could in principle be baryons
- Jupiters? Brown dwarfs?

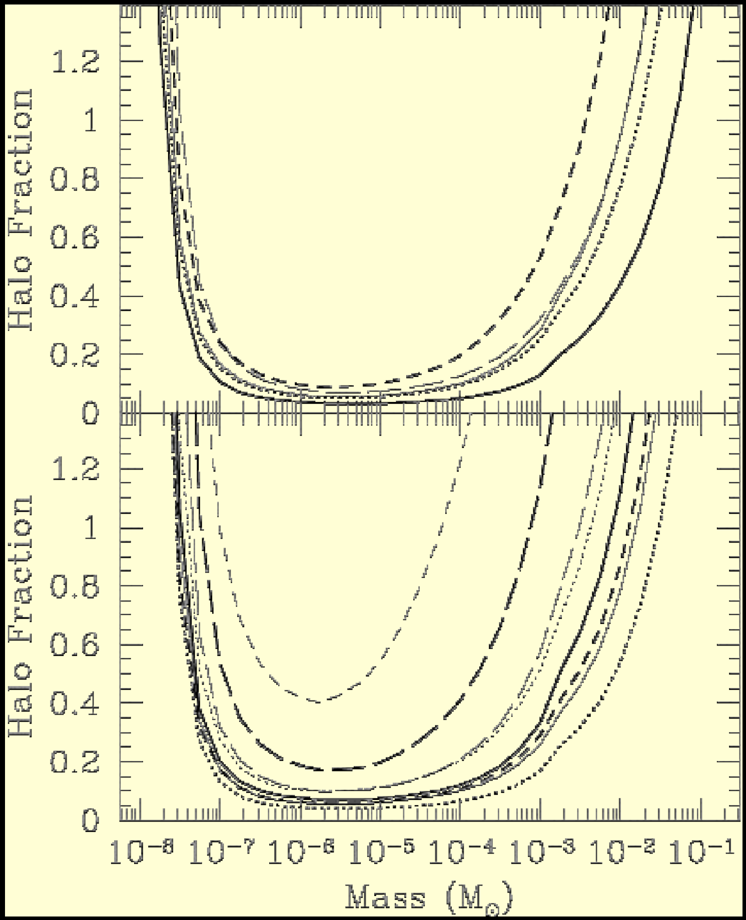
MAssive Compact Halo Objects (MACHOs)

- Search for microlensing towards LMC, SMC
- When a “Jupiter” passes the line of sight, the background star brightens

MACHO & EROS collab.

Joint limit astro-ph/9803082

- Need non-baryonic dark matter in halo
- Primordial BH of ~$M_\odot$?



Dark Matter in Galaxy Clusters

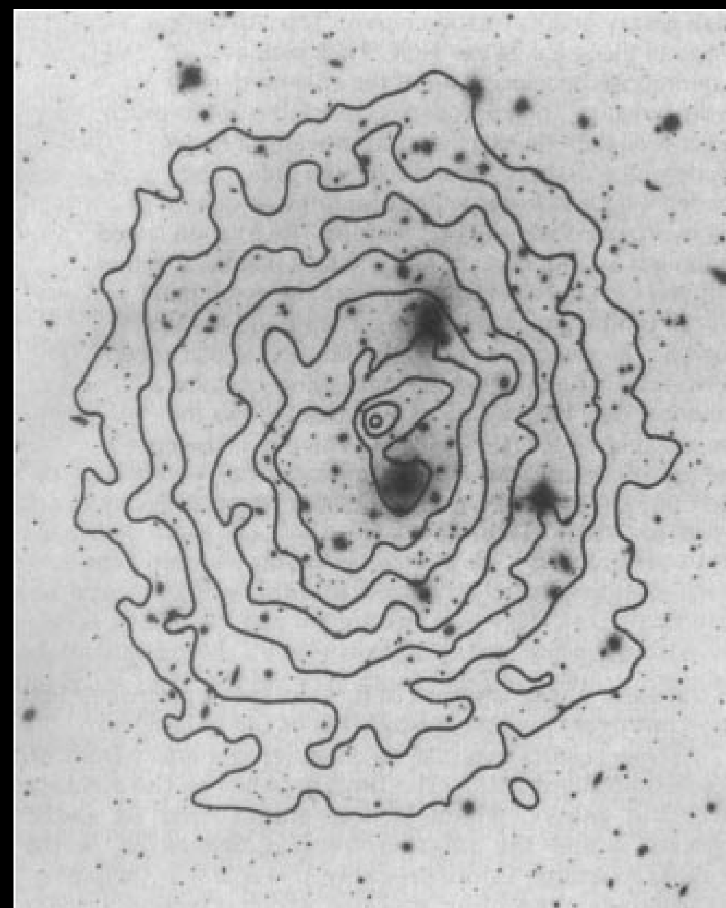
- Galaxies form clusters bound in a gravitational well
- Hydrogen gas in the well get heated, emit X-ray
- Can determine baryon fraction of the cluster

$$f_B h^{3/2} = 0.056 \pm 0.014$$

- Combine with the BBN

$$\Omega_{matter} h^{1/2} = 0.38 \pm 0.07$$

Agrees with SZ, virial



Particle-physics implications

Neutrino Dark Matter?

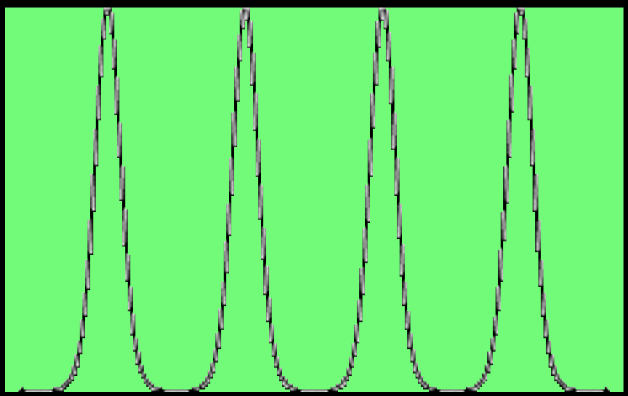
- Now that we seem to know neutrinos are massive, can't they be dark matter?

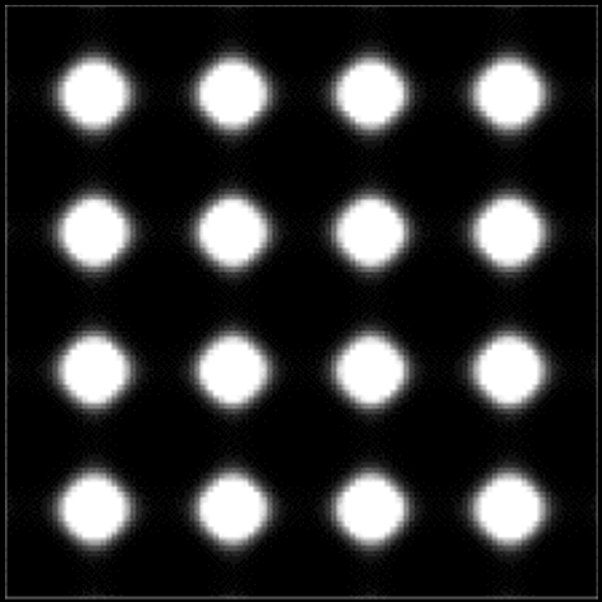
$$\Omega_\nu h^2 = \frac{m_\nu}{97\,\mathrm{eV}}$$

- Problem: neutrinos don't clump!

Cold Dark Matter

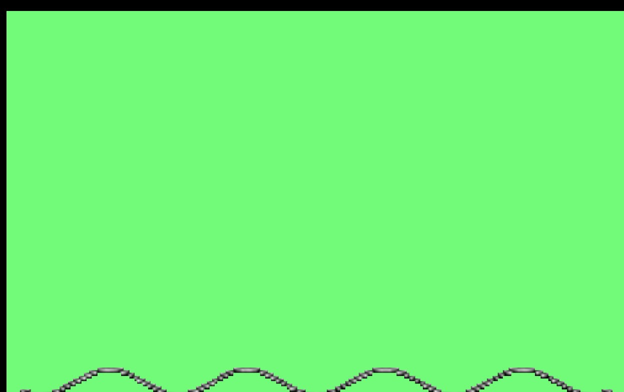
- Cold Dark Matter is not moving much
- Gets attracted by gravity

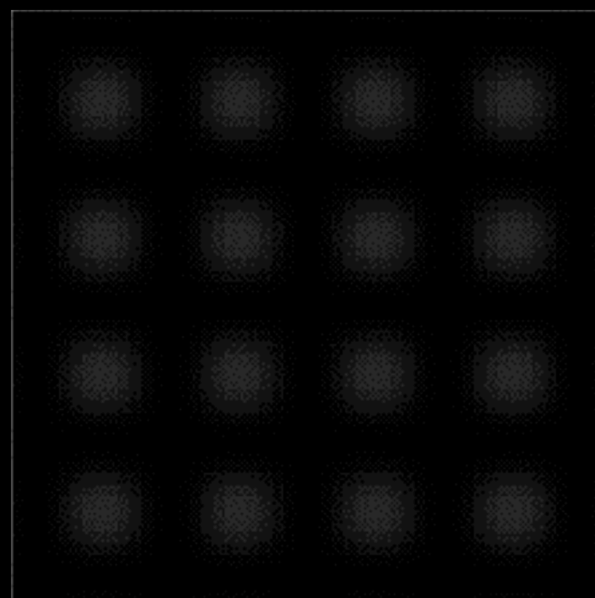




Neutrino Free Streaming

- Neutrinos, on the other hand, move fast and tend to wipe out the density contrast.





Particle Dark Matter

- Suppose an elementary particle is the Dark Matter
- WIMP (Weakly Interacting Massive Particle)
- Stable heavy particle produced in early Universe, left-over from near-complete annihilation

$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}{}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(TeV)^2}{\sigma_{ann}}$$

- Electroweak scale the correct energy scale!
- We may produce Dark Matter in collider experiments.

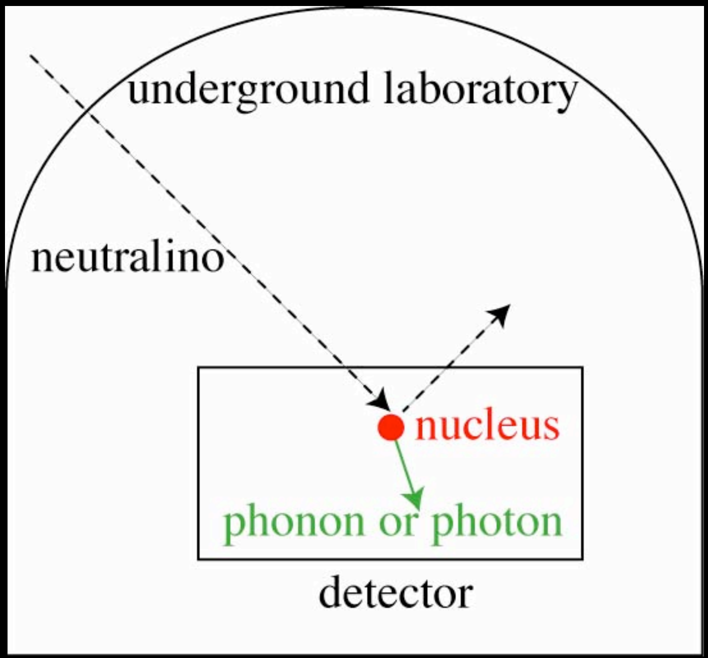
Particle Dark Matter

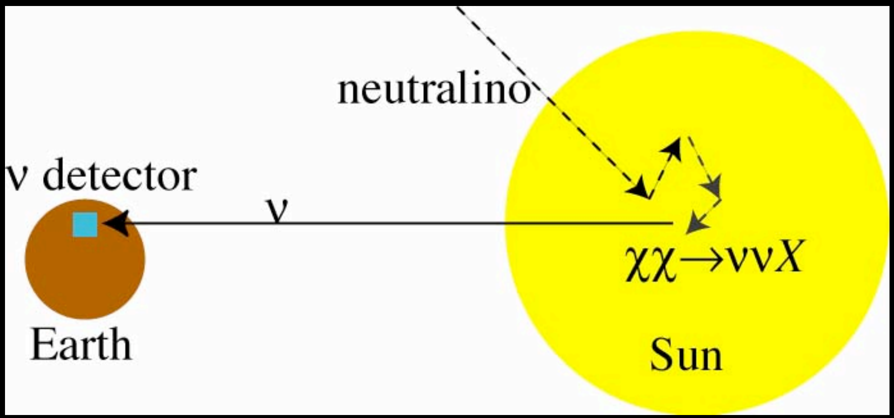
- Stable, TeV-scale particle, electrically neutral, only weakly interacting
- No such candidate in the Standard Model
- Supersymmetry: (LSP) Lightest Supersymmetric Particle is a superpartner of a gauge boson in most models: "bino" a perfect candidate for WIMP
- But there are many other possibilities (techni-baryons, gravitino, axino, invisible axion, WIMPZILLAS, etc)

Detection of Dark Matter

- Direct detection
- CDMS-II, Edelweiss, DAMA, GENIUS, etc

- Indirect detection
- SuperK, AMANDA, ICECUBE, Antares, etc

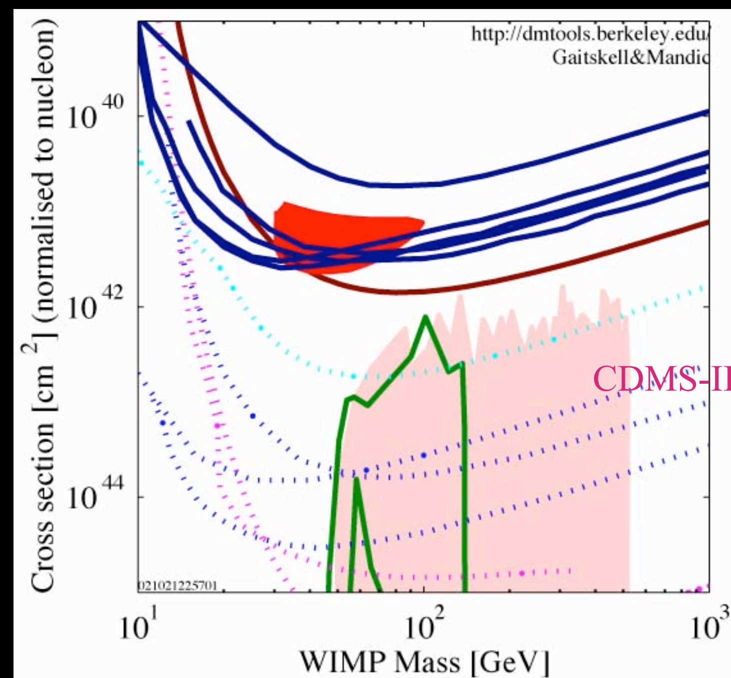




complementary techniques are getting into the interesting region of parameter space

Particle Dark Matter

- Stable, TeV-scale particle, electrically neutral, only weakly interacting
- No such candidate in the Standard Model
- Lightest Supersymmetric Particle (LSP): superpartner of a gauge boson in most models
- LSP a perfect candidate for WIMP

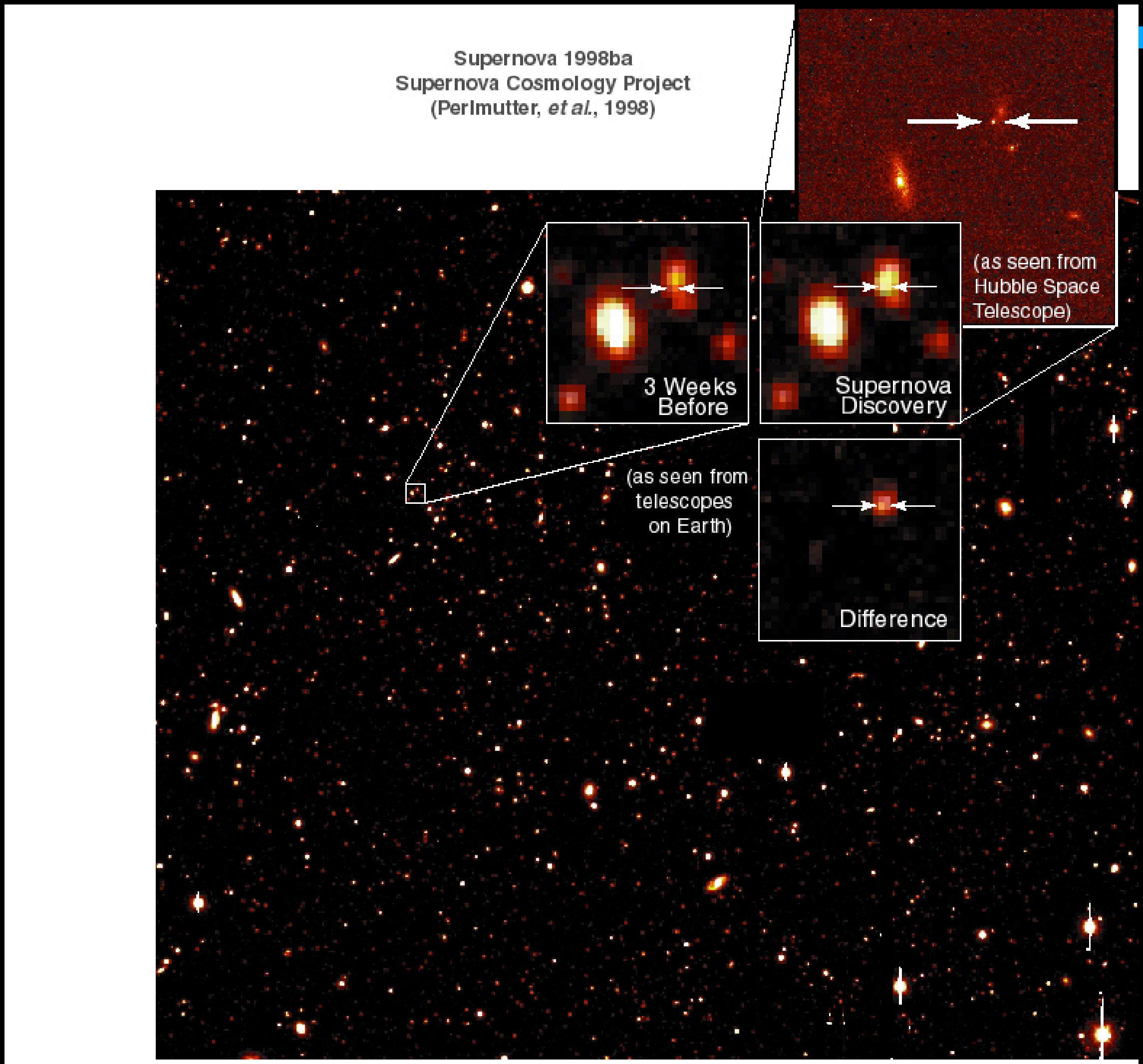


Detect Dark Matter to see *it is there*.

Produce Dark Matter in accelerator experiments to see *what it is*.

Observational evidence for Dark Energy

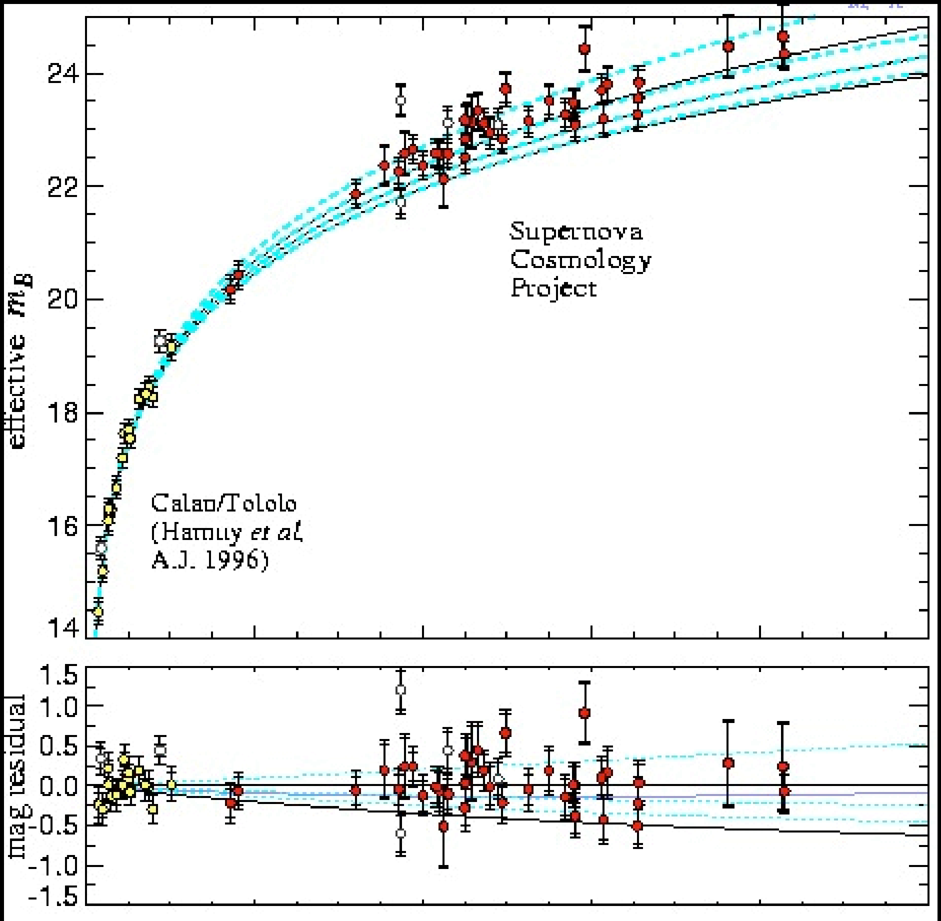
Type-IA Supernovae



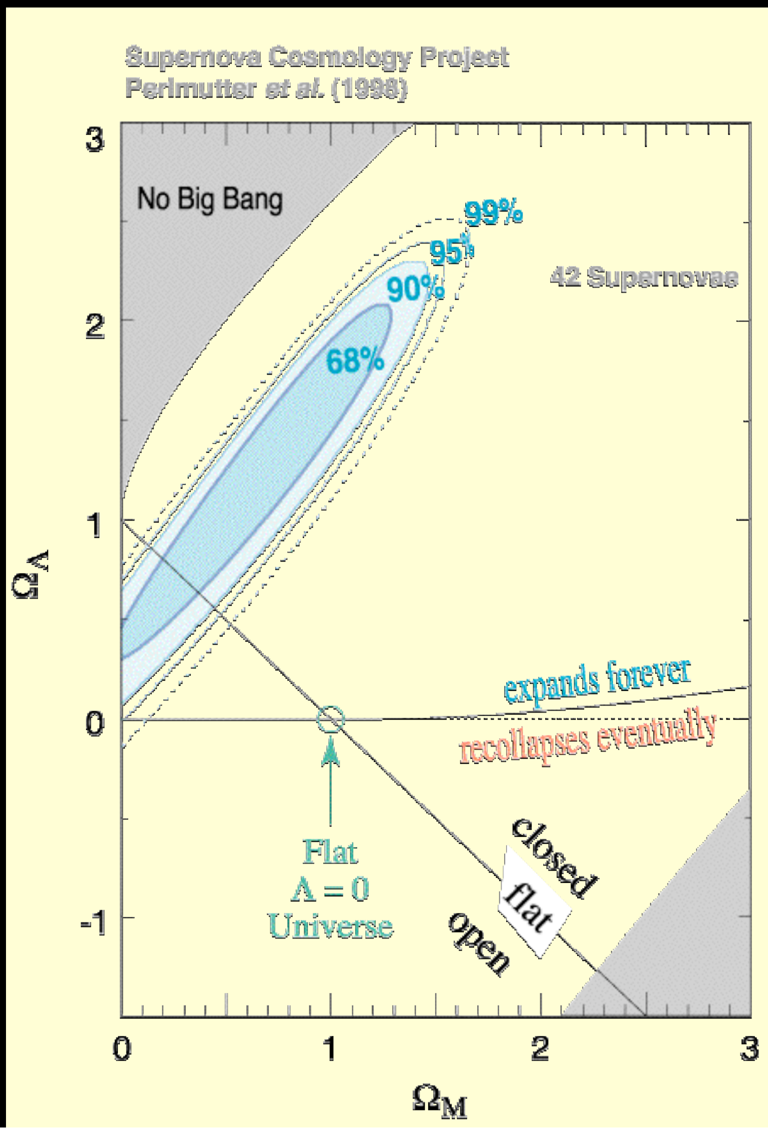
As bright as the host galaxy

Type-IA Supernovae

- Type-IA Supernovae “standard candles”
- Brightness not quite standard, but correlated with the duration of the brightness curve
- Apparent brightness
   how far (“time”)
- Know redshift
   expansion since then



Type-IA Supernovae



- Clear indication for "cosmological constant"
- Can in principle be something else with negative pressure
- With $w=-p/\rho$,

$$\rho \propto R^{-3(1+w)}, R \propto t^{2/3(1+w)}$$

- Generically called "Dark Energy"

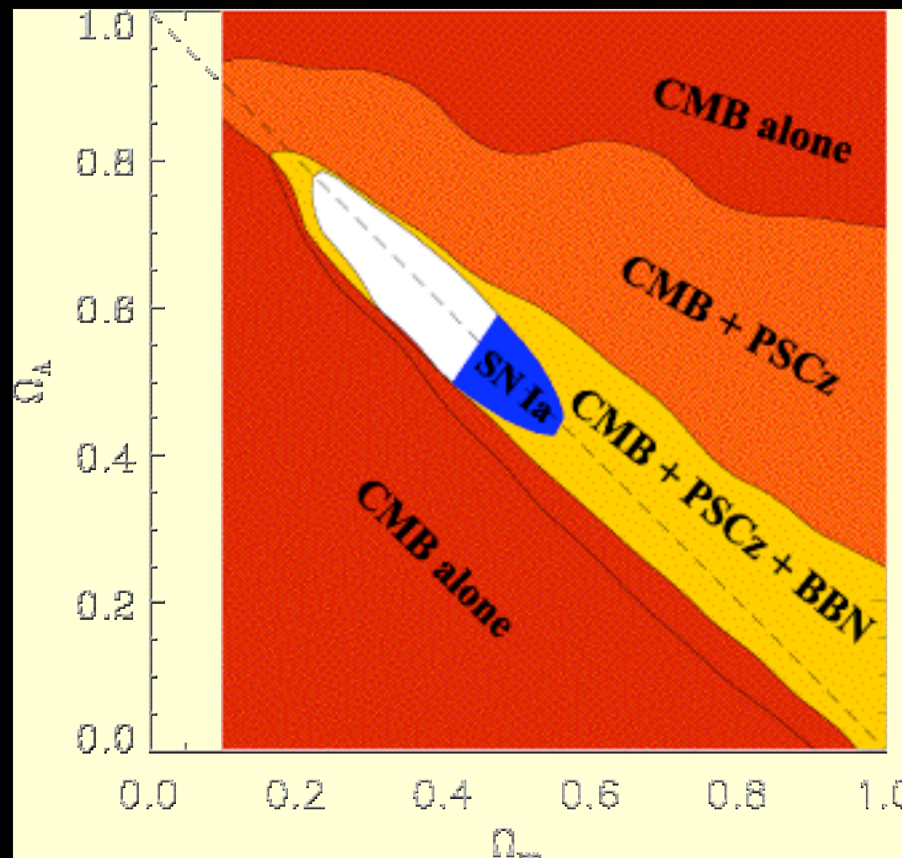
Cosmic Concordance

- CMBR: flat Universe

  $\Omega \sim 1$
- Cluster data etc:

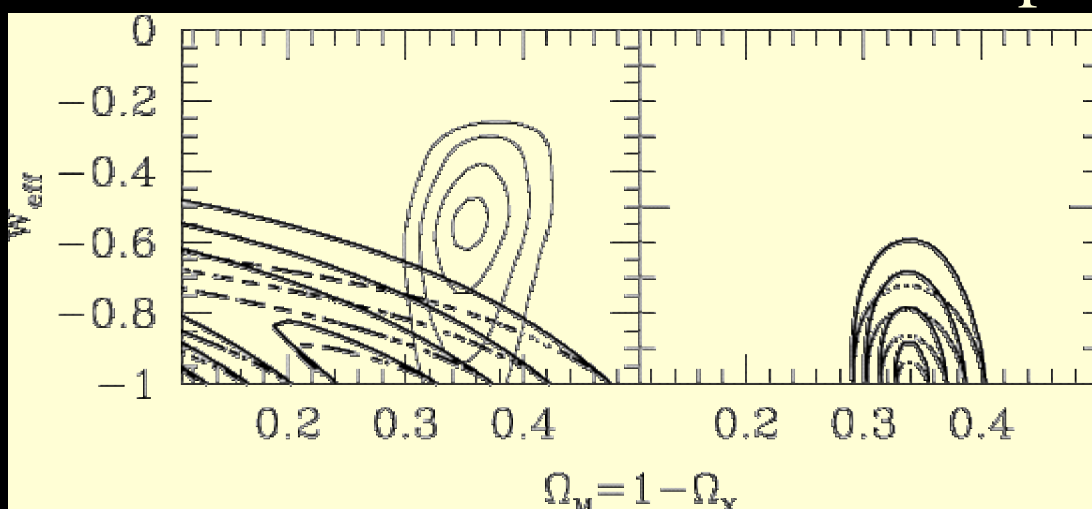
  $\Omega_{matter} \sim 0.3$
- SNIA:

  $(\Omega_{\Lambda} - 2\Omega_{matter}) \sim 0.1$
- Good concordance among three



Constraint on Dark Energy

- Data consistent with cosmological constant $w = -1$
- Dark Energy is an energy that doesn't thin much as the Universe expands!



Embarrassment with Dark Energy

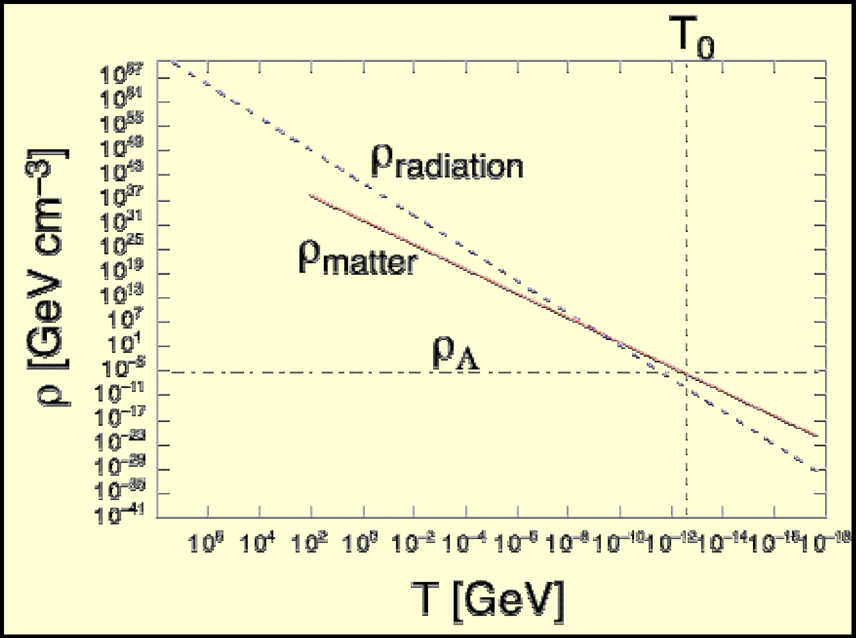
- A naïve estimate of the cosmological constant in Quantum Field Theory: $\square_{\square} \sim M_{\mathrm{Pl}}^{4} \sim 10^{120}$ times observation
- *The worst prediction in theoretical physics!*
- People had argued that there must be some mechanism to set it zero
- But now it seems finite???

Quintessense?

- Assume that there *is* a mechanism to set the cosmological constant exactly zero.
- The reason for a seemingly finite value is that we haven't gotten there yet
- A scalar field is slowly rolling down the potential towards zero energy
- But it has to be extremely light: 10^{-42} GeV. Can we protect such a small mass against radiative corrections? It shouldn't mediate a "fifth force" either.

Cosmic Coincidence Problem

- Why do we see matter and cosmological constant almost equal in amount?
- "Why Now" problem
- Actually a triple coincidence problem including the radiation
- If there is a fundamental reason for $\rho_\Lambda \sim ((\mathrm{TeV})^2/M_{\mathrm{Pl}})^4$, coincidence natural



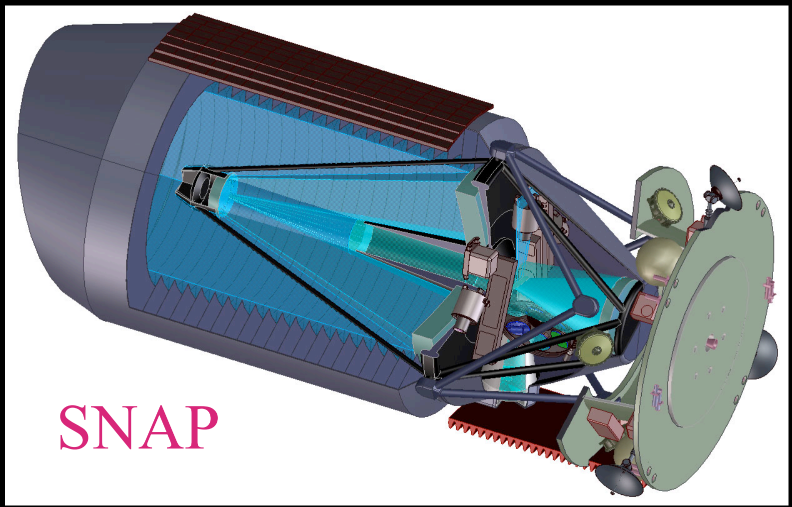
Arkani-Hamed, Hall, Kolda, HM

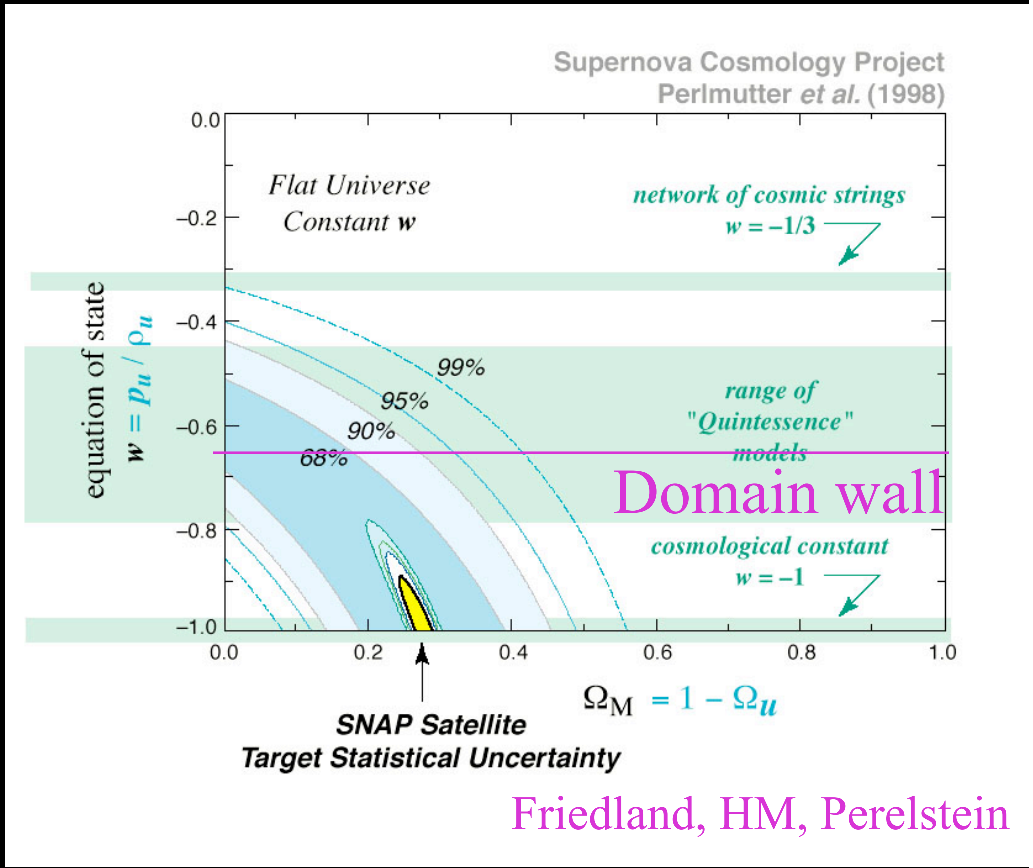
Amusing coincidence?

- The dark energy density $\rho_\Lambda \sim (2\text{meV})^4$
- The Large Angle MSW solution
  $\Delta m^2 \sim (5\text{–}10\text{meV})^2$
- *Any deep reason behind it?*
- Again, if there is a fundamental reason for $\rho_\Lambda \sim ((\text{TeV})^2/M_{\text{Pl}})^4$, and using seesaw mechanism $m_\nu \sim (\text{TeV})^2/M_{\text{Pl}}$, coincidence may not be an accident

What is the Dark Energy?

- We have to measure *w*
- For example with a dedicated satellite experiment





Baryogenesis

Baryon Asymmetry
Early Universe

10,000,000,001

q

10,000,000,000

$\bar{q}$

They basically have all annihilated away
except a tiny difference between them

Baryon Asymmetry
Current Universe

us

1

q $\bar{q}$

They basically have all annihilated away
except a tiny difference between them

Sakharov's Conditions for Baryogenesis

- *Necessary* requirements for baryogenesis:
  - Baryon number violation
  - CP violation
  - Non-equilibrium

    $\Rightarrow$ $\Gamma(\Delta B>0) > \Gamma(\Delta B<0)$
- Possible new consequences in
  - Proton decay
  - CP violation

Original GUT Baryogenesis

- GUT necessarily breaks *B*.
- A GUT-scale particle *X* decays out-of-equilibrium with direct CP violation

$$B(X \to q) \neq B(\bar{X} \to \bar{q})$$

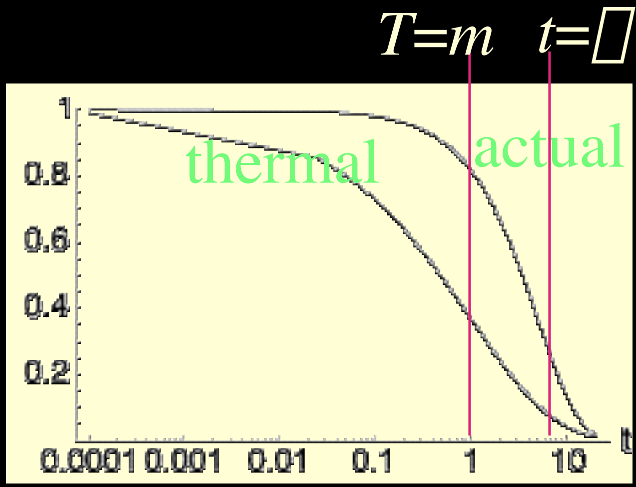
- Now direct CP violation observed: ε'!

$$B(K^0 \to \pi^+\pi^-) \neq B(\bar{K}^0 \to \pi^+\pi^-)$$

- But keeps B–L=0 $\Rightarrow$ "anomaly washout"

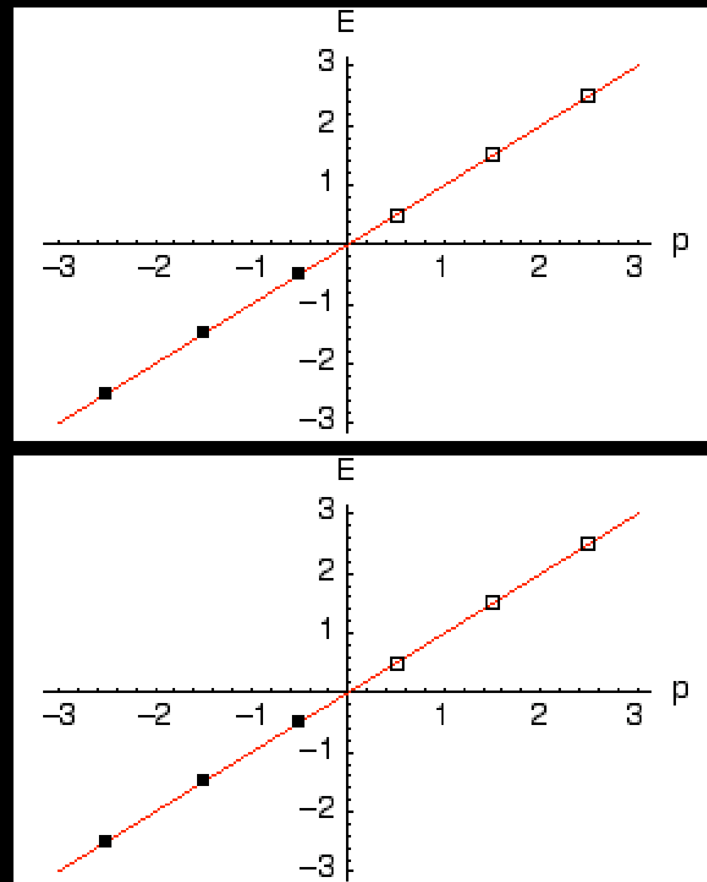
Out-of-Equilibrium Decay

- When in thermal equilibrium, the number density of a given particle is $n µ e^{-m/T}$
- But once a particle is produced, they "hang out" until they decay $n µ e^{-t/\tau}$
- Therefore, a long-lived particle ($\tau > M_{Pl}/m^{-2}$) decay out of equilibrium



Anomaly washout

- Actually, SM violates *B* (but not *B*–*L*).
  - In Early Universe ($T >$ 200GeV), *W*/*Z* are massless and fluctuate in *W*/*Z plasma*
  - Energy levels for left-handed quarks/leptons fluctuate correspon-dingly



□*L*=□*Q*=□*Q*=□*Q*=□*B*=1 □ *B*=*L*=0

Two Main Directions

- $B = L \neq 0$ gets washed out at $T > T_{EW} \sim 174$GeV
- Electroweak Baryogenesis (Kuzmin, Rubakov, Shaposhnikov)
  - Start with $B = L = 0$
  - First-order phase transition non-equilibrium
  - Try to create $B = L \neq 0$
- Leptogenesis (Fukugita, Yanagida)
  - Create $L \neq 0$ somehow from L-violation
  - Anomaly partially converts L to B

Electroweak Baryogenesis

Electroweak Baryogenesis

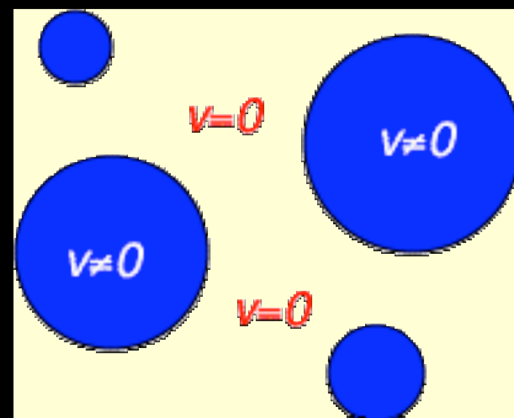
- Two big problems in the Standard Model
  - First order phase transition requires m_H<60GeV
  - Need new source of CP violation because

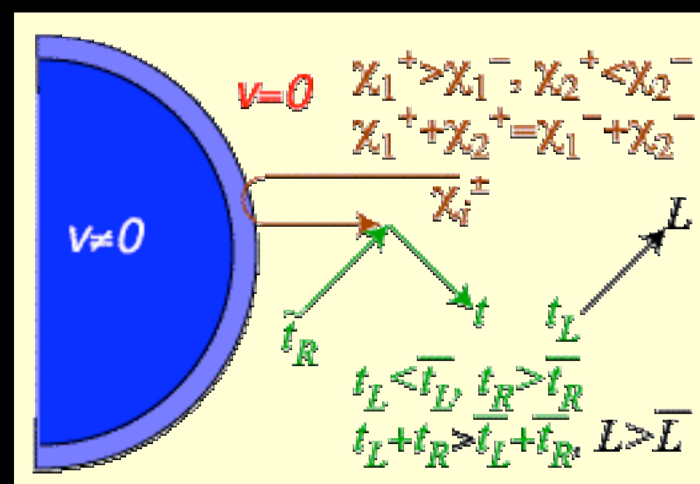
    J μ $\det[M_u^\dagger M_u, M_d^\dagger M_d]/T_{EW}^{12} \sim 10^{-20} << 10^{-10}$
- Minimal Supersymmetric Standard Model
  - First order phase transition possible if $m_{\tilde{t}_R} < 160\text{GeV}$
  - New CP violating phase $\arg(\Box^* M_2)$

e.g., (Carena, Quiros, Wagner), (Cline, Joyce, Kainulainen)

scenario

- First order phase transition
- Different reflection probabilities for chargino species
- Chargino interaction with thermal bath produces an asymmetry in top quark
- Left-handed top quark asymmetry partially converted to lepton asymmetry via anomaly
- Remaining top quark asymmetry becomes baryon asymmetry





parameters

- Chargino mass matrix

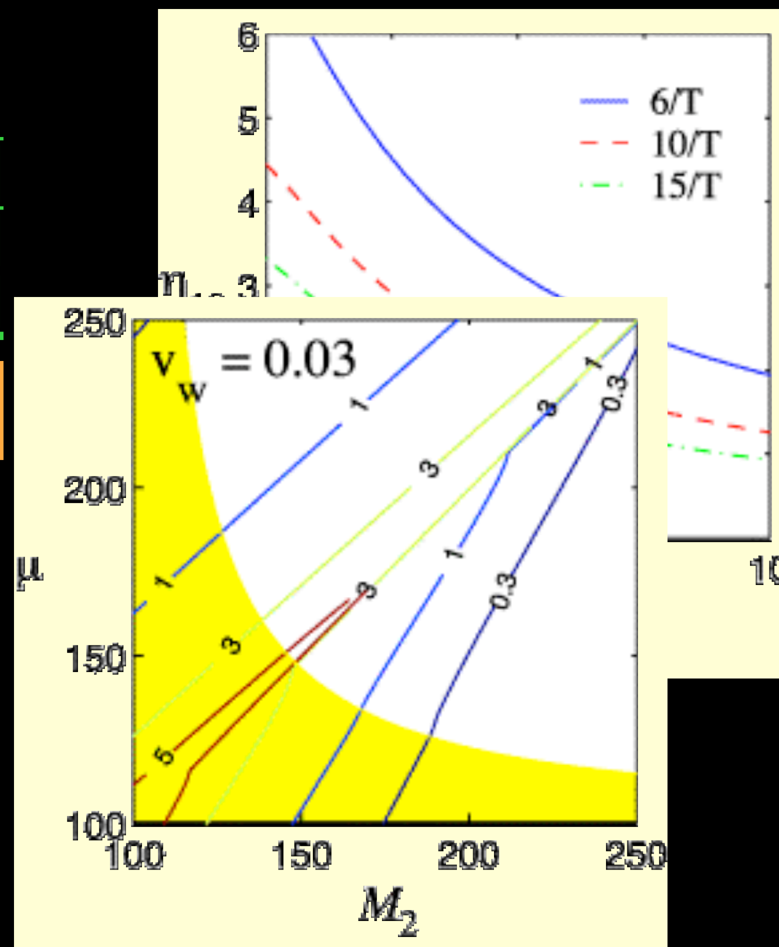
$$\begin{pmatrix} M_2 & \sqrt{2}m_W \cos\beta \\ \sqrt{2}m_W \sin\beta & \mu \end{pmatrix}$$

  Relative phase $\arg(\mu^* M_2)$

  unphysical if $\tan\beta = 1$

- Need fully mixed charginos $\Rightarrow \mu \approx M_2$

  (Cline, Joyce, Kainulainen)



mass spectrum

- Need $\arg(\mu^* M_2) \sim O(1)$ with severe EDM constraints from *e*, *n*, Hg

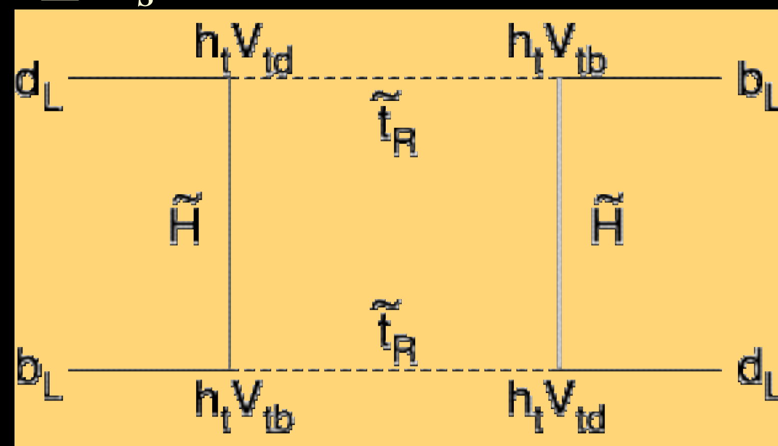
  ⇒ 1st, 2nd generation scalars > 10 TeV
- To avoid LEP limit on lightest Higgs boson, need left-handed scalar top ~ TeV
- Light right-handed scalar top, charginos

cf. Carena, Quiros, Wagner claim $\arg(\mu^* M_2) > 0.04$ enough

EDM constraint is weaker, but rest of phenomenology similar

Signals of Electroweak Baryogenesis

- *O*(1) enhancements to Δm_d, Δm_s with the same phase as in the SM
- B_s mixing vs lattice $f_{Bs}{}^2 B_{Bs}$
- B_d mixing vs V_{td} from V_{ub} and angles



- Find Higgs, stop, charginos (Tevatron?)
- Eventually need to measure the phase in the chargino sector at LC to establish it

(HM, Pierce)

Leptogenesis

Seesaw Mechanism
Prerequisite for Leptogenesis

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, but ν_R SM neutral

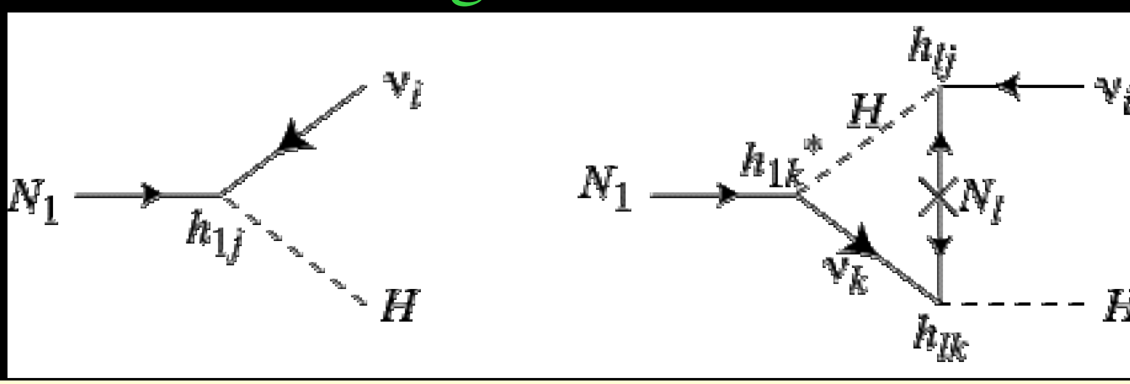
$$\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_R\end{pmatrix}\begin{pmatrix} & m_D \\ m_D & M\end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R\end{pmatrix} \qquad m_\nu = \frac{m_D^2}{M} << m_D$$

To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)

Majorana neutrinos: violate lepton number

Leptogenesis

- You generate *Lepton Asymmetry* first.
- *L* gets converted to *B* via EW anomaly
  - Fukugita-Yanagida: generate *L* from the direct CP violation in right-handed neutrino decay



$$\Gamma(N_1 \to \ell_i H) - \Gamma(N_1 \to \bar{\ell}_i H) \propto \mathrm{Im}(h_{1j} h_{1k} h^*_{lk} h^*_{lj})$$

Leptogenesis

- Two generations enough for CP violation because of Majorana nature (choose 1 & 3)

$$\epsilon = \frac{\Gamma(N_1 \to \ell_i H) - \Gamma(N_1 \to \bar{\ell}_i H)}{\Gamma(N_1 \to \ell_i H) + \Gamma(N_1 \to \bar{\ell}_i H)} \sim \frac{1}{8\pi} \frac{\mathrm{Im}(h_{13} h_{13} h_{33}^* h_{33}^*)}{|h_{13}|^2} \frac{M_1}{M_3}$$

- Right-handed neutrinos decay out-of-equilibrium
- Much more details worked out in light of oscillation data (Buchmüller, Plümacher; Pilaftsis)
- $M_1 \sim 10^{10}$ GeV OK $\Rightarrow$ want supersymmetry

Can we prove it experimentally?

- We studied this question at Snowmass2001

  (Ellis, Gavela, Kayser, HM, Chang)

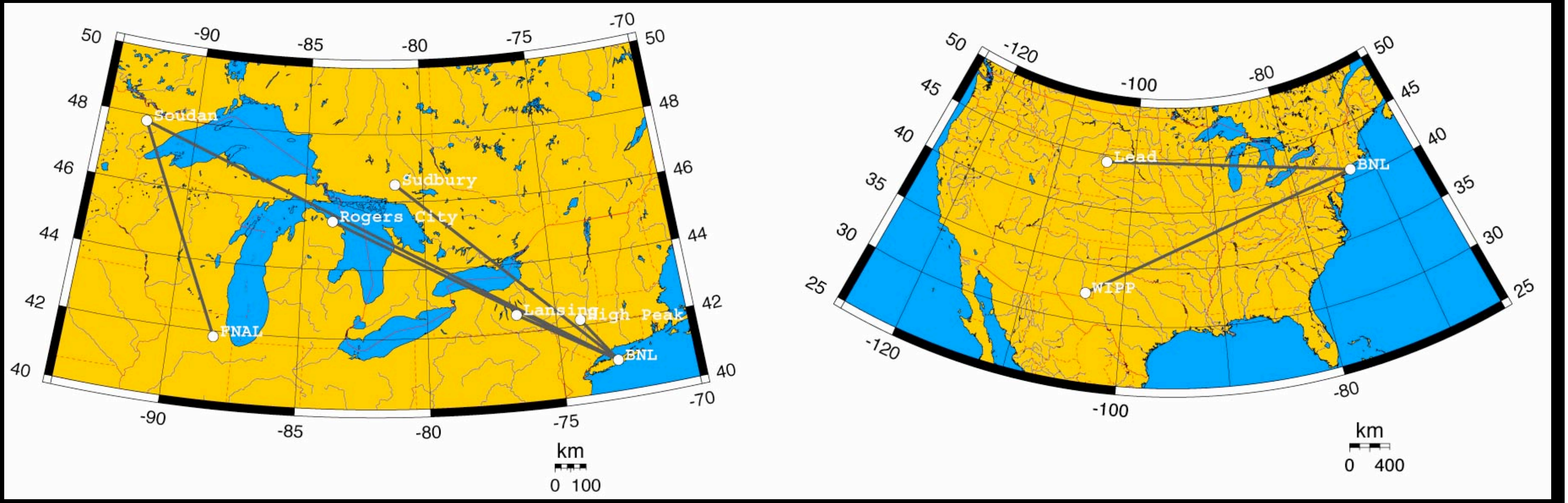
  – Unfortunately, no: it is difficult to reconstruct relevant CP-violating phases from neutrino data
- But: we will probably believe it if
  – 0□□□ found
  – CP violation found in neutrino oscillation
  – EW baryogenesis ruled out

CP Violation in Neutrino Oscillation

- CP-violation may be observed in neutrino oscillation

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

- Plans to shoot neutrino beams over thousands of kilometers to see this



Conclusions

- Mounting evidence that non-baryonic Dark Matter and Dark Energy exist
- Immediately imply physics beyond the SM
- Dark Matter likely to be TeV-scale physics
- Search for Dark Matter via
  - Collider experiment
  - Direct Search (e.g., CDMS-II)
  - Indirect Search via neutrinos (e.g., SuperK, ICECUBE)
- Dark Energy best probed by SNAP (LSST?)

Conclusions (cont)

- The origin of matter anti-matter asymmetry has two major directions:
  - Electroweak baryogenesis
  - leptogenesis
- Leptogenesis definitely gaining momentum
- May not be able to prove it definitively, but we hope to have enough circumstantial evidences: 0□□□, CP violation in neutrino oscillation