# Particle Cosmology

John Terning

T-8

LANL

# Outline

Dark Matter

Baryogenesis

Extra Dimensions

Dark Energy?

# Friedman Equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{a^2}$$

$$H_0 = \frac{\dot{a}(t_{now})}{a(t_{now})}$$

$$\Omega_m = \frac{8\pi G}{3H_0^2}\rho_0$$

$$\Omega_\Lambda = \frac{\Lambda}{3H_0^2}$$

$$\Omega_k = -\frac{k}{a_0^2 H_0^2}$$

$$1 = \Omega_m + \Omega_\Lambda + \Omega_k$$

# Cosmic Expansion

$$p = w\rho$$

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 \approx \frac{4\pi G_N}{3} \frac{\rho_0}{a^{3(1+w)}}$$

$$w = \begin{cases} \frac{1}{3} & \text{radiation} \\ 0 & \text{matter} \\ -\frac{1}{3} & \text{cosmic strings} \\ -1 & \text{cosm. const.} \end{cases}$$

# Relic Densities

$$\dot{n} = -3Hn - \langle\sigma v\rangle n^2 + \langle\sigma v\rangle n_{\mathrm{eq}}^2$$

$$n_{\mathrm{eq}} = \frac{2}{(2\pi)^3}\int_0^\infty 4\pi p^2 dp \frac{1}{e^{E(p)/kT}+1}$$

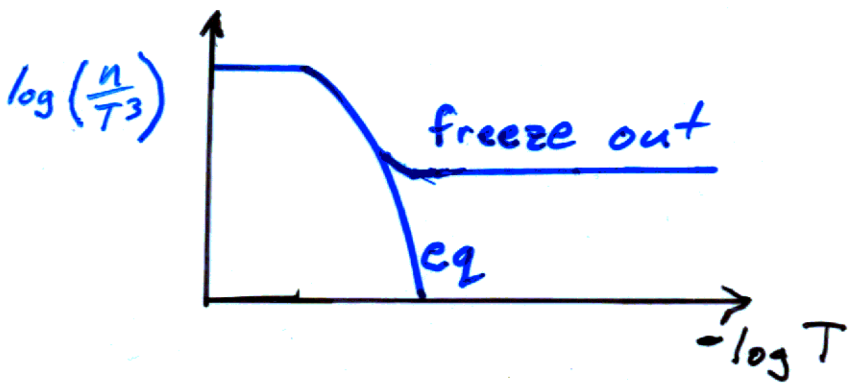
$$E(p) = \sqrt{p^2 + m^2}$$

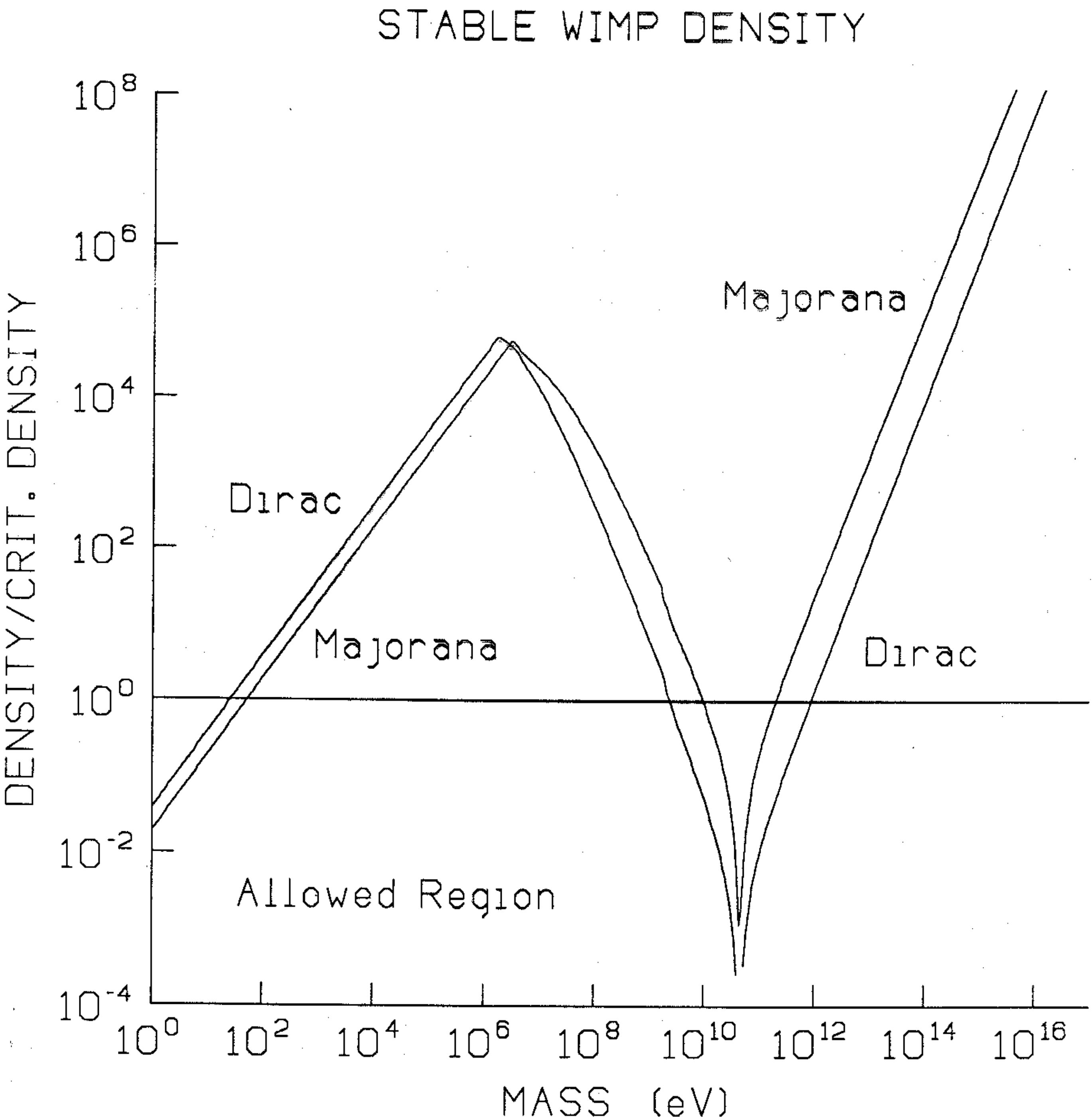
For high T, $H \ll \langle\sigma v\rangle n$,

$$n = n_{\mathrm{eq}}$$

below freeze-out: $H \gg \langle\sigma v\rangle n$

$$n \propto \frac{T^3\sqrt{G_N}}{\langle\sigma v\rangle kT_f}$$





STABLE WIMP DENSITY
DENSITY/CRIT. DENSITY
10^8
10^6
10^4
10^2
10^0
10^-2
10^-4
Majorana
Dirac
Majorana
Dirac
Allowed Region
10^0
10^2
10^4
10^6
10^8
10^10
10^12
10^14
10^16
MASS (eV)

# Axion Dark Matter

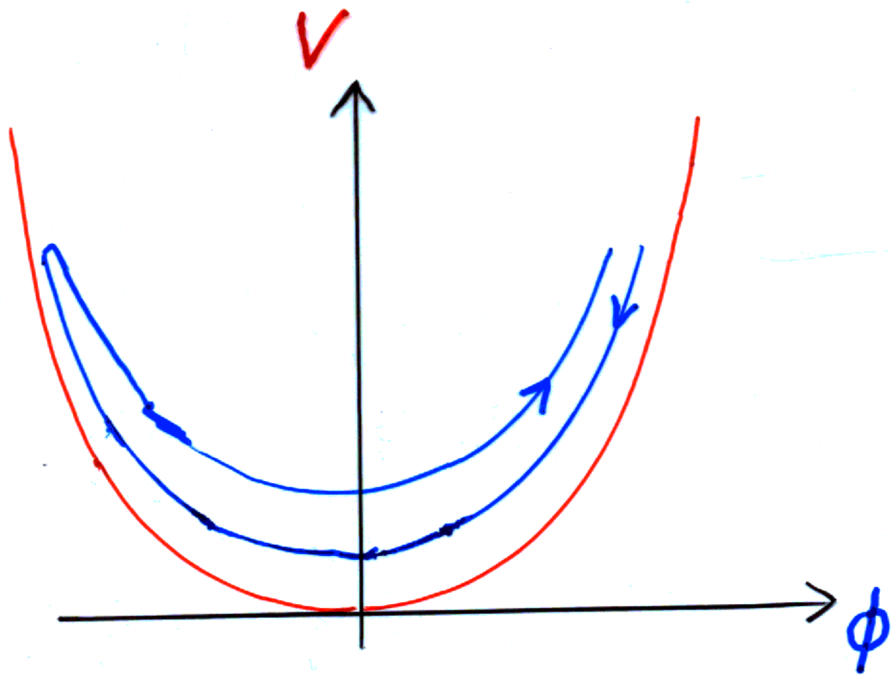
stable scalar field

slow roll until

$$H \sim m = 10^{-\text{few}}\ \text{eV},$$

then $\phi(t)$ can oscillate around its minimum

$$\rho_{ax} \sim \frac{\rho_i}{a(t)^3}$$



# Matter-Antimatter Asymmetry

matter $\gg$ antimatter

$$\frac{\text{Baryons}}{\text{photons}} \approx 10^{-10}$$

initial conditions: $\dfrac{q-\overline{q}}{q} \approx 10^{-10}$

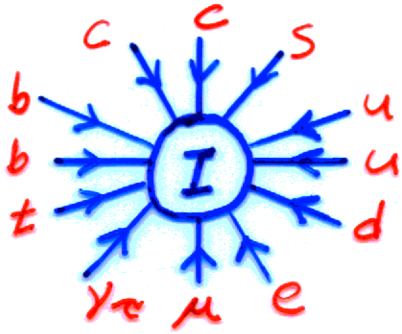
dynamics: Baryogenesis – Sakharov (1967)

- B violation
- C & CP violation
- out of equilibrium

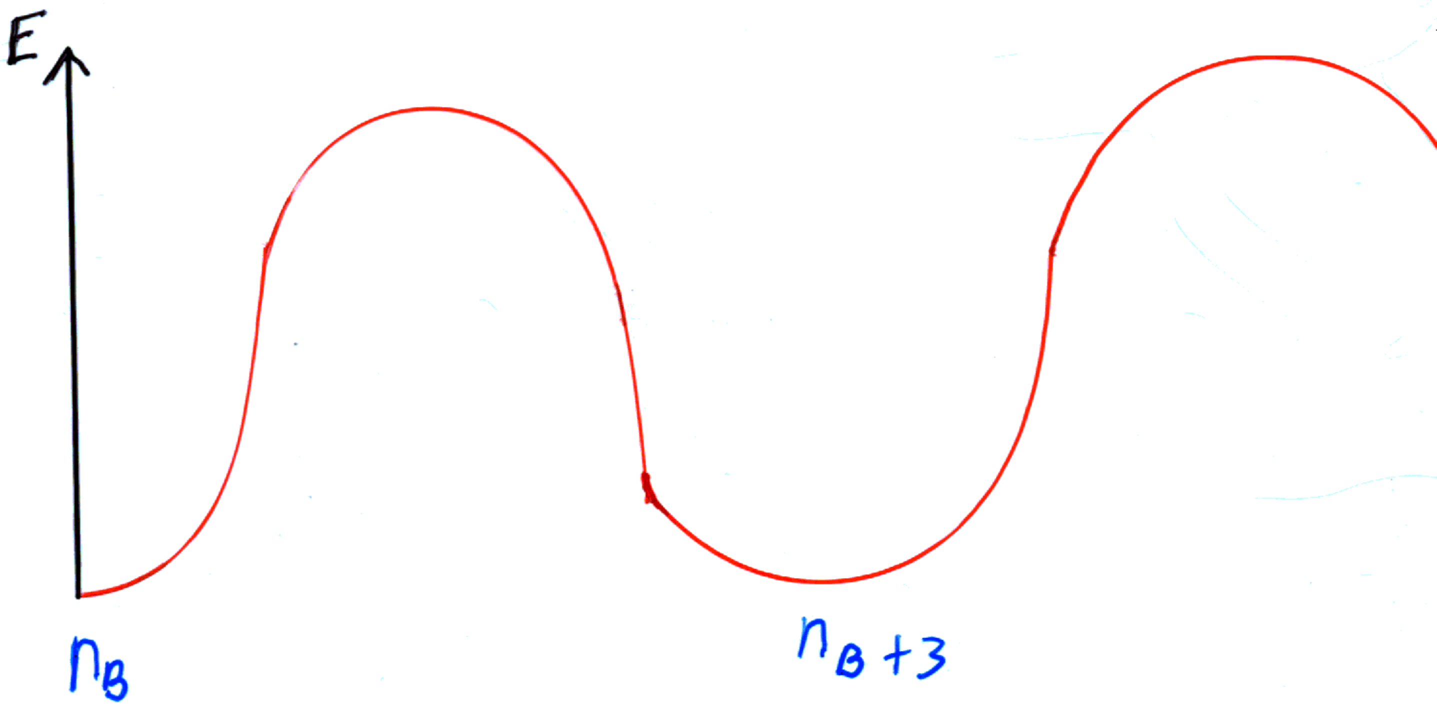
# Baryon Number Violation

$$
\begin{aligned}
B &= p + n - \overline{p} - \overline{n} \\
&= 3(q - \overline{q})
\end{aligned}
$$

instantons



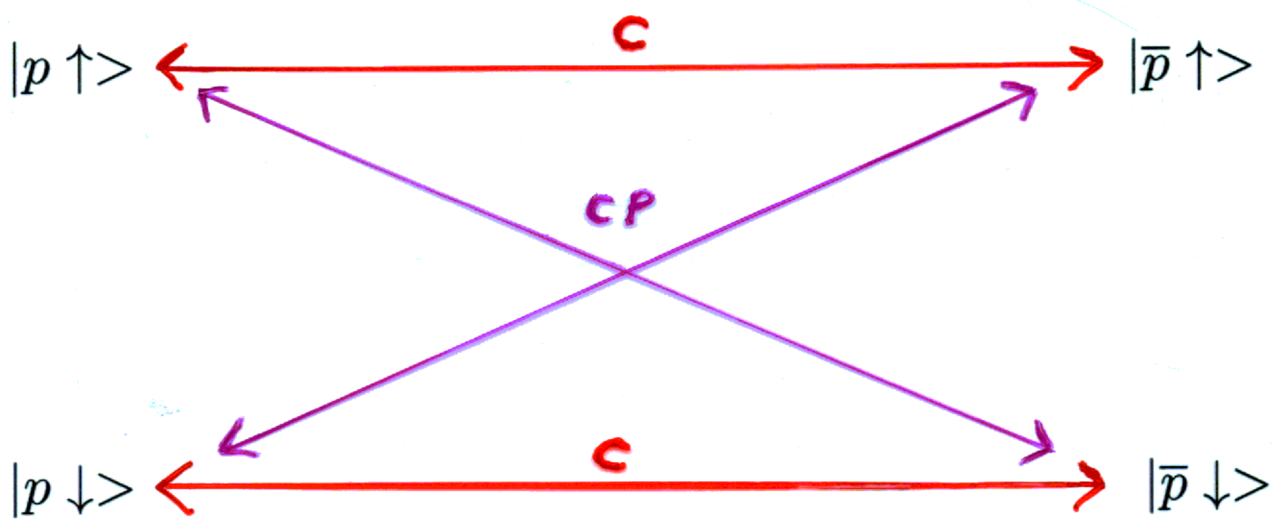

sphalerons



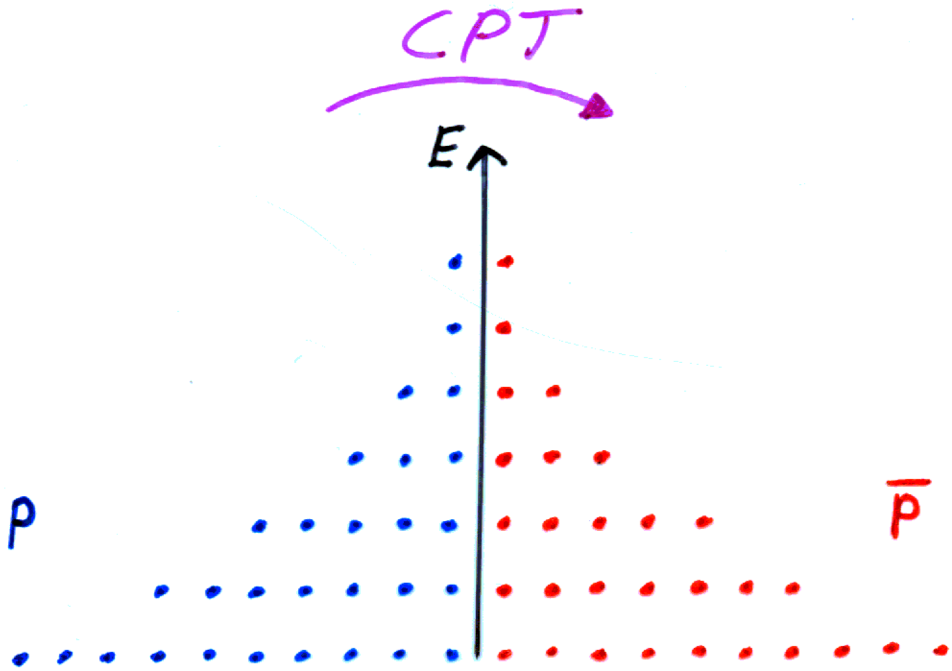
# C & CP Violation

C: interchanges particle and anti-particles

P: coordinate inversion



# Out of Equilibrium

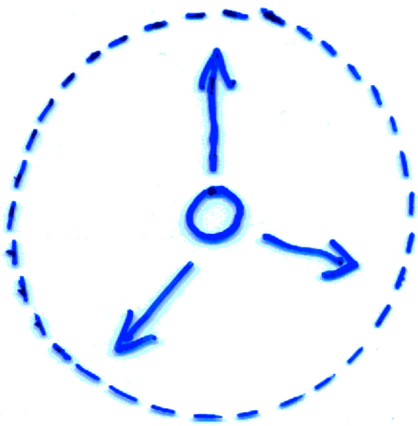


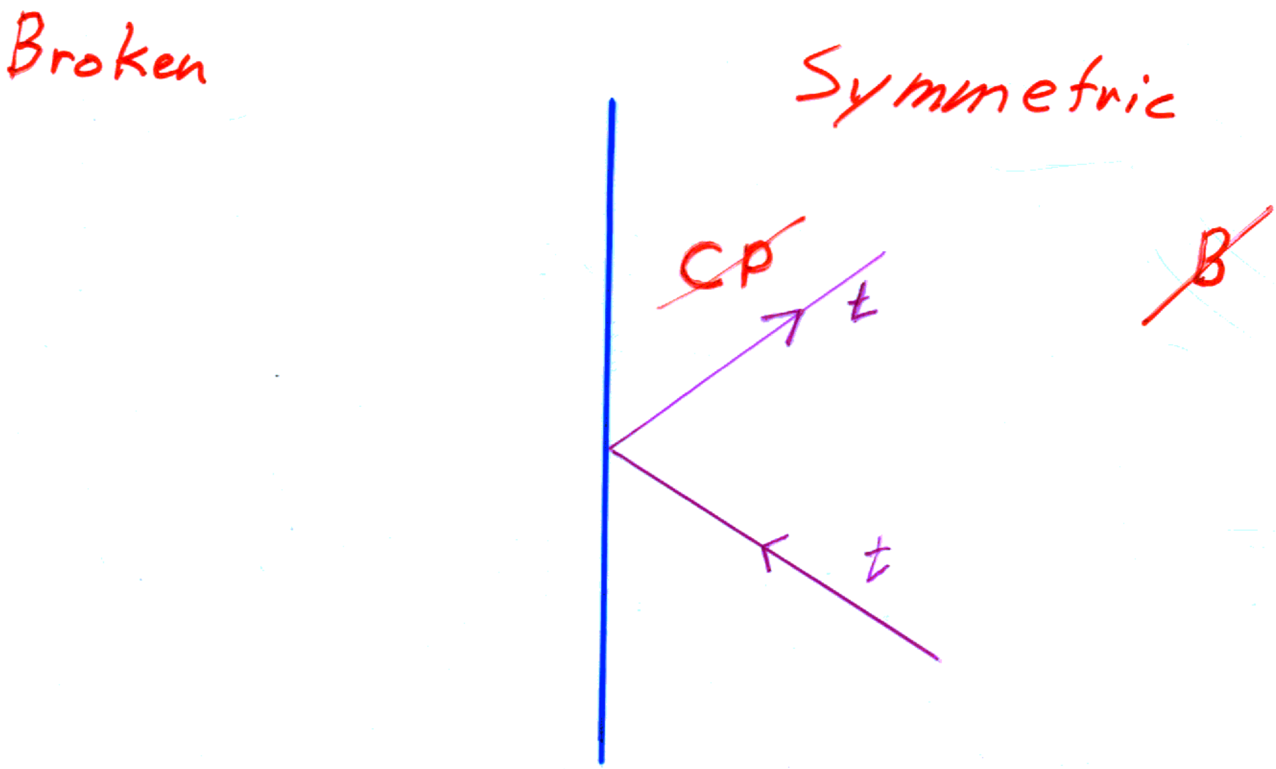

suggests a first order phase transition

# First Order EW Phase Transition

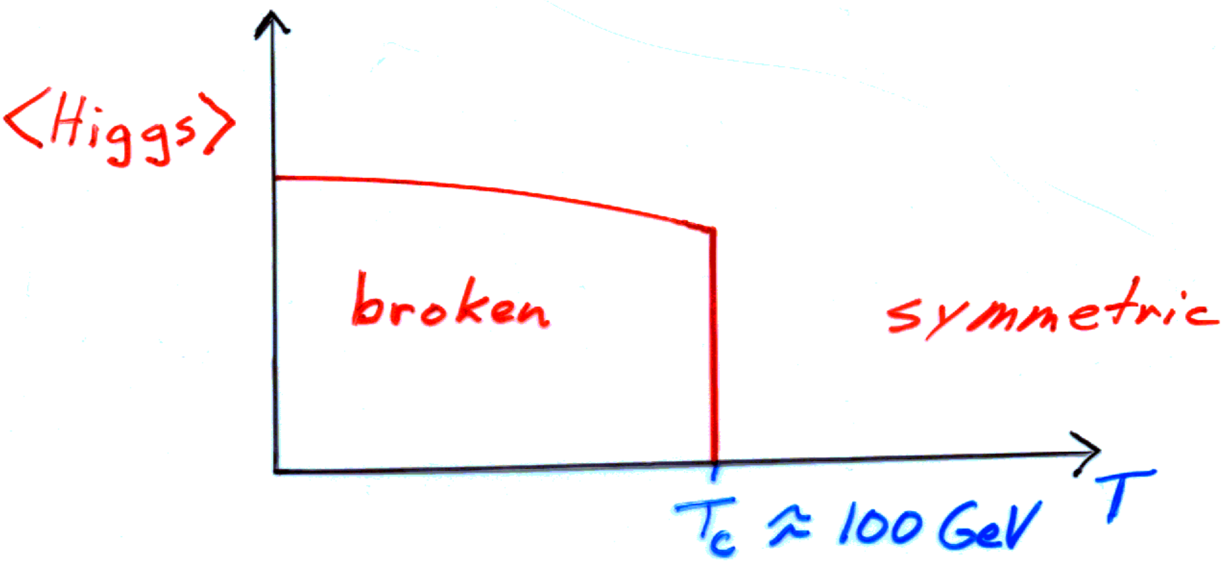
supercooling

bubble nucleation





# First Order EW Phase Transition



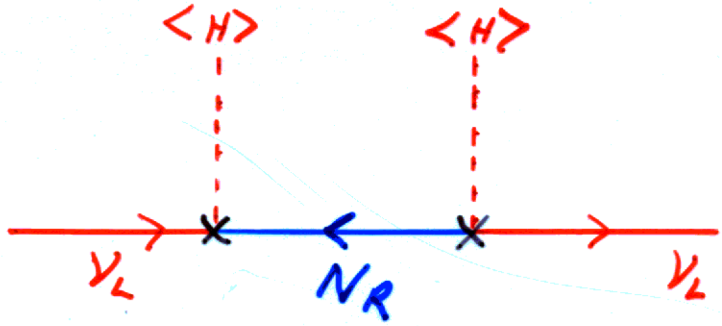

SM requires : $m_{\text{Higgs}} < 30\ \text{GeV}/c^2$

experiment : $m_{\text{Higgs}} > 115\ \text{GeV}/c^2$

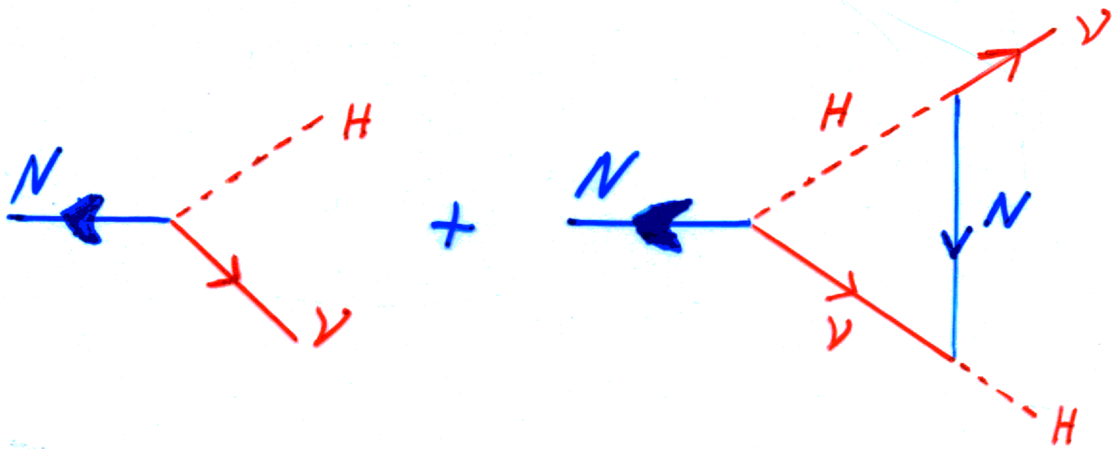
MSSM requires : $m_{\text{Higgs}} < 60\ \text{GeV}/c^2$

experiment : $m_{\text{Higgs}} > 91\ \text{GeV}/c^2$

# Leptogenesis




$$m_{\nu_L} = \frac{\lambda^2 \langle H \rangle^2}{M}$$



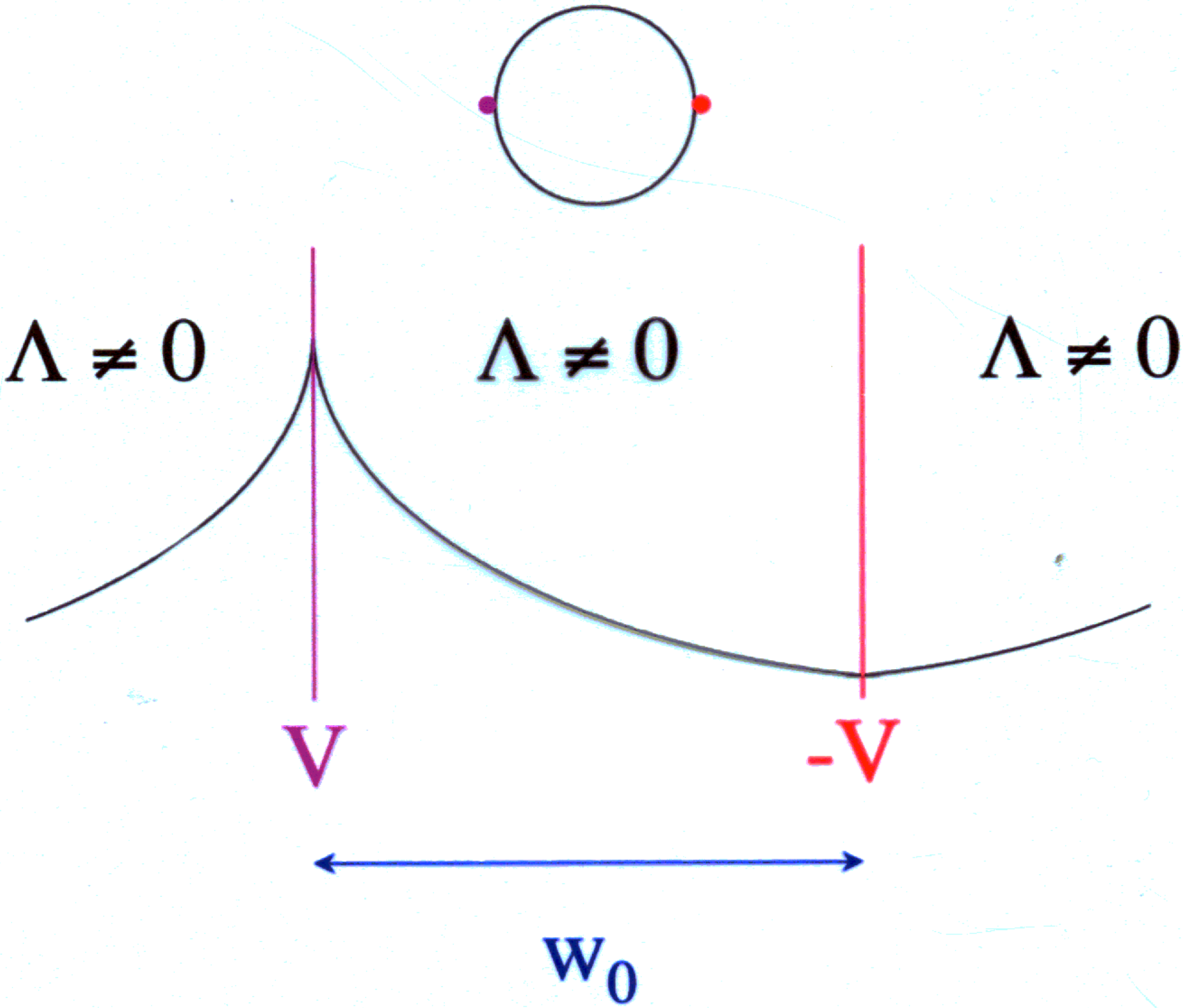

out of equilibrium decay

lepton asymmetry

↓

baryon asymmetry

# Two Brane RS Models




$$\frac{M_W}{M_{Pl}} \approx e^{-k\,w_0} \approx 10^{-17}$$

$$kw_0 \approx 40$$

# Two Brane Cosmology

$$\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3M_*^3} - \frac{1}{36M_*^6}(V+\rho)(\rho - 2V)$$

$$V^2 = -\frac{\Lambda M_*^3}{6}$$

$$\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2 \approx \frac{V}{36M_*^6}\rho$$

$$\left.\begin{array}{l} V < 0 \\ \rho > 0 \end{array}\right\} \Rightarrow \text{universe collapses}$$

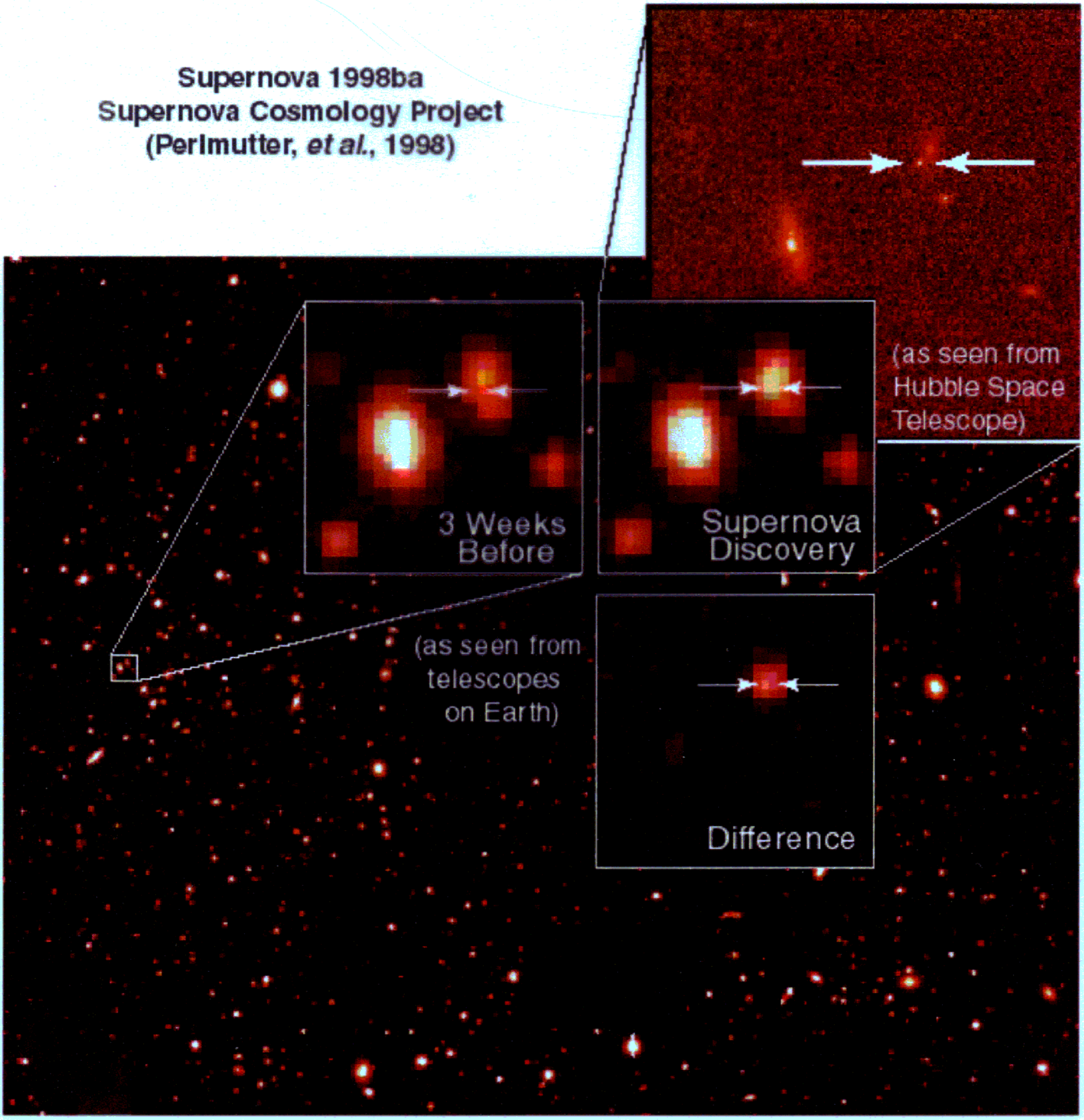
$$\text{static solution requires:} \left\{\begin{array}{l} \rho = -e^{4ky_b}\rho_{\mathrm{Pl}} \\ \text{or } y_b \to \infty \end{array}\right.$$

problem arises from massless (modulus) radion: $\phi$

stabilizing force (Goldberger, Wise hep-ph/9907218) gives $\phi$ a mass and a proper cosmology (Csáki, Graesser, Randall, J.T. hep-ph/9911406)

# Supernova Cosmology

**Supernova 1998ba**
**Supernova Cosmology Project**
**(Perlmutter, *et al.*, 1998)**



# Luminosity Distance

$$1 + z = \frac{a_0}{a}$$

For $\Omega_k = 0$:

$$dr = (1+z)\frac{dt}{a_0} = \frac{1}{H_0 a_0}\frac{dz}{\sqrt{(1+z)^2(1+\Omega_m z) - z(2+z)\Omega_\Lambda}}$$

$$H_0 a_0 r(z) = \int_0^z \frac{dz'}{\sqrt{(1+z')^2(1+\Omega_m z') - z'(2+z')\Omega_\Lambda}}$$

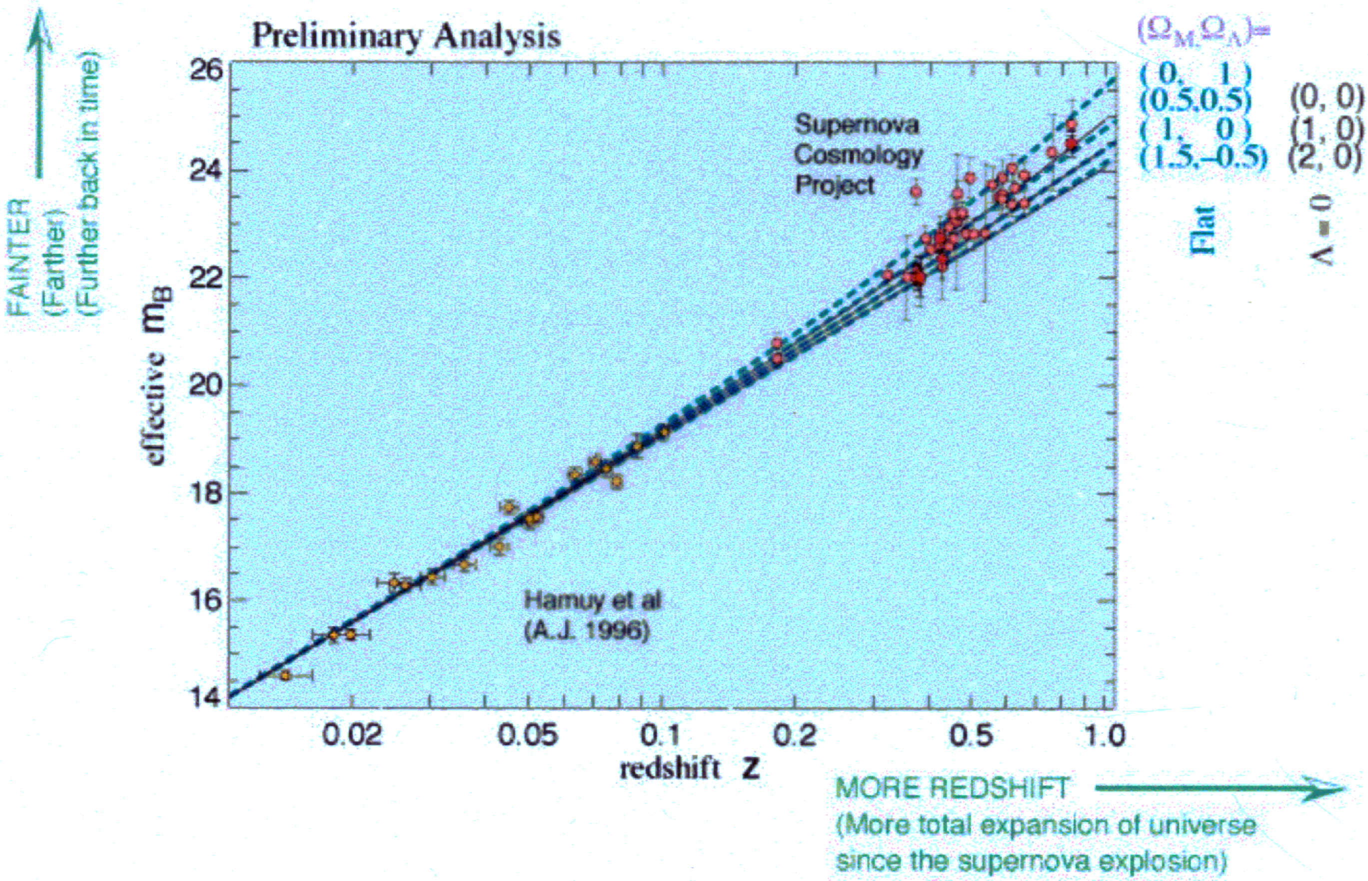
luminosity distance

$$l(z) = (1+z)a_0 r(z)$$

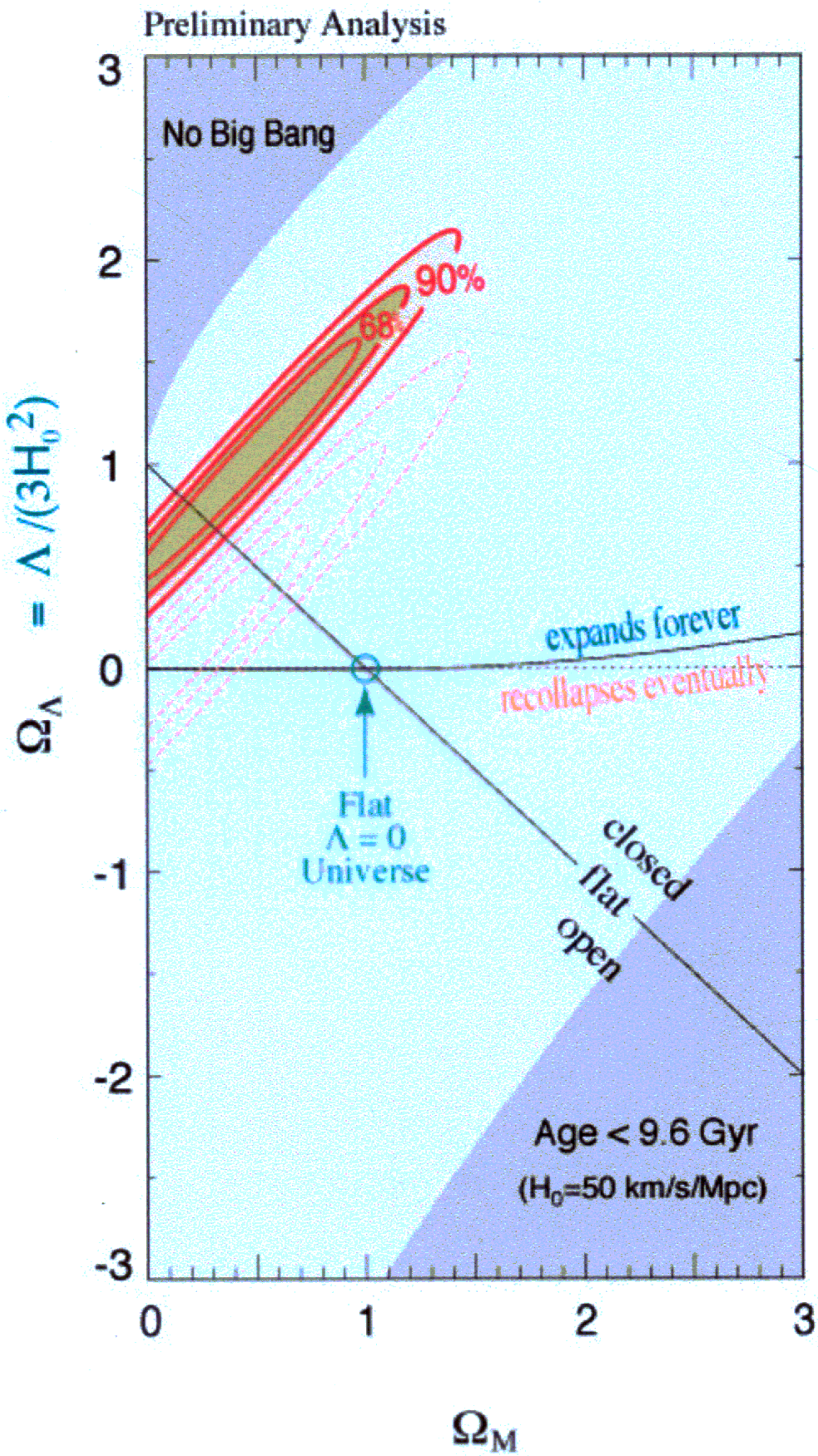
$$m = 5\log l(z) + const.$$

$$\Delta(m - M) = 5\log\frac{l(z)}{l_{empty}(z)}$$

# Hubble Expansion



# "Observed" Λ



Preliminary Analysis
No Big Bang
90%
68%
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
Age < 9.6 Gyr
($H_0$=50 km/s/Mpc)
$\Omega_\Lambda = \Lambda/(3H_0^2)$
$\Omega_M$
3
2
1
0
-1
-2
-3
0
1
2
3

# Quintessence

$$p = w\rho$$

$$\left(\frac{\dot{a}}{a}\right)^2 \approx \frac{4\pi G_N}{3}\frac{\rho}{a^{3(1+w)}}$$

$$w = \begin{cases} \frac{1}{3} & \text{radiation} \\ 0 & \text{matter} \\ -\frac{1}{3} & \text{cosmic strings} \\ -1 & \text{cosm. const.} \end{cases}$$

data requires $w < -2/3$

slowly evolving quintessence field:

$$\ddot{\phi} + 3H\dot{\phi} + m^2(T)\phi = 0$$

slow roll: $\begin{cases} m_\phi = \sqrt{|V''|} < 3H \sim 3 \times 10^{-33}\text{eV} \\ V(\phi) \sim H^2 M_{Pl}^2 \sim 10^{-12}\text{eV}^4 \\ \phi \sim M_{Pl} \end{cases}$

# A Light Axion

$$\mathcal{L}_{int} = \frac{a}{M}\vec{E}\cdot\vec{B}$$

$$\{\frac{d^2}{dy^2} + \mathcal{E}^2 - \begin{pmatrix} 0 & i\mathcal{E}\frac{B}{M} \\ -i\mathcal{E}\frac{B}{M} & m^2 \end{pmatrix}\}\begin{pmatrix} |\gamma\rangle \\ |a\rangle \end{pmatrix} = 0$$

$$|\vec{B}| \sim 5\cdot 10^{-9}\ \mathrm{G}$$
$$\vec{B}^2 \sim 10^{-11} H_0^2 M_{Pl}^2$$

$$\mathcal{M}^2 = \begin{pmatrix} 0 & i\mathcal{E}\mu \\ -i\mathcal{E}\mu & m^2 \end{pmatrix}$$

eigenvalues $\lambda_1$ and $\lambda_2$ are:

$$\lambda_1 = \frac{m^2}{2} - \sqrt{\frac{m^4}{4} + \mu^2\mathcal{E}^2}$$
$$\lambda_2 = \frac{m^2}{2} + \sqrt{\frac{m^4}{4} + \mu^2\mathcal{E}^2}$$

Csáki, Kaloper, J.T. hep-ph/0111311

# Intergalactic Magnetic Fields

| domain size | bound |
|---|---|
| $H_0^{-1}$ | $B < 10^{-9}$ G |
| 50 Mpc | $B < 6 \cdot 10^{-9}$ G |
| 1 Mpc | $B < 10^{-8}$ G |

We assume

$B \sim 5 \cdot 10^{-9}$ G

1 Mpc domain


P. P. Kronberg, Rept. Prog. Phys. **57**, 325 (1994).

P. Blasi, S. Burles and A. V. Olinto, Astrophys. J. **514**, L79 (1999).

# Photon-Axion Mixing

$$|\gamma\rangle = \frac{\mu\mathcal{E}}{\sqrt{\lambda_1^2+\mu^2\mathcal{E}^2}}|\lambda_1\rangle\ e^{-i\phi_1} + \frac{i\mu\mathcal{E}}{\sqrt{\lambda_2^2+\mu^2\mathcal{E}^2}}|\lambda_2\rangle\ e^{-i\phi_2}$$
$$|a\rangle = \frac{-i\lambda_1}{\sqrt{\lambda_1^2+\mu^2\mathcal{E}^2}}|\lambda_1\rangle\ e^{-i\phi_1} + \frac{\lambda_2}{\sqrt{\lambda_2^2+\mu^2\mathcal{E}^2}}|\lambda_2\rangle\ e^{-i\phi_2}$$

where $\phi_k = \mathcal{E}t + \sqrt{\mathcal{E}^2 - \lambda_k}\Delta y$.

$$\sin\theta = \frac{\mu\mathcal{E}}{\sqrt{\lambda_2^2+\mu^2\mathcal{E}^2}}$$

$$P_{\gamma\to\gamma} = |\langle\gamma(y_0)|\gamma(y)\rangle|^2$$

for $\mathcal{E} \gg m, \mu \to \mathcal{E}^2 \gg \lambda_i$

$$P_{\gamma\to\gamma} = 1 - \frac{4\mu^2\mathcal{E}^2}{m^4+4\mu^2\mathcal{E}^2}\sin^2\left[\frac{\Delta y\sqrt{m^4+4\mu^2\mathcal{E}^2}}{4\mathcal{E}}\right]$$

oscillation length:

$$L_O \sim \frac{4\pi\mathcal{E}}{\sqrt{m^4+4\mu^2\mathcal{E}^2}}$$

# Varying Magnetic Field

domain size $L_{\rm dom} \sim 1$ Mpc

$$P_{\gamma\to\gamma} = \frac{2}{3} + \frac{1}{3} e^{-\Delta y / L_{\rm dec}}$$

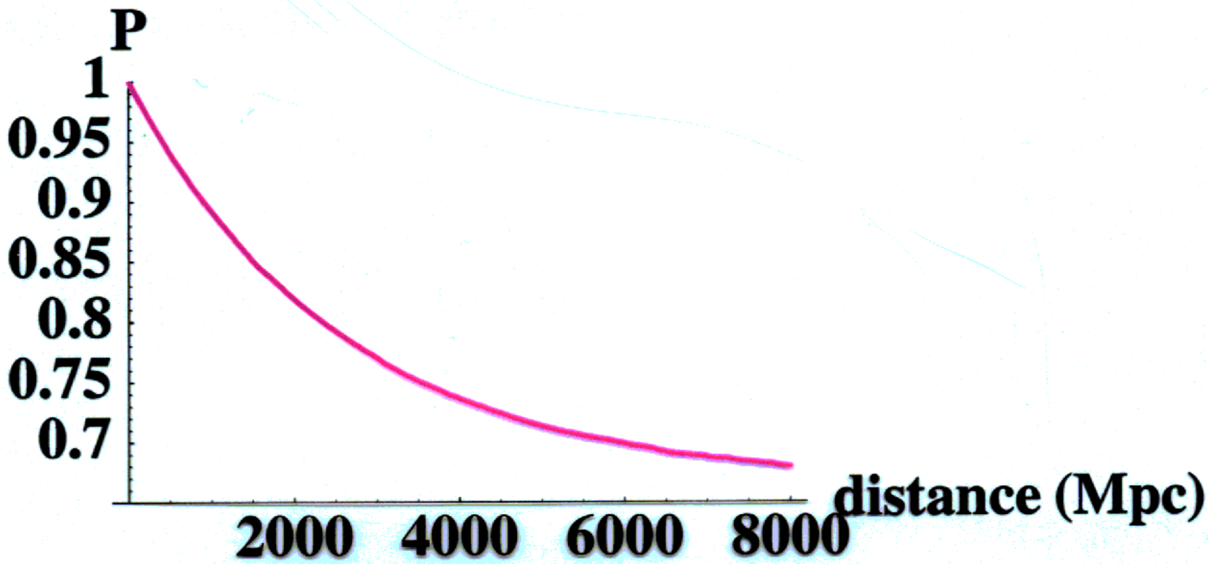
where the inverse decay length is given by

$$L_{\rm dec} = \frac{L_{\rm dom}}{\ln\left(\frac{4}{1+3\cos\mu L_{\rm dom}}\right)} \,.$$

For $\mu L_{\rm dom} \ll 1$ this reduces to

$$L_{\rm dec} = \frac{8}{3\mu^2 L_{\rm dom}} \,.$$

# Decaying Light Intensity



# Intensity Decay

$$L_{\text{dec}} \sim H_0^{-1}/2$$

$$M \sim 4 \cdot 10^{11}\ \text{GeV}$$

PDG limit: $M \geq 1.7 \cdot 10^{10}$ GeV

more model dependent limit from SN1987A:

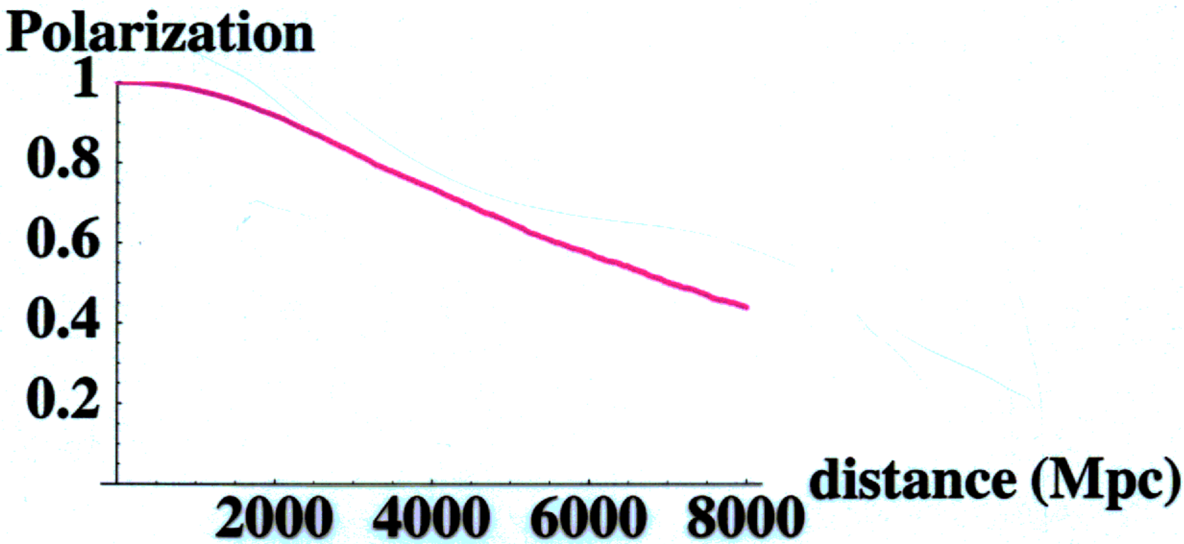
$$M \geq 10^{11}\ \text{GeV}$$

disturbances of CMBR ($\mathcal{E} \sim 10^{-4}$ eV):

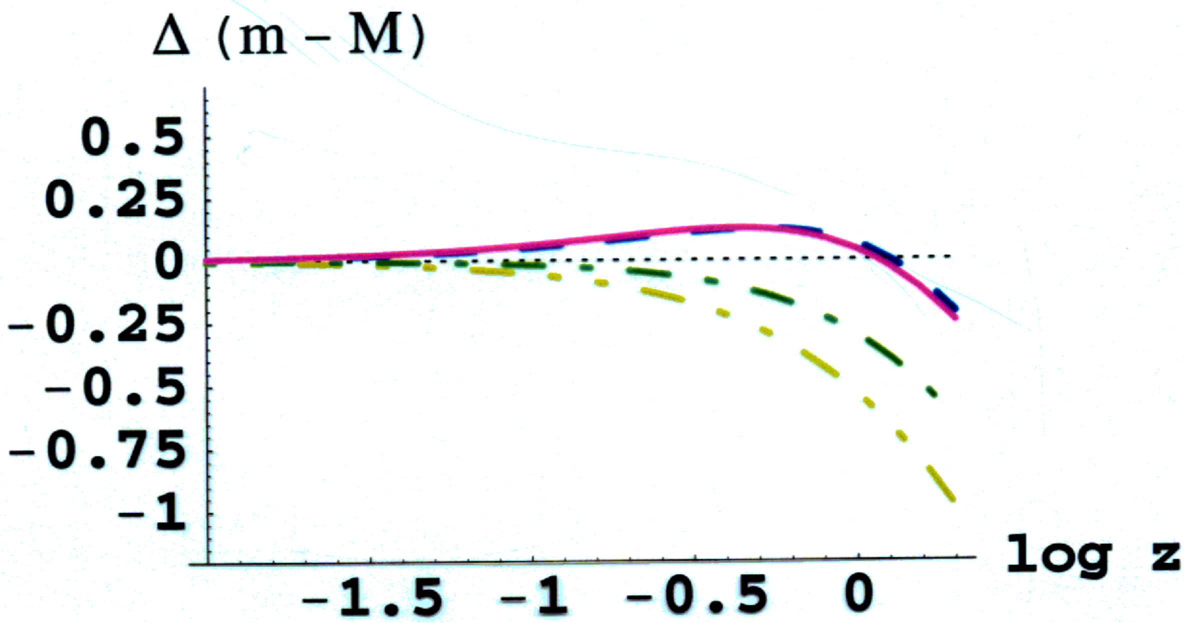
$$P_{\gamma \to a} \leq 4 \frac{B^2 \mathcal{E}^2}{m^4 M_L^2} \sim 4 \cdot 10^{-11} \frac{M_{Pl}^2 H_0^2 \mathcal{E}^2}{M_L^2 m^4}$$

$$P_{\gamma \to a} \leq 10^{-7} \Rightarrow m \sim 10^{-16} \text{eV}$$

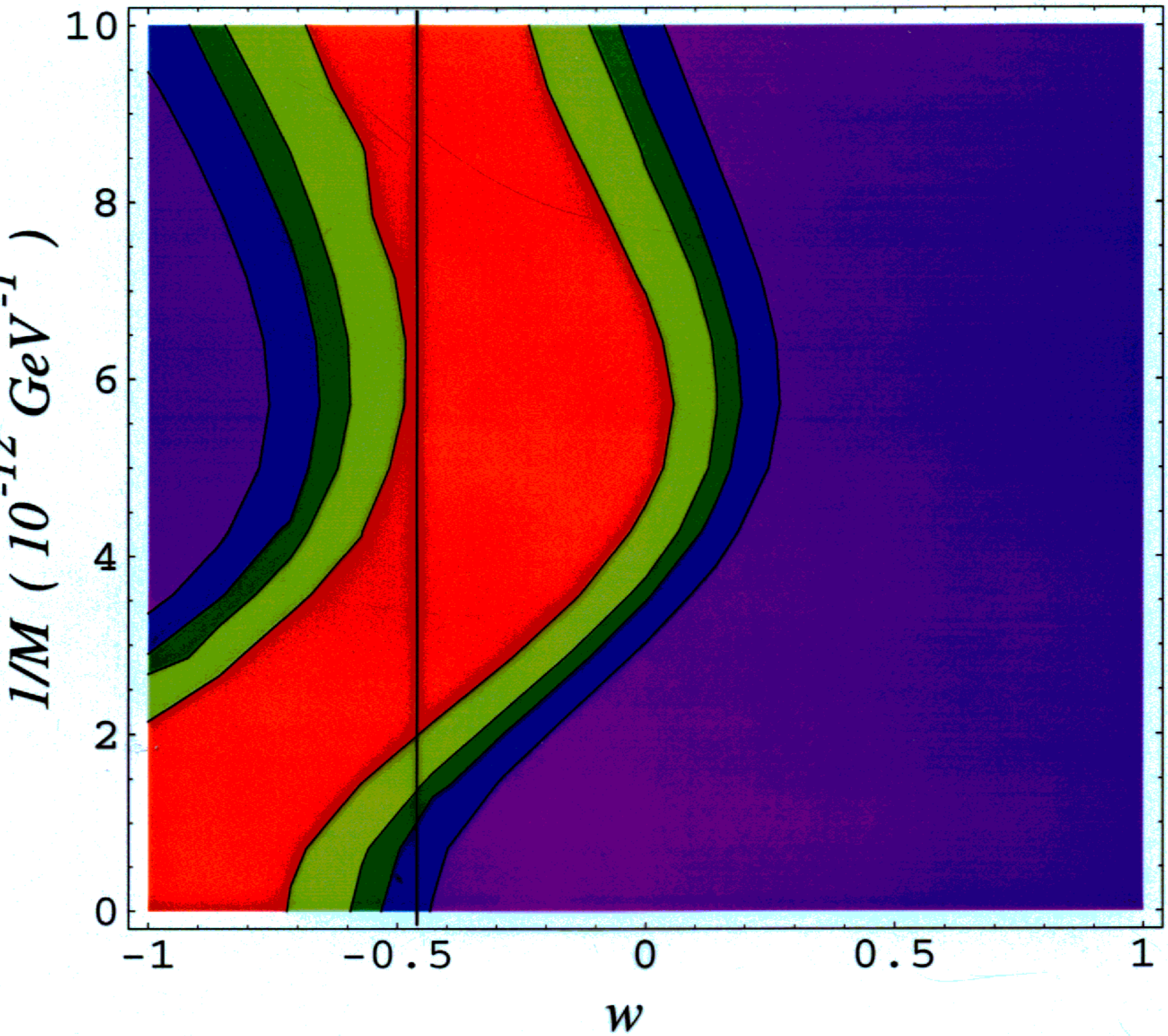
# Polarization



# Comparison with "Data"



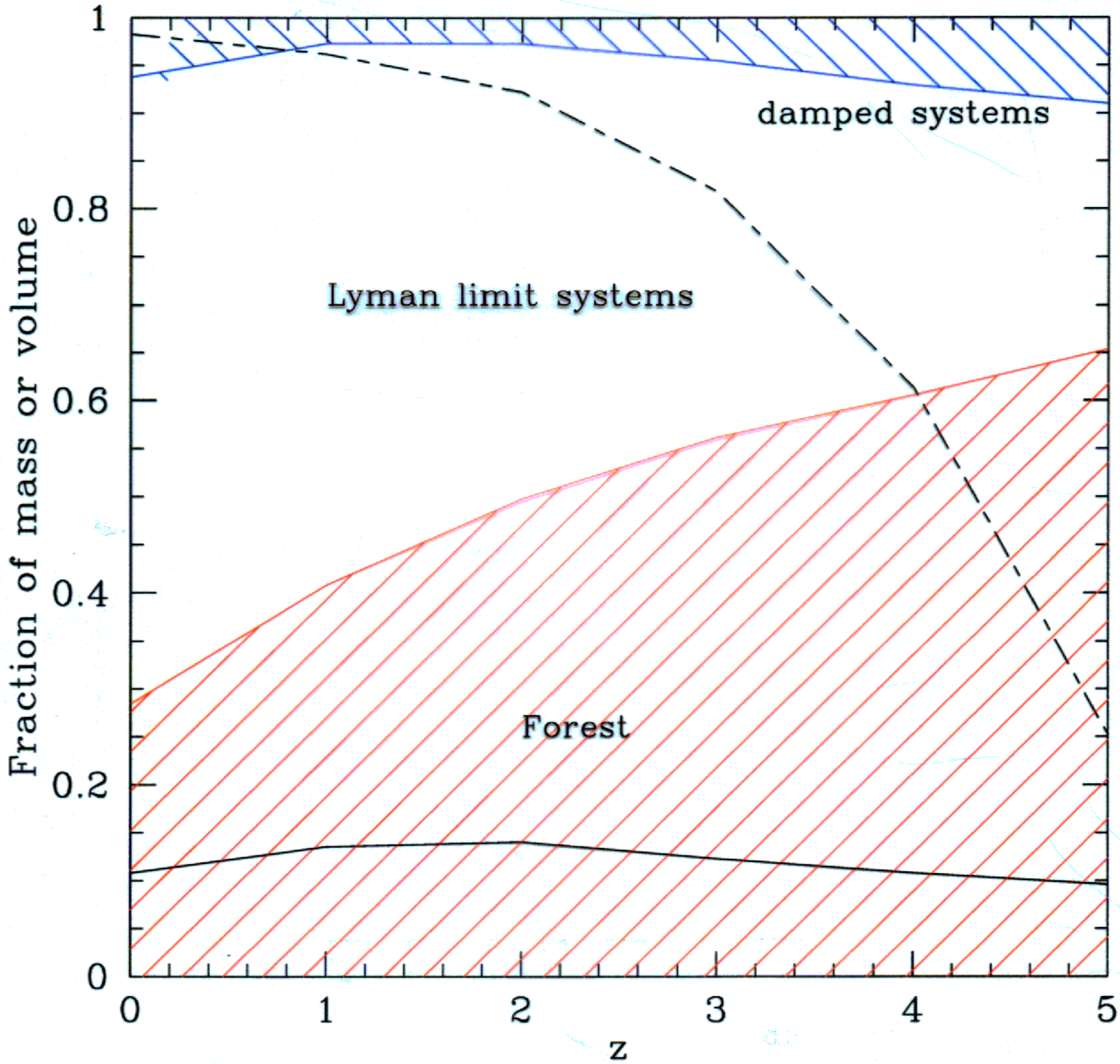
# Fit to Data




J. Erlich and C. Grojean, hep-ph/0111335

# Intergalactic Plasma

at low redshift 1/3 of baryons are in photoionized intergalactic gas (Lyman $\alpha$ forests)



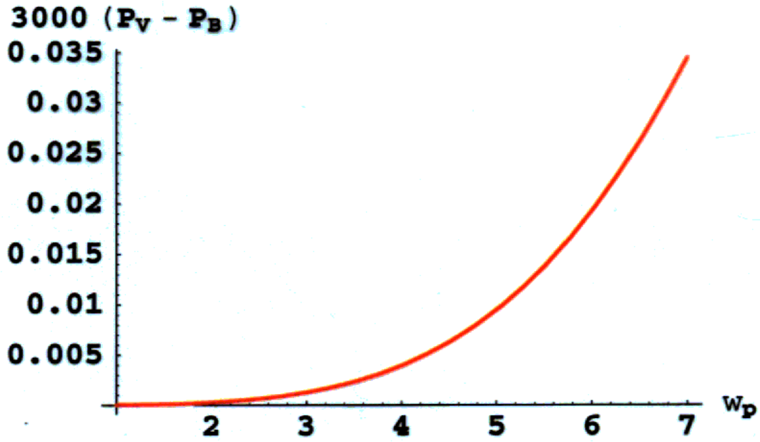

P. Valageas, R. Schaeffer and J. Silk, Astron. Astrophys. **345**, 691 (1999) [astroph/9903388]

# Photon Plasma Mass

$$\omega_p^2 = 4\pi\alpha \frac{n_e}{m_e}$$

$$P_{\gamma\to a} = \frac{4\mu^2\mathcal{E}^2}{(\omega_p^2 - m^2)^2 + 4\mu^2\mathcal{E}^2} \sin^2\left[\frac{y\sqrt{(\omega_p^2-m^2)^2+4\mu^2\mathcal{E}^2}}{4\mathcal{E}}\right]$$

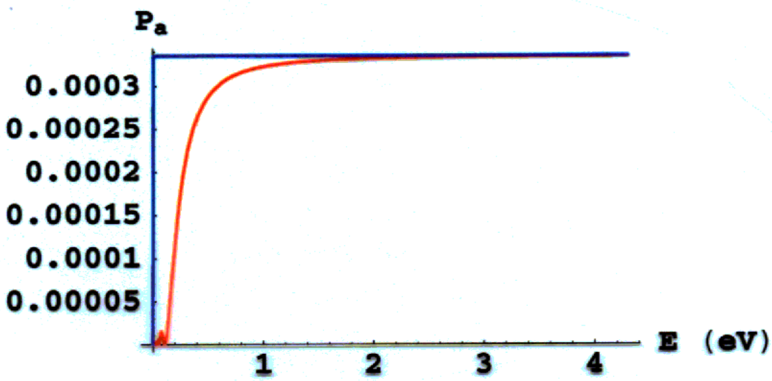
- uniform distribution: $n_e = 1.8 \cdot 10^{-7}\mathrm{cm}^{-3}$
- estimate: $n_e < 6 \cdot 10^{-9}\mathrm{cm}^{-3} \to \omega_p < 3 \cdot 10^{-15}$ eV
- data: $n_e < 2.5 \cdot 10^{-8}\mathrm{cm}^{-3} \to \omega_p < 6 \cdot 10^{-15}$ eV




C. Csáki, N. Kaloper, J.T. hep-ph/0112212

# Photon Plasma Mass

assuming: $n_e = 6 \cdot 10^{-9}\mathrm{cm}^{-3}, \omega_p = 3 \cdot 10^{-15}$ eV




C. Csáki, N. Kaloper, J.T. hep-ph/0112212

# Conclusions???

- Dark Matter May Be Elementary Particles

- the Baryon Asymmetry May Be Produced Dynamically

- Extra Dimensions May Exist

- the Cosmic Expansion May Be Accelerating