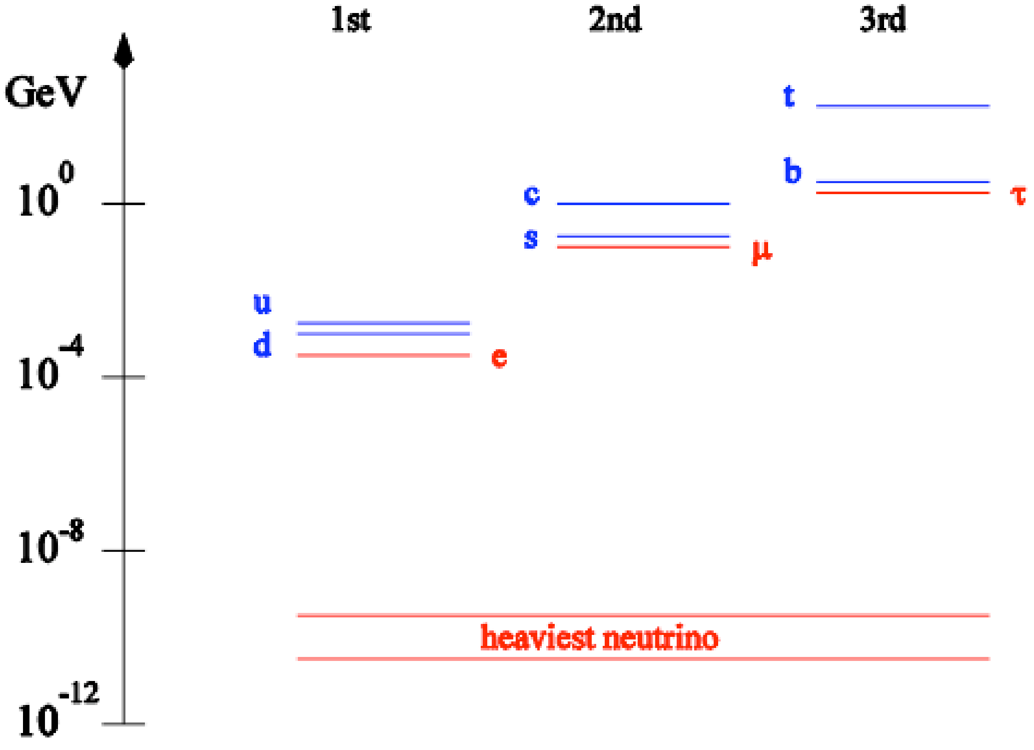
Some Cutting-Edge Neutrino Topics:

Majorana Neutrinos, the See-Saw Mechanism, Sphalerons, and Leptogenesis

Did neutrinos cause the matter-antimatter asymmetry of the Universe?

Neutrino mass is fundamentally different from the other fermions....
we need new physics to understand it.

Standard model fermion mass spectrum



A simple Dirac mass for the neutrino requires a Higgs coupling of 10^{-13}.

Fermion mass is closely tied to particle/antiparticle nature.

Charged fermions can only have a Dirac mass

$$L_D = \boxed{m_D \bar{\nu}_R \nu_L} + h.c,$$

Higgs only generates Dirac masses

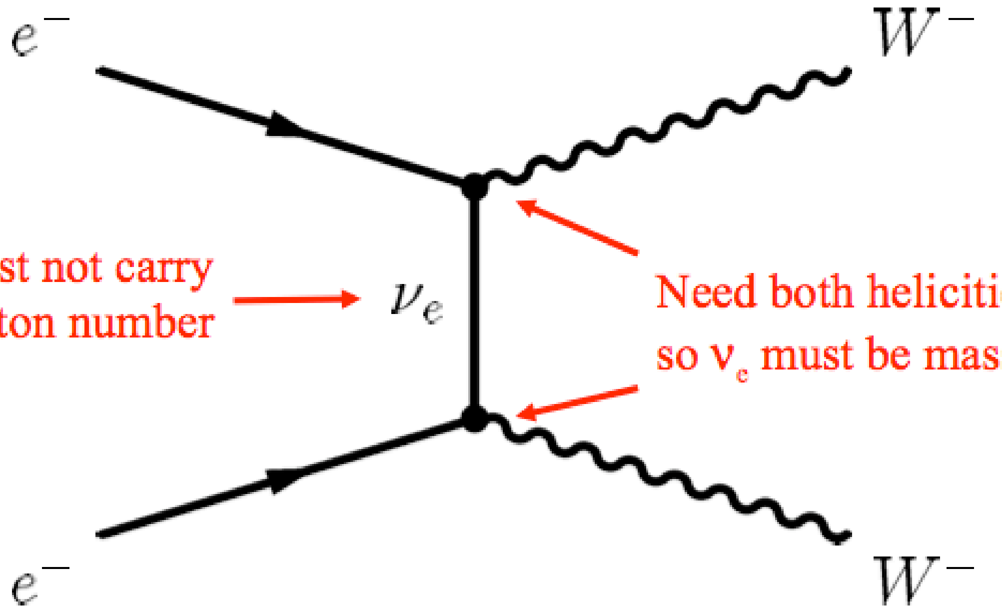
$$L_{M_L} = \frac{1}{2} m_L \overline{\nu_L^c} \nu_L + h.c,$$

neutral fermions can also have
two types of Majorana masses

$$L_{M_R} = \frac{1}{2} m_R \overline{\nu_R^C} \nu_R + h.c.$$

Pure Dirac fermions carry charge: e-, μ-, τ-, ect.
Majorana fermions are their own antiparticles... maybe neutrinos?
Is lepton number conserved or not?

We need a process which violates total lepton number:

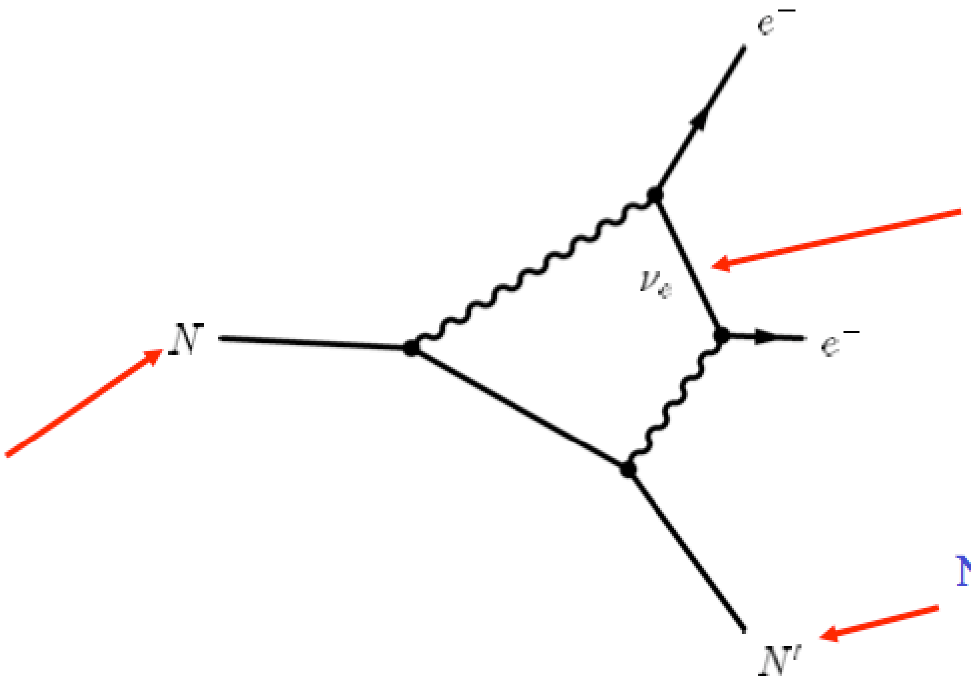


must not carry lepton number

Need both helicities, so ν_e must be massive

Observation of this process at an e-e- ILC
would indicate the existence of TeV-scale Majorana neutrinos.
To get information on the known light neutrinos,
we need a low energy equivalent process.

ββ0ν is the same physics at low Q^2



amplitude ~ m(ν)/E(ν),
E(ν) ~ 100 MeV

N(Z,A)

N(Z+2,A)

“Neutrino mass mechanism” for double beta decay

The process most sensitive to the possible Majorana nature of ν_j - $(\beta\beta)_{0\nu}$-decay

$$(A,Z) \rightarrow (A,Z+2) + e^- + e^-$$

of even-even nuclei, ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd.

PMNS Matrix: Standard Parametrization

$$U = V \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix} \tag{4}$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \tag{5}$$

- $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, $\theta_{ij} = [0, \frac{\pi}{2}]$,
- δ - Dirac CP-violation phase, $\delta = [0, 2\pi]$,
- α_{21}, α_{31} - the two Majorana CP-violation phases.
- $\Delta m^2_{\odot} \equiv \Delta m^2_{21} \cong 8.0 \times 10^{-5}$ eV$^2 > 0$, $\sin^2\theta_{12} \cong 0.30$, $\cos 2\theta_{12} \gtrsim 0.28$ (2σ),
- $|\Delta m^2_{\text{atm}}| \equiv |\Delta m^2_{31}| \cong 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} \cong 1$,
- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} < 0.027$ (0.041) 2σ (3σ).

Theββ0ν half-life depends directly on the absolute neutrino masses:

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = \underbrace{G^{0\nu\beta\beta}}_{\text{phase space}} \cdot \underbrace{\left|NME\right|^{2}}_{\text{Nuclear Matrix Element}} \cdot \underbrace{\left|\langle m_{\nu}\rangle\right|^{2}}_{\text{effective mass}},$$

$$\langle m_{\nu}\rangle = \sum_{i} \underbrace{U_{ei}^{2}}_{\text{mixing matrix (with phases)}} \underbrace{m_{i}}_{\text{mass eigenvalues}} \underbrace{e^{i\alpha_{i}}}_{\text{Majorana phases}}$$

Two caveats to ββ0ν as a mass measurement:

1) we must have a reliable calculation of the nuclear matrix element
2) the neutrino mass mechanism must dominate the decay

One of the most attractive ideas for explaining small neutrino masses is the one based on the

Seesaw Mechanism

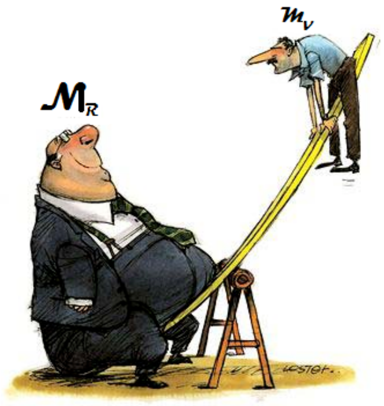
Minkowski, PLB 1977
Gell-Mann, Ramond & Slansky, 1979
Yanagida, 1979
Glashow, 1980
Mohapatra & Senjanovic, PRL 1980

The tiny masses of light neutrinos are naturally understood if we introduce heavy Majorana neutrinos to the SM.

$$\mathcal{L} = -\frac{1}{2} M\, N^T N + \left(-h\, N^T \ell\, \varphi + h.c.\right)$$

By integrating out the heavy right-handed neutrinos, one obtains the small Majorana masses for light neutrinos

$$m_\nu \sim \frac{h^2 \langle \varphi \rangle^2}{M}$$



Thanks to MIKE LESTER (and FRJ)

Leptogenesis

Fukugita & Yanagida, PLB 1986

When the heavy Majorana neutrinos decay into leptons and Higgs scalars they violate lepton number, and the interference between the tree-level and the one-loop amplitudes yields a non-zero CP-asymmetry. This leads to a lepton asymmetry which is then partially converted into baryon asymmetry by sphaleron processes.

- simple seesaw formula $\boxed{m_\nu = -m_D \frac{1}{M} m_D^T}$

m_D, m_ν and M are complex matrices $\Rightarrow$ natural source of CP violation

- heavy RH neutrino mass matrix $M \Rightarrow$ three new heavy RH neutrinos N_1,N_2 and N_3 with masses $M_{\rm ew} \ll M_1 \leq M_2 \leq M_3$
- Dirac neutrino mass matrix $m_D \sim M_{\rm ew}$
- light neutrino mass matrix m_ν $(m_\nu = m_D^2/M \sim 10^{-2}\,{\rm eV}$ for $M \sim 10^{15}\,{\rm GeV})$
- lightest RH neutrinos play the role of the decaying particles $X \equiv N_1$ (Fukugita,Yanagida '86)

Adding to the SM (3) RH neutrinos with Yukawa couplings h and a Majorana mass M,

$$\mathcal{L}_Y = -\bar{l}_L\,\phi\,h\,\nu_R - \frac{1}{2}\,\overline{\nu_R^c}\,M_R\,\nu_R + h.c.\ ,$$

a usual Dirac mass $m_D = v * h$ is also generated after SSB. For $M >> m_D$:

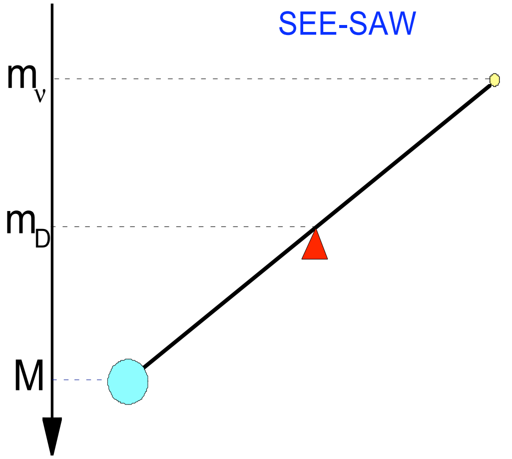
3 light LH neutrinos:

$$\boxed{m_\nu = -m_D \frac{1}{M} m_D^T}$$

Typical example:
$m_D \sim 100$ GeV , $M \sim 10^{14}$ GeV
$\Rightarrow m_\nu \sim m_{\rm atm} \sim 0.1$ eV

3 heavy RH neutrinos: N_1, N_2, N_3

$$100\ \text{GeV} \sim M_{\rm ew} \simeq m_D \ll M_1 \leq M_2 \leq M_3$$



Leptogenesis

Fukugita & Yanagida, PLB 1986

Leptogenesis via heavy Majorana neutrino decay

Seesaw Mechanism

Neutrino masses

Asymmetry in the lepton number

Can be converted into baryon number through

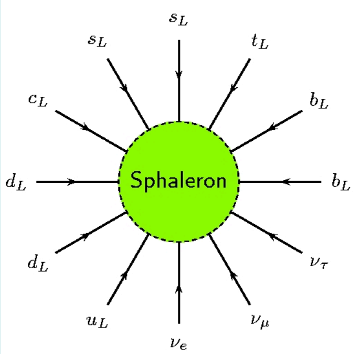
Sphalerons

Non-perturbative effects

Violate B+L

Conserve B-L

Efficient above the EW scale



$$Y_B \equiv \frac{n_B}{s} = \xi \, Y_L$$

$\xi = 28/79$ (SM)

$\xi = 8/23$ (MSSM)

Kuzmin et al 1985

Khlebnikov et al 1985

In the SM Baryon Number conserved at classical level but violated at quantum level : $\Delta B = \Delta L$

Anomalies arise in the process of regularization of divergences.

Impossible to do it preserving gauge and B and L symmetries.

$$\partial^{\mu} j_{\mu}^{B,L} = \frac{\mathrm{N}_f\, g^2}{32\,\pi^2} Tr\left(\varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta}\right)$$

Instantons are minimal action configuration with non-vanishing values of the integral of the right –hand side of the above Eq.

Instanton configurations may be regarded as semiclasical amplitudes for tunelling effect between vacuum states with different baryon number

$$S_{inst} = \frac{4\pi}{\alpha_W} \qquad\qquad \Gamma_{\Delta B \neq 0} \propto \exp(-S_{inst})$$

Weak interactions: Transition amplitude exponentially small.
No observable baryon number violating effects at T = 0

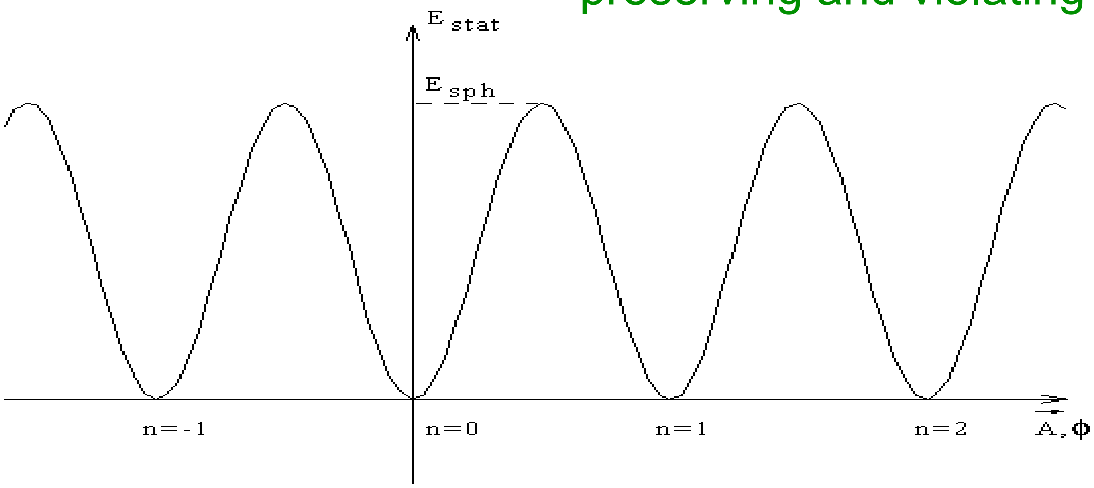
Non-equivalent Vacua and Static Energy in Field Configuration Space

The sphaleron is a static configuration with non-vanishing values of the Higgs and gauge boson fields.

Its energy may be identified with the height of the barrier separating vacua with different baryon number

$$E_{sph} = \frac{8\pi \, \mathrm{v}}{g_W}$$

The quantity v is the Higgs vacuum expectation value,   < H > = v.
This quantity provides an order parameter which distinguishes the electroweak symmetry preserving and violating phases.



Baryon Number Violation at Finite Temperature

Anomalous processes violate both B and L number, but preserve B-L.
(Important for the explanation of the Baryon Asymmetry of the Universe)

- *At T = 0, Baryon number violating processes exponentially suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \exp(-2\pi / \alpha_{\mathrm{W}})$$

- *At very high temperatures they are highly unsuppressed,*

$$\Gamma_{\Delta B \neq 0} \propto T$$

- *At Finite Temperature, instead, only Boltzman suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, \mathrm{T} \exp(-\mathrm{E}_{\mathrm{sph}}(\mathrm{T}) / \mathrm{T})$$

with $\mathrm{E}_{\mathrm{sph}} \cong 8\pi \, \mathrm{v(T)} / \mathrm{g}$ and v(T) the Higgs v.e.v.

Klinkhammer and Manton’84; Arnold and Mc Lerran’88, Khlebnikov and Shaposhnikov ’88

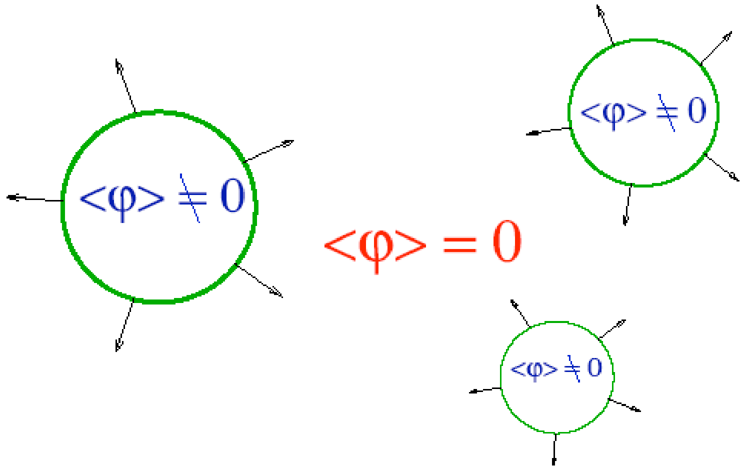
Baryogenesis at the Electroweak Phase transition

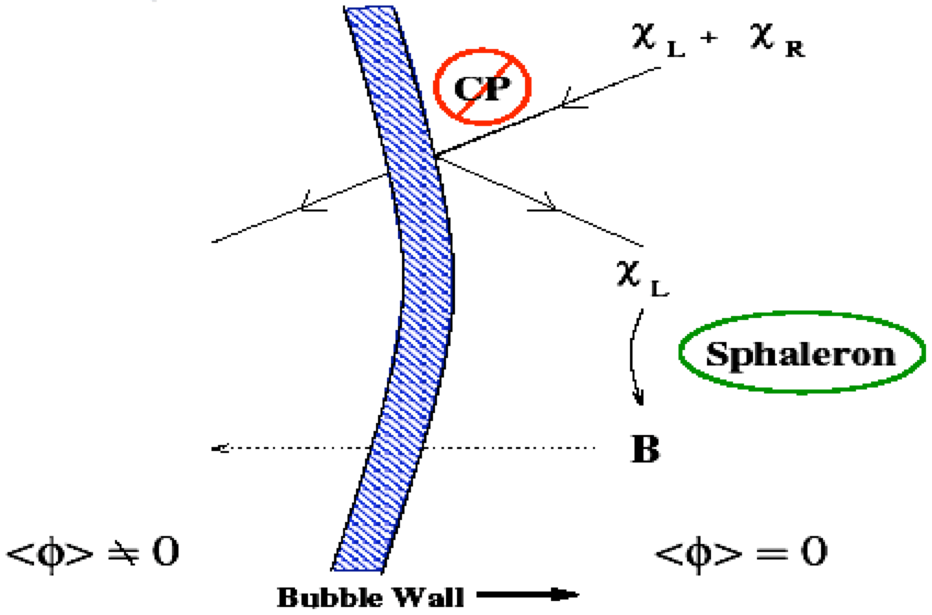
Kuzmin, Rubakov and Shaposhnikov, '85-'87
Cohen, Kaplan and Nelson '93

- Start with B=L=0 at T>Tc
- CP violating phases create chiral baryon-antibaryon asymmetry in the symmetric phase. $n_L + n_R = n_{\bar{L}} + n_{\bar{R}} \Rightarrow B = \bar{B}$ but $\Delta_{n_L} = \Delta_{n_{\bar{R}}} \neq 0$
- Sphaleron processes create net baryon asymmetry.

Sphalerons violate B+L but conserve B-L ; change net B into -L only for left handed

- Net Baryon Number diffuse in the broken phase





Baryon Asymmetry Preservation

if $n_{\mathbf{B}} = 0$ at T > Tc, independently of the source of baryon asymmetry

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(- \frac{10^{16}}{\mathrm{T_c(GeV)}} \exp\left(- \frac{\mathrm{E_{sph}(T_c)}}{\mathrm{T_c}} \right) \right)$$

Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase. $\Gamma_{\Delta B \neq 0} < H \Rightarrow \not{B}$ processes frozen

$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, \mathrm{T} \exp(\mathrm{-E_{sph}(T)/T})$$

$$H \cong g_*^{1/2} \, T^2 / M_{Pl}$$

$$\Rightarrow \frac{\mathrm{M_{Pl}}}{\mathrm{T}} \exp(\mathrm{-E_{sph}(T)/T}) \ll 1$$

To preserve the generated baryon asymmetry:

strong first order phase transition:

$$\mathrm{v}(T_c)/T_c > 1$$

Shaposhnikov '86-'88

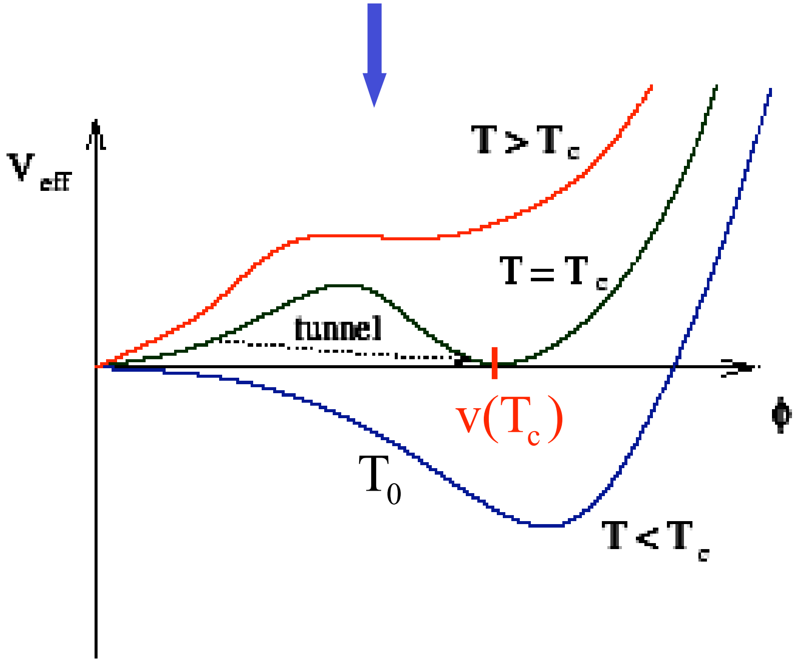
Electroweak Phase Transition

- The critical temperature is the one for which the symmetry breaking vaccum has the same depth as the symmetry conserving one

$$V(v=0, T_c) = V(v(T_c), T_c)$$

- If the phase transition is second order: $T_c = T_0$

Higgs Potential Evolution in the case of a first order Phase Transition



SM Electroweak Baryogenesis fufills the Sakharov conditions

- **SM Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

Leptogenesis

- Out of equilibrium decays of

$$N_{heavy} \rightarrow l + \text{ Higgs } \neq N_{heavy} \rightarrow \bar{l} + \text{ Higgs}$$

  created a *lepton* asymmetry

- Electroweak tunneling (actually thermal fluctucation) then converts some of the lepton asymmetry into a baryon asymmetry!
- Difficulties in supersymmetric version: gravitino problem suggests reheating temperature too low (unless N_{heavy} produced nonthermally)

Leptogenesis II

$$N_L^c \rightarrow \overline{\Phi} + \ell$$

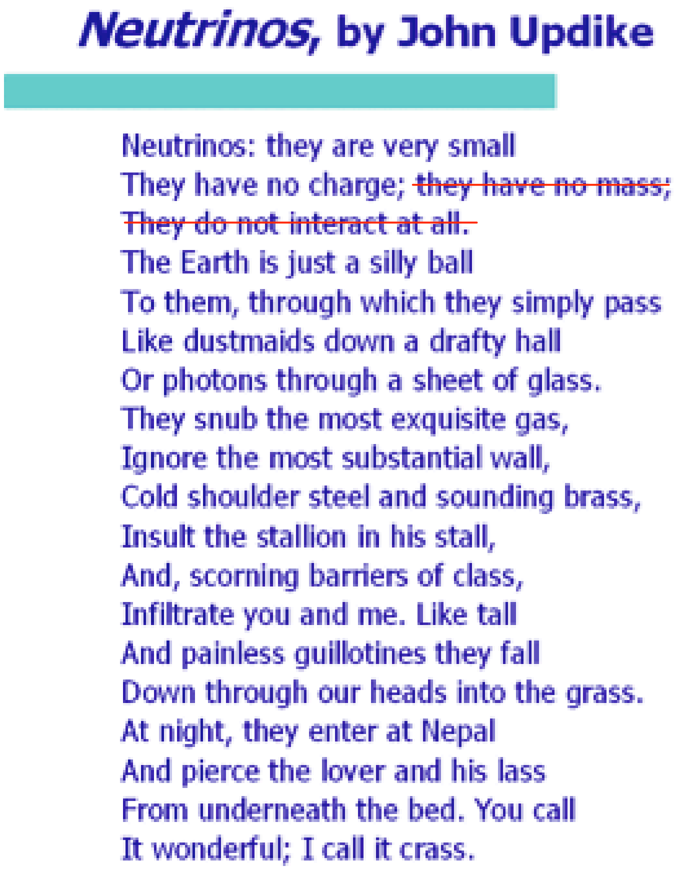
$$N_L^c \rightarrow \Phi + \overline{\ell}$$

Interference between tree-level & absorptive part of 1-loop verte gives asymmetry.

- Usually requires right-handed mass ~ 10^{10} GeV
- Decays are out of equilibrium because of expansion of universe

- Attractive because such massive RH neutrinos needed to get now-observed neutrino masses.
- Less attractive because hard to test in colliders.
- Some low-scale versions exist, but not compelling.

This is More Popular than Ever



Neutrinos, by John Updike

Neutrinos: they are very small
They have no charge; ~~they have no mass;~~
~~They do not interact at all.~~
The Earth is just a silly ball
To them, through which they simply pass
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me. Like tall
And painless guillotines they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed. You call
It wonderful; I call it crass.

- We now know neutrinos do have mass!
- In fact, as much of the mass of the Universe comes from neutrinos as from stars and galaxies

•Most popular way to explain this (the seesaw mechanism) requires a heavy right-handed neutrino of about the right scale for leptogenesis