

Baryogenesis, Leptogenesis, and New Interactions



- The baryon (matter) asymmetry
- The Sakharov conditions
- Possible mechanisms
- A new very weak interaction

Recent Reviews

- A. Riotto and M. Trodden, *Ann. Rev. Nucl. Part. Sci.* 49, 35 (1999) [[arXiv:hep-ph/9901362](#)].
- M. Trodden, Electroweak baryogenesis, *Rev. Mod. Phys.* 71, 1463 (1999) [[arXiv:hep-ph/9803479](#)].
- W. Bernreuther, CP violation and baryogenesis, *Lect. Notes Phys.* 591, 237 (2002) [[arXiv:hep-ph/0205279](#)].
- M. Dine and A. Kusenko, The origin of the matter-antimatter asymmetry, [arXiv:hep-ph/0303065](#).
- A. D. Dolgov, Cosmological matter antimatter asymmetry and antimatter in the universe, [arXiv:hep-ph/0211260](#).

The baryon (matter) asymmetry

The baryon asymmetry:

- Matter and antimatter are (almost) symmetric, but our part of the universe involves matter only
- $\frac{n_B}{n_\gamma} \sim 6.1_{-0.5}^{+0.7} \times 10^{-10}$ (Big Bang Nucleosynthesis (BBN)),
 $6.14 \pm 0.25 \times 10^{-10}$ (WMAP)
- $n_{\bar{B}} \sim 0$ (small amounts consistent with secondary production)

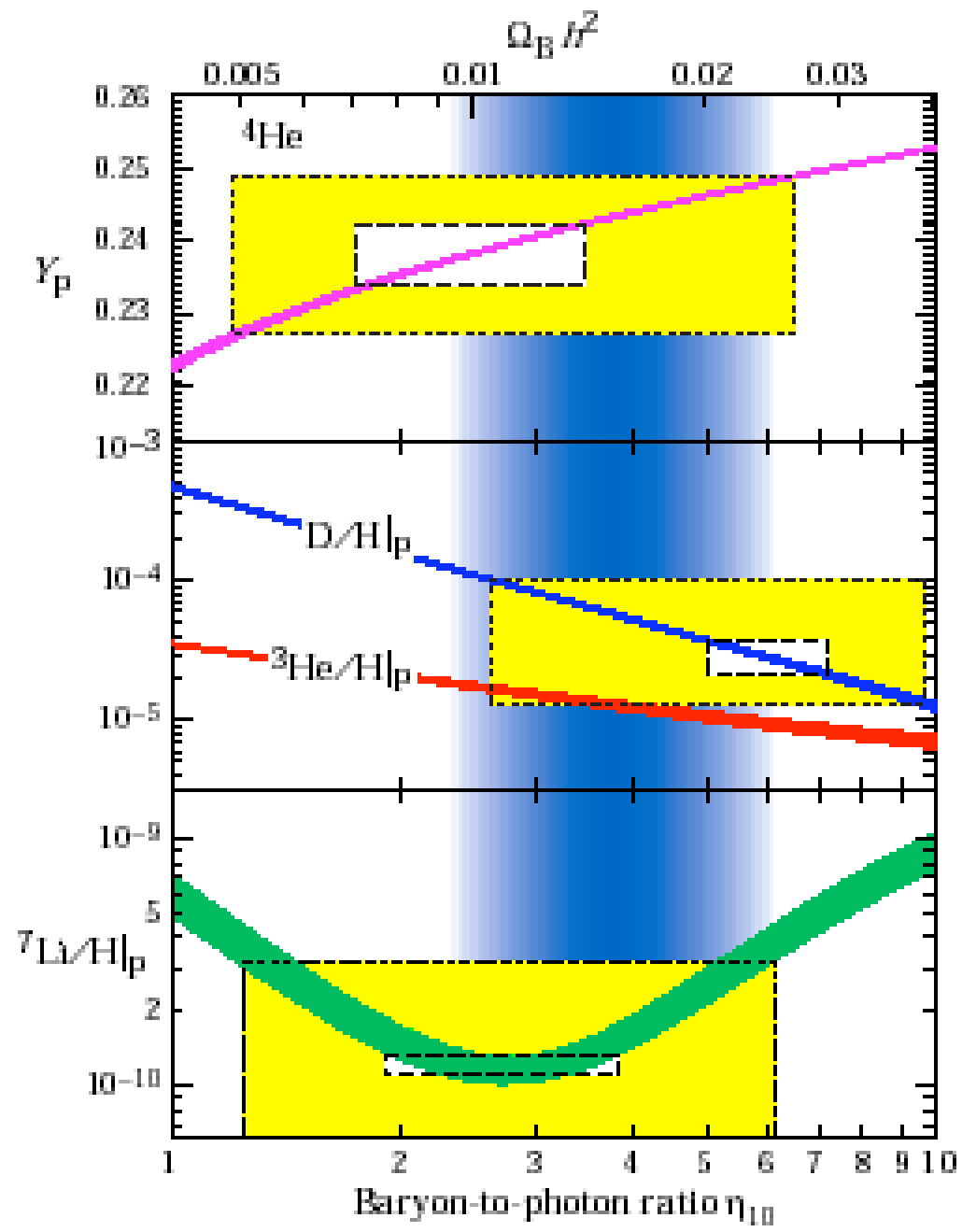
BBN: $\nu_e n \leftrightarrow e^- p$ and $e^+ n \leftrightarrow \bar{\nu}_e p$ keep n_n/n_p in equilibrium as long as it is rapid enough

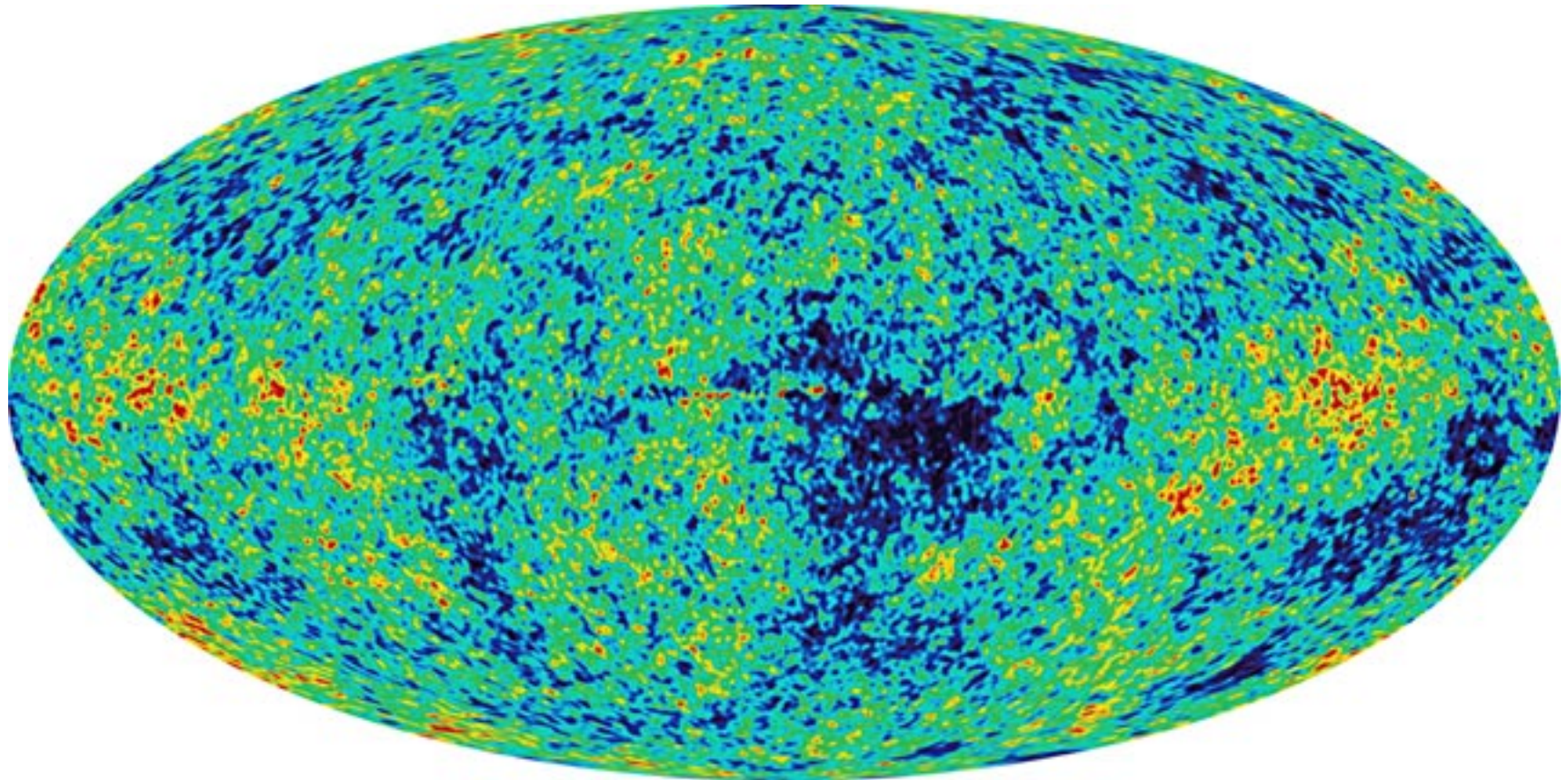
Freezeout at $T_\star \sim 1$ MeV, when $\Gamma_{\text{weak}} \sim H$

$$\frac{n_n}{n_p} = e^{-(m_n - m_p + \mu_{\nu_e})/T_\star} \rightarrow {}^4\text{He} \quad (\mu_{\nu_e} \sim \nu_e - \bar{\nu}_e \text{ asymmetry})$$

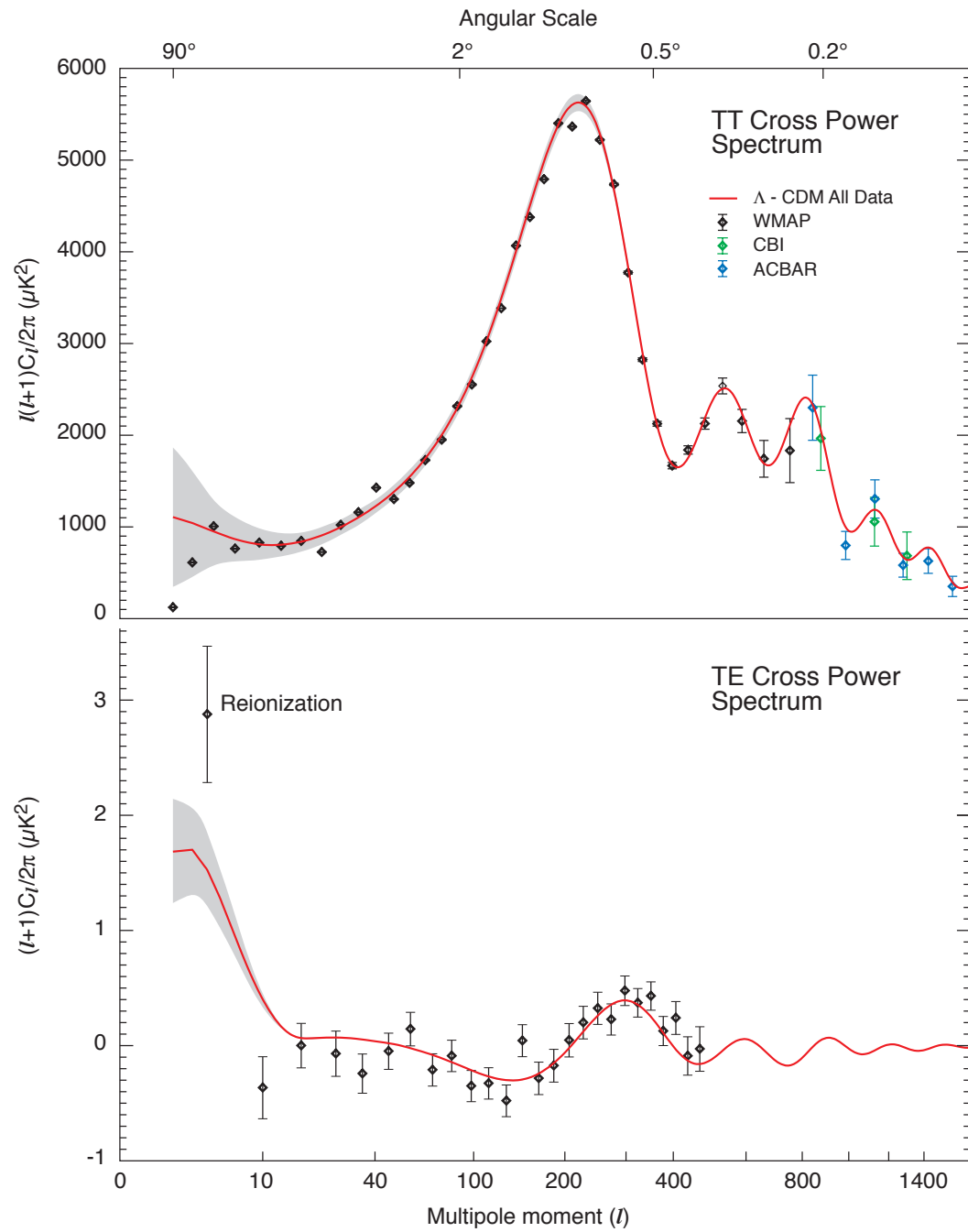
${}^4\text{He}$ mass fraction: $Y_p = \frac{4n_{{}^4\text{He}}}{n_H}$ depends strongly on $\xi_e \equiv \mu_{\nu_e}/T_\star$, weakly on $\eta \equiv \frac{n_B}{n_\gamma}$

$$Y_2 = \frac{D}{H} \text{ depends on } \eta \text{ (baryometer)} \Rightarrow \frac{n_B}{n_\gamma} \sim 6.1_{-0.5}^{+0.7} \times 10^{-10}$$

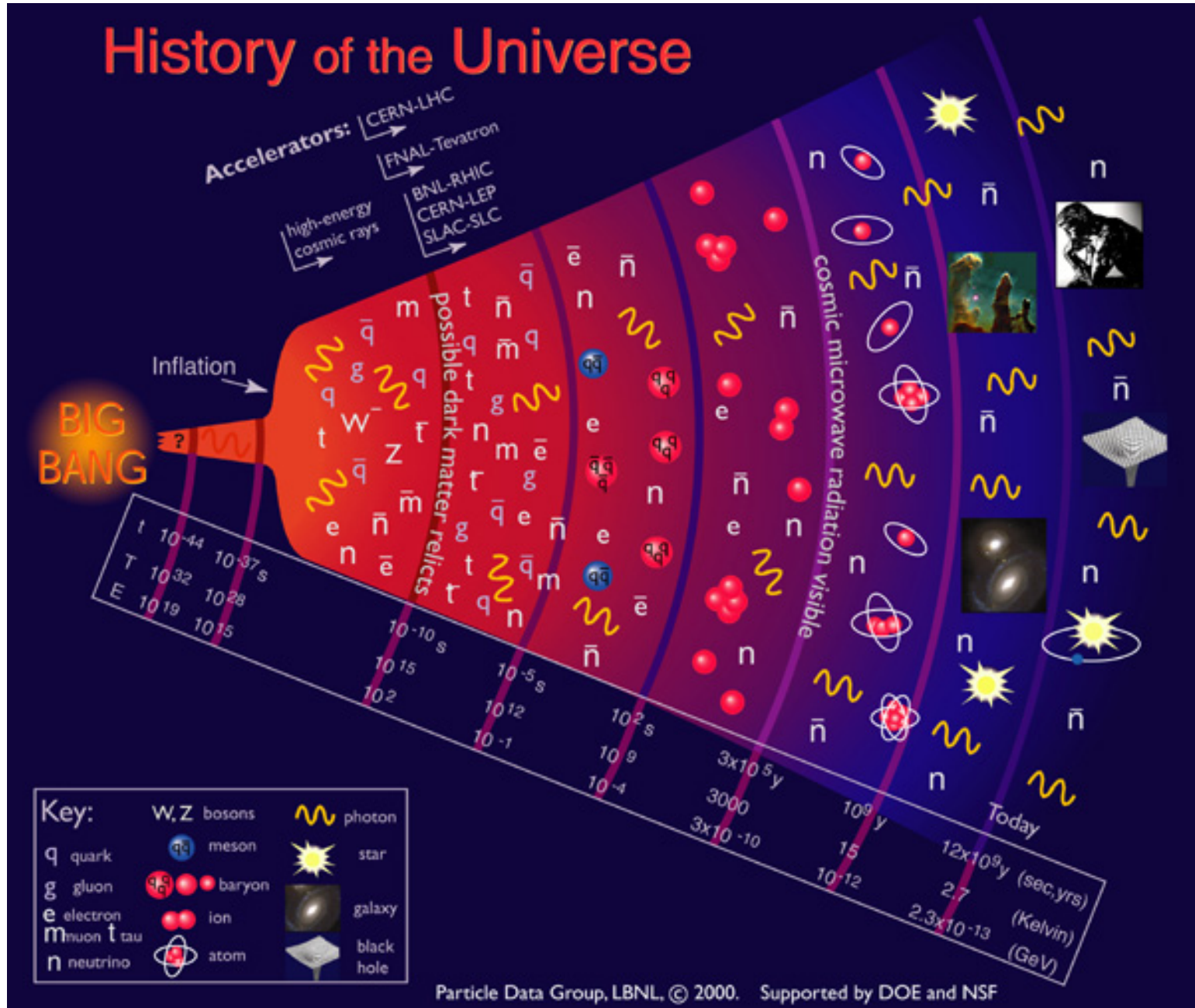




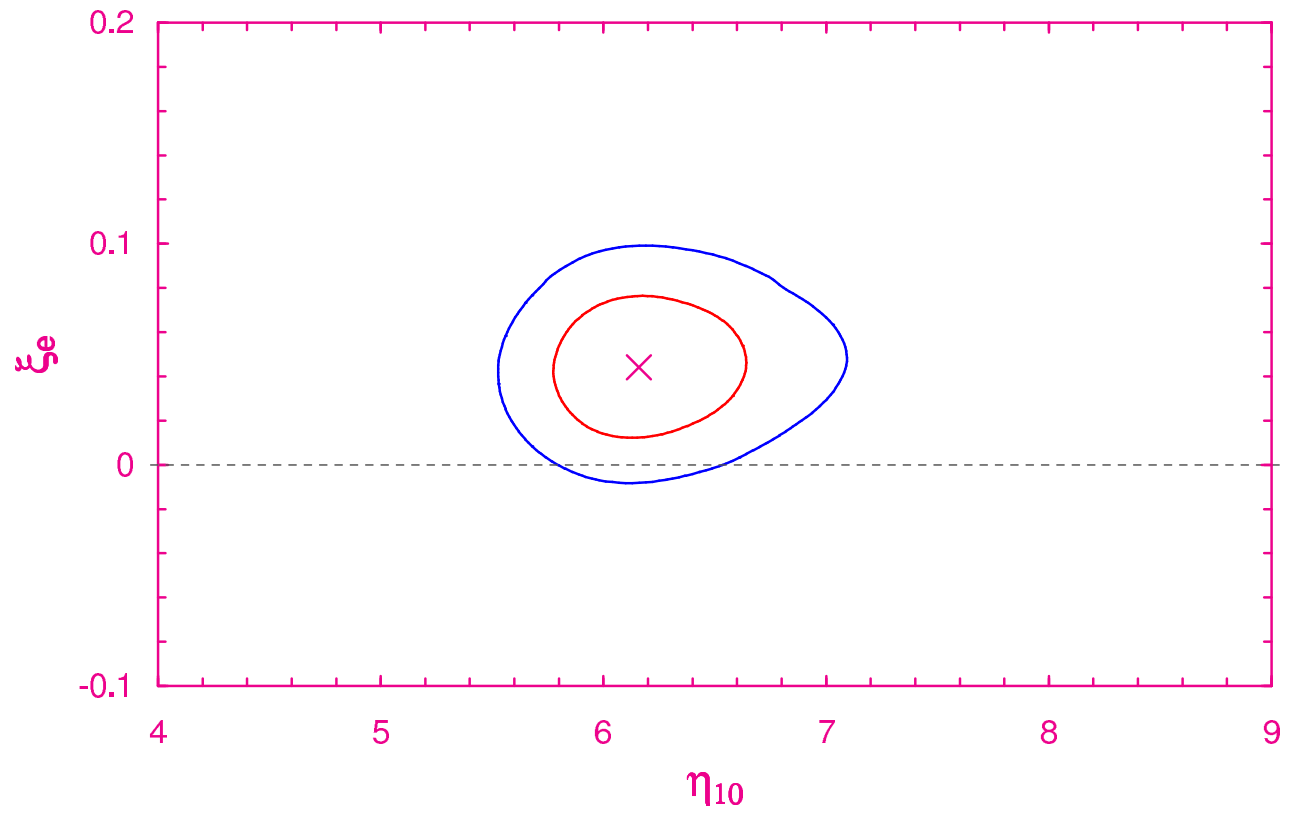
Independent determination of η from CMB $\Rightarrow \frac{n_B}{n_\gamma} \sim 6.14 \pm 0.25 \times 10^{-10}$



History of the Universe



- $n_{\bar{B}} \sim 0$ (small amounts consistent with secondary production)
- For $T \gtrsim \text{GeV}$, had $n_B \sim n_{\bar{B}} \sim n_\gamma$; most $B\bar{B}$ pairs annihilated, leaving small baryon excess (Otherwise, $n_B = n_{\bar{B}} \sim 10^{-18} n_\gamma$)
- Hence, need $\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$ for $T \gtrsim \text{GeV}$
- Neutrality: $n_{e^-} \sim n_B$; $n_{e^+} \sim 0$ (up to secondary production)
- Large neutrino-antineutrino asymmetry possible (important for BBN), but unlikely



(Barger, Kneller, Marfatia, PL, Steigman)

Origin: Where did the asymmetry come from?

Preexisting asymmetry? Only if no inflation

Domains of matter and antimatter?

- Absence of annihilation radiation implies separation > 10 Mpc
(probably much stronger by CMB)
- Separation of symmetric plasma? No known mechanism.
Causality constraints imply regions contain less than $10^{-6} M_{\odot}$
- Domains by spontaneous CP breaking possible, but hard to avoid domain wall difficulties

Baryogenesis: dynamical generation of asymmetry from initially symmetric conditions

The Sakharov conditions

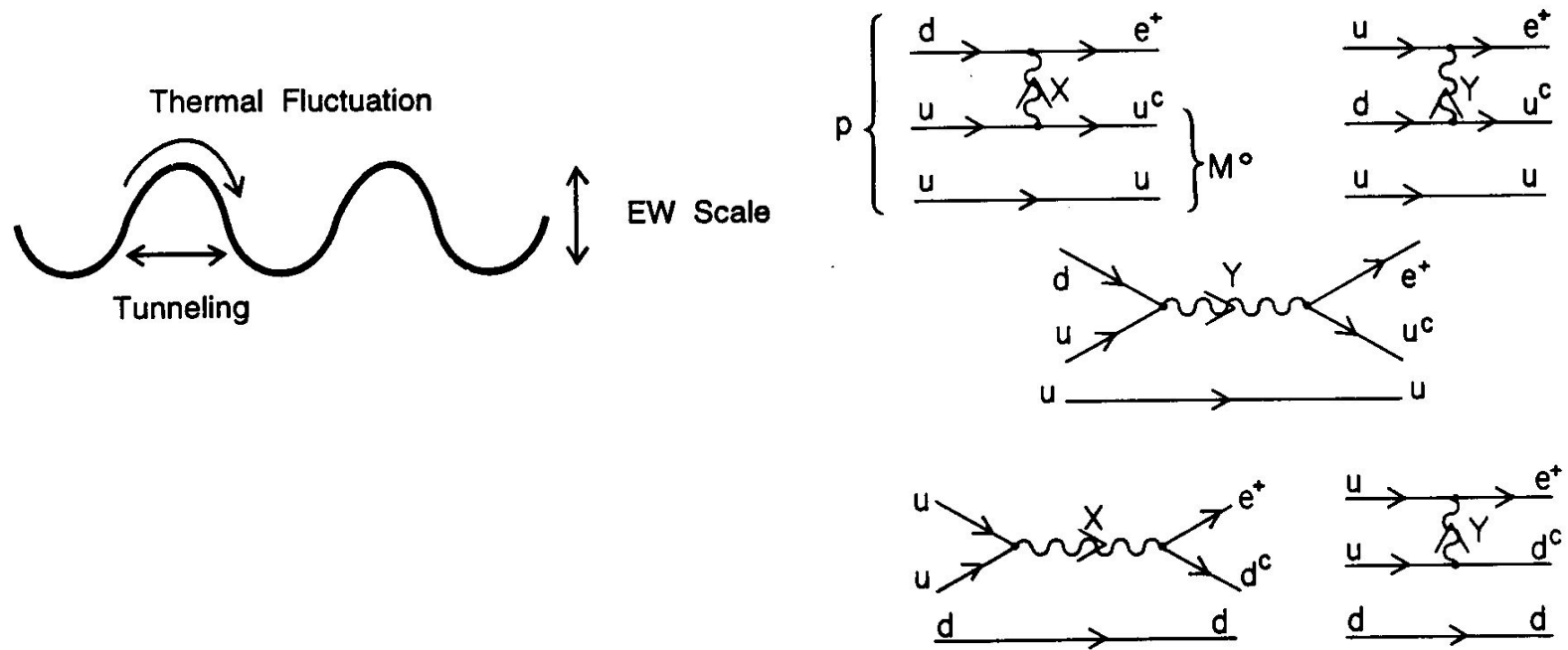
Basic ideas worked out by Sakharov in 1967, but no concrete model



1. Baryon number violation
2. CP violation: to distinguish baryons from antibaryons
3. Nonequilibrium of B -violating processes

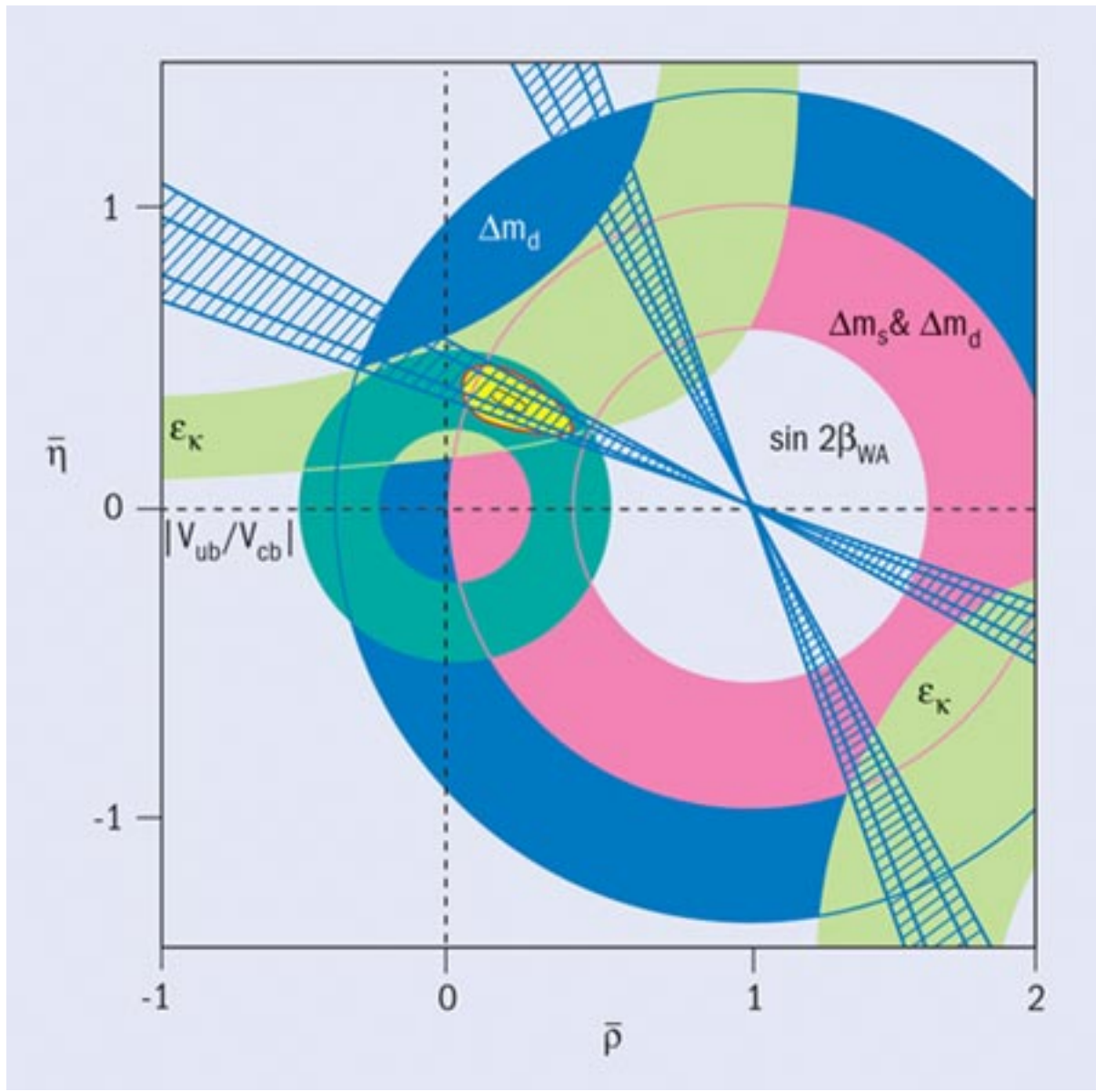
1. Baryon number violation

- Processes involving black holes
- Standard model: tunneling between vacua with different B (Rate at $T = 0$ is $\sim e^{-4\pi\sin^2\theta_W/\alpha} \sim 10^{-170}$!)
- Grand unification (GUT): new interactions lead to proton decay



2. CP violation: to distinguish baryons from antibaryons

- Complex phases introduced by mass terms or interactions with spin-0
- Need interference of two amplitudes
- Active programs in neutrino physics and heavy (b) quark decays to further explore CP violation



3. Nonequilibrium of B -violating processes (or CPT violation due to expanding universe)

- Out of equilibrium decays of heavy particles ($n \gg e^{-m/T}$)
- Phase transitions
- Classical field dynamics (e.g., inflaton)

Grand Unification

Pati-Salam, 73; Georgi-Glashow, 74

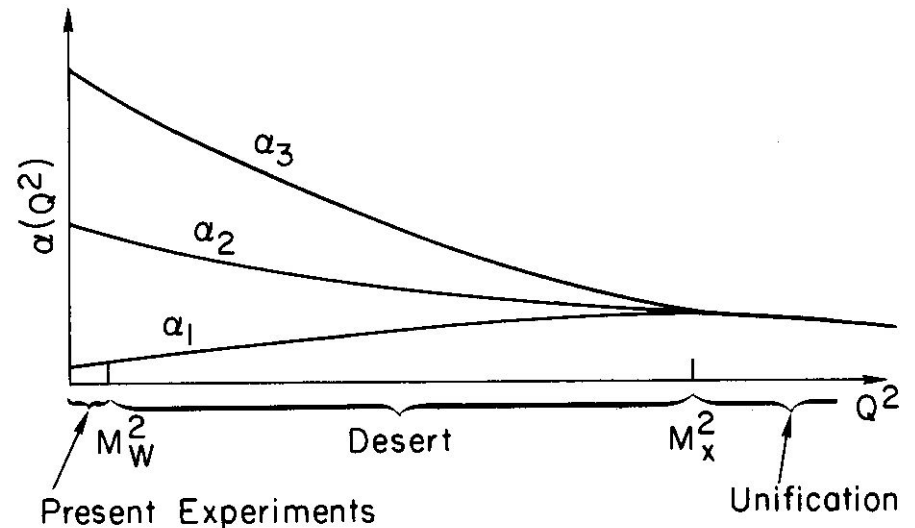
Strong, weak, electromagnetic unified at $Q \gtrsim M_X \gg M_Z$

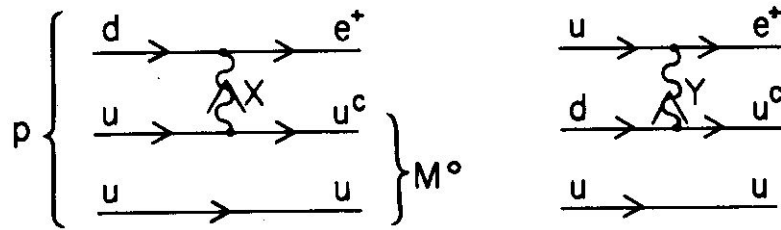
- Simple group

$$G \xrightarrow{M_X} SU(3) \times SU(2) \times U(1)$$

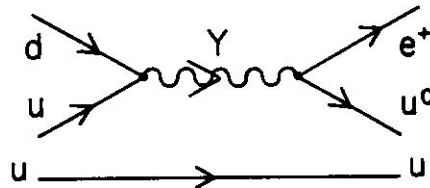
- Gravity *not* included
(perhaps not ambitious enough)

- Couplings meet at $M_X \sim 10^{14}$ GeV (w/o SUSY)
(works much better with SUSY
 $\rightarrow M_X \sim 10^{16}$ GeV)

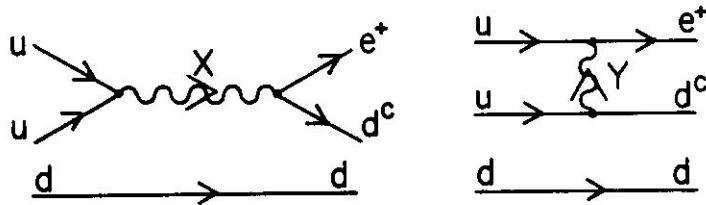




$$q_X = \frac{4}{3}$$



$$q_Y = \frac{1}{3}$$



- q, \bar{q}, l, \bar{l} unified (in same multiplets) \Rightarrow

- Charge quantization (no $U(1)$ factors)

- Proton decay mediated by new gauge bosons, e.g. $p \rightarrow e^+ \pi^0$
(other modes in SUSY GUTS)

- $\tau_p \sim \frac{M_X^4}{\alpha^2 m_p^5} \sim 10^{30}$ yr for $M_X \sim 10^{14}$ GeV
(10^{38} yr in SUSY, but faster $p \rightarrow \bar{\nu} K^+$)

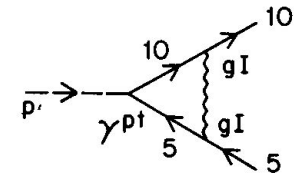
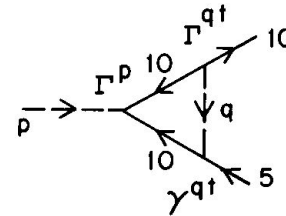
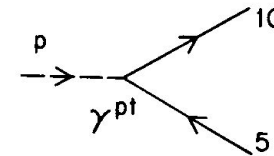
Possible mechanisms for generating the asymmetry

GUT baryogenesis (Yoshimura, 1979)

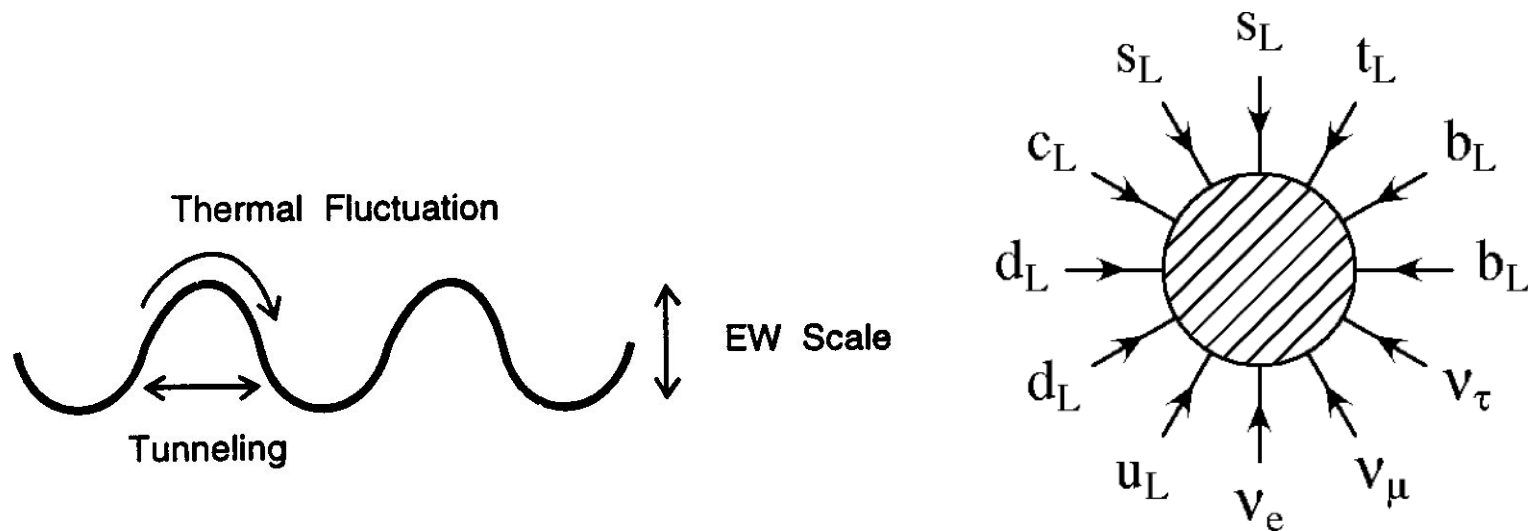
- Out of equilibrium decay of heavy ($M \gtrsim 10^{13}$ GeV) colored spin-0 particle H (grand unification partner of Higgs boson):

$$H \rightarrow \bar{q}\bar{q} \text{ or } ql; \bar{H} \rightarrow qq \text{ or } \bar{q}\bar{l}$$

- Equal total rates (CPT conservation) but unequal partial rates (CP violation)
- Large enough asymmetry generated (for nonminimal model)
- $B - L$ conserved $\Rightarrow B = L$



- Hard to combine with inflation unless very high reheating T
- Electroweak baryon number unsuppressed at $T \gtrsim 100 \text{ GeV}$ (electroweak scale); wipes out asymmetry with $B = L$



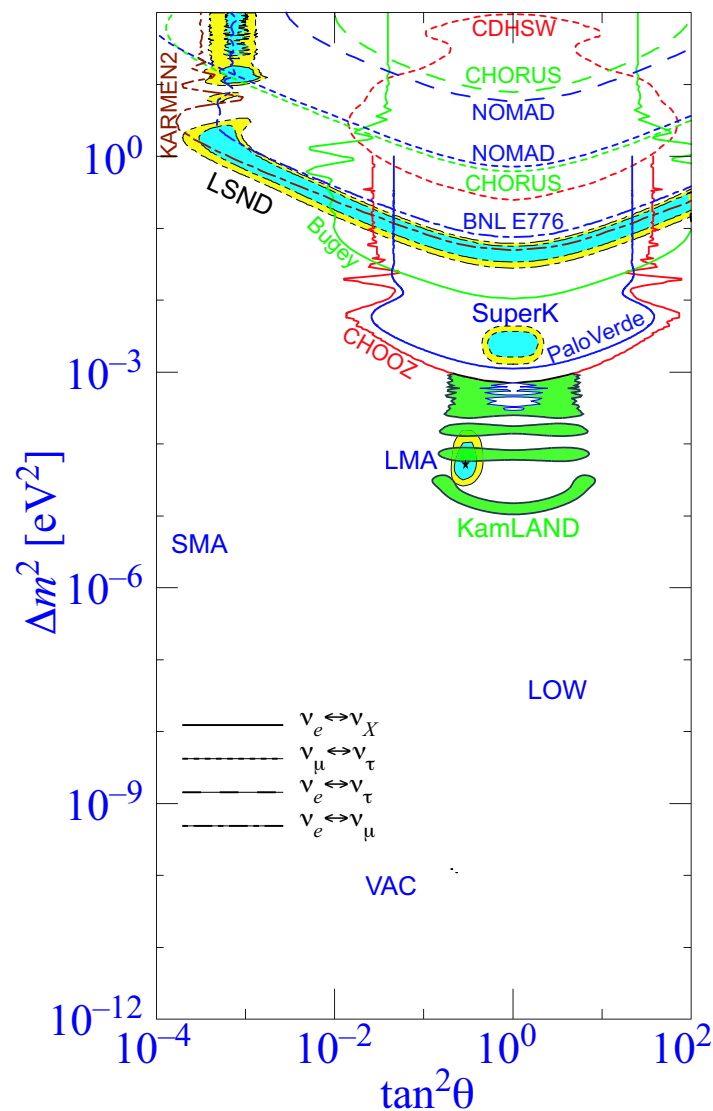
Leptogenesis: (Fukugita, Yanagida)

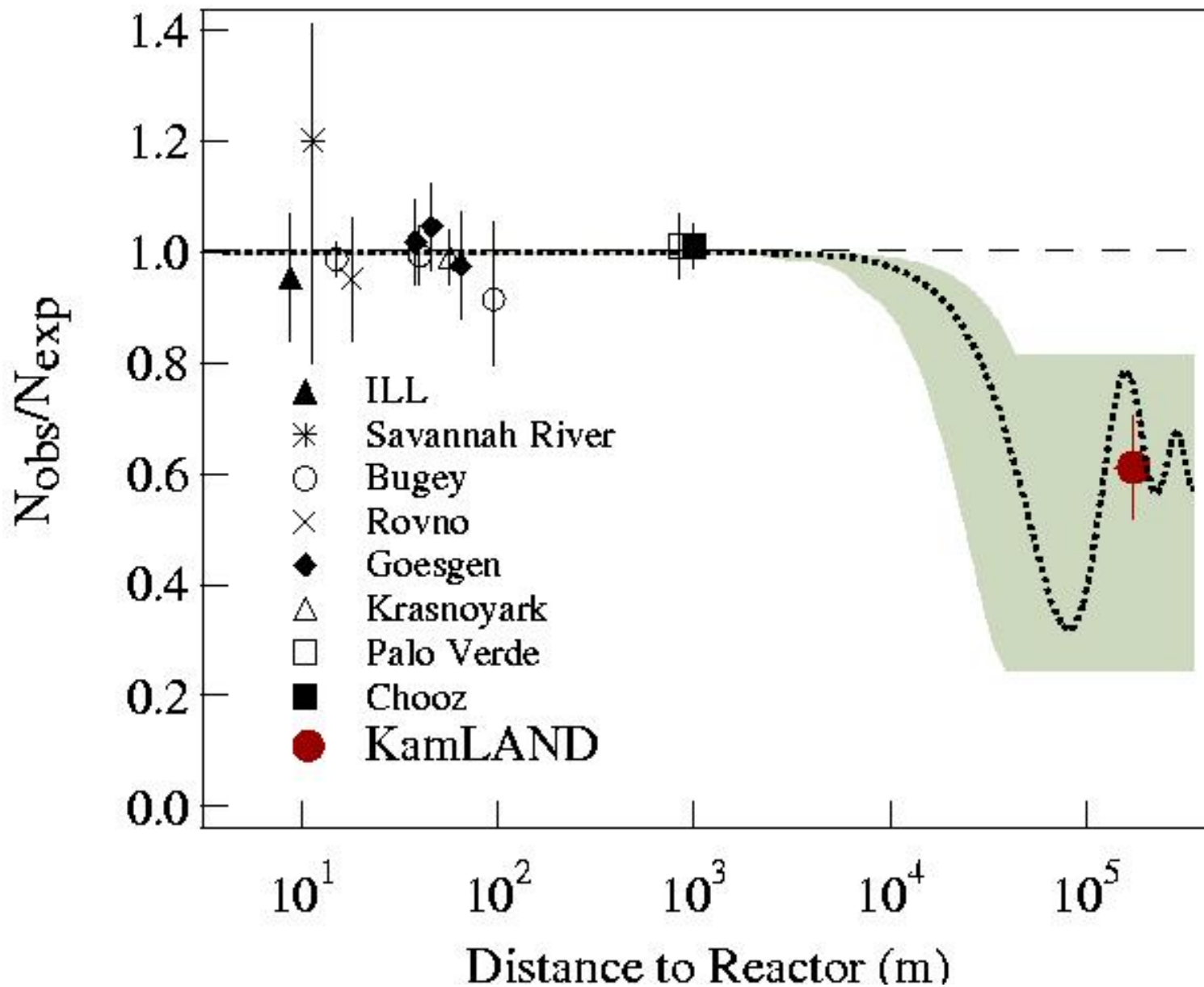
- Seesaw model of neutrino mass: mixing between light and heavy neutrino

$$m_{\text{light}} \sim \frac{m_D^2}{m_{\text{heavy}}} \ll m_D$$

where m_D is similar to quark or charged lepton mass, and $m_{\text{heavy}} \sim 10^{12}$ GeV

- Successful for neutrino mass scales, but mixings problematic





Leptonic CP violating Phases

- Weak charge-raising current

$$\begin{aligned} J_W^{\mu\dagger} &= \sum_{m=1}^3 [\bar{\nu}_m^0 \gamma^\mu (1 - \gamma^5) e_m^0 + \bar{u}_m^0 \gamma^\mu (1 - \gamma^5) d_m^0] \\ &= (\bar{\nu}_1 \bar{\nu}_2 \bar{\nu}_3) \gamma^\mu (1 - \gamma^5) V_{MNS} \begin{pmatrix} e^- \\ \mu^- \\ \tau^- \end{pmatrix} \\ &\quad + (\bar{u} \bar{c} \bar{t}) \gamma^\mu (1 - \gamma^5) V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \end{aligned}$$

- $V_{CKM} = A_L^{u\dagger} A_L^d$ is 3×3 unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix from mismatch between weak and Yukawa interactions

- $V_{MNS} = A_L^{\nu\dagger} A_L^e$ is leptonic analogue
- A_L^f relates weak and mass eigenstate left-handed fields
- V_{CKM} has 3 angles and 1 CP-violating phase
- For Dirac neutrinos, V_{MNS} also has one CP-violating phase, measurable in oscillations, e.g., $\nu_\mu \rightarrow \nu_e$ vs $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- For Majorana neutrinos, V_{MNS} has additional factor **diag** ($e^{i\phi_1}$, $e^{i\phi_2}$, **1**) (Majorana phases, due to fewer physical fields with unobservable phases)
 - Observable *in principle* in neutrinoless double beta decay, which depends on $\sum_{i=1}^3 V_{ei}^2 m_{\nu_i}$
 - Probably impossible in practice due to nuclear matrix element uncertainties (Barger, Glashow, PL, Marfatia)
- Leptogenesis has 3 additional phases from Yukawa couplings to heavy right-handed neutrinos

- Out of equilibrium decays of

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

created a *lepton* asymmetry

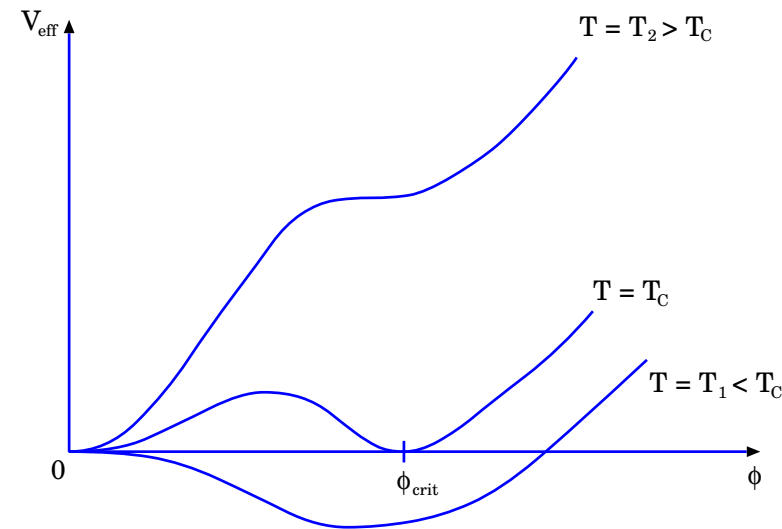
- Electroweak tunneling (actually thermal fluctuation) then converts some of the lepton asymmetry into a baryon asymmetry!
- Difficulties in supersymmetric version: gravitino problem suggests reheating temperature too low (unless N_{heavy} produced nonthermally)

Electroweak baryogenesis

Utilize the electroweak (B -violating) tunneling to *generate* the asymmetry at time of electroweak phase transition (Kuzmin, Rubakov, Shaposhnikov)

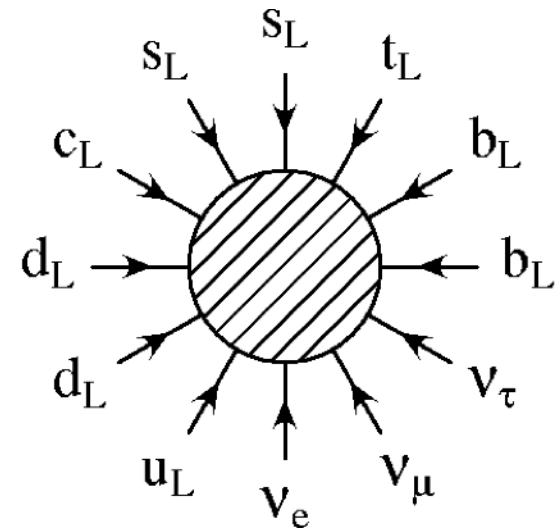
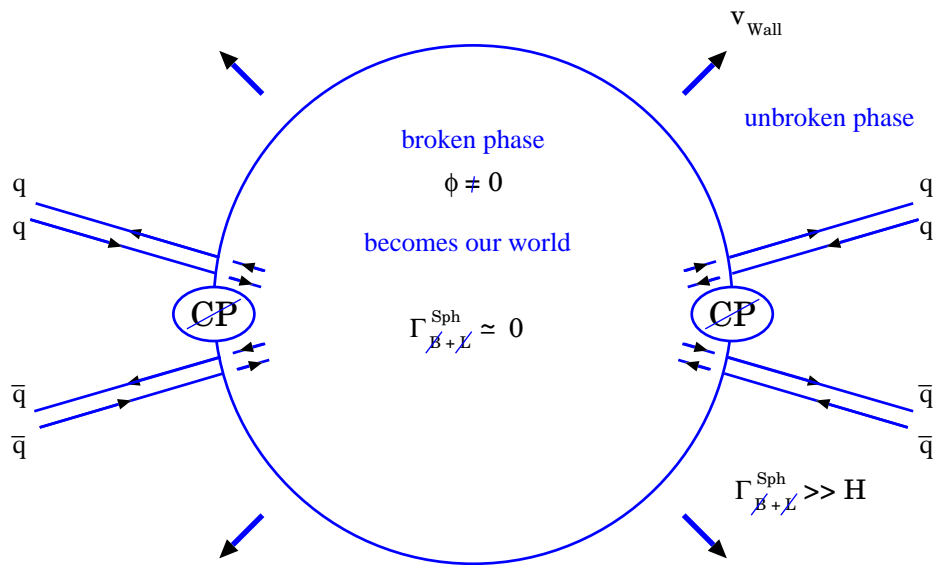
Off the wall scenario (Cohen, Kaplan, Nelson)

- Strong first order phase transition from electroweak symmetry unbroken (massless W , Z , fermions) to broken phase (massive W , Z , fermions) proceeds by nucleation and expansion of bubbles



(Figures: W. Bernreuther, hep-ph/0205279)

- CP violation by asymmetric reflection/transmission of quarks and leptons from the wall (e.g. quarks transmitted, antiquarks reflected)
- Electroweak B violation in unbroken phase outside wall
- Scenario requires strong first order transition, $v(T_c)/T_c \gtrsim 1-1.3$ and adequate CP violation in expanding bubble wall



Implementation of “off the wall”

Standard model: no strong first order for $M_h > 114.4$ GeV; CP violation too small

Minimal supersymmetric extension (MSSM): small parameter space for light Higgs and stop

NMSSM (extension to include extra Higgs fields): can have strong first order *but* **cosmological domain walls**

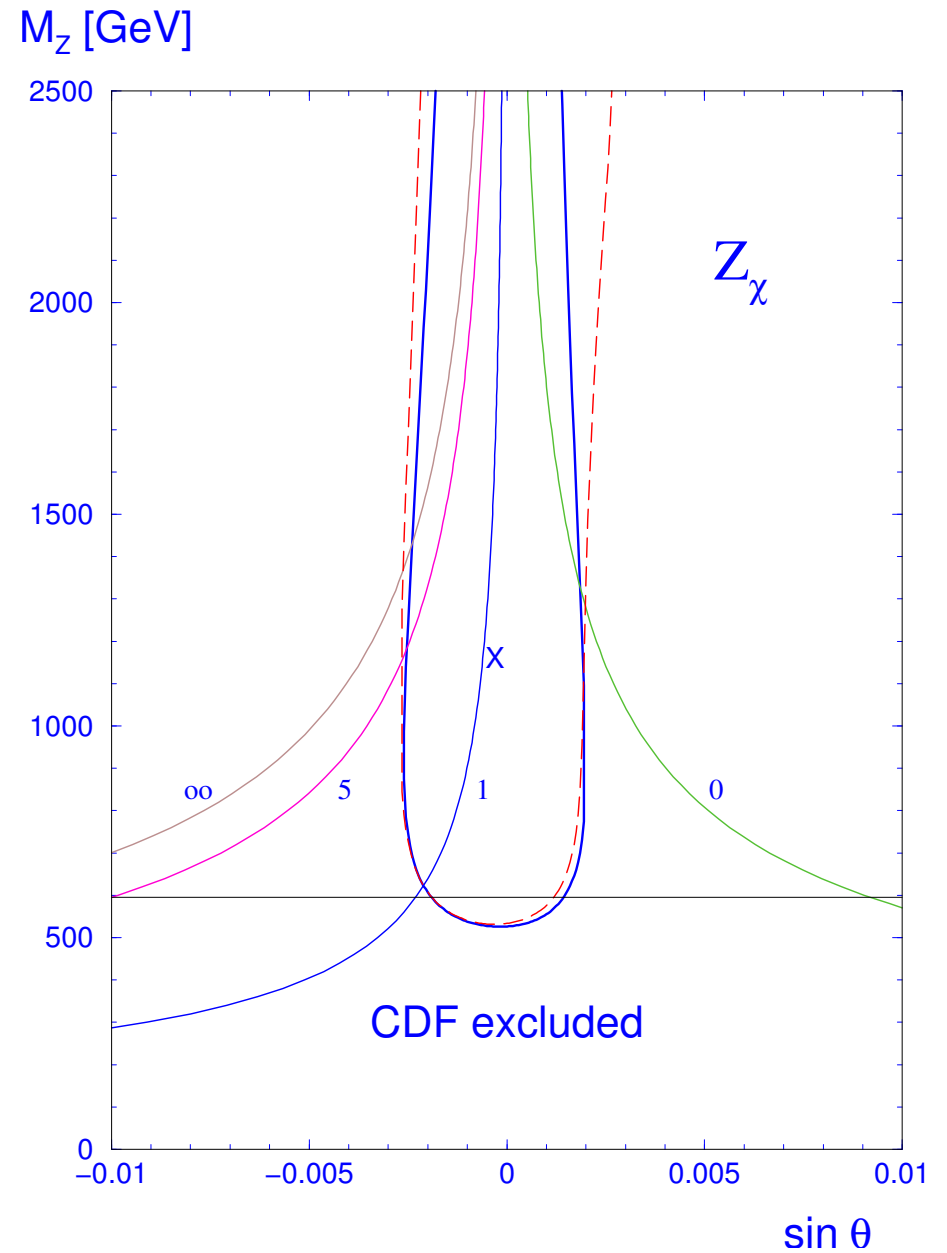
A new very weak interaction?

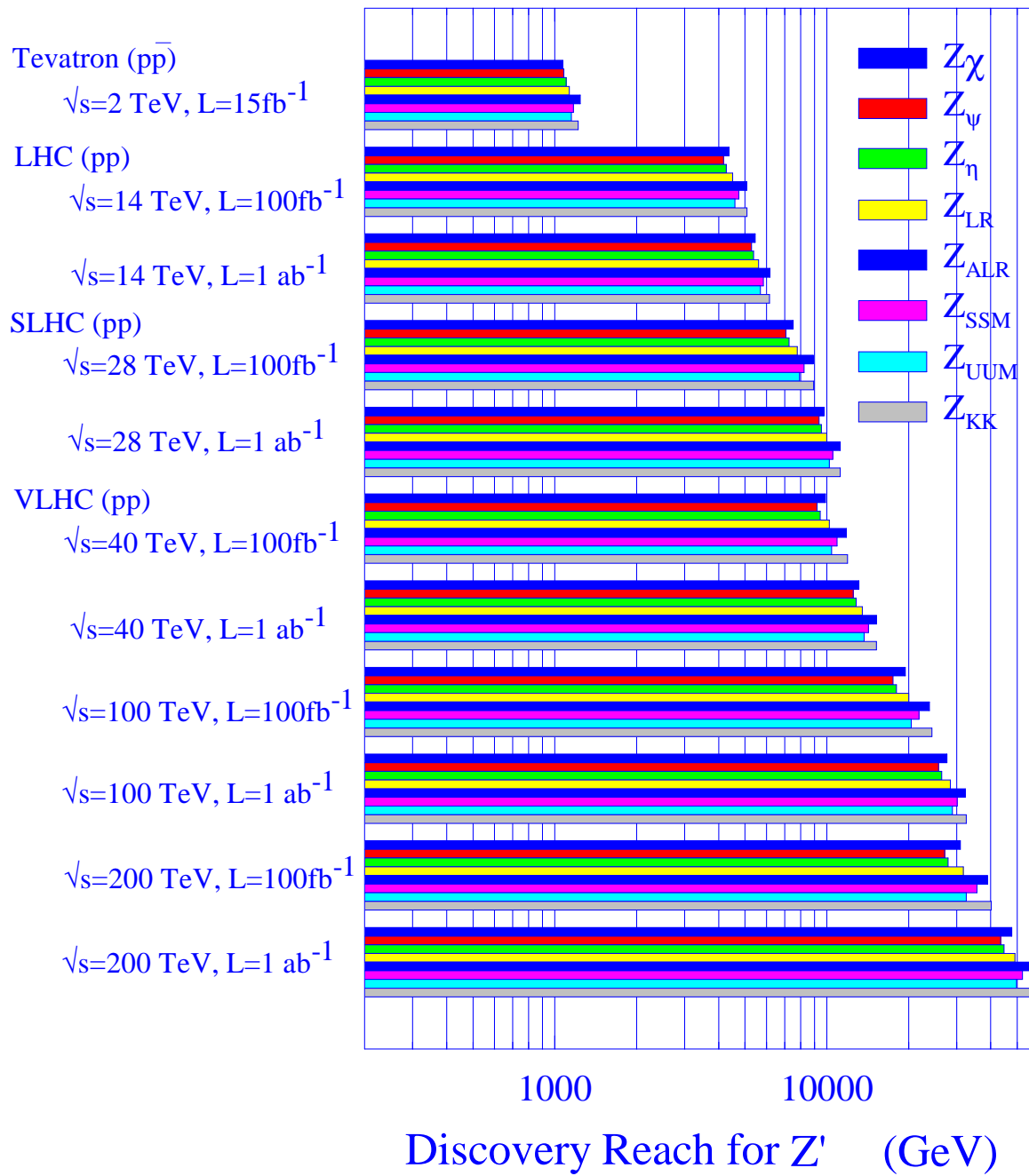
Extended gauge symmetry: (extra Z boson with mass \sim TeV)

(M. Cvetič, PL, et al; J. Erler, PL, T. Li)

- Expected in many string theories, grand unification, dynamical symmetry breaking
- Solves supersymmetric mass (μ) problem

- Typically $M_{Z'} > 500 - 800$ GeV (Tevatron, LEP 2, WNC), $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ (Z-pole)
(PL, Jens Erler)
(cf., $M_W \sim 80$ GeV, $M_Z \sim 91$ GeV)
- Discovery to $M_{Z'} \sim 5 - 8$ TeV at LHC, LC
- Diagnostics to 1-2 TeV (asymmetries, y distributions, associated production, rare decays)





Implications of $U(1)'$

- Solution to μ problem
- Exotics; needed for anomaly cancellation (can be consistent with gauge unification)
- Non-standard sparticle spectrum
- Neutrino implications: Dirac, natural ν_R decoupling, TeV seesaw
- Dirac neutrinos and BBN (Barger, PL, Lee)
- FCNC (especially in string models) (PL, Plümacher); rare B decays (Barger, Chiang, PL, LI)

- **Non-standard Higgs masses, couplings (doublet-singlet mixing)**
(Han, PL, McElrath)
- **Enhanced possibility of EW baryogenesis** (Kang, Liu, PL, Li)

Nonstandard Higgs

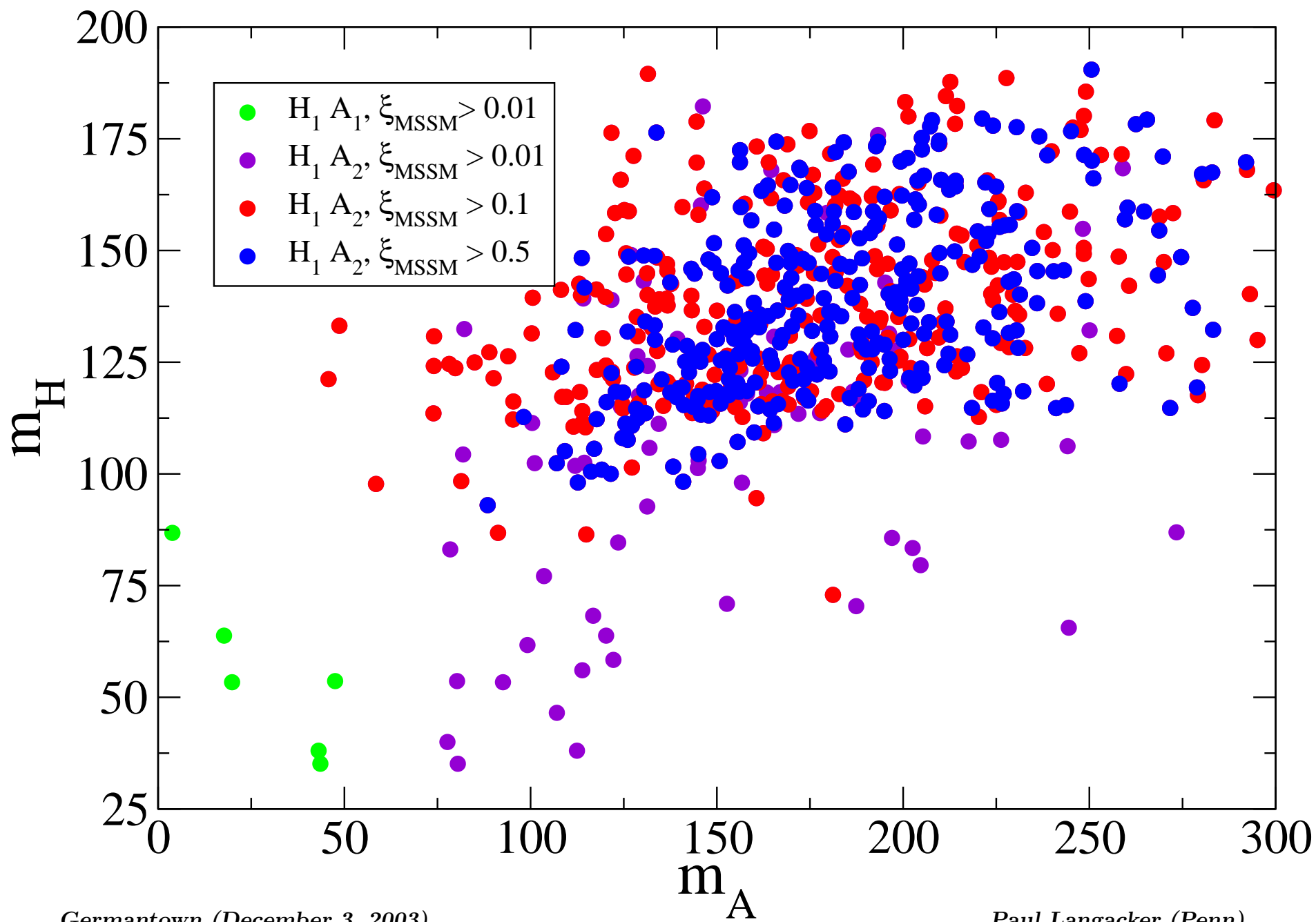
(T. Han, PL, B. McElrath)

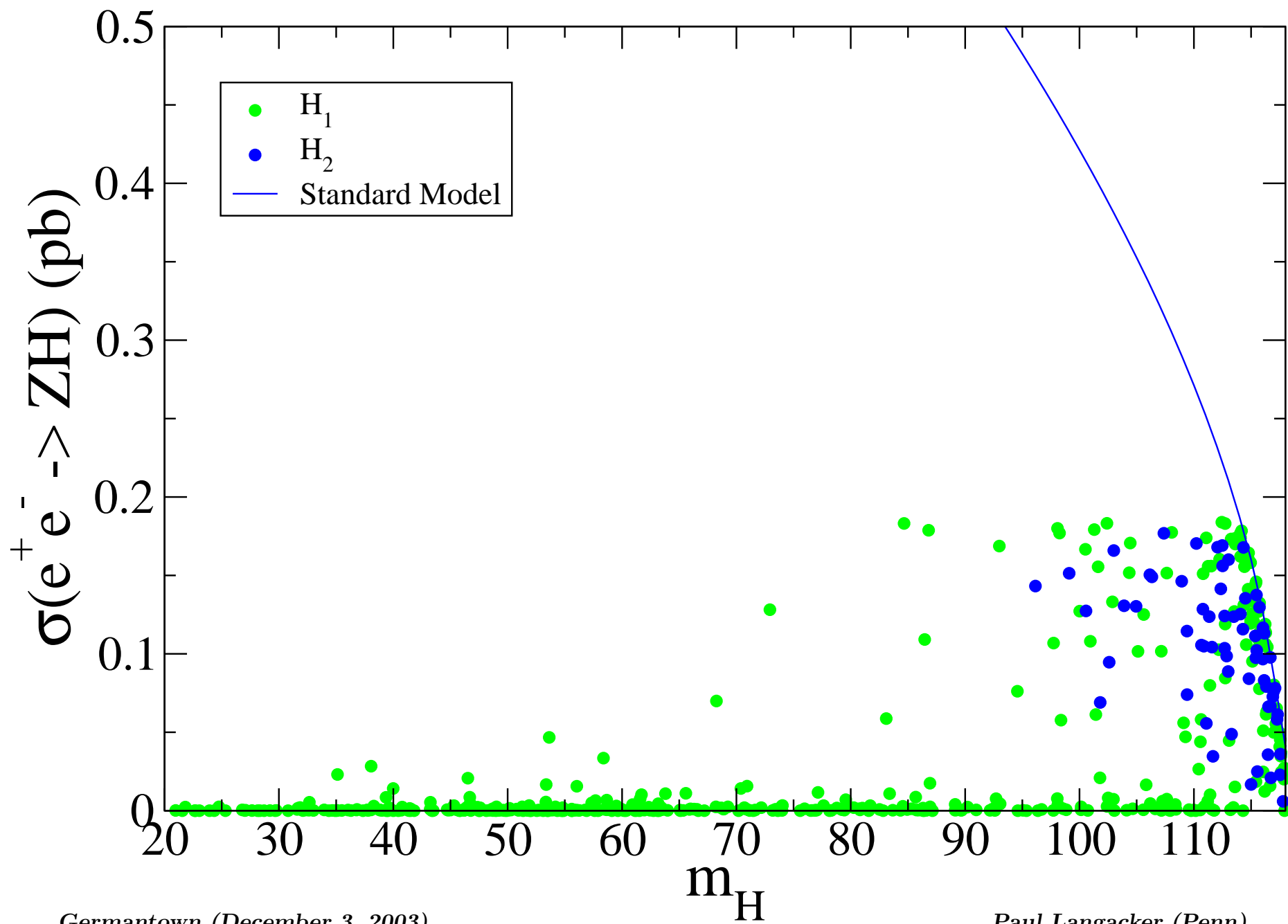
- Complex Higgs, neutralino spectrum and decays, very different from MSSM and NMSSM because of mixing and D terms

- 6 scalars and 4 pseudoscalars

- Can have tree level CP breaking \Rightarrow mixing
- Separate into two sectors, one decoupled
- Often light scalars with significant doublet admixture, but reduced coupling due to singlet admixture; $M_A < 65$ GeV
- Can have lightest Higgs up to 185 GeV with all couplings perturbative to M_P because of D terms

$$\begin{aligned}
 M_h &\leq h^2 v^2 + (M_Z^2 - h^2 v^2) \cos^2 2\beta \\
 &+ 2g_{Z'}^2 v^2 (Q_{H_2} \cos^2 \beta^2 + \sin^2 \beta Q_{H_1})^2 \\
 &+ \frac{3 \cos^2 \beta m_t^4}{2 v^2 \pi^2} \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}.
 \end{aligned}$$

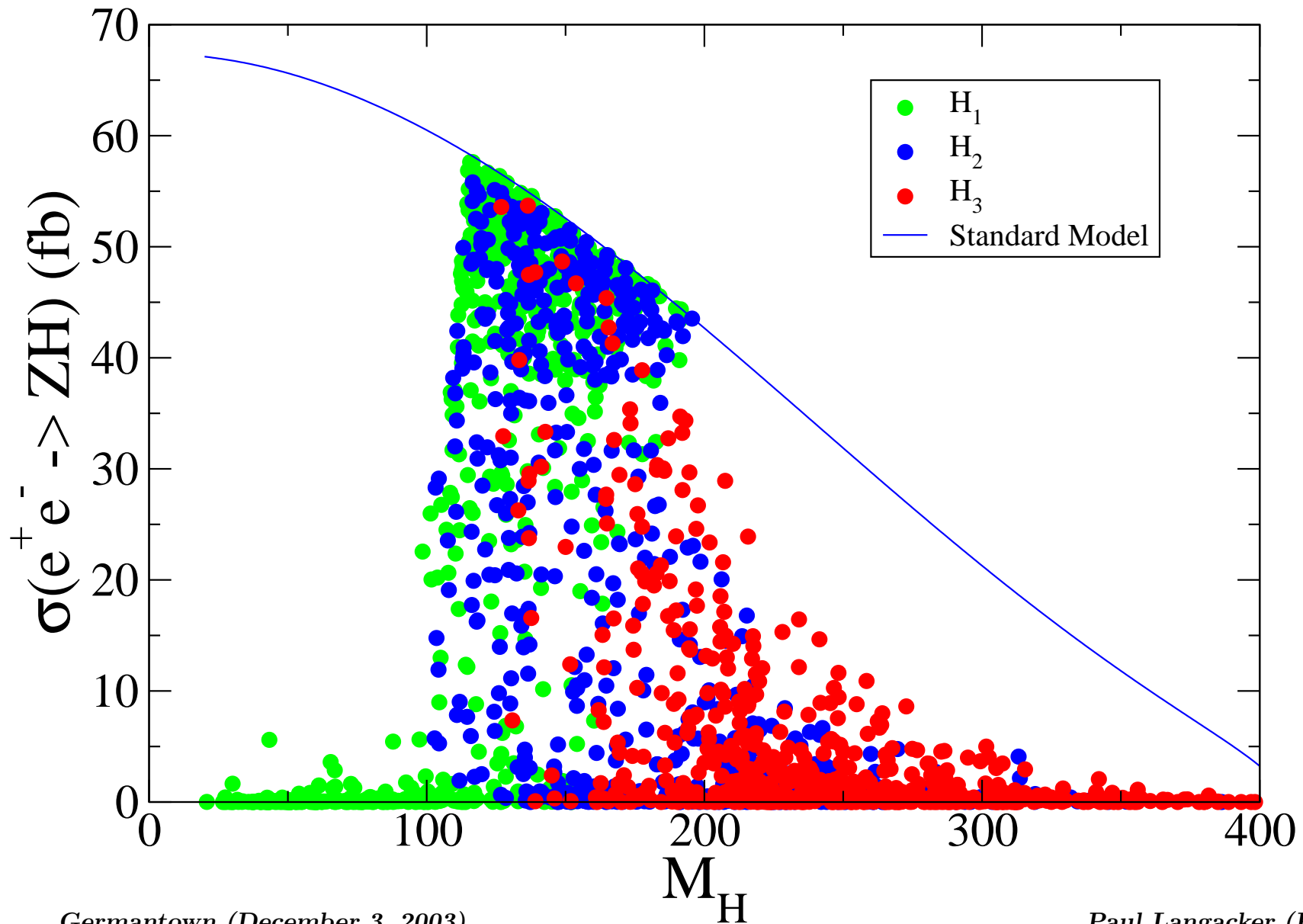




Germantown (December 3, 2003)

Paul Langacker (Penn)

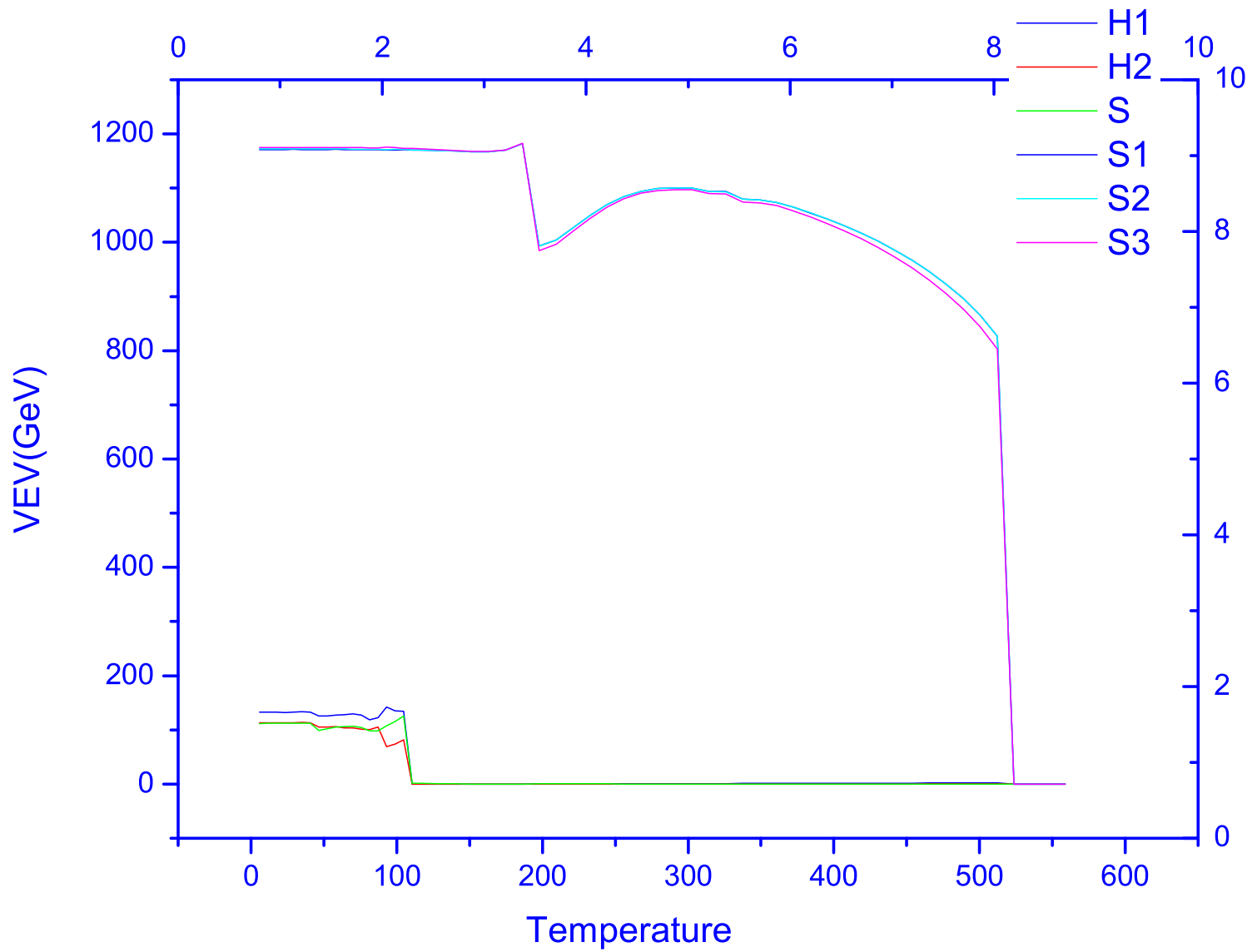
Linear Collider (500 GeV) Higgsstrahlung Cross Section

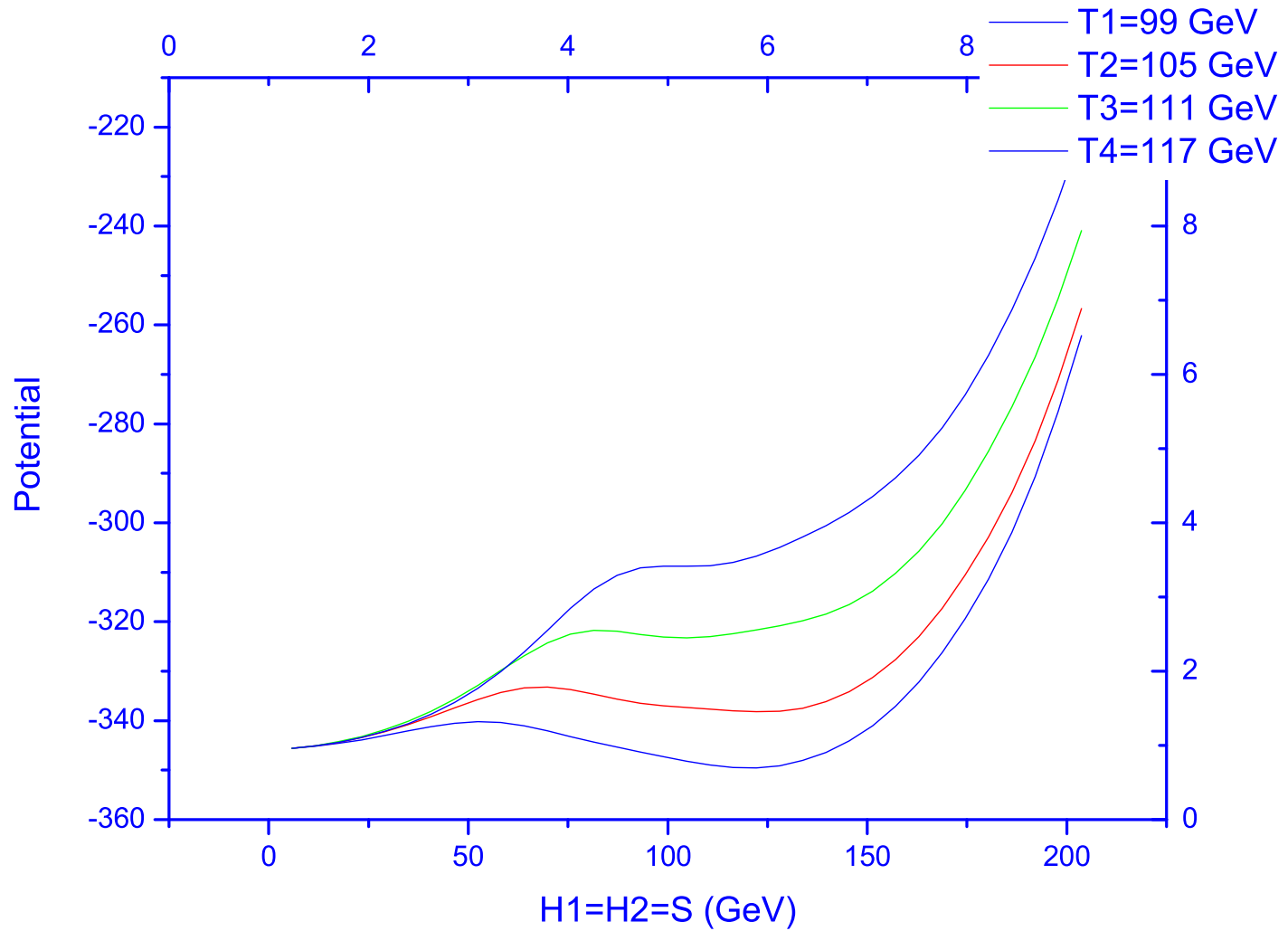


Electroweak Baryogenesis with an extra $U(1)'$

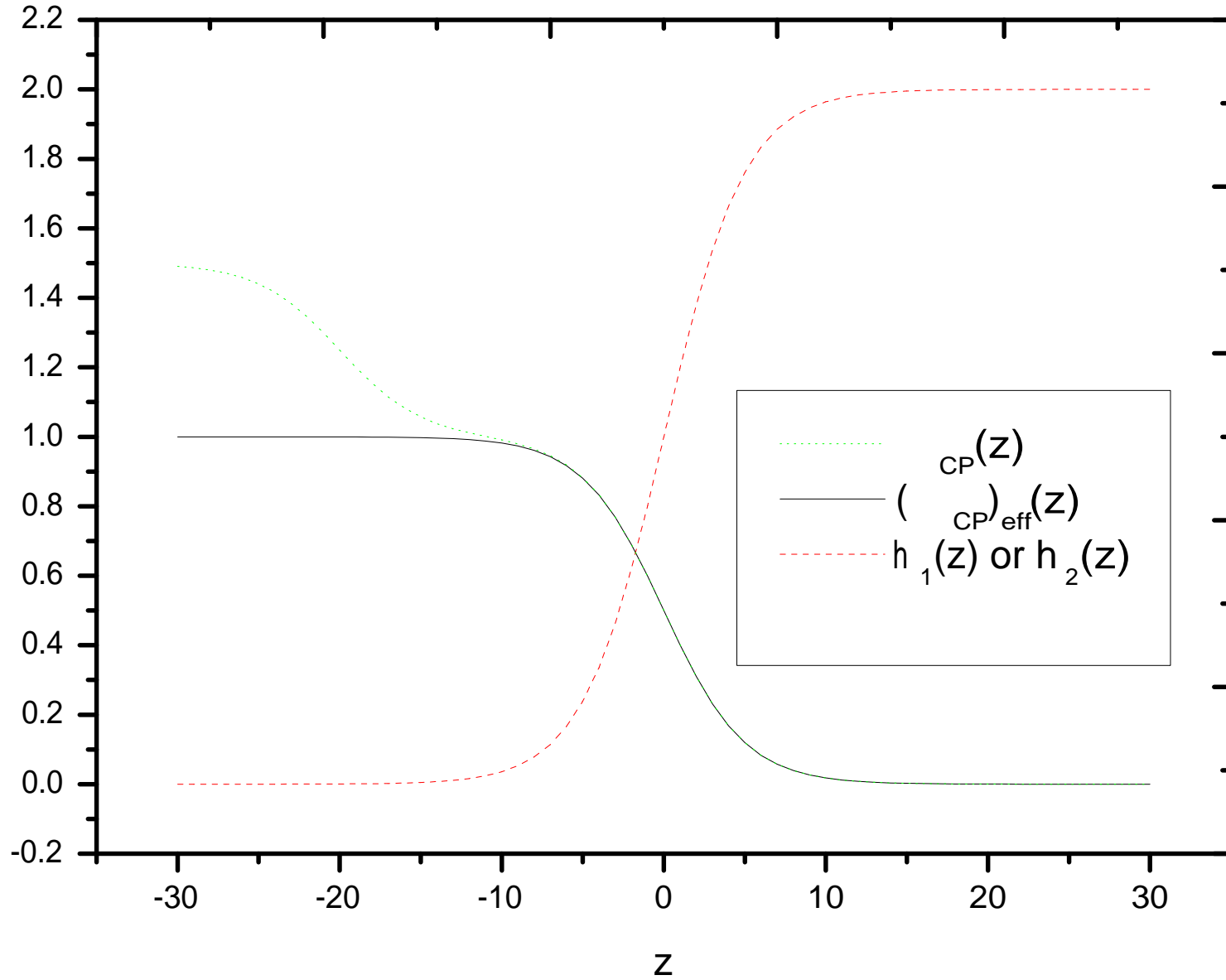
Generates adequate baryon asymmetry (J. Kang, PL, T. Li, T. Liu)

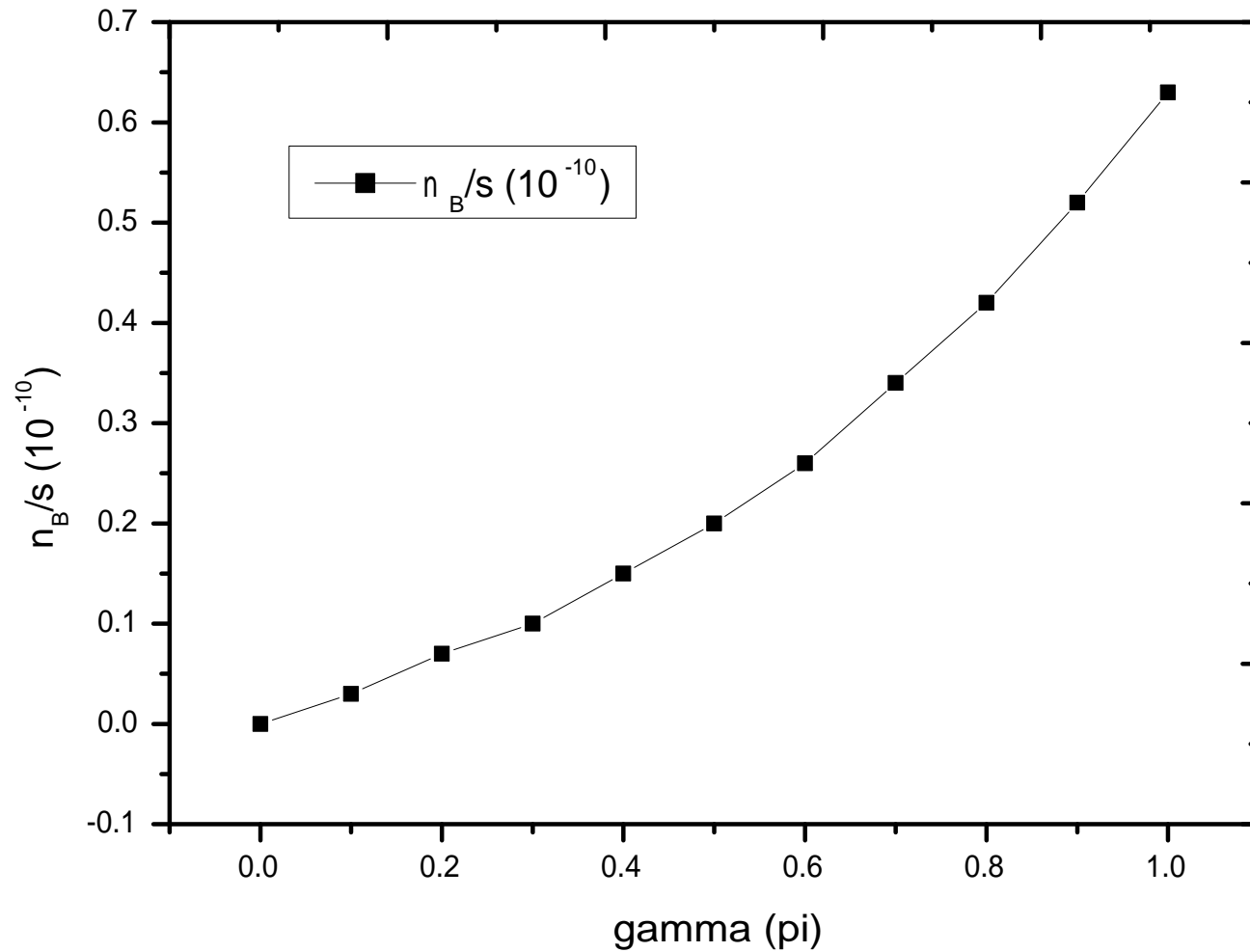
- First phase transition breaks extended gauge symmetry, second breaks $SU(2) \times U(1)$
- Strong first order phase transition
- Explicit CP breaking in Higgs sector, different for $SU(2) \times U(1)$ broken, unbroken
- New contributions to electric dipole moments very small





Transition at $T_c = 100$ GeV, $v(T_c)/T_c = 2.3$





$\gamma = \text{explicit CP phase. Need } n_B/s \sim (0.8 - 0.9) \times 10^{-10}.$
 (No theory error. Parameters not optimized.)

Conclusions

- The matter-antimatter asymmetry is one of the most important issues in particle physics and cosmology
- Several possible mechanisms: leptogenesis, electroweak baryogenesis, Affleck-Dine (decay of coherent (classical) scalar quark fields in supersymmetry)
- Heavy Z' ?
 - Very well motivated in grand unification, strings, dynamical symmetry breaking
 - Many new features, including enhanced possibility of electroweak baryogenesis, non-standard Higgs, contributions to rare B decays
 - Should be observable at LHC, linear collider, possibly Tevatron *if it exists*