Electroweak baryogenesis in the MSSM

Electroweak baryogenesis in the MSSM

- The basics of EWBG in the MSSM
- Where do light stops (charginos) come from?
- Constraints from d_e-, Ω_{CDM}, colliders ...

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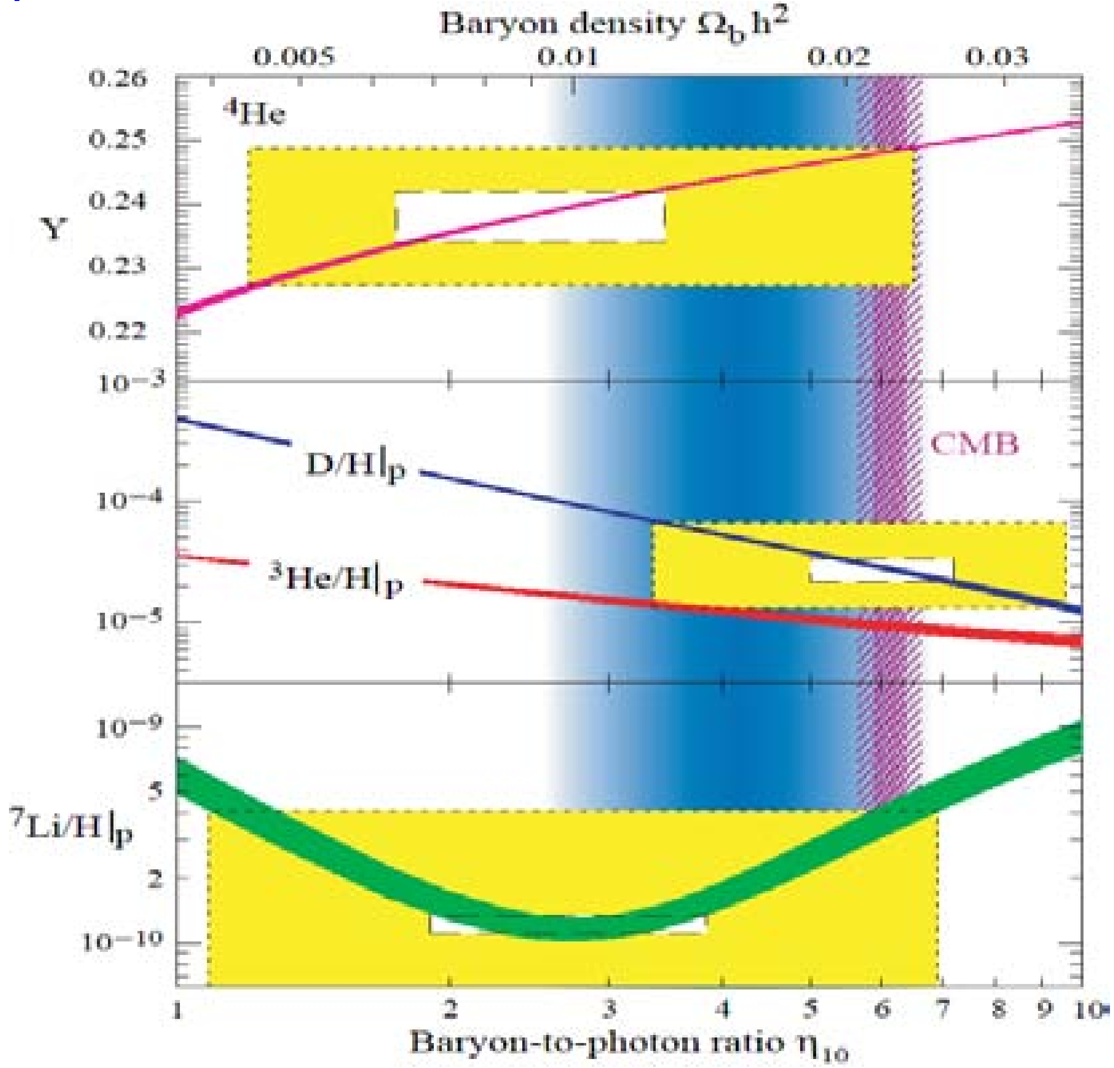
Baryon content of the Universe

– WMAP: $\eta = \frac{n_B}{n_\gamma} = (6.1 \pm 0.4) \times 10^{-10}$



PDB 2004

- $n_{\bar{B}}$ is consistent with zero (only secondary production is known)
- no experimental (or theory) indication of large amounts of anti-matter

Genesis

— Baryo- or leptogenesis

- preexisting asymmetry →← inflation → dynamic mechanism
- genesis: dynamical generation of asymmetry from symm. initial cond.s
- relies on thermodyn. phase transition (symmetric → asymmetric phase)
- has to satisfy the Sakharov conditions

0. initially: matter-antimatter symmetric phase
1. $\not{B}$ is efficient before a thermodynamic phase transition
2. $\not{C}$ & $\not{CP}$ interactions allow to generate asymmetry
3. $\not{T}$ preserves asym.: at phase transition Universe falls out equilibrium, and new vacuum B conserving

— Baryo- or leptogenesis in the SM

- only $\not{CP}$ distinguishes matter and anti-matter in the SM
- not enough $\not{CP}$ in the SM to account for baryon asymmetry

Gavela et al '94; Huet,Sather '94

Baryogenesis

— Sakharov conditions for the MSSM in the early Universe

1. $\not{B}$: (classical) B+L breaks anomalously

   transitions between inequivalent $SU(2)_L$ gauge vacua lead to $\not{B}$

2. $\not{C}$ & $\not{CP}$: new complex phases can arise when SUSY is softly broken

3. $\not{T}$: expansion of Universe → departure from equilibrium

   1st order phase transition → even larger departure

— Electroweak baryogenesis

- concrete mechanism to generate baryon asymmetry
- consistent with particle physics and cosmology (inflation)
- utilizes existing phase transition: EWSB
- connected to weak scale → testable at Tevatron, LHC and ILC
- alternatives: GUT scale baryogenesis, leptogenesis, etc.

— Off the wall

- 1st order EW phase transition proceeds by nucleating bubbles

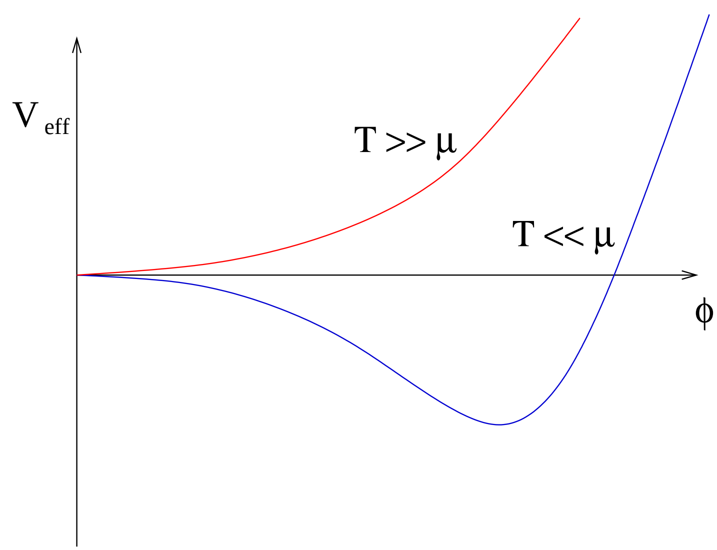
The Electroweak Phase Transition

- The order parameter for the transition is the local expectation value of the Higgs boson field, $\langle\phi\rangle$.

$$\langle\phi\rangle = 0 \Rightarrow SU(2)_L \times U(1)_Y \text{ is unbroken.}$$
$$\langle\phi\rangle \neq 0 \Rightarrow SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}.$$

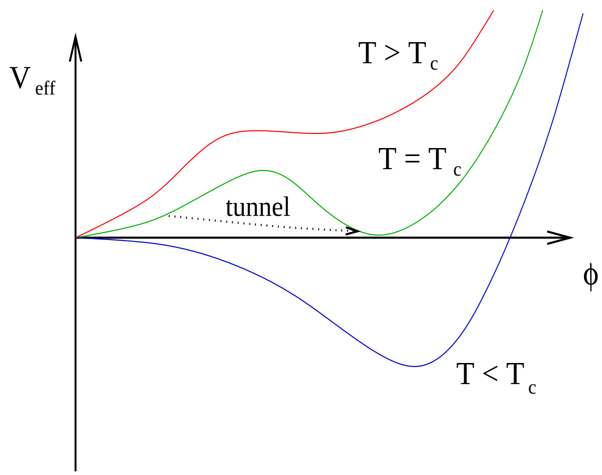
- $\langle\phi\rangle$ is the minimum of the effective potential at temperature T:

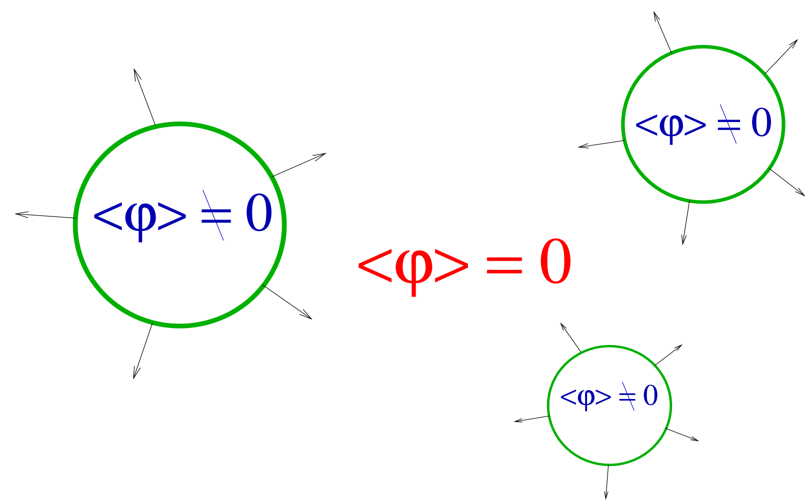
$$V_{eff} = (-\mu^2 + \alpha T^2)\phi^2 - \gamma T\phi^3 + \frac{\lambda}{4}\phi^4 + \ldots$$



Bubble Nucleation

- First order phase transition:

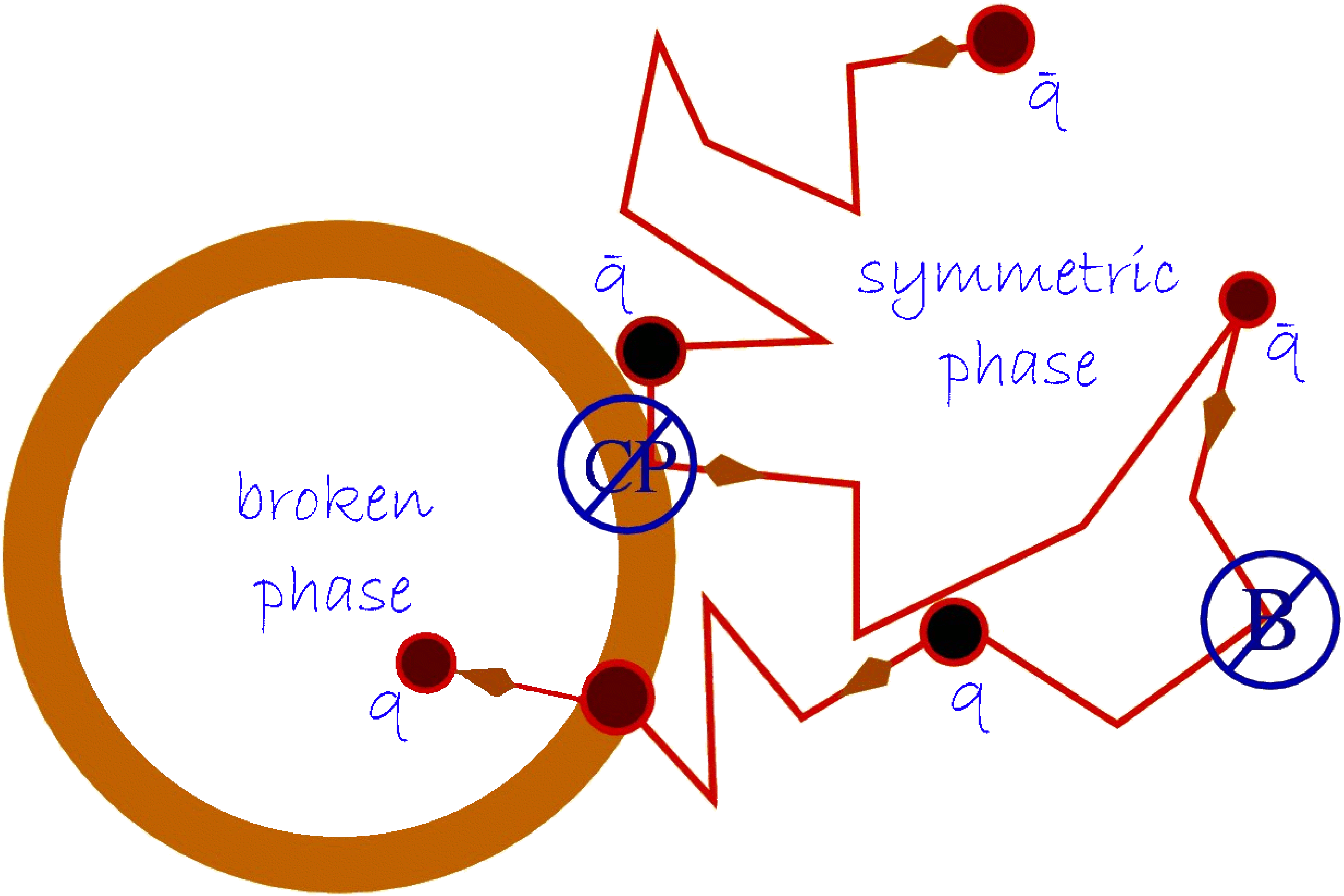




$\Rightarrow$ degenerate minima at temperature T_c.

- The Universe starts in the $\langle\phi\rangle = 0$ phase.
- For $T < T_c$, the $\langle\phi\rangle \neq 0$ phase is favoured, but is blocked the potential.
- By tunnelling, small regions pass to the $\langle\phi\rangle \neq 0$ phase.
- This nucleates bubbles of $\langle\phi\rangle \neq 0$ phase.
- Bubbles expand until they fill all of space.

Off the wall mechanism (simplified)



Strongly 1st order PT → light stop (& higgs)

– Generation of $\eta = \frac{n_B}{n_\gamma}$ requires a strongly 1st order EW phase transition

- strongly 1st order EWPT ↔ large order parameter: $\phi_c/T_c \gtrsim 1$
- type & strength of EWPT ⇐ minimum of finite T effective potential

$$V_{eff}(\phi,T) = (-\mu^2+\alpha T^2)\phi^2 - \gamma T\phi^3 + \frac{\lambda}{4}\phi^4 + \ldots$$

- V_{eff} is minimal (for $\alpha, \mu \to 0$) if

$$\phi_c/T_c \sim \gamma/\lambda$$

→ coefficient of cubic term (γ) determines order of phase transition

- γ generated by loops in (MS)SM

  bosonic loops → $\gamma \sim g^3$ (SM)

  scalar loops → $\gamma \sim y^3$ (MSSM)

  tree level cubic → $\gamma \sim A_\lambda$ (nMSSM)

- in MSSM light scalars induce strongly 1st order EW phase transition
- light, 3rd generation, right handed scalar invoked → light $t_1 \sim t_R$
- $t_2 \sim t_L > 1$ TeV needed to evade EW precision

Enough ~~CP~~ → light W_1, small μ

— ~~CP~~ in the chargino sector

- SM: CKM phase is not enough for EWBG   Gavela et al '94; Huet,Sather '94
- MSSM: additional sources of ~~CP~~ from μ term & soft SSB parameters
- charginos generate the largest ~~CP~~ contribution

— Enough ~~CP~~ if

$M_2, \mu \lesssim 500$ GeV & $Arg(M_2\,\mu) \gtrsim 0.1$ Carena,Seco,Quiros,Wagner 2002

→ light $\tilde{W}_1$

— Minimal setup: $Arg(\mu) \gtrsim 0.1$ & $Arg(M_2) = 0$

↔ ~~CP~~ only in gaugino sector

- baryon asymmetry $\eta = \frac{n_B}{n_\gamma} \sim Sin(Arg(\mu))$

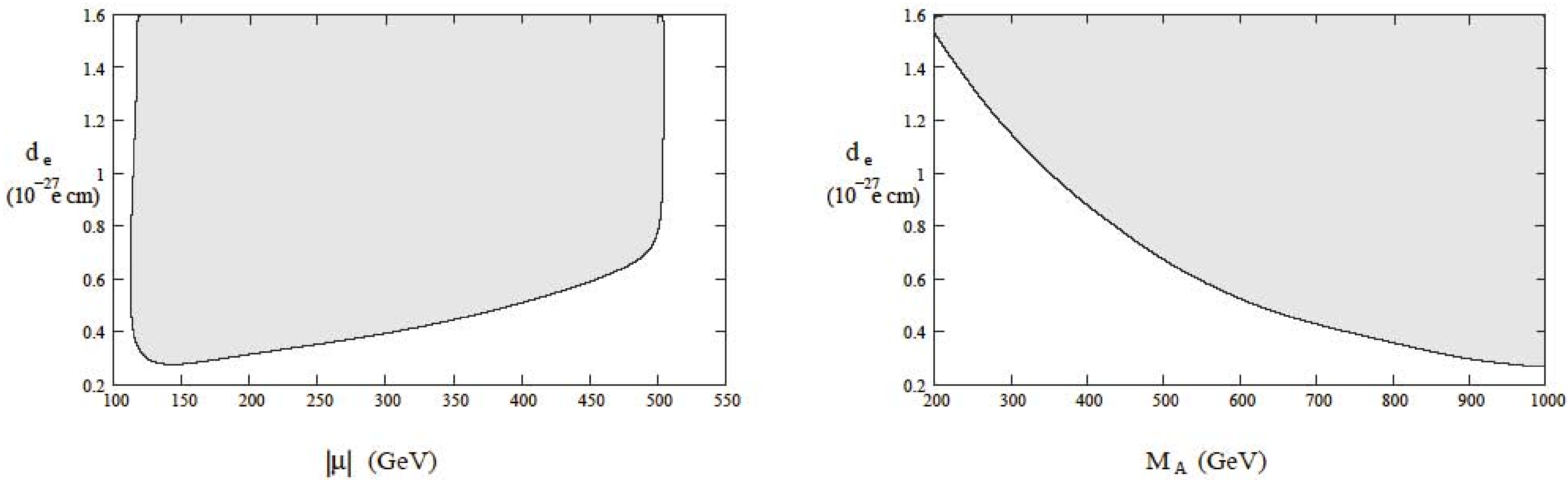
— Experimental constraints

- strongest limits from e^- EDM: $d_{e^-} \sim Sin(Arg(\mu))$
- less severe limits from $b \to s\,\gamma$

Electron electric dipole moment constraint

– e^- EDM is one of the most sensitive probes of EWBG

- EWBG requires complex phases →← complex phases generate EDM
- EWBG requires Arg(μ) $\gtrsim$ 0.1 → 2×10^{-28} e cm $\lesssim |d_e|$
- experimental limit: $|d_e| < 1.6 \times 10^{-27}$ e cm



Balázs,Carena,Menon,Morrissey,Wagner 2004

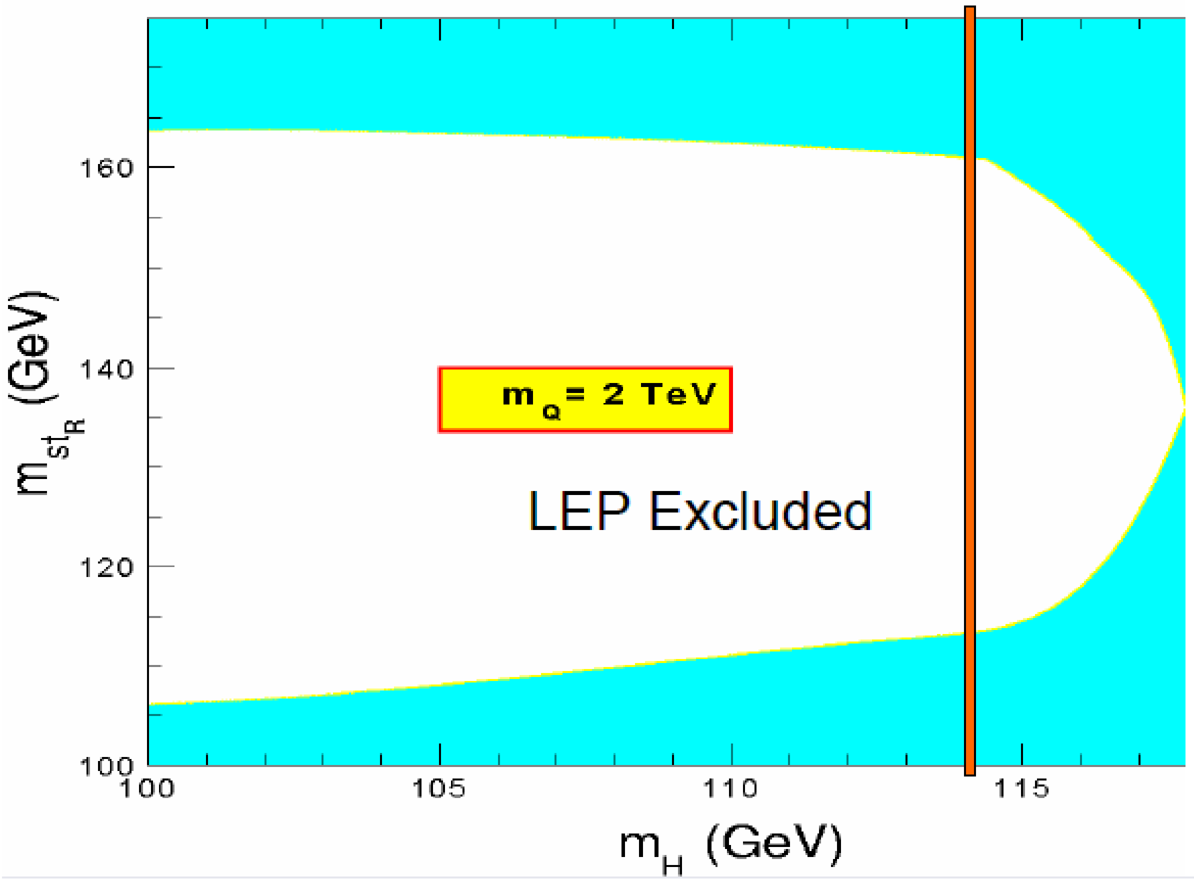
- Minimal model probed if d_e- limits improve by 10-100 (next few years)
- Escape e^- EDM: specific phase arrangements, m_A > 1 TeV, non-min. models

EWBGMSSM: MSSM constrained by EWBG

– EW phase transition strongly 1st order → constraints on stop sector
$m_{\tilde{t}_1} < m_t$, $m_{\tilde{t}_2} \gtrsim 1$ TeV,
$0.3 < |X_t| / m_{\tilde{Q}_3} < 0.5$,
constraint on h^0
$m_h \lesssim 120$ GeV

– Enough $\not{CP}$ → constraints on charginos
$M_2, \mu \lesssim 500$ GeV,
$Arg(M_2 \mu) \gtrsim 0.1$

Carena, Seco, Quiros, Wagner 2002



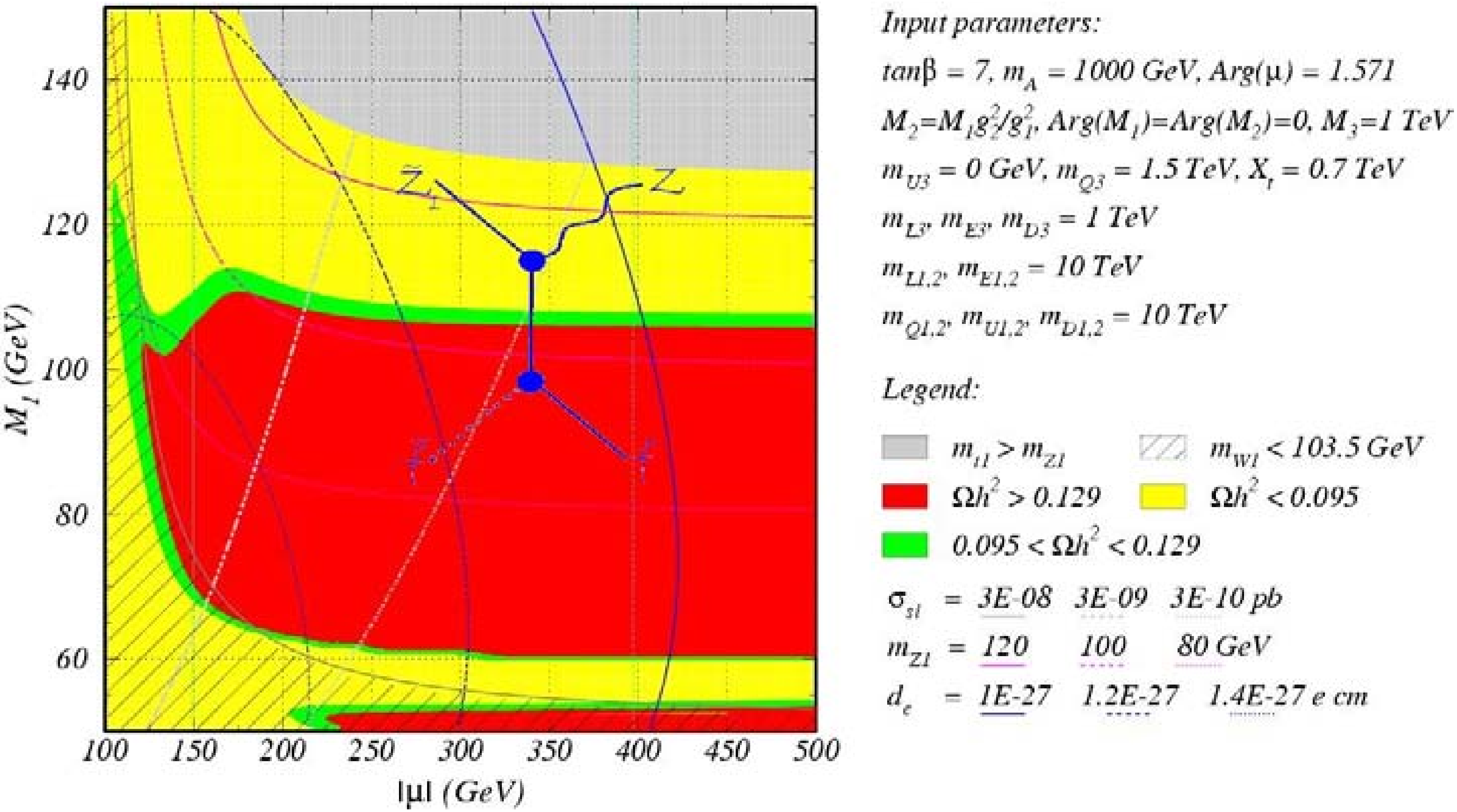
– EDM limits → heavy 1st & 2nd generation scalars

– Scenario is strongly constrained by LEP2: 114 GeV $< m_{h^0}$

- Does EWBG survive the stringent astro (collider & lowE) constraints?

The supersymmetric origin of matter

– $\tilde{t}_1$-$\tilde{Z}_1$ coannihilation lowers the neutralino relic density to agree with WMAP where $m_{\tilde{t}_1} \sim m_{\tilde{Z}_1}$



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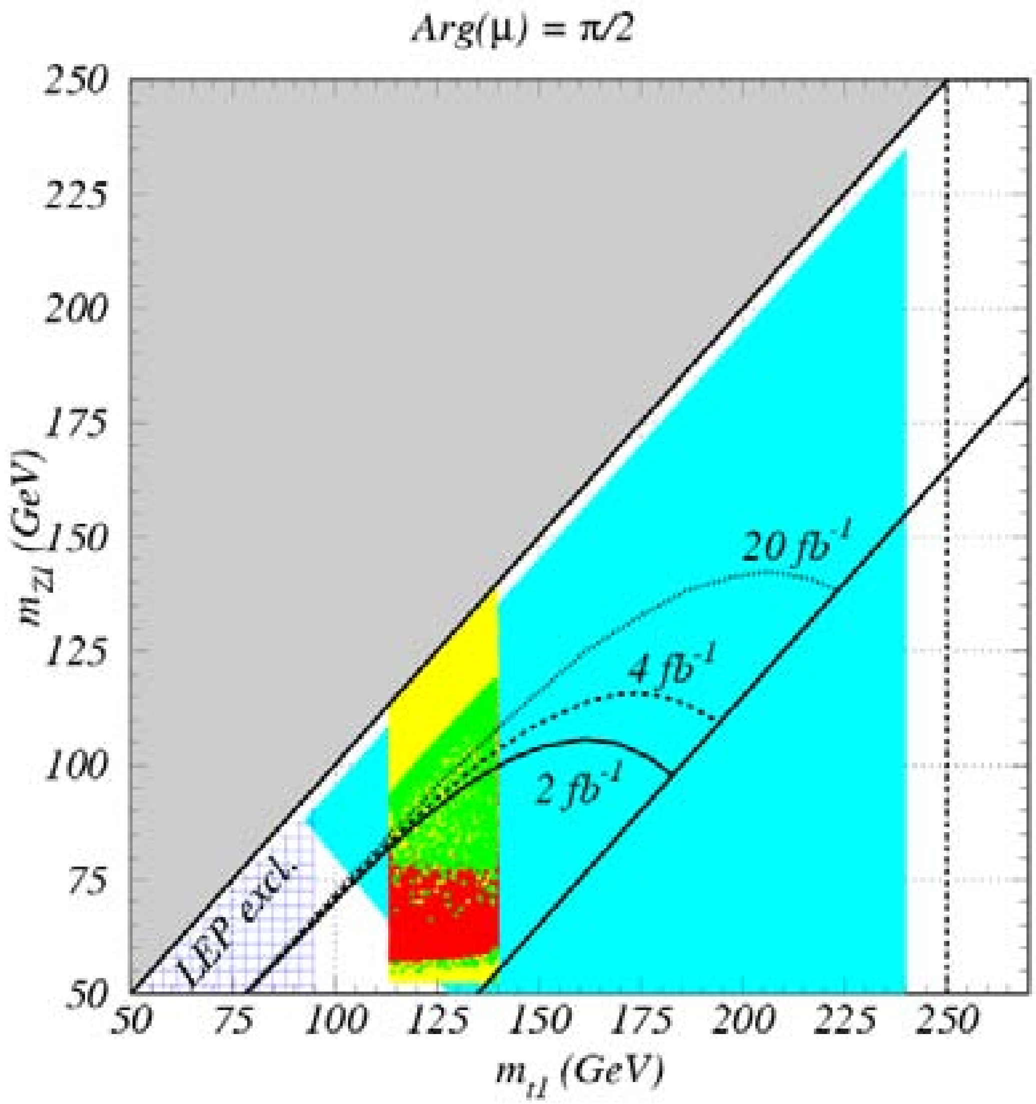
Collider implications → Caroline's & Ayres' talk

— If $\tilde{t}_1 \to c\,\tilde{Z}_1$ dominant
considerable part of para. space observable at Tevatron depending on L

— If $\tilde{t}_1 \to b\,\tilde{Z}_1\,W$ or
$m_{\tilde{t}_1} \lesssim 1.25\, m_{\tilde{Z}_1}$
(Higgs resonance or $\tilde{t}_1$ - $\tilde{Z}_1$ coannihilation)
difficult at Tevatron

— LHC : similar situation

— ILC expected to cover essentially all regions



Balázs 2005

Summary

— Universe carries baryon-asymmetry

— Baryogenesis: dynamic mechanism to explain the baryon-asymmetry

1 SM anomalies lead to $\not{B}$

2 MSSM contains enough $\not{CP}$

3 EW phase transition enhances departure from equilibrium

— Electroweak baryogenesis

- "off the wall" mechanism satisfies Sakharov conditions
- enough $\not{CP}$ $\leftrightarrow$ light charginos, small μ
- strongly 1st order phase transition $\leftrightarrow$ light stop, (lightest) Higgs

— Experimental constraints

- LEP2 Higgs constraint leaves only a small window in the MSSM
- e^- EDM is one of the strongest constraint on Arg(μ) $\leftrightarrow$ "stop split SUSY"
- neutralino relic abundance narrows the parameter space to 'strips'

— EWBG in the MSSM will be discovered/excluded by the ILC