TAPIR
Theoretical AstroPhysics Including Relativity

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Probing Supersymmetric Baryogenesis: from Electric Dipole Moments to Neutrino Telescopes

Based on: ***V.Cirigliano, SP and M.Ramsey-Musolf, JHEP07(2006)002***

SP and M.Ramsey-Musolf (Caltech/Madison) [work in progress]
S.Ando (Caltech), V.Barger (Madison), SP, M.Ramsey-Musolf,
G.Shaughnessy (Madison) [work in progress]

INT, University of Washington

Seattle, WA, Thursday, March 22, 2007

Phenomenology of SUSY EW Baryogenesis

Systematic Treatment of Baryon Asymmetry Computation in **Electroweak Baryogenesis**(*)

↓

Consider a specfic, viable **Supersymmetric** setup

↓

Study the **Phenomenology**

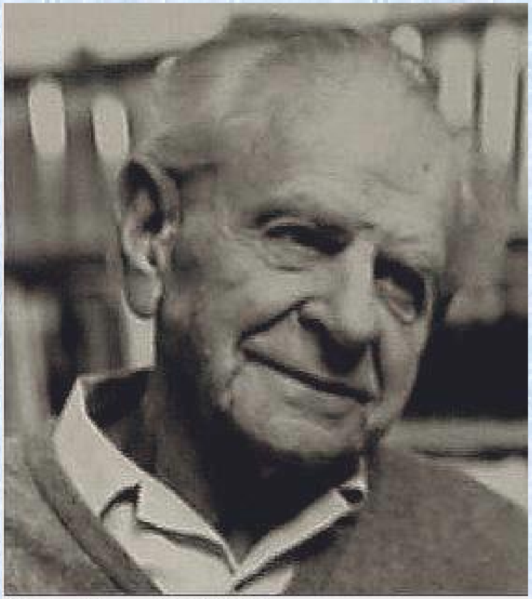
↓

- Outline the MSSM **Parameter Space** compatible with EW Baryogenesis
- Explore the resulting **EDM's** (1 and 2 loop)
- Connection with **Dark Matter** (relic abundance and detection)
- Prospects for **Collider** searches (Tevatron-II, LHC and ILC)

(*) Cirigliano, Lee, Ramsey-Musolf, Tulin; see C.Lee's and M.J.Ramsey-Musolf's talks

The Nightmare of Popper's Quote

"In so far as a scientific statement
speaks about reality,
it must be falsifiable:
And in so far as it is not falsifiable
it does not speak about reality"



Sir Karl Popper (1902-1994)

Karl Popper, "*The Logic of Scientific Discovery*"

Supersymmetric Electro-Weak Baryogenesis:

a <u>falsifiable</u> theory

Supersymmetric EW Baryogenesis

In the **Minimal Supersymmetric Extension of the Standard Model (MSSM)**

- **Additional bosonic degrees of freedom** couple to the Higgs (e.g. a light scalar top, x6)

  A strongly first order EW Phase Transition occurs for larger, LEP-viable values of m_h

- The theory features potential **additional** ***CP*****-violating sources**

  - *Gaugino/Higgsino sector*
  - *Scalar quark sector*

BONUS: **the MSSM provides ideal candidates for non-baryonic Dark Matter as well !**

(*) see C.Lee's and M.J.Ramsey-Musolf's talks

EWB in the MSSM: Requirements

In the **MSSM**, successful EW baryogenesis requires: …at **odds** with:

1. **Light enough stop** $m_{\tilde{t}_1} < m_t$ — $m_{\tilde{t}_1} > 95\text{GeV}$ *(LEP-II)*

2. **Light enough Higgs** $m_h < 120\text{GeV}$ — $m_h > 114\text{GeV}$ *(LEP-II)*

3. **Strong enough CP-violating sources** (3rd generation squarks, higgsinos) — *e, n and atomic EDM's*

Interludium: Neutralinos and Charginos

Gaugino Mass Relations
$(\mathbf{M}_1 = \alpha\, \mathbf{M}_2)$

$$\mathbf{M}_N = \begin{pmatrix} M_1 & 0 & & \ldots\beta \cos\theta_W \\ 0 & M_2 & m_Z \sin\beta \sin\theta_W & -m_Z \sin\beta \sin\theta_W \\ -m_Z \cos\beta \sin\theta_W & m_Z \cos\beta \cos\theta_W & 0 & -\mu \\ m_Z \sin\beta \sin\theta_W & -m_Z \sin\beta \sin\theta_W & -\mu & 0 \end{pmatrix}$$

$$\chi = N_{11}\mathbf{B}^0 + N_{12}\mathbf{W}^0 + N_{13}\mathbf{H_d}^0 + N_{14}\mathbf{H_u}^0$$

BINO **WINO** **HIGGSINO**

$$\mu \rightarrow |\mu| e^{i\phi_\mu}$$

T ~T$_{EW}$: *scattering of $\tilde{H},\tilde{W}$ from background field*

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

$$\frac{g\, v_d(x)}{\sqrt{2}}$$

$$\frac{g\, v_u(x)}{\sqrt{2}}$$

T << T$_{EW}$: *mixing of $\tilde{H},\tilde{W}$ to $\tilde{\chi}^+, \tilde{\chi}^0$*

EWB in the MSSM: Setup

- **Free parameters** in the game: $M_1,\ M_2,\ |\mu|,\ \phi_\mu$

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- The second stop must be **heavy**, and mostly **"left-handed"**

$$m_{\tilde{t}_1} \approx m_t,\ m_{\tilde{t}_2} = 10\,\mathrm{TeV}$$

  - Increase the **Higgs mass**
  - Reduce the SUSY contribution to **Δρ**

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- Other **sfermions** must be **heavy** to suppress CP-violating processes (*e.g.* 1-loop EDM's)

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$$m_{\tilde{f}} \approx 10\,\mathrm{TeV}$$

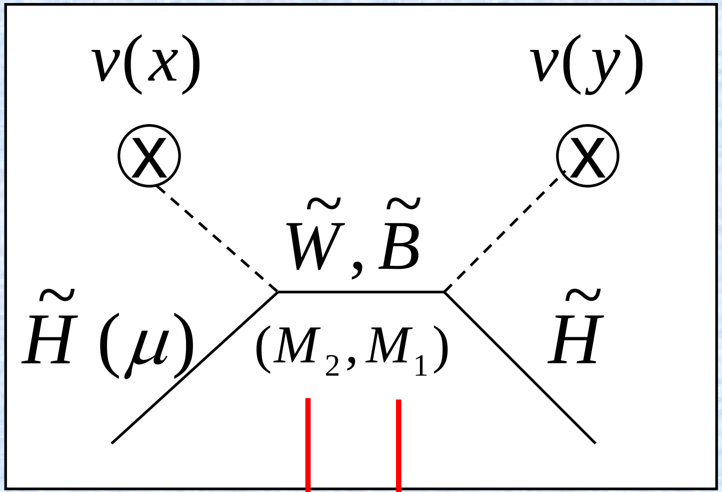
- The generated **BAU** also depends on the **heavy** MSSM **Higgs** sector through **Δβ**

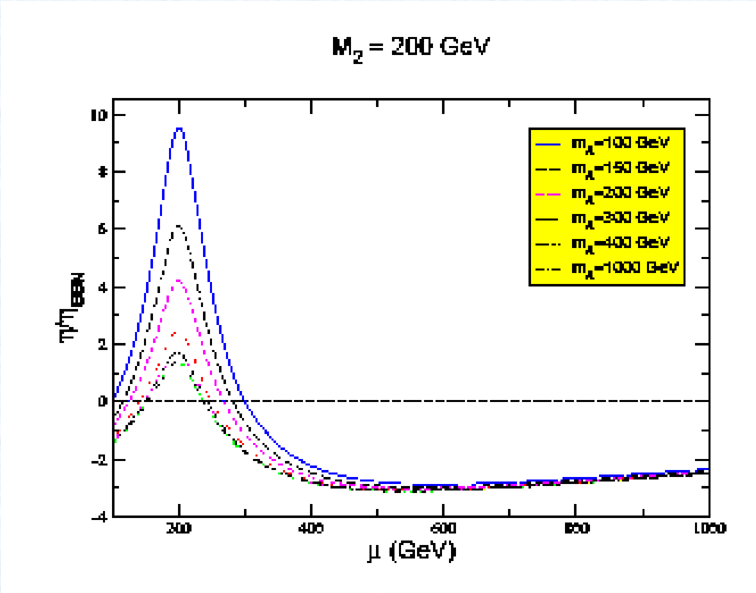
$$m_A = 150\,\mathrm{GeV},\ 1000\,\mathrm{GeV}$$

Resonant EW Baryogenesis

…even if all these conditions hold, **CP**-violating sources are large enough if close-to-**resonant conditions** are met in the **gaugino-higgsino** sector

$$M_{1,2} \approx \mu$$





Resonant Chargino Source: Well known fact(*)

Resonant Neutralino Source: **Novelty**! (**)

Connection with **Dark Matter** !!

(*) M.Carena et al., (2003); Lee et al., (2005) (**) V.Cirigliano, S.Profumo, M.Ramsey-Musolf (2006)

EW Baryogenesis and DM

In the (R-parity conserving) MSSM **the LSP is stable**

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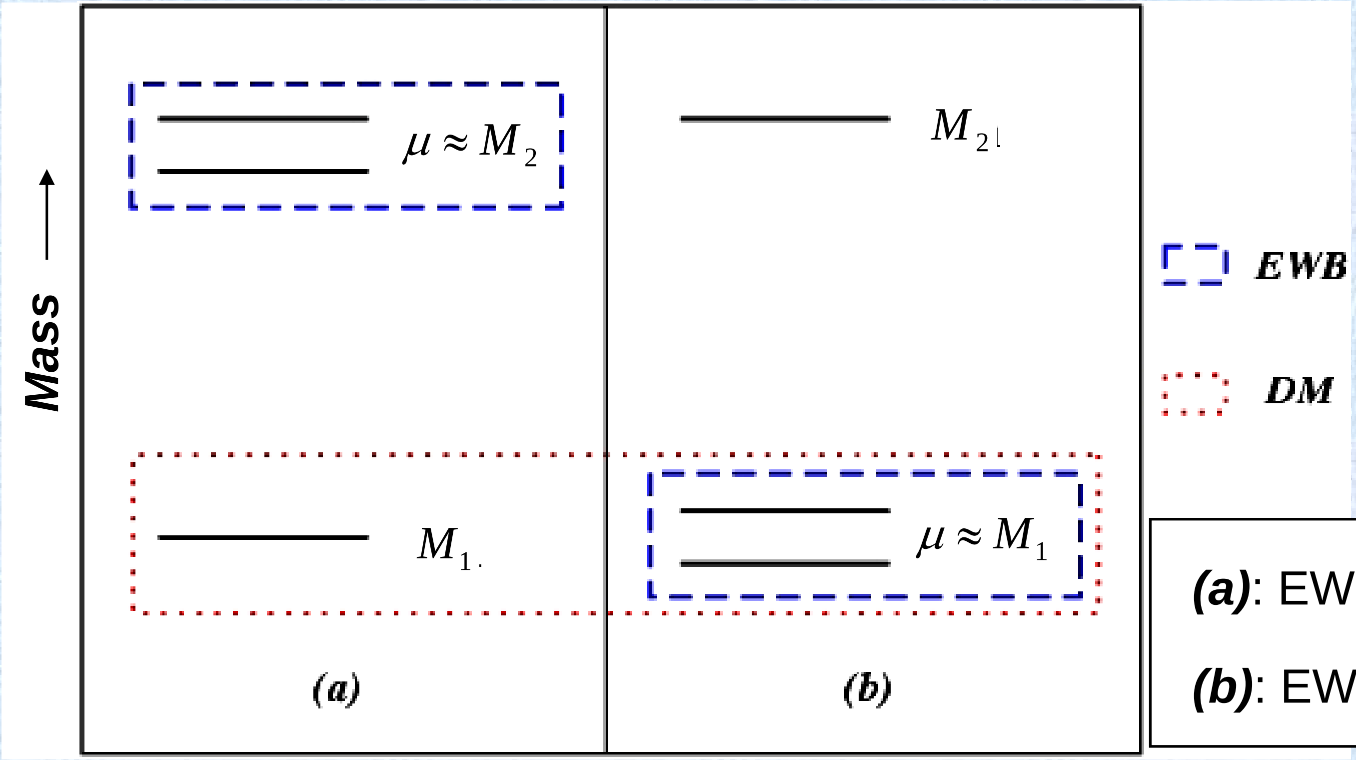
The LSP must be a phenomenologically viable relic

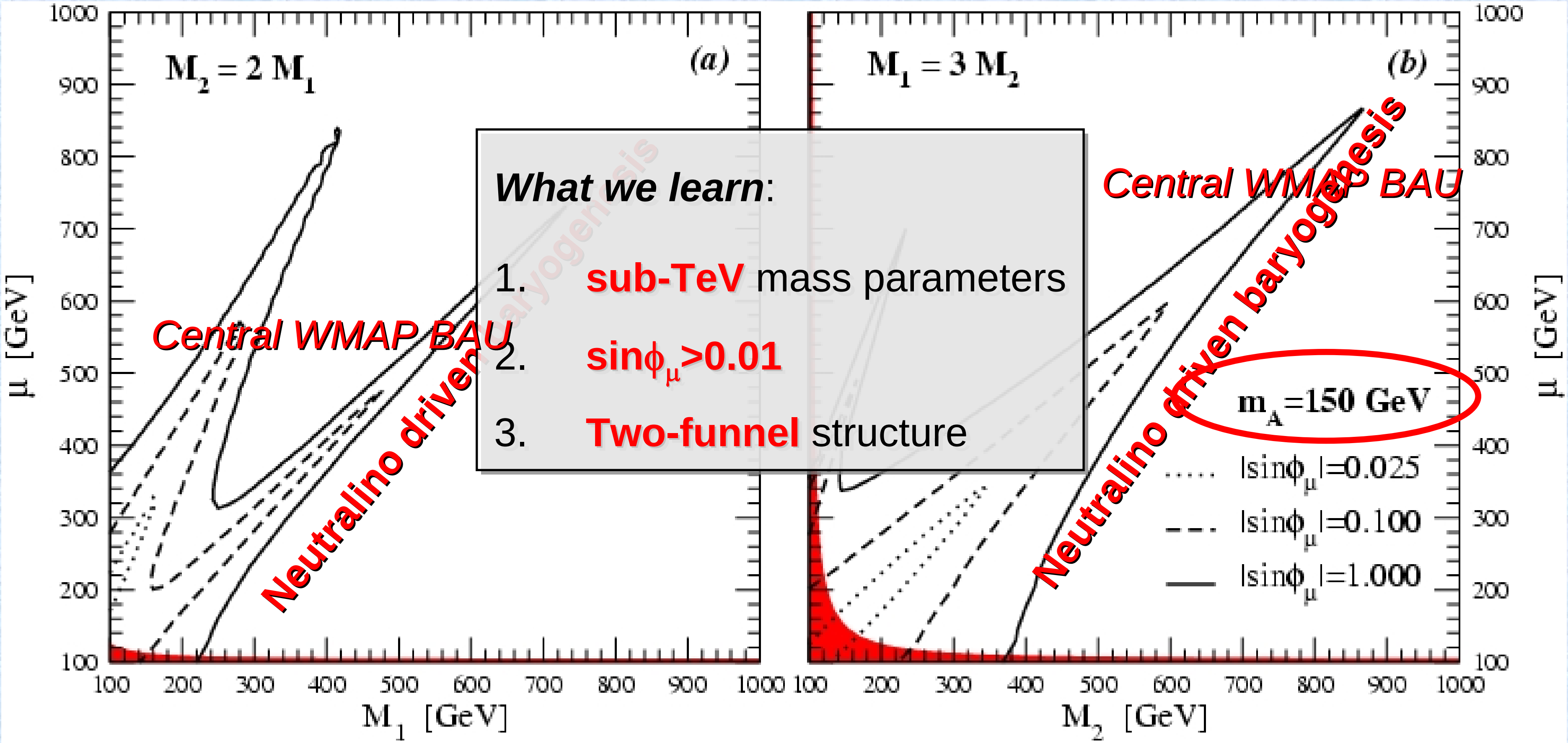
(electrically and color neutral, low enough relic abundance and direct detection rates)



(a): EWB and DM are unrelated

(b): EWB-DM connection

Baryon Asymmetry in the MSSM



What we learn:

1. **sub-TeV** mass parameters
2. **$\sin\phi_\mu > 0.01$**
3. **Two-funnel** structure

- "**Supergravity**"-like gaugino mass pattern

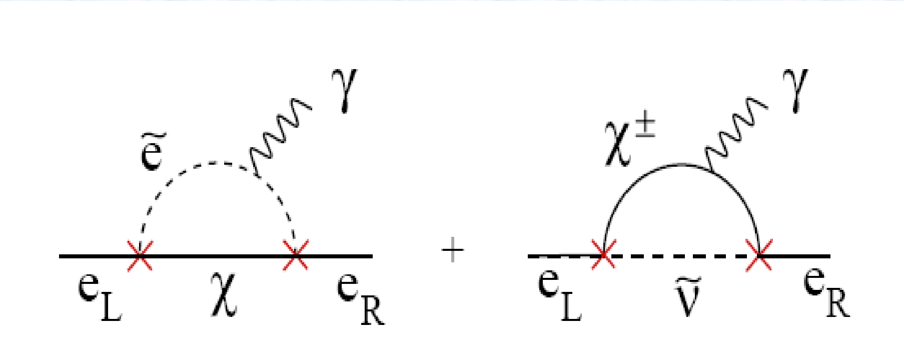
$$M_1 = \frac{5}{3}\frac{\sin^2\vartheta_W}{1-\sin^2\vartheta_W} \approx M_2/2$$

- "**Anomaly mediation**"-like gaugino mass pattern

$$M_1 = \frac{\beta_{g_1}}{\beta_{g_2}}\frac{g_2}{g_1} M_2 \approx 3M_2$$

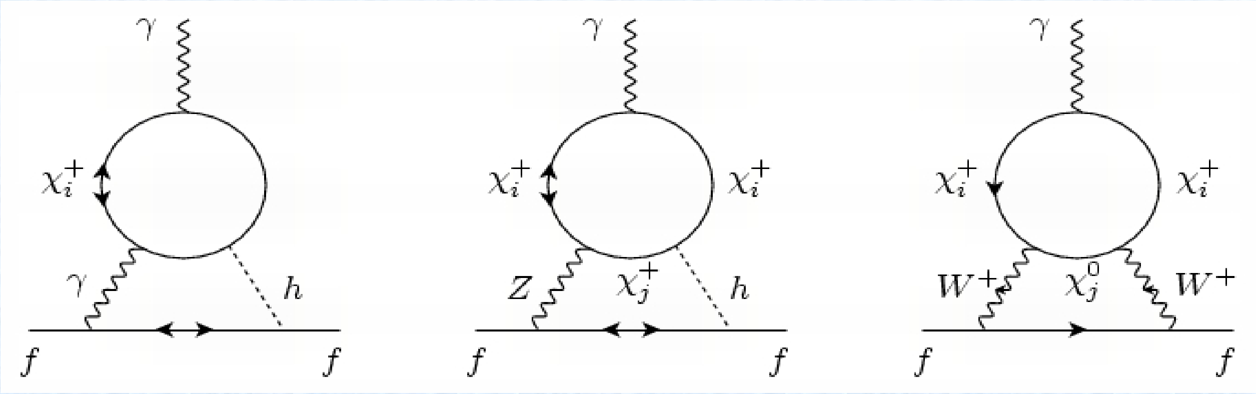
Electric Dipole Moments

CP-violating interactions in the SUSY sector induce EDMs
In the present setup, the best probe is the **electron** EDM



1-loop (electron) **EDM**

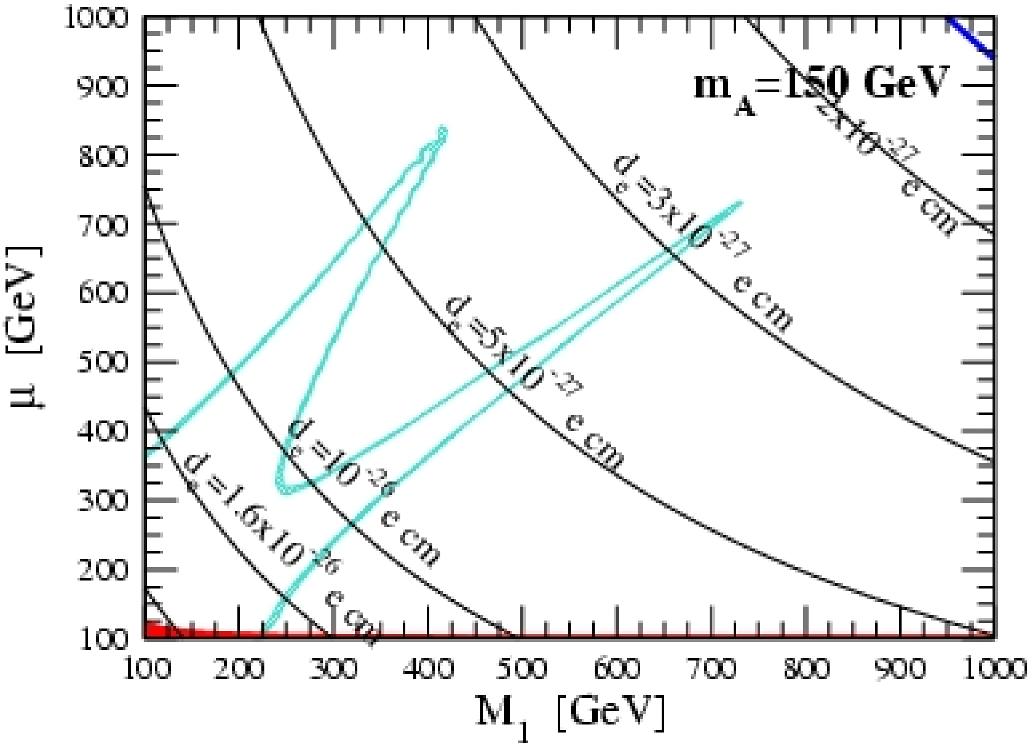
Asymptotically vanish in the limit of large sfermion masses



2-loop EDM

Only contribution In, e.g., SplitSUSY

EDMs and EW Baryogenesis

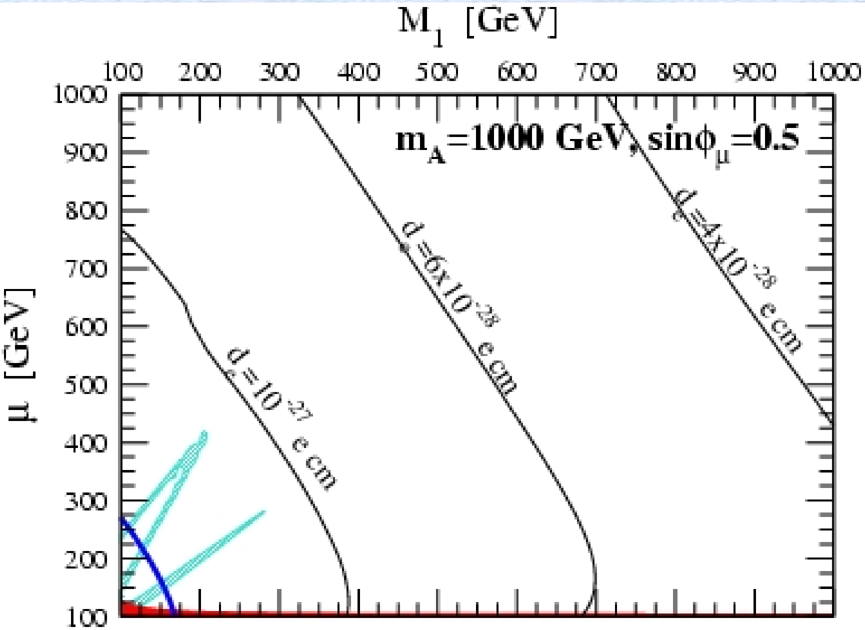


$$\sin\phi_\mu \approx 1$$

- Only **two-loop** EDMs (*heavy sfermions limit*)
- Anomaly mediated case even **worse**!
- **Maximal phases are not compatible with EW Baryogen.**

$$d_e^{\text{exp, cur}} \approx 1.6\times 10^{-27}\,\text{e}\cdot\text{cm}$$

EDMs and EW Baryogenesis



$$\sin\phi_\mu < 1$$

What we learn:

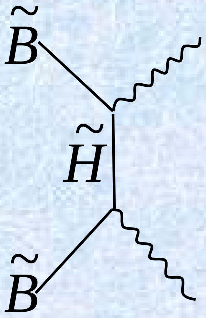
1. EDM and EWB are **compatible**
2. **maximal phases** are **excluded** by current data
3. there is a **lower bound** on the el. EDM

$$d_e \geq 10^{-28}\,\mathrm{e\cdot cm} >> d_e^{\mathrm{exp,\,fut}} \approx 10^{-29\div 30}\,\mathrm{e\cdot cm}$$

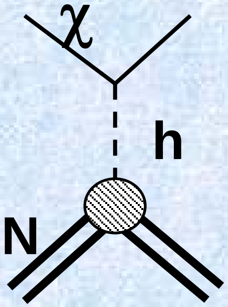
EDM experiments will conclusively test the EW Baryogenesis scenario!

EWB and DM: a closer look

$M_{1,2} \approx \mu$



- The **higgsino mixing** is required to have a low enough **relic abundance** in the $M_1 \approx \mu$ case and fulfill EWB + right thermal χ production

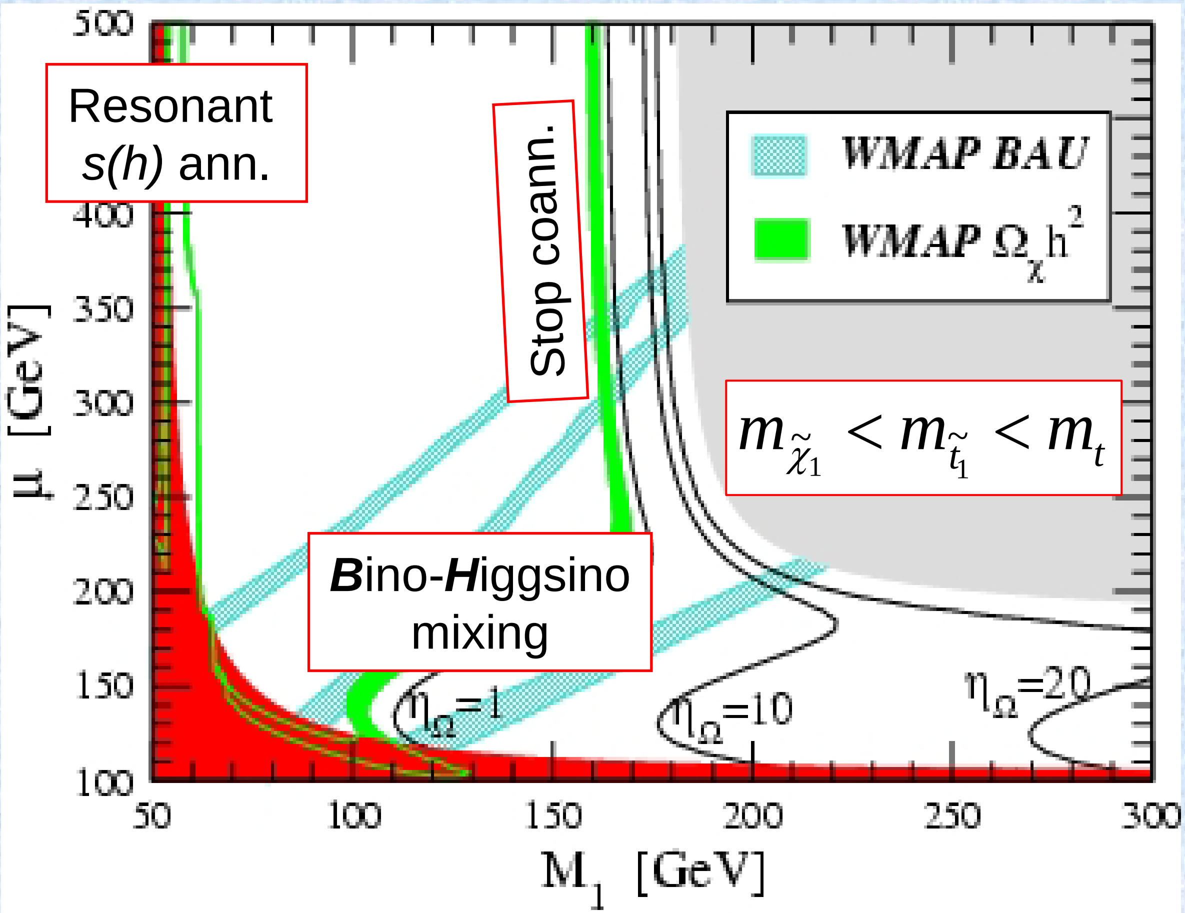


- Large higgsino mixing implies large couplings to the Higgses, and hence **large direct detection rates** even with heavy s-quarks

- Since $m_{\tilde{\chi}_1} < m_{\tilde{t}_1} < m_t$ the DM particle is **light**

this means that
- the local DM **number density** is large $\left(\rho_{\rm DM} = m_{\rm DM} \cdot n_{\rm DM}\right)$
- the number of **pair annihilations** is large $\left(\propto n_{\rm DM}^2\right)$

The Neutralino Relic Abundance & EWB



m$_A$=1 TeV, sin(ϕ_μ)=0.5

- **Excessive** relic abundance regions are **ruled out** (caveat: low-*T* reheating)
- **Low** relic abundance regions are viable assuming either **non-thermal** production or cosmological enhancement

$$\eta_\Omega \equiv \left(\Omega_{CDM}^{WMAP} - \Omega_\chi^{th}\right) / \Omega_\chi^{th}$$

- In the anomaly mediated SUSY bckg. case

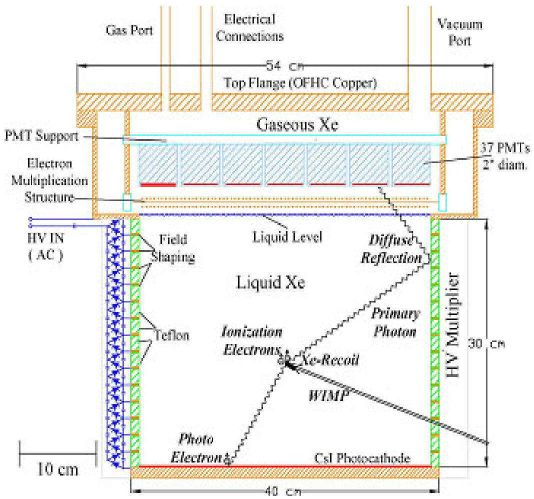
$$30 \le \eta_\Omega \le 300$$

Neutralinos can be responsible for both Baryogenesis and Dark Matter

Direct & Indirect Dark Matter Searches

DIRECT DETECTION

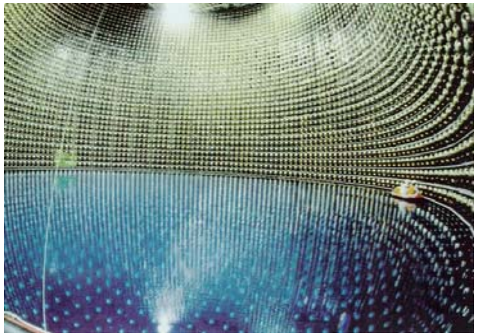
Observation of scattering events of WIMPs off nuclei in low background environments

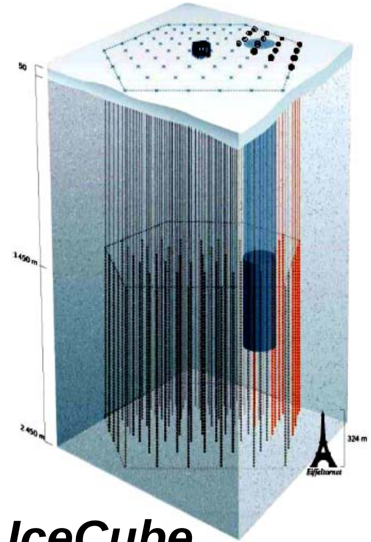


XENON 1-t

HIGH ENERGY NEUTRINOS FROM THE SUN / EARTH

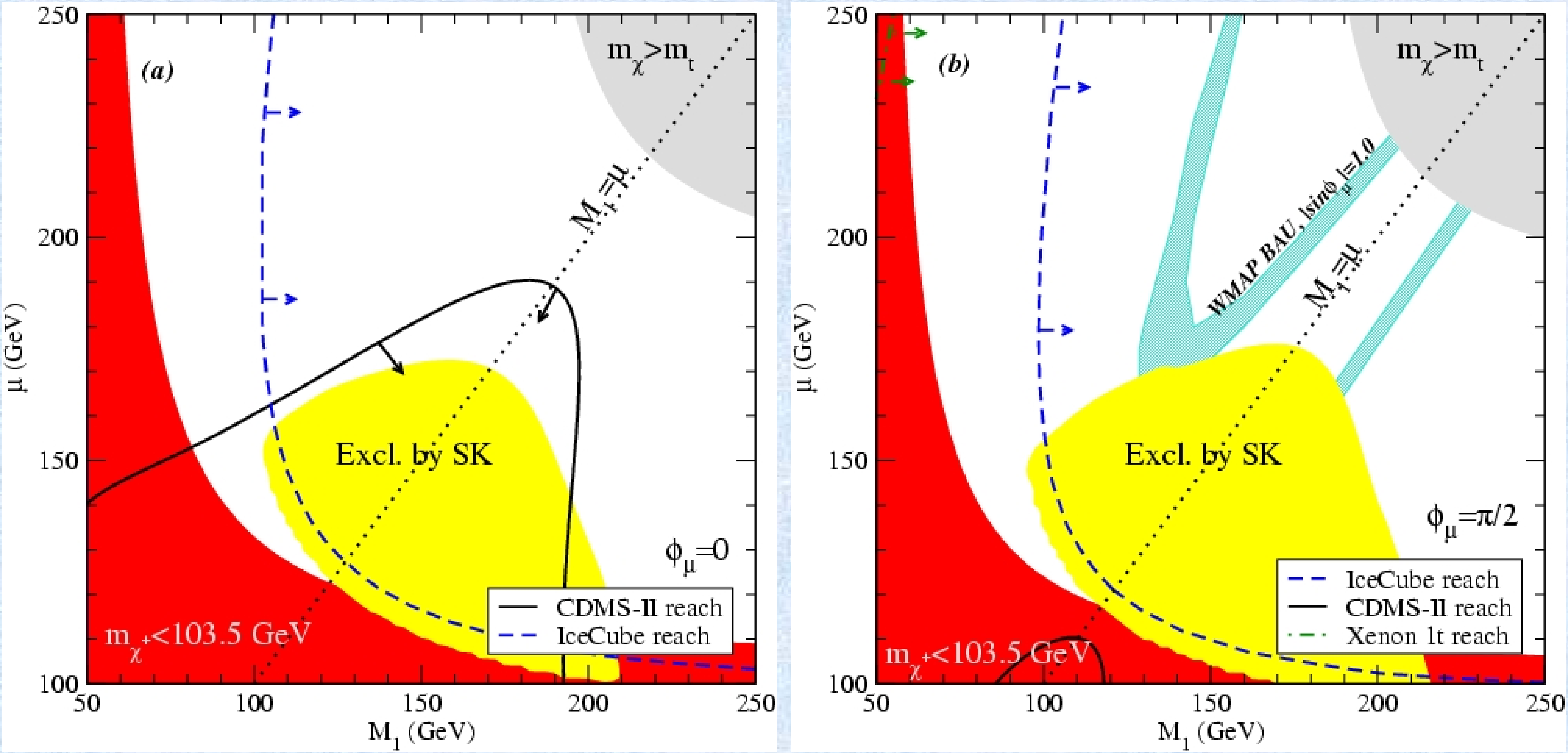
Search for energetic neutrinos produced in $\chi\chi$ pair annihilations in the core of nearby gravitational dips, as the center of the Sun or of the Earth





Super-K ***IceCube***

Dark Matter searches and EWB



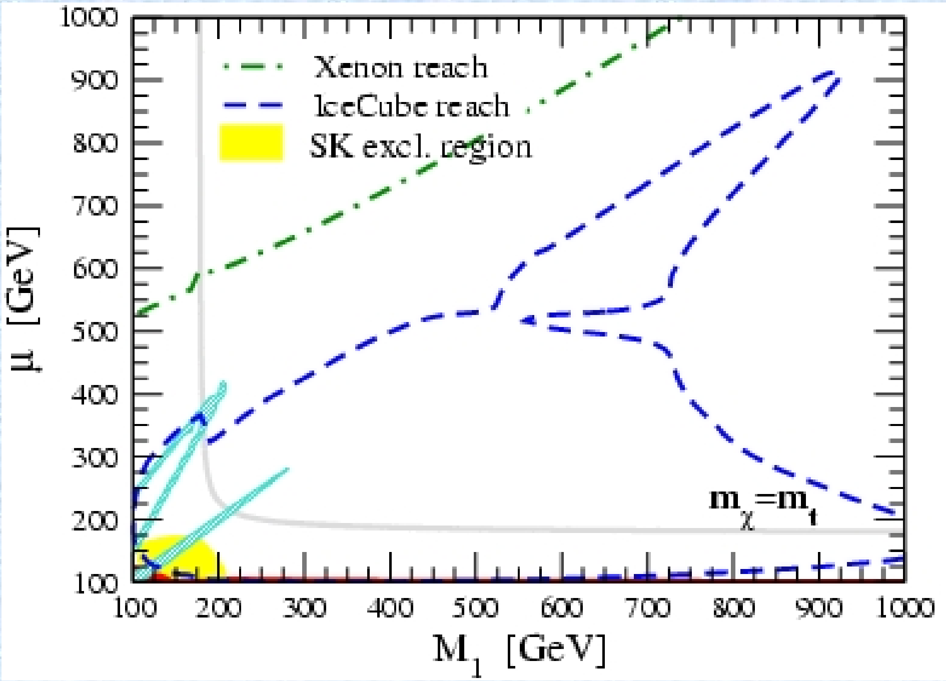
- All ... h reach of ne... ors and of km² size neutrino telescopes (e..g IceCube)

CP conserving case (no EWB)

CP violating case (EWB)

- A sizable portion of the parameter space which we expect to be compatible with EWB is **already ruled out by SuperK** data on the neutrino flux from the Sun
- CP phases **suppress direct detection** and **enhance the neutrino flux f/Sun**

Dark Matter searches and EWB: Zooming Out

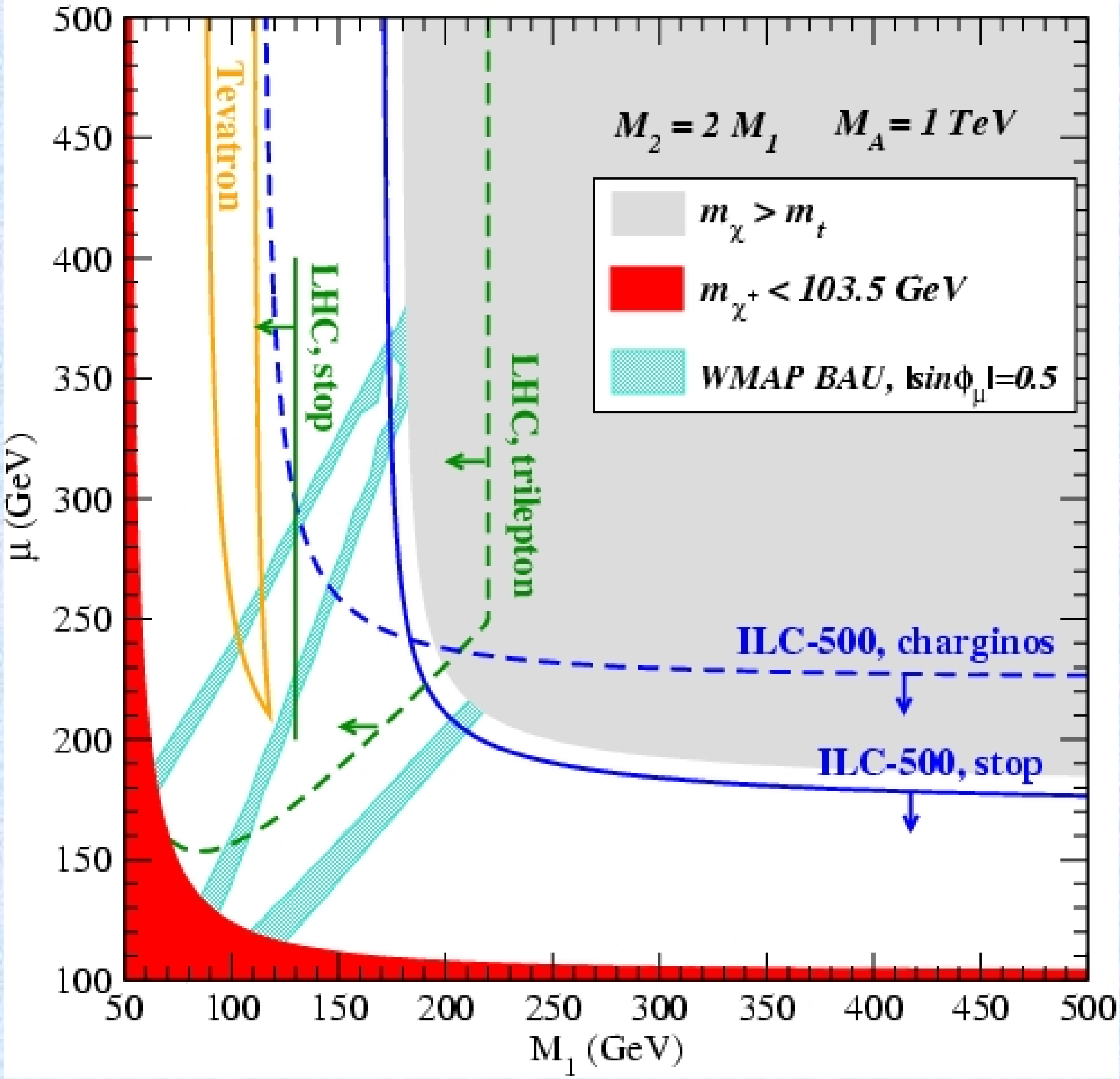


Supergravity mediated SUSY breaking

Anomaly mediated SUSY breaking

Both ton-sized direct detectors AND neutrino telescopes will conclusively probe EW Baryogenesis!

Collider Searches



Tevatron (*)

$$m_{\tilde{t}_1} < m_{\tilde{\chi}_1^+} \qquad \tilde{t}_1 \to c\tilde{\chi}_1^0$$

LHC – same sign top (**)

$$\tilde{g}\tilde{g} \to \tilde{t}_1^* t\ \tilde{t}_1^* t$$

$\tilde{t}_1^* \to c\chi$, $t \to bW$

LHC – trilepton(***)

$$\tilde{\chi}_1^\pm\ \tilde{\chi}_2^0$$

$$\tilde{\chi}_1^\pm \to l\bar{\nu}\chi \text{ and } \tilde{\chi}_2^0 \to l\bar{l}\chi$$

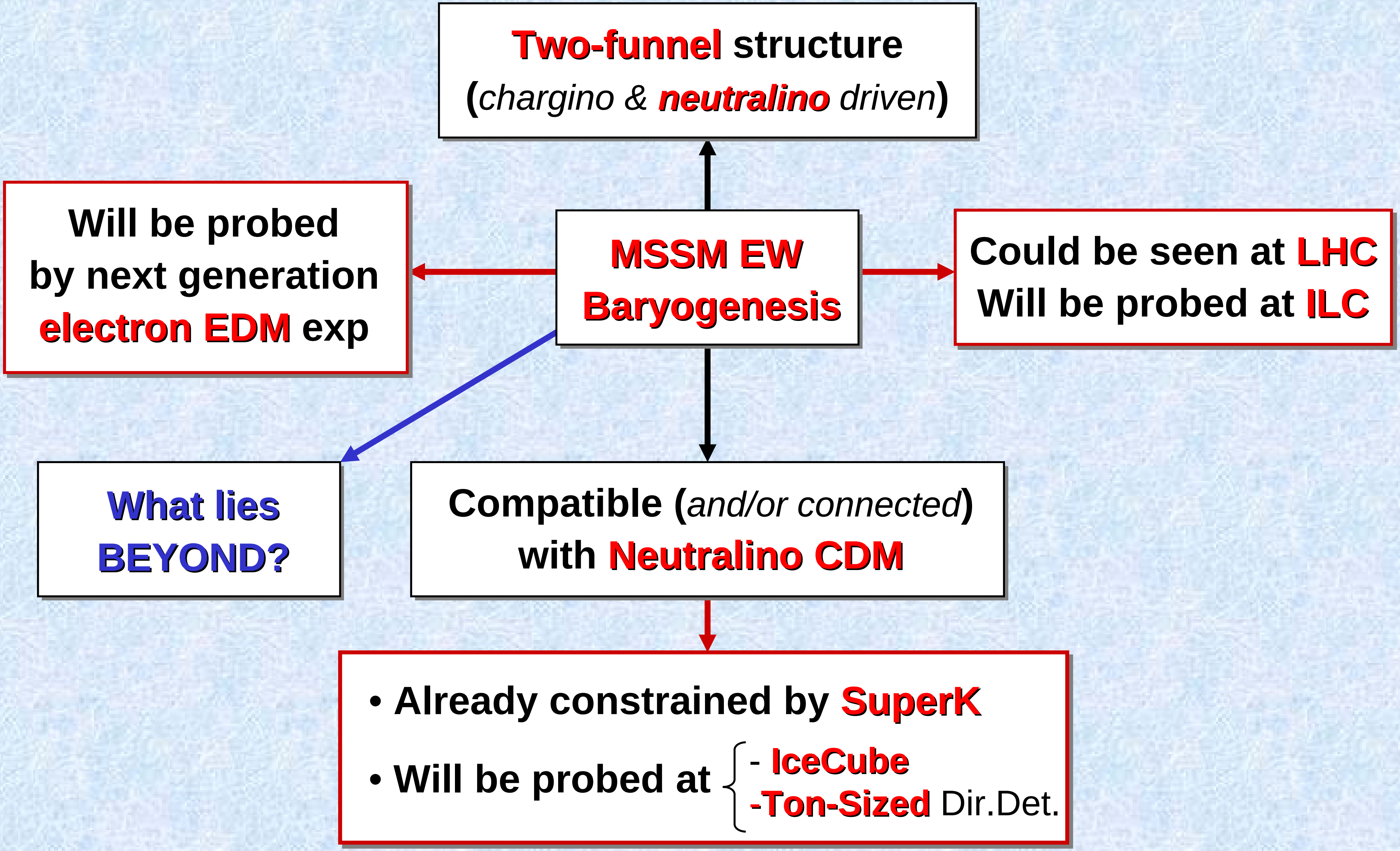
ILC (****)

$$e^+e^- \to \tilde{\chi}_1^+\ \tilde{\chi}_1^-$$

$$e^+e^- \to \tilde{t}_1^*\ \tilde{t}_1$$

(*)Demina et al, PRD (2000); (**) Kraml&Raklev, 2005; (***) Profumo et al, 2006; (****) Carena et al, 2005

EW Baryogenesis in the MSSM: Summary



Beyond the Minimal SUSY SM

Adding a **Gauge Singlet** Superfield **S** to the Superpotential strongly affects SUSY EWB, adding tree-level cubic terms (*)

$$W = \mu H_d H_u + h_s H_d H_u S + \frac{1}{3} k S^3 + \alpha S + \left(g_u Q u^c H_u + g_d Q d^c H_d g_u + g_e L e^c H_d \right)$$

(*as general as possible, including the* μ*-term,* ***linear*** *and* ***cubic*** *terms in S*) (**)

The corresponding tree level scalar field potential reads:

$$\begin{aligned} V_F &= \left| h_s \, H_d \cdot H_u + \alpha + \kappa S^2 \right|^2 + \left(|H_d|^2 + |H_u|^2 \right) |\mu^* + h_s \, S|^2 \\ V_D &= \frac{g_1^2 + g_2^2}{8} \left(|H_d|^2 - |H_u|^2 \right)^2 + \frac{g_2^2}{2} \left(H_d^\dagger H_u \right) \left(H_d H_u^\dagger \right) \\ V_{\rm soft} &= m_d^2 \, |H_d|^2 + m_u^2 \, |H_u|^2 + m_s^2 \, |S|^2 + \\ & -m_4 \left(H_d \cdot H_u \, S + \text{ h.c.} \right) + \left(b \, H_d \cdot H_u + \text{ h.c.} \right) + \\ & + m_1^3 \left(S + \text{ h.c.} \right) + m_2^2 \left(S^2 + \text{ h.c.} \right) + m_3 \left(S^3 + \text{ h.c.} \right) \end{aligned}$$

(*) M.Pietroni, Nucl.Phys. **B402** (1993) 27; (**) Davies et al., Phys.Lett. **B372** (1996) 88

Beyond the Minimal SUSY SM

1. The **EWPT** is more “naturally” strongly **first order** (*e.g. if the singlet Higgs is light*)
2. The bound on the **Higgs mass** is alleviated (*both for EWB and theoretically*)
3. No need for **light stops**
4. Extra possible non-trivial **CP**-structure

Scopes of the projects:

- ✓ Study the dynamics of the **EWPT** (*bubble walls, diffusion, wash-out…*)
- ✓ Assess the new contribution to **EW precision** observables
- ✓ Study the **CP-structure**
- ✓ Evaluate the new contributions to **Electric Dipole Moments**
- ✓ **DM** physics (*light singlino…*)(*)

(*) F.Ferrer, L.Krauss and S.Profumo, PRD **74** (2006) 115007

The EW Phase Transition in Singlet Models

A **Toy Model** Warm-up: Minimal **Singlet Extension** of the SM Higgs Sector(*)

$$V(H,S) = \frac{m^2}{2} H^+ H + \frac{\lambda}{4}\left(H^+ H\right)^2 + a_1 S\left(H^+ H\right)/2 + a_2 S^2\left(H^+ H\right)/2 + b_2 S^2/2 + b_3 S^3/3 + b_4 S^4/4$$

(*) D O'Connell, M.Ramsey-Musolf, M.Wise, hep-ph/0611014; S.Profumo and M.Ramsey-Musolf

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- **Singlet v.e.v.** before the EW Phase Transition

$$R = \frac{b_2 b_4}{b_3^2}(T_c)$$

$$\langle \text{Singlet} \rangle_{T>T_c} \neq 0 \iff R < 2/9$$

$$\langle \text{Singlet} \rangle_{T>T_c} = 0 \iff R \geq 2/9$$

- Obtain Strongly **First Order** EWPT **without tree-level cubic terms** ($a_1 = b_3 = 0$)

- Connect the "**order parameter**" ϕ_c / T_c to low-energy, collider **observables**

(*) D O'Connell, M.Ramsey-Musolf, M.Wise, hep-ph/0611014; S.Profumo and M.Ramsey-Musolf

Cosmological probes: Gravitational Waves

- When two or more bubbles **collide**, spherical symmetry is broken; A fraction of their kinetic energy is released in **Gravitational Waves**
- **Turbolent motions** provide another source of GW's
- The **dynamics** of the **EWPT** enter through

$$\alpha = \Delta V / T_*^4$$

"Latent Heat" (False vacuum energy) over Transition T

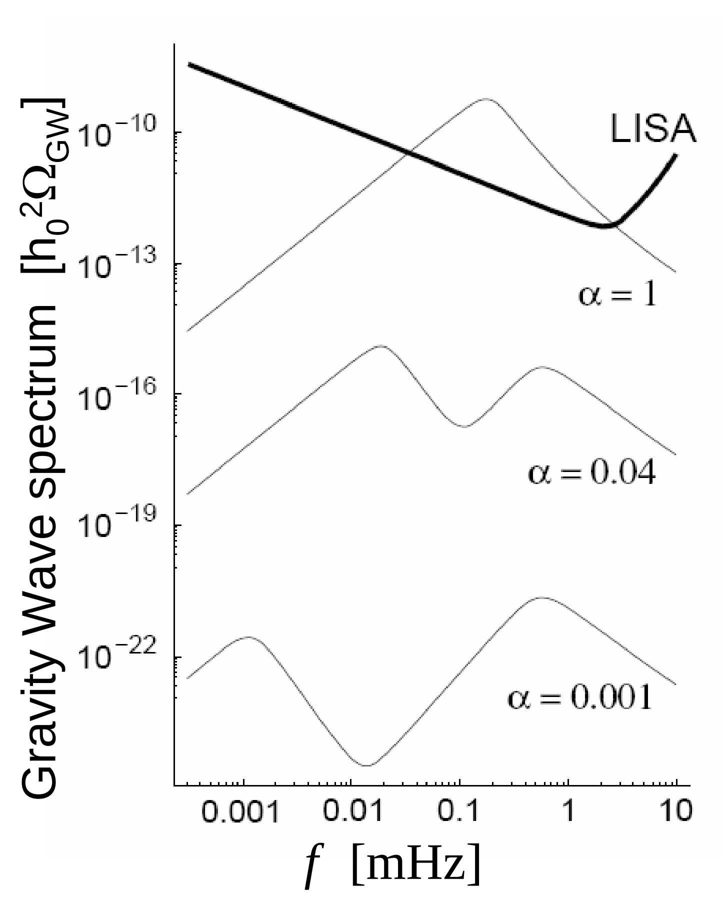
$$\beta = \dot{\Gamma} / \Gamma \Big|_{T=T_*}$$

Bubble Nucleation Time Scale

$$\beta >> H_*$$

$$f_{coll} = 5.2 \times 10^{-3}\ \text{mHz} \left[\frac{\beta}{H_*}\right] \left[\frac{T_*}{100\,\text{GeV}}\right] \left[\frac{g_*}{100}\right]$$

$$h_0^2 \Omega_{GW}(f_{coll}) \propto \left[\frac{H_*}{\beta}\right]^2 \left[\frac{\alpha}{1+\alpha}\right]^2 \left[\frac{g_*}{100}\right]^{-1/3}$$



(*) Kamionkowski, Kosowski, Turner (1994); Nicolis (2003)

Cosmological probes: Heavy Relic Abundances

"**Super-Cooling**" dilutes the abundance of **Heavy Relics**

- If $T_{\text{f.o.}} \approx m_\chi / 20 \geq T_c$ the **EWPT** affects the χ **relic density**

Cosmological probes: Heavy Relic Abundances

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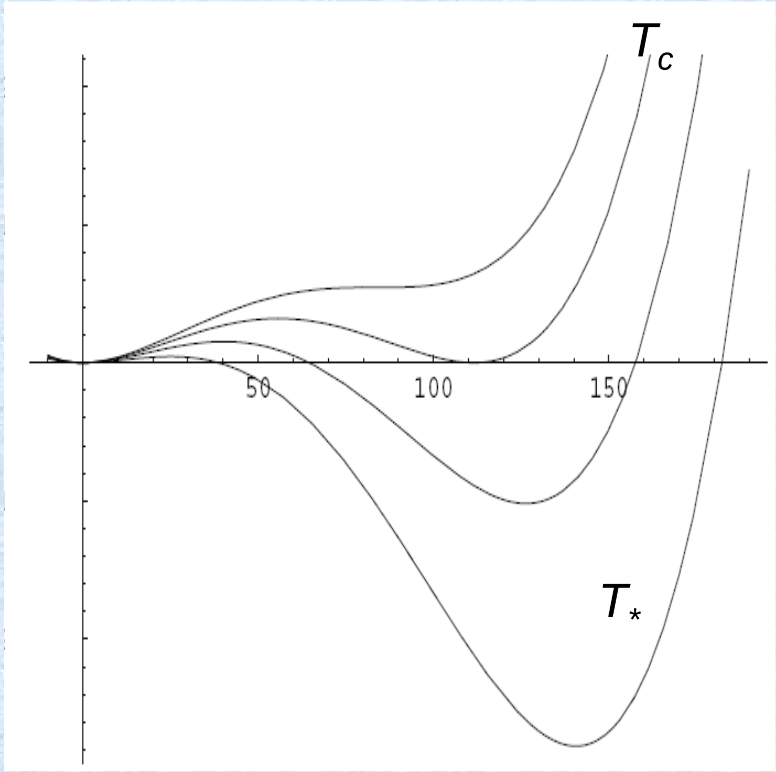

With a **strongly** first order EWPT, the Universe is trapped in **false vacuum** ϕ_c=0 until quantum tunneling becomes efficient (T_*)

The **vacuum energy** is then released, **re-heating** the Universe to T_c

$$\frac{s_f}{s_i} \approx \left(\frac{T_c}{T_*}\right)^3 \qquad \frac{(n_\chi)_f}{(n_\chi)_i} \approx \left(\frac{T_*}{T_c}\right)^3$$

Superheavy Relic Density Dilution