Astroparticle Physics and the ILC

Manuel Drees

Bonn University

Contents

1) Introduction: A brief history of the universe

Contents

Contents

Contents

Contents

1 Introduction: History of the Universe

- Before the Big Bang: Speculations about pre–BB universe, e.g. in superstring theory. Few predictions, no known connections with collider physics.

1 Introduction: History of the Universe

- Before the Big Bang: Speculations about pre–BB universe, e.g. in superstring theory. Few predictions, no known connections with collider physics.

- Inflation: Scale factor ("radius") $R \longrightarrow e^N R, \; N \geq 60$

1 Introduction: History of the Universe

- Before the Big Bang: Speculations about pre–BB universe, e.g. in superstring theory. Few predictions, no known connections with collider physics.
- Inflation: Scale factor ("radius") $R \longrightarrow \mathrm{e}^N R, \; N \geq 60$
  - Universe was dominated by vacuum energy; empty at end of inflation

1 Introduction: History of the Universe

- Before the Big Bang: Speculations about pre–BB universe, e.g. in superstring theory. Few predictions, no known connections with collider physics.
- Inflation: Scale factor (“radius”) $R \longrightarrow e^N R, \; N \geq 60$
  - Universe was dominated by vacuum energy; empty at end of inflation
  - Quantum fluctuations can cause density perturbations: confirmed by CMB observations (WMAP, . . .)

1 Introduction: History of the Universe

- Before the Big Bang: Speculations about pre–BB universe, e.g. in superstring theory. Few predictions, no known connections with collider physics.
- Inflation: Scale factor ("radius") $R \longrightarrow e^N R, \; N \geq 60$
  - Universe was dominated by vacuum energy; empty at end of inflation
  - Quantum fluctuations can cause density perturbations: confirmed by CMB observations (WMAP, . . .)
  - Scalar fields can get large vevs due to these fluctuations

1 Introduction: History of the Universe

- Before the Big Bang: Speculations about pre–BB universe, e.g. in superstring theory. Few predictions, no known connections with collider physics.
- Inflation: Scale factor ("radius") $R \longrightarrow e^N R, \; N \geq 60$
  - Universe was dominated by vacuum energy; empty at end of inflation
  - Quantum fluctuations can cause density perturbations: confirmed by CMB observations (WMAP, . . .)
  - Scalar fields can get large vevs due to these fluctuations
  - No known connections to collider physics

History (cont.d)

- Reheating: (Re-)populates Universe with particles.
  Re-heat temperature $T_{\rm R}$ not known: $T_{\rm R} \geq 1$ MeV (BBN)

History (cont.d)

- Reheating: (Re-)populates Universe with particles.
  Re-heat temperature T_{R} not known: $T_{\mathrm{R}} \geq 1$ MeV (BBN)
  - Thought to begin with coherent oscillation of inflaton field

History (cont.d)

- Reheating: (Re-)populates Universe with particles.
  Re-heat temperature $T_{\rm R}$ not known: $T_{\rm R} \geq 1$ MeV (BBN)
  - Thought to begin with coherent oscillation of inflaton field
  - No direct connections to collider physics

History (cont.d)

- Reheating: (Re-)populates Universe with particles.
  Re-heat temperature $T_{\rm R}$ not known: $T_{\rm R} \geq 1$ MeV (BBN)
  - Thought to begin with coherent oscillation of inflaton field
  - No direct connections to collider physics
  - Dynamics of thermalization has some connection to dynamics of heavy ion collisions ($\longrightarrow$ RHIC, LHC)

History (cont.d)

- Reheating: (Re-)populates Universe with particles.
  Re-heat temperature $T_{\rm R}$ not known: $T_{\rm R} \geq 1$ MeV (BBN)
  - Thought to begin with coherent oscillation of inflaton field
  - No direct connections to collider physics
  - Dynamics of thermalization has some connection to dynamics of heavy ion collisions ($\longrightarrow$ RHIC, LHC)

- Baryogenesis: Happened sometime after end of inflation

History (cont.d)

- Reheating: (Re-)populates Universe with particles.
  Re-heat temperature $T_{\rm R}$ not known: $T_{\rm R} \geq 1$ MeV (BBN)
  - Thought to begin with coherent oscillation of inflaton field
  - No direct connections to collider physics
  - Dynamics of thermalization has some connection to dynamics of heavy ion collisions ($\rightarrow$ RHIC, LHC)

- Baryogenesis: Happened sometime after end of inflation
  - Many models exist

History (cont.d)

- Reheating: (Re-)populates Universe with particles.
  Re-heat temperature $T_{\rm R}$ not known: $T_{\rm R} \geq 1$ MeV (BBN)
  - Thought to begin with coherent oscillation of inflaton field
  - No direct connections to collider physics
  - Dynamics of thermalization has some connection to dynamics of heavy ion collisions ($\to$ RHIC, LHC)
- Baryogenesis: Happened sometime after end of inflation
  - Many models exist
  - Work at different temperatures

History (cont.d)

- Reheating: (Re-)populates Universe with particles.
  Re-heat temperature $T_{\rm R}$ not known: $T_{\rm R} \geq 1$ MeV (BBN)
  - Thought to begin with coherent oscillation of inflaton field
  - No direct connections to collider physics
  - Dynamics of thermalization has some connection to dynamics of heavy ion collisions ($\rightarrow$ RHIC, LHC)

- Baryogenesis: Happened sometime after end of inflation
  - Many models exist
  - Work at different temperatures
  - Some models make predictions for colliders!

History (cont.d)

- Creation of Dark Matter: Happened sometime after end of inflation

History (cont.d)

- Creation of Dark Matter: Happened sometime after end of inflation
  - Many models exist

History (cont.d)

- Creation of Dark Matter: Happened sometime after end of inflation
  - Many models exist
  - Work at different temperatures

History (cont.d)

- Creation of Dark Matter: Happened sometime after end of inflation
  - Many models exist
  - Work at different temperatures
  - Most models have connections to collider physics!

History (cont.d)

- Creation of Dark Matter: Happened sometime after end of inflation
  - Many models exist
  - Work at different temperatures
  - Most models have connections to collider physics!

- Electroweak Phase Transition: Happened at $T = T_{\rm EW} \simeq 100$ GeV, if $T_{\rm R} > T_{\rm EW}$

History (cont.d)

- Creation of Dark Matter: Happened sometime after end of inflation
  - Many models exist
  - Work at different temperatures
  - Most models have connections to collider physics!

- Electroweak Phase Transition: Happened at $T = T_{\rm EW} \simeq 100$ GeV, if $T_{\rm R} > T_{\rm EW}$
  - May be related to baryogenesis

History (cont.d)

- Creation of Dark Matter: Happened sometime after end of inflation
  - Many models exist
  - Work at different temperatures
  - Most models have connections to collider physics!

- Electroweak Phase Transition: Happened at $T = T_{\rm EW} \simeq 100$ GeV, if $T_{\rm R} > T_{\rm EW}$
  - May be related to baryogenesis
  - May have some connection to collider physics (sphalerons)

History (cont.d)

- QCD phase transition: Happened at $T = T_{\rm QCD} \simeq 170$ MeV, if $T_{\rm R} > T_{\rm QCD}$

History (cont.d)

- QCD phase transition: Happened at $T = T_{\rm QCD} \simeq 170$ MeV, if $T_{\rm R} > T_{\rm QCD}$
  - Related to dynamics of heavy ion collisions, "soft" QCD (at negligible baryon density)

History (cont.d)

- QCD phase transition: Happened at $T = T_{\rm QCD} \simeq 170$ MeV, if $T_{\rm R} > T_{\rm QCD}$
  - Related to dynamics of heavy ion collisions, “soft” QCD (at negligible baryon density)
- Big Bang Nucleosynthesis (BBN): Started at $T \simeq 1$ MeV

History (cont.d)

- QCD phase transition: Happened at $T = T_{\rm QCD} \simeq 170$ MeV, if $T_{\rm R} > T_{\rm QCD}$
  - Related to dynamics of heavy ion collisions, “soft” QCD (at negligible baryon density)
- Big Bang Nucleosynthesis (BBN): Started at $T \simeq 1$ MeV
  - Constrains many extensions of SM, if $T_{\rm R}$ was sufficiently high to create new particles

History (cont.d)

- QCD phase transition: Happened at $T = T_{\rm QCD} \simeq 170$ MeV, if $T_{\rm R} > T_{\rm QCD}$
  - Related to dynamics of heavy ion collisions, "soft" QCD (at negligible baryon density)
- Big Bang Nucleosynthesis (BBN): Started at $T \simeq 1$ MeV
  - Constrains many extensions of SM, if $T_{\rm R}$ was sufficiently high to create new particles
  - Sets lower bound on $T_{\rm R}$, if standard BBN is essentially correct

History (cont.d)

- QCD phase transition: Happened at $T = T_{\rm QCD} \simeq 170$ MeV, if $T_{\rm R} > T_{\rm QCD}$
  - Related to dynamics of heavy ion collisions, “soft” QCD (at negligible baryon density)
- Big Bang Nucleosynthesis (BBN): Started at $T \simeq 1$ MeV
  - Constrains many extensions of SM, if $T_{\rm R}$ was sufficiently high to create new particles
  - Sets lower bound on $T_{\rm R}$, if standard BBN is essentially correct
- Matter–Radiation Equilibrium: Happened at $T \simeq 3$ eV.

History (cont.d)

- QCD phase transition: Happened at $T = T_{\rm QCD} \simeq 170$ MeV, if $T_{\rm R} > T_{\rm QCD}$
  - Related to dynamics of heavy ion collisions, "soft" QCD (at negligible baryon density)
- Big Bang Nucleosynthesis (BBN): Started at $T \simeq 1$ MeV
  - Constrains many extensions of SM, if $T_{\rm R}$ was sufficiently high to create new particles
  - Sets lower bound on $T_{\rm R}$, if standard BBN is essentially correct
- Matter–Radiation Equilibrium: Happened at $T \simeq 3$ eV.
  - Energy density of the Universe begins to be dominated by (dark) matter

History (cont.d)

- Decoupling of Matter and Radiation: Happened at $T \simeq 0.3$ eV

History (cont.d)

- Decoupling of Matter and Radiation: Happened at $T \simeq 0.3$ eV
  - "Last scattering" of CMB photons

History (cont.d)

- Decoupling of Matter and Radiation: Happened at $T \simeq 0.3$ eV
  - "Last scattering" of CMB photons
  - Visible structures (galaxies etc.) start to form

History (cont.d)

- Decoupling of Matter and Radiation: Happened at $T \simeq 0.3$ eV
  - "Last scattering" of CMB photons
  - Visible structures (galaxies etc.) start to form
- Equilibrium of Matter and Dark Energy: Probably happened at redshift $z \simeq 1$ $(T \simeq 6 \cdot 10^{-4}\ \mathrm{eV})$.

History (cont.d)

- Decoupling of Matter and Radiation: Happened at $T \simeq 0.3$ eV
  - "Last scattering" of CMB photons
  - Visible structures (galaxies etc.) start to form
- Equilibrium of Matter and Dark Energy: Probably happened at redshift $z \simeq 1$ ($T \simeq 6 \cdot 10^{-4}$ eV).
  - Nobody knows when (or if) Dark Energy was created

History (cont.d)

- Decoupling of Matter and Radiation: Happened at $T \simeq 0.3$ eV
  - "Last scattering" of CMB photons
  - Visible structures (galaxies etc.) start to form
- Equilibrium of Matter and Dark Energy: Probably happened at redshift $z \simeq 1$ $(T \simeq 6 \cdot 10^{-4}\ \mathrm{eV})$.
  - Nobody knows when (or if) Dark Energy was created
  - If Dark Energy $\simeq$ const: Plays no role for $T > 0.1$ eV

History (cont.d)

- Decoupling of Matter and Radiation: Happened at $T \simeq 0.3$ eV
  - "Last scattering" of CMB photons
  - Visible structures (galaxies etc.) start to form
- Equilibrium of Matter and Dark Energy: Probably happened at redshift $z \simeq 1$ $(T \simeq 6 \cdot 10^{-4}\ \mathrm{eV})$.
  - Nobody knows when (or if) Dark Energy was created
  - If Dark Energy $\simeq$ const: Plays no role for $T > 0.1$ eV
  - In models with dynamical Dark Energy ("quintessence"): Can affect dynamics of BBN, creation of Dark Matter, . . .

2 Dark Energy

- Origin and nature of DE are completely unclear:
  Biggest mystery in current cosmology!

2 Dark Energy

- Origin and nature of DE are completely unclear:
  Biggest mystery in current cosmology!
- In 4 dimensions: No connection to collider physics

2 Dark Energy

- Origin and nature of DE are completely unclear: Biggest mystery in current cosmology!
- In 4 dimensions: No connection to collider physics
- In models with extra dimensions: Connections to collider physics may exist (radion–Higgs mixing; spectrum of KK states), but no example is known (to me)

3 Baryogenesis

- Reminder: Sakharov conditions: Need

3 Baryogenesis

- Reminder: Sakharov conditions: Need
  - Violation of C and CP symmetries

3 Baryogenesis

- Reminder: Sakharov conditions: Need
  - Violation of C and CP symmetries
  - Violation of baryon or lepton number

3 Baryogenesis

- Reminder: Sakharov conditions: Need
  - Violation of C and CP symmetries
  - Violation of baryon or lepton number
  - Deviation from thermal equilibrium (or CPT violation)

3 Baryogenesis

- Reminder: Sakharov conditions: Need
  - Violation of C and CP symmetries
  - Violation of baryon or lepton number
  - Deviation from thermal equilibrium (or CPT violation)

- Many models work at very high temperatures (GUT baryogenesis; most leptogenesis; most Affleck–Dine): Have no connection to collider physics

3 Baryogenesis

- Reminder: Sakharov conditions: Need
  - Violation of C and CP symmetries
  - Violation of baryon or lepton number
  - Deviation from thermal equilibrium (or CPT violation)
- Many models work at very high temperatures (GUT baryogenesis; most leptogenesis; most Affleck–Dine): Have no connection to collider physics
- Some models work at rather low temperature: can be tested at colliders! Will discuss two such models.

Leptogenesis with degenerate neutrinos

- Basic idea of leptogenesis:

Leptogenesis with degenerate neutrinos

- Basic idea of leptogenesis:
  - Out–of–equilibrium decay of heavy “right–handed” neutrinos N_i creates lepton asymmetry

Leptogenesis with degenerate neutrinos

- Basic idea of leptogenesis:
  - Out–of–equilibrium decay of heavy "right–handed" neutrinos N_i creates lepton asymmetry
  - Is partially transformed to baryon asymmetry via elw sphaleron transitions

Leptogenesis with degenerate neutrinos

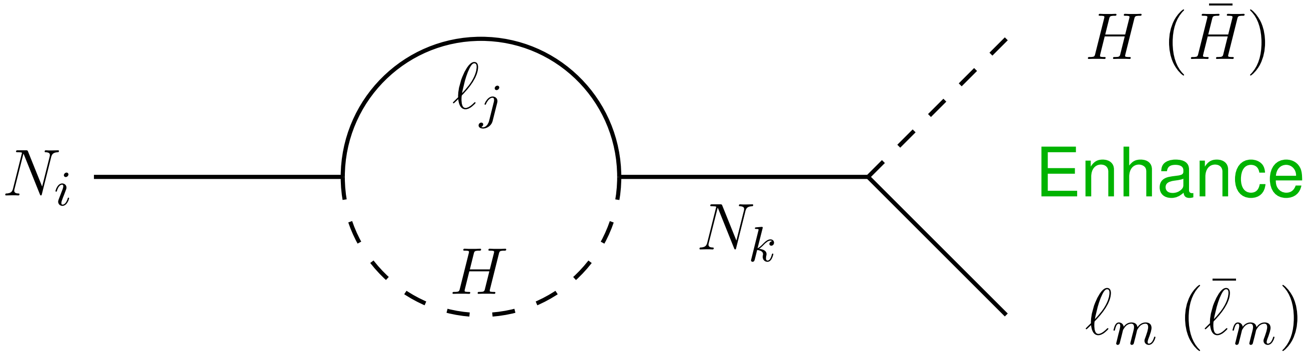
- Basic idea of leptogenesis:
  - Out–of–equilibrium decay of heavy “right–handed” neutrinos N_i creates lepton asymmetry
  - Is partially transformed to baryon asymmetry via elw sphaleron transitions

- Standard thermal leptogensis with hierarchical heavy neutrinos reqires $T_{\rm R} \geq M_1 \geq 10^8$ GeV: Not testable at colliders Buchmüller, Di Bari, Plümacher 2002/3/4; Davidson 2003; Giudice et al. 2004

Leptogenesis with degenerate neutrinos

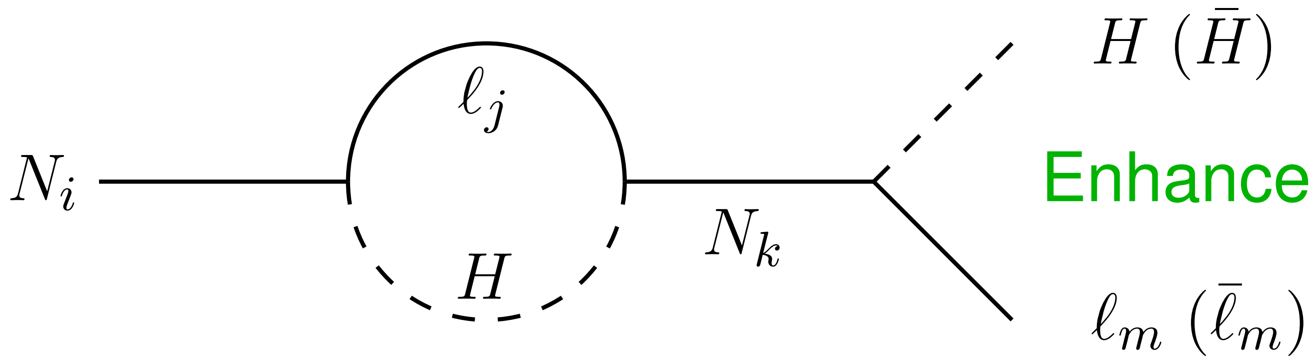
- Basic idea of leptogenesis:
  - Out–of–equilibrium decay of heavy “right–handed” neutrinos N_i creates lepton asymmetry
  - Is partially transformed to baryon asymmetry via elw sphaleron transitions
- Standard thermal leptogensis with hierarchical heavy neutrinos reqires $T_{\rm R} \geq M_1 \geq 10^8$ GeV: Not testable at colliders Buchmüller, Di Bari, Plümacher 2002/3/4; Davidson 2003; Giudice et al. 2004
- If $M_2 - M_1 \ll M_1$: effective CP violation enhanced: Can have $M_1 \simeq$ TeV! Pilaftsis 1997/9; Pilaftsis & Underwood 2004

Leptogenesis (cont.d)



Enhanced for $i = 1,\ k = 2$

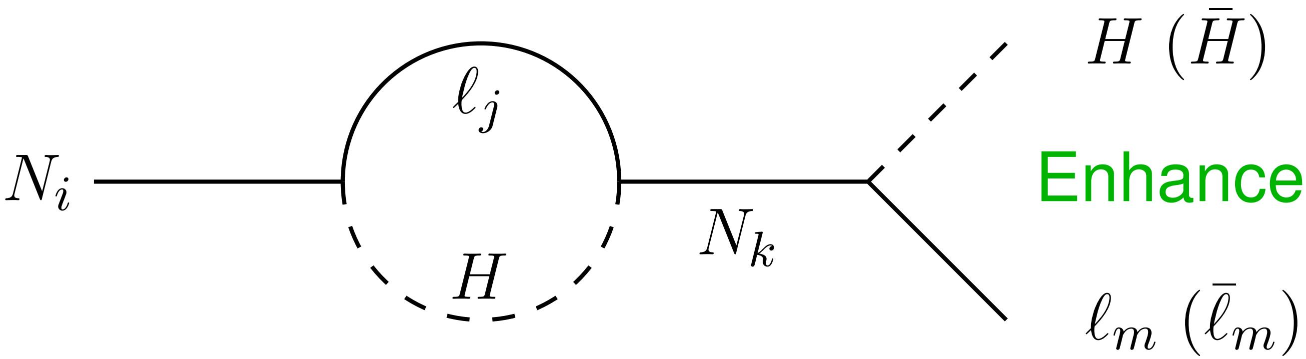
Leptogenesis (cont.d)



Enhanced for $i = 1,\ k = 2$

- N_i only couple to Higgs boson(s): productions at colliders not easy!

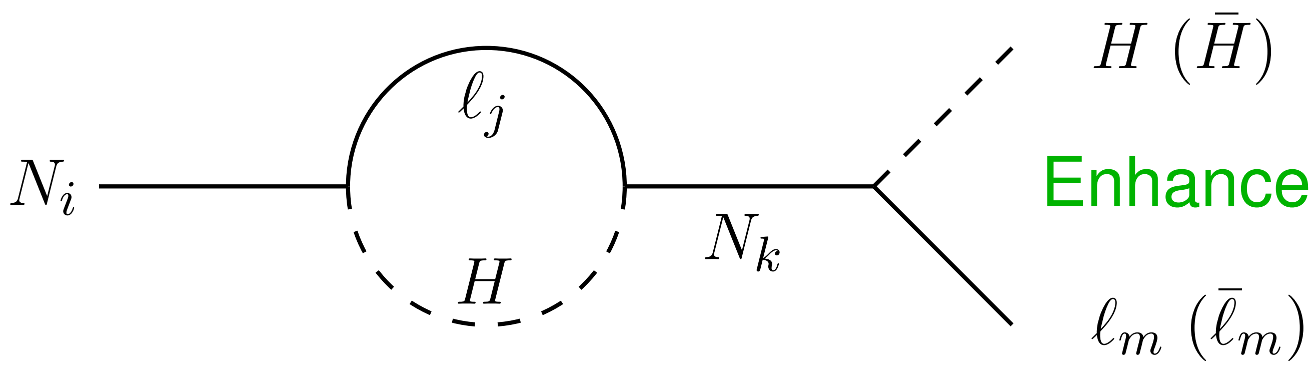
Leptogenesis (cont.d)



Enhanced for $i = 1,\ k = 2$

- N_i only couple to Higgs boson(s): productions at colliders not easy!
- Constrain via precision measurements of Higgs properties?

Leptogenesis (cont.d)



Enhanced for $i = 1,\ k = 2$

- N_i only couple to Higgs boson(s): productions at colliders not easy!
- Constrain via precision measurements of Higgs properties?
- Other scenarios with low-scale leptogenesis: Grossman, Kashti, Nir, Roulet 2004; Hambye et al. 2003; Raidal, Strumia, Turzynski 2004

Electroweak Baryogenesis

- Basic idea: Bubbles of true vacuum form in phase of exact $SU(2)$. Baryon asymmetry generated during transport through bubble walls.

Electroweak Baryogenesis

- Basic idea: Bubbles of true vacuum form in phase of exact $SU(2)$. Baryon asymmetry generated during transport through bubble walls.
  - B violation: elw sphalerons

Electroweak Baryogenesis

- Basic idea: Bubbles of true vacuum form in phase of exact $SU(2)$. Baryon asymmetry generated during transport through bubble walls.
  - B violation: elw sphalerons
  - Out of equlibrium: Elw. phase transition was strongly $1^{\rm st}$ order

Electroweak Baryogenesis

- Basic idea: Bubbles of true vacuum form in phase of exact $SU(2)$. Baryon asymmetry generated during transport through bubble walls.
  - B violation: elw sphalerons
  - Out of equlibrium: Elw. phase transition was strongly 1$^{\rm st}$ order
  - CP violation: in bubble wall

Electroweak Baryogenesis

- Basic idea: Bubbles of true vacuum form in phase of exact $SU(2)$. Baryon asymmetry generated during transport through bubble walls.
  - B violation: elw sphalerons
  - Out of equlibrium: Elw. phase transition was strongly 1$^{\rm st}$ order
  - CP violation: in bubble wall
- Does not work in SM: cross–over (no phase transition) for $m_H \gtrsim 60$ GeV!

Baryogenesis (cont.d)

- Mechanism can work in MSSM! Requirements:

Baryogenesis (cont.d)

- Mechanism can work in MSSM! Requirements:
  - Light Higgs: $m_h \lesssim 120$ GeV

Baryogenesis (cont.d)

- Mechanism can work in MSSM! Requirements:
  - Light Higgs: $m_h \lesssim 120$ GeV
  - Light stop: $m_{\tilde{t}_1} \lesssim m_t$

Baryogenesis (cont.d)

- Mechanism can work in MSSM! Requirements:
  - Light Higgs: $m_h \lesssim 120$ GeV
  - Light stop: $m_{\tilde{t}_1} \lesssim m_t$
  - Little $\tilde{t}_L - \tilde{t}_R$ mixing: $\theta_{\tilde{t}} \simeq \pi/2$

Baryogenesis (cont.d)

- Mechanism can work in MSSM! Requirements:
  - Light Higgs: $m_h \lesssim 120$ GeV
  - Light stop: $m_{\tilde{t}_1} \lesssim m_t$
  - Little $\tilde{t}_L - \tilde{t}_R$ mixing: $\theta_{\tilde{t}} \simeq \pi/2$
  - CP violation in $\tilde{\chi}$ sector: $\phi_\mu \gtrsim 0.1, \ |M_2|, \ |\mu| \lesssim 150$ GeV

Baryogenesis (cont.d)

- Mechanism can work in MSSM! Requirements:
  - Light Higgs: $m_h \lesssim 120$ GeV
  - Light stop: $m_{\tilde{t}_1} \lesssim m_t$
  - Little $\tilde{t}_L - \tilde{t}_R$ mixing: $\theta_{\tilde{t}} \simeq \pi/2$
  - CP violation in $\tilde{\chi}$ sector: $\phi_\mu \gtrsim 0.1, \ |M_2|, \ |\mu| \lesssim 150$ GeV
- Remains to be checked:

Baryogenesis (cont.d)

- Mechanism can work in MSSM! Requirements:
  - Light Higgs: $m_h \lesssim 120$ GeV
  - Light stop: $m_{\tilde{t}_1} \lesssim m_t$
  - Little $\tilde{t}_L - \tilde{t}_R$ mixing: $\theta_{\tilde{t}} \simeq \pi/2$
  - CP violation in $\tilde{\chi}$ sector: $\phi_\mu \gtrsim 0.1, \; |M_2|, \; |\mu| \lesssim 150$ GeV
- Remains to be checked:
  - Determination of $\theta_{\tilde{t}}$ in presence of CP violation

Baryogenesis (cont.d)

- Mechanism can work in MSSM! Requirements:
  - Light Higgs: $m_h \lesssim 120$ GeV
  - Light stop: $m_{\tilde{t}_1} \lesssim m_t$
  - Little $\tilde{t}_L - \tilde{t}_R$ mixing: $\theta_{\tilde{t}} \simeq \pi/2$
  - CP violation in $\tilde{\chi}$ sector: $\phi_\mu \gtrsim 0.1, \ |M_2|, \ |\mu| \lesssim 150$ GeV
- Remains to be checked:
  - Determination of $\theta_{\tilde{t}}$ in presence of CP violation
  - Determination of ϕ_μ in relevant region of parameter space

4 Dark Matter

Several observations indicate existence of non-luminous Dark Matter (DM) (more exactly: missing force)

4 Dark Matter

Several observations indicate existence of non-luminous Dark Matter (DM) (more exactly: missing force)

- Galactic rotation curves imply $\Omega_{\mathrm{DM}} h^2 \geq 0.05$.

Ω: Mass density in units of critical density; $\Omega = 1$ means flat Universe.
h: Scaled Hubble constant. Observation: $h = 0.72 \pm 0.07$

4 Dark Matter

Several observations indicate existence of non-luminous Dark Matter (DM) (more exactly: missing force)

- Galactic rotation curves imply $\Omega_{\mathrm{DM}} h^2 \geq 0.05$.

Ω: Mass density in units of critical density; $\Omega = 1$ means flat Universe.
h: Scaled Hubble constant. Observation: $h = 0.72 \pm 0.07$

- Models of structure formation, X ray temperature of clusters of galaxies, ...

4 Dark Matter

Several observations indicate existence of non-luminous Dark Matter (DM) (more exactly: missing force)

- Galactic rotation curves imply $\Omega_{\rm DM} h^2 \geq 0.05$.

Ω: Mass density in units of critical density; $\Omega = 1$ means flat Universe.
h: Scaled Hubble constant. Observation: $h = 0.72 \pm 0.07$

- Models of structure formation, X ray temperature of clusters of galaxies, ...

- Cosmic Microwave Background anisotropies (WMAP) imply $\Omega_{\rm DM} h^2 = 0.111 \pm 0.009$ **Bennet et al., astro–ph/0302207**

Density of thermal DM

Decoupling of DM particle χ defined by:

$$n_\chi(T_f)\langle v\sigma(\chi\chi \to \text{any})\rangle = H(T_f)$$

n_χ: χ number density $\propto \mathrm{e}^{-m_\chi/T}$

v: Relative velocity

$\langle \ldots \rangle$: Thermal average

H: Hubble parameter; in standard cosmology $\sim T^2/M_{\text{Planck}}$

Density of thermal DM

Decoupling of DM particle χ defined by:

$$n_\chi(T_f)\langle v\sigma(\chi\chi \to \text{any})\rangle = H(T_f)$$

n_χ: χ number density $\propto \mathrm{e}^{-m_\chi/T}$

v: Relative velocity

$\langle \dots \rangle$: Thermal average

H: Hubble parameter; in standard cosmology $\sim T^2/M_{\text{Planck}}$

Gives average relic mass density

$$\Omega_\chi \propto \frac{1}{\langle v\sigma(\chi\chi \to \text{any})\rangle}$$

Gives roughly right result for weak cross section!

Assumptions

- χ is effectively stable, $\tau_\chi \gg \tau_{\rm U}$: partly testable at colliders

Assumptions

- χ is effectively stable, $\tau_\chi \gg \tau_{\rm U}$: partly testable at colliders
- No entropy production after χ decoupled: Not testable at colliders

Assumptions

- χ is effectively stable, $\tau_\chi \gg \tau_{\rm U}$: partly testable at colliders
- No entropy production after χ decoupled: Not testable at colliders
- H at time of χ decoupling is known: partly testable at colliders

SUSY Dark Matter

Conditions for successful DM candidate:

- Must be stable $\Rightarrow \ \chi =$ LSP and $R-$parity is conserved (if LSP in visible sector)

SUSY Dark Matter

Conditions for successful DM candidate:

- Must be stable $\Rightarrow \ \chi =$ LSP and $R-$parity is conserved (if LSP in visible sector)
- Exotic isotope searches $\Rightarrow \ \chi$ must be neutral

SUSY Dark Matter

Conditions for successful DM candidate:

- Must be stable $\Rightarrow\ \chi =$ LSP and $R-$parity is conserved (if LSP in visible sector)
- Exotic isotope searches $\Rightarrow\ \chi$ must be neutral
- Must satisfy DM search limits $\Rightarrow\ \chi \neq \tilde{\nu}$

And the winner is . . .

SUSY Dark Matter

Conditions for successful DM candidate:

- Must be stable $\Rightarrow \chi =$ LSP and $R-$parity is conserved (if LSP in visible sector)
- Exotic isotope searches $\Rightarrow \chi$ must be neutral
- Must satisfy DM search limits $\Rightarrow \chi \neq \tilde{\nu}$

And the winner is ...

$$\chi = \tilde{\chi}_1^0$$

(or in hidden sector)

$\tilde{\chi}_1^0$ relic density

To predict thermal $\tilde{\chi}_1^0$ relic density: have to know

$$\sigma(\tilde{\chi}_1^0 \tilde{\chi}_1^0 \longrightarrow \text{SM particles})$$

In general, this requires knowledge of almost all sparticle and Higgs masses and of all couplings of the LSP!

$\tilde{\chi}_1^0$ relic density

To predict thermal $\tilde{\chi}_1^0$ relic density: have to know

$$\sigma(\tilde{\chi}_1^0 \tilde{\chi}_1^0 \longrightarrow \text{SM particles})$$

In general, this requires knowledge of almost all sparticle and Higgs masses and of all couplings of the LSP!

Neutralino mass matrix in the MSSM:

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin\theta_W & M_Z \sin\beta \sin\theta_W \\ 0 & M_2 & M_Z \cos\beta \cos\theta_W & -M_Z \sin\beta \cos\theta_W \\ -M_Z \cos\beta \sin\theta_W & M_Z \cos\beta \cos\theta_W & 0 & -\mu \\ M_Z \sin\beta \sin\theta_W & -M_Z \sin\beta \cos\theta_W & -\mu & 0 \end{pmatrix}$$

$\tilde{\chi}_1^0$ relic density

To predict thermal $\tilde{\chi}_1^0$ relic density: have to know

$$\sigma(\tilde{\chi}_1^0\tilde{\chi}_1^0 \longrightarrow \text{SM particles})$$

In general, this requires knowledge of almost all sparticle and Higgs masses and of all couplings of the LSP!

Neutralino mass matrix in the MSSM:

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -\mu \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix}$$

$\Longrightarrow$ Can determine decomposition of $\tilde{\chi}_1^0$ by studying $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0, \tilde{\chi}_3^0$.

$\tilde{\chi}_1^0$ relic density

To predict thermal $\tilde{\chi}_1^0$ relic density: have to know

$$\sigma(\tilde{\chi}_1^0 \tilde{\chi}_1^0 \longrightarrow \text{SM particles})$$

In general, this requires knowledge of almost all sparticle and Higgs masses and of all couplings of the LSP!

Neutralino mass matrix in the MSSM:

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin\theta_W & M_Z \sin\beta \sin\theta_W \\ 0 & M_2 & M_Z \cos\beta \cos\theta_W & -M_Z \sin\beta \cos\theta_W \\ -M_Z \cos\beta \sin\theta_W & M_Z \cos\beta \cos\theta_W & 0 & -\mu \\ M_Z \sin\beta \sin\theta_W & -M_Z \sin\beta \cos\theta_W & -\mu & 0 \end{pmatrix}$$

$\Longrightarrow$ Can determine decomposition of $\tilde{\chi}_1^0$ by studying $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0, \tilde{\chi}_3^0$.
Well studied in the MSSM, but not much is known about extensions (e.g. NMSSM)

$\tilde{\chi}_1^0$ annihilation in the MSSM

- $m_{\tilde{f}_L}$, $m_{\tilde{f}_R}$, $\theta_{\tilde{f}}$: Needed for $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to f \bar{f}$

$\tilde{\chi}_1^0$ annihilation in the MSSM

- $m_{\tilde{f}_L}, m_{\tilde{f}_R}, \theta_{\tilde{f}}$: Needed for $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f}$
- $m_h, m_H, m_A, \alpha, \tan\beta$: Needed for $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f}, VV, V\phi, \phi\phi$ (V: Massive gauge boson; ϕ: Higgs boson).

$\tilde{\chi}_1^0$ annihilation in the MSSM

- $m_{\tilde{f}_L}, m_{\tilde{f}_R}, \theta_{\tilde{f}}$: Needed for $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f}$
- $m_h, m_H, m_A, \alpha, \tan\beta$: Needed for $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f},\ VV,\ V\phi, \phi\phi$ (V: Massive gauge boson; ϕ: Higgs boson).
- For many masses: lower bounds may be sufficient

$\tilde{\chi}_1^0$ annihilation in the MSSM

- $m_{\tilde{f}_L}$, $m_{\tilde{f}_R}$, $\theta_{\tilde{f}}$: Needed for $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f}$
- m_h, m_H, m_A, α, $\tan\beta$: Needed for $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f},\ VV,\ V\phi, \phi\phi$ (V: Massive gauge boson; ϕ: Higgs boson).
- For many masses: lower bounds may be sufficient
- If coannihilation is important: final answer depends exponentially on mass difference

$\tilde{\chi}_1^0$ annihilation in the MSSM

- $m_{\tilde{f}_L}$, $m_{\tilde{f}_R}$, $\theta_{\tilde{f}}$: Needed for $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f}$
- m_h, m_H, m_A, α, $\tan\beta$: Needed for $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f},\ VV,\ V\phi, \phi\phi$ (V: Massive gauge boson; ϕ: Higgs boson).
- For many masses: lower bounds may be sufficient
- If coannihilation is important: final answer depends exponentially on mass difference
- Parameters in Higgs and squark sector are also needed to predict $\tilde{\chi}_1^0$ detection rate, i.e. $\sigma(\tilde{\chi}_1^0 N \to \tilde{\chi}_1^0 N)$

Impact on particle physics (mSUGRA)

w./ A. Djouadi, J.-L. Kneur, P. Slavich

Parameter space is constrained by:

- Sparticle searches, in particular $\tilde{\chi}_1^{\pm}$, $\tilde{\tau}_1$ searches at LEP: $\sigma < 20$ fb

Impact on particle physics (mSUGRA)

w./ A. Djouadi, J.-L. Kneur, P. Slavich

Parameter space is constrained by:

- Sparticle searches, in particular $\tilde{\chi}_1^{\pm}, \tilde{\tau}_1$ searches at LEP: $\sigma < 20$ fb
- Higgs searches, in particular light CP–even Higgs search at LEP (parameterized)

Impact on particle physics (mSUGRA)

w./ A. Djouadi, J.-L. Kneur, P. Slavich

Parameter space is constrained by:

- Sparticle searches, in particular $\tilde{\chi}_1^\pm, \ \tilde{\tau}_1$ searches at LEP: $\sigma < 20$ fb
- Higgs searches, in particular light CP–even Higgs search at LEP (parameterized)
- Brookhaven $g_\mu - 2$ measurement: Take envelope of constraints using τ and e^+e^- data for SM prediction

Impact on particle physics (mSUGRA)

w./ A. Djouadi, J.-L. Kneur, P. Slavich

Parameter space is constrained by:

- Sparticle searches, in particular $\tilde{\chi}_1^\pm,\ \tilde{\tau}_1$ searches at LEP: $\sigma < 20$ fb
- Higgs searches, in particular light CP–even Higgs search at LEP (parameterized)
- Brookhaven $g_\mu - 2$ measurement: Take envelope of constraints using τ and e^+e^- data for SM prediction
- Radiative b decays (BELLE, . . .): Take $2.65 \cdot 10^{-4} \leq B(b \to s\gamma) \leq 4.45 \cdot 10^{-4}$

Impact on particle physics (mSUGRA)

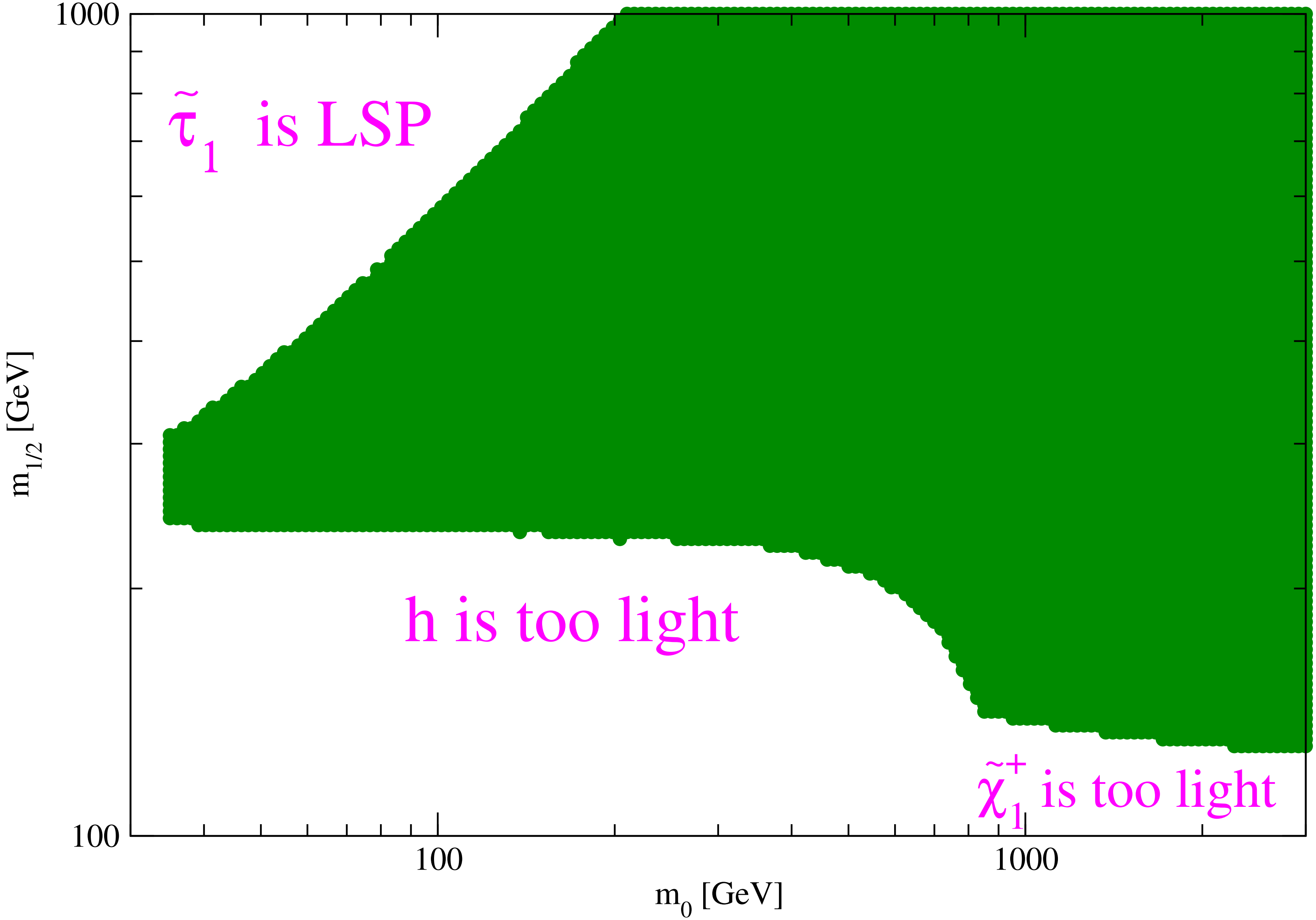
w./ A. Djouadi, J.-L. Kneur, P. Slavich

Parameter space is constrained by:

- Sparticle searches, in particular $\tilde{\chi}_1^\pm, \ \tilde{\tau}_1$ searches at LEP: $\sigma < 20$ fb
- Higgs searches, in particular light CP–even Higgs search at LEP (parameterized)
- Brookhaven $g_\mu - 2$ measurement: Take envelope of constraints using τ and e^+e^- data for SM prediction
- Radiative b decays (BELLE, . . .): Take $2.65 \cdot 10^{-4} \leq B(b \to s\gamma) \leq 4.45 \cdot 10^{-4}$
- Simple CCB constraints (at weak scale only)

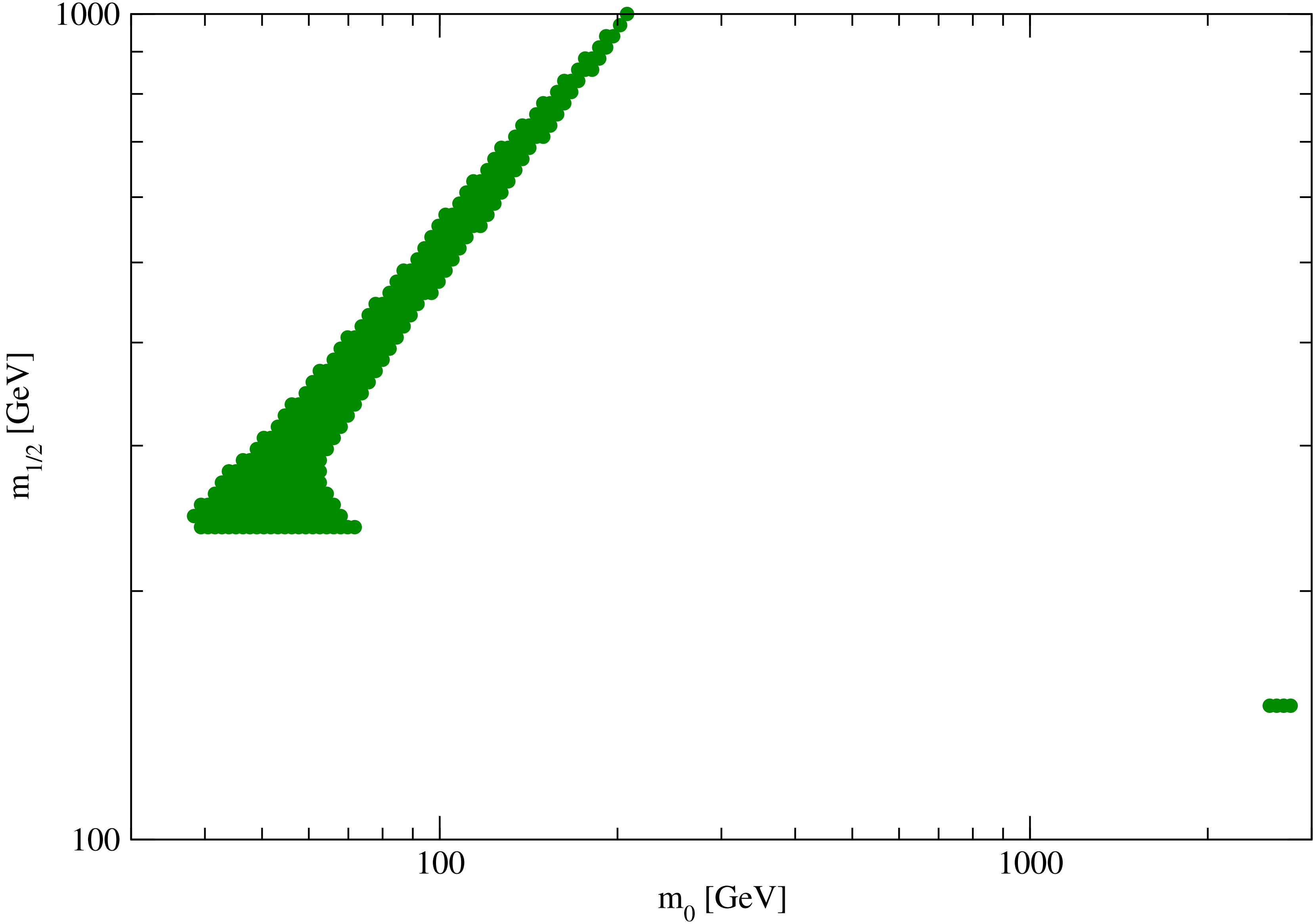
mSUGRA, m_t = 178 GeV, $\tan\beta$ = 10, $\mu>0$, A_0 = 0

All constraints except DM included



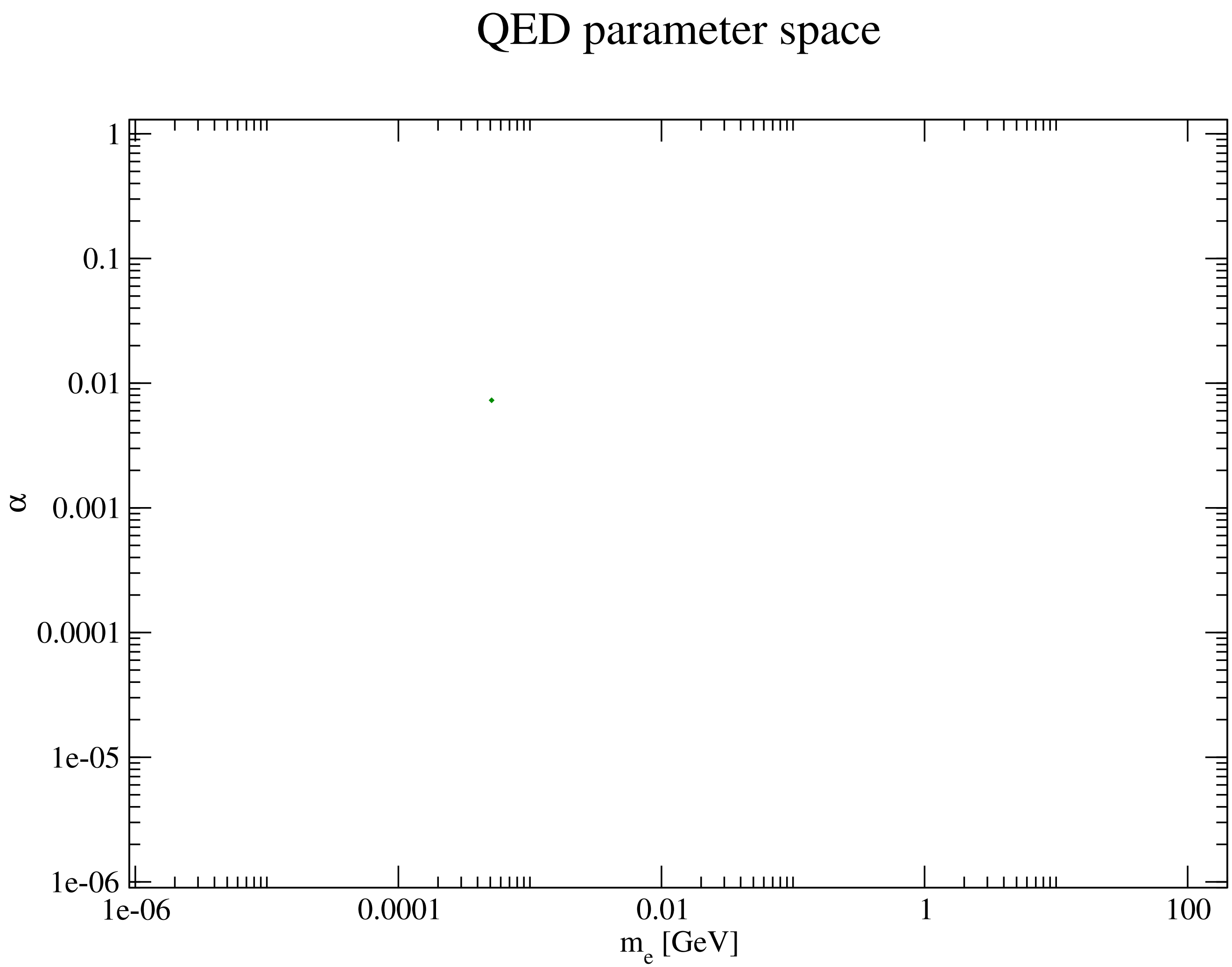
mSUGRA, m_t = 178 GeV, tanβ = 10, μ>0, A_0 = 0

All constraints included

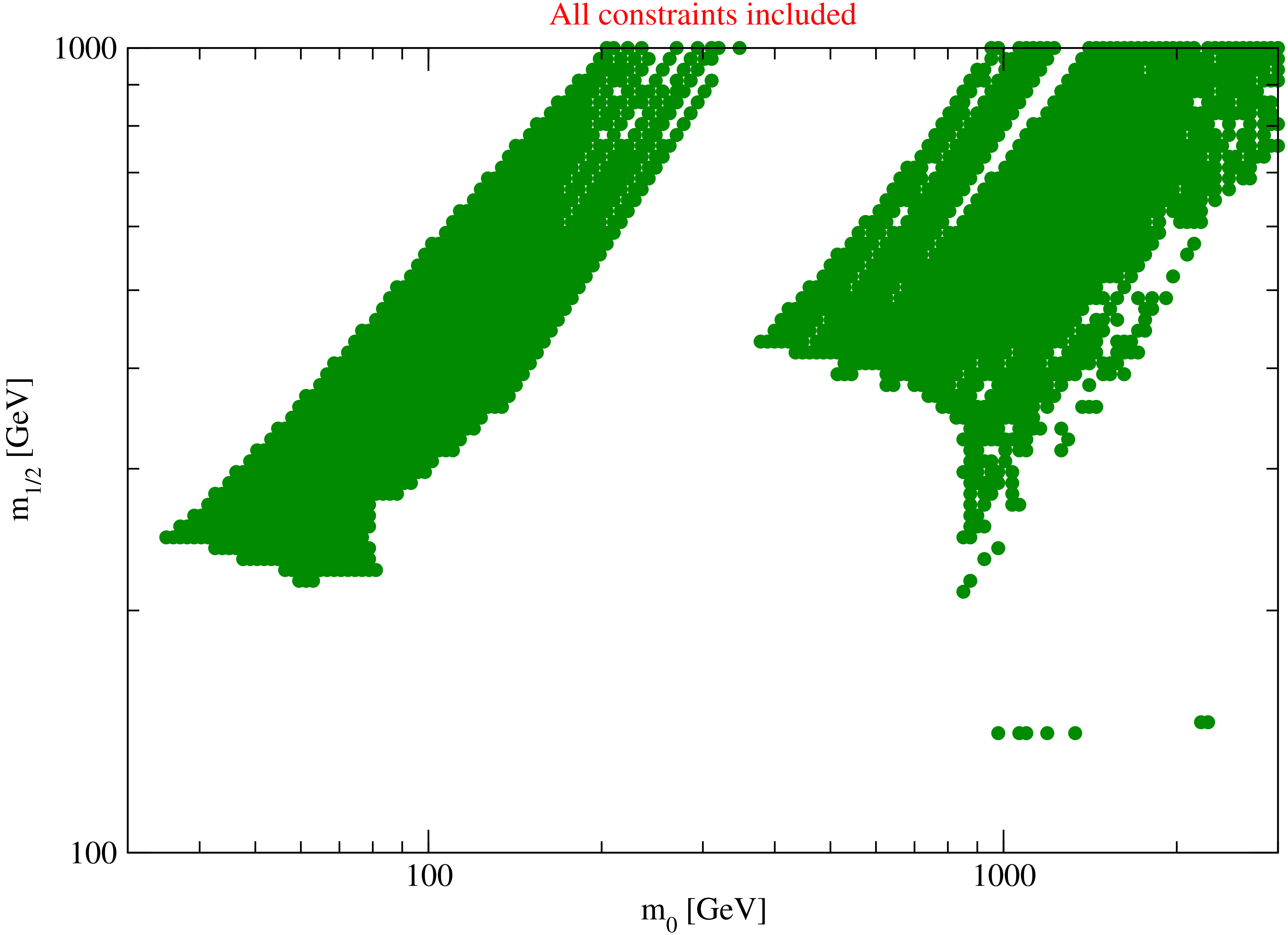


Is the apparently small size of the allowed parameter parameter space a problem? Not necessarily …

Is the apparently small size of the allowed parameter parameter space a problem? Not necessarily . . .

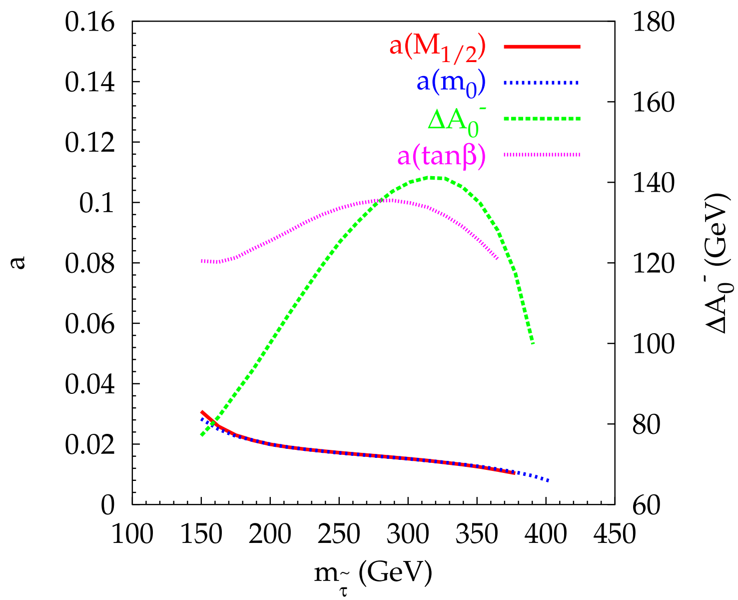


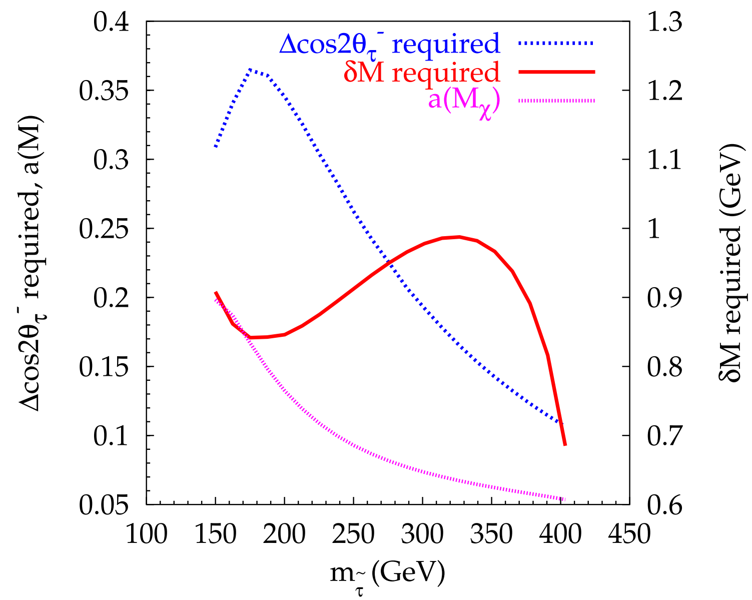
mSUGRA, m_t = 178 GeV, tanβ = 10, μ>0, A_0 scanned



Example: $\tilde{\tau}$ co–ann. region in mSUGRA **Allanach et al. 2004**

Precision with which one has to measure parameters in order to predict thermal $\tilde{\chi}_1^0$ relic density with WMAP accuracy:





Beyond mSUGRA

The predicted Dark Matter density can be altered by modifying the SUSY model and/or by modifying the cosmological model.

Reducing $\Omega_{\tilde{\chi}_1^0}$ by changing the SUSY model:

- Dial up co-annihilation

Beyond mSUGRA

The predicted Dark Matter density can be altered by modifying the SUSY model and/or by modifying the cosmological model.

Reducing $\Omega_{\tilde{\chi}_1^0}$ by changing the SUSY model:

- Dial up co-annihilation
- Increase $\tilde{h}$ component of $\tilde{\chi}_1^0$

Beyond mSUGRA

The predicted Dark Matter density can be altered by modifying the SUSY model and/or by modifying the cosmological model.

Reducing $\Omega_{\tilde{\chi}_1^0}$ by changing the SUSY model:

- Dial up co-annihilation
- Increase $\tilde{h}$ component of $\tilde{\chi}_1^0$
- Increase $\widetilde{W}_3$ component of $\tilde{\chi}_1^0$

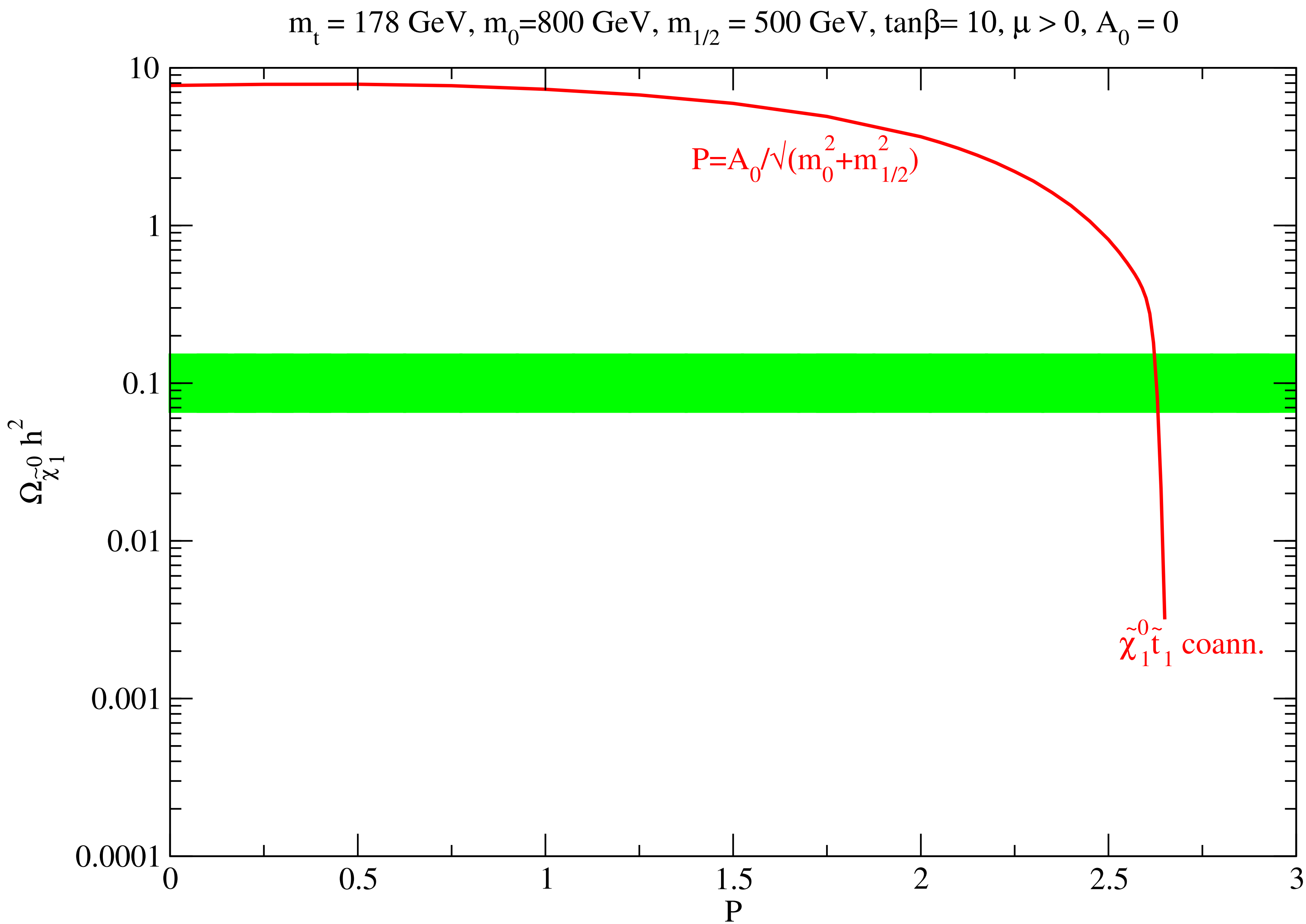
Beyond mSUGRA

The predicted Dark Matter density can be altered by modifying the SUSY model and/or by modifying the cosmological model.

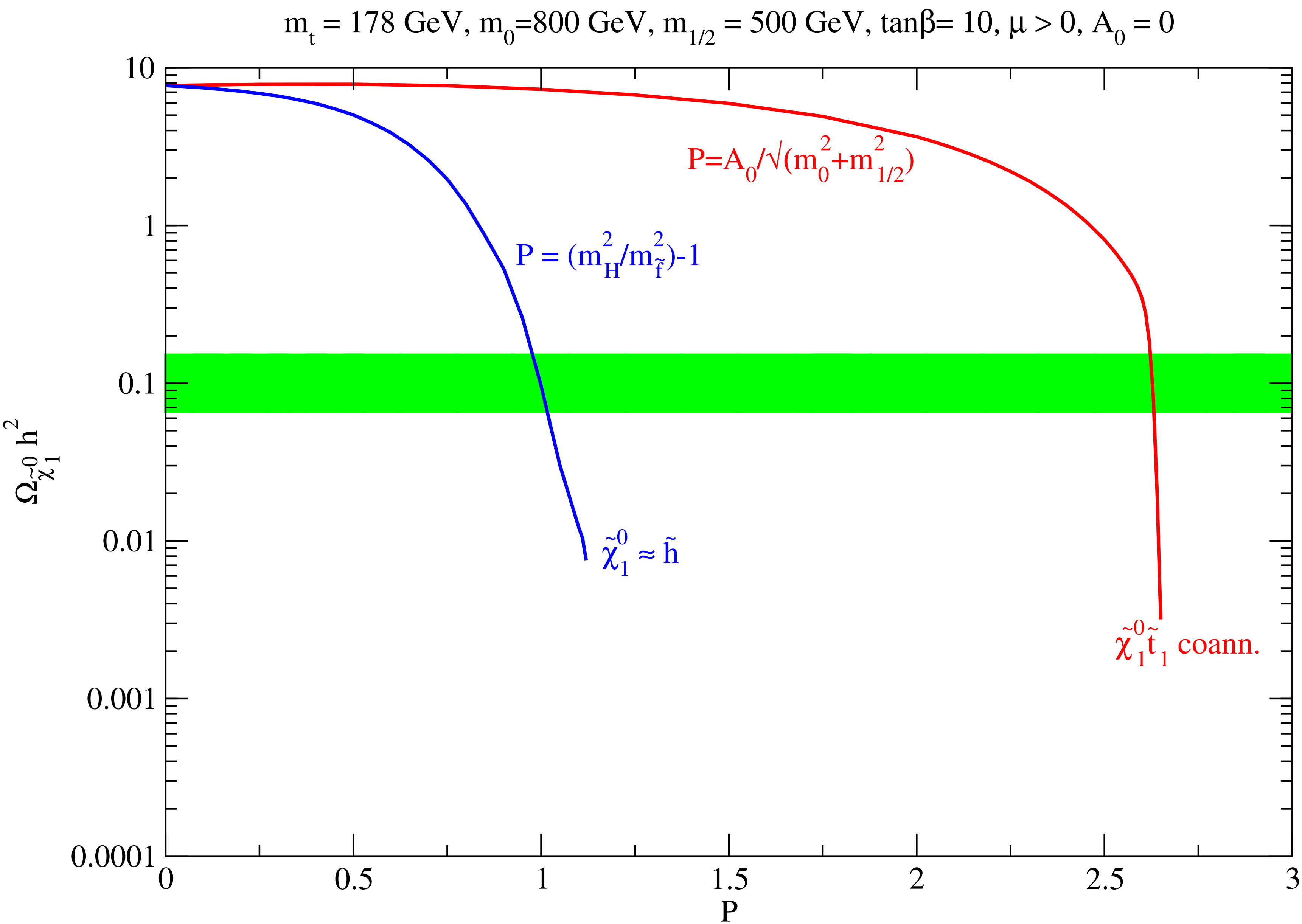
Reducing $\Omega_{\tilde{\chi}_1^0}$ by changing the SUSY model:

- Dial up co-annihilation
- Increase $\tilde{h}$ component of $\tilde{\chi}_1^0$
- Increase $\widetilde{W}_3$ component of $\tilde{\chi}_1^0$

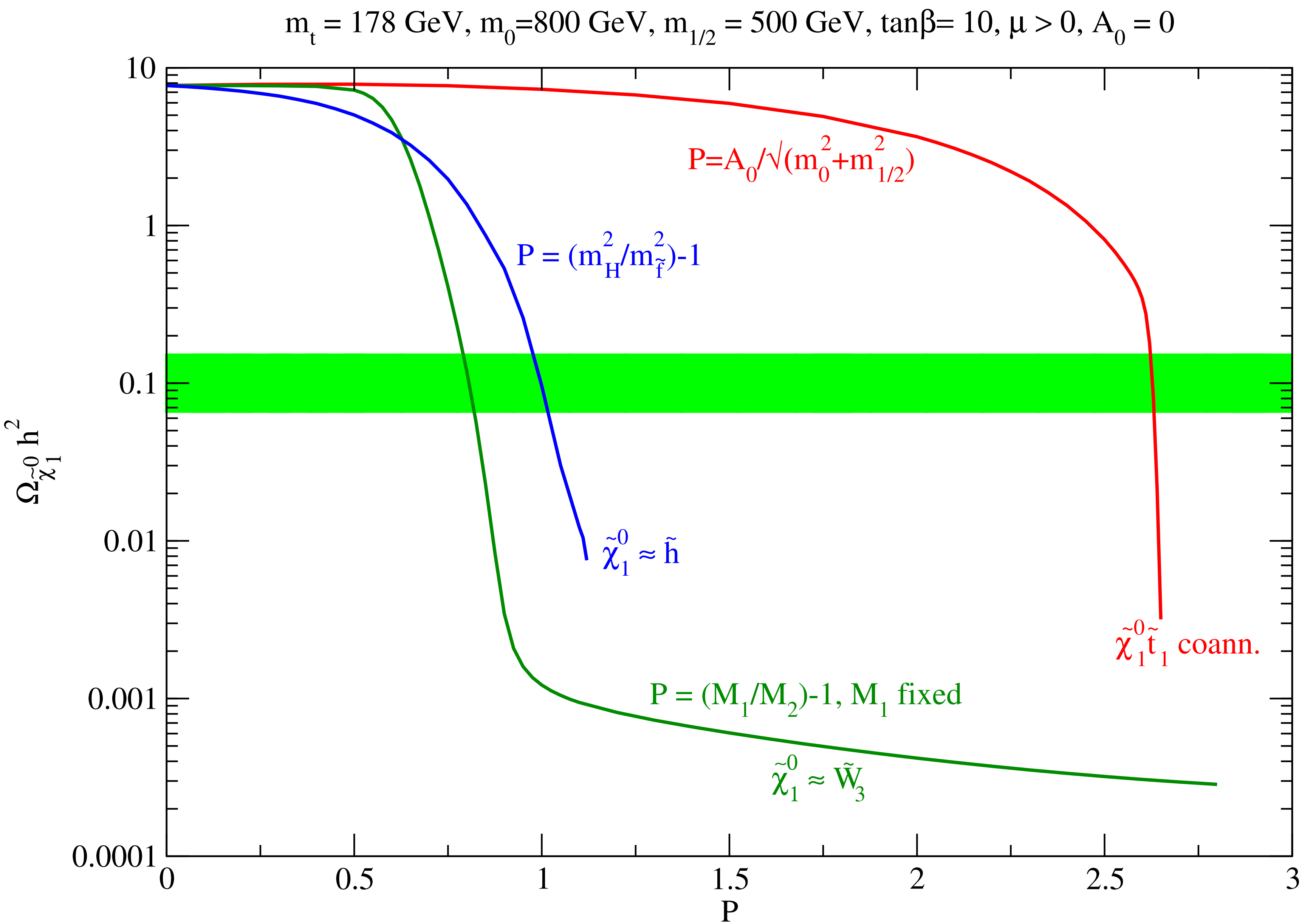
These modifications lead to greatly altered collider phenomenology!



m_t = 178 GeV, m_0=800 GeV, m_1/2 = 500 GeV, tanβ= 10, μ > 0, A_0 = 0
10
1
0.1
0.01
0.001
0.0001
0
0.5
1
1.5
2
2.5
3
P
Ω_χ̃_1^0 h^2
P=A_0/√(m_0^2+m_1/2^2)
χ̃_1^0 t̃_1 coann.



m_t = 178 GeV, m_0=800 GeV, $m_{1/2}$ = 500 GeV, tanβ= 10, μ > 0, A_0 = 0
$\Omega_{\tilde{\chi}^0_1} h^2$
P
10
1
0.1
0.01
0.001
0.0001
0
0.5
1
1.5
2
2.5
3
$P=A_0/\sqrt{(m_0^2+m_{1/2}^2)}$
$P = (m_H^2/m_{\tilde{f}}^2)-1$
$\tilde{\chi}^0_1 \approx \tilde{h}$
$\tilde{\chi}^0_1 \tilde{t}_1$ coann.



m_t = 178 GeV, m_0=800 GeV, $m_{1/2}$ = 500 GeV, tanβ= 10, μ > 0, A_0 = 0
$P=A_0/\sqrt{(m_0^2+m_{1/2}^2)}$
$P = (m_H^2/m_{\tilde{f}}^2)-1$
$\tilde{\chi}_1^0 \approx \tilde{h}$
$\tilde{\chi}_1^0 \tilde{t}_1$ coann.
$P = (M_1/M_2)-1$, M_1 fixed
$\tilde{\chi}_1^0 \approx \tilde{W}_3$
$\Omega_{\tilde{\chi}_1^0} h^2$
P
10
1
0.1
0.01
0.001
0.0001
0
0.5
1
1.5
2
2.5
3

Hidden Sector Dark Matter

Any mSUGRA parameter set can have the right DM density if LSP is in hidden or invisible sector. It could be:

- The axino Covi et al., hep-ph/9905212 . . .

Hidden Sector Dark Matter

Any mSUGRA parameter set can have the right DM density if LSP is in hidden or invisible sector. It could be:

- The axino Covi et al., hep-ph/9905212 . . .
- The gravitino Buchmüller et al.; J.L. Feng et al.; J. Ellis et al.; Di Austri and Roszkowski; . . .

Hidden Sector Dark Matter

Any mSUGRA parameter set can have the right DM density if LSP is in hidden or invisible sector. It could be:

- The axino Covi et al., hep-ph/9905212 . . .
- The gravitino Buchmüller et al.; J.L. Feng et al.; J. Ellis et al.; Di Austri and Roszkowski; . . .
- A modulino

Hidden Sector DM (contd.)

Unfortunately,

- Ω_{DM} can no longer be predicted from particle physics alone; e.g. $\Omega_{\tilde{G}} h^2 \propto T_{\mathrm{reheat}}$

Hidden Sector DM (contd.)

Unfortunately,

- Ω_{DM} can no longer be predicted from particle physics alone; e.g. $\Omega_{\tilde{G}} h^2 \propto T_{\mathrm{reheat}}$
- hidden sector LSP may leave no imprint at colliders, unless lightest visible sparticle (LVSP) is charged; LVSP is quite long-lived

Hidden Sector DM (contd.)

Unfortunately,

- $\Omega_{\rm DM}$ can no longer be predicted from particle physics alone; e.g. $\Omega_{\tilde{G}} h^2 \propto T_{\rm reheat}$
- hidden sector LSP may leave no imprint at colliders, unless lightest visible sparticle (LVSP) is charged; LVSP is quite long-lived
- Detection of hidden sector DM seems impossible: Cross sections are way too small!

Nonstandard cosmology

Can either reduce or increase density of stable $\tilde{\chi}_1^0$

Nonstandard cosmology

Can either reduce or increase density of stable $\tilde{\chi}_1^0$

- Increase: through incease of $H(T_f)$; or through non-thermal $\tilde{\chi}_1^0$ production mechanisms.

Nonstandard cosmology

Can either reduce or increase density of stable $\tilde{\chi}_1^0$

- Increase: through incease of $H(T_f)$; or through non-thermal $\tilde{\chi}_1^0$ production mechanisms.
- Reduce: through decrease of $H(T_f)$; through late entropy production; or through low $T_{\rm reheat}$.

Nonstandard cosmology

Can either reduce or increase density of stable $\tilde{\chi}_1^0$

- Increase: through incease of $H(T_f)$; or through non-thermal $\tilde{\chi}_1^0$ production mechanisms.
- Reduce: through decrease of $H(T_f)$; through late entropy production; or through low $T_{\rm reheat}$.

None of these mechanisms in general has observable consequences (except DM density).

Nonstandard cosmology

Can either reduce or increase density of stable $\tilde{\chi}_1^0$

- Increase: through incease of $H(T_f)$; or through non-thermal $\tilde{\chi}_1^0$ production mechanisms.
- Reduce: through decrease of $H(T_f)$; through late entropy production; or through low $T_{\rm reheat}$.

None of these mechanisms in general has observable consequences (except DM density).

If $\tilde{\chi}_1^0$ makes DM: Can use measurements at colliders to constrain cosmology!

4 Summary

- Dark Energy: Difficult to probe at colliders; perhaps some possibilities if $D > 4$

4 Summary

- Dark Energy: Difficult to probe at colliders; perhaps some possibilities if $D > 4$
- Baryogenesis: Some models can be tested at colliders, others cannot

4 Summary

- Dark Energy: Difficult to probe at colliders; perhaps some possibilities if $D > 4$
- Baryogenesis: Some models can be tested at colliders, others cannot
- Dark Matter:

4 Summary

- Dark Energy: Difficult to probe at colliders; perhaps some possibilities if $D > 4$
- Baryogenesis: Some models can be tested at colliders, others cannot
- Dark Matter:
  - Many models can be tested at colliders, some cannot

4 Summary

- Dark Energy: Difficult to probe at colliders; perhaps some possibilities if $D > 4$
- Baryogenesis: Some models can be tested at colliders, others cannot
- Dark Matter:
  - Many models can be tested at colliders, some cannot
  - SUSY WIMPs: Relic density often depends very sensitively on parameters: need very accurate measurements in collider experiments!