SUSY from Cosmology Point of View

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1. Introduction

The standard model of particle physics is successful

- It well explains results of collider experiments
- Theoretically consistent (renormalizable)

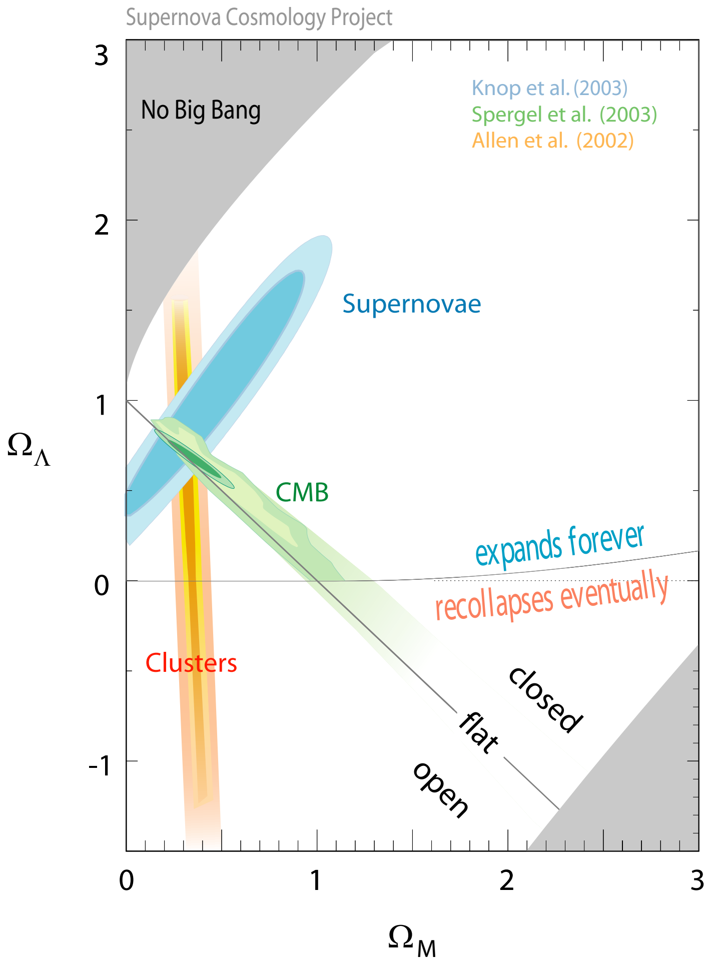
The ΛCDM model (with inflation) is successful

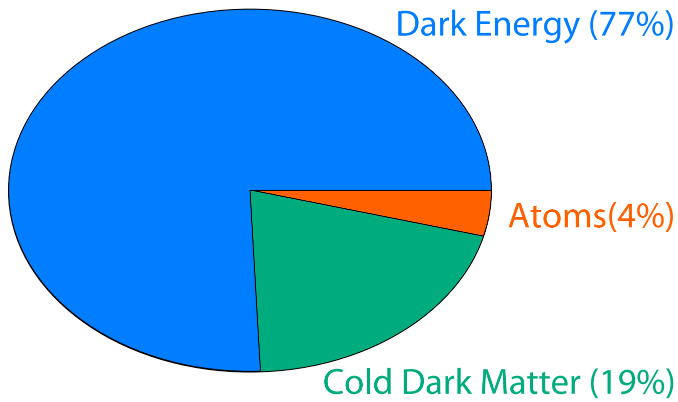
- CMB anisotropy obseved by the WMAP is well explained by (almost) scale-invariant primordial fluctuation

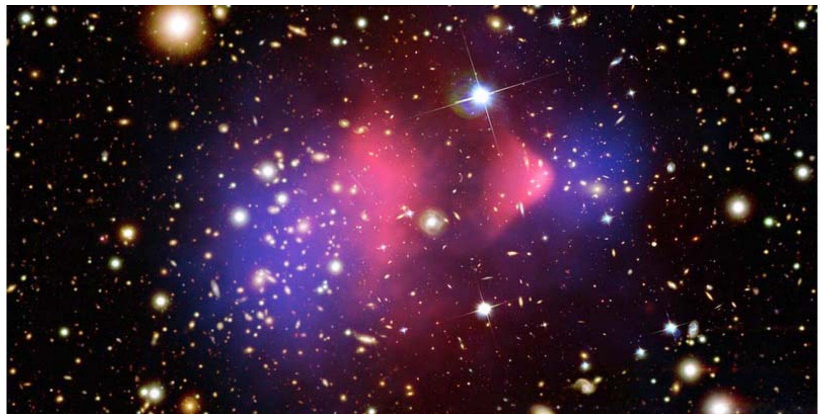
  $\Rightarrow$ (Maybe) inflation

- Sizable amount of dark matter
- Non-vanishing dark energy (cosmological constant?)

Current status of the observation of the universe







Blue: mass density via gravitatinal lensing (by HST)
Pink: X-ray from baryons (by Chandra)

The standard model is unsatisfactory for cosmology

- No candidate of inflaton
- No mechanism of generating baryon asymmetry
- No candidate of dark matter $\Leftrightarrow \Omega_{\text{CDM}} \simeq 0.2$
- $\cdots$

We need a candidate of dark matter

- Stable (or long-lived)
- Weakly coupled
- Massive (heavier than ~ 1 keV, if particle-like)

$\Rightarrow$ There is no such particle in the particle content of the standard model

We need new physics which contains dark-matter candidate

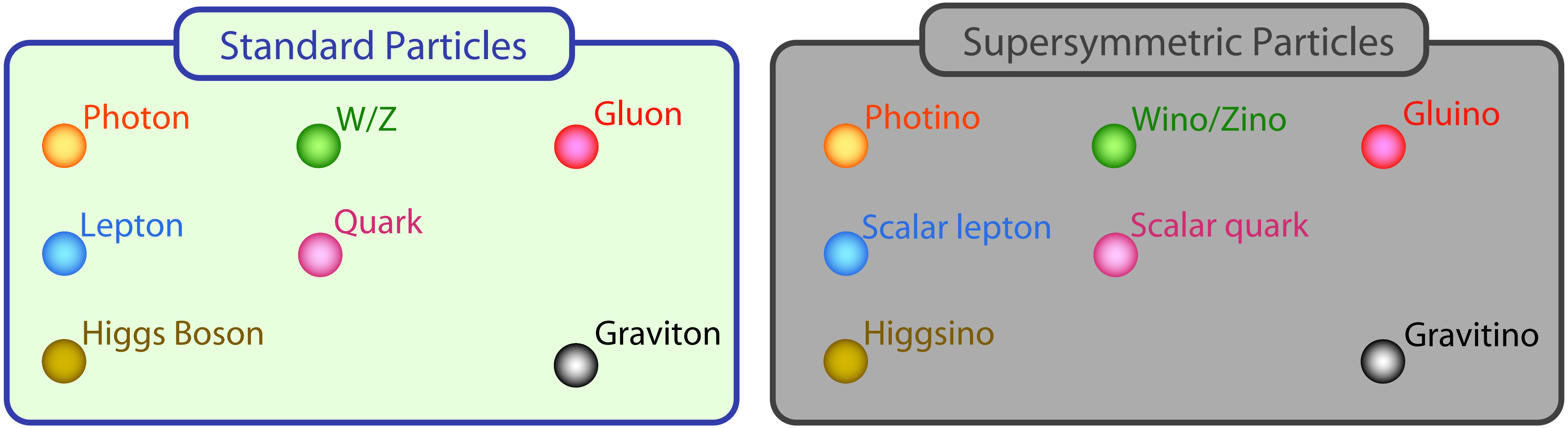
- SUSY
- UED
- Little Higgs (with T-parity)
- $\cdots$

What happens if dark-matter particle is produced in collider?

- Dark-matter particle is undetectable
- It becomes a source of missing p_T
- Missing p_T signal is very important, although it is not always the case

2. SUSY

Particle content



Important symmetry: R-parity

- $R = +/-$ for SM/SUSY particles
- R-parity is important to suppress nucleon decay

The LSP becomes stable if R-parity is conserved

$\Rightarrow$ Implications to cosmology

The LSP is a well-motivated candidate of dark matter

- If so, the LSP should be charge-neutral
- Otherwise, R-parity should be violated

Properties of dark matter depend what the LSP is

- LSP in the MSSM sector, or
- LSP as a superpartner of more exotic particles

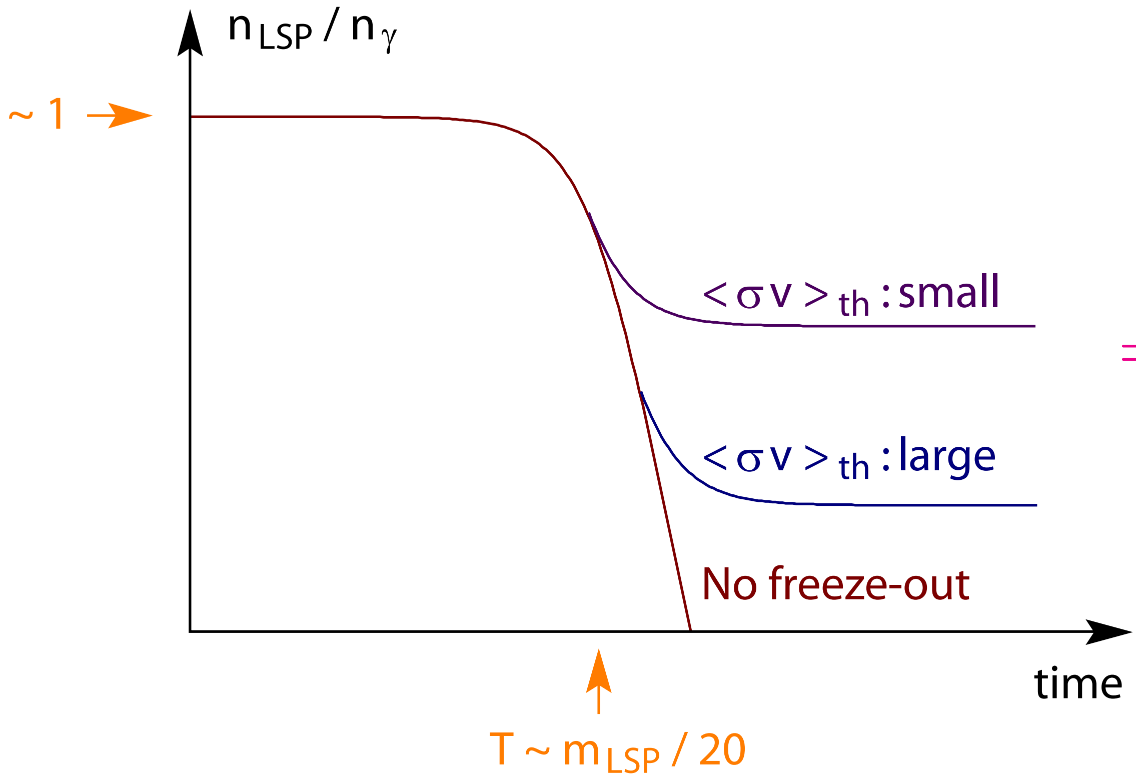
Candidates of the LSP (with R-parity)

- The lightest neutralino
- Gravitino
- Exotic ones (axino, right-handed sneutrino, moduli, $\cdots$)

3. Case with Neutralino LSP

If the lightest neutralino χ_1^0 is the LSP, $\cdots$

- Relic abundance of the LSP is thermally determined (in the simplest case)
- $\Omega_{\mathrm{LSP}} \propto$ (annihilation cross section)$^{-1}$



$$\Rightarrow \quad \Omega_{\mathrm{LSP}} \simeq 0.2 \times \left(\frac{\langle \sigma v \rangle}{0.9 \ \mathrm{pb}} \right)^{-1}$$

We should see if $\Omega_{\text{MSSM-LSP}} = \Omega_{\text{CDM}}$ holds using colliders

$\Rightarrow$ If $\Omega^{(\text{rec})}_{\text{MSSM-LSP}} = \Omega_{\text{CDM}}$, it supports the LSP-CDM scenario

$\Rightarrow$ If not, we need some exotic scenario

$\Rightarrow$ Test of the thermal history up to $T \sim O(10 \text{ GeV})$

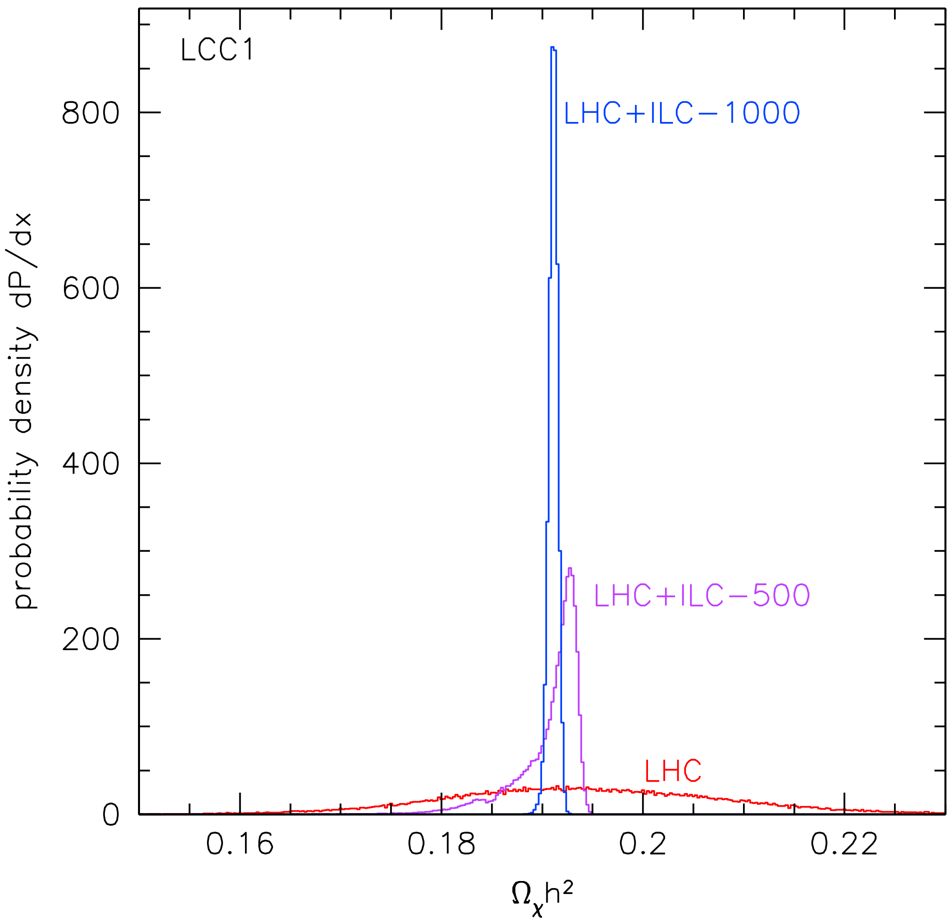
For the reconstruction of $\Omega_{\text{MSSM-LSP}}$, we need to measure

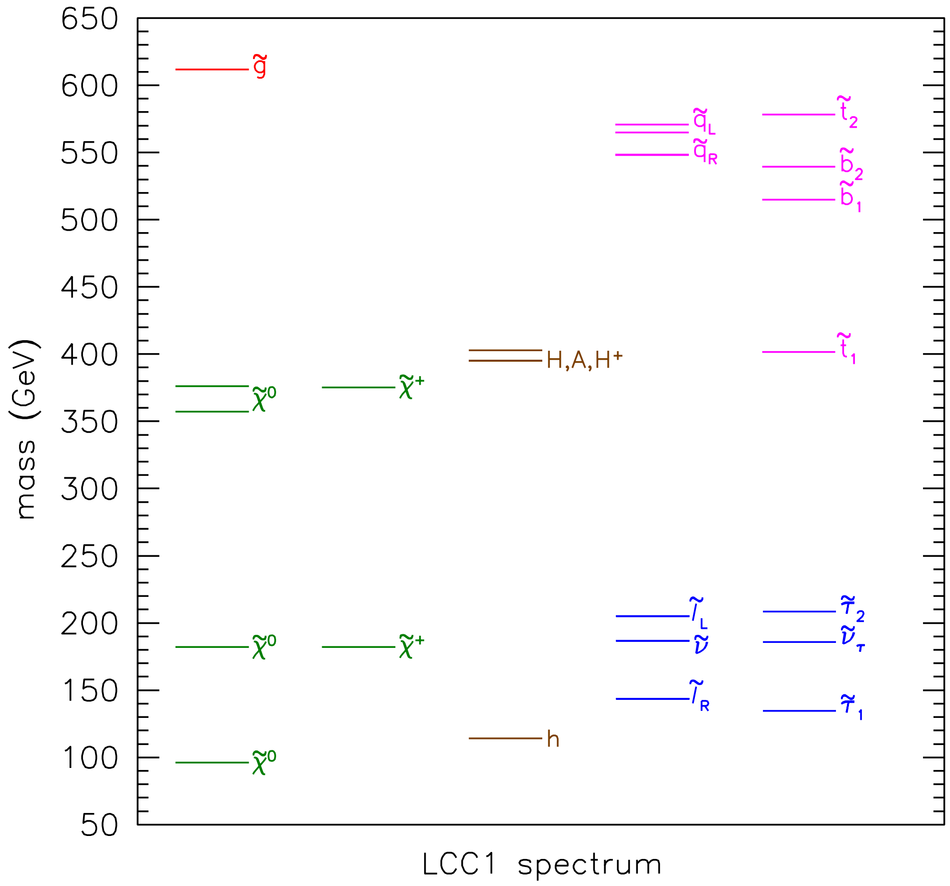
- Masses of (MSSM) superparticles
- Mixing angles (of mass matrices of superparticles)
- Coupling parameters
- $\cdots$

Accuracy of $\Omega^{(\text{rec})}_{\text{MSSM-LSP}}$ depends on underlying parameters

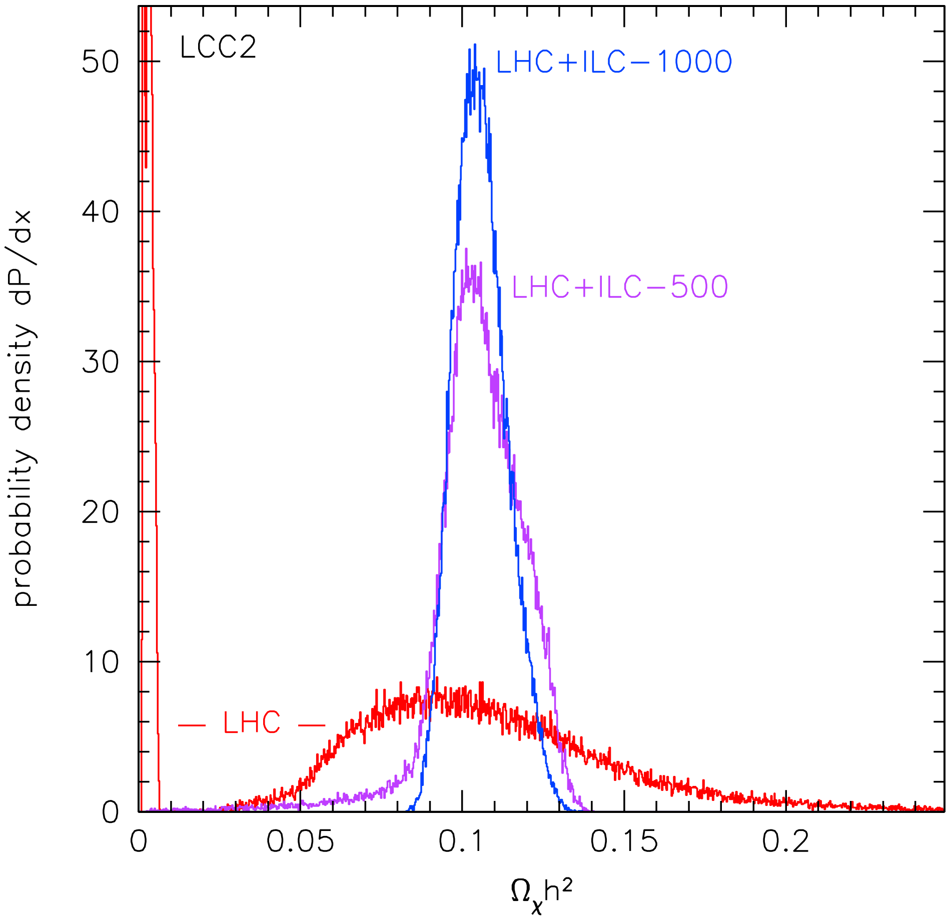
In some case, $\Omega_{\mathrm{MSSM\text{-}LSP}}$ is determined only with the LHC

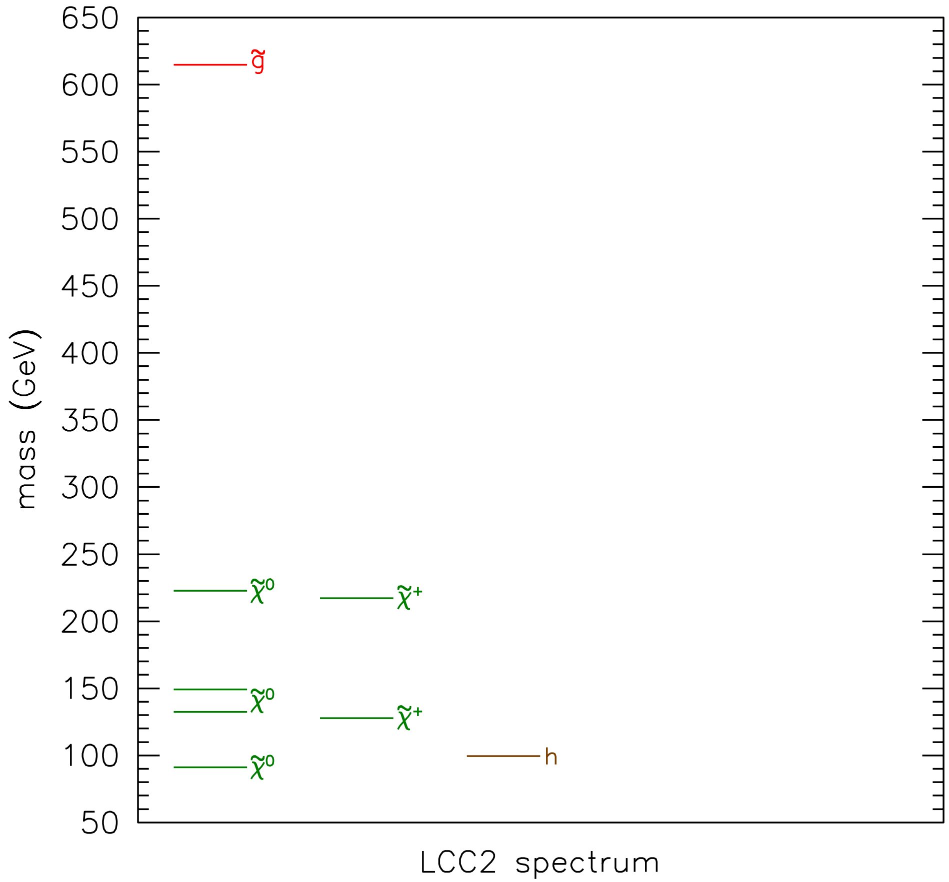
[Baltz, Battaglia, Peskin & Wizansky]



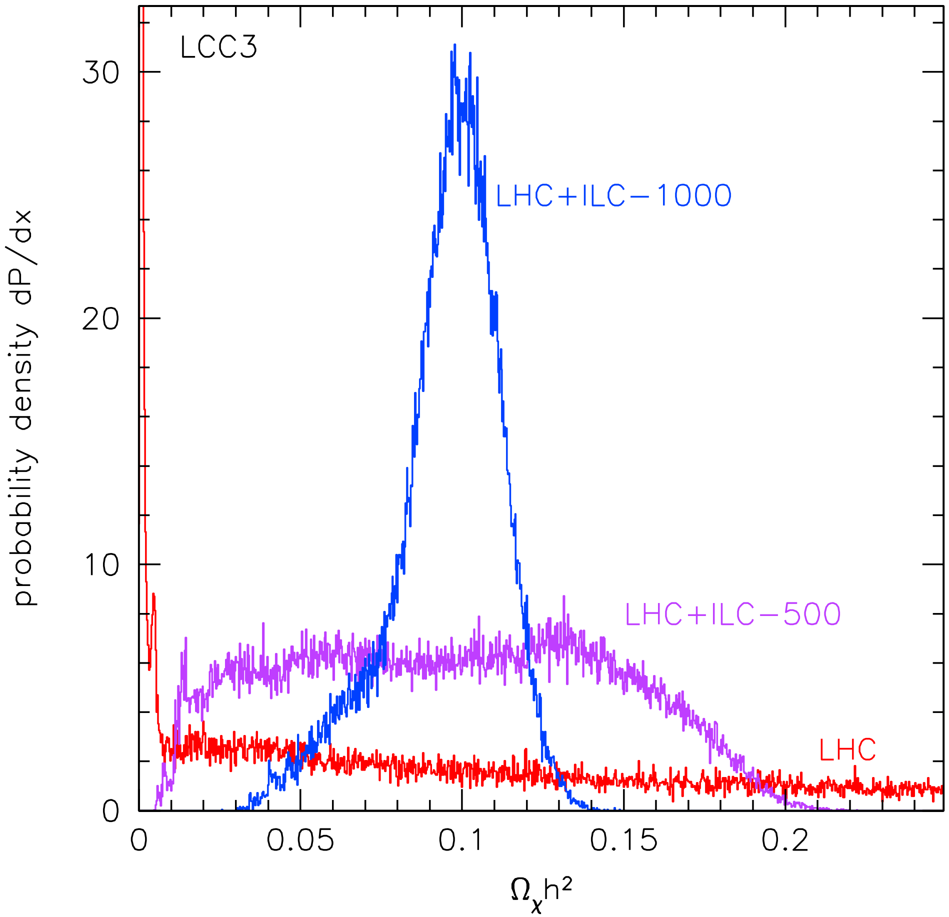


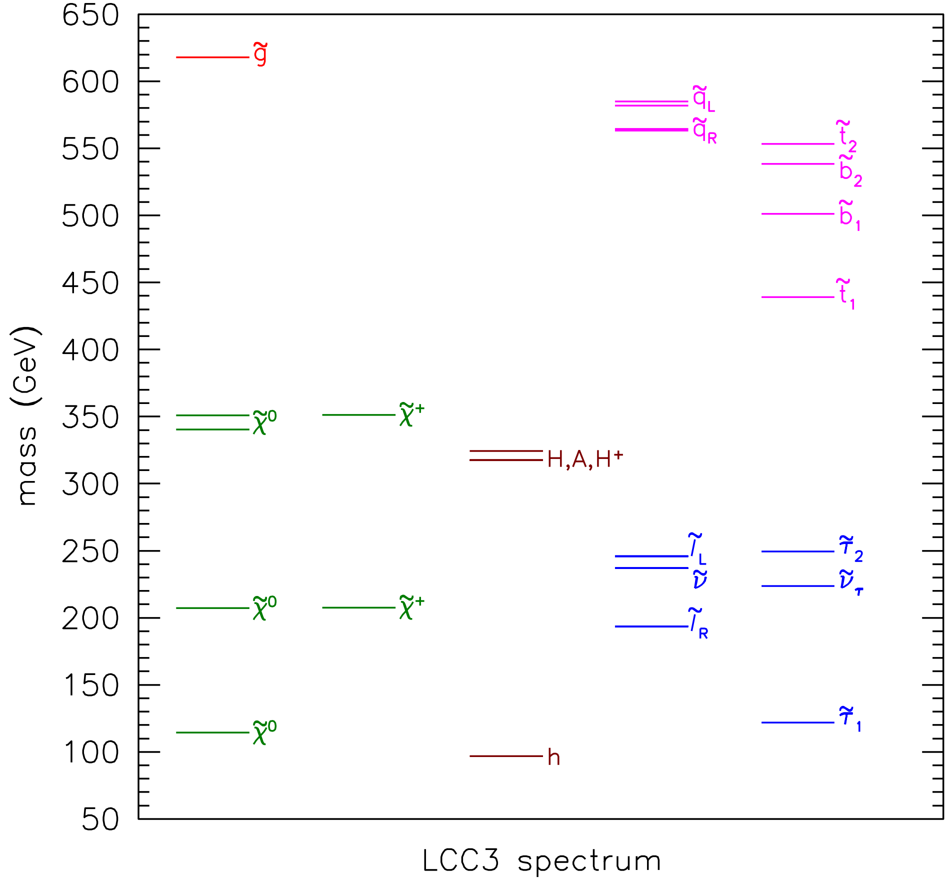
In other case, accuracy gets worse: focus-point case





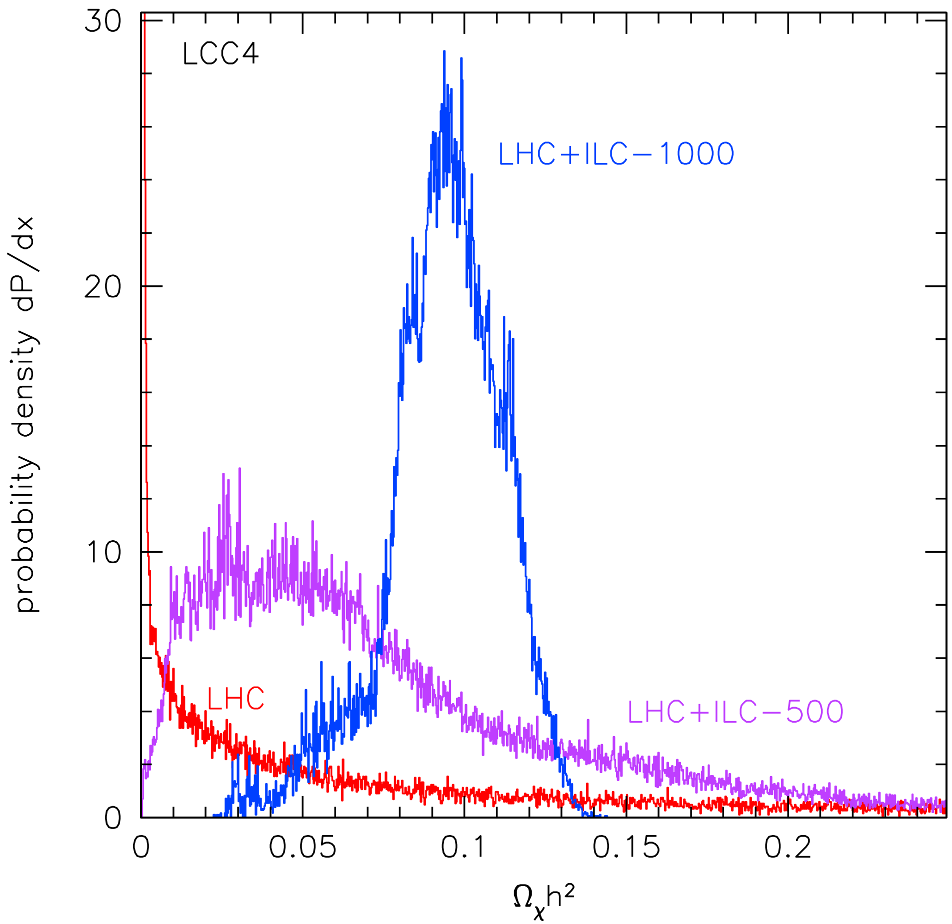
Or we may need 1 TeV ILC: co-annihilation case

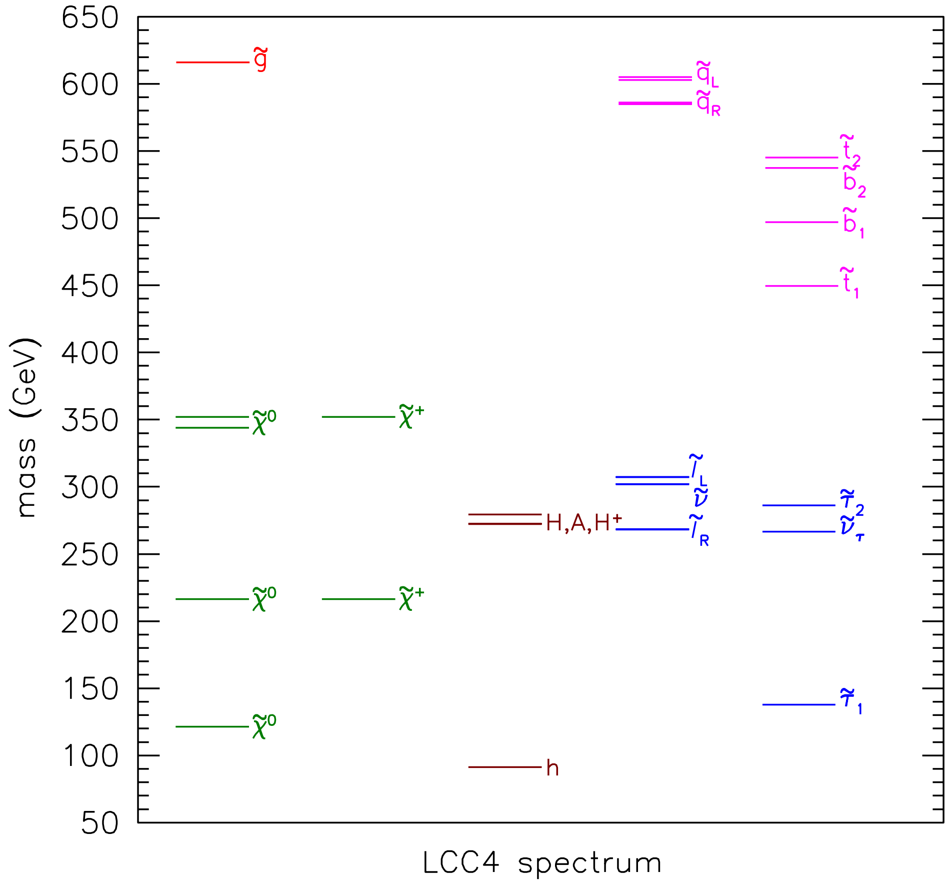




⇒ $m_{\tilde{\tau}} - m_{\chi_1^0}$ is hard to measure

Another difficult case: Funnel region





$\Rightarrow m_A$ and Γ_A are hard to measure

In fact, χ_1^0 may have non-thermal origin:

- Decay of other exotics (gravitino, moduli fields, $\cdots$)

Gravitino: superpartner of graviton

- Very weakly interacting: (interaction) $\propto M_{\rm Pl}^{-1}$
- Very long-lived (if it's unstable)

$$\tau_{3/2} \sim 10^4 \text{ sec} \times \left(\frac{m_{3/2}}{1 \text{ TeV}} \right)^{-3}$$

In SUSY cosmology, gravitino is important (and dangerous)

1. Gravitino is produced at the reheating era after inflation
2. Primordial gravitino decays at later epoch
3. The LSP (like χ_1^0) is produced by the decay of gravitino

Standard BBN well explains abundances of light elements

$\Rightarrow$ Gravitino may spoil the success of standard BBN

- Hadro-dissociation
- Photo-dissociation
- $p \leftrightarrow n$ conversion

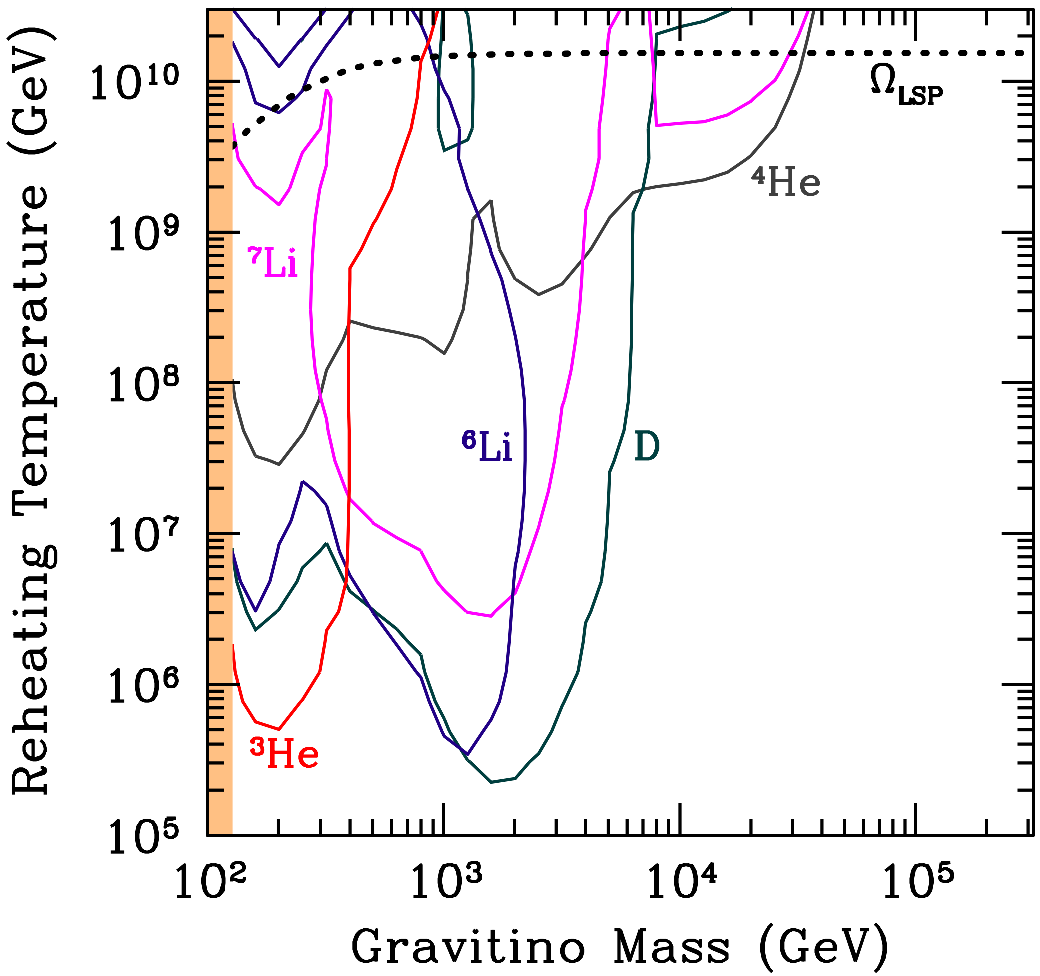
$\Rightarrow$ Too large gravitino abundance is dangerous

Gravitino production at the reheating era after inflation

$$n_{3/2} \sim 2 \times 10^{-14} \times (\text{entropy density}) \times \left(\frac{T_{\mathrm{R}}}{10^8 \ \text{TeV}} \right)$$

Upper bound on the reheat temperature

[Kawasaki, Kohri, Moroi & Yotsuyanagi, preliminary]



LSP is produced by the decay of gravitino

- $T_{\mathsf{R}} \gtrsim 10^{9-10}$ GeV is necessary to produce sufficient LSP

$$\Omega_{\mathsf{LSP}} = \frac{m_{\mathsf{LSP}}}{m_{3/2}} \left[\Omega_{3/2}\right]_{\mathsf{would\text{-}be}}$$

- Stringent constraints from BBN

$\Rightarrow m_{3/2} \gtrsim 30$ TeV

In the anomaly-mediated model, this possibility is important

- In AMSB, Wino may be the LSP: $\Omega_{\mathsf{LSP}}^{(\mathsf{thermal})} \ll 0.1$
- In AMSB, gravitino mass is $O(10 - 100 \text{ TeV})$

LHC phenomenology in the AMSB case (with $\tilde{W}^0$ LSP)

- Masses of $\tilde{W}^\pm$ and $\tilde{W}^0$ are very close: $m_{\tilde{W}^\pm} - m_{\tilde{W}^0} \lesssim 200$ MeV

  $\Rightarrow \tilde{W}^\pm \to \tilde{W}^0 \pi^\pm$

  $\Rightarrow c\tau_{\tilde{W}^\pm} \sim 5$ cm

- It is non-trivial to detect $\tilde{W}^\pm$

  $\Rightarrow \tilde{W}^\pm$ may be observed as a short charged track

- In some class of anomaly-mediated model, squark and slepton masses are $O(10$ TeV$)$

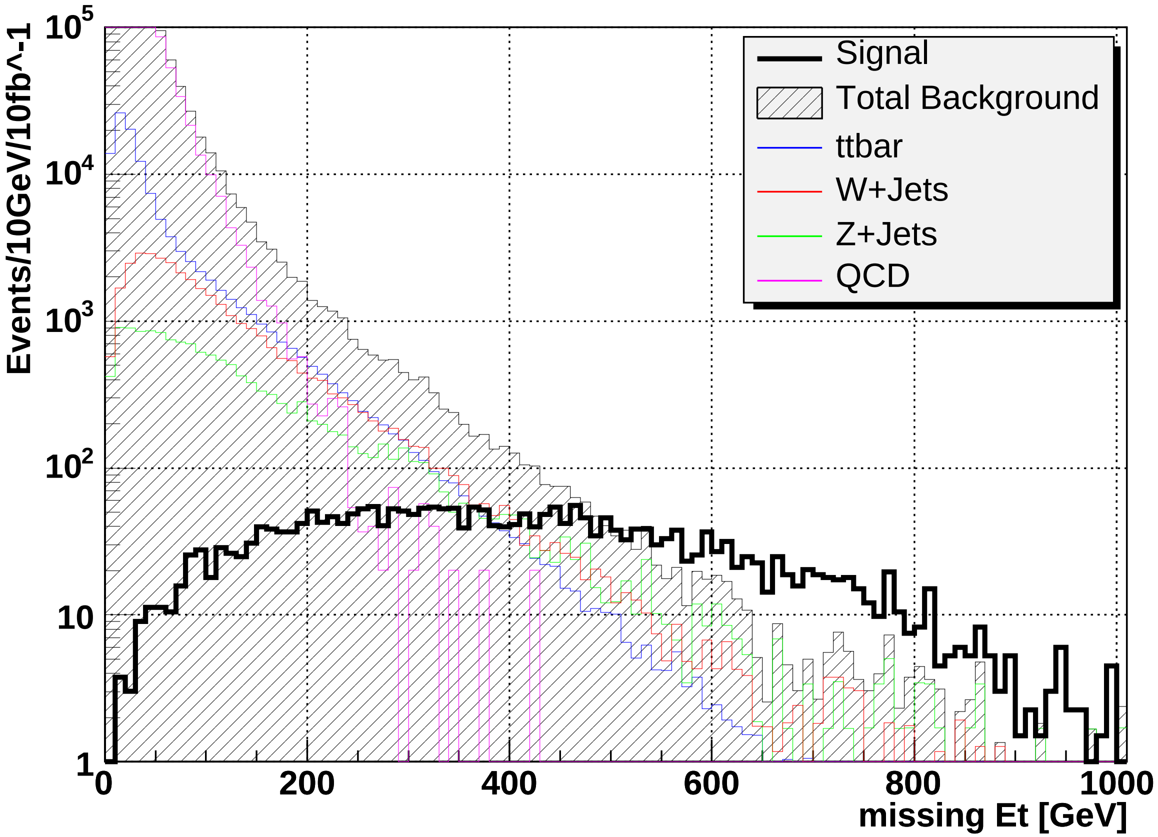
  $\Rightarrow$ Hard to see signals from squark productions

Dominant production process of SUSY particles: $pp \to \tilde{g}\tilde{g}$

$\Rightarrow$ Gluon decays as $\tilde{g} \to \tilde{W}qq/\tilde{B}qq$

For discovery of "SUSY" signal, missing E_T is useful as usual

[Asai, Moroi, Nishihara & Yanagida]



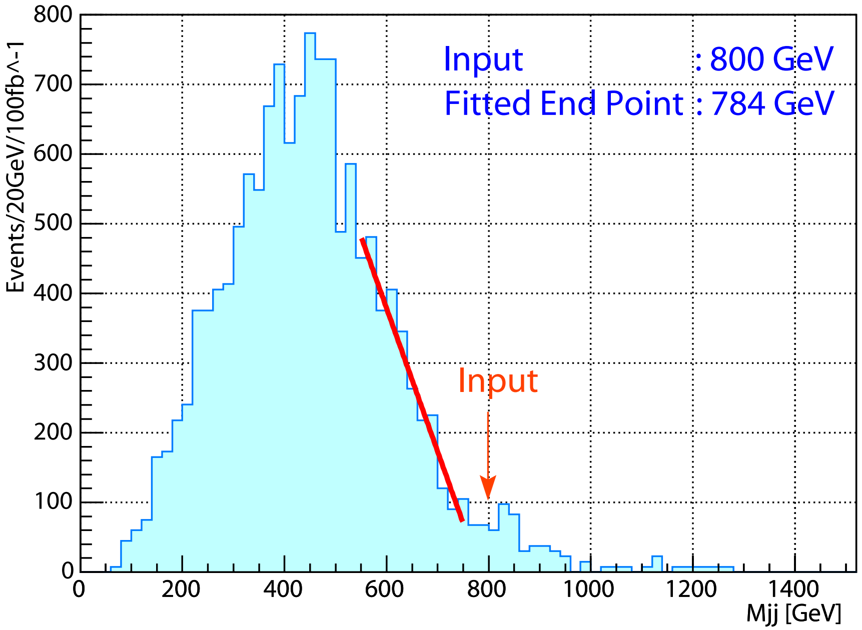
$m_{\tilde{g}} - m_{\tilde{W}}$ can be measured from dijet invariant mass

[Asai, Moroi, Nishihara & Yanagida]

For $\tilde{g} \to \tilde{W} q\bar{q}$: $M_{q\bar{q}} \leq m_{\tilde{g}} - m_{\tilde{W}} \Leftarrow$ parton-level relation

Dijet invariant mass: $Br(\tilde{g} \to \tilde{W} q\bar{q}) = 0.75$

- $(M_{13},\ M_{24})$ or $(M_{14},\ M_{23})$, whichever $|M_{ij} - M_{kl}|$ is smaller

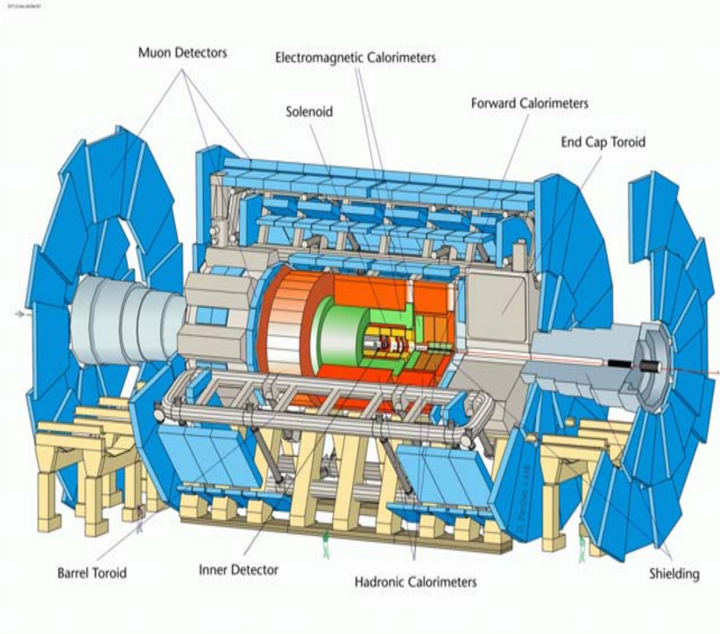


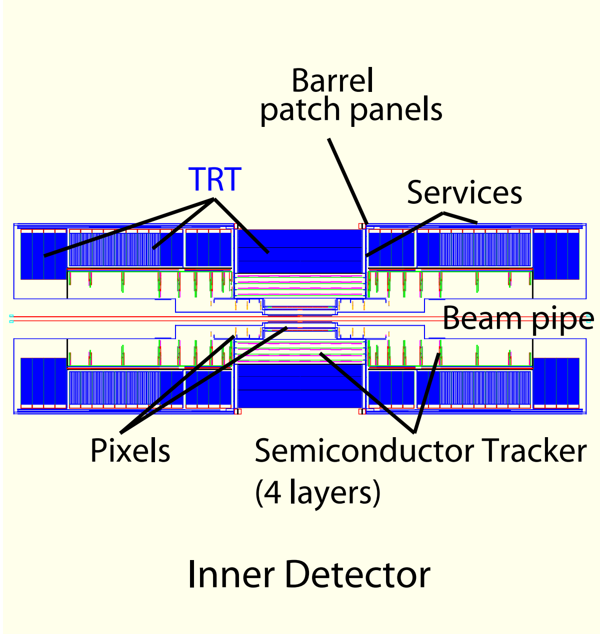
$\Rightarrow \delta(m_{\tilde{g}} - m_{\tilde{W}}) \simeq 5\ \%$

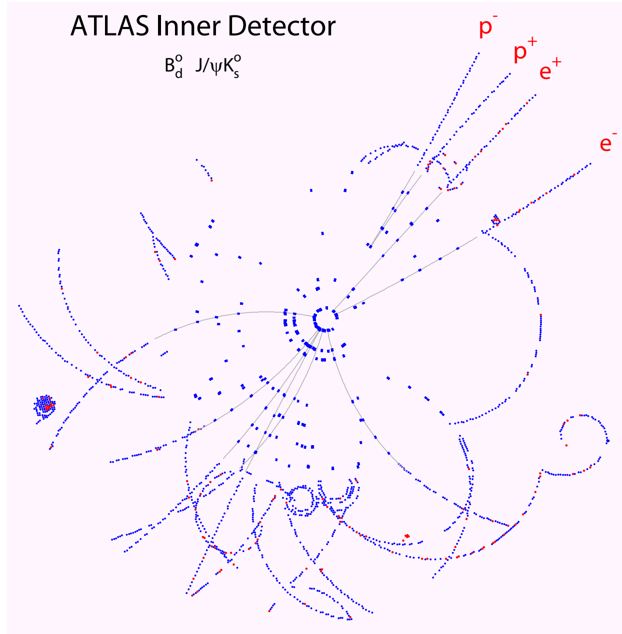
Can we find charged Wino even if $c\tau_{\tilde{W}^\pm} \sim 5$ cm?

[For Tevatron, see Feng, Moroi, Randall, Strasslar & Su]

⇒ ATLAS has Transition Radiation Tracker (TRT)

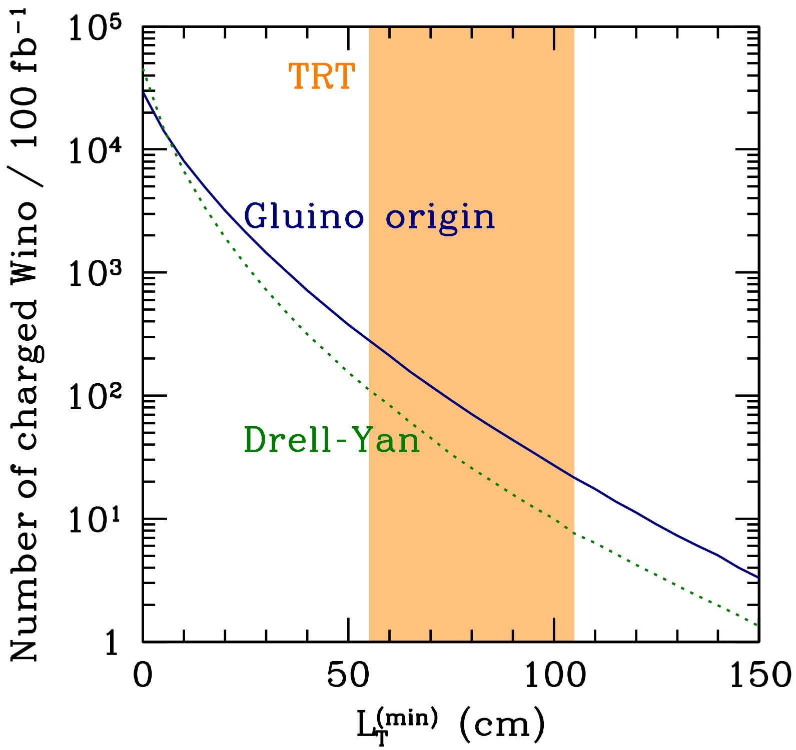






- TRT: 54 – 106 cm from the beam pipe
- TRT continuously follows charged tracks

Searches for short-charged tracks is strongly recommended



⇒ Sizable number of charged Wino tracks

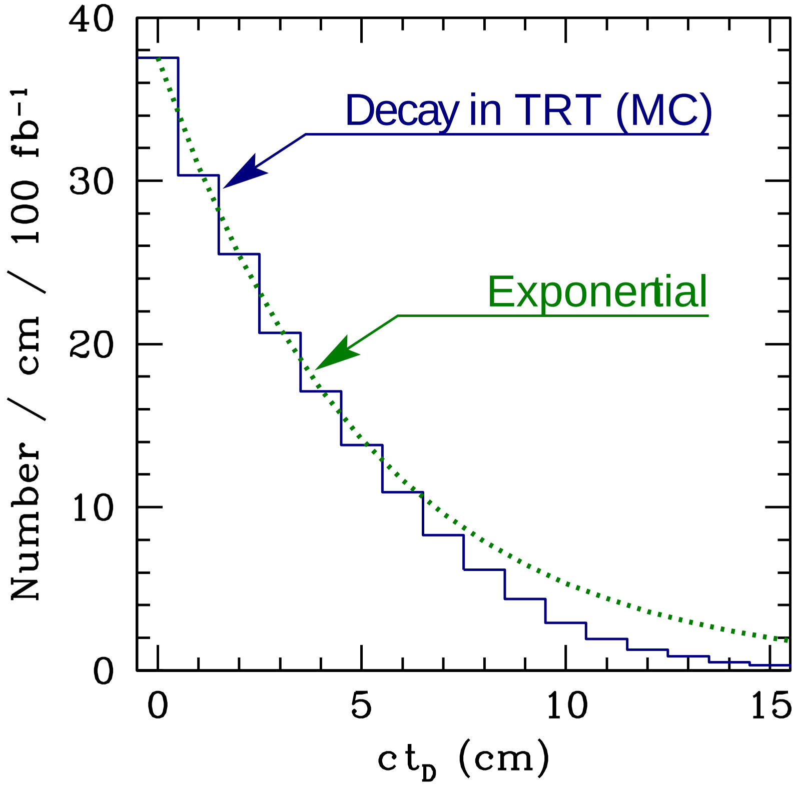
TRT has timing information: $\delta\beta \sim 0.1$ for $\beta < 0.85$

⇒ Wino mass may be determined: $\delta m_{\tilde{W}} \sim 10$ %

Measurement of Wino lifetime

[Asai, Moroi & Yanagida]

We may be able to use the distribution of travel length



$$t_D = \frac{m_{\tilde{W}^\pm}}{|\mathbf{p}_T|}(L_T - L_T^{(\min)})$$

$$\Rightarrow\ P(t_D) \propto e^{-t_D/\tau_{\tilde{W}^\pm}}$$

$$L_T^{(\min)} = 60\ \text{cm}$$

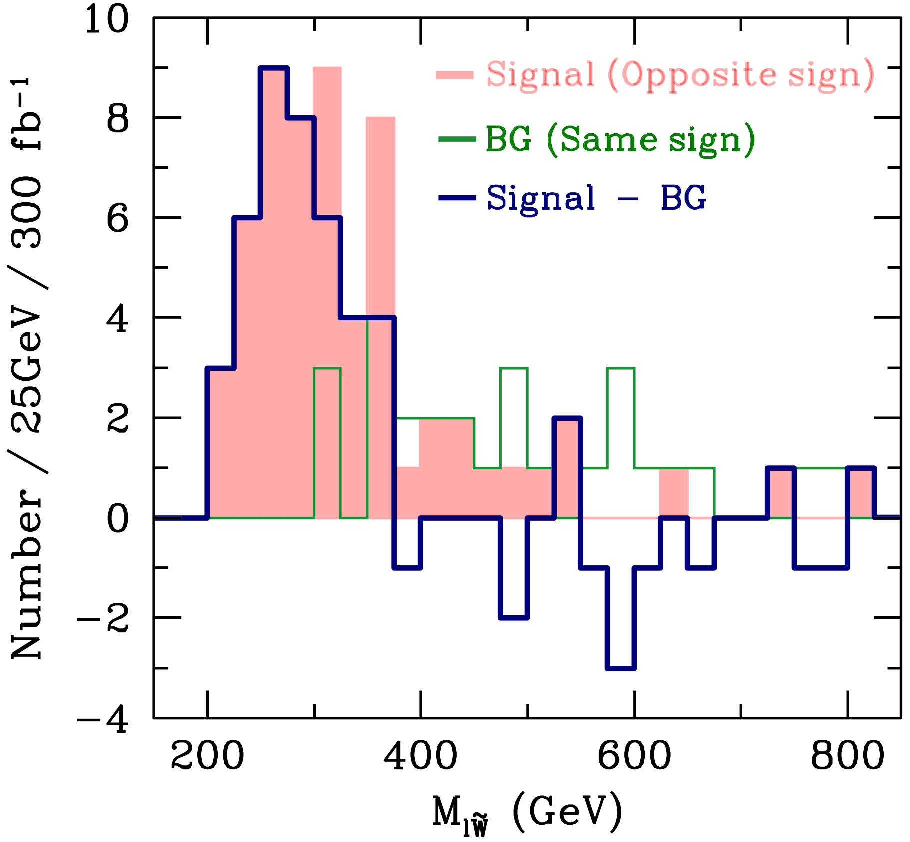
$$L_T^{(\max)} = 100\ \text{cm}$$

$\Rightarrow \tau_{\tilde{W}^\pm}$ may be determined with the accuracy of $10 - 20\ \%$

Study of the Bino mass: $\tilde{g} \to \tilde{B} q \bar{q}$ / $\tilde{B} \to \tilde{W}^{\pm} W^{\mp}$ / $W^{\mp} \to l\nu$

[Asai, Jinnouchi, Moroi, Shirai & Yanagida, preliminary]

$$\Rightarrow M_{l\tilde{W}^{\pm}}^{(\mathrm{max})} \simeq m_{\tilde{B}} + \cdots$$



- $L_{\mathrm{T}} > 45$ cm is used
- $M_2 = 200$ GeV
- $M_1 = 400$ GeV
- $M_3 = 1000$ GeV
- $M_{l\tilde{W}^{\pm}}^{(\mathrm{max})} \simeq 390$ GeV

3. Case with Gravitino LSP

Gravitino mass depends on the mechanism of SUSY breaking

- Anomaly mediation: $m_{3/2} \sim O(10 - 100 \text{ TeV})$
  [Randall & Sundrum; Giudice, Luty, Murayama & Rattazzi]
- Gravity mediation: $m_{3/2} \sim O(10 \text{ GeV} - 1 \text{ TeV})$
- Gauge mediation: $m_{3/2} \lesssim O(10 \text{ GeV})$
  [Dine & Nelson; Dine, Nelson, Nir & Shirman]

Gravitino is a well-motivated candidate of the LSP

- Missing p_T signal may not exist

  $\Rightarrow$ Heavy charged (or colored) particle (?)
- It may be the dark matter, although its confirmation is non-trivial

Gravitino may be dark matter, if it is the LSP

$\Rightarrow \Omega_{3/2} = \Omega_{\text{CDM}}$?

Origins of gravitino

- Decay of the MSSM-LSP
- Production at the very early universe (like reheating era)

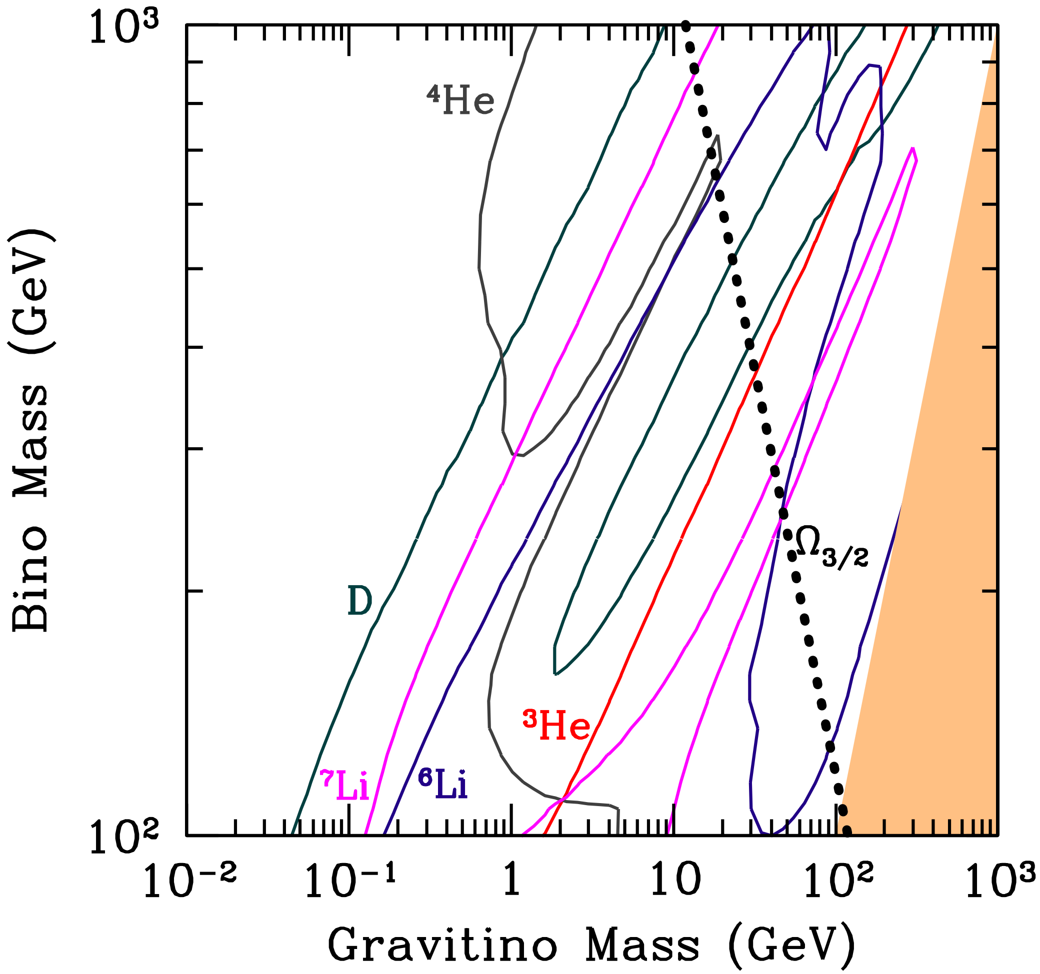
Check point: effects of the MSSM-LSP decay on BBN

- The MSSM-LSP decays only into gravitino ($+\cdots$)
- Lifetime of the MSSM-LSP becomes very long

$$\tau_{\text{MSSM-LSP}} \sim 10^8 \text{ sec} \left(\frac{m_{\text{MSSM-LSP}}}{100 \text{ GeV}} \right)^{-5} \left(\frac{m_{3/2}}{100 \text{ GeV}} \right)^2$$

BBN constraints: Bino as the MSSM-LSP

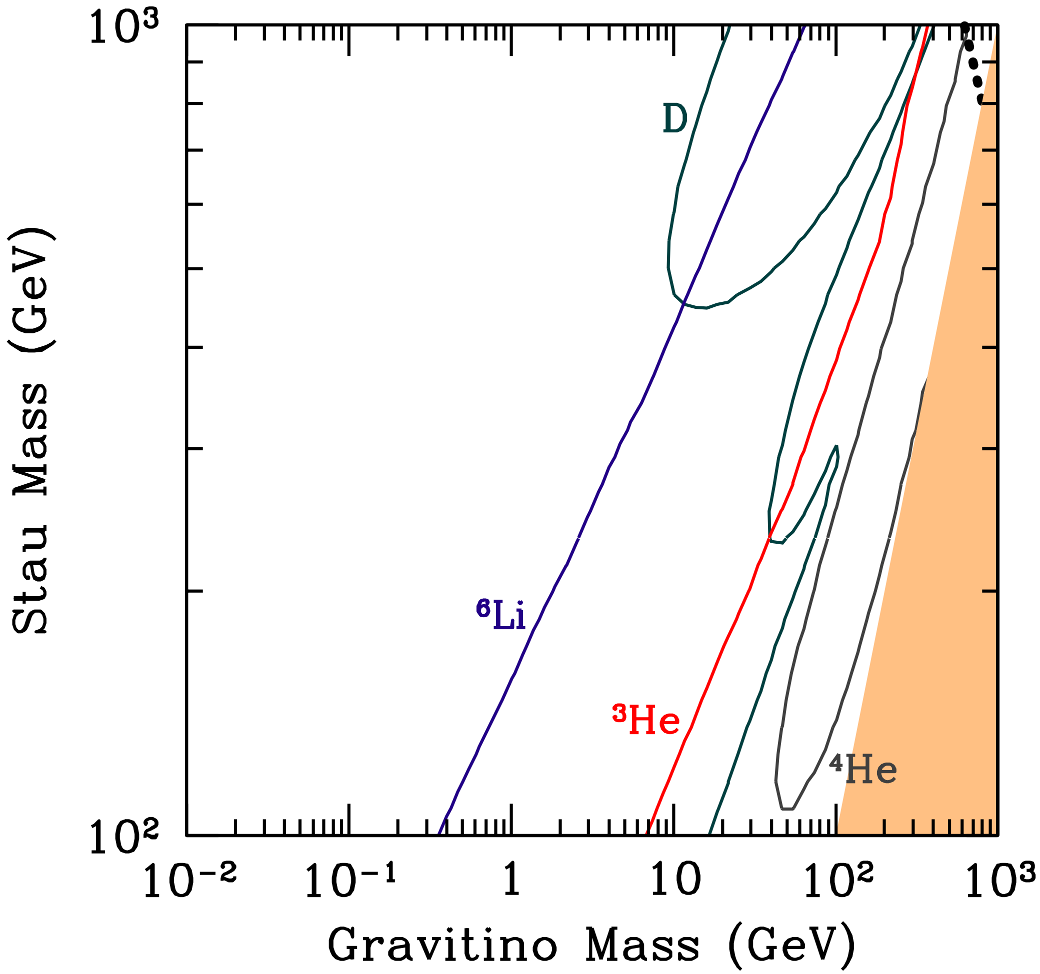
[Kawasaki, Kohri, Moroi & Yotsuyanagi, preliminary]



$$\Omega_{\tilde{B}}^{(\text{Thermal})} \simeq 0.2 \times \left(\frac{m_{\tilde{B}}}{200 \text{ GeV}} \right)^2$$

BBN constraints: Stau as the MSSM-LSP

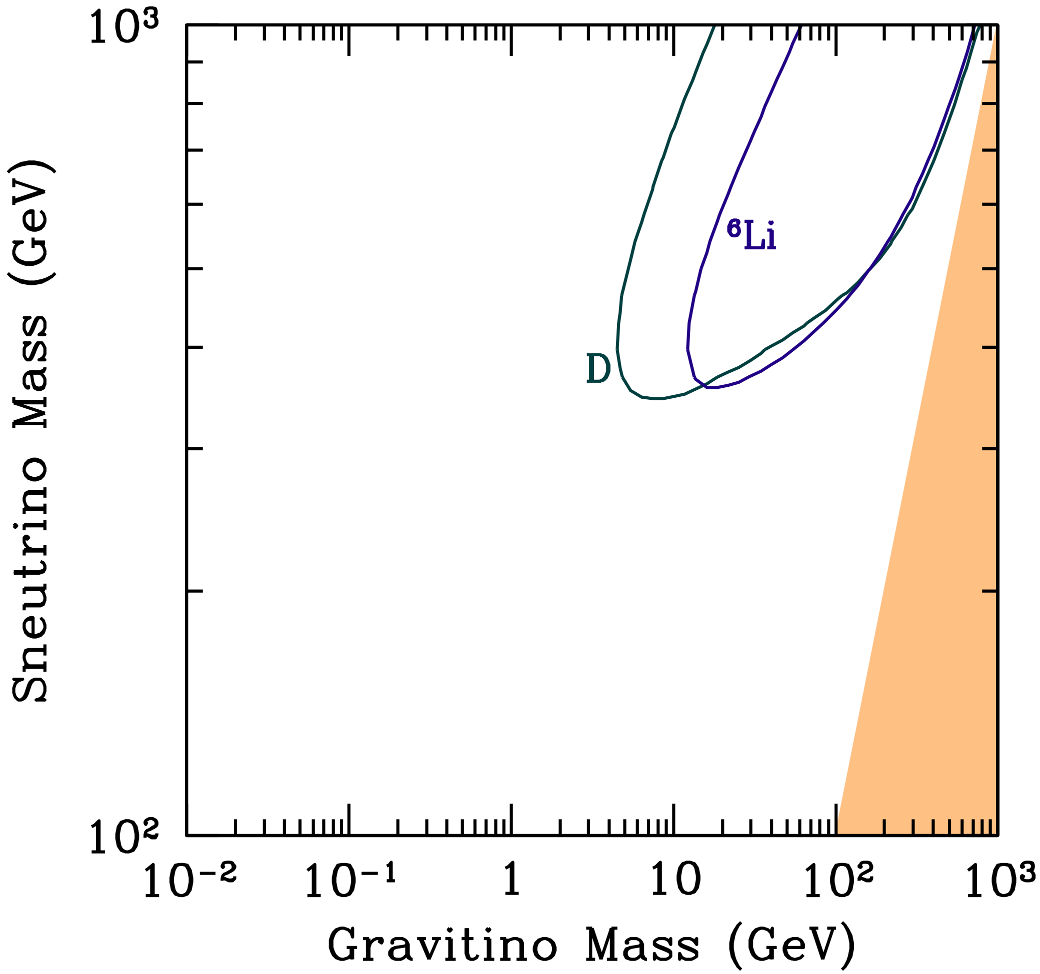
[Kawasaki, Kohri, Moroi & Yotsuyanagi, preliminary]



$$\Omega_{\tilde{\tau}}^{(\text{Thermal})} \simeq 0.4 \times \left(\frac{m_{\tilde{\tau}}}{1 \text{ TeV}} \right)^2$$

BBN constraints: Sneutrino as the MSSM-LSP

[Kawasaki, Kohri, Moroi & Yotsuyanagi, preliminary]



$$\Omega_{\tilde{\nu}}^{(\mathsf{Thermal})} \simeq 0.1 \times \left(\frac{m_{\tilde{\nu}}}{1\ \mathsf{TeV}} \right)^2$$

In order to realize gravitino-CDM scenario:

- Serious BBN constraints on the decay of MSSM-LSP
- Relic gravitino should be mainly from scattering processes

If gravitino is the LSP, gravitino may be produced at the LHC

$\Rightarrow$ Study of gravitino at the LHC (Hamaguchi-san's talk)

BBN constraints may be relaxed if R-parity is broken

[Buchmuller, Covi, Hamaguchi, Ibarra & Yanagida]

$\Rightarrow$ MSSM-LSP decays via R-violating interaction

$\Rightarrow$ $\tau_{3/2} \gg 10^{10}$ yr is possible to realize gravitino dark matter

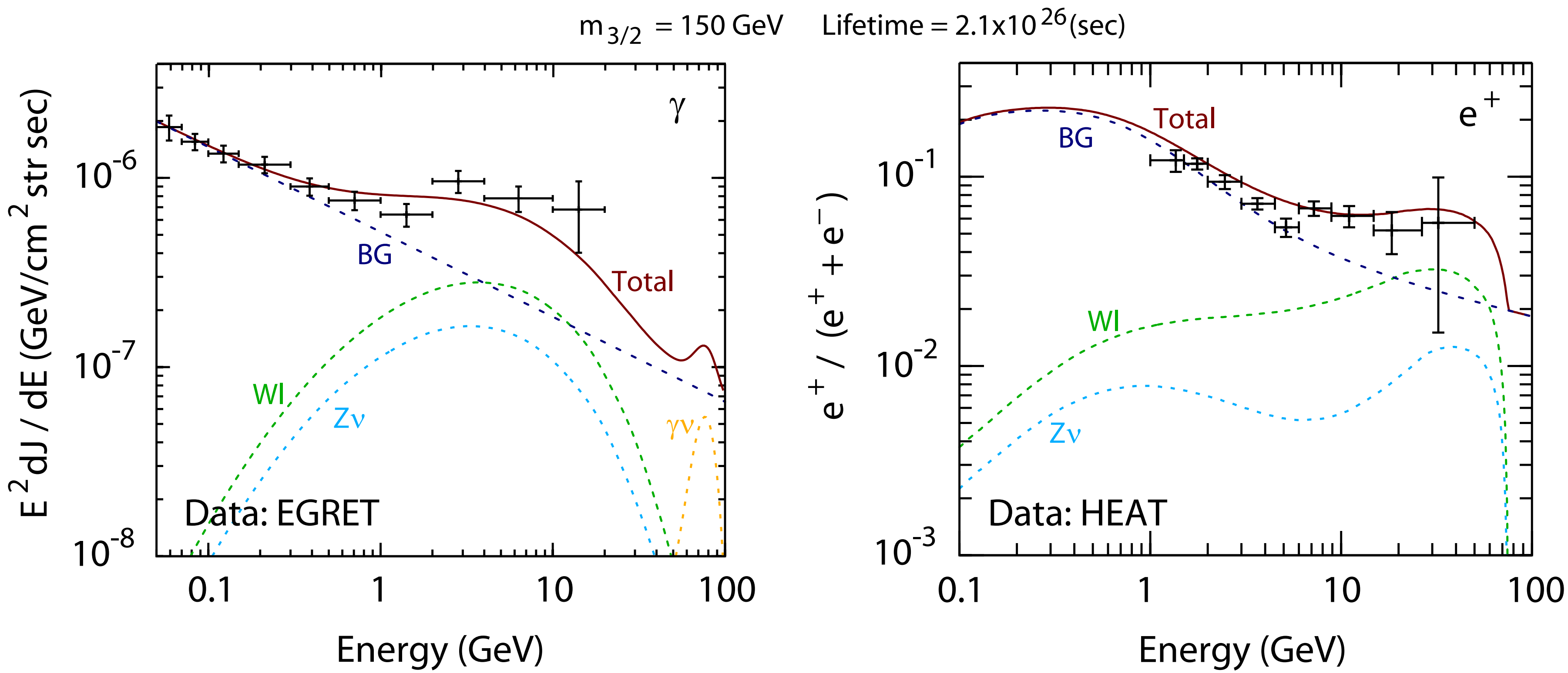
$\Rightarrow$ Interesting signals in colliders and in astrophysics

Possible signals from the gravitino dark matter with RPV

- Gamma ray from the decay of gravitino CDM

  [Buchmuller, Covi, Hamaguchi, Ibarra & Yanagida]

- Positron from the decay of gravitino CDM



[Ishiwata, Matsumoto & Moroi, preliminary]

4. (No) Conclusion

We are all waiting for results from the LHC