Pure Gravity Mediation

- A heavy sfermion scenario -

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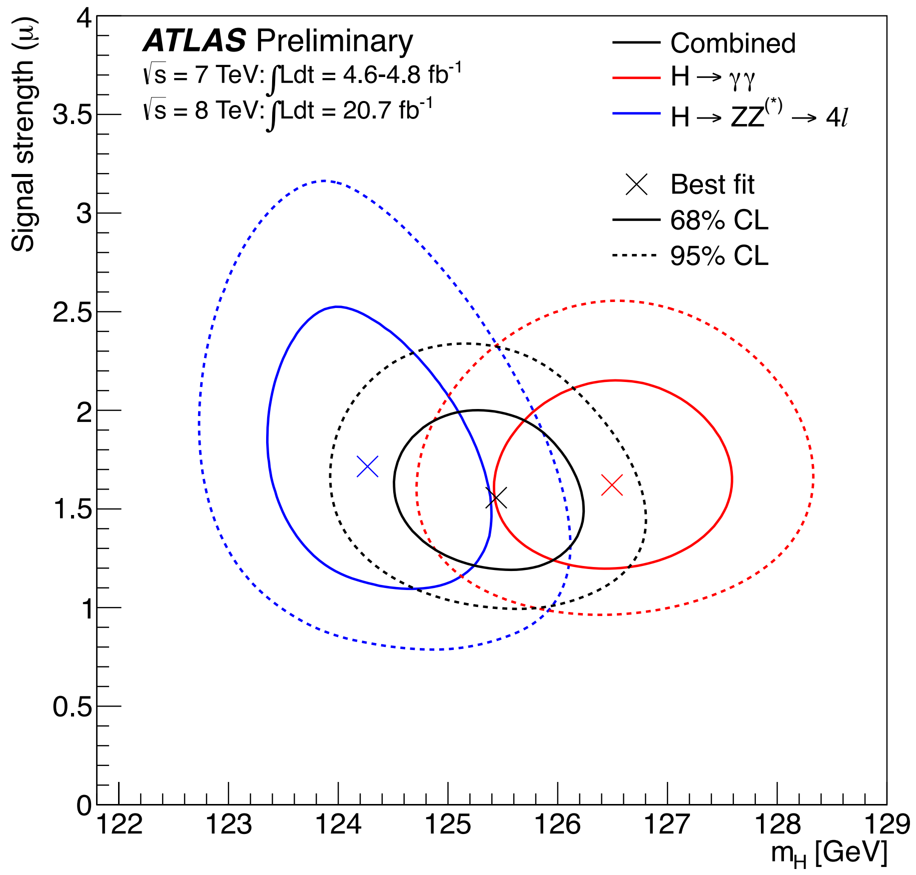
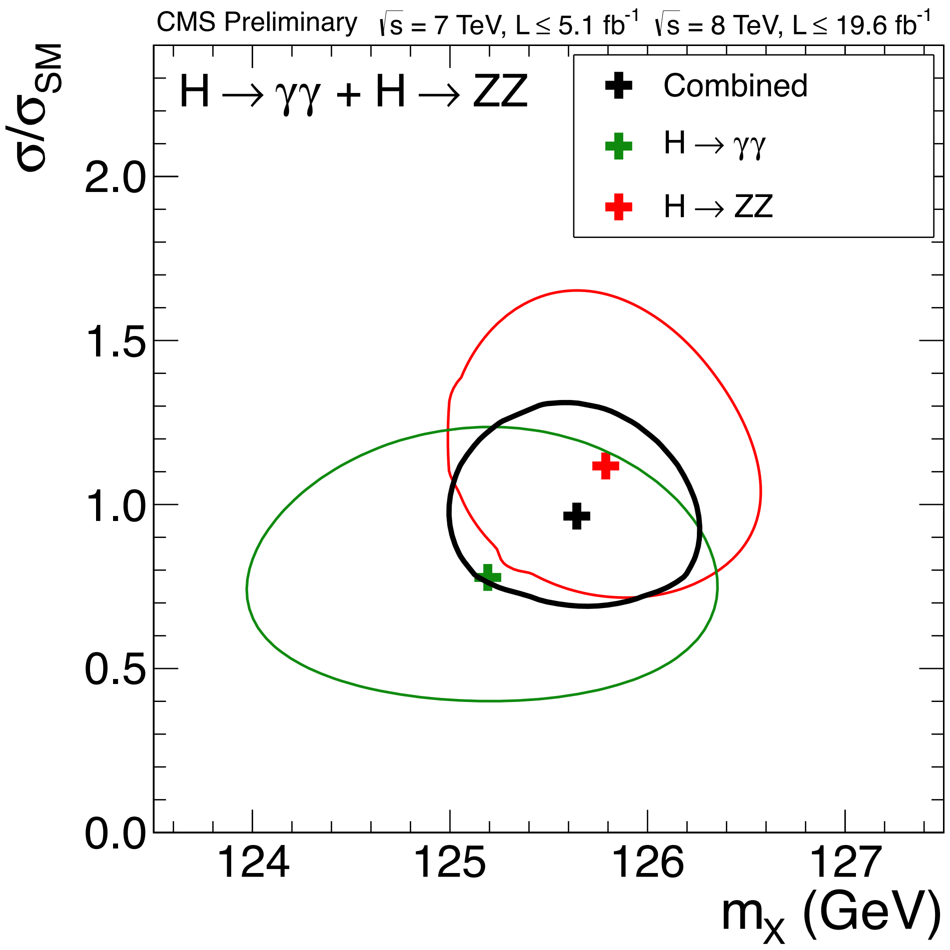
SUSY : Model-Building and Phenomenology
2013/12/4

SM is being completed

Higgs boson has been discovered!



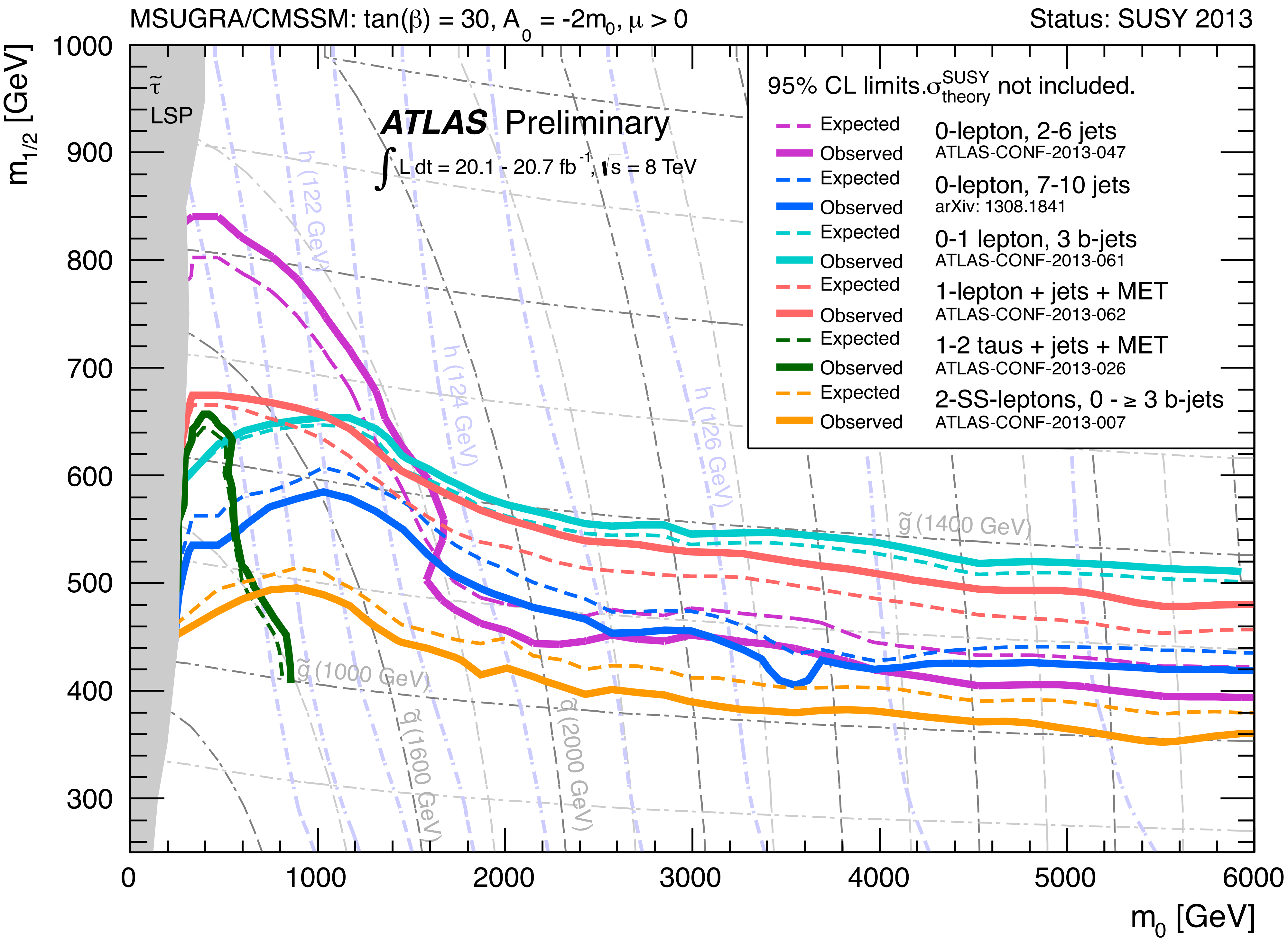


Both the ATLAS and the CMS discovered a new boson with mass around 125-126 GeV compatible with the SM Higgs boson!

[ATLAS:Phys.Lett.B716(2012)1, CMS:Phys.Lett.B716(2012)30]

Now the SM is being completed...

Limits on SUSY particles...



Supersymmetry?

No observation of superparticles so far....

Is SUSY still interesting?

✓ SUSY allows the vast separation between the Planck scale and much lower energy scale.

If $m_{SUSY} = O(1) TeV$ → SUSY discovery is around the corner!

Talks by H.Murayama, G.Ross, N.Yokozaki, J. Ruderman, T. Volansky...

Even if $m_{SUSY} > O(1) TeV$ → We need to rethink/relax "naturalness".
Interesting phenomenology is possible

Talks by J.Sunghoon, K.Harigaya, J. Ruderman, T. Volansky...

✓ "Light" weakly interacting Higgs fits well with SUSY !

We may have discovered a SUSY partner of the Higgsino :) .

✓ In the MSSM, the Higgs boson mass is interrelated to the mass scale of not yet observed sfermion masses!

Supersymmetry?

What does *126* GeV Higgs boson mean in SUSY models?

In the MSSM, the tree-level Higgs boson mass is given by the gauge coupling constants.

$$V = -\, m_{higgs}^{2}/2\; h^{\dagger}h + \lambda/4\; (h^{\dagger}h)^{2}$$

A combination of the SUSY breaking masses and the Higgsino mass

$\lambda = (g'^{2}+g^{2})/2\; \cos^{2}2\beta$
from gauge couplings

$[\tan\beta = v_{u}/v_{d}]$

The predicted Higgs boson mass is around Z-boson mass,

$$m_{higgs} = \lambda^{1/2}\, v \sim m_{Z} \cos 2\beta$$

at the tree-level.

Supersymmetry?

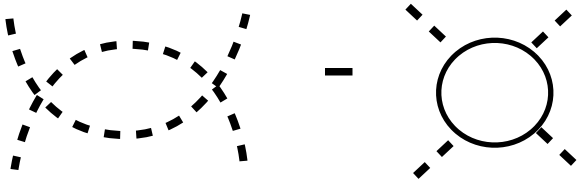
The radiative corrections to the Higgs boson mass logarithmically depend on the stop masses!

$$\boxed{m_{h^0}^2 \lesssim m_Z^2 \cos^2 2\beta + \boxed{\frac{3}{4\pi} y_t^2 m_t^2 \sin^2\beta \left(\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_t^2} - \frac{1}{12}\frac{X_t^4}{m_t^4} \right)}}$$

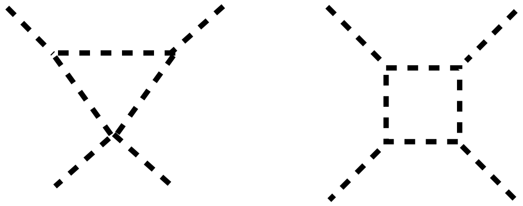
Tree-level quartic term:

$$\lambda = \frac{1}{2}(g_1^2 + g_2^2)\cos^2 2\beta$$

One-loop log enhanced:



One-loop finite:

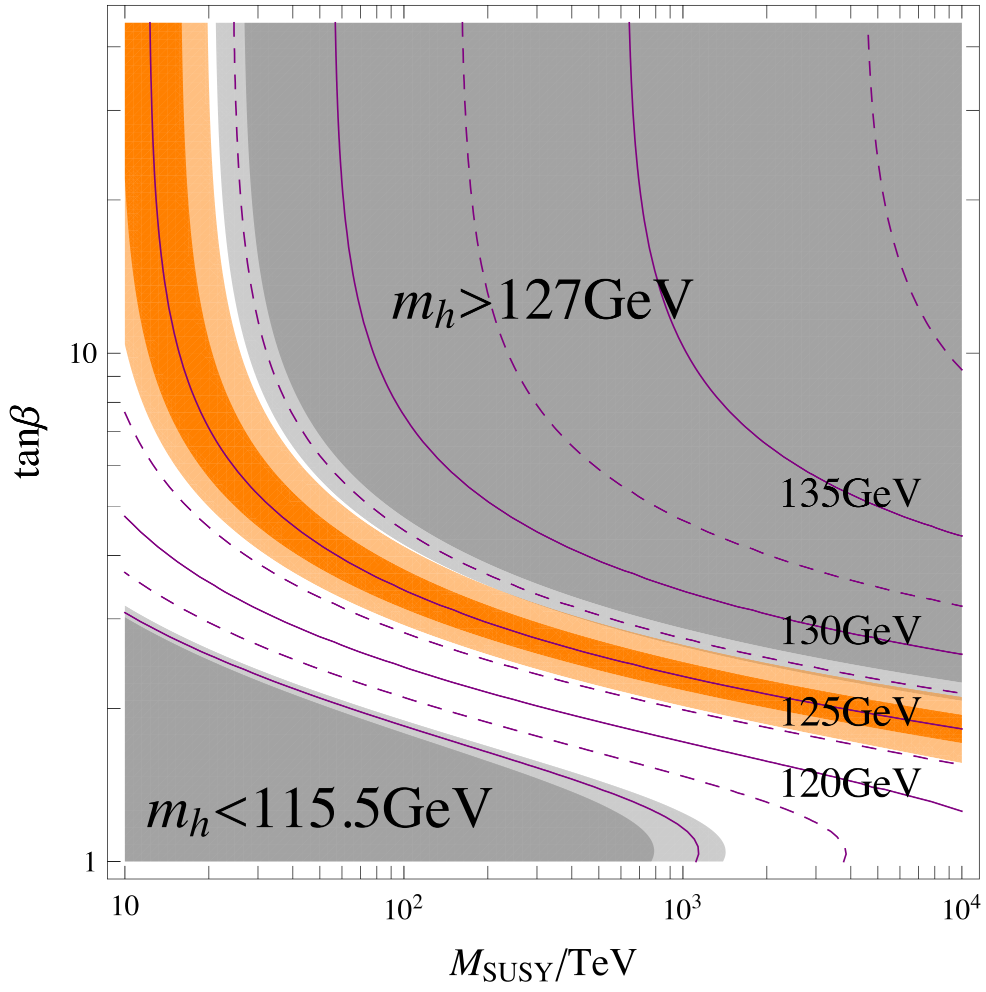


['91 Okada, Yamaguchi, Yanagida, '91 Haber, Hempfling, '91 Ellis, Ridolfi, Zwirner]

The heavier Higgs boson mass than *m_Z* can be obtained for larger SUSY breaking effects!

Supersymmetry?

In the simplest case, m_{higgs} ~ *126 GeV* suggests the sfermion (stop) masses much larger than *1TeV*, (*O(10-1000) TeV ?*) .



[’12, MI, Matsumoto,Yanagida ($\mu_H = O(M_{susy})$)]

Is $M_{SUSY} = O(10\text{-}1000)$ *TeV* good ?

✓ Consistent with negative results at the LHC experiments.

gluino mass >*1.4 TeV* for $M_{susy} \gg TeV$

✓ SUSY-FCNC/CP constraints are relaxed!

$$\sqrt{\tilde{m}_{LL}\tilde{m}_{RR}} \gtrsim 4000\ \text{TeV} \times \sqrt{\left|\text{Im}\left(\frac{m^{d\,2}_{12,LL}}{\tilde{m}^2_{LL}}\frac{m^{d\,2}_{12,RR}}{\tilde{m}^2_{RR}}\right)\right|}\,,$$

[’96 Gabbiani, Gabrielli, Masiero, Silvestrini]

(State of the art 3-loop analysis suggests that a bit smaller stop mass is OK.)

Talks by P.Kant.

Supersymmetry?

How about the naturalness arguments?

⟶ $m_{SUSY} = O(10\text{-}1000) TeV$ requires fine-tuning of $O(10^{-4}\text{-}10^{-8})$.

✓ This is not satisfactory at all, but it is much better than the SM which requires fine-tuning of $O(10^{-28}\text{-}10^{-32})$.

→ Better than the Standard Model !

In this relaxed sense, the naturalness arguments are still meaningful motivation for the "low scale" SUSY even for $m_{SUSY} = O(10\text{-}1000) TeV$.

Supersymmetry?

What fills the gap between *O(10-1000)TeV* and *O(100)GeV*?

- ✓ At this point, I do not have very convincing solutions....

- ✓ *O(100)GeV Weak scale* is chosen by anthropic arguments...

  (Talk by J.Ruderman : dangerous boundaries may put upper limit on the weak scale)

- ✓ *O(10-1000)TeV* SUSY could be *the least fine-tuned* scenario.

  Ex.) a *lower limit* on the SUSY breaking scale & anthropic arguments...

  (Talk by K.Harigaya : Inflation model puts a lower limit on the gravitino mass > *100TeV* !)

- ✓ Focus point mechanism ?

  → *weak scale Higgs sector* out of very heavy SUSY parameters.

  ['99 Feng, Matchev, Moroi]

  (Talks by R.Gross, N.Yokozaki, P.Kant...)

Supersymmetry?

In the simplest MSSM, $m_{higgs} \sim 126 GeV$ suggests the sfermion (stop) masses are rather high $O(10\text{-}1000) TeV$.

- ✓ Consistent with negative results at the LHC experiments.
- ✓ SUSY-FCNC/CP problems are relaxed.
- ✓ Fine-tuning problem between $O(10\text{-}100) TeV$ and $O(100) GeV$.

Supersymmetry?

In the simplest MSSM, $m_{higgs} \sim 126GeV$ suggests the sfermion (stop) masses are rather high $O(10\text{-}1000)TeV$.

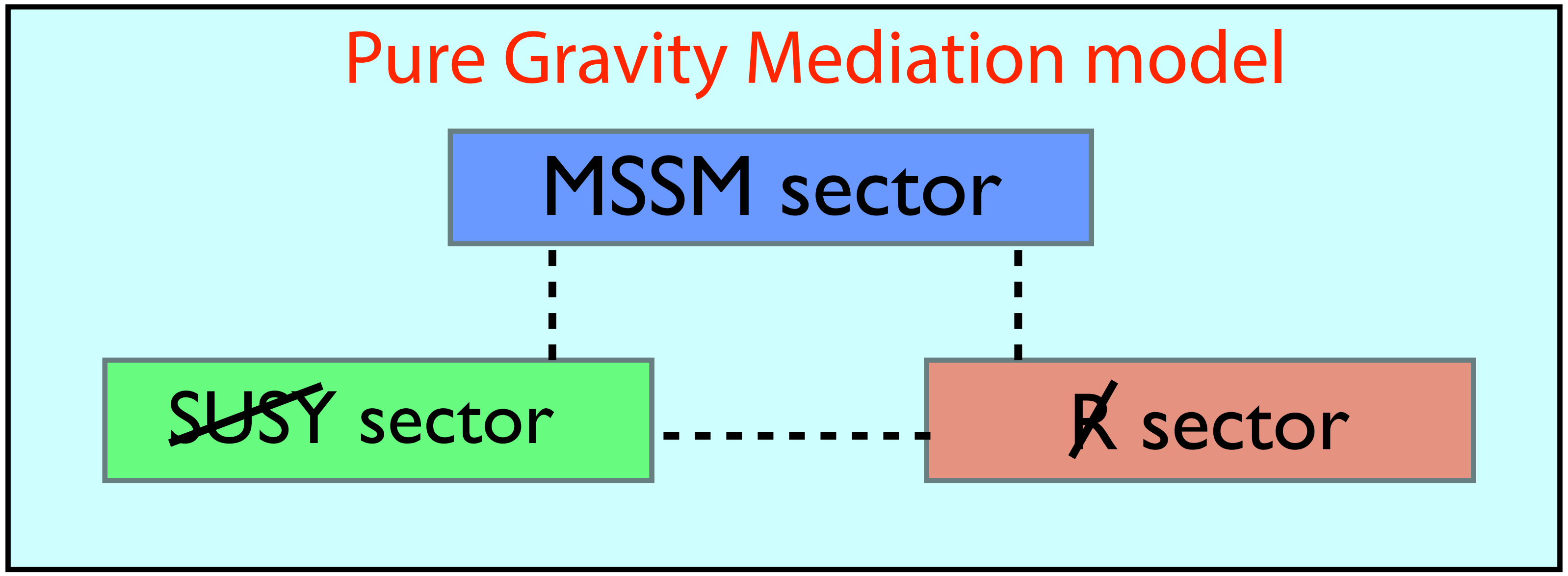
- ✓ Consistent with negative results at the LHC experiments.
- ✓ SUSY-FCNC/CP problems are relaxed.
- ✓ Fine-tuning problem between $O(10\text{-}100)TeV$ and $O(100)GeV$.

Once we accept fine-tuning between $O(10\text{-}1000)TeV$ and $O(100)GeV$?

The sfermion masses above $O(10\text{-}1000)TeV$ allow us to construct a very simple model, *Pure Gravity Mediation model*, consistent with cosmology!

- ✓ Good DM candidate.
- ✓ No gravitino problem.
- ✓ No Polonyi problem.
- ✓ Precise coupling unification.
- ✓ Can be tested at the LHC (via gaugino search)!
- ✓ Can be tested via dark matter search!

Pure Gravity Mediation Model


Pure Gravity Mediation model

MSSM sector

~~SUSY~~ sector

~~R~~ sector

['06 MI, Moroi, Yanagida, '11 MI, Yanagida, '12 MI, Matsumoto, Yanagida]

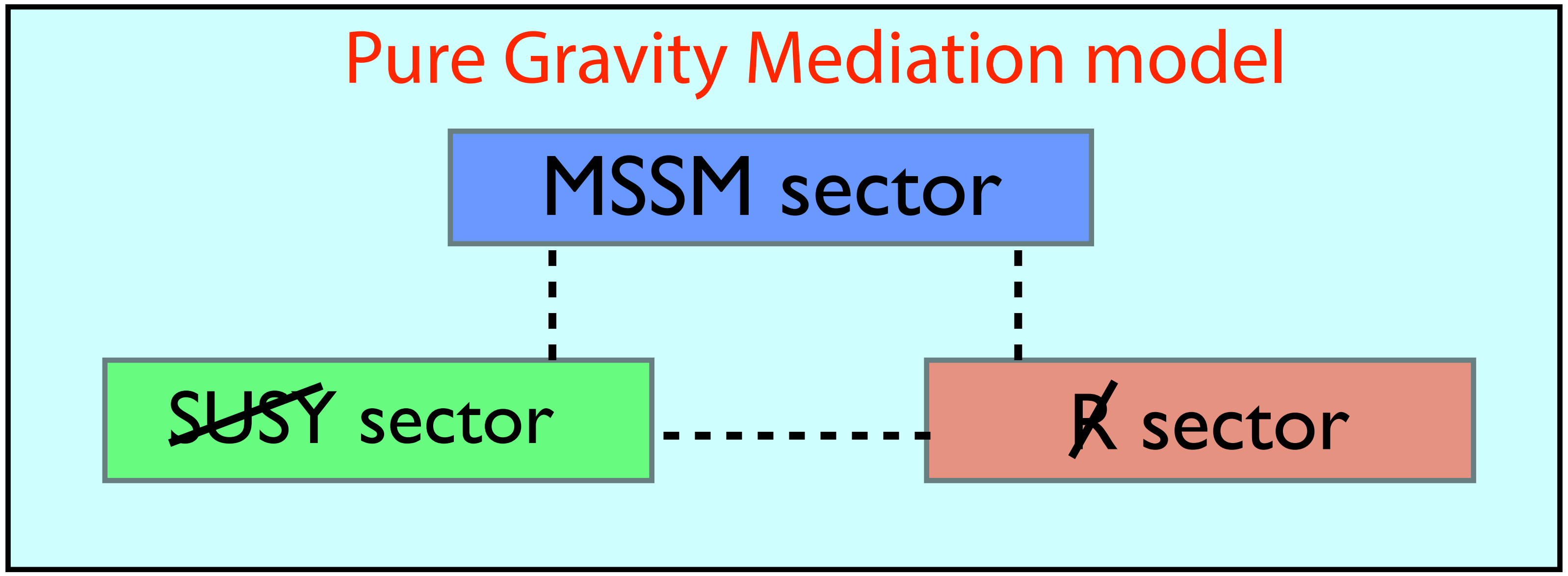
✓ They are connected by *Planck suppressed operators* with each other.

→ Pure Gravity Mediation

("without singlet" with heavy sfermions ['99 Giudice, Luty, Murayama, Rattazzi]
"PeV Supersymmetry" ['04 Wells] except for the origin of the μ-term)

✓ The Pure Gravity Mediation provides the simplest realization of *the minimal-SPLIT SUSY spectrum* ['12 Arkani-Hamed, Gupta, Kaplan, Weiner, Zorowski] !

Pure Gravity Mediation Model



Pure Gravity Mediation model

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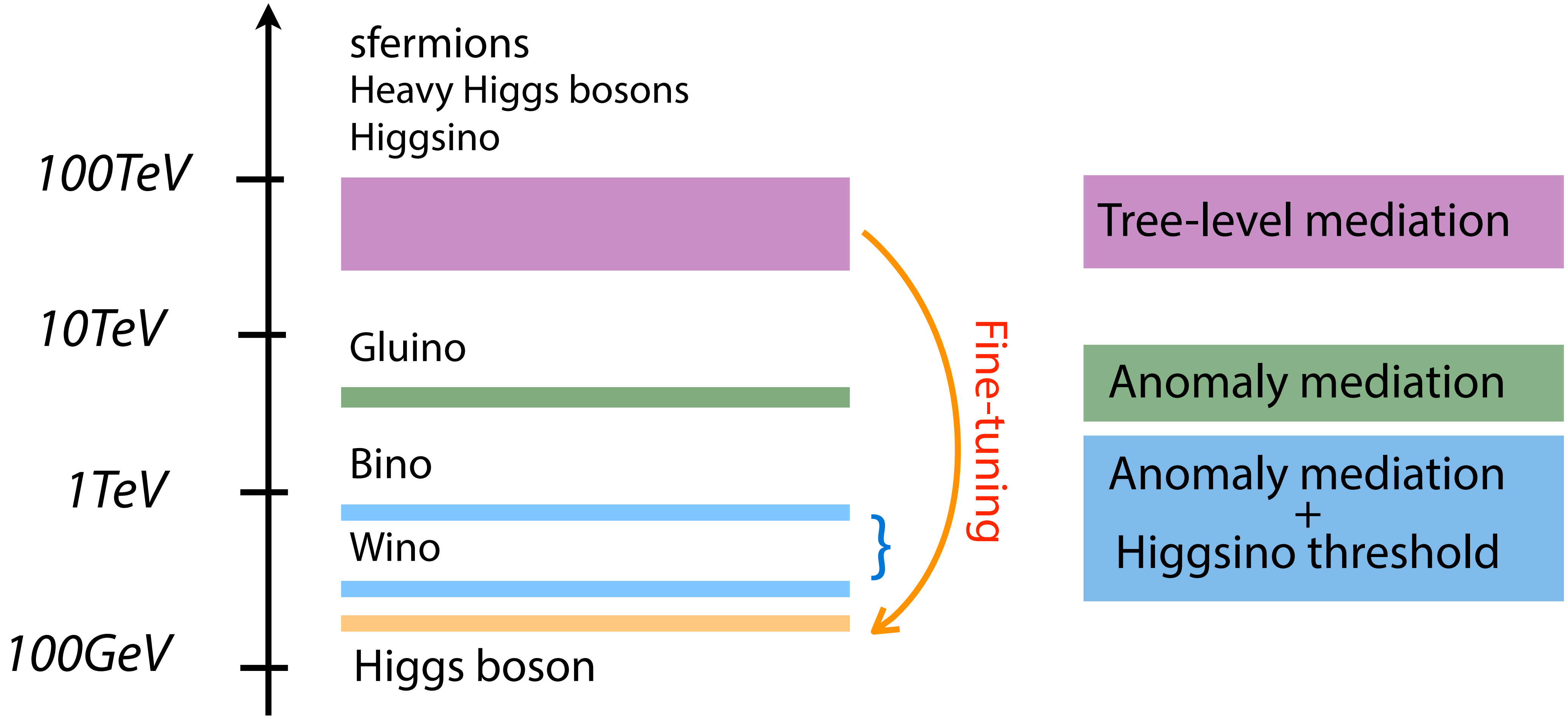


sfermions

Heavy Higgs bosons

Higgsino

100TeV

10TeV

1TeV

100GeV

Gluino

Bino

Wino

Higgs boson

Fine-tuning

Tree-level mediation

Anomaly mediation

Anomaly mediation
+
Higgsino threshold

[*minimal SPLIT spectrum* : E. Dudas, et.al., EPJ C73 (2013), M. Bose, M. Dine and JHEP 1303 (2013),A. Arvanitakia, et.al., JHEP 1302 (2013), L. Hall, et.al., JHEP 1031 (2013)...]

Pure Gravity Mediation Model

1. Origin of the sfermion masses of $O(10\text{-}100)TeV$?

The simplest realization → Gravity Mediation

$$K = \Phi^\dagger\Phi + c/M_{PL}^2\, Z^\dagger Z\, \Phi^\dagger\Phi + \ldots$$

$$\rightarrow\ m_{sfermion}^2 = m_{3/2}^2 + c\, m_{3/2}^2 + \ldots$$

[$m_{3/2}$: gravitino mass, Z : SUSY breaking field, Φ : sfermion]

$m_{sfermion} = O(10\text{-}100)TeV$ is realized for

$$m_{3/2} = O(10\text{-}100)TeV$$

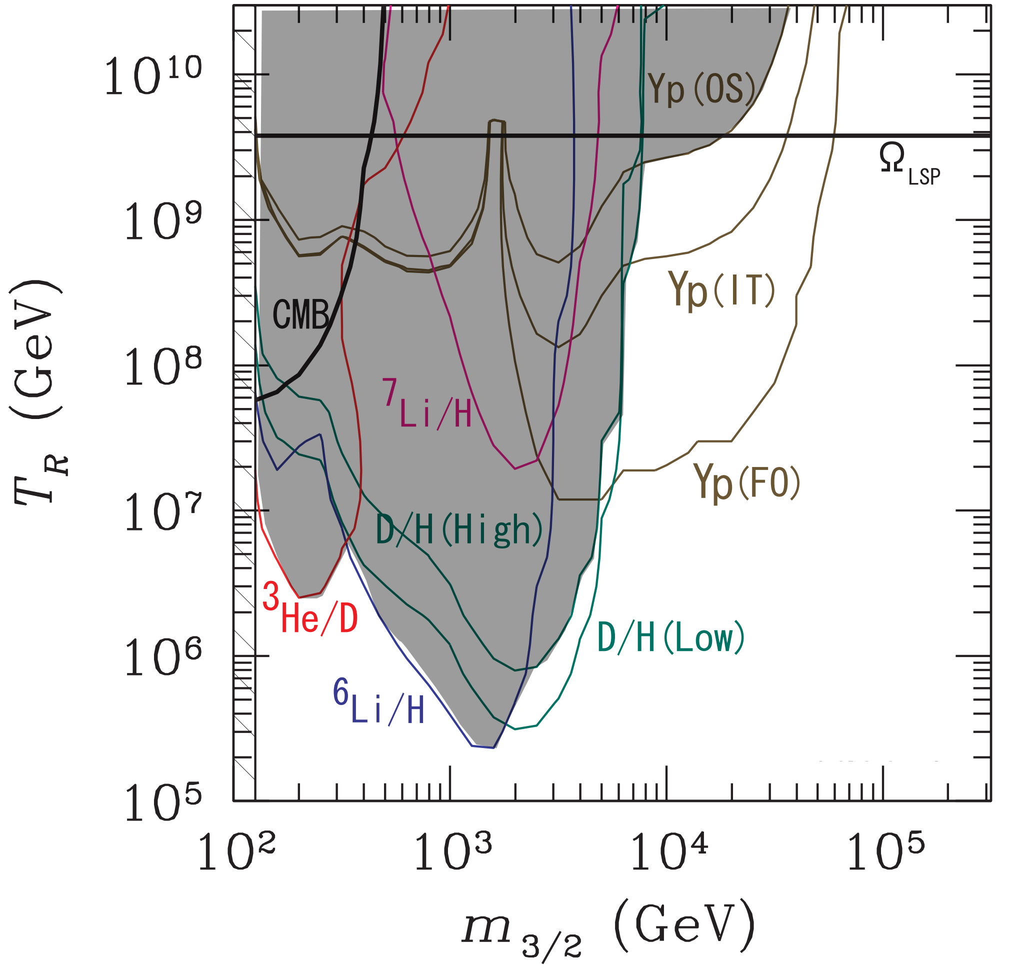
by the tree-level interactions in supergravity.

Pure Gravity Mediation Model

Heavy gravitino mass is a good news in cosmology!

✓ The gravitino problem is solved for $m_{3/2} = O(10\text{-}100)\,TeV$.

['05 Kawasaki, Kohri, Moroi, Yotsuyanagi]



The gravitinos are produced by particle scattering in thermal bath in the early universe (abundance proportional to T_R). ['82 Weinberg]

$$Y_{3/2} = n_{3/2}/s \sim 10^{-12} \times (T_R/10^9\ GeV)$$

[T_R : Reheating temperature after inflation]

✓ $m_{3/2}$=$O(1)TeV$ → BBN constrains thermal history of cosmology...

✓ The model with $m_{3/2} = O(10\text{-}100)$TeV is consistent with leptogenesis!

[Leptogenesis requires $T_R > 10^9$ GeV, '86 Fukugita,Yanagida]

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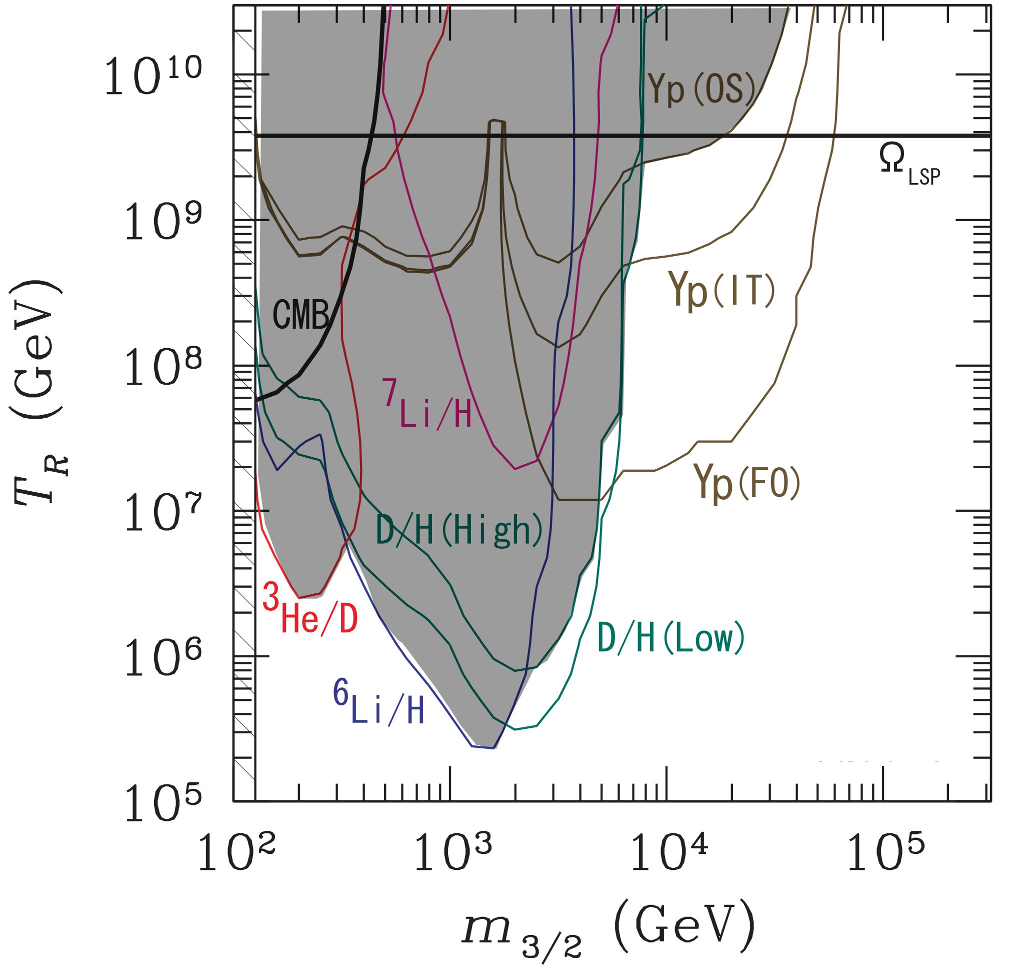

The gravitino decay rate is suppressed by the Planck scale ($\Gamma_{3/2} = m_{3/2}^3/M_{PL}^2$)

$$\tau_{3/2} \sim 0.01\text{sec} \times (100\text{TeV} / m_{3/2})^3$$
$$[\ \tau_{BBN} = O(1)\text{sec}\ ]$$

✓ $m_{3/2}=O(1)TeV$ → BBN constrains thermal history of cosmology...

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Pure Gravity Mediation Model

2. Origin of the gaugino masses

$m_{gaugino} = O(m_{3/2})$ as in conventional mSUGRA?

The gaugino masses of $O(m_{3/2})$ requires singlet SUSY breaking field :

$$W = c/M_{PL}\, Z\, W^a W_a + \ldots$$

$$\rightarrow\ m_{gaugino} = c\, m_{3/2} + \ldots$$

[Z : SUSY breaking field, i.e. $Z = F\,\theta^2$]

✓ The coefficient "c" can be $O(1)$ only when Z is neutral !

Pure Gravity Mediation Model

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✓ $m_{gaugino} = O(m_{3/2})$ is realized only when the SUSY breaking field is a complete singlet = Polonyi field!

✓ A complete neutral SUSY breaking field causes the so-called *Polonyi problem*!

Pure Gravity Mediation Model

✓ **Polonyi Problem I** [unavoidable Moduli problem]

['83 Coughlan, Fischler, Kolb, Rabi, Ross]

In F-term SUSY breaking model, there is a pseudo-flat direction.

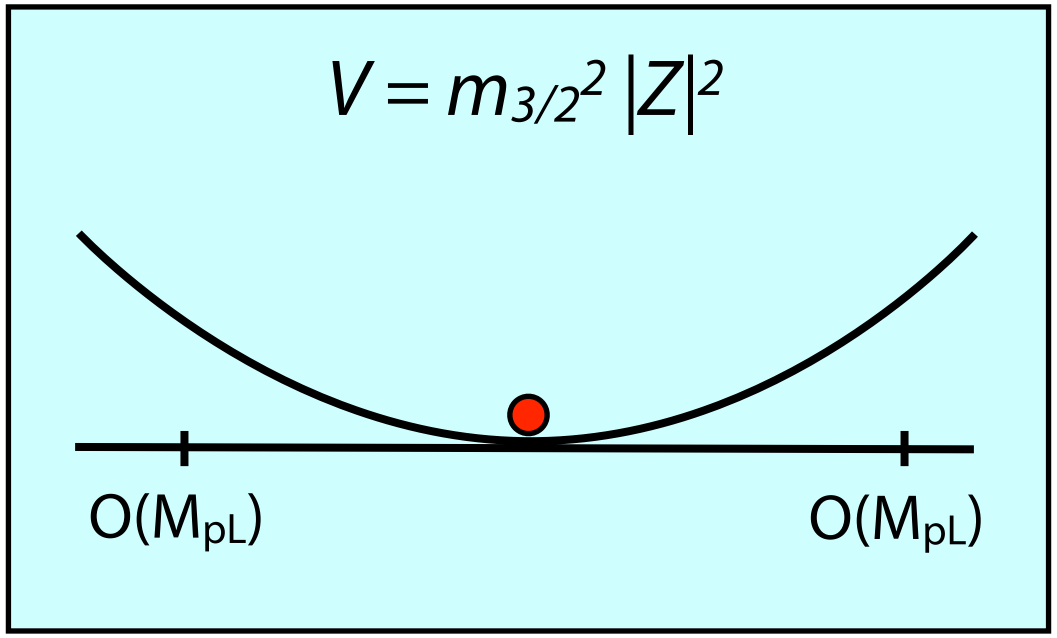
cf. The simplest SUSY breaking model:

$$K = Z^\dagger Z + Z^\dagger Z Z^\dagger Z / M_{PL}^2 + \dots$$

$$W = \Lambda^2 Z$$

F-term SUSY breaking

$$F_Z = \Lambda^2$$



$$V = m_{3/2}^2\, |Z|^2$$

Pure Gravity Mediation Model

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F-term SUSY breaking

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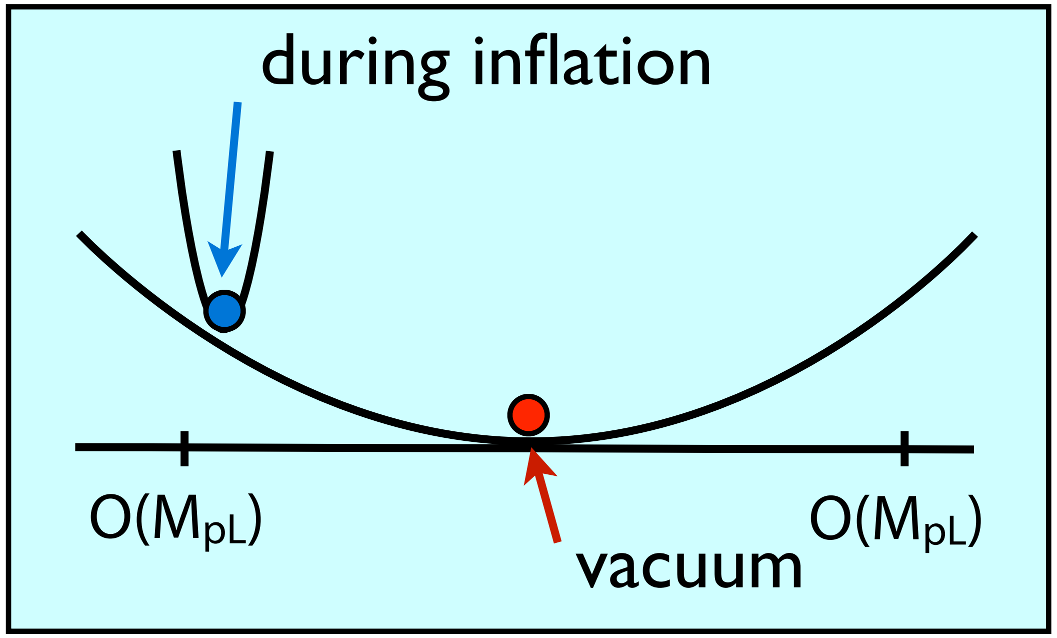
If Z is a completely neutral filed... → No special meaning at $Z = 0$!



During inflation, Z is expected to be at $Z = O(M_{PL})$!

$$V = m_{3/2}^2 |Z|^2 + H^2 |Z - Z_*|^2$$

$(Z_* = O(M_{pl}))$

Pure Gravity Mediation Model

✓ **Polonyi Problem I** [unavoidable Moduli problem]

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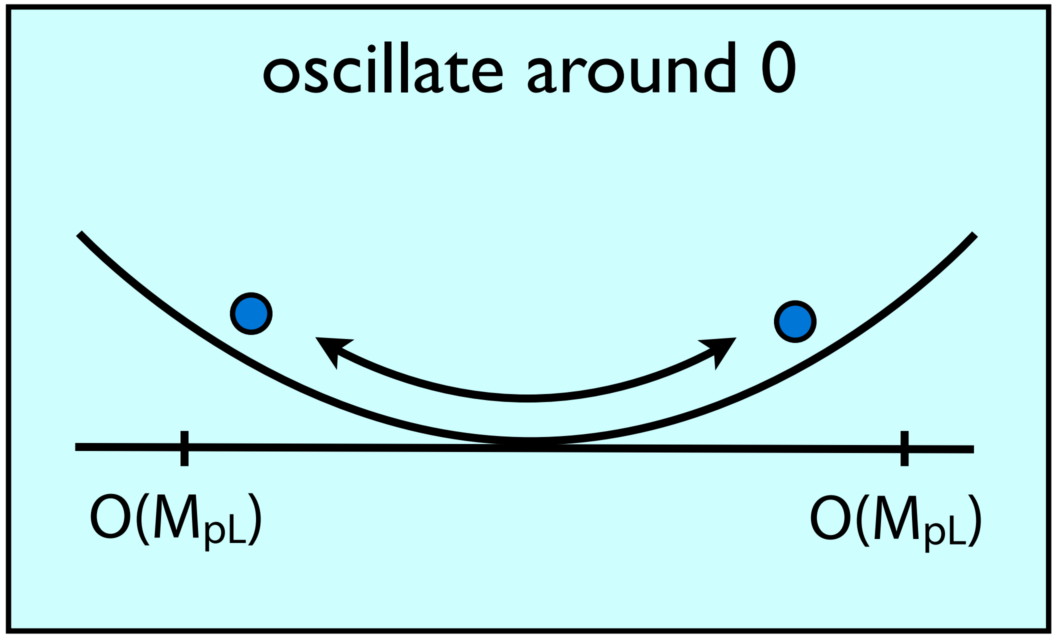
F-term SUSY breaking

$F_Z = \Lambda^2$

After inflation, Z oscillates with a large amplitude ...



dominate energy of the universe

→ Entropy production !

$$\Delta \sim (M_{PL} / m_{3/2}) \times (Z_{inf} / M_{PL})^2$$
$$\sim 10^{13} \times (Z_{inf} / M_{PL})^2$$

Moduli-Induced Gravitino problem is also serious ! ['06 Endo, Hamaguchi, Takahashi]

Pure Gravity Mediation Model

✓ Polonyi Problem II [unavoidable Moduli problem]

['06 MI, Shinbara, Yanagida]

The Polonyi mass can be enhanced in dynamical SUSY breaking model:

$$K = Z^\dagger Z + \kappa^2 Z^\dagger Z Z^\dagger Z/\Lambda^2 + \ldots$$

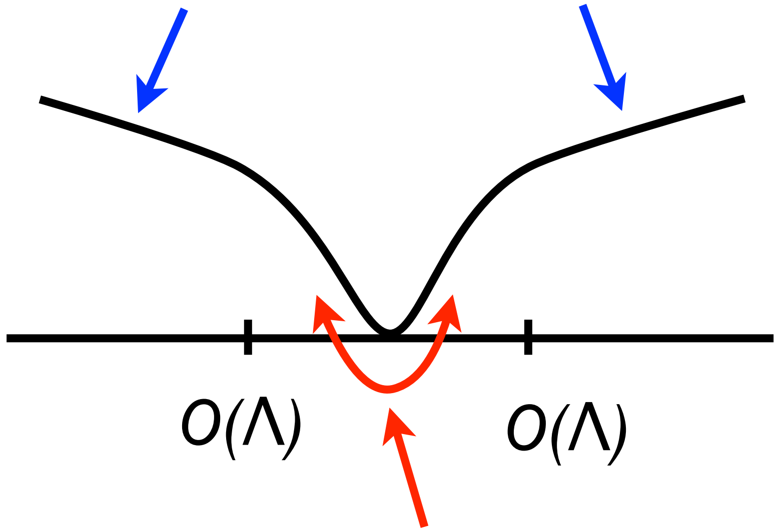
$$W = \Lambda^2 Z$$

F-term SUSY breaking

$F_Z = \Lambda^2$

[$\kappa = O(1)$ for strong interacting model]

Curvature of $O(m_{3/2}^2)$



dynamically enhanced mass

- ✓ The Polonyi mass can be larger than the Hubble parameter during inflation.
- ✓ The Polonyi field can decay much faster.

Pure Gravity Mediation Model

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['06 MI, Shinbara, Yanagida]

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F-term SUSY breaking

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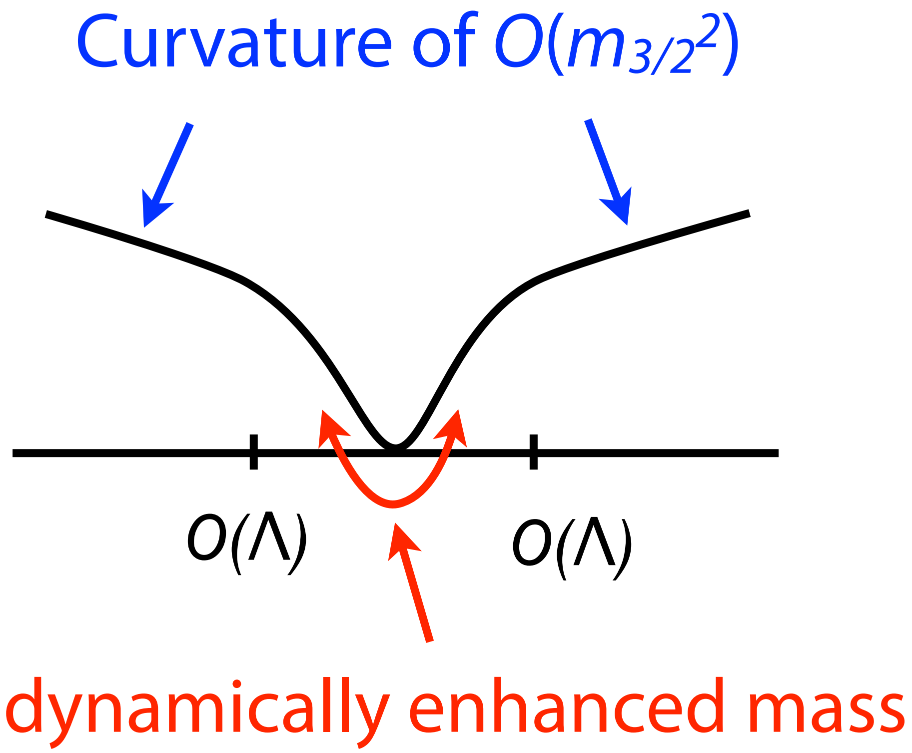


If Z is a completely neutral filed,
Z is again at far away from its origin
during inflation...

→ *Polonyi Problem,*
Polonyi induced gravitino problem

Pure Gravity Mediation Model

2. Origin of the gaugino masses

✓ Models without Polonyi field !

[‘99 Giudice, Luty, Murayama, Rattazzi, ’04 Wells]

In this case, there is no Polonyi problem but the tree-level gaugino masses are highly suppressed by such as $O(\Lambda/M_{PL})$.

Radiative Gaugino mass (anomaly mediation)

$$m_{\text{gluino}} = -\frac{3g_3^2}{16\pi^2} m_{3/2} \qquad m_{\text{wino}} = \frac{g_2^2}{16\pi^2} m_{3/2} \qquad m_{bino} = \frac{33}{5}\frac{g_1^2}{16\pi^2} m_{3/2}$$

at the sfermion mass sale, i.e. $m_{3/2}$.

[‘99 Giudice, Luty, Murayama, Rattazzi, ’99 Randall, Sundram]

✓ $m_{3/2} = O(10\text{-}1000)\ TeV \rightarrow m_{gaugino} = O(1)\ TeV$

Pure Gravity Mediation Model

3. Origin of the Higgsino mass

✓ μ-term not from SUSY breaking sector but from R-breaking sector !

['92 Inoue,Kawasaki,Yamaguhi,Yanagida,'93 Casas, Munoz]

$$K = c\, H_u H_d + c'/M_{PL}^2\, X^\dagger X\, H_u H_d + h.c. + \ldots$$

R-charge of $H_u H_d = 0$

charged SUSY breaking fields

$$W = m_{3/2}\, M_{pl}^2 + \ldots$$

R-breaking constant from spontaneous discrete R-symmetry breaking !

$$\mu_H = c\, m_{3/2}, \quad B\,\mu_H = 2\, c\, m_{3/2}^2 + c'\, m_{3/2}^2 .$$

✓ The Higgsino mass originates from *R-symmetry breaking!*

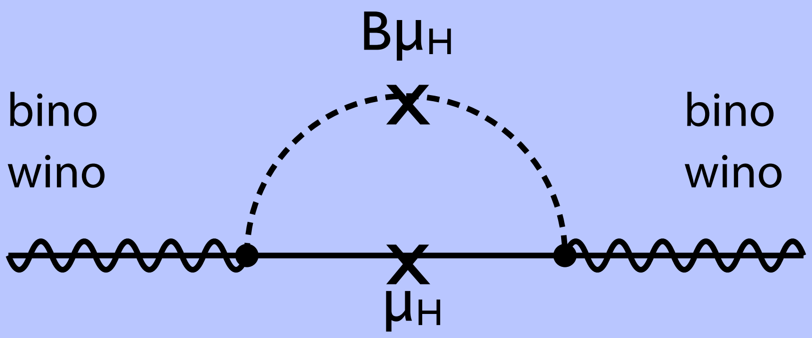
$$\mu_H = O(10\text{-}1000)\ TeV, \ B = O(10\text{-}1000)\ TeV$$

Pure Gravity Mediation Model

4. Origin of the gaugino masses II

[‘99 Giudice, Luty, Murayama, Rattazzi, ’99 Gherghetta, Giudice, Wells]

~ Gauge Mediation!



$$L = \mu_H \sin 2\beta \frac{m_A^2}{|\mu_H|^2 - m_A^2} \log \frac{|\mu_H|^2}{m_A^2}$$

$$m_{gluino} = -\frac{3g_3^2}{16\pi^2} m_{3/2}$$

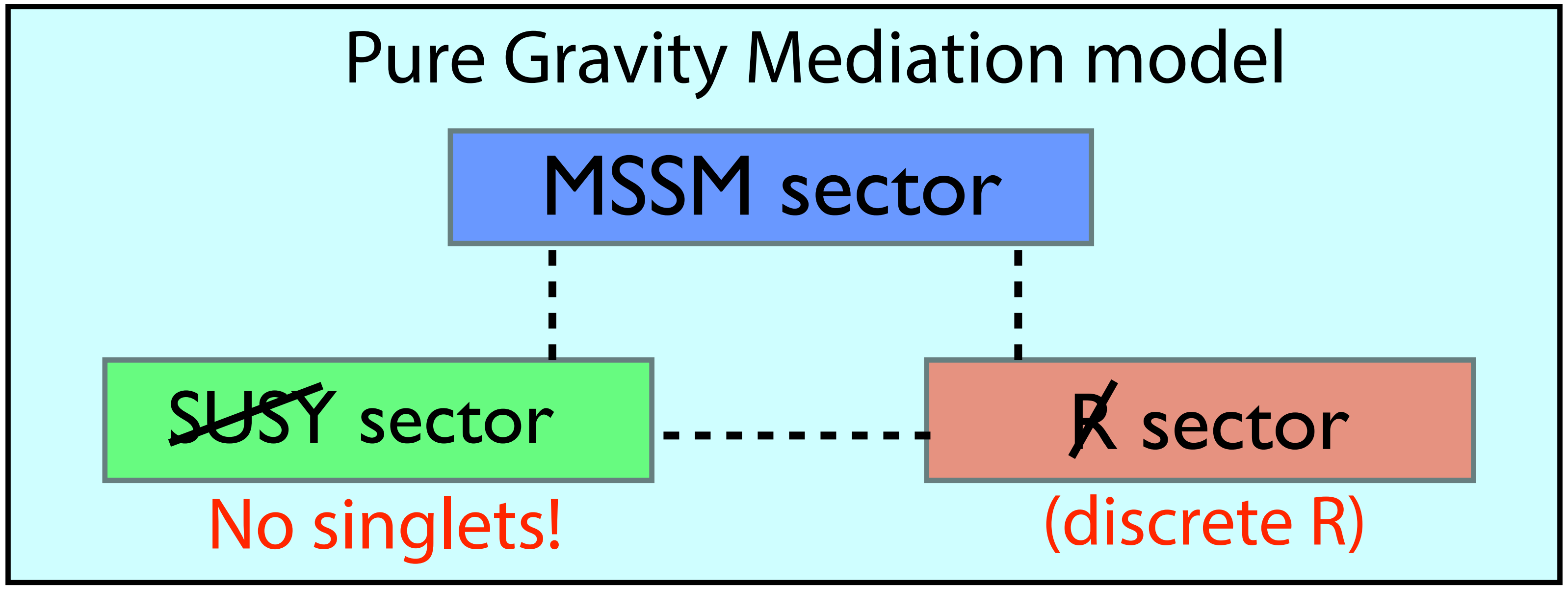
$$m_{wino} = \frac{g_2^2}{16\pi^2}(m_{3/2} + \underline{L})$$

$$m_{bino} = \frac{33}{5}\frac{g_1^2}{16\pi^2}\left(m_{3/2} + \frac{L}{\underline{11}}\right)$$

$$L = O(m_{3/2}) \text{ for } \tan\beta = O(1),\ \mu_H, B, m_A = O(m_{3/2})$$

✓ These contributions affect the SUSY search at the LHC!

Pure Gravity Mediation Model



Pure Gravity Mediation model

MSSM sector

~~SUSY~~ sector

No singlets!

~~R~~ sector

(discrete R)

['06 MI, Moroi, Yanagida, '11 MI, Yanagida, '12 MI, Matsumoto, Yanagida]

(1) Sfermion masses : tree-level interactions to the SUSY breaking sector

$$m_{sfermion} = O(m_{3/2})$$

$$m_{higgs} \sim 126 GeV \Leftrightarrow m_{3/2} = O(10\text{-}1000) TeV$$

(2) Higgsino masses : tree-level interactions to the R-breaking sector.

$$\mu_H, B = O(m_{3/2}), \quad \tan\beta = O(1)$$

(3) Gaugino masses : anomaly mediation and Higgsino effects.

$$m_{3/2} = O(10\text{-}1000) TeV \rightarrow m_{gaugino} = O(1)\ TeV$$

Predictions of the PGM

Fine-tuning condition:

$$V = (m_{Hu}^2 + |\mu_H|^2)\,|H_u|^2 + (m_{Hd}^2 + |\mu_H|^2)\,|H_d|^2$$
$$+ B\mu_H\, H_u H_d + h.c.$$

We need a "light" Higgs doublet boson which plays a role of the SM Higgs boson.

$$(m_{Hu}^2 + |\mu_H|^2)(m_{Hd}^2 + |\mu_H|^2) - (B\mu_H)^2 = O(m_{higgs}^2 m_{3/2}^2)$$

✓ Fine-tuning of $O(m_{higgs}^2/m_{3/2}^2) = O(10^{-(4\text{-}6)})$.

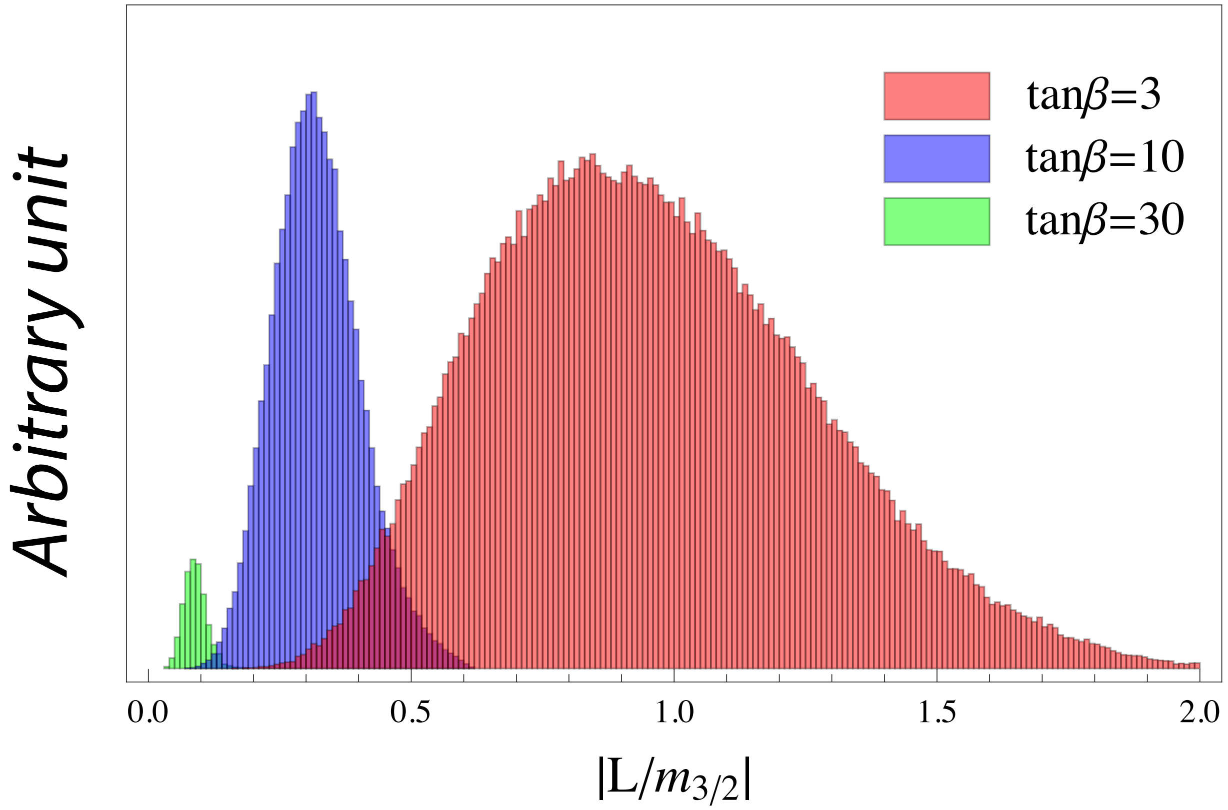
✓ $\tan\beta$ is predicted to be $O(1)$.

$$\sin 2\beta = \frac{2B\,\mu_H}{m_A^2} \qquad (m_A^2 = m_{Hu}^2 + m_{Hd}^2 + 2|\mu_H|^2)$$

For μ_H, B, $m_A = O(m_{3/2}) \rightarrow \tan\beta = O(1)$.

Predictions of the PGM

Typical size of the Higgsino threshold parameter *L* :



The ratios of the areas of each histogram roughly represent the relative consistency of the value of *tanβ* in the pure gravity mediation.

['12 MI, Matsumoto, Yanagida]

We distributed μ_H , B_H roughly in [$m_{3/2} / 3$, $m_{3/2} \times 3$] .

→ required values m_{Hu}^2 and m_{Hu}^2 for fine-tuning for a given *tanβ* :

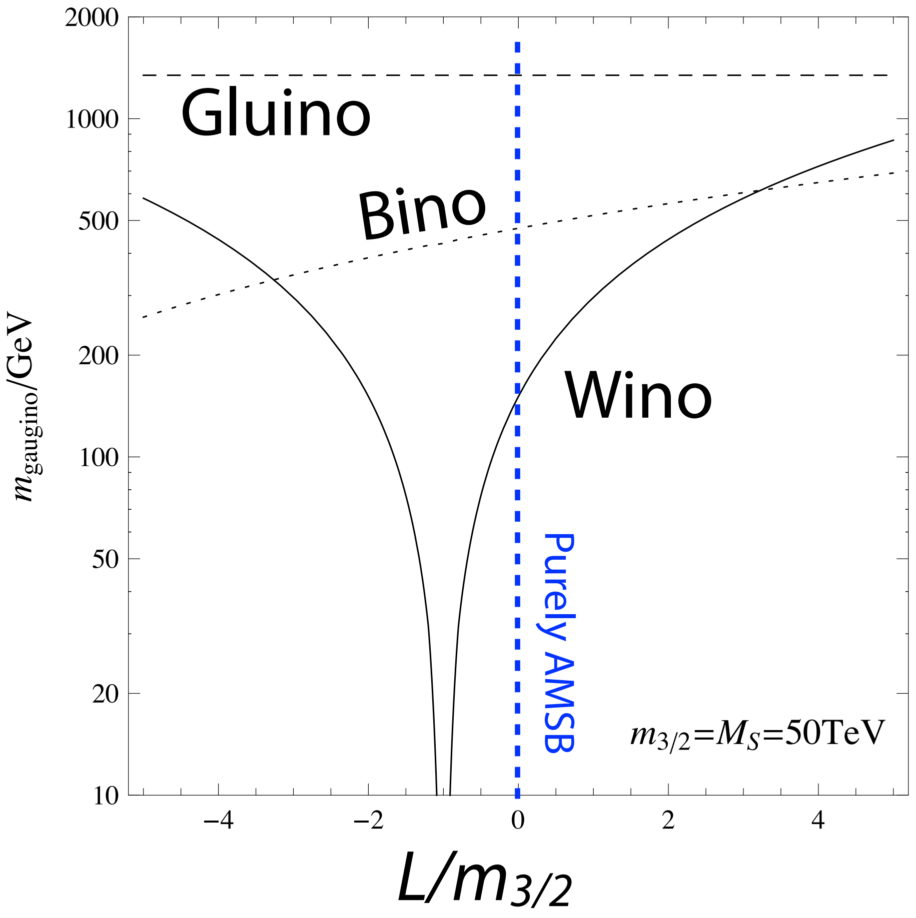
$$(m_{Hu}^2 \simeq -|\mu_H|^2 + B_H \mu_H \cot\beta \, , \; m_{Hd}^2 \simeq -|\mu_H|^2 + B_H \mu_H \tan\beta)$$

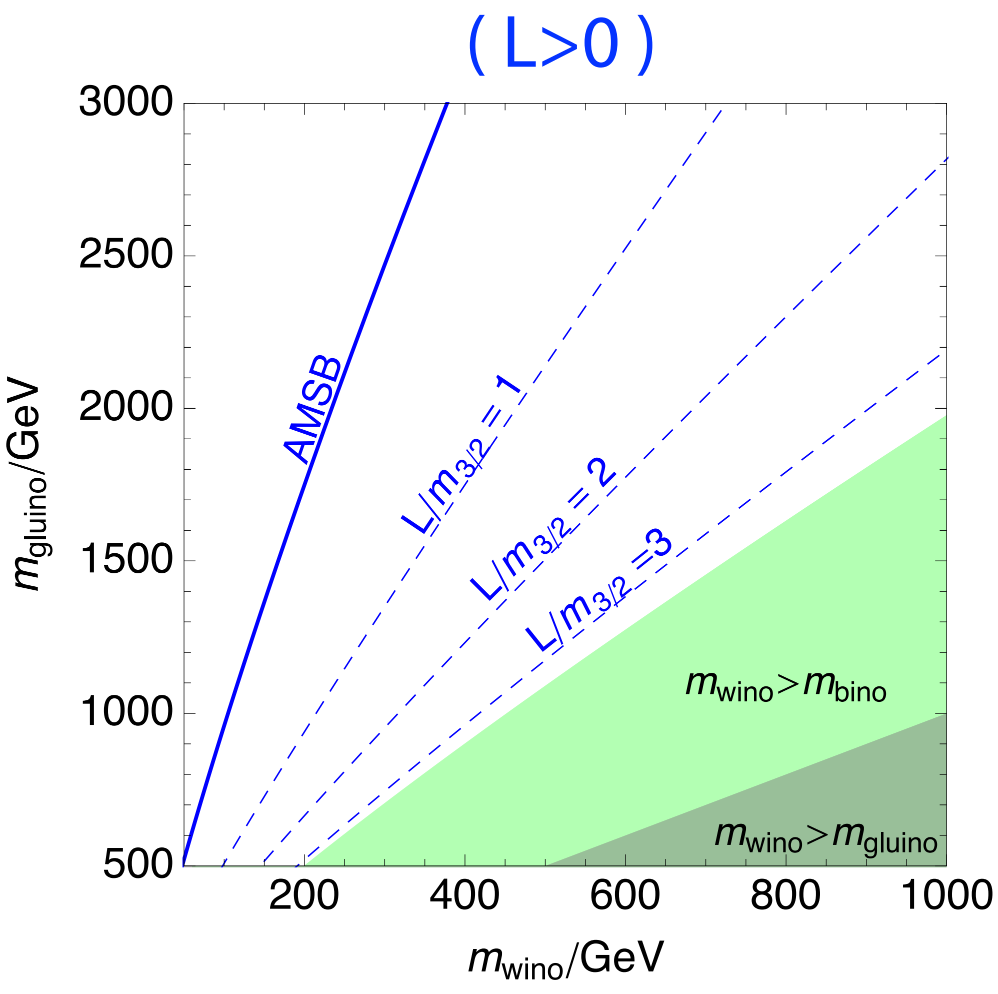
Then, we allow only when $| m_{Hu,Hd}^2 / m_{3/2}^2 | < 5$.

Pure gravity mediation : $\tan\beta = O(1)$ $L = O(m_{3/2})$

Predictions of the PGM

Gaugino Masses:





['12, MI, Matsumoto,Yanagida ($\mu_H=O(M_{susy})$)]

$$m_{gluino} = 2.5\text{x}10^{-2} m_{3/2}$$

$$m_{wino} = 3.0\text{x}10^{-3} (m_{3/2} + L)$$

$$m_{bino} = 9.6\text{x}10^{-3} (m_{3/2} + L/11)$$

for $m_{3/2}=O(100)$TeV.

✓ The wino is the LSP in the most parameter space.

✓ The gluino can be lighter than the prediction in AMSB for $L/m_{3/2} = O(1)$.

Phenomenology of PGM

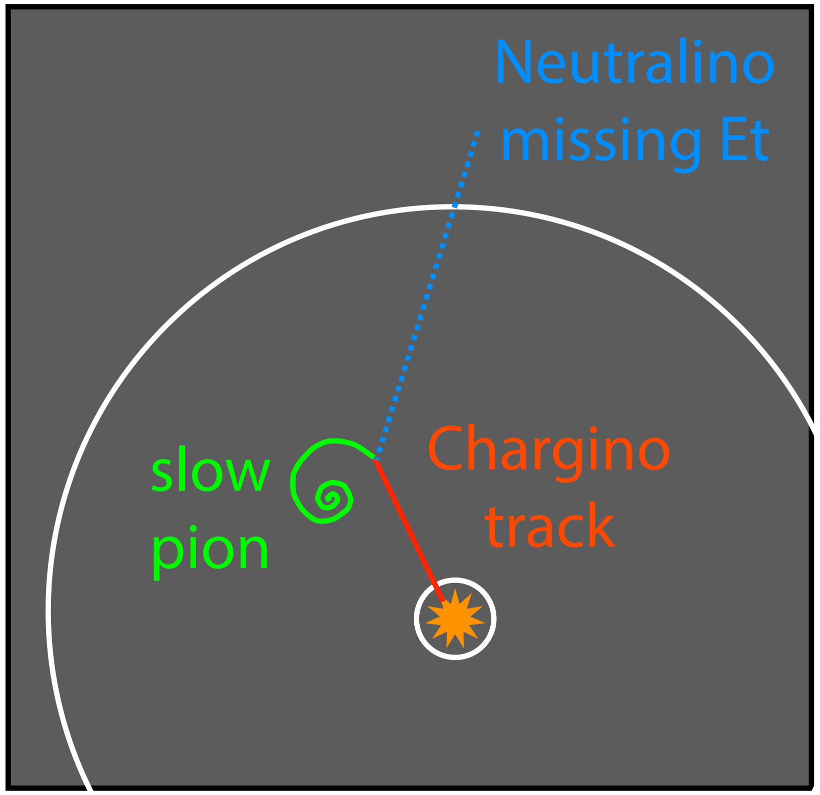
The model can be tested at the LHC!

- ✓ The neutral and charged winos are degenerated due to an approximate custodial symmetry.

- ✓ The dominant mass splitting comes from gauge boson loop contributions

$$\boxed{\Delta m_{wino} = m_{chargino} - m_{neutralino} = 160\text{-}170\ \mathrm{MeV}}$$

['99 Feng, Moroi, Randall, Strassler]



- ✓ Main decay mode : $\chi^{\pm} \rightarrow \chi^{0} + \pi^{\pm}$

$$\boxed{\tau_{wino} = O(10^{-10})\ sec.}$$

The charged wino produced at the LHC travels $O(1\text{-}10)cm$ before it decays.

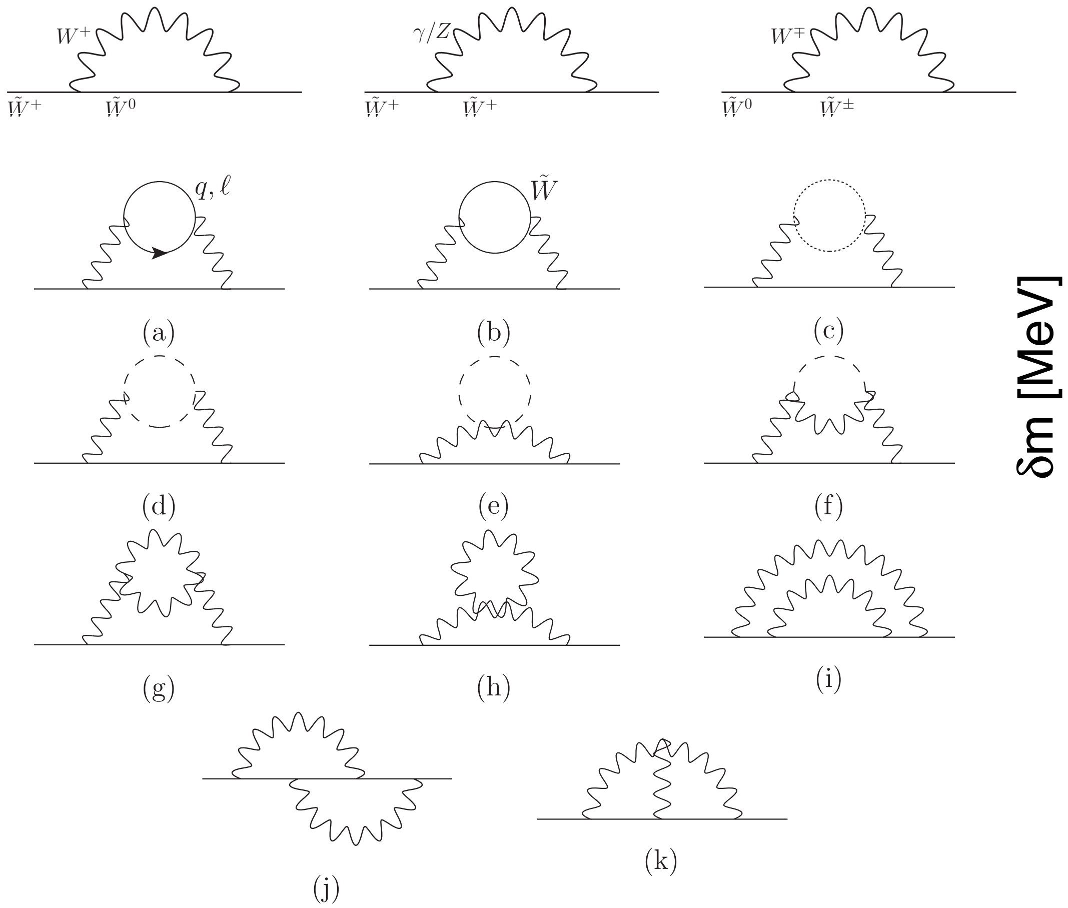
['06 MI, Moroi, Yanagida]

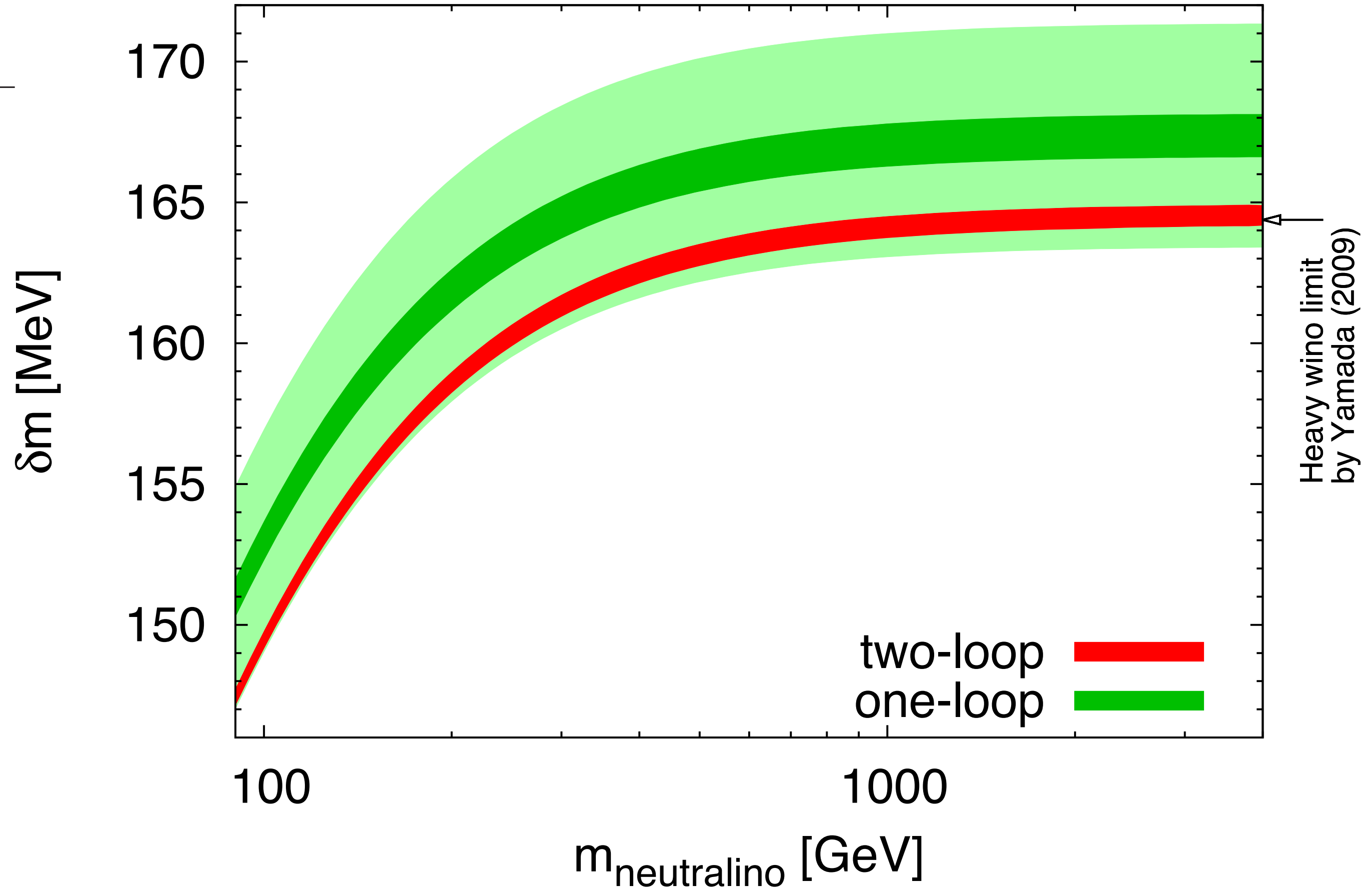
Phenomenology of PGM

- ✓ Wino width is sensitive to the mass difference

$$\boxed{\Gamma(\tilde{\chi}^{\pm} \to \tilde{\chi}^{0}\pi^{\pm}) = \Gamma(\pi^{\pm} \to \mu^{\pm}\nu_{\mu}) \times \frac{16\delta m^3}{m_\pi m_\mu^2}\left(1 - \frac{m_\pi^2}{\delta m^2}\right)^{1/2}\left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^{-2}}$$

Wino mass difference at two-loop level ['12 MI, Matsumoto, Sato]



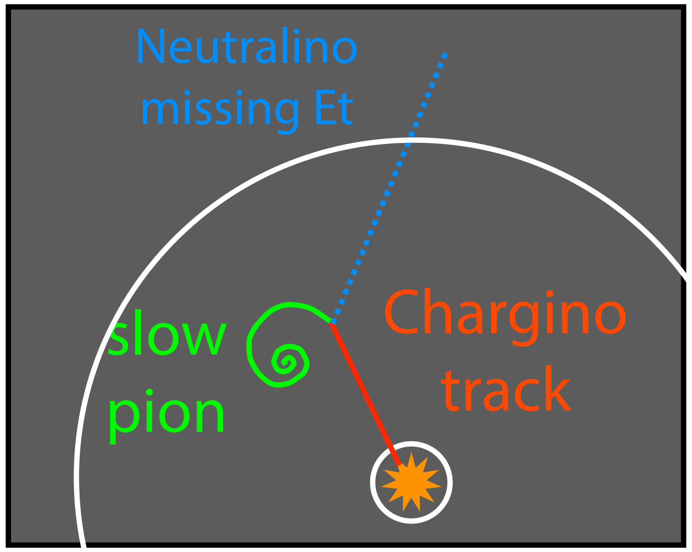


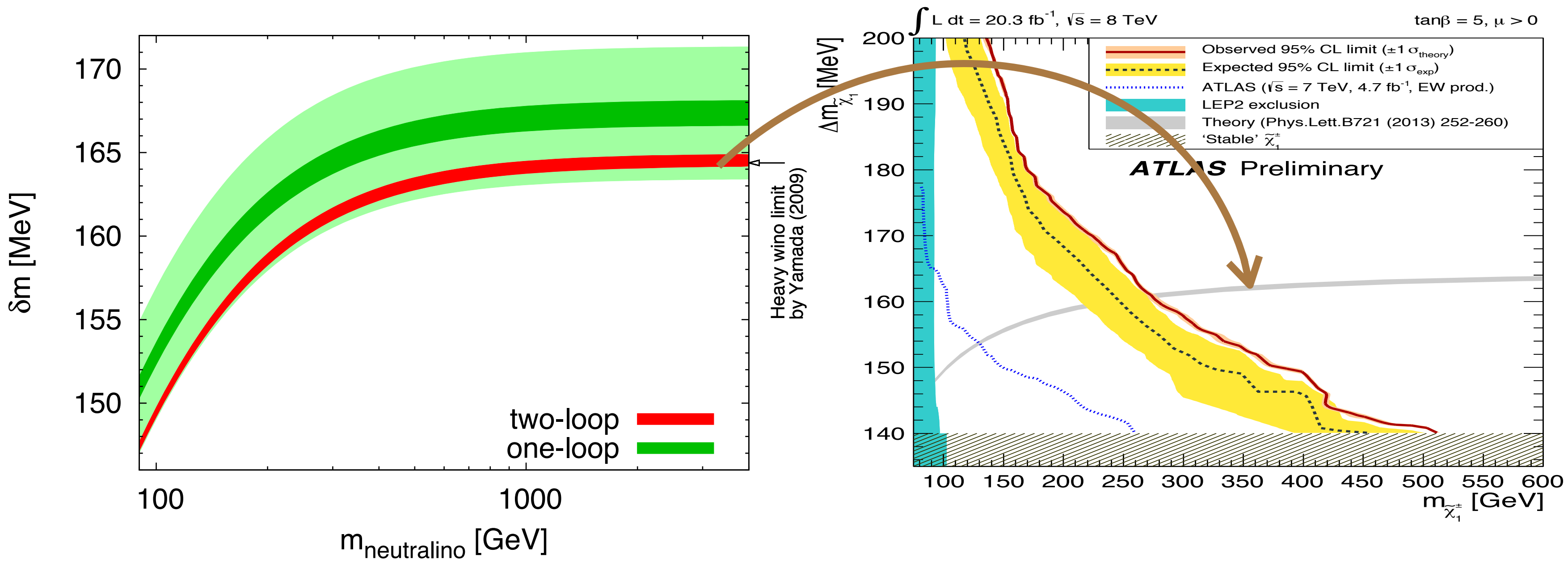
Uncertainty at the one-loop : ~ ± 5MeV

Uncertainty at the two-loop : ~ ± 0.5MeV

Phenomenology of PGM

Direct Wino Production





✓ Main decay mode : $\chi^\pm \to \chi^0 + \pi^\pm$: $\tau_{wino} = O(10^{-10})$ sec.

✓ Limits (disappearing track search):

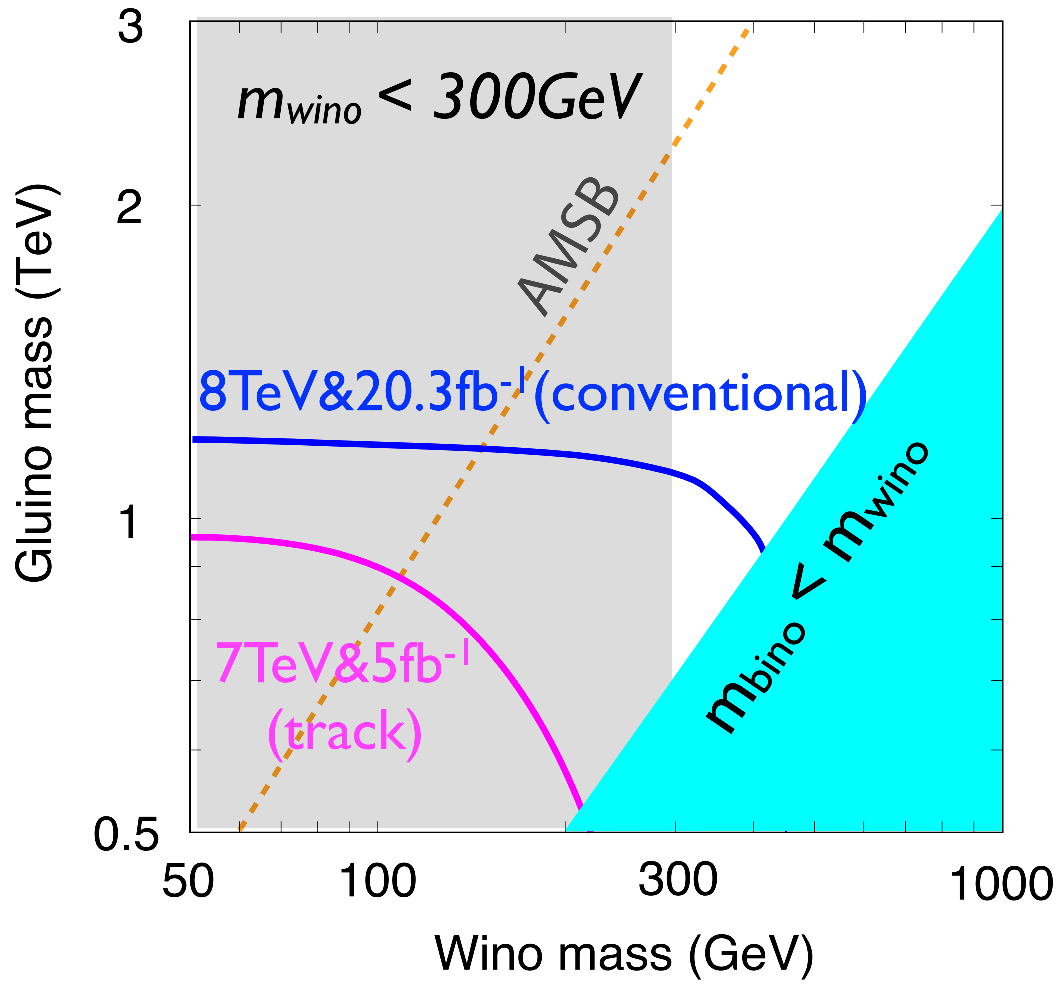
$m_{wino} > 130$GeV (7TeV&5fb^{-1}) using TRT [arxiv:1210.2852]

$m_{wino} > 270$GeV (8TeV&20fb^{-1}) using SCT & TRT [ATLAS-CONF-2013-069]

→ In future, the LHC will reach up to *500GeV* wino via disappearing track search

Phenomenology of PGM

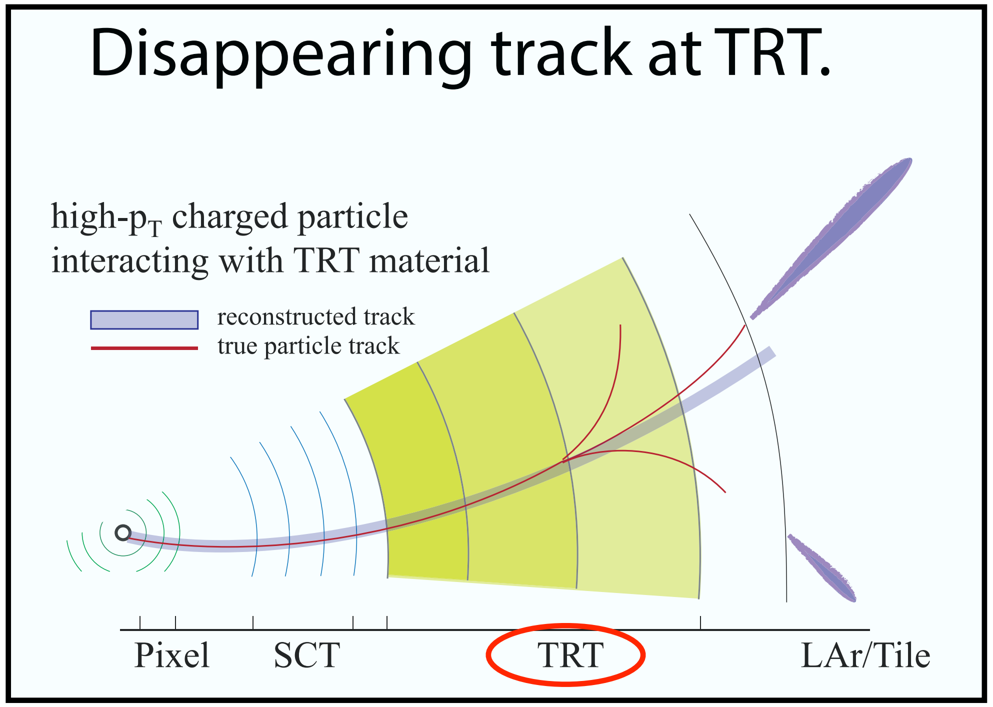
Current limits via gluino production



✓ Multi-jets + Missing E_T search (conventional SUSY search)

$m_{gluino} > 1.3TeV$ or $m_{wino} > 300GeV$
$m_{gluino} > 1TeV$ or $m_{wino} > 500GeV$
[@2σ: ATLAS-CONF-2013-047]

For *gluino→tt+wino* or *bb+wino*, the constraints get a little more stringent.



✓ Disappearing track search via gluino decay

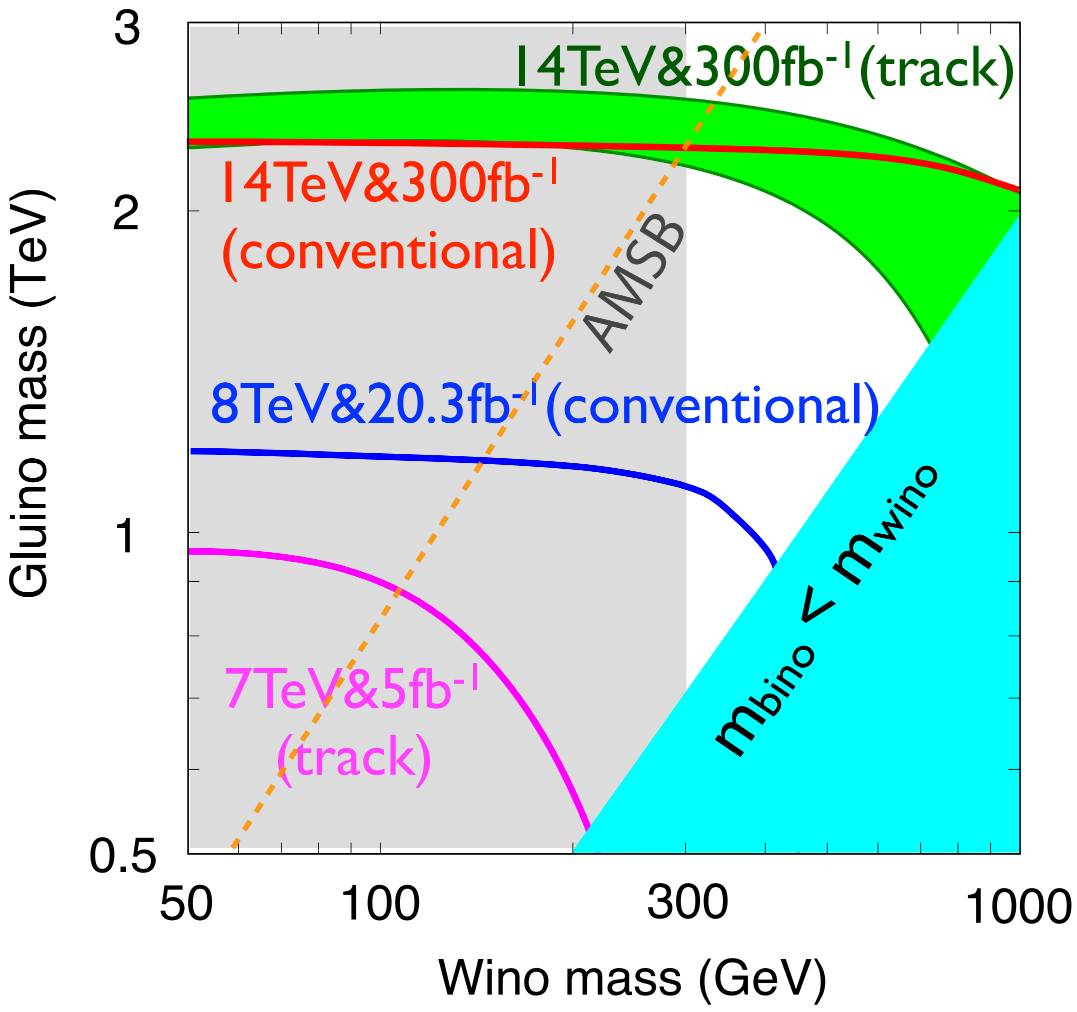
$m_{gluino} > 0.9TeV$ or $m_{wino} > 100GeV$
[@2σ: ATLAS-CONF-2012-034]

This is weaker than the conventional analysis, since the TRT(50-100cm) are used to find a track.

Phenomenology of PGM

Future reach at the LHC via gluino production

['12, Bhattacherjee, Feldstein, MI, Matsumoto, Yanagida]



✓ Multi-jets + Missing E_T search (conventional SUSY search)

$m_{gluino} < 2.3\text{TeV}$ for $m_{wino} < 1\text{TeV}$

✓ Disappearing track search

$m_{gluino} < 2.5\text{TeV}$ for $m_{wino} < 1\text{TeV}$

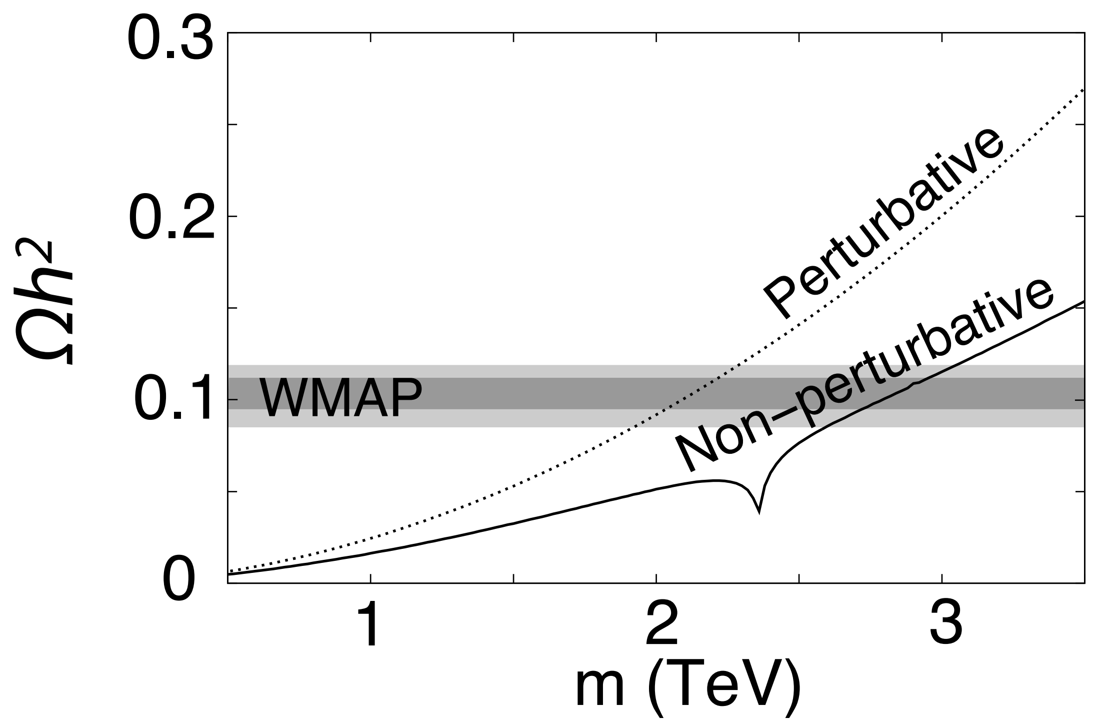
Pixel and SCT are assumed to be used.
We assumed background rejection rate by charged track selection between 0.1-0.01.

For *O(100)TeV* collider : talk by S.Jung

Phenomenology of PGM

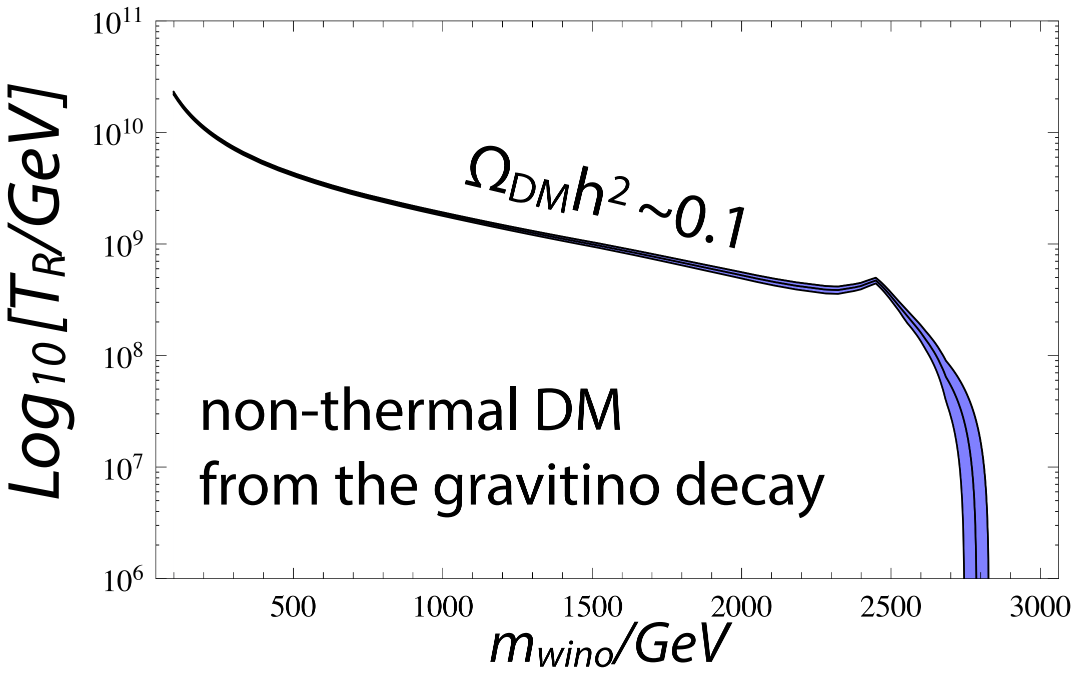
Wino Dark Matter

Thermal Wino Dark Matter



['07 Hisano, Matsumoto, Nagai, Saito, Senarmi]

Non-Thermal Wino Dark Matter



non-thermal DM
from the gravitino decay

['11 MI, Yanagida]

Thermal Wino Dark Matter

The wino has a large annihilation cross section into W-boson pairs.

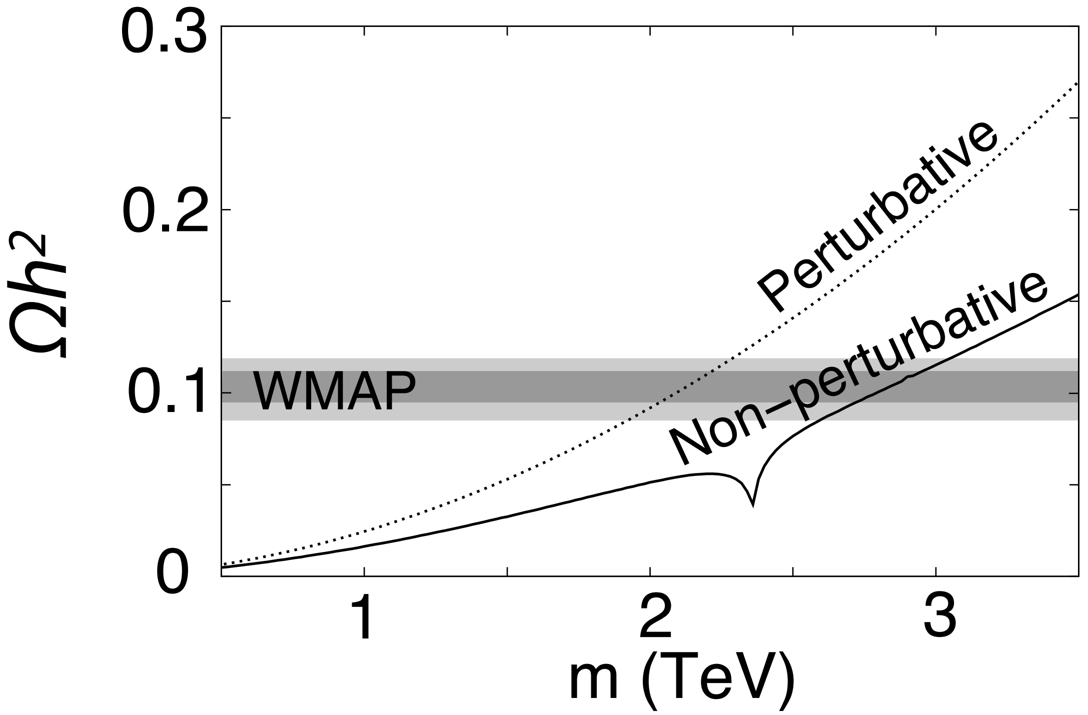
DM abundance from thermal relic → $m_{wino} \sim 3$ *TeV.*

- ✓ This is the most simplest possibility.
- ✓ Too heavy to be searched for at the LHC...

Phenomenology of PGM

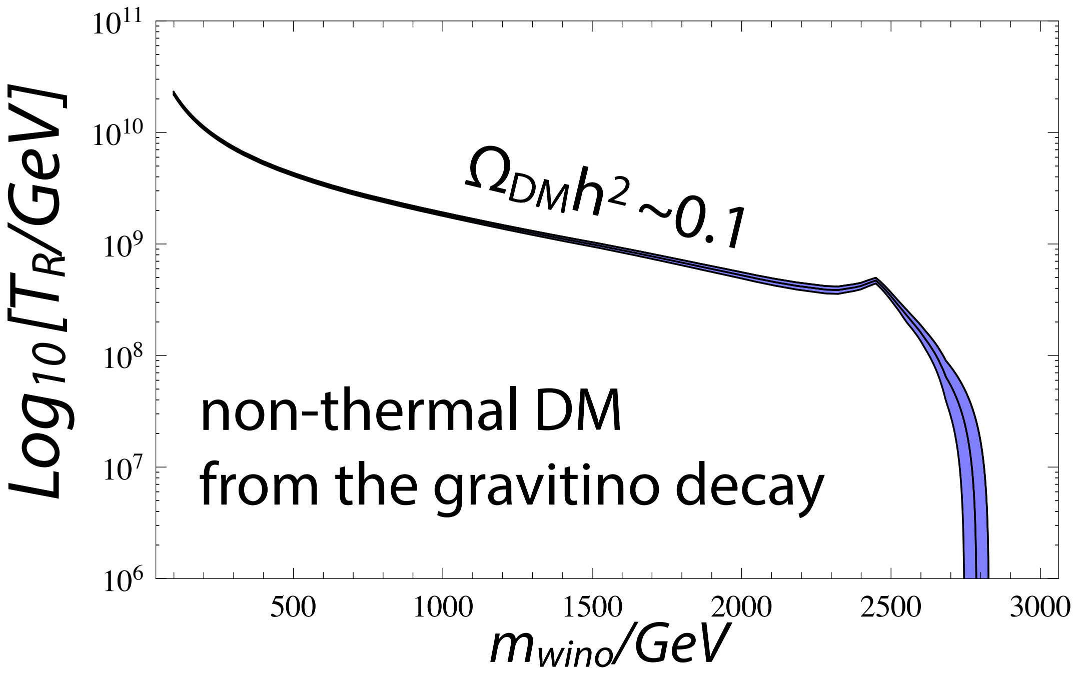
Wino Dark Matter

Thermal Wino Dark Matter



['07 Hisano, Matsumoto, Nagai, Saito, Senarmi]

Non-Thermal Wino Dark Matter



['11 MI, Yanagida]

Non-Thermal Wino Dark Matter

The decay of the gravitino provides additional wino DM :

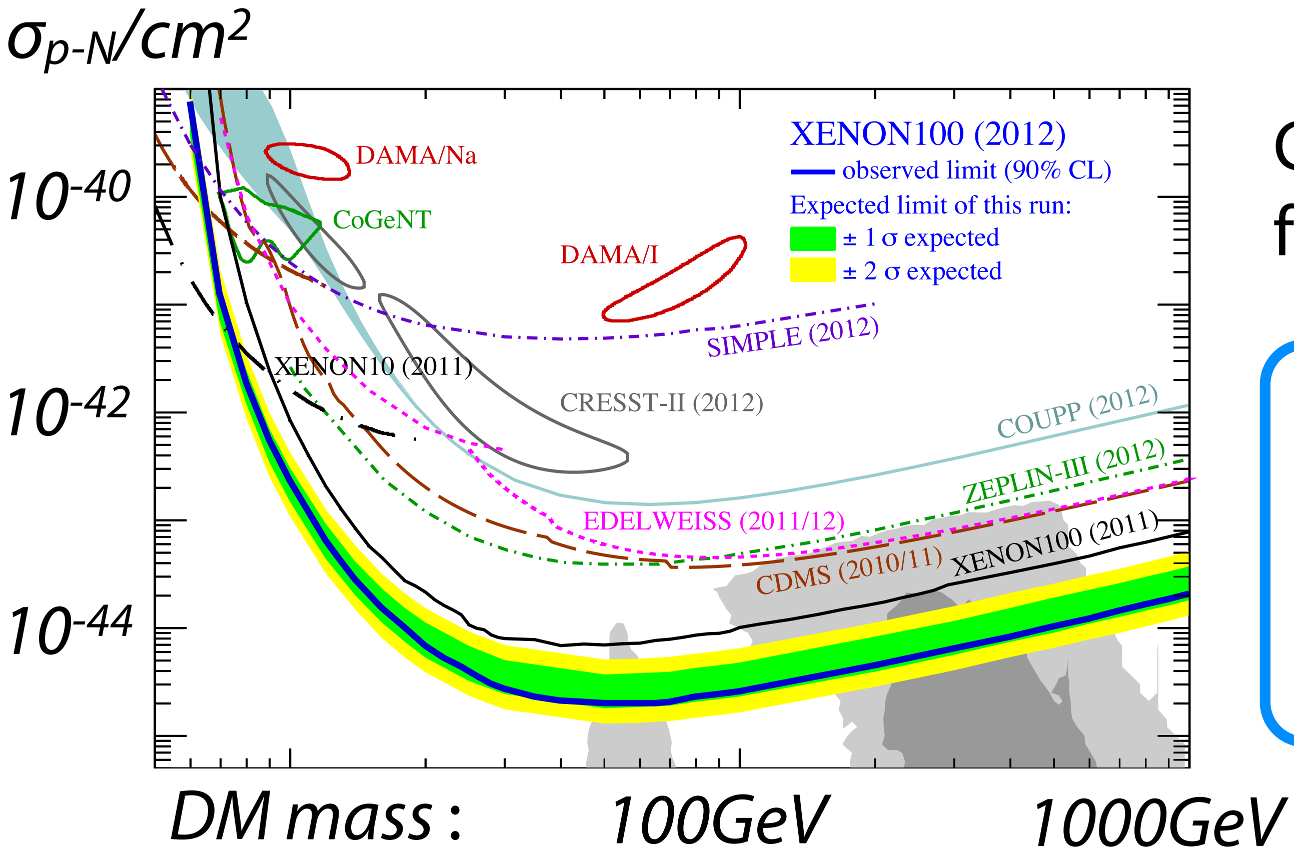
$$\Omega^{NT}_{DM}h^2 = 0.16\left(\frac{m_{wino}}{300\text{GeV}}\right)\left(\frac{T_R}{10^{10}\text{GeV}}\right)$$

['99 Gherghetta, Giudice, Wells, '99 Moroi, Randall]

Thermal leptogenesis, $T_R > 10^9 GeV \rightarrow m_{wino} \lesssim 1\ TeV$!

Phenomenology of PGM

Wino Dark Matter Search (direct detections, $\chi N \rightarrow \chi N$)



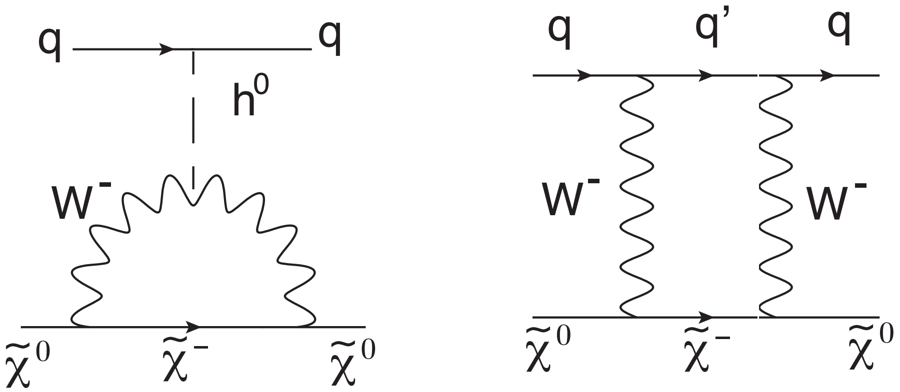
Coupling to *H* and *Z* are highly suppressed for $\mu_H = O(10\text{-}100)$ TeV at the tree-level.

Wino-Nucleon @ higher loop level

$$\sigma_{p\text{-}N} = (10^{-47}) cm^2$$

(much smaller than the current reach...)

['10 Hisano, Ishiwata, Nagata]



One-loop diagrams which contribute to the Wino-nucleon scatterings.

['10 Hisano, Ishiwata, Nagata]

- ✓ Darwin (multi-ton Argon/Xe detector) will reach down to 10^{-47}cm² for WIMP mass below 300GeV.

- ✓ The irreducible background from atmospheric neutrinos at about 10^{-48}cm². [arxiv:1003.5530]

Phenomenology of PGM

Wino Dark Matter Search (indirect detections, $\chi\chi \to WW$,...)

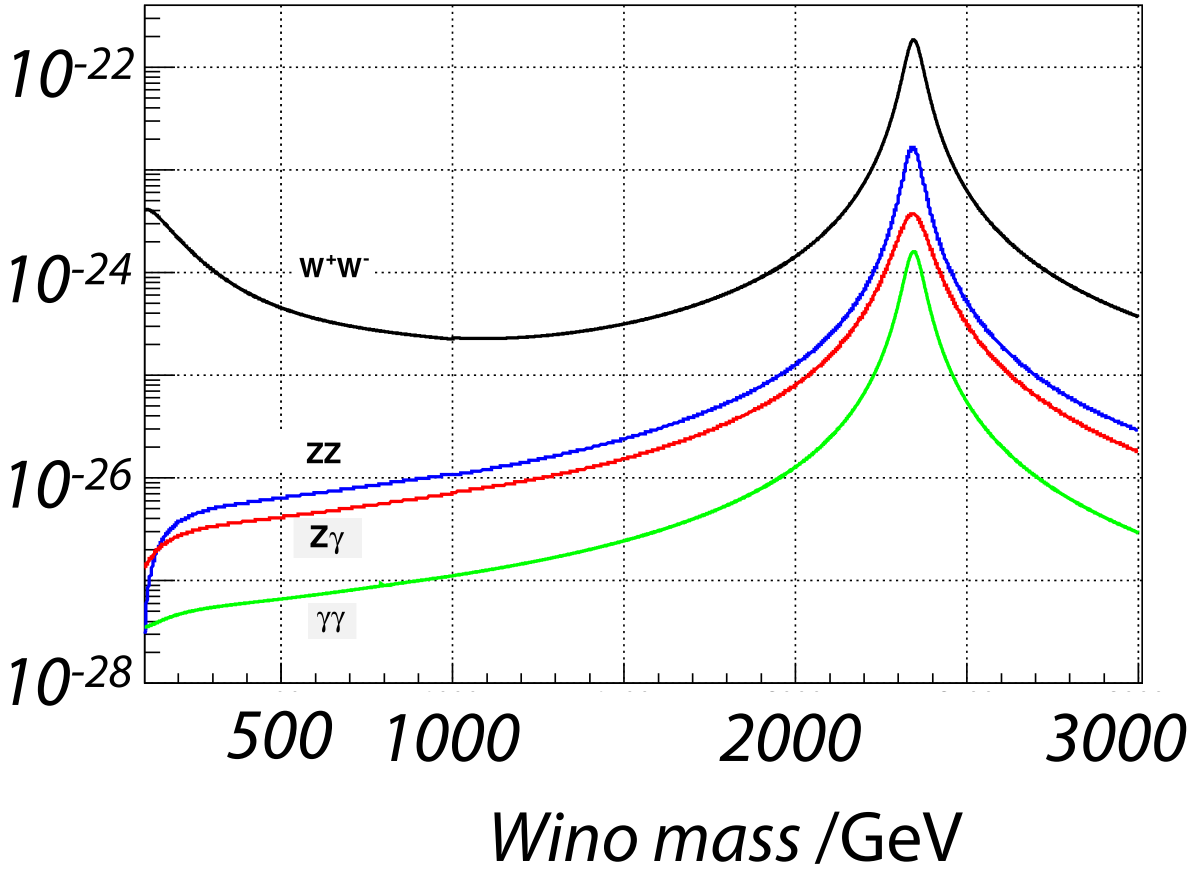
Wino Dark Matter has a large annihilation cross section!

✓ Detecting Gamma-Ray (line/continuum spectrum)

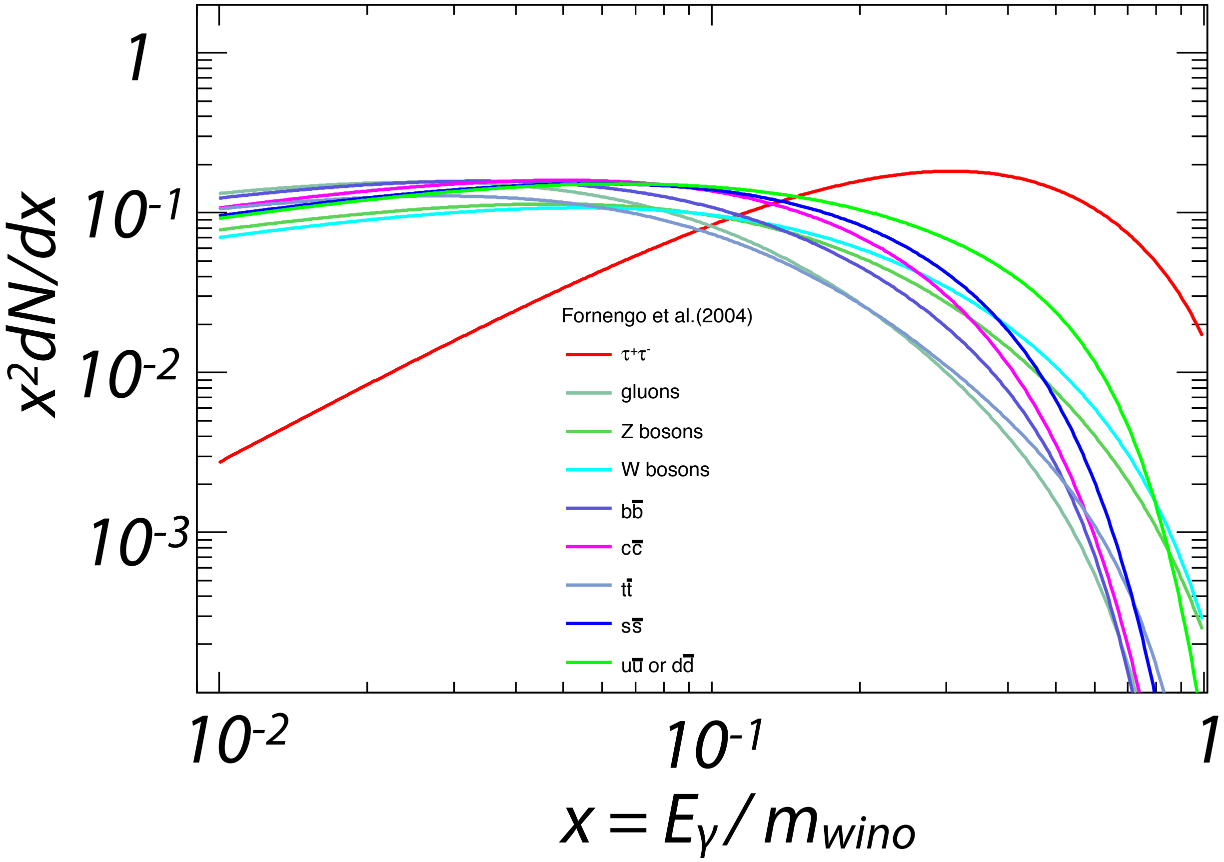
continuum spectrum → Milky Way Satellite Galaxy (dSphs)
line spectrum → Galactic Center Region

→ FERMI-LAT, H.E.S.S.

Annihilation cross section (cm³/s)



Continuum γ spectrum from WW



['04 Hisano, Matsumoto, Nojiri]

Phenomenology of PGM

Wino Dark Matter Search (indirect detections, $\chi\chi \to WW, \ldots$)

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\Phi_{\rm PP}} \cdot \underbrace{\int_{\Delta\Omega}\left\{\int_{\rm l.o.s.}\rho^2(\boldsymbol{r}){\rm d}l\right\}{\rm d}\Omega'}_{\text{J-factor}} .$$

✓ Continuum gamma ray from dSph

Fermi-LAT 4year data (15-dSph)

$m_{wino} < 400\,GeV$

$2200\,GeV < m_{wino} < 2500\,GeV$

Current J-factor uncertainties:

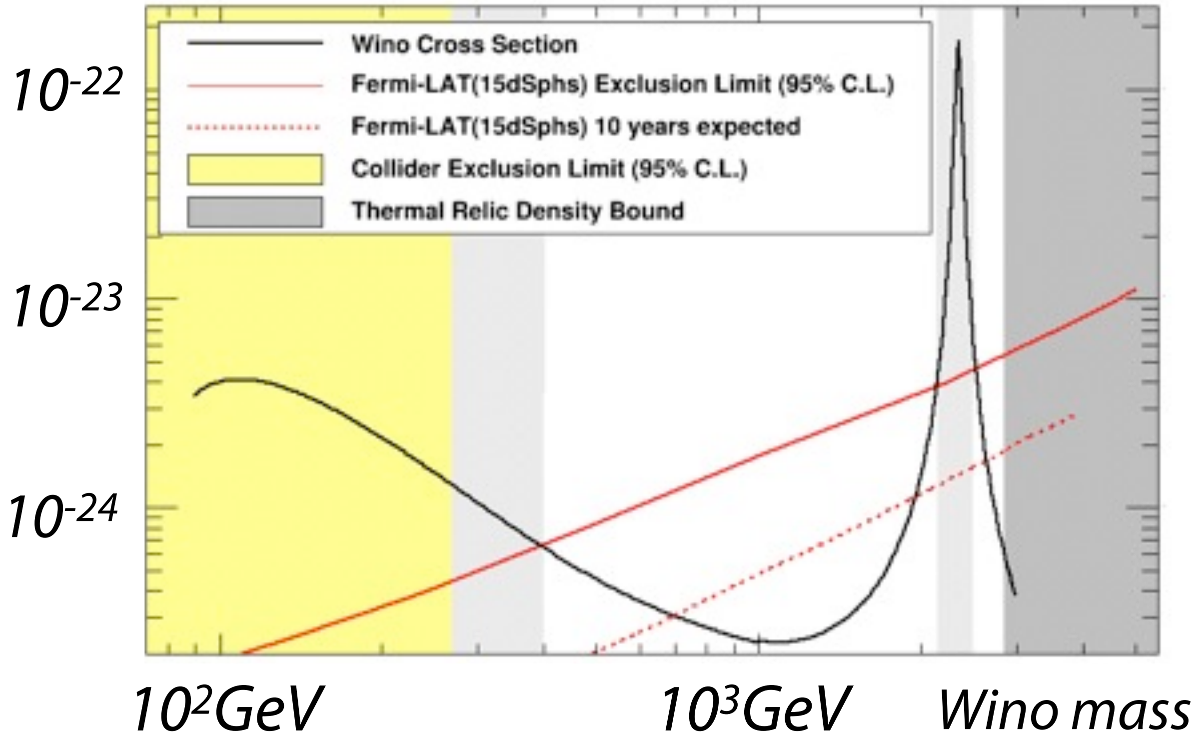
$\delta \, Log_{10} J = 0.2 - 0.3$

cf. Ursa-Minor (distance : 76kpc)

$J(NFW) = 10^{18.8 \pm 0.19}\, GeV^2/cm^{-5}\, sr$

$J(Burkert) = 10^{18.7 \pm 0.2}\, GeV^2/cm^{-5}\, sr$

Annihilation cross section (cm³/s)



[Fermi-LAT:1310.0828 (Translated by K.Ichikawa)]

If we reduce the J-factor uncertainties

$\delta \, Log_{10} J < 0.1$

GAMMA 400 experiment covers full Wino DM mass region.

[Bhattacherjee(a), MI, Ichikawa, Matsumoto, Nishiyama in preparation]

Phenomenology of PGM

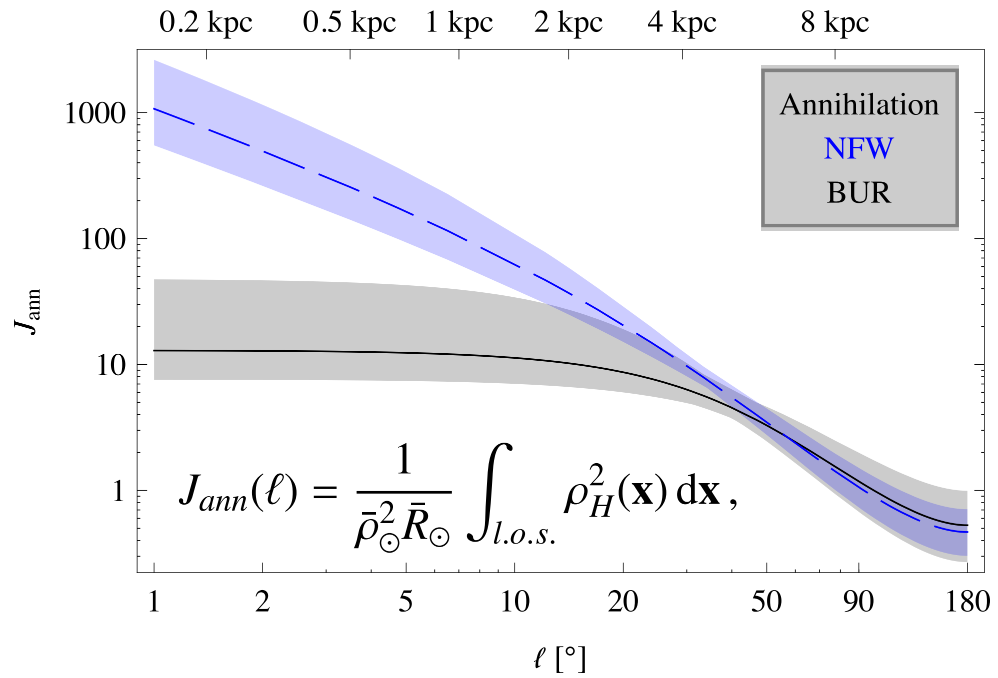
Wino Dark Matter Search (indirect detections, $\chi\chi \to WW$)

✓ Line gamma ray from GC

The line gamma ray search from GC by H.E.S.S. (1301.1173) has excluded the wino mass in

$2200\mathrm{GeV} < m_{wino} < 2500\mathrm{GeV}$

assuming the Burkert (cored) profile.

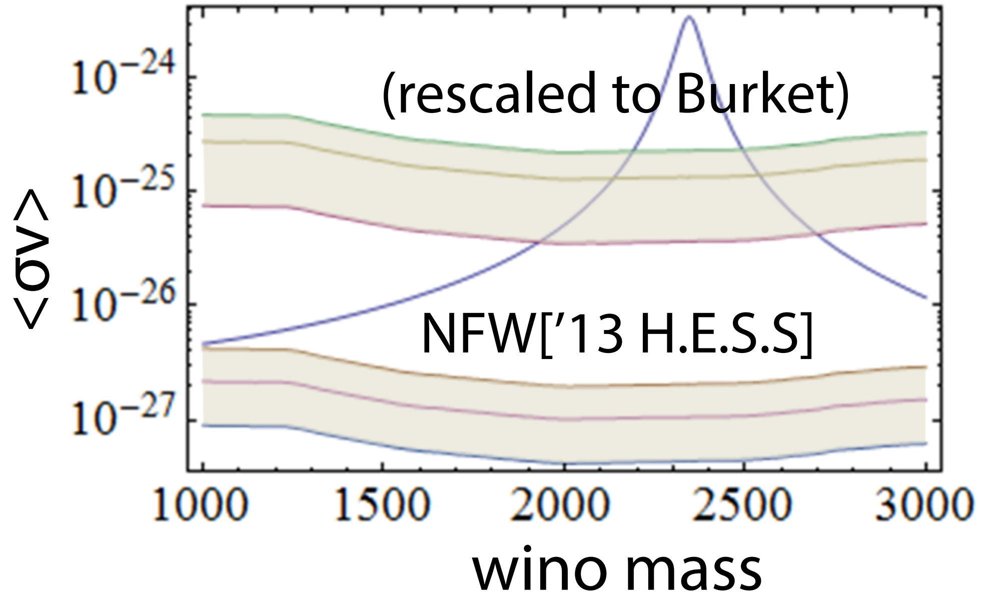


['13 Nesti, Salucci]

The constraints depend on the DM density profile (i.e. the J-factor) ...

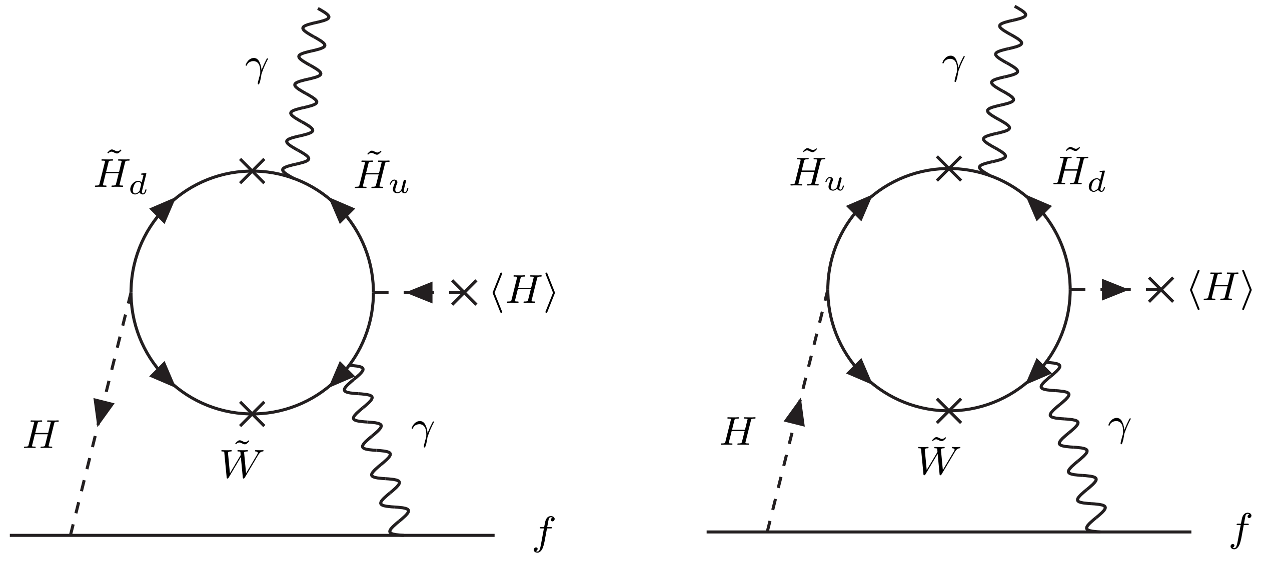
A stringent constraint is obtained by assuming the NFW (cuspy) DM profle ['13 Fan, Reece].

→ still CTA has a lot of chance to find the wino DM!

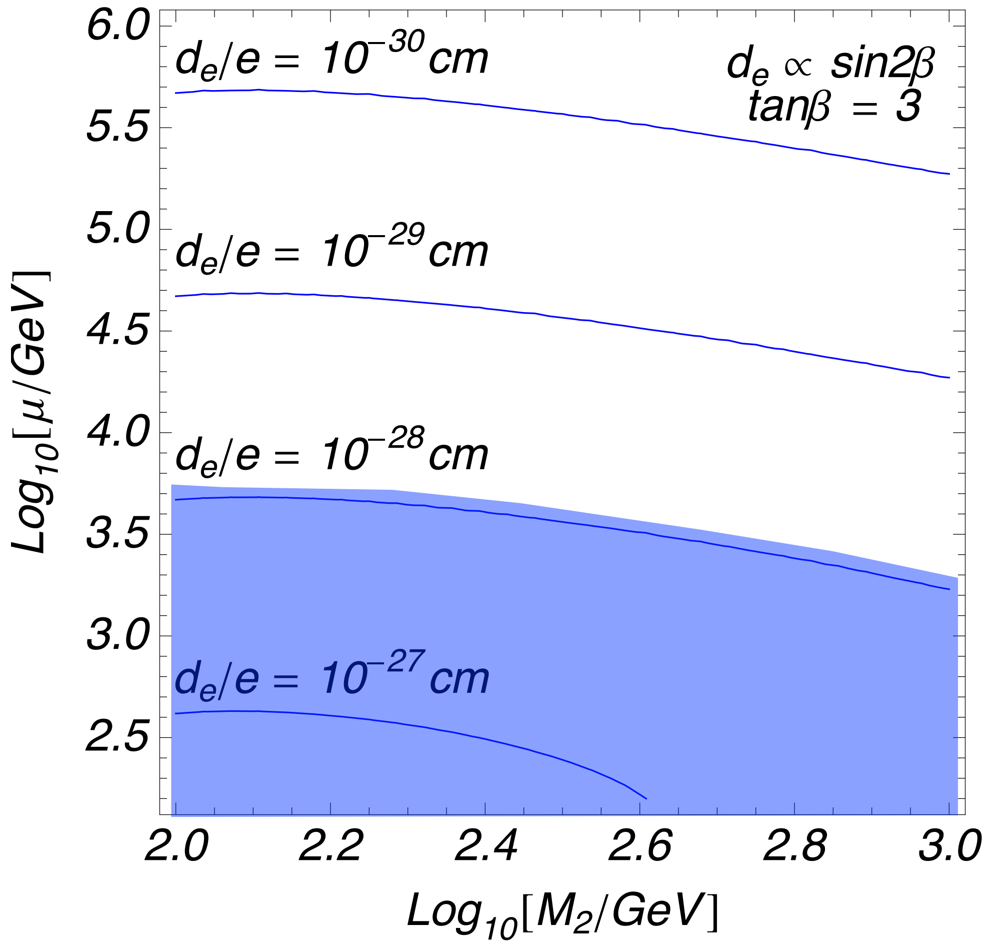


[Figure by S.Matsumoto]

CP-phases



['04 Arkani-hamed,Dimopoulos,Giudice, Rommanio]



Physical CP-violation is suppressed by O($m_{3/2}$).

- ✓ EDM via one-loop slepton diagrams is suppressed by $m_{\mathrm{slepton}}^{-2}$.
- ✓ EDM are dominated by two-loop diagrams in which the light Higgs boson is circulating (suppressed by $\mu_H^{-1} \sin 2\beta$)

The current limits $d_e/e < 8.7 \times 10^{-29}$cm is reaching to μ_H of $O(10^4)$ TeV !

[1310.7534 ACME : ThO]

FCNC

CP-violation in K-K mixing strongly constraints the 1-2 elements of the left and the right down quark mass matrices:

$$\sqrt{\tilde{m}_{LL}\tilde{m}_{RR}} \gtrsim 4000\,\mathrm{TeV} \times \sqrt{\left|\mathrm{Im}\left(\frac{m^{d\,2}_{12,LL}}{\tilde{m}^2_{LL}}\frac{m^{d\,2}_{12,RR}}{\tilde{m}^2_{RR}}\right)\right|}\,,$$

['96 Gabbiani, Gabrielli, Masiero, Silvestrini]

If we have generic mass matrices with O(1) phases, K-K mixing requires $m_{3/2}$ of $O(10^3\text{-}10^4)\,TeV$ or fine-tuning!

→ $O(10^3)\,TeV$ gravitino leads to 3TeV wino which is consistent with the thermal Wino scenario. (No hope at LHC...)

Phenomenology of PGM

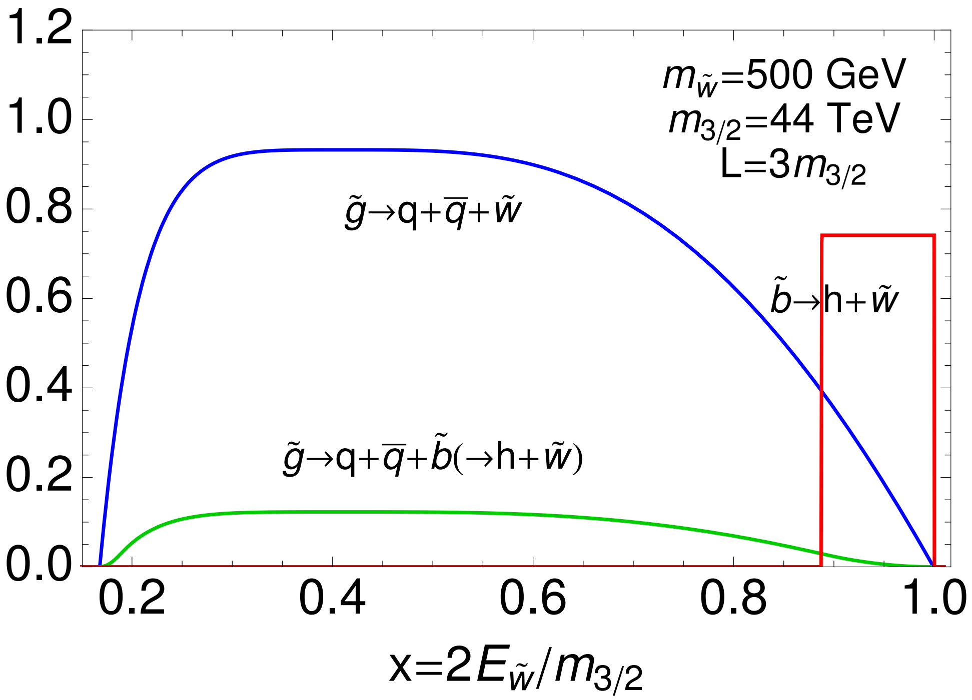
Is wino DM really cold?

['12, MI, Kamada, Matsumoto]

The wino DM lighter than 2.7TeV is mainly produced by the decay of the gravitino non-thermally.

$$\Omega^{NT}_{DM}h^2 = 0.16\left(\frac{m_{wino}}{300\mathrm{GeV}}\right)\left(\frac{T_R}{10^{10}\mathrm{GeV}}\right)$$

$$T_{decay} = 4\mathrm{MeV}\,(m_{3/2}/\,100\mathrm{TeV})^{3/2}$$



Wino production:

gravitino → W,Z + wino

gravitino → g + gluino →q+q + wino

gravitino → γ,Z + bino →W, h + wino

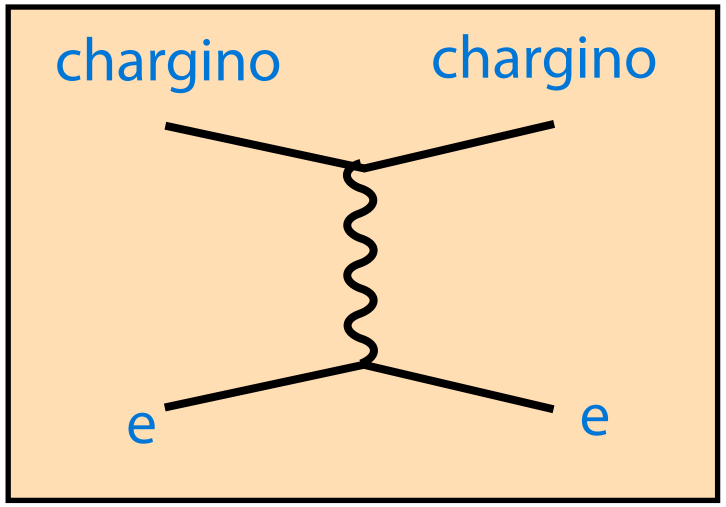
Wino is much more energetic than the thermal background!

Wino DM can be warmer!

How does it lose its energy?

Phenomenology of PGM

Fate of charged wino

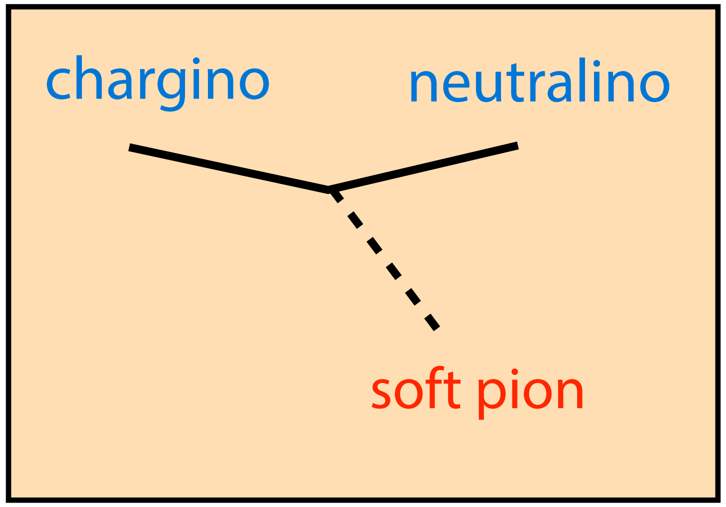


Charginos lose its energy by Coulomb scattering with the background electrons/positrons.

$$dE/dt \sim -\alpha^2 T^2$$

Due to its long lifetime $O(10^{-10})$ sec, charginos lose most of its energy before they decay!

$$\Delta E/E \sim 100(T/\mathrm{MeV})^2\,(100\mathrm{GeV}/m_{wino})$$



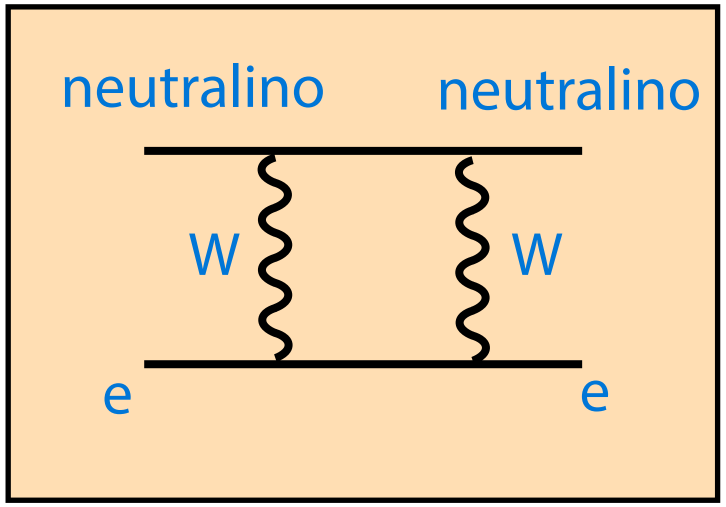
The charginos decay into neutralinos emitting soft pions after they are stopped by thermal bath!

✓ The wino DM via chargino decay is very slow and cold!

Phenomenology of PGM

Fate of neutral wino

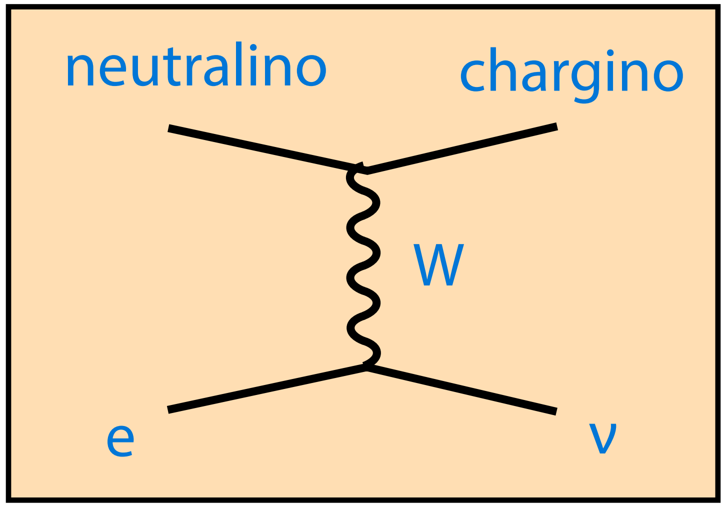
elastic scattering



The elastic scattering of the neutralino with thermal background is highly suppressed at tree-level.

One-loop process is dominant →negligible.

inelastic scattering

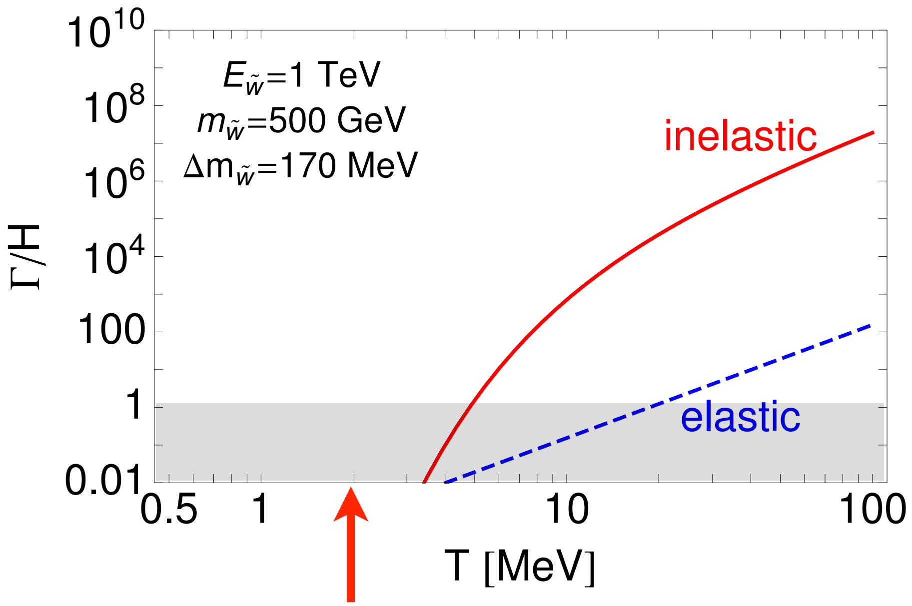


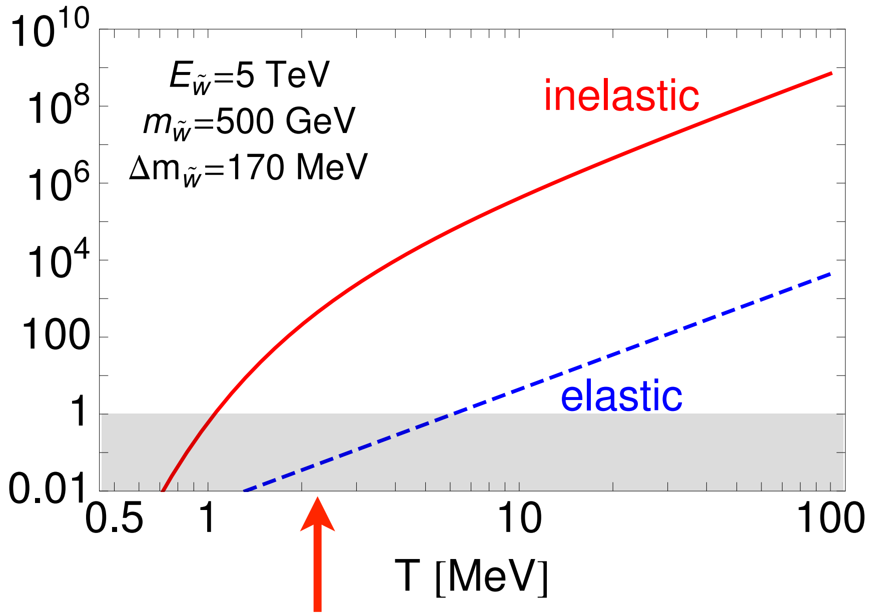
Suppressed by Boltzmann factor due to the mass difference chargino-neutralino.

✓ Once neutralino gets excited to the chargino, it’s easily stopped and the wino DM is again cold!

Phenomenology of PGM

Fate of neutral wino





For the wino energy below *O(1) TeV*, the inelastic scattering is freeze-out when the gravitino decays at *O(1) MeV*!

gravitino (10-100TeV) →

Wino DM (E>>1TeV) → Charged Wino → Stopped→ Cold!

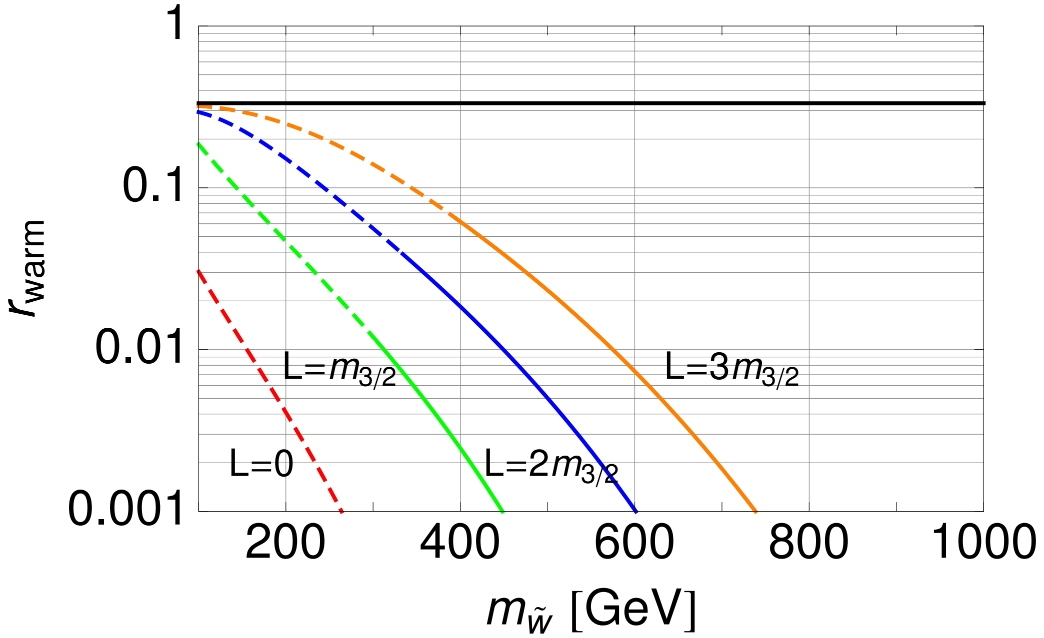
Wino DM (E<O(1)TeV) → never interact with thermal bath

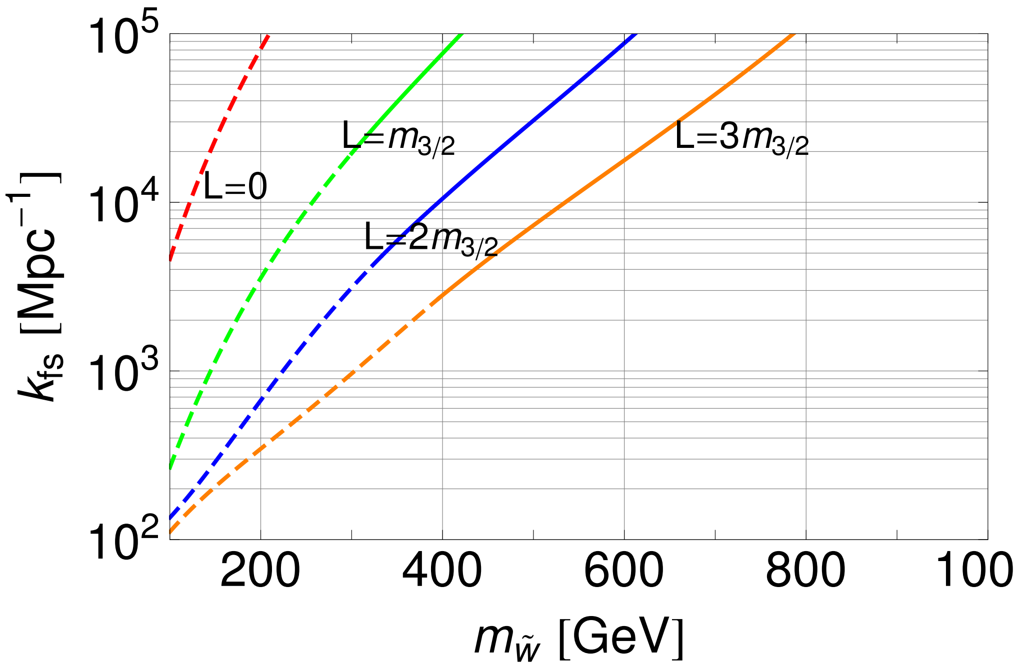
→ Warm!

✓ The low energy tail of the non-thermal wino spectrum can be warm DM!

Phenomenology of PGM

Warm component of wino DM


fraction of warm component


free-streaming wave number

- ✓ The wino DM has warm component with a fraction of *O(0.1-1)%* for $m_{wino} < 500GeV$.
- ✓ The free-streaming length is of *O(1-10) kpc.*

If we can observe warm component, we can check the non-thermal scenario! (*21cm* line survey?)

Summary

The Higgs boson mass, $m_{higgs} \sim 126 GeV$, indicates the sfermion (stop) masses are rather high...

✓ SUSY model should be fine-tuned to obtain O(100)GeV out of *O(10-100)*TeV...

✓ *O(10-100)*TeV gravitino mass allows us a very simple model the pure gravity mediation model.

Sfermion: Tree-level SUSY breaking
Higgsino : Tree-level *R*-breaking
Gaugino: AMSB+Higgsino threshold effects

✓ The PGM with $m_{3/2} = O(100)$TeV is also successful to explain DM abundance by the wino DM.

- ✓ Thermal wino *DM* → $m_{wino} \sim 3$ *TeV*.
- ✓ Non-thermal wino *DM* → $m_{wino} \ll 3$ TeV.

Summary

- ✓ Thermal DM → $m_{wino} \sim 3$TeV.
  - ✓ No LHC signal...
  - ✓ Low reheating temperature is required ⇔ Thermal leptogenesis
  - ✓ The DM direct search is challenging ($\langle\sigma v\rangle = O(10^{-47})cm^{2.}$).

  - ✓ The FCNC problem is solve.

  - ✓ The DM indirect search is interesting!

    Line gamma-ray search from the GC by ATC such as CTA.

    Continuous gamma-ray search from dSph by FERMI, GAMMA400...

    Anti-proton flux by AMS-02 (if the propagation is well understood.)

Summary

- ✓ Non-thermal wino DM → $m_{wino} << 3TeV$.
  - ✓ The DM direct search is challenging $<\sigma v> = O(10^{-47})cm^{2}$·.
  - ✓ The DM indirect search is promising for $m_{wino} < TeV$.
    - Line gamma-ray search from the GC by ATC such as CTA!
    - Continuous gamma-ray search from dSph by FERMI, GAMMA400...
    - Anti-proton flux by AMS-02...
  - ✓ Gluino pair production
    - LHC put limits : $m_{gluino} > 1.4TeV$ or $m_{wino} > 300GeV$ ($8TeV\&20fb^{-1}$).
    - LHC limits will reach to $m_{gluino} > 2.5TeV$ or $m_{wino} > 1TeV$ ($14TeV\&300fb^{-1}$).
  - ✓ Direct wino production
    - LHC puts limits : $m_{wino} > 270TeV$ by searching for disagreeing tracks.
    - LHC limits will reach to $m_{wino} > 500\ TeV$ in future.