Pure Gravity Mediation

--- Rethinking Naturalness in Landscape ---

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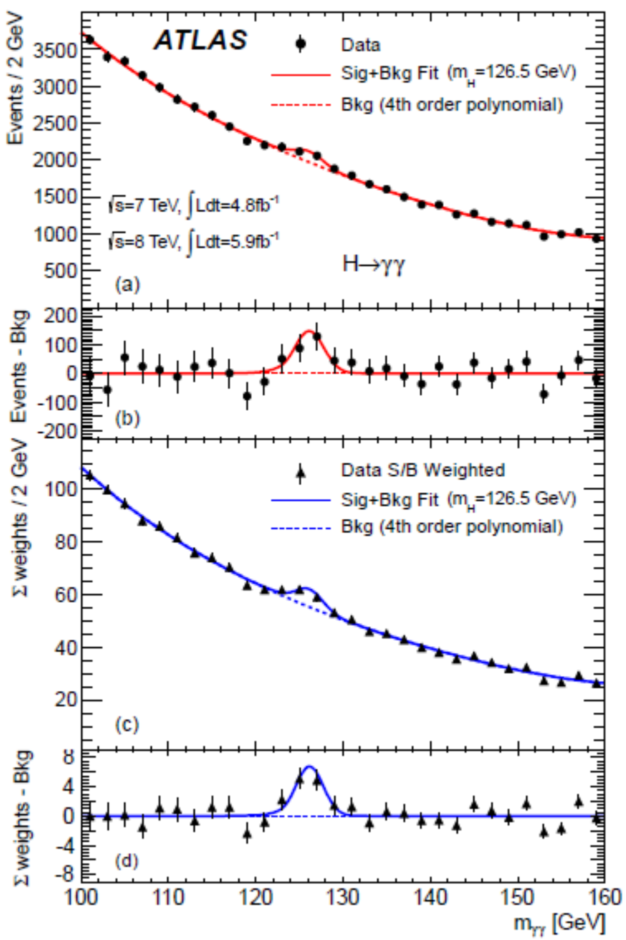
At Niels Bohr Institute, August 14, 2013

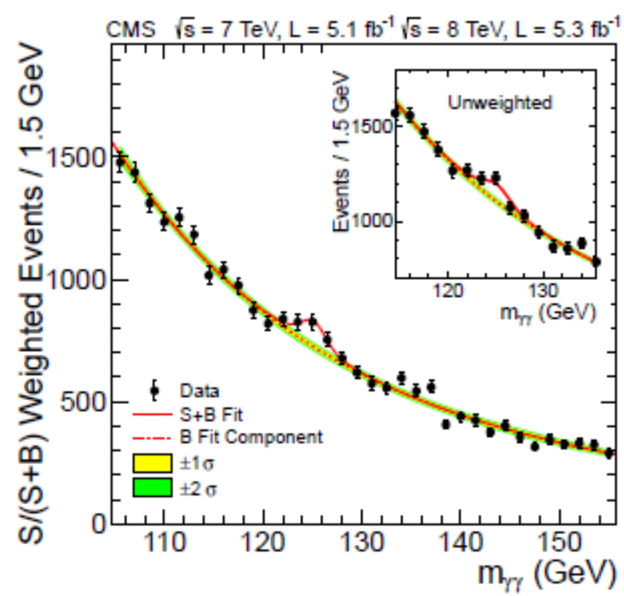
The Discovery of Higgs Boson (Dec. 13, 2011)

ATLAS and CMS reported the discovery of Higgs boson of mass about 125 GeV



$$m_h = 126.0 \pm 0.4(\text{stat}) \pm 0.4(\text{sys})\ \text{GeV}$$ (*ATLAS*)

$$m_h = 125.3 \pm 0.4(\text{stat}) \pm 0.5(\text{sys})\ \text{GeV}$$ (*CMS*)



CMS

Is there any theory which predicts such a Higgs boson mass ?

Yes !

The Minimal Supersymmetric Standard Model (MSSM)

The Higgs mass is predicted as

$$m_{\rm H}^2 \simeq m_{\rm Z}^2 \cos^2(2\beta) + \Delta m_{\rm H}^2$$

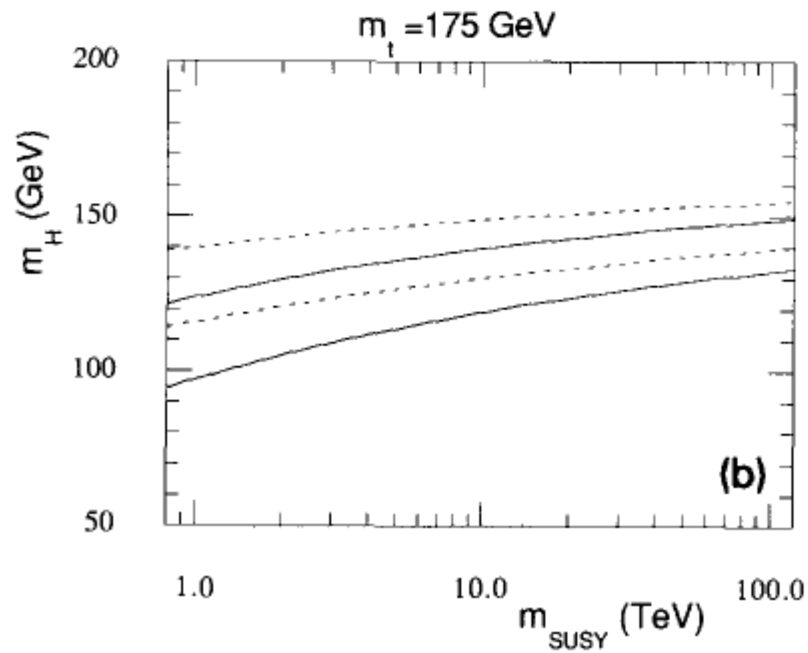
tree level

quantum corrections

The quantum corrections are non negligible if stop masses are large

Okada, Yamaguchi, Yanagida (1991)
J. Ellis et al (1991)
H. Haber et al (1991)

The Higgs mass predicted



Okada, Yamaguchi, Yanagida (1991)

We have calculated the mass of the lightest Higgs boson in the minimal SUSY standard model postulating the SUSY breaking scale is much larger than the Fermi scale. Our results can be used to probe the SUSY breaking scale, with the situation where both m_t and m_{H0} are given. For example, when $m_t = 150$ GeV, the existence of the Higgs boson below 70 GeV strongly suggests the presence of the SUSY below 1 TeV (see the lower solid line in fig. 1a). On the other hand, if the Higgs boson turns out to be heavier than 125 GeV, the SUSY breaking scale must be larger than

$$m_{\rm SUSY} = m_{stop} \geq O(10)\text{TeV}$$

There were various motivations to consider the large SUSY breaking scale,

I. Gravitino over-production problem
II. Polonyi (Moduli) problem
III. Flavor-changing neutral current problem
IV. CP-violation problem

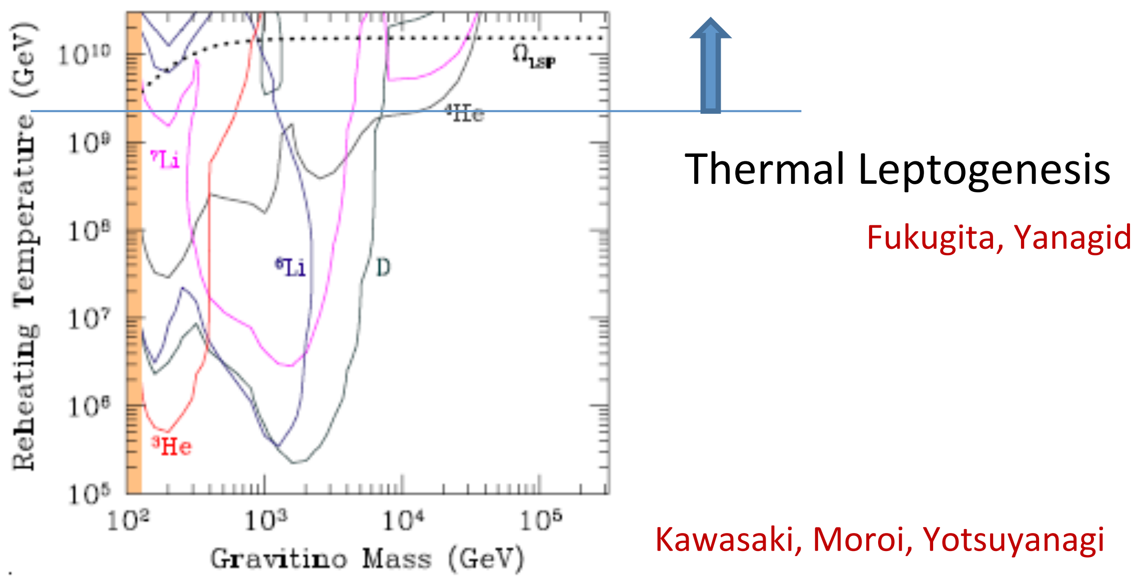
Solutions to each problems suggested the large SUSY breaking

$$m_{3/2} \simeq m_{\rm SUSY} \geq O(10){\rm TeV}$$

I. Gravitino over-production problem

S. Weinberg (1982)

The gravitinos are produced by particle scattering in thermal bath in the early universe. They decay after the BBN and destroy the light elements produced by the BBN. We have constraints on T_R and m_3/2 not to disturb the BBN (big bang nucleosynthesis).



Fukugita, Yanagida (1986)

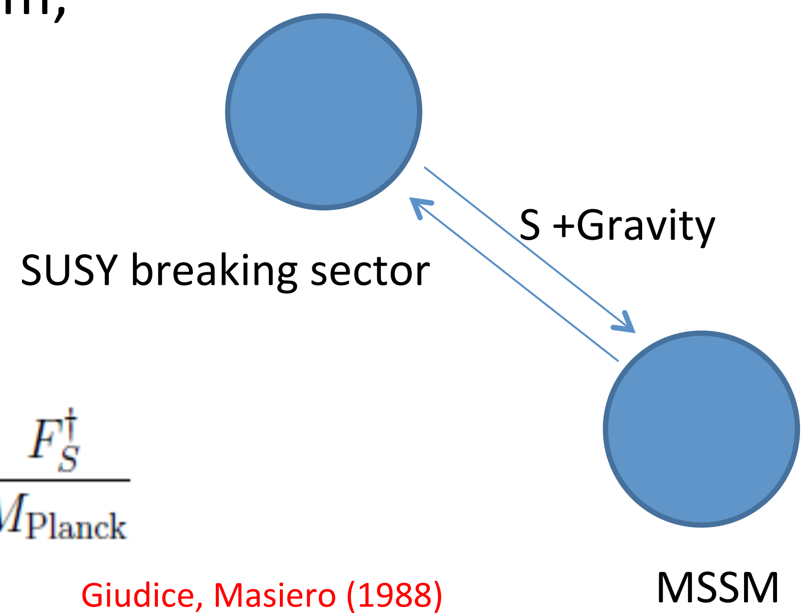
Kawasaki, Moroi, Yotsuyanagi

The thermal leptogenesis predicts $m_{3/2} \simeq m_{\rm SUSY} \geq O(10)\mathrm{TeV}$

II. Cosmological Polonyi (Moduli) problem

Gravity mediation SUSY breaking model assumes a Polonyi field S to generate masses for gauginos and Higgsino

The S has a SUSY-breaking F term;



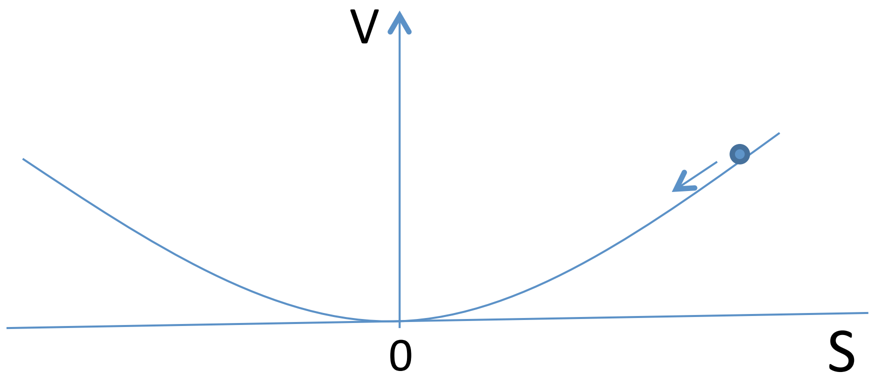
$$m_{\text{gaugino}} \simeq \frac{F_S}{M_{\text{Planck}}} \qquad m_{\text{Higgsino}} \simeq \frac{F_S^\dagger}{M_{\text{Planck}}}$$

Giudice, Masiero (1988)

The Polonyi field S is completely neutral and has a mass of O(m_3/2)

During inflation the S sits nearly at the Planck scale, S=O(M_PL)
After the inflation the expansion rate of the universe decreases and becomes smaller than the Polonyi mass m_S

Then, the S starts its coherent oscillation which dominates the universe's energy density



The S decays after the BBN destroy the light elements if m_S=O(1) TeV

For the successful BBN we should require m_3/2~m_S > O(100) TeV

Even for m_S=100 TeV we have a serious problem

The decay of the Polonyi field S produces a huge entropy and the primordial baryon asymmetry is diluted by a factor $\sim 10^{14}$

The observed baryon asymmetry is

$$\frac{n_B}{s} \simeq 10^{-10}$$

Even if this problem is solved, we have a tension with DM

$$m_{DM} \simeq O(0.1 - 1)\ \text{TeV} << m_{3/2} \simeq O(100)\ \text{TeV}$$

neutralino

A simple solution is to take out the Polonyi field S

Just after the LHC discovery of the Higgs boson of mass about 125 GeV, we proposed a SUSY breaking mediation model

Ibe, Yanagida (Dec., 2011)
Ibe, Matsumoto, Yanagida (2012)

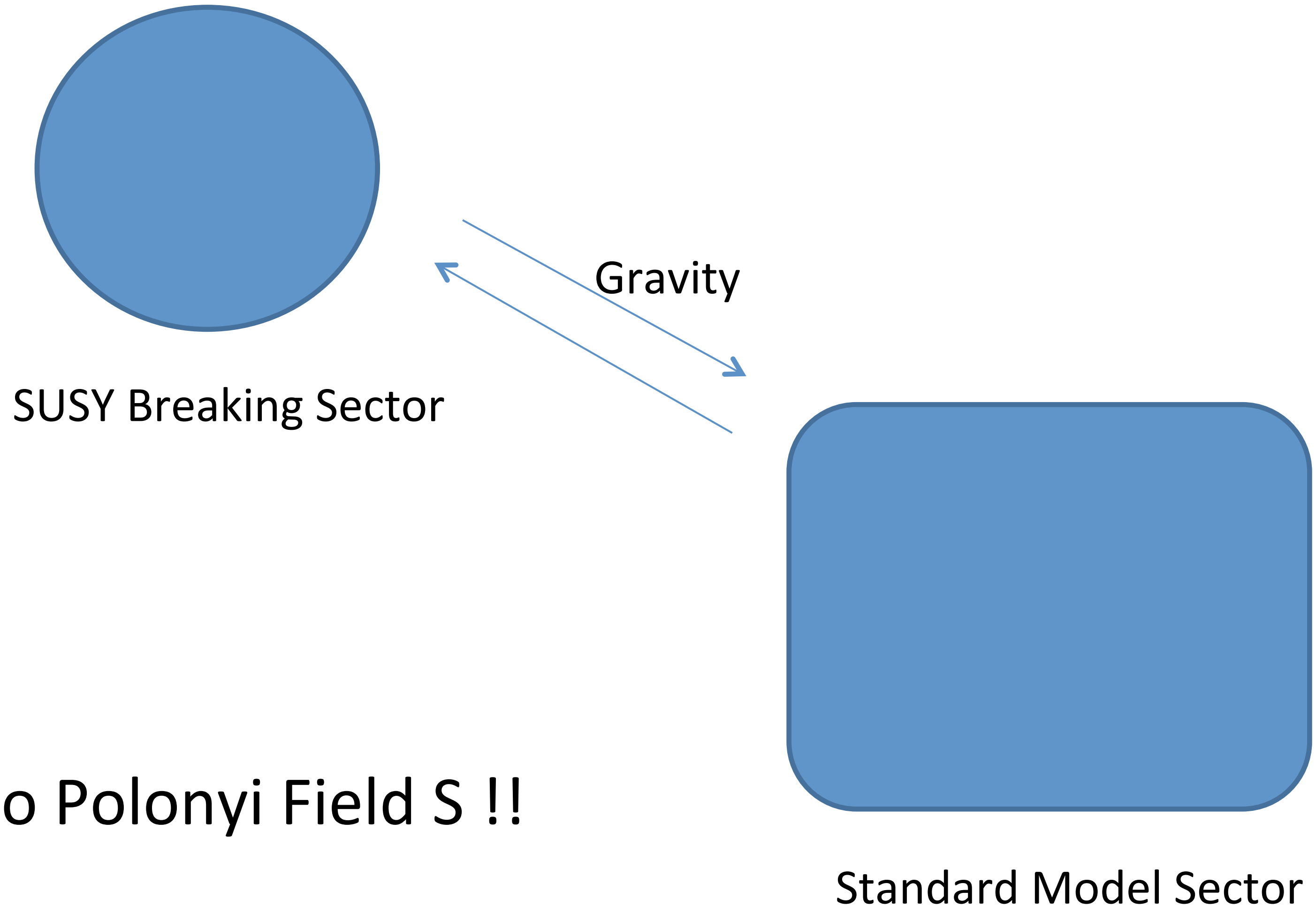
Pure Gravity Mediation

= Minimal Split SUSY

Nima Arkani-Hamed (Dec., 2011)

Pure Gravity Mediation

Ibe, Moroi, Yanagida (2006)



No Polonyi Field S !!

I. The gaugino masses can be generated by quantum corrections without the Polonyi field in supergravity

H. Murayama et al (1998)
Randall, Sundrum (1999)

Anomaly mediation:

$$\begin{aligned} m_{\rm bino} &\simeq 10^{-2} m_{3/2} \ , \\ m_{\rm wino} &\simeq 3\times 10^{-3} m_{3/2} \ , \\ m_{\rm gluino} &\simeq (2-3)\times 10^{-2}\, m_{3/2} \ . \end{aligned}$$

$$m_{\rm gluino} > 1.5\ {\rm TeV} \rightarrow m_{3/2} > 50\ {\rm TeV}$$

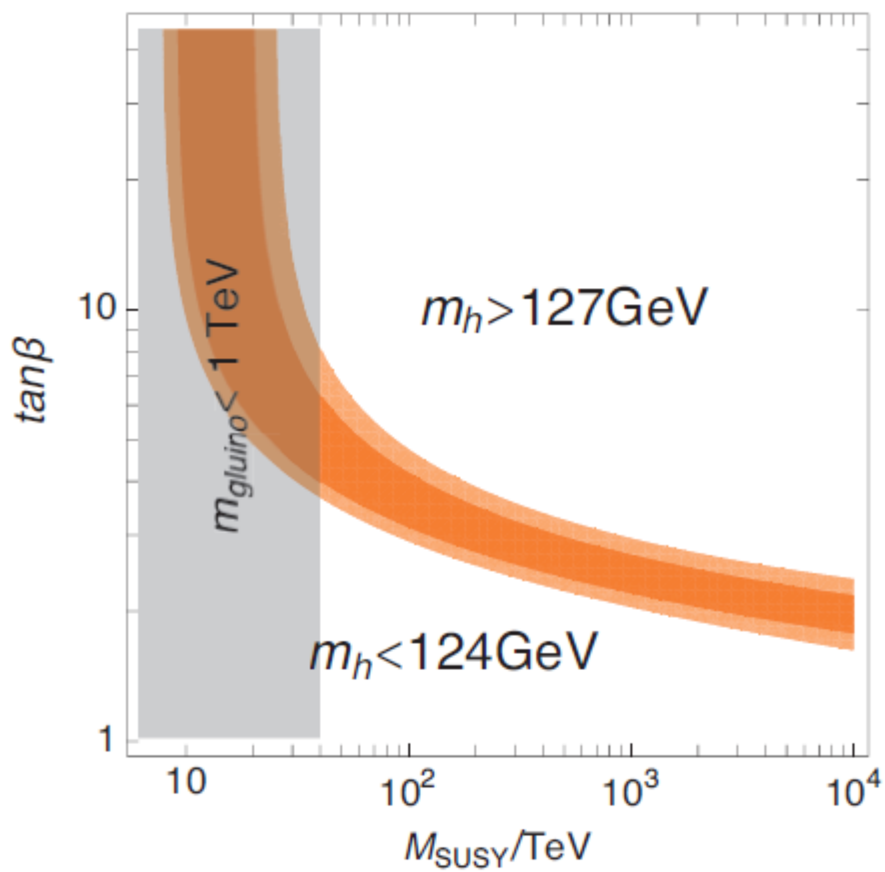
II. The Higgsino mass can be generated by the supergravity effects without the Polonyi field at the classical level

$$K = H_u H_d + \ldots. \quad \Longrightarrow \quad m_{\rm Higgsino} = \mu \simeq m_{3/2} \quad ; \quad \tan\beta \simeq O(1)$$

Inoue, Kawasaki, Yamaguchi, Yanagida (1992)
Casas, Munoz (1993)

The Higgs mass about 125 GeV can be explained for small

$\tan\beta \simeq O(1)$ and $m_{3/2} \simeq 50 - 1000$ TeV



The wino is the LSP and a candidate for the DM

If the thermal wino is the dominant DM, its mass is predicted as

Hisano, Matsumoto, Nojiri

$$m_{\rm wino} \simeq 2.7 \text{ TeV}$$

The wino can be produced non-thermally by the gravitino decay and its abundance depends on the reheating temperature

The thermal leptogenesis needs $T_R > 2 \times 10^9 \text{ GeV}$

which predicts $m_{\rm wino} < 1.5 \text{ TeV}$

The wino mass O(1) TeV region is very interesting !!!

The Pure Gravity Mediation is very satisfactory

I. It easily explains 125 GeV Higgs mass
II. Successful gauge coupling unification
III. No Gravitino over-production problem
IV. No Polonyi (Moduli) problem
V. No Flavor-changing neutral current problem
VI. No CP-violation problem

It predicts the wino LSP of mass O(1) TeV
which is a good candidate for the DM

But, one problem remains

The Unnaturalness Problem

$$m_{\rm sfermions} \simeq m_{3/2} \simeq 100 \text{ TeV}$$

$$m^2_{\rm stops} \simeq m^2_{\rm H_u, H_d} \simeq (100 \text{ TeV})^2 \quad \Longrightarrow \quad m^2_{\rm Higgs\ boson} \simeq -(100 \text{ GeV})^2$$

quantum corrections

We need $\Delta \simeq (m_Z/m_{3/2})^2 \simeq 10^{-6} = 10^{-4}\%$ fine tuning !

Rethinking in the Landscape

We assume a dynamical SUSY breaking and log flat distribution for the dynamical scale Λ

$$m_{3/2} \simeq \frac{\mathrm{F}}{M_{\mathrm{PL}}} \simeq \frac{\Lambda^2}{M_{\mathrm{PL}}}$$

The log flat distribution for the gravitino mass $m_{3/2}$

Consider a conditional probability for the correct electroweak scale

$$\mathcal{P}_{\mathrm{cond.}}$$

$\mathcal{P}_{\rm cond.}$ (Anthropic principle condition)

Arkani-Hamed, Dimopoulos (2005)

$$v^2 \simeq (\mu)^2 - (m_{H_u})^2 = (km_{3/2})^2 - \kappa(m_{3/2})^2$$

$$\mathcal{P}_{\rm cond.} \simeq 1 \; dk \; d\kappa \; d[log(m_{3/2})]$$

$$\simeq \frac{dv^2}{m_{3/2}\sqrt{v^2+\kappa m_{3/2}^2}} \; d\kappa \; \frac{dm_{3/2}}{m_{3/2}}\Big|_{v^2=O(v_0^2)}$$

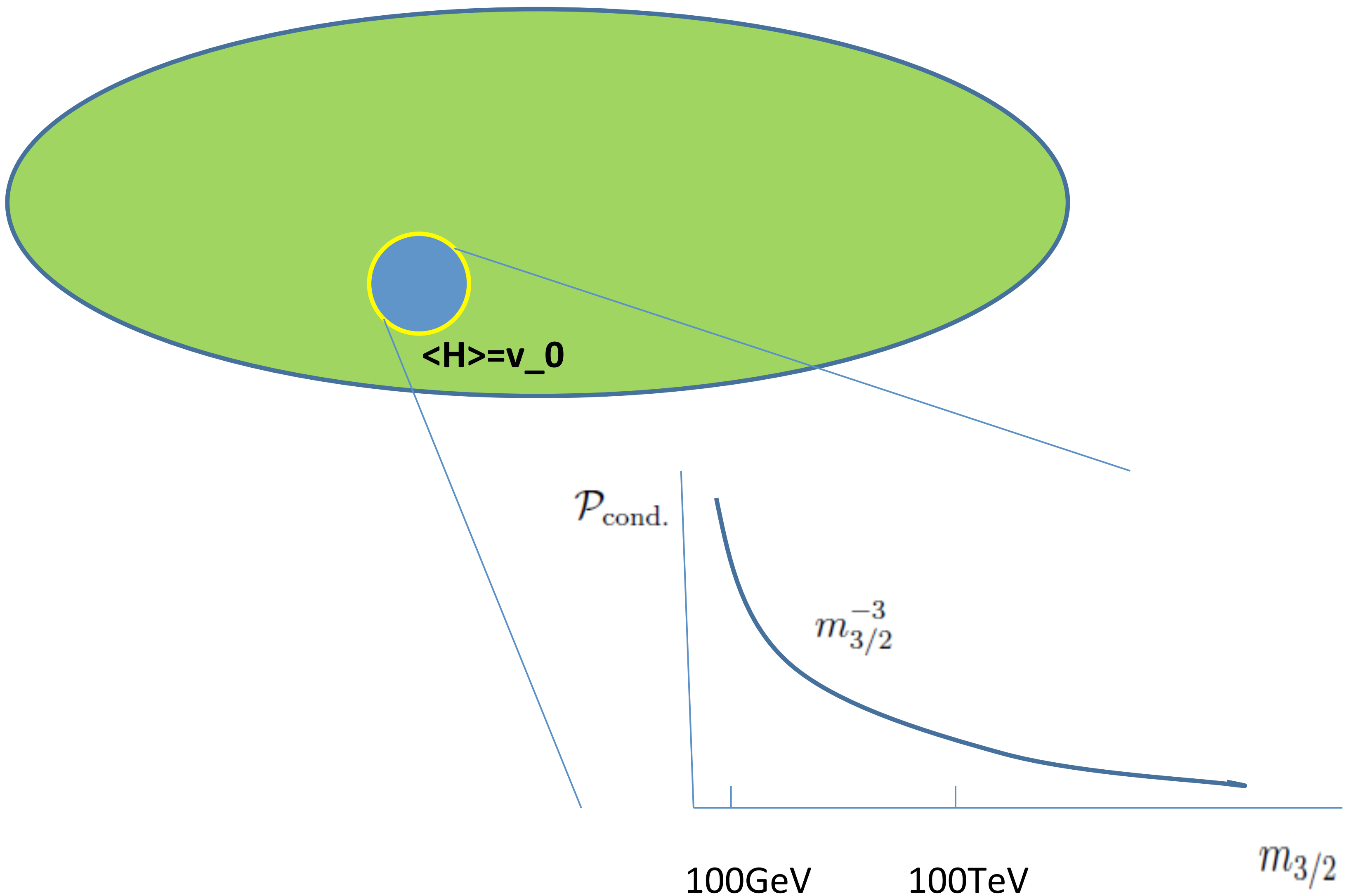
anthropic window

For $v_0 << m_{3/2}$ ⟹ $\mathcal{P}_{\rm cond.} \dot{\simeq} \mathcal{N} \, (\frac{1}{m_{3/2}})^3 \, dm_{3/2}$!

$$\int_{m_{3/2}=100{\rm TeV}} \mathcal{P}_{\rm cond.} / \int_{m_{3/2}=100{\rm GeV}} \mathcal{P}_{\rm cond.} \simeq (\frac{100{\rm GeV}}{100{\rm TeV}})^2 \simeq 10^{-6}$$

We reproduce the naïve argument

The Landscape



Consider the small cosmological constant (anthropic condition)

$$\rho_{\rm vacu.} \simeq |F|^2 - |W|^2$$

We assume a linear flat distribution for the superpotential W

$$\mathcal{P}_{\rm cond.} \simeq 1 \; dk \; d\kappa \; d[log(\Lambda)] \; dW$$

$$\rho_{\rm vacu.} \simeq |\Lambda|^4 - |W|^2 \qquad ; \qquad \frac{d\rho_{\rm vacu.}}{d\Lambda^4} = 1$$

$$\mathcal{P}_{\rm cond.} \simeq 1 \; dk \; d\kappa \; \frac{d\rho}{\rho + |W|^2} \; dW|_{\rho=\rho_0}$$

anthropic window

$$\simeq 1 \; dk \; d\kappa \; (\frac{1}{m_{3/2}})^2 dm_{3/2} \simeq (\frac{1}{m_{3/2}})^4 dm_{3/2} \quad !!$$

$$|W|^2 = m_{3/2}^2 >> \rho_0 \quad (M_{\rm PL} = 1)$$

More low-energy biases !!!

Even for m_{SUSY}>1 TeV, we need 0.1 % fine tuning !

Log flat distribution for the dynamical scale Λ ???

$$S = \frac{4\pi}{g^2(M_*)} \simeq -\frac{b_i}{2\pi} log(\frac{\Lambda_i}{M_*})$$

We have assumed a linear flat distribution for S

S corresponds to a size of volume moduli and the S>1 region may be suppressed in the Landscape

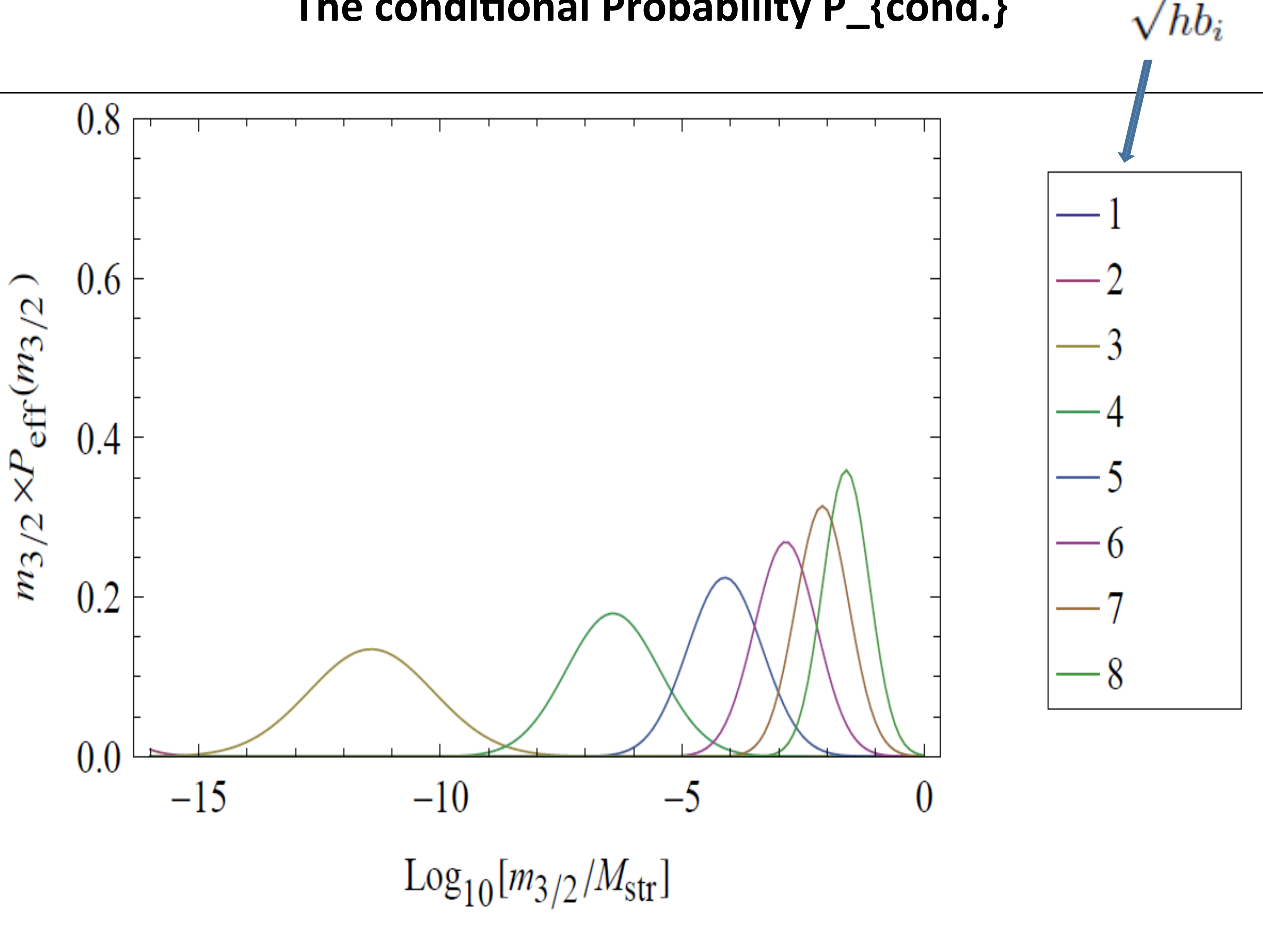
Feldstein, Ibe, Matsumoto, Yanagida

The low-energy region for Λ may be suppressed

For a demonstration we take

$$\mathcal{P} = \exp(-hS^2)$$

The conditional Probability P_{cond.}



Discovery Potential for SUSY Particles

The wino is most likely the DM of mass 300 GeV-3 TeV

The direct detection of the wino DM is very difficult, since the spin independent cross section off nuclei is very small   10^{-47} cm^2

Indirect detection may be possible

$$\tilde{\chi}^0\tilde{\chi}^0 \to W^+W^- \to \begin{cases} \gamma + \ldots \\ \bar{p} + \ldots \\ e^+ + \ldots \end{cases}$$

photon continuum

$\tilde{\chi}^0\tilde{\chi}^0 \to \gamma\gamma$ $\tilde{\chi}^0\tilde{\chi}^0 \to Z\gamma$ photon line

Photon continuum constraints

m_wino < 300 GeV seems excluded

Fermi dwarf

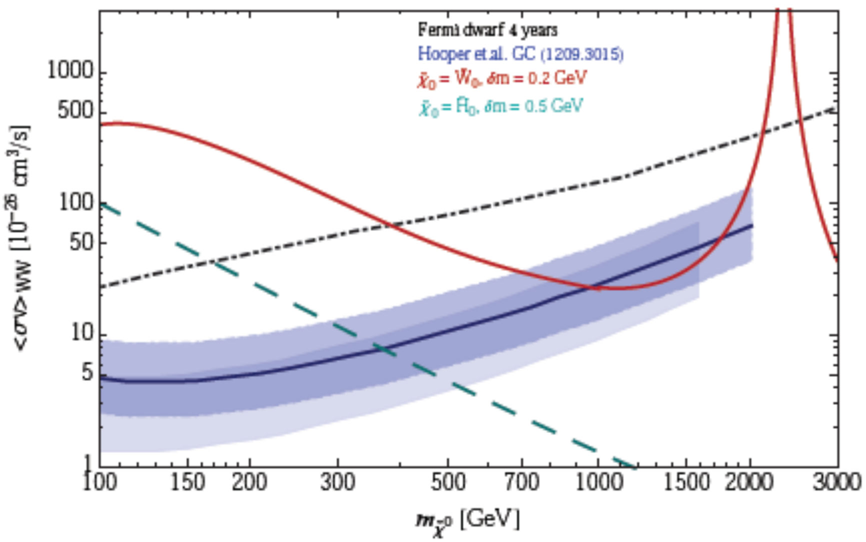


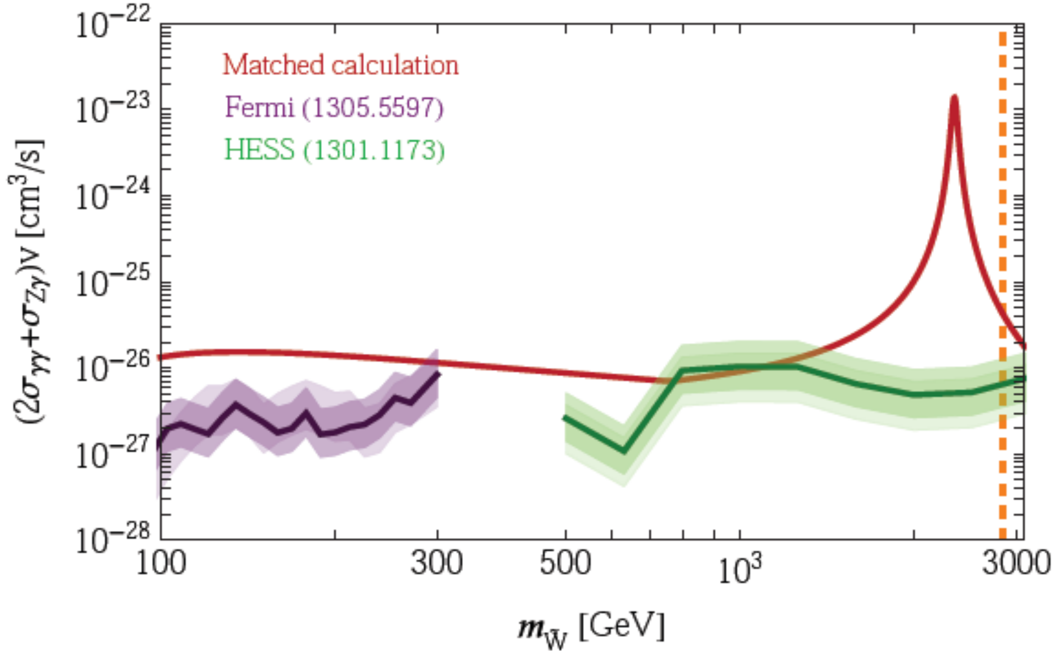
Figure 1: Constraints on the cross section of annihilation into $WW(+ZZ)$ final state and wino/higgsino annihilation cross section as a function of neutralino mass. The black dot-dashed curve is the constraint from the continuum photon spectrum of Milky Way satellite galaxies [41]; the dark blue curve is the constraint from the photon continuum in our galactic center assuming an NFW profile with $\rho(r_\odot) = 0.4$ GeV/cm³ and $r_\odot = 8$ kpc [42]. The blue (lighter blue) bands are derived by varying $\rho(r_\odot)$ of NFW (Einasto) dark matter profiles as discussed in the text. The burgundy solid (cyan dashed) curve is the cross section of wino (higgsino) annihilation into $WW(+ZZ)$ final states.

Photon line constraints

m_wino about 2.2 TeV region seems excluded

Fan, Reece (2013)
Cohen et al (2013)

The Cherenkov Telescope Array experiments may see photon line



strongly depends on the core density of our galaxy !

Figure 3: Constraints on the cross section of wino annihilation into photon(s). The burgundy solid curve is the wino annihilation cross section by matching one-loop calculation [54–57] and the Sommerfeld enhancement calculation [50]. Details can be found in Appendix B. The purple curve is the constraint from the Fermi line search [52] assuming an NFW profile with $\rho(r_\odot) = 0.4$ GeV/cm³ and $r_\odot = 8$ kpc. The purple (lighter purple) bands are derived by varying $\rho(r_\odot)$ of NFW (Einasto) dark matter profiles as discussed in the text. The green curve is the constraint from the HESS line search [53] assuming an NFW profile with $\rho(r_\odot) = 0.4$ GeV/cm³ and $r_\odot = 8$ kpc. The green (lighter green) bands are derived by varying $\rho(r_\odot)$ of NFW (Einasto) dark matter profiles as discussed in the text. The vertical dashed orange line marks the wino with thermal relic abundance $\Omega_{\rm thermal} h^2 = 0.12$.

Anti-proton search will be reported soon by AMS-02

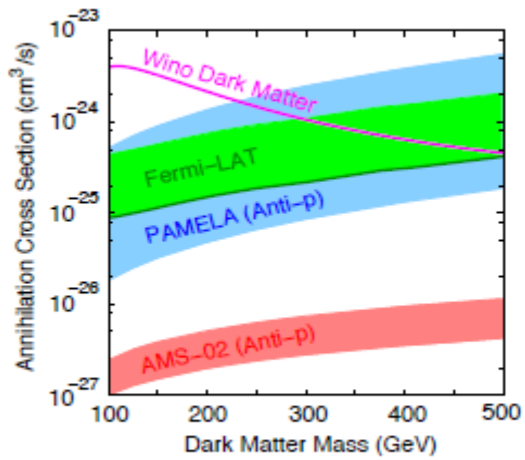


Figure 6: *Constraints and future prospects of indirect detection experiments of dark matter. Theoretical prediction of the neutral wino dark matter is also shown.*

Ibe, Matsumoto, Yanagida

It will exclude below 1 TeV or see anti-proton excess !

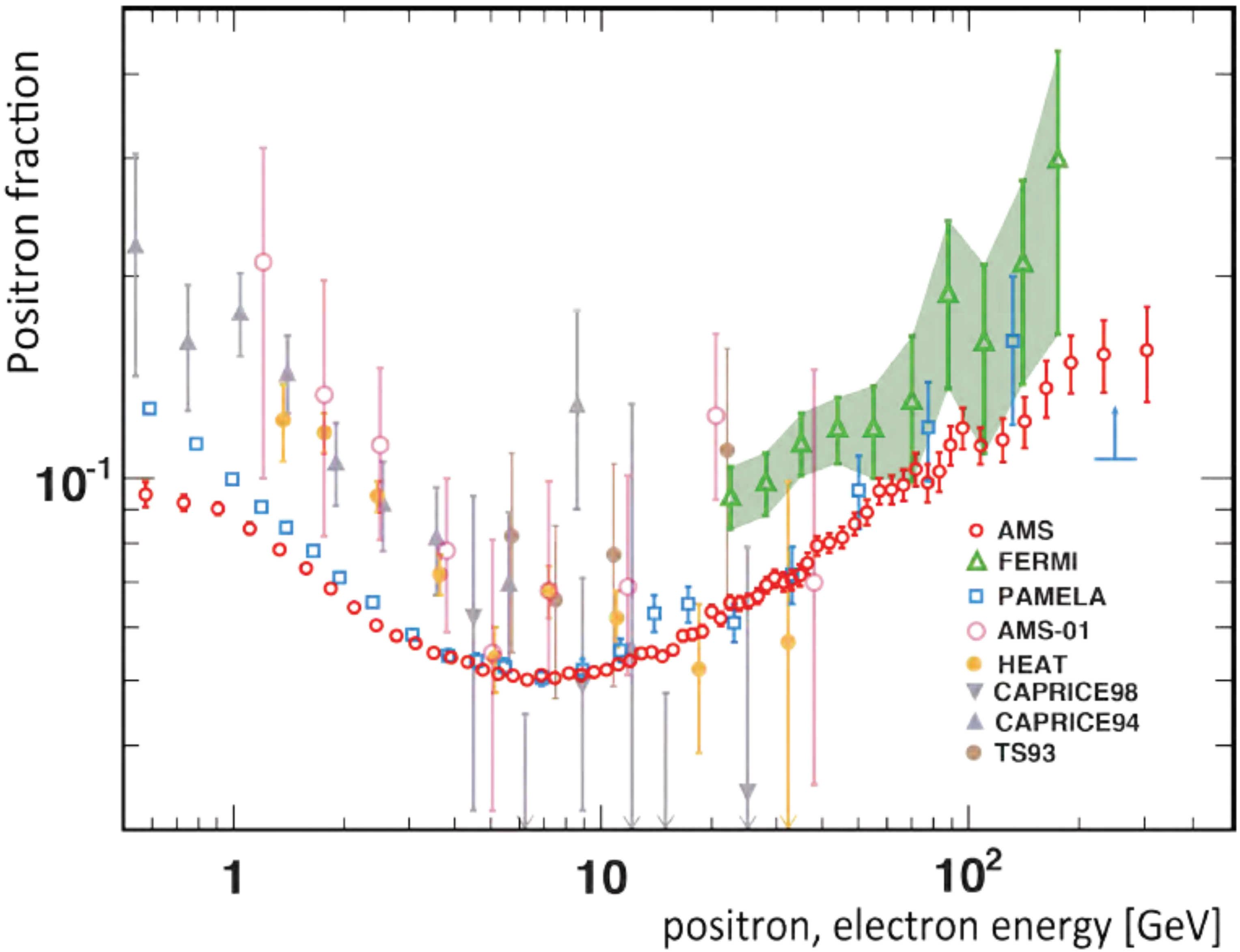
But, the prediction depends largely on details of the propagation models

Dependence of the positron flux on the propagation model is relatively weak, since only positrons produced in small distance from us (<1-2 kpc) can reach us

But, the flux of positrons is suppressed below background and we have no constraint so far

However, the AMS-02 confirmed, recently, the PAMELA anomaly in the cosmic-ray positron flux

AMS-02

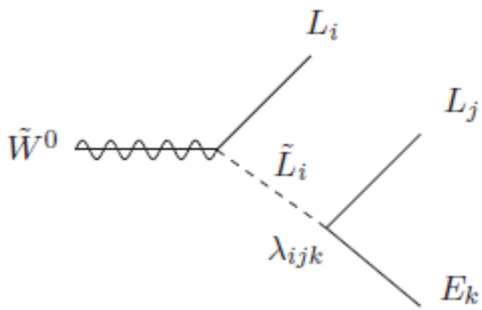


Positron fraction
10⁻¹
1
10
10²
positron, electron energy [GeV]
AMS
FERMI
PAMELA
AMS-01
HEAT
CAPRICE98
CAPRICE94
TS93

With a tiny violation of R parity the wino can decay, explaining the positron excess

Ibe, Matsumoto, Shirai, Yanagida

$$\mathcal{W}_{R\!\!\!/} = \lambda_{ijk}\, L_i L_j E^c_k$$



$$\tau_{\rm wino} \sim 10^{27}\,[\text{sec.}]\,(\lambda/10^{-19})^{-2}\,(m_{\rm wino}/1\ \text{TeV})^{-5}\,(m_{\tilde{L}}/10^3\ \text{TeV})^4$$

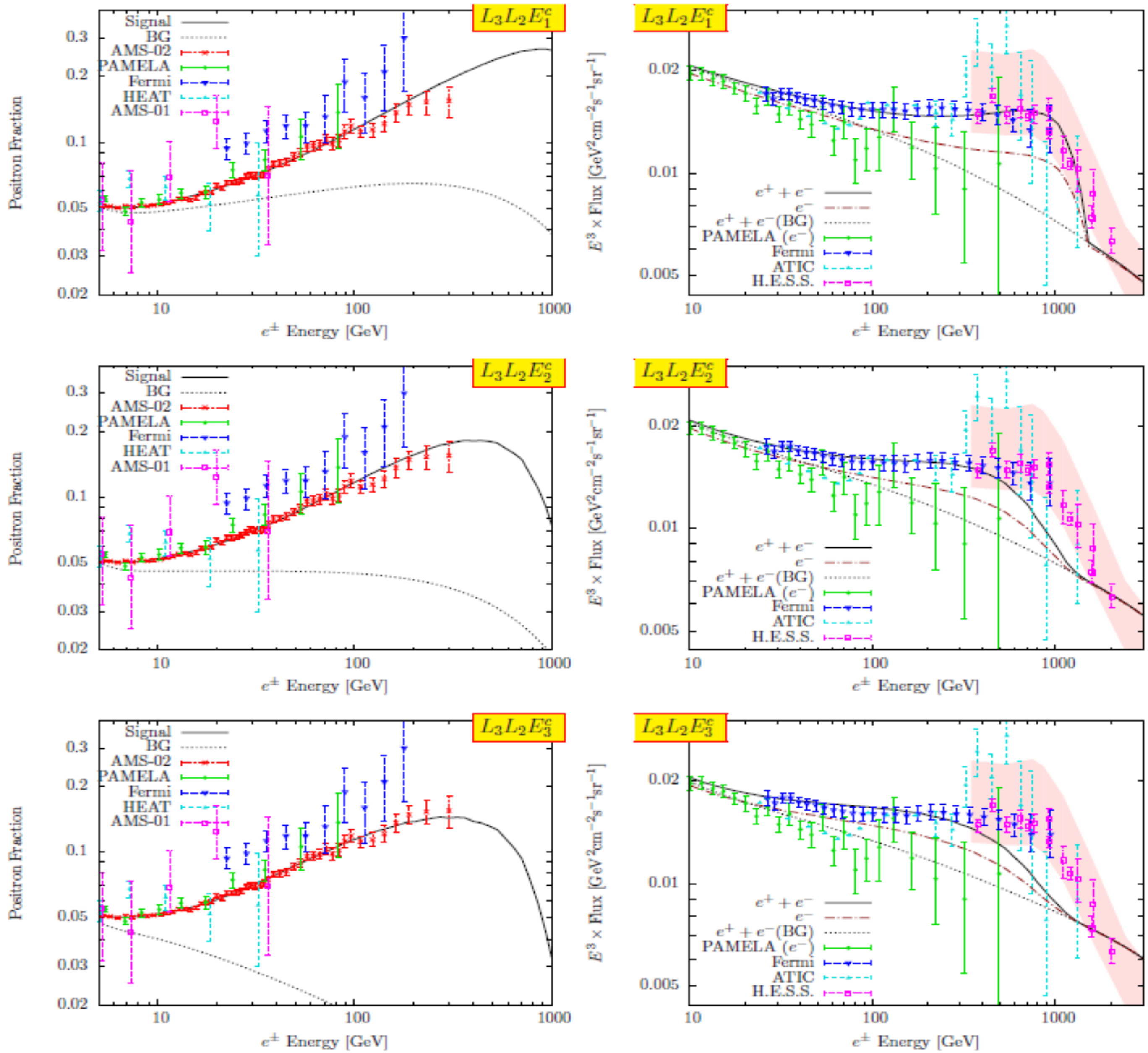
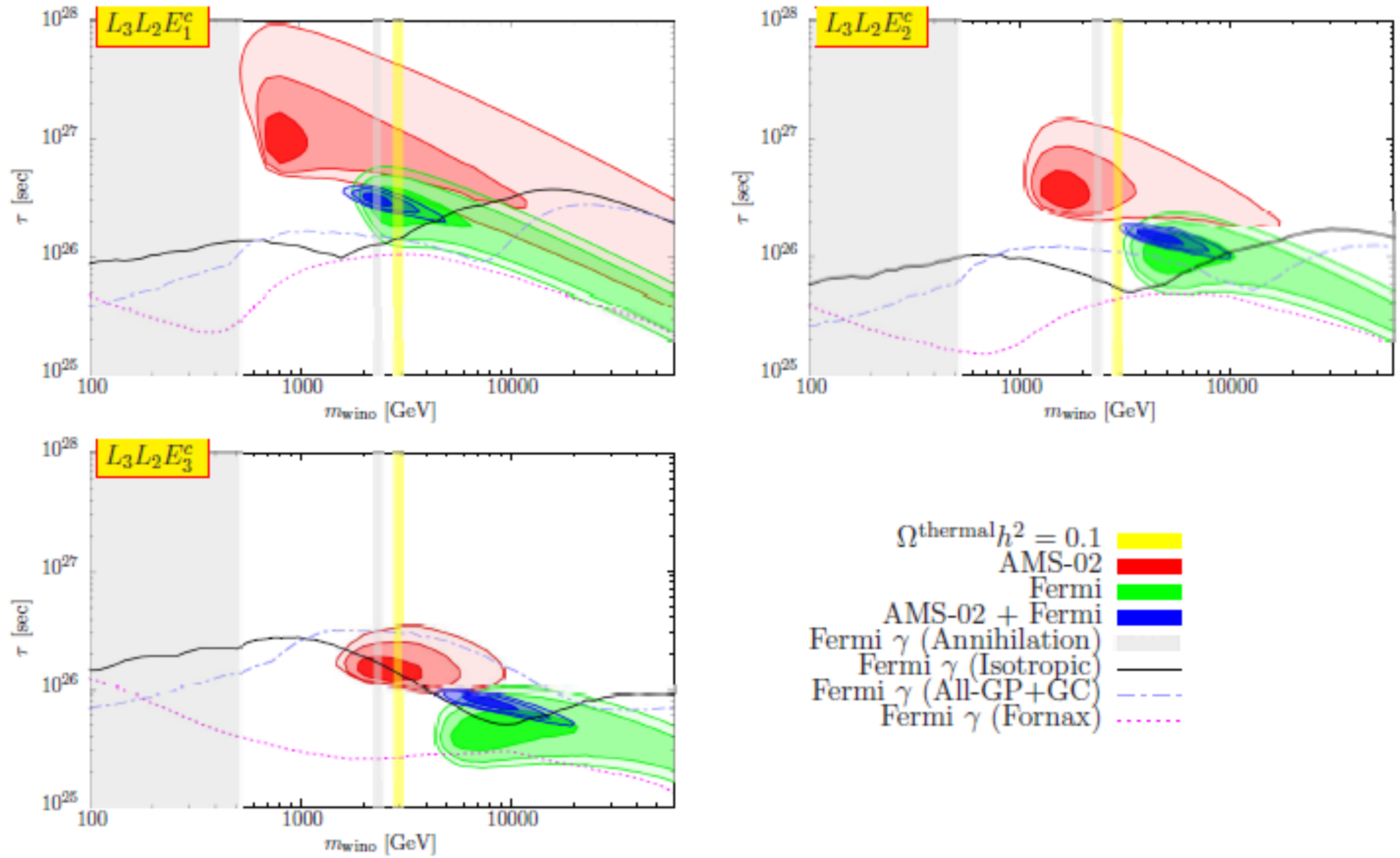


Figure 3: *Some examples of cosmic-ray signals with the wino mass of $m_{\rm DM} = 3$ TeV: Left*



m_wino =1-3 TeV is very consistent with the Pure Gravity Mediation !!!

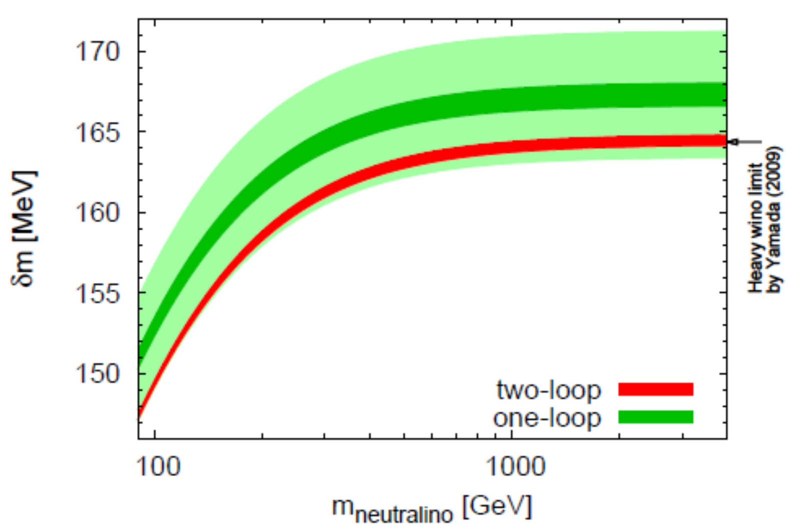
Discovery potential at LHC

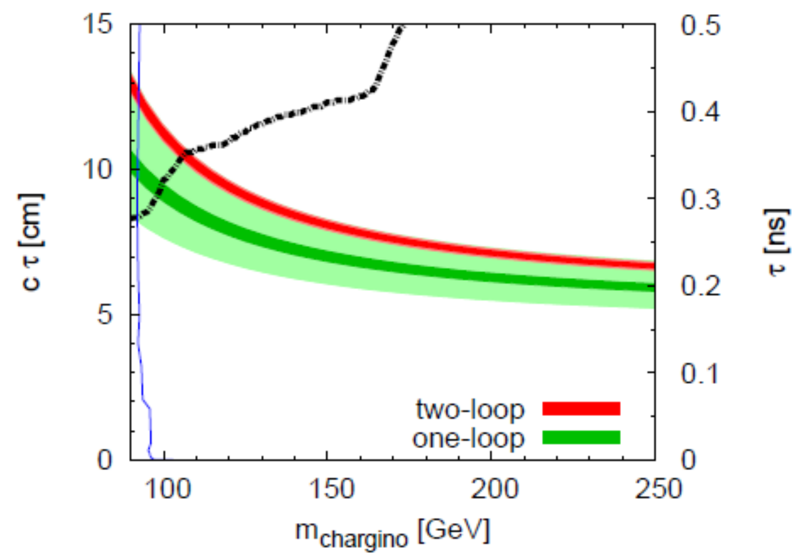
The charged wino decay to the neutral wino and charged pion

$$\chi^+ \rightarrow \chi^0 + \pi^+$$

The decay distance is ct = 5-10 cm, since the mass difference is very small

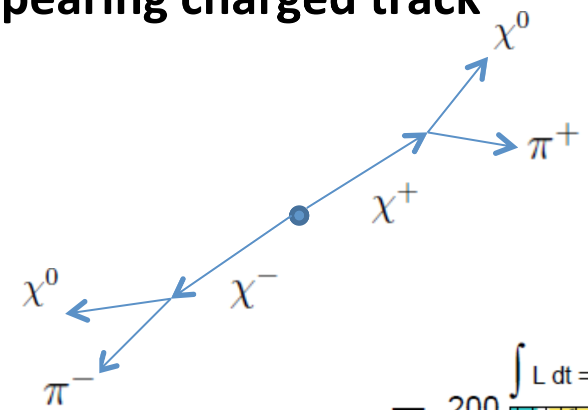
Feng, Moroi, Randall,..





Ibe, Matsumoto, Sato

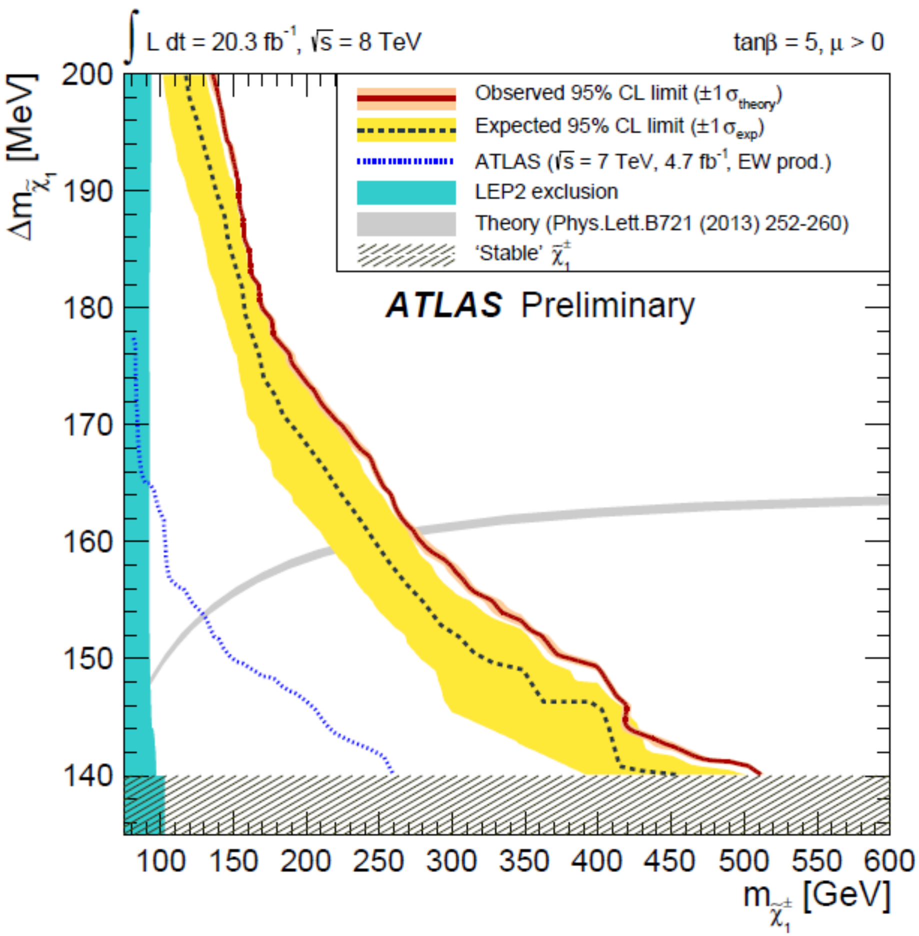
Search for disappearing charged track



Ibe, Moroi, Yanagida (2007)
Asai, Moroi, Yanagida (2008)

The region of m_wino <250 GeV has been excluded

ATLAS (2013)



The region of m_wino <500 GeV will be excluded in 14 TeV LHC

The discovery for the gluino is very limited

The present bound is m_gluino >1.5 TeV
The discovery region will be <2.3 TeV at
the 14 TeV LHC

Bhattacherjee et al

We need a lucky factor !

If masses of squarks in the 1st and 2nd generations and the gluino are degenerate, the discovery region will be enlarged up to <3.0 TeV !!!

Come back to the early 80'th

The small Yukawa couplings may suggest that quarks and leptons are nothing but the fermions of Nambu-Goldtone supermultiplets

Buchmuller, Love, Peccei, yanagida (1982)

Hidden Local symmetry ?

NG multiplets of E_7/SO(10) xU(1)^3

Kugo, Yanagida (1984)

$$\text{two } \mathbf{16} + \mathbf{10} + \mathbf{1}$$

The 1st and 2nd generations

Masses for 1st and 2nd generations may be very small
<< masses of the 3d generations

Evans, Ibe, Olive, Yanagida

Why nature has chosen E_7 ?

Proton Decay

SUSY GUT predicts d=5 operators contributing to the proton decays

Sakai, Yanagida (1982)
S. Weinberg (1982)

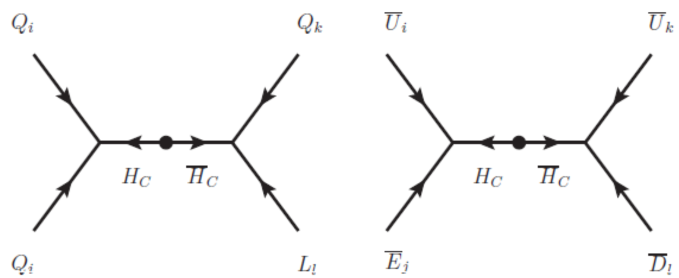
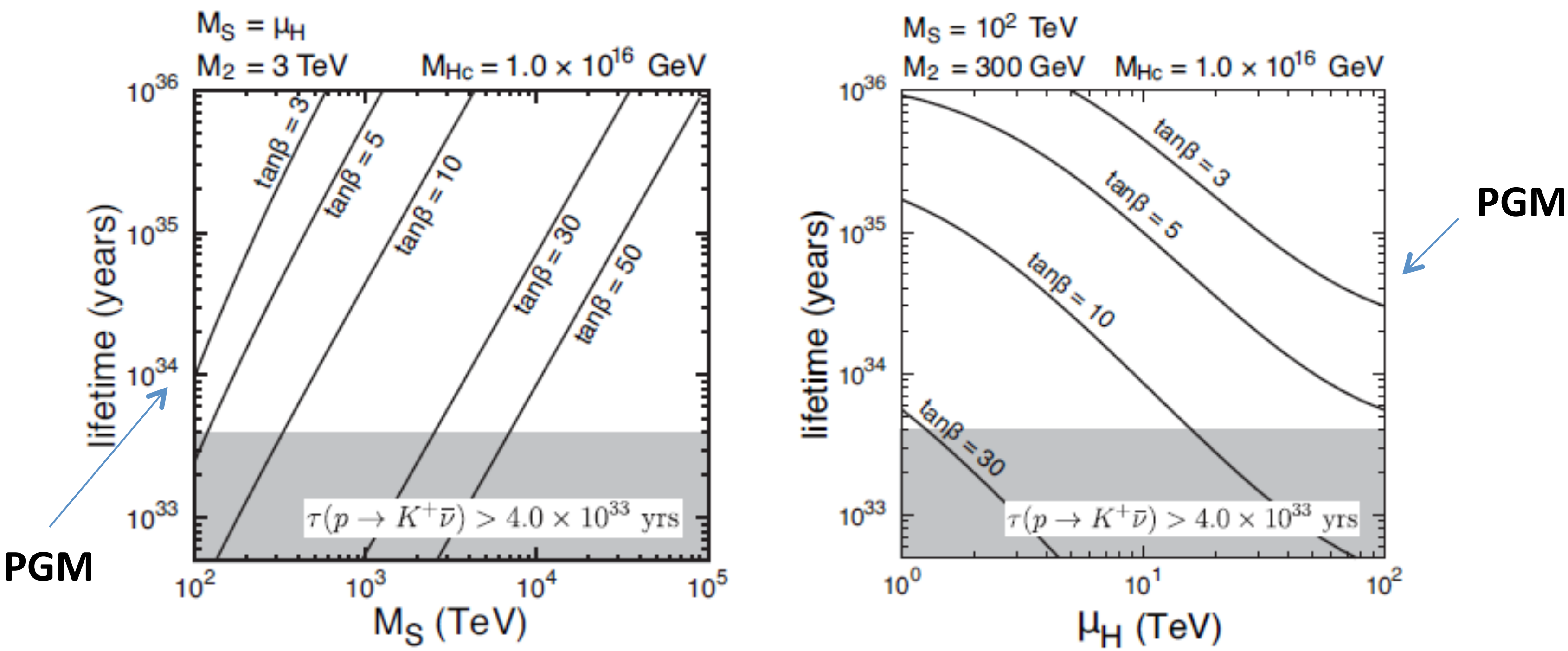


Figure 1: Supergraphs which illustrate color-triplet Higgs exchanging processes where dimension-five effective operators for proton decay are induced. Bullets indicate color-triplet Higgs mass term.

Interesting decay mode is $p \to K^+ + \nu$

$$\tau_p \simeq 4 \times 10^{35} \times \sin^4 2\beta \left(\frac{0.1}{\overline{A}_R}\right)^2 \left(\frac{M_S}{10^2\ \text{TeV}}\right)^2 \left(\frac{M_{H_C}}{10^{16}\ \text{GeV}}\right)^2\ \text{yrs}\ ,$$

$\tau(p \to K^+\bar{\nu}) > 4.0 \times 10^{33}$ yrs   Super K (2011)



Hisano et al (2013)

The PGM predicts $\tau(p \to K^+ + \nu) \simeq 10^{34} - 10^{35}$ yrs

Hyper Kamiokande will see the decay !!!

Conclusions

The Pure Gravity Mediation is very consistent and interesting which will be partially seen in near future experiments

To solve the unnaturalness problem, we need information on the distribution of gauge coupling constants in string theory landscape

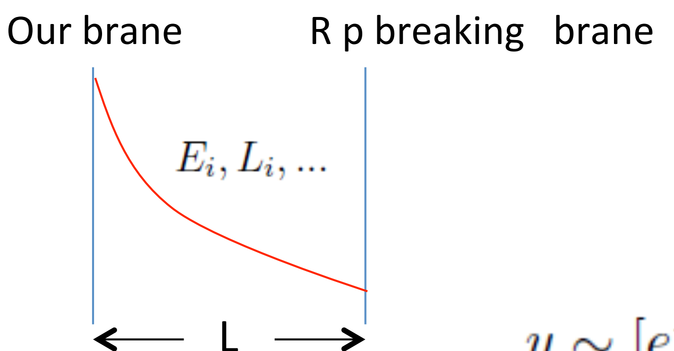
The gluino mass is predicted as 2 TeV-10 TeV

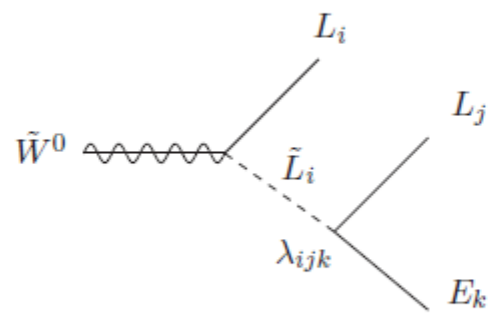
Evans, Ibe, Olive, Yanagida

To discover it we need
a BIG high-energy collider !!!

A comment on the R-parity breaking

$$\mathcal{W}_{\not R} = \lambda_{ijk} L_i L_j E^c_k$$





$$y \sim [e^{-\mathrm{LM}_*}]^3$$

$$\sim 10^{-19} \quad \text{for} \quad \mathrm{LM}_* \simeq 20$$