Neutrino Masses
&
DM candidate in Inverse See saw scenarios

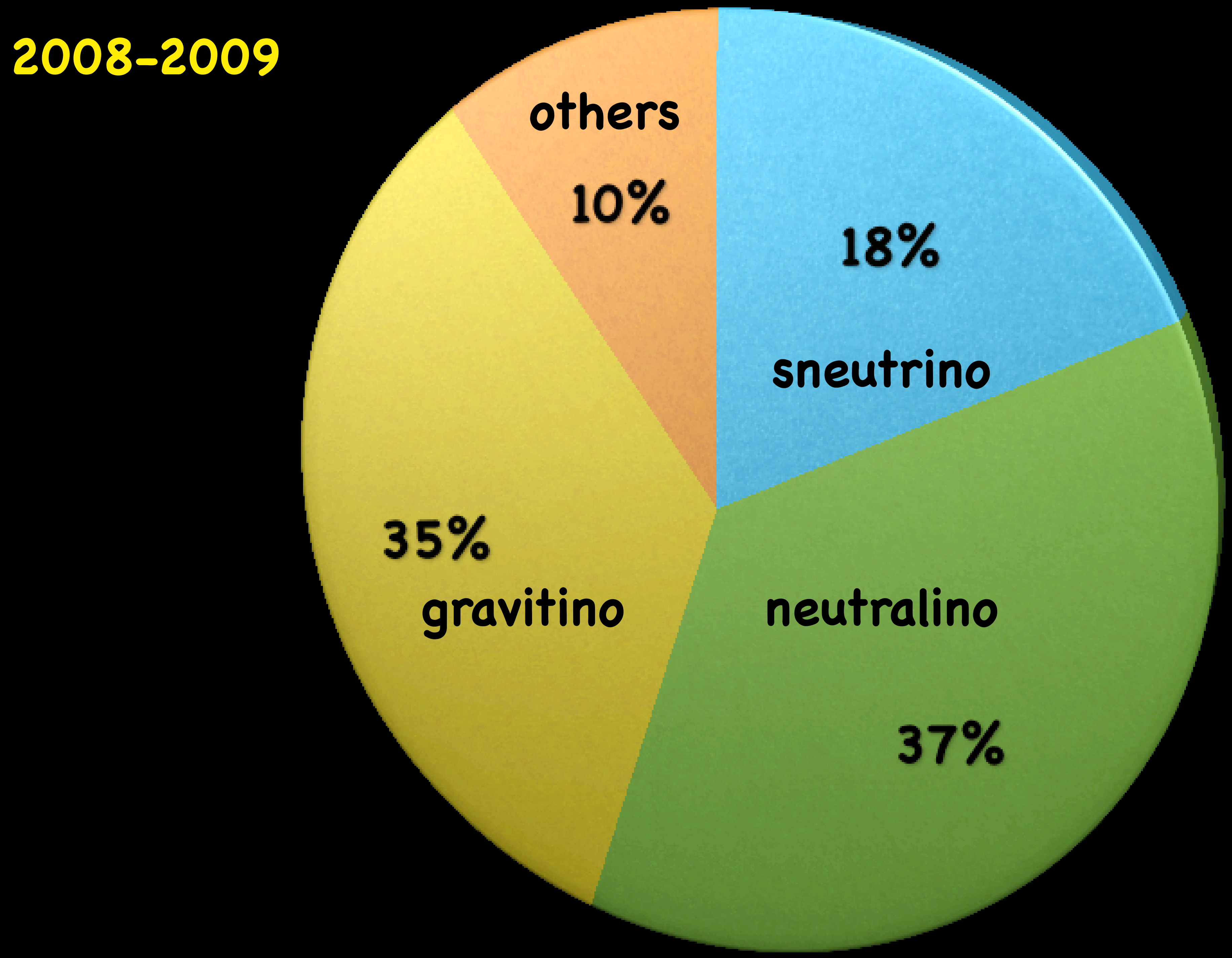
Federica Bazzocchi

Vrije Universitet Amsterdam

C. Arina, F.B., N. Fornengo, J. Romao, J. Valle PRL101 (2008)

FB,D. Cerdeno, C. Munoz, J.F. Valle arXiv:0907.1262

Theoretical miniWorkshop on Dark Matter, Madrid, 16-18/09/9


2008-2009
others
10%
18%
sneutrino
35%
gravitino
neutralino
37%

sneutrino

sneutrino

- in MSSM no good DM candidate

sneutrino

- in MSSM no good DM candidate
- in extended MSSM can be DM candidate

sneutrino

- in MSSM no good DM candidate
- in extended MSSM can be DM candidate
- possible MSSM extensions : tightly related to the origin of

neutrino masses

sneutrino

- in MSSM no good DM candidate
- in extended MSSM can be DM candidate
- possible MSSM extensions : tightly related to the origin of

neutrino masses

from a single sector : both
neutrino masses & CDM

sneutrino as LSP & DM candidate

Arina & Fornengo, JHEP112007029

- ☐ MSSM
- ☑ MSSM + $\hat{N}$ (dirac neutrinos)
- ☐ MSSM + L-viol
- ☑ MSSM + $\hat{N}$ + L-viol (see-saw)

sneutrino as LSP & DM candidate

Arina & Fornengo, JHEP112007029

Gopalakrishna et al. JHEP0611:050,2006
Lee et al. PRD76:041302,2007
Cerdeno et al. PRD79(2009)
Deppish&Pilaftsis arXiv:0808.0490

- ☐ MSSM
- ☑ MSSM + $\hat{N}$ (dirac neutrinos)
- ☐ MSSM + L-viol
- ☑ MSSM + $\hat{N}$ + L-viol (see-saw)

sneutrino as LSP & DM candidate

Arina & Fornengo, JHEP112007029

Gopalakrishna et al. JHEP0611:050,2006
Lee et al. PRD76:041302,2007
Cerdeno et al. PRD79(2009)
Deppish&Pilaftsis arXiv:0808.0490

- ☐ MSSM
- ☑ MSSM + $\hat{N}$ (dirac neutrinos)
- ☐ MSSM + L-viol
- ☑ MSSM + $\hat{N}$ + L-viol (see-saw) ← best scenario

sneutrino as LSP & DM candidate

Arina & Fornengo, JHEP112007029

Gopalakrishna et al. JHEP0611:050,2006
Lee et al. PRD76:041302,2007
Cerdeno et al. PRD79(2009)
Deppish&Pilaftsis arXiv:0808.0490

- ☐ MSSM
- ☑ MSSM + $\hat{N}$ (dirac neutrinos)
- ☐ MSSM + L-viol
- ☑ MSSM + $\hat{N}$ + L-viol (see-saw) ← best scenario

" Problems "

- not compatible with mSUGRA universality
- scale M_R around TeV -> unnatural small Y_D

Why

- $m_R^2 = m_0^2 + 0.15\ m_{1/2}^2$, $m_L^2 = m_0^2 + 0.52\ m_{1/2}^2$ -> stau no LSP -> neutralino LSP
- low see-saw scale -> > sterile component-> < $\sigma_{\tilde{\nu}}$

sneutrino as LSP & DM candidate

Arina & Fornengo, JHEP112007029

Gopalakrishna et al. JHEP0611:050,2006
Lee et al. PRD76:041302,2007
Cerdeno et al. PRD79(2009)
Deppish&Pilaftsis arXiv:0808.0490

- ☐ MSSM
- ☑ MSSM + $\hat{N}$ (dirac neutrinos)
- ☐ MSSM + L-viol
- ☑ MSSM + $\hat{N}$ + L-viol (see-saw) ← best scenario

" Problems "

- not compatible with mSUGRA universality
- scale M_R around TeV -> unnatural small Y_D ← any model?

Why

- $m_R^2 = m_0^2 + 0.15\ m_{1/2}^2$, $m_L^2 = m_0^2 + 0.52\ m_{1/2}^2$ -> stau no LSP -> neutralino LSP
- low see-saw scale -> > sterile component-> < $\sigma_{\tilde{\nu}}$

InMSSM model

inverse see-saw : SM + ν_L^c, S with L (-1,1)

$$M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_{RS} \\ 0 & M_{RS} & \mu_S \end{pmatrix}$$

μSS

$$m_L^\nu \sim m_D \frac{1}{M_{RS}} \mu_S \frac{1}{M_{RS}^T} m_D^T$$

low scale mechanism

1 keV-MeV

1 TeV

InMSSM model

inverse see-saw : SM + ν_L^c, S with L (-1,1)

$$M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_{RS} \\ 0 & M_{RS} & \mu_S \end{pmatrix}$$

μSS

$$m_L^\nu \sim m_D \frac{1}{M_{RS}} \mu_S \frac{1}{M_{RS}^T} m_D^T$$

low scale mechanism

1 keV-MeV

1 TeV

InMSSM : inverse SUSY see-saw: MSSM + $\hat{N}, \hat{S}$ with L (-1,1)

InMSSM model

inverse see-saw : SM + ν_L^c, S with L (-1,1)

$$M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_{RS} \\ 0 & M_{RS} & \mu_S \end{pmatrix}$$

$$\mu S S$$

$$m_L^\nu \sim m_D \frac{1}{M_{RS}} \mu_S \frac{1}{M_{RS}^T} m_D^T$$

low scale mechanism

1 keV-MeV

1 TeV

InMSSM : inverse SUSY see-saw: MSSM + $\hat{N}, \hat{S}$ with L (-1,1)

$$\mu_S \hat{S} \hat{S} \qquad M_{RS} \hat{\nu^c} \hat{S}$$

InMSSM model

inverse see-saw : SM + ν_L^c, S with L (-1,1)

$$M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_{RS} \\ 0 & M_{RS} & \mu_S \end{pmatrix}$$

$$\mu S S$$

$$m_L^\nu \sim m_D \frac{1}{M_{RS}} \mu_S \frac{1}{M_{RS}^T} m_D^T$$

low scale mechanism

1 keV-MeV

1 TeV

InMSSM : inverse SUSY see-saw: MSSM + $\hat{N}, \hat{S}$ with L (-1,1)

$$\mu_S \hat{S}\hat{S} \qquad M_{RS}\hat{\nu^c}\hat{S}$$

$$\left(\begin{array}{c} \mathcal{O}(M_{RS}) \sim \mathcal{O}(\mu) \\ \mu \hat{H}_u \hat{H}_d \end{array} \right)$$

InMSSM model

$$\Phi^\dagger = (\tilde{\nu}_+^*,\, \tilde{\nu}_+^{c*},\, \tilde{S}_+^*,\, \tilde{\nu}_-^*,\, \tilde{\nu}_-^{c*},\, \tilde{S}_-^*)$$

$$\begin{pmatrix} \mathcal{M}_+^2 & \mathbf{0} \\ \mathbf{0} & \mathcal{M}_-^2 \end{pmatrix}$$

CP-eigenstate basis

$$\mathcal{M}_\pm{}^2 = \begin{pmatrix} m_L^2 + D + m_D^2 & m_D + A_{h_\nu} v_u + \mu m_D cotg\beta & m_D M_R \\ m_D + A_{h_\nu} v_u + \mu m_D cotg\beta & m_{\nu^c}^2 + M_R^2 + m_D^2 + m_{\nu^c}^2 & \mu_S M_R \pm B_{M_R} \\ m_D M_R & \mu_S M_R \pm B_{M_R} & m_S^2 + \mu_S^2 + M_R^2 \pm B_{\mu_S} \end{pmatrix}$$

InMSSM model

$$\Phi^\dagger = (\tilde{\nu}_+^*, \tilde{\nu}_+^{c*}, \tilde{S}_+^*, \tilde{\nu}_-^*, \tilde{\nu}_-^{c*}, \tilde{S}_-^*)$$

$$\begin{pmatrix} \mathcal{M}_+^2 & \mathbf{0} \\ \mathbf{0} & \mathcal{M}_-^2 \end{pmatrix}$$

CP-eigenstate basis

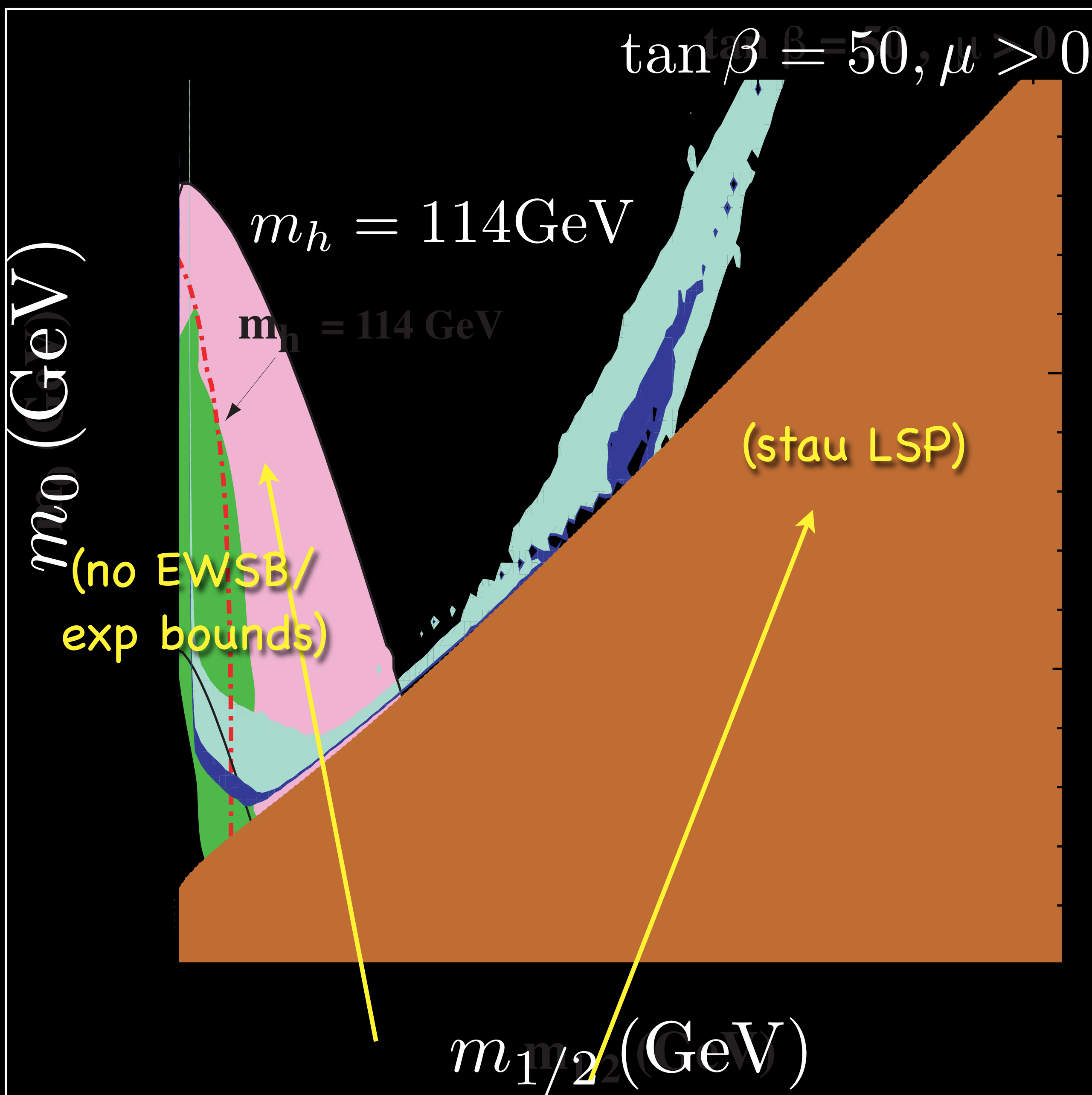
$$\mathcal{M}_\pm{}^2 = \begin{pmatrix} m_L^2 + D + m_D^2 & m_D + A_{h_\nu} v_u + \mu m_D cotg\beta & m_D M_R \\ m_D + A_{h_\nu} v_u + \mu m_D cotg\beta & m_{\nu^c}^2 + M_R^2 + m_D^2 + m_{\nu^c}^2 & \mu_S M_R \pm B_{M_R} \\ m_D M_R & \mu_S M_R \pm B_{M_R} & m_S^2 + \mu_S^2 + M_R^2 \pm B_{\mu_S} \end{pmatrix}$$

- mSUGRA universality-> $m_R^2 = m_0^2 + 0.15\, m_{1/2}^2$, $m_L^2 = m_0^2 + 0.52\, m_{1/2}^2$ but the sneutrino mass matrix has changed (more freedom!)
- soft L-viol-> control splitting $m_+ - m_-$: inelastic scattering with nucleons suppression
- role of the singlet -> $\sigma_{\tilde{\nu}}$ suppression, freedom

What we expect ?

Large values of $m_{1/2}$ (neutralino heavier than sneutrino)-->heavy spartners

MSSM

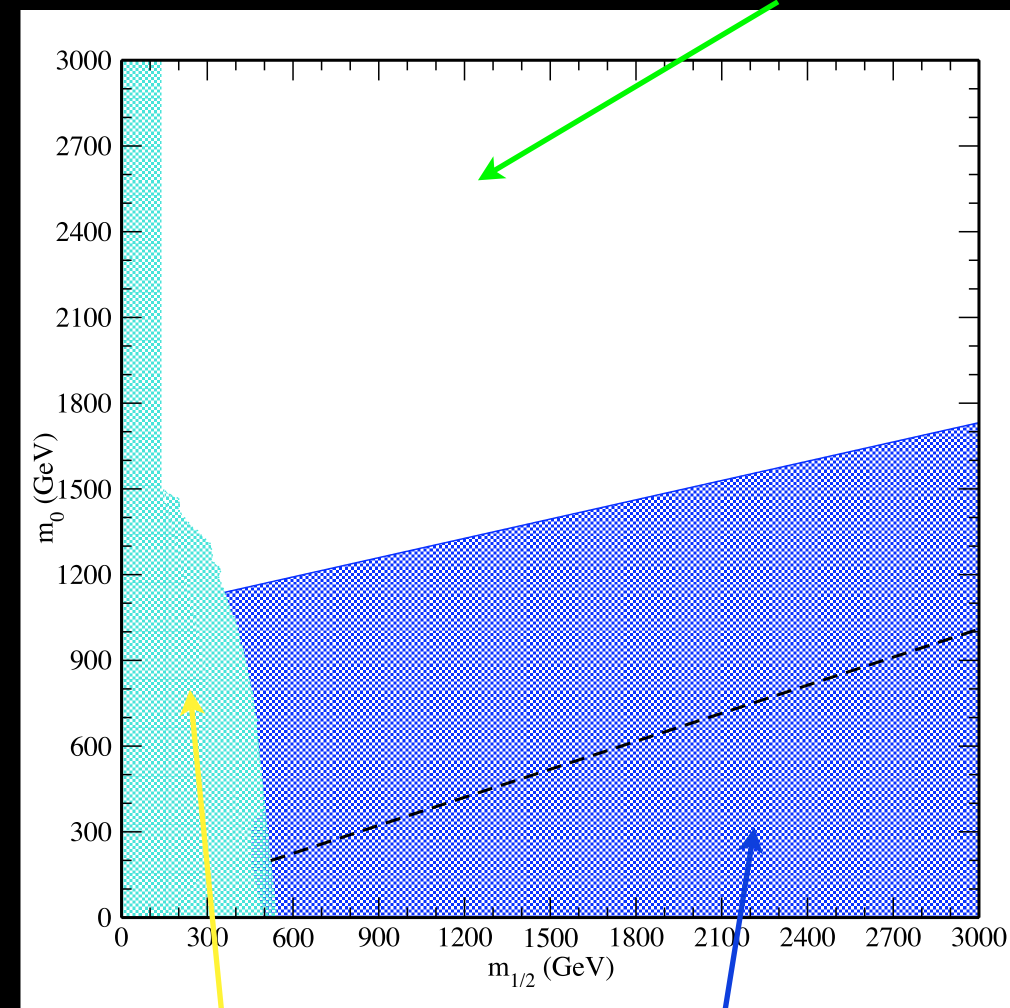


not allowed

InMSSM

$\tan\beta = 35, A_0 = 0, \mu > 0, B_{\mu_S} = 10\,\text{GeV}^2$

allowed & neutralino LSP



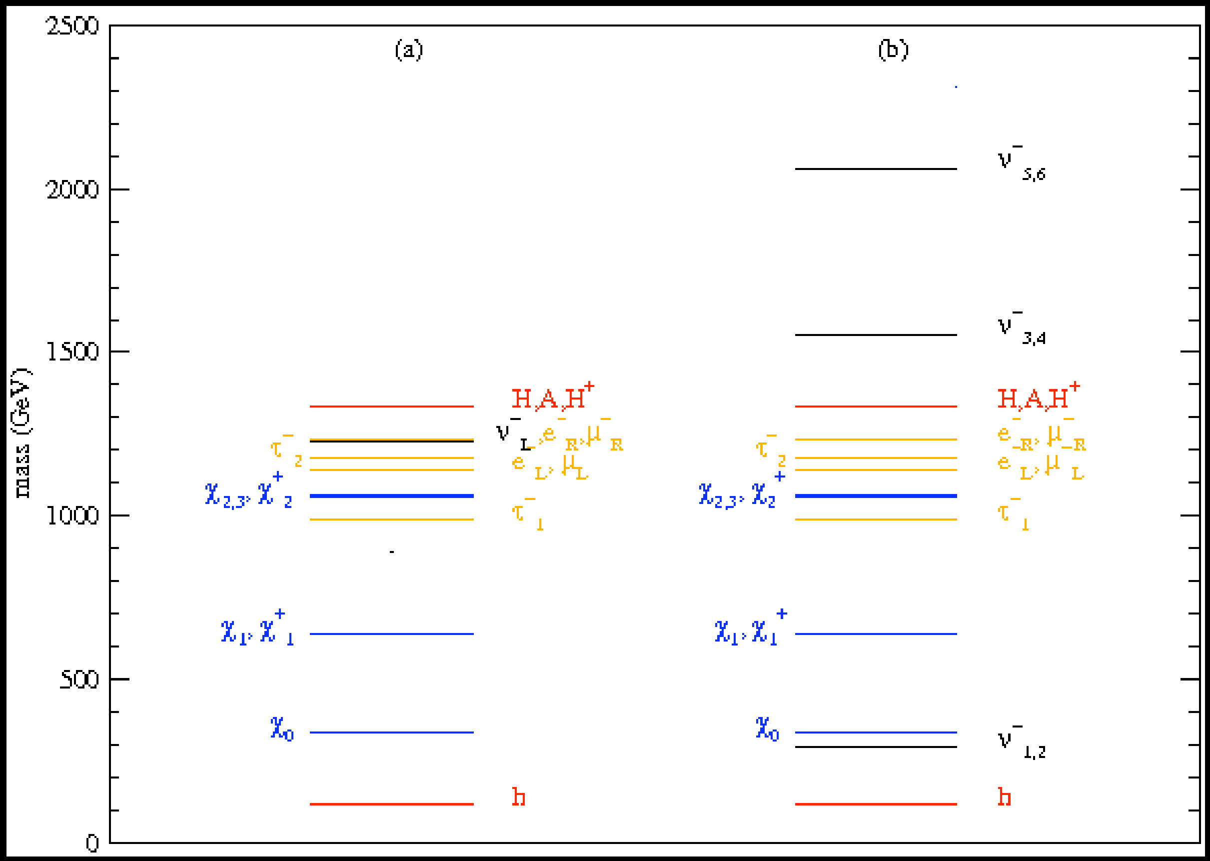
not allowed

(no EWSB/exp bounds)

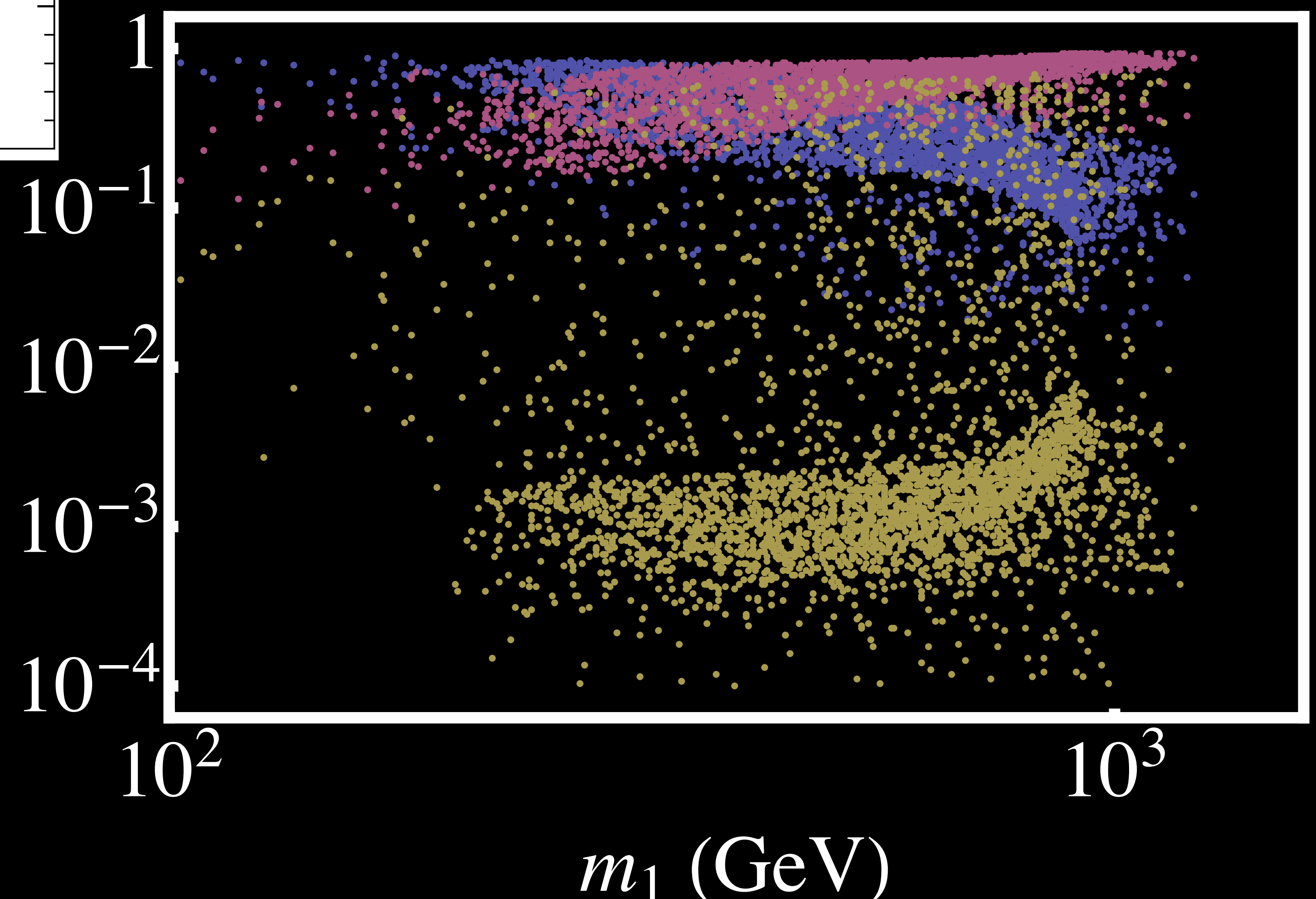
allowed & sneutrino LSP

the spectrum

$$\tan\beta = 35, A_0 = 0, m_0 = 358\,\text{GeV}, m_{1/2} = 693\,\text{GeV}, \mu > 0, B_{\mu_S} = 10\,\text{GeV}^2$$



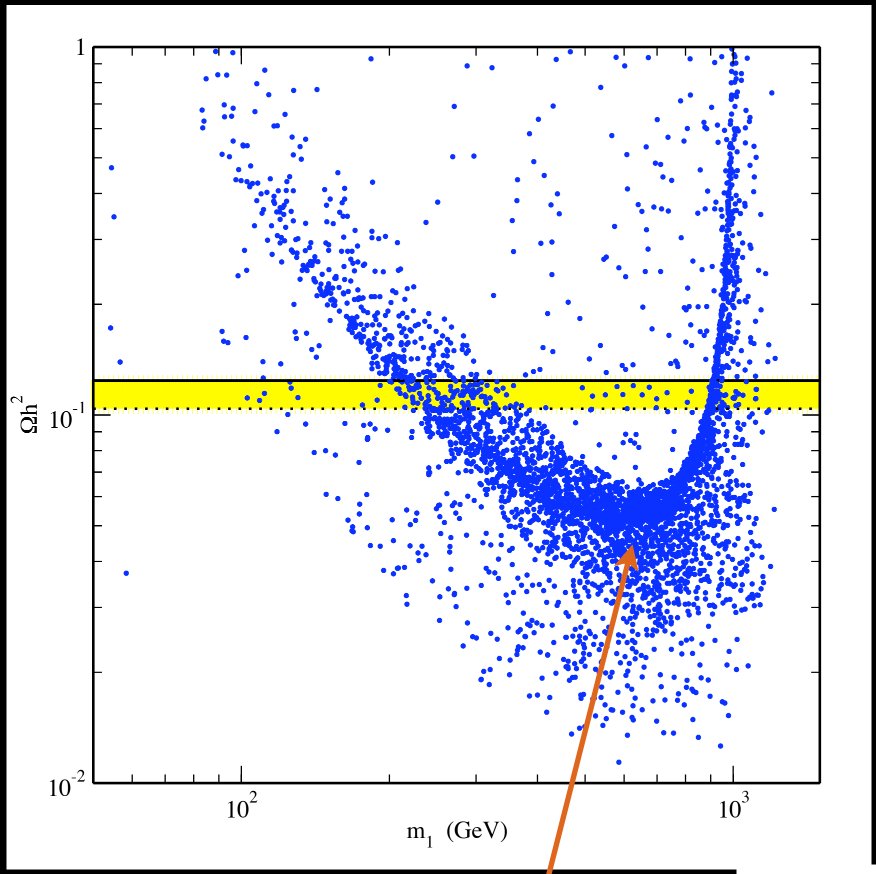
$$\begin{aligned} m_{\tilde\nu_{1,2}} &= 290\,\text{GeV} \\ m_{\chi_0} &= 340\,\text{GeV} \\ m_{\chi_1,\chi_1^+} &= 650\,\text{GeV} \\ m_{\tau_1} &= 950\,\text{GeV} \\ m_{\chi_{2,3},\chi_2^+} &= 950\,\text{GeV} \\ m_{\tilde e_L,\tilde\mu_L} &= 1150\,\text{GeV} \end{aligned}$$



$$0.1 < m_{0,1/2}/\text{TeV} < 3, , A_0 = 0, 3 < \tan\beta < 50$$
$$10^{-9} < \mu_S/\text{GeV} < 10^{-6}, \mu > 0, 1 < B_{\mu_S}/\text{GeV}^2 < 100\,\text{GeV}^2$$

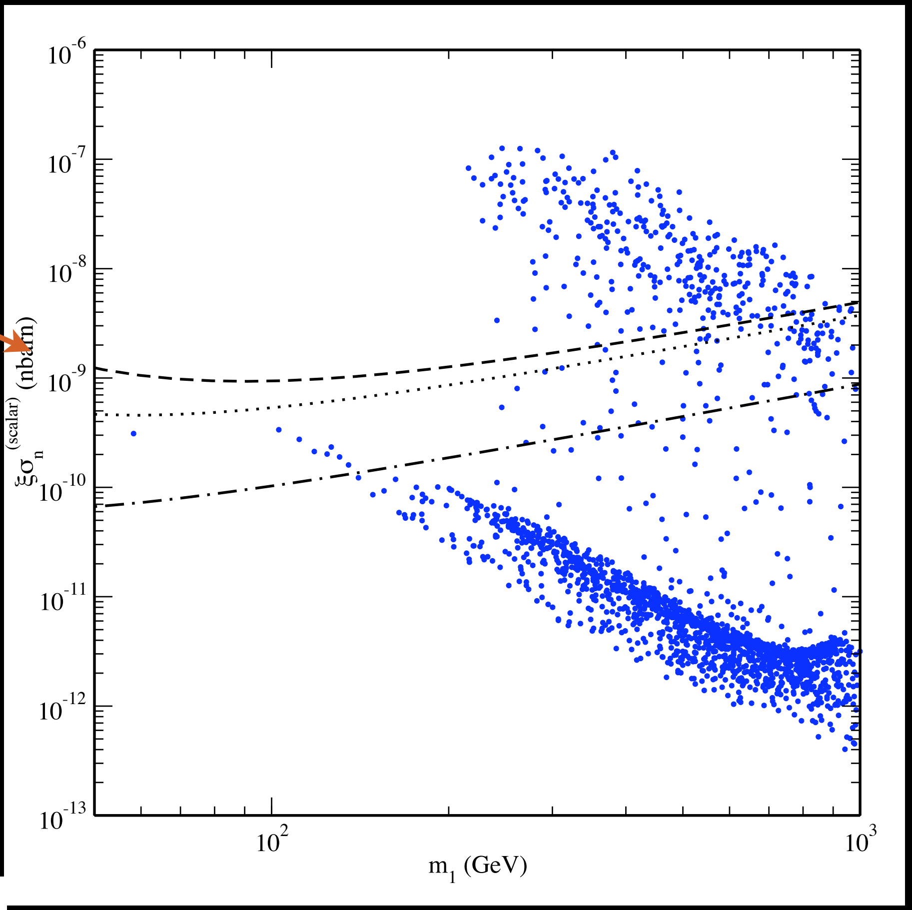
relic abundance

direct searches



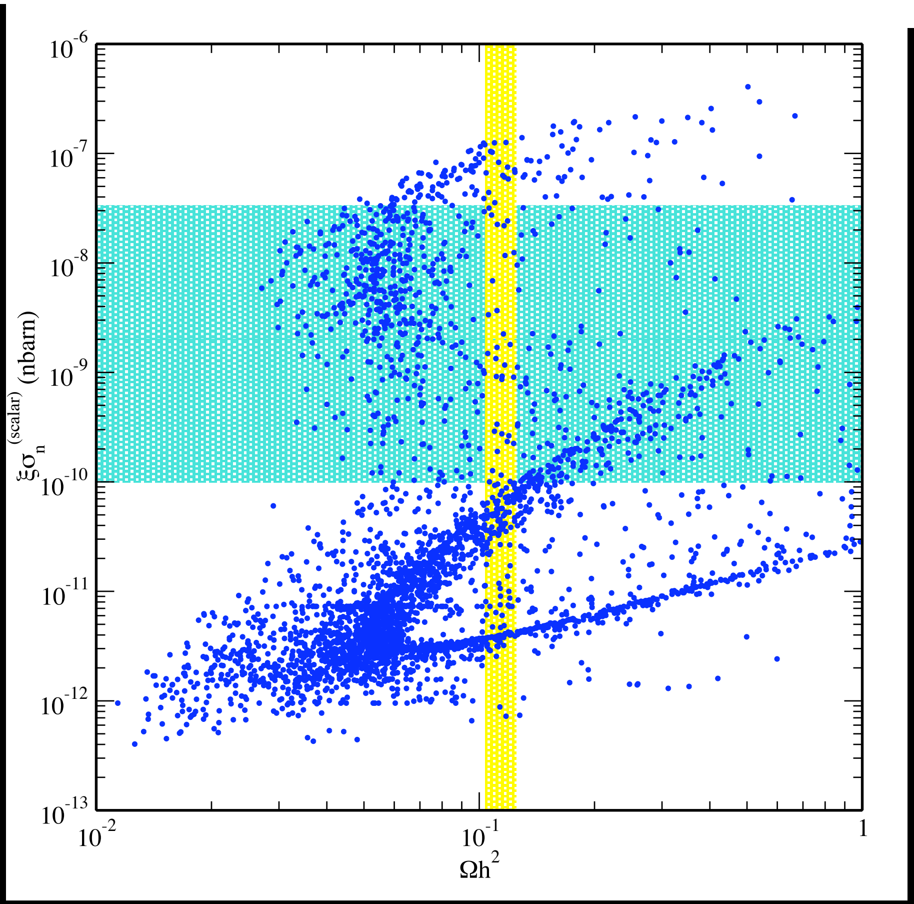
$m_{\tilde{\nu}} - \Omega h^2$

upper limits from CDMS (3 galactic halo)



$m_{\tilde{\nu}} - \xi\sigma$

annhilation through the H channel



$\Omega h^2 - \xi\sigma$

crucial ingredient of the InMSSM

crucial ingredient of the InMSSM

μSS ← small ! (keV-MeV)

$$m_L^\nu \sim m_D \frac{1}{M_{RS}} \mu_S \frac{1}{M_{RS}^T} m_D^T$$

crucial ingredient of the InMSSM

μSS

small !
(keV-MeV)

$$m_L^\nu \sim m_D \frac{1}{M_{RS}} \mu_S \frac{1}{M_{RS}^T} m_D^T$$

try to find a dynamical way to justify it!

dynamical InMSSM μ_S, μ, M_{RS}

$$\mu_S \hat{S}\hat{S}$$

$$\mu \hat{H}_u \hat{H}_d$$

$$M_{RS} \hat{\nu}^c \hat{S}$$

dynamical InMSSM μ_S, μ, M_{RS}

Cerdeno et al. PRD79(2009)

$$\mu_S \hat{S}\hat{S} \quad \rightarrow \quad \hat{\Delta}\hat{S}\hat{S}$$

$$\mu \hat{H}_u \hat{H}_d \quad \rightarrow \quad \hat{\Phi}\hat{H}_u\hat{H}_d$$

$$M_{RS}\hat{\nu^c}\hat{S} \quad \rightarrow \quad \hat{\Phi}\hat{\nu^c}\hat{S}$$

$$\mu_S \sim \langle \Delta \rangle$$

$$\mu, M_{RS} \sim \langle \Phi \rangle$$

dynamical InMSSM μ_S, μ, M_{RS}

Cerdeno et al. PRD79(2009)

$\mu_S \hat{S}\hat{S}$

$\mu \hat{H}_u \hat{H}_d$

$M_{RS} \hat{\nu^c} \hat{S}$

→

$\hat{\Delta}\hat{S}\hat{S}$

$\hat{\Phi}\hat{H}_u \hat{H}_d$

$\hat{\Phi}\hat{\nu^c}\hat{S}$

$\mu_S \sim \langle \Delta \rangle$

$\mu, M_{RS} \sim \langle \Phi \rangle$

InNMSSM : NMSSM + $\hat{\nu^c}, \hat{S}, \hat{\Delta}$

L (-1,1,-2)

dynamical InMSSM μ_S, μ, M_{RS}

Cerdeno et al. PRD79(2009)

$\mu_S \hat{S}\hat{S}$ → $\hat{\Delta}\hat{S}\hat{S}$

$\mu \hat{H}_u \hat{H}_d$ → $\hat{\Phi}\hat{H}_u\hat{H}_d$

$M_{RS}\hat{\nu^c}\hat{S}$ → $\hat{\Phi}\hat{\nu^c}\hat{S}$

$$\mu_S \sim \langle \Delta \rangle$$

$$\mu, M_{RS} \sim \langle \Phi \rangle$$

InNMSSM : NMSSM + $\hat{\nu^c}, \hat{S}, \hat{\Delta}$

L (-1,1,-2)

$$\langle \Delta \rangle = 0$$

dynamical InMSSM μ_S, μ, M_{RS}

Cerdeno et al. PRD79(2009)

$\mu_S \hat{S}\hat{S}$

$\mu \hat{H}_u \hat{H}_d$

$M_{RS} \hat{\nu^c} \hat{S}$

→

$\hat{\Delta}\hat{S}\hat{S}$

$\hat{\Phi}\hat{H}_u\hat{H}_d$

$\hat{\Phi}\hat{\nu^c}\hat{S}$

$\mu_S \sim \langle \Delta \rangle$

$\mu, M_{RS} \sim \langle \Phi \rangle$

InNMSSM : NMSSM + $\hat{\nu^c}, \hat{S}, \hat{\Delta}$

L (-1,1,-2)

$$\langle \Delta \rangle = 0$$

$$m_\nu \propto \mu_S \sim \langle \Delta \rangle$$

neutrinos massless!

InNMSSM : NMSSM + $\hat{\nu^c}, \hat{S}, \hat{\Delta}, \hat{\tilde{\Delta}}$

L (-1,1,-2,1)

InNMSSM : NMSSM + $\hat{\nu}^c, \hat{S}, \hat{\Delta}, \hat{\tilde{\Delta}}$

L (-1,1,-2,1)

$$\mathcal{W} \longrightarrow \frac{1}{2}\xi\hat{\Delta}\hat{\tilde{\Delta}}\hat{\tilde{\Delta}}$$

$$V_{soft} \longrightarrow \frac{1}{2}a_{\Delta}\Delta\tilde{\Delta}\tilde{\Delta}$$

InNMSSM : NMSSM + $\hat{\nu}^c, \hat{S}, \hat{\Delta}, \hat{\tilde{\Delta}}$

L (-1,1,-2,1)

$\mathcal{W} \longrightarrow \frac{1}{2}\xi\hat{\Delta}\hat{\tilde{\Delta}}\hat{\tilde{\Delta}}$

$V_{soft} \longrightarrow \frac{1}{2}a_{\Delta}\Delta\tilde{\Delta}\tilde{\Delta}$

$\langle\tilde{\Delta}\rangle \sim \langle\Phi\rangle$

$\langle\Delta\rangle \propto a_{\Delta}$

$m_{\nu} \propto \mu_S \sim \langle\Delta\rangle$

InNMSSM : NMSSM + $\hat{\nu}^c, \hat{S}, \hat{\Delta}, \hat{\tilde{\Delta}}$

L (-1,1,-2,1)

$$\mathcal{W} \longrightarrow \frac{1}{2}\xi\hat{\Delta}\hat{\tilde{\Delta}}\hat{\tilde{\Delta}}$$

$$V_{soft} \longrightarrow \frac{1}{2}a_{\Delta}\Delta\tilde{\Delta}\tilde{\Delta}$$

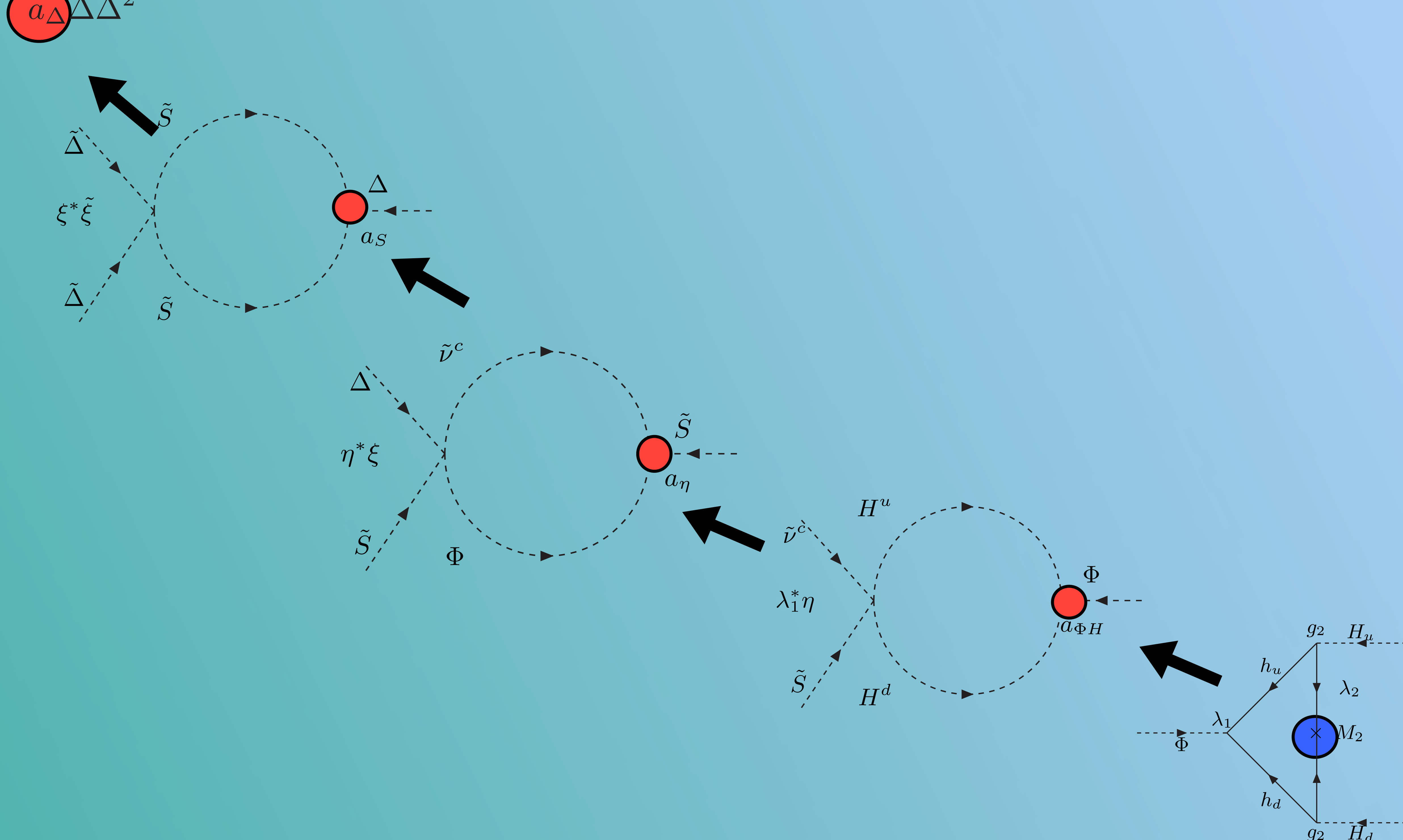
$$\langle\tilde{\Delta}\rangle \sim \langle\Phi\rangle$$

$\langle\Delta\rangle \propto a_{\Delta}$ justify its smallness

$$m_{\nu} \propto \mu_S \sim \langle\Delta\rangle$$

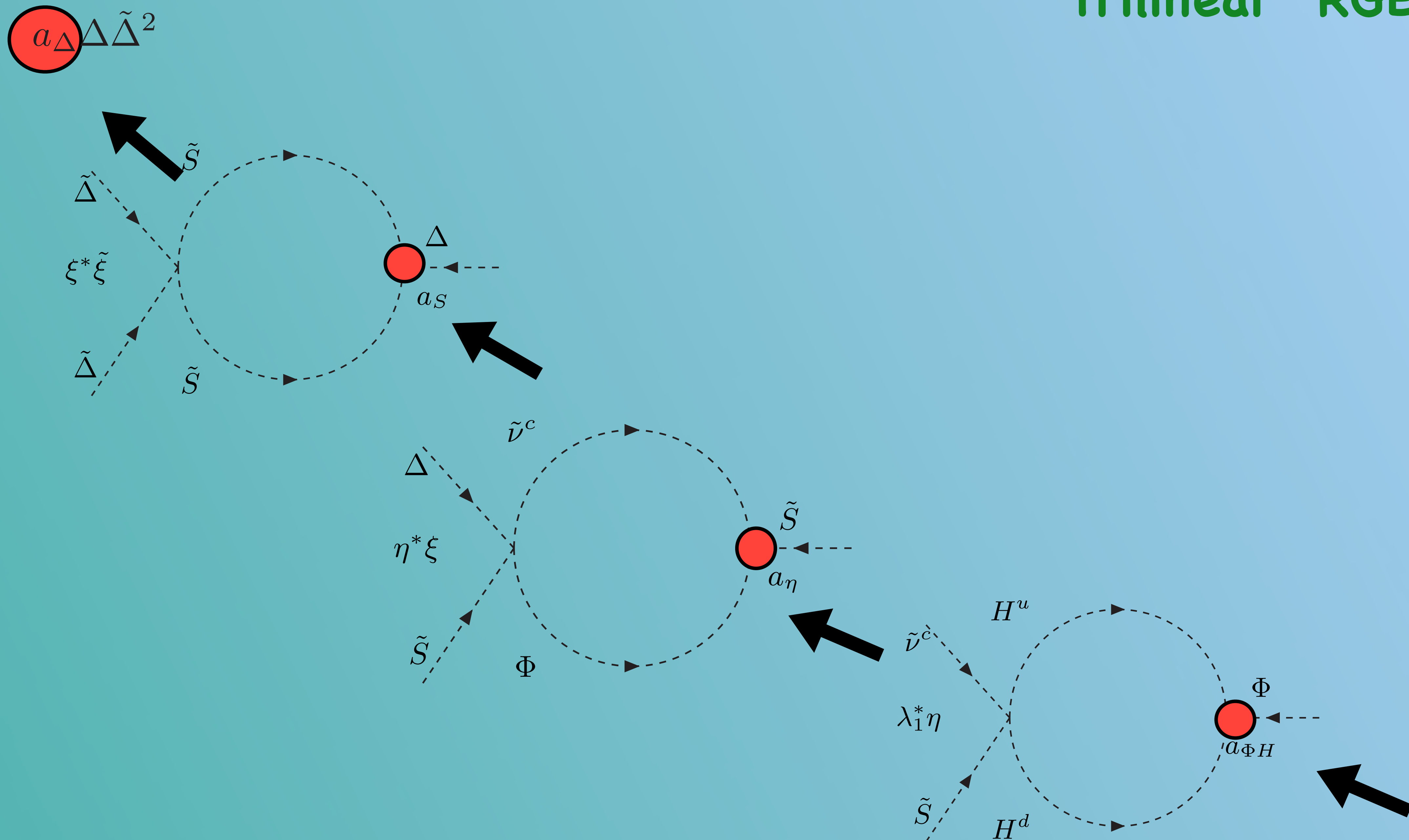
assumption : all the SUSY trilinear soft terms vanish at GUT

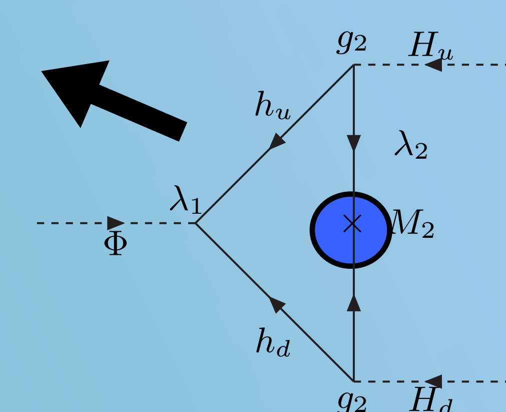
trilinear RGEs



$$a_0 = 0 \, , M_{1/2} > 0$$
$$m_0^2 < 0 \, , \tilde{m}_0^2 > 0$$

trilinear RGEs

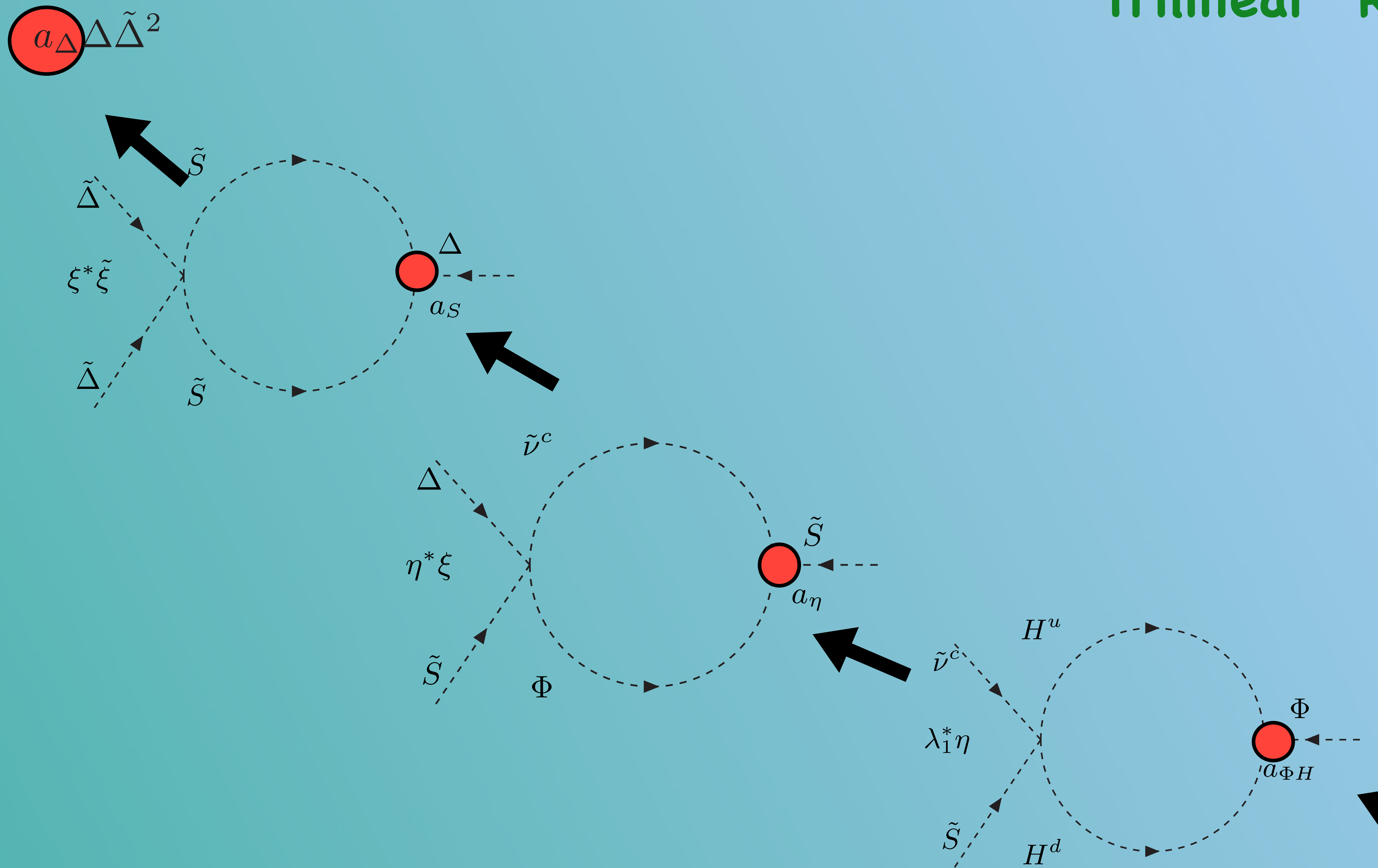


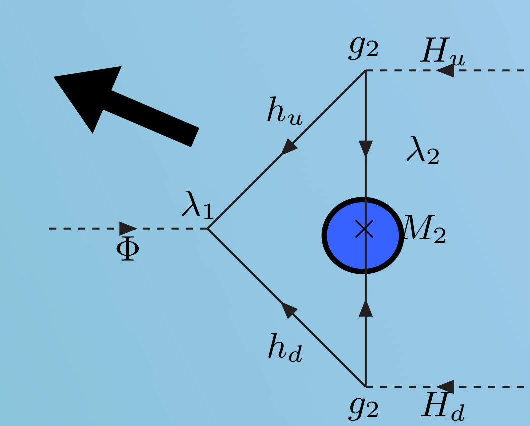


crucial assumption : a motivation by understanding the SUSY breaking mechanism

$$a_0 = 0\,,\, M_{1/2} > 0$$
$$m_0^2 < 0\,,\, \tilde{m}_0^2 > 0$$

trilinear RGEs



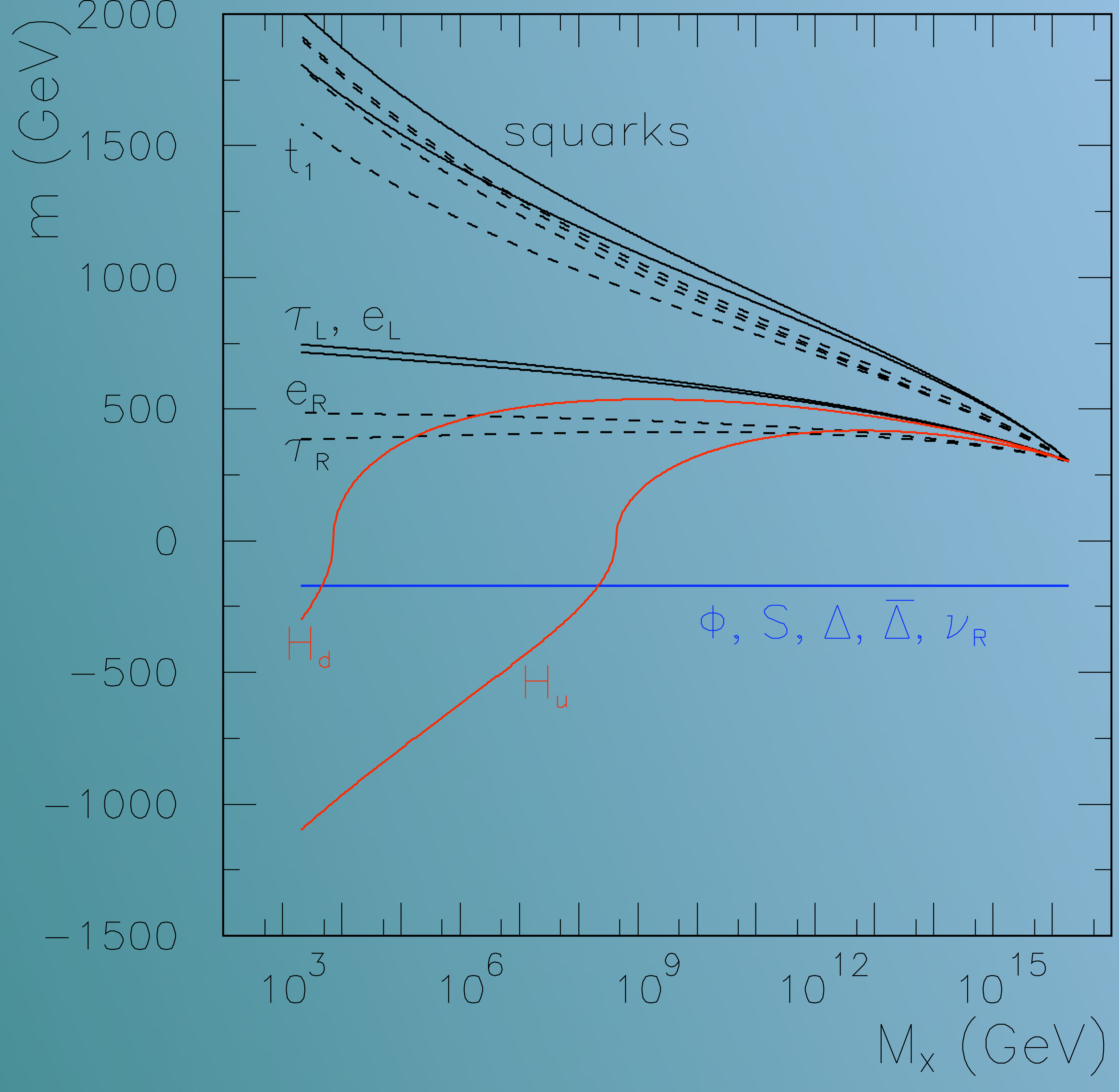


crucial assumption : a motivation by understanding the SUSY breaking mechanism

$$a_0 = 0\,,\, M_{1/2} > 0$$
$$m_0^2 < 0\,,\, \tilde{m}_0^2 > 0$$

(next step?)

mass RGEs



$$a_0 = 0\,, M_{1/2} > 0$$
$$m_0^2 < 0\,, \tilde{m}_0^2 > 0$$

LSP ? DM candidates?

LSP ? DM candidates?

★ NMSSM neutralino sector

LSP ? DM candidates?

★ NMSSM neutralino sector

★ extended scalar neutrino sector

LSP ? DM candidates?

★ NMSSM neutralino sector

★ extended scalar neutrino sector

$$\Phi^\dagger = (\tilde{\nu}_+^*,\ \tilde{\nu}_+^{c*},\ \tilde{S}_+^*,\ \tilde{\nu}_-^*,\ \tilde{\nu}_-^{c*},\ \tilde{S}_-^*)$$

$$\begin{pmatrix} \mathcal{M}_+^2 & \mathbf{0} \\ \mathbf{0} & \mathcal{M}_-^2 \end{pmatrix}$$

CP-eigenstates basis

$$a_\Delta \sim 0$$

$$M_{\tilde{\nu}\pm}^2 \sim \begin{pmatrix} m_L^2 & 0 & 0 \\ 0 & m_0^2 + \alpha_\pm v^2 & \pm\delta v^2 \\ 0 & \pm\delta v^2 & m_0^2 + \beta_\pm v^2 \end{pmatrix}$$

LSP ? DM candidates?

★ NMSSM neutralino sector

★ extended scalar neutrino sector

$$\Phi^\dagger = (\tilde{\nu}_+^*,\ \tilde{\nu}_+^{c*},\ \tilde{S}_+^*,\ \tilde{\nu}_-^*,\ \tilde{\nu}_-^{c*},\ \tilde{S}_-^*)$$

$$\begin{pmatrix} \mathcal{M}_+^2 & \mathbf{0} \\ \mathbf{0} & \mathcal{M}_-^2 \end{pmatrix}$$

CP-eigenstates basis

$$a_\Delta \sim 0$$

$$M^2_{\tilde{\nu}\pm} \sim \begin{pmatrix} m_L^2 & 0 & 0 \\ 0 & m_0^2 + \alpha_\pm v^2 & \pm\delta v^2 \\ 0 & \pm\delta v^2 & m_0^2 + \beta_\pm v^2 \end{pmatrix}$$

$$m_L^2 > 0, m_0^2 < 0$$

LSP ? DM candidates?

★ NMSSM neutralino sector

★ extended scalar neutrino sector

$$\Phi^\dagger = (\tilde{\nu}_+^*,\ \tilde{\nu}_+^{c*},\ \tilde{S}_+^*,\ \tilde{\nu}_-^*,\ \tilde{\nu}_-^{c*},\ \tilde{S}_-^*)$$

$$\begin{pmatrix} \mathcal{M}_+^2 & \mathbf{0} \\ \mathbf{0} & \mathcal{M}_-^2 \end{pmatrix}$$

CP-eigenstates basis

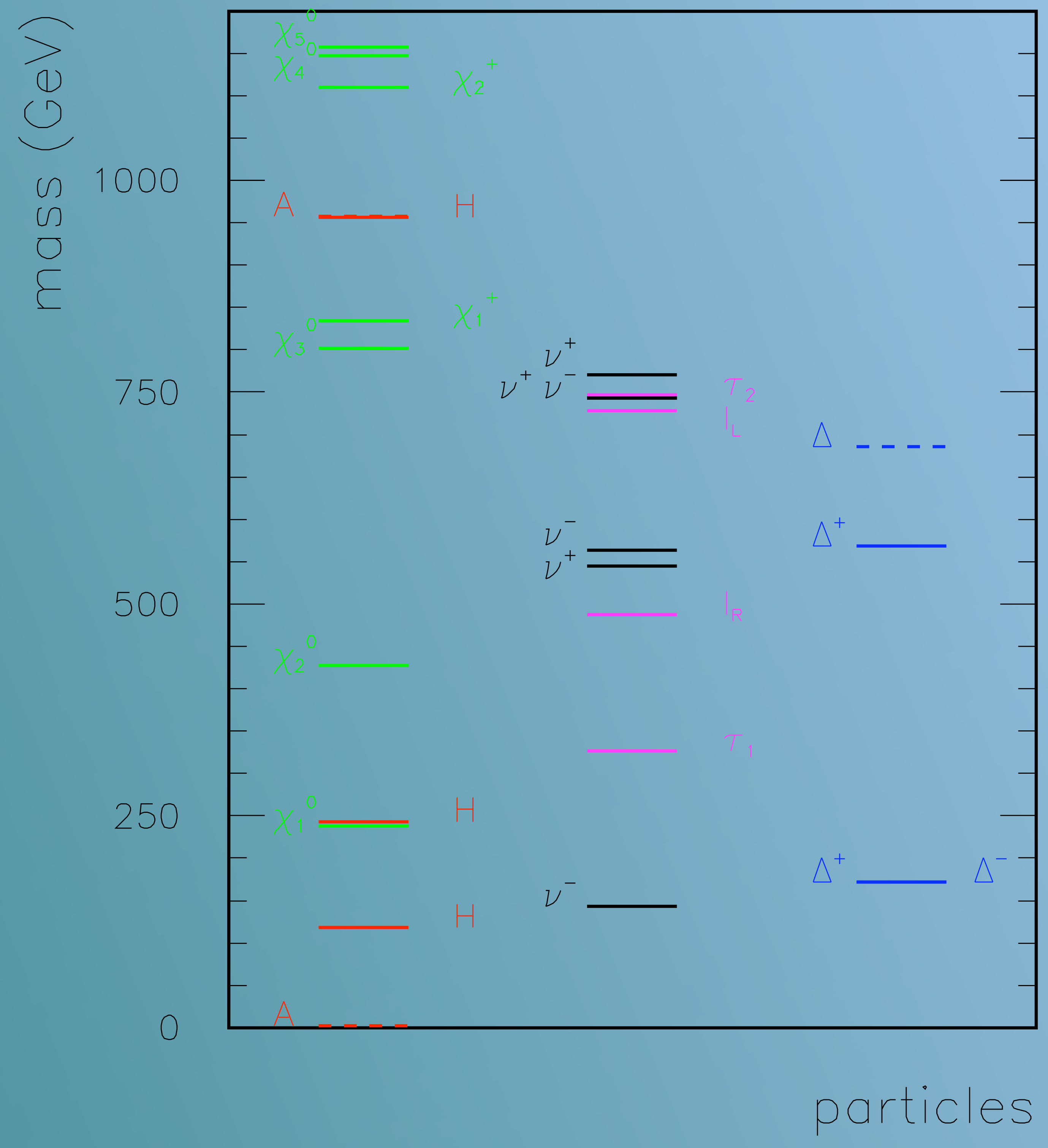
$$a_\Delta \sim 0$$

$$M_{\tilde{\nu}\pm}^2 \sim \begin{pmatrix} m_L^2 & 0 & 0 \\ 0 & m_0^2 + \alpha_\pm v^2 & \pm\delta v^2 \\ 0 & \pm\delta v^2 & m_0^2 + \beta_\pm v^2 \end{pmatrix}$$

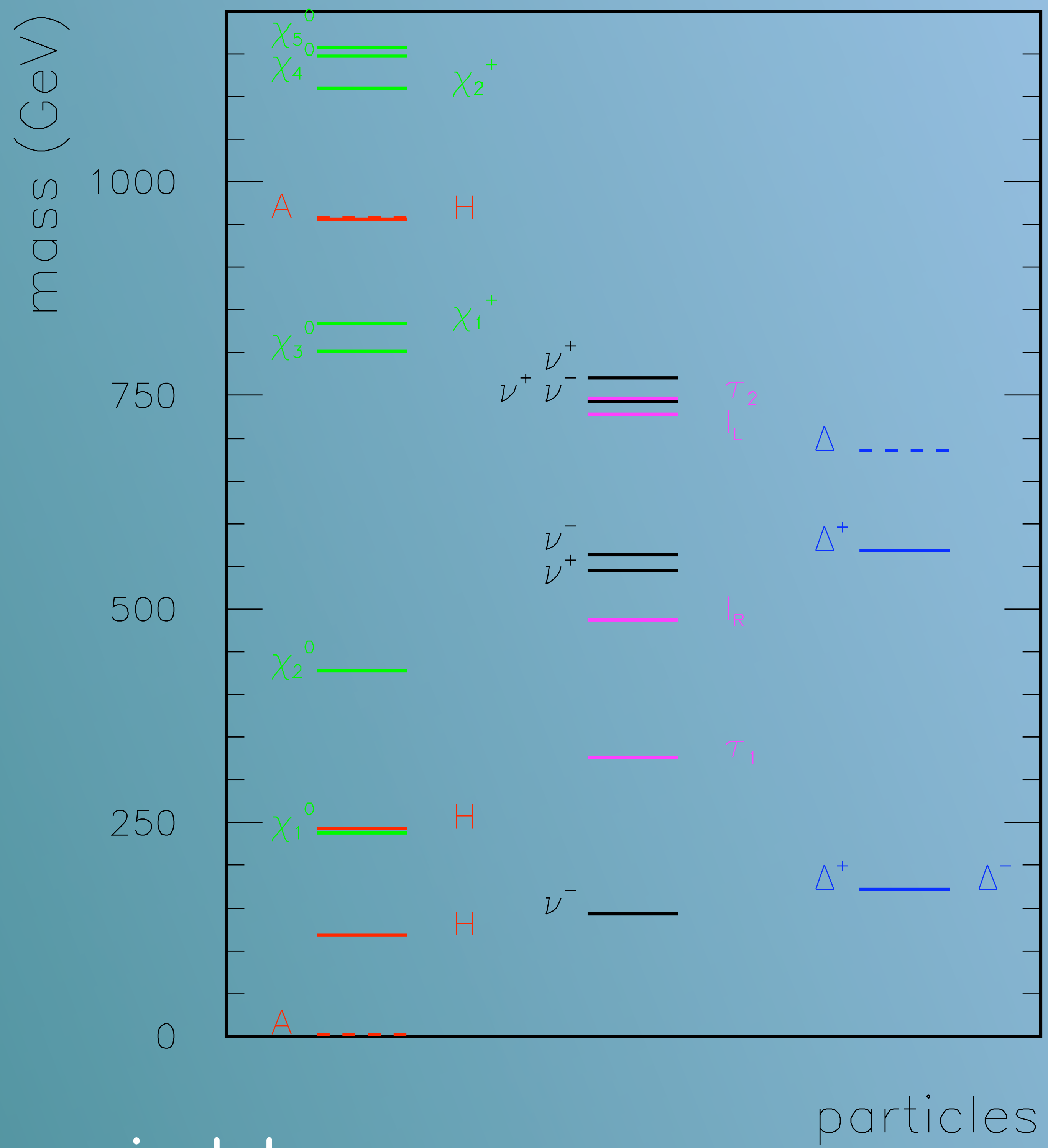
$$m_L^2 > 0, m_0^2 < 0$$

pure gauge singlet, mixing right handed and S scalar neutrino

spectrum

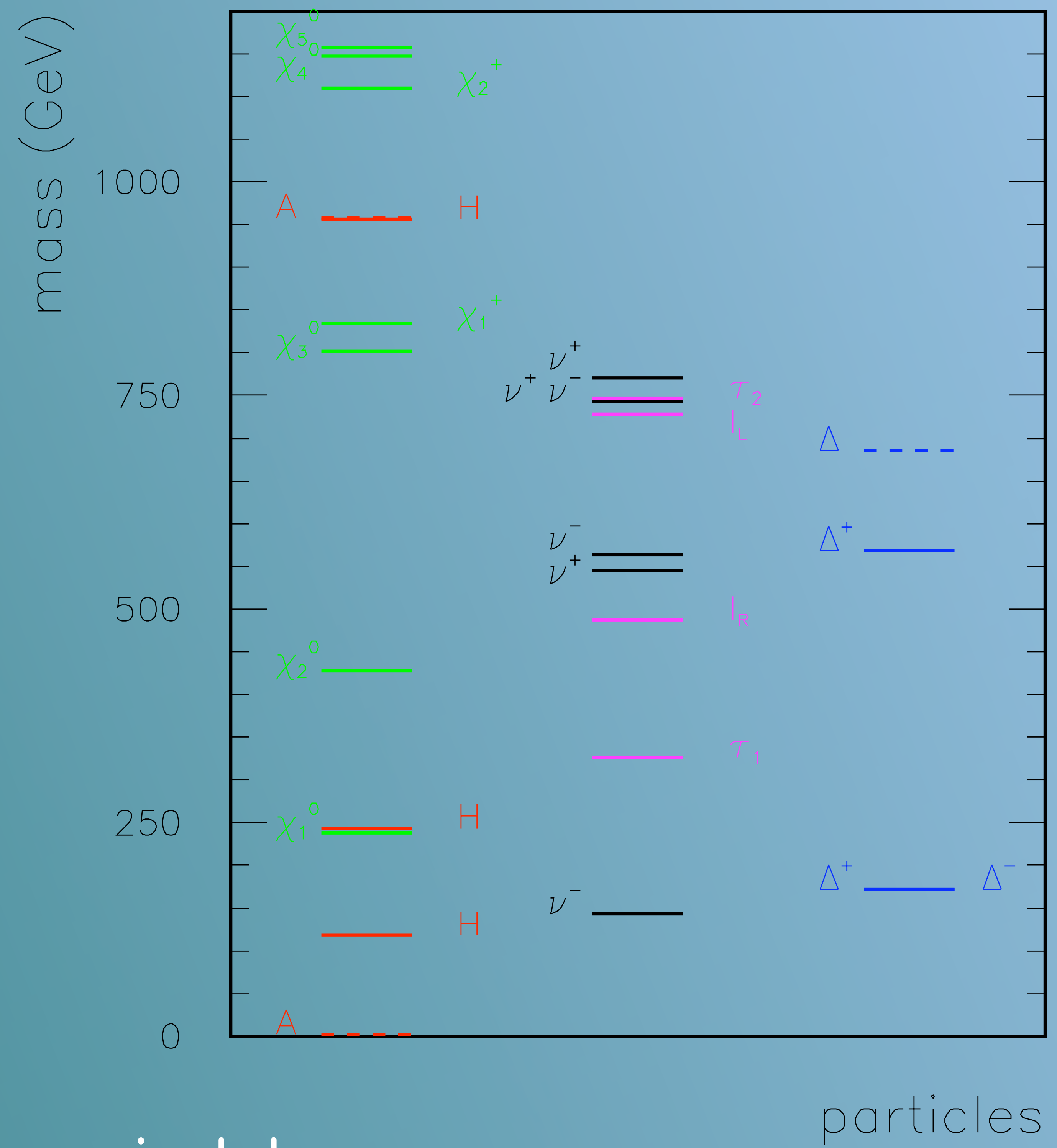


spectrum



if mainly gauge singlet,
how can provide correct
relic abundance?

spectrum



if mainly gauge singlet,
how can provide correct
relic abundance?

Cerdeno et al. PRD79(09)

new Higgs channel through

$\hat{\Phi}\hat{H}_u\hat{H}_d \qquad \hat{\Phi}\hat{\nu}^c\hat{S}$

Conclusions

★ different kind of extensions of MSSM leads the sneutrino to be a natural LSP as the neutralino

★inverse see-saw mechanism is a very appealing mechanism to give mass to neutrinos (low scale)

★ in the InMSSM sneutrino LSP is also a valid CDM (indeed many configurations have the correct relic abundance & satisfy the direct search bounds)

★ 'standard prejudice' to justify the smallness of the mu-parameter

★built a model (InNMSSM) in which both the 'mu' parameters arise dynamically

★neutrino masses linked to soft SUSY breaking terms

★ region where the singlet sneutrino is the LSP

★ new possible DM scenario

★complete DM analysis & phenomenological LHC implications...work in progress

Conclusions

★ different kind of extensions of MSSM leads the sneutrino to be a natural LSP as the neutralino

★inverse see-saw mechanism is a very appealing mechanism to give mass to neutrinos (low scale)

★ in the InMSSM sneutrino LSP is also a valid CDM (indeed many configurations have the correct relic abundance & satisfy the direct search bounds)

★ 'standard prejudice' to justify the smallness of the mu-parameter

★built a model (InNMSSM) in which both the 'mu' parameters arise dynamically

★neutrino masses linked to soft SUSY breaking terms

★ region where the singlet sneutrino is the LSP

★ new possible DM scenario

★complete DM analysis & phenomenological LHC implications...work in progress

Thanks!