Reconciling dark matter and neutrino masses in mSUGRA

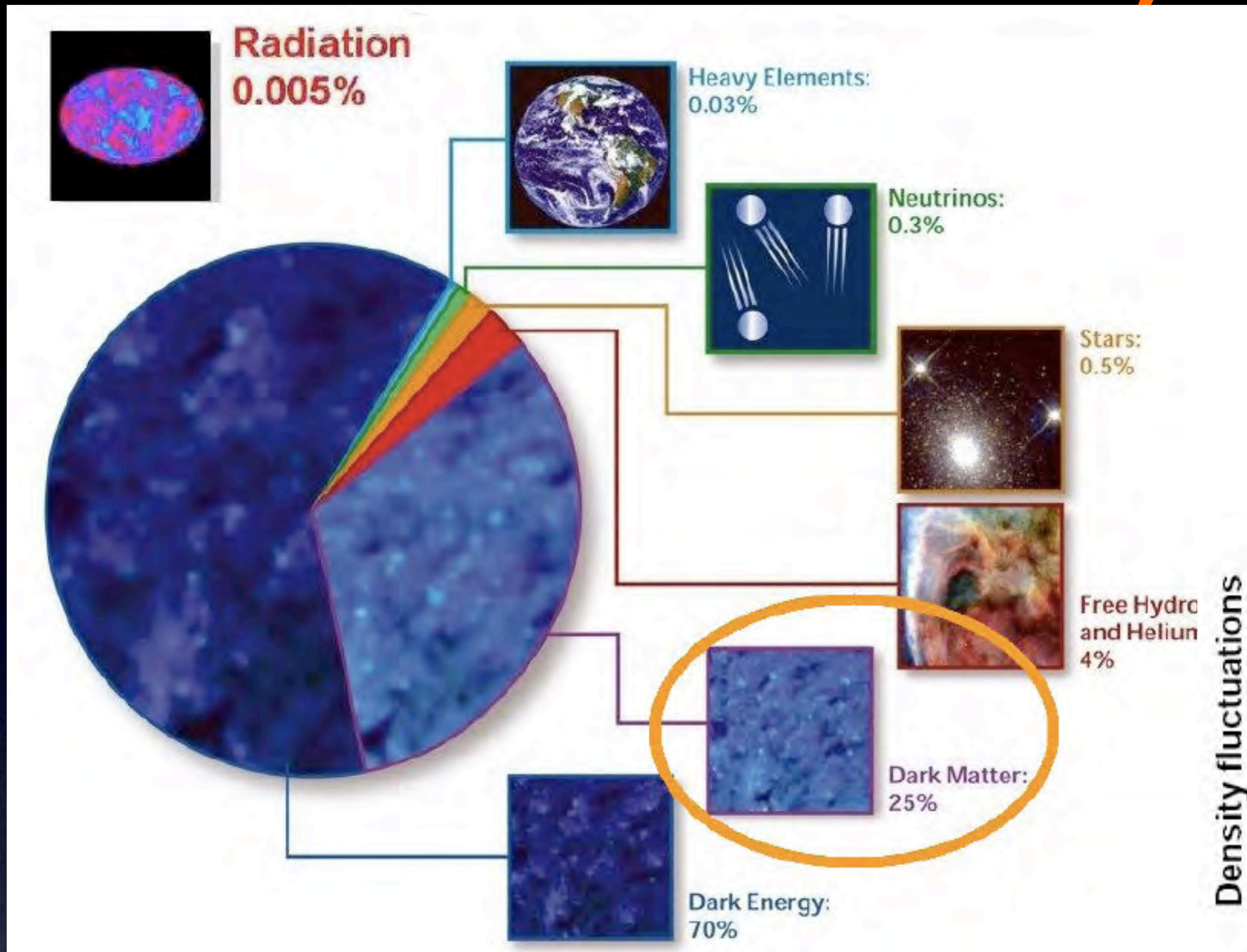
Chiara Arina

Moriond EW 2009 - 7/14 March

Service de Physique Theorique

Universite Libre de Bruxelles (ULB)

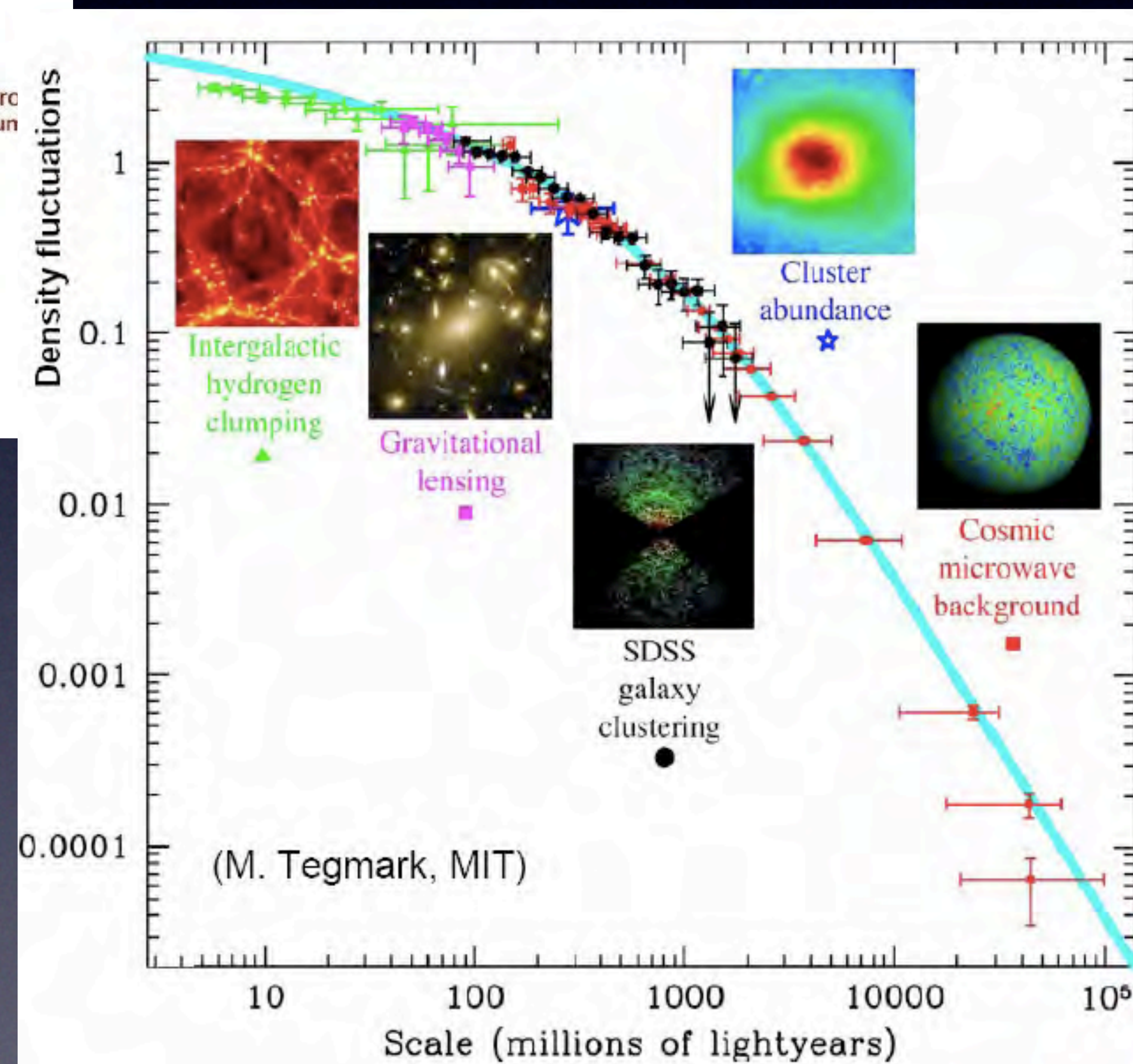
Non baryonic Cold Dark Matter (CDM)



WMAP 5 years

$\Omega_M h^2$	0.1369 ± 0.0037
$\Omega_b h^2$	0.02265 ± 0.00059
$\Omega_{DM} h^2$	0.1143 ± 0.0034

Evidence at all scales



Standard CDM scenarios

- Neutral, stable, thermal relic, massive and weakly interacting (WIMP)

- Many candidates
  - extra dimensions
  - IDM
  - SUSY (neutralino, gravitino...)

Sneutrinos in effective MSSM

Scalar and lepton sector

$\tilde{L}^* = (\tilde{\nu}^* \; \tilde{e}^{*-})_L$	$L^T = (\nu^T \; e^{T-})_L$
$\tilde{R} = \tilde{e}_R^-$	$R = e_R^-$

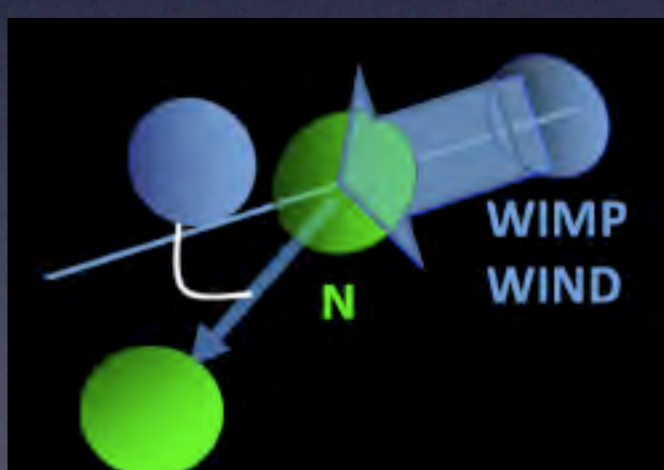
$$W_{\mathrm{MSSM}} = \epsilon_{ij}(\mu \hat{H}_i^1 \hat{H}_j^2 - Y_l \hat{H}_i^1 \hat{L}_j \hat{R})$$

$$V_{\mathrm{soft}} = (M_L^2) \tilde{L}_i^* \tilde{L}_i + [\epsilon_{ij}(\Lambda_l H_i^1 \tilde{L}_j \tilde{R}) + h.c.]$$

Stable by R-parity
neutral and WIMP
CDM candidate

mass parameter driving
the sneutrino sector

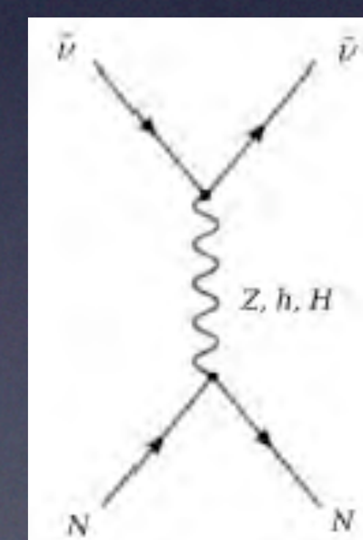
Direct detection = elastic scattering on nucleus



Sneutrino:

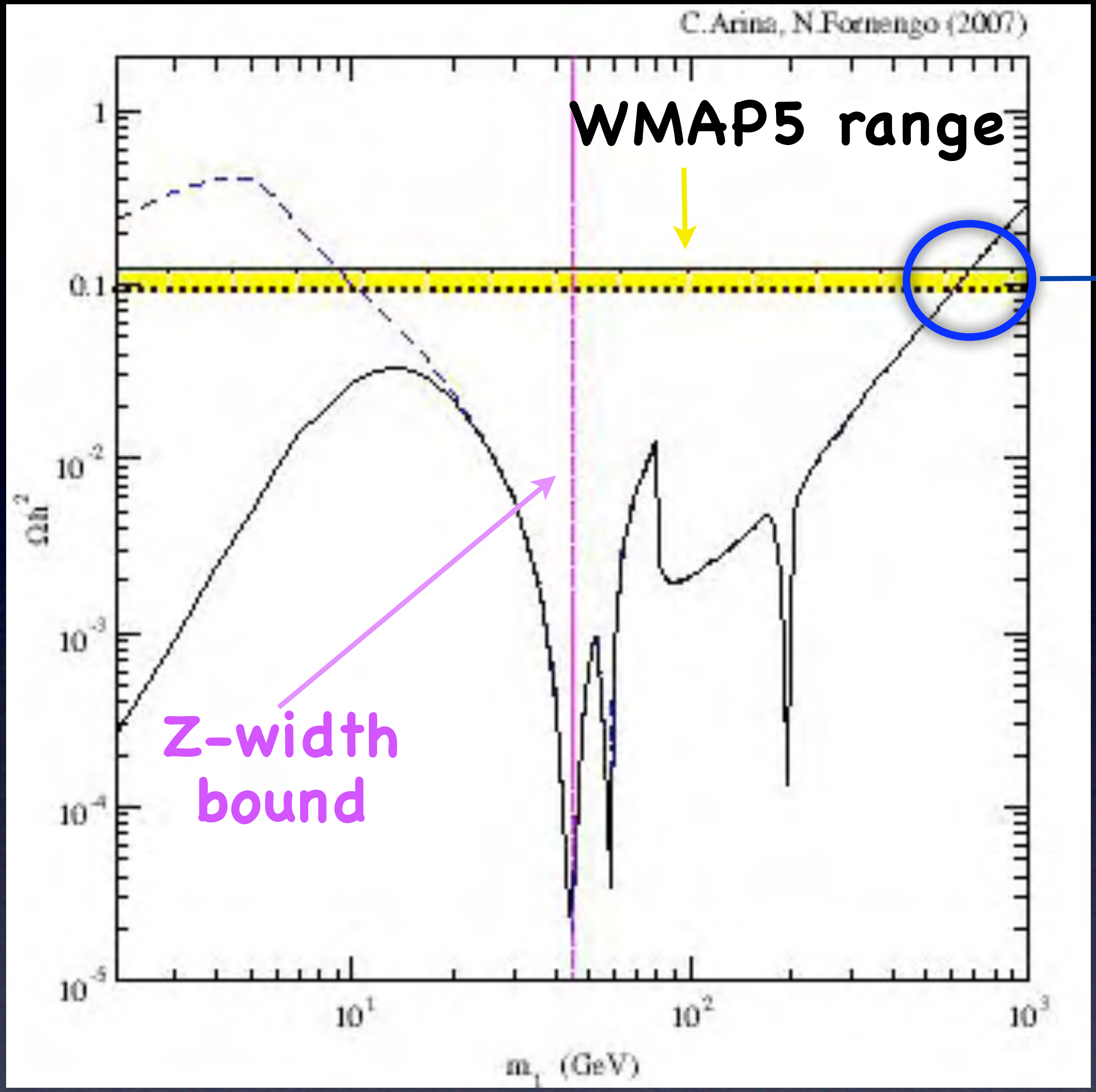
- scalar interaction
- exchange of a Z boson, of the h and H fields
- can be subdominant

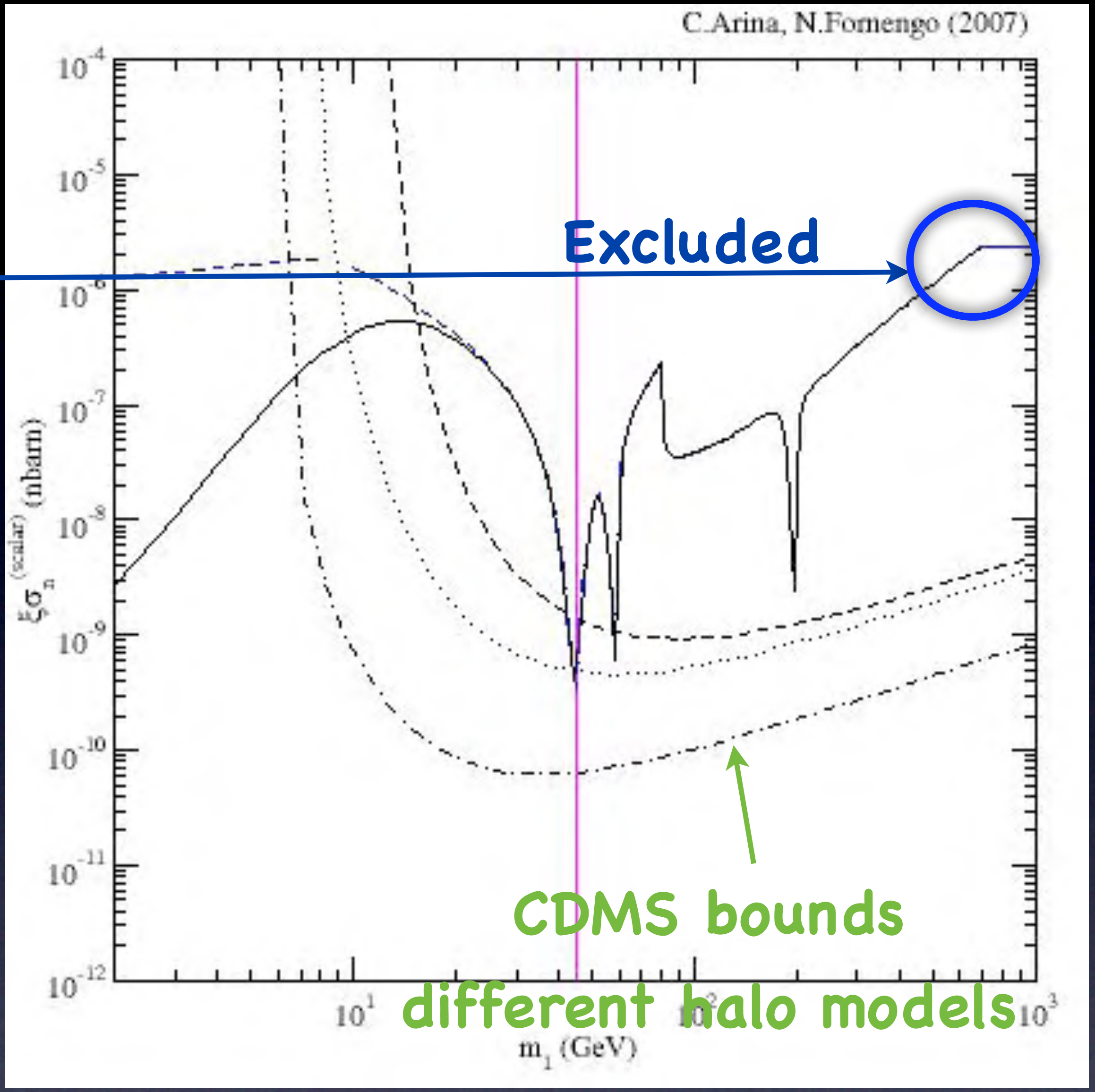
$$\xi = \min(1, \frac{\Omega_{\tilde{\nu}} h^2}{\Omega_{CDM} h^2})$$



Why MSSM sneutrinos are not good DM candidates?

Ωh^2 and $\xi\sigma_{nucleon}^{(scalar)}$ versus the sneutrino mass m_1 effMSSM





- dips $\longrightarrow$ Higgs poles
- sharp drop $\longrightarrow$ WW threshold

$\tilde{\nu} - Z$ coupling is huge:

- low relic abundance (underabundant)
- enhanced scattering on nucleon (excluded by direct detection exp)

Sneutrinos excluded as CDM except in fine-tuned conditions

Extension of the MSSM required by neutrino physics

↓

changes in the sneutrino sector as well

- MSSM + N^c (right-handed neutrino superfield)
  - neutrino dirac mass
  - sneutrino good CDM
  - but large off-diagonal in the mass matrix
- MSSM + L violating 5-dim operator
  - majorana neutrino mass
  - sneutrino as in the MSSM due to strong constraints from neutrino physics
- See-saw model
- Inverse See-saw model (invMSSM)

effMSSM + right-handed neutrinos + Majorana mass term

C.A. and N.Fornengo, JHEP 0711:029(2007)

$$W_{Maj} = \epsilon_{ij}(\mu \hat{H}_i^1 \hat{H}_j^2 - Y_l \hat{H}_i^1 \hat{L}_j \hat{R} + Y_\nu \hat{H}_i^2 \hat{L}_j \hat{N}) + \frac{1}{2} M \hat{N}\hat{N}$$

$$V_{\rm soft} = (M_L^2)\, \tilde{L}_i^* \tilde{L}_i + (M_N^2)\, \tilde{N}^* \tilde{N} - [(m_B^2) \tilde{N}\tilde{N} + \epsilon_{ij}(\Lambda_l H_i^1 \tilde{L}_j \tilde{R} + \Lambda_\nu H_i^2 \tilde{L}_j \tilde{N}) + h.c.]$$

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Neutrino sector

$$-\mathcal{L}_\nu = \frac{1}{2} \begin{pmatrix} \nu_L^T & \nu_L^{cT} \end{pmatrix} \mathcal{M}_\nu \begin{pmatrix} \nu_L \\ \nu_L^c \end{pmatrix} + h.c.$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}$$

See-saw mechanism

$$m_D = v_2 Y_\nu$$
$$m_\nu = \frac{m_D^2}{M}$$

Smallness of neutrino masses given by the large value of M

effMSSM + right-handed neutrinos + Majorana mass term

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Neutrino sector

Sneutrino sector

$$-\mathcal{L}_\nu = \frac{1}{2} \left(\nu_L^T \quad \nu_L^{cT} \right) \mathcal{M}_\nu \begin{pmatrix} \nu_L \\ \nu_L^c \end{pmatrix} + h.c.$$

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See-saw mechanism

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Smallness of neutrino masses given by the large value of M

CP basis:

$$\Phi_{\rm Maj}^\dagger = (\tilde{\nu}_+^* \ \tilde{N}_+^* \ \tilde{\nu}_-^* \ \tilde{N}_-^*)$$

$$\tilde{\nu}_+ = \frac{1}{\sqrt{2}} (\tilde{\nu}_L + \tilde{\nu}_L^*)$$
$$\tilde{\nu}_- = \frac{-i}{\sqrt{2}} (\tilde{\nu}_L - \tilde{\nu}_L^*)$$

$$\mathcal{M}_{\rm Maj}^2 = \begin{pmatrix} m_L^2 + \frac{1}{2} m_Z^2 \cos 2\beta + m_D^2 & F^2 + m_D M & 0 & 0 \\ F^2 + m_D M & m_N^2 + M^2 + m_D^2 + m_B^2 & 0 & 0 \\ 0 & 0 & m_L^2 + \frac{1}{2} m_Z^2 \cos 2\beta + m_D^2 & F^2 - m_D M \\ 0 & 0 & F^2 - m_D M & m_N^2 + M^2 + m_D^2 - m_B^2 \end{pmatrix}$$

$$F^2 = \nu \Lambda_\nu \sin\beta - \mu m_D \mathrm{cotg}\beta$$

Typically $M = 10^{10}$ GeV
less interesting for sneutrinos, since N sector decoupled from low energy phenomenology, recovered MSSM

M = 1 TeV mixed sneutrino as CDM (Z coupling reduced but small dirac mass for neutrino masses)

effMSSM + right-handed neutrinos + Majorana mass term

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$$V_{\rm soft} = (M^2_L)\, \tilde{L}^*_i \tilde{L}_i + (M^2_N)\, \tilde{N}^* \tilde{N} - [(m^2_B)\tilde{N}\tilde{N} + \epsilon_{ij}(\Lambda_l H^1_i \tilde{L}_j \tilde{R} + \Lambda_\nu H^2_i \tilde{L}_j \tilde{N}) + h.c.]$$

Sneutrino sector

CP basis:

$$\Phi^\dagger_{\rm Maj} = (\tilde{\nu}^*_+ \; \tilde{N}^*_+ \; \tilde{\nu}^*_- \; \tilde{N}^*_-)$$

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V_{\rm soft} &= (M^2_L)\, \tilde{L}^*_i \tilde{L}_i + (M^2_{\tilde{N}})\, \tilde{N}^* \tilde{N} - [(m^2_B) \tilde{N}\tilde{N} + \epsilon_{ij}(\Lambda_l H^1_i \tilde{L}_j \tilde{R} + \Lambda_\nu H^2_i \tilde{L}_j \tilde{N}) + h.c.]
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effMSSM + right-handed neutrinos + Majorana mass term

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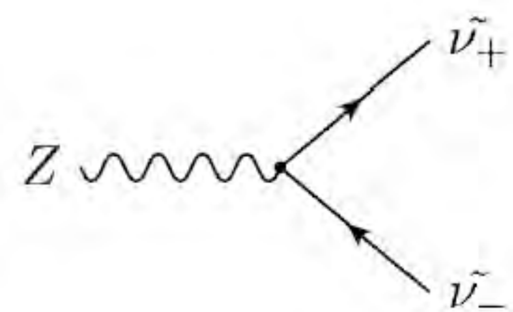
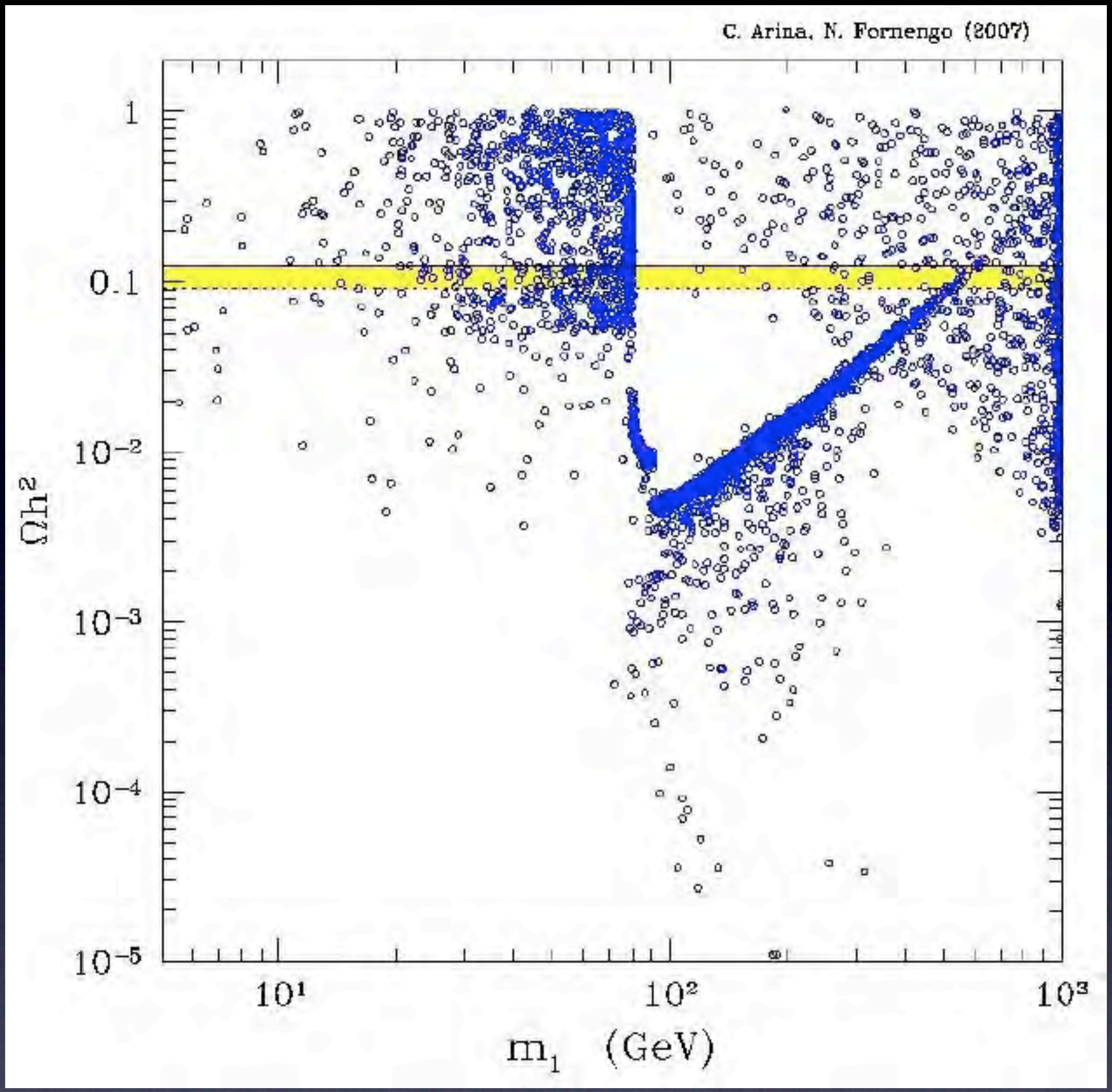
Mixing with the right-handed N $\quad \tilde{\nu}_i = Z_{i1}\tilde{\nu}_+ + Z_{i2}\tilde{N}_+ + Z_{i3}\tilde{\nu}_- + Z_{i4}\tilde{N}_- \qquad i = 1, 2, 3, 4$

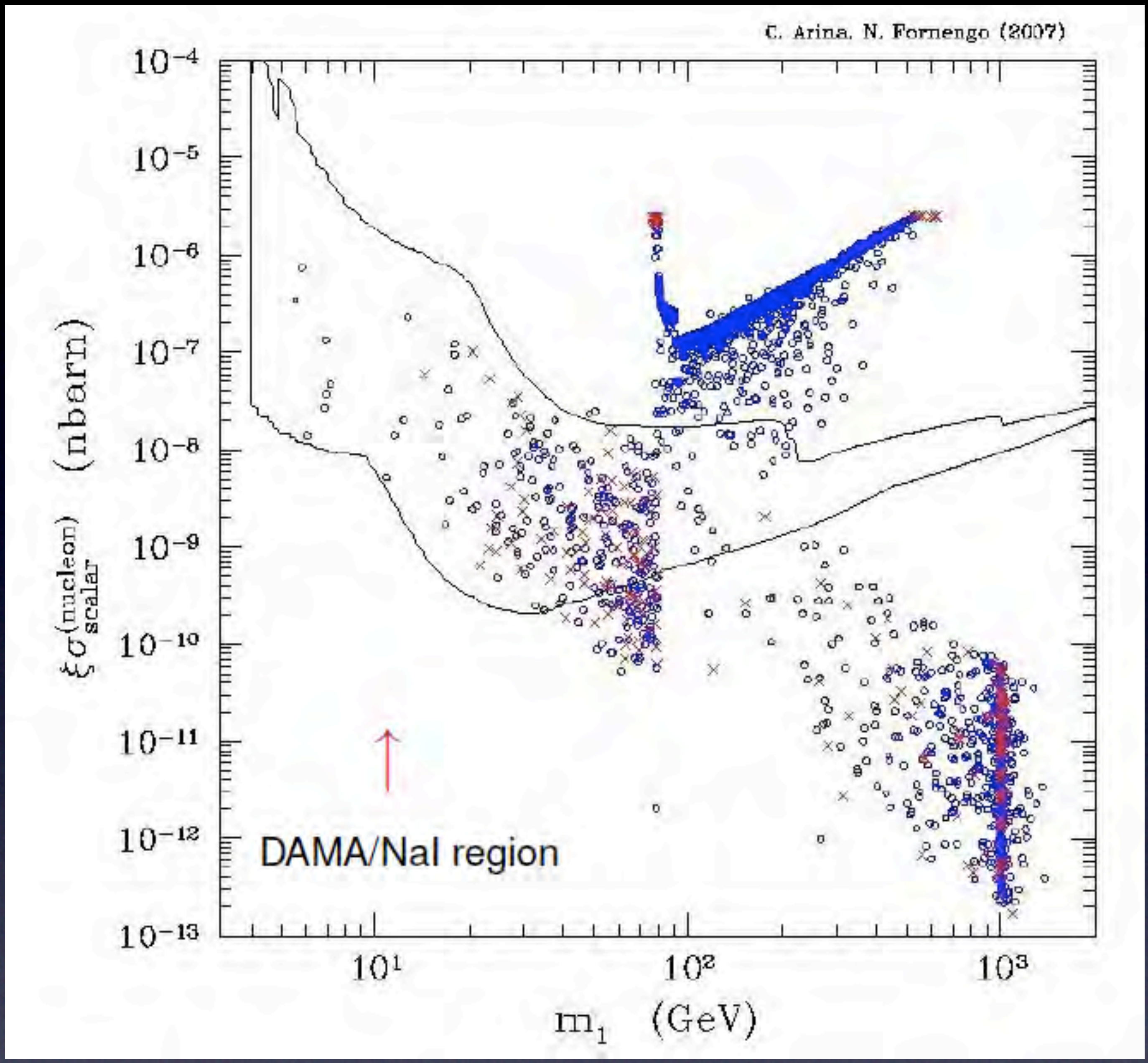
- Z coupling reduced proportionally to the mixing angle
- Z coupling off-diagonal:



- inelastic scattering on nucleus $\longrightarrow$ $\Delta m < \dfrac{\beta^2 m_- m_{\mathcal{N}}}{2(m_- + m_{\mathcal{N}})}$ and $\Delta m^2 \equiv m^2_+ - m^2_- = 2m^2_B$

Relic density and scalar cross-section prediction M=1TeV





dominant subdominant

- viable sneutrinos as CDM in all the mass range from 5 GeV up to 1 TeV (dominant or subdominant halo component)
- allowed light sneutrinos due to the mixing with the sterile right-handed fields
- compatible with the direct detection experiments (inelastic DM)

See-saw models with M = 1 TeV provide good phenomenology for the sneutrinos as CDM but require an unnaturally small Dirac mass for the neutrinos

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Inverse see-saw model (invMSSM)

- recover the same phenomenology for the sneutrino sector
- moreover it accommodates sneutrino as the LSP and CDM in mSUGRA scenarios
- neutrino masses

MSSM + right-handed neutrinos + singlet S (invMSSM)

C.A., F.Bazzocchi, N.Fornengo, J.Romao and J.Valle, PRL101:161802 (2008)

$$
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W_{inv} &= \epsilon_{ij}(\mu \hat{H}^1_i \hat{H}^2_j - Y_l \hat{H}^1_i \hat{L}_j \hat{R} + Y_\nu \hat{H}^2_i \hat{L}_j \hat{N}) + M \hat{N}\hat{S} + \tfrac{1}{2}\mu_S \hat{S}\hat{S} \\
V_{soft} &= (M^2_L)\,\tilde{L}^*_i \tilde{L}_i + (M^2_N)\,\tilde{N}^*\tilde{N} + (M^2_S)\,\tilde{S}^*\tilde{S} - [B_M \tilde{N}\tilde{S} + \tfrac{1}{2} B_{\mu_S} \tilde{S}\tilde{S} + \epsilon_{ij}(\Lambda_l H^1_i \tilde{L}_j \tilde{R} + A_{h_\nu} H^2_i \tilde{L}_j \tilde{N}) + h.c.]
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μ_S = 0 L is conserved

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Neutrino sector

$$-\mathcal{L}_\nu = \frac{1}{2}\begin{pmatrix}\nu_L^T & \nu_L^{cT} & S^T\end{pmatrix} \mathcal{M}_\nu \begin{pmatrix}\nu_L \\ \nu_L^c \\ S\end{pmatrix} + h.c.$$

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

Inverse see-saw mechanism

$$m_D = v_2 Y_\nu$$
$$m_\nu \simeq \mu_S \frac{m_D^2}{M^2}$$

The smallness of the neutrino mass is given by the smallness of μ_S O(KeV)

MSSM + right-handed neutrinos + singlet S (invMSSM)

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Sneutrino sector

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

$$V_{mass} = \frac{1}{2}\Phi^\dagger \mathcal{M}_\pm^2 \Phi$$

$$\mathcal{M}_\pm{}^2 = \begin{pmatrix} m_L^2 + \frac{1}{2}m_Z^2\cos 2\beta + m_D^2 & A_{h_\nu} v_2 - \mu m_D cotg\beta & m_D M \\ A_{h_\nu} v_2 - \mu m_D cotg\beta & m_N^2 + M^2 + m_D^2 & \mu_S M \pm B_M \\ m_D M & \mu_S M \pm B_M & m_S^2 + \mu_S^2 + M^2 \pm B_{\mu_S} \end{pmatrix}$$

$$\tilde{\nu}_i = Z_{i1}\tilde{\nu}_+ + Z_{i2}\tilde{N}_+ + Z_{i3}\tilde{S}_+ + Z_{i4}\tilde{\nu}_- + Z_{i5}\tilde{N}_- + Z_{i6}\tilde{S}_- \qquad i = 1, 2, ..., 6$$

- mixed state of the left-handed sneutrino, the right-handed sneutrino and the singlet scalar field
- again Z coupling off-diagonals

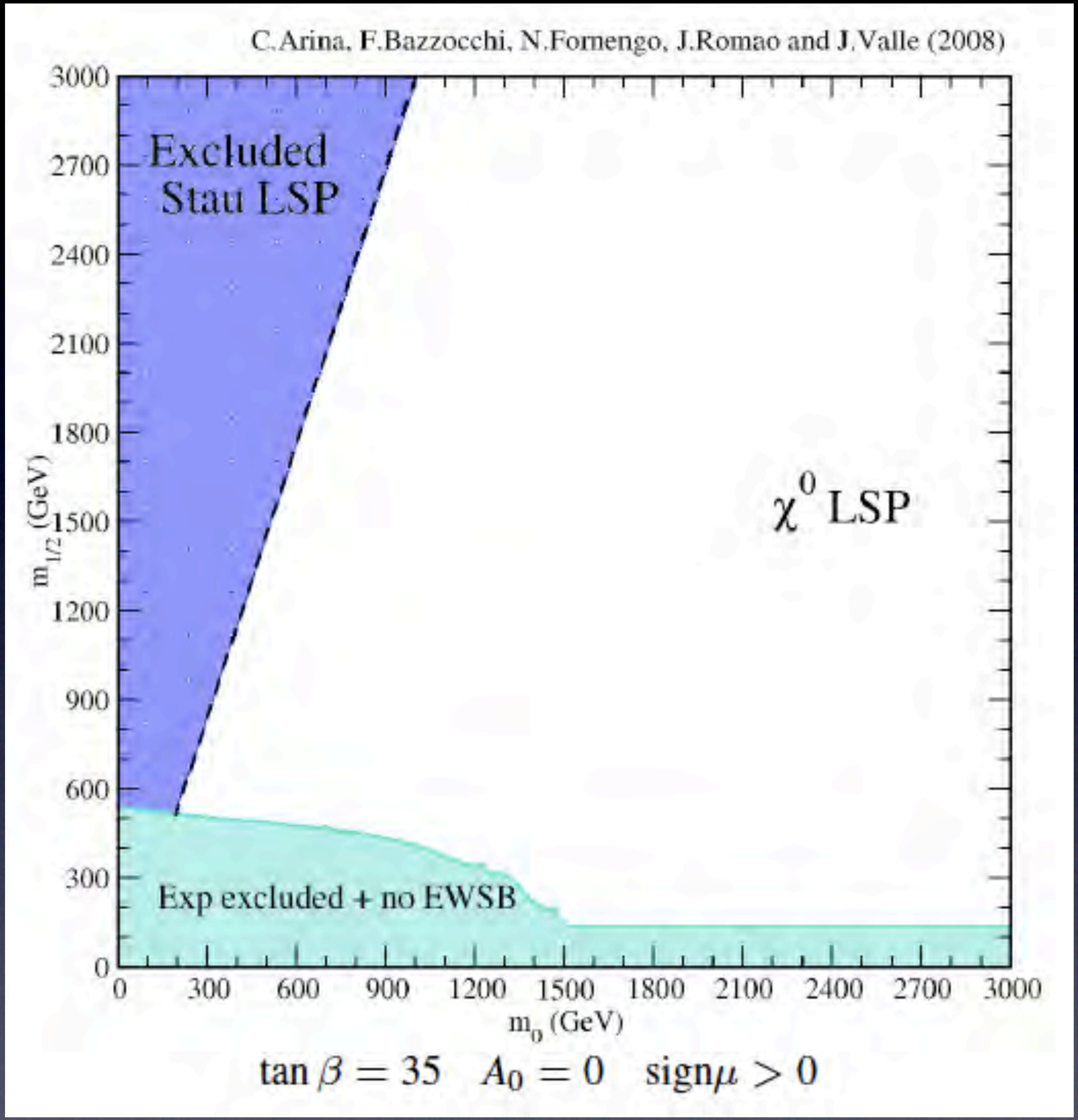
mSUGRA universality MSSM

GUT scale

- m_0 unified scalar mass
- $m_{1/2}$ gaugino mass
- $A_0, \tan\beta$ and $\text{sign}\mu$

EW scale

- $m_l^2 = m_0^2 + 0.52\ m_{1/2}^2$
- $m_r^2 = m_0^2 + 0.15\ m_{1/2}^2$



Sneutrino never the LSP

mSUGRA universality invMSSM

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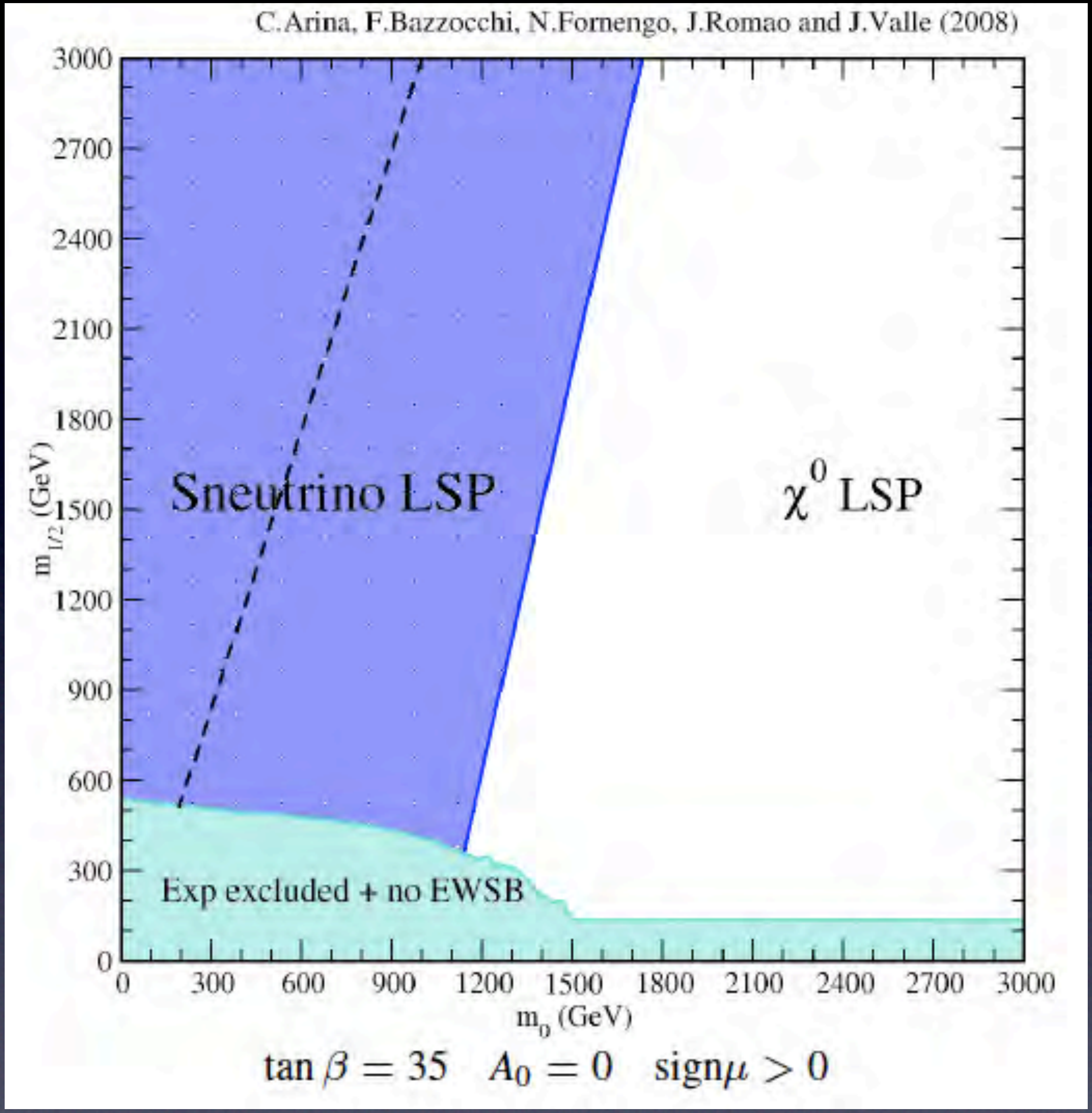
Sneutrino is the LSP naturally as the neutralino

freedom given by μ_S and M (related to neutrino physics)



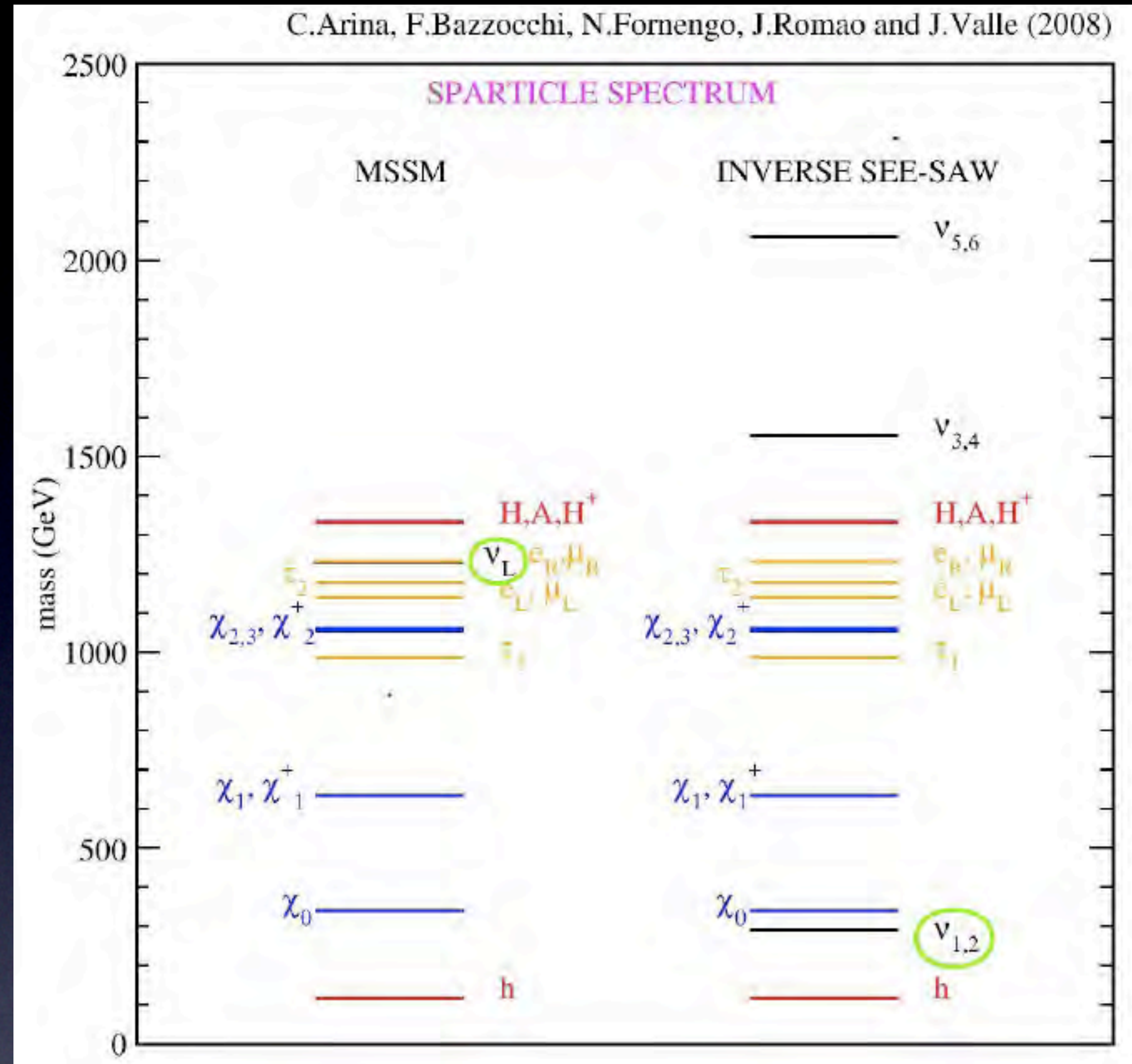
Additional sneutrino sector parameters: $m_S^2 = m_N^2 = m_0^2$, $A_{h_\nu} = A_0$ and $B_{\mu_S} = B_M \propto \mu_S$

InvMSSM spectrum

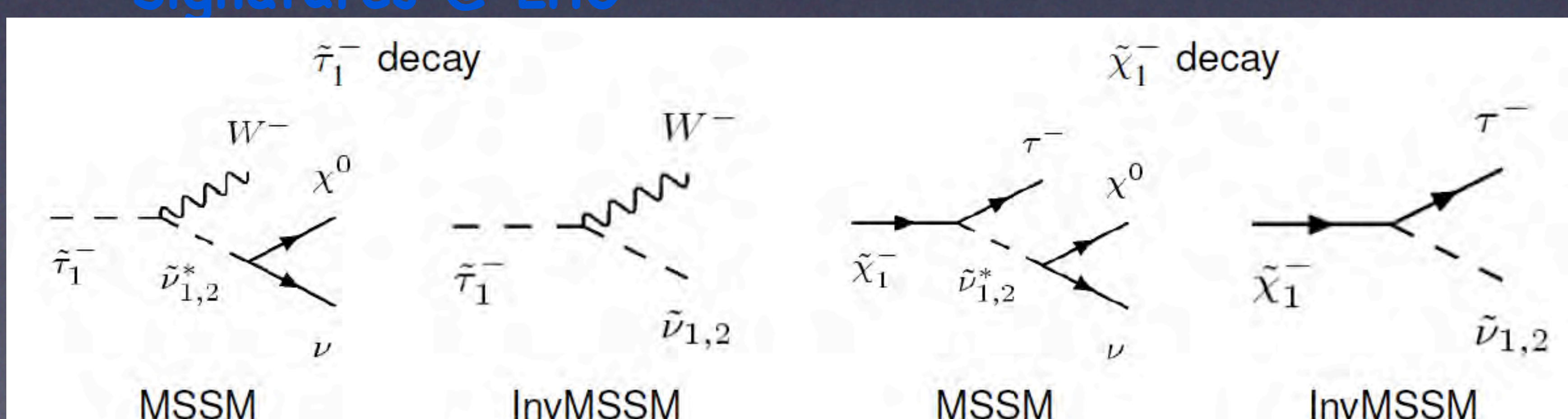
- $\tilde{\nu}_1$ and $\tilde{\nu}_2$ almost degenrate, splitting O(Kev), example of inelastic DM

- heavy SUSY spectrum, in particular sleptons. The NNLSP is the neutralino

- At LHC expected a similar phenomenology as in the neutralino case, however qualitatively expected more leptons in the final state and a different invariant mass distribution

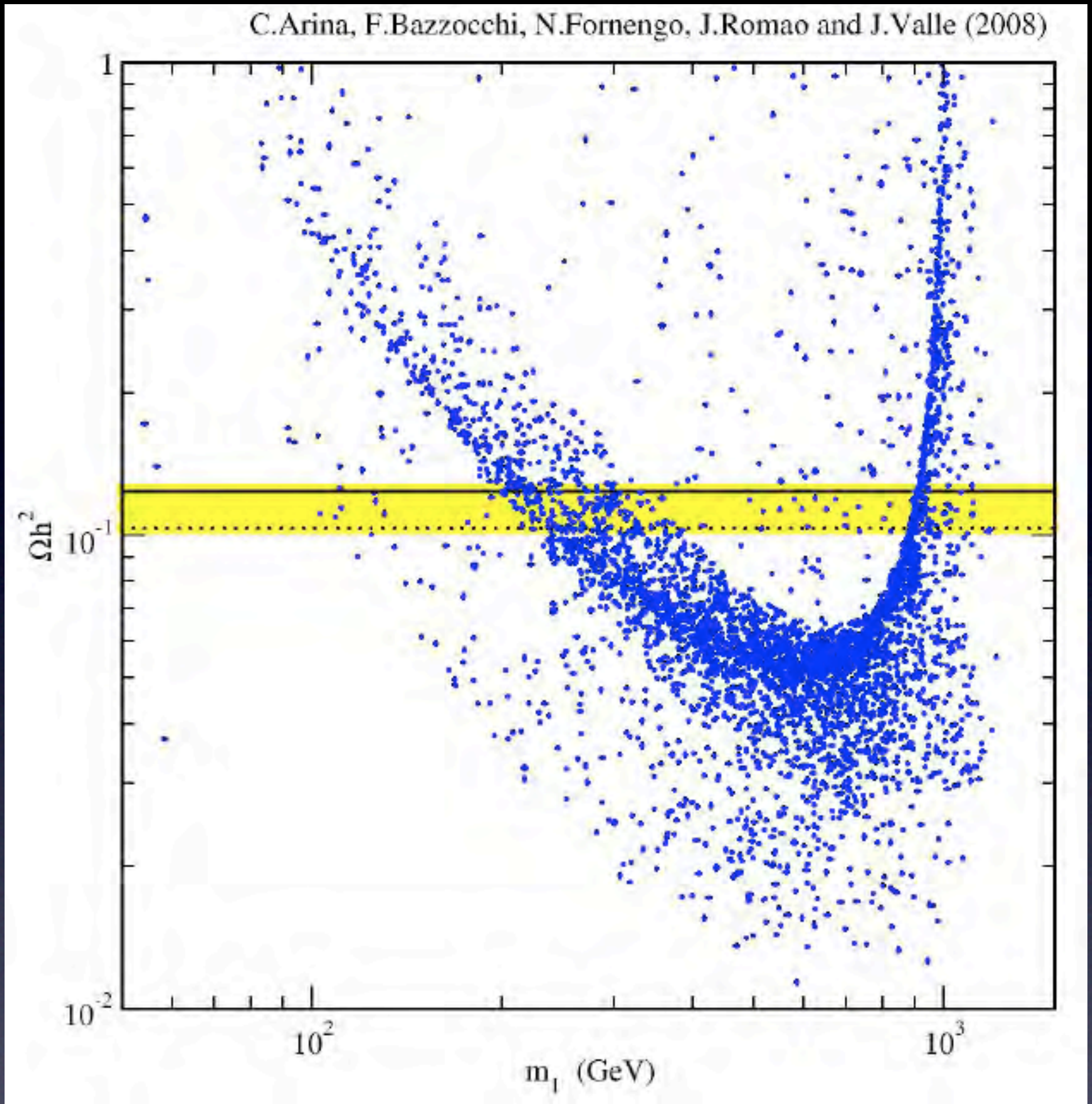


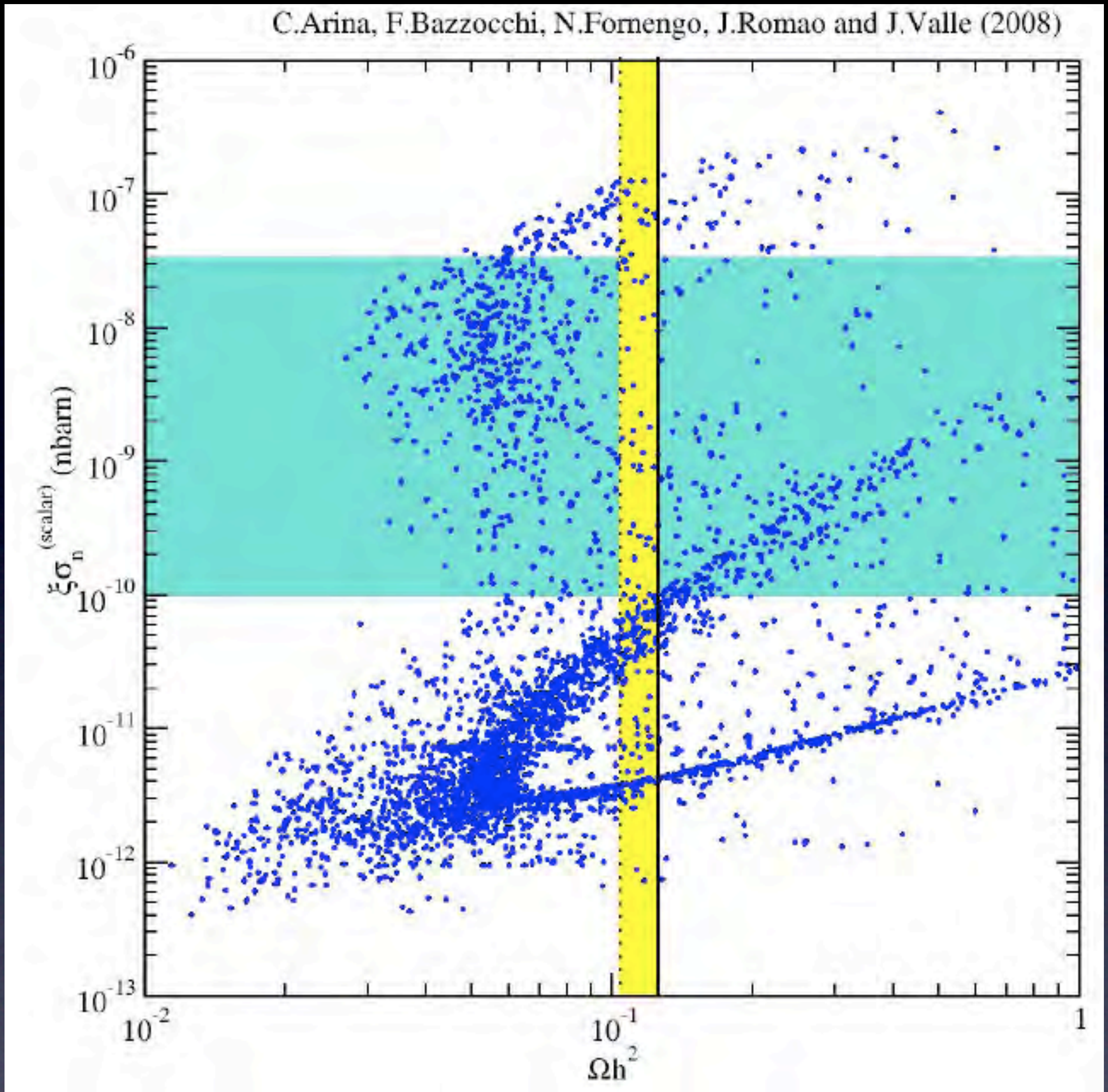
Signatures @ LHC



MSSM: processes suppressed because three body decays and leptons are heavy

Relic density and scalar cross-section prediction





- Inverse see-saw model accommodate sneutrinos as CDM in mSUGRA scenarios

- from m>100 GeV sneutrino are compatible with WMAP5 or subdominant halo components
- direct detection predictions in the sensitivity range of current experiments

Conclusions

- CDM needed $\longrightarrow$ SUSY models conserving R-parity:

thermal SNEUTRINO
neutral, stable particle and WIMP

but excluded in the MSSM
due to the huge coupling with the Z

- Neutrino physics requires extension of the MSSM:

See-saw model with low scale Majorana mass

The relic density and the direct detection rate are compatible with the experimental bounds in an effective extended MSSM (small Dirac mass for neutrino)

Inverse see-saw model

- freedom given by the extra singlet S
- Viable sneutrino as CDM in mSUGRA
- Different signatures @ LHC compared to a mSUGRA neutralino (qualitatively heavier spectrum and more leptons in the final states)

Thank you!

Back-up slides

See-saw model M = 1 TeV sneutrino properties

Mixing with the right-handed N $\quad \tilde{\nu}_i = Z_{i1}\tilde{\nu}_+ + Z_{i2}\tilde{N}_+ + Z_{i3}\tilde{\nu}_- + Z_{i4}\tilde{N}_- \qquad i = 1,2,3,4$

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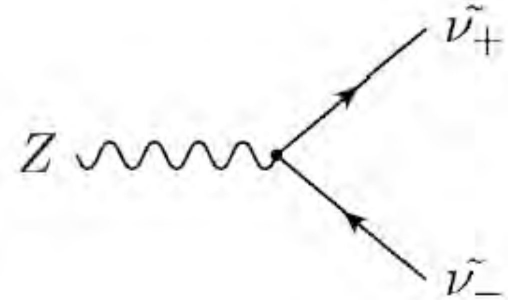
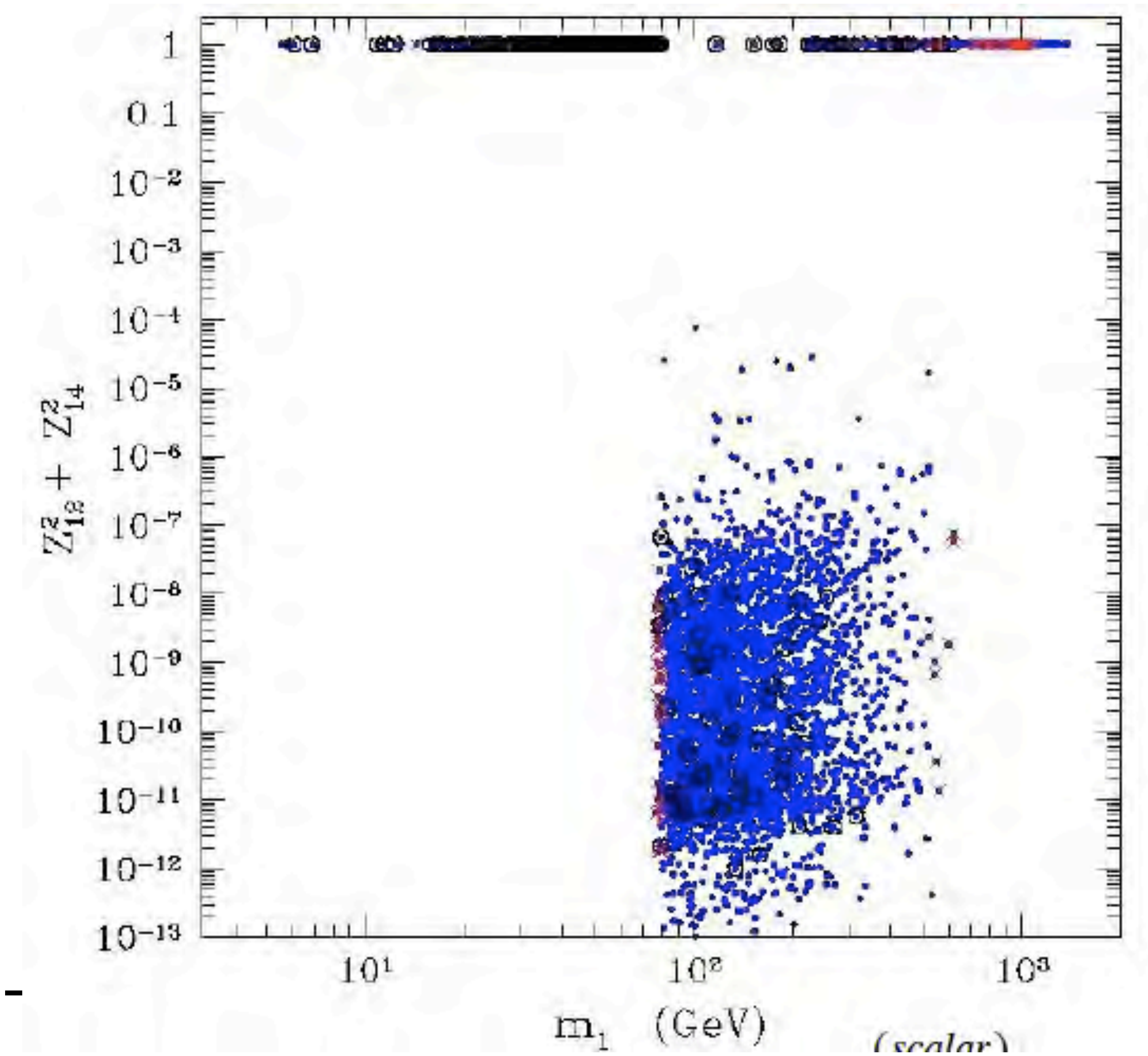
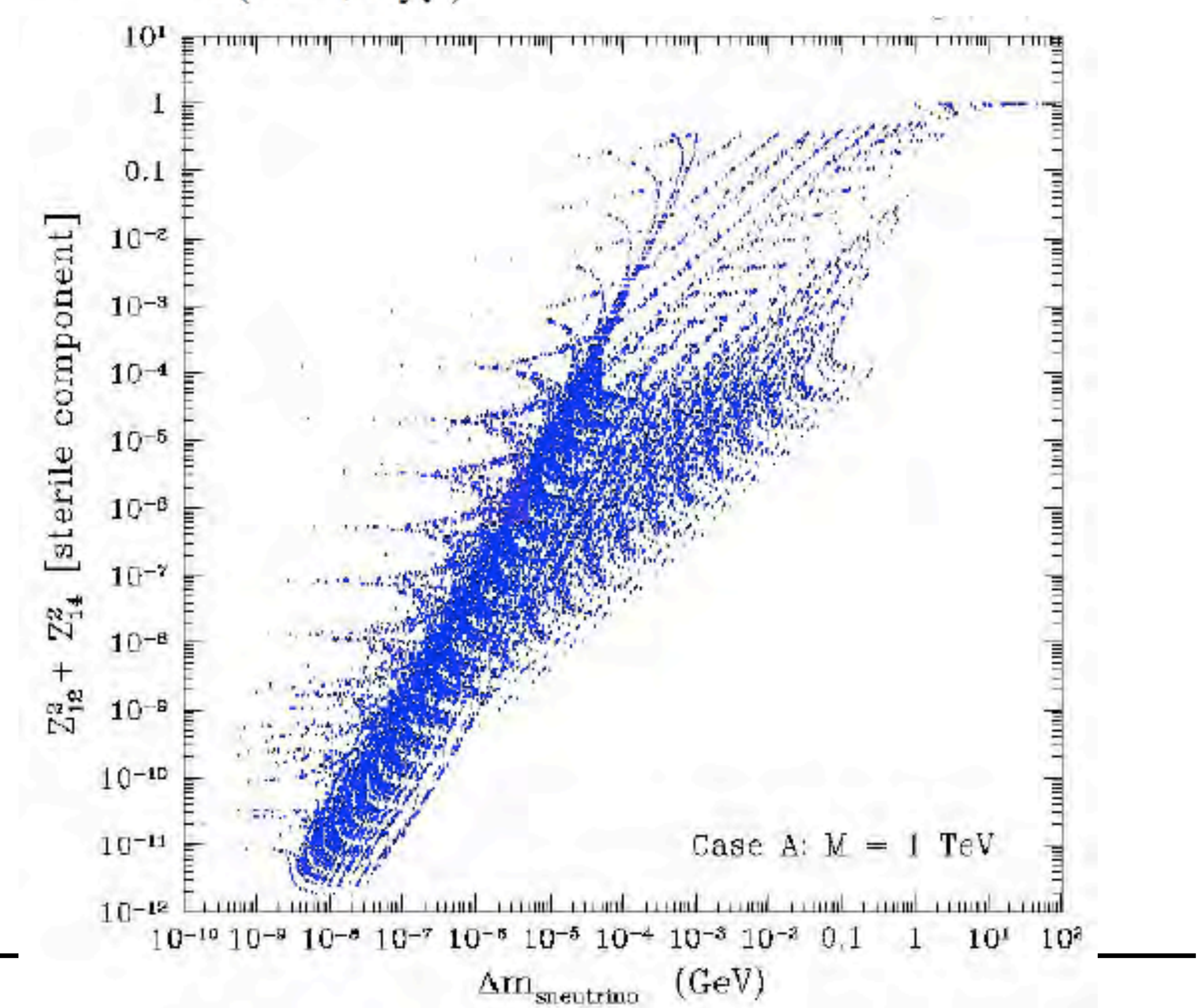
- Z coupling off-diagonal:

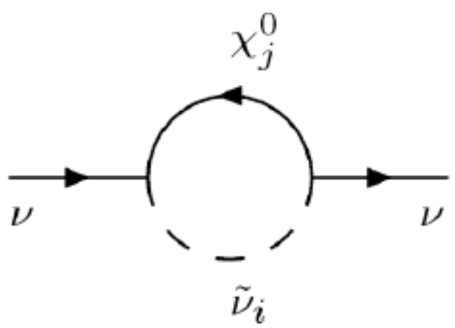


- inelastic scattering on nucleus $\longrightarrow$ $\Delta m < \dfrac{\beta^2 m_- m_{\mathcal{N}}}{2(m_- + m_{\mathcal{N}})}$ and $\Delta m^2 \equiv m_+^2 - m_-^2 = 2m_B^2$



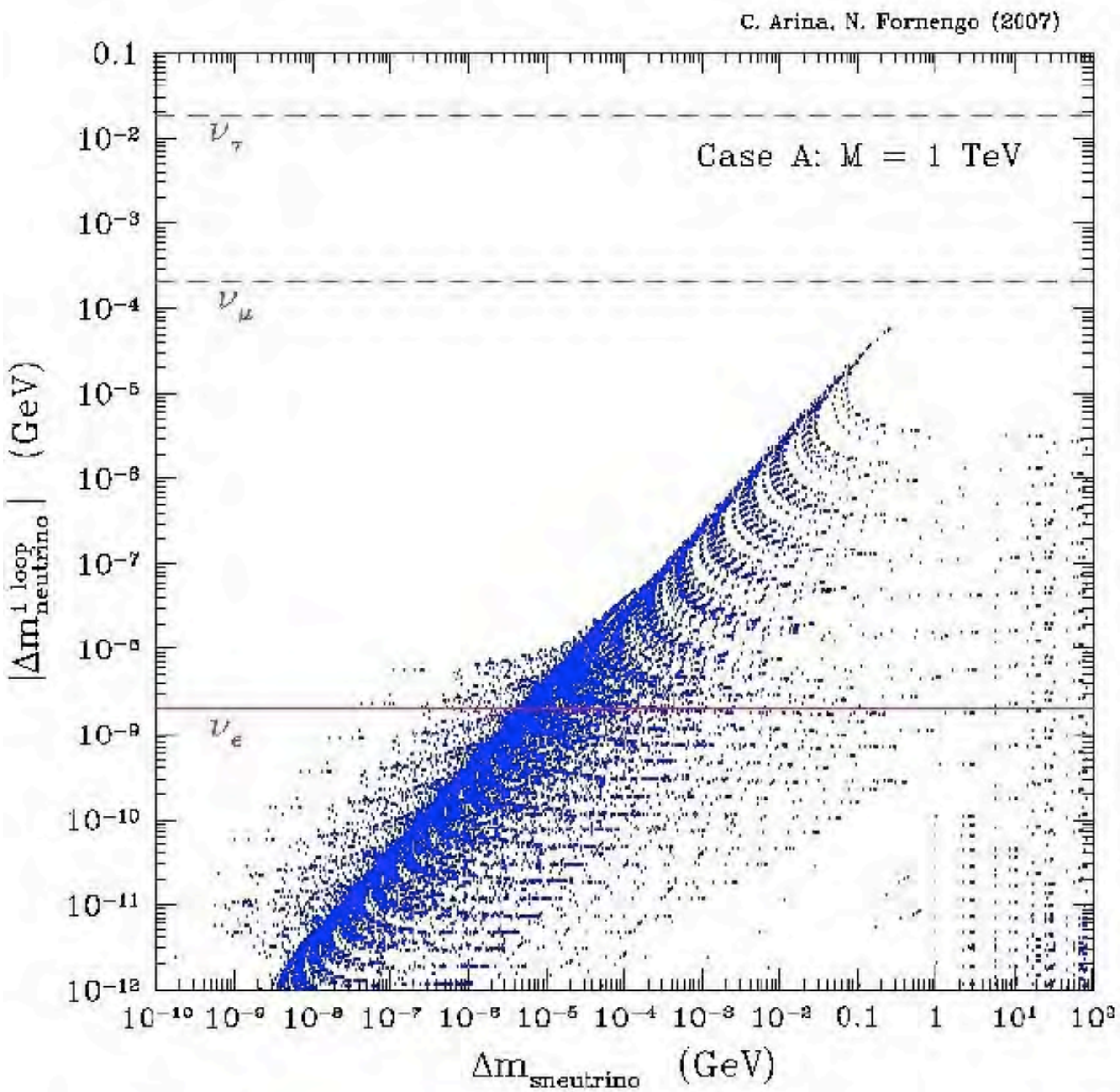


One loop correction to neutrino mass and inelastic scattering

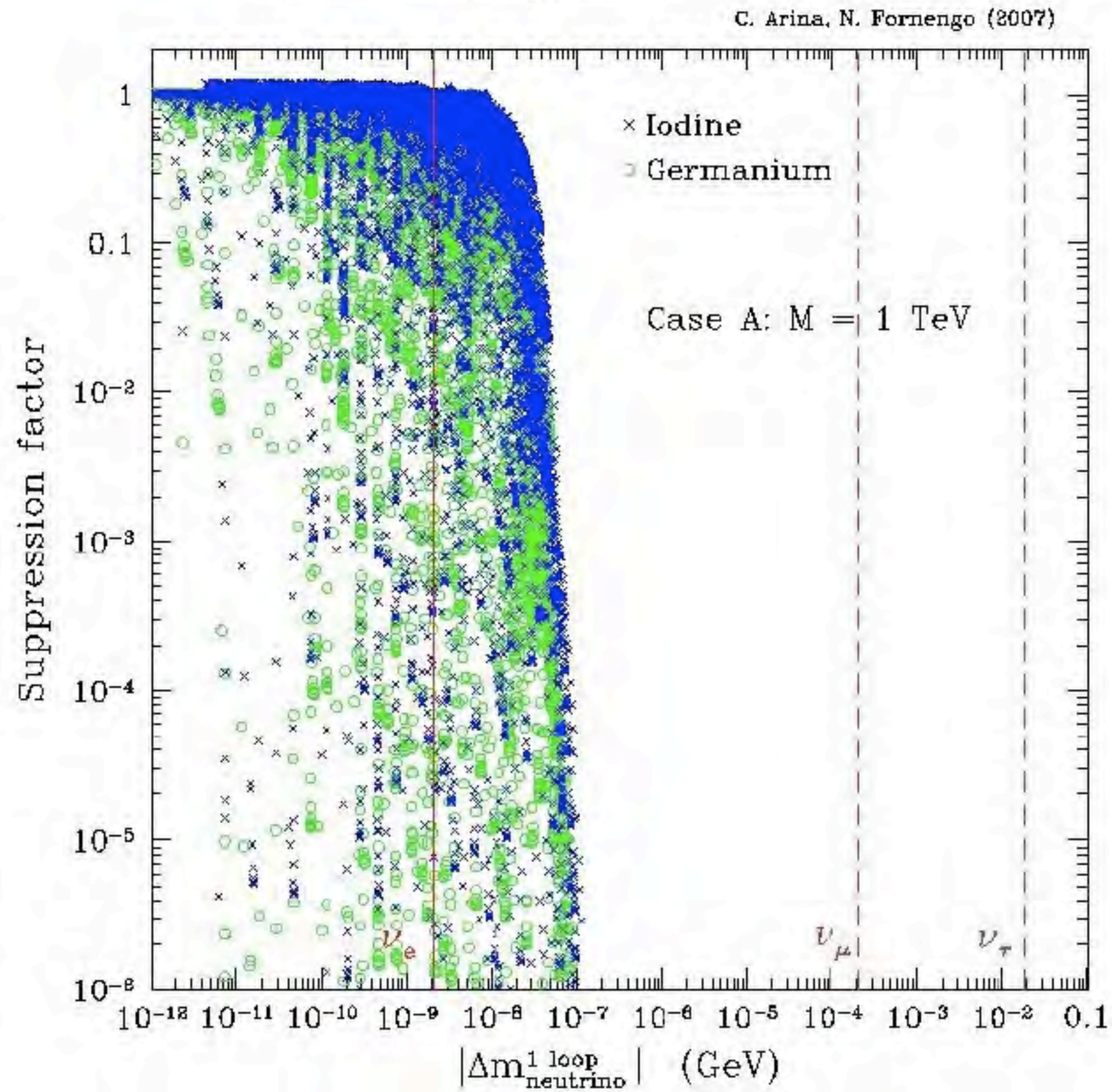


$$\Delta m_\nu^{1loop} \propto \Delta m$$

Neutrino mass bound $m_{\nu e} \leq 2eV$



$$\mathcal{S} = \frac{\mathcal{R}(E_1, E_2; \Delta m)}{\mathcal{R}(E_1, E_2; 0)} \qquad \mathcal{S}_{Ge} \neq \mathcal{S}_I$$

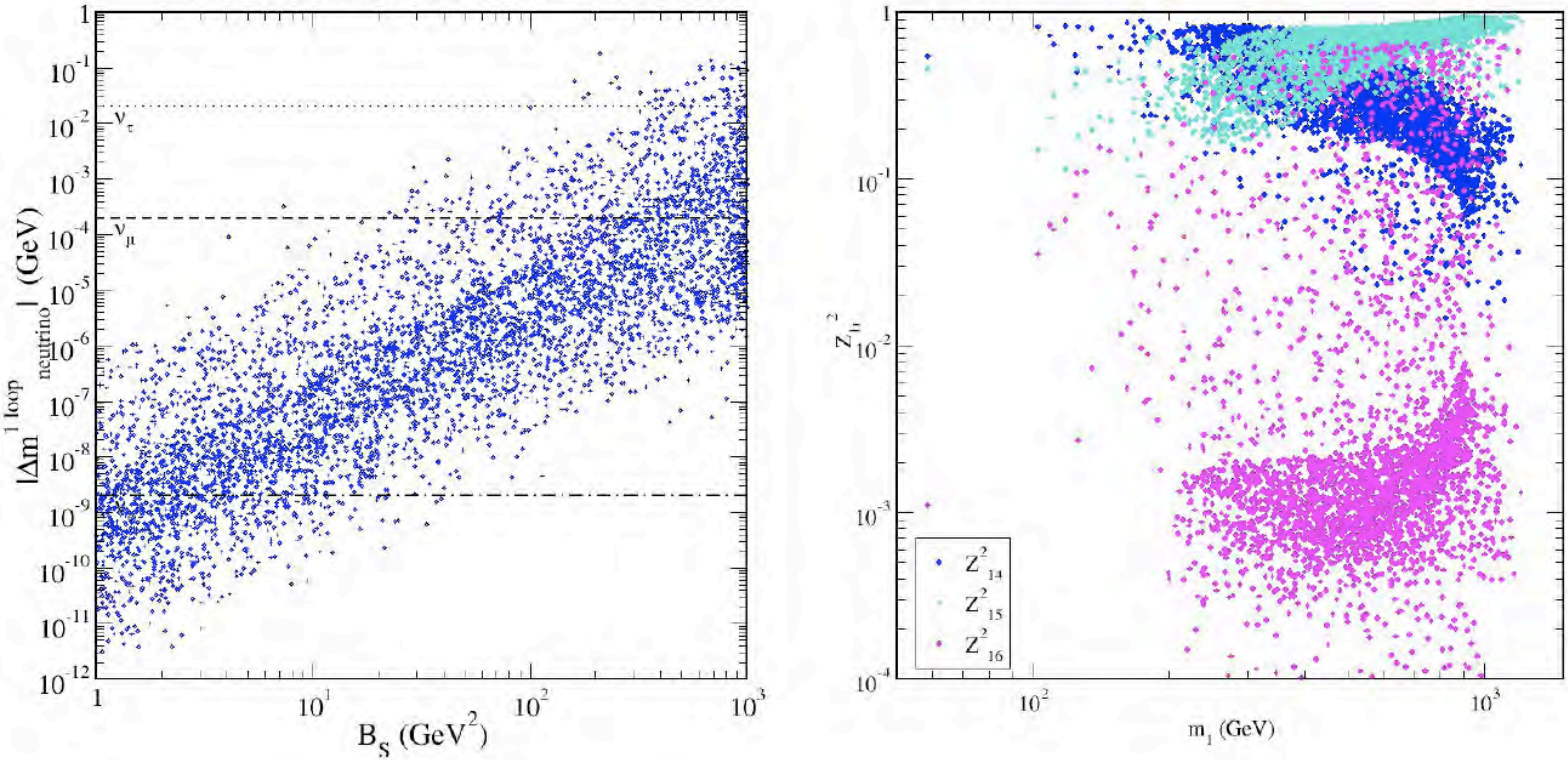


Suppression of the Z channel

$$\left[\xi\sigma^{(\mathrm{scalar})}_{\mathrm{nucleon}}\right]_{\mathrm{eff}} = \mathcal{S}(\xi\sigma^{(\mathrm{scalar})}_{\mathrm{nucleon}})^{Z} + (\xi\sigma^{(\mathrm{scalar})}_{\mathrm{nucleon}})^{h,H}$$

invMSSM sneutrino properties

C.Arina, F.Bazzocchi, N.Fornengo, J.Romao and J.Valle (2008)



- One loop corrections to neutrino mass under control $\Delta m \propto B_{\mu S}$
- small mixing with the sterile singlet S (●) O(10^-4)