Constraints on sneutrino dark matter from LHC Run 1

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RU meeting, October 28 2015,
Bethe Center Bonn

- **CA, M.E. Cabrera, S. Kraml, S. Kulkarni and U. Laa, JHEP 1505 (2015), arXiv:1503.02960**
- **CA, S. Kulkarni and J. Silk, Phys.Rev.D 92, arXiv: 1506.08202**

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INNOVIRIS EMPOWERING RESEARCH

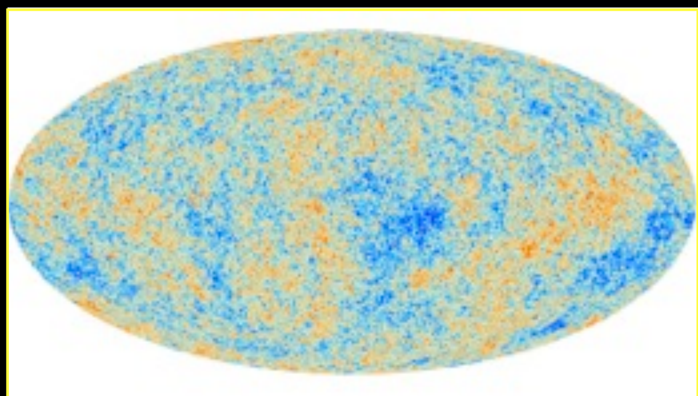
attract BRAINS FOR BRUSSELS

Credit: The Marenostrum Numerical Cosmology Project

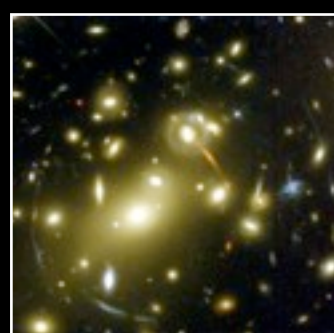
Outline

- Why sneutrino as Dark Matter (DM) candidate?
- Model parameter space compatible with DM constraints
- Constraints from LHC Run 1
- Missing topologies
- Specific indirect detection signature for sneutrino DM

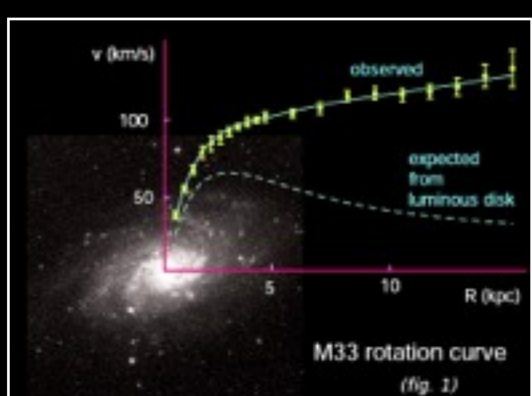
Evidence for DM in 1 slide



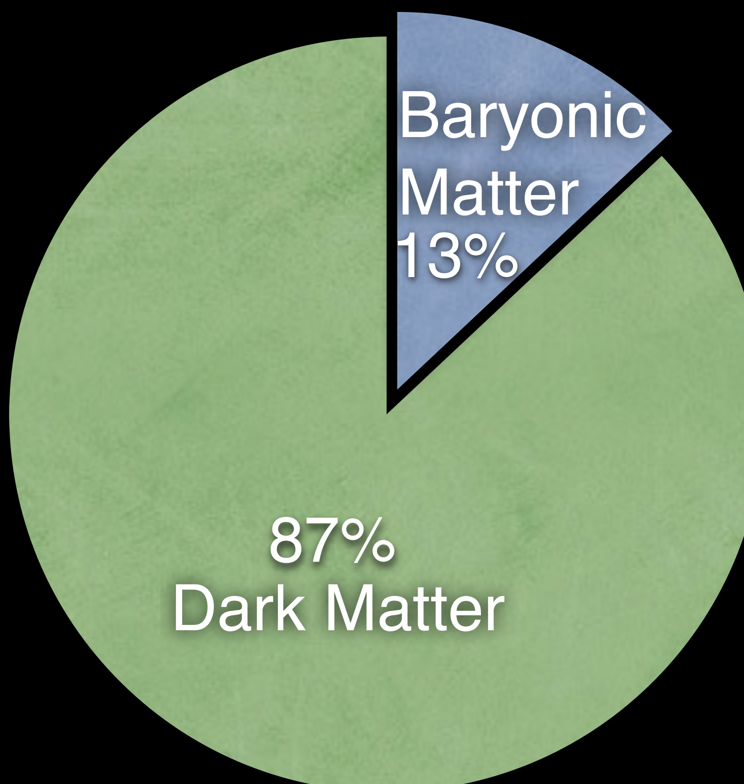
CMB



Cluster of galaxies



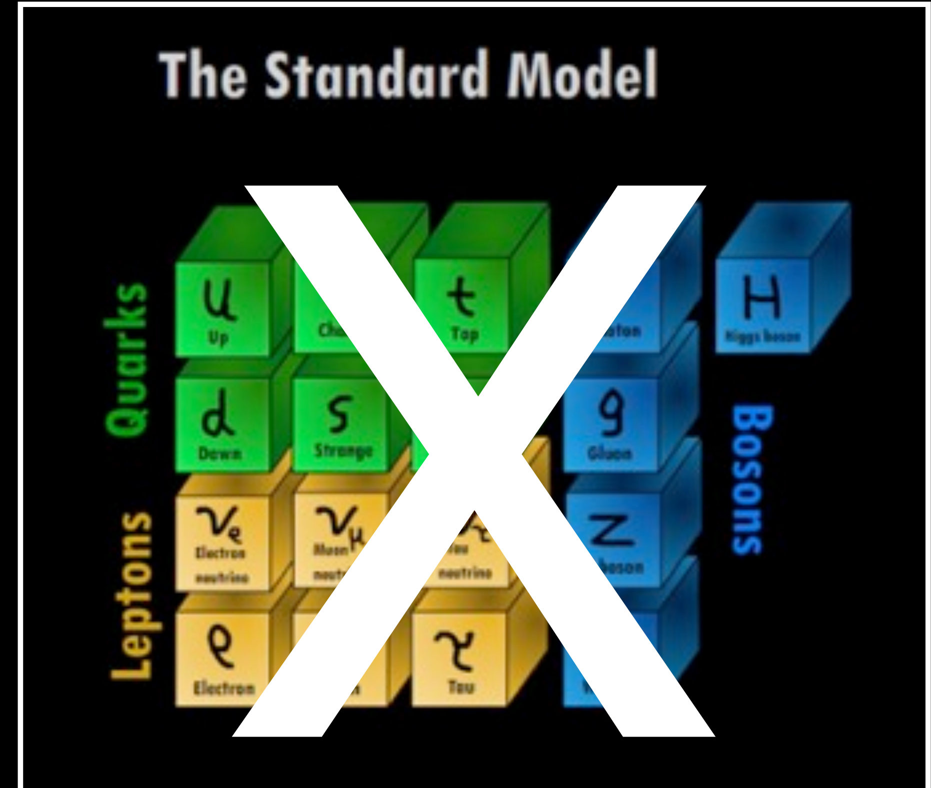
Rotation curves

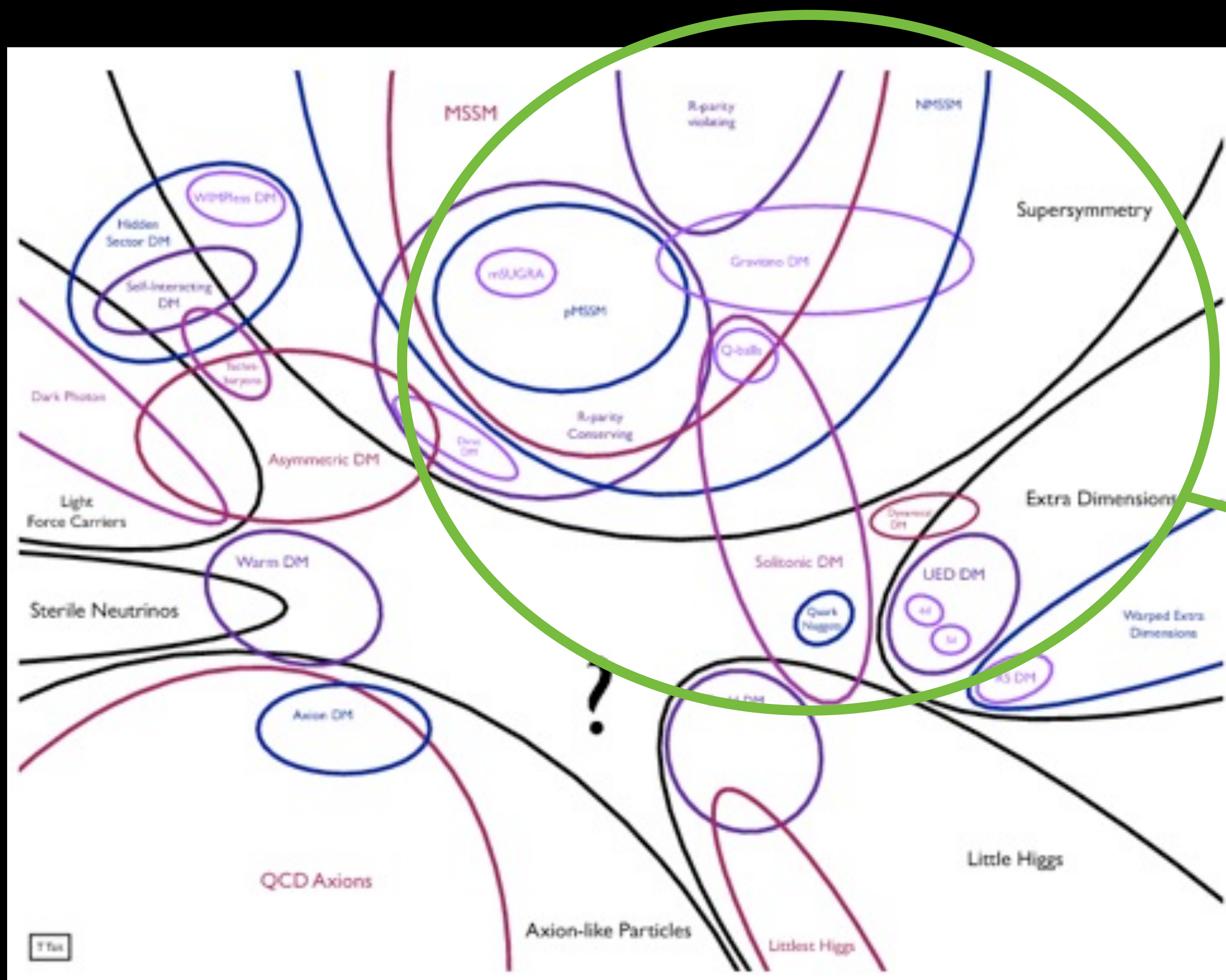


Gravitational evidence from cosmology and astrophysics

Particle physics perspective: what is DM?

- Neutral
- Massive enough to cluster and account for large scale structures
- Stable at least on cosmological scale

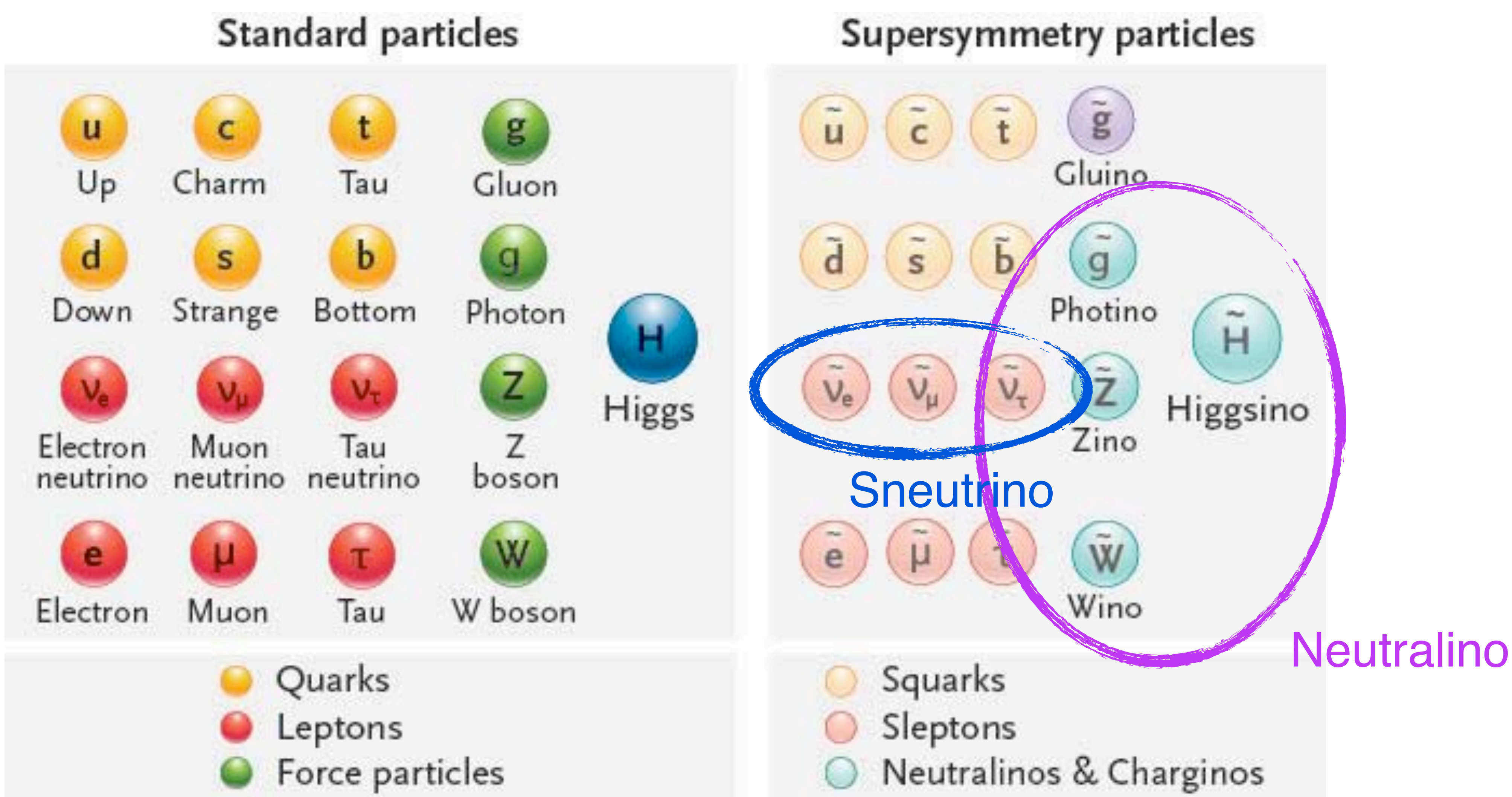




WIMPS

- Weakly Interacting Massive Particles
- Achieve thermally the relic density in GeV- TeV mass range
- Huge experimental effort to detect them

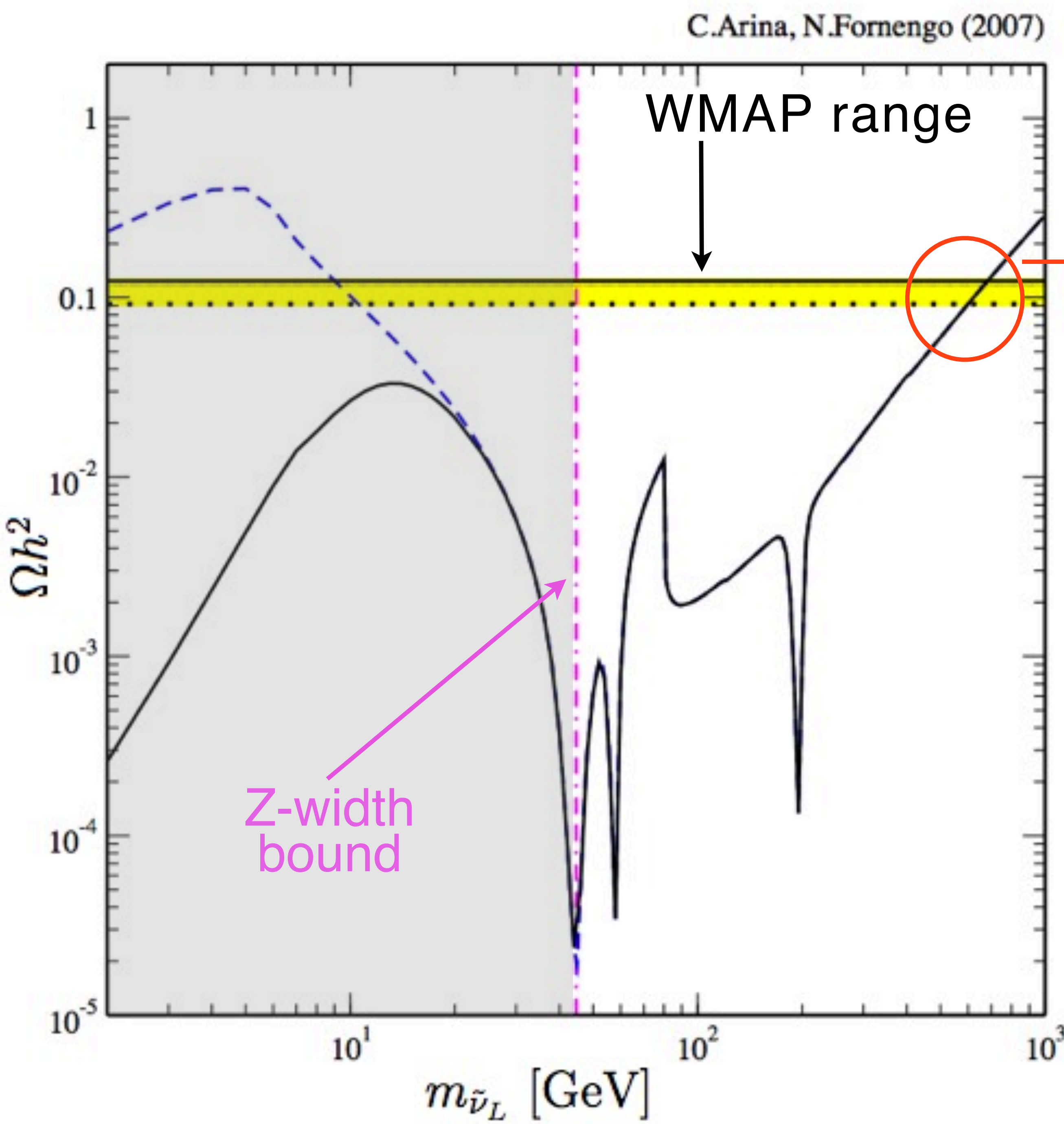
MSSM: WIMP candidates

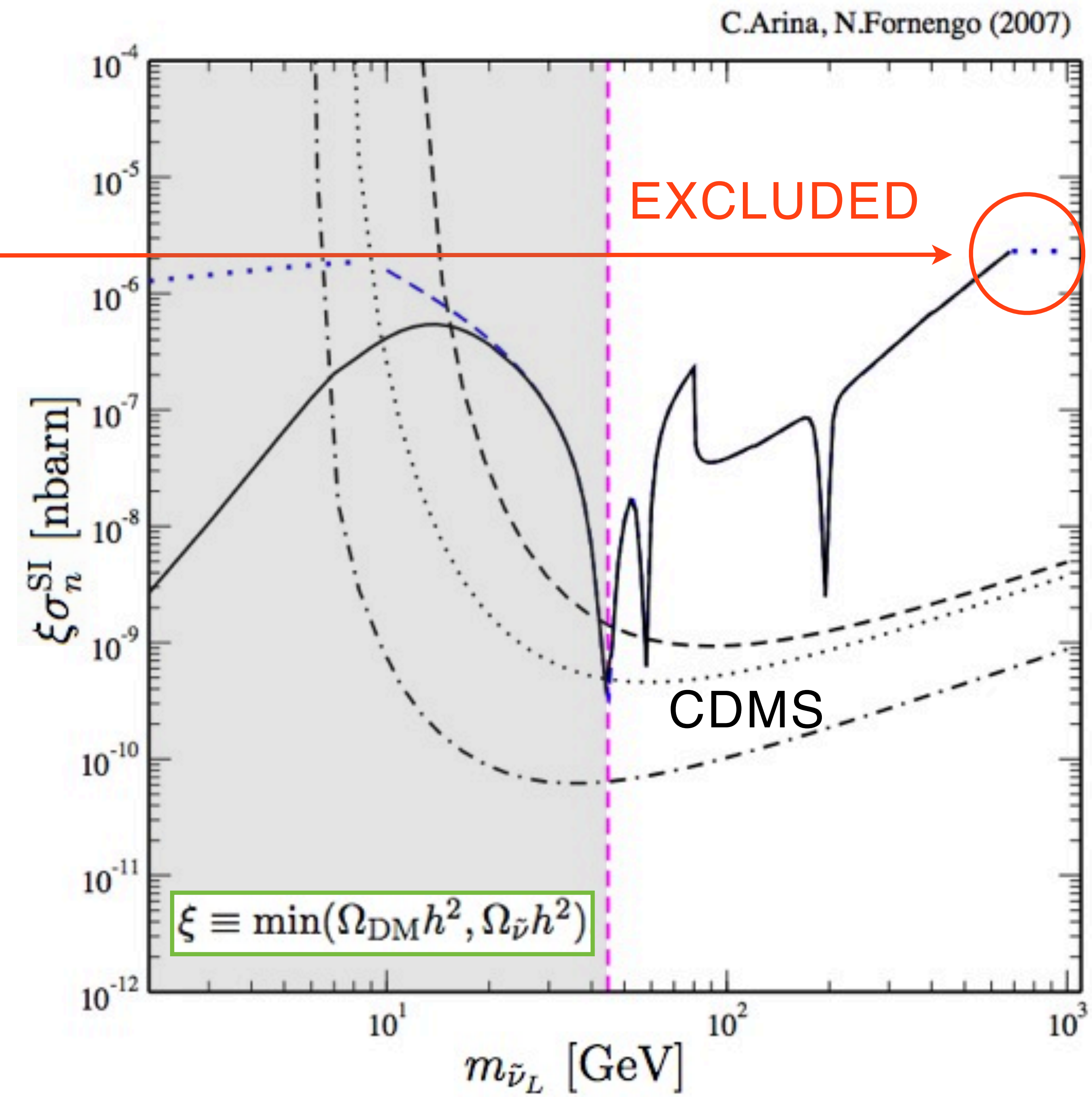


Neutralino: viable DM candidate in (non)-constrained MSSM scenarios (bino, wino, higgsino, well-tempered, ...) or extensions of the MSSM

Sneutrino: $SU(2)_L$ doublet (Y=1 ⟶ couples to the Z boson) proposed by Ibanez 1984, Falk et al 1994

Sneutrino DM in the MSSM?





What happens if we extend the MSSM to include neutrino masses?

MSSM + inverse seesaw

J.Valle, PRL 2008

W_{inv} :

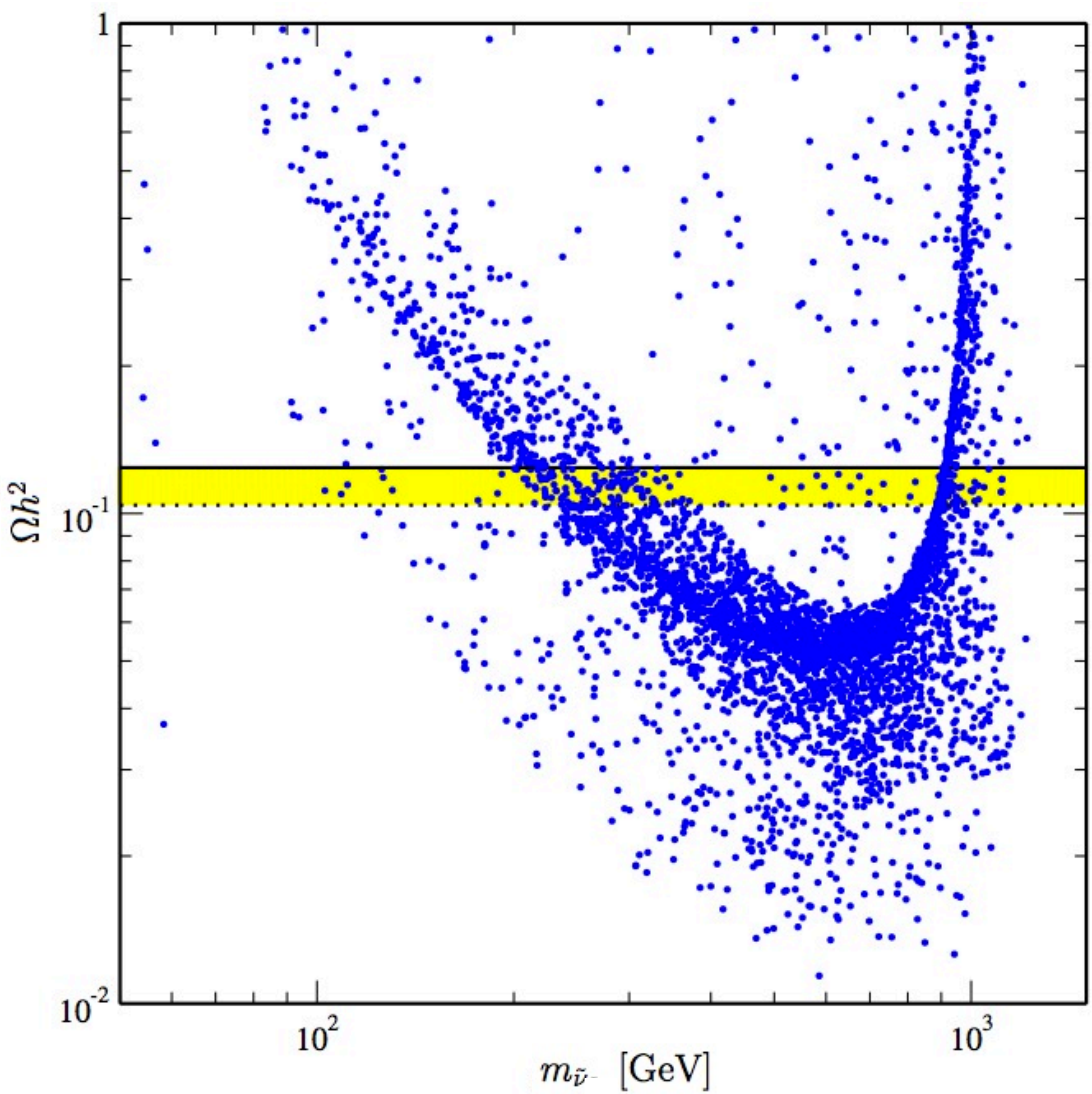
V_{soft} : $_{\nu} H_i^2 \tilde{L}_j \tilde{N}) + h.c.]$

Neutrino

Inverse

m_D

m_ν



The sma… S sneutrinos
mass is … nasses at the
of μ_S 0(k

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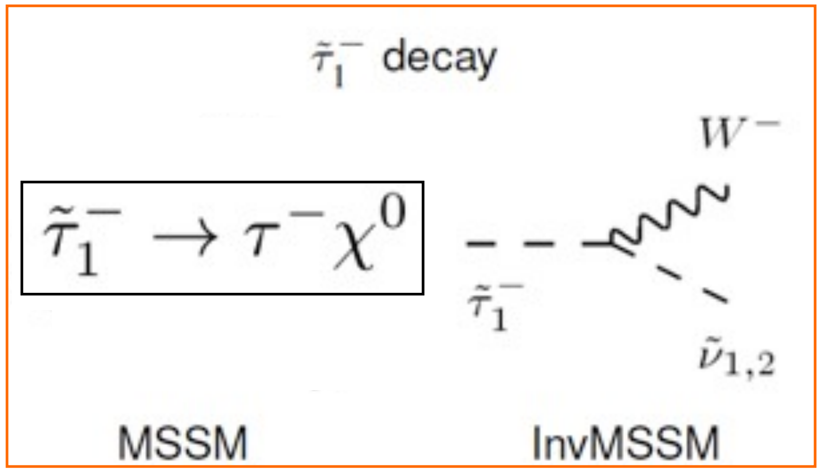
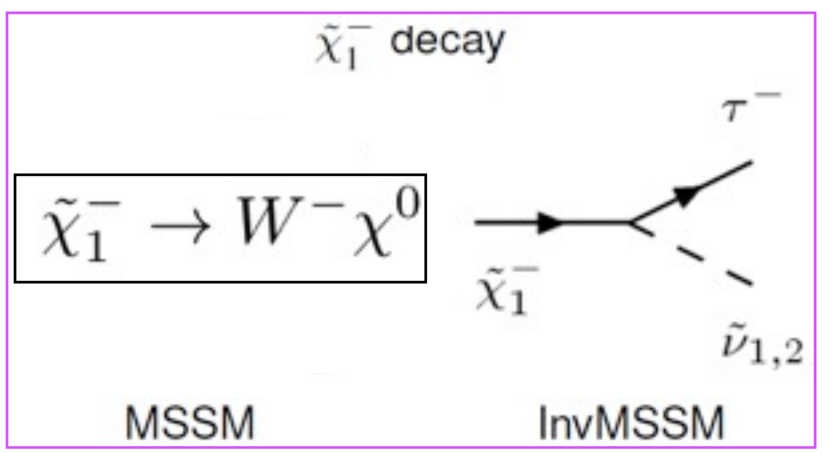
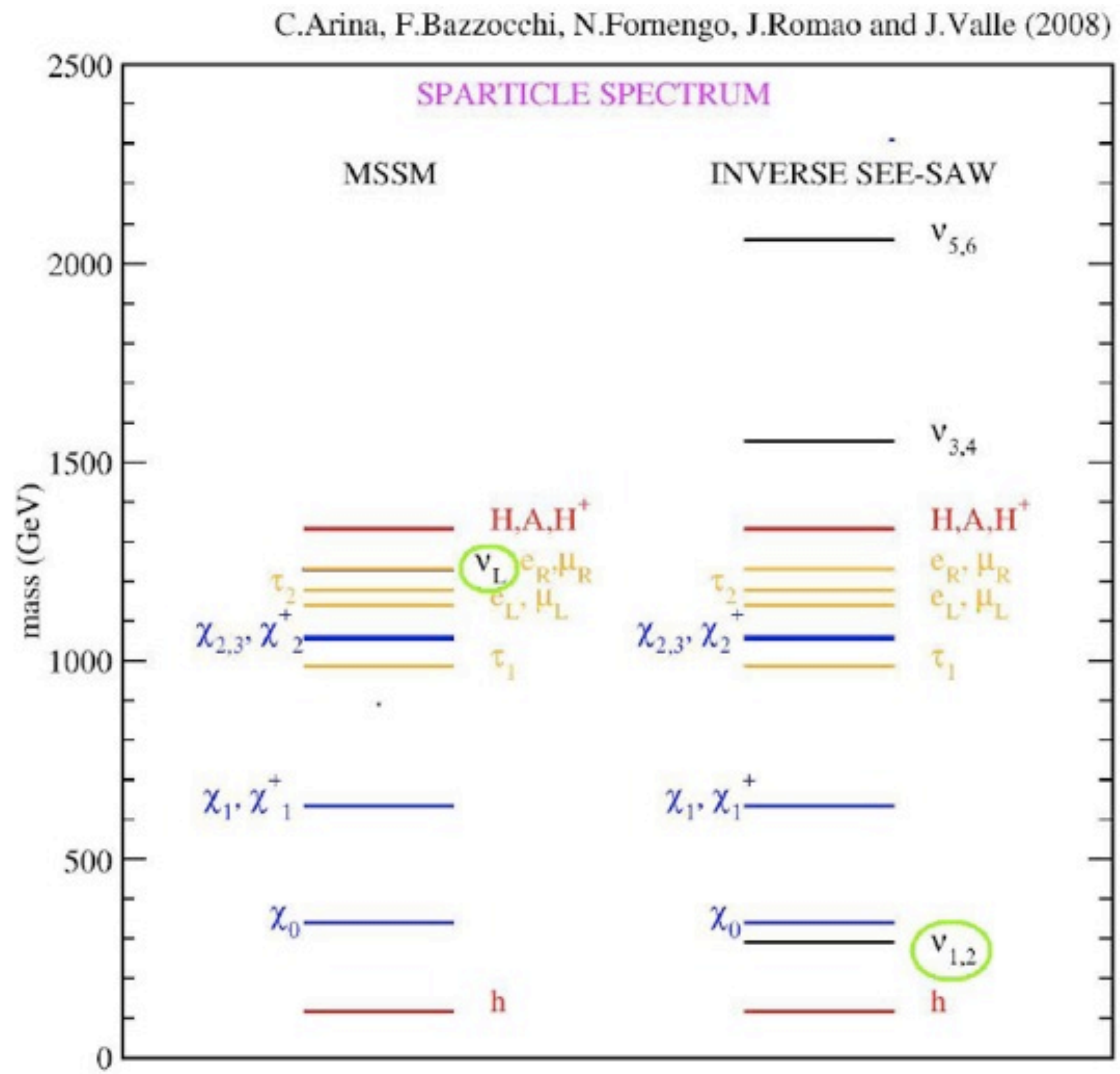
off nucleus

SUSY mass spectrum with sneutrino LSP







Sneutrino LSP: Topologies @ LHC are different from MSSM !

Relation between the dark sector and the neutrino sector

- Several mechanisms to give mass to neutrinos:
    - Dirac masses (G. Belanger et al 2010, B. Dumont et al 2012, CA and M.E. Cabrera 2014, CA et al 2015, ...)
    - Seesaw type I, II, III (high scale) (H. Haber et al 1997, N. Arkani-Hamed et al 2000, D. Hooper et al 2005, CA and N. Fornengo 2007, ...)
    - Inverse seesaw, linear seesaw (low scale) (CA et al 2008, H. An et al 2012, V. De Romeri and M. Hirsch 2012, S. Banerjee et all 2013, ...)
- Modification of the MSSM scalar sector as well
- Mixed sneutrino is again a viable DM candidate
- Sneutrino as DM addresses two issues at once

Current status of sneutrino DM with Dirac neutrino masses

1. This is the simplest sneutrino DM model that one can design

2. It captures the main LHC features due to the change in nature of the LSP

3. DM phenomenology might be different but again main features are captured (direct detection and indirect signatures)

4. The set up of the model (micromegas, softsusy, madgraph, calchep, ...) is quite technical: easier to validate with the simplest model

MSSM + Right-handed Neutrinos (MSSM+RN)

$$W = \epsilon_{ij}(\mu \hat{H}_i^u \hat{H}_j^d - Y_l \hat{H}_i^d \hat{L}_j \hat{R} + Y_\nu \hat{H}_i^u \hat{L}_j \hat{N})$$

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

Dirac masses for neutrinos: $m_D = v_u Y_\nu$

LSP

Sneutrino left and right components mix:

$$\begin{cases} \tilde{\nu}_{\tau_1} = -\sin\theta_{\tilde{\nu}}\ \tilde{\nu}_L + \cos\theta_{\tilde{\nu}}\ \tilde{N} \\ \tilde{\nu}_{\tau_2} = +\cos\theta_{\tilde{\nu}}\ \tilde{\nu}_L + \sin\theta_{\tilde{\nu}}\ \tilde{N} \end{cases}$$

$$\mathcal{M}_{LR}^2 = \begin{pmatrix} m_L^2 + \frac{1}{2} m_Z^2 \cos(2\beta) + m_D^2 & \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin\beta - \mu m_D \text{cotg}\beta \\ \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin\beta - \mu m_D \text{cotg}\beta & m_N^2 + m_D^2 \end{pmatrix}$$

MSSM+RN model parameters

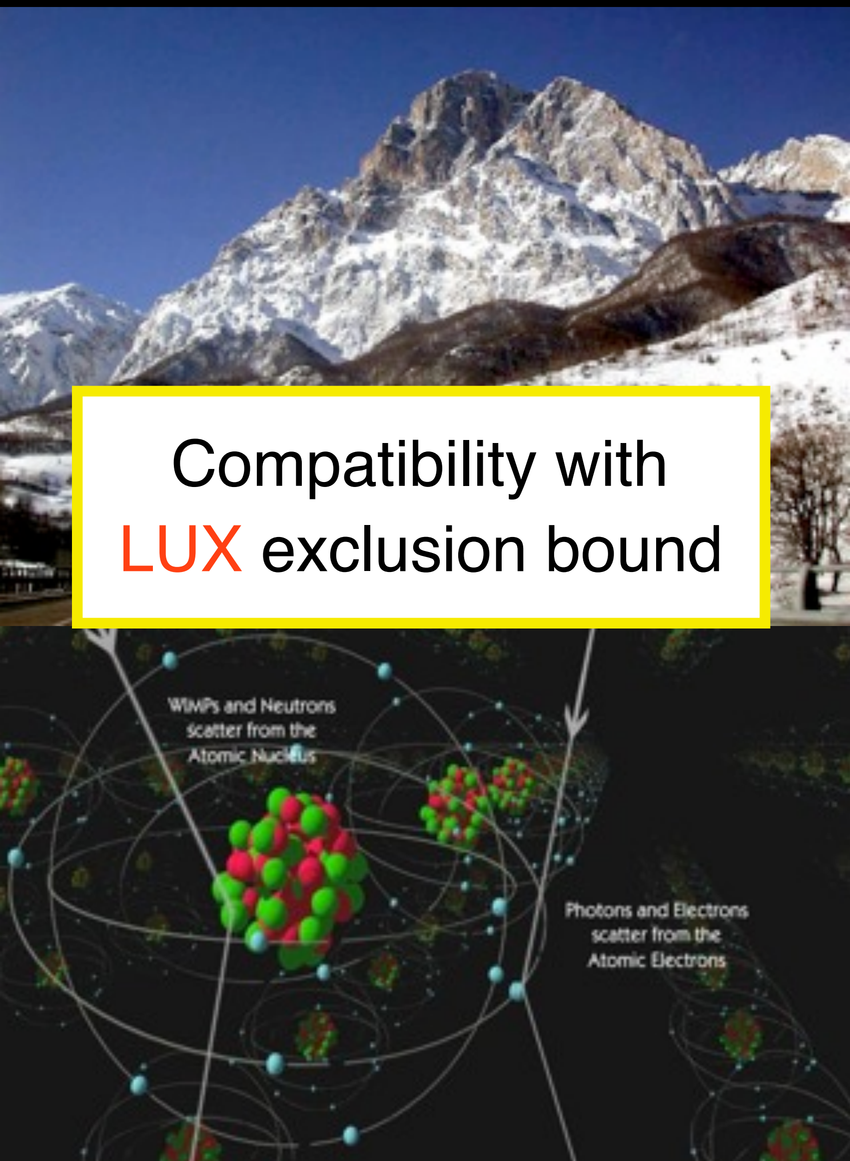
$$M_1, M_2, M_3, m_L, m_R, m_N, m_Q, m_H, A_l, A_{\tilde{\nu}}, A_q, \tan\beta, \text{sgn}\mu$$

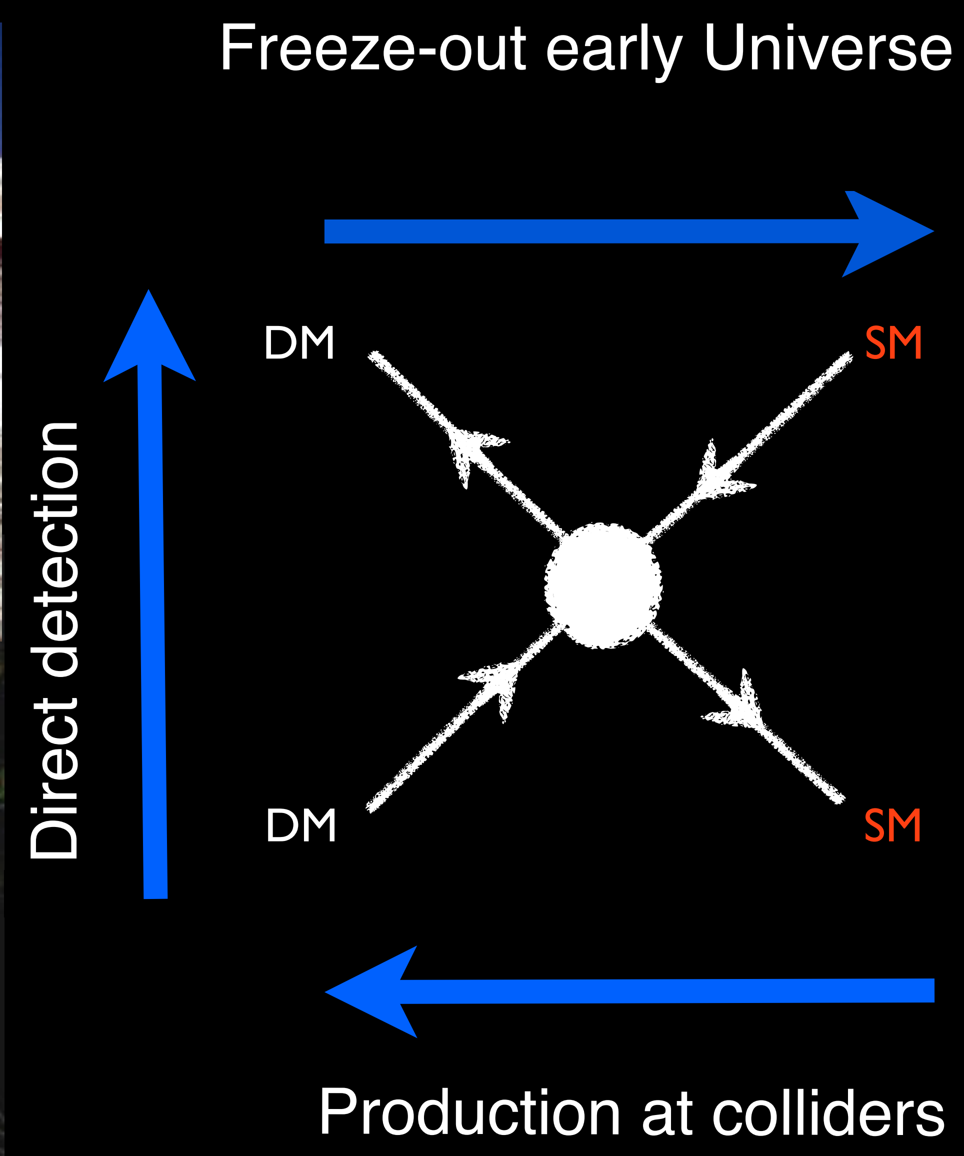
Nested sampling (several chains) with both log and flat priors on the free parameters

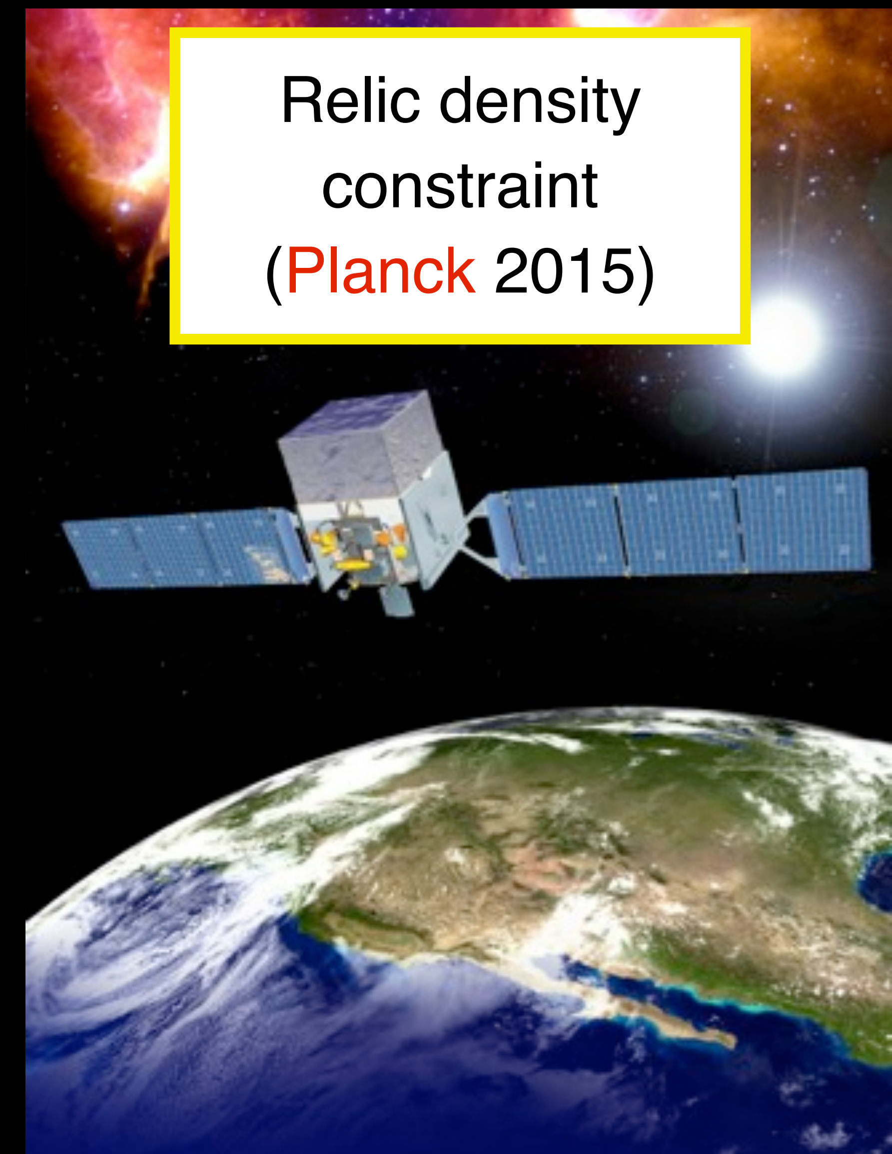
	Observable	Value/Constraint
Measurements (Gaussian likelihood function)	m_h	125.85 ± 0.4 GeV (exp) ± 4 GeV (theo)
	$\text{BR}(B \to X_s\gamma) \times 10^4$	$3.55 \pm 0.24 \pm 0.09$ (exp)
	$\text{BR}(B_s \to \mu^+\mu^-) \times 10^9$	$3.2^{+1.4}_{-1.2}$ (stat) $^{+0.5}_{-0.3}$ (sys)
Limits (Step likelihood function)	$\Delta\Gamma_Z^{\text{invisible}}$	< 2 MeV (95% CL)
	$\text{BR}(h \to \text{invisible})$	$< 20\%$ (95% CL)
	$m_{\tilde{\tau}_1^-}$	> 85 GeV (95% CL)
	$m_{\tilde{\chi}_1^+}, m_{\tilde{e},\tilde{\mu}}$	> 101 GeV (95% CL)
	$m_{\tilde{g}}$	> 308 GeV (95% CL)

+ DM constraints

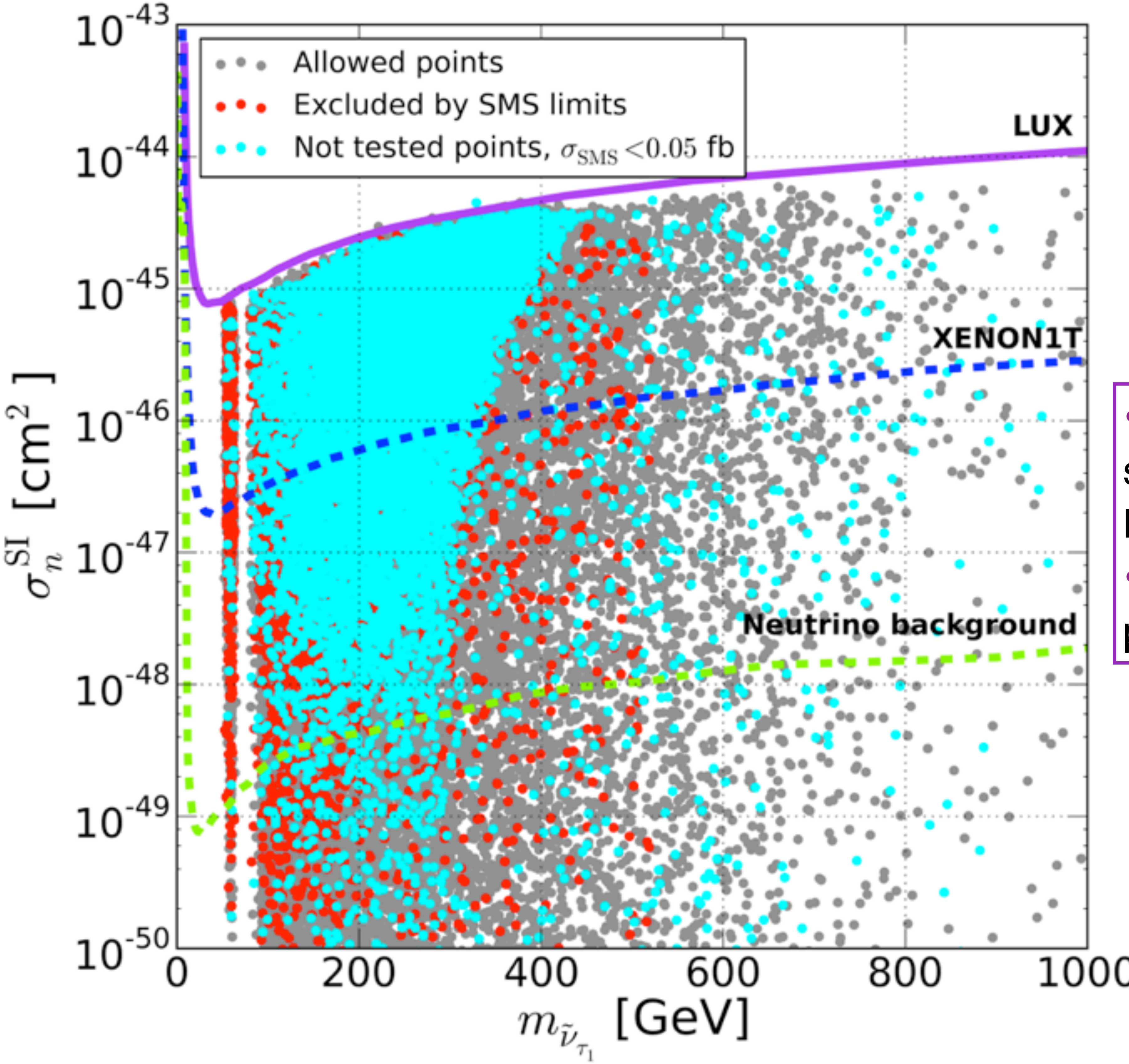
DM constraints for sneutrino in MSSM+RN







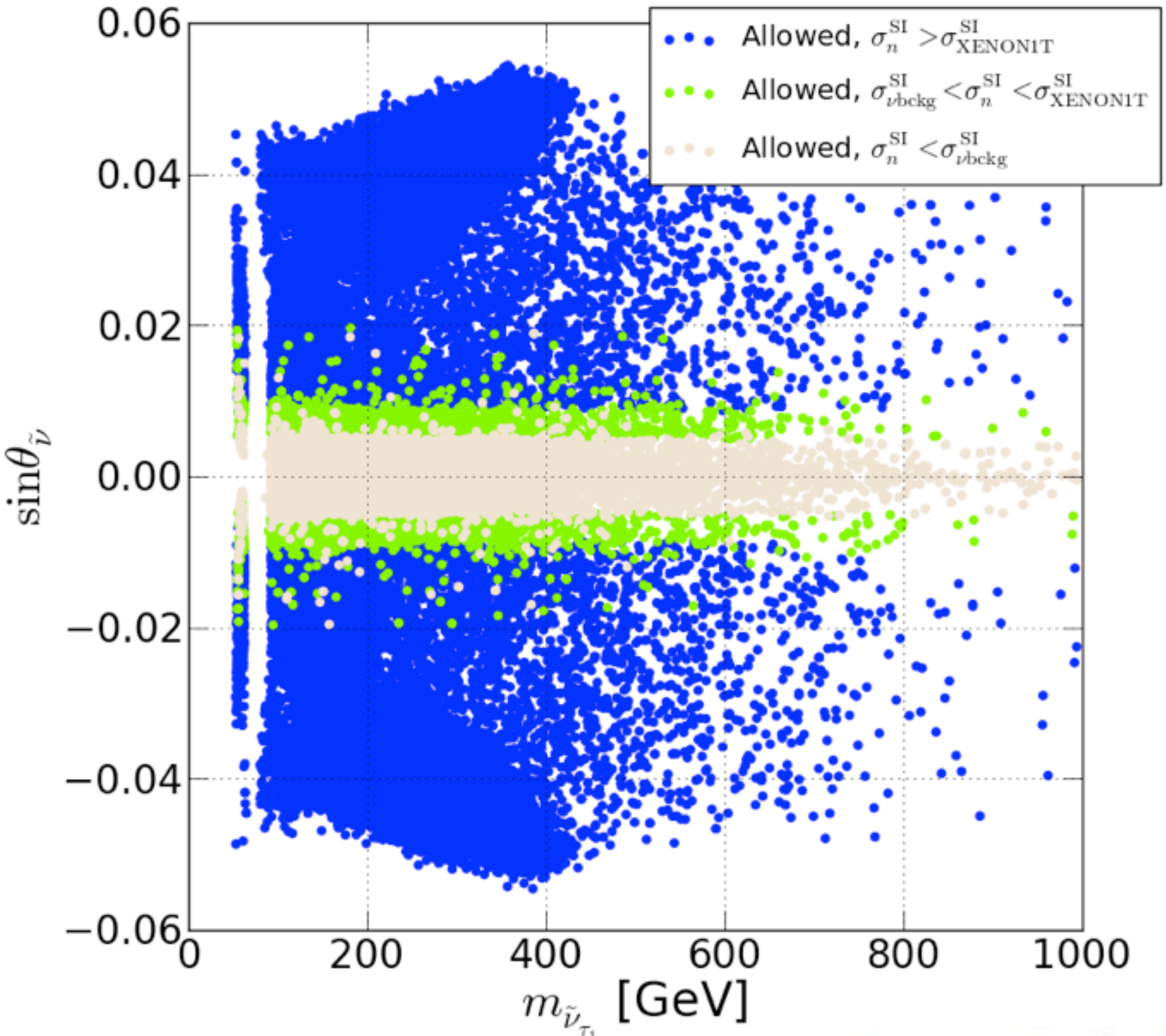
MSSM+RN: viable DM parameter space



All points are OK for SUSY, Higgs, flavour and DM constraints

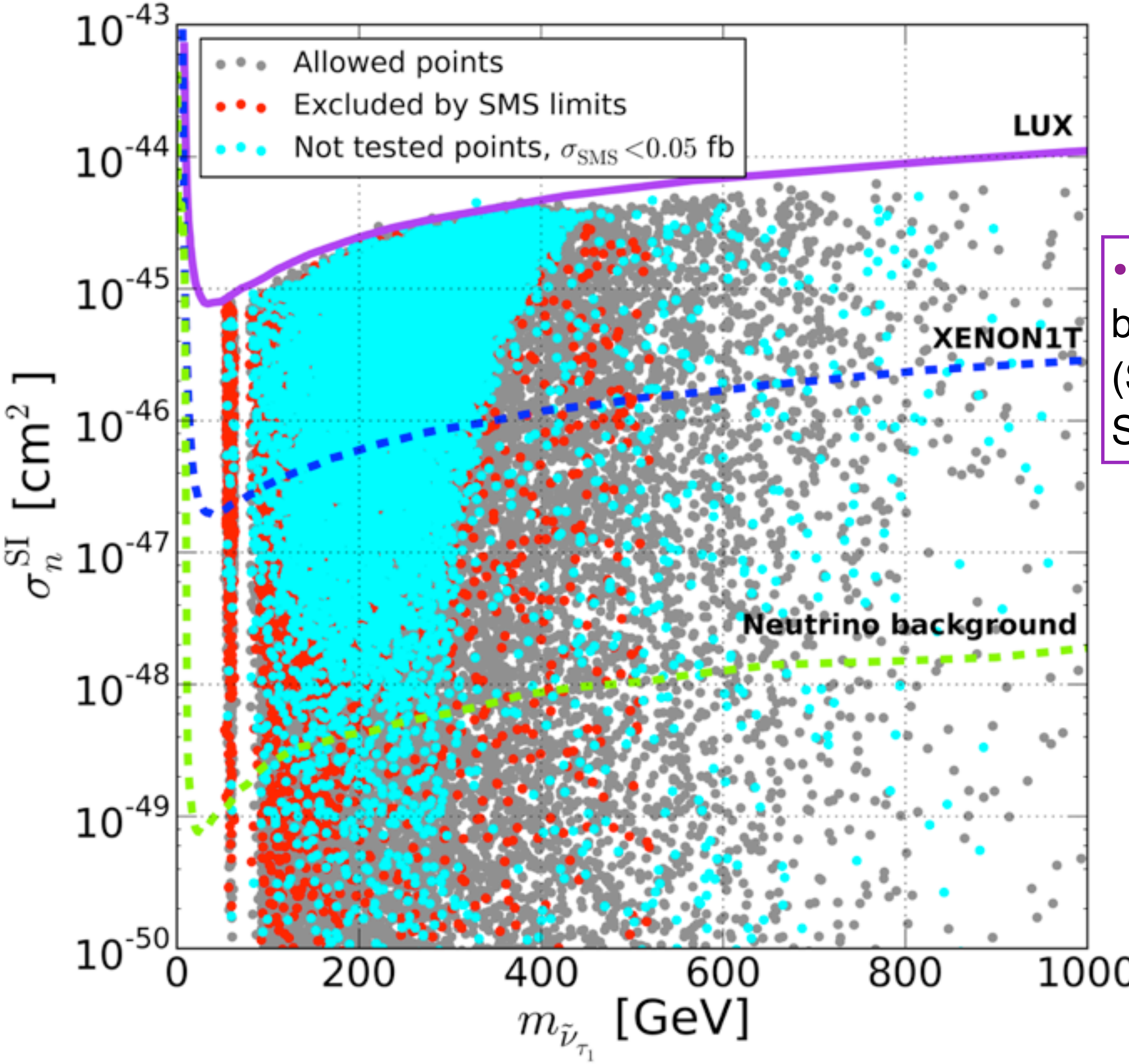
- LUX exclusion bound: strongest constraint for the MSSM+RN
- It dictates how much LH part can survive (Z coupling)

Almost sterile sneutrinos



$$\tilde{\nu}_1 = -\sin\theta_{\tilde{\nu}}\ \tilde{\nu}_L + \cos\theta_{\tilde{\nu}}\ \tilde{N}$$

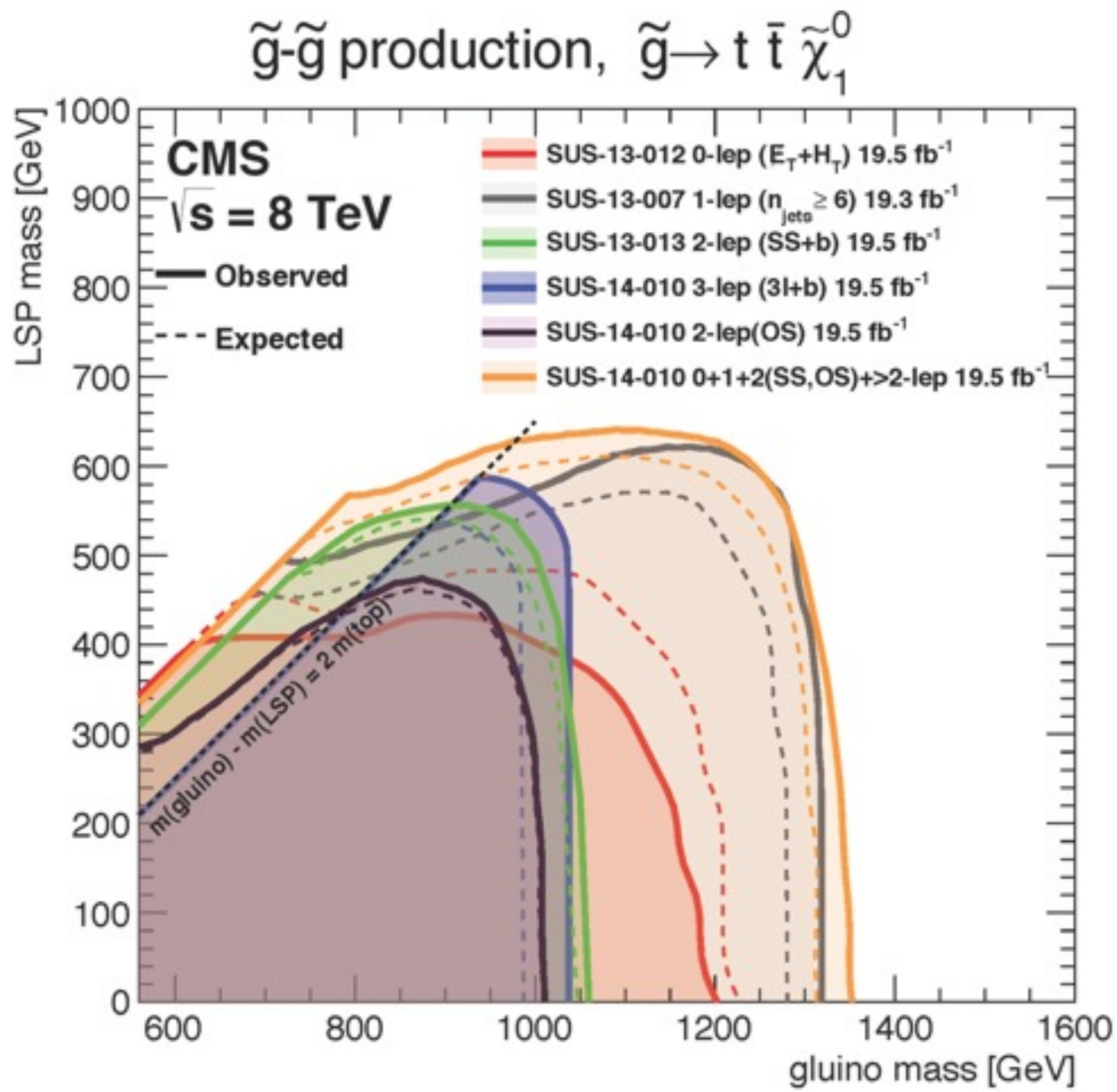
MSSM+RN: viable DM parameter space



- COMPLEMENTARITY between LHC searches (Simplified Model Spectra, SMS) and Direct Detection

Testing the model with LHC constraints

1. To test against large number of results we use the Simplified Model Spectra (SMS) interpretation of LHC searches

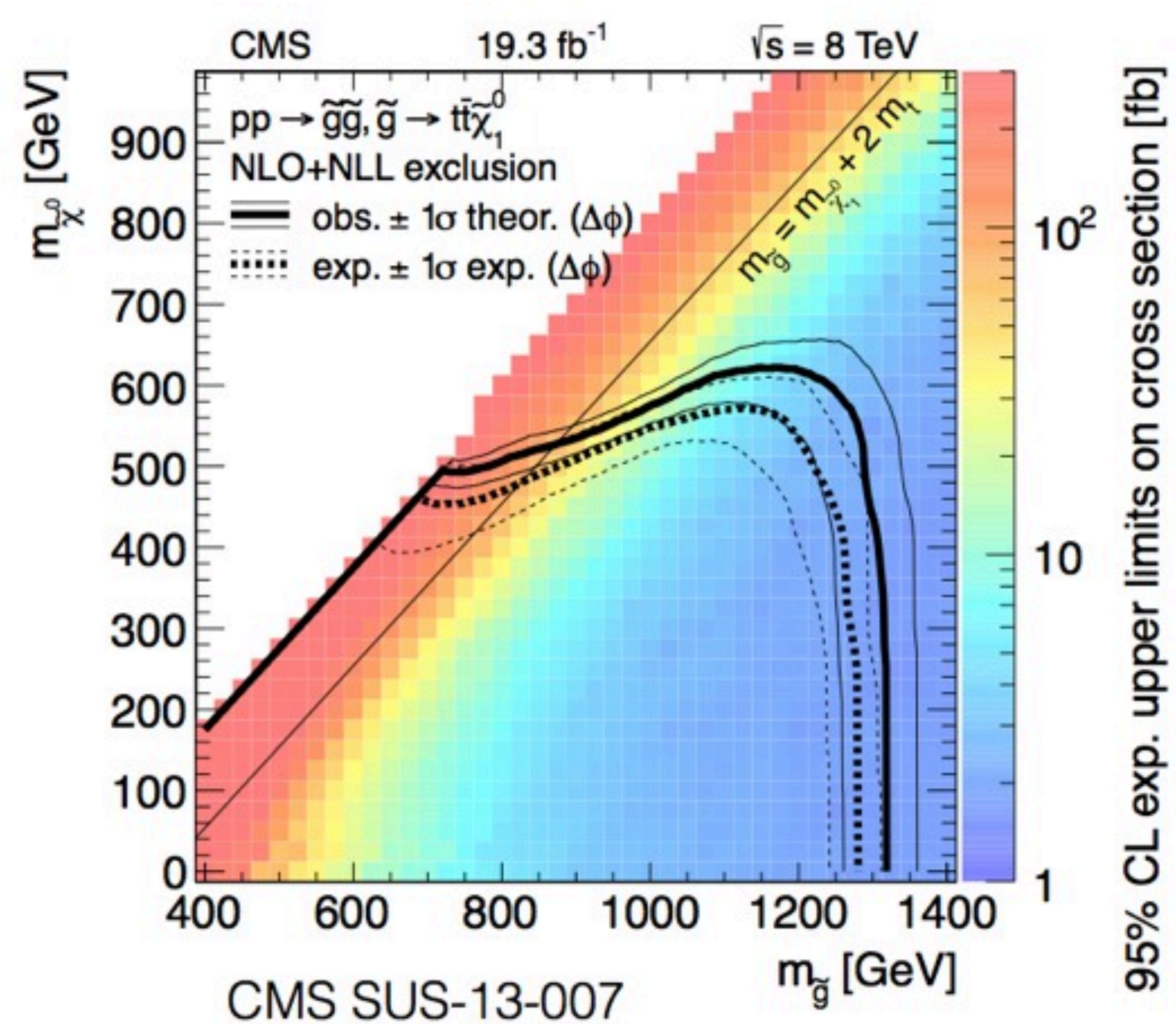


SMS are an effective Lagrangian description, containing only a few particles, 100% BR

The masses of the new particles are the free parameters of the Simplified Model

Testing the model with LHC constraints

2. Decompose realistic model into SMS components which can be tested against limits presented by ATLAS and CMS



To test realistic models, use upper limits on $\sigma \times \mathcal{BR}$

Main assumption: upper limits on $\sigma \times \mathcal{BR}$ depend mainly on the masses of the new particles

Testing the model with LHC constraints

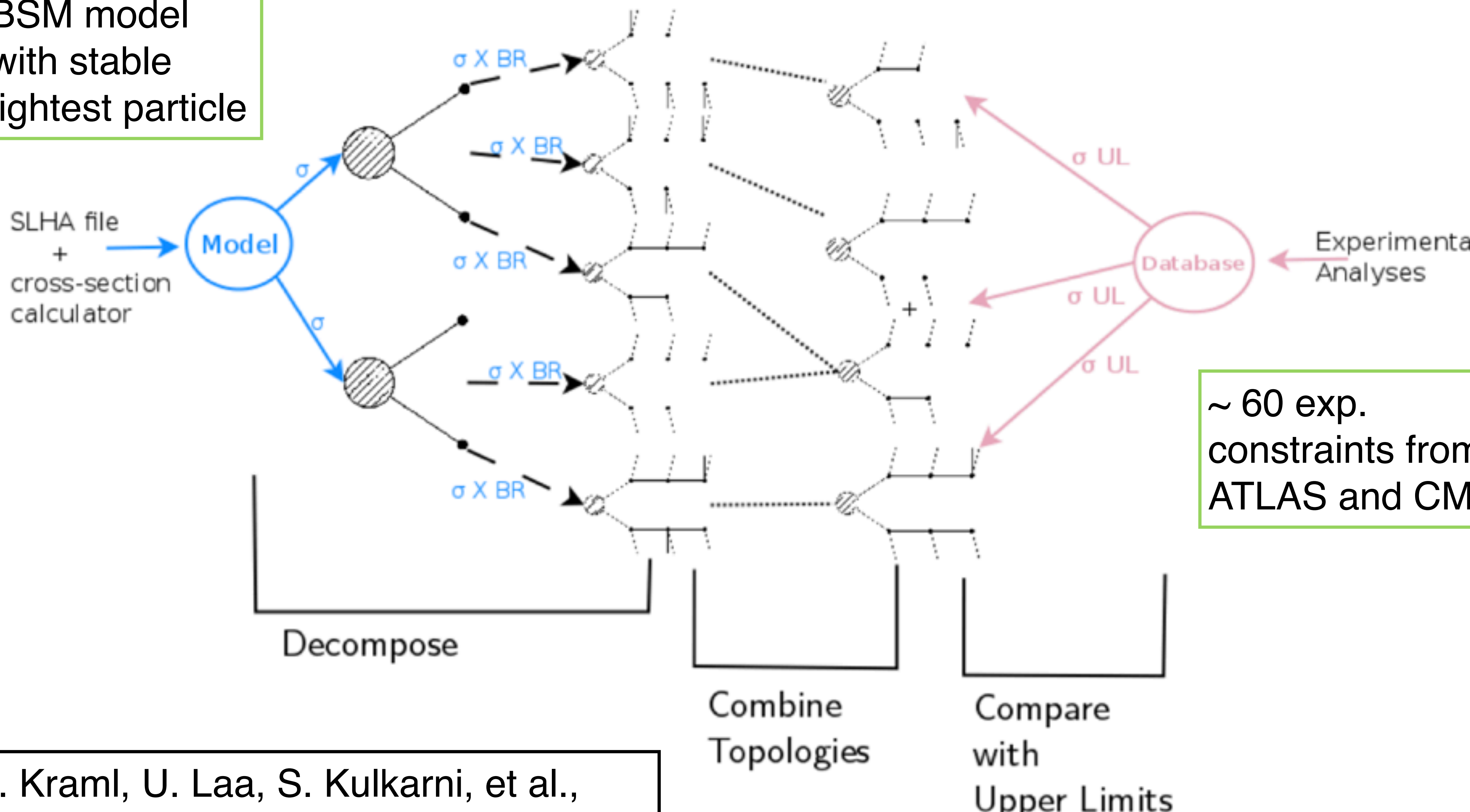
1. To test against large number of results we use the Simplified Model Spectra (SMS) interpretation of LHC searches

2. Decompose realistic model into SMS components which can be tested against limits presented by ATLAS and CMS

3. Keep track only on the mass of the new particles and neglected other quantum numbers more specific to the model (spin function, production mechanism, ...)

SModelS

BSM model with stable lightest particle

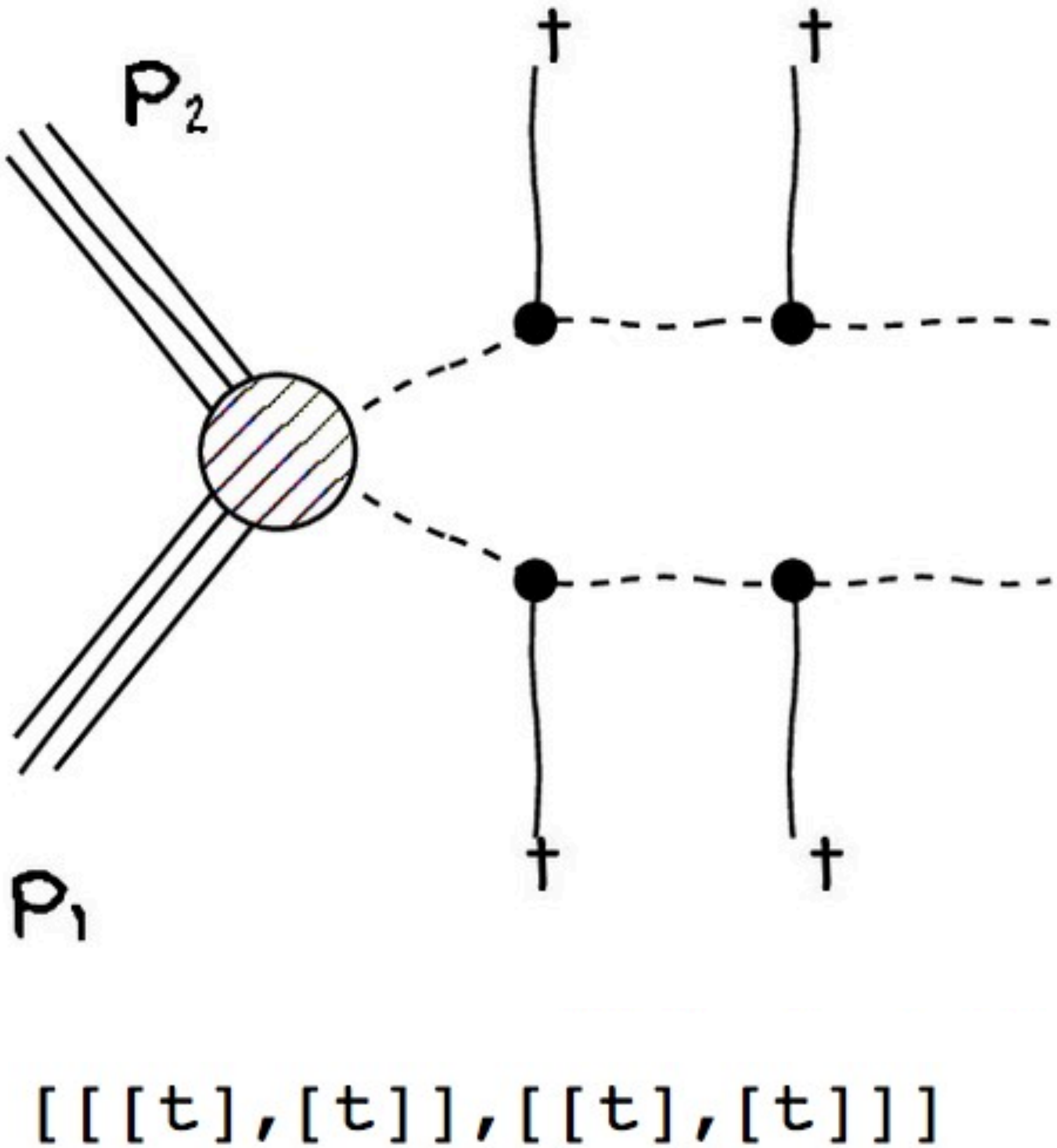


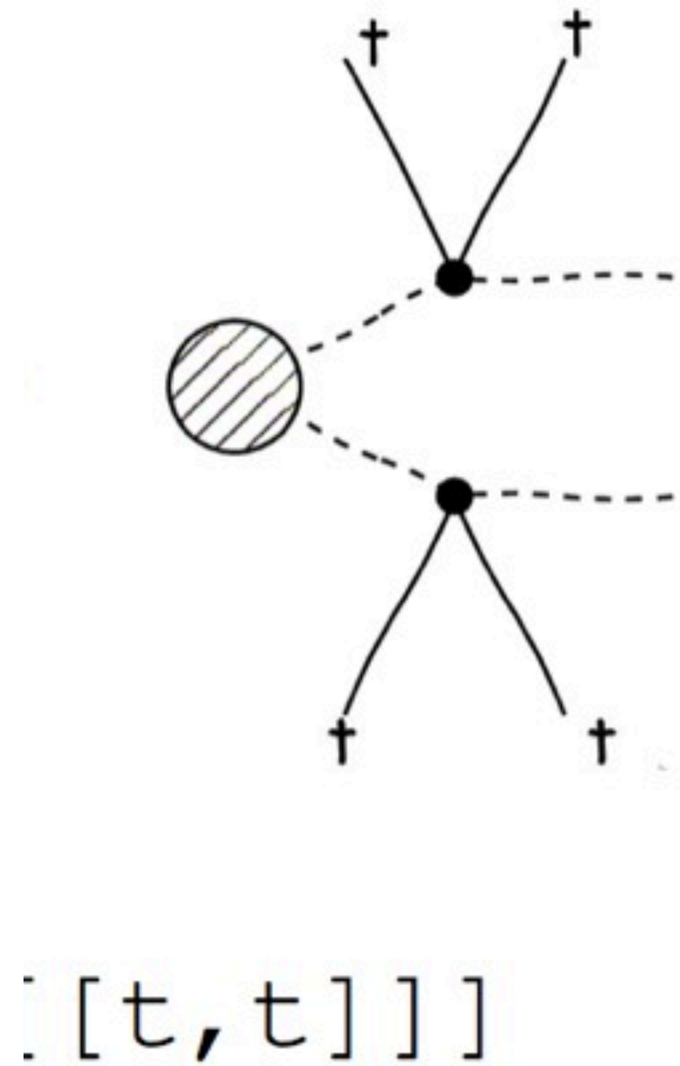
~ 60 exp. constraints from ATLAS and CMS

S. Kraml, U. Laa, S. Kulkarni, et al., arXiv:1312.4175

Definition of topology in SModelS

The topology is described by:
1. vertex structure
2. outgoing SM particles only in each vertex



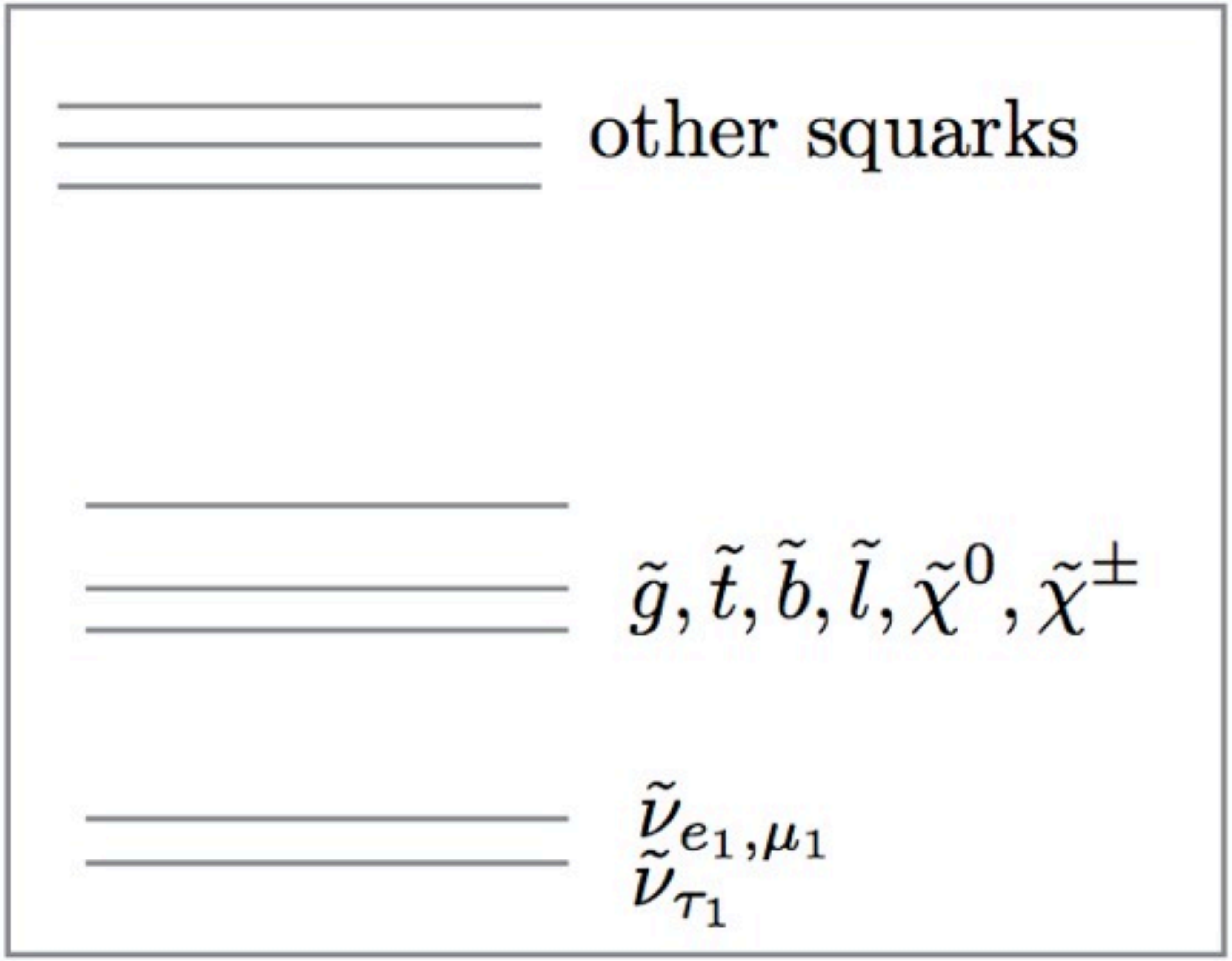


Typical MSSM+RN mass spectra

- We used different samples with either light EWinos, light sleptons or light stops/gluinos to cover most of the possible topologies

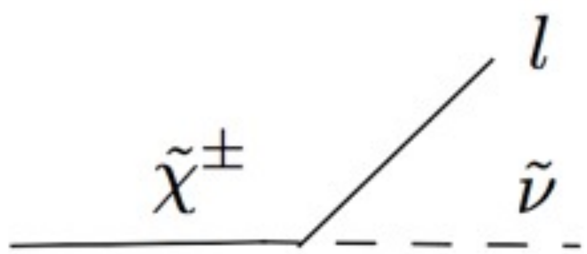
- 1st/2nd squark generations always heavy

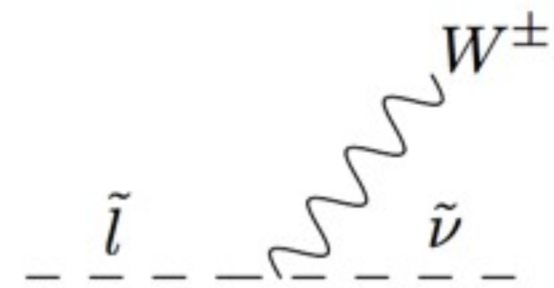
- Sneutrino tau always lighter (due to RGE running) but most of the time small mass gap ~ 5, 10 GeV



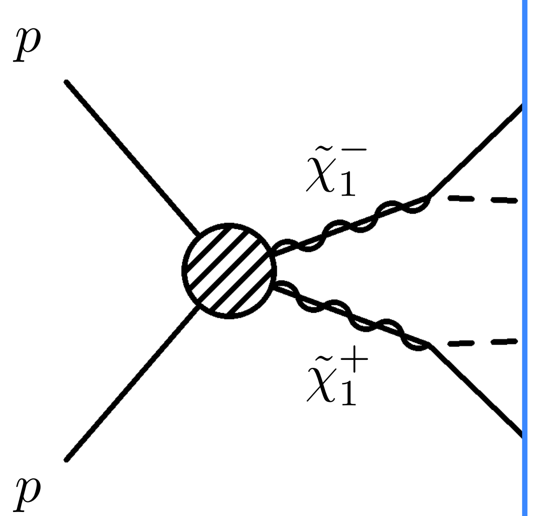
Example of topologies in the MSSM+RN

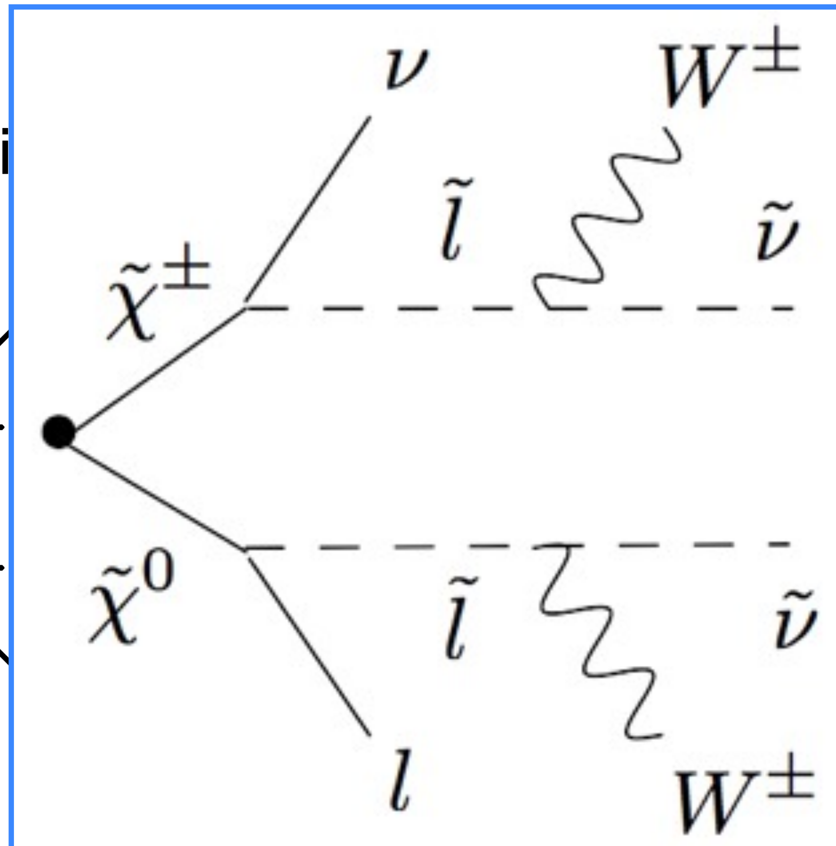
Main decay modes for charginos/sleptons:





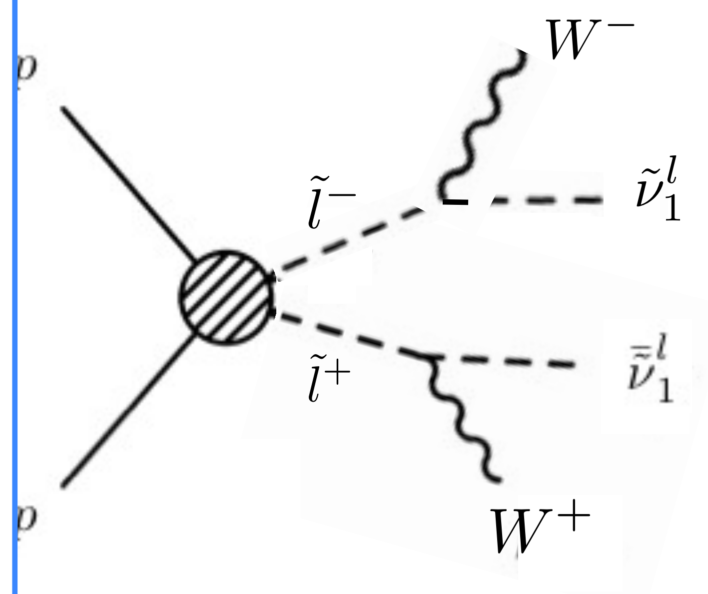
Chargino producti





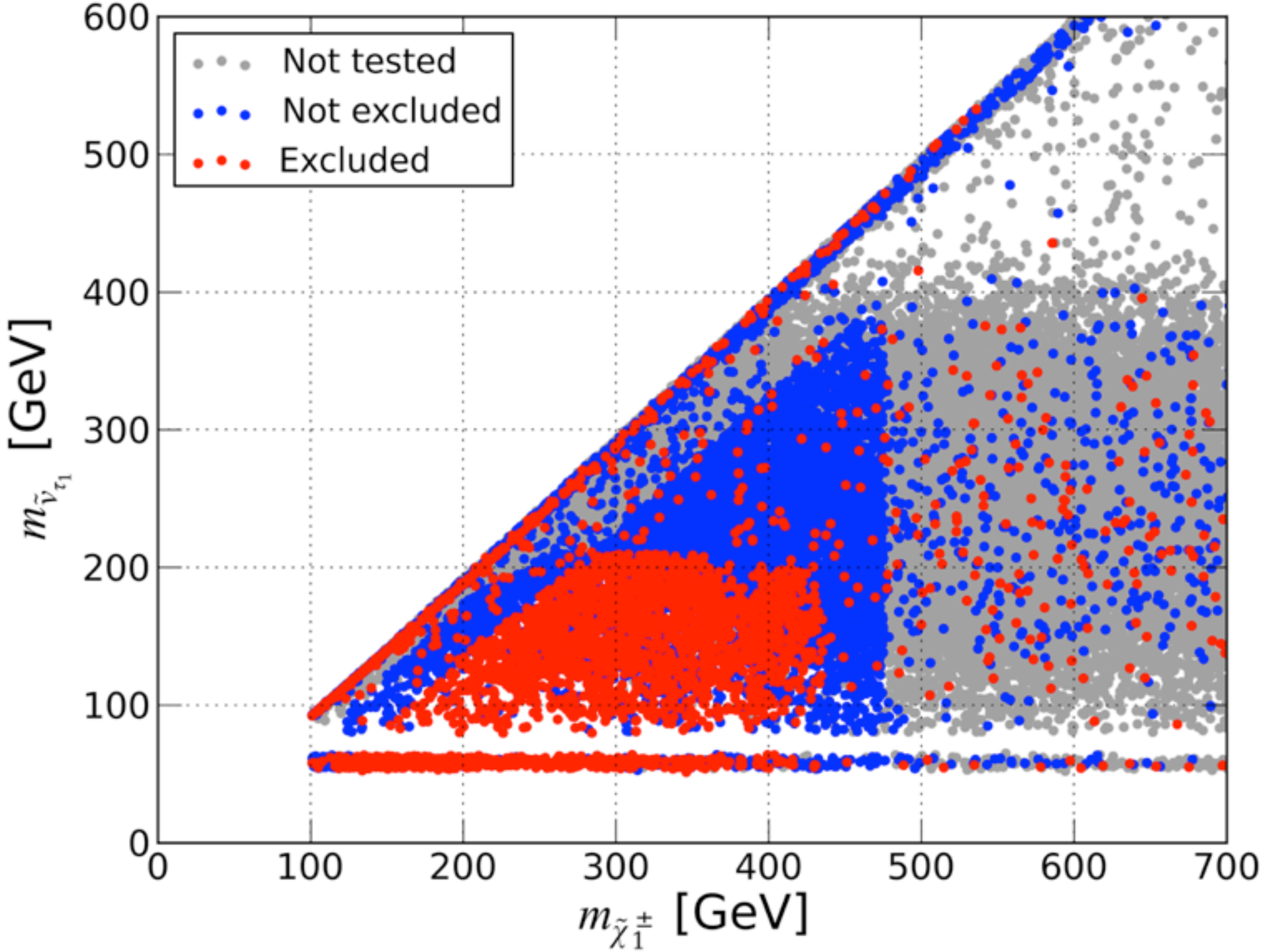
2 same sign Ws

Slepton production

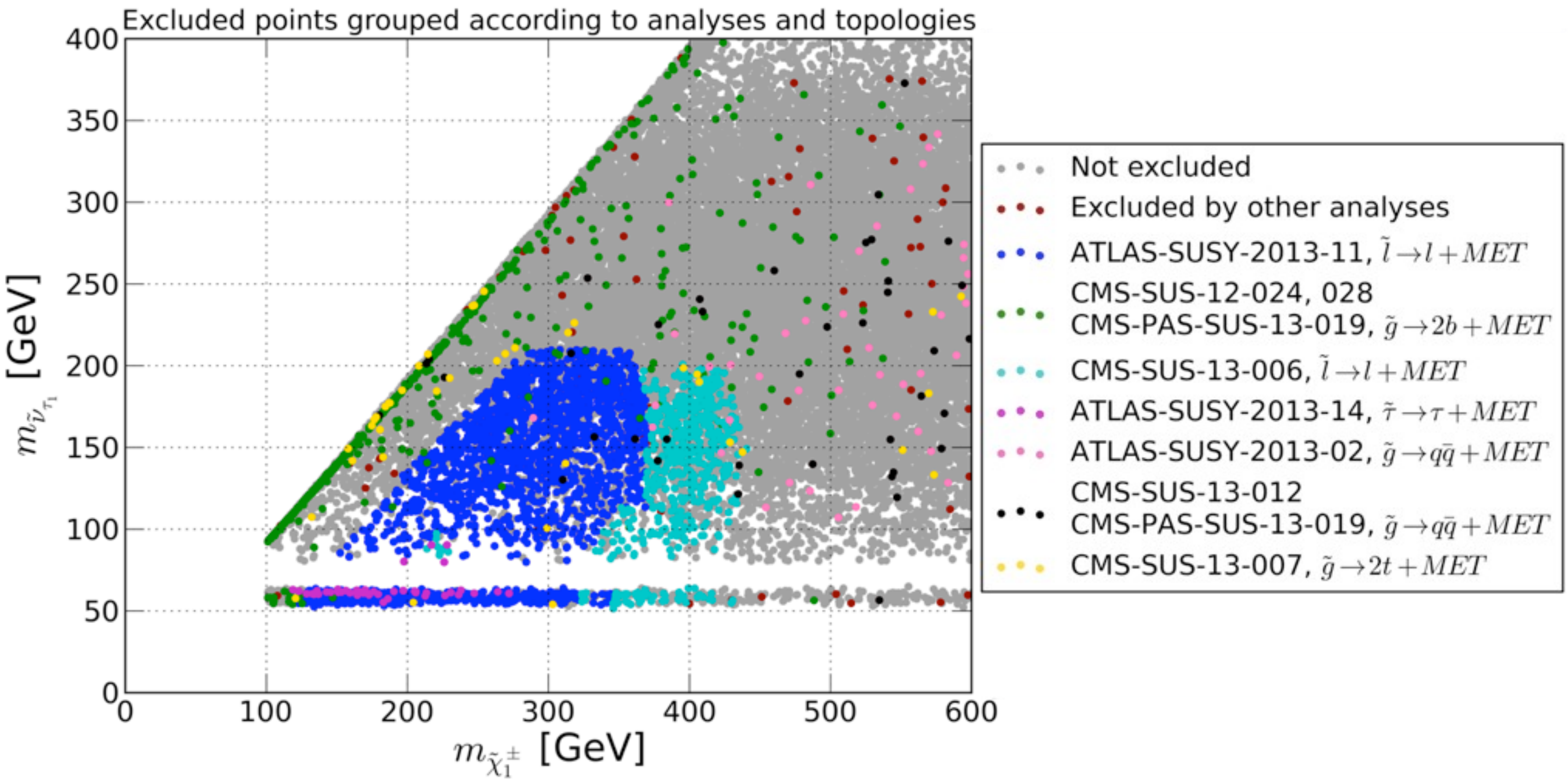


2 leptons of opposite sign and uncorrelated flavor (CA and M.E.Cabrera JHEP 1404 2014)

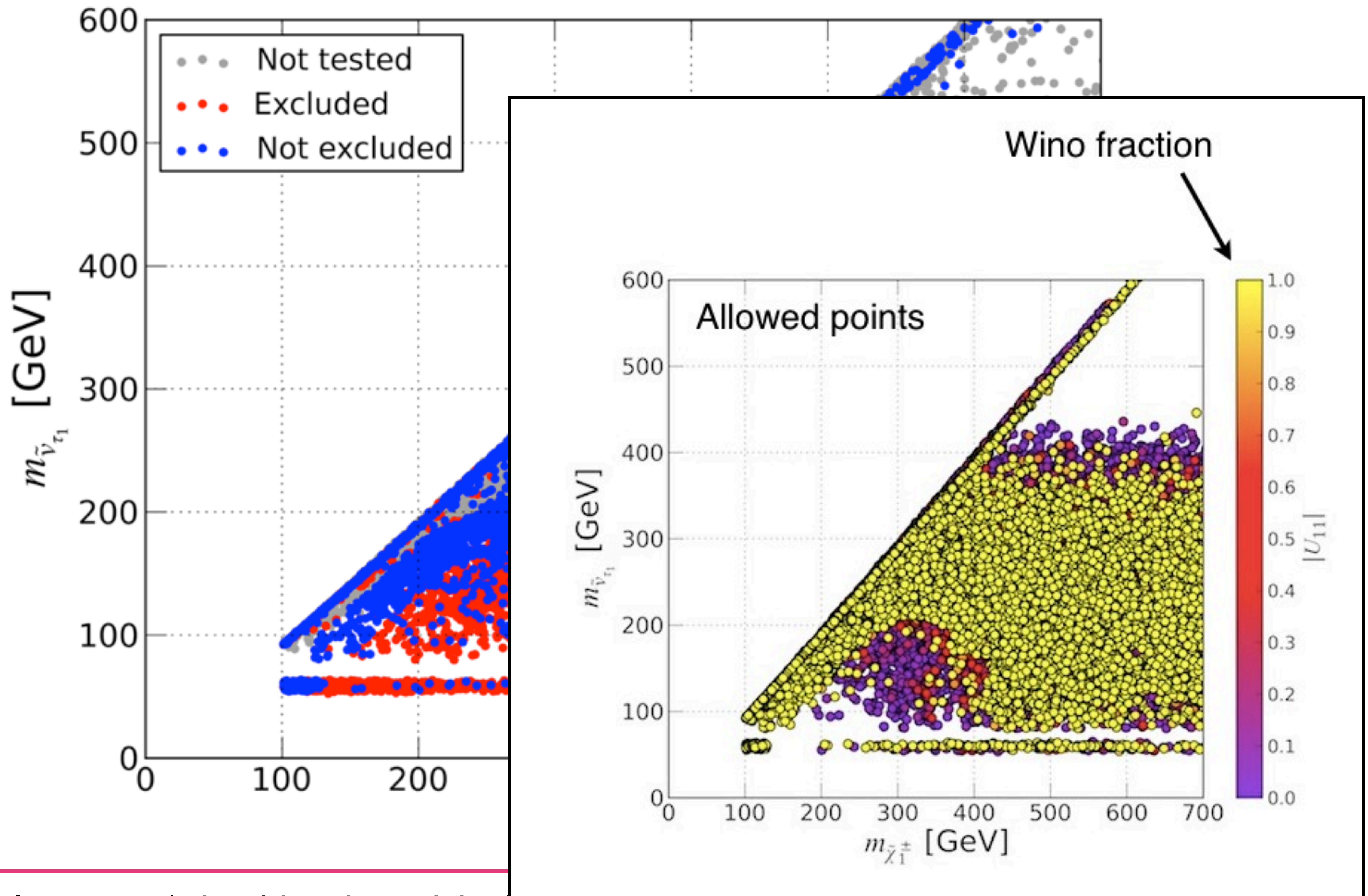
Summary plot of excluded/allowed points



The most constraining analyses

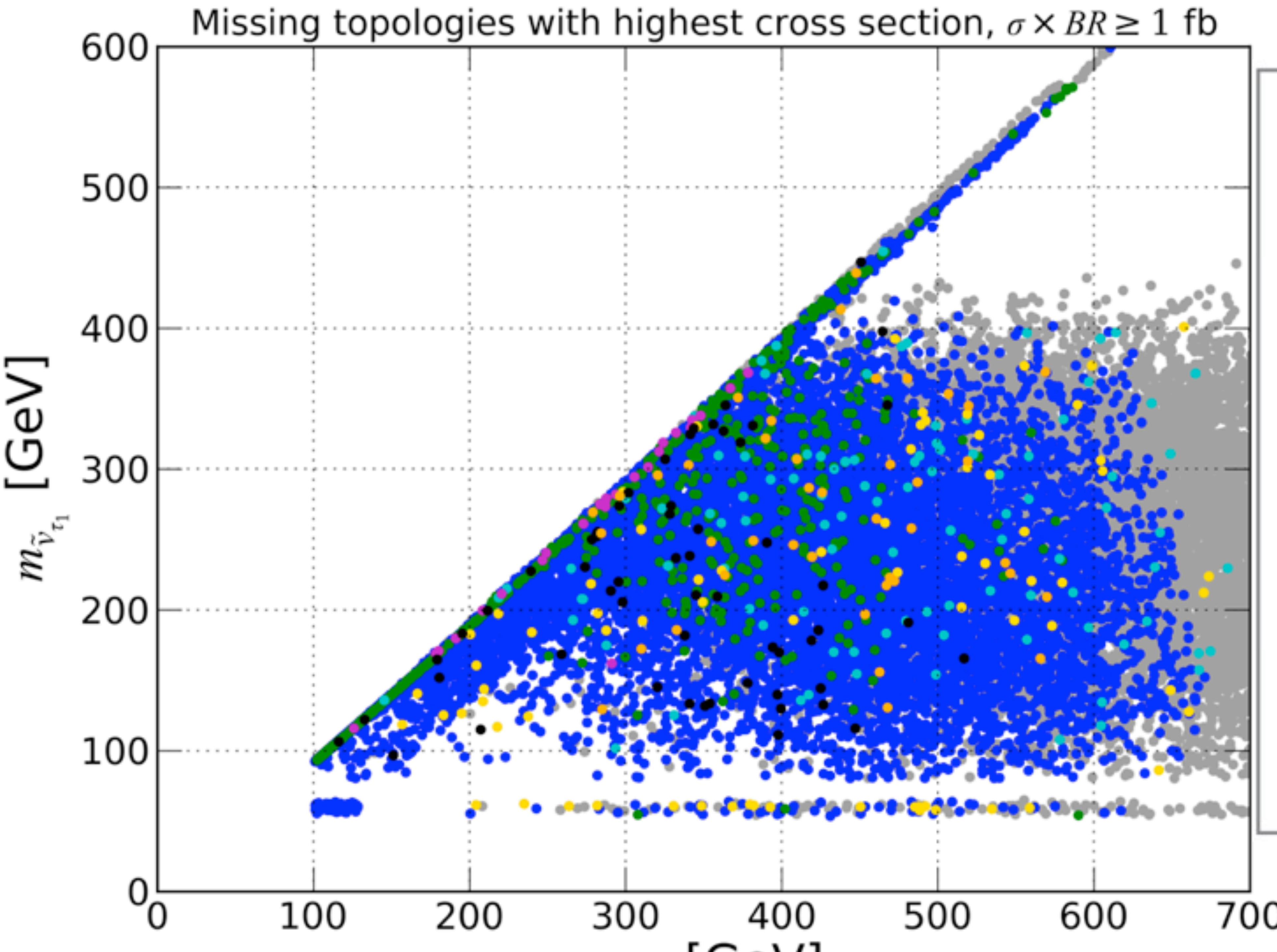


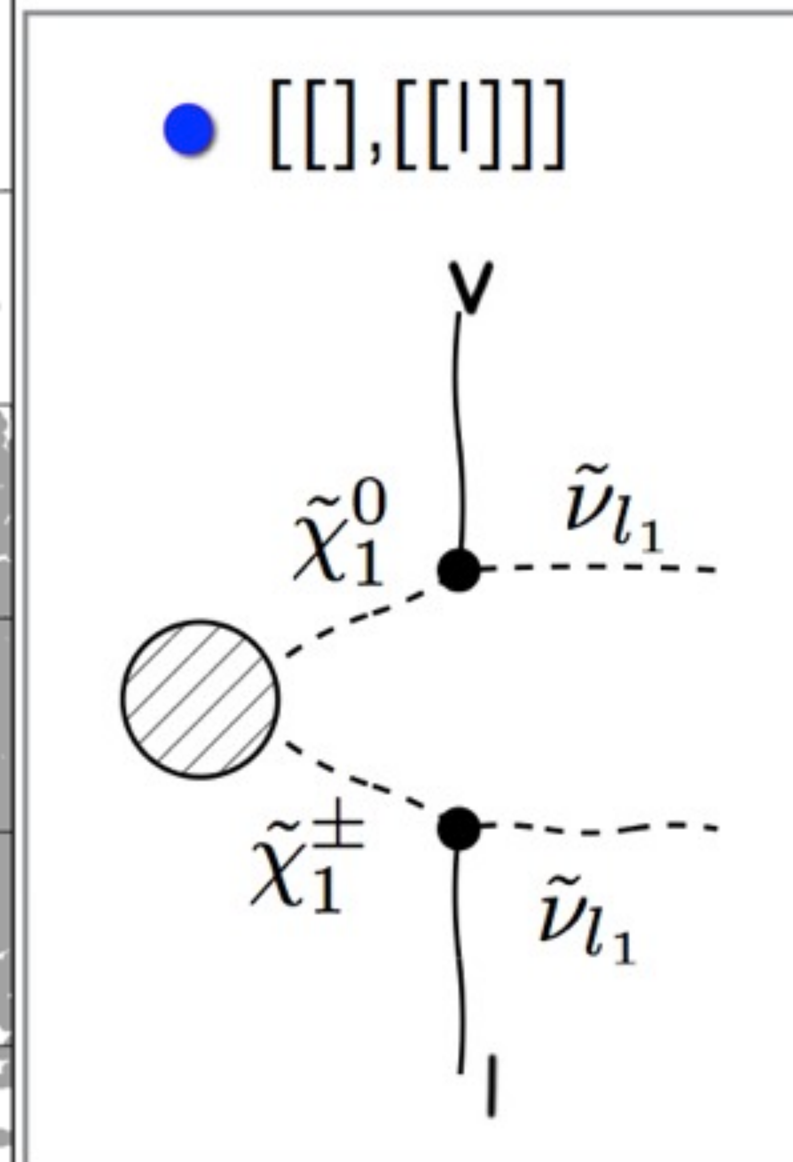
Still many points are allowed



Sparticle nature (wino-higgsino mixing) matters, the production cross-section depends on it

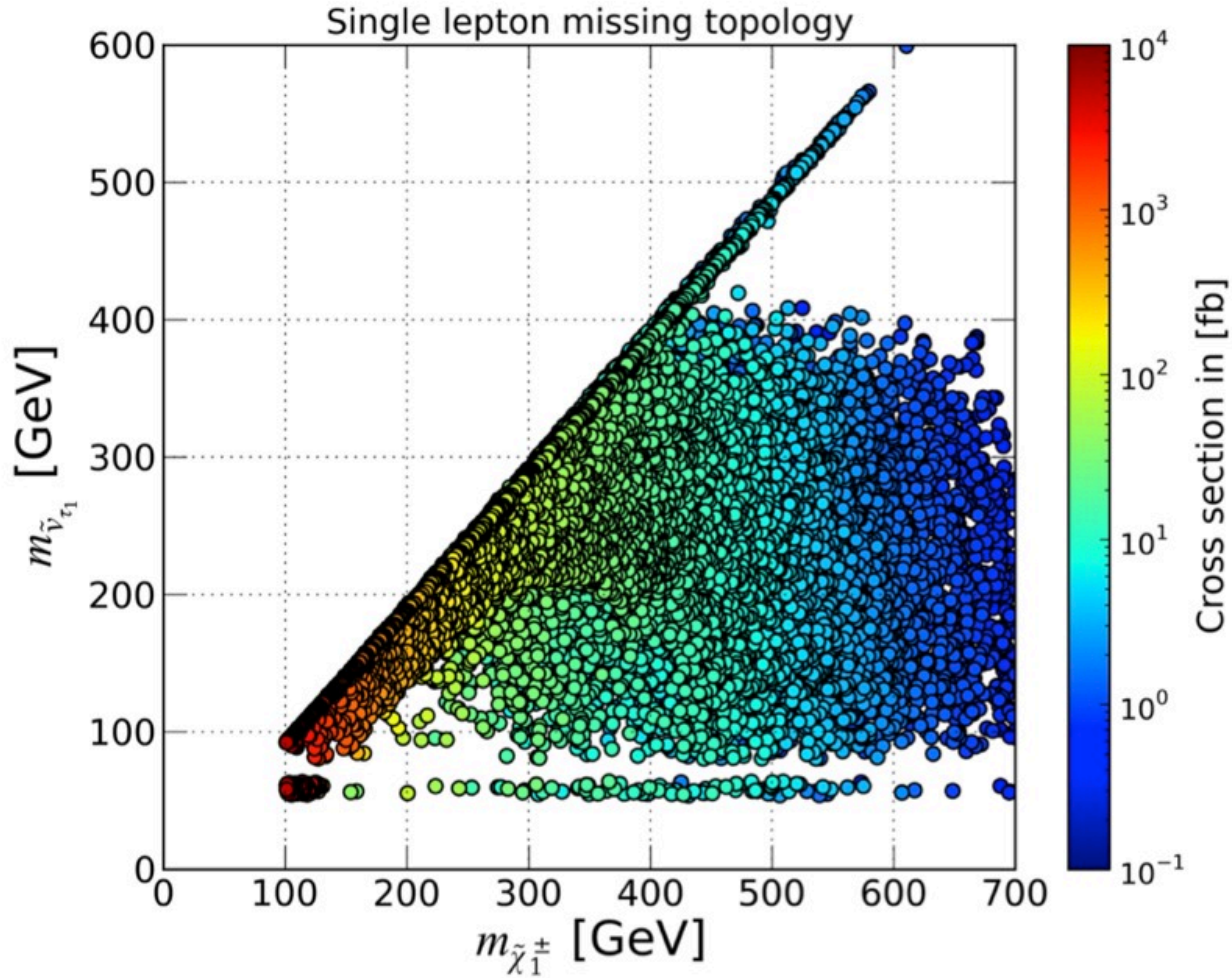
Missing topologies



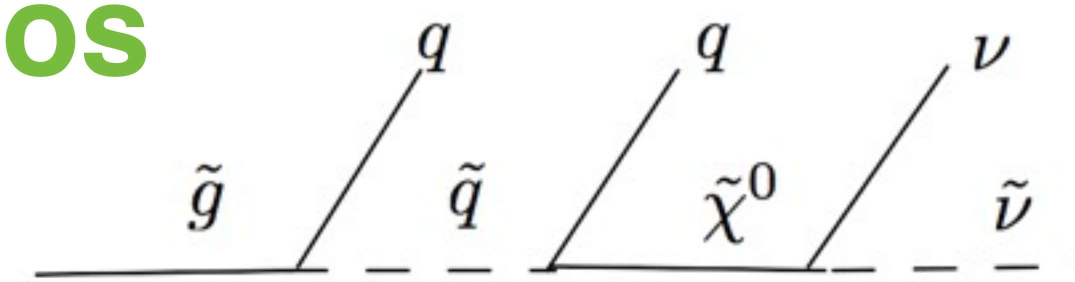


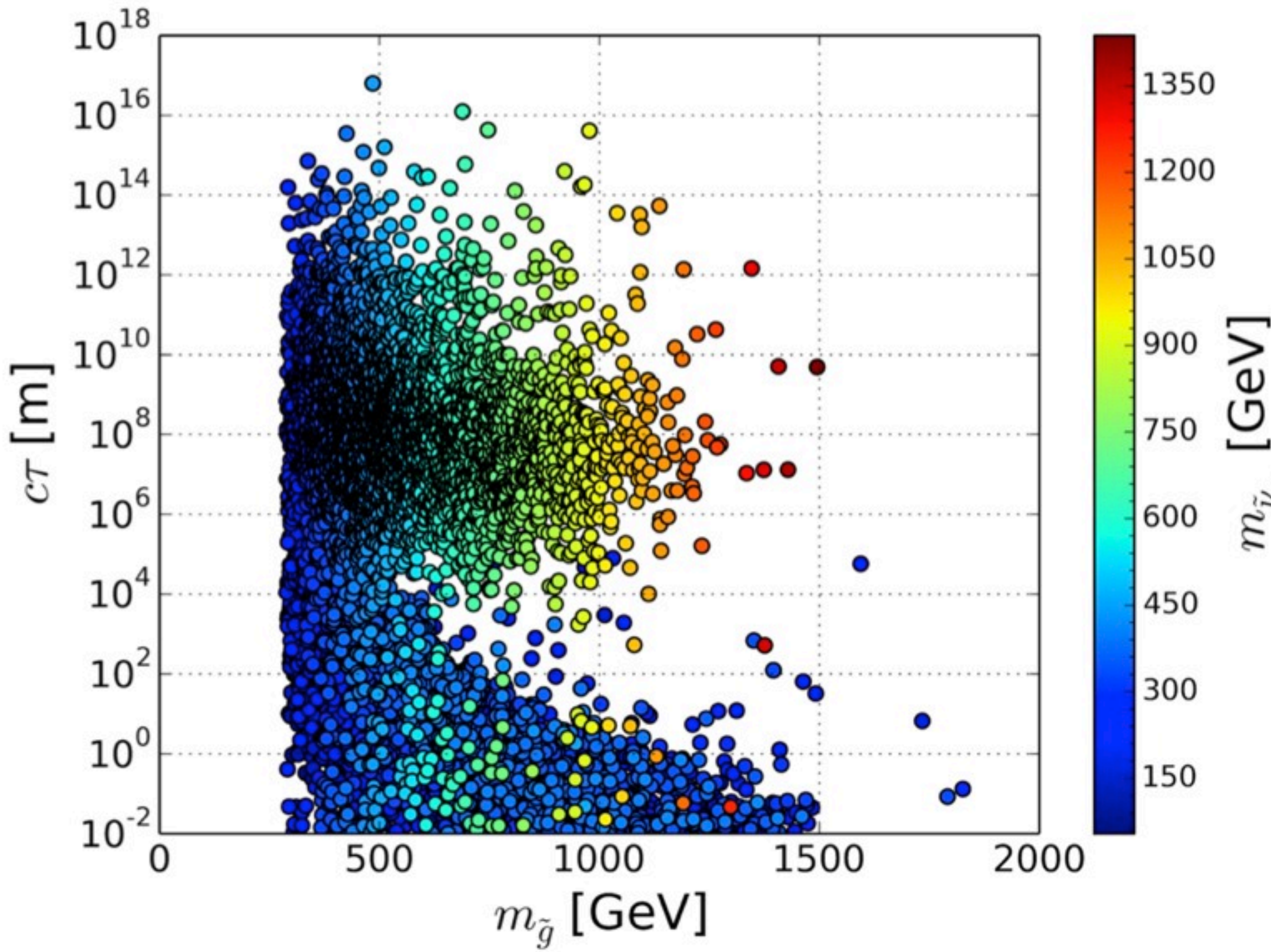
Need of a SMS interpretation of mono-lepton search

Mono lepton cross section

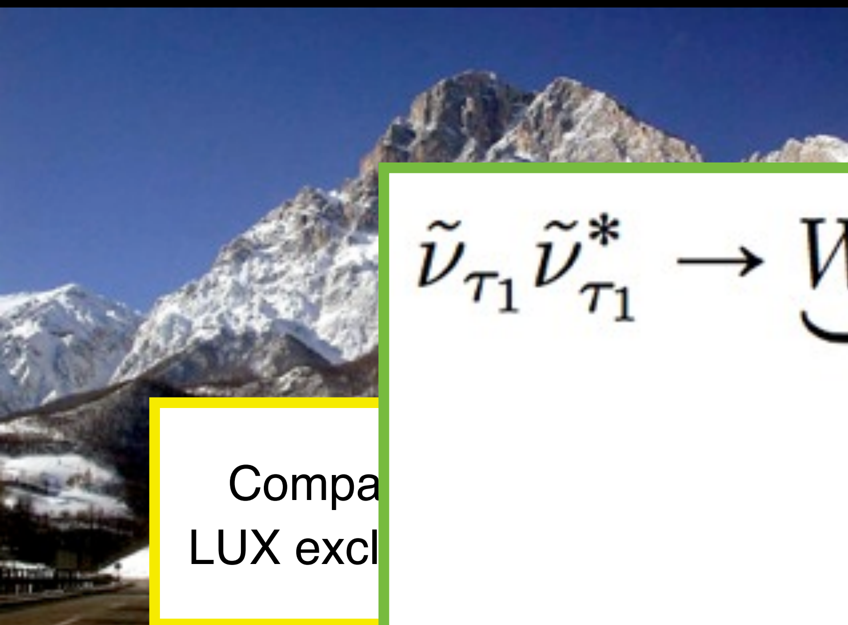


Long lived NLSP gluinos



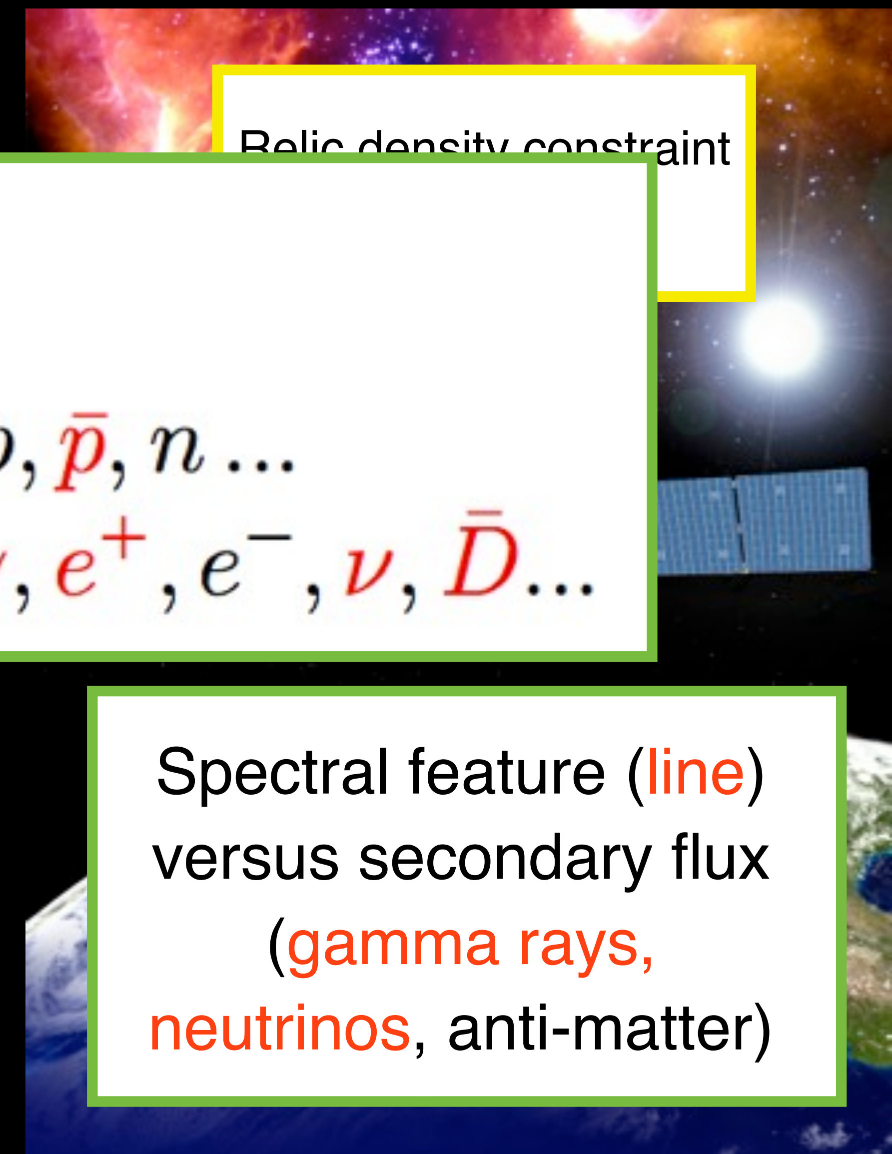


Signature for sneutrino DM



Freeze-out early Universe

Indirect detection



Relic density constraint

$$\tilde{\nu}_{\tau_1}\tilde{\nu}^*_{\tau_1} \to \underbrace{W^+W^-, ZZ, hh, t\bar{t}, \ldots}$$

$$\hookrightarrow \tau^\pm, \pi^0, \pi^\pm, p, \bar{p}, n \ldots$$

$$\hookrightarrow \gamma, e^+, e^-, \nu, \bar{D} \ldots$$

Compa

LUX excl

Direct

DM

SM

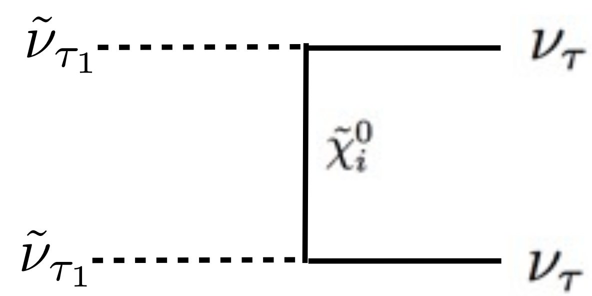
Spectral feature (line) versus secondary flux (gamma rays, neutrinos, anti-matter)

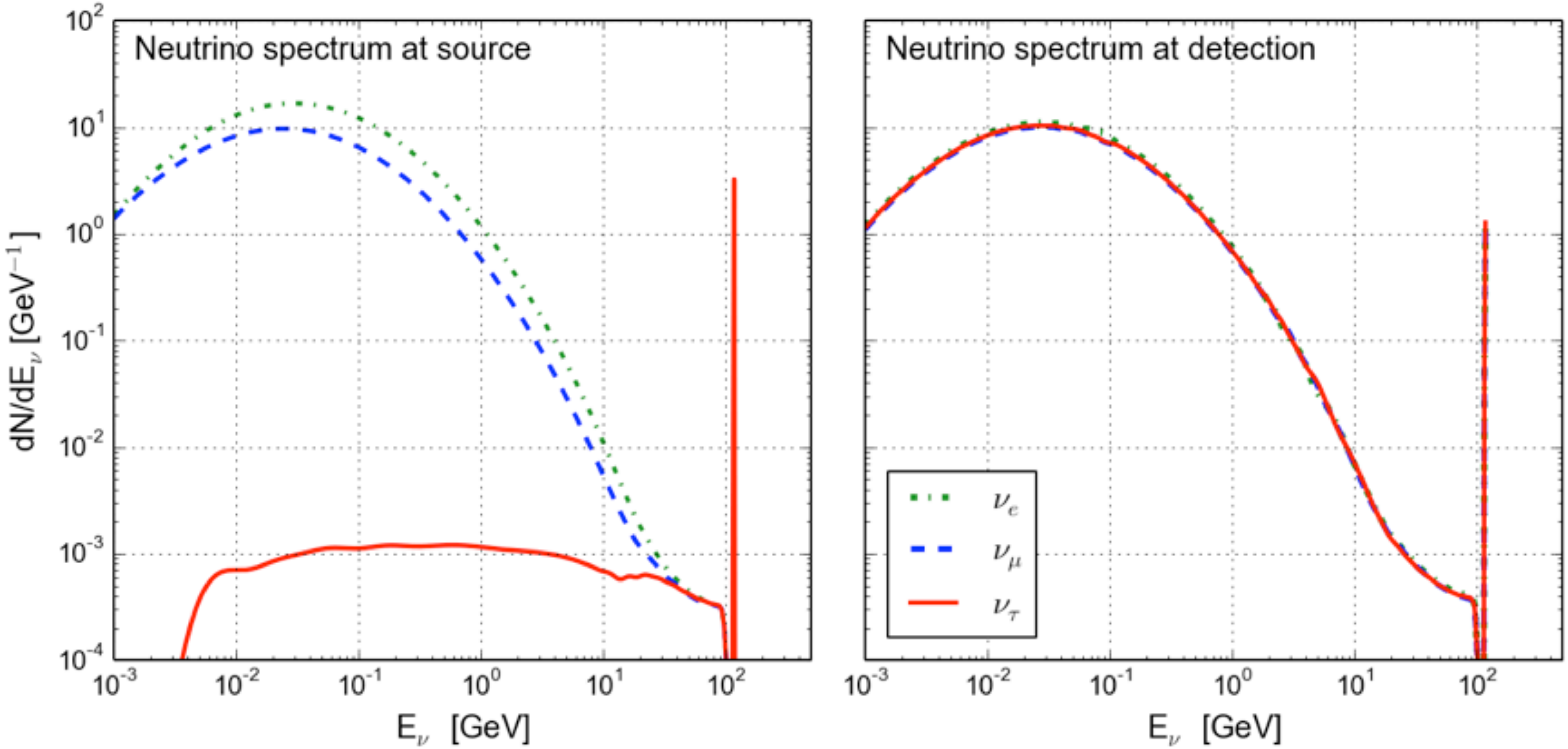
Production at colliders

Constraints from LHC run-I simplified models

The monochromatic neutrino line

- The LSP and DM is a sneutrino tau
- t-channel exchange of neutralino gives rise to neutrino tau sharp line at TREE LEVEL with $E_{nu} = m_{DM}$

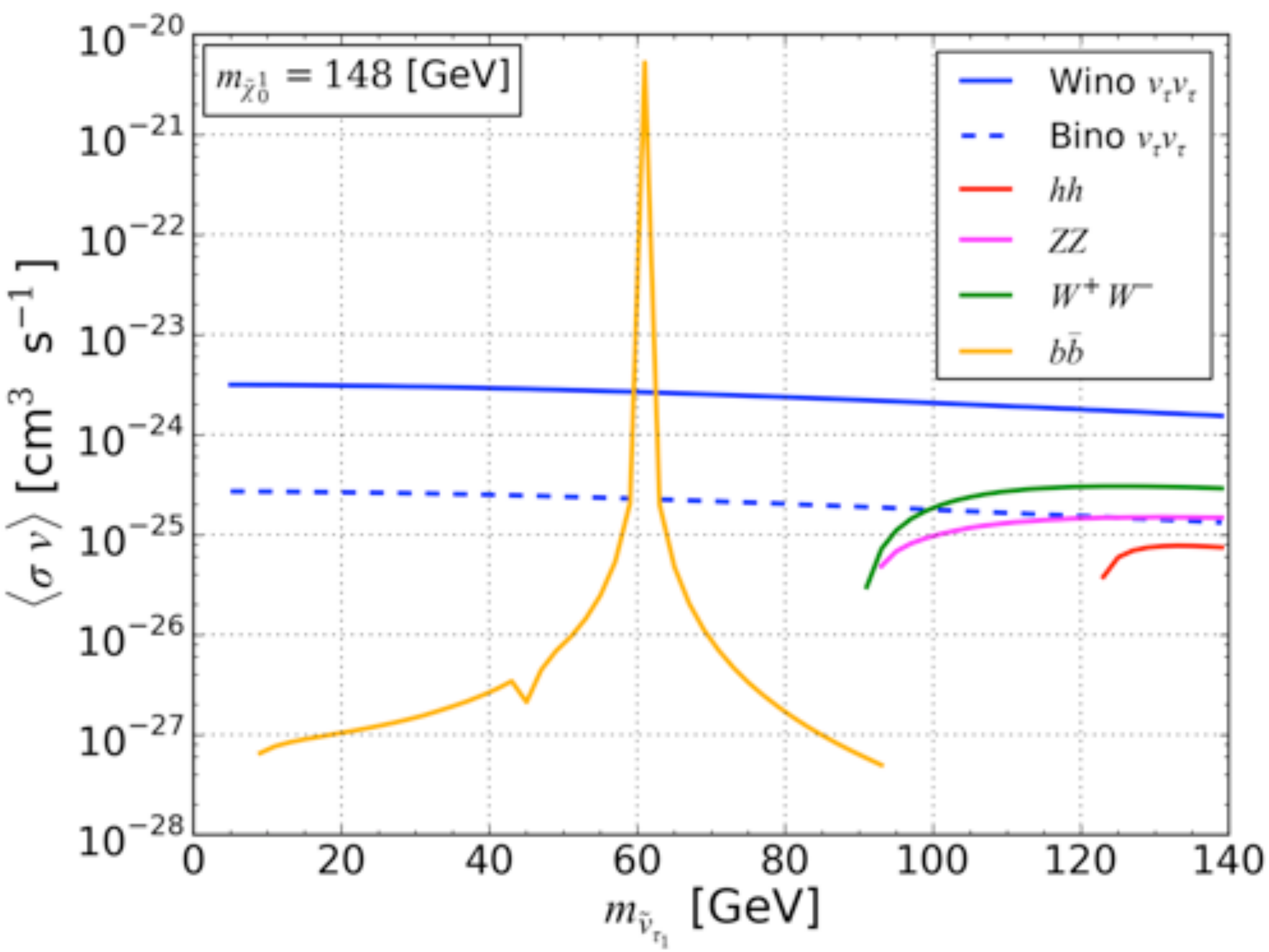


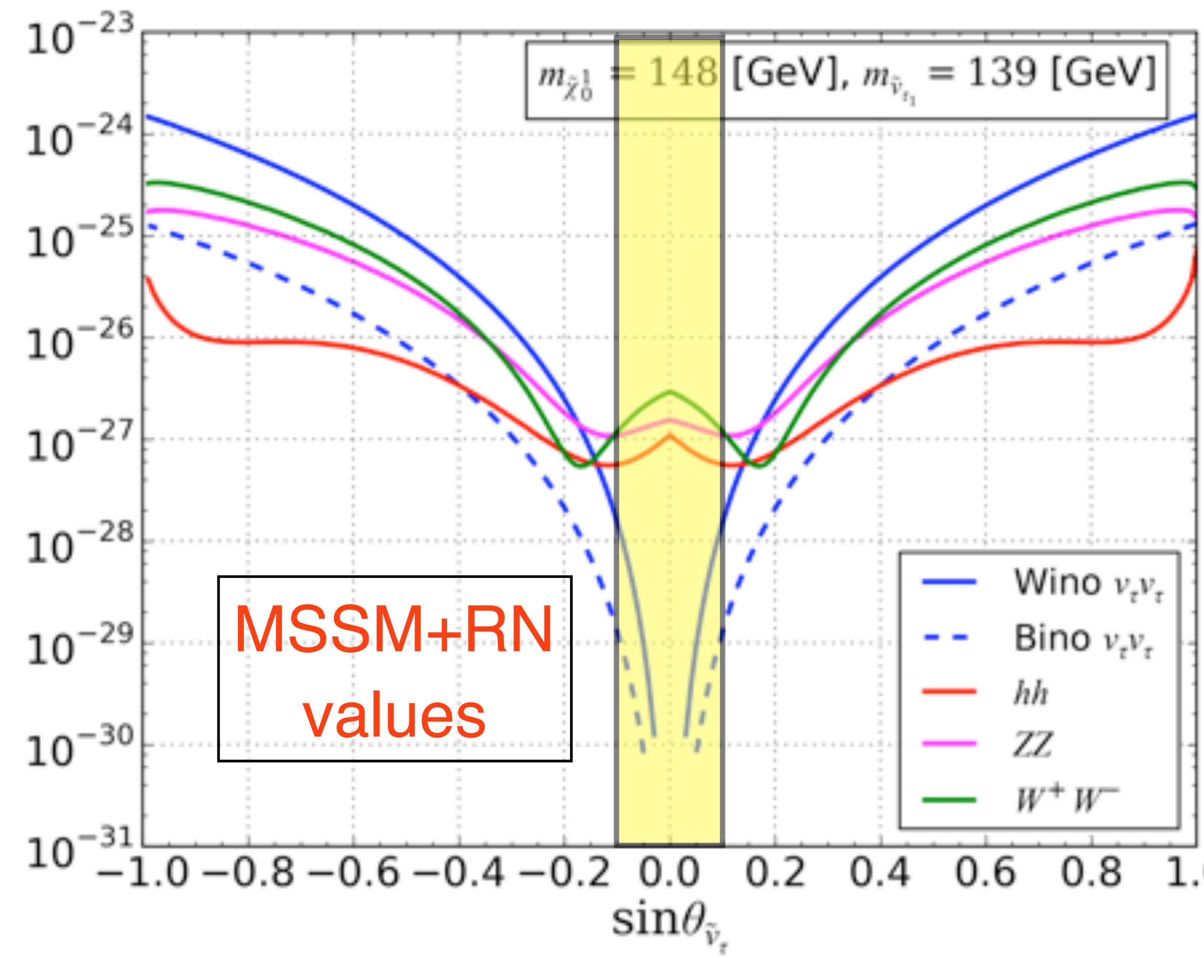


Line versus secondary flux

$$\langle \sigma v \rangle_{\nu_\tau \nu_\tau} = \frac{C_{P_L}^2 + C_{P_R}^2}{8\pi} \frac{m_{\tilde{\chi}_1^0}^2}{(m_{\tilde{\chi}_1^0}^2 + m_{\tilde{\nu}_1}^2)^2}$$

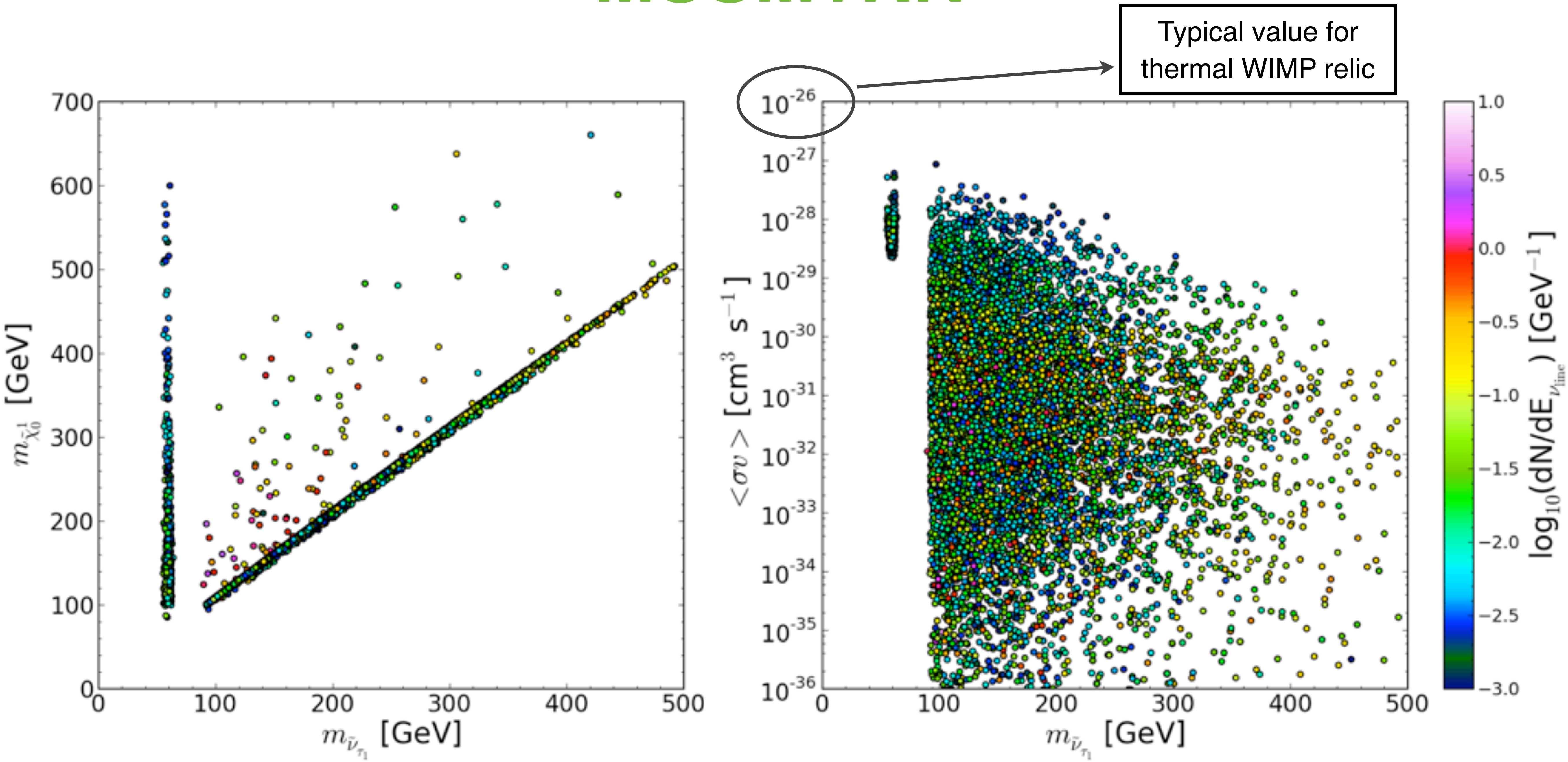
$$C_{P_R} \propto \sin\theta_{\tilde{\nu}_\tau} Y_\nu N_{14} \sim 0$$
$$C_{P_L} \propto C_a N_{11} \sin\theta_{\tilde{\nu}_\tau} + C_b N_{12} \sin\theta_{\tilde{\nu}_\tau}$$





- Neutrino line emission is typical of sneutrino DM (neutralino DM is p-wave)
- Dirac masses have negligible neutrino Yukawa: suppression of the signal

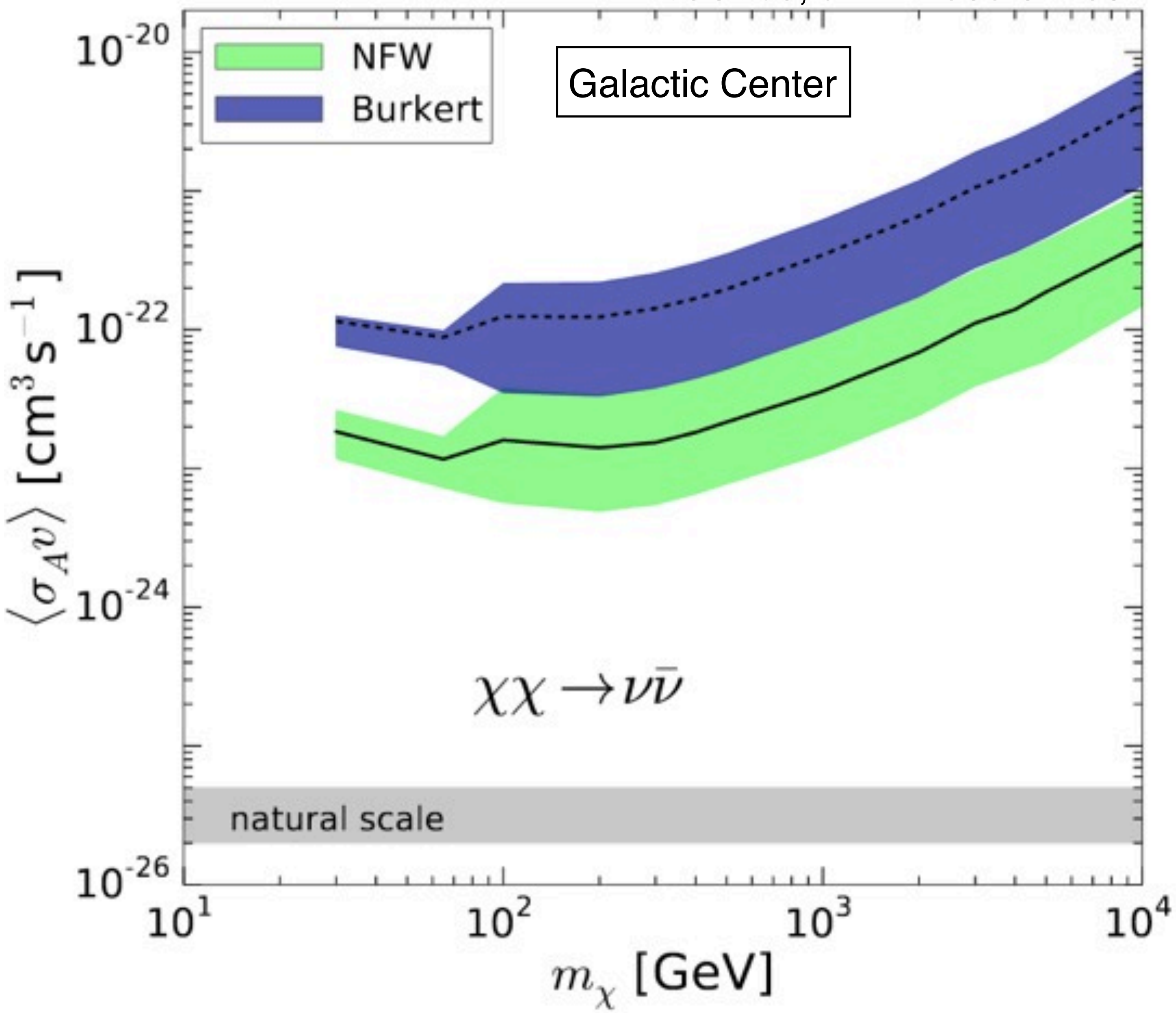
MSSM+RN



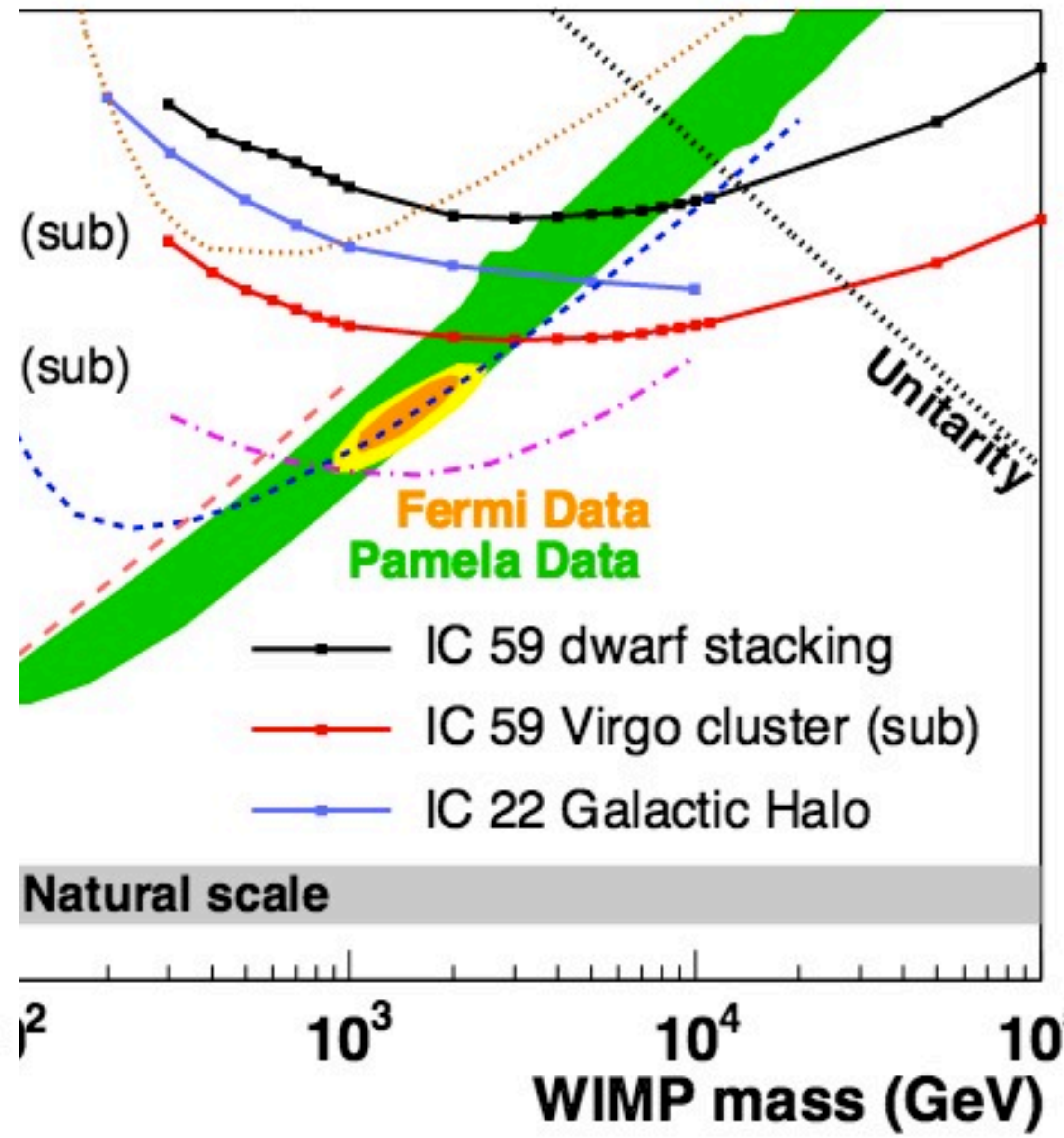
- The largest enhancements are for large neutralino-sneutrino mass splitting
- Sneutrino-neutralino tends to be degenerated because of relic density constraint
- Sigma v today small because relic density fixed by cohannihilation of neutralino-chargino and then communicated to sneutrino sector

IceCube bounds on DM annihilation

IceCube, arXiv:1505.07259



IceCube, arXiv:1307.3473

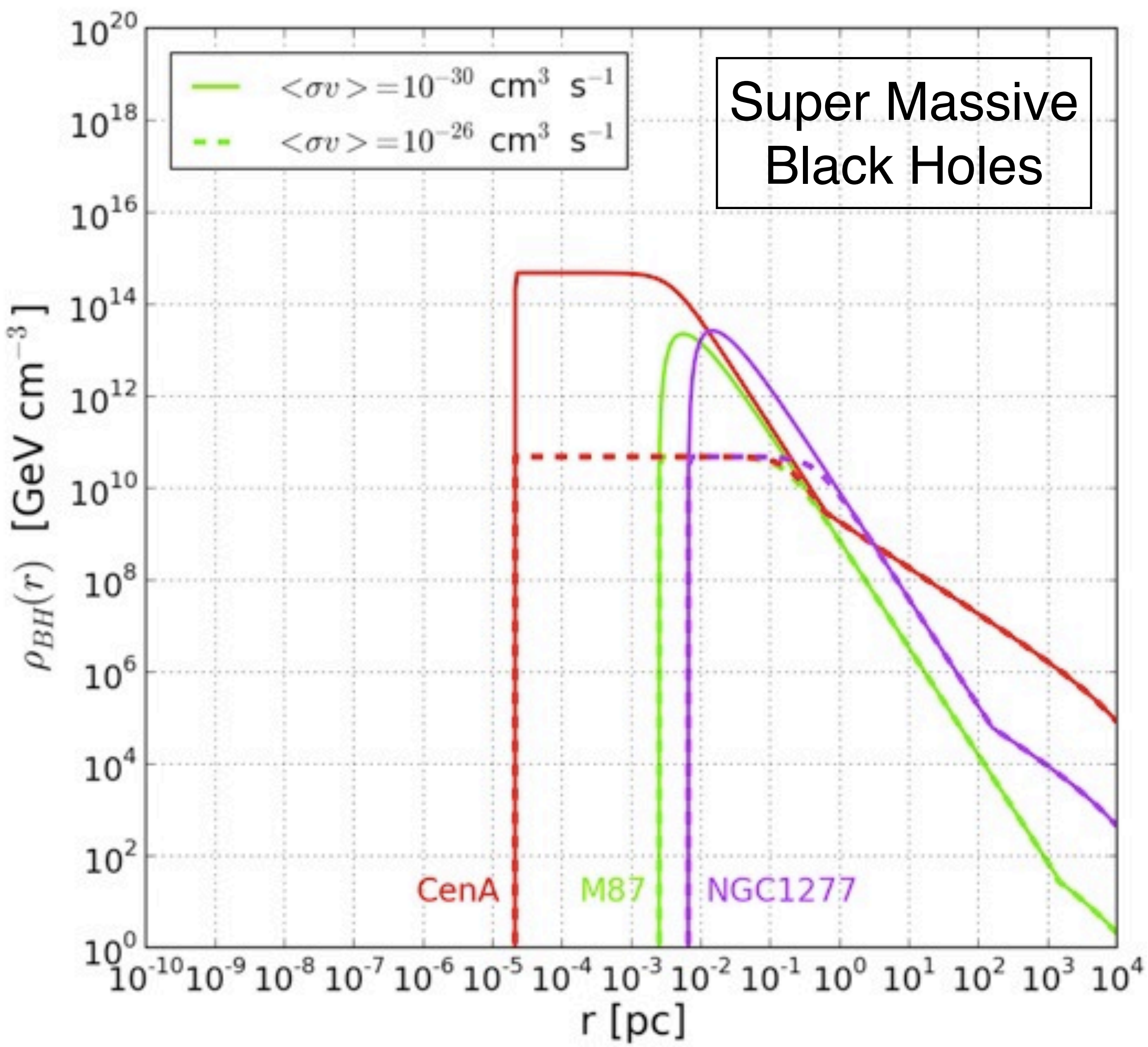


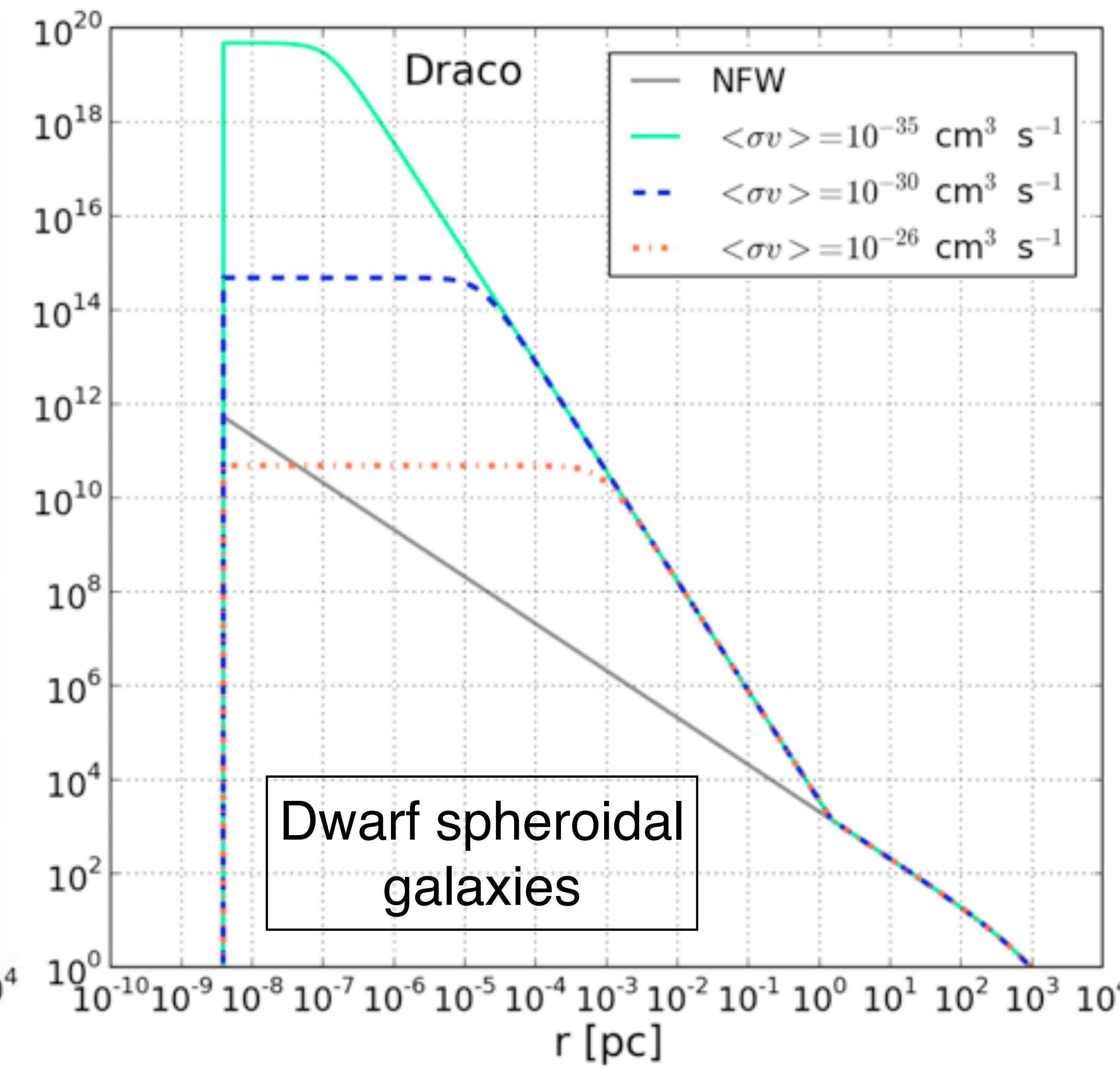
Due to the smallness of sigma v the monochromatic line from sneutrinos is not detectable by present astrophysical probes

Astrophysics: how to boost the signal

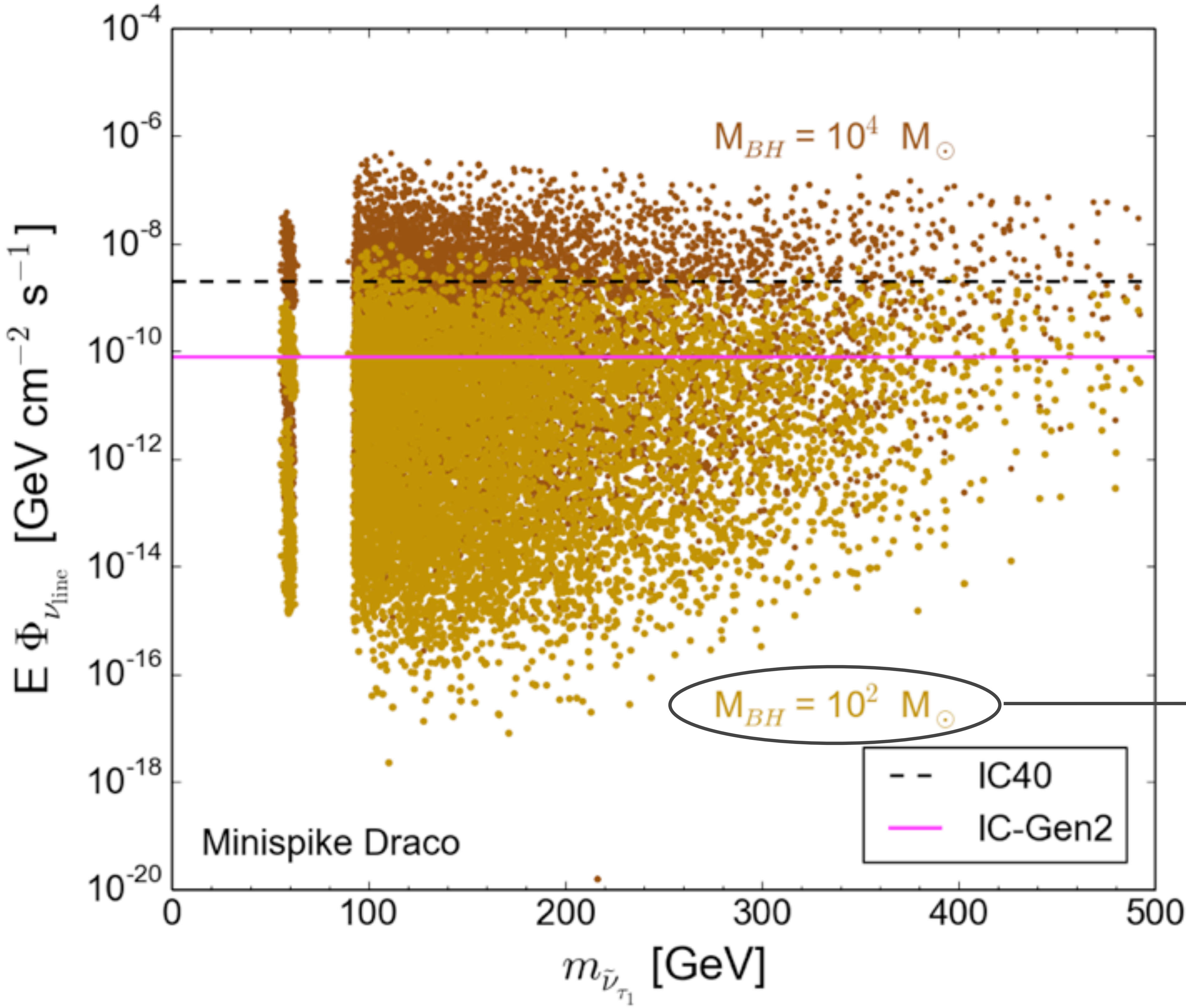
When black holes (BHs) form, DM density MIGHT increase to form a DM spike $\rho \sim r^{-7/3}$

$$\frac{d\Phi_\nu}{dE} = \frac{1}{8\pi}\,\xi^2\,\frac{\langle\sigma v\rangle}{m^2_{\tilde\nu_{\tau_1}}}\,\frac{dN_\nu}{dE}\,\Phi_{\rm Astro} \qquad \Phi_{\rm Astro} = \int_{\Delta\Omega} d\Omega' \int_{los} \rho^2_{\rm dwarf}(r(s,\theta))\,ds$$





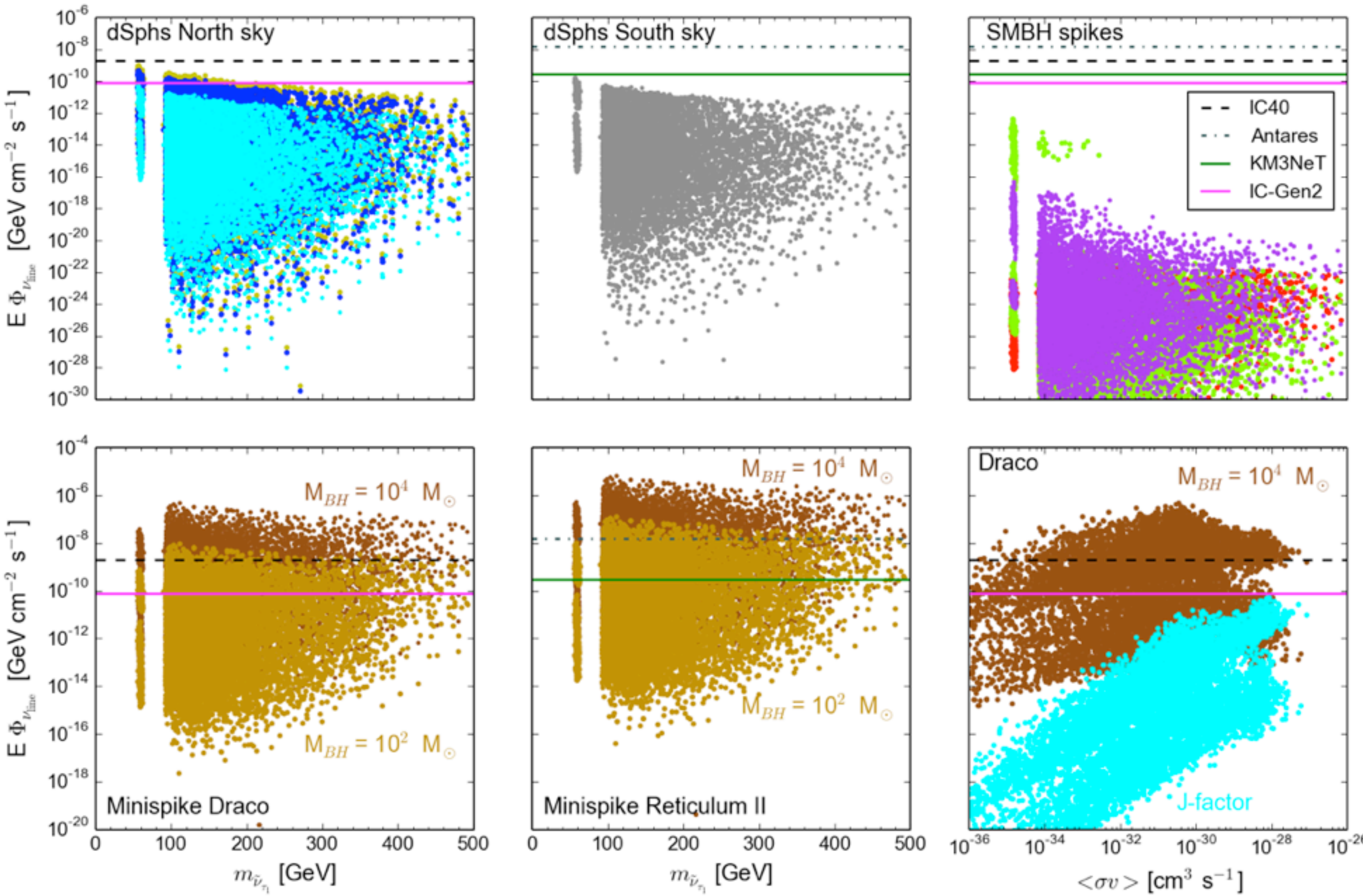
Expected neutrino flux from Draco dSPh



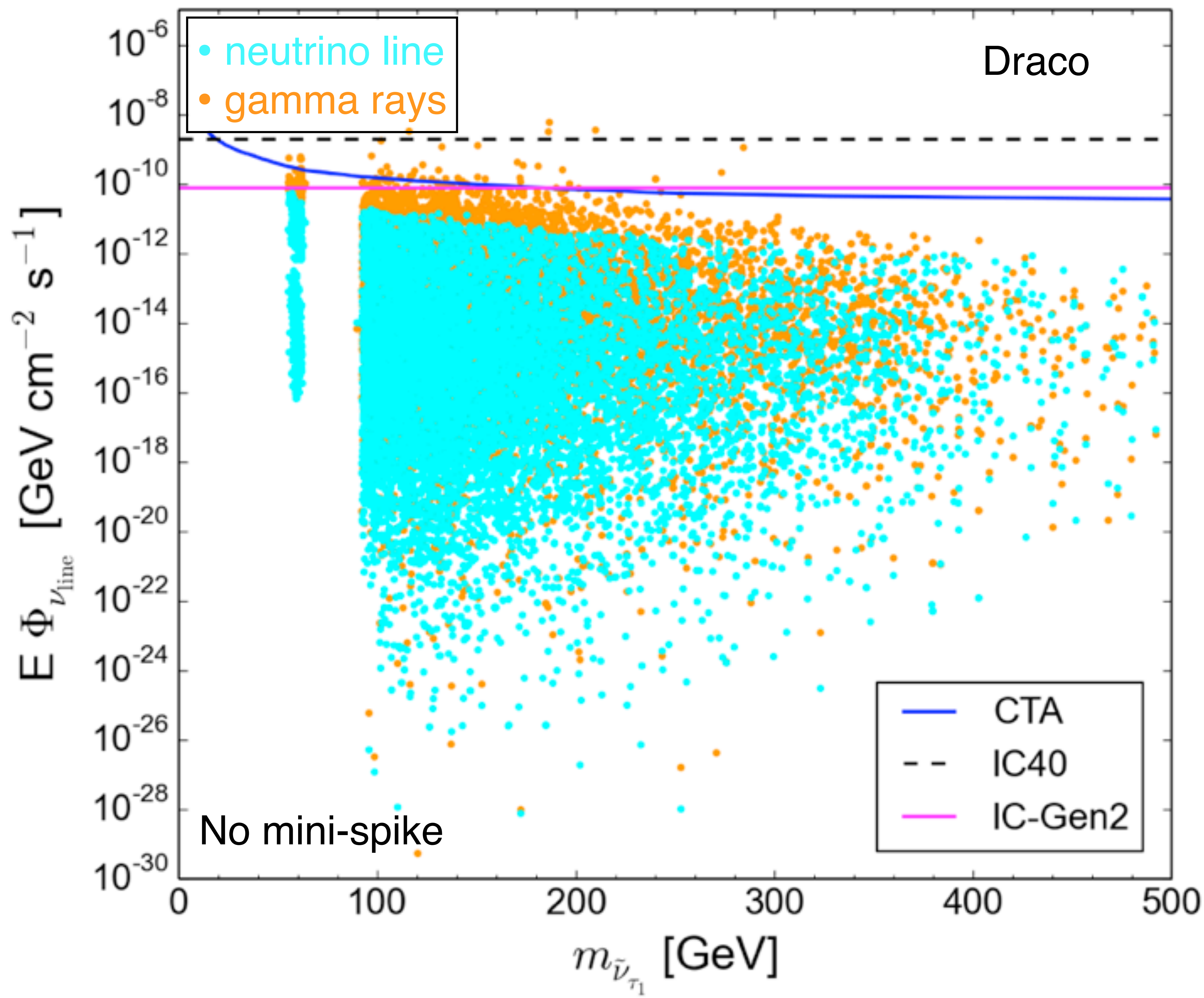
- Idealistic neutrino telescope set up
- Point source sensitivity for TeV neutrinos extrapolated down to GeV energies

Typical expected BH mass for Draco-like system (from simulation)

Expected neutrino flux



Complementarity with gamma-ray searches



Conclusion and prospects

- Sneutrino LSP models address two issues at once: DM and neutrino masses
- Crucial to have recasting of existing searches to apply to BSM physics (for example mono-lepton search for sneutrino DM)
- It would be interesting to test low energy seesaw models with sneutrino DM at LHC and indirect detection with neutrino line