LONG LIVED STAUS IN ICECUBE FROM ATMOSPHERIC NEUTRINOS

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- charged NLSPs and dark matter
- neutrino fluxes
- stau cross sections
- stau fluxes

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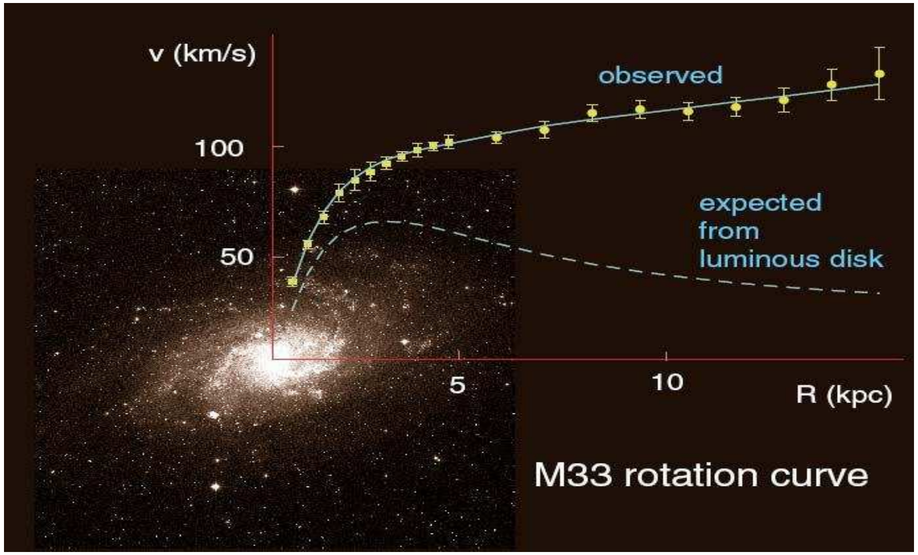
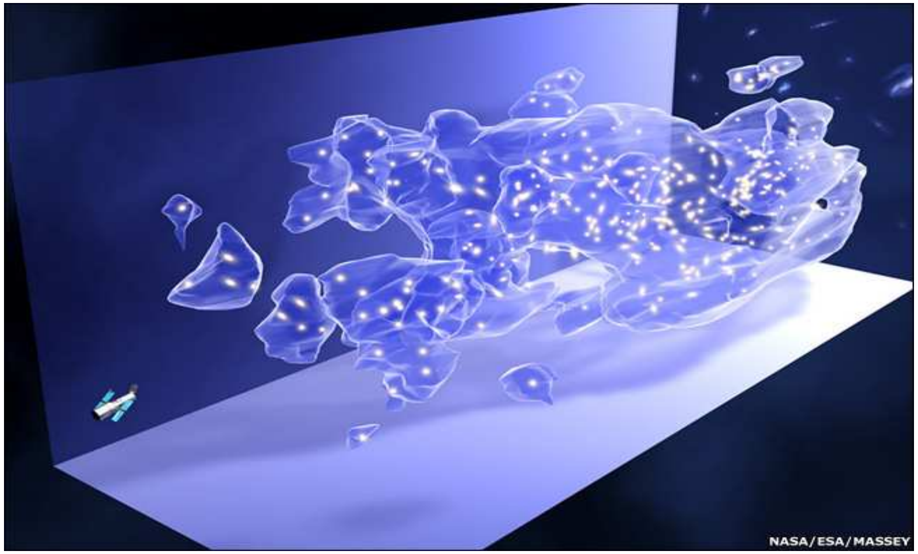
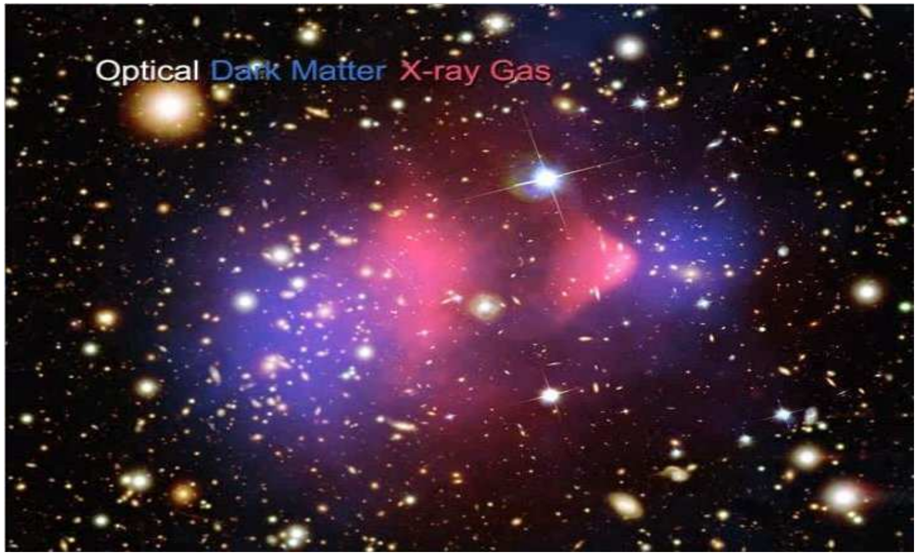
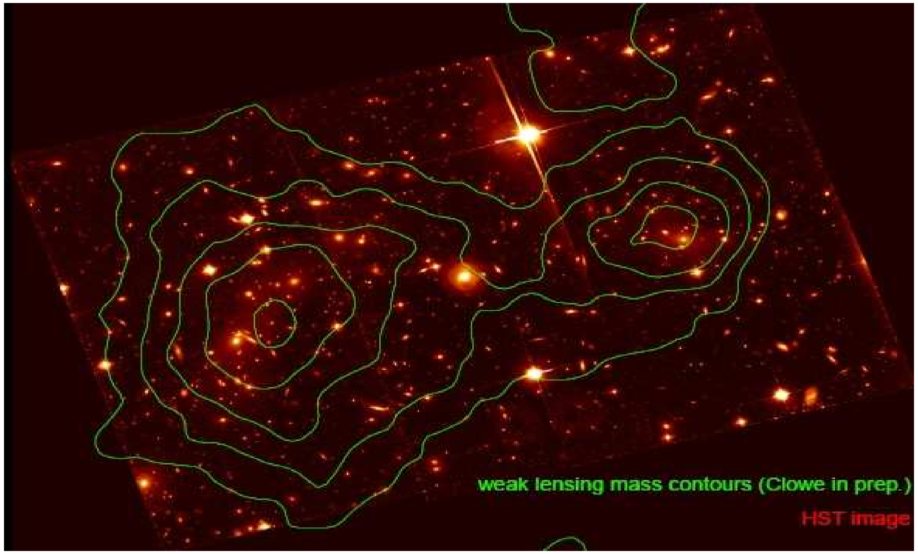
Motivation: dark matter! (among other things)









We know it’s out there – but what is it?

If DM was thermally produced, we can calculate its relic density
(in convenient units):

$$\Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}\cdot c}{\langle\sigma_A v\rangle}$$

EW-sized cross section!

Reinterpret as a mass:

$$\langle\sigma_A v\rangle = \frac{m_\chi^2}{m_W^4} \longrightarrow m \sim 100\ \mathrm{GeV}$$

Perhaps connected to EW scale?

⇒ if so, expect to produce DM at colliders, soon

→ *but what if this particle decays after freeze-out?*

Late-decaying particles

New physics can have long-lived next-to-lightest particles (“NLSP”s):

- supersymmetry (SUSY):
  - · gravitino lightest SUSY particle (LSP) – slow NLSP decay
  - · near NLSP–LSP mass-degeneracy – again, slow NLSP decay
- universal extra dimensions (UED):
  - · Kaluza-Klein graviton excitation is DM – long-lived “NLSP”
- $\langle\langle$ your favorite model with $\gamma c\tau \sim R_\oplus$ here $\rangle\rangle$

→ no DM underground detector signal (effectively sterile),
no galactic center γ rays, etc.

But NLSP likely light, could be produced at colliders:

If neutral, looks like DM in collider, but isn’t. (How to sort out?)

If charged NLSP, stands out (is a major discovery):
would suggest super-WIMP DM.

[Feng, Su, Takayama, PRD 70:063514(2004)]

Charged NLSPs and dark matter

→ C-NLSPs could be produced by cosmic neutrinos in upper atmosphere, then observed in neutrino telescopes (IceCube):

$\nu p \to \chi\chi \to \widetilde{\tau}\widetilde{\tau}$ gives "double upgoing muon" signal

[Albuquerque, Burdman, Chacko, PRL 92:221802 & PRD 75:035006]
[Ahlers, Kersten, Ringwald, JCAP 0607, 005]

These studies used SUSY: gravitino LSP and stau NLSP.

We adopt the same framework.

These studies assumed cosmogenic high-energy neutrinos (the Waxman-Bahcall flux).

Our big question: what really are the largest neutrino sources?

Our goal: calculate stau flux at detector:

$$\frac{dF_{\widetilde{\tau}}}{dE_\nu} \propto \frac{dF_\nu}{dE_\nu}\,\sigma(\nu p \to \widetilde{\tau}\widetilde{\tau}) \quad \text{(and stau energy losses)}$$

NEUTRINO FLUXES

Cosmogenic ν’s: the Waxman-Bahcall limit on fluxes

Assumption: ultra-high-energy (UHE) ν’s from AGNs, GRBs, etc. (never observed), normalized to UHE protons (known observed flux).

→ previous C-NLSP/IceCube studies relied on the maximal flux

W–B is actually an *upper limit* on cosmogenic UHE ν fluxes.

It assumes:

- optically thin sources
- extrapolation for $E_\nu < 5 \times 10^7$ GeV
- maximal possible values at various steps

The normalization could be much lower.

The normalization could also be much higher: opaque ν sources.

Other possible UHE ν sources

① Atmospheric conventional neutrinos

· cosmic ray protons create atmospheric pions & kaons

· pions & kaons lose energy, decay to lower-energy ν's

→ well-known/measured flux

[cf. Candia & Roulet, JCAP 0309,005]

② Atmospheric prompt-decay neutrinos

· cosmic ray protons create atmospheric charmed mesons

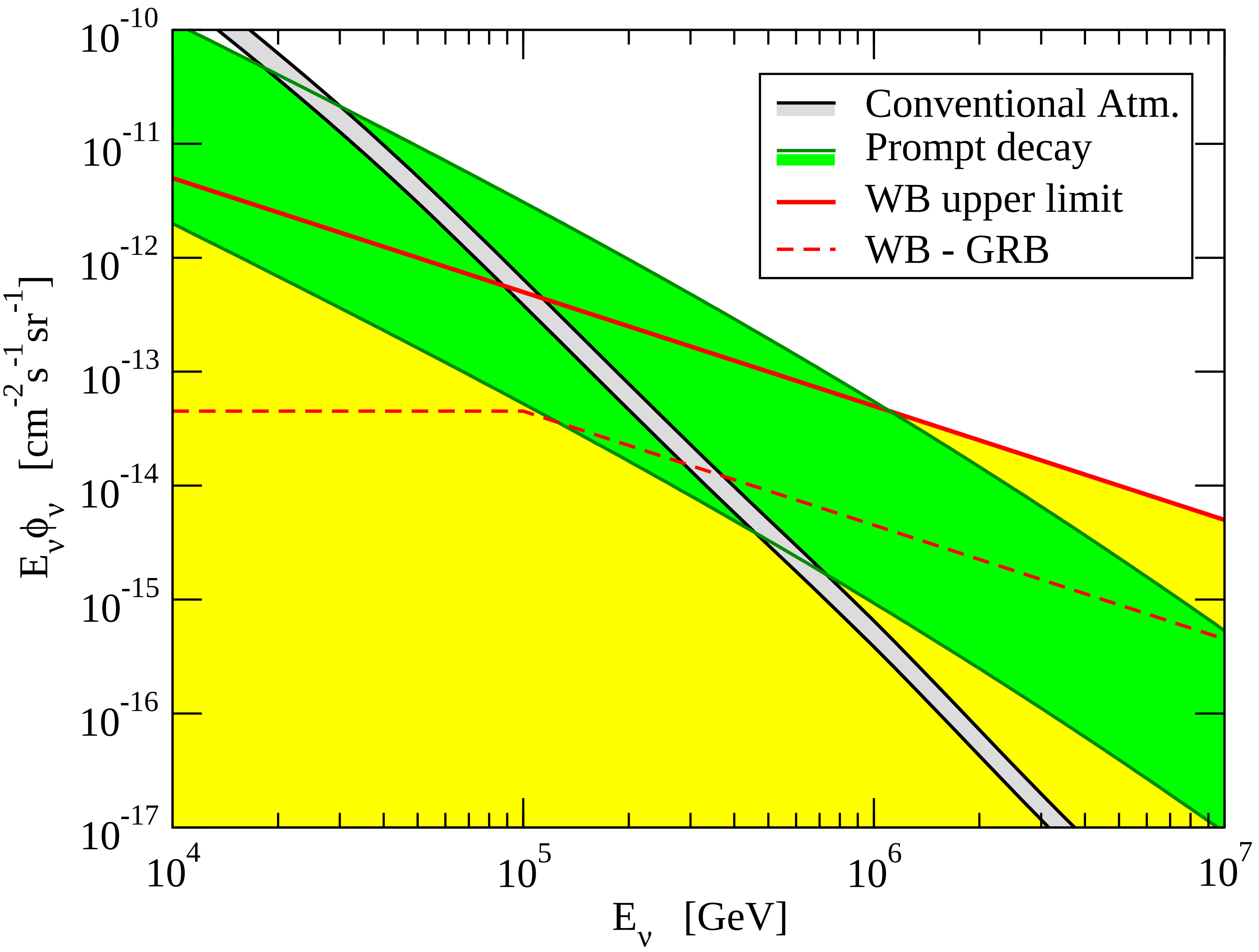
· charmed mesons decay promptly to high-energy ν's

→ normalization still unknown, depends on PDFs & NLO QCD (IceCube will measure)

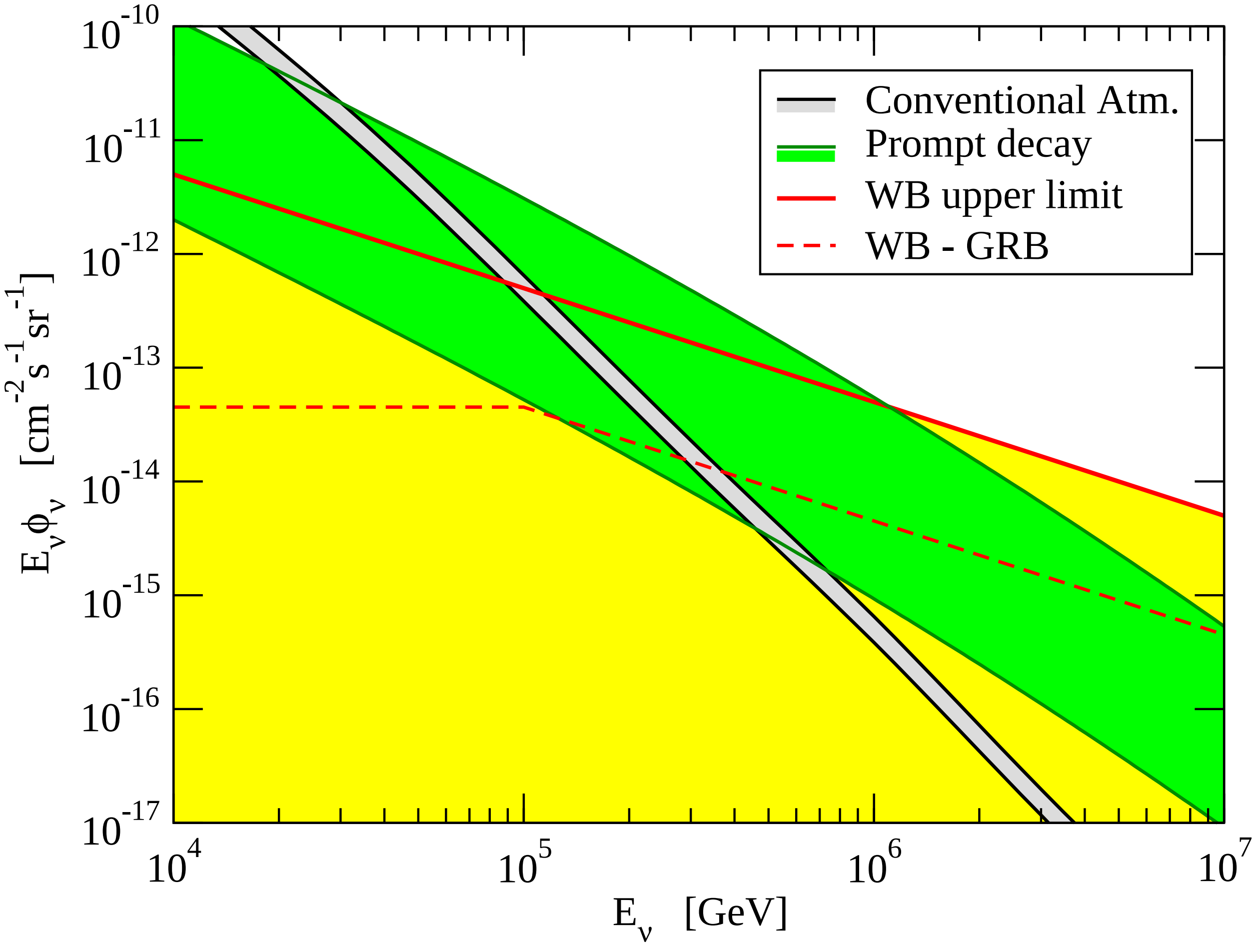
[cf. Beacom & Candia, JCAP 0411,009;
Martin, Ryskin & Stasto, Acta Phys. Polon. B34,3273]

▶ These sources are naïvely "small", but is that really so?

The neutrino fluxes – some surprises!



The neutrino fluxes – some surprises!



► depending on E_ν, prompt decay ν flux can dominate
(also, WB-GRB predicted flux is far lower)

• prompt flux is highly uncertain (IceCube will measure)

► atmospheric ν flux dominates at even lower E_ν

STAU CROSS SECTIONS

$\nu - p$ cross sections in SUSY

We first need to calculate the neutrino-proton xsec for SUSY pairs.

Points and assumptions:

1. $2 \to 2$ xsec dominated by production threshold – squark/gluino plus slepton/sneutrino masses
2. All sparticles decay promptly to NLSPs.
3. σ via LO SUSY-MADEVENT: [Plehn, DR, 2005]
   NLO results not known (our result thus conservative)
   CTEQ6L1 LO PDFs
4. Sum over NC & CC, squark + antisquark, etc.
   – note not equal near threshold, but irrelevant for calc'n
5. SUSY model points chosen not to conflict with existing data.
6. Gravitino mass irrelevant provided $\gamma c \tau_{\tilde{\tau}} \gtrsim R_{\oplus}$

   (typically 1 MeV to 1 GeV minimum)

The SUSY model points

We choose 2 mSUGRA and 2 GMSB points to study:

[cf. DeRoeck et al., hep-ph/0508198; SPS benchmarks, hep-ph/0202233]

$\mathrm{sgn}(\mu) > 0$ always

Input parameters:

mSUGRA	$M_{1/2}$	m_0	$\tan\beta$	A_0
I	280 GeV	10 GeV	11	0
ε	440 GeV	20 GeV	15	−25 GeV

GMSB	M_{mes}	Λ	$\tan\beta$	N_{mes}
II	70 TeV	35 TeV	15	3
SPS7	80 TeV	40 TeV	15	3

The SUSY model points

We choose 2 mSUGRA and 2 GMSB points to study:

[cf. DeRoeck et al., hep-ph/0508198; SPS benchmarks, hep-ph/0202233]

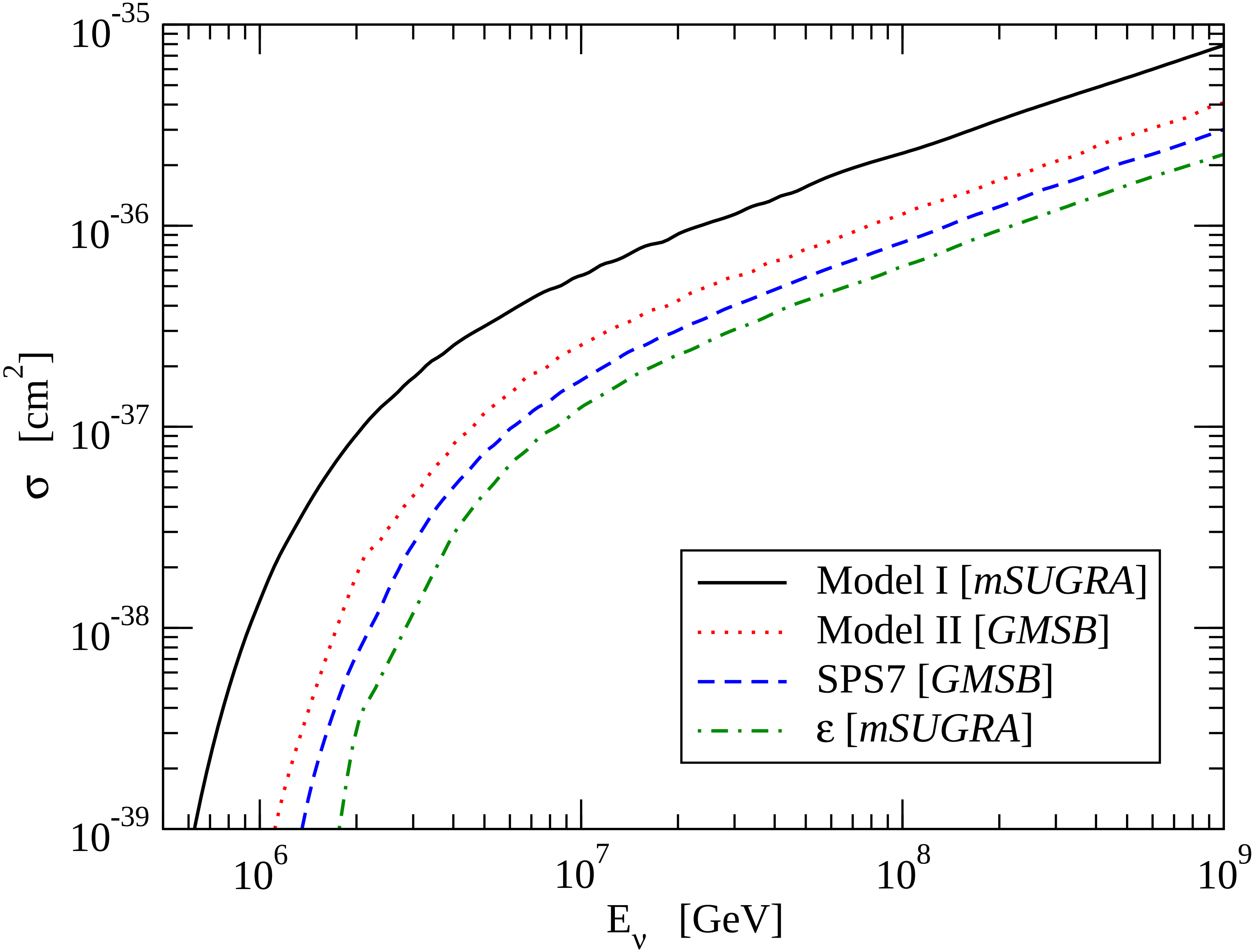
sgn(μ) > 0   always

Mass spectra (GeV):

mSUGRA	$m_{\tilde{q}}$	$m_{\tilde{l}}$	$m_{\tilde{\nu}}$	$m_{\chi_1^\pm}$	$m_{\chi_1^0}$
I	620	200	180	200	110
ε	940	300	290	340	180

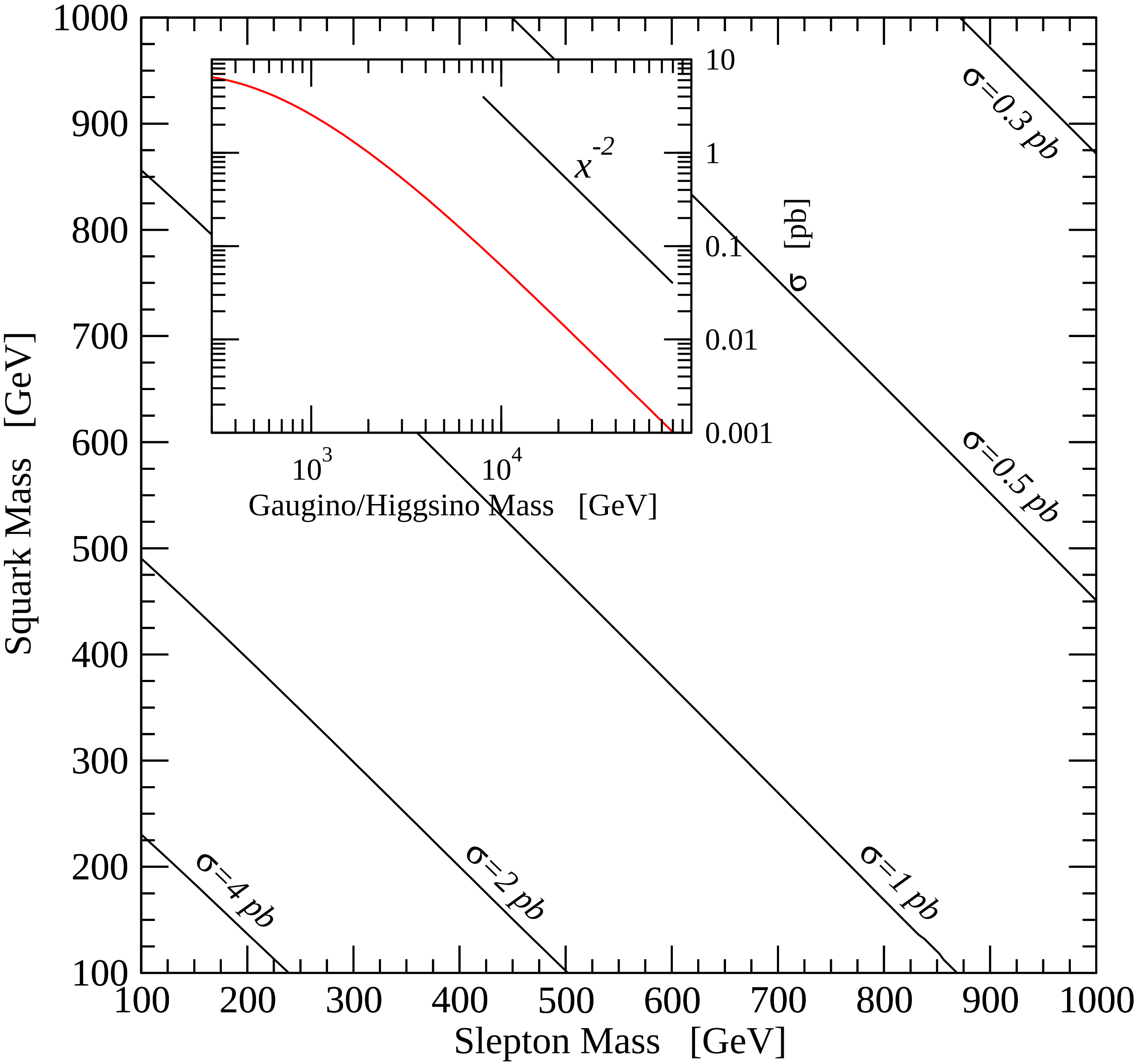
GMSB	$m_{\tilde{q}}$	$m_{\tilde{l}}$	$m_{\tilde{\nu}}$	$m_{\chi_1^\pm}$	$m_{\chi_1^0}$
II	800	230	210	240	140
SPS7	900	260	250	270	160

Results for SUSY cross sections



→ consistent with previous studies [Ahlers ... ; Albuquerque ...]

Cross sections depend on masses (fixed $E_\nu = 10^8$ GeV)



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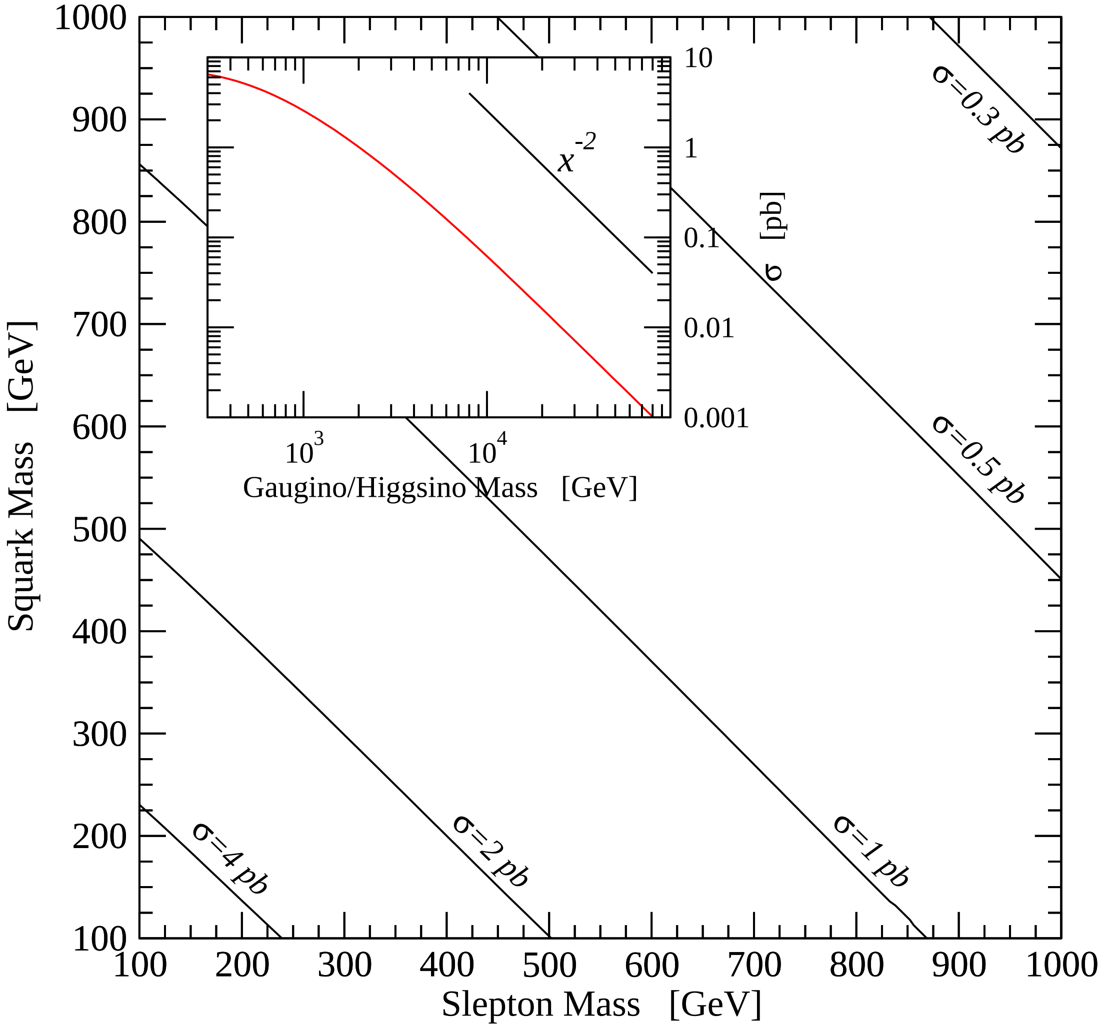


$$\sigma_{\nu p} \sim \frac{1}{m_{\widetilde{W}}^2}\left(\frac{s}{4m_S^2}\right)^{1/3}$$

STAU FLUXES

Translating stau cross sections to fluxes

Recall: prompt sparticle decay (squarks, sleptons), to staus.

Assume each stau gets half incoming energy: $E_{\tilde{\tau}} = E_\nu/2$

$$
\begin{aligned}
\frac{\mathrm{d}F_{\tilde{\tau}}}{\mathrm{d}E_\nu} &\equiv \int_{2\pi} \Omega \, \frac{\mathrm{d}\Phi_{\tilde{\tau}}(E_\nu, \Omega)}{\mathrm{d}E_\nu} \\
&= \int_{2\pi} \Omega \int_0^{X_{\mathrm{tot}}(\Omega)} \frac{\mathrm{d}X}{m_p} \, 2\sigma_{\nu N}^{\mathrm{SUSY}}(E_\nu) \exp\left(-\frac{X}{m_p}\sigma_{\nu N}^{\mathrm{tot}}\right) \frac{\mathrm{d}\Phi_\nu(E_\nu)}{\mathrm{d}E_\nu}
\end{aligned}
$$

· integrate solid angle only below horizon

· exponential suppression for SM interaction depletion of ν flux

· X is the column depth, $dX = \rho(l, \Omega) dl$
(Earth density is a homogenous 3 g/cm^{-3})

→ this gets us the stau flux *before energy losses*

Stau energy losses in earth

- ionization losses negligible

- dominant losses from Bremsstrahlung in atomic $\vec{E}$ fields
  [Albuquerque et al.; Ahlers et al.]
  [Reno, Sarcevic, Su, Astropart. Phys. 24:107(2005)]

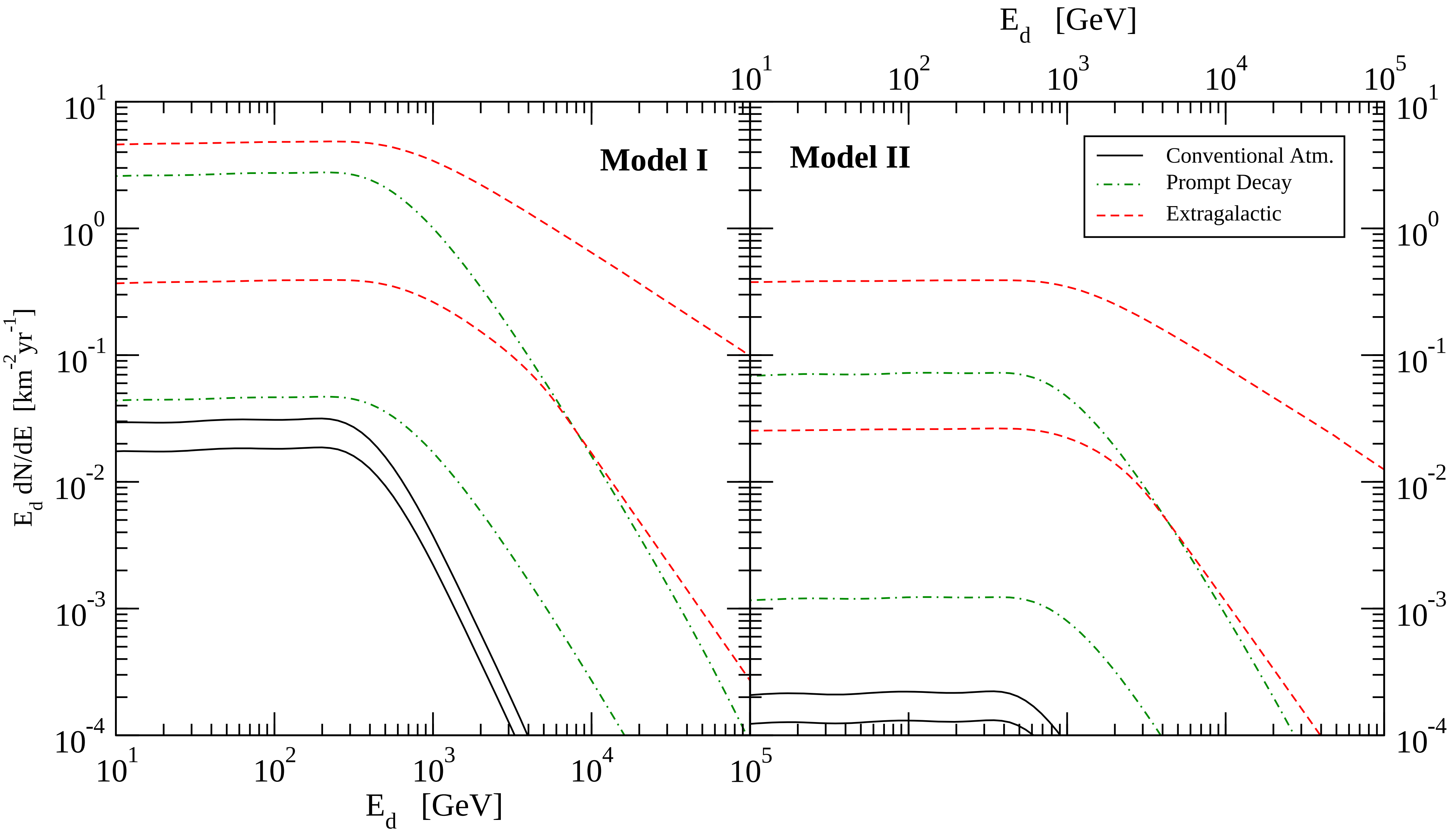
▶ solve the energy loss equation

$$\frac{dE_{\tilde{\tau}}}{dX} = \beta_{\tilde{\tau}} E_{\tilde{\tau}}$$

where $\beta_{\tilde{\tau}} = \beta_\mu \cdot m_\mu / m_{\tilde{\tau}}$ (ratio of charged-particle masses)

- weak-interaction energy losses must be included for $E > 10^9$ GeV
  [Reno, Sarcevic, Uscinski, PRD 74:115009(2006)]

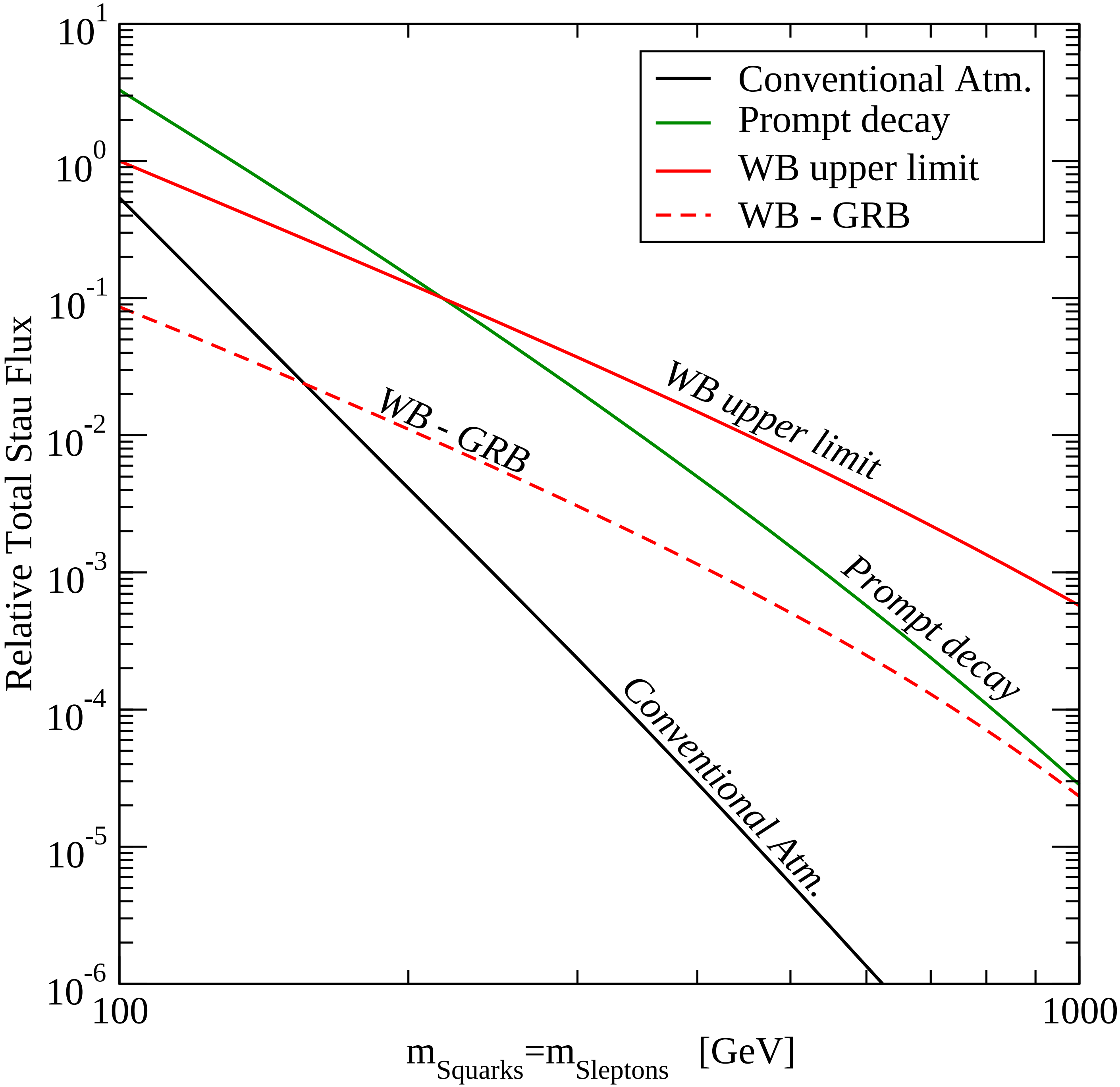
Stau event rates at the detector



- ▶ prompt ν's can be significant component or even dominant

  (depends on the real WB flux, if it exists)

Relative stau flux contributions (at the detector)



CONCLUSIONS

- Thermally-produced DM may be at EW scale, produced at colliders; or perhaps could be in some scenarios.
- Long-lived NLSPs also (pair) produced via UHE cosmic ν's.
- Charged NLSPs (e.g. staus) could be observed by IceCube.
- Observation: prompt ν flux from cosmic protons large, possibly larger than WB extra-galactic flux.
- Charged NLSP flux in IceCube could be larger than expected, and are more "guaranteed" is NLSPs exist.

▶ paper in draft, should appear soon