Detecting Superheavy Dark Matter

Neutrino Signature

Ivone Albuquerque

UC Berkeley

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Outline

- Intro: SIMPZILLAS.
- Trapping in the Sun.
- Neutrino Energy Spectrum: from Sun to Earth.
- Detectability in current and proposed neutrino telescopes.
  - Event Rate.
  - Background.
  - Energy threshold, volume and location.
- ν oscillation.
- Conclusions.

IA, Lam Hui and Rocky Kolb – Phys. Rev. D **64**, 083504 (2001)

IA, J. Lamoureux and George Smoot Hep-ph/0204301

SIMPZILLAs

D.Chung, A.Riotto,R.Kolb

- WIMPZILLA: superheavy WIMP
- MUST:
  - be stable
  - low interaction rate such that thermal equilibrium with primordial plasma never happened
    $\Rightarrow$ EXTREMELY MASSIVE (close to the inflaton mass $\sim 10^{12}$ GeV)
    $\Rightarrow$ condition for non equilibrium: annihilation rate $<$ expansion rate
- large mass prevents from thermalizing
- abundance depends on its mass **NOT on interaction strength** $\Rightarrow$ **SIMPZILLAS**

Trapping in the Sun

ESTIMATE

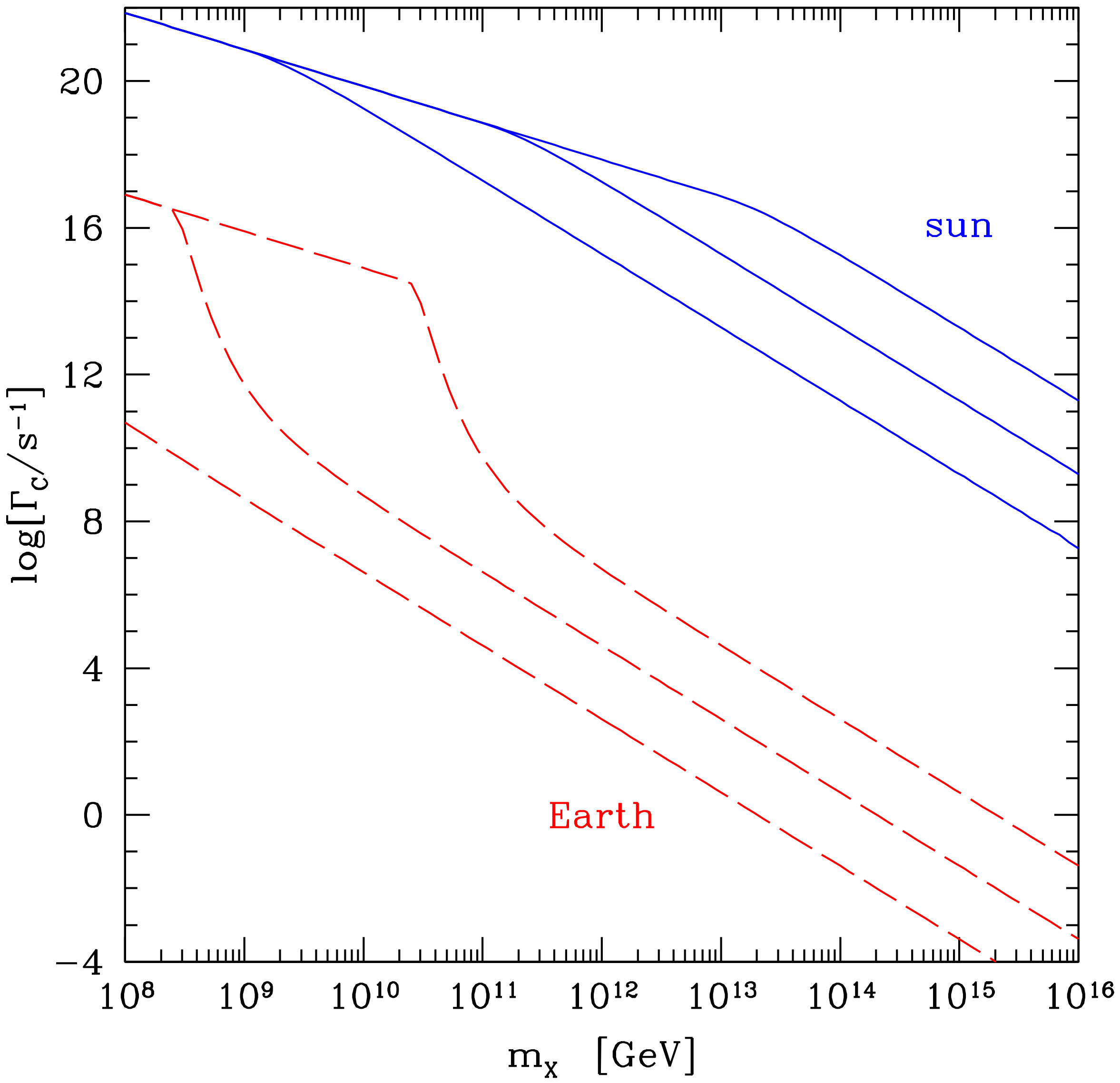
- Number of SIMPZILLAs that hit the Sun (N_H):
  - local DM: $\rho = 0.3$ GeV/cm^3

    $n_\chi = \rho/m_\chi \qquad < v > \sim 240$Km/s
  - N_H = flux in the solar neighborhood $\times A_\odot = \frac{n<v>}{4\pi} A_\odot \sim 4 \times 10^{16} M_{12}^{-1} s^{-1}$
- Trapping in the Sun
  - $N_{\rm int} = n_\odot \sigma_{\chi-N} R_\odot$
  - energy loss per collision ($v = v_{\rm esc}$):

    $m_\chi >> m_N \Rightarrow \Delta E = \frac{m_p v^2}{2}$
  - $\Delta E_{\rm total} = \Delta E_{\rm col} \times N_{\rm int\odot} \sim 2 \times 10^6 \mathrm{M}_{12}\mathrm{GeV}$
  - initial energy: $E_\chi \sim 2 \times 10^6 M_{12} GeV \Rightarrow$ most χ are captured!!

$$\mathbf{C} \sim 4 \times 10^{16} s^{-1}$$

Capture Rate in the Sun



- Simpzilla - Nuclei crosssections are 10^{-26} cm^2 for lower curves, 10^{-24} cm^2 for curve in the middle and 10^{-22} cm^2 for top curve.

SIMPZILLA ANNIHILATION

$$\begin{tikzcd} & \chi\overline{\chi} \arrow[dl] \arrow[dr] & \\ q\overline{q} \arrow[d] & & gg \arrow[d] \\ \text{hadronic jets} & & \text{hadronic jets} \end{tikzcd}$$

– Fragmentation Function (C.Hill):

$$\frac{dN_H}{dx} = \frac{15}{16} x^{-3/2} (1-x)^2 \qquad x \equiv \frac{E}{E_{\rm jet}} = \frac{E}{m_\chi}$$

ANNIHILATION:

$2.8 \times 10^5 M_{12}^{1/2}$	$t + \bar{t}$
$1.6 \times 10^6 M_{12}^{1/2}$	Bs
$2.8 \times 10^6 M_{12}^{1/2}$	Cs
$7.4 \times 10^6 M_{12}^{1/2}$	light hadrons

ν_τs escape the Sun

τs decay before interacting !

μs and es do not

$$\nu_\tau \rightarrow \tau \rightarrow \nu_\tau \rightarrow \ldots$$
$$\nu_\mu \rightarrow \mu \; .$$
$$\nu_e \rightarrow e \; .$$

ν_τ Energy Spectrum - Core of the Sun

$$
\begin{array}{lll}
t \rightarrow W + b & & (\sim 100\%) \\
\quad \hookrightarrow \tau + \nu_\tau & & (\sim 10\%) \\
\qquad \hookrightarrow X + \nu_\tau & &
\end{array}
$$

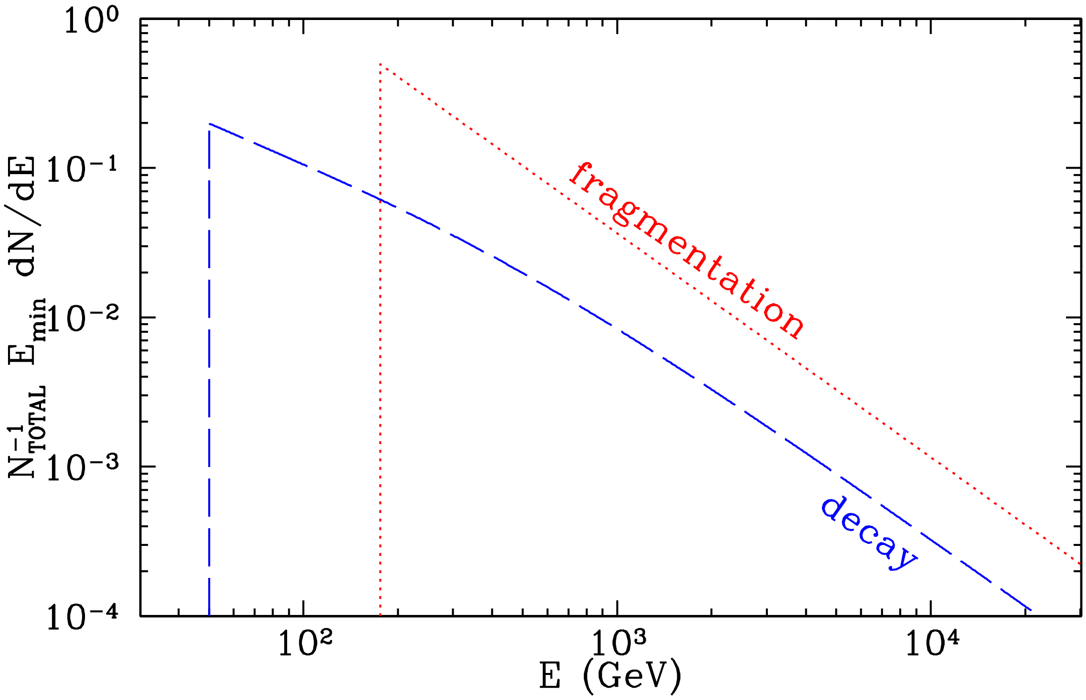
$$\frac{dN}{dE} = N \frac{E + m_W}{\sqrt{(E+m_t)[(E+m_t)^2 - m_t^2][(E+m_W)^2 - m_W^2]}}$$

$2.8 \times 10^5 M_{12}^{1/2}$ tops per χ annihilation

$5.6 \times 10^4 M_{12}^{1/2} \nu_\tau$s per χ annihilation
(from top decays)

Emission Rate $>$ 50 GeV: 20% $\Rightarrow \sim 10^4 M_{12}^{1/2} \nu_\tau$s in the core

top and ν_τ energy spectrum at core of the Sun



- Fragmentation into tops and decay into ν_τs. The decay curve has a cut at 50 GeV which is a reasonable experimental threshold.

ν PROPAGATION THROUGH THE SUN

$$f_{core} \sim 10^4 M_{12}^{1/2} \Gamma_A$$

transparency energy E_t: interaction length $\sim R_\odot$

$$E_t = 150 \text{ GeV}$$

Below E_t:

$$\left(\frac{df}{dE}\right)_{\text{unscattered}} = \left(\frac{df}{dE}\right)_{\text{core}} \exp(-\sigma_{cc}(E) \int n(r) dr)$$

Above E_t:

$$\nu_\tau \to \tau \to \nu_\tau \to \ldots$$

$\sim 20\%$ energy loss

- energy will be degraded to E_t or below and ν_τ will escape
- scatterred ν_τs have a lognormal distribution (P. Crotty - Halzen,Saltzberg)

$$\left(\frac{df}{dE}\right)_{\text{emergent}} = \left(\frac{df}{dE}\right)_{\text{unscattered}} + \left(\frac{df}{dE}\right)_{\text{scattered}}$$

ν ENERGY SPECTRUM AT EARTH

- Sun emission rate $\Rightarrow$ flux spectrum at Earth

$$\left(\frac{dF}{dE}\right)_{\oplus} = \frac{1}{4\pi D^2_{\odot\oplus}} \left(\frac{df}{dE}\right)_{\odot} = 3.5 \times 10^{-18} \left(\frac{df}{dE}\right)_{\odot} \mathrm{km}^{-2}$$

DETECTABILITY IN ν TELESCOPES

- attenuation through the Earth (just for completeness)

$$a = \exp\left(-\int n_{\oplus}\sigma_{CC}dx\right)$$

- fraction of incident ν with E that converts inside the detector:

$$\frac{dR}{dE} = a\frac{dF}{dE}[n_{\mathrm{ice}}\sigma_{cc}(E)L]A\Theta(E - 50\mathrm{GeV})$$

- ν_τs $\Rightarrow$ ONLY CONTAINED EVENTS!

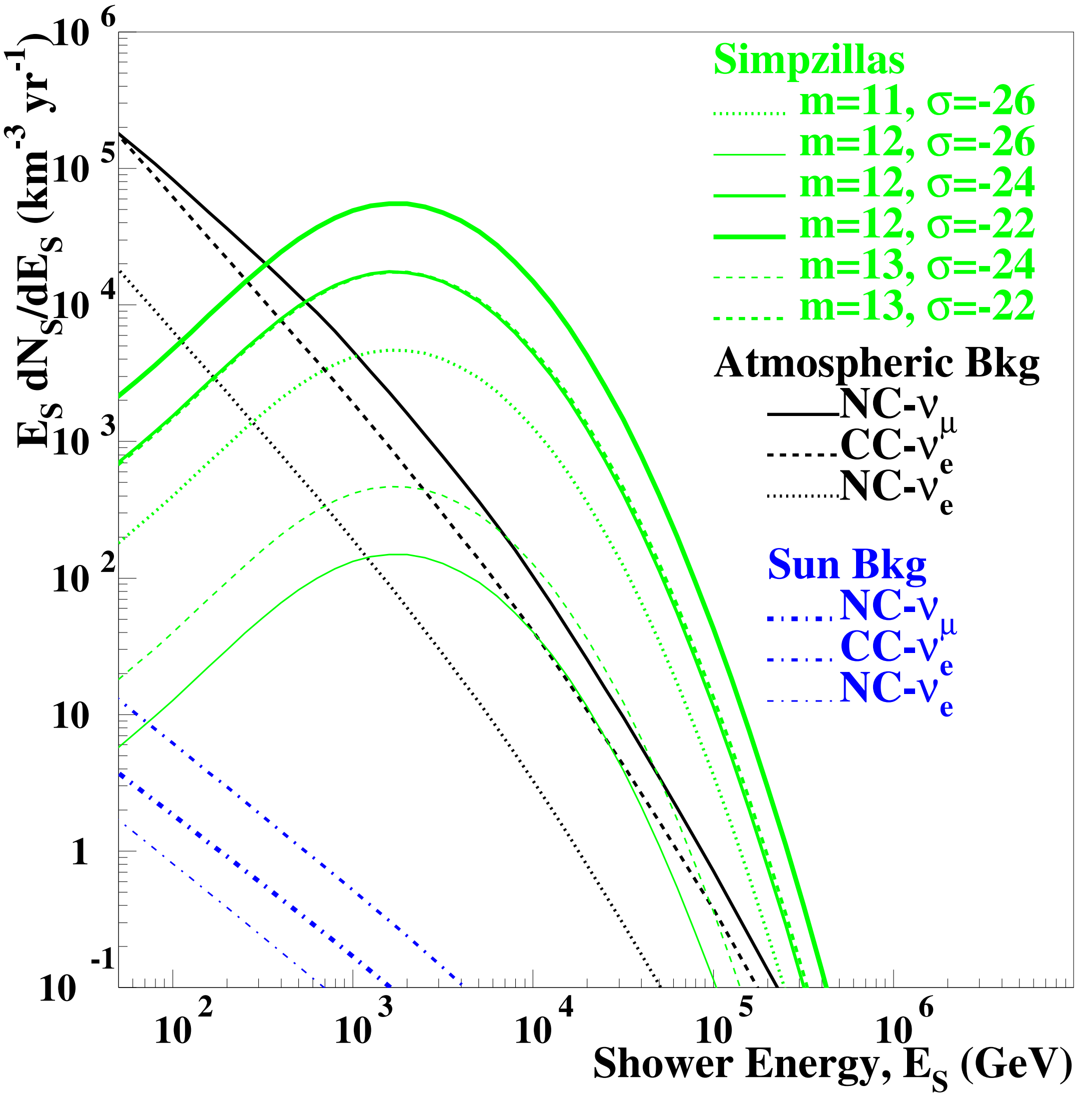
BACKGROUND

- any interaction that generate showers !
- CR interactions in Sun and Earth atmospheres (Ingelman and Thunman – Volkova)
  - $\nu_e + n \rightarrow e + X$ (CC)
  - $\nu_e + n \rightarrow \nu_e + X$ (NC)
  - $\nu_\mu + n \rightarrow \nu_\mu + X$ (CC)
- energy loss $\equiv y = (1 - E_l/E_\nu) \sim 0.2$ at HE
- Reduction
  - double bang (Learned and Pakvasa)
    above 100 TeV
    5 m separation
  - zenith angle dependence (Halzen and Saltzberg) for ν_μs and ν_es

Simpzilla spectrum softer than 100 TeV!

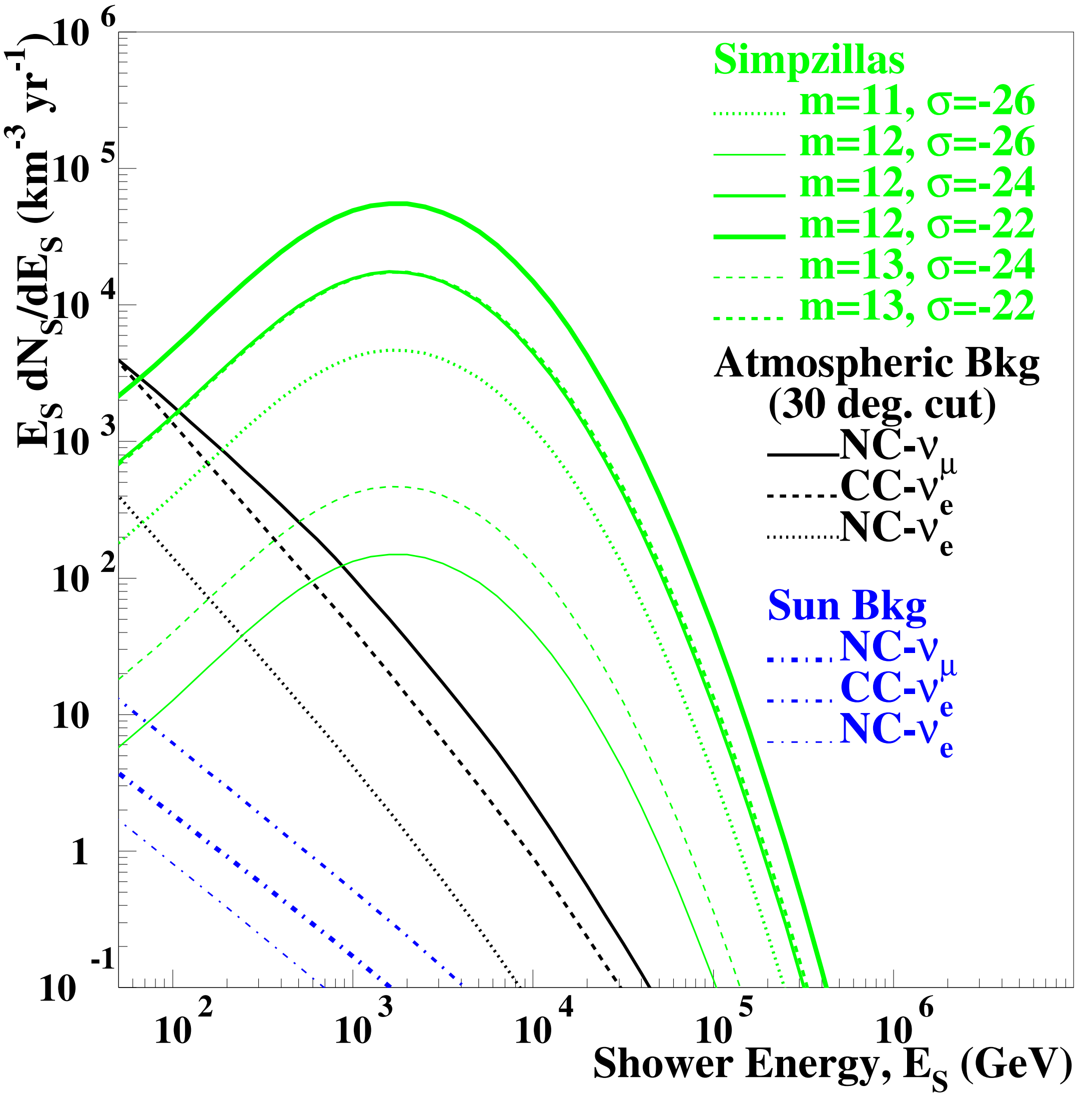
30^o angular cut

Simpzilla and Background Energy Spectra



- Simpzillas: mass in 10^m GeV, crosssection in 10^σ cm^2, shower energy from ν_τ interaction inside detector. No cut applied.

Simpzilla and Background Energy Spectra



- Simpzillas: mass in 10^m GeV, crosssection in 10^σ cm^2, shower energy from ν_τ interaction inside detector. 30^o angular cut applied.

DETECTORS
LOCATION, THRESHOLD AND VOLUME

Location

- South Pole and Mediterranean Sea $\Rightarrow$ Sun 1/2 year
- Mediterranean has lower energy threshold (same PMT distance) $\Rightarrow$ WIMPs

Energy Threshold

- Simpzilla analysis can have high threshold $\Rightarrow$ good for fighting background
- Feldman Cousins analysis to optimize energy threshold

Volume

- IceCube: 1 km^3
- ANTARES: 3×10^{-2} km^3
- AMANDA-II: 1.6×10^{-2} km^3
- NESTOR: 9×10^{-3} km^3

Table 1: Optimum energy threshold (in TeV) for Simpzilla detection. The results considering background from full sky and using a 30^o angular cut are shown.

		95% CL		
	IceCube (km3)	ANTARES	AMANDA-II	NESTOR
full sky (TeV)	20.0	6.3	4.0	3.2
30^o sky (TeV)	2.5	0.5	0.3	0.25
		5σ		
30^o sky (TeV)	1.3	0.25	0.16	0.10

- ν oscillations
  - HE $\Rightarrow$ no effect on background
  - effect on signal has to be understood
    - three flavor oscillations (A. de Gouvea)
      - $\nu_\mu \rightarrow \nu_\tau \neq \nu_\mu \rightarrow \nu_\tau$
    - no significant change in detectability
    - ν_μ detection
    - P.Crotty analysis

CONCLUSIONS

- If DM is very MASSIVE and STRONGLY interacting:
  - should be collected in $\odot$ and $\oplus$ and attain equilibrium between capture and annihilation rate.
- Annihilation will produce hadronic jets with production of HE νs..
- Only νs from top decays were considered
  - B decay should enhance the signal and conserve energy spectrum.
- ν detectors of a km^3 scale (ICE3 or expanded ANTARES or NESTOR) can confirm or exclude the most natural scenarios for SIMPZILLAS.
- Smaller detectors (ANTARES, AMANDA-II and NESTOR) can probe a large region of the Simpzilla parameter space.