Dark Matter Induced Neutrinos from the Sun

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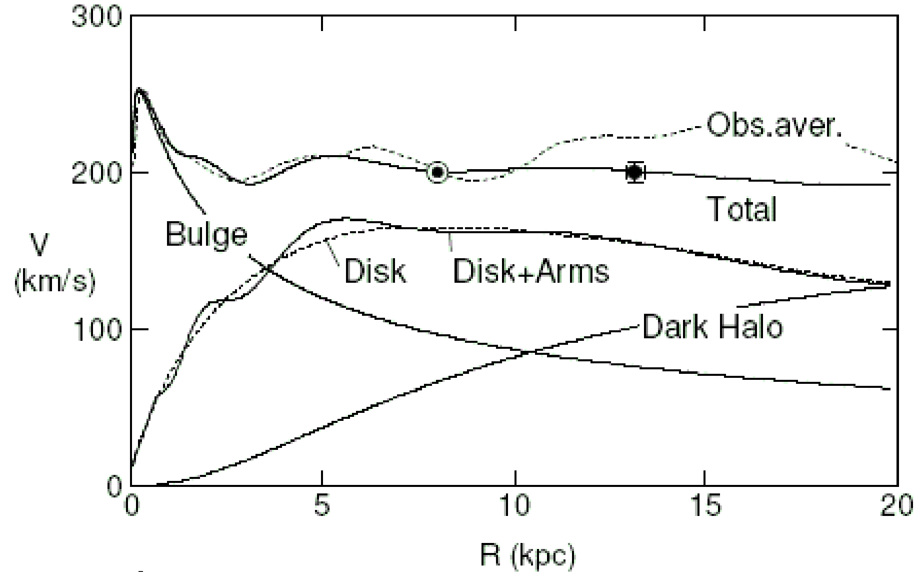
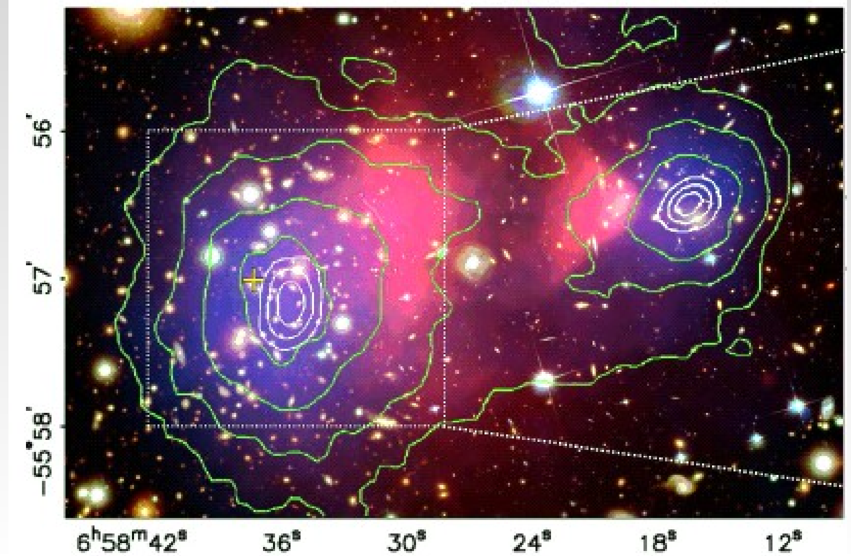
Dark Matter Implications

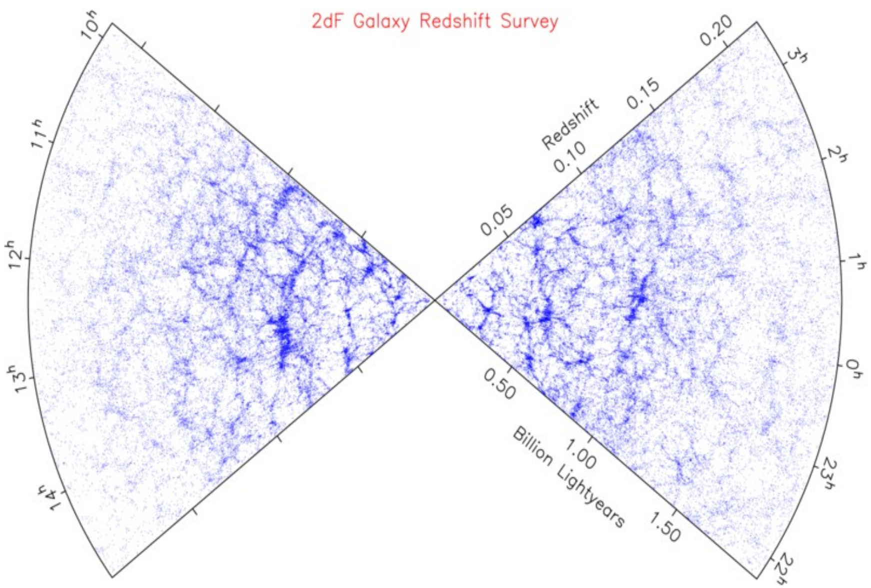
Milky Way rotation curve

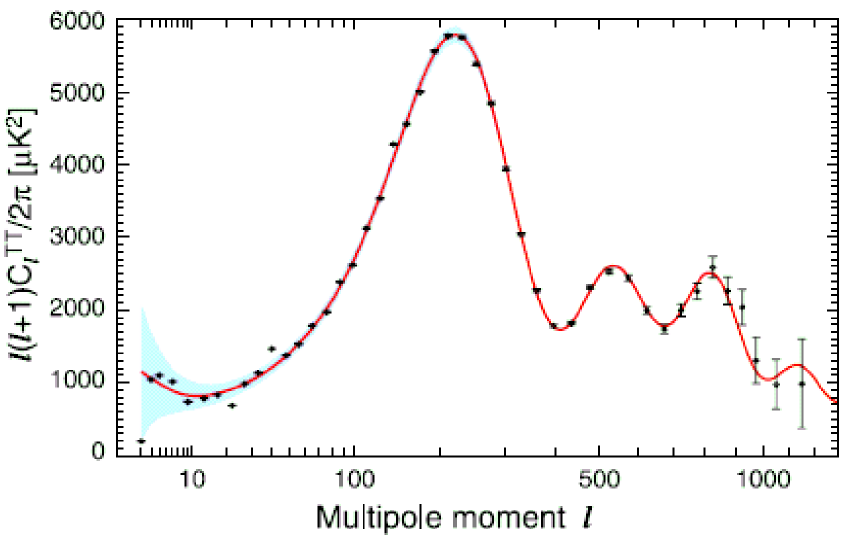


1E0657-56 'Bullet cluster'



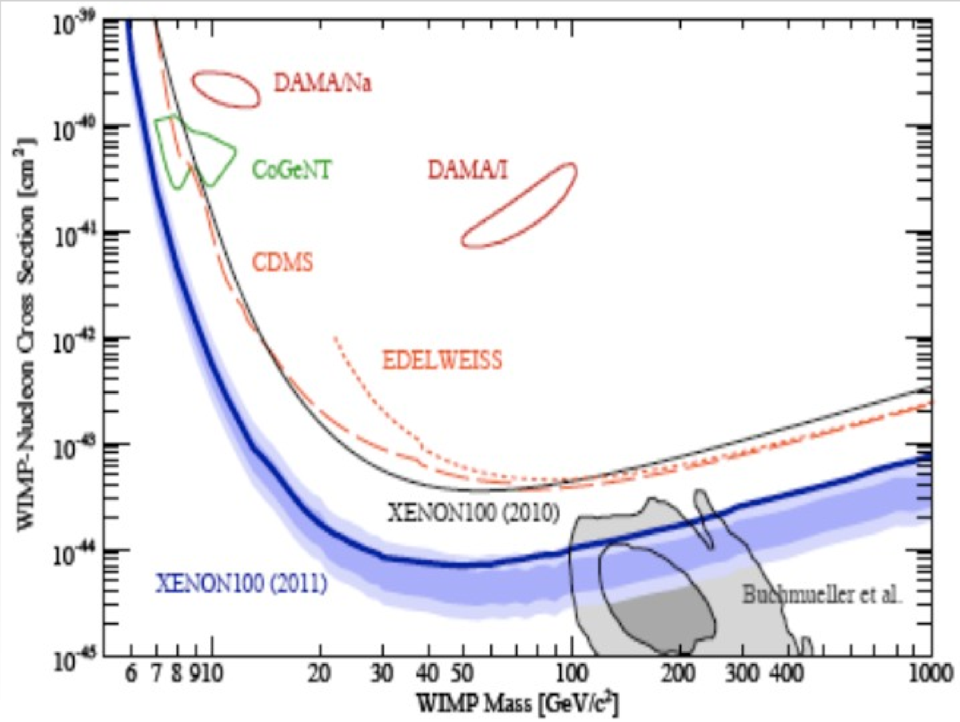
Large scale structure





CMB, WMAP 7 yr

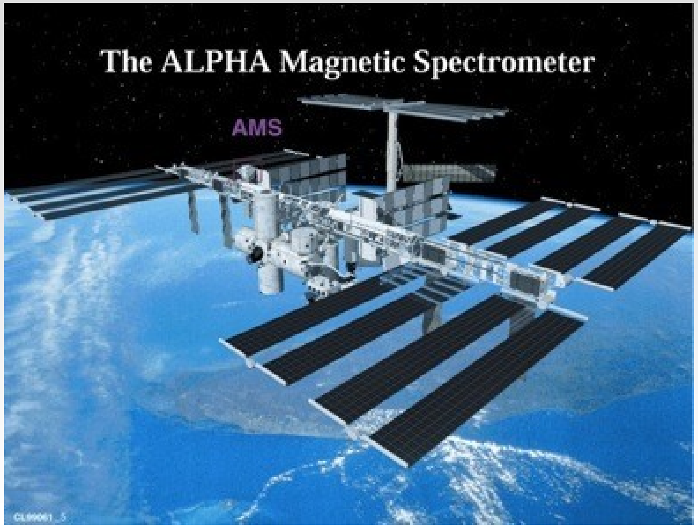
Searches for DM

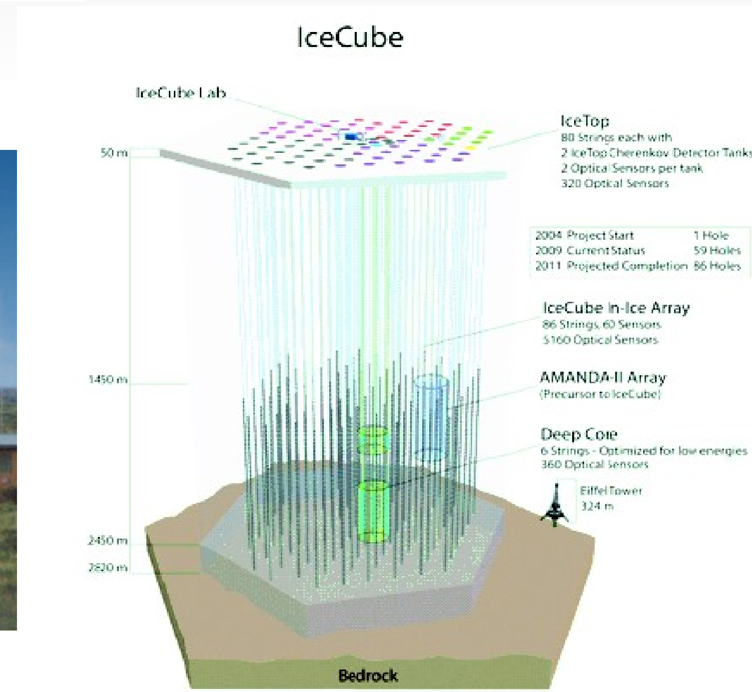


Nuclear recoils:
Upper bound on WIMP- nucleon scattering cross-section

Collider searches
Search for large missing E_T

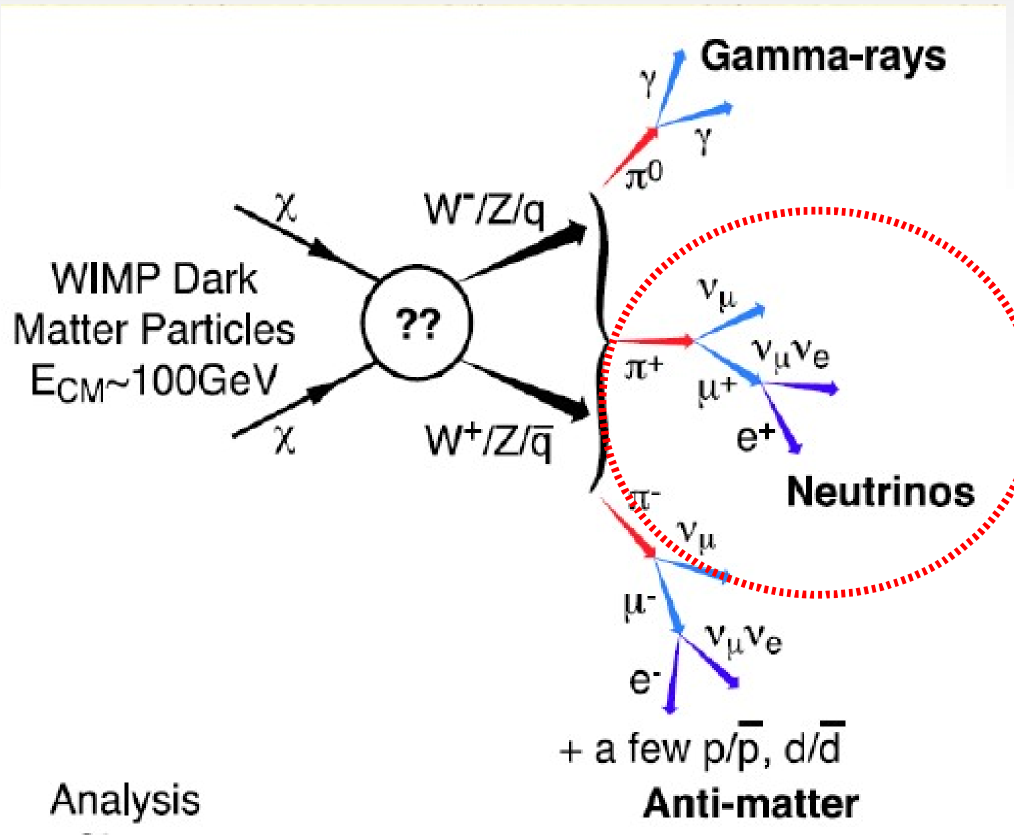
Cosmic Ray Experiments



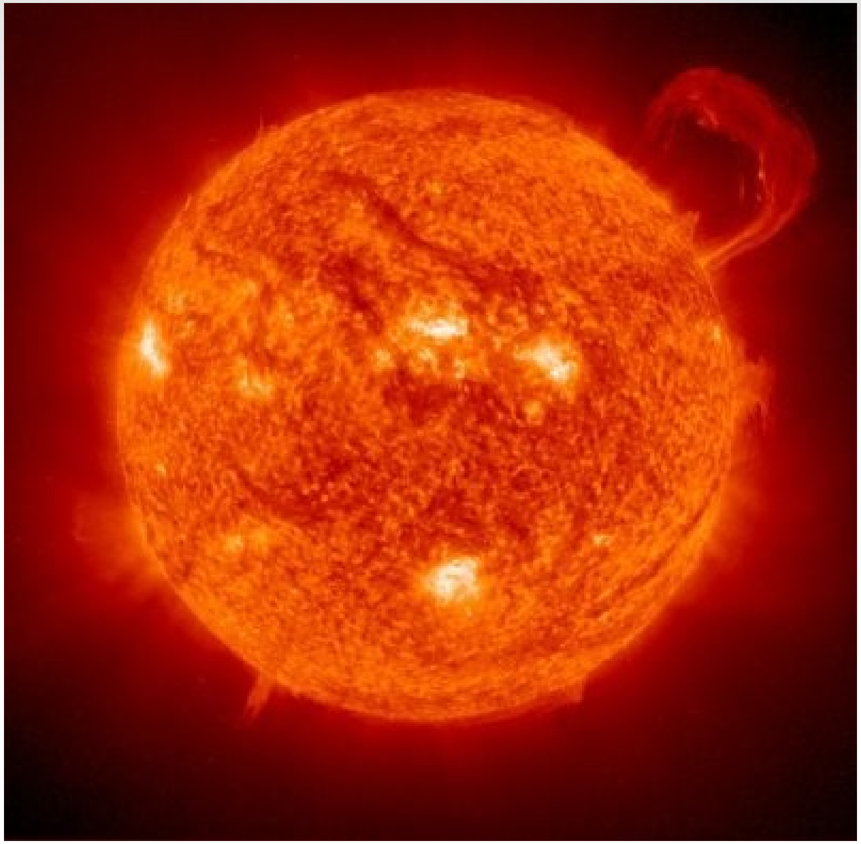


What is in the slides...

- Neutrinos from dark matter annihilations at the center of the Sun



Solar DM neutrino signal: three stage process



- Dark matter capture/annihilation in the Sun
- Neutrino propagation
- Event rates at the IceCube/DeepCore detector

Wimp Capture

- Solar gravity accelerates pass-by wimps
- WIMP-nuclear scattering: wimp velocity below escape velocity and becomes gravitationally captured

$$\frac{\mathrm{d}C_i}{\mathrm{d}M}(v) = \frac{\rho_\chi \sigma_i}{m_\chi m_i}\,\epsilon_i \int \mathrm{d}^3u\, \frac{f(u)}{u}\,(u^2+v^2)\,\mathcal{G}_i(u,v)$$

Velocity distribution * "capture-scatter" probability

Gould, 1987

- Chemical composition:

  H, He + heavier elements

- Large escape velocity

  ~ 1300 km/s at center, 800 km/s at surface

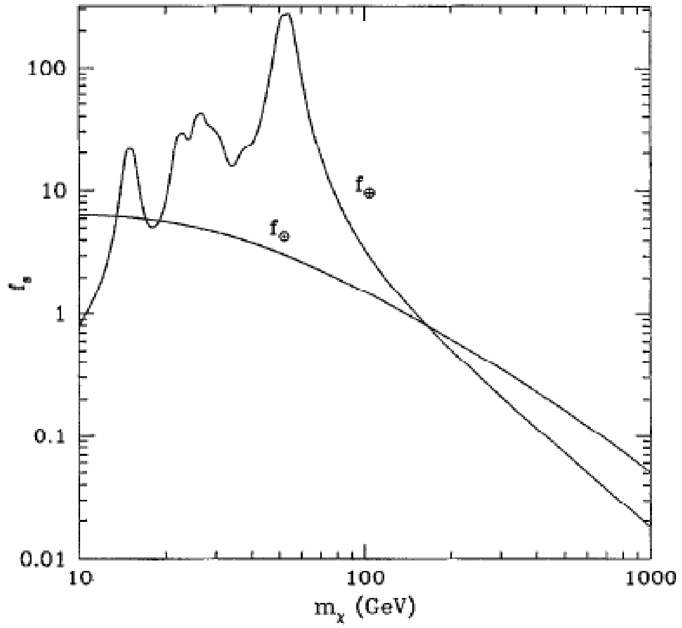
- Spin-dependent scattering:
  mainly off hydrogen
- Spin-independent scattering:
  A^4 enhancement, heavy elements are important

$$C_C^{SI} = 4.8 \times 10^{28} s^{-1} \frac{\rho_{0.3}}{\bar{v}_{270} m_{DM}} \sum_i F_i f_i \phi_i \frac{\sigma_i^{SI}}{m_{N_i}} S\left(\frac{m_{DM}}{m_{N_i}}\right)$$

$$C_C^{SD} = 1.3 \times 10^{29} s^{-1} \frac{\rho_{0.3}}{\bar{v}_{270} m_{DM}} \sigma_H^{SD} S\left(\frac{m_{DM}}{m_{N_i}}\right)$$

J.K.G. 1996

- Kinematical factor $S(m_X/m_N)$:
  wimp mass close to abundant nuclear masses receives a bonus



Thermalization

- Solar center temperature: 10^7 K

  equilibrium r ~ 1/1000 solar radius

- Wimps wimps lose energy and settle inside the Sun

  Thermal equilibrium: stopping time << solar age

Annihilation in the center

- Small region near the solar center
- Non-relativistic annihilation, velocity suppression, Sommerfeld enhancement may apply

DM density evolution equation

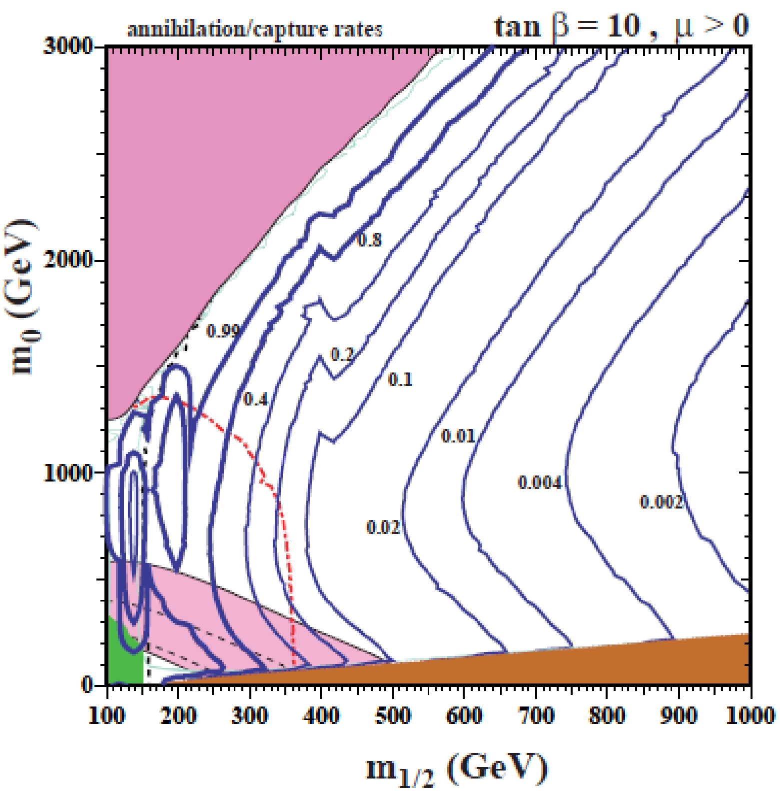
$$\frac{\mathrm{d}N}{\mathrm{d}t} = C - C_E N - C_A N^2$$

capture — evaporation — annihilation

Equilibrium!

- DM density builds up over time
- Annihilation negates capture rate

$$C_A = <\sigma_A v> \left(\frac{3kT_c}{2Gm_\chi \rho_c}\right)^{-3/2}$$



$$2\Gamma = C \tanh^2\left(\frac{t_\odot}{\tau}\right)$$

$$\tau = 1/\sqrt{CC_A}$$

Equilibrium isn't always reached!

J. Ellis, et. al. 2009

Neutrino Propagation

- Standard 3-gen propagation:

vac oscillation+ matter effects + scattering

$$\frac{d\boldsymbol{\rho}}{dr} = -i\left[\mathbf{H}, \boldsymbol{\rho}\right] - \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{NC,CC}$$

$$\mathbf{H} = \frac{1}{2E_\nu}\mathbf{V}\,\mathbf{diag}\left(0, \delta m^2_{21}, \delta m^2_{31}\right)\mathbf{V}^\dagger \pm \sqrt{2}G_F n_e \mathbf{diag}(1,0,0)$$

Oscillation is independent of the absolute nu mass scale

matter effect term flip sign between nu and anti-nu

diagonal terms are conserved inside homogeneous medium

DM neutrinos from the Solar center ...

- Low production rate: incoherent at the source

- Each ν propagates on its own: mixed flavors can be propagated separately, independent of initial phases

- Time/spatial averaging: removing oscillatory (off-diagonal) terms on the mass basis

Collisions: (NC+CC)

- Neutral current (NC) scattering
  - t-channel Z exchange
  - flavor independent
  - soften neutrino spectrum

- Charged current (CC) scattering
  - t-channel W exchange
  - flavor independent for $E > m_l$
  - neutrino flux attenuation
  - regeneration

Tau regeneration

- Neutrino regeneration:

$$\nu \xrightarrow{CC} l \xrightarrow{decay} \nu \longrightarrow \dots \longrightarrow \nu \longrightarrow l \longrightarrow \nu$$

High energy — low energy

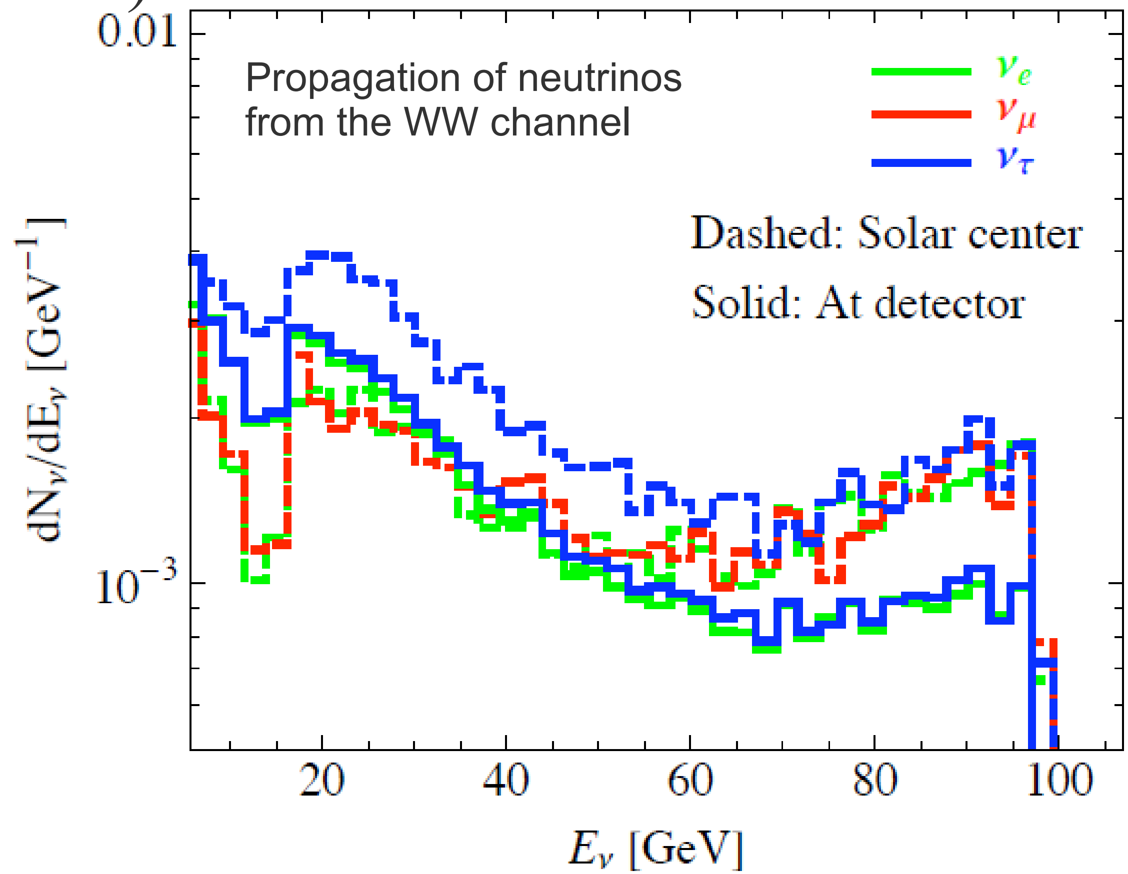
- τ decay's leptonic branching: 36%

ν_τ re-gen creates secondary *e, μ* anti-neutrinos

- ν_μ regeneration negligible

Propagation effects

- Spectra smeared towards lower energy
- Fully mixed $\nu_\mu \nu_\tau$: almost identical spectra at the solar surface (on ave.)
- Vacuum oscillation:
  Only the diagonal terms inside $\boldsymbol{\rho}$ are kept



Spin-correlated calculation of the neutrino source spectrum

Madgraph/Pythia/Calchep

Annihilation channels

- Monotonic neutrinos

$$\chi\chi \longrightarrow \nu\bar{\nu}$$

"Hard channels"

- Gauge boson production

$$\chi\chi \longrightarrow WW,\ ZZ,\ Zh,\ \ldots$$

- Heavy fermion production

$$\chi\chi \longrightarrow \tau\bar{\tau},\ c\bar{c},\ b\bar{b},\ t\bar{t}$$

"Soft channels"

Spin correlation

- Non-relativistic chirality suppression

  $\nu\bar{\nu}$ channel forbidden for self-conjugate spin-1/2 or spin-0 wimps;

- Polarization in W Z decays

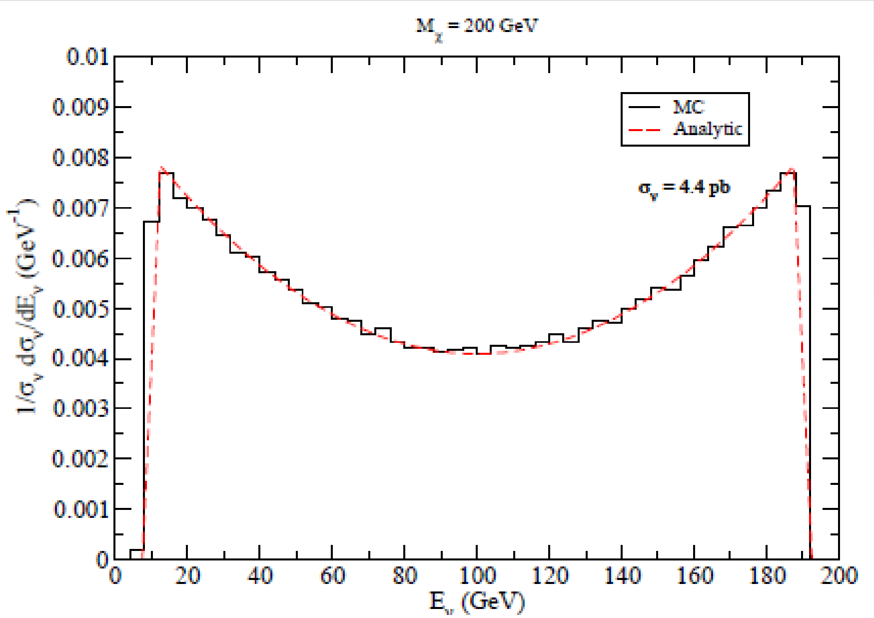
spin	s-channel Higgs	t, u-channel fermion	t, u-channel boson
0	LL, TT	X	LL
$\frac{1}{2}$	0	TT	X
1	LL, TT	X	LL, TT

Wai-Yee Keung, et. al. 2008

- τ helicity

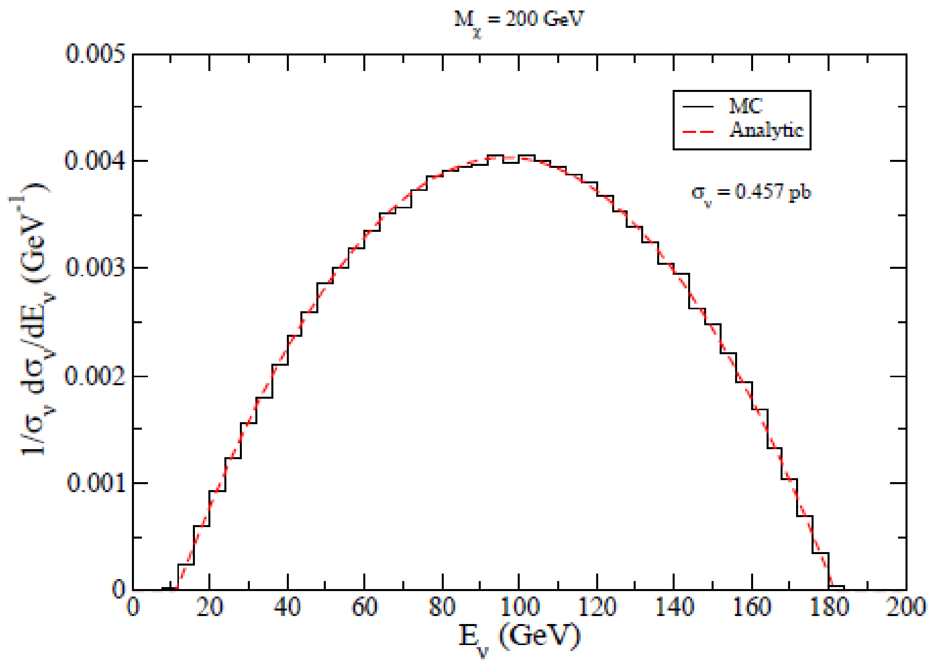
Transverse W/Z and left-handed τ produce harder neutrino spectra

W/Z polarization



Transverse polarization:
Concave ν spectrum
Example: $\chi\chi \to W^+W^-$

Longitudinal polarization:
Convex ν spectrum
Example: $\chi\chi \to Zh$

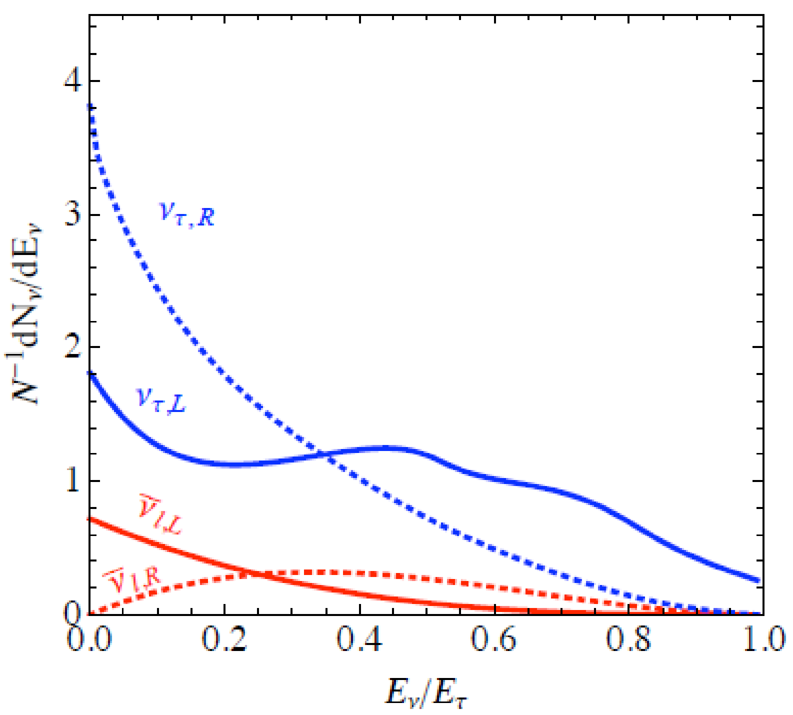


Handedness in tau decay

- Higher neutrino production rate from (left)right-handed (anti-)taus

P: τ helicity number

$$\frac{1}{N_0}\frac{dN}{dy} = g_0(y) + P g_1(y)$$



Decay mode (ν_τ)	BF	$g_0(y)$	$g_1(y)$
$\nu_\tau \ell \bar{\nu}_\ell$	0.18	$\frac{5}{3} - 3y^2 + \frac{4}{3}y^3$	$\frac{1}{3} + \frac{8}{3}y^3 - 3y^2$
$\nu_\tau \pi$	0.12	$\frac{1}{1-r_\pi}\theta(1-r_\pi-y)$	$-\frac{2y-1+r_\pi}{(1-r_\pi)^2}\theta(1-r_\pi-y)$
$\nu_\tau a_1$	0.13	$\int_y^1 f_0^*(x)x^{-1}dx$	$\int_y^1 (y-2x)f_1^*(x)x^{-2}dx$
$\nu_\tau \rho$	0.26	$\int_y^1 f_0^*(x)x^{-1}dx$	$\int_y^1 (y-2x)f_1^*(x)x^{-2}dx$
$\nu_\tau X$	0.13	$\int_y^1 f_X(x)x^{-1}dx$	0
Decay mode ($\bar{\nu}_l$)	BF	$g_0(y)$	$g_1(y)$
$\nu_\tau \ell \bar{\nu}_\ell$	0.18	$2 - 6y^2 + 4y^3$	$-2 + 12y - 18y^2 + 8y^3$

f(x): neutrino spectrum harmonics in τ's rest frame
asterisk: smeared f functions by particle width

Absorptions in the Sun

- Muons, light hadrons are completely absorbed before decay
- c, b hadrons may decay before scattering
- Elastic scattering / inelastic scattering / decay probabilities calculated during showering Monte Carlo

Numerical implementation

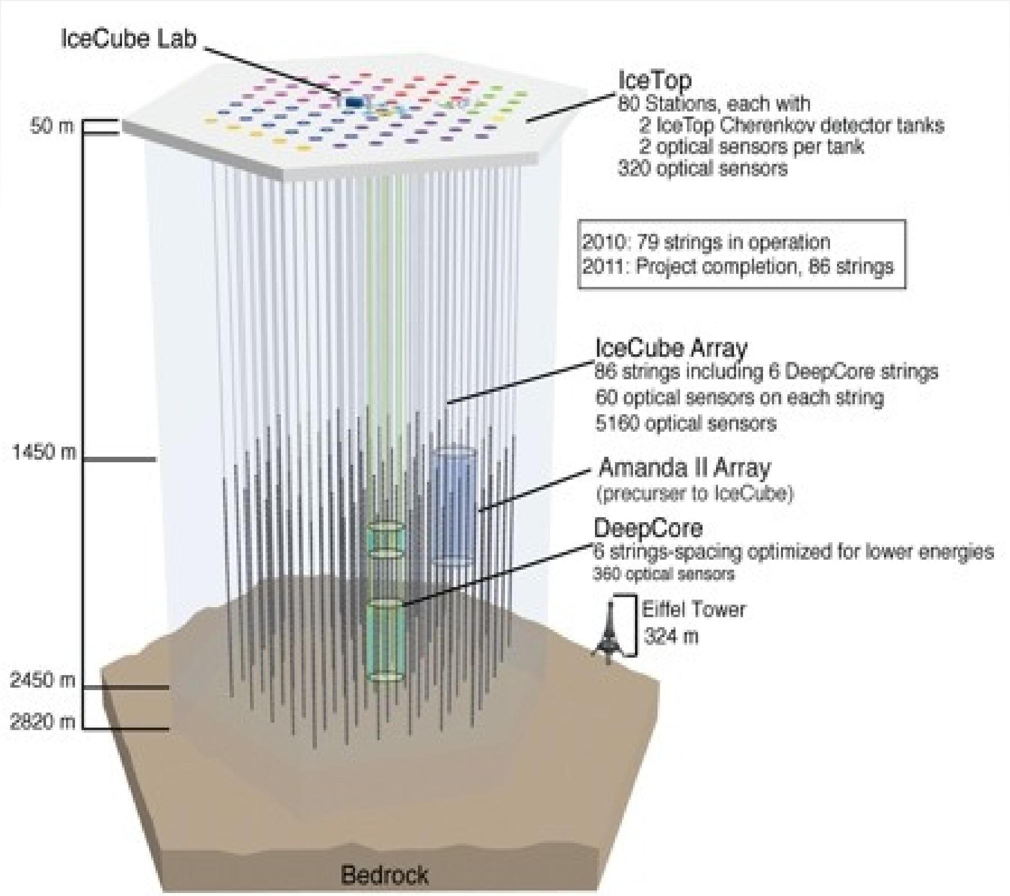
- Parton level @ Madgraph/ Calchep
- Showered by Pythia6
- τ helicity decay treated separately
- Modified Pythia shower for b,c hadron absorption

Channel	Final state
W^+W^-	$W^{+*}\bar{\nu}_\tau\tau^-$, $W^{+*}s\bar{c}$, $W^{+*}d\bar{c}$
$t\bar{t}$	$t^*\bar{b}\bar{\nu}_\tau\tau^-$, $t^*\bar{b}s\bar{c}$, $t^*\bar{b}d\bar{c}$
ZZ	$Z^*\tau^+\tau^-$, $Z^*\nu_l^+\nu_l^-$, $Z^*b\bar{b}$, $Z^*c\bar{c}$
Zh	$h^*\tau^+\tau^-$, $h^*\nu_l^+\nu_l^-$, $h^*b\bar{b}$, $h^*c\bar{c}$,
	$Z^*\tau^+\tau^-$, $Z^*b\bar{b}$, $Z^*c\bar{c}$
$\tau^+\tau^-$	$\tau^+\tau^-$
$b\bar{b}$	$b\bar{b}$
$c\bar{c}$	$c\bar{c}$

Particles with * are made stable inside shower

Neutrino events at IceCube/DeepCore

- Cerenkov detector at the South Pole
- Good ν_μ angular resolution
- Low energy threshold (DeepCore)
- Known atmospheric background (Super-K)



Event categories

- (Contained events) Muon tracks initiated inside detector

$$\frac{d\phi_\mu}{dE_\mu d\Omega} = V(E_\mu)\eta(\theta_z)\int_{E_\mu}^{E_\nu^{max}} dE_\nu \sum_{i=\nu_\mu,\bar{\nu}_\mu} n_{n/p} \frac{d\sigma_i^{n/p}(E_\nu, E_\mu)}{dE_\mu} \frac{d\phi_\nu^i}{dE_\nu}$$

- (Up-going events) muon tracks initiated outside detector

$$\frac{d\phi_\mu}{dE_\mu d\Omega} = A_\mu(E_\mu, \theta_z) \int_0^\infty dz \int_{E_\mu}^{E_\nu} dE_\mu^0 \; P(E_\mu^0, E_\mu; z)$$
$$\int_{E_\mu}^{E_\nu^{max}} dE_\nu \sum_{i=\nu_\mu,\bar{\nu}_\mu} n_{n/p} \frac{d\sigma_i^{n/p}(E_\nu, E_\mu^0)}{dE_\mu^0} \frac{d\phi_\nu^i}{dE_\nu}$$

- (Cascade events) hadronic showers, poor angular res.

'up-going events': muon propagation

- Muon loses energy before reaching the detector
- Important for thin detectors (Amanda)
- Muon propagation:

$$v_\mu \, \partial_z \phi_\mu(E_\mu, z) = -\int_0^{E_\mu} dE'_\mu \phi_\mu(E_\mu, z) n(z) \frac{d\sigma(E_\mu, E'_\mu)}{dE'_\mu} + \int_{E_\mu}^{E_{max}} dE''_\mu \phi_\mu(E''_\mu, z) n(z) \frac{d\sigma(E''_\mu, E_\mu)}{dE''_\mu} + \partial_{E_\mu}(\alpha(E_\mu)\phi_\mu(E_\mu, t))$$

- Muon energy loss calculation

Average E_{loss} :
$$\frac{dE_\mu}{dz} = -\rho(\alpha + \beta E_\mu)$$

MMC (monte carlo)

Background: atmospheric neutrinos

- Neutrinos from cosmic ray hitting atmosphere as the major background for up-ward neutrinos
- Dominantly ν_μ and ν_e (from hadronic shower)
- Measured by Super-Kamiokande [Honda, 2006]

Tracking the Sun

$$\theta_z(t) = 90^\circ + 23.43^\circ \sin(2\pi t) \qquad (0 \leqslant t \leqslant 0.5)$$

t: time of the year

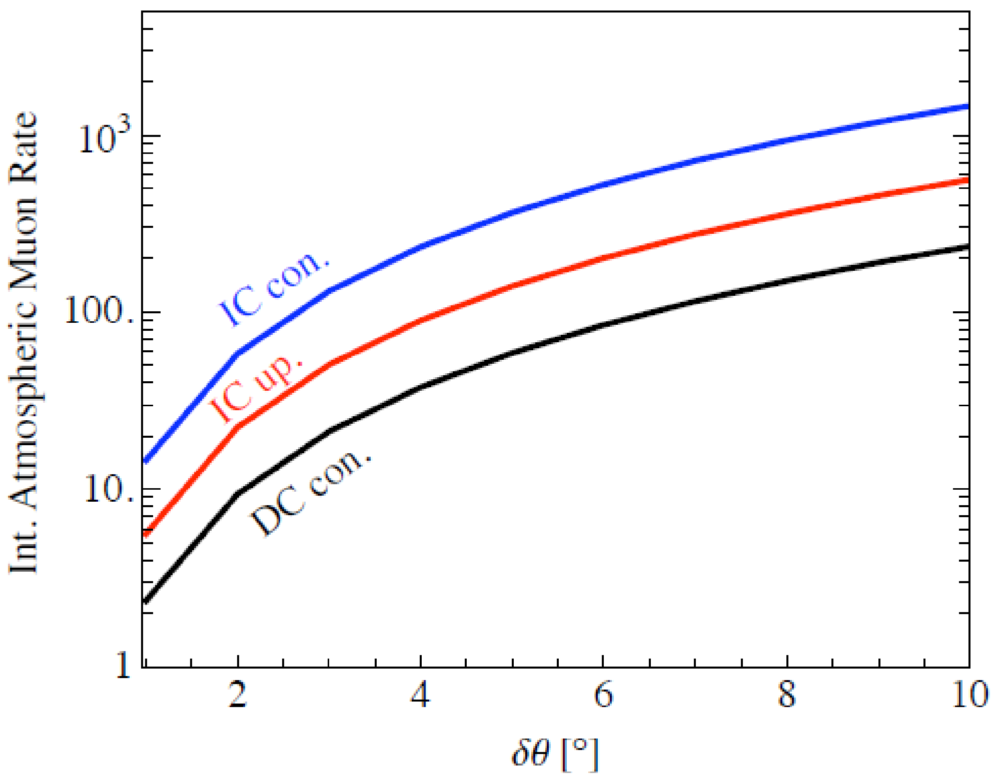
Point source against angular resolution

- Angular resolution limited by kinematics at low energy
- Atm. flux increases as $\delta\theta^2$

Bkg muon events at $\delta\theta$=1°

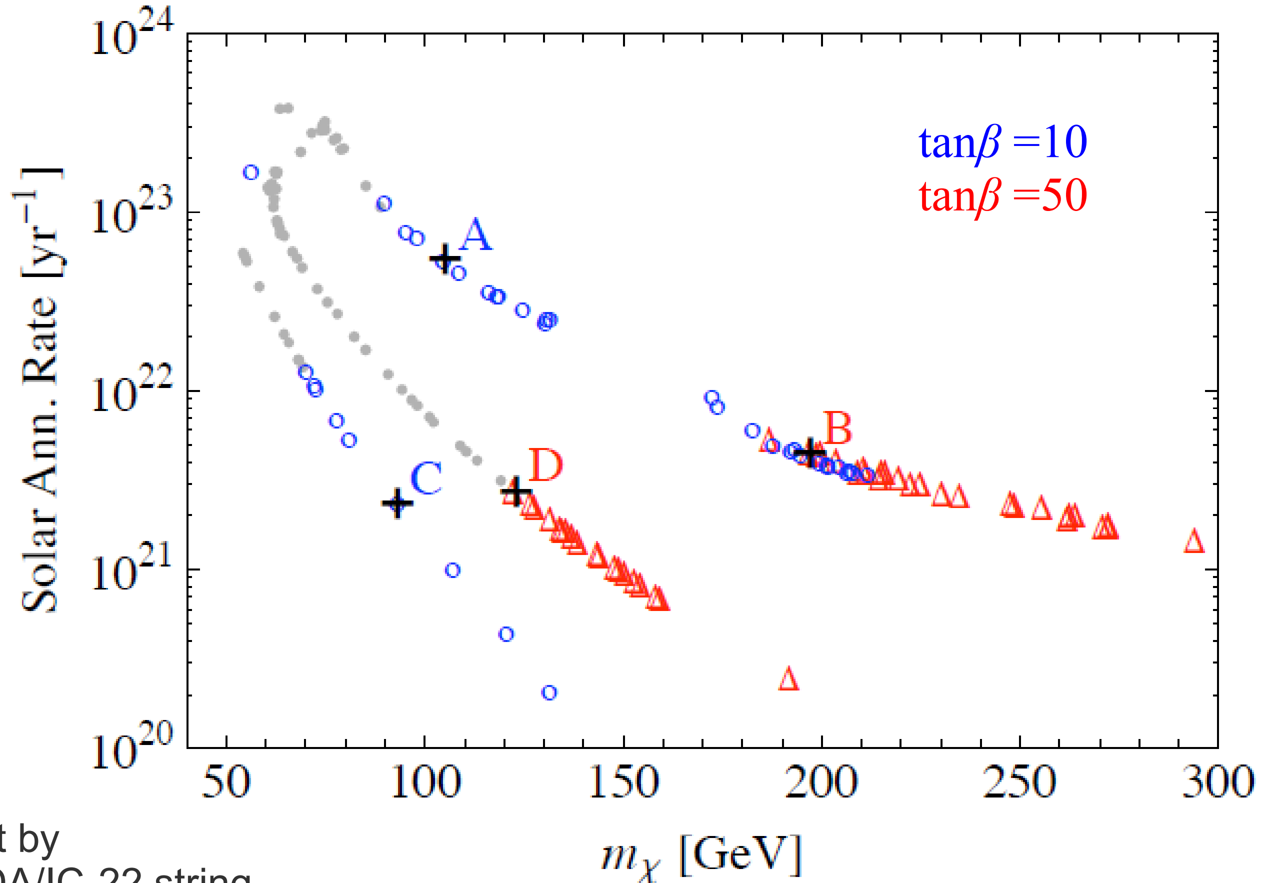
	Event # [(half) yr^{-1}]	μ threshold [GeV]
IC contained*	14	100
	21	70
IC up-going	5.6	100
	6.1	70
DC	2.3	35

IC values are for half-year
* theoretical upper limit, w/o cuts



Searching for "good" mSUGRA points

- Large capture/annihilation rate
- Wimp mass above IC/DC threshold
- Neutrino copious annihilation channels



Gray points: ruled out by XENON100+ AMENDA/IC-22 string

Benchmark points

Point	m_0	$m_{1/2}$	A_0	$\tan\beta$	m_{χ^0}	$\tau^+\tau^-$	W^+W^-	ZZ	$b\bar{b}$	$c\bar{c}$	$t\bar{t}$	Ann.(s^{-1})
A (Focus Point)	2154	288	0	10	105	—	90%	8.4%	1.0%	0.11%	—	5.4×10^{22}
B	2268	488	0	50	197	1.3%	12%	5.4%	9.5%	—	69%	4.4×10^{21}
C ($\tilde{\tau}$ co-ann.)	54	241	0	10	93	16%	4.4%	—	76%	—	—	2.3×10^{21}
D (A-funnel)	483	304	0	50	123	12%	—	—	88%	—	—	2.7×10^{21}
E ($\tilde{t}$ co-ann.)	150	302	-1099	5	121	95%	0.24%	—	2.9%	—	—	1.2×10^{18}
F (Bulk)	80	170	-250	10	64	36%	—	—	63%	—	—	7.7×10^{21}
G (h-funnel)	2000	130	-2000	10	55	7.4%	—	—	83%	3.5%	—	4.4×10^{16}

Signal rates

Source	IC up.	IC con.*	IC up.	IC con.*	DC
$E^{\mu}_{\rm thr}$ (GeV)	100	100	70	70	35
Atm. bkg.	5.6	14	6.1	21	2.3
A	1.8×10^{-4}	0.042	8.2	9.7×10^{2}	196
B	2.4	66	5.4	1.7×10^{2}	21
C	0	0	0.016	2.9	2.2
D	0.011	1.3	0.18	14	3.2
E	3×10^{-5}	4×10^{-3}	6×10^{-4}	0.05	0.011
F	0	0	0	0	4.3
G	0	0	0	0	$\sim 10^{-6}$

Signal rates

Source	IC up.	IC con.	IC up.	IC con.	DC
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B	2.4	66	5.4	1.7×10^{2}	21
C	0	0	0.016	2.9	2.2
D	0.011	1.3	0.18	14	3.2
E	3×10^{-5}	4×10^{-3}	6×10^{-4}	0.05	0.011
F	0	0	0	0	4.3
G	0	0	0	0	$\sim 10^{-6}$

W/Z dominated

$t\bar{t}$ dominated

$b\bar{b}$ dominated

$\tau\bar{\tau}$ dominated

wimps too light

too few captures

Summary

- TAKE-HOME INFO
- Detection level: 10^{21} annihilations per second for WIMP mass ~ 10^2 GeV
- Signal depends on both annihilation and nucleon scattering cross-sections
- Signal is annihilation channel dependent
- (Signal) ν energy spectrum reconstruction needs high statistics

- OUR Calculation:
- Spin-correlation for primary (partially in secondary) neutrinos from DM annihilation
- Full propagation effects on neutrino spectra
- Contained/Up-going event rates for IceCube/DeepCore detector