Dark matter searches with icecube

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Kavli Institute, 11 June, 2013

Thanks in absentia to C. Rott, M. Danninger, J. Miller, R. Reimann

- **IceCube is complete:** taking data with 86 strings since May 2011
- Results from 2010/11 (79/86 strings) are being released
- Analyses on 86 strings in the pipeline
- The low-energy extension, DeepCore, useful to lower energy threshold to ~ 10 GeV

  Already useful in converting IceCube to an all-sky detector:

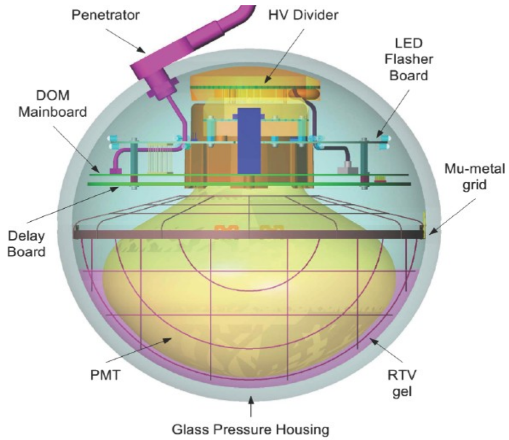
  IceCube reaches the Southern Sky (Galactic Center)

  doubles exposure of the detector for solar DM searches
- competitive limits on dark matter searches
- on the high-energy side: ν_e atmospheric neutrinos

  observation of $\mathcal{O}$(100)TeV-PeV events

  sensitivity to point sources reaching the level where a non-observation constrains models (GRBs for example)
- several "target of opportunity" programs with satellites, CTAs and GW detectors working

THE ICECUBE NEUTRINO TELESCOPE



- PMT: Hamamatsu, 10''
- Digitizers:
  - ATWD: 3 channels. Sampling 300MHz, capture 400 ns
  - FADC: sampling 40 MHz, capture 6.4 μs
  - Dynamic range 500pe/15 nsec, 25000 pe/6.4 μs
- Flasher board:
  - 12 controllable LEDs at 0° or 45°

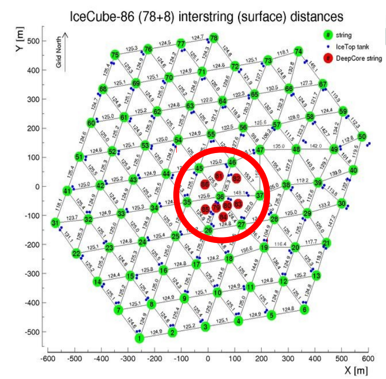
- Dark Noise rate ~ 400 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Timing resolution ≤ 2-3 ns
- Power consumption: 3W

Clock stability: 10^{-10} ≈ 0.1 nsec / sec
Synchronized to GPS time every ≈5 sec at 2 ns precision

IceTop: Air shower detector

80 stations/2 tanks each

threshold ~ 300 TeV



InIce array:

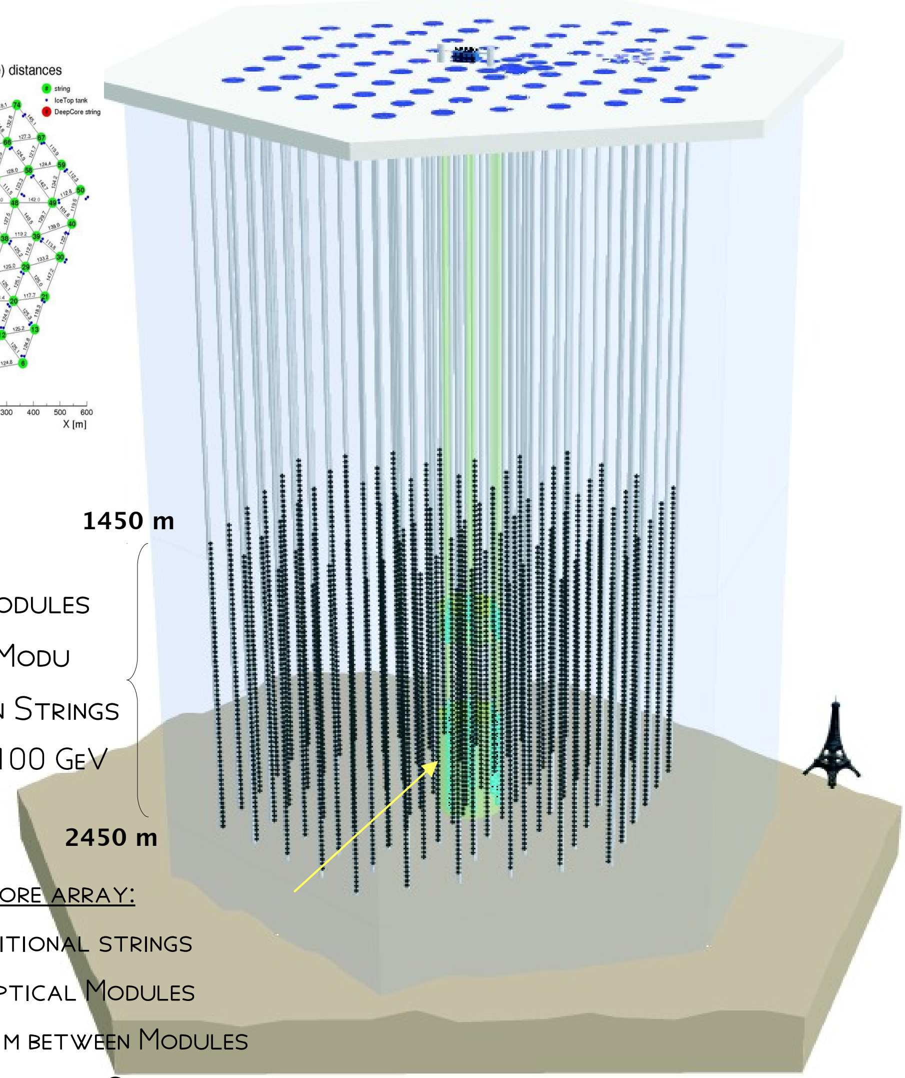
80 Strings

60 Optical Modules

17 m between Modu

125 m between Strings

ν threshold ≲ 100 GeV



DeepCore array:

6 additional strings

60 Optical Modules

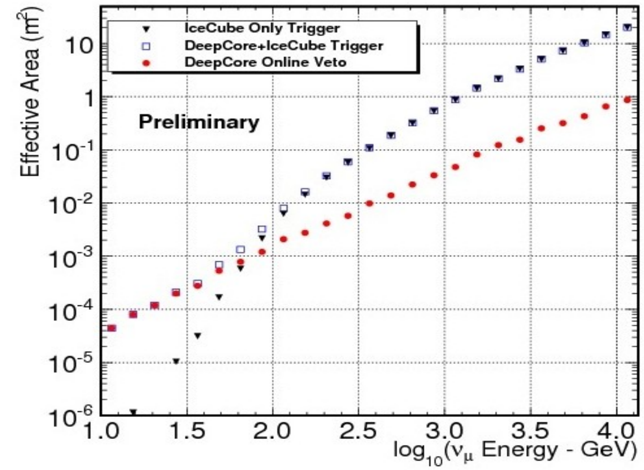
7/10 m between Modules

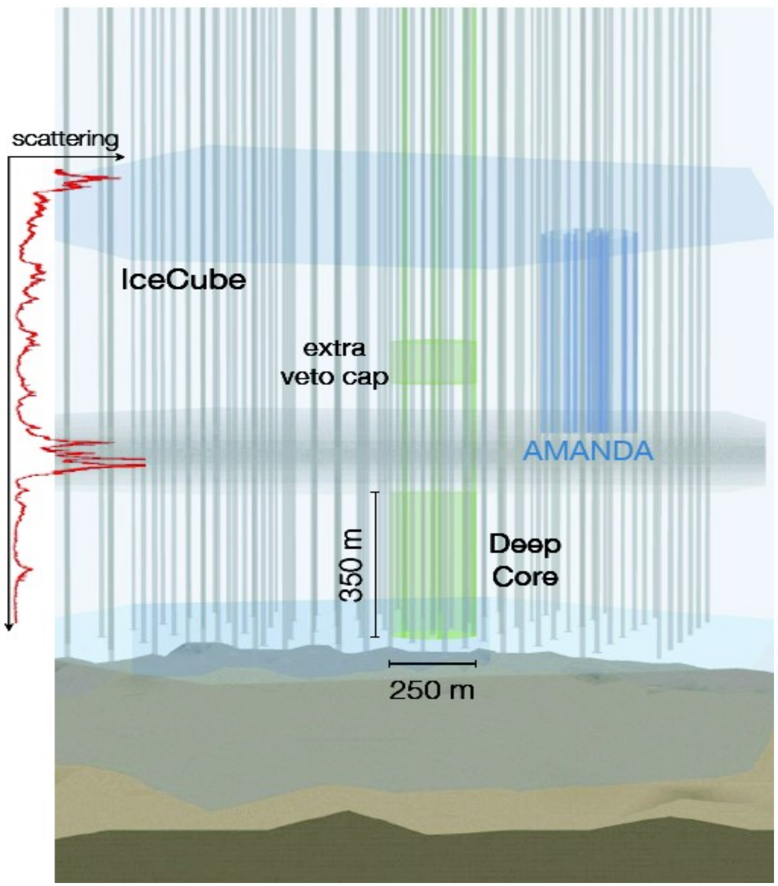
72 m between Strings

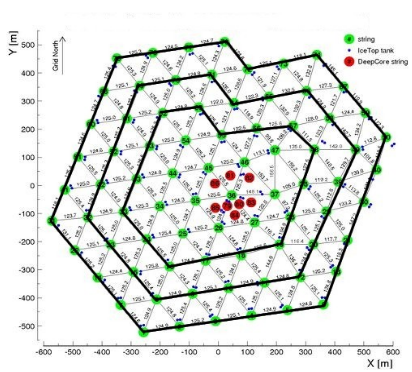
ν threshold ~ 10 GeV

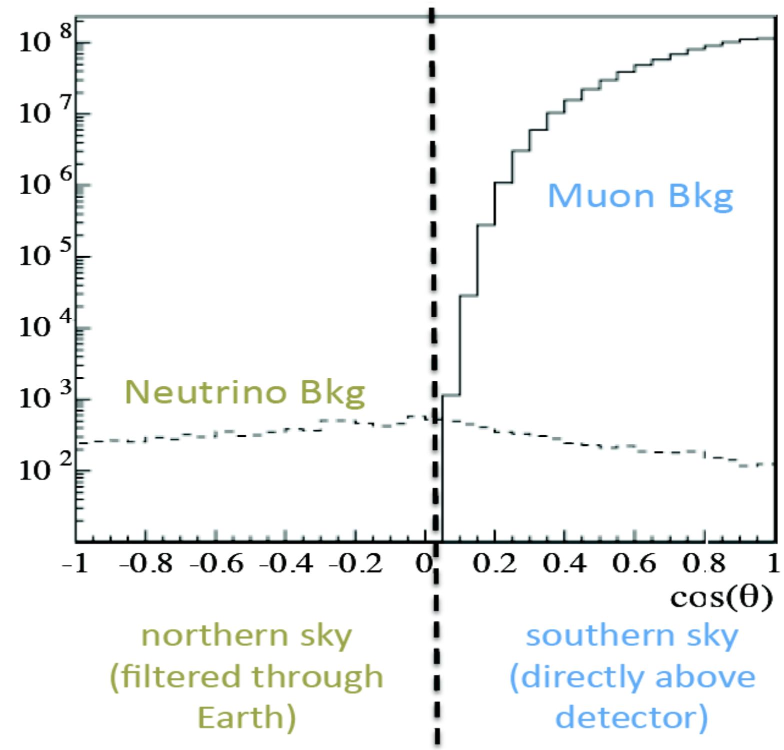
Complete detector → **full sky sensitivity** using IceCube outer strings as a veto

Define starting tracks == neutrinos









Complete detector → **full sky sensitivity**
using IceCube outer strings as a veto

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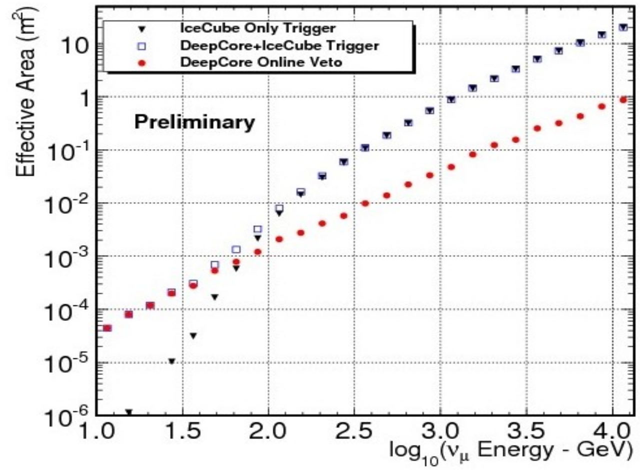

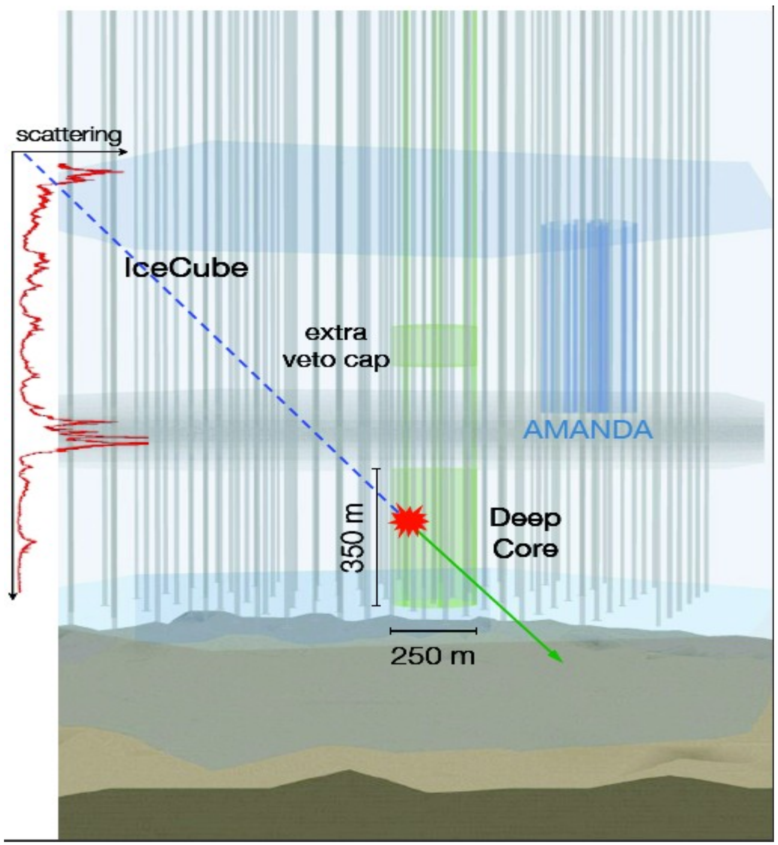

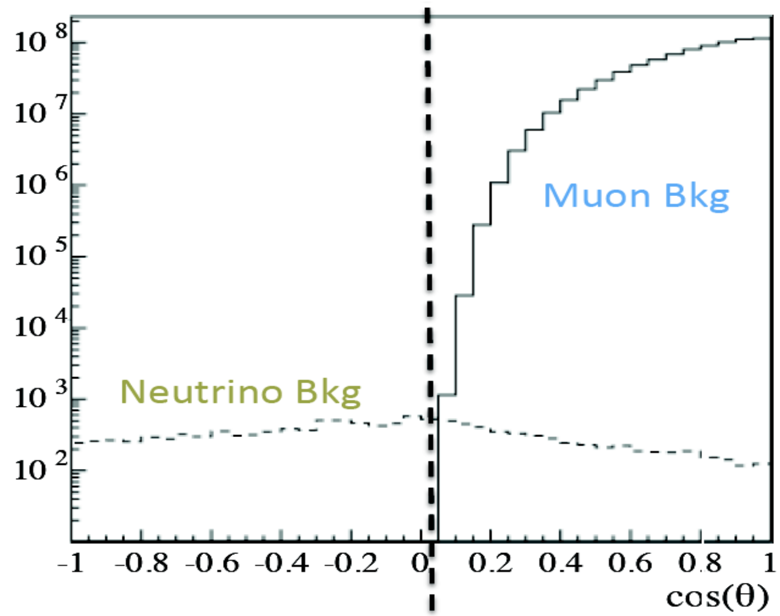

Complete detector → **full sky sensitivity** using IceCube outer strings as a veto

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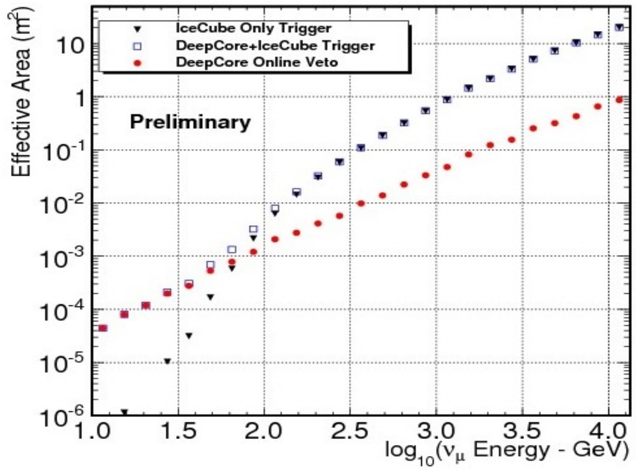
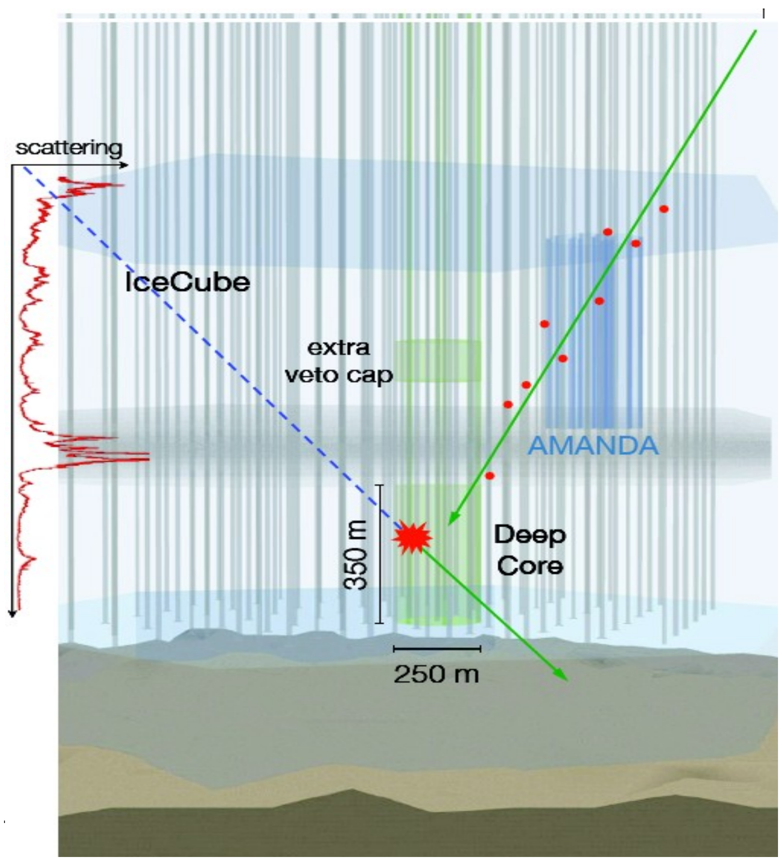
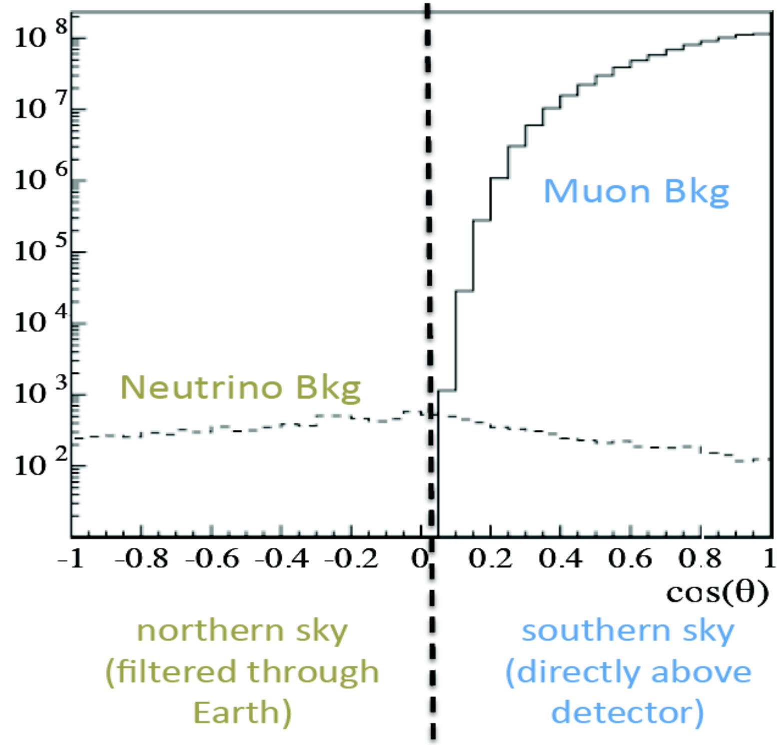




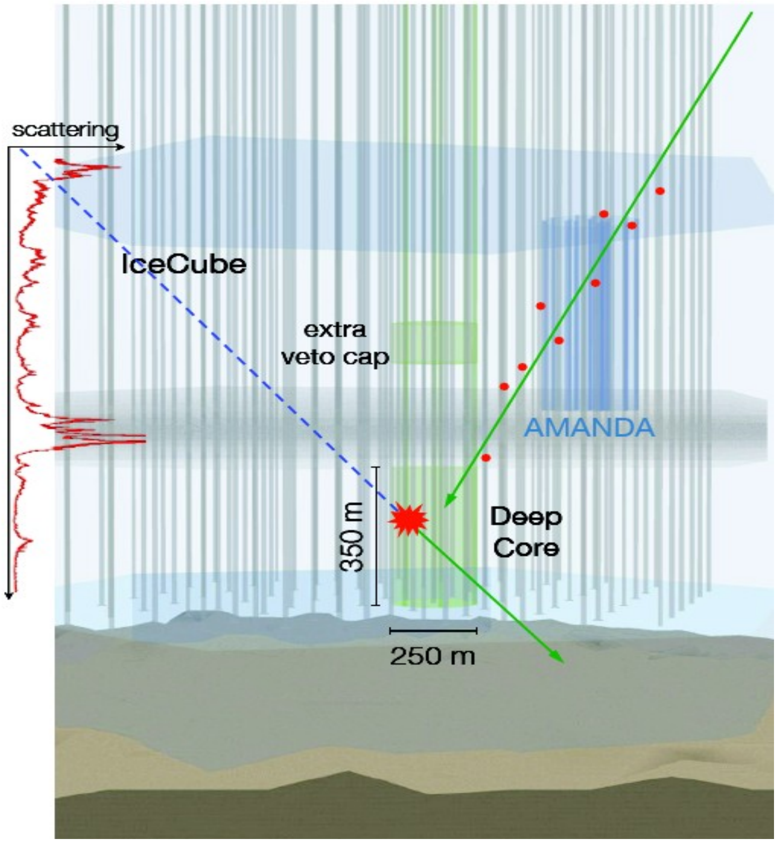


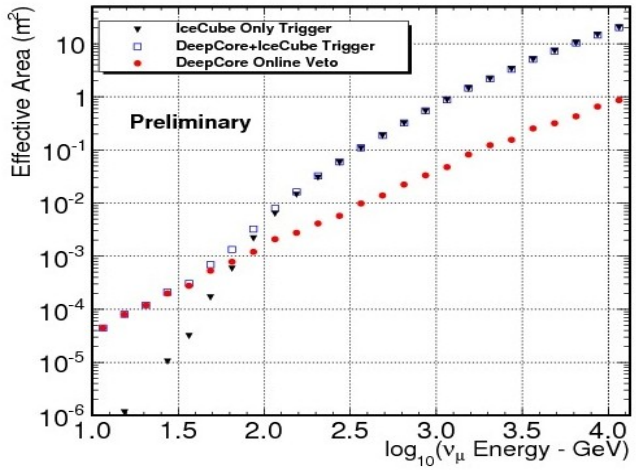
Complete detector → **full sky sensitivity**
using IceCube outer strings as a veto

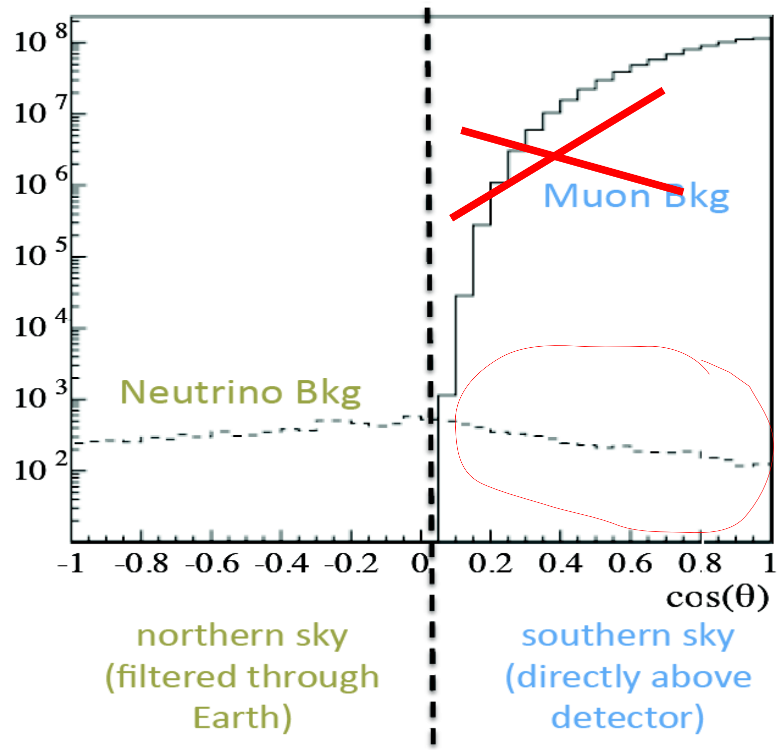
Define starting tracks == neutrinos

—> access to southern hemisphere, galactic center and all-year Sun visibility

IceCube is a 4π detector







WIMPS

- Arise in extensions of the Standard Model
- Assumed to be stable: relics from the Big Bang
- weak-type Xsection gives needed relic density

$$\Omega_\delta h^2 \approx \frac{10^{-27}}{\langle \sigma_{ann} v \rangle_{fr}} \mathrm{cm}^3 \mathrm{s}^{-1}$$

- mass from few GeV to few TeV
- MSSM candidate: lightest neutralino,

$$\chi^0_1 = N_1\mathbf{B} + N_2\mathbf{W}^3 + N_3\mathrm{H}^0_1 + N_4\mathbf{H}^0_2$$

- UED: lightest 'rung' in the Kaluza-Klein ladder

SIMPZILLAS

- Non-thermal, non-weakly interacting stable relics

A wealth of candidates from different theoretical models:

- dark baryons (primordial nucleosynthesis constraints)
- MACHOs – BHs, neutron stars, white/brown dwarfs... (microlensing constraints)
- neutrinos (mass constraint)
- primordial Black Holes (cosmological constraints)
- **W**eakly **I**nteracting **M**assive **P**articles (LSPs from "x"MSSM, Kaluza-Klein modes...)

  Non-weakly Interacting Supermassive particles (Simpzillas)
- axions (too light+astrophysical constrains)
- many others

... + (alternative gravity theories)

DM-induced SM particles:

$$\kappa\kappa,\ \chi\chi, SS \rightarrow \begin{Bmatrix} q\bar{q} \\ \ell^+\ell^- \\ W, Z, H \\ \ldots \end{Bmatrix} \rightarrow \nu,\ \gamma,\ e^+e^-,\ \bar{p}$$

Kaluza-Klein modes an additional useful channel:

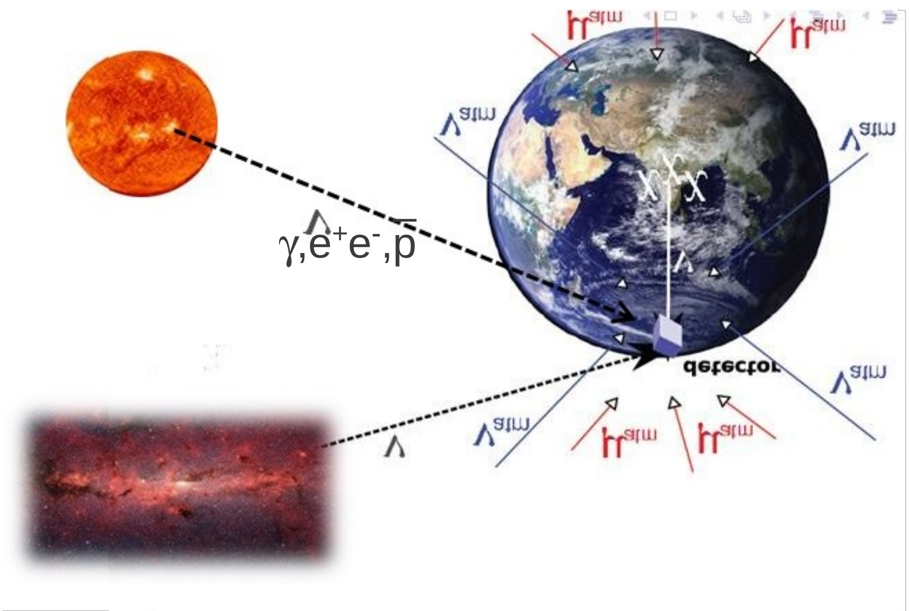
$$\kappa\kappa \rightarrow \nu\nu$$

signature:
ν excess over background from Sun/Earth/Galactic Halo/nearby galaxies

A lot of physics uncertainties involved:
- relic density calculations
- DM distribution in the halo
- velocity distribution
- χ,K,S properties (MSSM/UED...)
- interaction of χ,K,S with matter (capture)
- self interaction (annihilation)

Look at objects where dark matter can have accumulated gravitationally over the evolution of the Universe

Sun, Earth, Galactic Halo/Center, dwarf spheroids



Atmospheric muons ~$O(10^{10})$ events/year (downwards)

Atmospheric neutrinos ~$O(10^4)$ events/year (all directions)

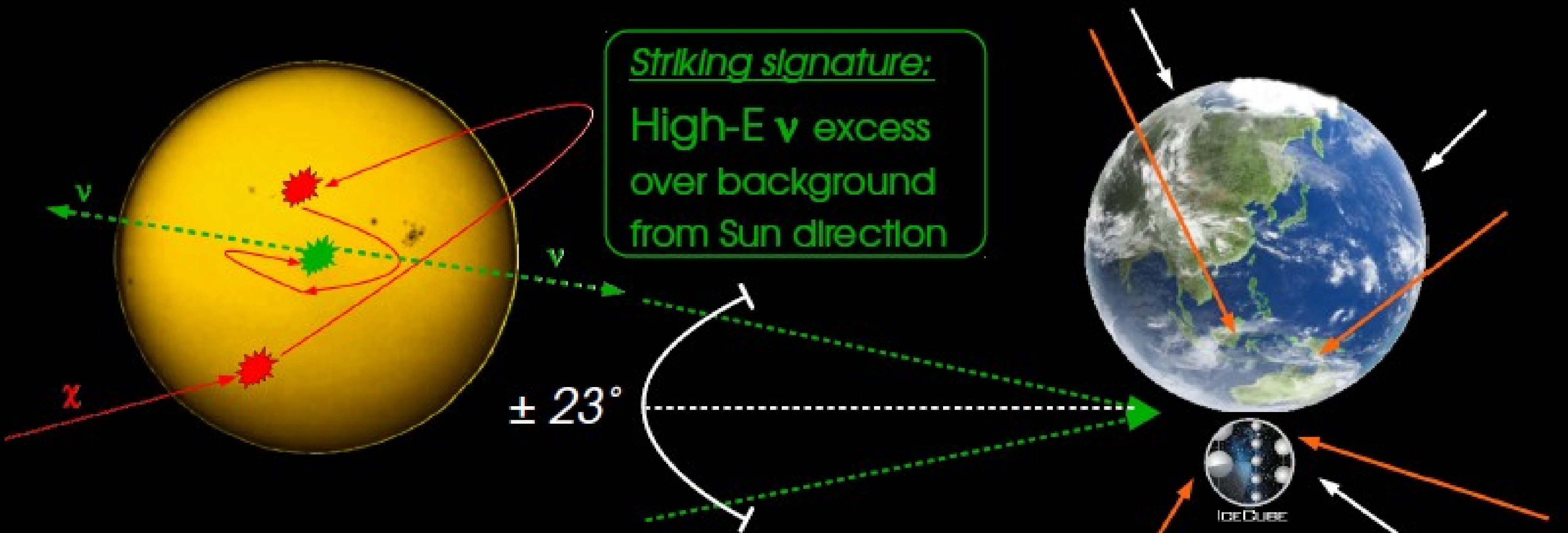
Solar Dark Matter Search with IceCube

- All processes depend on WIMP mass
- Annihilation channel (branching ratios)
- Annihilation cross-section
- Capture (scattering)
  → Scattering cross-sections (SI & SD)

main analysis backgrounds:

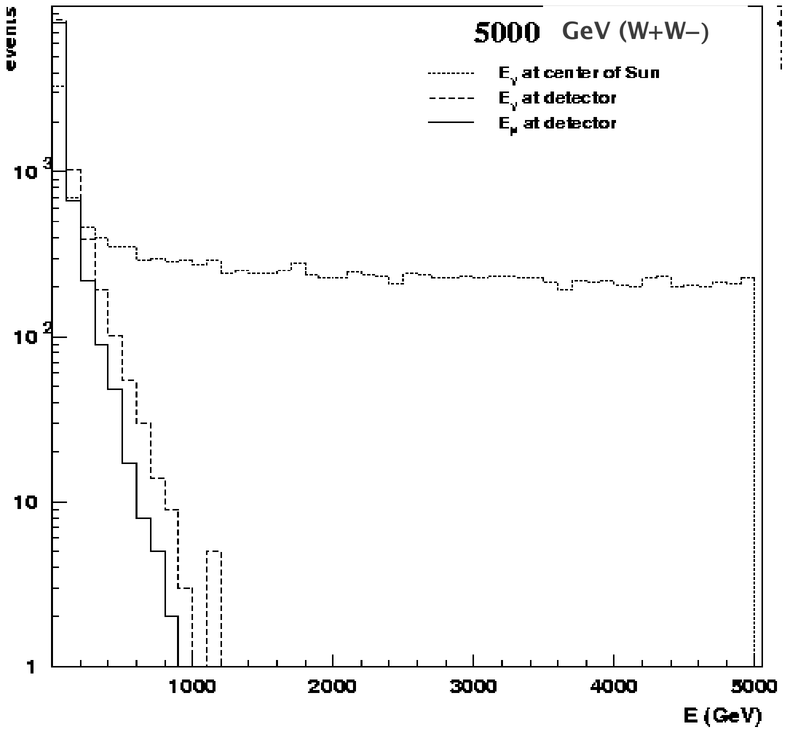
atm. $\nu \sim O\,(10^3$ triggering events/day$)$

atm. $\mu \sim O\,(10^8$ triggering events/day$)$

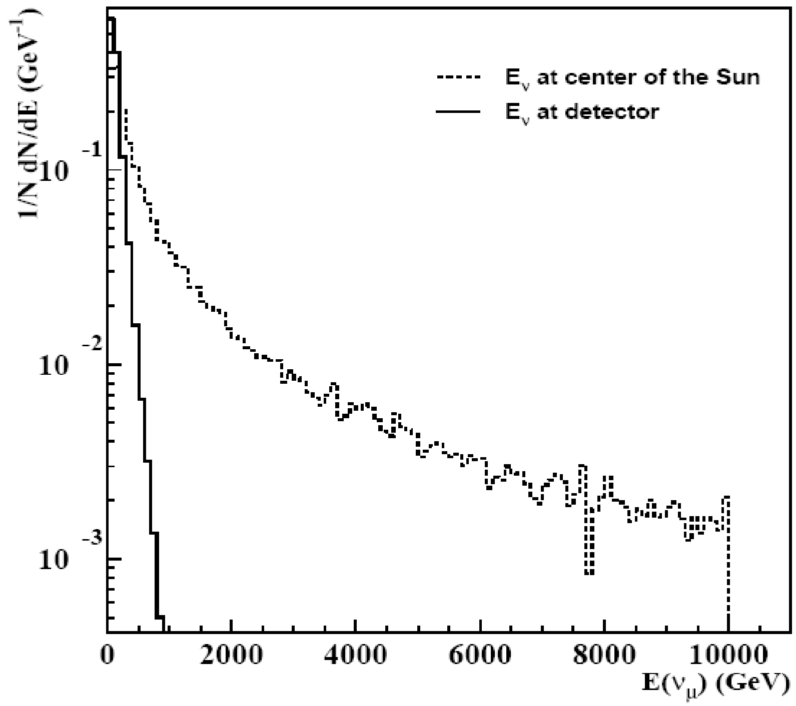


*Blind analysis with respect to true Sun azimuth

5000 GeV Neutralino → WW @ Sun



Simpzilla → $t\bar{t}$ @ Sun



: Indirect dark matter searches from the **Sun** are a low-energy analysis in neutrino telescopes: even for the highest DM masses, we do not get muons above few 100 GeV

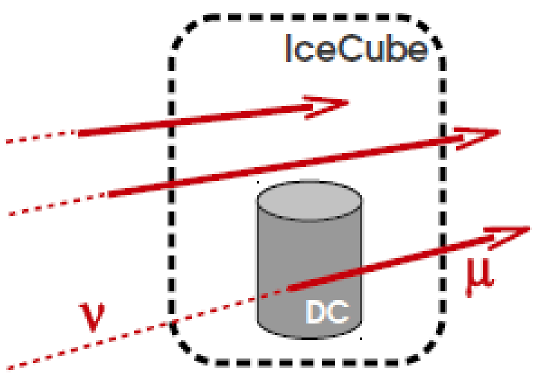
Not such effect for the Earth and Halo (no ν energy losses in dense medium)

IceCube-79 string analysis details

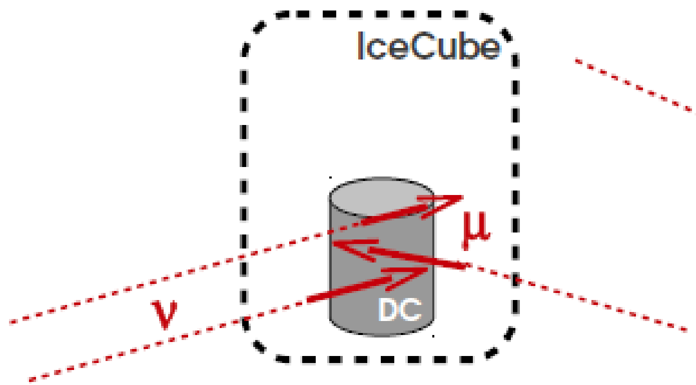
(PRL 110 (2013) 131302) ICECUBE

- Analysis for the whole year! Used 317 days livetime (151 days austral winter & 166 days austral summer)
- more than *60 billion* recorded events
- At final level *~25000* signal-like events in 3 independent samples
- With DeepCore, analysis reaches neutrino energies of *10-20GeV*

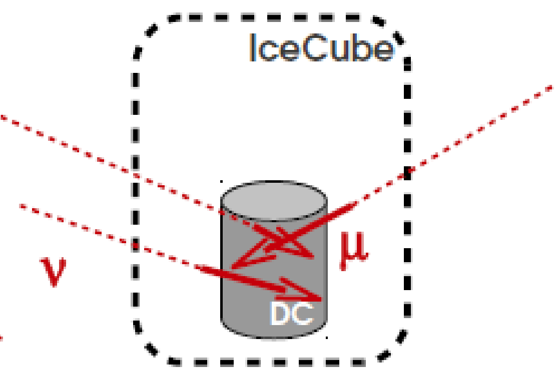
- ***Up-going*** ①
- No containment



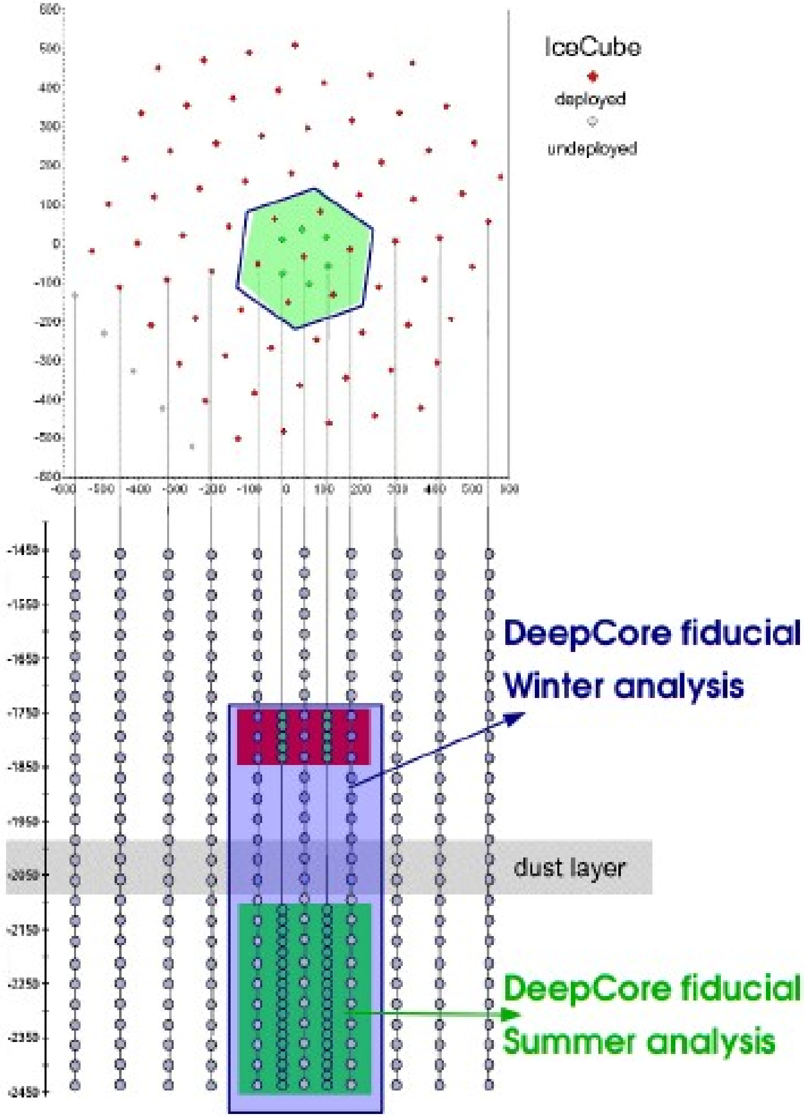
- ***Up-going*** ②
- strong containment

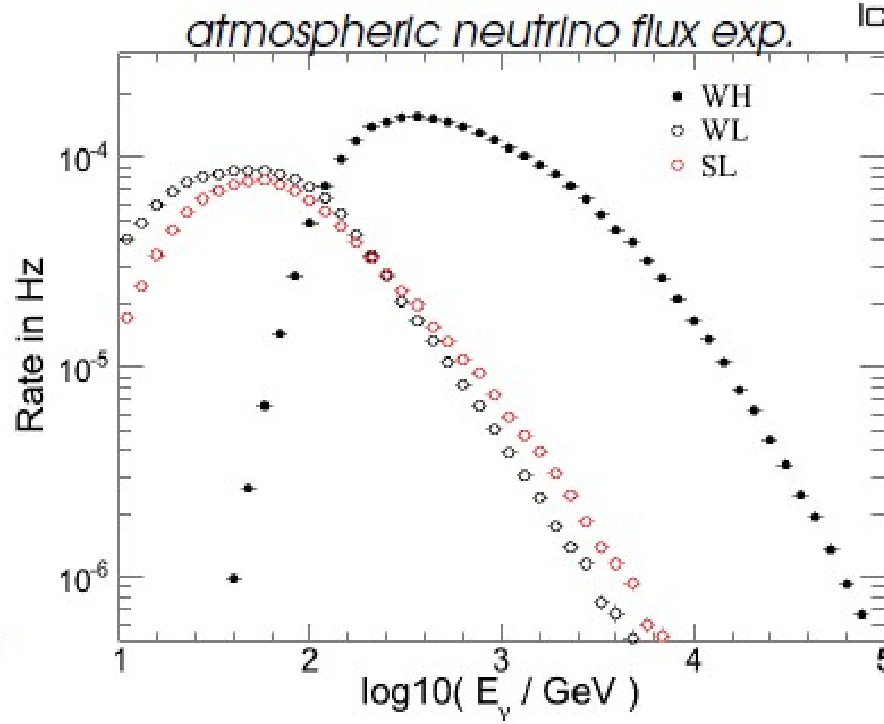


- ***Down-going*** ③
- strong containment



IceCube-79 string analysis details





Signal event topology very different for low & high WIMP mass
→ find *geometrical cut* to split dataset into 2 non-overlaping datasets

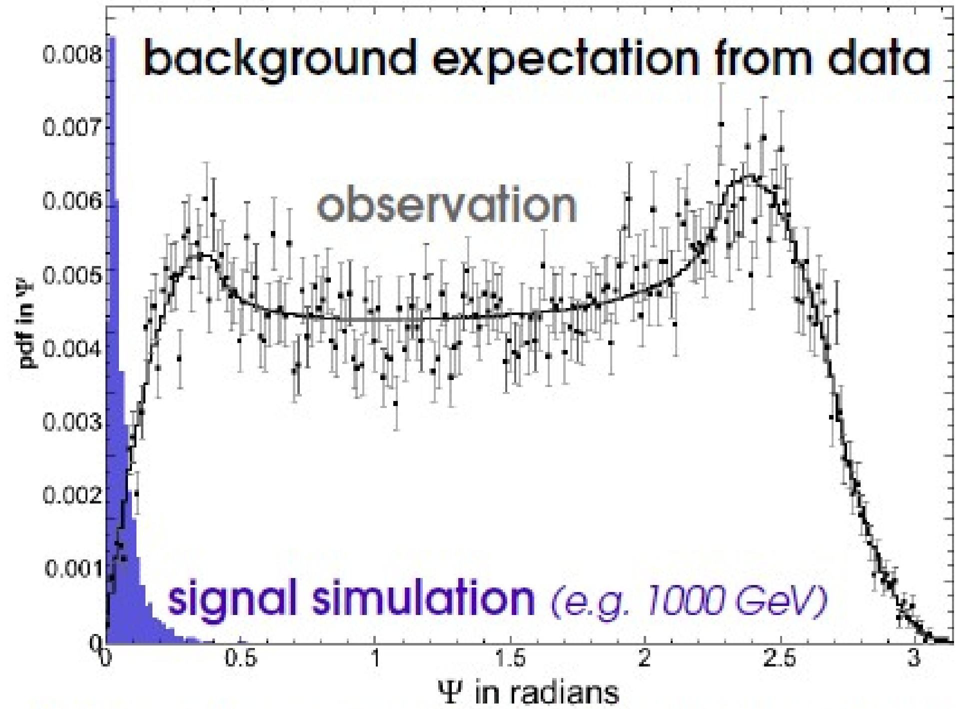
Maximum llh-analysis

The observed angle to the Sun is fitted with *signal* and *background* pdf:s

Evaluate shape fit with log-likelihood rank (Feldman-Cousins) to construct confidence regions for the number of signal events μ_s

$$R(\mu) = \frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})}$$

where ***L*** is the pdf product over the final sample



(Angle between event track & direction from the Sun)

$$f(\psi|\mu_s) = \frac{\mu_s}{n_{obs}} f_S(\psi) + \left(1 - \frac{\mu_s}{n_{obs}}\right) f_B(\psi)$$

$$\mathcal{L}(\mu_s) = \prod_{i=1}^{n_{obs}} f(\psi_i|\mu_s)$$

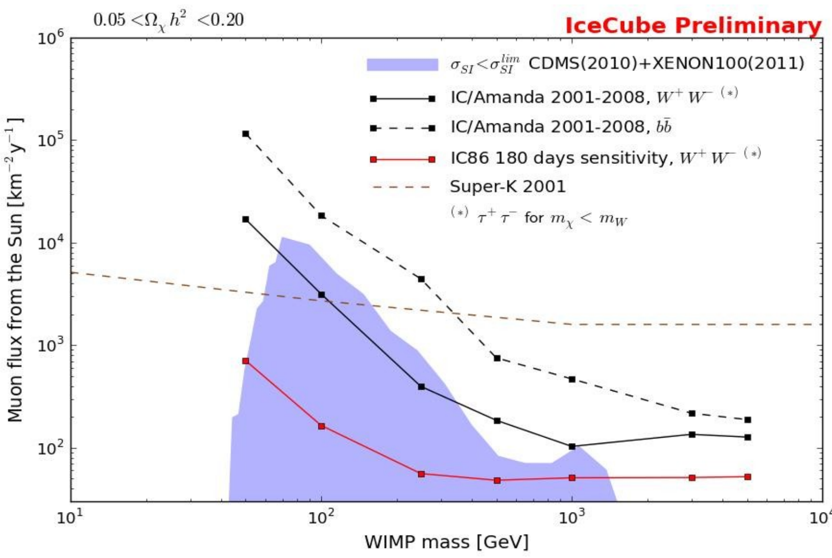
Ψ_{data}, Ψ_{bck} $\rightarrow$ N_{90} $\longrightarrow$ $\Gamma_{\nu\mu} \leqslant \dfrac{N_{90}}{V_{eff} \cdot t}$

Experimentally obtained quantity: allowed number of signal events still compatible with background, at 90% confidence level

$$\Gamma_{\nu\mu}(m_\chi) = \Gamma_A \cdot \frac{1}{4\pi R_\oplus^2} \int_0^{m_\chi} \sum B_{\chi\bar{\chi}\to X} \left(\frac{dN_\nu}{dE_\nu}\right) \times \sigma_{\nu+N\to\mu+\ldots}(E_\nu | E_\mu \geqslant E_{thr})\, \rho_N\, dE_\nu$$

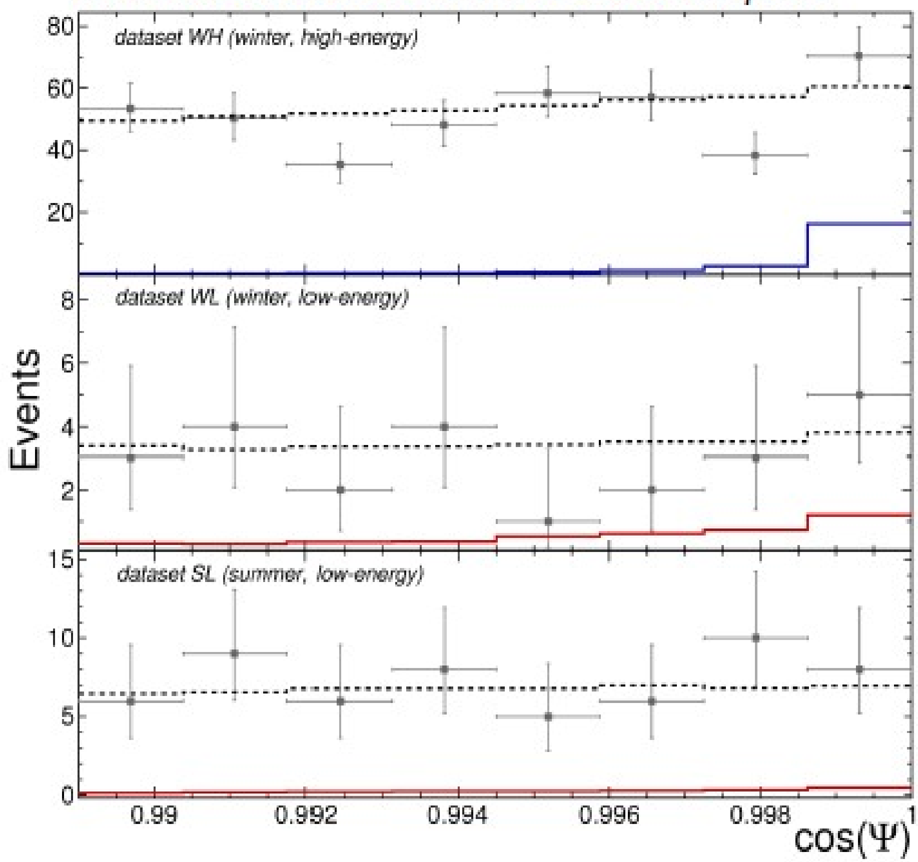
Use model to convert to a muon flux

$$\longrightarrow \quad \phi_\mu(E_\mu \geqslant E_{thr}) = \frac{\Gamma_A}{4\pi D_\odot^2} \int_{E_{thr}}^{\infty} dE_\mu \frac{dN_\mu}{dE_\mu}$$

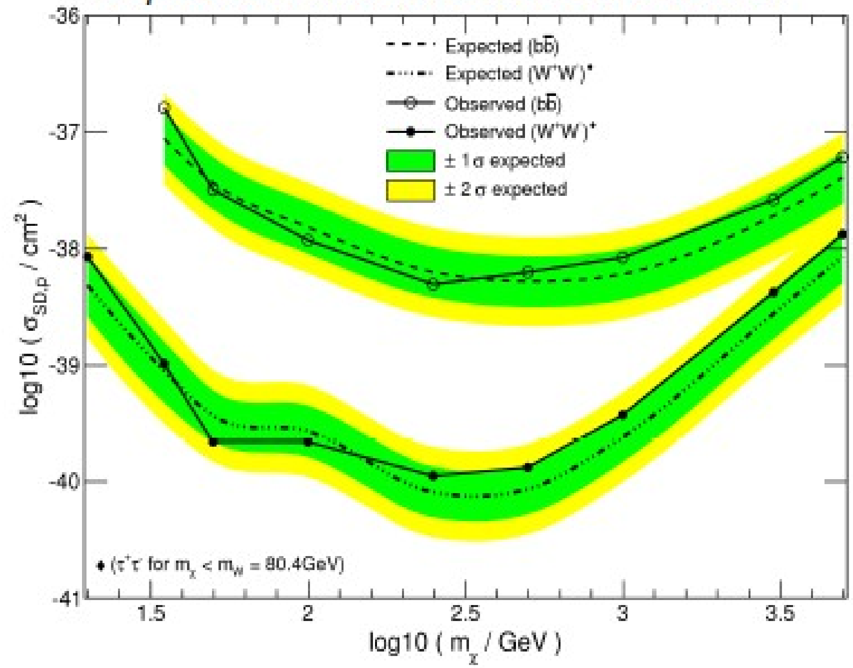


Solar WIMP search results (observed events)

Unblinded events in different samples



Expected sens. vs. observed result



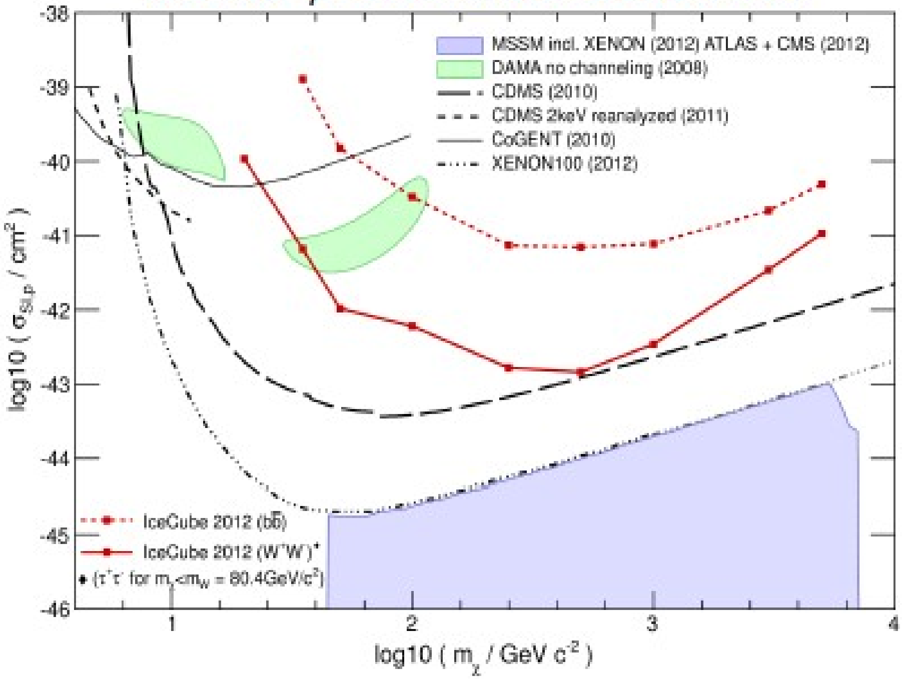
details on systematic uncertainties, see *PRL* **110** (2013) 131302

$\Phi_\mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{X+p}$

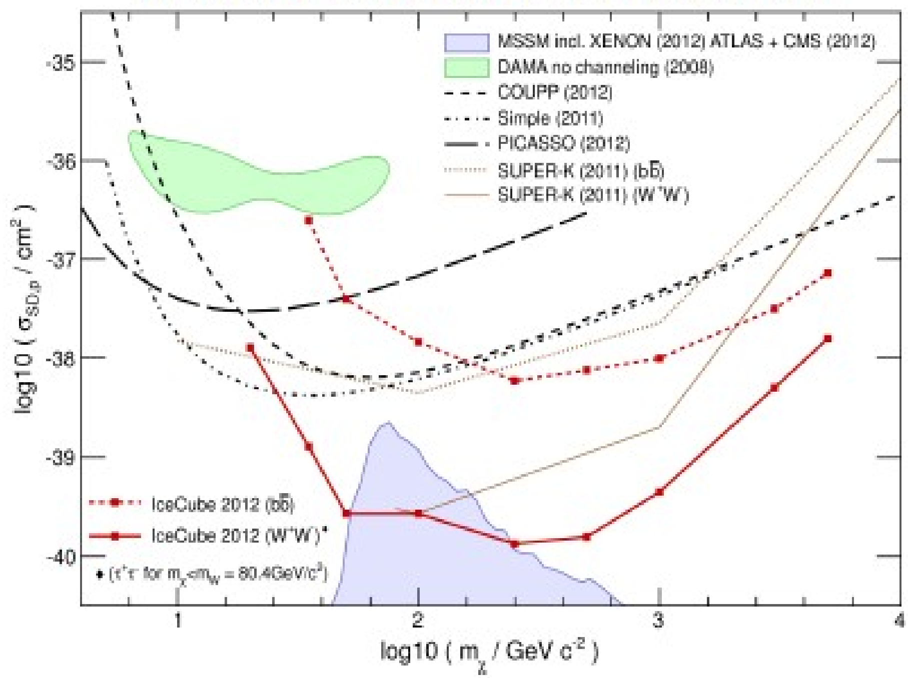
(particle physics and solar model)

Solar WIMP search results (cross-section limit)

SI WIMP-proton cross-section limit



SD WIMP-proton cross-section limit



→ most stringent SD cross-section limit for most models

→ complementary to direct detection search efforts

→ Different astrophysical & nuclear form-factor uncertainties

Assume (ie. model dependent) effective quark-DM interaction,

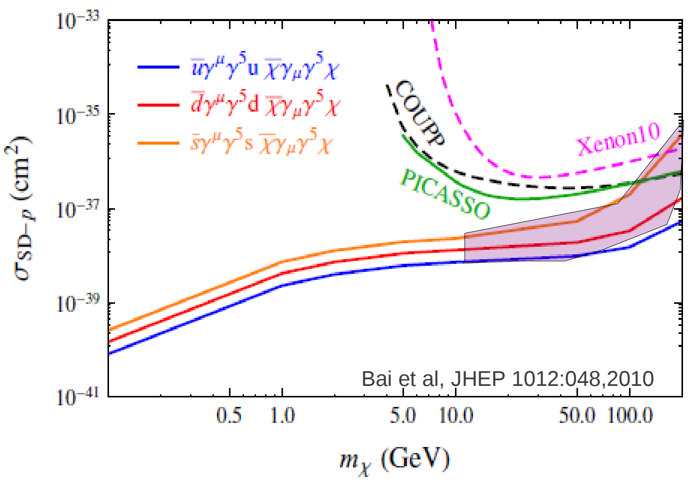
$$\lambda^2/\Lambda^2\,(\bar{q}\gamma_5\gamma_\mu q)(\bar{\chi}\gamma_5\gamma^\mu\chi)$$

and look for monojets in $p\bar{p}$ collisions,

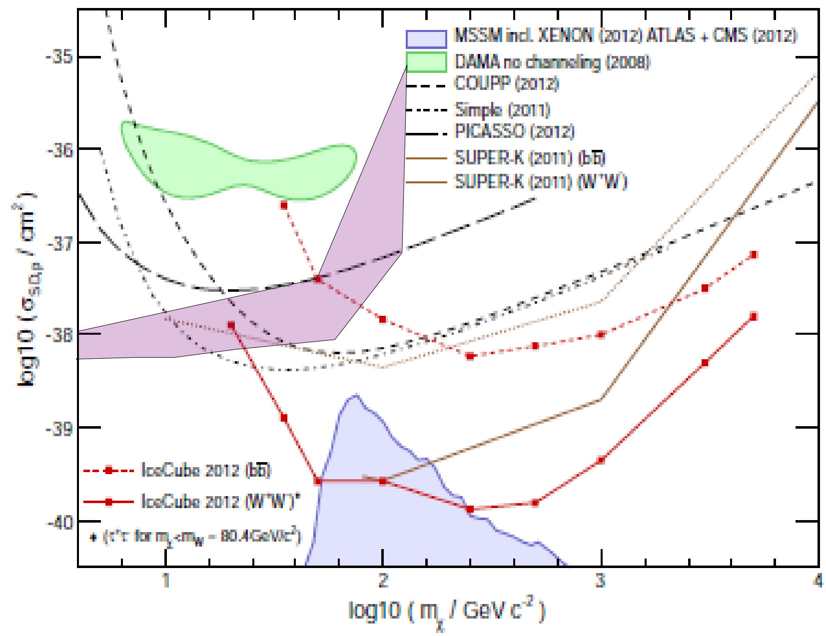
$$p\bar{p} \rightarrow \chi\bar{\chi} + \text{jet}$$

(as opposed to the SM process $p\bar{p} \rightarrow Z+\text{jet}$ and $p\bar{p} \rightarrow W+\text{jet}$)

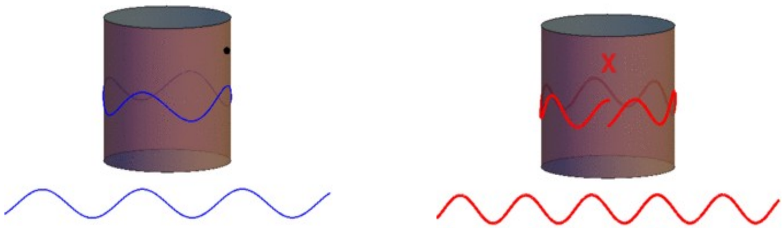
Constrains from monojet searches at the TeVatron:



90% CL **neutralino-p Xsection** limit



- **Universal Extra Dimensions**:



$$n\frac{\lambda}{2} = 2\pi R, \quad n\frac{h}{2p} = 2\pi R \Rightarrow p = n\frac{h}{4\pi R}$$

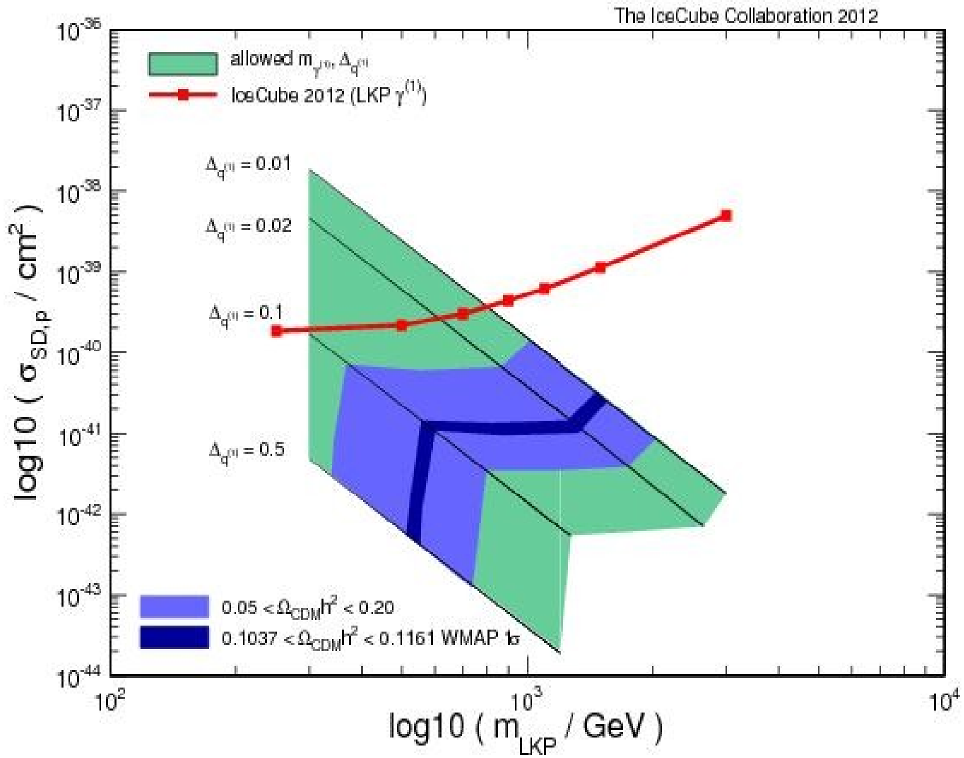
$$E^2 = p^2c^2 + m_o{}^2c^4 = n^2\frac{1}{R^2}c^2 + m_o{}^2c^4 = m_n{}^2c^4$$

$$m_n^2 = \frac{n^2}{c^2R^2} + m_o^2$$

n=1 → Lightest Kaluza-Klein mode, **B**^{1}

good DM candidate

90% CL LKP-p Xsection limit vs LKP mass



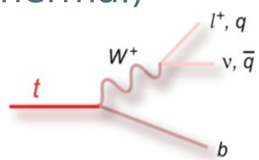
SIMPZILLAS (Superheavy DM)

- Produced **non-thermally** at the end of inflation through vacuum quantum fluctuations or decay of the inflaton field

- strong Xsection (simply means non-weak in this context)

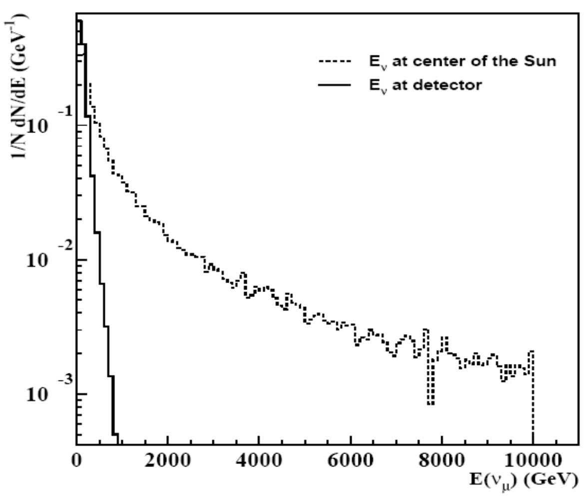
- m from ~10^4 GeV to 10^{18} GeV (no unitarity limit since production non thermal)

S+S → t $\bar{t}$



$2.8\times10^5\sqrt{m_{X/12}}$ tops per annihilation

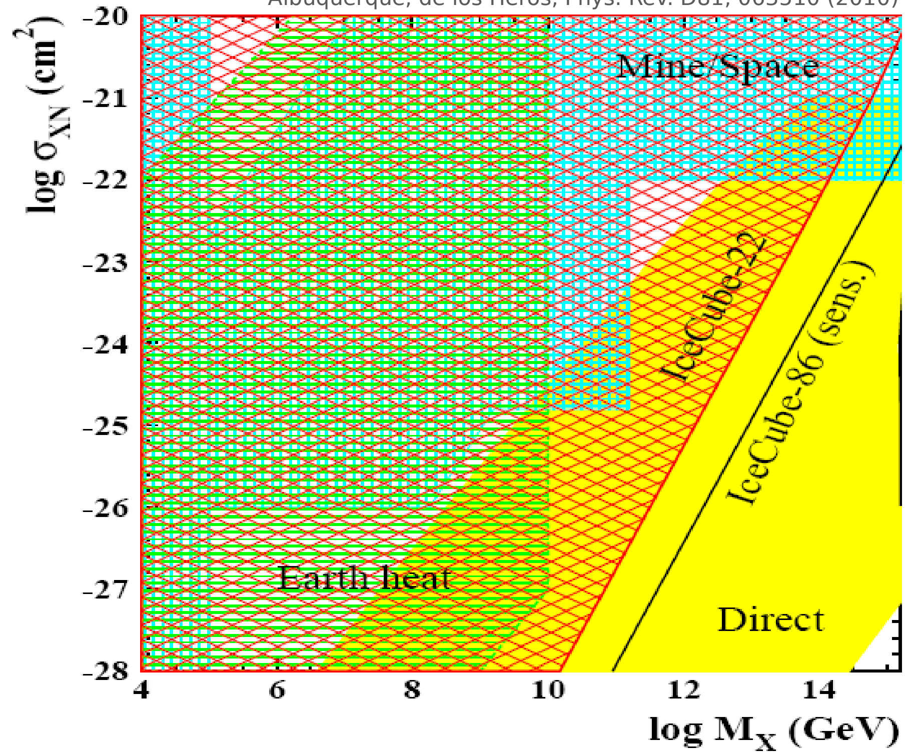
$$\frac{dN}{dE_\nu} \propto \frac{E_\nu + \mathrm{m_W}}{\sqrt{(E_\nu+\mathrm{m}_t)[(E_\nu+\mathrm{m}_t)^2-\mathrm{m}_t^2][(E_\nu+\mathrm{m_W})^2-\mathrm{m_W^2}]}}$$

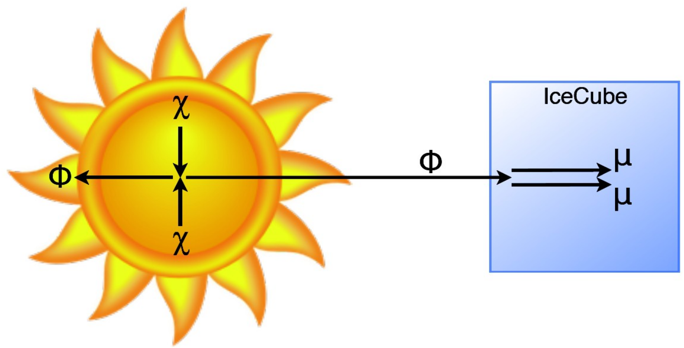


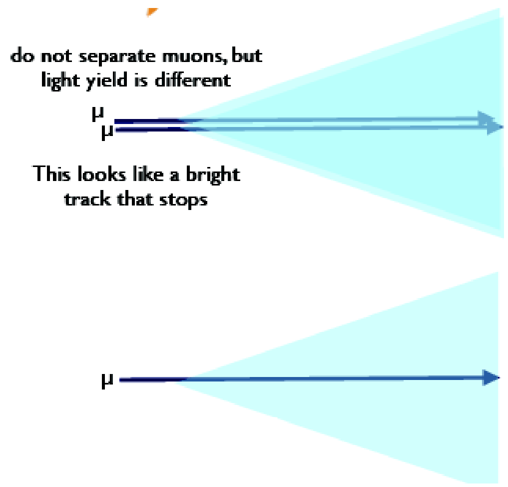
$$N_s(m_X,\sigma_{XN}) = N_t \cdot BR_W \cdot \Gamma_A(m_X,\sigma_{XN}) \cdot T \cdot \int \frac{dN_\nu}{dE} A_{eff}\, dE$$

90% CL simpzilla-p Xsection limit *vs* simpzilla mass

Albuquerque, de los Heros, Phys. Rev. D81, 063510 (2010)







Secluded dark matter

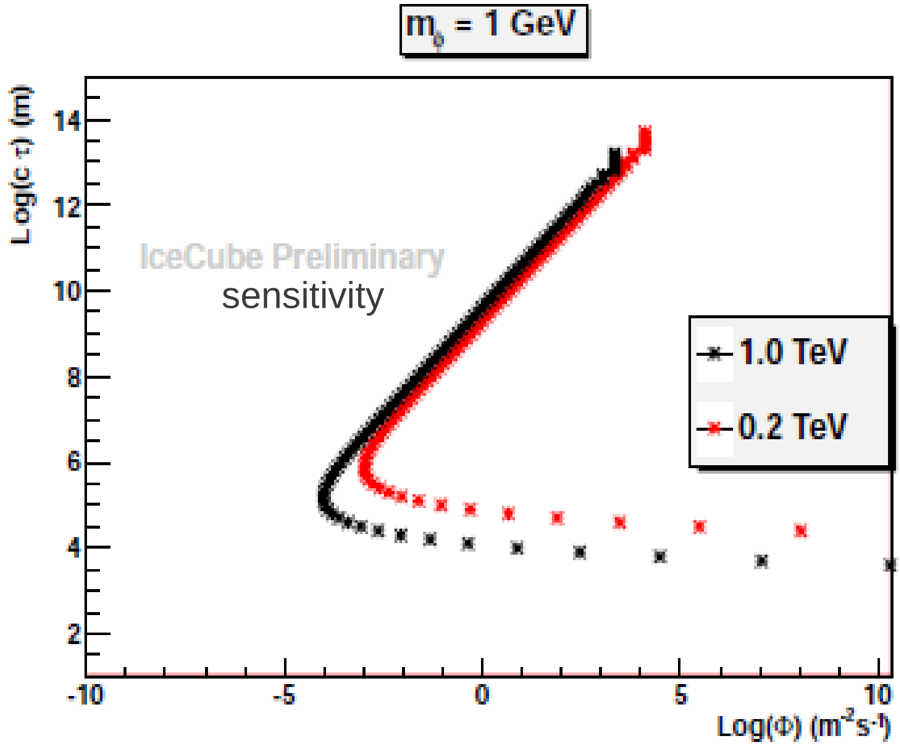
$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_{mediator}$

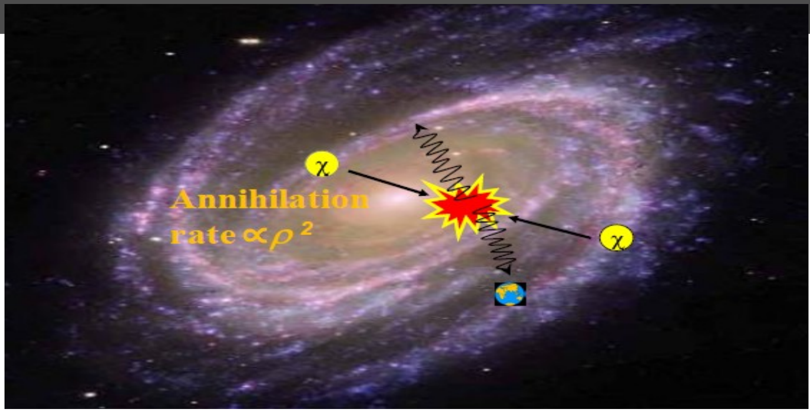
DM annihilates into mediator, $\chi\chi \rightarrow \phi\phi \rightarrow$SM
with $m_\phi = \mathcal{O}$(GeV)

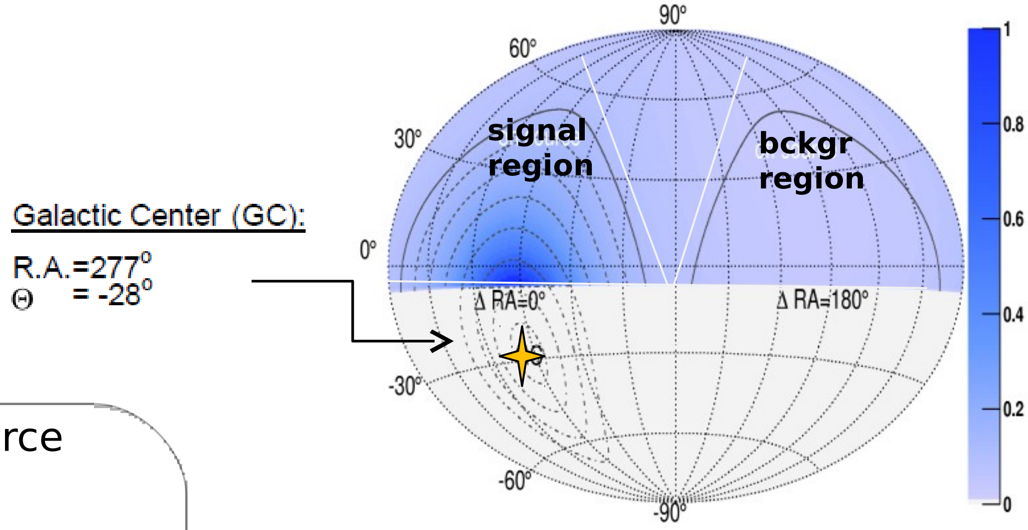
ϕ is long lived, escapes the Sun and decays into $\mu^+\mu^-$ in or near the detector

→ signature: two closely separated muon tracks (~ 1m)

look for stopping pairs of tracks in order to further reduce the background.



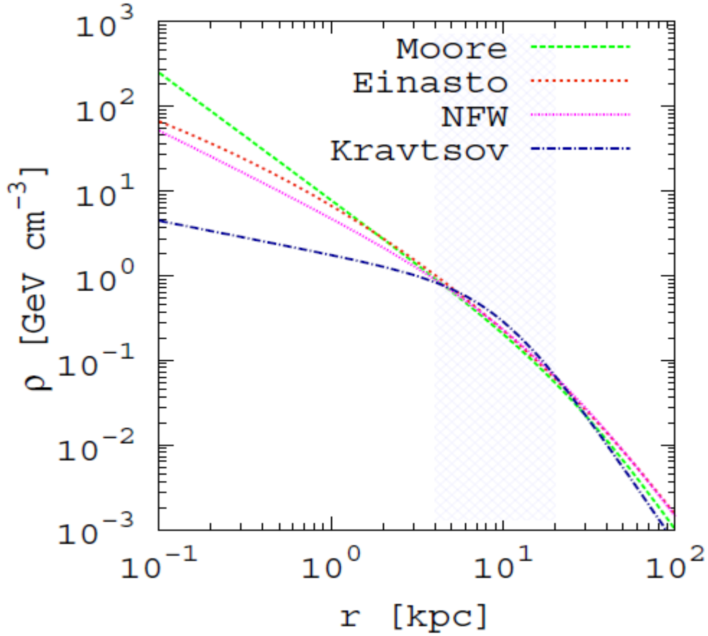




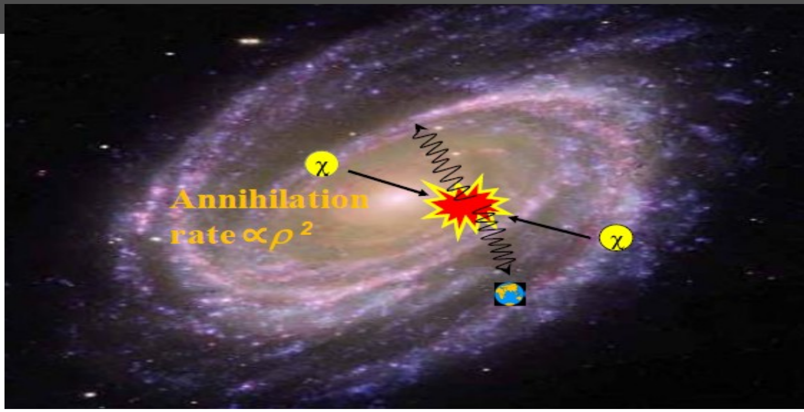
- Look for an excess of events in the on-source region w.r.t. the off-source:
- **IC22**: observed on-source: 1367 evts

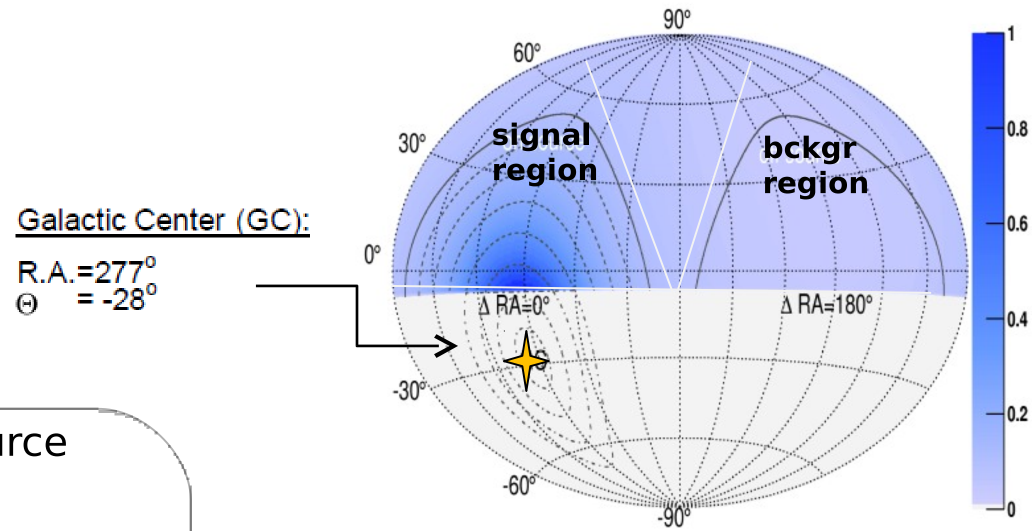
  observed off-source: 1389 evts
- Need expected neutrino flux from SUSY and halo model. Limit on the self annihilation cross section:

$$\phi_\nu = \frac{dN}{dE\, dA_{eff}\, dt\, d\Omega} = \frac{1}{2}\frac{1}{4\pi}\langle\sigma v\rangle J_\Omega R_{SC}\frac{\rho_{SC}^2}{m_\chi^2}\frac{dN_\nu}{dE}$$



DM searches from the Galactic Halo





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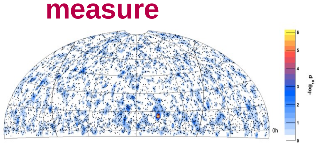
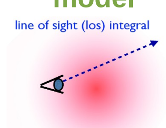
  observed off-source: 1389 evts

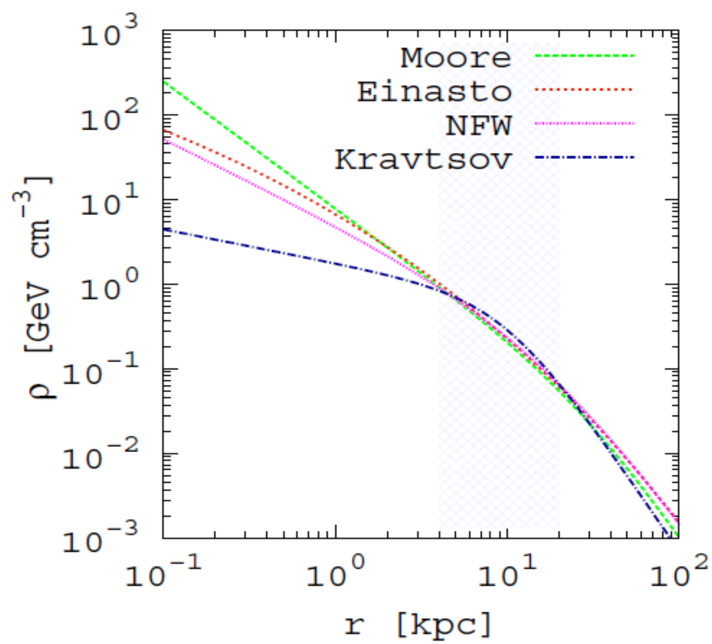
- Need expected neutrino flux from SUSY and halo model. Limit on the self annihilation cross section:

$$\phi_\nu = \frac{dN}{dE\, dA_{eff}\, dt\, d\Omega} = \frac{1}{2}\frac{1}{4\pi}\langle\sigma v\rangle J_\Omega R_{SC}\frac{\rho_{SC}^2}{m_\chi^2}\frac{dN_\nu}{dE}$$

measure — CONSTRAIN — halo model (line of sight (los) integral) — particle physics



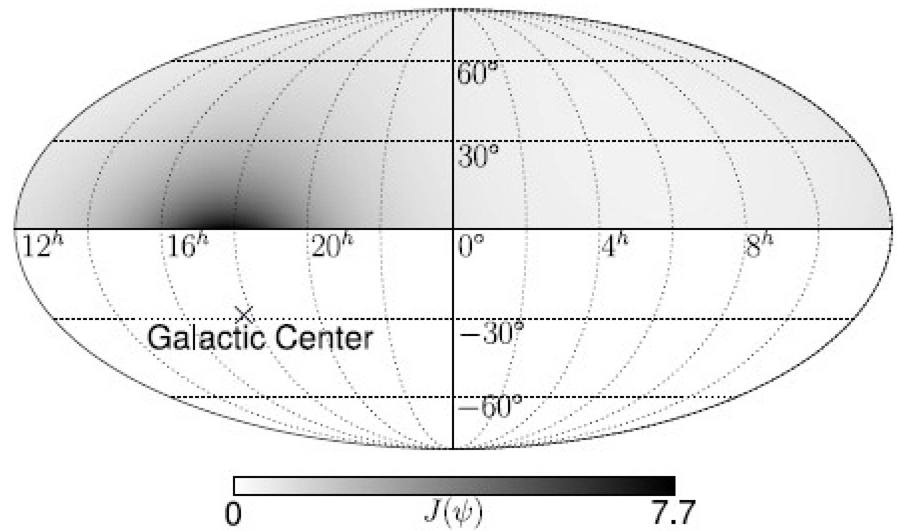




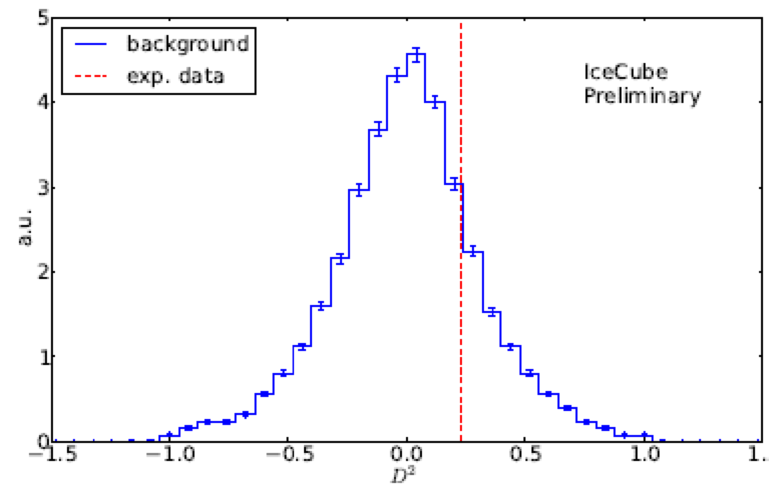
$$Y_\ell^m(\theta,\phi) = \sqrt{\frac{(2\ell+1)(\ell-m)!}{4\pi(\ell+m)!}} P_\ell^m(\cos(\theta))\exp(im\phi)$$

$$a_\ell^m = \int_\Omega d\Omega\, f(\theta,\phi) Y_\ell^{m*}(\theta,\phi)$$

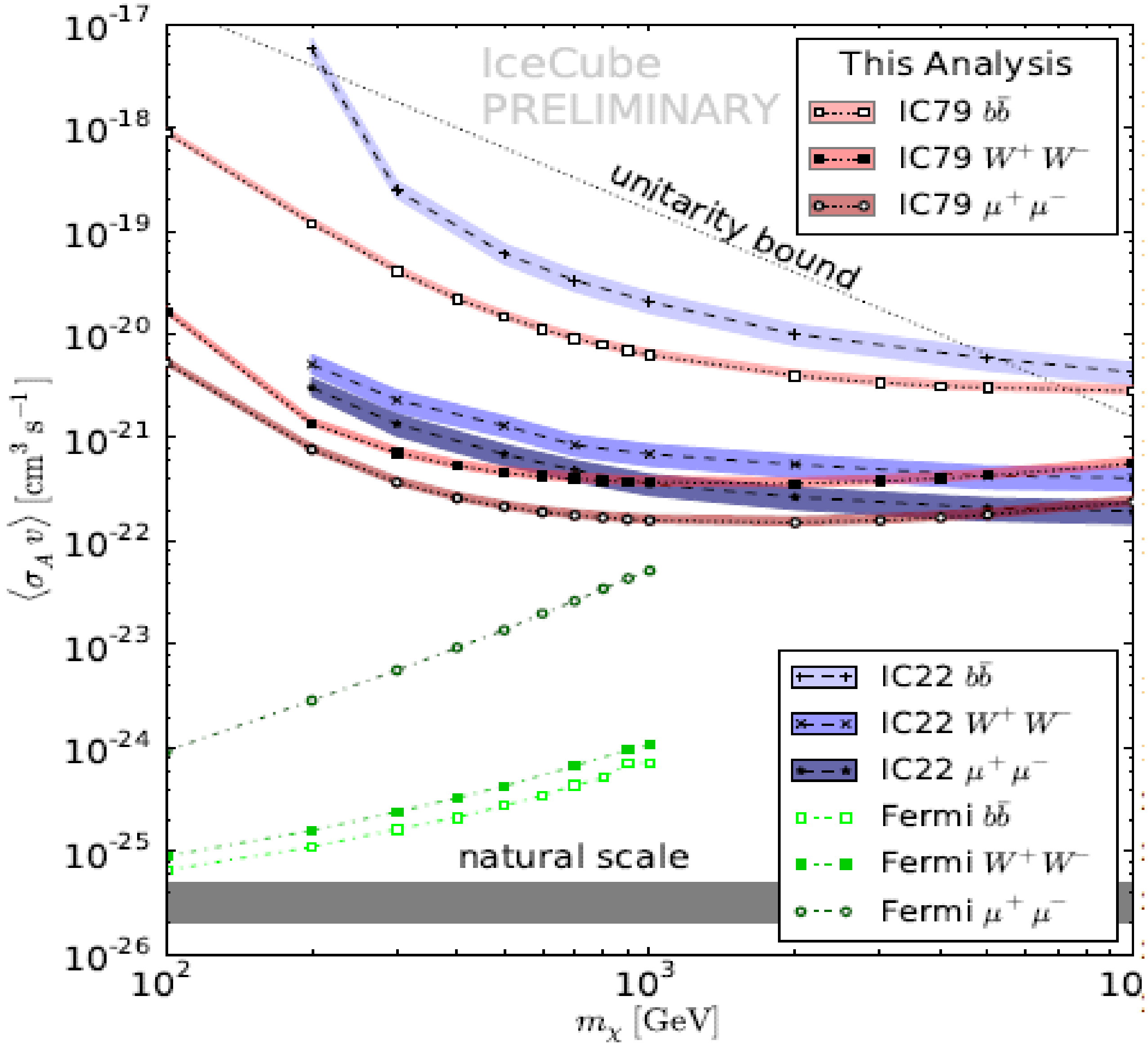
$$f(\theta,\phi) = \sum_{i=1}^{N_\nu} \delta(\theta-\theta_i)\cdot\delta(\phi-\phi_i)$$



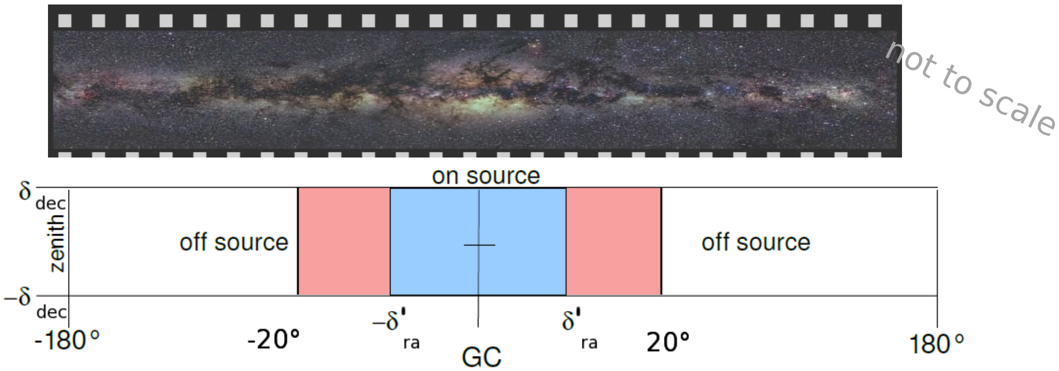
$$D^2 = \frac{1}{\sum w_\ell^m} \sum_{\ell=1}^{\ell_{\max}} \sum_{m=1}^{\ell} \mathrm{sign}(\mathscr{A}_\ell^m)\, w_\ell^m \left(\frac{\mathscr{A}_\ell^m - \left\langle \mathscr{A}_{\ell,\mathrm{atm}}^m \right\rangle}{\sigma\left(\mathscr{A}_{\ell,\mathrm{atm}}^m\right)} \right)^2$$

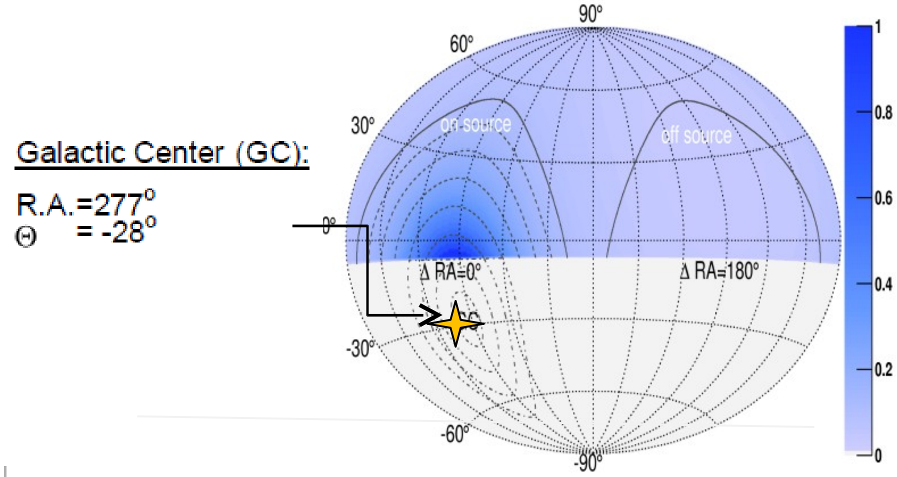


$$\langle \sigma_A v \rangle_{90} = \frac{8\pi m_\chi^2}{R_{SC}\rho_{SC}^2} \frac{1}{T_{\mathrm{live}}} \frac{1}{\int\int J(\psi) A_{\mathrm{eff}} \frac{d\mathcal{N}_\nu}{dE} dE\, d\Omega} N_{90}$$


IceCube
PRELIMINARY
This Analysis
IC79 $b\bar{b}$
IC79 W^+W^-
IC79 $\mu^+\mu^-$
unitarity bound
IC22 $b\bar{b}$
IC22 W^+W^-
IC22 $\mu^+\mu^-$
Fermi $b\bar{b}$
Fermi W^+W^-
Fermi $\mu^+\mu^-$
natural scale
$\langle\sigma_A v\rangle$ [cm^3 s^{-1}]
m_χ [GeV]
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^2
10^3
10

Searches from the Galactic Center

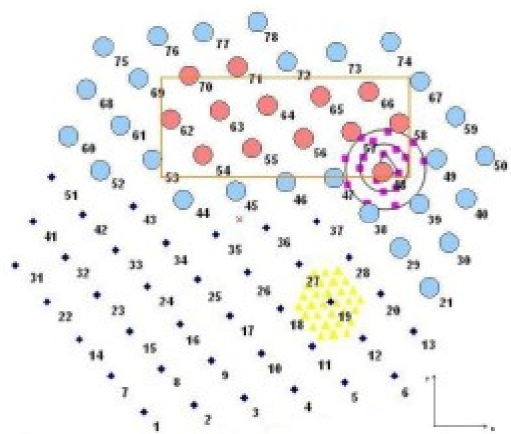


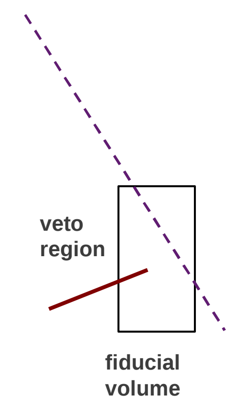


Look for an excess of events in the on-source region w.r.t. the off-source

on-source region below the horizon: need to veto downgoing μs.

Use central strings of detector as fiducial volume, surrounding layers as veto.
Only from IC40 this is possible.





IC40: observed on-source: 798842 evts

observed off-source: 798819 evts

Same strategy as in the galactic halo analysis:

$$\frac{d\Phi}{dE} = \frac{<\sigma_A v>}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$

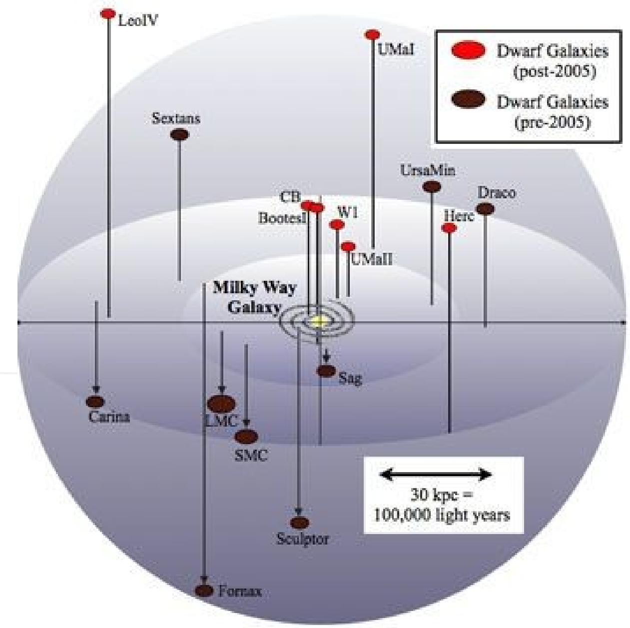
Measure

Constrain

Halo

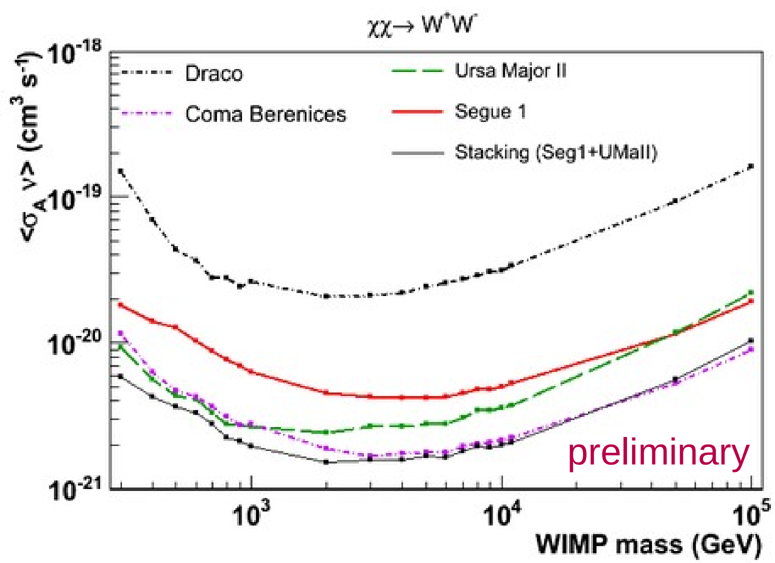
SUSY

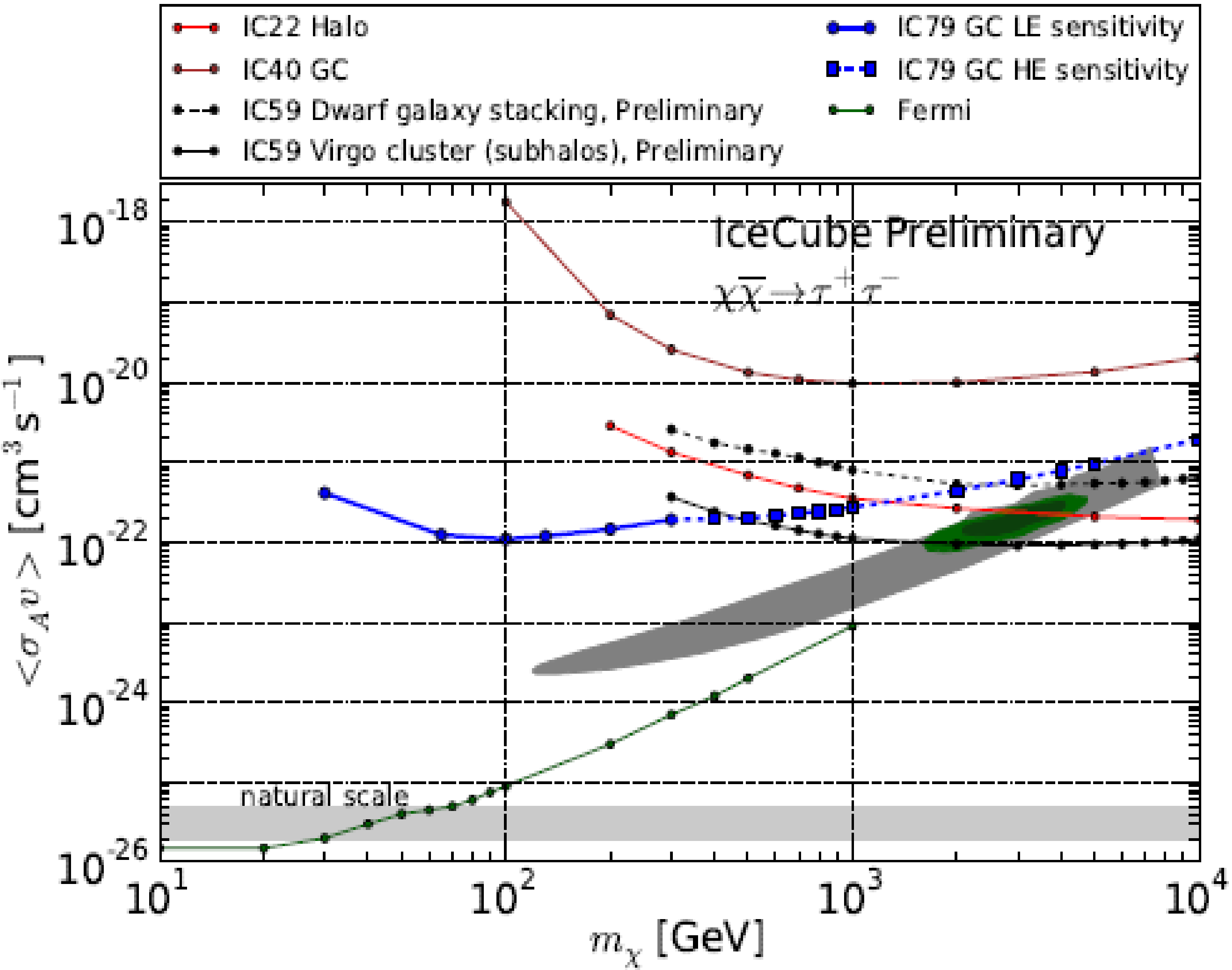
- dwarf galaxies: high mass/light ratio
- → high concentration of DM in the halos
- known location. Distributed both in the north and southern sky.
  - Point-like search techniques: stacking
  - known distance -> determination of absolute annihilation rate if a signal is detected
- same expected neutrino spectra as for the galactic center/halo
- IceCube results from various sources



Same strategy as in the galactic halo analysis:

$$\phi_\nu = \frac{dN}{dE\, dA_{eff}\, dt\, d\,\Omega} = \frac{1}{2}\frac{1}{4\pi}\langle\sigma v\rangle J_\Omega R_{SC}\frac{\rho_{SC}^2}{m_\chi^2}\frac{dN_\nu}{dE}$$



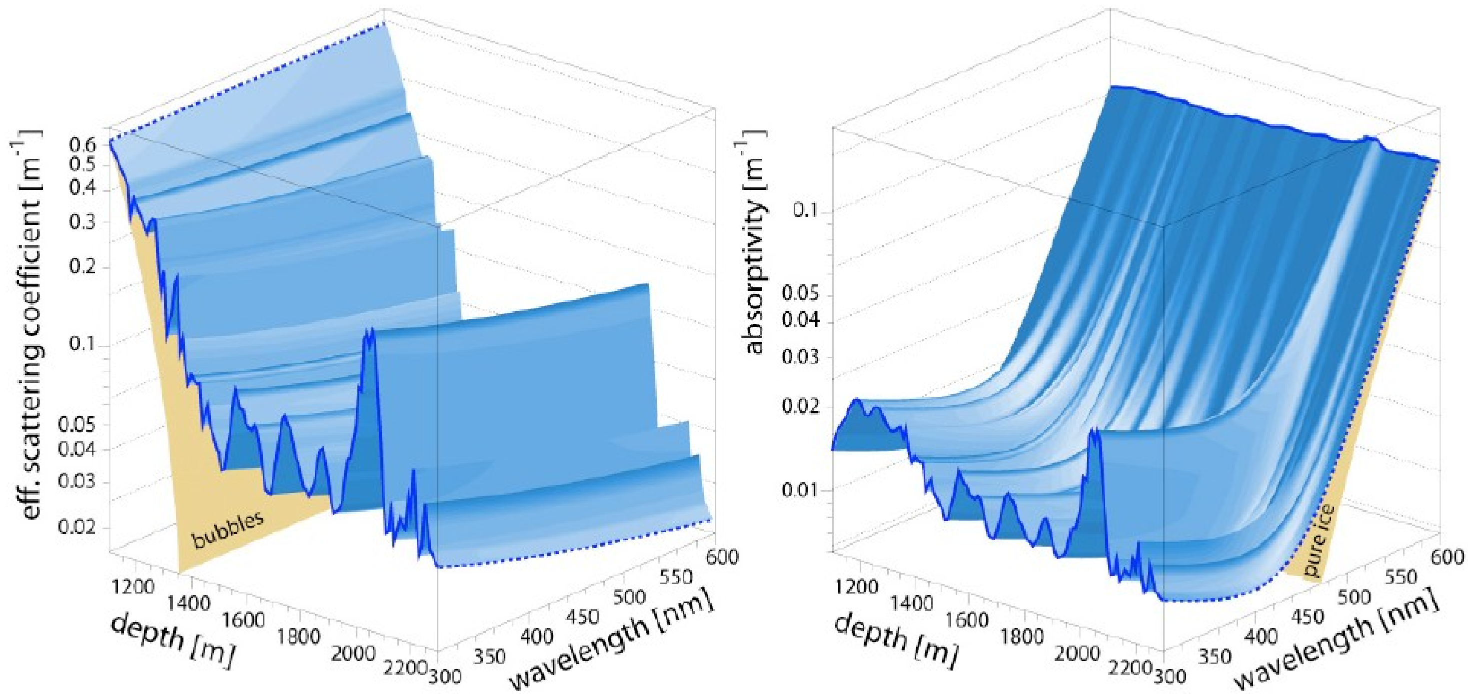

IC22 Halo
IC40 GC
IC59 Dwarf galaxy stacking, Preliminary
IC59 Virgo cluster (subhalos), Preliminary
IC79 GC LE sensitivity
IC79 GC HE sensitivity
Fermi
IceCube Preliminary
$\chi\bar{\chi} \to \tau^+\tau^-$
natural scale
$<\sigma_A v>$ [cm^3 s^{-1}]
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^1
10^2
10^3
10^4
m_χ [GeV]

- we have 1 km^3 of ice instrumented with optical modules
- we can detect flavours (muon tracks, e/τ cascades)
- we can define through-going, starting and contained tracks
- we cover a wide neutrino energy range, from O(10) GeV to PeV
- we can look at all the sky (at once and continuously)

…… **if you have a model of exotic physics that involves neutrinos, we can probe it**

FIN

- Depth dependence of λ_{eff} and λ_{abs} from *in situ* LEDs
- Ice below 2100 m in DeepCore fiducial region <u>very</u> clear
  - $<\lambda_{eff}> \sim 47$ m, $<\lambda_{abs}> \sim 155$ m



- Constant temperature ~ -35C

Compare observed number of events n and predicted number θ for each model, taking into account error σ_ϵ on acceptance:

$$\mathcal{L}_{\mathrm{num}}(n|\theta) = \frac{1}{\sqrt{2\pi}\sigma_\epsilon}\int_0^\infty \frac{(\epsilon\theta)^n \mathrm{e}^{-\epsilon\theta}}{n!} \exp\left[-\frac{1}{2}\left(\frac{1-\epsilon}{\sigma_\epsilon}\right)^2\right] \mathrm{d}\epsilon. \tag{1}$$

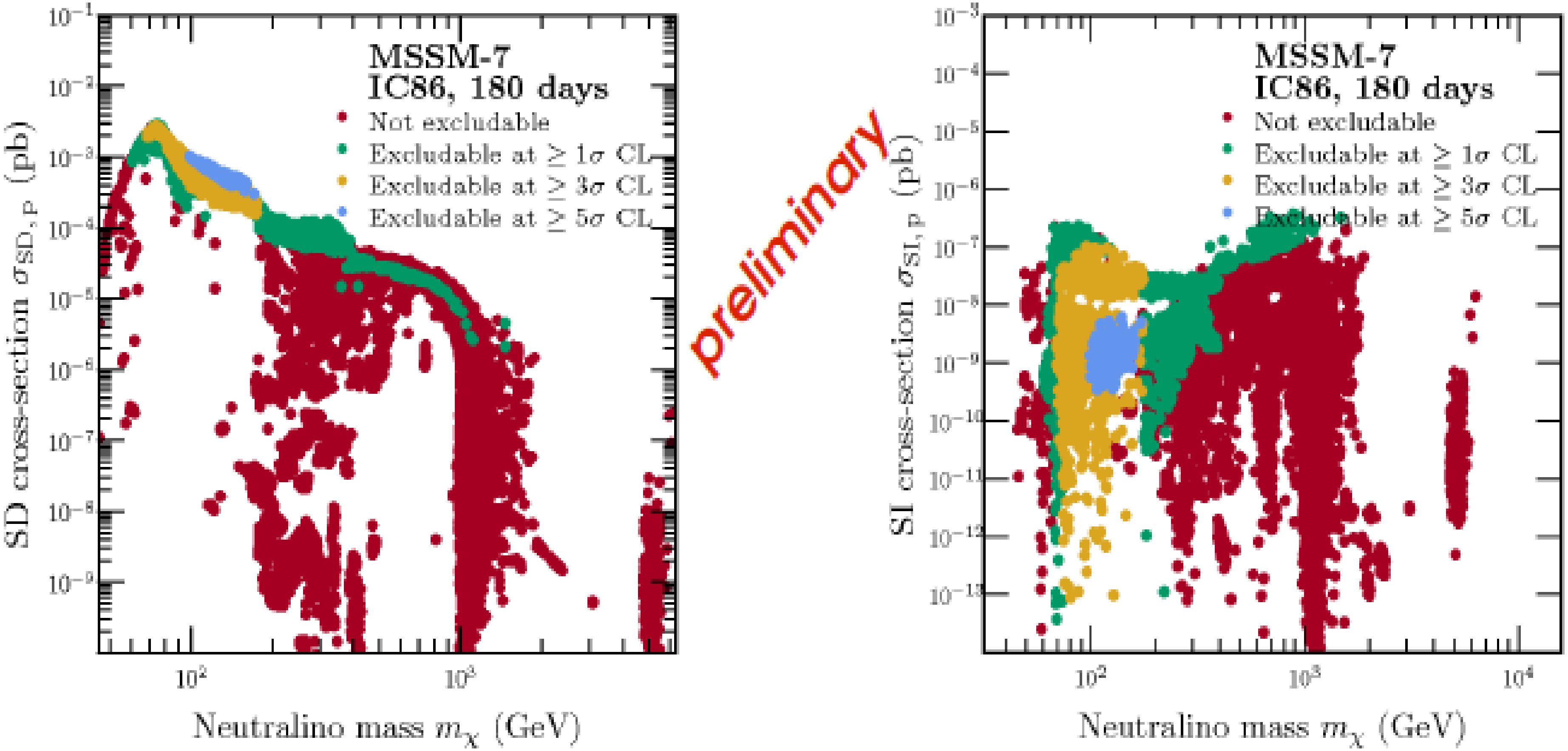
From this, construct a modified p-value as

$$p(n) = \frac{p_{\mathrm{signal+BG}}(n)}{p_{\mathrm{BG}}(n)} = \frac{\sum_{n_i \le n} \mathcal{L}_{\mathrm{num}}(n_i|\theta_{\mathrm{signal+BG}})}{\sum_{n_i \le n} \mathcal{L}_{\mathrm{num}}(n_i|\theta_{\mathrm{BG}})} \tag{2}$$

Can now say immediately, for a single point, that the point is excluded at a confidence level of $1-p$.

$\Longrightarrow$ **model exclusion** exercise – IN/OUT analysis

Assuming preliminary (conservative) estimate of IC-86 effective area



- ✗ Only partial goodness of fit, no measure of convergence, no idea how to generalise to regions or whole space.
- ✗ Frequency/density of models in IN/OUT scans means essentially nothing.

Full unbinned likelihood with number ($\mathcal{L}_{\rm num}$), spectral ($\mathcal{L}_{\rm spec}$) and angular ($\mathcal{L}_{\rm ang}$) parts

$$\mathcal{L} = \mathcal{L}_{\rm num}(n|\theta_{\rm signal+BG}) \prod_{i=1}^{n} \mathcal{L}_{{\rm spec},i}\, \mathcal{L}_{{\rm ang},i} \tag{3}$$

with Number of lit channels (energy estimator)

theory

$$\mathcal{L}_{{\rm spec},i}(N_i,\Xi) = \frac{\theta_{\rm BG}}{\theta_{\rm signal+BG}} \frac{dP_{\rm BG}}{dN_i}(N_i) + \frac{\theta_{\rm signal}}{\theta_{\rm signal+BG}} \int_0^\infty E_{\rm disp}(N_i|E_i') \frac{dP_{\rm signal}}{dE_i'}(E_i',\Xi)\, dE_i' \tag{4}$$

SUSY parameters

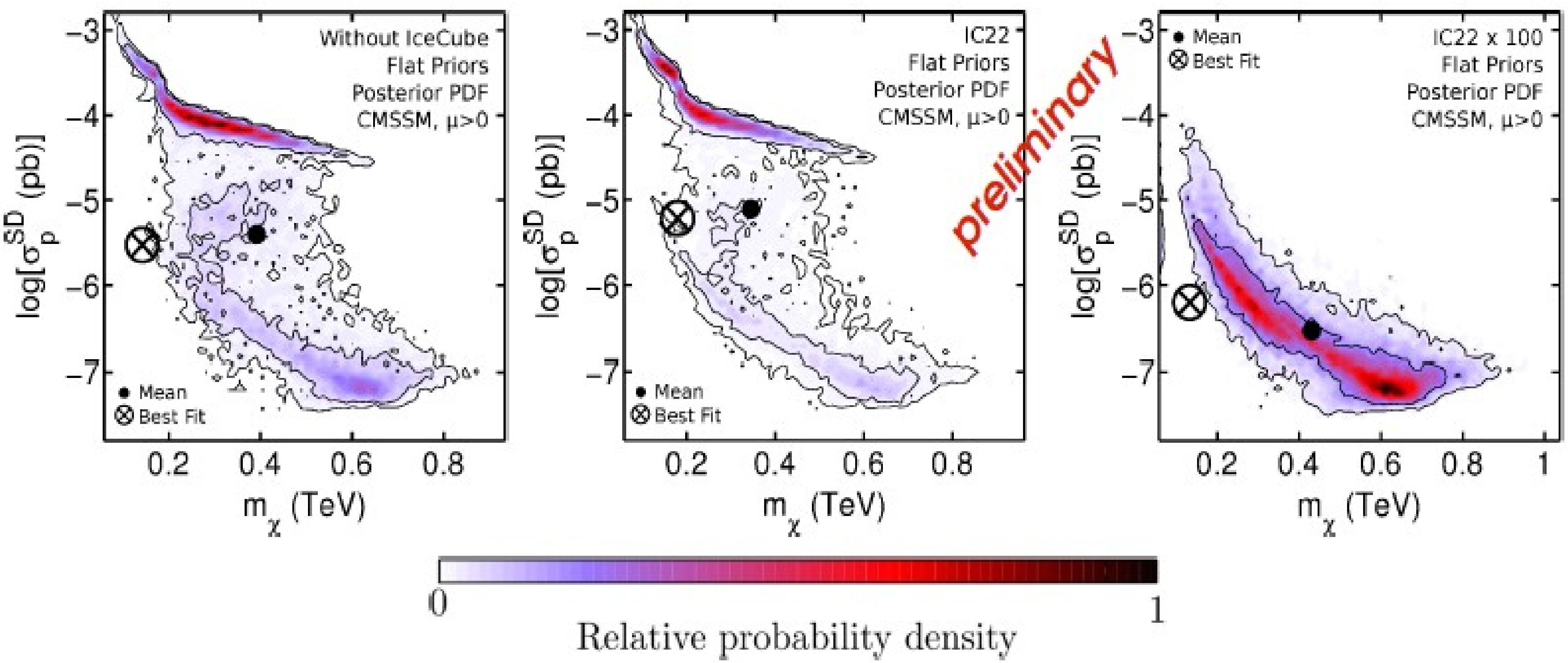
and

$$\mathcal{L}_{{\rm ang},i}(\cos\phi_i) = \frac{\theta_{\rm BG}}{\theta_{\rm signal+BG}} \frac{dP_{\rm BG}}{d\cos\phi_i}(\cos\phi_i) + \frac{\theta_{\rm signal}}{\theta_{\rm signal+BG}} PSF(\cos\phi_i|1) \tag{5}$$

Event arrival angle

Example of what we want in the end (work for IC86 in progress):

SD nuclear scattering cross-section in the CMSSM with IceCube-22 events



- Contours indicate 1σ and 2σ credible regions
- Shading+contours indicate relative probability only, not overall goodness of fit
- Scans performed with modified SuperBayes 1.5.1 and unreleased DarkSUSY