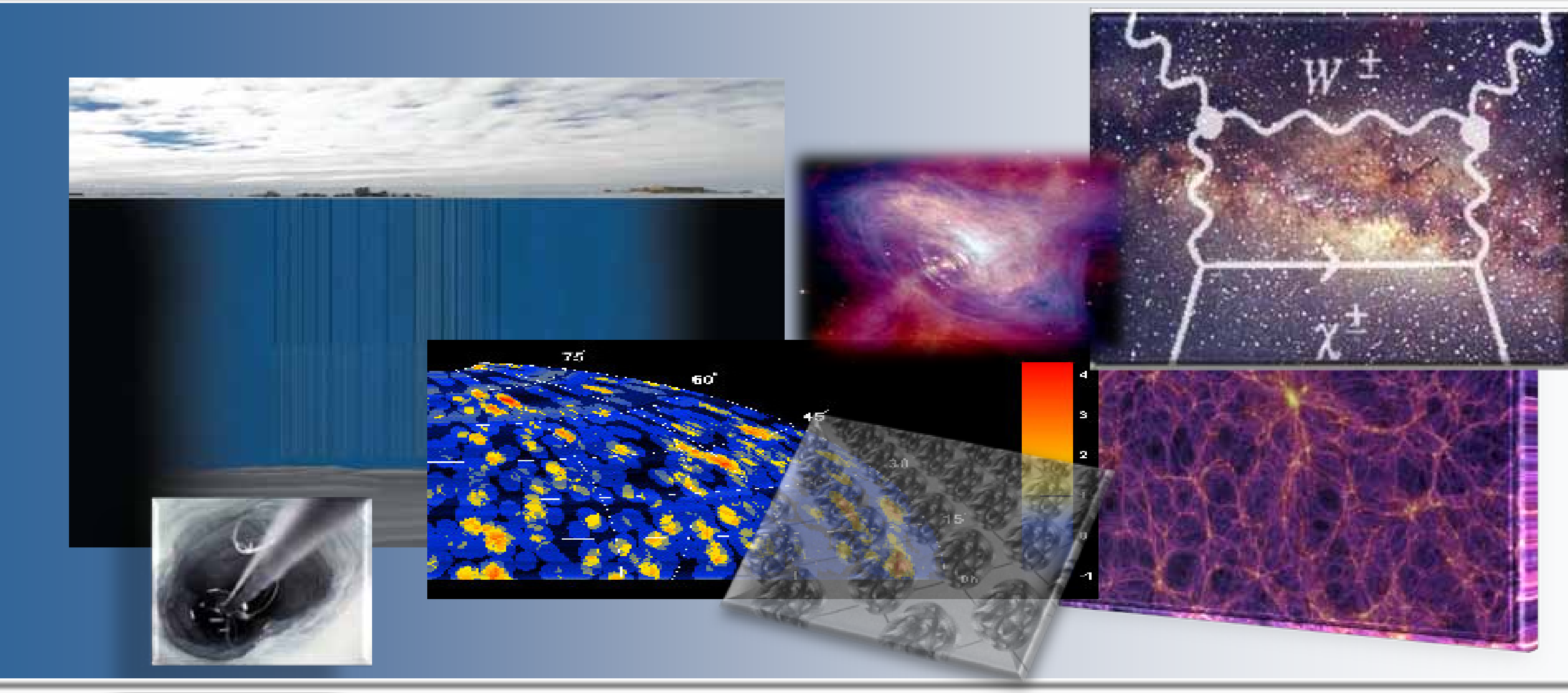
IceCube & indirect detection of dark matter



Carlos de los Heros,
Uppsala University

CosmoOLE09, Valencia, Nov. 2009

conclusions

- IceCube is 75% complete (taking data with 59 strings from April)
- Plan to reach 77 strings after the 2009/10 deployment season
- First results from the 2007 data taking period (22 strings) are coming
- Two papers this year on dark matter searches

  (Phys. Rev. Lett.102, 201302, 2009, and arXiv:0910.4480)
- New analysis on DM search from the halo/galactic center in preparation
- Indirect searches for DM competitive/(better) than direct searches
- The low-energy extension, DeepCore, funded. First string taking data.

  Remaining five strings to be deployed this year

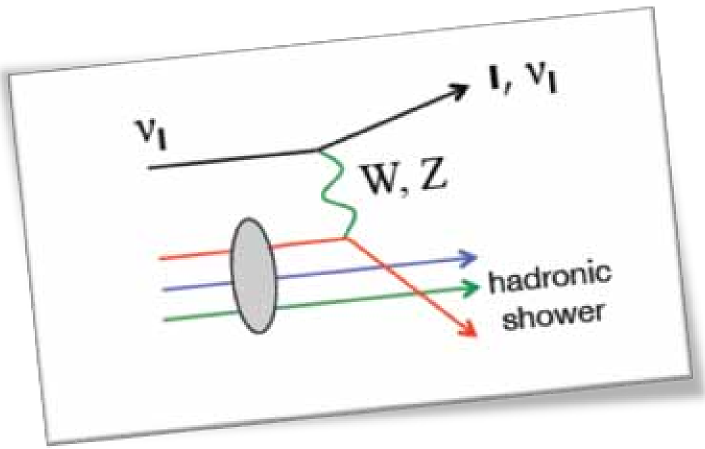
outline

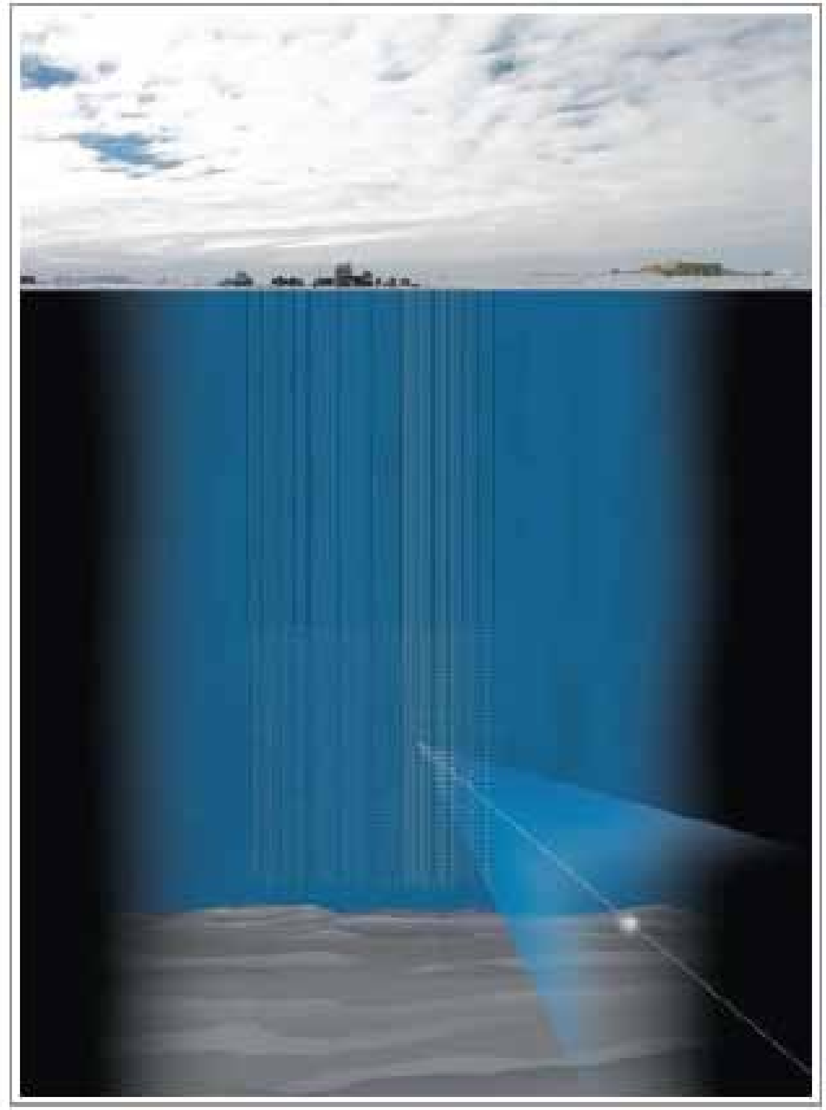
status of IceCube construction

candidates and sources of DM for indirect searches

search techniques and results

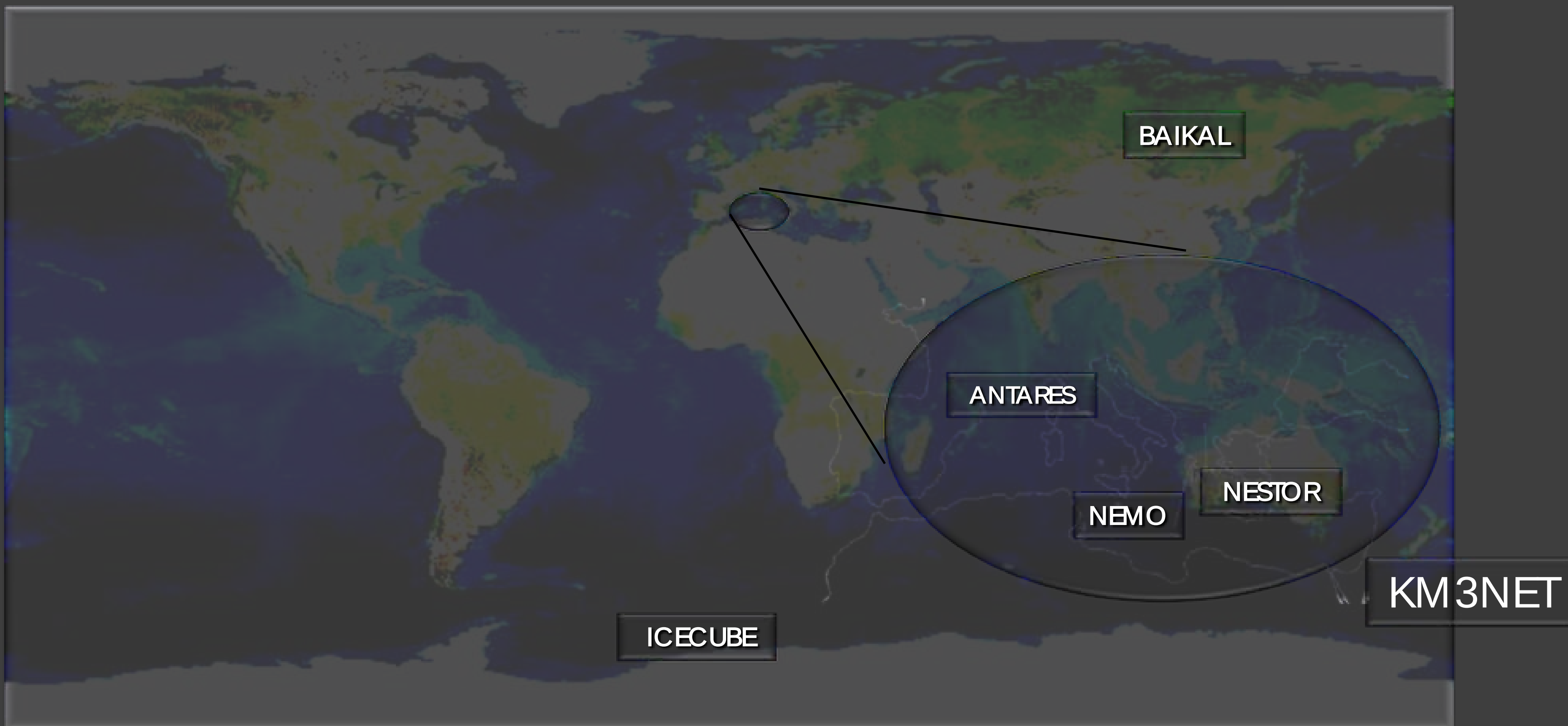
- Neutrinos interact in or near the detector





- O(km) muon tracks from ν_μ CC
- O(10 m) cascades from ν_e CC, low energy ν_τ CC, and ν_x NC
- Cherenkov radiation detected by 3D array of optical sensors (OMs)

neutrino telescopes in operation/R&D

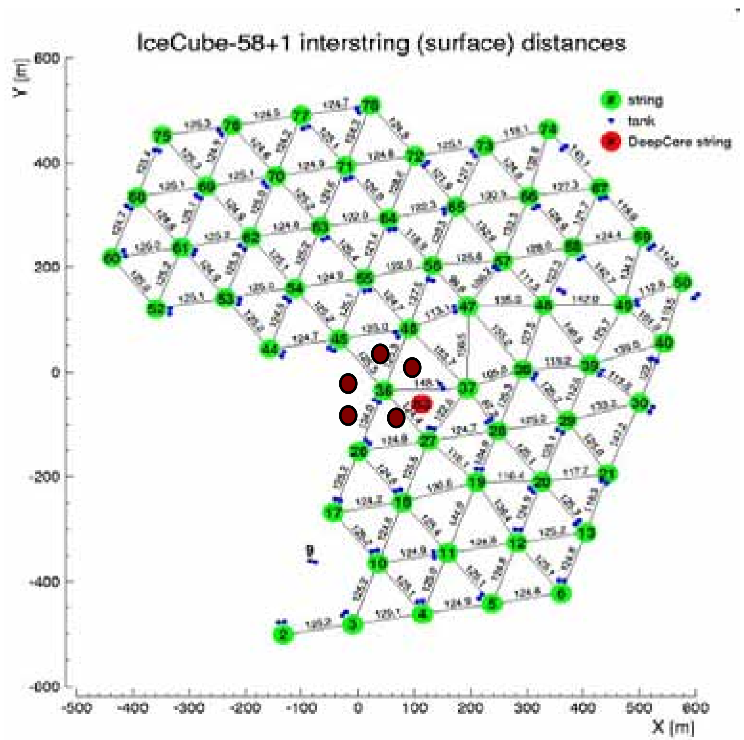


19 strings/stations installed during the 2008-2009 austral summer

Total of 59 strings and 118 IceTop tanks

à over two thirds complete!

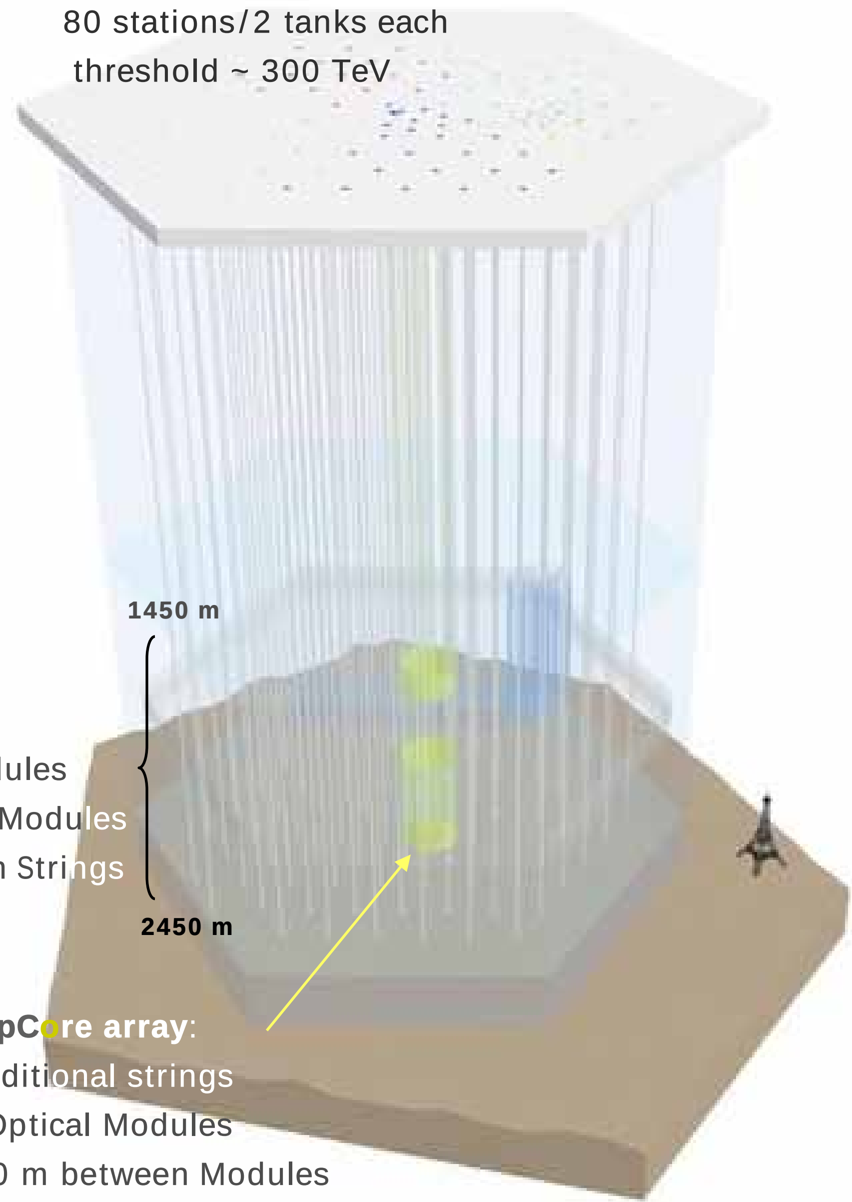
Integrated exposure reaching 1 km^3.year



IceTop: Air shower detector

80 stations/2 tanks each

threshold ~ 300 TeV



InIce array:

80 Strings

60 Optical Modules

17 m between Modules

125 m between Strings

DeepCore array:

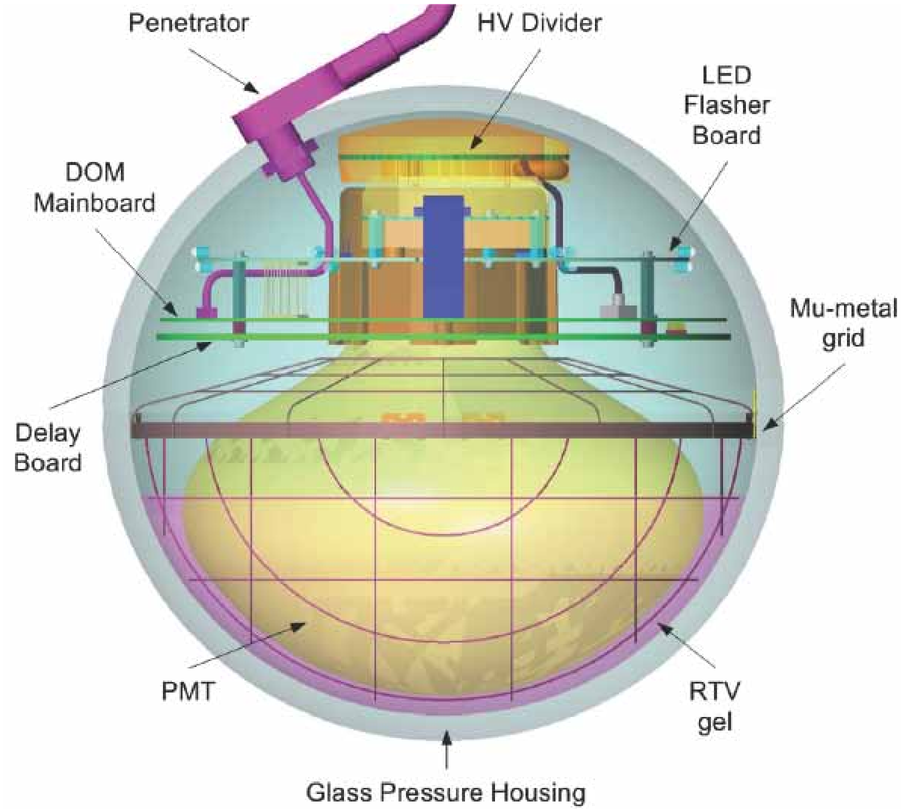
6 additional strings

60 Optical Modules

7/10 m between Modules

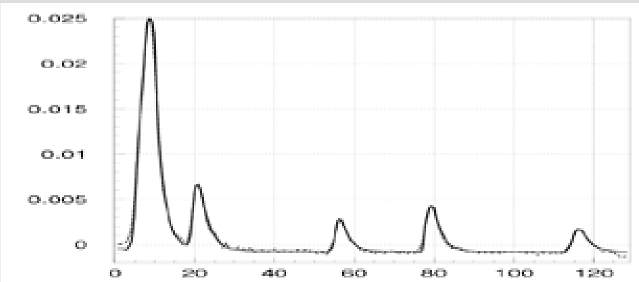
72 m between Strings

Each DOM is an autonomous data collection unit



- **PMT**: Hamamatsu, 10''
- **Digitizers**:
  - ATWD: 3 channels. Sampling 300MHz, capture 400 ns
  - FADC: sampling 40 MHz, capture 6.4 ms
  - Dynamic range 500pe/15 nsec, 25000 pe/6.4 ms

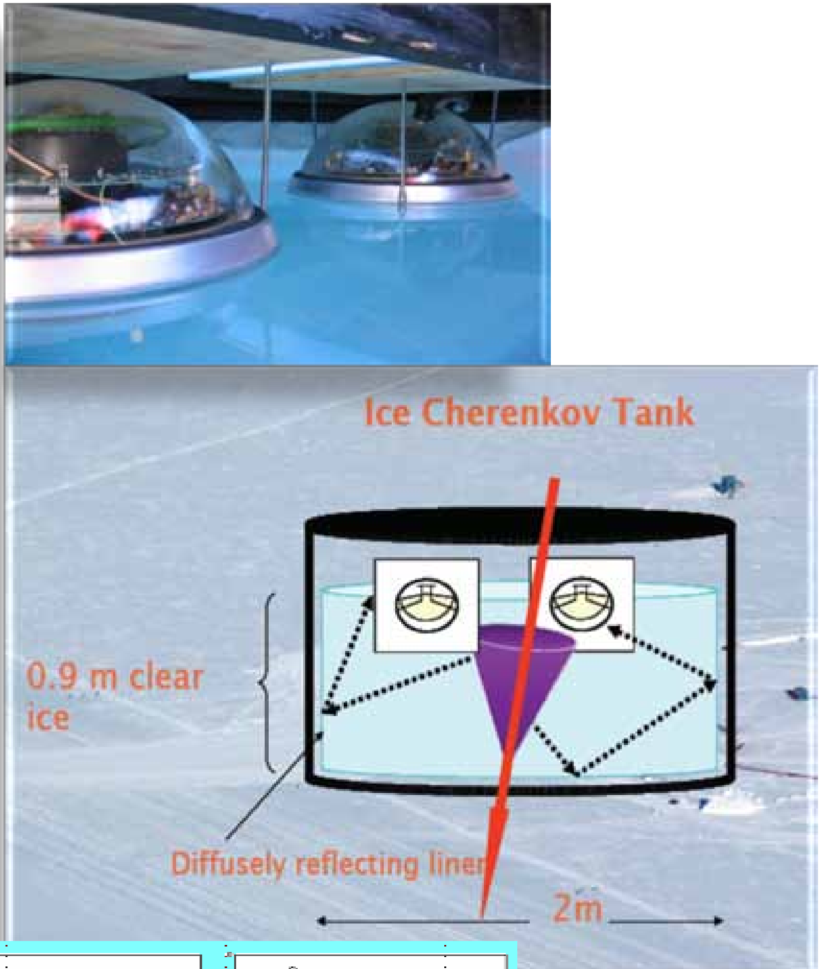
digitized Waveform

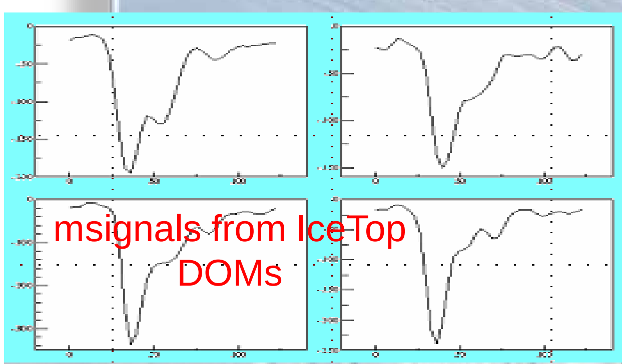


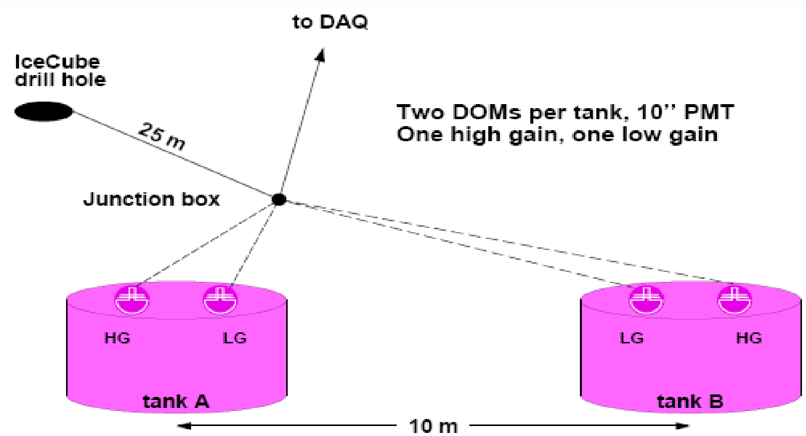
- **Flasher board**:
  12 controllable LEDs at 0º or 45º

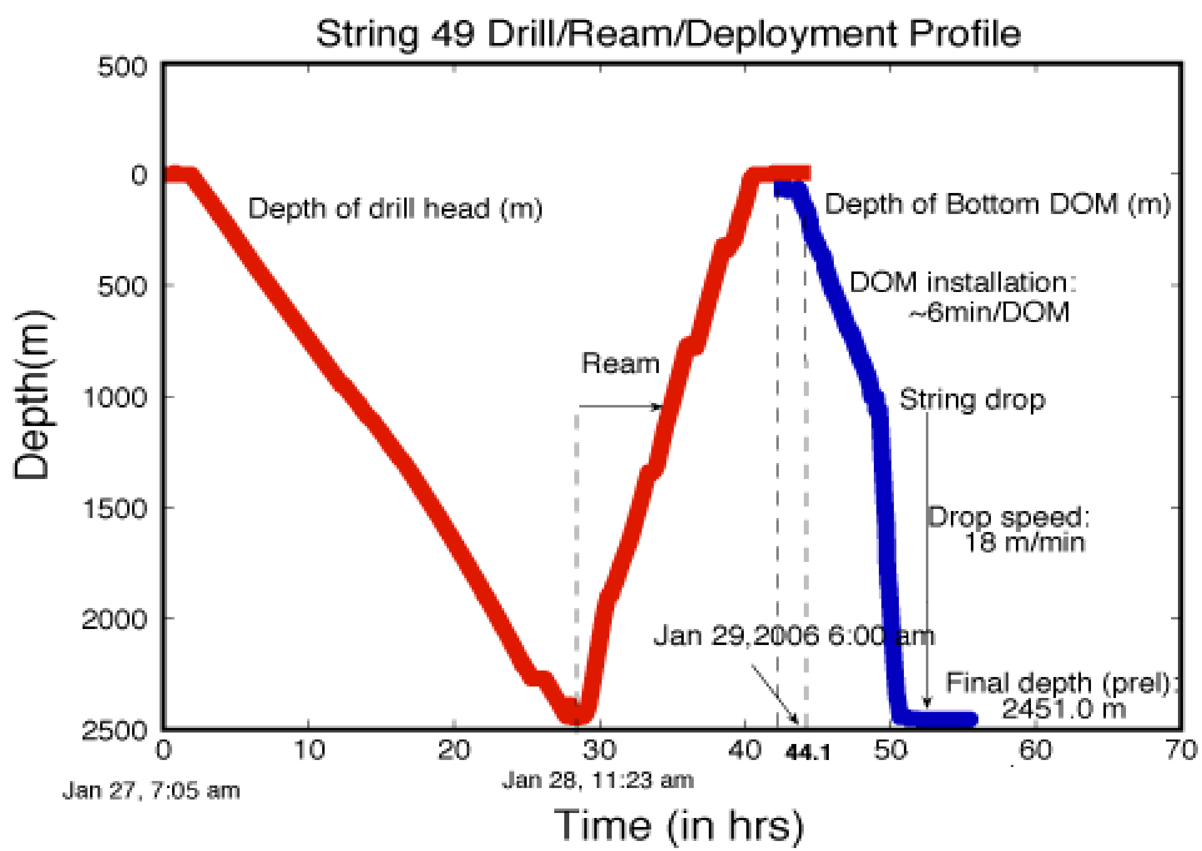
- Dark Noise rate ~ 400 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Timing resolution ≤ 2-3 ns
- Power consumption: 3W

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


Ice Cherenkov Tank
0.9 m clear ice
Diffusely reflecting liner
2m


msignals from IceTop DOMs


to DAQ
IceCube drill hole
25 m
Two DOMs per tank, 10'' PMT
One high gain, one low gain
Junction box
HG
LG
LG
HG
tank A
tank B
10 m



5MW x 30 hrs = 0.56 TJ!

AMANDA drilling (1950m) 90 hrs deployment: 18 hrs

IceCube drilling (2450m) 40 hrs, deployment: 10 hours

the drill camp

Analyses sensitive to the optical properties of ice

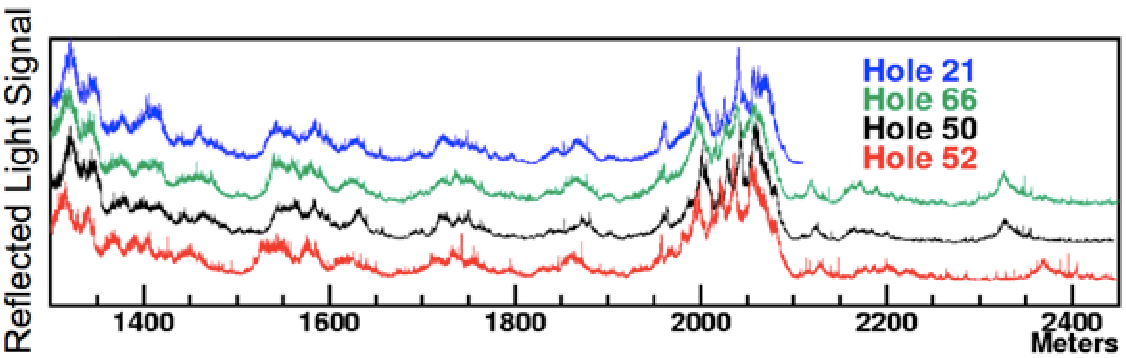
South Pole Ice: extremely pure but presence dust layers

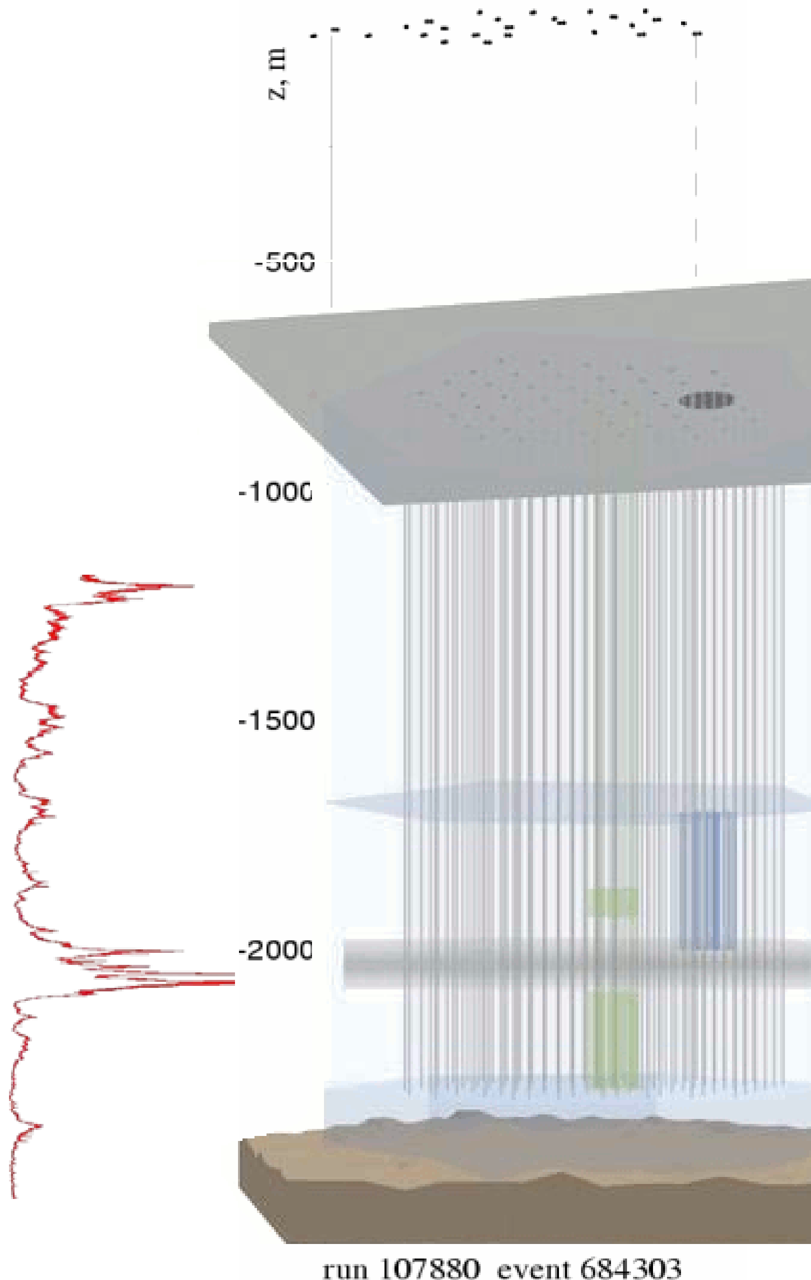
Determine optical properties using LED and LASER sources

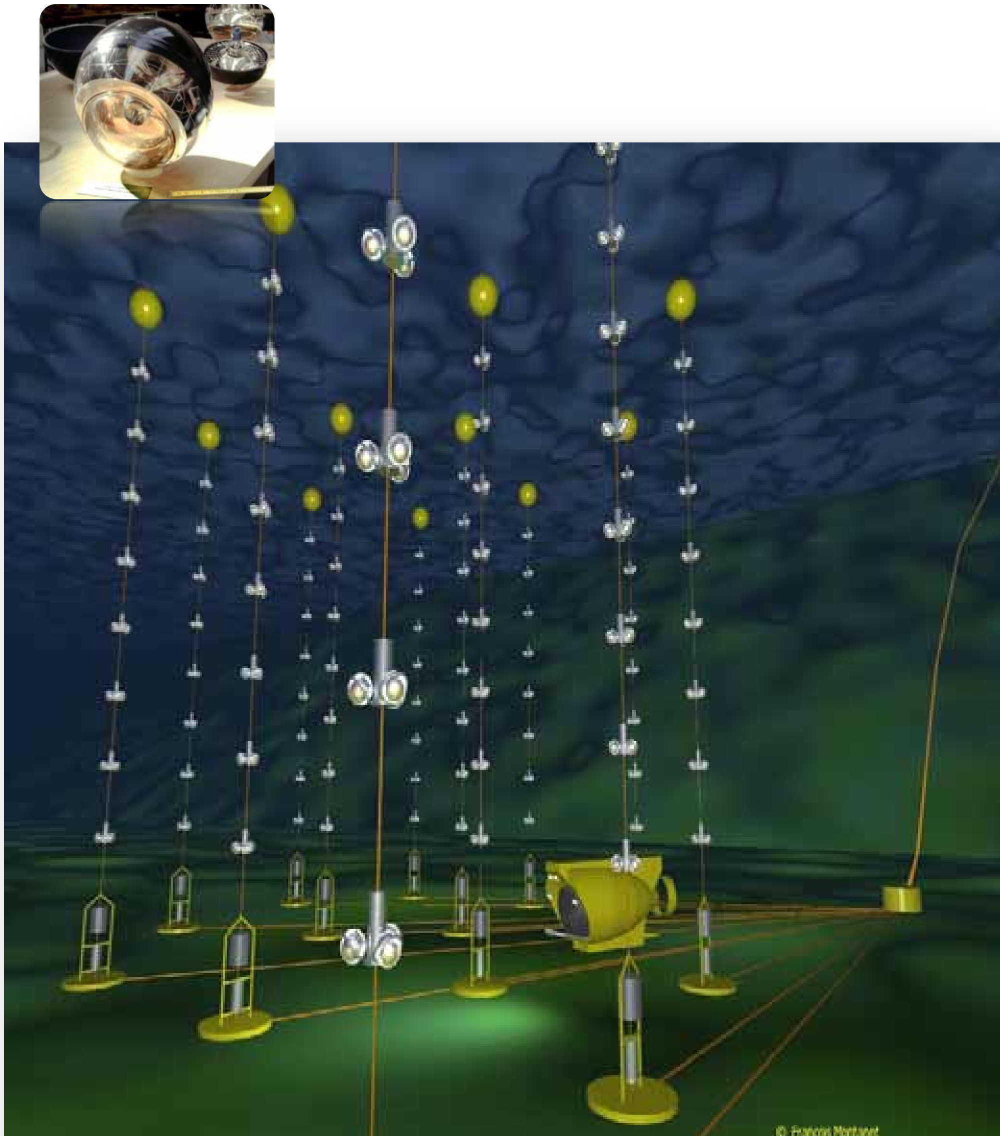
Average optical parameters at 400 nm:

λ_{abs} ~110 m, λ_{sca} ~20 m above the dust layer

λ_{abs} ~220 m, λ_{sca} ~40 m below the dust layer







2.5 Km deep in the Mediterranean

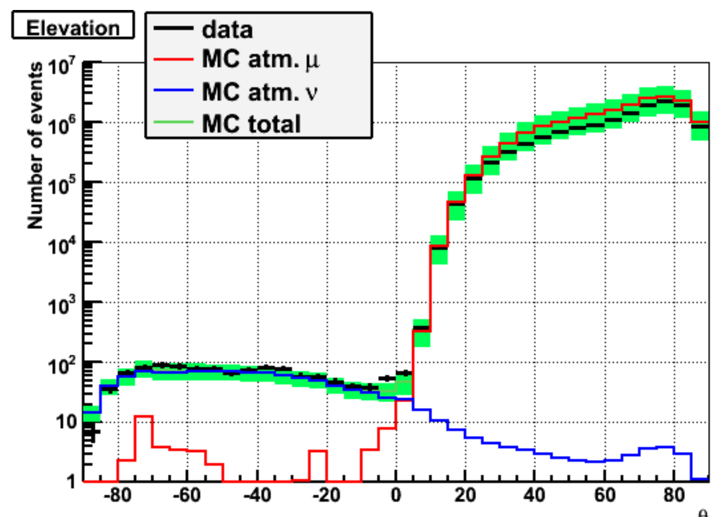
12 lines

25 'storeys' with 3 PMTs each

~70 m inter-string separation

14.5 m vertical storey separation

0.02 km3 instrumented volume



event reconstruction needs Cherenkov light timing:
array of PMTs with ~1ns resolution

à optical properties of the medium of prime importance

	absorption length	scattering length
South Pole ice (IceCube)	**110 m (@ 400nm)**	**20 m (@ 400nm)**
Lake Baikal	**25 m (@ 480nm)**	**59 m (@ 480nm)**
Mediterranean (ANTARES/NESTOR)	**~50 m (@ 470nm)**	**100-300 m (@ 470nm)**

longer absorption length → larger effective volume

longer scattering length → better timing, (ie pointing resolution)

Astrophysics

- point source search (steady/transient)
- diffuse search
- supernova

Cosmic Ray physics (with IceTop)

- composition
- primary energy spectrum

Particle Physics/New Physics

- neutrino oscillations
- dark matter search
- SUSY searches
- magnetic monopoles
- TeV gravity

A flavour of ongoing analyses in IceCube:

- Extreme high-energy diffuse search
- High-energy point source search (steady, time dependent, flares)
- Low-energy point source search
- Atmospheric neutrino oscillation measurements
- Measurement of the atmospheric neutrino energy spectrum
- Search for atmospheric neutrino-induced cascades
- Searches for neutralino dark matter (Sun, Earth, Halo)
- Searches for Kaluza-Klein dark matter (Sun)
- Search for relativistic and slow monopoles
- Search for staus in cosmic ray showers
- Supernova search
- All-particle cosmic ray energy spectrum
- Study of high p_T muons in cosmic ray air showers
- Large scale cosmic rays anisotropy
- Search for high energy tau neutrinos
- Search for Quantum Gravity with high-energy atmospheric neutrinos

There is no a single effective area of a neutrino telescope

A_{eff} is analysis-dependent

As a rule, the A_{eff} at trigger level is useless to make predictions

- W_m » 23%, W_b » 4% à non-baryonic matter

Candidates: **W**eakly **I**nteracting **M**assive **P**articles

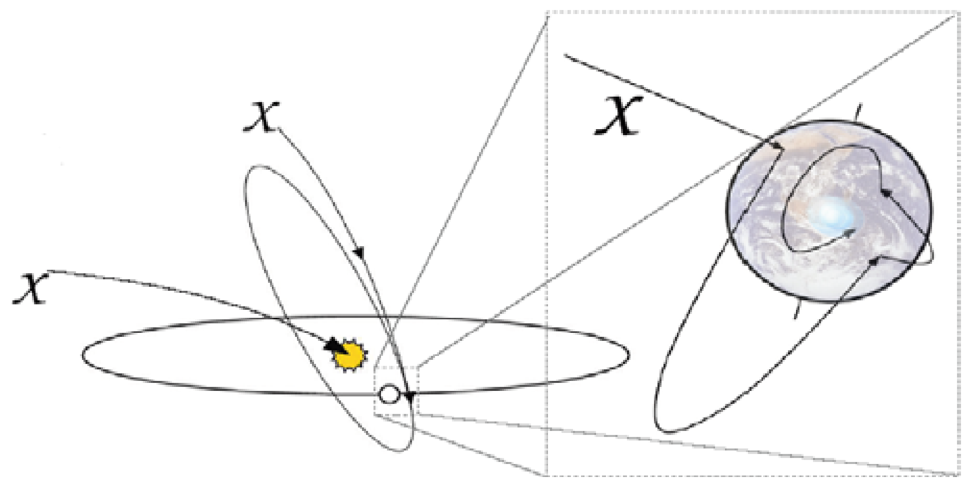
à MSSM candidate: the neutralino, **C**

à UED candidate: lightest Kaluza-Klein mode

look at objects where the WIMP can be gravitationaly trapped and annihilate:

Sun, Earth and galactic halo

A lot of physics uncertainties involved:
- relic density calculations
- DM distribution in the halo
- velocity distribution
- c/K properties (MSSM/UED)
- interaction of c/Kwith matter (capture)



The good old MSSM neutralino:

From MSSM. Partner of the B, W and H's

$$\tilde{\chi}_i^0 = N_{i1}\tilde{B} + N_{i2}\tilde{W}^3 + N_{i3}\tilde{H}_1^0 + N_{i4}\tilde{H}_2^0$$

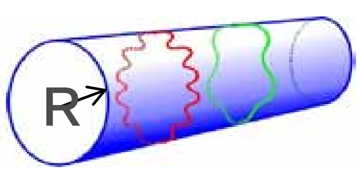
Lightest is stable à relic from Big Bang

good candidate for dark matter

The lightest Kaluza- Klein particle (LKP):

- from UED (Universal Extra Dimension) theories
- 2 free parameters, R and cutoff scale L .
- finite space dimension à momentum is quantized
- p = *n*/R which can be interpreted as mass = *n*/R

  à tower of mass eigenstates.
- The lightest is stable à candidate for dark matter



WIMP-induced neutrinos:

cc ® { qq, l^+l^-, W, Z, H } ® n

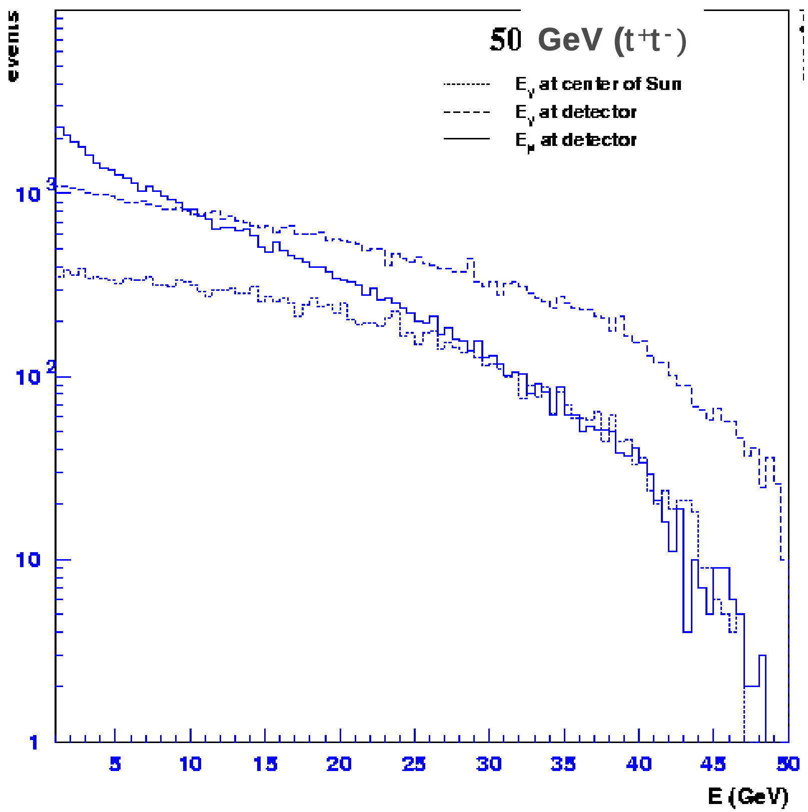
KK ® nn

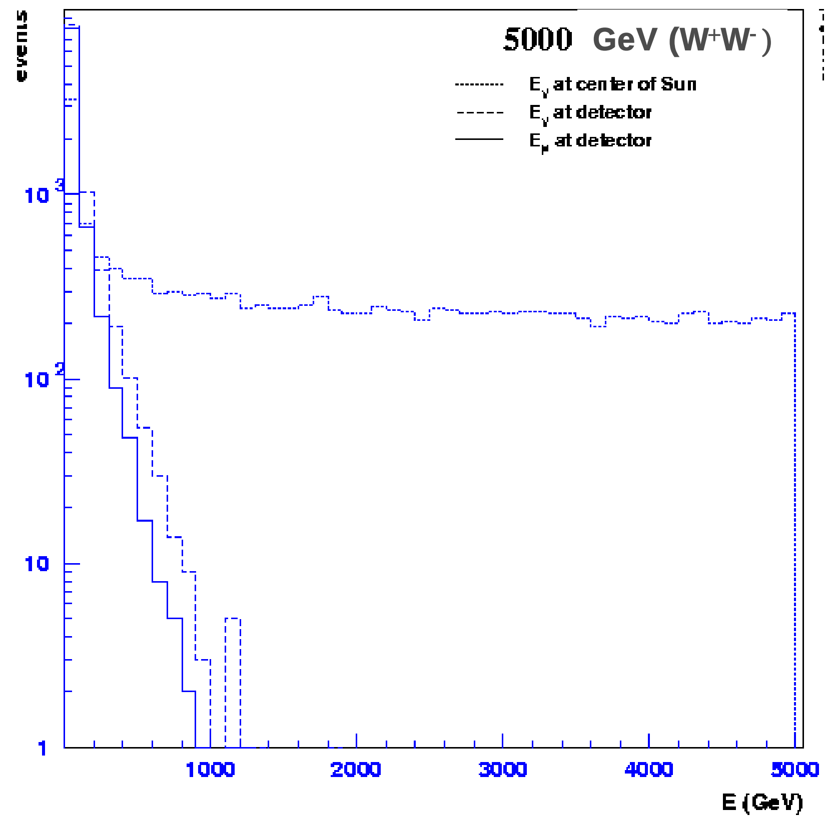
signature: n excess over background from

Sun/Earth/Halo direction

Channel	Branching ratio	
	$\Delta_{q^{(1)}} = 0$	$\Delta_{q^{(1)}} = 0.14$
$(e^+e^-), (\mu^+\mu^-), \tau^+\tau^-$	0.20	0.23
$(u\bar{u}), c\bar{c}, t\bar{t}$	0.11	0.077
$(d\bar{d}), (s\bar{s}), b\bar{b}$	0.007	0.005
$\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$	0.012	0.014
$(\Phi, \Phi^*)^\dagger$	0.023	0.027

from the Sun:





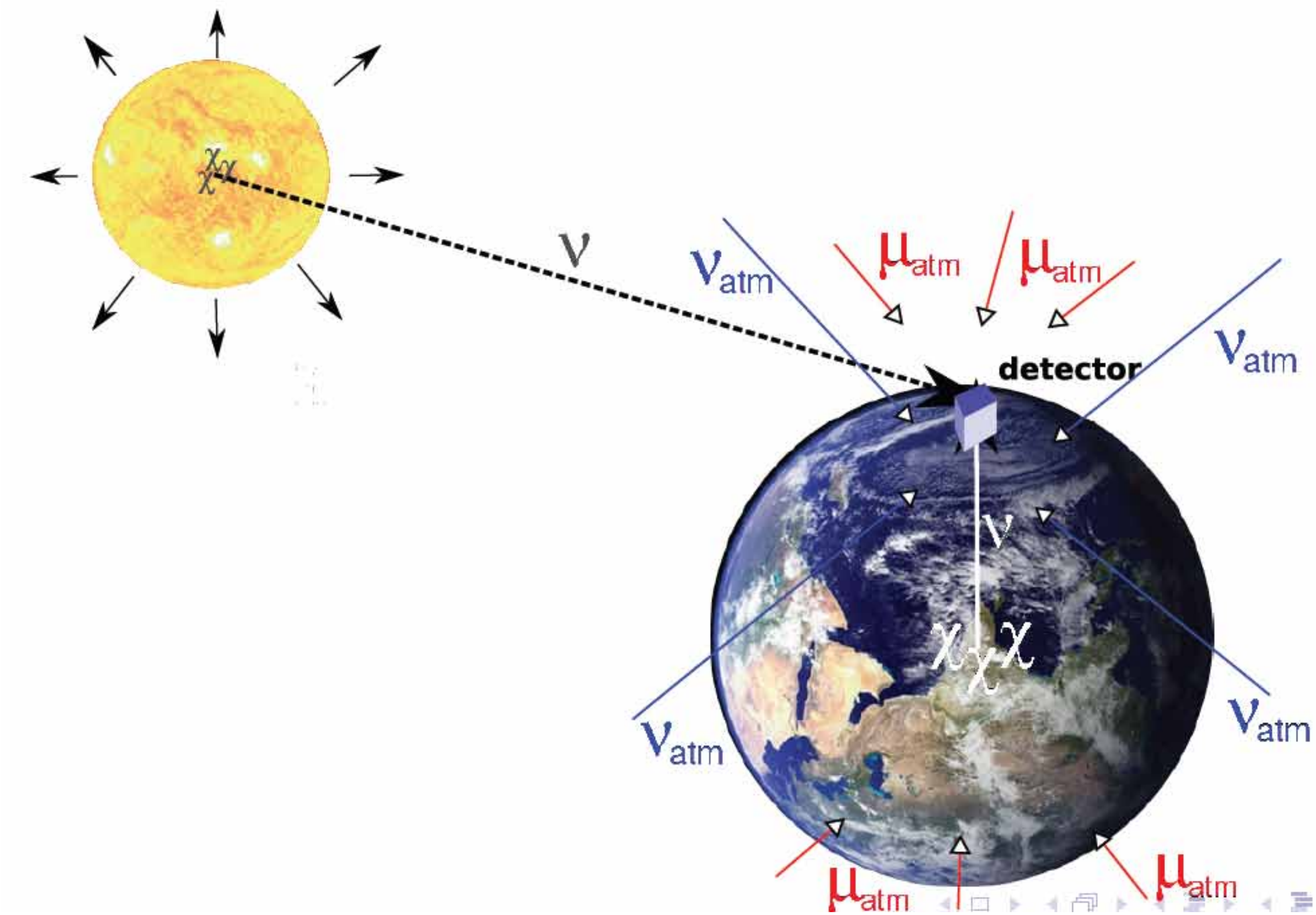
Even for the highest WIMP masses, we do not get muons above 1TeV

à Indirect dark matter searches from the **Sun** are a low-energy analysis in neutrino telescopes.

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

Atmospheric muons ~ $\mathcal{O}(10^9)$ events/year (downwards)

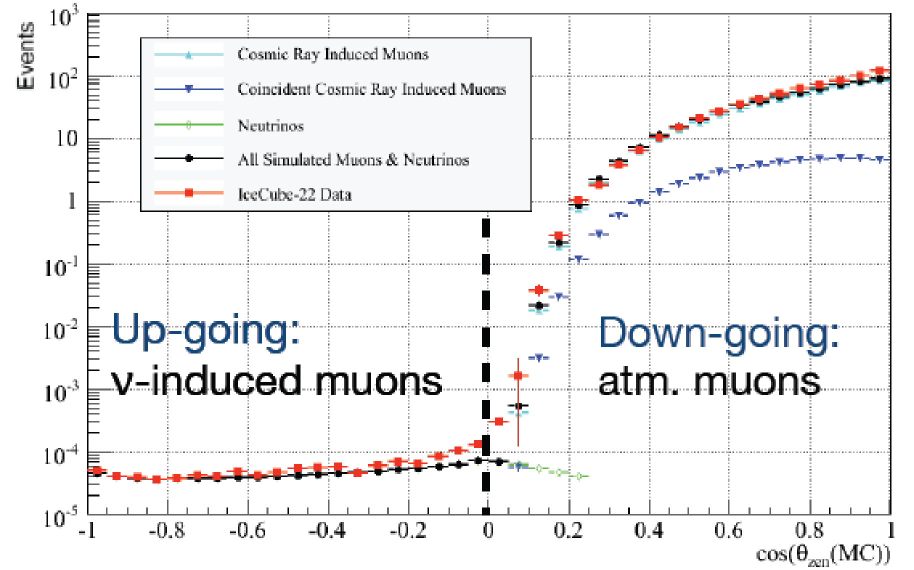
Atmospheric neutrinos ~ $\mathcal{O}(10^3)$ events/year (all directions)



example: background rejection in IceCube-22

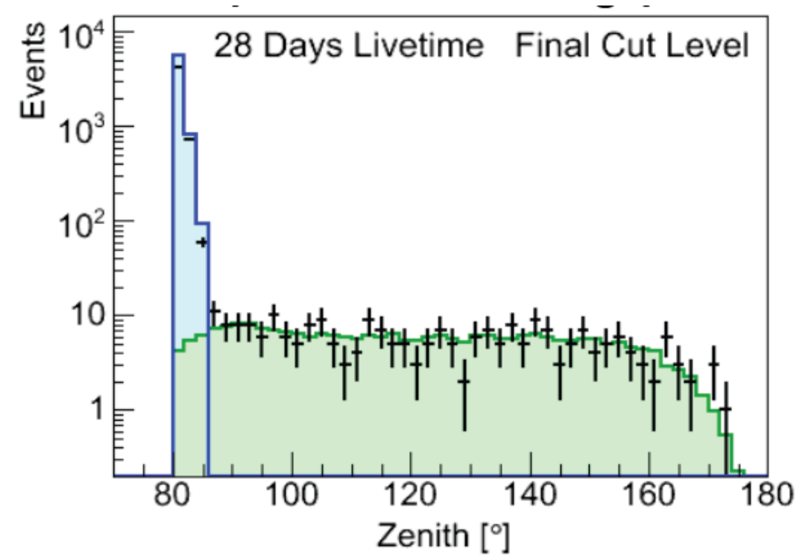
Background:

- atmospheric muons
- coincident atmosph. muons
- atmospheric neutrinos



High-purity atmospheric neutrino sample achieved after quality cuts

Data/MC comparison IceCube-22



analysis strategies

Triggered data still dominated by atmospheric muons

Northern hemisphere contaminated by misreconstructions

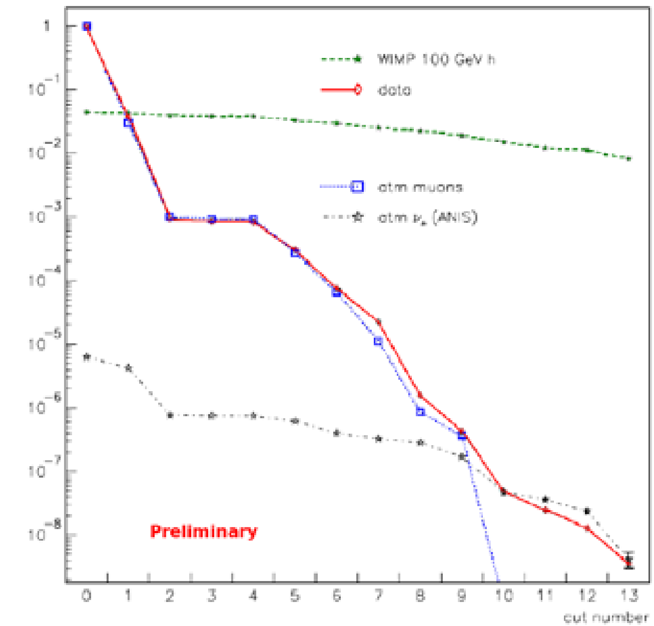
Reject mis-reconstructed atmospheric muon background through event and track quality parameters

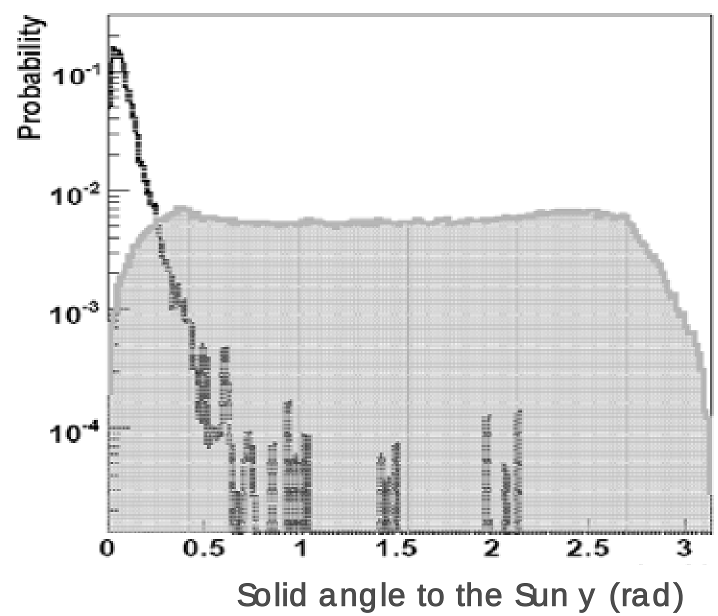
typical variables:

first guess direction, ‘smoothness’ of hits along the track, number of direct hits, c.o.g. of hits, quality of final reconstruction…

Use of linear cuts and/or multivariate methods (Neural Nets, Support Vector Machines, Boosted Decision Trees)

DM searches directional: good additional handle on event selection





Cut and count analysis

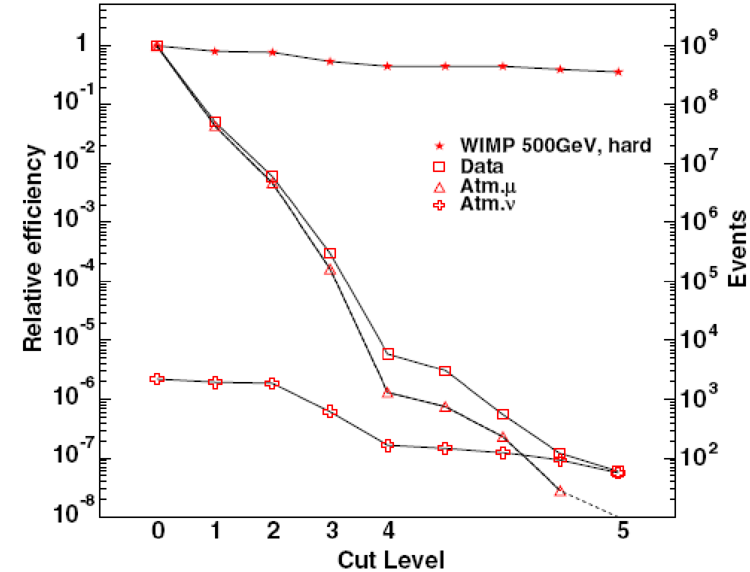
1D and/or 2D cuts to extract irreducible atmospheric neutrino background

N_{data}, N_{bck} à N_{90}

Experimentally obtained quantity

$$\Gamma_{\nu\mu} \leqslant \frac{N_{90}}{V_{\text{eff}} \cdot t}$$

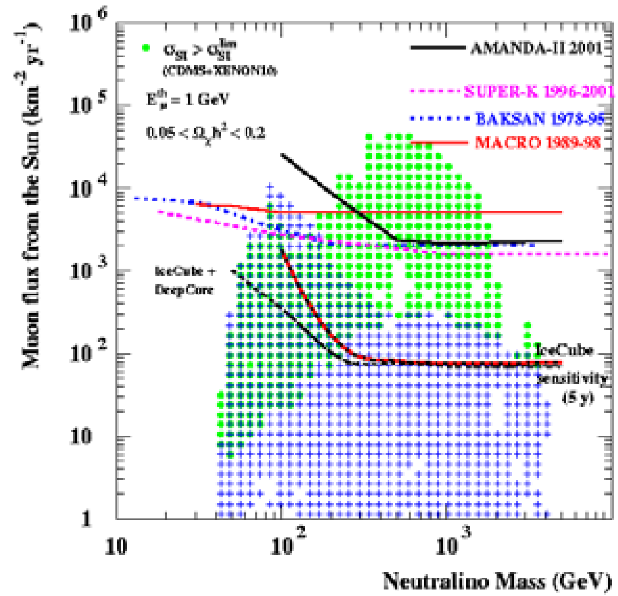
From MC



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

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

Use additional MC-based scripts for conversion to a muon flux



Drawback: need high statistics for background simulations

Systematic uncertainties

- Due to systematic uncertainties the expected number of events, N_{bck} is really N_{bck}+-s_{bck}, ie,

  the comparison is between N_{data} and N_{bck}+-s_{bck}

- Systematic uncertainties: in the background expectation (flux of atm **n**) and on the detector performance

- We include systematic uncertainties in the calculation of N_{90} using a modified Feldman-Cousins scheme (Phys. Rev. D67, 012002, (2003), Phys. Rev. D67, 118101, (2003)).

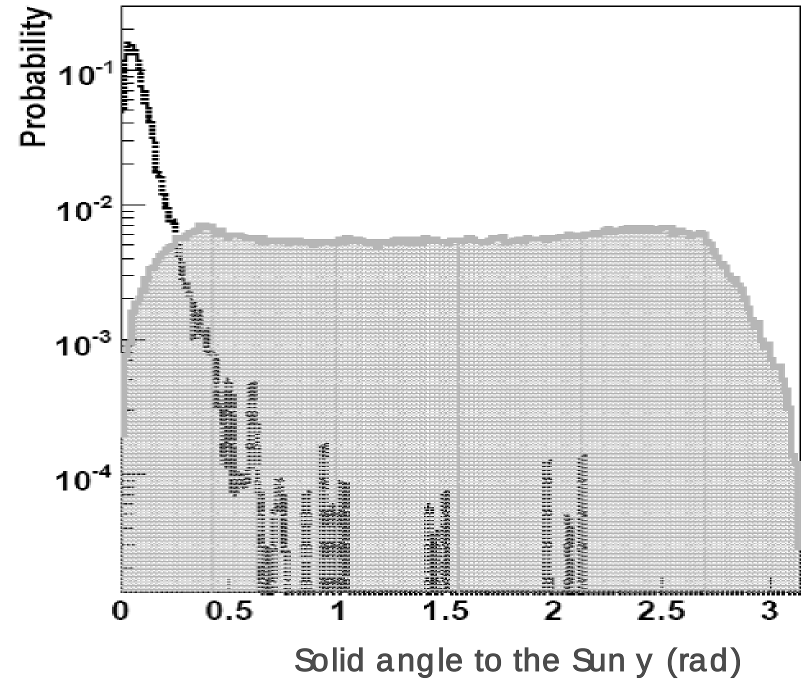
$$\sum_{n'=n_1}^{n_2} p(n')_{s+b} = 1-\alpha \quad \Longrightarrow \quad q(n)_{s+b} = \frac{1}{2\pi\sigma_b\sigma_\epsilon}\int_0^\infty\int_0^\infty p(n)_{b'+\epsilon' s} \times e^{-(b-b')^2/2\sigma_b^2} e^{-(1-\epsilon')^2/2\sigma_\epsilon^2} db'\, d\epsilon'$$

- Method improved and implemented in ROOT as class TRolke

Sun/Earth/Galactic center are point sources

Possible to perform a test on the signal content in the angular distribution of detected events w.r.t. the source

Possible to have less stringent cuts



from signal MC

from randomized data

$$f_\xi(\Psi) = \xi \cdot f_s(\Psi) + (1-\xi) \cdot f_b(\Psi)$$

where x is the signal fraction in f_x(y), $\xi = \frac{\mu_s}{n_{obs}}$

- Probability of observing n_{obs} events at angles Y_i: $\mathscr{L}(\xi) = \prod_{i=1}^{n_{obs}} f_\xi(\Psi_i)$

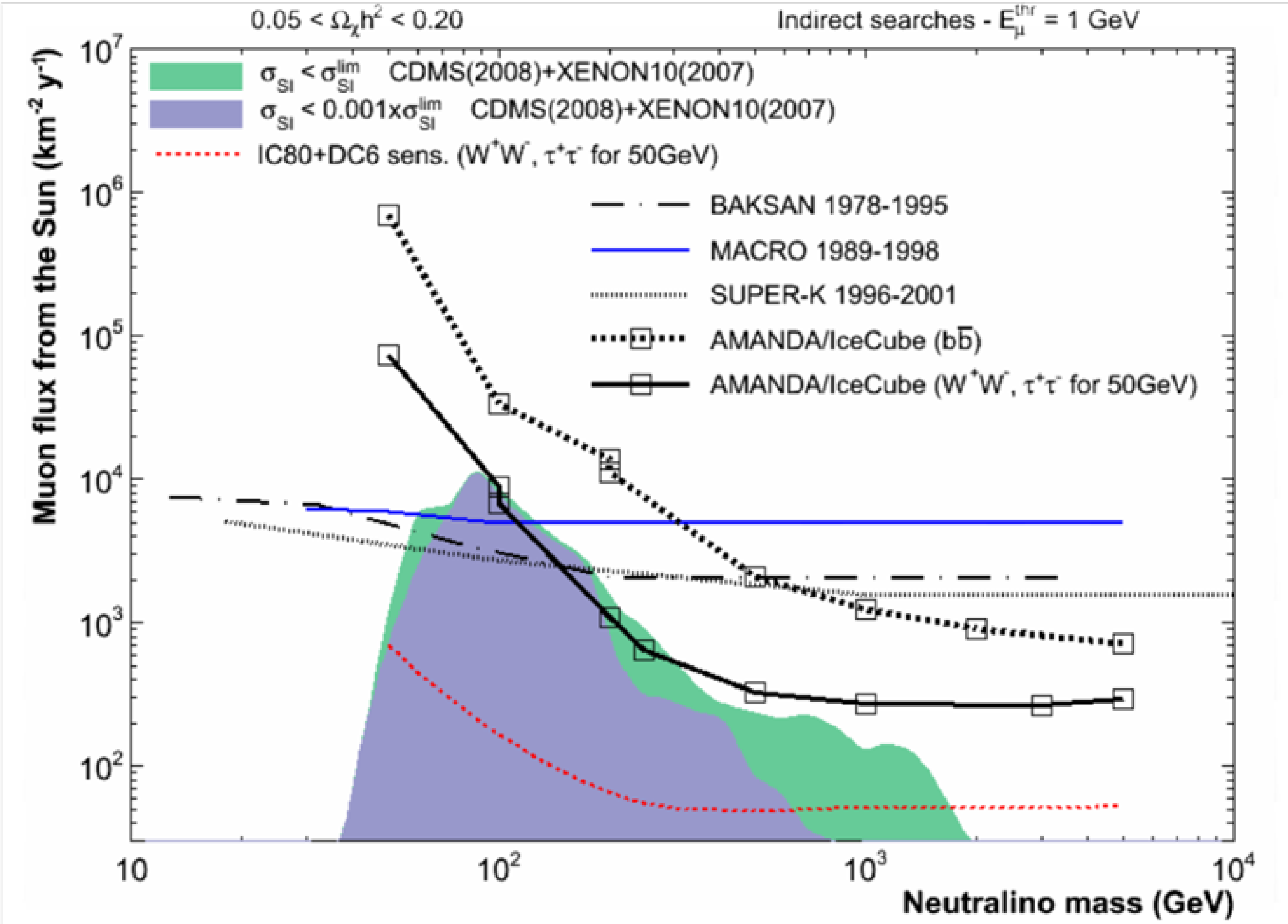
- Likelihood of x can be compared with the background-only hypothesis, x =0

$$\Lambda = \frac{\mathscr{L}(\xi)}{\mathscr{L}(0)} = \frac{\prod_{i=1}^{n_{obs}} f_\xi(\Psi_i)}{\prod_{i=1}^{n_{obs}} f_0(\Psi_i)} = \prod_{i=1}^{n_{obs}} \frac{f_\xi(\Psi_i)}{f_0(\Psi_i)}$$

x=0 can be rejected if L>c, with c found from P(L>c| x=0) > a for chosen a

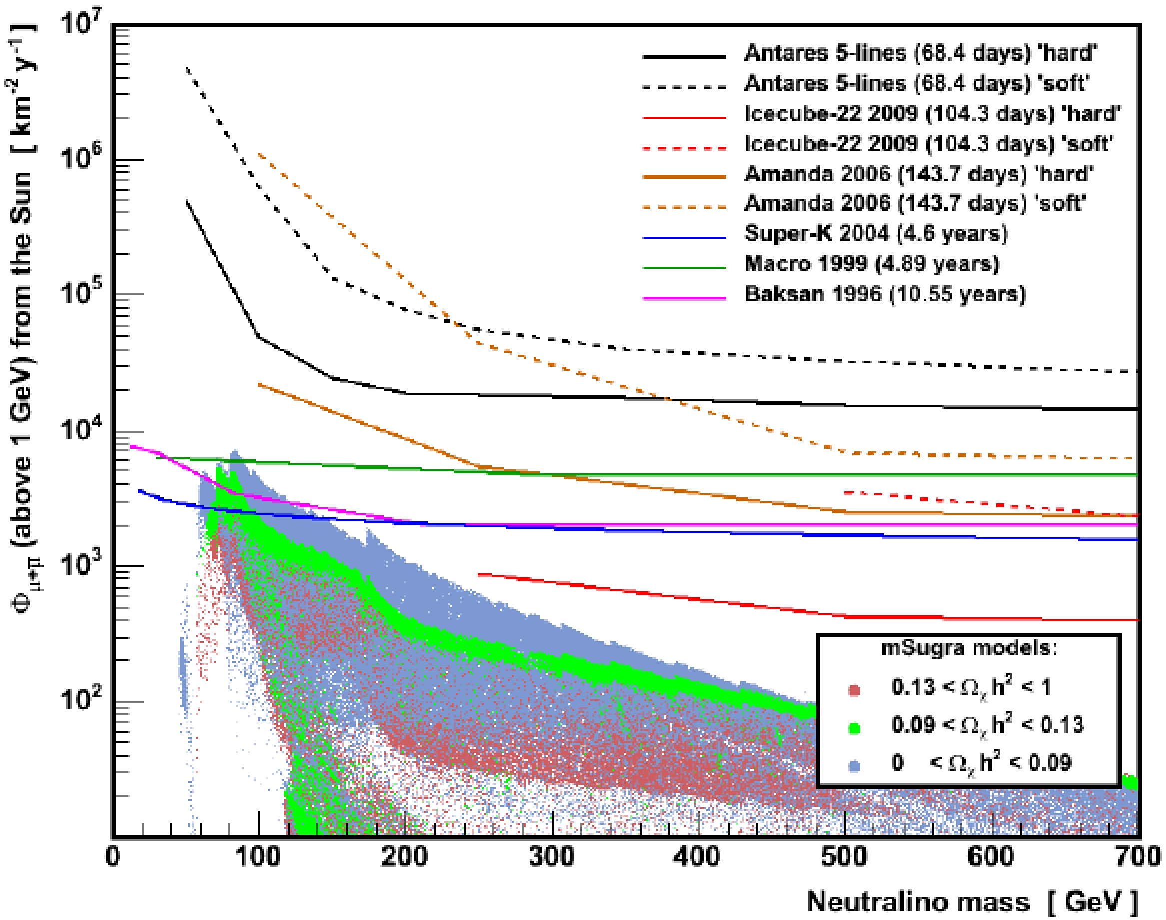
(in reality we use the unified Feldman-Cousins approach, defining a rank instead of using L directly)

90% CL muon flux limit from the Sun vs neutralino mass
(compared to MSSM scans)

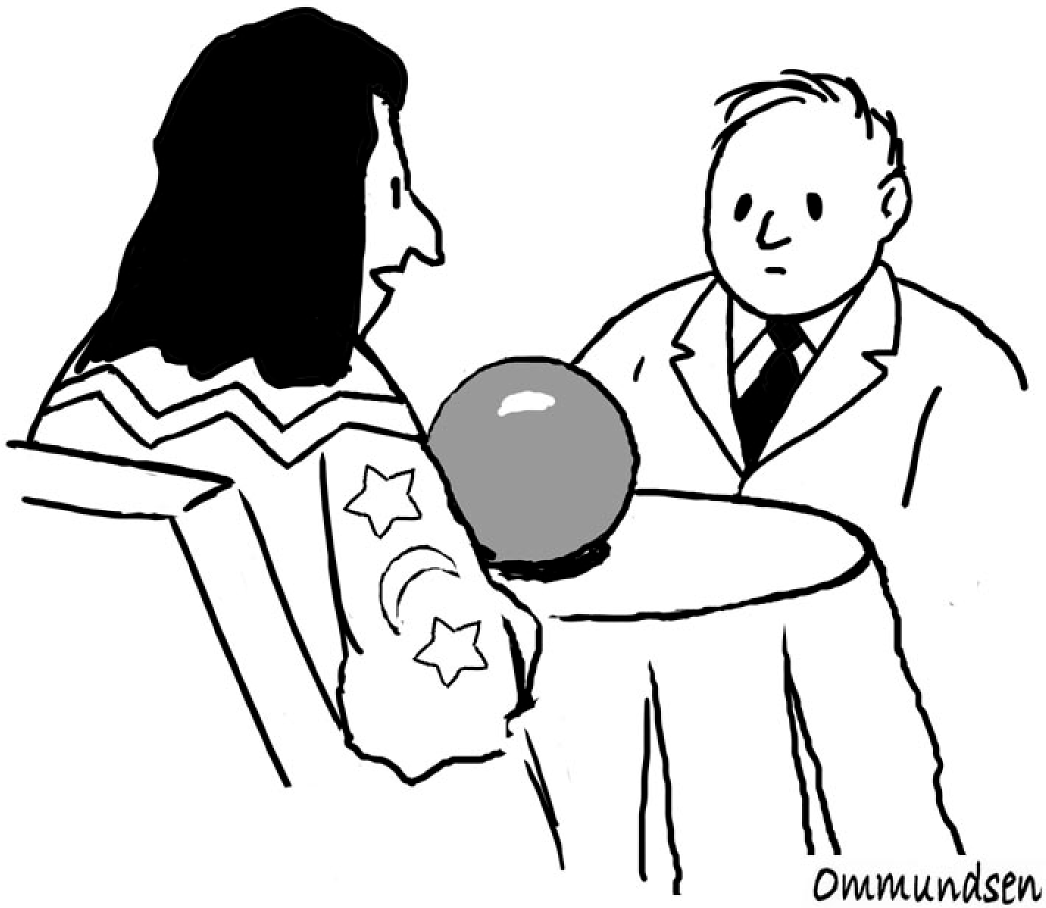


90% CL muon flux limit from the Sun vs neutralino mass

(compared to CMSSM scans)



Bayesian (c)MSSM scans



“Is this needed for a Bayesian analysis?”

- Standard sampling

- Uniform scan within chosen MSSM parameter ranges (m, M_2, m_A, tanb, m_0, A_t, A_b)

- Calculate derived quantities and plot

- No statistical information in dot distribution.

- CPU time consuming

- Misleading

- Markov Chain sampling

- Navigate the parameter space according to a target probability

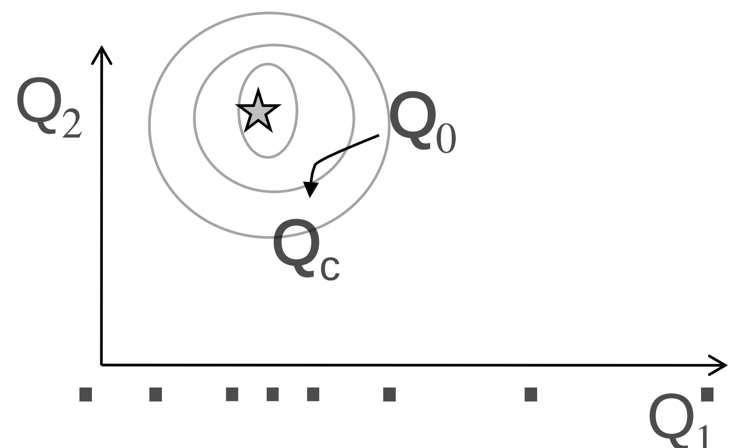
$$P(\mathbf{Q}|d) = L(d|\mathbf{Q})\, P(\mathbf{Q})$$

Q = vector of scanned parameters (m, M_2, m_A, tanb...)

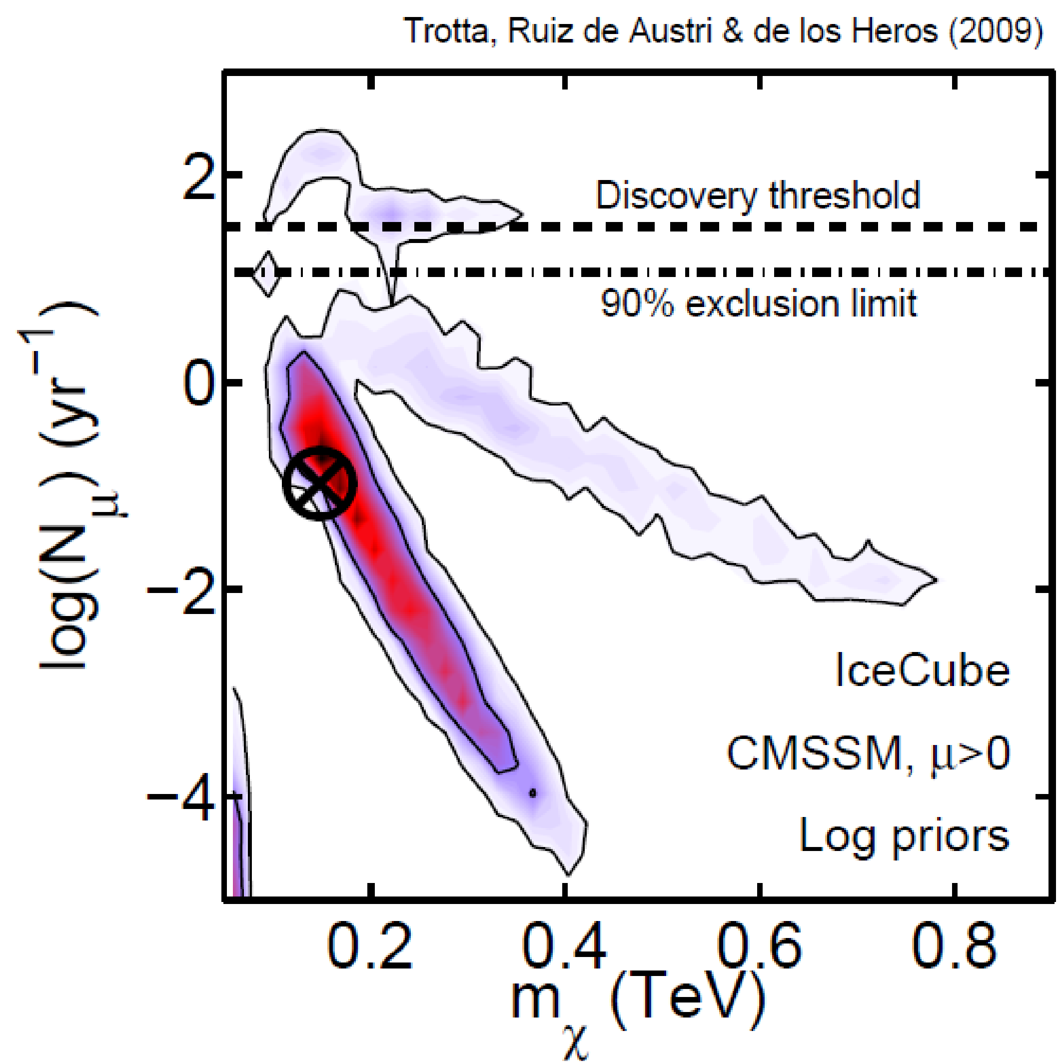
P(**Q**) = prior (chosen by user)
d= existing experimental data
L(d|**Q**) = likelihood of model (how well the model fits current data)

- The density of sampled points is proportional to the probability density

- Choose randomly Q_0
- Calculate $P_0 = P(\mathbf{Q}_0|d)$
- Calculate $P_c = P(\mathbf{Q}_c|d)$
- Accept Q_c with prob. $P_c = \min\{1, P_c/P_0\}$

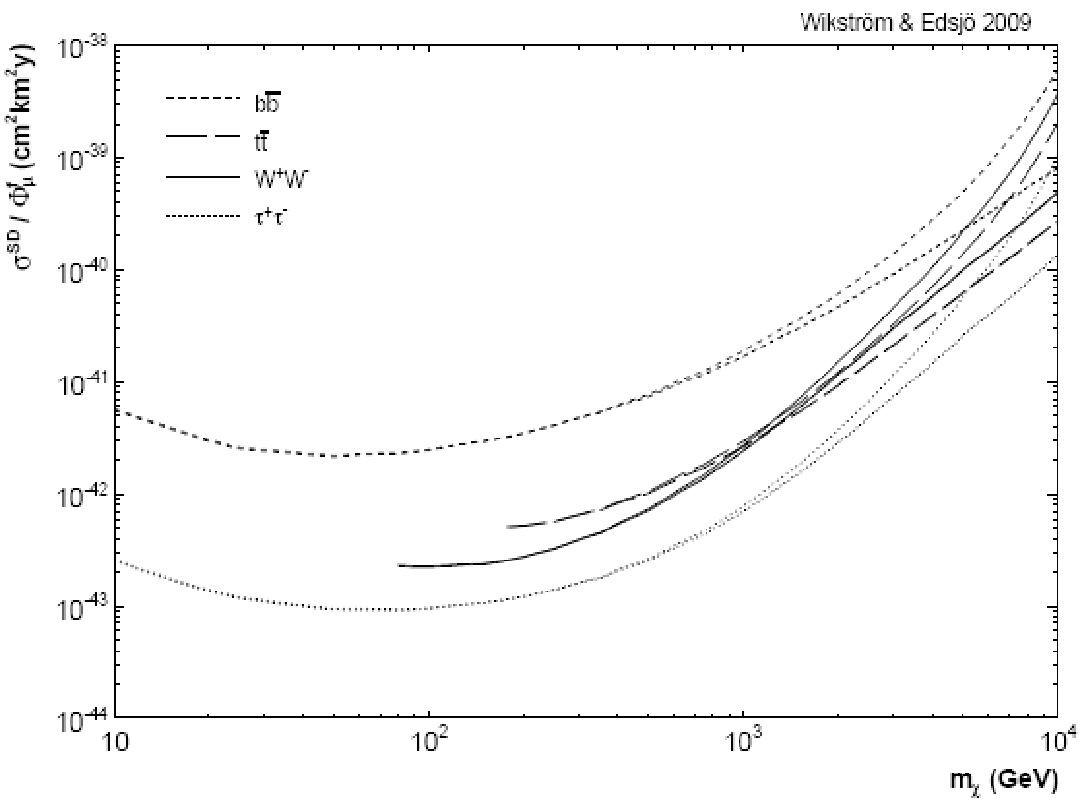


MCMC sampling allows to make statements about the relative probability of different models, given the current data



Converting to Xsection: (JCAP04 (2009) 09. arXiv 0903.2986)

$$\Phi_\mu = \frac{\Gamma_A \cdot n}{4\pi D_\odot^2} \int_{E_\mu^{\rm th}}^\infty {\rm d}E_\mu \int_{E_\mu^{\rm th}}^\infty {\rm d}E_\nu \int_0^\infty {\rm d}\lambda \int_{E_\mu}^{E_\nu} {\rm d}E'_\mu P(E_\mu, E'_\mu, \lambda) \times \frac{{\rm d}\sigma_\nu(E_\nu, E'_\mu)}{{\rm d}E'_\mu} \sum_i P(\mu, i) \sum_f B_f \frac{{\rm d}N_i^f}{{\rm d}E_\nu},$$



$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$

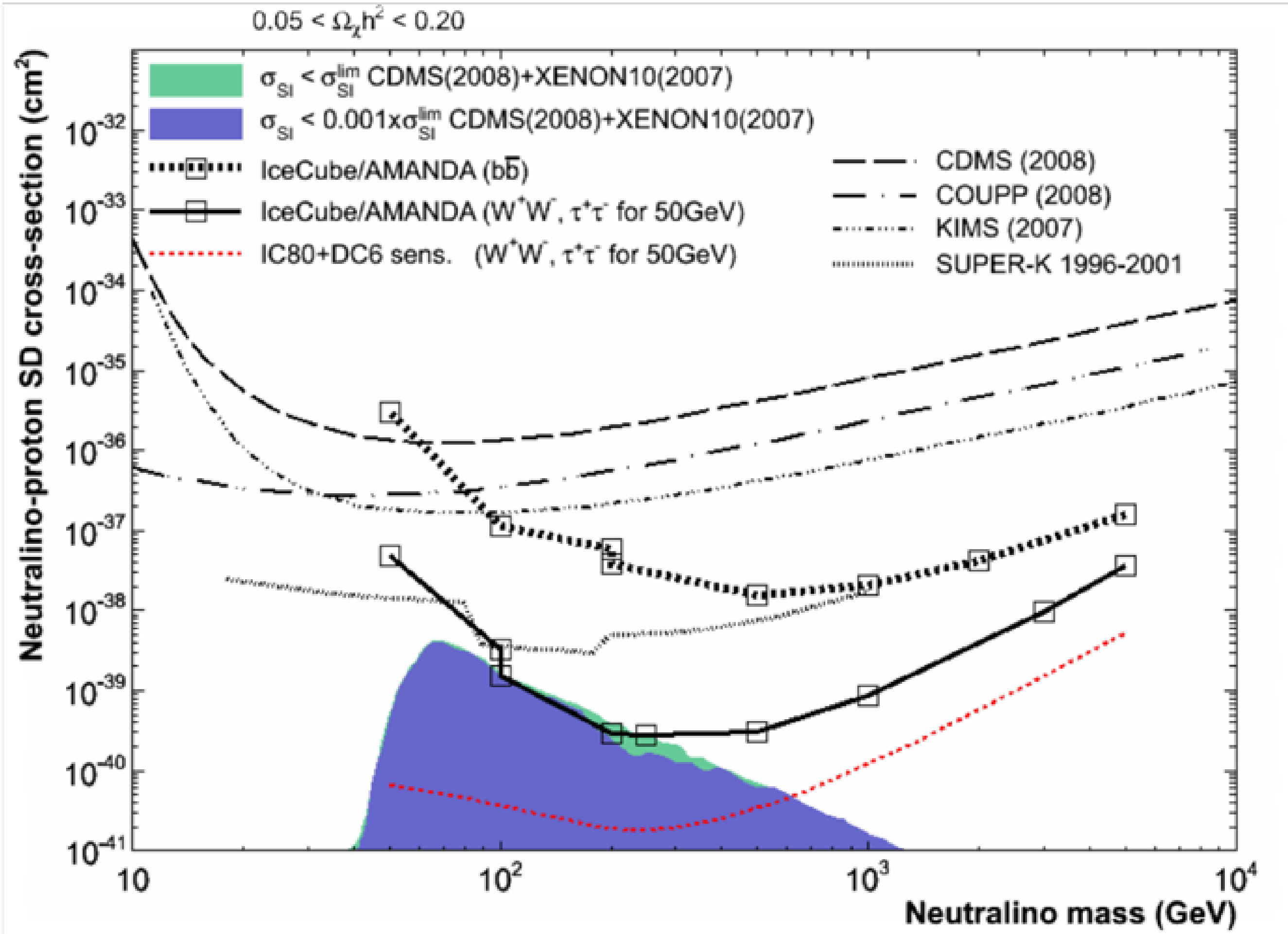
in equilibrium, dN/dt=0 and

$$\Gamma_A = \frac{1}{2} C_C$$

prop. to s^{SD}(c+p)

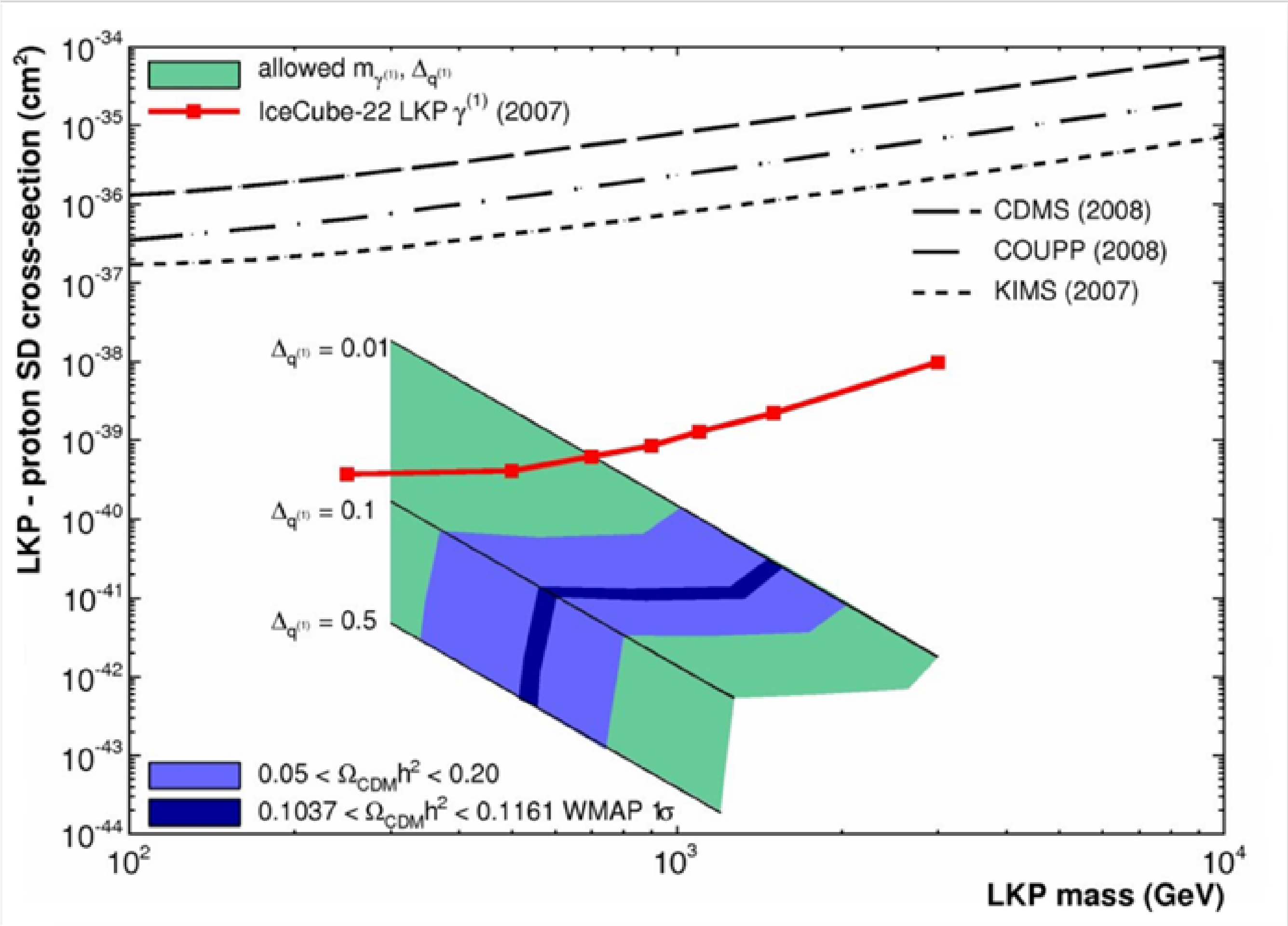
(and also dependent on the solar model)

90% CL neutralino-p Xsection limit vs neutralino mass

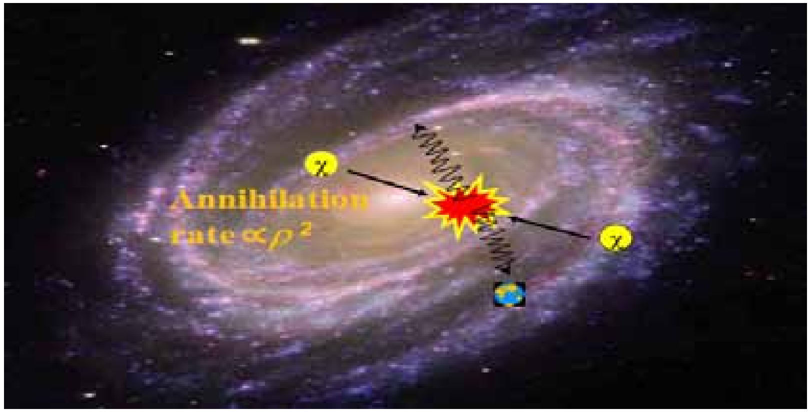


We have a proton target!

90% CL LKP-p Xsection limit vs LKP mass

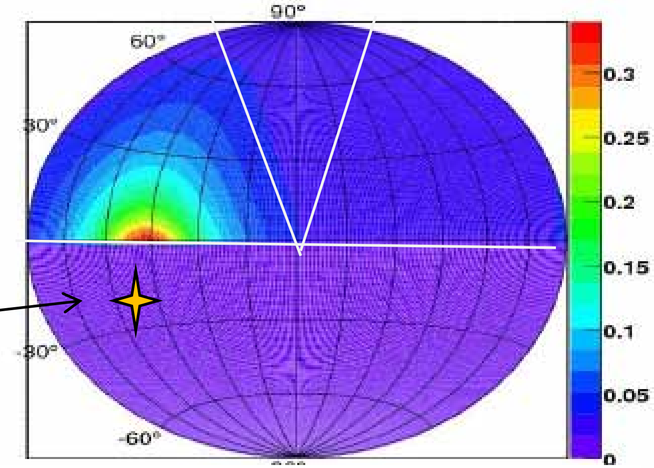


Galactic halo search



Galactic Center (GC):

R.A.=277°
Θ = -28°



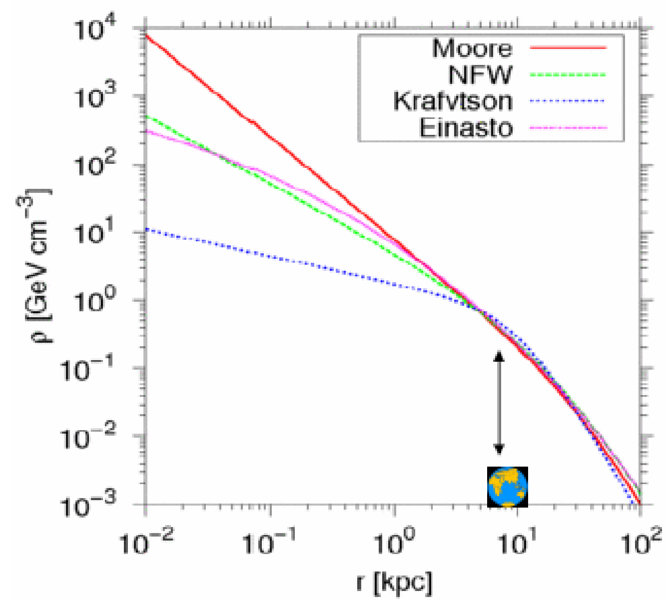
- Look for an excess of events in the on-source region w.r.t. the off-source

- Interesting for comparison with satellites

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

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

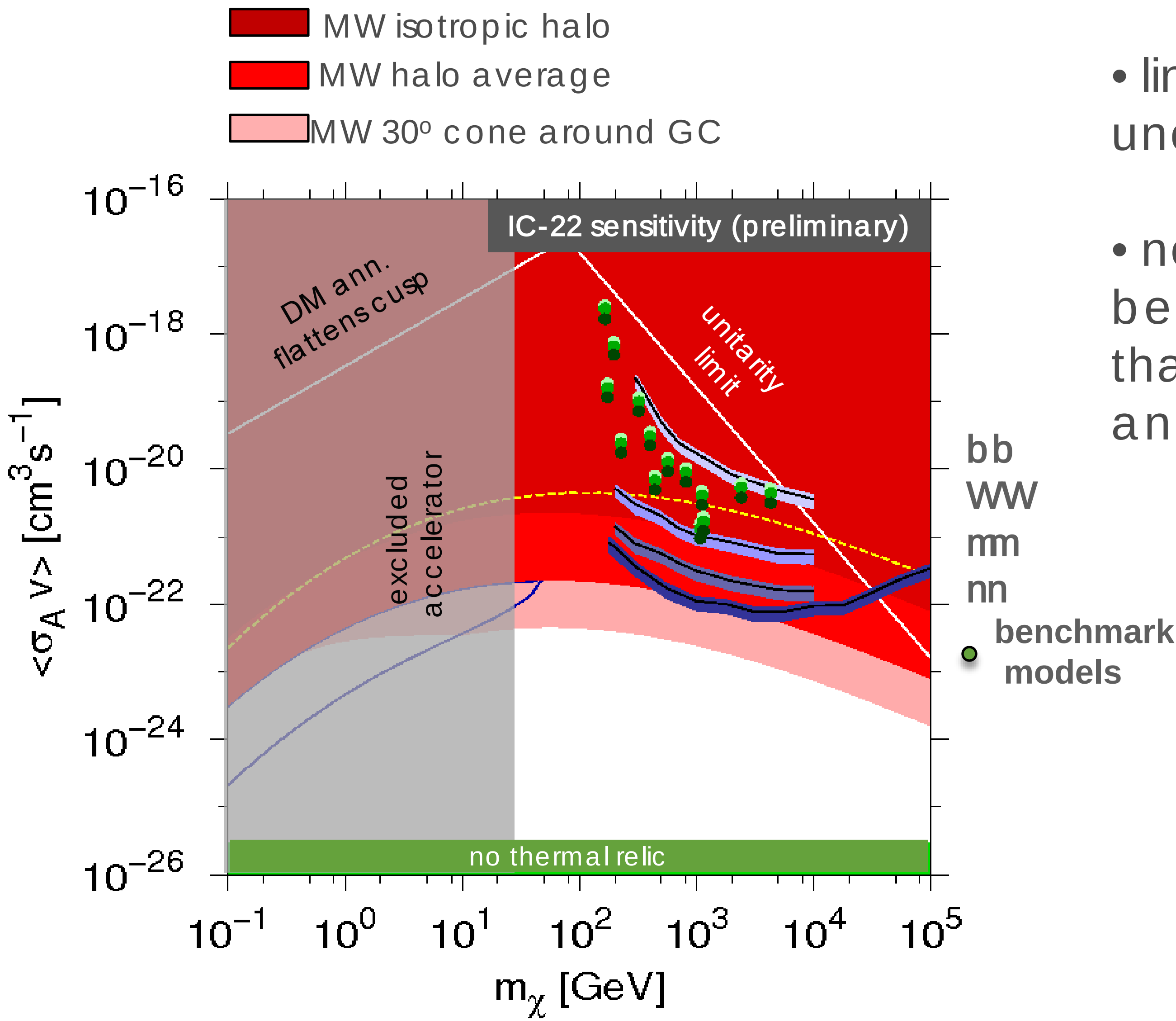
measure | limit | halo | SUSY



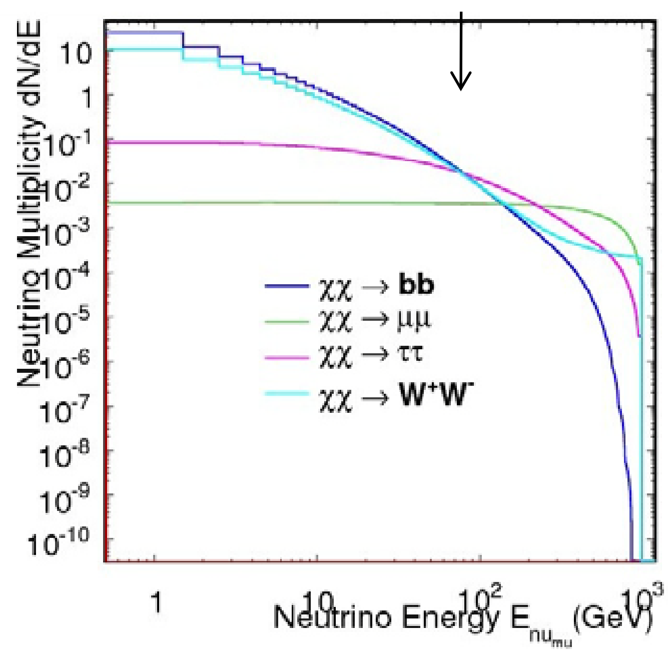
Analyses on-going with IC 22-string and IC 40-string configurations

IC40 and IC+DeepCore will reach the galactic center

IC-22 halo sensitivity



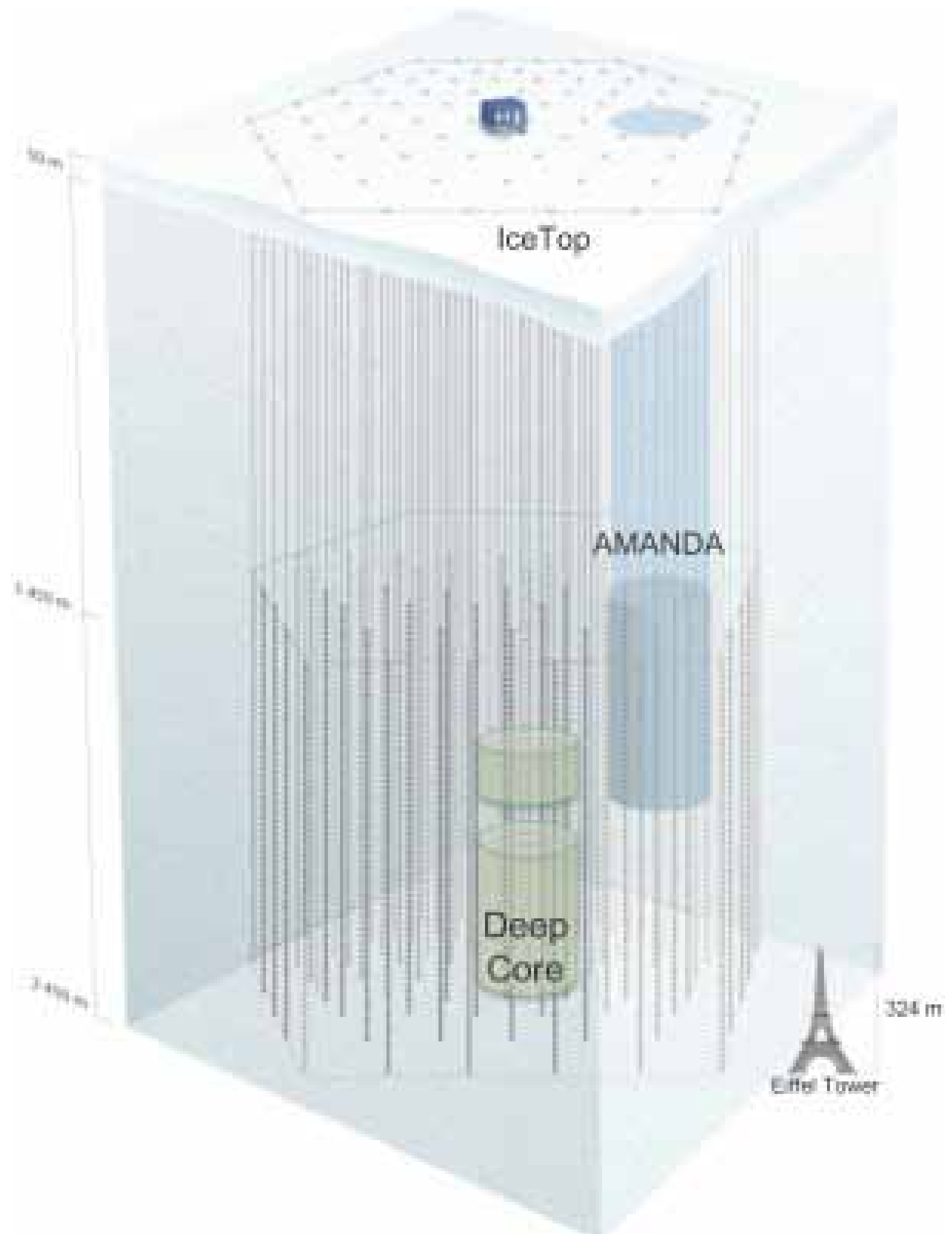
- line thickness reflects uncertainty due to halo profile
- no energy loss of secondaries before decay: harder spectra than in Sun for same annihilation channel



• Aim: lower energy threshold through a denser core in the center of the IceCube array

• 6 additional strings of 60 high quantum efficiency PMTs

• denser instrumentation:
7 m DOM vertical spacing (17m in IceCube),
72 m inter string spacing (125m in IceCube)



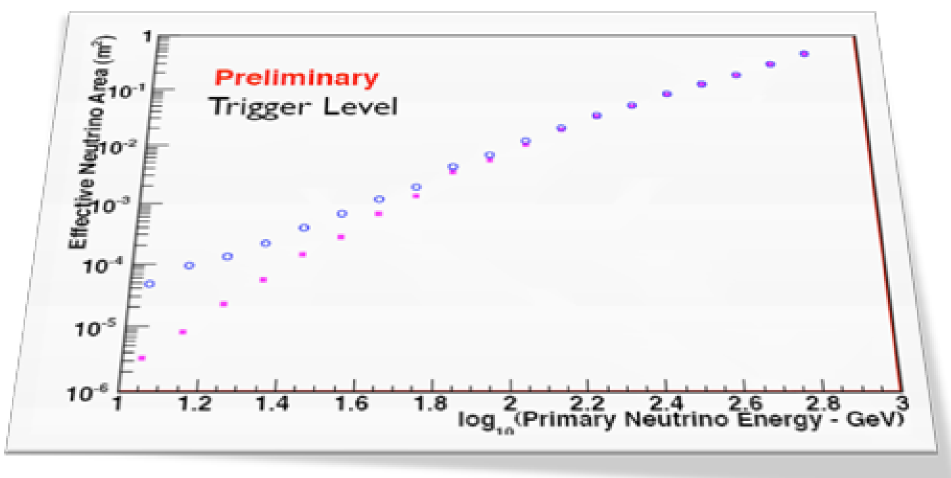
Vetoing capabilities

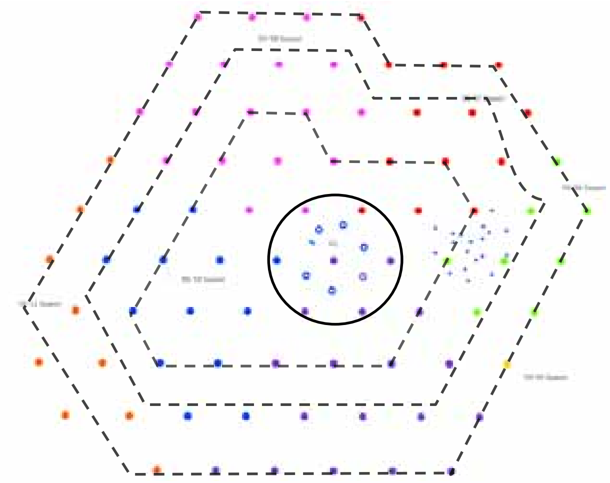
• **full sky sensitivity** using IceCube surrounding strings as a veto:

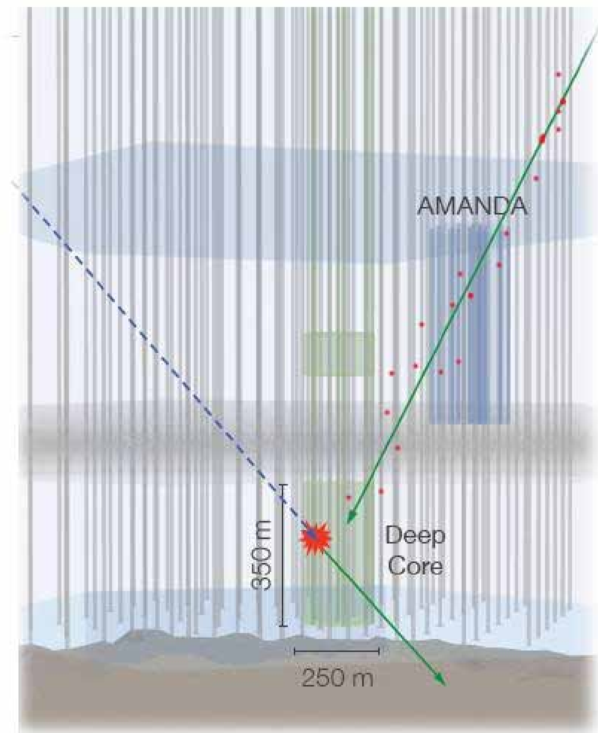
375m thick detector veto: three Complete IceCube string layers Surround DeepCore

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

• preliminary studies show 10^4 background rejection with 98% signal efficiency possible







- IceCube is 75% complete (taking data with 59 strings from April)
- Plan to reach 77 strings after the 2009/10 deployment season
- First results from the 2007 data taking period (22 strings) are coming
- Two papers this year on dark matter searches

  (Phys. Rev. Lett.102, 201302, 2009, and arXiv:0910.4480)
- New analysis on DM search from the halo/galactic center in preparation
- Indirect searches for DM competitive/(better) than direct searches
- The low-energy extension, DeepCore, funded. First string taking data.

  Remaining five strings to be deployed this year

FIN