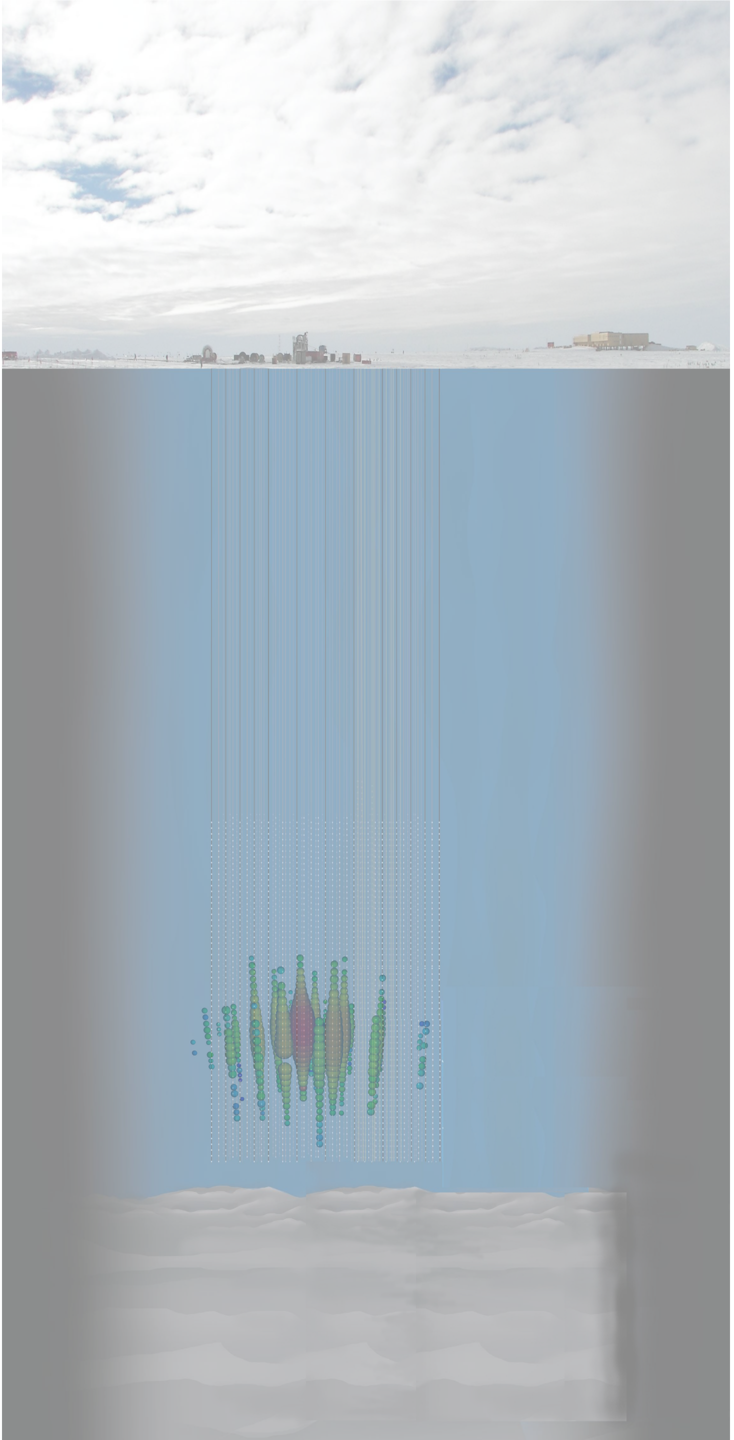


dark matter searches with IceCube/PINGU

Carlos de los Heros
Uppsala University

Astroparticle physics in Antarctica Workshop
Niels Bohr Institute. 13 January, 2014

DM detection

direct detection

Xenon, CDMS, Edelweiss... (CoGeNT, Dama/Libra...)

production at colliders

LHC

indirect

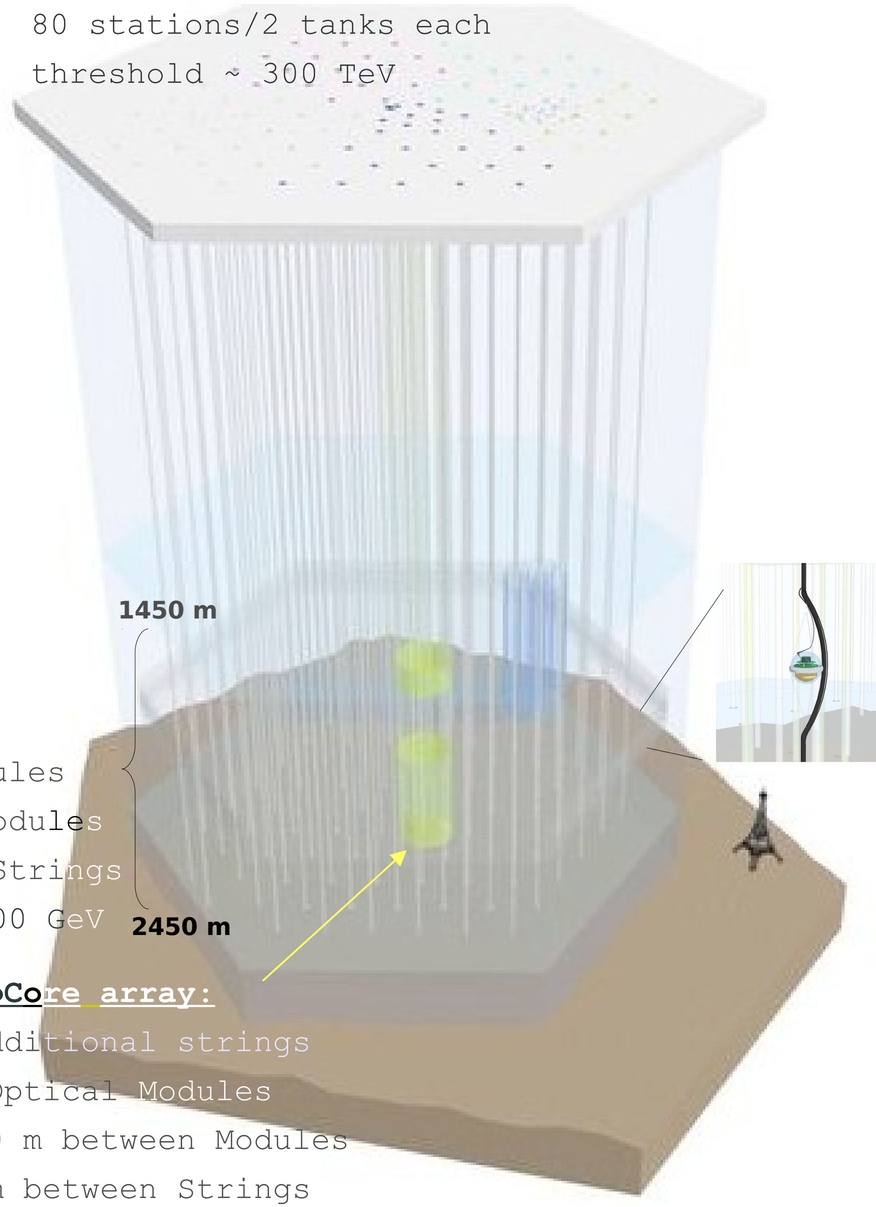
- γ from annihil in galactic center or halo and from synchrotron emission
  - Fermi, ICT, radio telescopes..
- e^+ from annihil in galactic halo or center
  - PAMELA, Fermi, HESS, AMS, balloons..
- $\bar{p}$ from annihil in galactic halo or center
- $\bar{d}$ from annihil in galactic halo or center
  - GAPS
- $\nu, \bar{\nu}$ from annihil in massive bodies
  - SK, Icecube, Km3Net

(from M. Cirelli)

detector completed in 2010

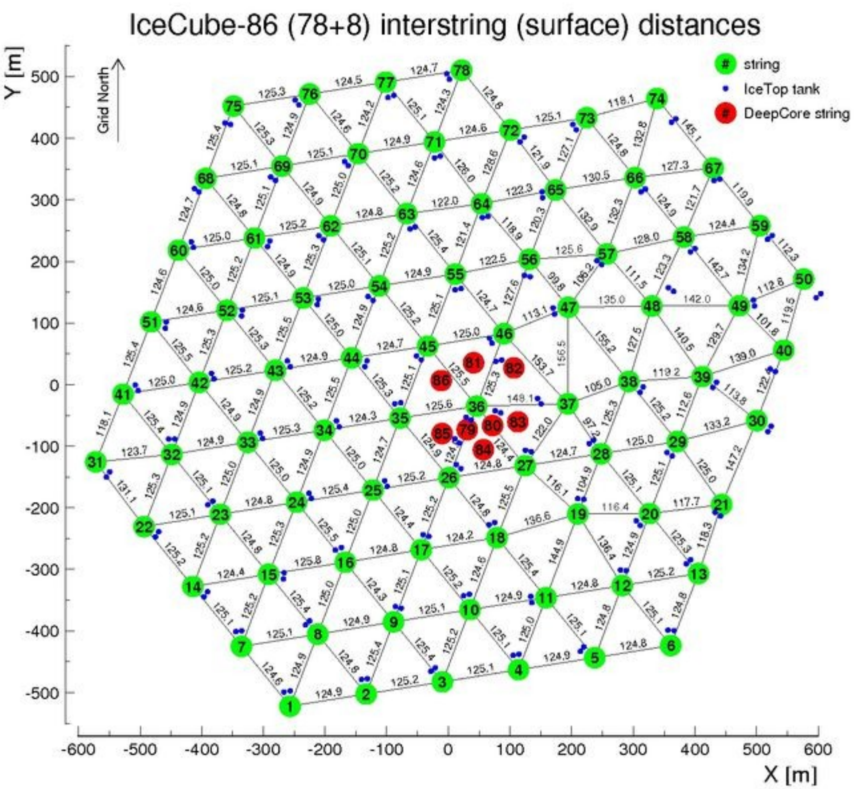
86 strings, 80 IceTop tanks

IceTop: Air shower detector
80 stations/2 tanks each
threshold ~ 300 TeV



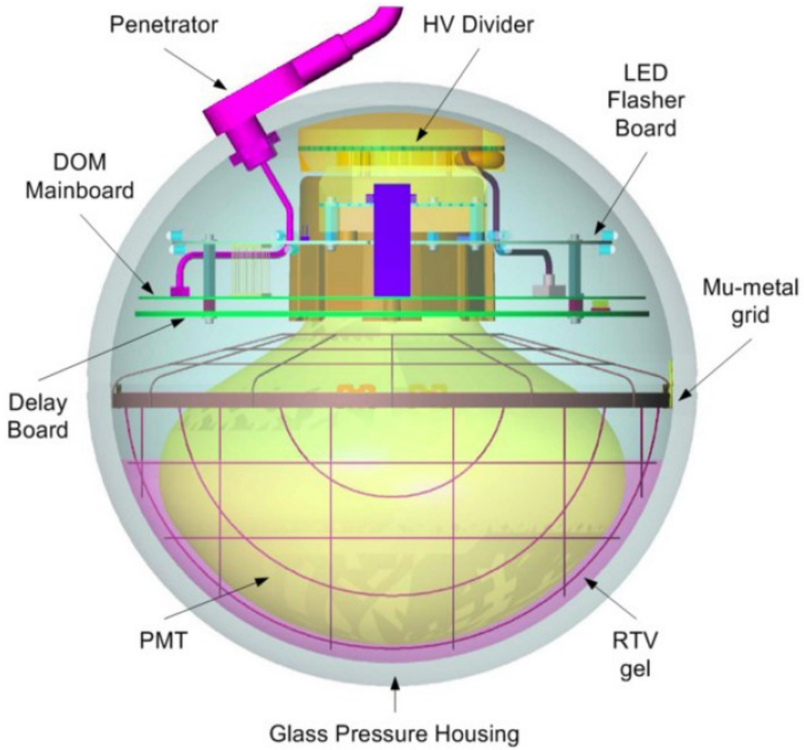
InIce array:
80 Strings
60 Optical Modules
17 m between Modules
125 m between Strings
E threshold ≲100 GeV

DeepCore array:
6 additional strings
60 Optical Modules
7/10 m between Modules
72 m between Strings
E threshold ~10 GeV



the Digital Optical Module

Each DOM is an autonomous data collection unit



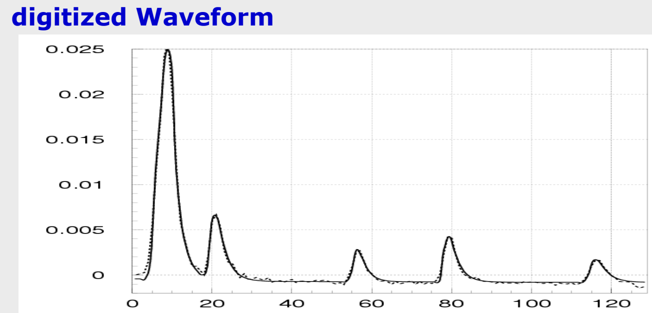
- **PMT**: Hamamatsu, 10''

-**Digitizers**:

ATWD: 3 channels. Sampling 300MHz, capture 400 ns

FADC: sampling 40 MHz, capture 6.4 μs

Dynamic range 500pe/15 nsec, 25000 pe/6.4 μs

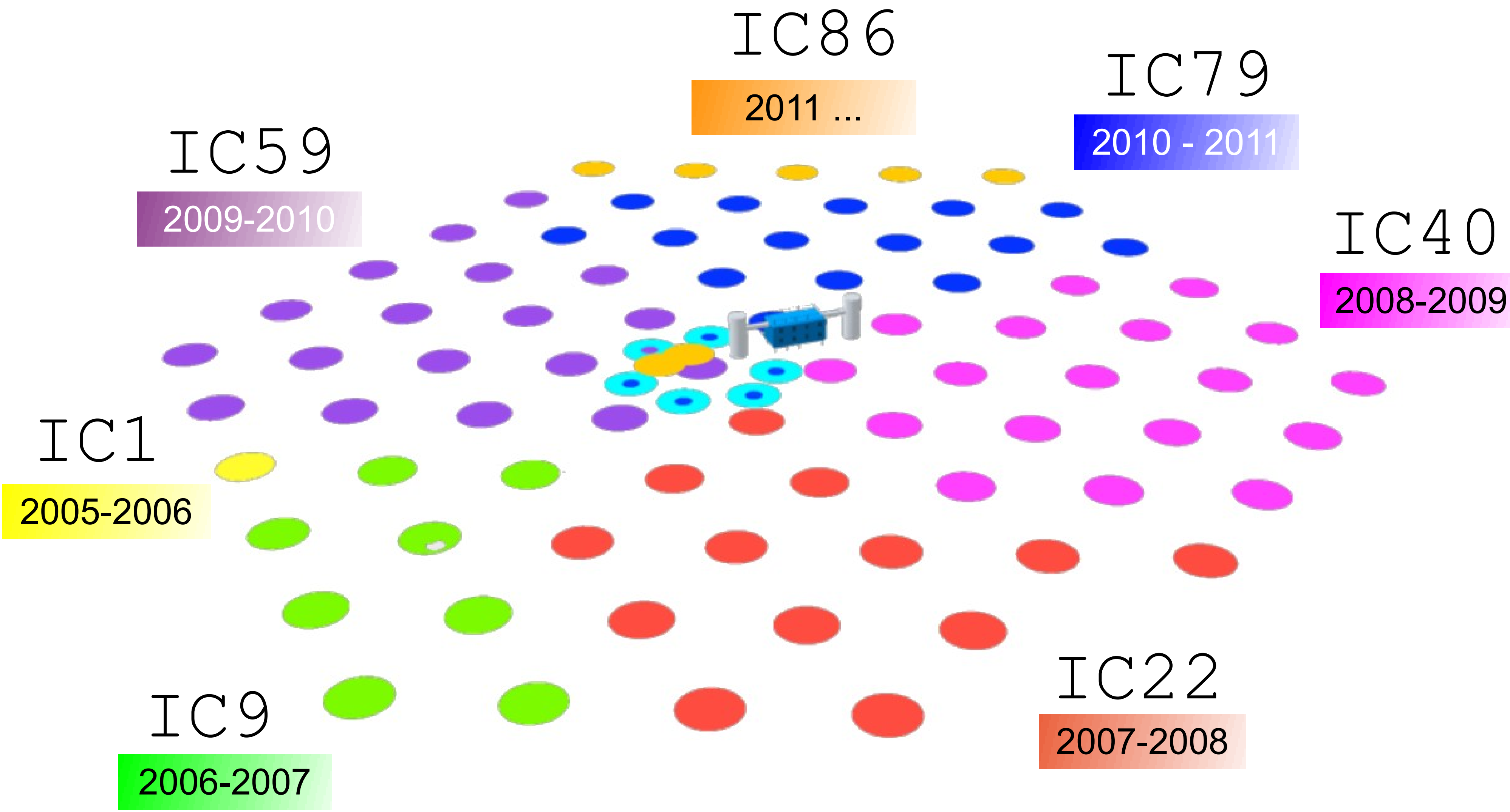


- **Flasher board**:

12 controllable LEDs at 0^{o} or 45^{o}

- 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 with 2 ns precision



Data taking since 2005 - completed in 2010!

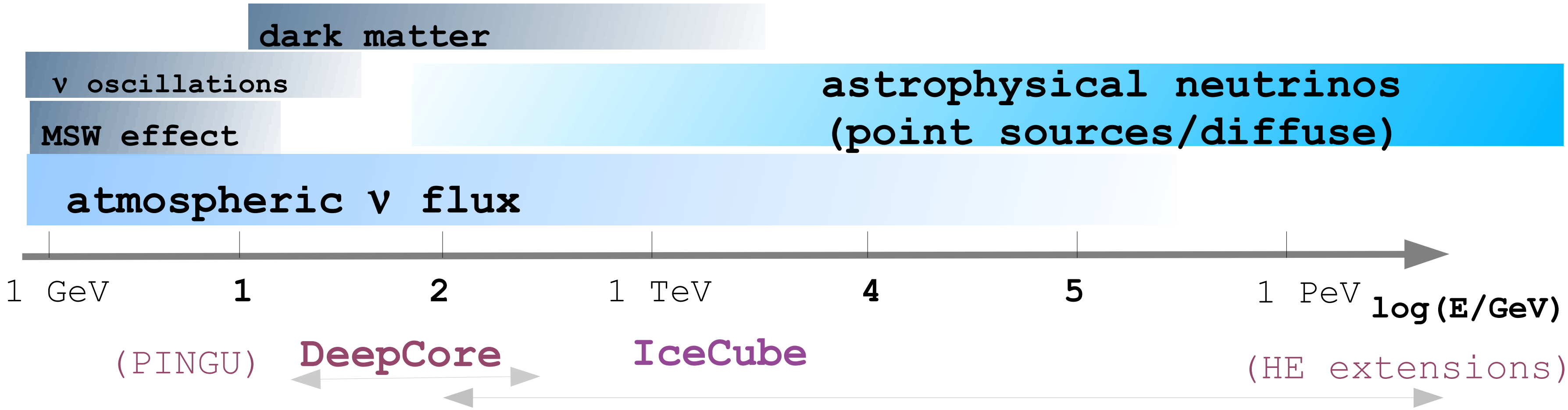
- Detector completed on December 2010
- Full operation with 86 strings starts in May 2011
- Full detector → Veto techniques possible.

  IceCube becomes a 4π detector with access to the Galactic Center and whole southern sky

- **Recent results**:
  - dark matter: competitive spin-dependent limits above WIMP mass 35 GeV (PRL 110, 131202, 2013)
  - atmospheric electron neutrinos (PRL 110, 151105, 2013)
  - highest energy neutrinos ever observed (PRL 111, 021103, 2013)
  - follow up on high energy neutrinos (Science 342, no. 6161, 2013)
  - neutrino oscillations at high energies (PRL 111, 081801, 2013)

Many of these results only possible with the low-energy extension, DeepCore.... which paves the ice for PINGU, an even lower-energy extension under study (E_ν threshold of ~ O(1 GeV))

a multipurpose – multiflavor detector



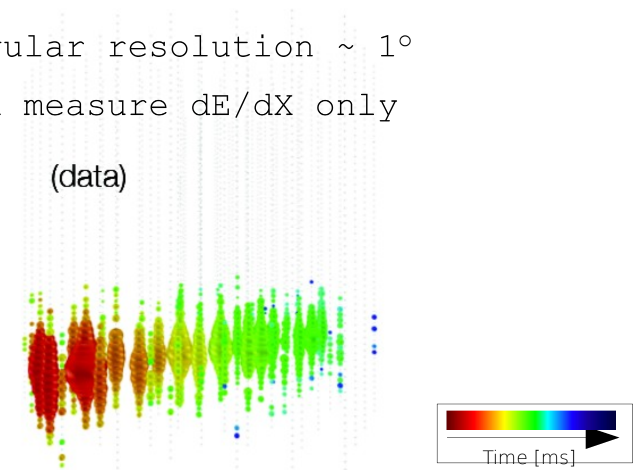
neutrino event signatures in IceCube:

tracks:

ν_μ CC

angular resolution ~ 1°

can measure dE/dX only



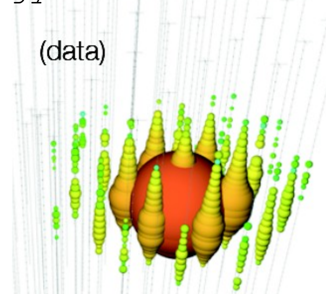
cascades:

ν_e, ν_τ CC

all flavours NC

angular resolution ≳ 10°

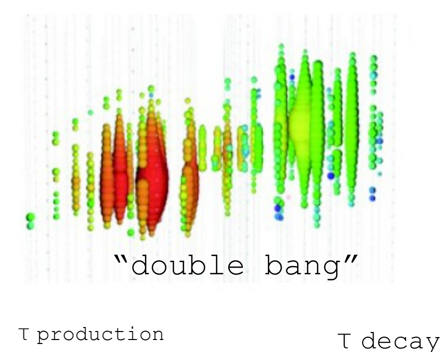
energy resolution ~ 15%



Tau neutrino, CC

$$\nu_\tau + N \rightarrow \tau + X$$

(simulation)

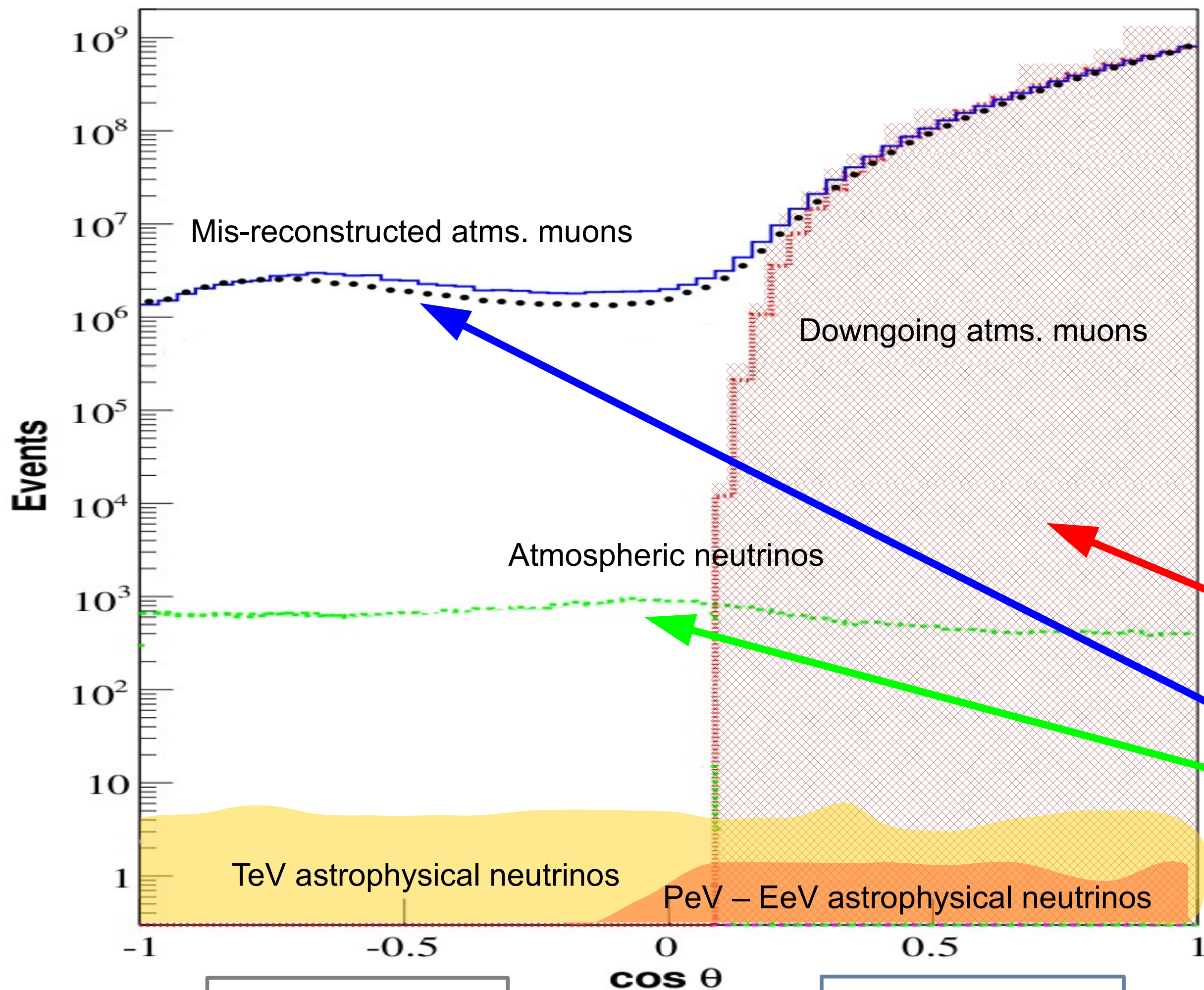


Trigger rates:

Atm. muons: **~3 kHz**,

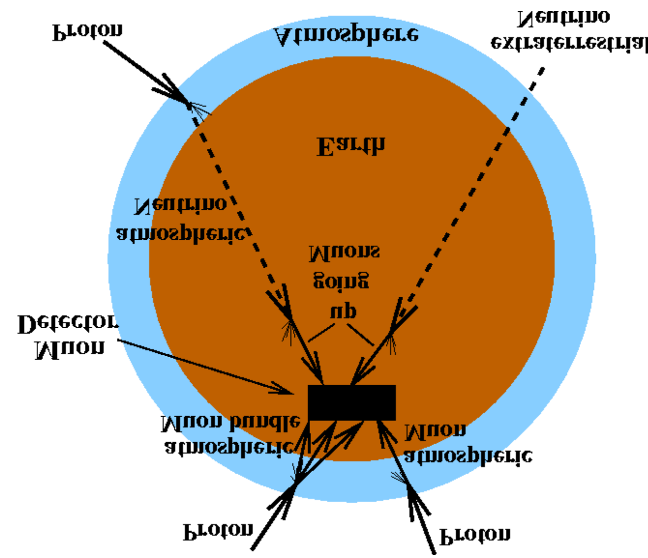
~200 atm. ν /day (with E >100 GeV in IceCube)

Atmospheric neutrino and muon production in cosmic ray air showers (→ background for neutrino analyses)



upgoing (Northern sky)

downgoing (Southern sky)



Muons are absorbed inside the Earth → coming from above

Only mis-reconstructed events from below

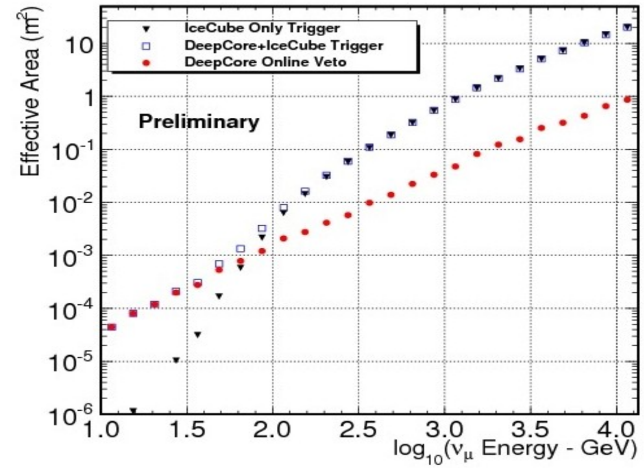
Atmospheric neutrino background → from North and South

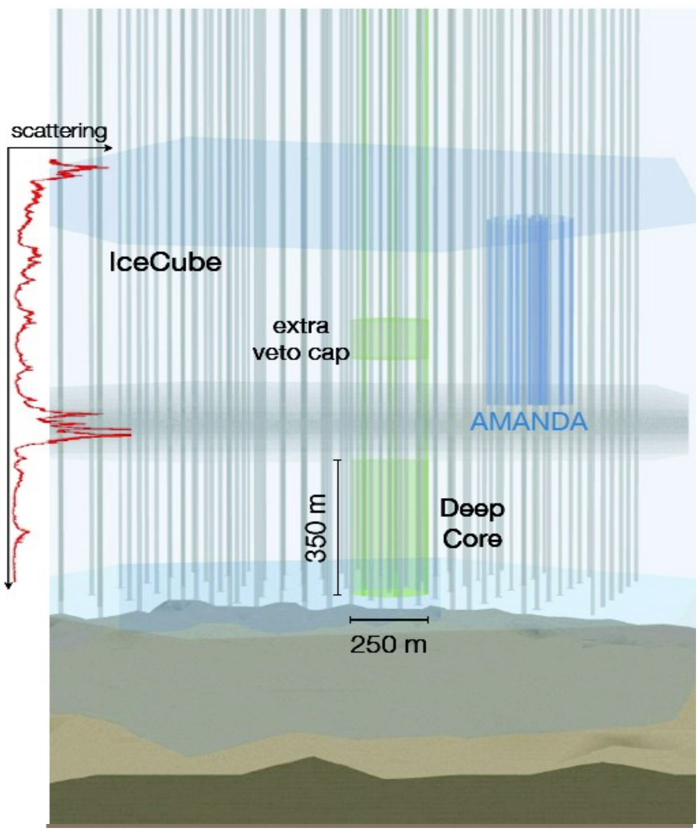
Earth becomes opaque to high-energy neutrinos! > PeV events are coming from above

full sky sensitivity using IceCube surrounding strings as a veto:

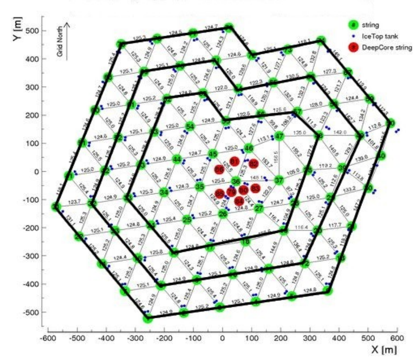
375m thick detector veto: three complete IceCube string layers surround DeepCore

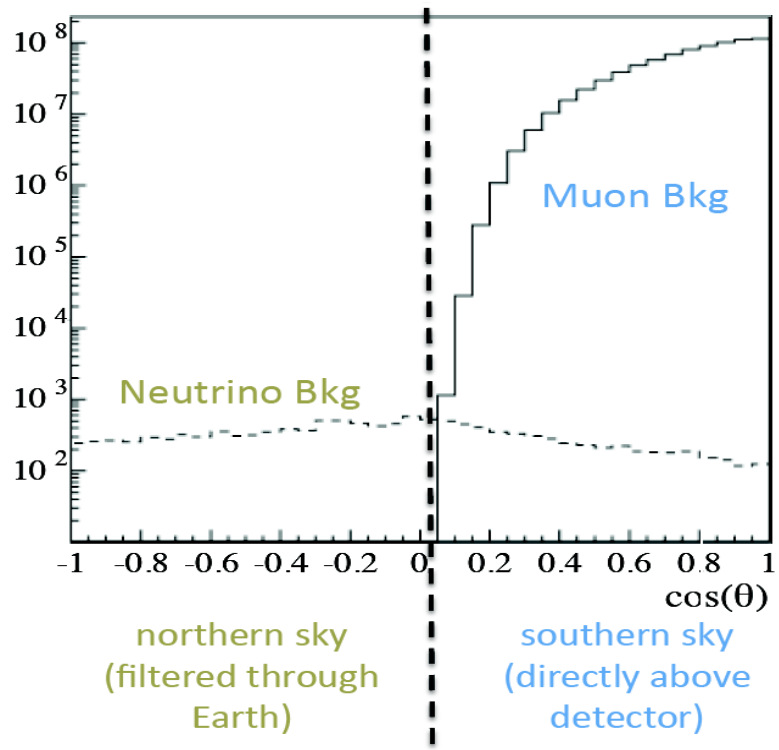
--> access to southern hemisphere, galactic center and all-year Sun visibility





can use IceCube outer string layers to define starting and througoing tracks





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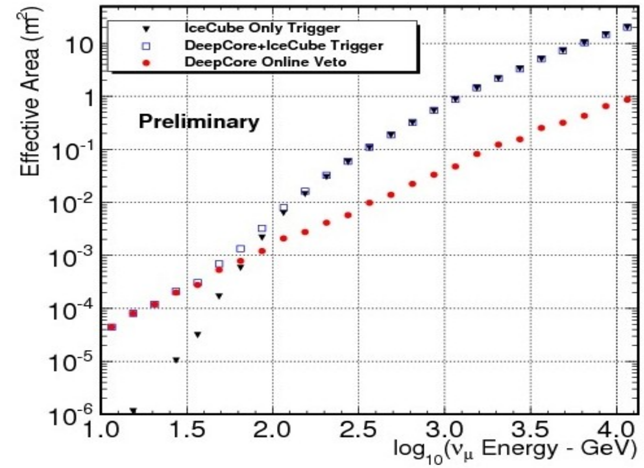

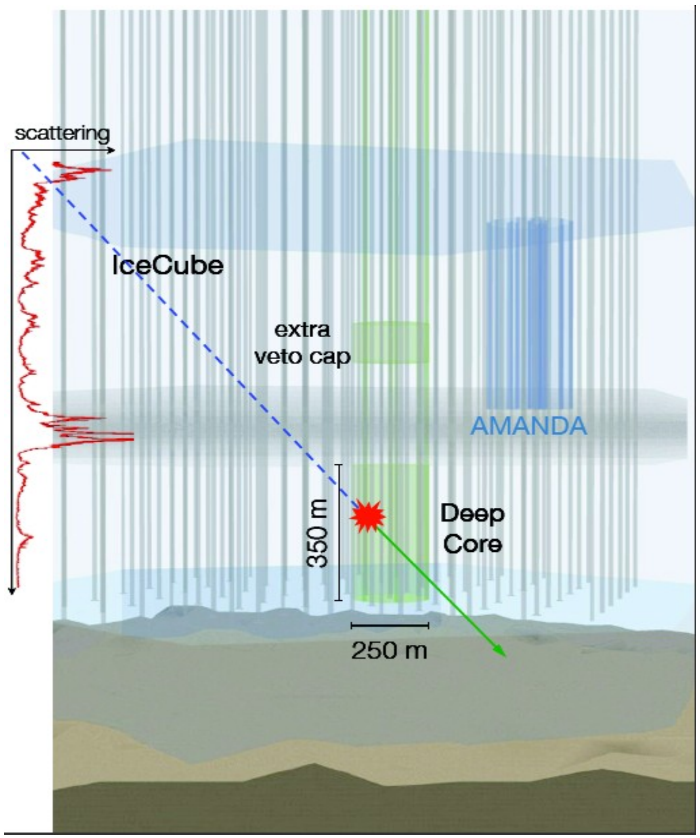

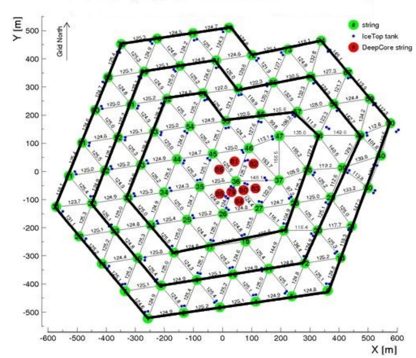

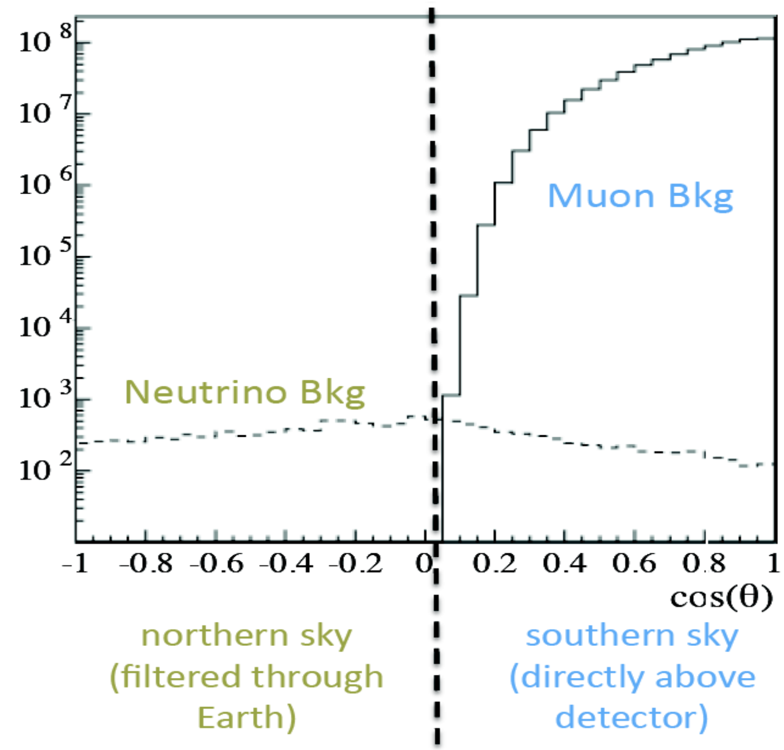

full sky sensitivity using IceCube surrounding strings as a veto:

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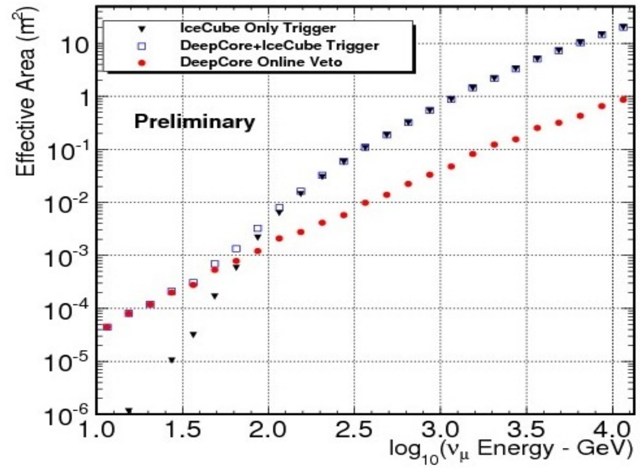
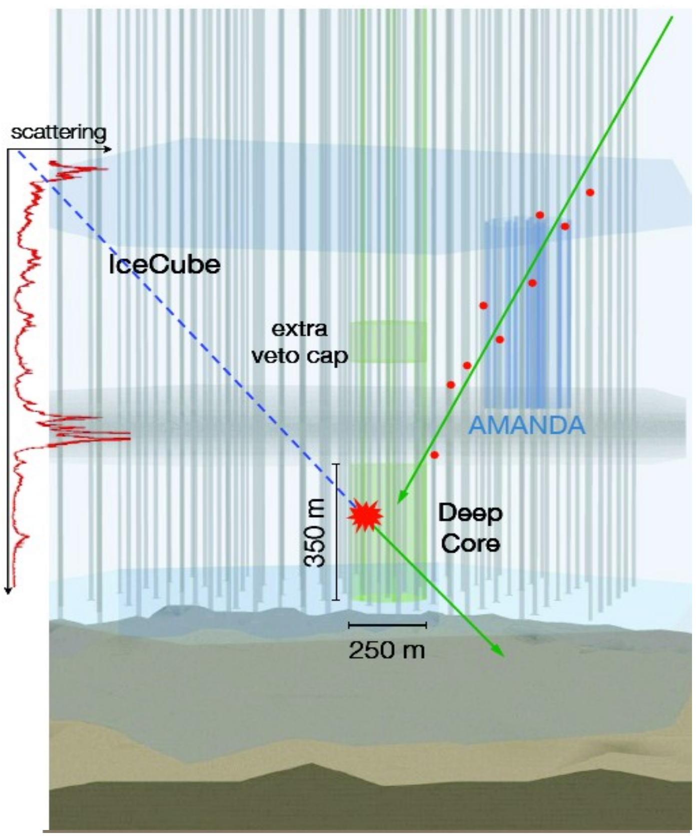
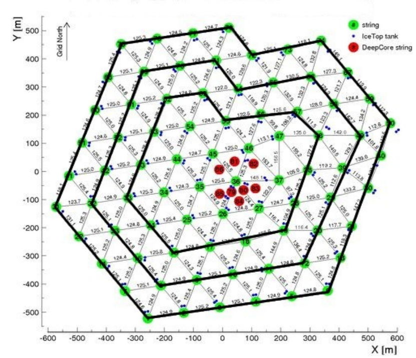
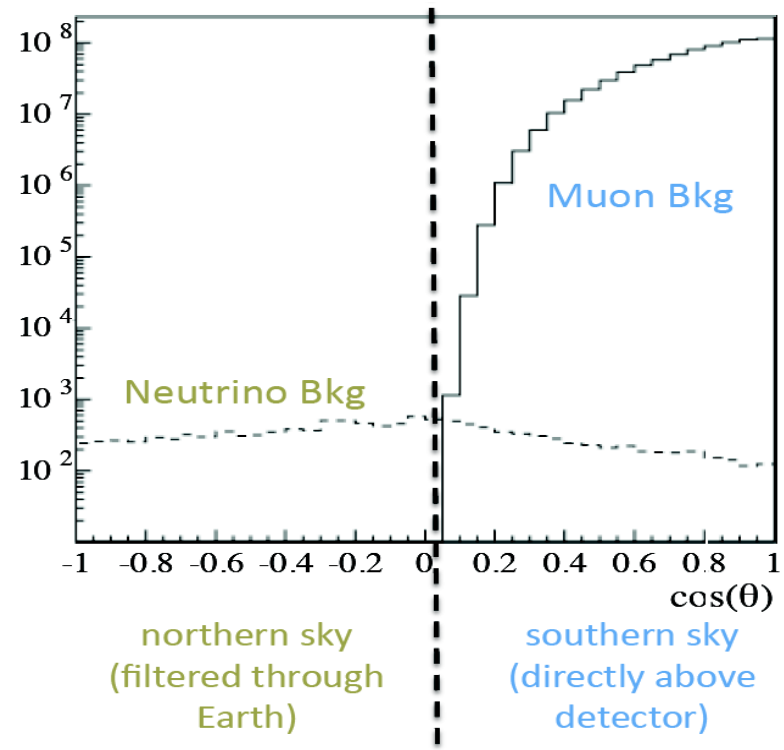






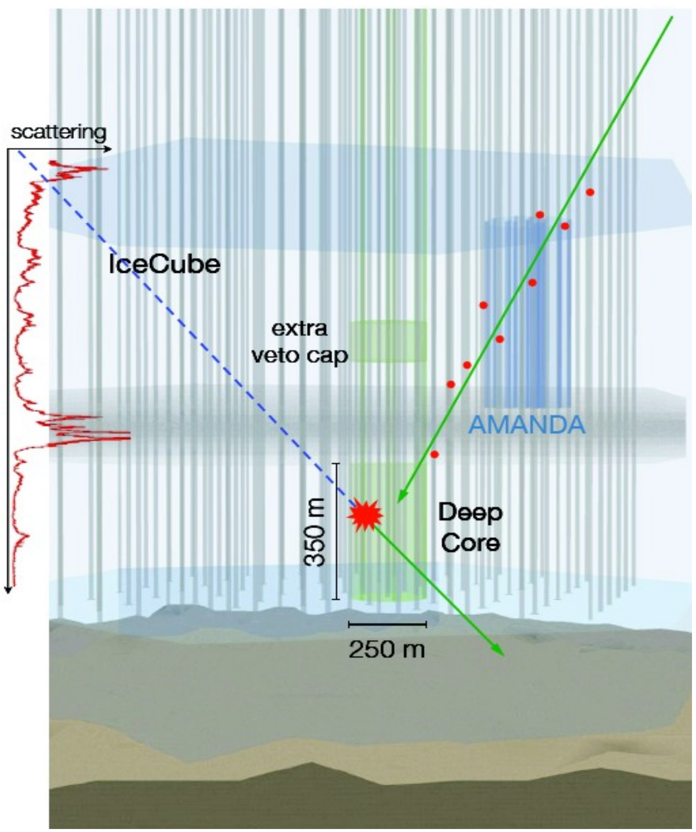


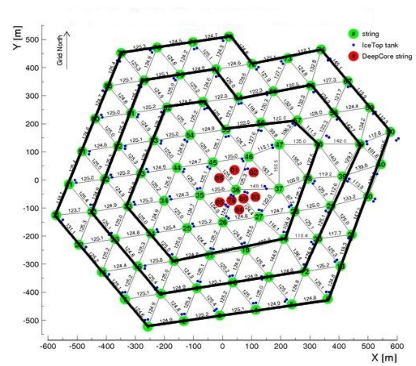
full sky sensitivity using IceCube surrounding strings as a veto:

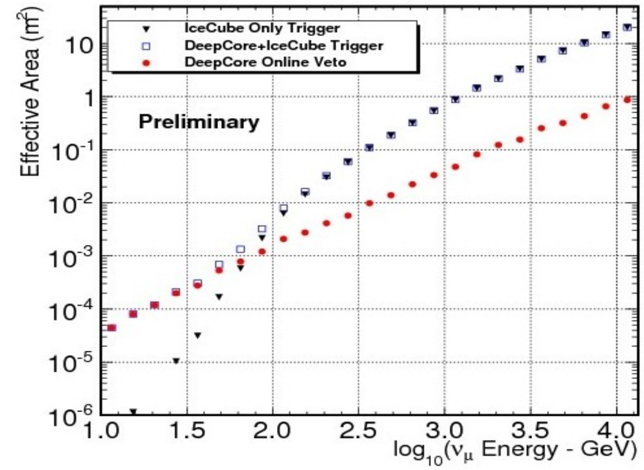
375m thick detector veto: three complete IceCube string layers surround DeepCore

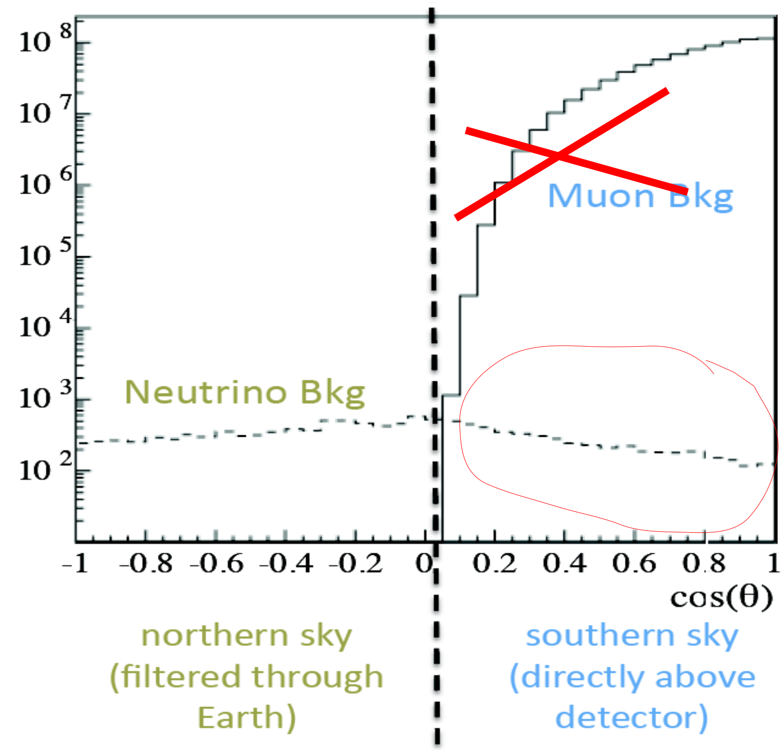
--> access to southern hemisphere, galactic center and all-year Sun visibility

IceCube is a 4π detector







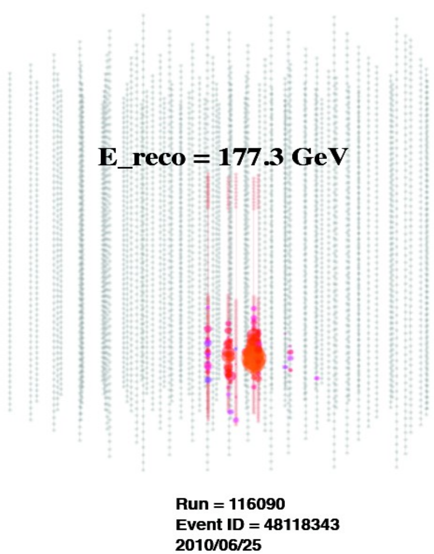


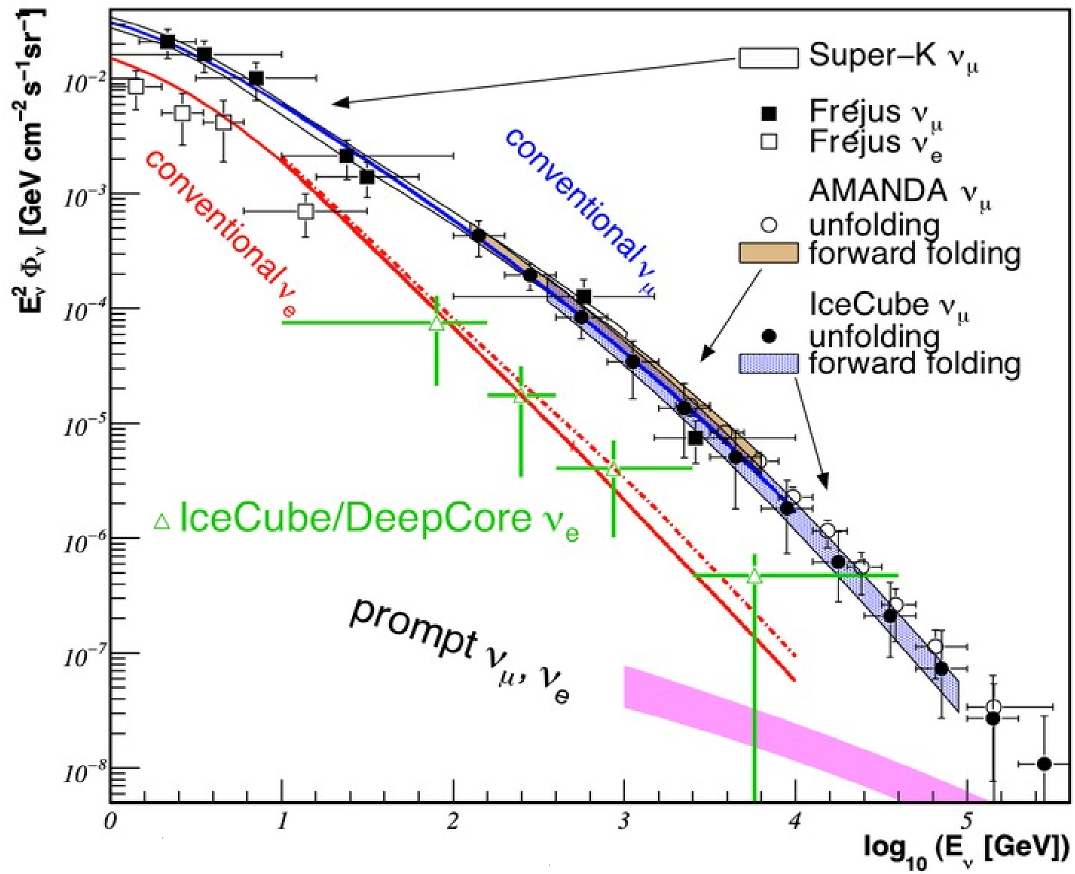
•**atmospheric neutrinos.** Our “beam”. Irreducible: our background

use DeepCore with surrounding IceCube strings as a veto

define fiducial volume for starting events

measure ν_e-induced cascades





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
- R-parity (x)SSM candidate: lightest SS particle
- UED: lightest 'rung' in the Kaluza-Klein ladder

SIMPZILLAS

- Non-thermal, non-weakly interacting heavy stable relics

DM-induced SM particles

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

...

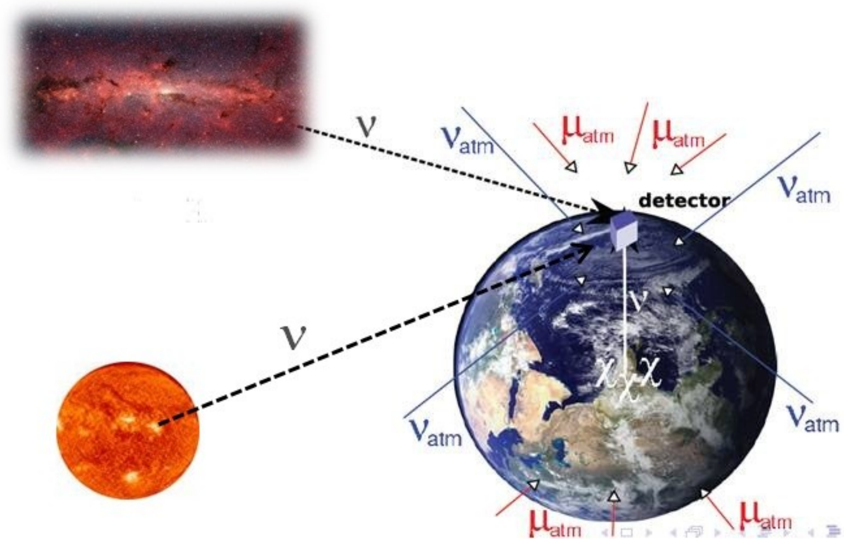
Kaluza-Klein modes an additional useful channel: $\kappa\kappa \rightarrow \nu\nu$

signature:

ν excess over background from Sun/Earth/Galactic Halo/near galaxies

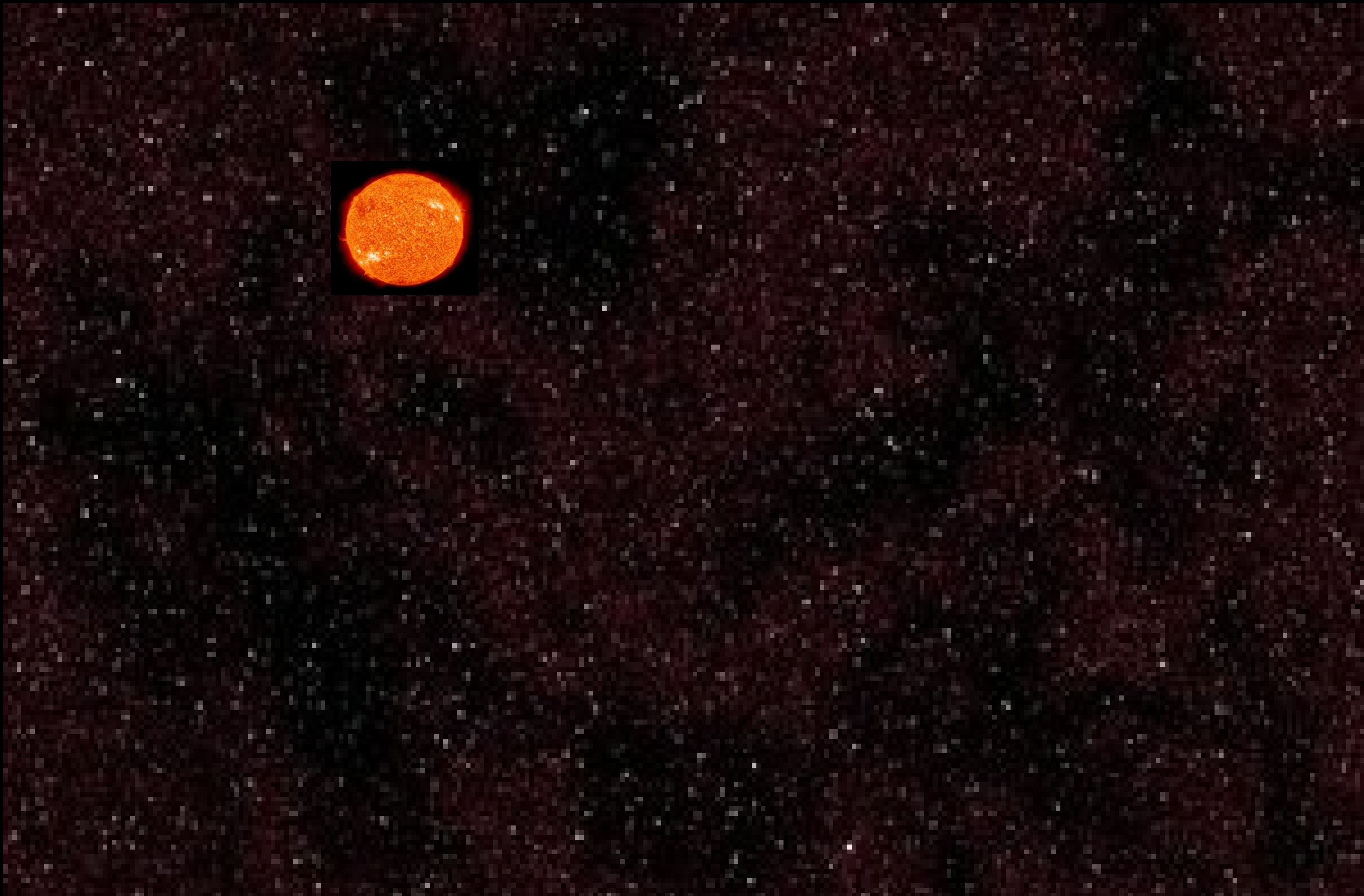
Look at objects where dark matter might have accumulated gravitationally over the evolution of the Universe

Sun, Earth, Galactic Halo/Center, dwarf spheroids

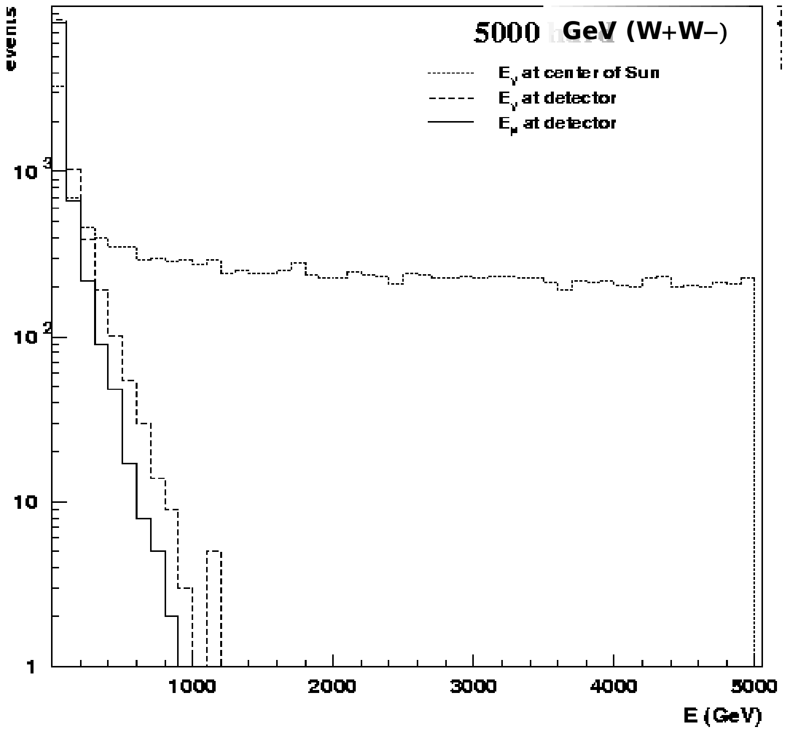


note: astrophysical / hadronic uncertainties

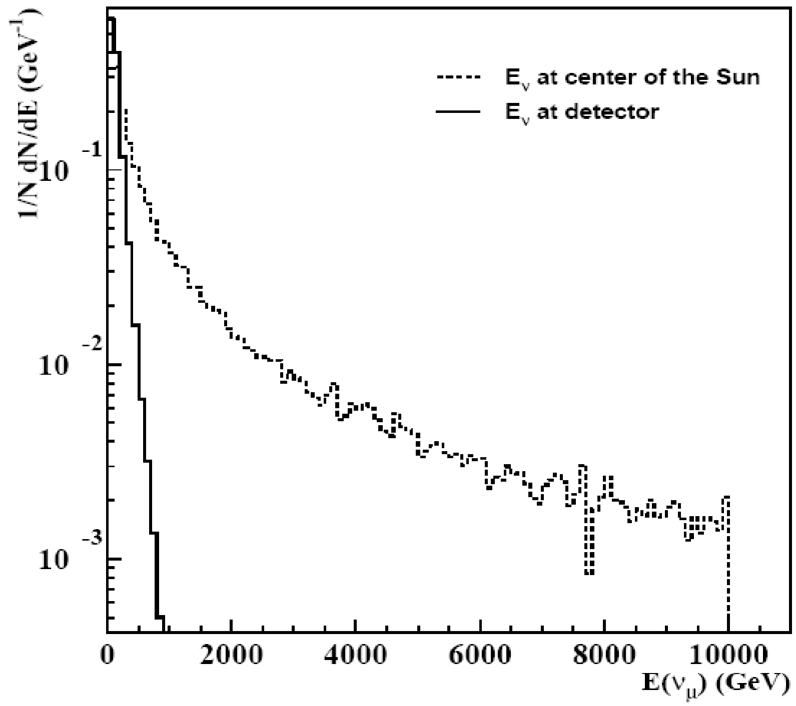
dark matter searches from the Sun



5000 GeV Neutralino → WW @ Sun



Simpzilla → $t\bar{t}$ @ Sun

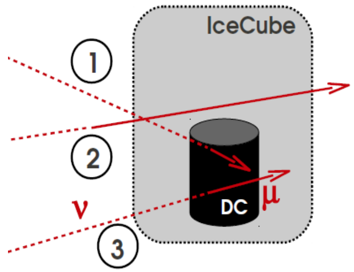


Indirect dark matter searches from the **Sun** are typically a low-energy analysis in neutrino telescopes: even for the highest DM masses, we do not get muons above few 100 GeV

Not such effect for the Earth and Halo

IceCube results from 317 days of livetime between 2010-2011:

All-year round search:



Extend the search to the southern hemisphere by selecting starting events

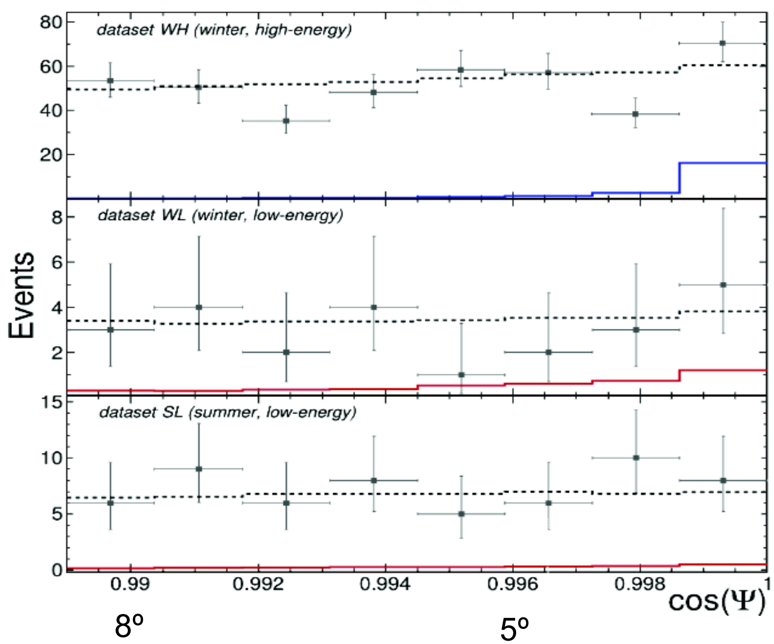
→ Veto background through location of interaction vertex

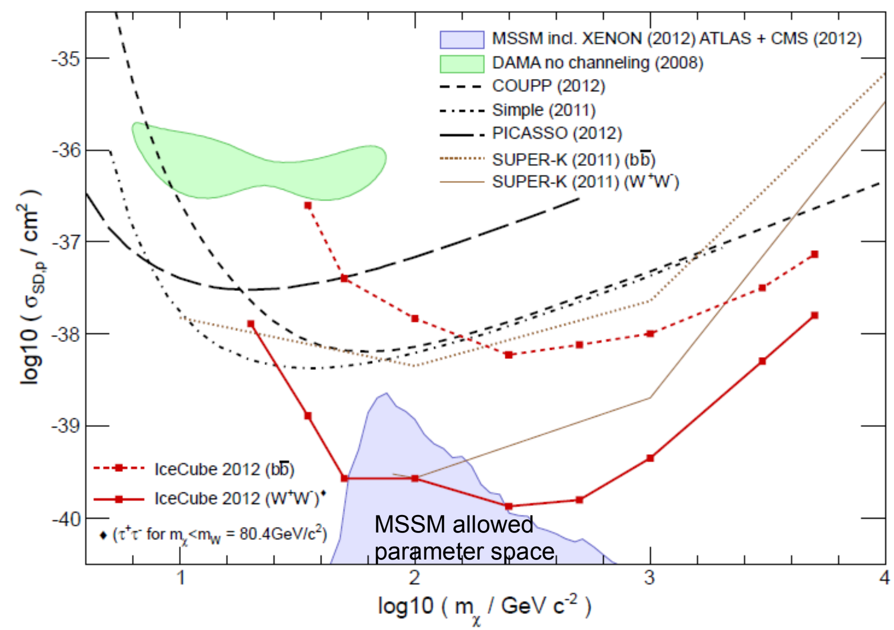
- muon background: downgoing, no starting track
- WIMP signal: require interaction vertex within detector volume

Analysis reaches neutrino energies of ~20 GeV.

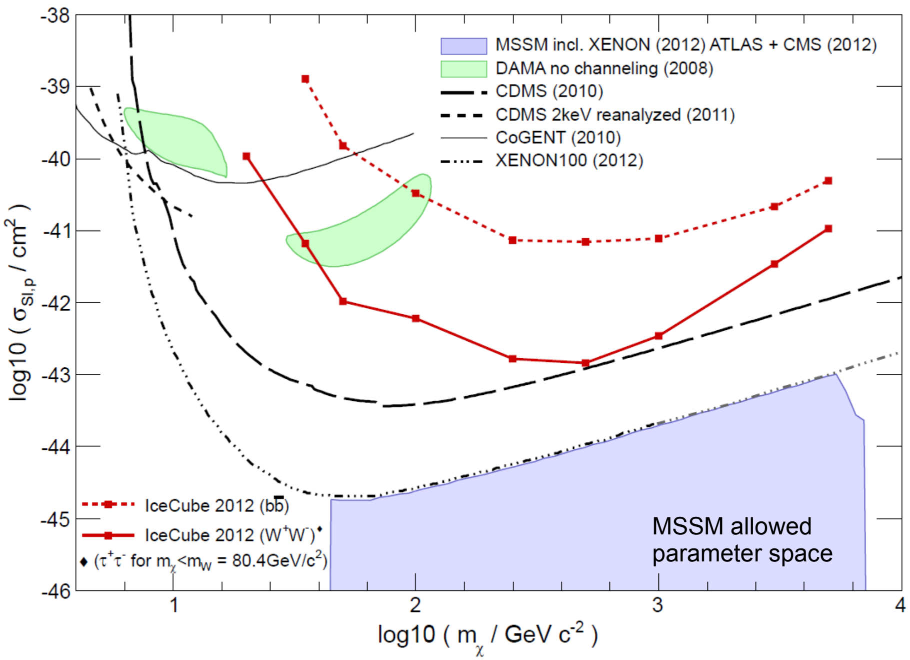
$$\Phi_\mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{X+p}$$

Unblinded events in different samples

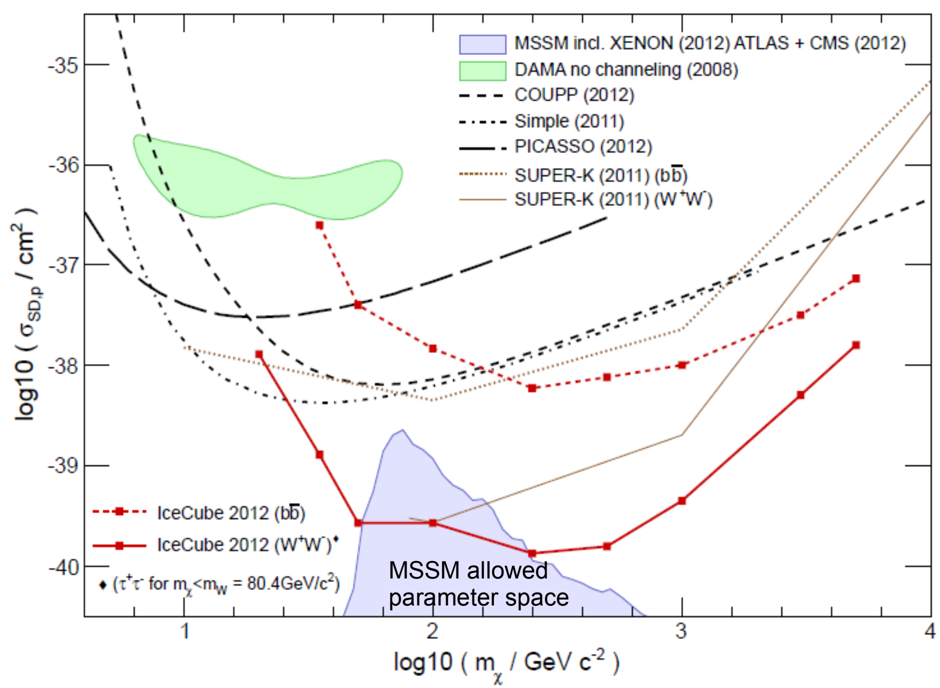




90% CL neutralino-p **SI** Xsection limit



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

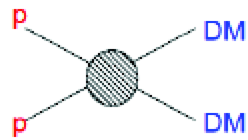


- most stringent SD cross-section limit for most models
- complementary to direct detection search efforts
- different astrophysical & nuclear form-factor uncertainties

searches from the Sun: comparison with LCH results

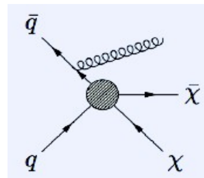
Assume (ie. model dependent) effective quark-DM interaction,

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



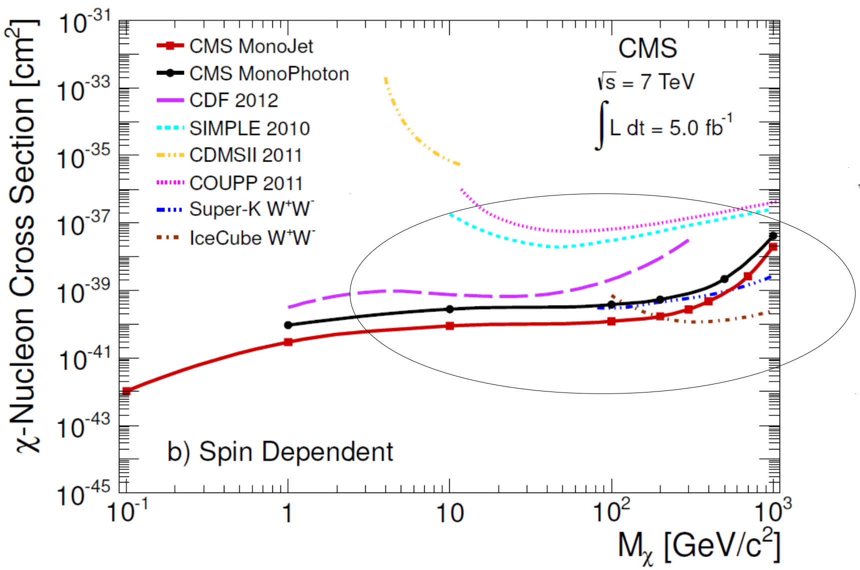
and look for monojets in pp collisions,

$$pp \rightarrow \chi\bar{\chi} + \text{jet} = \text{jet} + \not{E}_t$$

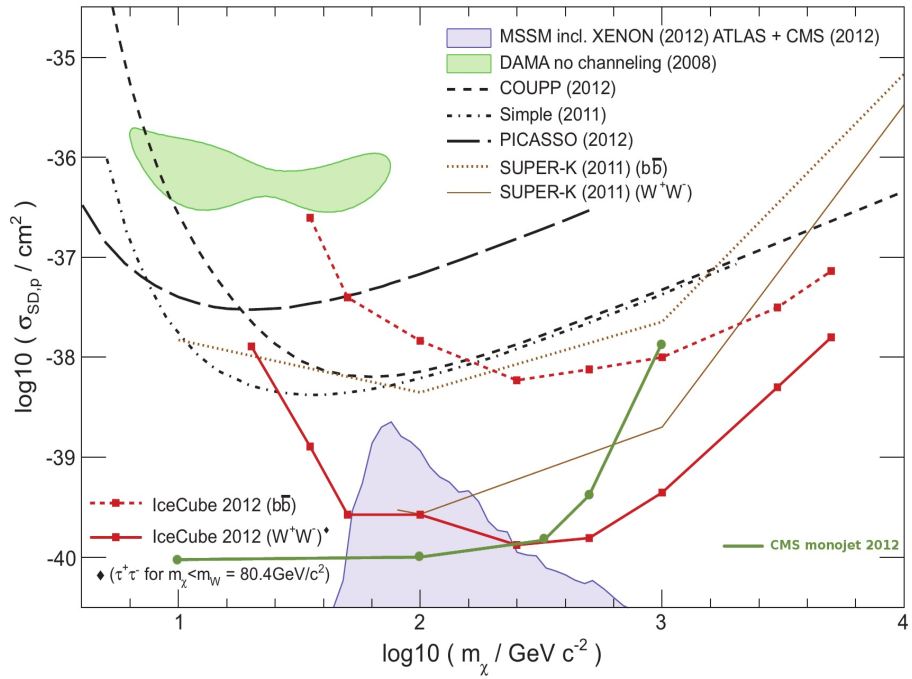


(as opposed to the SM process
$pp \rightarrow Z$+jet and $pp \rightarrow W$+jet)

Constrains from monojet searches at the LHC (CMS):



90% CL neutralino-p Xsection limit



Universal Extra Dimensions:

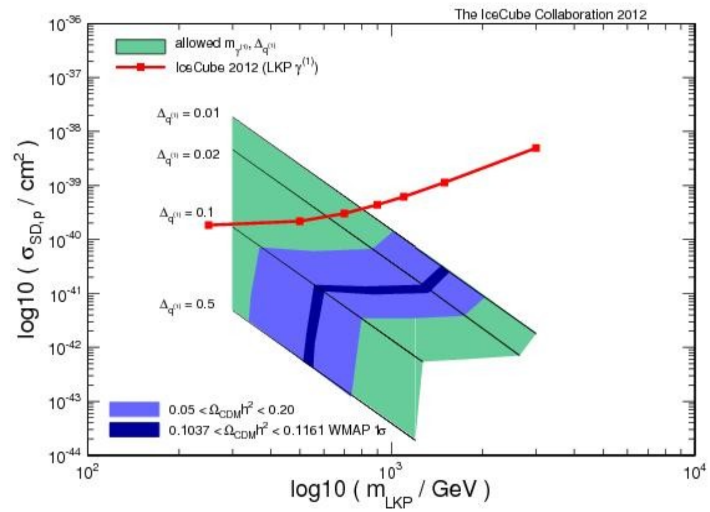
$$n\frac{\lambda}{2} = 2\pi R, \quad n\frac{h}{2p} = 2\pi R \;\Rightarrow\; p = n\frac{h}{4\pi R}$$

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

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

n=1 → Lightest Kaluza-Klein mode, $\mathbf{B}^1$
good DM candidate

90% CL LKP-p Xsection limit vs LKP mass



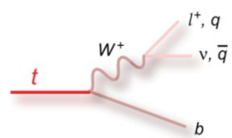
Superheavy dark matter:

- 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)

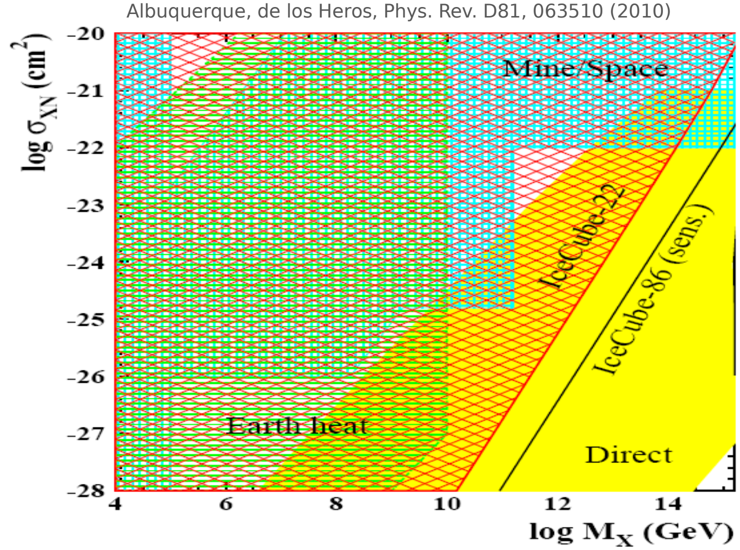
- m from ~10^4 GeV to 10^{18} GeV (no unitarity limit since production non thermal)

S+S → t $\bar{t}$



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

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



self-interacting dark matter

If the dark matter has a self-interaction component, $\sigma_{\chi\chi}$, the capture in astrophysical objects should be enhanced

$$\frac{dN_\chi}{dt} = \Gamma_C - \Gamma_A = (\Gamma_{\chi N} + \Gamma_{\chi\chi}) - \Gamma_A$$

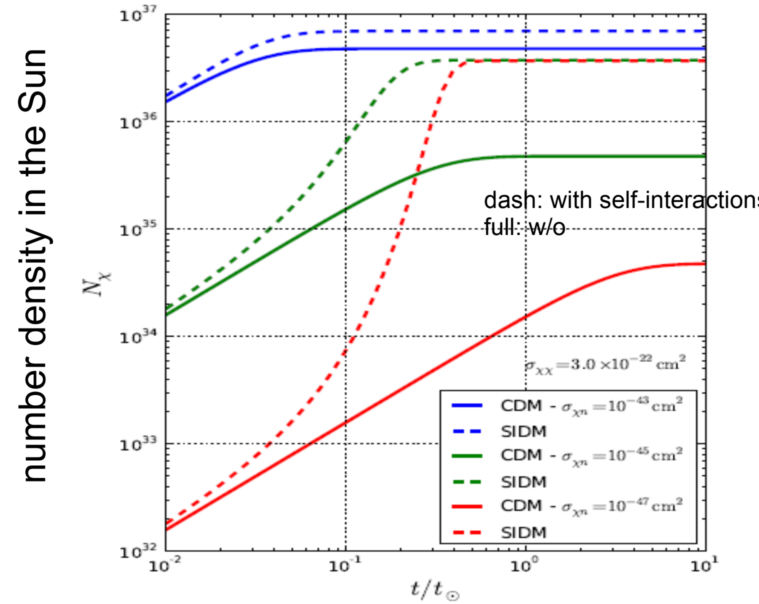
(Zentner, Phys. Rev. D80, 063501, 2009)

→ maximum annihilation rate reached earlier than in collisionless models

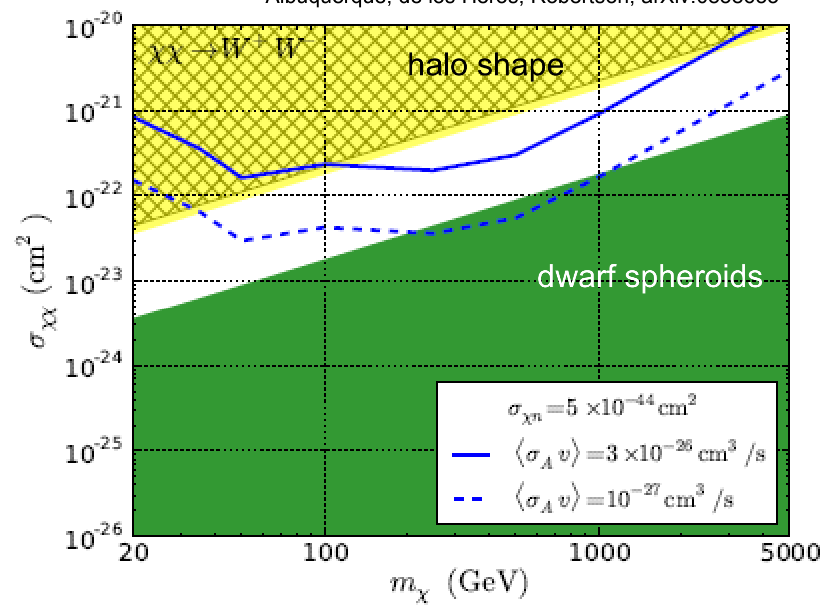
$\sigma_{\chi\chi}$ can naturally avoid cusped halo profiles

can induce a higher neutrino flux from annihilations in the Sun

limits on $\sigma_{\chi\chi}$ can be set by neutrino telescopes

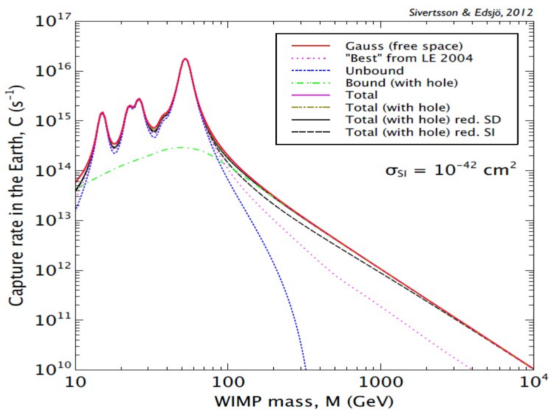


Albuquerque, de los Heros, Robertson, arXiv:0858653



dark matter searches from the Earth

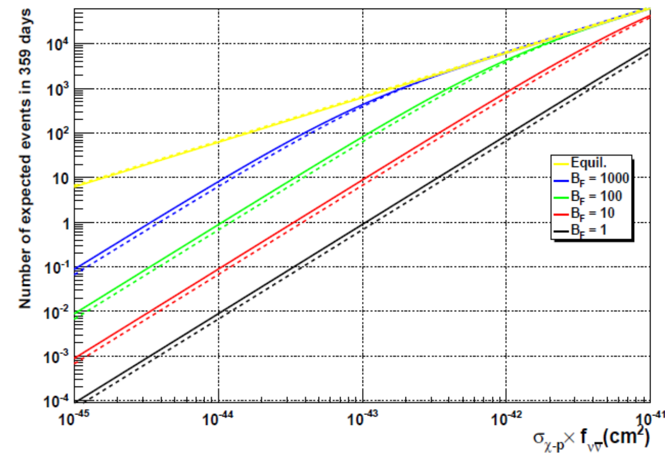
Earth capture rate dominated by resonance with heavy inner elements



→ however, initial standard assumptions on the capture rate, based on a value of $\sigma_{\chi-n}^{SI} \sim 10^{-42}$ cm^2, have been recently ruled out by direct experiments

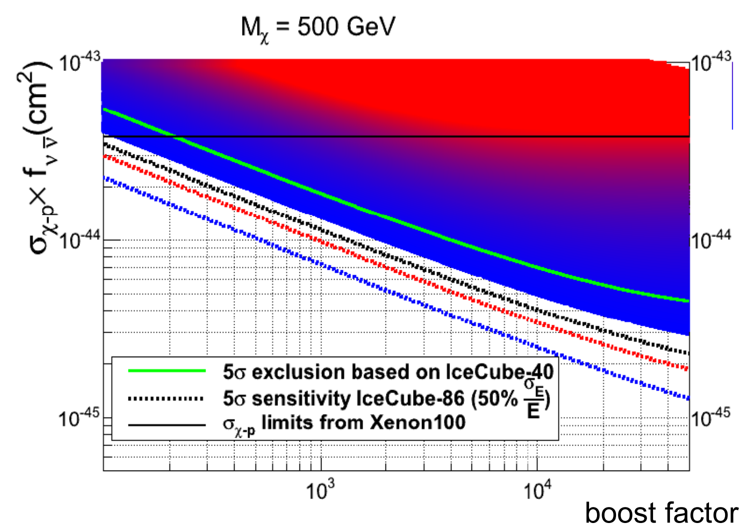
→ Normalization in the plot must be rescaled down, or a boost factor in the DM interaction cross section assumed

→ an enhanced capture Xsection could produce a detectable neutrino flux from the center of the Earth (C. Delaunay, P. J. Fox and G. Perez, JHEP 0905 , 099 (2009)).

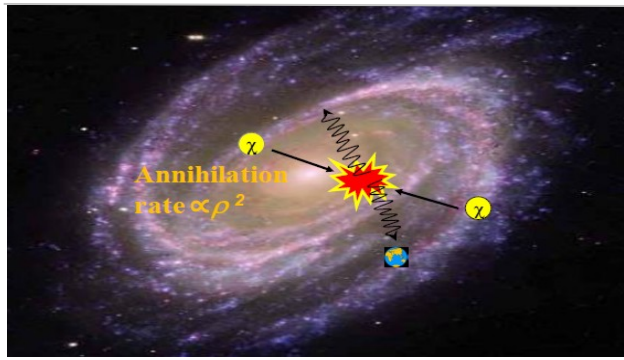


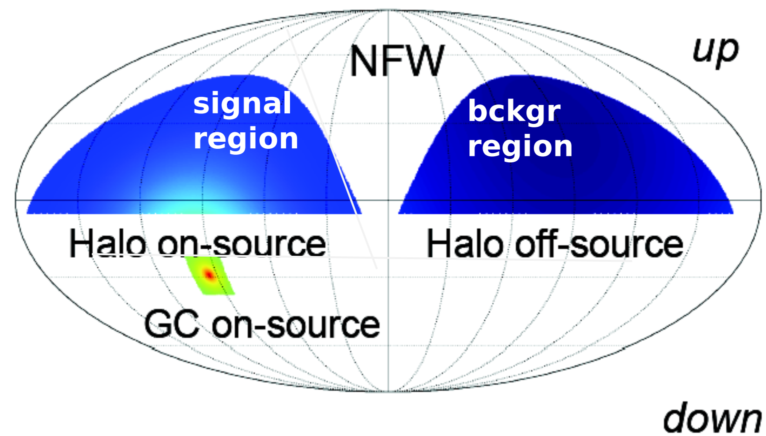
Using the atmospheric neutrino measurement of IceCube (ie, no excess from the center of the Earth detected), model-independent limits on boost factors can be set

Albuquerque, Belardo Silva and P. de los Heros. Phys Rev. D 85, 123539 (2012)



DM search from the Galactic Halo





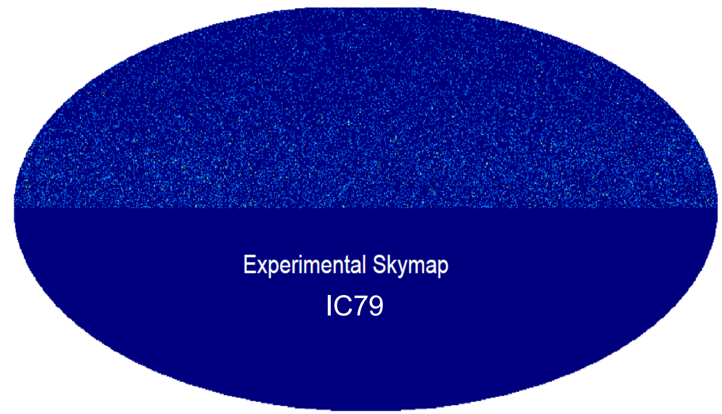
- Look for an excess of events in the on-source region w.r.t. the off-source

  or,

- Use a multipole analysis 'a la' CMB in search for large-scale anisotropies

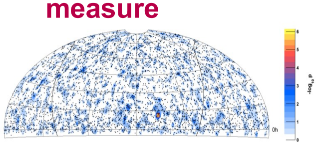
  Need expected neutrino flux from SUSY and halo model.

- Limit on the self-annihilation cross section:

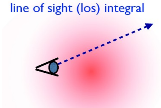


$$\varphi_\nu = \frac{dN}{dE\, dA_{eff}\, dt\, d\Omega} = \frac{1}{2}\frac{1}{4\pi}\langle\sigma v\rangle J_\Omega R_{SC}\frac{\rho_{SC}^2}{m_\chi^2}\frac{dN_\nu}{dE}$$

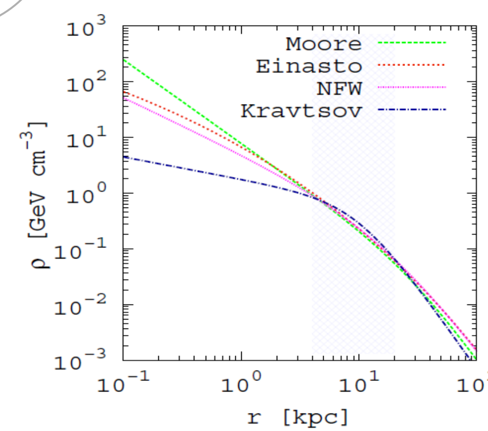
measure

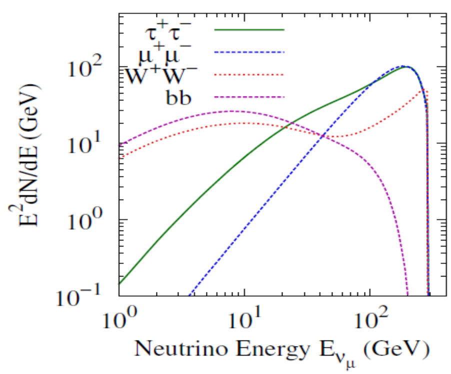


halo model

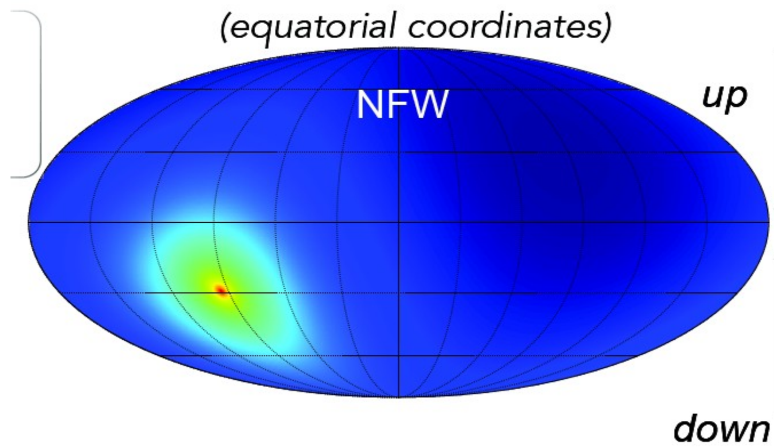


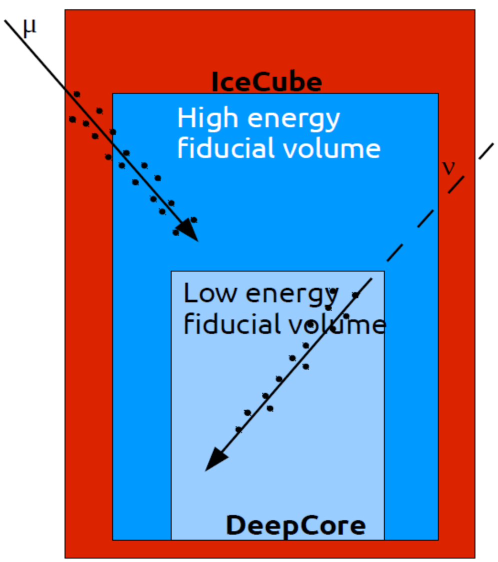
particle physics

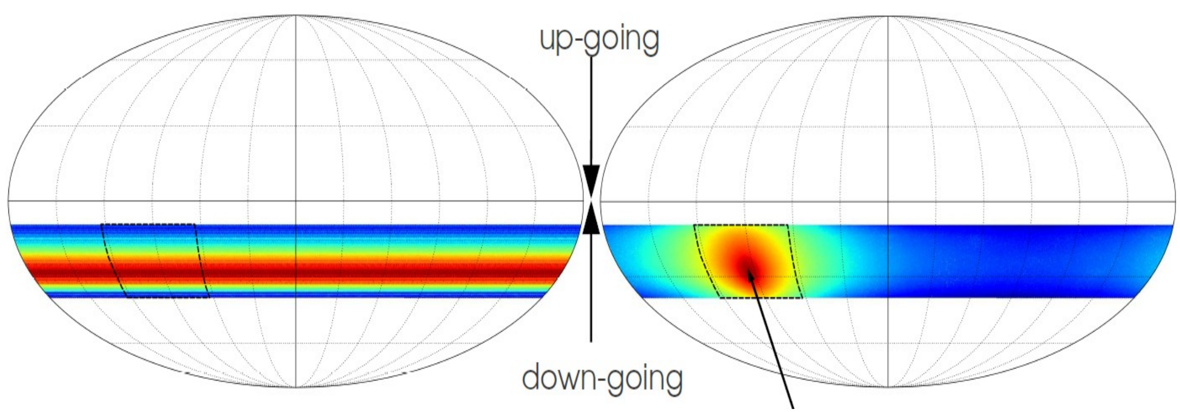




- 79-string configuration
- Use DeepCore to lower the energy threshold to ~10 GeV
- Analysis rely on veto methods to reject incoming tracks
- Use scrambled data for background estimation







dark matter searches from dwarf Galaxies

DM search from dwarf galaxies and galaxy clusters

- Dwarf galaxies: high mass/light ratio
- → high concentration of DM in the halos

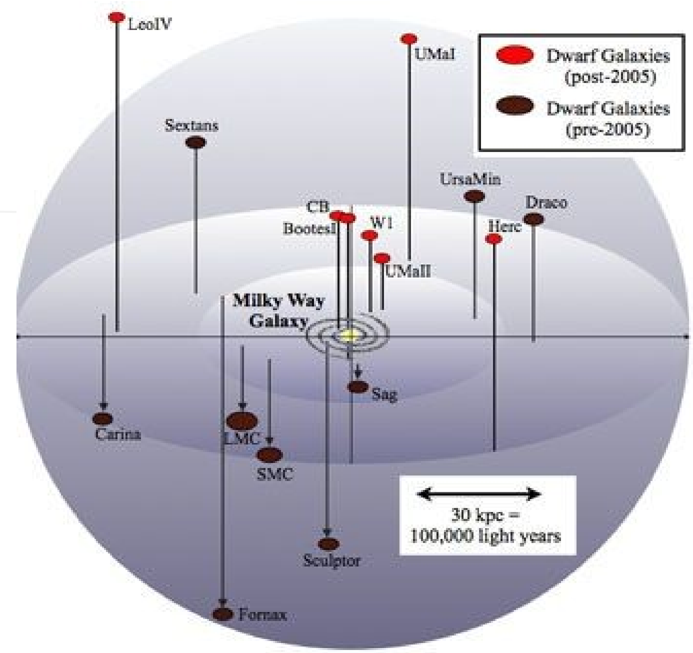
- known location. Distributed both in the north and southern sky.
  - Point-like search techniques: stacking
  - known distance -> determination of absolute annihilation rate if a signal is detected

- Galaxy clusters: enhance signal due to accumulation of sources

  But: extended sources with possible substructure

- Same expected neutrino spectra as for the galactic center/halo

- IceCube results from various sources



Galactic Halo:

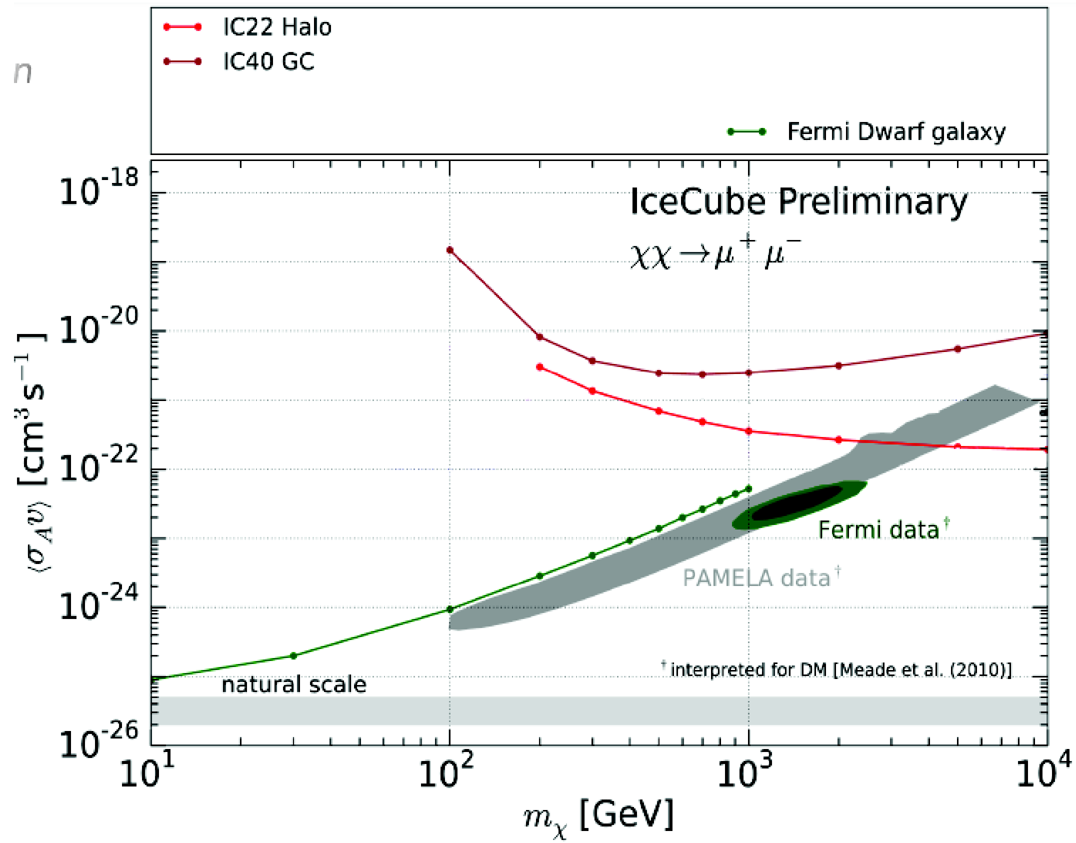
IC22 PRD 84, 022004 (2011)

Galactic Center

IC40 arxiv:1210.3557

Dwarf spheroids:

Clusters of galaxies



Search for many interesting potential annihilation channels:
(Various DM-Halo models tested)

$$\chi\chi \begin{cases} \nu\bar{\nu},\ \mu^+\mu^-,\ \tau^+\tau^-,\ W^+W^-,\ b\bar{b} \\ Z^0Z^0,\ Z^0\gamma \end{cases}$$

Galactic Halo:

IC22 PRD 84, 022004 (2011)

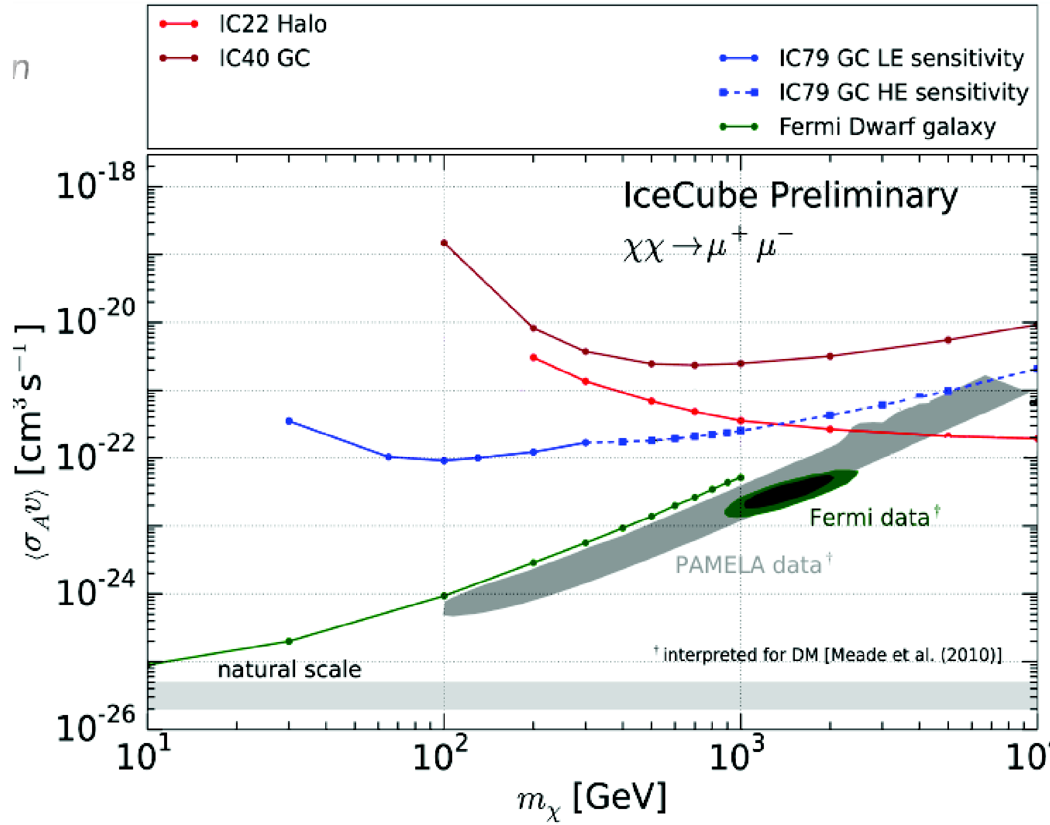
Galactic Center

IC40 arxiv:1210.3557

IC79 in preparation

Dwarf spheroids:

Clusters of galaxies



IceCube-79 Galactic Center analysis *(sensitivity):*

- First IceCube analysis looking at GC for low WIMP masses (< 100 GeV)
- 4 orders of magnitude improved sensitivity @ 100 GeV
- Unblinding is going on within the collaboration

Galactic Halo:

IC22 PRD 84, 022004 (2011)

IC79 in preparation

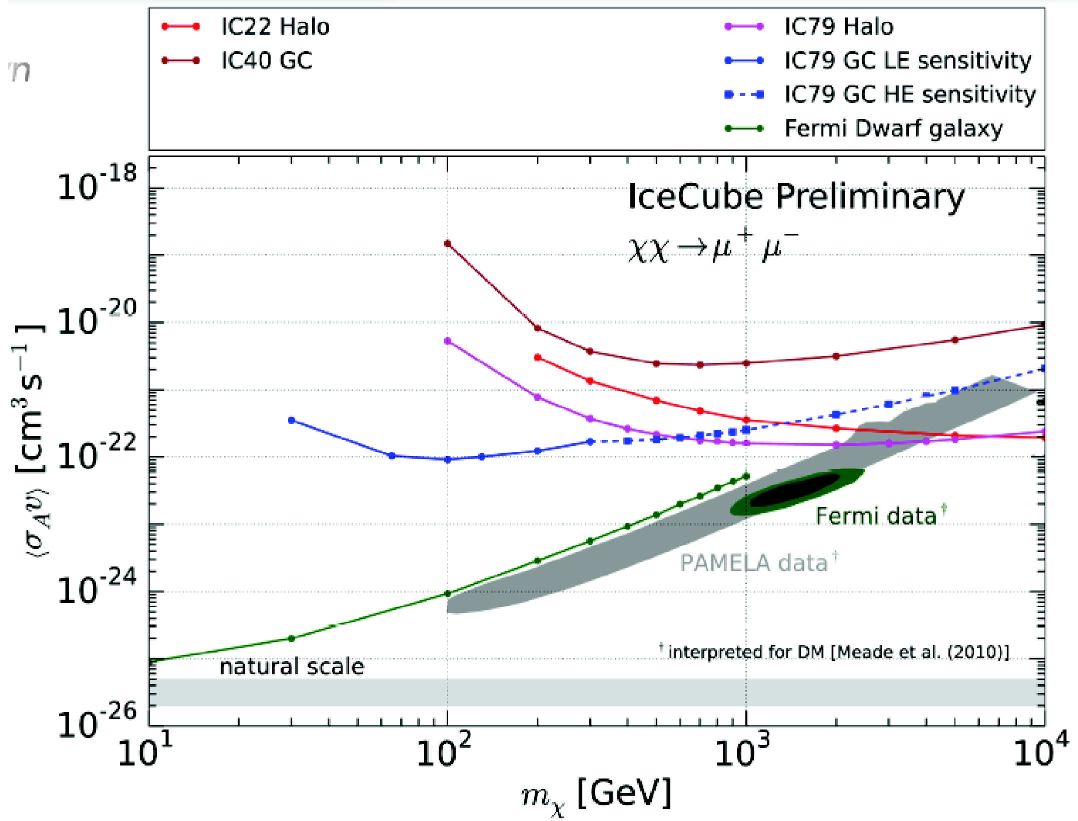
Galactic Center

IC40 arxiv:1210.3557

IC79 in preparation

Dwarf spheroids:

Clusters of galaxies



IceCube-79 Multipole analysis to search for Dark Matter in the Galactic Halo:

- focus on large scale anisotropies (l<100)
- small Halo-model dependency
- results are compatable with the background-only hypothesis

Galactic Halo:

IC22 PRD 84, 022004 (2011)

IC79 in preparation

Galactic Center

IC40 arxiv:1210.3557

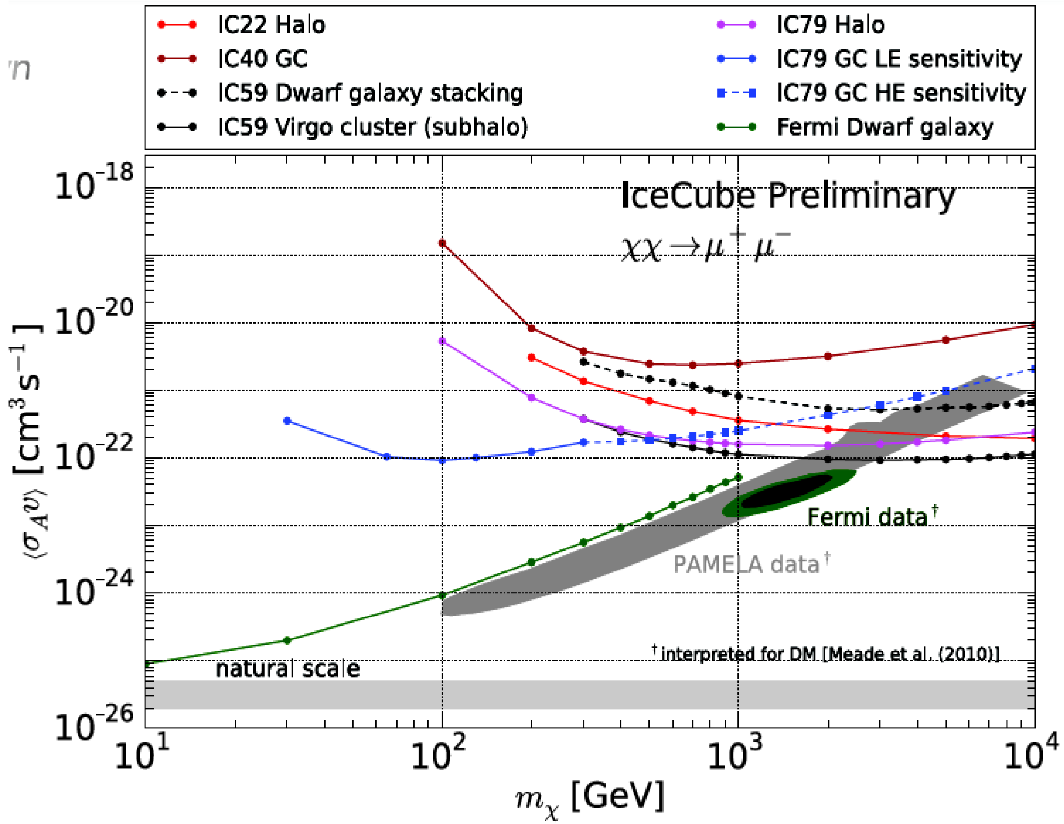
IC79 in preparation

Dwarf spheroids:

IC59 submitted

Clusters of galaxies

IC59 submitted



IceCube-59 Dwarf galaxy searches:

- Source stacking analysis
- Optimized size of search window

IceCube-59 Galaxy cluster analysis:

- Extended point source search
- Optimized size of search window
- Substructures taken into account

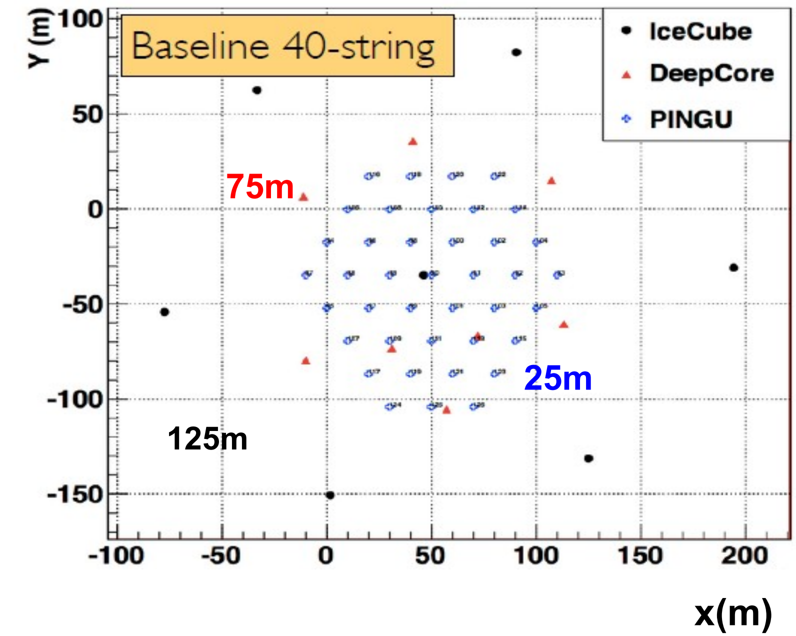
DeepCore showed the potential of going down in energy.

How low could we go?

Add 40 strings within the current DeepCore volume to bring down energy threshold to O(1 GeV)

→ **PINGU:**

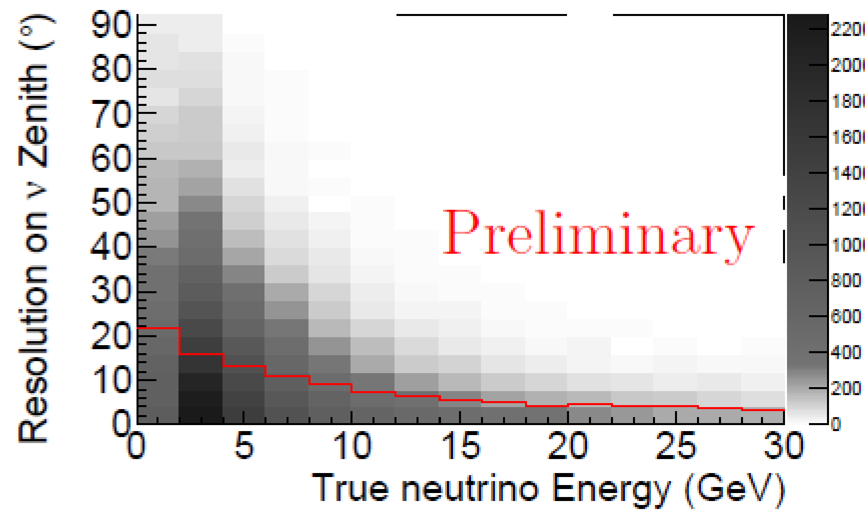
Precision **I**cecube **N**ext **G**eneration **U**pgrade



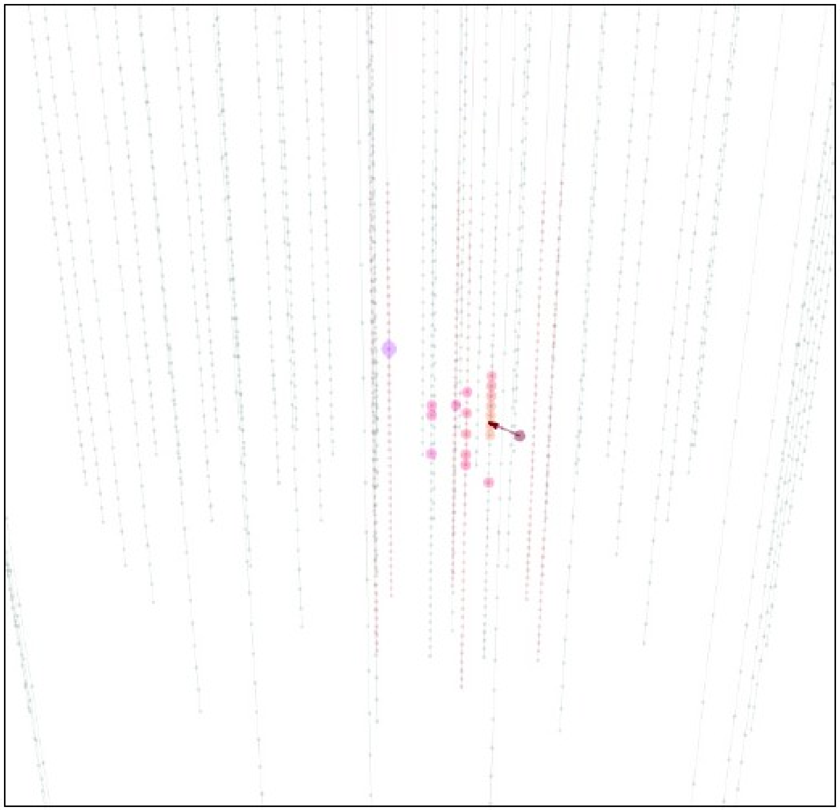
Aims:

Physics @few GeV:

- neutrino hierarchy, low-mass WIMPs
- R&D for Megaton ring Cherenkov reconstruction detector for p-decay and high statistics SuperNova detection

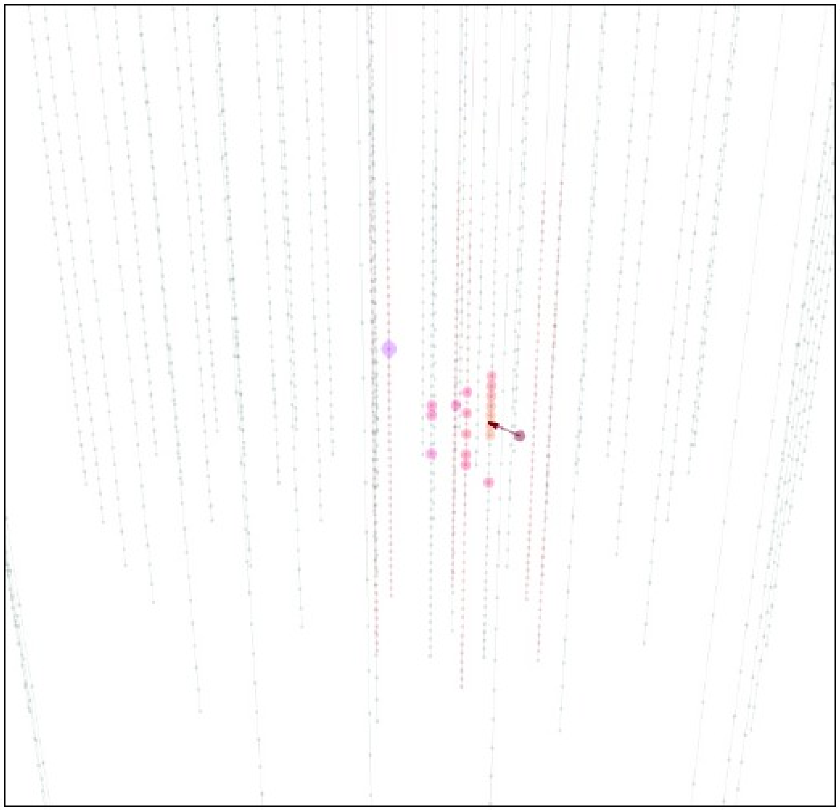


9.3 GeV neutrino producing a 4.9 GeV muon and a 4.4 GeV cascade



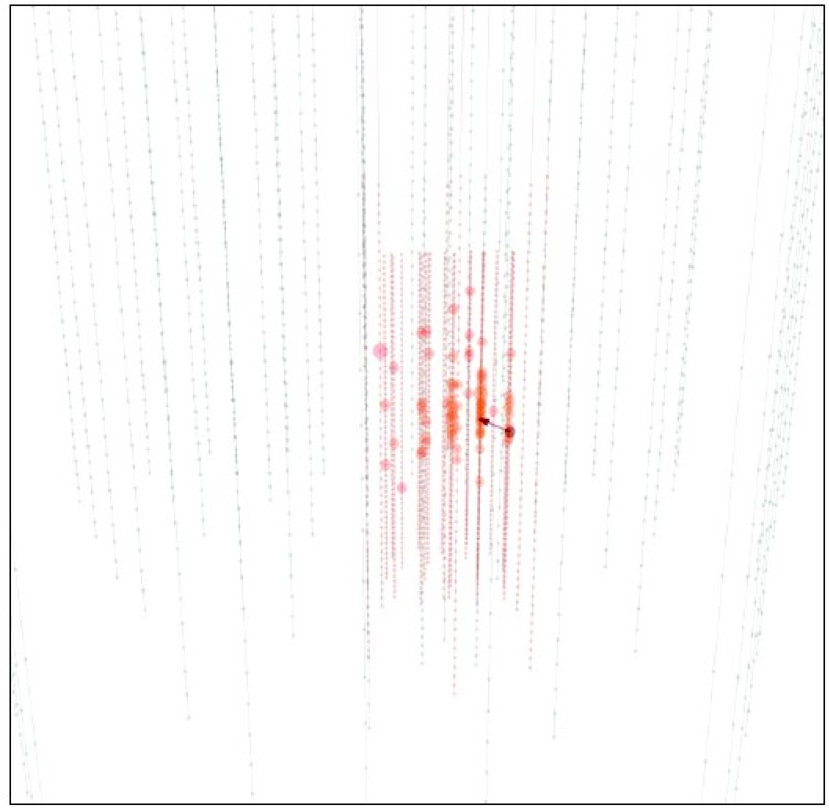
DeepCore only

9.3 GeV neutrino producing a 4.9 GeV muon and a 4.4 GeV cascade



DeepCore only

20 DOMs hit



DeepCore + PINGU

50 DOMs hit

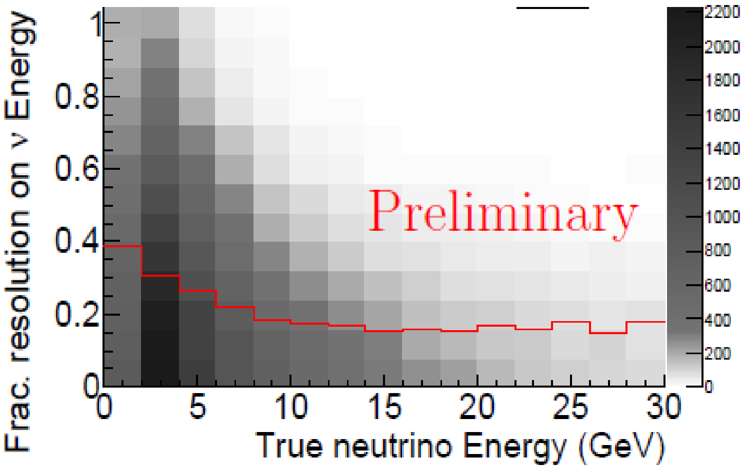
sensitivity study based on current IceCube analysis techniques

- Assume complete background rejection of downgoing atmospheric muons through veto technique
- On-source search window of 10°

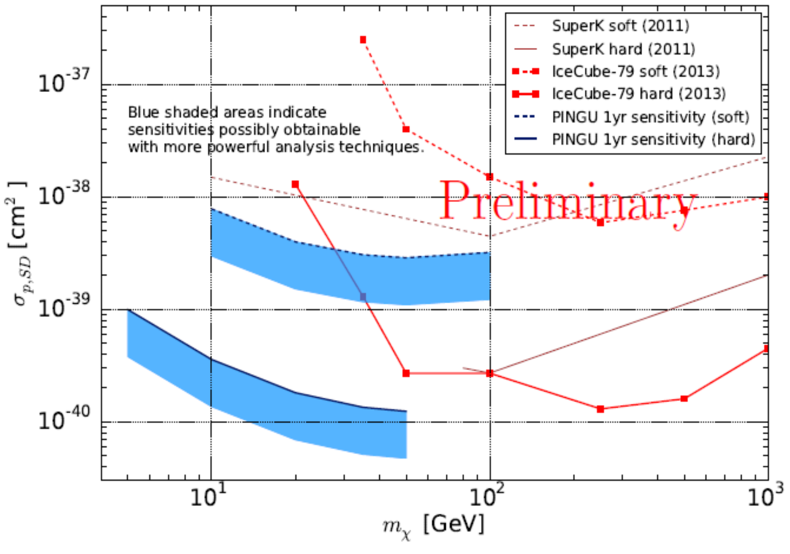
→ reach WIMP masses of 5 GeV

blue shaded areas ==> range of possibly obtainable sensitivity with improved analysis techniques

↳ use of signal and background spectral information



Sun, σ_p^{SD} (1 yr live time)



on the dark matter side

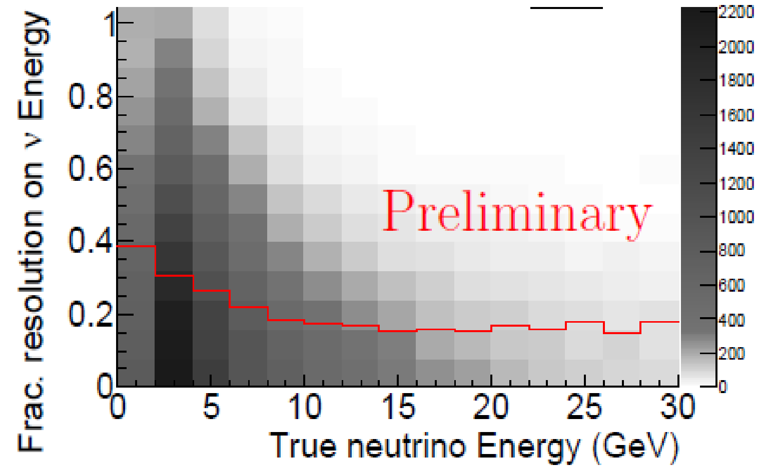
sensitivity study based on current IceCube analysis techniques

- Assume complete background rejection of downgoing atmospheric muons through veto technique
- On-source search window of 10°

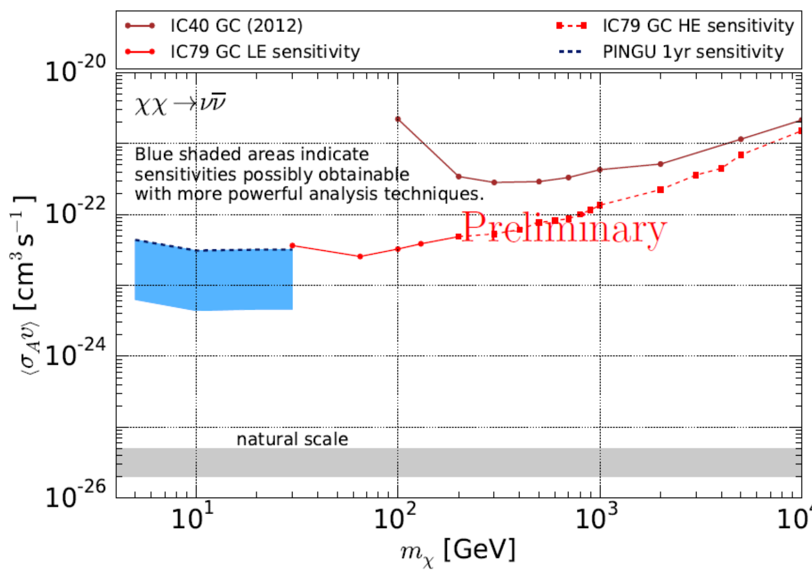
→ reach WIMP masses of 5 GeV

blue shaded areas ==> range of possibly obtainable sensitivity with improved analysis techniques

└> use of signal and background spectral information



Galactic Center, $\langle\sigma_A v\rangle$ (1 yr live time)



- IceCube is completed and delivering first-class science on a wide range of physics topics

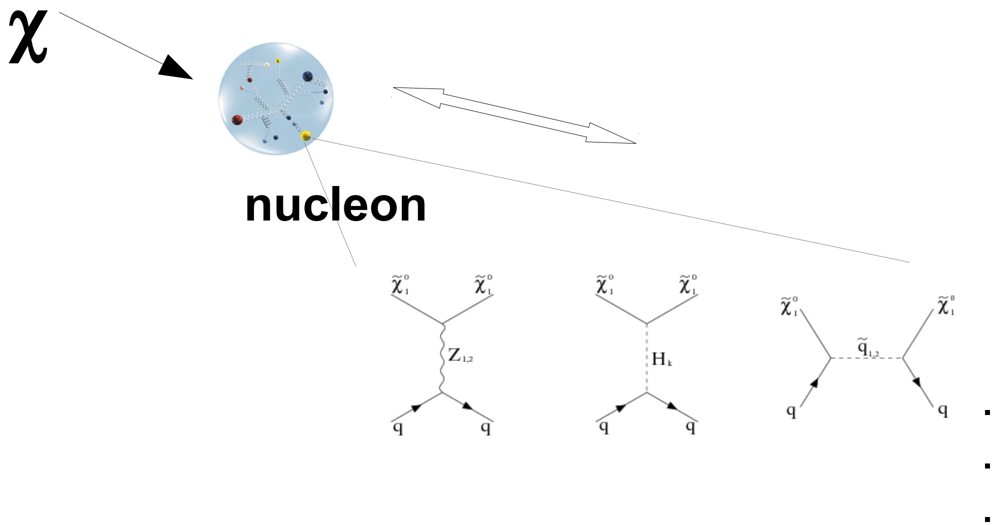
- Competitive searches for dark matter in the Sun and galaxies. Complementary to accelerator, direct and other indirect searches (photons, e^+e^-, CRs)

- Still on the way to extract full search capability with DeepCore (ie, searches with cascades)

- PINGU will allow to extend searches for DM candidates to the ~few GeV region

FIN

- Signals in indirect (≈WIMP capture) and direct (nuclear recoil) experiments depend on the WIMP-nucleon cross section (WIMP-nucleus cross section not considered here)



Structure of the nucleon plays an essential role in calculating observables

$$\sigma_{SD}^{\chi N} \propto \Sigma_{q=u,d,s} \langle N | \bar{q} \gamma_\mu \gamma_5 q | N \rangle \propto \Sigma_{q=u,d,s} \alpha_q^a \Delta q^N$$

$$\sigma_{SI}^{\chi N} \propto \Sigma_{q=u,d,s} \langle N | m_q \bar{q} q | N \rangle \propto \Sigma_{q=u,d,s} m_N \alpha_q^s f_{Tq}^N$$

need to be calculated in QCD or measured experimentally

The problem lies in the determination of Δ_q^N and f_{Tq}. These quantities are measured experimentally in π-nucleon scattering or calculated from LQCD.

There are large discrepancies between the LQCD calculations and the experimental measurements, as well as between the experimental results themselves

– **Δ_q^N**: relatively good agreement (within 10%) between LQCD and experimental determinations of Δ_u^n and Δ_d^n. Some tension between the LQCD calculation of Δ_s^N (0.02±0.001) and the experimental values (0.09±0.02), which translates into the calculation of $\sigma_{SD}^{\chi N} \propto \Sigma_{q=u,d,s} \alpha_q^a \Delta q^N$

– **f_{Tq}**: Depends on the measurement of

$$\sigma_{\pi N} = \frac{1}{2}(m_u + m_d)\langle N|\bar{u}u + \bar{d}d|N\rangle \qquad y = 2\frac{\langle N|s\bar{s}|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle}$$

and their extrapolation to zero-momentum. Here is where the uncertainties originate

Values of σ_{p-N} in the literature vary between ~40 MeV and 80 MeV, which gives values of f_{Ts} between 0.043 and 0.5.

This in turn introduces big uncertainties in $\sigma_{SI}^{\chi N} \propto \Sigma_{q=u,d,s} m_N \alpha_q^s f_{Tq}^N$

effect of nucleon matrix element uncertainties

to appear in JCAP

check the effect of the uncertainties of Δ_q^N and f_{Tq} on the interpretation of results of direct and indirect DM search experiments

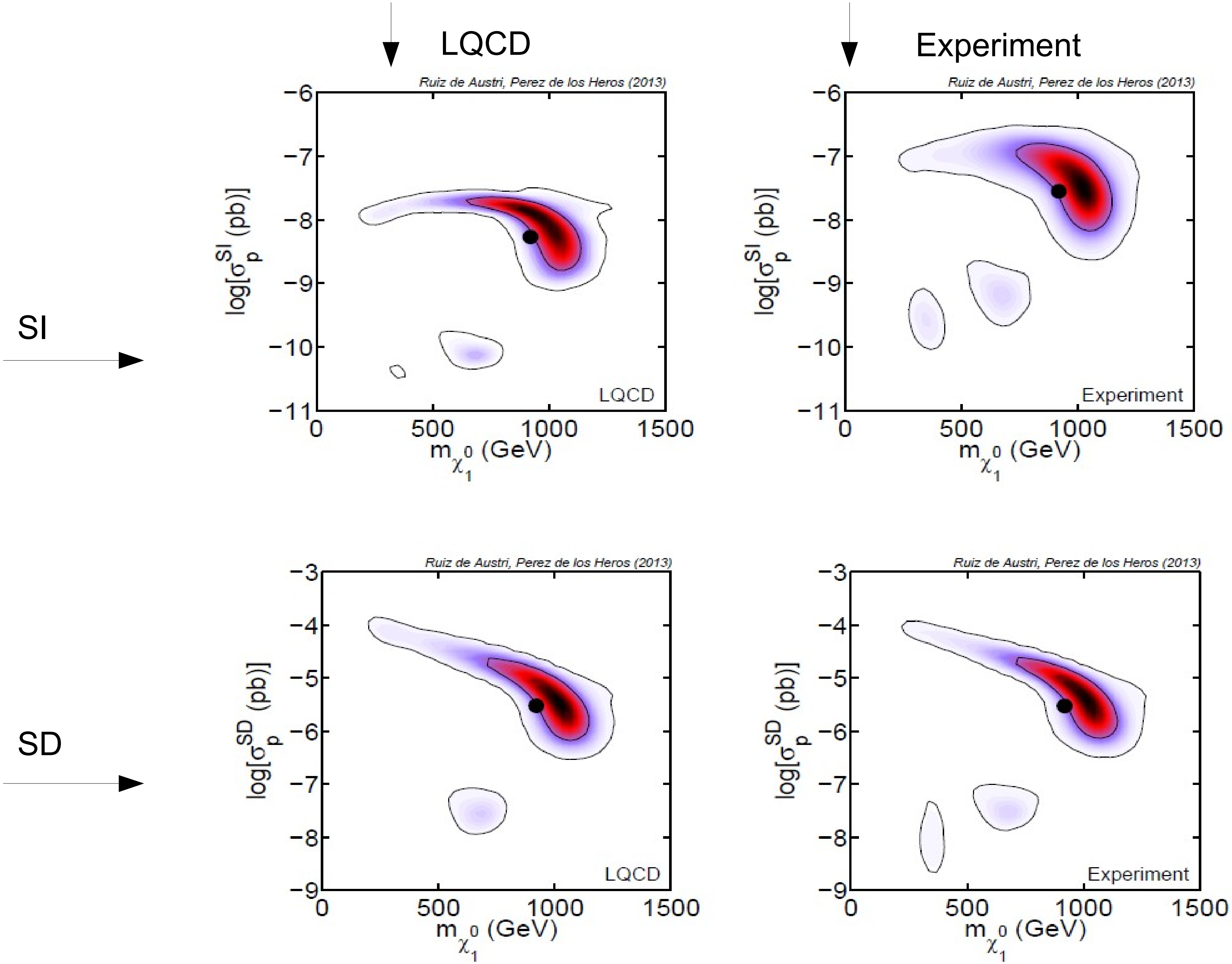
- Perform scans on the cMSSM parameter space, calculating σ_{SD} and σ_{SI} for each model, but using two extreme values of Δ_q^N and f_{Tq}

Nuisance parameters			
Standard Model			
M_t [GeV]	173.1 ± 1.3		[22]
$m_b(m_b)^{\bar{MS}}$ [GeV]	4.20 ± 0.07		[22]
$[\alpha_{em}(M_Z)^{\bar{MS}}]^{-1}$	127.955 ± 0.030		[22]
$\alpha_s(M_Z)^{\bar{MS}}$	0.1176 ± 0.0020		[23]
Astrophysical			
$\rho_{\rm loc}$ [GeV/cm^3]	0.4 ± 0.1		[24]
$v_\odot$ [km/s]	230.0 ± 30.0		[24]
v_d [km/s]	282.0 ± 37.0		[24]
Hadronic			
	LQCD	Experiment	
f_{Tu}	0.0190 ± 0.0029	0.0308 ± 0.0061	[25], [14]
f_{Td}	0.0246 ± 0.0037	0.0459 ± 0.0089	[25], [14]
f_{Ts}	0.043 ± 0.011	0.493 ± 0.159	[12], [14]
Δ_u	0.787 ± 0.158	0.75 ± 0.05	[9], [16]
Δ_d	-0.319 ± 0.066	-0.34 ± 0.07	[9], [16]
Δ_s	-0.020 ± 0.011	-0.09 ± 0.02	[9], [17]

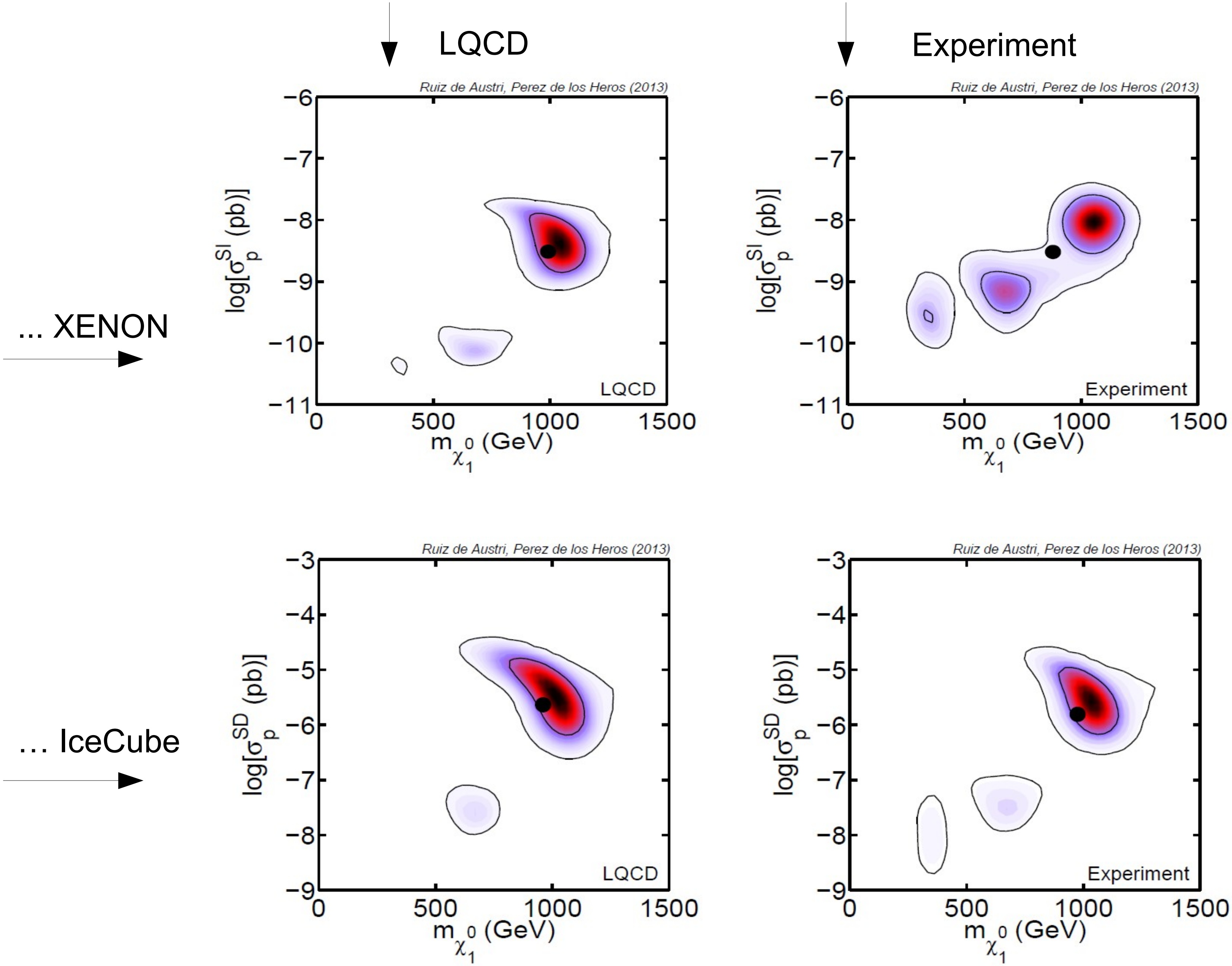
Study the resulting model rejection power of the experiments (Xenon and IceCube taken as benchmark) depending on the value of the hadronic parameters chosen

$$\ln \mathcal{L} = \underbrace{\ln \mathcal{L}_{\rm LHC} + \ln \mathcal{L}_{\rm Planck} + \ln \mathcal{L}_{\rm EW} + \ln \mathcal{L}_{\rm B(D)} + \ln \mathcal{L}_{g-2}} + \underbrace{\ln \mathcal{L}_{\rm Xe100}} + \underbrace{\ln \mathcal{L}_{\rm IC86}}$$

allowed regions of the cMSSM with particle physics and Planck constrains



allowed regions of the cMSSM with particle physics, Planck and ...



Conclusions of the study:

Spin-independent experiments:

Dark matter experiments sensitive to spin-independent cross sections, like XENON100, are strongly affected by the large differences in the determination of the strangeness content of the nucleon. The reason is that spin-independent cross sections can vary up a factor of 10 depending on which input for the nucleon matrix elements is used.

Spin-dependent experiments:

The conclusion is more optimistic for experiments sensitive to the spin-dependent cross section, like neutrino telescopes. They are practically not affected by the choice of values of the nuclear matrix elements which drive the spin-dependent neutralino-nucleon cross section.

[..] current limits from neutrino telescopes on the spin-dependent neutralino-nucleon cross section are robust in what concerns the choice of nucleon matrix elements, and these quantities should not be a concern in interpreting neutrino telescope results.