indirect dark matter searches with neutrino telescopes

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KUBEC International Workshop on Dark Mater Searches
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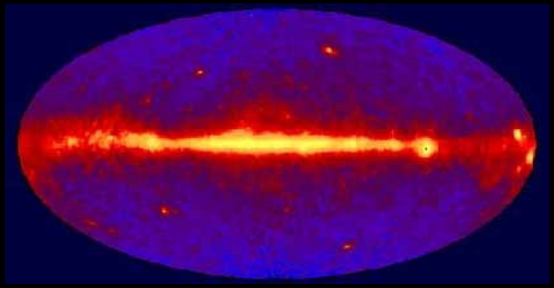
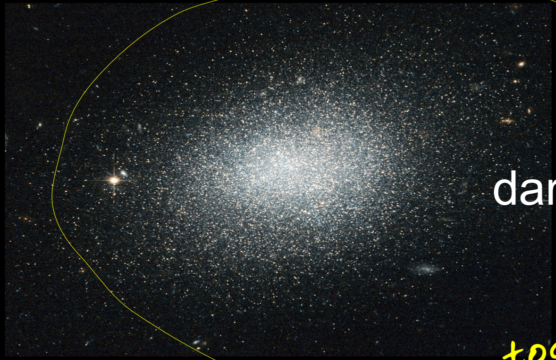
physics with neutrino telescopes

cosmic accelerators
AGN, GRBs, μQSrs, SN remnants
(point-source searches)

Supernovae

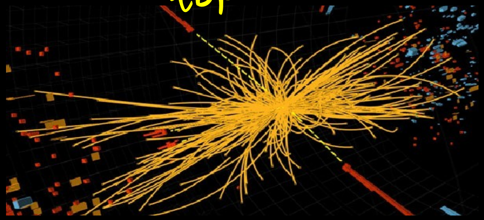


diffuse neutrino flux
(all-sky searches)



dark matter

today's topic



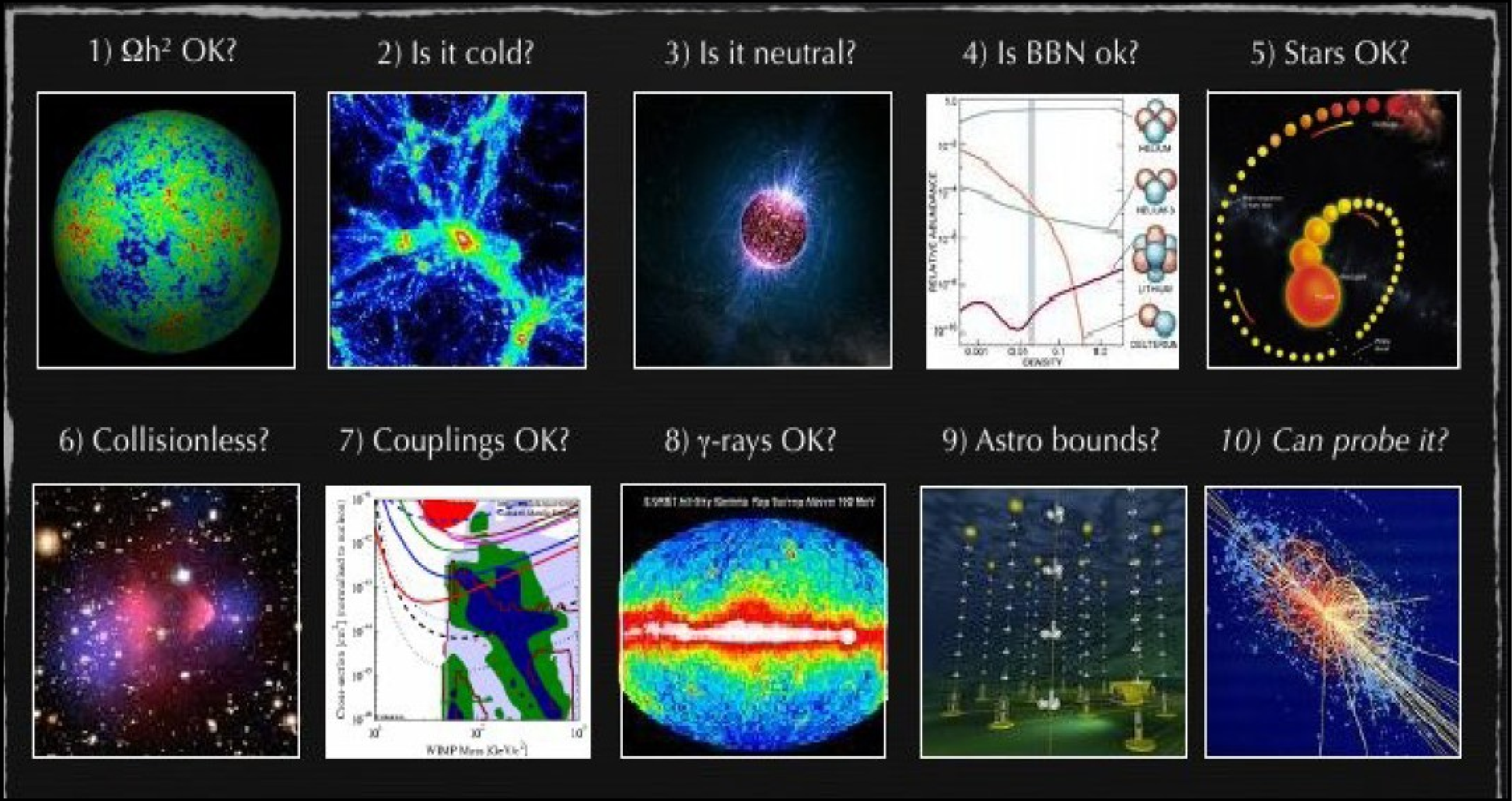
particle physics:
neutrino properties
fundamental laws...

cosmic rays

generic properties of a particle dark matter candidate

- new (the Standard Model seems not to be able to provide good candidates)
- weakly interacting (not to spoil the history of the universe), or not produced thermally
- massive (we want it to have gravitational effects)
- stable (we want it to solve the DM problem now)
- neutral (otherwise we would have probably seen it)
- does not spoil any astrophysical observation (in γs, cosmic rays… etc)

generic constrains of a particle dark matter candidate



1) Ωh^2 OK?

2) Is it cold?

3) Is it neutral?

4) Is BBN ok?

5) Stars OK?

6) Collisionless?

7) Couplings OK?

8) γ-rays OK?

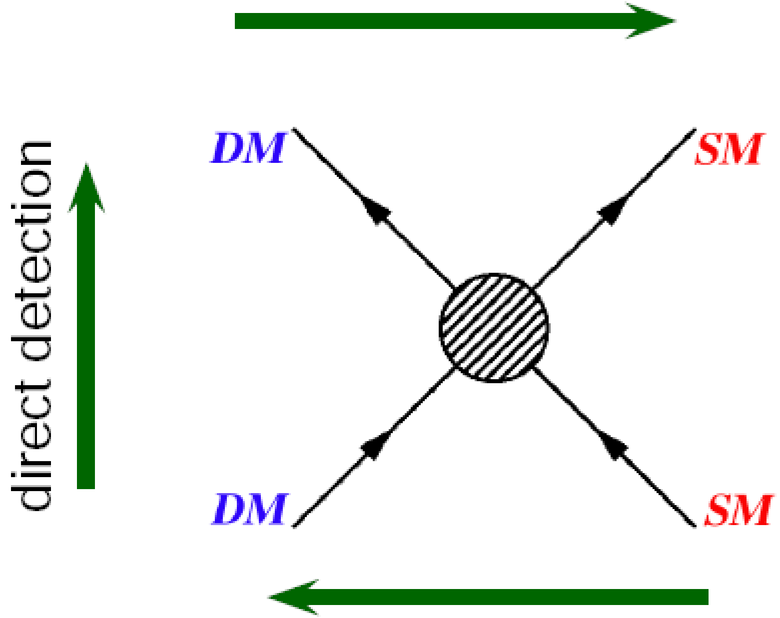
9) Astro bounds?

10) Can probe it?

(graphic from G. Bertone)

dark matter detection approaches

thermal freeze-out (early Univ.)
indirect detection (now)



recoils of a
suitable target

direct detection

XENON, CDMS, Edelweiss,
CRESST, CoGENT,
DAMA/Libra, SIMPLE,
COUPP, ZEPLIN, KIMS,
PICASSO, DRIFT....

production at colliders

search for
missing energy

LHC

γ's
e^+'s
$\bar{p}$'s
$\bar{d}$

from annihilation
in Galactic Center/Halo

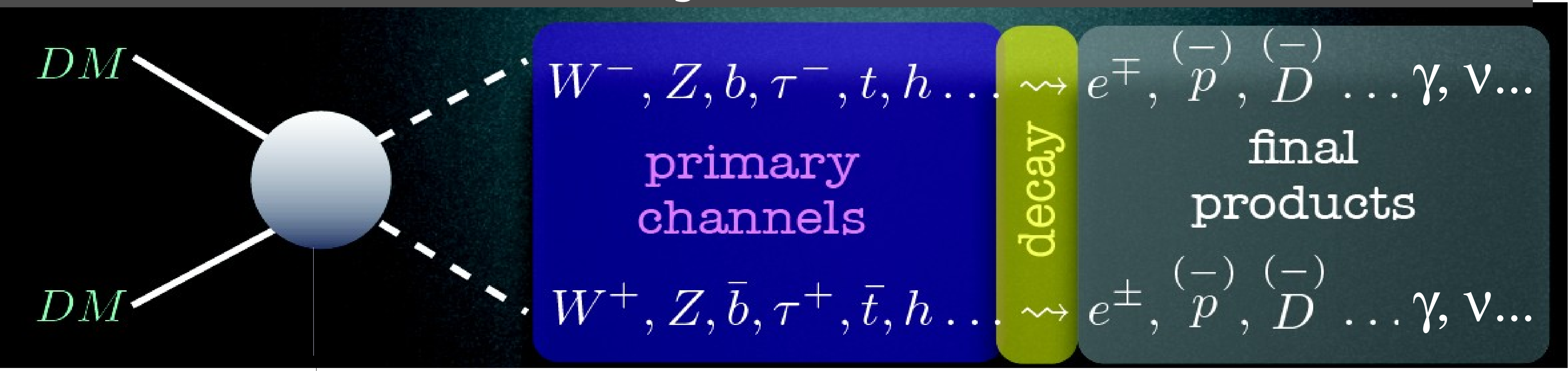
Fermi, Pamela, AMS
IACTs, balloons

ν's

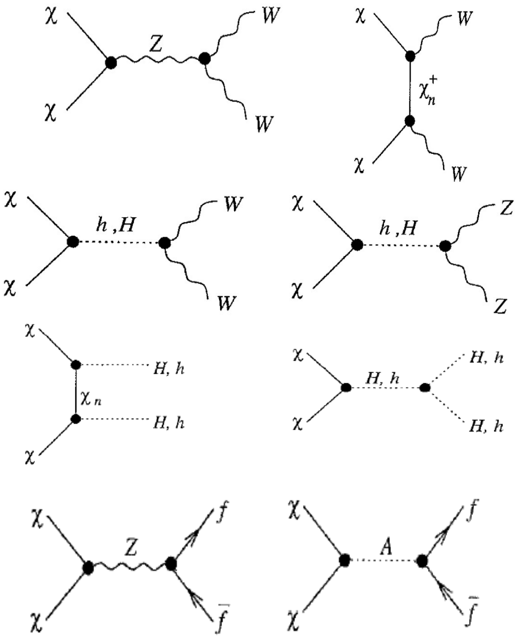
from annihilation
massive bodies

IceCube, ANTARES,
Km3NET, SK...

indirect signatures from dark matter annihilation



your theory here
(not necessarily SUSY...)



…. etc

astrophysics inputs
(and uncertainties...):
products have to be
transported to the Earth

Here is where ν's are
advantageous

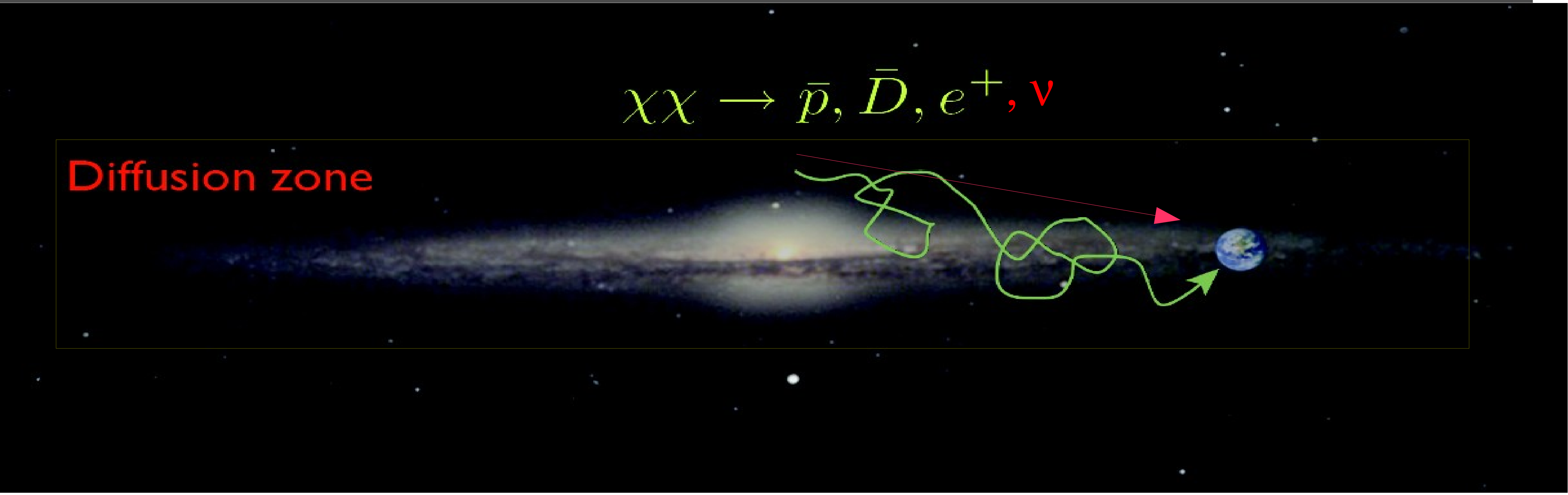
indirect searches for dark matter

The prediction of a neutrino signal from dark matter annihilation is complex and involves many subjects of physics

- relic density calculations (cosmology)
- dark matter distribution in the halo (astrophysics)
- velocity distribution of the dark matter in the halo (astrophysics)
- physical properties of the dark matter candidate (particle physics)
- interaction of the dark matter candidate with normal matter (for capture)

  (nuclear physics/particle physics)
- self interactions of the dark matter particles (annihilation) (particle physics)
- transport of the annihilation products to the detector (astrophysics/particle physics)

do we know our galaxy well enough?



Particles, emitted by whatever process, must reach the detector (Earth) travelling through a medium with structure (the galaxy): interstellar gas, magnetic field

We have a standard diffusion model which assumes the galaxy is a flat cylinder with free scape at the boundaries

$$\partial_z \left(V_C\, \psi\right) - K\, \Delta\psi + \partial_E \left\{ b^{\mathrm{loss}}(E)\, \psi - K_{EE}(E)\, \partial_E \psi \right\} = Q\left(\mathbf{x}, E\right)$$

spatial diffusion

energy losses

energy gain (reacceleration)

source

galactic model

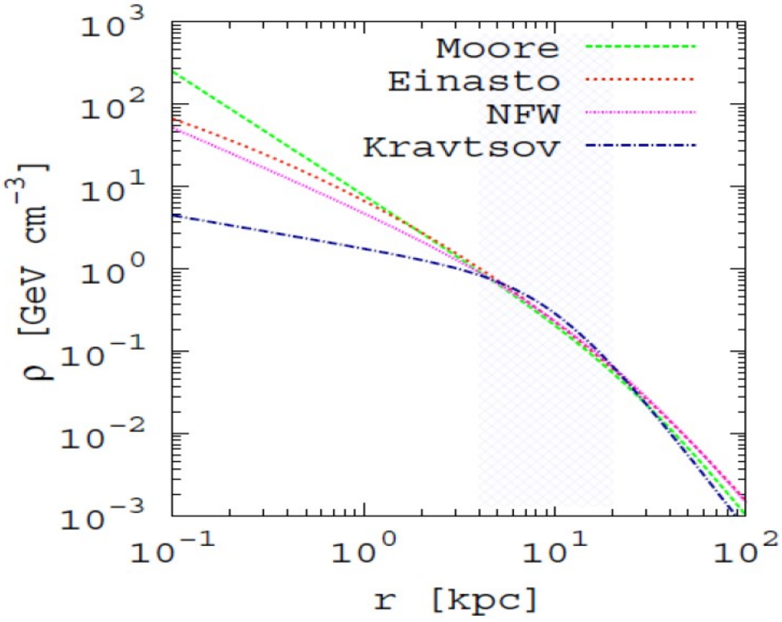
source model

Astrophysical inputs needed for reliable calculations and data analyses:

- dark matter distribution in the halo of galaxies (including the Milky Way)

DM annihilation ∞ DM density^2 (it takes two particles per annihilation)

$$\rho_{\mathrm{DM}}(r) = \frac{\rho_0}{\left(\delta + \frac{r}{r_s}\right)^{\gamma} \cdot \left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$



$$\frac{d\Phi(\Delta\Omega)}{dE} = \frac{\langle\sigma_A v\rangle}{4\pi \cdot 2m_\chi^2}\frac{dN}{dE} J(\Delta\Omega)$$

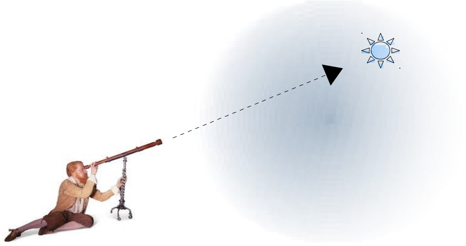
$\langle\sigma_A v\rangle$ Annihilation cross-section, velocity averaged

$\frac{dN}{dE}$ Neutrino spectrum per annihilation

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s.}} \rho(l)^2 dl$$

J-Factor:
“line-of-sight” Integral over
squared mass density

line-of-sight (los) integral

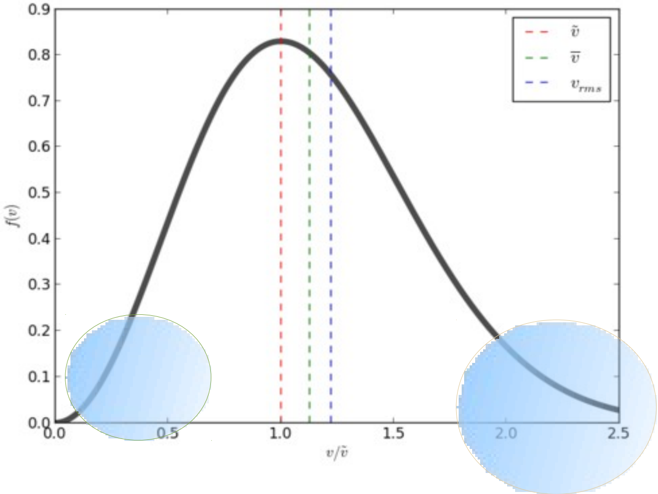


Astrophysical inputs needed for reliable calculations and data analyses:

- Velocity distribution of the dark matter particles in the halo

Usually assumed Boltzman, but deviations
from a pure Boltzmann distribution can occur

$$f(v)dv = 4\pi v^2 \left(\frac{m}{2\pi k_B T}\right)^{3/2} \exp\left(\frac{-mv^2}{2k_B T}\right) dv$$



ν-telescopes sensitive
to this part of the velocity
distribution
(low-energy particles easily
captured gravitationally)

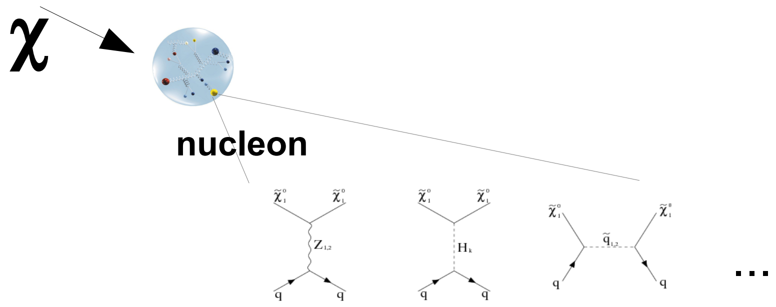
direct DM experiments
sensitive to this part of the
velocity distribution
(high-energy particles produce
stronger recoils in target)

Astrophysical inputs needed for reliable calculations and data analyses:

- Structure of the nucleon

Signals in indirect (gravitational capture) and direct (nuclear recoil) experiments depend on

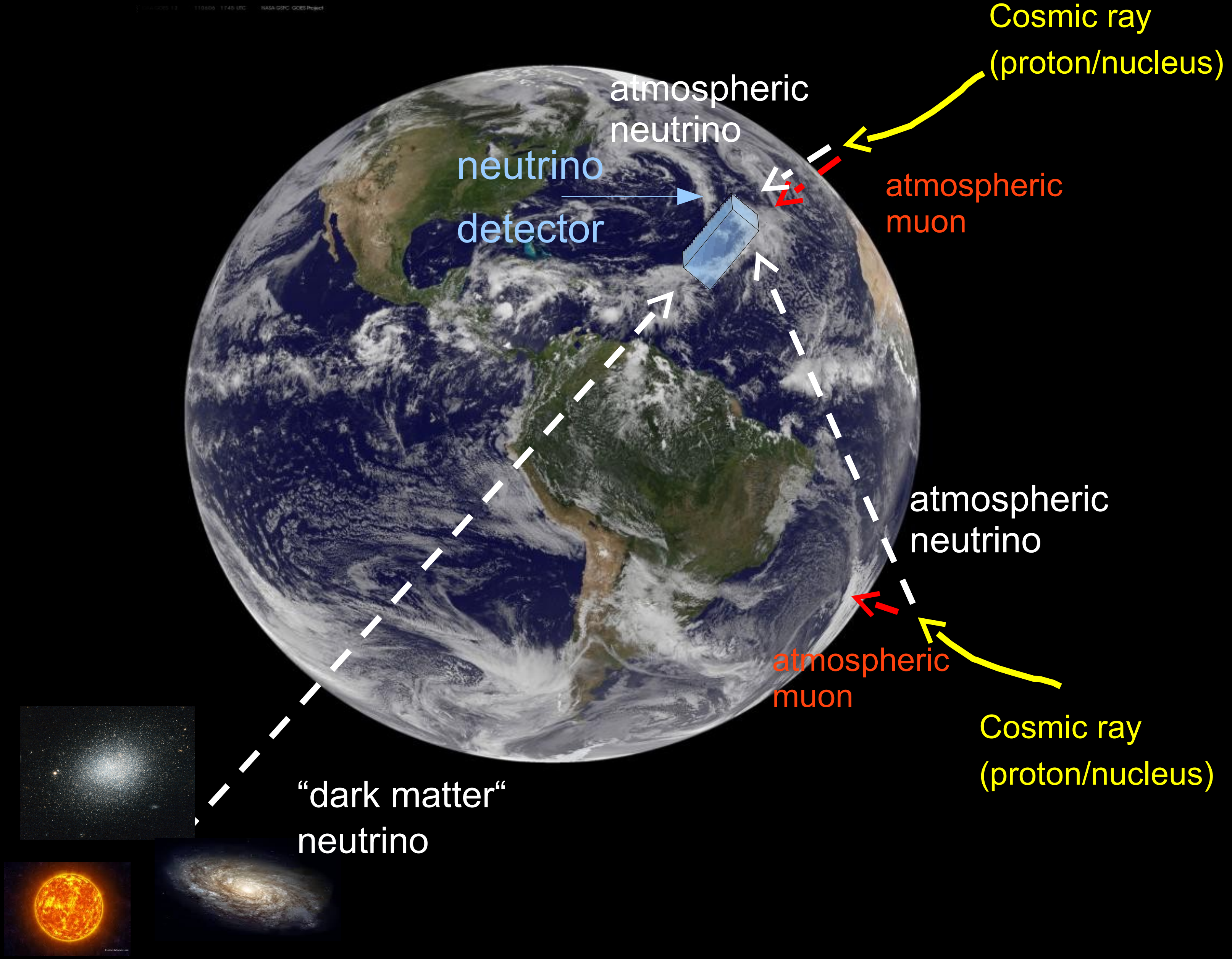
WIMP-nucleon cross section x nucleon distribution in the target nuclei



Structure of the nucleon plays an essential role in calculating observables

$$\left.\begin{aligned}\sigma_{SD}^{\chi N} &\propto \Sigma_{q=u,d,s}\langle N|\bar{q}\gamma_\mu\gamma_5 q|N\rangle \propto \Sigma_{q=u,d,s}\alpha_q^a \boxed{\Delta q^N} \\ \sigma_{SI}^{\chi N} &\propto \Sigma_{q=u,d,s}\langle N|m_q\bar{q}q|N\rangle \propto \Sigma_{q=u,d,s} m_N \alpha_q^s \boxed{f_{Tq}^N}\end{aligned}\right\}\text{need to be calculated in QCD or measured experimentally}$$

some terminology



Cosmic ray
(proton/nucleus)

atmospheric
neutrino

neutrino
detector

atmospheric
muon

atmospheric
neutrino

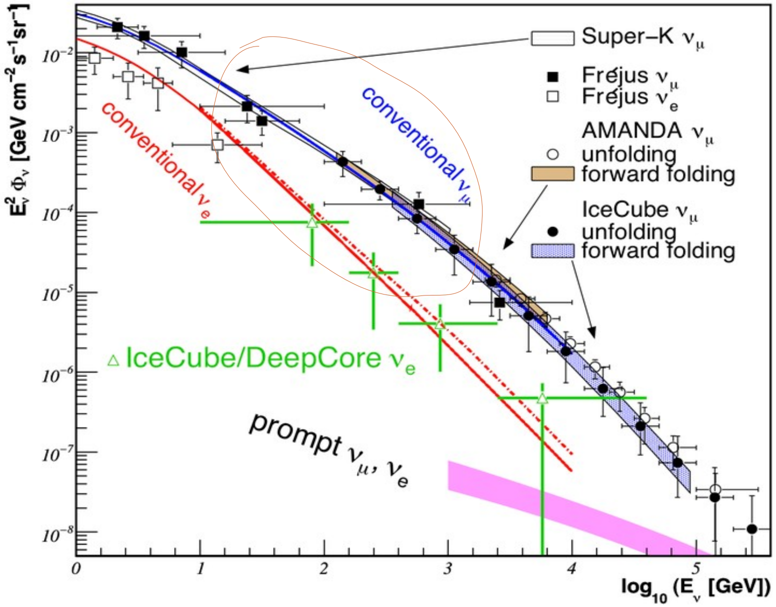
atmospheric
muon

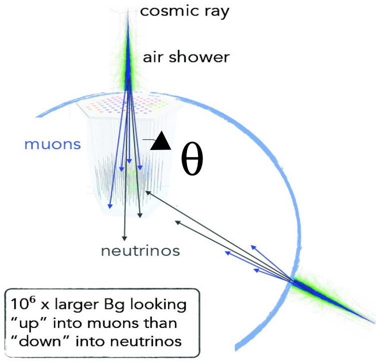
Cosmic ray
(proton/nucleus)

“dark matter“
neutrino

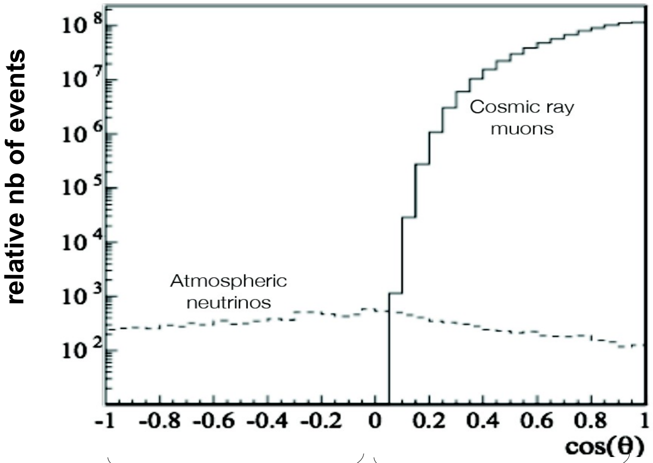
the background: the atmospheric neutrino flux

dark matter searches are low-energy searches in neutrino telescopes





10^6 x larger Bg looking "up" into muons than "down" into neutrinos



below the horizon
(upgoing tracks)

Earth has filtered all cosmic ray products except neutrinos

above the horizon
(downgoing tracks)

High energetic muons can penetrate km in water or ice

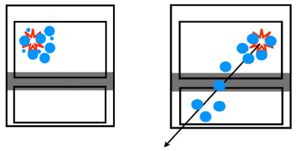
backgrounds in a km3 detector:

- atmospheric neutrinos: ~10^5 /year
- misreconstructed downgoing atmospheric muons: ~10^{11} /year

To identify ν's:

a) use Earth as a filter, ie, look for upgoing tracks, cos(θ)<0

b) define "starting tracks" in the detector. Use any angle



analysis strategies in neutrino telescopes

- Convert the observed neutrino flux into particle-physics related quantities:

WIMP-nucleon scattering cross section

WIMP self-annihilaton cross section

- Background taken from data when possible

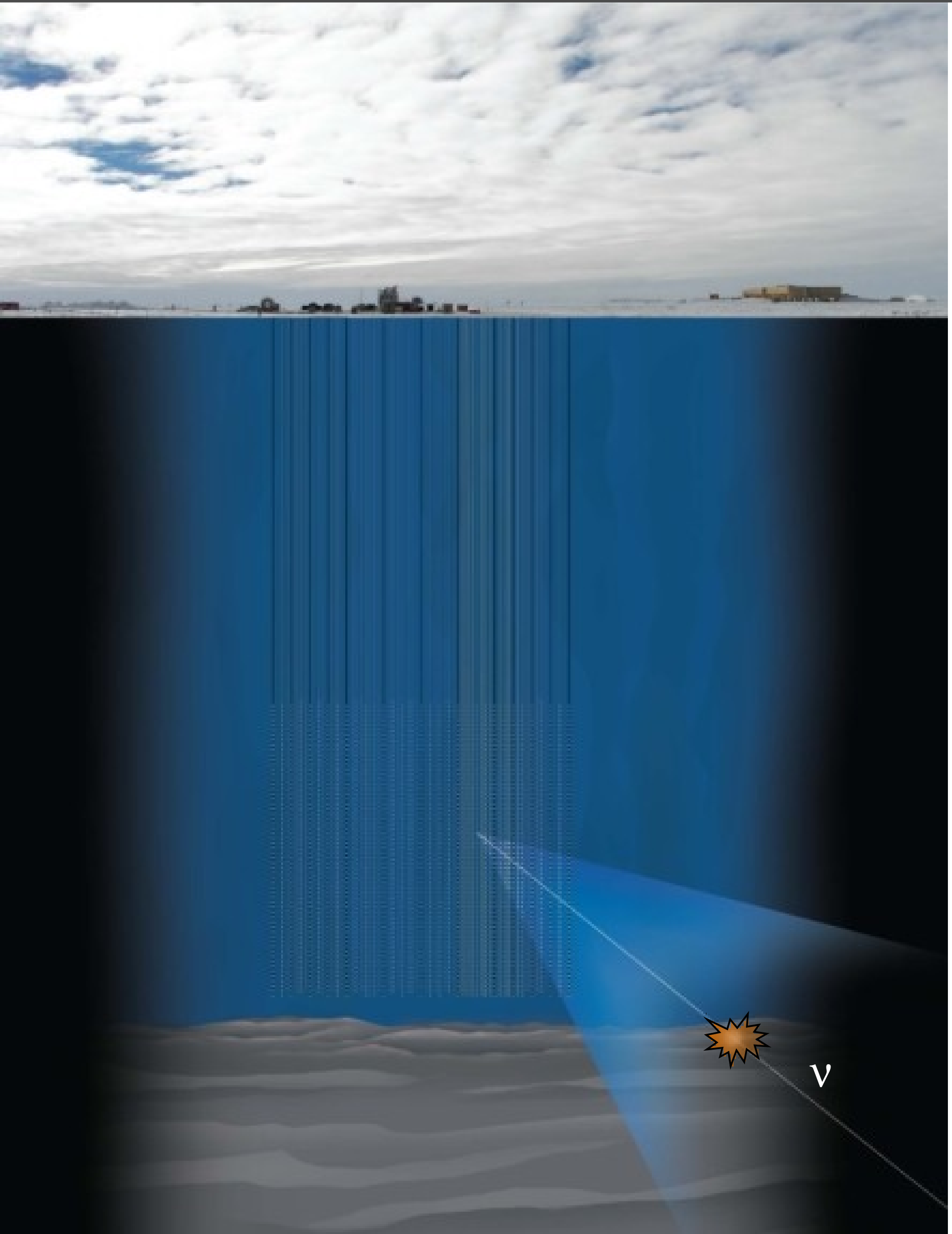
- Since WIMP mass and branching ratios are unknown, choose a few benchmark models, typically

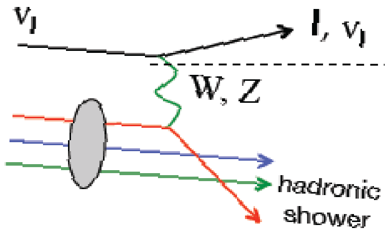
$\chi\chi \rightarrow \mathbf{W^+W^-}$ (or $\tau^+\tau^-$ for $M\chi$ below threshold), which gives a hard neutrino spectrum from the decays of the Ws

$\chi\chi \rightarrow \mathbf{b\bar{b}}$, which gives a softer neutrino spectrum

the projects

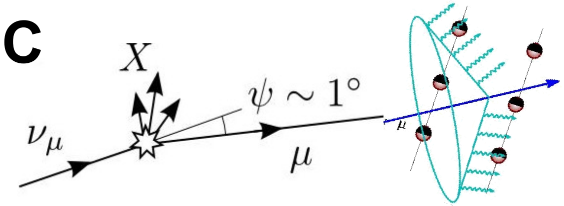
neutrino detection principle



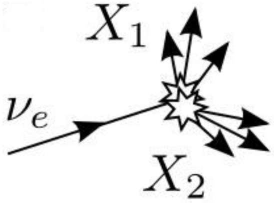


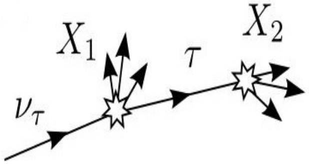
Detect Cherenkov light of interaction products

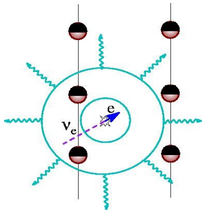
CC



μ tracks >100m @ E>100 GeV



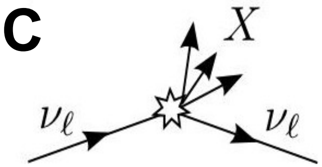




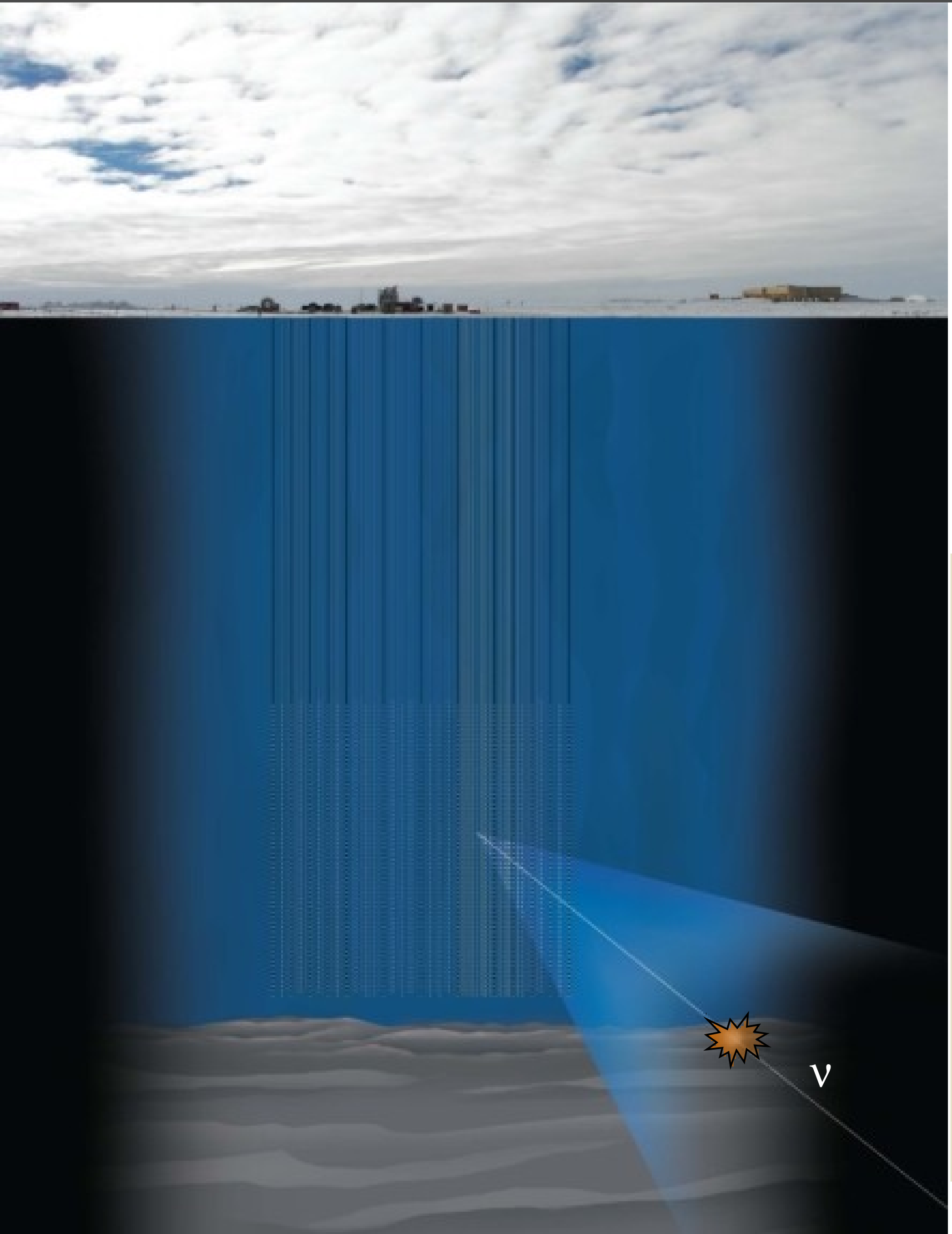
e^{+-} :electromagnetic shower

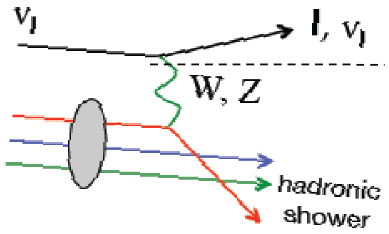
τ^{+-} : hadronic shower

NC



neutrino detection principle





Detect Cherenkov light of interaction products

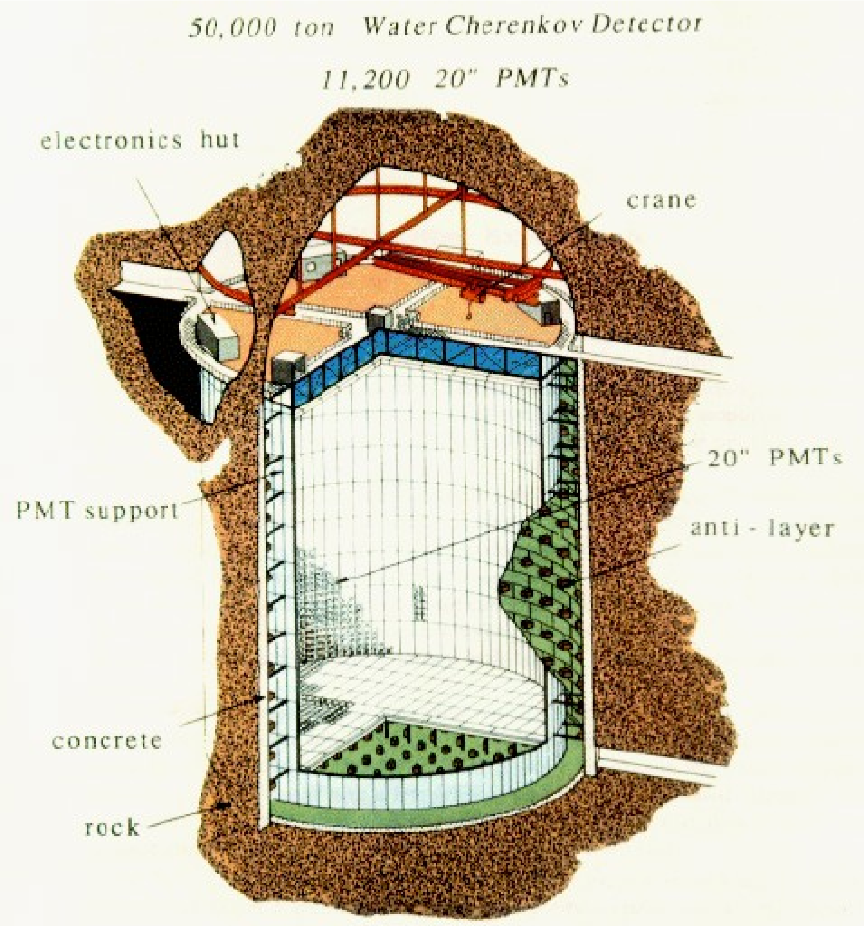
Array of optical modules in a transparent medium to detect the light emitted by relativistic secondaries produced in charged-current ν-nucleon interactions

Need ns timing resolution

Need HUGE volumes (tiny Xsects & fluxes)

the projects

the Super-Kamiokande neutrino detector



in operation since 1996

1 Km deep in Mozumi mine, japan

11,146 20' optical modules in outer detector

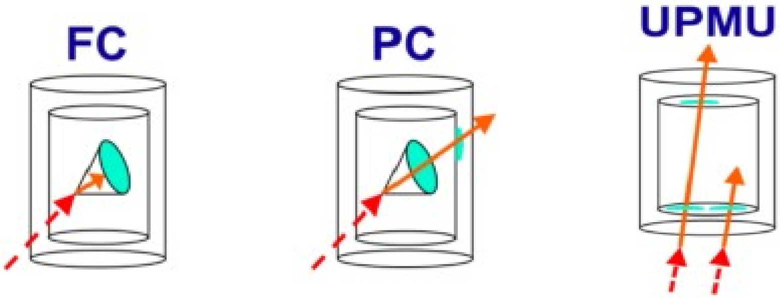
1,800 8' optical mudules in inner detector

41 m height x 39 m diameter

50,000 tons pure water

energy threshold ~5 MeV

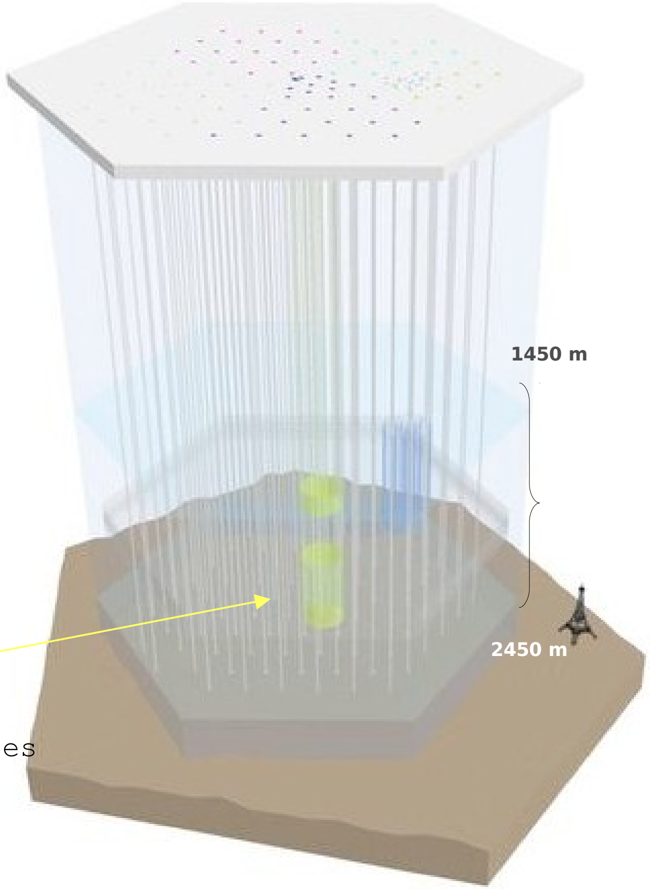
compact detector →



the IceCube neutrino telescope

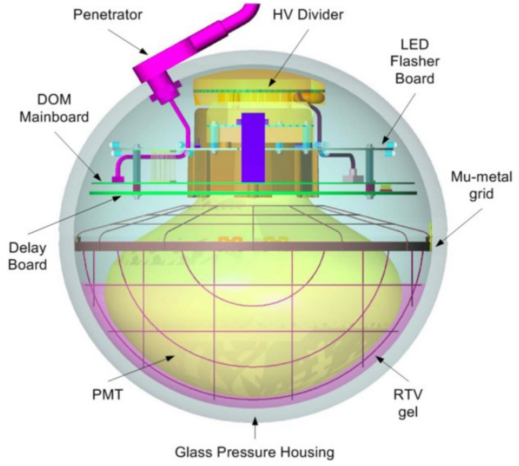
- Detector completed on December 2010
- Full operation with 86 strings starts in May 2011

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



InIce array:
80 Strings
60 Optical Modules
17 m between Module
125 m between Stri
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



- **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

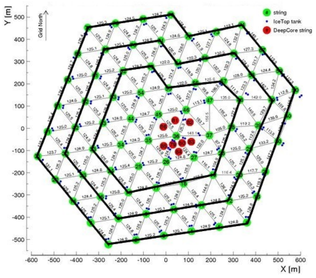
the IceCube neutrino telescope

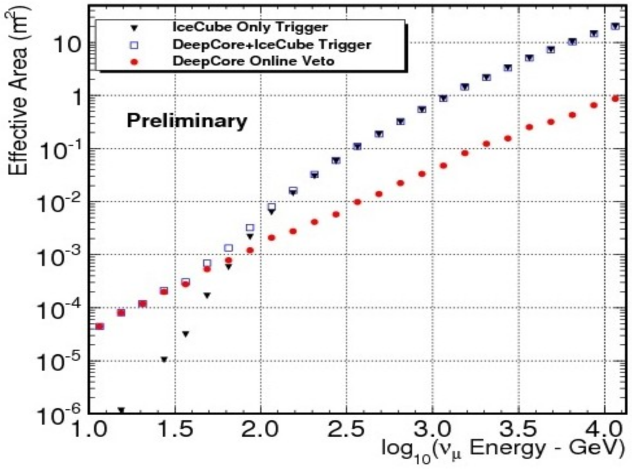
- Detector completed on December 2010
- Full operation with 86 strings starts in May 2011
- Full detector → Veto techniques possible.

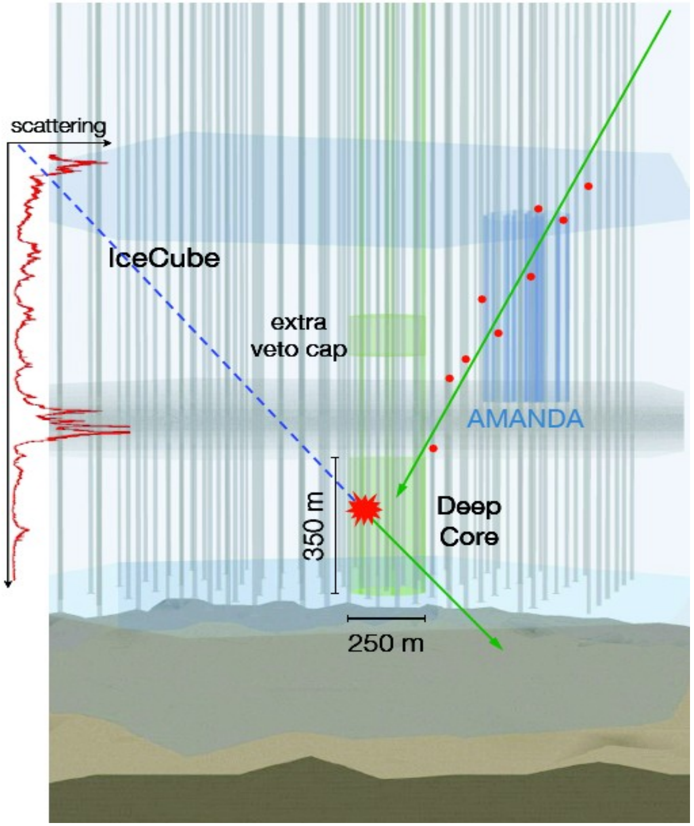
```
can use IceCube outer string
layers to define starting and
througoing tracks
```

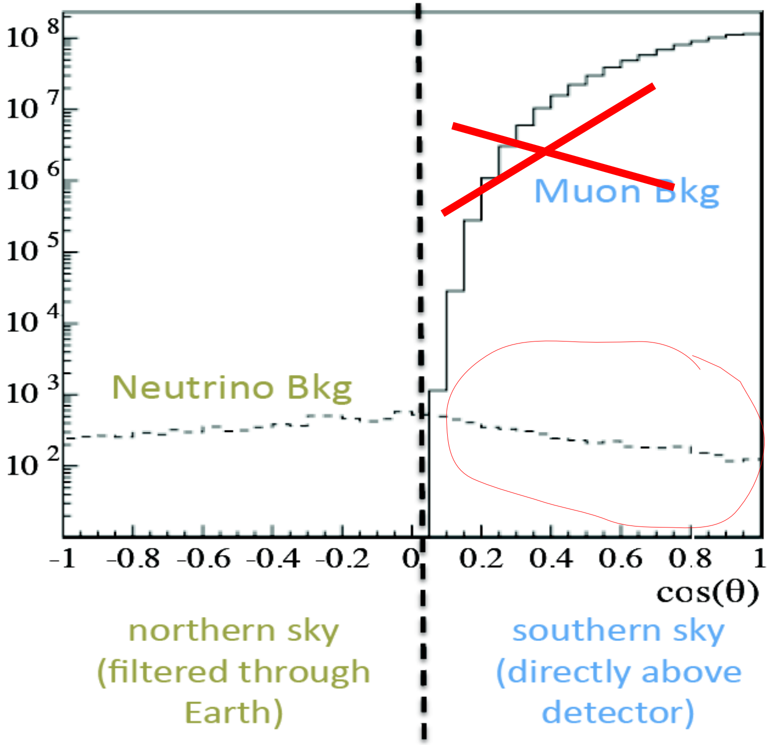
IceCube becomes a 4π detector with access

to the Galactic Center and whole southern sky

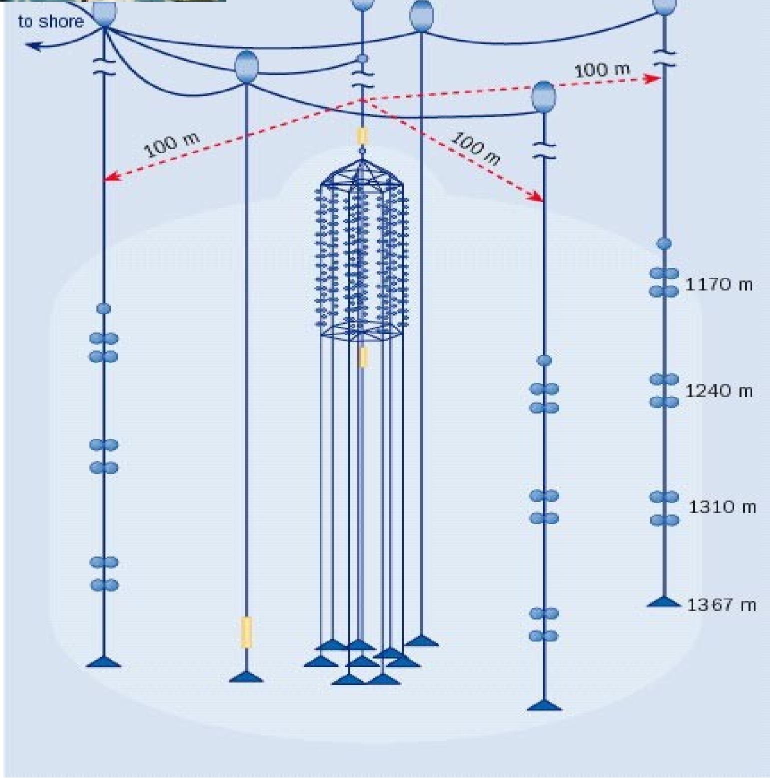








the Baikal neutrino telescope



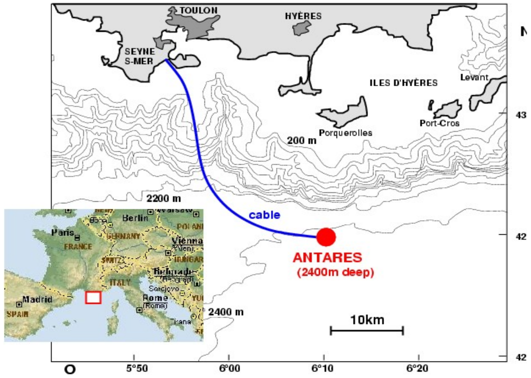
NT-200

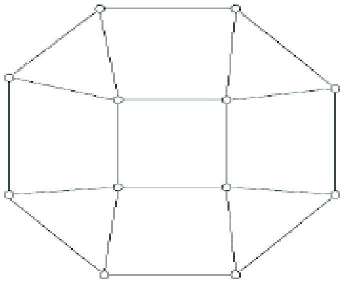
- 8 strings with 192 optical modules
- 72 m height, 1070 m depth
- μ effective area >2000 m² (E_μ>1 TeV)
- Running since 1998

NT-200+

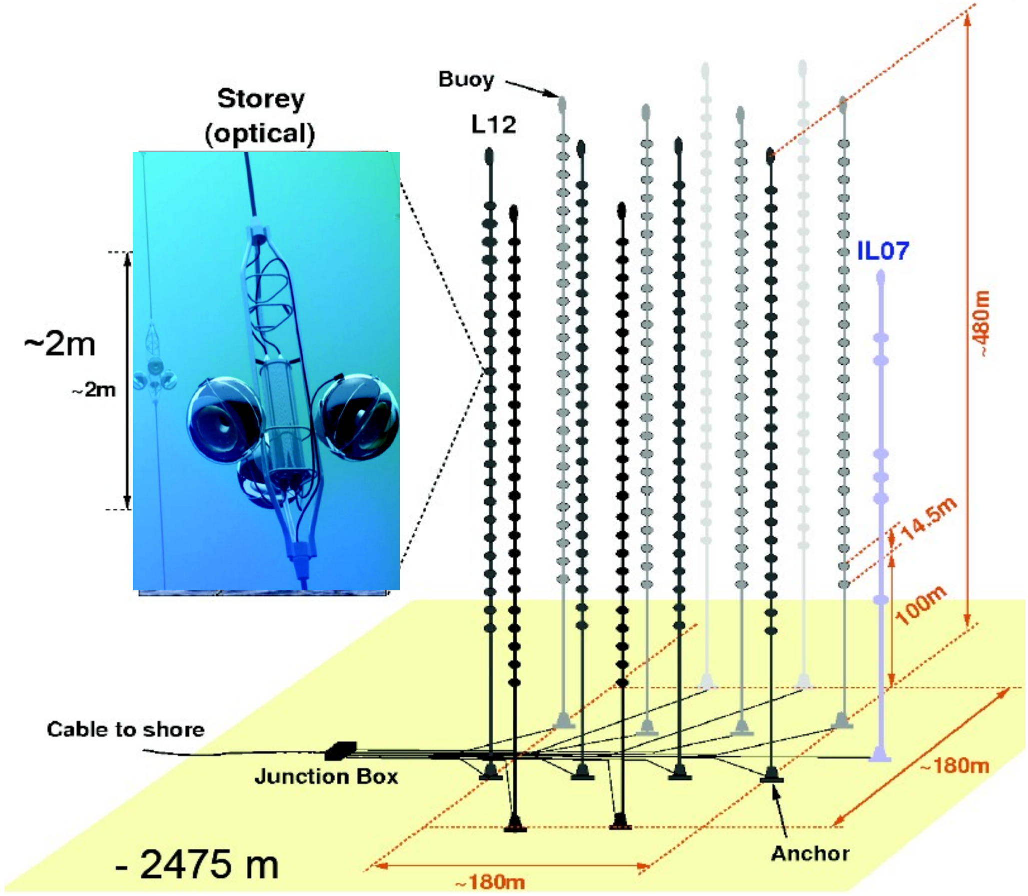
- **commisioned April 9, 2005.**
- 3 new strings, 200 m height
- 1 new bright Laser for time calibration
- new DAQ
- 2 new 4km cables to shore

the ANTARES neutrino telescope





Horizontal layout



2.5 Km deep in the Mediterranean

12 lines, 885 Optical modules

25 ‘storeys’ with 3 OMs each

350 m long strings (active height)

~70 m inter-string separation

14.5 m vertical storey separation

0.04 km^3 instrumented volume

effective area ~ 1m^2@ 30 TeV

median angular resolution ~0.4^o

the KM3NET neutrino telescope

Optical module
31 x 3'' PMTs

prototype on ANTARES line

2.5-3.5 Km deep in the
Mediterranean

distributed sites (Fr, It, Gr)

600 m long strings

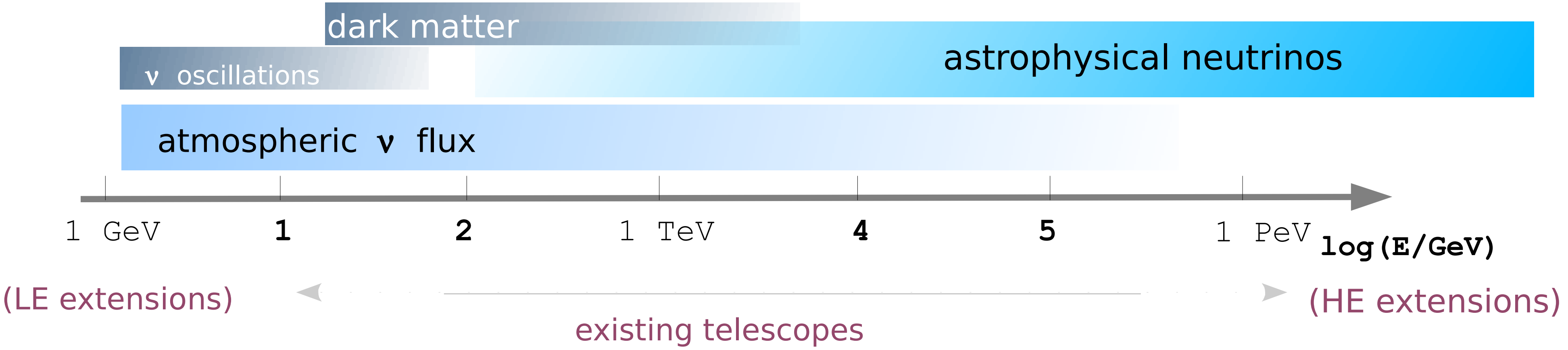
multi-PMT optiocal modules

(O) km^3 instrumented volume

confirm IceCube discovery +
neutrino astronomy

first line deployed on May 7, 2014
@ the italian site, off the coast of
Sicily

neutrino telescopes: multipurpose....



dark matter

ν oscillations

astrophysical neutrinos

atmospheric ν flux

(LE extensions)

existing telescopes

(HE extensions)

...multi-flavour detectors

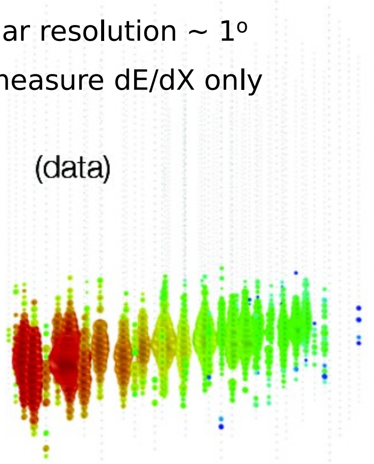
neutrino event signatures:

tracks:

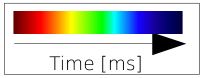
ν_μ CC

angular resolution ~ 1°

can measure dE/dX only



(data)



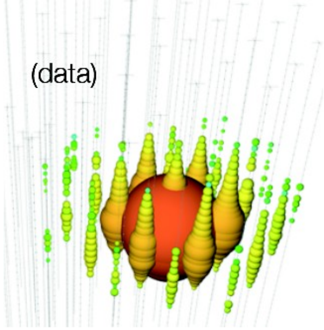
cascades:

ν_e, ν_τ CC

all flavours NC

angular resolution ≥ 10°

energy resolution ~ 15%

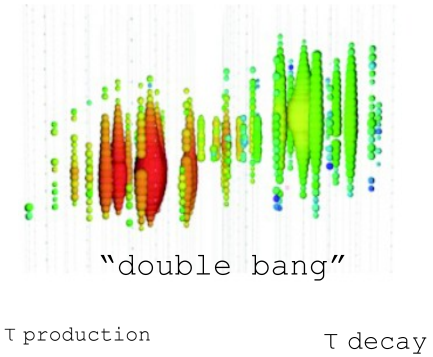


(data)

tau neutrino, CC

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

(simulation)



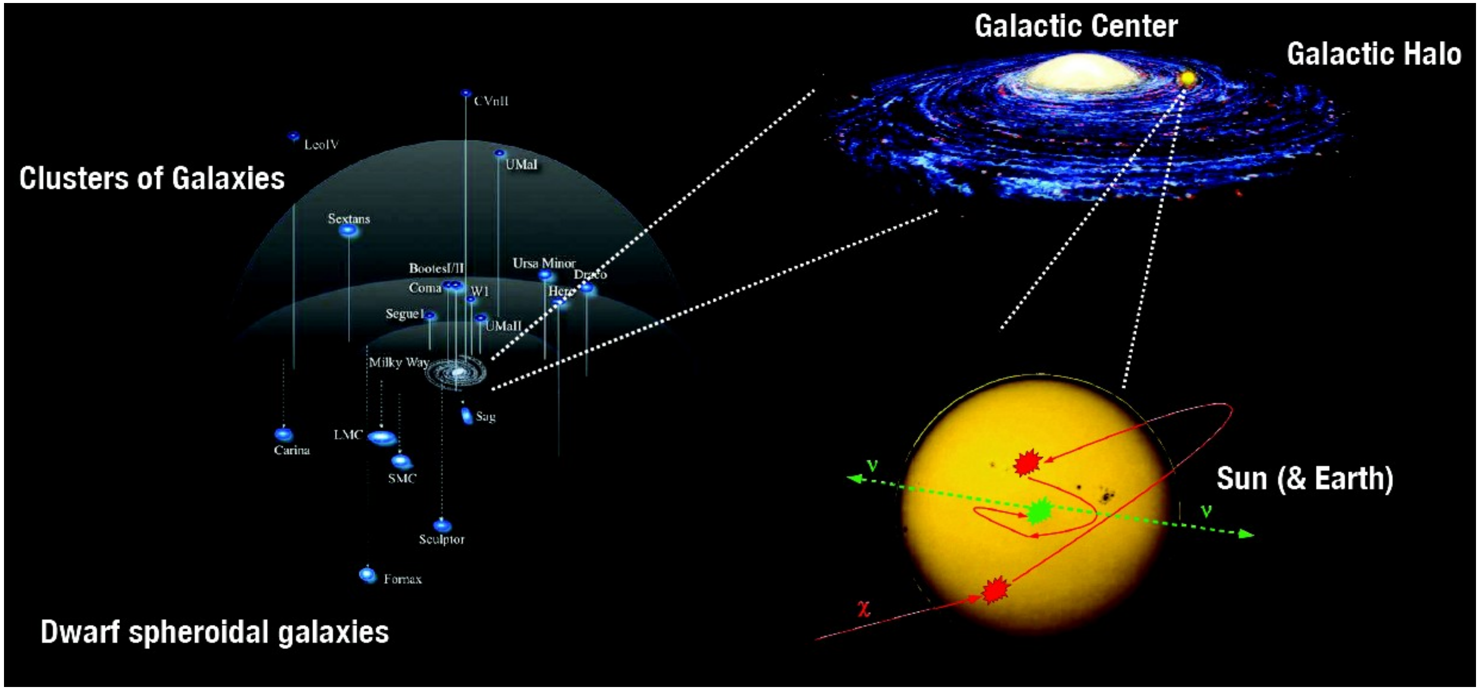
"double bang"

dark matter searches with neutrino telescopes

dark matter searches with neutrino telescopes

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

signature: an excess of ν over the atmospheric neutrino background



note: astrophysical & hadronic uncertainties

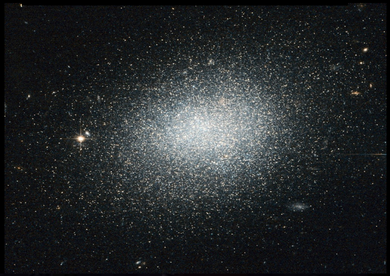
dark matter searches with neutrino telescopes

Sun

Earth

probes $\sigma^{SD}_{\chi-N}$, $\sigma^{SI}_{\chi-N}$

- complementary to direct detection
- different systematic uncertainties
  - hadronic (not nuclear)
  - local density
  - can benefit from co-rotating disk



dwarves & distant halos

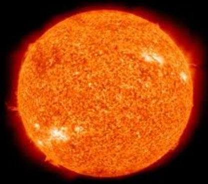
Milky Way Halo

Milky Way Center

probes $\langle\sigma_A v\rangle$

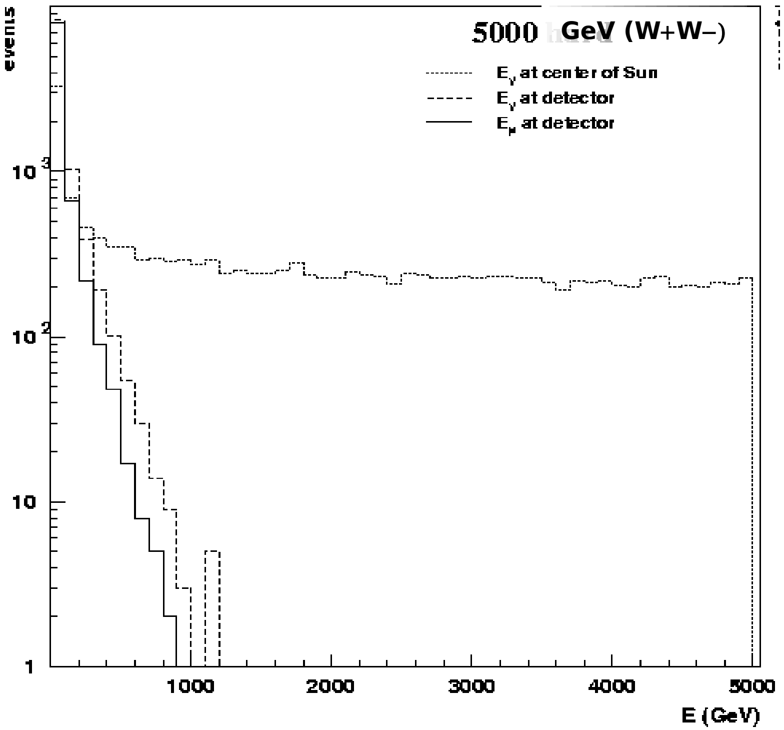
- complementary to searches with other messangers (γ, CRs...)
- shared astrophysical systematic uncertainties (halo profiles...)
- more background-free

dark matter searches from the Sun

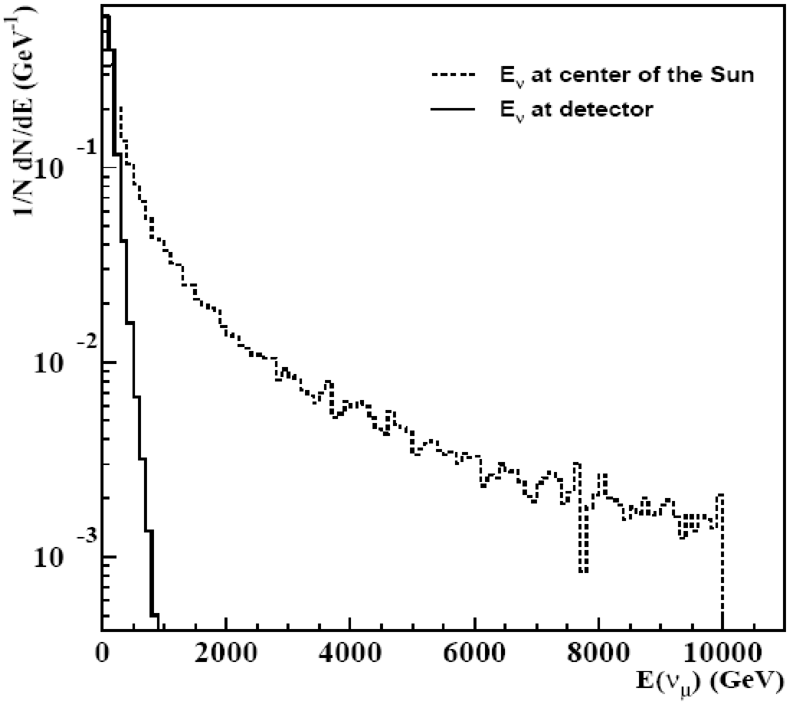


dark matter searches from the Sun

5000 GeV Neutralino → WW @ Sun



Simpzilla → $t\bar{t}$ @ Sun

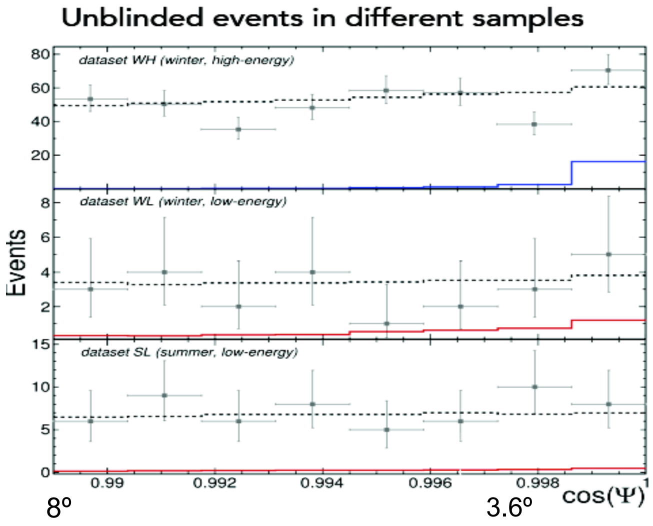


Indirect dark matter searches from the **Sun** are typically a low-energy analysis in neutrino telescopes: even for the highest dark matter candidate masses, we do not get muons above few 100 GeV

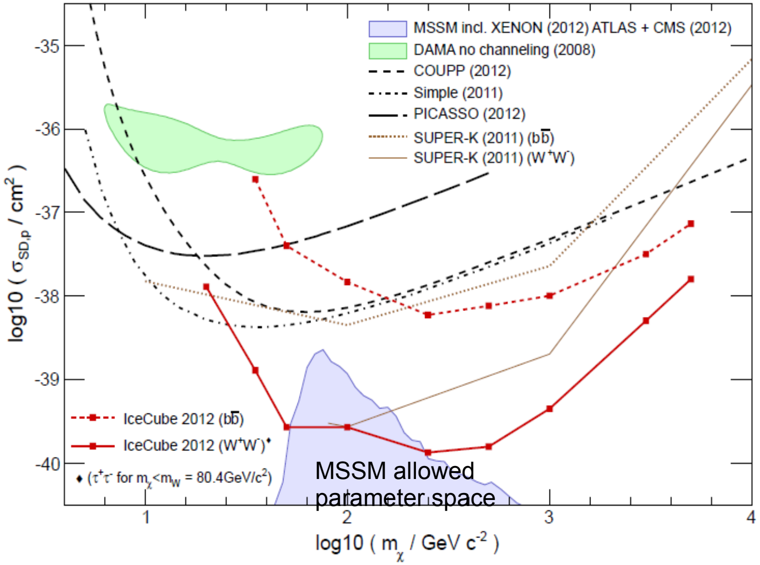
Not such effect for the Earth and Halo

solar search results

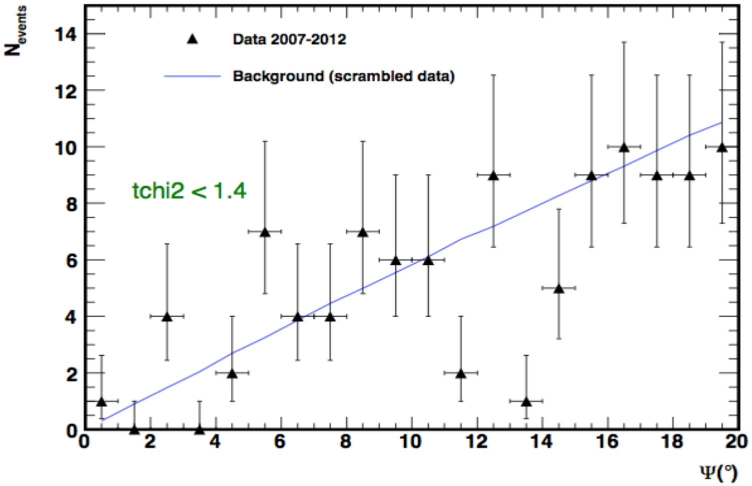
IceCube results from 317 days of livetime between 2010-2011:

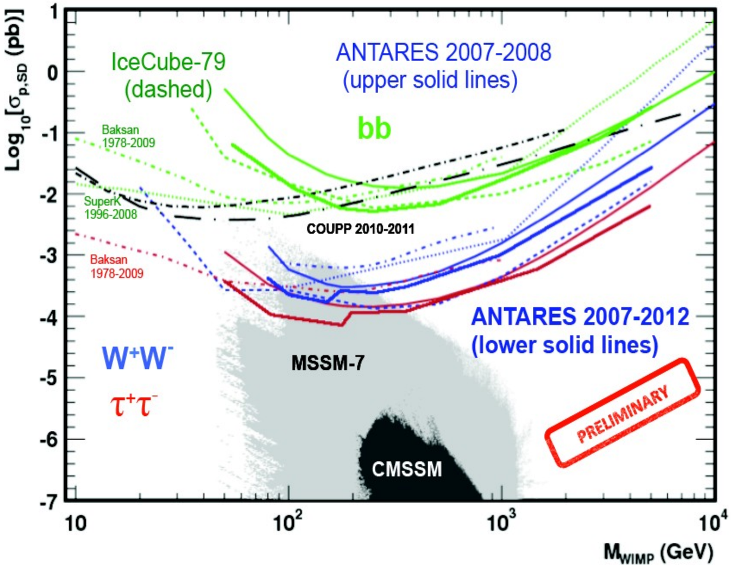


$\Phi_\mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{X+p}$



ANTARES results from 1321 days of livetime between 2007-2012:



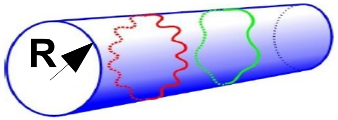


solar search results: Kaluza-Klein and superheavy dark matter

Universal Extra Dimensions:

models originally devised to unify gravity and electromagnetism.

No experimental evidence against a space 3+δ+1 as long as the extra dimensions are ‘compactified’



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

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

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

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

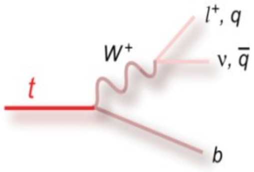
Superheavy dark matter:

- 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)

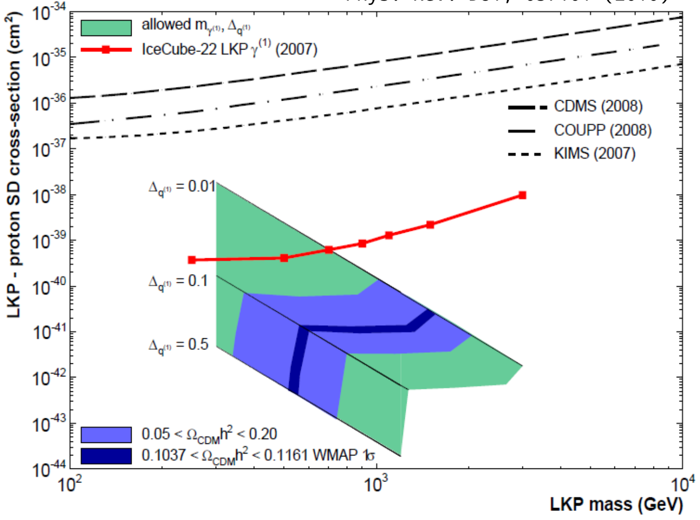
- m from ~10^4 GeV to 10^{18} GeV (no unitarity limit since production non thermal)

S+S → t $\bar{t}$ dominant



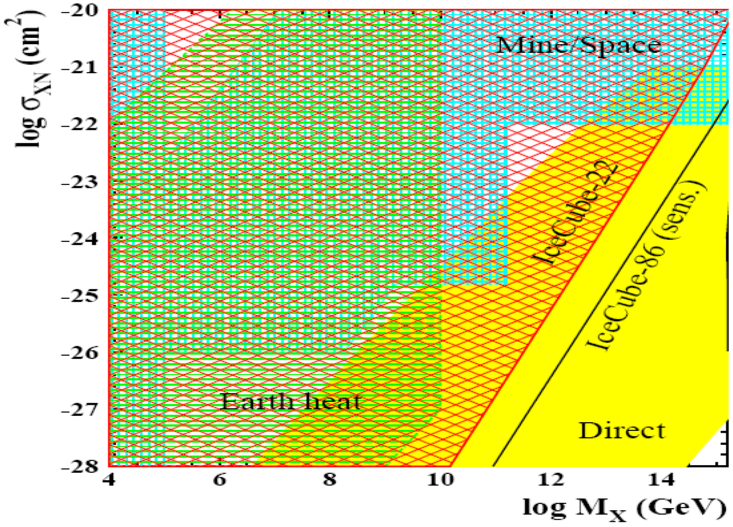
90% CL LKP-p Xsection limit vs LKP mass

Phys. Rev. D81, 057101 (2010)



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

Phys. Rev. D81, 063510 (2010)



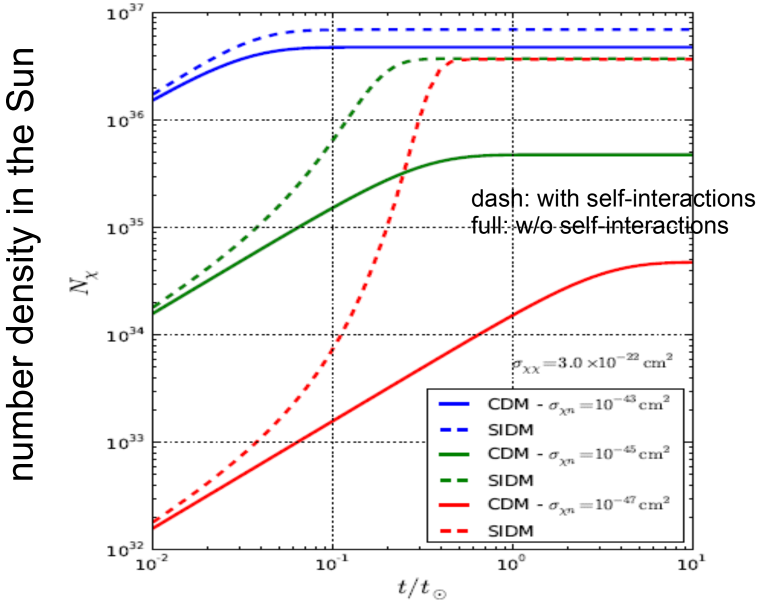
solar search results: self-interacting dark matter

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)



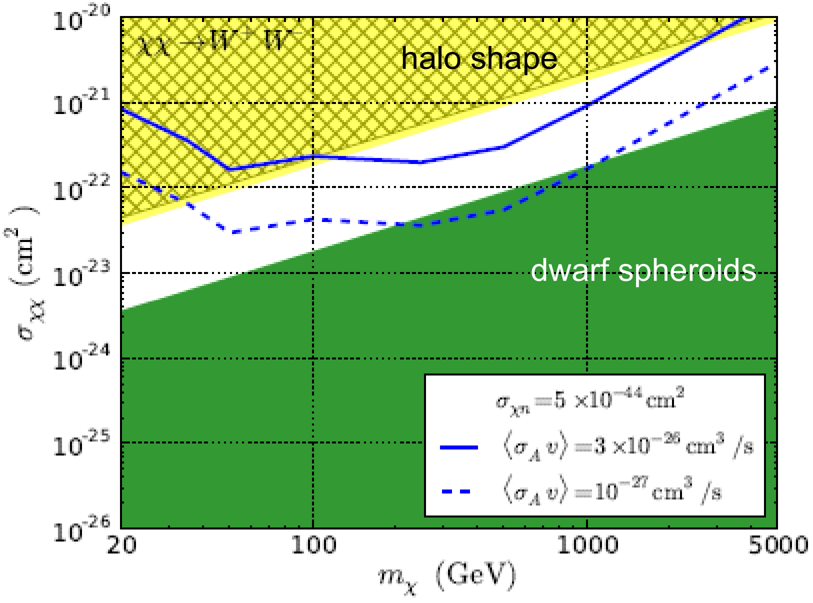
→ maximum annihilation rate reached earlier than in collisionless models

$\sigma_{\chi\chi}$ 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

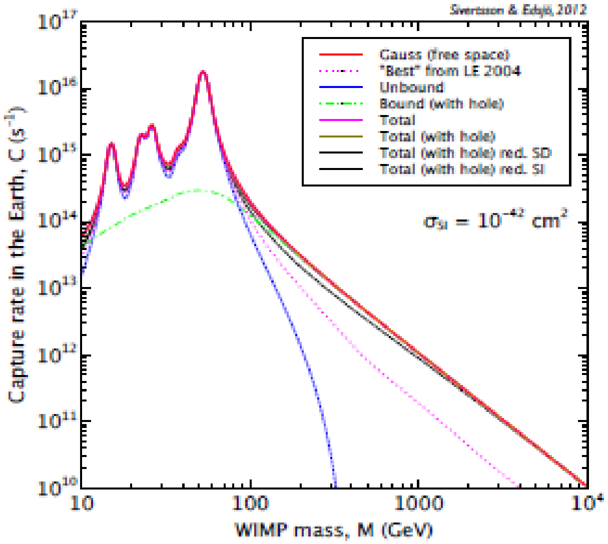
Albuquerque, de los Heros, Robertson, JCAP02(2014)047



dark matter searches from the Earth

Earth search results

Earth capture rate dominated by resonance with heavy inner elements



capture mostly depends on σ^{SI}

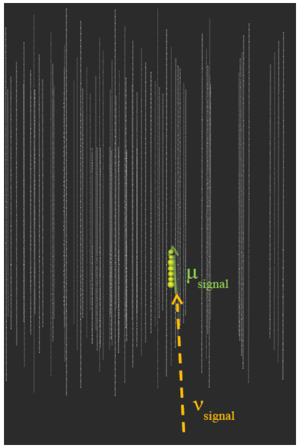
resonances increase sensitivity to low-mass WIMPs, ~50 GeV

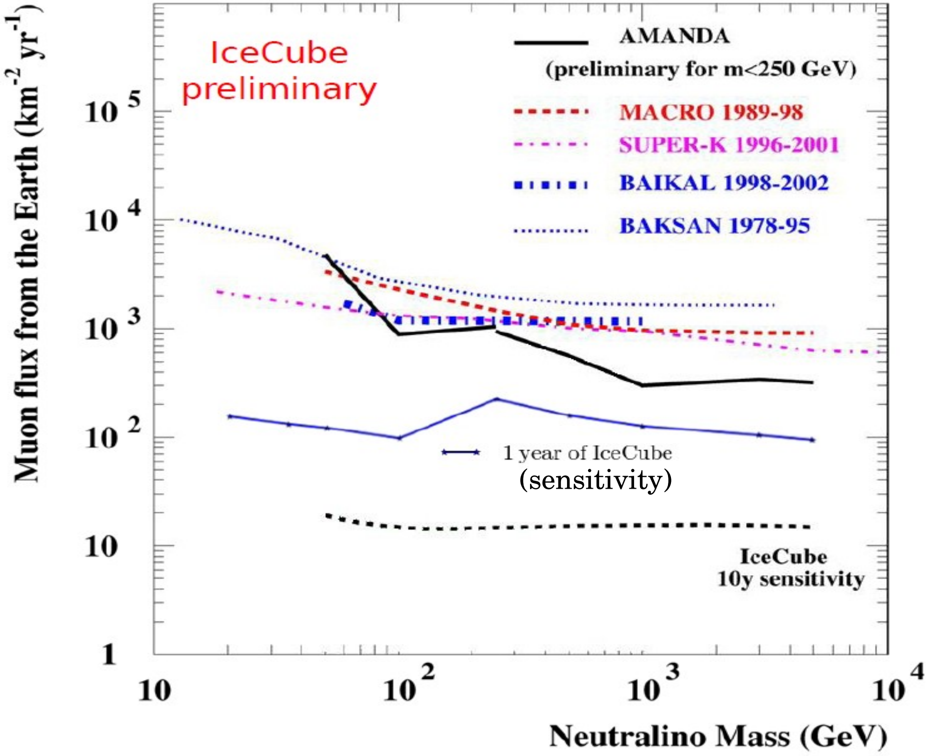
ongoing analysis with IceCube

older results with smaller AMANDA detector
(Astropart. Phys. 26, 129 (2006))

focus on vertically upgoing events.

No off-source region at dame declination: analysis based on MC and extrapolation methods





Earth search results

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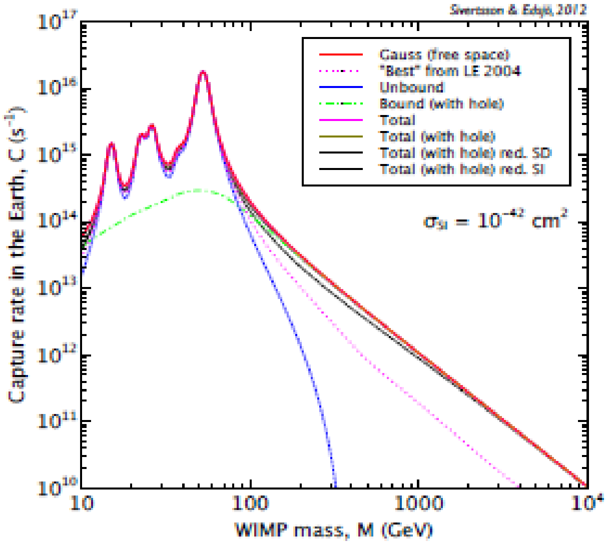

capture mostly depends on σ^{SI}

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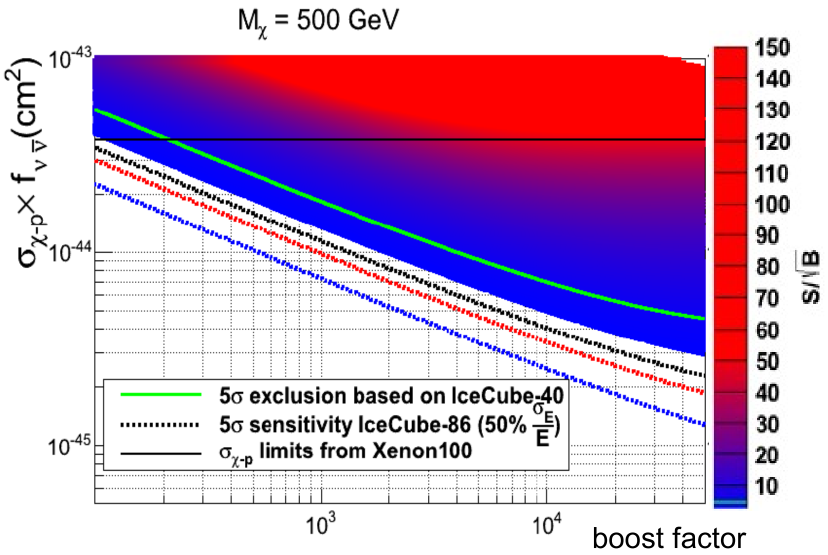
ongoing analysis with IceCube

older results with smaller AMANDA detector (Astropart. Phys. 26, 129 (2006))

→ however, $\sigma_{\chi-n}^{SI} \sim 10^{-42}$ cm^2, 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 (boosted) 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)

dark matter searches from the Galaxy/other galaxies

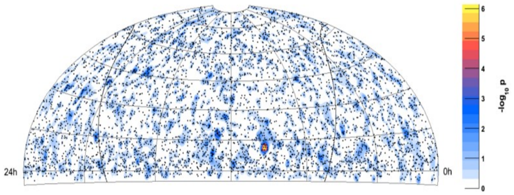
dark matter searches from the Galactic center/halo

probe DM annihilation cross section

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{A}} v\rangle}{2m_\chi^2}\Sigma_f \frac{dN}{dE}B_f \quad \mathbf{x} \quad \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\mathrm{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$

Ingredients:

measurement



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Ingredients:

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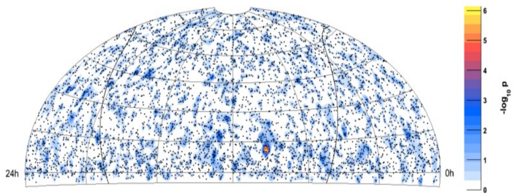
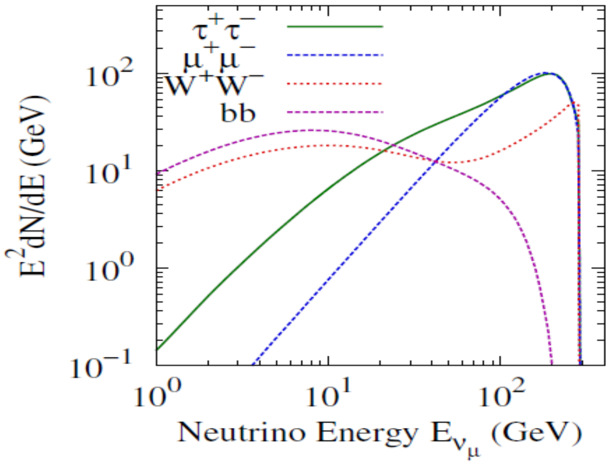


particle physics model



dark matter searches from the Galactic center/halo

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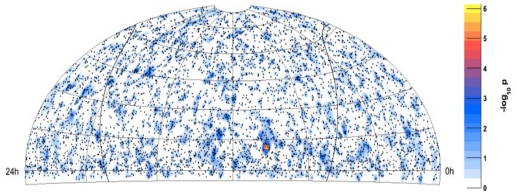
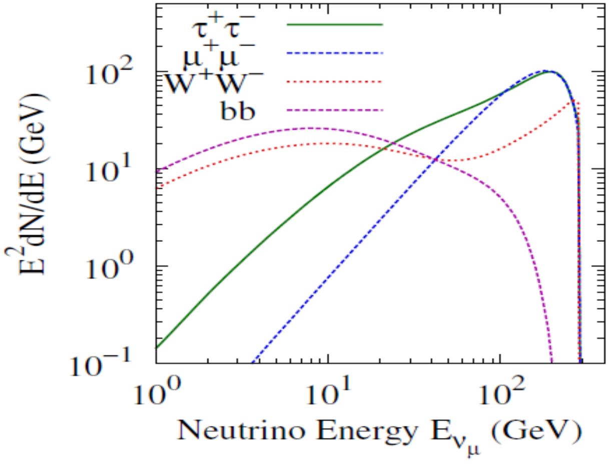
$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f\frac{dN}{dE}B_f \; \mathrm{x} \; \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\mathrm{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$

Ingredients:

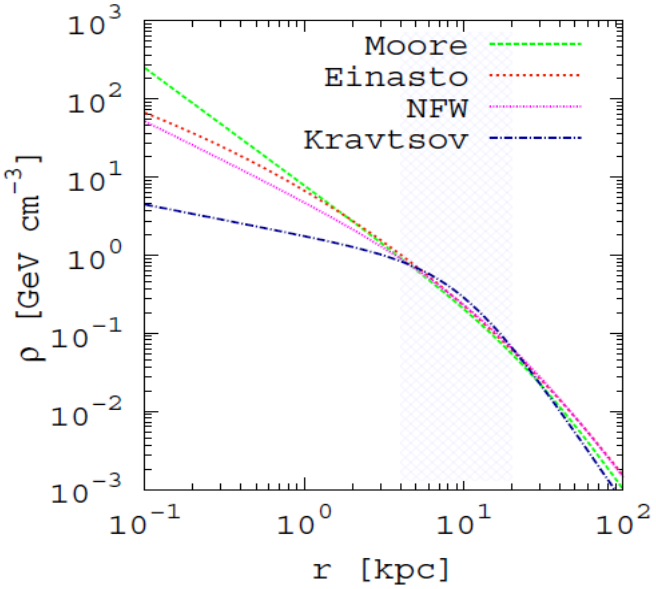
measurement



particle physics model



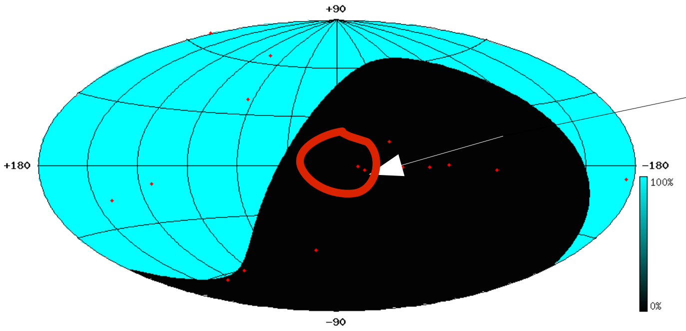
halo model



dark matter searches from the Galactic center

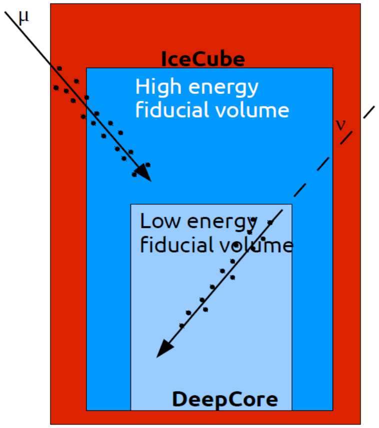
At the South Pole the GC is above the horizon. No possibility of using the Earth as a filter.

→ Analysis must rely on veto methods to reject incoming atmospheric muons

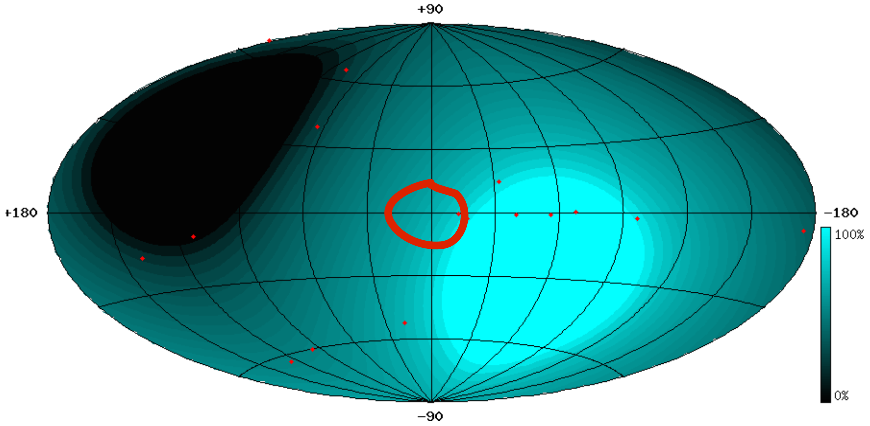


accessible by
defining starting tracks.

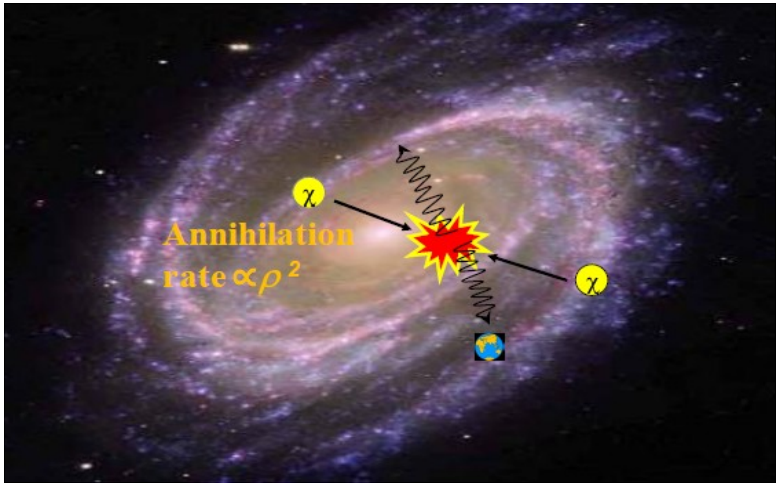
different energy reach
than with full fiducial volume



At the ANTARES site the GC is below the horizon ~60% of the time. The Earth can be used as a filter



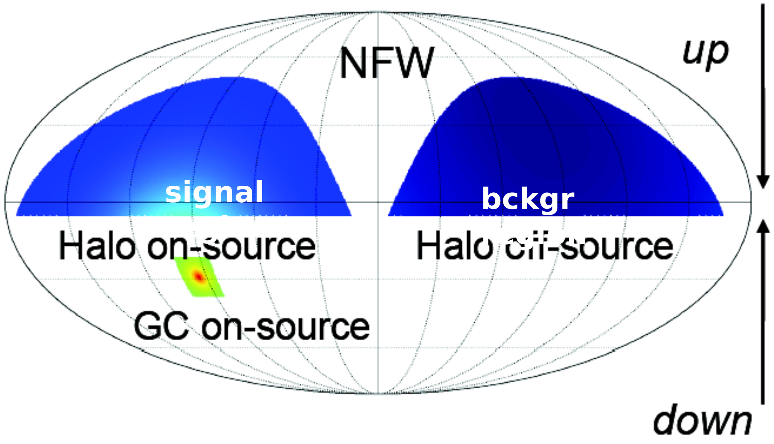
dark matter searches from the Galactic halo

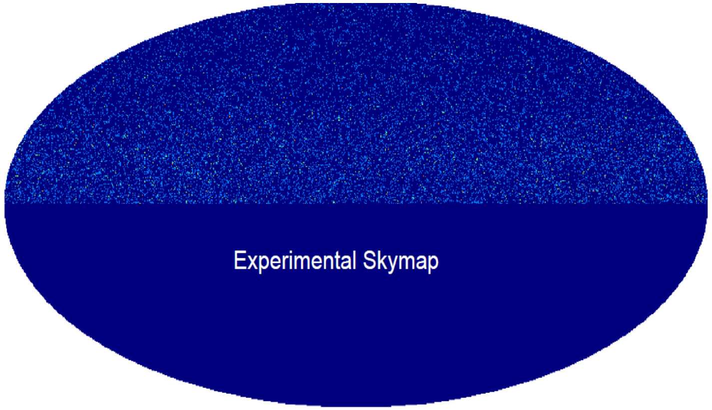


- Look for an excess of events in the on-source region w.r.t. the off-source

or,

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



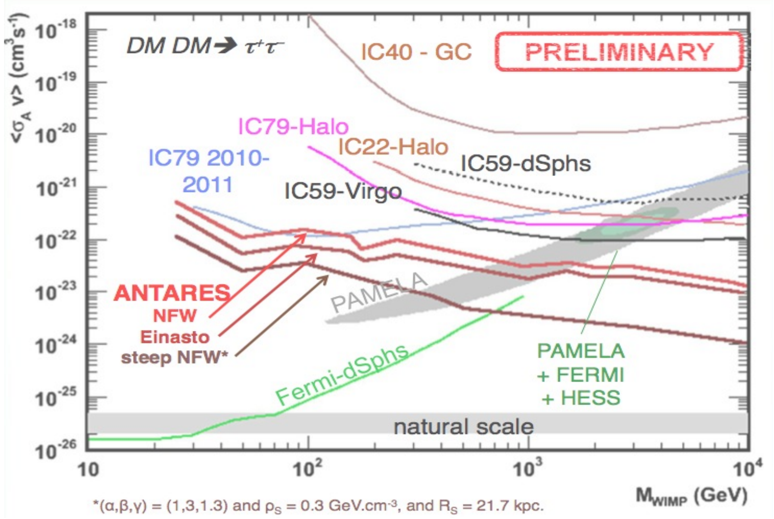


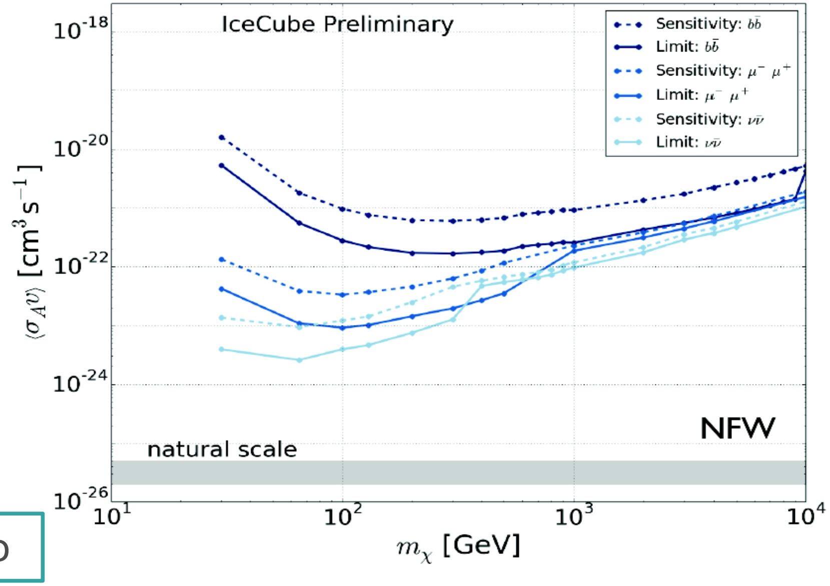
dark matter searches from the Galaxy: results

ANTARES Galactic Center ττ channel

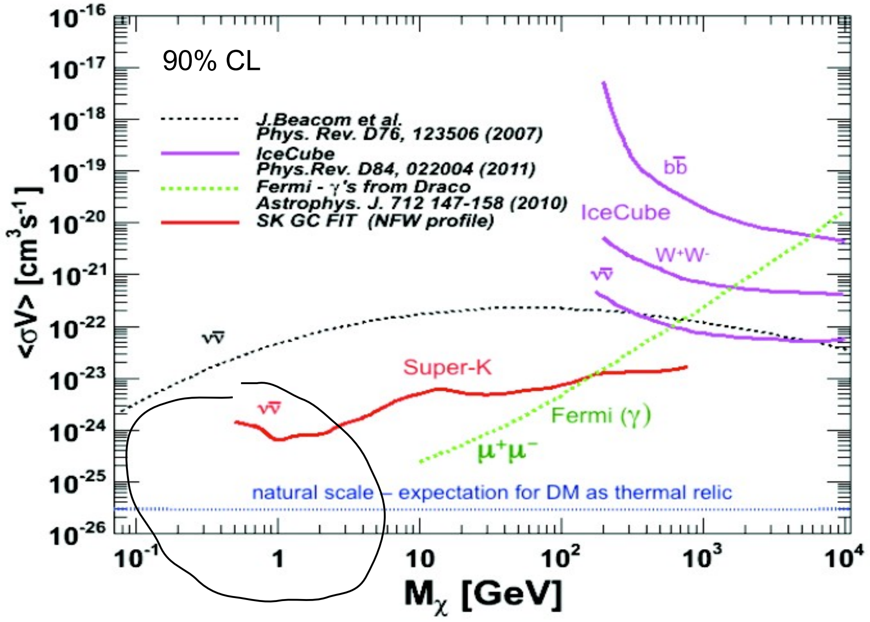
all measure <σv>:

IceCube Galactic Center



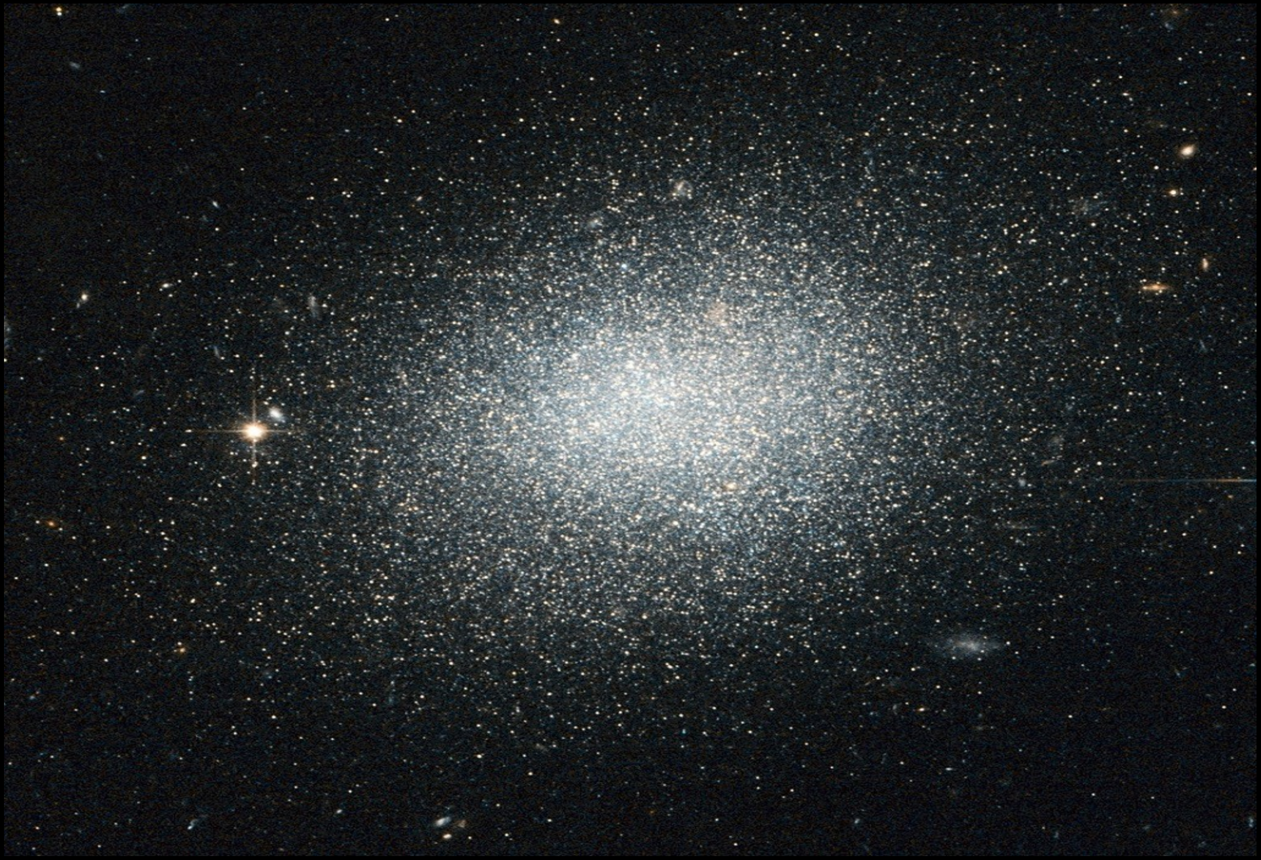


Super-K Galactic Halo



note the access to the very low mass region

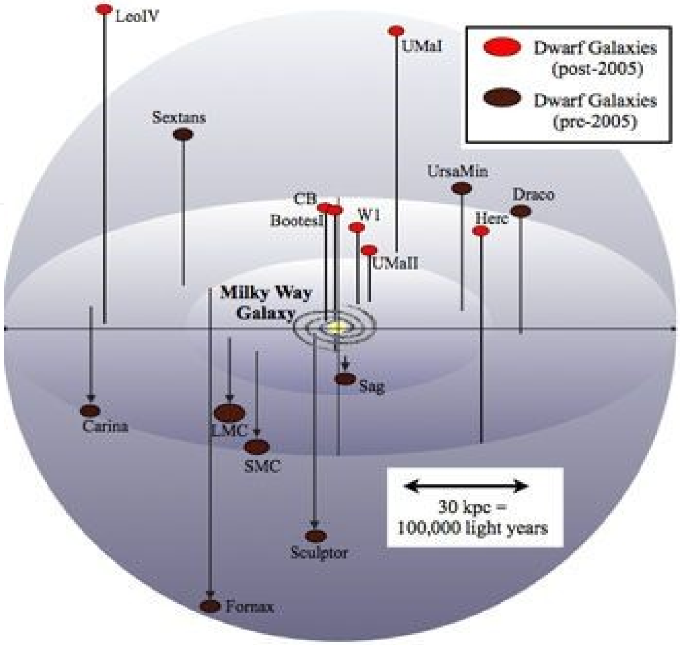
dark matter searches from dwarf galaxies/galaxy clusters



dark matter searches from the dwarf galaxies/galaxy clusters

- Dwarf galaxies: high mass/light ratio
- → high concentration of dark matter 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

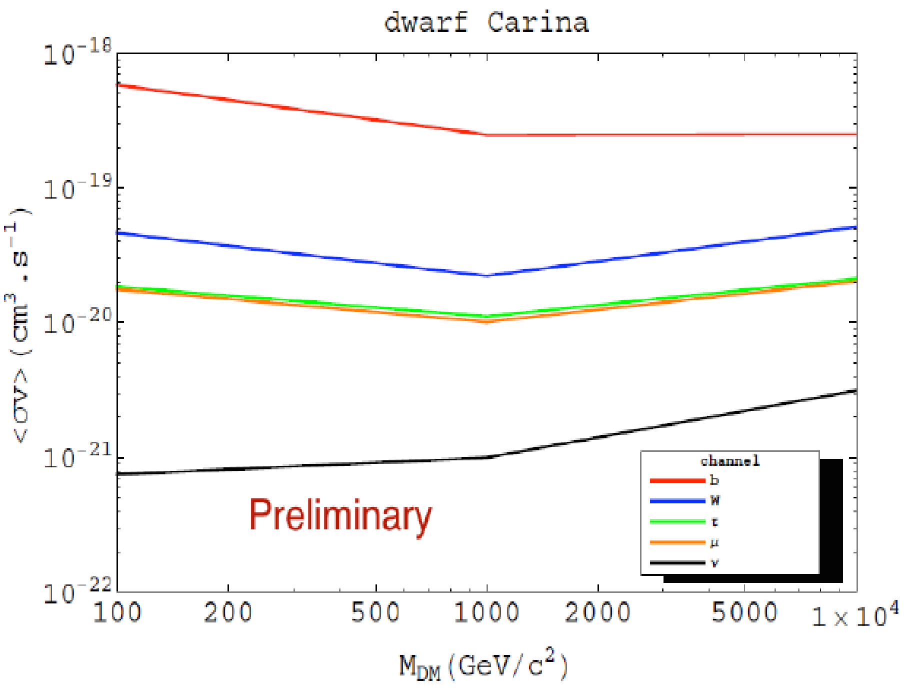
  But: extended sources with possible substructure
- Same expected neutrino spectra as for the galactic center/halo



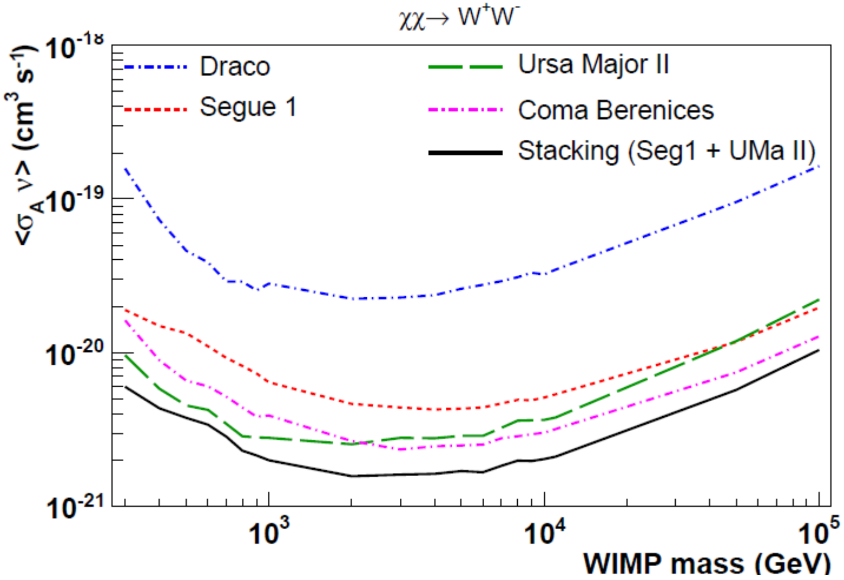
dark matter searches from galaxies: results

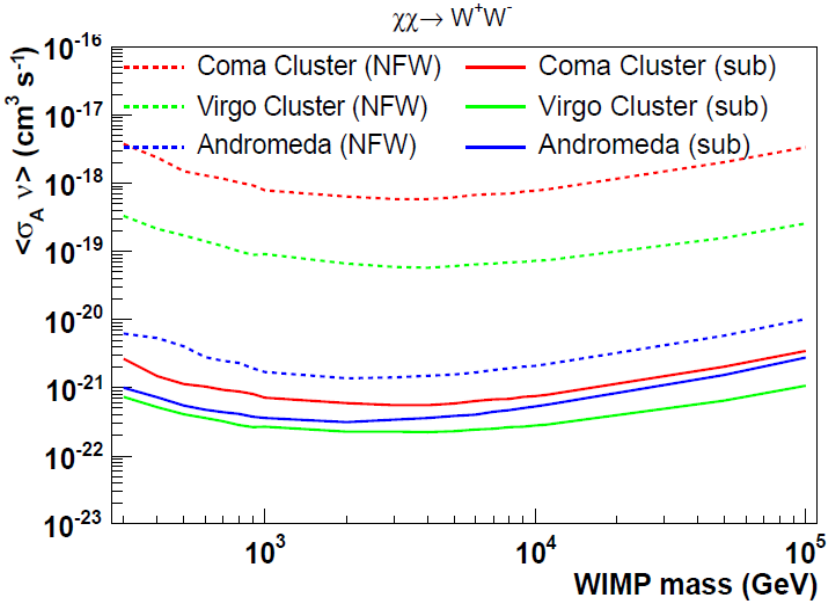
all measure <σv>:

ANTARES work in progress

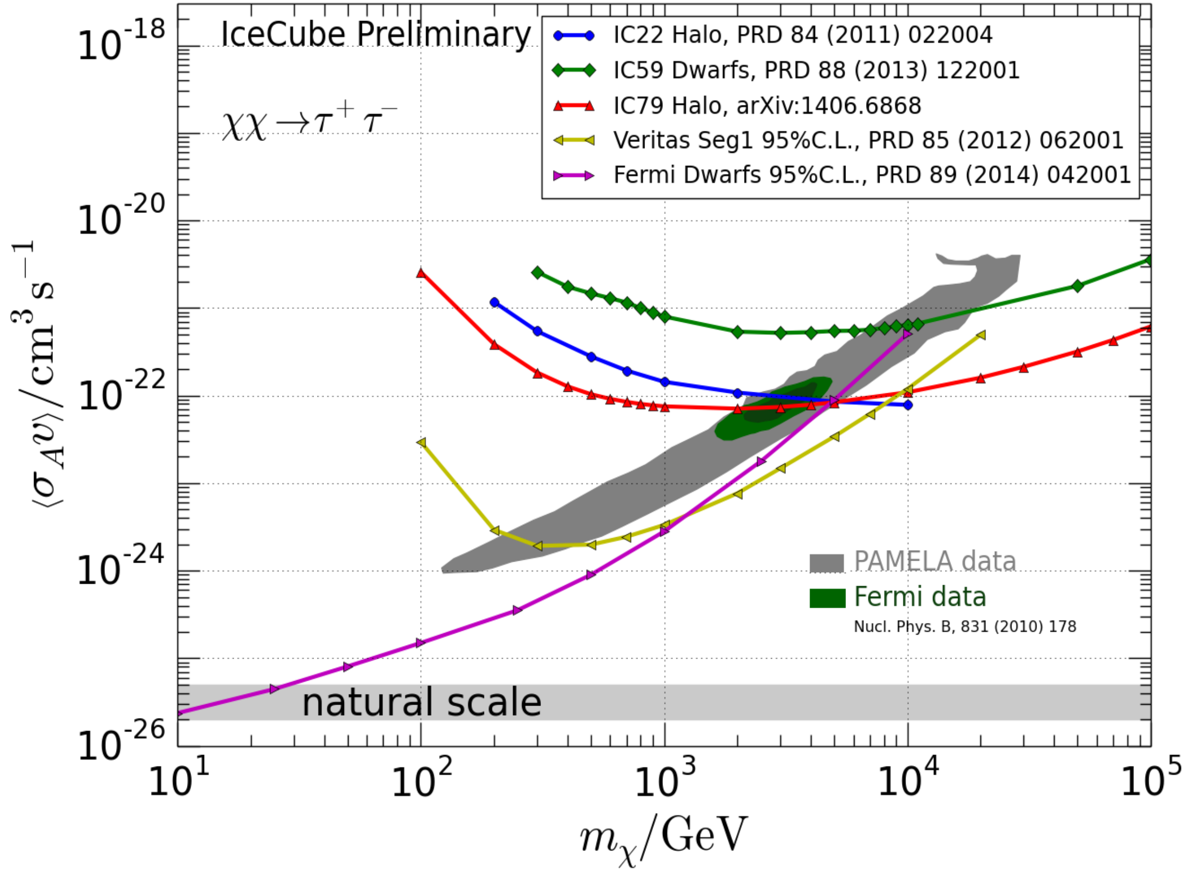


IceCube Phys. Rev. D88 (2013) 122001





dark matter searches from galaxies: comparison with other experiments



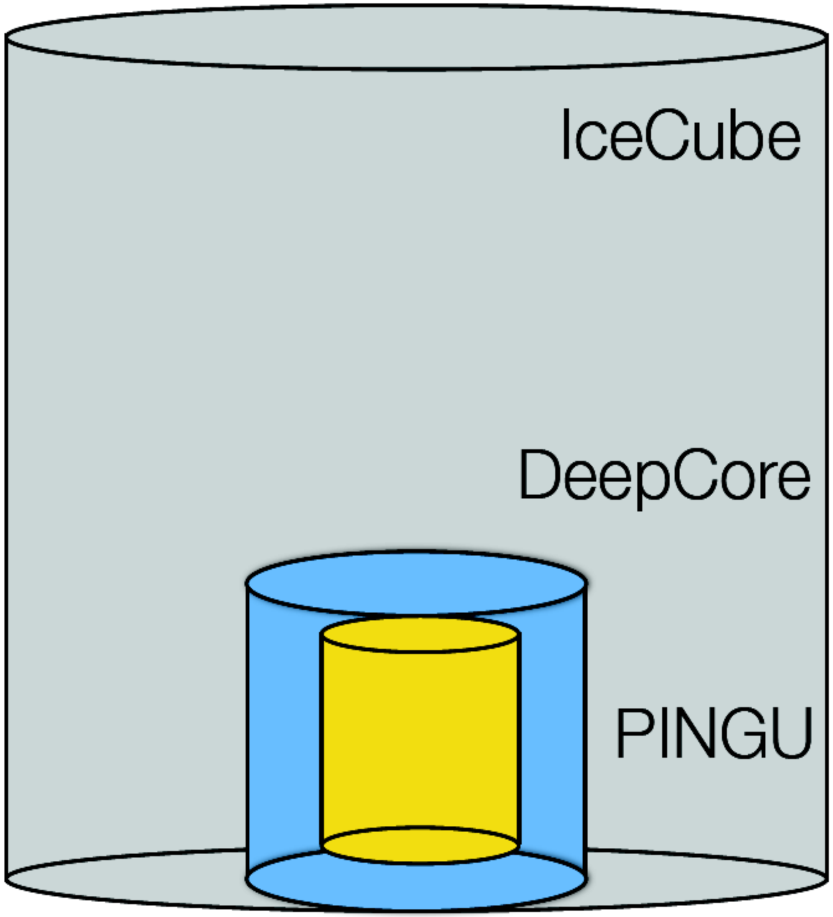
and @ lower energies...

- PINGU
- (Precision IceCube next Generation Upgrade)

  arXiv:1401.2046

  - 40 trings
  - 60 DOMs/string
  - 20 m interstring separation
  - 5 m vertical DOM separation

- Aim: ν hierarchy



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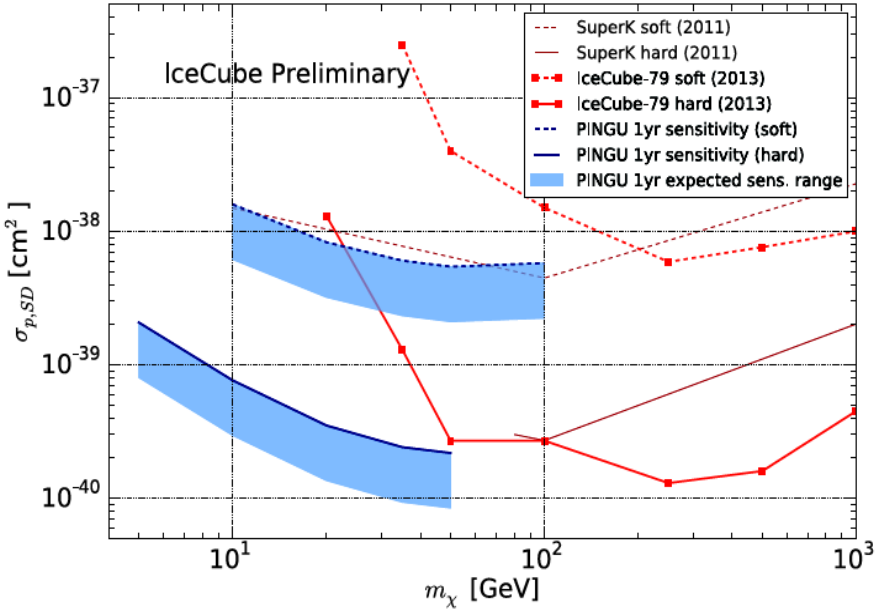
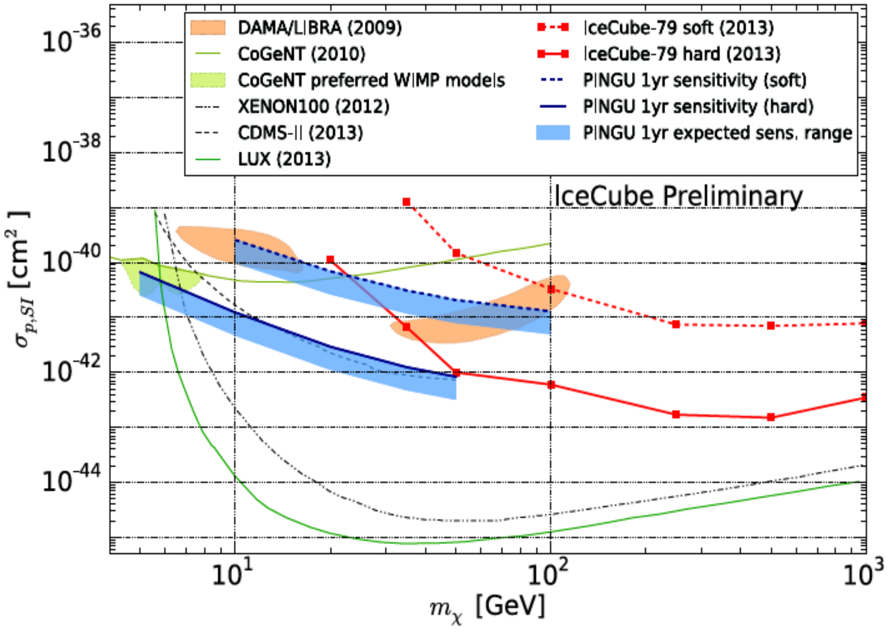
  - 60 DOMs/string
  - 20 m interstring separation
  - 5 m vertical DOM separation

- Aim: ν hierarchy

- Can also be used to lower the mass threshold of dark matter searches





summary

- ANTARES and IceCube are 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)

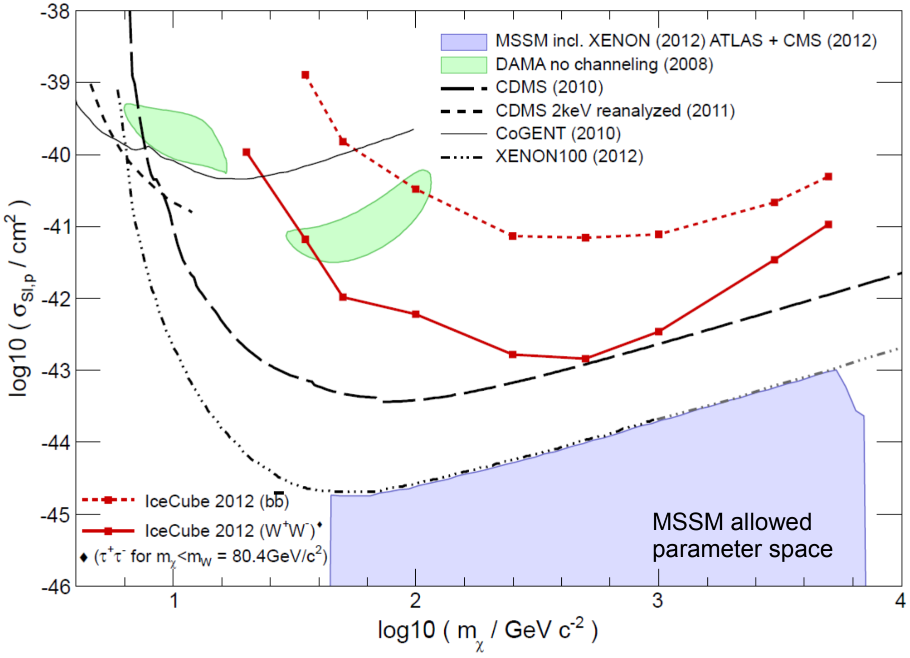
- Work in progress on:
  searches using the cascade channel (GC)
  searches from galaxy clusters/spheroids and Earth
  updated searches from the Sun and Galactic Halo and Center

- Low-energy extensions (ie, PINGU) planned which will allow to extend searches for DM candidates to the ~few GeV region

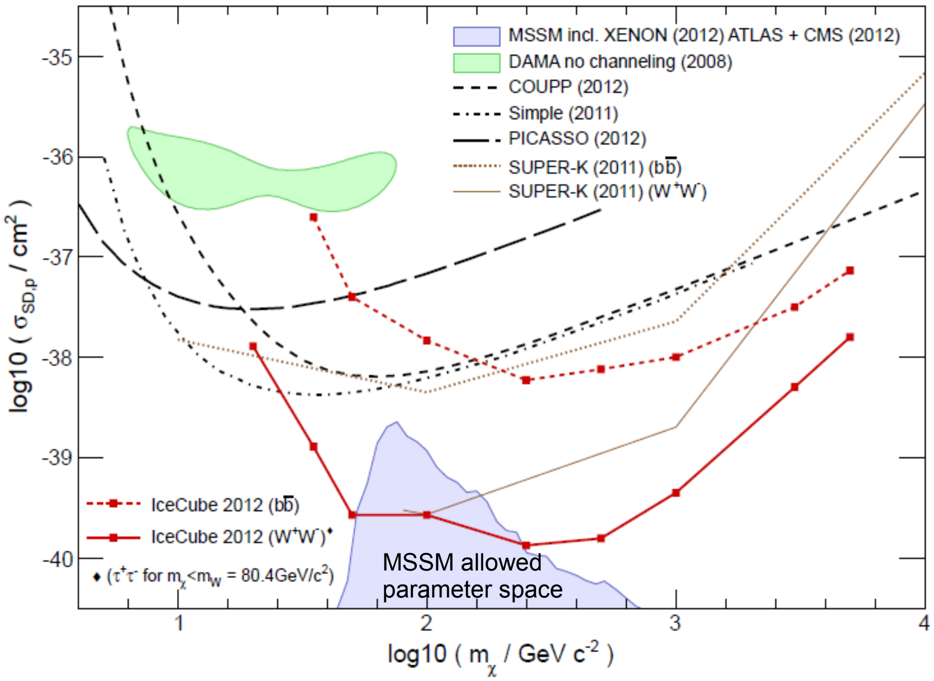
FIN

IceCube-79 Solar search results

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



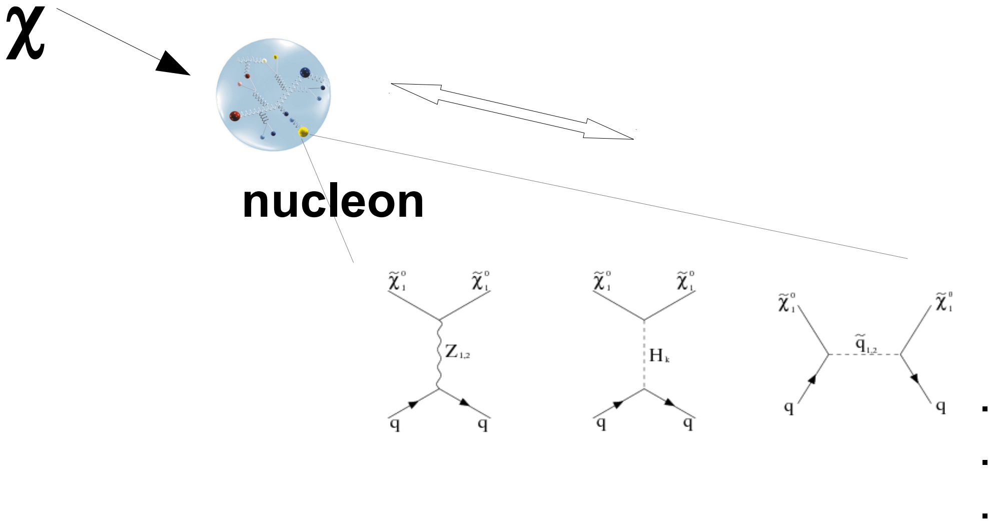
90% CL neutralino-p **SD** Xsection limit



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

a detour on systematics

- 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

nucleon matrix element uncertainties

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

– $\mathbf{\Delta_q^N}$: 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 $\sigma_{SD}^{\chi N} \propto \Sigma_{q=u,d,s} \alpha_q^a \Delta q^N$

– $\mathbf{f_{Tq}}$: Depends on the measurement of

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

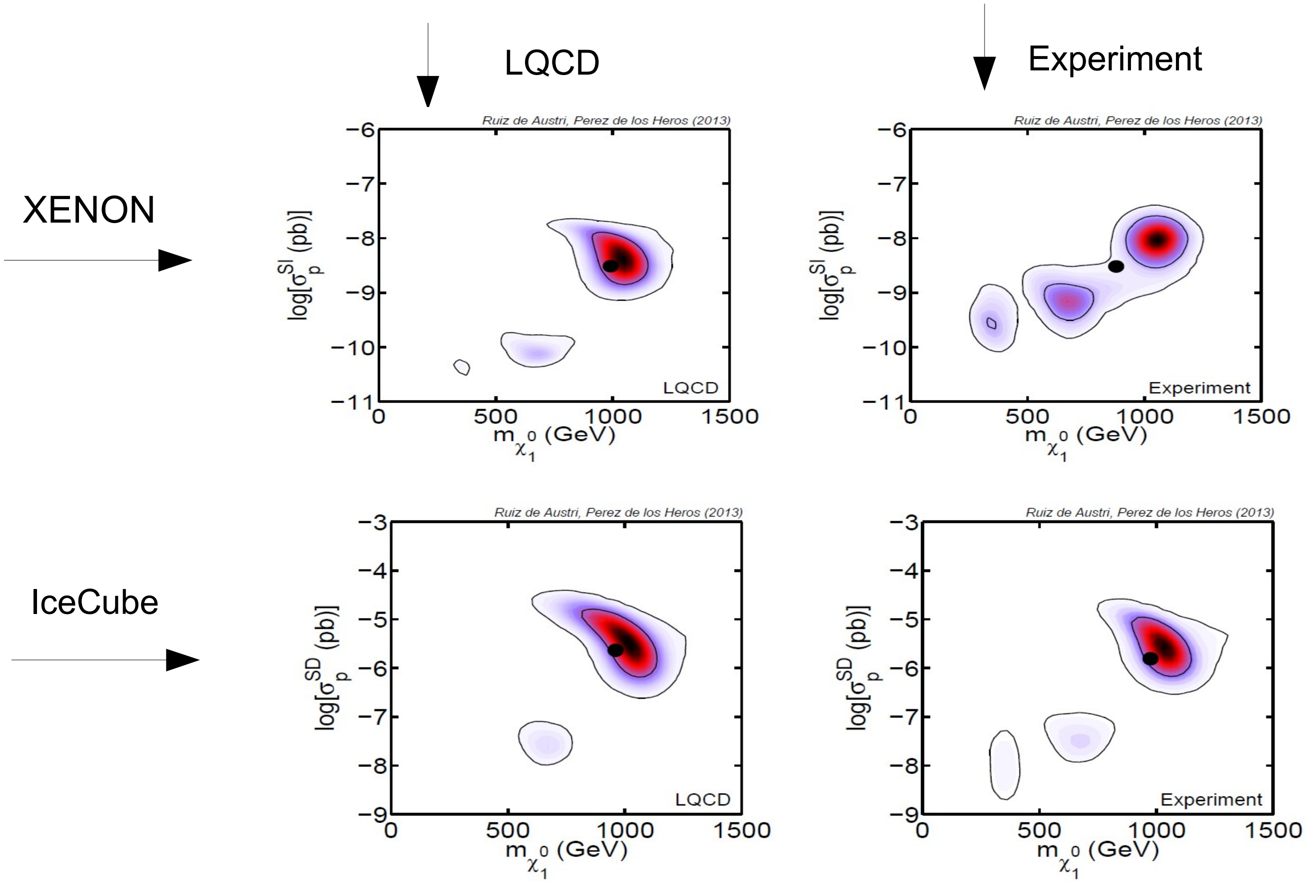
and their extrapolation to zero-momentum. Here is where the uncertainties originate

Values of $\sigma_{p\text{-}N}$ 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 $\sigma_{SI}^{\chi N} \propto \Sigma_{q=u,d,s} m_N \alpha_q^s f_{Tq}^N$

allowed regions of the cMSSM with particle physics, Planck constrains and:

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}



LQCD

Experiment

XENON

IceCube

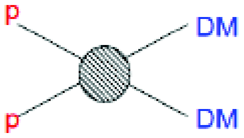
Dark matter experiments sensitive to spin-independent cross sections can be strongly affected by the large differences in the determination of the strangeness content of the nucleon. The reason is that spin-independent cross sections can vary up a factor of 10 depending on which input for the nucleon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

Experiments sensitive to the spin-dependent cross section, like neutrino telescopes, 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.

SD Xsection limits: comparison with LCH results

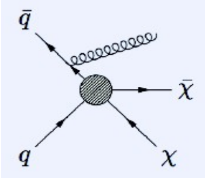
Assume (ie. **model dependent**) effective quark-DM interaction,

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



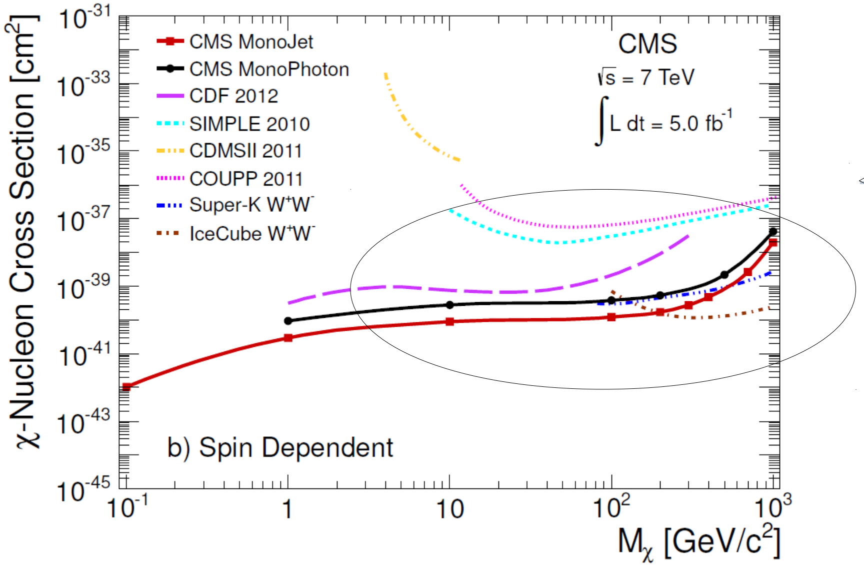
and look for monojets in pp collisions,

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

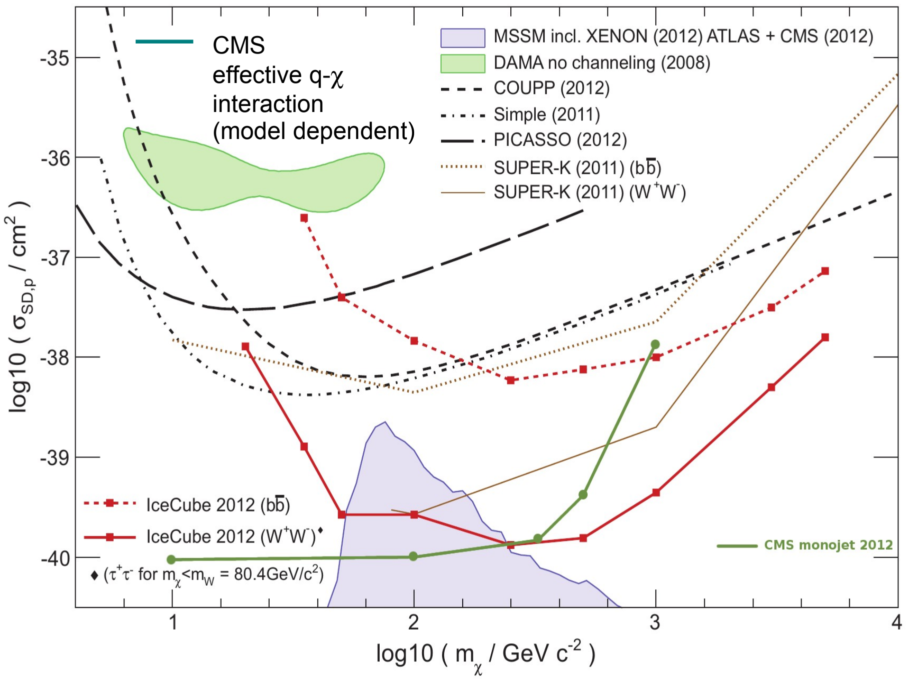


(as opposed to the SM process
pp → Z+jet and pp → W+jet)

Constrains from monojet searches at the LHC (CMS):



90% CL neutralino-p Xsection limit



aiming at even lower energies: PINGU

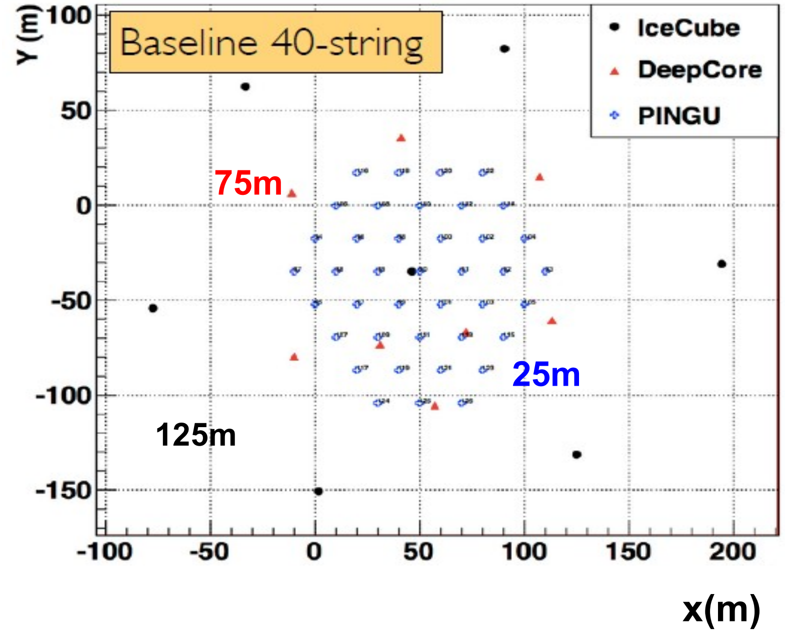
DeepCore showed the potential of going down in energy.

How low could we go?

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

→ **PINGU:**

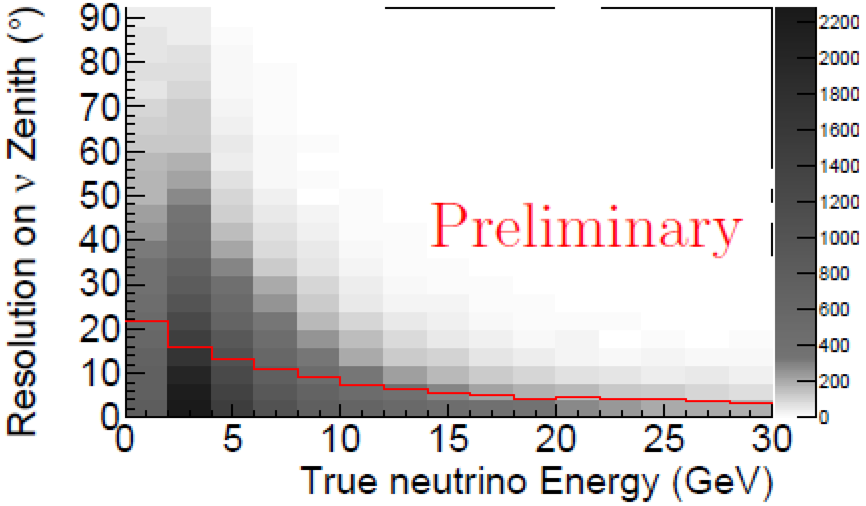
Precision **I**cecube **N**ext **G**eneration **U**pgrade



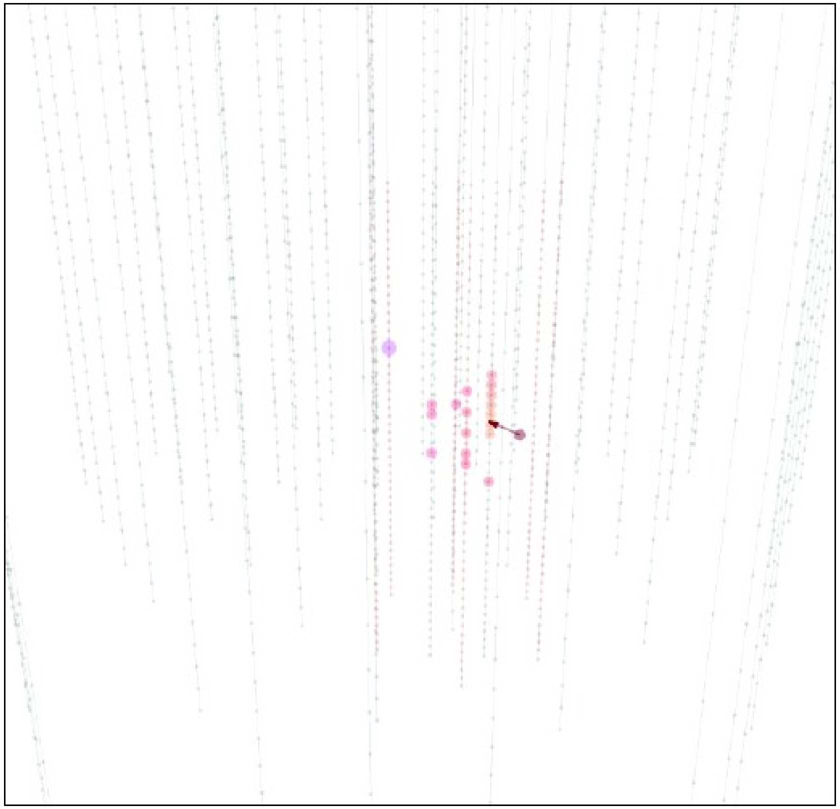
Aims:

Physics @few GeV:

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

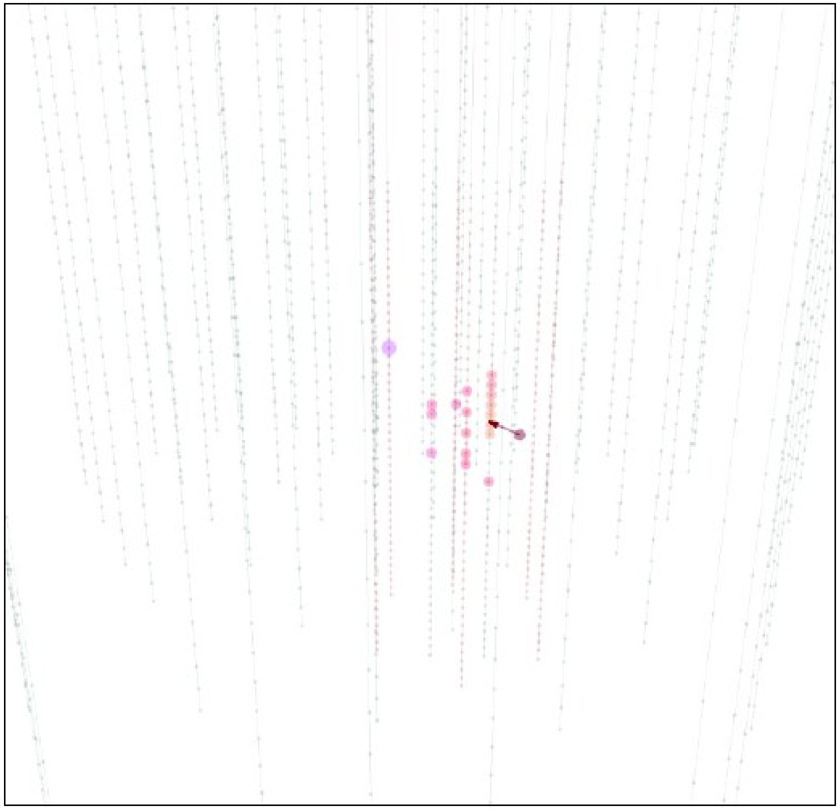


9.3 GeV neutrino producing a 4.9 GeV muon and a 4.4 GeV cascade



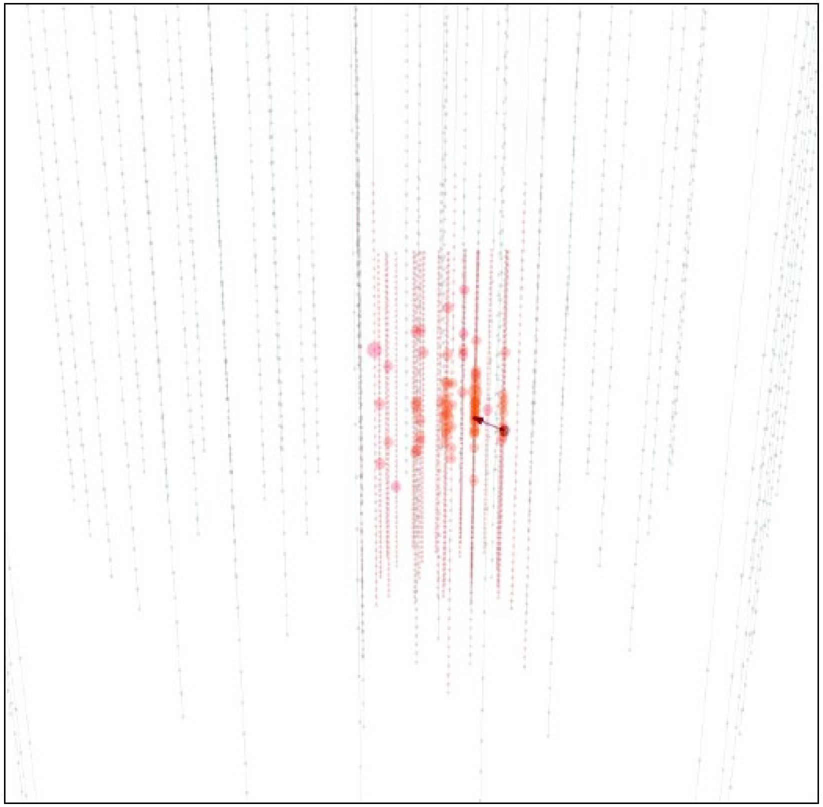
DeepCore only

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

on the dark matter side

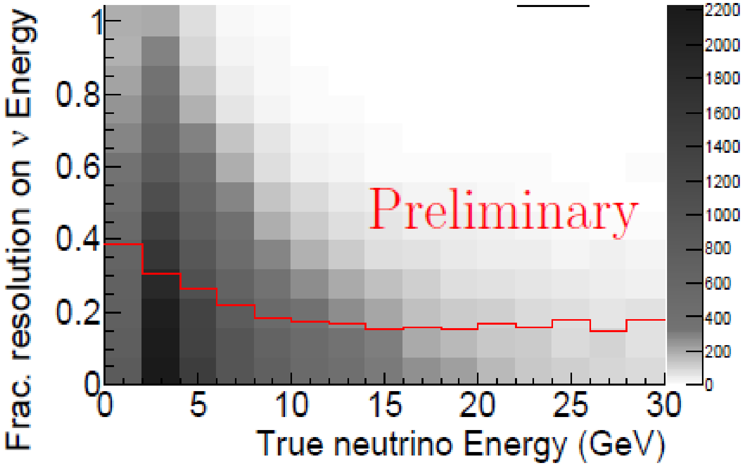
sensitivity study based on current IceCube analysis techniques

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

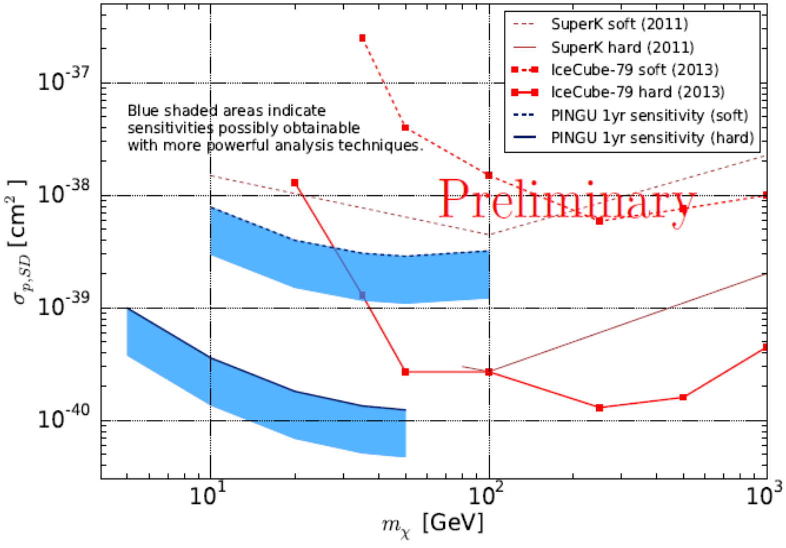
→ reach WIMP masses of 5 GeV

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

└> use of signal and background spectral information



Sun, σ_p^{SD} (1 yr live time)



on the dark matter side

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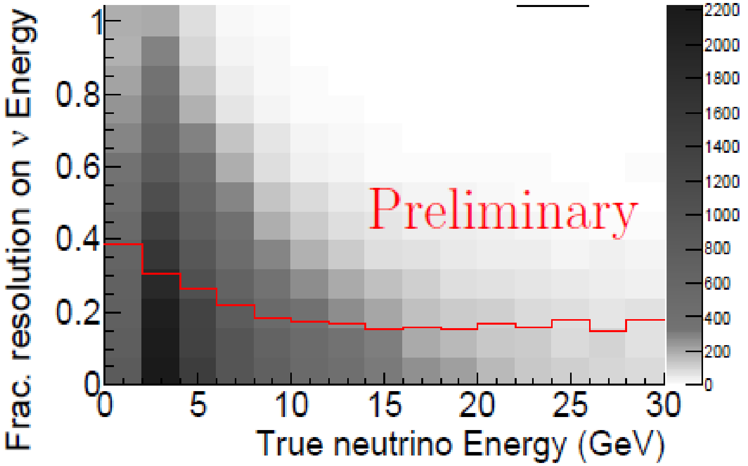

Galactic Center, $<\sigma_A v>$ (1 yr live time)