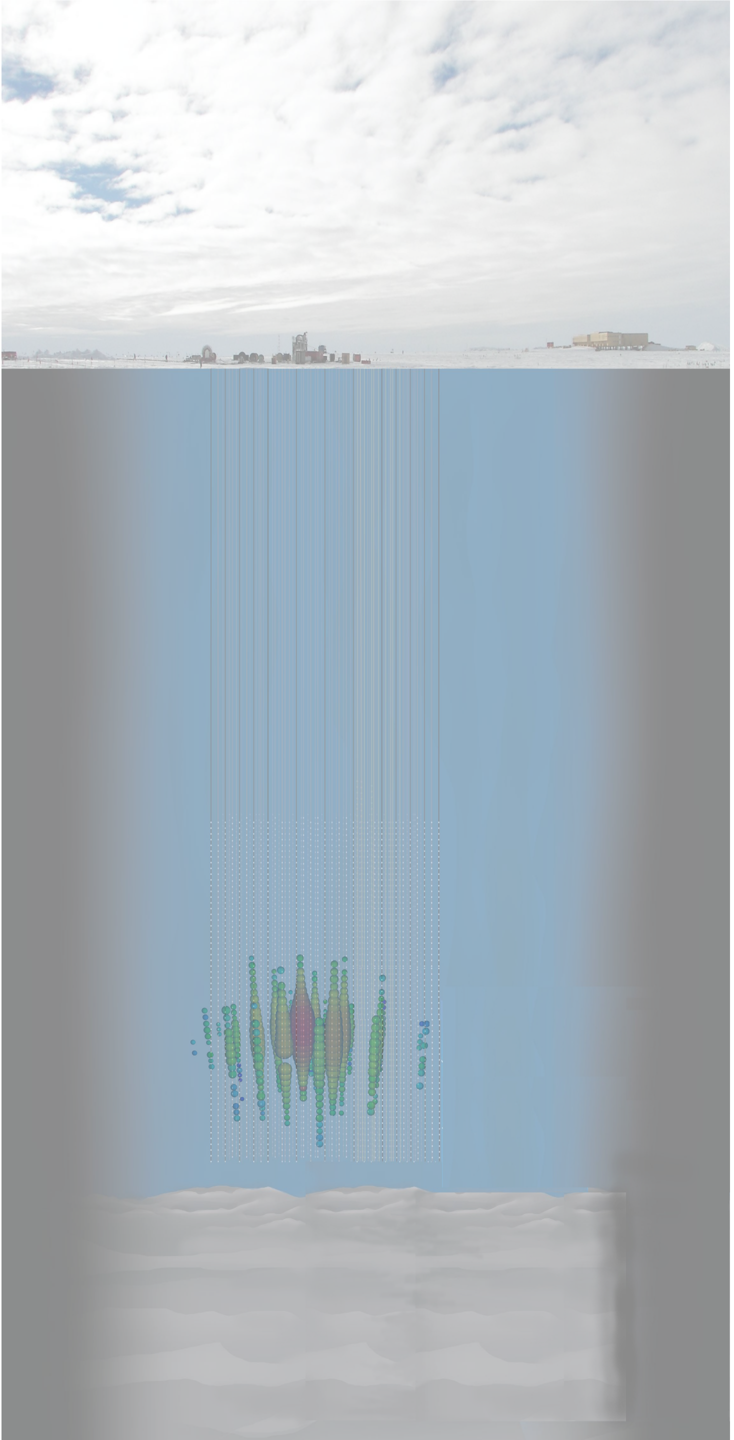


indirect searches for dark matter with neutrinos

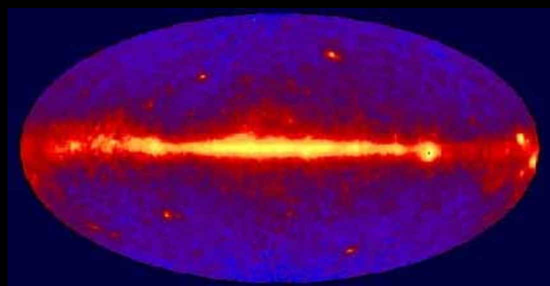
Carlos de los Heros
Uppsala University

Solvay-Francqui Workshop on Neutrinos, Brussels, May 2015

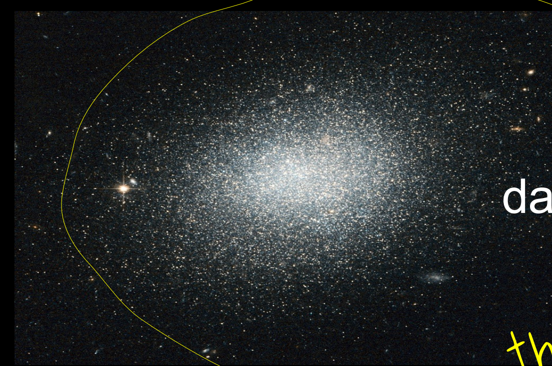
physics with neutrino telescopes

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

Supernovae



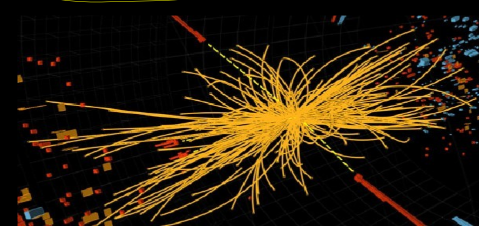
diffuse neutrino flux
(all-sky searches)



dark matter

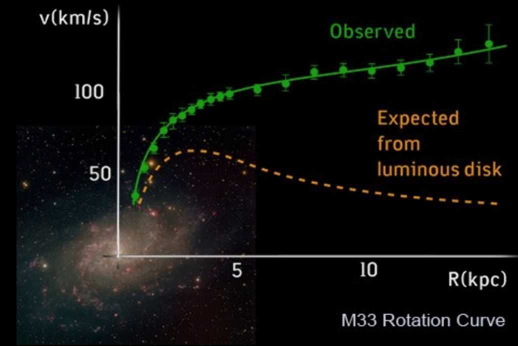
this talk

cosmic rays



particle physics:
neutrino properties
fundamental laws...

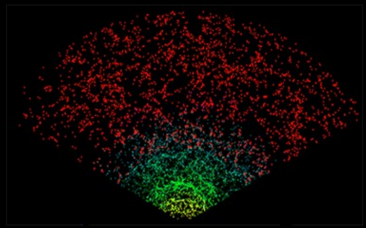
galaxy clusters



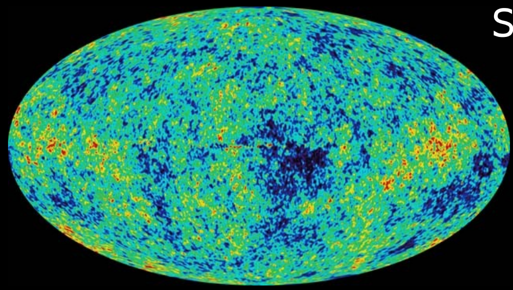
galaxy rotation curves

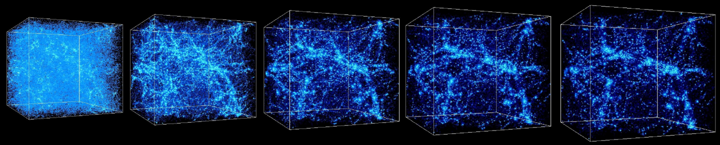
gravitational lensing

a weakly-interacting relic "dark matter" particle can explain the observations



structure formation





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)

Possible characteristics of a dark matter particle:

Spin: from 0 (sneutrino), ½ (neutralino), to 3/2 (gravitino)

Mass: from 10^{-15} GeV (axion) to 10^{18} GeV (Wimpzillas)

Self-annihilation Xsection or interaction Xsection to SM particles:

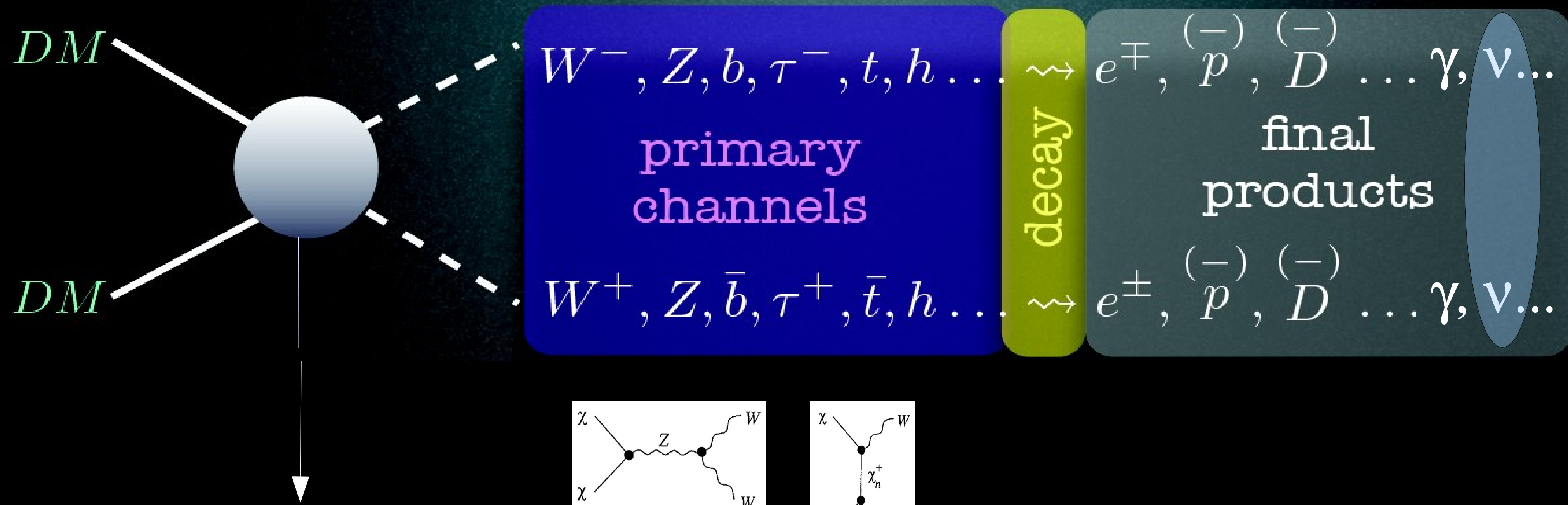
from 10^{-10} pb to 10^{-5} pb

(total γ-p Xsection ~ 200 μb)

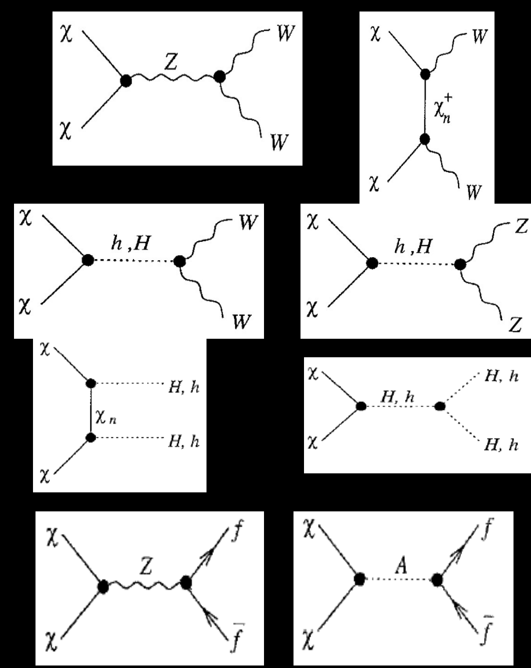
Lifetime: 10^{9} yr to infinity

Can be constrained by neutrino telescopes

how do neutrinos come in?



your theory here
(not necessarily SUSY...)



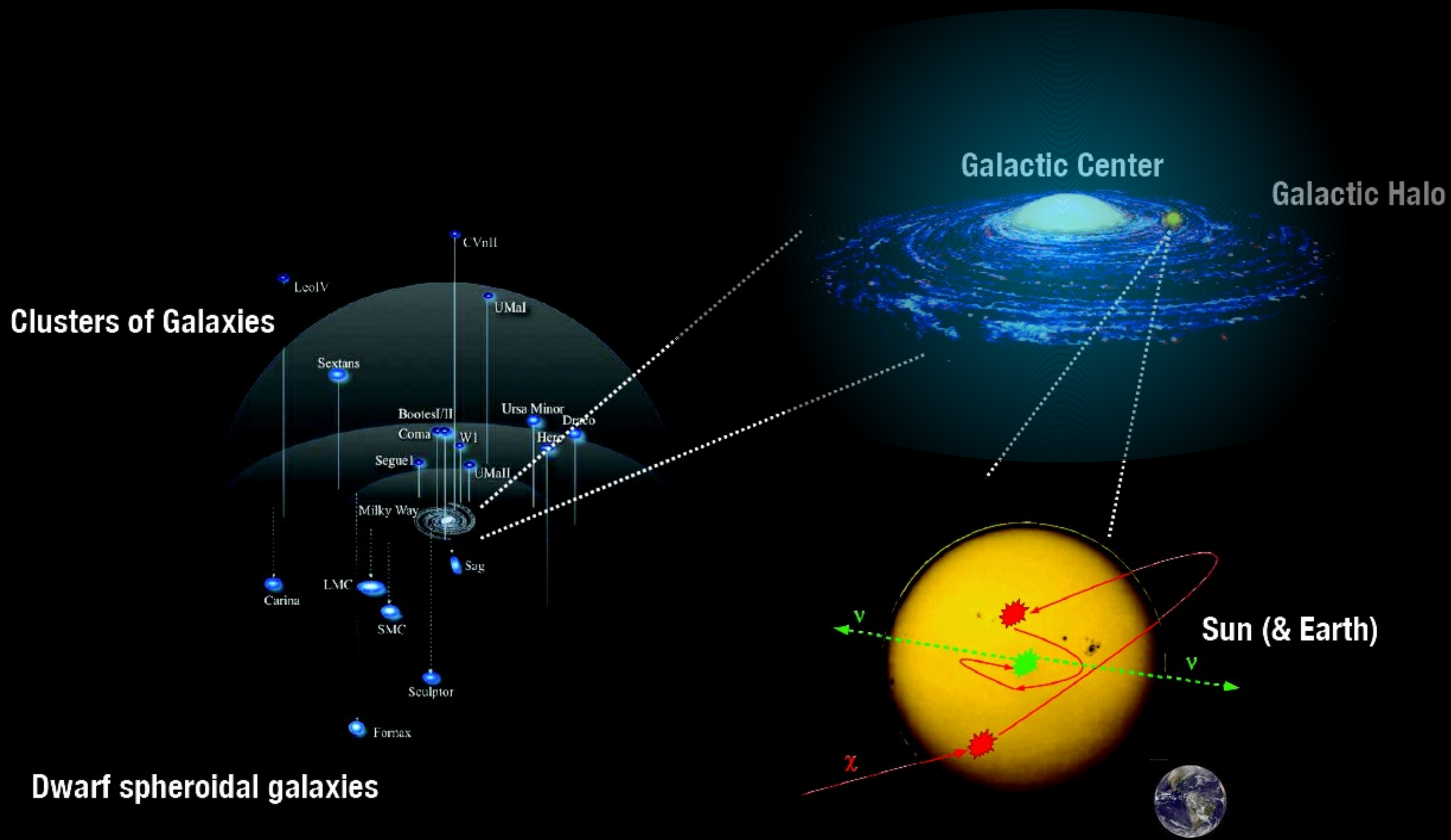
.... etc

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

Here is where ν's are advantageous

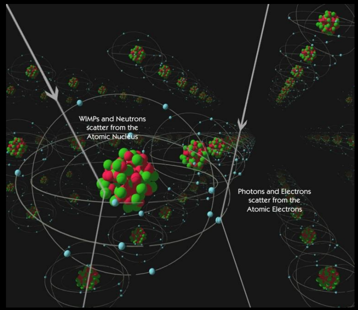
Look at objects where dark matter might have accumulated gravitationally over the evolution of the Universe

signature: an excess of ν over the atmospheric neutrino background



DIRECT

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

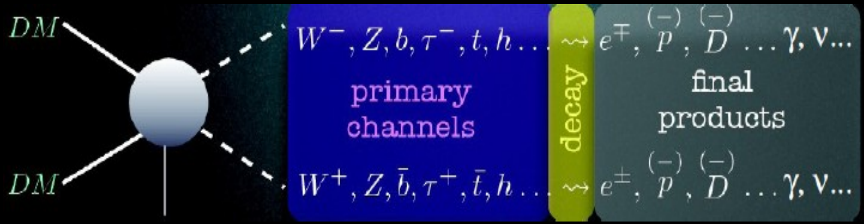


INDIRECT

γ: Fermi, Veritas, HESS, MAGIC...

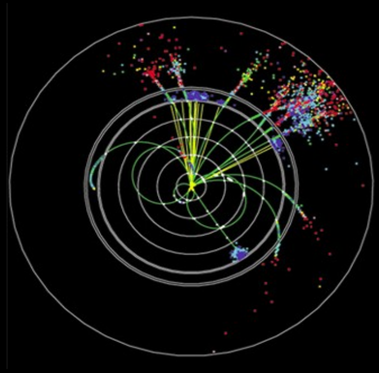
$e^+, \bar{p}$: PAMELA, AMS...

ν: ANTARES, Baikal, Baksan, Super-K



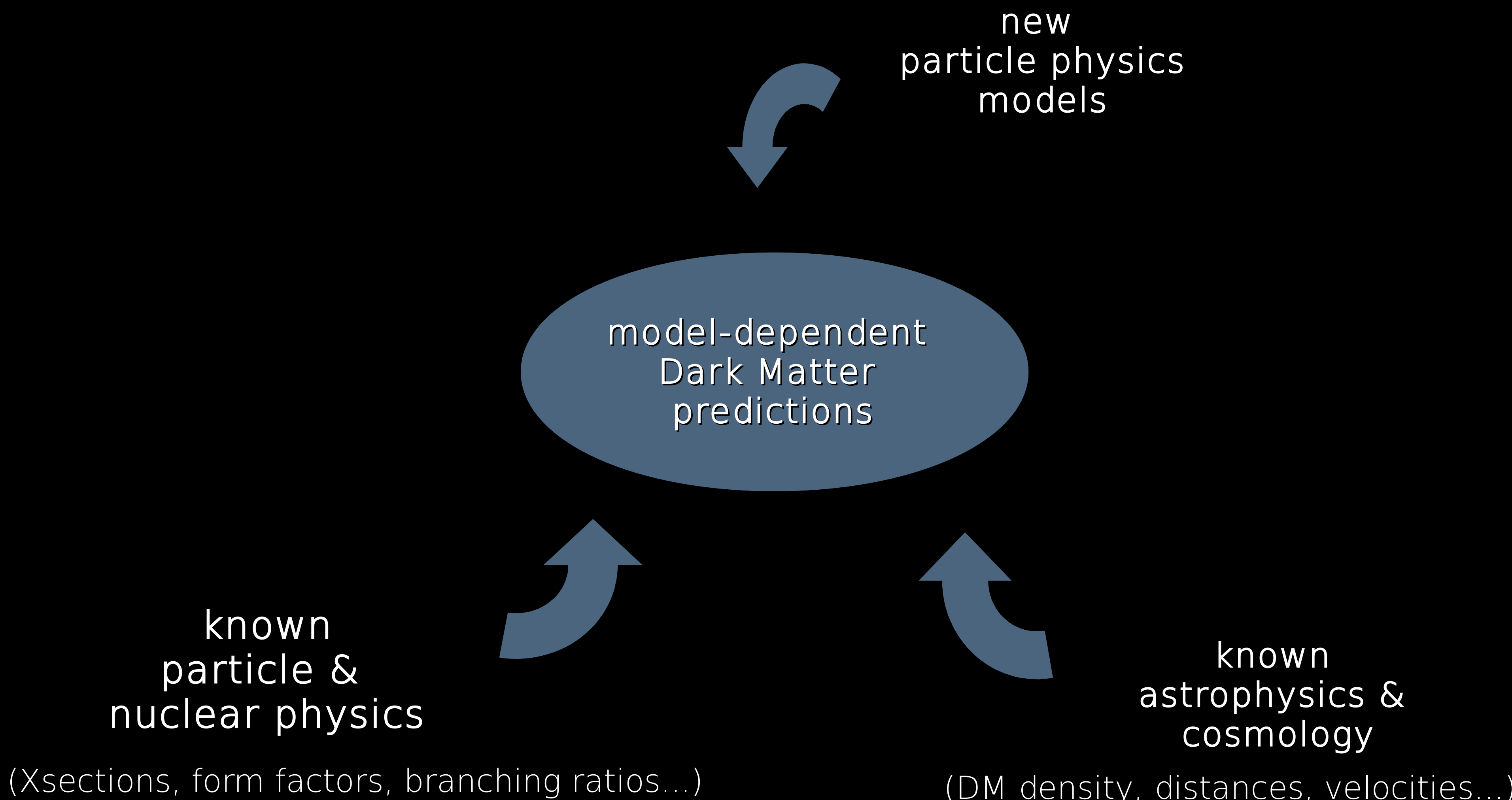
ACCELERATOR

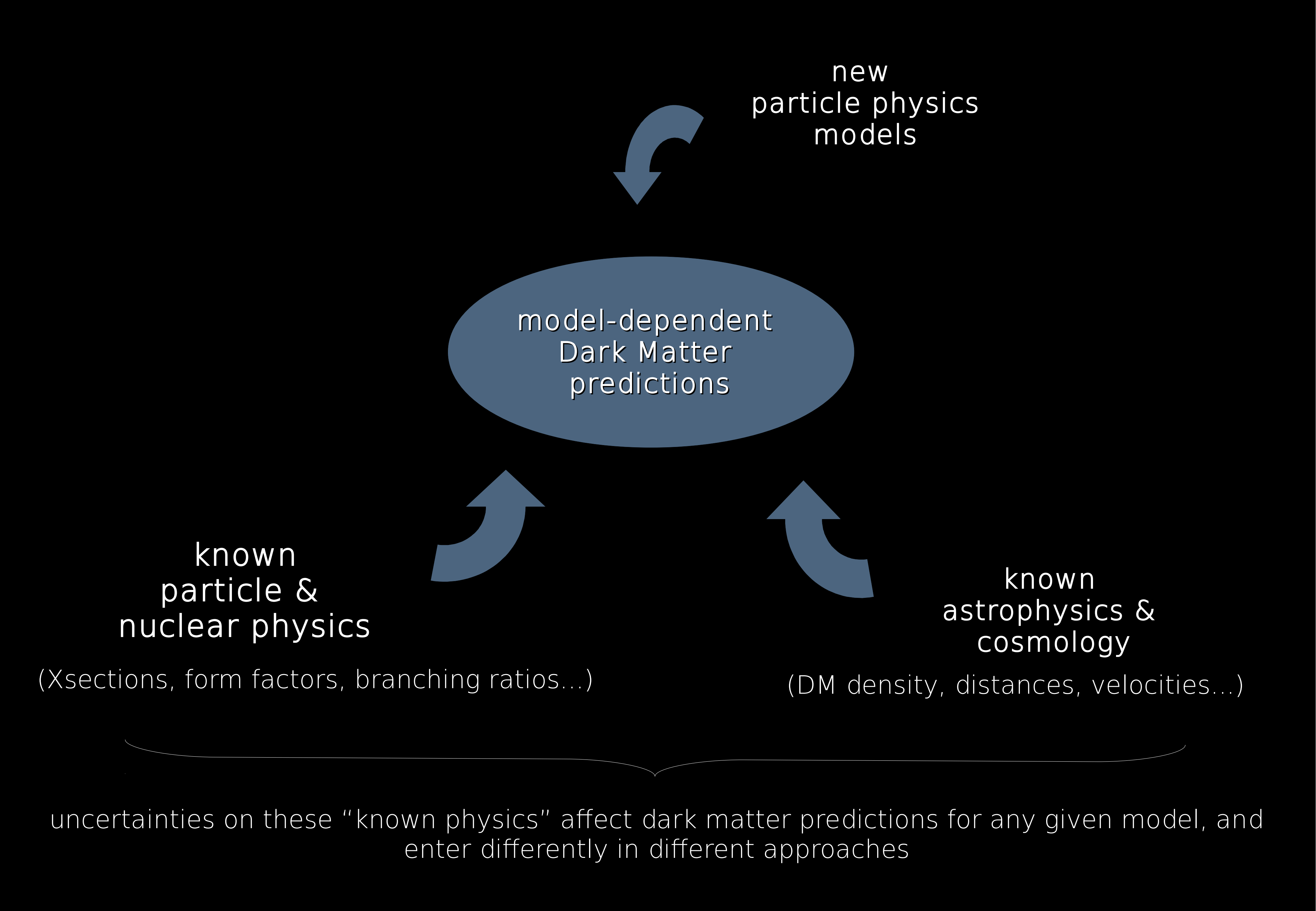
ATLAS CMS



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)


new
particle physics
models
model-dependent
Dark Matter
predictions
known
particle &
nuclear physics
(Xsections, form factors, branching ratios...)
known
astrophysics &
cosmology
(DM density, distances, velocities...)


new
particle physics
models
model-dependent
Dark Matter
predictions
known
particle &
nuclear physics
(Xsections, form factors, branching ratios...)
known
astrophysics &
cosmology
(DM density, distances, velocities...)
uncertainties on these “known physics” affect dark matter predictions for any given model, and
enter differently in different approaches

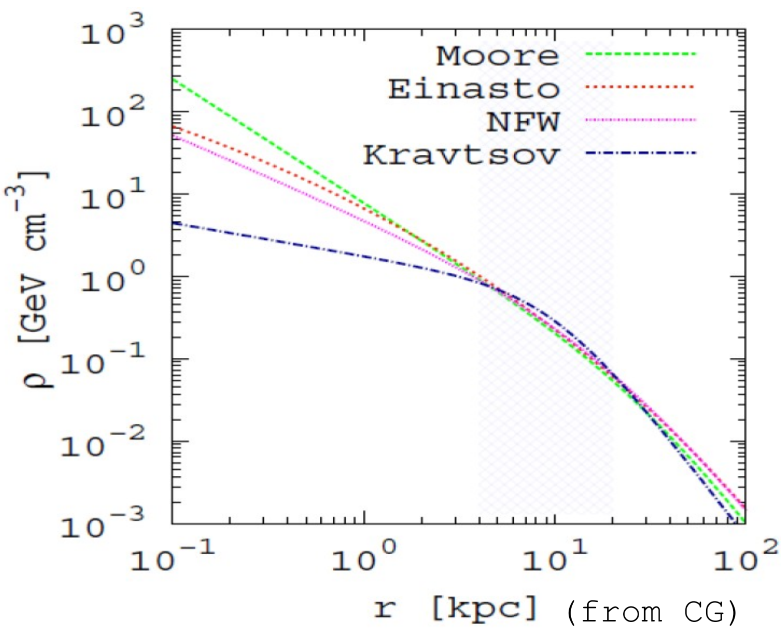
indirect searches for dark matter: external inputs

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)

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



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

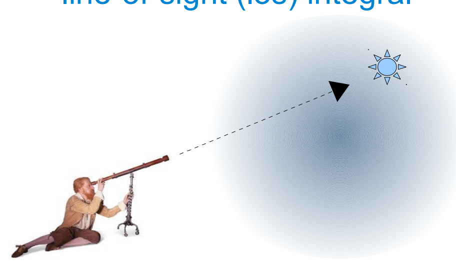
$\langle \sigma_A v \rangle$ Annihilation cross-section, velocity averaged

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

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

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

line-of-sight (los) integral

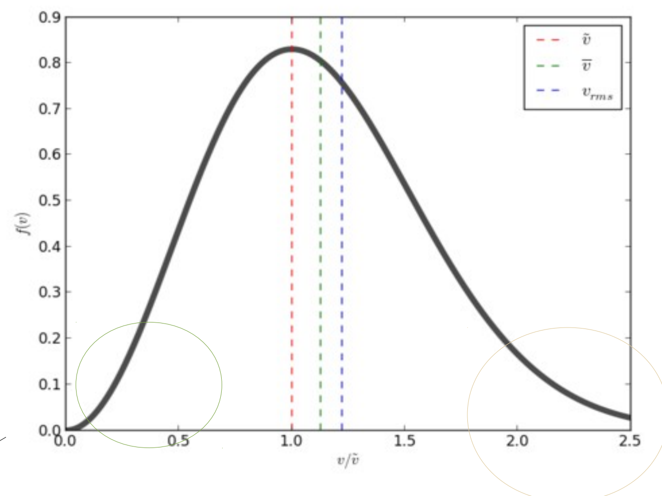


Astrophysical inputs needed for reliable calculations and data analyses:

- Velocity distribution of the dark matter particles in the halo

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

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

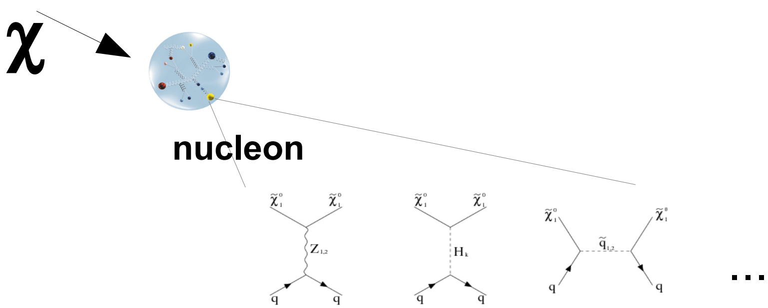


ν-telescopes sensitive to this part of the velocity distribution (low-energy particles easily captured gravitationally)

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

Structure of the nucleon plays an essential role in calculating observables

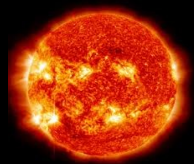
$$\sigma^{\chi N}_{SD} \propto \Sigma_{q=u,d,s} \langle N | \bar{q} \gamma_\mu \gamma_5 q | N \rangle \propto \Sigma_{q=u,d,s} \alpha^a_q \Delta q^N$$

$$\sigma^{\chi N}_{SI} \propto \Sigma_{q=u,d,s} \langle N | m_q \bar{q} q | N \rangle \propto \Sigma_{q=u,d,s} m_N \alpha^s_q f^N_{Tq}$$

need to be calculated in QCD or measured experimentally

Uncertainties up to one order of magnitude present in the calculation of f_T^N

dark matter searches with neutrino telescopes: sources



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

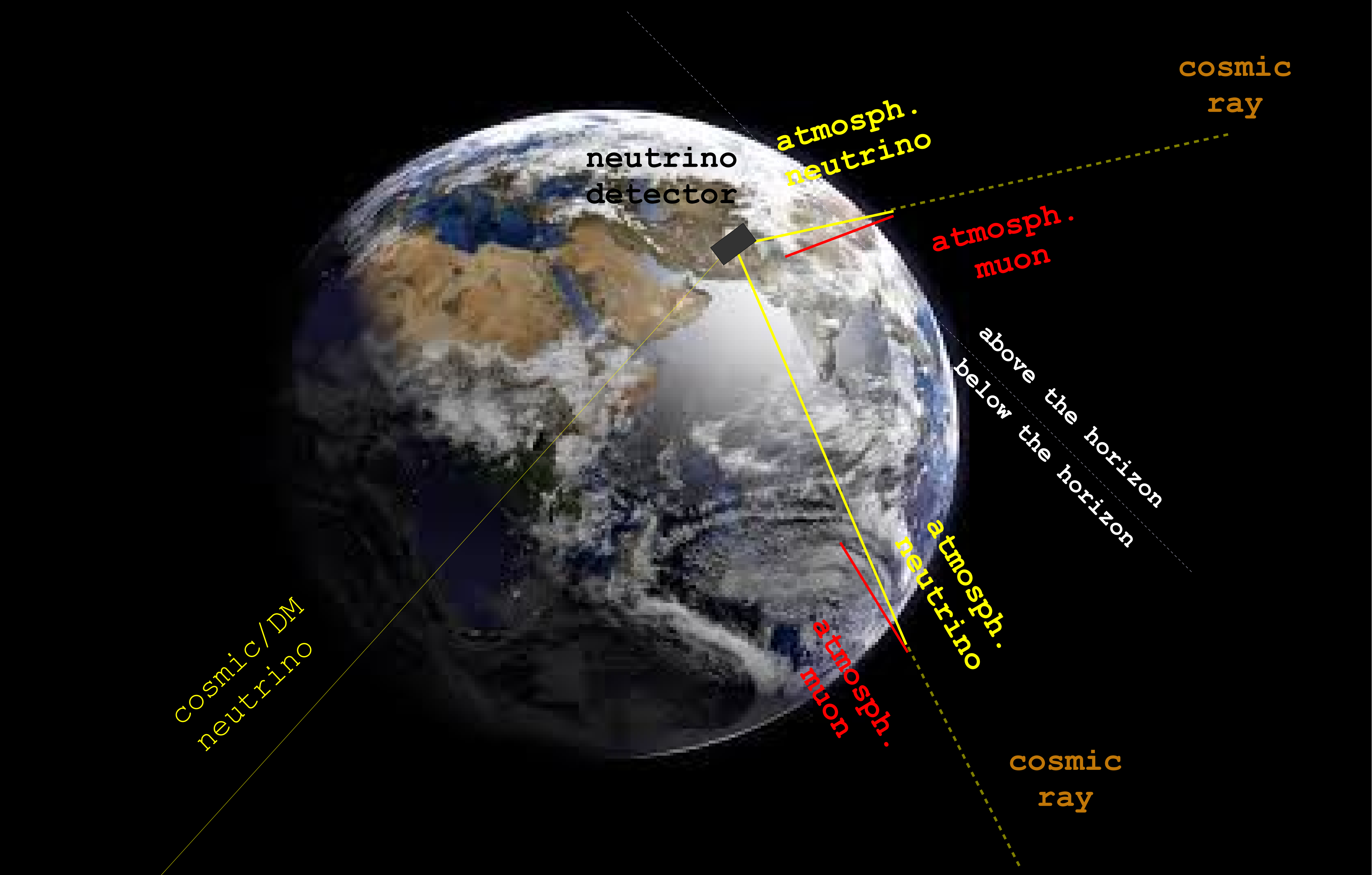
dwarf galaxies
&
distant galaxies

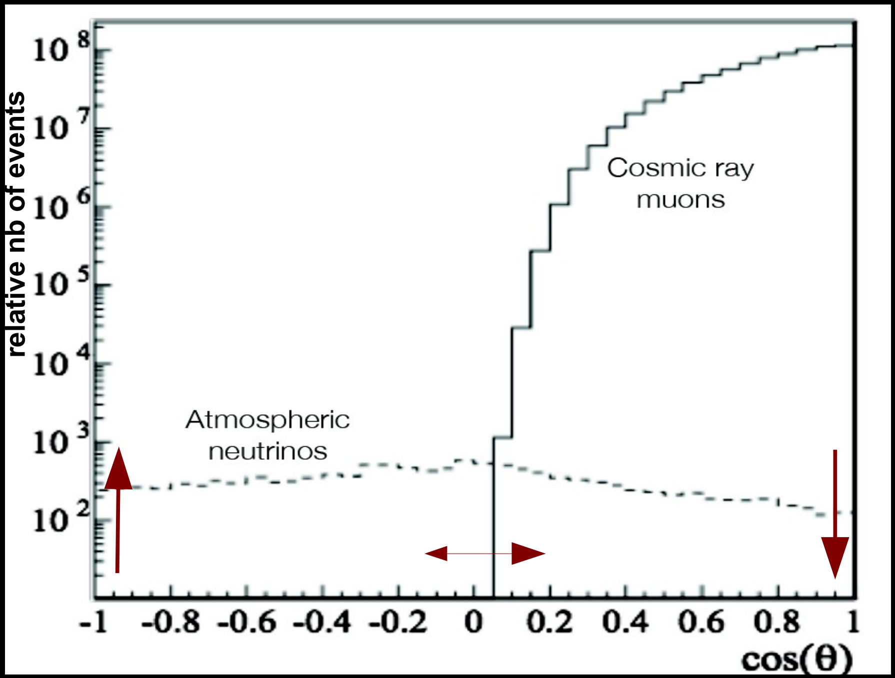
Galactic
Halo

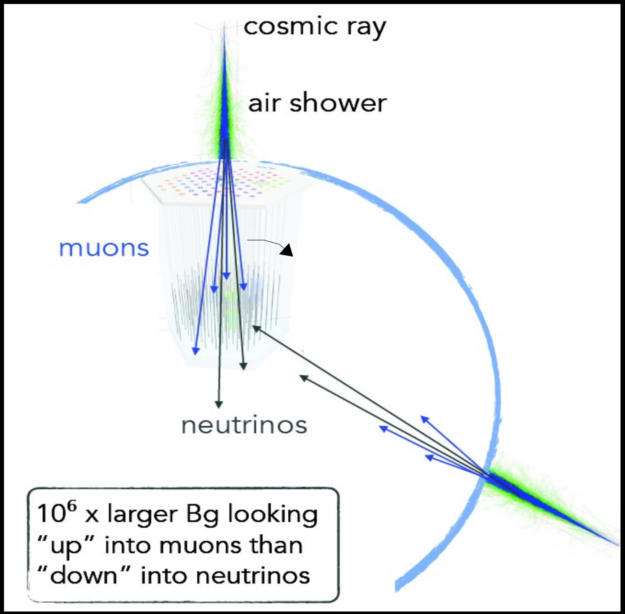
Galactic
Center

probes $<\sigma_A v>$

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


cosmic
ray
atmosph.
neutrino
neutrino
detector
atmosph.
muon
above the horizon
below the horizon
atmosph.
neutrino
atmosph.
muon
cosmic/DM
neutrino
cosmic
ray





below the horizon
(upgoing tracks)

Earth has filtered all cosmic ray products except neutrinos

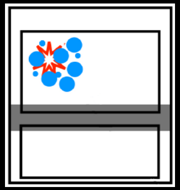
above the horizon
(downgoing tracks)

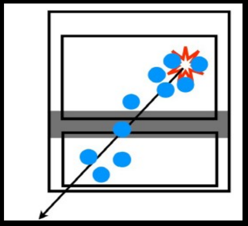
High energetic muons can penetrate km in water or ice

To identify ν's:

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

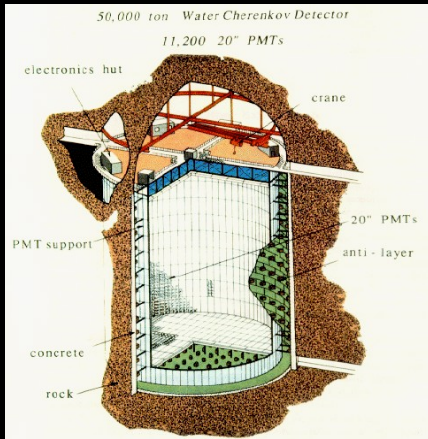
b) define "starting tracks" in the detector. Use any angle





current projects

current projects



in operation since 1996

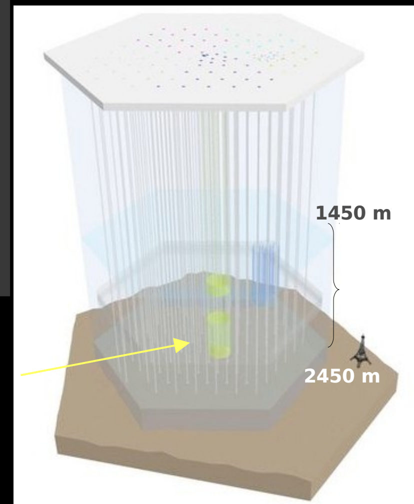
1 Km deep in Mozumi mine, japan

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



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

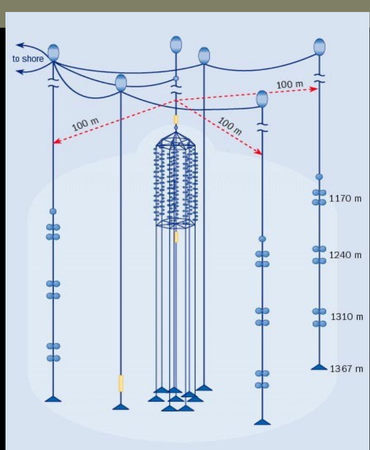
E threshold ~10 GeV

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+

- commissioned 2005
- 3 additional strings 200m long



in operation since 1977!

850 m w.e. in Andyrchi range, Russia

4 storeys, 3.6 vertical distance

3150, 0.5 m² scintillator detectors

5330 tons of scintillator

2.5 Km deep in the Mediterranean

12 lines, 885 Optical modules

25 ‘storeys’ with 3 OMs each

350 m long strings (active height)

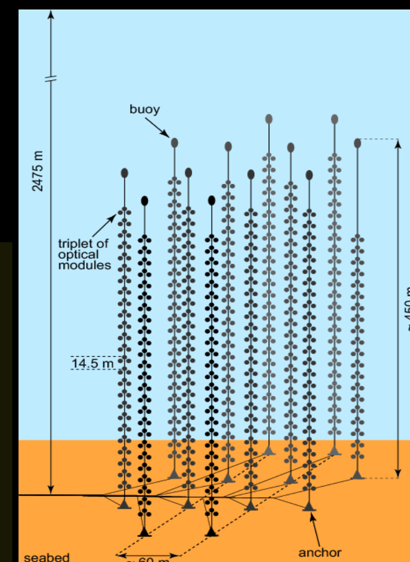
~70 m inter-string separation

14.5 m vertical storey separation

0.04 km³ instrumented volume

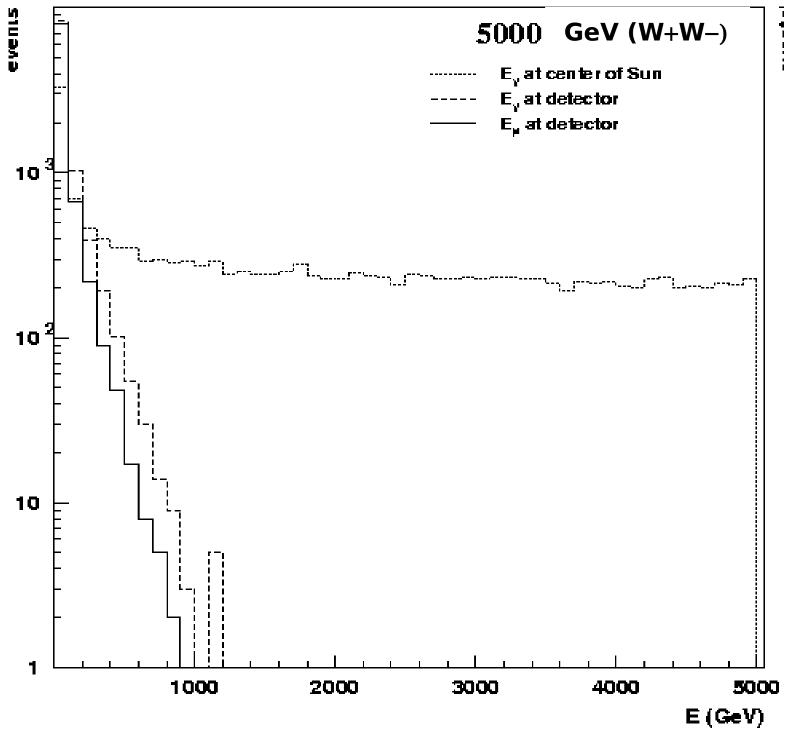
effective area ~ 1m²@ 30 TeV

median angular resolution ~0.4º



dark matter searches from the Sun

5000 GeV Neutralino → WW @ 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

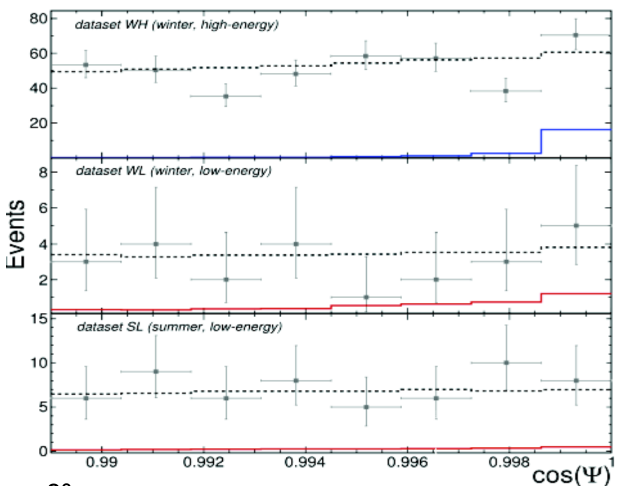
Not such effect for the Earth and Halo

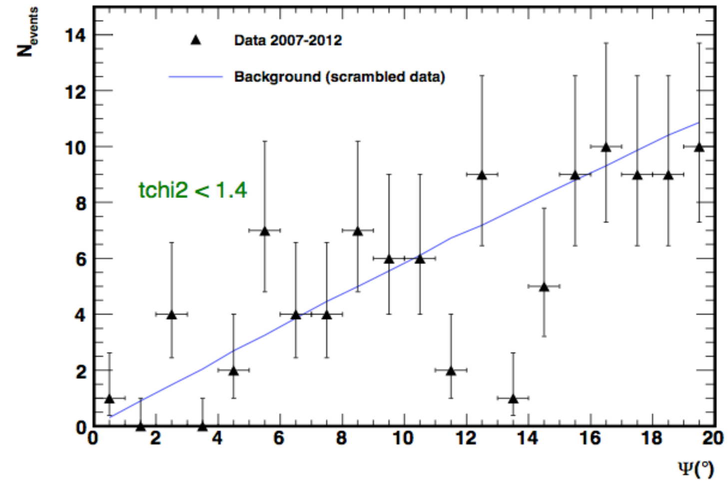
IceCube results from 317 days of livetime between 2010-2011
PRL 110, 123302 (2013)

measure: muon flux

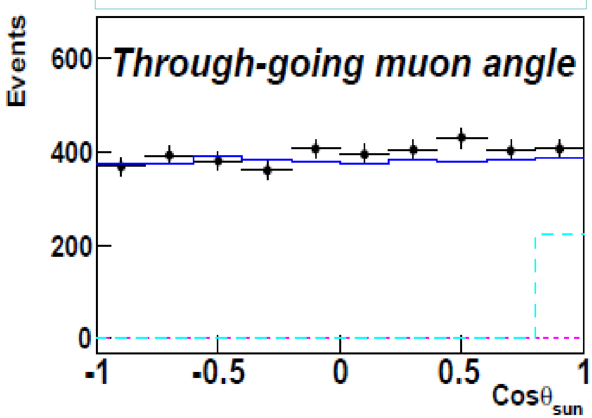
ANTARES results from 294.6 days of livetime between 2007-2009 (arxiv:1302.6516)

Unblinded events in different samples

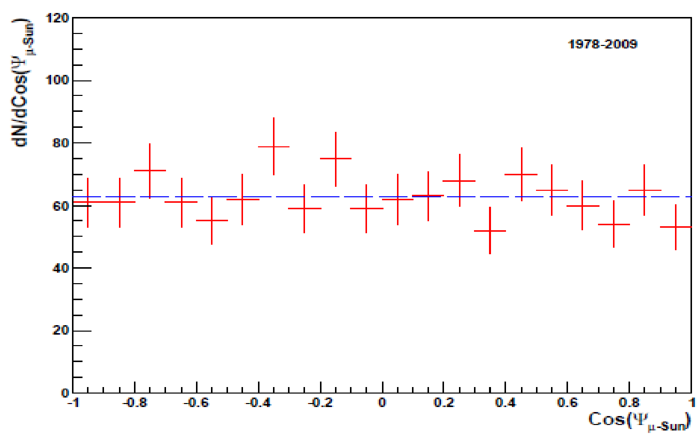




Super-K results from 3903 days of livetime between 1996-2008 (arxiv: 1503.04858)



Baksan results from 24.12 years of livetime between 1978-2009:

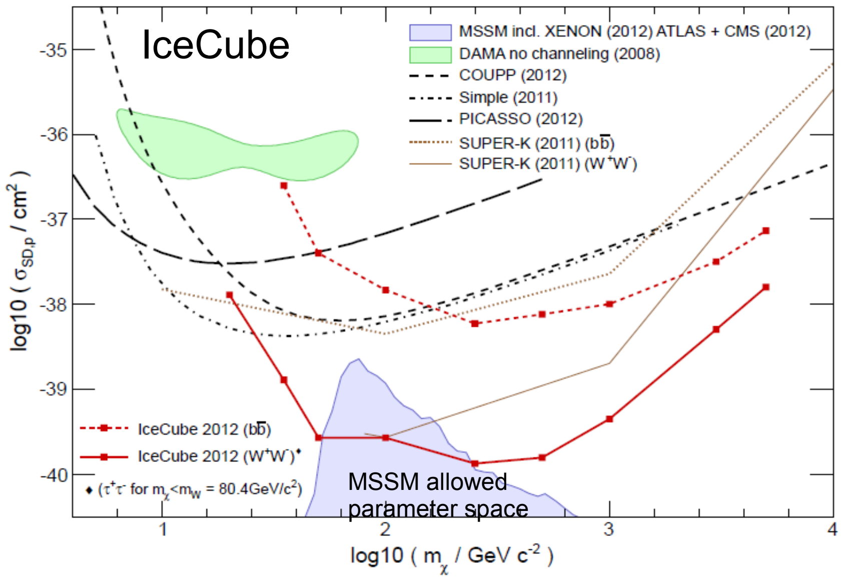


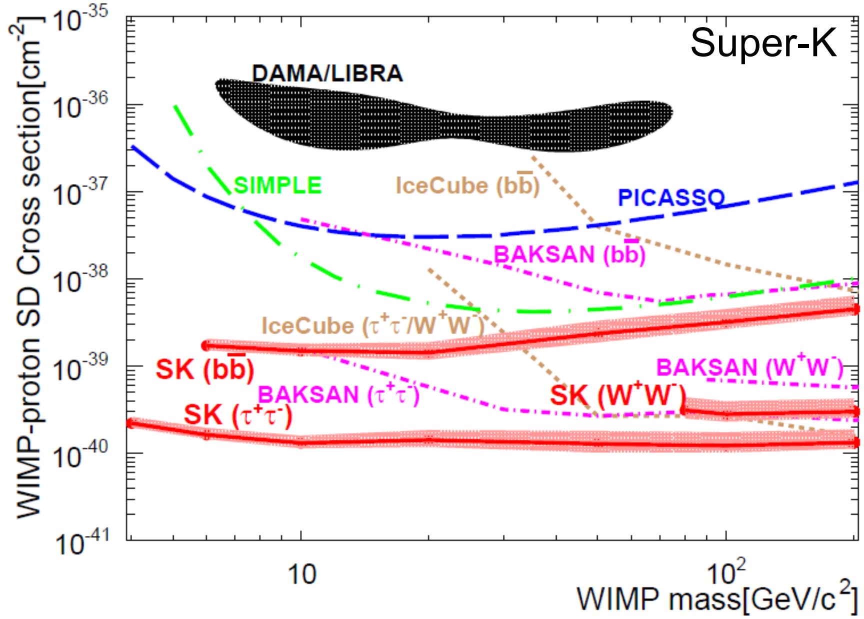
$$\frac{dN}{dt} = C_{capt.} - C_{ann.}$$

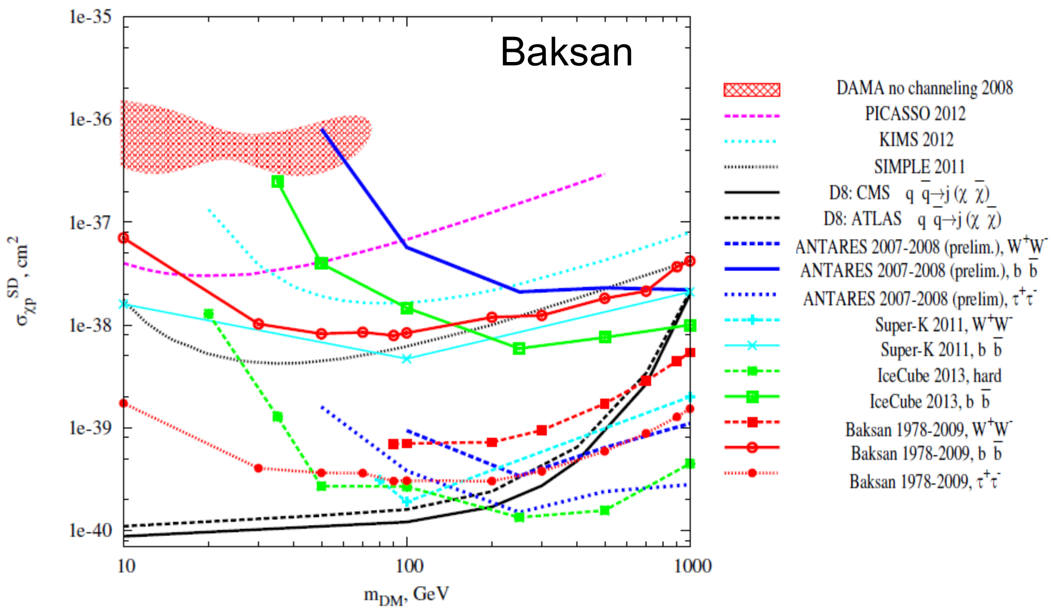
$$C_{ann.} = C_{capt.} \rightarrow \sigma_{total}$$

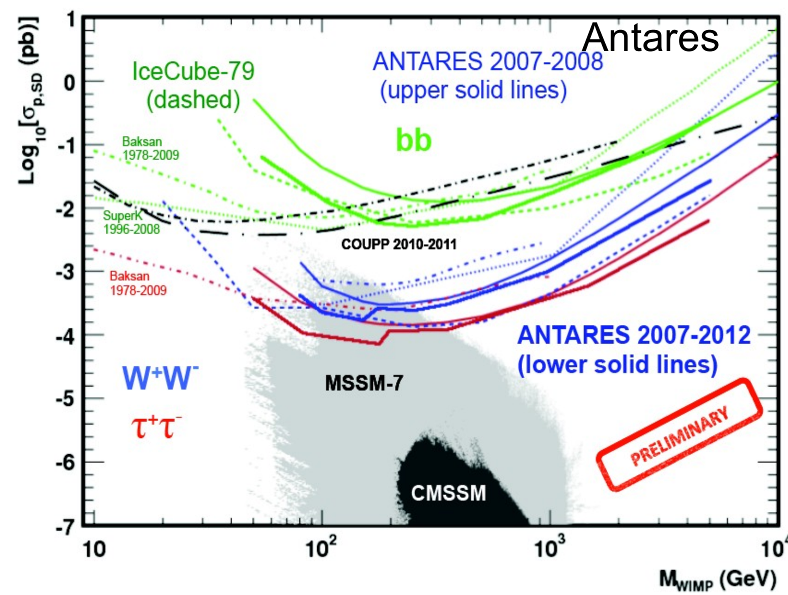
$$\Phi_\mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{X+p}$$

solar search results

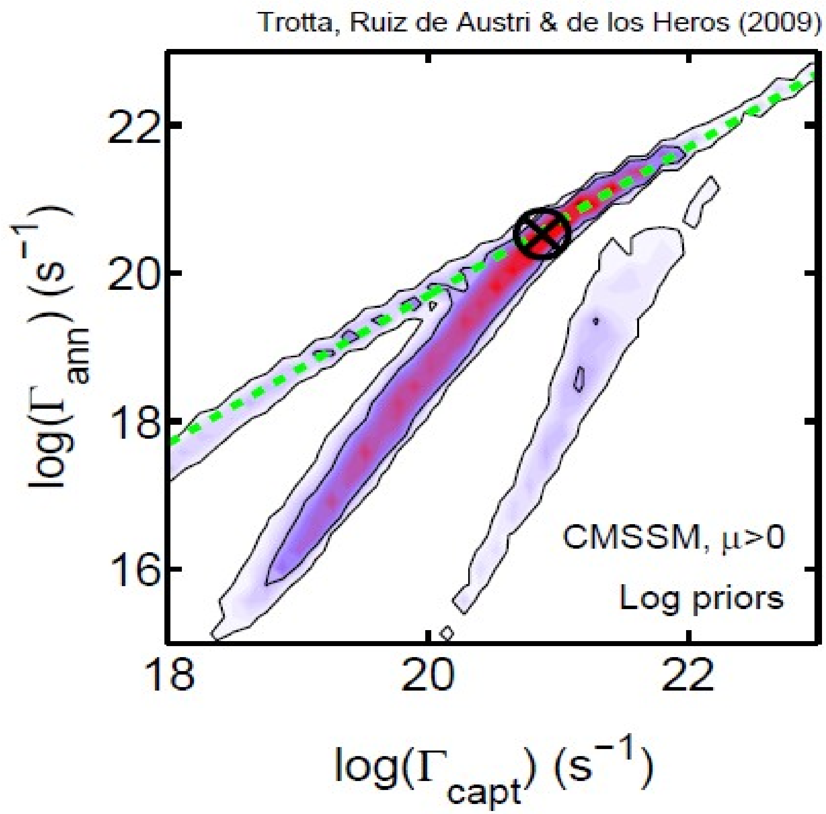








How well does the assumption of capture-annihilation equilibrium in the Sun face reality?

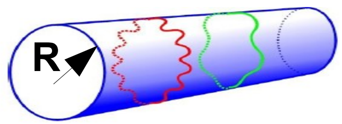


There are indeed models which predict equilibrium, but given a DM framework, it is not guaranteed to happen in all cases

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'



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

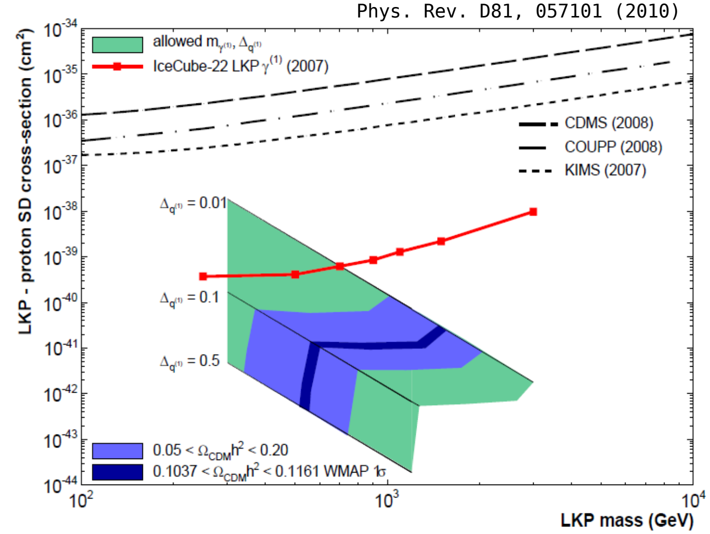
$$E^2 = p^2c^2 + m_o{}^2c^4 = n^2\frac{1}{R^2}c^2 + m_o{}^2c^4 = m_n{}^2c^4$$

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

n=1 → Lightest Kaluza-Klein mode, **B**[1]
good DM candidate

90% CL LKP-p Xsection limit vs LKP mass

Phys. Rev. D81, 057101 (2010)



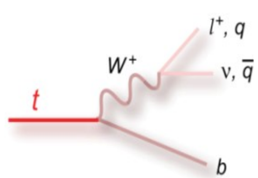
Superheavy dark matter:

- 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)

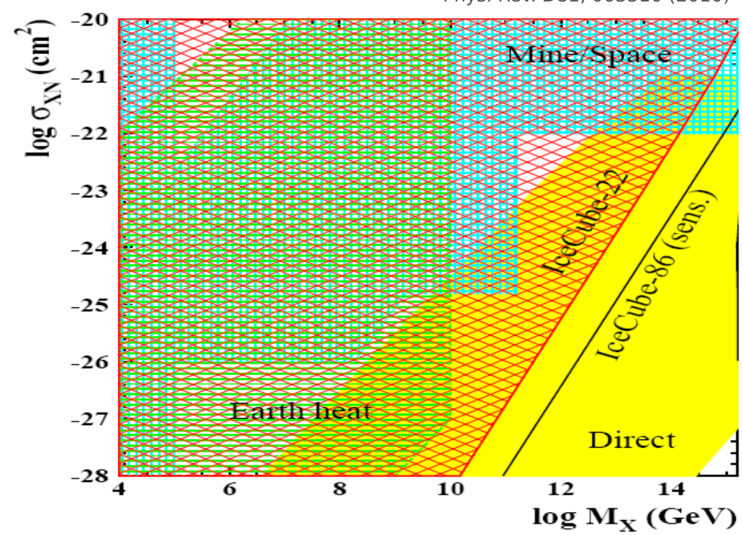
- m from ~10^4 GeV to 10^{18} GeV (no unitarity limit since production non thermal)

S+S → t $\bar{t}$ dominant



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

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

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

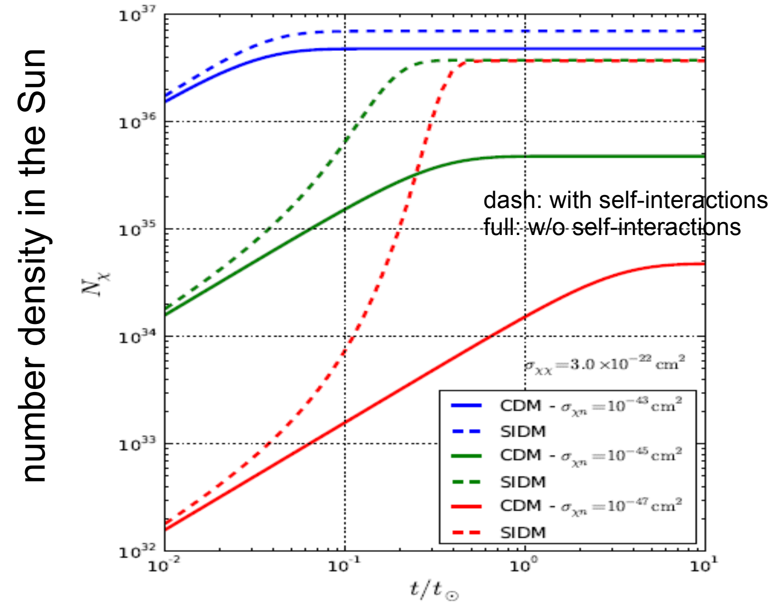
(Zentner, Phys. Rev. D80, 063501, 2009)

→ maximum annihilation rate reached earlier than in collisionless models

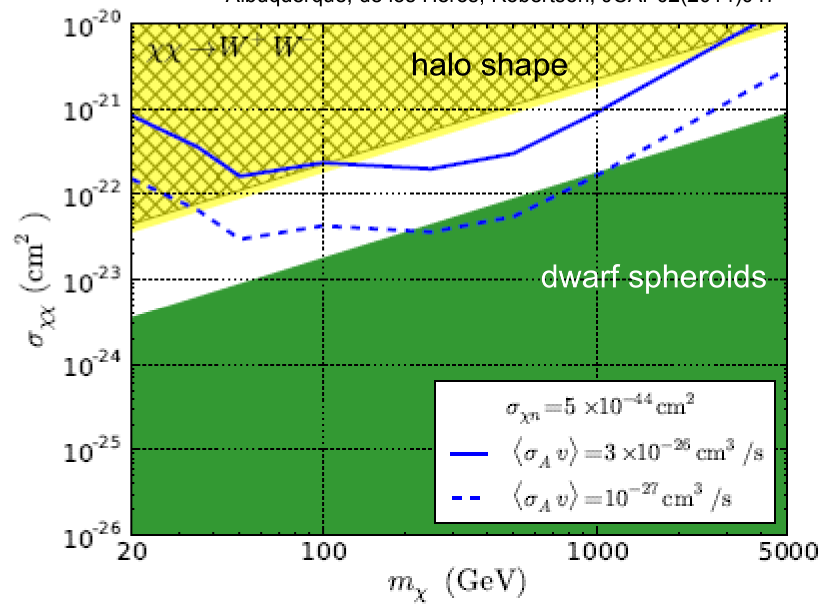
$\sigma_{\chi\chi}$ can naturally avoid cusped halo profiles

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, JCAP02(2014)047

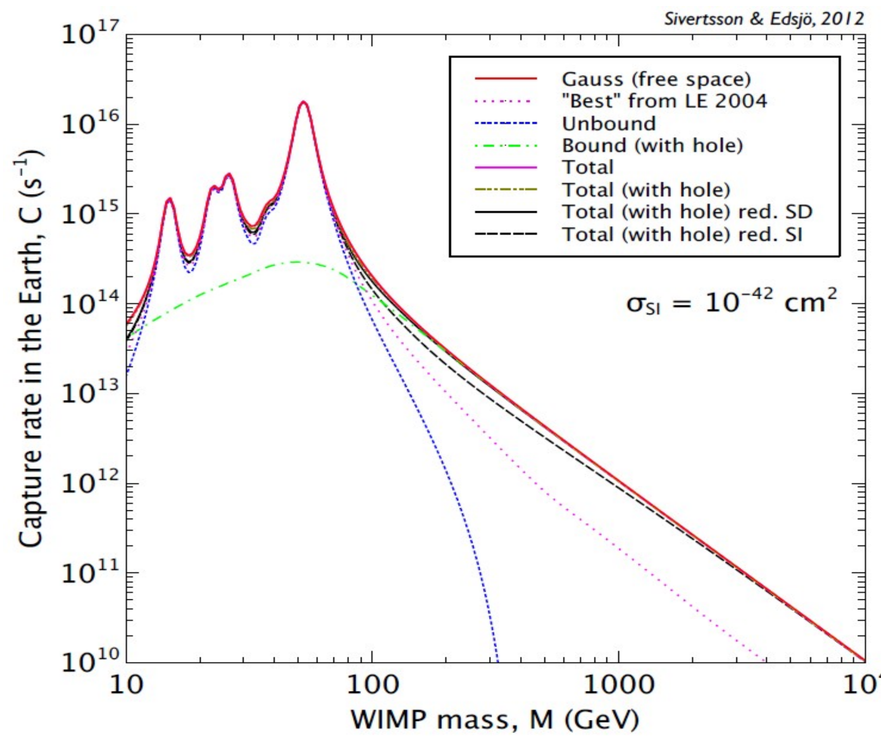


dark matter searches from the Earth

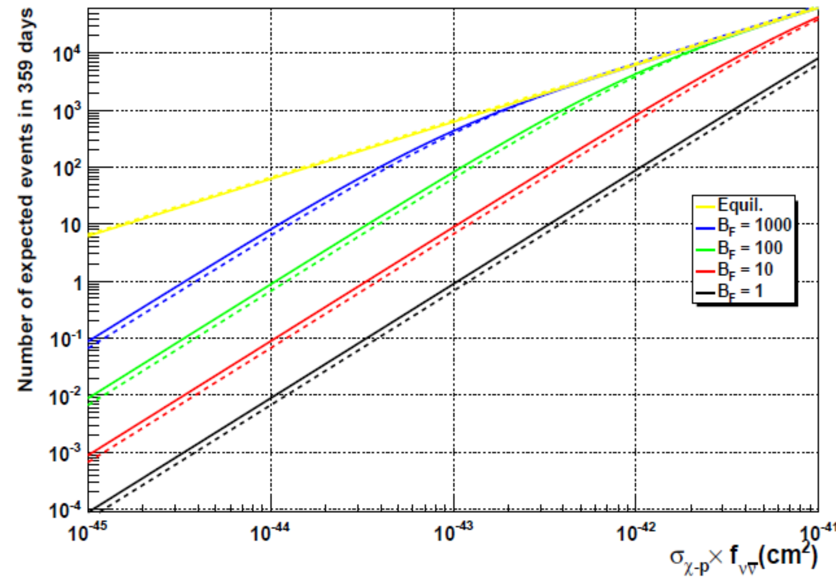
Earth capture rate dominated by resonance with heavy inner elements

→ however, initial standard assumptions on the capture rate, based on a value of $\sigma_{\chi\text{-}n}^{SI}\sim10^{-42}$ cm^2, have been recently ruled out by direct experiments

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



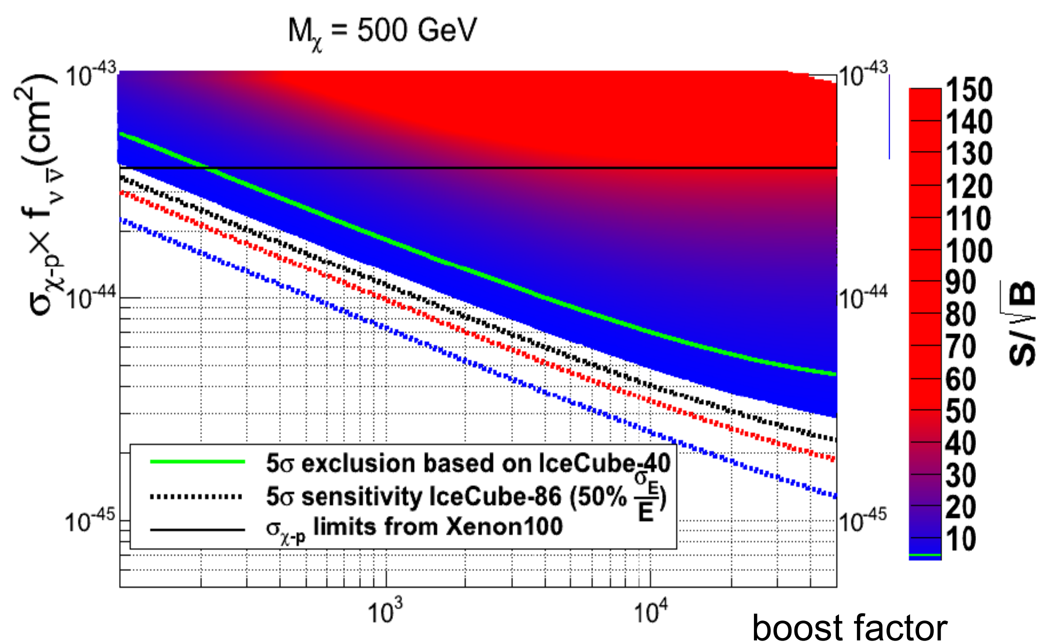
Albuquerque, Belardo Silva and P. de los Heros, arXiv:1107.2408 (2011)



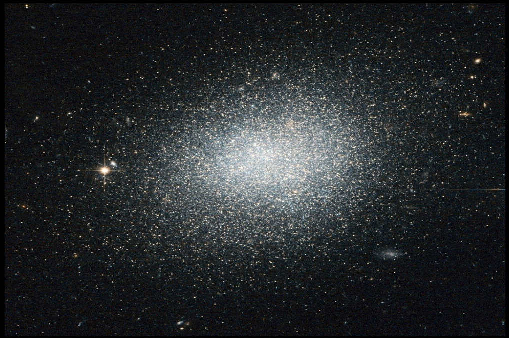
If the dark matter capture rate is enhanced, the timescale for equilibrium diminishes → flux of annihilation products can be much larger than away from equilibrium.

→ an enhanced capture Xsection could produce a detectable neutrino flux from the center of the Earth (while it is possible not to enhance the Solar flux)
(C. Delaunay, P. J. Fox and G. Perez, JHEP 0905 , 099 (2009)).

Using the atmospheric neutrino measurement of IceCube-40, model-independent limits on boost factors can be set



searches from the Galaxy and nearby galaxies



probe DM annihilation cross section

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

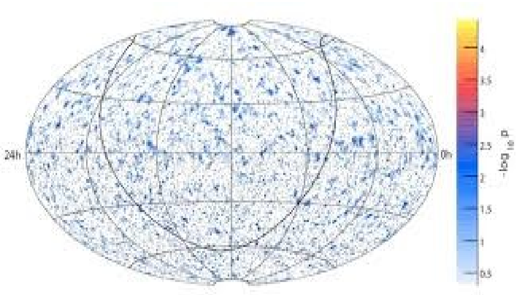
Ingredients:

probe DM annihilation cross section

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

Ingredients:

measurement



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

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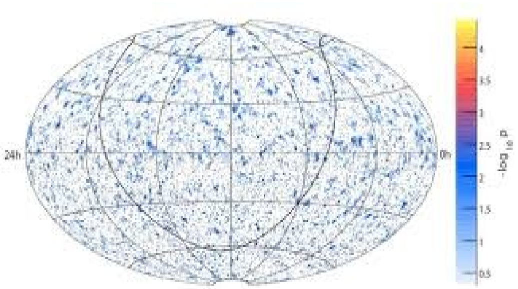
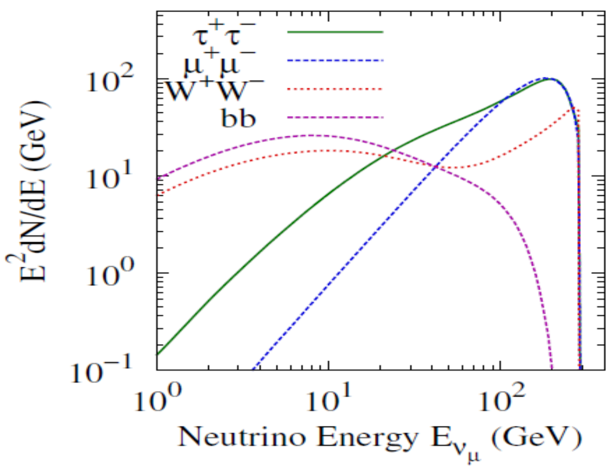


particle physics model

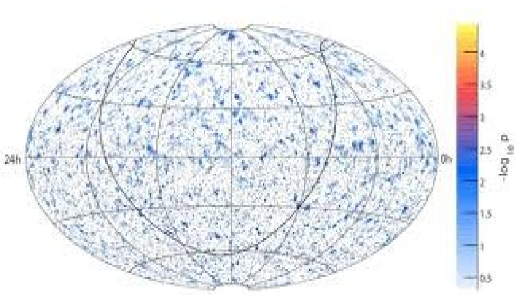


probe DM annihilation cross section

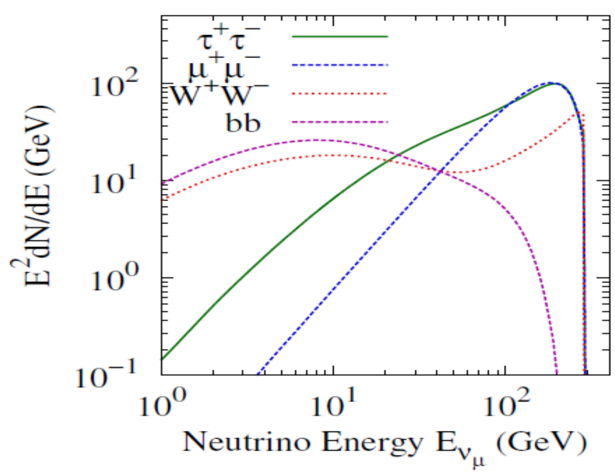
$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f\frac{dN}{dE}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$

Ingredients:

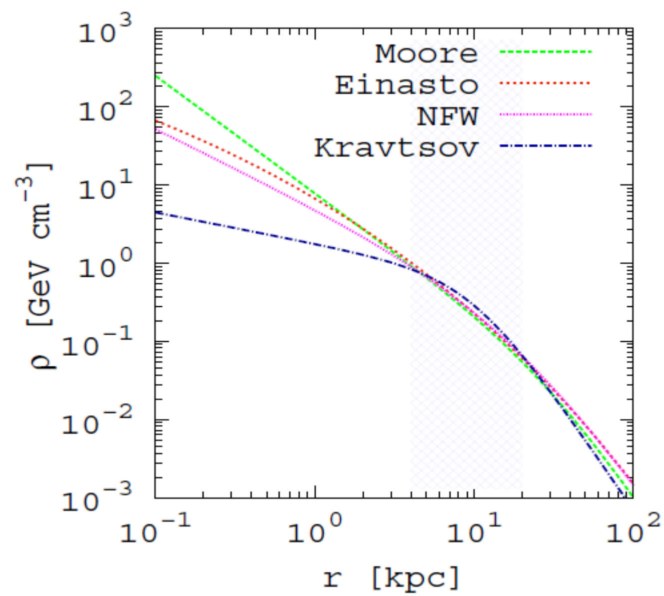
measurement



particle physics model

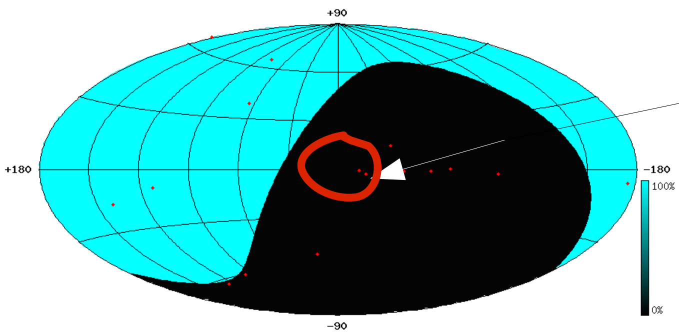


halo model



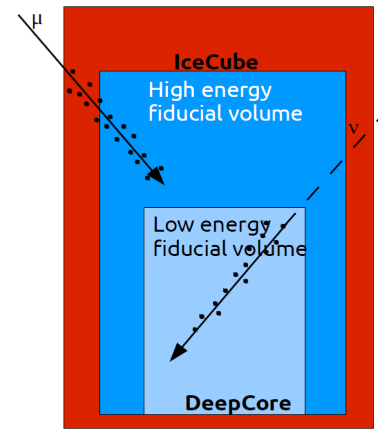
At the South Pole the GC is above the horizon. No possibility of using the Earth as a filter.

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

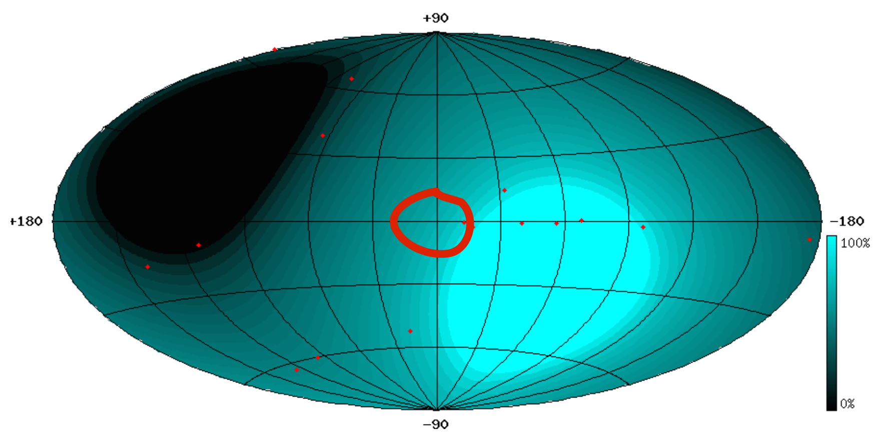


accessible by defining starting tracks.

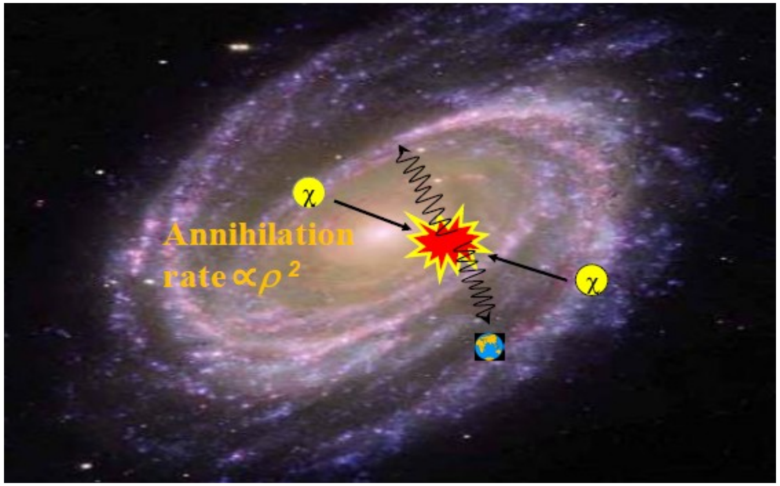
different energy reach than with full fiducial volume



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



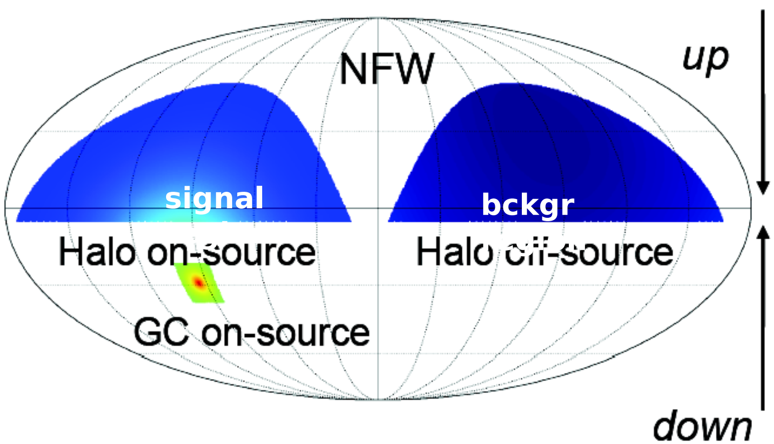
dark matter searches from the Galactic halo

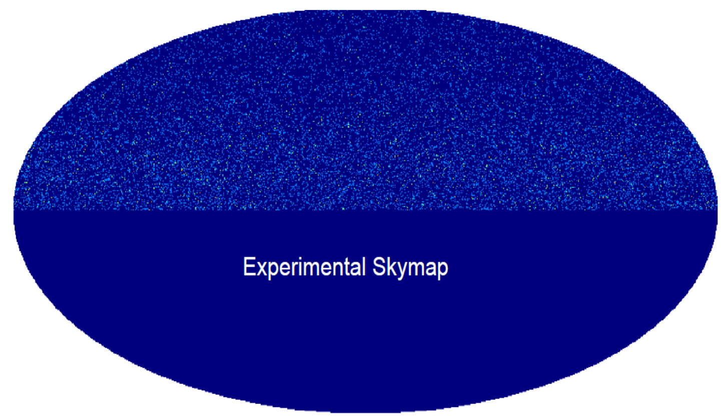


- Look for an excess of events in the on-source region w.r.t. the off-source

or,

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

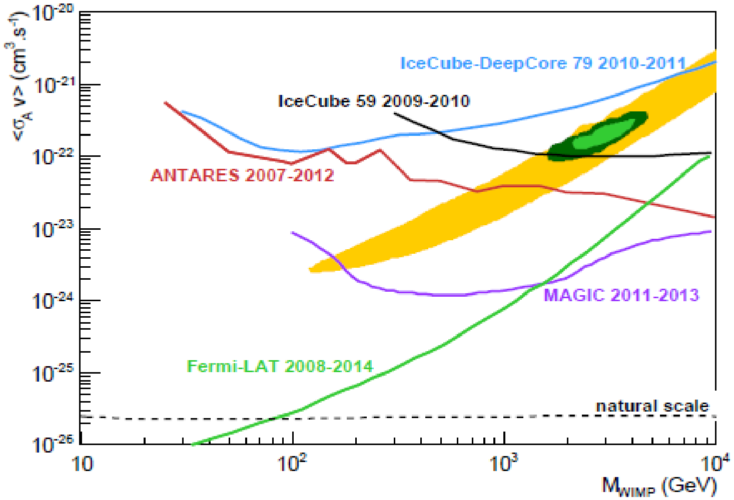




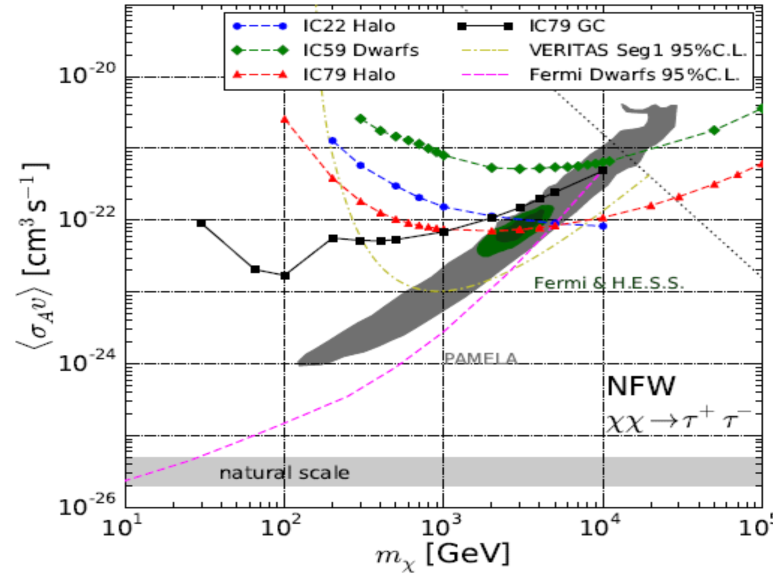
dark matter searches from the Galaxy: results

all measure <σv>:

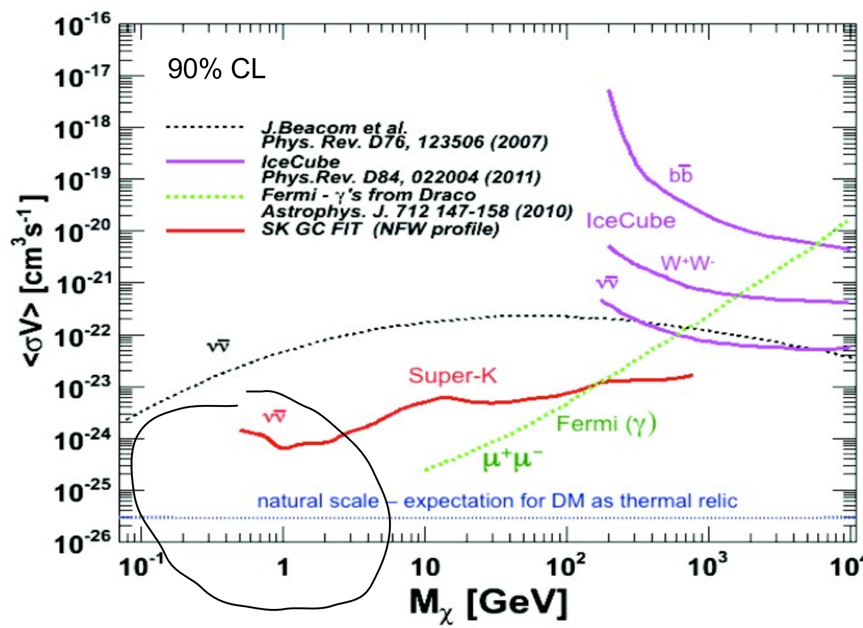
ANTARES Galactic Center ττ channel



IceCube Galactic Center ττ channel



Super-K Galactic Halo



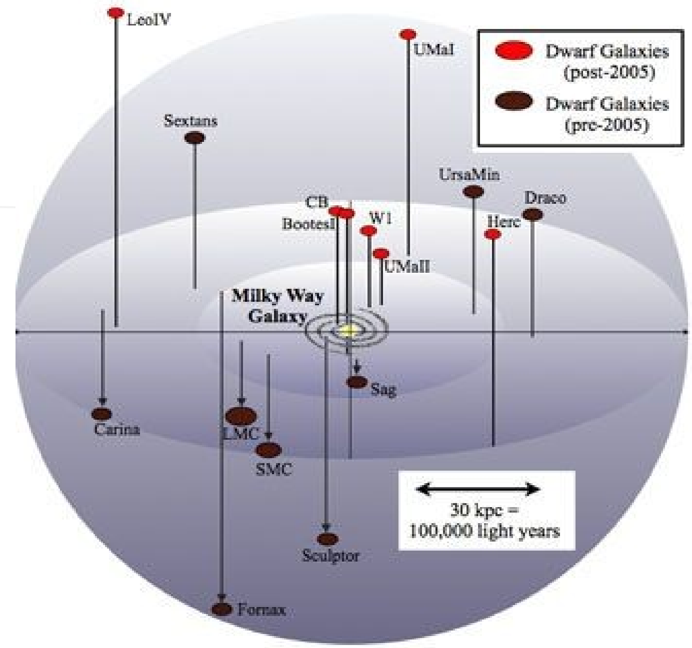
note the access to the very low mass region

dark matter searches from the dwarf galaxies/galaxy clusters

- <u>Dwarf galaxies</u>: 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
- <u>Galaxy clusters</u>: enhance signal due to accumulation of sources

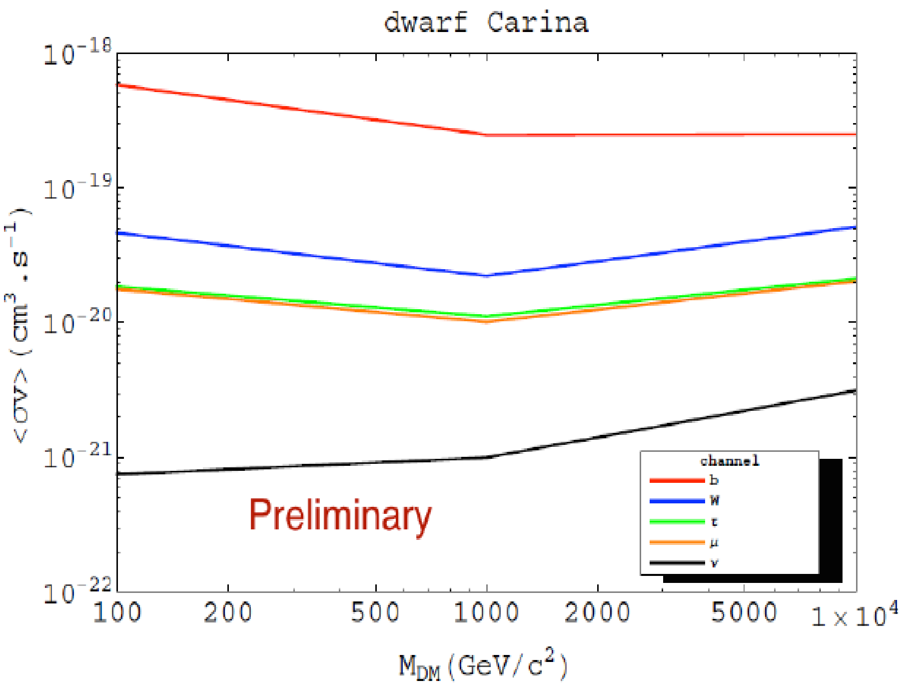
  But: extended sources with possible substructure

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

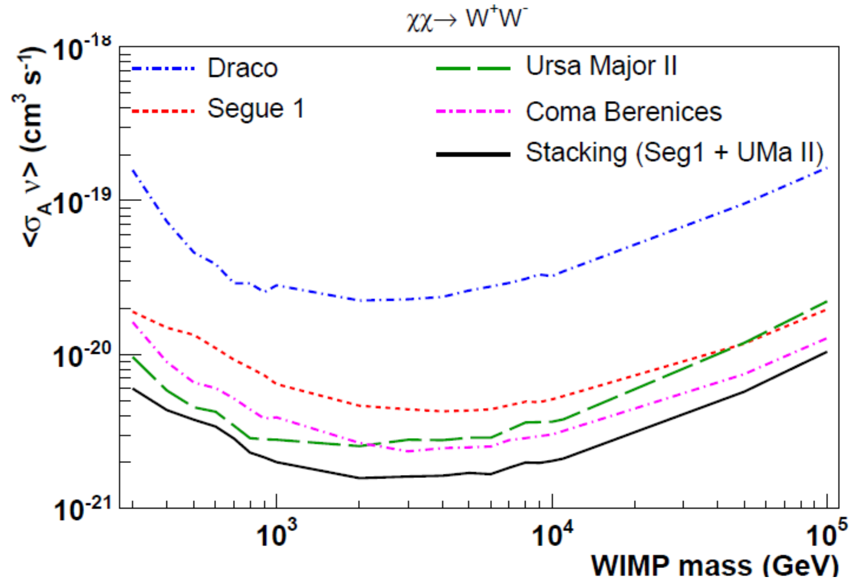


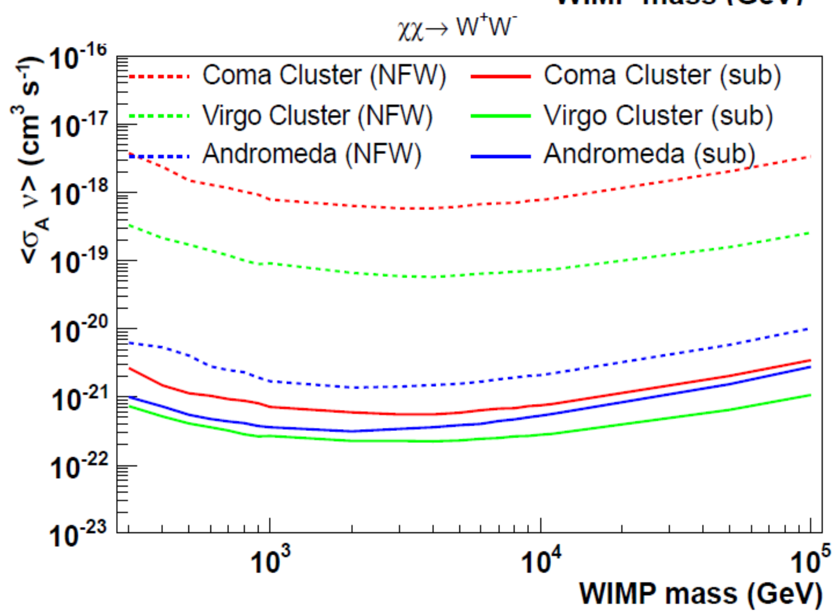
all measure <σv>:

ANTARES work in progress



IceCube Phys. Rev. D88 (2013) 122001





- Neutrino telescopes 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) end

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

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

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]
$m_b(m_b)^{\overline{MS}}$ [GeV]	4.20 ± 0.07		[22]
$[\alpha_{em}(M_Z)^{\overline{MS}}]^{-1}$	127.955 ± 0.030		[22]
$\alpha_s(M_Z)^{\overline{MS}}$	0.1176 ± 0.0020		[23]
Astrophysical			
ρ_{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]

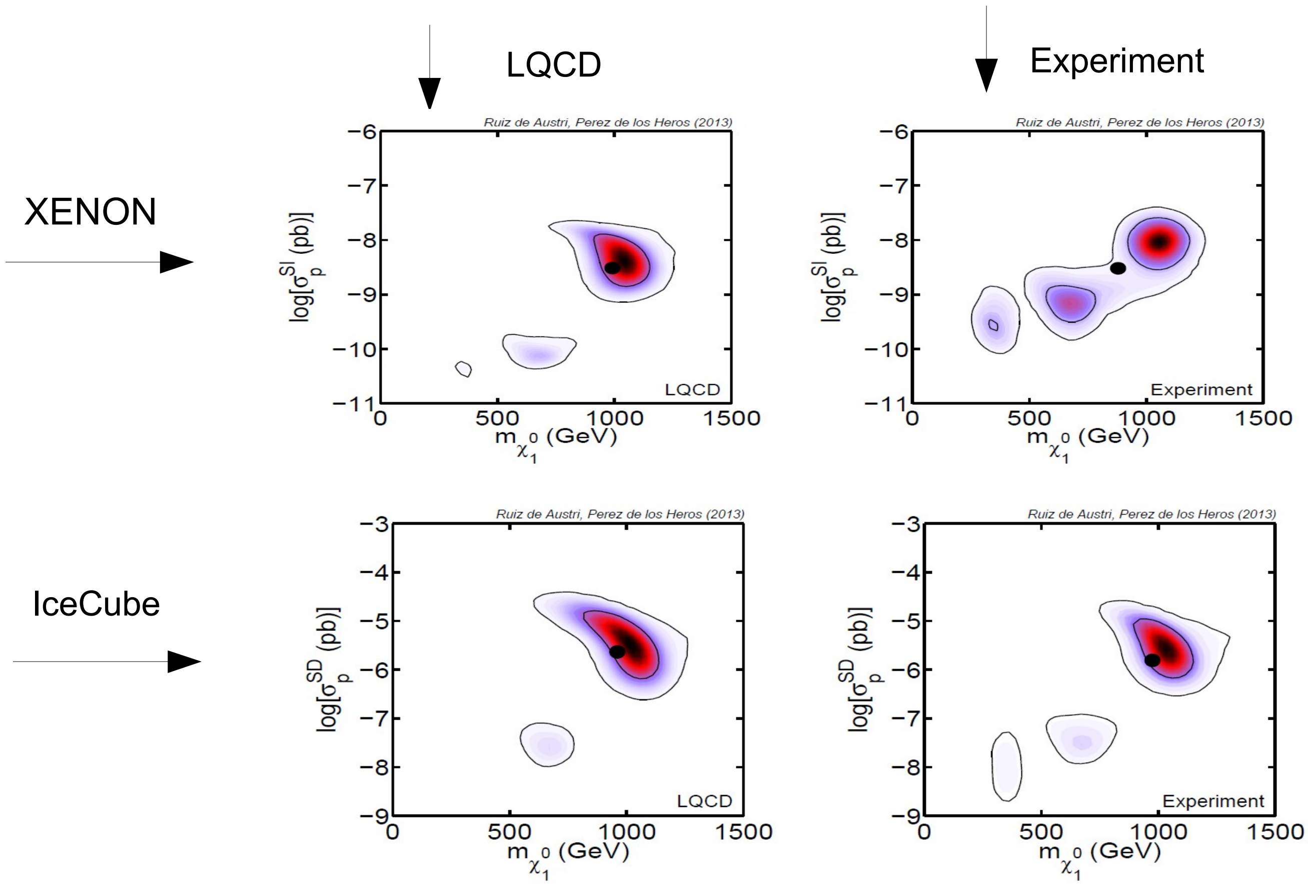
Study the resulting model rejection power of the experiments

(Xenon and IceCube taken as benchmark) depending on the value of the hadronic parameters chosen

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

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

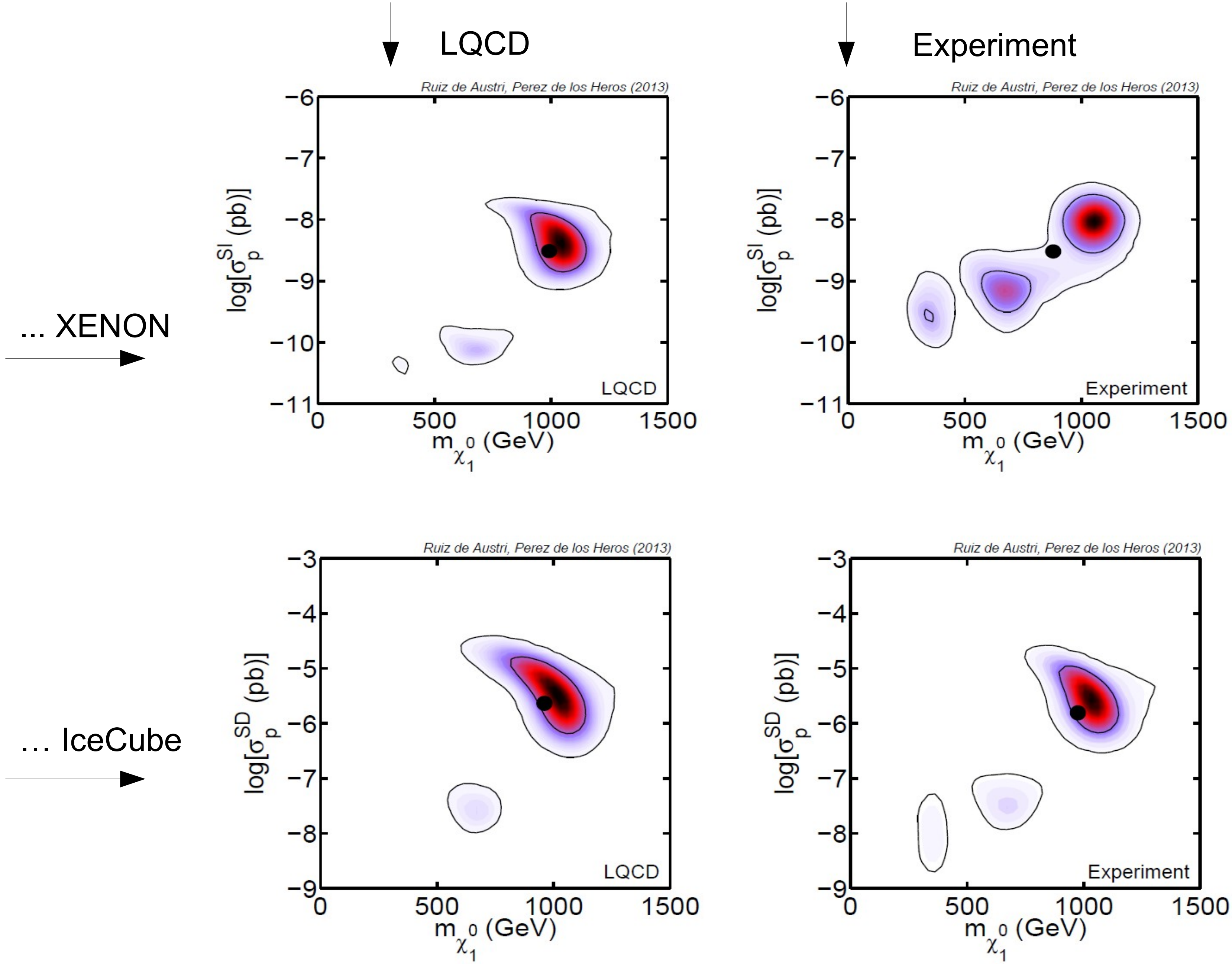
Perform scans on the cMSSM parameter space, calculating σ_{SD} and σ_{SI} for each model, but using two extreme values of Δ_q^N and f_{Tq}



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.

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

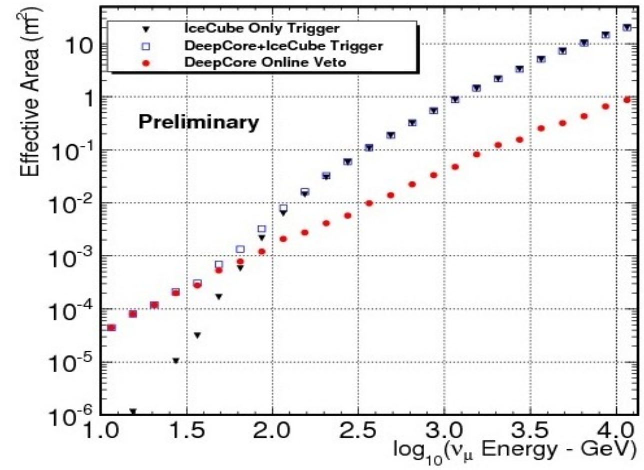


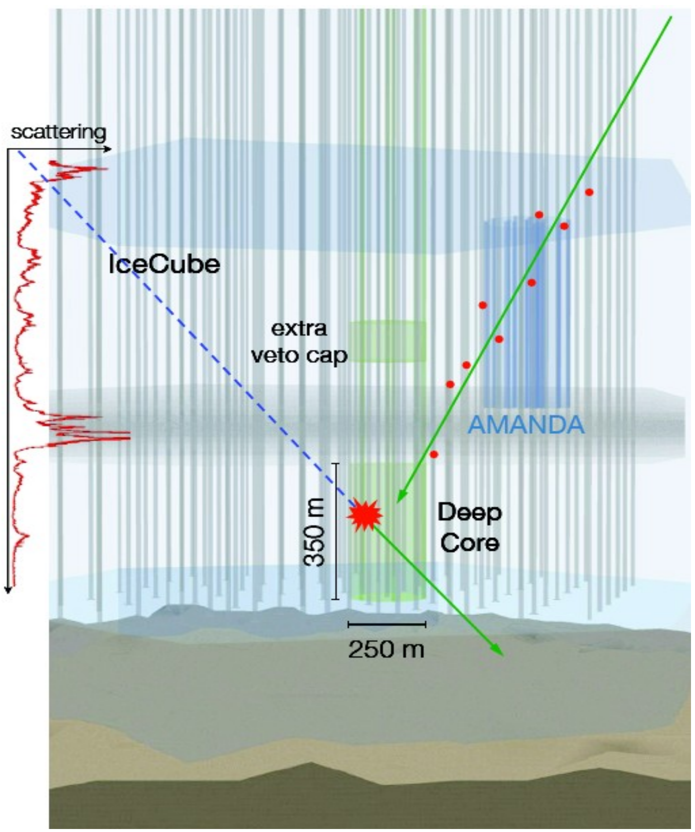
full sky sensitivity using IceCube surrounding strings as a veto:

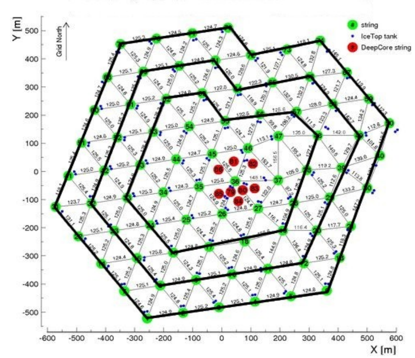
375m thick detector veto: three complete IceCube string layers surround DeepCore

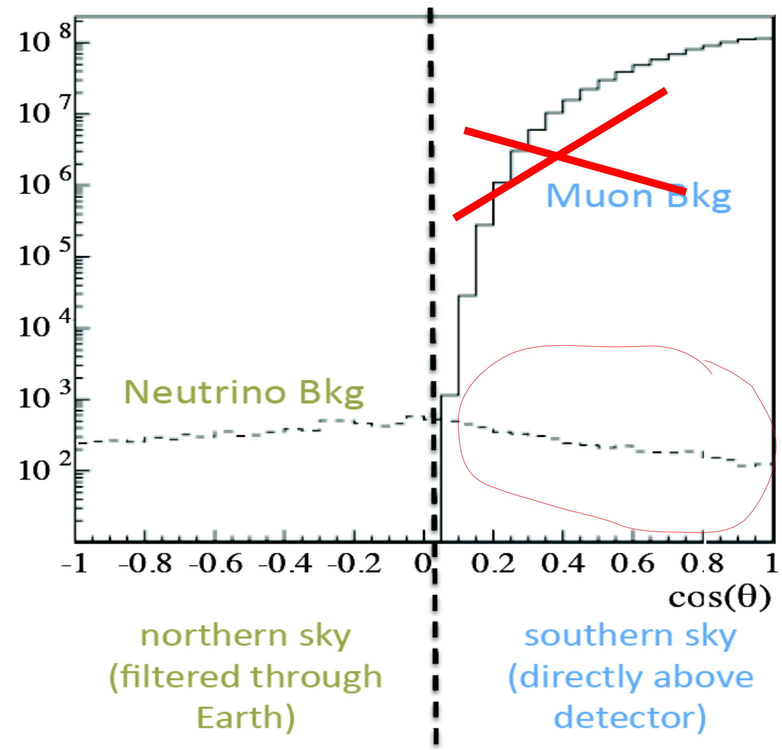
--> access to southern hemisphere, galactic center and all-year Sun visibility

IceCube is a 4π detector





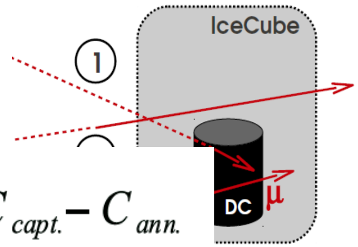




IceCube solar search results

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

All-year round search:



$$\frac{dN}{dt} = C_{capt.} - C_{ann.}$$

$$C_{ann.} = C_{capt.} \rightarrow \sigma_{total}$$

Extend the search to the southern hemisphere by selecting starting events

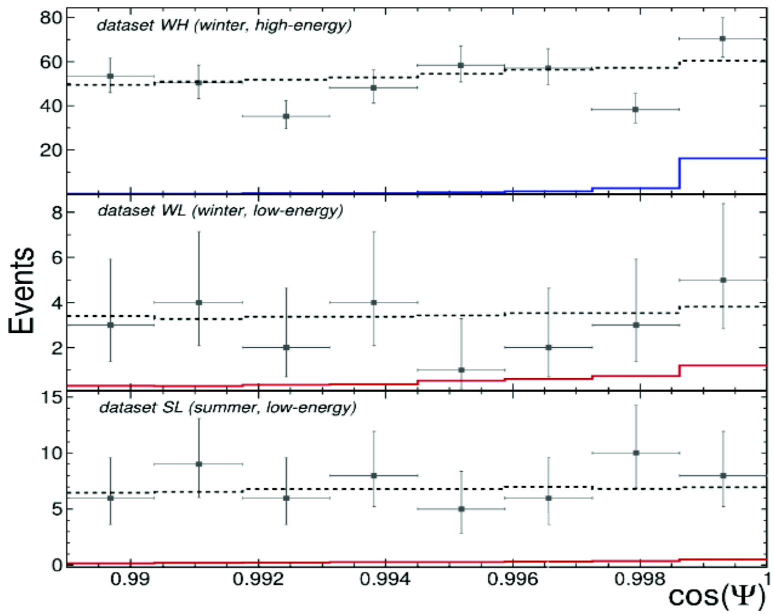
→ Veto background through location of interaction vertex

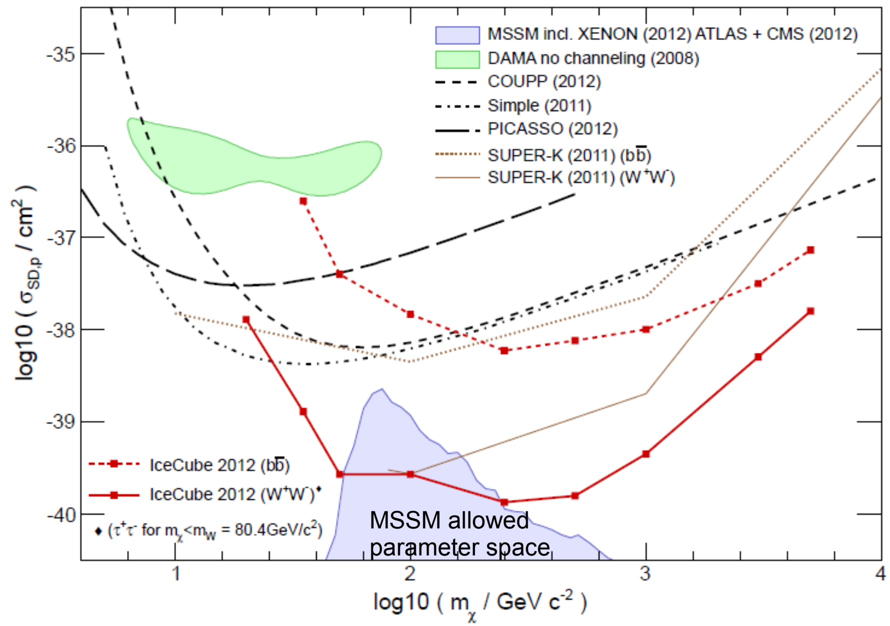
- muon background: downgoing, no starting track
- WIMP signal: require interaction vertex within detector volume

Analysis reaches neutrino energies of ~20 GeV.

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

Unblinded events in different samples



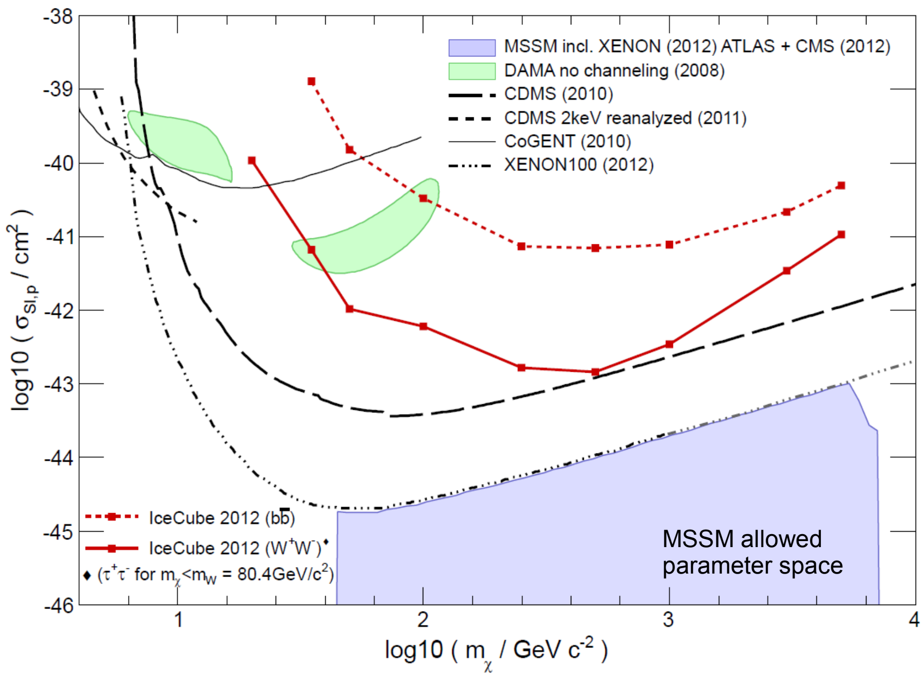


$$\frac{dN}{dt} = C_{capt.} - C_{ann.}$$

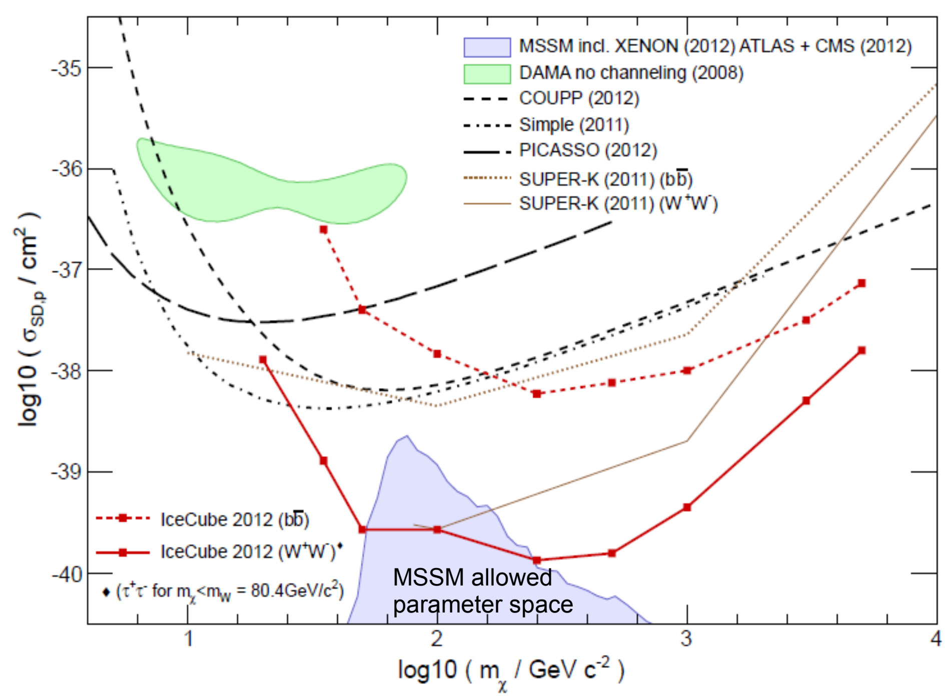
$$C_{ann.} = C_{capt.} \rightarrow \sigma_{total}$$

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

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



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

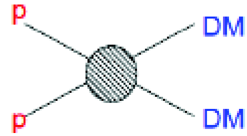


- most stringent SD cross-section limit for most models
- complementary to direct detection search efforts
- different astrophysical & nuclear form-factor uncertainties

searches from the Sun: comparison with LCH results

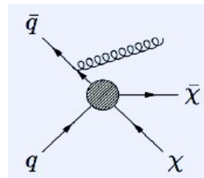
Assume (ie. model dependent) effective quark-DM interaction,

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



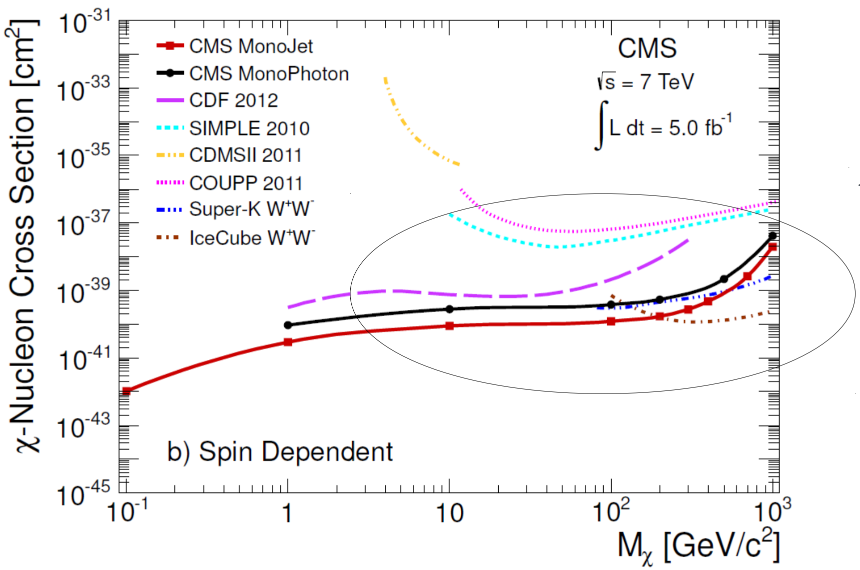
and look for monojets in pp collisions,

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



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

Constrains from monojet searches at the LHC (CMS):



90% CL neutralino-p Xsection limit