Lecture 2:
Neutrinos as signals for dark matter

Carlos de los Heros
Uppsala University

ISAPP Summer School "The Multiwavelength Universe"
Belgirate, July 21-30, 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

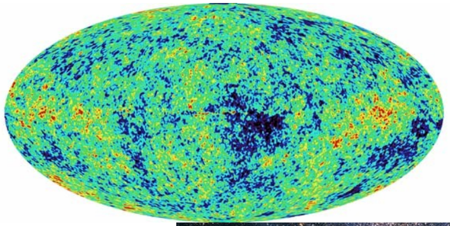
$\nu, \bar{\nu}$ from annihil in massive bodies

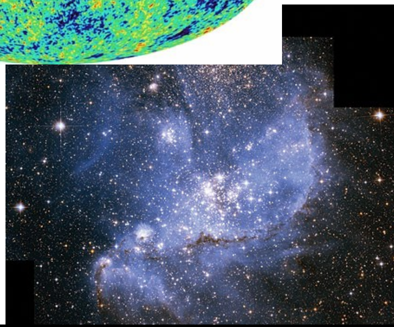
SK, **Icecube**, Km3Net

(from M. Cirelli)

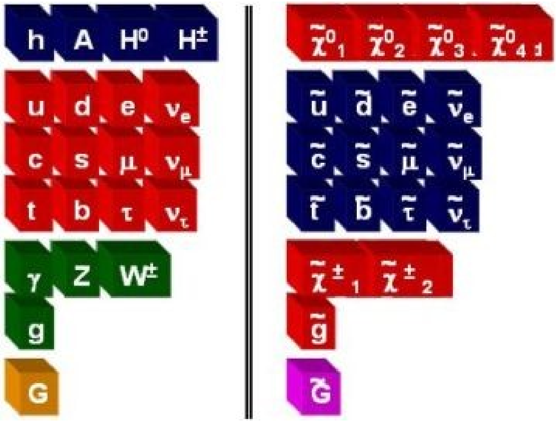
this is **also** a simple lecture: outline

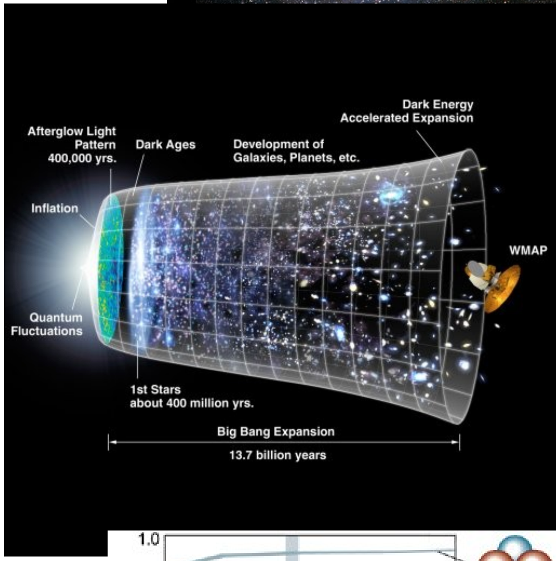
- Candidates
- Sources
- Detection techniques



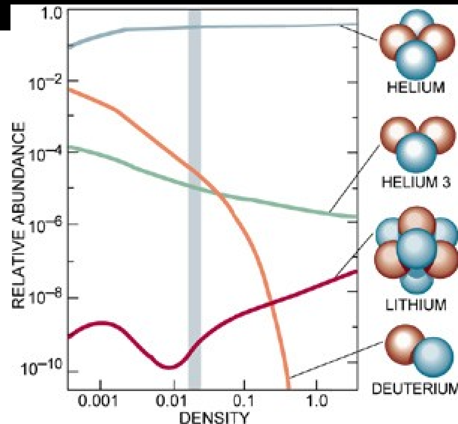


Models to explain the elementary particles and their interactions as studied in laboratory experiments can not spoil the understanding we have of the early universe and its evolution towards what we observe today.





This provides a strong link between particle physics and astrophysics/cosmology



Cosmology limits the possible models of particle physics

Particle Physics ‘decides’ what is possible in the Universe

how does dark matter fit in all this?

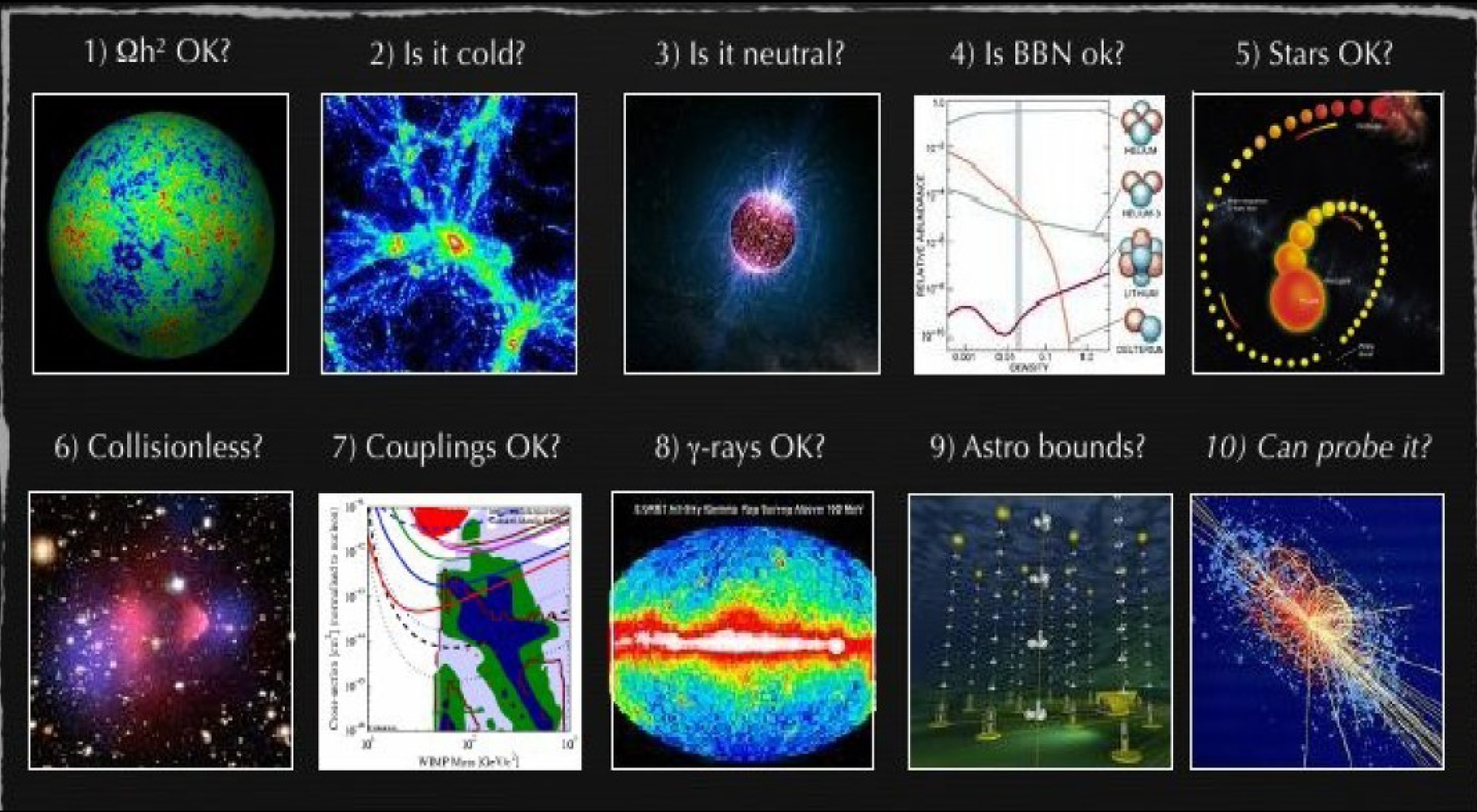
- Rotation curves of stars in galaxies
- Movement of galaxies in clusters
- Cosmic microwave background
- Gravitational lensing

- … and the result is:
  - The Universe is 23% dark, ie, composed of matter that does not emit electromagnetic radiation
  - It has to be non-baryonic, ie, not 'normal'

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



(graphic stolen from G. Bertone)

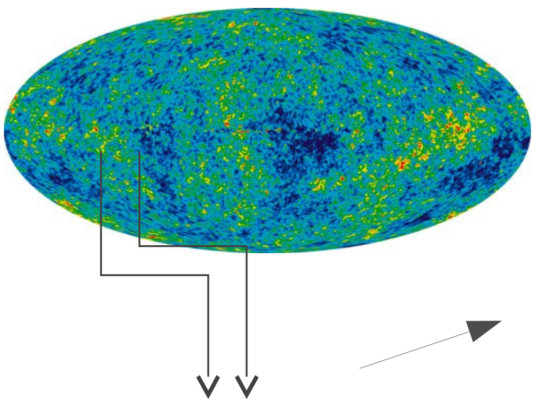
Things that do not shine?

(‘MACHOs’ , Massive Compact Halo Objects): dead stars, unobserved planets, cold gas clouds...

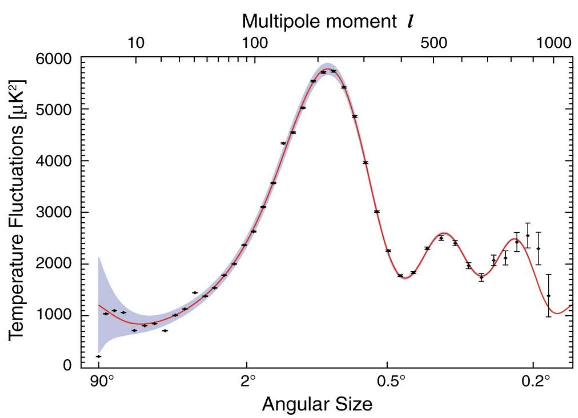
But these are objects made of **baryonic matter** (usual stuff: p’s and n’s).

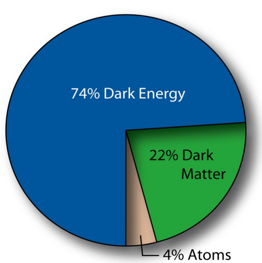
How much unseen baryonic matter can we accommodate in the Universe?

CMB analysis

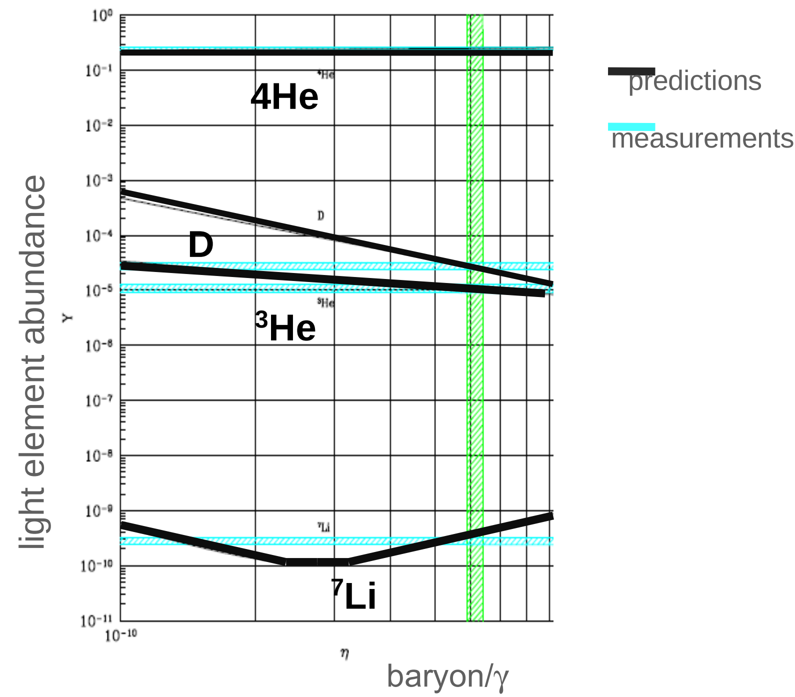


$\Delta T, \Theta$





primordial nucleosynthesis



Not enough: big bang nucleosynthesis and CMB data put a very precise limit on how many baryons there are in the Universe. Otherwise the amount of observed primordial light elements (D, He, Li) can not be explained

Neutrinos: They exist! And we know they have mass, not much, but there are many of them. However, not enough to explain the missing mass:

experimental limits on the neutrino mass:

$$\sum m_\nu \leqslant 2\, eV$$

The cosmic mass density of neutrinos calculated from Big-Bang theory

$$\Omega_\nu h^2 = \sum_{i=1}^{3} \frac{m_i}{93 eV}$$

$$\Omega_\nu h^2 \leq 0.07 << 1$$

$$\left(h = H_o / 100 \;\; km\, s^{-1}\; Mpc^{-1} \right)$$

ie, neutrinos are not abundant enough to be **the dominant** dark matter

Besides, the Pauli exclusion principle limits the number of neutrino states that can be accommodated in a galactic halo:

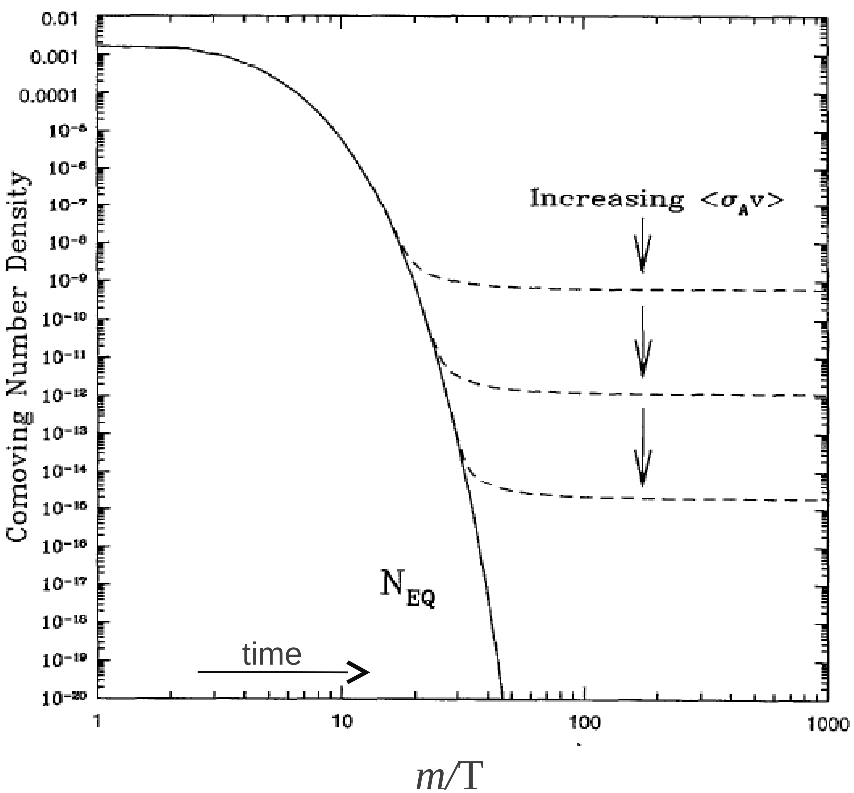
$$n_\nu (E) = g_\nu \frac{1}{e^{E/kT} + 1}$$

(g_ν=nb. of helicity states)

Need other candidates!

Solution: Non-baryonic matter as WIMPS (Weakly Interacting Massive Particles)

Assumed to be stable relics of the Big Bang with weak-type cross section



Relic-density calculations of a thermally produced particle are based on the Boltzmann equation describing the number density of a species as a function of time and its interaction probability (cross section)

(just thermodynamics of an expanding gas)

$$\frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle \left(n^2 - n_{eq}^2 \right)$$

$$\Omega_i h^2 \approx \frac{10^{-27}}{\langle \sigma_A v \rangle} \ \mathrm{cm^3 s^{-1}}$$

This solution has a problem: non-baryonic matter has never been observed.

The particles proposed as candidates are theoretical predictions of models not yet verified, **Supersymmetry, Extra dimensions…**

the particle physics connection: Supersymmetry

- MSSM: Minimal Supersymmetric extension of the Standard Model
- An extension of the Standard Model
- Introduces (predicts) many new particles (one per existing elementary particle, differing in spin by 1/2)
- One has to be stable
- Is a good candidate for dark matter: neutralino, $\tilde{\chi}^0_1 = N_1\mathbf{B} + N_2\mathbf{W}_3 + N_3\mathbf{H}^o{}_1 + N_4\mathbf{H}^o{}_2$
- It is produced in the big bang and a 'sea' of them remains as relics
- They interact only weakly and gravitationally
- Can be gravitationally bound in the halos of galaxies and be further trapped in heavy bodies: Sun, Earth, Galactic Center
- Increase concentration → annihilation $\underbrace{\chi\chi \rightarrow \text{SM particles} \rightarrow \nu\nu,\ \gamma,\ p\ldots}_{\text{Indirect detection!}}$

Standard Model particles and fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	quark	$\tilde{q}_L$, $\tilde{q}_R$	squark	$\tilde{q}_1$, $\tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L$, $\tilde{l}_R$	slepton	$\tilde{l}_1$, $\tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino		
H^-	Higgs boson	$\tilde{H}_1^-$	higgsino	$\tilde{\chi}^\pm_{1,2}$	chargino
H^+	Higgs boson	$\tilde{H}_2^+$	higgsino		
B	B-field	$\tilde{B}$	bino		
W^3	W^3-field	$\tilde{W}^3$	wino		
H_1^0	Higgs boson			$\tilde{\chi}^0_{1,2,3,4}$	neutralino
H_2^0	Higgs boson	$\tilde{H}_1^0$	higgsino		
H_3^0	Higgs boson	$\tilde{H}_2^0$	higgsino		

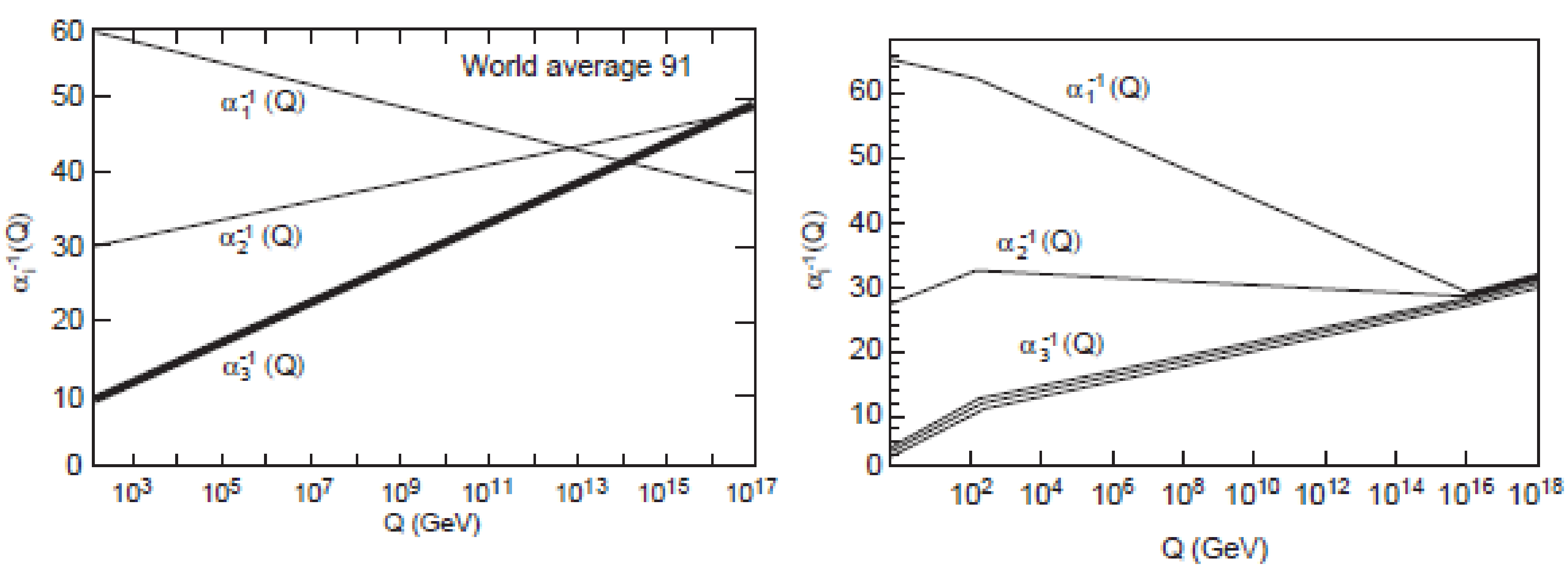


Fig. 10. The measurements of the gauge coupling strengths at LEP do not (left) evolve to a unified value if there is no supersymmetry but do (right) if supersymmetry is included [29,220].

- “elementary” particles known in 1928:

the **electron** and the **proton**

- in 1928 Dirac published his relativistic equation that predicted that every particle could have a partner of the same mass and opposite charge. The particle zoo was immediately doubled:

electron, positron and **proton, antiproton**

although it took some years to identify the e^+ (1932) and $\bar{p}$ (1955)

given the astrophysical/cosmological constrains, still possibilities

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 (Simpzillas)

Self-annihilation Xsection or interaction Xsection to SM particles:

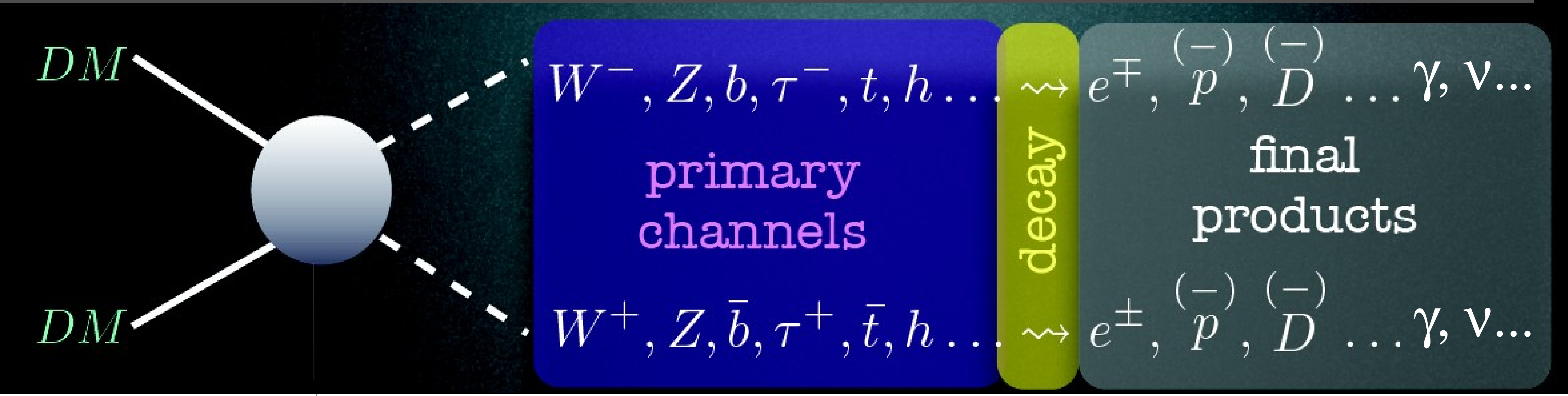
from 10^{-10} pb to 10^{-5} pb

(total γ-p Xsection ~ 200 μb)

Lifetime: 10^9 yr to infinity

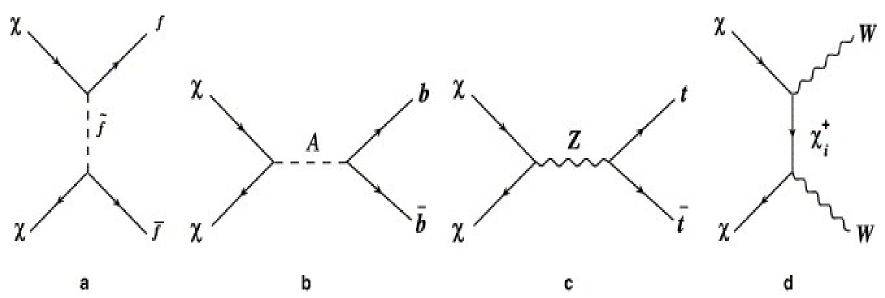
Can be constrained by neutrino telescopes

(slide from A. Ibarra)

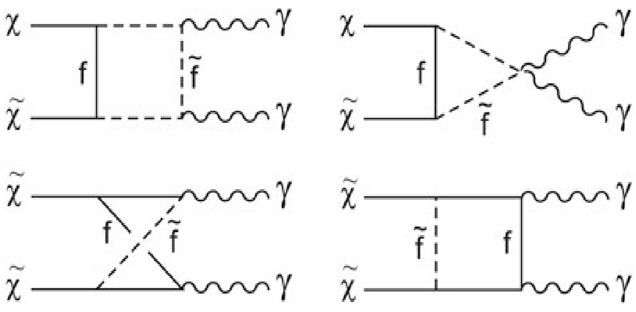


your theory here
(not necessarily SUSY...)

astrophysics inputs:
products have to be transported to the Earth
Here is where νs are advantageous



(broad spectrum)

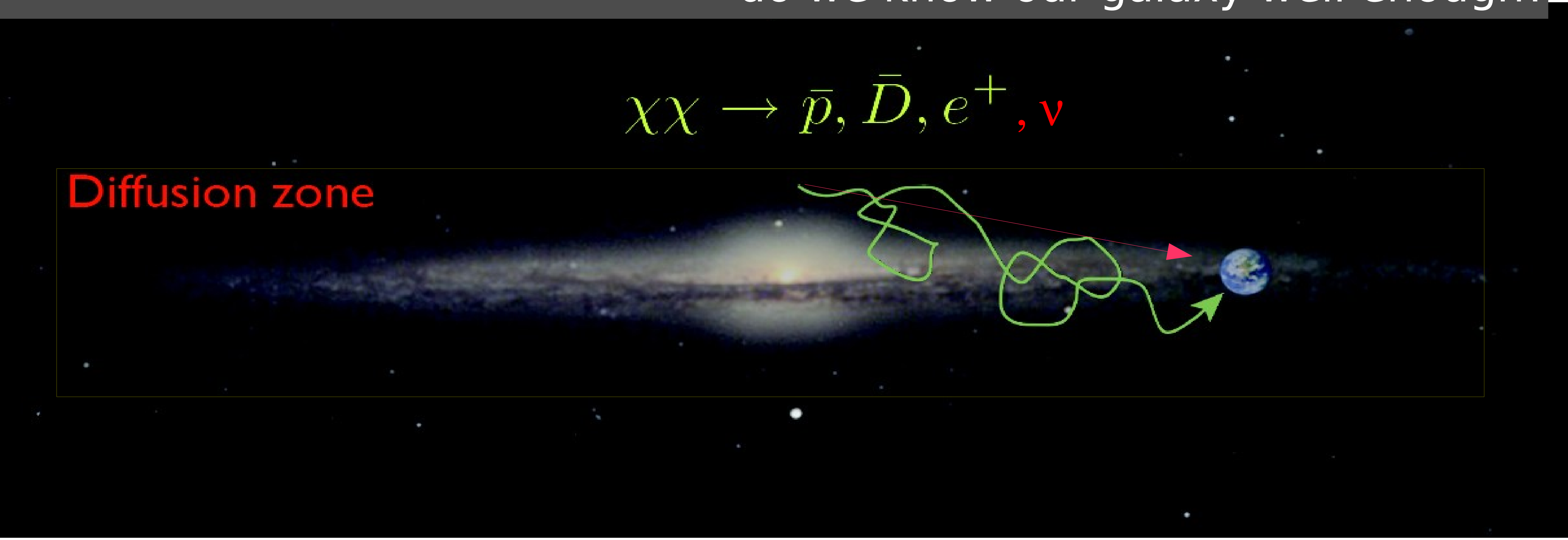


(line spectrum)

$E_\gamma = \sim m_\chi c^2$

....

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

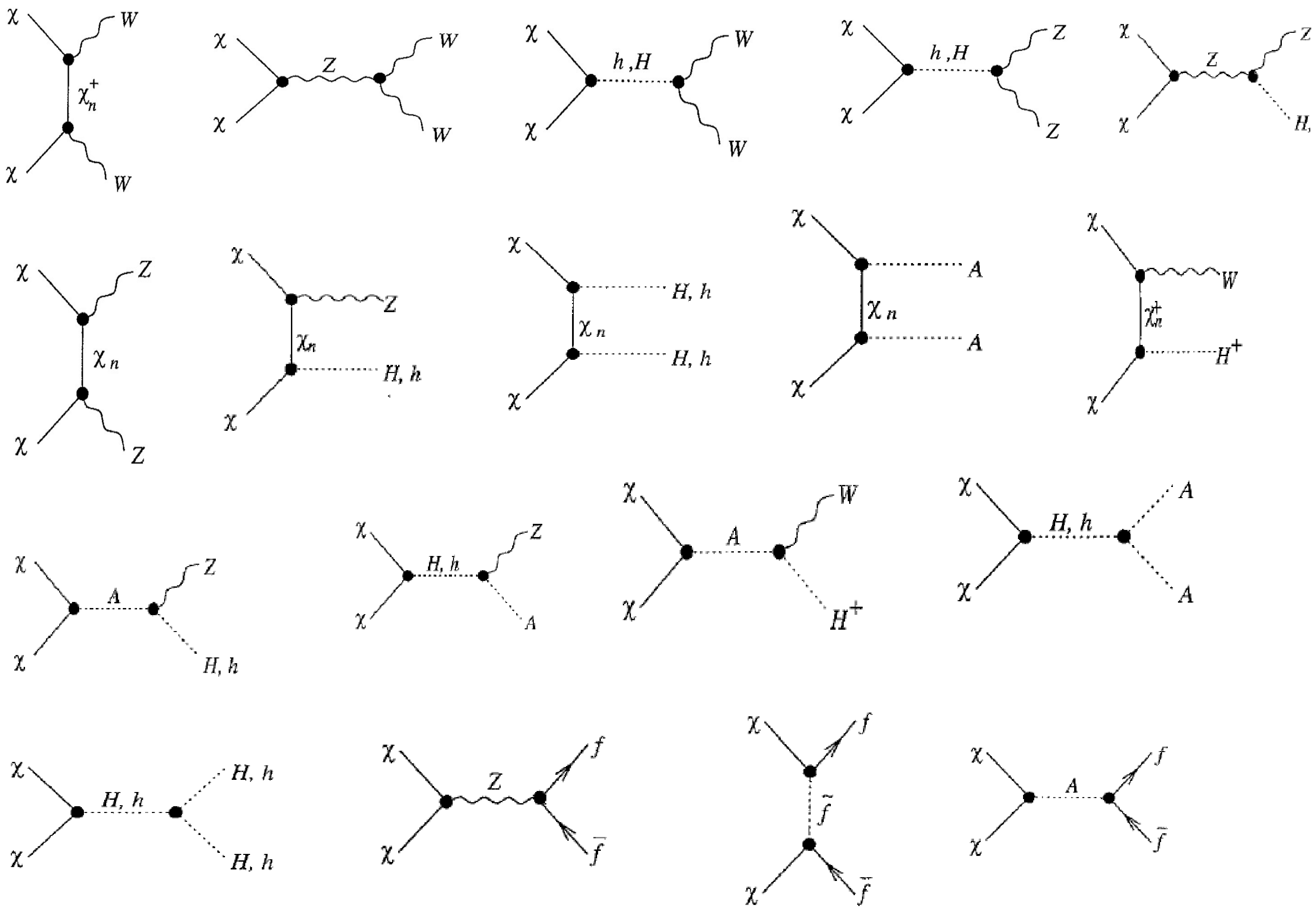
energy gain
(reacceleration)

source

galactic model

source model

… a bit more in detail...

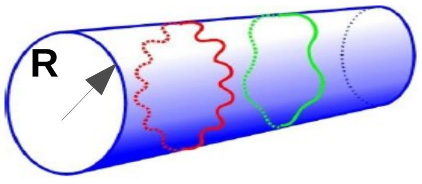


…

other candidates

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'.



- Simple quantum mechanics argument:
- Lightest Kaluza-Klein mode (n=1)
- m≈1/R~ 400 -1500 GeV

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

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

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

Superheavy dark matter (Simpzillas)

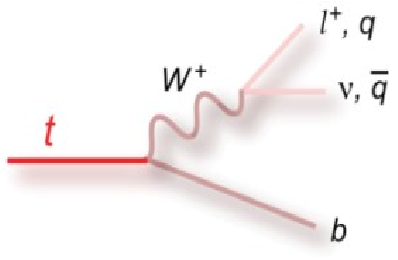
Produced **non-thermally** at the end of inflation through vacuum quantum fluctuations

strong Xsection (= not-weak)

m from **~10^4 GeV to 10^{18} GeV**

Can be accommodated in supersymmetric or UED models

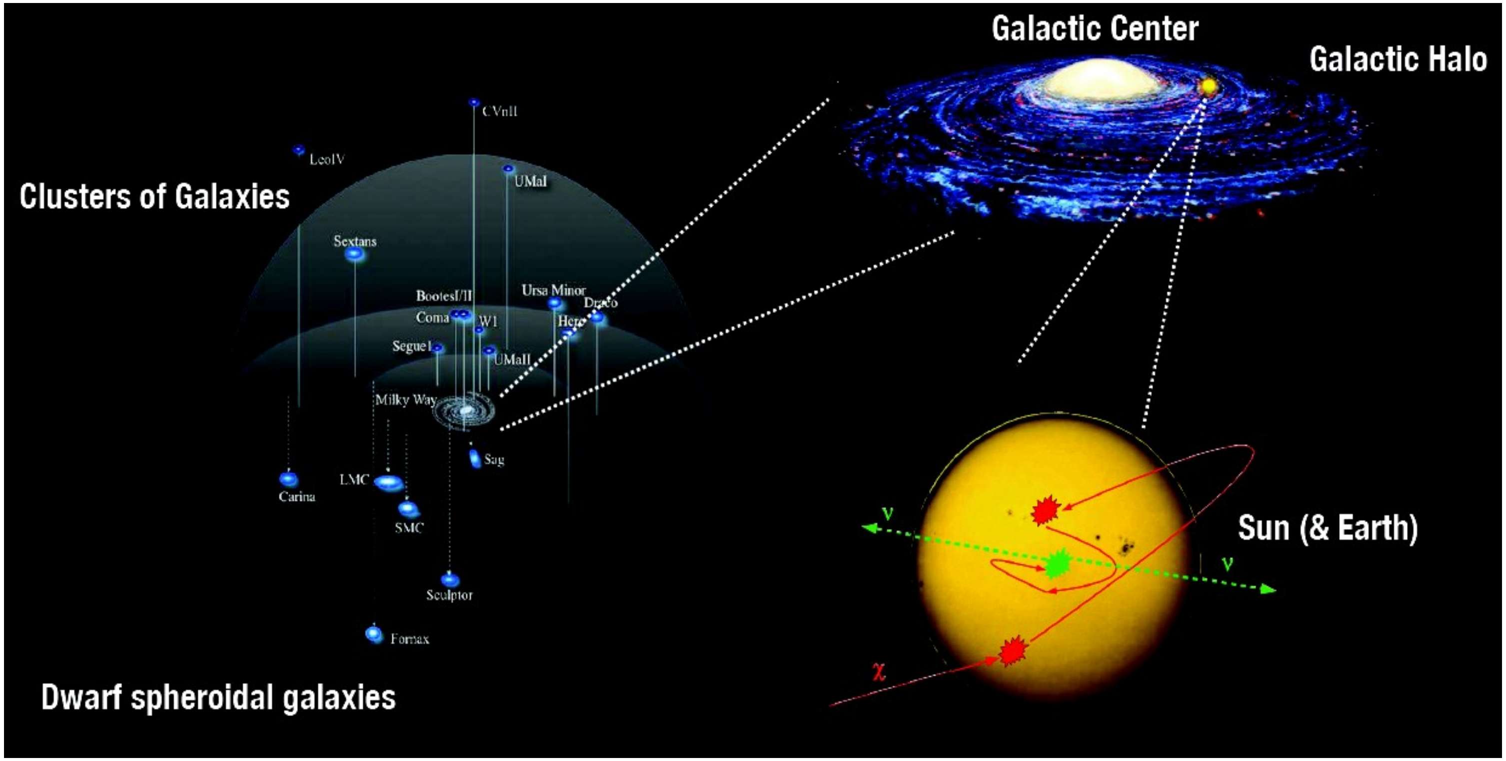
S+S → t $\bar{t}$, ~3x10^5 $\sqrt{m_S/10^{12}\mathrm{GeV}}$ tops per annihilation



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

dwarf galaxies
&
distant galaxies

Galactic
Halo

Galactic
Center

probes $\langle\sigma_A v\rangle$

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

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

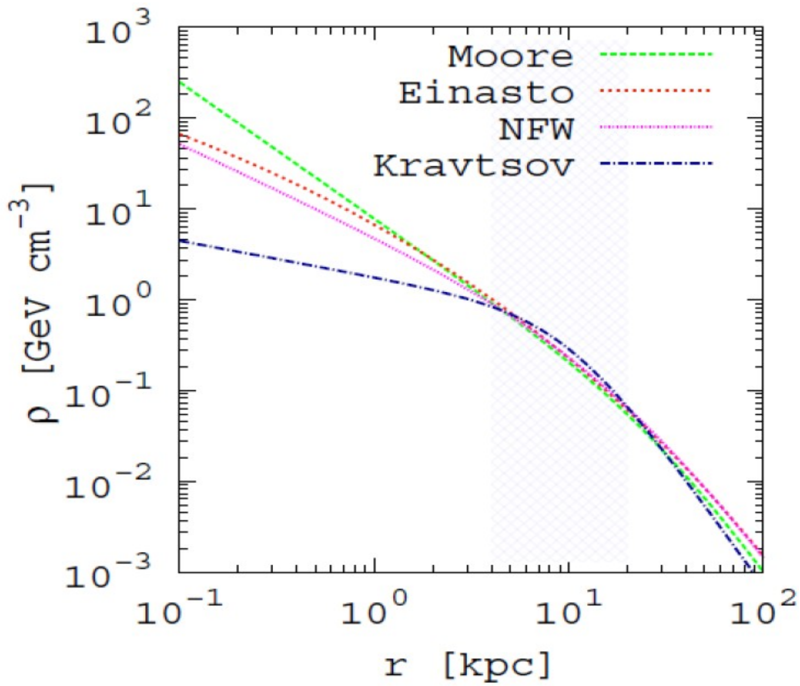
- relic density calculations (cosmology)
- dark matter distribution in the halo (astrophysics)
- velocity distribution of the dark matter in the halo (astrophysics)
- physical properties of the dark matter candidate (particle physics)
- interaction of the dark matter candidate with normal matter (for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

Astrophysical inputs needed for reliable calculations and data analyses:

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

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

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



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

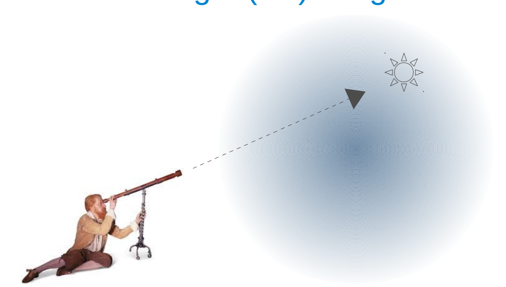
$\langle \sigma_A v \rangle$ Annihilation cross-section, velocity averaged

$\frac{dN}{dE}$ 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

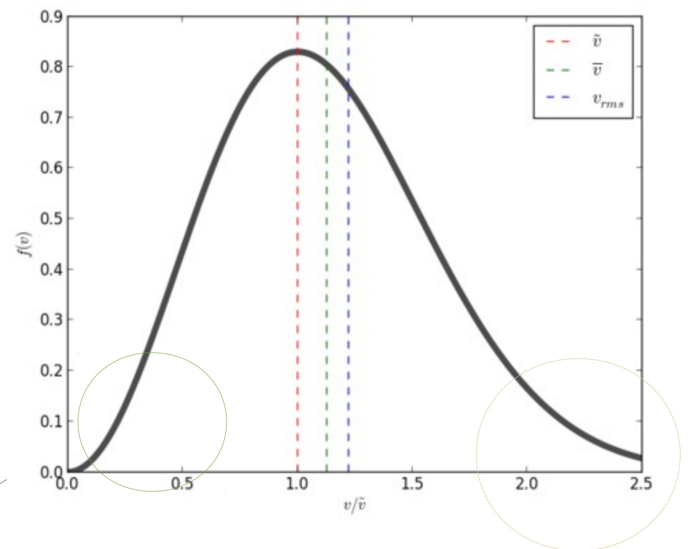


Astrophysical inputs needed for reliable calculations and data analyses:

- Velocity distribution of the DM particles in the halo

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

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

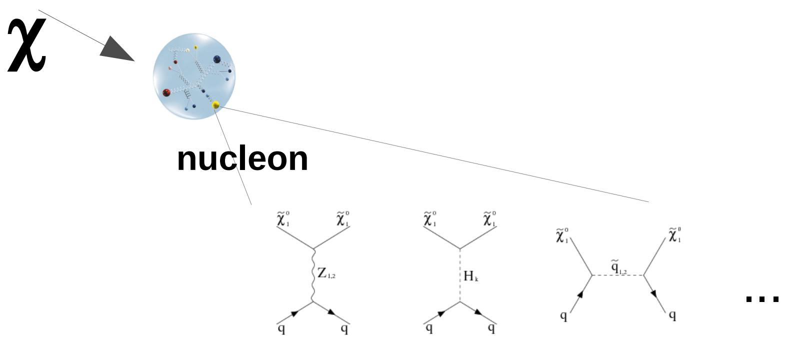


ν-telescopes sensitive
to this part of the velocity
distribution
(low-energy particles easily
captured gravitationally)

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



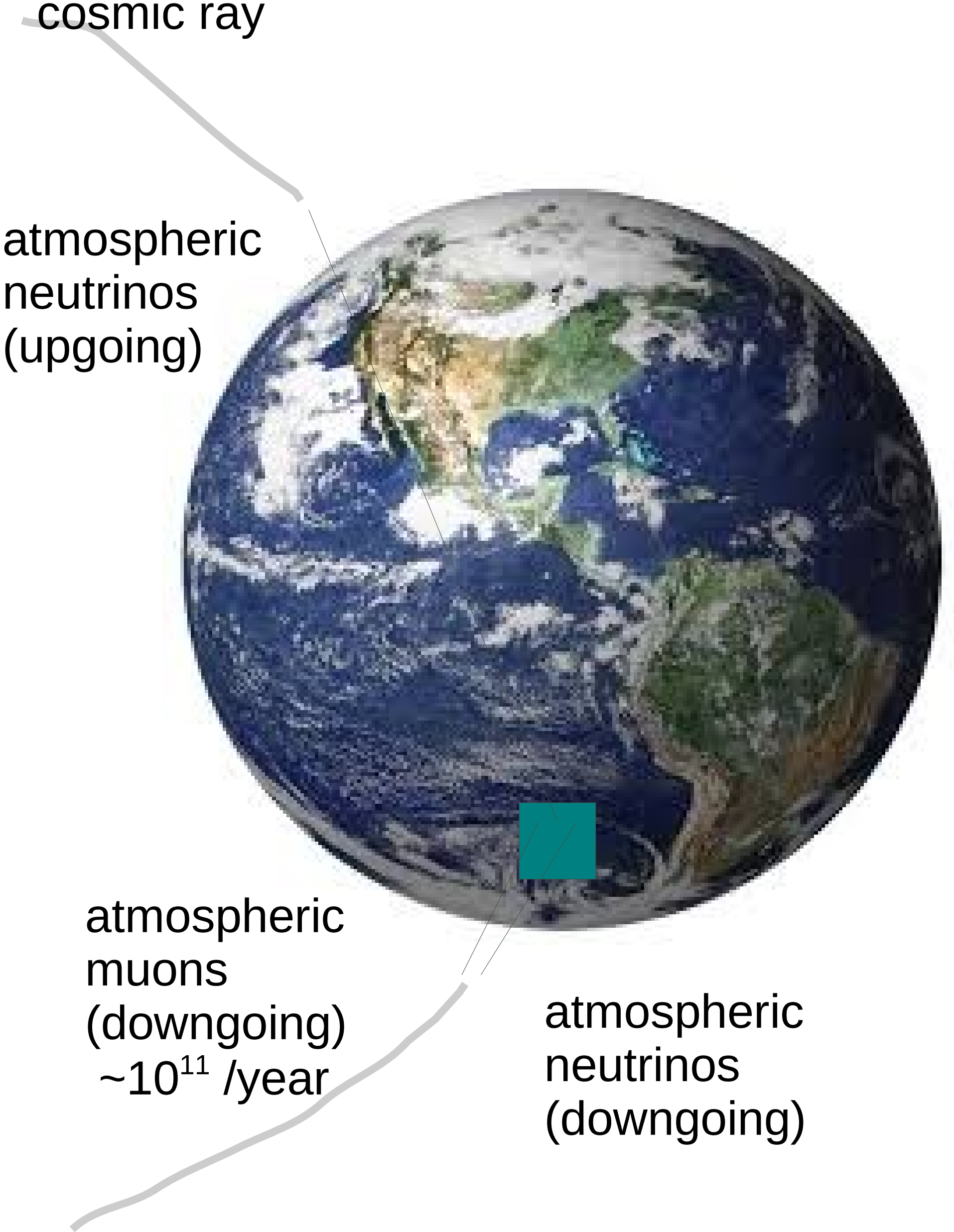
Signals in indirect (gravitational capture) and direct (nuclear recoil) experiments depend on

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

Structure of the nucleon plays an essential role in calculating observables

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

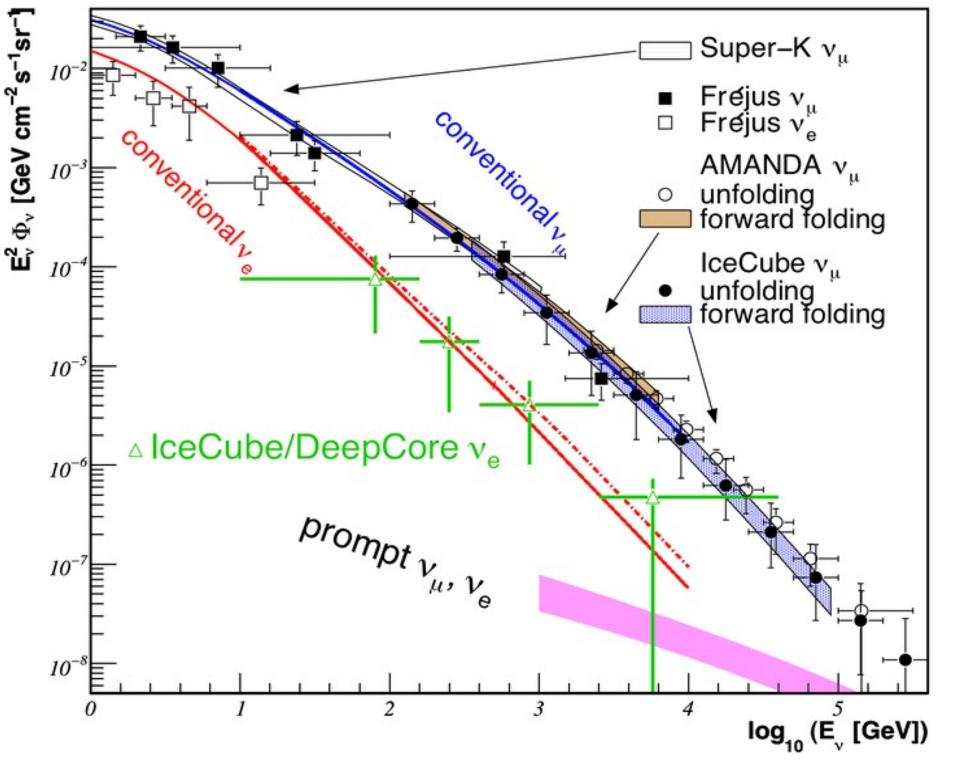
the background: the atmospheric neutrino flux



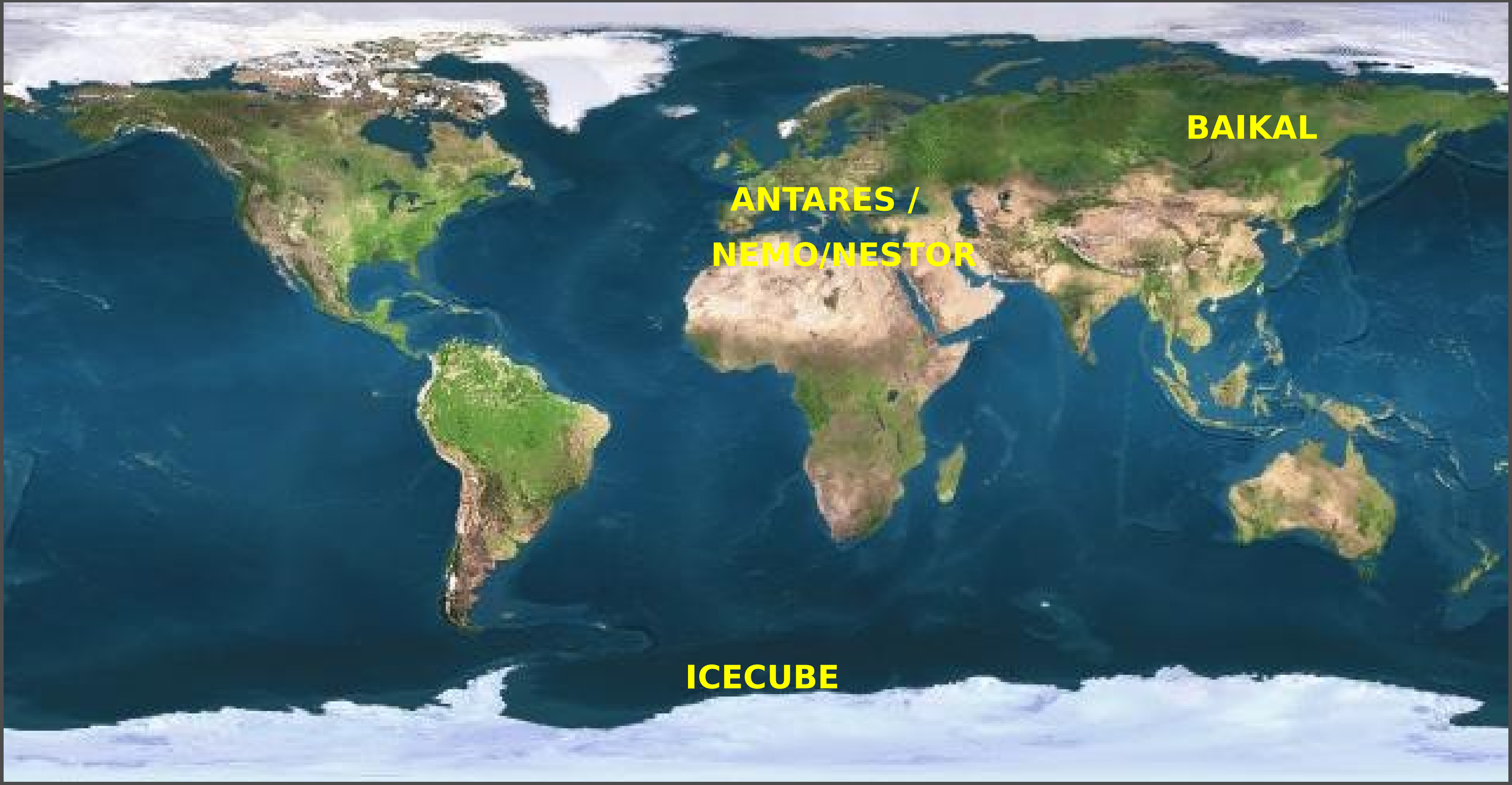
DM searches are a low-energy search in neutrino telescopes

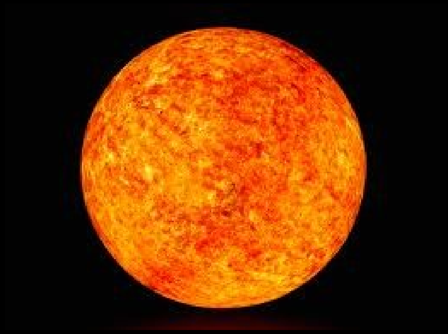
backgrounds:

- atmospheric neutrinos: $\sim 10^5$ /year
- misreconstructed downgoing atmospheric muons: $\sim 10^{11}$ /year



searches with neutrino telescopes





Let's take 5000 GeV ν_e as an example:

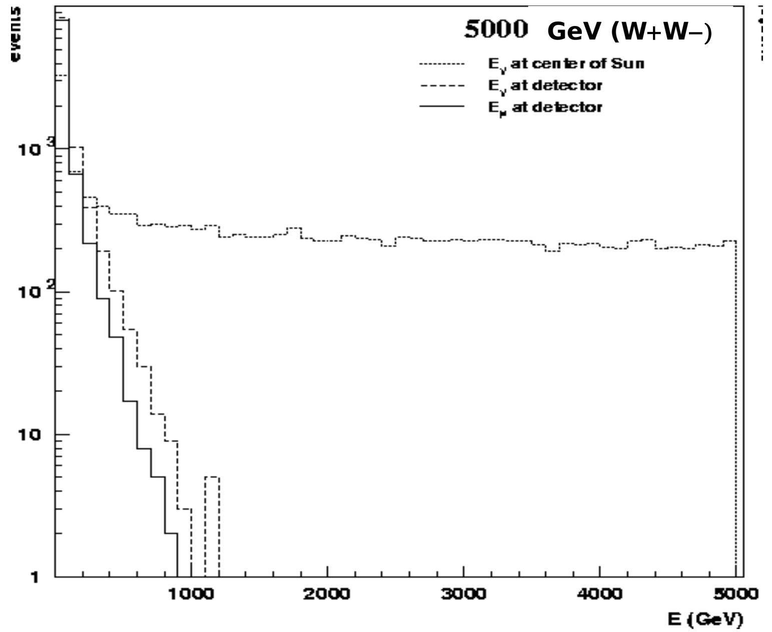
$\sigma^{NC}(\nu_e e^- \rightarrow \nu_e e^-) = 0.95\text{x}10^{-41} E_\nu/\text{GeV}$ (cm^2)

$\rho_{sun} = 1.6\text{x}10^5$ gr/cm^3

$R_{sun} = 7\text{x}10^{10}$ cm

mean free path between interactions:

$$\langle L \rangle = \frac{A_H}{N_A \rho \sigma} = \frac{1\, mol}{6.023\text{x}10^{23}\, mol/gr\; 1.6\text{x}10^5\, gr/cm^3\; 0.95\text{x}10^{-41}\, cm^2/GeV\; 5000\text{GeV}} = 2.2\text{x}10^8\, cm, < 7\text{x}10^{10}\, cm = R_{sun}$$



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

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

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

WIMP-nucleon scattering cross section

WIMP self-annihilaton cross section

Background taken from data

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

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

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

Triggered data still dominated by atmospheric muons

Reject misreconstructed atmospheric muon background through event and track quality parameters

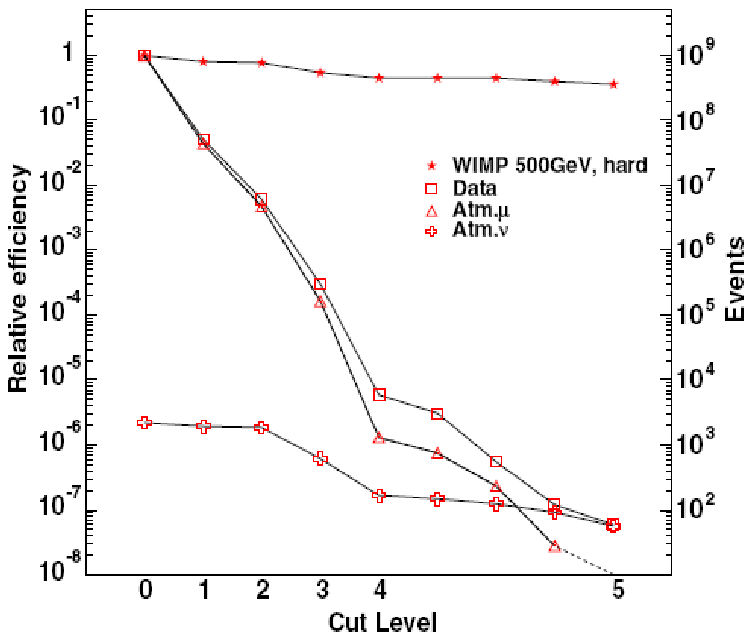
Use of **linear cuts** and/or multivariate methods to extract irreducible atmospheric neutrino background
(Neural Nets, Support Vector Machines, Boosted Decision Trees)

DM searches directional: good additional handle on event selection

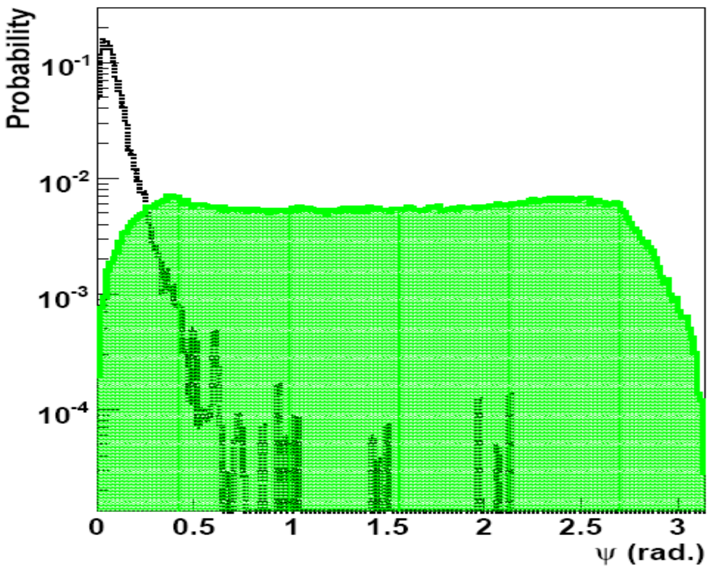
distribution-shape analysis

(allow for a higher background contamination)

sequential cuts



shape analysis



Solid angle to the Sun ψ (rad)

analysis strategies in neutrino telescopes

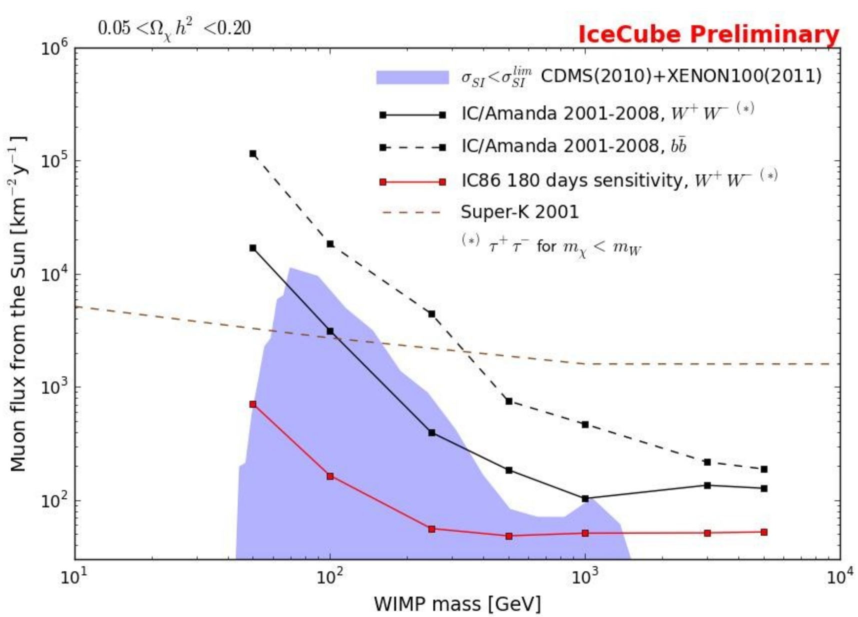
$$\left.\begin{array}{l} N_{data}, N_{bck} \\ \Psi_{data}, \Psi_{bck} \end{array}\right\} \rightarrow N_{90}$$

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

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

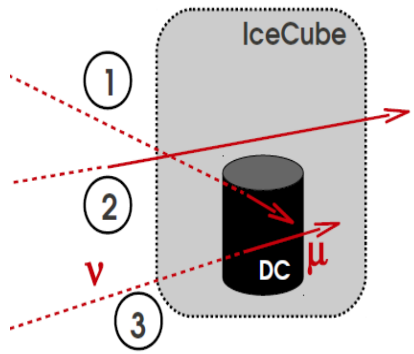
Use model to convert to a muon flux

$$\left.\begin{array}{l} \Gamma_{\nu\mu}(m_\chi) = \Gamma_A \cdot \dfrac{1}{4\pi R_\oplus^2} \displaystyle\int_0^{m_\chi} \sum B_{\chi\bar{\chi}\to X} \left(\frac{dN_\nu}{dE_\nu}\right) \\ \quad \times\, \sigma_{\nu+N\to\mu+\ldots}(E_\nu | E_\mu \geqslant E_{\text{thr}})\, \rho_N\, dE_\nu \end{array}\right\} \longrightarrow \phi_\mu(E_\mu \geqslant E_{\text{thr}}) = \frac{\Gamma_A}{4\pi D_\odot^2} \int_{E_{\text{thr}}}^{\infty} dE_\mu \frac{dN_\mu}{dE_\mu}$$



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

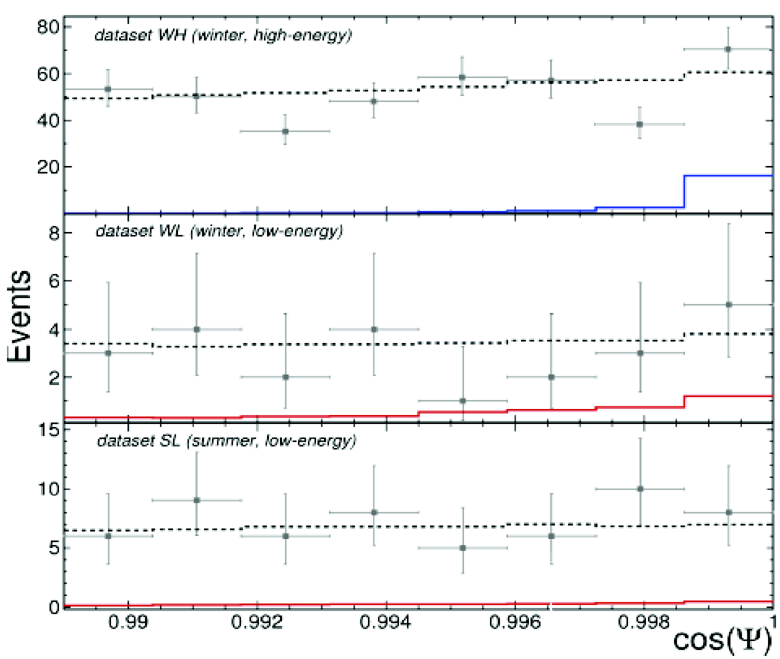
→ Veto background through location of interaction vertex

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

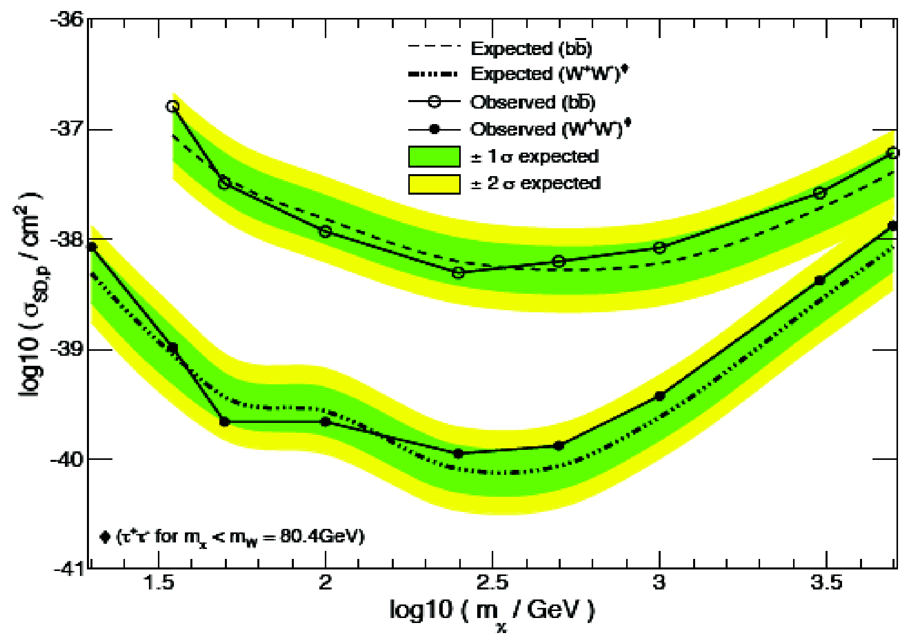
Background estimated from time-scrambled data
Analysis reaches neutrino energies of ~20 GeV
Assumes equilibrium between capture and annihilation

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

Unblinded events in different samples

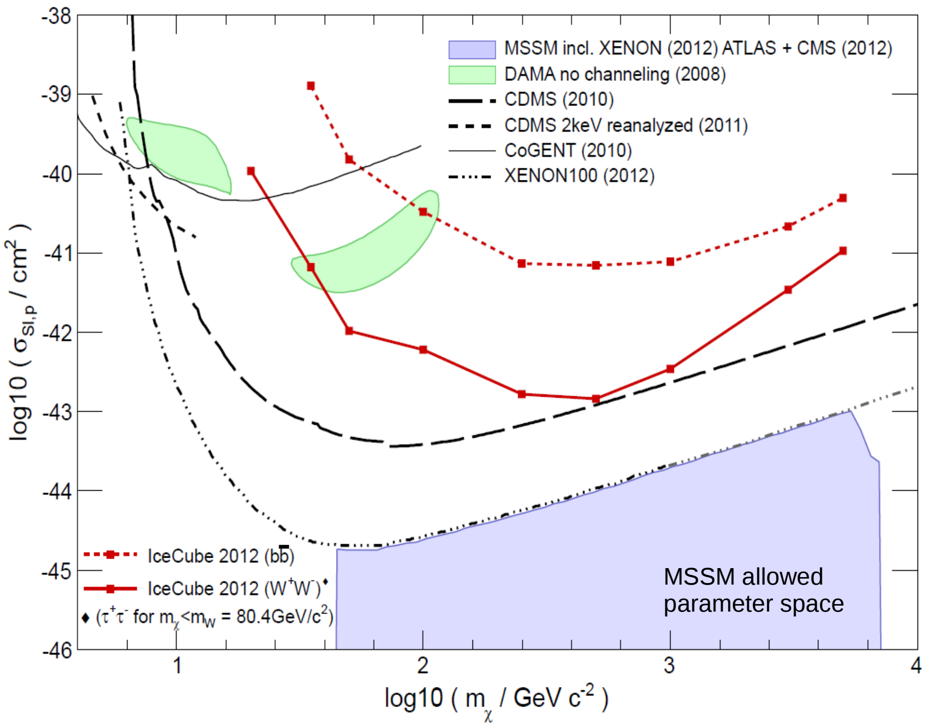


Expected sens. vs. observed result

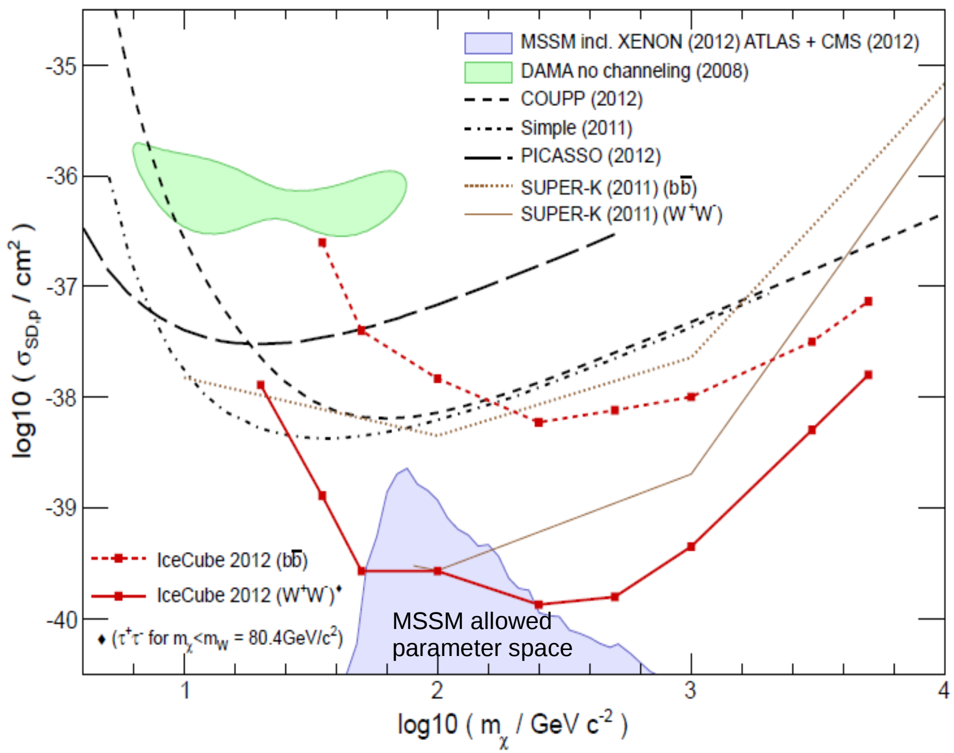


IceCube-79 solar search results

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

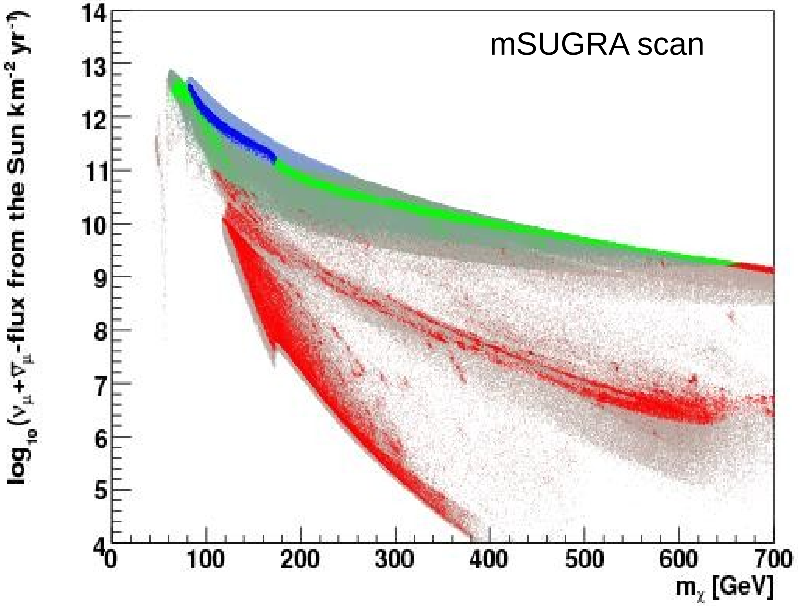


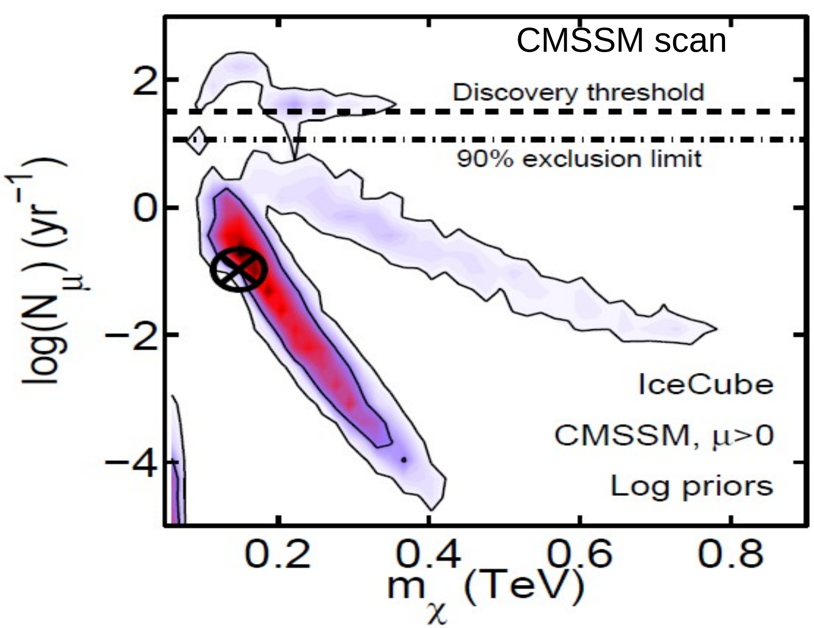
90% CL neutralino-p **SD** Xsection limit



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

what are these kind of plots and what do they mean?





A drawback with supersymmetry is the amount of free parameters (128 in the minimal supersymmetric extension of the Standard Model)

This limits the prediction power of the theory since many combinations of parameters are in principle possible.

Assumptions on the behavior of some parameters can be made and reduce the number of free ones to a few. This gives rise to the different flavours of supersymmetry: cMSSM, NMSSM... etc, with just a handful of parameters

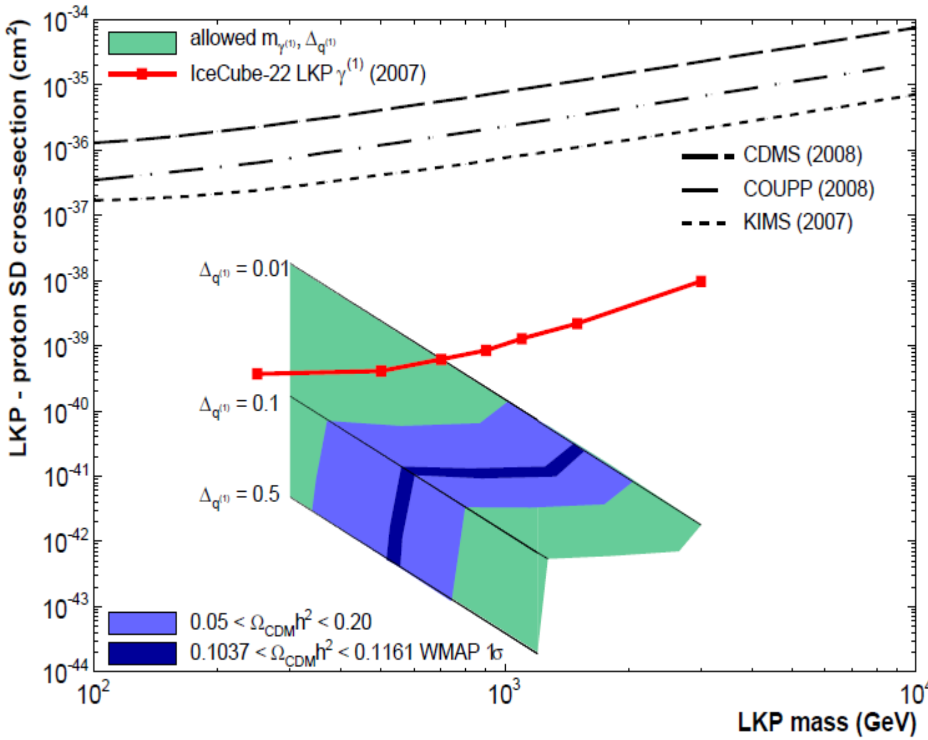
→ manageable computationally

Given a model, all quantities (masses, couplings...) can be derived from the knowledge of the free parameters of the model.

→ a multidimensional parameter scan can be performed and compare the predictions with experimental constrains: the specific combination of parameters is allowed or rejected depending on whether some prediction is in conflict with experimental results.

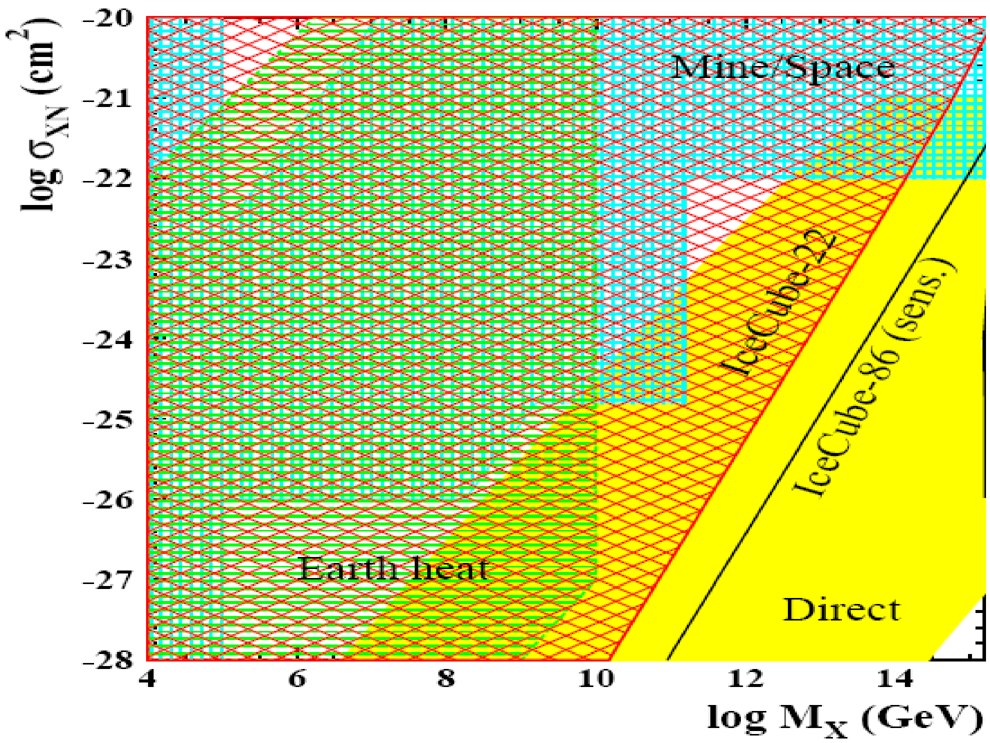
90% CL LKP-p Xsection limit vs LKP mass

PRD 81 (2010) 057101



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

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

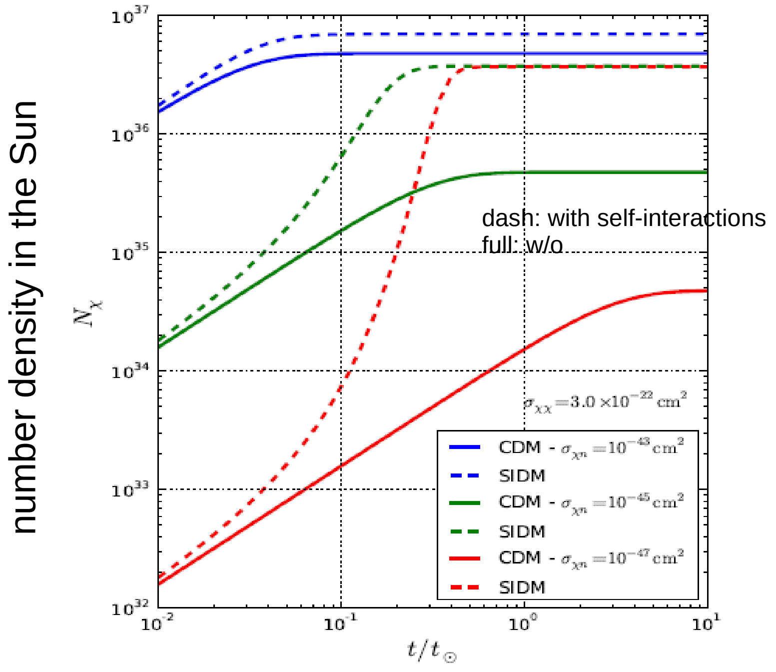
(Zentner, Phys. Rev. D80, 063501, 2009)

→ maximum annihilation rate reached earlier than in collisionless models

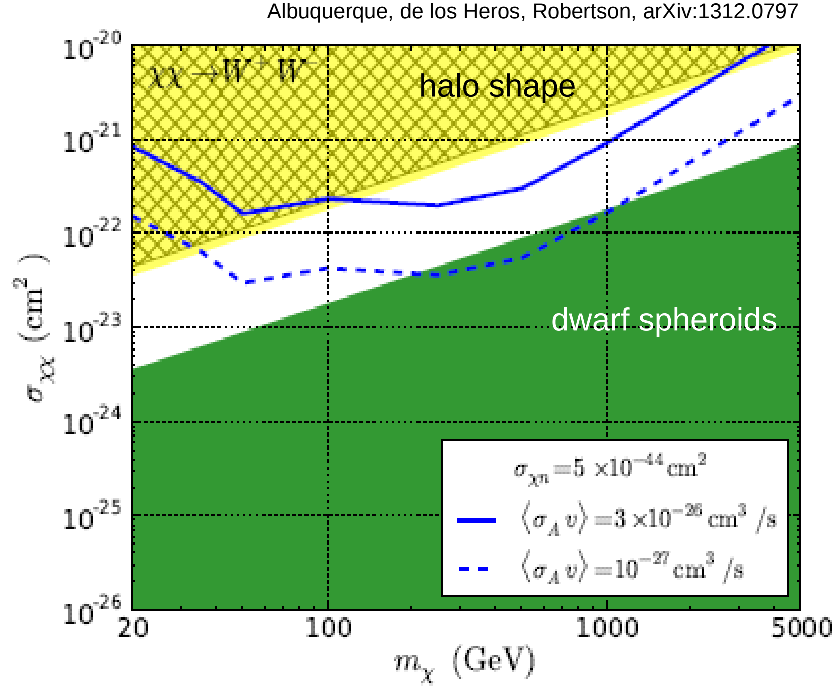
$\sigma_{\chi\chi}$ can naturally avoid cusped halo profiles

can induce a higher neutrino flux from annihilations in the Sun

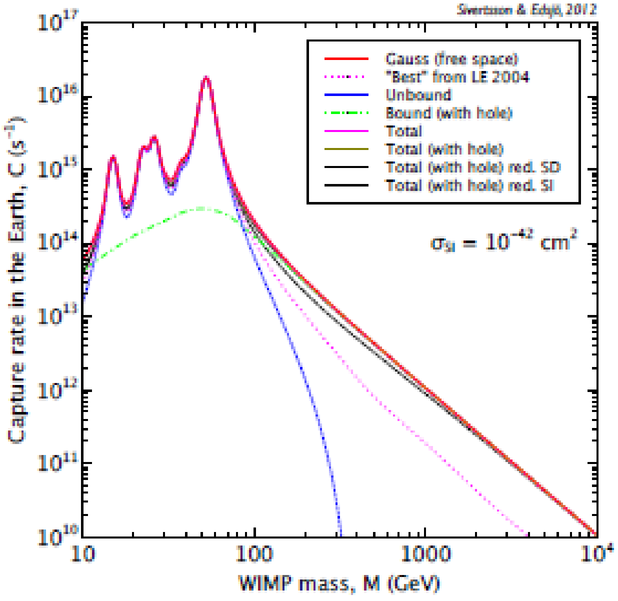
limits on $\sigma_{\chi\chi}$ can be set by neutrino telescopes



Albuquerque, de los Heros, Robertson, arXiv:1312.0797



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

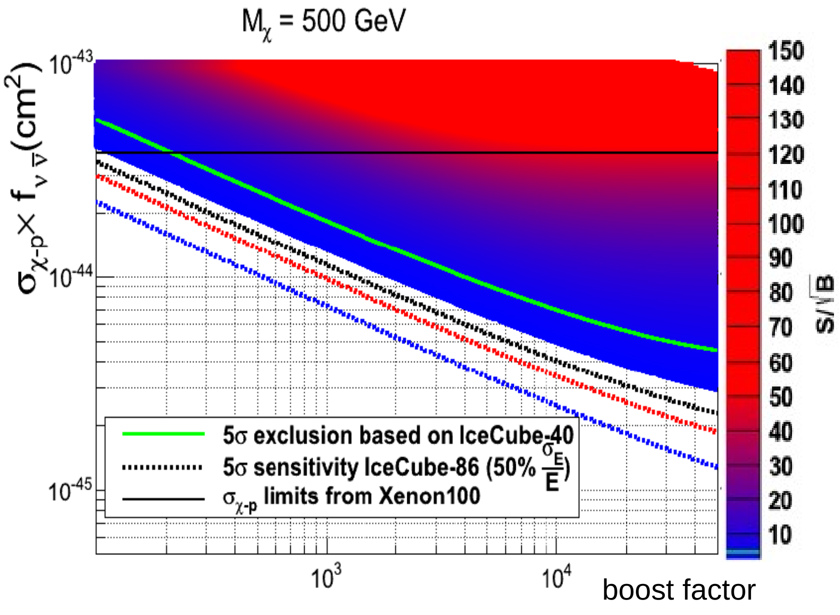
older results with smaller AMANDA detector (Astropart. Phys. 26, 129 (2006))

→ however, $\sigma_{c\text{-}n}^{SI} \sim 10^{-42}$ 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)).

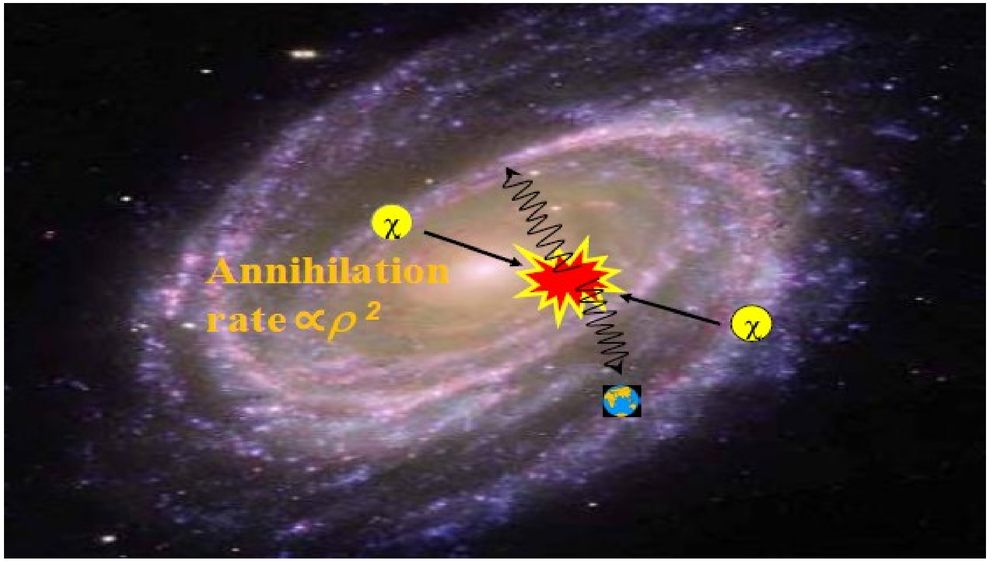
Using the atmospheric neutrino measurement of IceCube (ie, no excess from the center of the Earth detected), model-independent limits on boost factors can be set

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

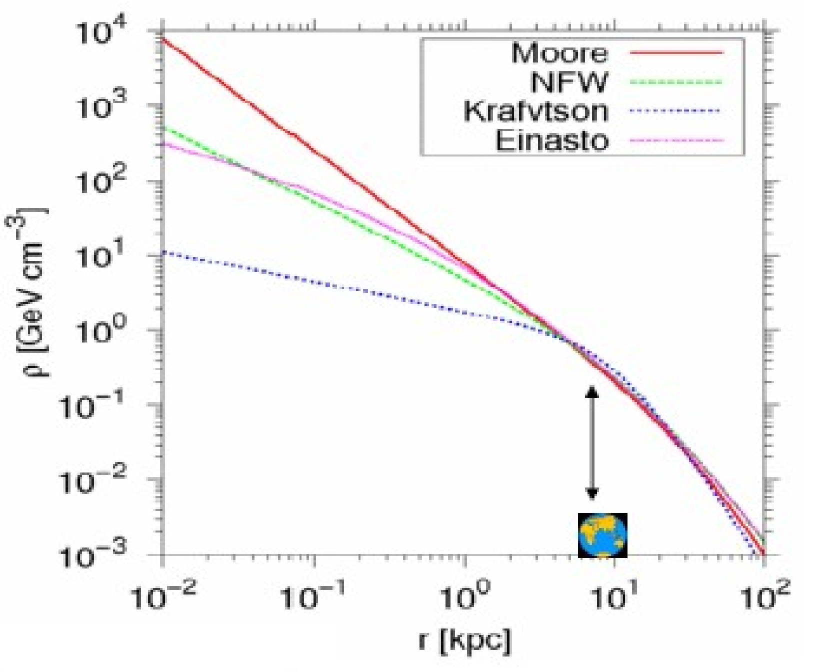


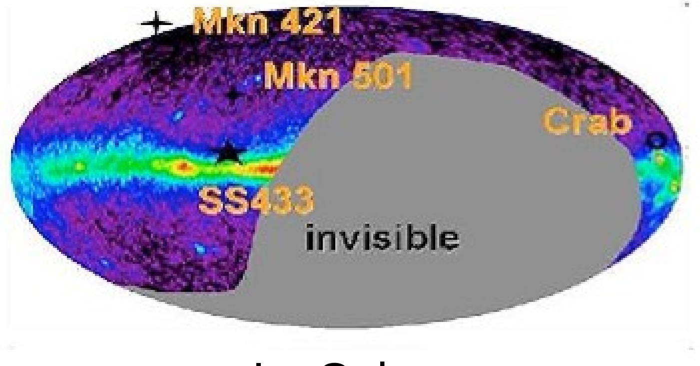
dark matter searches from the galactic center and halo

- Problem: strong dependence on the dark matter distribution in the galaxy
- We do not know for sure how dark matter is distributed in the galaxy

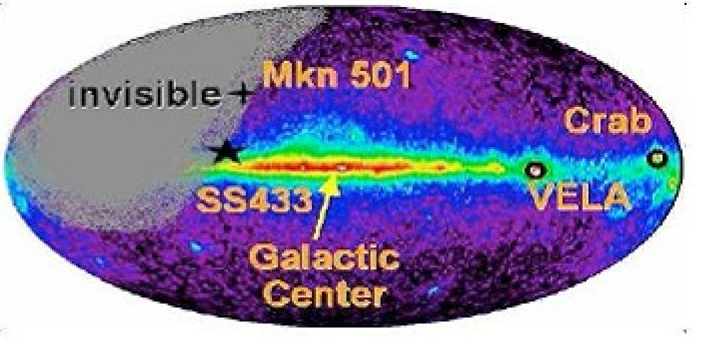


models of the dark matter density as a function of distance to the galactic center





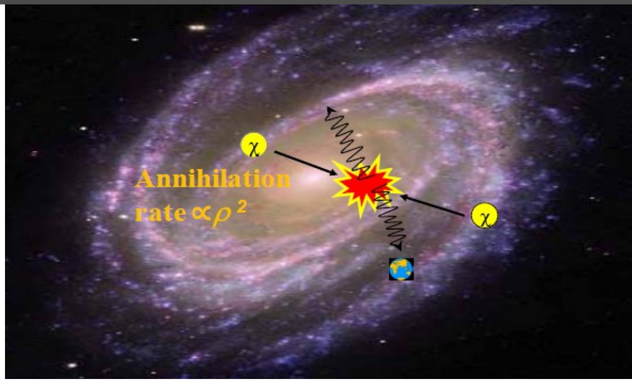
IceCube

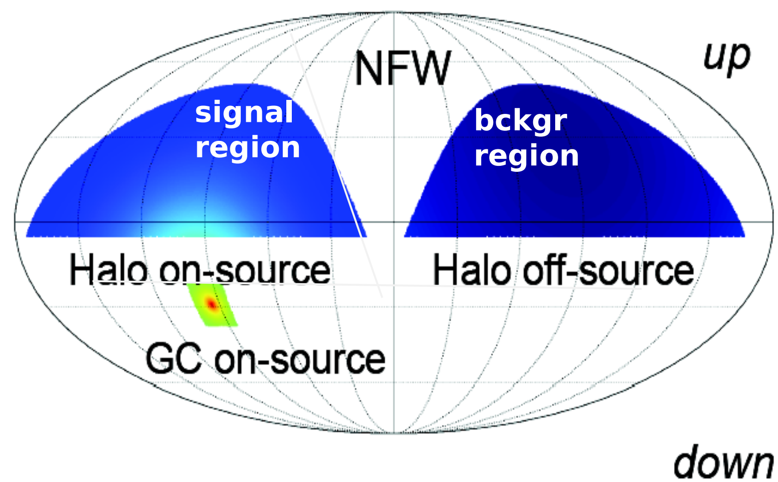


ANTARES

1 billion particle simulation of dark matter structure formation during the evolution of the universe. The dark matter are the bright spots! (note the scale)

example: IceCube dark matter searches from the galactic halo

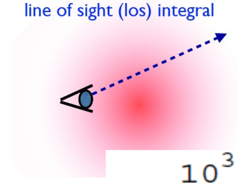




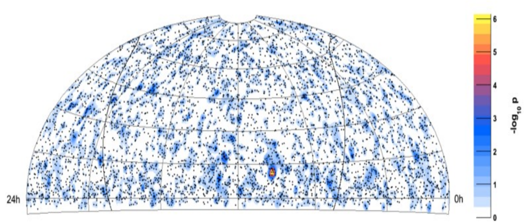
$$\boxed{\frac{d\Phi}{dE}(E,\phi,\theta)} = \boxed{\frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f \frac{dN}{dE}B_f} \times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')}$$

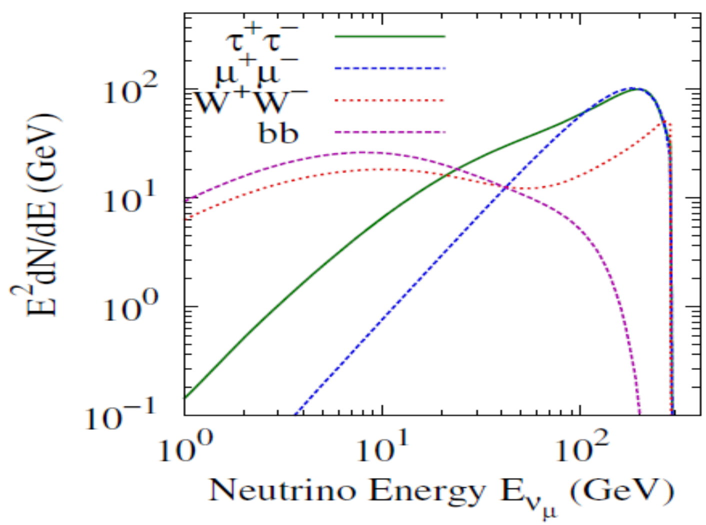
measure

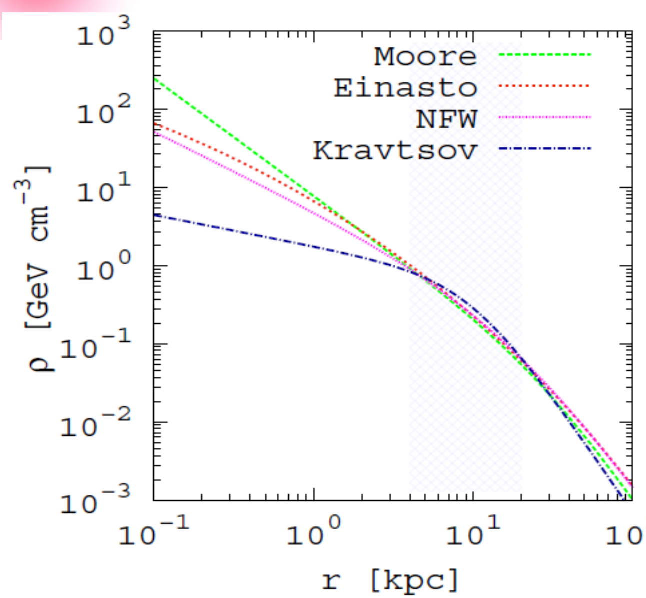
particle physics model



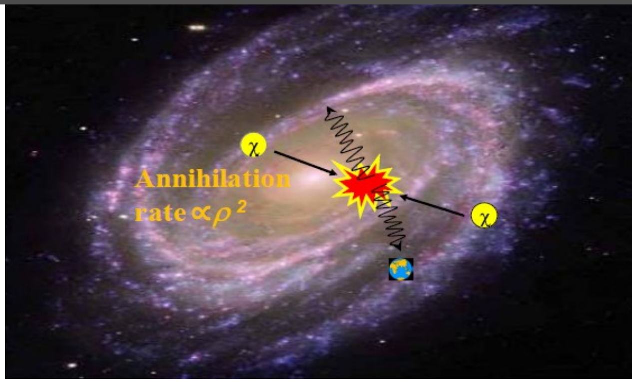
halo model

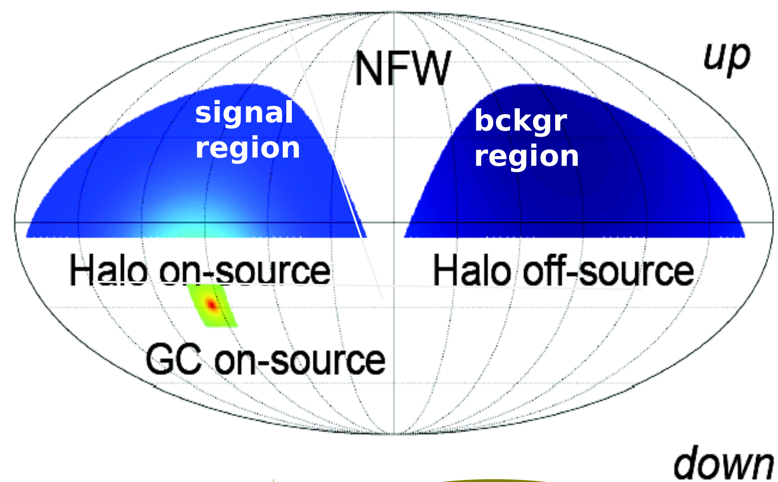






example: IceCube dark matter searches from the galactic halo



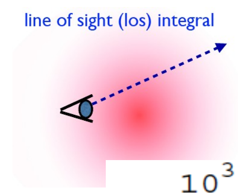


assume

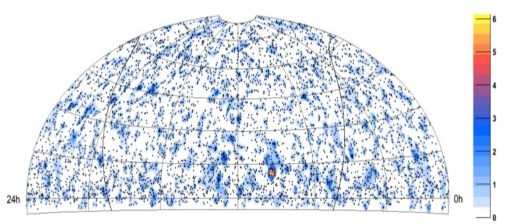
$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f \frac{dN}{dE}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\mathrm{los}} \rho^2(r(l,\phi'))\,dl(r,\phi')$$

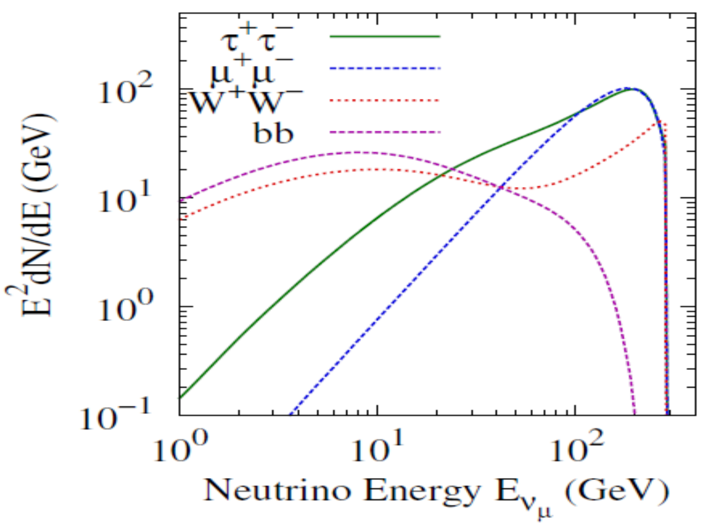
measure

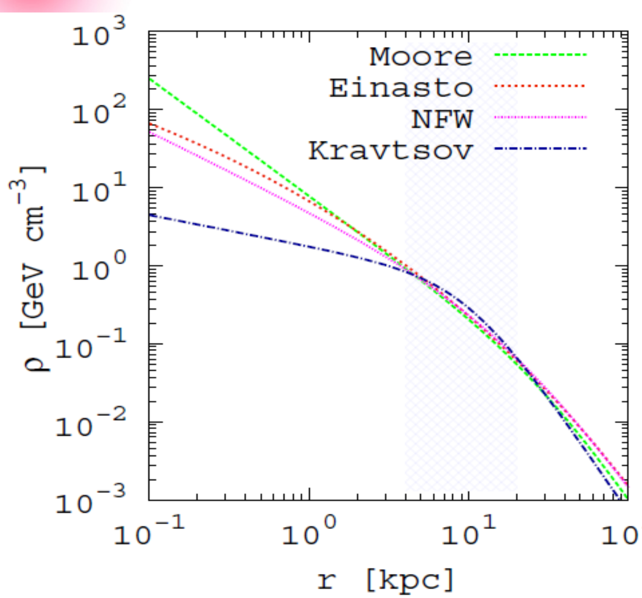
particle physics model



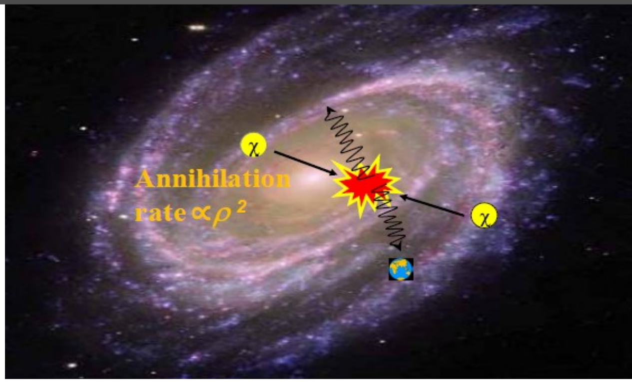
halo model

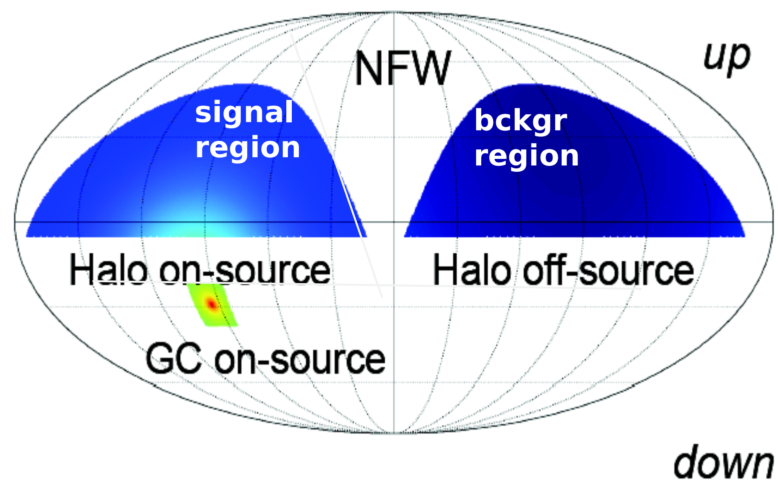






example: IceCube dark matter searches from the galactic halo





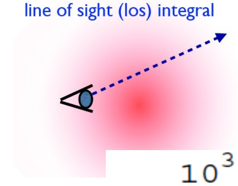
constrain

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

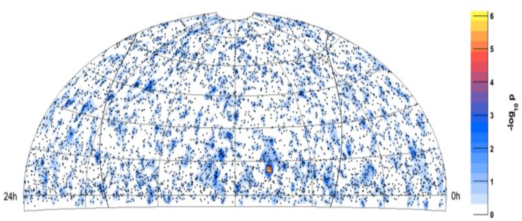
measure

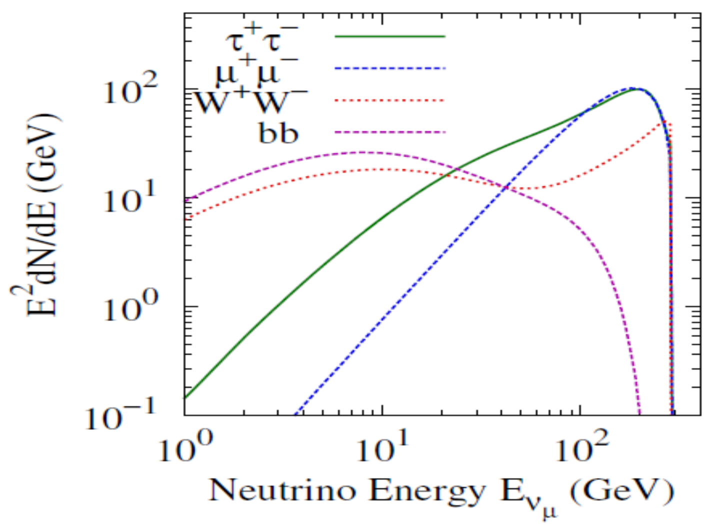
particle physics model

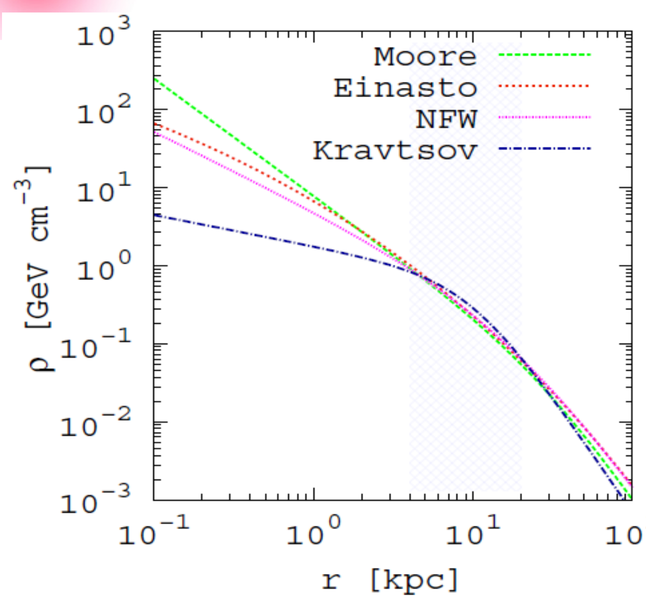
line of sight (los) integral



halo model

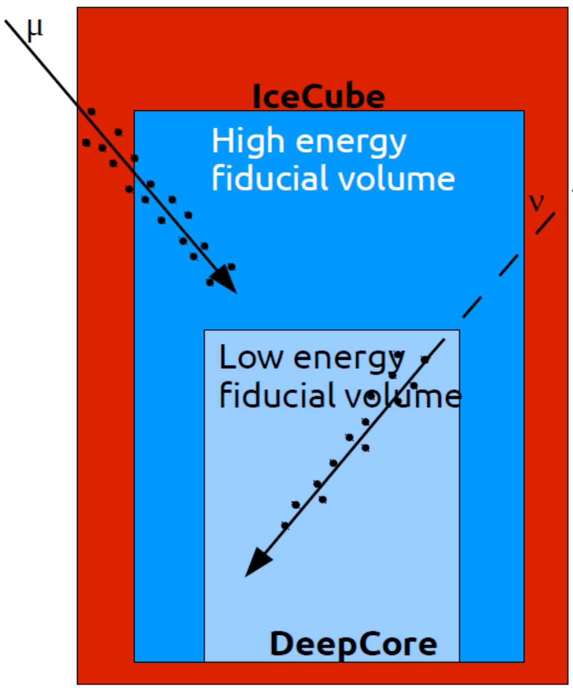


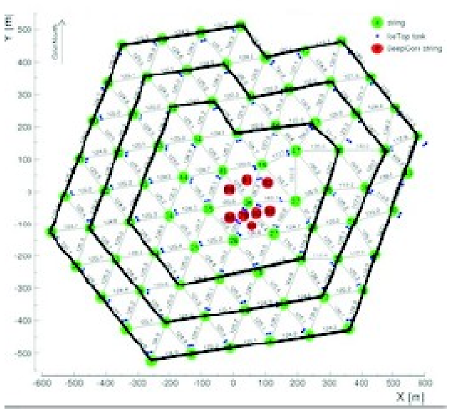


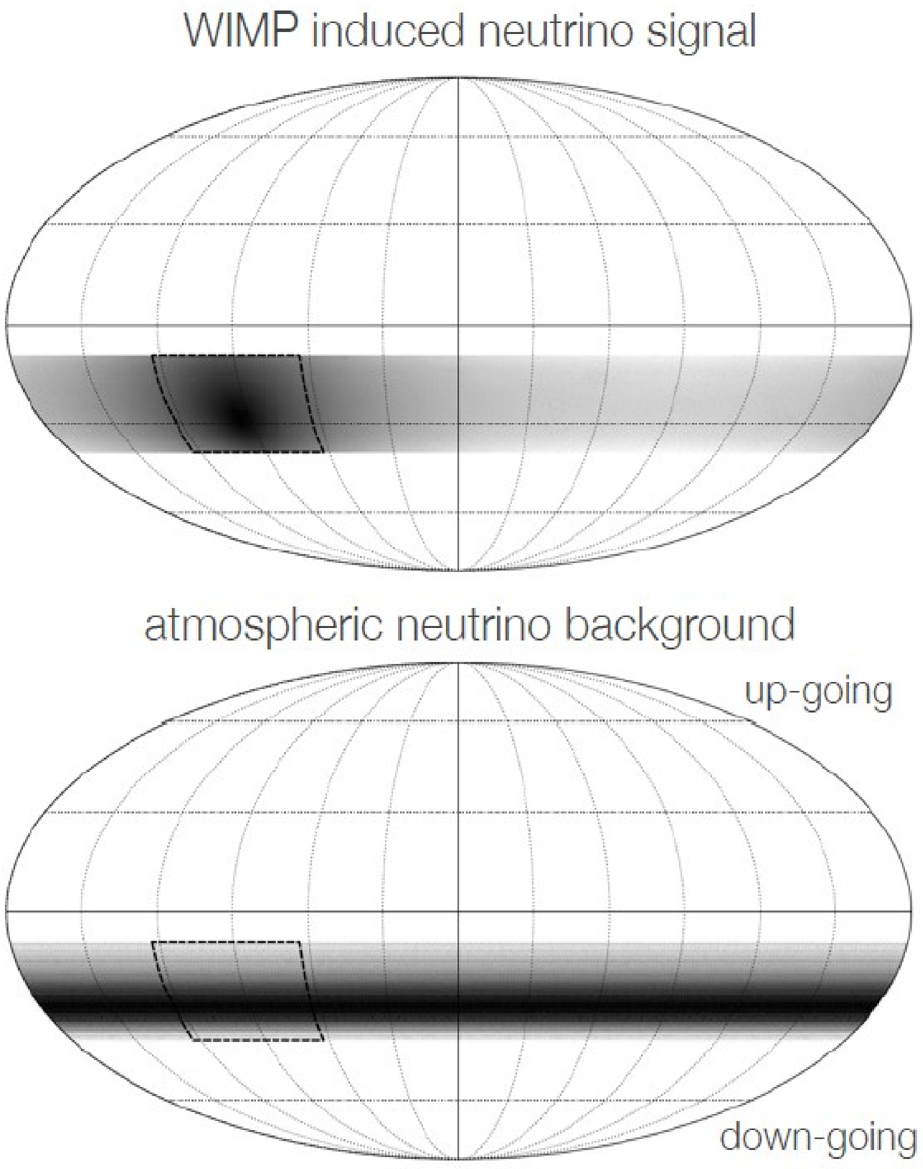


- At the South Pole the GC is above the horizon
- → Analysis must rely on veto methods to reject incoming atmospheric muons

- Use data with randomized directions for
- background estimation





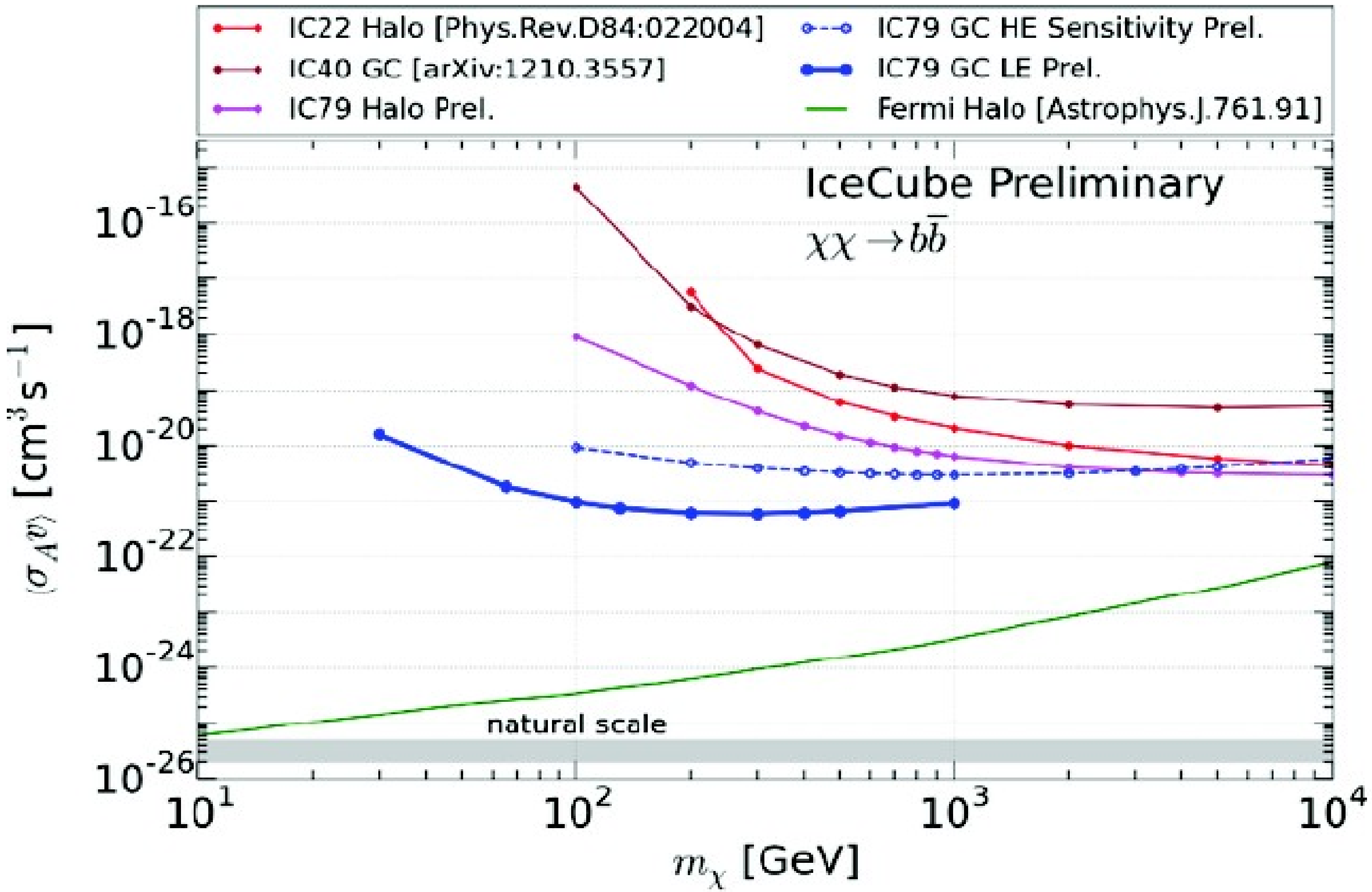


results from dark matter searches from the Galactic Center and halo

Look for an excess of neutrinos from the galactic halo and center

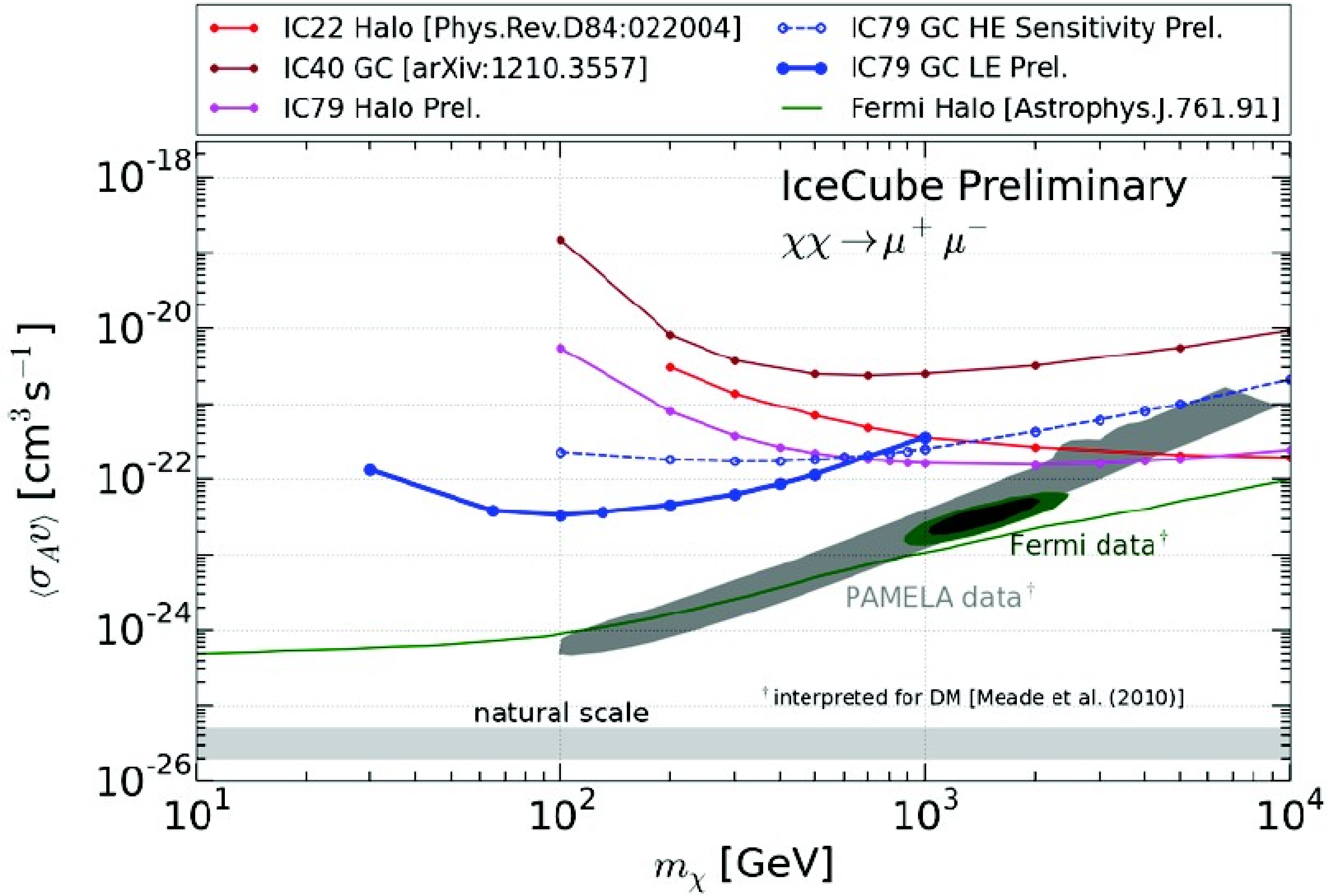
(excess over the measured atmospheric neutrino flux)

Non-detection so far → limits on the WIMP self-annihilation cross section



multi-wavelength approach to dark matter searches:

IceCube results in the context of Pamela and Fermi e^+ and e^- measurements



conclusions/outlook

I hope I have convince you that searching for dark matter is a complex business but also, that I have convinced you that it is fun!

There are plenty of approaches/experiments running or in R&D phase for indirect dark matter detection.

(and I have not mentioned the LHC and direct detection techniques!, covered in other lectures in this school)

The smoking gun for any claim is a coherent signal from indirect, direct and accelerator experiments. The complexity of the backgrounds can make single-detector claims controversial

Neutrino telescopes are definitely a player in the field of DM searches, being complementary to direct and accelerator searches

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