Search for Dark Matter with IceCube

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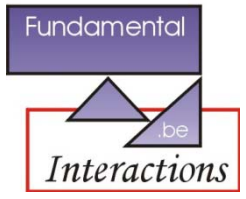
Dark Matter in LHC Era
Kolkata 2011



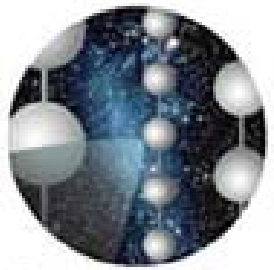
Outline

- Weakly Interacting Massive Particles as Cold Dark Matter
- The IceCube neutrino detector
- Search for neutrino signals of WIMP annihilations in the Sun and near the Galactic Centre
- IceCube + DeepCore : prospects for Dark Matter discovery in the coming years

Evidence for Dark Matter from observations

Indirect detection

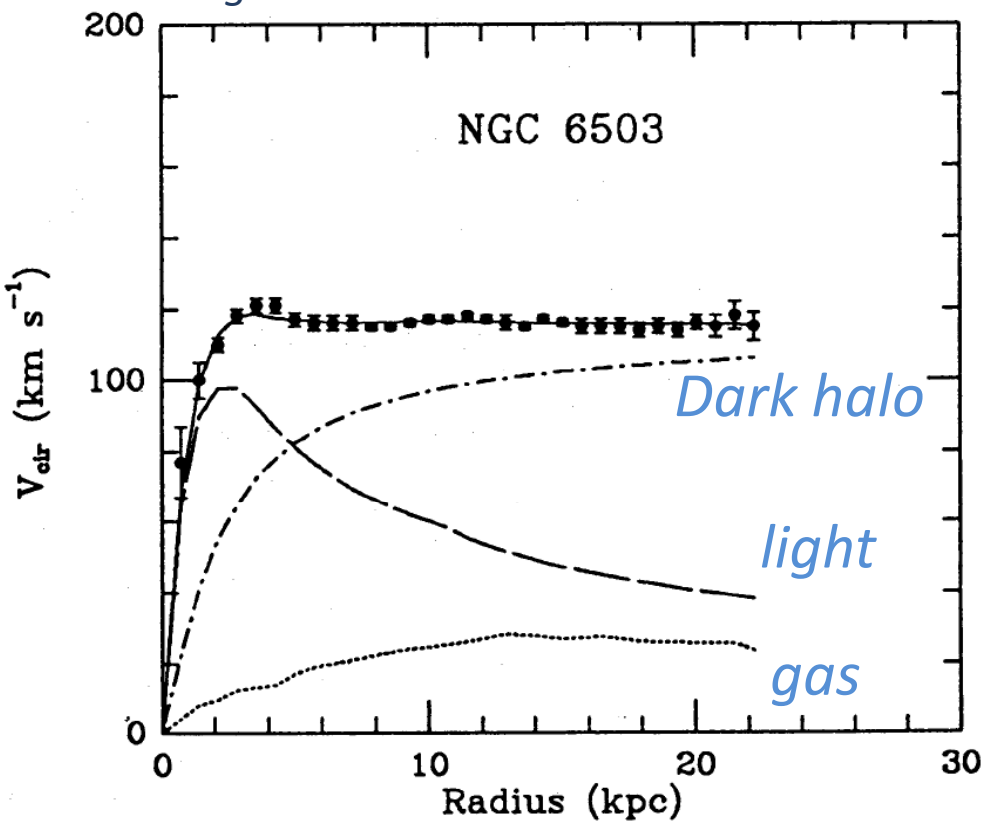
Dark matter



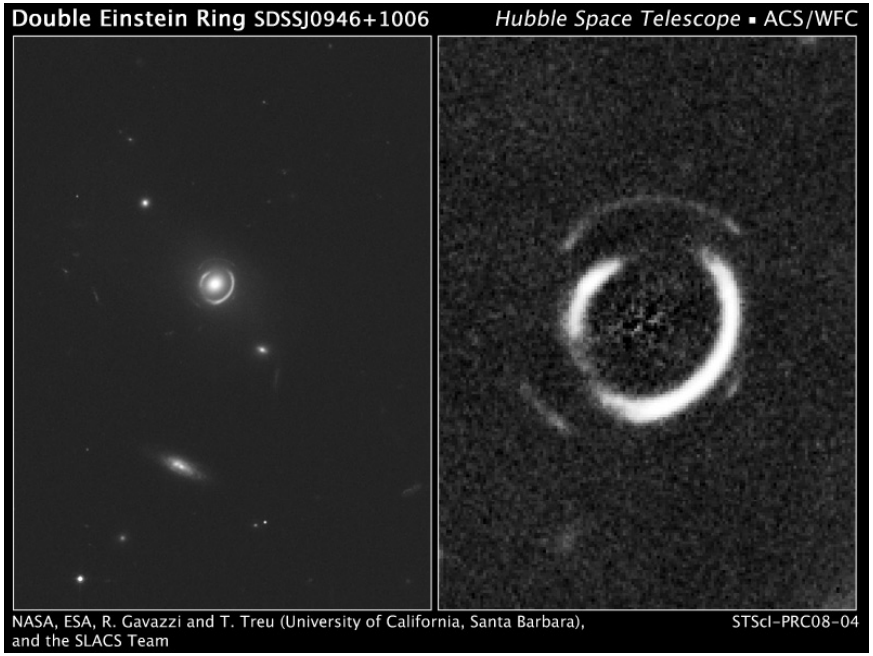
Observations

Galaxy rotation curves

Begeman et al. 1991



Gravitational lensing



WIMPs as cold Dark Matter

- **W**eakly **I**nteracting **M**assive **P**articles

- Non-relativistic at freeze-out
- Mass [GeV-TeV]
- Can make up cold DM with observed abundance

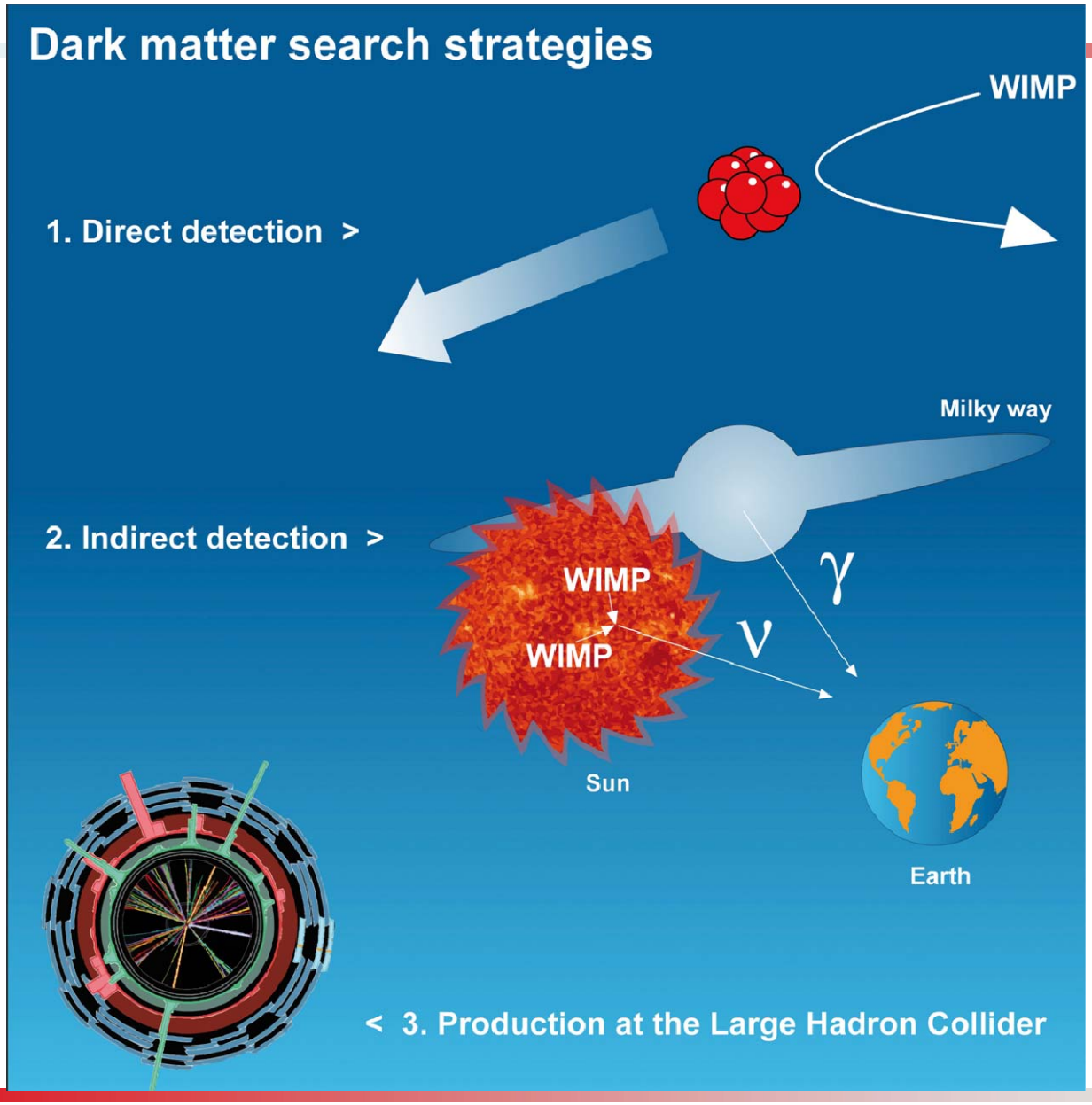
Bullet Cluster @ *NASA*

≈ 0.21 WMAP

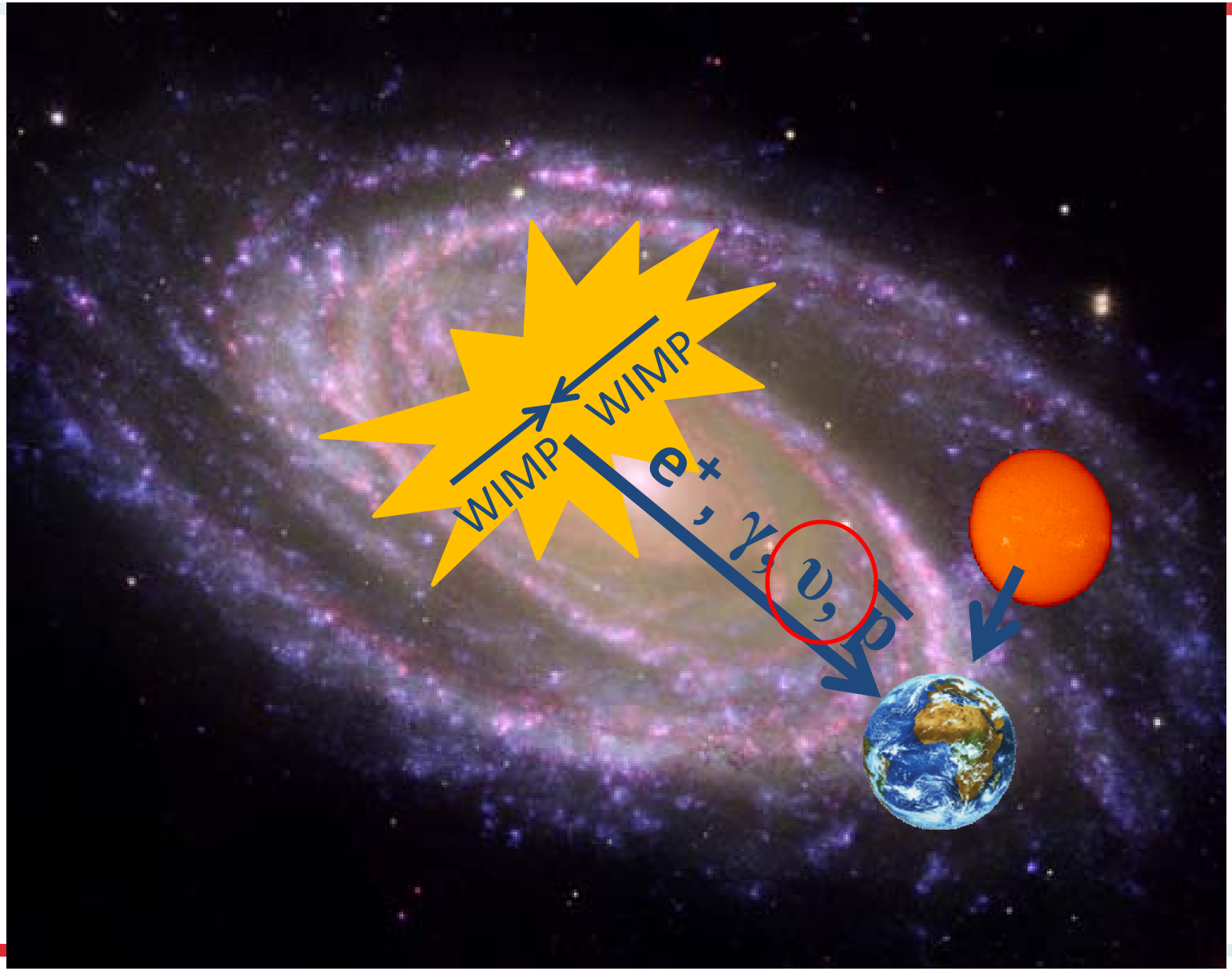
$$\Omega_\chi = \frac{\rho_\chi}{\rho_{crit}} \sim \frac{10^{-25}}{\langle \sigma_{Ann} v \rangle} cm^3 s^{-1}$$

O(Weak interactions)

Detection


Dark matter search strategies
WIMP
1. Direct detection >
Milky way
2. Indirect detection >
WIMP
WIMP
γ
ν
Sun
Earth
< 3. Production at the Large Hadron Collider

Indirect detection



Mission

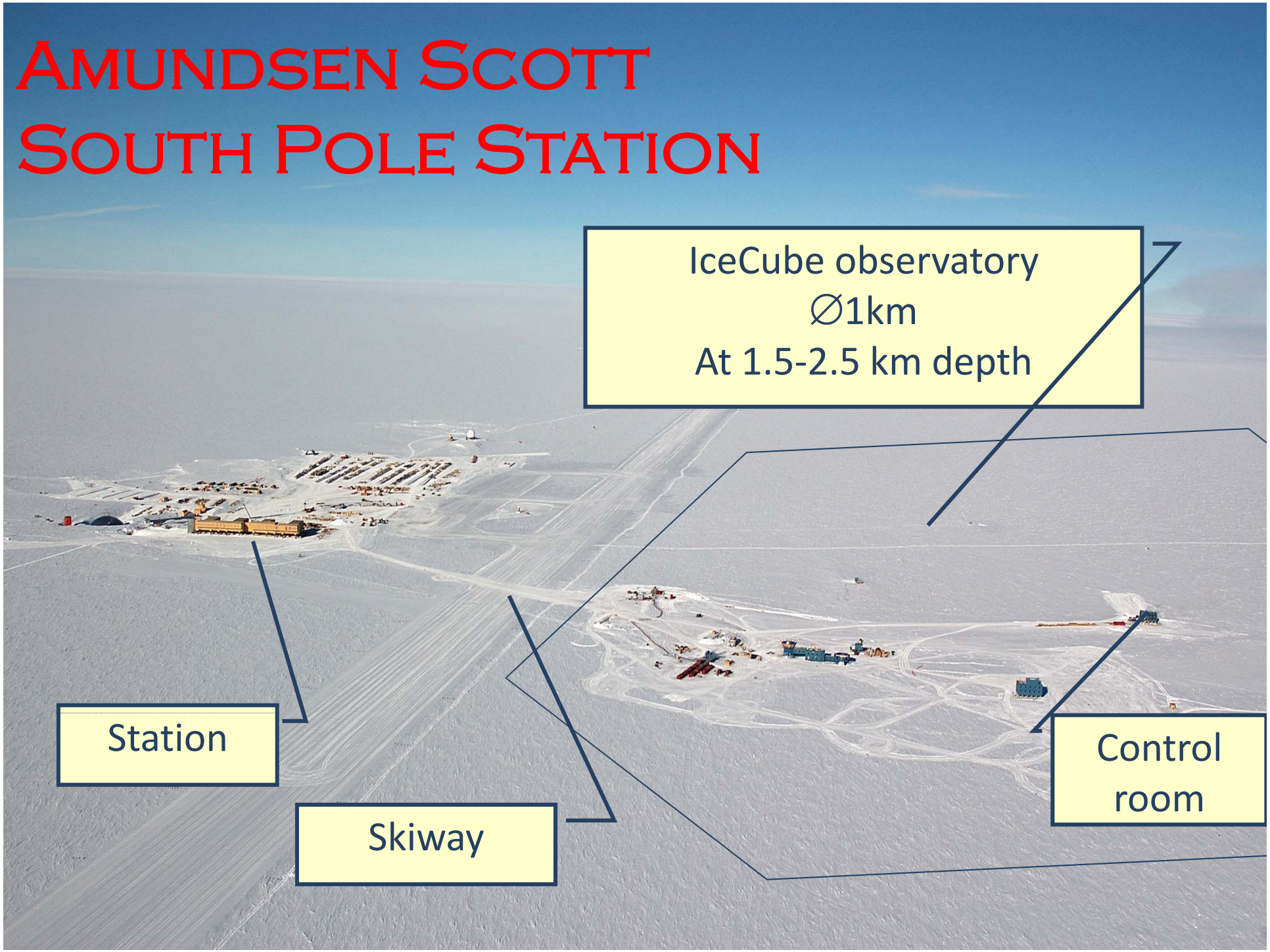
Instrument

Neutrino detection

IceCube

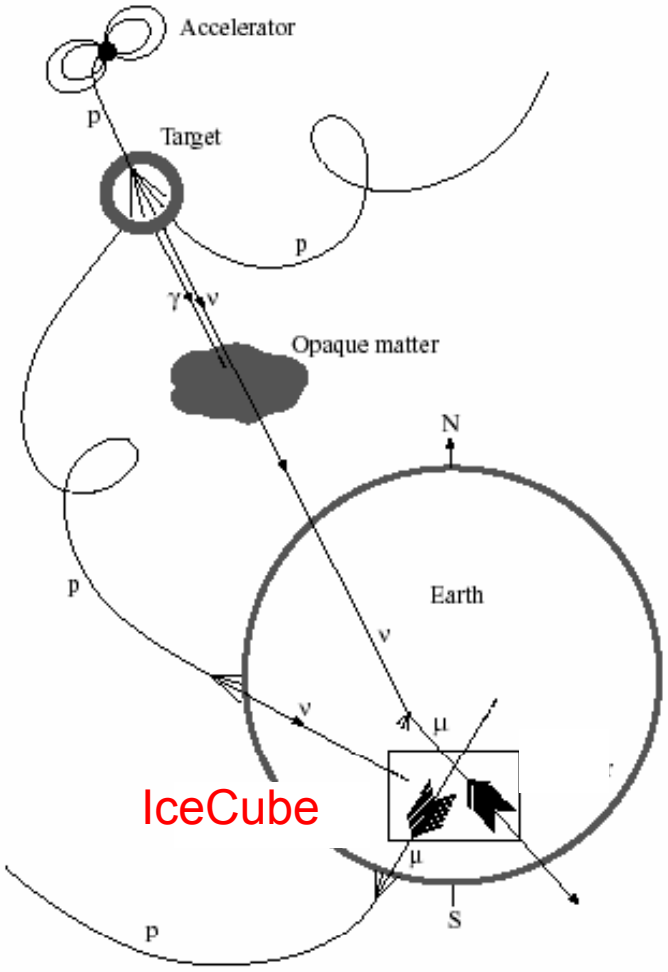
IceCube

Amundsen Scott South Pole Station

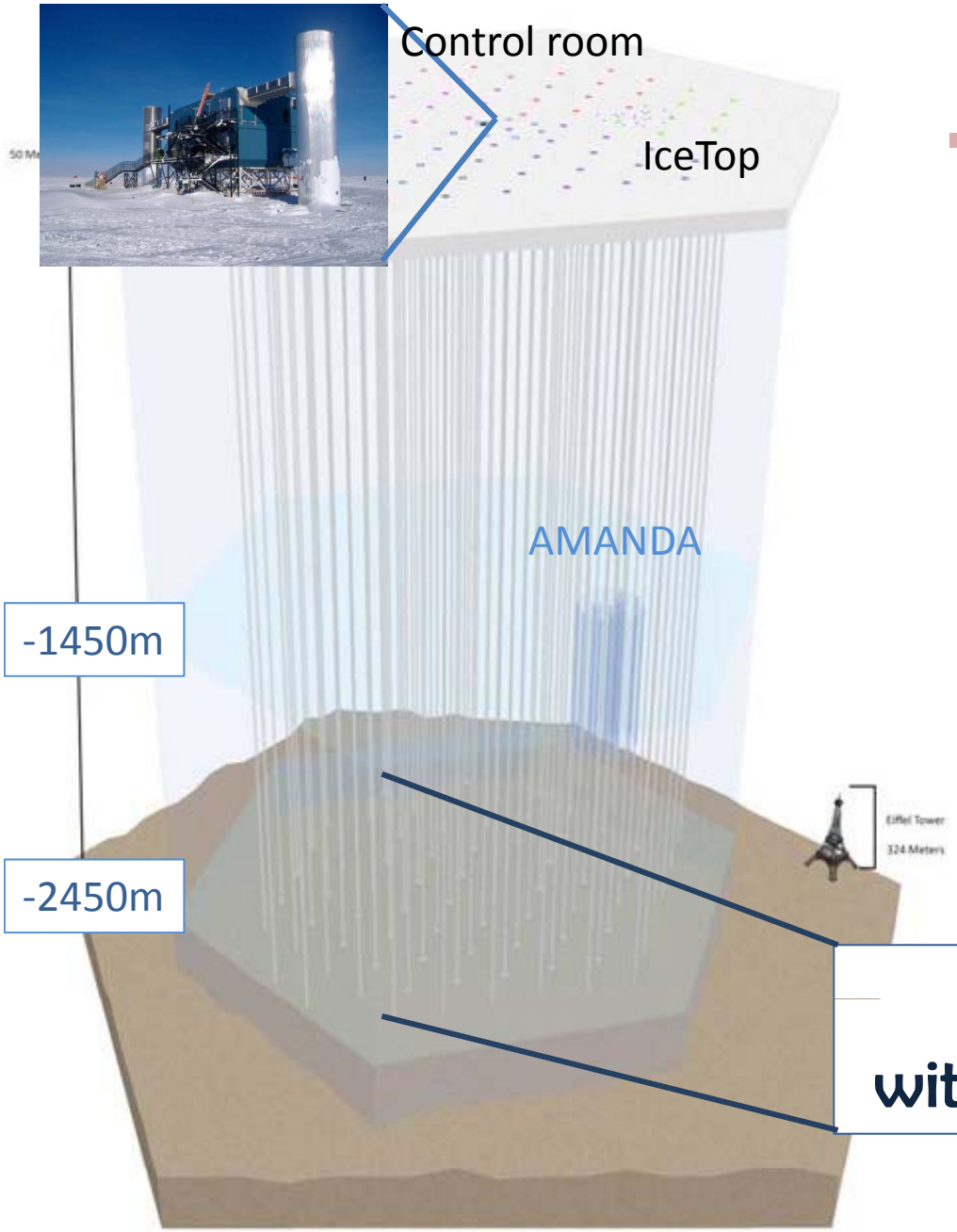


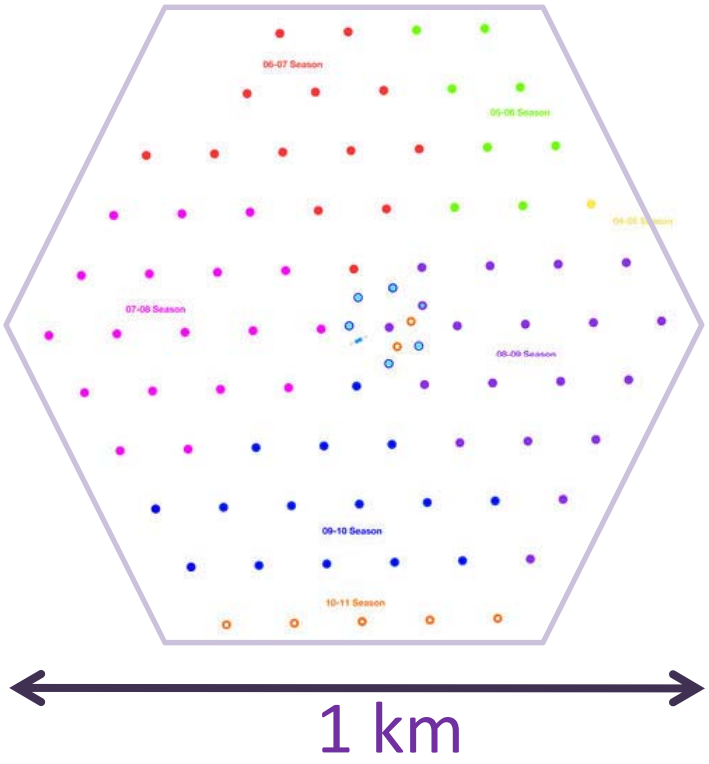
IceCube Mission

- search for extra-terrestrial neutrinos → natural accelerators producing HE cosmic rays
- Such as
  - Active Galactic Nuclei
  - Gamma Ray Bursts
  - SuperNovae
- Indirect Dark Matter search
- Cosmic ray air showers with IceTop



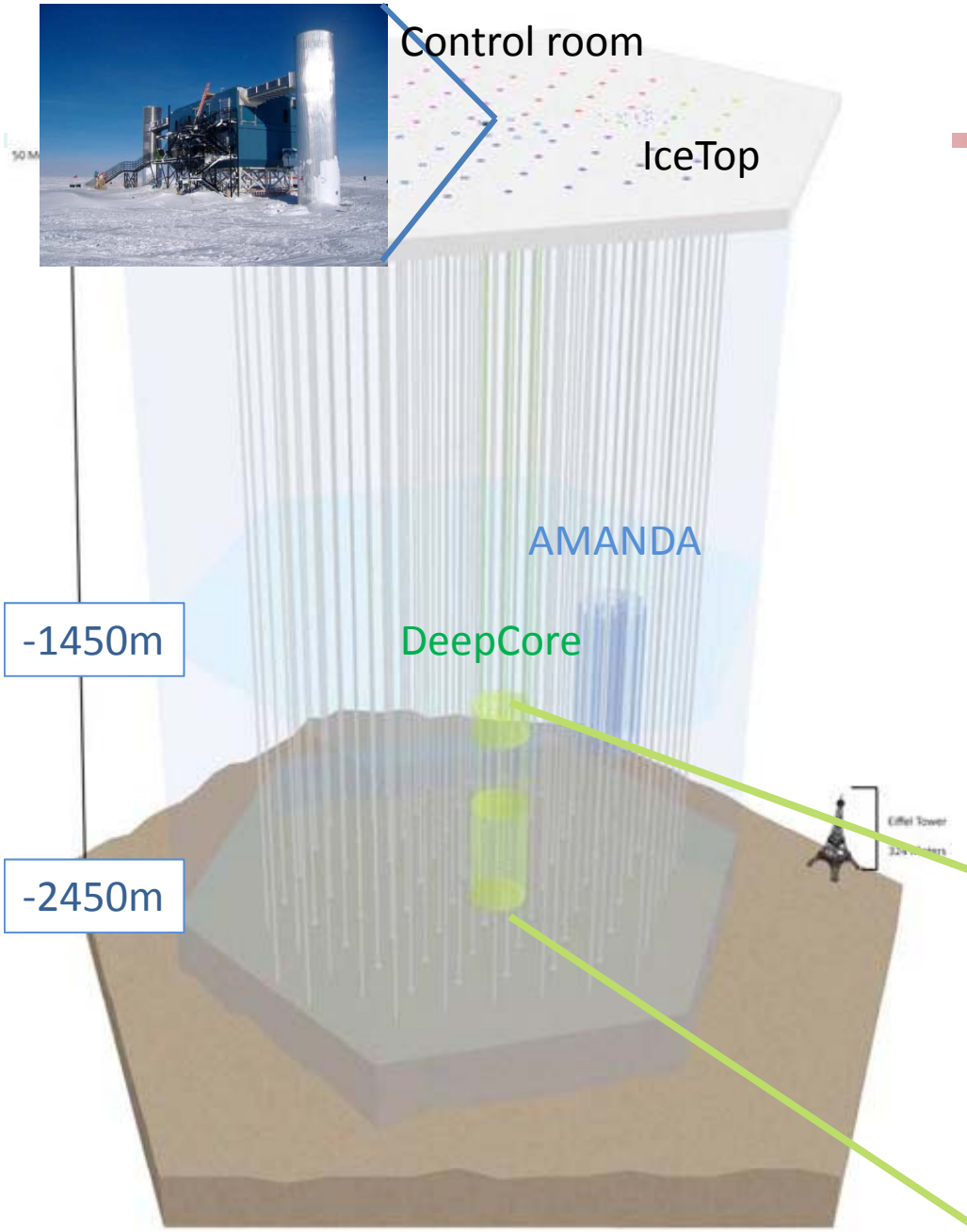
IceCube detector

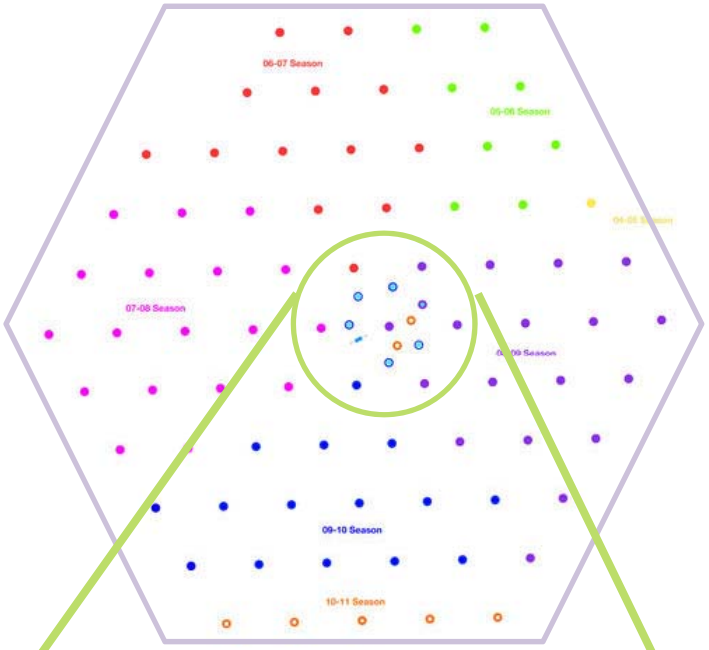




Array of 80 strings with 60 Digital Optical Modules

IceCube detector





DeepCore

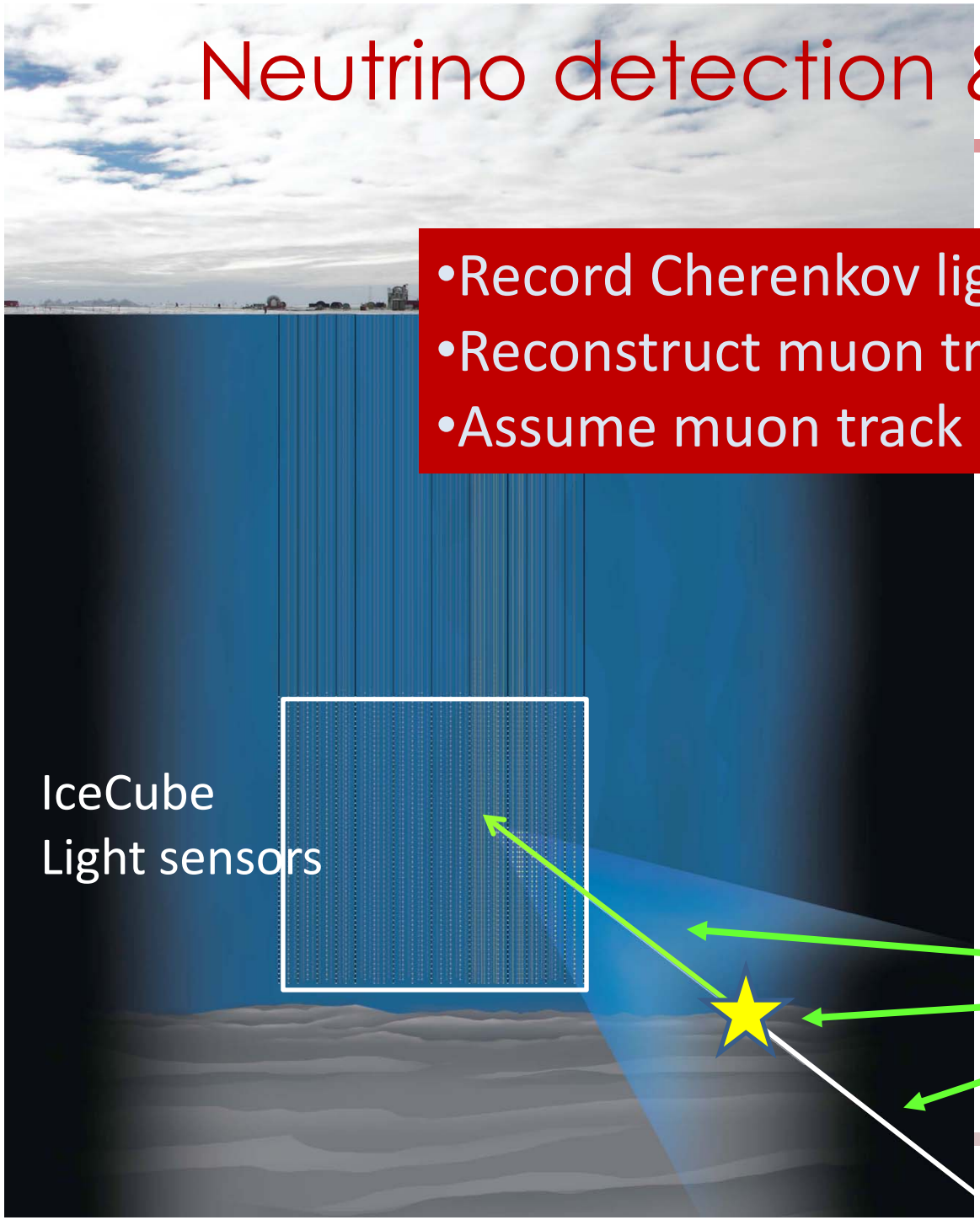
- Denser spacing
- Low energy GeV-TeV
- Southern hemisphere

Neutrino detection & reconstruction

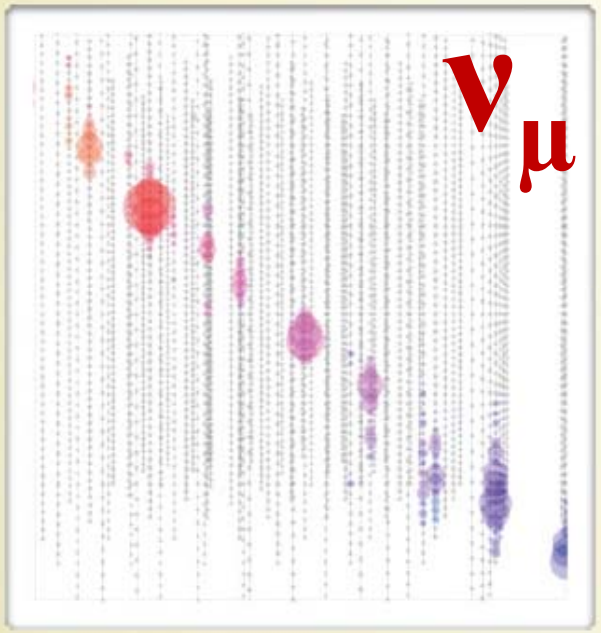
- Record Cherenkov light pattern
- Reconstruct muon track
- Assume muon track aligned to neutrino path

$$\theta(\nu,\mu) \approx 30° \bullet \sqrt{1/E(GeV)}$$

$$1TeV \rightarrow 1°$$



NEUTRINO SIGNATURES



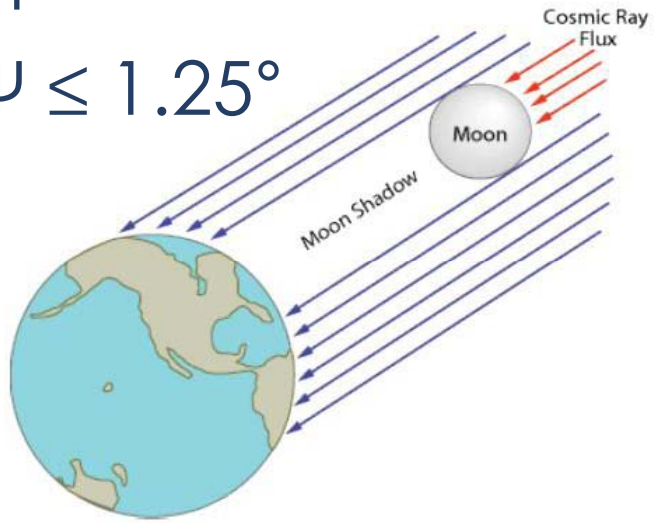
Tracks
- Through-going muons
- 1° pointing resolution

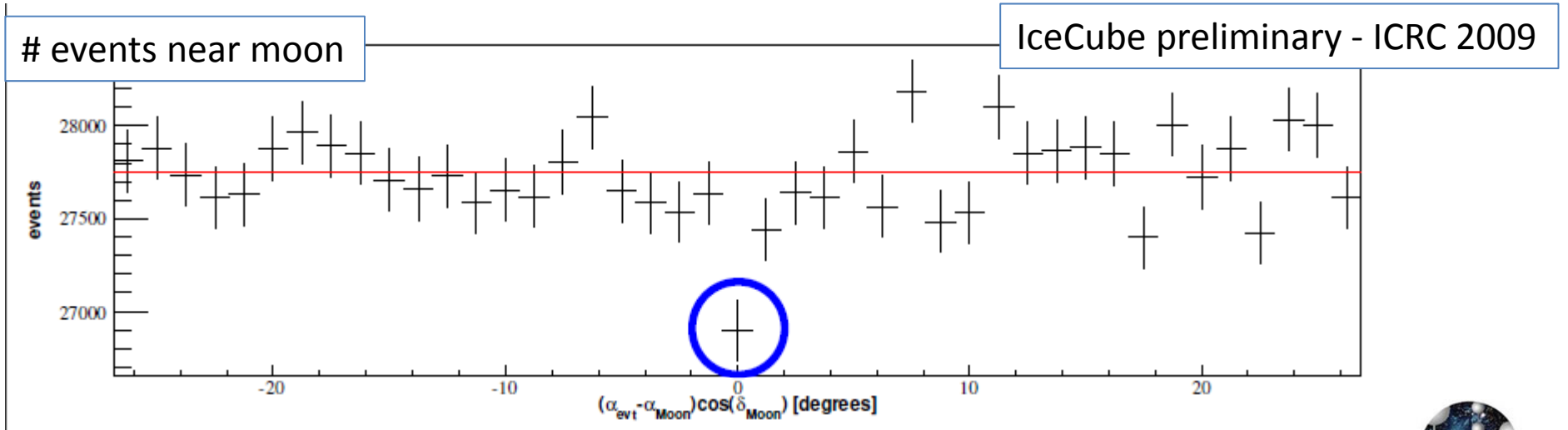
Cascades
- Neutral current
- Charged current ν_e
- 10% resolution in log(energy)

Composites
- Starting tracks, double bangs
- Good directional and energy resolution

Pointing resolution

- Simulation : 1 TeV muon → $\Delta\Psi \approx 1°$
- moon shadow observation → $\Delta\Psi \leq 1.25°$
  - IC40 (2008) 8 lunar months
  - 5σ deficit in atmospheric muon flux





IceCube was completed on 18 December!

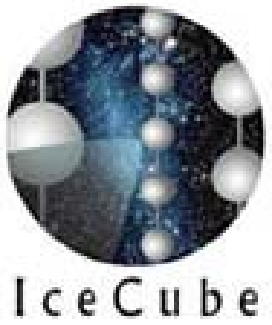
(Nature.com) Giant, frozen neutrino telescope completed - December 18, 2010

ScienceDaily (Dec. 19, 2010) — Culminating a decade of planning, innovation and testing, construction of the world's largest neutrino observatory, installed in the ice of the Antarctic plateau at the geographic South Pole, was successfully completed December 18, 2010, New Zealand time.

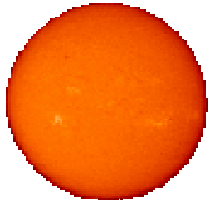
WIMP annihilations in the Sun

WIMP annihilations near the Galactic Centre

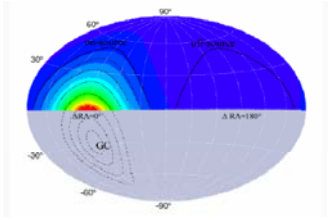
Search for dark matter



Different strategies



- Neutrinos from WIMP annihilations in the Sun: AMANDA, IC22



- Neutrinos from WIMP annihilations in the galactic halo and near the galactic centre: IC22, IC40

- Neutrinos from WIMP annihilations in the centre of the Earth : work in progress

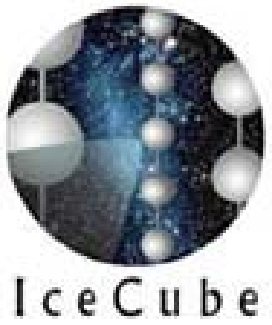
IceCube

Data filtering

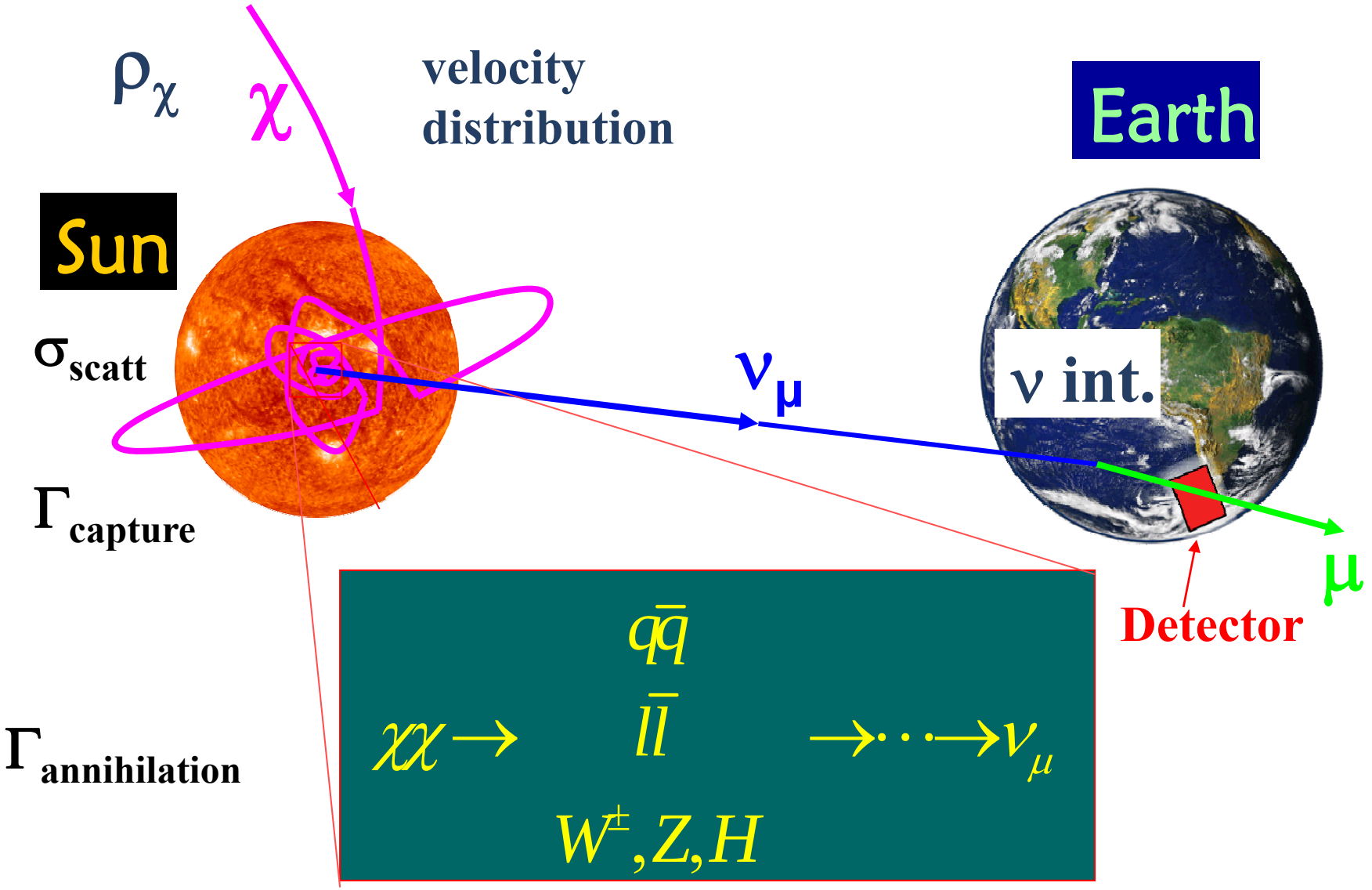
Muon flux and WIMP annihilation rate

WIMP-proton scattering cross section

Solar WIMPs



Solar WIMPs: detection principle



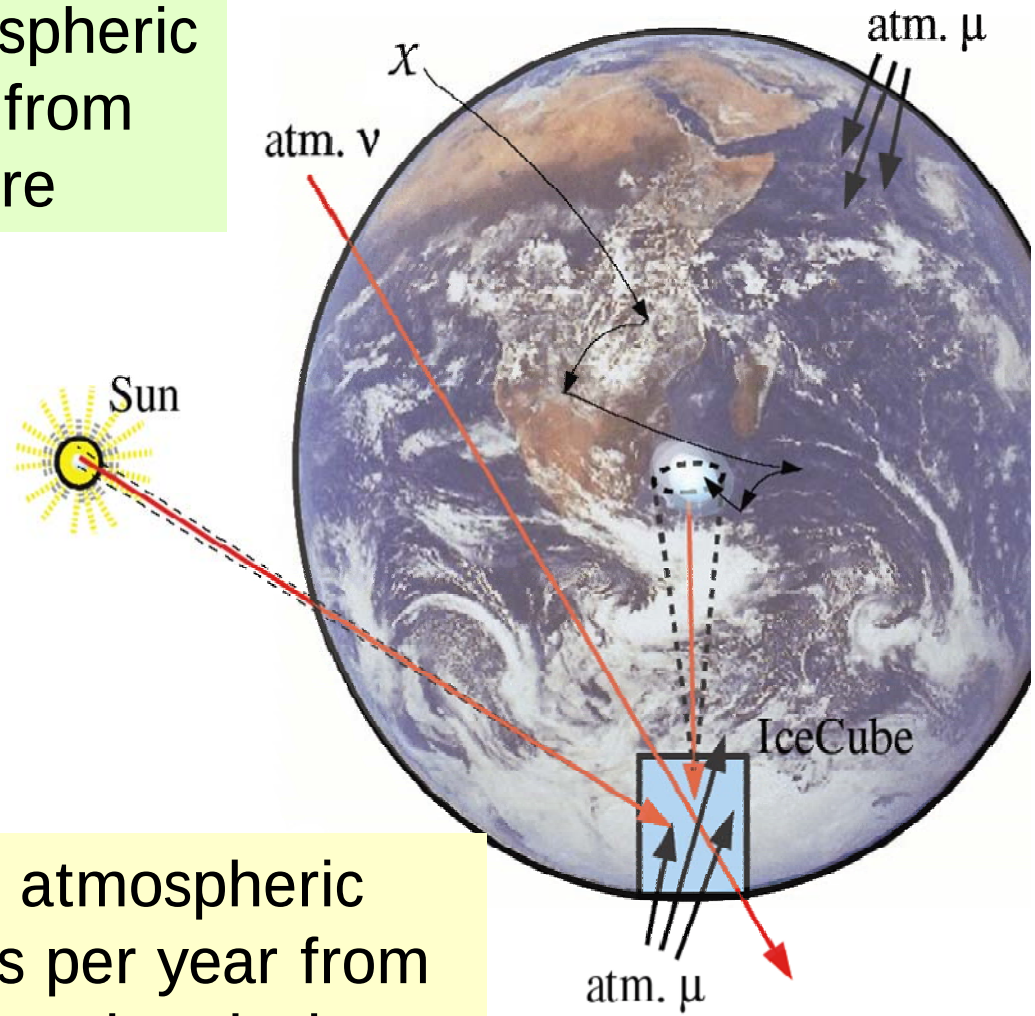
signal and background

BG

A few 10'000 atmospheric neutrinos per year from northern hemisphere

signal

Max. a few neutrinos per year from WIMPs

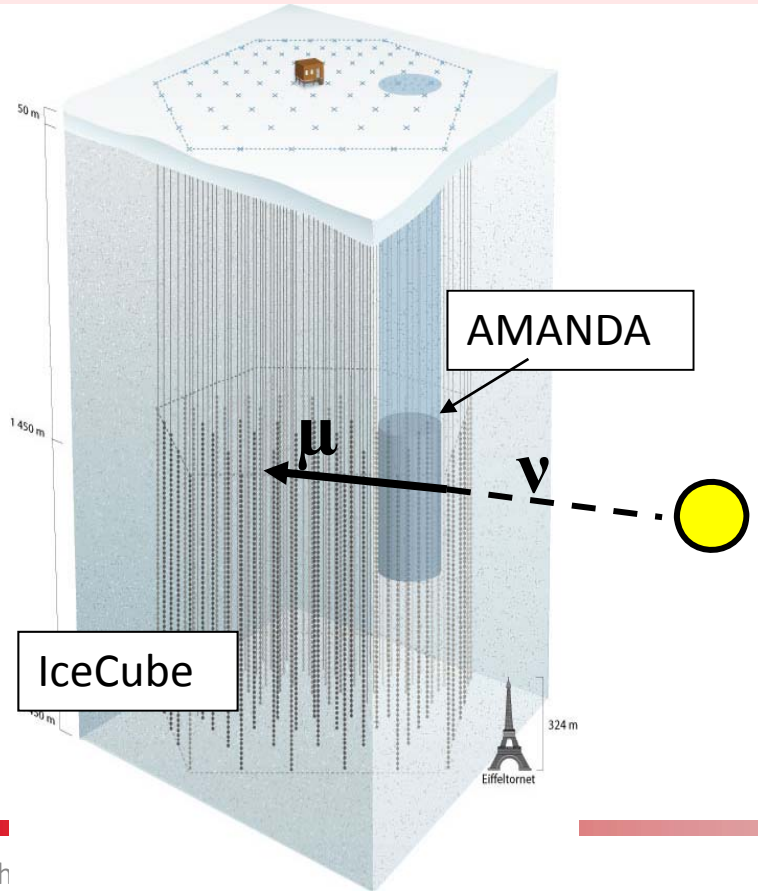


BG

~10^{10} atmospheric muons per year from southern hemisphere

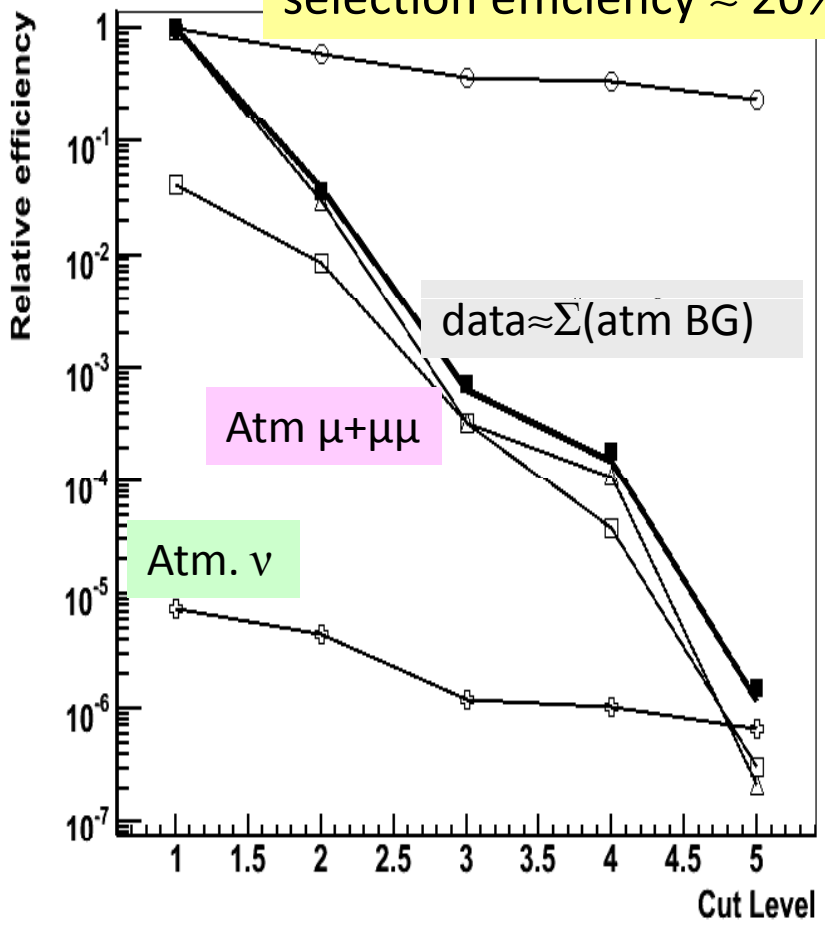
Data filtering

- Muon tracks from ν_μ Charged Current interactions
- When Sun below horizon: March-September
- Nearly horizontal tracks



Different levels of filtering

1TeV WIMP, hard channel selection efficiency ≈ 20%

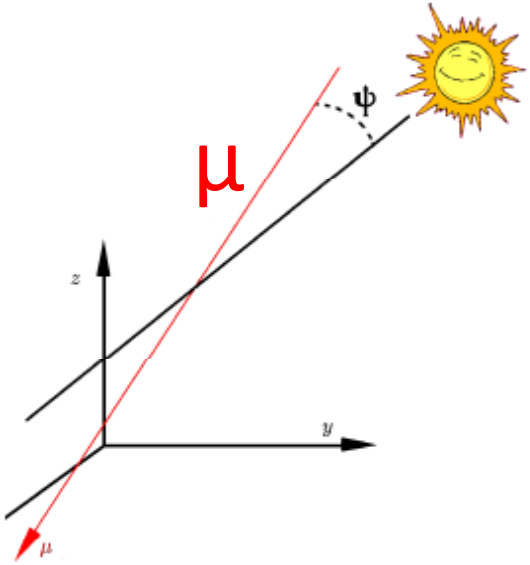


Signal content from fit

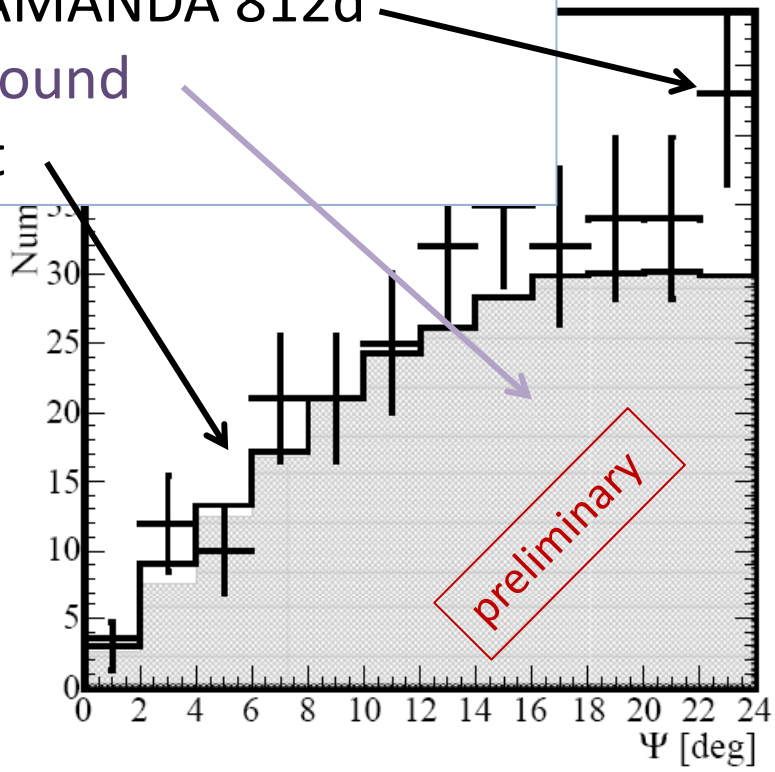
$$f(\psi|\mu) = \frac{\mu}{n_{obs}} f_S(\psi) + \left(1 - \frac{\mu}{n_{obs}}\right) f_B(\psi)$$

Model dependent
From MC simulations

From off-source data



Neutralino 250 GeV to WW
Data, AMANDA 812d
Background
Best fit

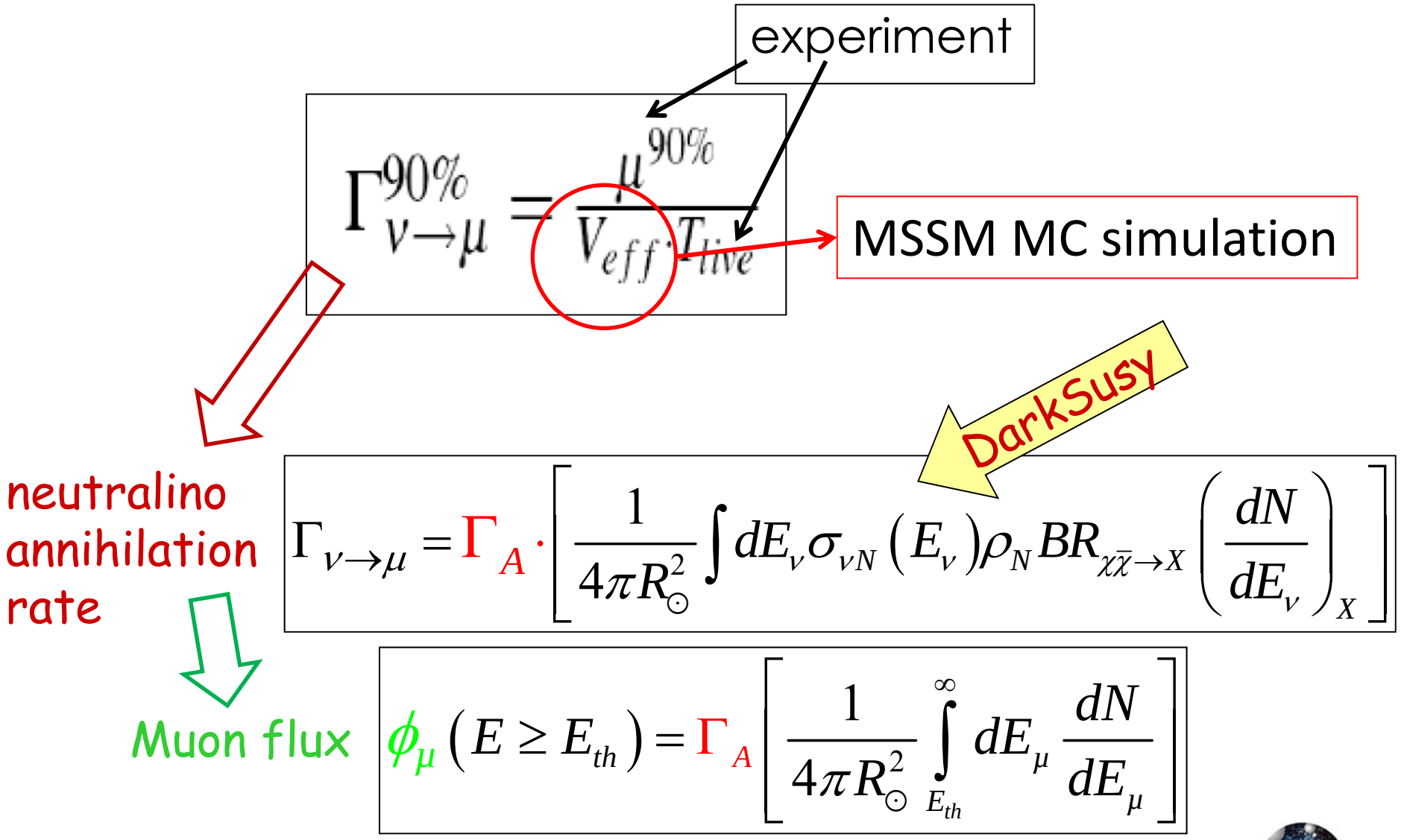


Search results

AMANDA dedicated search M(WIMP) [50-5000 GeV]	**Angular resolution 3 – 7 degrees**	**812 days livetime**	**2001-06**
IceCube 22 strings dedicated search M(WIMP) [250-5000 GeV]	≈ 3 degrees	104 days	2007

- No evidence for a signal in ~ 900 days livetime
- → upper limits on neutralino annihilation rate in Sun & resulting muon flux

Annihilation rate & muon flux



Neutralino models considered

- Assume MSSM with R-parity conservation
- Neutralino χ_0^1 (LSP) is popular CDM candidate: weakly interacting, stable, massive

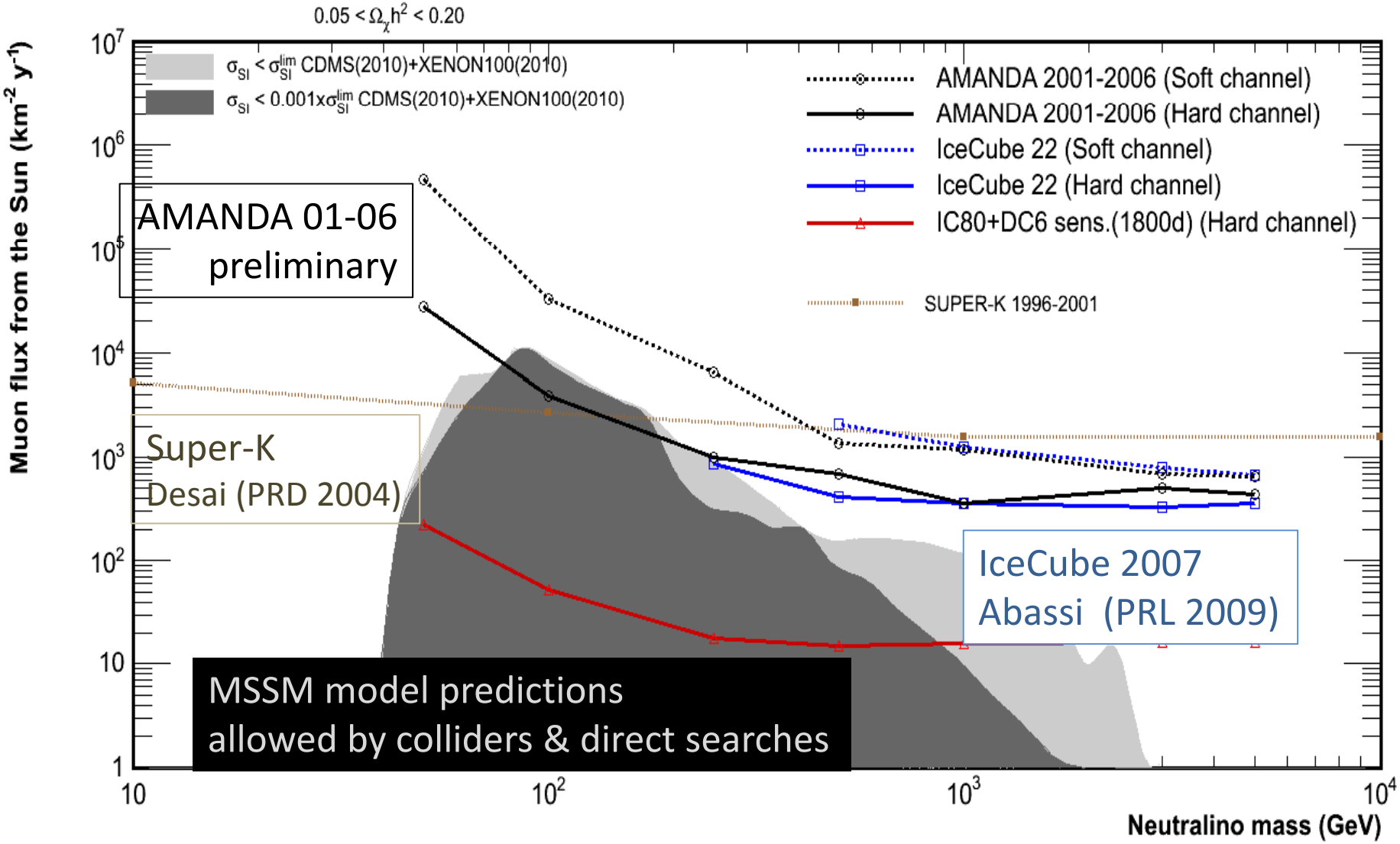
- Consider 7 masses $50\ GeV < m(\chi_0) < 5000\ GeV/c^2$
- and 2 annihilation channels

$$\chi\chi \rightarrow W^+W^-\left(\tau^+\tau^-\right) \rightarrow \nu \qquad \text{hard } E_\nu \text{ spectrum}$$

$$\chi\chi \rightarrow \bar{b}b \rightarrow \nu \qquad \text{soft } E_\nu \text{ spectrum}$$

- Simulation with WIMPSIM (Blennow & Edsjö JCAP 2008)

Muon flux from solar neutralinos



Scattering cross section

- muon flux → scattering cross section
- Assume
  - equilibrium between capture in Sun and annihilation
  - Spin-dependent scattering dominates capture in Sun
- For given final state $\chi\chi \rightarrow f\bar{f}$

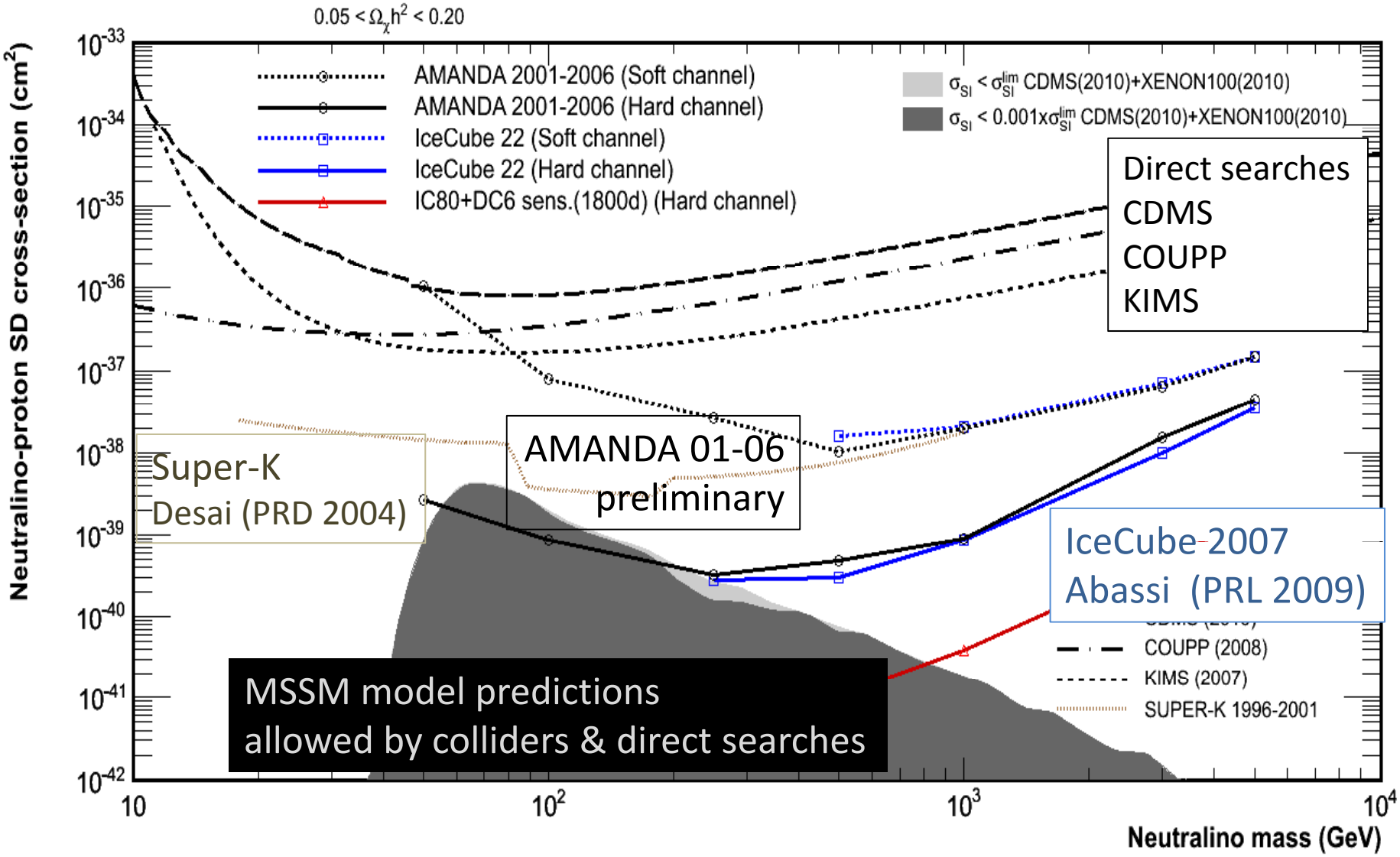
$$\phi_\mu^f = \Gamma_A \left[\eta^f \left(m_\chi \right) \right]$$

$$\Gamma_{Annihilation} = \frac{1}{2} C_{capture}$$

$$C_C \propto \sigma^{\chi N} \Rightarrow \sigma^{SD} = \frac{\lambda^{SD}\left(m_\chi\right)}{\eta^f\left(m_\chi\right)} \phi_\mu^f$$

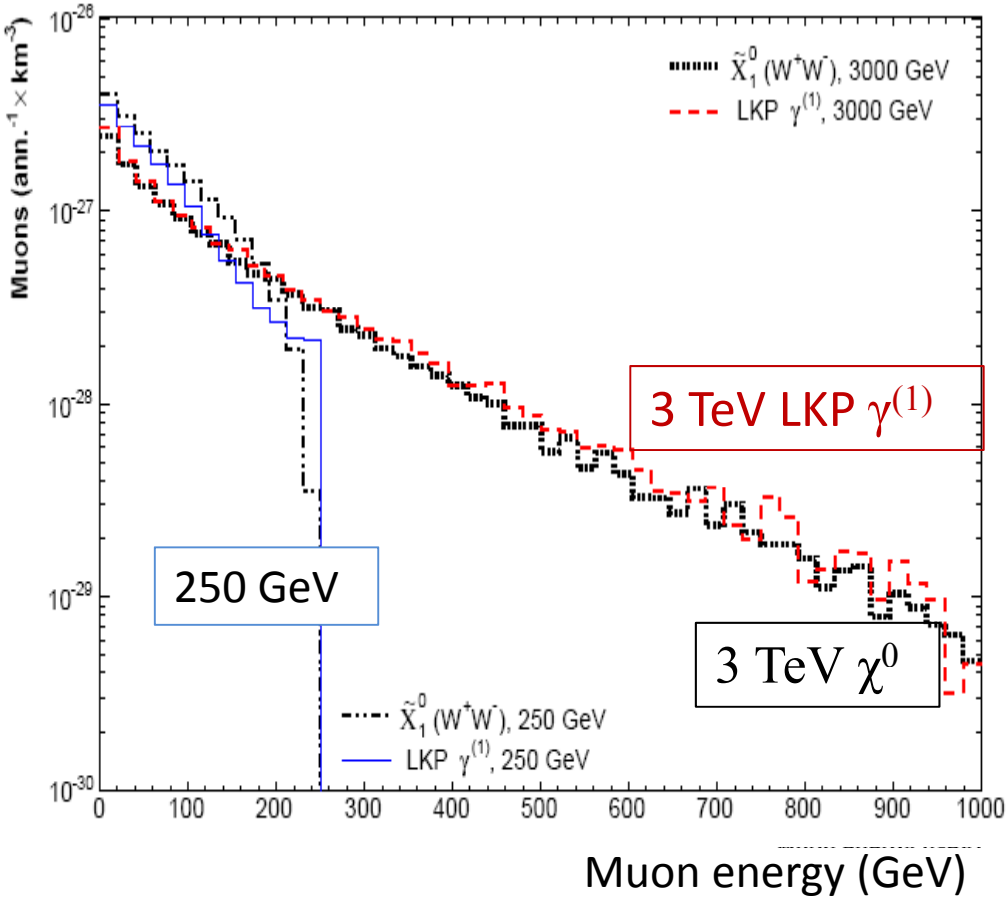
Wikström & Edsjö, JCAP 2009

Spin dependent scattering cross section



LKP annihilations in the Sun

- IC22 data re-interpreted in model of Universal Extra Dimensions
- KK-parity conserved → **L**ightest **K**aluza Klein **P**article $\gamma^{(1)}$ is DM candidate
- similar observed muon energy spectra for neutralino & LKP



LKP annihilations in the Sun

Experiment – IC22 angular distribution

$$\Gamma^{90\%}_{\nu\to\mu} = \frac{\mu^{90\%}}{V_{eff}\cdot T_{live}}$$

UED MC simulation

LKP annihilation rate in Sun

$$\Gamma_{\nu\to\mu} = \Gamma_A \cdot [\, factor \,]$$

DarkSusy

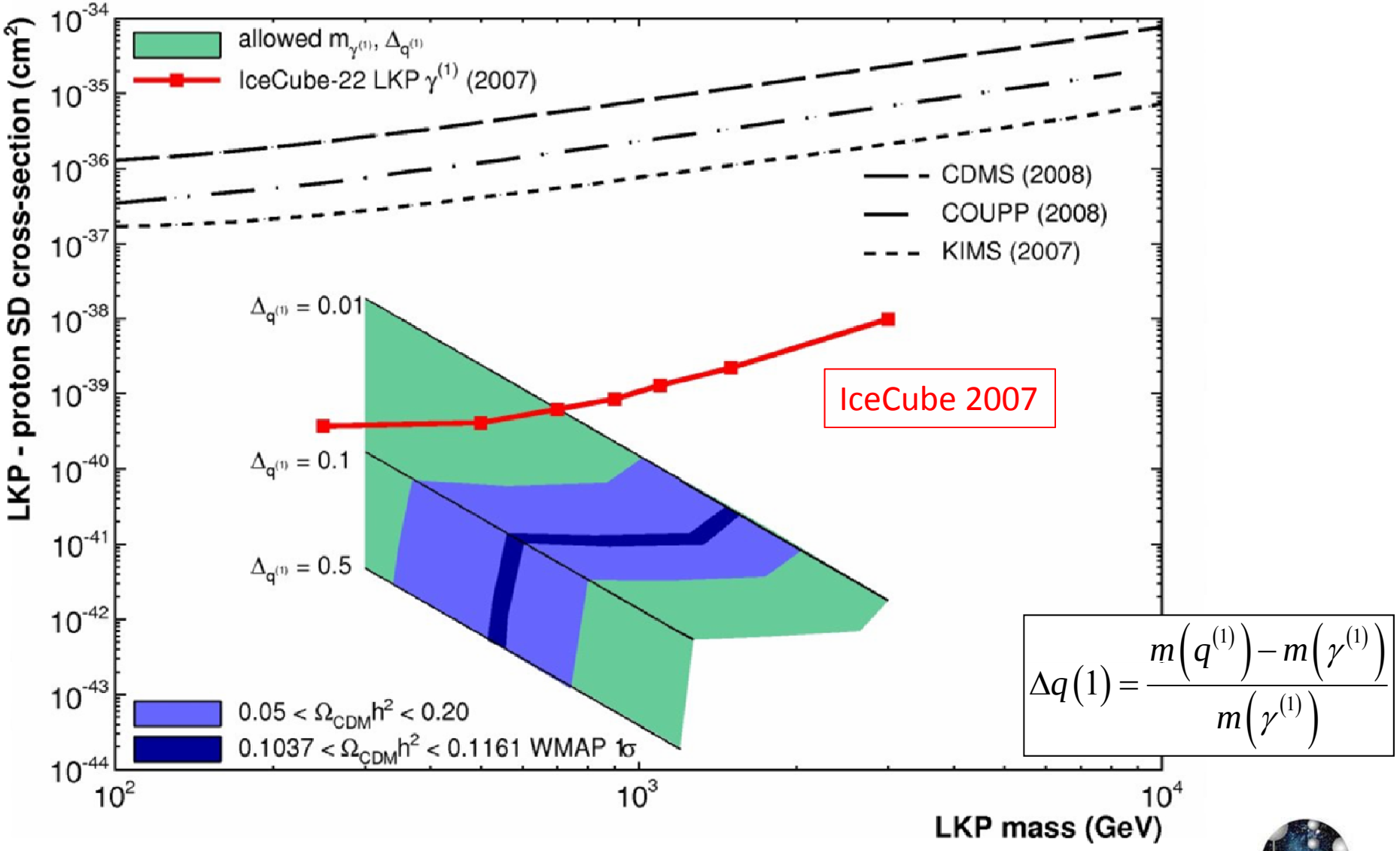
Muon flux at Earth

$$\phi_\mu \left(E \geq E_{th} \right) = \Gamma_A \left[\, factor \, \right]$$

$\gamma^{(1)}$p Scattering cross section

$$\sigma^{SD} = \kappa'^{SD}_f \left(m_{\gamma^{(1)}} \right) \phi^f_\mu$$

LKP-proton SD cross section

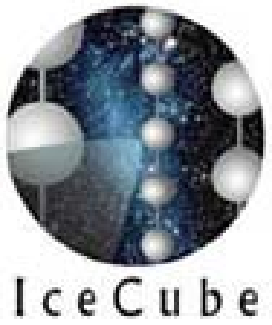


Large scale anisotropy near Galactic Centre

Dedicated GC search

Self-annihilation cross section

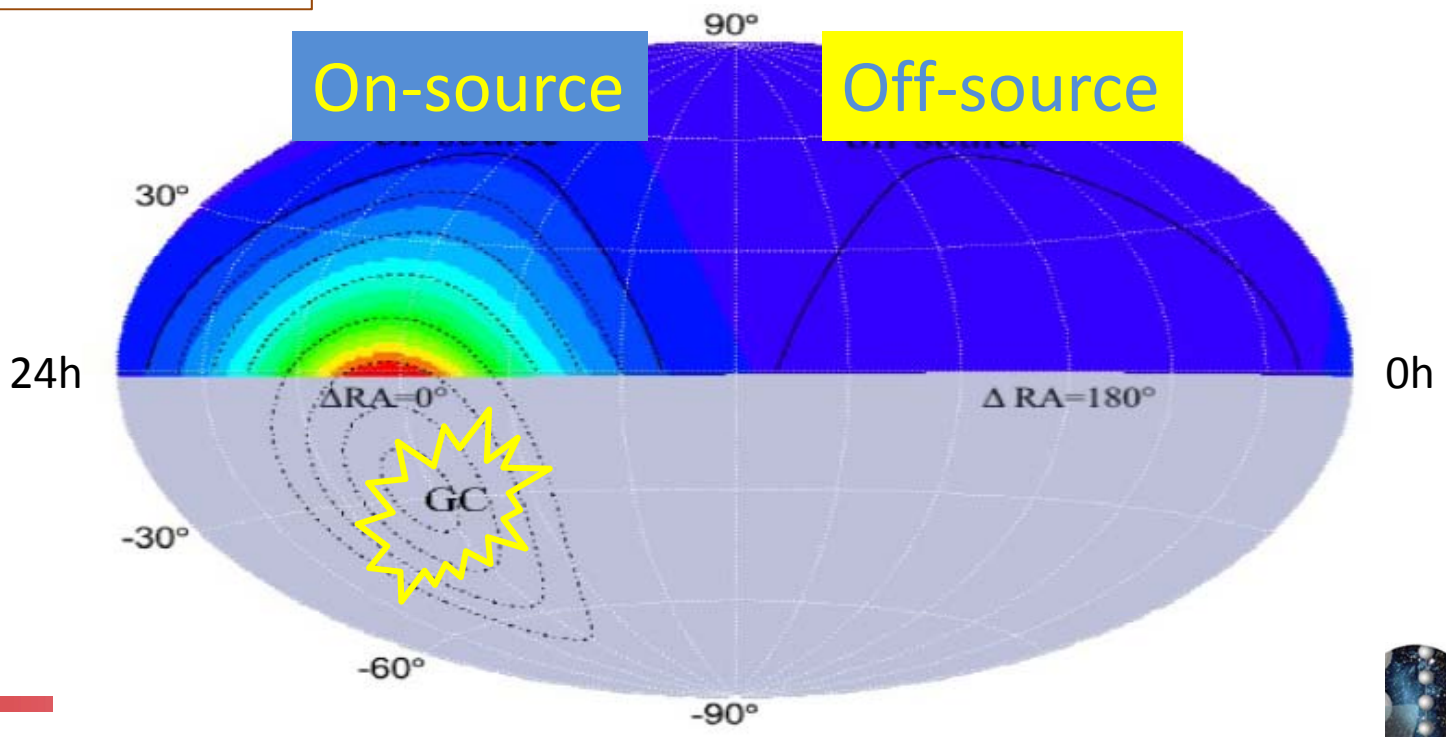
WIMPs IN THE HALO



Large scale neutrino anisotropy

- Search for anisotropy near Galactic Centre in IC22 point source sample
- Background in 'ON' = BG in 'OFF' = atmospheric $\nu + \mu$

Northern hemisphere = IceCube ν field of view

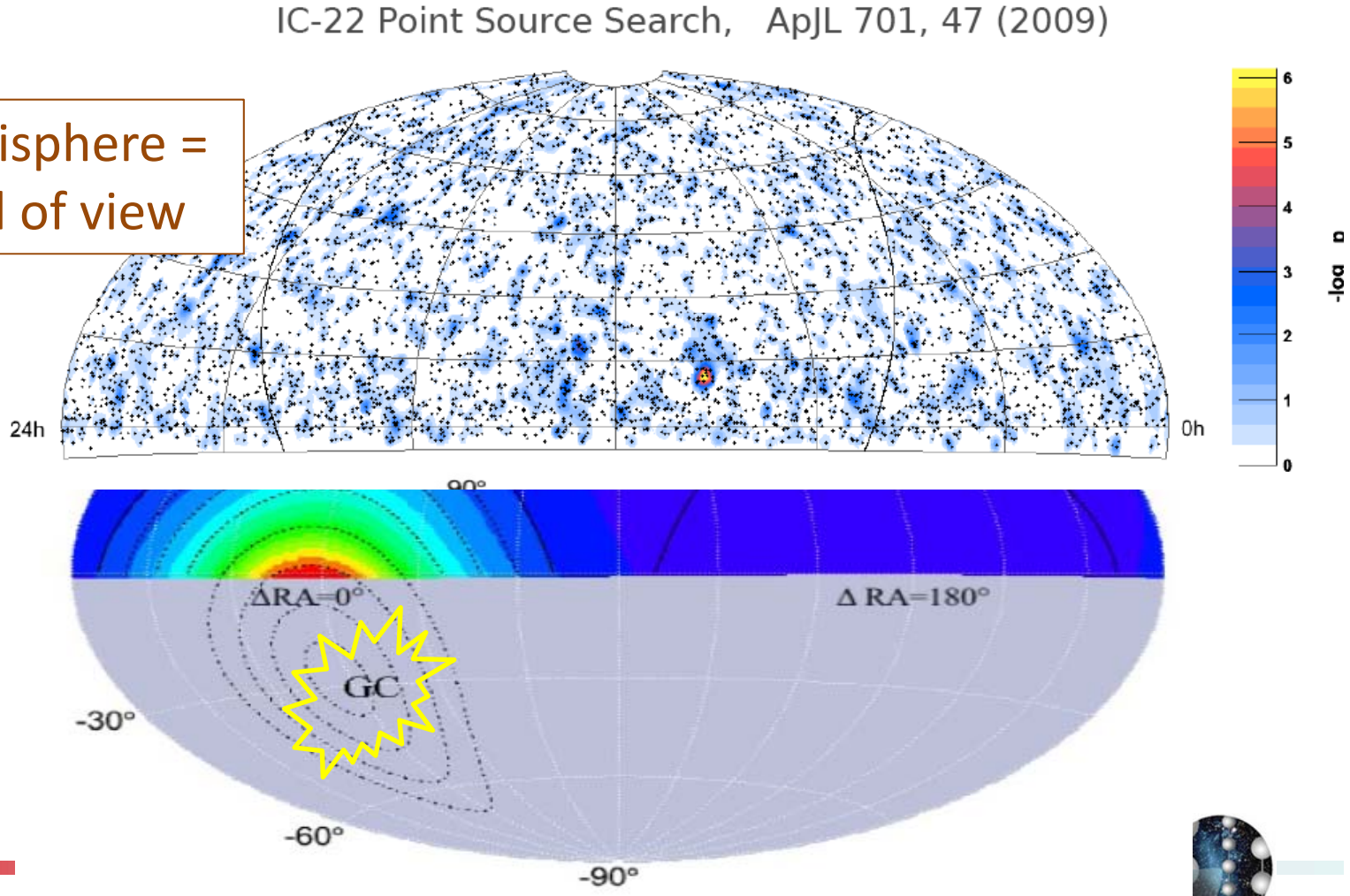


IceCube

Large scale neutrino anisotropy

- 5114 events in 276 days in 2007
- No anisotropy found

Northern hemisphere = IceCube ν field of view



IceCube

Neutralino annihilation in the halo

$$\frac{d\Phi_\nu}{dE} = \frac{\langle \sigma_A \upsilon \rangle}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

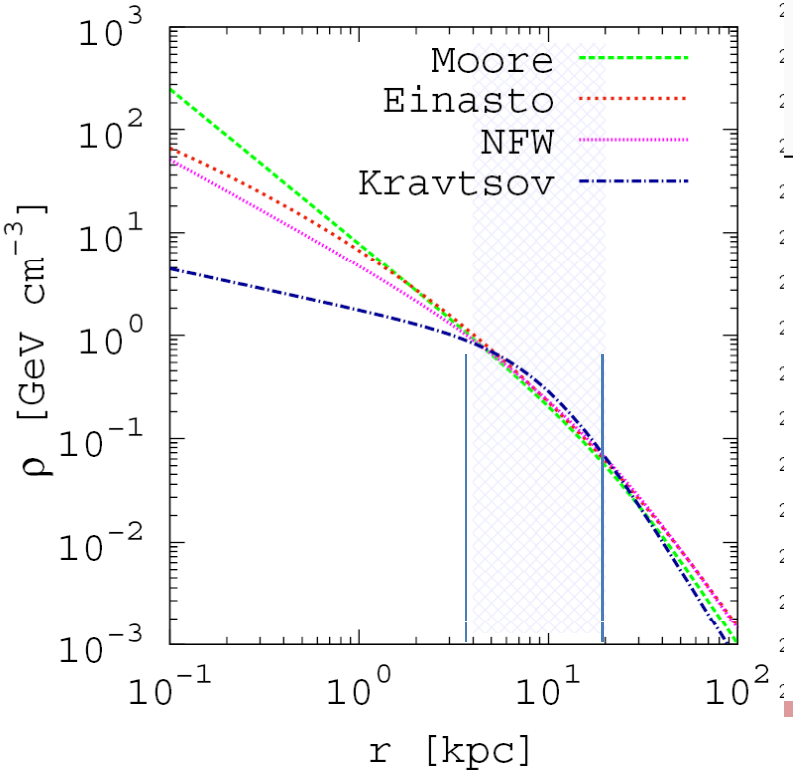
Measure

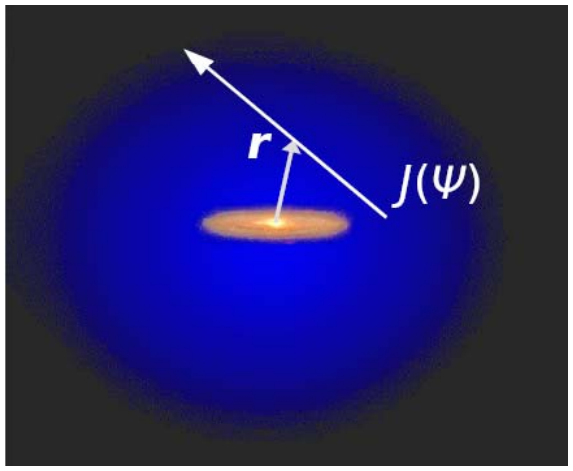
Constrain

Halo

SUSY

Halo models

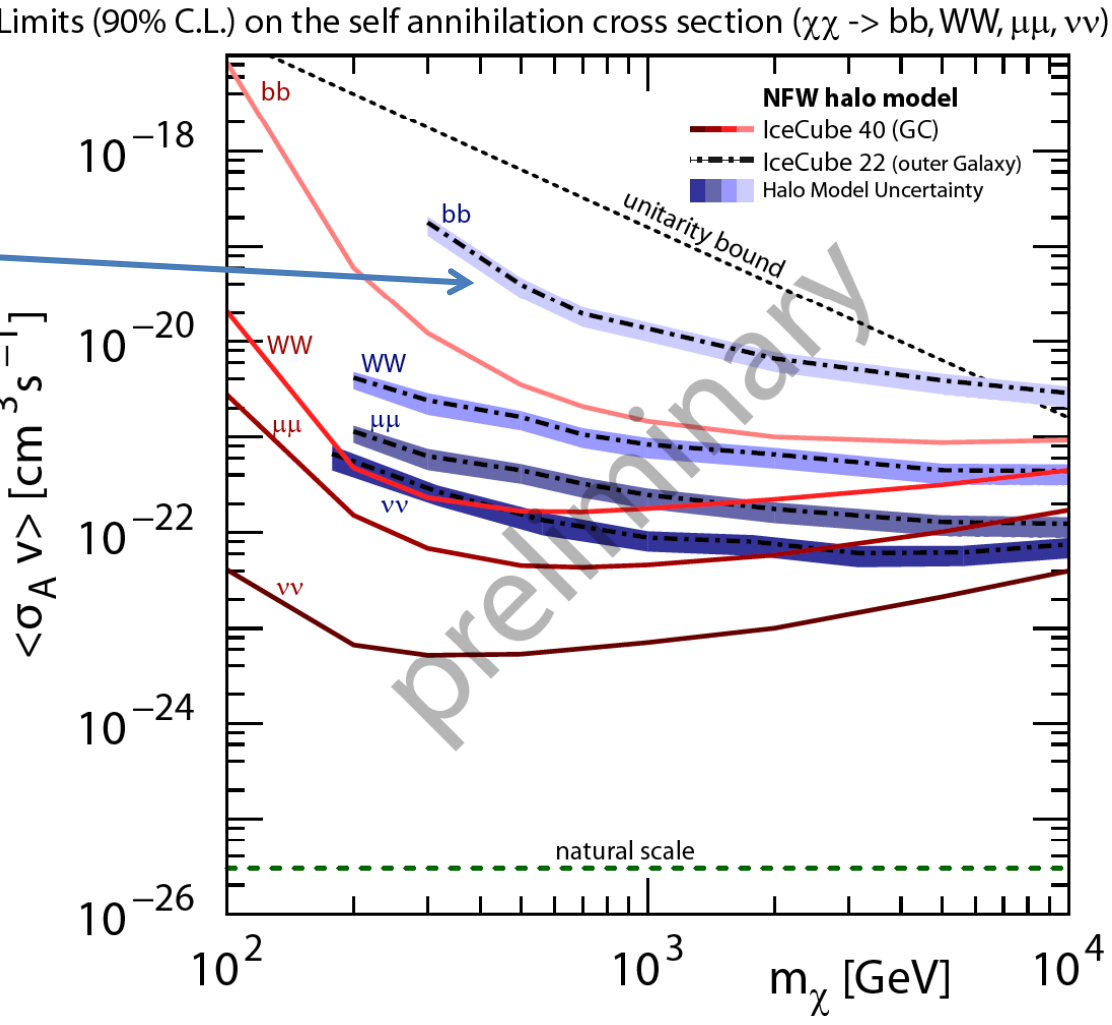




Limits on self-annihilation cross section

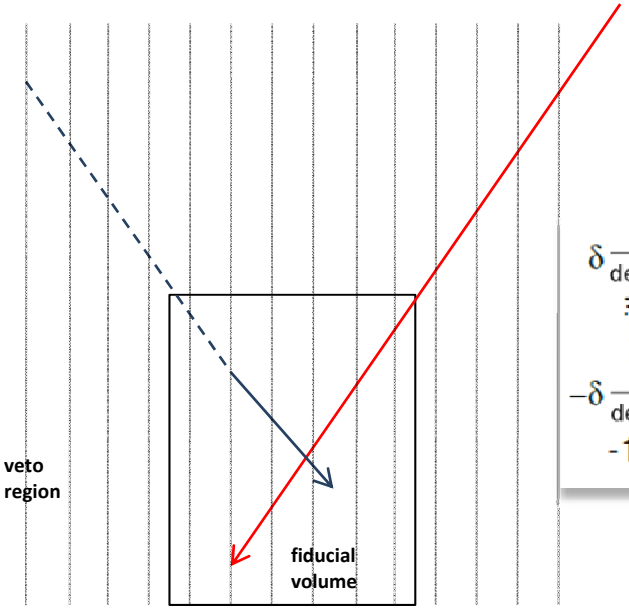
$$< \sigma_{Ann} v >$$

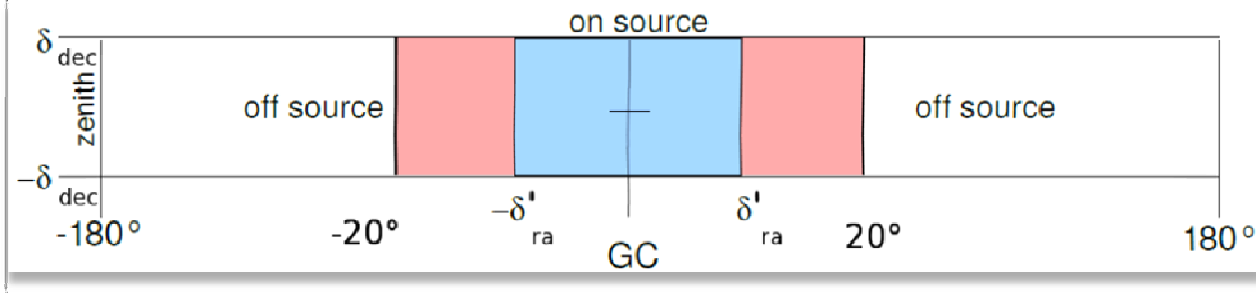
- IC22 anisotropy
- NFW halo model
- 4 annihilation channels



Neutrinos from Galactic Centre

- Search in IC40 point source sample (2008) for excess in direction of Galactic Centre
- ! Southern hemisphere : use few outer layers as veto against atmospheric muon background
- No excess found in GC search bin

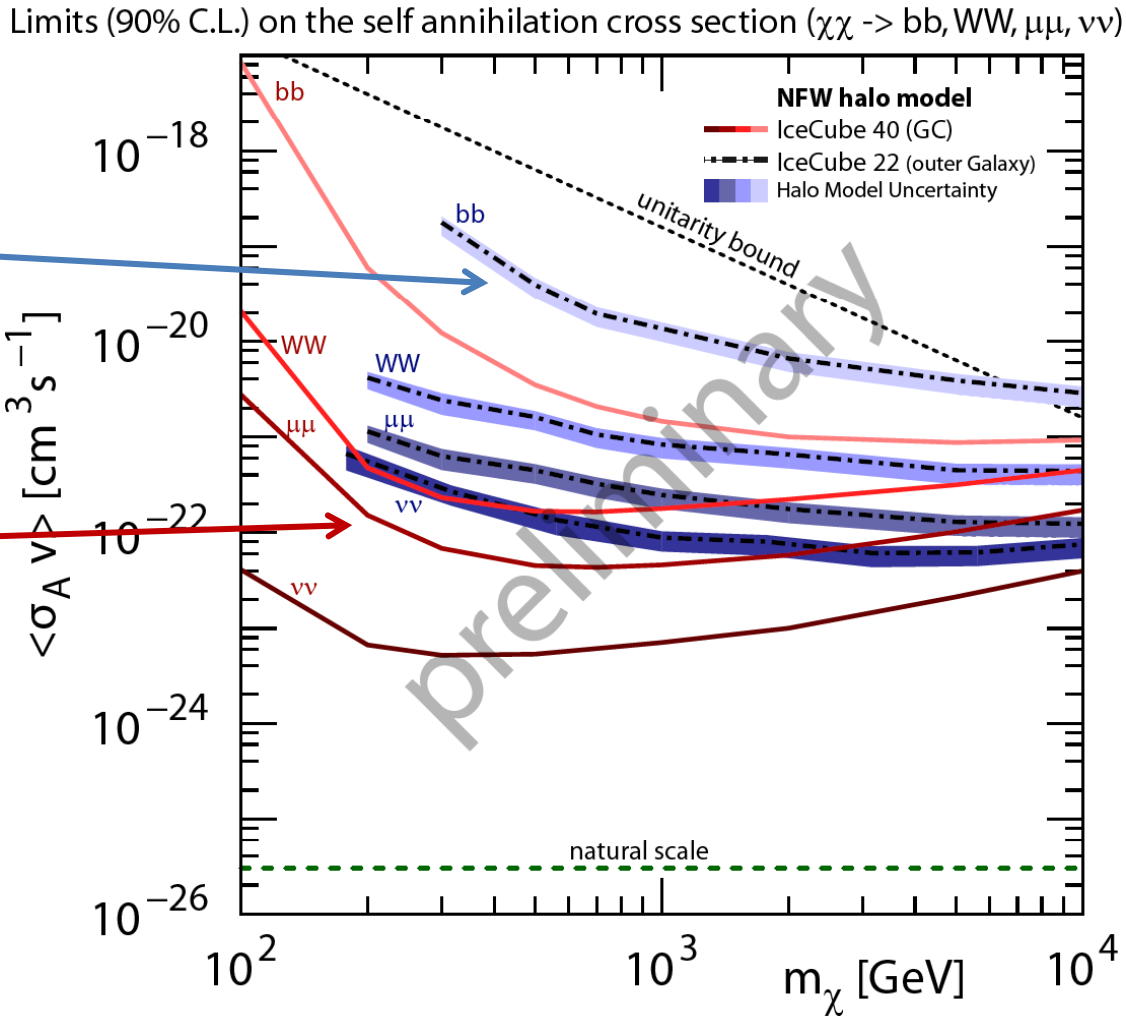




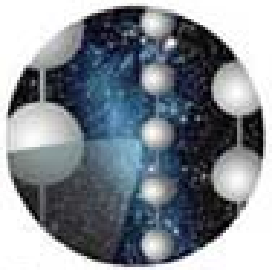
Limits

$$< \sigma_{Ann} v >$$

- IC22 anisotropy
- IC40 Galactic centre search
  - NFW halo model
  - 4 annihilation channels



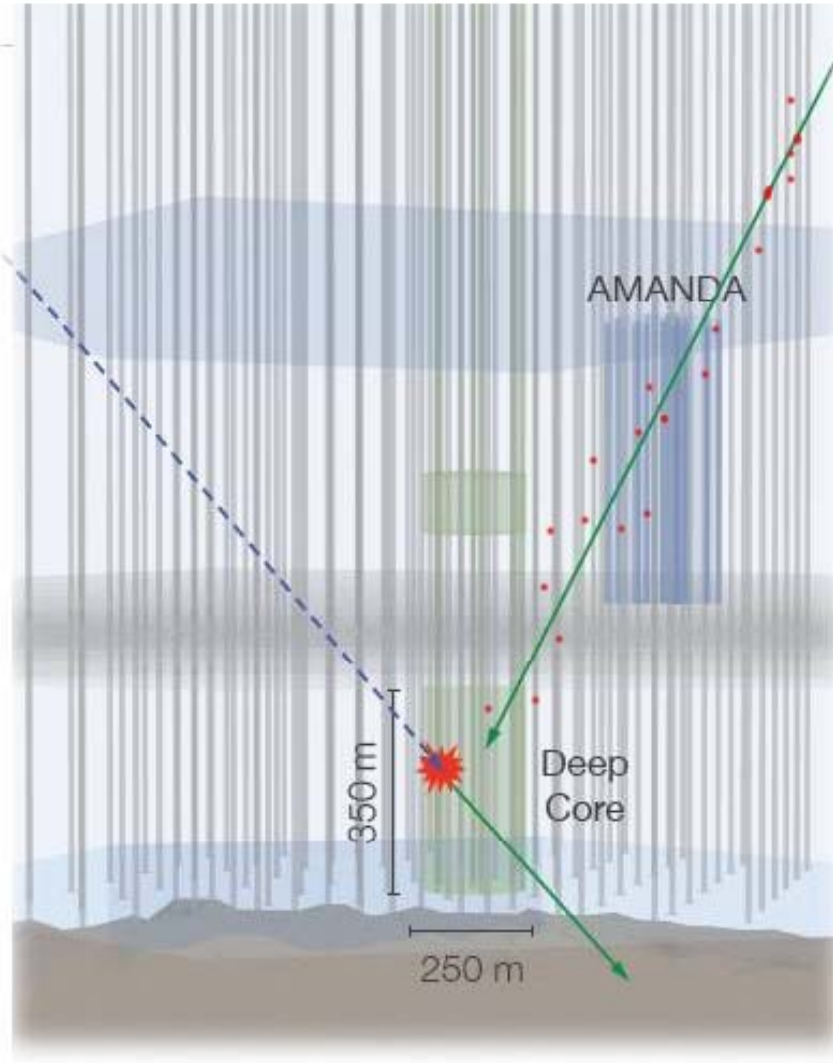
IceCube + DeepCore prospects



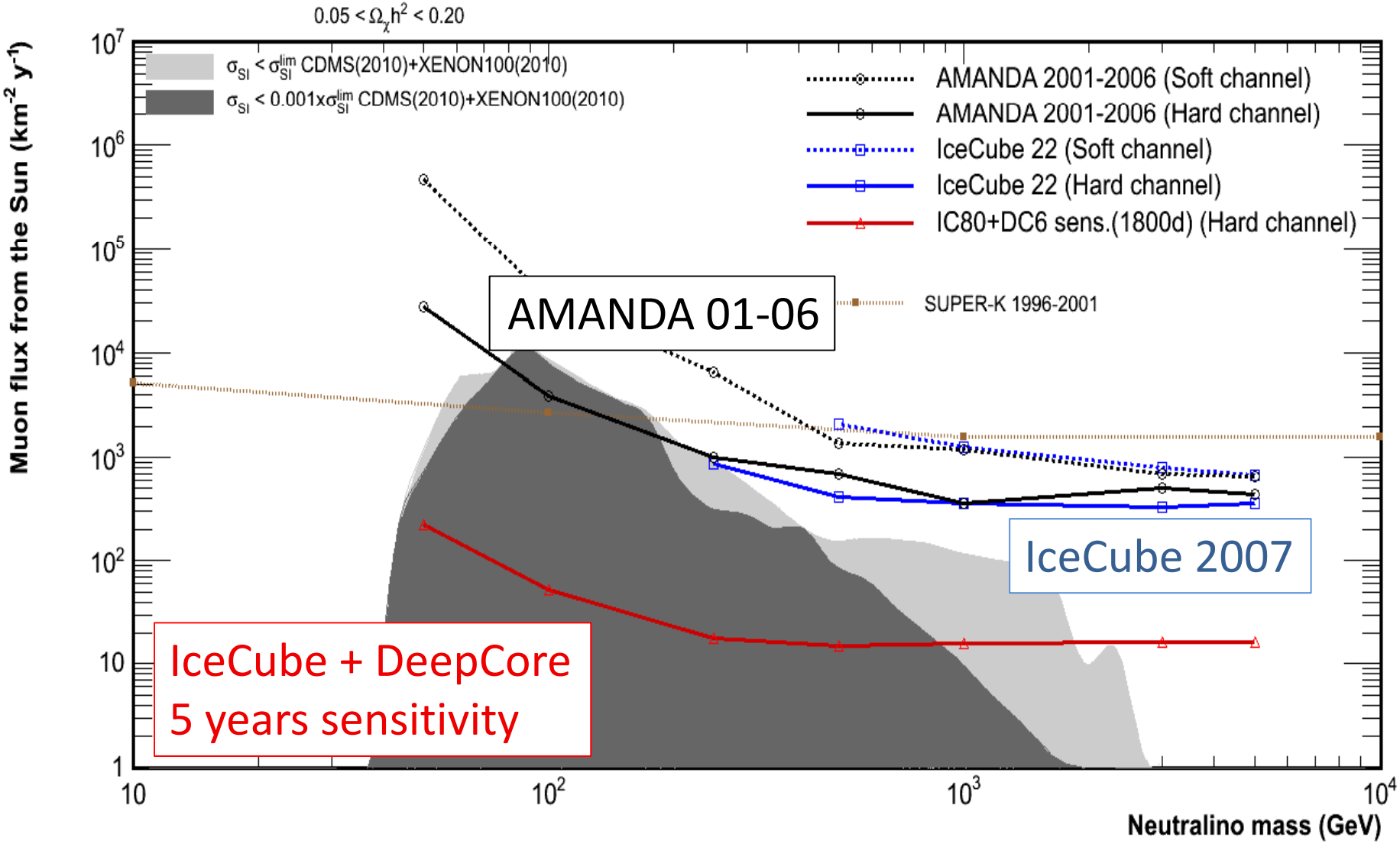
DeepCore and WIMPs

- DeepCore : low energy extension in deep clear ice
- Use IceCube as veto against downgoing atmospheric muons
- Extend field of view to southern hemisphere in [10GeV-fewTeV] domain

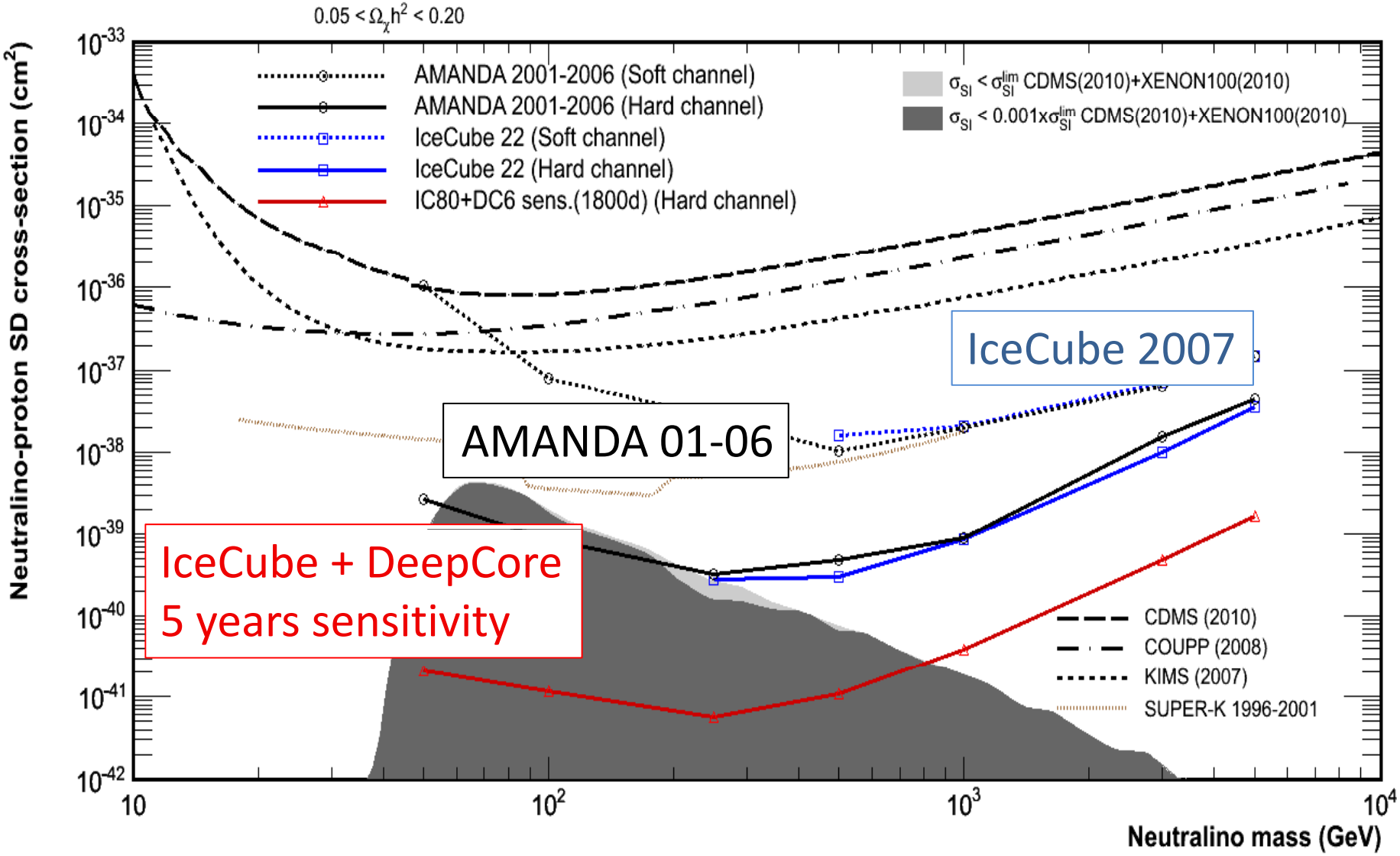
- Galactic Centre
- year round solar WIMPs



Muon flux from solar neutralinos



Neutralino scattering in Sun



Summary

- Icecube/AMANDA data was used to search for indirect neutrino signal from WIMP annihilations in Sun & near Galactic Centre
- No signal was found & upper limits were set on muon flux at Earth and Spin Dependent cross sections
- IceCube is completed and is largest ν detector in operation
- Within 5 years sensitivity to DM signals will

➢ improve by order of magnitude in [30GeV-5TeV]

➢ Unclude sources in Southern hemisphere

IceCube collaboration

Icecube.wisc.edu