Astroparticle Physics with IceCube

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for the IceCube collaboration

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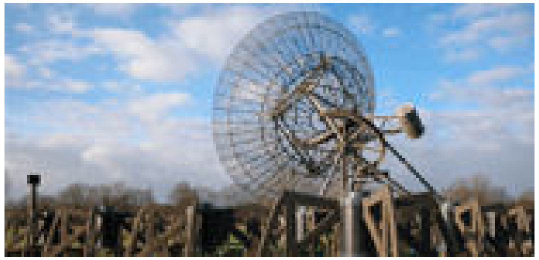
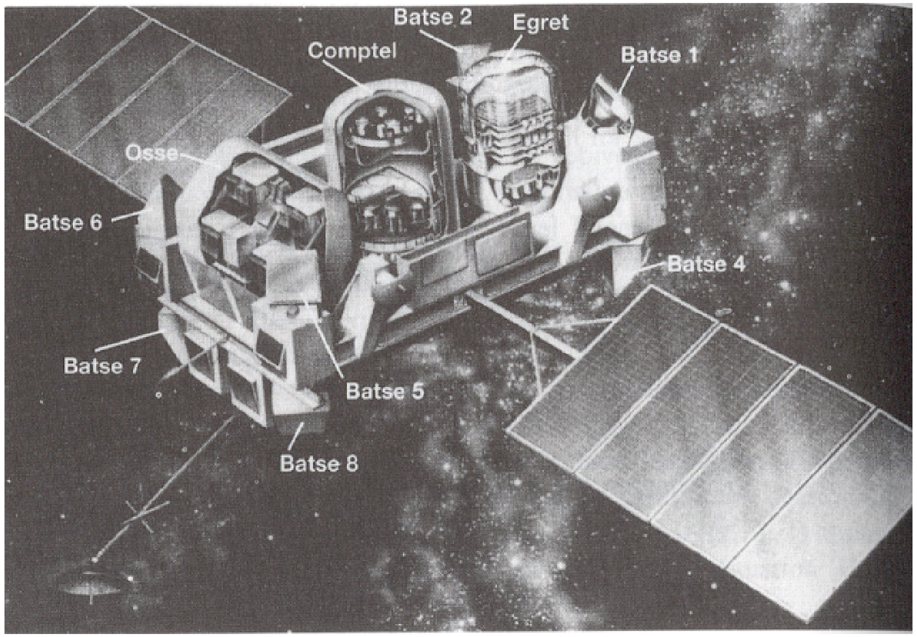
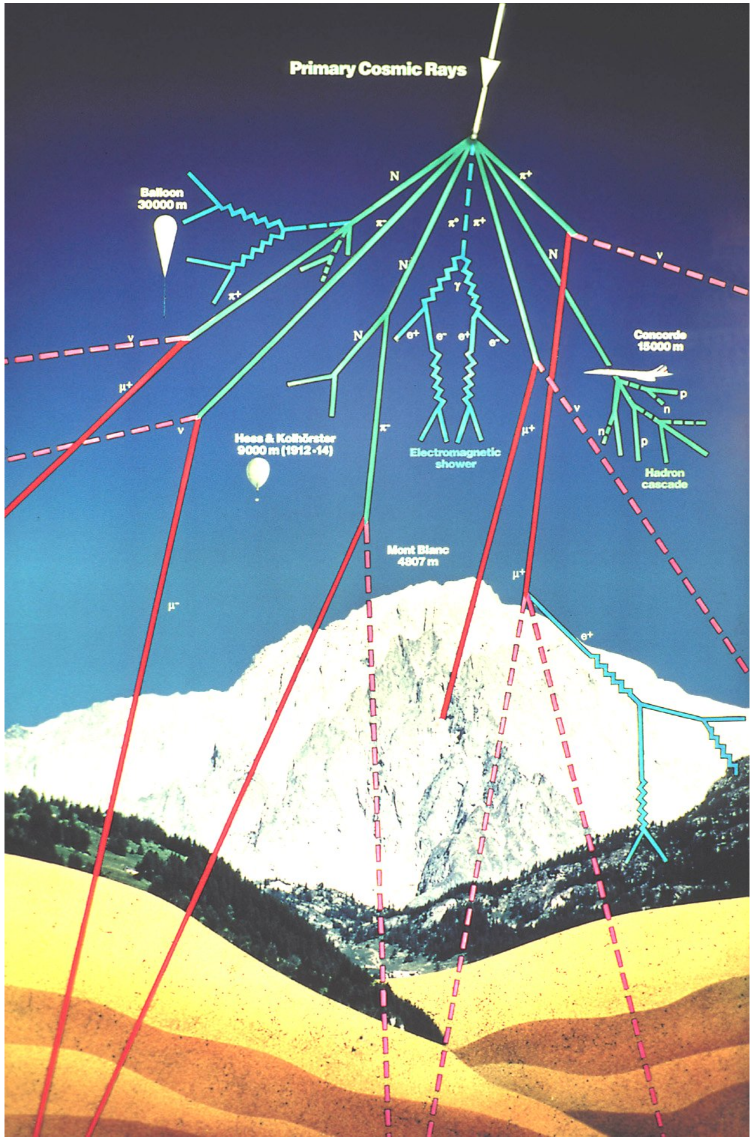
Overview

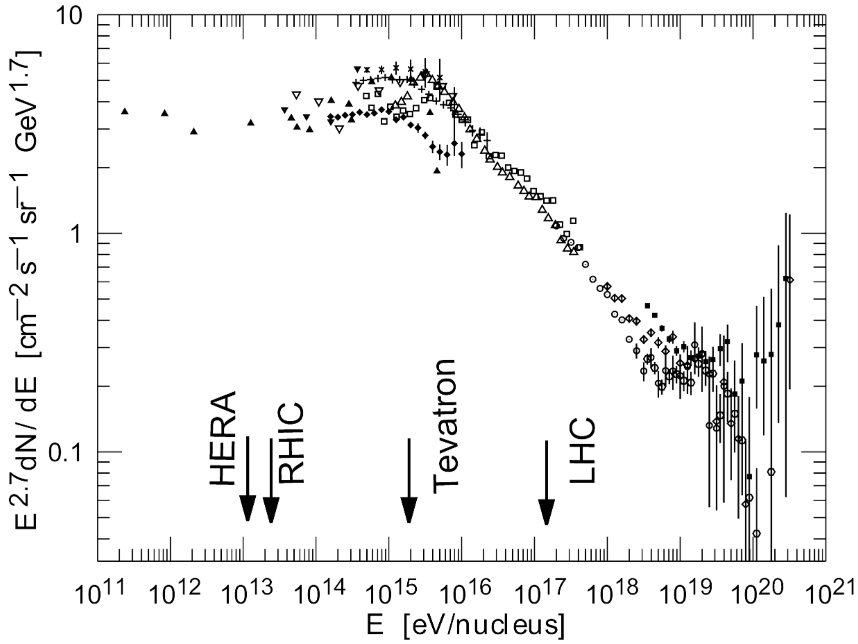
Electromagnetic radiation







$E^{2.7}$ scaled flux



- **Spectral features (knee, ankle)**

  E limits of cosmic accelerators ?
- **What are these accelerator sites ?**

  Violent explosive phenomena
  - **Supernovae**
  - **Gamma Ray Bursts**
  - **Black holes (AGN)**

Supernova blast waves

Protons : $E_{max} \approx 10^{15}$ eV ('knee')

Larger nuclei : $E_Z = ZE_{proton}$

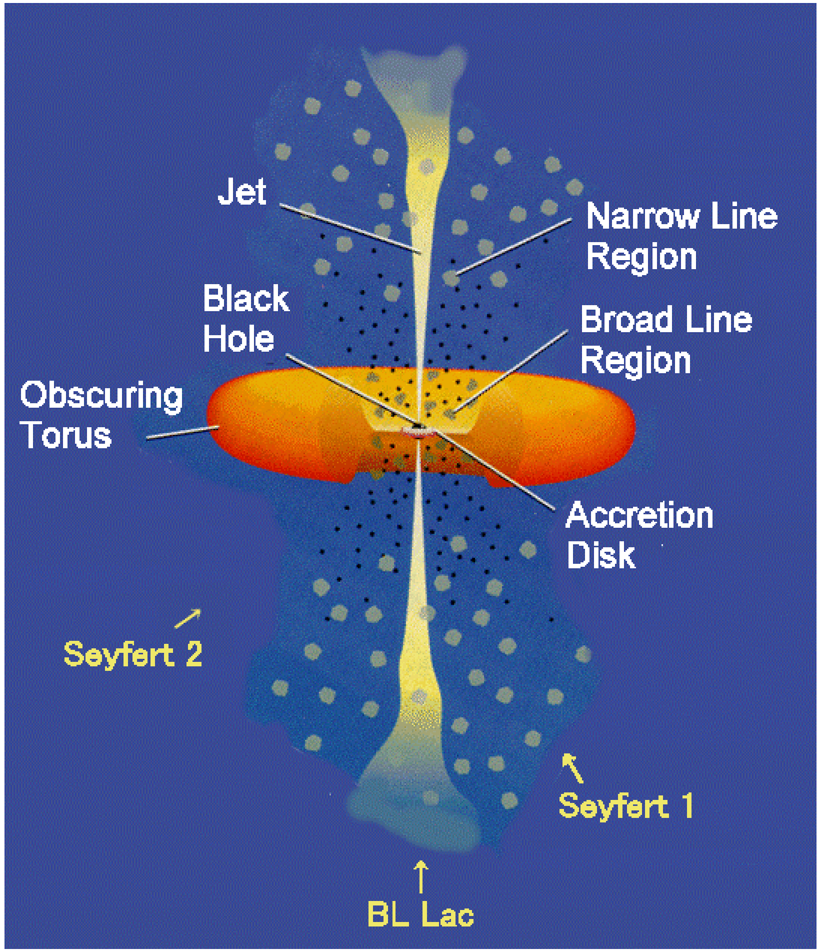
Above 10^{19} eV

Only candidates : GRBs & AGN

Out of reach for terrestrial accel.

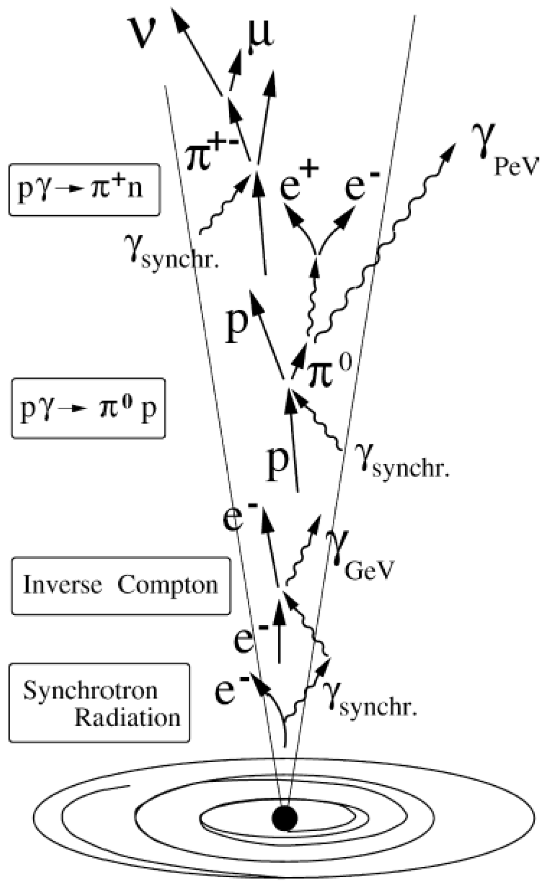
Possible high-energy engine

General picture



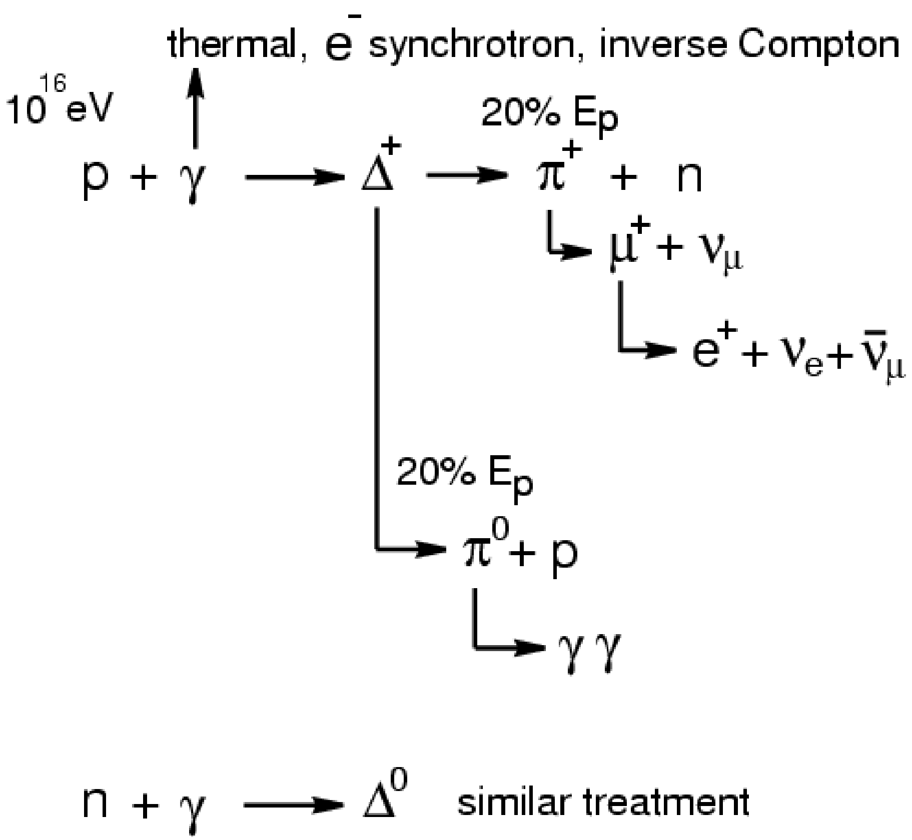
Acceleration in shock waves

Processes in the jet



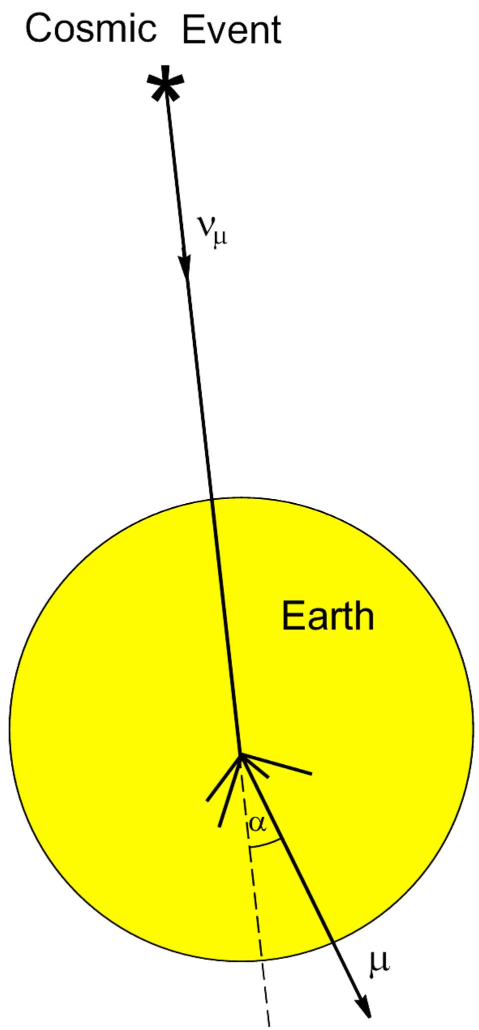
High-energy photons and neutrinos

Neutrino production mechanism



- **Δ prod. threshold : $E_\gamma \geq 10$ eV (UV photons)**

Neutrino detection mechanism

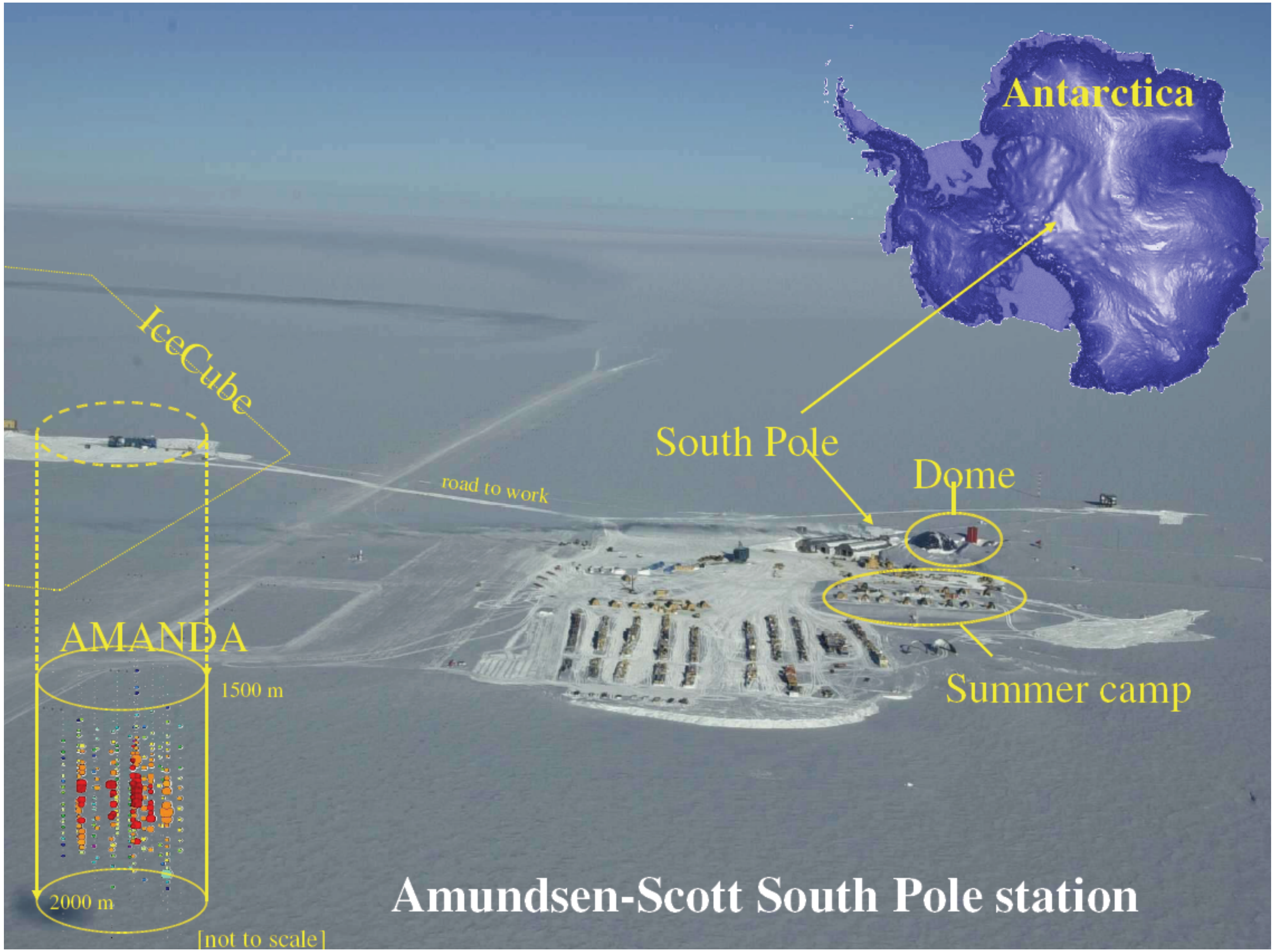


The IceCube Collaboration

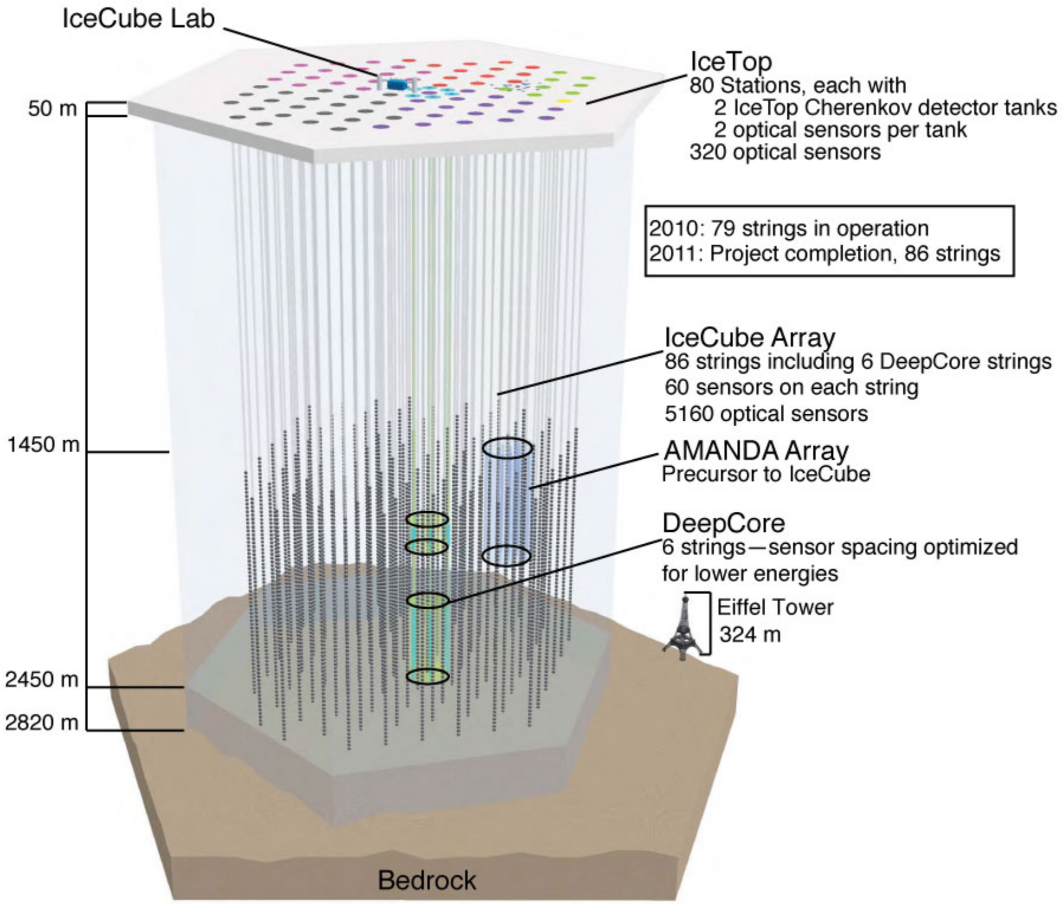
34 institutions, 250 members

http://icecube.wisc.edu

The IceCube Neutrino Observatory

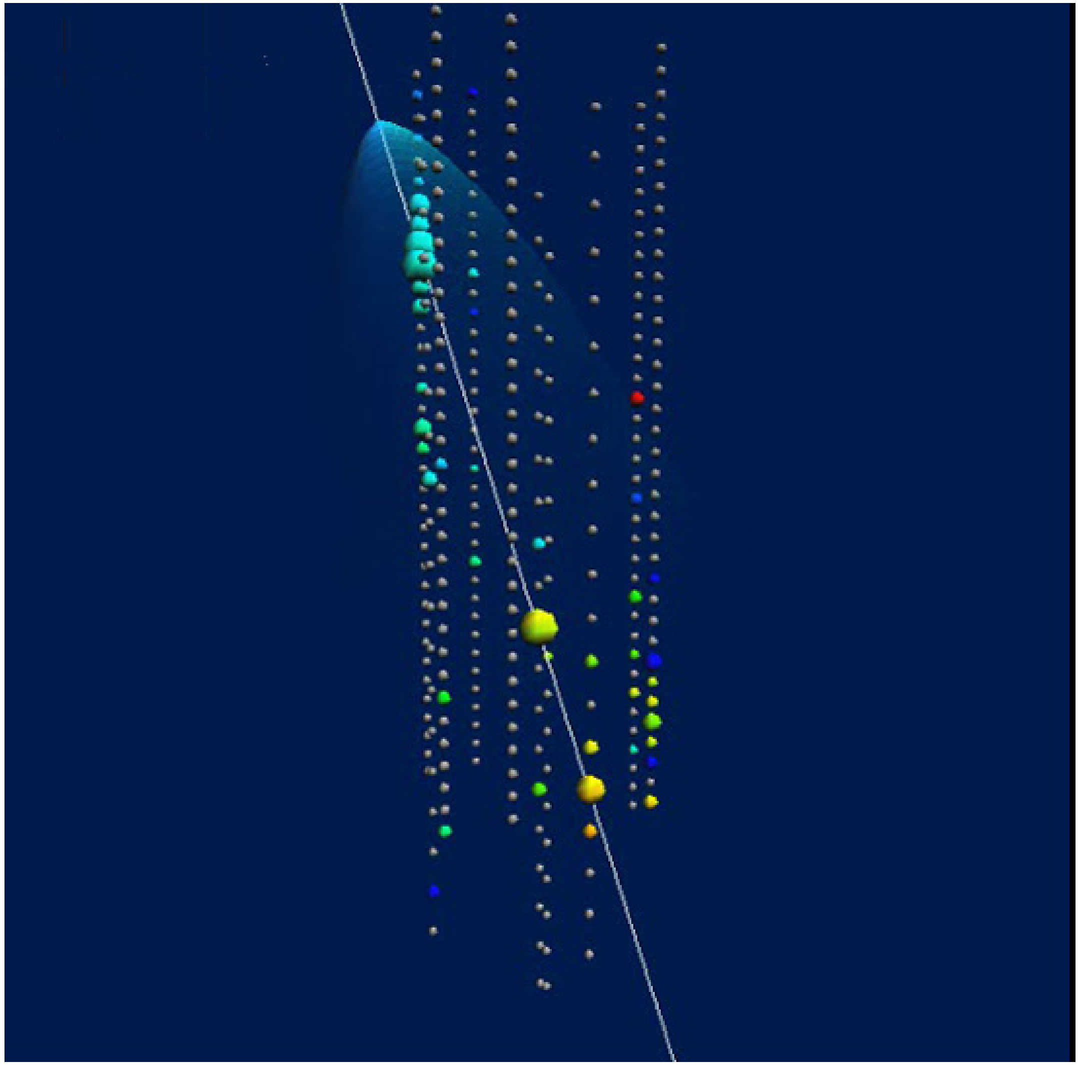


The IceCube Neutrino Observatory



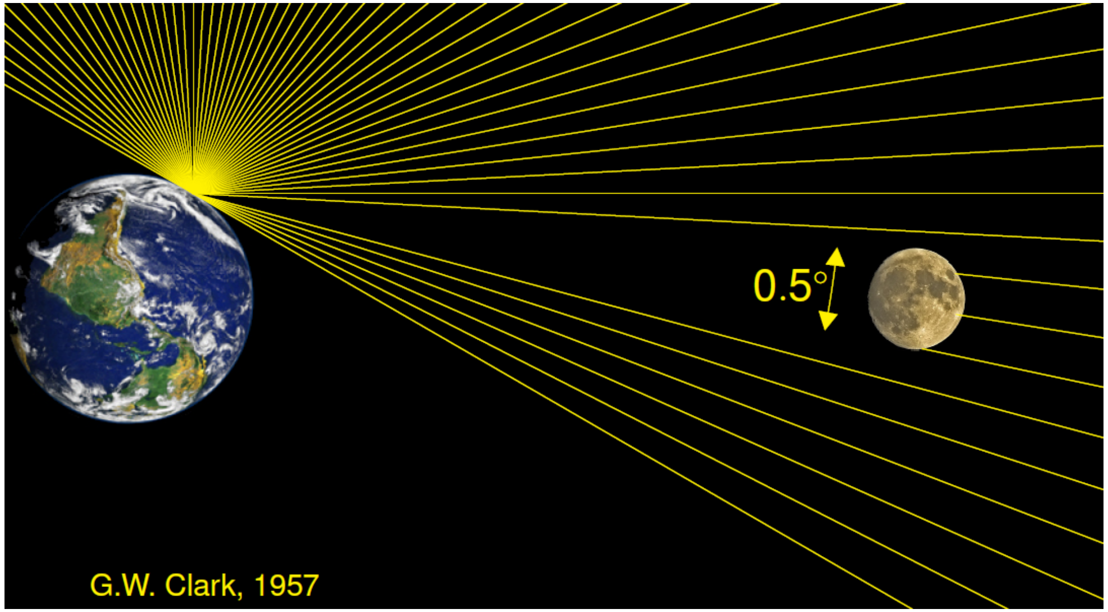
Number of strings : 1 (05) 9 (06) 22 (07) 40 (08) 59 (09) 79 (10) 86 (11)

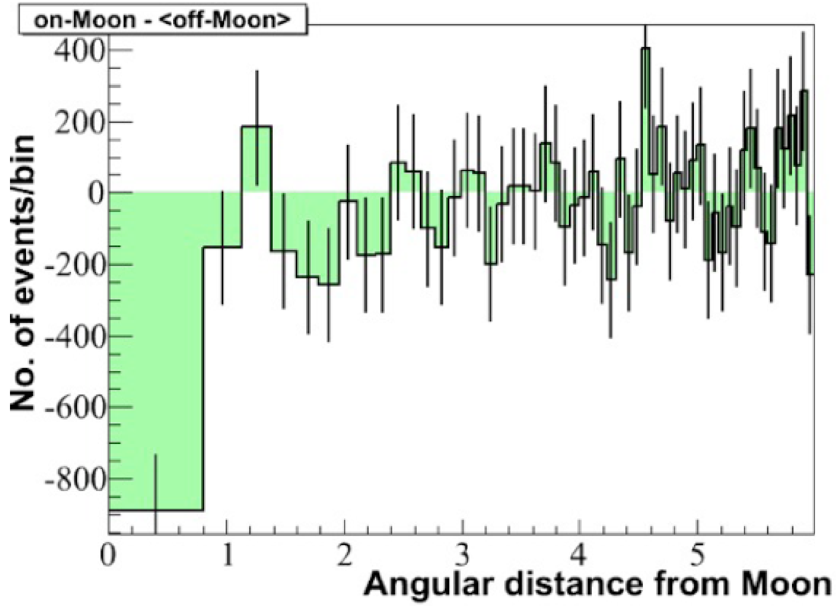
InIce detection principle (both upgoing and downgoing μ)



Using downgoing μ's from air showers

The shadow of the Moon (40-string detector, preliminary)

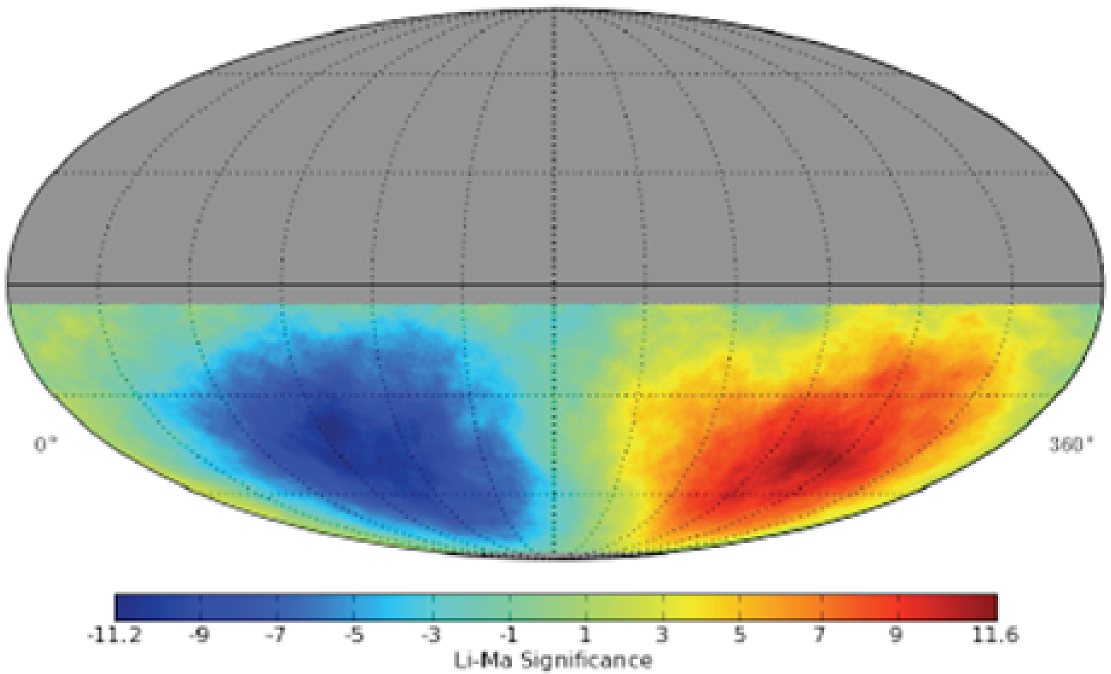




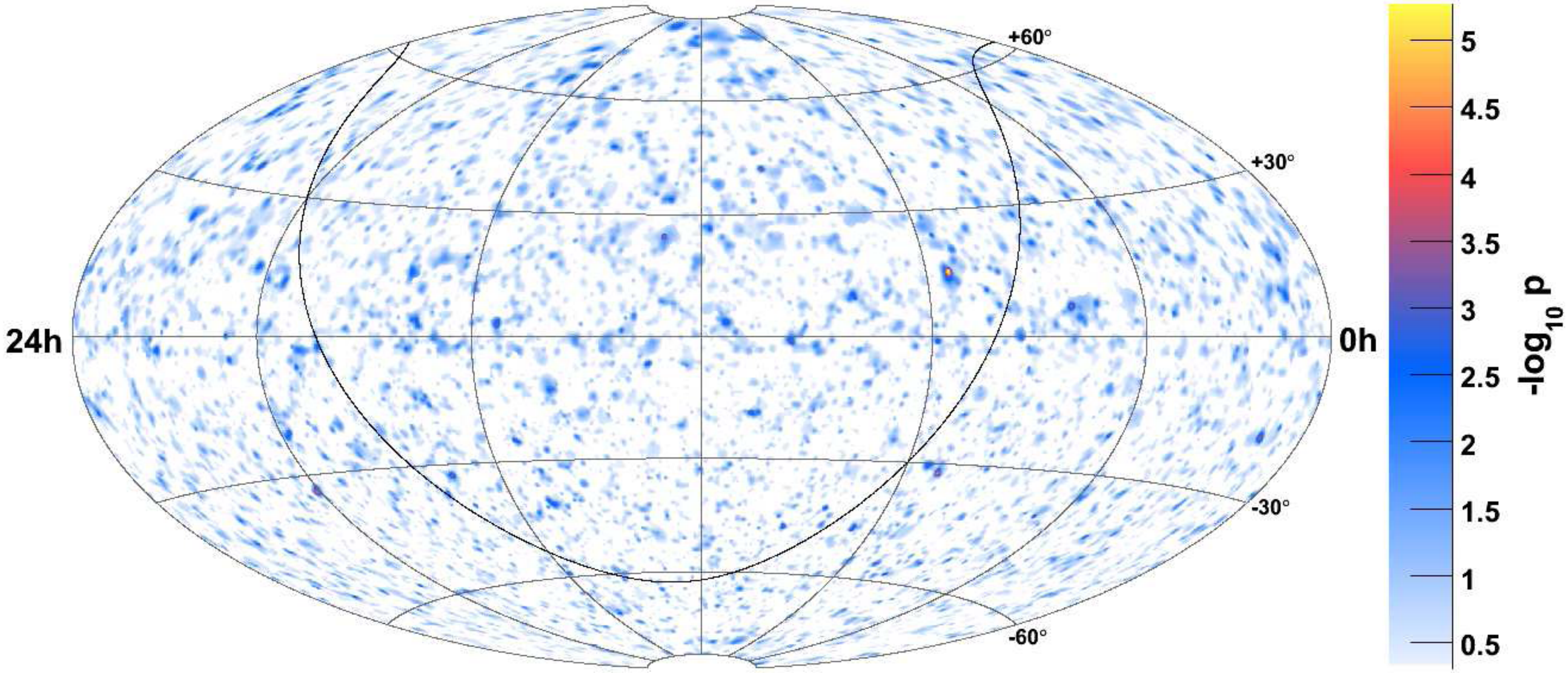
Angular resolution : $\sim 0.8^\circ$

Using downgoing μ's from air showers

Large scale Cosmic Ray anisotropy (40-string detector, preliminary)



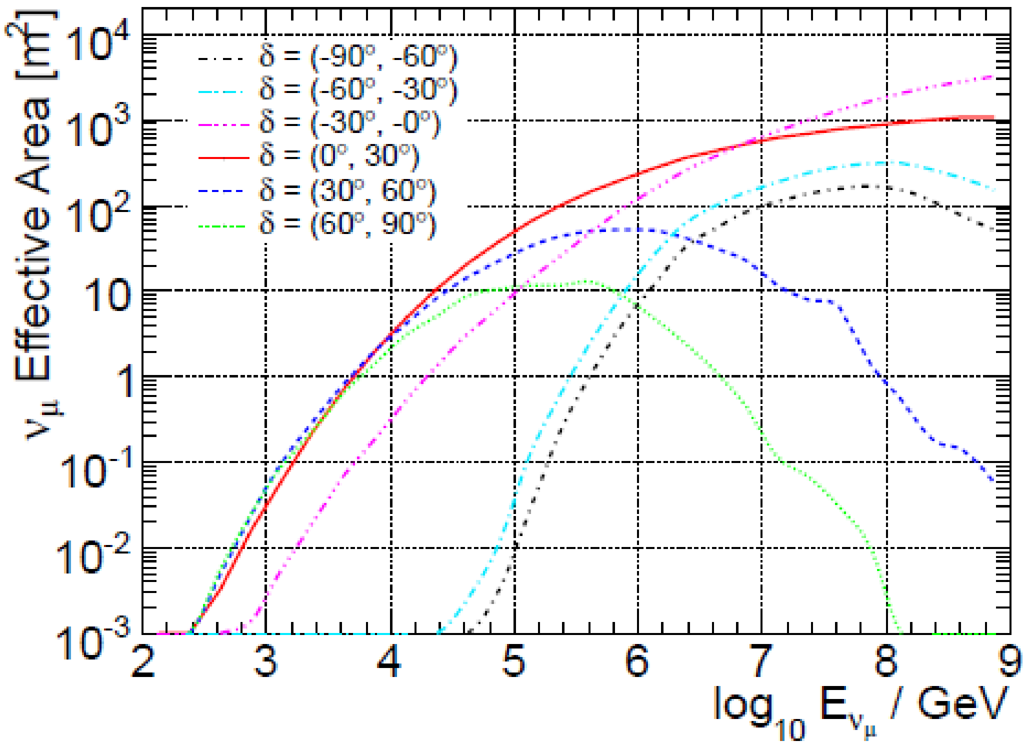
Equatorial skymap (40-strings all-sky point source search 2008-2009)



- **Decl. range :** $-85° < \delta < 85°$ **Grid search :** $0.1° \times 0.1°$ **(Gaussian PDF)**
- **Colours indicate pre-trial significances (P-values)**
- **Most significant excess at location** $\alpha =$ **7h 35m 0s** $\delta = 15.15°$
  Randomised α **data sets** $\rightarrow$ **post-trial : P-value=0.1817**

Effective area $\equiv$ observed event rate / incoming flux (from simulations)

$\nu_\mu + \bar{\nu}_\mu$ Effective area at final cuts (40-strings solid angle averaged)



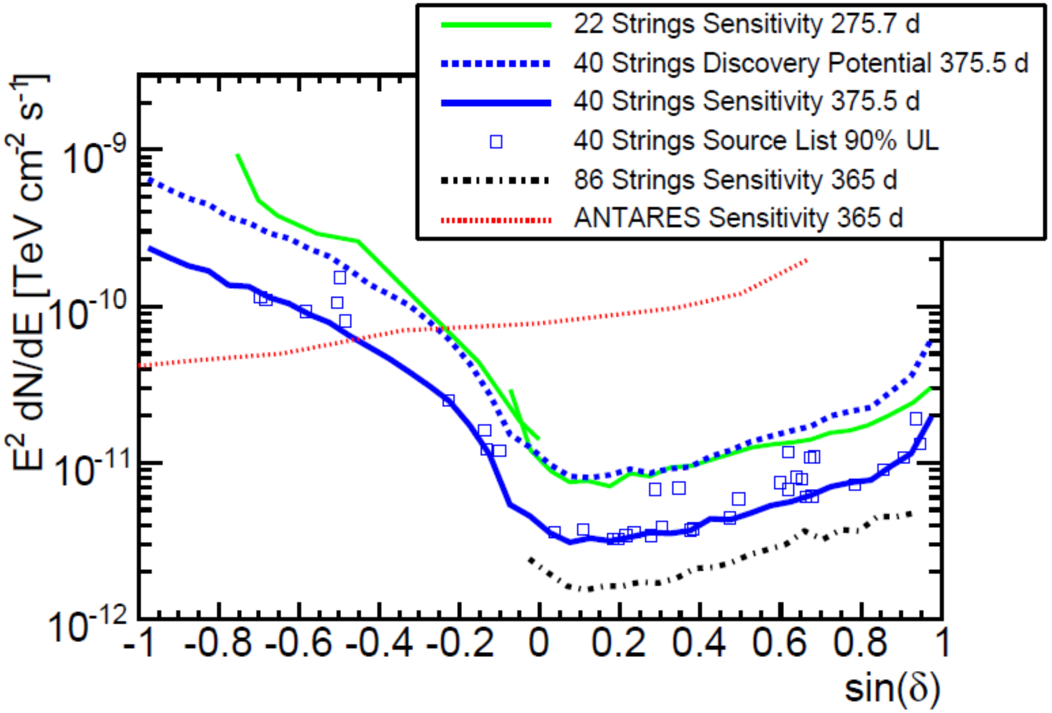
- **Turn over at high E due to absorbtion by the Earth**

  North : 10 TeV$-$PeV South : $>$PeV Atm : 250 GeV$-$15 TeV

- Observed event rate = incoming flux $\cdot A_{eff}$ $\rightarrow$ In case no signal is observed
  - Provide median sensitivity and (90% CL) upper limits (Feldman-Cousins)
  - Increase model flux until a certain significance is reached $\rightarrow$ Disc. potential

  Benchmark : 50% chance that a 5σ post-trial detection is made for E^{-2}

Various sensitivities



Search for Dark Matter particles

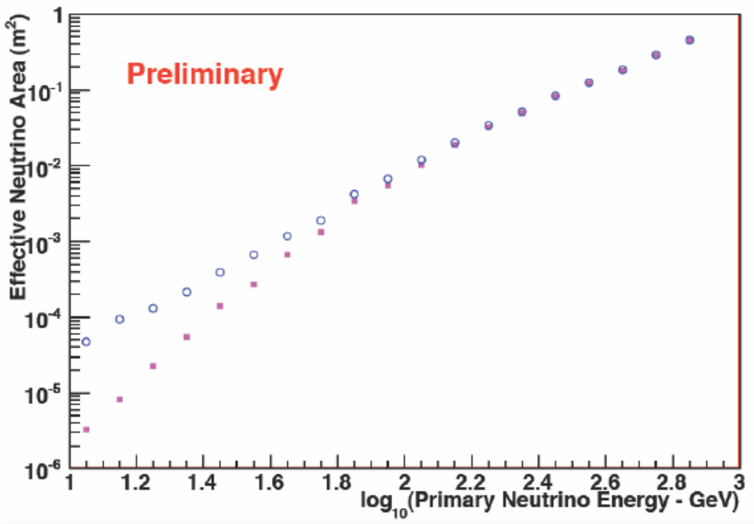
- Observations of cosmic motions and gravitational lensing
  $\longrightarrow$ Most of the matter in the Universe is (yet) undetected
- This exotic invisible matter must be made of particles that
  - Have mass (since they induce gravitational lensing)
  - Only interact weakly (if at all) with ordinary particles

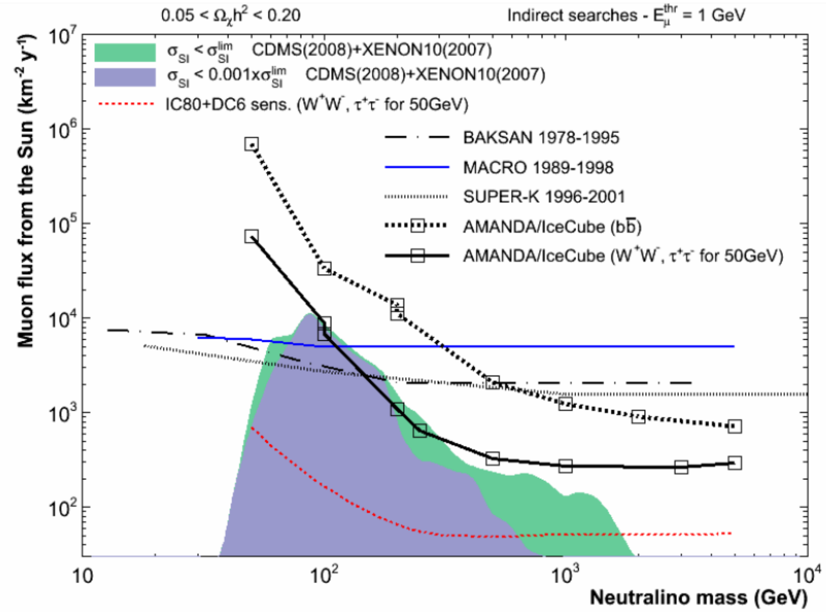
  Hence the name Weakly Interacting Massive Particles (WIMPS)
- Within the Minimal Supersymmetric Standard Model (MSSM)
  Possible candidate : Lightest supersymmetric particle (neutralino $\tilde{\chi}$)
- How to detect these MSSM particles ?
  - Direct searches : Recoil of nuclei or production in accelerators
  - Indirect searches via their decay in detectable normal SM particles

The IceCube Neutrino Observatory

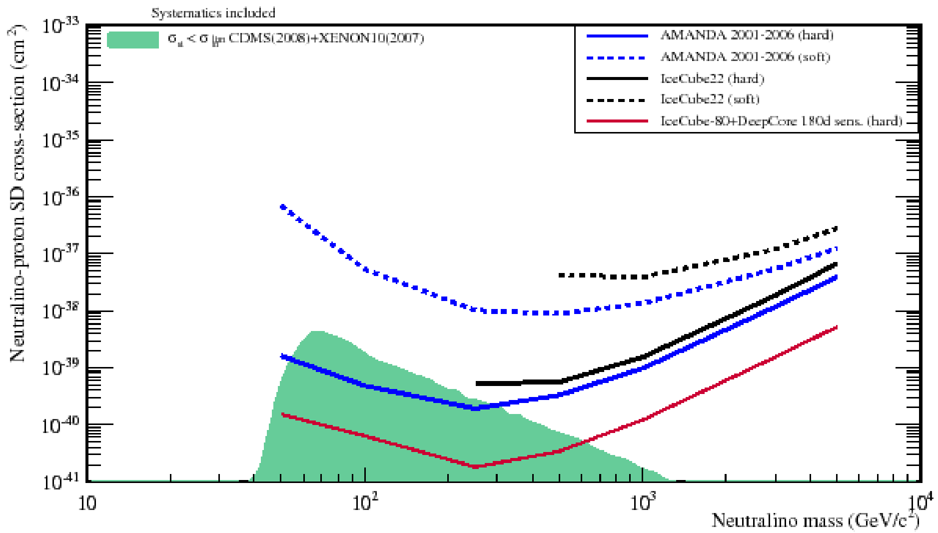
- WIMPS loose energy via NC interactions while traversing massive objects
  $\rightarrow$ Get trapped around/in the Sun, Galactic Centre (GC) or Halo (GH)
- Large concentrations of $\tilde{\chi} \rightarrow$ High self-annihilation rate
  Self-annihilation into neutrinos : $\tilde{\chi}\,\tilde{\chi} \rightarrow b\bar{b}, \tau^+\tau^-, W^+W^-, \ldots \rightarrow \nu$'s
- IceCube : search for high-E ν's from the center of the Sun, the GC or GH
  - Might discover the $\tilde{\chi}$ via indirect detection
  - Determination of ν flux enables probing the $\sigma_{\tilde{\chi}N}$
    Note : σ_{SI} is expected to be too small but σ_{SD} might be significant
- E_ν depends on $M_{\tilde{\chi}}$ and annihilation channel
  Hard channel : $\tilde{\chi}\,\tilde{\chi} \rightarrow W^+W^-, \tau^+\tau^- \rightarrow \nu$'s
  Soft channel : $\tilde{\chi}\,\tilde{\chi} \rightarrow b\bar{b} \rightarrow \nu$'s
  For $M_{\tilde{\chi}} = 1$ TeV $\rightarrow E_\nu <$ a few 100 GeV
- Extend IceCube sensitivity to lower energies
  $\rightarrow$ DeepCore component is sensitive down to ~ 20 GeV

A_{eff} improvement with DeepCore



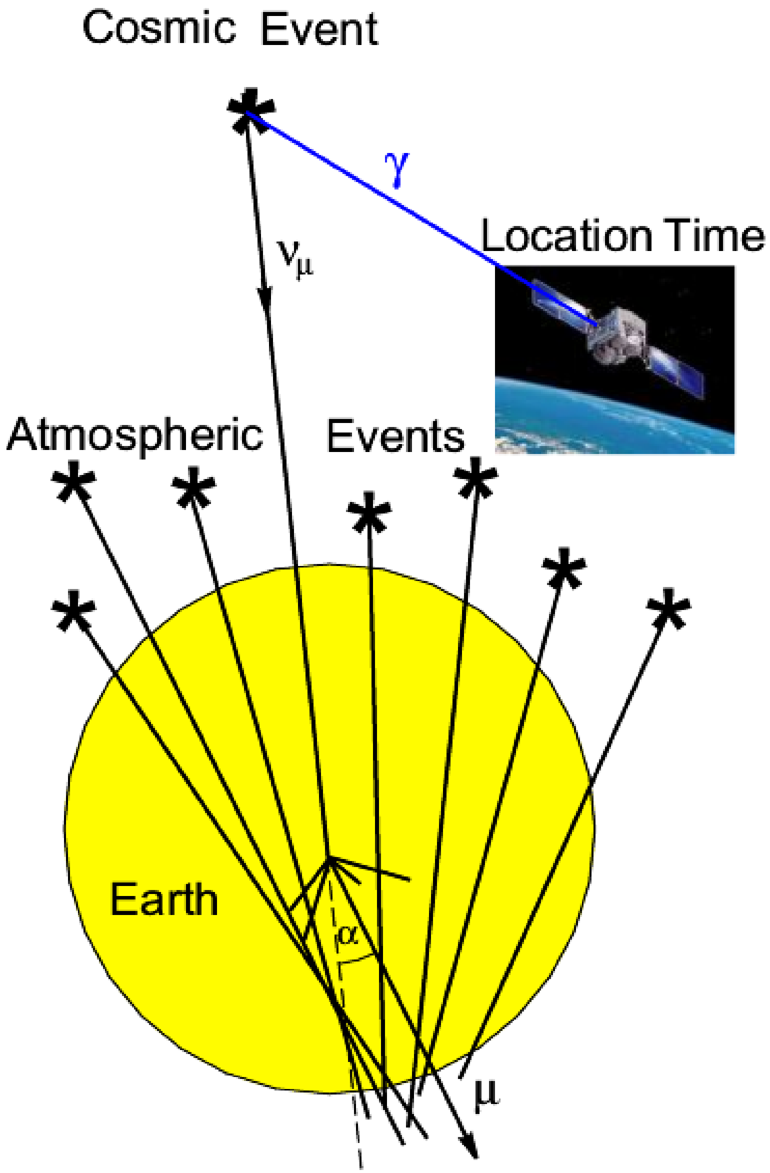


- Solar WIMP analysis with 22 strings (PRL 102 (2009) 201302)
  No signal observed
  $\longrightarrow$ Provide limits
- Total Amanda data nearly analysed
  $\longrightarrow$ Provide sensitivity



Neutrinos from transients (GRBs & AGN)

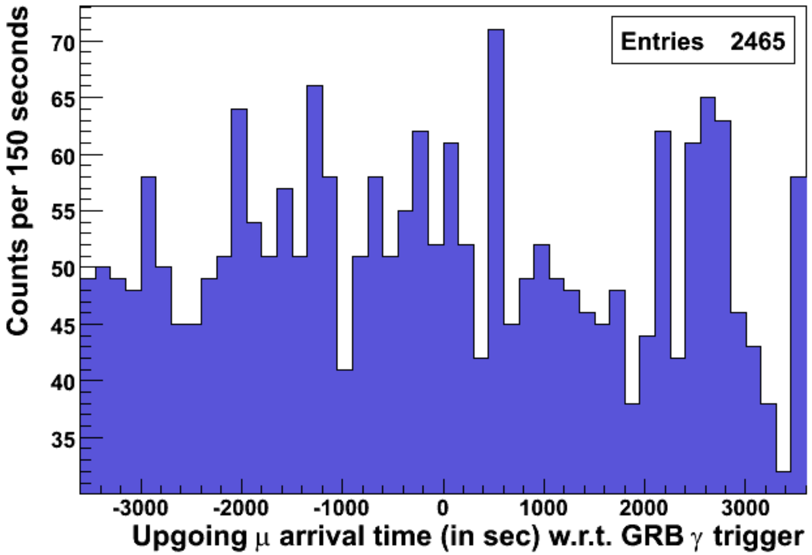
- Signals are atm. background ν
  Not distinguishable from cosmic ν
- Extend exposure time $\longrightarrow$ Hot spots
- Or : Look at transient phenomena
  Specific location and time (satellite)
  $\longrightarrow$ nearly no background
- Simultaneous $\gamma - \nu$ signal
  Fails in case of time difference
- Rolling time window
  Can only investigate individual bursts
  Needs : bursts with multi ν signals
- New more sensitive method
  Stacking of time info of various bursts
  Signal $\longrightarrow$ clustering of data bins

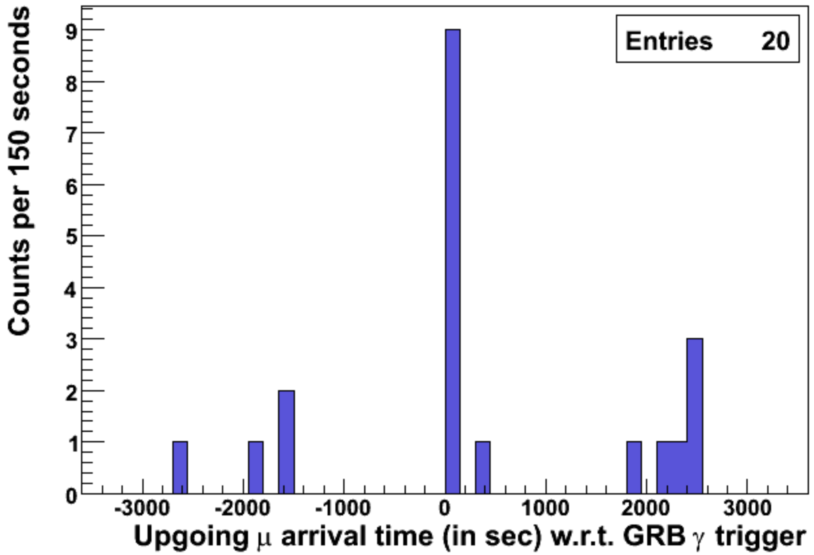


Toy model simulation

100 GRBs of which ∼10% yield 1 detected μ (homogeneous over Northern sky)
Atm. background from the entire Northern hemisphere : ∼300 upmu/day

All Northern sky data | **5° area around GRB position**



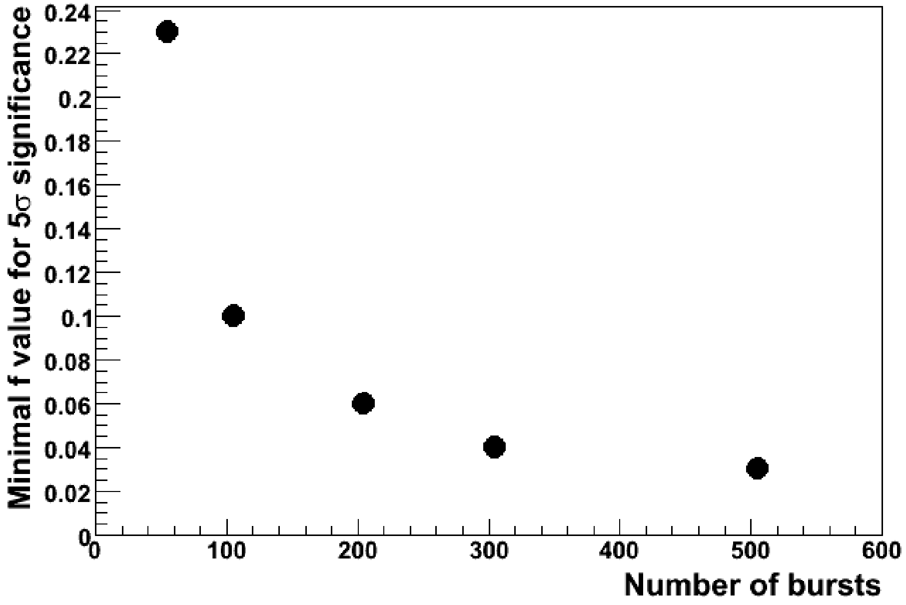


- $\gamma - \nu$ time difference irrelevant
- Low rates revealed with large stats.

GRB Discovery Potential

- **Sensitivity parameters**
  Number of GRBs in the sample
  Fraction f which yields a μ signal
- ∗ **Model expectations $f \approx 0.01 - 0.1$**
  (Halzen et al., ApJ 527 (1999) L93)
- **Sensitivity for a discovery**
  Minimal f for a 5σ signal
  (NvE, Astrop. Phys. 28 (2008) 540)

Sensitivity for 5σ discovery



Neutrinos from AGN flares

- AGN flare → like a GRB

  Timescales much longer (days)

  → Accumulate more background

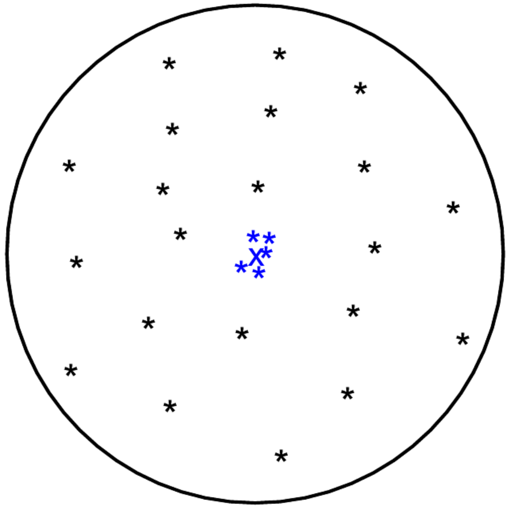
  Position is known before the flare

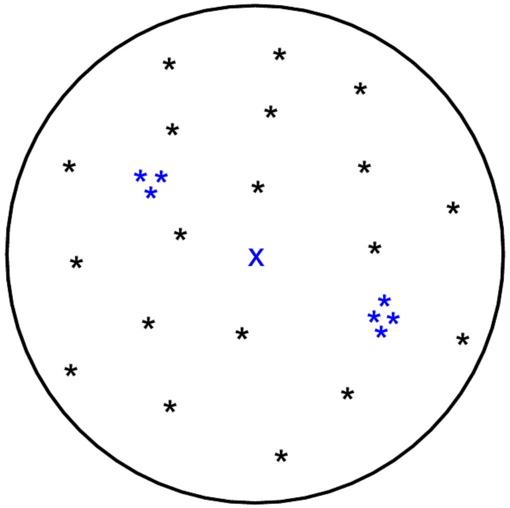
  → Observe specific patch on the sky

  Clustering in position instead of time
- Relative positions w.r.t. AGN

  Signal → clustering at AGN position
- Relative positions of all μ pairs

  Allows detection of extended sources



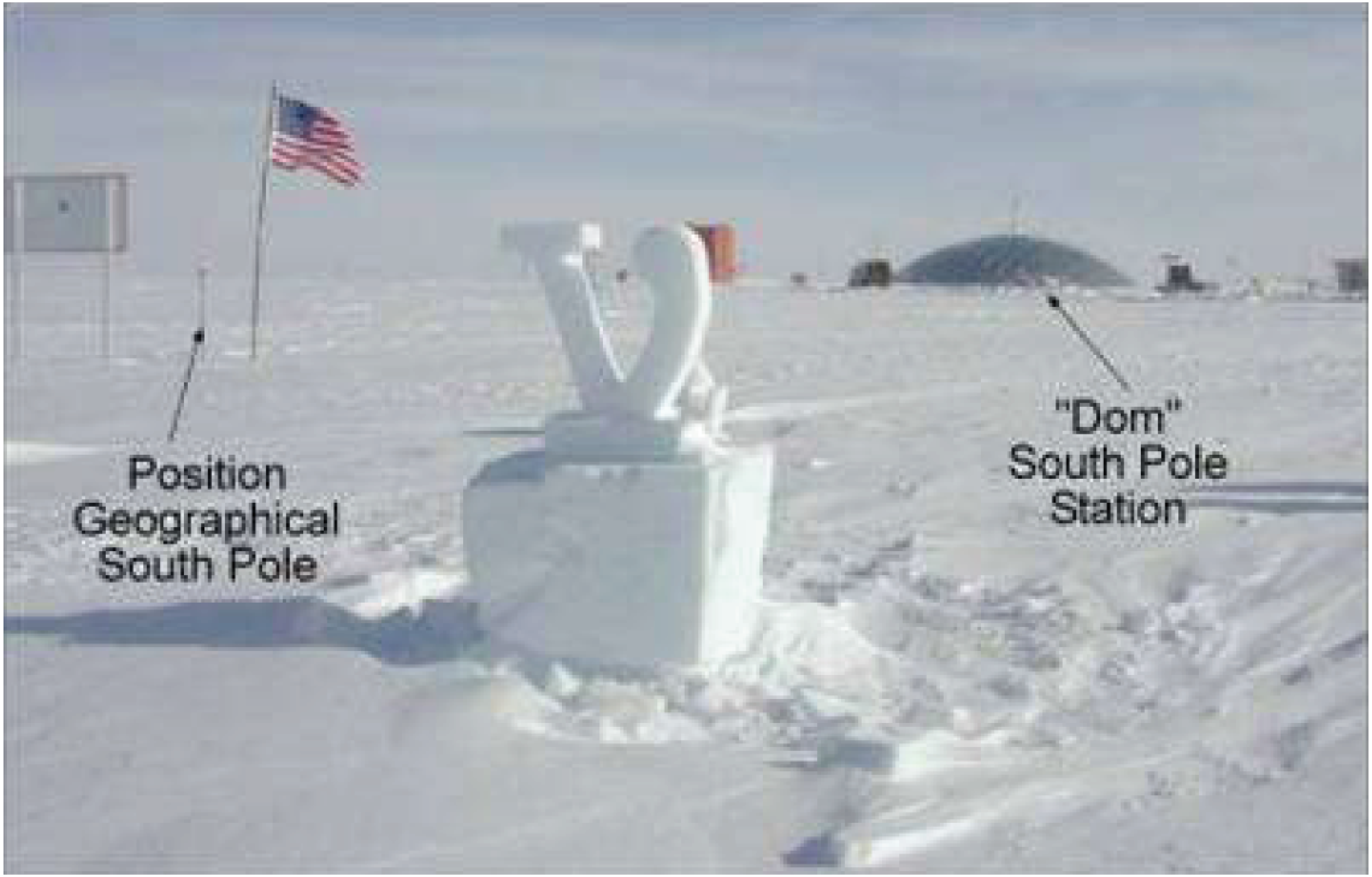


Outlook

- World's largest neutrino observatory (IceCube) operational at the South Pole
  > 90% of the foreseen IceCube detector has been deployed
  IceCube sensors are working correctly (Moon shadow, CR-anisotropy, skymap)
- IceCube will be completed late 2010/ early 2011
  Nicely in time with satellite observations (Swift, Fermi)
  $\longrightarrow$ Perfect for research of transients
- Very detailed investigation of the Northern Sky
- DeepCore extension will open up Southern Sky (Galactic Center) and lower E
  Increase of sensitivity for low mass WIMP searches
  Additional (transient) sources to be studied
- Very sensitive method for detection of GRB neutrinos (AGN is in progress)
  Expect new discoveries in the next 5 years

Advent of very interesting times for Neutrino Astronomy !

Outlook



Origin of cosmic rays

- **Supernova blast waves**

  Moving charge in static mag. field

  Gyroradius $r = \frac{p}{ZeB}$ $(\vec{p} \perp \vec{B})$

  $\rightarrow \left(\frac{p}{1\ \mathrm{eV}}\right) = 0.03 \cdot Z \left(\frac{B}{1\ \mu\mathrm{G}}\right) \left(\frac{r}{1\ \mathrm{m}}\right)$

- Accelerator of size R

  $r > R \rightarrow$ particles escape $\rightarrow E_{max}$

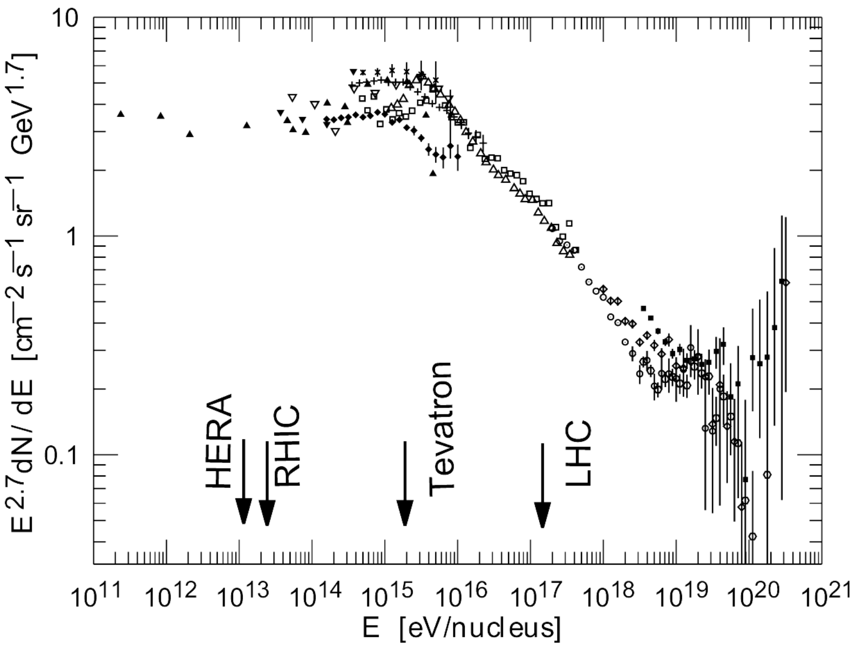
  Typical : $B \approx \mu$G $R \approx 10$ pc

  $\rightarrow$ **Protons : $E_{max} \approx$ PeV** ('knee')

$*$ At a certain $r \rightarrow E_Z = ZE_{proton}$

$*$ $E > 10^{19}$ eV $\rightarrow r > R_{galaxy}$

$\Rightarrow$ Extra-galactic origin



What causes the 'ankle' ?

Even more violent phenomena

(AGN and GRBs)

Energy spectra for $M_{\tilde{\chi}} = 1$ TeV