Finding Dark Matter in Galaxy Clusters with IceCube

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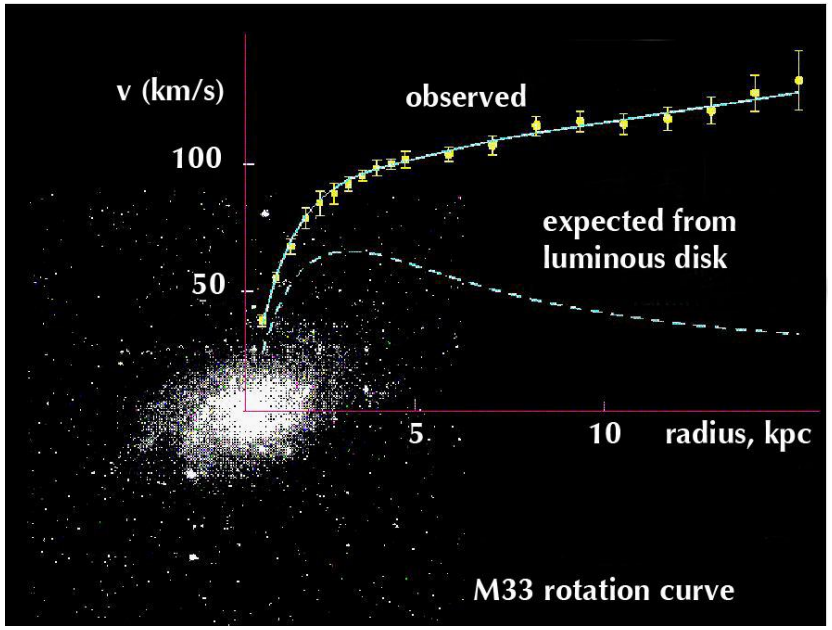
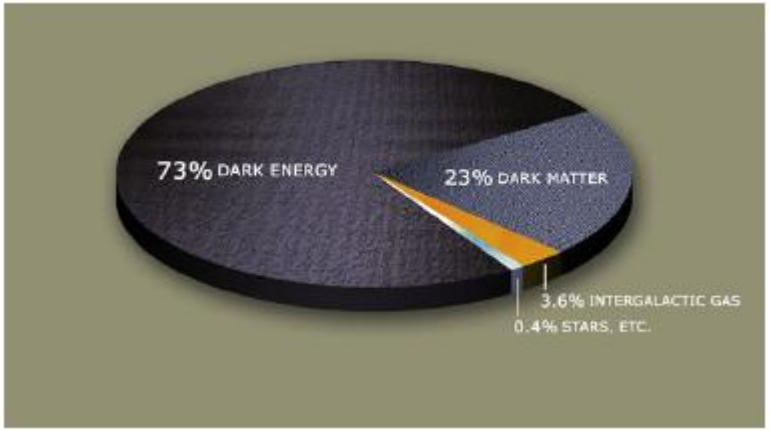
Dark matter

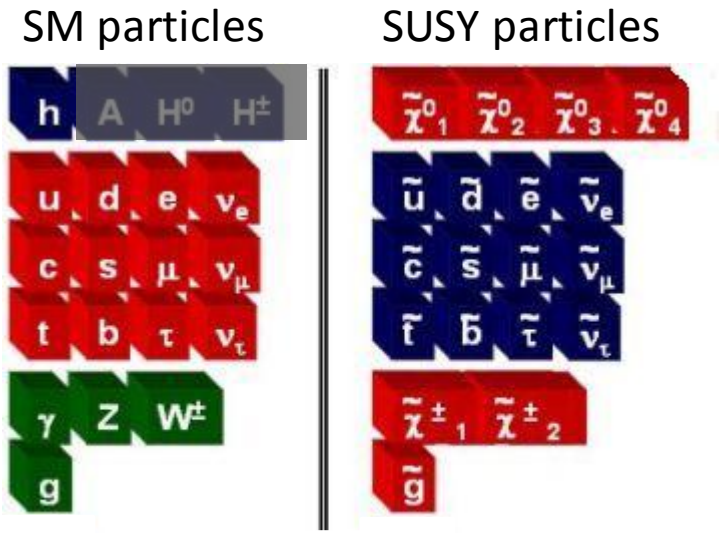
- Non-luminous matter
- Evidence for dark matter can be found on different scales:
  - Rotation curves of galaxies
  - Cosmic Microwave Background anisotropies
  - Gravitational lensing
  - Bullet Cluster
  - …
- Expected to be non-baryonic and form a halo around galaxies and clusters



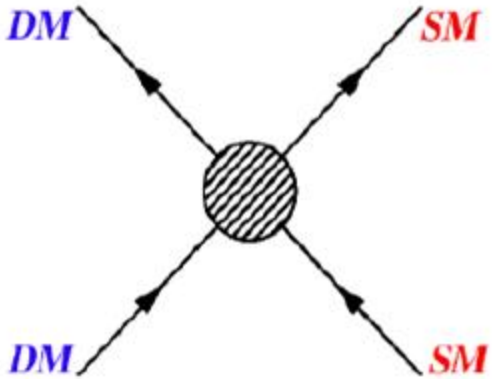


WIMPs

- Weakly Interacting Massive Particles (‘cold dark matter’)
- WIMP miracle: WIMPs have the right relic density to be dark matter
- Different models:
  - Supersymmetry (SUSY)
  - (Universal) extra dimensions
  - …



Detecting WIMPs



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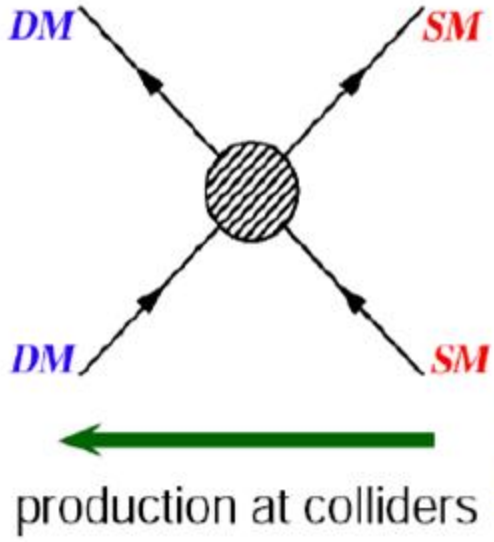

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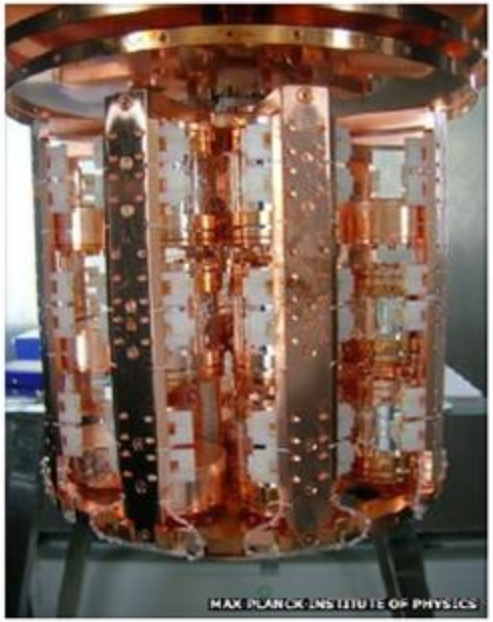
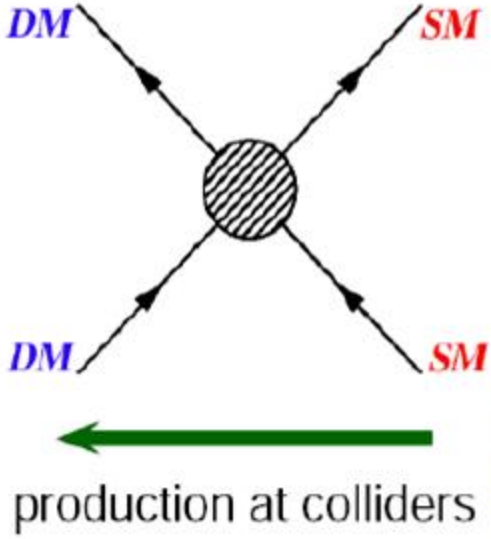
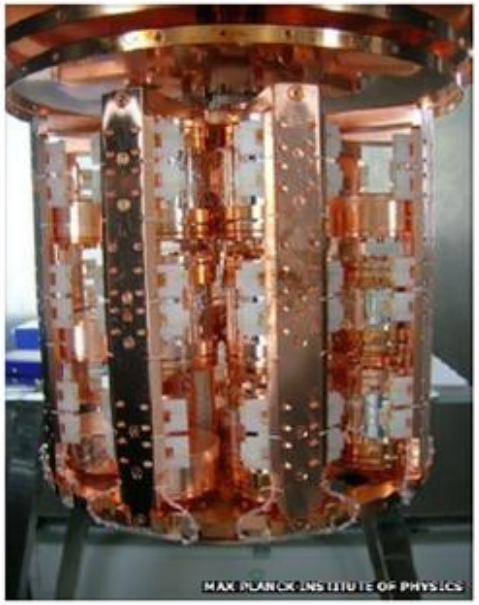
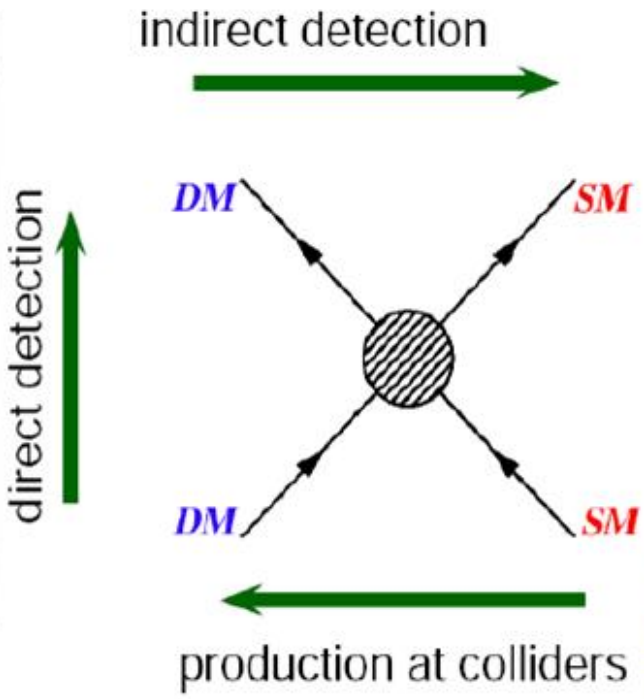


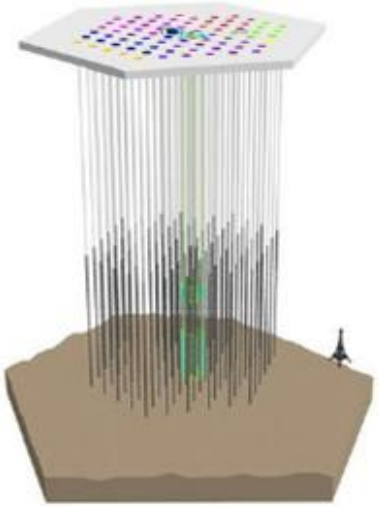
direct detection



Detecting WIMPs





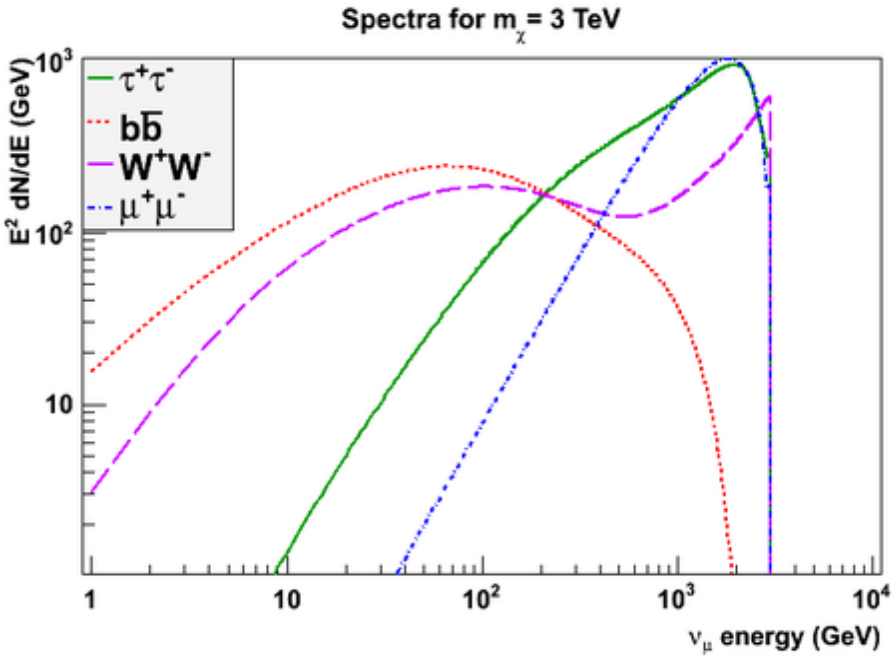


Detecting dark matter with neutrinos

- Search for an excess of neutrinos from regions with high dark matter density:
  - Galactic dark matter halo and center
  - Dwarf spheroidal galaxies and galaxy clusters
  - The Sun and the Earth

- For setting limits, benchmark channels are used:
  - $\chi\chi \rightarrow W^+W^-$
  - $\chi\chi \rightarrow \tau^+\tau^-$
  - $\chi\chi \rightarrow b\bar{b}$
  - $\chi\chi \rightarrow \upsilon\bar{\upsilon}$

- Signal neutrinos have energies up to ~ 100 TeV



Dark matter in galaxy clusters

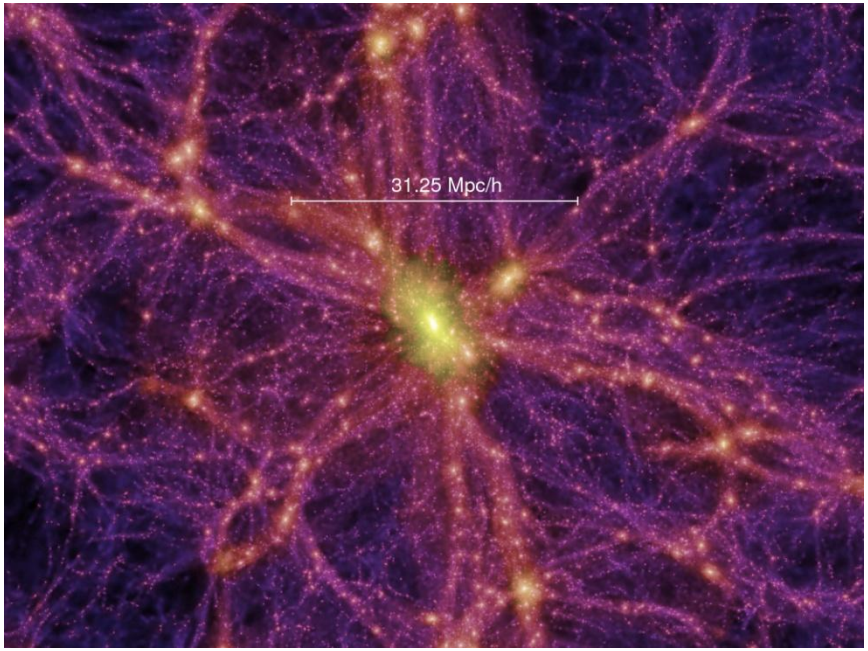
- Mass ~ 10^{14} to 10^{15} $M_{\odot}$, about 85 % of their mass consists of dark matter
- Diameter is a few Mpc, for close-by clusters this is a few degrees
- Exact form of dark matter profile is not known at the moment

Abell 1689

Substructures

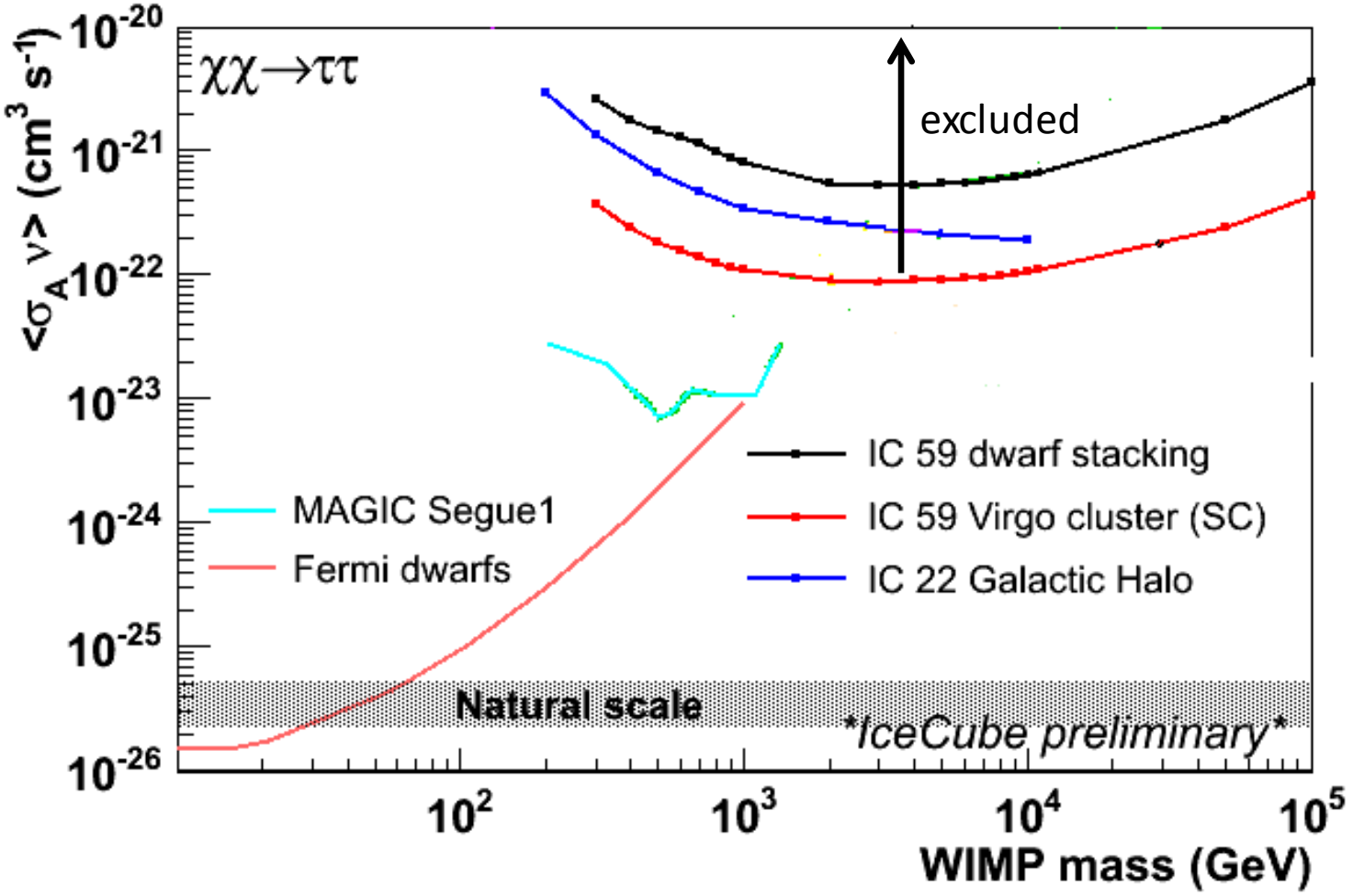
- N-body simulations show that a large population of dark matter substructures is present:
  - gives boost factor of ~ 1000 (but still many uncertainties)
  - dark matter signal extended (a few degrees for clusters that are close)

- Galaxy clusters interesting targets for neutrino telescopes



V. Springel et al., *Nature* **435**, 2005

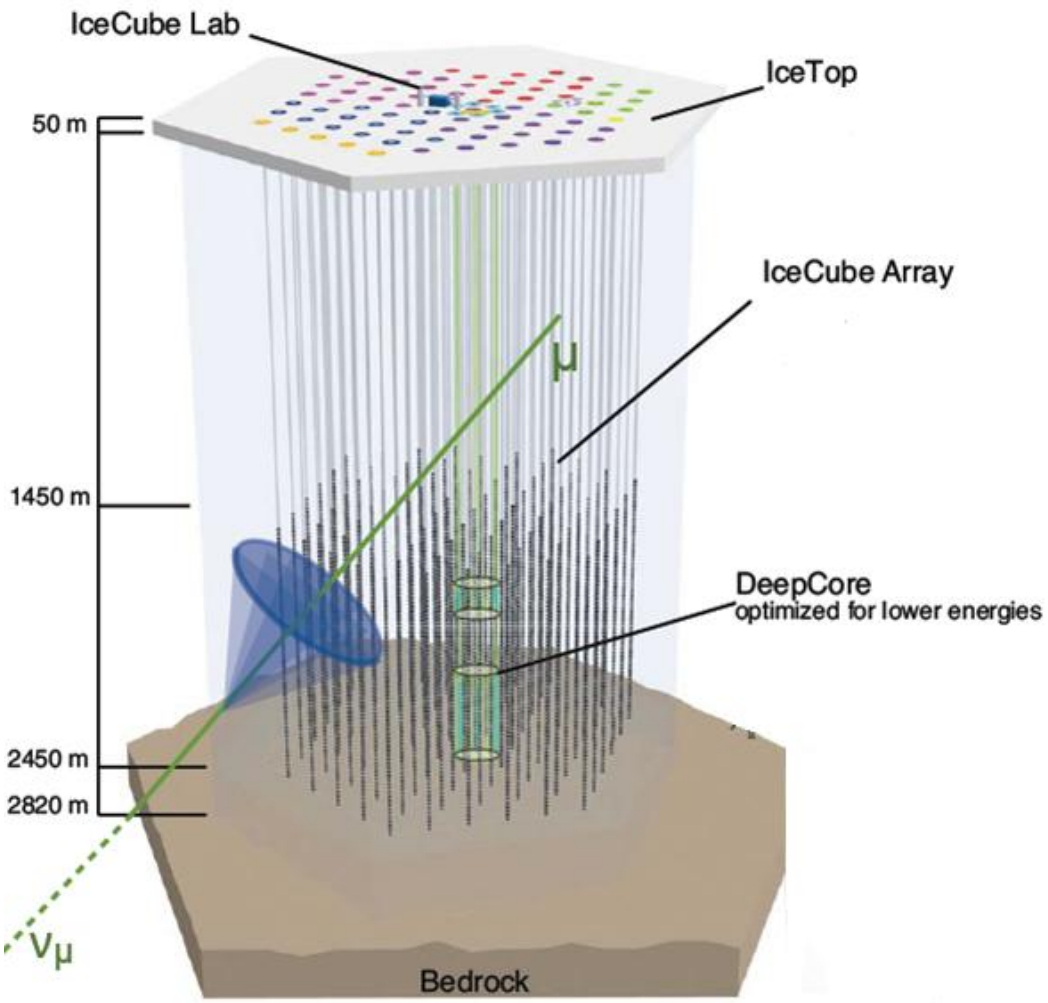
Current constraints



The plan for my PhD

- Goals:
  - Improve current constraints on annihilation cross section by looking at galaxy clusters
  - Improve understanding of how limits from different experiments (including LHC) can be combined
- Work plan:
  - Improve current event reconstruction techniques, especially for low-energy neutrinos
  - Determine which galaxy clusters will be used for this analysis
  - Create event selection and determine new constraints

The IceCube observatory

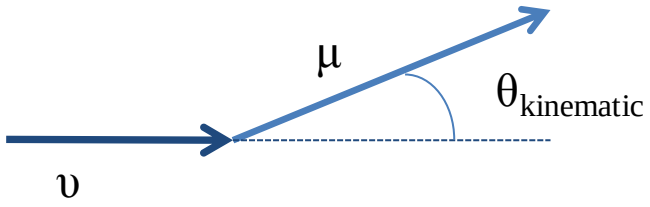


- IceCube:
  - 125 m string spacing
  - 17 m DOM spacing
- DeepCore:
  - 70 m string spacing
  - 7 m DOM spacing

DOM: Digital Optical Module

Direction reconstructions in IceCube

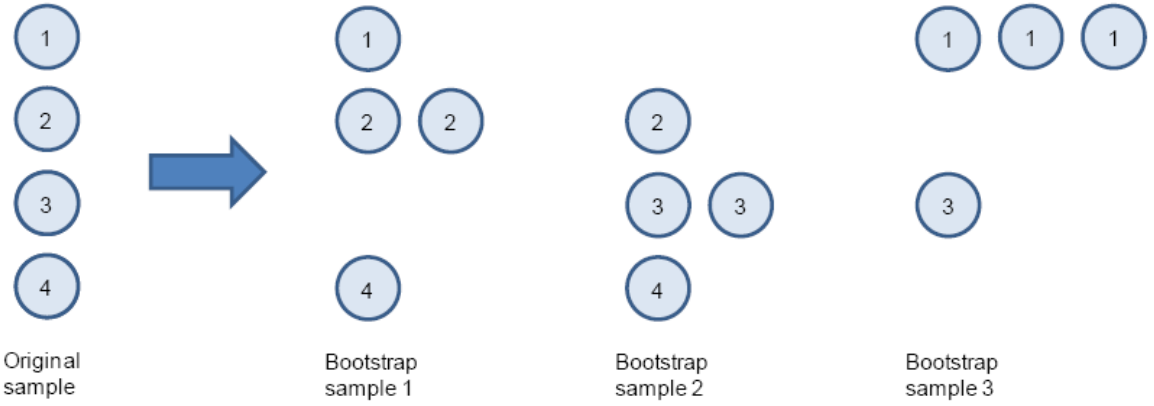
- Reconstruct muon track using detected Cherenkov photons (which have usually been scattered)
- $E_\upsilon > 1$ TeV: angular resolution $< 1^o$
- Lower energies: angular resolution is (much) larger
- Impossible to reconstruct direction of neutrino to precision smaller than the kinematic angle



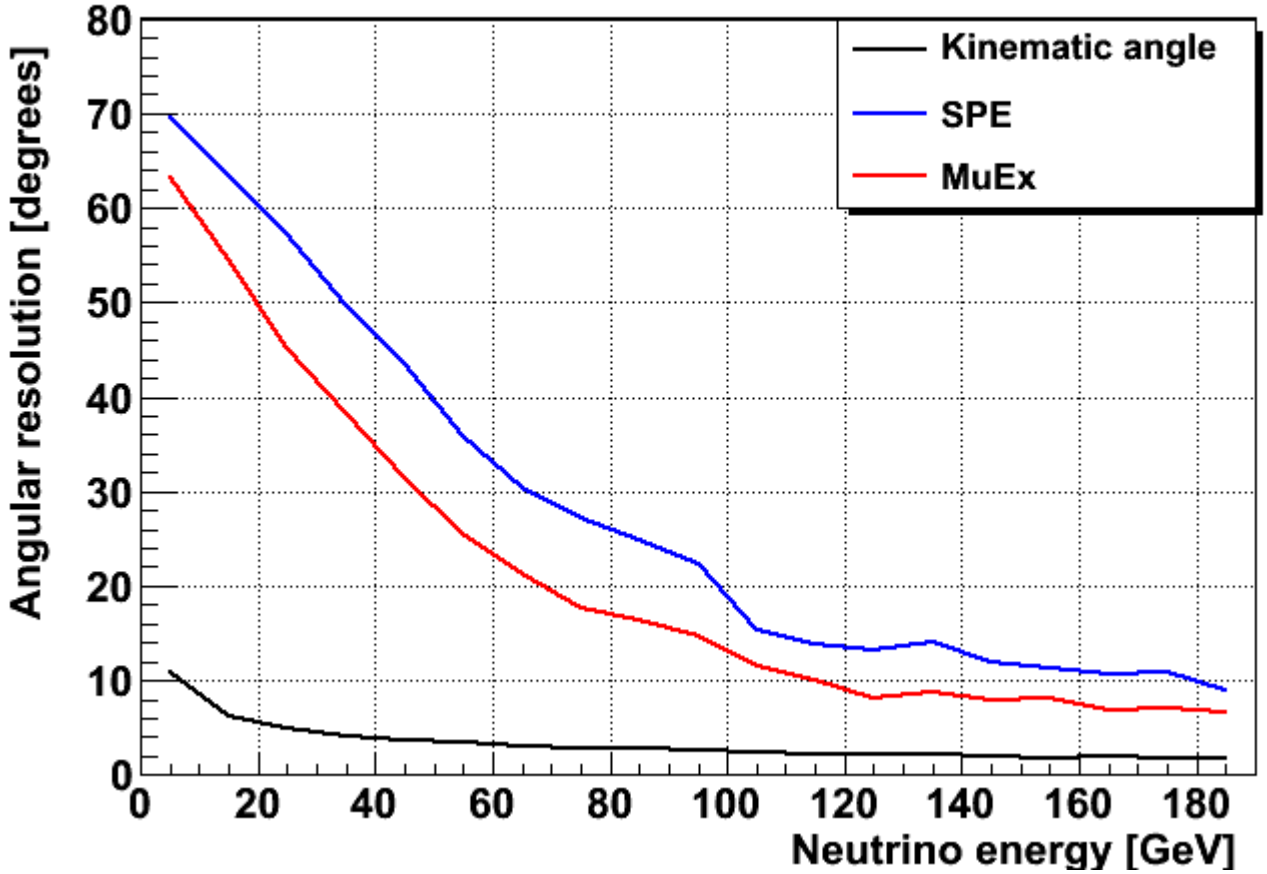
Improving low-energy direction reconstruction

- SPE fit (Single PhotoElectron):
  - Search for track hypothesis which has maximal likelihood of this track giving the times and locations of the hits that we see in the DOMs

- SPE needs a starting point for its iterations:
  - Current standard: linear fit to the hits
  - New algorithm called MuEx:
    - Create bootstrap samples of hits from original sample of hits
    - Do SPE fit on bootstrap samples of hits
    - Use average of 'bootstrap fits' as seed for fit on original sample of hits



Angular resolution for SPE and MuEx



Summary and outlook

- Overwhelming evidence points to a significant fraction of the total matter density in our Universe being ‘dark’ matter.
- WIMPs are an important dark matter candidate for which many experiments (LHC, direct, indirect) are searching.
- Galaxy clusters with substructure are a promising source for neutrino searches with IceCube. Current results will be improved by using more galaxy clusters and improving direction reconstructions and event selection.
- Constraints from different experiments are complementary, so combining them is crucial for their full exploitation.