Closing in on Dark Matter

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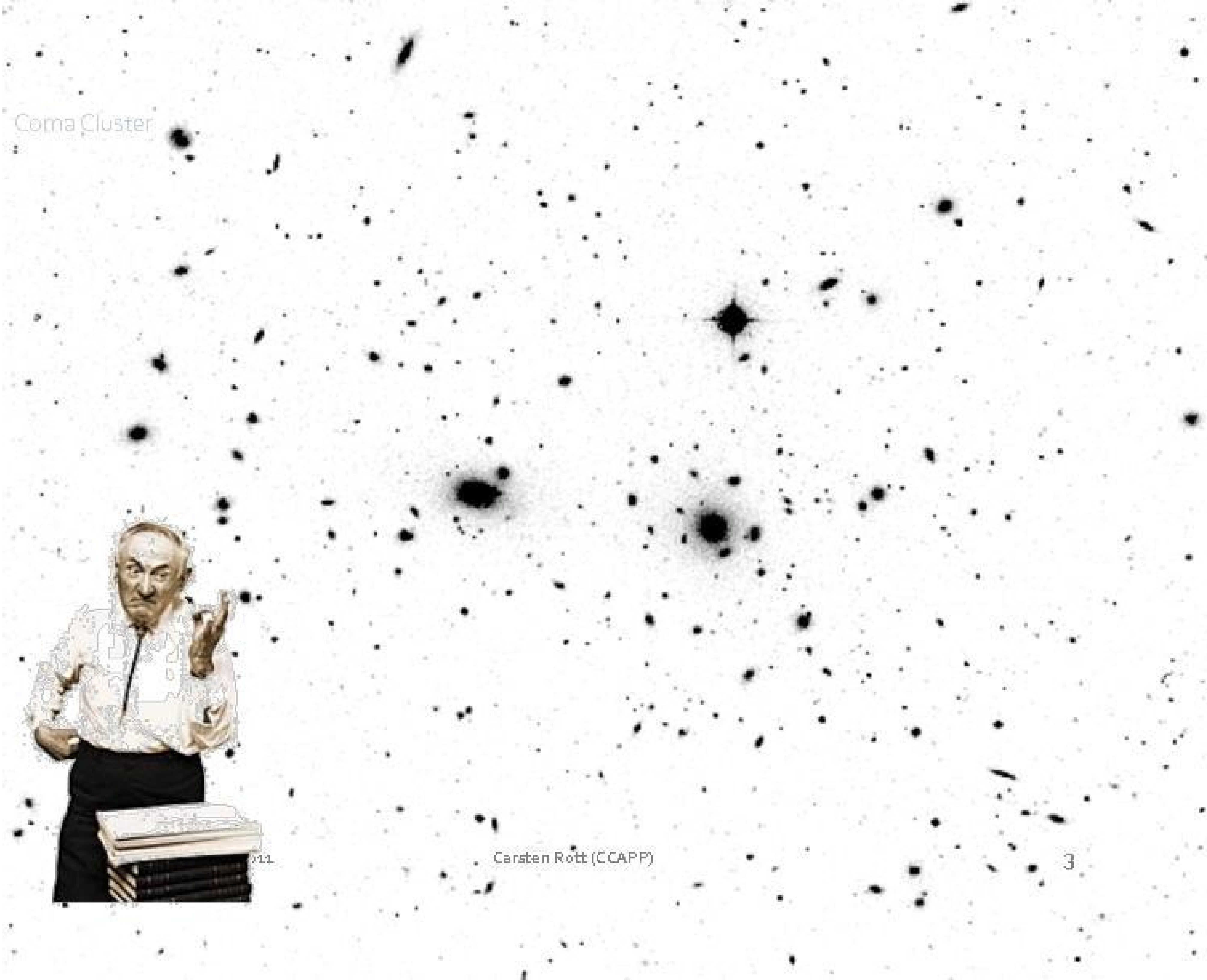
神岡宇宙素粒子研究施設

Overview

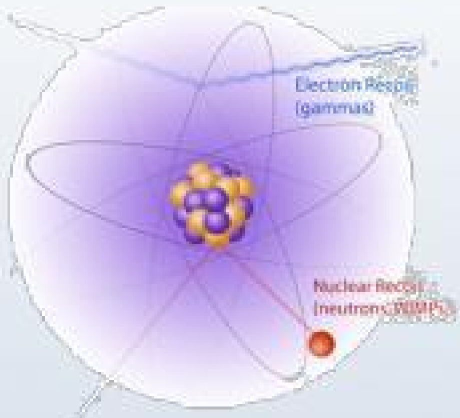
- Motivation
- Constraining the Dark Matter Self-annihilation Cross Section with Neutrinos
- Neutrinos from the Sun
- … more Dark Matter Searches at the Pole
- Closing in on Dark Matter

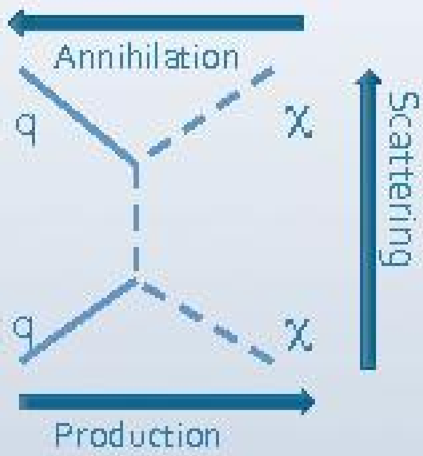
Coma Cluster

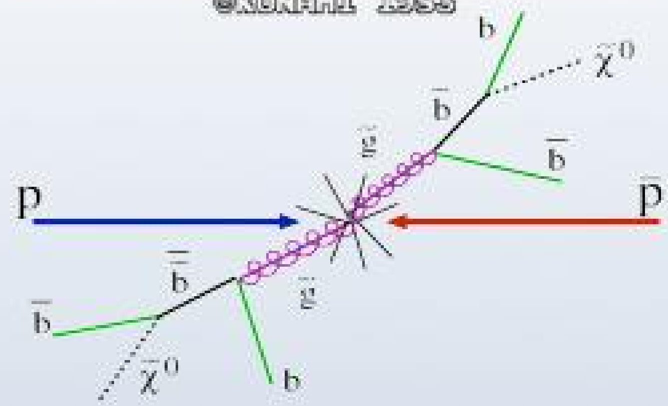


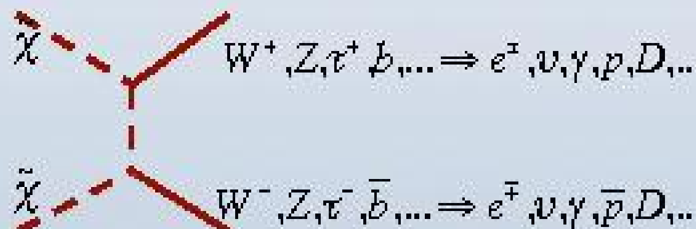
The Dark Matter Mystery

- Overwhelming observational evidence for the existence of dark matter, but still clueless about its nature









WIMP = Weakly Interacting Massive Particle

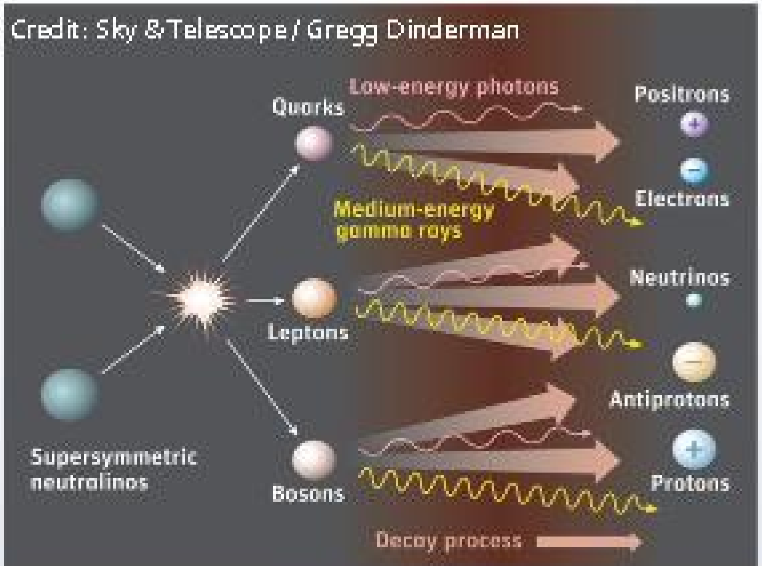
Strategies for WIMP Detection

- Direct Detection
  - WIMP scattering of nucleons → Nuclear recoils
- Indirect Detection
  - Annihilation signals from WIMPs accumulated in the Sun or Earth → Neutrinos
  - Annihilating Dark Matter in the Galactic Halo
    - Gamma-rays, Neutrinos
    - Anti-matter (e^+,D,pbar) – local neighborhood (few kpc)
- Colliders
  - Production of dark matter

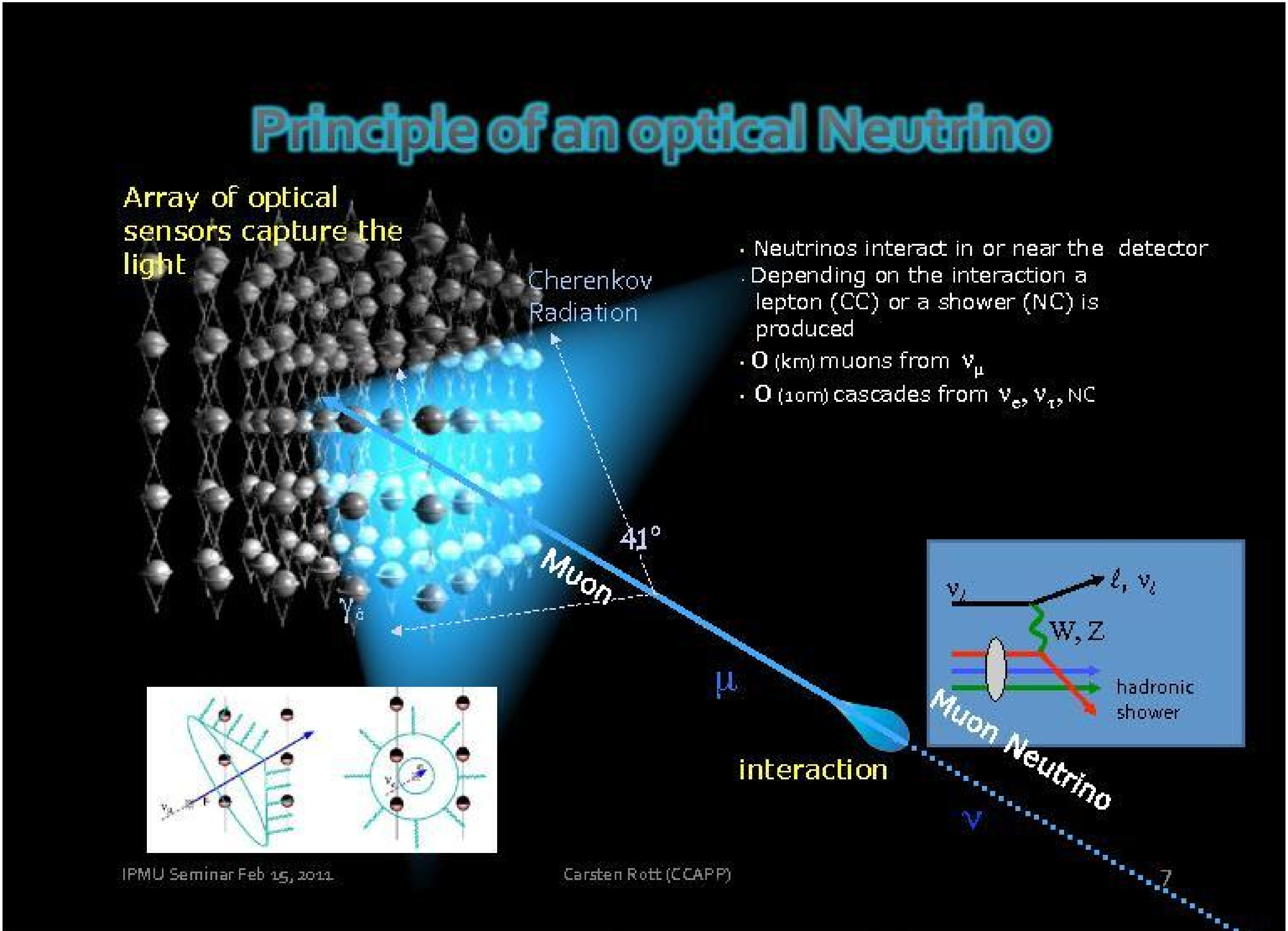
WIMP-Nucleon Scattering cross-section

WIMP Self-annihilation cross-section

What makes Neutrinos so exciting ?



- Neutrinos offer unobscured view of the universe
- Unattenuated and do not bend in magnetic field
- Neutrinos point back to their sources and cover entire energy spectrum


Principle of an optical Neutrino
Array of optical sensors capture the light
Cherenkov Radiation
Neutrinos interact in or near the detector
Depending on the interaction a lepton (CC) or a shower (NC) is produced
O (km) muons from ν_μ
O (10m) cascades from ν_e, ν_τ, NC
41°
Muon
γ_c
μ
interaction
Muon Neutrino
ν
ν_l
l, ν_l
W, Z
hadronic shower
IPMU Seminar Feb 15, 2011
Carsten Rott (CCAPP)
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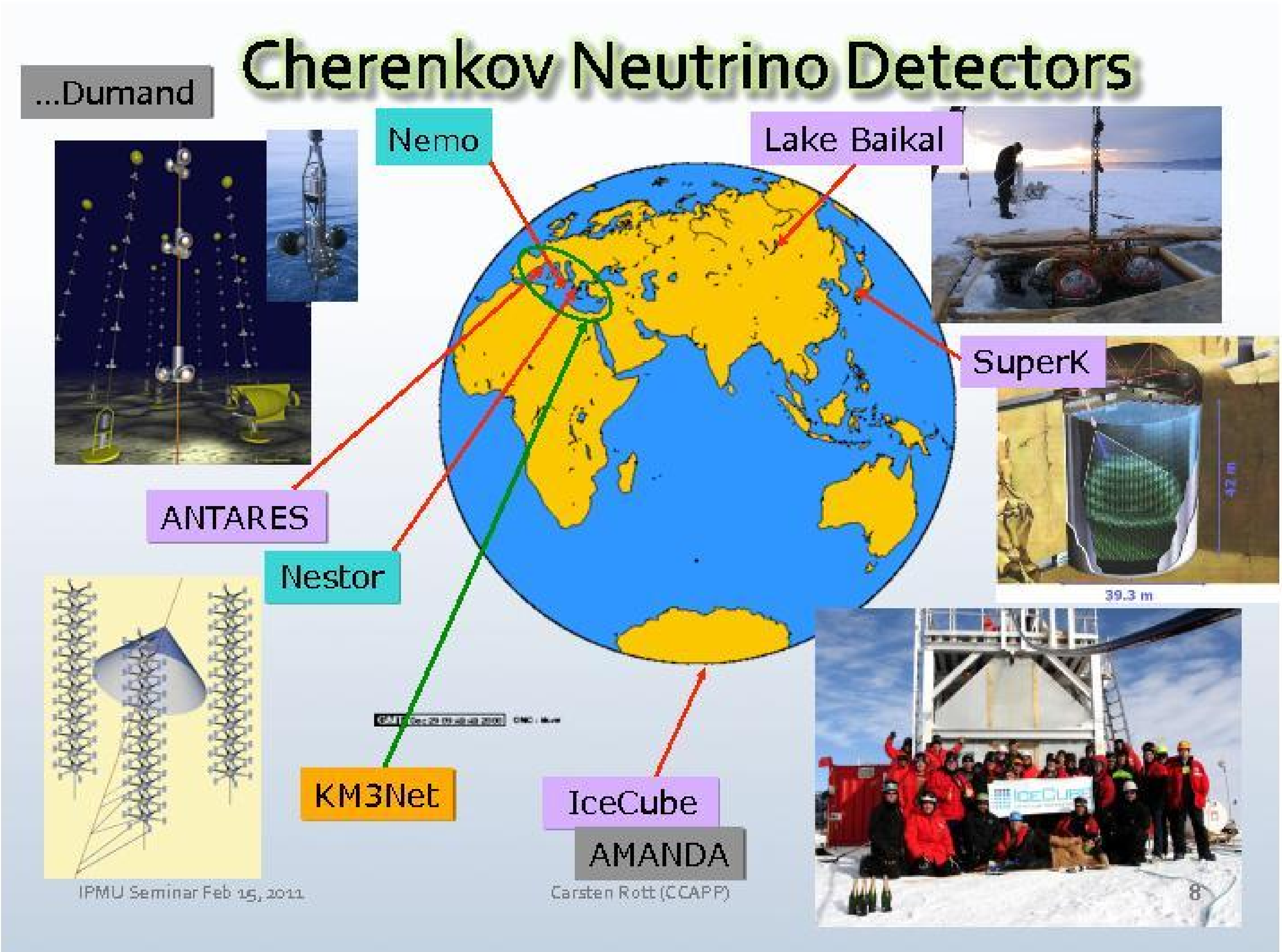
Cherenkov Neutrino Detectors
...Dumand
Nemo
Lake Baikal
SuperK
42 m
39.3 m
ANTARES
Nestor
KM3Net
IceCube
AMANDA
IPMU Seminar Feb 15, 2011
Carsten Rott (CCAPP)
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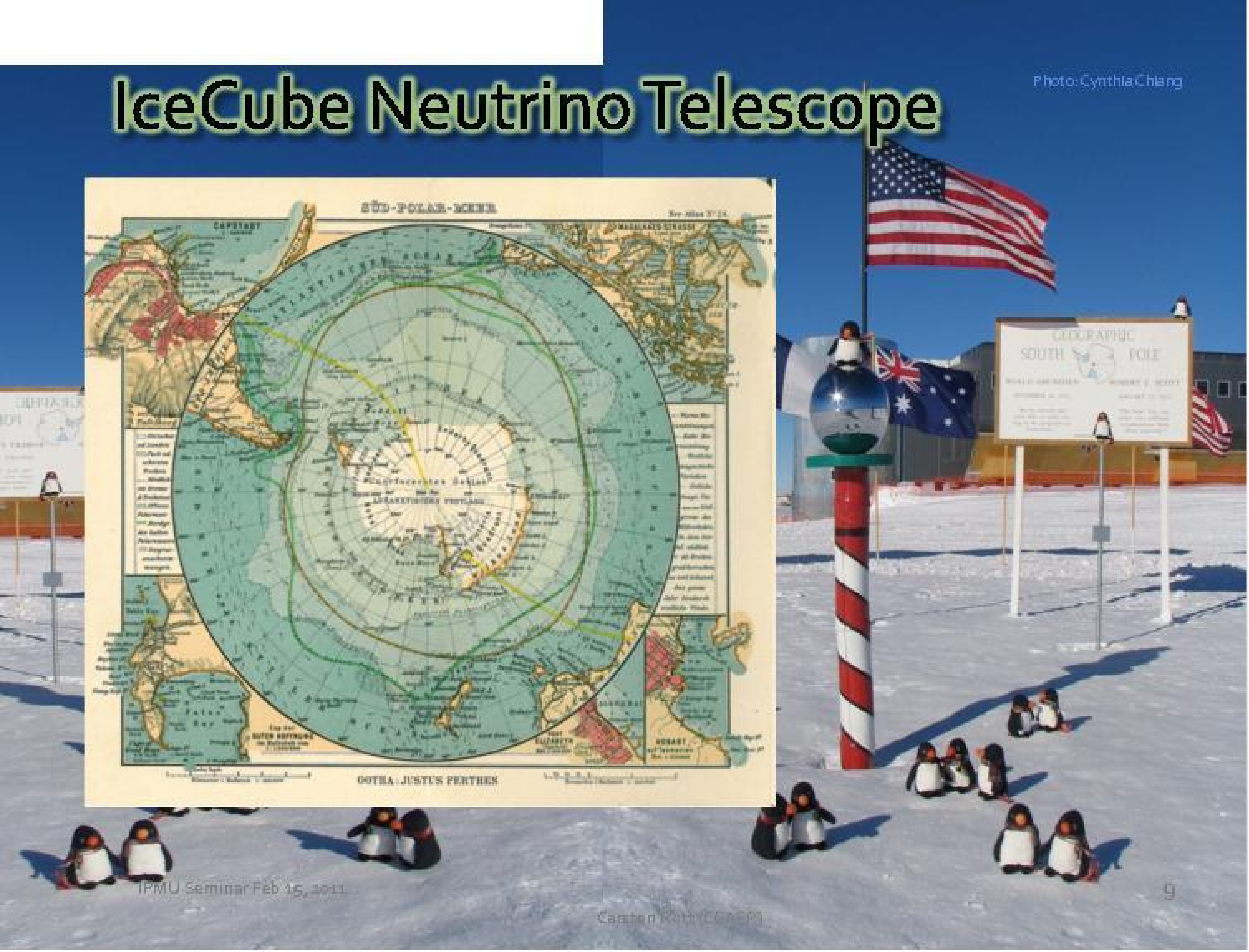
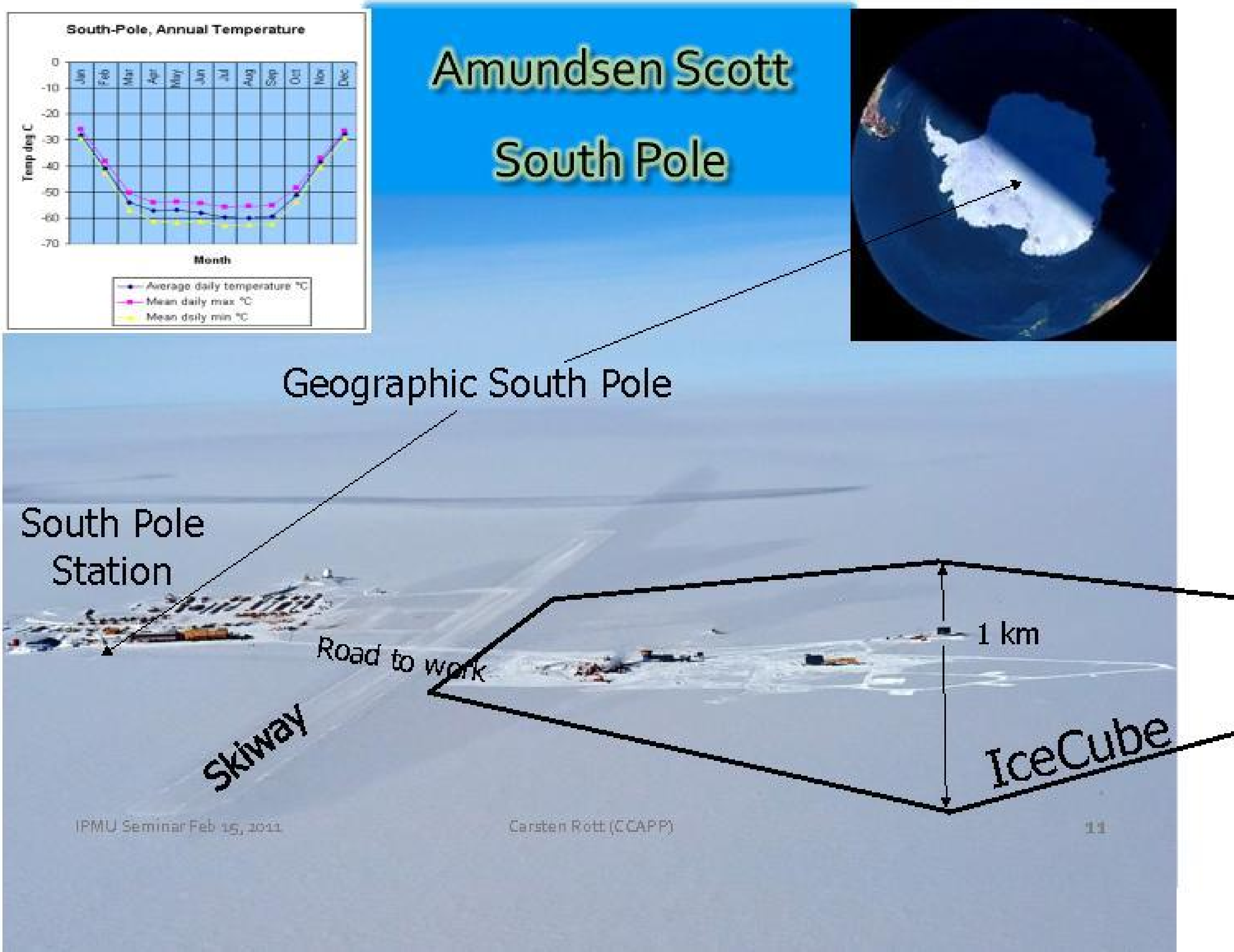
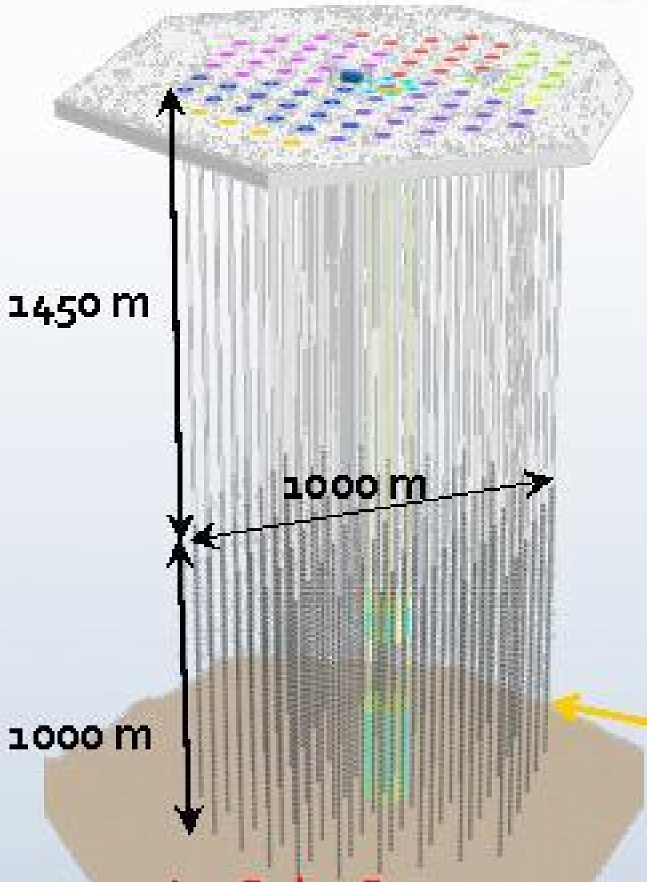
IceCube Neutrino Telescope



The IceCube Collaboration


Amundsen Scott
South Pole
South-Pole, Annual Temperature
Temp deg C
Month
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
0 -10 -20 -30 -40 -50 -60 -70
Average daily temperature °C
Mean daily max °C
Mean daily min °C
Geographic South Pole
South Pole
Station
Road to work
Skiway
1 km
IceCube

The IceCube Neutrino Observatory



86 strings each containing 60 sensors
(autonomous DAQ in the ice)

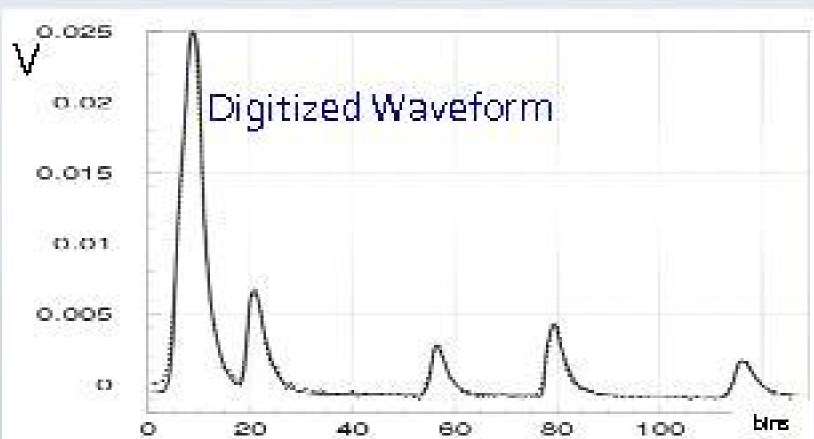
- 78 sparsely instrumented strings
  - ⇨ 17 m vertical sensor distance
  - ⇨ 125 m horizontal string distance
    (~100GeV – EeV Neutrinos)
- 8 densely instrumented strings
  - ⇨ 7-10 m sensor distance
  - ⇨ 60 m horizontal string distance
    (>10GeV Neutrinos)

IceCube Detector construction was completed on Dec 18, 2010

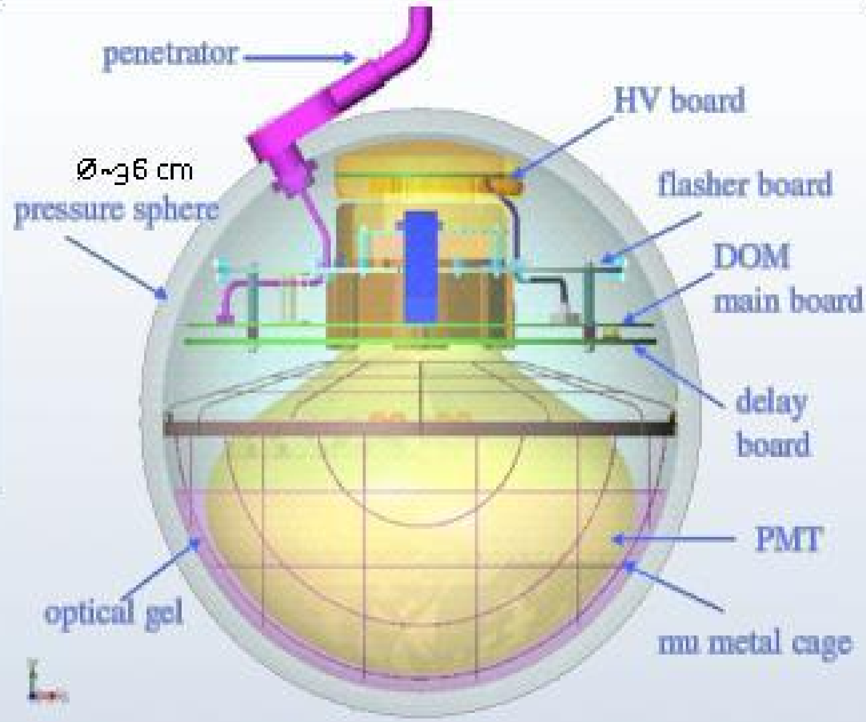
Digital Optical Module (DOM)

Measure individual photon arrival time:

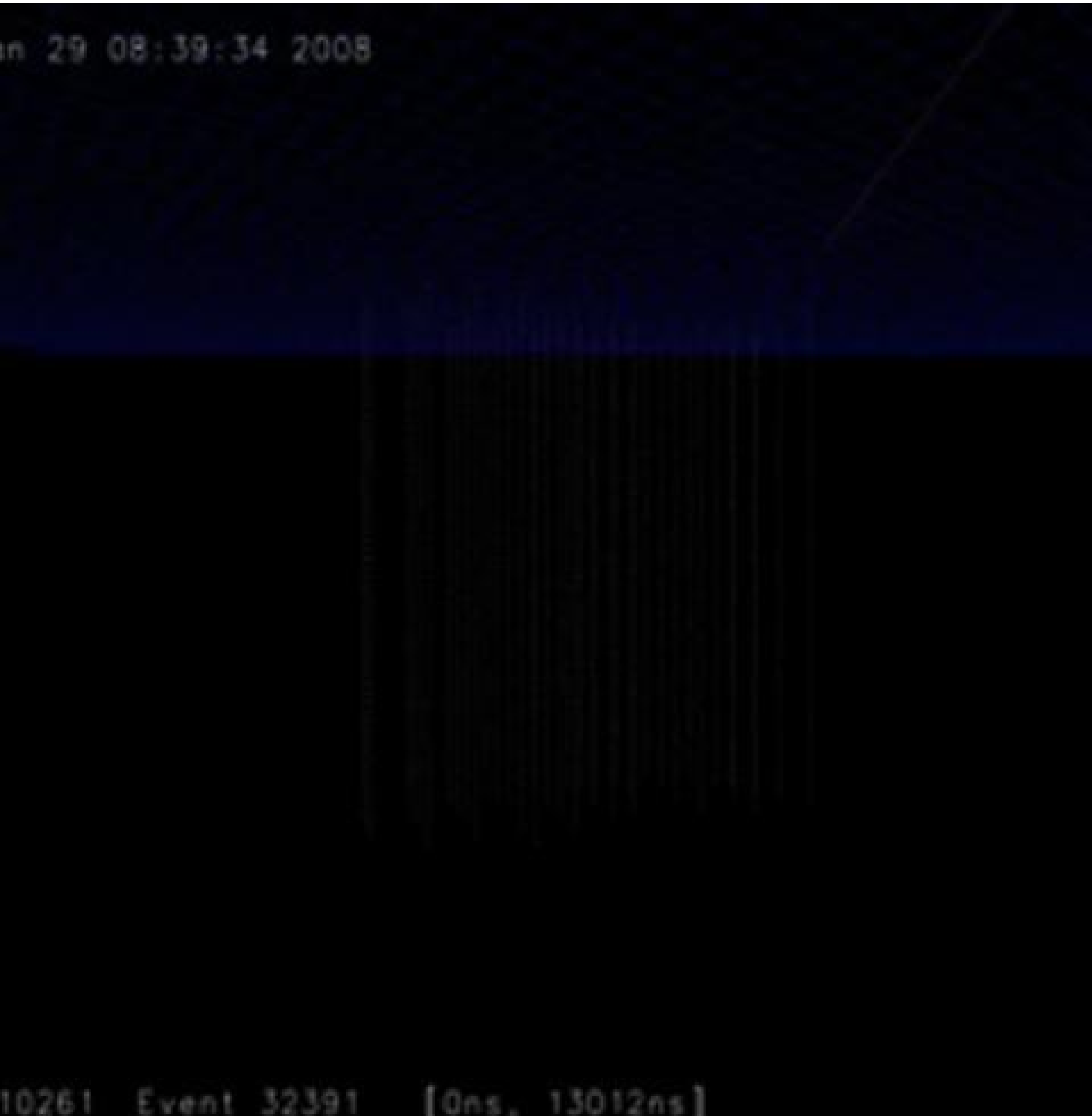
- 2 ping-ponged four-channel ATWDs:
  - Analog Transient Waveform Digitizer
  - 200-700 Megasamples/s
  - 400 ns range
  - 400 pe / 15 ns
- fADC (fast 'ADC'):
  - 40 Megasamples/s
  - 6.4 μs range



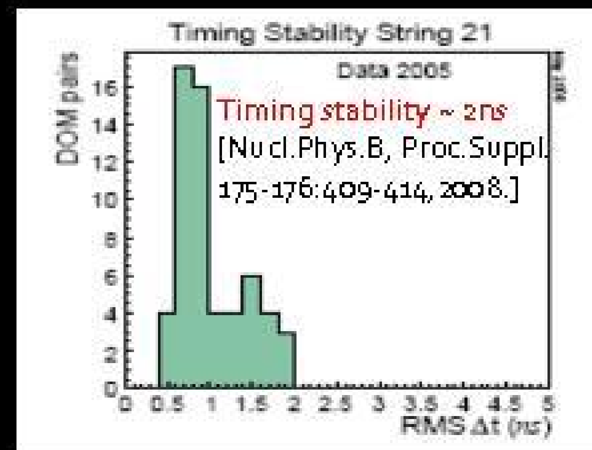
10 inch Hamamatsu PMT (R-7081-02)



- Dark Noise rate ~ 350 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Timing resolution ≤ 2 ns

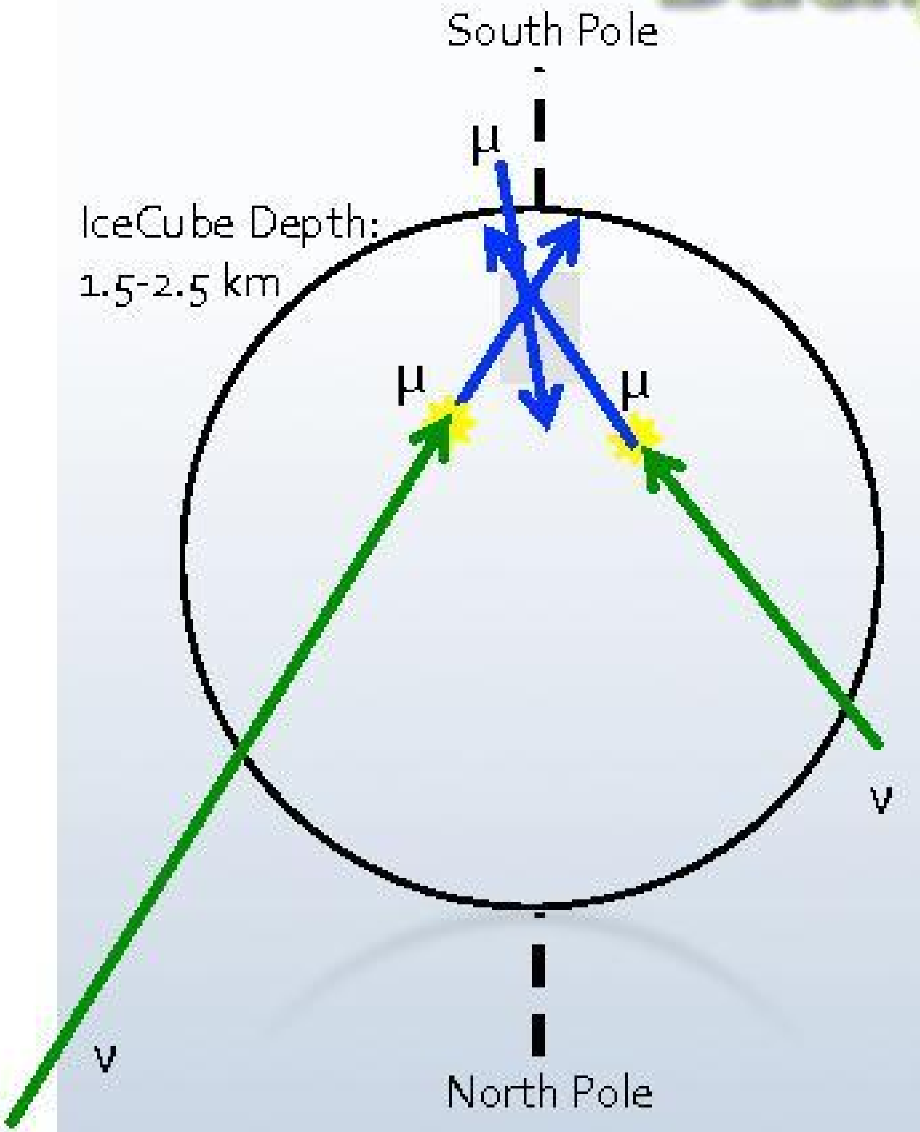


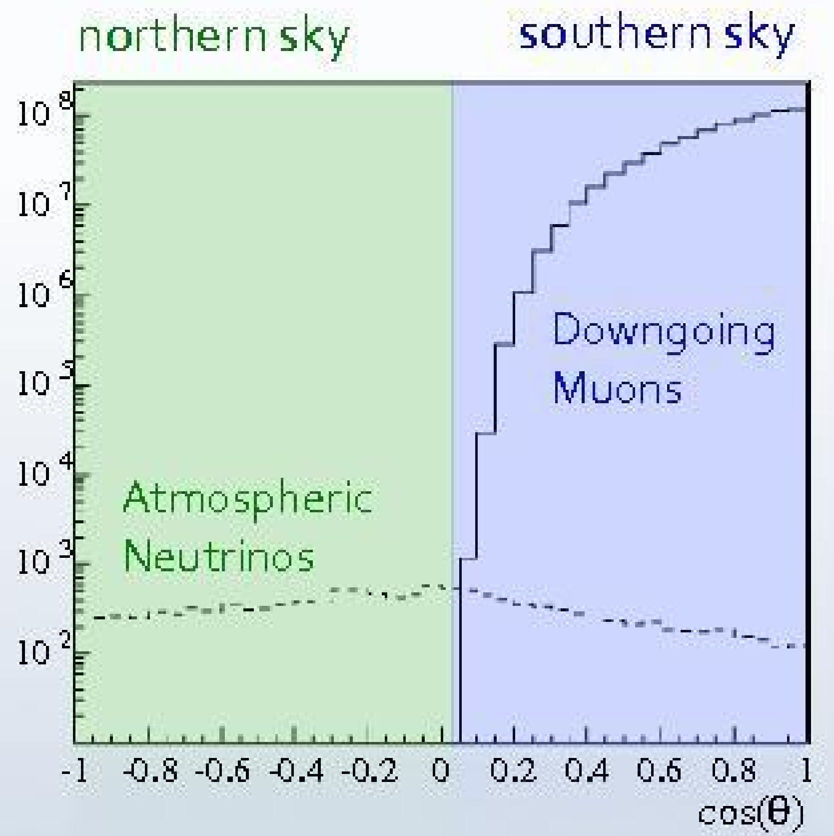
- High energy muons created in airshowers produce continuous stream of muons
  - $p + A \rightarrow \pi^{\pm} (K^{\pm})$ + other hadrons
    - $\pi^{+} \rightarrow \mu^{+} \nu_{\mu} \rightarrow e^{+} \nu_{e} \nu_{\mu} \nu_{\mu}$
- Ideal also as calibration beam



- Down-going muons provide timing calibration beam @ ~2.5kHz
- Signal up-going muons initiated by neutrinos @ 10 per hour
- Detector uptime >95%

Backgrounds

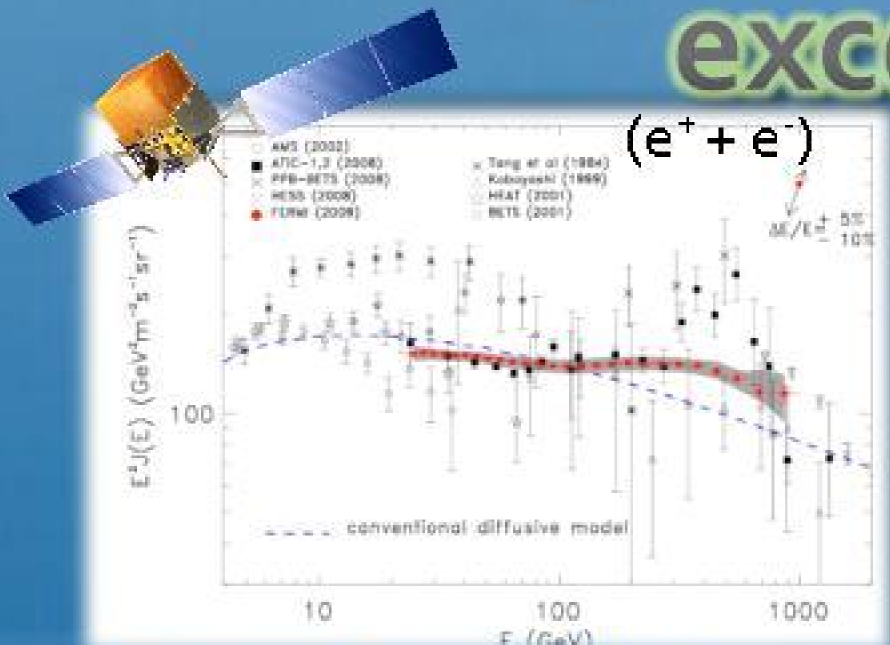




Atmospheric backgrounds for extra-terrestrial neutrino searches at the depth of IceCube

Dark Matter Searches

A mysterious lepton excess...

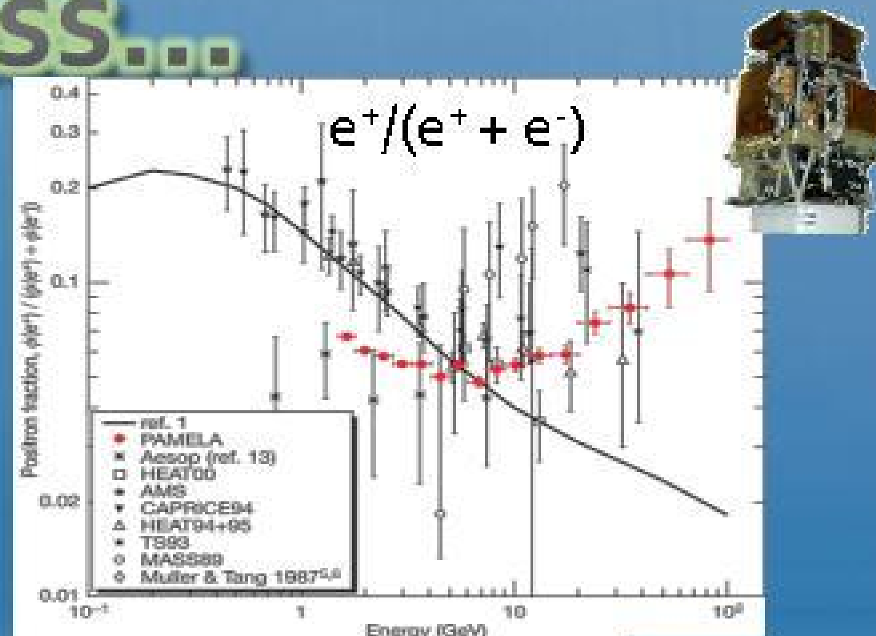


arXiv:0809.0760v1 Nature 456 (2008) 362

M. Ackermann, "Observation of the extragalactic diffuse continuum gamma-ray emission with Fermi LAT," talk at TeVPA 2009

F. Aharonian et al., Phys. Rev. Lett. 101, 261104 (2008).

F. Aharonian et al., arXiv:0905.0105.

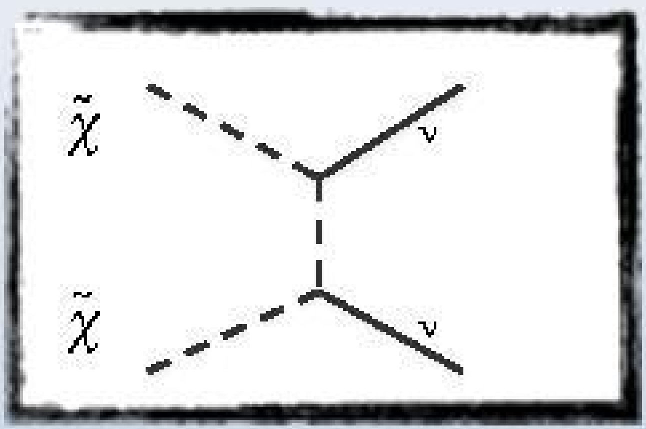


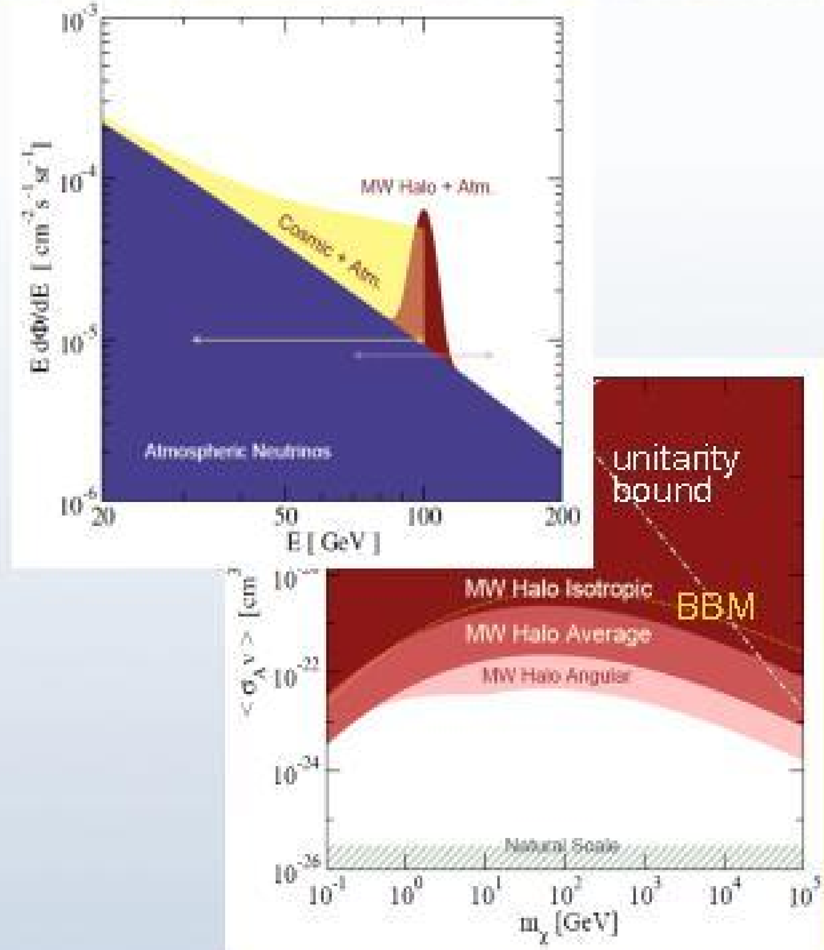
Moskalenko & Strong 1998

O. Adriani, et al., Nature 458, 607 (2009)

Limit on the total Dark Matter Self-annihilation cross section

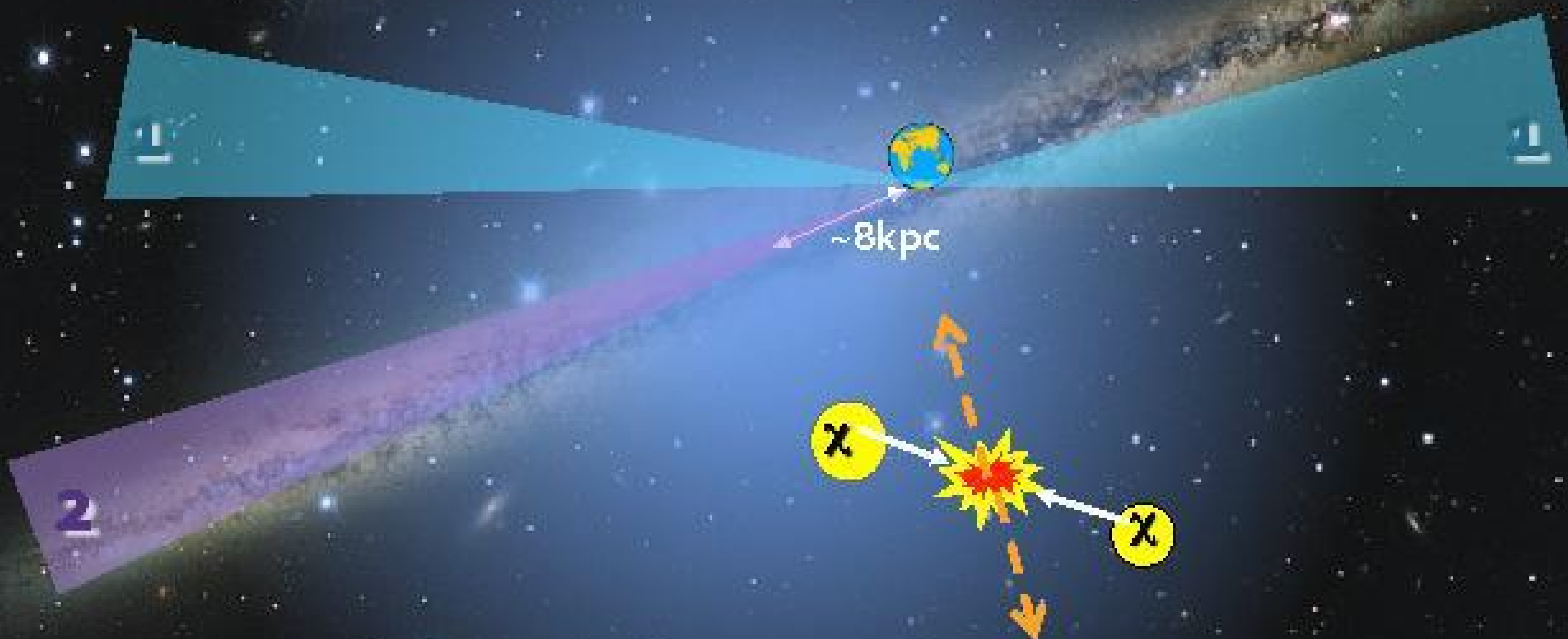
- Smoking gun: Observed particle spectrum may show feature at $E=M_{WIMP}$
- Neutrinos are least detectable messenger -> conservative upper limit on total $\langle\sigma_A v\rangle$
- Signal from Milky Way halo dominant over cosmic signal





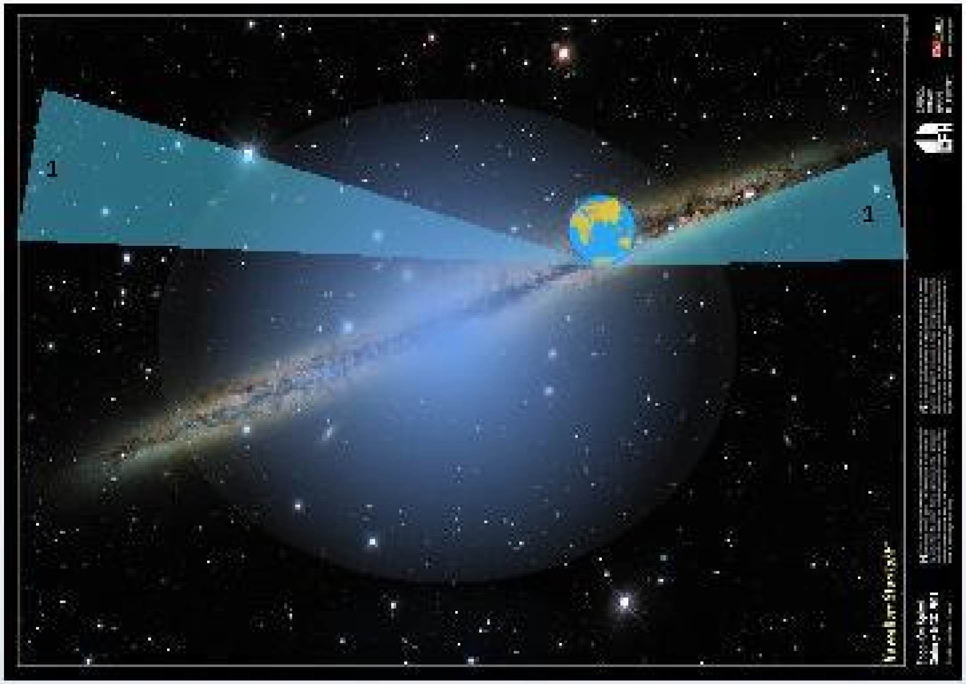
Yuksel, Horiuchi, Beacom, Ando (2007)
Beacom, Bell, Mack (2007)

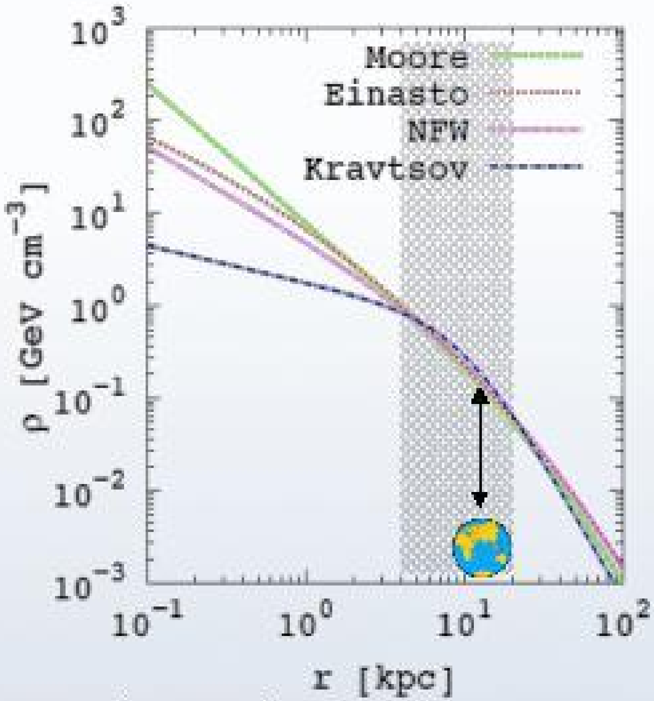
Dark Matter Searches



- Annihilation ~ρ^2
- Decay ~ρ

Dark Matter Halo Analysis





J. Einasto, Trudy Inst. Astrof. Alma-Ata 5, 87 (1965),
Navarro, Frenk, White, Astrophys. J. 490, 493–508 (1997),
Moore, et al. Mon. Not. Roy. Astron. Soc. 310, 1147 (1999) [arXiv:astro-ph/9903164],
Kravtsov et al. Astrophys. J. 501, 48 (1998) [arXiv:astro-ph/9708176].

- Search for a neutrino anisotropy
- Up-going event sample provides pure neutrino sample → Northern Hemisphere
- Analysis based on 275.7 days of livetime acquired during 2007-2008 with IceCube in the 22-string configuration

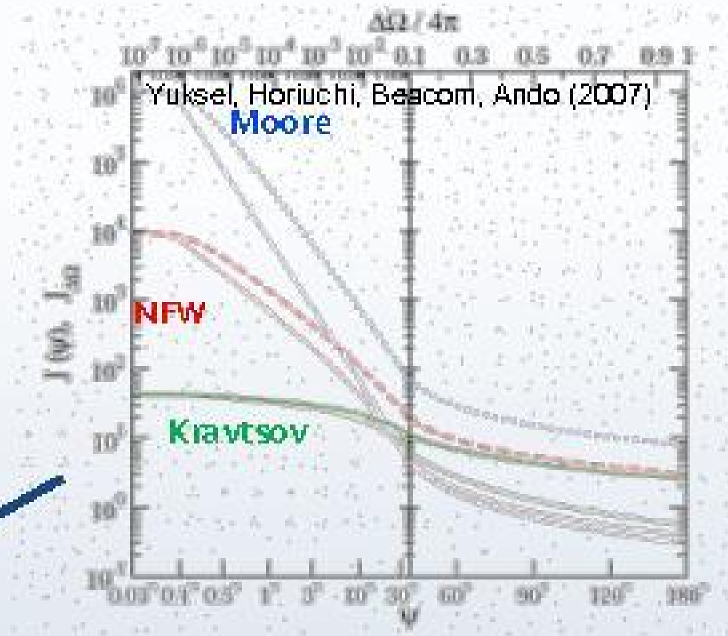
Neutrino Flux from Annihilations

Line of sight integral:

$$\ell_{max} = \sqrt{(R_{MW}^2 - \sin^2\psi R_{sc}^2)} + R_{sc}\cos\psi$$

$$\mathcal{J}(\psi) = \frac{1}{R_{sc}\rho_{sc}^2}\int_0^{\ell_{max}} \rho^2(\sqrt{R_{sc}^2 - 2l\,R_{sc}\cos\psi + l^2})\,d\ell$$

$$\mathcal{J}_{\Delta\Omega} = \frac{1}{\Delta\Omega}\int_{\cos\psi}^{1} \mathcal{J}(\psi')\,2\pi\,d(\cos\psi')$$



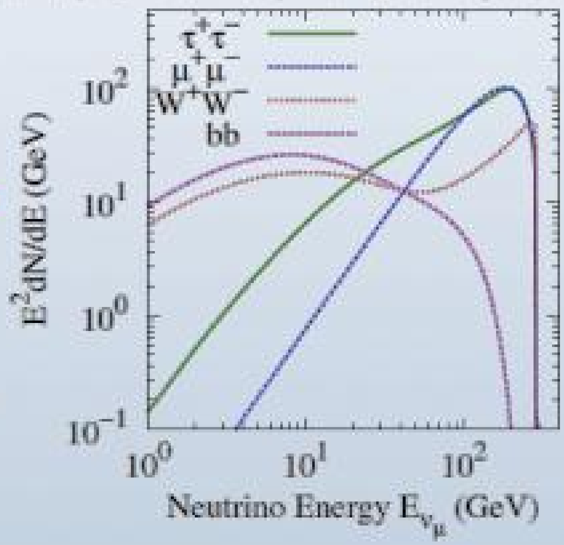
Expected differential neutrino Flux:

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

?

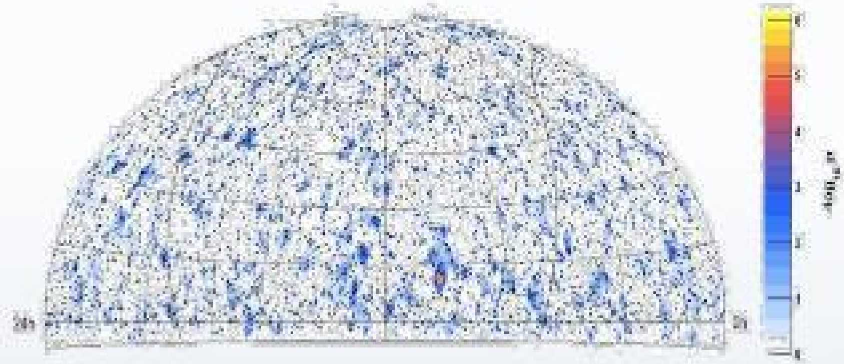
Measure integrated flux

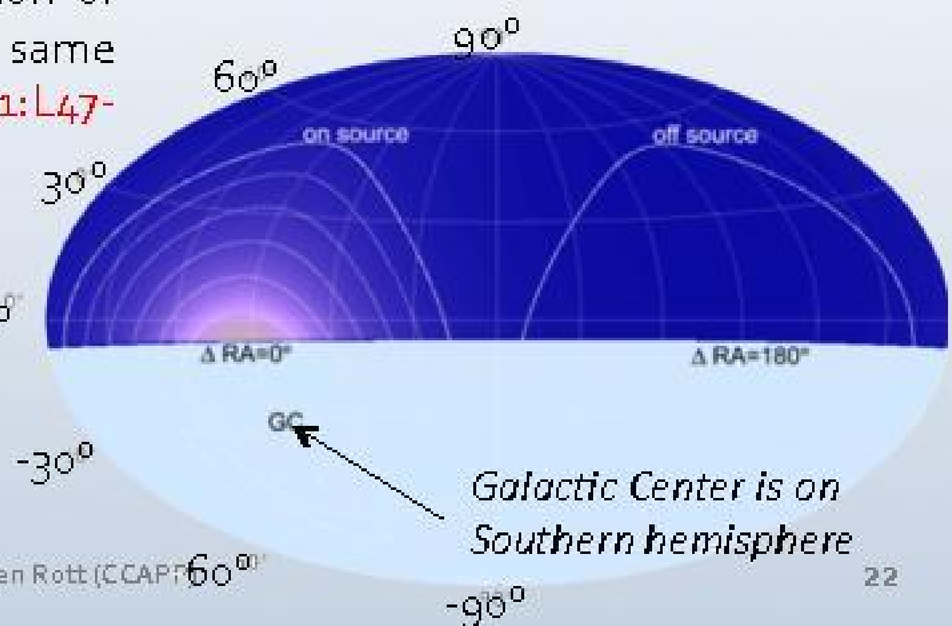
Isotropic emission



Galactic Halo Analysis

- Compare regions of equal "size" (on vs. off-source)
  - This technique allows to reduce systematic uncertainties by estimating the background from data itself
- Track selection criteria have been well established for the IceCube point source search, for simplicity and minimization of systematic effects we apply the same selection criteria (Astrophys.J.701:L47-L51,2009.)

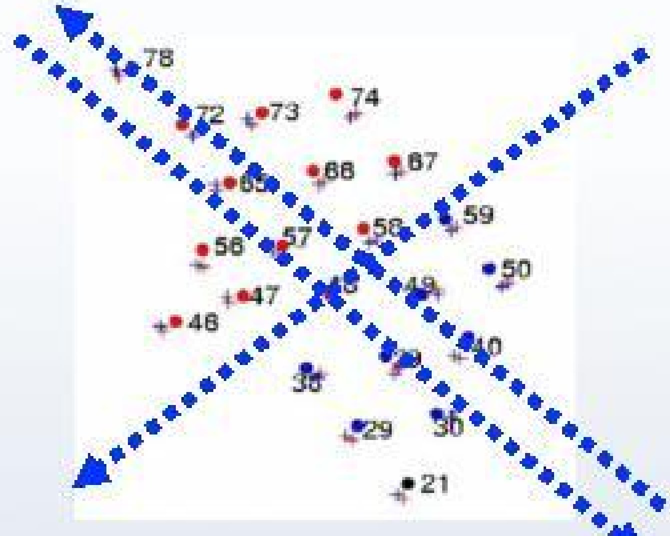


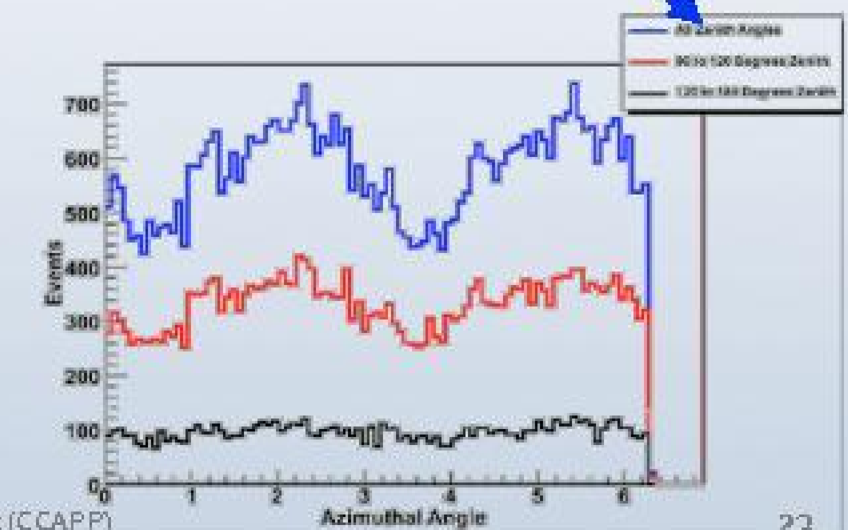


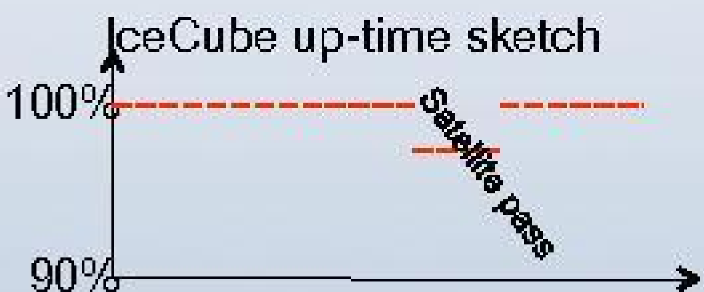
- **Do we see any effects on Dark Matter in our neutrino sample ?**

Uneven Exposure

- Track reconstruction efficiency varies in detector coordinates
- In equatorial coordinates this reconstruction efficiency is smeared out (as the detector rotates)
- Uneven detector up-time can however reduce this smearing effect
- Detector down-time correlates with satellite visibility (maintenance mode)
- Detector uptime in sidereal days defines this impact





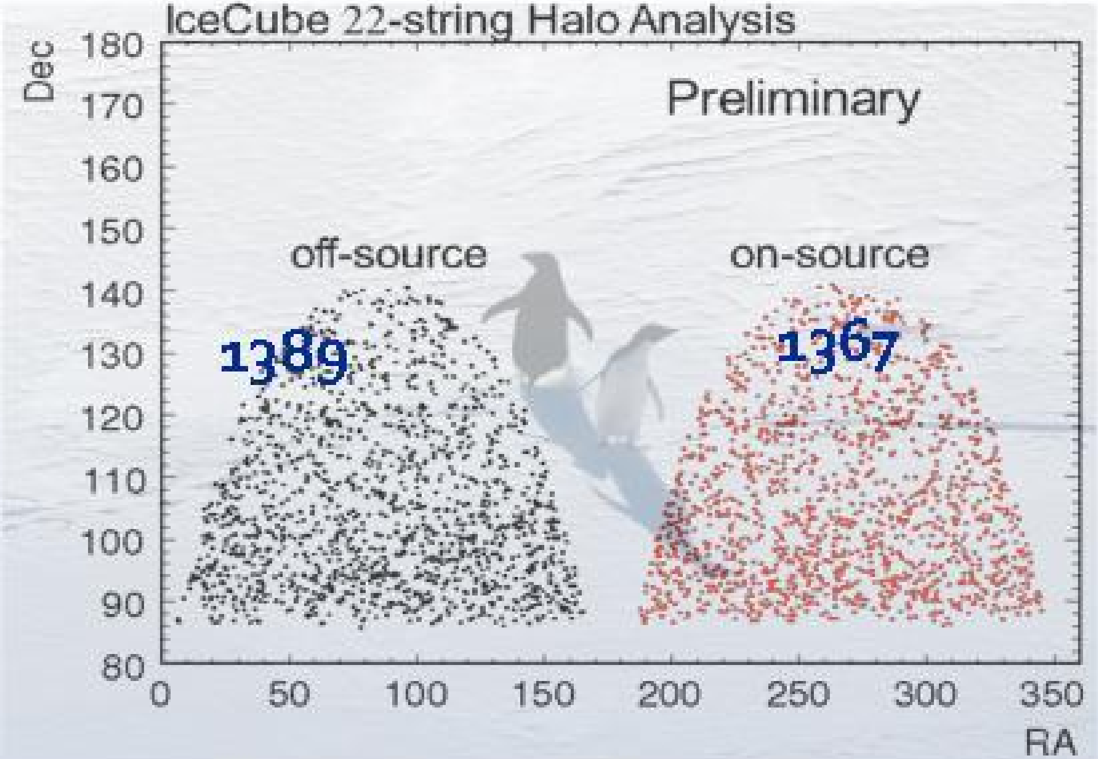


Galactic Halo Systematics

- **Background:**
  - Majority of systematics cancel out (as we use the data itself)
    - What remains: "existing" large scale anisotropy
      - Uneven "exposure" (~0.1%)
      - Neutrino anisotropy caused by cosmic ray anisotropy (~0.2%)
- **Signal acceptance:**
  - Uneven "exposure" (negligible ~1%)
  - Theoretical Uncertainties
    - Neutrino cross section, muon propagation, bed rock uncertainty(~2-4%)
  - Ice properties / DOM efficiency
    - MC/data disagreement (horizontal events) (~30%)
  - MC statistics

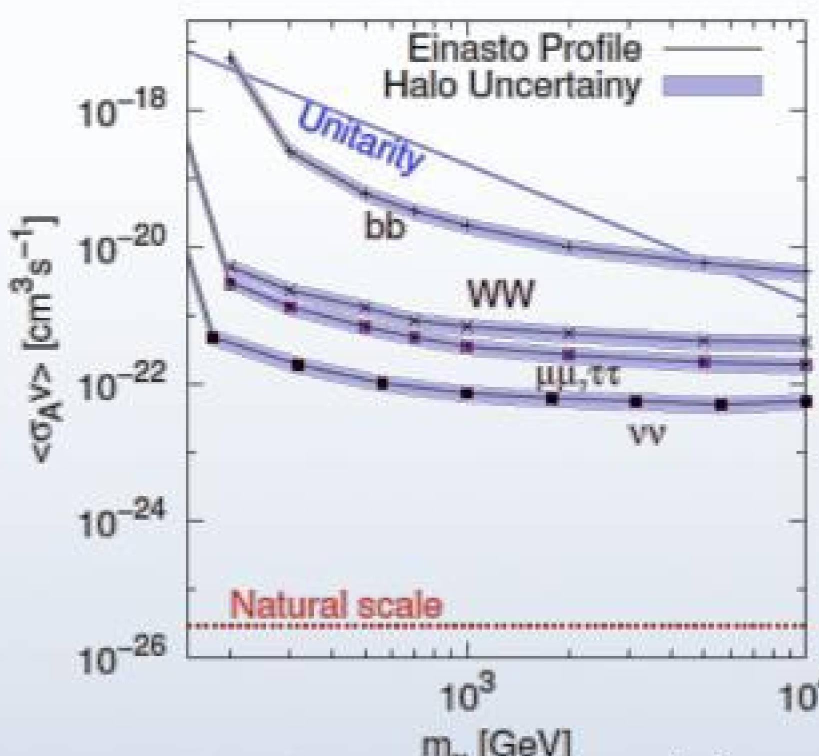
Galactic Halo Analysis

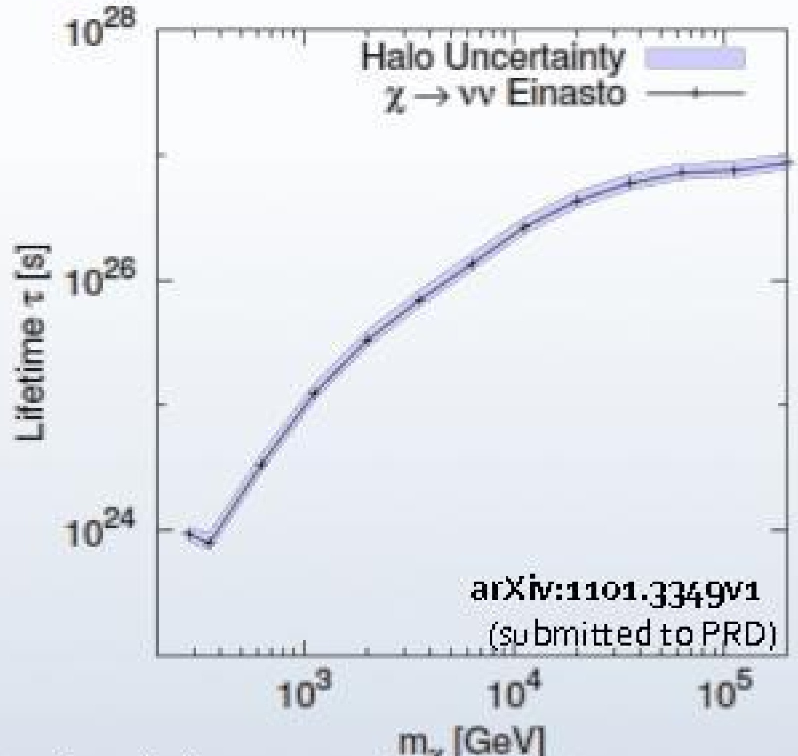
- 5114 Events after selection from -5° to +85° declination
- $N_{observed}$ in on and off source regions are consistent with each other.
- No excess flux in the region, closer to the Galactic Center, proceed to set limits



C. Rott arXiv 0912.5183, arXiv:1101.3349v1 (submitted to PRD)

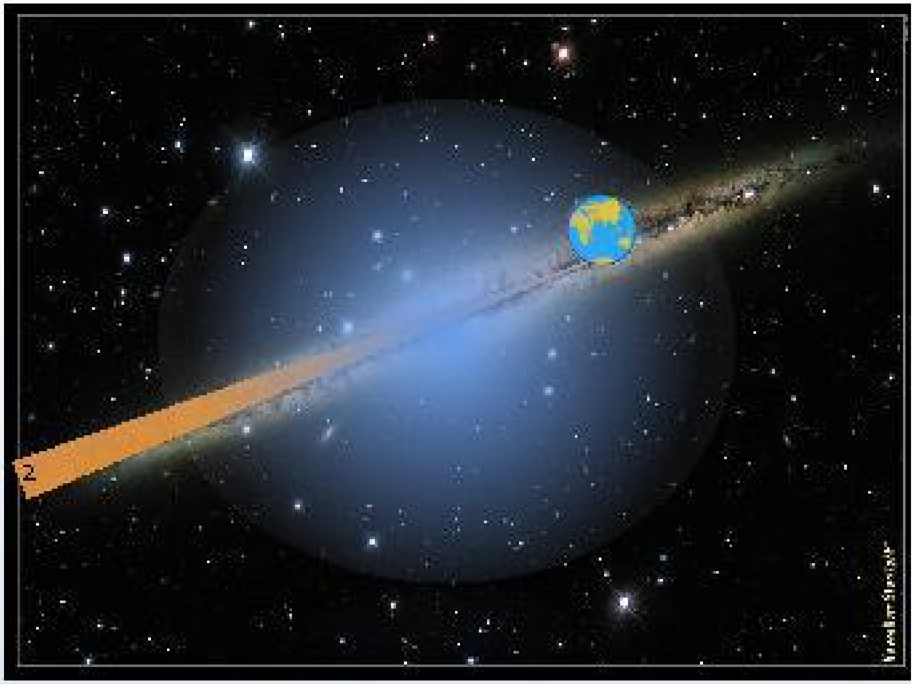
Limits

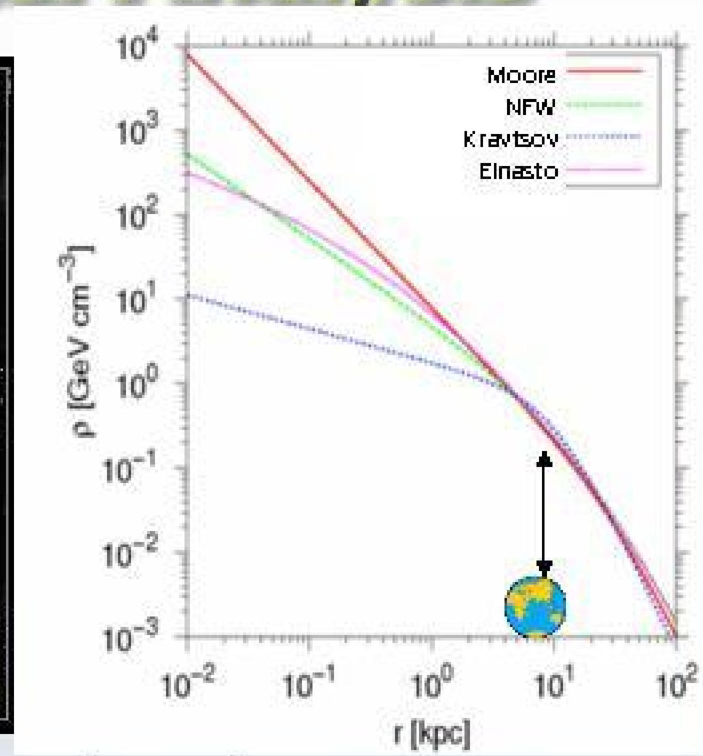




- No anisotropy was observed → constrain the dark matter self-annihilation cross section, compute limits are at 90% C.L.
- Small dependence on halo profile
- Dedicated analysis improved upon initial theoretical predictions

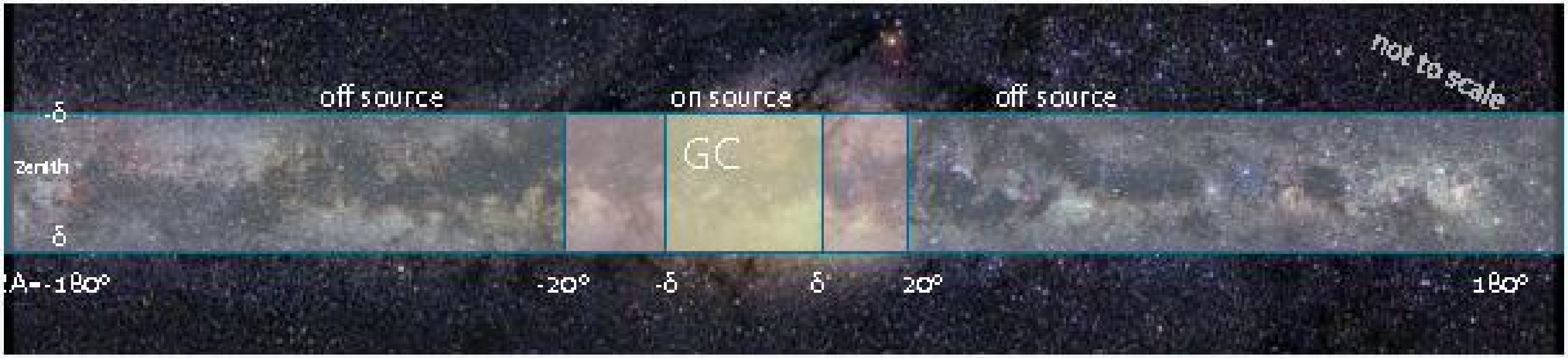
Galactice Center Analysis





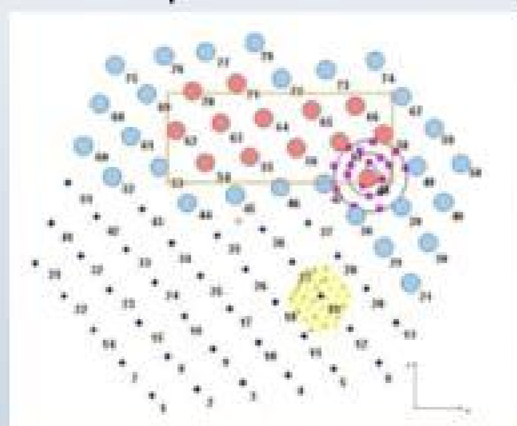
- Search for excess neutrino flux from the Galactic Center
- Rely on down-going starting events
- Analysis based on 375.7days of livetime acquired during 2008-2009 with IceCube in the 40-string configuration

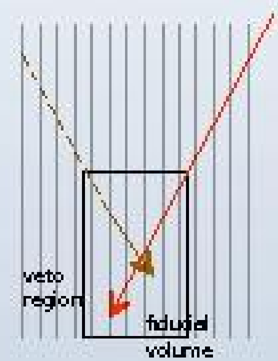
Galactic Center Analysis



- Dark Matter profiles are peaked at the Galactic Center
- Optimize the size of the on-source region
  - → δ = 8°
- Compare the amount of events in the on- and off-source region
- From off-source prediction 798919 events
- On-source observed: 798842 events

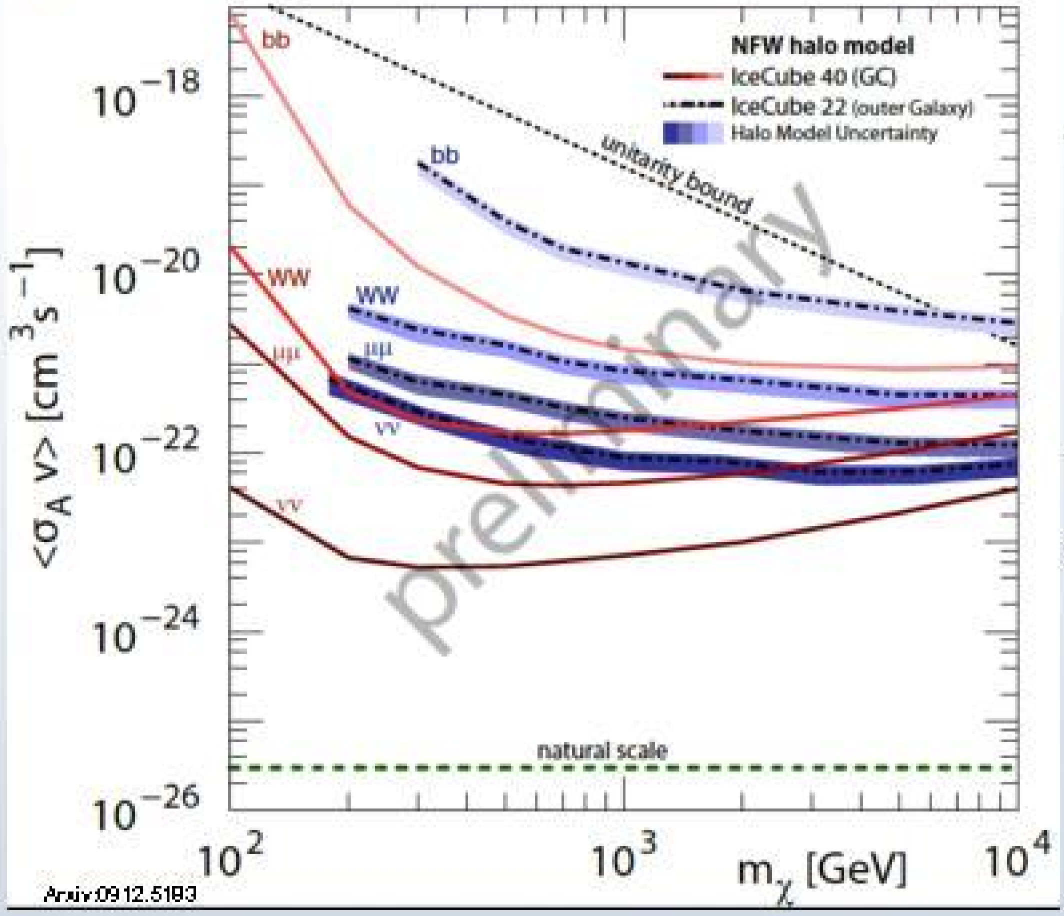
- Galactic Center is above the horizon → events are down-going in IceCube
  - Use starting events to reduce atmospheric muon background





Galactic Center Analysis

Limits (90% C.L.) on the self annihilation cross section (χχ -> bb, WW, μμ, νν)

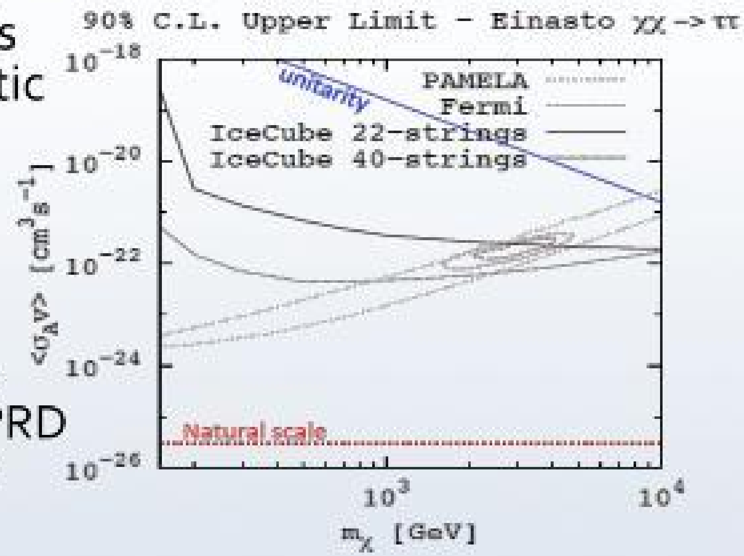


- Number of observed events in on- and off-source region compatible
- Pursue same stratgy as in halo analysis:

- Proceed to set limit
- The high DM density predicted near the Galactic Center is very beneficial to constraining the dark matter self-annihilation cross section.
    - Limits however strongly depend on the choice of halo model

Galactic Halo Analyses Summary

- Performed two searches for neutrino signals from dark matter annihilations in the Galactic dark matter halo and the Galactic Center
  - Observations are consistent with the background only hypothesis
  - Limits on the dark matter self-annihilation cross section and lifetime have been set (PRD submitted arXiv:1101.3349) in the physical interesting parameter space
- Searches on-going using "full" IceCube detector and Deep Core
  - Dwarf Spheriodals (ICRC2011)
  - Various Galactic Halo analysis

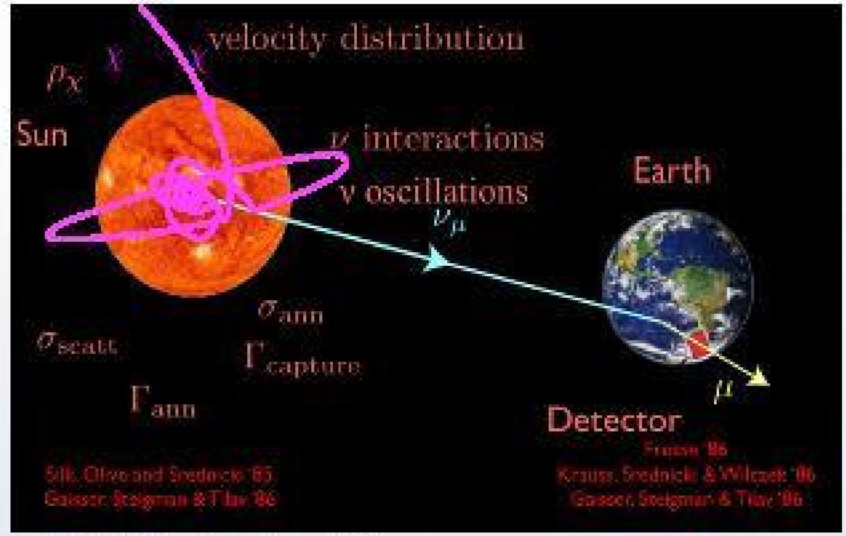


Solar WIMPs

Credit: "The [illegible] of brightness or lightness"
Akiyoshi Kitaoka, Associate professor, Ph.D (Ritsumeikan University, Dept. of Psychology)

Solar WIMPs

- Dark Matter could get gravitationally captured by massive bodies (Sun)
- Dark Matter accumulates and starts annihilating → Neutrinos are the only particles that can make it out
- At equilibrium ($\Gamma_A = 1/2\Gamma_C$) the neutrino flux does not depend on the self annihilation cross section !
  - Measure WIMP-nucleon scattering cross section

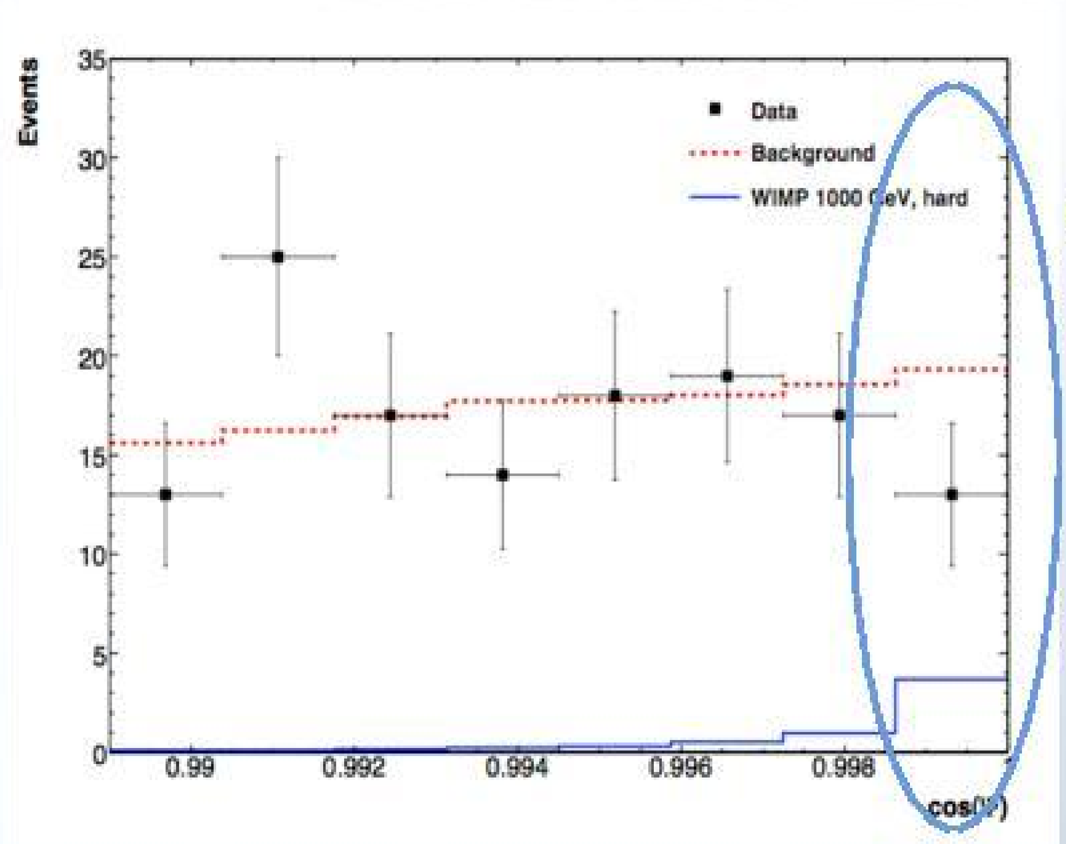


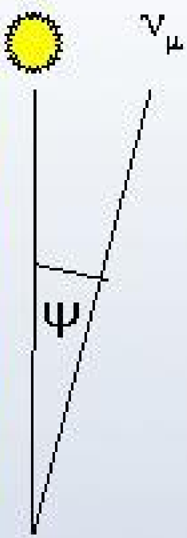
A. Gould, Astrophys. J. 321 (1987) 571
G. Jungman, M. Kamionkowski, and K. Griest Phys. Rept. 267 (1996) 195
G. Wikstrom and J. Edsjo, JCAP 04, 009 (2009)

$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$

C_C – Capture Rate
$C_A N^2$ – Annihilation Rate (2x)
$C_E N$ - Evaporation Rate (can often be neglected but should not be forgotten)

Solar WIMP Analysis
IceCube 22-strings





Up-going events (Sun below the horizon) acquired during 2007-2008

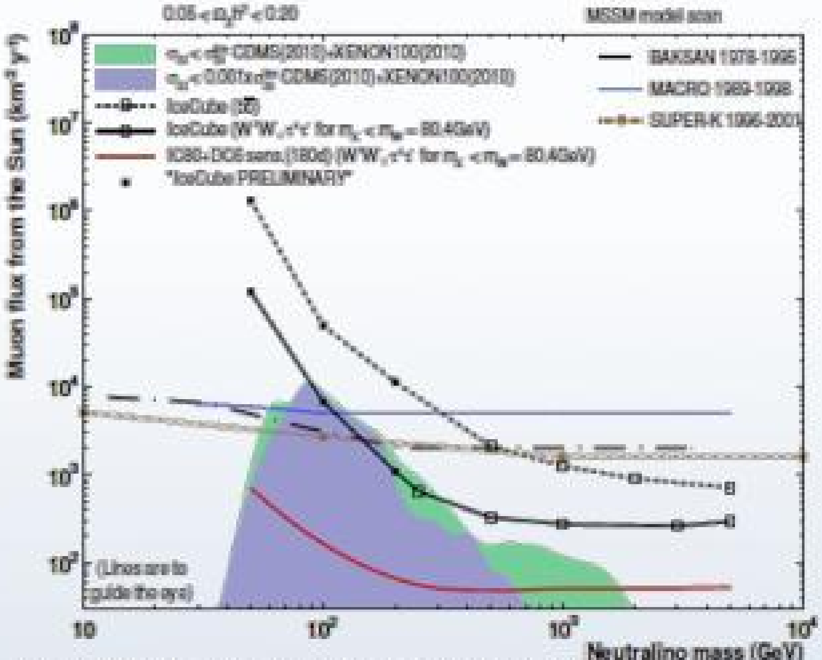
Muon flux in direction of the Sun

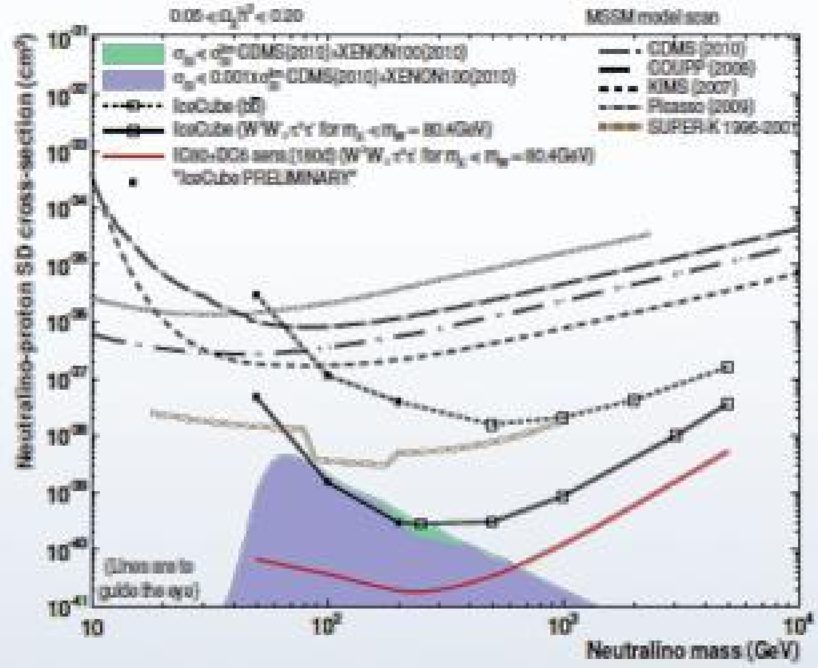
Examine angular distribution Ψ for Sun and muon tracks.

Angular resolution @ (>500 GeV) ~3°

Observation consistent with expectations from atmospheric neutrinos backgrounds and misreconstructed events ⇒upper limit

Solar WIMP Limits





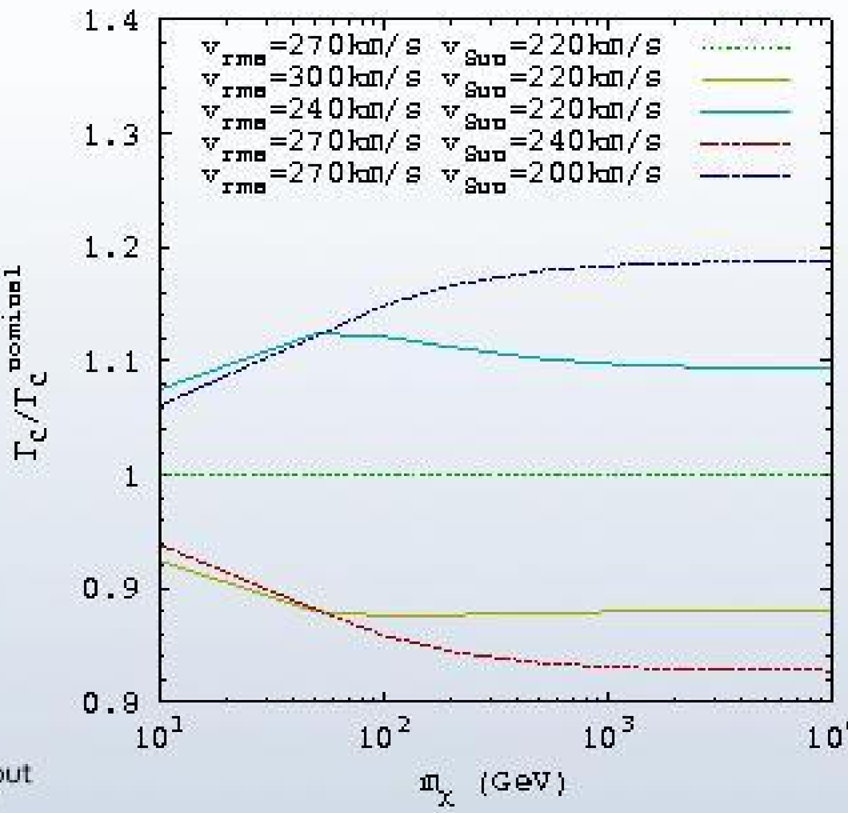
Phys. Rev. Lett. 102, 201302 (2009) arXiv:0902.2460

- No excess flux observed
- Obtain limit on the muon flux in direction of the Sun
- Constraints are computed in terms of annihilation modes (hard, soft)

- Under the assumption of the equilibrium condition and standard halo parameters, a limit on the WIMP-proton scattering cross-section can be obtained
  - IceCube's limit 2-orders of magnitude better than direct searches
  - Spin independent cross section tightly constrained in direct detection experiments

Halo Uncertainties on the Capture Rate

- Dark Matter Density
  - $\Delta\Gamma_A / \Gamma_A = \Delta\rho_{DM} / \rho_{DM} = 10\%$
  - $dN/dt = C_C - C_A N^2 - C_E N$
- Velocity Distributions
  - $\Delta\Gamma_A / \Gamma_A \sim \Delta v_{rms} / v_{rms}$
  - $\Delta v_{sun} / v_{sun}$ complex dependence
  - Non-maxwellian velocity distribution - complex dependence
- Sub structure
  - Can be ignored <ρ_{DM}(8 kpc)>
  - Smooth halo well motivated at 8 kpc (CDM Simulations)
  - Extreme cases -> "Deviation from equilibrium"
  - Conversion factor can not easily be derived with out detailed knowledge of solar substructure history
- Suppression of capture, composition, evaporation



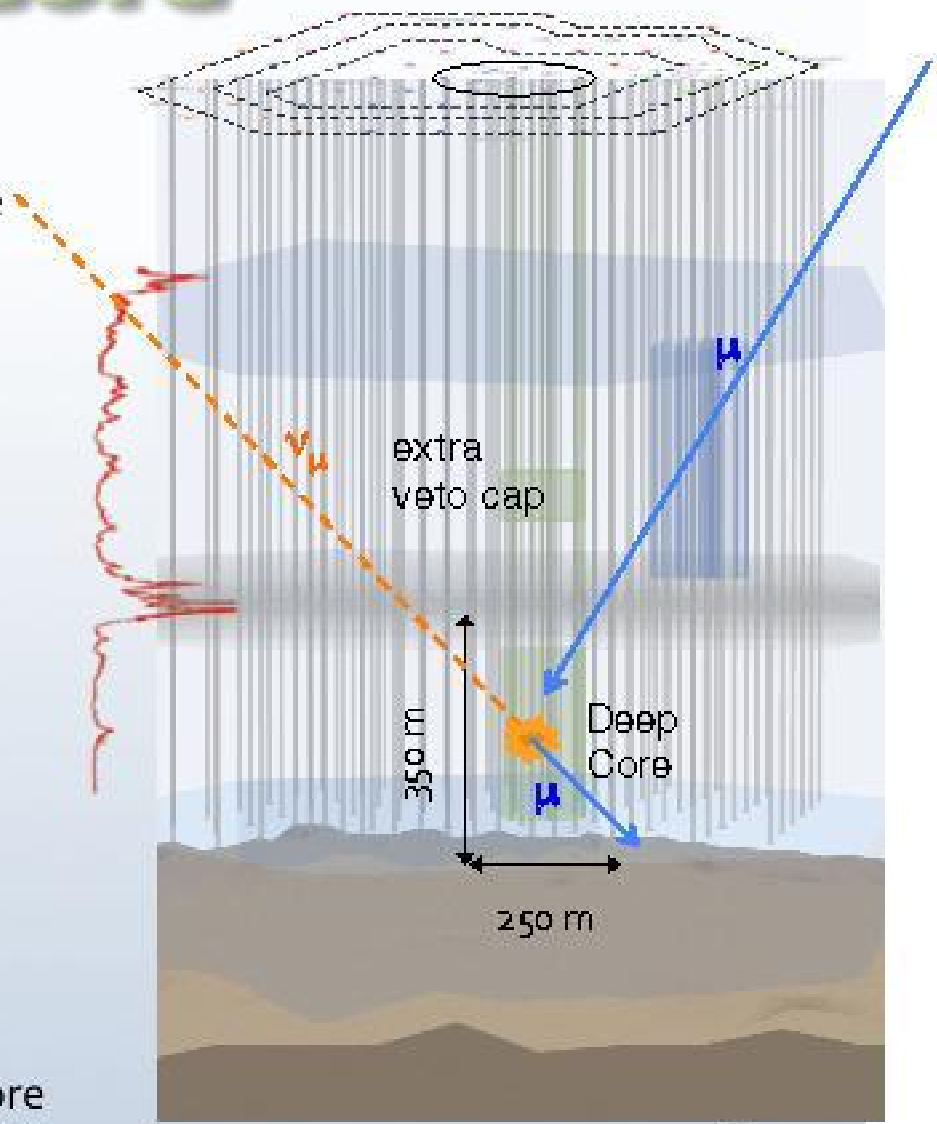
C.Rott, T. Tanaka, Y. Itow, J. Beacom 2010 – IDM 2010 (in prep.)

Outlook for Dark Matter at the Pole

- IceCube/DeepCore Physics
- Dark Matter direct detection in the ice (DM-ice)
- Extension to DeepCore "Hyper-K style detector"
- 1 MT 10 MeV threshold ring-imaging Cherenkov detector

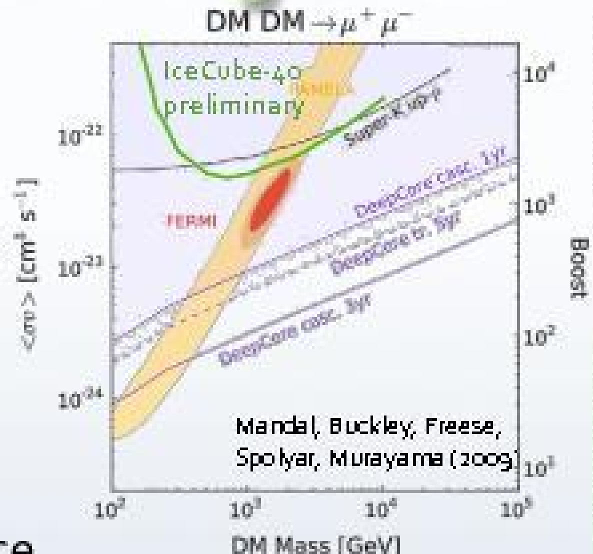
DeepCore

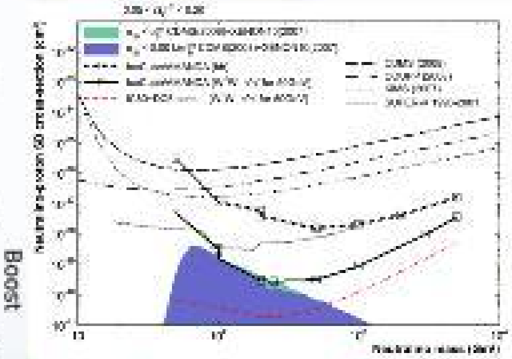
- DeepCore deployed and taking data since June 2010
- 8 special strings plus 7 nearest standard IceCube strings
  - 72 m interstring spacing
  - 7 m DOM spacing on string
- High Q.E. PMTs (~40% better)
  - ~10x higher eff. photocathode density
- Clearest ice below 2100m
  - $\lambda_{atten} \approx$ 40-45 m
- Look for starting events in DeepCore to veto atmospheric muons
- Top and outer layers of IceCube can be used to veto down-going muons
  - Three veto string layers surrounding DeepCore

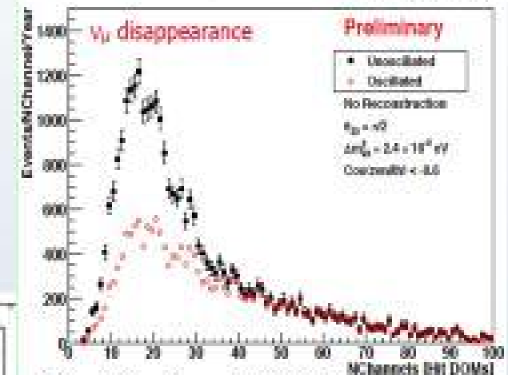


DeepCore Physics Goals

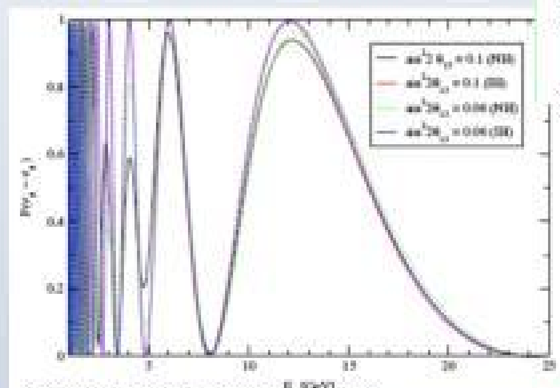
- Dark Matter
  - Solar WIMPs all year and down to accelerator bounds
  - Halo WIMPs
- Neutrino oscillations
  - Muon neutrino disappearance
  - Tau appearance
  - Neutrino Mass Hierarchy ?
- Point Sources
- New ideas !
- etc ...



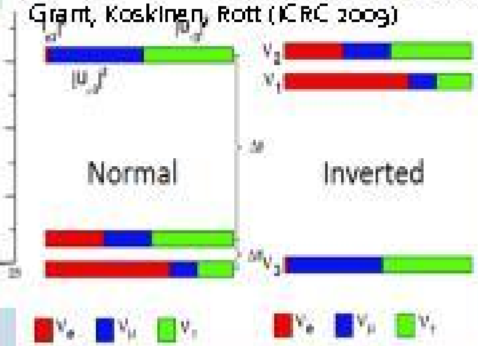




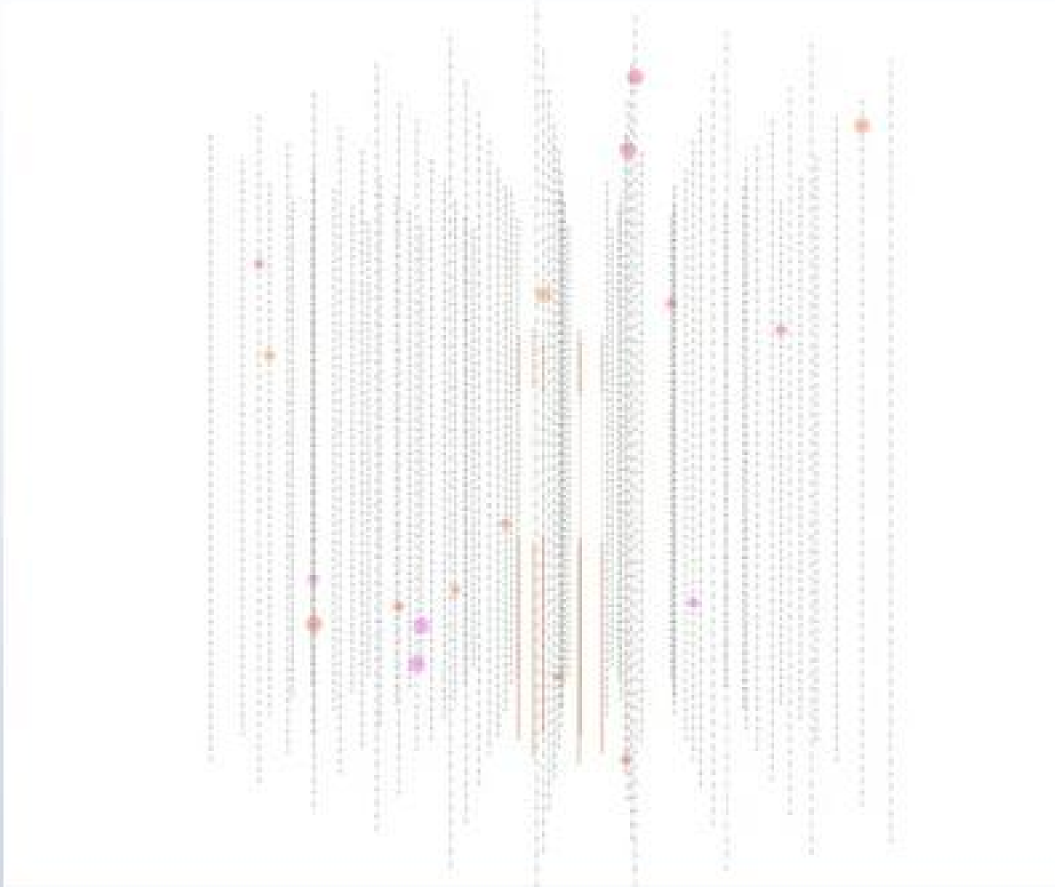
Grant, Koskinen, Rott (ICRC 2009)



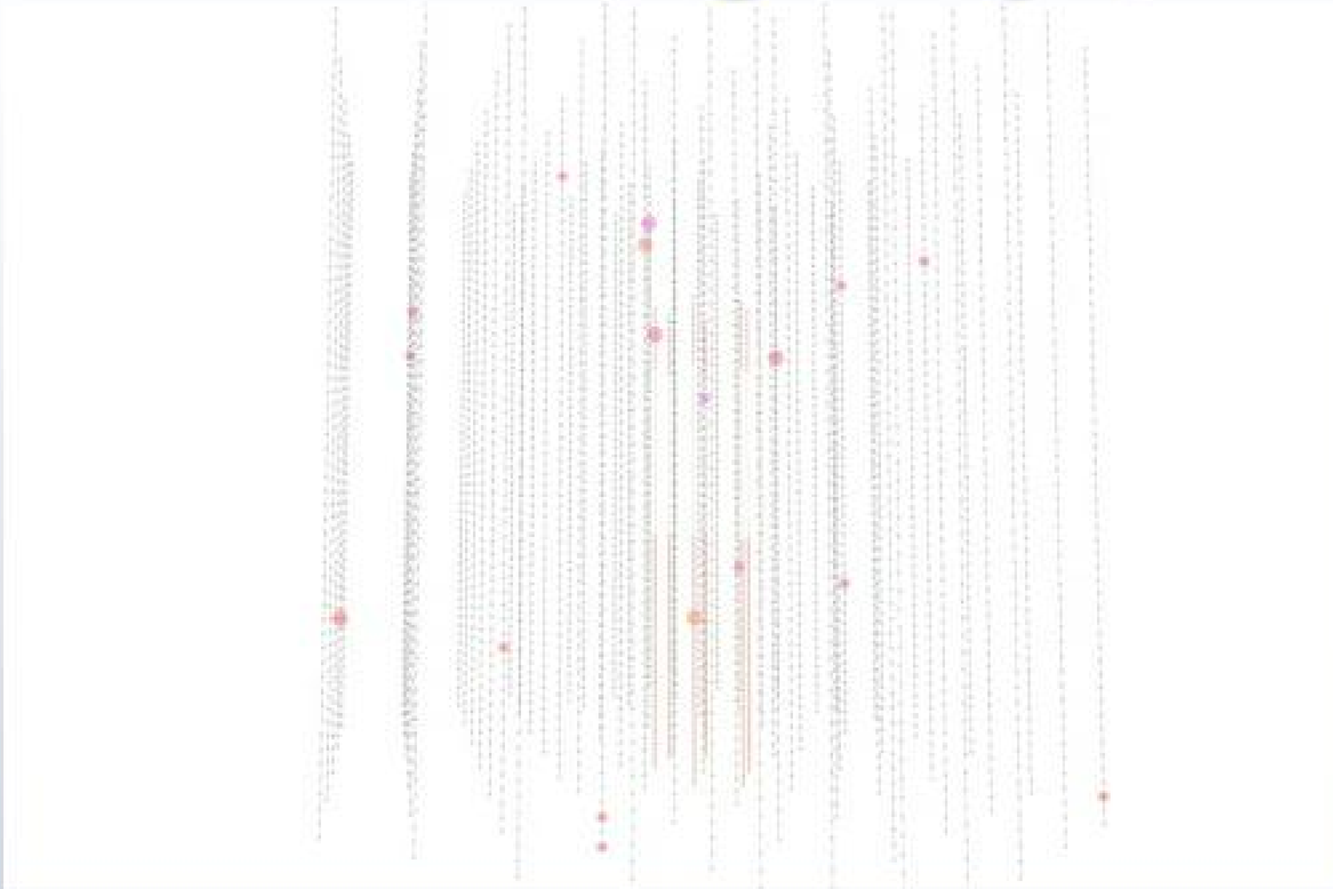
Mena, Mocioiu, Razzaque (2008)



DeepCore ~10GeV ν_μ Candidate Event



DeepCore Cascade-like Event (ν_e or ν_τ ?)



Megaton Scale Detector

- Strong Physics Case for Megaton neutrino detector

(1) Low-mass dark matter searches (down to GeV range)

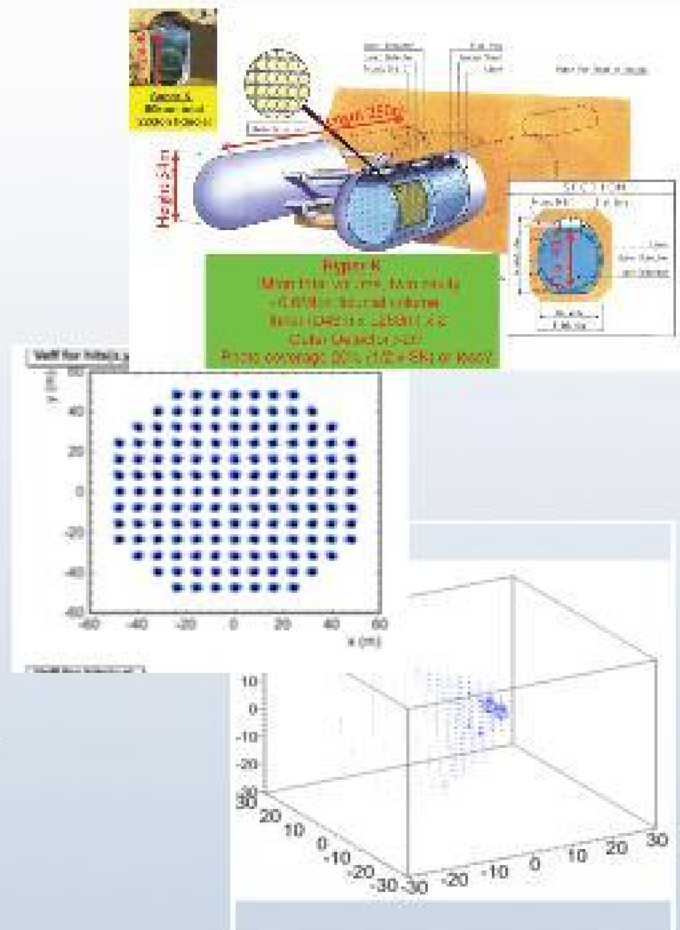
(2) Precision measurements of atmospheric neutrino oscillations , long baseling

(3) Improved sensitivity to supernova neutrinos, relic SN neutrinos

(4) Proton Decay, …

Hyper-K, DeepTitand, or could also be build as an extension to DeepCore with very dense sensor spacing.

- Deep ice (~2.0-2.5km) has scattering length ~50m and absorption length ~230m. Ideal conditions to build large neutrino detector
  - Dominant cost driver PMTs (66%)

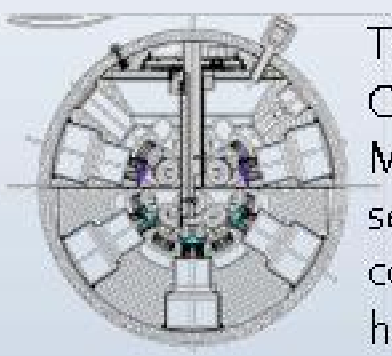


Masato Shirazawa, NNN2010

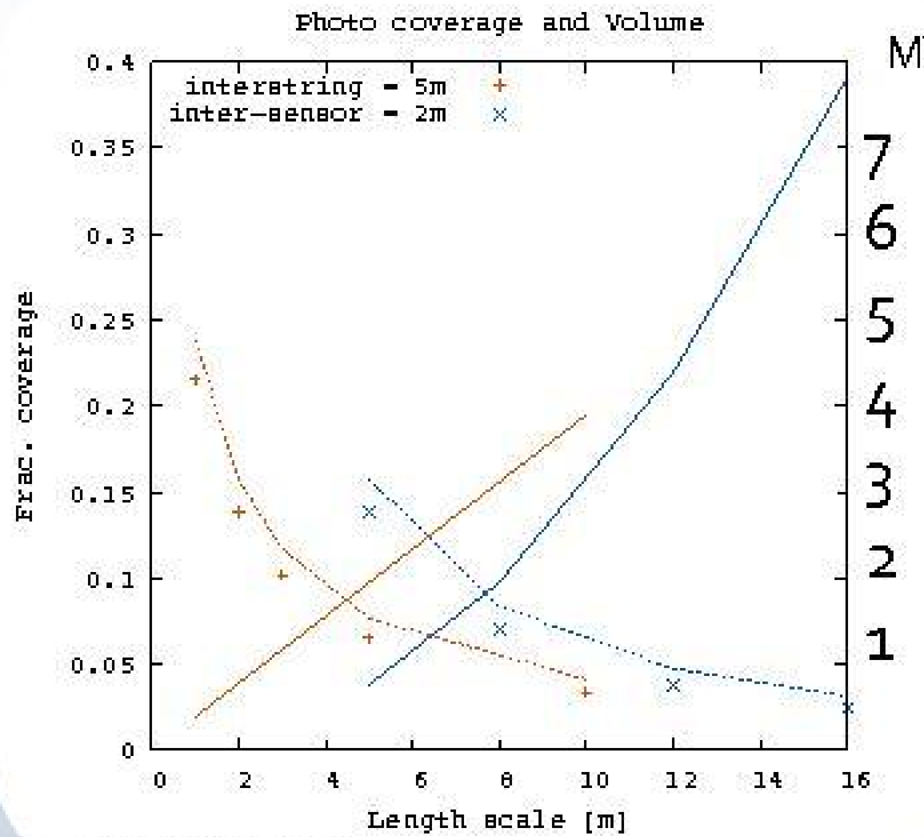
C. Rott NNN 2010

Megaton scale Detector

- How close can we drill, what is the impact of hole ice (refrozen ice) ?
- Impact of segmentation of Photo-sensors still uncertain
- Any increase in QE or reduction in sensor cost will help will help



The KM3Net Consortium has studied Multi-PMT OMs. These segmented sensors consist of 31 3" PMTs housed in a 17" sphere



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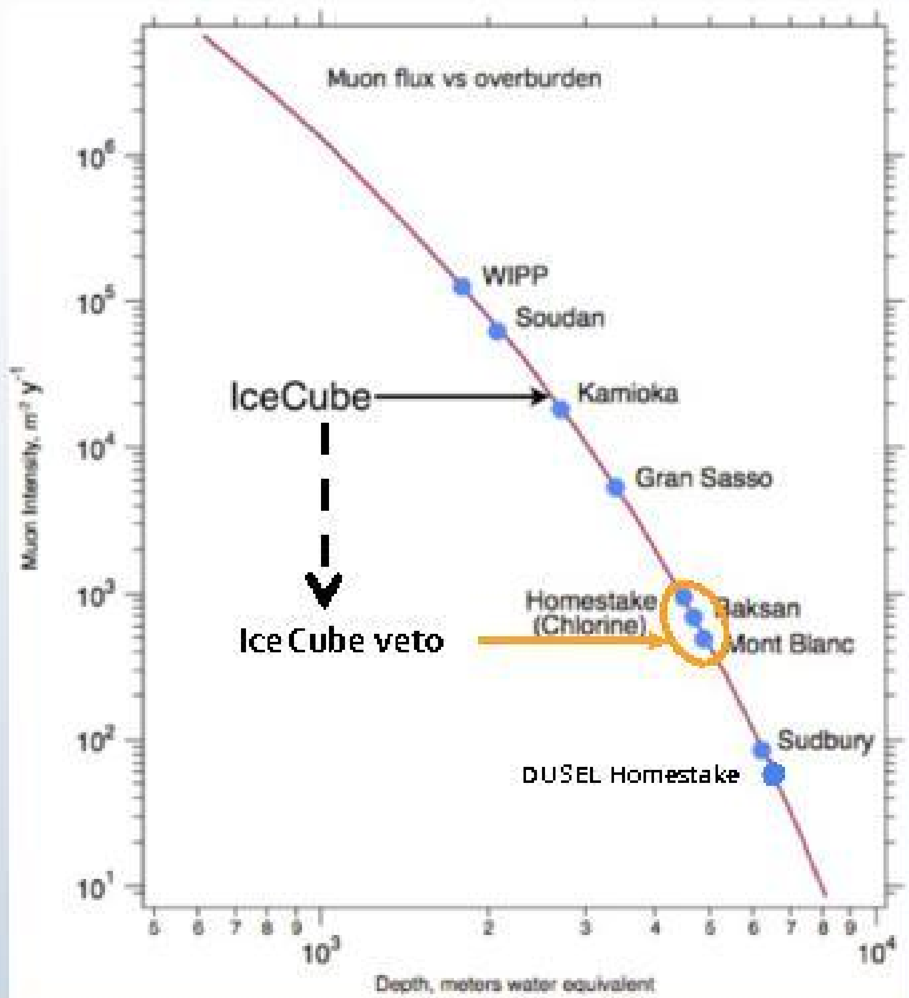
Dark Matter Direct Detection at the South Pole

- Feasibility of operating NaI crystal remotely in the ice
- Use NAIAD detector assembly
- Deployed 2 test devices (2x8.5kg)in December 2010
- Very stable environment
- Muon and neutrino flux precisely measured
- IceCube can veto muons
- Search for annual modulation signal
- Proof of principle, ultimate goal obtain ultra-pure NaI and build scaled up version



Direct Detection

XMASS

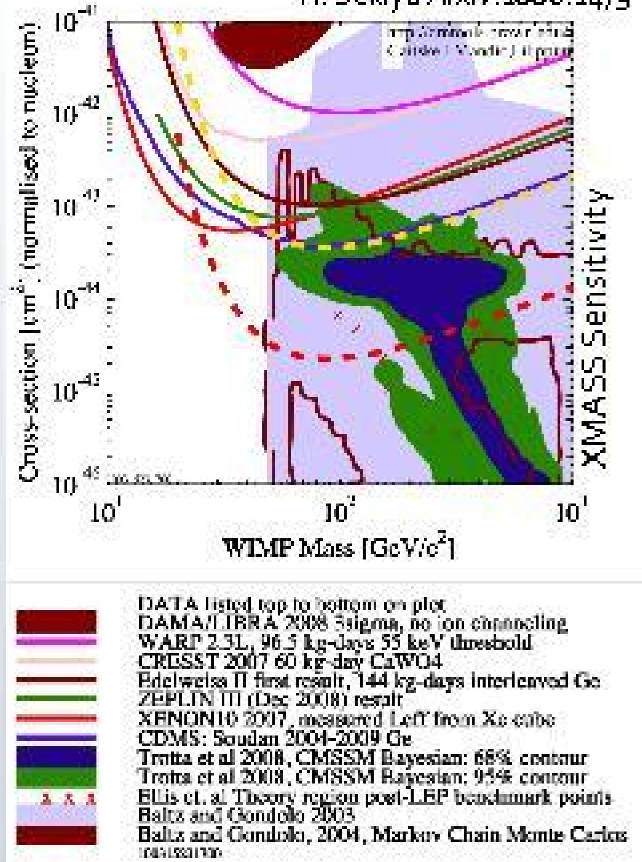
- Liquid Xenon:
  - High light yield and fast scintillator (178nm)
  - High atomic number Z=54, high density (~3kg/l)→ effective self-shielding, compact detector
  - High mass number (A~131) SI: high WIMP rate, SD: 50% odd isotopes
  - No long lived Xe isotopes, Kr-85 can be removed to ppt
- 800kg detector operational and exploring new WIMP territory
- Scalability to large detectors → Exciting for solar neutrino studies and eventually astro-particle physics

Closing in on Dark Matter

- Complementary approaches pushes ahead fast:
  - 1.96TeV → 14TeV Energy Frontier LHC
  - Self-annihilation cross sections ~10^{-22}-10^{-23}cm^3 s^{-1} → Natural scale
  - WIMP nucleon scattering cross section
    - σ^{SD} ~ 10^{38} cm^2 → ~ 10^{40} cm^2
    - σ^{SI} ~ 10^{43} cm^2 → ~ 10^{45} cm^2

- Discovery of Dark Matter will not be the end !
  - Answering one question leads to more
    - Particle properties, exploration of underlying theory → NLC, Muon Collider
    - Role in our Galaxy and Universe → Large Neutrino Detectors , ...

H. Sekiya Arxiv:1006.1473

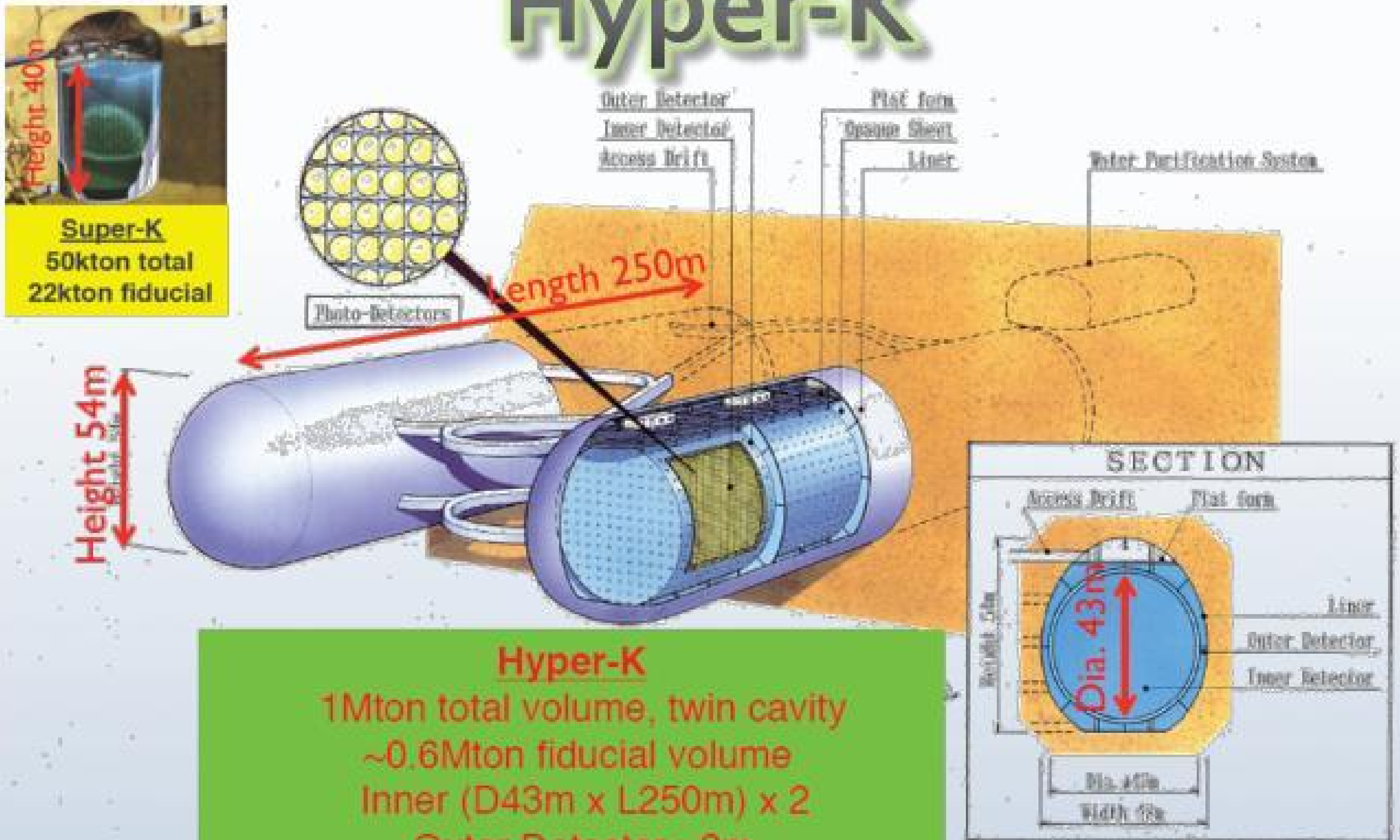


Conclusions

- New approaches and analysis methods have resulted in more and more stringent constraints on dark matter properties
  - Neutrinos are ideal messengers to look indirectly for dark matter
    - Stringent limits on dark matter properties (from IceCube, SK)
- There is very realistic chance that we can finally discover dark matter
- Unraveling its nature and role in the universe will be the mission of next generation detectors


Thanks !

Hyper-K



Masato Shinazawa, NNN2010

Hyper-K

1Mton total volume, twin cavity

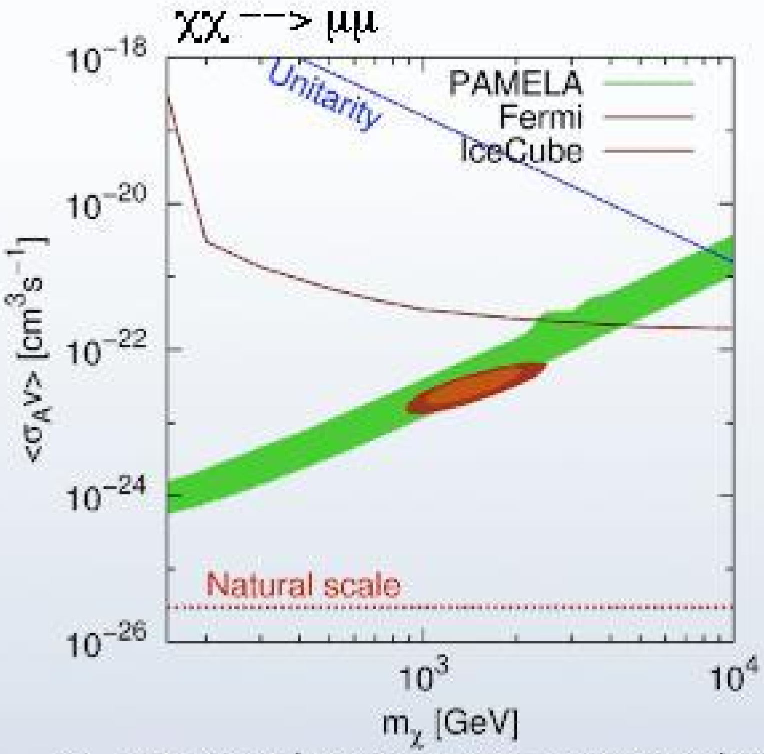
~0.6Mton fiducial volume

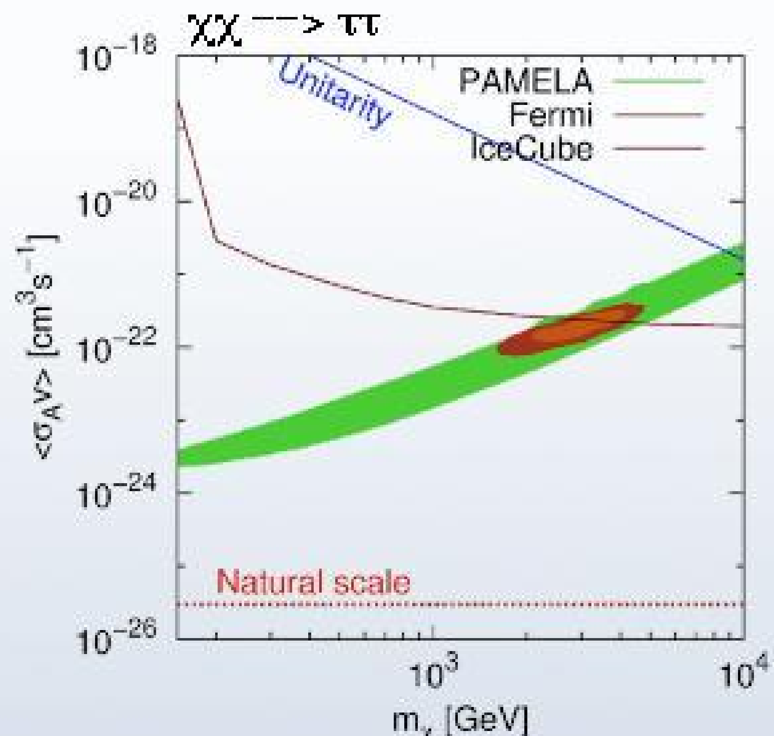
Inner (D43m x L250m) x 2

Outer Detector >2m

Photo coverage 20% (1/2 x SK) or less?

Relevance of Limits





- Neutrino limits start to constrain dark matter models motivated by the lepton excess in PAMELA / Fermi
- Using the partial instrumented (~25%) IceCube detector and one year of data we can set limits in the physical interesting parameter space