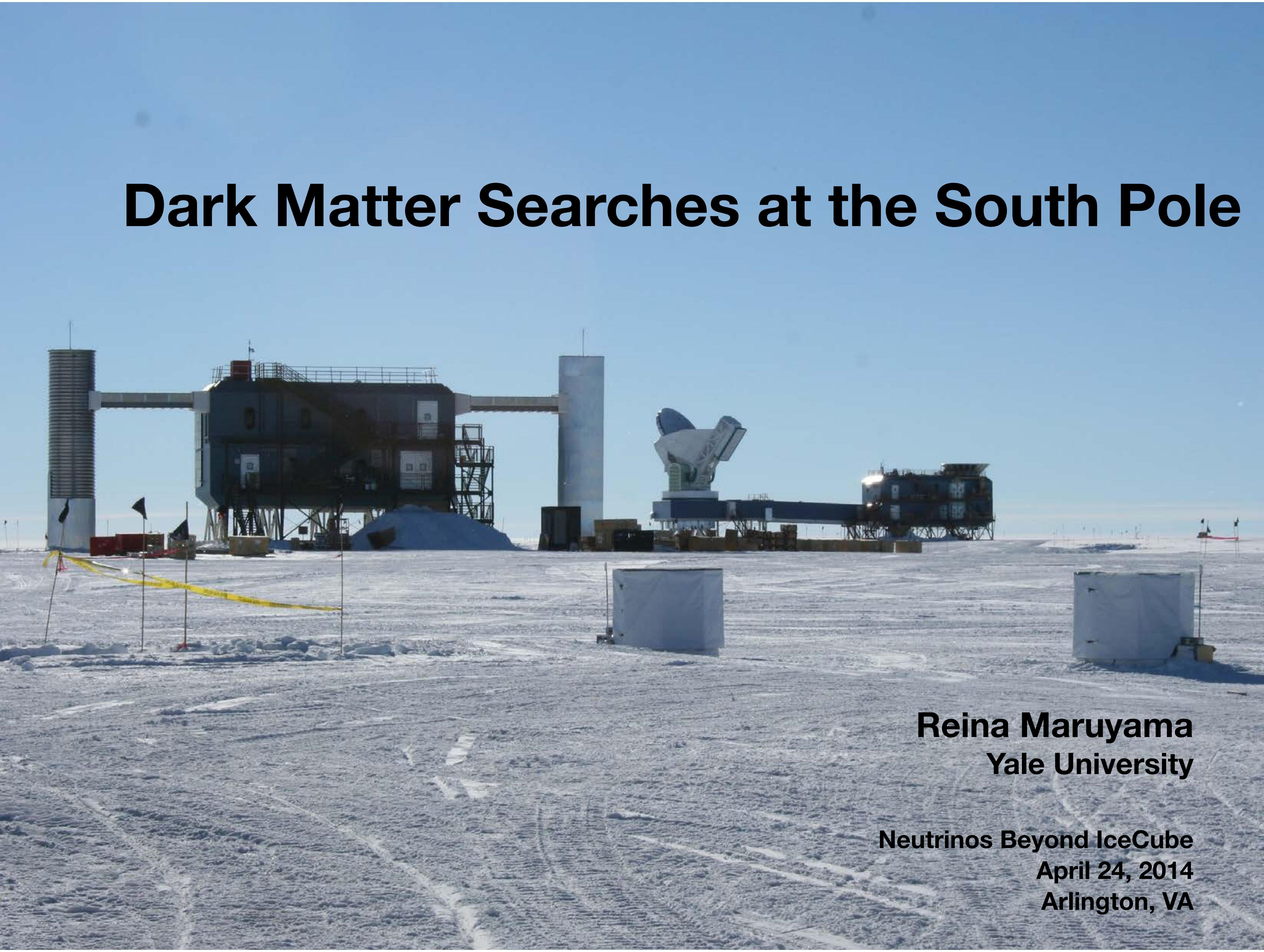


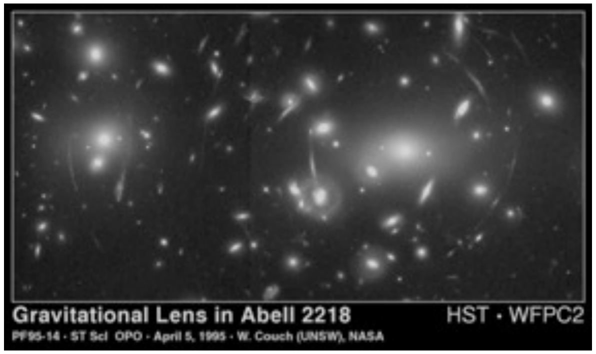
Dark Matter Searches at the South Pole

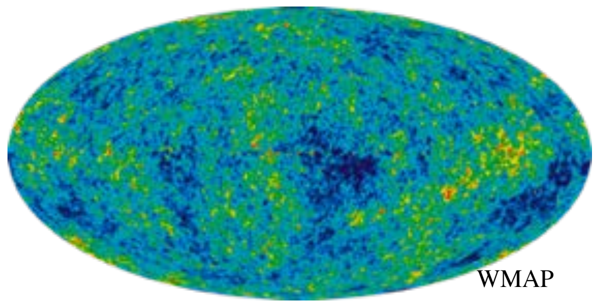
Reina Maruyama
Yale University

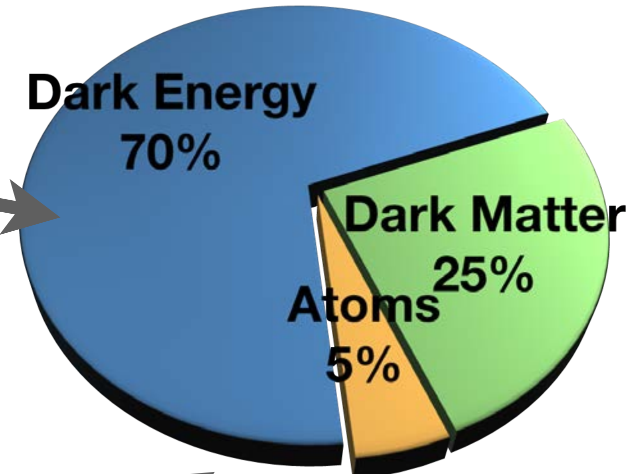
Neutrinos Beyond IceCube
April 24, 2014
Arlington, VA

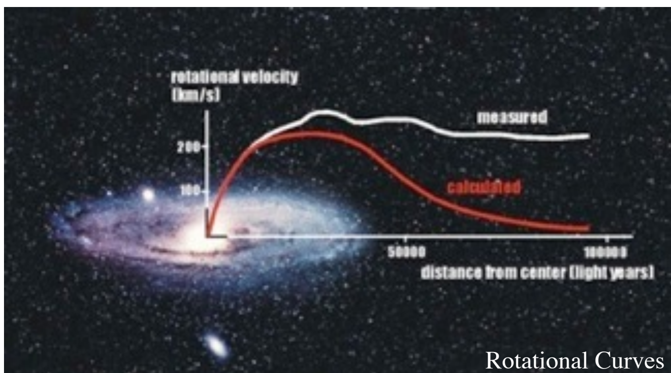
Evidence for Dark Matter

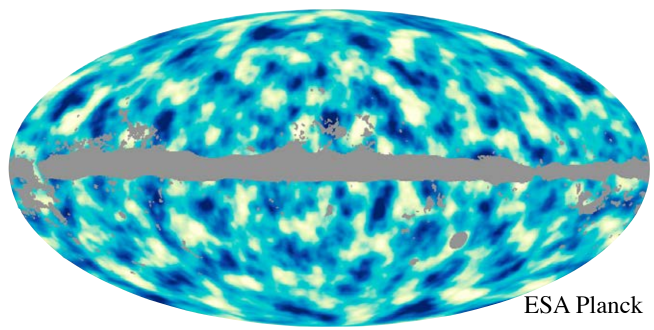
- Many gravitational evidence for dark matter

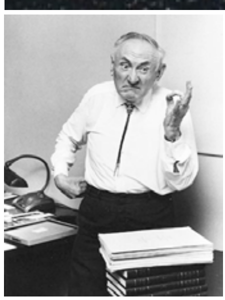


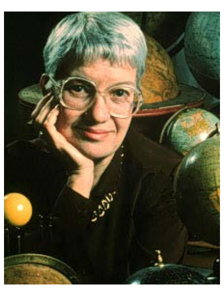


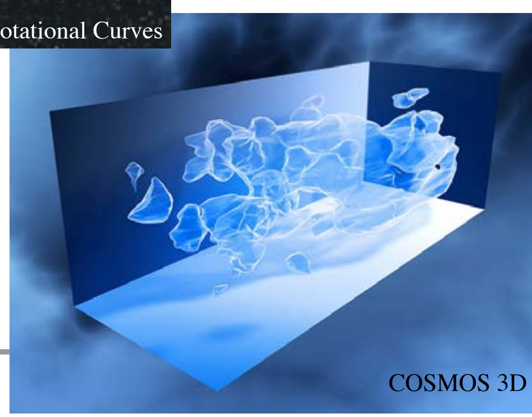












All consistent with ~25% dark matter.

But... what is it?

What is Dark Matter?

Leading Candidates:

Axions

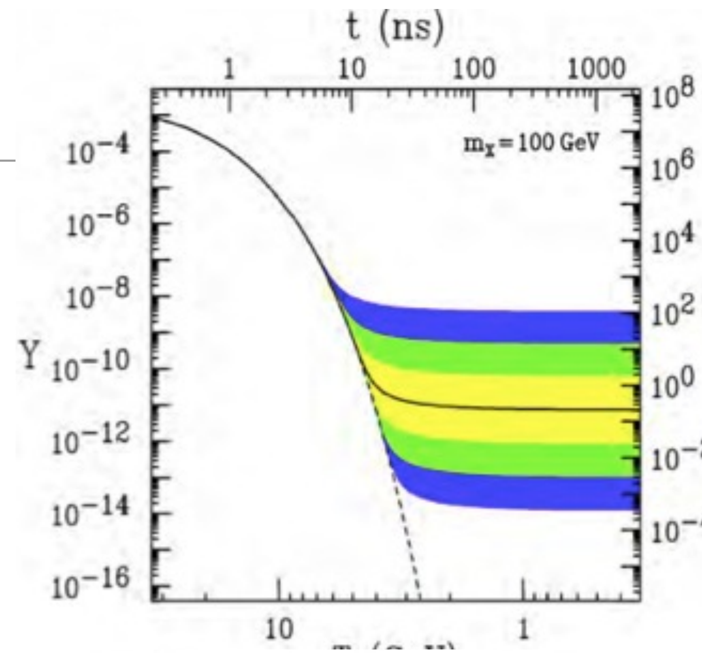
- mass ~$10^{-3} – 10^{-6}$ eV
- Arises in the Peccei-Quinn solution to the strong-CP problem

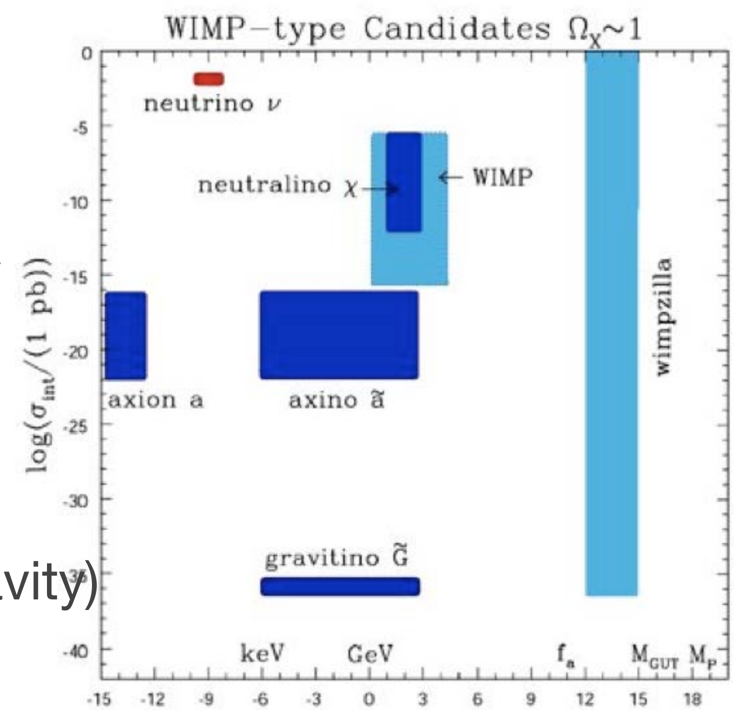
WIMPs: Weakly Interacting Massive Particles

- mass of 1 GeV – 10 TeV
- weak scale cross sections results in observed abundance

$$\sigma \approx 10^{-39} - 10^{-46}\ \mathrm{cm}^2$$

$$\langle \sigma_A v \rangle \approx 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \qquad m_\chi \approx 100\ \mathrm{GeV}$$



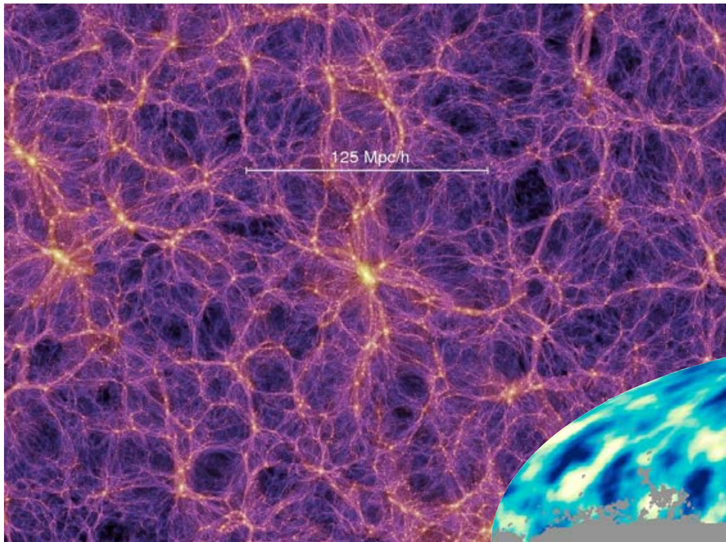


(Roszkowski 2004)

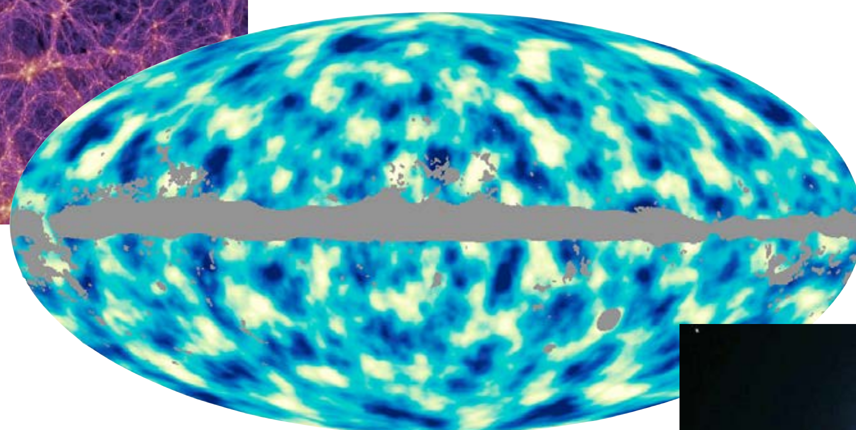
Observational evidence indicates:

- Non-baryonic
- Cold and massive (non-relativistic and exerts gravity)
- Interact little with ordinary matter
- Stable and long-lived

Dark Matter Distribution



Large scale dark matter distribution
Millenium Simulation
http://www.mpa-garching.mpg.de/galform/virgo/millennium/



Planck all-sky image of the distribution of dark matter via distortions on CMB by gravitational lensing (April 2013)

Artist's impression of the Milky Way galaxy. The blue halo of material surrounding the galaxy indicates the expected distribution of dark matter. (ESO/Calçada)

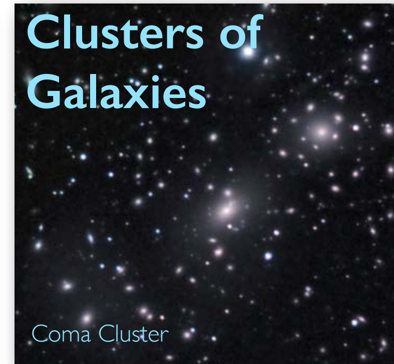
Regions Dense in Dark Matter

small halo model dependence, boost factors

Large DM content, nearby source, O(10) larger flux than extra-galactic

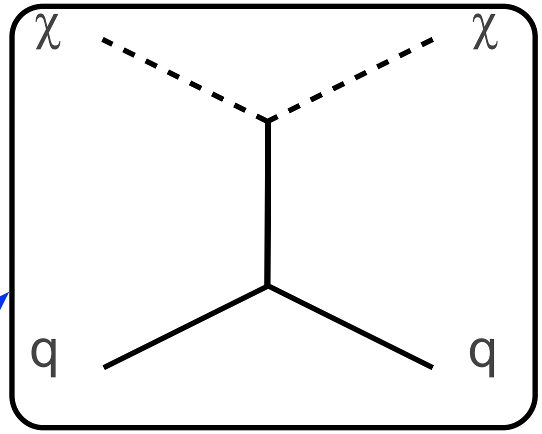
Very dense DM accumulation, nearby source

no astrophysical backgrounds



large DM content, high boost factors from sub structure

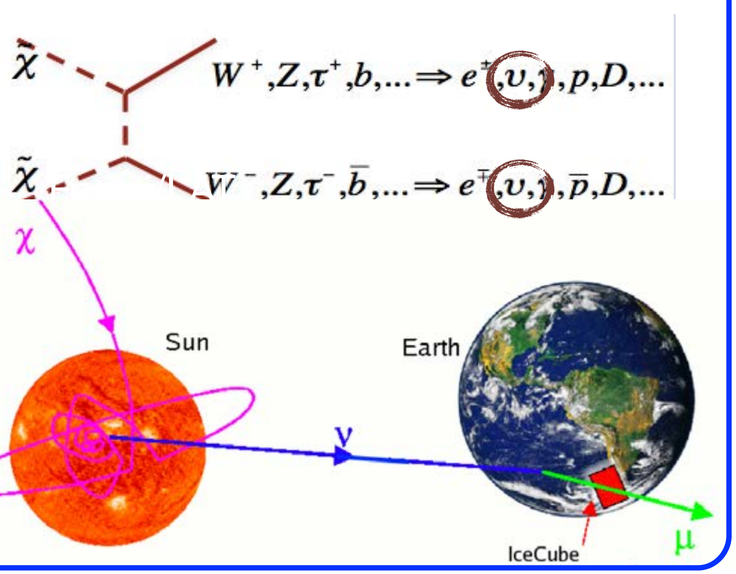
Detecting WIMPs



annihilation

"Indirect Detection"

Look for decay products from self-annihilation of dark matter collected in massive objects.

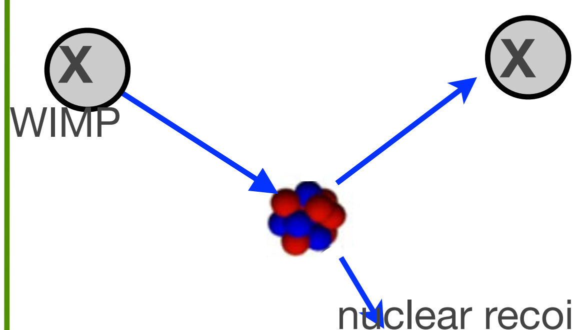


scattering

"Direct Detection"

Let dark matter recoil off of nuclei

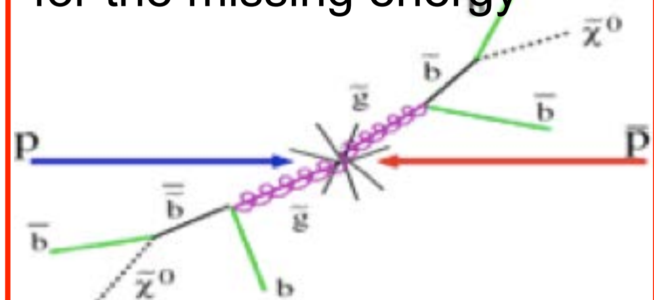
Look for nuclear recoil

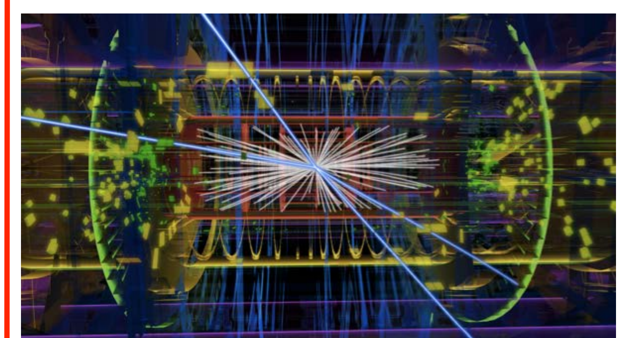


production

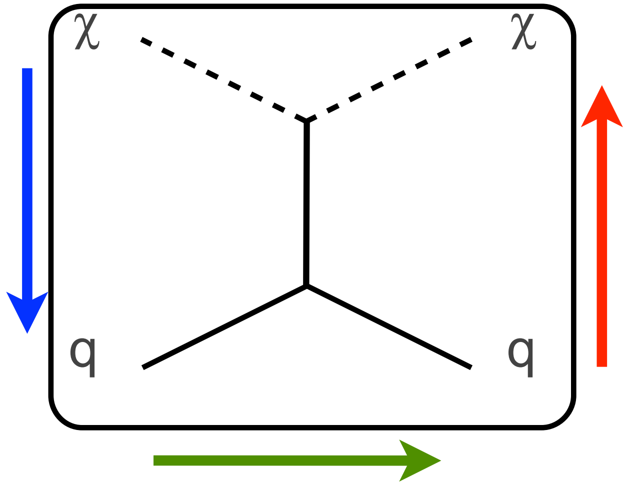
Colliders

Create dark matter. Look for the missing energy





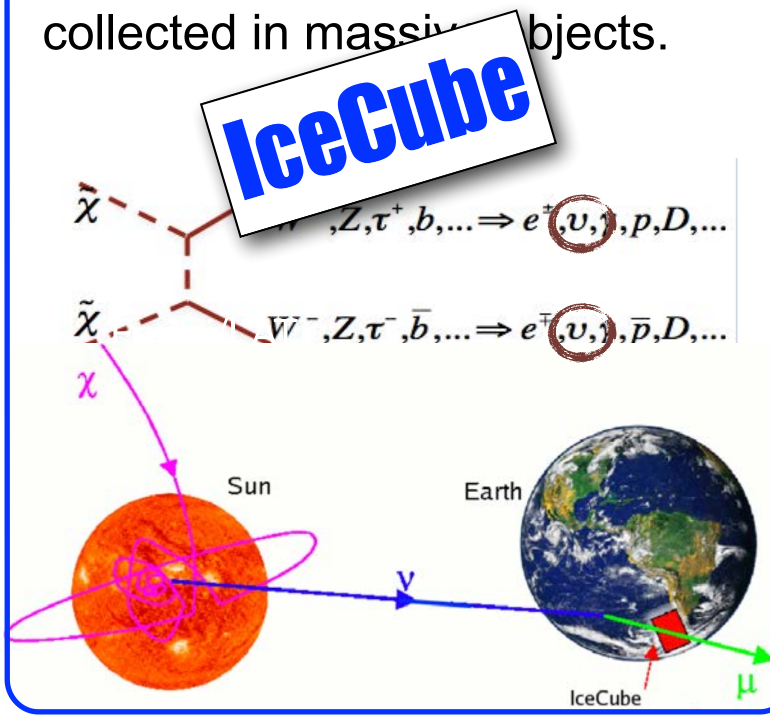
Detecting WIMPs



annihilation

“Indirect Detection”

Look for decay products from self-annihilation of dark matter collected in massi bjects.

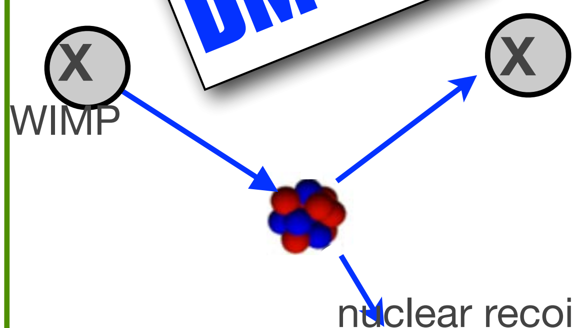


scattering

“Direct Detection”

Let dark matter recoil off of nuclei

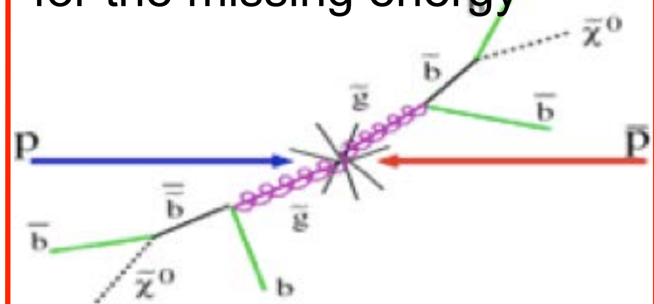
Look f oil

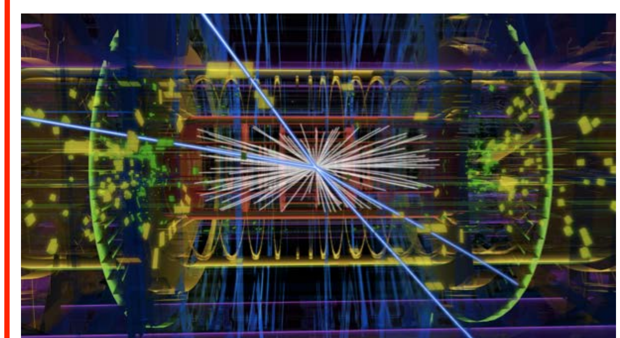


production

Colliders

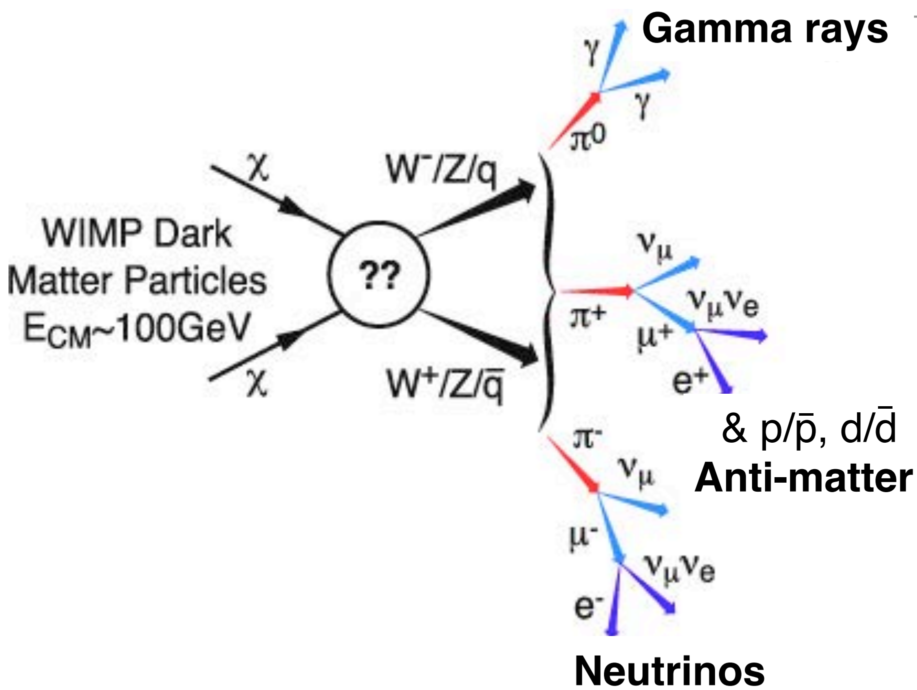
Create dark matter. Look for the missing energy

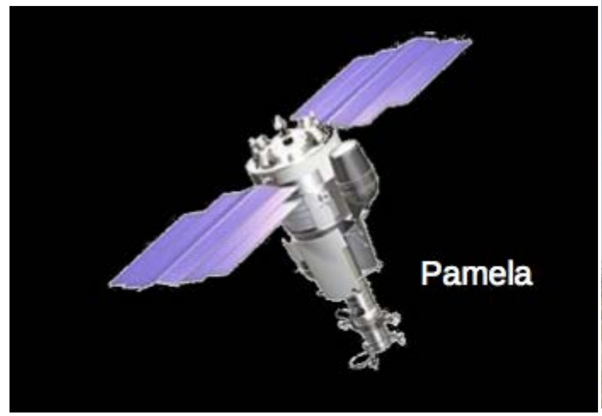




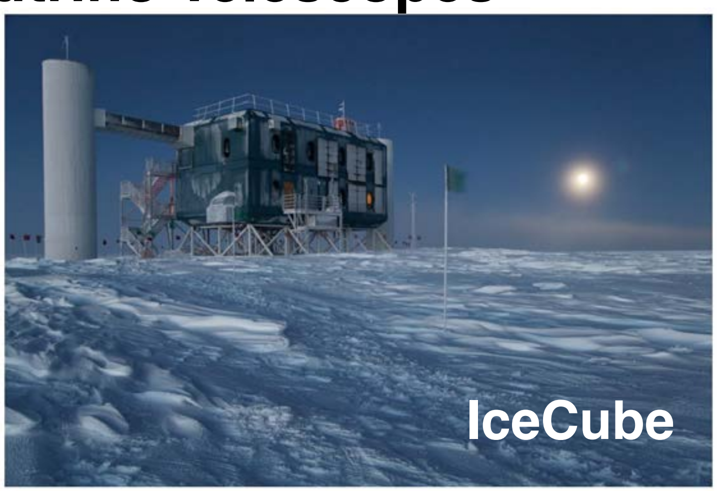
Current Detectors: Annihilation signals

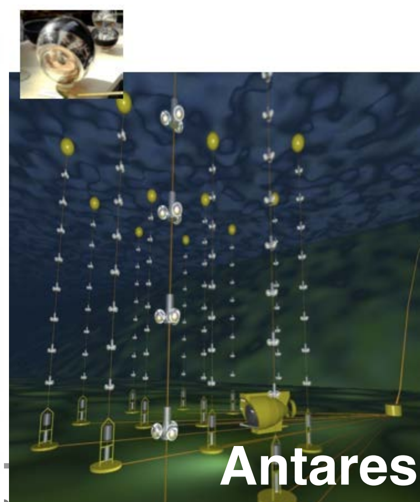
Cherenkov telescopes & satellites





Neutrino Telescopes



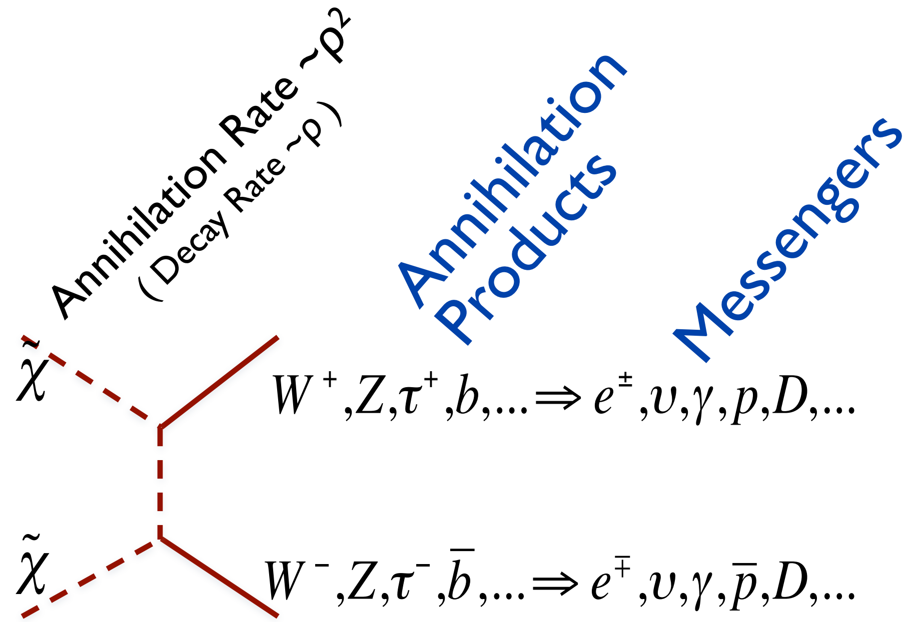


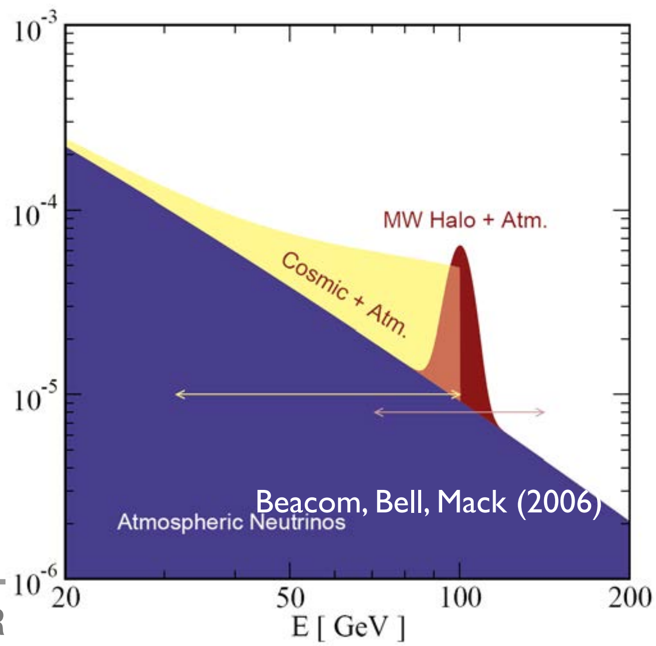
Annihilation Signals

- Identify dense regions of matter

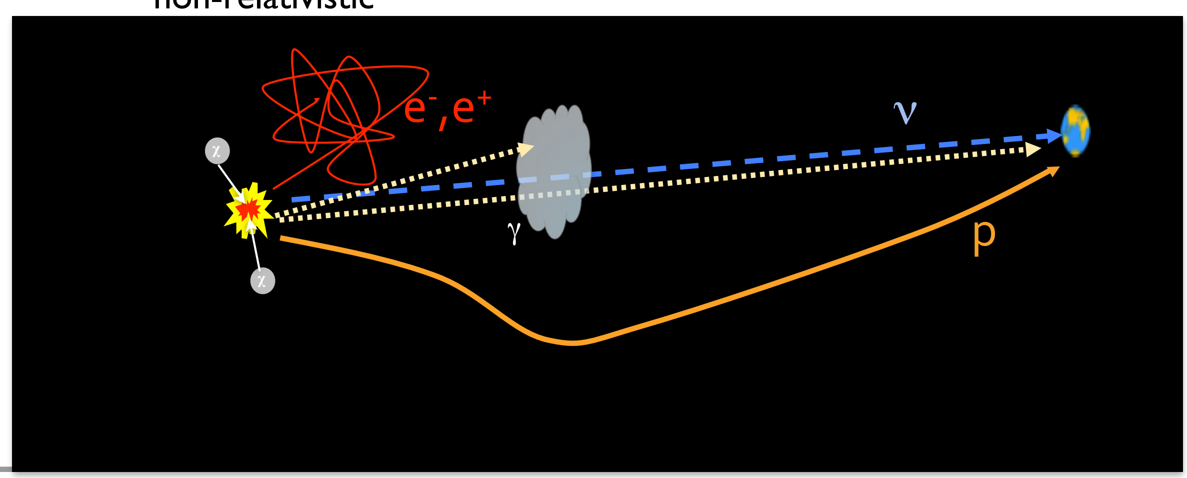
  ⇒ self-annihilation can occur at significant rates

- Pick prominent Dark Matter target
- Understand backgrounds
- Features in the signal can be used to better distinguish backgrounds
  - Line / End-point
- Neutrinos and gammas point straight back to the source





non-relativistic



Regions Dense in Dark Matter

small halo model dependence, boost factors

Diffuse flux, spectral feature

Large DM content, nearby source, O(10) larger flux than extra-galactic

Anisotropy

Very dense DM accumulation, nearby source

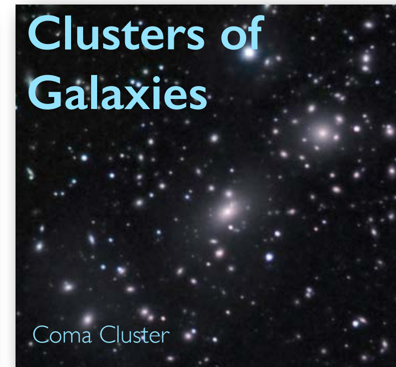
Extended Source

very strong dependence on DM density profile

no astrophysical backgrounds

Point source

cored profiles favored, less flux



large DM content, high boost factors from sub structure

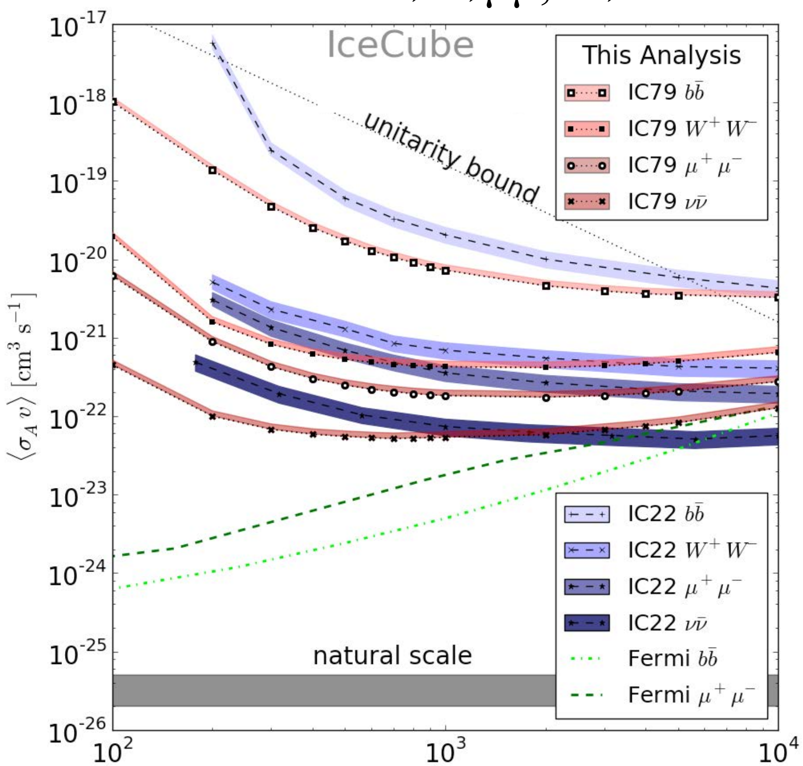
Extended source

understanding of boost factors

slide by C. Rott

Galactic Halo

- Galactic Center (GC) is on the southern hemisphere for IceCube
  - large backgrounds from down-going muons
- For the northern hemisphere IceCube searches for anisotropy using the high-purity up-going neutrino sample
- Assume annihilation into νν, bb, μμ, ττ, WW



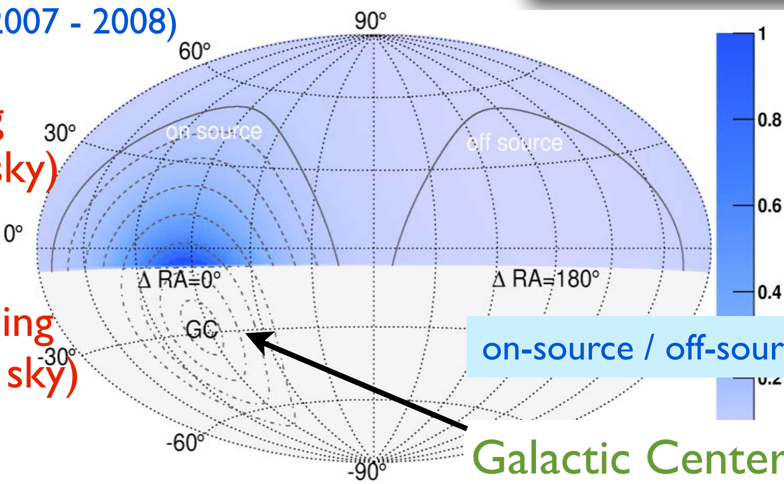
R. Abbasi et al., Phys. Rev. D 84 (2011) 022004.
M. Ackermann et al., Astrophys. J. 761 (2012) 91.

22-strings Halo Analysis

276 days (2007 - 2008)

up-going (northern sky)

down-going (southern sky)



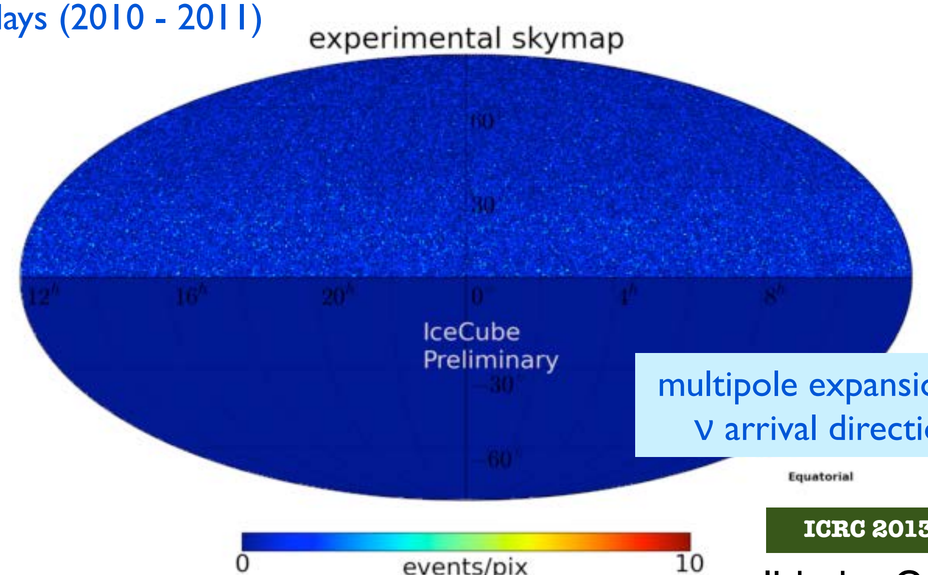
on-source / off-source

Galactic Center

Phys.Rev.D84:022004,2011

79-strings multipole analysis

316 days (2010 - 2011)



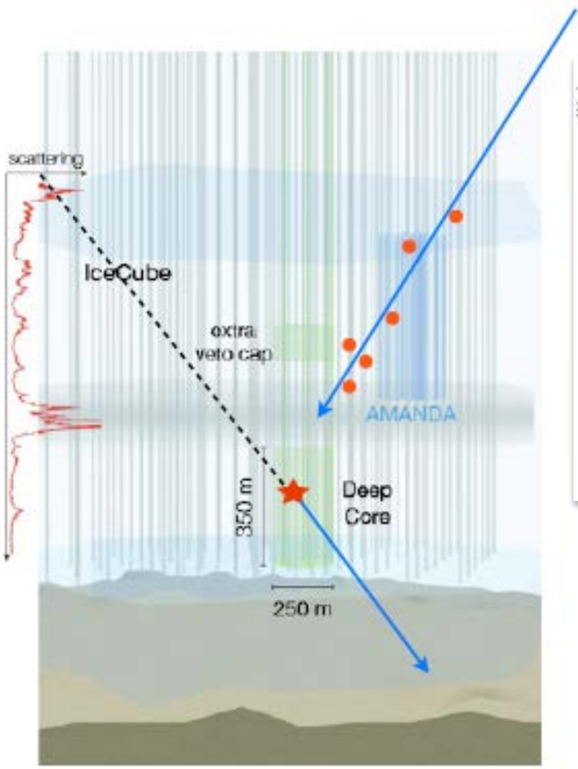
multipole expansion of ν arrival direction

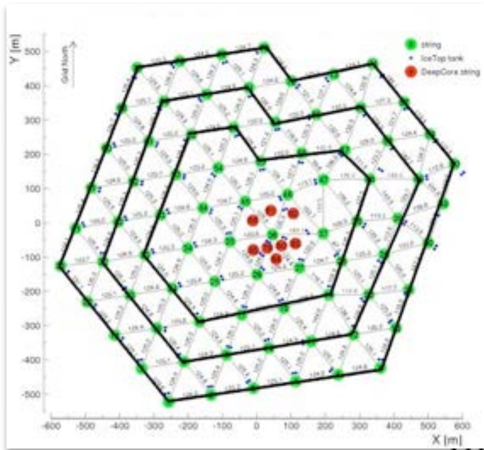
ICRC 2013

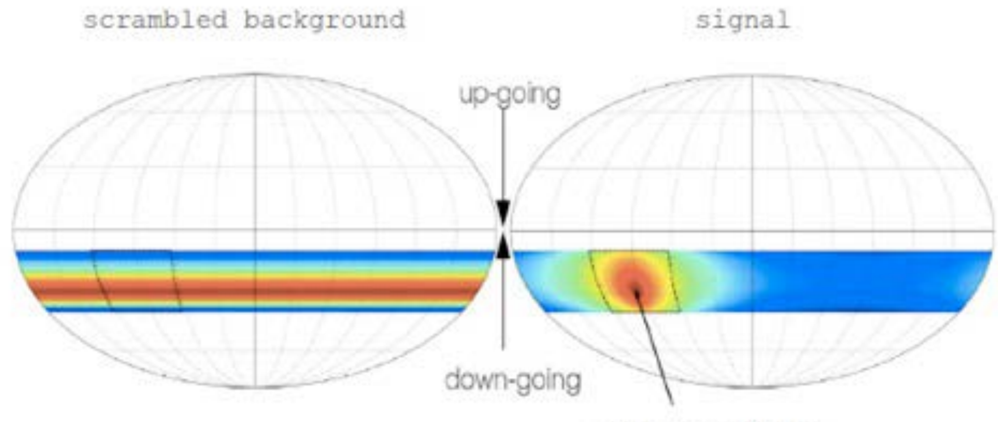
slide by C. Rott

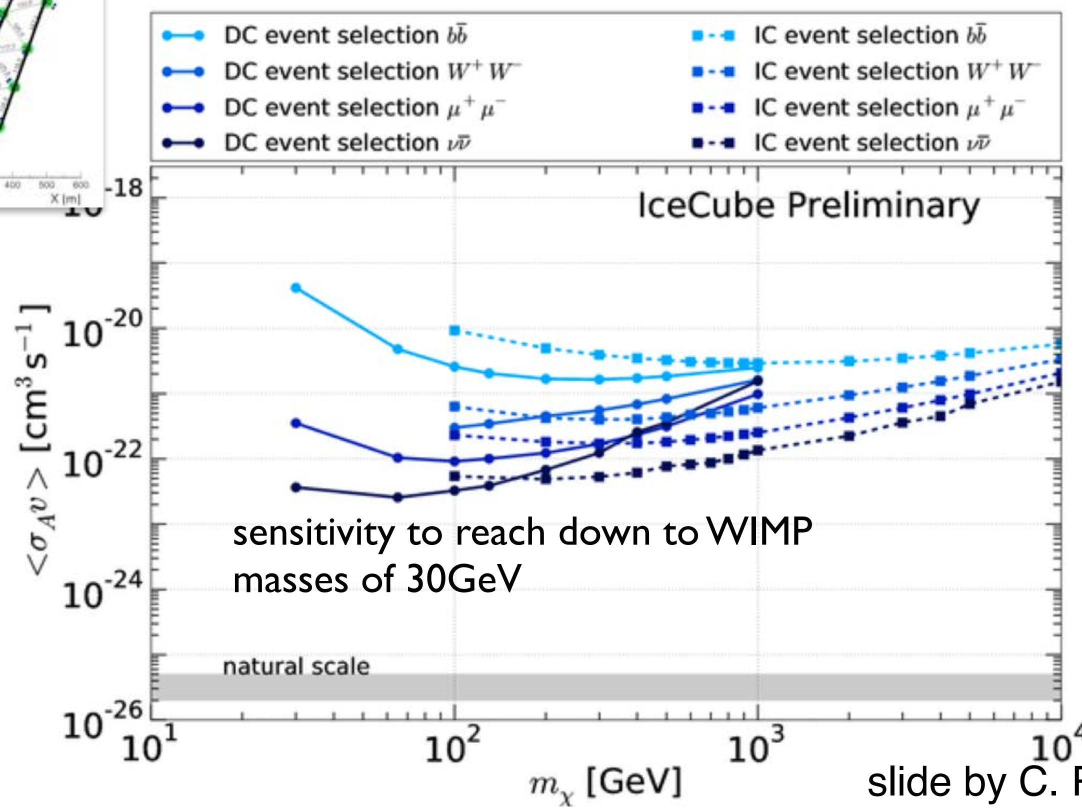
Galactic Center

Use IceCube external strings as a veto:
- 3 complete layers around DeepCore (~ 375m)
- Full sky sensitivity: access to southern hemisphere





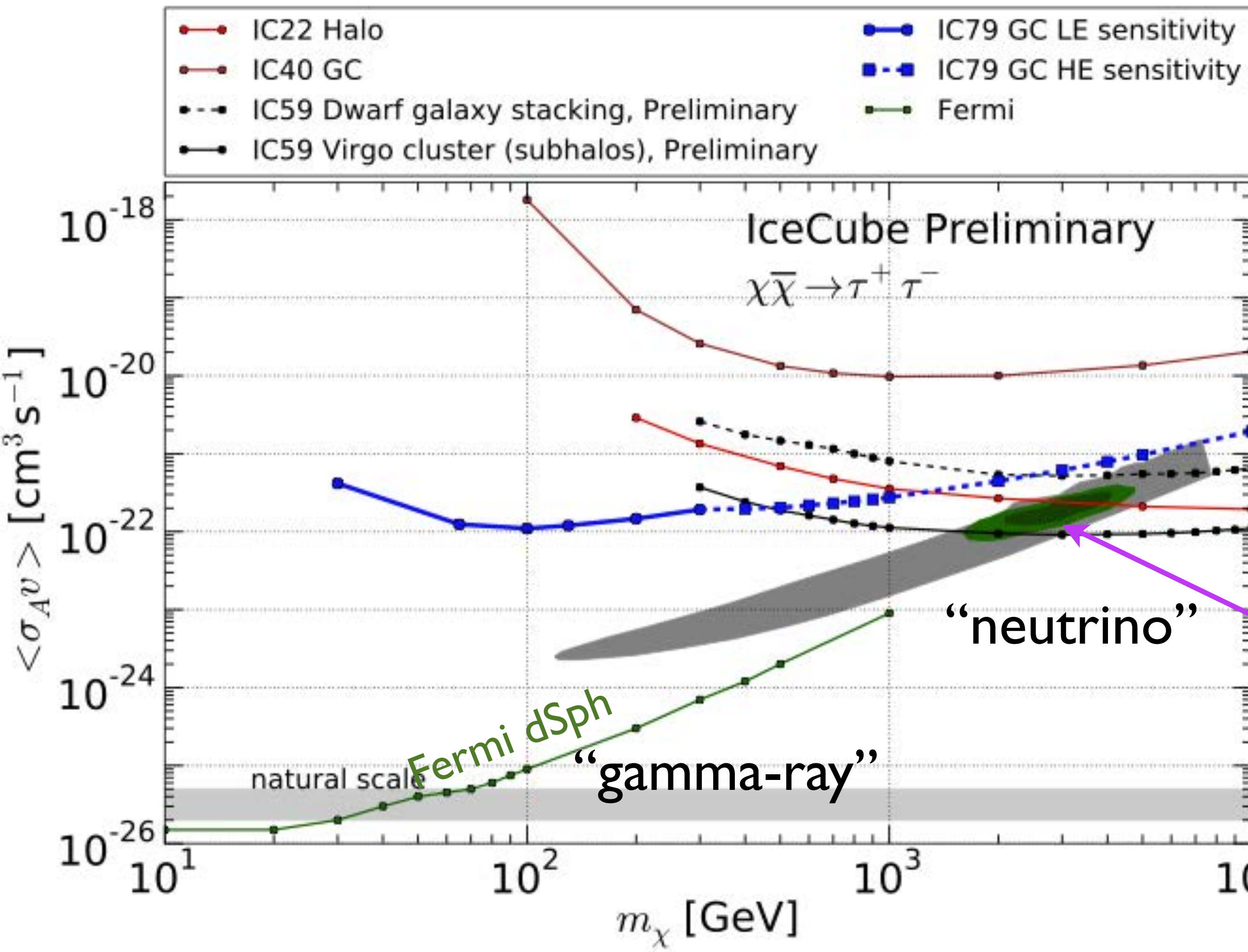


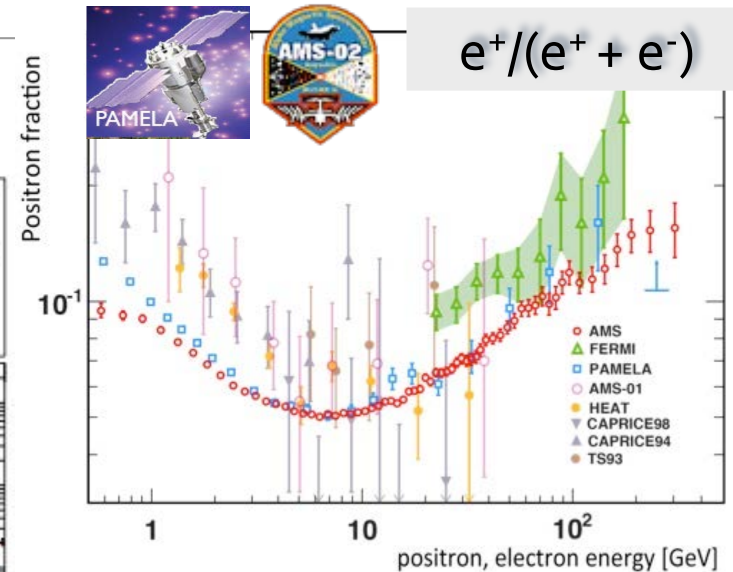


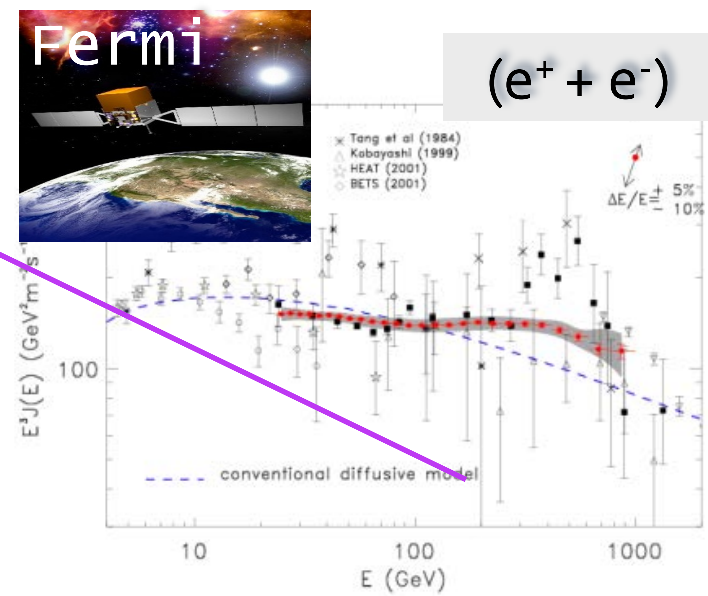
Separate Low energy and High energy optimizations:
GC is above the horizon
→ Fiducial volume in central strings
→ refined muon veto from surrounding layers
Use scrambled data for background estimation

slide by C. Rott

Testing Pamela’s Positron Excess



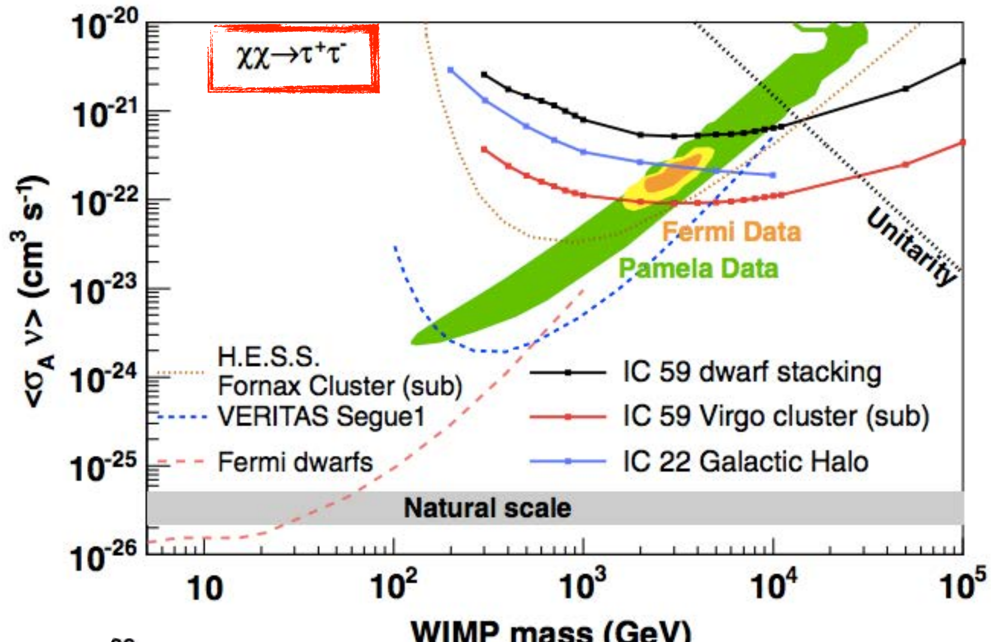


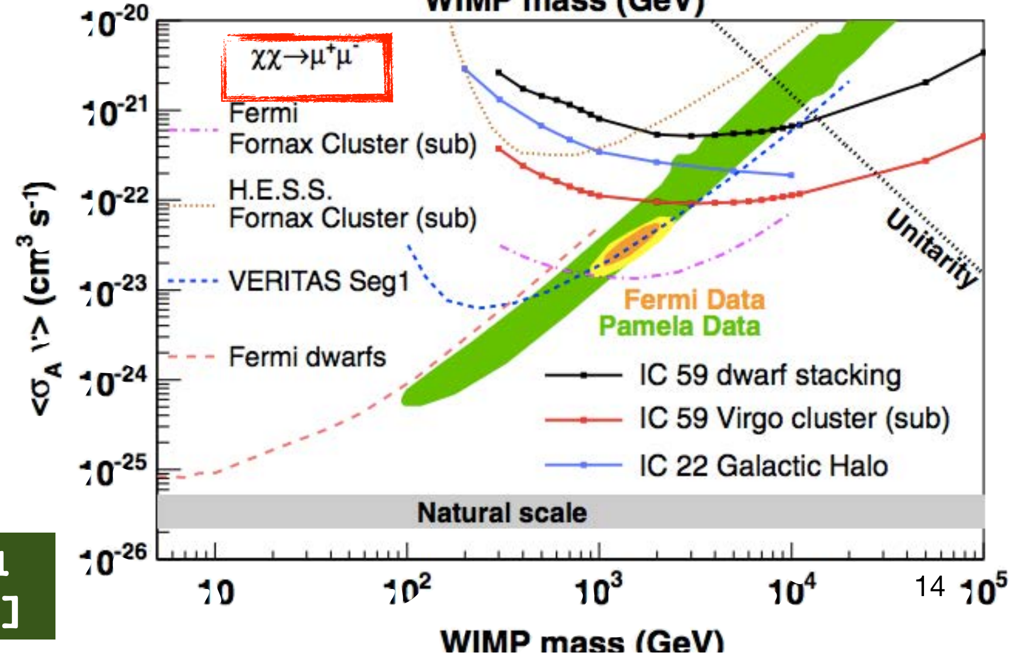


IceCube can probe models motivated by the observed lepton anomalies

Dwarf Spheroidal Galaxies

- Dwarf spheriodal galaxies, clusters of galaxies, and large galaxies represent well defined sources of Dark Matter
- Dark Matter distribution critical for optimization, assume conservative density profile
- IceCube measurements are complementary to Pamela, Fermi, & HESS





340days of IceCube 59 string data

Event selection via Boosted Decision Tree

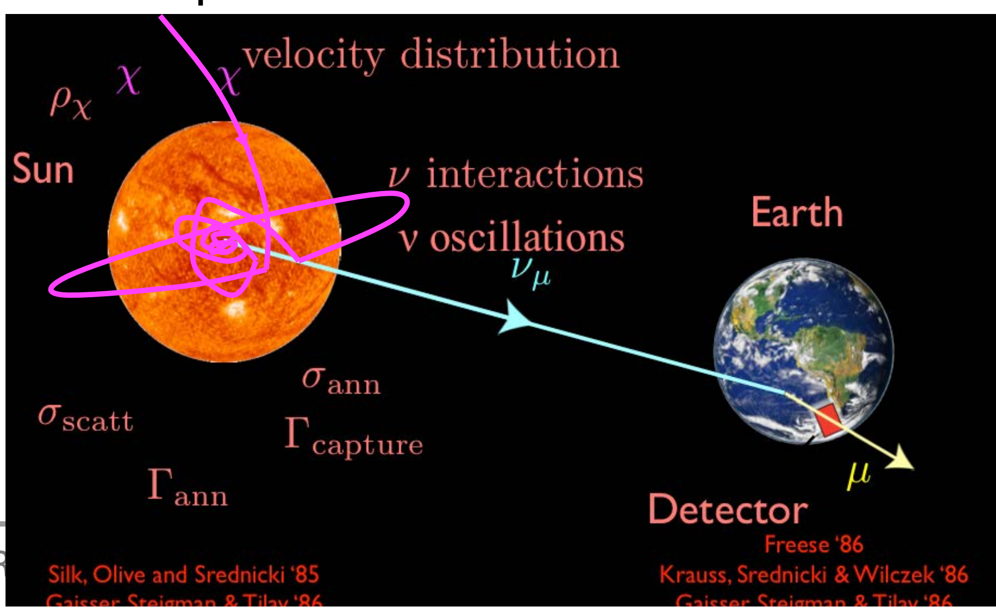
For robustness the search windows and cut values were **optimized for 5 TeV WIMPs** and used for all WIMP-masses.

Phys.Rev. D88 (2013) 122001
arXiv:1111.2738 [astro-ph.HE]

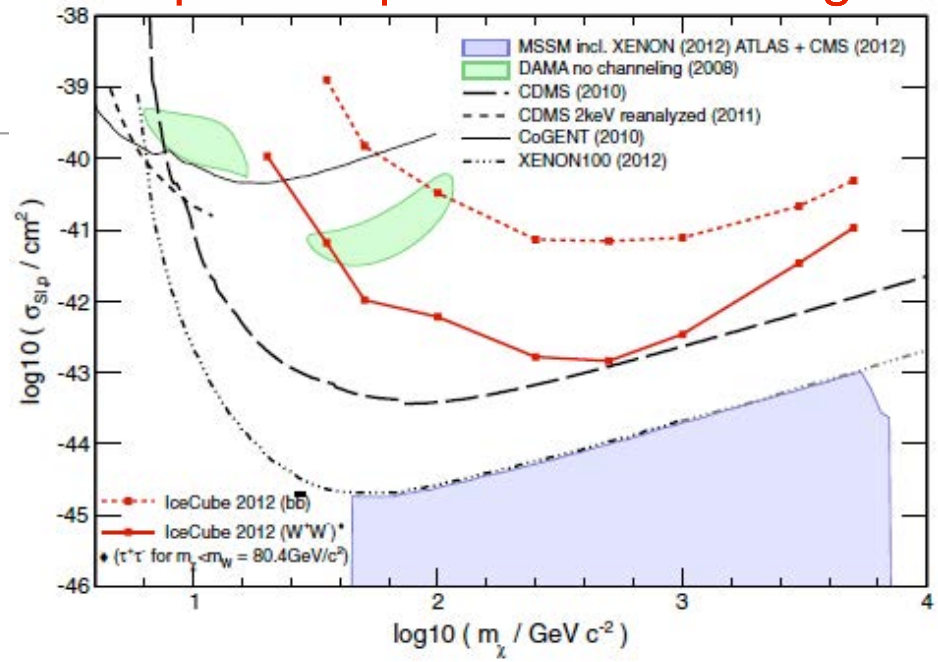
PRL 110, 131302 (2013)

Solar WIMP Searches

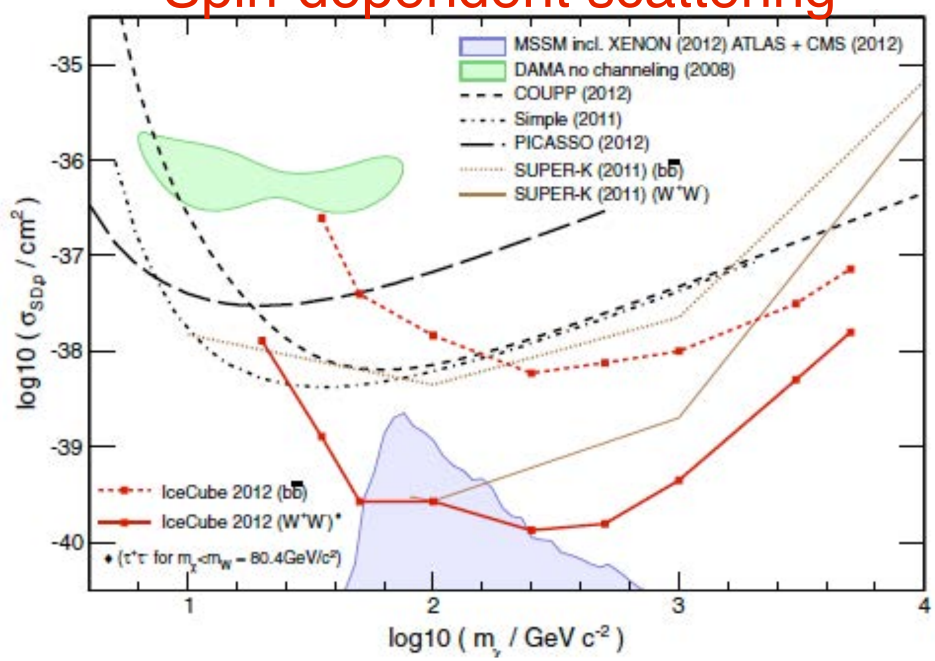
- Neutrino detectors are competitive for spin-independent scattering
- IceCube competitive for higher mass WIMPS
- IceCube extension will increase the reach both low and high energy
- Solar WIMP searches mostly sensitive to WIMP-proton cross section



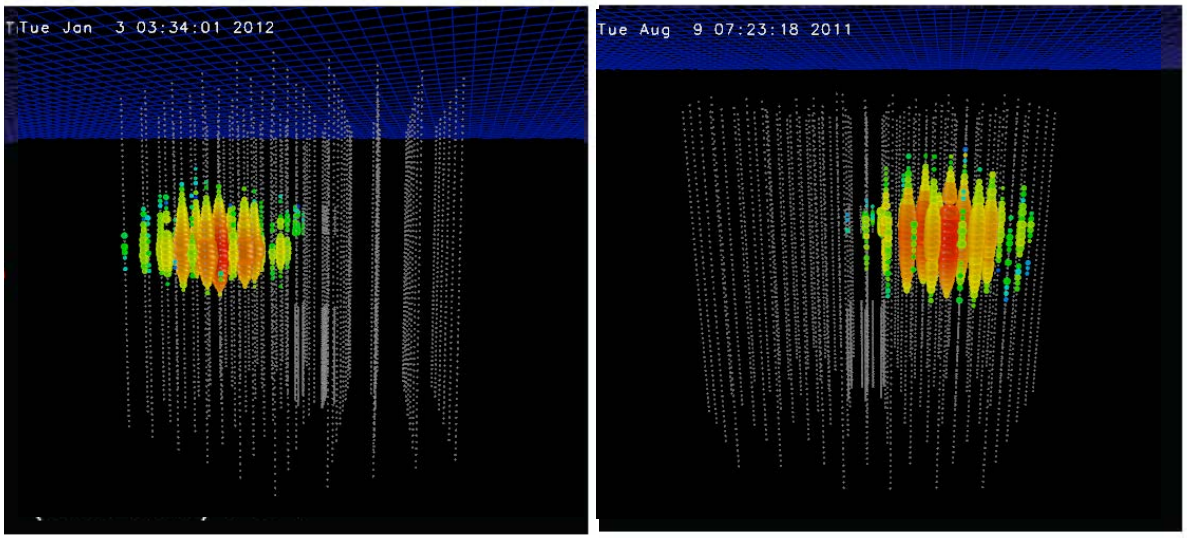
Spin-independent scattering



Spin-dependent scattering

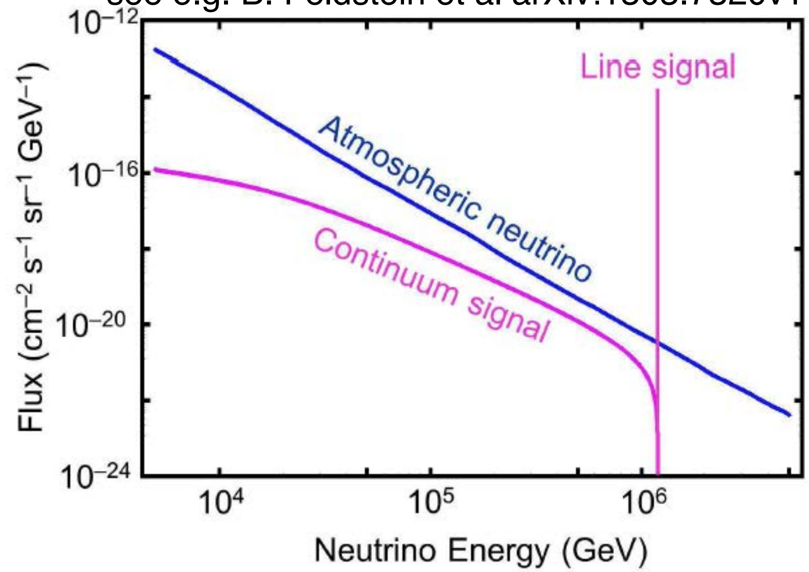


Origin of the PeV Events?



IceCube, Phys.Rev.Lett. 111 (2013) 021103) arXiv:1304.5356

see e.g. B. Feldstein et al arXiv:1303.7320v1



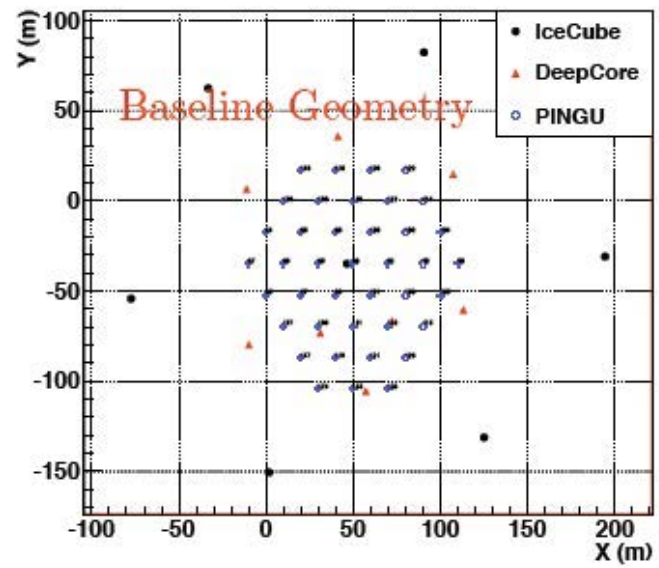
- What do the two IceCube events tell us ? and the additional 26 events ?

GZK neutrinos	a few events at ~ 100 TeV - 1 PeV implies many more events at higher energies	***Impossible***
Conventional atm. neutrinos	Very low flux predictions. Flavor ratio favors strongly favors muon neutrinos	***Implausible***
Prompt	Coincidence in down-going events. Possible only if proton composition; upward statistical fluctuation needed	***Unlikely***
Astrophysical	Most natural. Events are isotropic. Cannot be continuum spectrum. power law with break at ~ 2 PeV ?	***Plausible***
Dark Matter	2 events overlap in energy	**Intriguing**

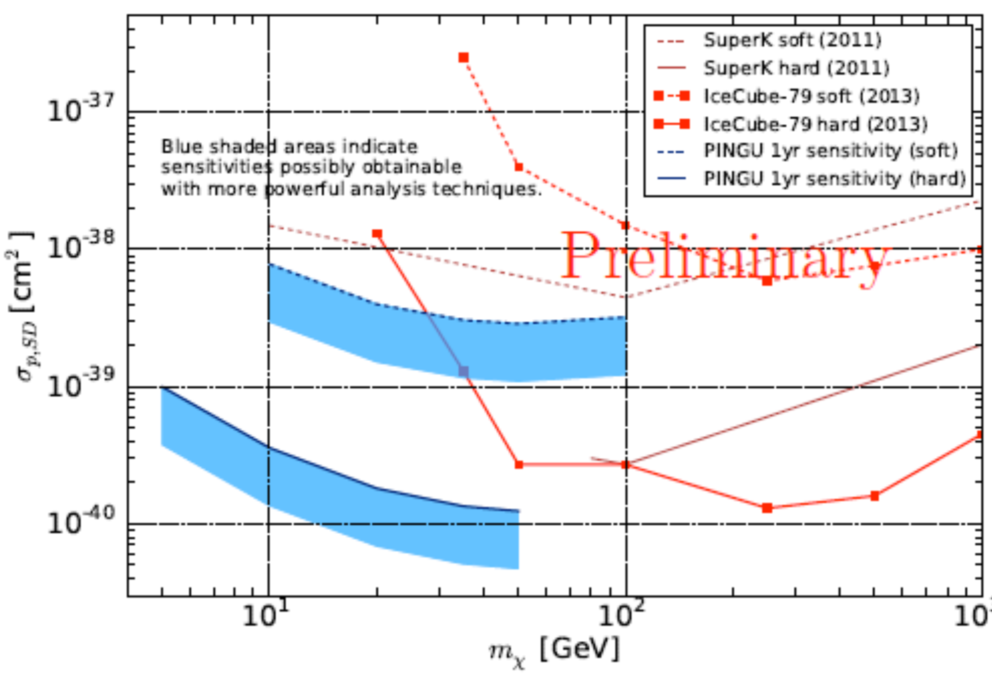
Many papers based on the 2 IceCube Events: e.g. R.Laha et al. Phys. Rev. D 88, 043009

Looking Forward: PINGU

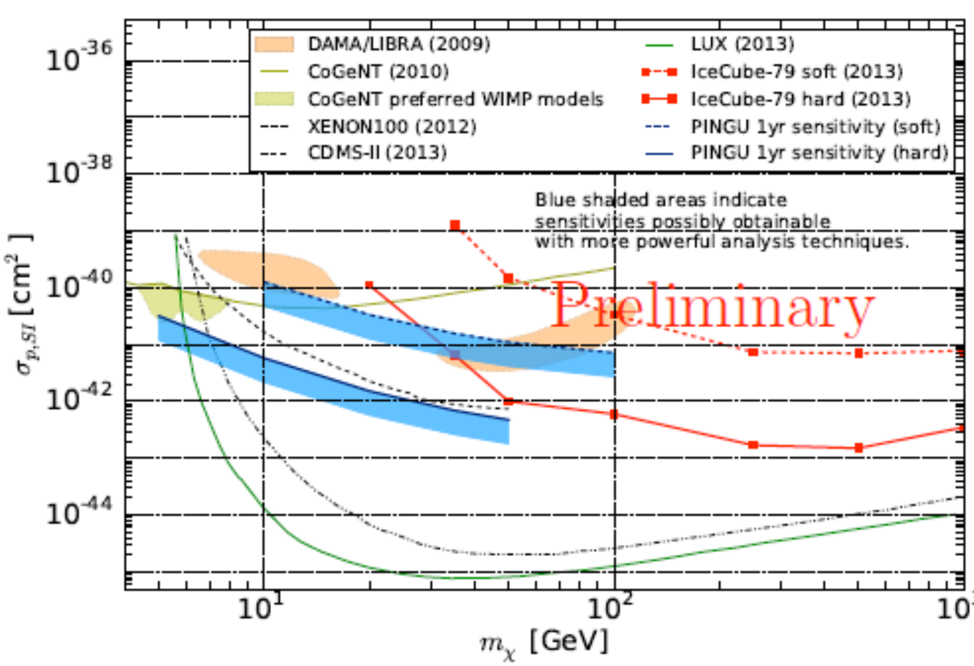
- High density instrumentation:
  - baseline geometry: 40 strings x 60 DOMs
  - Threshold ~ 1GeV
- Test low mass WIMP region -- capable to comfortably test DAMA/Libra



Spin-dependent scattering



Spin-independent scattering

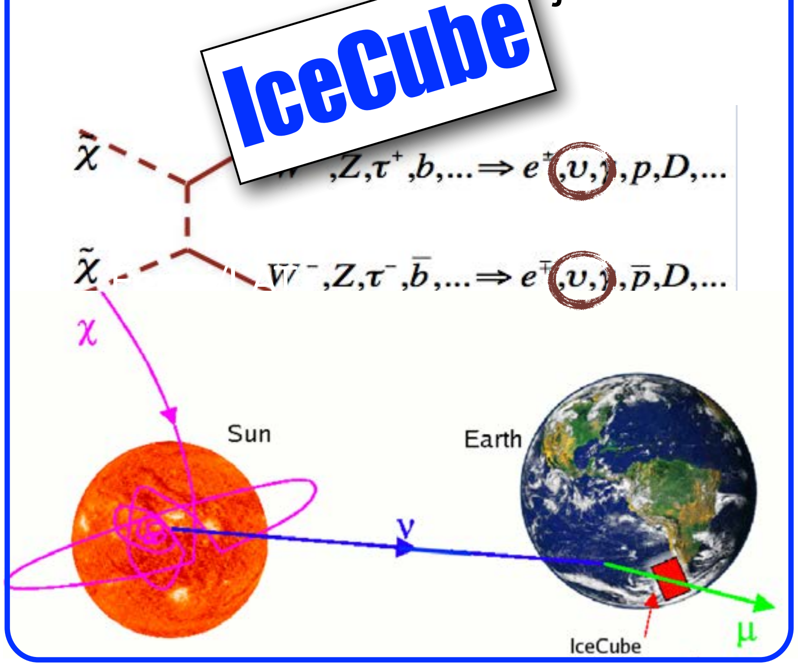


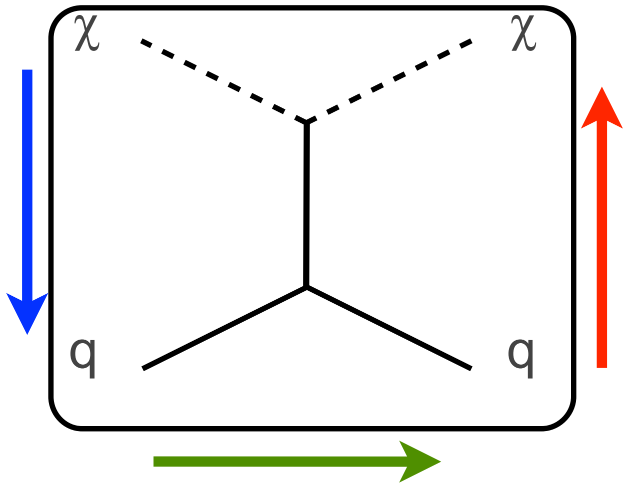
Detecting WIMPs

annihilation

“Indirect Detection”

Look for decay products from self-annihilation of dark matter collected in massiv[illegible]bjects.

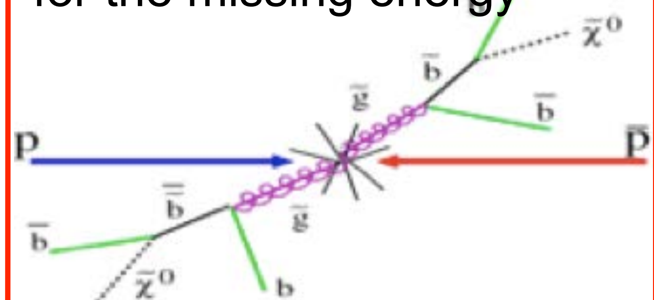


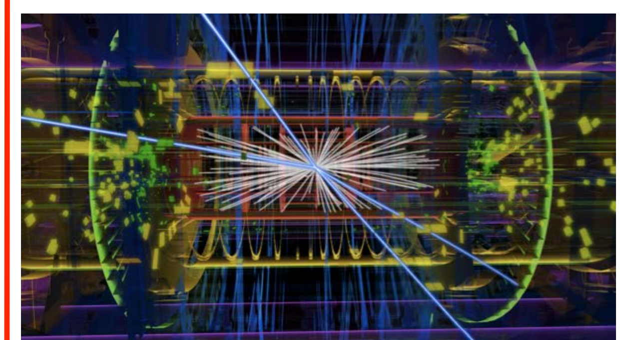


production

Colliders

Create dark matter. Look for the missing energy



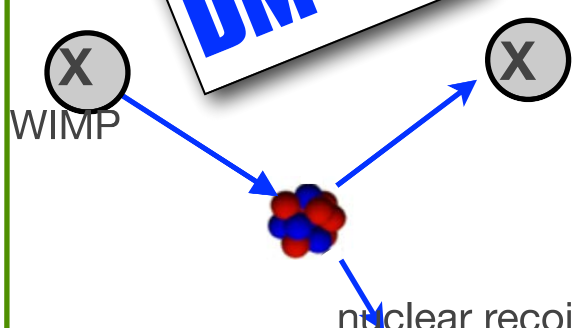


scattering

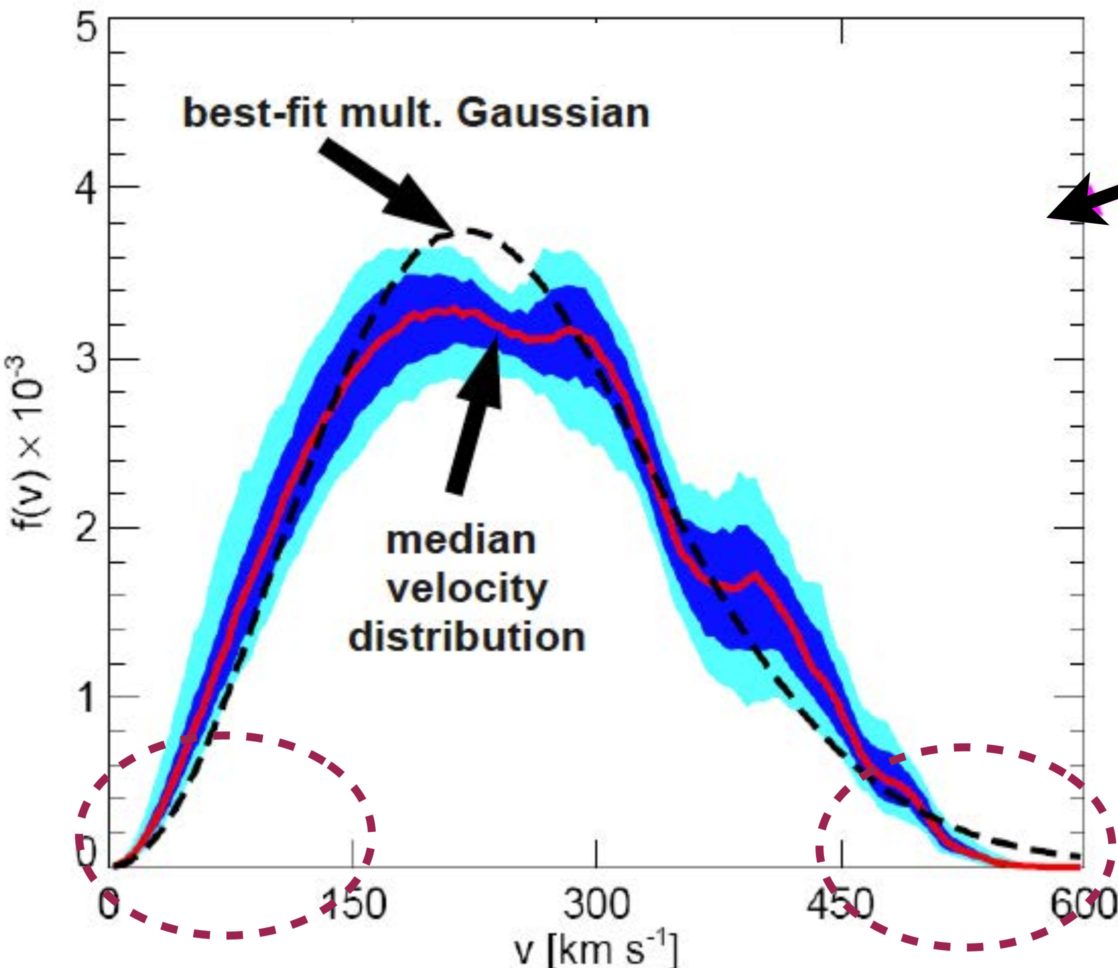
“Direct Detection”

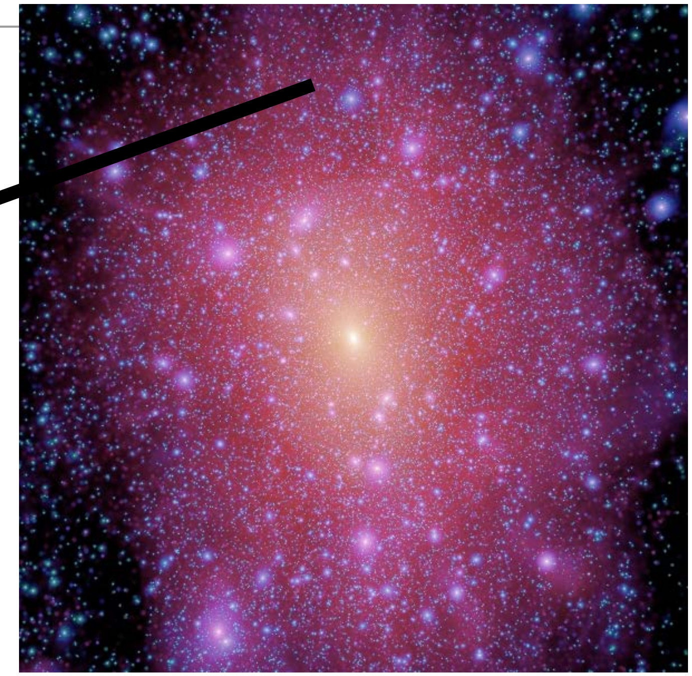
Let dark matter recoil off of nuclei

Look f[illegible]oil



Local Dark Matter Density / Velocity





small recoils
"easiest" to be captured in the Sun/Earth - indirect searches

large recoils
"best sensitivity" with direct detection

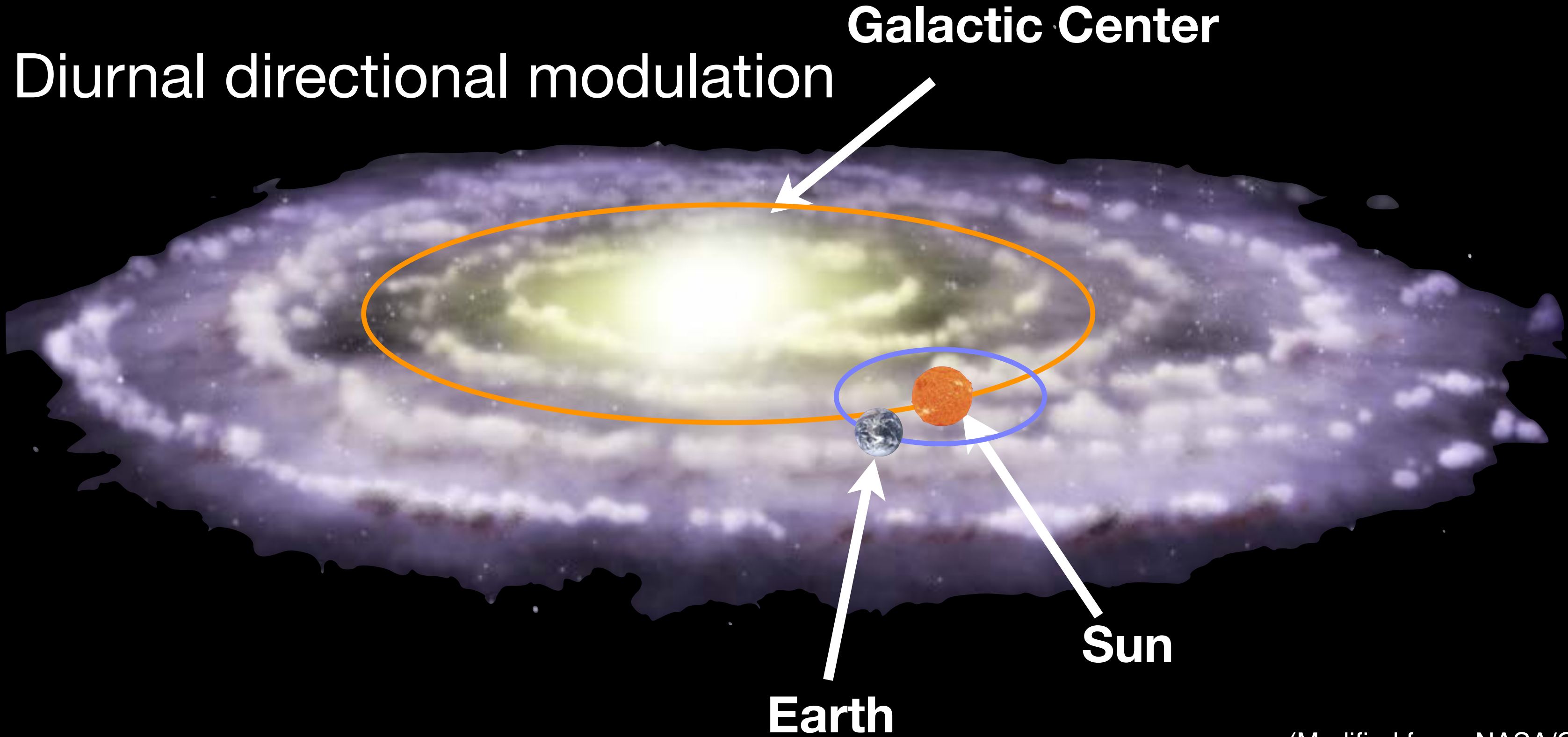
Maxwellian is reasonable

Velocity distribution still not very well understood

Local dark matter density ~0.3GeV/cm^3

Direct Detection Search Strategies

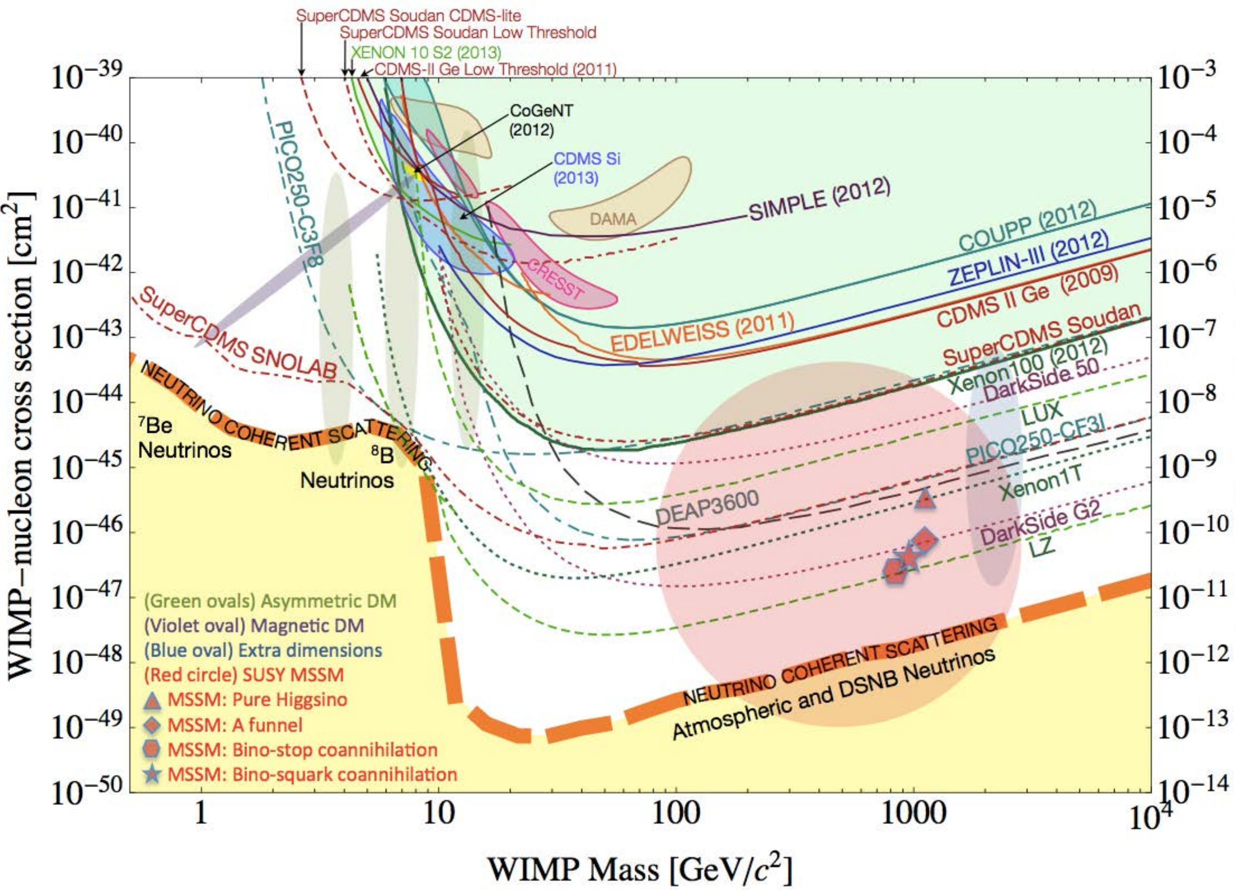
1. Count individual nuclear recoils
2. Look for annual modulation
3. Diurnal directional modulation



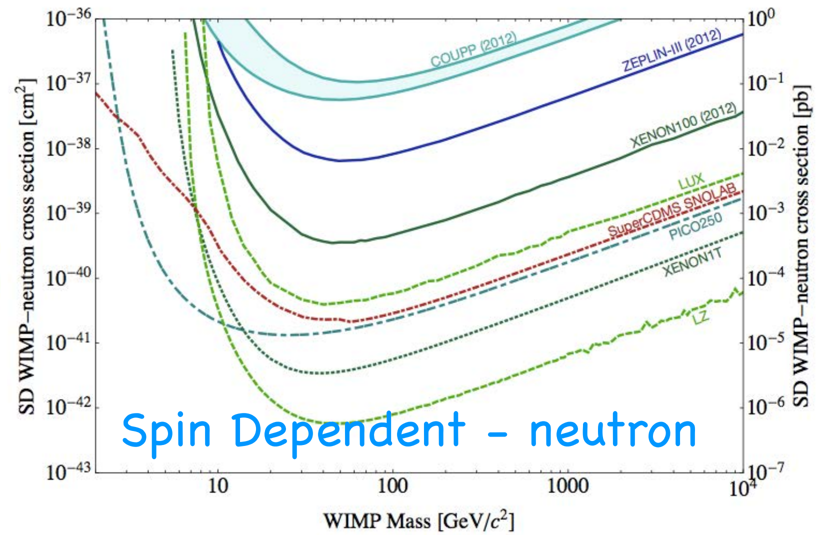
(Modified from: NASA/CXC/M.Weiss)

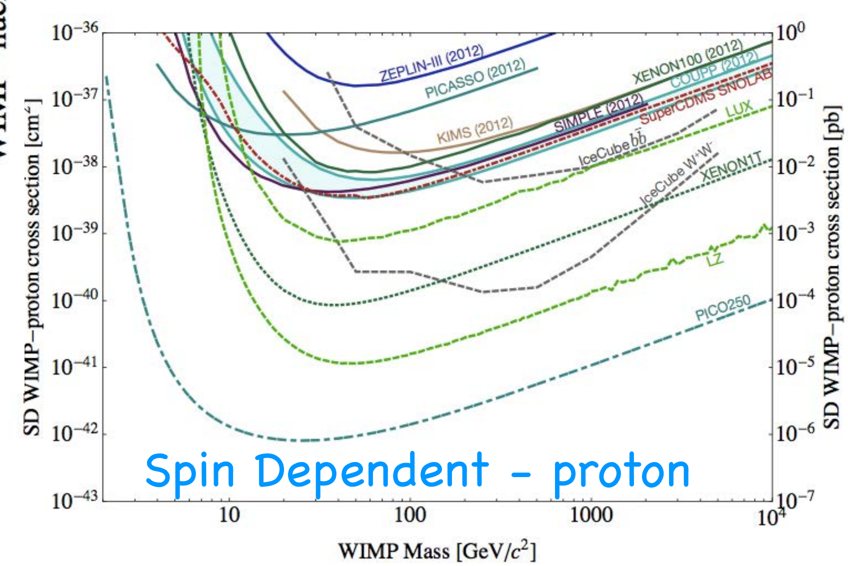
Direct Detection Experiments

Direct Detection, Current and Future



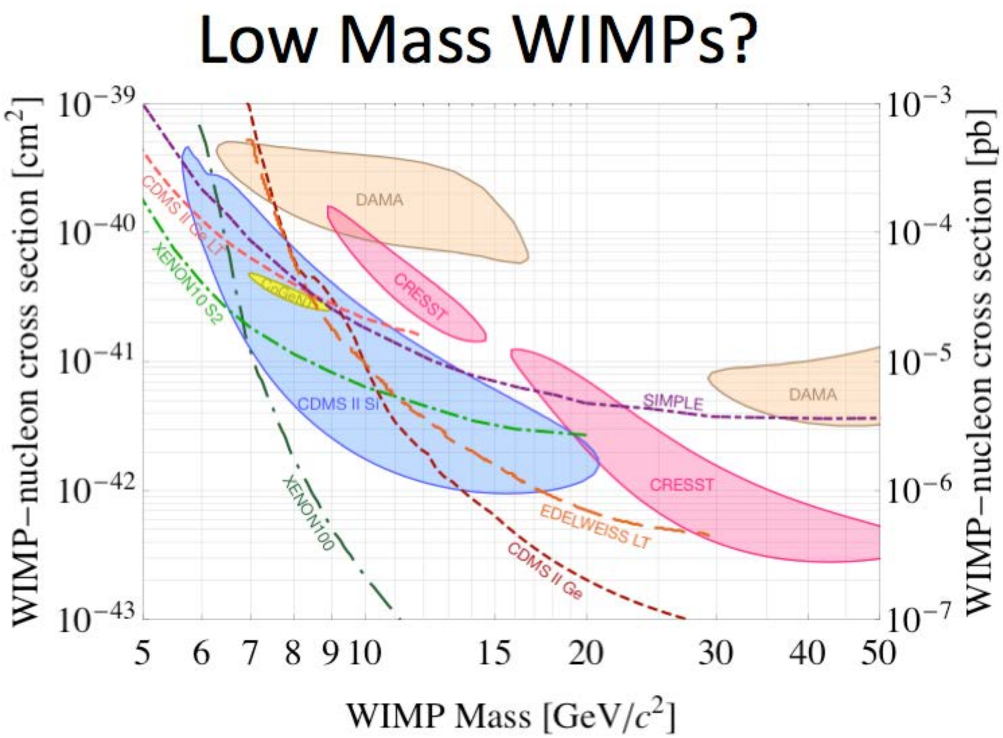
Spin Independent WIMP-nucleon cross section



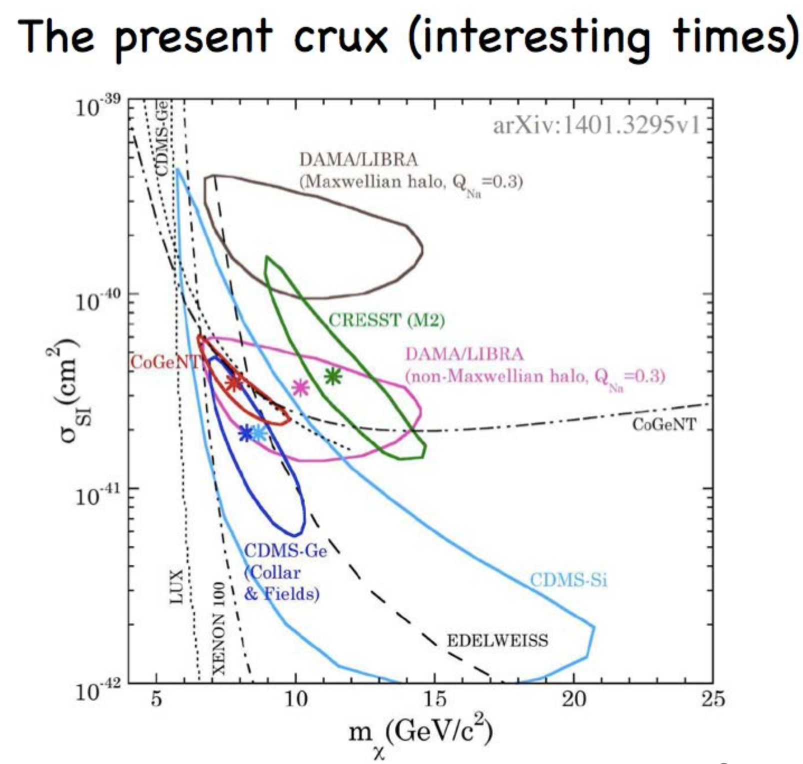


SNOWMASS 2013: arXiv:1310.8327

Hints and Claims for Direct Detection of DM



SNOWMASS 2013: arXiv:1310.8327



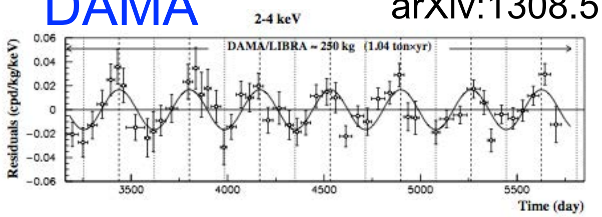
Juan Collar,
arXiv:1401.3295

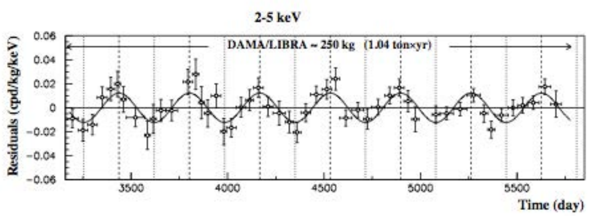
Challenges: Astrophysics, Particle Physics, & Instrumental Effects

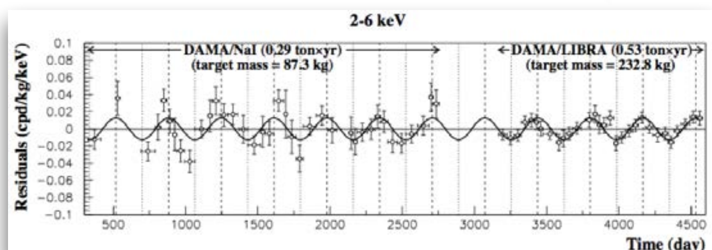
Dark Matter Signal or Background?

DAMA

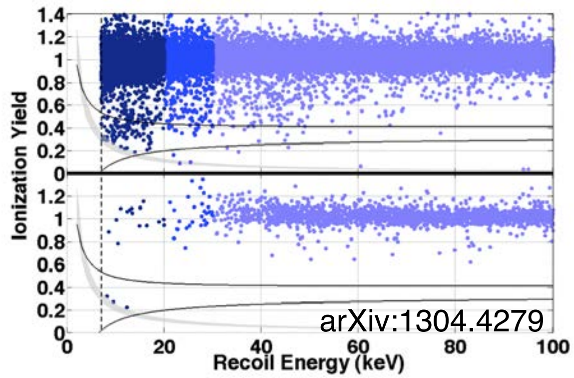
arXiv:1308.5109



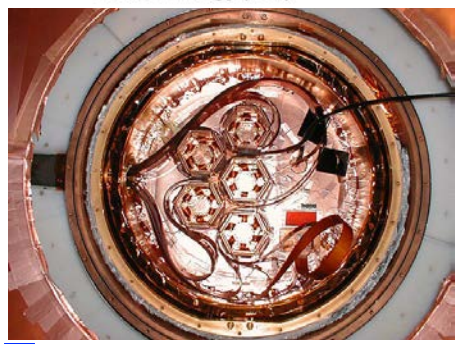




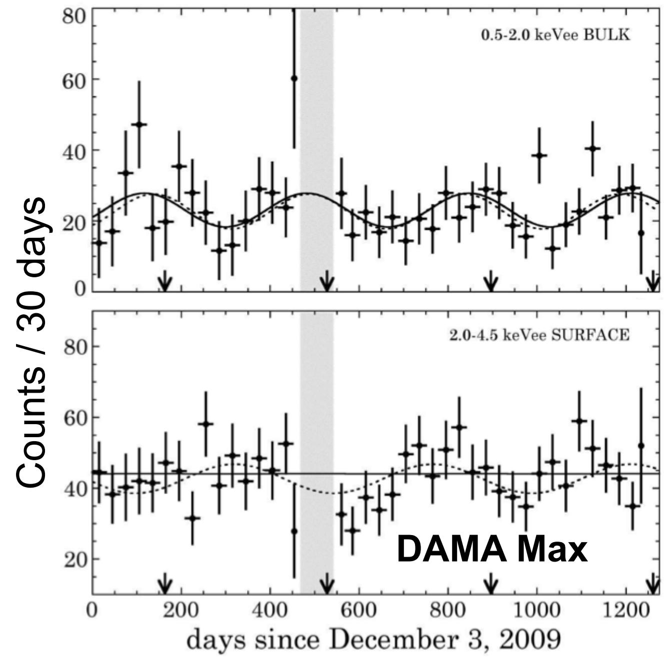
CDMS-Si



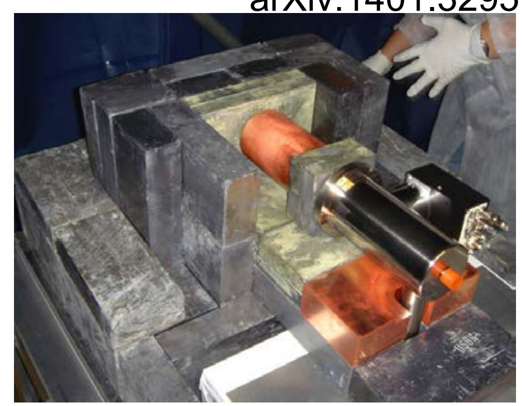
arXiv:1304.4279



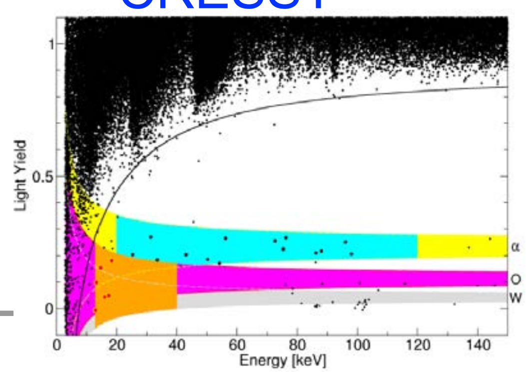
CoGeNT



arXiv:1401.3295



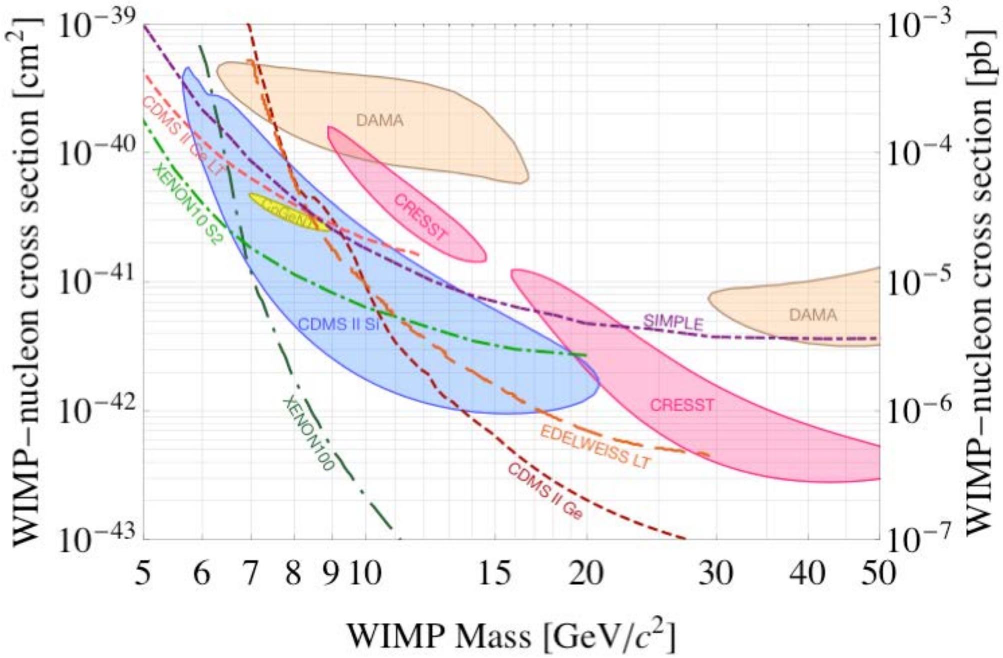
CRESST



Eur. Phys. J. C (2012) 72:1971

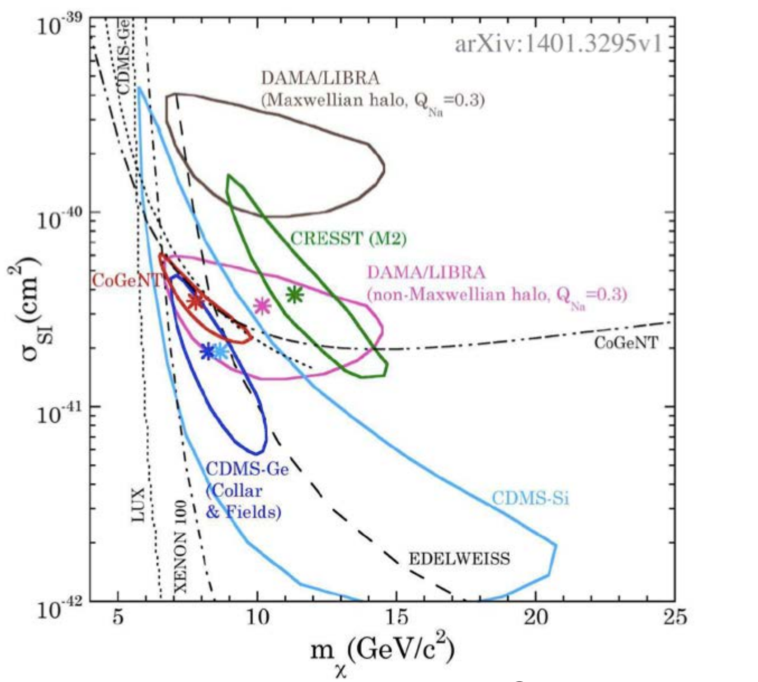
Does DAMA see Dark Matter?

Inconsistent Picture for WIMPs



SNOWMASS 2013: arXiv:1310.8327

The present crux (interesting times)



Juan Collar, LLWI 2014
arXiv:1401.3295

Challenges: Astrophysics, Particle Physics, & Instrumental Effects

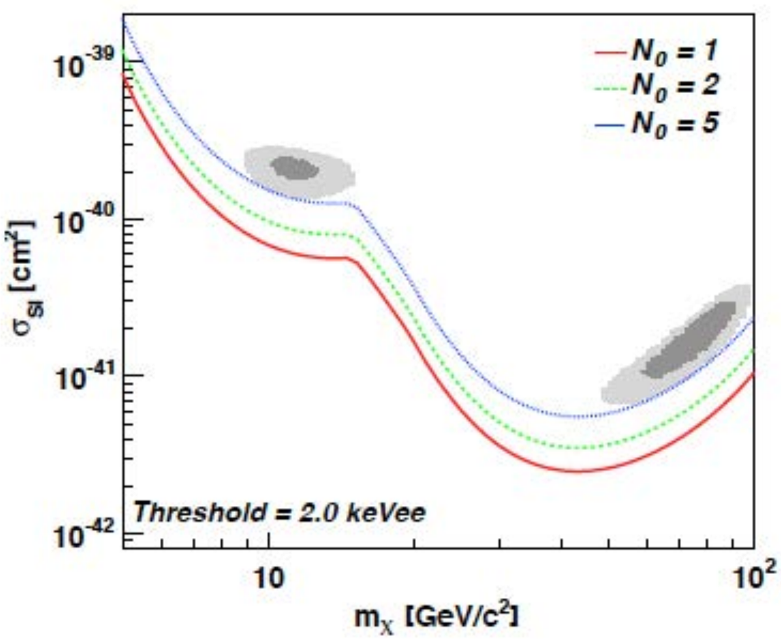
Solution: Repeat the same experiment with same detector medium, but with better handle on background(s)

Testing DAMA's Dark Matter Claim

Definitive (5σ) detection or exclusion with

- 500 kg-yr NaI(Tl) (DAMA x 2 yrs)
- same or lower threshold (< 2 keV_{ee})
- background < (DAMA x 5)

arXiv:1106.1156



500 kg·year NaI detector sensitivity

(2 - 4 keV) with bgd of 1, 2, and 5 cnts/keV/kg/day.

	Years	DM-Ice17 17.0 kg	NAIAD-scale 44.5 kg	DAMA-scale 250 kg
x8 DAMA background	1	0.45	0.72	1.71
	3	0.77	1.25	2.96
	5	1.00	1.61	3.82
	7	1.18	1.91	4.52
x4 DAMA background	1	0.63	1.02	2.42
	3	1.09	1.77	4.18
	5	1.41	2.28	5.40
	7	1.67	2.70	6.39
Double DAMA background	1	0.85	1.37	3.26
	3	1.47	2.38	5.64
	5	1.90	3.07	7.29
	7	2.25	3.64	8.62
DAMA background	1	1.20	1.94	4.61
	3	2.08	3.37	7.98
	5	2.69	4.35	10.31
	7	3.18	5.14	12.19
1/10 DAMA background	1	3.80	6.15	14.57
	3	6.58	10.65	25.24
	5	8.50	13.75	32.59
	7	10.06	16.27	38.56

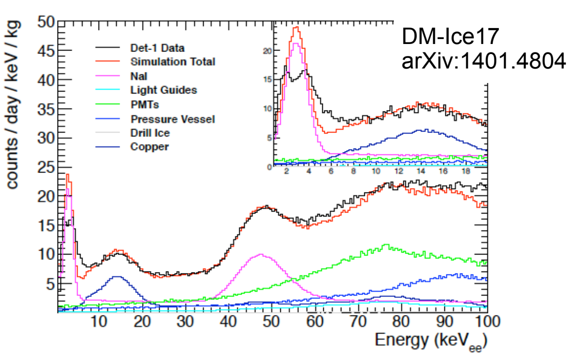
Additional Information by lowering the threshold below 2 keV.

Phased Program for DM-Ice

- low-background NaI(Tl) target
- moveable detector array
- access to both Northern & Southern Hemispheres

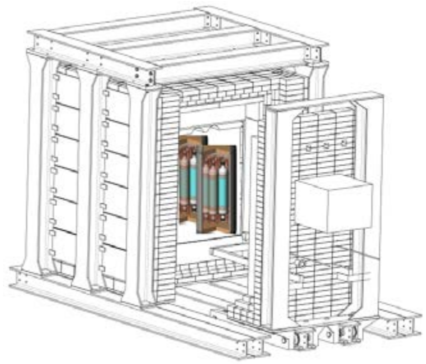
A Phased Experimental Program

DM-Ice17



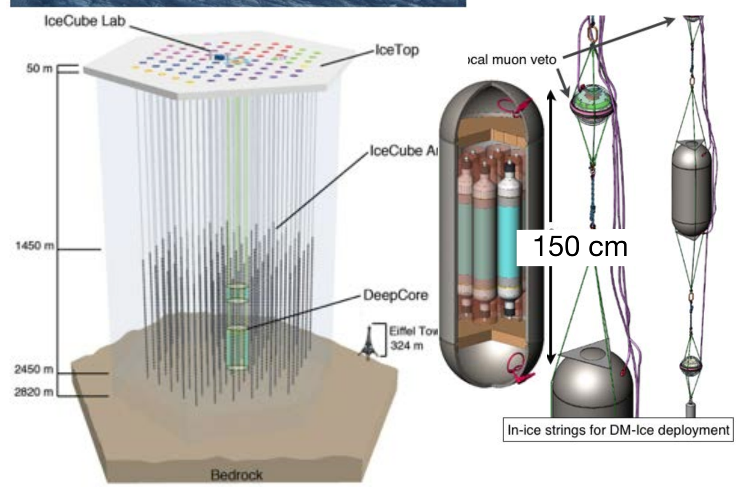
Test Detector at South Pole
17 kg of NaI(Tl) at 2450m depth at South Pole

DM-Ice 250 North



Modulation Search in Northern Hemisphere
portable 250 kg NaI(Tl) detector, first deployment in the Northern Hemisphere

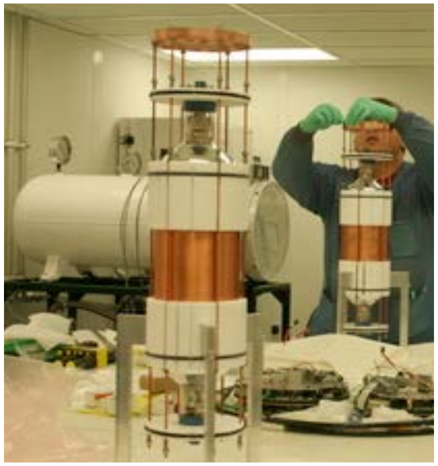
DM-Ice 250 South

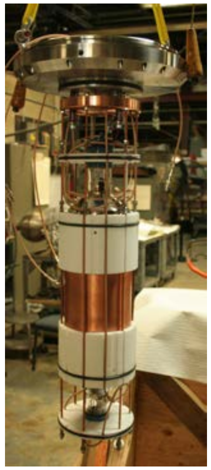


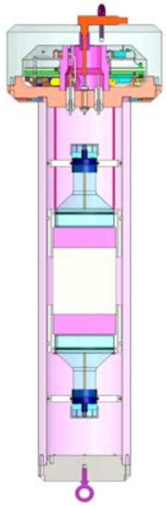
Modulation Search at the South Pole
if modulation seen in North & ice drilling becomes available

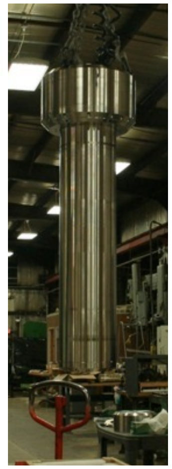
DM-Ice17 - Deployment, Operation, Data Taking

Built in summer 2010

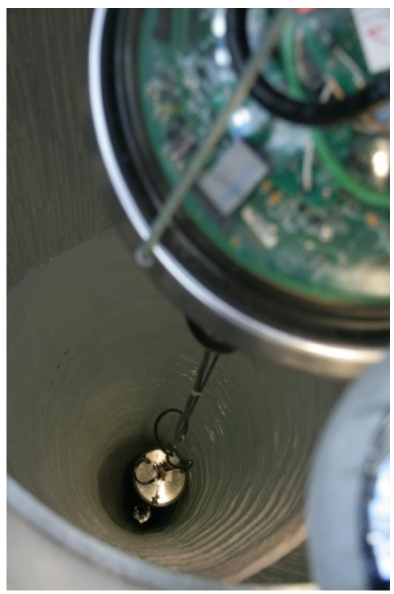


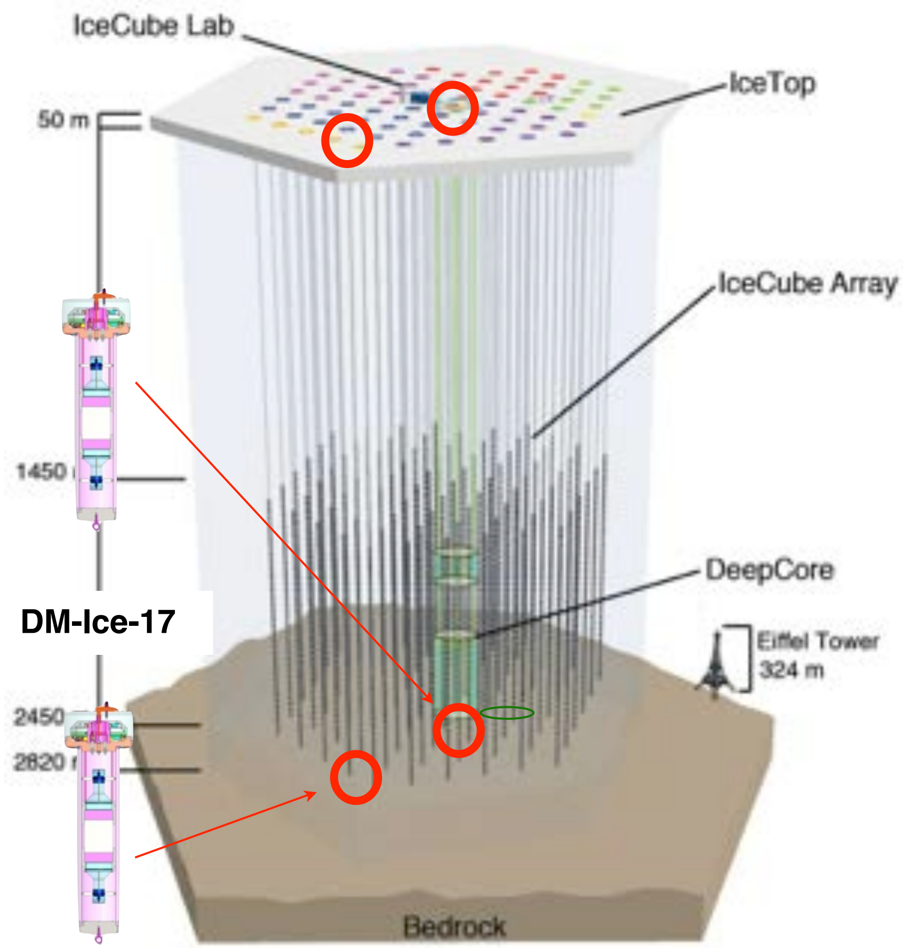






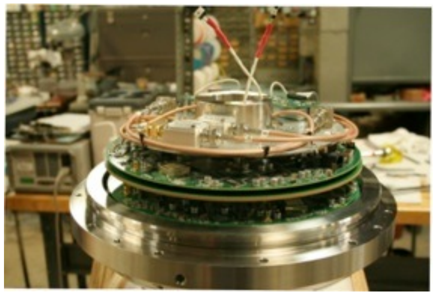
Deployed at the South Pole in December 2010

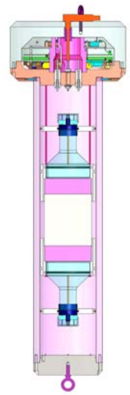




DM-Ice17 - Deployment, Operation, Data Taking

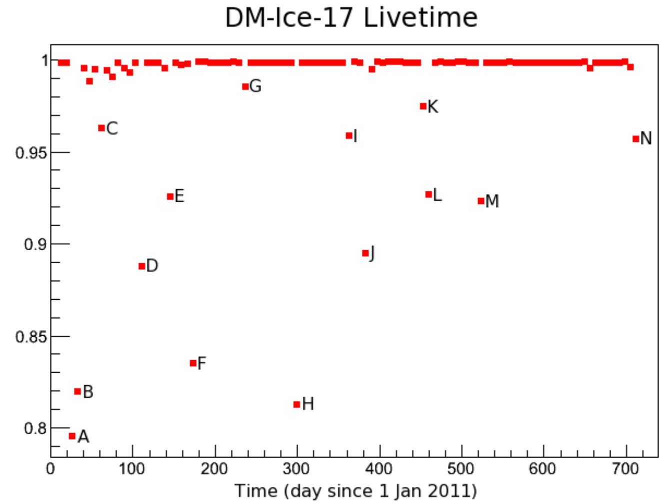
Test Detector Operation & Data





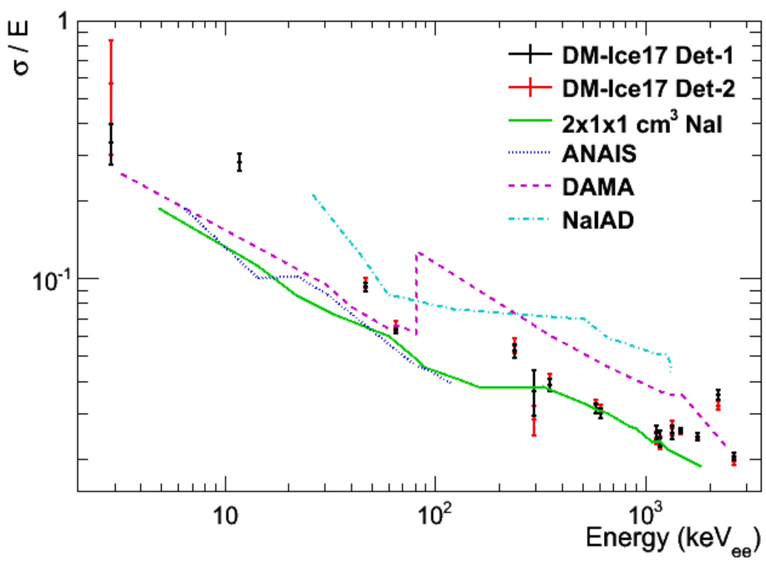
uses NaIAD crystals

Data run since June 2011, 99.8% uptime



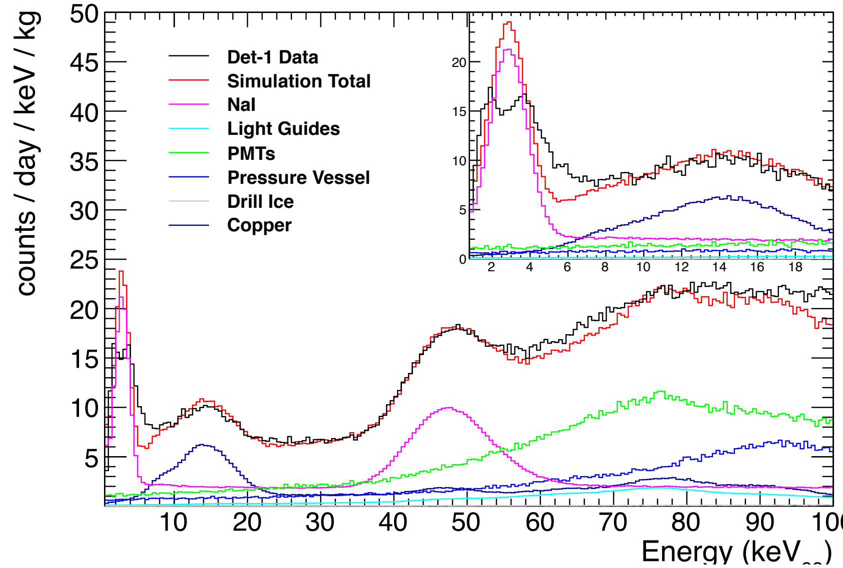
Light Collection and Energy Resolution

DM-Ice17: 4-6 pe/keV



DM-Ice Collaboration, arXiv:1401.4804v1

Energy Spectrum < 100 keV



Event ROI dominated by ^{40}K, ^{210}Pb, and ^{129}I in the crystal.

3 keV peak from ^{40}K observed

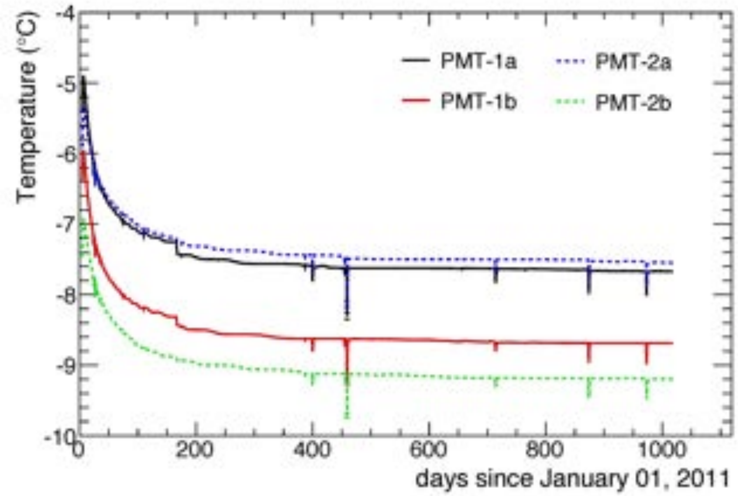
DM-Ice17 - A Proof of Concept

Stable Operation for >2 Years

Calibration achieved using internal contamination

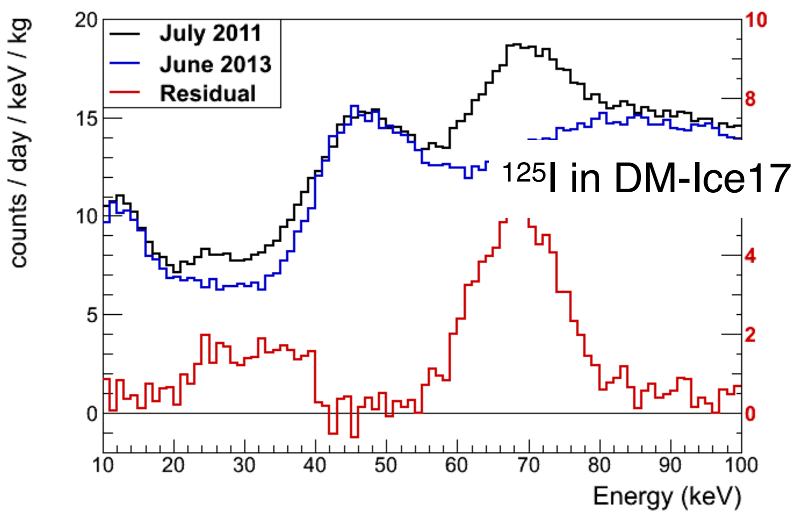
Negligible environmental background
(drill Ice and glacial Ice ≲ 0.1 dru)

Temperature stability, high livetime (> 98%)

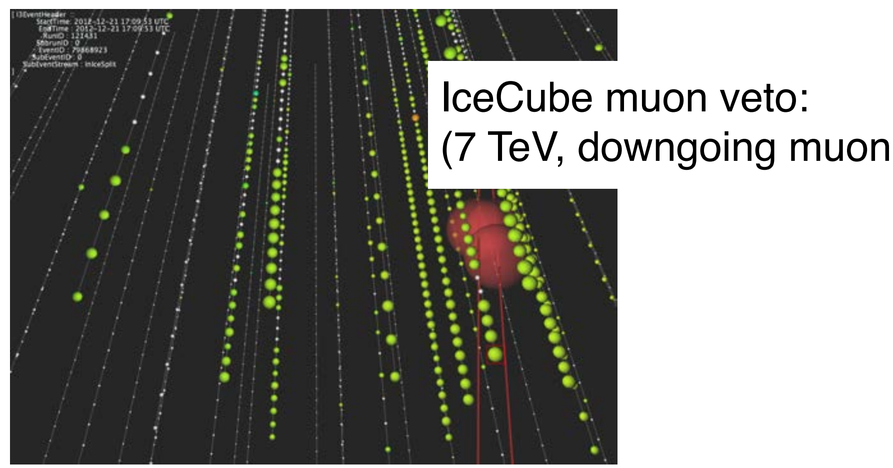


Ongoing Analyses

Cosmogenic production



Coincidence muons with IceCube



DM-Ice17 demonstrated feasibility of dark matter search at South Pole

DM-Ice / IceCube Coincident Event

A. Hubbard

DOM 60 highlighted

December 2012- Event #14

~10% of muons seen in Det-1 in DM-Ice17 trigger in muon channel in IceCube

New Low-Background NaI(Tl) Crystals

Development of NaI(Tl) detectors with Alpha Spectra, Inc (ASI) in CO, USA
Three groups work with Alpha Spectra: DM-Ice, ANAIS, KIMS.
Communication and sharing of R&D results

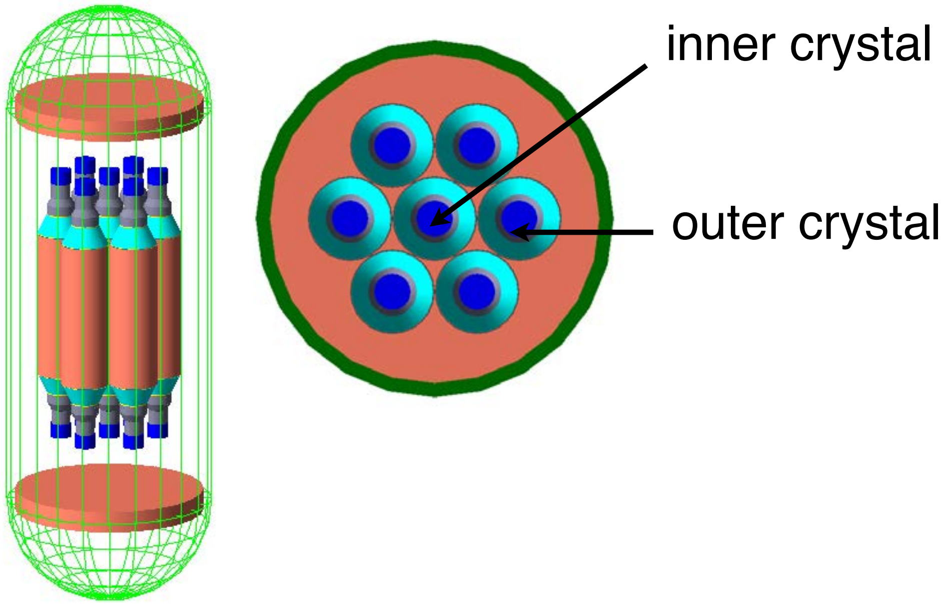
- 2 x 18 kg crystals from Alpha Spectra are at Fermilab MINOS near hall for testing.

- If these crystals confirm specifications, total of 250 kg can be grown and encapsulated as detectors at ASI in less than 12 months.

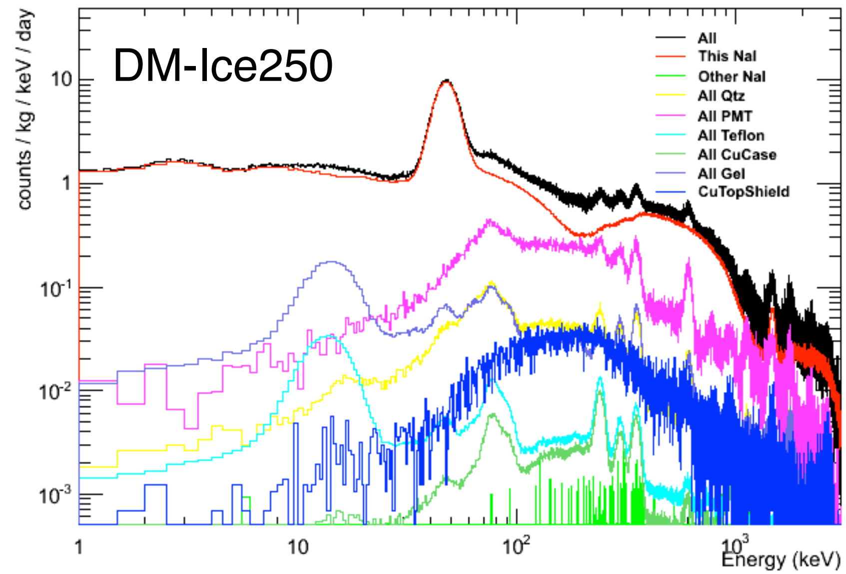
Backgrounds are within acceptable levels for an experiment with 2 counts/day/keV/kg.
Sufficient to test the DAMA signal at > 5σ with 3 years of data.

DM-Ice250 Simulations

Close-Packed Detector Array



Inner Crystal Vetoed Spectrum



Sensitivity to DAMA Modulation Signal

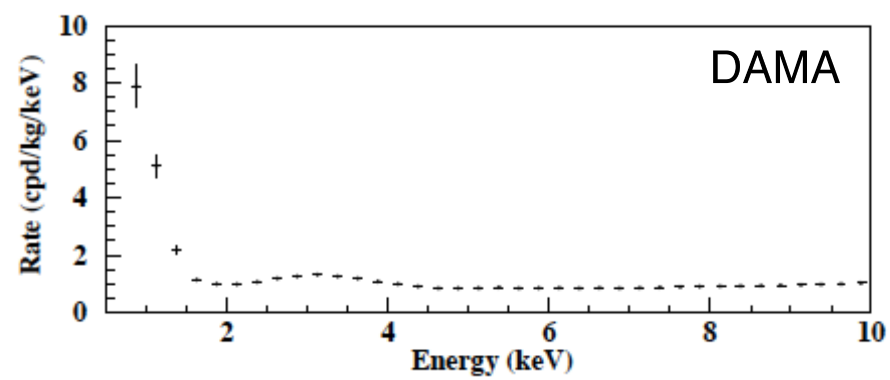
assume 225 kg exposure/yr (90% livetime)

1 year: 3.3σ
2 years: 4.6σ
3 years: 5.7σ

Based on MC sample of modulated signal, using same binning and analysis method as DAMA, fit to fixed phase and period.

DM-Ice250 Background

2-6 keV region: 1.75 dru average
(worst case with veto)



Summary

The fields of direct and indirect dark matter searches are highly active and rapidly evolving.

- The race is on!
- Solar WIMP paper is still the most cited physics paper in IceCube.
- Neutrino detectors leads in spin-dependent dark matter searches
- Neutrinos point back to sources and have fewer background sources. Complementary to searches with gamma and charged particles.
- IceCube & DM-Ice have established the South Pole as a viable “underground” laboratory.
- DM-Ice will directly test DAMA’s claim for lab-based observation for dark matter.

NSF
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WARF
WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER

The IceCube Collaboration

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DigiPen
Charles Duba, Eric Mohrmann

Boulby Underground Science Facility
Sean Paling

SNOLAB
Bruce Cleveland