# Indirect Detection of Dark Matter

*Spencer Klein,* *LBNL & UC Berkeley*

- Indirect Detection from Capture and Annihilation in the Sun and Earth
- Signatures of Annihilation in the Milky Way & beyond
  - $\nu$, $\gamma$ and $e^{\pm}$, pbar, dbar
- Conclusions

# Caveats

- Indirect detection is a very broad subject, involving at least five message-carriers ($\gamma$,pbar, antideuterons $e^{\pm}$, $\nu$), more than a dozen experiments, and many hundreds of papers.
- I can't cover this all; I will try to include a representative sampling of newer results.
  - Only modest reference to history
  - Possibly slightly $\nu$-centric
- Comparisons between different searches are generally rather model dependent.
  - There are model dependencies and loopholes in most of the comparisons I will present today.

# Classes of signatures

- Indirect Signatures are focused on Weakly Interacting Massive Particles
- Two main types of signatures for cold particle DM
  - DM scatters elastically from a massive body (e.g. the Earth or Sun) and is gravitationally captured. It builds up, and eventually starts self-annihilating, producing observable $\nu$ and other, non-observable particles.
  - DM accumulates in a galaxy/halo/… then self-annihilates.
- Many other signatures possible for light $\nu$, axions, secluded or decaying dark matter, etc.

# Indirect detection - assumptions

- We measure a limit on the $\gamma/\nu$/antimatter flux from annihilation of dark matter in different 'reservoirs.' These limits are then interpreted in terms of a dark matter model.
- Dark matter density distribution
  - In our galaxy, and compared to others.
  - Different halo matter distributions do not give very different answer for matter abundance at the Earth, but matter a lot at the center of the galaxy.
- Dark matter velocity distribution
  - Maxwellian velocity distribution usually assumed
    - N-body simulations hint at a high-velocity tail
  - More important for direct detection than indirect

# WIMPs build up in Sun & annihilate

- At equilibrium: annihilation rate = capture rate

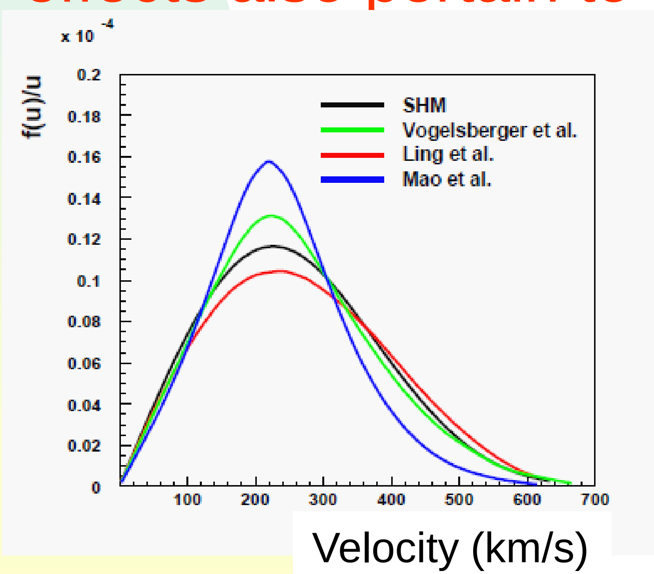
$$\frac{d\mathcal{N}}{dt} = C_{\mathrm{C}} - C_{\mathrm{A}}\mathcal{N}^2 - C_{\mathrm{E}}\mathcal{N}.$$

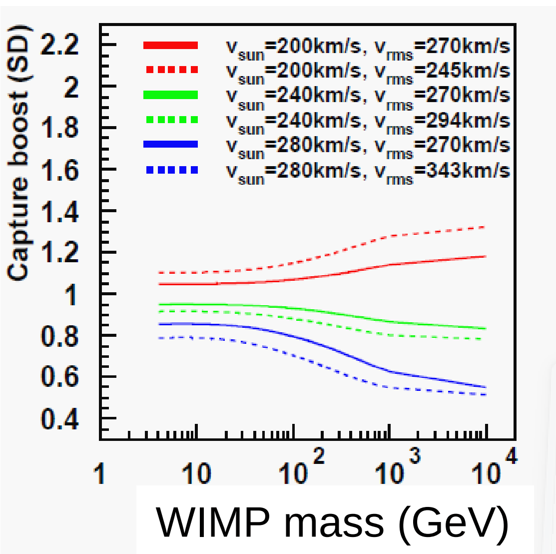
Evaporation is negligible

  - For most of considered SUSY parameter range, the Sun has reached equilibrium
- Dark matter annihilates (must be Majorana particle) or decays
- Mass and final states are unknown. Some final state choices:
  - $\chi\chi \rightarrow \nu\bar{\nu}$
    - Not expected in most SUSY models
  - "Hard" $\chi\chi \rightarrow W^+W^-$ ($\tau^+\tau^-$ for $M_\chi$ below threshold)
  - "Soft" $\chi\chi \rightarrow b\bar{b}$
  - Dark matter decay also considered.
- Consider these variables by scanning over different possibilities (mass, decays), or as systematic uncertainties

# Capture in the Sun - rate uncertainties

- Capture rate depends on inelastic cross-section
- 15- 20% variation from velocity profile variations
- For heavy WIMPs, 3-body calculations find a capture rate decrease caused by the presence of Jupiter.
  - Compensated by WIMPs scattered by Jupiter into the Sun, or out of the Solar system?
- These effects also pertain to Earth WIMPs




C. Rott *et al.*, JCAP 09, 029 (2011); Sivertsson & Edsjo, arXiv:1201.1895; Choi et al.arXiv:1312.0273

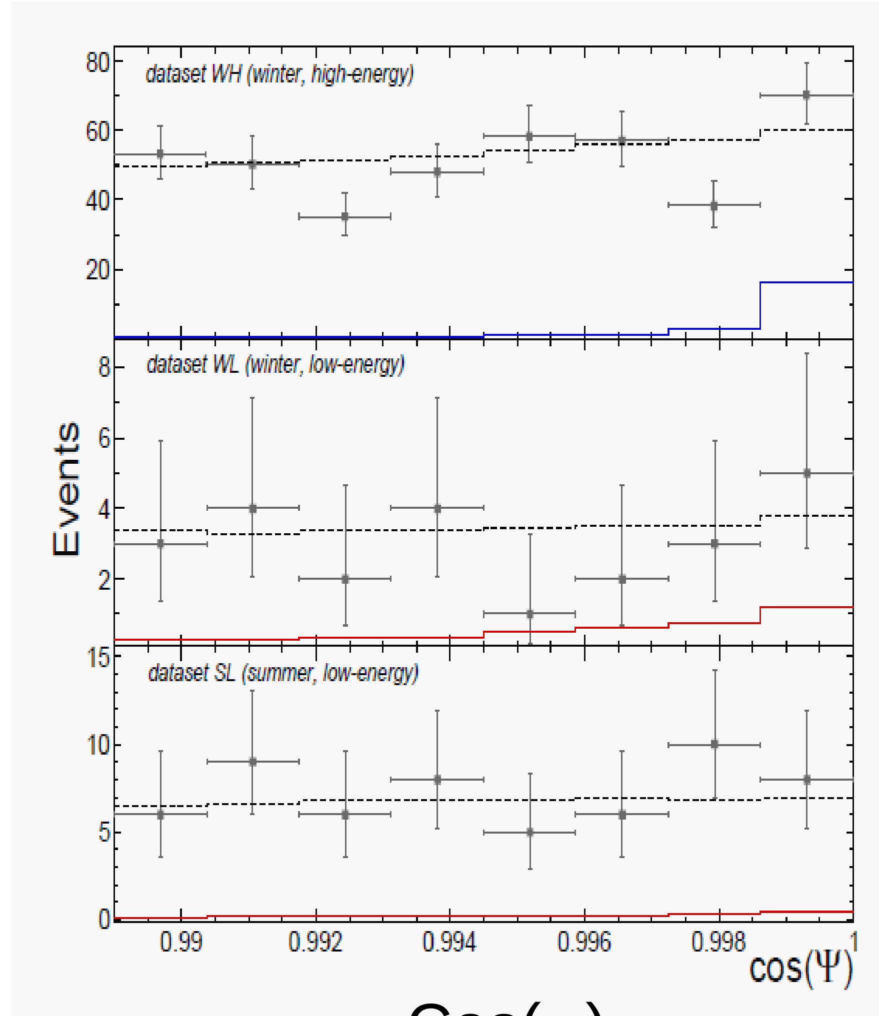
# IceCube Solar analyses

- The sun is dense enough so that neutrinos with E > ~ 200 GeV interact before escaping
  - NC & some CC interactions produce lower energy $\nu$
  - Neutrino energy spectrum is of lesser diagnostic value
- Multiple studies of 1 year of 79-string data (w/ 2 DeepCore strings)
  - Winter: High & low energy analyses w/ Sun below horizon
  - Summer: Low energy (contained) analysis with Sun above horizon
- Cuts were optimized separately for each analysis
- Likelihoods calculated for each WIMP mass, for hard and soft channels

IceCube – PRL 110, 131302 (2013)

# Results

- Background determined by time-scrambling data
- The shape of the space angle distribution ($\psi$) wrt. the sun was used to determine the size of the signal
- No signal seen
- Main systematic uncertainties due to optical properties of ice & sensitivity of optical modules



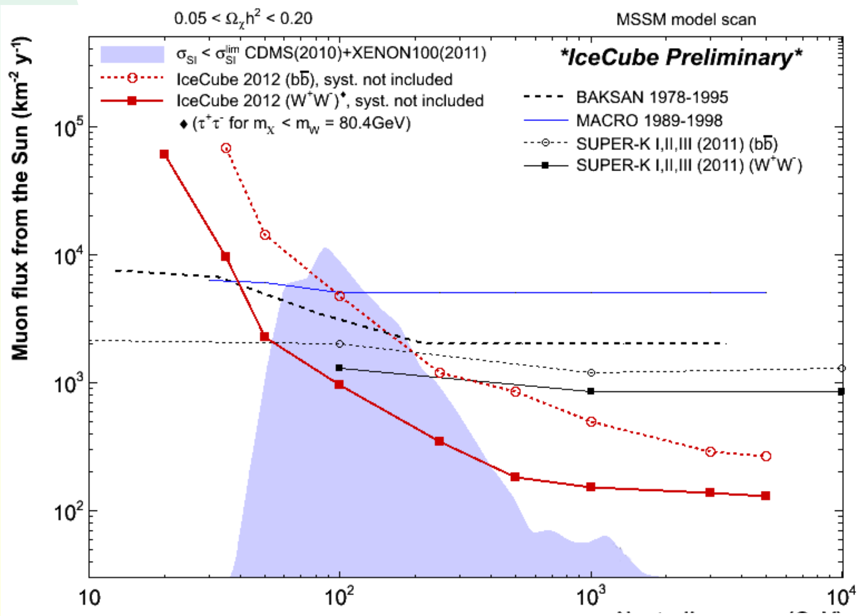

Cos($\psi$)

Blue curve is for 1 TeV $\chi\chi$ -> $W^+W^-$

Red curve is for 50 GeV $\chi\chi$ -> bb

# 90 % CL μ flux combined limits

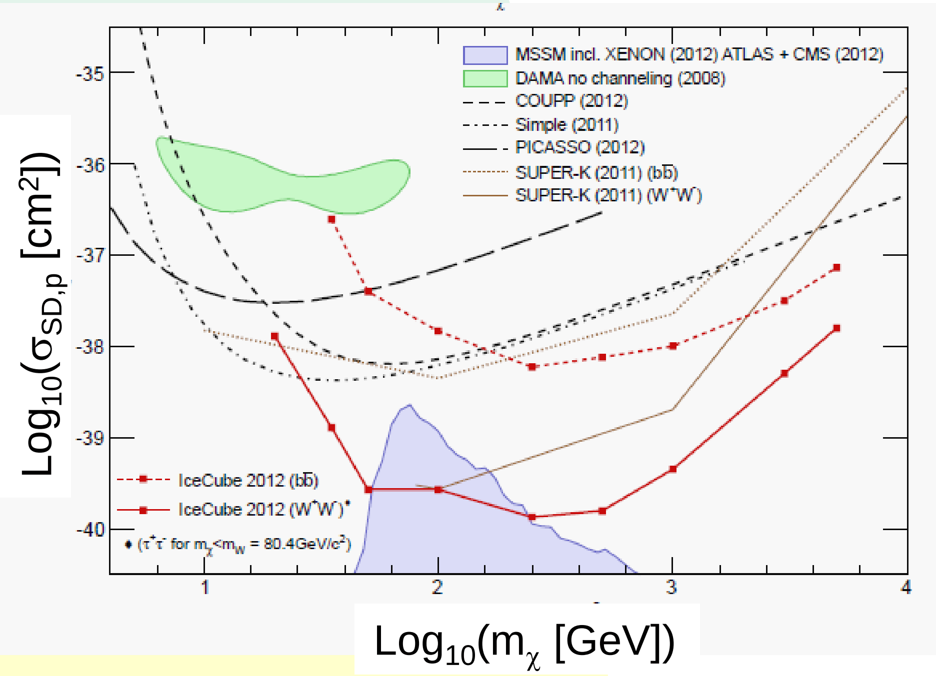
- A model-independent flux limit is obtained for the 3 analyses.
  - Then combined, including IC22 limits.
- Limits on the flux of μ from ν, for specific annihilation channels
  - Mass and branching mode
- These limits are compared with the range of predictions from a 7-parameter MSSM scan using DarkSUSY (shaded area)
  - Incorporates direct limits, LHC limits (as of 2012)

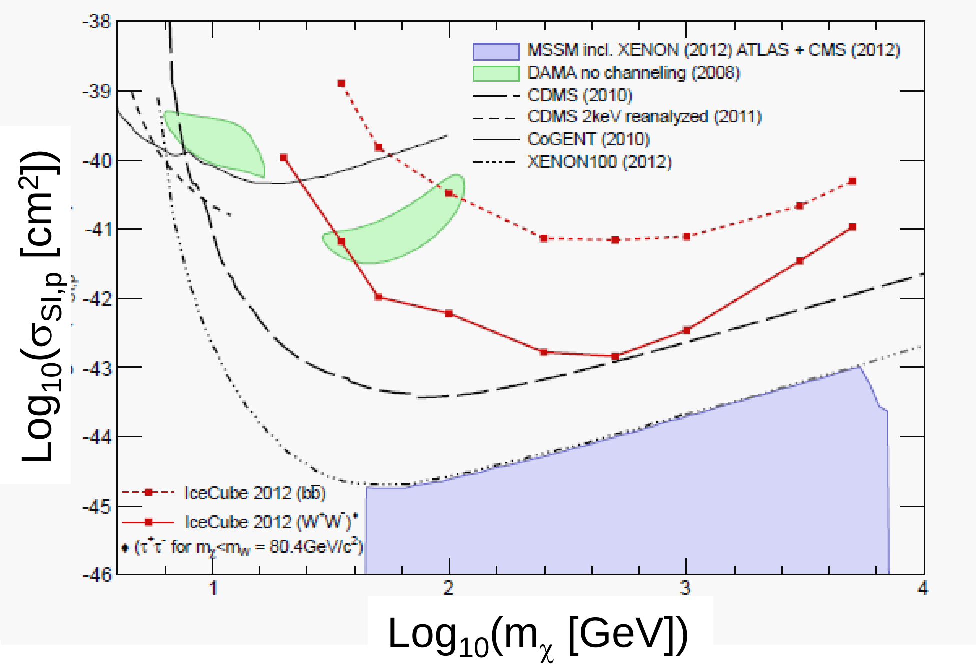



WIMP Mass (GeV)

# Cross-section limits

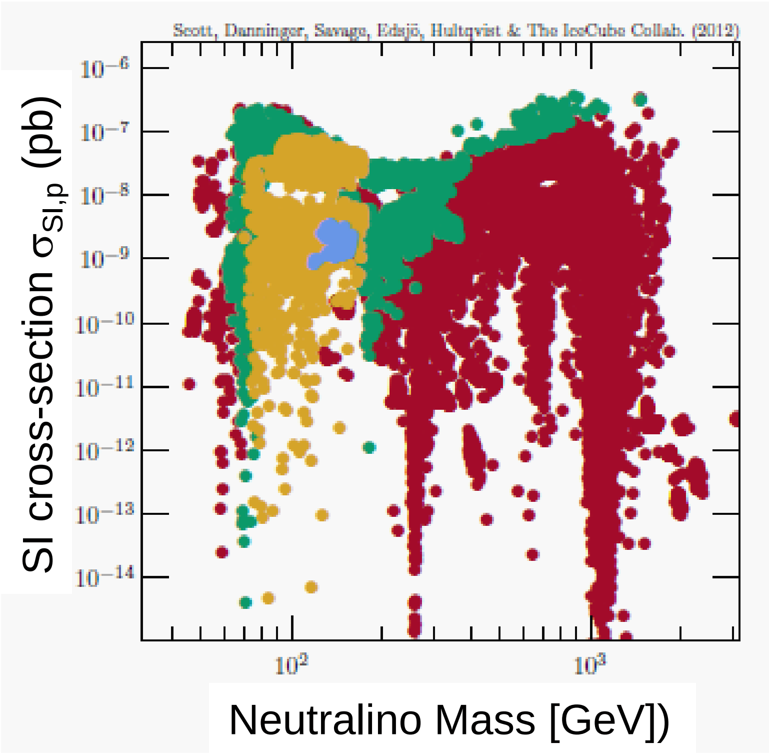
- Assuming equilibrium, these limits are converted to spin-dependent (SD, left) & spin-independent (SI) limits
  - Independent of WIMP model.
- Shaded band shows predictions based on MSSM scans
  - Comparison as of paper publication; the LHC is continually restricting parameter space.



# Direct comparison with models

- An alternative approach is to directly simulate models
  - Directly include theoretical branching ratios, etc.
- Pick CMSSM (or other model) parameters and see if they are compatible with ν limits.
  - Likelihood based comparison could involve individual ν event energies, directions etc.
  - More accurate comparison, but heavy model dependence.
- Can include likelihoods from other experiments…..

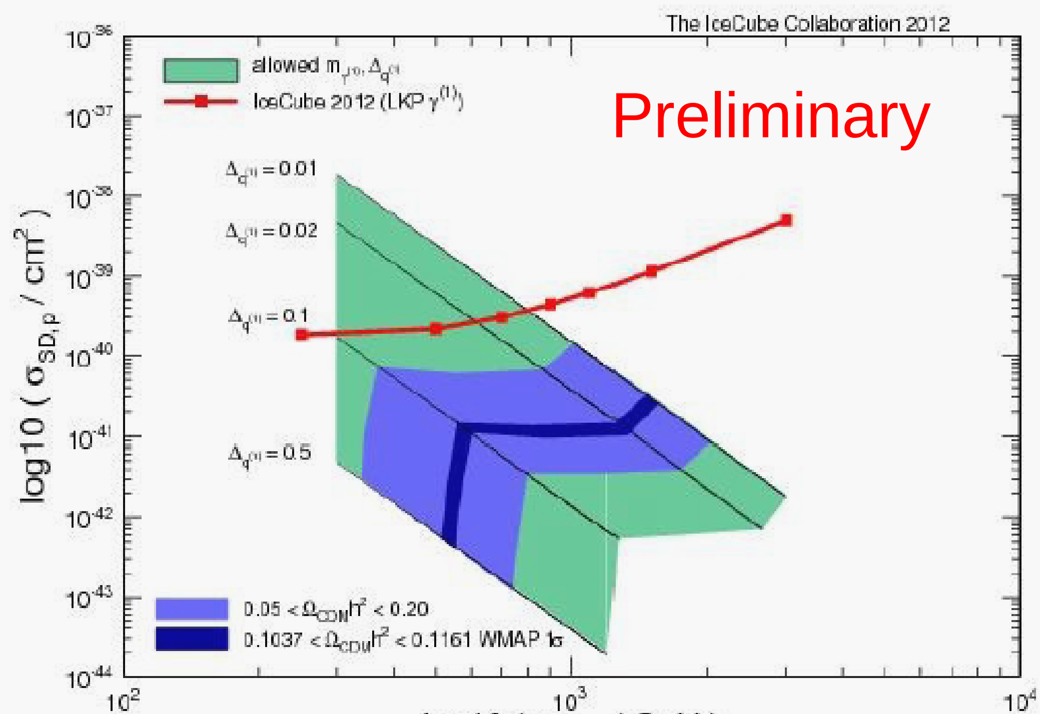



Simulated Exclusion Projection IC86
Red – not excludable
Green – 1 σ
Yellow 3 σ
Blue 5 σ

IceCube *et al.* (w/ theorists Scott *et al*.) JCAP 1211, 057 (2012)

# Kaluza-Klein dark matter

- The IC79 analyses were also used to put limits on Kaluza-Klein dark matter
  - Probes allowed phase space for LKPs
- Same data, reinterpreted in different parameter space




LKP Mass [GeV]

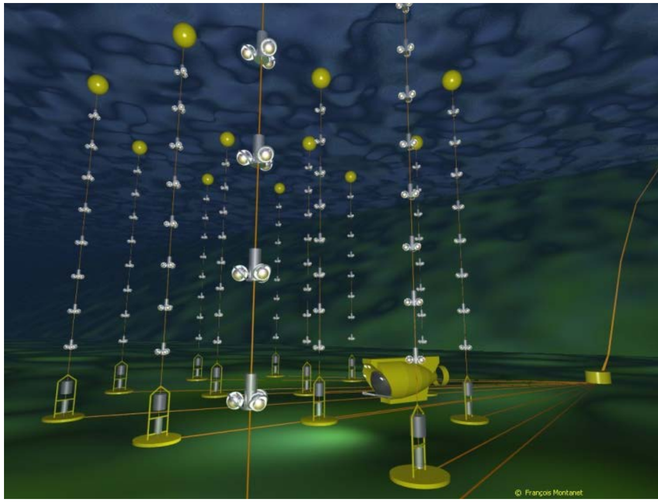
$\Delta$q is the mass splitting between q and $\gamma$

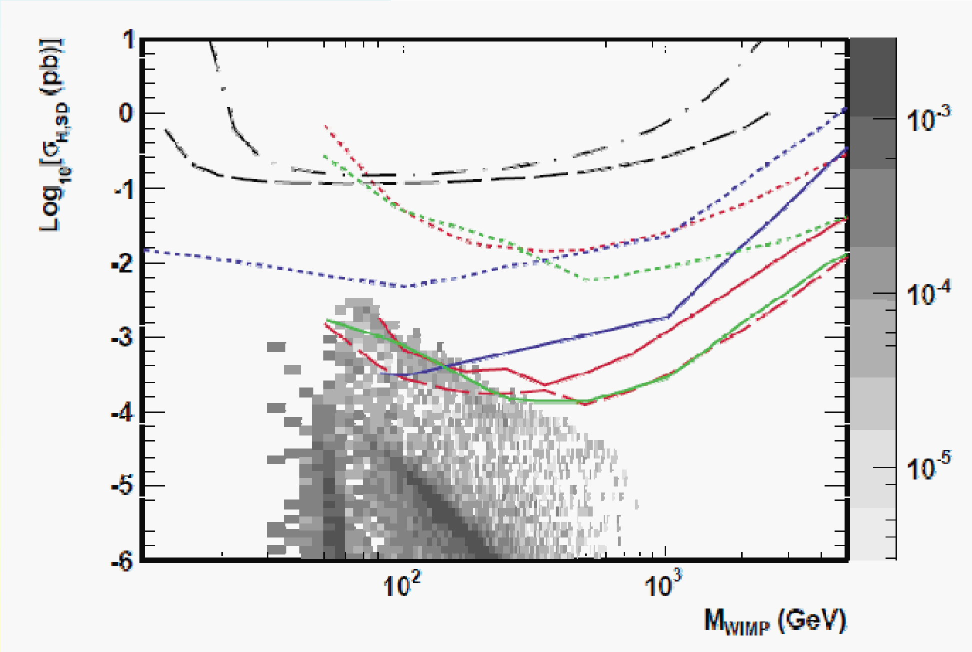
Not yet in the cosmologically Interesting region.

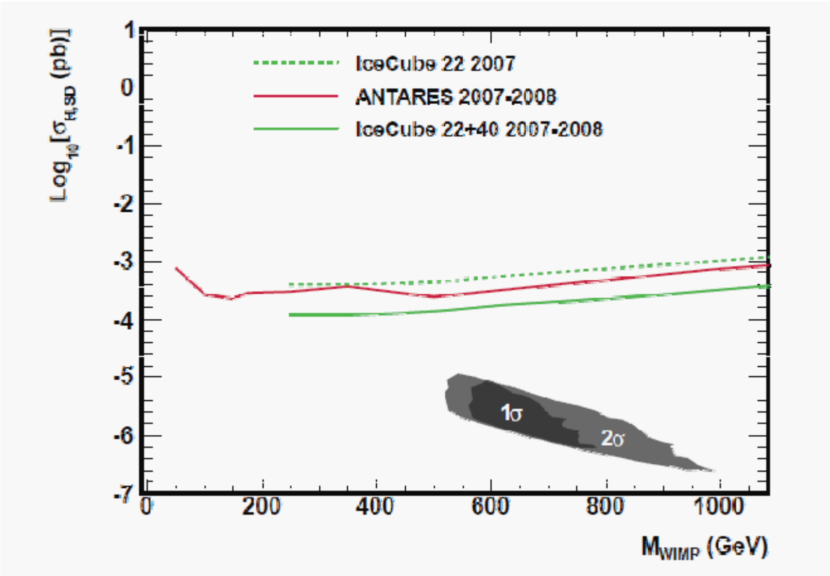
IceCube – M. Danzinger PhD dissertation, 2012

# ANTARES solar limit

- 0.05 km$^2$ (Effective area) Cherenkov detector in the Mediterranean
  - 12 strings holding 885 10” PMTs
- Search for $\nu$ coming from the Sun



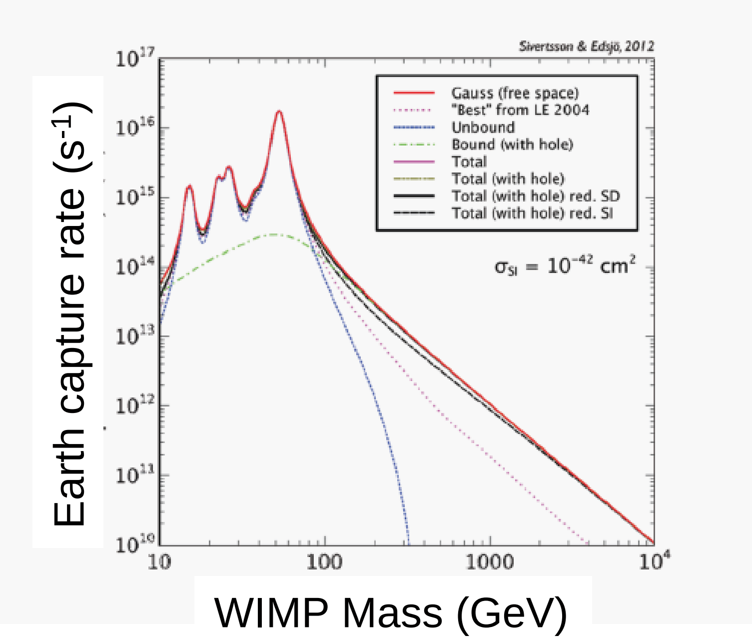



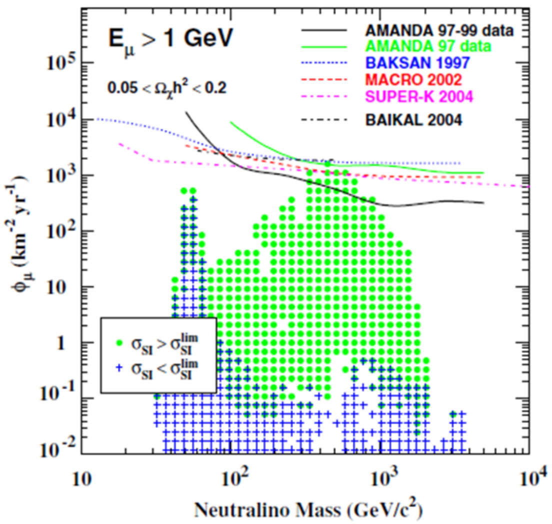




ANTARES collaboration EPJ Web Conf. 70, 0049 (2014)

# WIMP annihilation in the Earth

- Closer than the sun, but lighter
- Varied nuclear content
  - Mostly depends on $\sigma_{SI}$
  - Resonant capture for $M_{WIMP}=M_N$
- Detectors like IceCube are sensitive to WIMP masses from 50 GeV on up.
  - Resonances increase sensitivity at selected masses
- AMANDA 2006 results are old, with a small detector
  - Newer results are coming

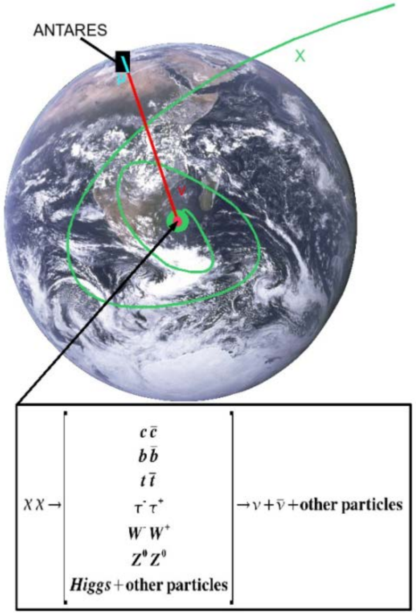


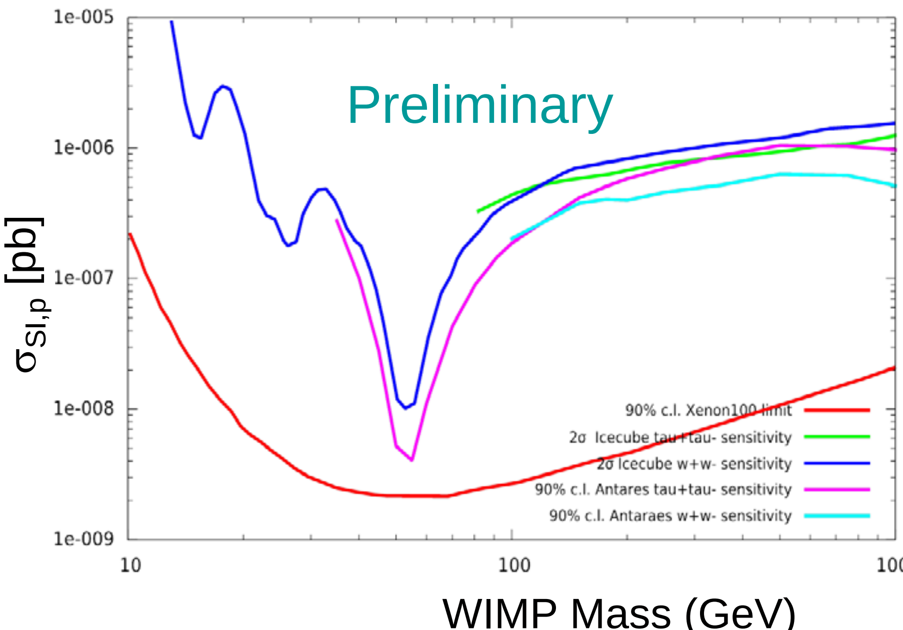




AMANDA – Astropart. Phys. 26, 129 (2006)

# Earth WIMPs- ANTARES

- Look for ν coming from within $5^0$ of the center of the Earth
  - 4 years of data
- Sensitivity shown below.
  - For 'standard' (SUSY) scenarios, less sensitive than direct searches.
- Unlike the sun, the WIMP density in the Earth is unlikely to have reached equilibrium
  - Models with enhanced annihilation cross-section lead to much higher ν rates & more sensitivity




Juan de Dios Zornoza (ANTARES), Moriond, March 24, 2014
Delauney et al., JHEP 0905, 099 (2009)

# Multiple Searches for galactic WIMPs

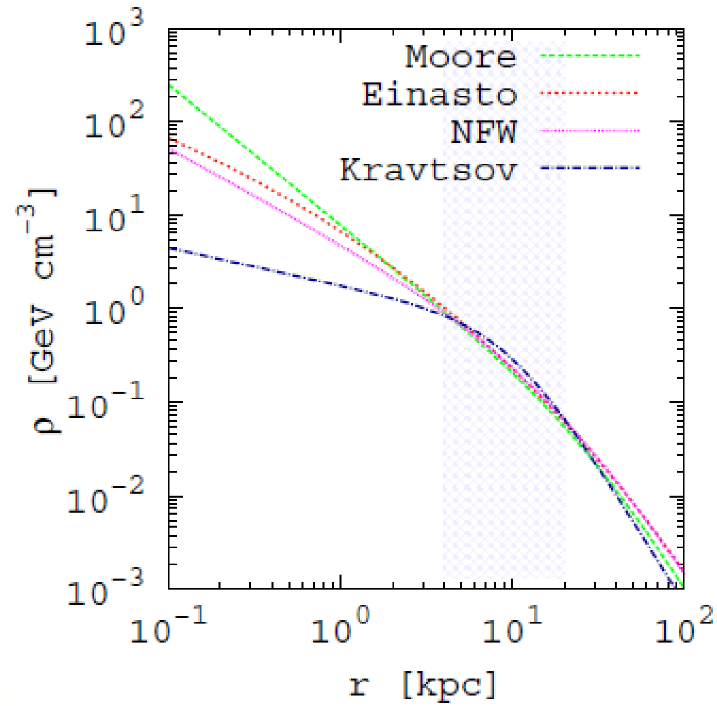
- $e^+/e^-$ excesses - PAMELA, Fermi, HESS
  - Can be interpreted as due to dark matter
  - Could also have other causes
    - Nearby cosmic-ray sources
    - Other processes in galactic center
- $\gamma$ – HESS
  - No excess seen. Limits set.
- $\nu$ – IceCube, ANTARES
  - No excess seen. Limits set.
- Antiprotons and antideuterons
  - No pbar excess seen. No antideuterons seen
  - Modern limits needed.

# Different probes for different final states

- The different final state probes (e,g,n,pbar, dbar) are most sensitive to different WIMP annihilation products
  - The optimal probe depends on the assumed WIMP annihilation final states
    - A good review, comparing sensitivities, is needed
- $e^{\pm}$, pbar, dbar are not directional – they arrive at the Earth via diffusion

# WIMP Annihilation in the Milky Way

- WIMPs in our galaxy can collide and annihilate, producing secondary particles: ν, γ, e±, antibaryons
  - Protons are already too copious to be a useful signature
  - ν are fully mixed
- Sets limits on $<\sigma_A \cdot v>$, modulated by branching ratios
  - Limits are model specific




$$\frac{d\Phi_\nu}{dE} = \frac{<\sigma_A \upsilon>}{2} J(\psi) \frac{1}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

Measure

Constrain

Galaxy

SUSY

# Line-of-sight density integrals

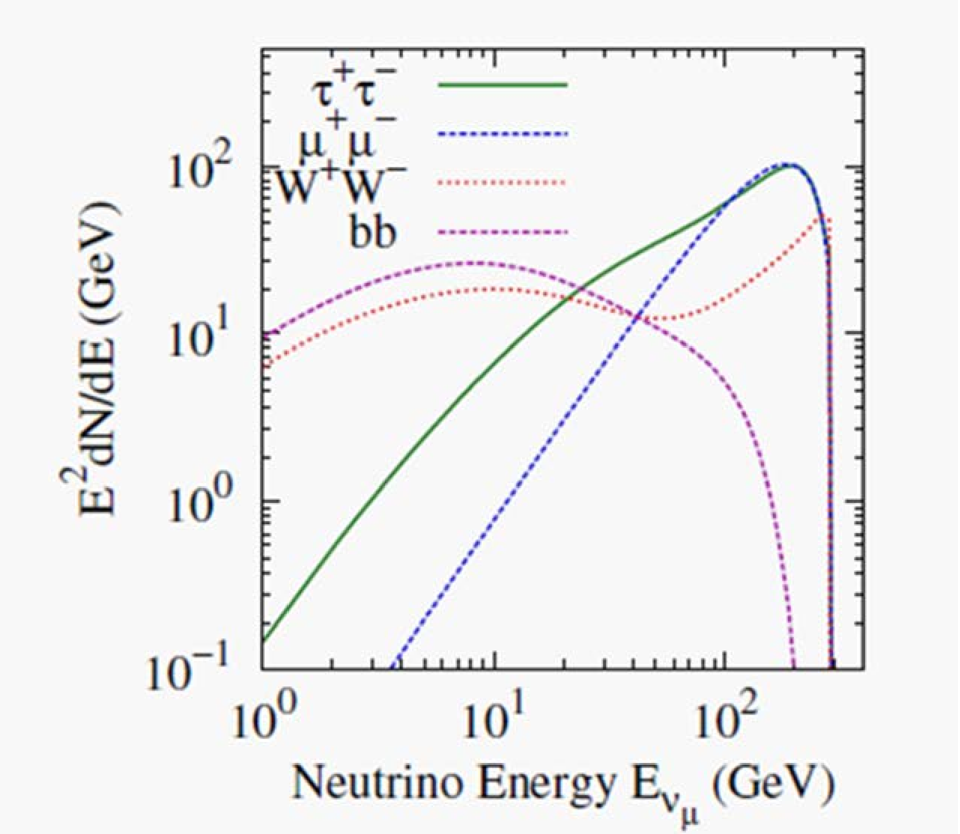
- In any given direction, the expected DM signal depends on the square of the dark matter density along that direction

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho(l)^2 dl \quad ,$$

  - Particularly sensitive to high-density regions
  - For $\gamma$, may need absorption correction
    - Or additions, from bremsstrahlung/showers/…
- The signal is the integral of J over the appropriate (optimum) solid angle

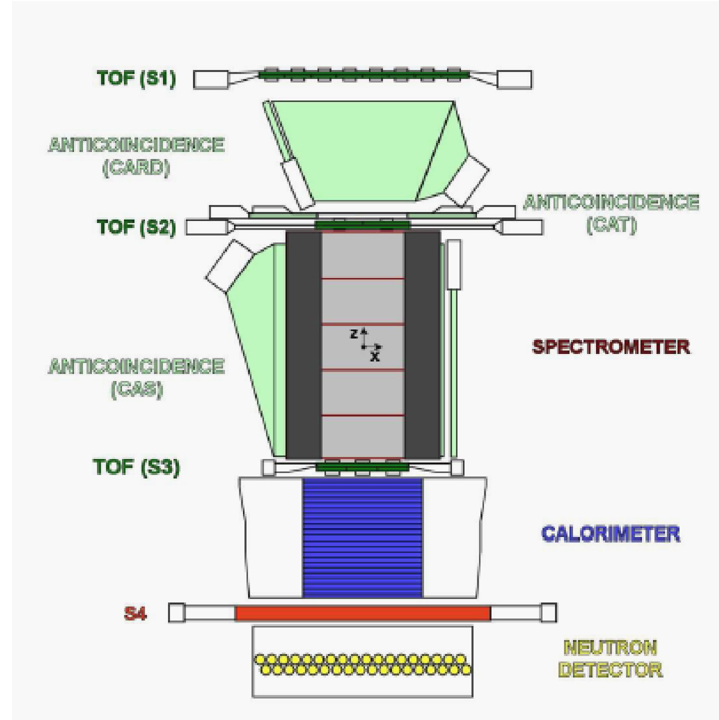
# ν flux from different annihilation modes

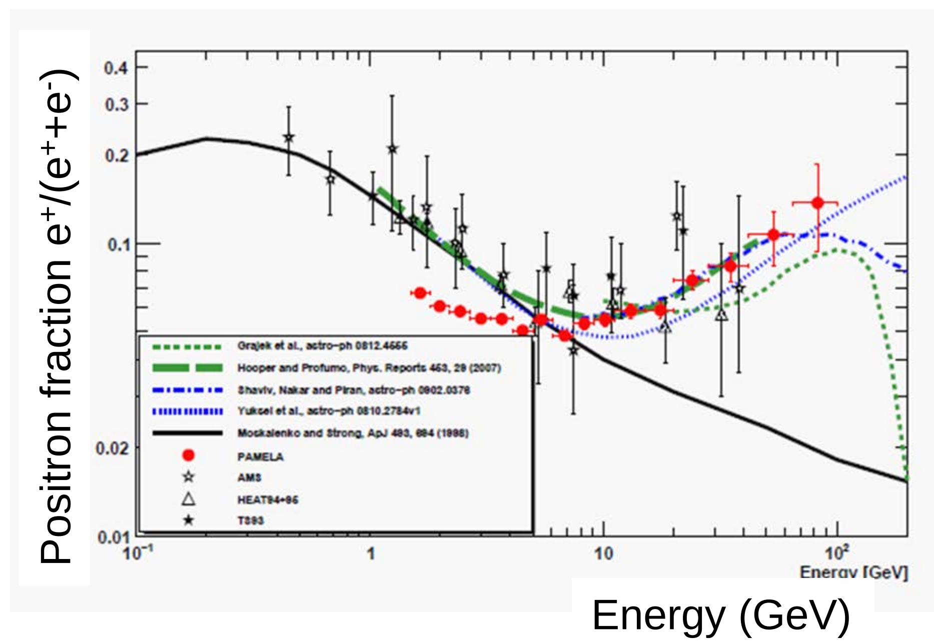
- ν energy spectrum depends on DM annihilation channels
  - SUSY (or other) model
- This also applies to photon energy spectra
- Lines are not expected in most models
  - But $\chi\chi \rightarrow \nu\nu$ or $\gamma\gamma$ is not ruled out.
    - Potential 'smoking gun'



# PAMELA 2009

- Cosmic-ray spectrometer launched on a Russian earth observations satellite in 2006
- Permanent magnet spectrometer, TOF and calorimeter
- In 2009, announced evidence for an excess of positrons with energies ~ 10-100 GeV
- Similar results from ATIC
  - In disagreement with standard cosmic-ray expectations
  - Consistent with dark matter
  - 100s of theory papers ensued..

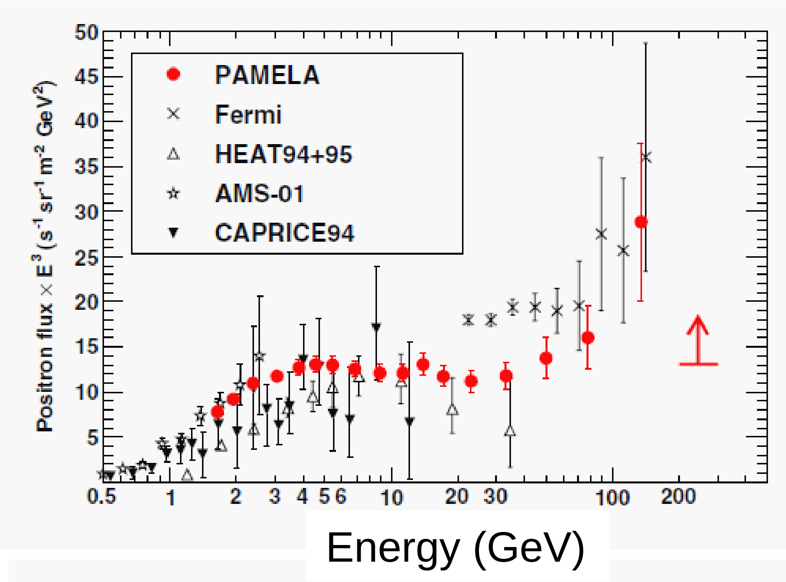


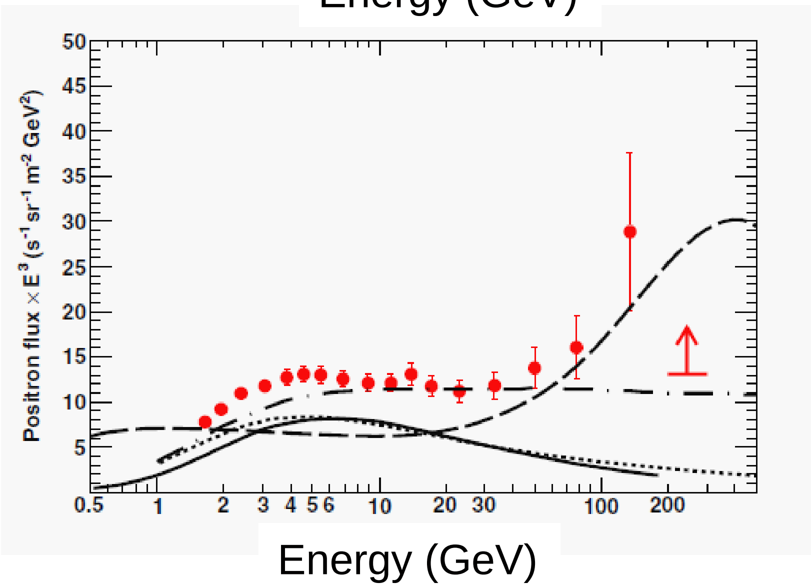




PAMELA – Nature 458 , 607 (2009)

# PAMELA, 2013

- Data in better agreement with standard cosmic-ray expectations.
- Collaboration still claims an excess, but it is much smaller, and the emphasis is now on nearby galactic sources



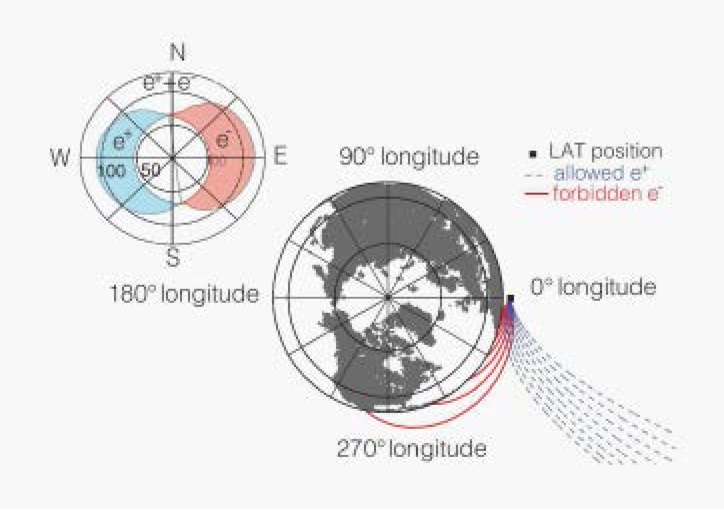



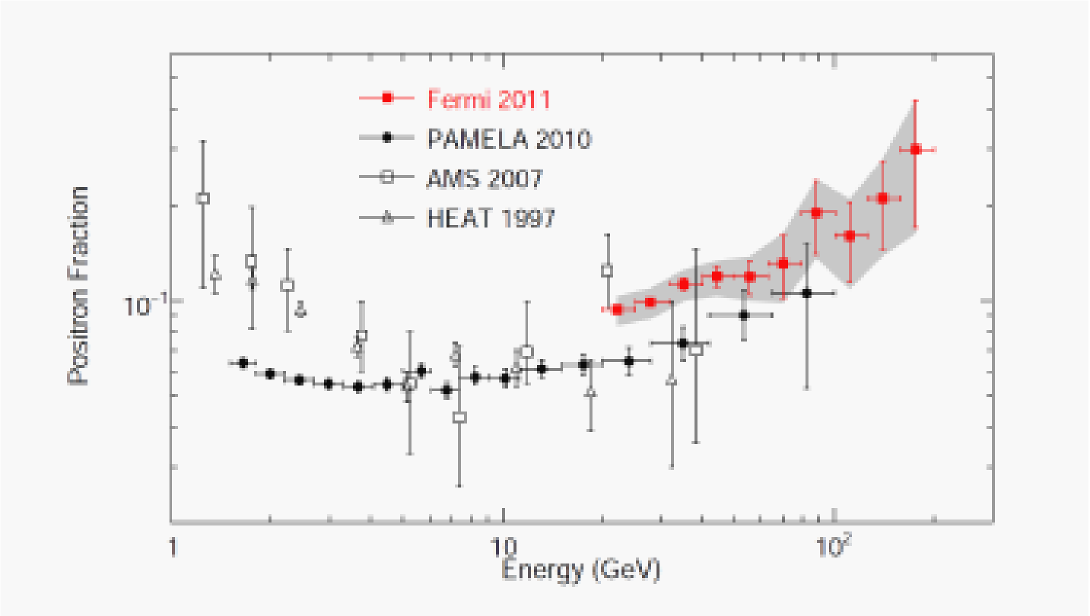

PAMELA collaboration,
PRL 111, 081102 (Aug., 2013)

Solid GALPROP only
Dotted, dashed w/ astrophysical sources
Dashed – w/ dark matter

# Fermi positrons

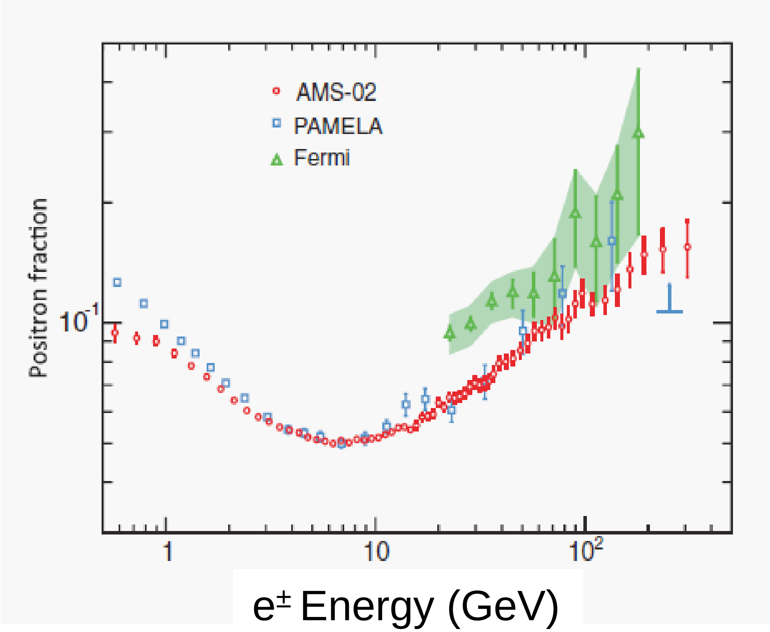
- The Earths magnetic field + satellite detector were a magnetic spectrometer to separate $e^+$ and $e^-$
- $e^+$ fraction increases with energy, up to ~ 300 GeV.



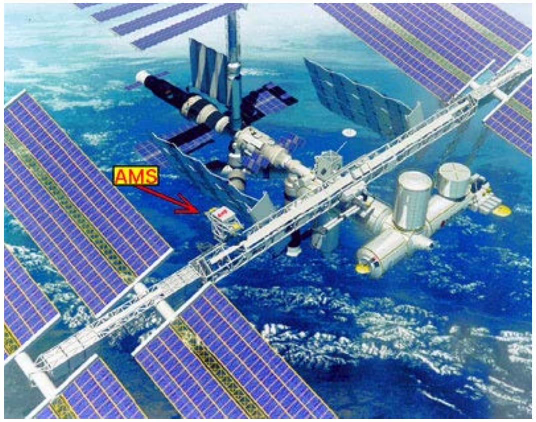




Fermi collaboration, arXiv:1210.2558

# AMS results

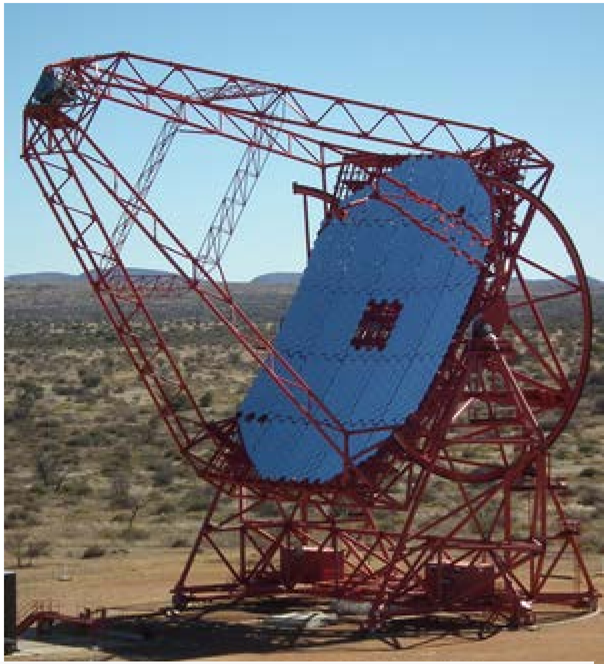



- Large spectrometer with calorimeter etc.
- Mounted on Intl. Space Station
- Larger than PAMELA; very high statistics measurements
- Consistent with PAMELA
  - Below Fermi measurements using Earth absorption to separate $e^+$ & $e^-$
    - Apparent excess… possible DM excess
- AMS sees no anisotropy
- Per AMS, consistent with diffuse background + single, power law source (i.e. a nearby source)

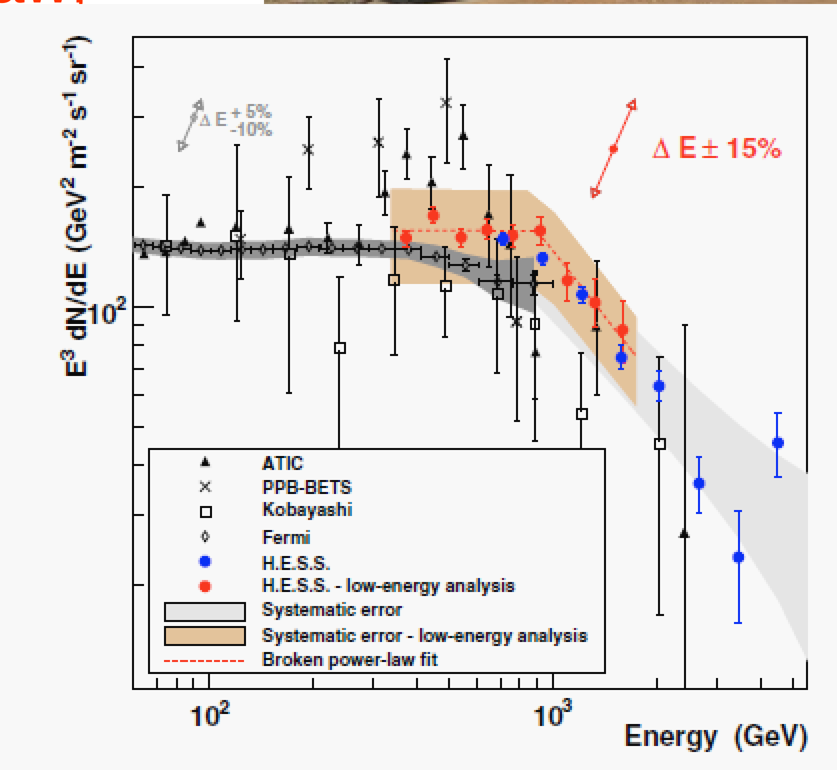



AMS collaboration, PRL 110, 141102 (2013)

# HESS & TeV $e^{\pm}$

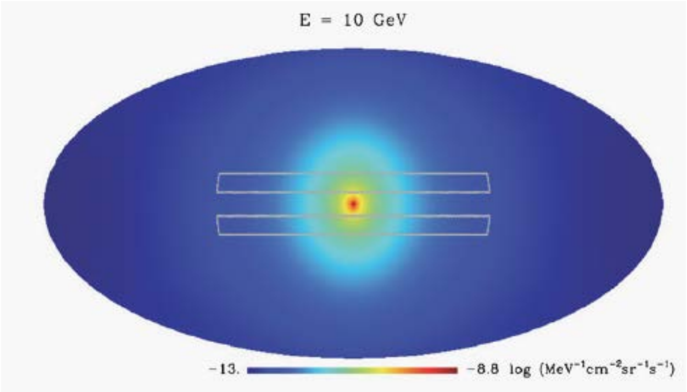


- 5 ground based ~ TeV Cherenkov telescopes, with ‘wide’ field of view.
- HESS looked for electromagnetic showers in the atmosphere
  - Cannot separate $e^+$, $e^-$ and $\gamma$
- Data well fit with a broken power law, with break at 0.9 ± 0.1 TeV.
- Broadly consistent with an excess over theoretical expectations at energies of a few hundred GeV.
- No newer results from Cherenkov telescopes?




HESS Collaboration, A & A, 508, 561 (2009)

# Fermi γ-rays

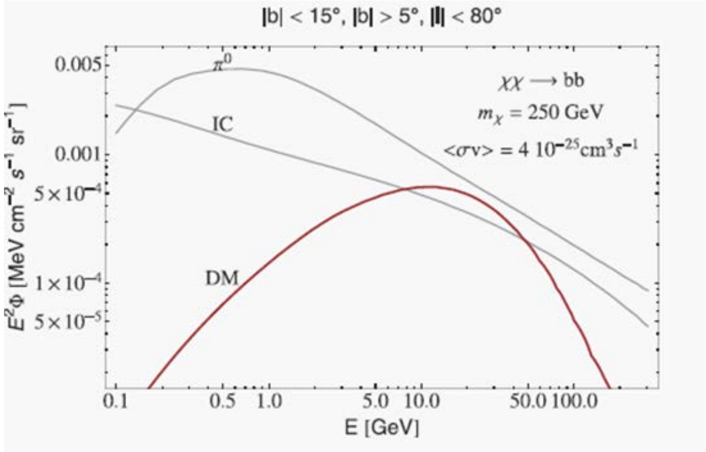


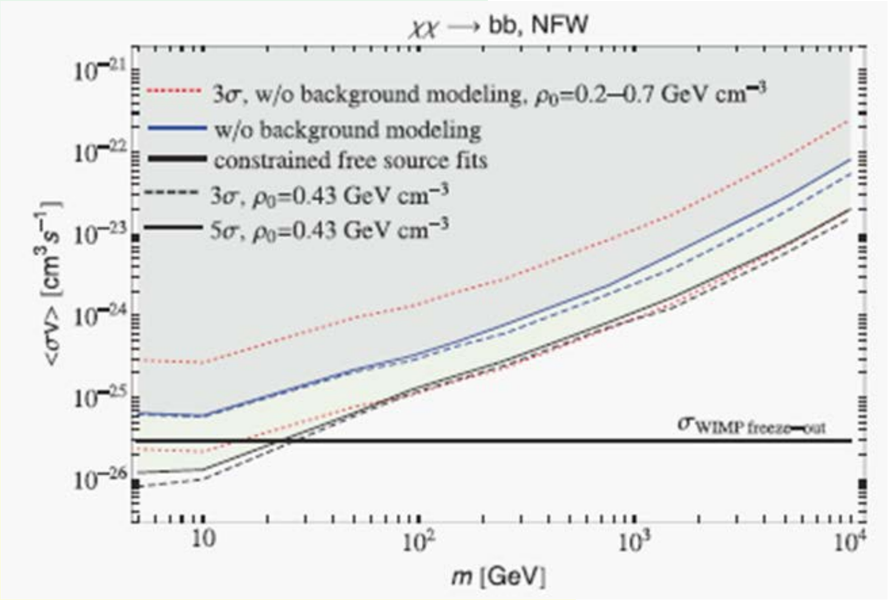

- Satellite….
  - Maximum energy depends on flux
    - ~ 30 GeV
- Looked for excess diffuse γ-ray emission in the inner galaxy, $10^0$-$20^0$ from the galactic center.
  - The GC itself contains γ sources
  - γ from DM annihilation & Compton scattered from $e^{\pm}$ produced in DM annihilation
- Look for excess above diffuse astrophysical expectations
  - No excess seen
  - Conservative limit – no BG subtraction
  - Tighter limit – subtract foreground, based on modelling, measurements

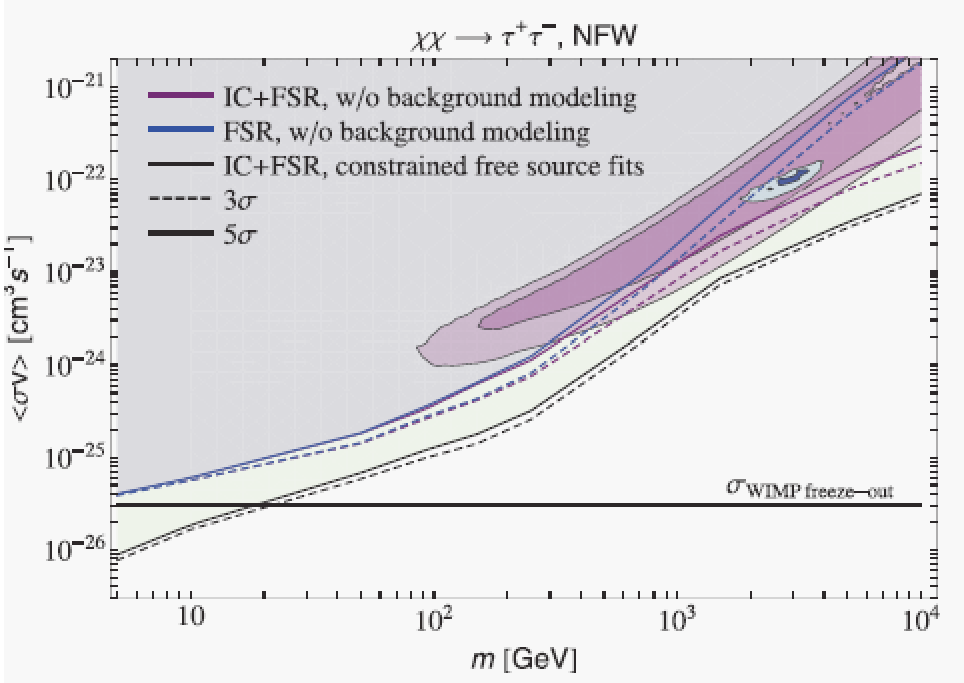
Fermi Collaboration, Ap J. 761, 91 (2012)

# Fermi γ-ray limits

- Limits set for a wide variety of models.
  - For some models, limits are compatible with $e^+$ excess. For other models, not compatible.

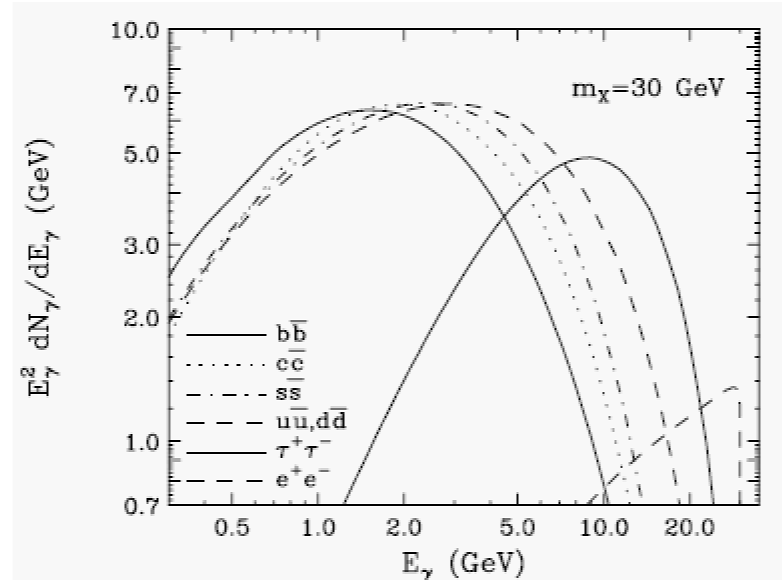


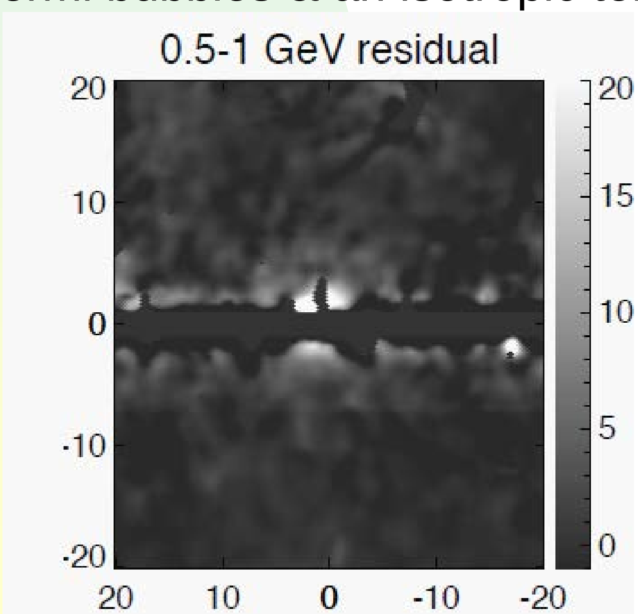



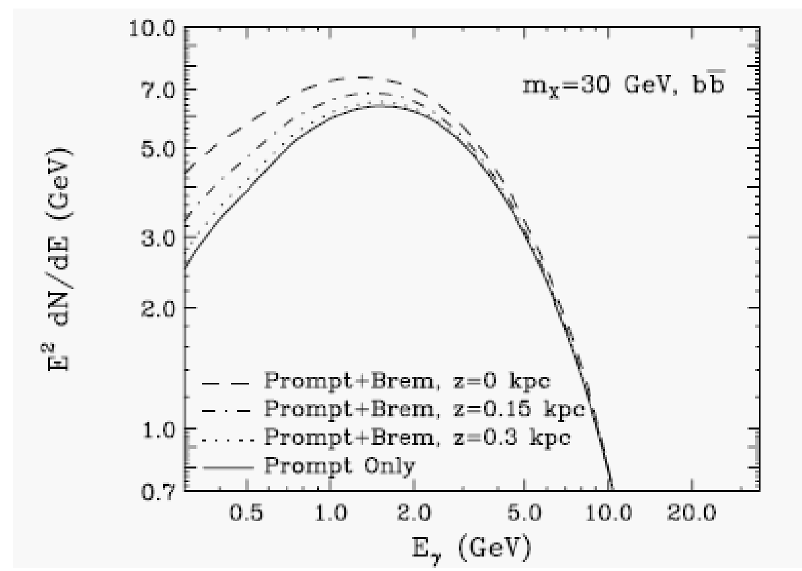
# Fermi, theorists & the galactic center

- An excess of few-GeV $\gamma$-rays seen by Fermi has been interpreted as from light (7-50 GeV?) DM annihilation (+bremsstrahlung…)
- Many other high-energy processes in GC



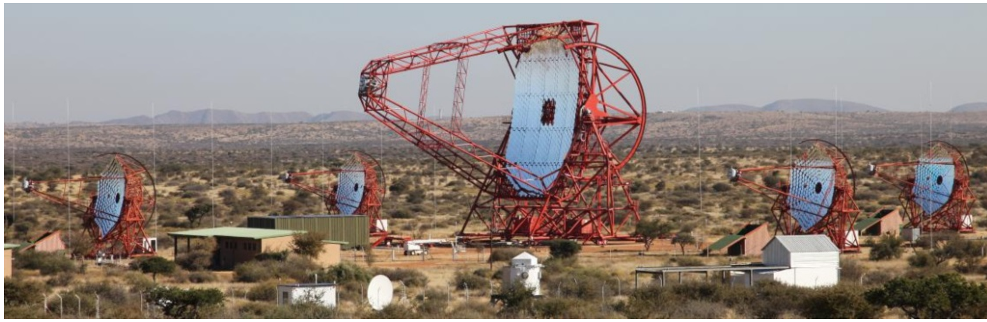

Residual after subtracting diffuse galactic $\gamma$, the Fermi bubbles & an isotropic term



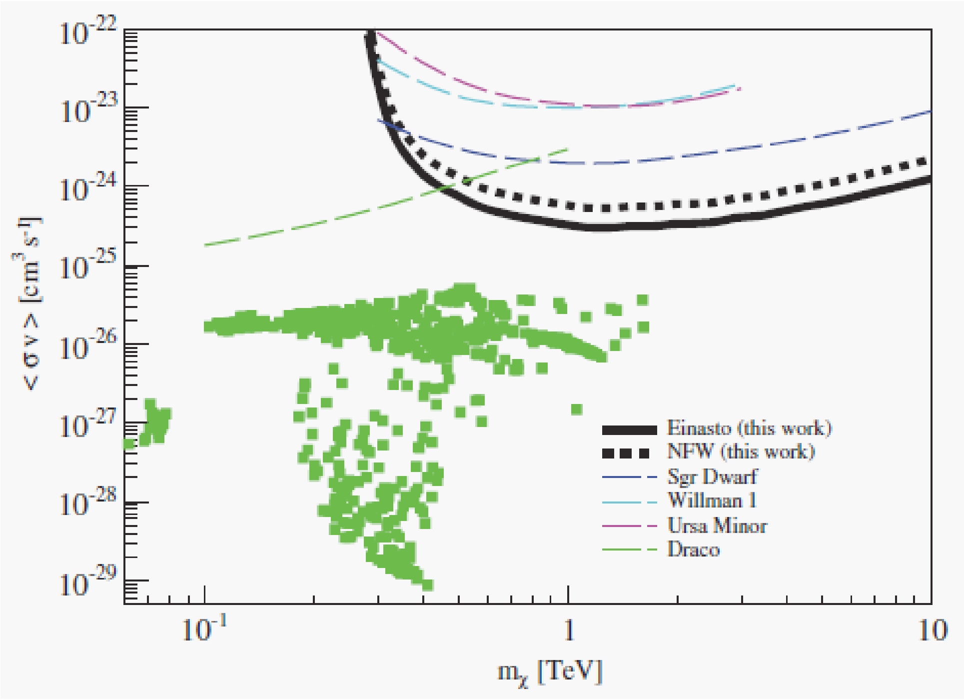




T. Dasylan et a. (D. Hooper) arXiv:1402.6703

# HESS $\gamma$ limits



- Searches for photons from DM annihilation in region near (not in) galactic center
- Threshold ~ 300 GeV
- No evidence for any photon excess



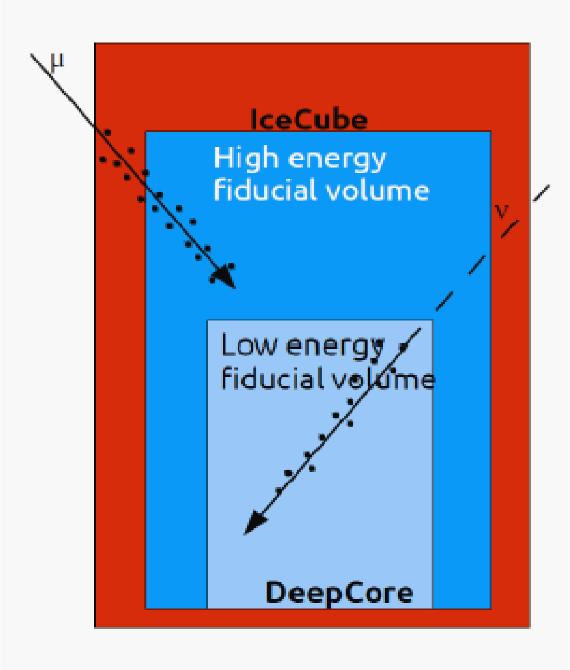

HESS collaboration,
PRL 106, 161301 (2011)

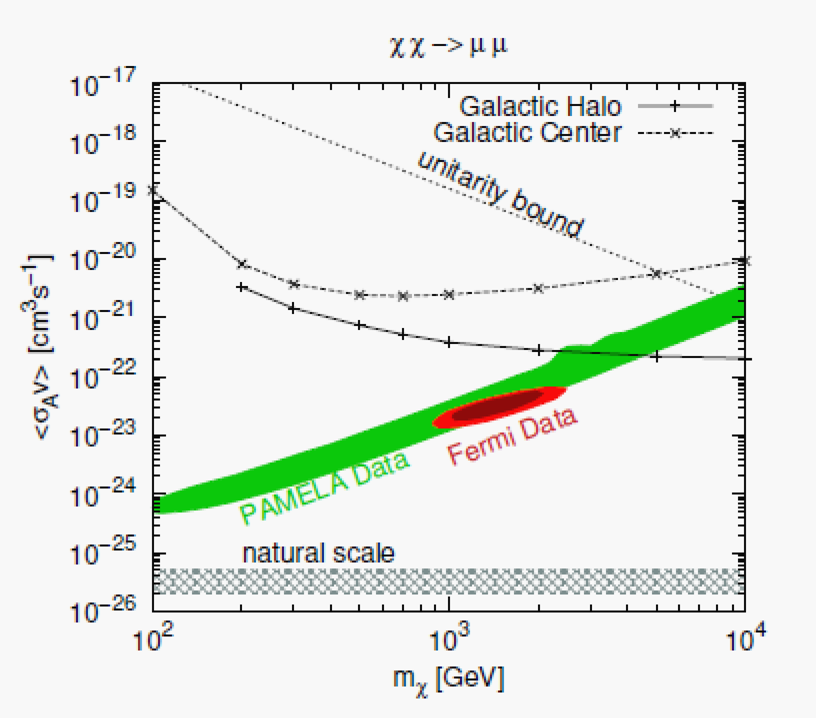
Black – HESS limits from near GC
Green – DARKSUSY points
Dashed Lines –HESS & VERITAS limits from dwarf galaxies

# IceCube galactic ν searches

- At the South Pole, the galactic center is above the horizon.
  - ◆ Use starting events.
    - Much less common -> less sensitivity
- No signal seen; limits from 40-string data at left.
- “Natural Scale” == consistency with thermal relics
- An alternative is to look at the parts of the galactic halo that are below the horizon.

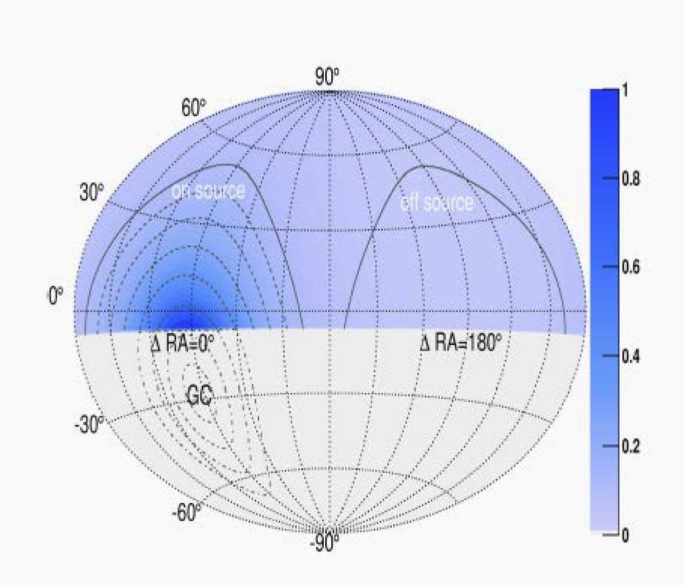
IceCube collaboration, arXiv:1210.3557

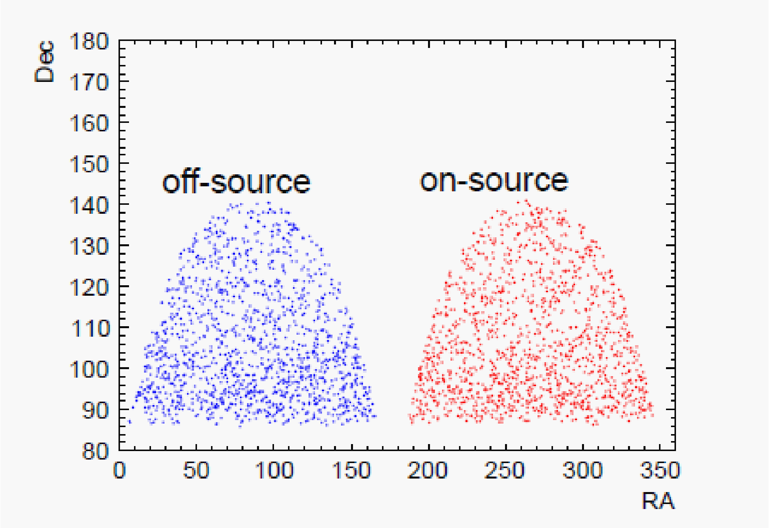


# IceCube Galactic Halo Search

- Lower density, so lower <$\sigma_{A}$ v>
  - Much less uncertainty on halo density
- Find background from off-source region
  - Exposures, detector asymmetries cancel out

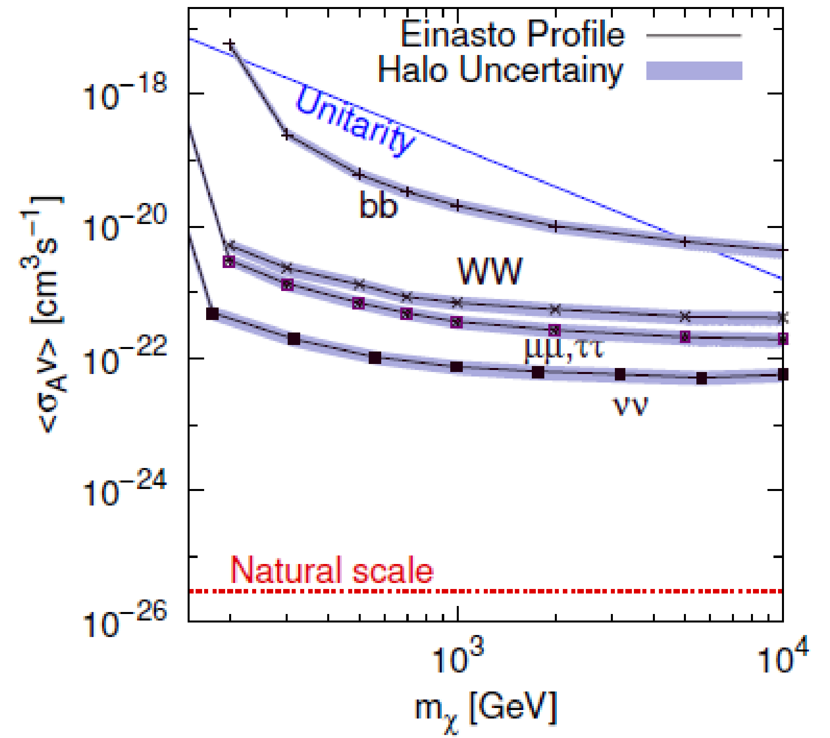


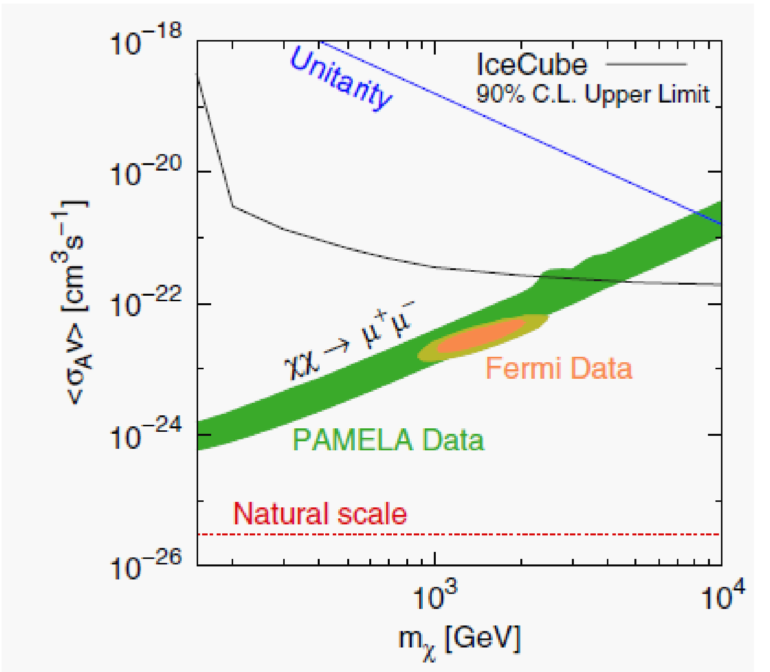




IceCube collaboration PRD 84 022004 (2011)

# Galactic halo results

- 1367 events on-source
- 1389 events off-source
- Limits conservatively assume that dark matter is evenly distributed
  - Substructure will increase the annihilation rate by boosting $<\rho^2>$
    - Substructure might 'boost' the limits by a factor of ~2
  - Not very sensitive to size of galactic halo & choice of halo model.
    - Widths of lines to right show uncertainty due to halo model.

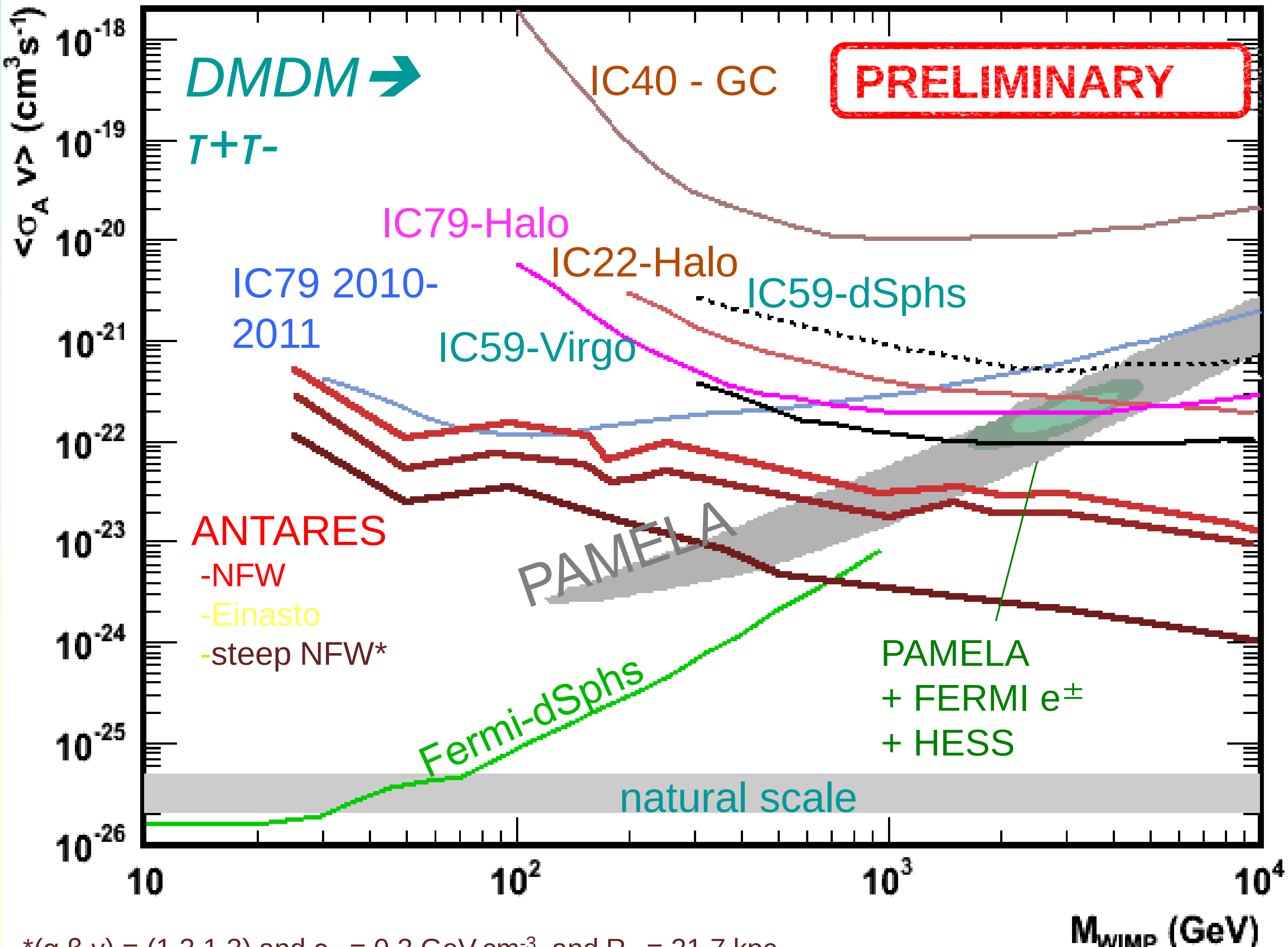


# ANTARES galactic center results

- 1321 days of data
- Backgrounds from scrambled data
  - Elsewhere in the sky
- Two tracking algorithms
  - Single line $\chi^2$ fit for lower energies
  - Likelihood fit at higher energies
- Cuts determined separately for each model (final state, WIMP mass)
  - Angular distance between track & galactic center
    - Resolution improves from $6^0$ to $<1^0$ w/ increasing mass
- Different halo models, etc. are systematic uncertainty

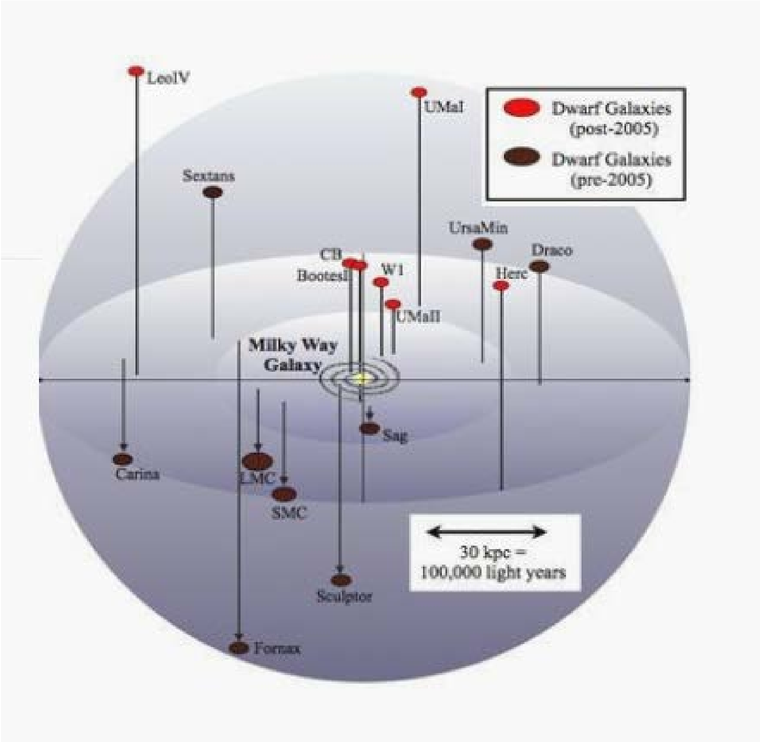
# Results...




*$(\alpha,\beta,\gamma) = (1,3,1.3)$ and $\rho_S = 0.3$ GeV.cm$^{-3}$, and $R_S = 21.7$ kpc.

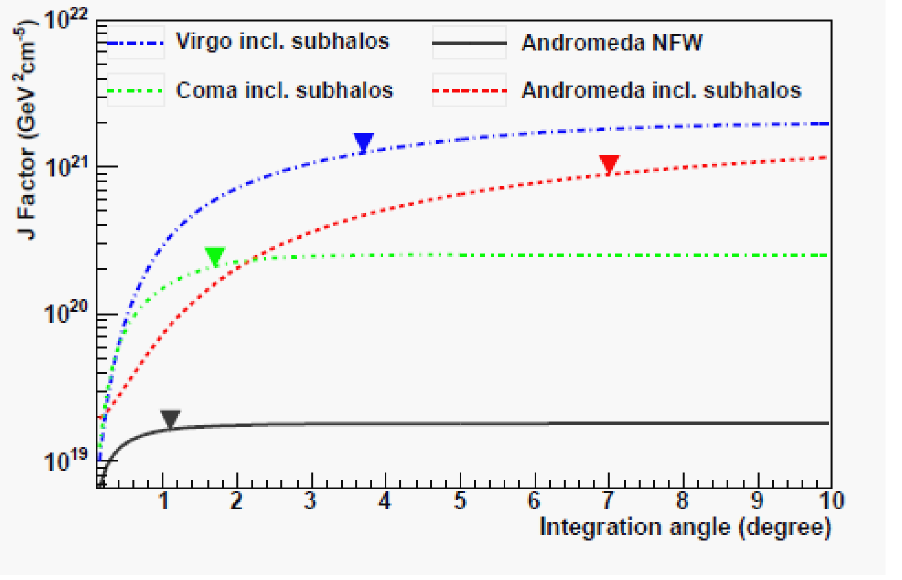
# Beyond the Milky Way

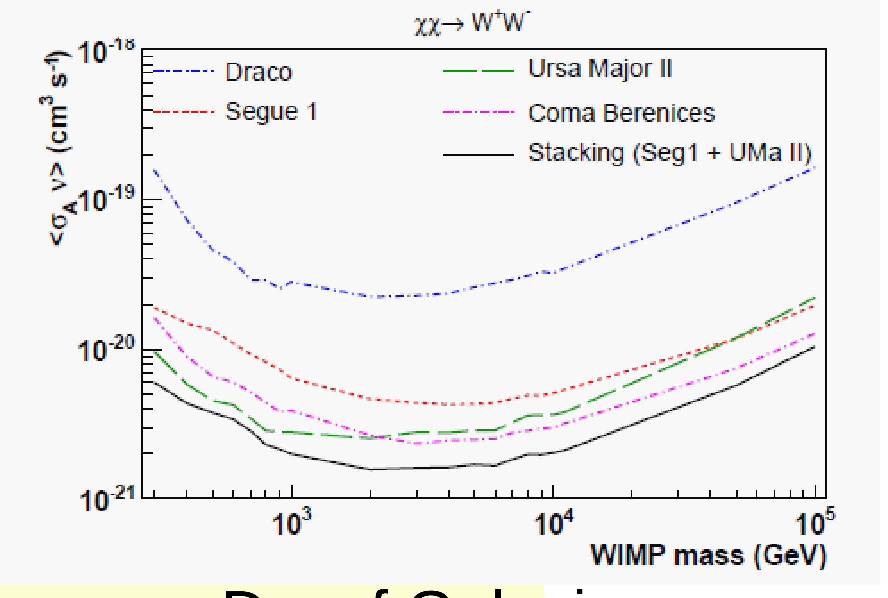
- Insensitivity to dark matter in our galaxy
- Dwarf spheroidal galaxies are expected to have a high ratio of dark:normal matter
  - Low photon luminosity, no high-energy $\gamma$ background
- The Andromeda Galaxy
- Galaxy Clusters
- Quasi-point sources, so improve sensitivity with source stacking.



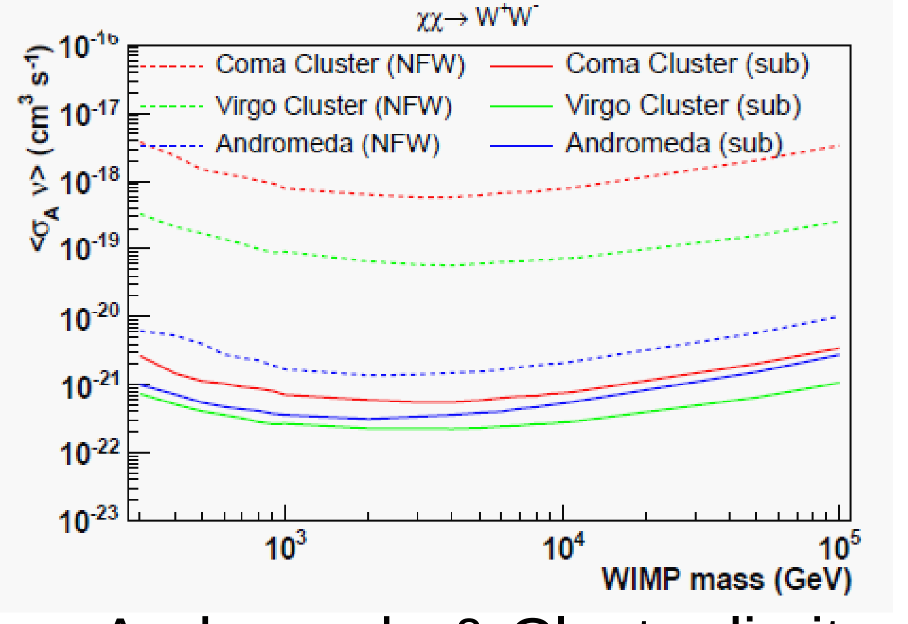
# IceCube results

- 1 year of data with 59 strings
- Matter density profiles considered
- No signal seen




Dwarf Galaxies

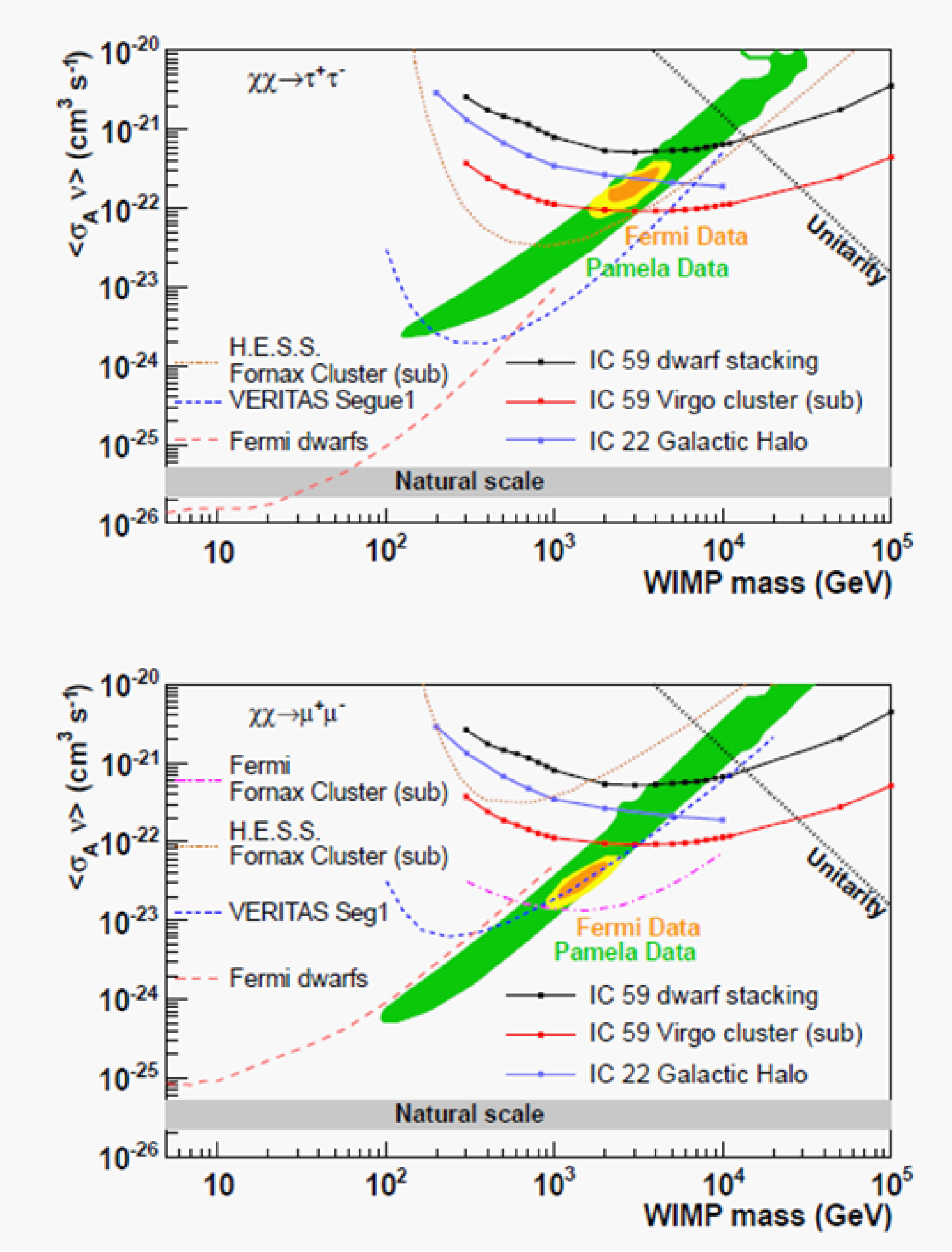



Andromeda & Cluster limits

IceCube Collaboration, PRD88, 122001 (2013)

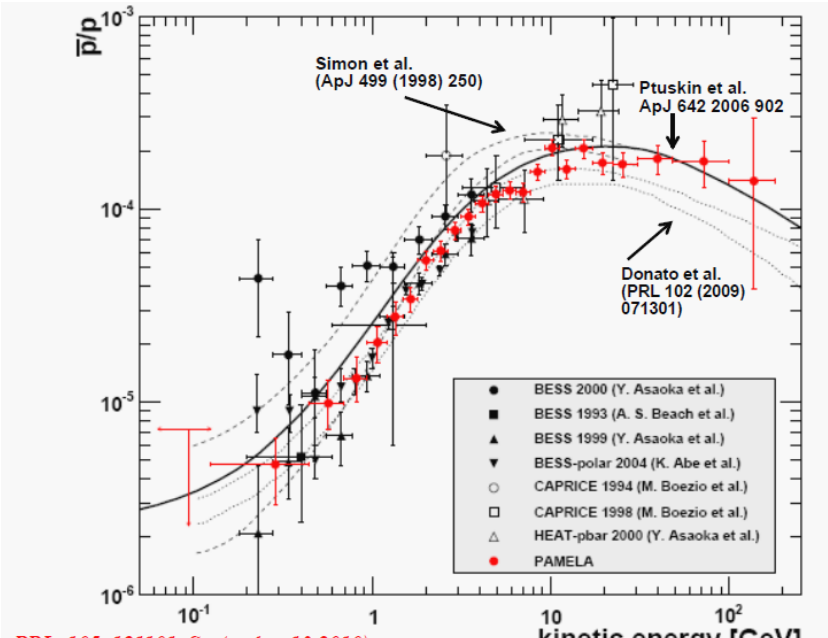
# Dwarf Galaxy comparison

- HESS has similar results, as does Veritas
- The photon limits are somewhat tighter than the $\nu$ limits
- These limits partially infringe on the predicted parameter space if the $e^+$ excess is taken as a DM signal for $\chi\chi \to \mu^+\mu^-$ & $\tau^+\tau^-$
  - $e^+$, $\nu$, $\gamma$ fairly prolific for these channels
    - $\chi\chi \to e^+e^-$ would produce $\gamma$, e+, but not $\nu$



# Antiprotons

- DM annihilation may also produce antihadrons.  The most useful search target are antiprotons.
- PAMELA has measured the pbar/p ratio
- The ratio increases with energy and then levels off, ~ consistent with previous data and expectations.
  - "Places strong constraints on dark matter models…"
    - Publication and limit calculations needed
- Nothing from AMS yet




PRL. 105, 121101, September 13,2010)

PAMELA Collaboration,  NIM A623, 672 (2010)

# Antideuterons

- $\bar{d}$ are produced by coalescence of two anti-baryons produced by dark matter annihilation
  - If 2 baryons are close enough together in phase space
  - Production understood from studies at RHIC & LHC
- It is argued that backgrounds from other sources should be very small
  - $\bar{d}$ were originally proposed to search for antimatter in the universe
- Propagation through the galaxy via diffusion
- Current limits set by BESS balloon experiment
  - $\phi < 1.9*10^{-4}$ $(m^2 s\ sr\ GeV/nucleon)^{-1}$ @ 95% C.L.
    - For energies from 0.17-1.15 GeV/nucleon
- Limits from AMS eagerly awaited

BESS Collaboration, PRL 95, 081101 (2005); Y. Cui *et al.* JHEP 11, 017 (2010)

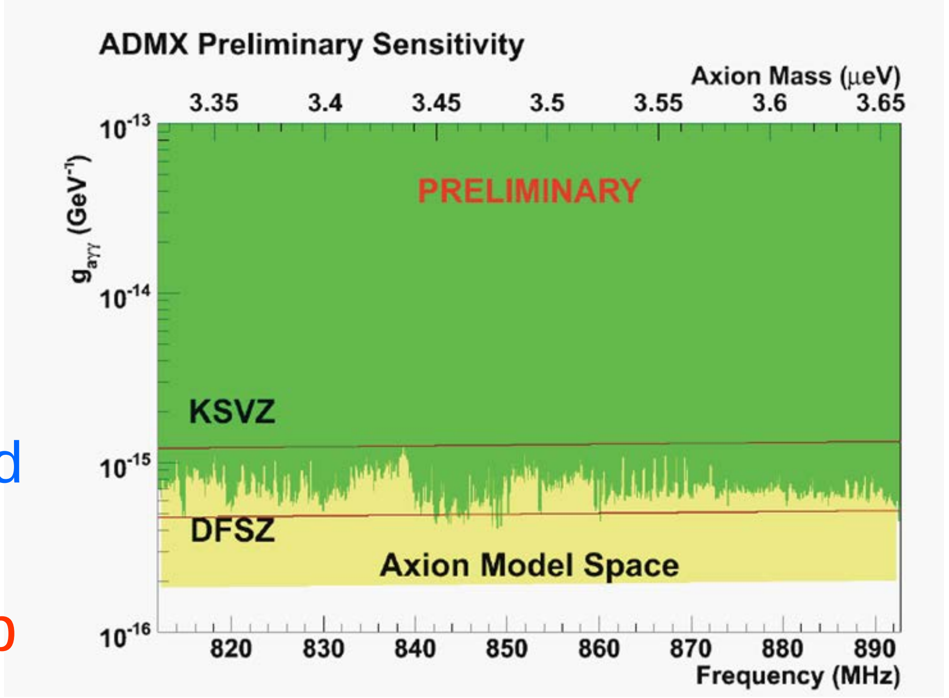
# Other types of searches

- Many other indirect searches exist.  Many do not fit in to the standard approaches.
- Some representative examples:
  - Axions
  - Photon lines
    - 130 GeV and 7.5 keV
      - Many theoretical explanations: sterile neutrinos, scalar dark matter, axino….
  - Secluded dark matter
  - Decaying WIMPs
  - WIMPzillas – ultra-heavy dark matter
  - Strangelets
    - Witten PRD **30**, 272 (1983)
    - Issues with baryon number, etc.

(cf. Surjeets & Georges talks)

# Axions

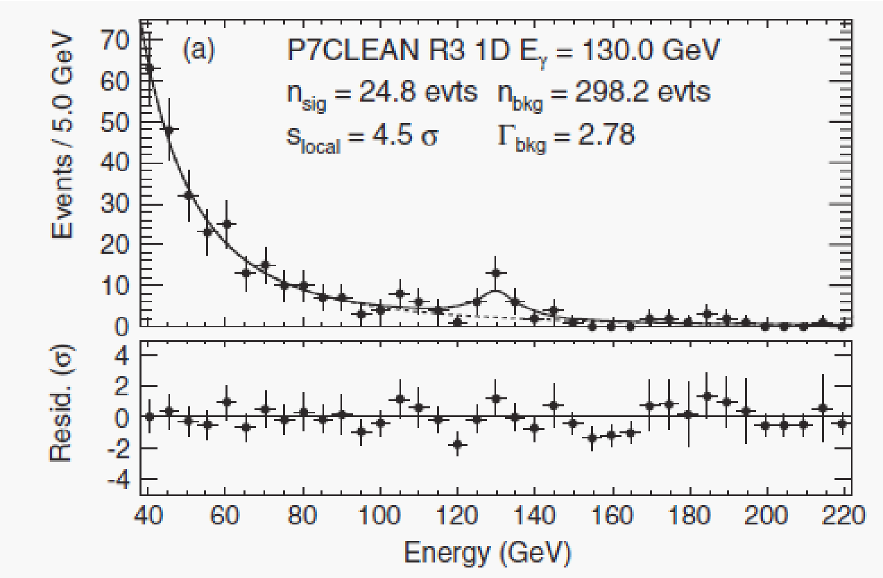
- Particle postulated to solve strong CP problem
  - Why do hadronic interactions conserve CP?
- Mass unknown, couplings depend (modulo theory) on mass
  - Experimentally, if they exist, they are probably light
    - Light dark matter
- Detectable via their coupling to two photons
  - Use high-Q microwave cavity in a strong magnetic field
  - Look for a ‘resonance’ as the cavity frequency is scanned
- Also produced in the Sun, can be studied using a similar setup ‘pointed’ at the Sun




ADMX Collaboration, AIP Conf. Proc. 1274, 109 (2010)

# Fermi $\gamma$ -lines

- An ouside investigator found a 130 GeV $\gamma$-ray line in the data.
  - Consistent with DM annihilation
- Massive publicity
- Detailed investigation by Fermi scientists
  - Very small signal to noise ratio, but significant at a few $\sigma$
  - Seen in all data sets, including those looking at the limb of the Earth
    - Instrumental effect
  - Not dark matter
  - Monochromatic lines are not expected in most WIMP models

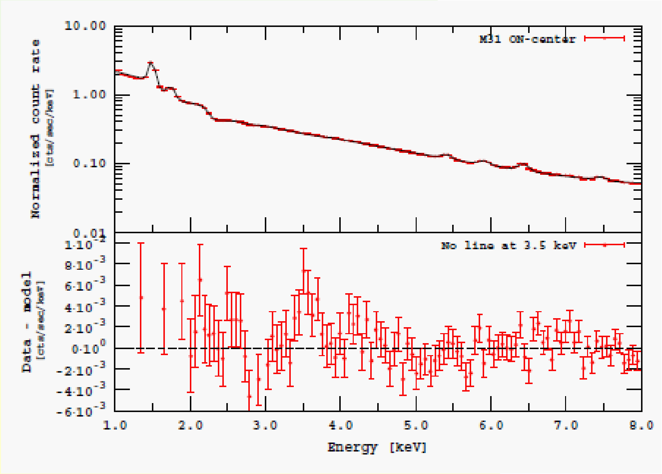



Fermi Collaboration PRD 88 082002 (2013)

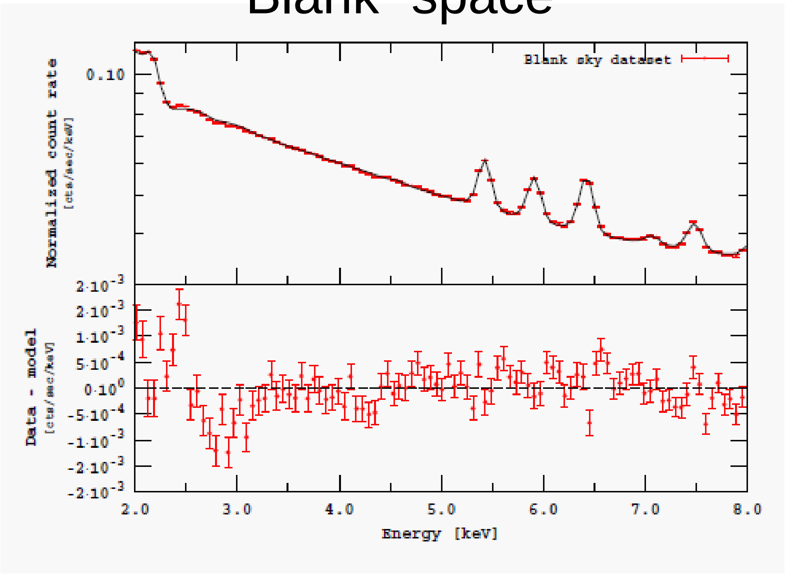
# Light dark matter

- The XMM-Newton telescope sees evidence of a very weak X-ray line
  - E = (3:55 - 3:57) ± 0:03 keV
- XMM is an satellite with 3 grazing-incidence x-ray telescopes
- Lines seen Andromeda galaxy, Perseus galaxy
- Also seen by Chandra telescope

“Line” in the M31 galaxy



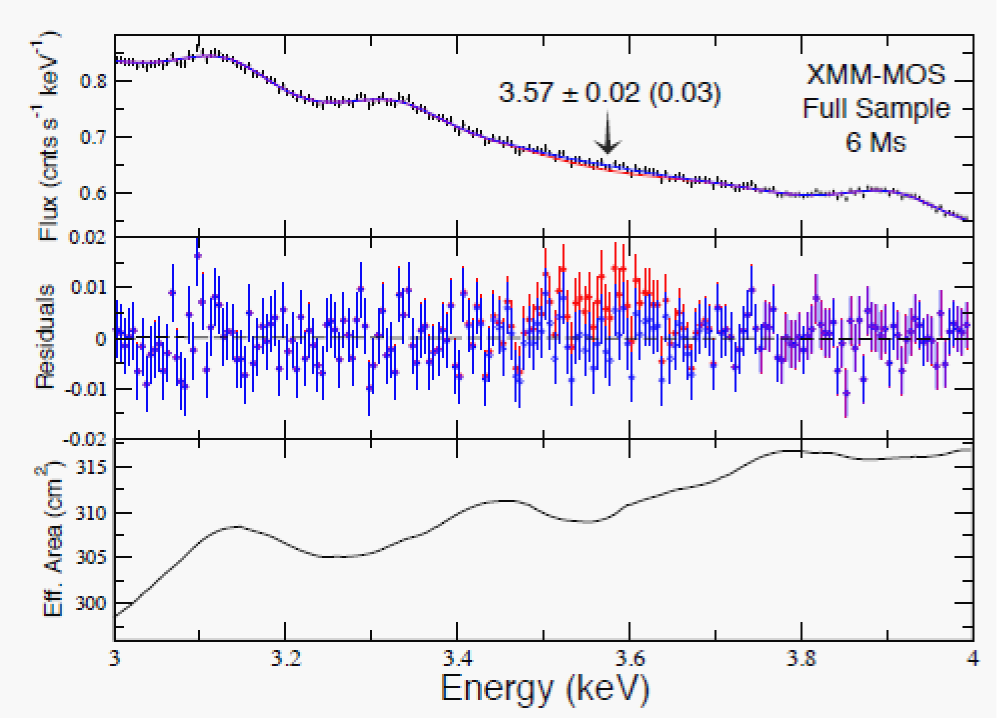

“Blank” space




A. Boyarski et al., arXiv:1402.4119

# The same peak in galactic clusters

- The same peak is seen in a stacked XMM spectrum comprising galactic clusters



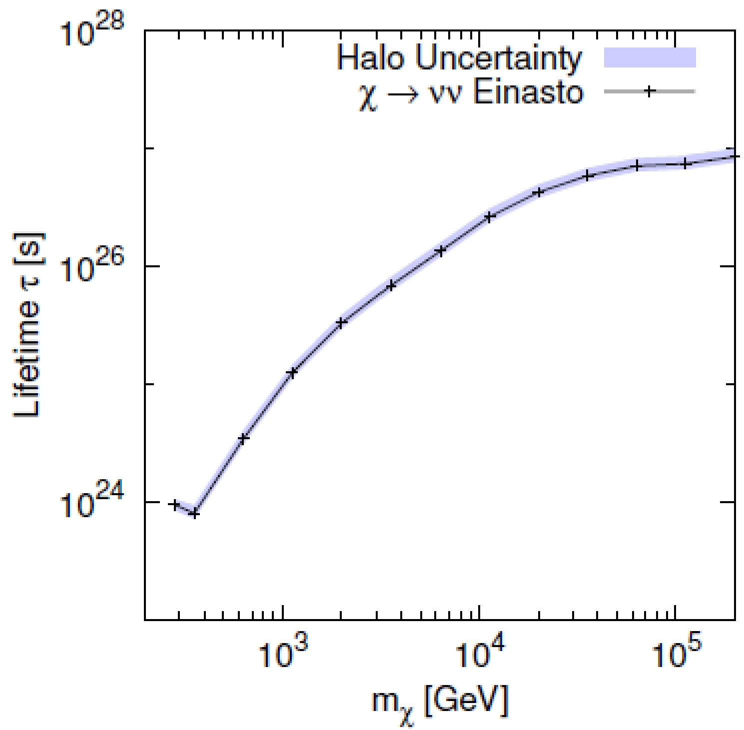

E. Bulbul et al., arXiv:1402.2301

# Theoretical explanations

- Consistent with the decay of a light (7 keV) radiative neutrino
  - J. Cline *et al.*, arXiv:1404.3729
  - S. Baek & H. Okada, arXiv:1403.1710
- Scalar dark matter
  - K.S. Babu *et al.*, arXiv:1404.2220
- Axino
  - K. Kong et al., arXiv:1403.1536
- Etc.

# WIMP decay

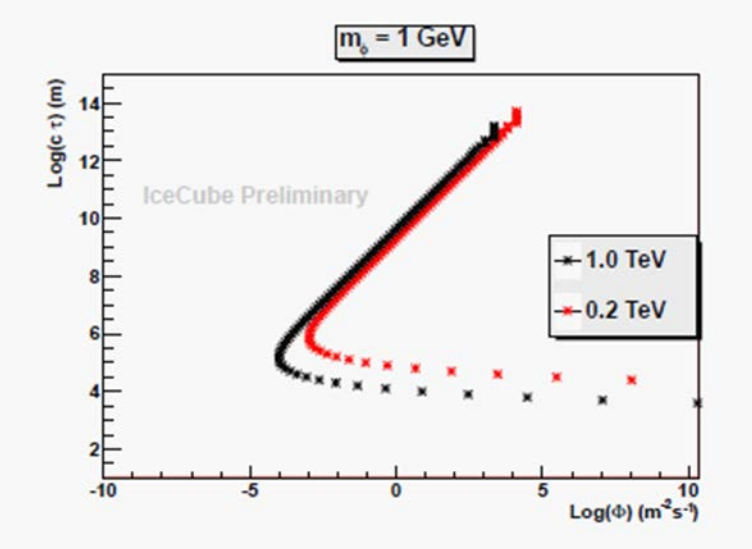
- Look for WIMPs decaying to a set of final states (e.g. $\nu\nu$, gg…)
- Same abundance assumptions as WIMP annihilation searches
- … similar analyses
  - WIMP may cluster in Earth, Sun, galactic center, halo….
- IceCube galactic halo search set a limit on lifetimes $>10^{24}$ s
  - Similar caveats to WIMP annihilation search.




IceCube – Phys. Rev. D84, 022004 (2011)

# Secluded Dark Matter

- Decoupled from standard model
- WIMPs annihilate to metastable mediators, which later decay to standard model particles
- Many signatures are similar to more conventional dark matter
- However, secluded dark matter mediators can also decay inside a neutrino detector
  - The challenge is to separate this from a neutrino interaction
  - Signature depends on mediator mass
- Secluded DM with a light mediator produces two not-quite parallel muon tracks.

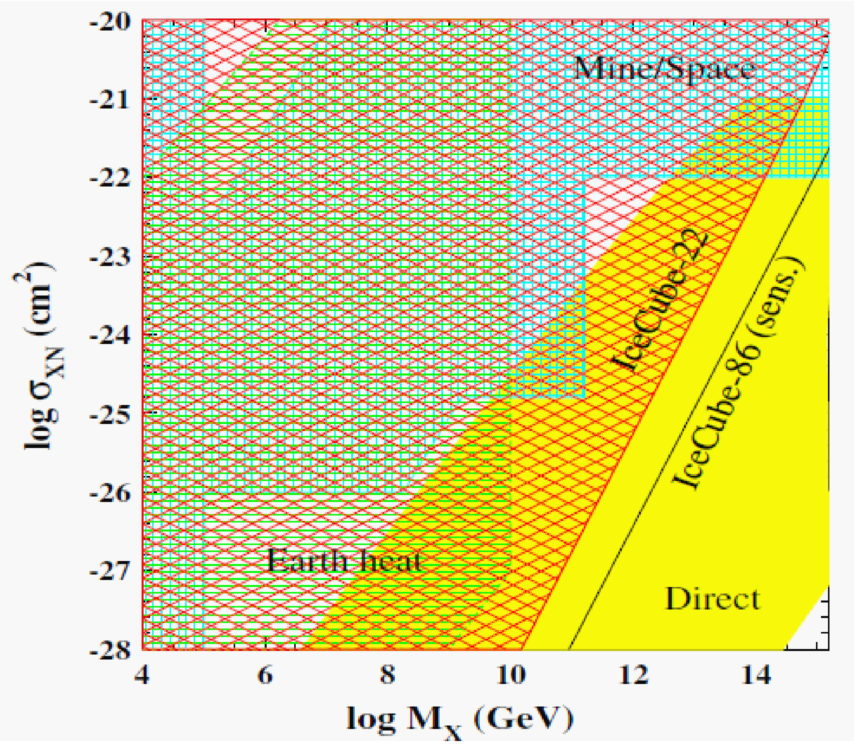



IceCube projected sensitivity for A 1 GeV mediator & DM masses of 200 GeV & 1 TeV

IceCube Collaboration arXiv:1309.7007

# WIMPzillas, SIMPzillas

- Ultra-heavy dark matter particles
  - $10^{15}$ GeV > M >> $10^{4}$ GeV
  - Produced in early Universe, not in thermal equilibrium
  - Wimpzillas interact weakly
  - simpzillas interact strongly
- Direct detection limits exist
- Can also be captured in Sun & annihilate
  - IceCube ν flux limits provide tightest limits on WIMP/SIMPzillas with spin-dependent interactions

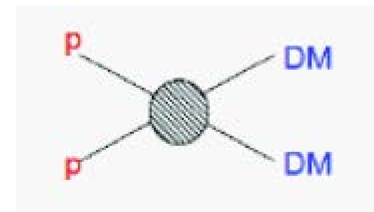



Albuquerque & Perez de los Heros – PRD81, 063510 (2010)

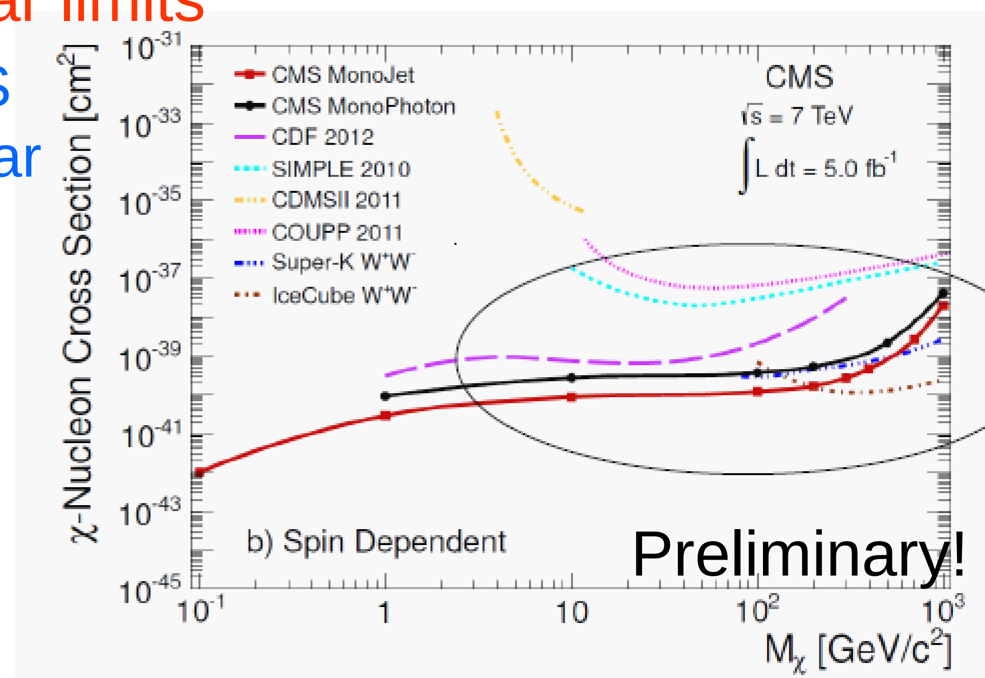
# Solar limit comparisons with the LHC

- Heavily model dependent
- Assume an effective quark-DM point interaction
- This interaction produces monojets in pp collisions
- Compare CMS monojet results with IceCube spin-dependent solar limits
  - At high WIMP masses, CMS limits lose strength, and Solar limits are the most stringent
- **Many** theoretical caveats…

$$\lambda^2/\Lambda^2\,(\bar{q}\gamma_5\gamma_\mu q)(\bar{\chi}\gamma_5\gamma^\mu\chi)$$




Ian covered…




IceCube + theorists

# Channel sensitivity comparison

- Relative sensitivity depends on the decay model.
- General comparisons are lacking
  - A specific case: a heavy WINO, which would not be seen in direct detection or at the LHC
    - Mostly decays $\chi\chi \to W^+W^-$ (also $\gamma\gamma$, $\gamma Z$)

Cosmic $\mu$wave

$\gamma$-line from galactic center

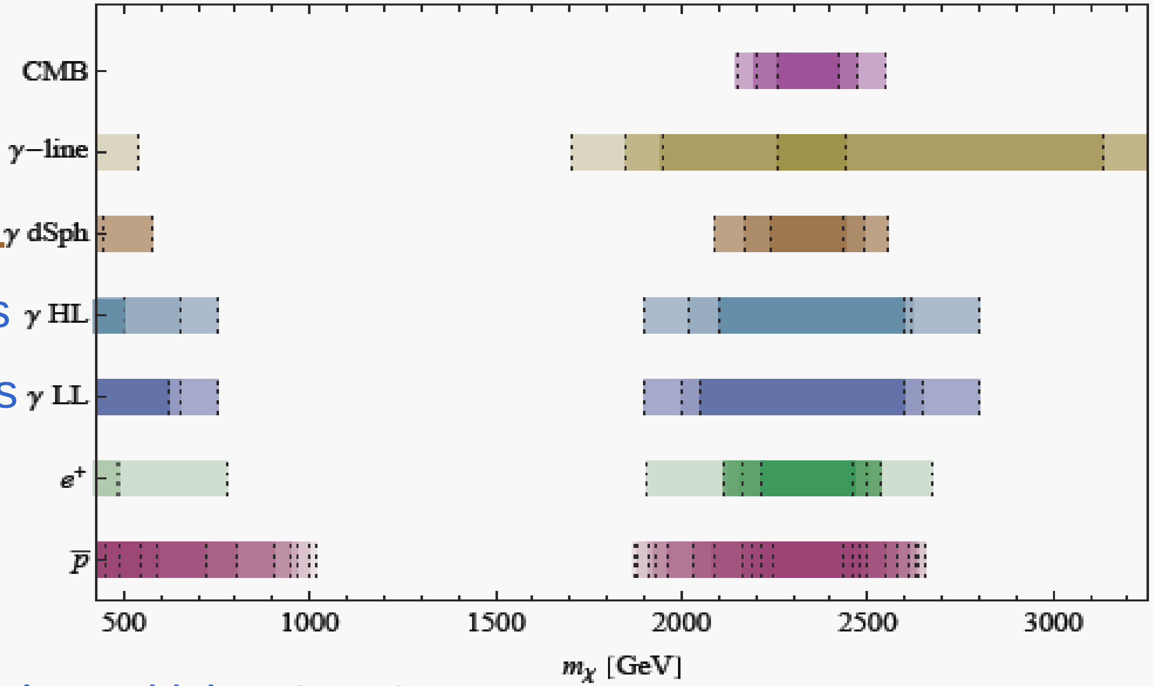
$\gamma$ from dwarf spheroidal.

$\gamma$ from high gal. latitudes

$\gamma$ from low gal. latitudes

$e^+$

antiprotons




dbar – AMS may have marginal sensitivity; GAPS

Shadings show range of assumptions

A. Hryczuk et al., arXiv:1401.6212

# Future prospects: $\nu$ & $\gamma$

- $\nu$
  - IceCube continues to gather data. Combining multiple years should give a factor of ~3 improvement in sensitivity.
    - PINGU will push thresholds down to a few GeV
  - ANTARES will continue to gather data, but the relative improvements will be smaller.
  - KM3NeT would improve on the ANTARES limits by a factor of ~ 10.
- $\gamma$:
  - HESS, Magic etc. can take more data; factor of ~ several improvements possible
  - CTA (Cherenkov Telescope Array) offers a factor of 10 more data, leading to significantly improved limits.

Bullet cluster (Surjeet – this morning)

# Future prospects: antimatter

- $e^+$: May already be systematics limited, but data at higher energies would be helpful
  - AMS can push to higher energies
  - Further understanding of nearby sources would help.
- Antiprotons
  - AMS should provide high quality measurements up to high energies.
  - Can potentially provide good limits for models where hadronic final states predominate.
  - Calculations needed
- Antideuterons
  - AMS results expected any day now.

# Future prospects - general

- With current detectors, expect mostly incremental progress over next few years.
  - KM3NET and CTA offer the possibility of a factor-of-10 improvement over existing detectors.
  - The AMS deuteron limit will be ~100 improvement
    - Or a signal????
- Theoretical/computational work will lead to improved limits
  - Density profile near the galactic center
  - Understanding of final states
  - For $e^{\pm}$,pbar, modelling of backgrounds due to nearby cosmic-ray sources
- Indirect detection proves a very diverse set of dark matter models; it is the only way to test some non-standard models.

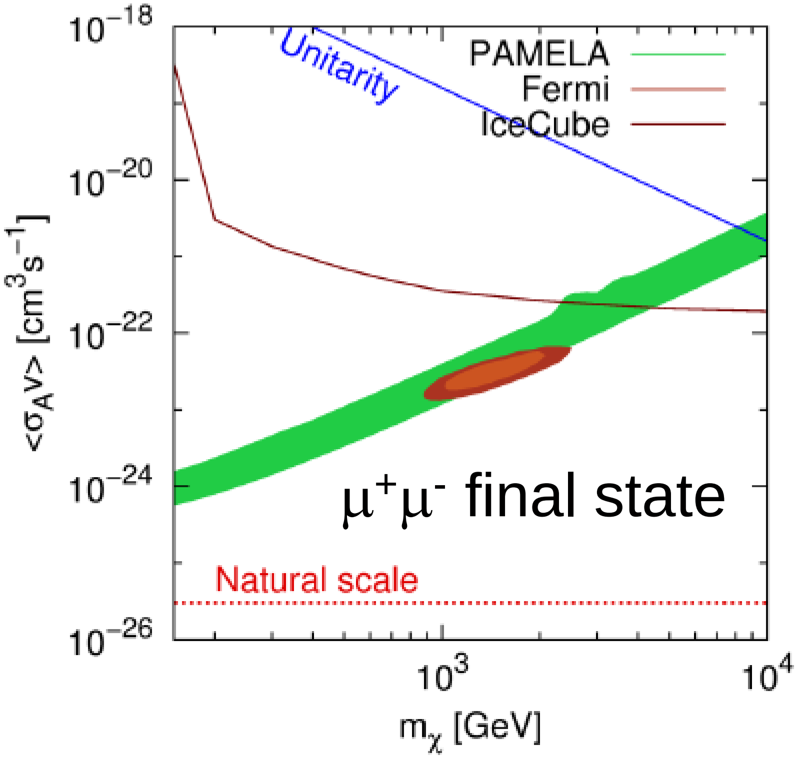
# Conclusions

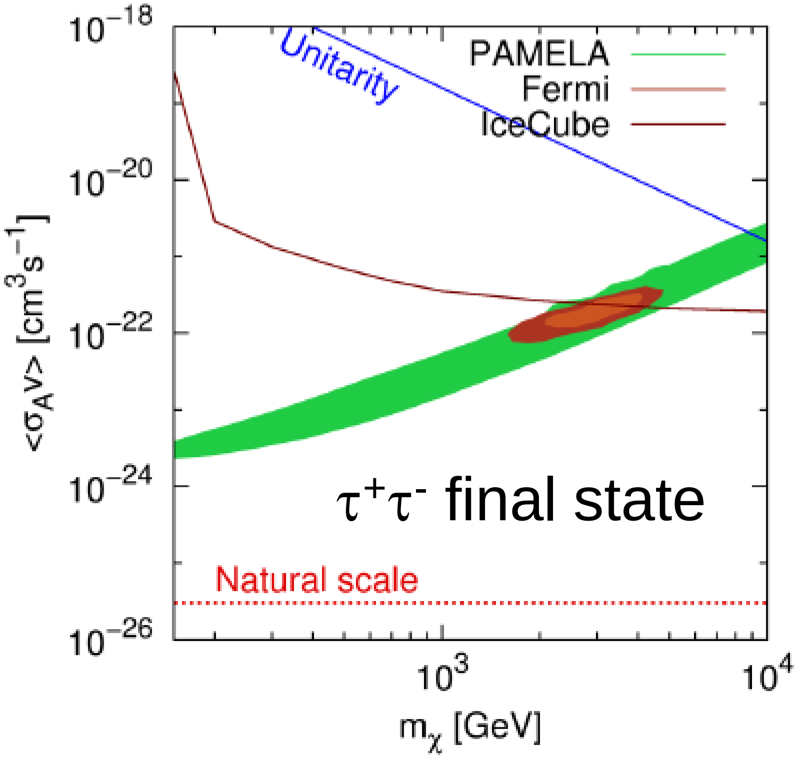
- Dark matter was first observed in the cosmos, so it is natural to search for particle DM there.
- A very wide range of searches are possible:
  - Many probes have been studied: $e^{\pm}$, antiprotons, $\overline{d}$ $\gamma$ and $\nu$
  - Many searches are insensitive to local DM sensity
- The Sun allows for unique studies of DM with spin-dependent couplings
  - Limits probe many open areas of SUSY phase space.
- Studies of $e^{\pm}$ find an excess, compatible with DM or with a nearby cosmic-ray sources. Other searches have set a variety of limits.
  - Many limits are competitive with those from direct searches.
- As new instruments appear (CTA, KM3NeT), much tighter limits will be set, or a signal seen.

# Backups

# IceCube, PAMELA & Fermi

- PAMELA, Fermi & HESS report excess positrons, electrons & electrons respectively from the galactic center.
  - If from leptophilic dark matter, annihilation should also produce $\nu$.
  - Due to $e^{\pm}$ energy loss, the annihilation must be nearby (1 kpc)
    - IceCube can constrain the masses of this dark matter

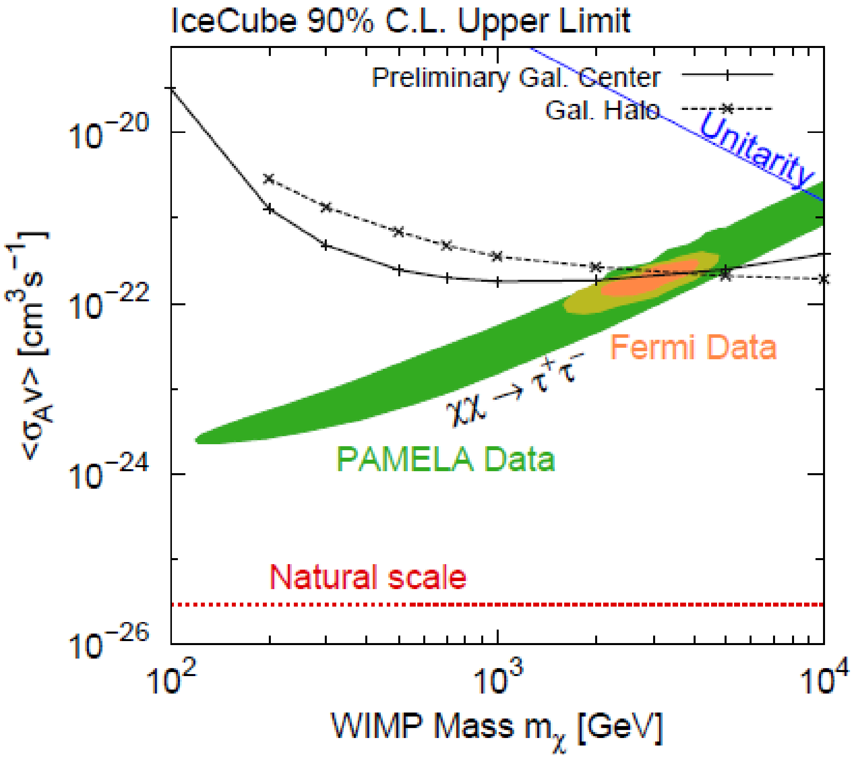


# Back to PAMELA & Fermi

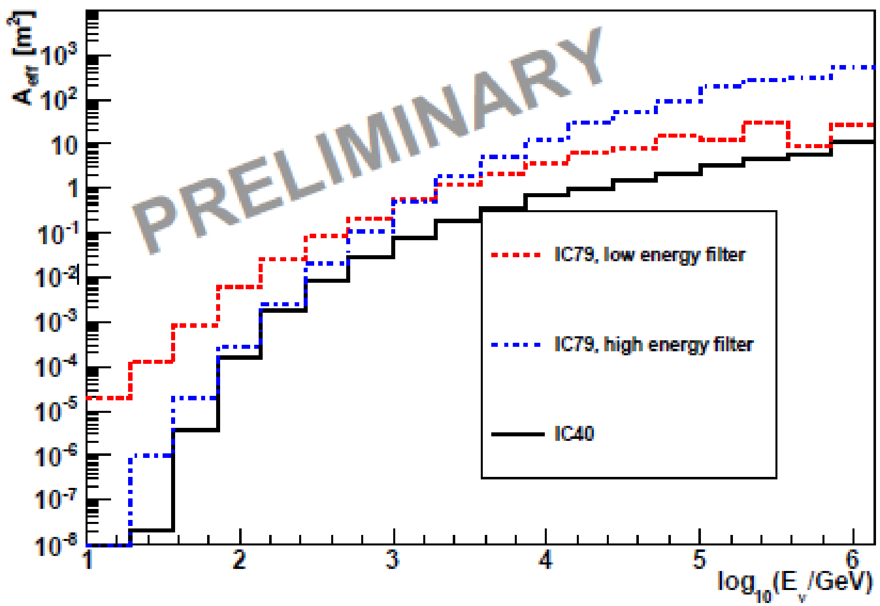
- The galactic center provides a similar constraint as the halo analysis
- N.b. IC40 ~ 2* the data of IC22

IceCube Preliminary



# Sensitivity vs. energy

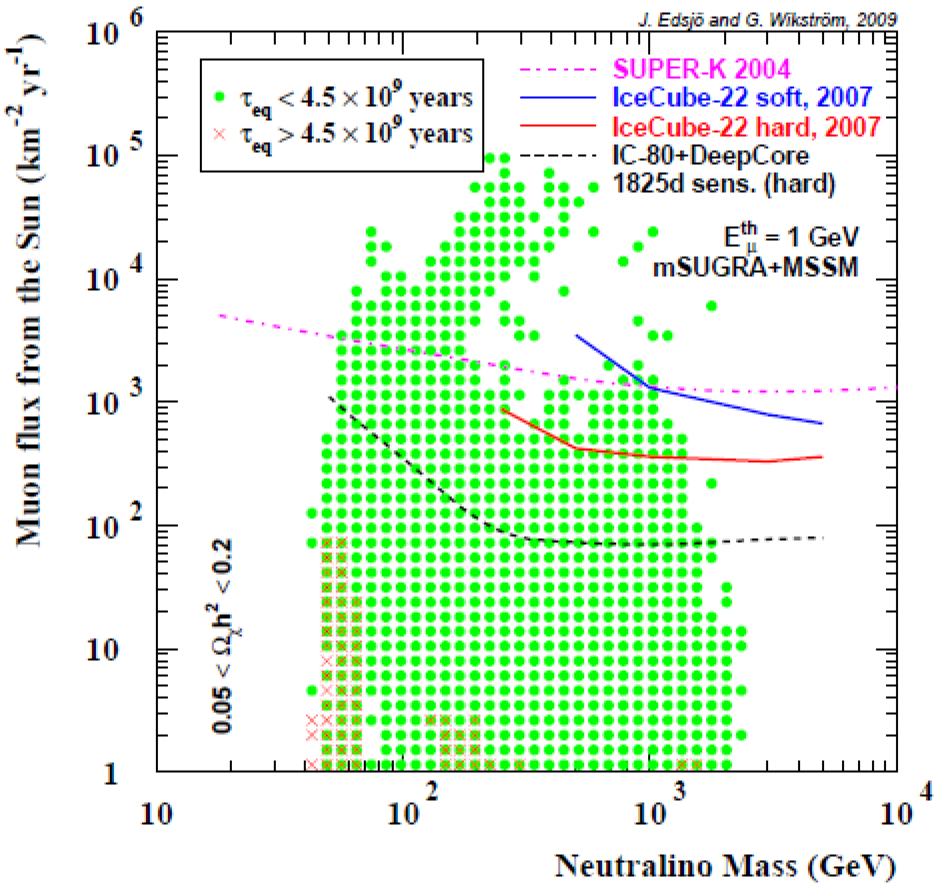
- Effective area increases with energy.
  - Neutrino cross-section and $\mu$ range both increase with energy
- At energies from 10-100 GeV DeepCore provides orders-of-magnitude improvement in sensitivity.
- In longer term, the proposed PINGU/MICA may push this down to ~1 GeV




Filter level effective area for IC40 & IC79 low-energy & high-energy filters.

IceCube – 2011 ICRC – arXiv:1111.2738

# Equilibrium Times vs. $T_{Sun}$



# IceCube & DeepCore

- 1 km$^3$ neutrino detector
- 5,160 optical modules
  - 10" PMT + Complete DAQ system
- 78 'standard' strings
  - 125 m string spacing
  - 17 m DOM spacing
  - ~100 GeV energy threshold
- 8 DeepCore Infill strings
  - with denser spacing
  - 50/60DOMs w/7 m spacing
    - In clearest, deepest ice
  - ~ 10 GeV energy threshold