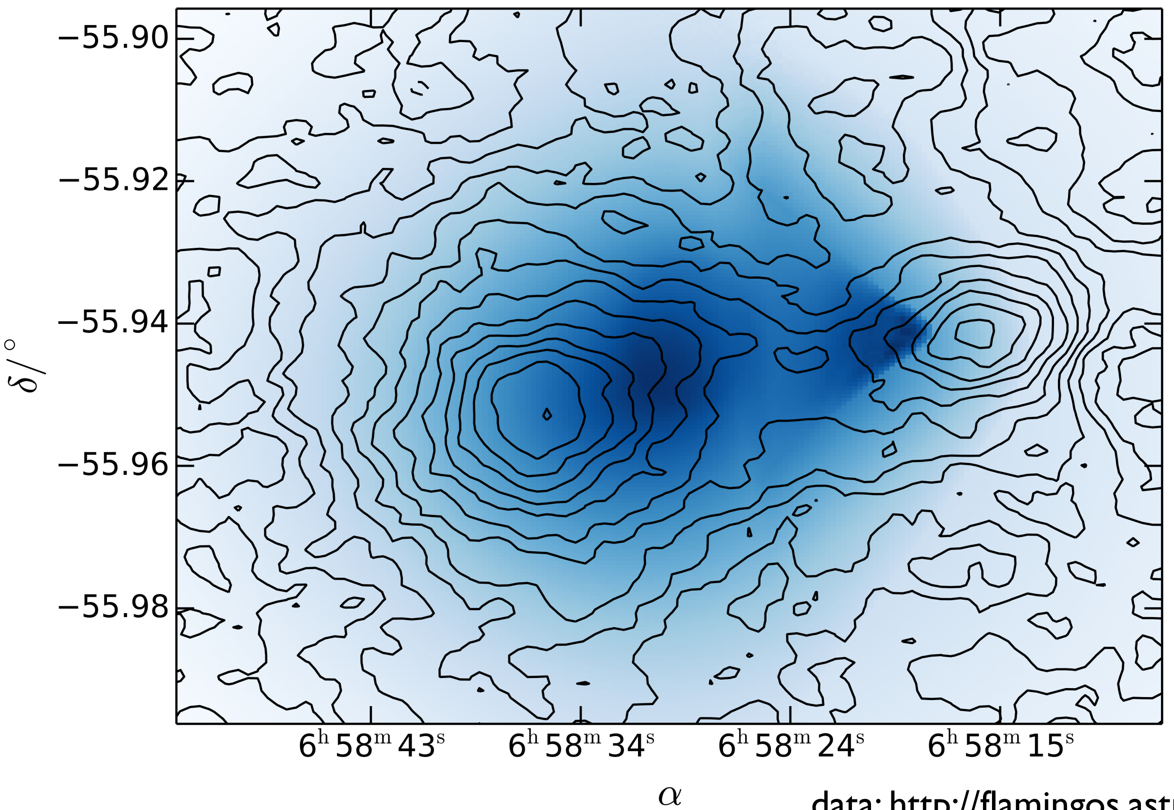
Search for Dark Matter with Neutrinos

HAP Dark Matter Workshop 2015

Martin Bissok

Bullet Cluster (1E 0657-558)

- two clusters post-collision, hot gas separated from mass
  - gas distribution from X-ray (blue shades)
  - mass distribution via weak lensing (contours)



majority of mass
- invisible
- collisionless

data: http://flamingos.astro.ufl.edu/1e0657/public.html

Searches for Dark Matter

production at colliders

- LHC

indirect detection via annihilation

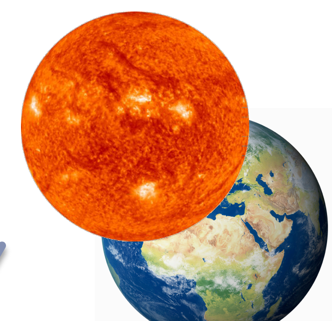
- accumulation in clusters, galaxies, Galactic halo
- accumulation in massive bodies

direct detection

- Xenon
- LUX
- CDMS
- CRESST
- EDELWEISS
- DAMA/Libra

γ (Fermi)
e^+,p^+ (Fermi, AMS, PAMELA)

ν (IceCube, Antares, SuperK)

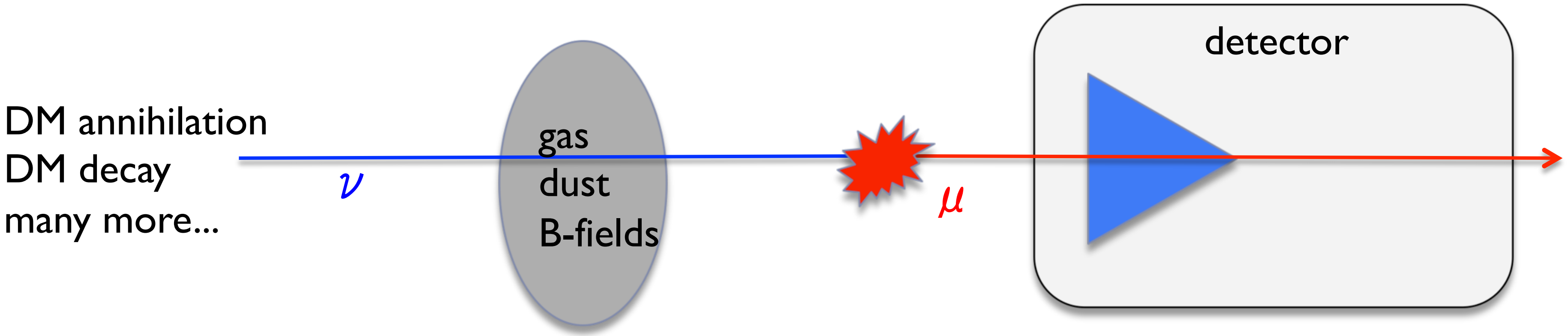


sensitive to annihilation cross section

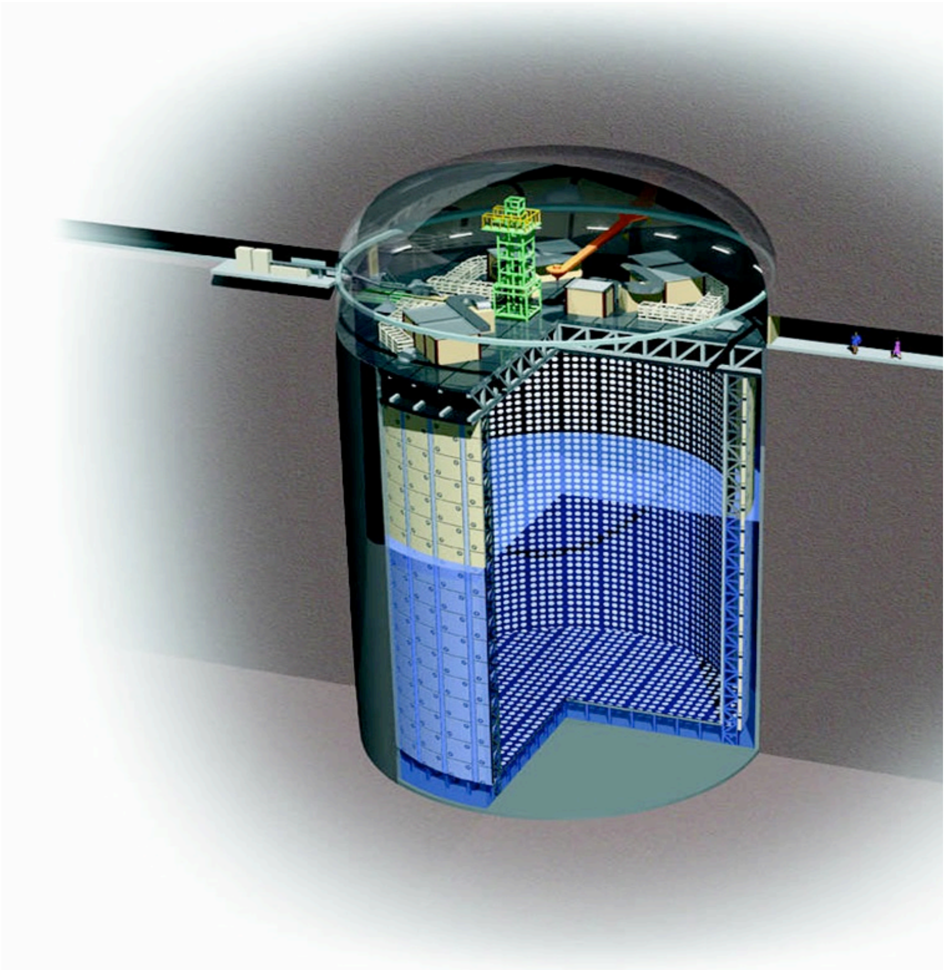
sensitive to WIMP-nucleon scattering cross section

Neutrino Detection via Cerenkov Light

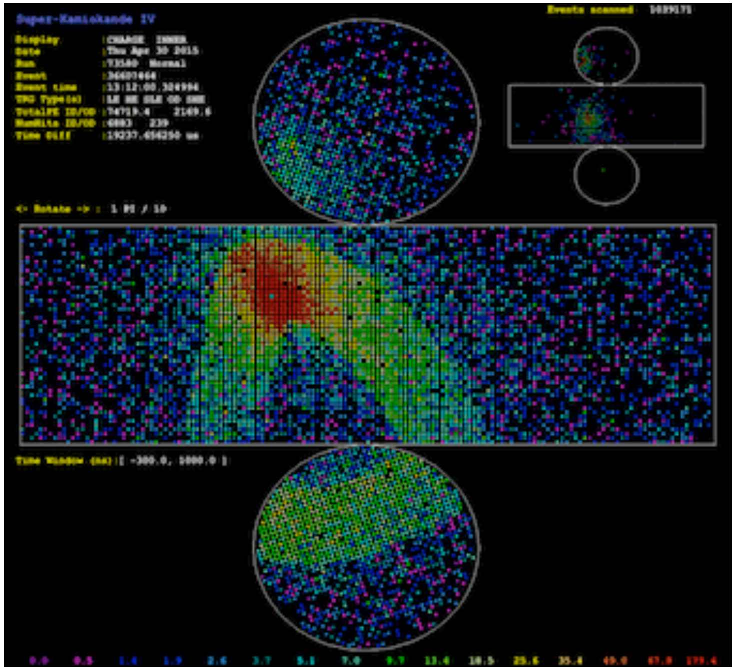
- neutrinos retain information on
  - direction
  - energy
  - absorption negligible (good and bad)
  - muon-neutrinos: simple direction reconstruction
- understood atm. backgrounds
- ~~no extraterrestrial background~~ (arXiv:1405.5303)



Densely Instrumented Arrays - SuperK

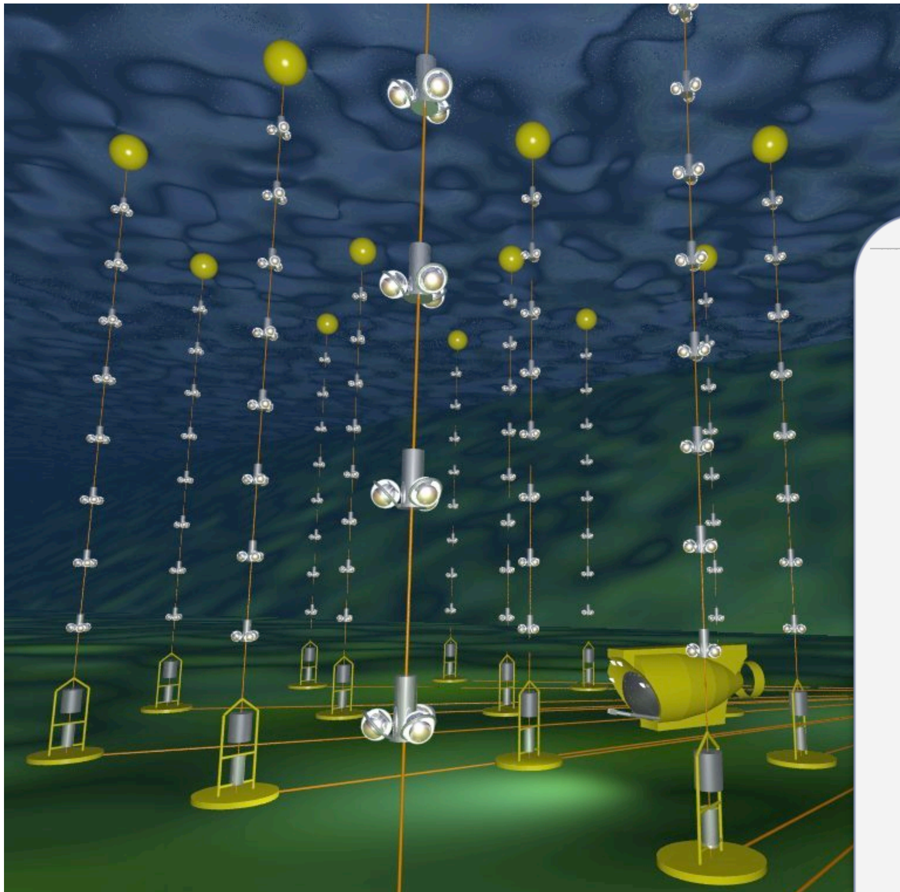


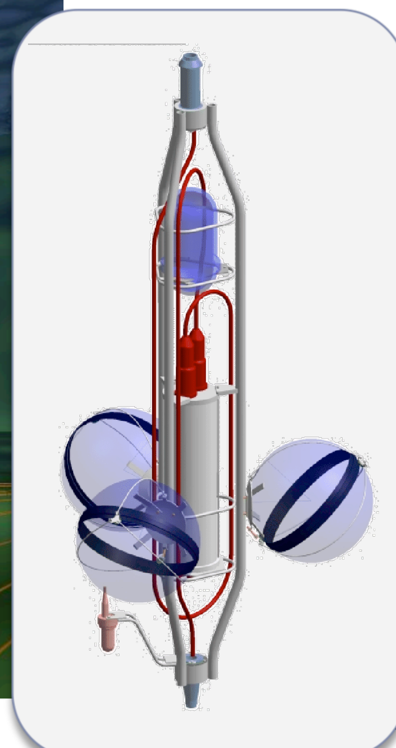
- 1km deep, Kamioka-mine, Japan
- 50kt purified water in tank: 32m (d), 42m (h)
- 11,146 PMTs on walls

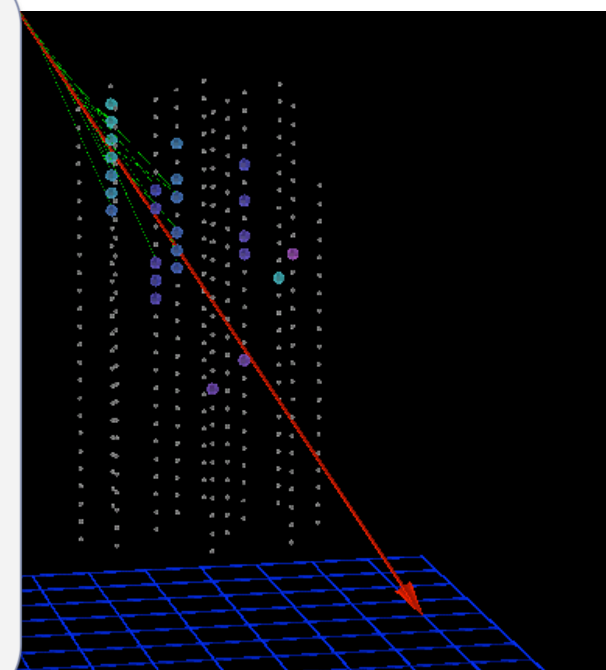


Large-Scale Sparse Arrays - ANTARES

- 2.5km below Mediterranean Sea
- about 900 OMs
  - 12 lines, 350m long
  - 75 OMs each, 3 per stage

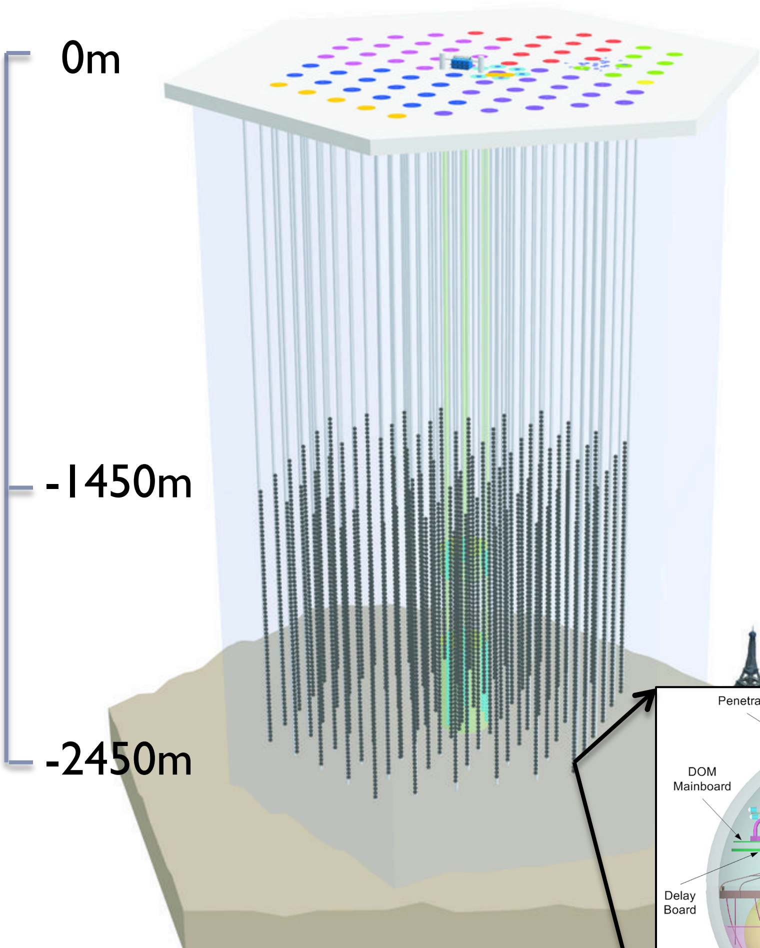


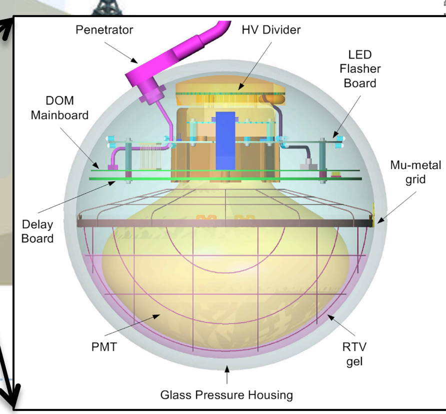


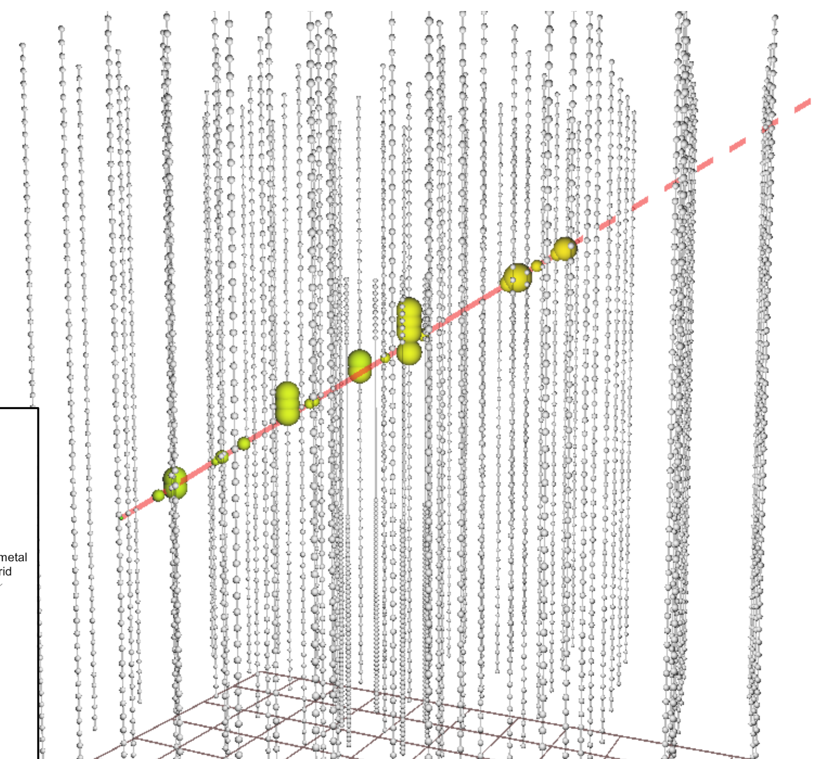


Large-Scale Sparse Arrays - IceCube

- at geographic south pole
- 5160 optical modules (OM)
  - 86 strings, 1km long
  - 60 OMs per string







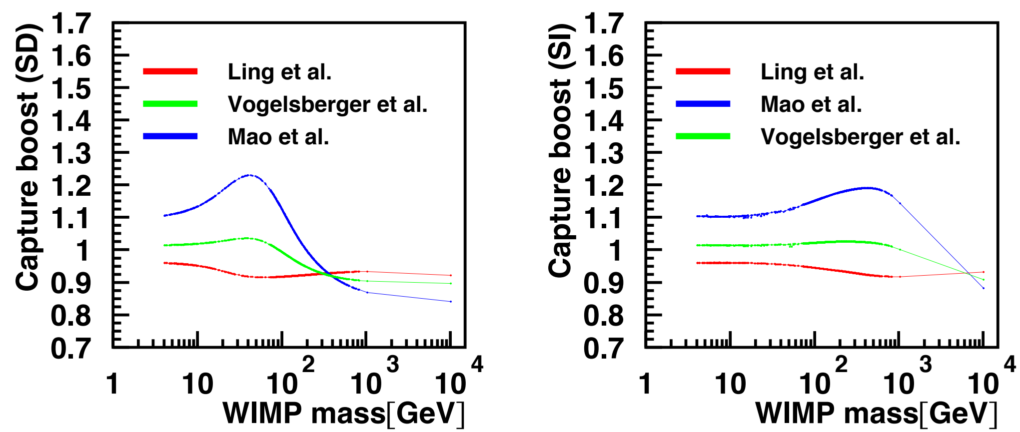
Search for DM in Massive Bodies

- DM accumulation in massive bodies due to scattering

$$\frac{\mathrm{d}N}{\mathrm{d}t} = C_C - C_A N^2 - C_E N$$

capture annihilation evaporation

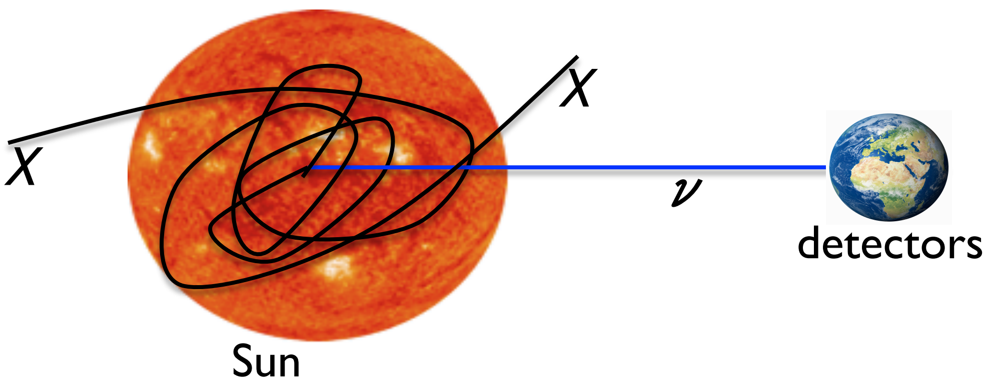
  - evaporation often negligible (e.g. above ~10GeV for Sun)
  - annihilation rate: $\Gamma_A(t) = \frac{1}{2} C_C \tanh^2\left(\frac{t}{\tau}\right) \approx \Gamma_A(t) = \frac{1}{2} C_C$ (in equilibrium)
  - capture mostly depends on $\sigma_{\text{WIMP-nucleon}}$, f(v), ρ_{local}
- ρ_{local} known within a factor of 2-3
- uncertainty from f(v) <30%

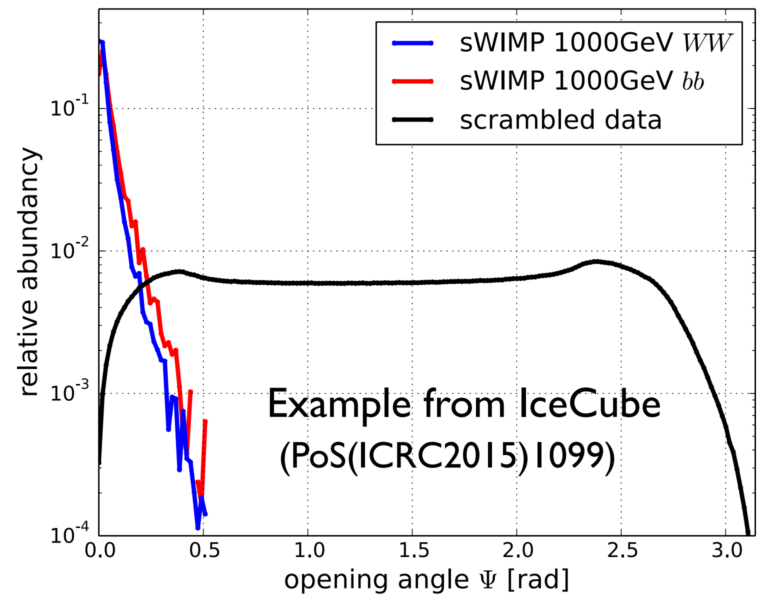


arXiv:1312.0273

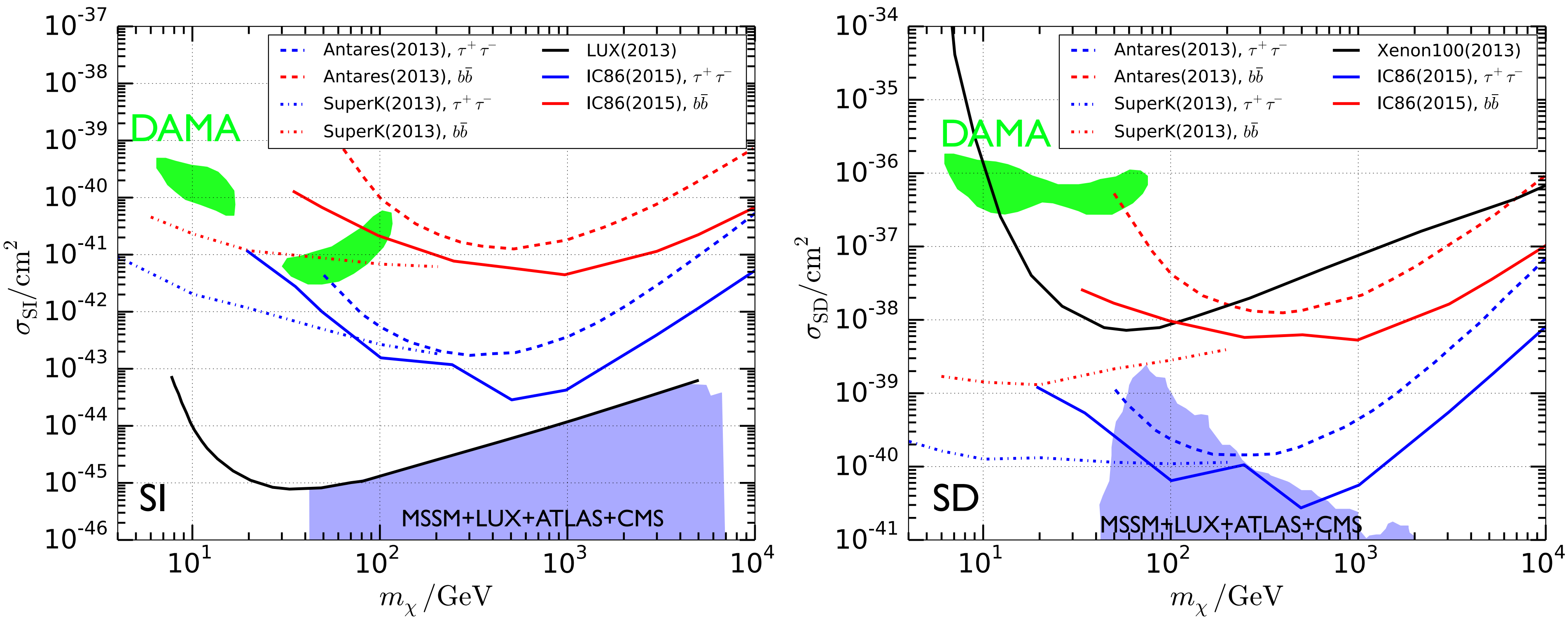
Search for DM in Massive Bodies - Sun

- analysis simple:
  - look for excess flux from Sun
  - assume annihilation benchmark channels (e.g. X X ➔bb, WW,...)
  - flux expectation from tools like WIMPSim (arXiv: 0709.3898)
- no signal observed so far





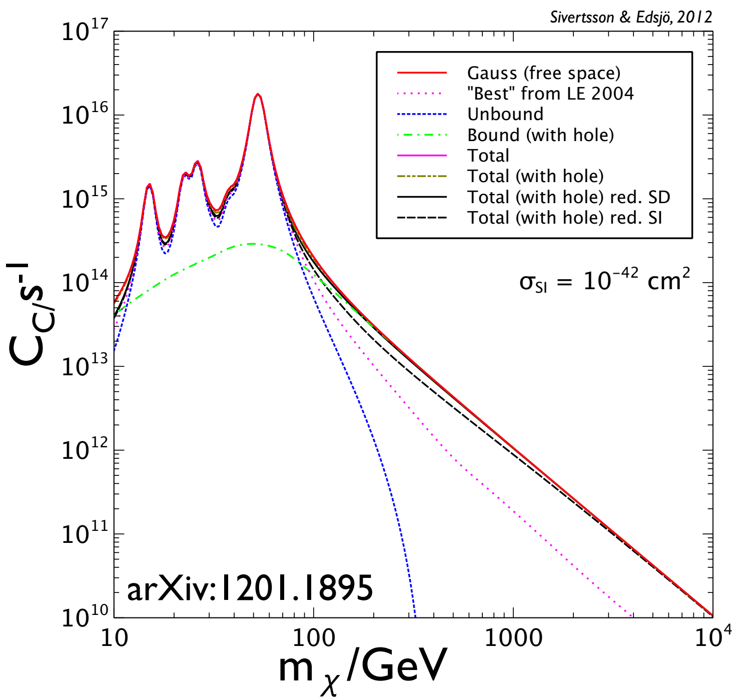
Search for DM in Massive Bodies - Sun

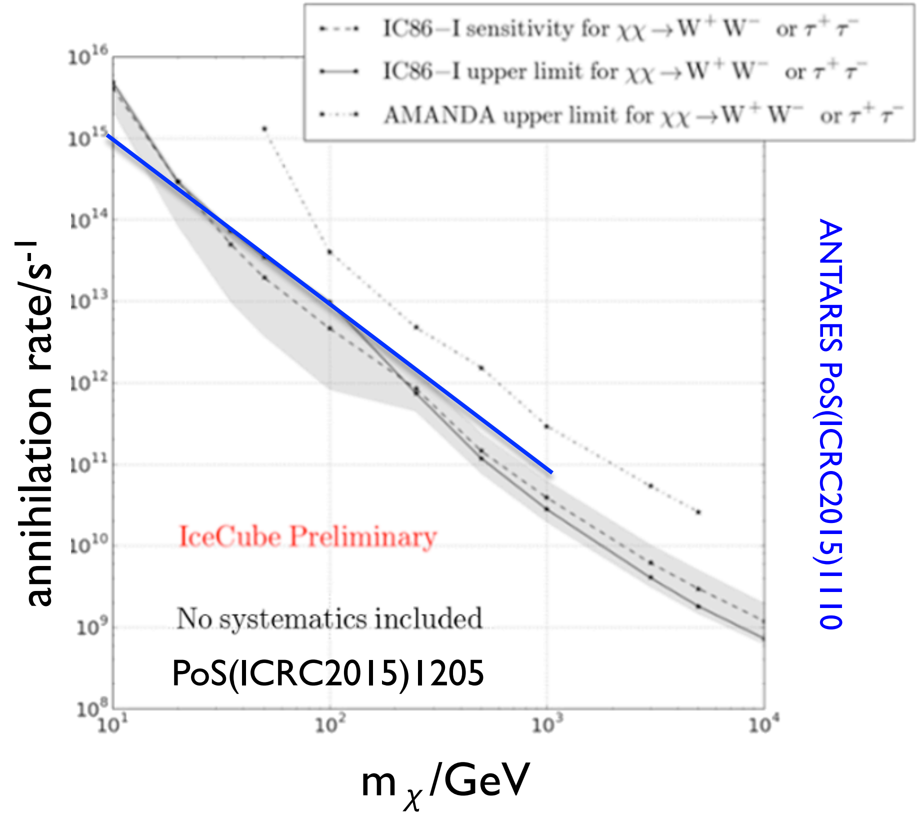


- SI limits benefit from target mass (σ_{SI}~A^2) ➔ direct searches excell
- neutrino searches very competitive in SD case

Search for DM in Massive Bodies - Earth

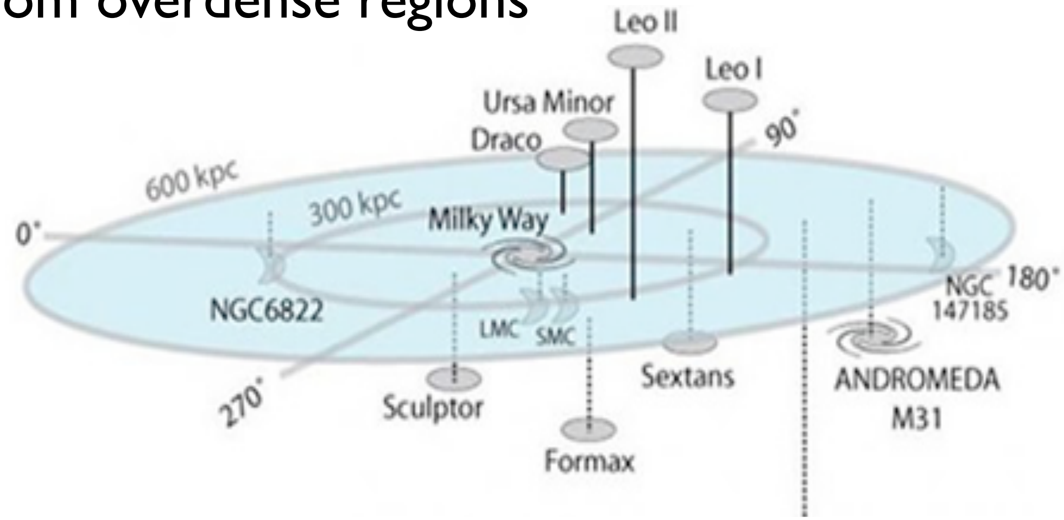
- analysis in principle simple: look at center of Earth
  - Earth not in equilibrium, difficult to limit cross-sections
  - present result as limit on annihilation rate





DM Searches in Selfbound Structures

- search for annihilation flux from overdense regions
  - galactic Center
  - galactic (outer) halo
  - dwarf satellites
  - extragalactic halos
    - galaxies
    - clusters



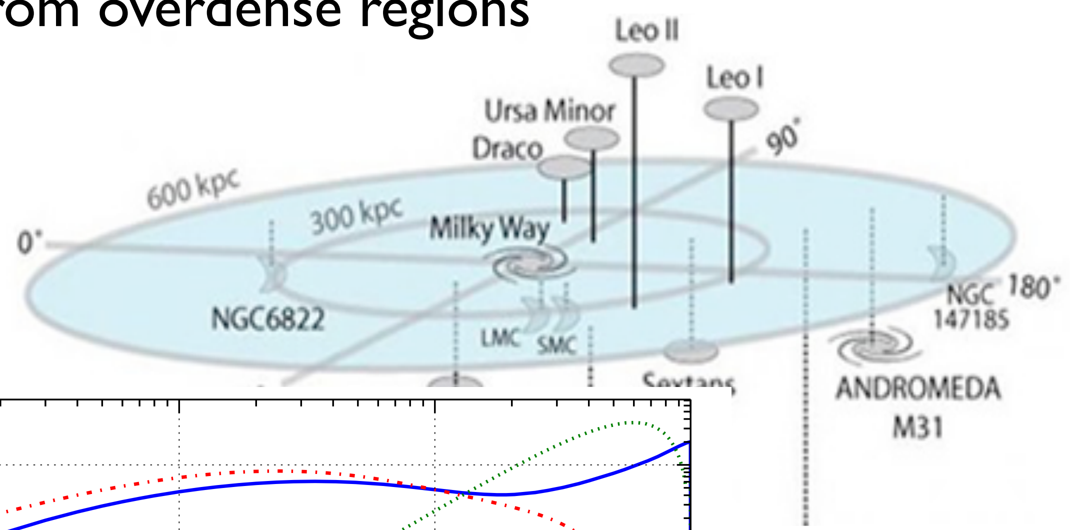
$$\frac{d\phi}{dE} = \frac{1}{2}\frac{1}{4\pi m_\chi^2} < \sigma v > \underbrace{\sum_i b_i \frac{dN_\nu}{dE}}_{\text{annihilation spectrum "particle physics"}} \underbrace{\int d\Omega \int dl \rho(l)}_{\text{line-of-sight integral (J-factors)}}$$

annihilation spectrum
“particle physics“

line-of-sight integral (J-factors)

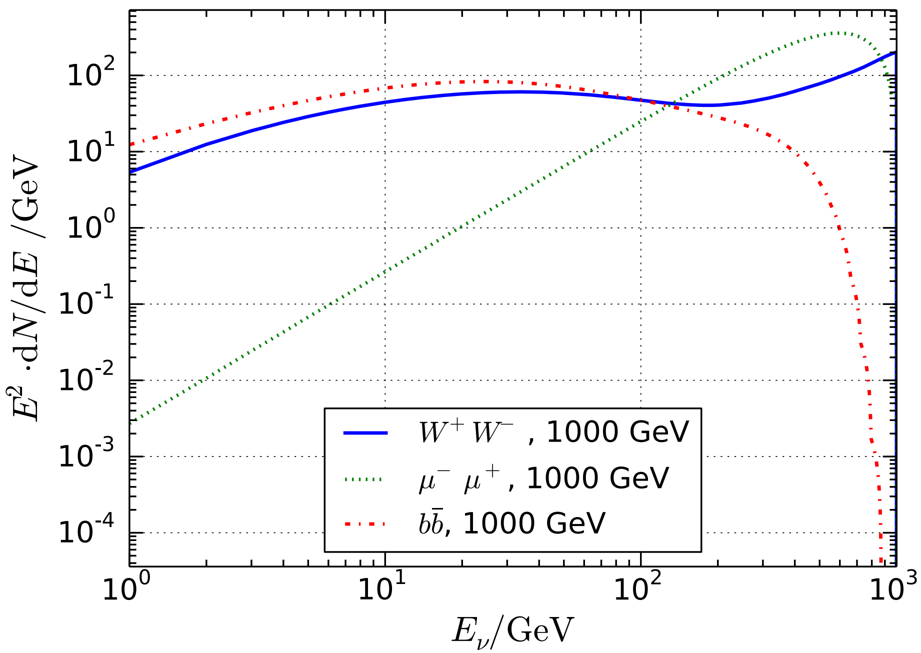
DM Searches in Selfbound Structures

- search for annihilation flux from overdense regions
  - Galactic center
  - Galactic (outer) halo
  - dwarf satellites
  - extragalactic halos
    - galaxies
    - clusters



$$\underbrace{\sum_i b_i \frac{dN_\nu}{dE}}$$

annihilation spectrum
"particle physics"

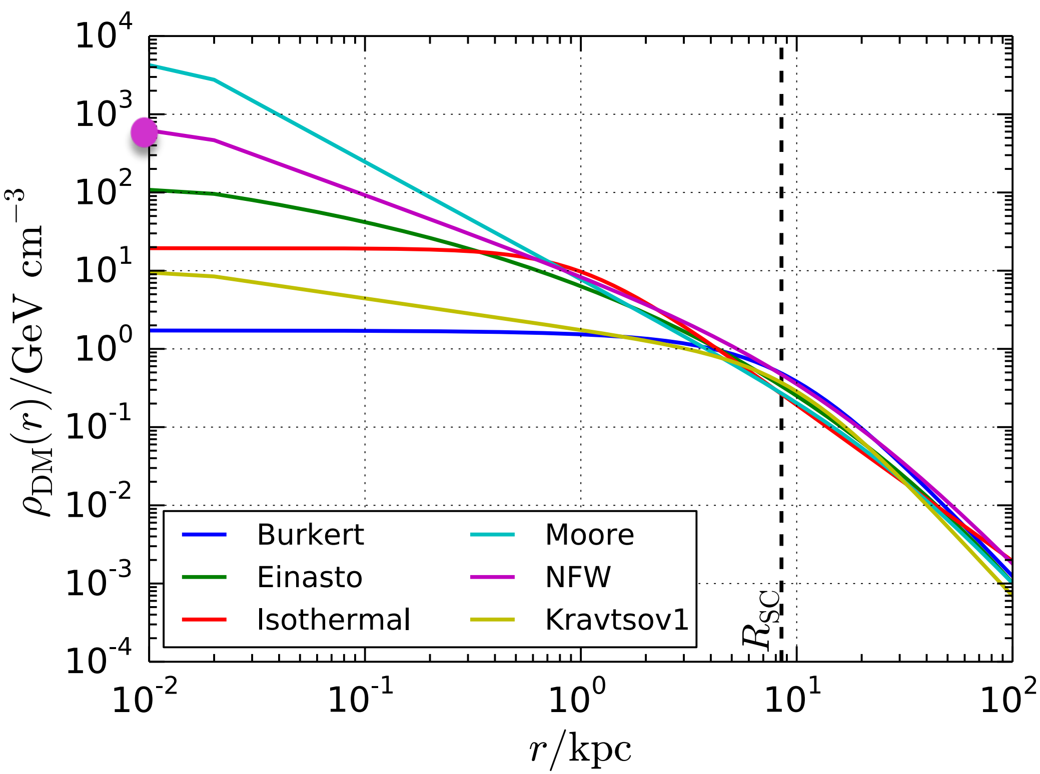


Dark Matter in the Milky Way - Center

- DM density is parametrized by spherically symmetric profiles

$$\rho(r) = \frac{\rho_0}{\left(r/r_s + \delta\right)^{\gamma}\left(1+(r/r_s)^{\alpha}\right)^{(\beta-\gamma)/\alpha}}$$

cusp-core problem



NFW baseline profile

- $(\alpha, \beta, \gamma, \delta)=(1,3,1,0)$
- $\rho_{local}=0.471$
- $r_s=16.1\mathrm{kpc}$

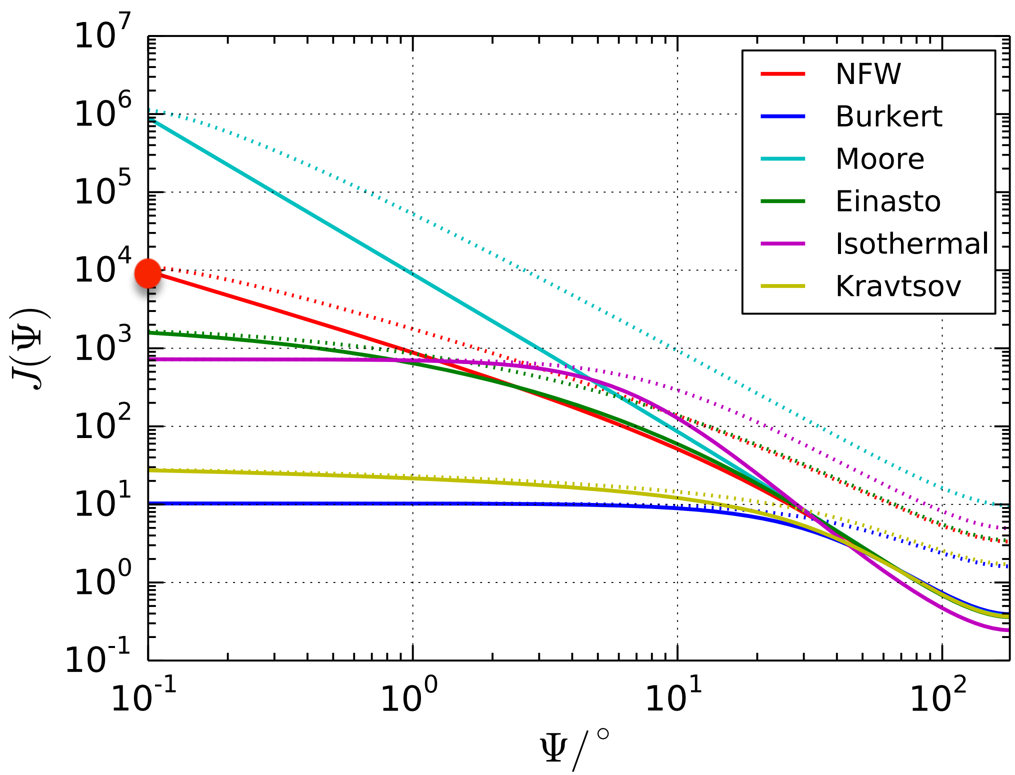
arXiv refs:
astro-ph/9508025
1202.5242, 1212.3670
0707.0196, 1304.5127
astro-ph/0311231

Dark Matter in the Milky Way - Center

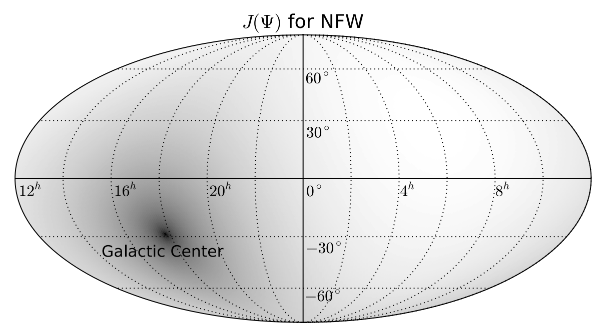
- we sit in the halo, thus J depends on search-window size

$$J = J(\psi) = \int d\Omega \int dl \rho^2(l)$$

cusp-core problem

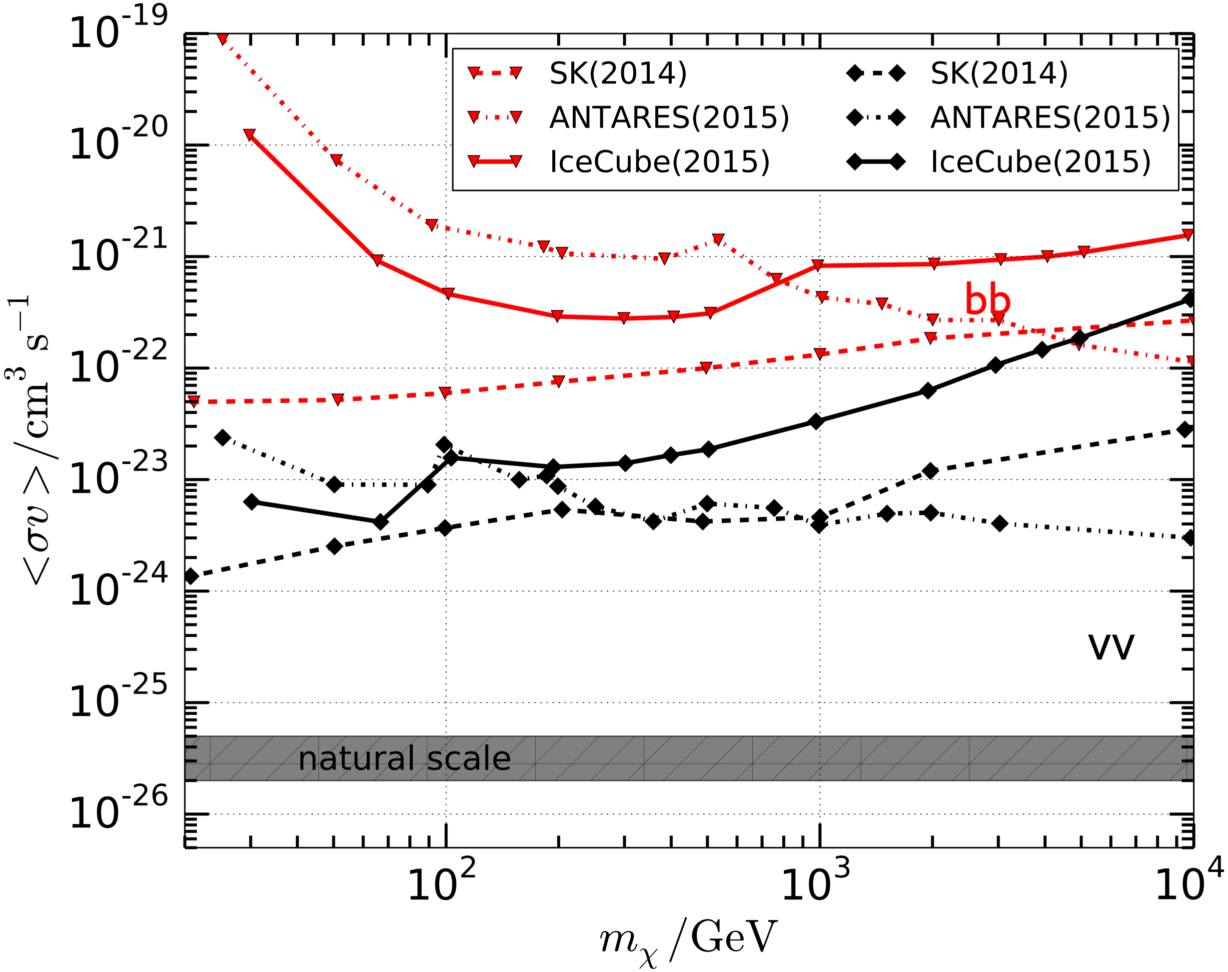


NFW baseline profile



log(J)/a.u.

Dark Matter in the Milky Way - Center



shape explained by:

$$Sens \propto m_\chi^2 / A_{eff}(E = m_\chi)$$

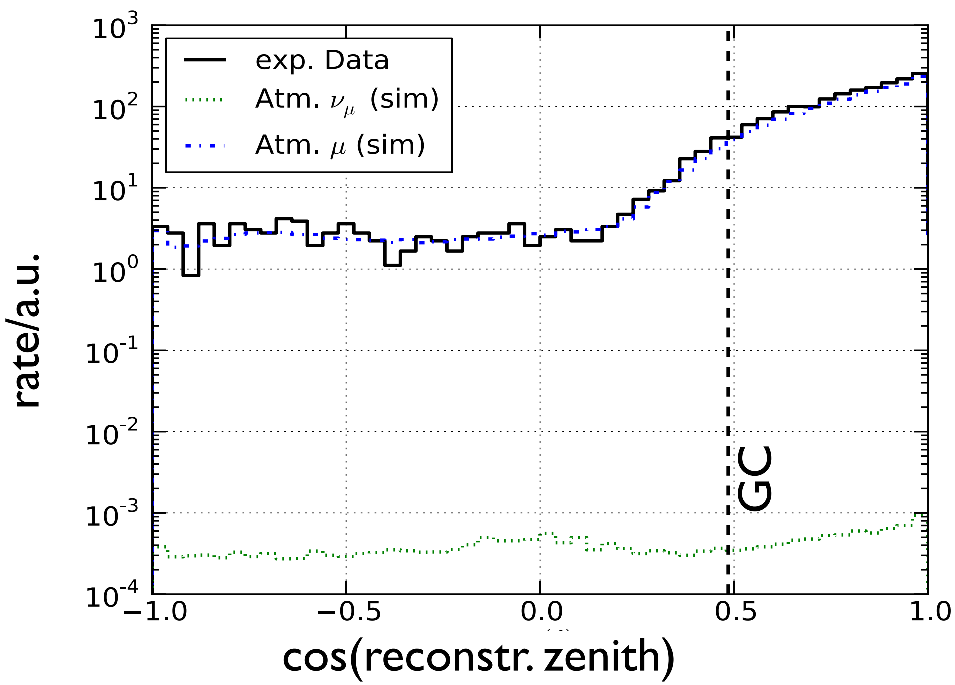
$$A_{eff} \propto E^2$$

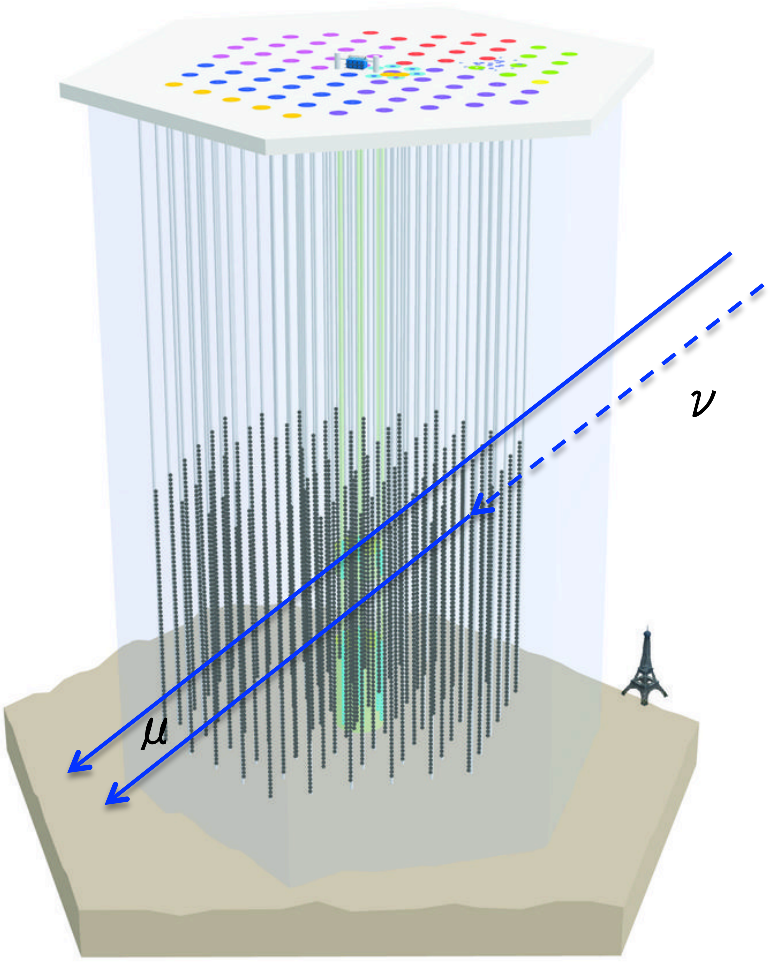
(due to σ_{DIS}, μ -range)
So what's the matter with IceCube?

ANTARES, SuperK limits rescaled to ρ_{local}=0.471

The Galactic Center and IceCube

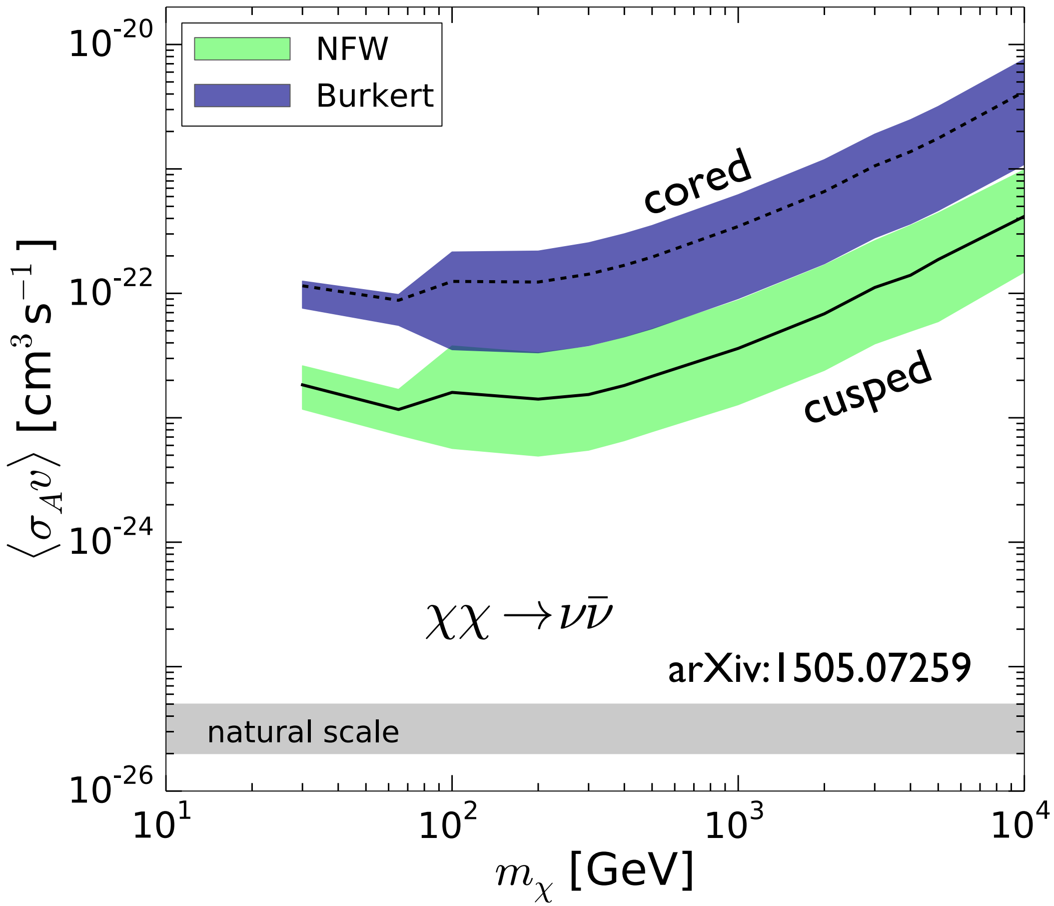
- Ggalactic center ~29° above horizon
  - can't use Earth as shield
  - challenge: atm. μ background dominant
  - use starting tracks





Dark Matter in the Milky Way - Center

- So what about the cusp-core issues?



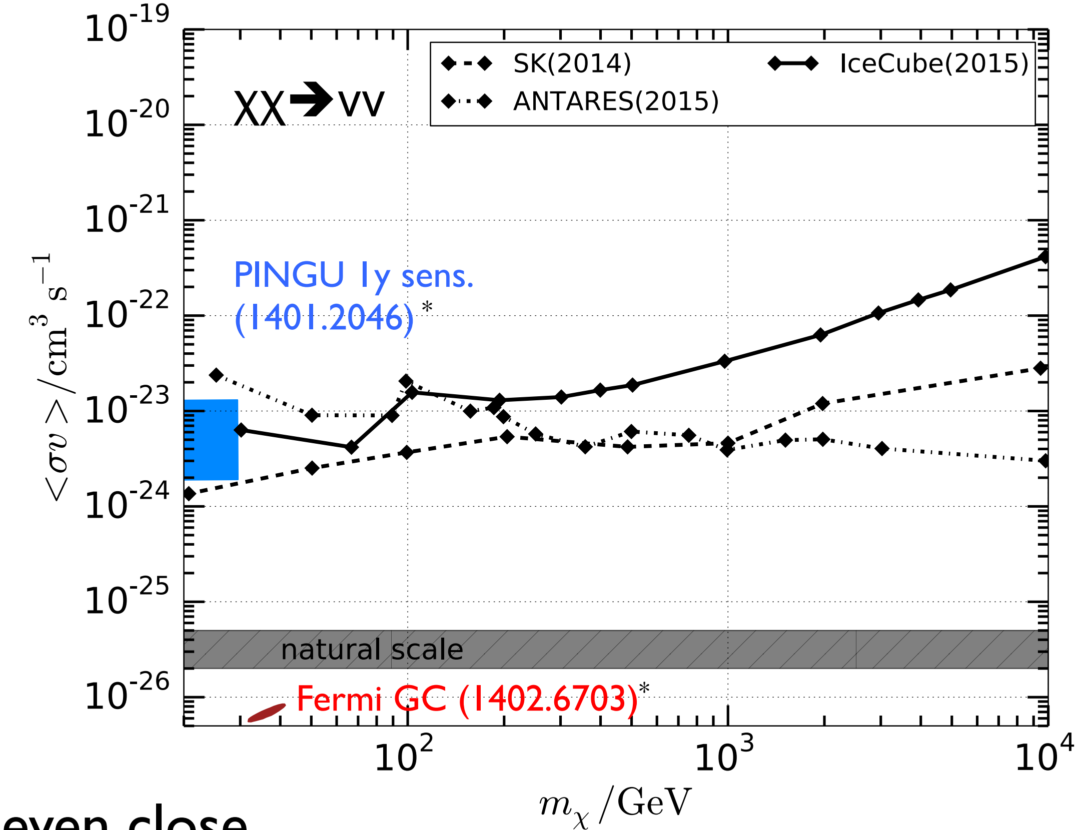
IceCube-79 result

- using two profiles
- varying r_{scale}, ρ_{local} within uncertainties from arXiv:1304.5127

Obviously a better understanding of the inner region would be desirable

Dark Matter in the Milky Way - Center

- can we say something about the Fermi GC excess?

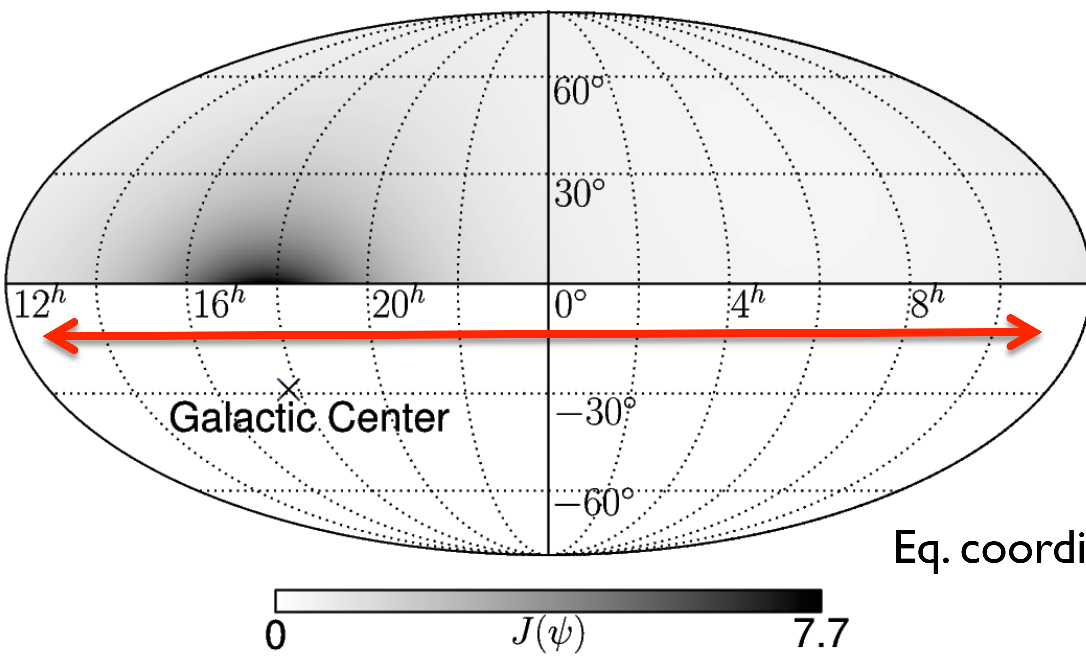


- not even close...
- despite unfair comparison (nu-channel)

*all rescaled to ρ_{local}=0.471

DM Searches in the Milky Way - Halo

- look for large-scale anisotropy
  - neutrino-detectors are 4π-detectors!
- IceCube-only (for now)
- constrained to northern hemisphere due to background

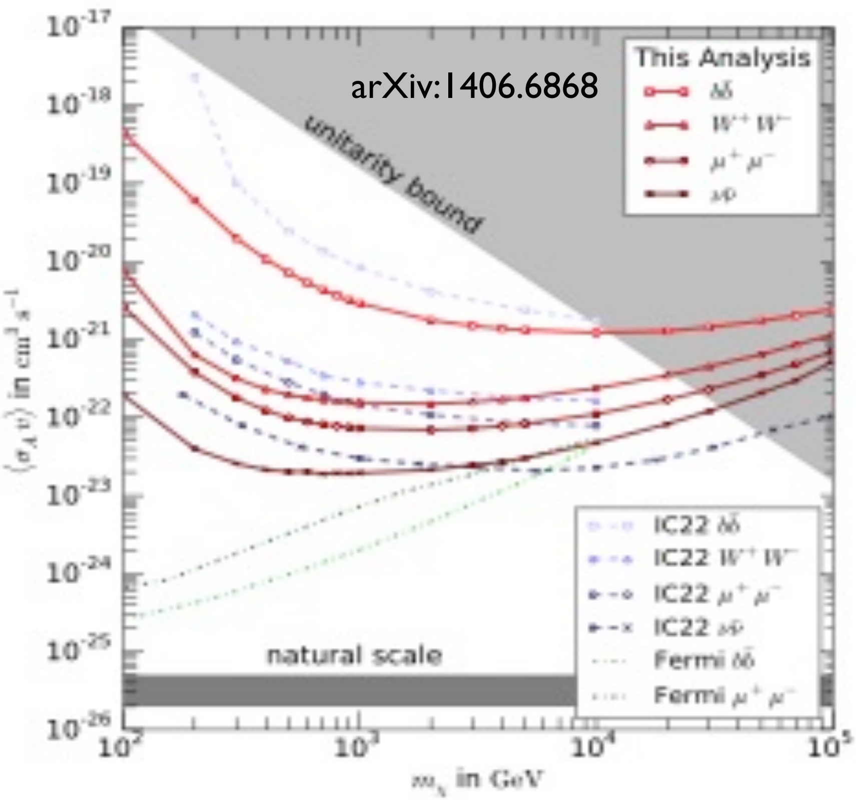


Eq. coordinates

DM Searches in the Milky Way - Halo

- performed on
  - IceCube-22 (cut&count)
  - IceCube-79 (multipole analysis)

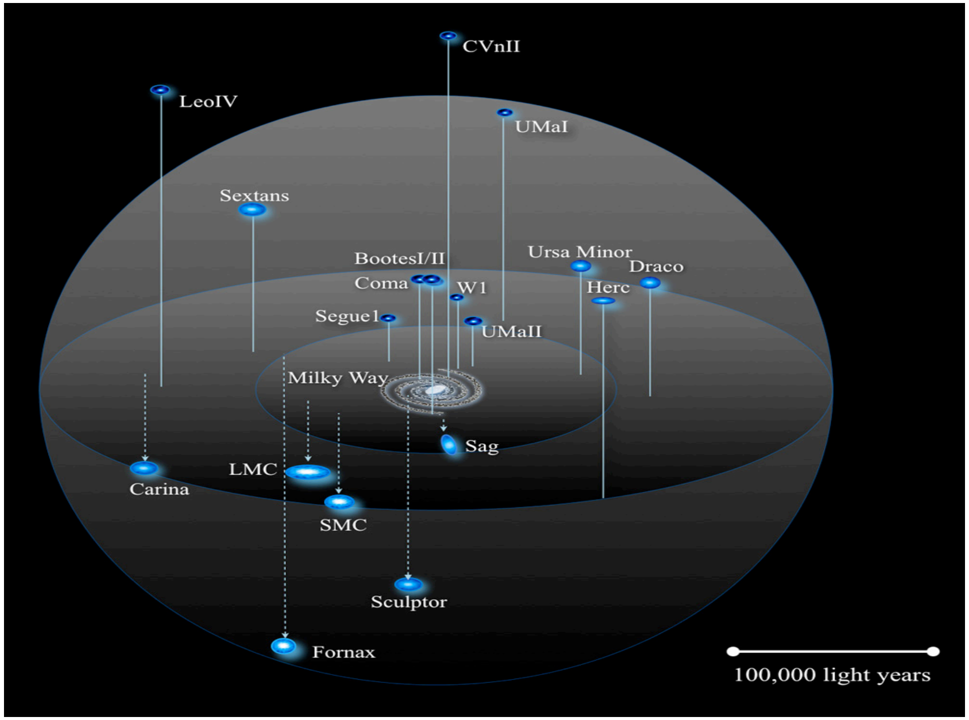
IceCube-22
IceCube-79



IC22 limits stronger at high masses despite larger IC79? Results depend strongly on event selection...

DM Searches in Dwarf Galaxies

- for neutrino telescopes
  - dwarfs=point source
- precomputed J-factors for many dwarfs available*
- perform stacking analysis



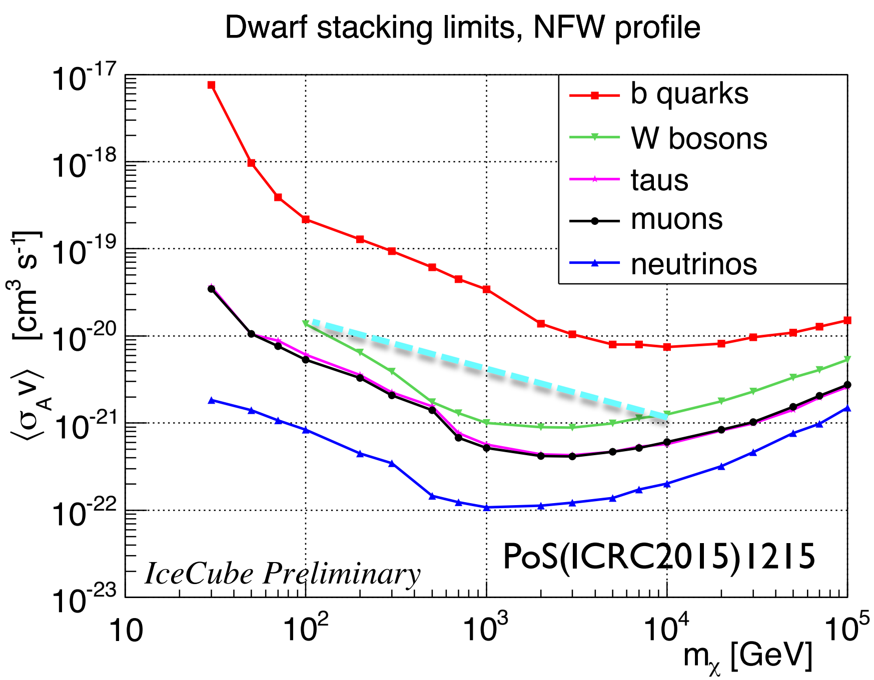
*e.g. Fermi Col. PRD 89 (2014)

DM Searches in Dwarf Galaxies

- for neutrino telescopes
  - dwarfs=point source
- here: IceCube stacking of 5 dwarfs

Targets	Distance [kpc]	$\log_{10}(J_{NFW}$ / GeV^2 cm^{-5})
Segue 1	23	19.5 ± 0.29
Ursa Major II	32	19.3 ± 0.28
Willman 1	38	19.1 ± 0.31
Coma Berenices	44	19.0 ± 0.25
Draco	76	18.8 ± 0.16

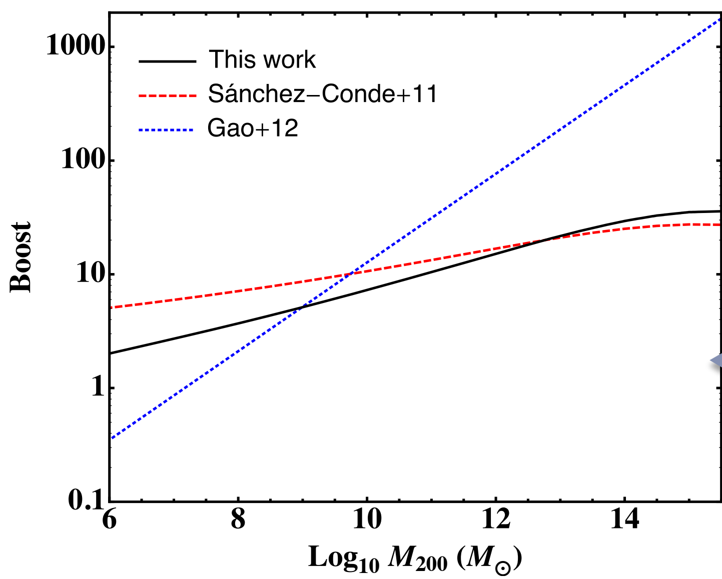
Fermi Col. PRD 89 (2014)



note: ANTARES released similar limits in PoS(ICRC2015)1207

DM Searches in Extragalactic Halos

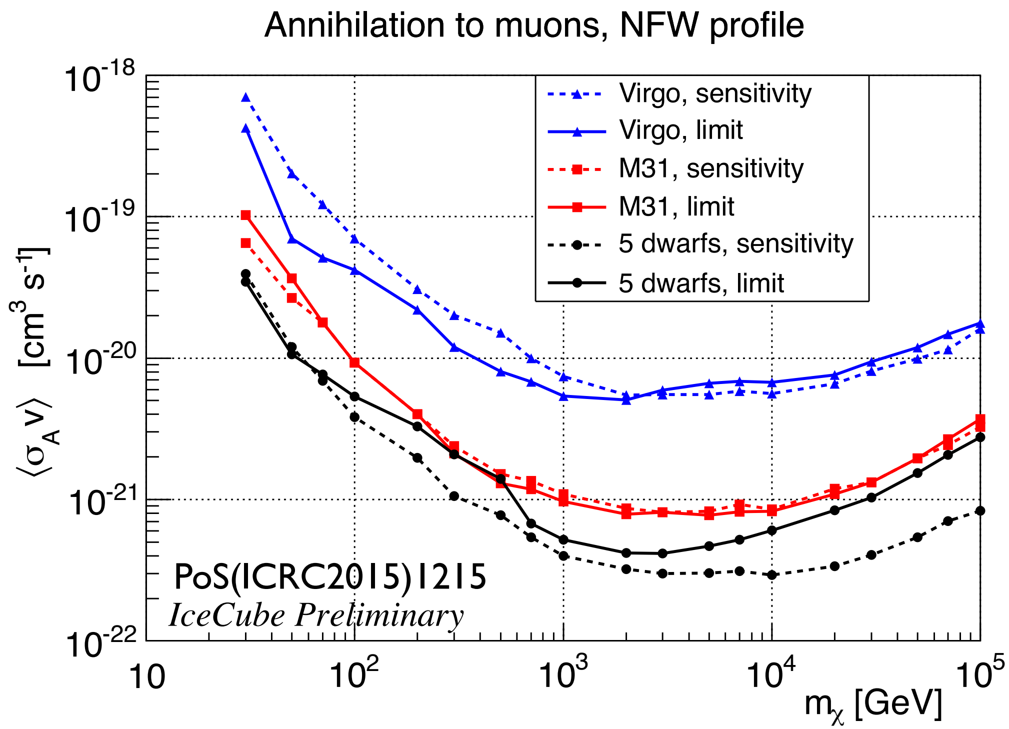
- galaxies and clusters are extended sources
- signal may be boosted due to substructure
- boost factors vary from few 10 to 1000*
  - the latter is probably too optimistic



*Gao et al. MNRAS (2012)
Anderhalden, Diemand, JCAP (2013)
Sánchez-Conde, Prada, MNRAS (2014)

DM Searches in Extragalactic Halos

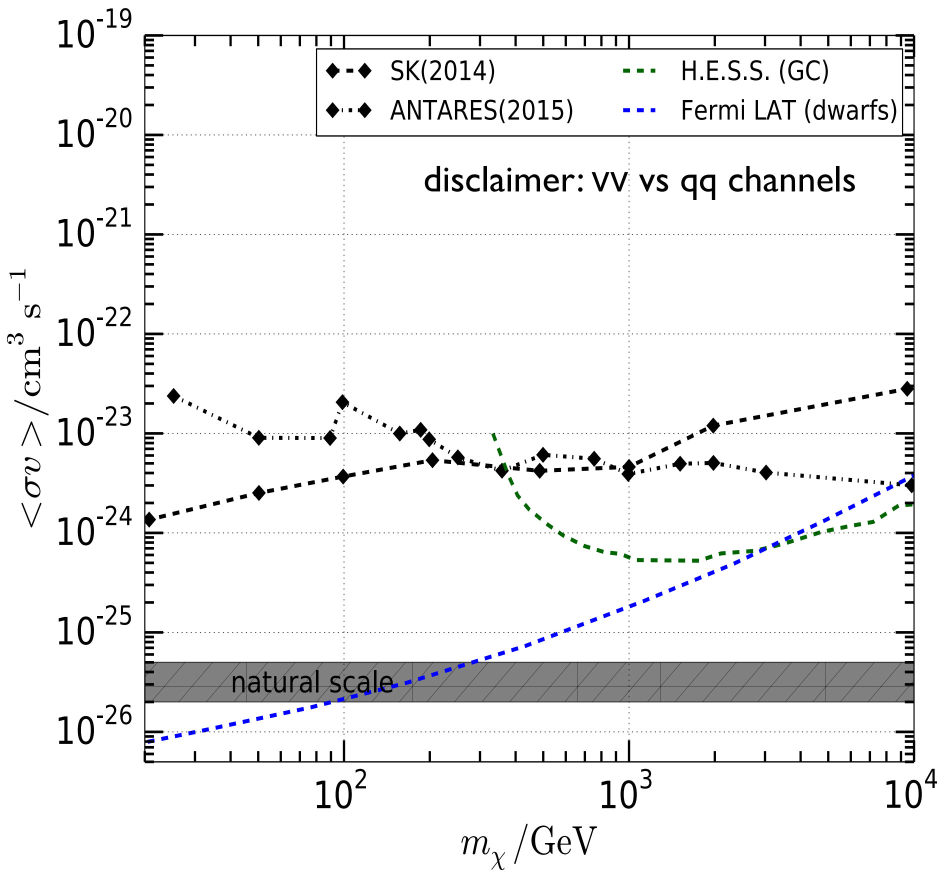
- IceCube results available for
  - Virgo
  - Andromeda



Targets	Distance [kpc]	$\log_{10}(J_{NFW}$ / GeV^2 cm$^{-5})$
M31	785	19.2 ± 0.1
Virgo	16800	18.5

Tamm et. al. A&A (2012)
Han et. al. MNRAS (2012)

Comparison to Photon Searches

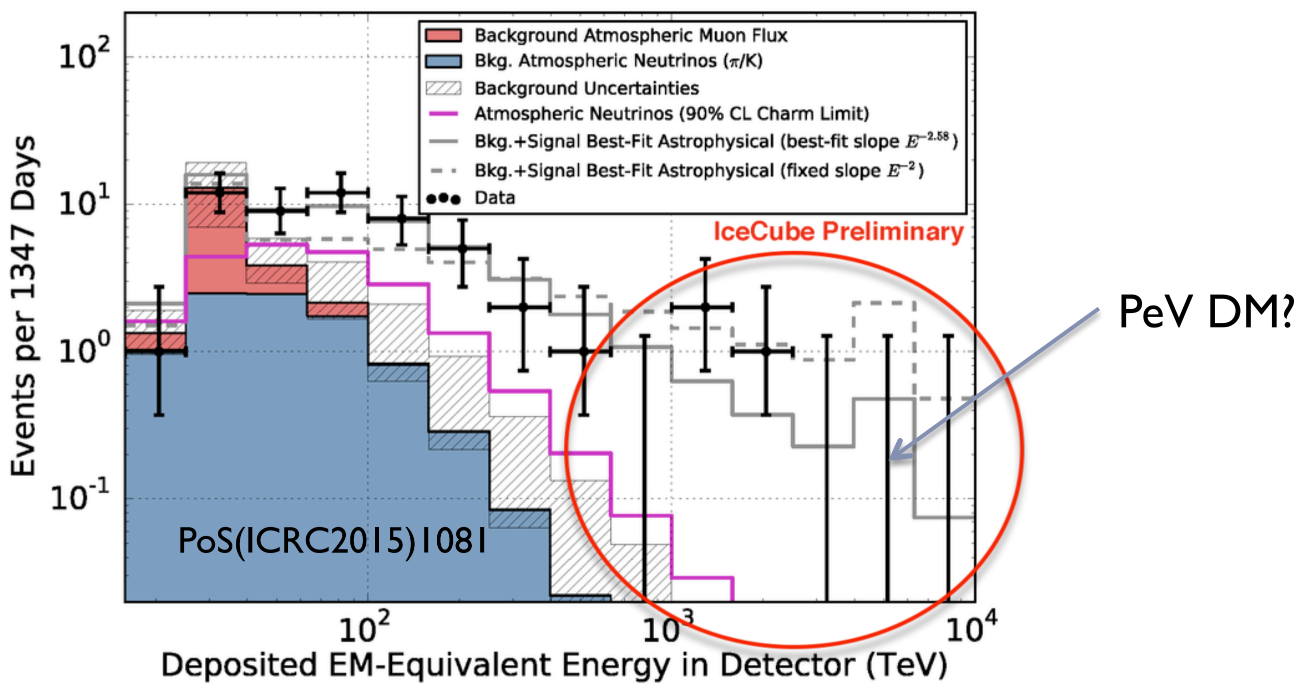


arXiv:1503.02641
PRL 114, 081301 (2015)

- photon searches very competitive
  - cs-advantage
  - excellent pointing
- neutrinos still can
  - provide "conservative" upper bounds
  - detect DM-> ν channels

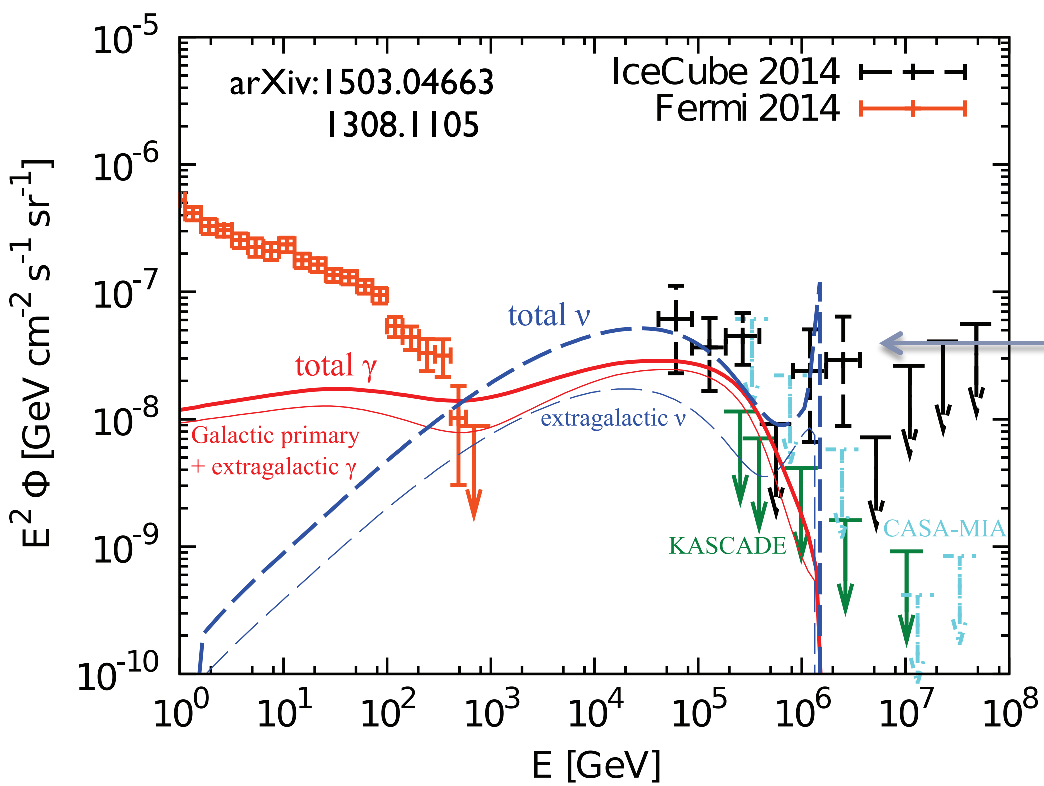
IceCube High-Energy Neutrino Flux

- IceCube discovered a high-energy neutrino flux
- sparked interest in decaying VHDM



IceCube High-Energy Neutrino Flux

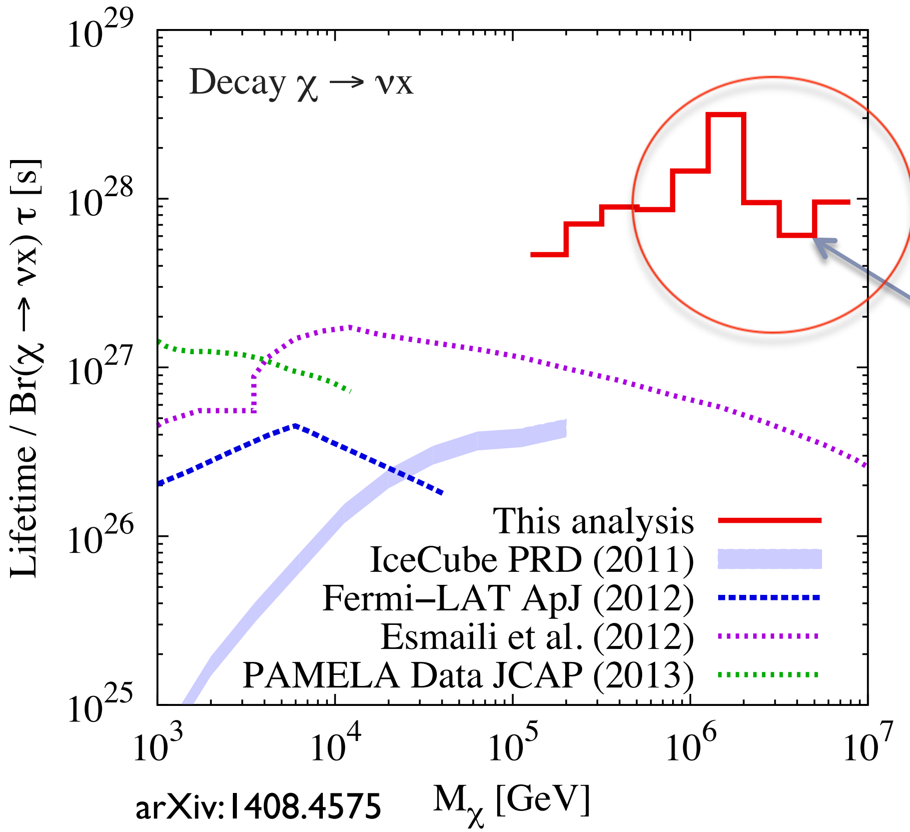
- IceCube discovered a high-energy neutrino flux
- sparked interest in decaying VHDM



PeV DM?
dedicated analysis
necessary

IceCube High-Energy Neutrino Flux

- few-authors analysis of public IceCube data
- looking for χ➔νX



arXiv:1408.4575

PeV DM?
dip in limit caused
by HE neutrino flux

Summary&Outlook

- DM
  - accumulates in massive bodies, galaxies, clusters
  - may be detectable via annihilation/decay flux
- neutrino searches
  - yield very competitive SD results from Sun
  - cannot compete (easily) with photon searches in selfbound halos
    - limits still orders of magnitude above thermal relic $\langle\sigma v\rangle$
- future prospects: extensions&new detectors
  - IceCube-Gen2 (arXiv:1412.5106)
    - PINGU – low-mass WIMPs
    - HEX – high-mass WIMPs
    - surface-based veto detectors: make GC accesible
  - KM3Net (arXiv:1403.4065)
  - Hyper-K (arXiv:1109.3262)