MANTS

# Dark Matter IceCube/Antares joined analysis/ analyses and latest results and estimations


Carsten Rott

Sungkyunkwan University, Korea

rott@skku.edu


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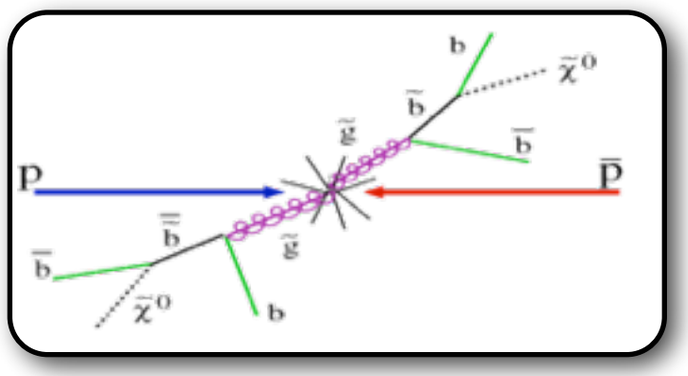
# Outline

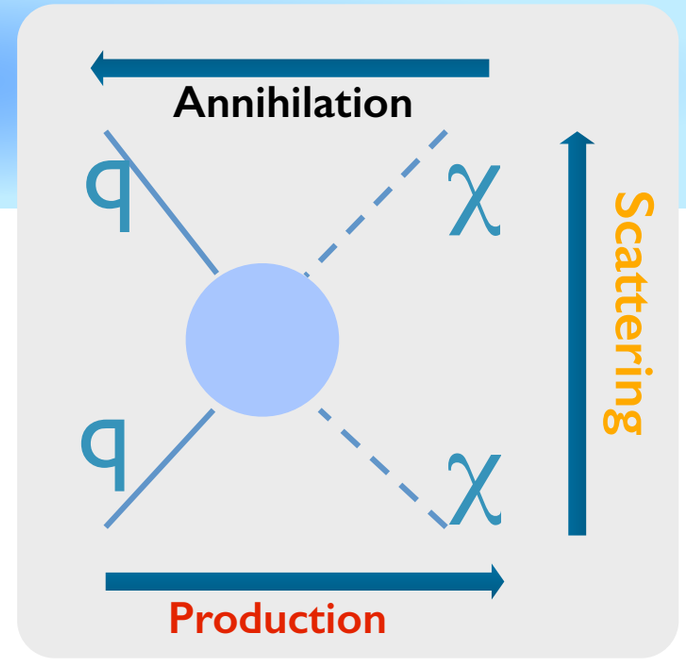
- Motivation
- Overview of current searches and results
  - Galactic Halo / Galactic Center
  - Solar WIMPs
  - Earth WIMPs
  - High-energy neutrinos
- Discussion topics
- Conclusions

# Motivation

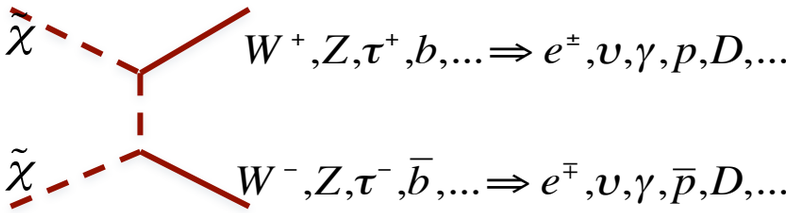
# Indirect Searches with Neutrinos

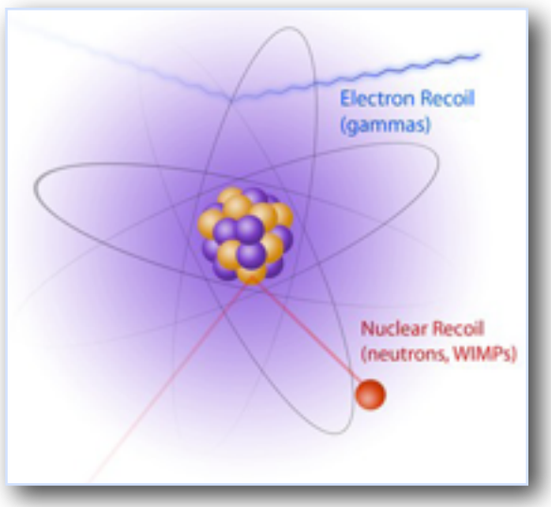
## WIMP - Weakly Interacting Massive Particle




- **Production**
  - Colliders
- **Indirect Searches**
  - Annihilation of Dark Matter in Galactic Halo, ...
    - Gamma-rays, electrons, neutrinos, anti-matter, ...
  - Annihilation signals from WIMPs captured in the Sun and Earth
    - Neutrinos
- **Direct Searches**
  - WIMP scattering of nucleons → Nuclear recoils

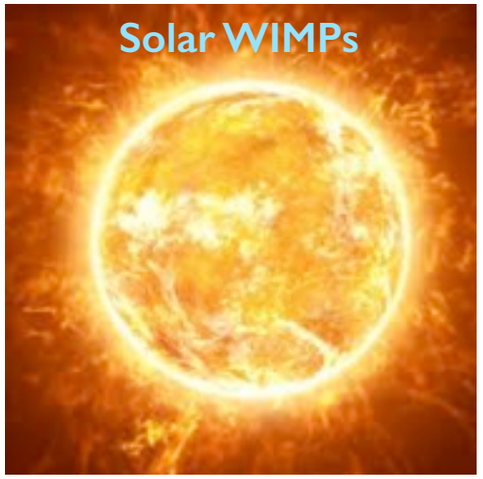


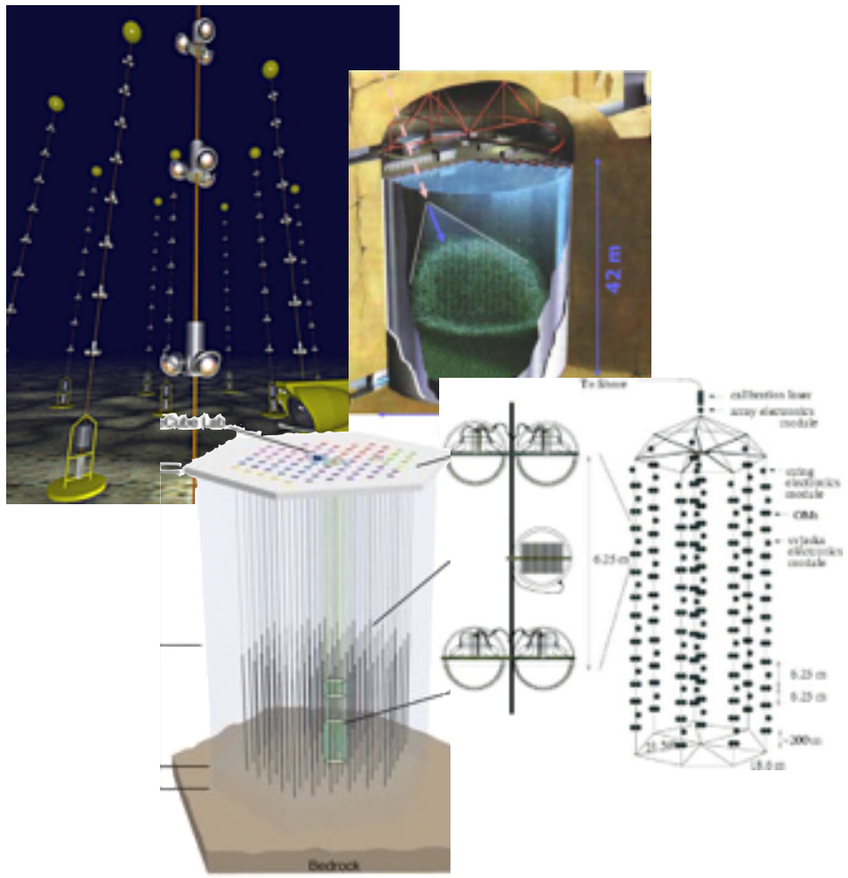




WIMP Self-annihilation cross section

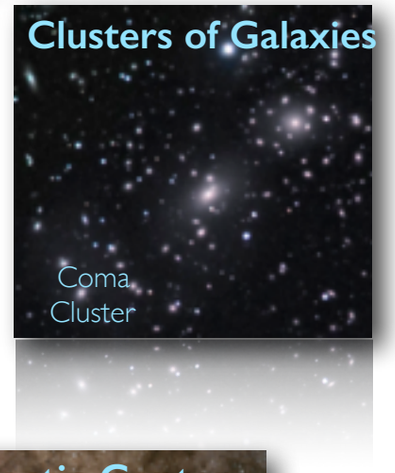
WIMP-Nucleon Scattering cross section

# Dark Matter Signals

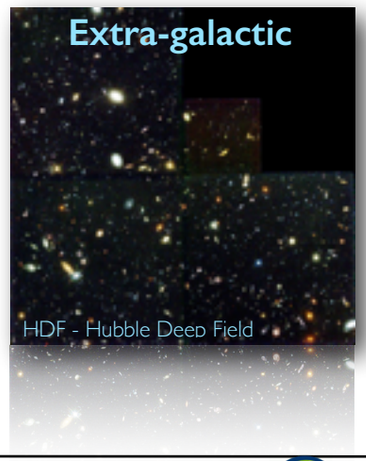


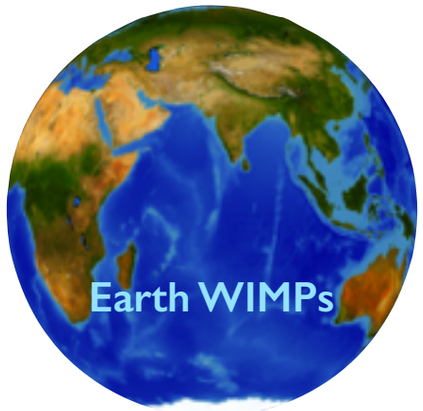









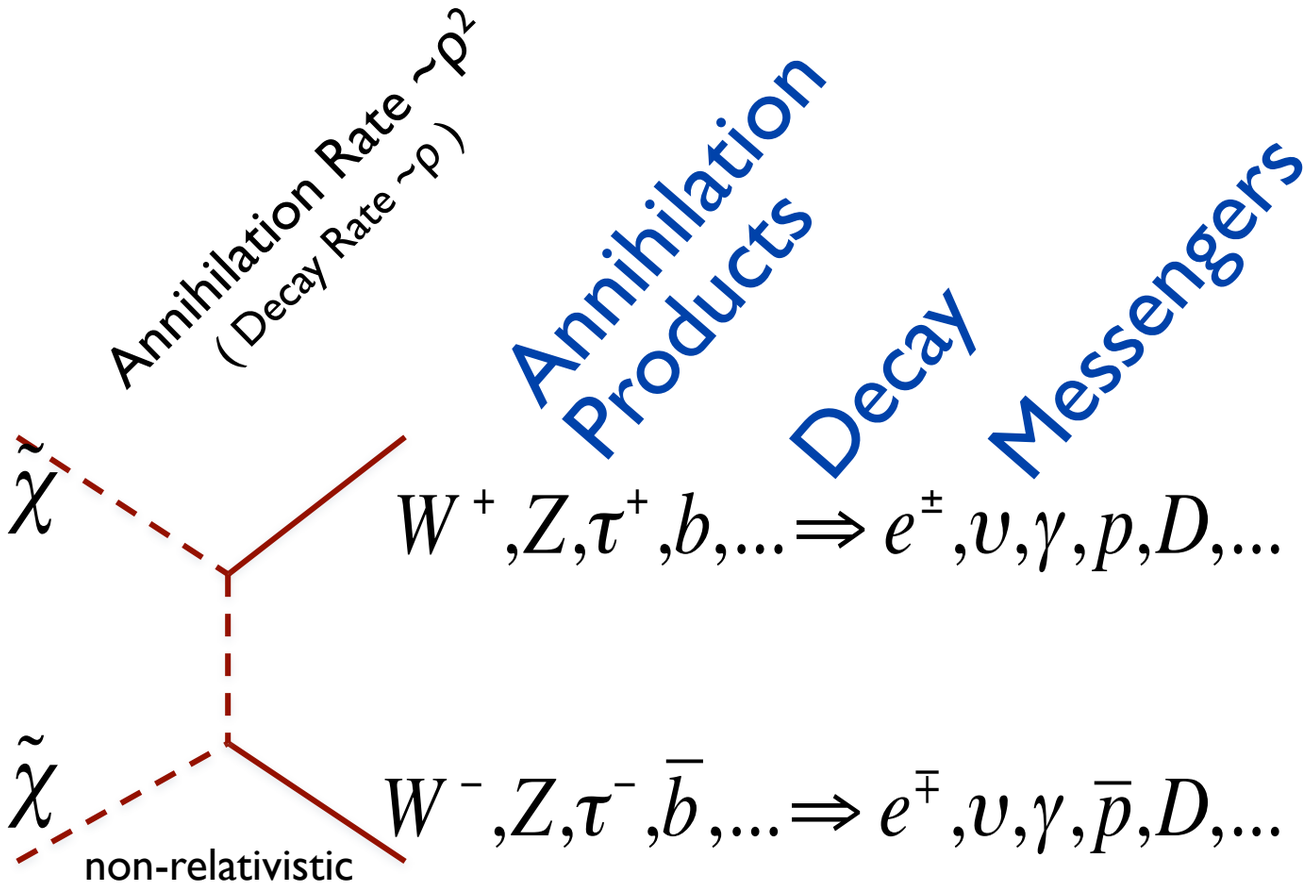
# Galactic Halo / Galactic Centre

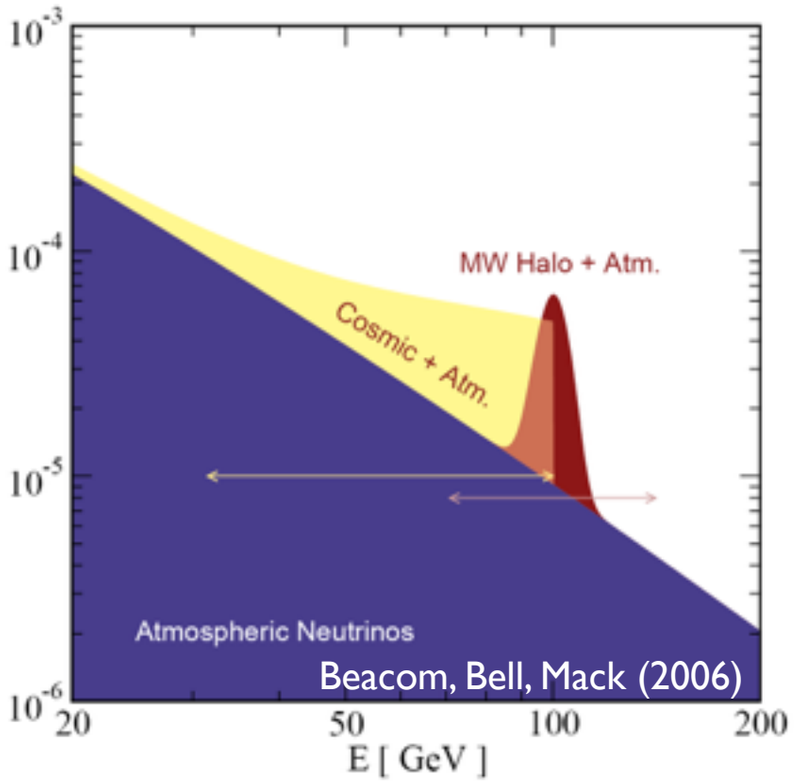
# Dark Matter Annihilation Signals

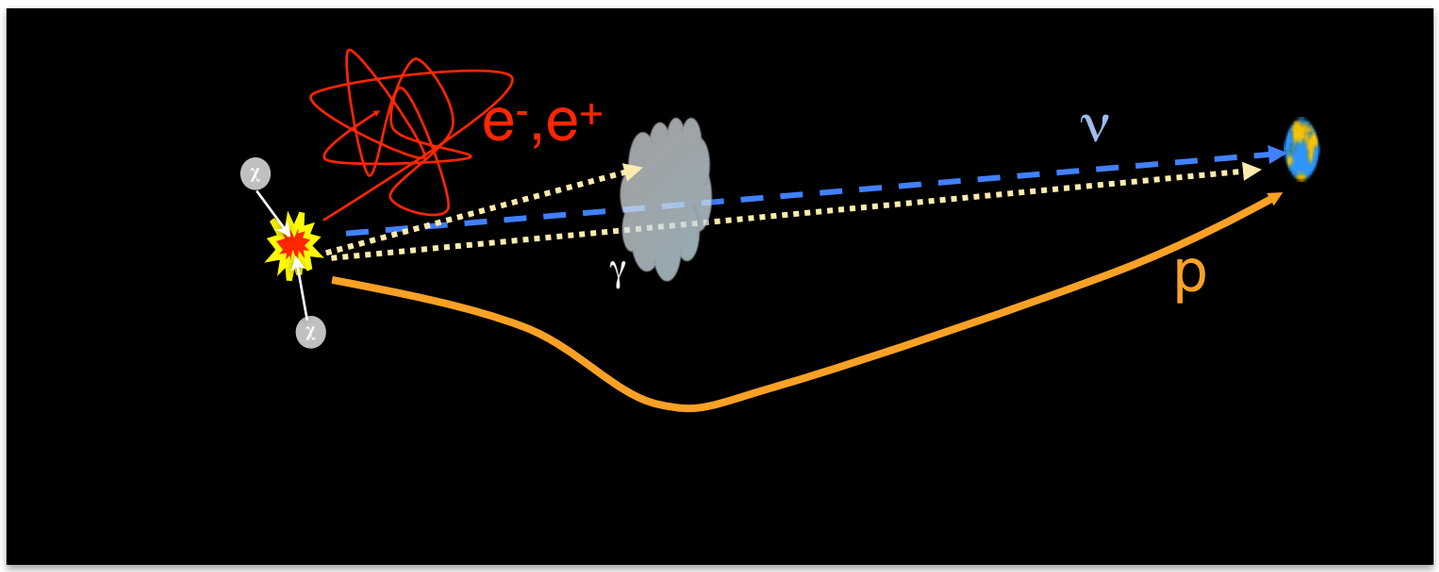
- Identify overdense regions of dark matter

  ⇒self-annihilation can occur at significant rates

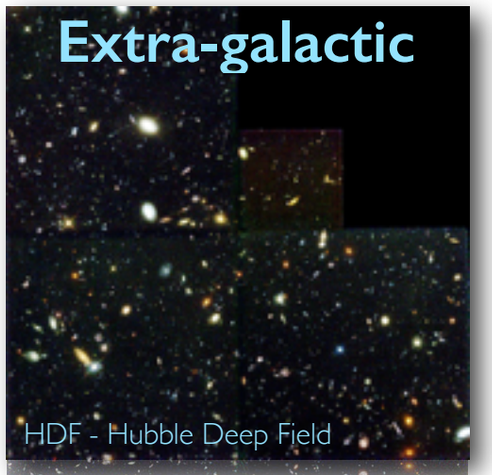
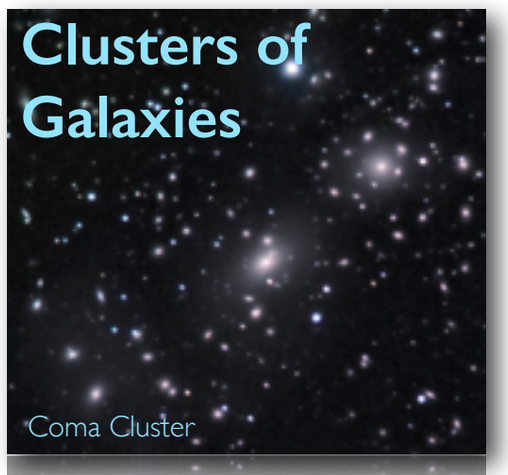
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds



# Sources

| Extra-galactic | Milky Way Halo | Galactic Center | Dwarf Spheroidal | Clusters of Galaxies |
|---|---|---|---|---|
|   |  |  |  |   |
| 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 |
| Diffuse flux, spectral feature | Anisotropy | Extended Source | Point source | Extended source |
| Signal weak compared to Galactic signal | Relatively independent from DM halo profile | Very strong dependence on DM density profile | Cored profiles favored, less flux | Understanding of boost factors |
| | **IceCube Coll. Phys.Rev. D84 (2011) 022004**<br>**IceCube Coll. Eur.Phys.J. C75 (2015) no.99, 20** | **IceCube Coll. arXiv: 1210.3557**<br>**IceCube Coll. Eur.Phys.J. C75 (2015) no.10, 492**<br>**ANTARES Coll. JCAP 1510 (2015) no.10, 068**<br>**Baikal AstroPhys 81 (2016)**<br>**IceCube Coll. arXiv: 1606.00209** | **IceCube Coll. Phys.Rev. D88 (2013) 122001** | |

# Dark Matter Annihilation

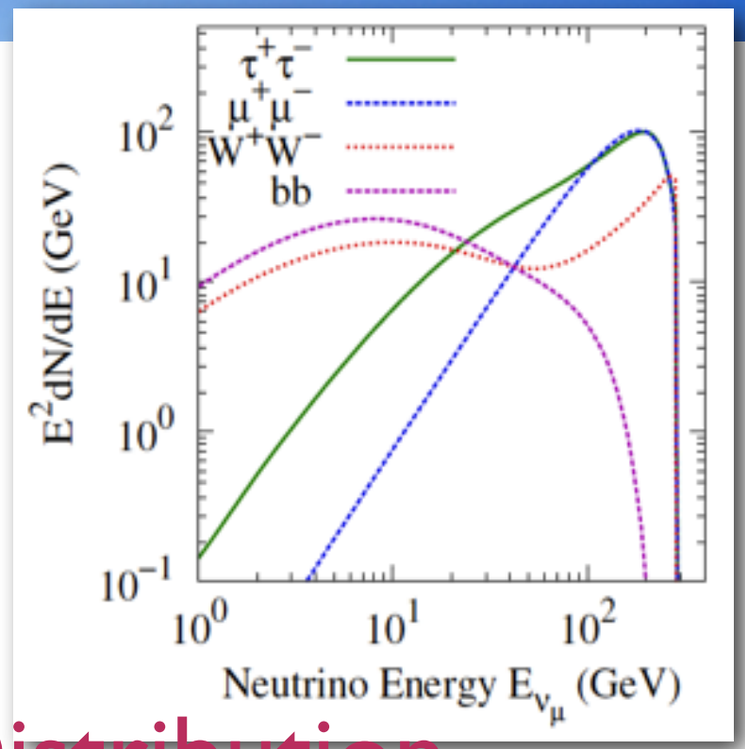
## Measure Flux

$$\frac{d\Phi}{dE}(E,\phi,\theta)$$

=

## Particle Physics

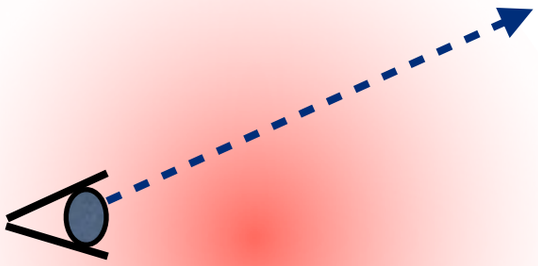
$$\frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f\frac{dN}{dE}B_f$$



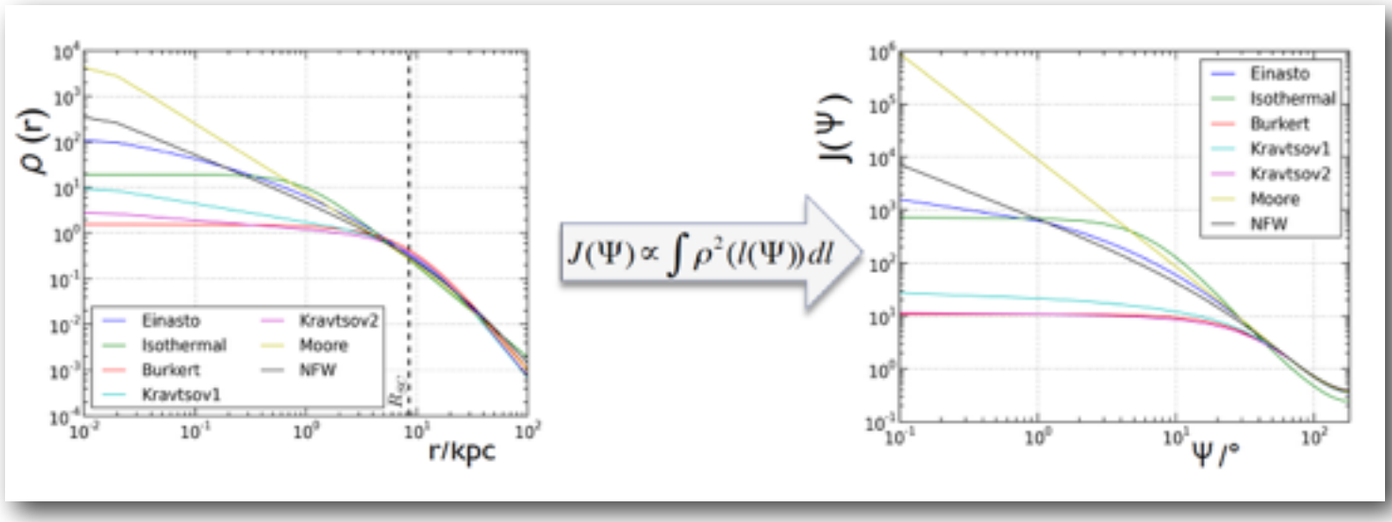

x

## Dark Matter Distribution

line of sight (los) integral

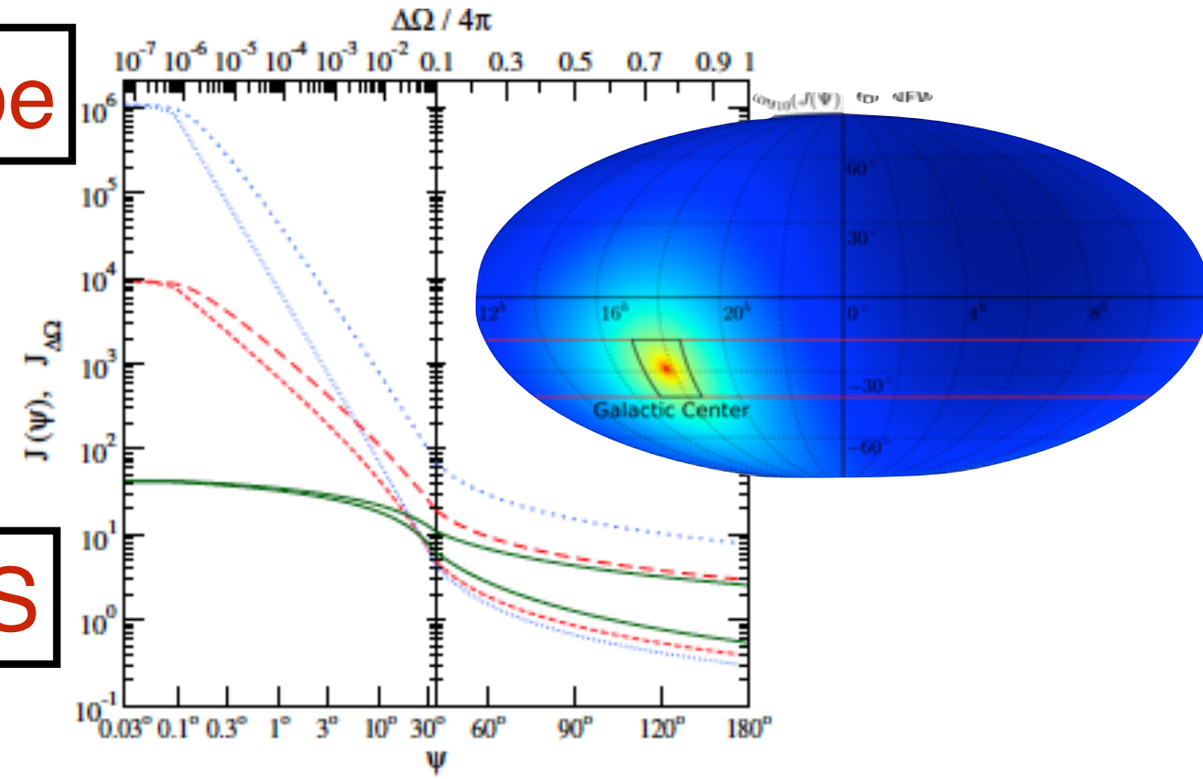


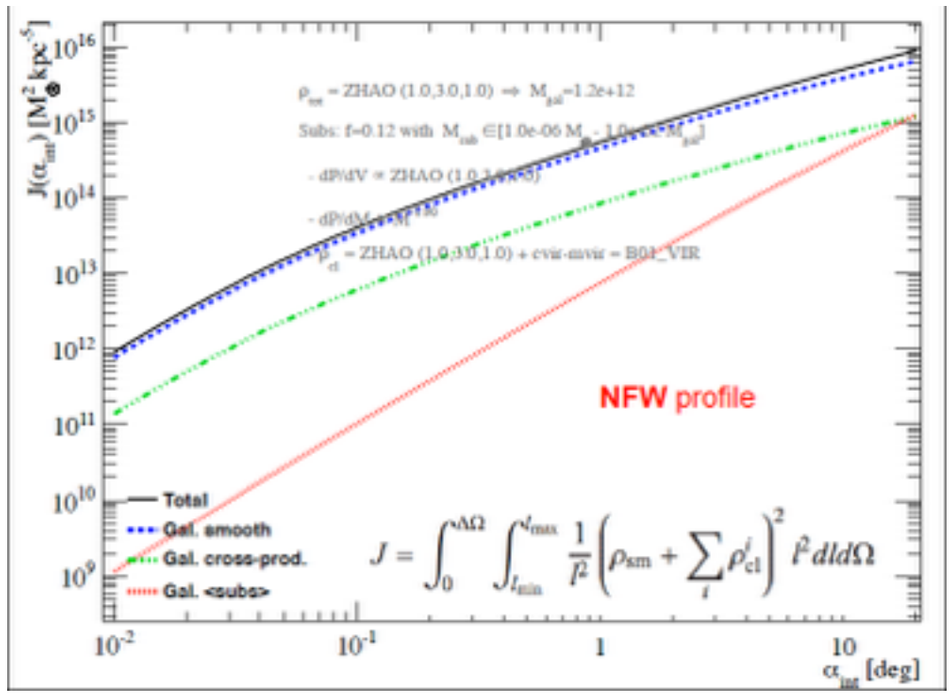
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$



# Halo Profiles and J-factors

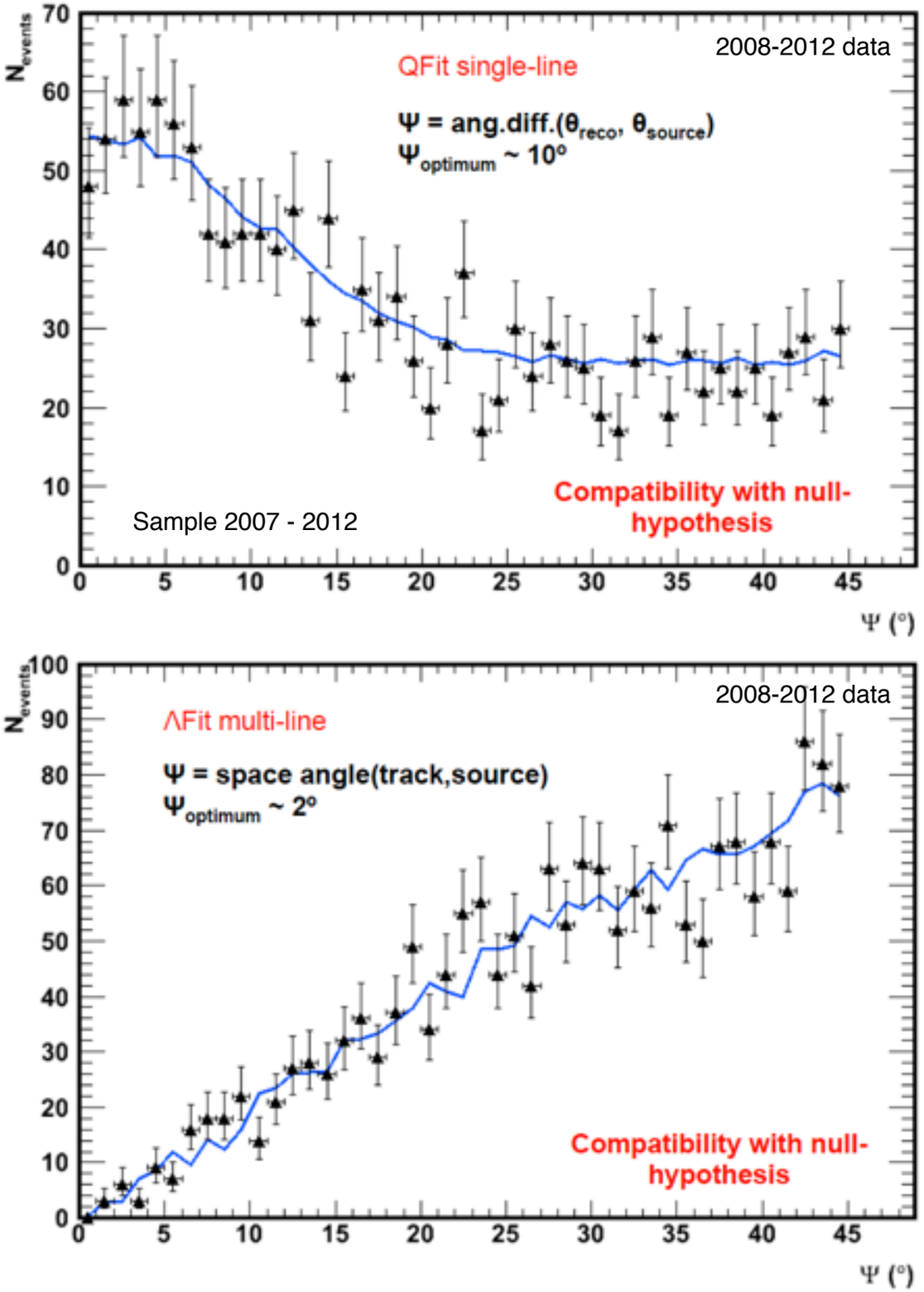
- Customised implementations IceCube
  - Following for example: Yuksel et al. PHYSICAL REVIEW D 76, 123506 (2007)
- Packages ANTARES
  - CLUMPY (computation of J-factors)
    - A. Chardonnier, C. Combet, D. Maurin, Comp. Phys. Comm. 183, 656 (2012)
    - http://lpsc.in2p3.fr/clumpy/ for the source code

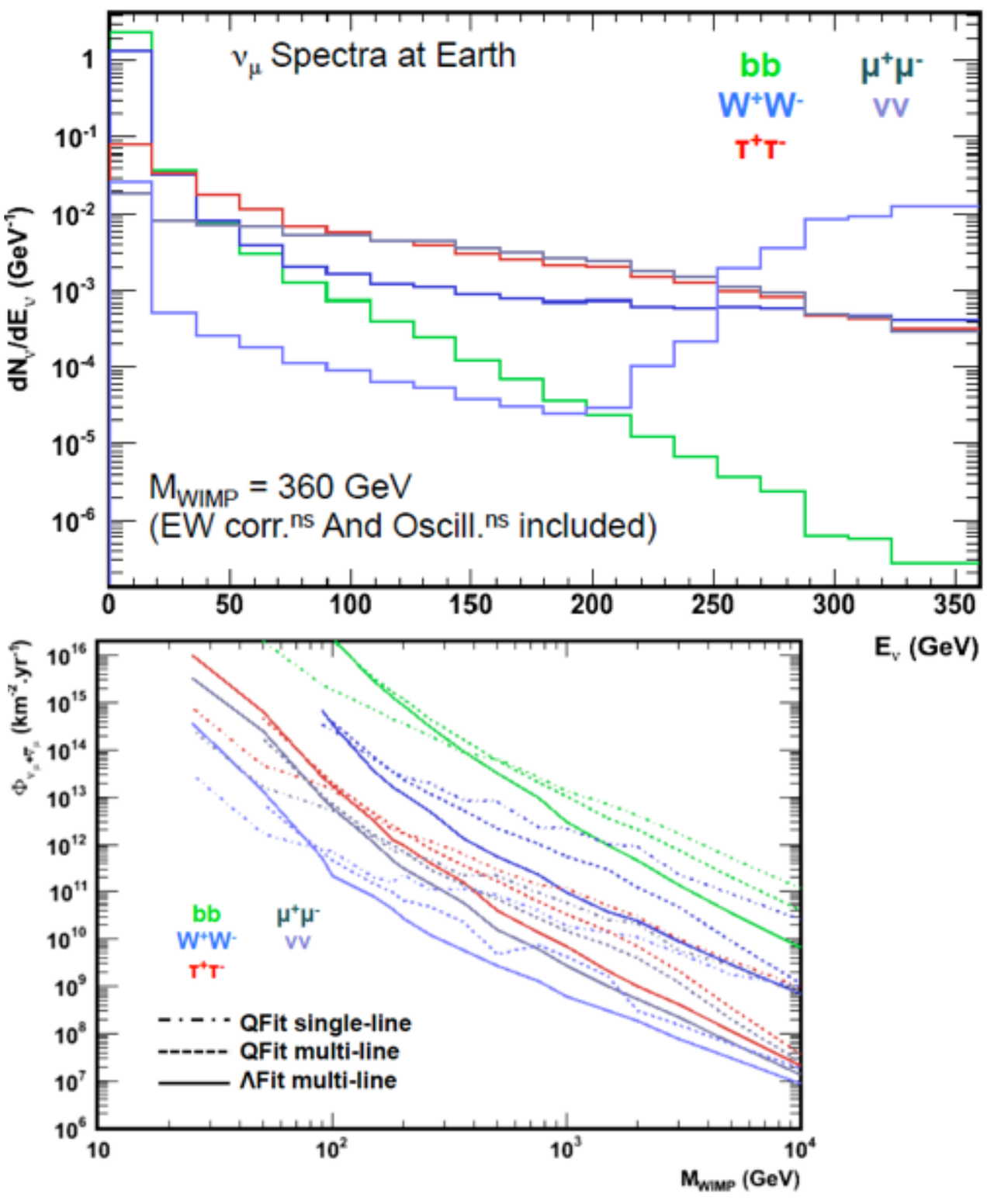


# ANTARES Galactic Center Analysis

**ANTARES Coll. JCAP 1510 (2015) no.10, 068**



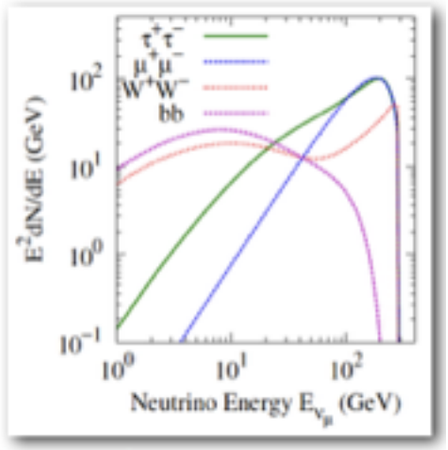



# IceCube Dark Matter Halo Analyses

IceCube Collaboration arXiv:1606.00209v1

**Measure Flux** = **Particle Physics**

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f \frac{dN}{dE}B_f$$

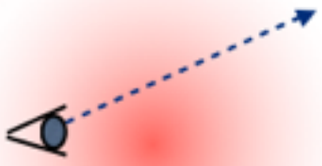


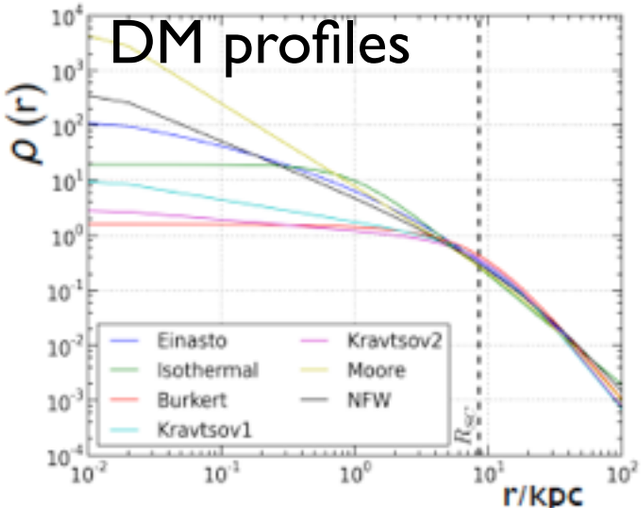

x

**Dark Matter Distribution**

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

line of sight (los) integral

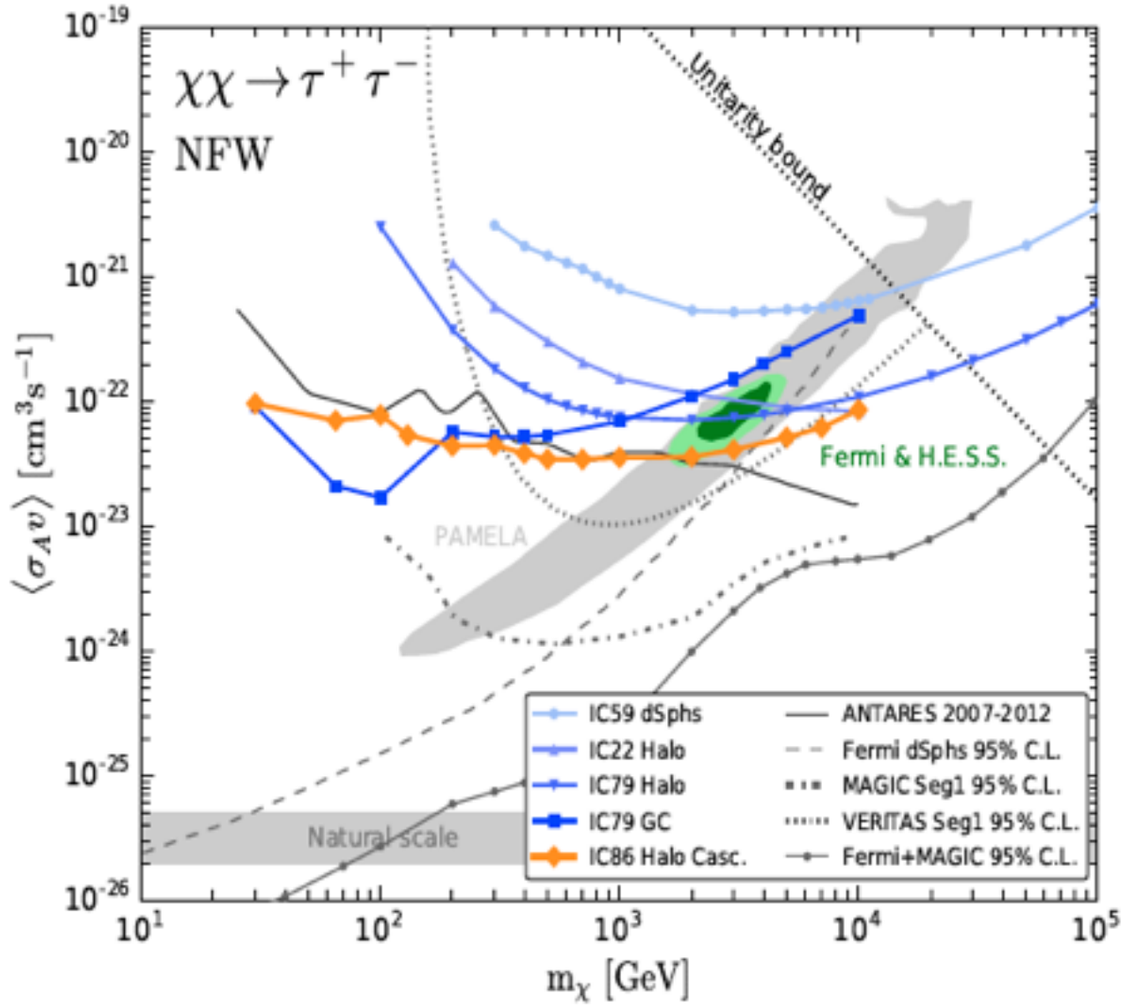





- Galactic Center (GC) on the Southern hemisphere
  - large backgrounds from down-going muons
- Search for anisotropy on Northern hemisphere
  - high-purity neutrino sample (up-going muon events)
  - large scale distribution (cascades event optimally suited)
- Assume annihilation into νν, bb, μμ, ττ, WW

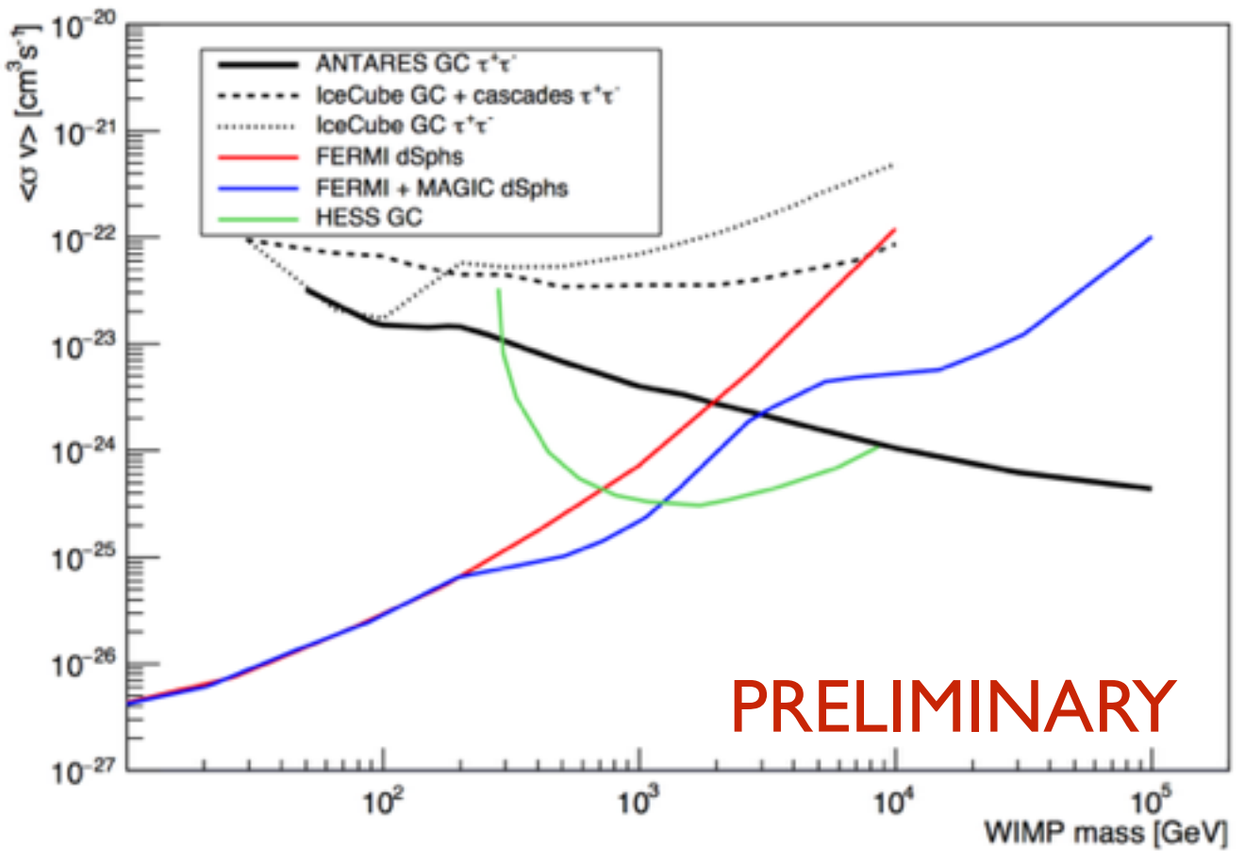
**Models motivated by increase in positron fraction can be tested**

$X_{\mathrm{WIMP}}\bar{X}_{\mathrm{WIMP}} \rightarrow \nu\bar{\nu},\ b\bar{b},\ W^-W^+,\ \tau^-\tau^+,\ \mu^-\mu^+$



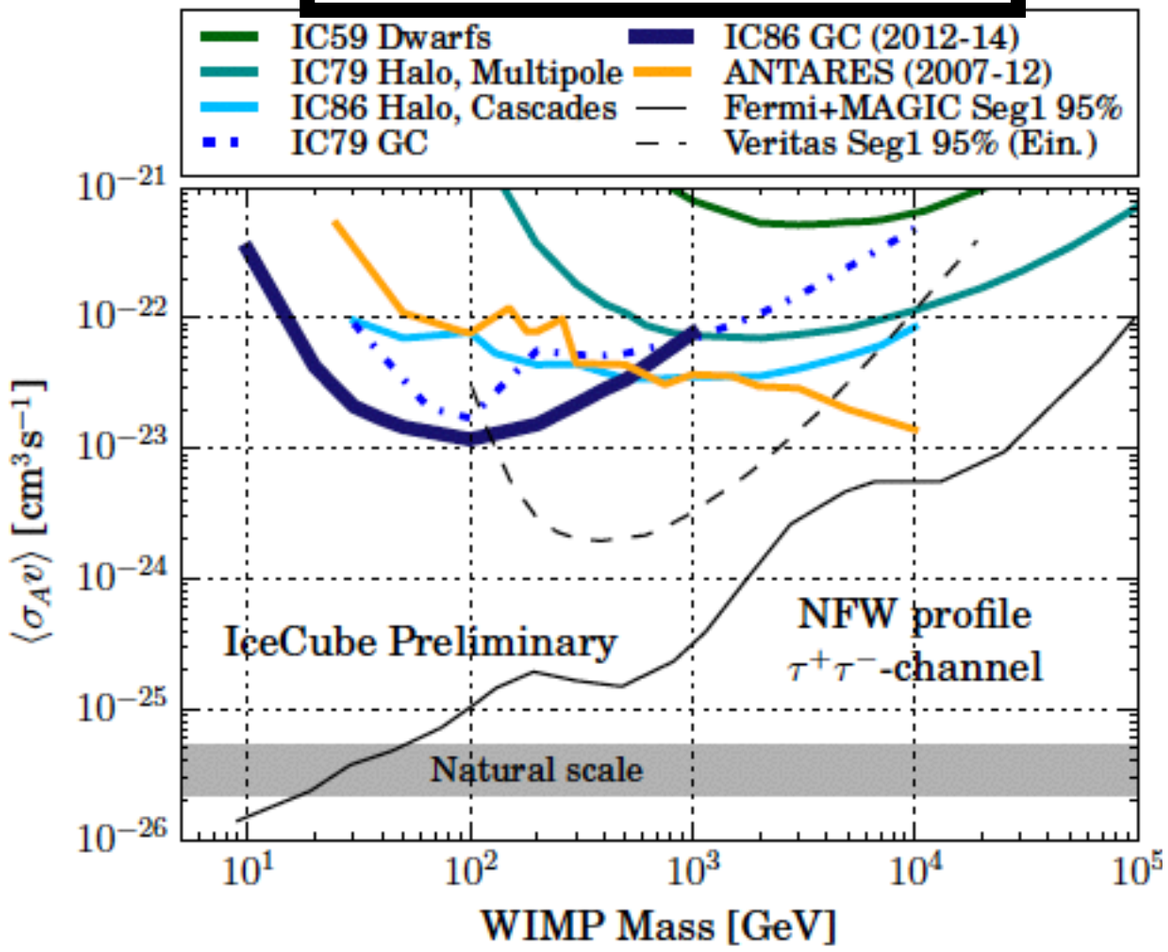
# Improved results Galactic Centre

## ANTARES




2007-2015 data
GC analysis including single line events

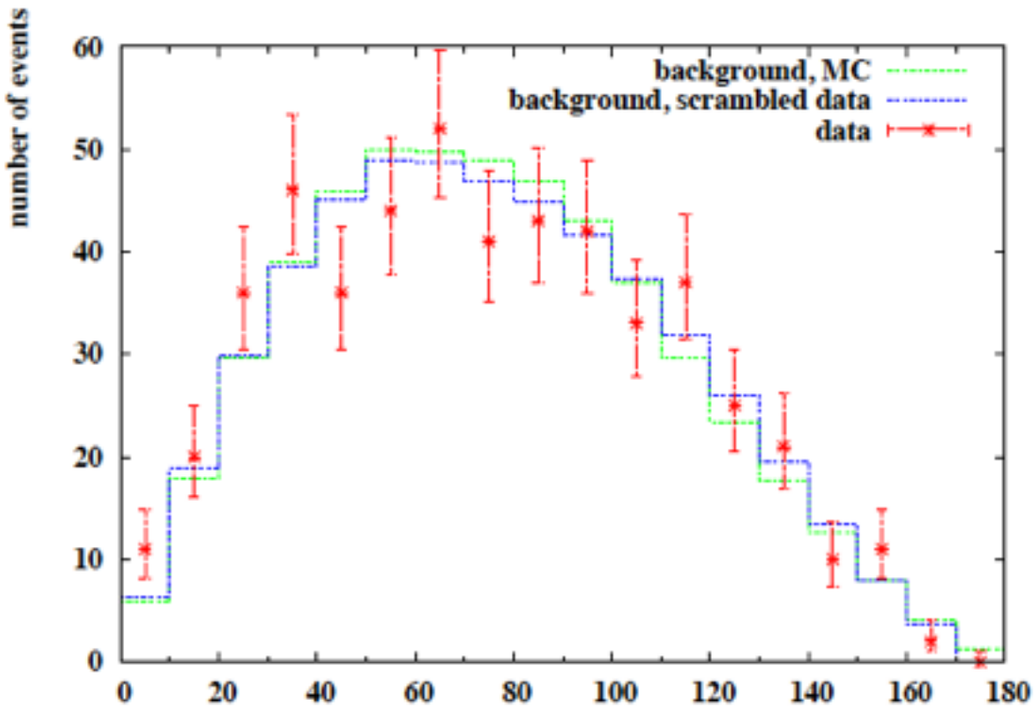
## IceCube

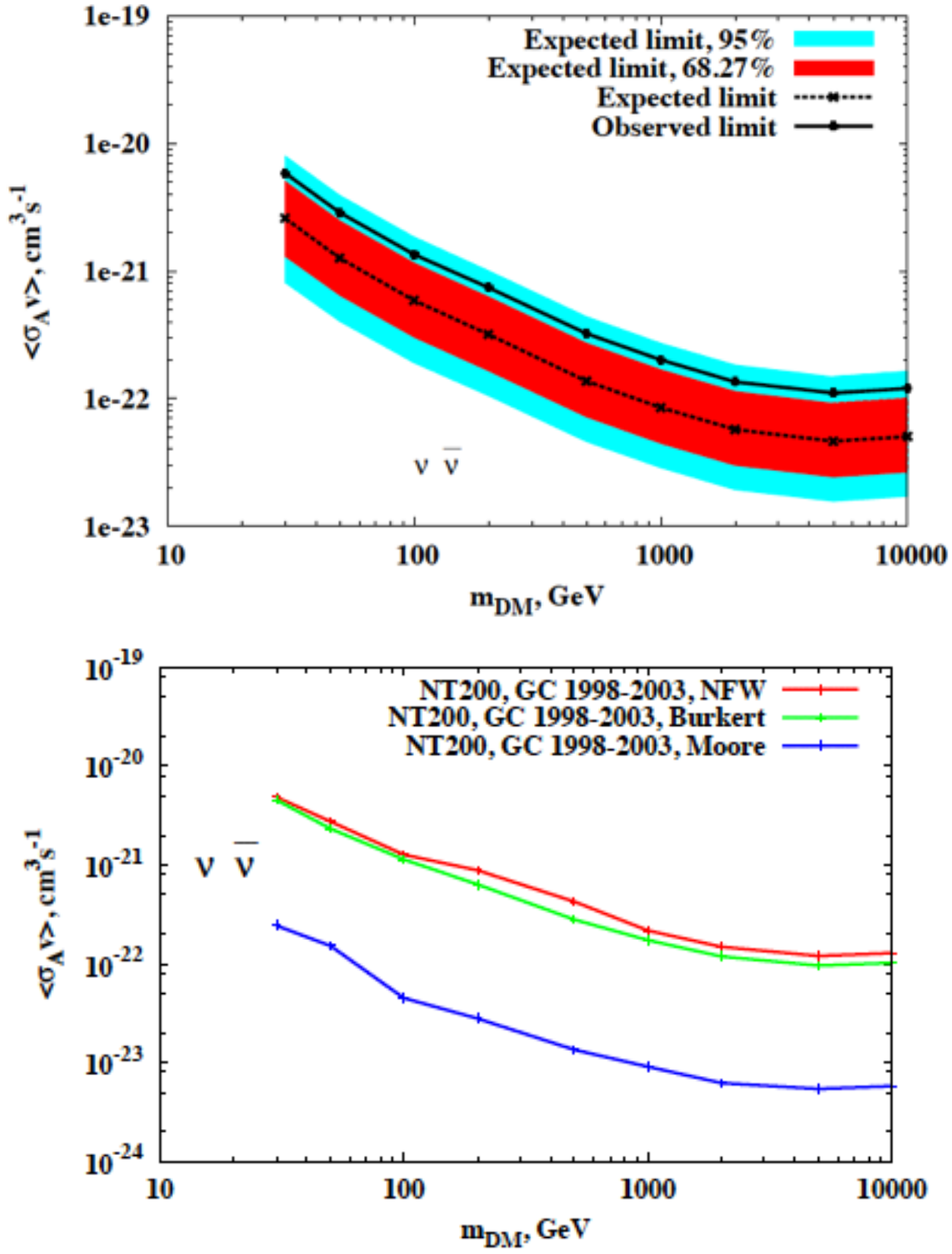



- 3 years of data: 1007 days of lifetime
- Rejection of atmospheric muons using containment, veto techniques
- 2D shape likelihood function to estimate the signal fraction

# Baikal Galactic Centre

**Baikal AstroPhys 81 (2016)**




- Dataset collected during 1998–2003
- Maximum likelihood method
- Limits computed for various channels

Astrophysical factor → $J_{a,\Delta\Omega}$ ← Visibility

$$J_{a,\Delta\Omega} = \int d(cos\psi)d\phi J_a(\psi)\epsilon(\psi,\phi).$$

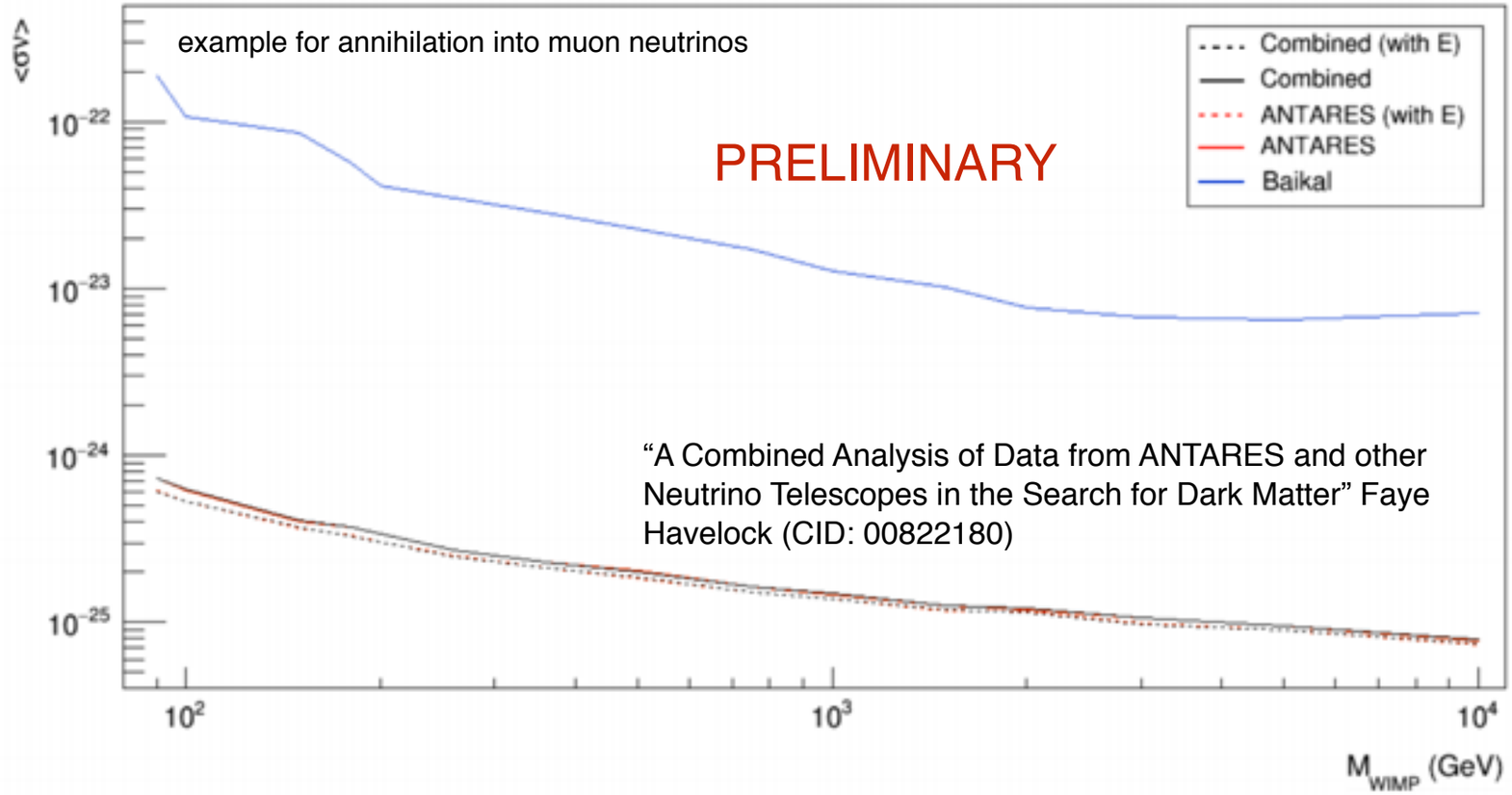
$$N(\Psi) = T\frac{\langle\sigma_a v\rangle R_0\rho_0^2}{8\pi m_{DM}^2} J_{a,\Delta\Omega} S^{eff} \int_{E_{th}}^{m_{DM}} dE \frac{dN_\nu}{dE_\nu}$$

# Understanding sensitivities

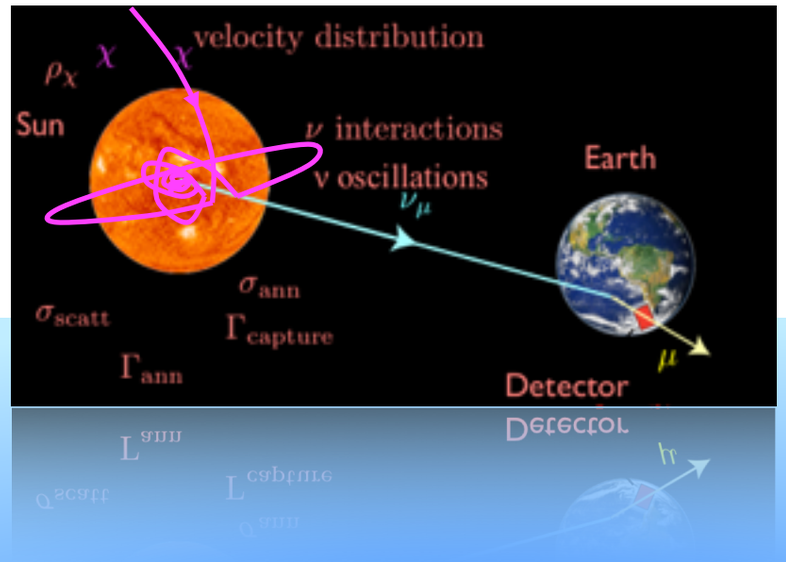
- Understanding the sensitivity of neutrino detectors
  - Neutrino distribution does not change with choice of annihilation channel or WIMP mass
    - There is however a dependence introduced due to the energy dependent angular resolution
  - The signal event rate are roughly flat as function of WIMP mass
    - Doubling the WIMP mass reduces the annihilation rate by a factor of four ($\Gamma_A \sim (\rho/m)^2$)
    - Neutrino cross section increases linear with neutrino energy
    - Muon range increases with neutrino energy
      - Can be exploited for ANTARES and Baikal for Galactic centre analysis
  - Backgrounds decrease with energy
    - Atmospheric neutrinos and Atmospheric Neutrinos
      - Energy dependence critical to improve bounds towards higher WIMP masses
        - Dependence on neutrino spectrum / annihilation channel

# Combined analysis

- Combined Galactic center analysis ?
  - Gain from the different sensitivity ranges on Northern and Southern hemisphere
- Small working group formed
  - ANTARES, IceCube, and Baikal
- A wikipage has been prepared in order to gather information related to the analysis and that we have held some phone calls
- Planned datasets to be used:
  - ANTARES scrambled data for 2007-2012
  - Initially IceCube IC79 scrambled data … and more years soon

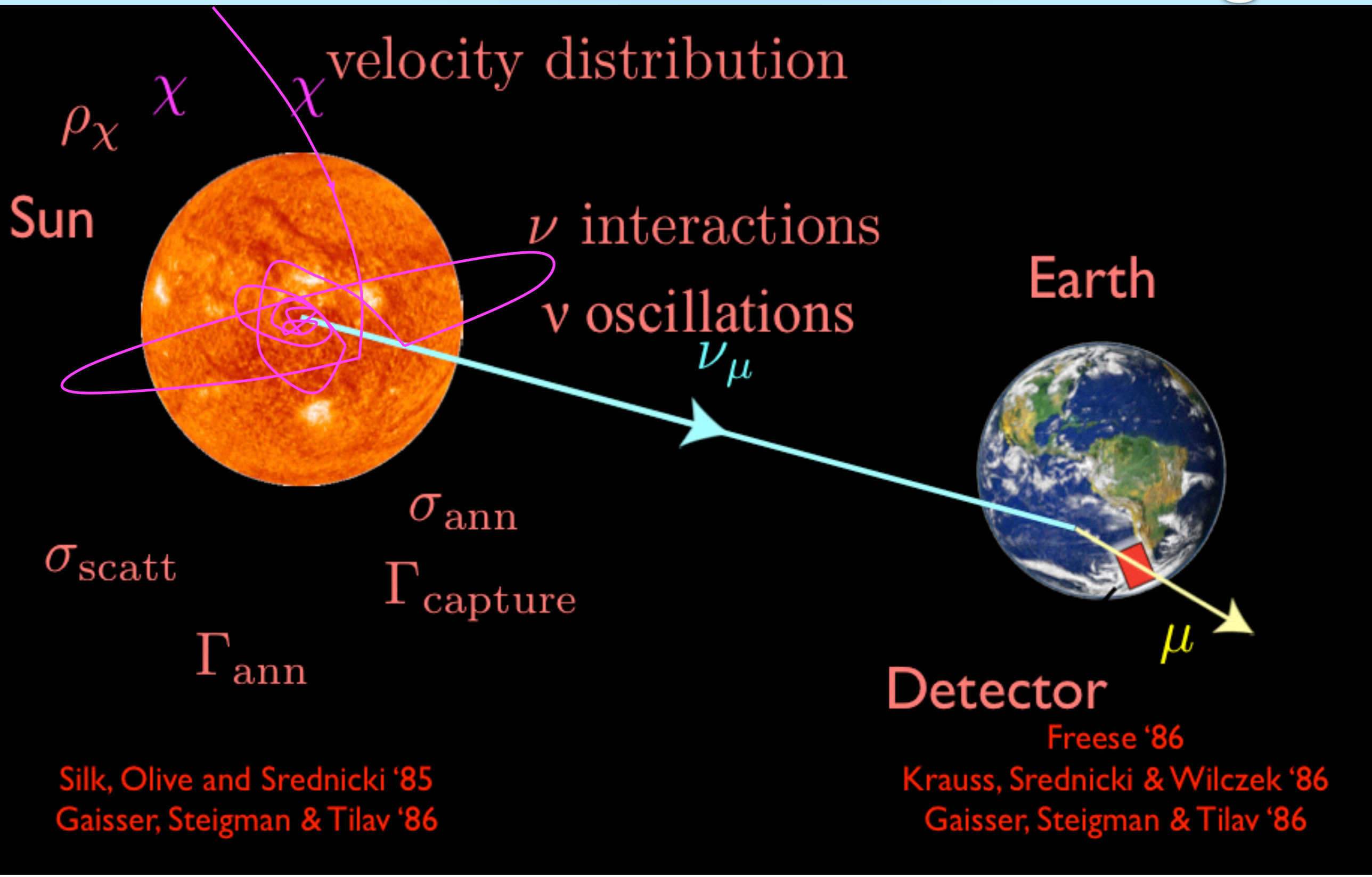



Initial focus is on combining the analyses


velocity distribution
$\rho_\chi$
$\chi$
$\chi$
Sun
$\nu$ interactions
$\nu$ oscillations
$\nu_\mu$
Earth
$\sigma_{\rm ann}$
$\sigma_{\rm scatt}$
$\Gamma_{\rm capture}$
$\Gamma_{\rm ann}$
$\mu$
Detector

# Solar WIMPs

# Solar WIMP Signal




Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

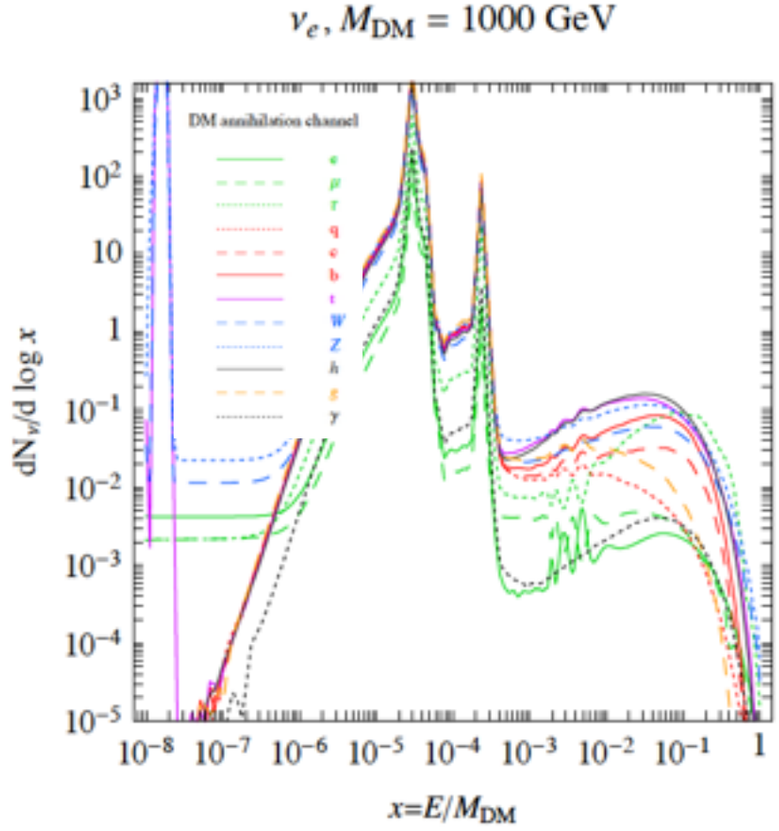
# Neutrino Spectra (Sun)

- WIMPSim
  - Pythia
  - http://copsosx03.fysik.su.se/wimpsim/

DarkSUSY

IceCube

- PPPC 4DMν
  - Pietro Baratella, Marco Cirelli, et al. … arXiv:1312.6408v2
  - Pythia and GEANT4

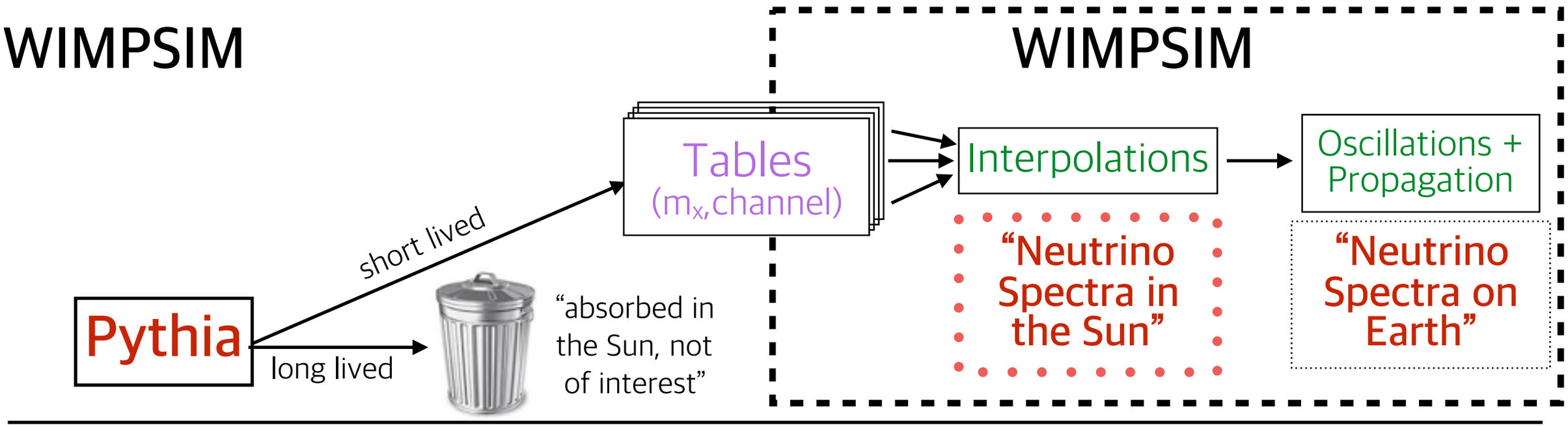



Baikal

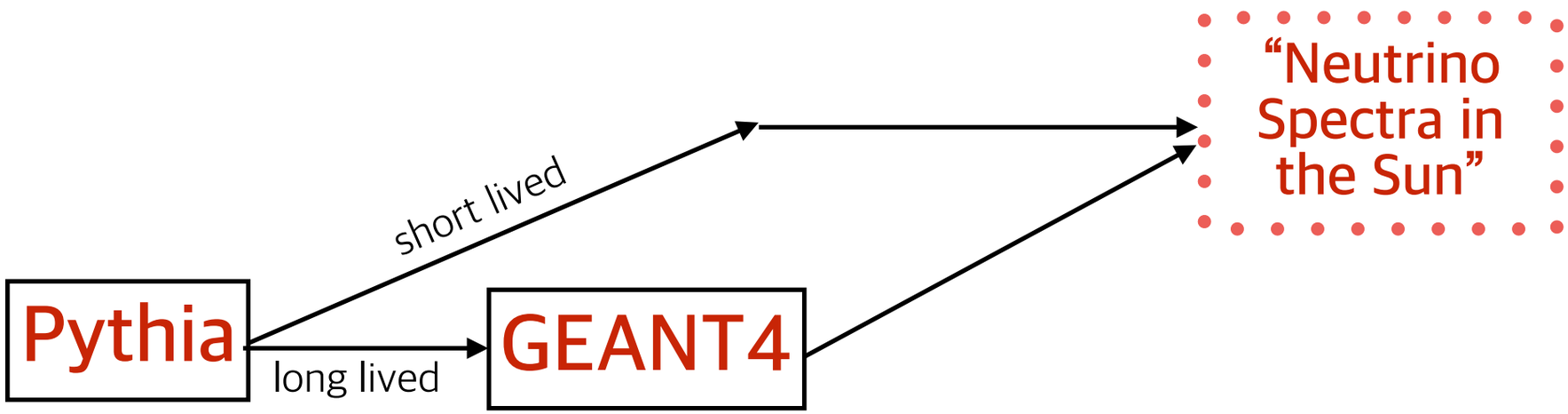
ANTARES

For any practical purpose, the two approaches yield results which are very well in agreement.

# How to get neutrino spectra

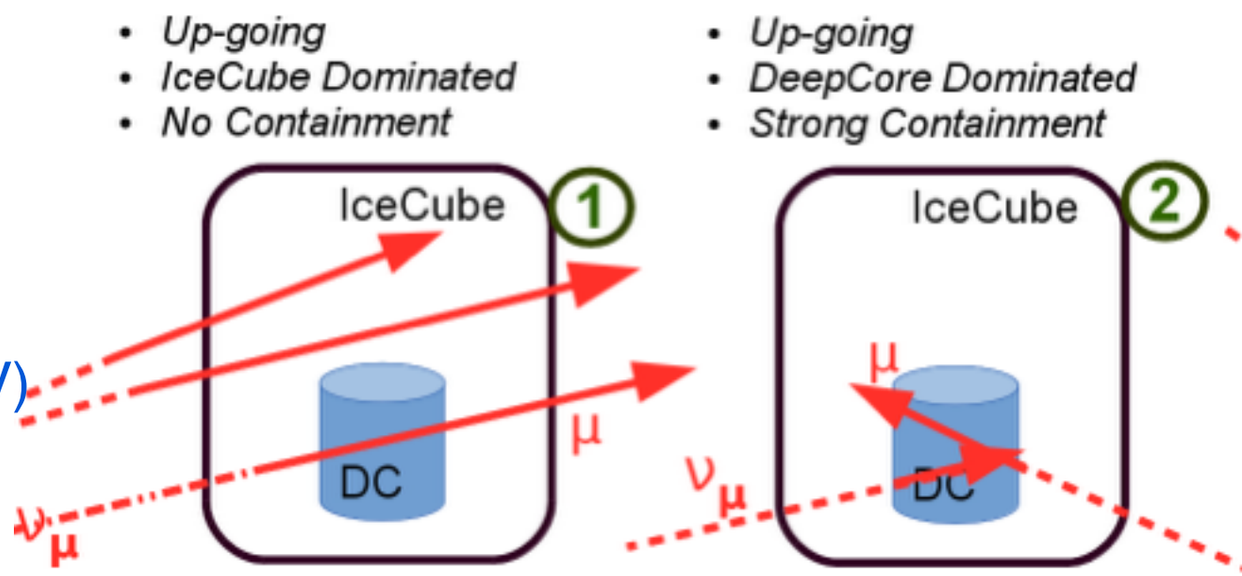



## PPPC 4DMv

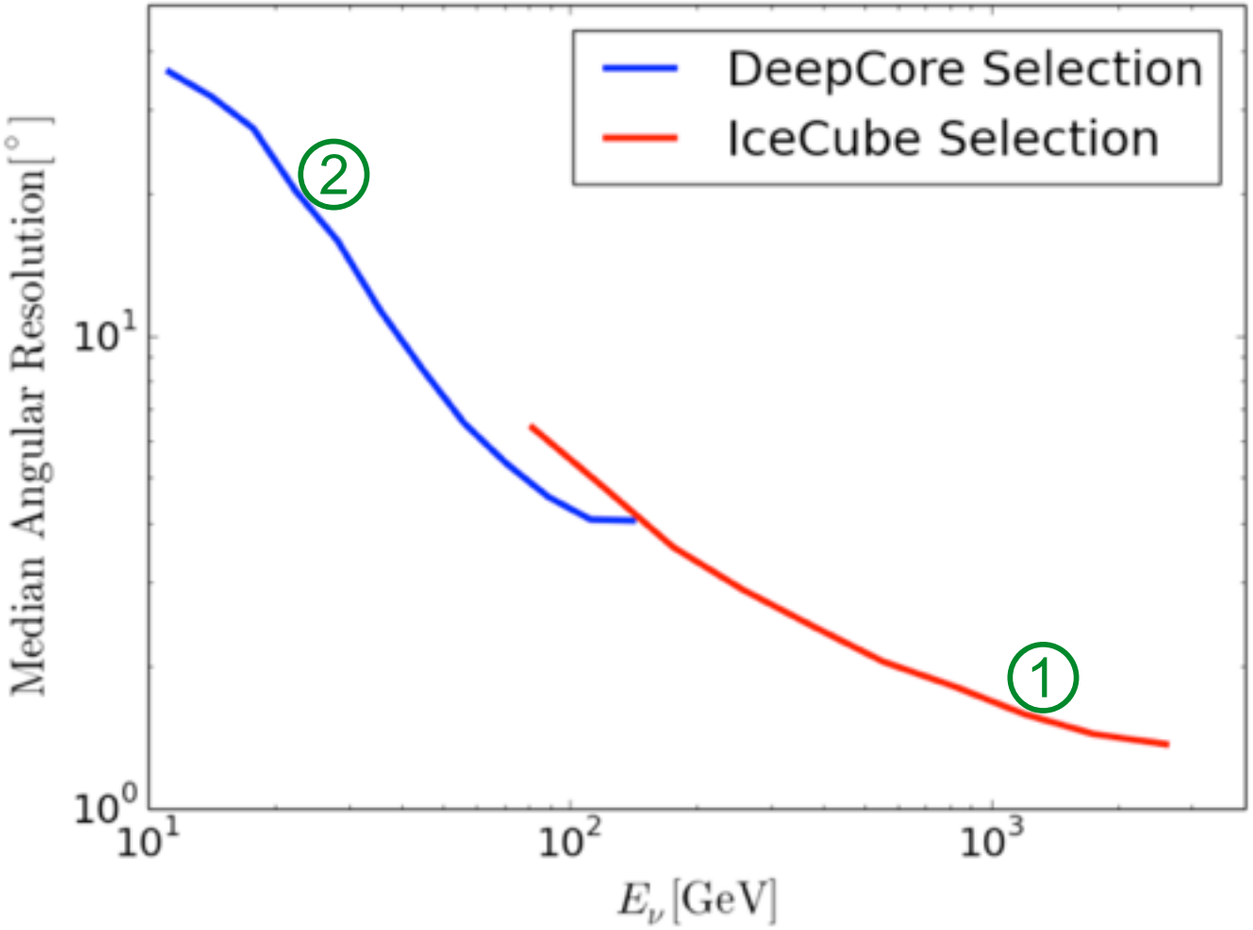


# 3yrs IceCube Solar WIMP Analysis

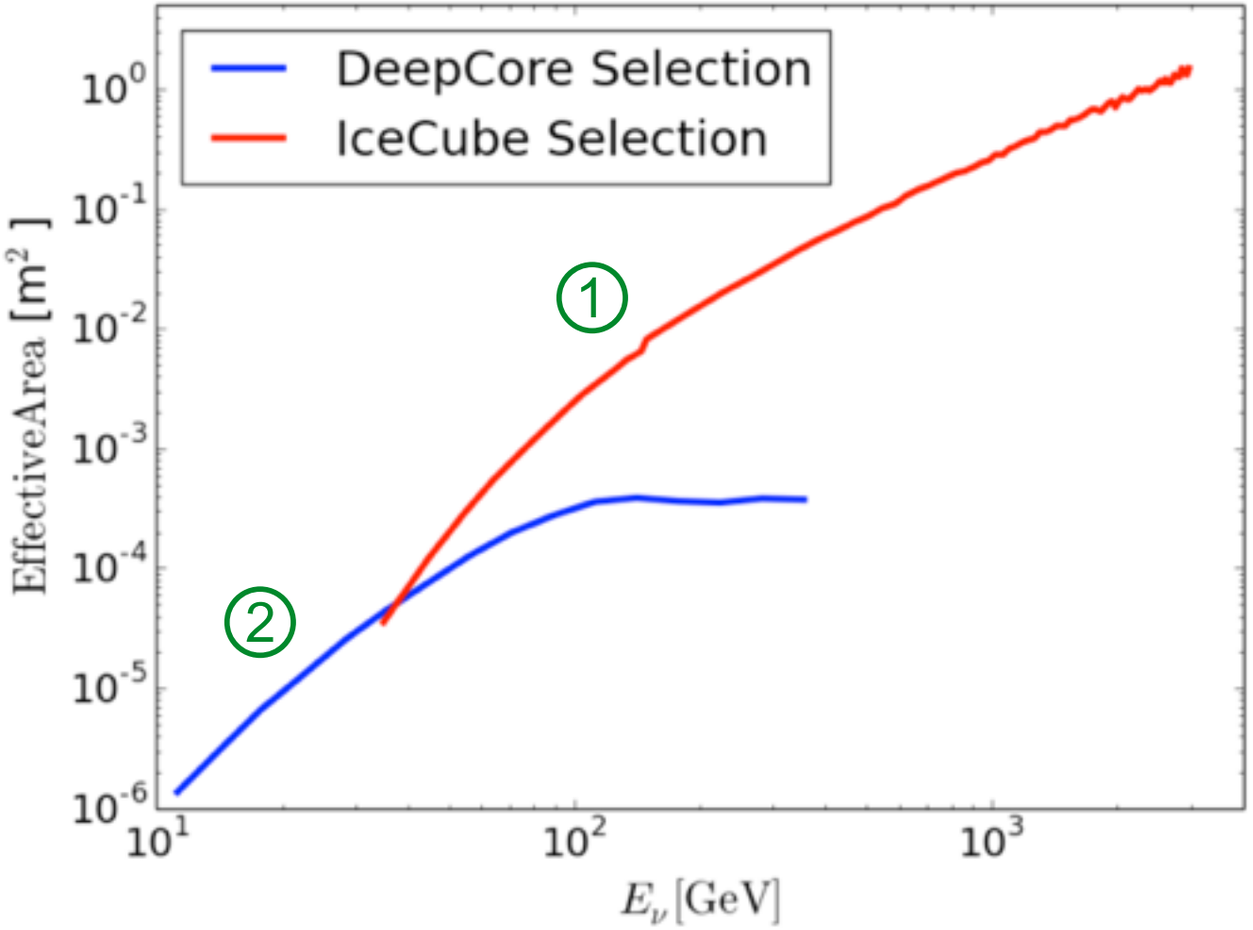
- Three years of data in 86-string configuration used (**May 2011 - May 2014**)
  - Only **up-going** events (Sun below the horizon) results in **532days of livetime**
- Two independent analysis performed
  - ① **IceCube**: Higher energy focus ($m_\chi > 100$GeV)
  - ② **DeepCore**: Low-energy focus ($m_\chi = 30$GeV - 100GeV)



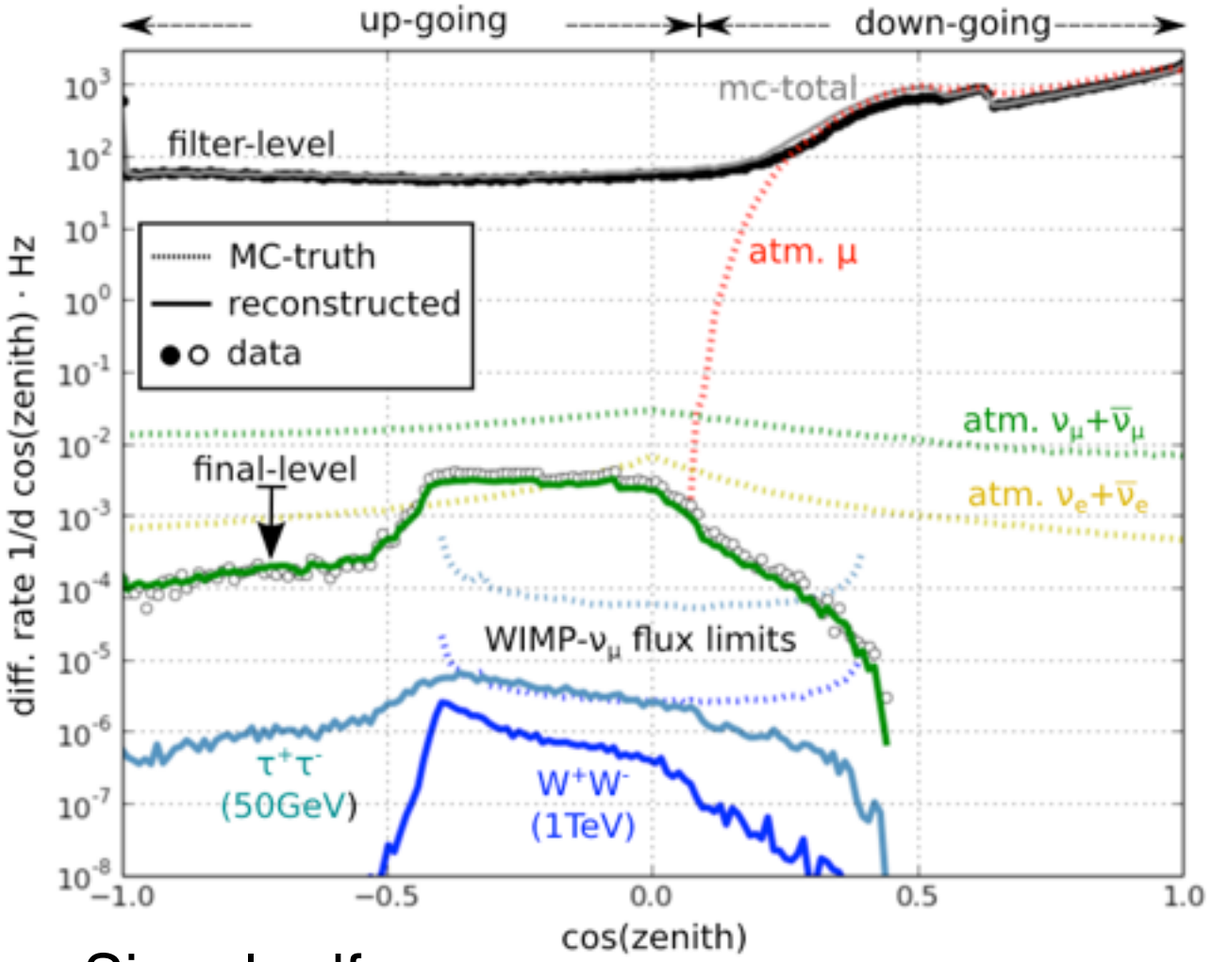

## Median angular resolutions



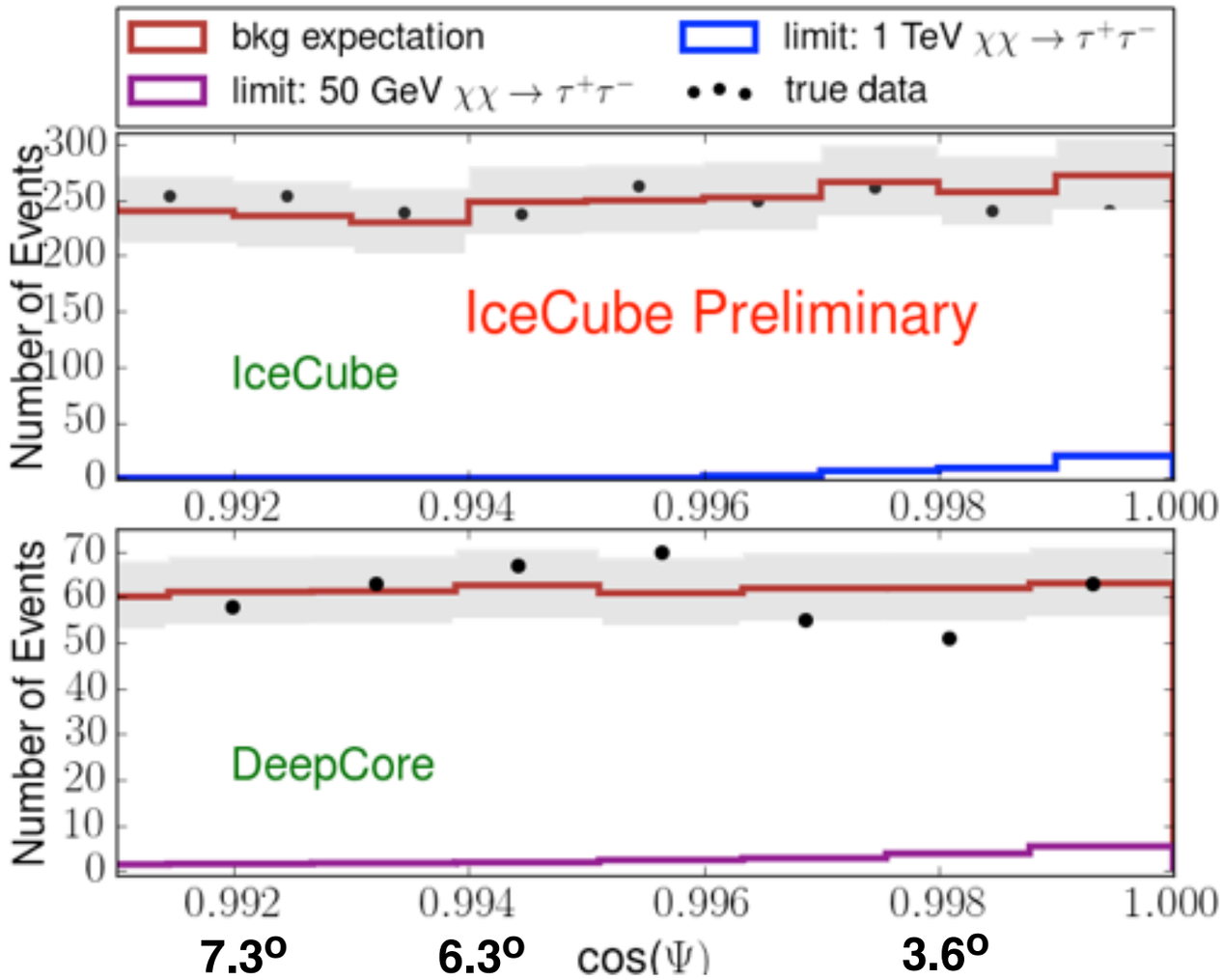

## Effective Areas



# 3yrs IceCube Solar WIMP Analysis




## Observed events




Signal pdf:

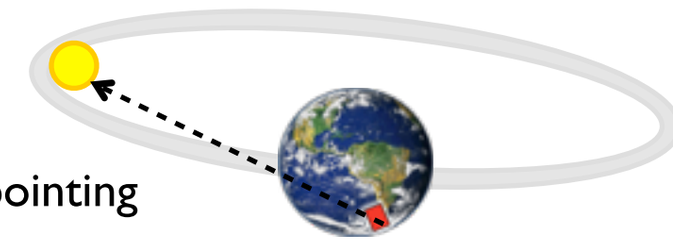
Spectral part

$$S_i(|\vec{x}_i - \vec{x}_{\rm sun}(t_i)|, E_i, m_\chi, c_{\rm ann}) = \mathscr{K}(|\vec{x}_i - \vec{x}_{\rm sun}(t_i)|, \kappa_i) \times \mathscr{E}_{m_\chi, c_{\rm ann}}(E_i)$$

**Monovariate Fisher Bingham distribution from directional statistics**

Background pdf: $\mathscr{B}_i(tx_i, E_i) = B(\delta_i) \times P(E_i|\phi_{\rm atm})$

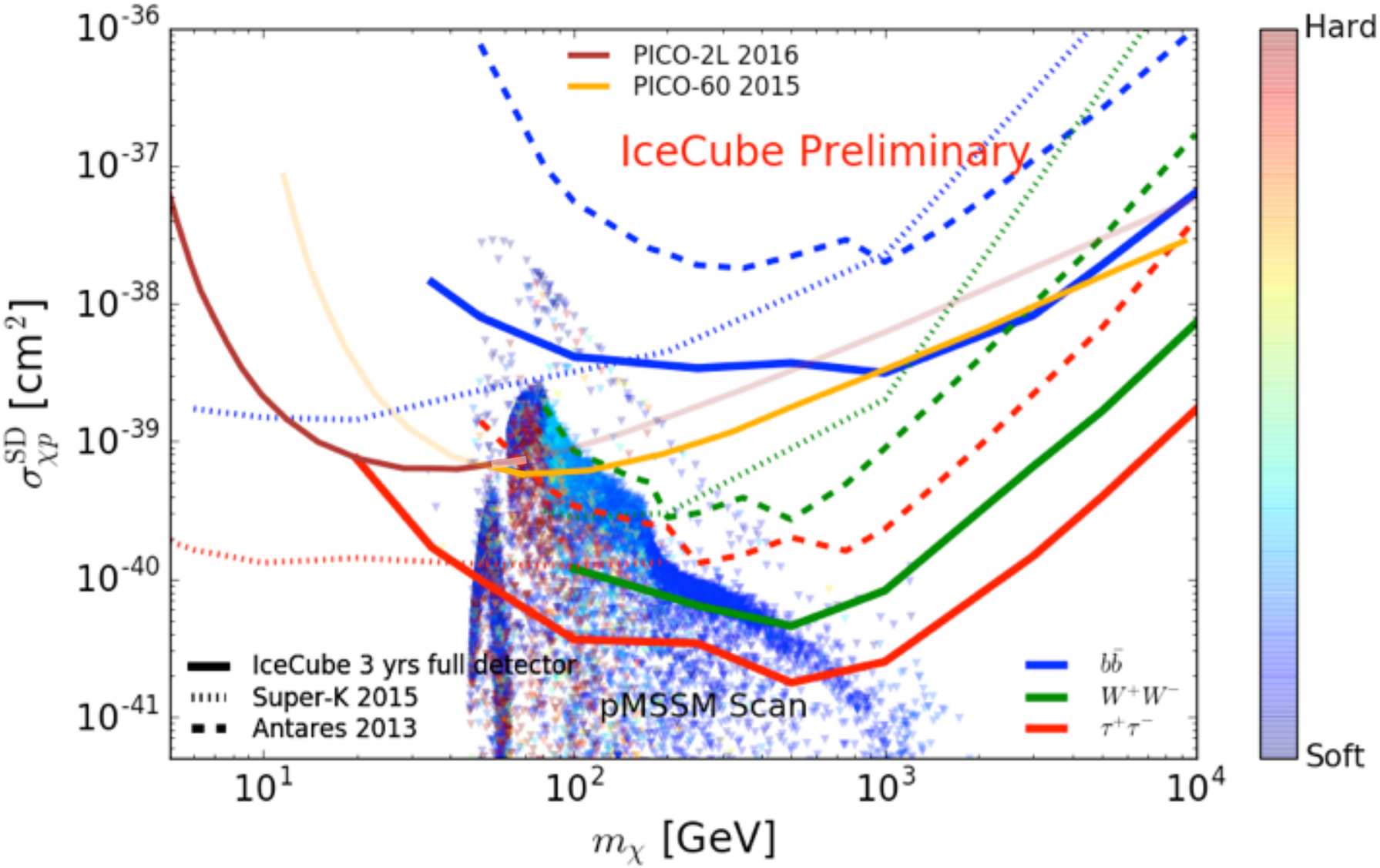
Likelihood: $\mathscr{L}(n_{\rm s}) = \prod_N \left(\frac{n_{\rm s}}{N} S_i + (1 - \frac{n_{\rm s}}{N})\mathscr{B}_i\right)$



- Use track events for better pointing
- Search for an excess of events from the direction of the Sun
- Observed events consistent with background only expectations

# Solar WIMPs (Spin-dependent)

**update from IceCubeColl., PoS(ICRC2015) 1099**

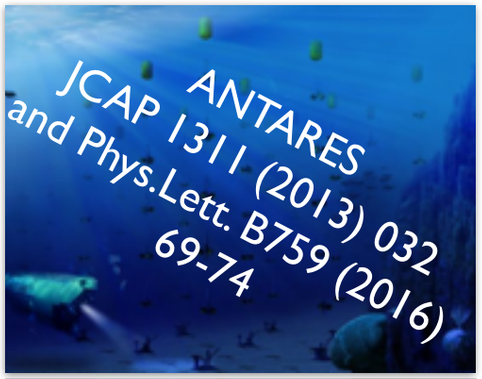


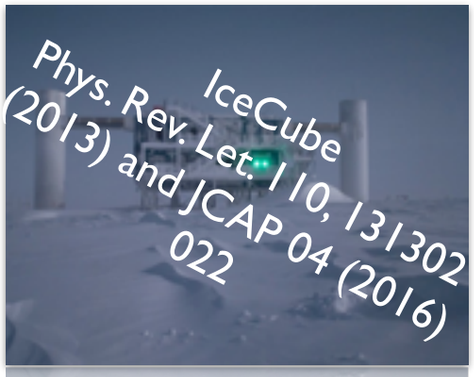

Neutrino bounds extremely competitive with Dark Matter direct detection
&
Can test models beyond the reach of LHC

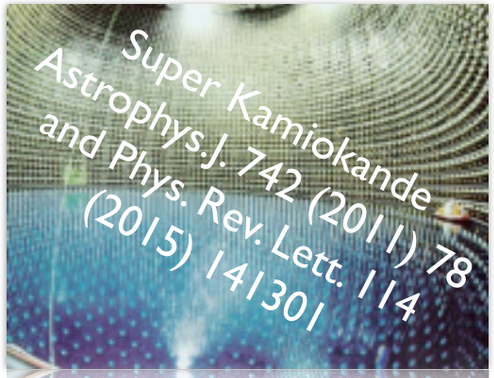
- pMSSM model scans
  - Hard / Soft defined by fraction of hard and soft final states

No evidence for dark matter

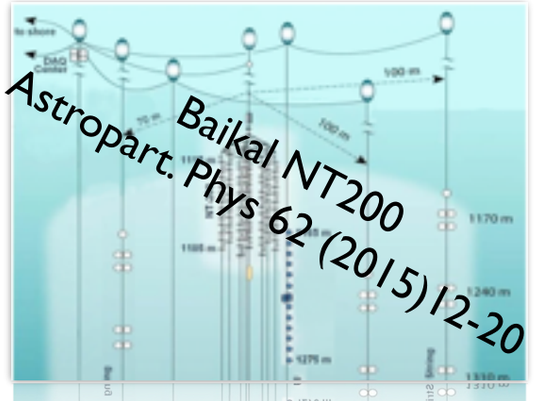
# Solar WIMPs Summary



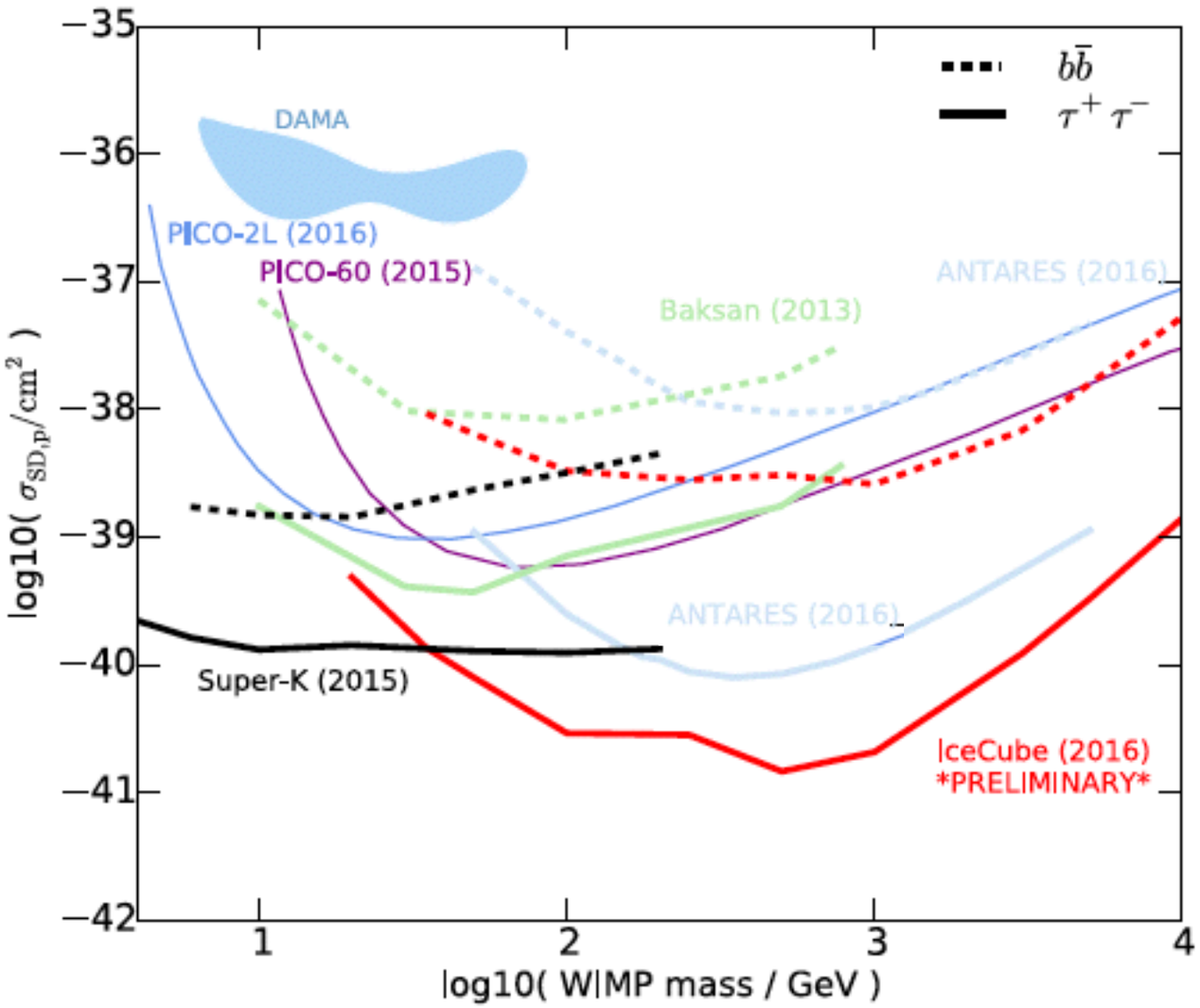





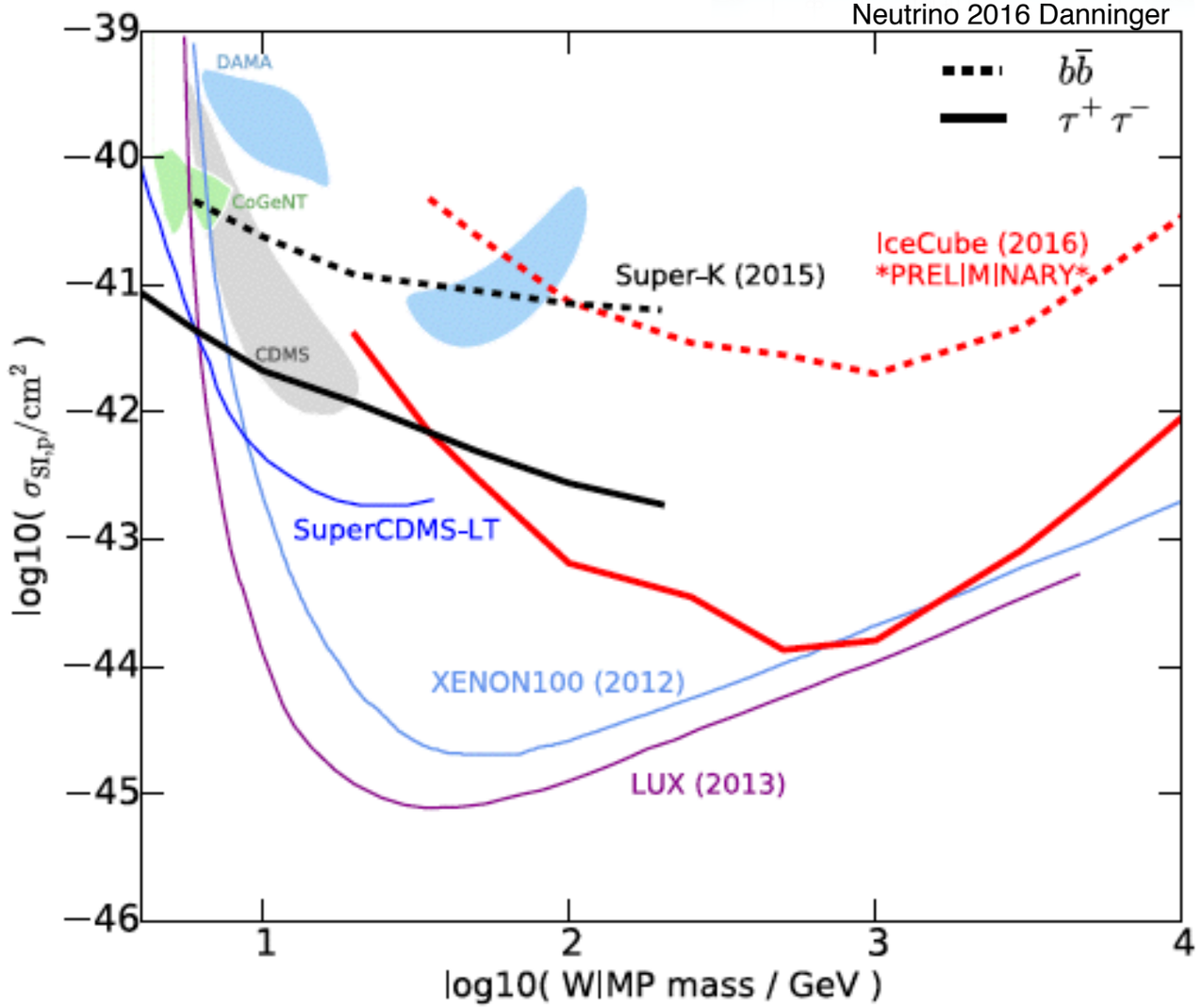



## Spin-dependent scattering




## Spin-independent scattering

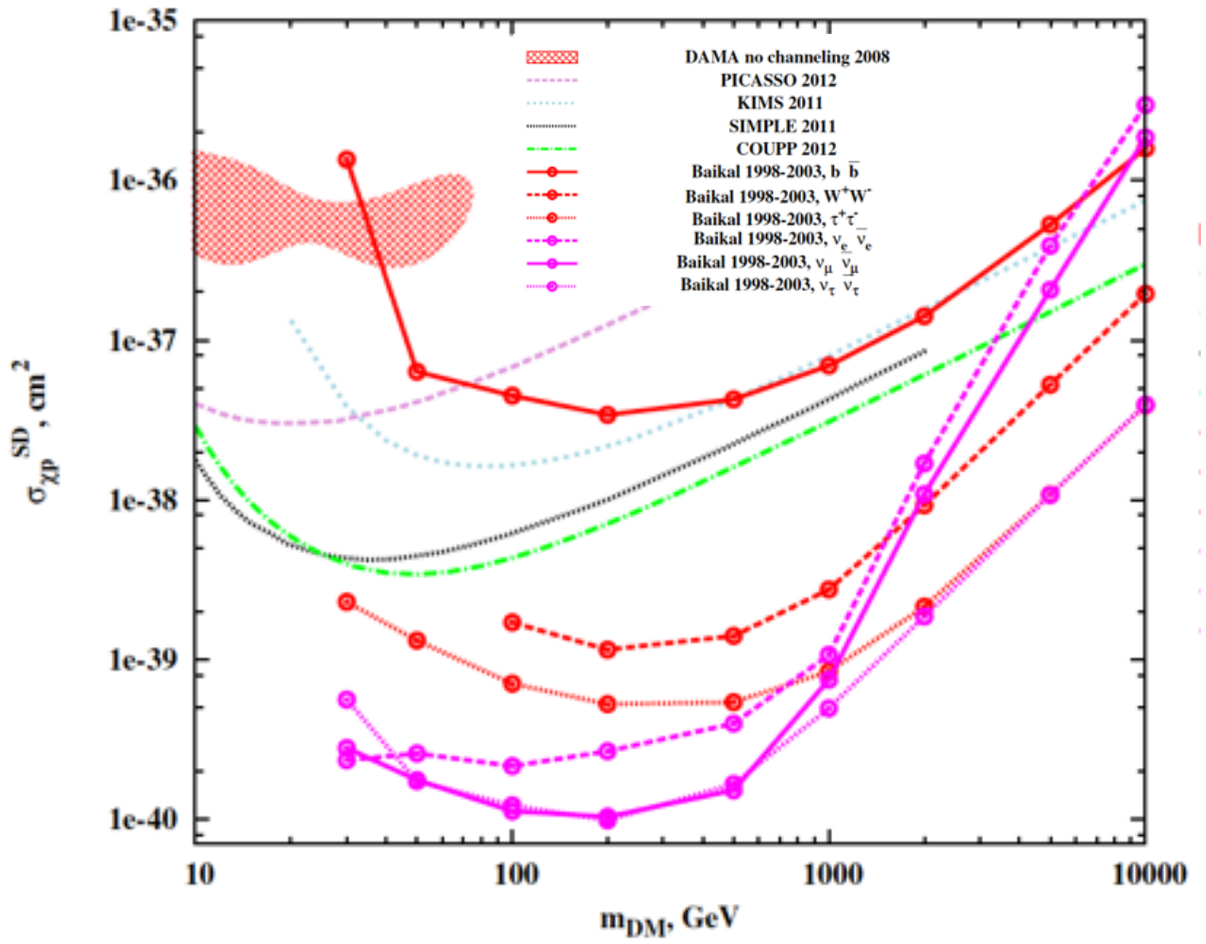
Neutrino 2016 Danninger



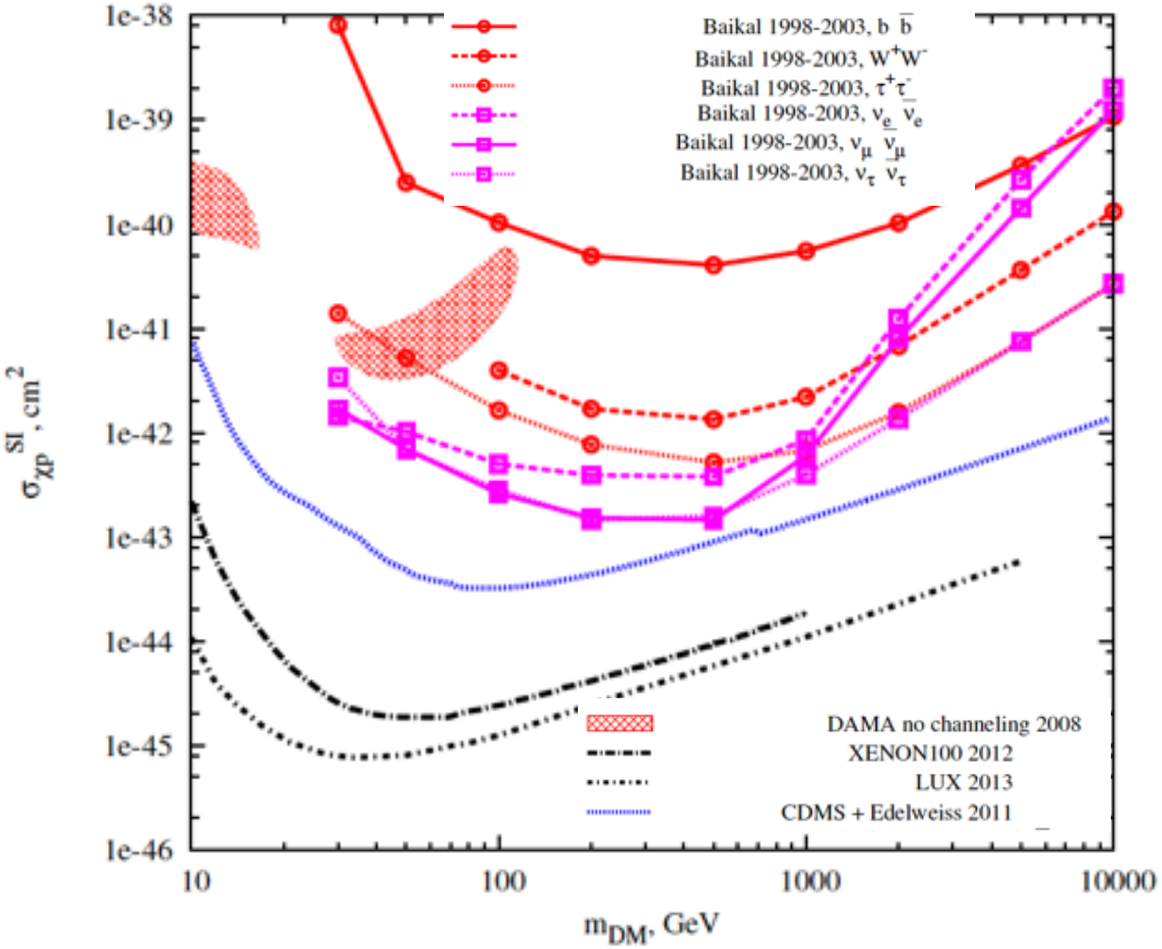
# Baikal Neutrino Line Search

**Search for neutrino emission from relic dark matter in the Sun with the Baikal NT200 detector**
Baikal Collaboration (A.D. Avrorin (Moscow, INR) *et al.*). May 14, 2014. 9 pp.
Published in **Astropart.Phys. 62 (2015) 12-20**
DOI: 10.1016/j.astropartphys.2014.07.006
e-Print: arXiv:1405.3551 [astro-ph.HE] | PDF

## Spin-dependent scattering



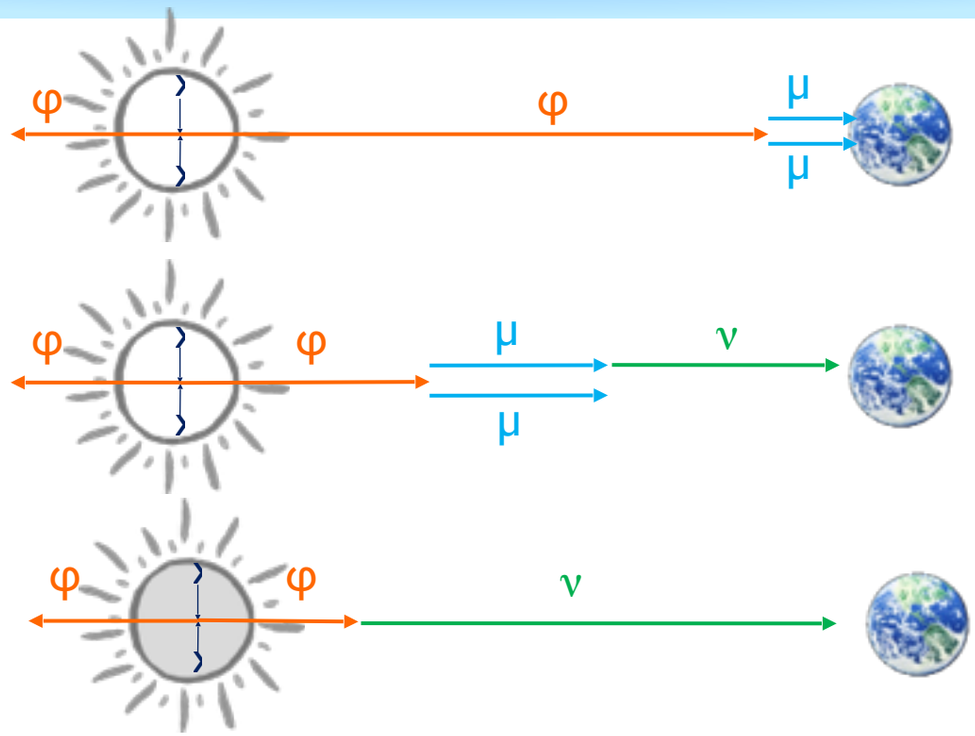

## Spin-independent scattering

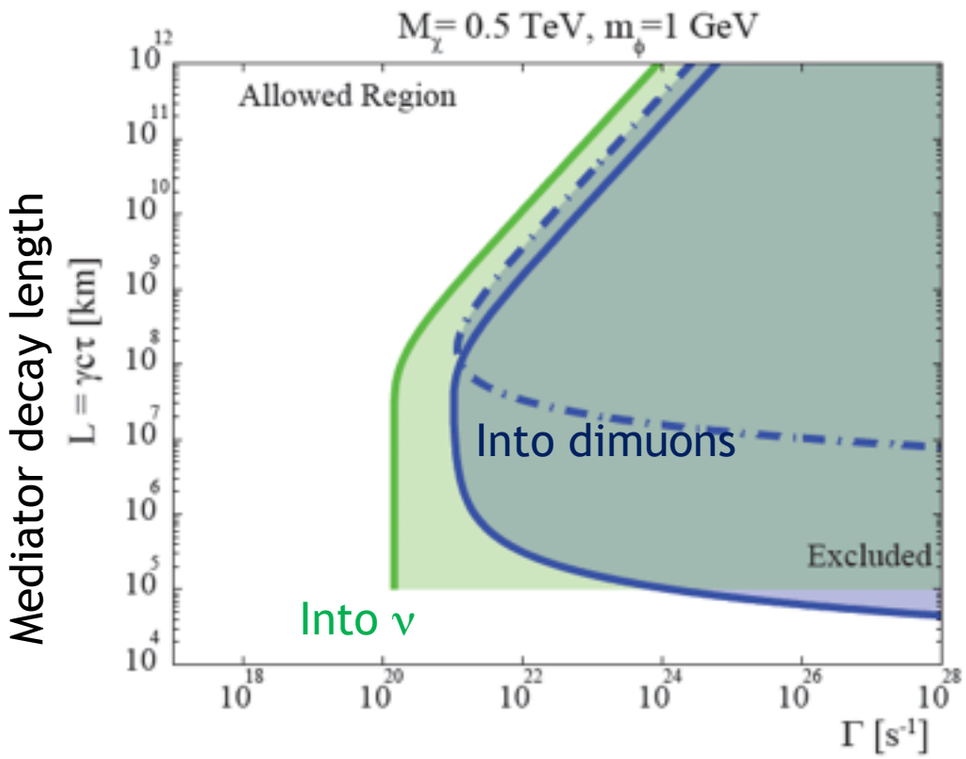



- 2.76 years live time with the Baikal neutrino telescope NT200
  - Including bounds for annihilation directly into neutrinos

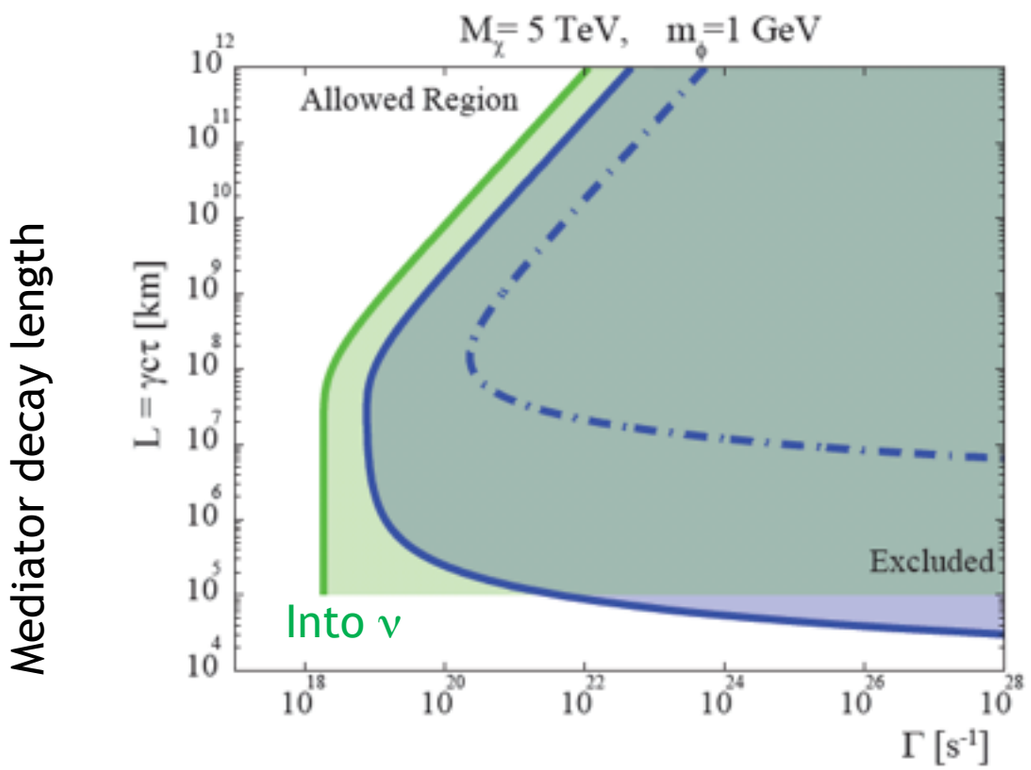
# ANTARES Secluded Dark Matter

- Dark matter annihilates into meta-stable particle
  - $\chi\ \chi$ annihilates into mediator $\phi$
    - $\phi \rightarrow \nu\ \nu$ or $\mu\ \mu$
- Livetime of 1321 days
  - Jan 2007 to Oct 2012




Annihilation of DM in the Sun x Branching ratio




Annihilation of DM in the Sun x Branching ratio

ANTARES Coll. JCAP 1605 (2016) no.05, 016

# ANTARES Secluded Dark Matter

- Dark matter annihilates into meta-stable particle
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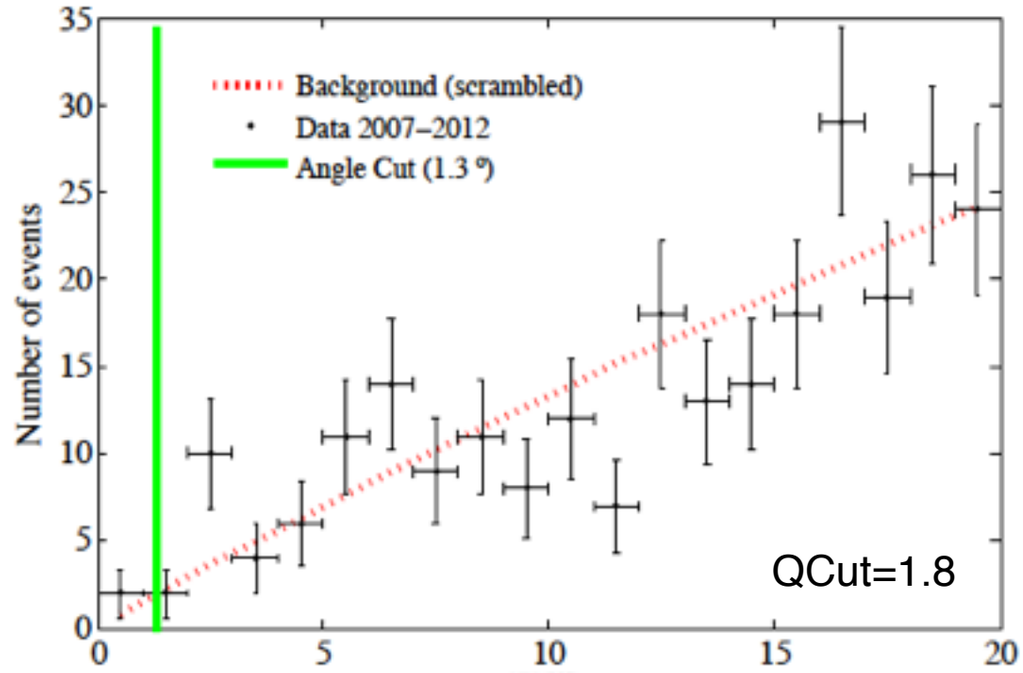
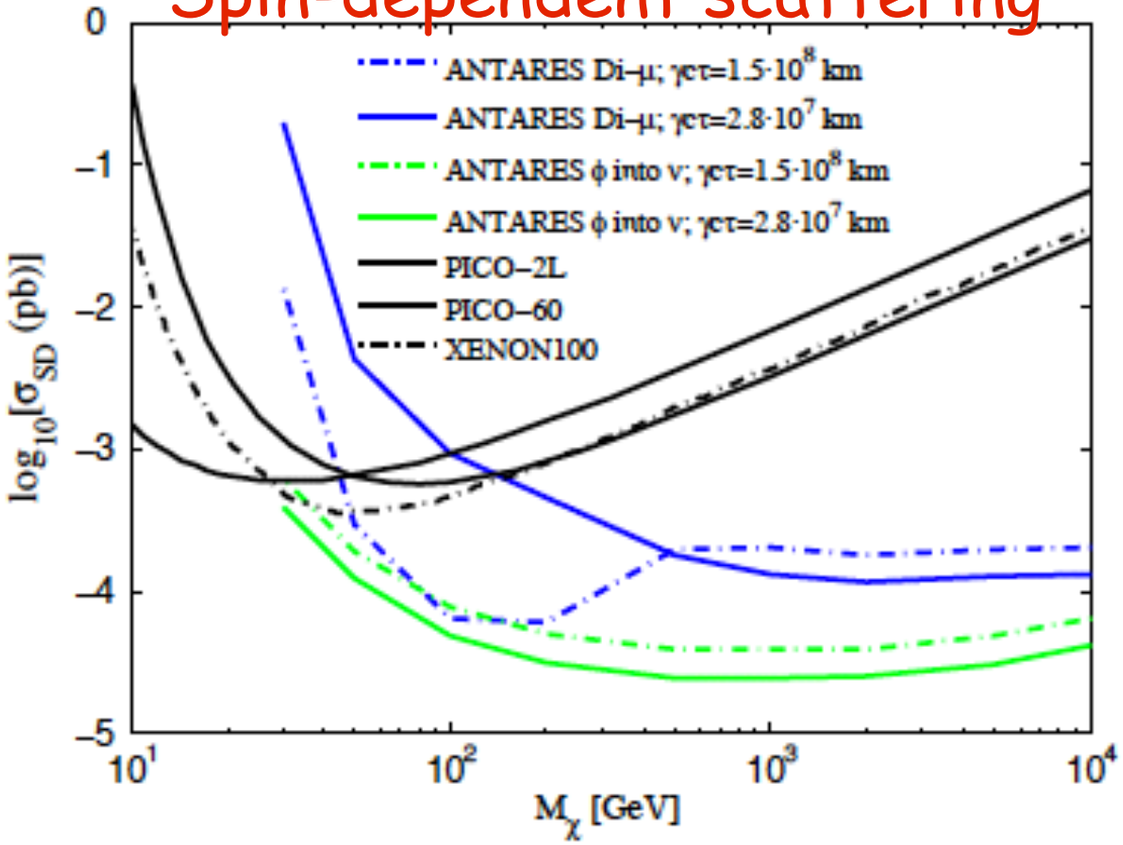
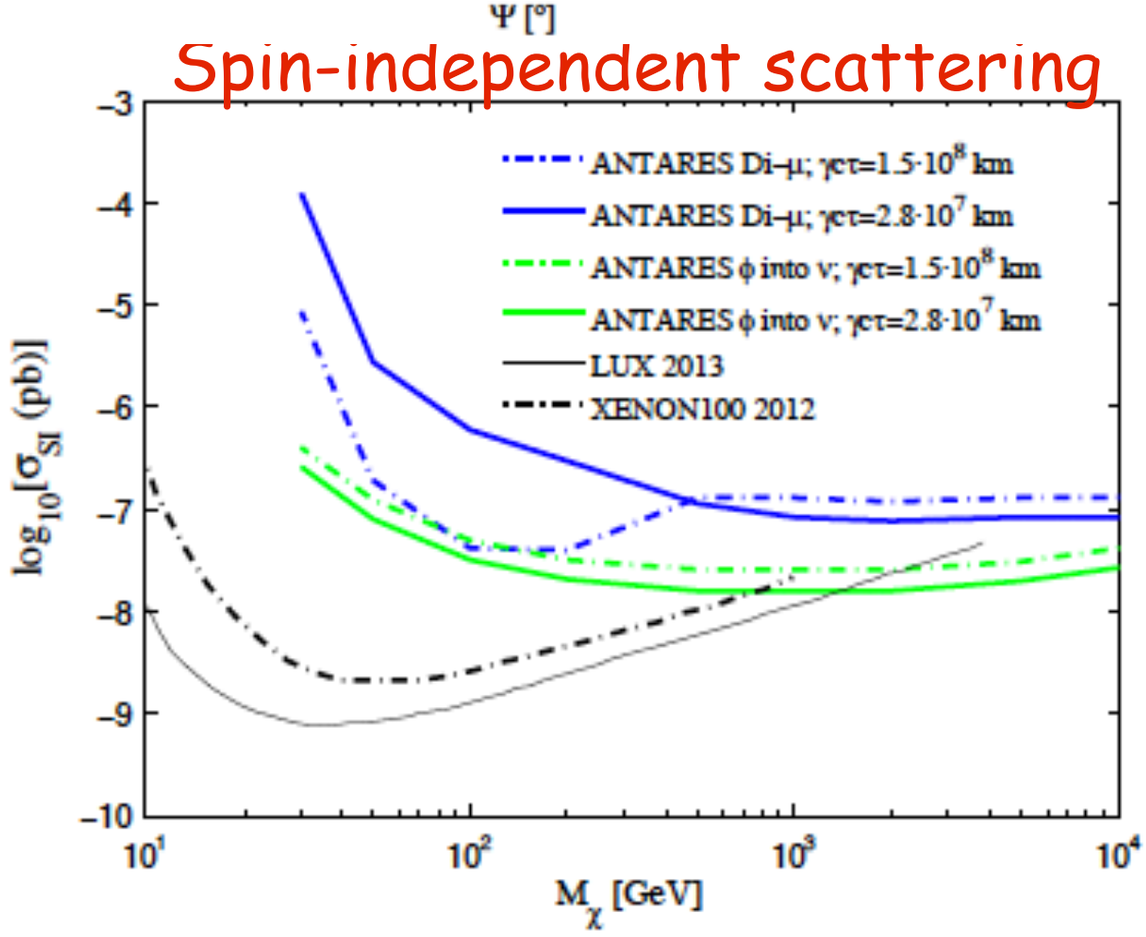
  - Jan 2007 to Oct 2012




## Spin-dependent scattering




## Spin-independent scattering



# A general word on how (not) to recast indirect detection limits

JCAP 04 (2016) 022 / http://arxiv.org/pdf/1601.00653.pdf

- Indirect limits always presented in terms of hard process final states
- Actual experiments do not measure those final states – they detect one type of SM particle produced later: $\gamma$s, $\nu$s, etc
- Limits as presented cannot be combined and applied to models with mixed final states (= all non-toy models)
- extra complications with neutrinos from capture-annihilation balance
- Proper treatment of indirect detection for BSM searches requires full phenomenological recast abilities
  → full experimental *and* theoretical treatment at the same time
- Actually not so dissimilar to LHC in this respect. . .

# Neutrino telescope likelihoods: `nulike`

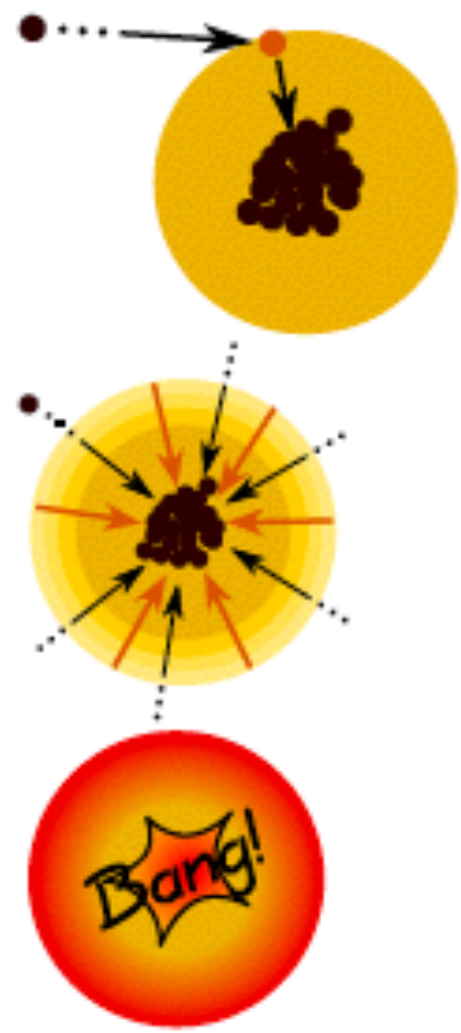
JCAP 04 (2016) 022 / http://arxiv.org/pdf/1601.00653.pdf

Unbinned $\nu$ telescope likelihood $\Longrightarrow$ full event-level angular and energy info

$$\mathcal{L}_{\rm unbin} \equiv \mathcal{L}_{\rm num}(n_{\rm tot}|\theta_{\rm tot}) \prod_{i=1}^{n_{\rm tot}} (f_{\rm S}\mathcal{L}_{{\rm S},i} + f_{\rm BG}\mathcal{L}_{{\rm BG},i})$$

Strategy: precompute partial likelihoods for each event, then reweight with the $\nu$ spectrum at Earth for each model

- precompute step uses `nusigma` with CTEQ6-DIS PDFs to get charged current $\nu - n$ and $\nu - p$ cross-sections as function of $x$ and $y$
- like step input: neutrino spectrum at Earth (from DarkSUSY or whatever else you want to use)
- like step output: num predicted events, likelihood
- → fully model-independent = future-proof for global fits



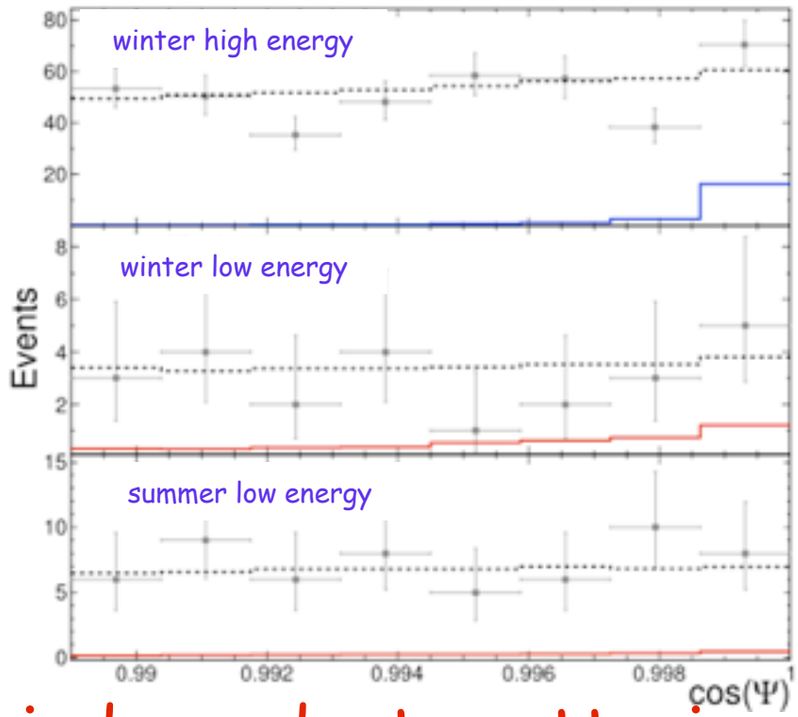

Imperial College London

# IceCube IC79 Solar WIMP Analysis

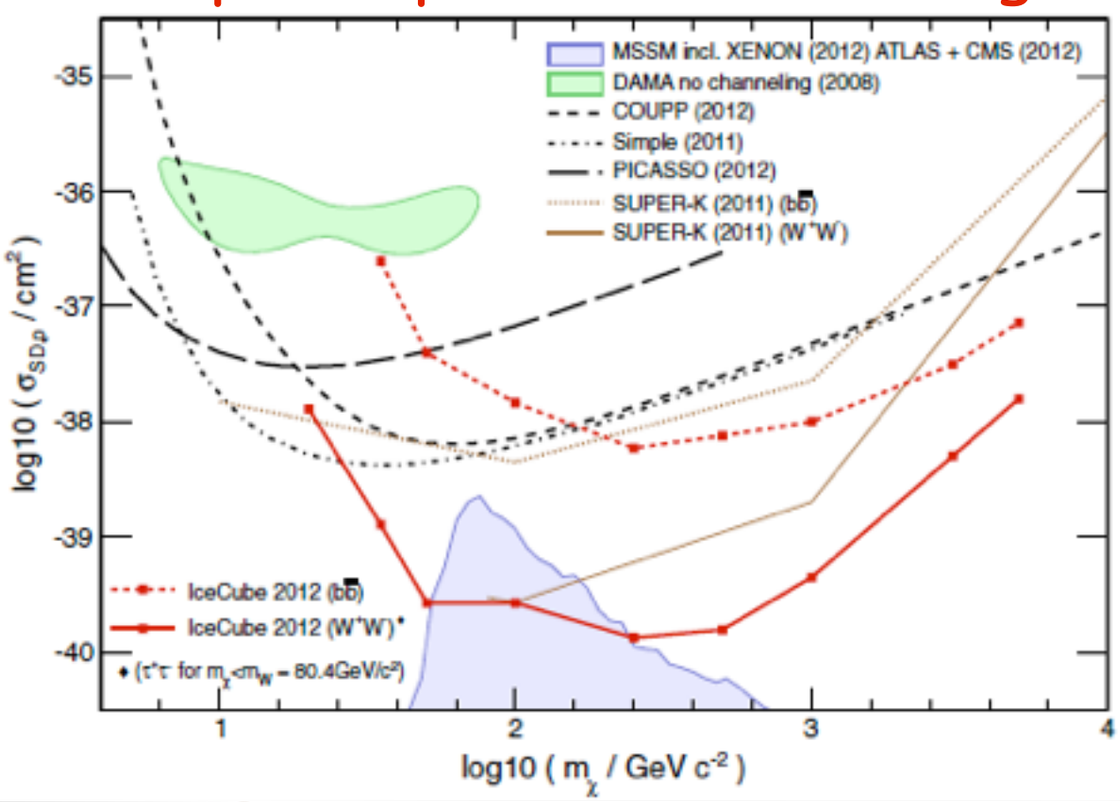
PRL 110, 131302 (2013)

- IceCube 79-strings configuration (partially completed DeepCore)
  - 318 days (May 2010 - May 2011)
- Search for an excess of events from the direction of the Sun
  - use track events for better pointing
- Separate summer and winter analysis
  - use outer detector to veto down-going muons for summer analysis

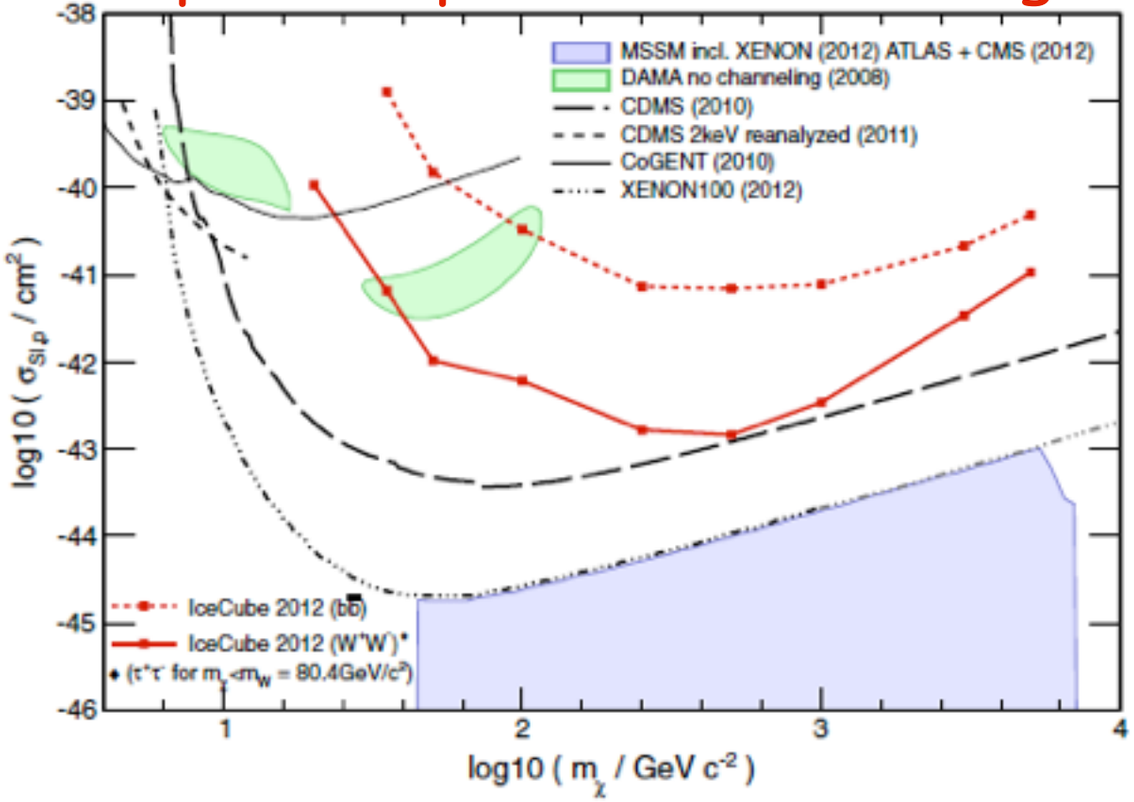
## Observed events




## Spin-dependent scattering



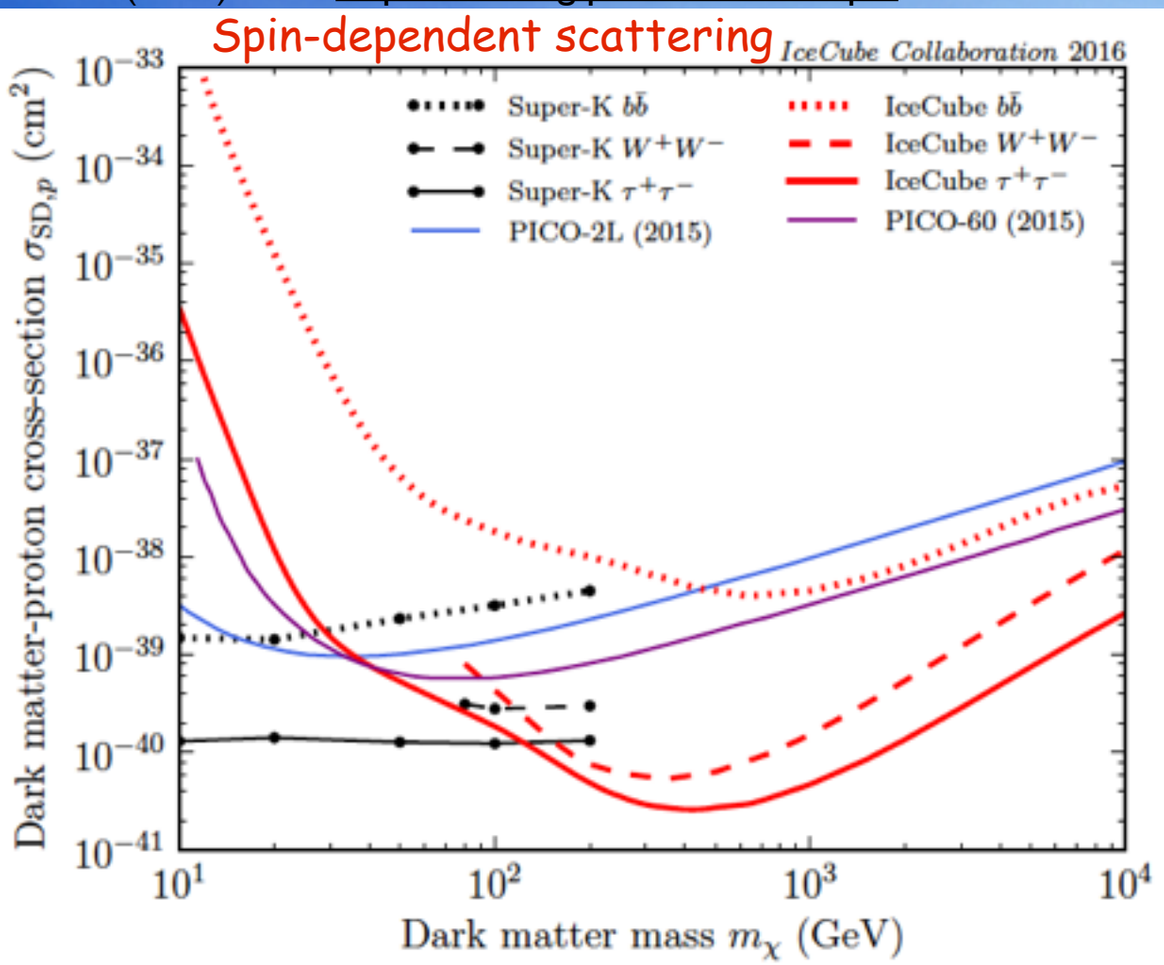

## Spin-independent scattering

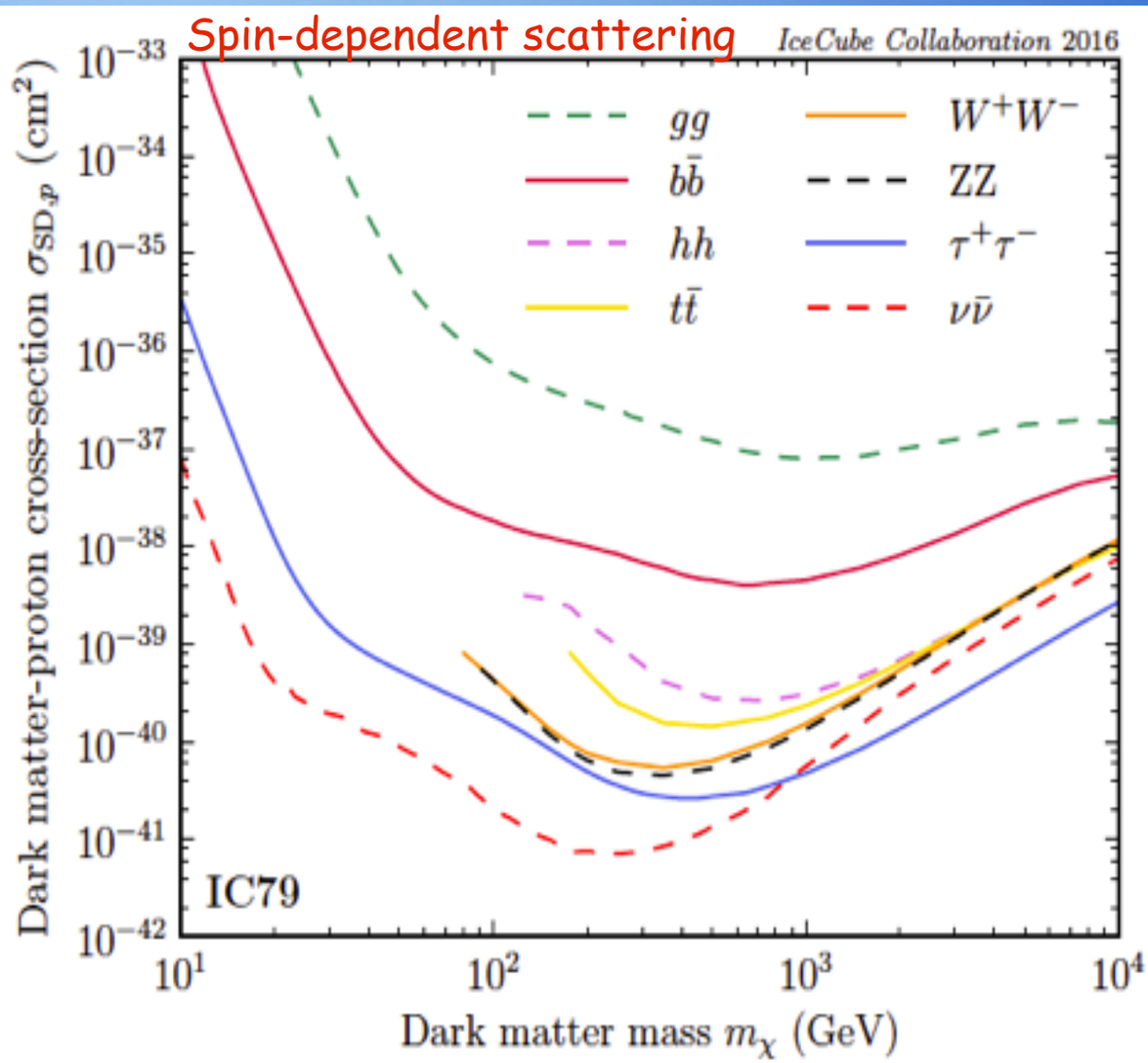


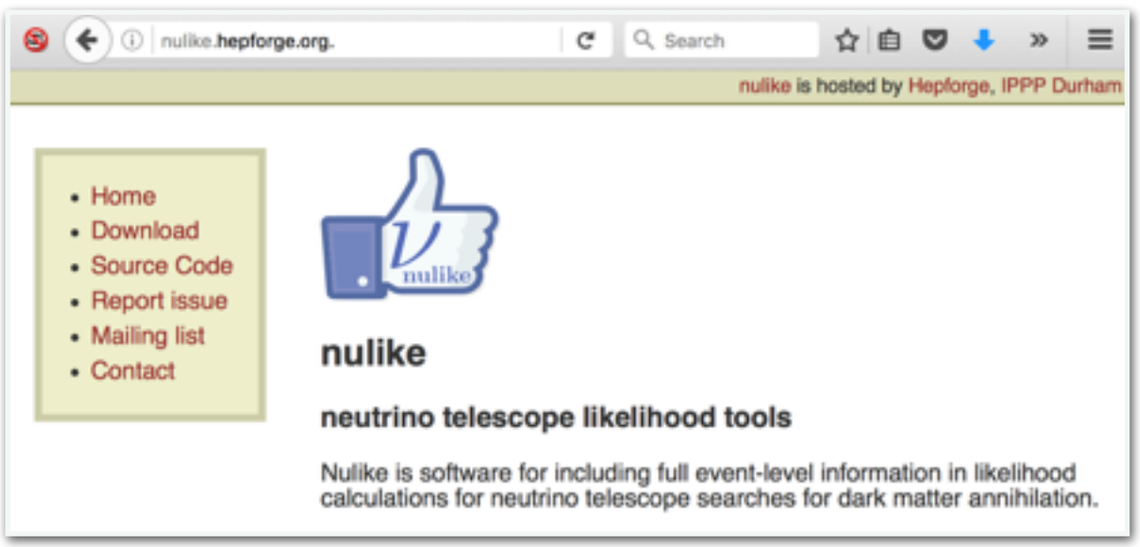
# Improved Solar WIMP Bounds

http://nulike.hepforge.org./

JCAP 04 (2016) 022 / http://arxiv.org/pdf/1601.00653.pdf



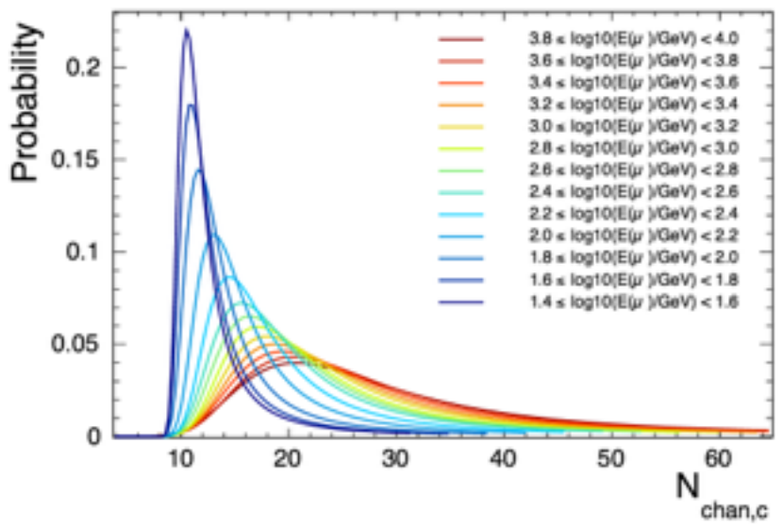




software to test your own model (cross section/ branching ratios)
• IceCube data released

Likelihood includes:

- energy and directional information



# The bigger picture

- Data released for nulike can also easily be digested for GAMBIT

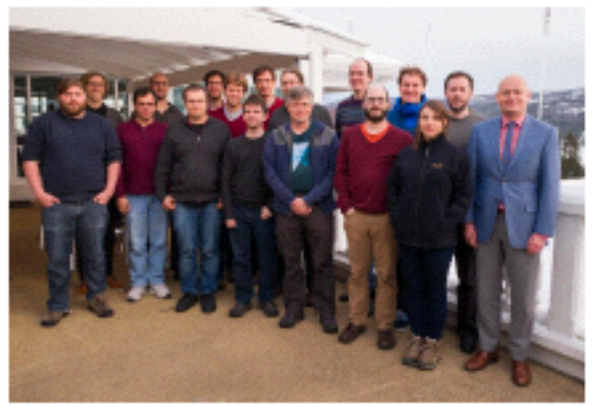


## GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org

- Fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source

| | |
|---|---|
| **ATLAS** | A. Buckley, P. Jackson, C. Rogan, M. White, |
| **LHCb** | M. Chrząszcz, N. Serra |
| **Belle-II** | F. Bernlochner, P. Jackson |
| **Fermi-LAT** | J. Conrad, J. Edsjö, G. Martinez, P. Scott |
| **CTA** | C. Balázs, T. Bringmann, J. Conrad, M. White |
| **HESS** | J. Conrad |
| **IceCube** | J. Edsjö, P. Scott |
| **XENON/DARWIN** | J. Conrad, R. Trotta |
| **Theory** | P. Athron, C. Balázs, T. Bringmann, J. Cornell, J. Edsjö, B. Farmer, T. Gonzalo, A. Fowlie, S. Hoof, F. Kahlhoefer, A. Krislock, A. Kvellestad, M. Pato, F. Mahmoudi, J. McKay, A. Raklev, R. Ruiz, P. Scott, R. Trotta, C. Weniger, M. White, S. Wild |

**29 Members, 9 Experiments, 4 major theory codes, 10 countries**

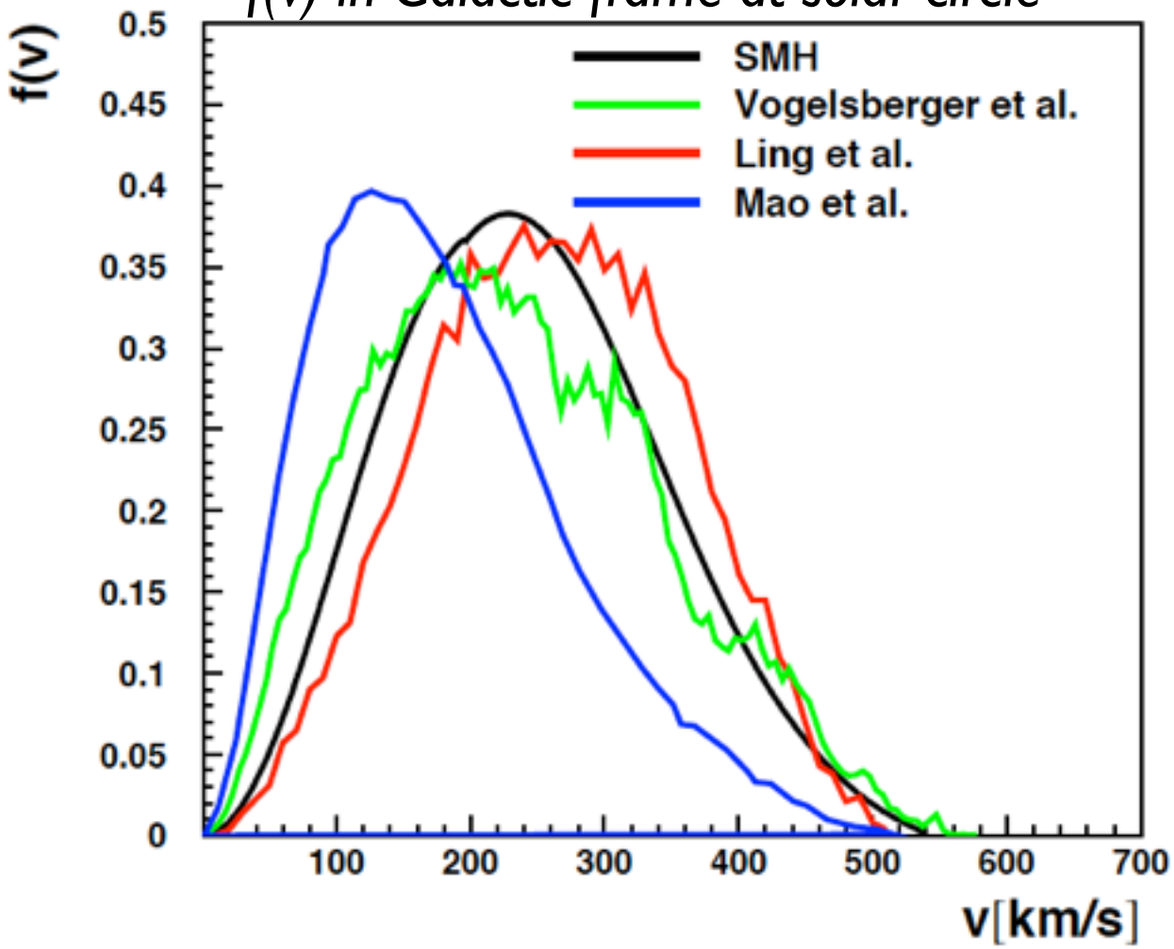
Imperial College London

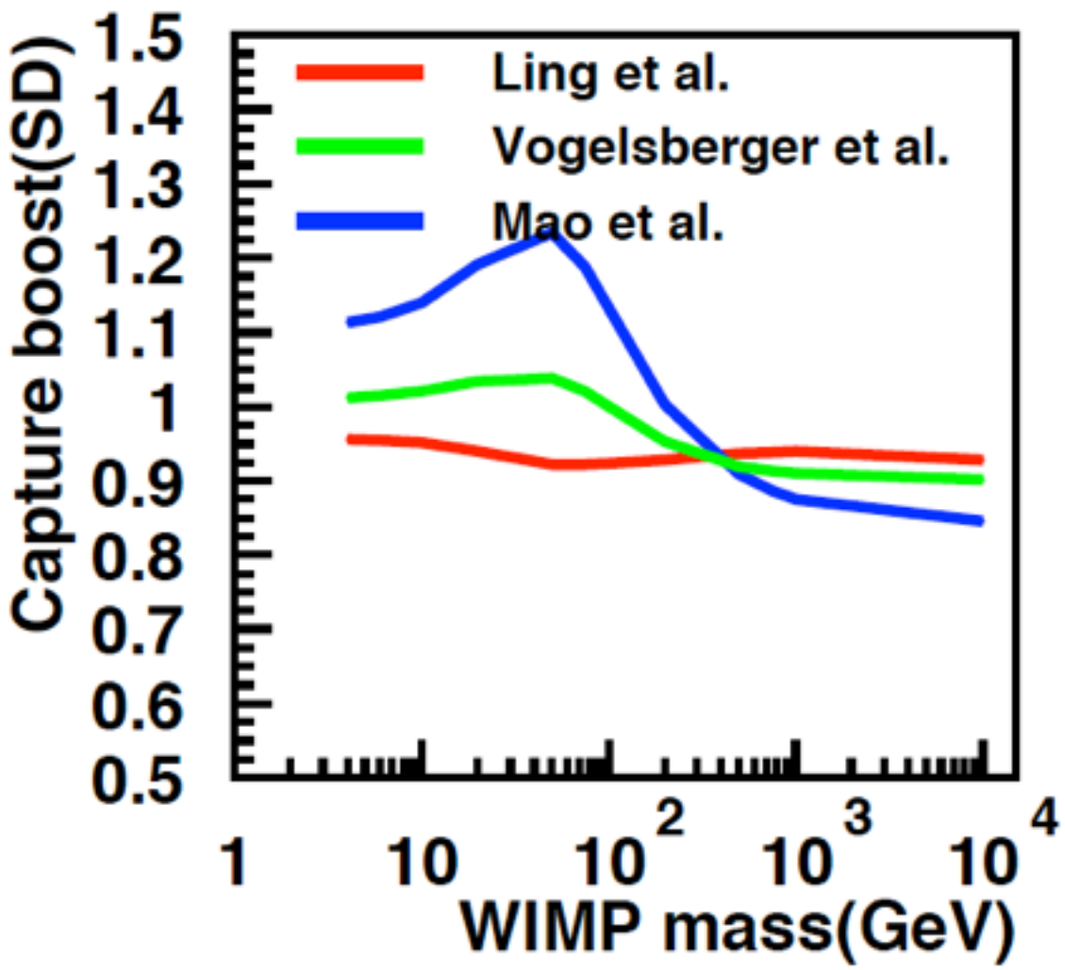
# Impact of velocity distribution

- Explore the change in capture rate using different velocity distributions obtained from dark matter simulations

Choi, Rott, Itow JCAP 1405 (2014) 049

*f(v) in Galactic frame at solar circle*



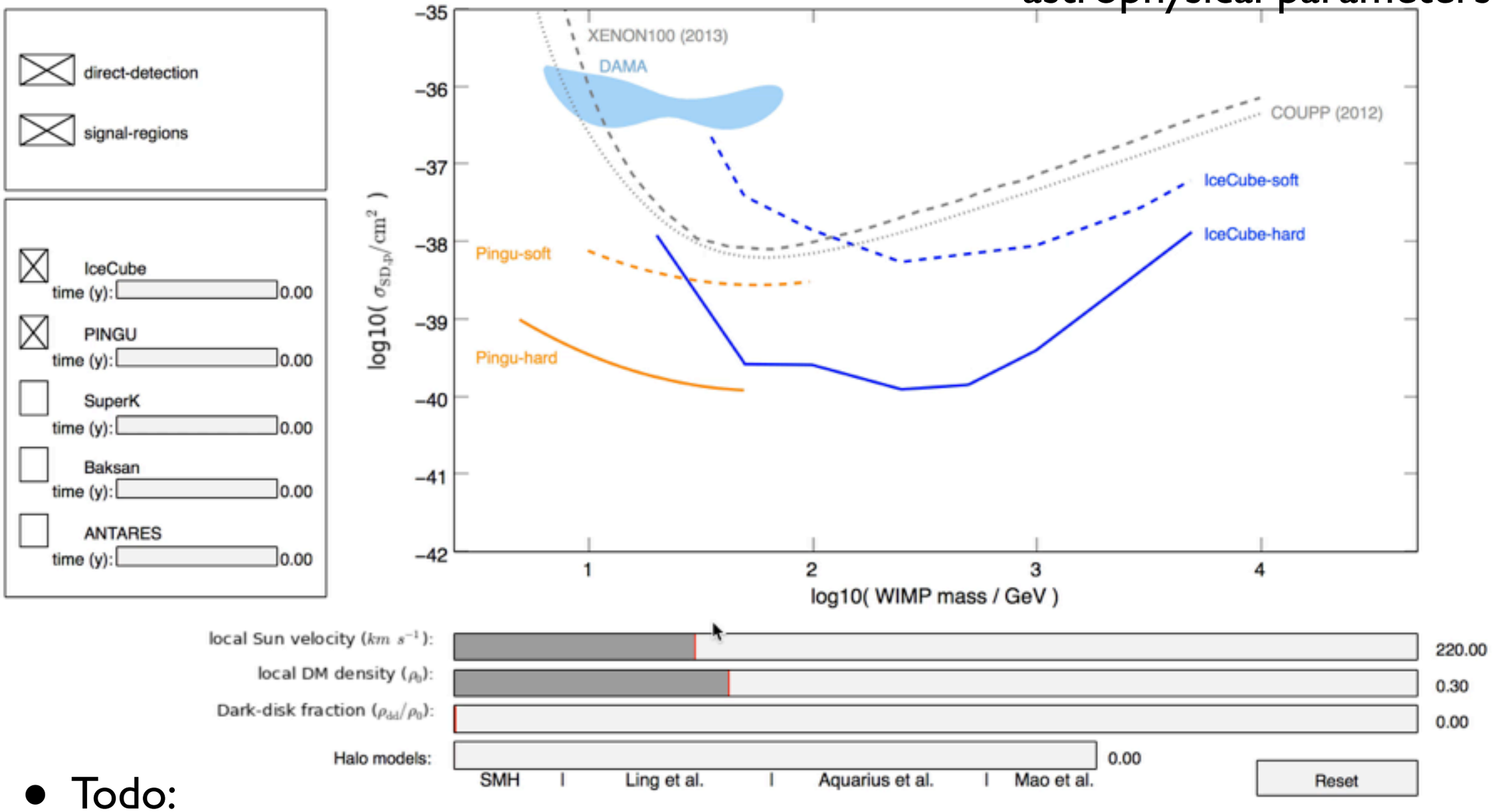




- A comparison of captures rates for different WIMP velocity distributions show that overall changes in the capture rate are smaller than 20%

# Impact of astrophysical uncertainties

*M. Danninger & C. Rott "Solar WIMPs Unraveled" – Invited Review for Physics of the Dark Universe (Nov 2014)*

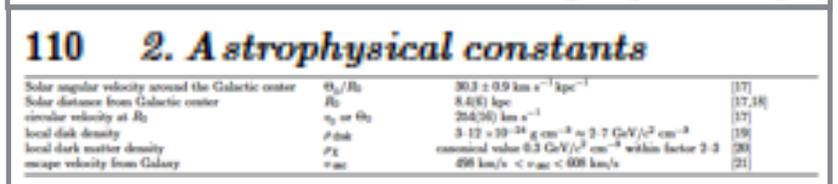
interactive tool to study impact of astrophysical parameters




- Todo:
  - Limits need to be updated
  - Include direct detection bounds

# Local Dark Matter Density

## Particle Data Group (PDG)



110 2. Astrophysical constants

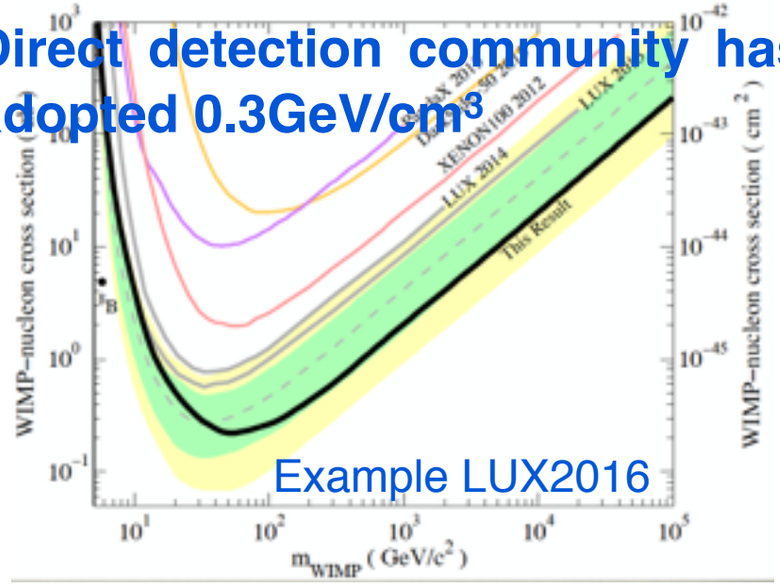
| | | | |
|---|---|---|---|
| Solar angular velocity around the Galactic center | $\Theta_0/R_0$ | $30.3 \pm 0.9$ km s$^{-1}$ kpc$^{-1}$ | [17] |
| Solar distance from Galactic center | $R_0$ | 8.4(6) kpc | [17,18] |
| circular velocity at $R_0$ | $v_0$ or $\Theta_0$ | 254(16) km s$^{-1}$ | [17] |
| local disk density | $\rho_{\rm disk}$ | $3\text{-}12 \times 10^{-24}$ g cm$^{-3} \approx 2\text{-}7$ GeV/c$^2$ cm$^{-3}$ | [19] |
| local dark matter density | $\rho_\chi$ | canonical value 0.3 GeV/c$^2$ cm$^{-3}$ within factor 2-3 | [20] |
| escape velocity from Galaxy | $v_{\rm esc}$ | 498 km/s $< v_{\rm esc} <$ 608 km/s | [21] |

Canonical value of 0.3GeV/cm$^3$ within a factor of 2 or 3

20. Sampling of many references:
M. Mori *et al.*, Phys. Lett. **B289**, 463 (1992);
E.I. Gates *et al.*, Astrophys. J. **449**, L133 (1995);
M. Kamionkowski and A.Kinkhabwala, Phys. Rev. **D57**, 325 (1998);
M. Weber and W. de Boer, Astron. & Astrophys. **509**, A25 (2010);
P. Salucci *et al.*, Astron. & Astrophys. **523**, A83 (2010);
R. Catena and P. Ullio, JCAP **1008**, 004 (2010) conclude $\rho_{\rm DM}^{\rm local} = 0.39 \pm 0.03\,{\rm GeV\,cm^{-3}}$.

## Dark Matter Direct Detection

**Direct detection community has adopted 0.3GeV/cm$^3$**




## Theorists response

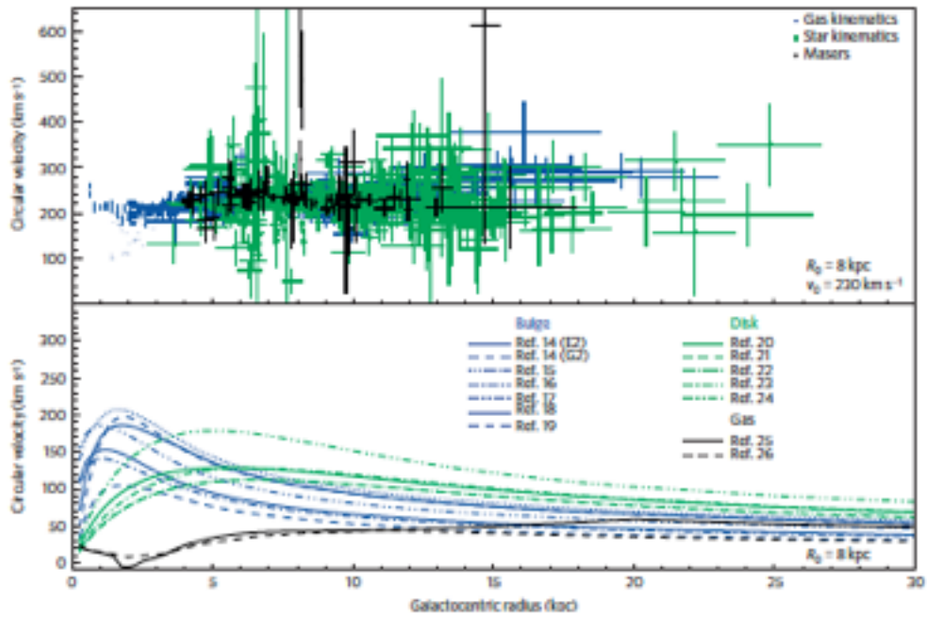
"Everybody is well aware of the uncertainty in the local dark matter density. Limits scale linear with local dark matter density. I believe theorists are capable of simple multiplication if they want to know a limit different from the standard local dark matter density."

## Local Dark Matter Density Determinations

- R. Catena, P. Ullio, A novel determination of the local dark matter density, JCAP 1008 (2010) 004.
- P. J. McMillan, Mass models of the Milky Way, Mon.Not.Roy.Astron.Soc. 414 (2011) 2446–2457.
- P. Salucci, F. Nesti, G. Gentile, C. Martins, The dark matter density at the Sun's location, Astron.Astrophys. 523 (2010) A83.
- F. Nesti, P. Salucci, The Dark Matter halo of the Milky Way, AD 2013, JCAP 1307 (2013) 016.

**Local dark matter density closer to around 0.4GeV/cm$^3$**

**On the horizon: With ESA's Gaia satellite (Perryman et al. 2001) we will soon have access to proper motions and parallaxes for a billion stars.**



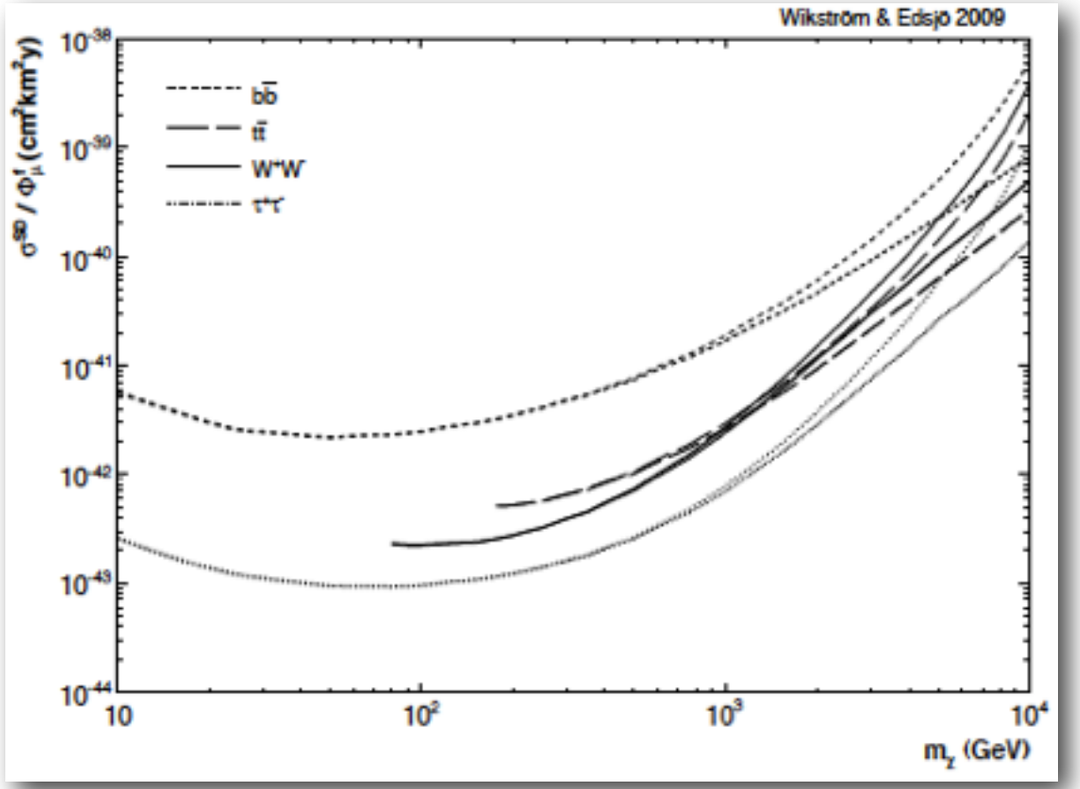

F. Iocco, M. Pato, G. Bertone, Nature Physics, DOI 10.1038

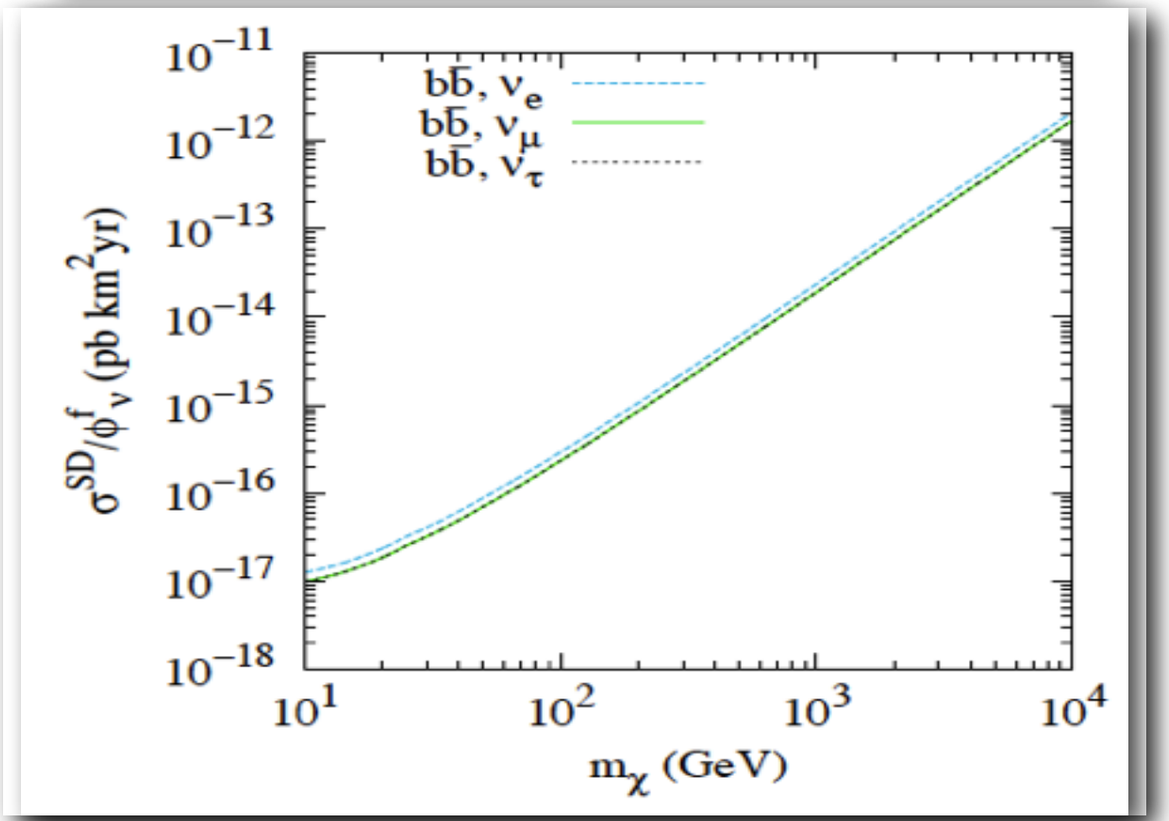
# Flux Conversion

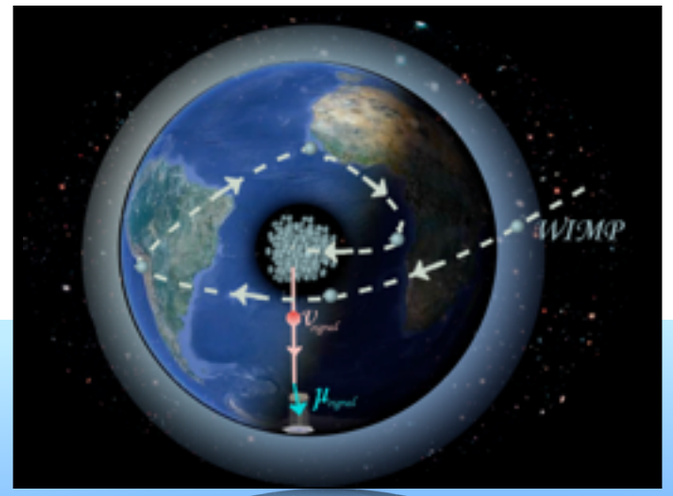
- Muon flux Conversion
  - M. Kamionkowski et al., Phys. Rev. Lett. 74 (1995) 5174
  - Wikstrom & Edsjo, JCAP04 (2009) 09. arXiv 0903.2986

- Neutrino flux Conversion
  - DarkSUSY [P. Gondolo et al., JCAP, 0407, 008 (2004)]
  - C.Rott, T. Tanaka, Y. Itow JCAP09(2011)029) based on a study using DarkSUSY version 5.0.4
    - Integrated neutrino flux above an energy threshold (here 1GeV) look very similar
    - Neutrino flux limits allow for easier comparison of different flavor channels

**Recent inconsistency in DarkSUSY online version and WIMPSim resulted in inconsistent bounds (now resolved)**

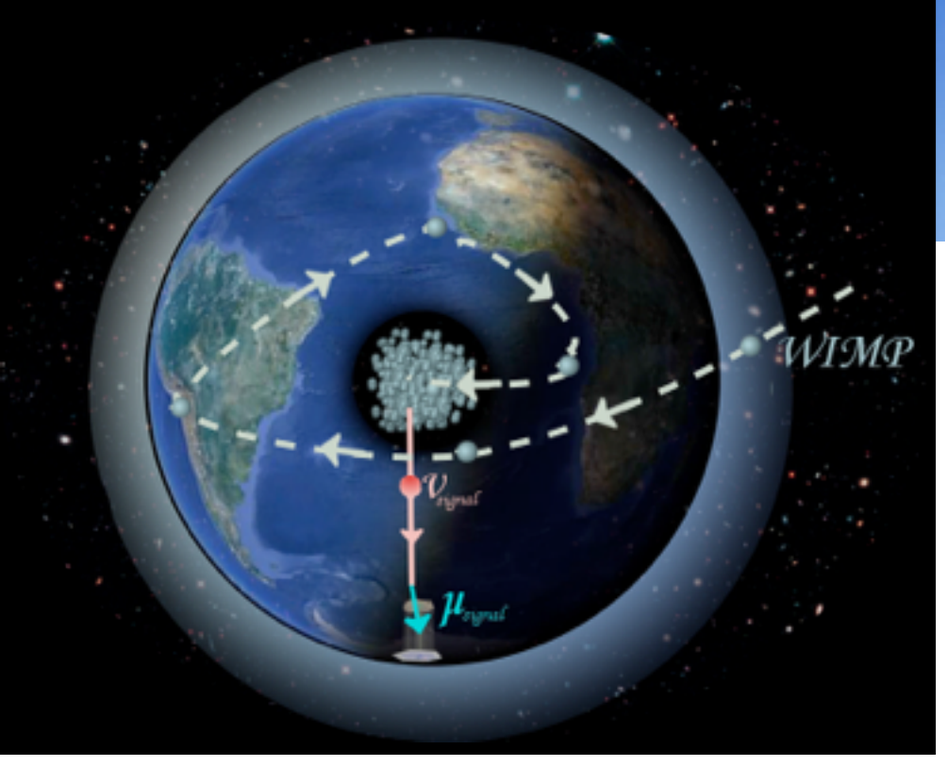


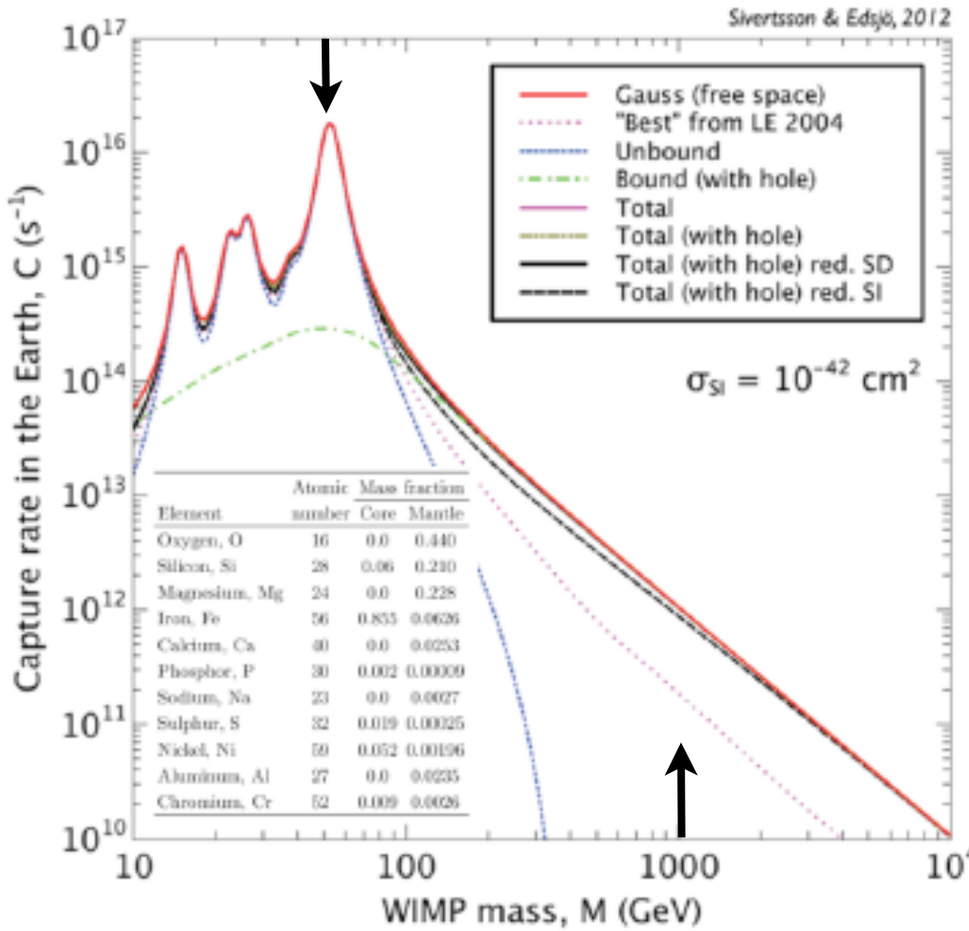


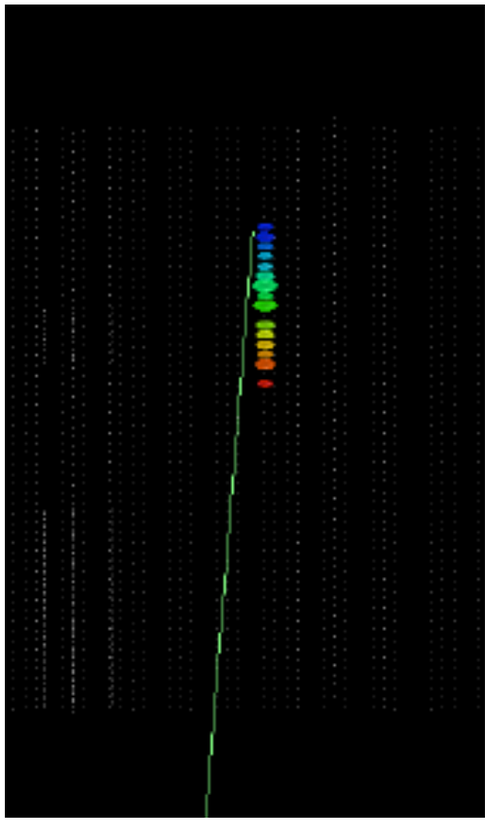

# Earth WIMPs

# IceCube Earth WIMPs




- Dark Matter could be captured in the Earth and produce a vertically up-going excess neutrino flux
- IceCube: Two statistically independent analyses
  - Low energy & High energy
  - IC86-I (327 days of livetime during 2011/12)



## IceCube Shape analysis

$$f(\Psi|\mu) = \frac{\mu}{n_{\rm obs}} f_s(\Psi) + (1 - \frac{\mu}{n_{\rm obs}}) f_{bg}(\Psi)$$

$$\mathcal{L} = \prod_i^{n_{\rm obs}} f(\Psi_i|\mu)$$

$$\mathcal{R}(\mu) = \frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})}$$

$\hat{\mu}$ is the best fit of $\mu$ to the observation

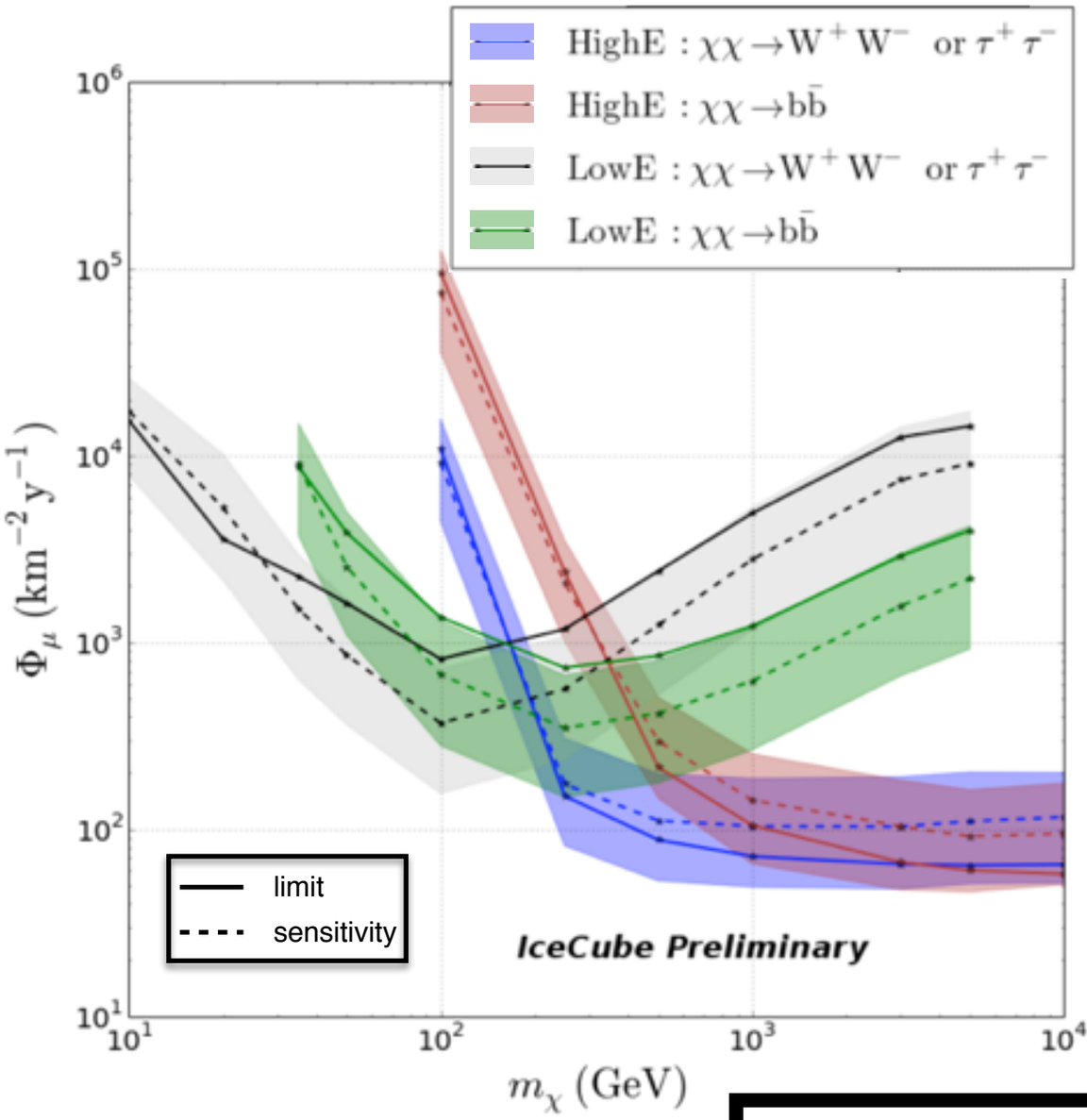
# Earth WIMPs

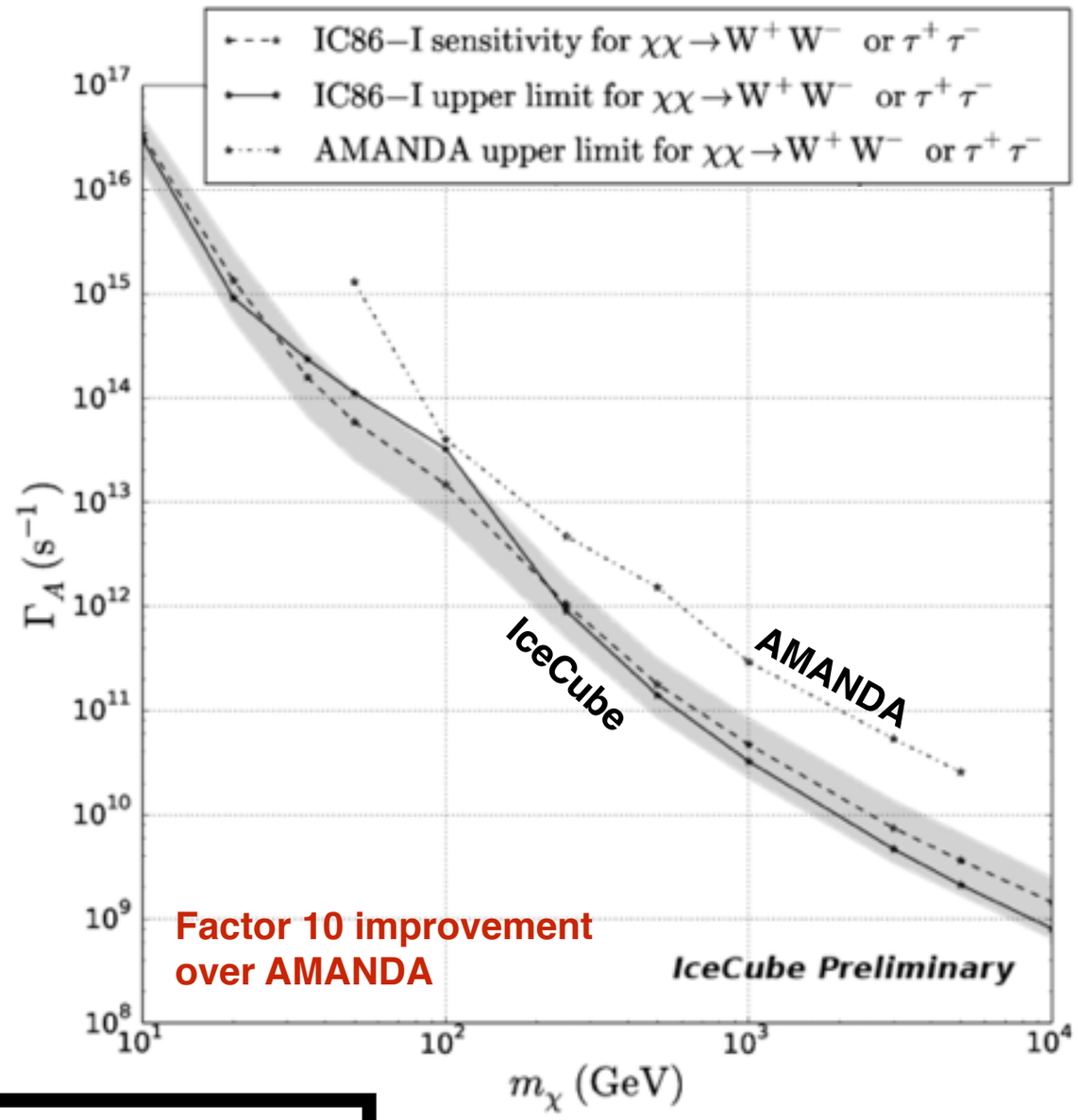
- Combine High-energy and low-energy analysis, based on the best sensitivity

$$\Gamma_A = \frac{C}{2}\tanh^2\left(\frac{t}{\tau}\right),\ \tau = (CC_A)^{-1/2}$$

4.5 $10^9$years

Earth typically not in equilibrium



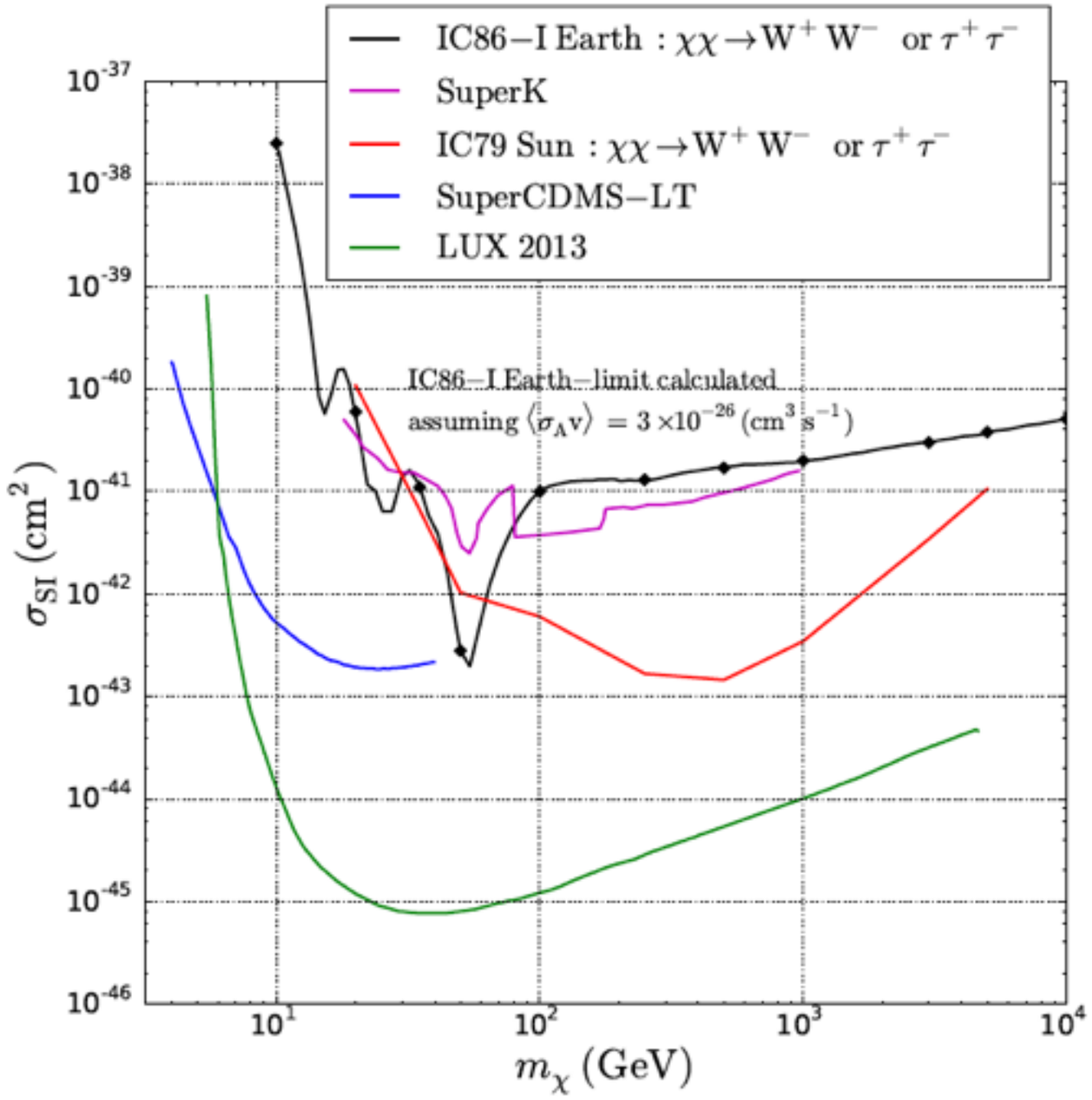



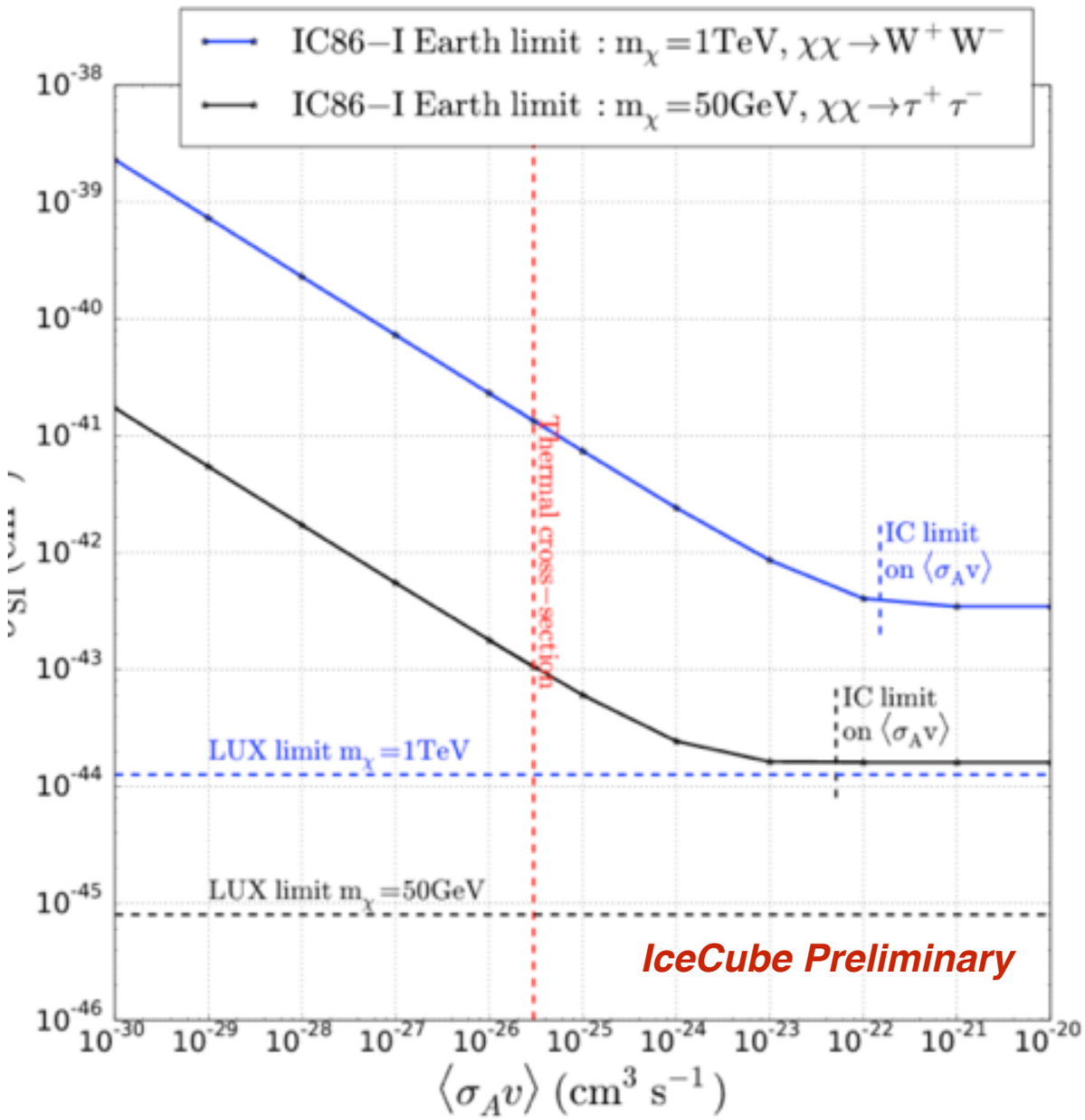

No evidence for dark matter

Publications:

- Super-K S.Desai et al (2004)
- IceCube arXiv:1609.01492
- ANTARES forthcoming

# Earth WIMPs



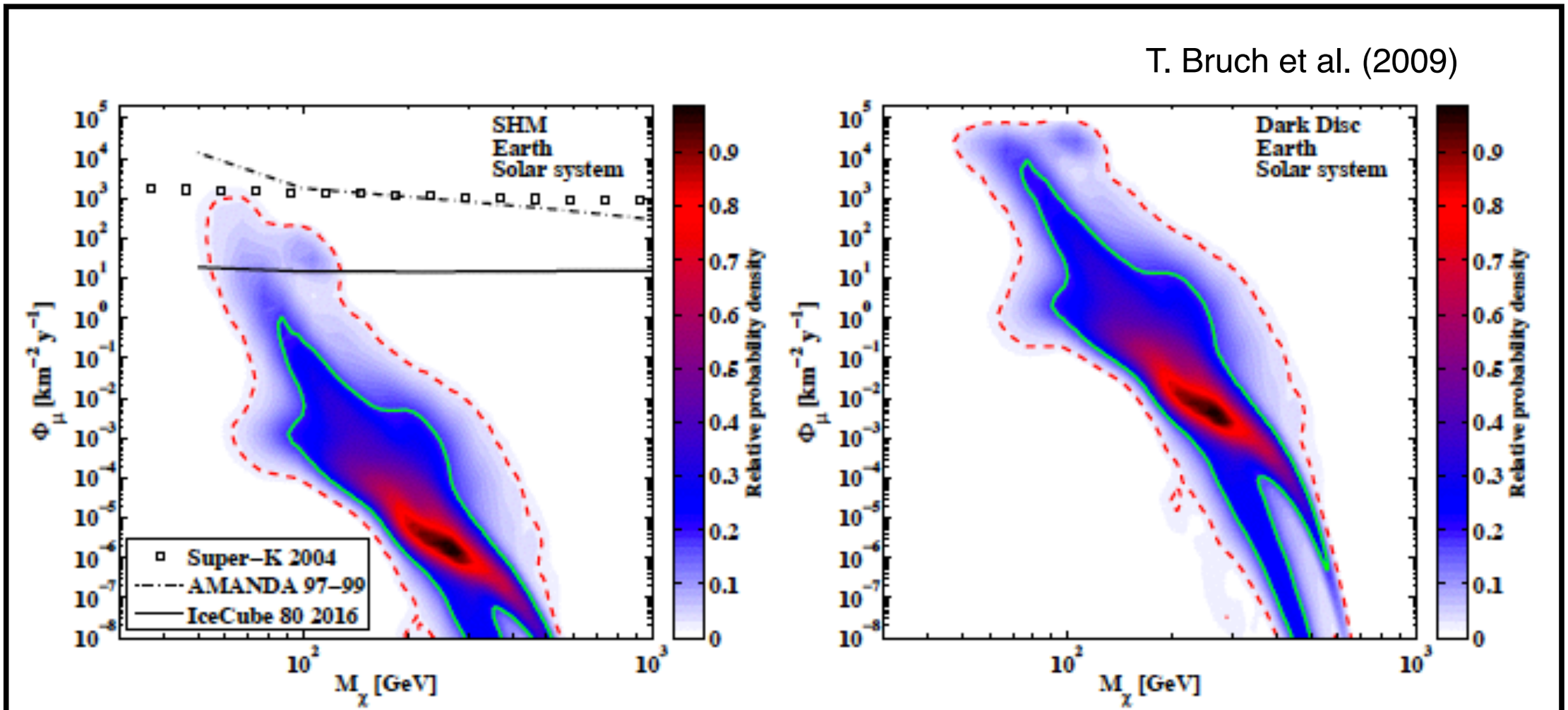



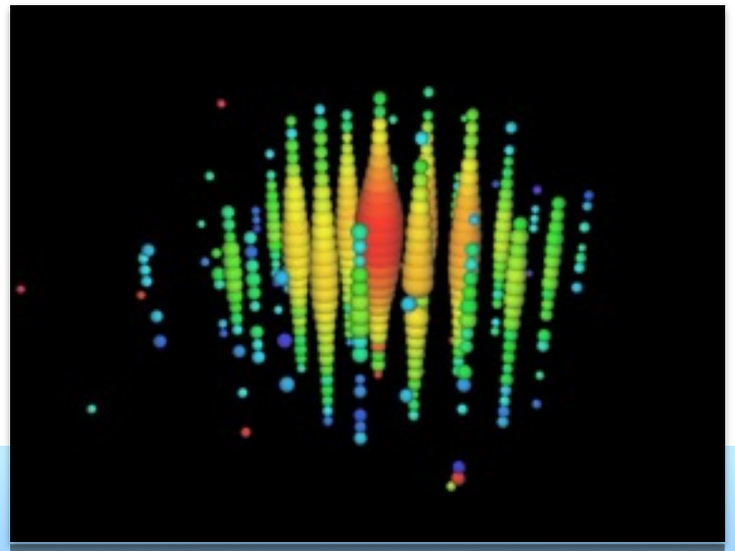

- Earth WIMP analysis more sensitivity than Solar WIMP analysis for SI scattering for $m_\chi$ close to Fe resonance
- Standard halo model was assumed. Possibility of dark disk could boost Earth WIMP bounds by two orders of magnitude

# Earth WIMPs

- Issues:
  - Earth is not in equilibrium
    - Strong dependence on velocity distribution
  - What benchmark channels to use ?
  - How to compare SD and SI ?

T. Bruch et al. (2009)

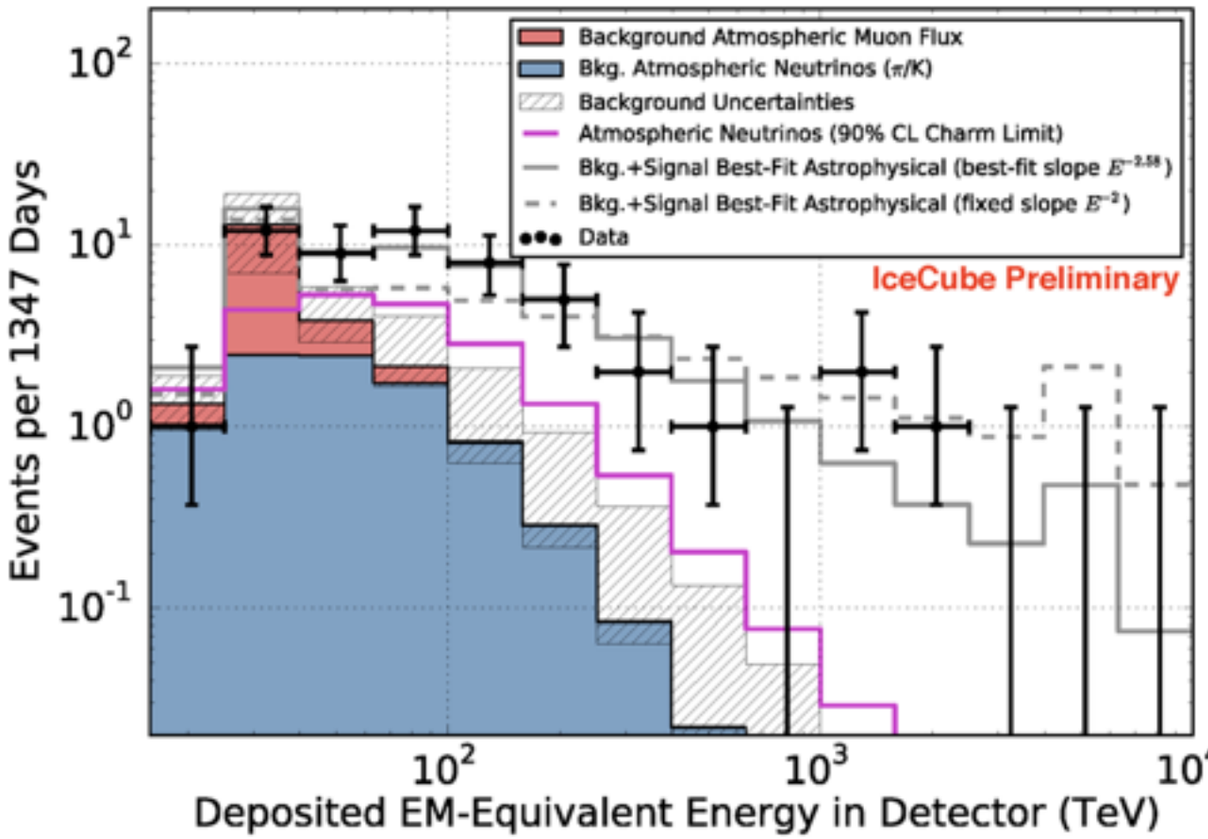




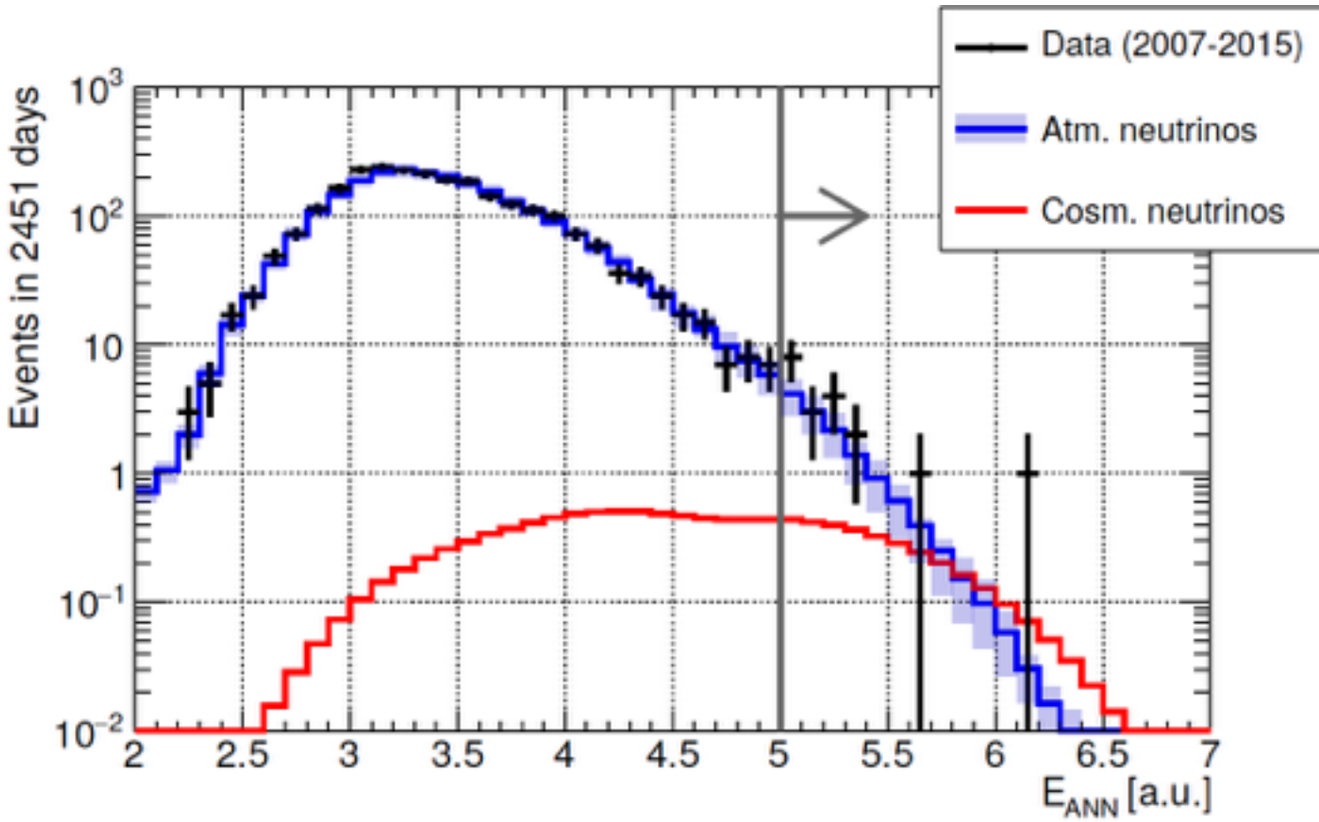
Astro-physical Neutrinos / Heavy Dark Matter / Boosted Dark Matter / …

# High energy neutrinos

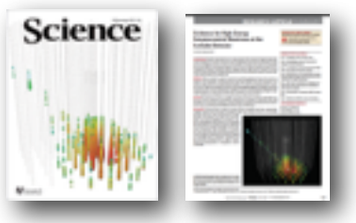
## IceCube




## ANTARES




***~7 sigma rejection of atmospheric-only hypothesis***




ICRC 2015 proceedings
IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

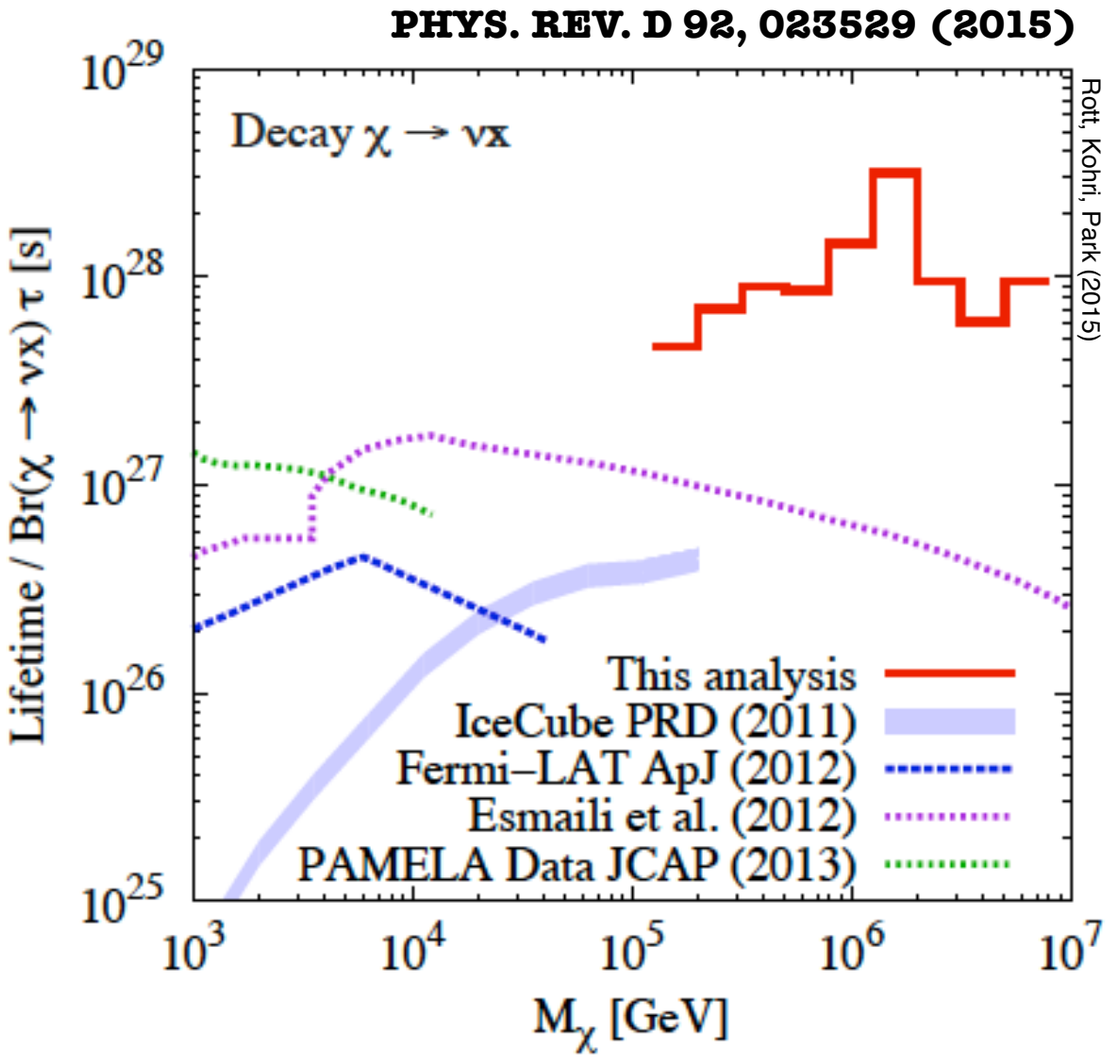
Observed : 19
Expected : 13.5 ± 3 from bkg

ANTARES Neutrino 2016

# Heavy Dark Matter Decay

- Heavy Decaying Dark Matter (example $\chi \rightarrow \nu h, \chi \rightarrow \nu x, \chi \rightarrow \nu\gamma, \chi \rightarrow \nu ee$)
- Focus on most detectable feature (neutrino line)
- Backgrounds steeply falling with energy, highest energy events provide best sensitivity
- Continuum and spacial distribution could help identify a signal
- Bounds from Fermi-LAT and PAMELA derived from search for $b\bar{b}$ annihilation channel (dominant decay channel of Higgs).

Bound on lifetime ~$10^{28}$s derived with IceCube data




Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034

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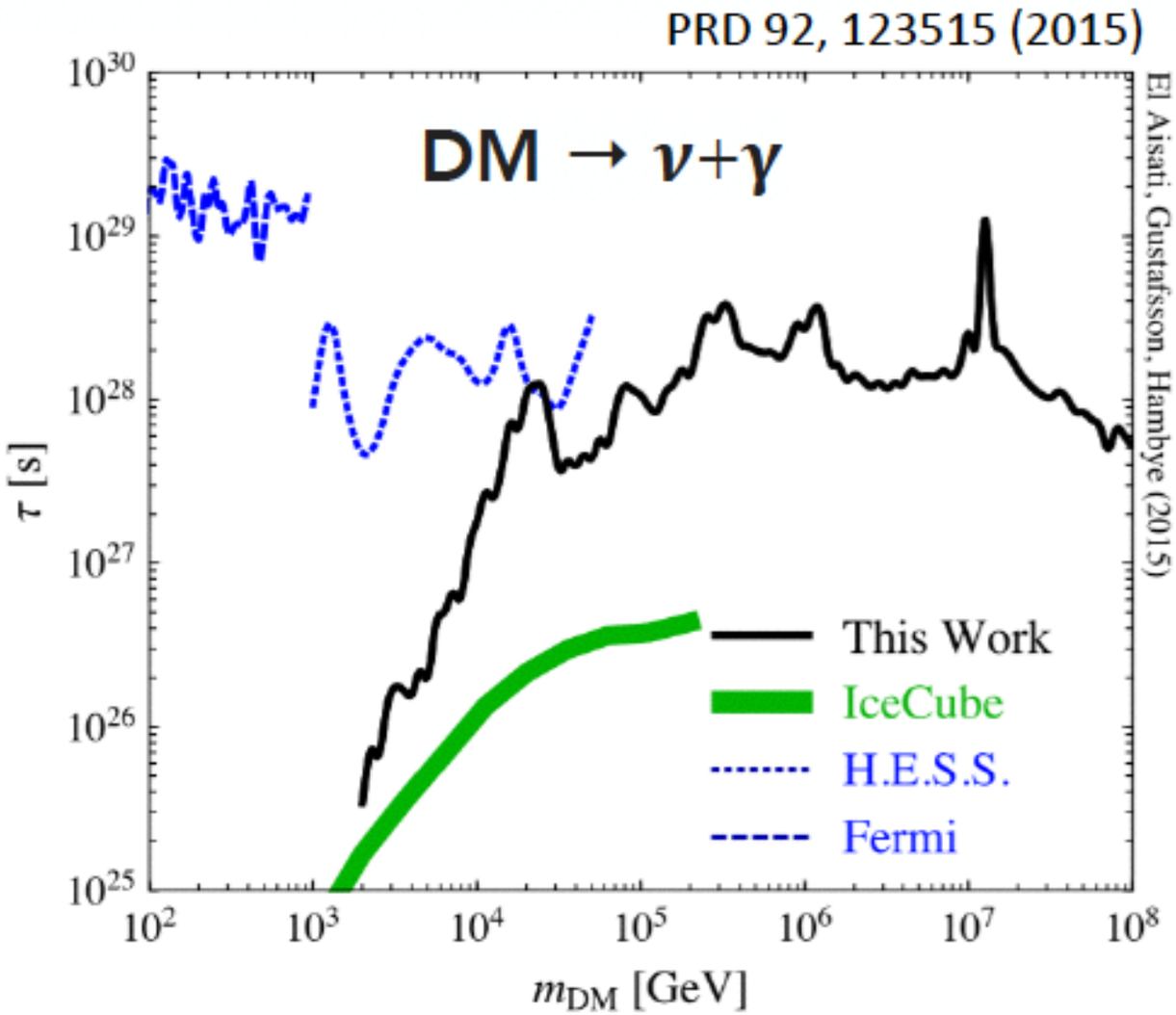


Heavy DM bounds with neutrinos, see also
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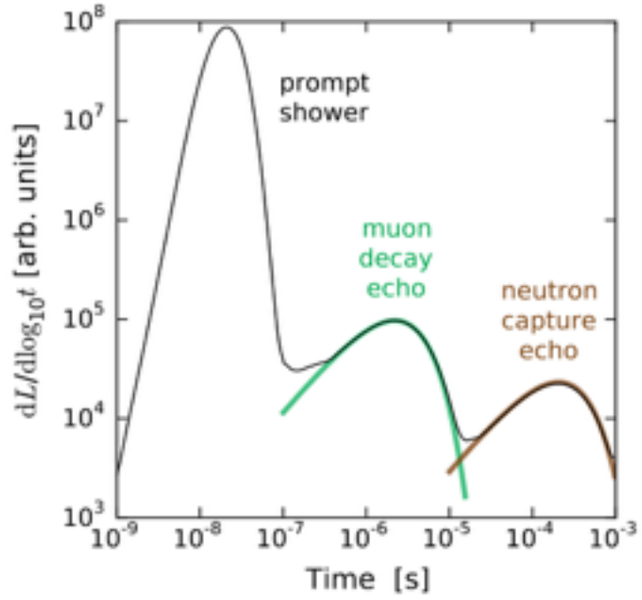
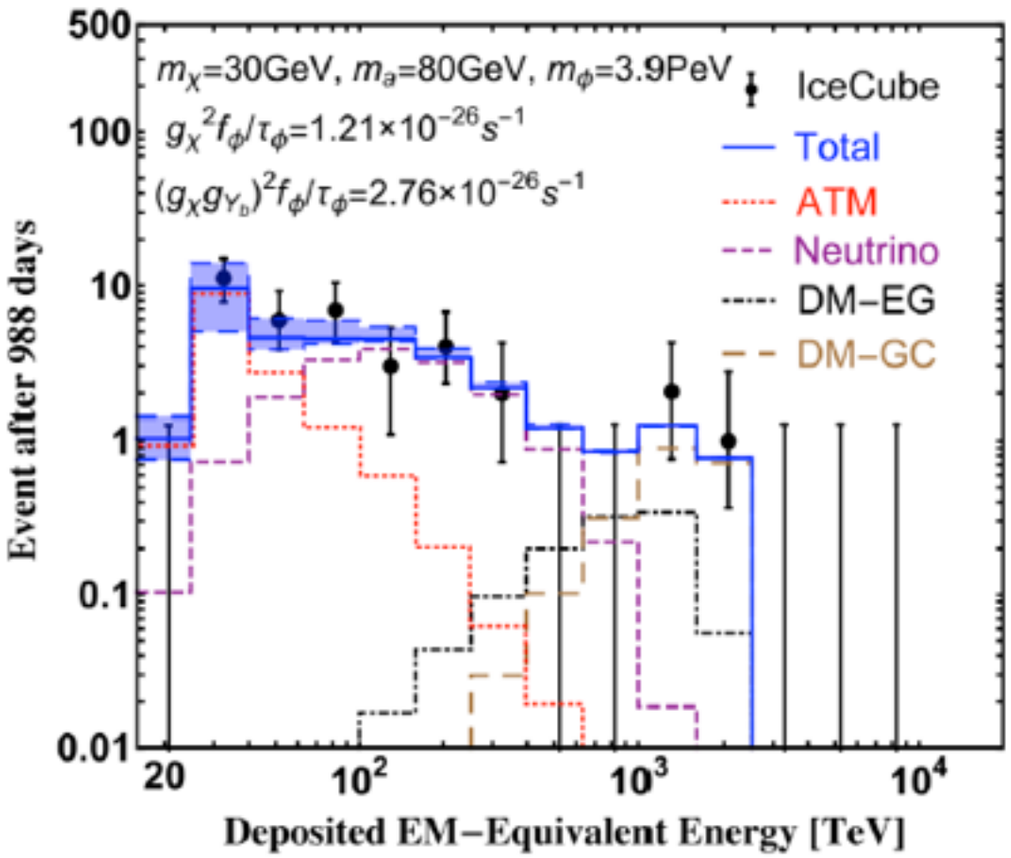
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034

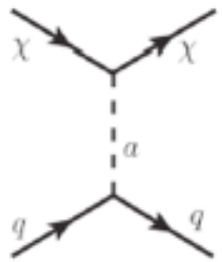
# Boosted Dark Matter

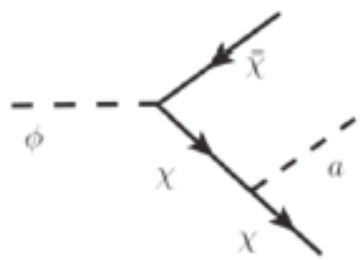
- "IceCube Boosted Dark Matter Search"
  - Following search proposed by Kopp, Liu, Wan (2015)
  - using "Echo Technique" Li, Bustamante, Beacom (2016)




Very heavy dark matter particle ϕ decays to lighter stable dark matter χ →boost!




Recoil (only hadronic cascades)

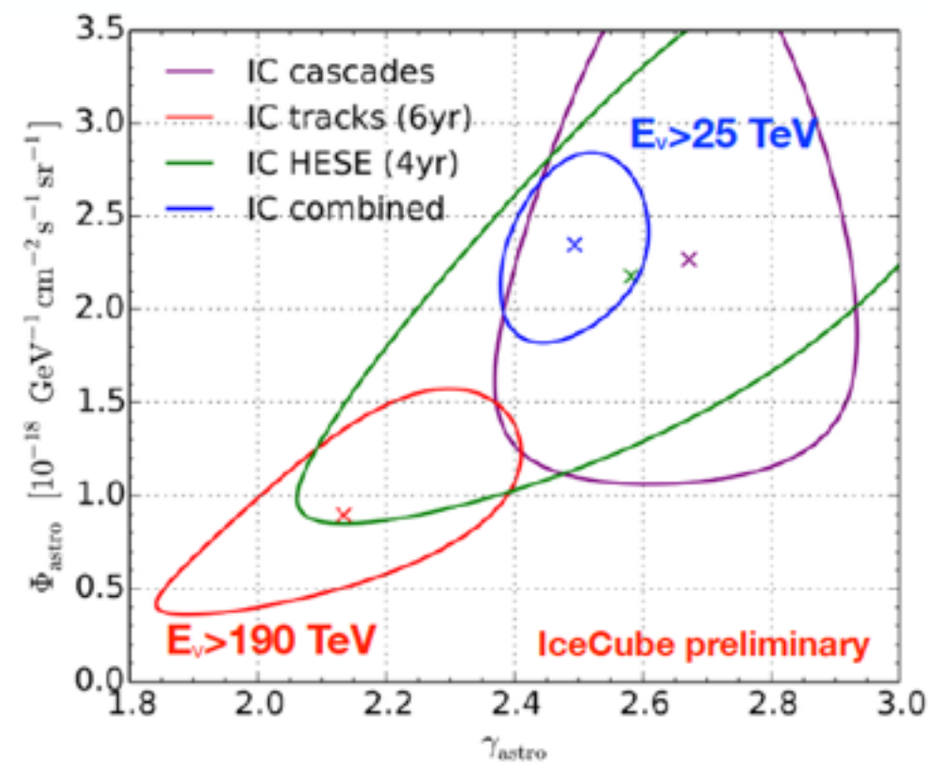
$\phi \to \chi\,\bar{\chi}\,a,\ a \to b\,\bar{b}$ →ν's

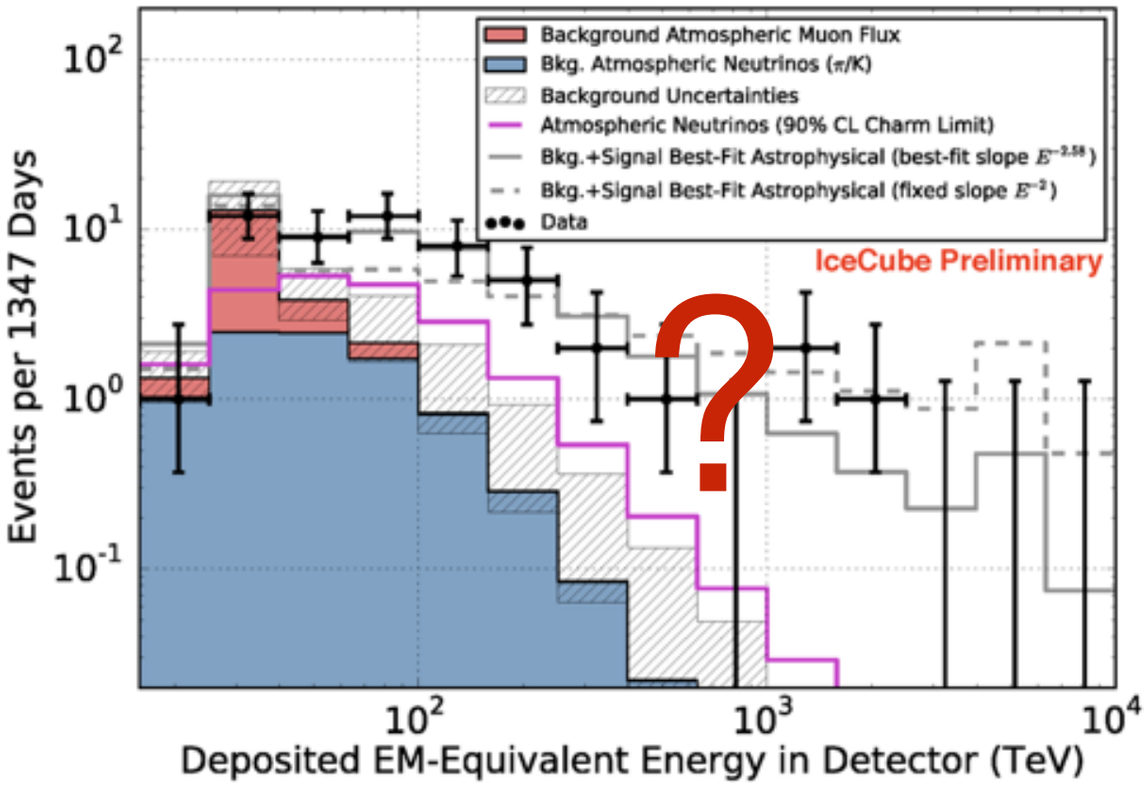
Neutrons capture on hydrogen and product 2.2MeV gamma. In seawater, 33% of neutrons capture on Cl; the emitted gamma rays have 8.6 MeV, making the neutron echoes more visible

"Echo Technique" holds prospects to individually tag high-energy NC and CC interactions !

*May sound crazy, but is just an example for exotic interactions in IceCube detectable via recoil*

# Beyond Standard Model Physics at the PeV scale

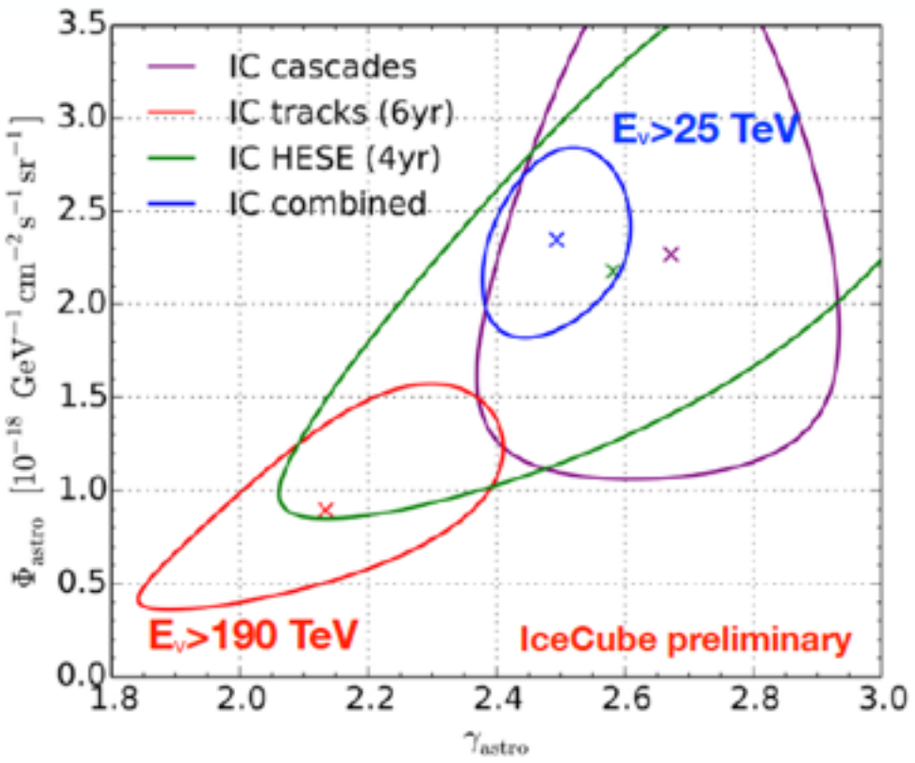



- Intense interest in high-energy neutrino region
  - Observations defy any simple explanation from a single generic source class
    - Multiple sources classes ?
    - Hints of new physics ?

- PeV Scale Right Handed Neutrino Dark Matter
- Super Heavy Dark Matter
- Neutrino Portal Dark Matter
- Right-handed neutrino mixing via Higgs portal
- Heavy right-handed neutrino dark matter
- Leptophilic Dark Matter
- PeV Scale Supersymmetric Neutrino Sector Dark Matter
- Dark matter with two- and many-body decays
- Shadow dark matter
- Boosted Dark Matter
- …

# Beyond Standard Model Physics at the PeV scale

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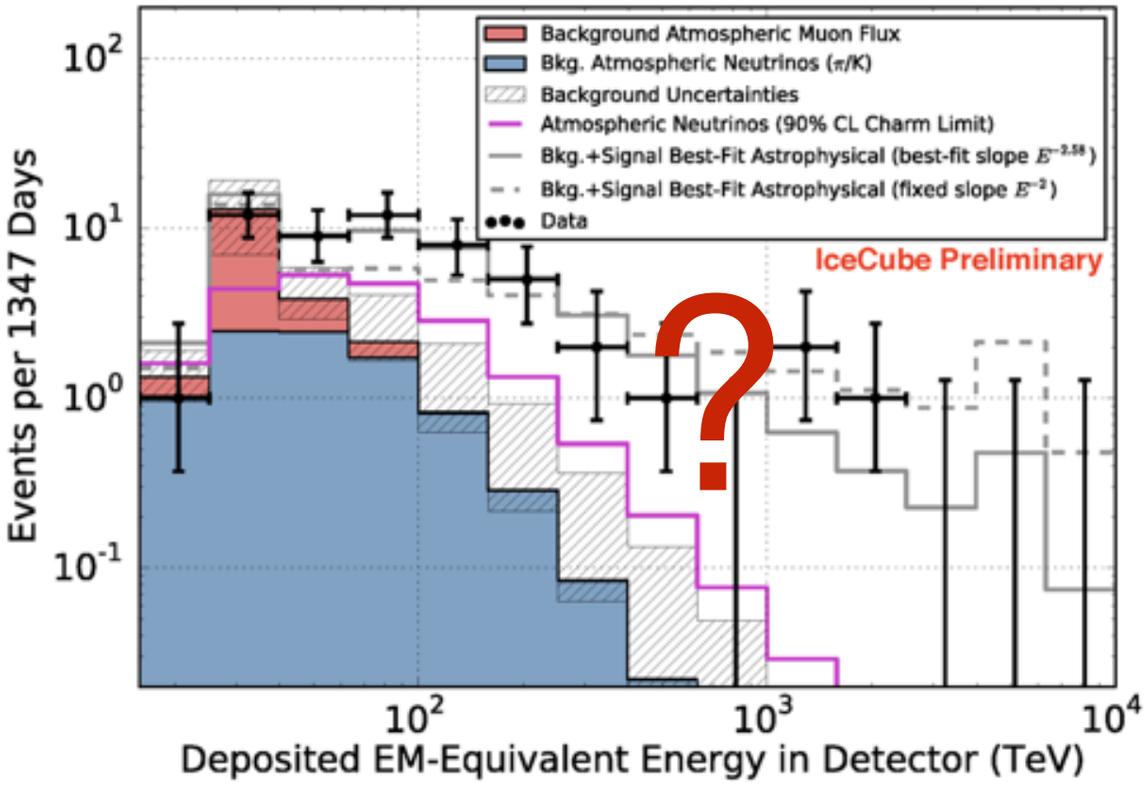
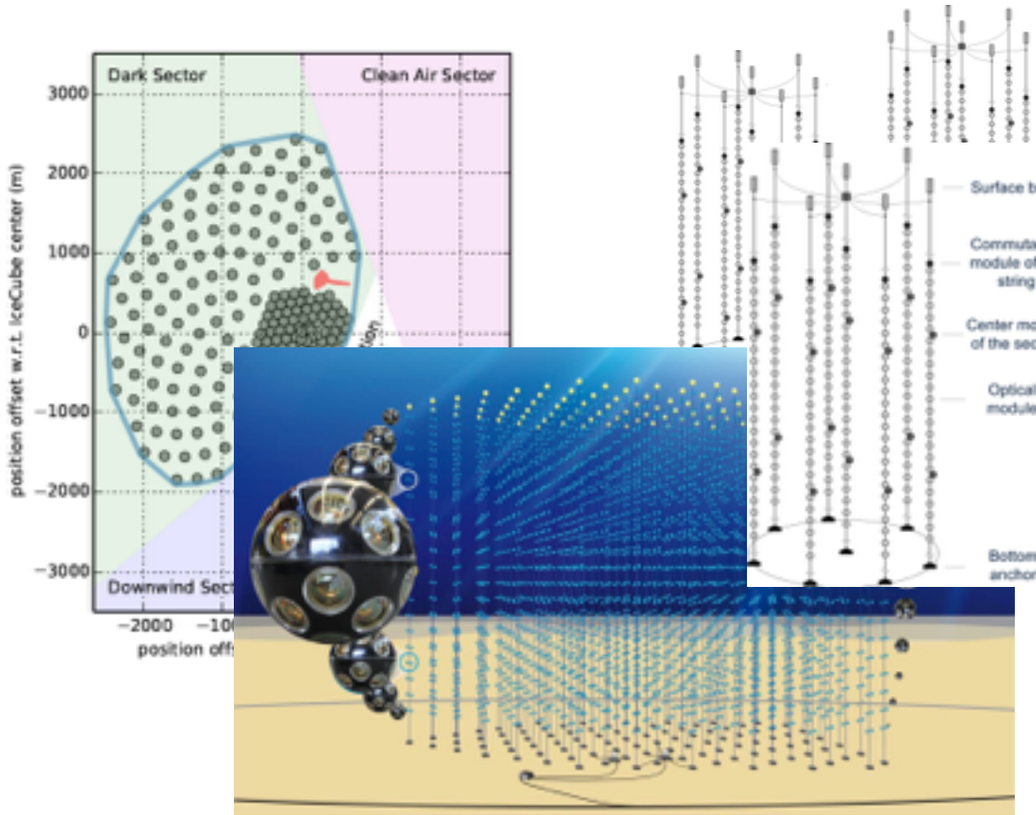
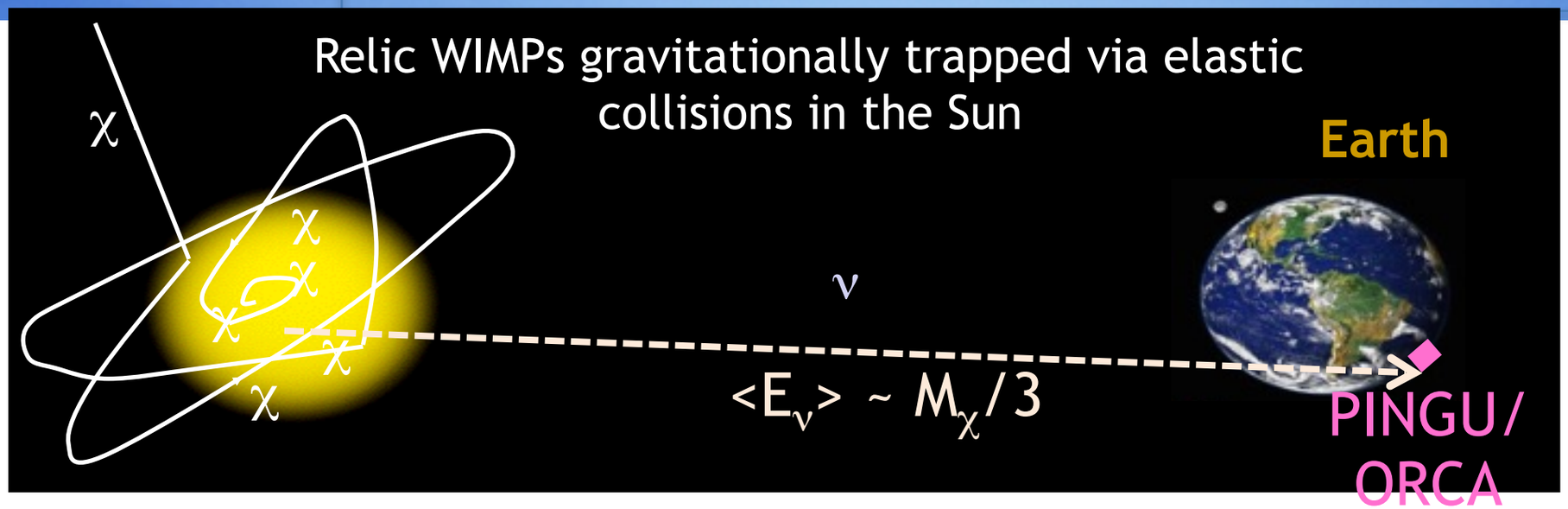


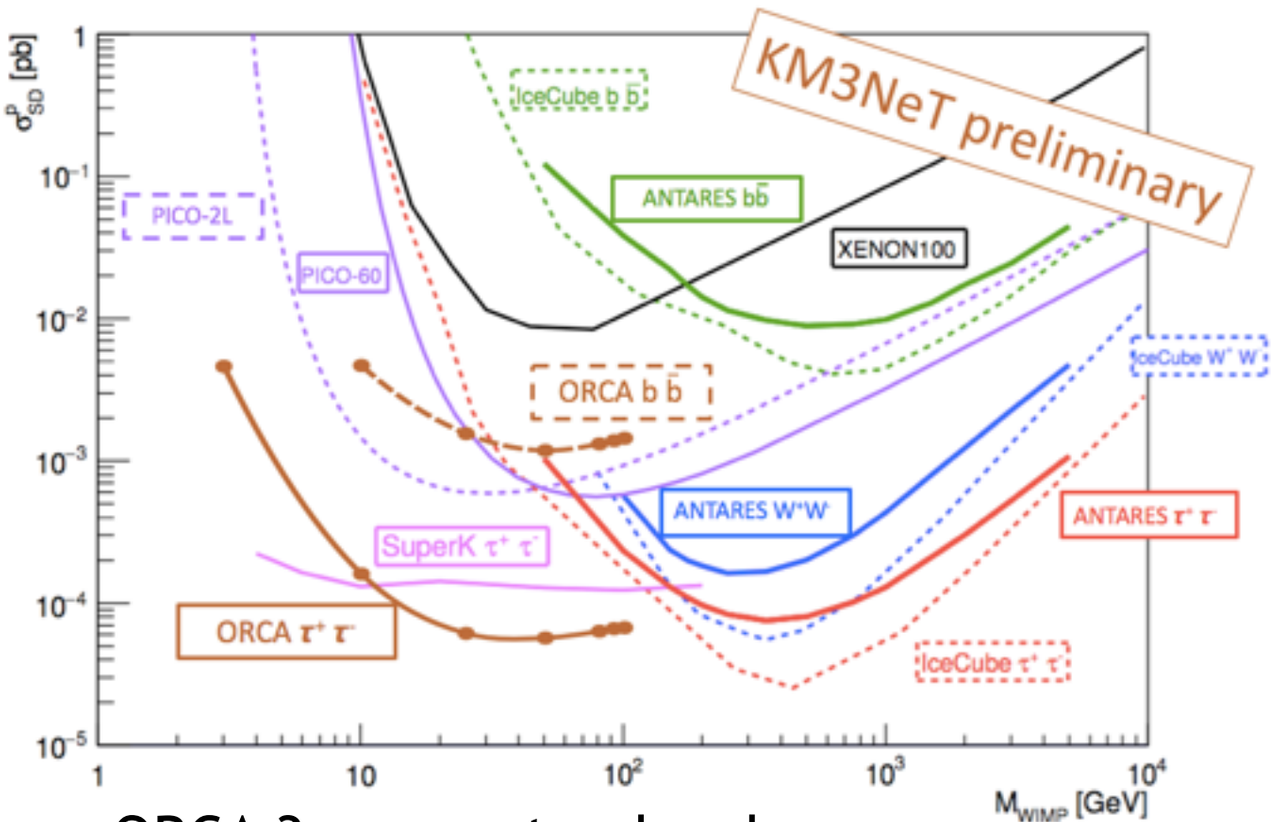



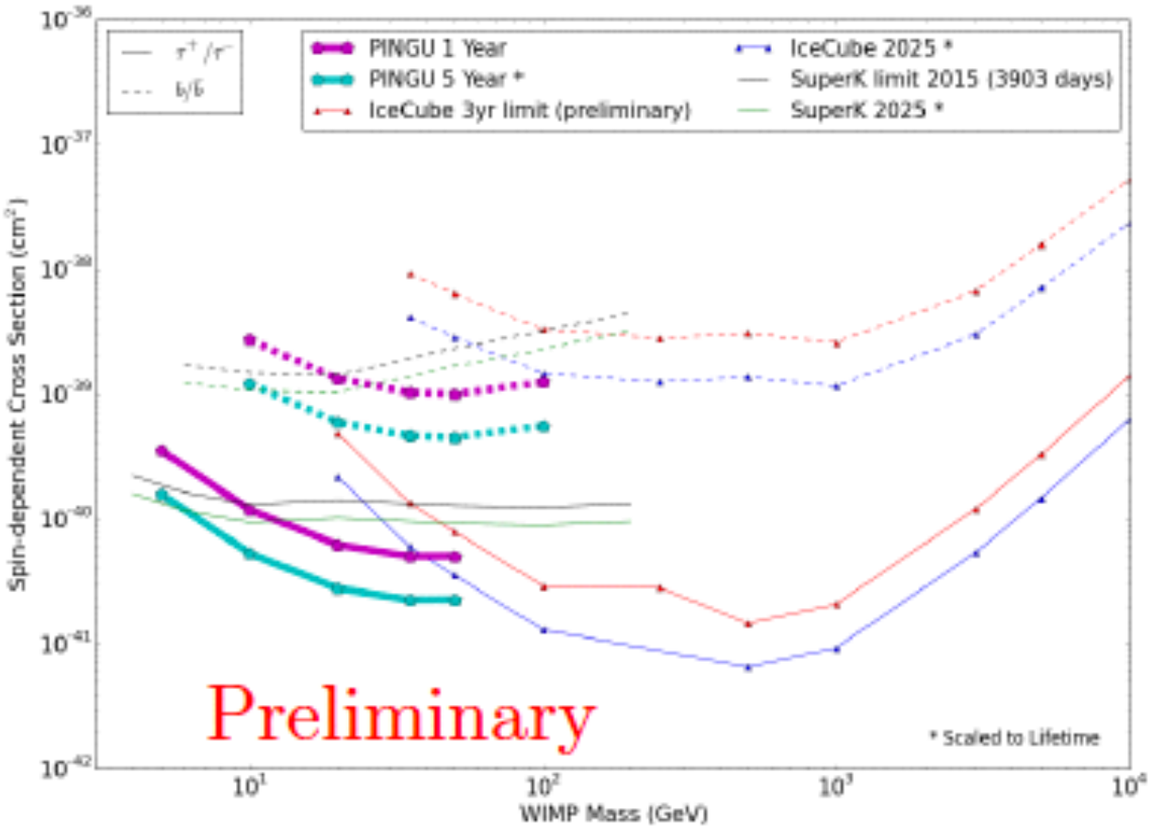

Baikal-GVD
KM3NeT LOI
IceCube Gen2 LOI

arXiv::1601.07459
arXiv:1412.5106

# Solar WIMP perspective with ORCA/PINGU




ORCA 3 years - tracks+showers

- Excellent sensitivity to dark matter below 50GeV

# Conclusions

- Striking WIMP signatures provide high discovery potential for indirect searches
- Models motivated by positron excess and gamma-ray observations can and have been tested by IceCube and ANTARES
- Neutrino Telescopes provide world best limits on SD WIMP-Proton scattering cross section
- Neutrinos extremely sensitive to test low-mass WIMP scenarios at current and future detectors
- Potential to strengthen competitiveness of neutrino bounds with combined analyses