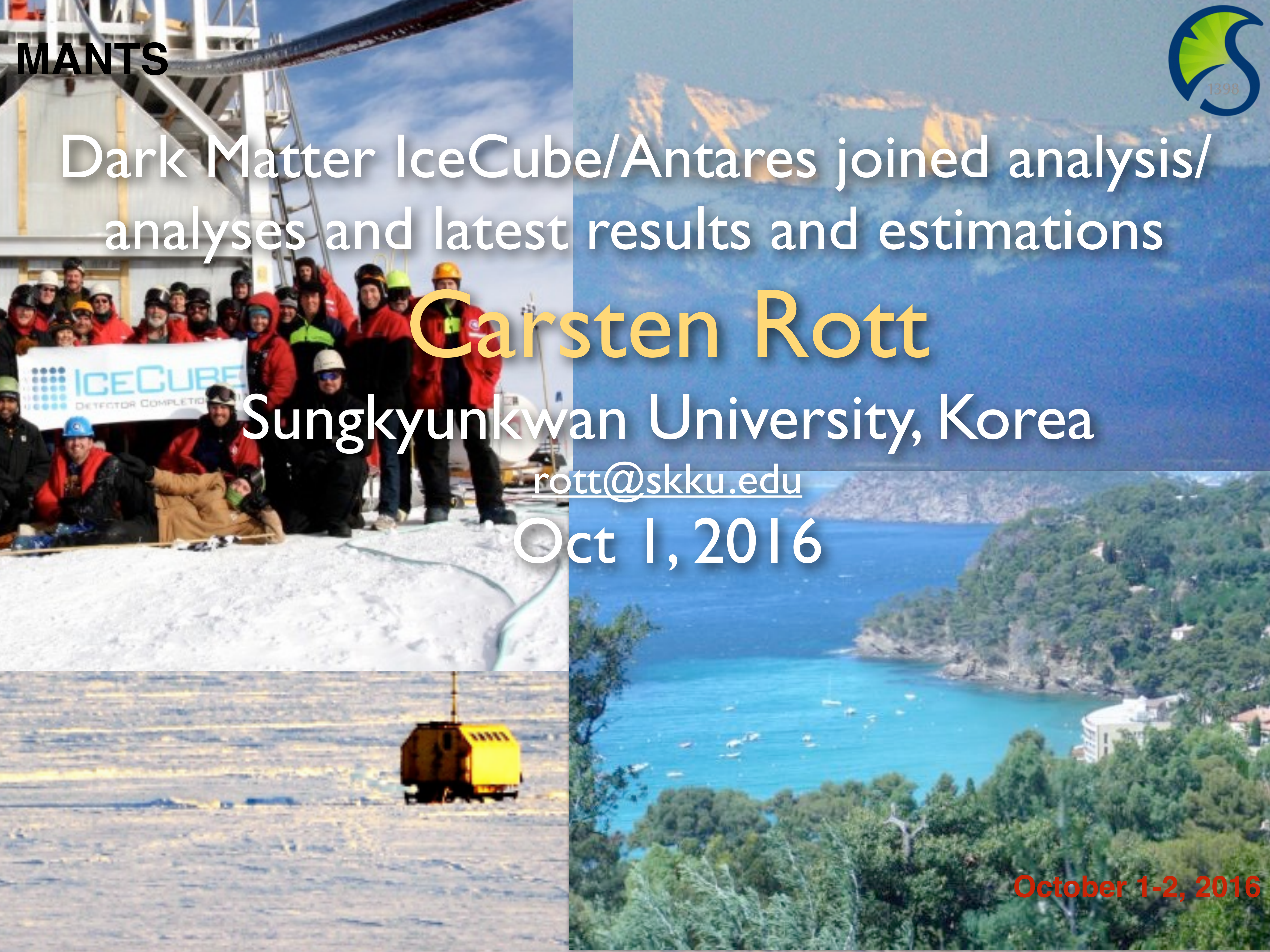


MANTS

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

Carsten Rott

Sungkyunkwan University, Korea

rott@skku.edu

Oct 1, 2016

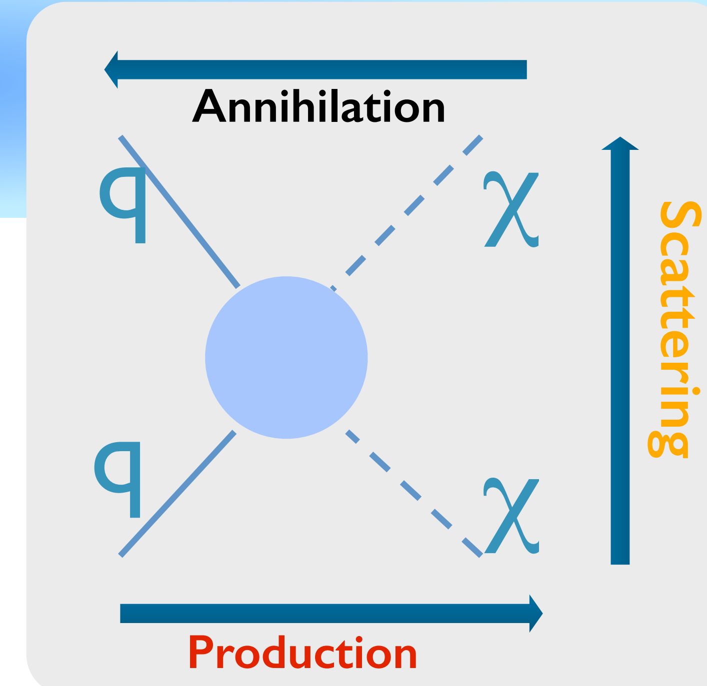
October 1-2, 2016

Outline

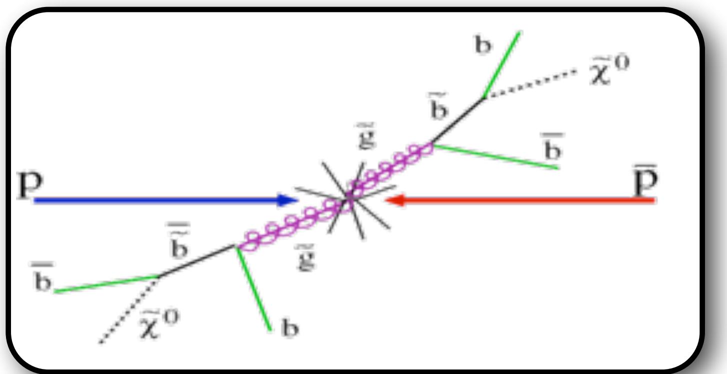
- Motivation
- Overview of current searches and results
  - Galactic Halo / Galactic Center
  - Solar WIMPs
  - Earth WIMPs
  - High-energy neutrinos
- Discussion topics
- Conclusions

Motivation

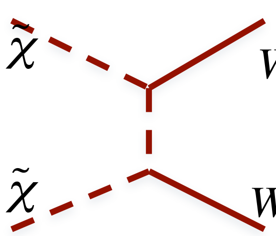
Indirect Searches with Neutrinos



WIMP - Weakly Interacting Massive Particle

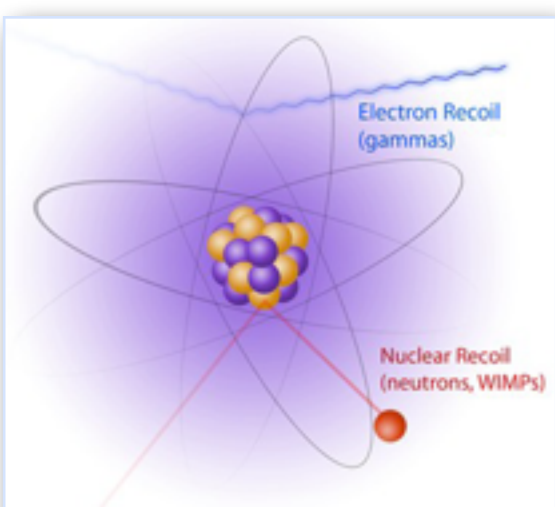


- Production
  - Colliders
- **Indirect Searches**
  - Annihilation of Dark Matter in Galactic Halo, ...
    - Gamma-rays, electrons, neutrinos, anti-matter, ...
  - Annihilation signals from WIMPs captured in the Sun and Earth
    - Neutrinos
- Direct Searches
  - WIMP scattering of nucleons → Nuclear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



$W^+, Z, \tau^+, b, \ldots \Rightarrow e^\pm, \upsilon, \gamma, p, D, \ldots$

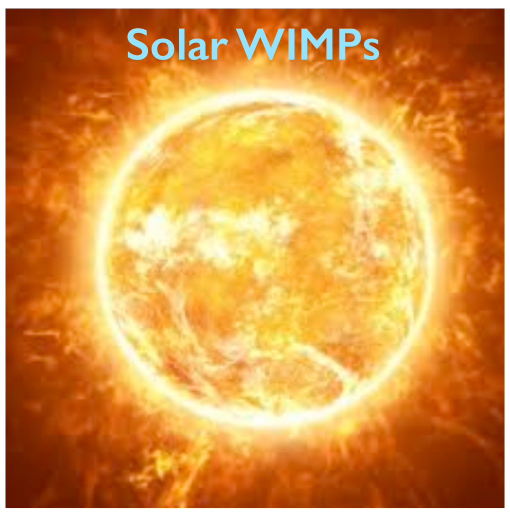
$W^-, Z, \tau^-, \bar{b}, \ldots \Rightarrow e^\mp, \upsilon, \gamma, \bar{p}, D, \ldots$

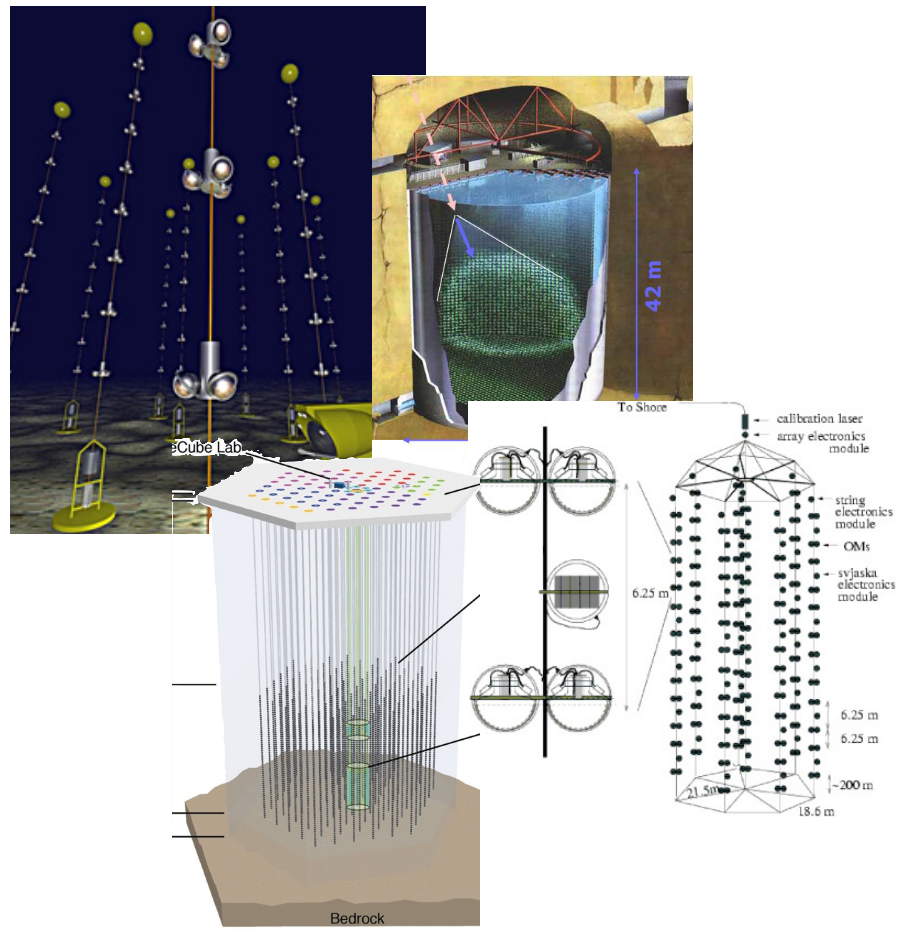


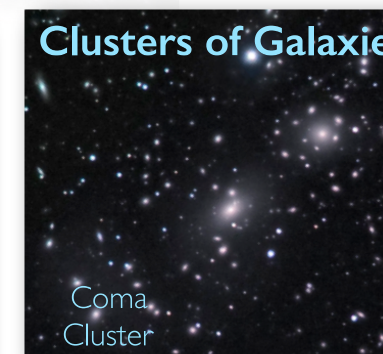
WIMP Self-annihilation cross section

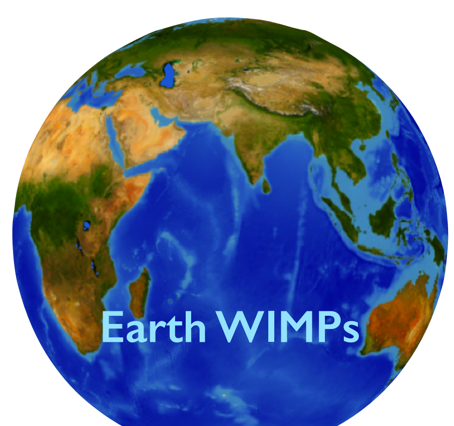
WIMP-Nucleon Scattering cross section

Dark Matter Signals









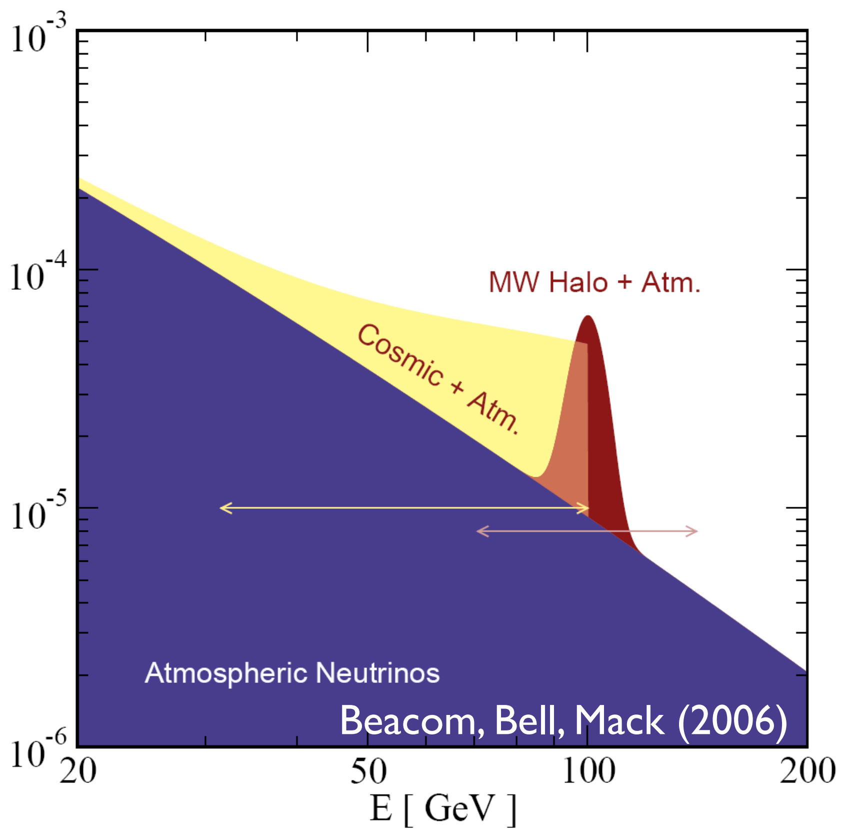
Galactic Halo / Galactic Centre

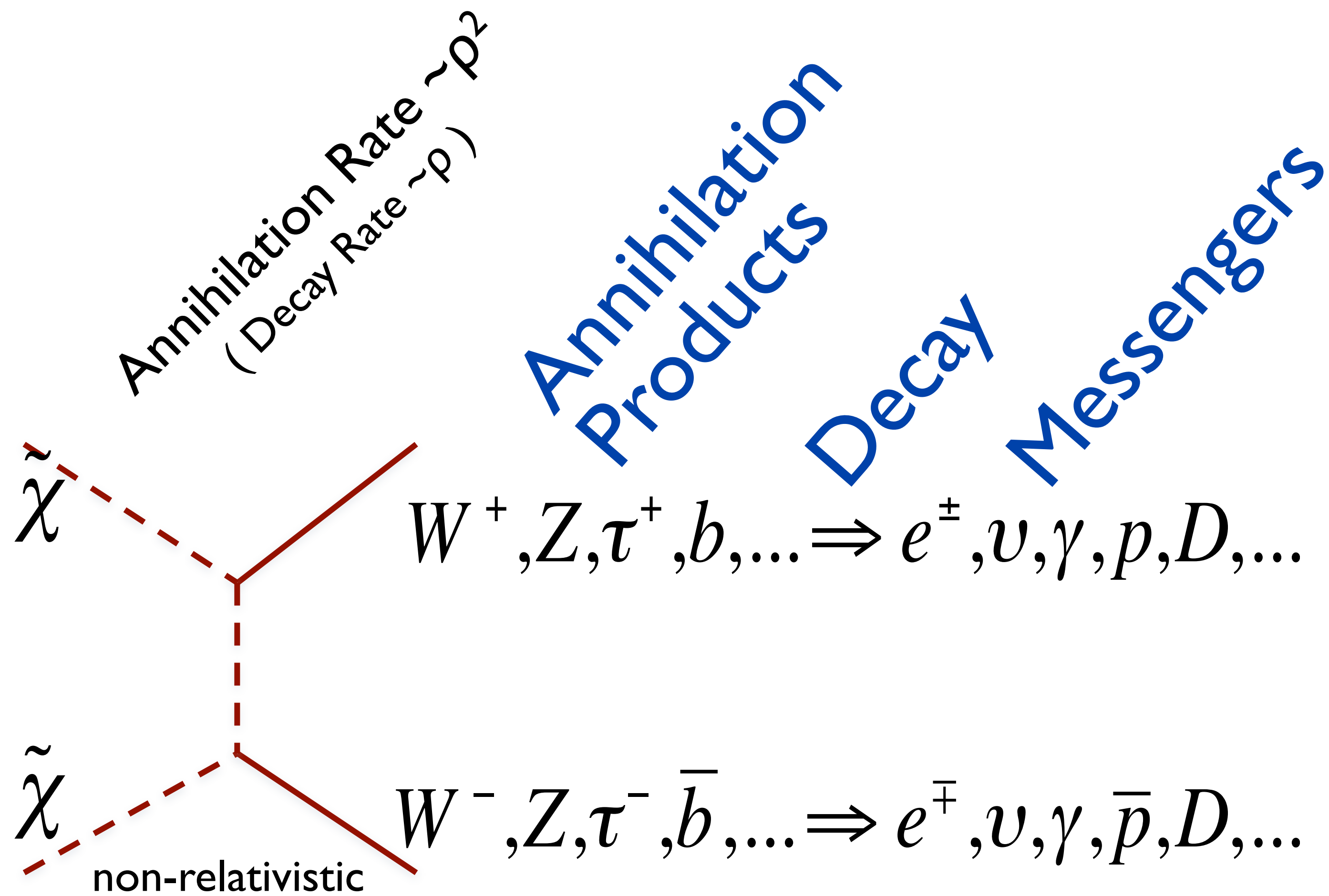
Dark Matter Annihilation Signals

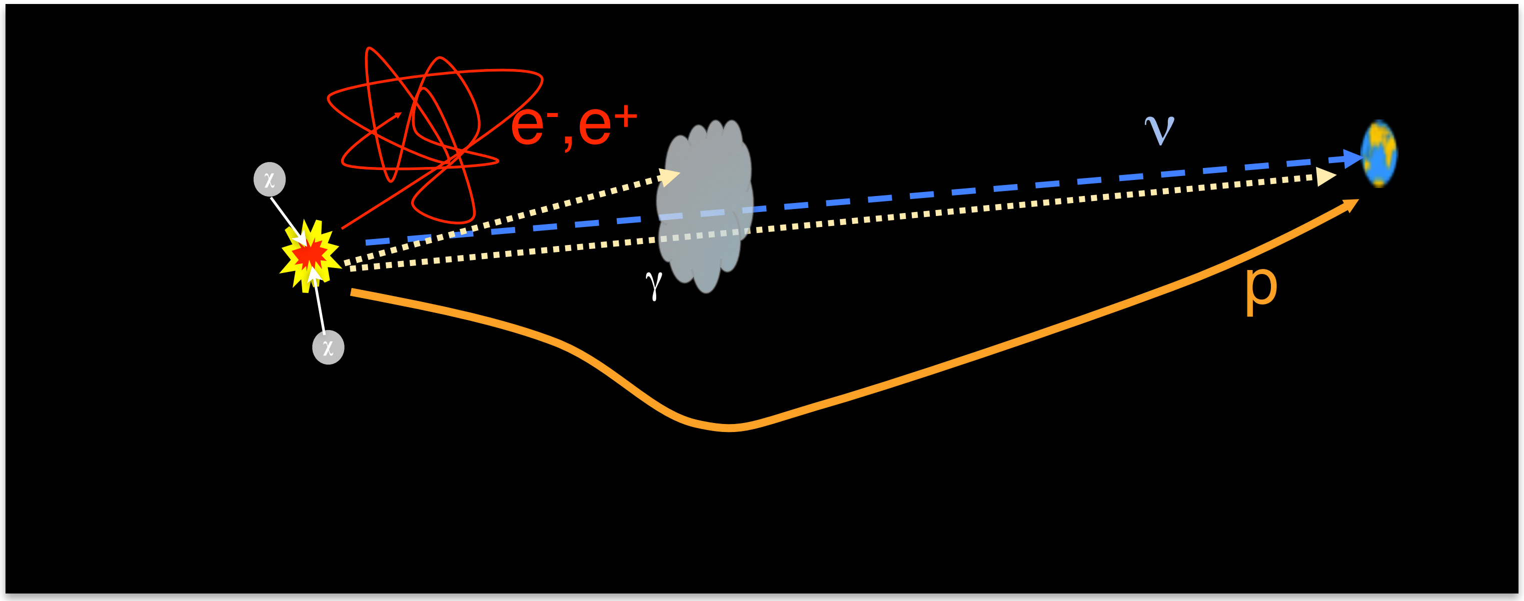
- Identify overdense regions of dark matter

  ⇒self-annihilation can occur at significant rates

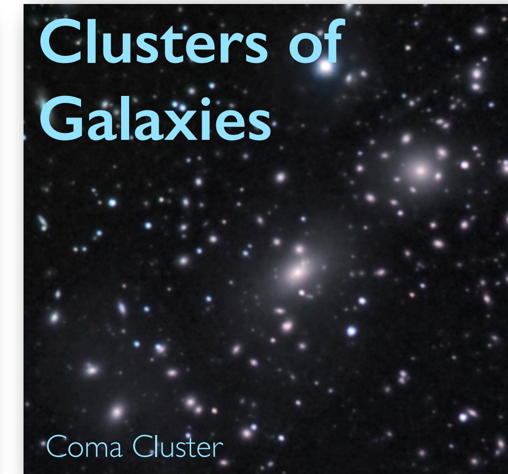
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds



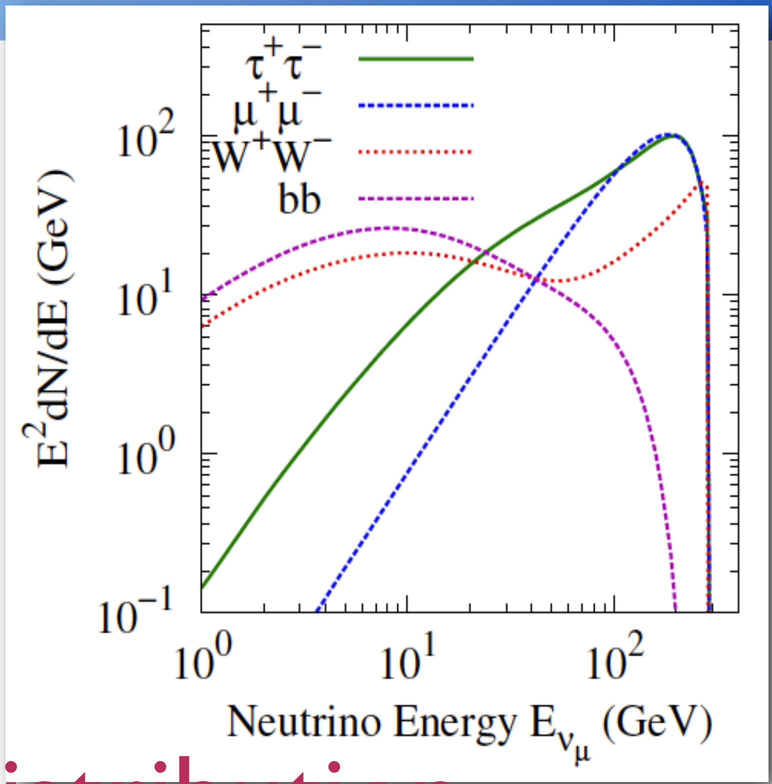




Sources

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 **IceCube Coll. Eur.Phys.J. C75 (2015) no.99, 20**	**IceCube Coll. arXiv: 1210.3557** **IceCube Coll. Eur.Phys.J. C75 (2015) no.10, 492** **ANTARES Coll. JCAP 1510 (2015) no.10, 068** **Baikal AstroPhys 81 (2016)** **IceCube Coll. arXiv: 1606.00209**	**IceCube Coll. Phys.Rev. D88 (2013) 122001**	

Dark Matter Annihilation



Measure Flux

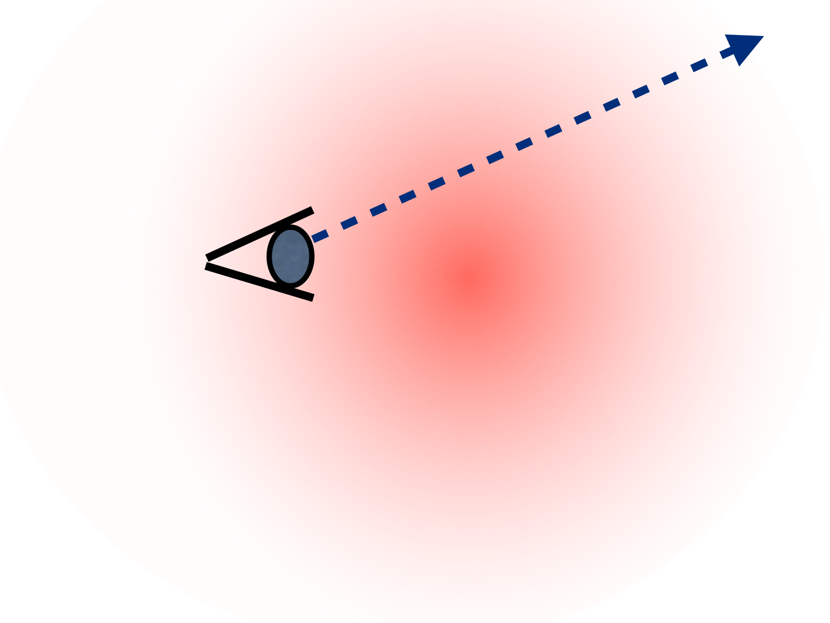
Particle Physics

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

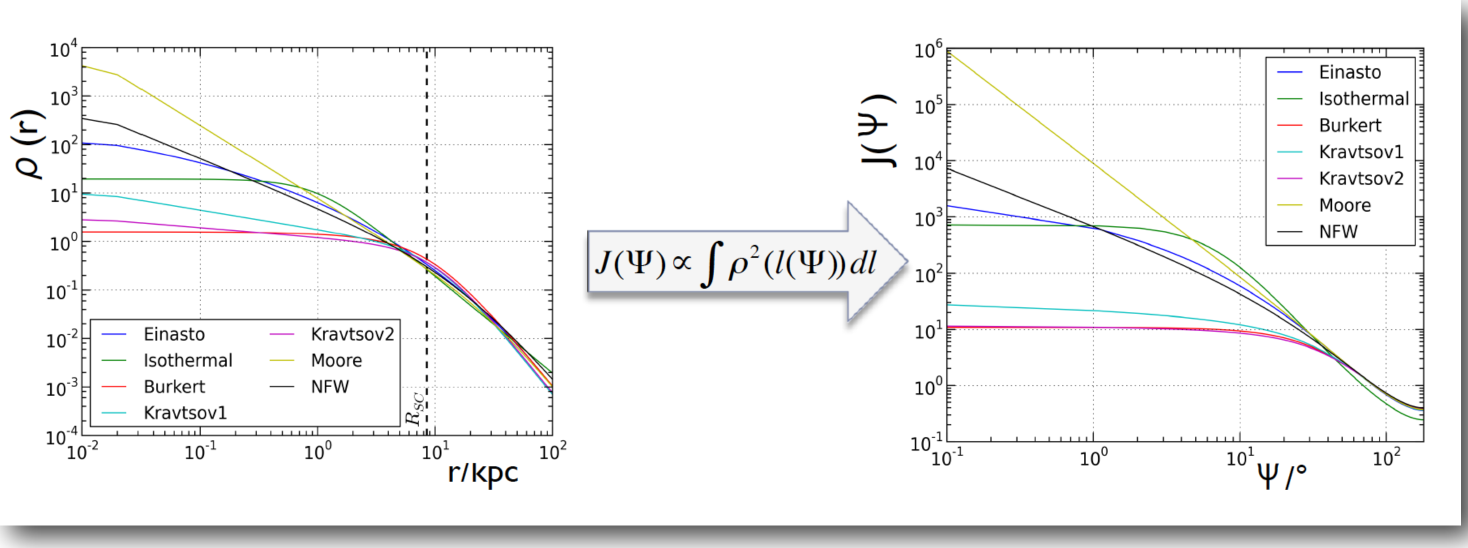
x

Dark Matter Distribution

line of sight (los) integral

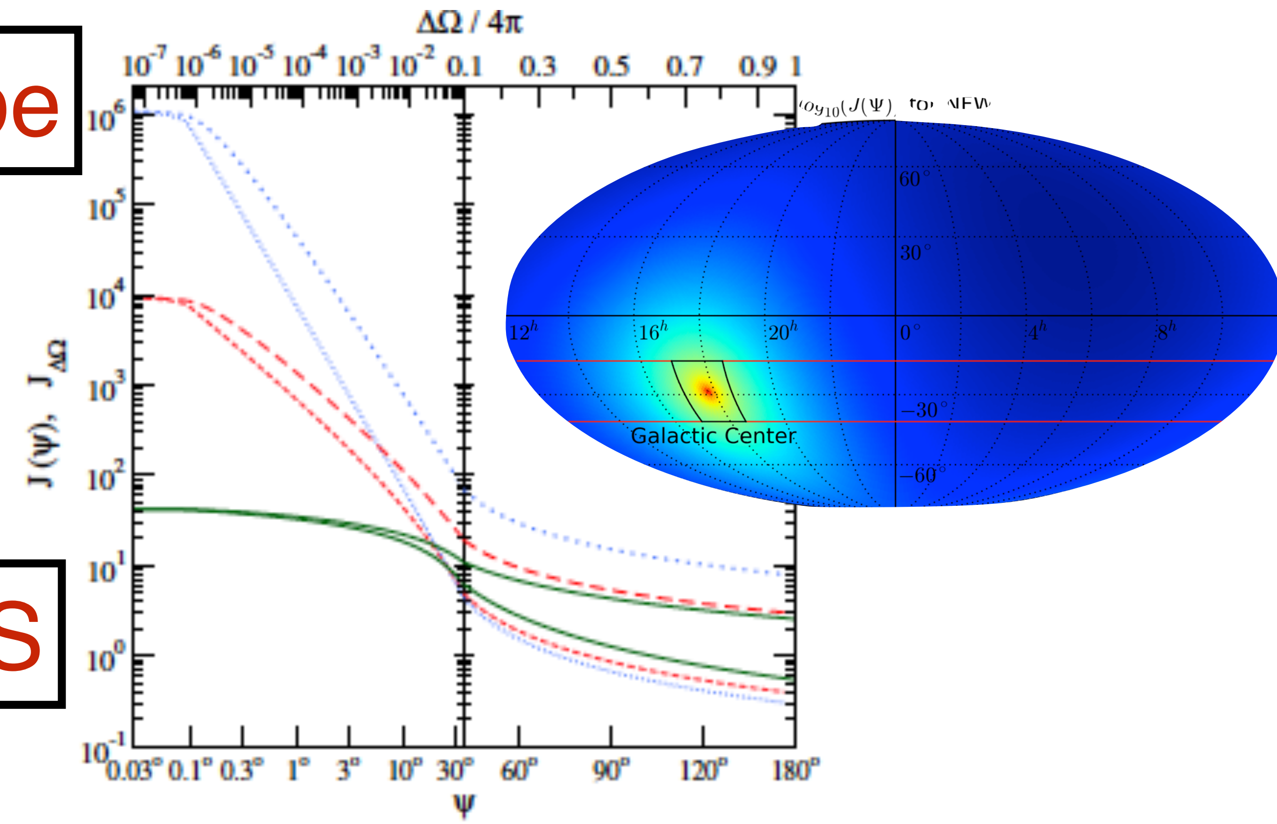


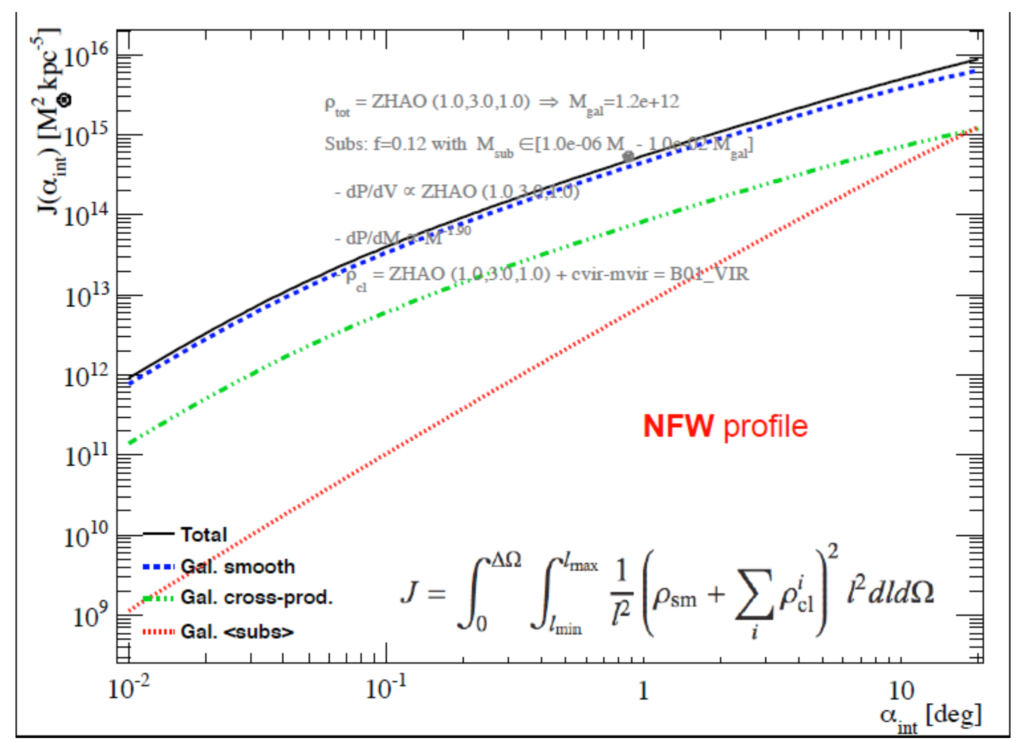
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$



Halo Profiles and J-factors

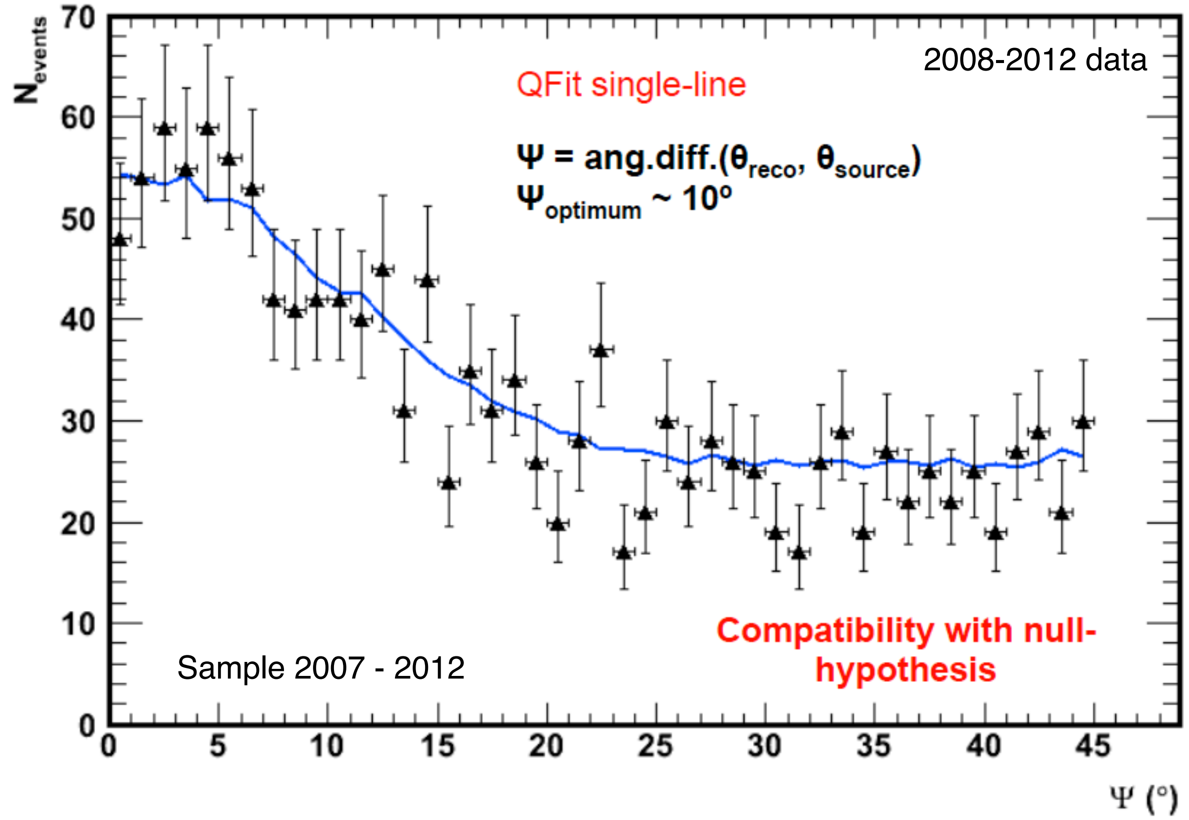
- Customised implementations **IceCube**
  - Following for example: Yuksel et al. PHYSICAL REVIEW D 76, 123506 (2007)
- Packages **ANTARES**
  - CLUMPY (computation of J-factors)
    - A. Chardonnier, C. Combet, D. Maurin, Comp. Phys. Comm. 183, 656 (2012)
    - http://lpsc.in2p3.fr/clumpy/ for the source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

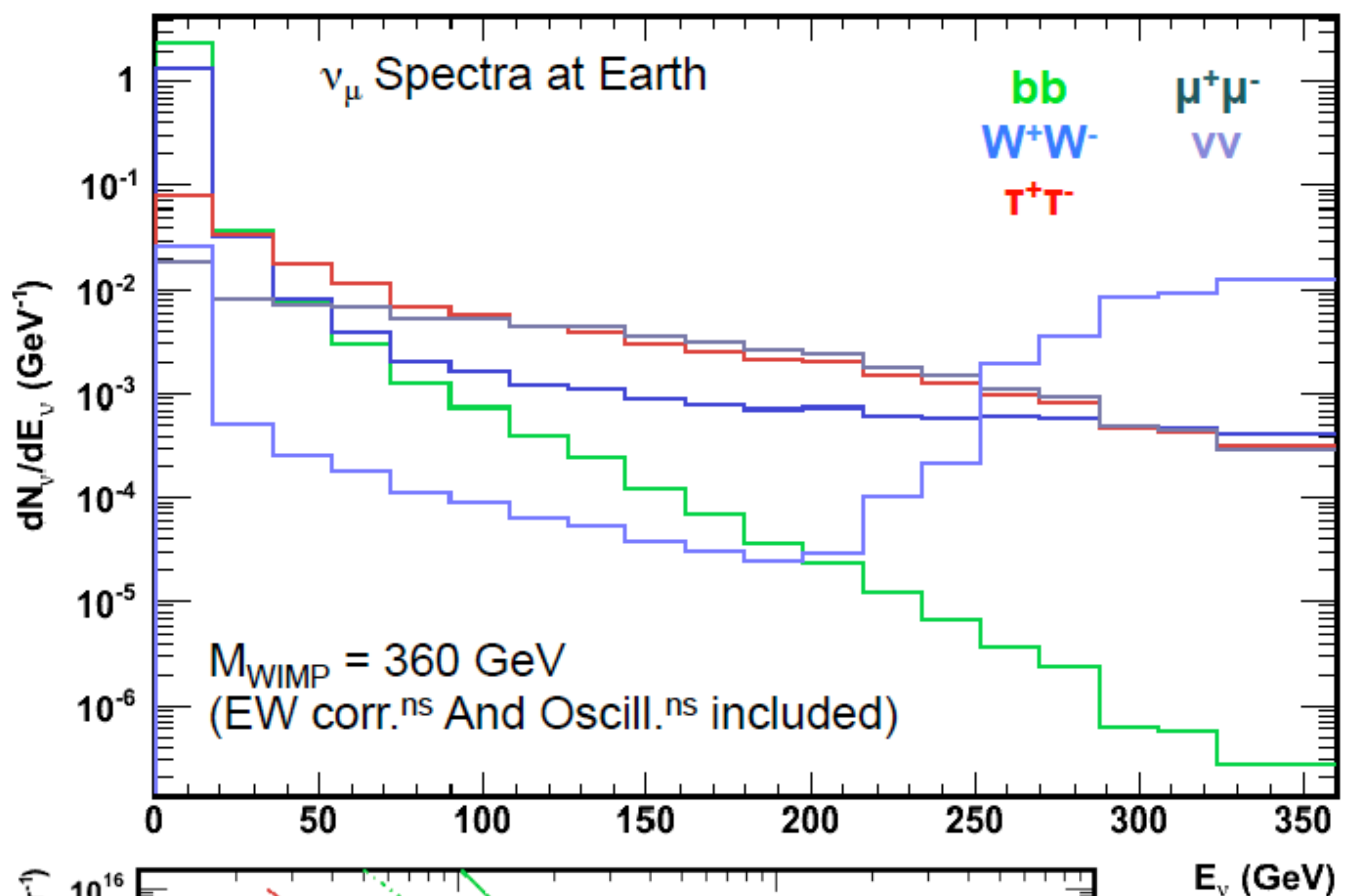


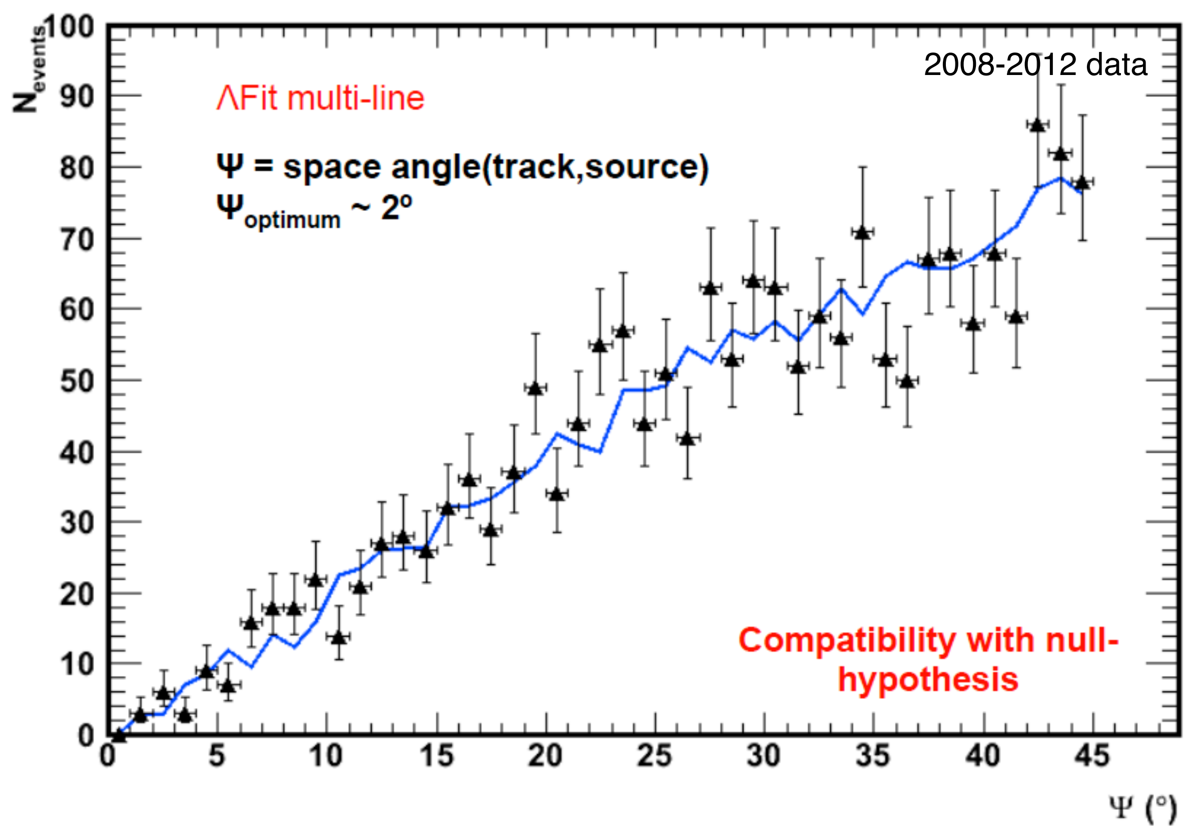


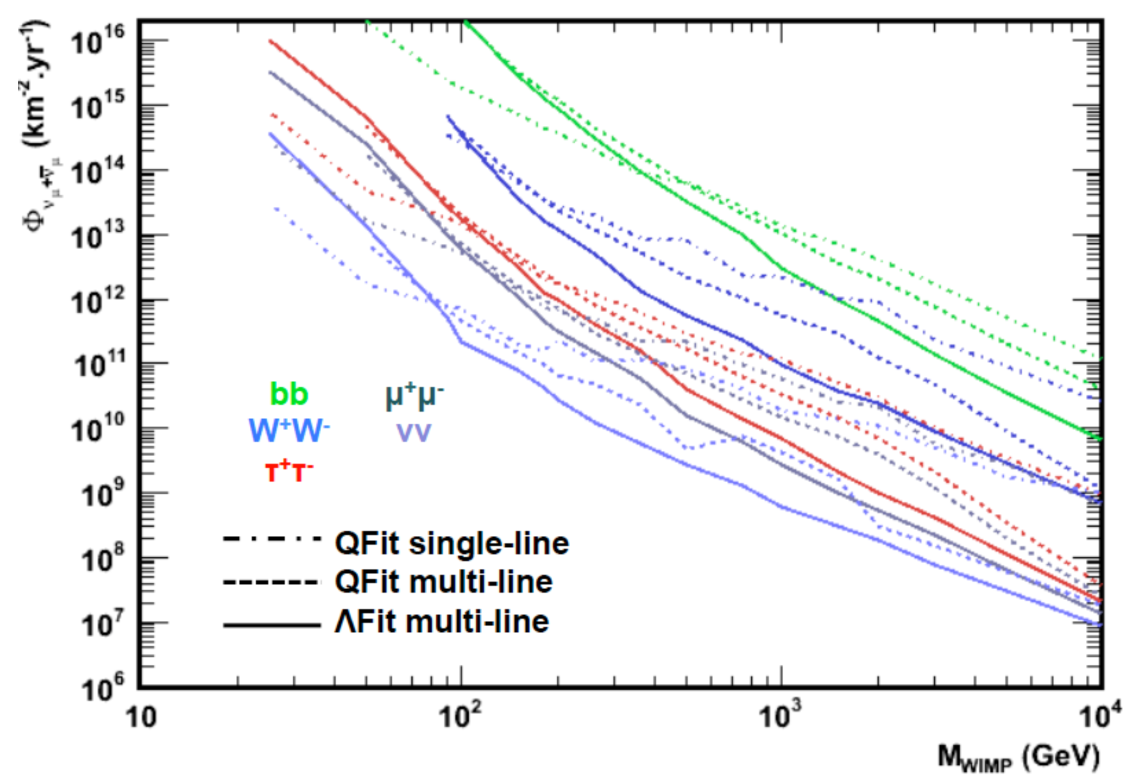
ANTARES Galactic Center Analysis

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







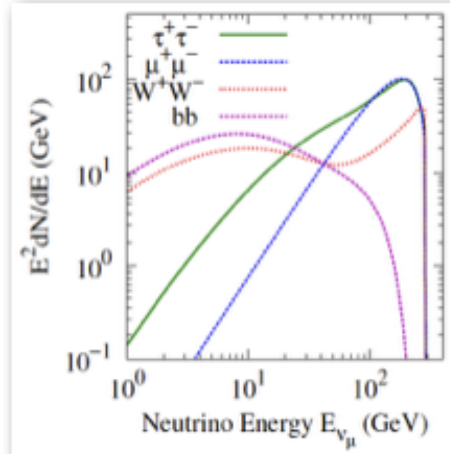


IceCube Dark Matter Halo Analyses

IceCube Collaboration arXiv:1606.00209v1

Measure Flux = **Particle Physics**

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

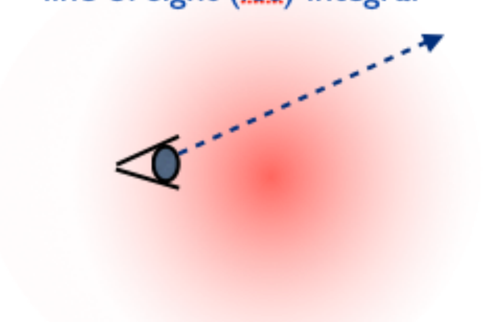


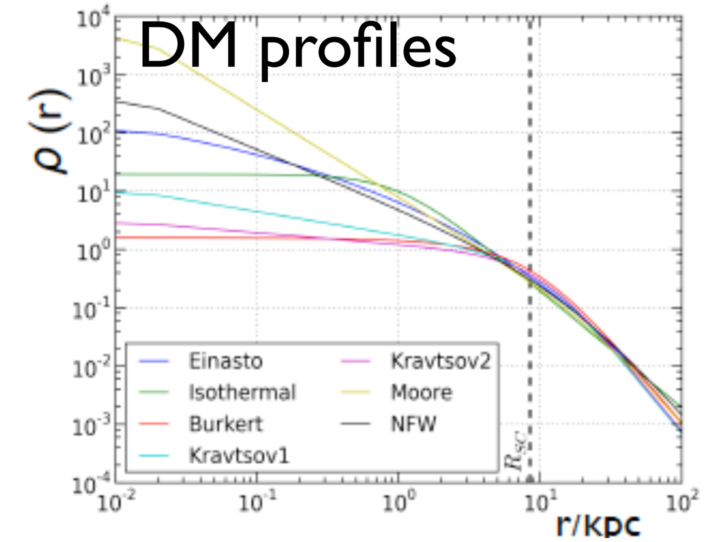
x

Dark Matter Distribution

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

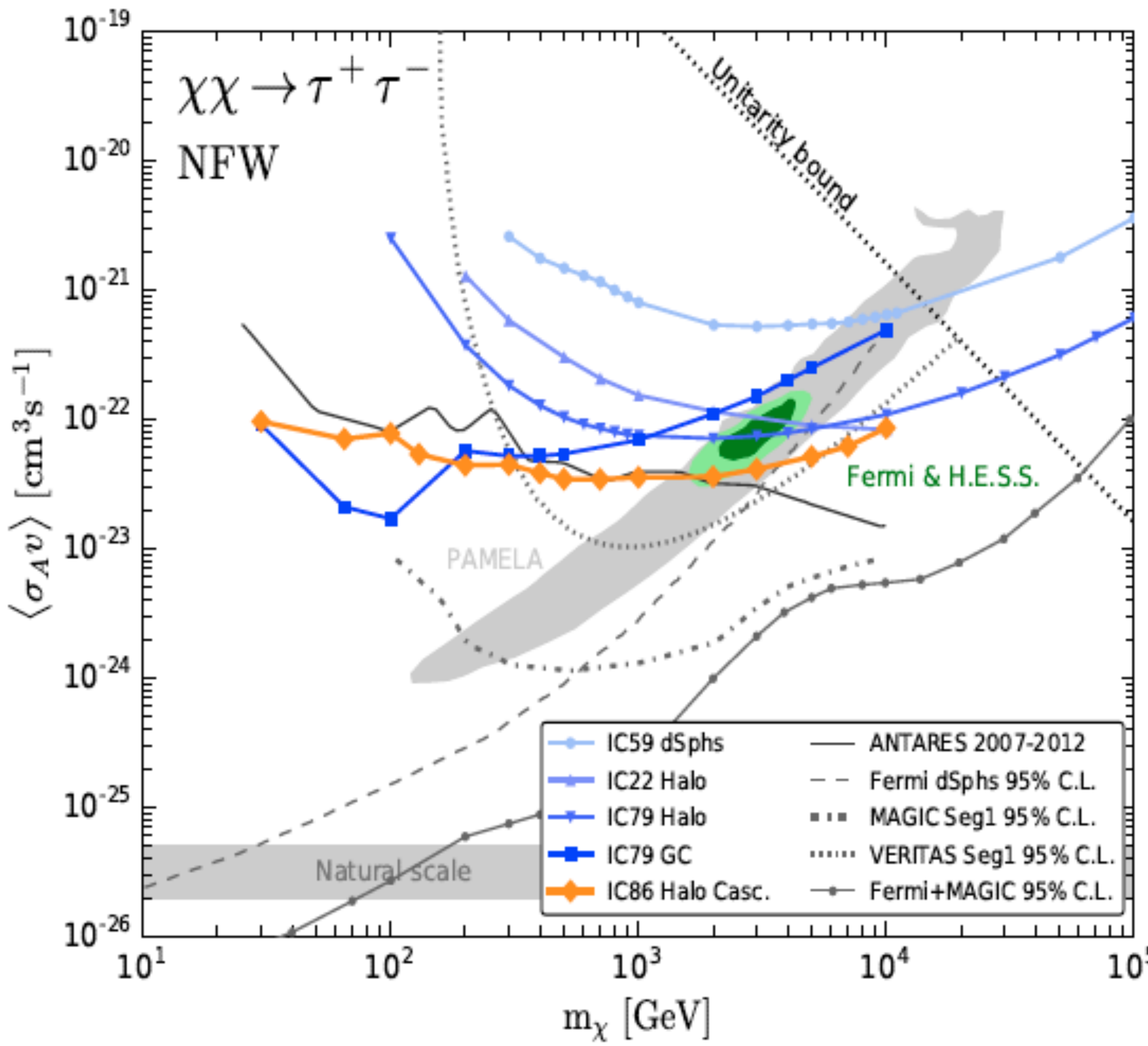
line of sight (los) integral





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

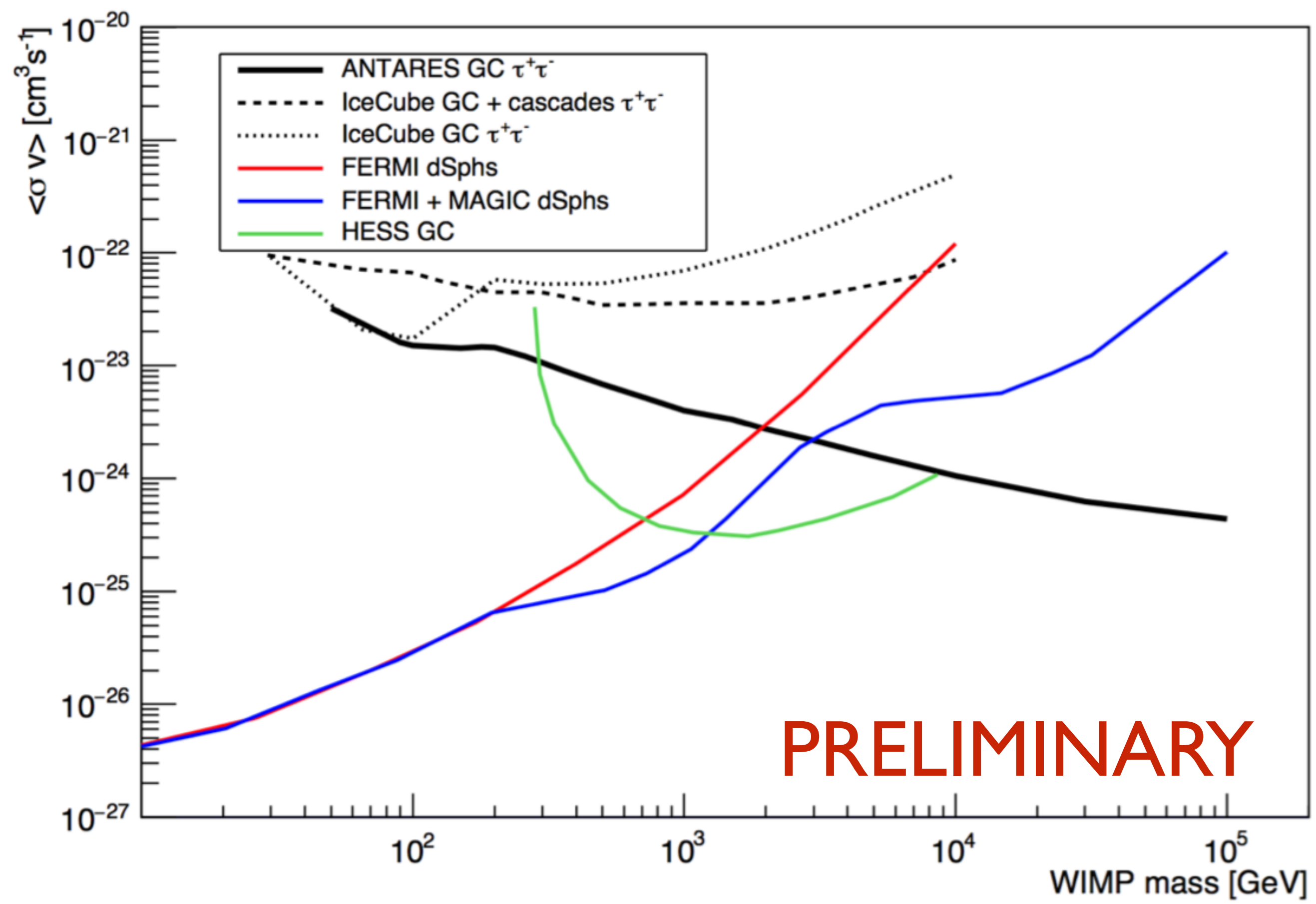
- Galactic Center (GC) on the Southern hemisphere
  - large backgrounds from down-going muons
- Search for anisotropy on Northern hemisphere
  - high-purity neutrino sample (up-going muon events)
  - large scale distribution (cascades event optimally suited)
- Assume annihilation into νν, bb, μμ, ττ,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



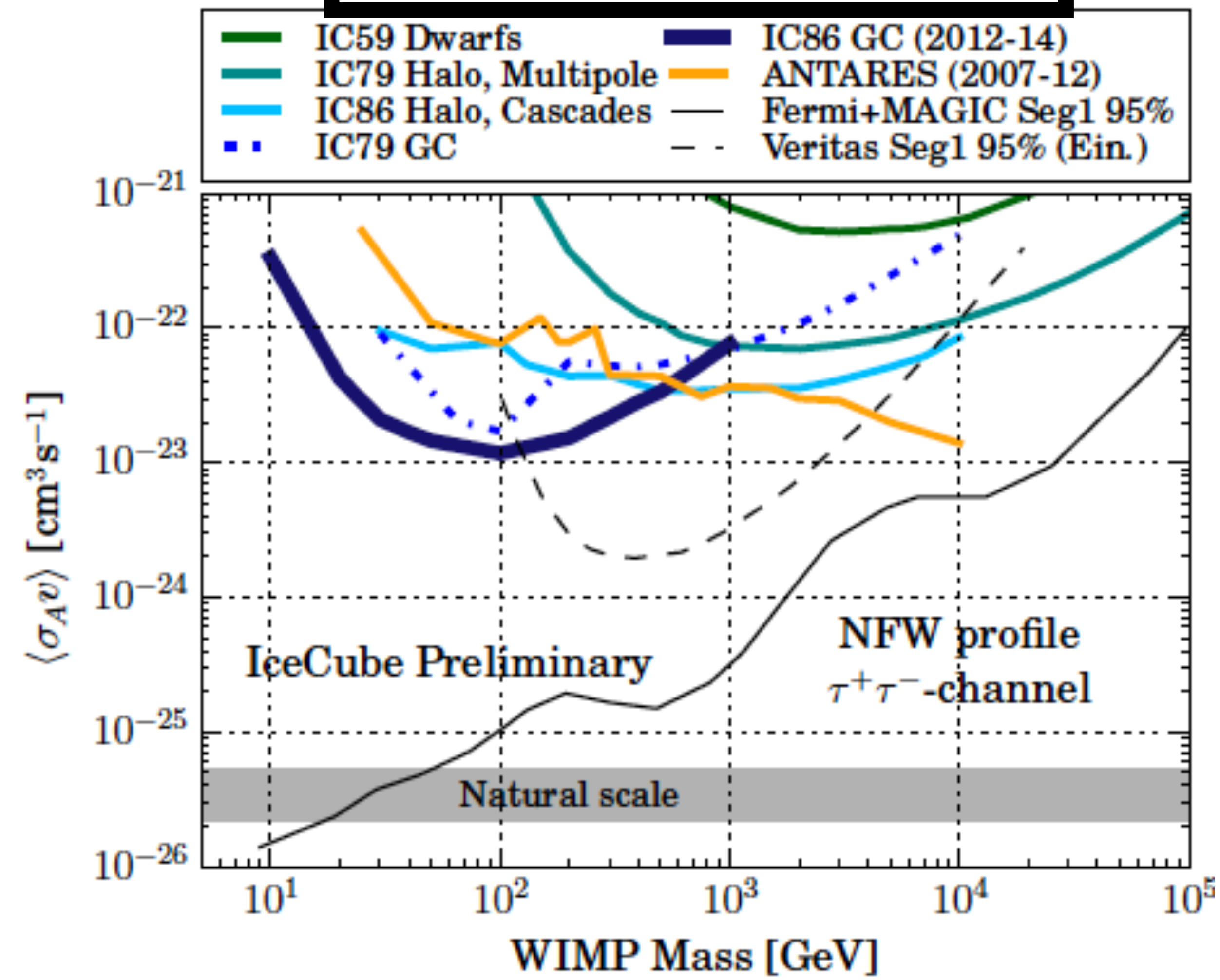
Models motivated by increase in positron fraction can be tested

Improved results Galactic Centre

ANTARES



IceCube

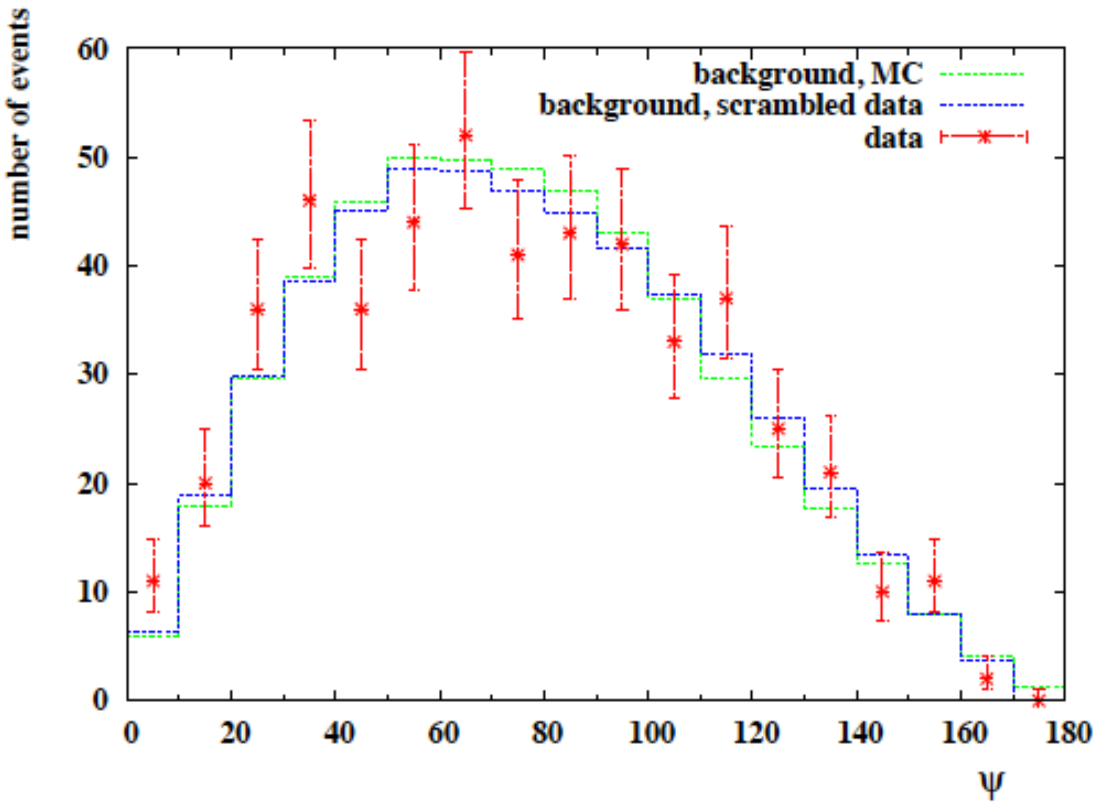


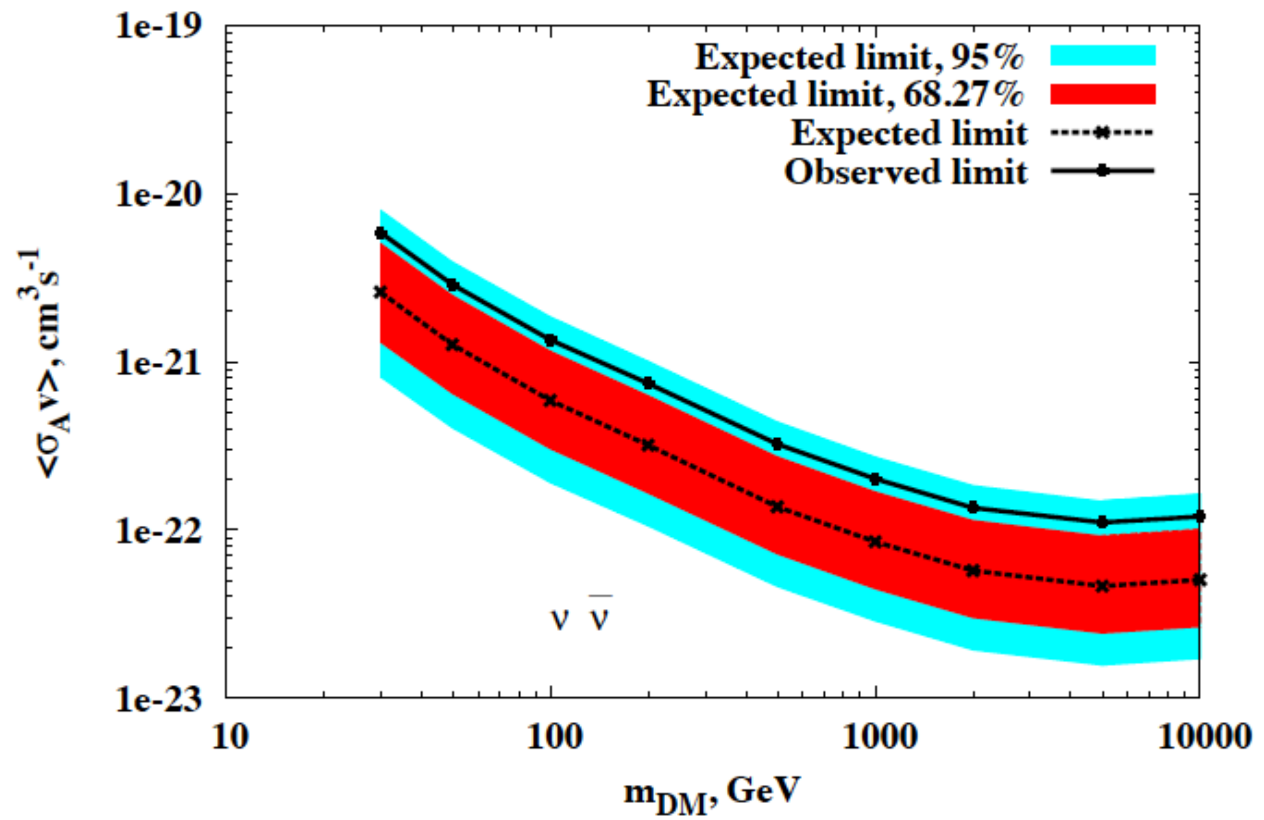
2007-2015 data
GC analysis including single line events

- 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)



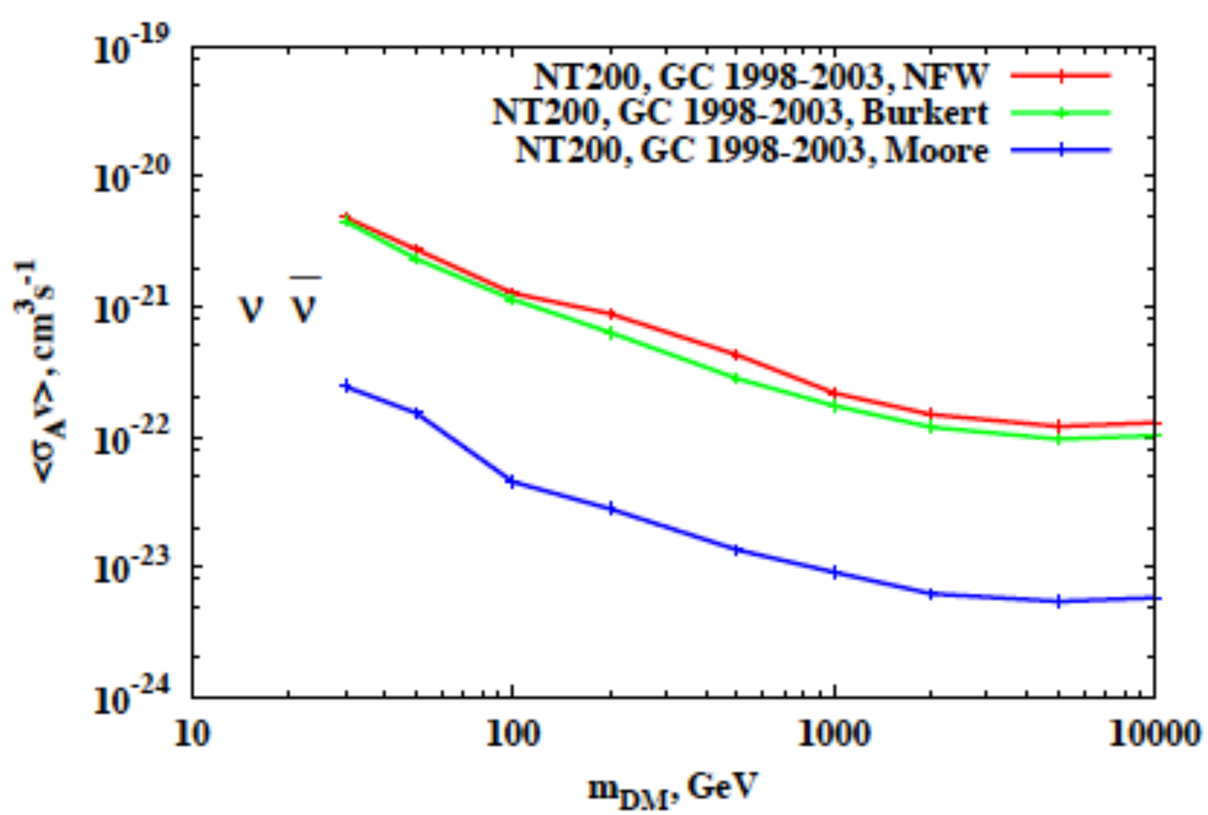


- Dataset collected during 1998–2003
- Maximum likelihood method
- Limits computed for various channels

Astrophysical factor → Visibility

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

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

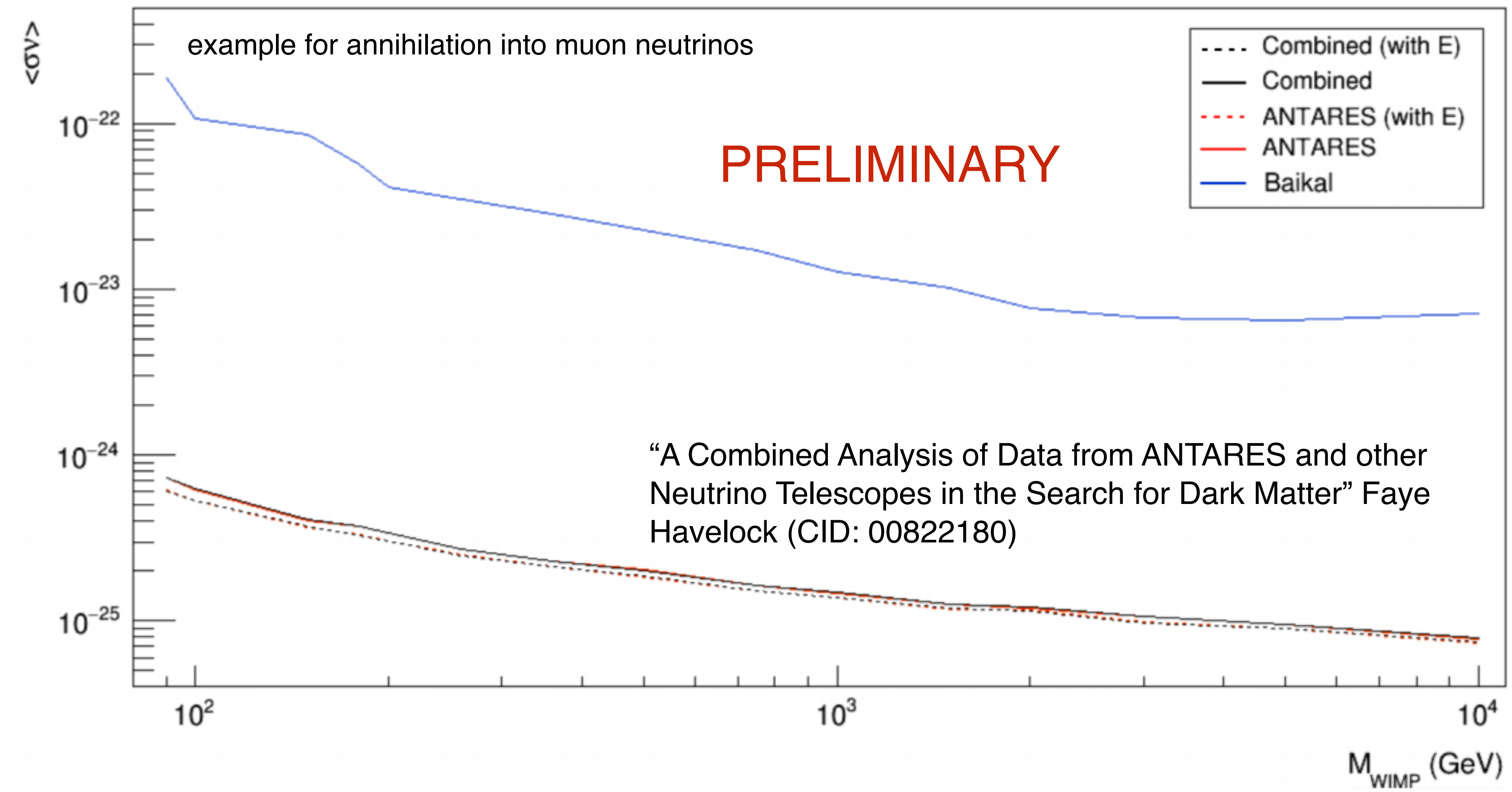


Understanding sensitivities

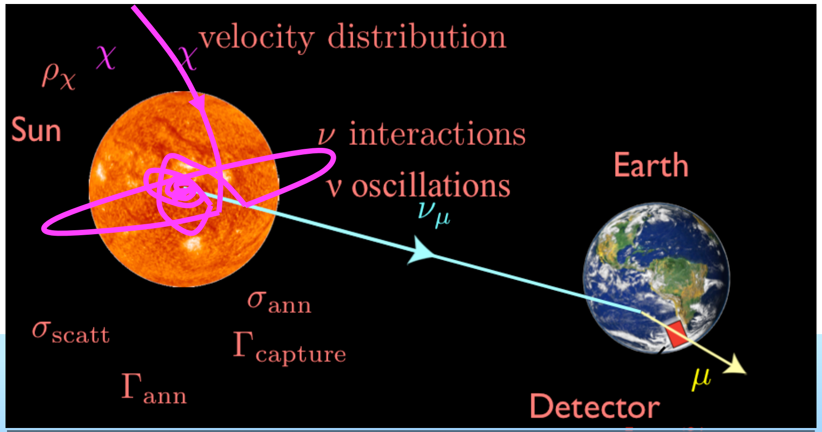
- Understanding the sensitivity of neutrino detectors
  - Neutrino distribution does not change with choice of annihilation channel or WIMP mass
    - There is however a dependence introduced due to the energy dependent angular resolution
  - The signal event rate are roughly flat as function of WIMP 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

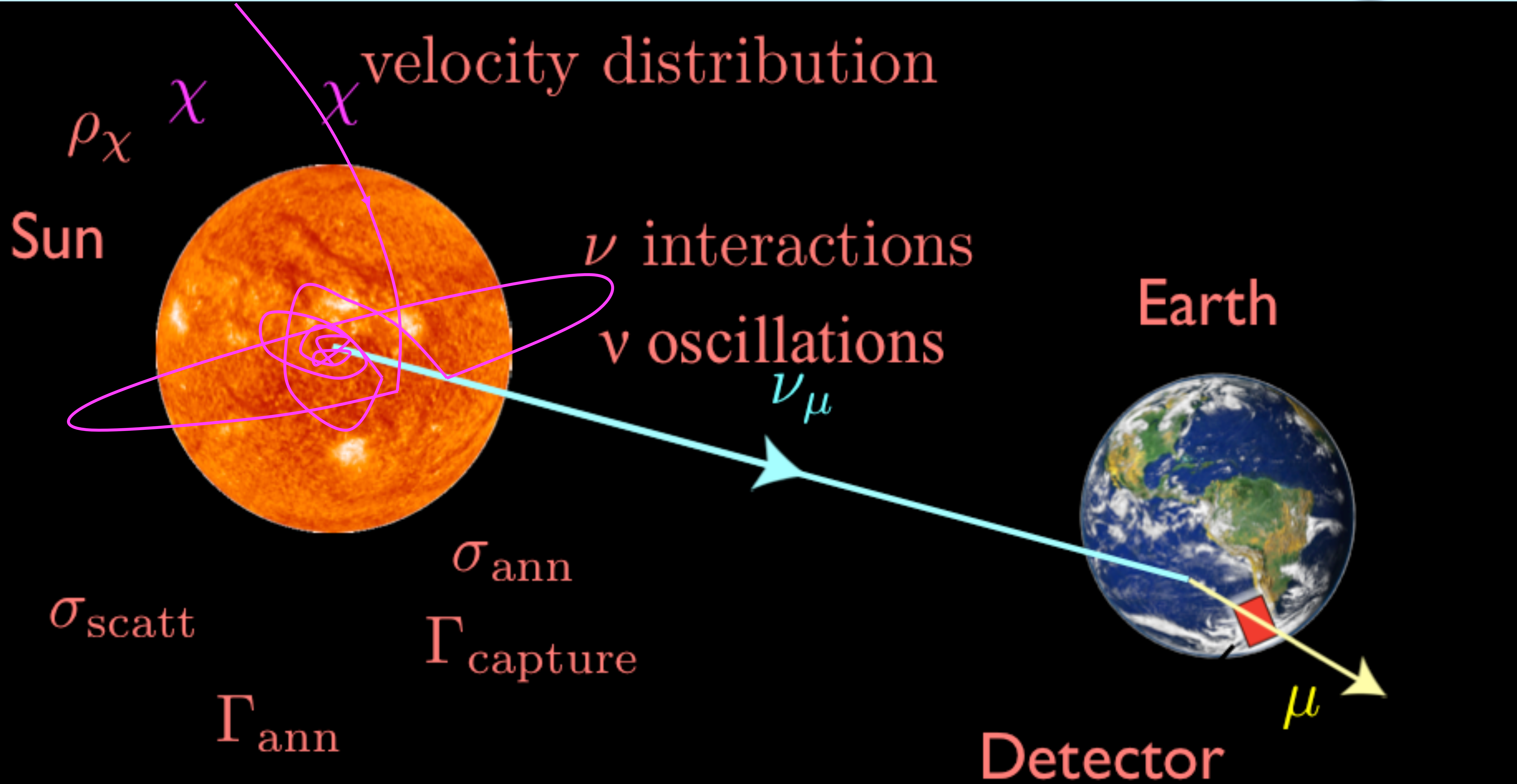


Initial focus is on combining the analyses


ρ_χ
χ
χ
velocity distribution
Sun
ν interactions
ν oscillations
Earth
ν_μ
σ_{ann}
σ_{scatt}
$\Gamma_{capture}$
Γ_{ann}
μ
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

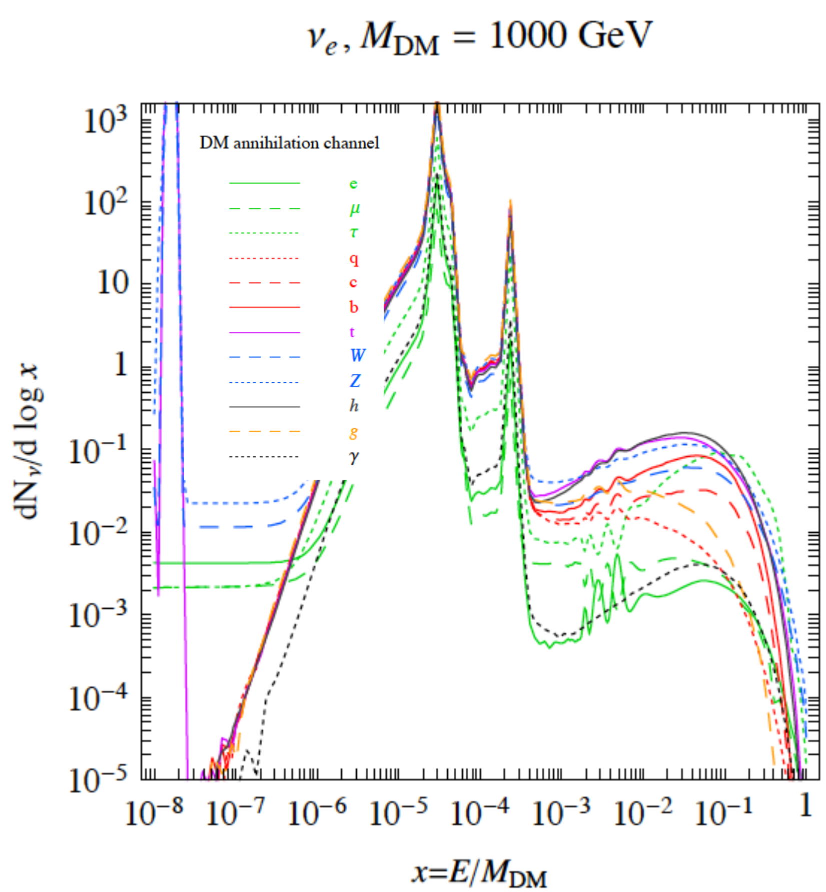
Neutrino Spectra (Sun)

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

Dark SUSY

IceCube

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



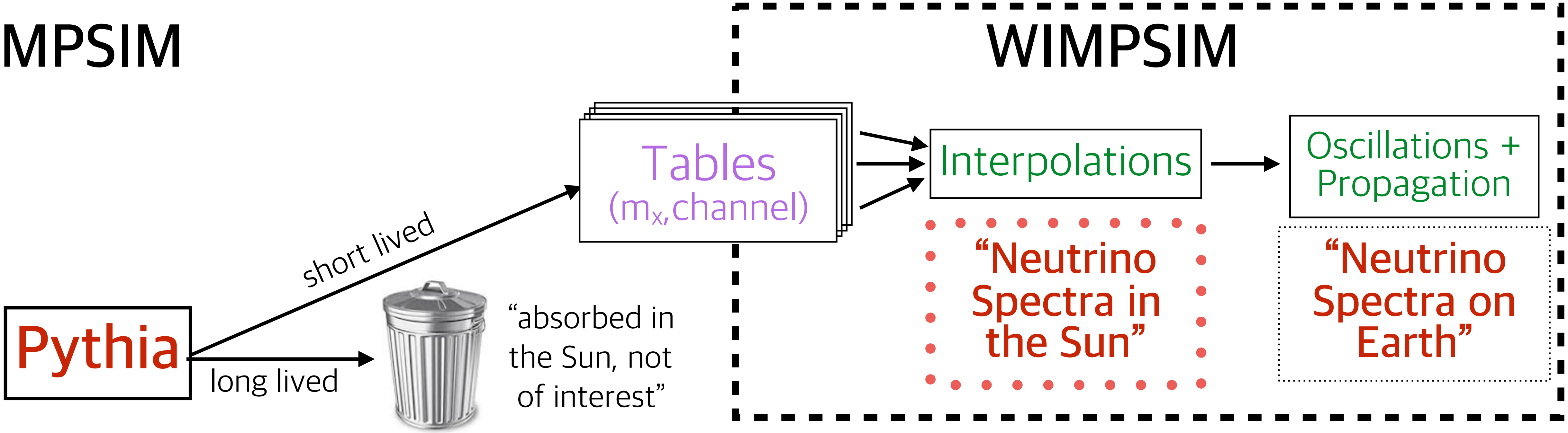
Baikal

ANTARES

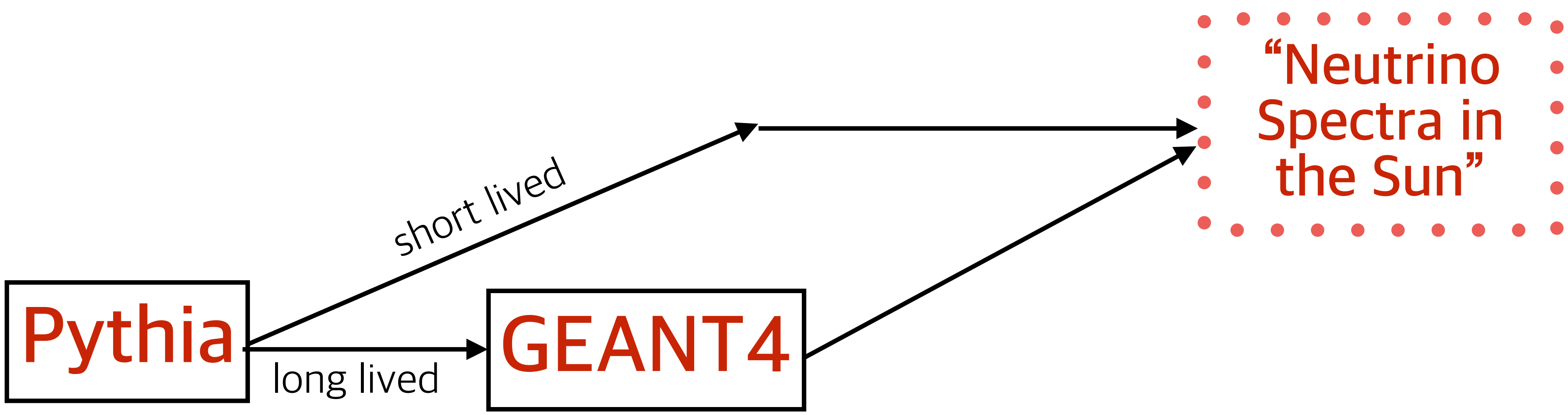
For any practical purpose, the two approaches yield results which are very well in agreement.

How to get neutrino spectra

WIMPSIM

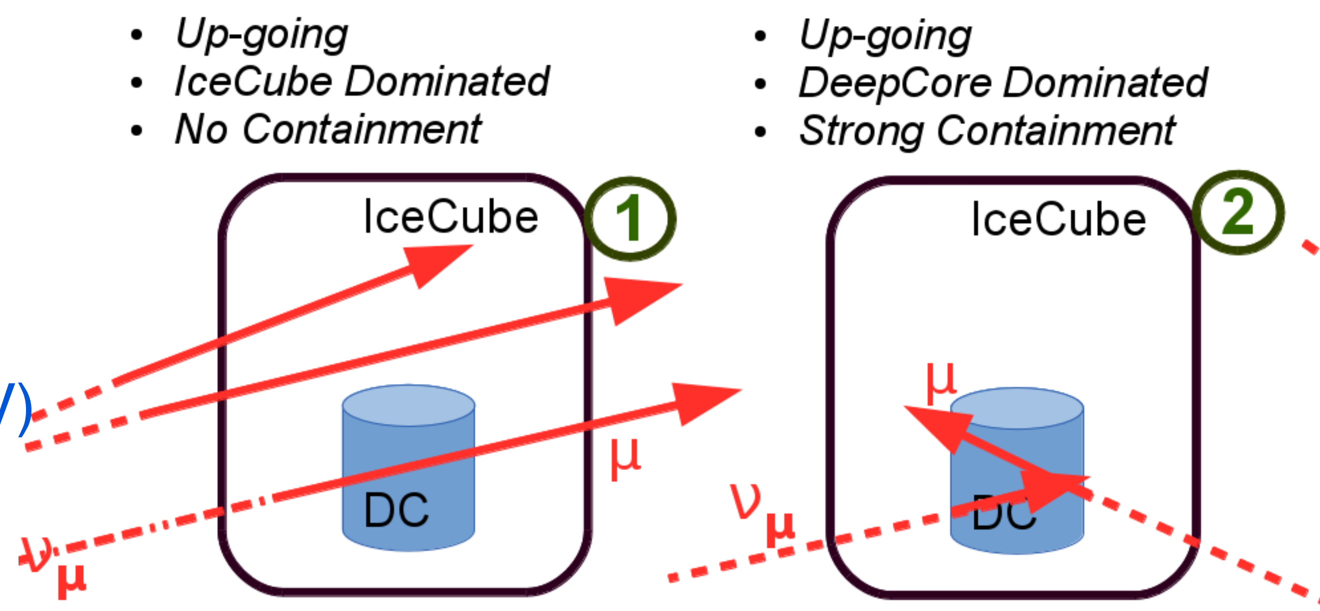


PPPC 4DMν

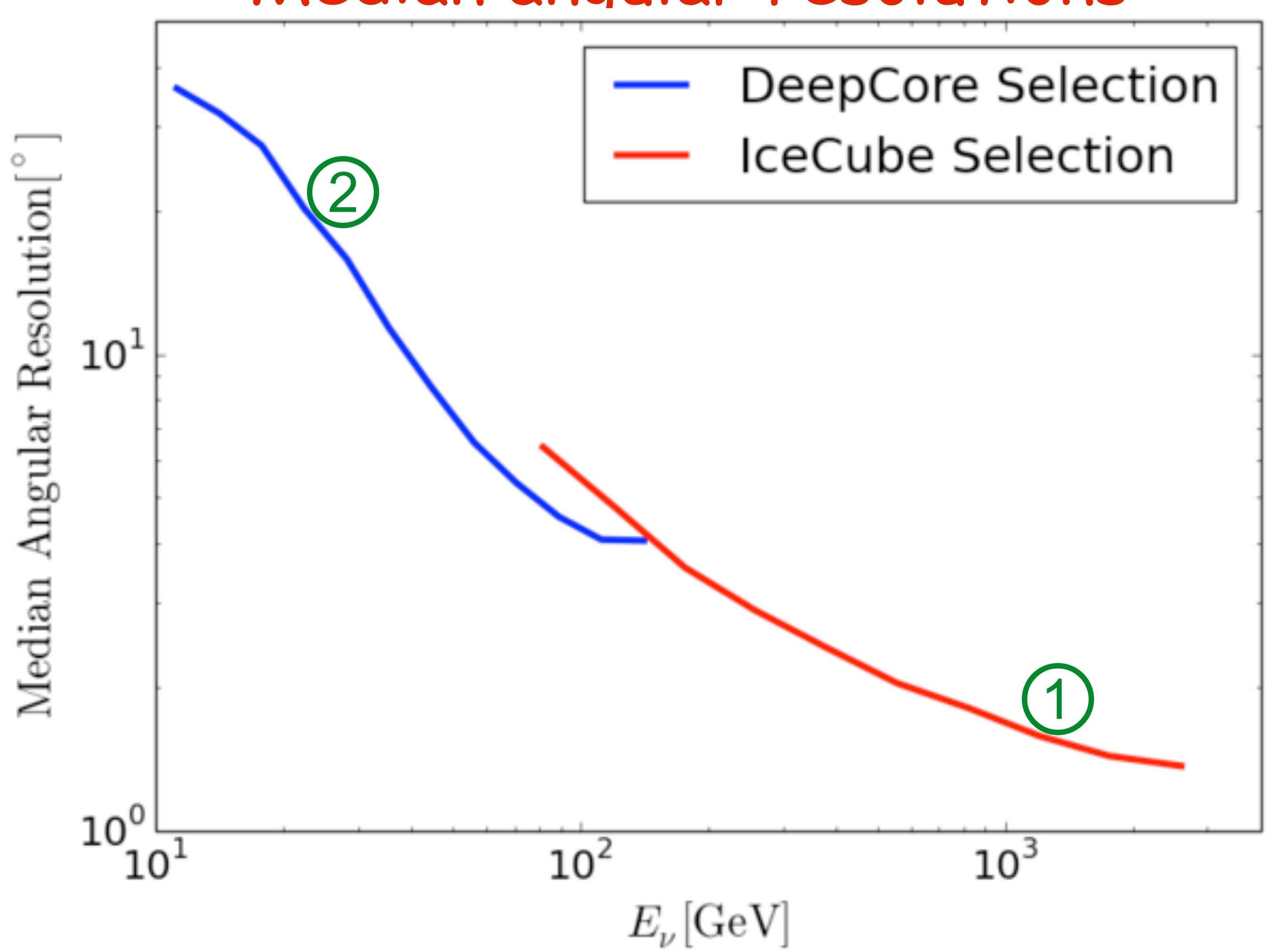


3yrs IceCube Solar WIMP Analysis

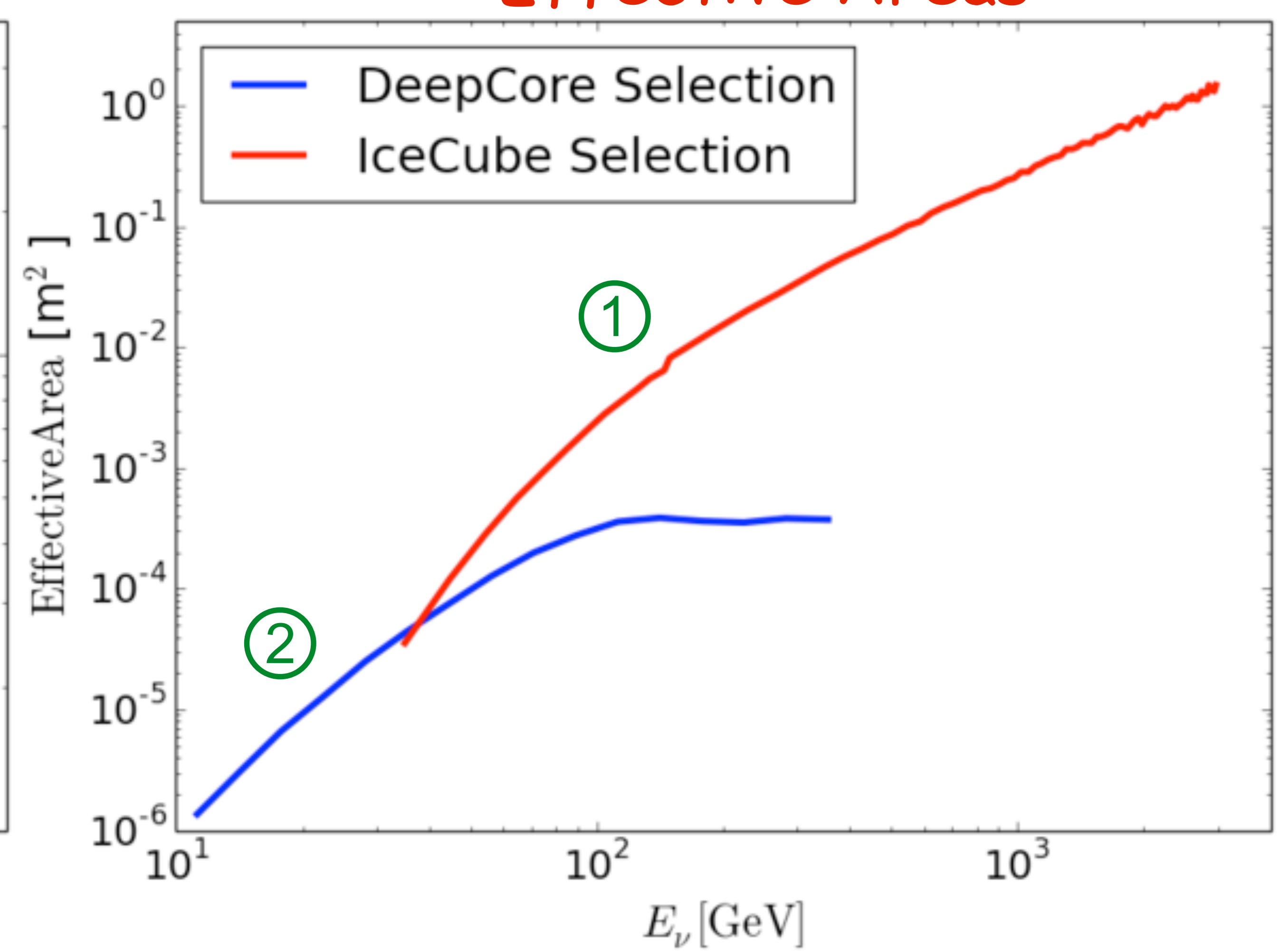
- Three years of data in 86-string configuration used (**May 2011 - May 2014**)
  - Only **up-going** events (Sun below the horizon) results in **532days of livetime**
- Two independent analysis performed
  - ① **IceCube**: Higher energy focus (m_χ > 100GeV)
  - ② **DeepCore**: Low-energy focus (m_χ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



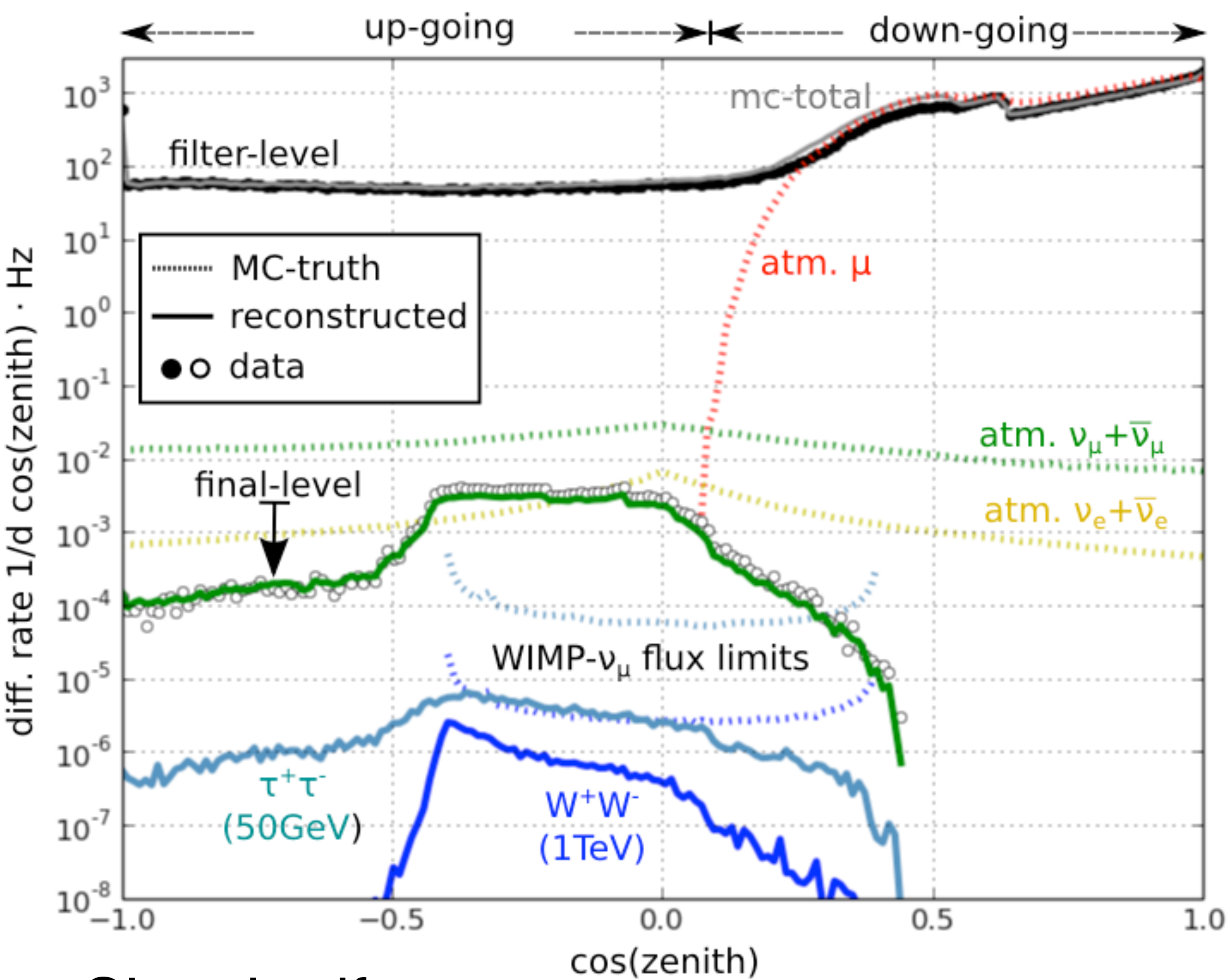
Median angular resolutions



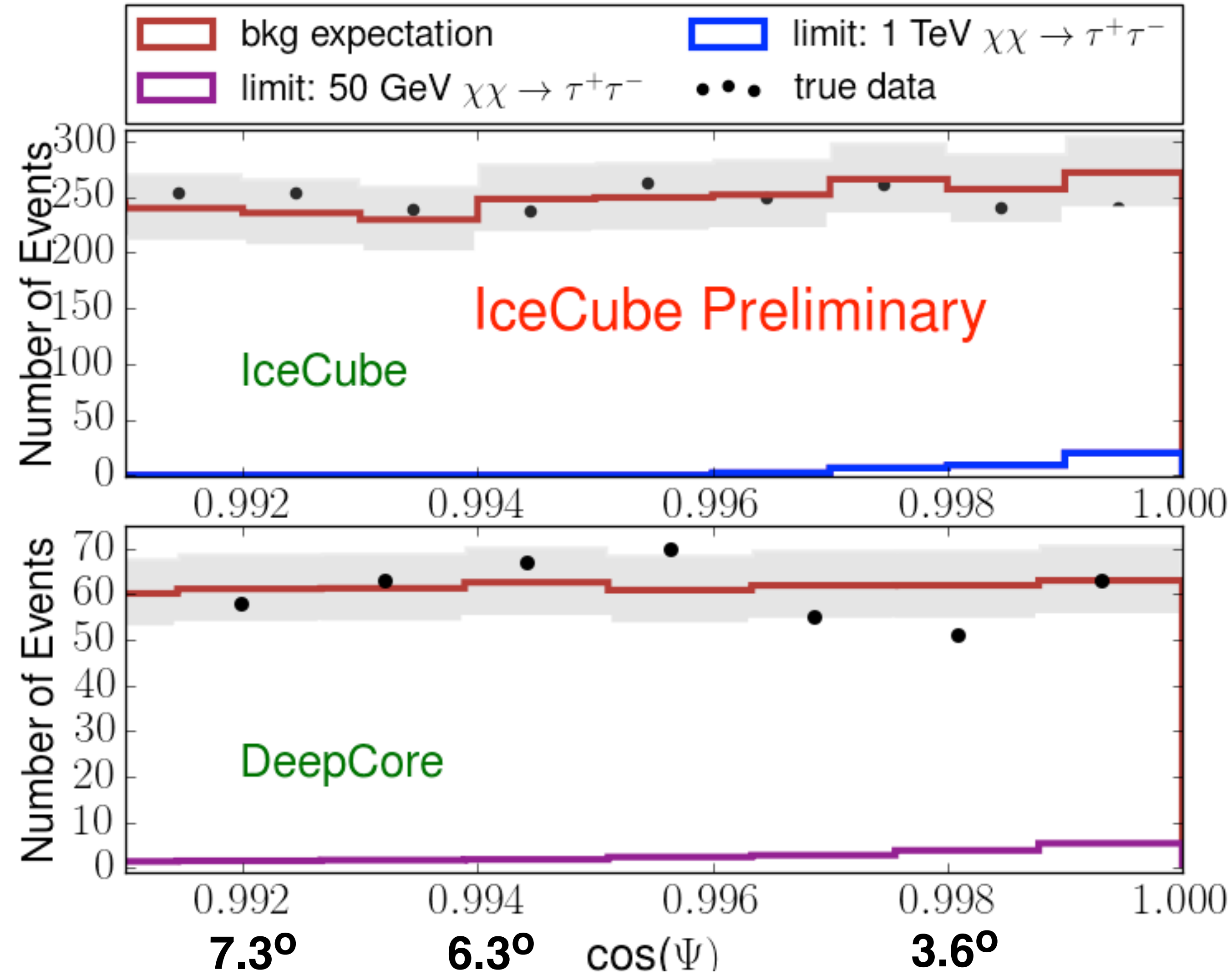
Effective Areas



3yrs IceCube Solar WIMP Analysis



Observed events



Signal pdf:

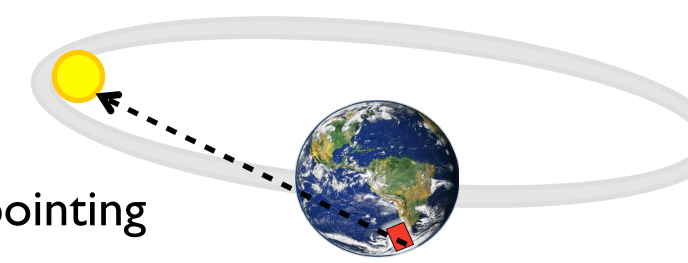
$$S_i(|\vec{x}_i - \vec{x}_{\rm sun}(t_i)|, E_i, m_\chi, c_{\rm ann})$$
$$= \mathscr{K}(|\vec{x}_i - \vec{x}_{\rm sun}(t_i)|, \kappa_i) \times \mathscr{E}_{m_\chi, c_{\rm ann}}(E_i)$$

Spectral part

Monovariate Fisher Bingham distribution from directional statistics

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

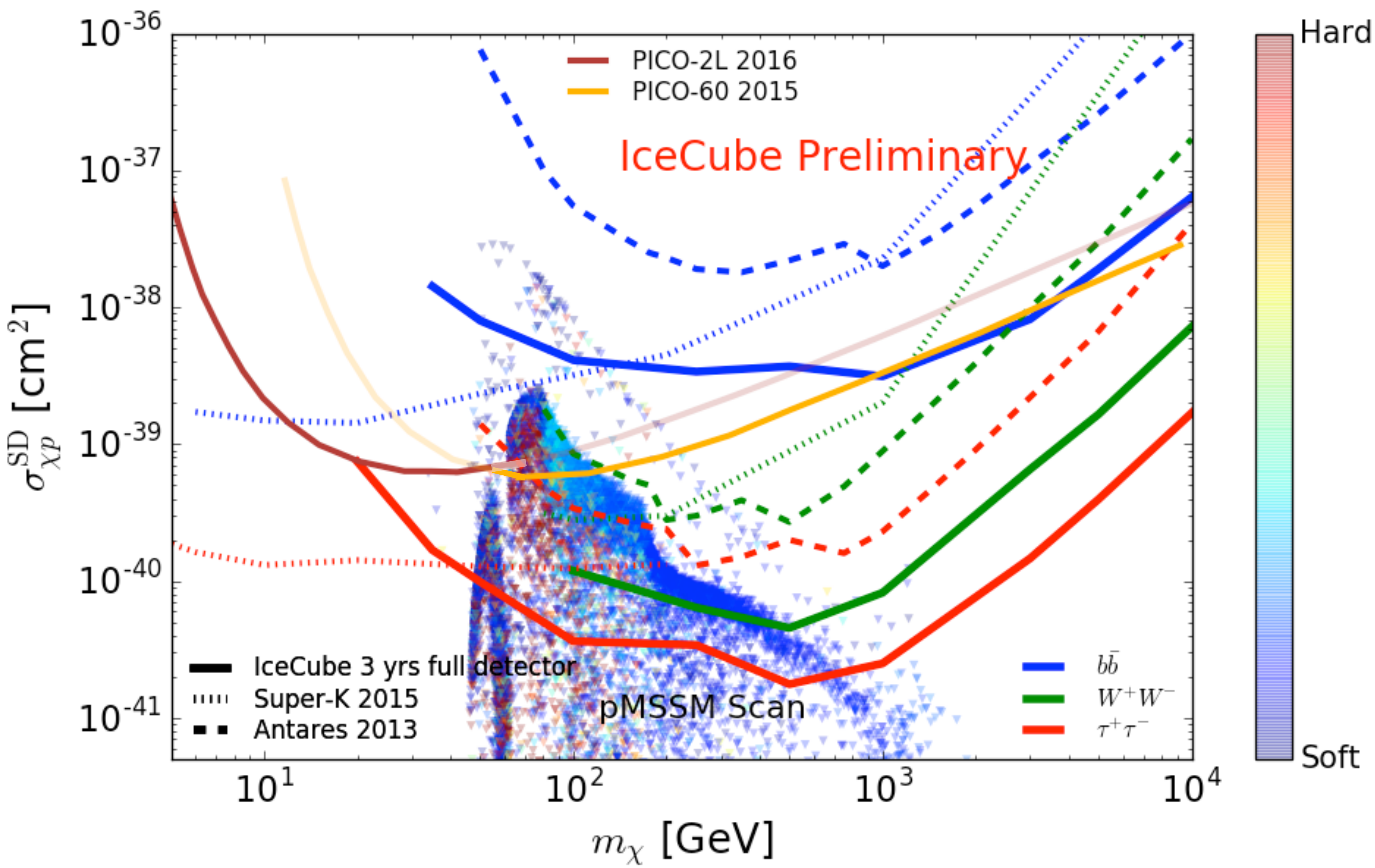
Likelihood: $\mathscr{L}(n_s) = \prod_N \left(\frac{n_s}{N} S_i + (1 - \frac{n_s}{N})\mathscr{B}_i\right)$



- 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

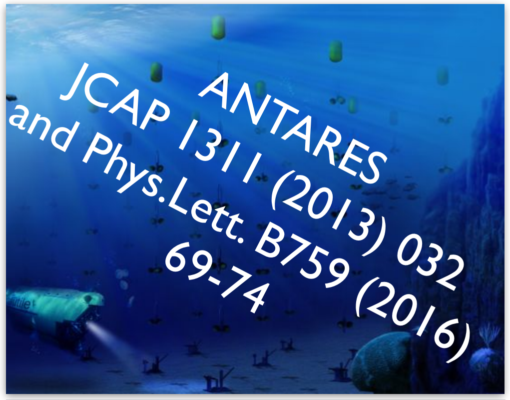


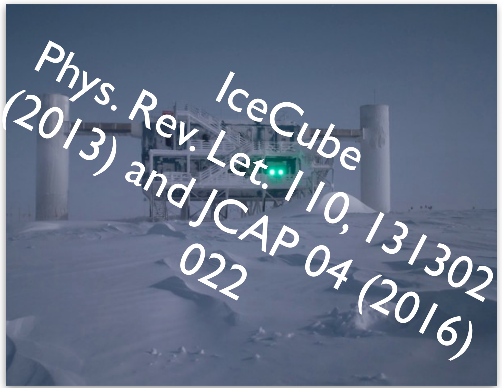
Neutrino bounds extremely competitive with Dark Matter direct detection & Can test models beyond the reach of LHC

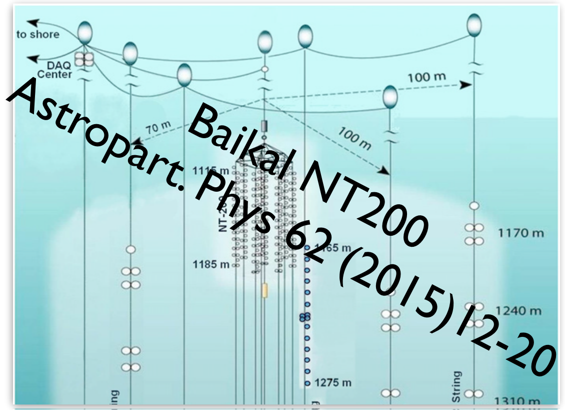
No evidence for dark matter

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

Solar WIMPs Summary

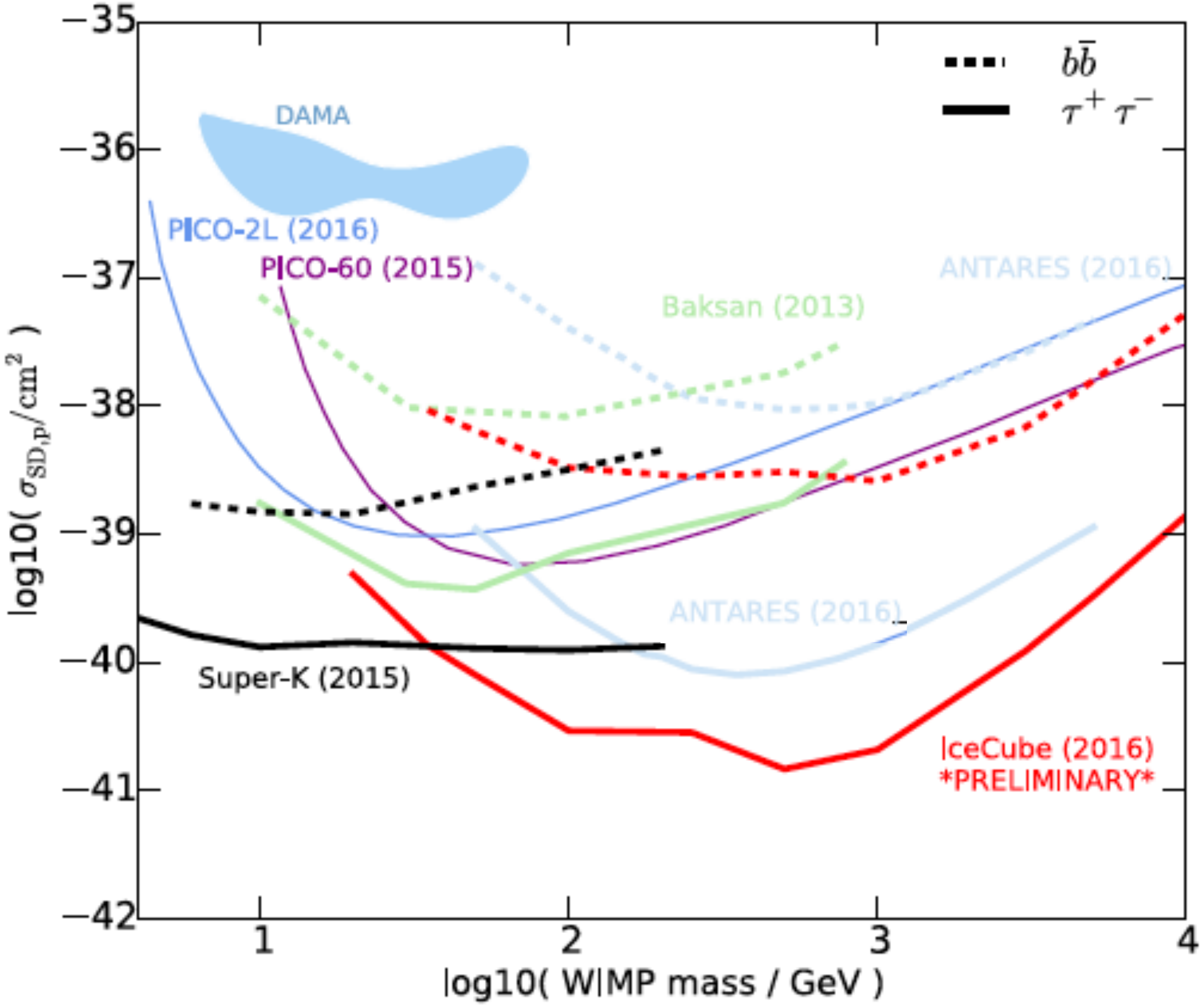




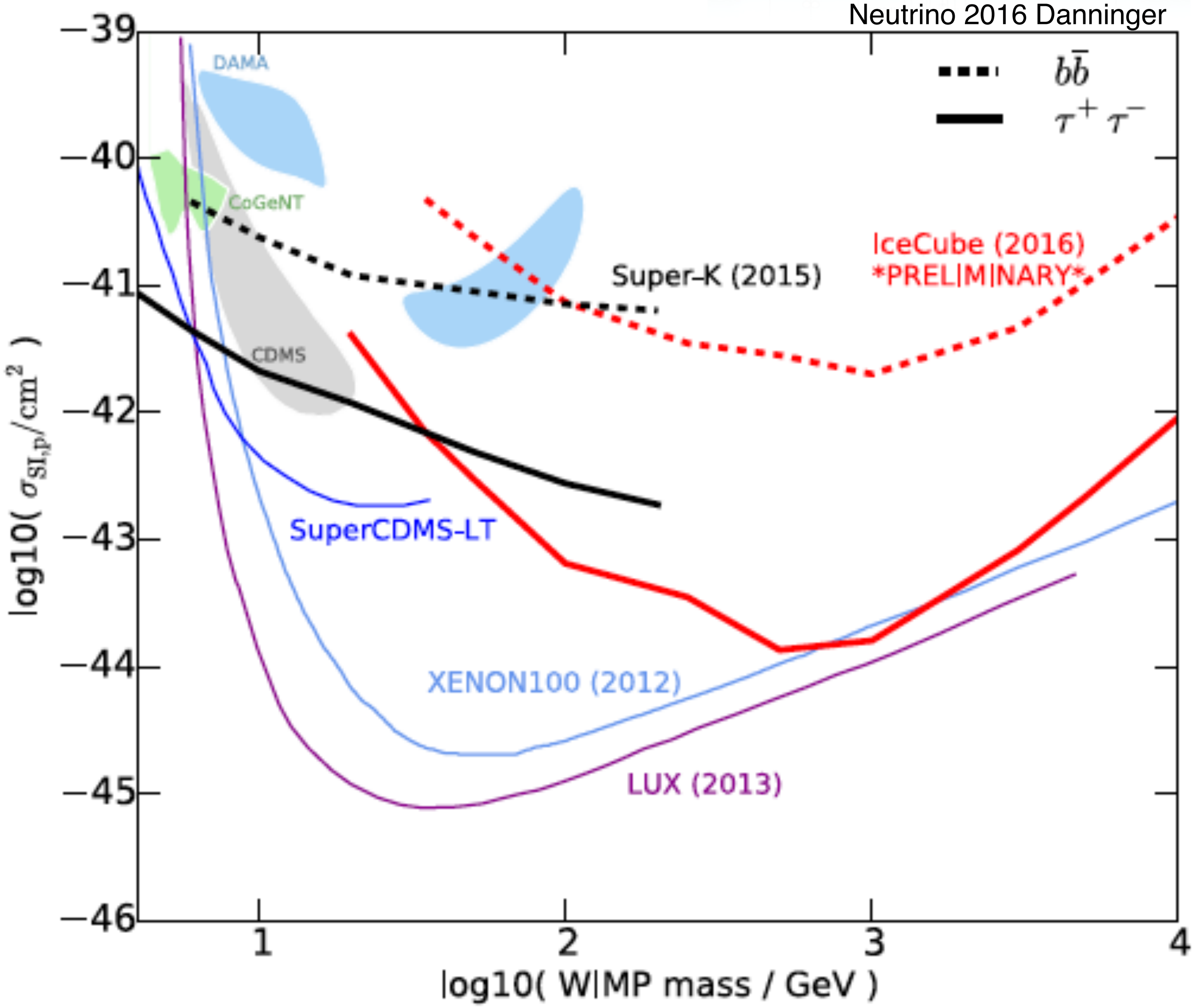


Spin-dependent scattering

Spin-independent scattering



Neutrino 2016 Danninger



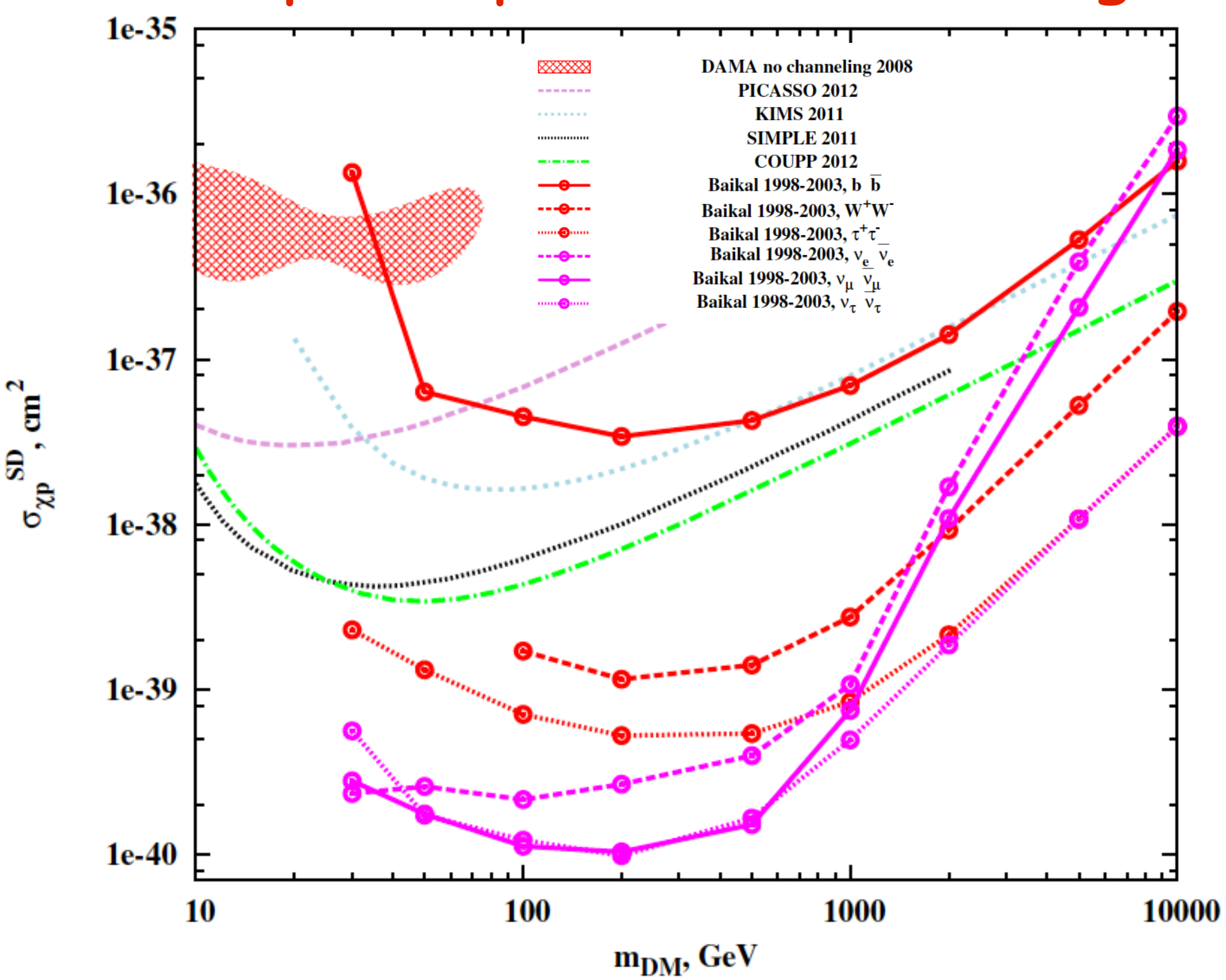
Baikal Neutrino Line Search

Search for neutrino emission from relic dark matter in the Sun with the Baikal NT200 detector

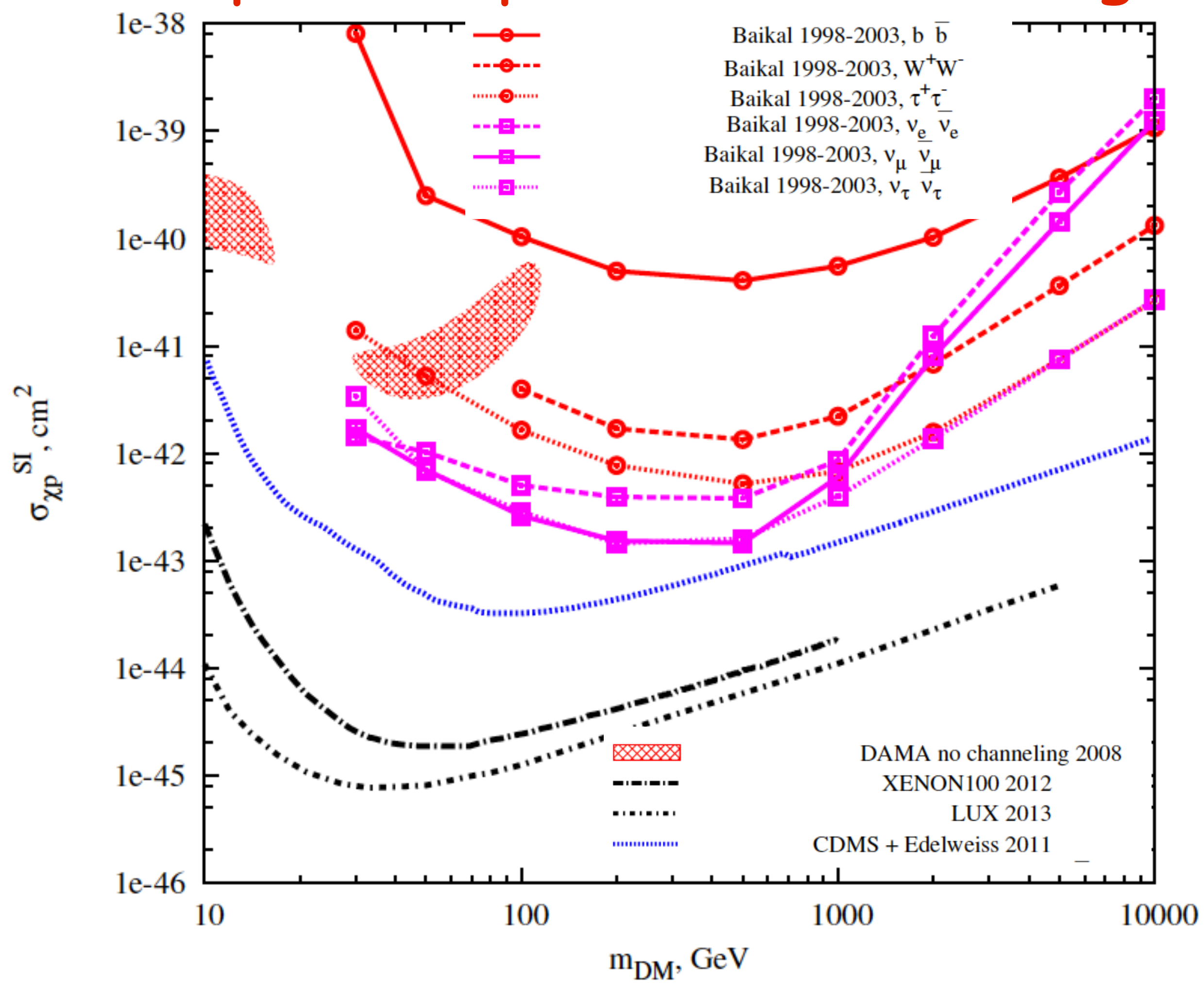
Baikal Collaboration (A.D. Avrorin (Moscow, INR) *et al.*). May 14, 2014. 9 pp.

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

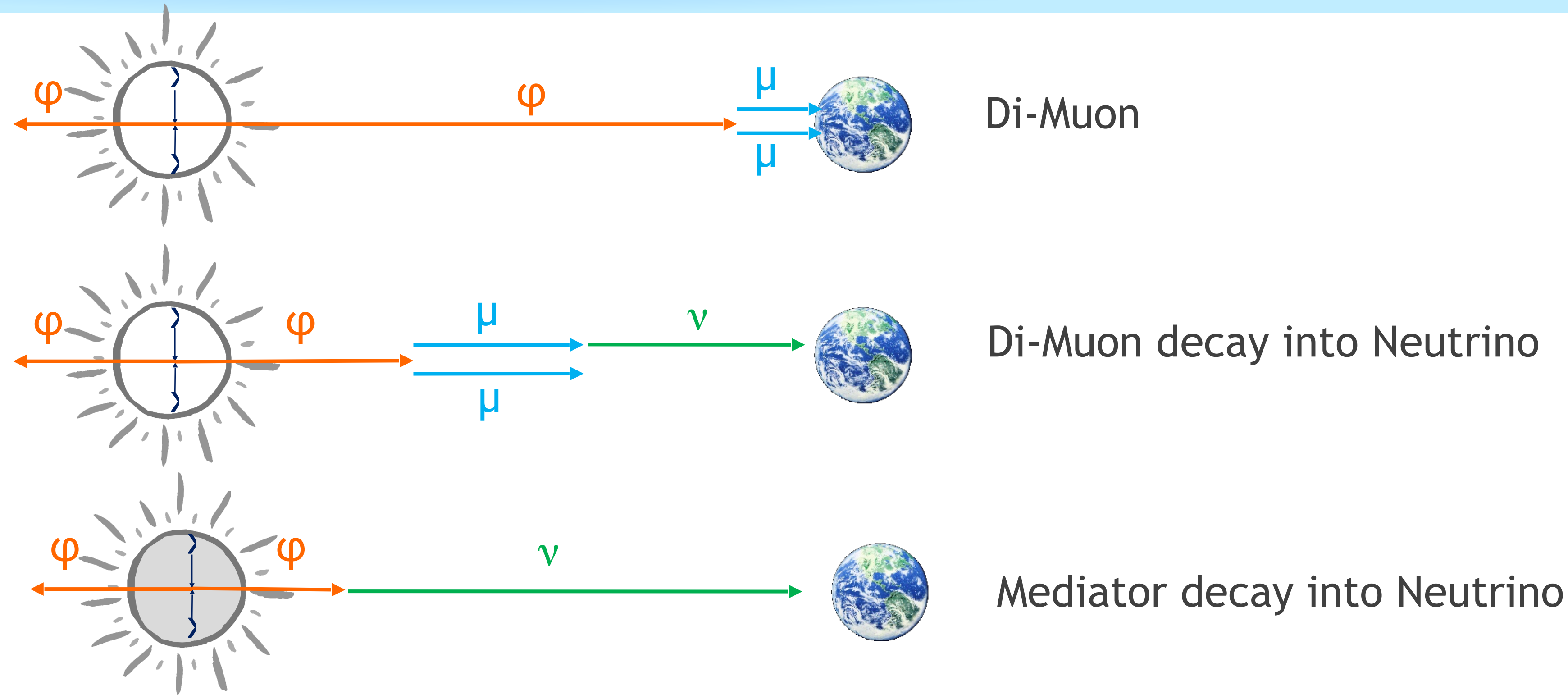


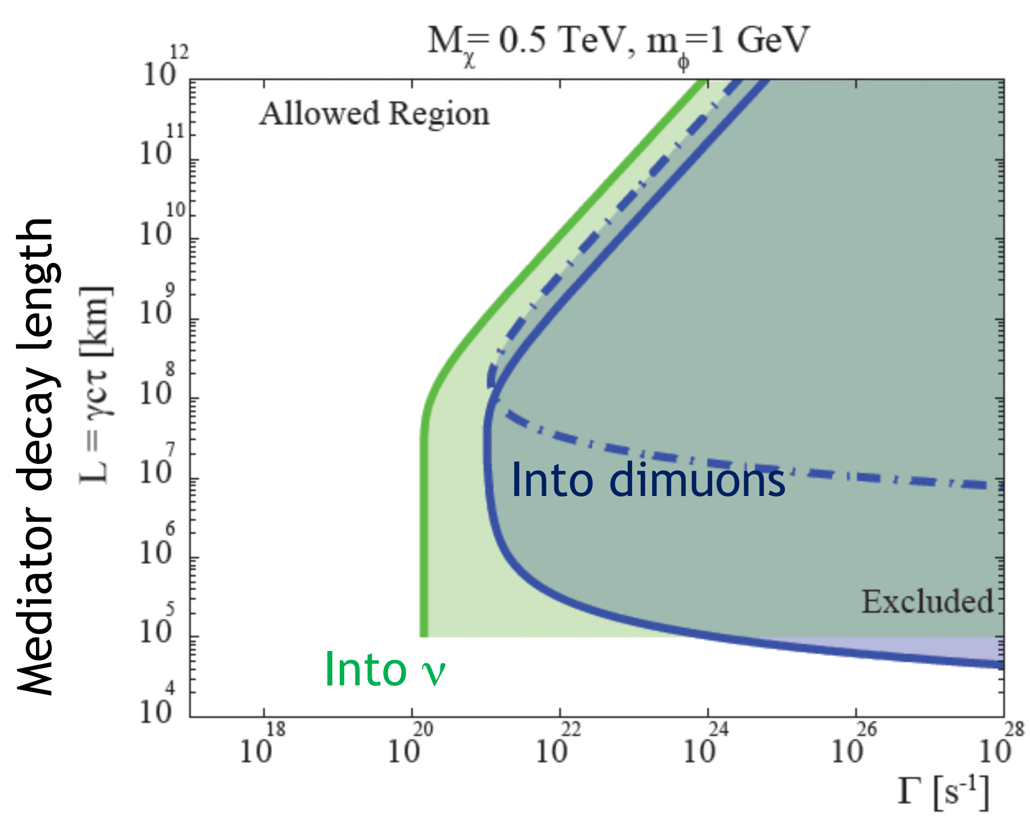
- 2.76 years live time with the Baikal neutrino telescope NT200
  - Including bounds for annihilation directly into neutrinos

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

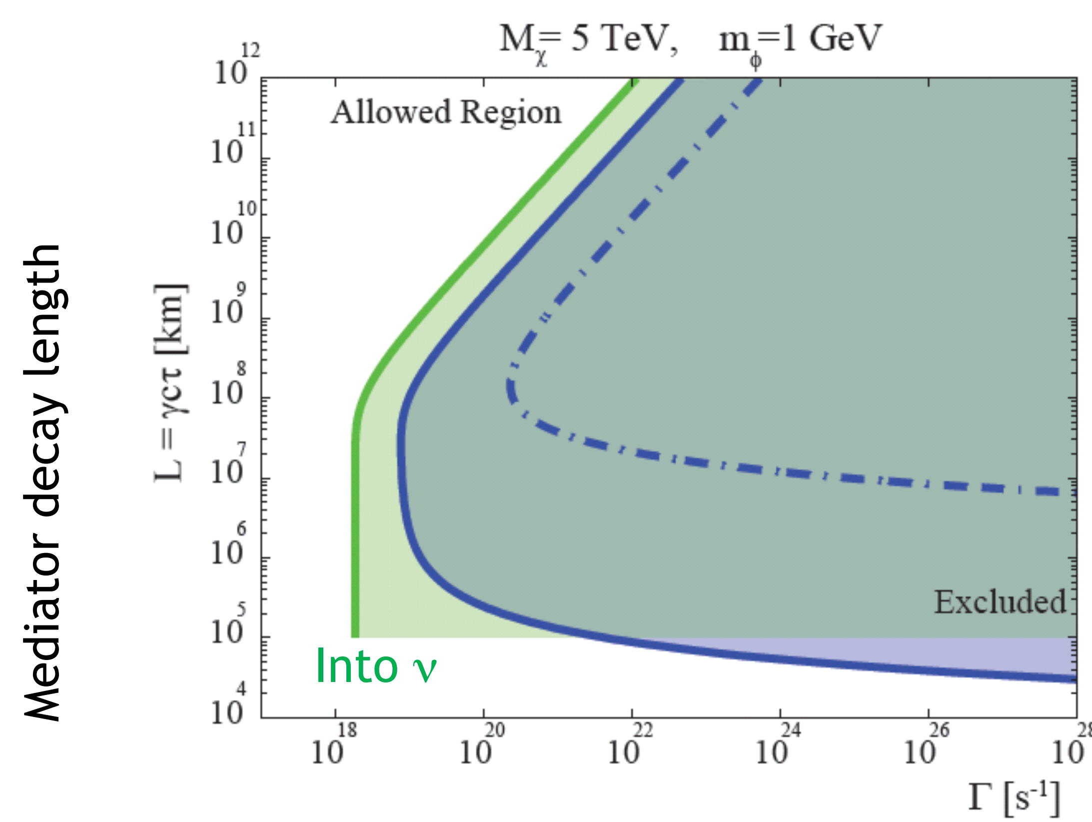
ANTARES Secluded Dark Matter

- Dark matter annihilates into meta-stable particle
  - $\chi\ \chi$ annihilates into mediator ϕ
    - $\phi \rightarrow \nu\ \nu$ 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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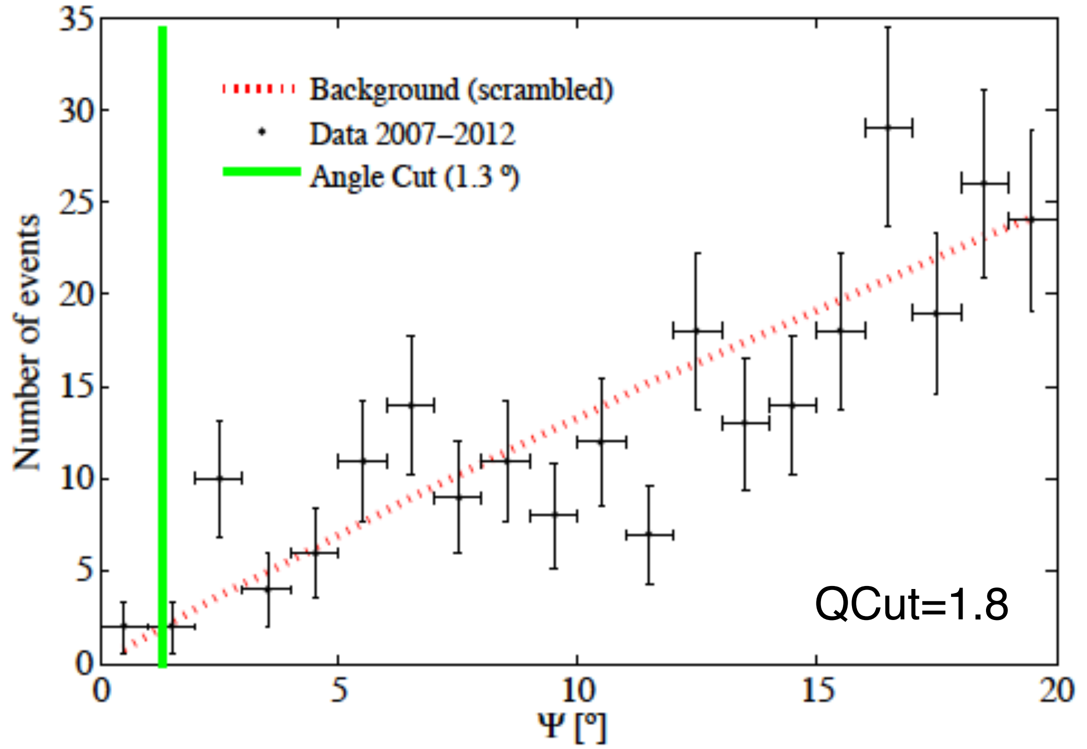
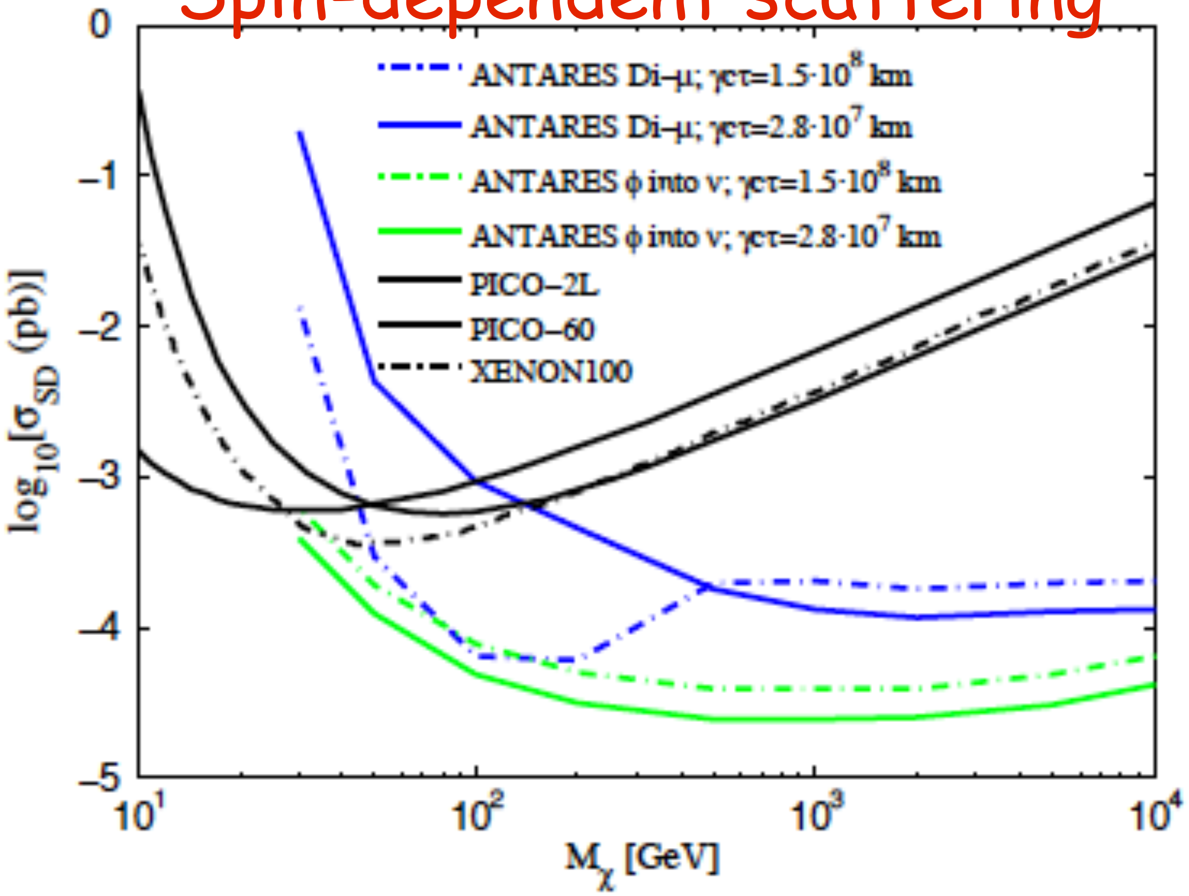
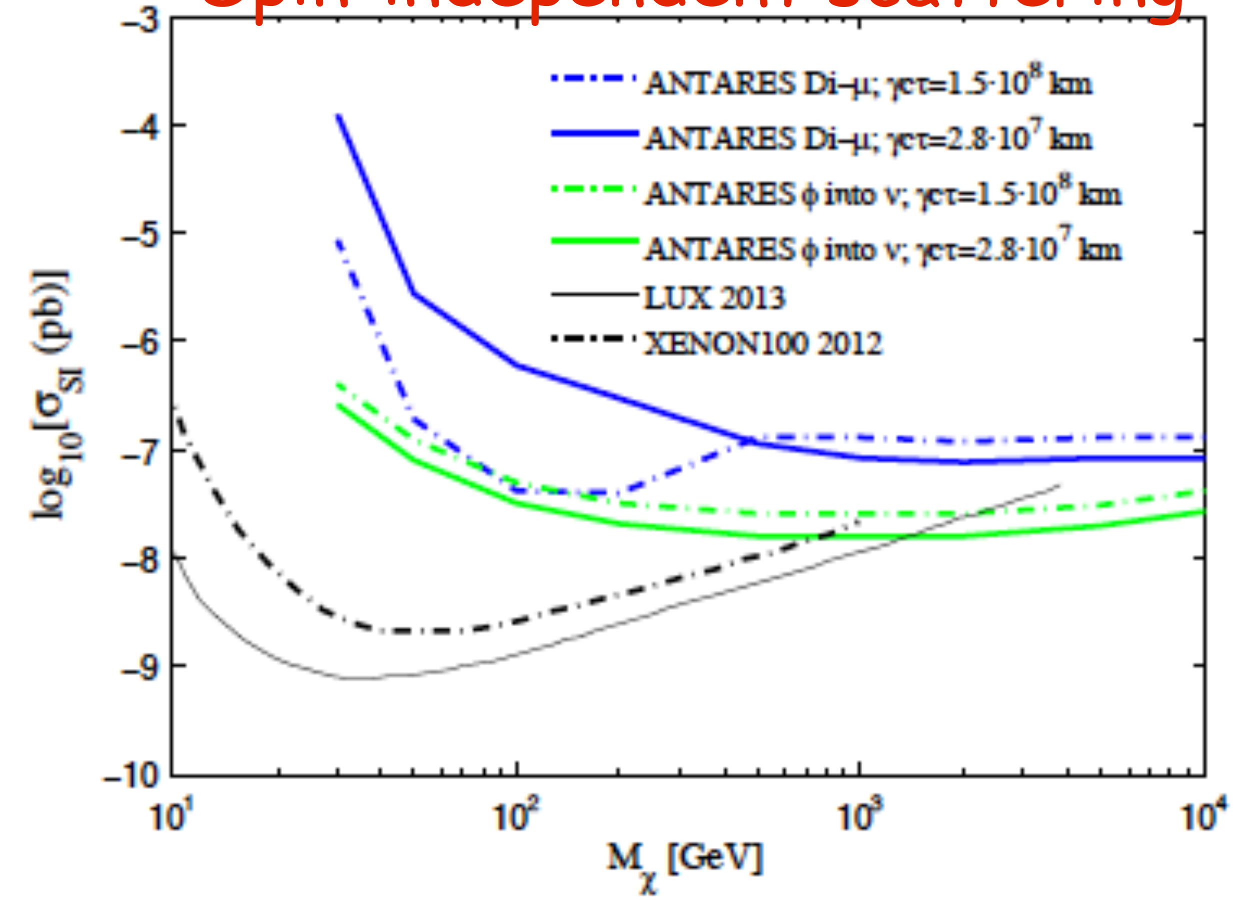


Spin-dependent scattering



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

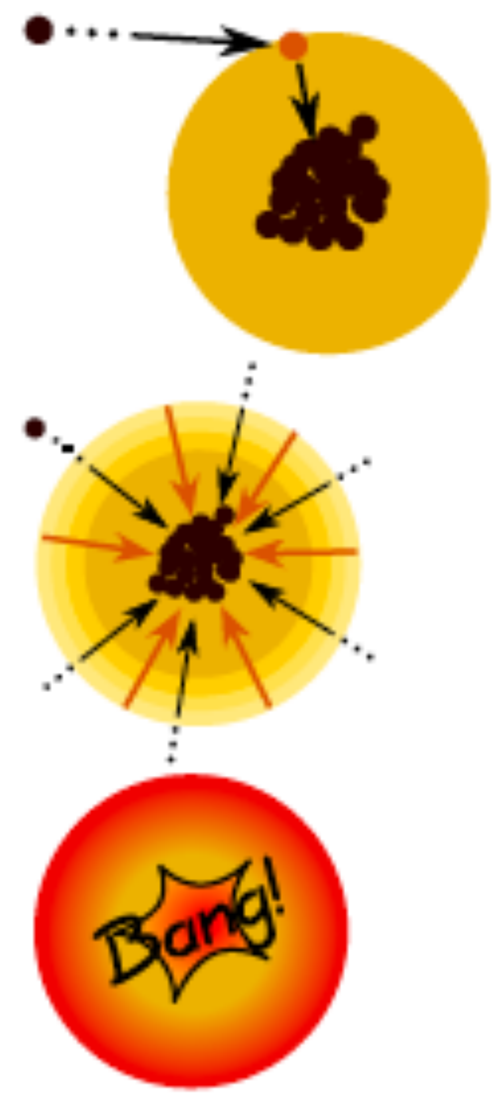
- Indirect limits always presented in terms of hard process final states
- Actual experiments do not measure those final states – they detect one type of SM particle produced later: γs, νs, etc
- Limits as presented cannot be combined and applied to models with mixed final states (= all non-toy models)
- extra complications with neutrinos from capture-annihilation balance
- Proper treatment of indirect detection for BSM searches requires full phenomenological recast abilities
  $\rightarrow$ 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 ν telescope likelihood $\Longrightarrow$ full event-level angular and energy info

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



Strategy: precompute partial likelihoods for each event, then reweight with the ν 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

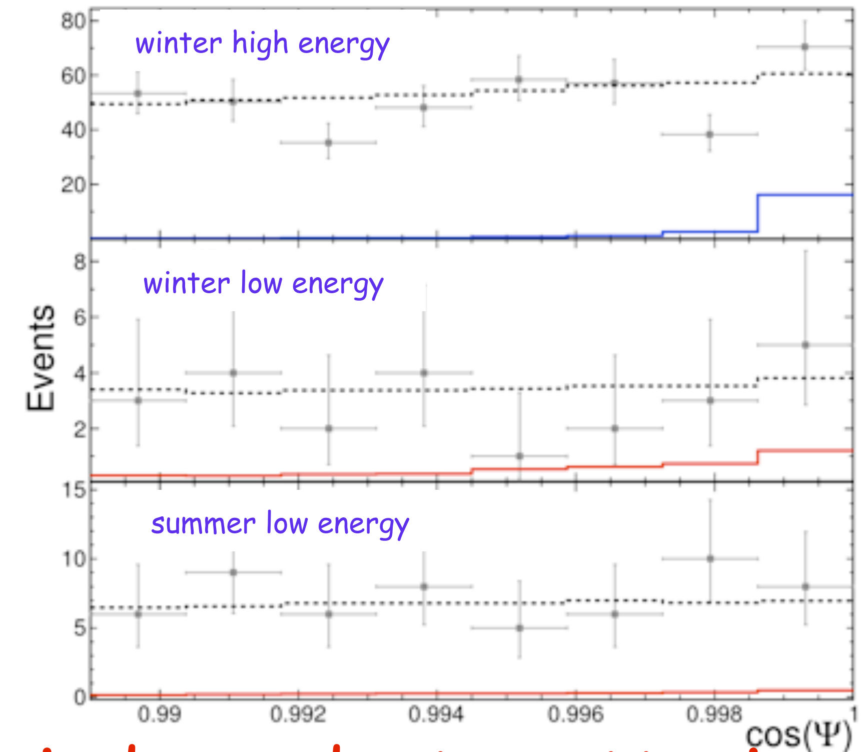
Imperial College London

IceCube IC79 Solar WIMP Analysis

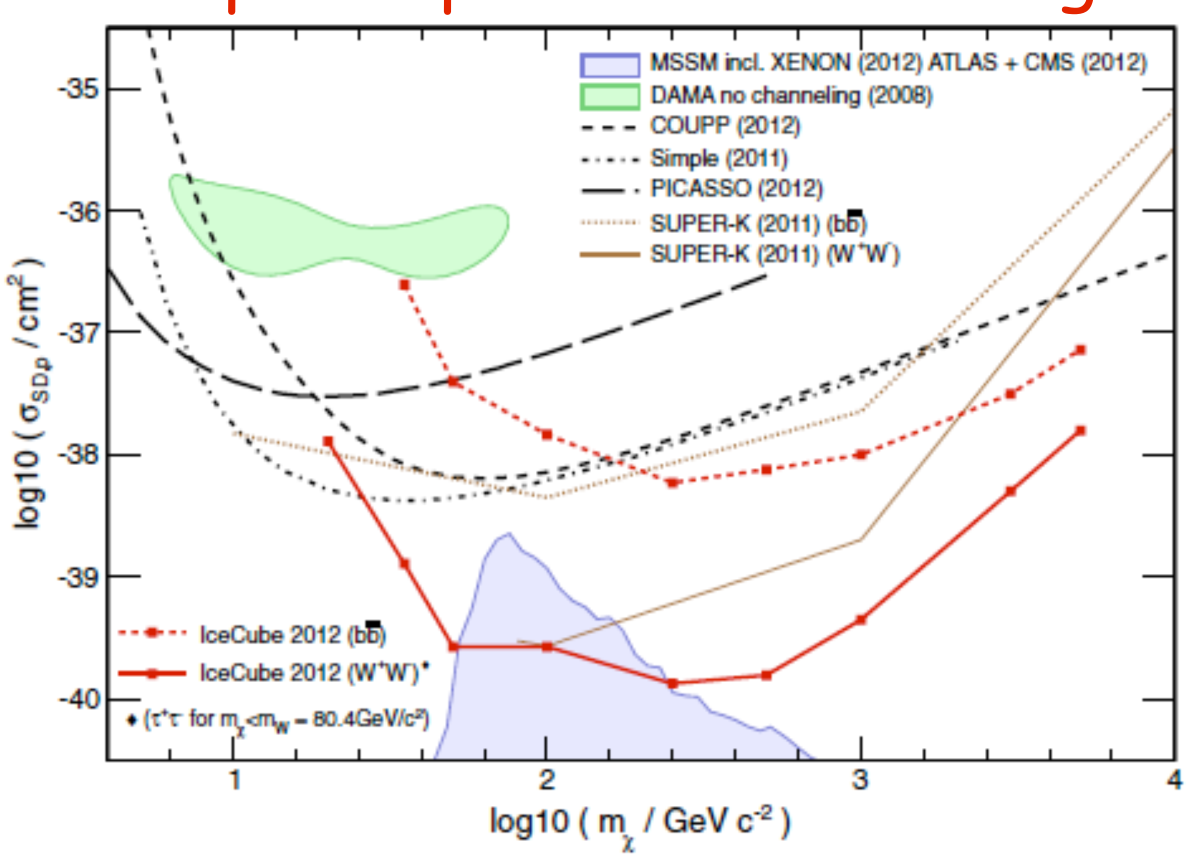
PRL 110, 131302 (2013)

- 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

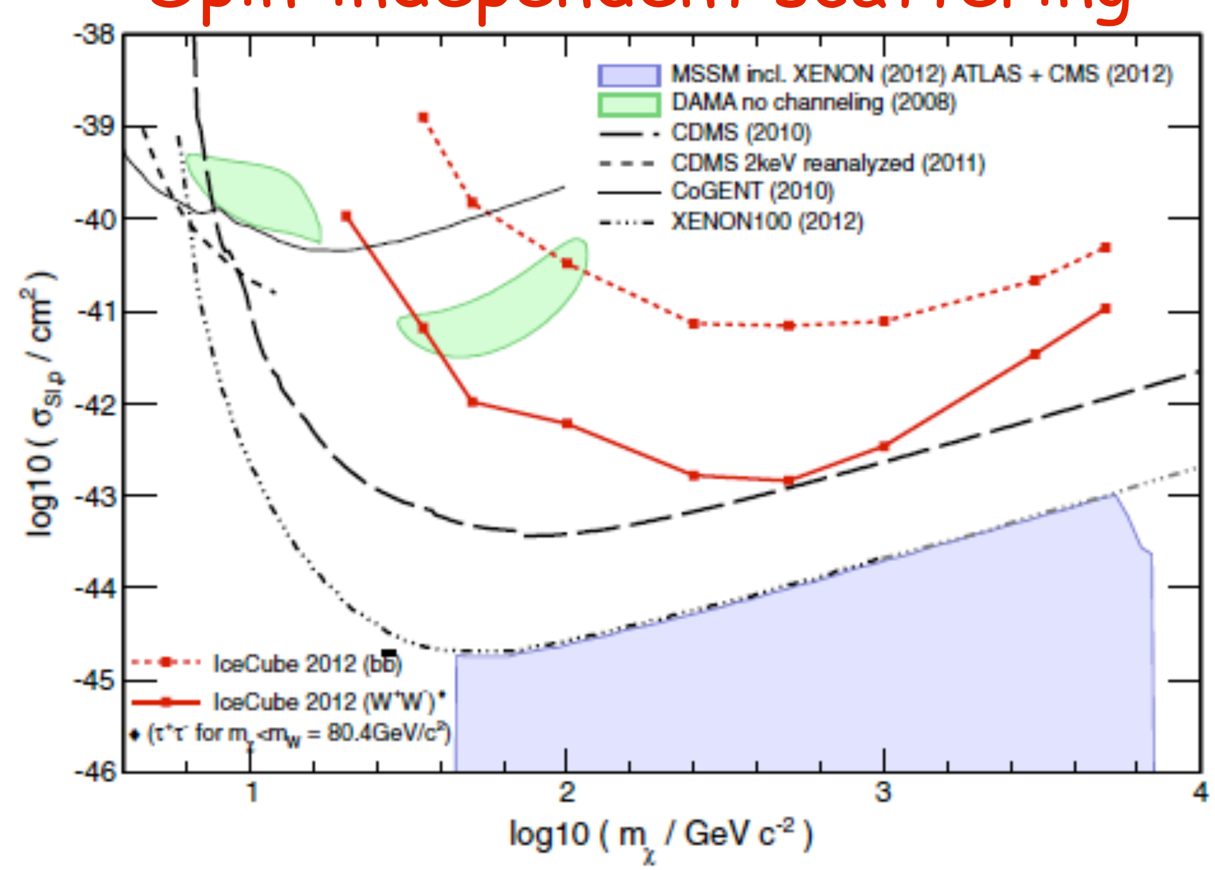
Observed events



Spin-dependent scattering



Spin-independent scattering

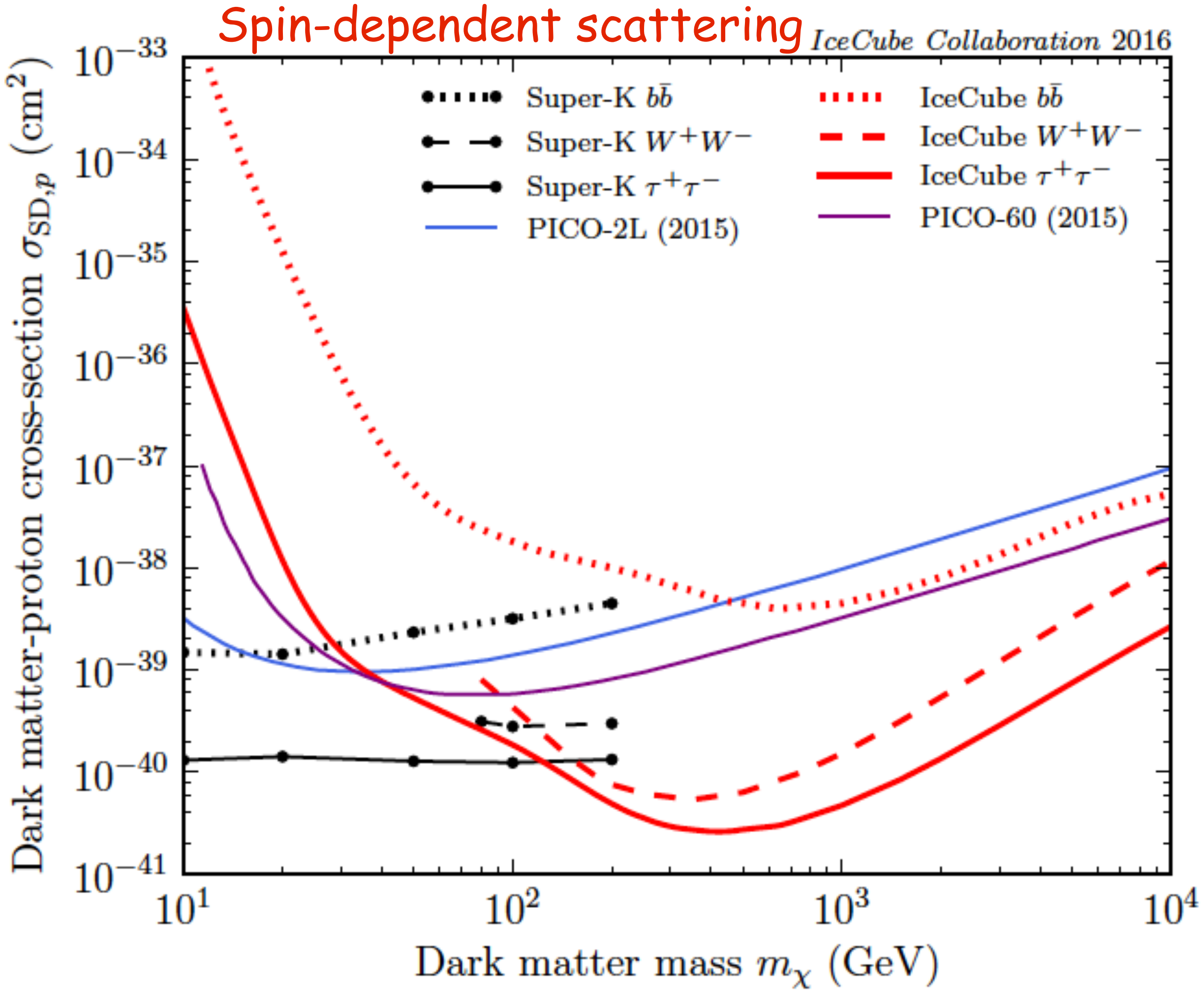


Improved Solar WIMP Bounds

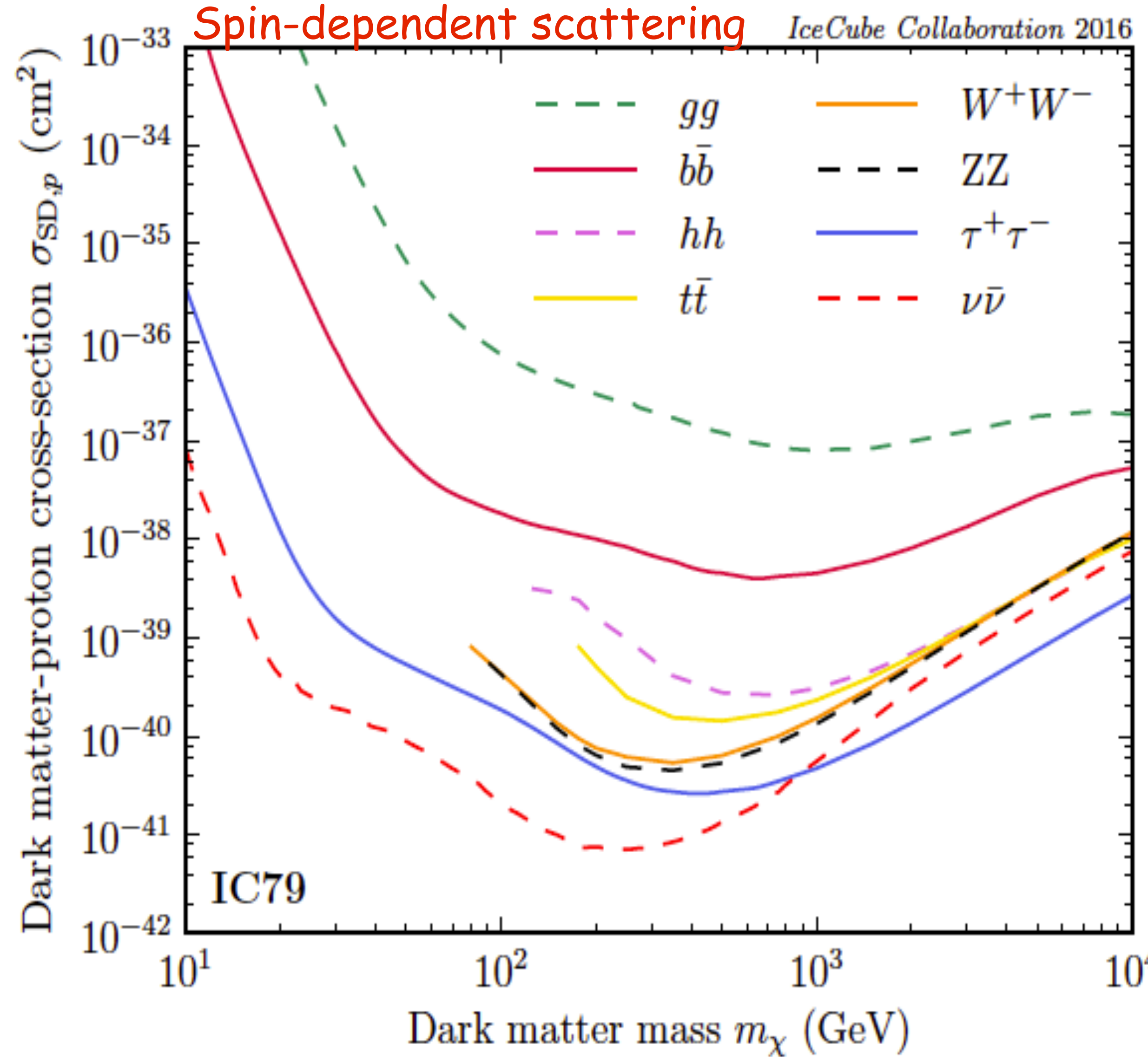
http://nulike.hepforge.org./

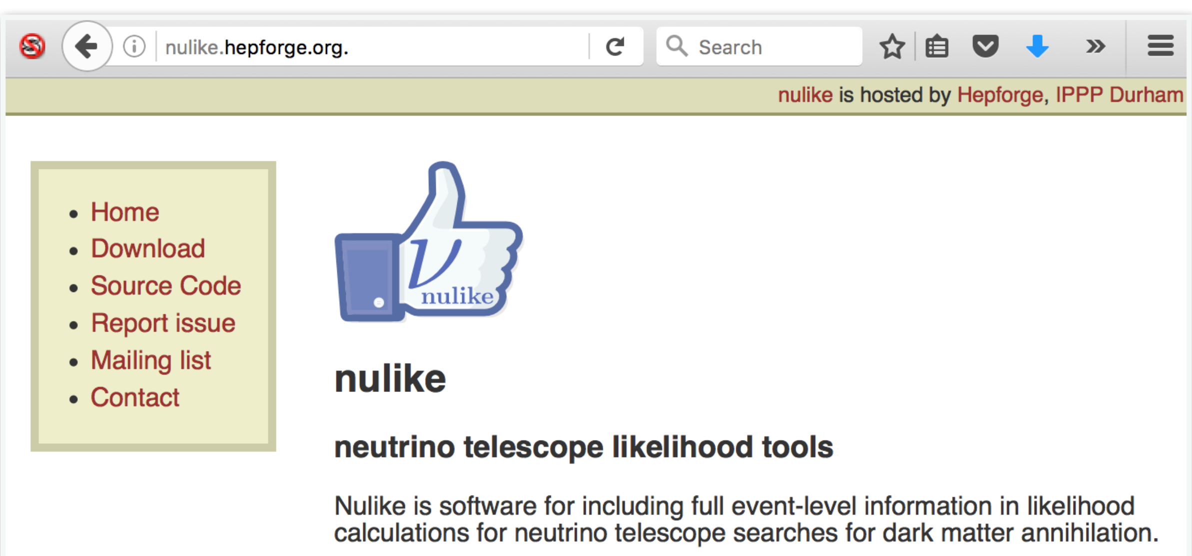
JCAP 04 (2016) 022 / http://arxiv.org/pdf/1601.00653.pdf

Spin-dependent scattering



Spin-dependent scattering

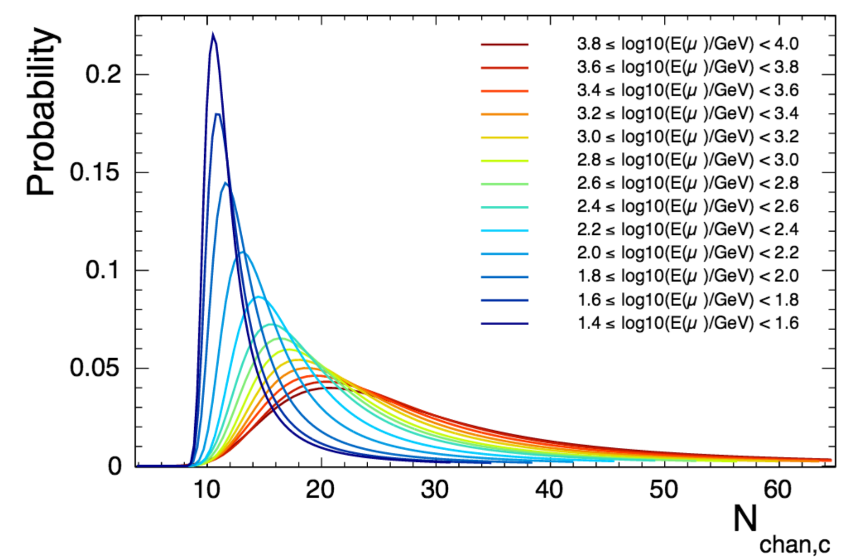




software to test your own model (cross section/ branching ratios)
• IceCube data released

Likelihood includes:

- energy and directional information



The bigger picture

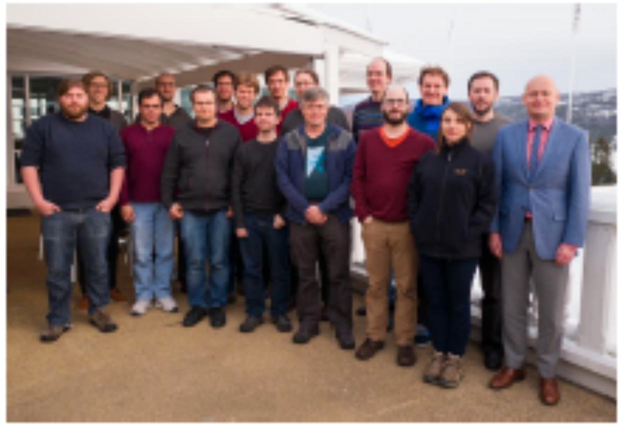
- Data released for nulike can also easily be digested for GAMBIT

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

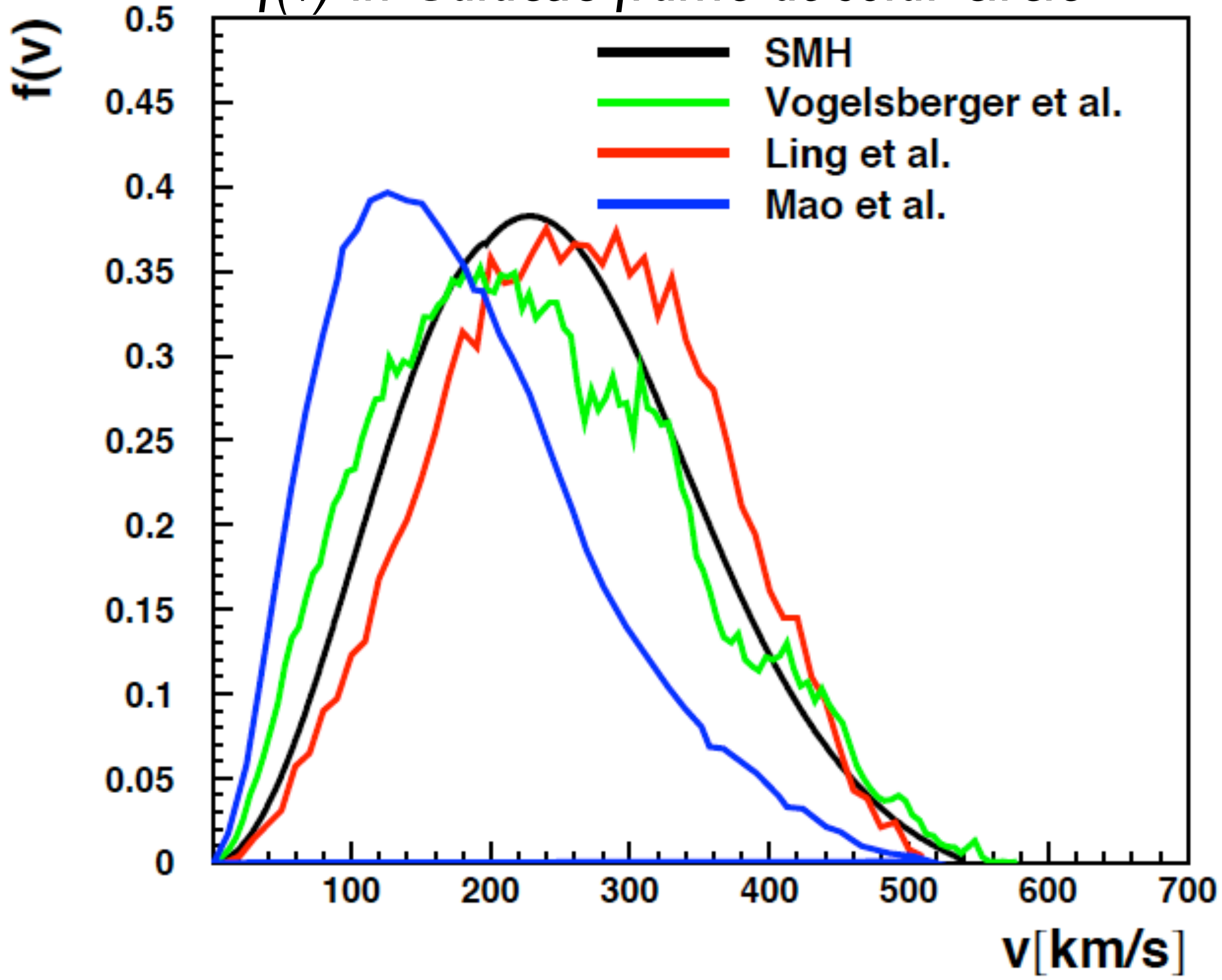
Imperial College London

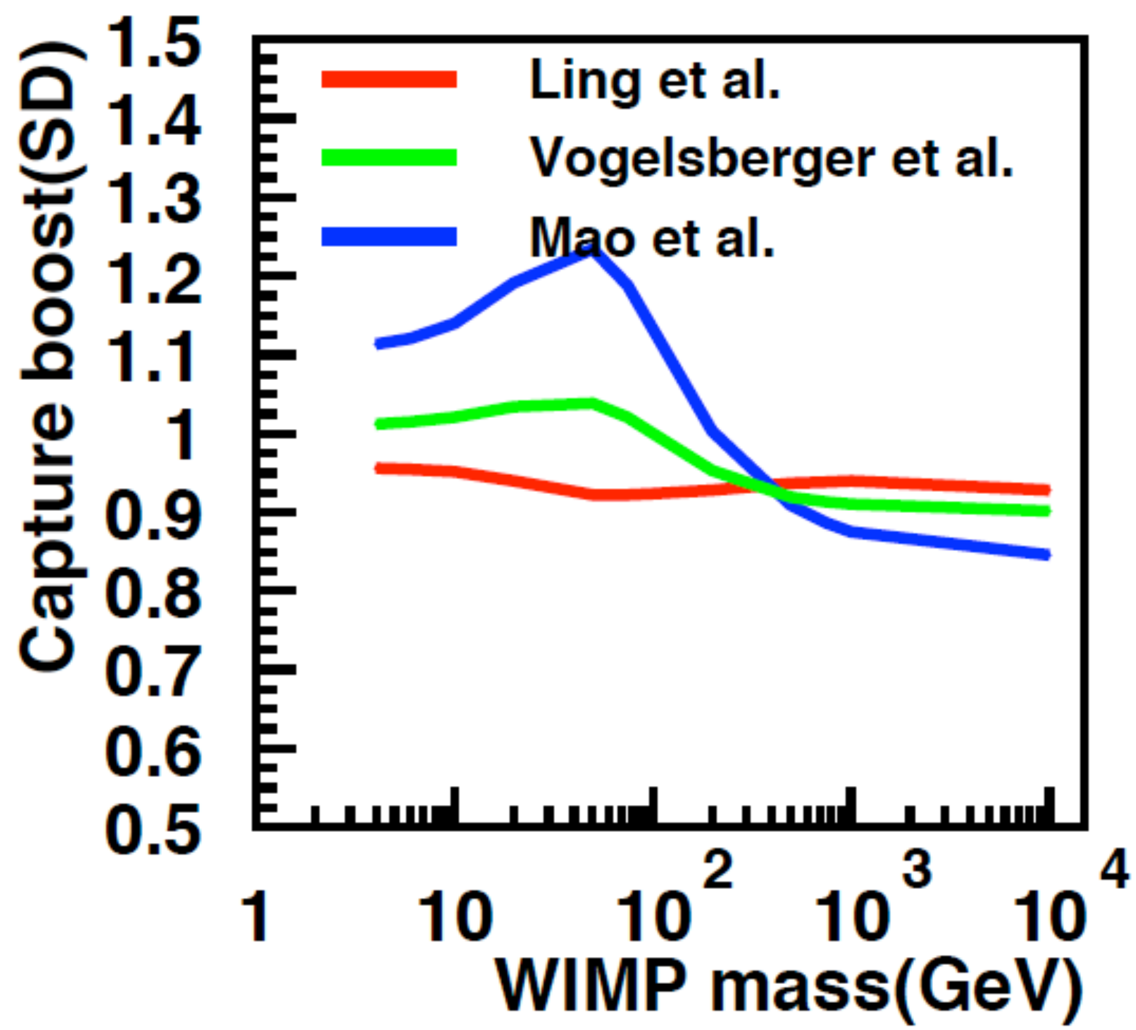
Impact of velocity distribution

- 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



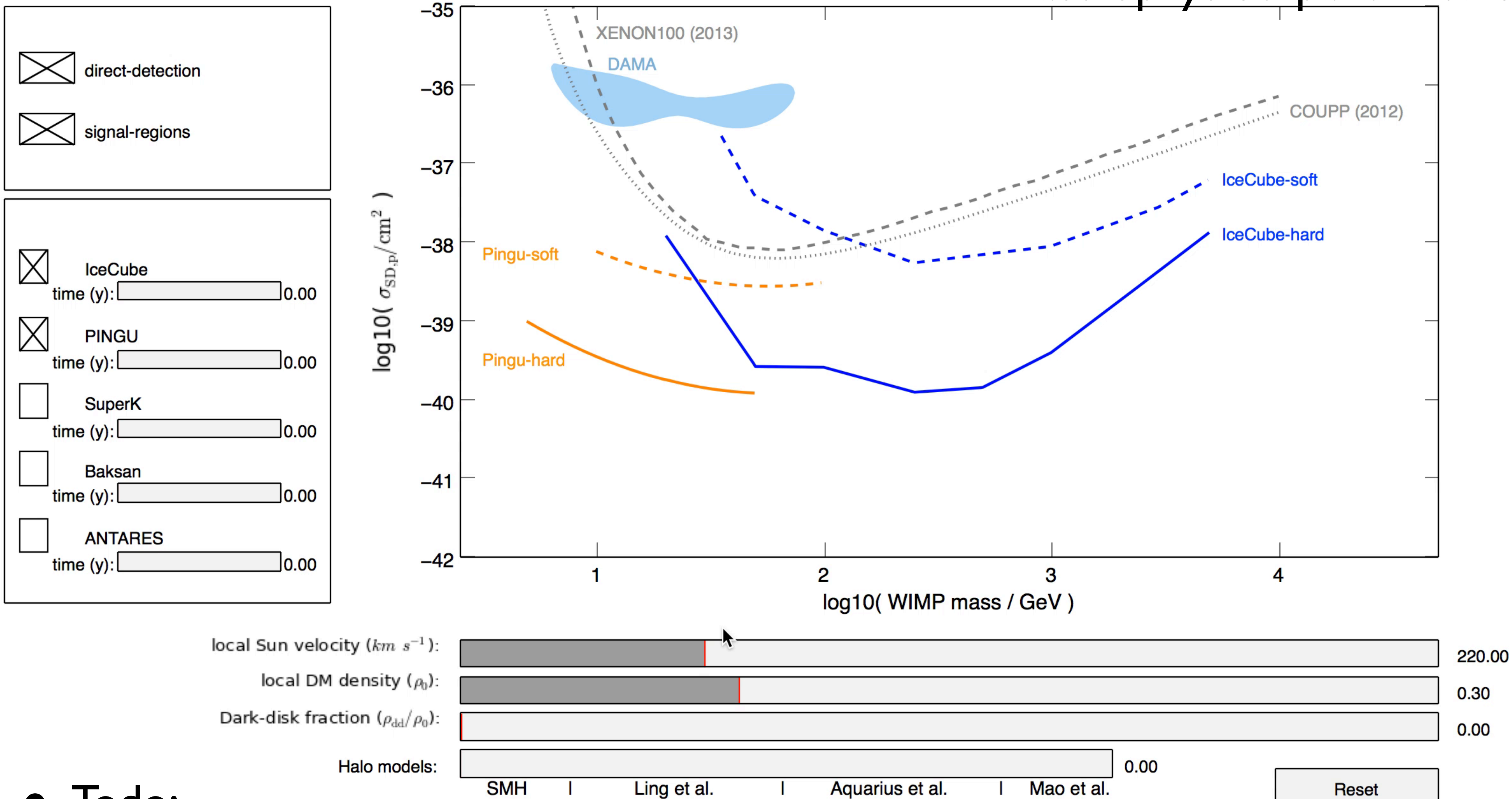


- A comparison of captures rates for different WIMP velocity distributions show that overall changes in the capture rate are smaller than 20%

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

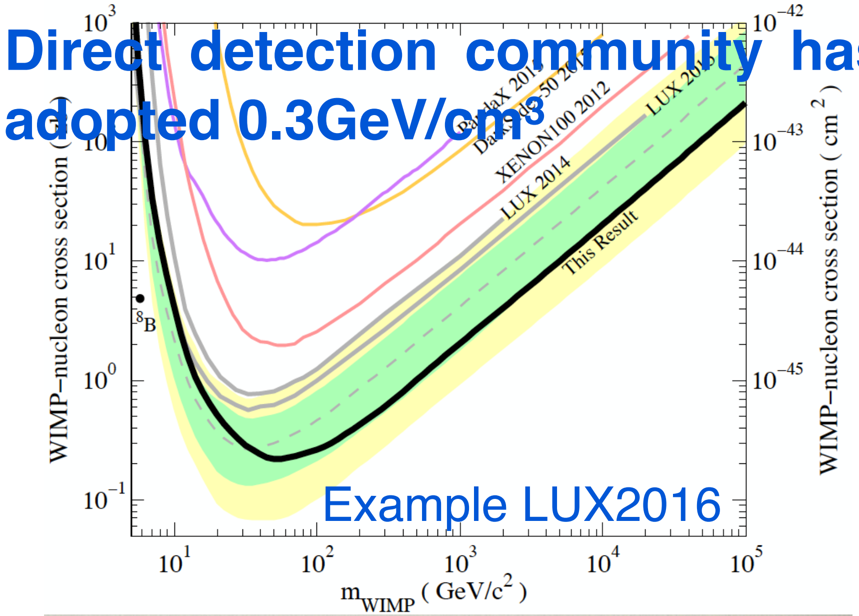
Solar angular velocity around the Galactic center	Θ_0/R_0	30.3 ± 0.9 km s^{-1} kpc^{-1}	[17]
Solar distance from Galactic center	R_0	8.4(6) kpc	[17,18]
circular velocity at R_0	v_0 or Θ_0	254(16) km s^{-1}	[17]
local disk density	ρ_{disk}	$3\text{–}12 \times 10^{-24}$ g cm^{-3} ≈ 2–7 GeV/c^2 cm^{-3}	[19]
local dark matter density	ρ_χ	canonical value 0.3 GeV/c^2 cm^{-3} within factor 2–3	[20]
escape velocity from Galaxy	v_{esc}	498 km/s $< v_{esc} <$ 608 km/s	[21]

Canonical value of 0.3GeV/cm³ 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 $\rho^{local}_{DM} = 0.39 \pm 0.03$ GeV cm^{-3}.

Dark Matter Direct Detection

Direct detection community has adopted 0.3GeV/cm³



Example LUX2016

Theorists response

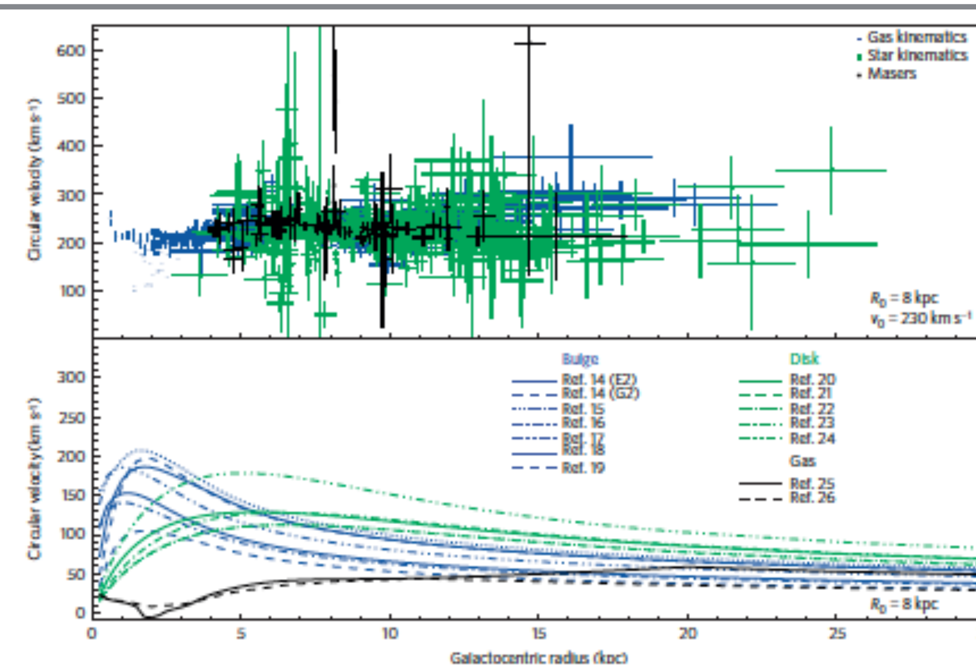
"Everybody is well aware of the uncertainty in the local dark matter density. Limits scale linear with local dark matter density. I believe theorists are capable of simple multiplication if they want to know a limit different from the standard local dark matter density."

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/cm³

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.

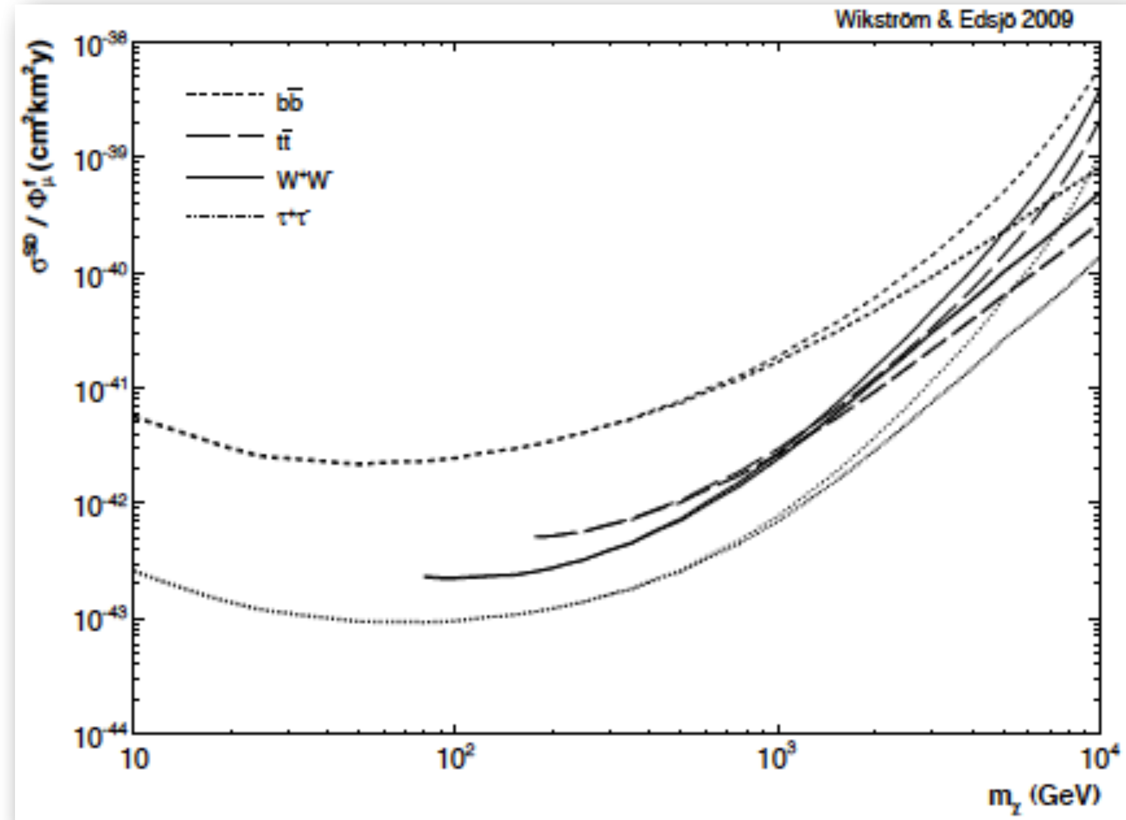


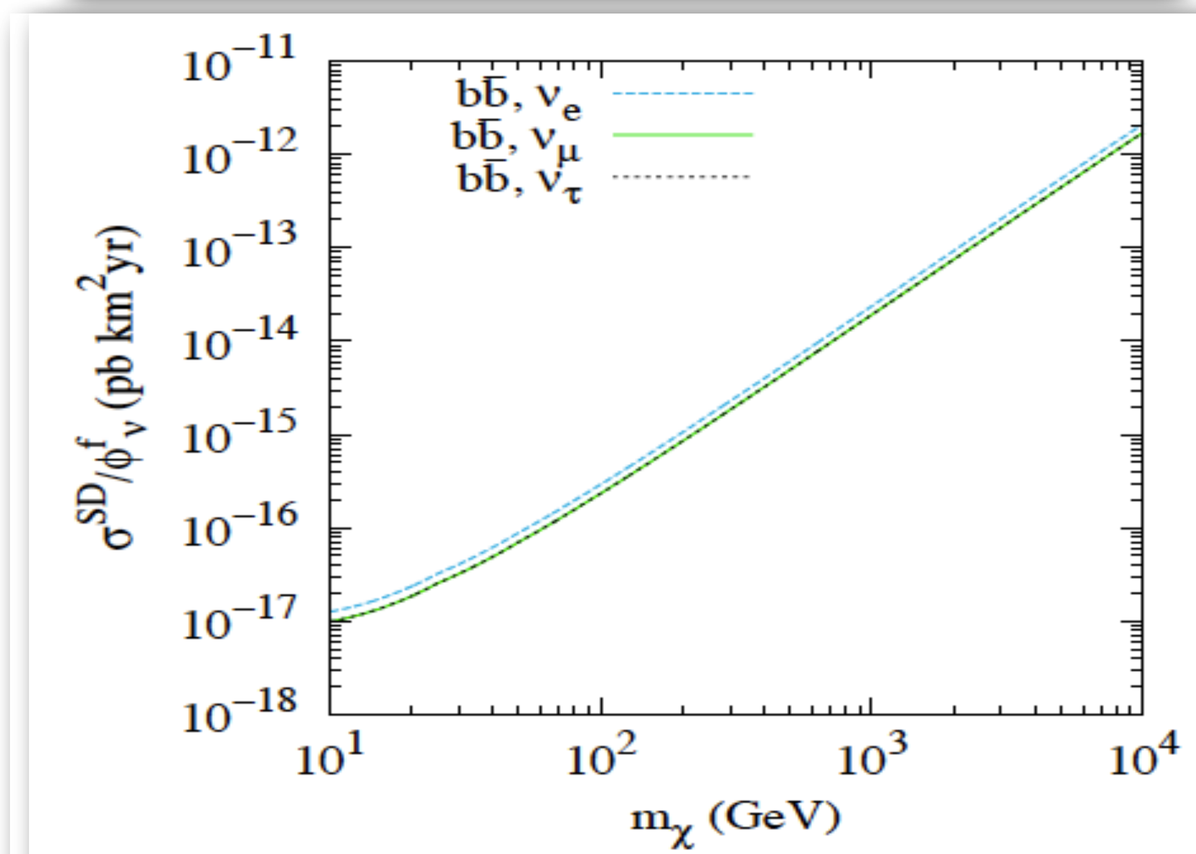
F. Iocco, M. Pato, G. Bertone, Nature Physics, DOI 10.1038

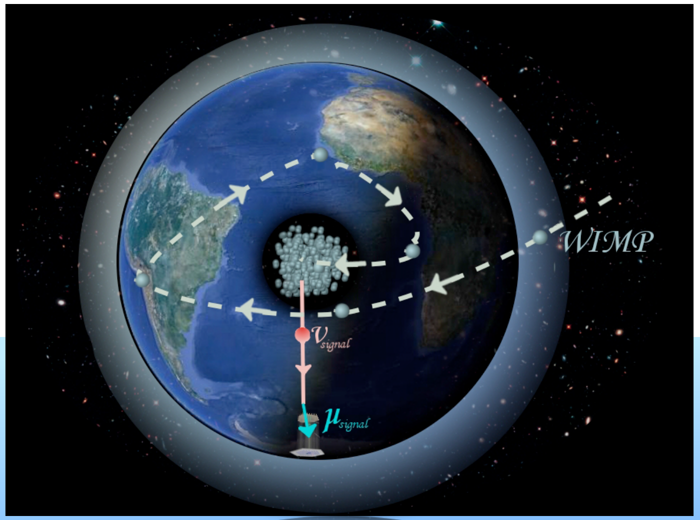
Flux Conversion

- 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)

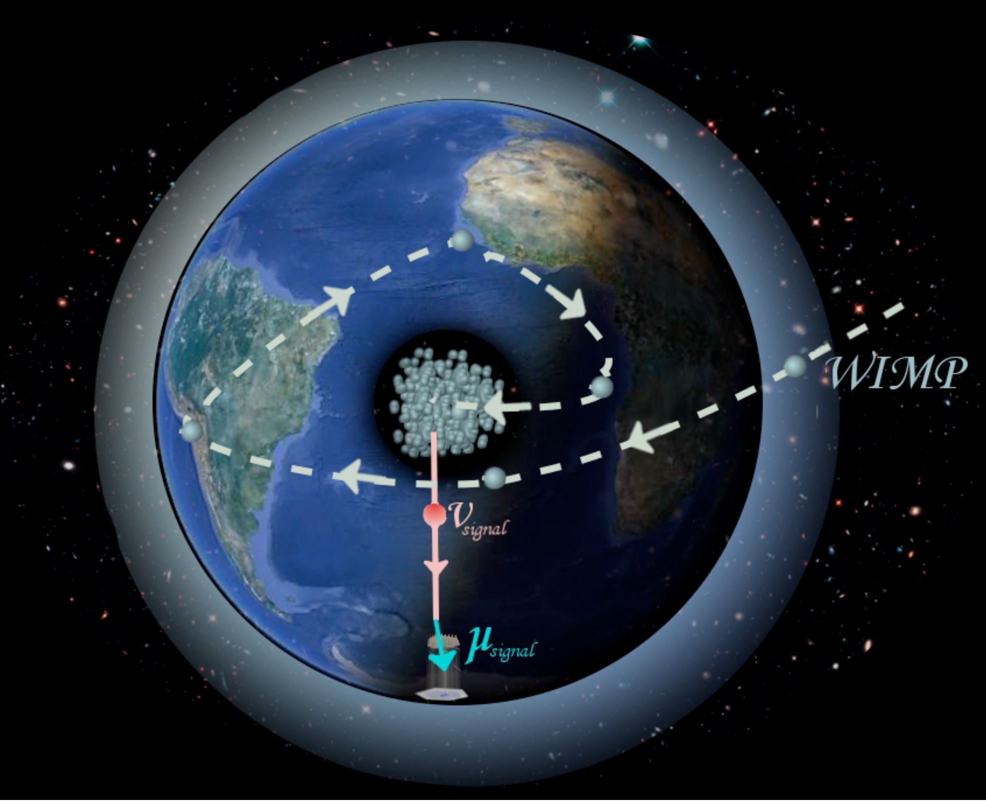




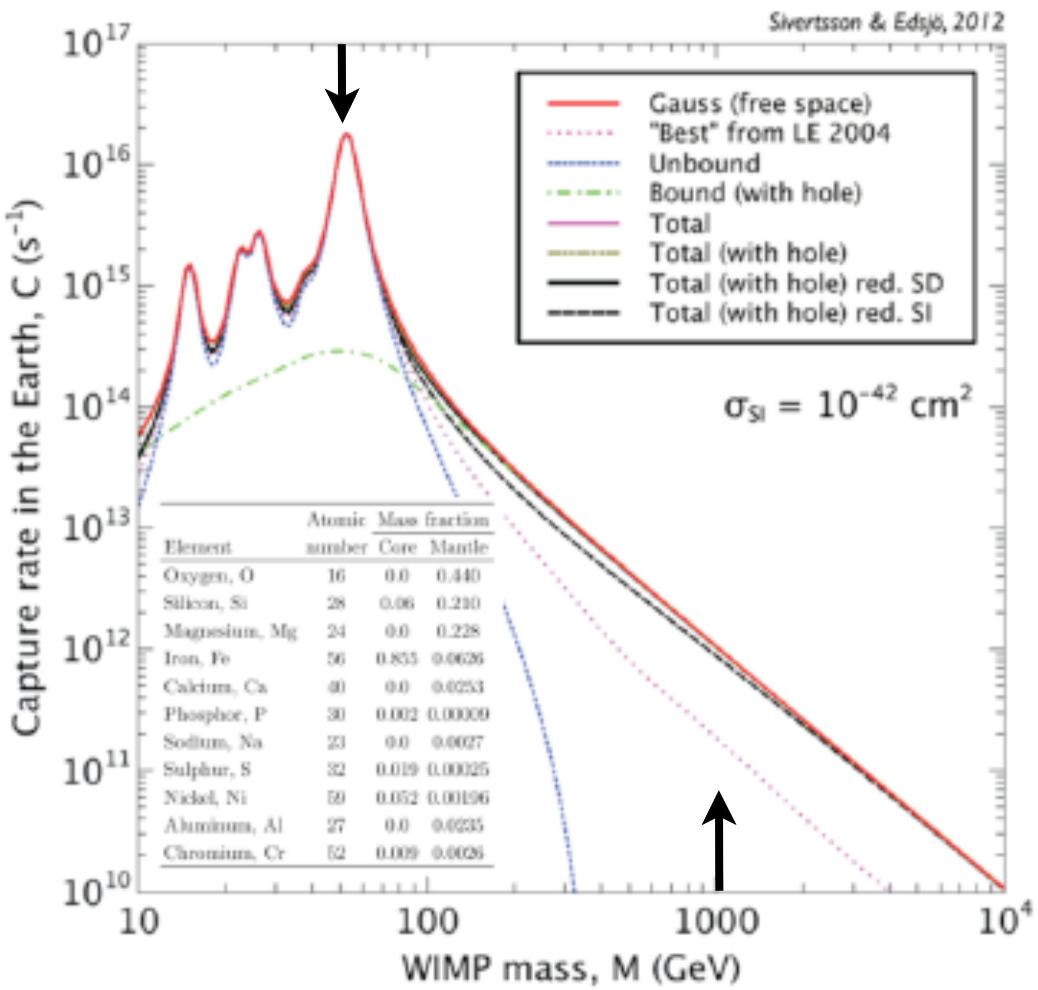


Earth WIMPs

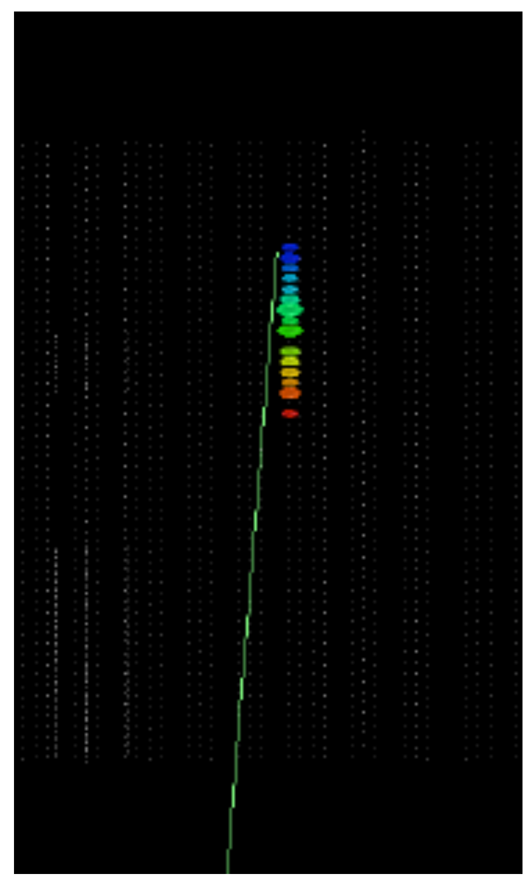
IceCube Earth WIMPs



- 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)



Element	Atomic number	Mass fraction Core	Mass fraction Mantle
Oxygen, O	16	0.0	0.440
Silicon, Si	28	0.06	0.210
Magnesium, Mg	24	0.0	0.228
Iron, Fe	56	0.855	0.0626
Calcium, Ca	40	0.0	0.0253
Phosphor, P	30	0.002	0.00009
Sodium, Na	23	0.0	0.0027
Sulphur, S	32	0.019	0.00025
Nickel, Ni	59	0.052	0.00196
Aluminum, Al	27	0.0	0.0235
Chromium, Cr	52	0.009	0.0026



IceCube Shape analysis

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

$$\mathcal{L} = \prod_{i}^{n_{\text{obs}}} f(\Psi_i|\mu)$$

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

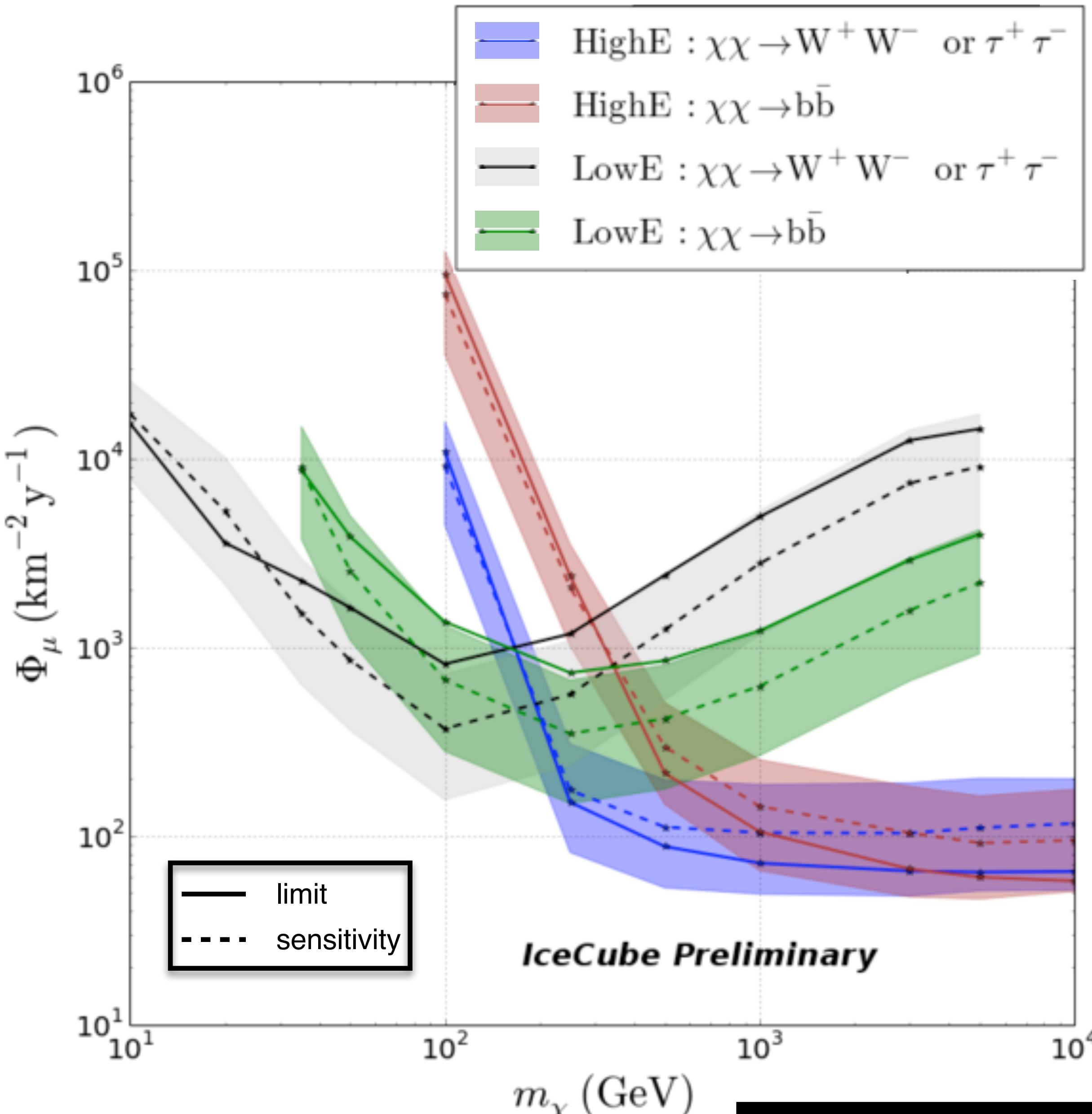
$\hat{\mu}$ is the best fit of μ to the observation

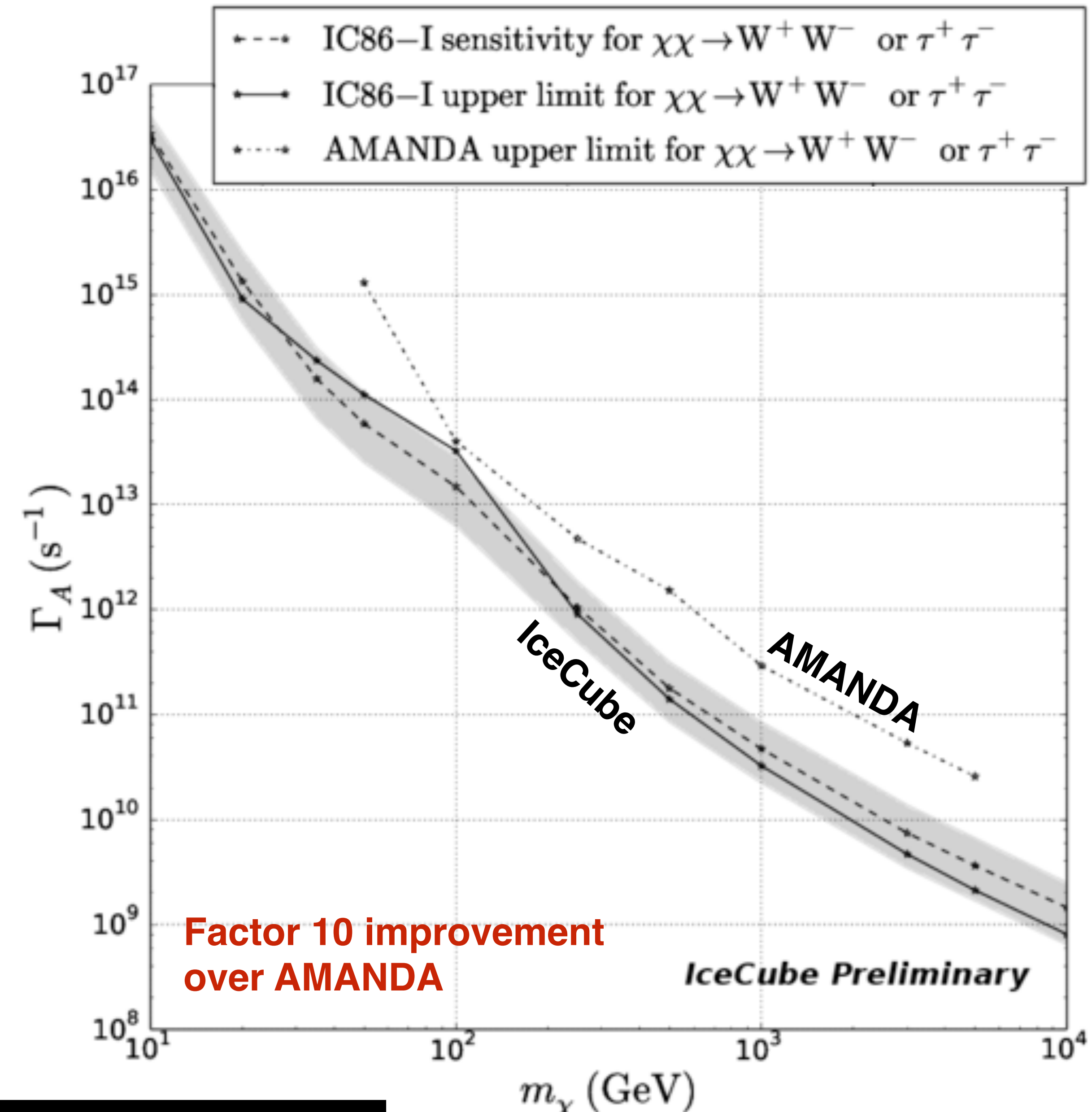
- Combine High-energy and low-energy analysis, based on the best sensitivity

4.5 10^9years

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

Earth typically not in equilibrium

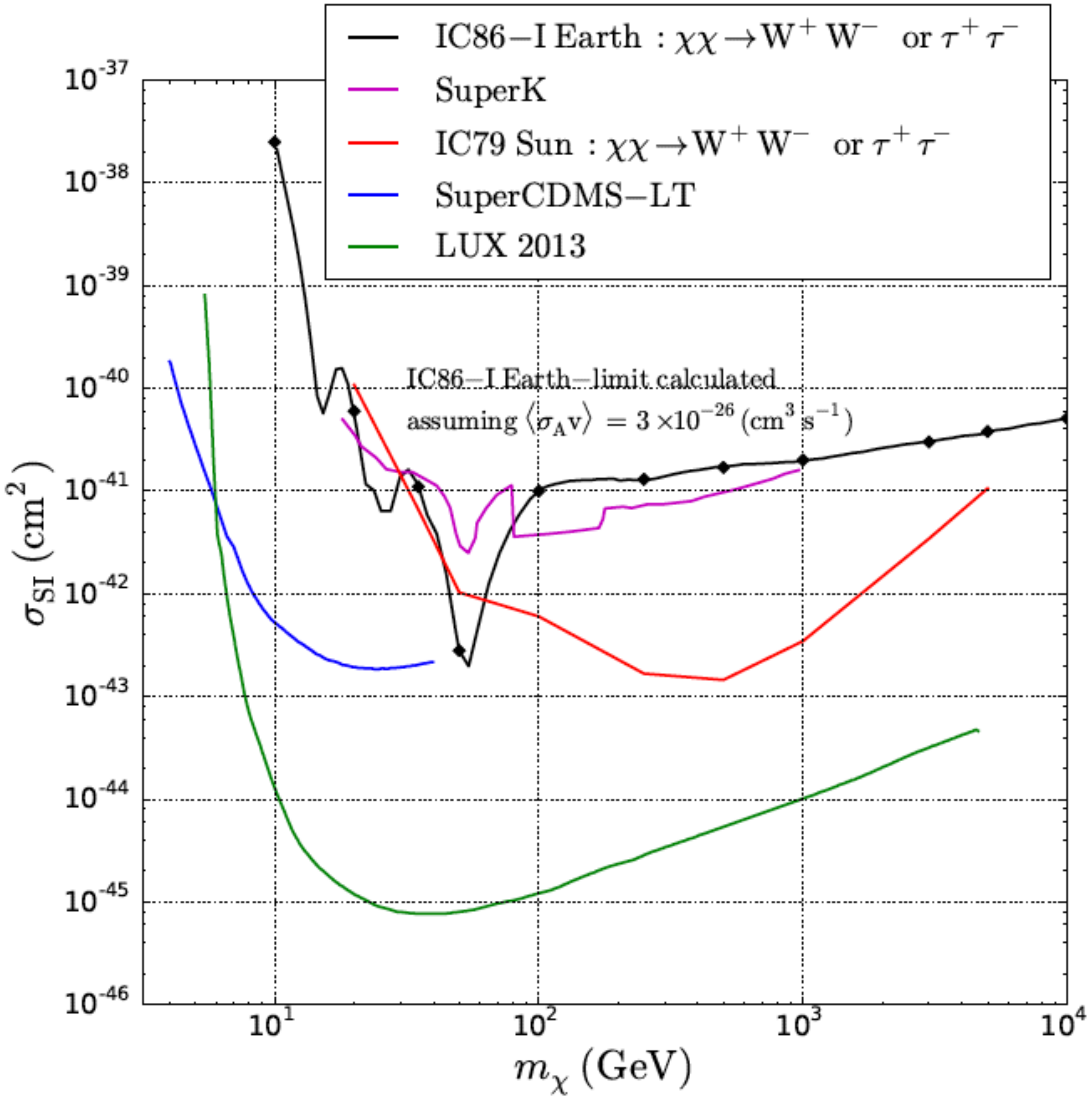


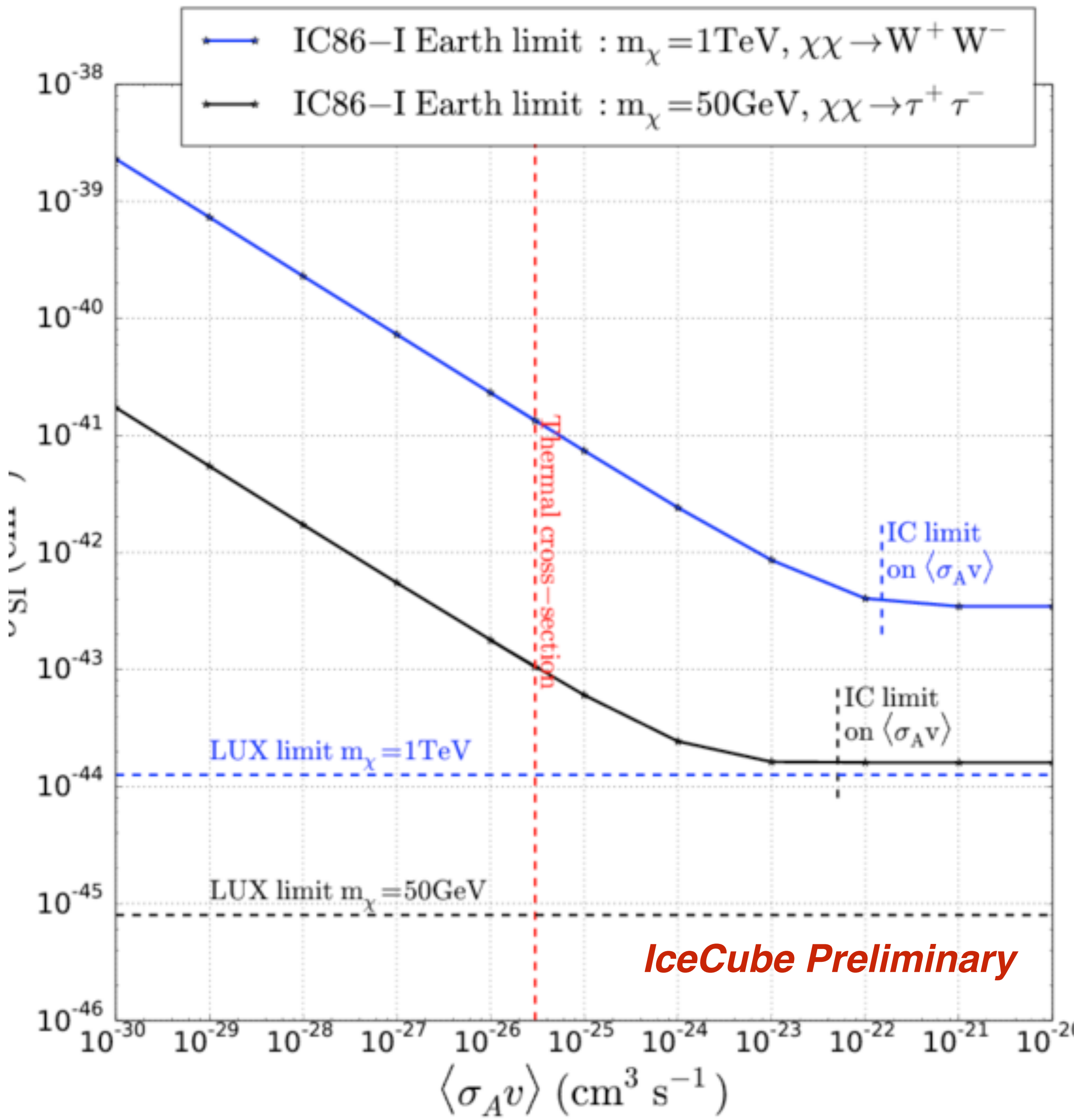


No evidence for dark matter

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

Earth WIMPs

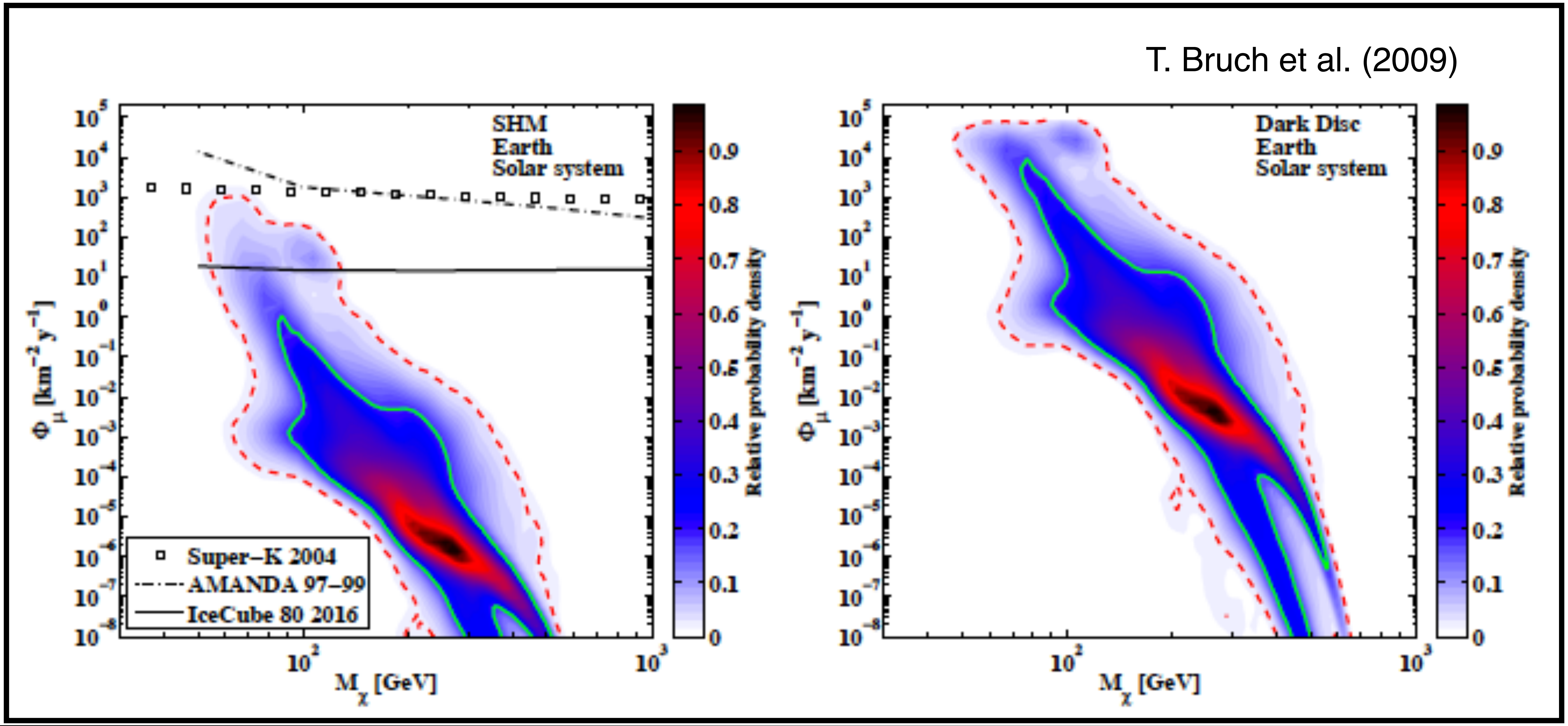


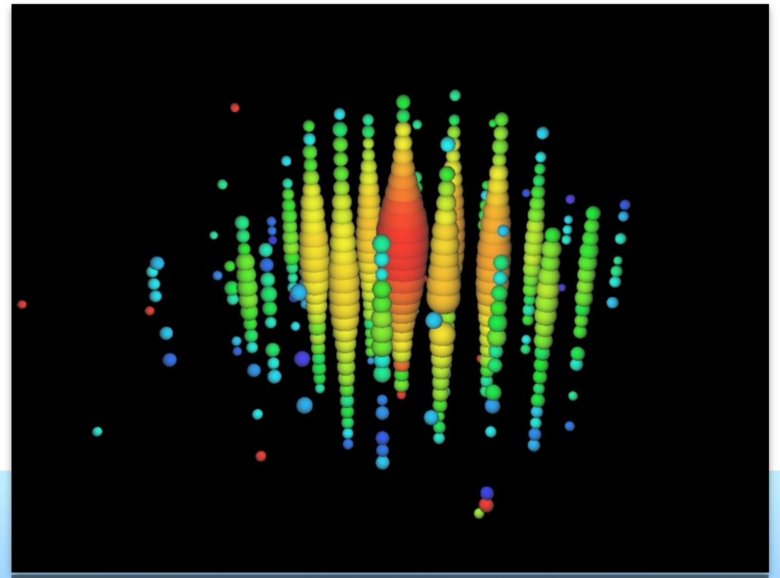


- Earth WIMP analysis more sensitivity than Solar WIMP analysis for SI scattering for m_χ close to Fe resonance
- Standard halo model was assumed. Possibility of dark disk could boost Earth WIMP bounds by two orders of magnitude

Earth WIMPs

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

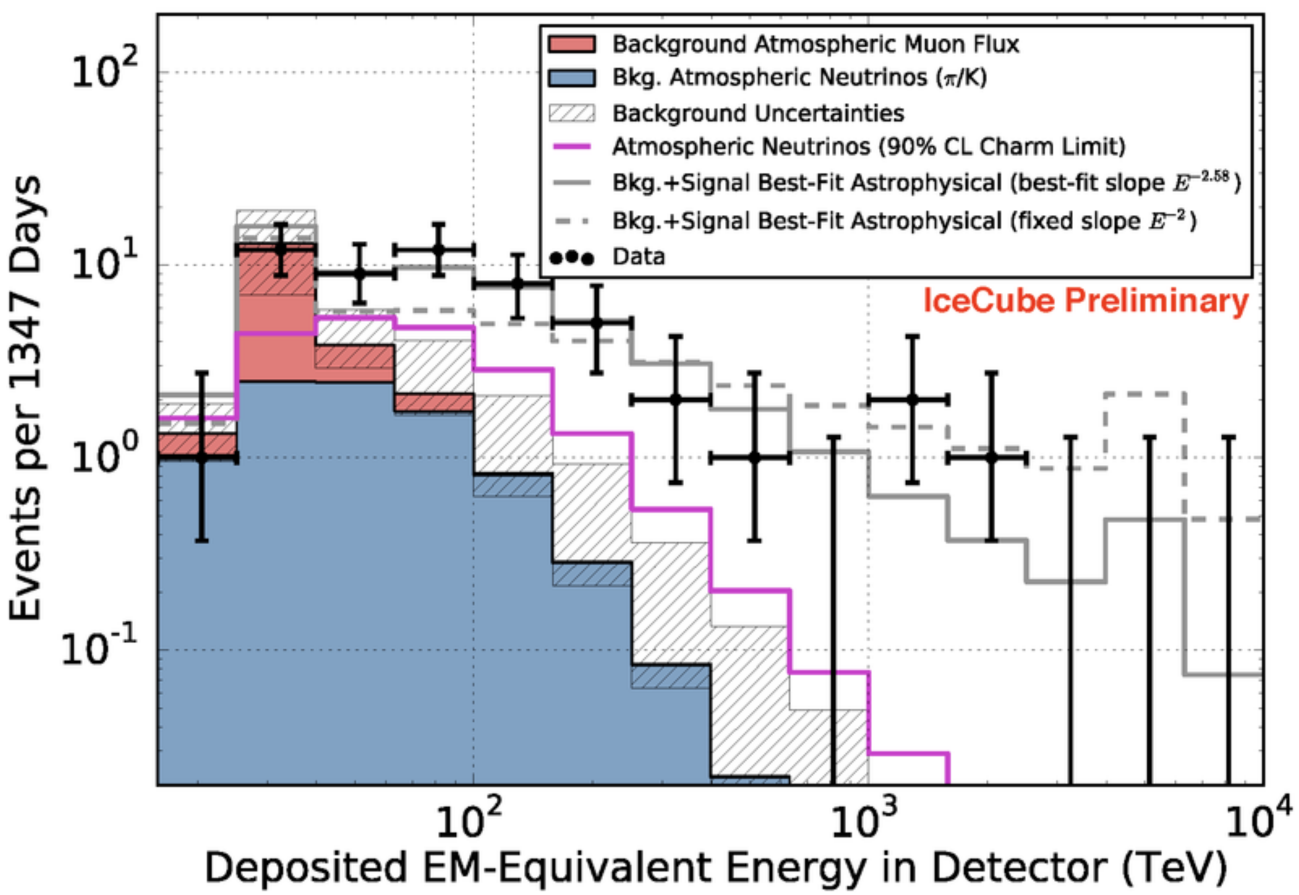




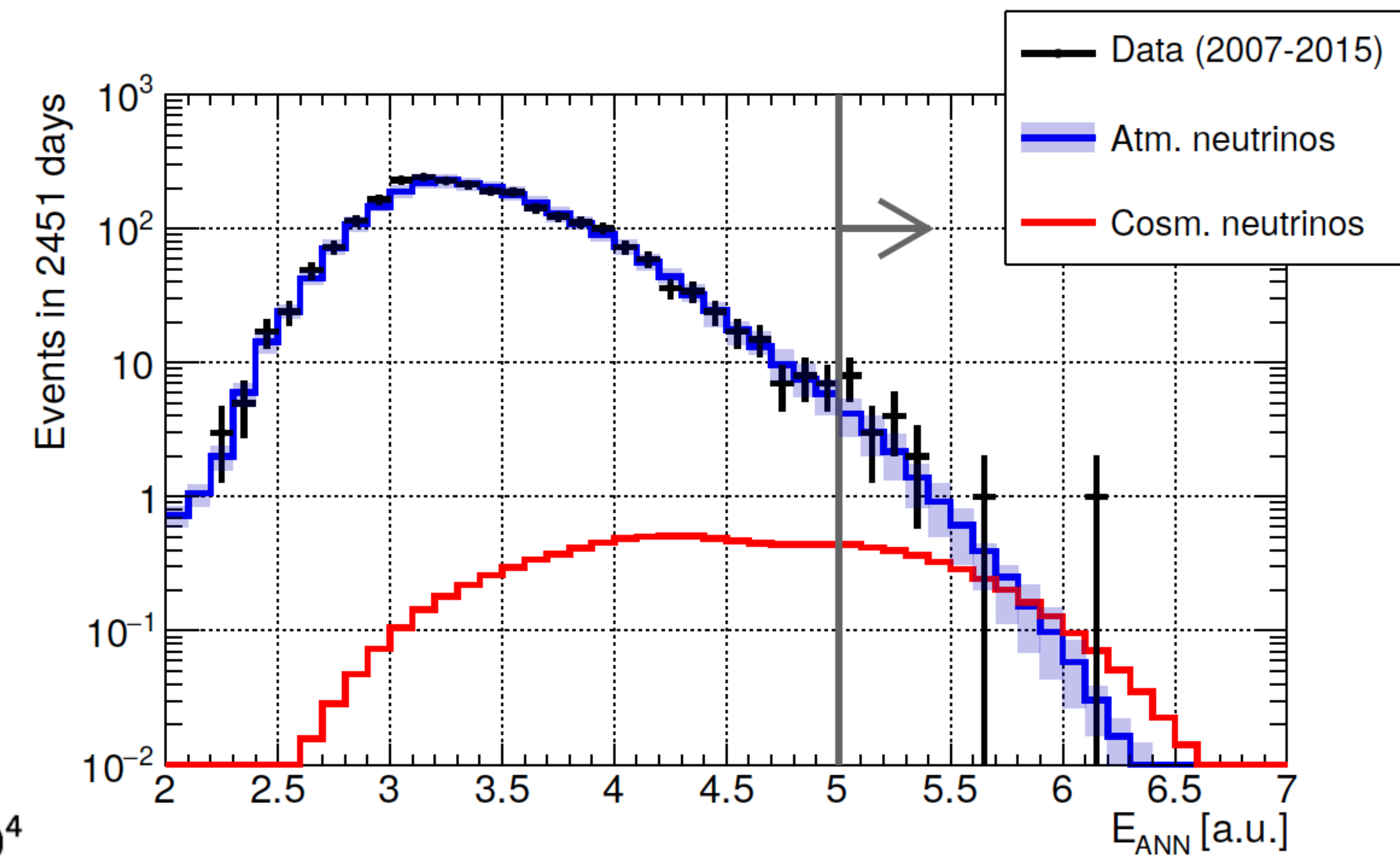
Astro-physical Neutrinos / Heavy Dark Matter / Boosted Dark Matter / …

High energy neutrinos

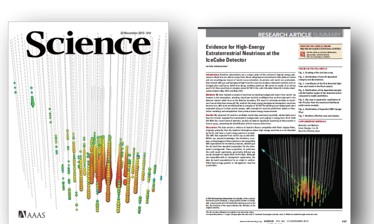
IceCube



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

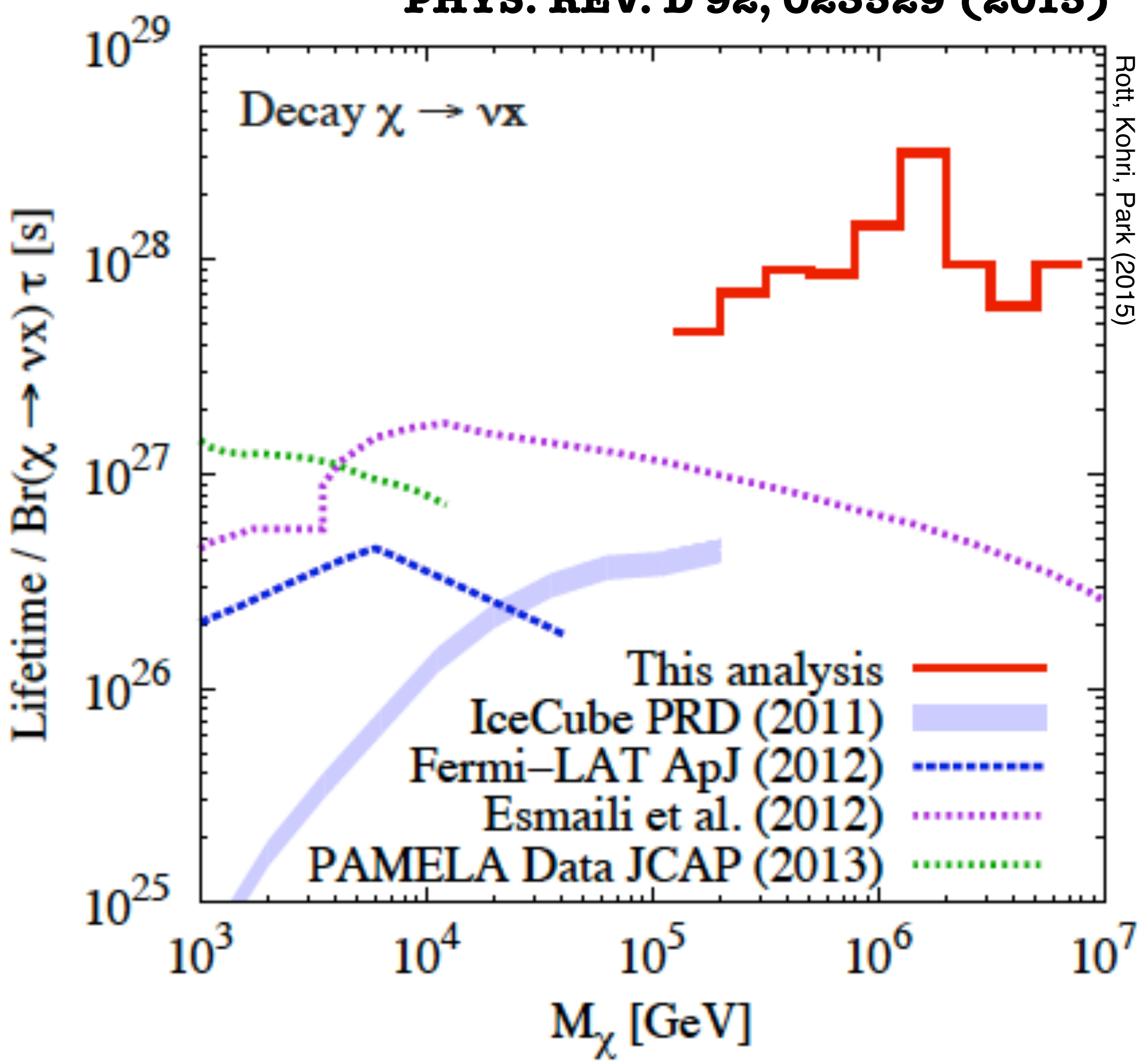
ANTARES Neutrino 2016

Heavy Dark Matter Decay

- Heavy Decaying Dark Matter (example $\chi \to \nu h, \chi \to \nu x, \chi \to \nu \gamma$, $\chi \to \nu ee$)
- 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

PHYS. REV. D 92, 023529 (2015)



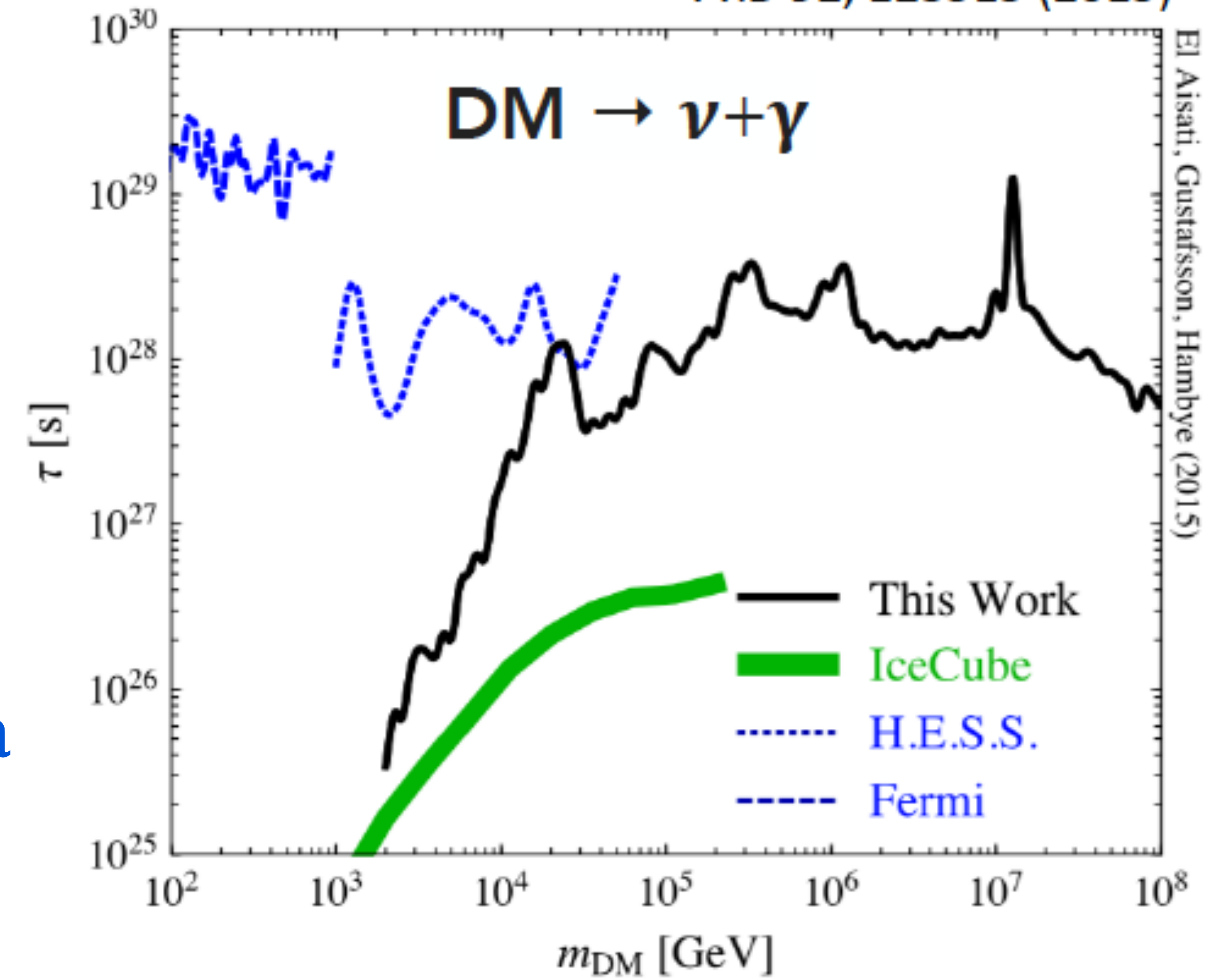
Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034

Heavy Dark Matter Decay

- Heavy Decaying Dark Matter (example $\chi \rightarrow \nu h$)
- 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 H.E.S.S from Galactic Centre line search analysis

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

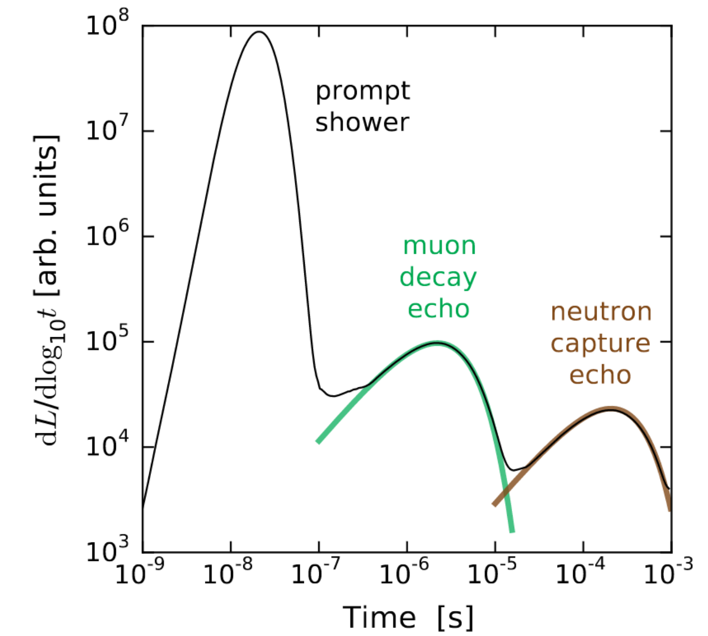
PRD 92, 123515 (2015)

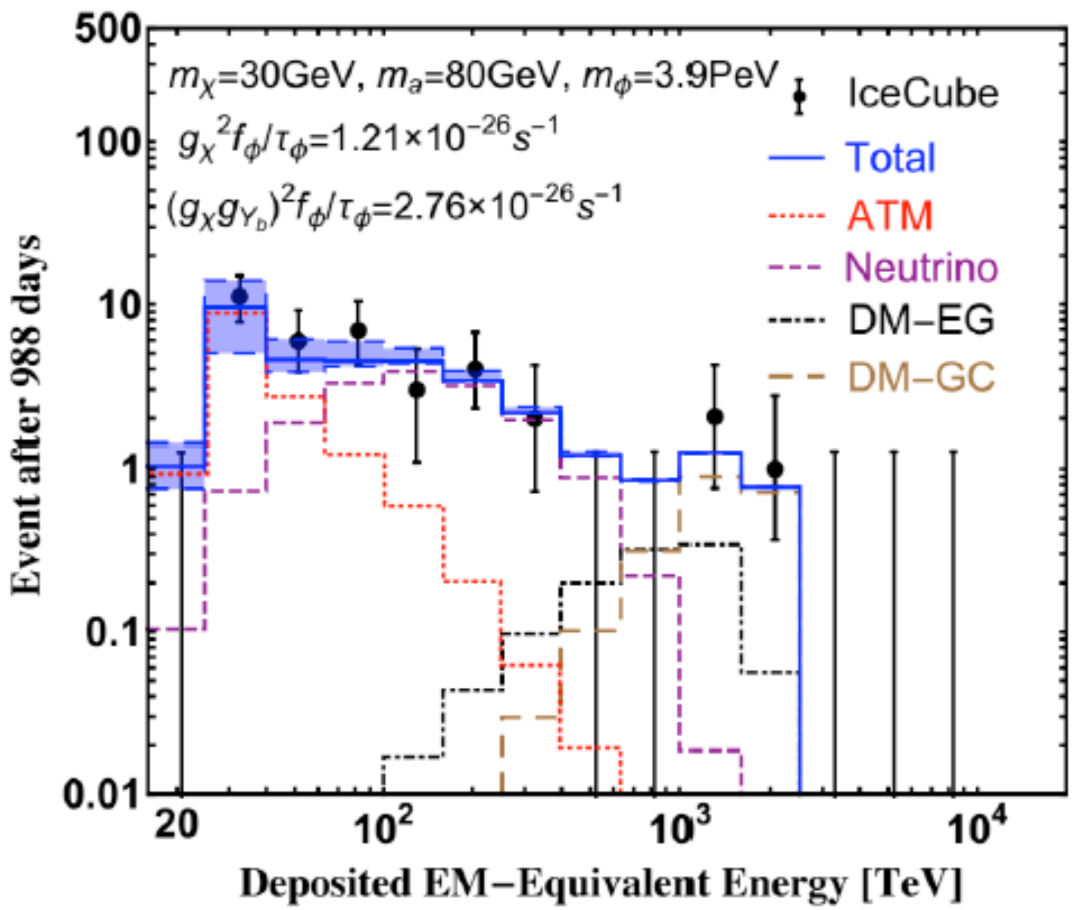


Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034

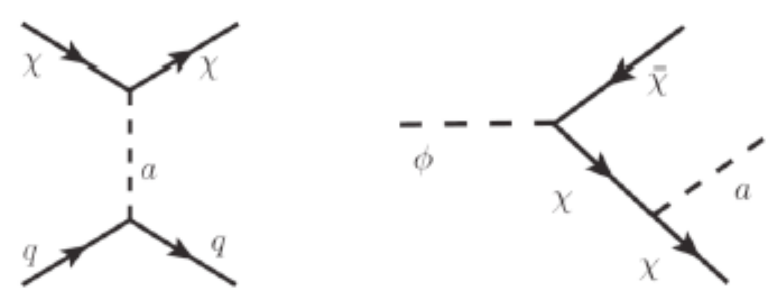
Boosted Dark Matter

- “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)

$\phi \rightarrow \chi \bar{\chi}\, a,\ a \rightarrow b\, \bar{b}$

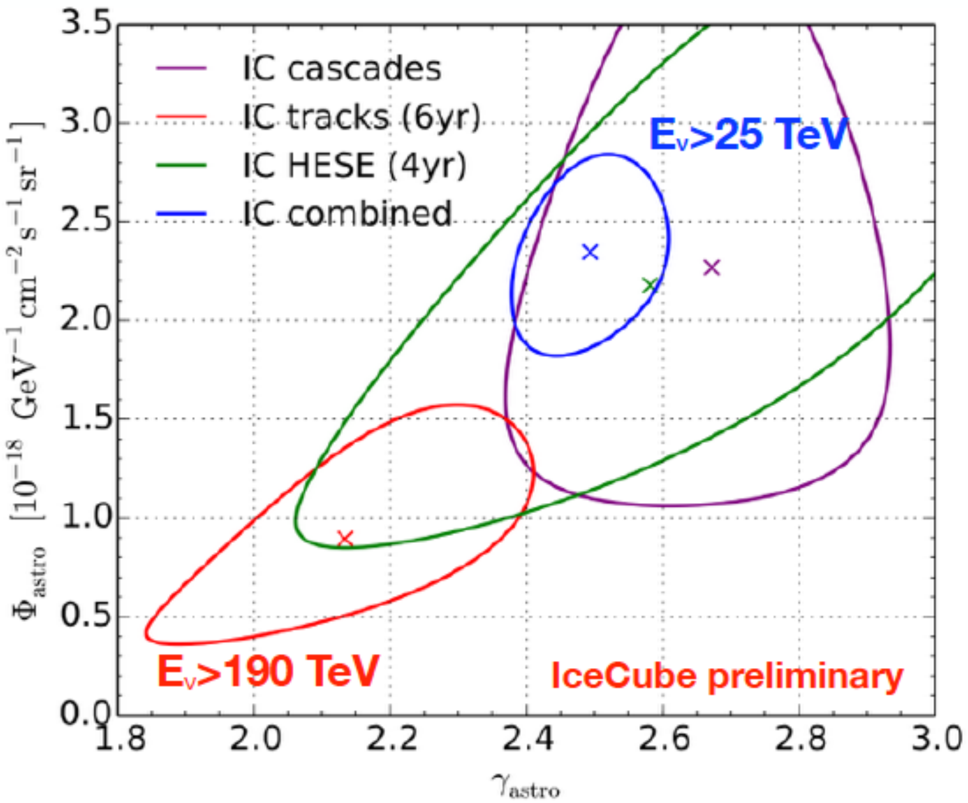
→ν‘s

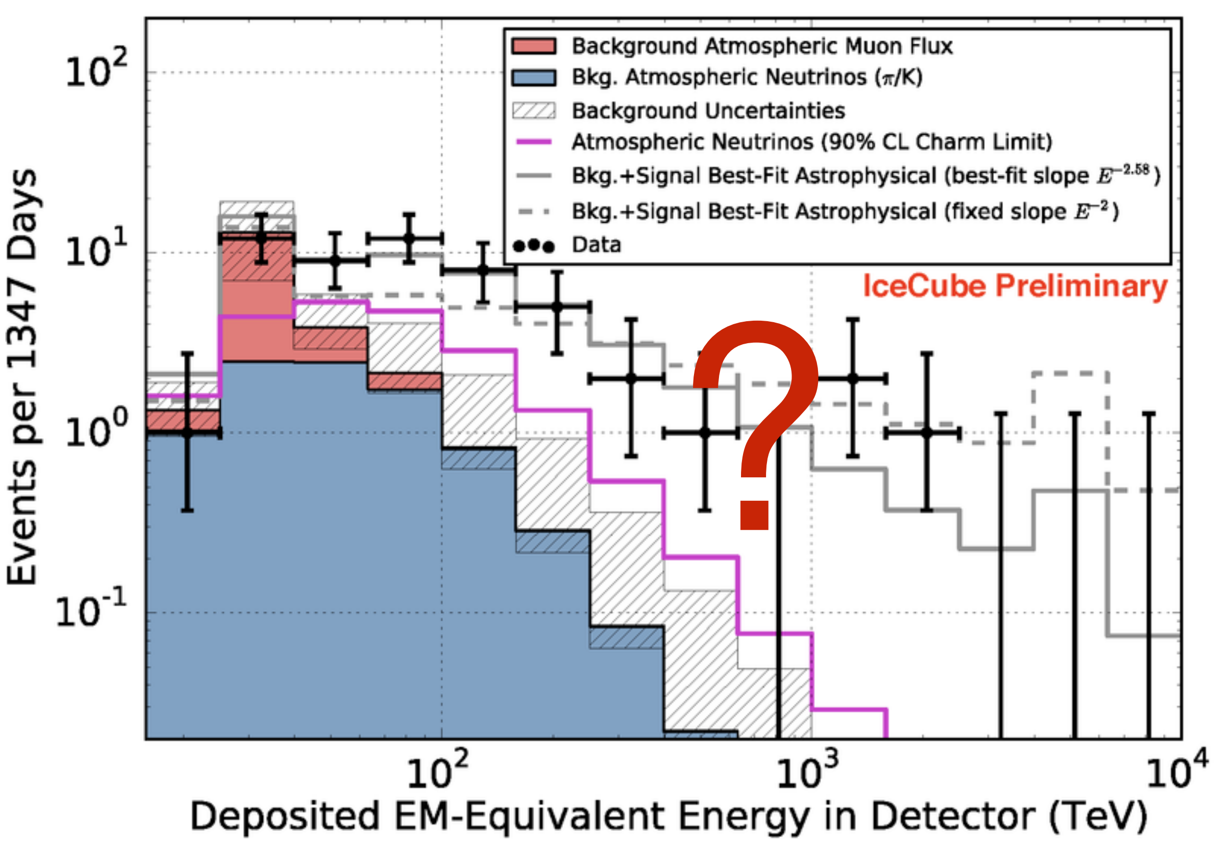
Neutrons capture on hydrogen and product 2.2MeV gamma. In seawater, 33% of neutrons capture on Cl; the emitted gamma rays have 8.6 MeV, making the neutron echoes more visible

“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

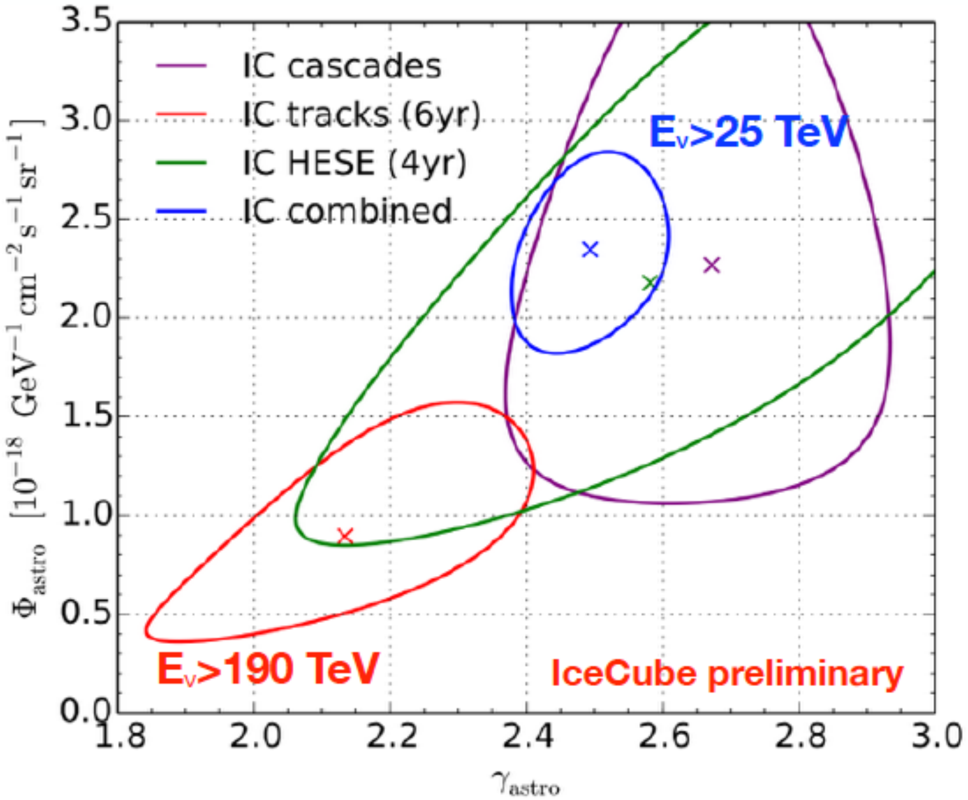
Beyond Standard Model Physics at the PeV scale



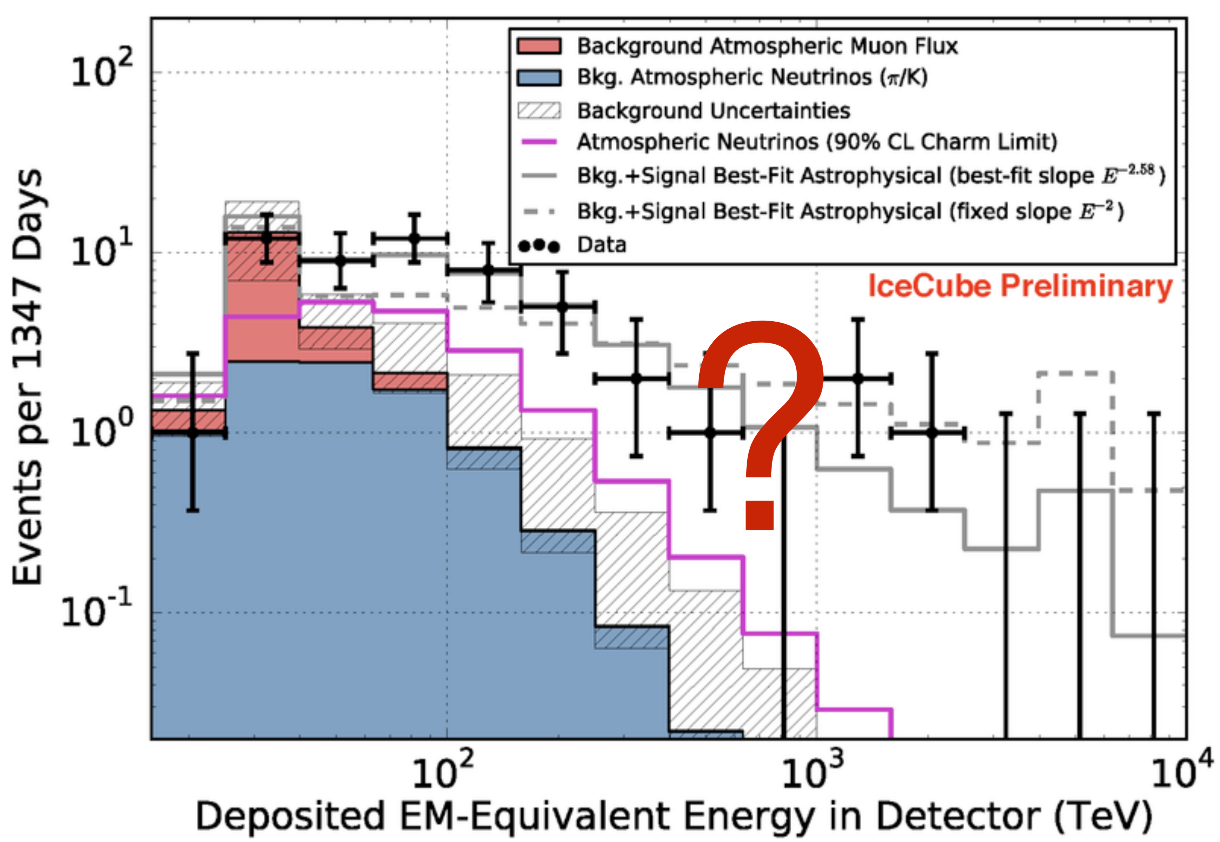


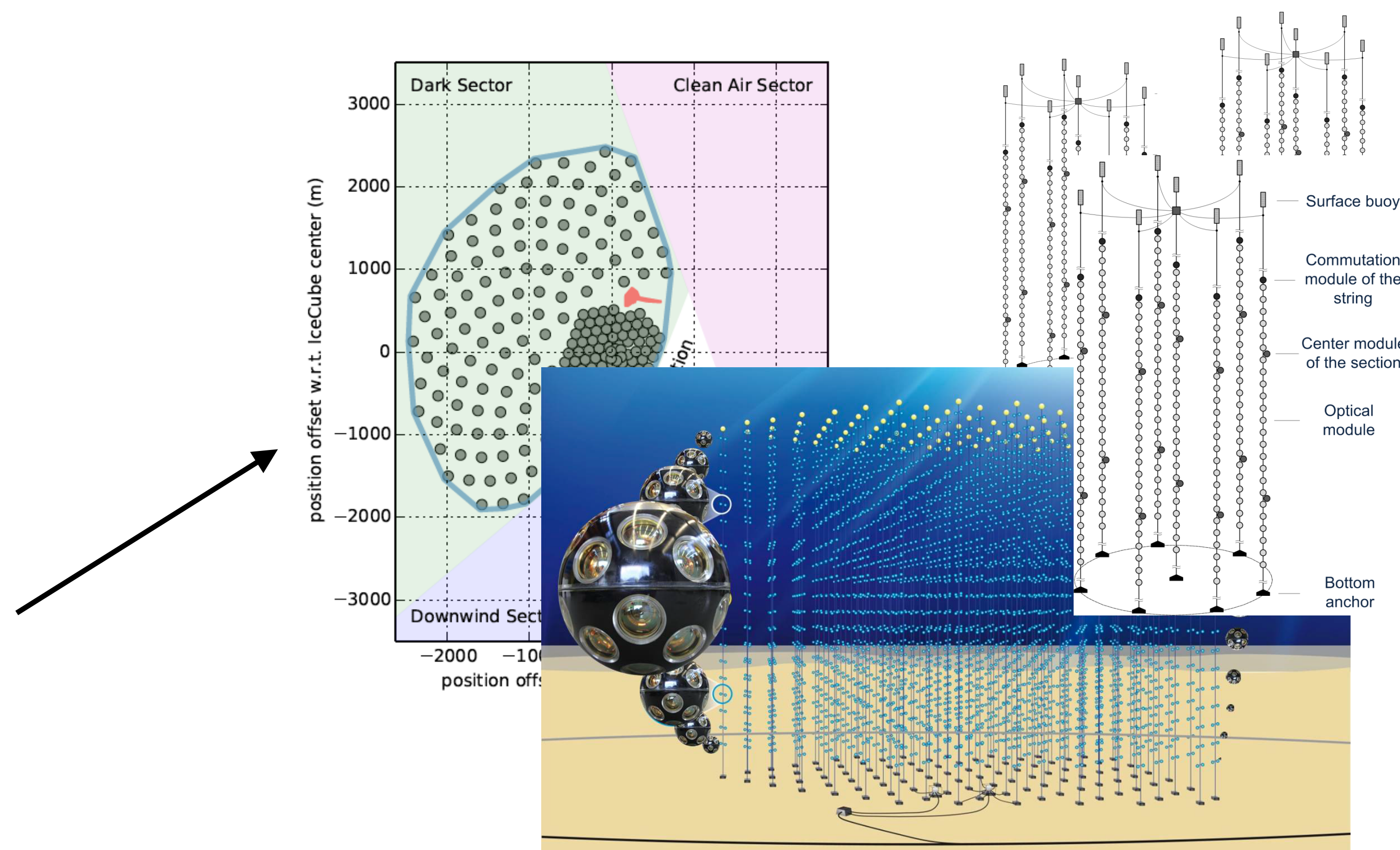
- Intense interest in high-energy neutrino region
  - Observations defy any simple explanation from a single generic source class
    - Multiple sources classes ?
    - Hints of new physics ?

- 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
- …



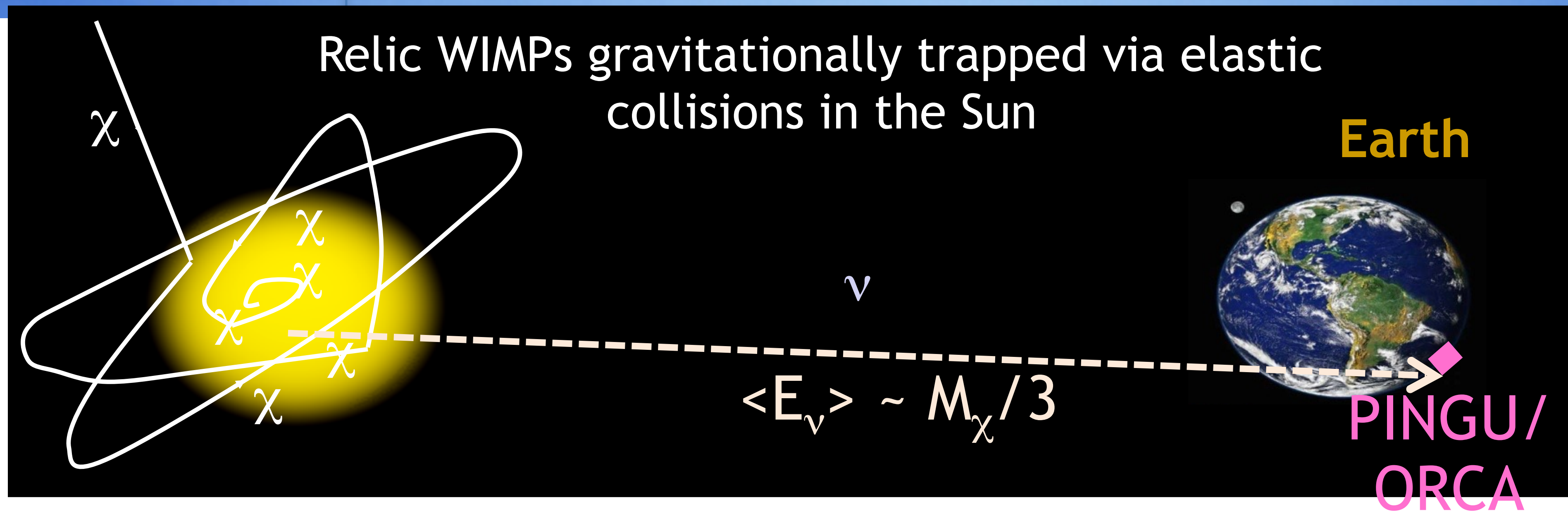
- Intense interest in high-energy neutrino region
  - Observations defy any simple explanation from a single generic source class
    - Multiple sources classes ?
    - Hints of new physics ?

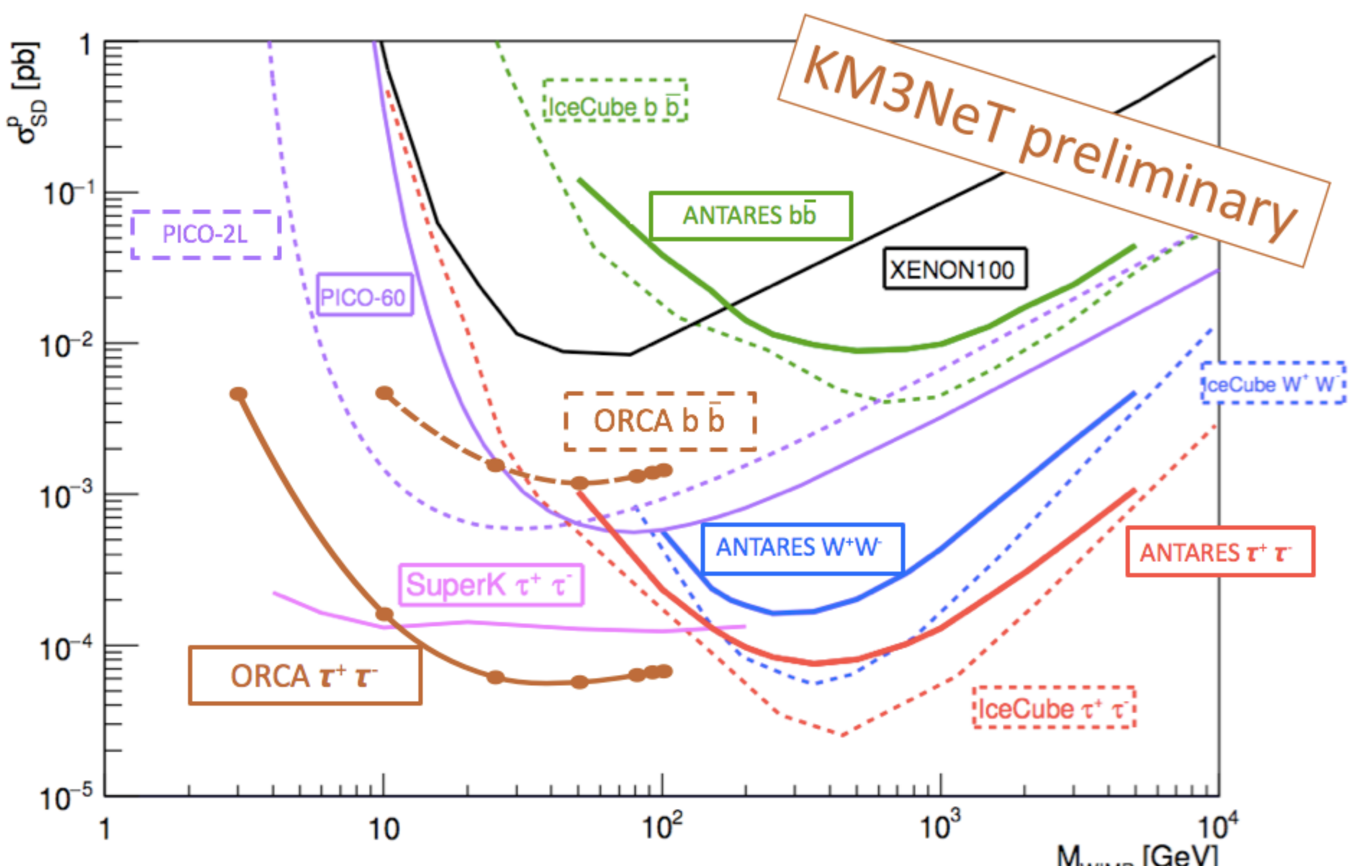




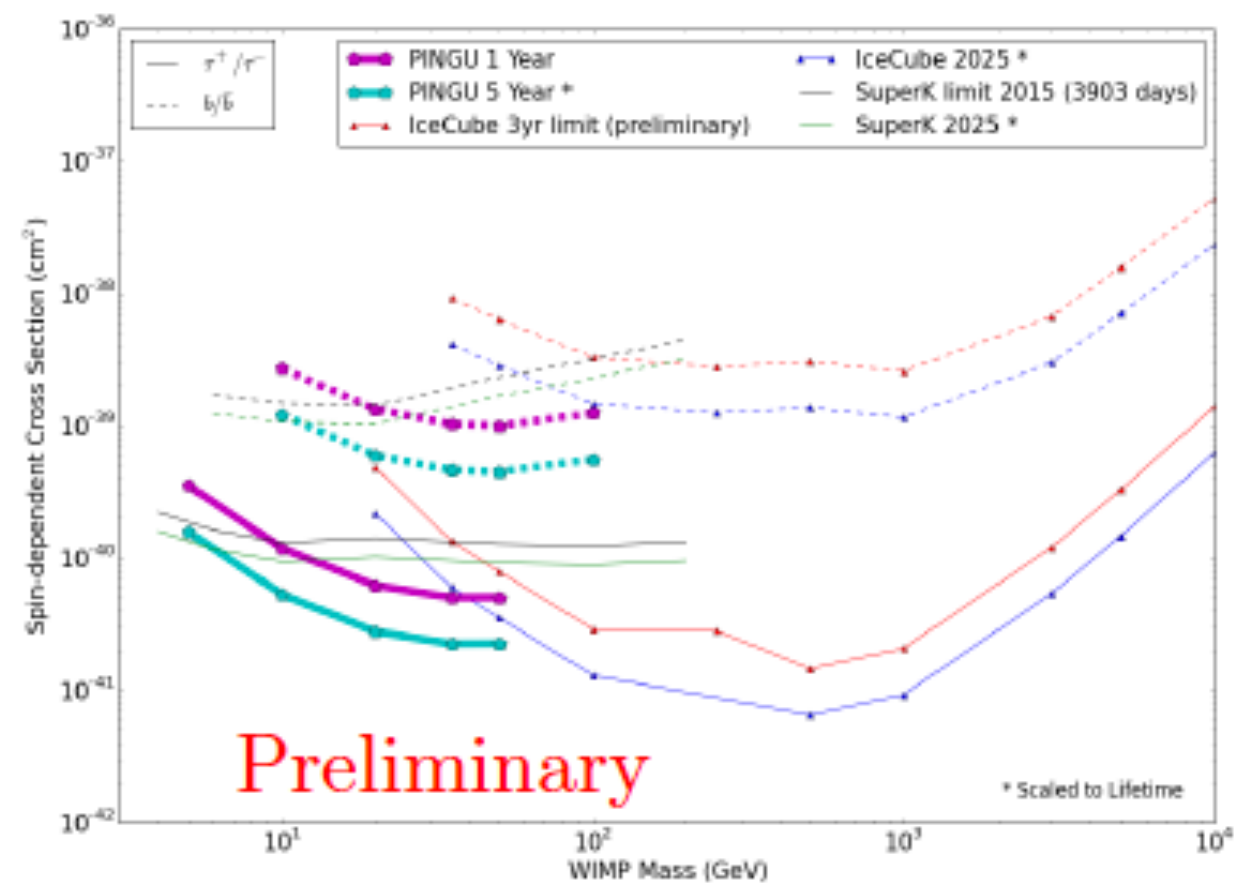
Baikal-GVD
KM3NeT LOI arXiv::1601.07459
IceCube Gen2 LOI arXiv:1412.5106

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