# New Methods for Solar Weakly Interacting Massive Particle Searches

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C.Rott, T.Tanaka, Y. Itow JCAP09(2011)029 (arXiv1107.3182)
C. Rott, J. Siegal-Gaskins, J.F.Beacom (in prep.)

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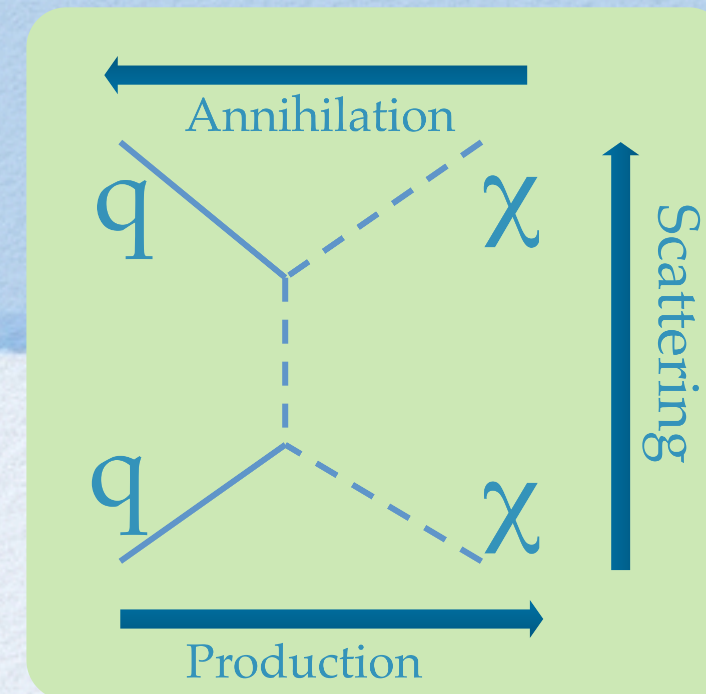
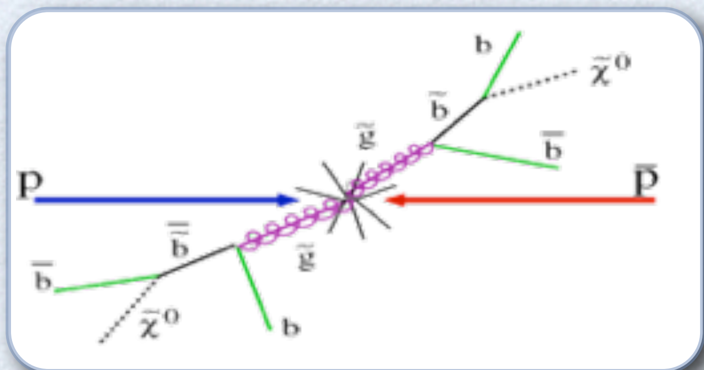
# OVERVIEW

- Motivation
  - WIMP Searches and Neutrinos
- Neutrino Detectors
- WIMPs in the Sun
  - Flux conversion
  - Methods and Strategies
  - Current Status and Results
  - Uncertainties
  - Future Prospects
- Conclusions

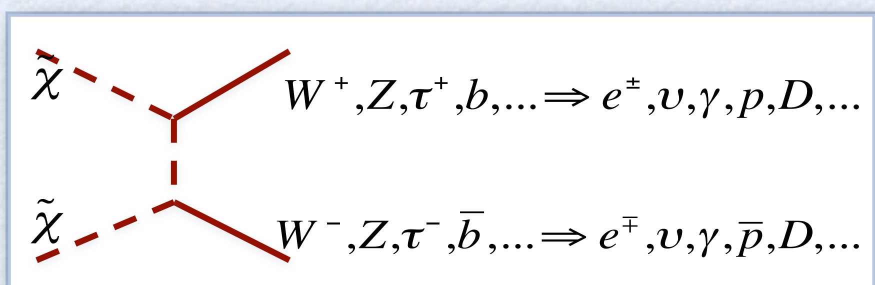
# Motivation

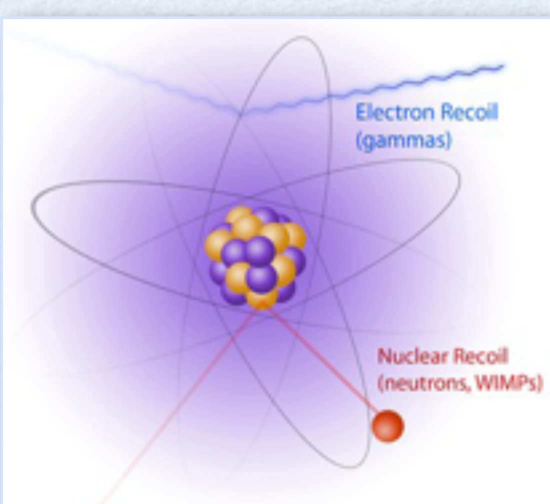
# Strategies for WIMP Detection




- **Production**
  - Colliders
- **Indirect Searches**
  - Annihilation of Dark Matter in Galactic Halo, ...
    - γ-rays, $e^+$, $e^-$, p, ν, ...
  - Annihilation signals from WIMPs captured in the Sun (or Earth)
    - only ν can escape
- **Direct Searches**
  - WIMP scattering of nucleons → Nuclear recoils




WIMP Self-annihilation cross section

WIMP-Nucleon Scattering cross section

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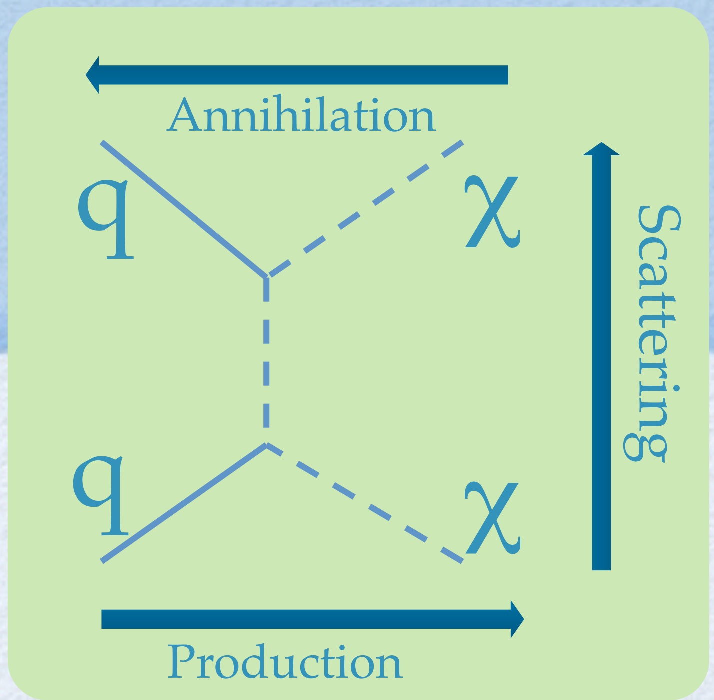


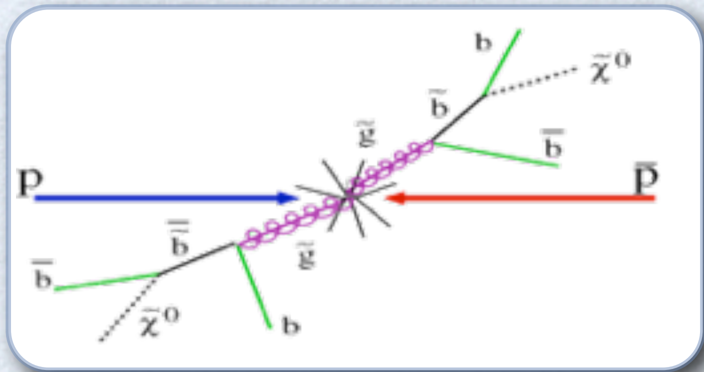


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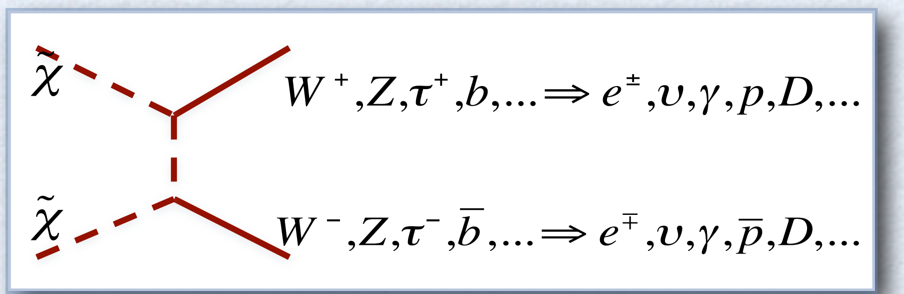
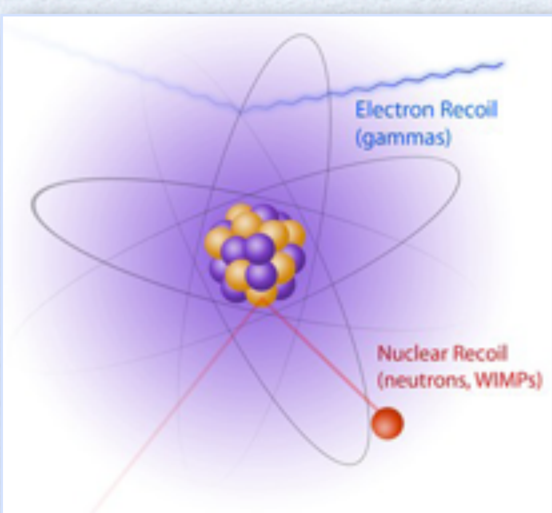



WIMP Self-annihilation cross section

WIMP-Nucleon Scattering cross section

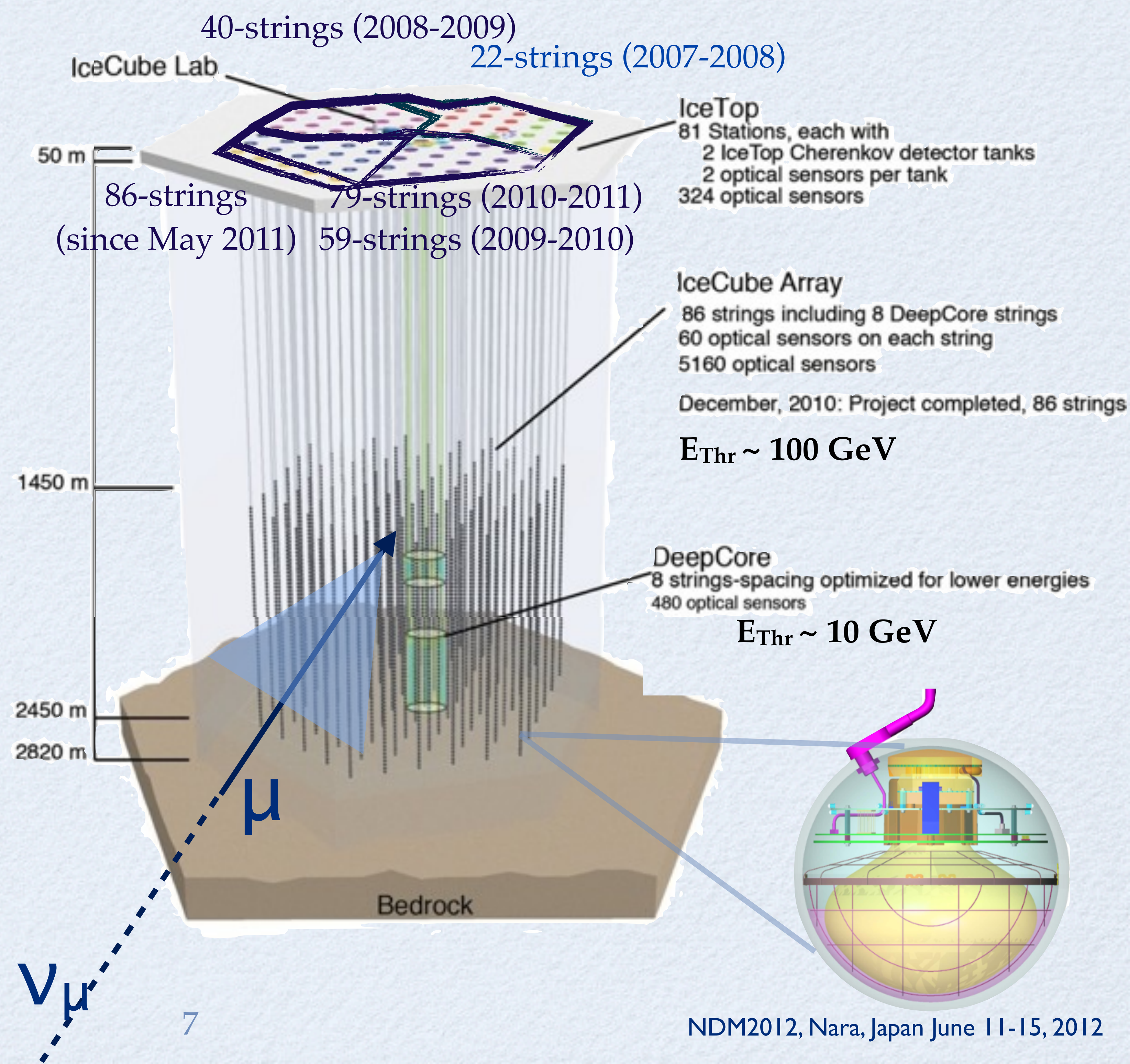
# Motivation

- Neutrino Telescope provide some of the best constraints on WIMP-Nucleon scattering through Solar WIMP searches
- How can we improve the sensitivity of present day and next generation instruments including those for low-mass WIMPs ?
- How well can neutrino results constrain WIMP properties in light of astrophysical uncertainties ?

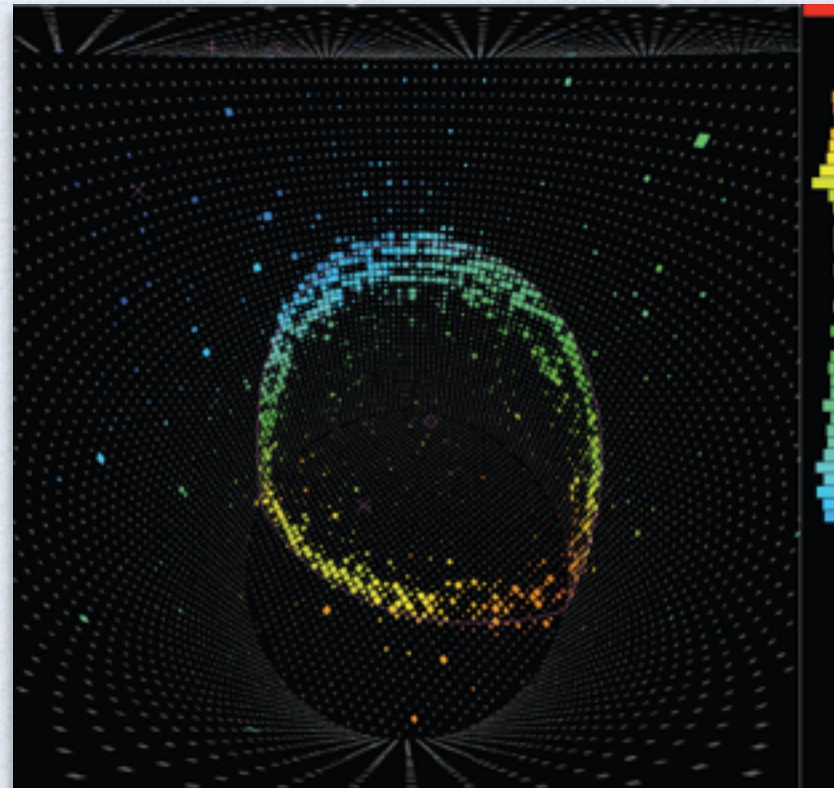
# DETECTORS

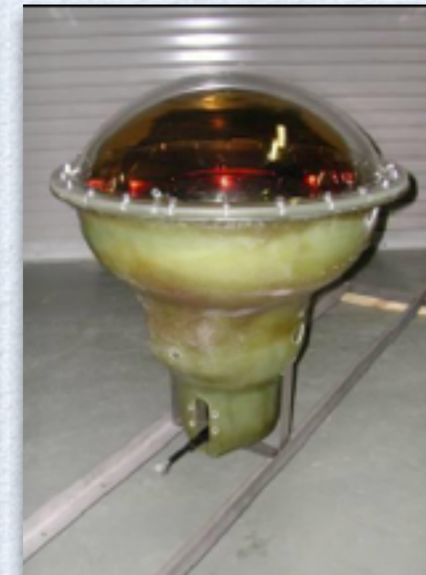
# The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010, start of data taking with full detector May 2011
- Data acquired during the construction phase has been analyzed
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

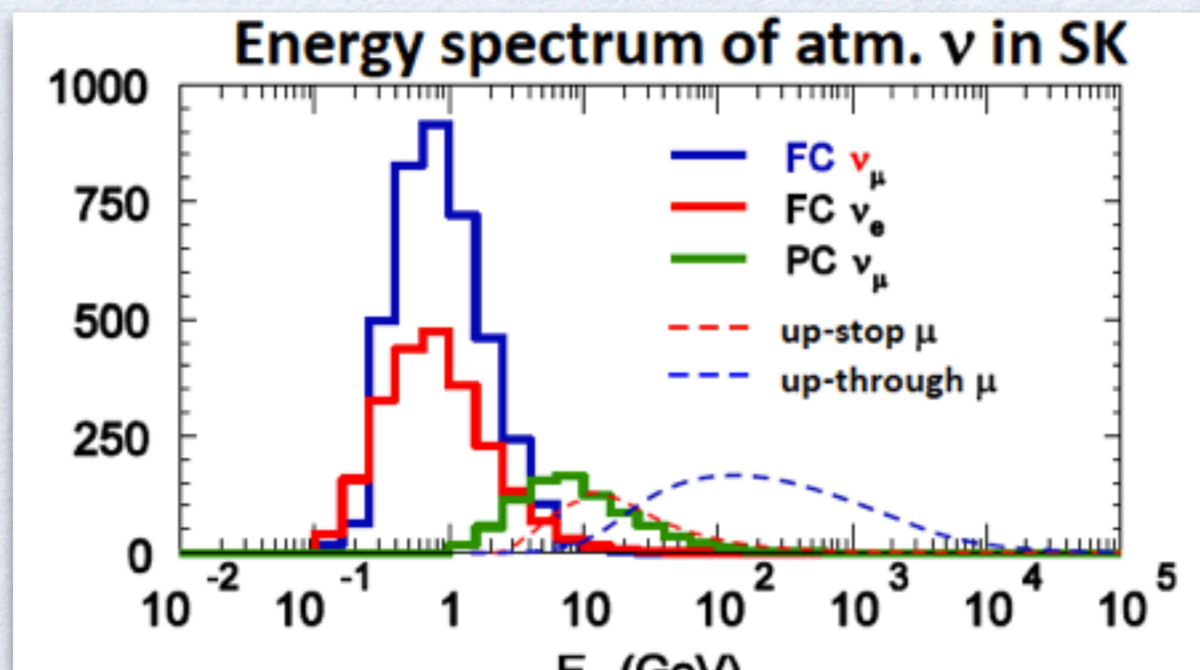


# SUPER-KAMIOKANDE

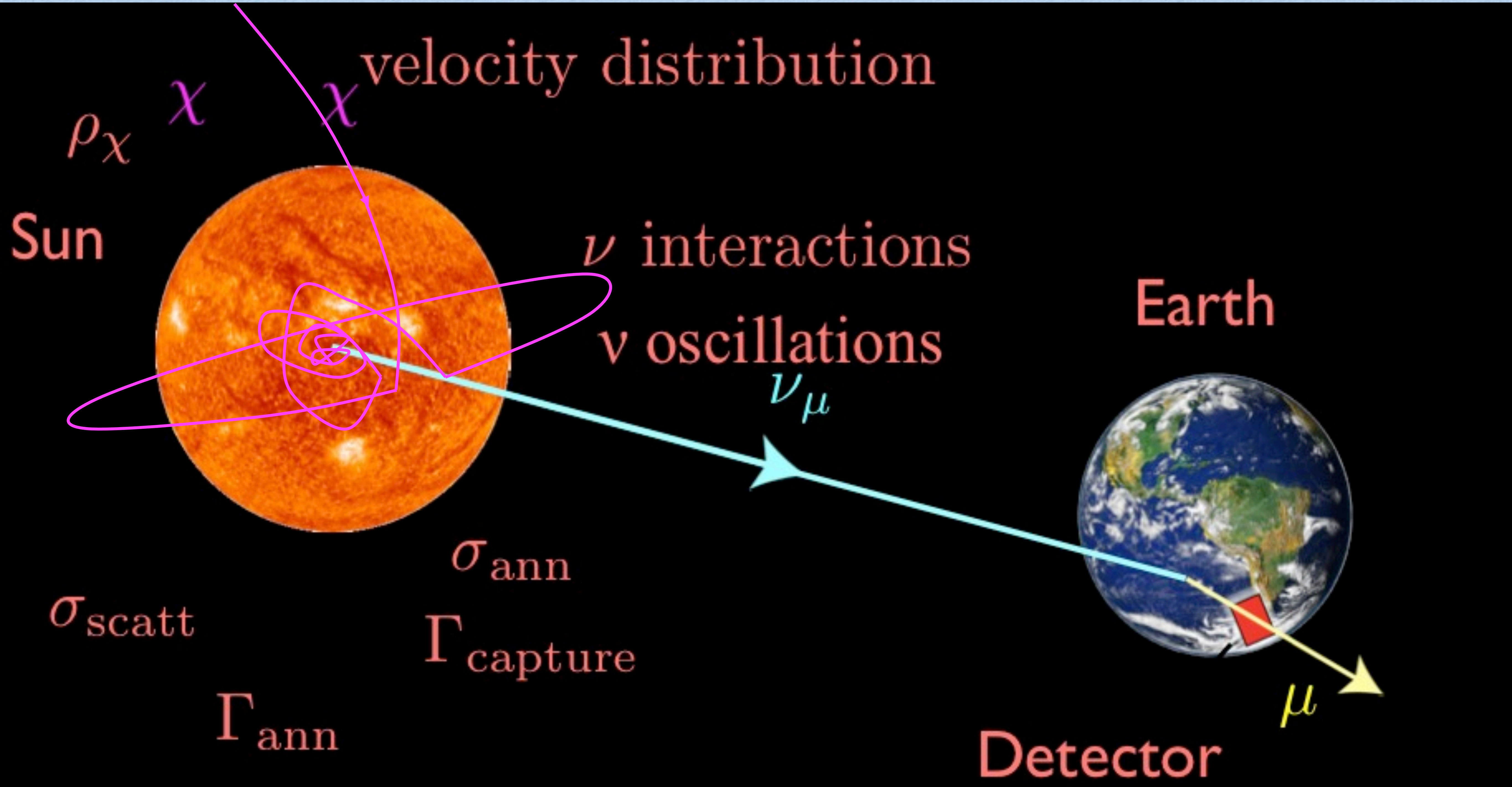


- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996
- ~11K 20" PMTs
- Photo coverage ~40%



# Solar WIMPs

# Solar WIMP Signal

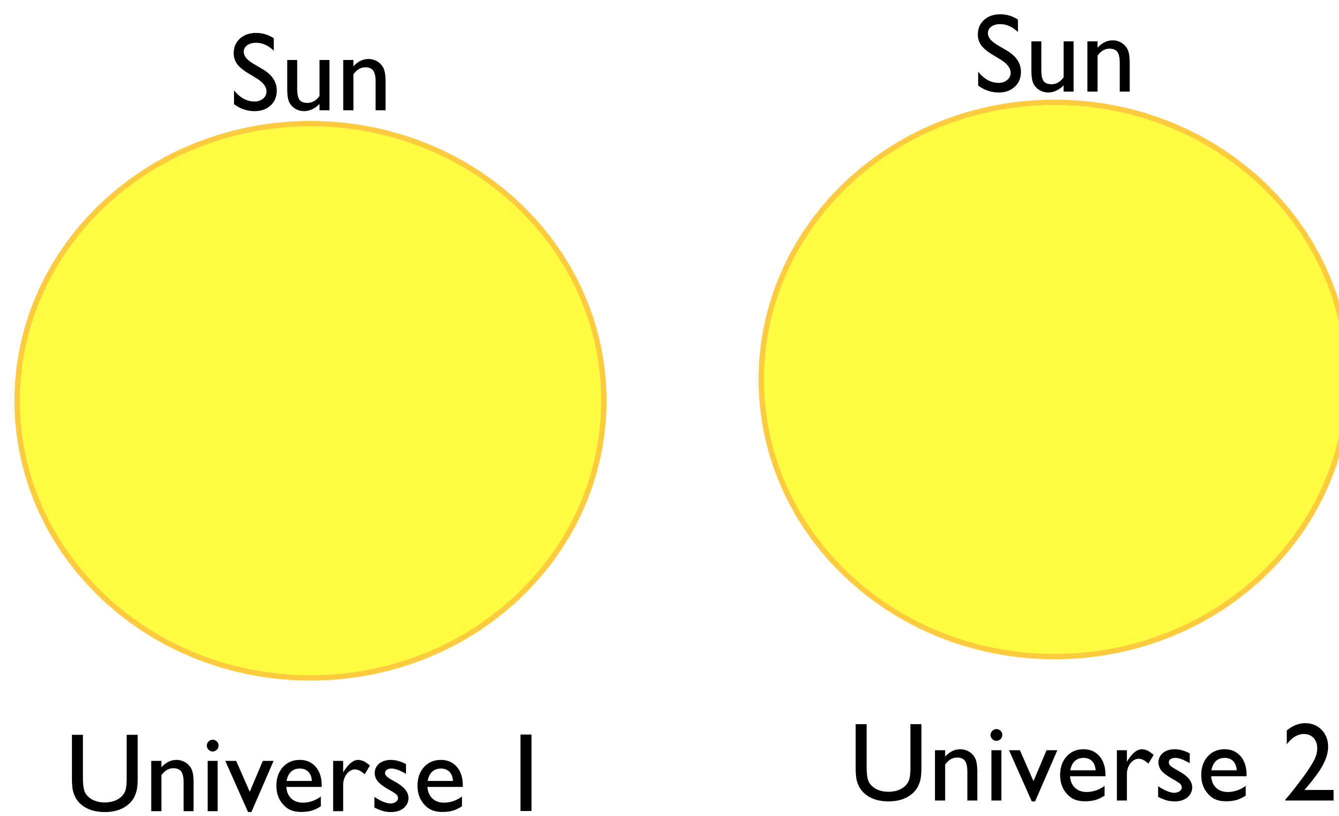



Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

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

# Solar WIMP Equilibrium

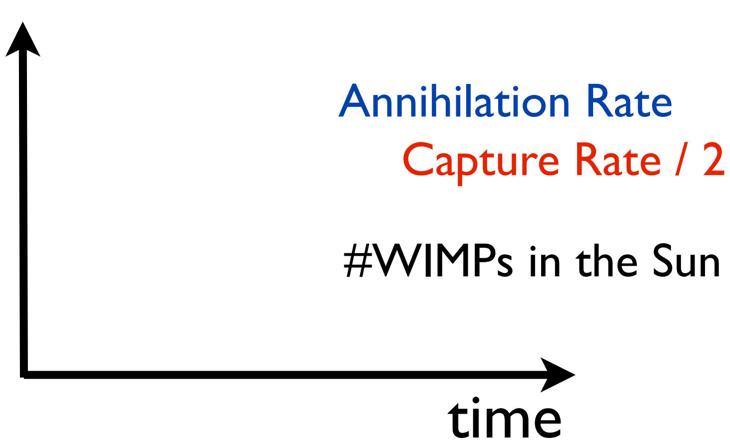
- Dark Matter accumulates and starts annihilating → Neutrinos are the only particles that can make it out
- At equilibrium ($\Gamma_A = 1/2\,\Gamma_C$) the neutrino flux does not depend on the self annihilation cross section !

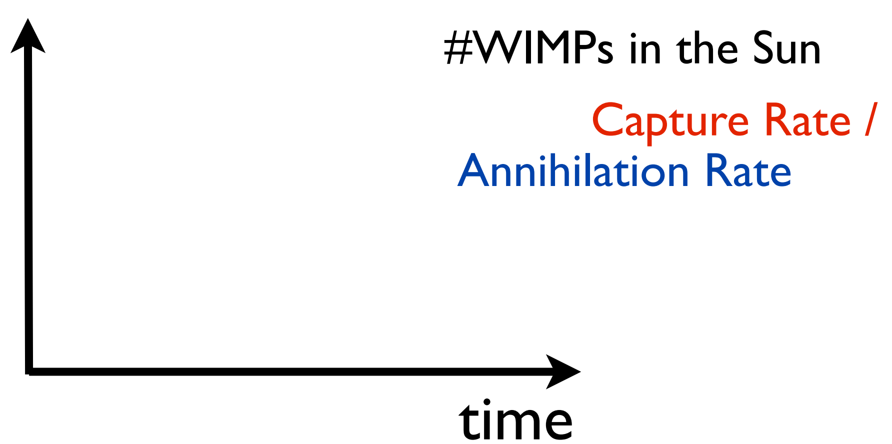



| | Universe 1 | Universe 2 |
|---|---|---|
| Self-annihilation cross section: | **large** | **small** |
| WIMP-Nucleon scattering: | same in both (⇒capture rates are identical) | |

N = #WIMPs, Capture Rate ($\Gamma_C$), Annihilation Rate ($\Gamma_A$), Evaporation

$$\frac{d\mathcal{N}}{dt} = C_C - C_A \mathcal{N}^2 - C_E \mathcal{N}$$



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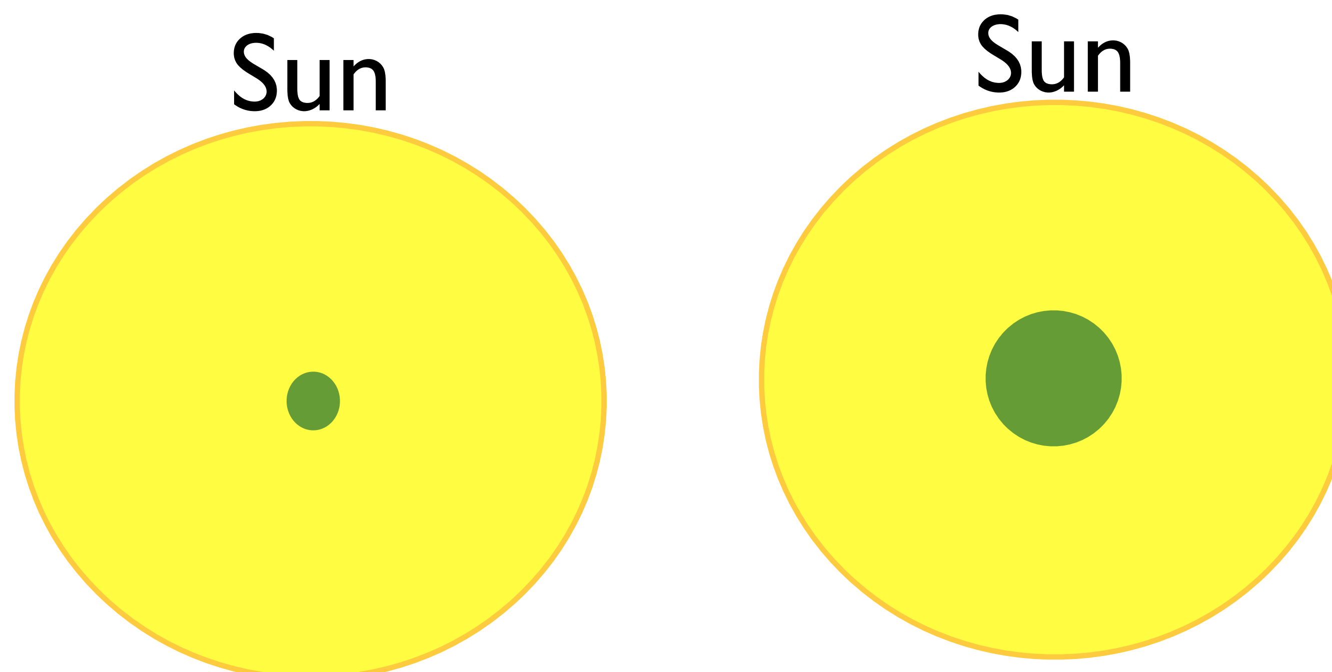


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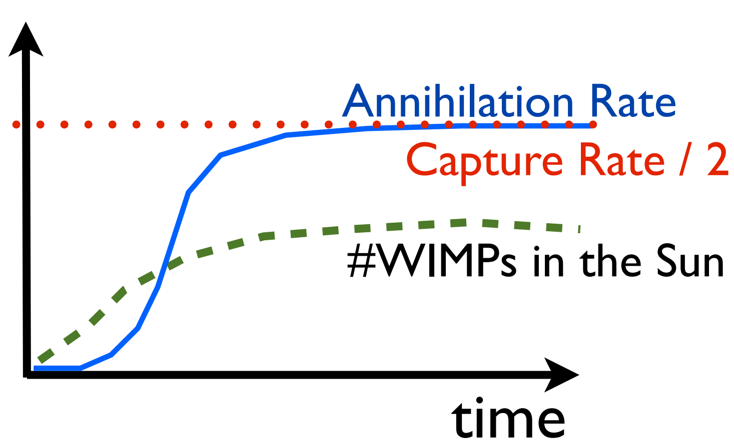
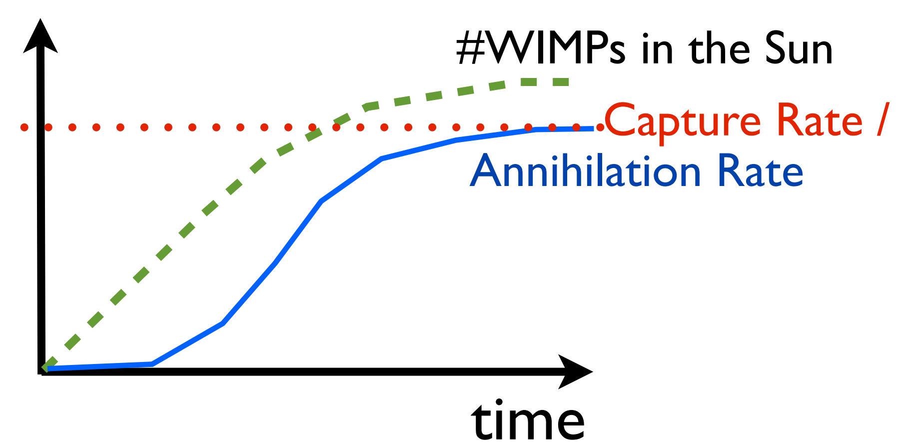
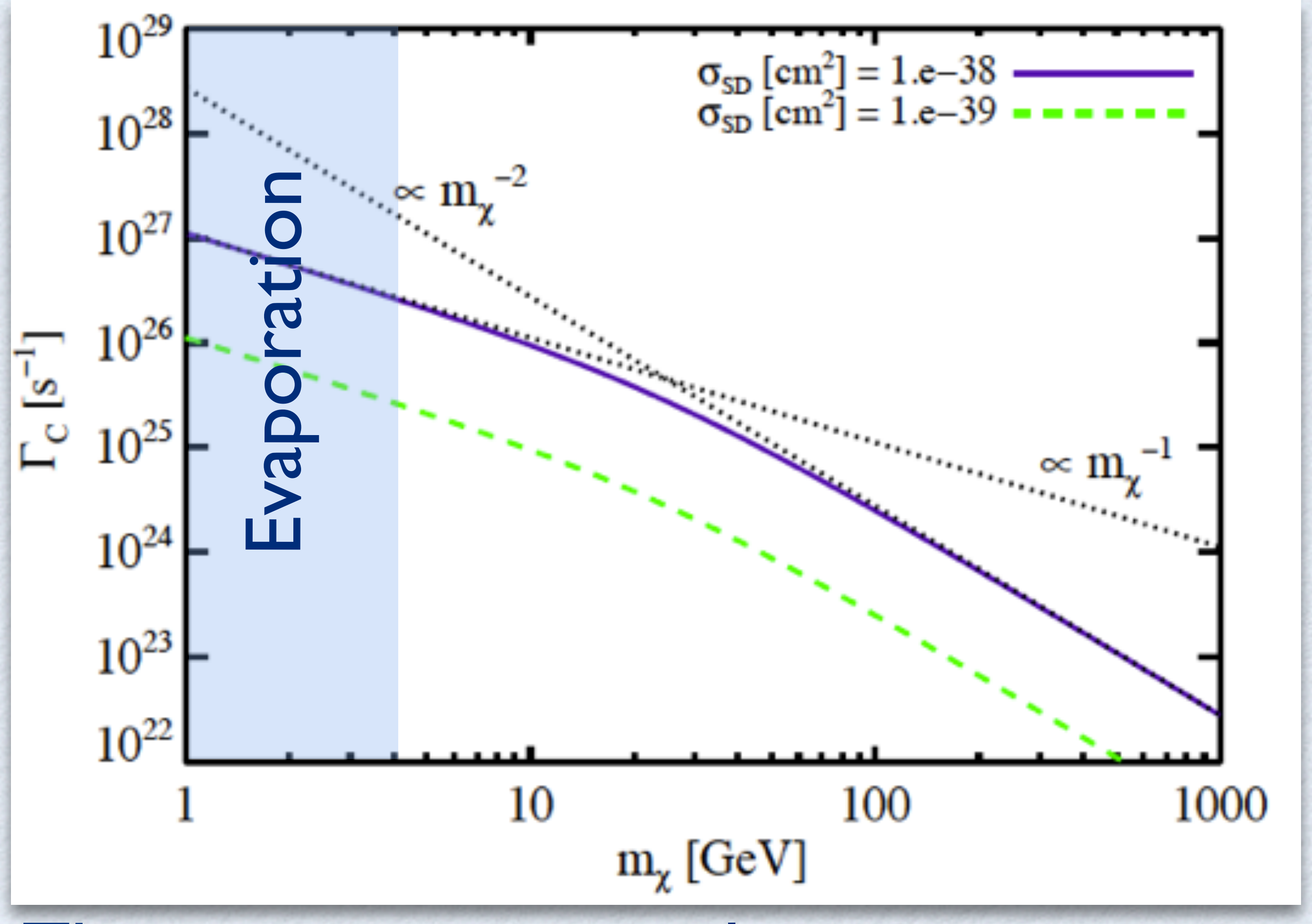


# Solar WIMP Capture

- WIMPs can get gravitationally captured by the Sun
  - Capture rate, $\Gamma_C$ ,depends on WIMP-nucleon scattering cross section
- Dark Matter accumulates and starts annihilating
  - → Only neutrinos can make it out
- Equilibrium: The capture rate regulates the annihilation rate ($\Gamma_A=1/2\Gamma_C$)
  - The neutrino flux only depends on the WIMP-Nucleon scattering cross section

Rott, Siegal-Gaskins, Beacom (in prep.)




The capture rates scales as:

$\Gamma_C \sim \rho_\chi m_\chi^{-1} \sigma_A$ for $m_\chi \sim m_A$

$\Gamma_C \sim \rho_\chi m_\chi^{-2} \sigma_A$ for $m_\chi >> m_A$

number density + kinematic suppression

$m_A$ - is the target mass

# Solar WIMPs Reminder

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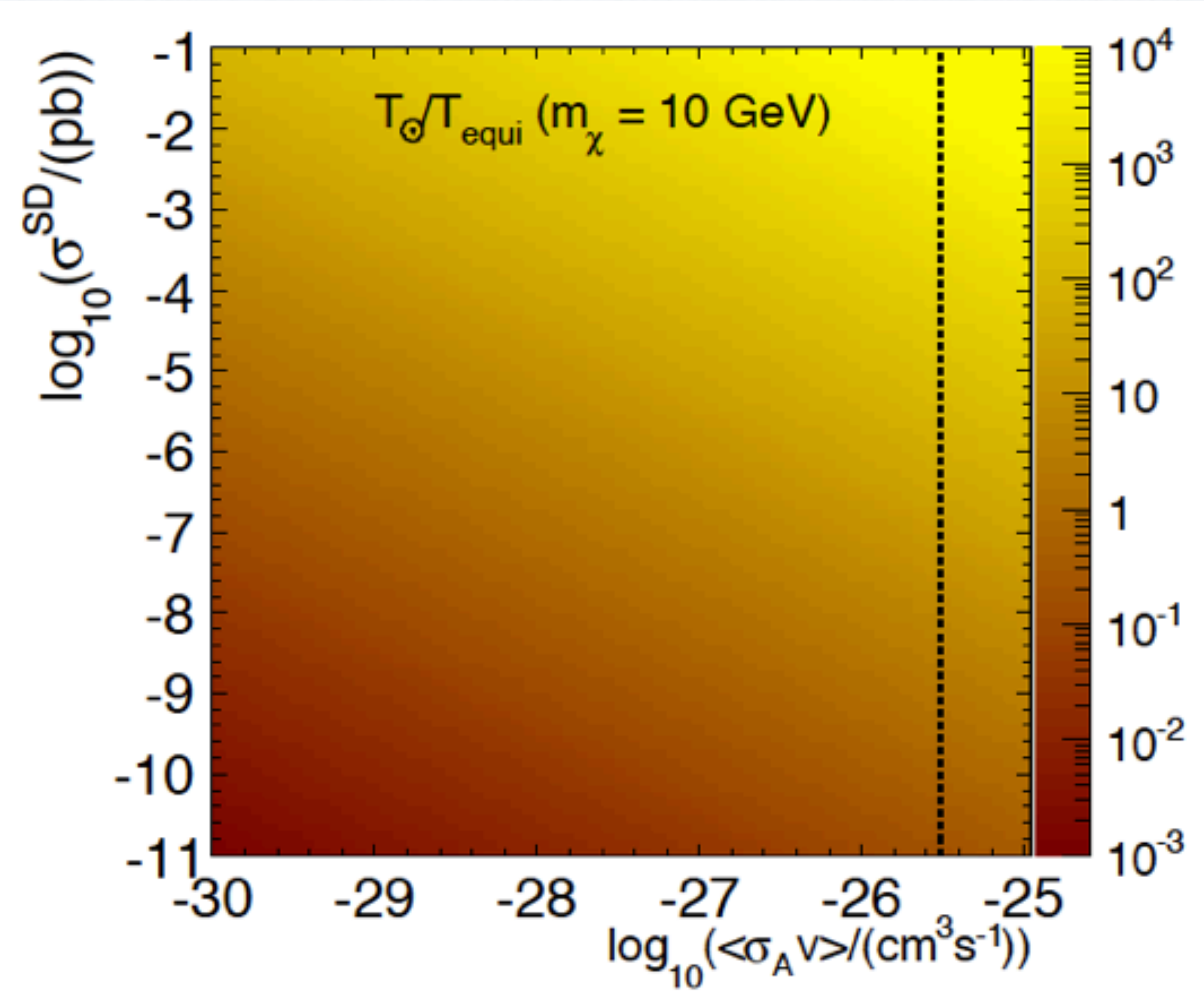


Sun is in equilibrium for thermal relic cross section and for $\sigma^{SD} > 10^{-45}cm^2$ (@$m_\chi$=10GeV)

$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$

$$\Gamma_A = \frac{1}{2} C_C \tanh^2(t/\tau)$$

$$\tau = 1/\sqrt{C_C C_A}$$

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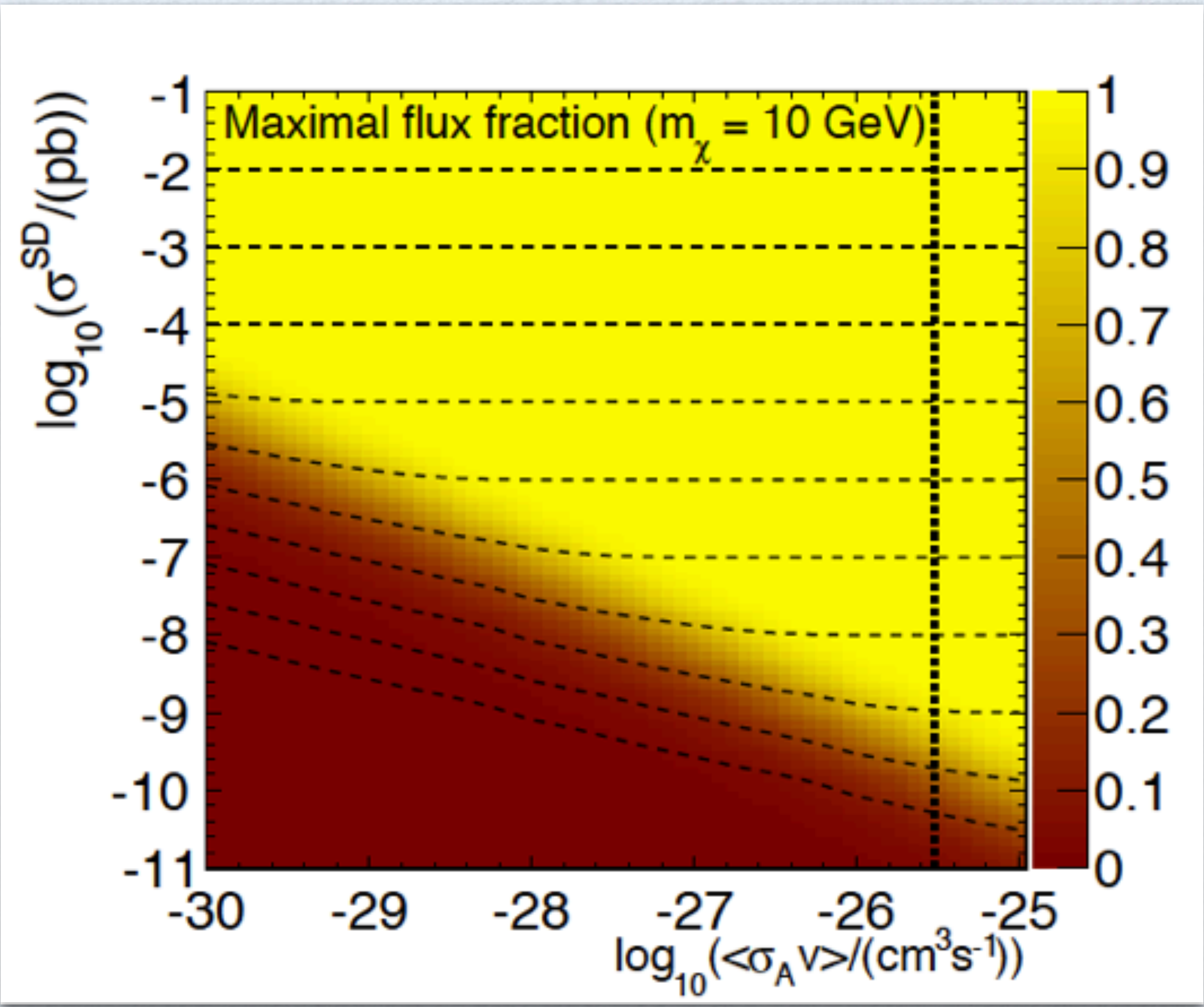


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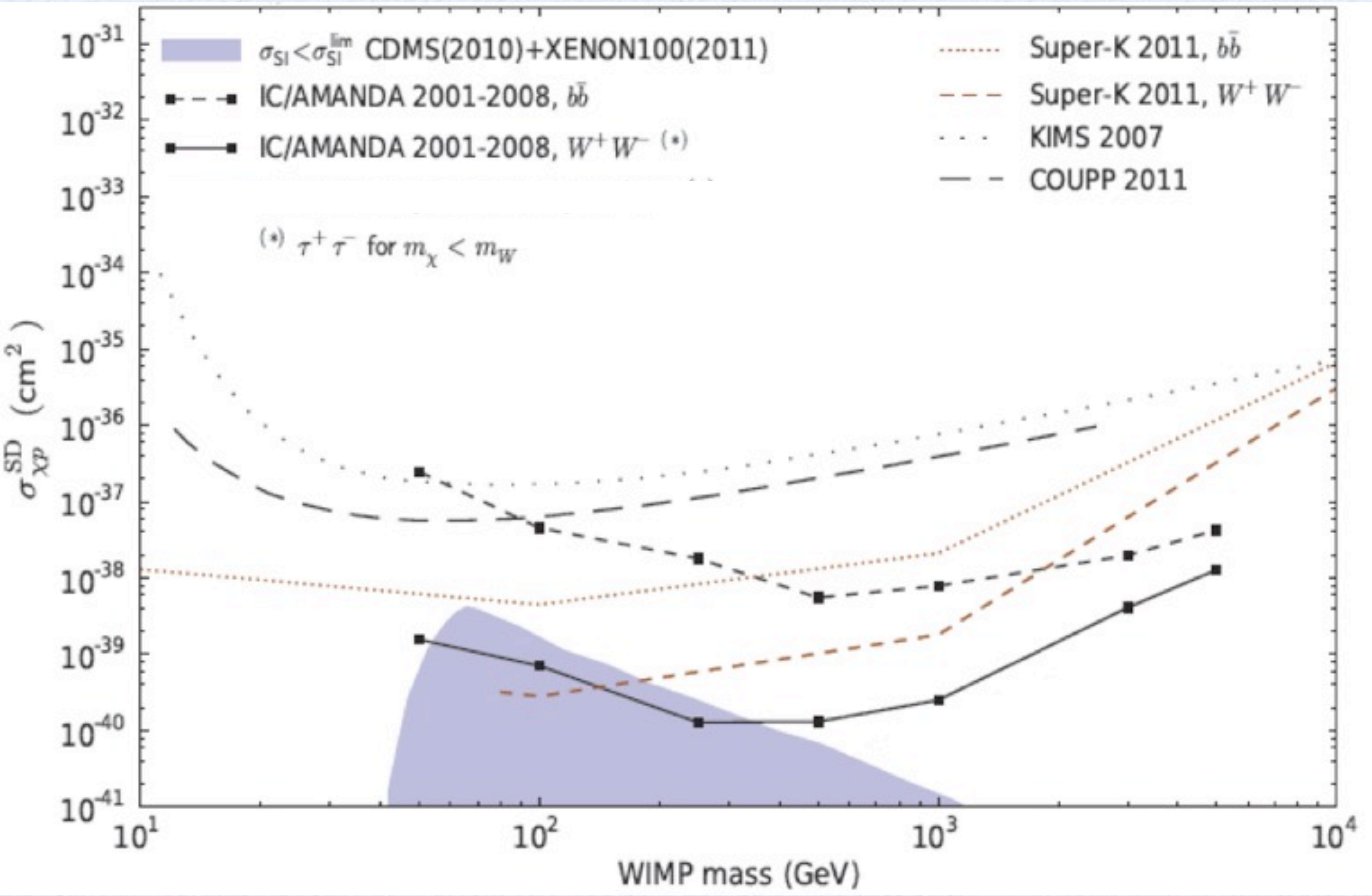
# Published limits on the WIMP-nucleon scattering cross section

T. Tanaka et al. Astrophys. J. 742, 78 (2011)
R. Abbasi et al. Phys. Rev. D 85, 042002 (2012)



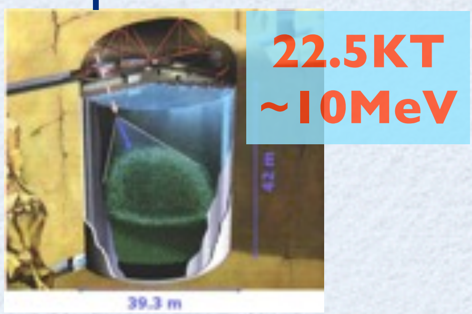

Neutrino constraints from neutrino induced up-going muon flux

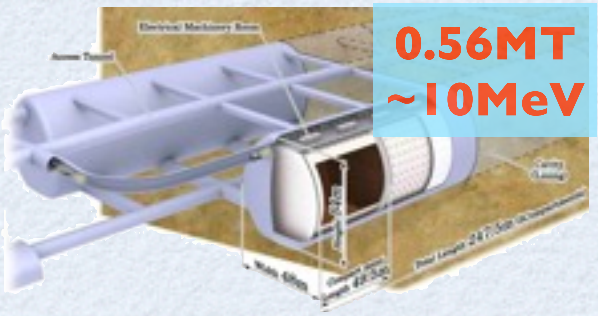
# Developments

- For obvious reasons Solar WIMP searches have relied on muon neutrino induced muon fluxes
    - Good pointing resolution
    - Muon range extends effective volume
- Recent developments:
    - Detectors get larger
    - Interest in low-mass WIMPs

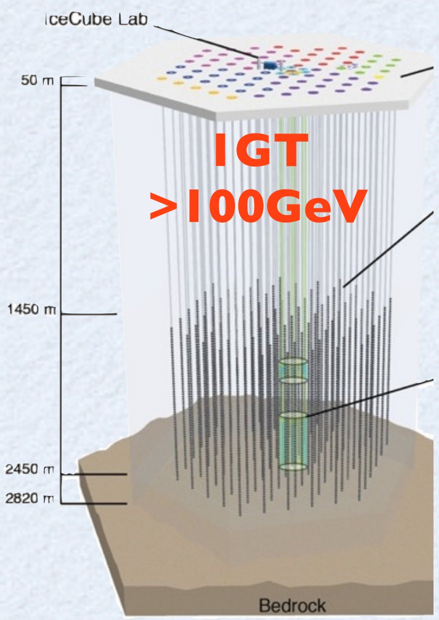
Examples:

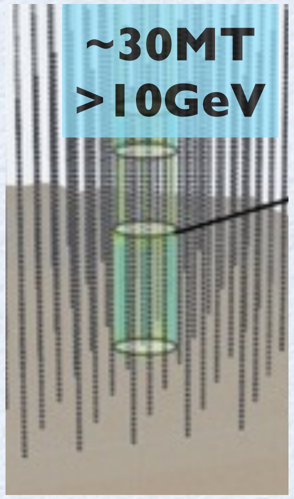
Super-K → Hyper-K

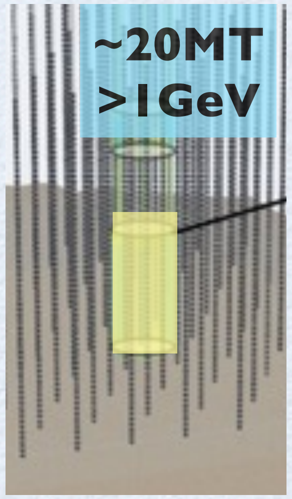


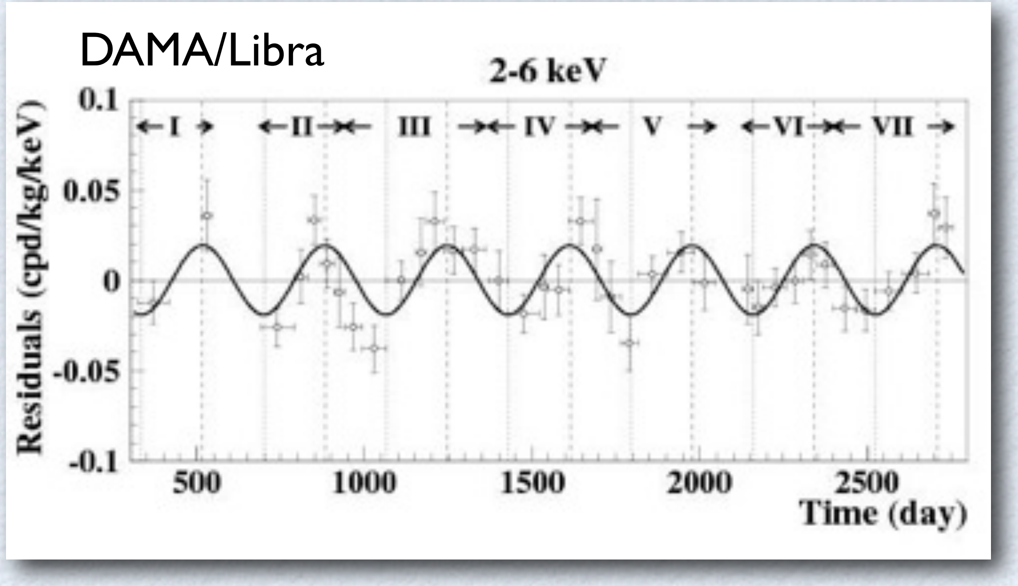




IceCube → DeepCore → PINGU → ...



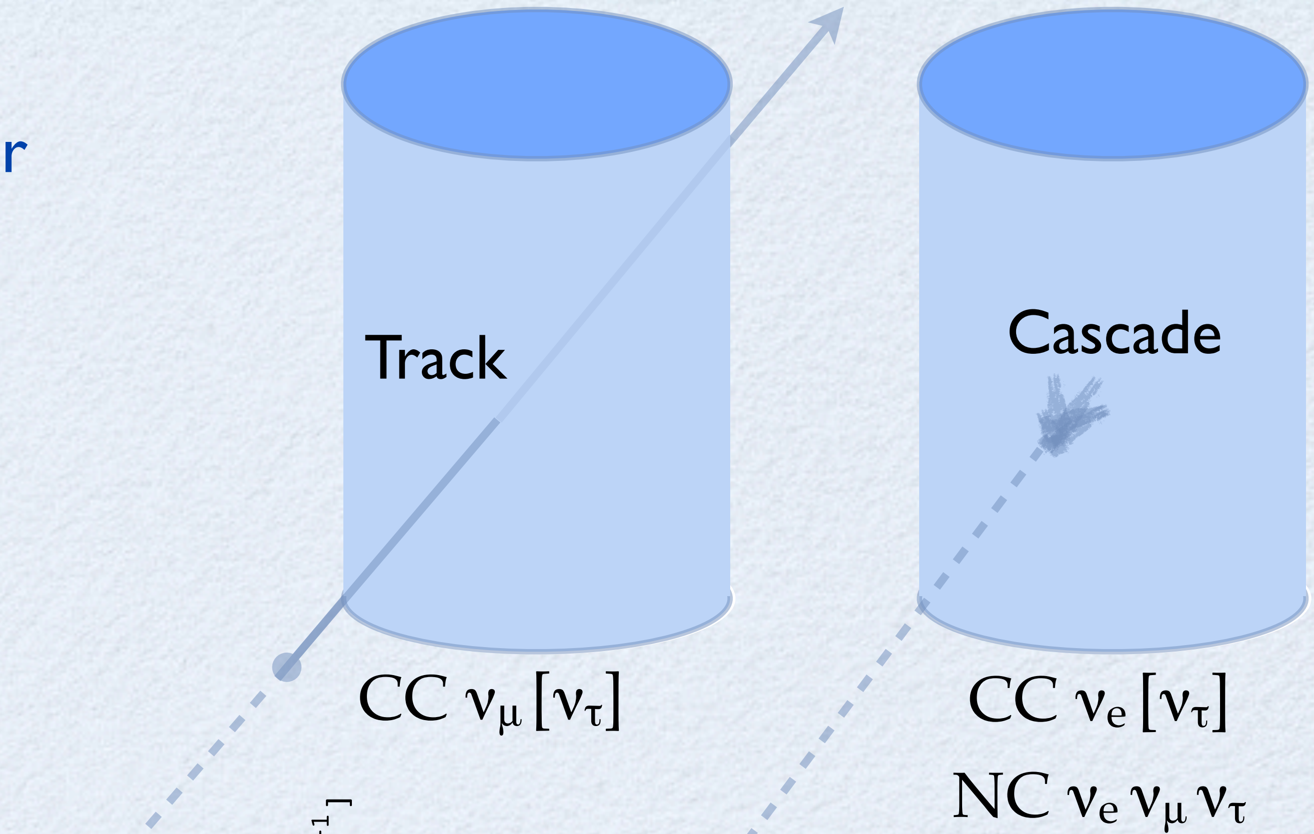



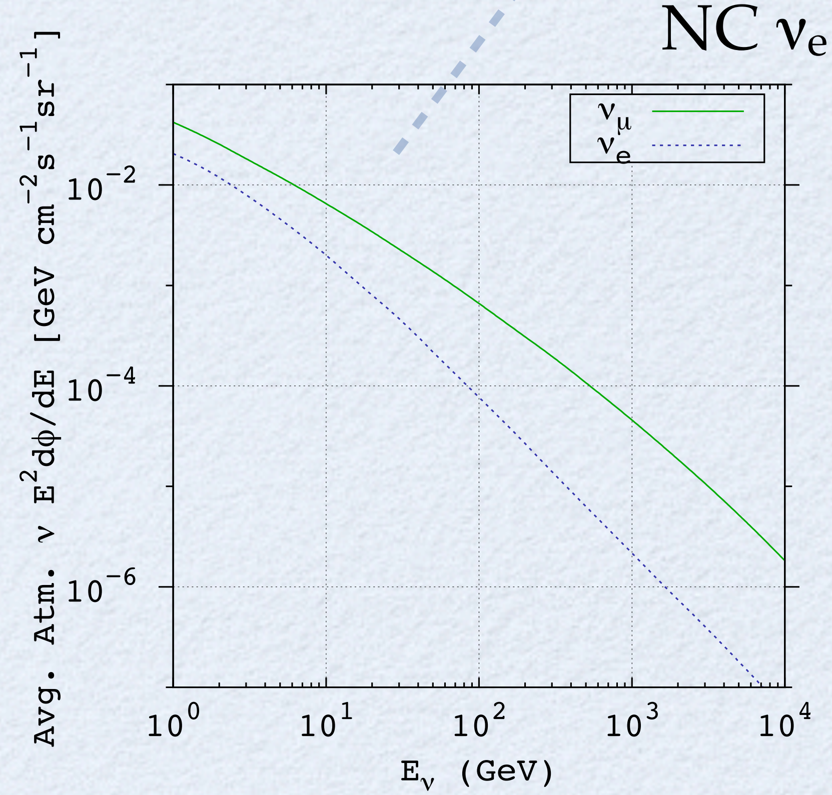



# Comparison of tracks and cascades

- For neutrino energies where the average muon track length approaches the detector diameter:
  - $\nu_\mu$ $\nu_e$ signal rates similar
  - but $R(\nu_\mu^{atm}) >> R(\nu_e^{atm})$
- $\nu_\tau$ and NC events also contribute to signal cascade rates
- Fully contained events
  - Better energy resolution
  - Utilize all data (not just up-going (Sun is below horizon))
  - Treat all flavors in a similar way
  - Less dependence on "muon propagation"



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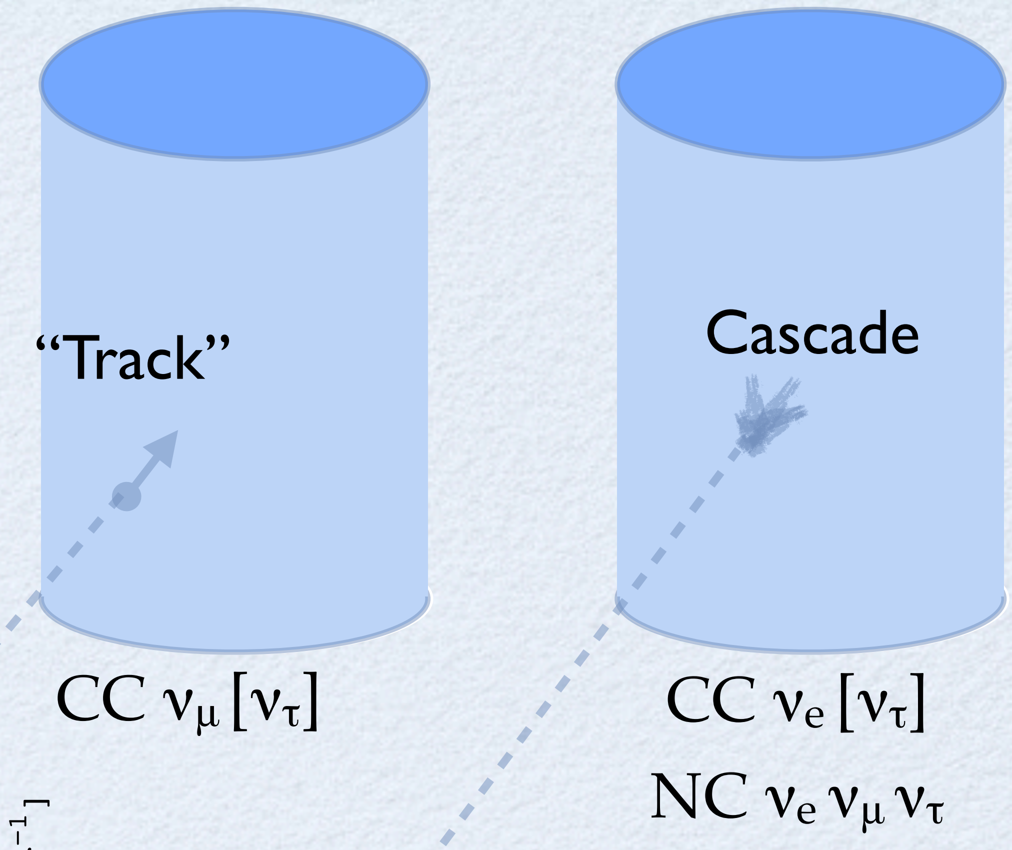


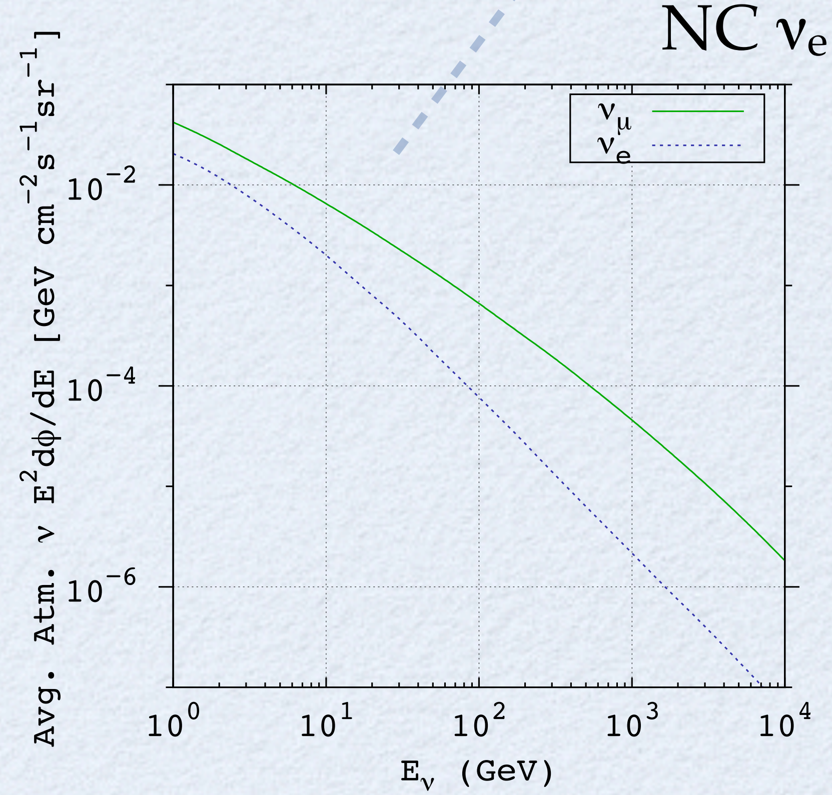

# Flux Conversion

Following results were obtained through a DarkSUSY study for a generic neutrino telescope

# Flux Conversion

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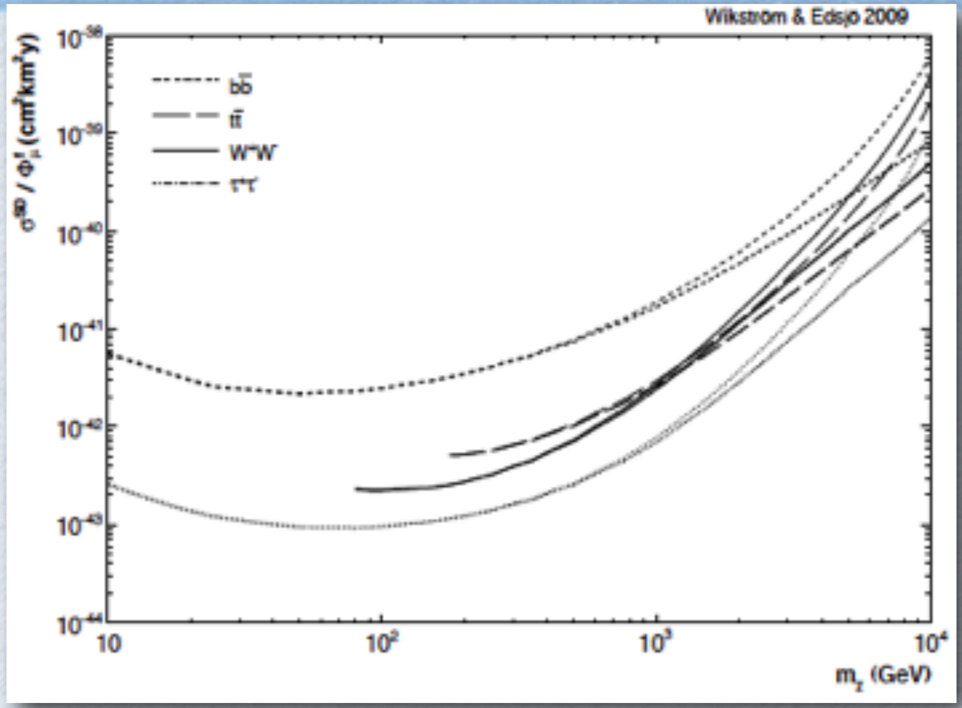
  - M. Kamionkowski et al., Phys. Rev. Lett. 74 (1995) 5174
  - Wikstrom & Edsjo, JCAP04 (2009) 09. arXiv 0903.2986

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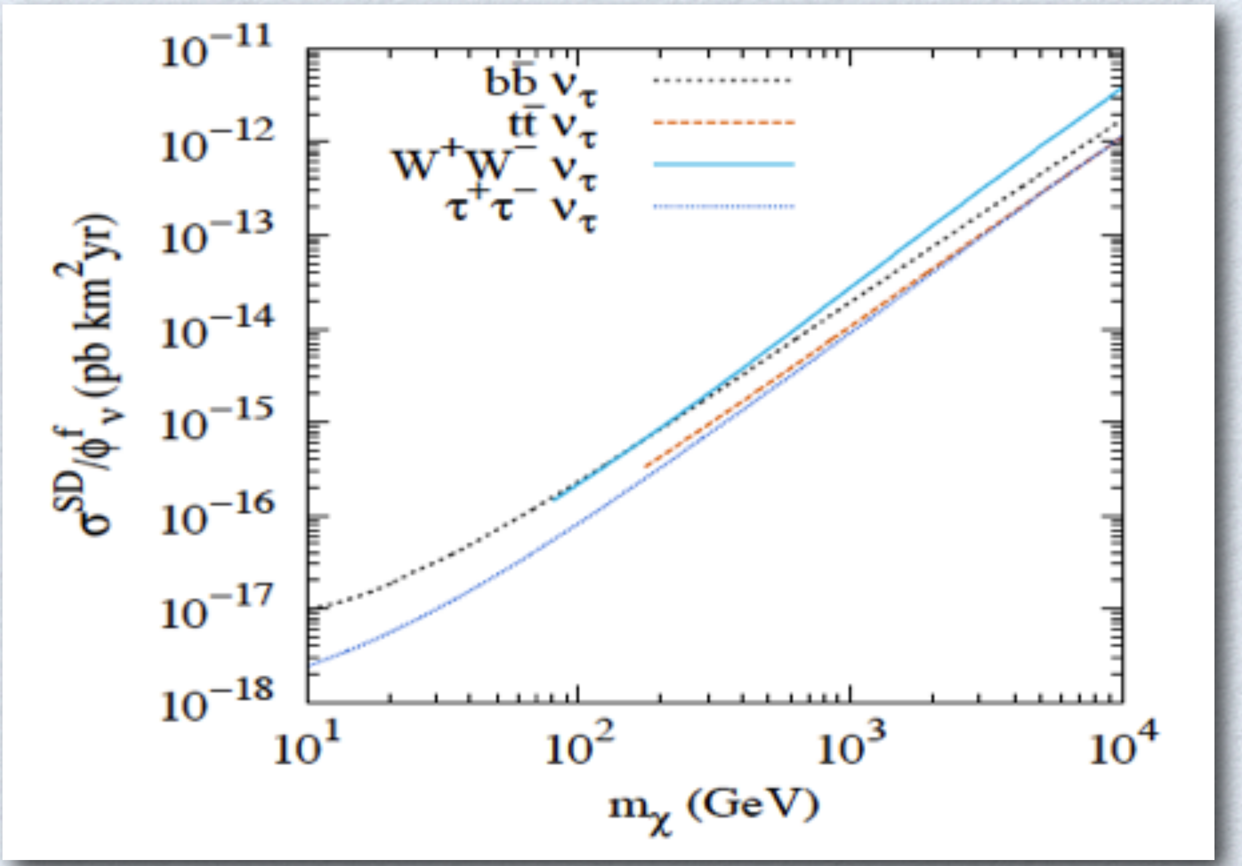

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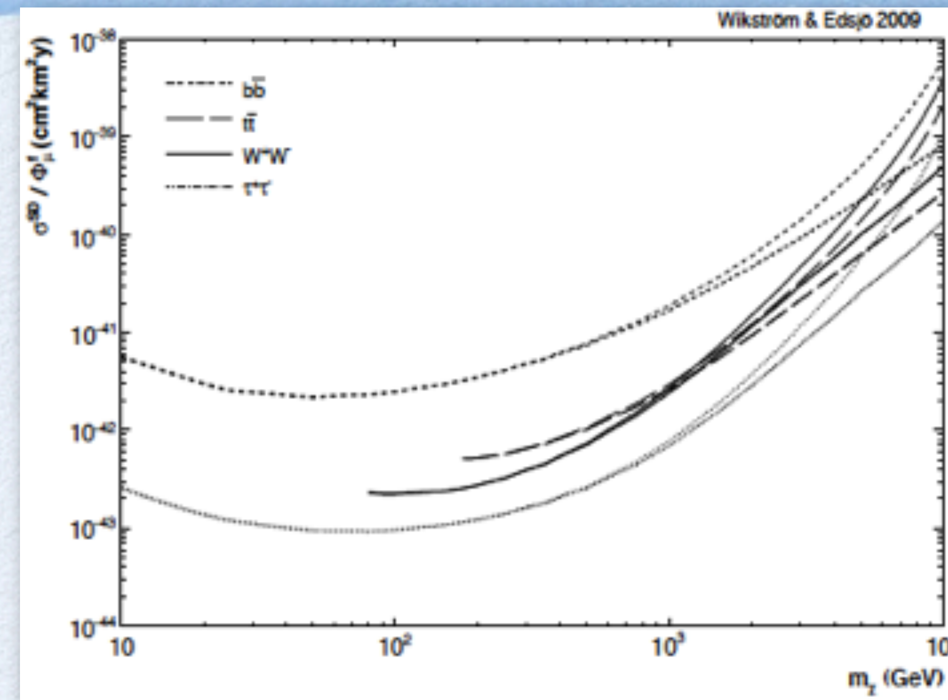


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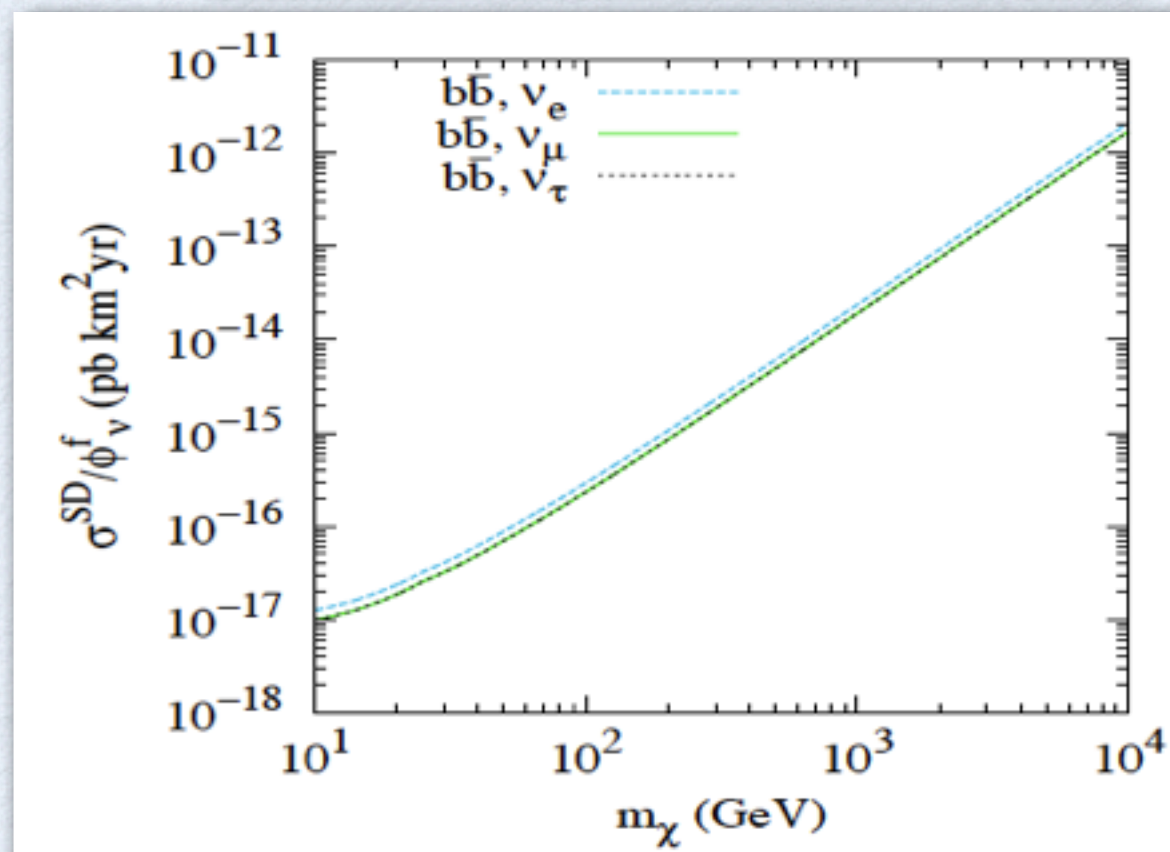
    - Integrated neutrino flux above an energy threshold (here 1GeV) look very similar
    - Neutrino flux limits allow for easier comparison of different flavor channels

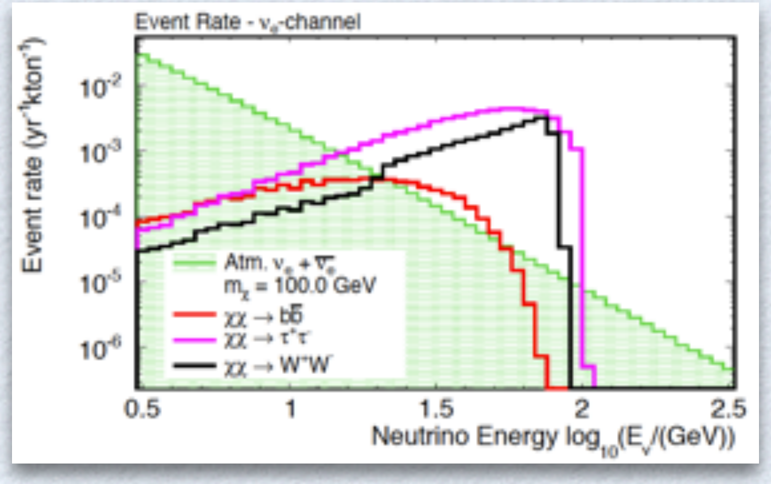


# Sensitivity

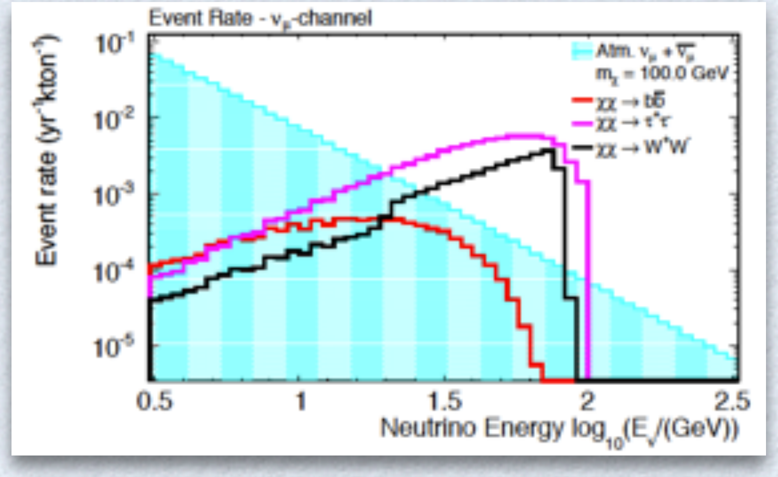
# WIMP Signal Comparison

- Example: Assume $m_\chi$=100GeV and annihilation rate of 1fb ($10^{-39}$cm$^2$)
    - ~$2.45 \times 10^{23}$ /s
- Event rates (of starting events) assume an opening angle around the Sun that is equivalent to the kinematic angle
- Assume angle average atmospheric neutrino flux (Honda) as background
- Event rates for neutrinos + antineutrinos of each flavor
- Regardless of annihilation channel the signal looks similar

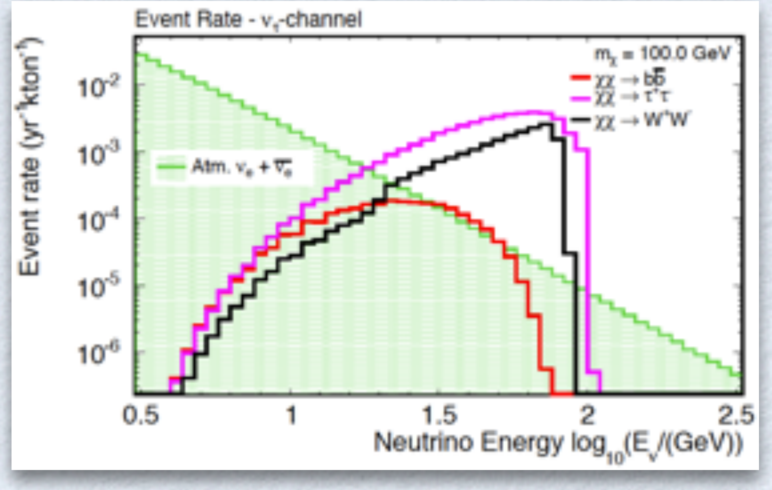
$\nu_e^{sig}$ vs. $\nu_e^{atm}$




$\nu_\mu^{sig}$ vs. $\nu_\mu^{atm}$

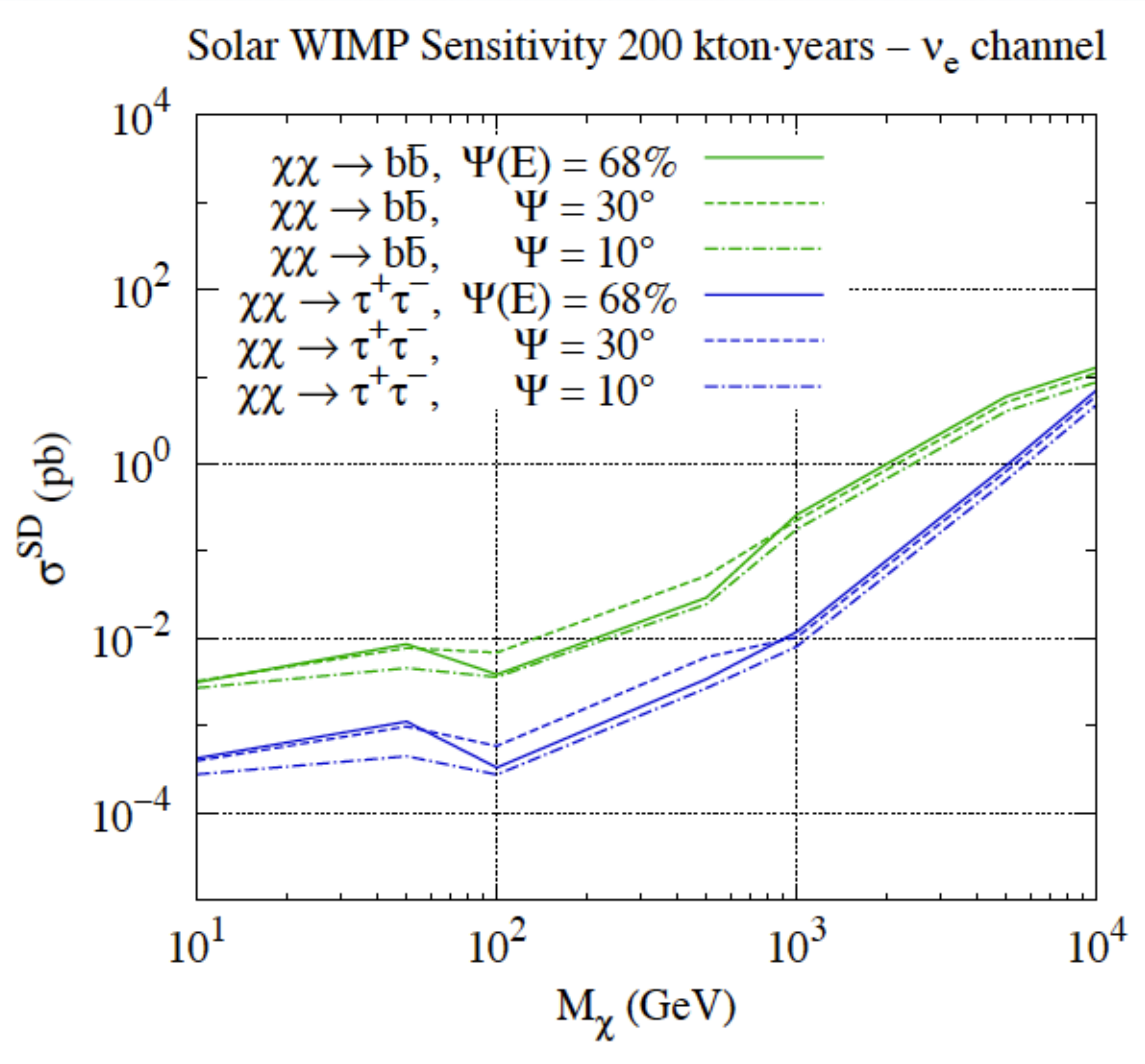



$\nu_\tau^{sig}$ vs. $\nu_e^{atm}$



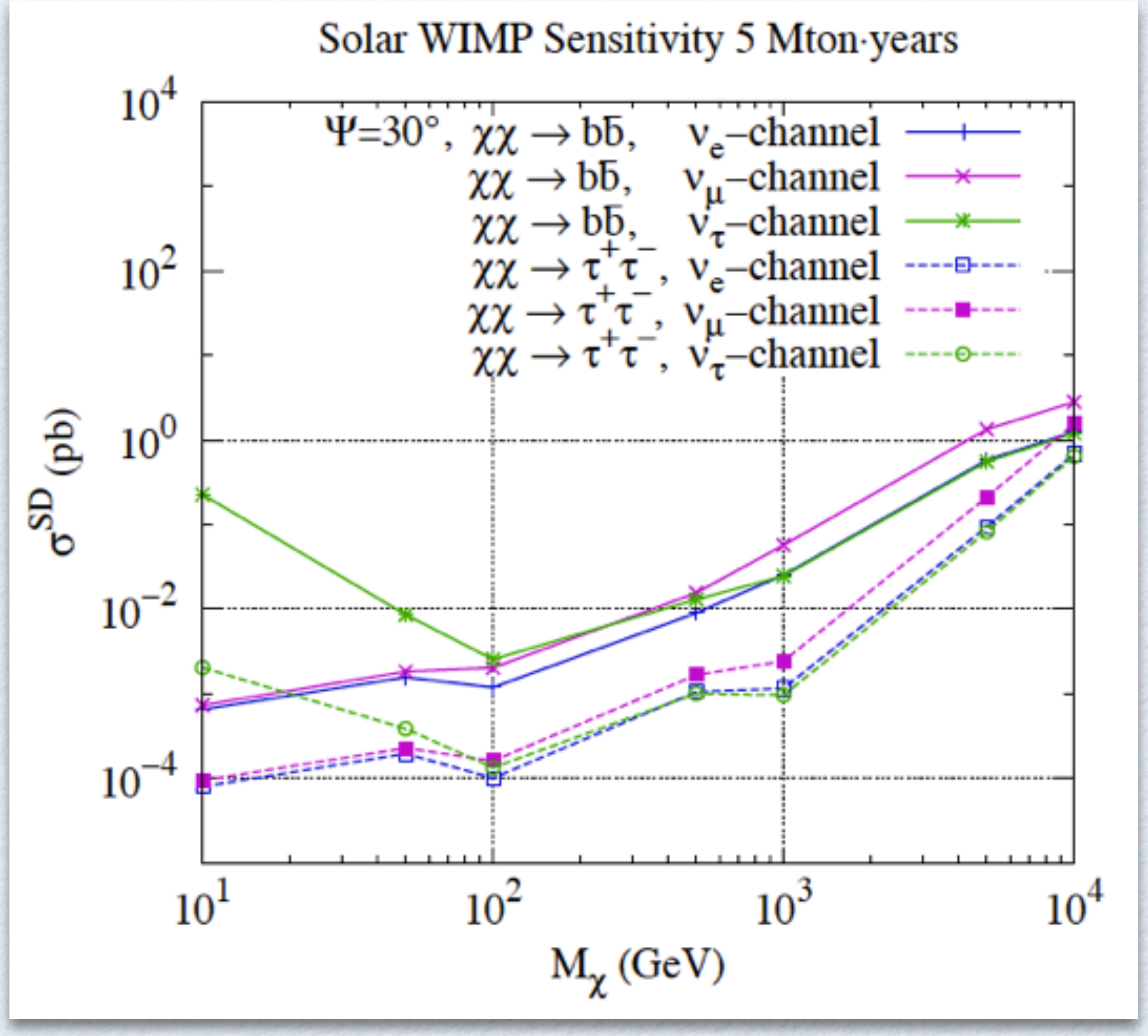
# Compute sensitivity for a generic detector

- Assume a generic detector
  - Consider vertex contained events (starting events)
    - results can be scaled to any detector size
- Compare different opening angles around the Sun
  - ψ=30°
  - ψ=10°
  - ψ(E)=68%
- Assume 3 different energy cuts:
  - $m_\chi$[10GeV,100GeV] $E_{Thr}$=1GeV
  - $m_\chi$[100GeV,1TeV] $E_{Thr}$=10GeV
  - $m_\chi$[1TeV,10TeV] $E_{Thr}$=100GeV



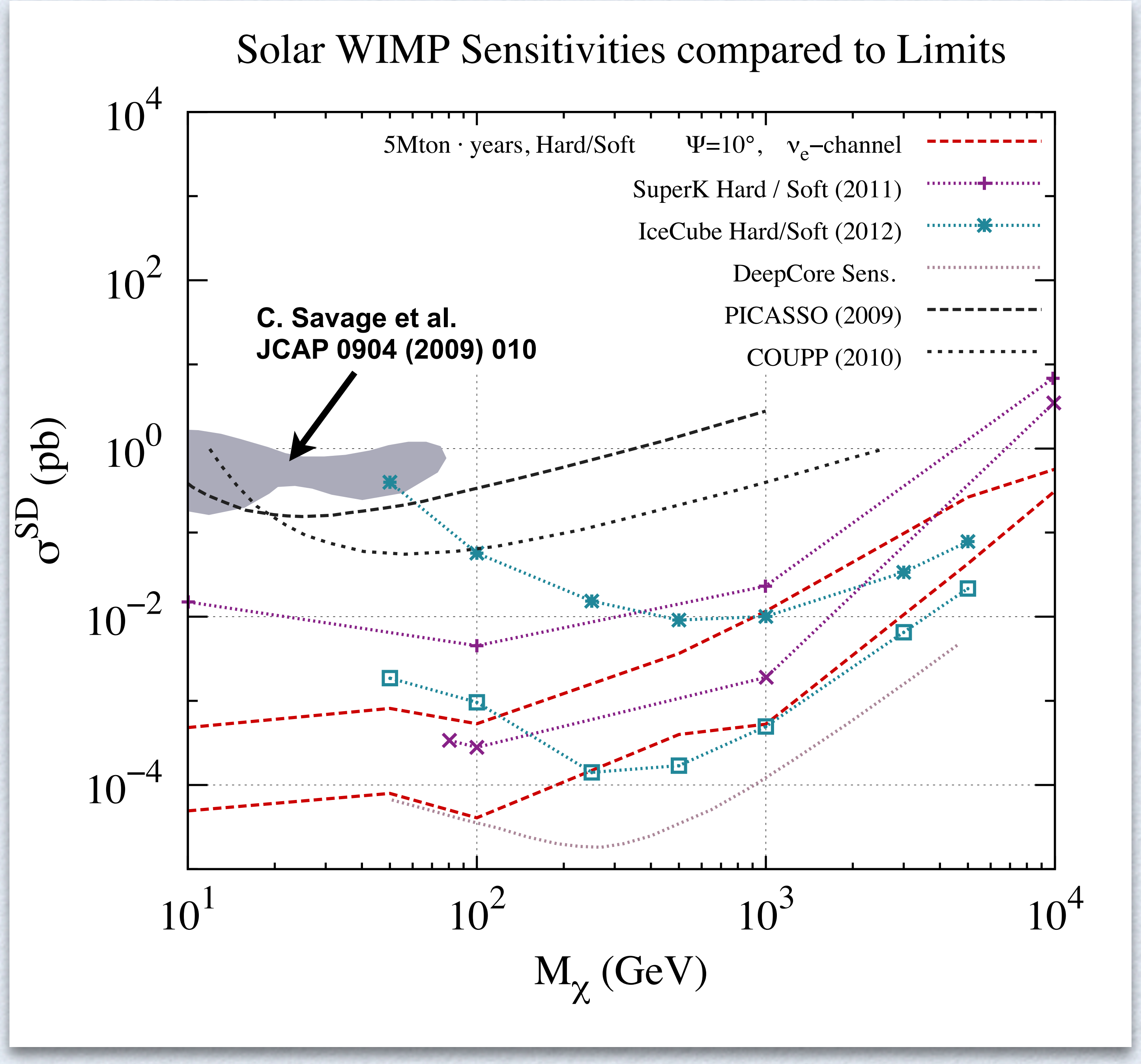
# Flavor Channel Comparison

- Obtain highly competitive sensitivities with all neutrino flavor channels for a Megaton sized detector through the application of basic spectral selection criteria.
- Best results are obtained with the electron neutrino channel



# Improvements for Low Mass WIMP Sensitivity

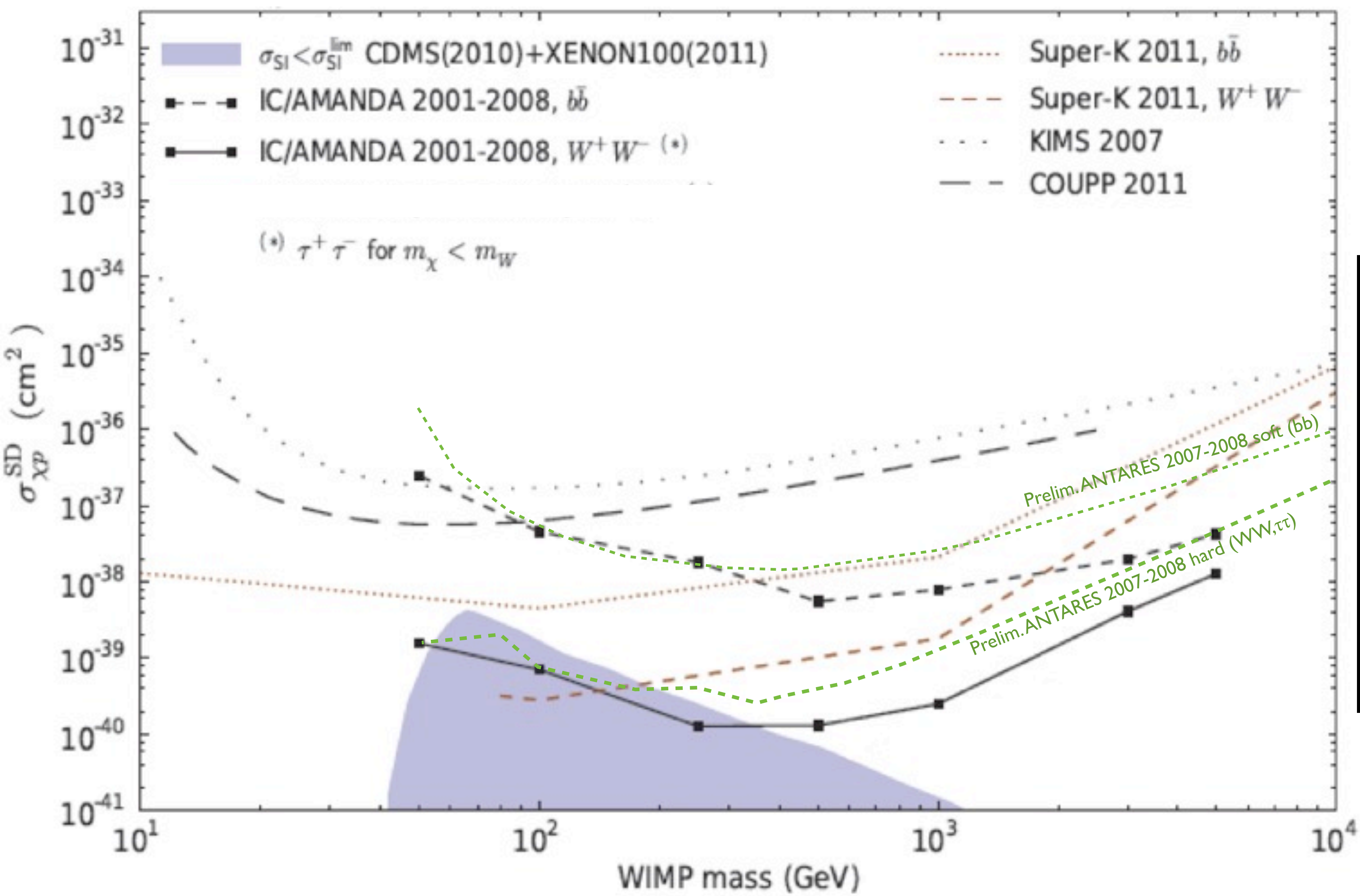
- Expanding searches to new neutrino flavors will significantly enhance the sensitivity to low-mass WIMPs
- Despite limited angular resolution competitive sensitivities can be obtained



# New experimental results (from Neutrino 2012)

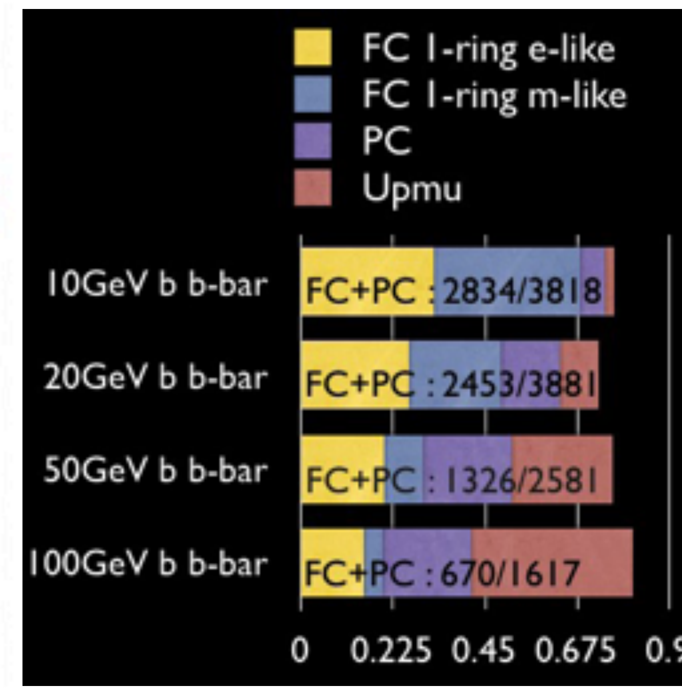
# New Preliminary SuperK 2012 Result

T. Tanaka et al. Astrophys. J. 742, 78 (2011)
R. Abbasi et al. Phys. Rev. D 85, 042002 (2012)




Significant improvement in low-mass WIMP region !

## Data from SKI-III (2806days)




Energy / Angular Fit
Derive 90% Bayesian upper limit on allowed WIMP induced events

see:
**69-3** K.Choi "Search of the WIMP from the Sun in Super-Kamiokande"

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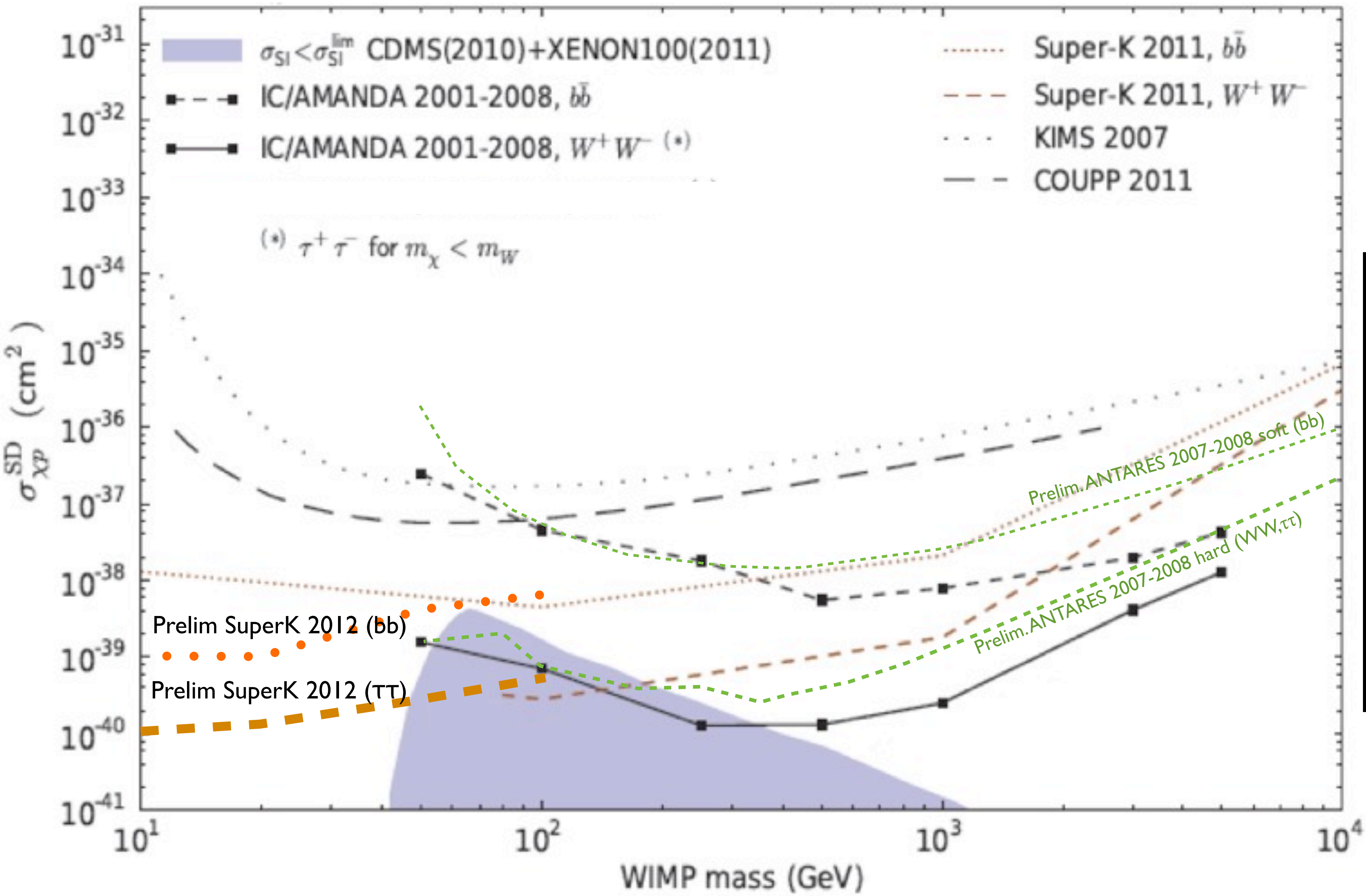
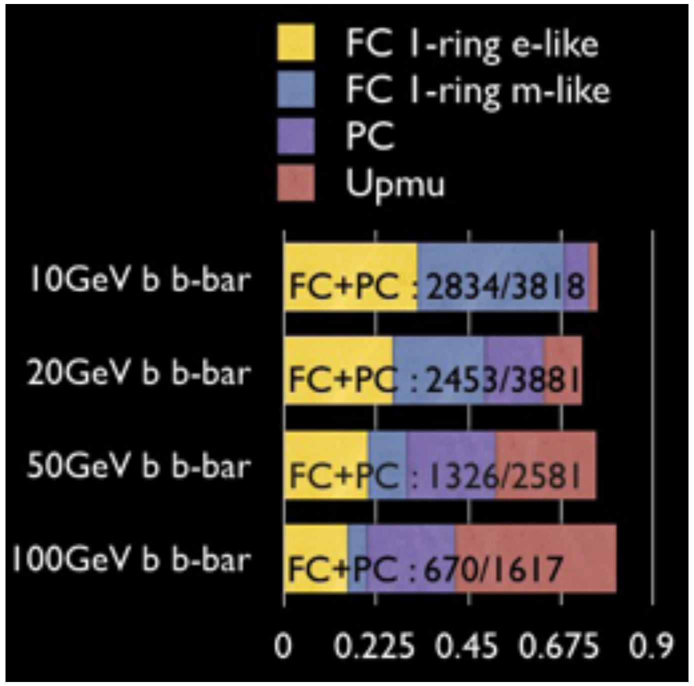



Significant improvement in low-mass WIMP region !

Data from SKI-III (2806days)




Energy / Angular Fit
Derive 90% Bayesian upper limit on allowed WIMP induced events

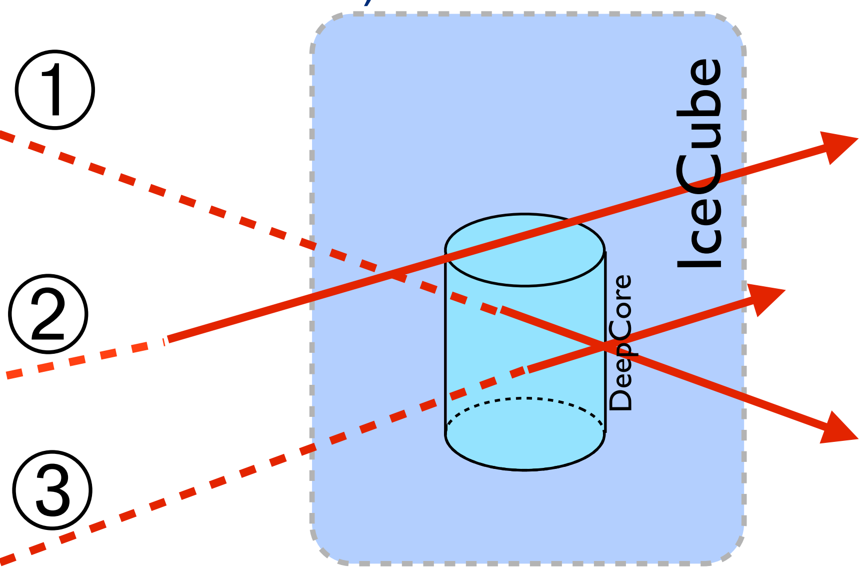
see:

**69-3** K.Choi "Search of the WIMP from the Sun in Super-Kamiokande"

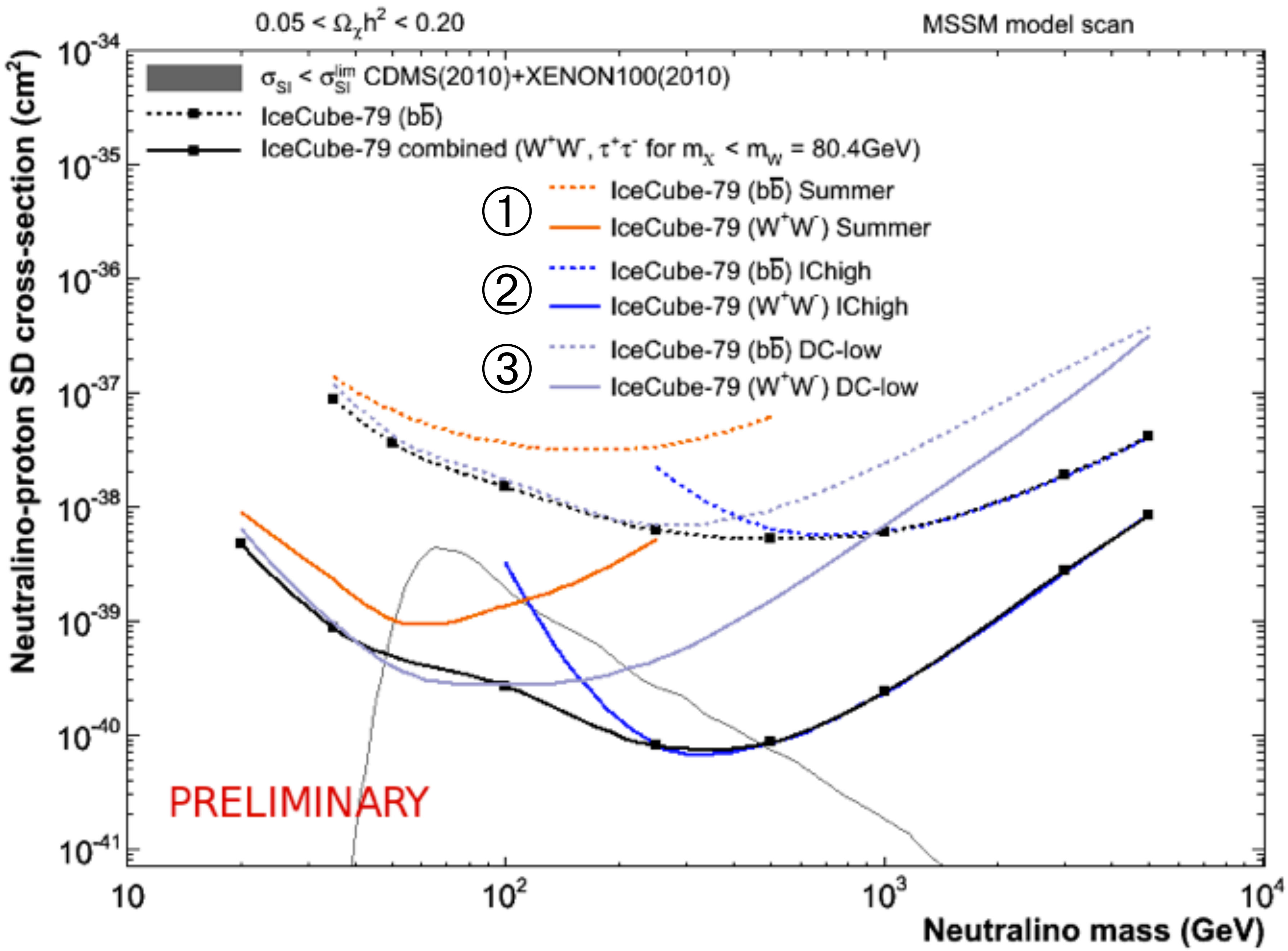
# New DeepCore Solar WIMP Sensitivity

IceCube 79-string 318days (May 2010 - May 2011)

Analysis performed separately for austral summer (Sun above horizon) and austral winter (Sun below horizon)




Compare distribution of the final sample to these PDFs of background and signal to determine most likely signal content and combine likelihoods, weighted by relative livetime




$$\mathcal{L}(\mu) = \prod_i^{n_{obs}} f(\Psi_i|\mu), \quad \text{where} \quad f(\Psi|\mu) = \frac{\mu}{n_{obs}} f_s(\Psi) + (1 - \frac{\mu}{n_{obs}}) f_{bg}(\Psi)$$

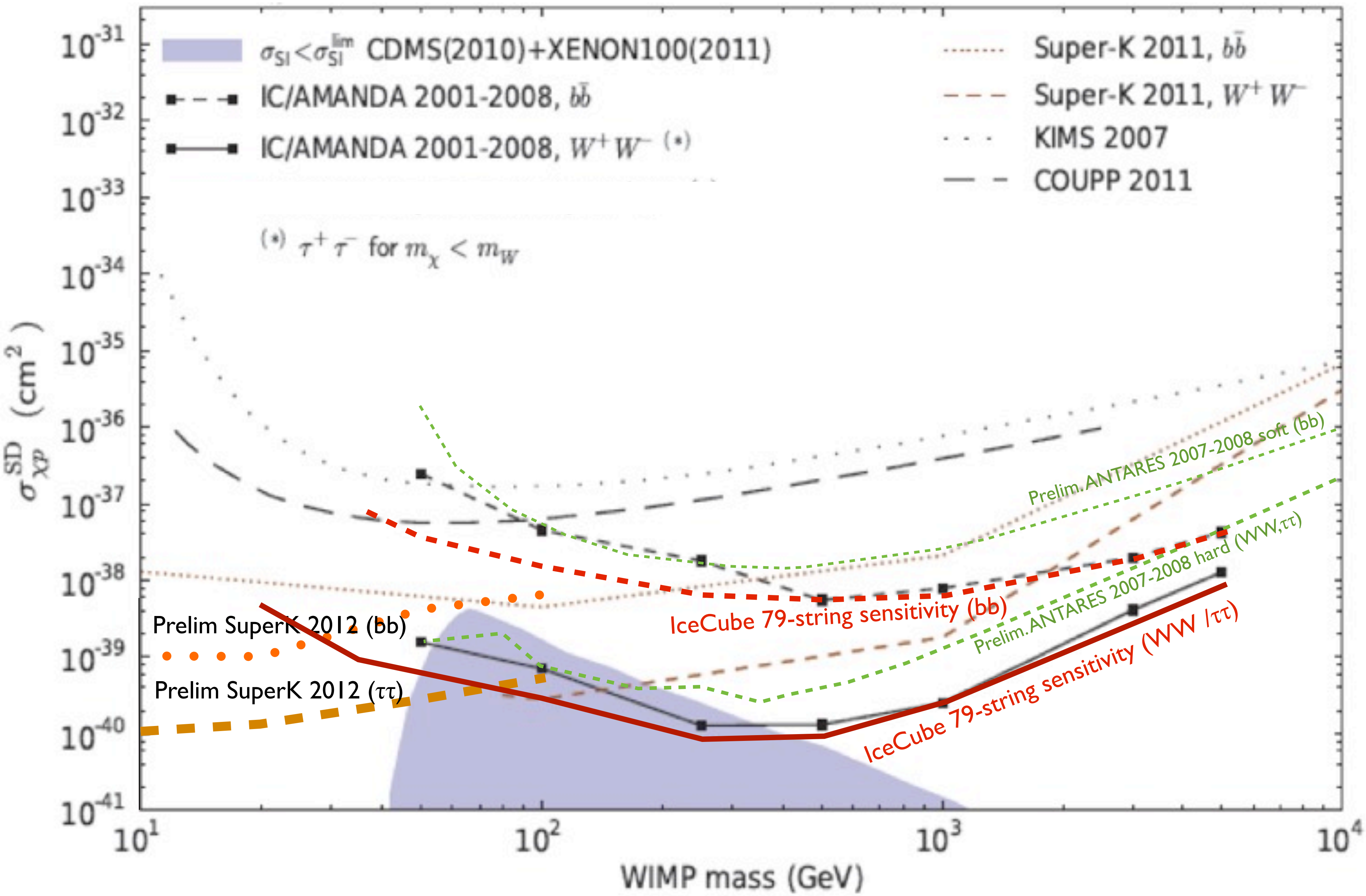
see also:

**74-2** M. Danninger and E. Strahler "Search for Dark Matter Captured in the Sun with the IceCube Neutrino Observatory"

**76-1** J.Miller "Search for Secluded Dark Matter using the IceCube Neutrino Observatory"

# New DeepCore Sensitivity

T. Tanaka et al. Astrophys. J. 742, 78 (2011)
R. Abbasi et al. Phys. Rev. D 85, 042002 (2012)




1 year of IceCube 79-string as sensitive as 7years of AMANDA + partially instrumented IceCube

Sensitivity extends to WIMP masses down to 20GeV

Full analysis results to be released soon ... stay tuned !

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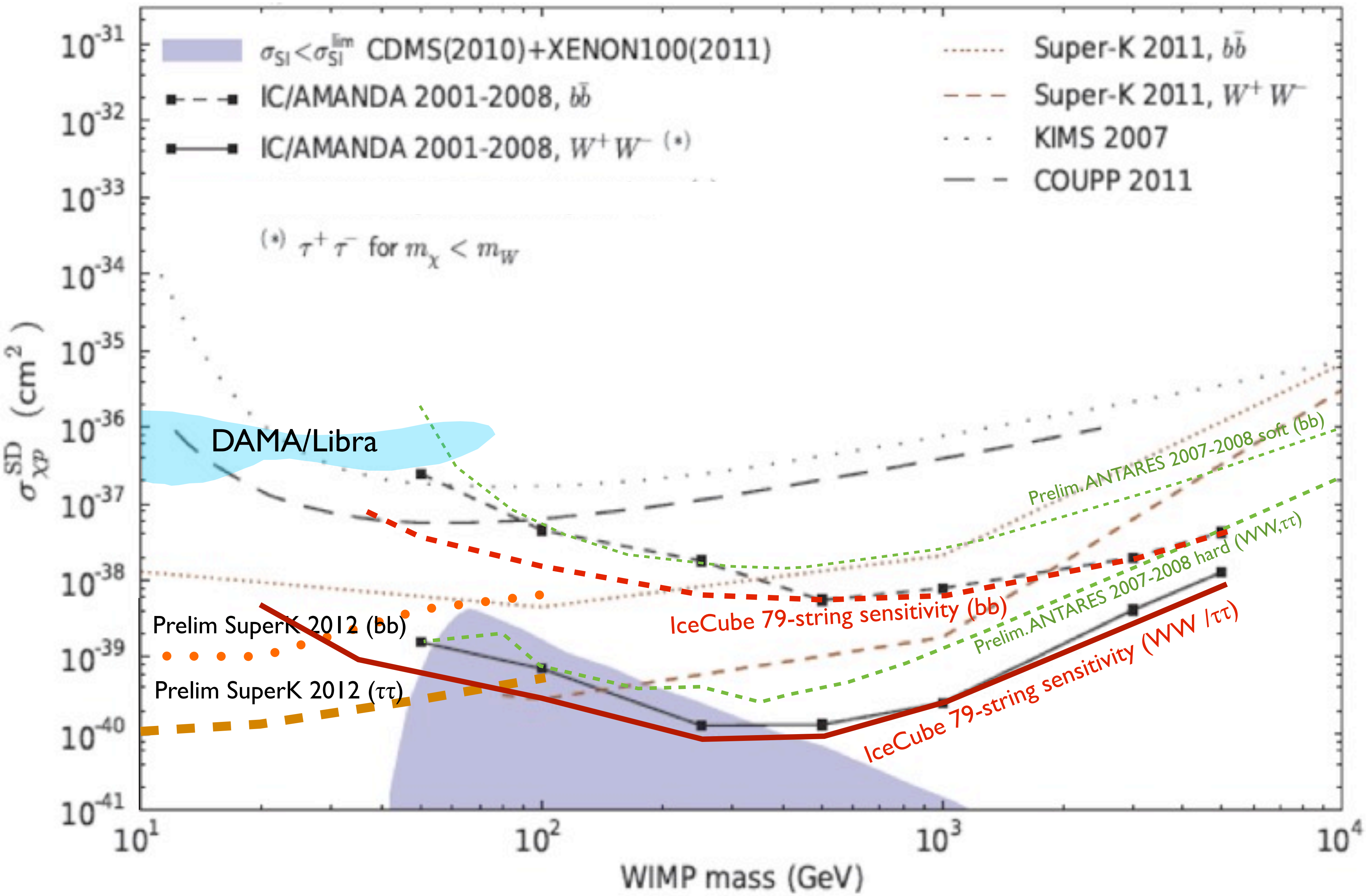


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# UNCERTAINTY

# Uncertainty categories

- Divide uncertainties conveniently into three uncorrelated categories:
- Annihilation Rate at Equilibrium
  - Capture Rate
  - Suppression factors
- Neutrino Propagation
  - Matter effects in the Sun
  - "Vacuum" oscillations Sun → Earth
  - Oscillation in the Earth
- Neutrino Detection
  - Detector site and Detector related effects

common to neutrino detectors

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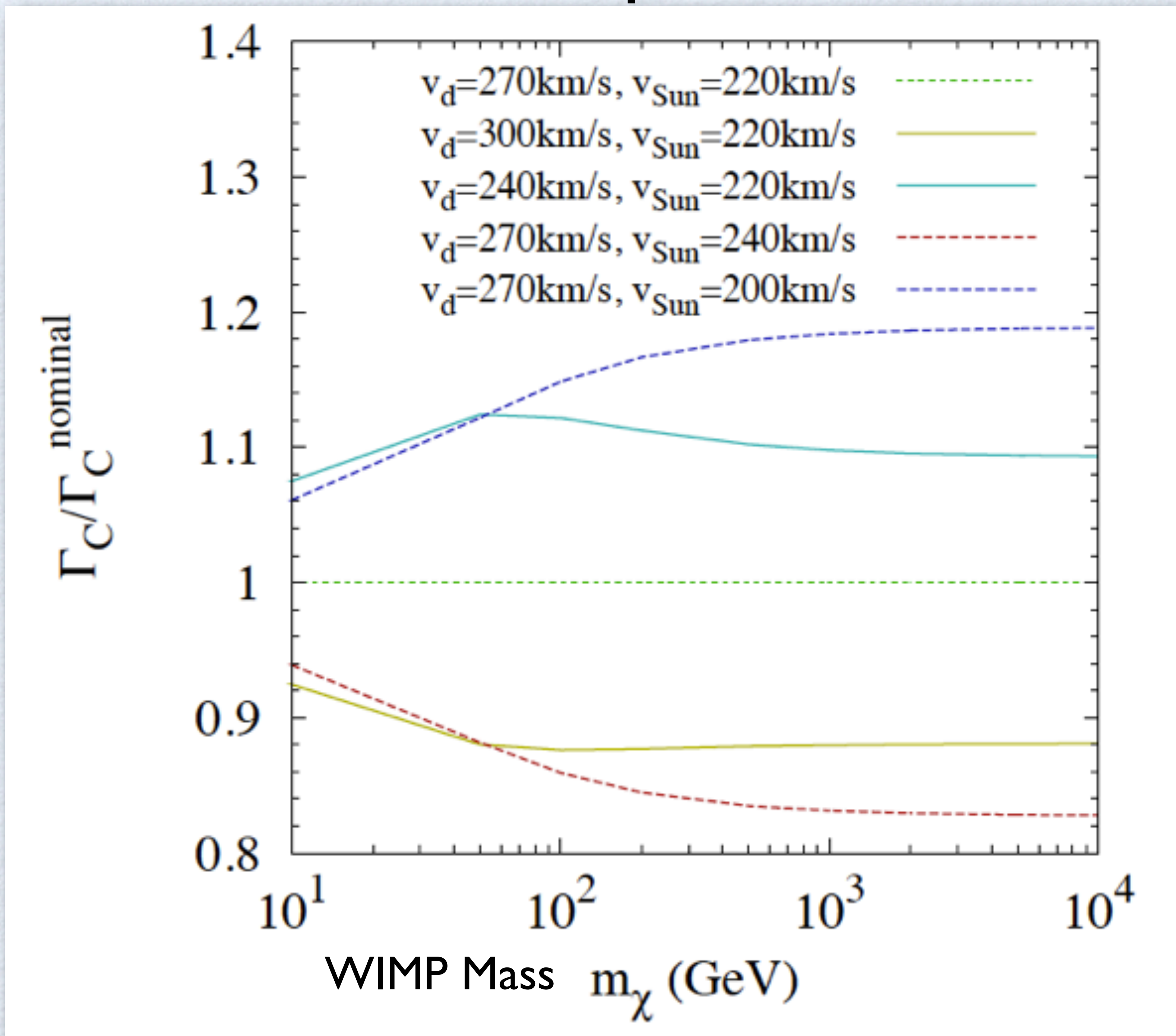
common to neutrino detectors

| | |
|---|---|
| Local Dark Matter Density<br><br>0.3GeV/cm$^3$ ? | Solar circular velocity<br><br>220km/s ? |
| WIMP velocity distribution<br><br>Maxwellian ?<br><br>velocity dispersion 270km/s ? | Capture process<br><br>impact of planets ? |

# Halo Uncertainties on the Capture Rate

## Effect on Capture Rate $\Gamma_C$




- Assume a Maxwellian velocity distribution of the WIMPs outside the potential well of the Sun with a dispersion of $v_d$ = 270km/s
- Circular velocity of the Sun is assumed to be $v_{SUN}$ = 220km/s
- Linear scaling of $\Gamma_C$ with local dark matter density

**NDM2012**

M. Honma (Talk):
favor "fast" angular velocity at Sun >220km/s

Y. Sofue (Poster):
local dark matter density = 0.235 ± 0.030 GeV/cm$^3$

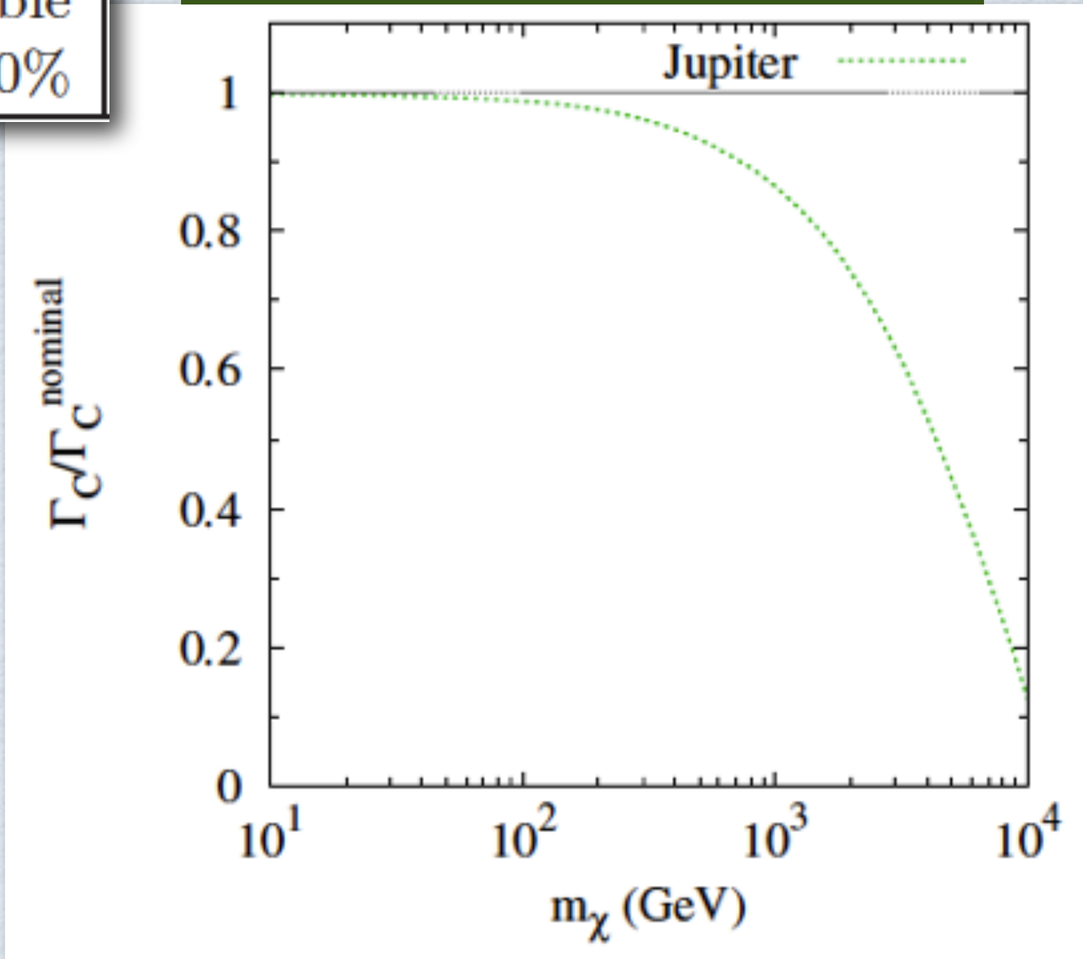
# Summary of Uncertainties

| Uncertainty | WIMP Mass $m_\chi$ 10 GeV | 100 GeV | 1 TeV |
|---|---|---|---|
| Dark matter density | $^{+130\%}_{-17\%}$ | $^{+130\%}_{-17\%}$ | $^{+130\%}_{-17\%}$ |
| Capture process (Planets) | $< 1\%$ | $\sim 1\%$ | $\pm 20\%$ |
| Solar composition | $\sim 1\%$ | $\sim 1\%$ | $\sim 1\%$ |
| Solar velocity | $\pm 6\%$ | $\pm 15\%$ | $\pm 18\%$ |
| Velocity dispersion | $\pm 8\%$ | $\pm 12\%$ | $\pm 10\%$ |
| Velocity distribution | Large enhancements possible | | |
| Evaporation | small | $\sim 0\%$ | $\sim 0\%$ |

R.Catena & P. Ullio JCAP 08 (2010) 004
M.Pato et al. Phys. Rev. D82 (2010) 023531
P.Salucci et al. Astron. Astrophys. 523 (2010) A83
J. Bovy & S. Tremaine 1205.4033

- While uncertainties in the dark matter distribution can result in significantly different annihilation rates in the Sun, results tend to be on the conservative side
- Direct detections have to deal with the same uncertainties, and interpretations of results is by no means simpler
- Sun irons out fluctuations in the local density or velocity distribution

A. Peter et al. Phys. Rev. D79 (2009) 103532
S. Sivertsson and J. Edsjo (2012)



# ANNIHILATION CHANNELS

# New Solar WIMP channel

Possible annihilation channels:

qq,gg,cc,ss,bb,tt,$W^+W^-$, ZZ, $\tau^+\tau^-$,$\mu^+\mu^-$, $\nu\nu$, $e^+e^-$,$\gamma\gamma$

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no neutrinos

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some "high energy" neutrinos in decays

⇒ basis of present day searches

$$\tau^- \longrightarrow \bar{\nu}_\mu \nu_\tau \mu^-$$

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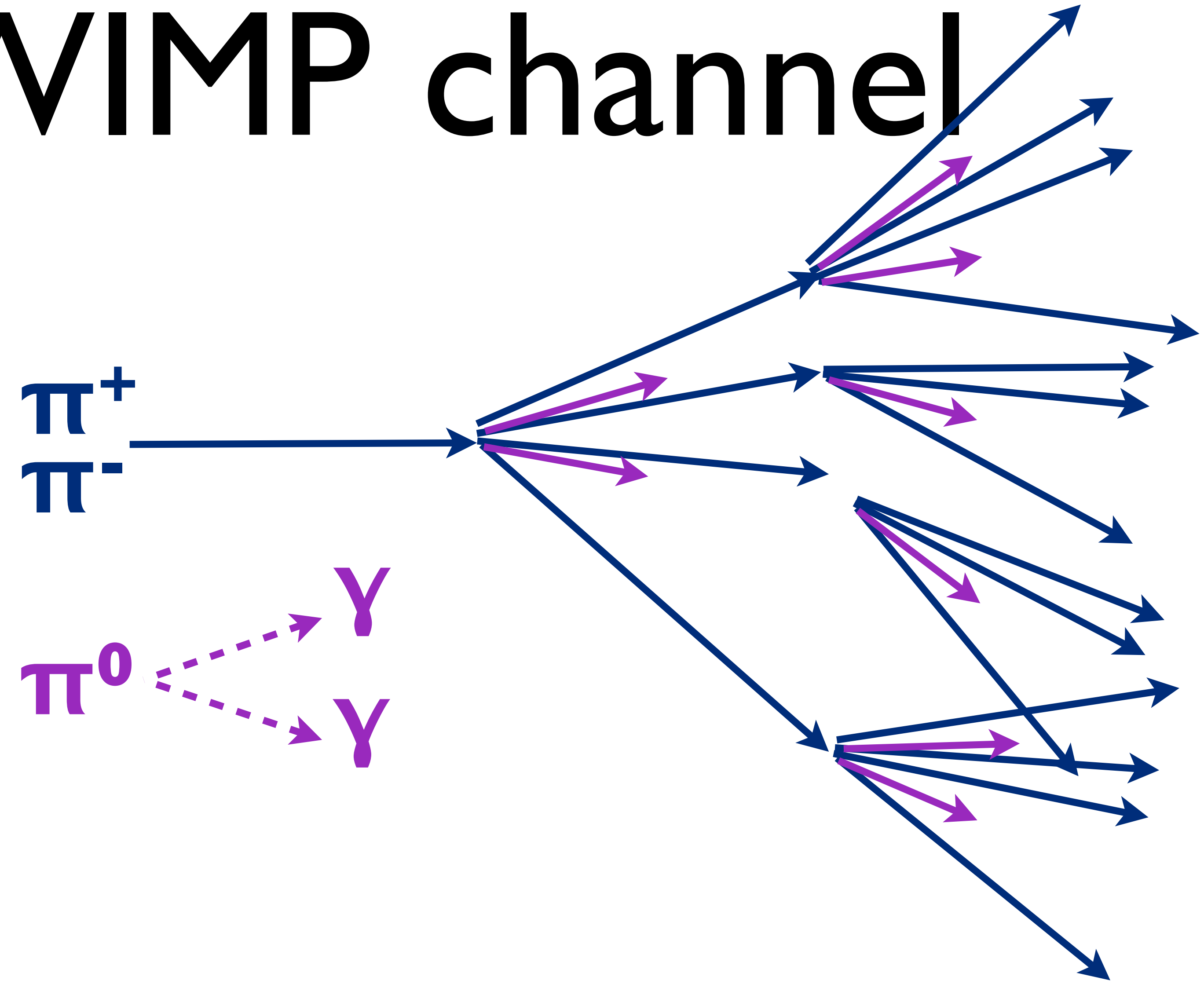

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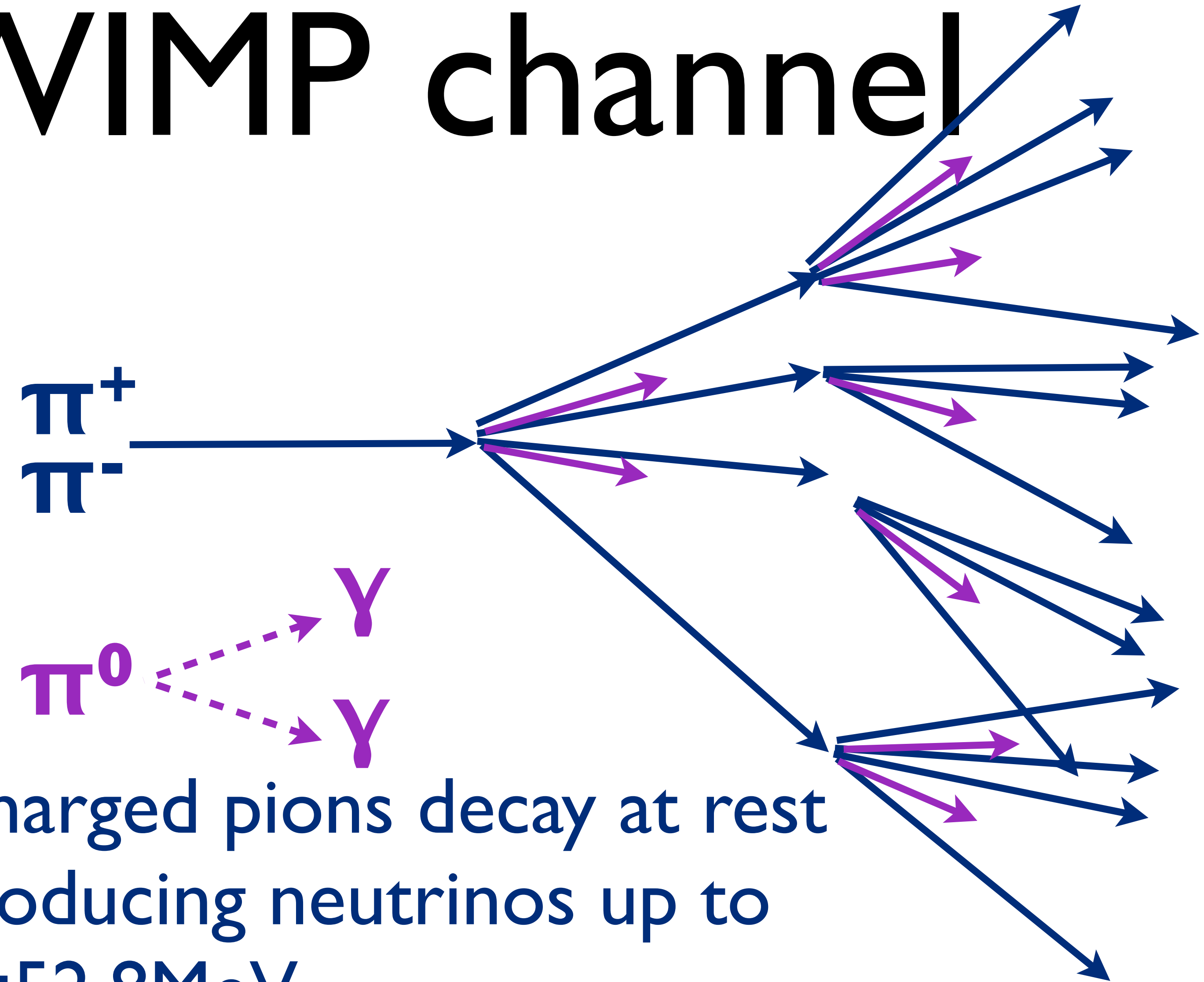


Charged pions decay at rest producing neutrinos up to E=52.8MeV

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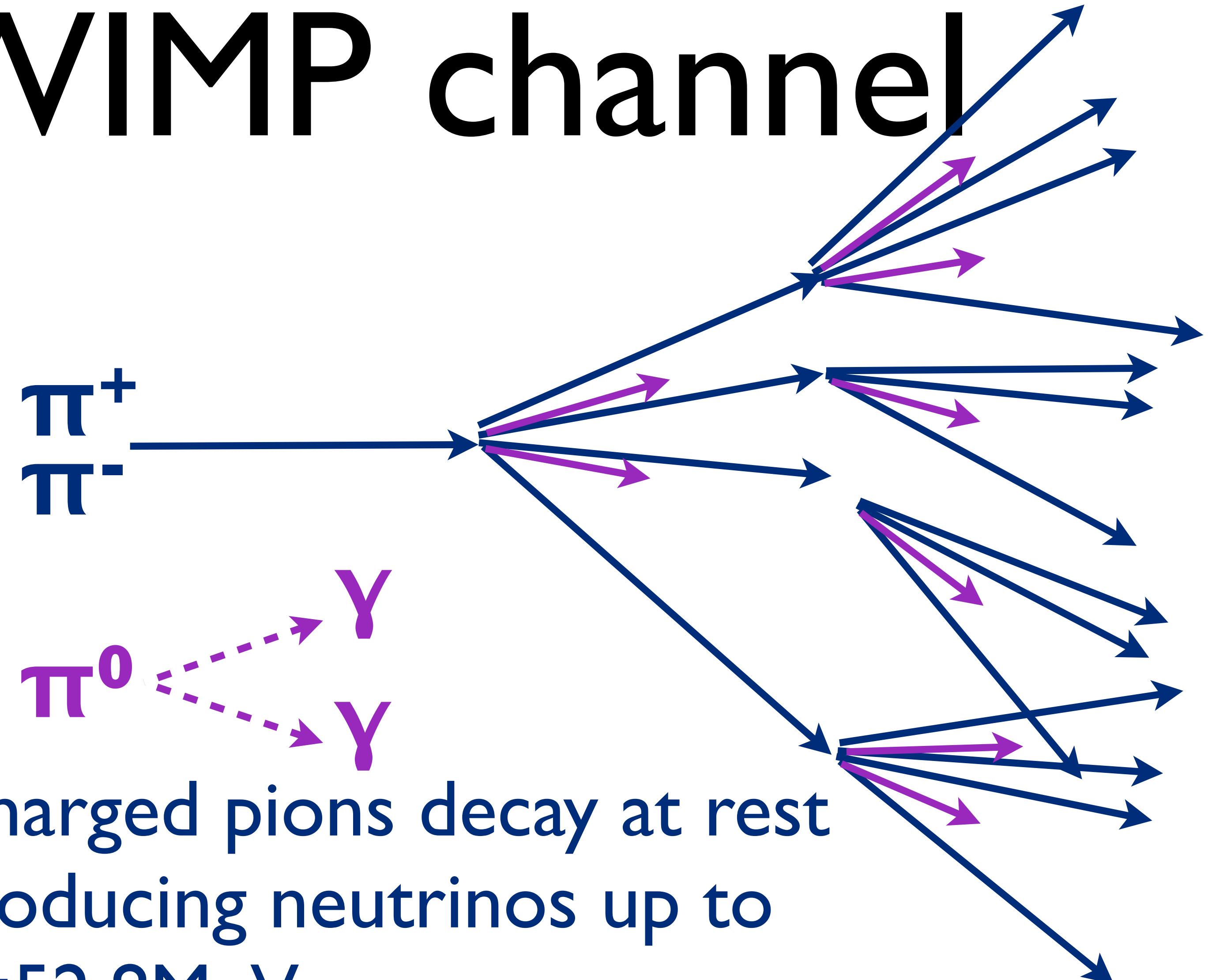


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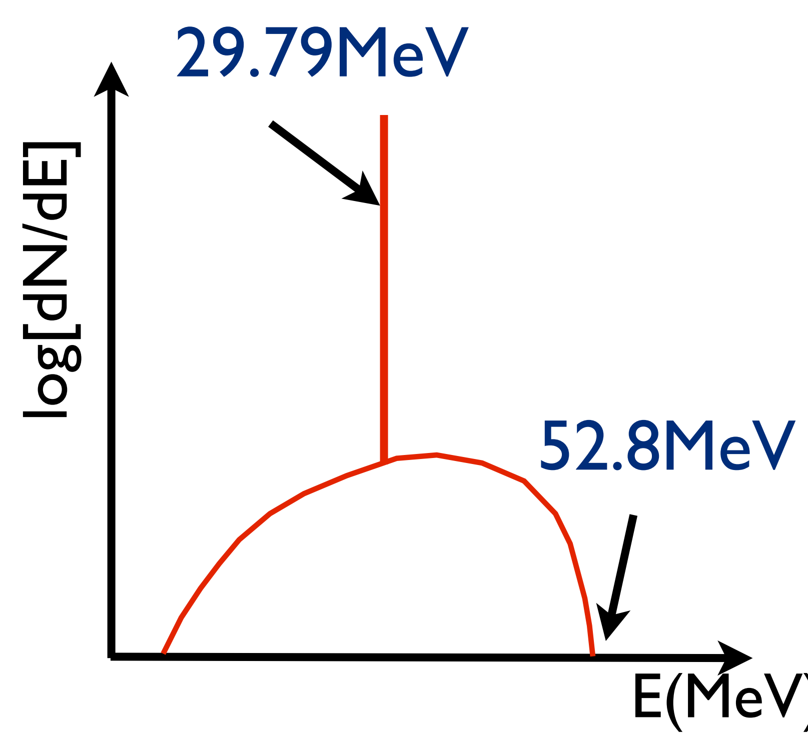

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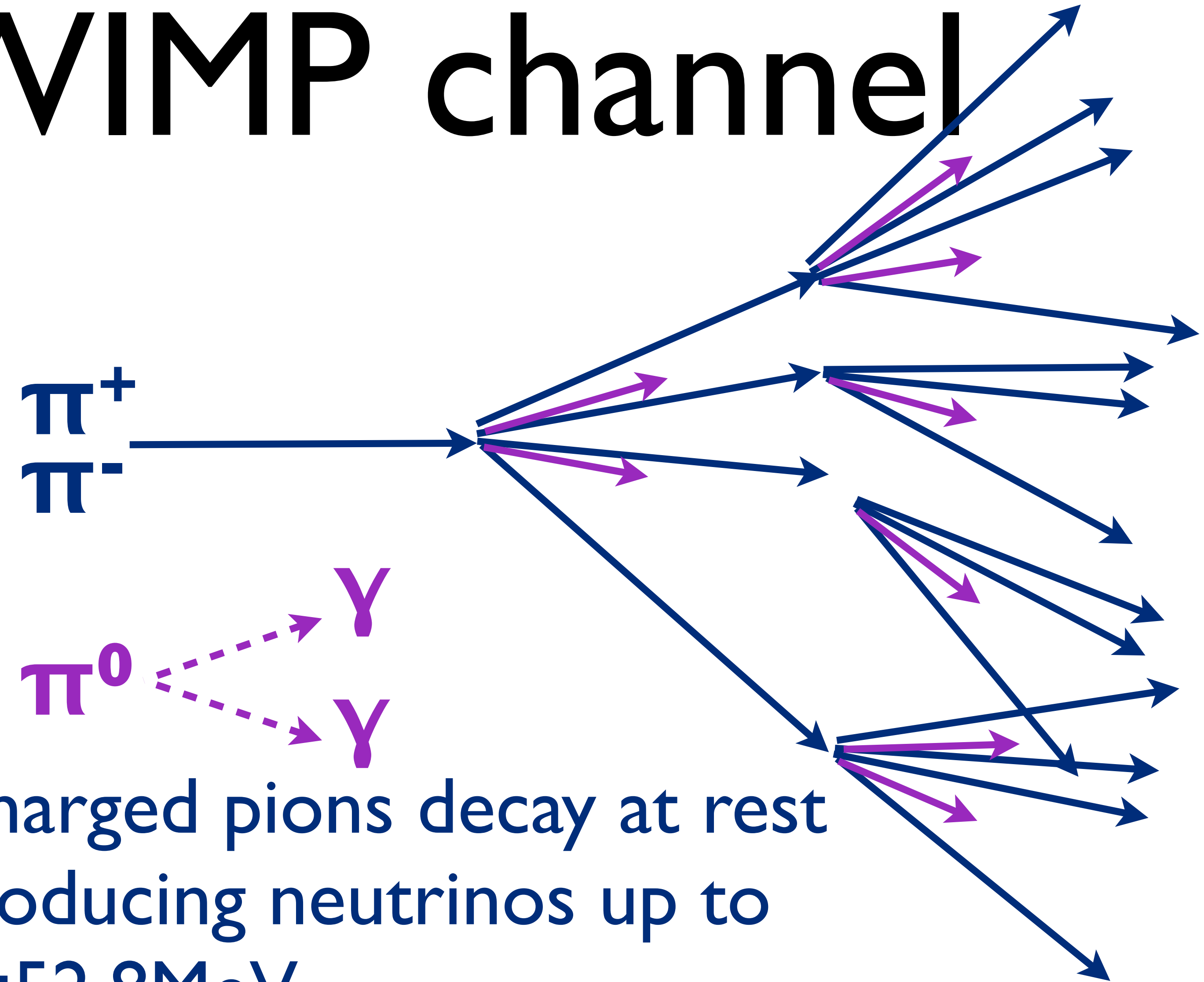
Rott, Siegal-Gaskins, Beacom 2012 in prep.

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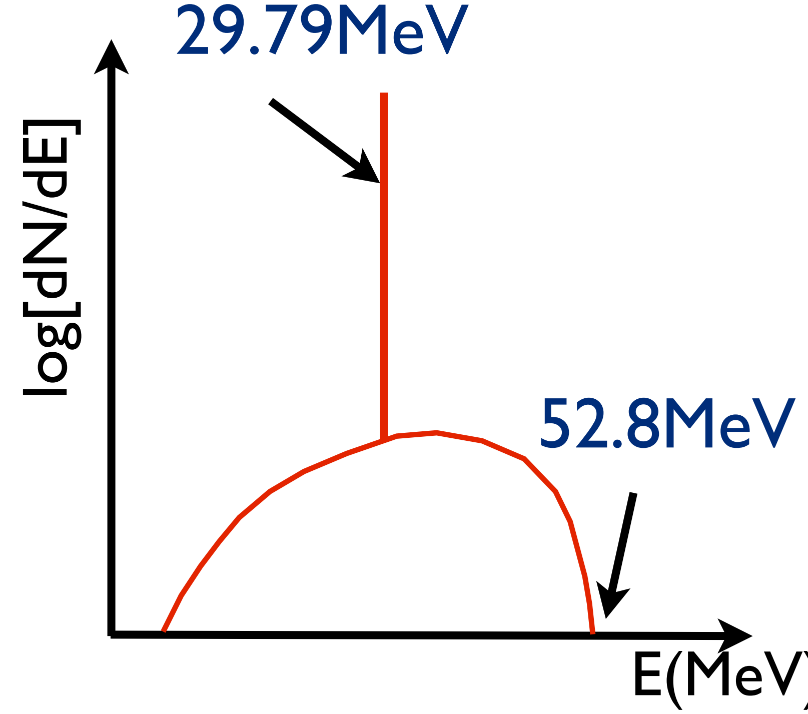
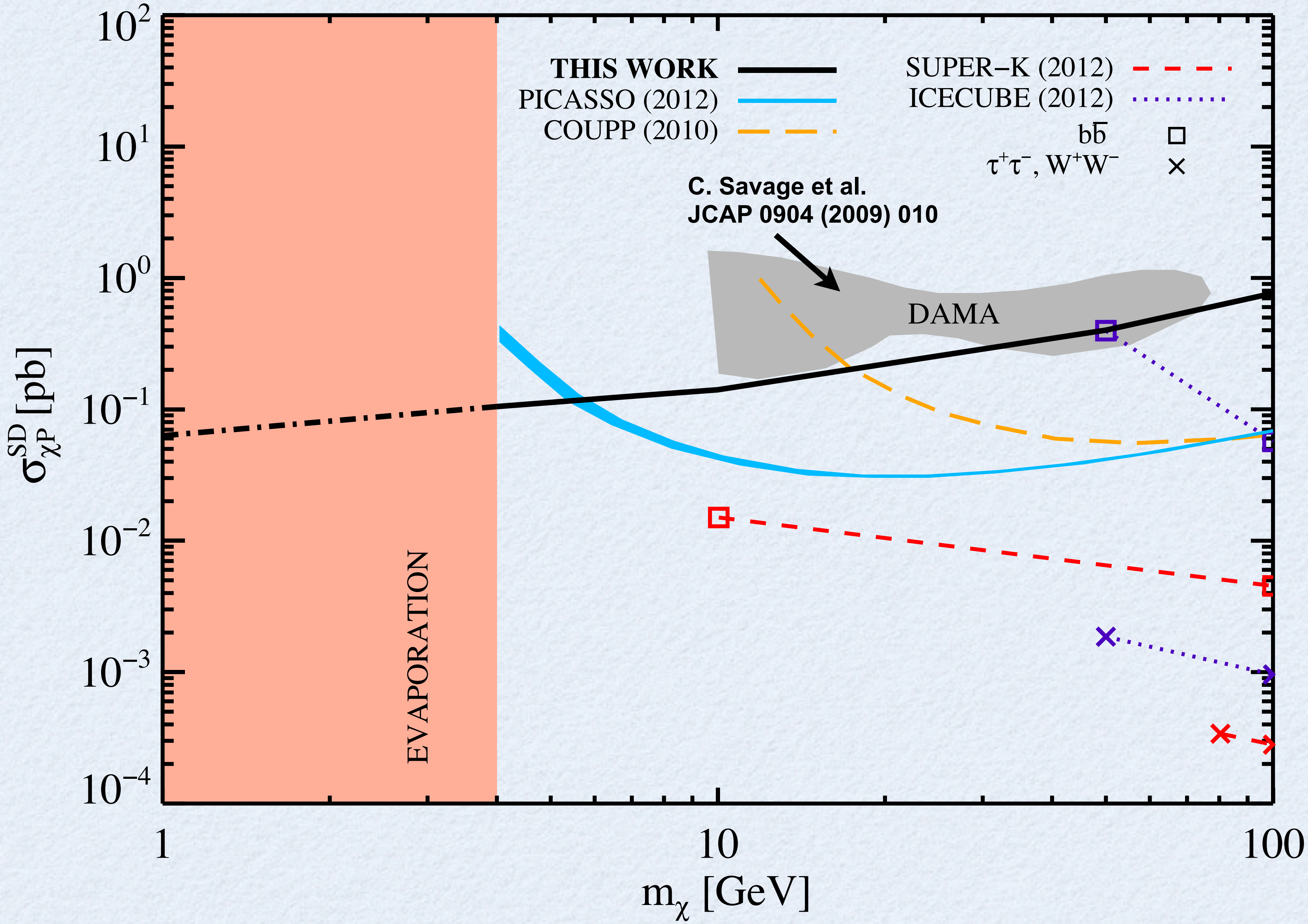


# New Methods to Search for Solar WIMPs

Rott, Siegal-Gaskins, Beacom 2012 in prep.




Preliminary Sensitivity for SuperK dataset

Previous searches relied on high energy neutrinos directly from the decays of annihilation products

Model the full hadronic shower in the Sun

WIMP sensitivity continues to improve for low masses

New key detection channel to compliment other searches

# Conclusions

- Solar WIMP analyses have reached a level where they can test low-mass WIMP scenarios
- Cascades ($\nu_e$ , $\nu_\tau$) sensitivities for Solar WIMPs compare favorably to tracks ($\nu_\mu$)
- Even limited angular resolution on cascade events will allow test low mass WIMP scenarios
- Important to better understand all astrophysical uncertainties
- Neutrino flux conversion makes experimental results more comparable
- New Detection channels of low energy neutrinos cover hadronic losses and will ultimately provide a better understanding on branching fractions of various annihilation channels