Weakly Interacting Massive Particles Sensitivity Studies

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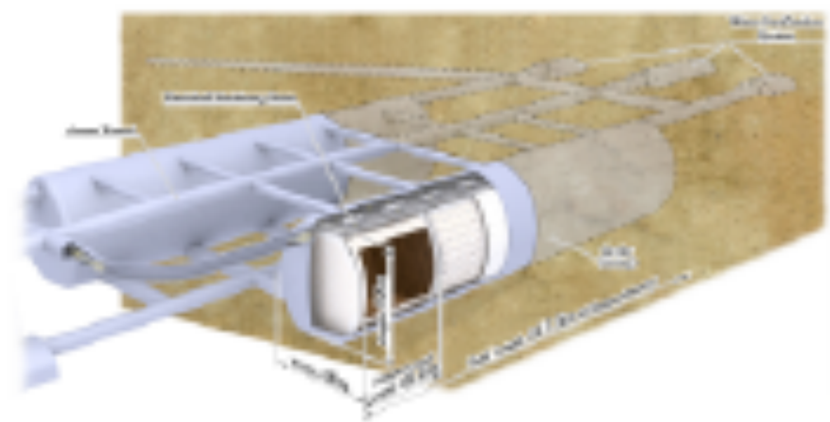
C.Rott, T.Tanaka, Y. Itow JCAP09(2011)029 (arXiv1107.3182)
C. Rott, J. Siegal-Gaskins, J.F.Beacom (arXiv1208.0827)

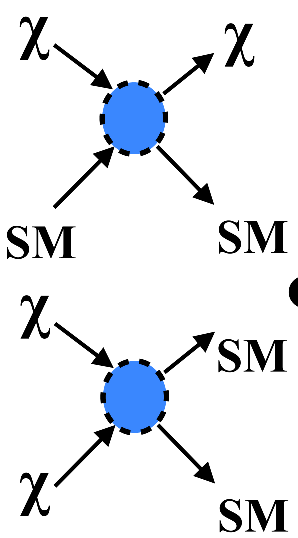
Outline



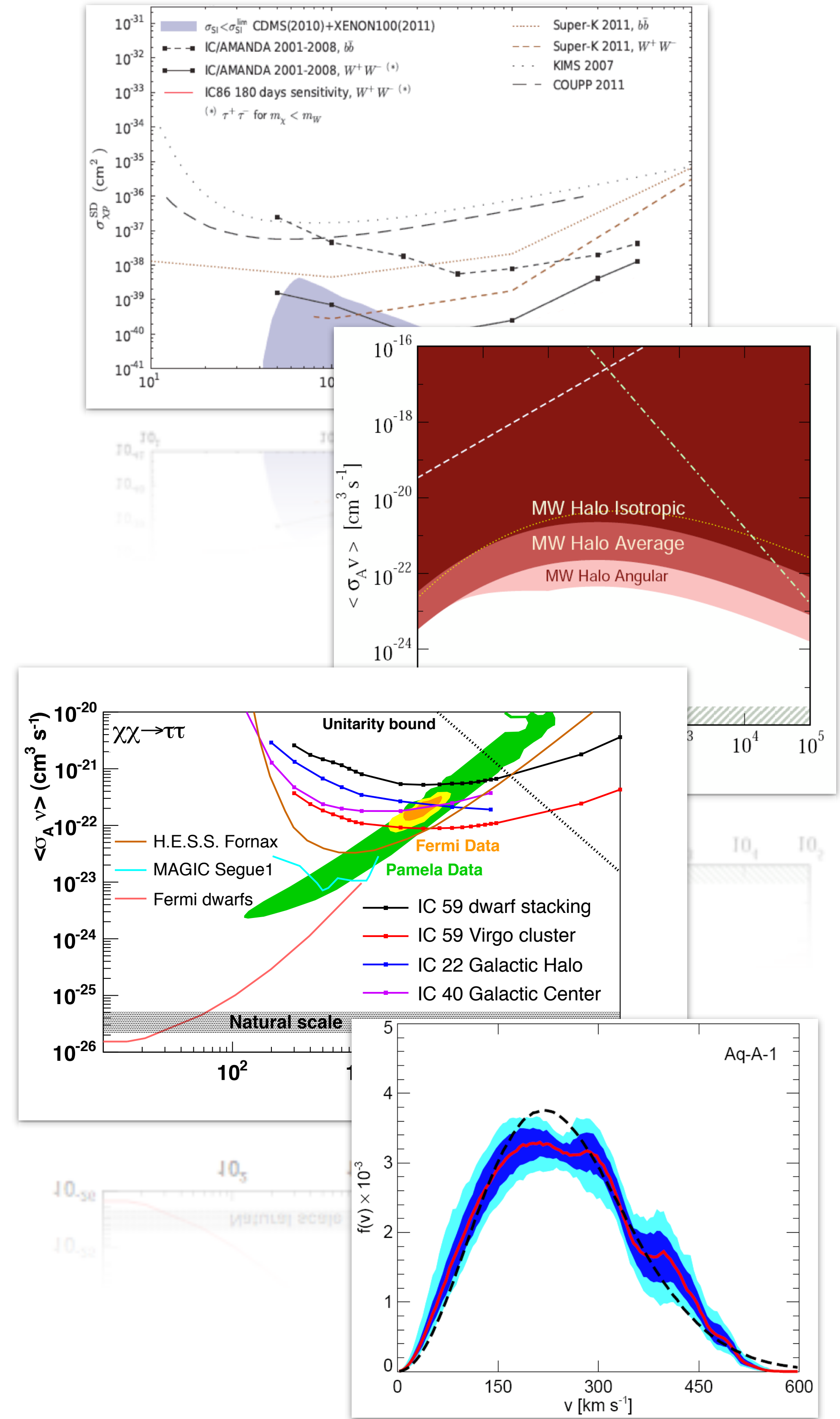
- Motivation and Signals
- Current Results
- Sensitivity estimates for Hyper-K
- Discussions and Conclusions

Motivation

Motivation

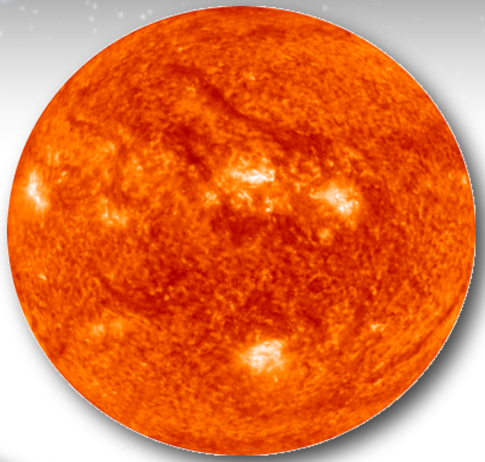


- Neutrino detectors are extremely competitive for probing WIMP Nucleon scattering cross section
- Neutrino signals can be used to set a conservative limit on the total dark matter self-annihilation cross section
- Neutrino signals have been able to test “claims” from other indirect channels or direct detection
  - Positron excess (PAMELA, Fermi, ...)
  - DAMA/Libra
  - ... 130 GeV Line ?
- Probe of average local dark matter density and velocity distribution, ...



Importance of Neutrinos

- **Galactic halo, Galactic center, Dwarf spheriodals, Cluster of Galaxies, ...**
  - Gamma-rays extremely competitive for low WIMP masses, but any detection would likely require an independent confirmation of neutrino signals
  - high masses(>1TeV) - large neutrino telescopes are most competitive
- **Dark Matter in the Sun**
  - Discovery channel for neutrinos
  - Due to significant neutrino absorption at high energies, Solar WIMP signals are detected in the energy range below 100GeV
- **Dark Matter in the Earth**
  - Capture mechanism highly favors low-mass (<50GeV) WIMPs
  - Very large uncertainties for any flux prediction as annihilation and capture rate are not expected to be in equilibrium

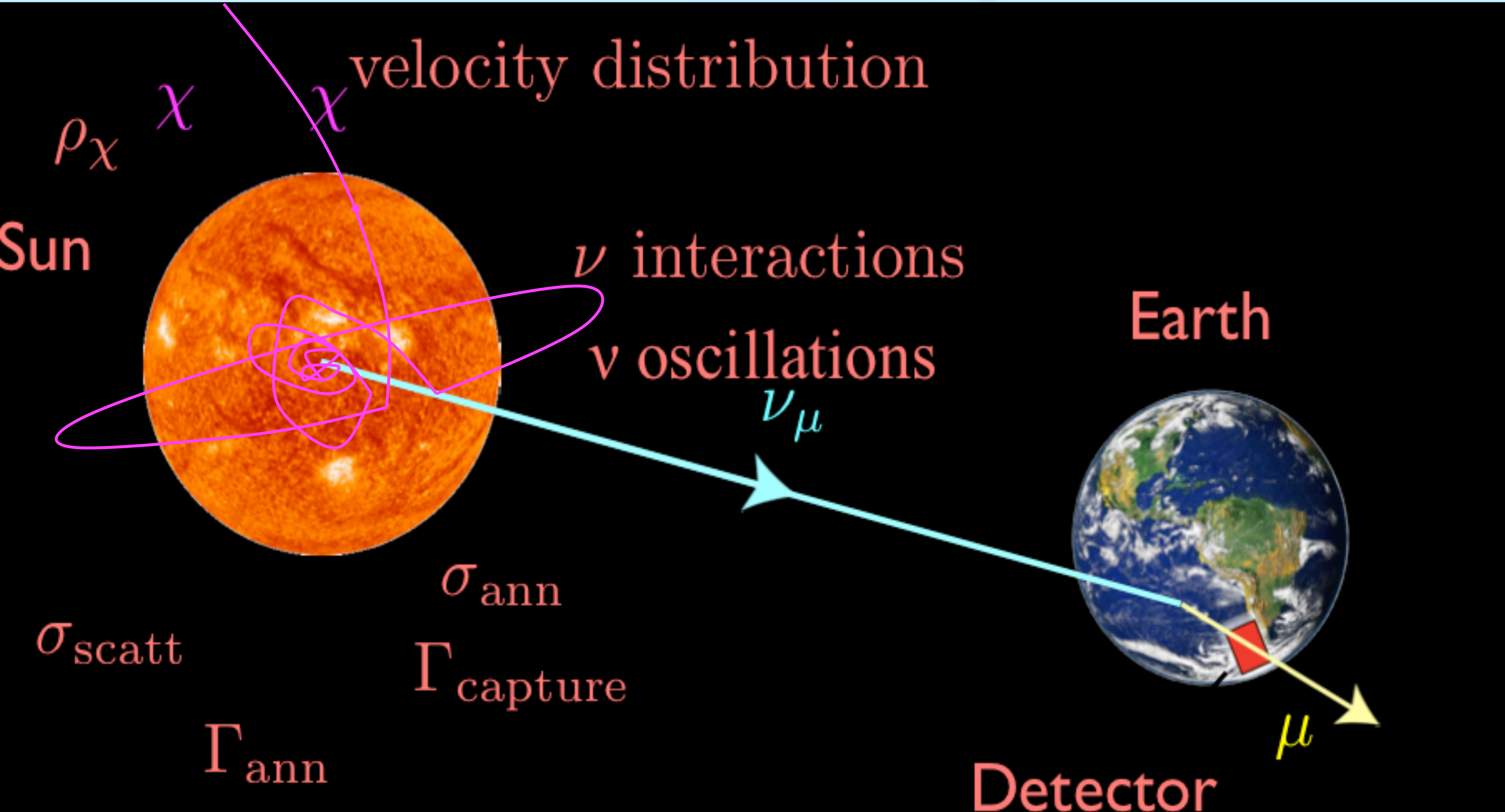


Current Results and Sensitivity Estimates

Sensitivity estimates

- Dark Matter Captured in the Sun
  - Review of Super-K High-Energy Neutrino Search
  - Low-Energy Neutrinos from the Sun
- Dark Matter in the Galactic Halo

Solar WIMP Signal

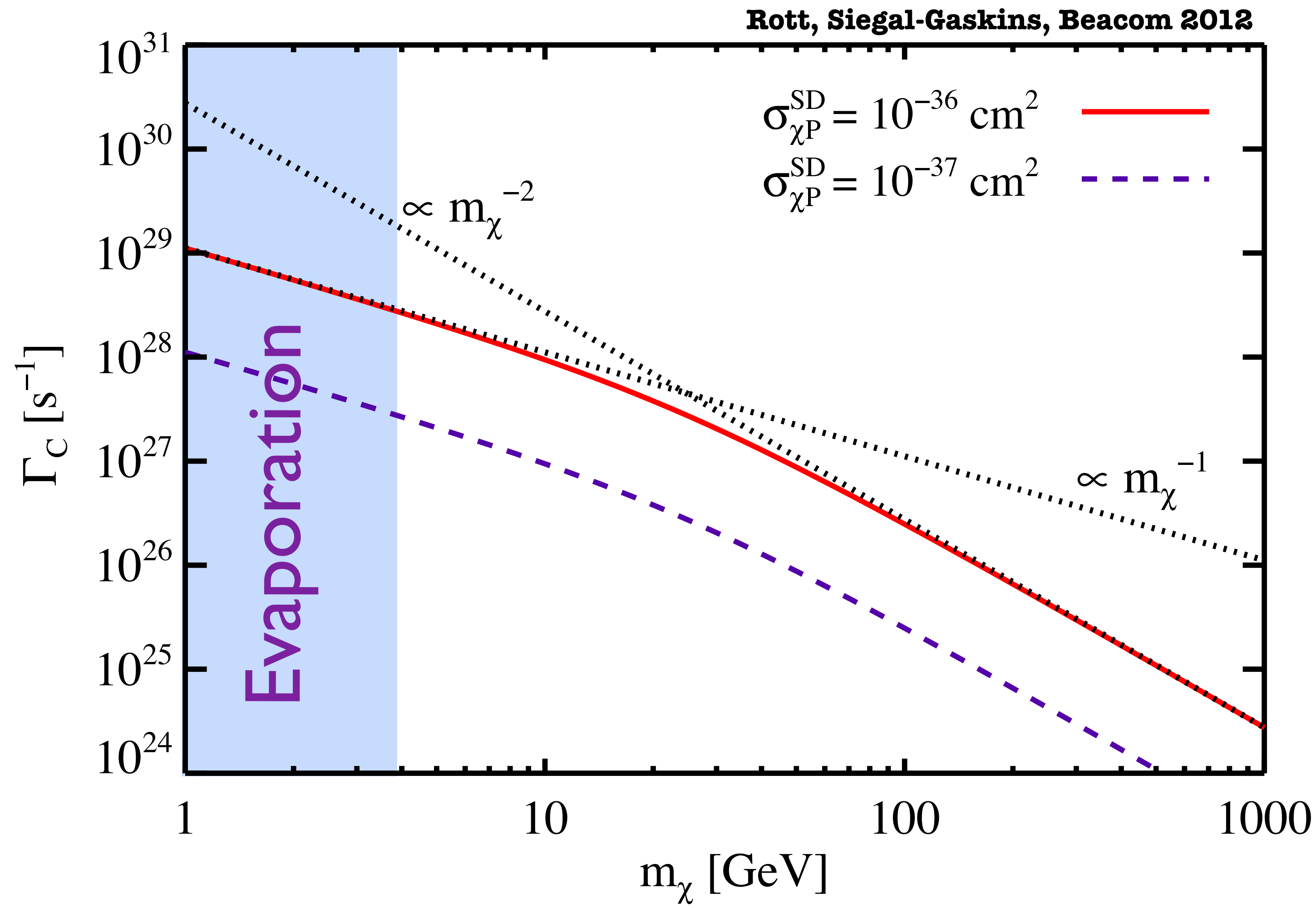


Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

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

Solar WIMP Capture

- WIMPs can get gravitationally captured by the Sun
  - Capture rate, Γ_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 ($\Gamma_A = \Gamma_C/2$)
  - The neutrino flux only depends on the WIMP-Nucleon scattering cross section



The capture rates scales as:

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

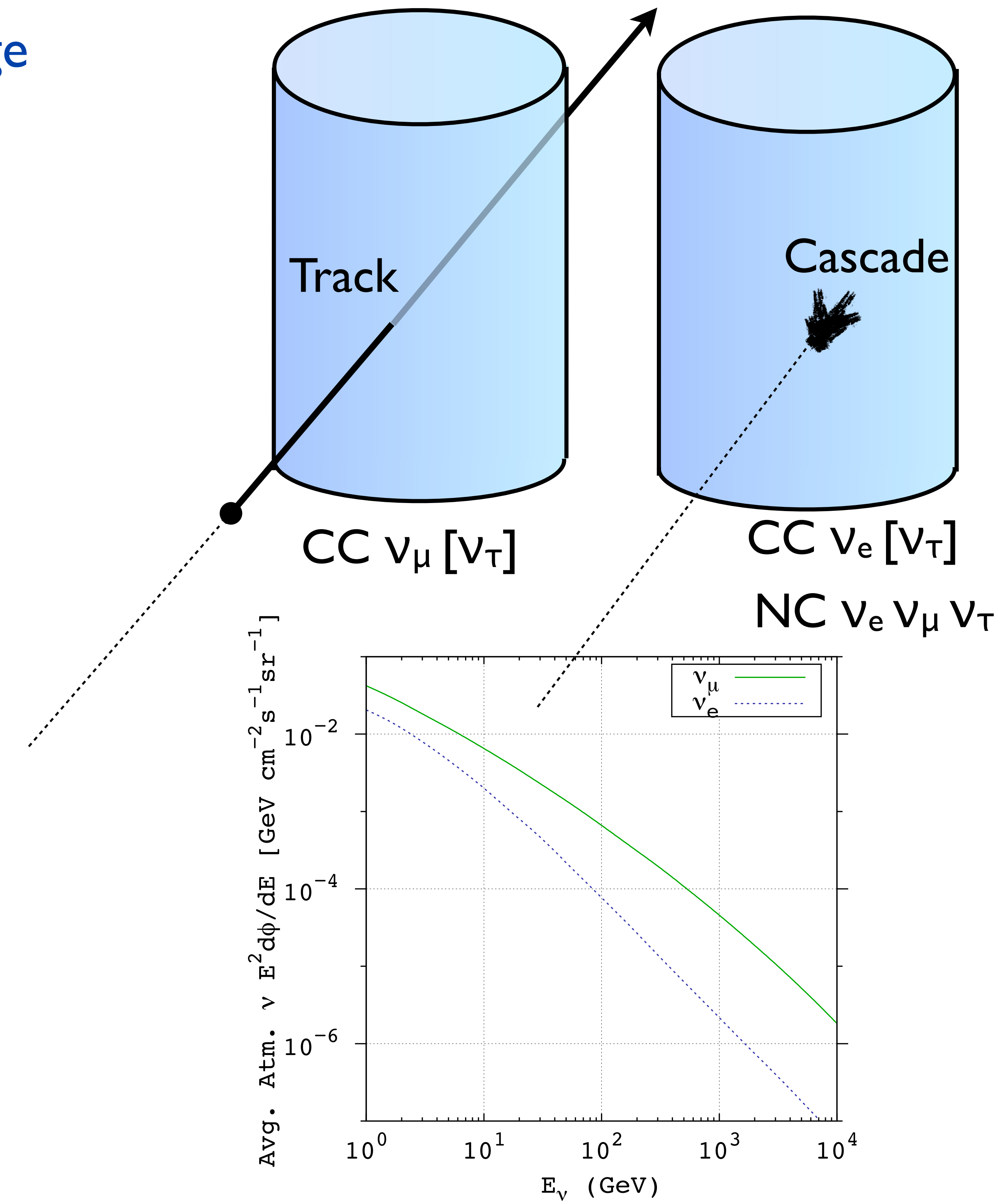
$\Gamma_C \sim \rho_\chi m_\chi^{-2} \sigma_A$ for $m_\chi >> m_A$

number density + kinematic suppression

m_A - is the target mass

Comparison of tracks and cascades

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



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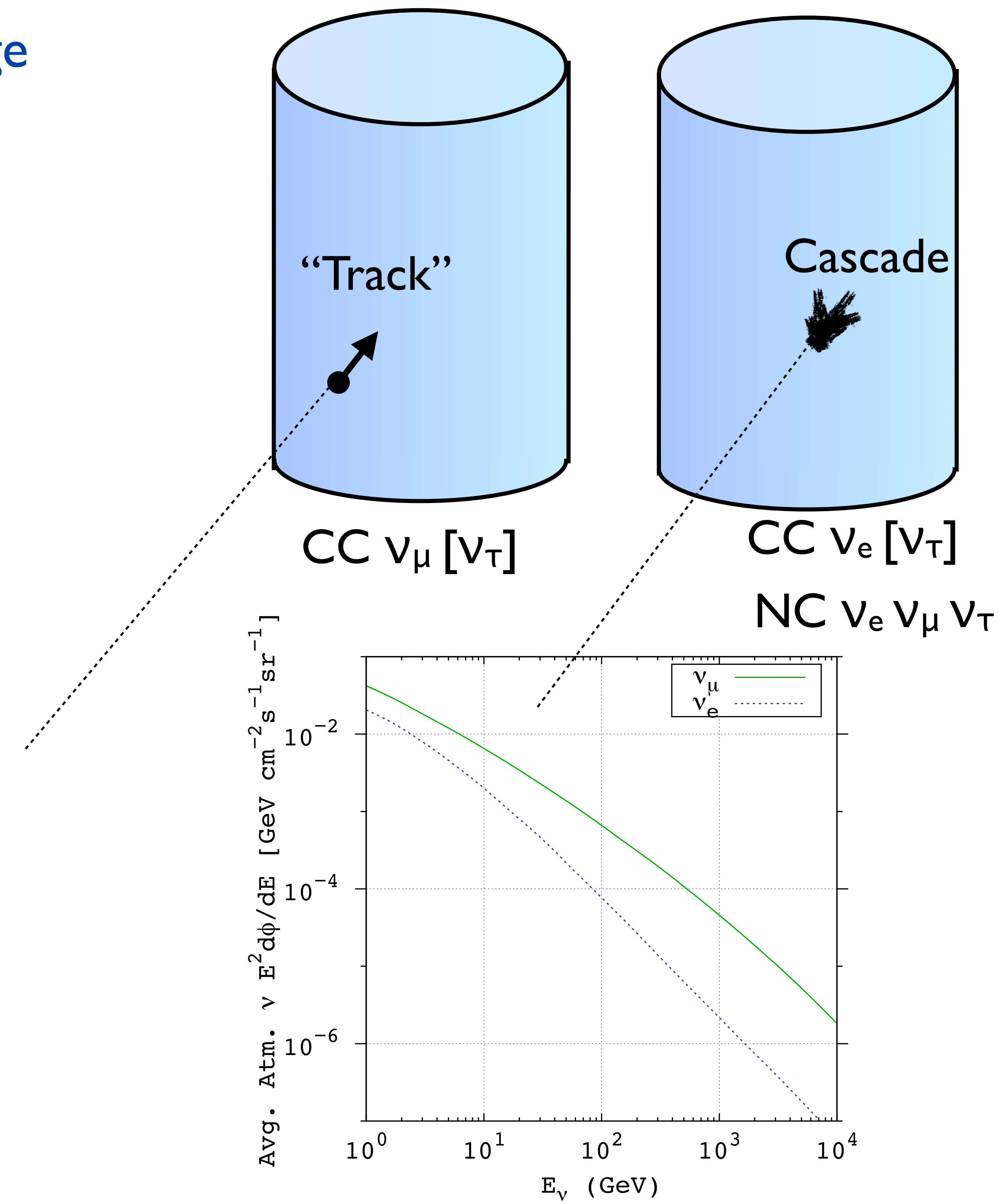
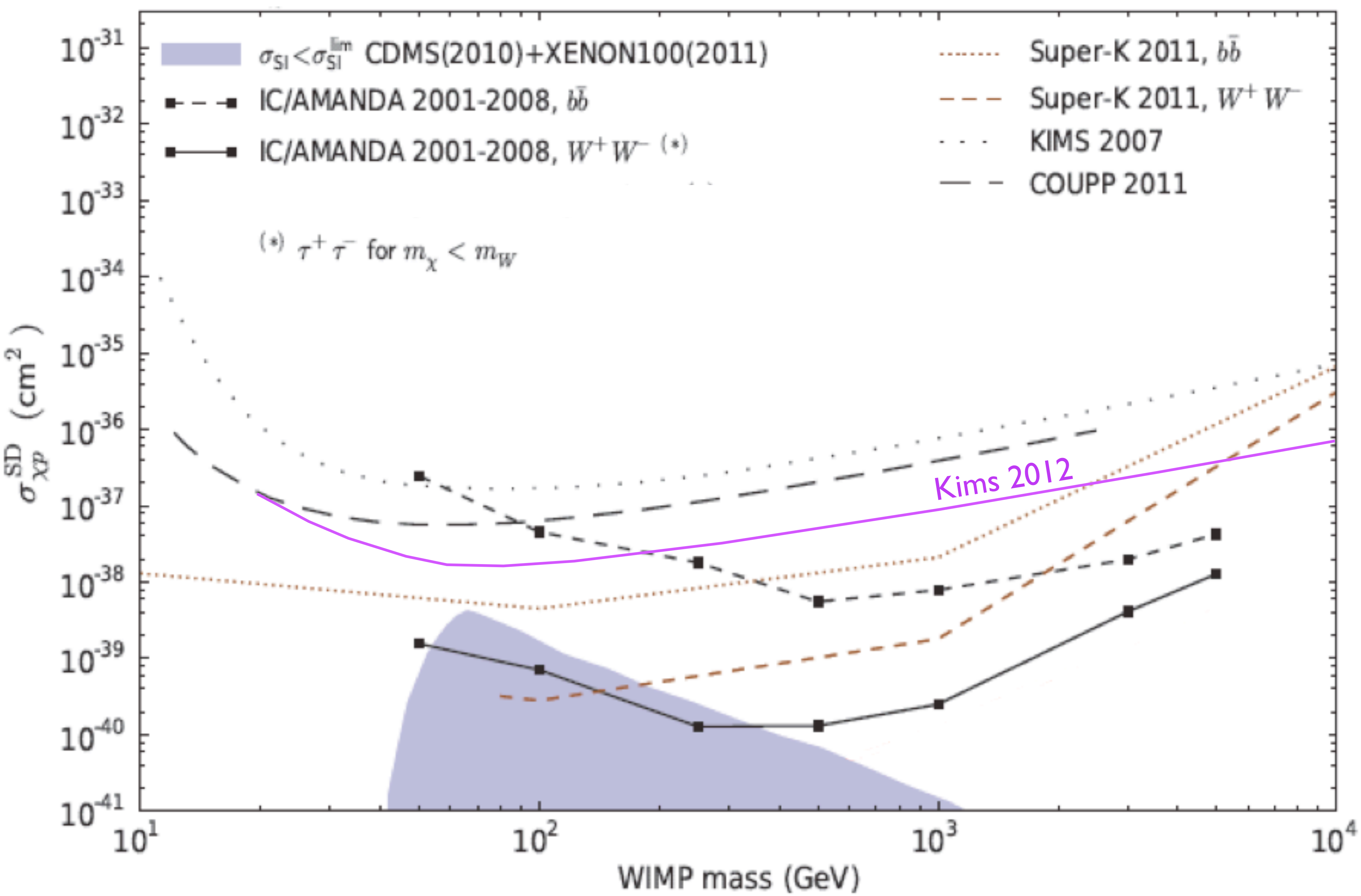


Published Limits

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



All currently published indirect limits rely on the muon neutrino induced muon flux

New Preliminary SuperK 2012 Result

T. Tanaka et al. Astrophys. J. 742, 78 (2011)
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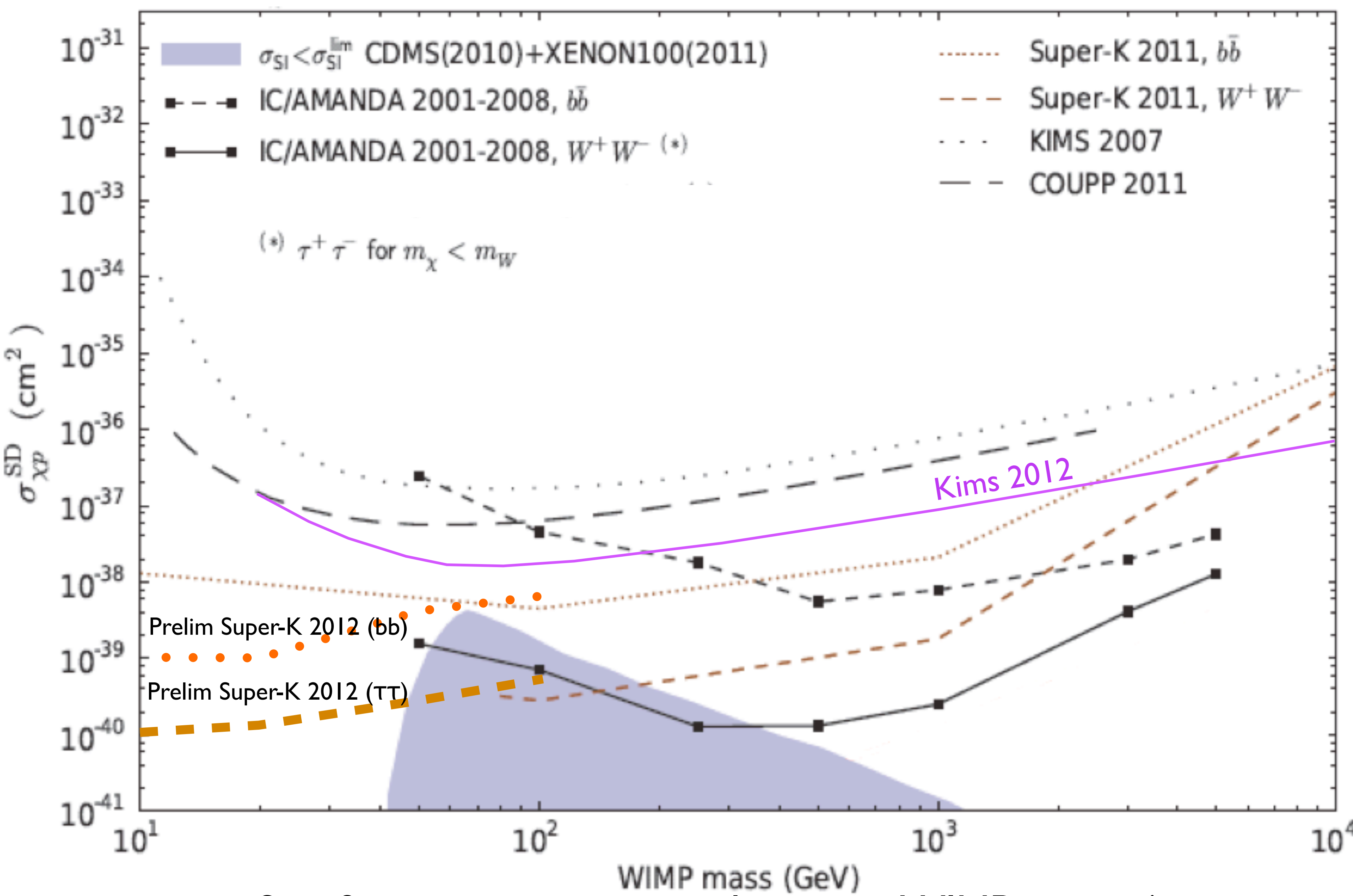
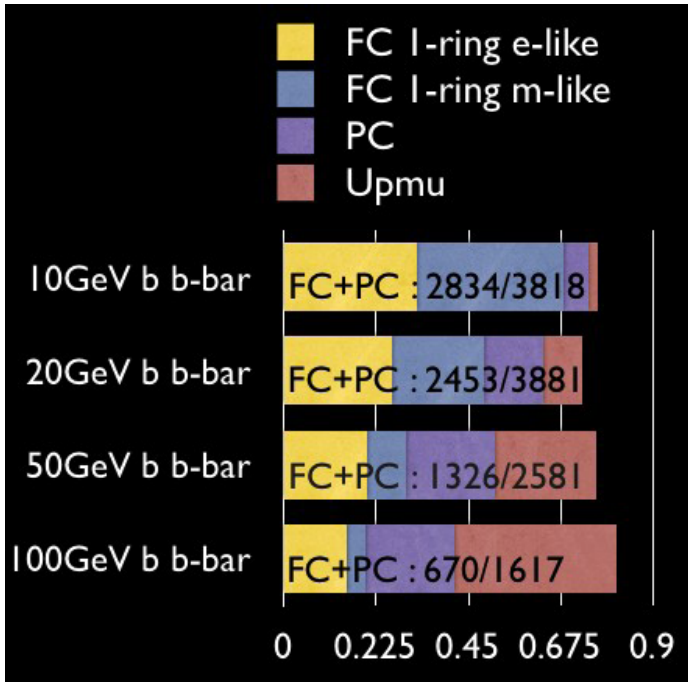


Data from SKI-III (2806days)



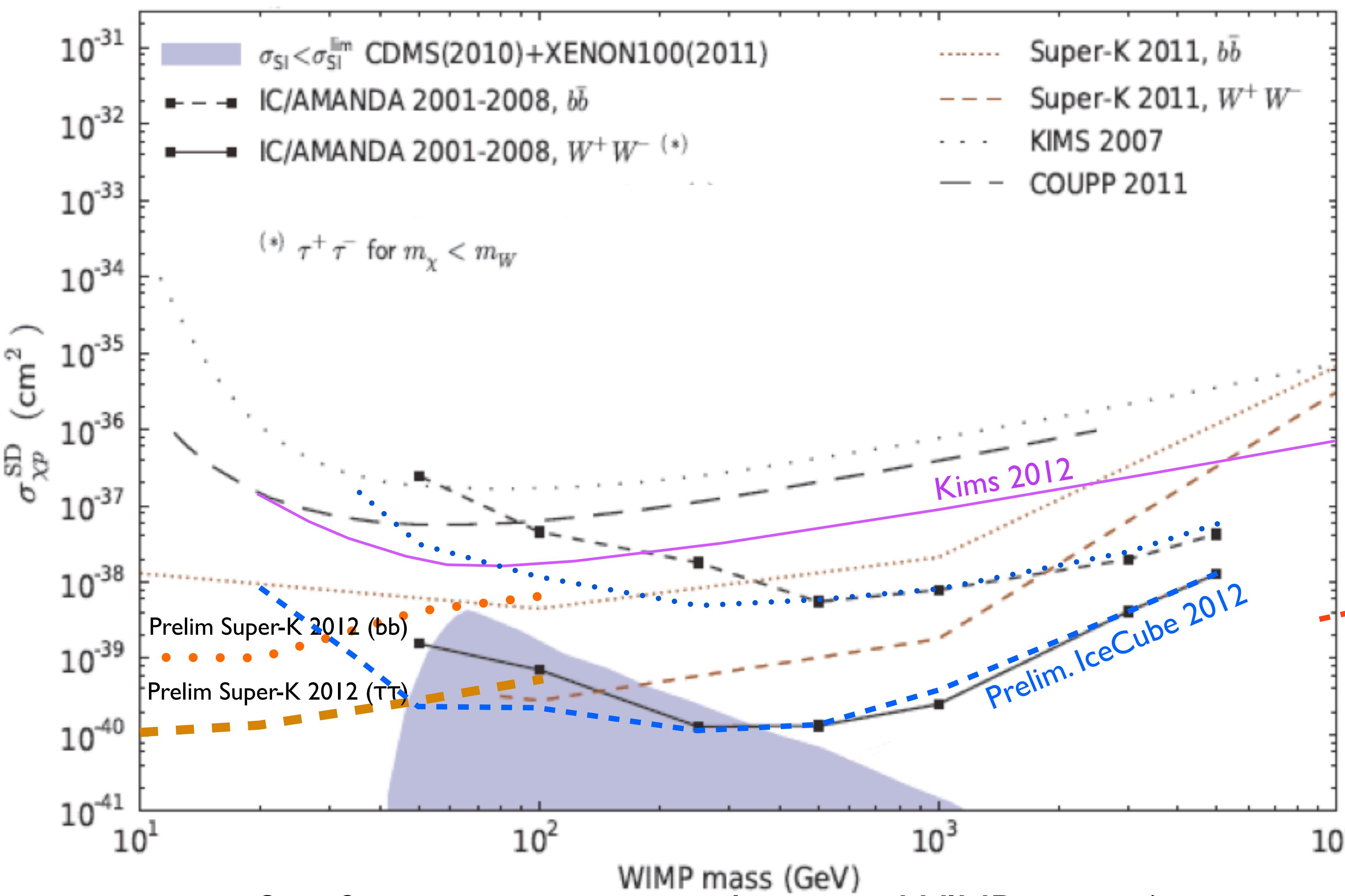
Significant improvement in low-mass WIMP region !

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

see:
Preliminary Super-K Limit Neutrino 2012

New Preliminary IceCube 2012 Results

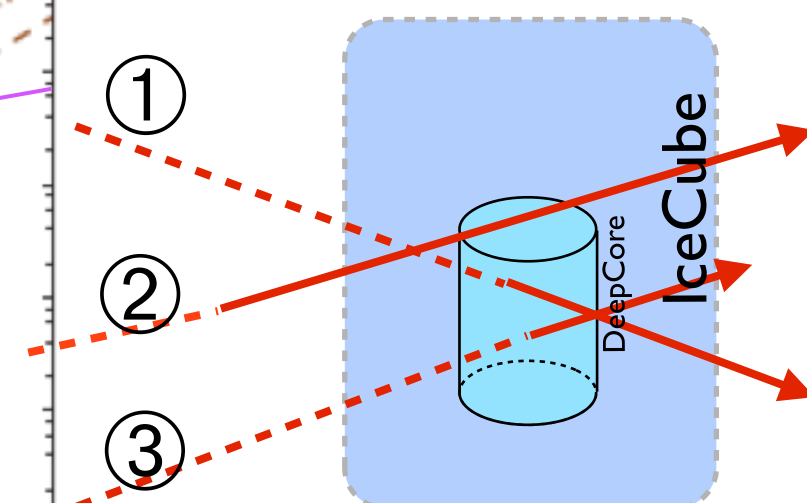
T. Tanaka et al. Astrophys. J. 742, 78 (2011)
R. Abbasi et al. Phys. Rev. D 85, 042002 (2012)



Significant improvement in low-mass WIMP region !

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

Analysis performed separately for austral summer (Sun above horizon) and austral winter (Sun below horizon) - 3 independent samples



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

see:
Preliminary Super-K Limit Neutrino 2012
Preliminary IceCube/DeepCore Limit IDM 2012

Comparison

T. Tanaka et al. Astrophys. J. 742, 78 (2011)
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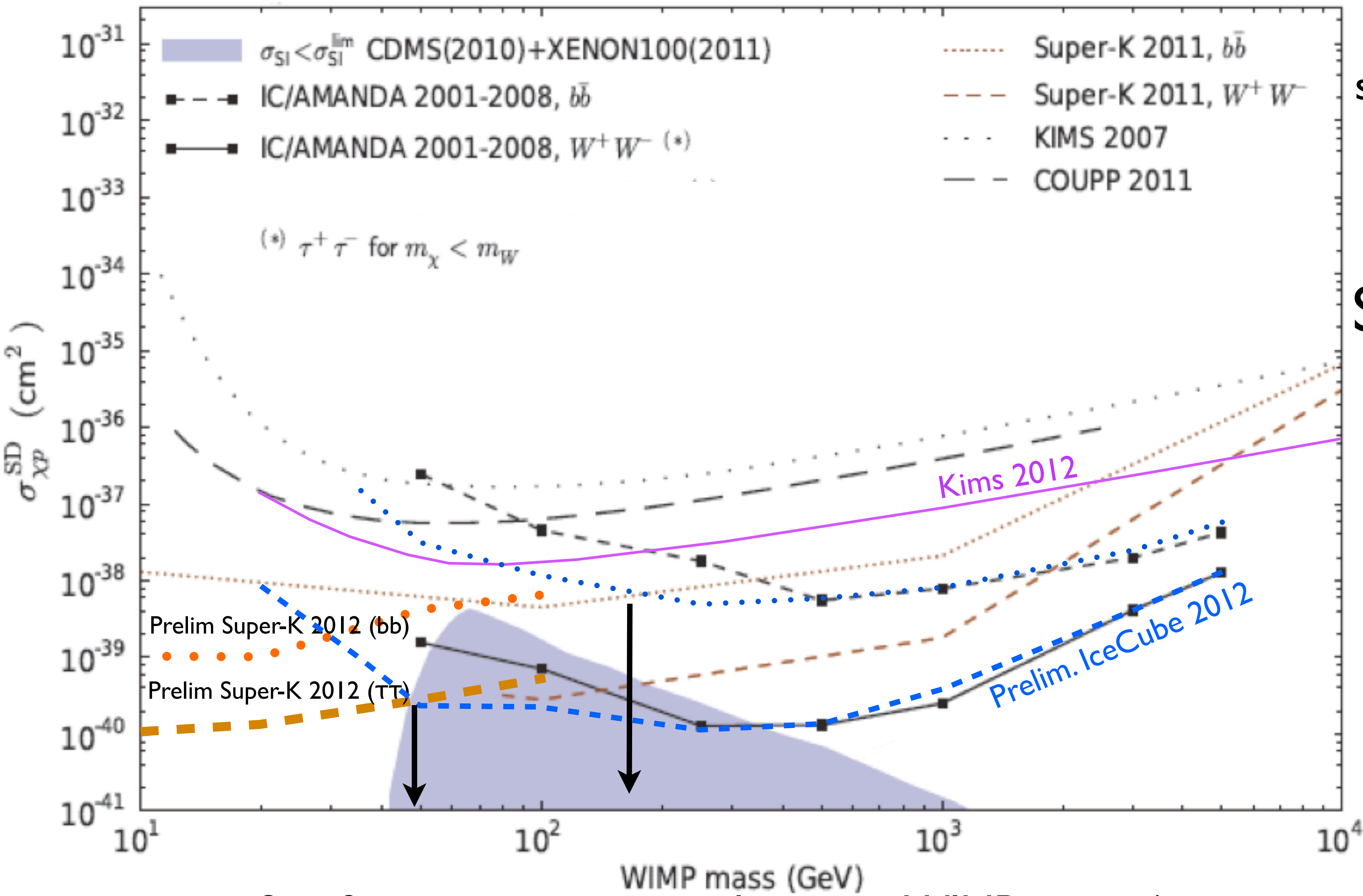


SK-I+II+III results more sensitive than one year of IceCube/DeepCore

Soft channel (bb): ~150GeV

Hard channel (ww,ττ): ~50GeV

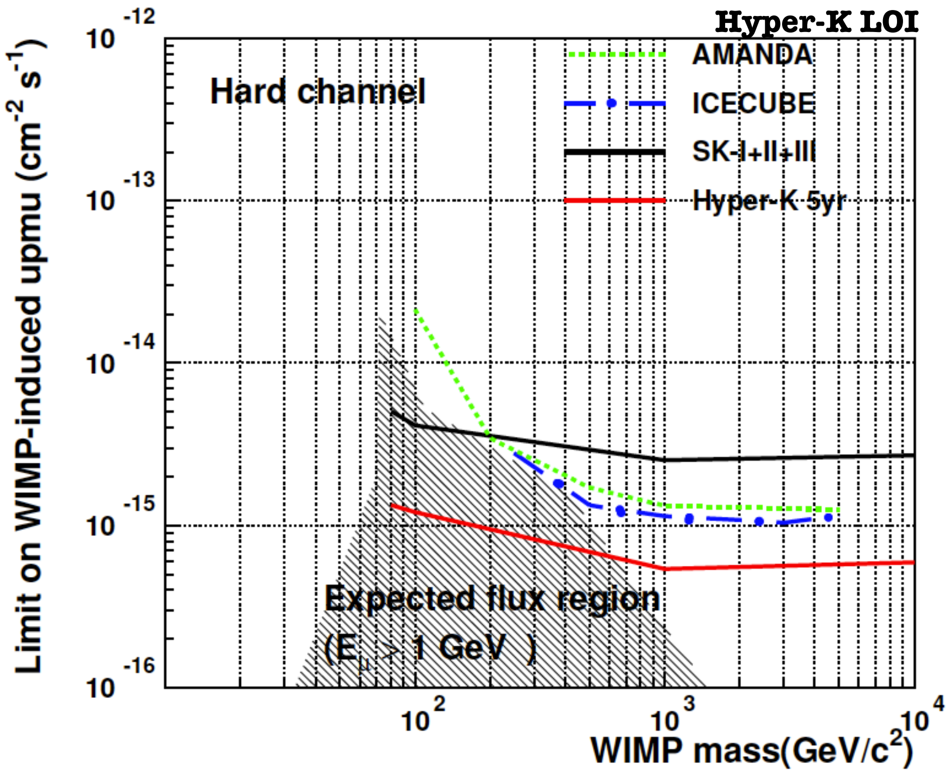
Significant improvement in low-mass WIMP region !

see:
Preliminary Super-K Limit Neutrino 2012
Preliminary IceCube/DeepCore Limit IDM 2012

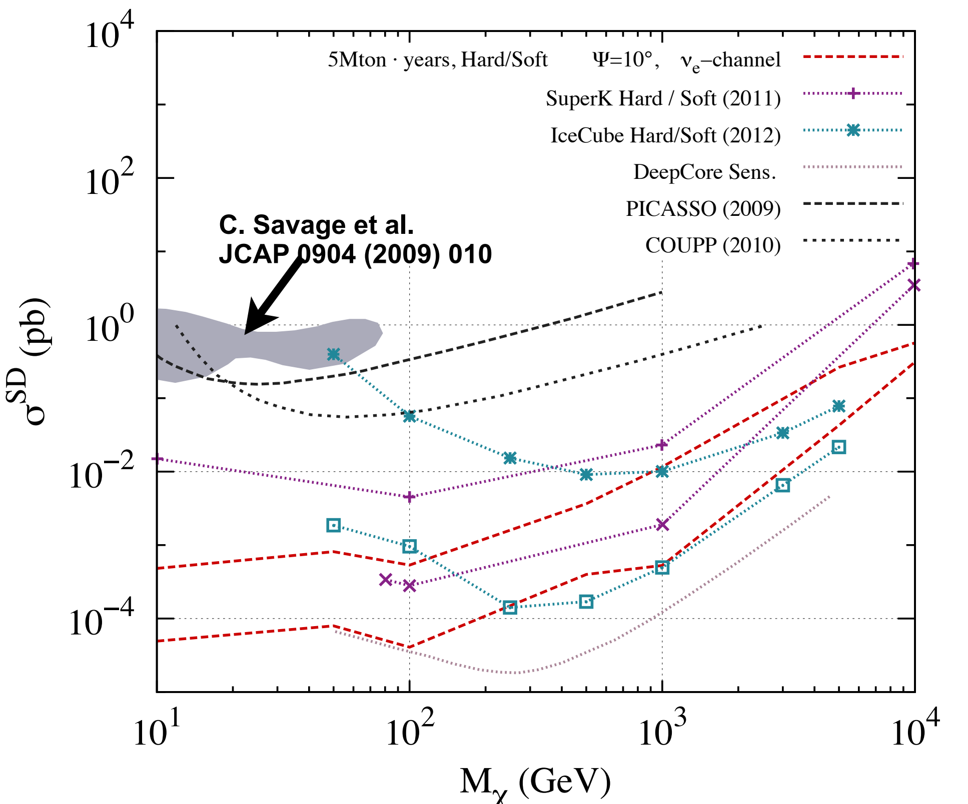
Hyper-K LOI

Hyper-K LOI

- Hyper-K LOI
  - Conservative estimate (by Ikeda-san) based on scaling the Super-K upmu results (Tanaka et al 2011) of SK-I-II-III to Hyper-K
  - Reference to improvements possible by using vertex contained events
    - Note: Improvements have largely been realized for Super-K

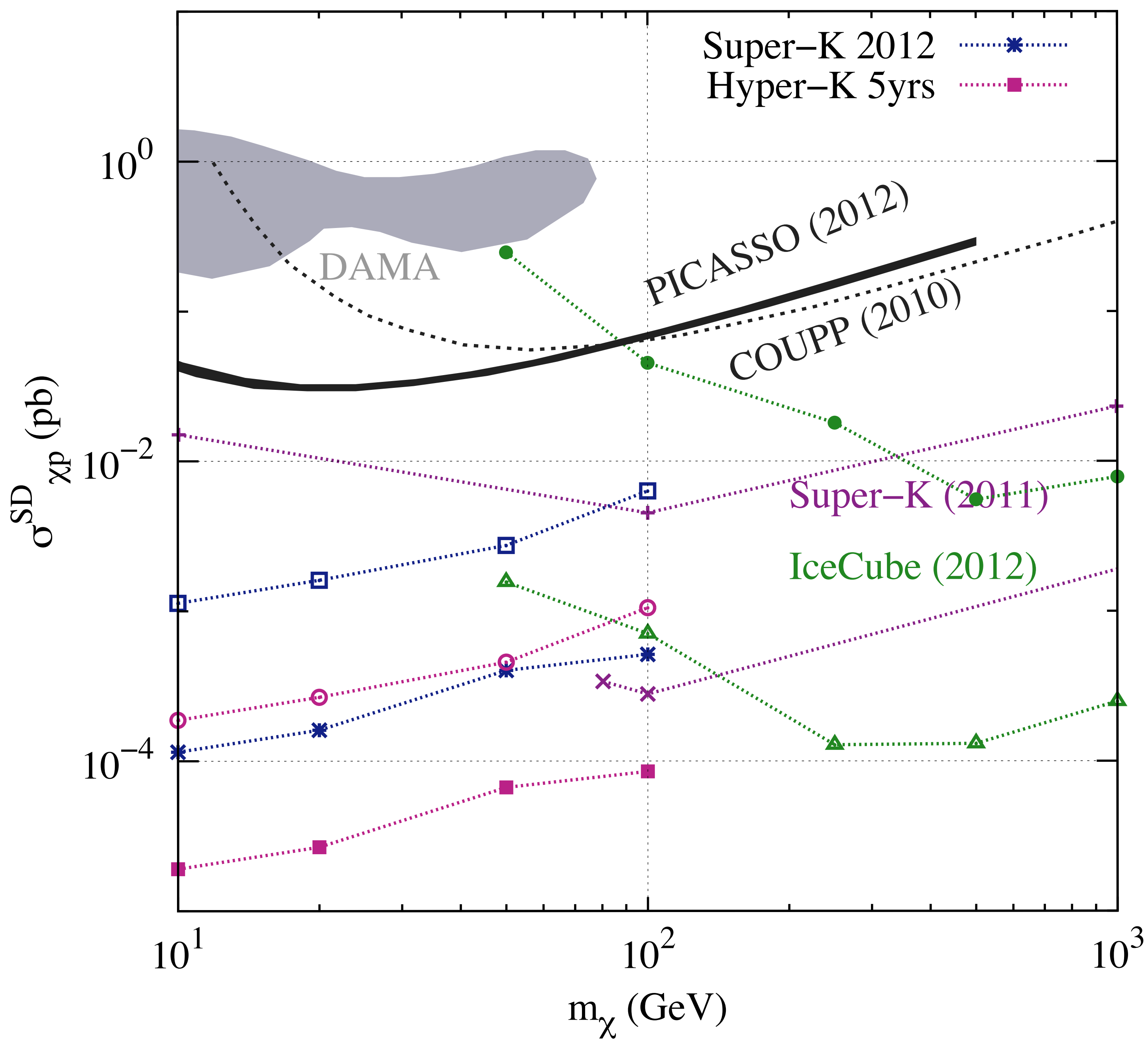


Solar WIMP Sensitivities compared to Limits



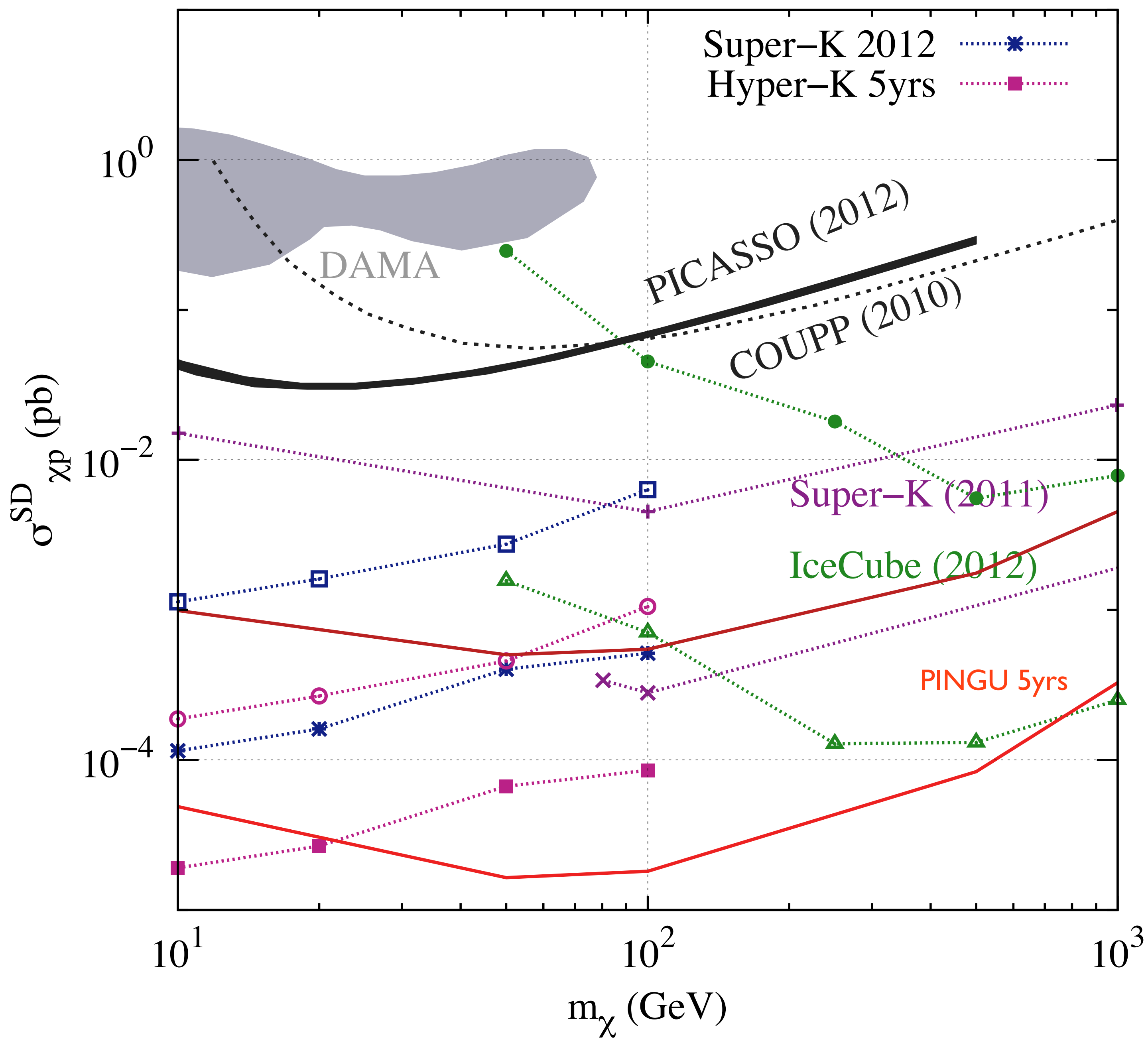
Rott, Tanaka, Itow 2011

New Hyper-K Sensitivity



Scaling of achieved SK-I +II+III results to Hyper-K

New Hyper-K Sensitivity Comparison



PINGU Sensitivity based on effective volume and applying it to Rott, Tanaka, Itow (2011)

Scaling of achieved SK-I +II+III results to Hyper-K

5yrs of Hyper-K compared to IceCube upgrade PINGU 5yrs of data

Hyper-K compares favorable to other indirect searches for WIMP masses below ~20-50GeV

Low energy neutrinos

C. Rott, J. Siegal-Gaskins, J.F.Beacom (arXiv1208.0827)

Low-Energy Neutrinos from the Sun Solar

Possible annihilation channels:

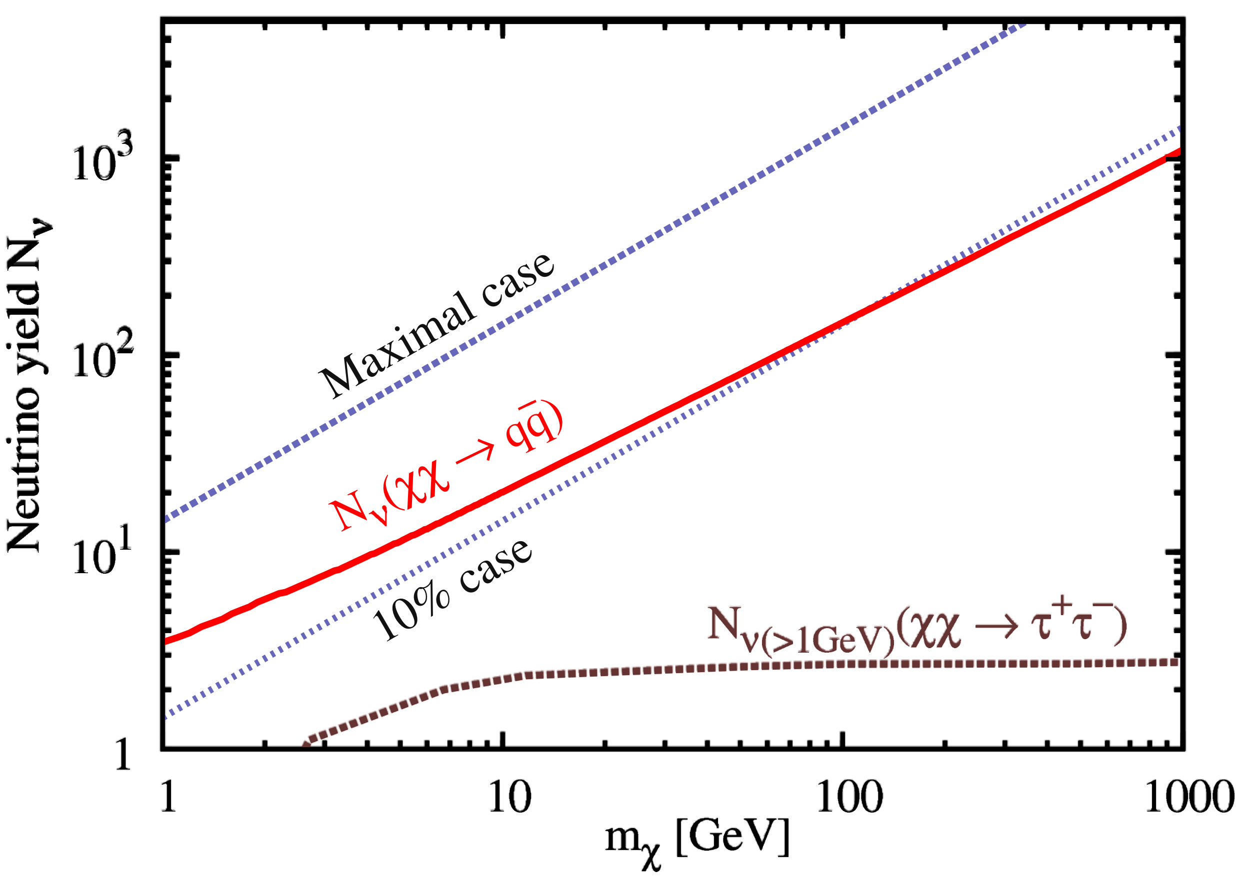
qq,gg,cc,ss,bb,tt,W^+W^-, ZZ, $\tau^+\tau^-$, $\mu^+\mu^-$, $\nu\nu$, e^+e^-, $\gamma\gamma$

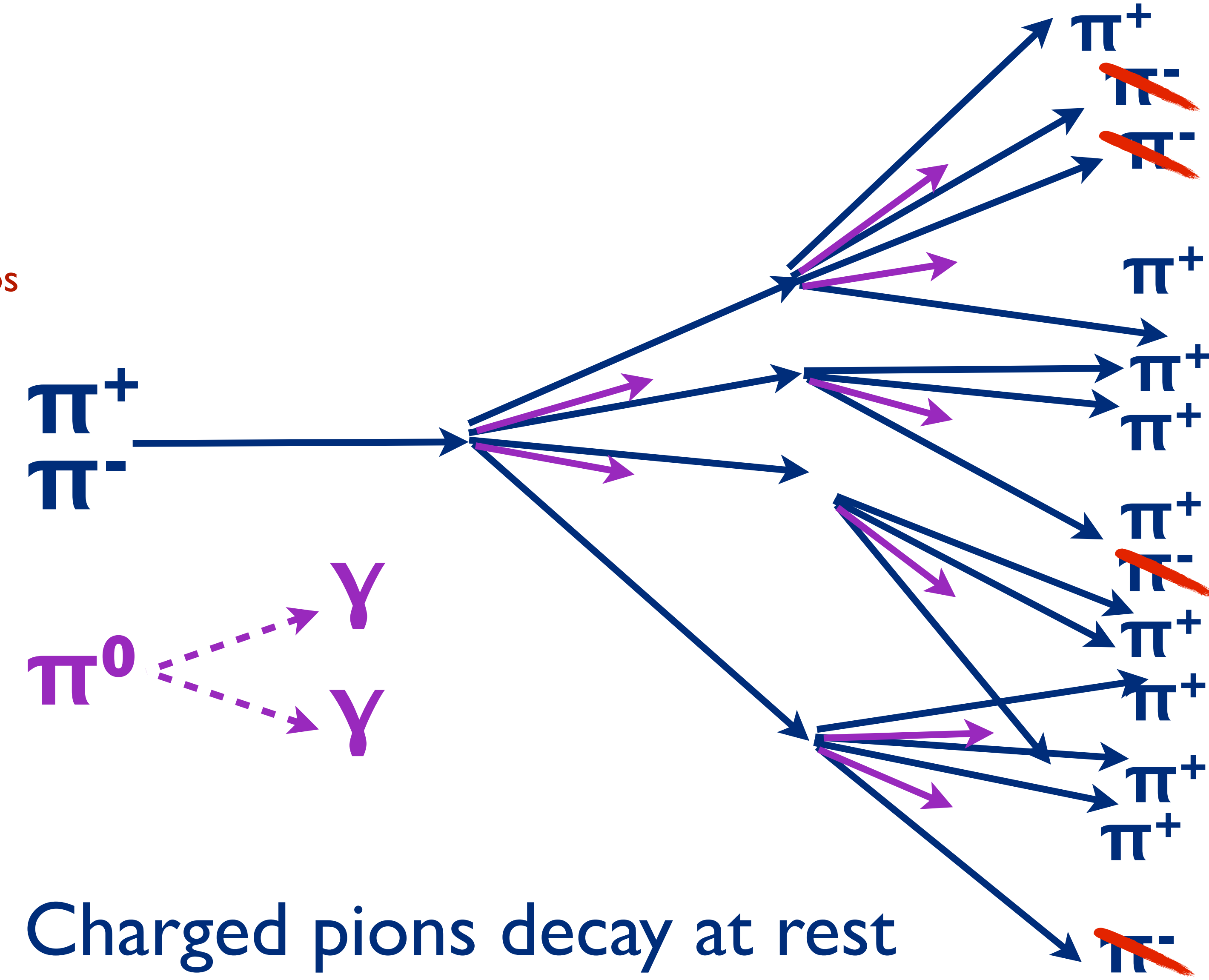
few neutrinos

some "high energy" neutrinos in decays
⇒ basis of present day searches

dominant decay into hadrons

$$\tau^- \rightarrow \bar{\nu}_\mu \nu_\tau \mu^-$$
$$\tau^- \rightarrow \bar{\nu}_e \nu_\tau e^-$$
$$\tau^- \rightarrow hadrons$$





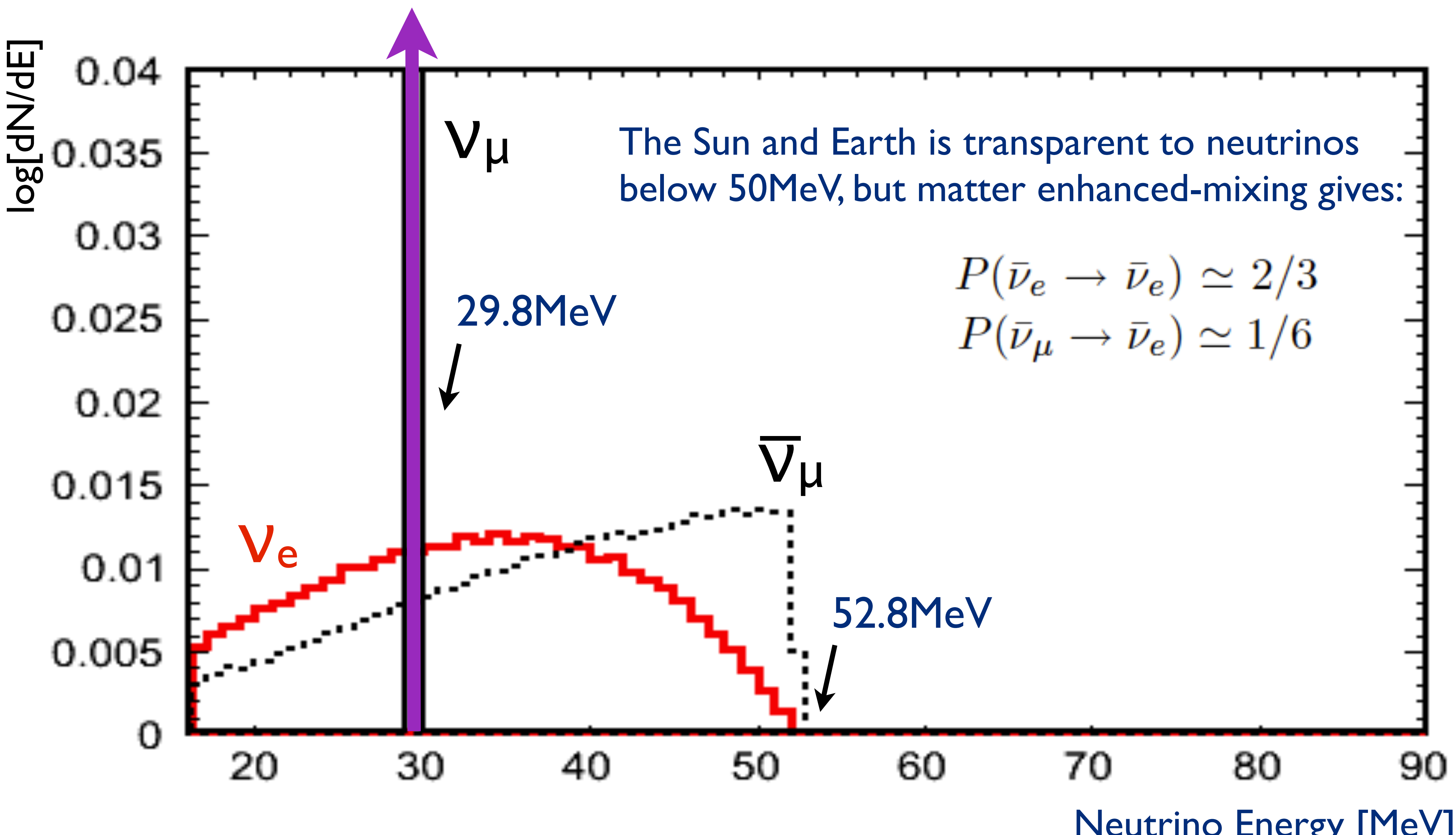
Charged pions decay at rest producing neutrinos up to E=52.8MeV

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

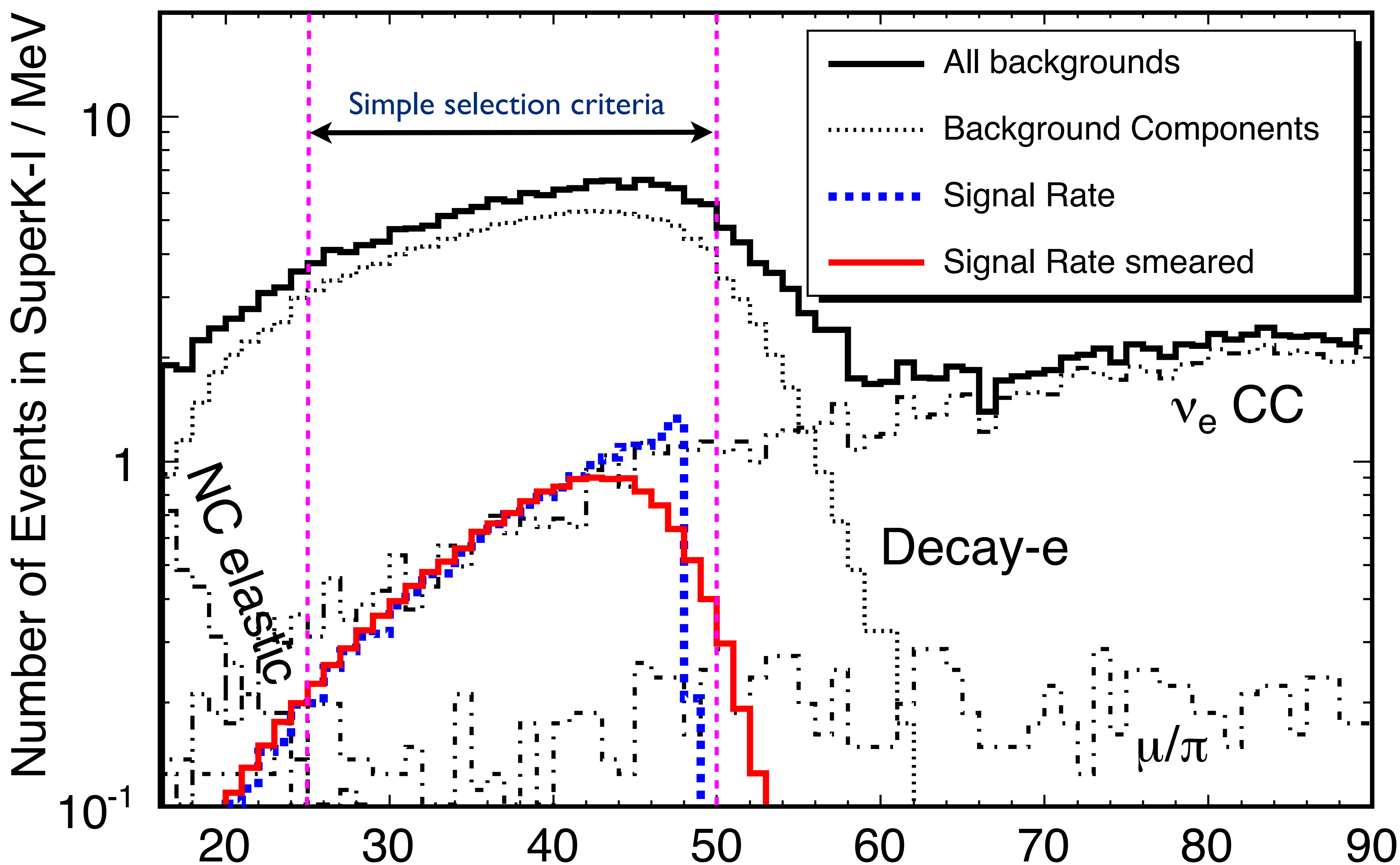
Expected low-energy Neutrino Signal

Neutrino Spectrum in the Sun (normalized to unity)



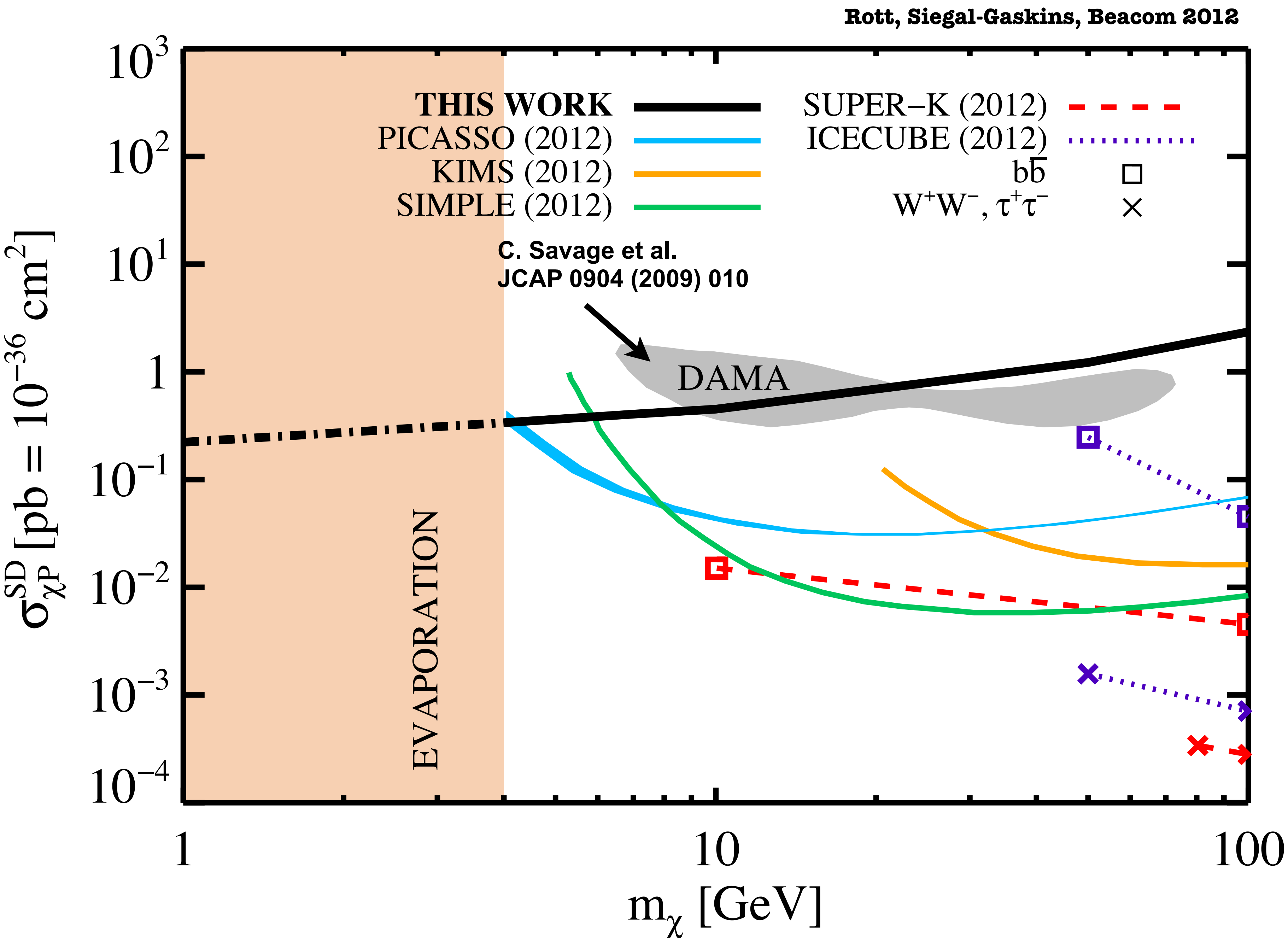
Sensitivity Calculation Super-K

To visualize the signal has been scaled to be "detectable"



Limit at 90%C.L. (one-sided Gaussian) is n_{90}=15

WIMP Sensitivity Super-K



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

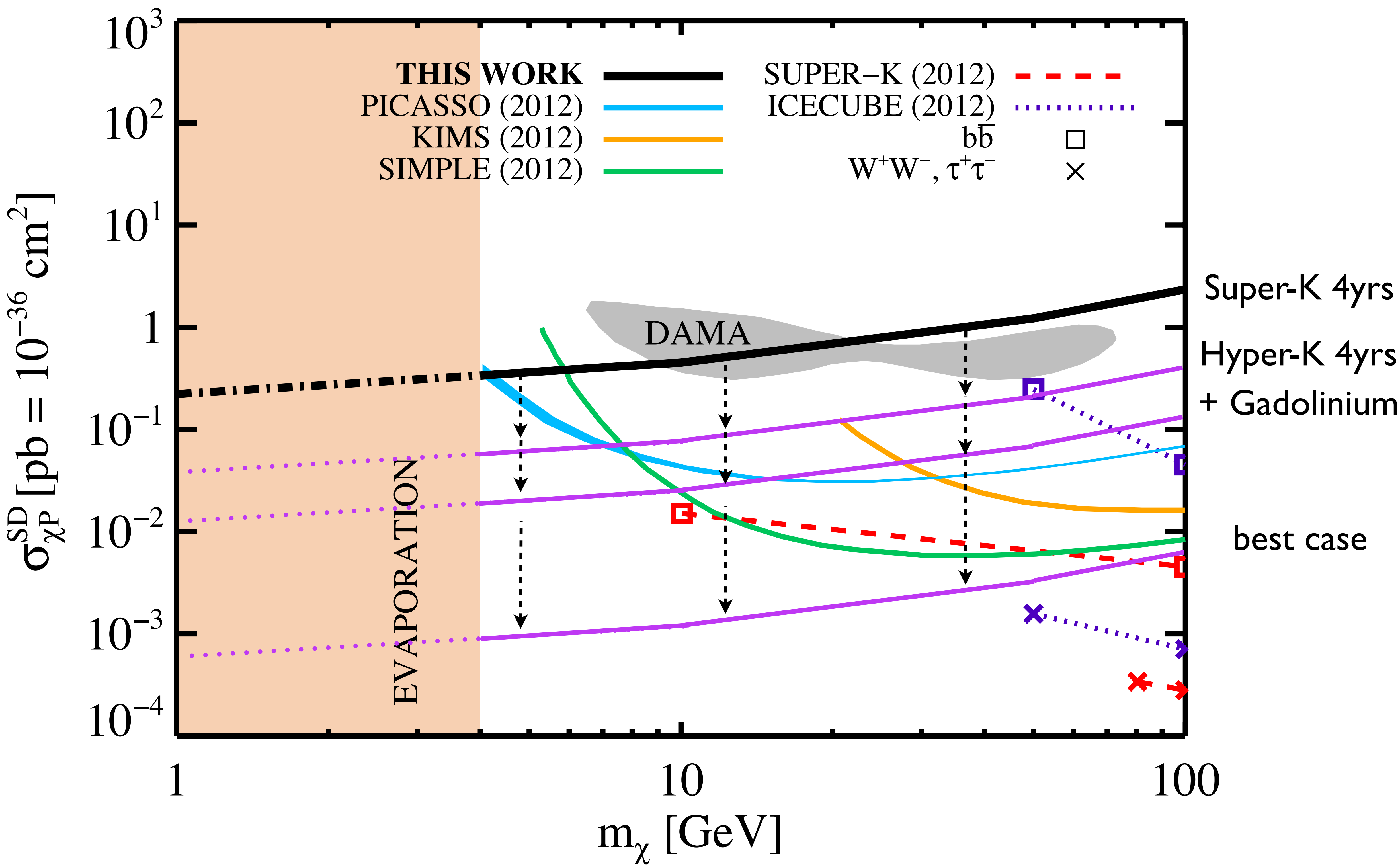
Model the full hadronic shower in the Sun

WIMP sensitivity continues to improve for low masses

New key detection channel to compliment other searches

Minimal dependence on annihilation channels

Hyper-K Sensitivity 4yrs

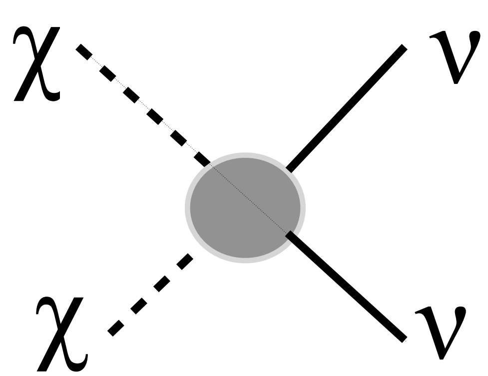


Improvements for Hyper-K

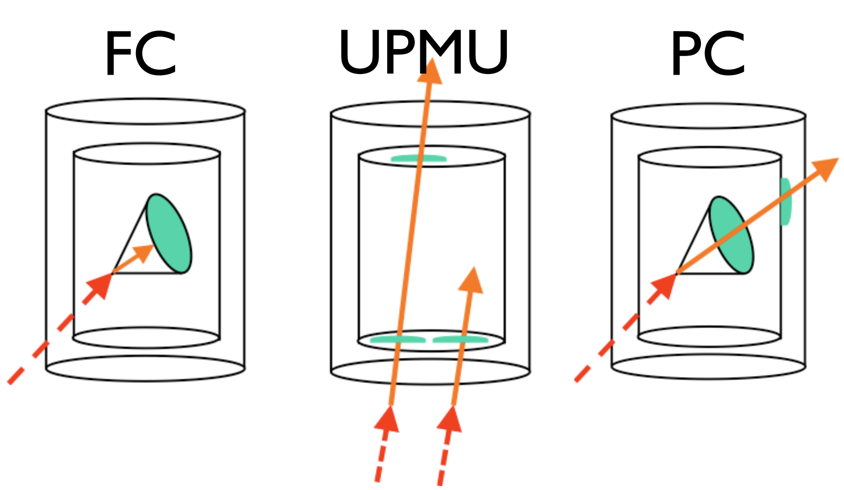
- 5years of Hyper-K (0.56Mton) data
  - Very conservative:
    - just based on statistics ~6 improvement
  - Conservative with gadolinium
    - background reduction by factor of 5
      - improvement ~14
  - Optimistic
    - 1event in background free environment ~400 improvement

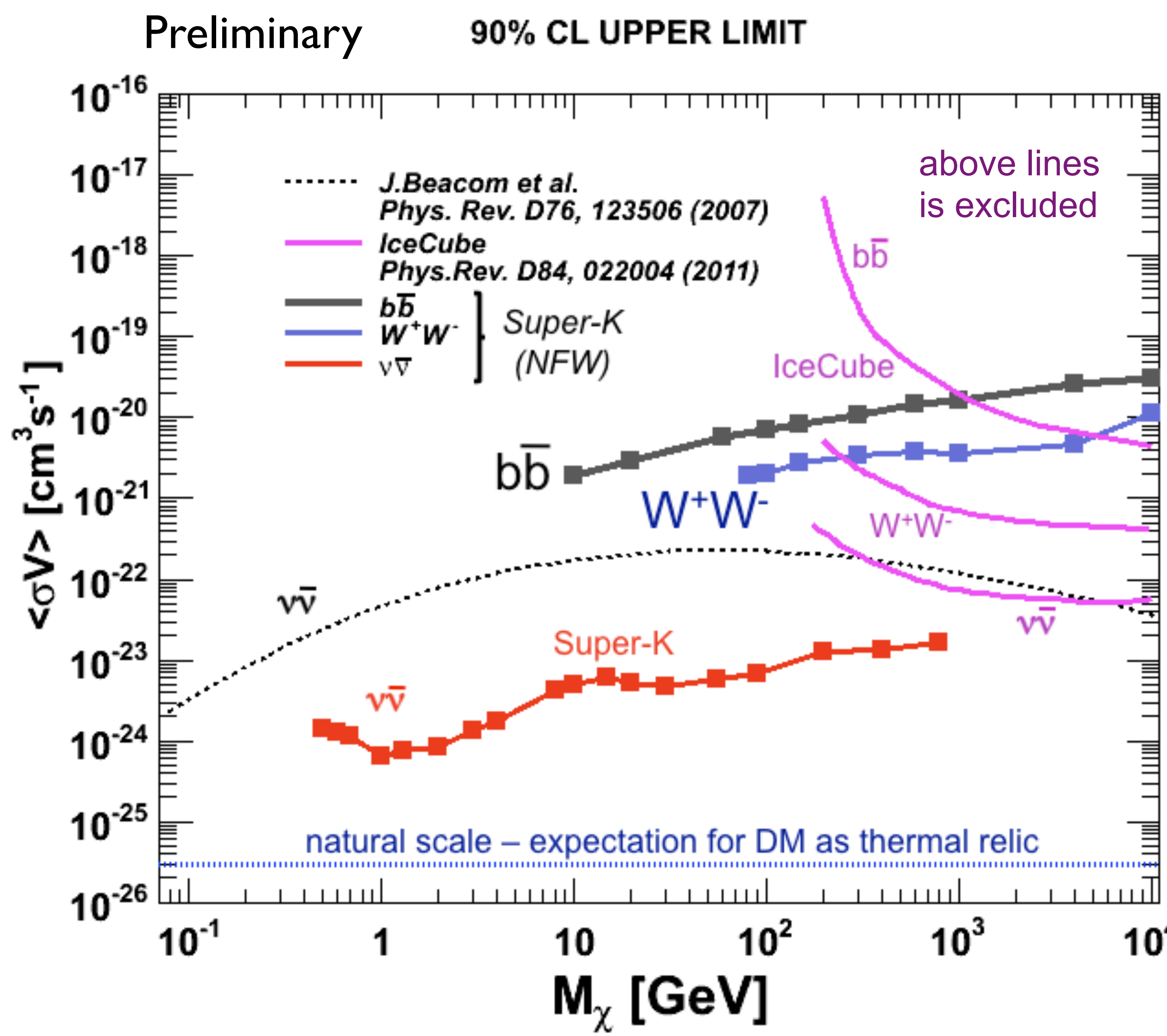
Galactic Halo

SuperK - Galactic Search



- Search for a diffuse signal from Milky Way halo
  - Assume annihilation into νν, bb, or WW
- Use all samples e-like + mu-like FC + PC (2806 days)+UPMU (3109 days)
- Use all neutrino flavors and topologies





Improvements for Hyper-K

- 5years of Hyper-K (0.56Mton) data
  - Very conservative:
    - just based on statistics ~6 improvement
  - Energy resolution
    - significant improvements possible
- Can the thermal relic cross section be breached ?

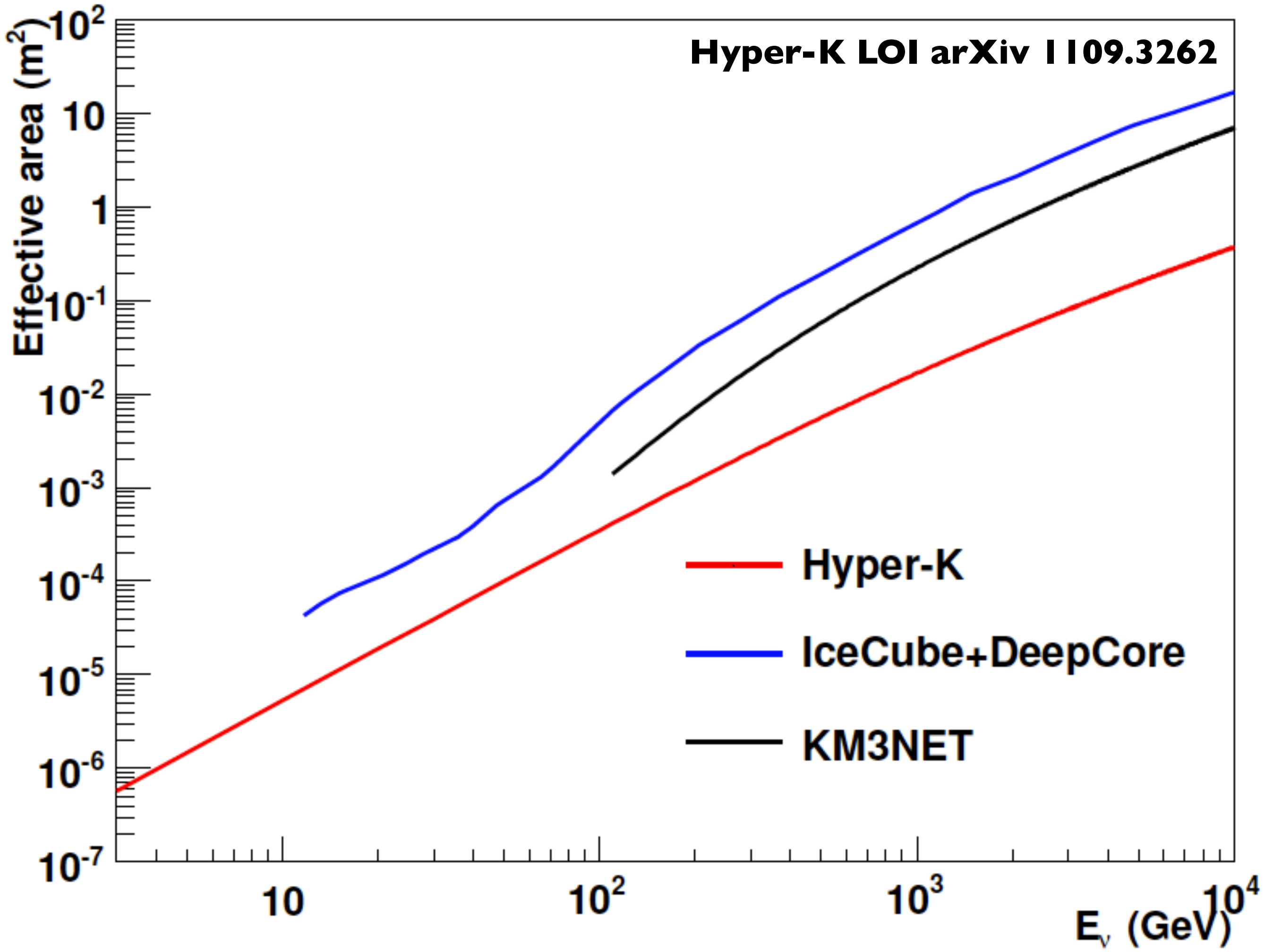
Outlook and Conclusions

Disclaimer: Some thoughts but more discussions needed

Outlook

- Dark Matter Annihilation in the Sun:
  - Reasonable high-energy neutrino yield ($\tau^+\tau^-$,bb,...)
    - Expect 5years of Hyper-K data would be more sensitive than DeepCore (15yrs) for WIMP masses below ~50GeV
    - IceCube with PINGU in-fill would be more sensitive above ~20GeV
    - Direct detection is expect to have reached similar or better sensitivity for WIMP masses above ~15GeV
  - For suppressed high-energy neutrino yield (qq,e^+e^-,$\gamma\gamma$, ...)
    - Hyper-K most sensitive for indirect searches, however not completive with direct searches unless WIMP mass is between 4-10GeV

Up-going muon neutrino effective area



KM3Net: S. Gabici, A. M. Taylor, R. J. White, S. Casanova, and F. A. Aharonian, Astropart. Phys. 30, 180 (2008), arXiv:0806.2459 [astro-ph]
IceCube: R. Abbasi et al. (2011) arXiv:1109.6096v1

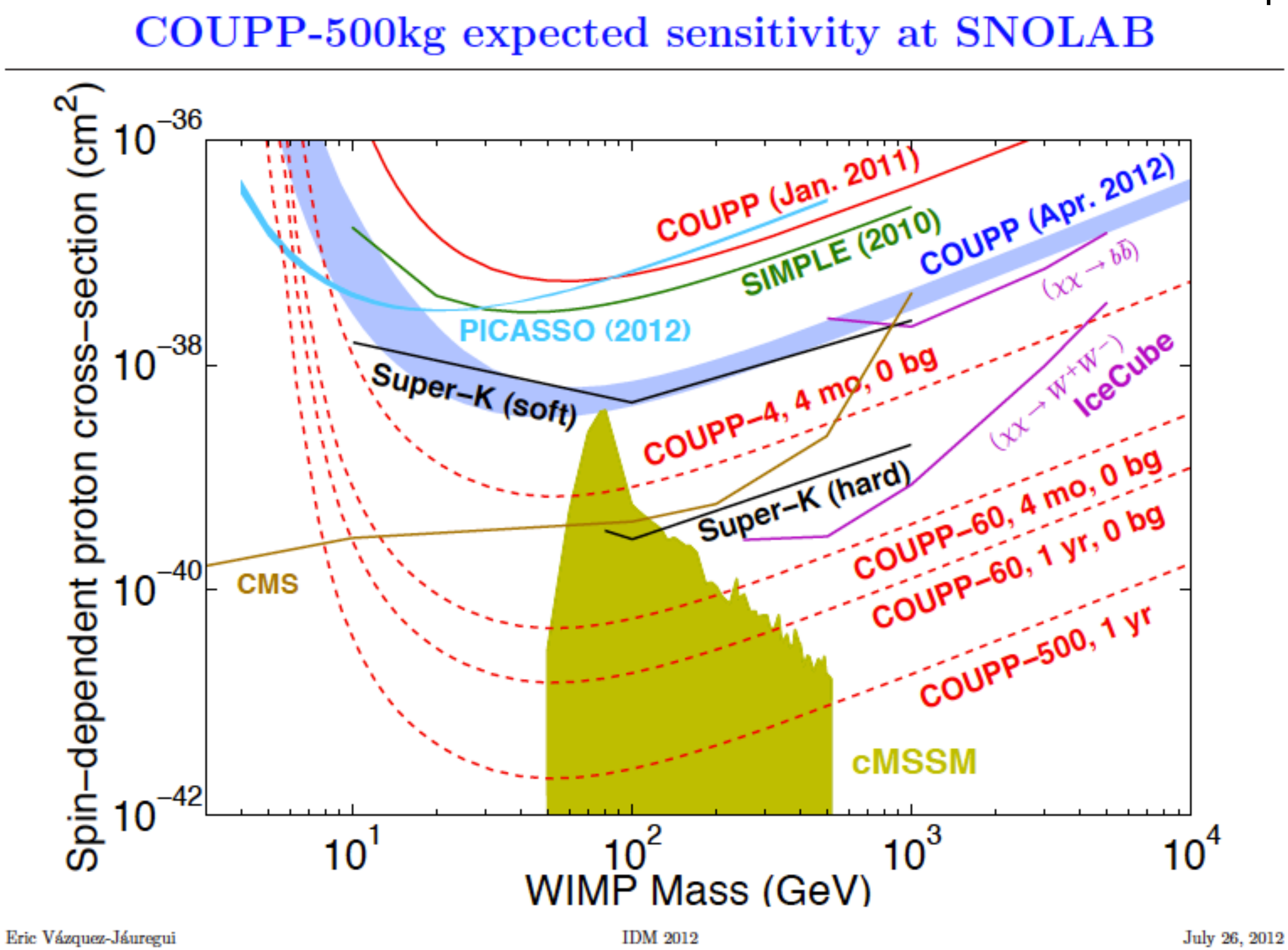
Conclusions

- ν_e , ν_τ sensitivities for Solar WIMPs compare favorably to tracks (ν_μ)
- Hyper-K will be most important to cover the WIMP mass region of 4-50GeV for indirect searches
- Discovery potential in physical interesting region or potential to study astro-physical properties of WIMP distributions
- New low-energy neutrinos from the Sun could offer very exciting unique prospects for Hyper-K
- Gadolinium could significantly improve sensitivity in low-mass neutrino channel

Backup

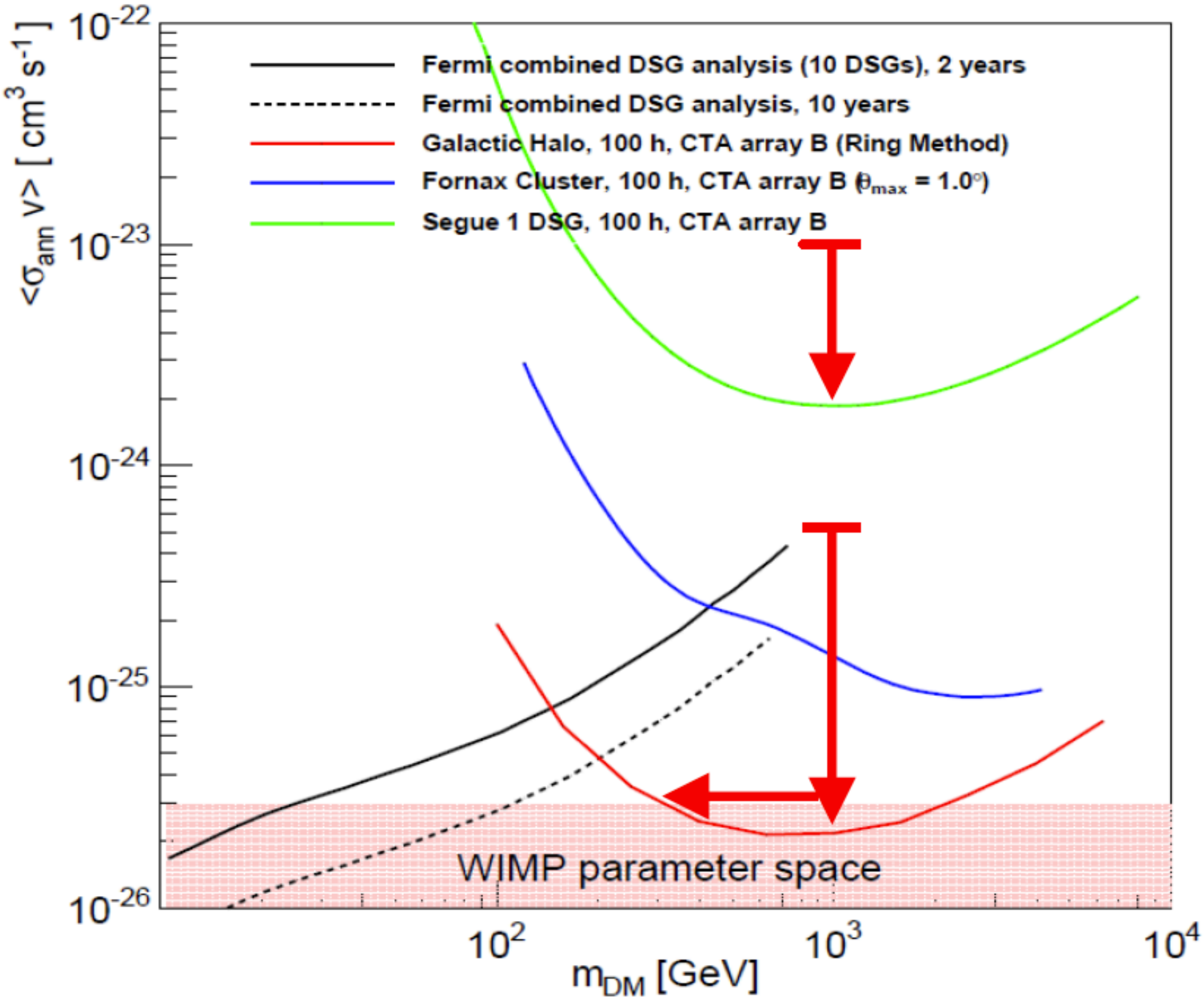
Direct Detection Progress

example COUPP



COUPP-500kg ready for physics in 2016

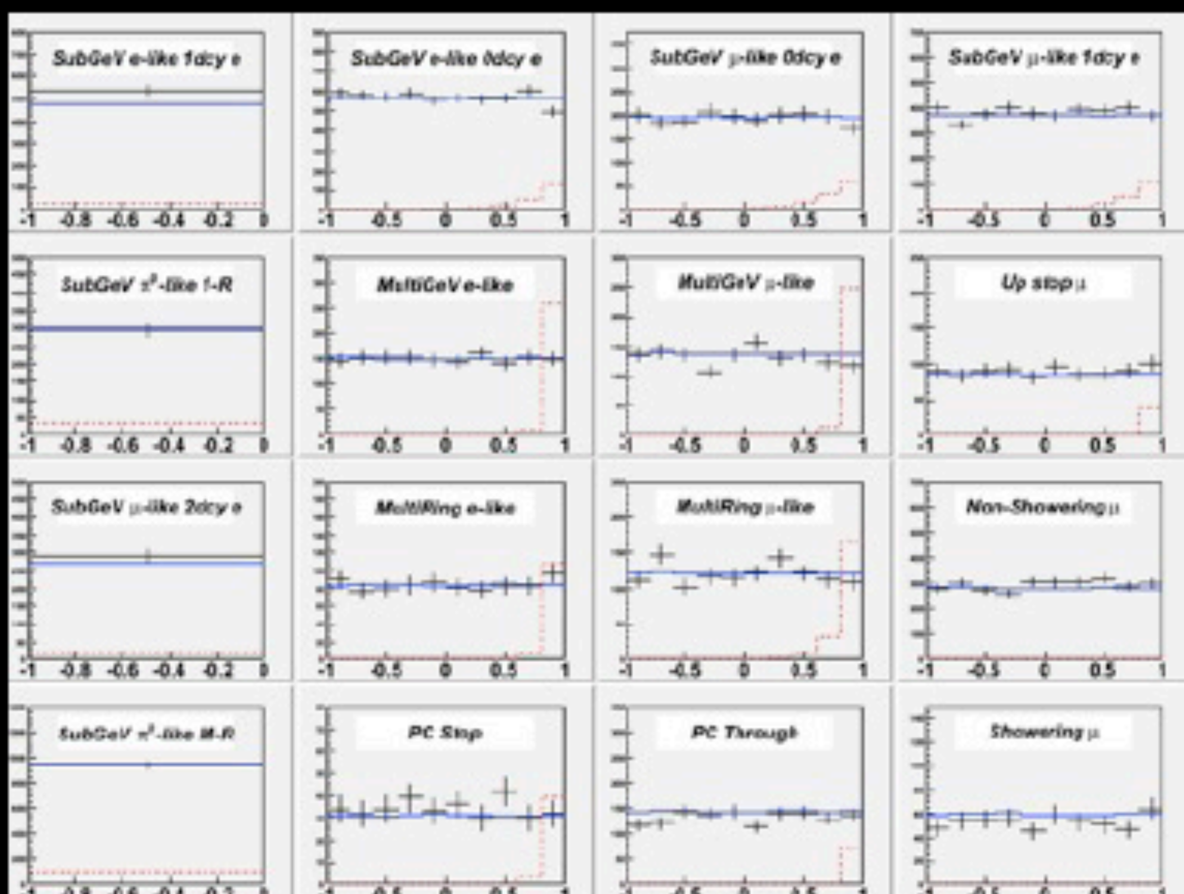
Fermi / CTA sensitivity

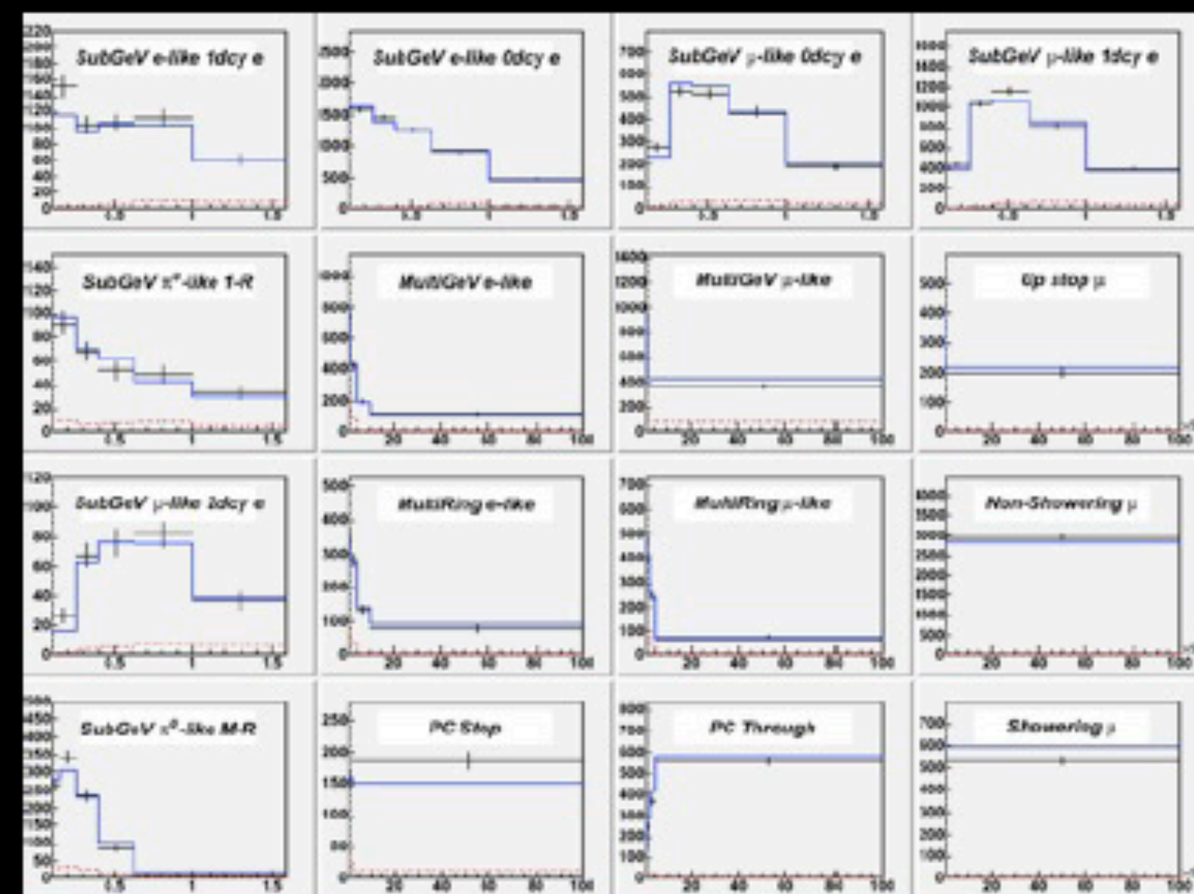


forthcoming special issue of Astroparticle Physics

Energy & angular fit

- Test the contribution of WIMP induced event to atmospheric neutrino data by minimizing x^2 distribution
- Derive 90% Bayesian upper limit on allowed WIMP induced events



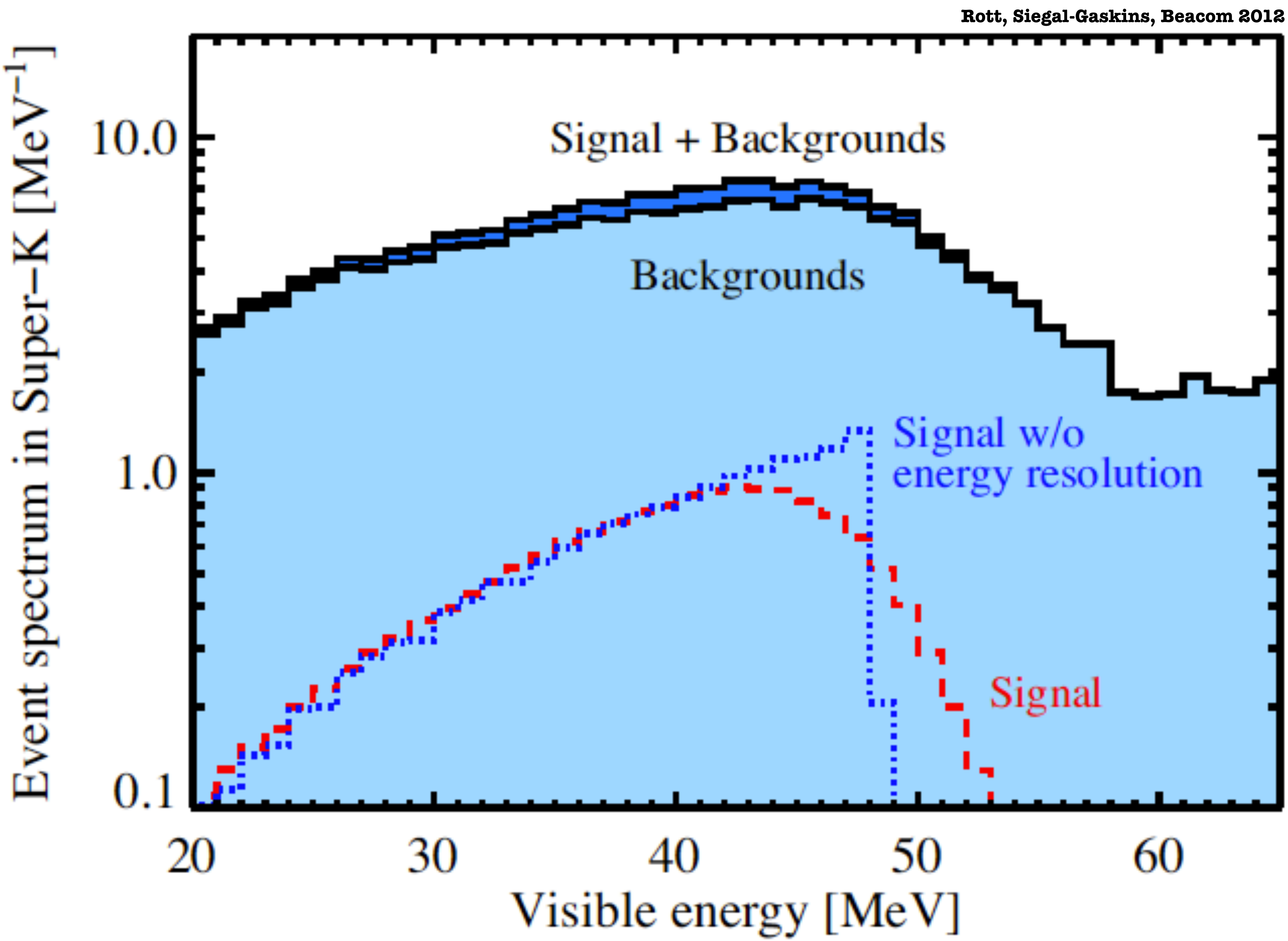


—— black cross: SK I-III Data

—— Blue solid : atmospheric MC

------ Red dashed : WIMP induced events (arbitrary normalized)

Low-Energy Neutrino Signal



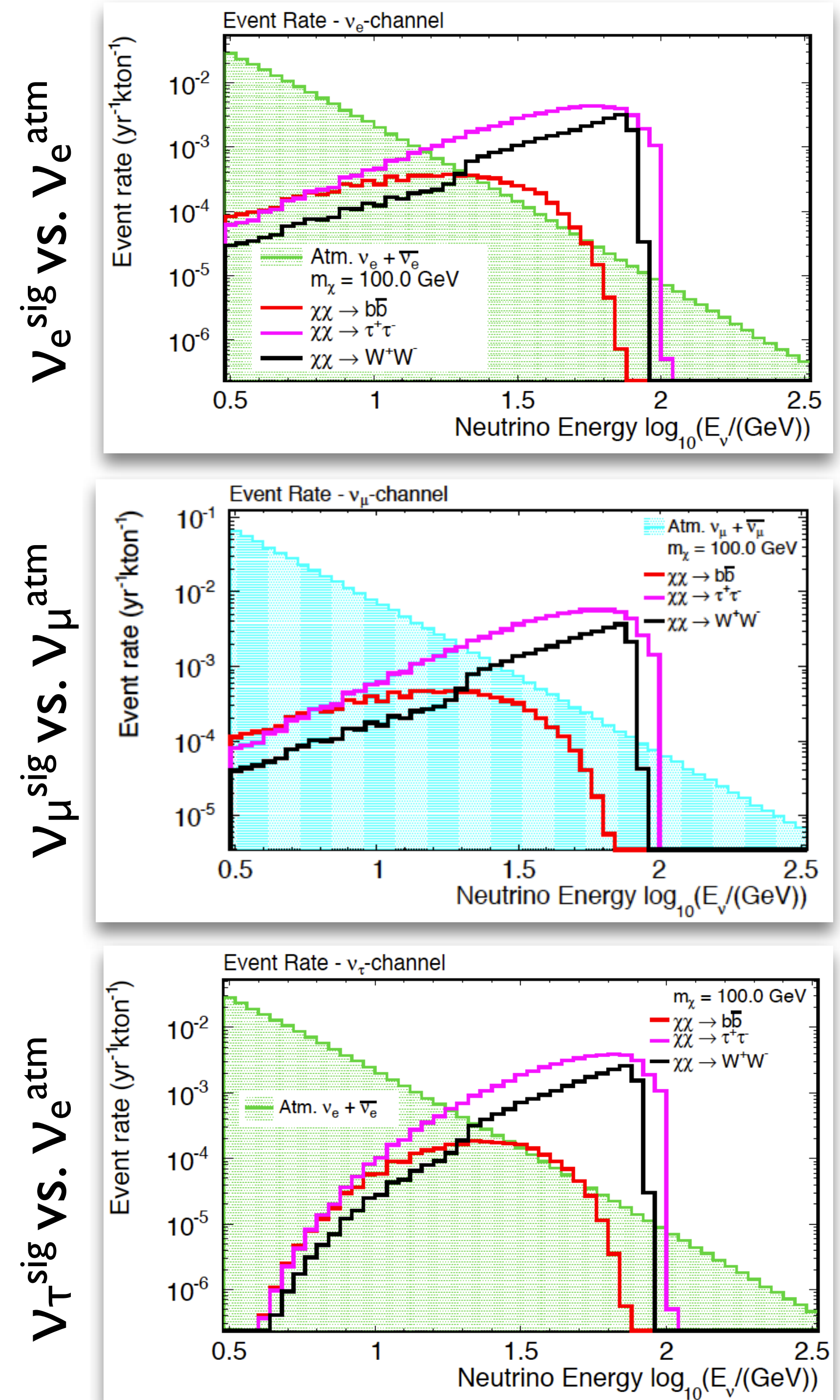
Design criteria

- Low signal rates - large detector
- Well defined targets
  - Sun, Earth, Galactic Center, ...
- Good flavor ID (tau) would really help
- Gadolinium and other background rejection methods could improve sensitivity further

WIMP Signal comparison

- Example: Assume m_χ=100GeV and annihilation rate of 1fb ($10^{-39}cm^2$)
  - ~2.45 x 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

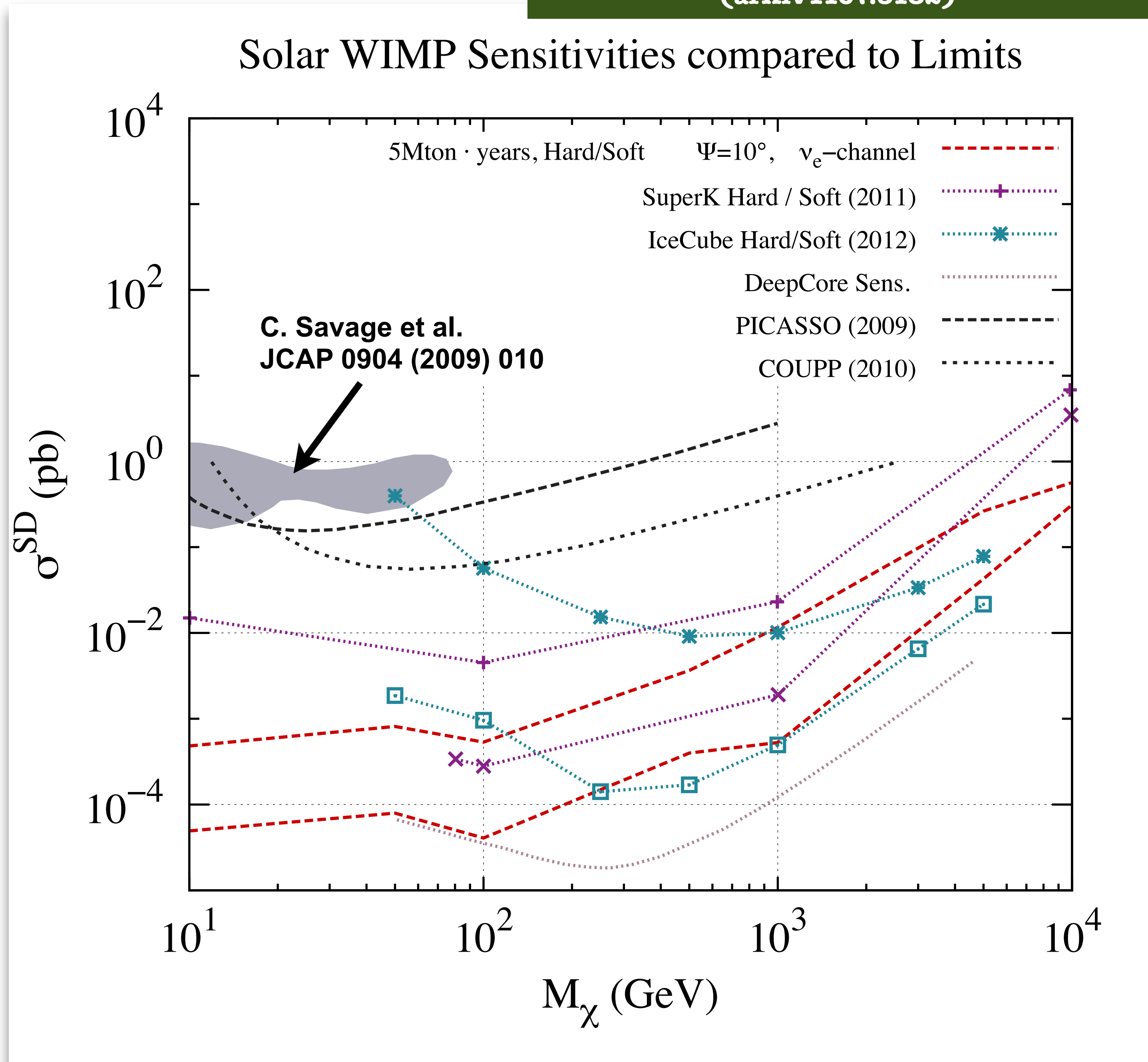
Rott, Tanaka, Itow JCAP09(2011)029



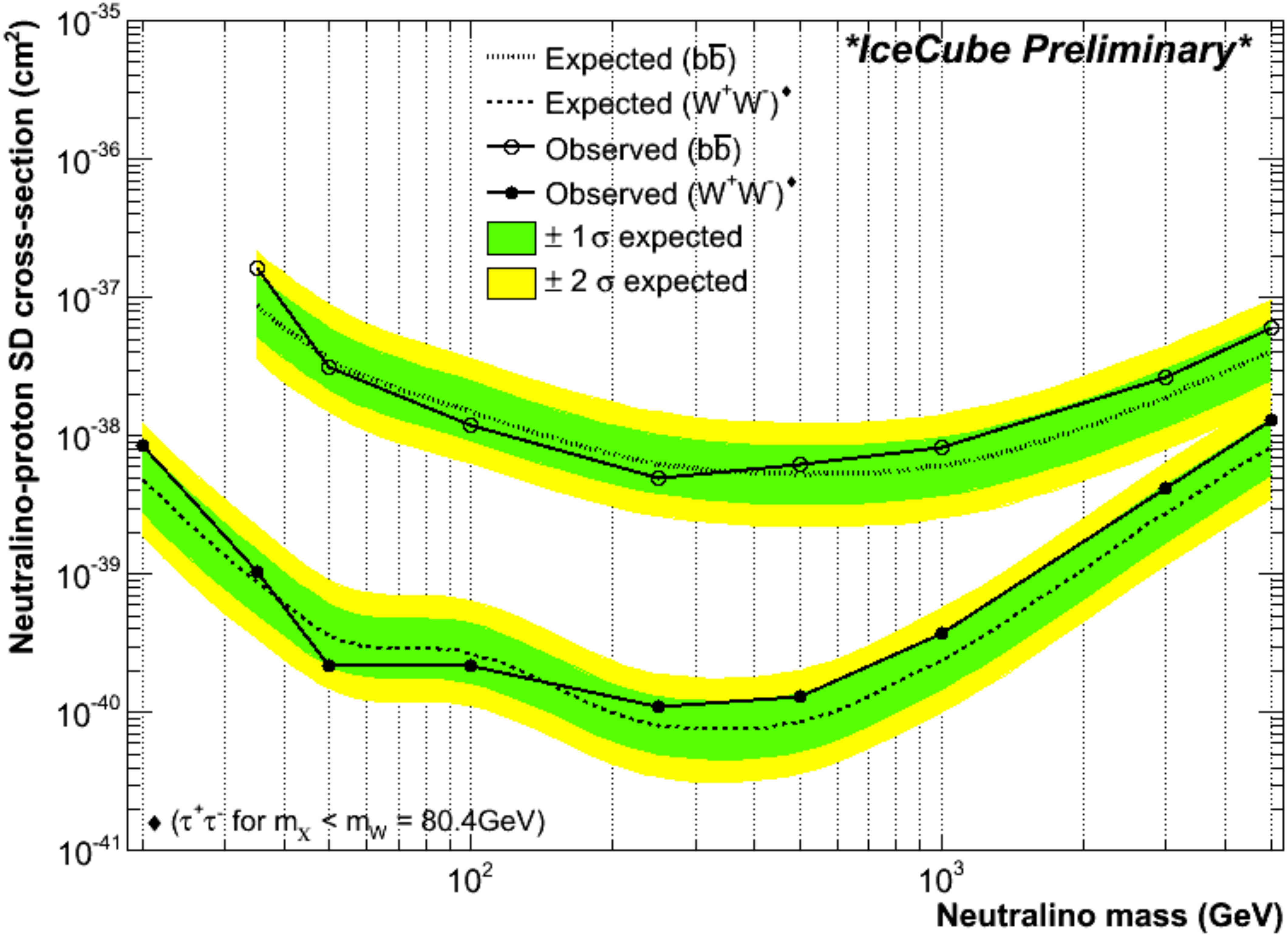
Improvements for Low mass WIMP sensitivity

- Expanding searches to new neutrino flavors will significantly enhance the sensitivity to WIMP in 10GeV range
- Benefit from better energy resolution
- Lower atmospheric neutrino background
- Despite limited angular resolution competitive sensitivities can be obtained
- Test of models motivated by anomalous annual modulation signals possible by Hyper-K

C.Rott, T.Tanaka, Y. Itow JCAP09(2011)029 (arXiv1107.3182)

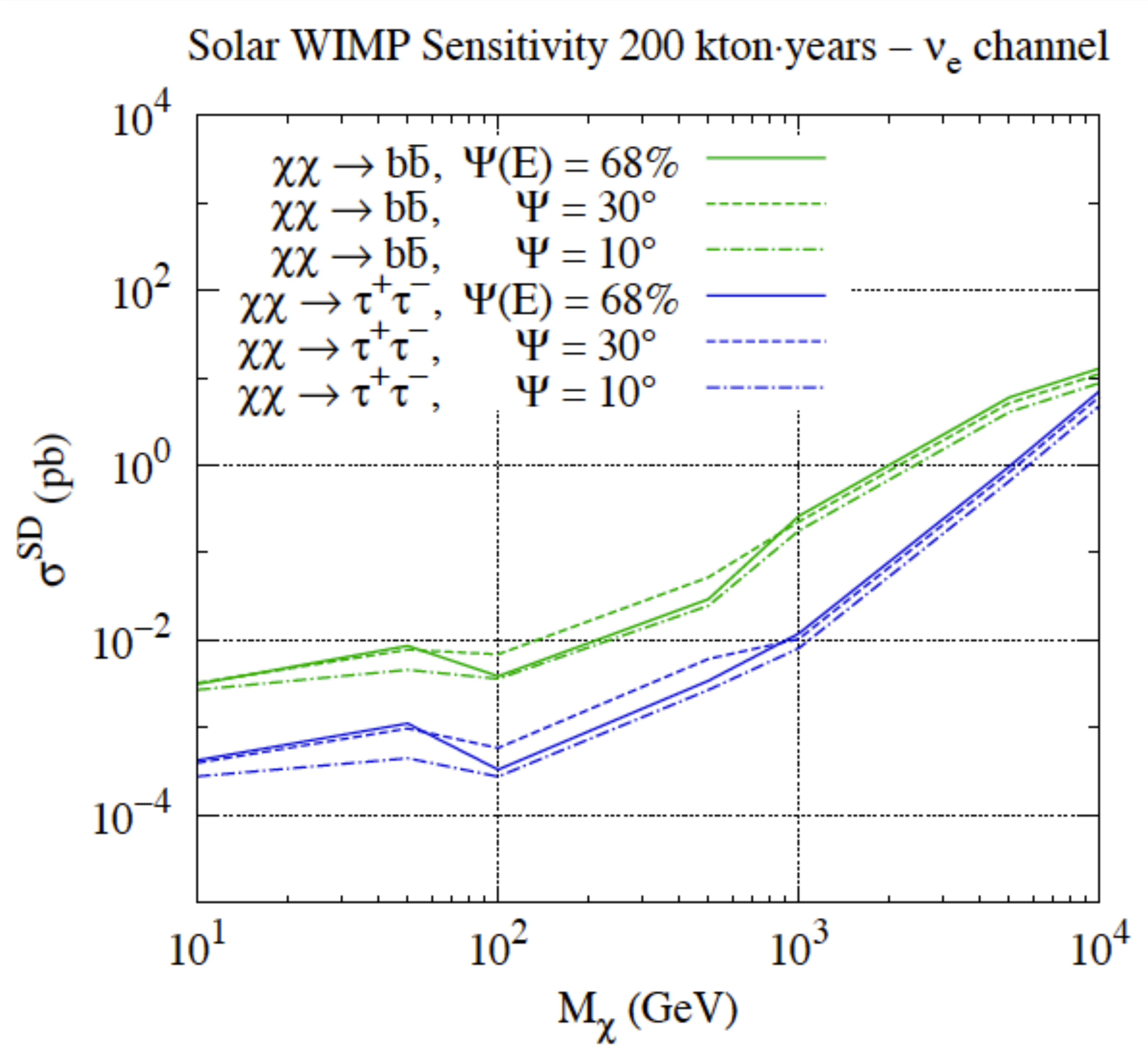


IceCube/DeepCore 2012



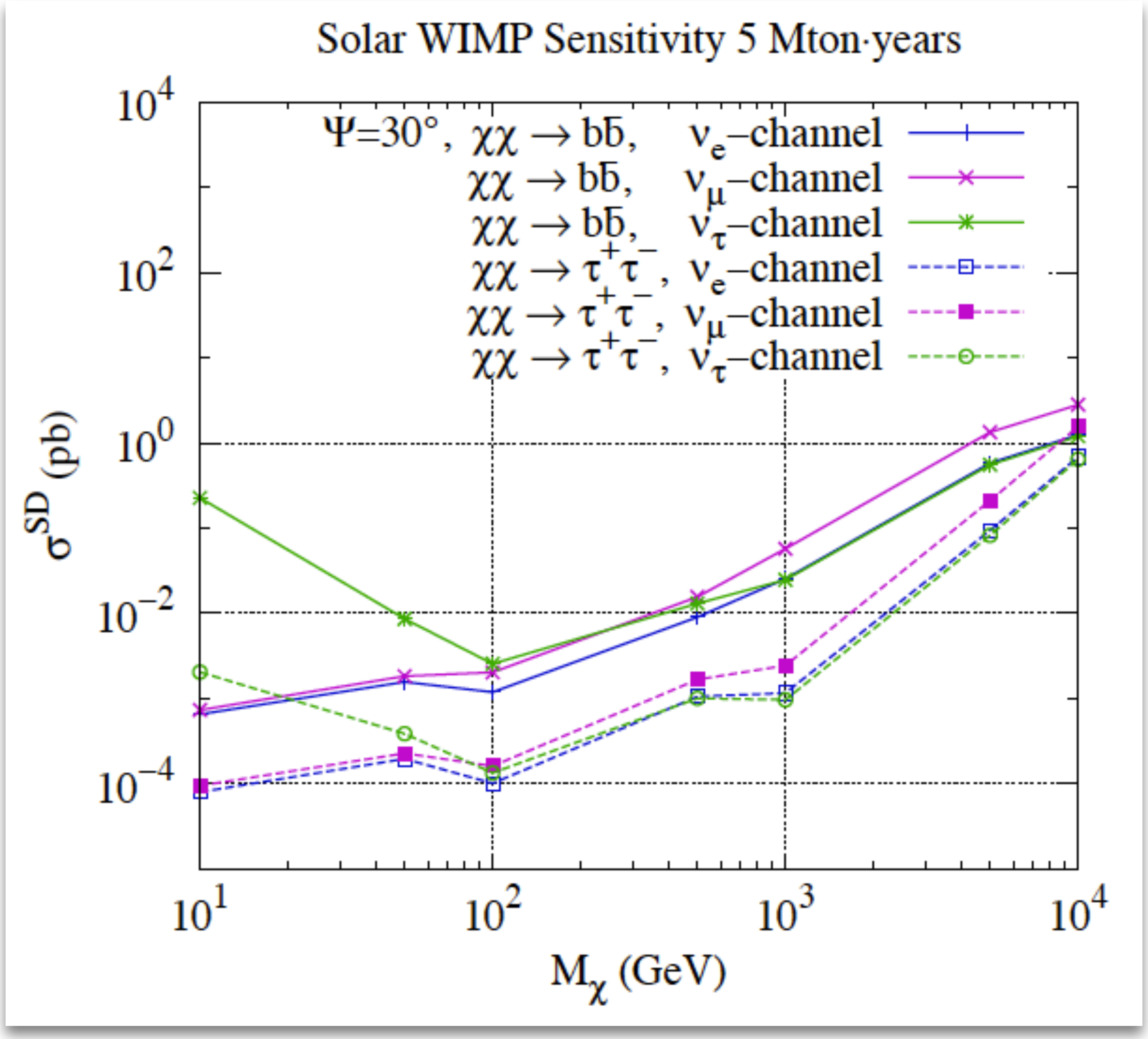
Compute Sensitivity for a Generic Detector

- 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_χ[10GeV,100GeV] E_{Thr}=1GeV
  - m_χ[100GeV,1TeV] E_{Thr}=10GeV
  - m_χ[1TeV,10TeV] E_{Thr}=100GeV

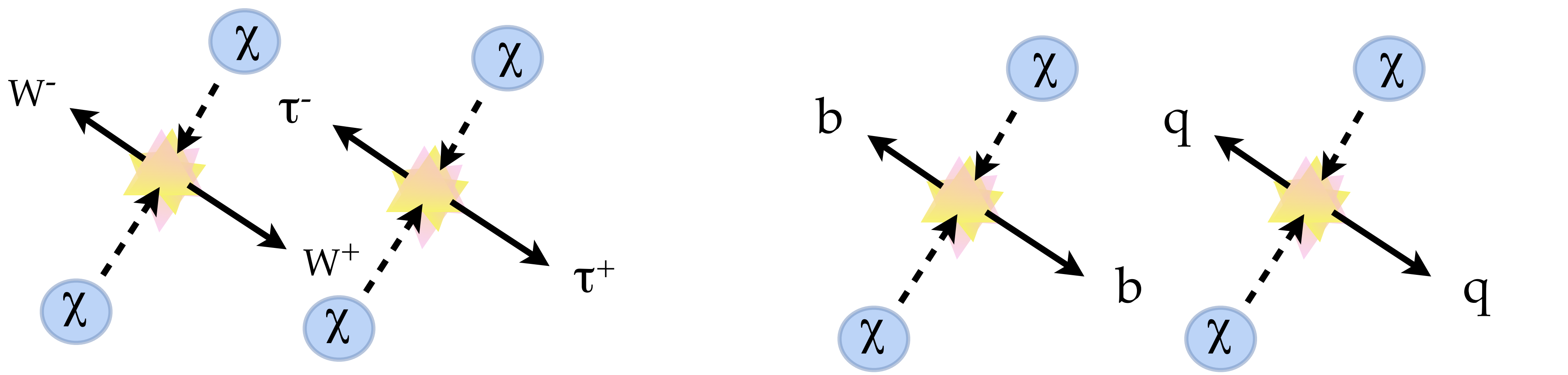


Flavor Channel Comparison

- Best results are obtained with the electron neutrino channel
- Tau neutrinos important for WIMP masses above 100GeV



Dark Matter Annihilation in the Sun



high energy neutrinos from annihilation / decay products

νν $W^- W^+$ bb   qq e^+e^-

highest energy neutrinos

fewest neutrinos

Benchmarks
Br 100%

Hard channel

Soft channel

Specific Model

$$\mathcal{L}_{\rm total}(n_{\rm tot}, \Xi|\psi) = \mathcal{L}_{\rm num}(n_{\rm tot}|\psi) \prod_{i=1}^{n_{\rm tot}} \mathcal{L}_{{\rm ang},i}(\phi_i'|\psi)\, \mathcal{L}_{{\rm spec},i}(N_i|\psi)$$

see: Scott, Savage, Edsjo and IceCube Collaboration "Use of event-level neutrino telescope data in global fits for theories of new physics" arXiv1207.0810

low energy neutrinos from hadronic shower

see: Rott, Siegal-Gaskins, Beacom arXiv1208.0827

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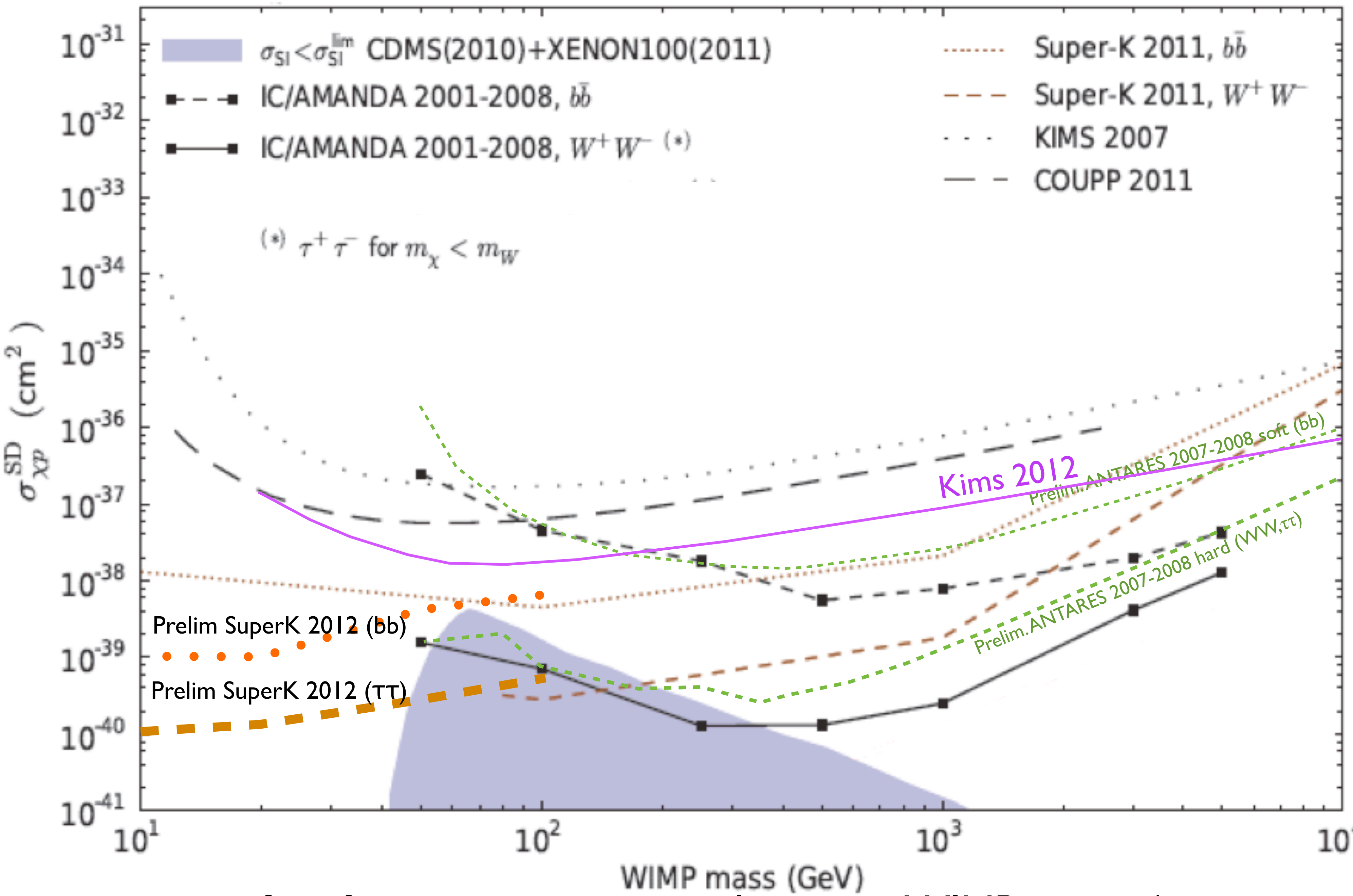

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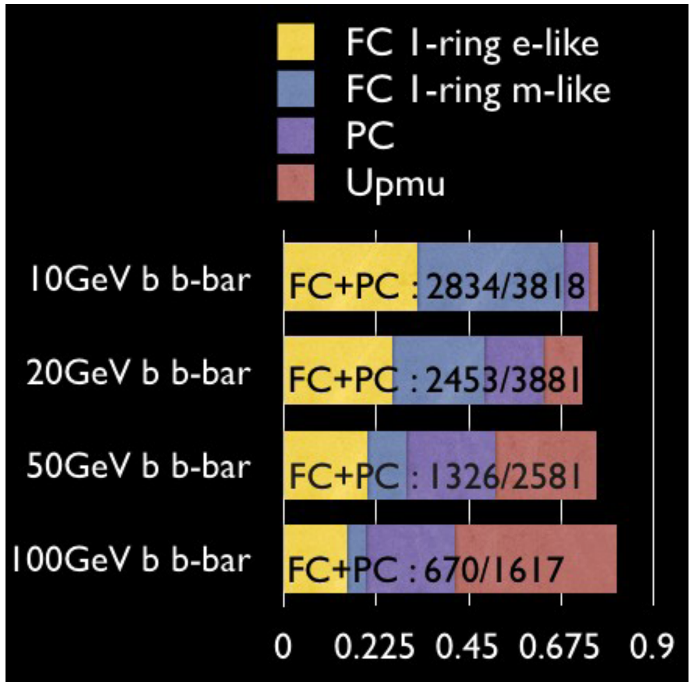
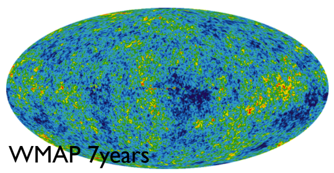
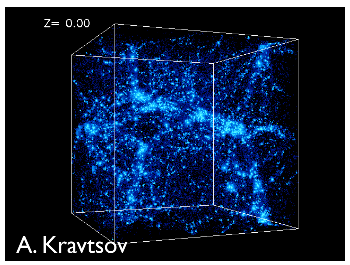


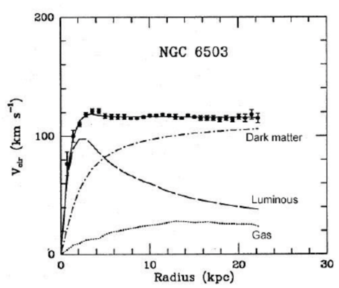
Energy / Angular Fit
Derive 90% Bayesian upper limit on allowed WIMP induced events

Dark Matter at all scales

“Evidence”



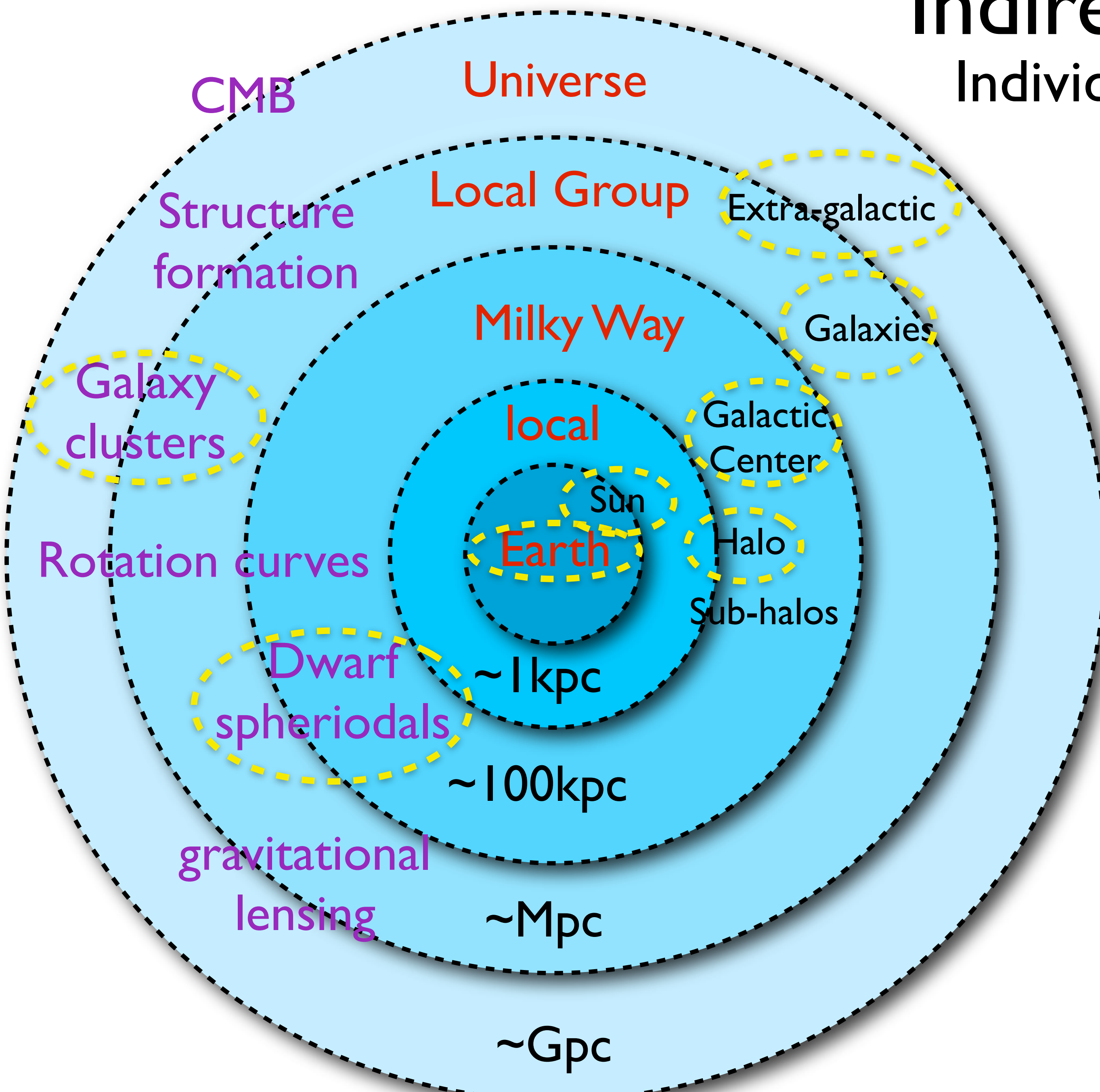




Begeman, Broels & Sanders (1991)

“Indirect Targets” for ν

Individual sources and diffuse



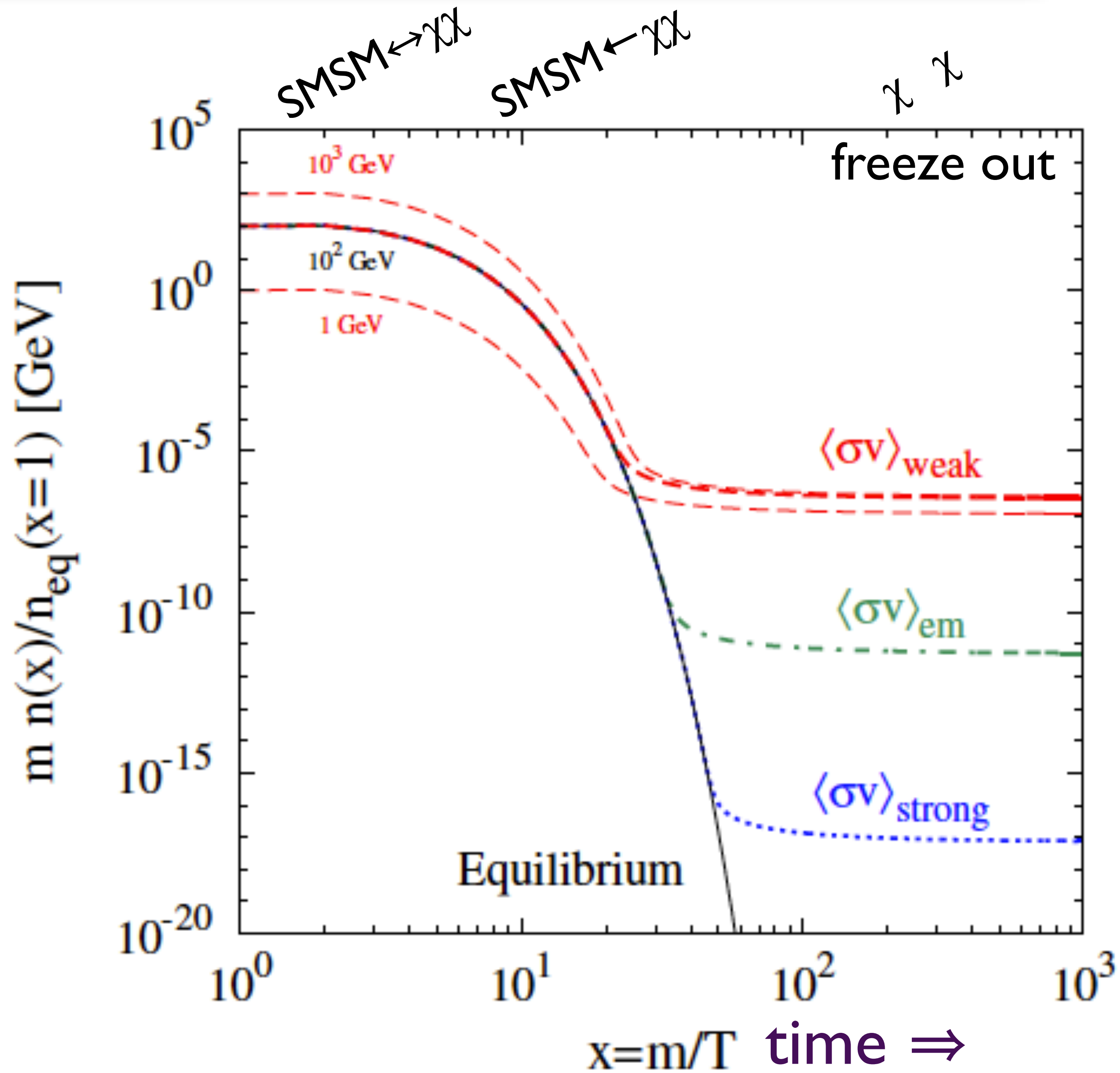
Thermal Relic

$<\sigma_A v>$ - total self-annihilation cross section averaged over the relative velocity distribution

- If dark matter is a WIMP (χ) that is a thermal relic of the early Universe, then its $<\sigma_A v>$ is revealed by its present-day mass density
- Evolution is determined by the competition between production and annihilation
- Common temperature T ($\equiv T_\gamma$)

$$\frac{dn}{dt} + 3Hn = \frac{d(na^3)}{a^3 dt} = \langle \sigma_A v \rangle \left(n_{eq}^2 - n^2\right)$$

$$n_{eq} = g_\chi (mT/(2\pi))^{3/2} \exp(-m/T)$$



$m_\chi \approx 1\text{GeV} \Rightarrow <\sigma_A v> \sim 4.5 \cdot 10^{-26}\ \text{cm}^3\text{s}^{-1}$

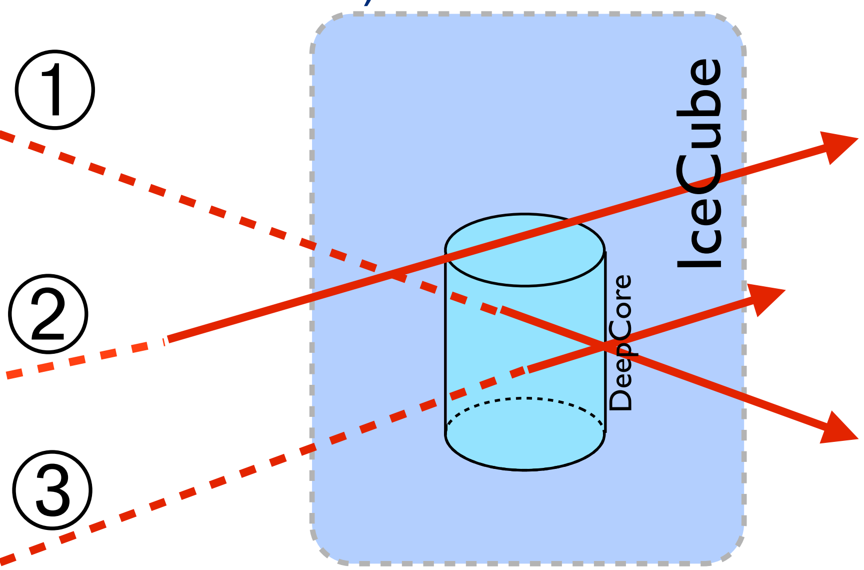
$m_\chi > 5\text{GeV} \Rightarrow <\sigma_A v> \sim 2 \cdot 10^{-26}\ \text{cm}^3\text{s}^{-1}$

G. Steigman, B. Dasgupta, J.F. Beacom 1204.3622
G. Jungman, M. Kamionkowski, K. Griest, Phys. Rept., 267 (1996) 195.

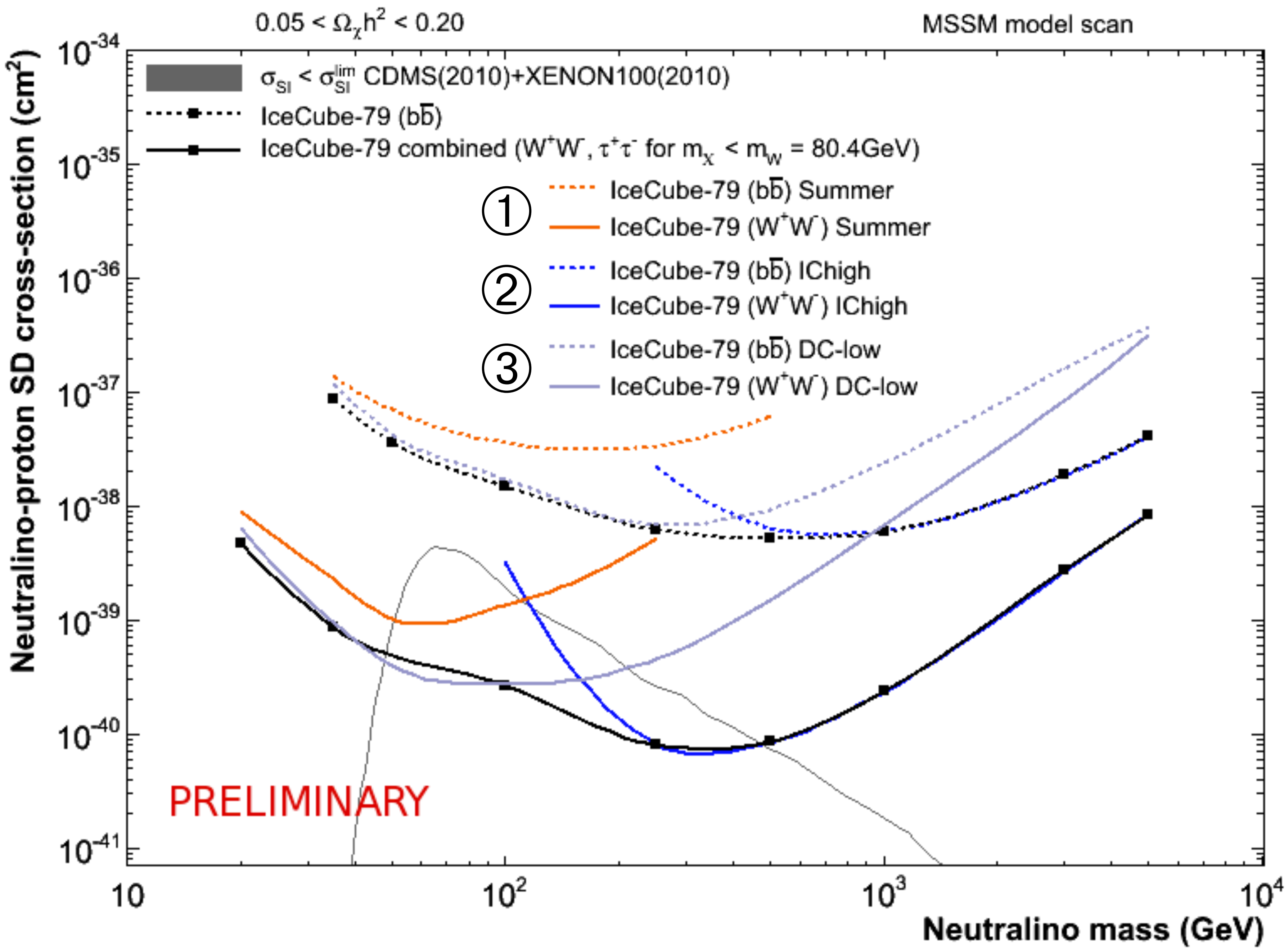
New DeepCore Solar WIMP Sensitivity

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:

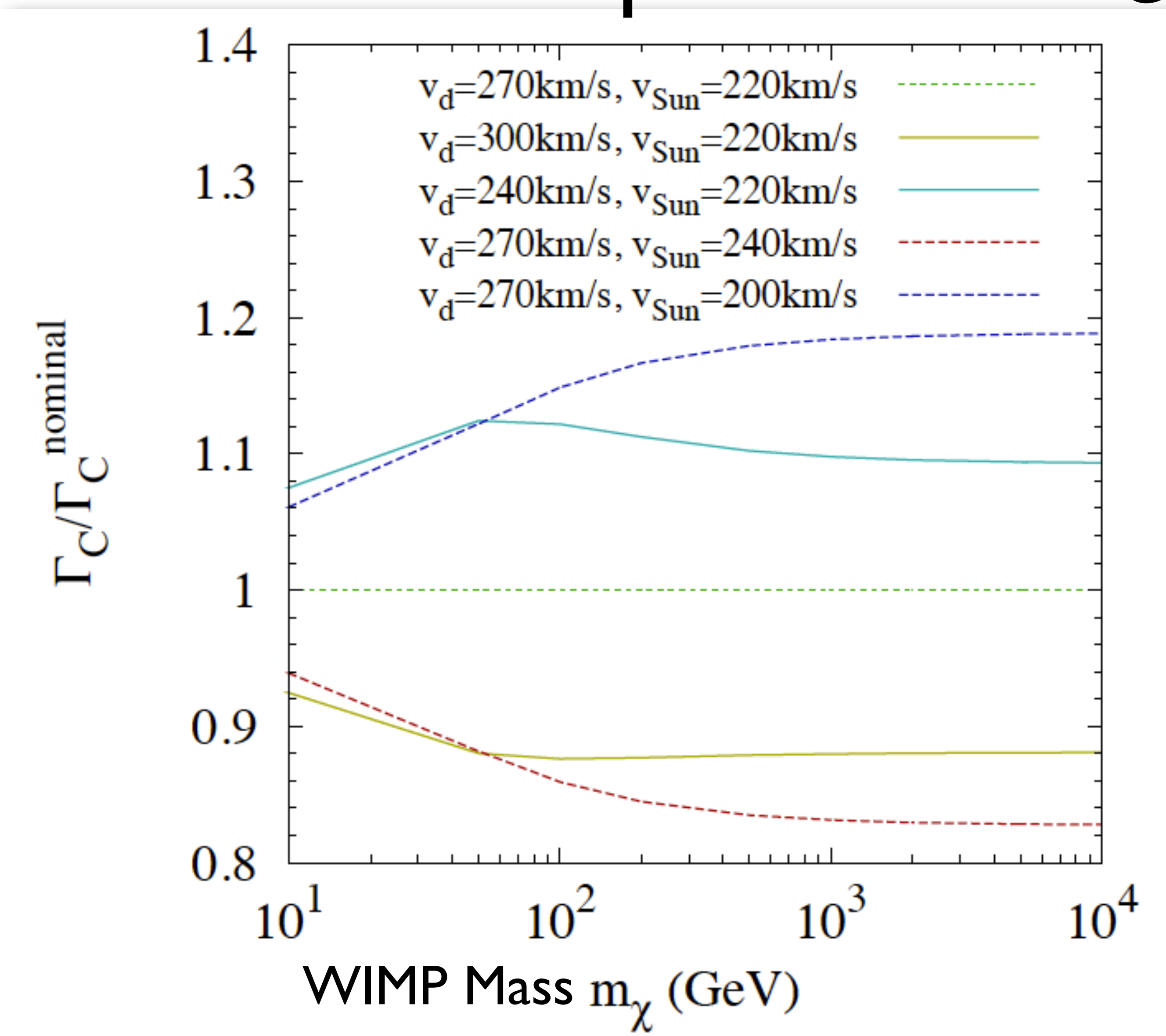
74-2 M. Danninger and E. Strahler "Search for Dark Matter Captured in the Sun with the IceCube Neutrino Observatory"

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

Halo Uncertainties on the capture rate

C.Rott, T. Tanaka, Y. Itow, JCAP09(2011)029
A. Peter et al. Phys. Rev. D79 (2009) 103532

Effect on Capture Rate Γ_C

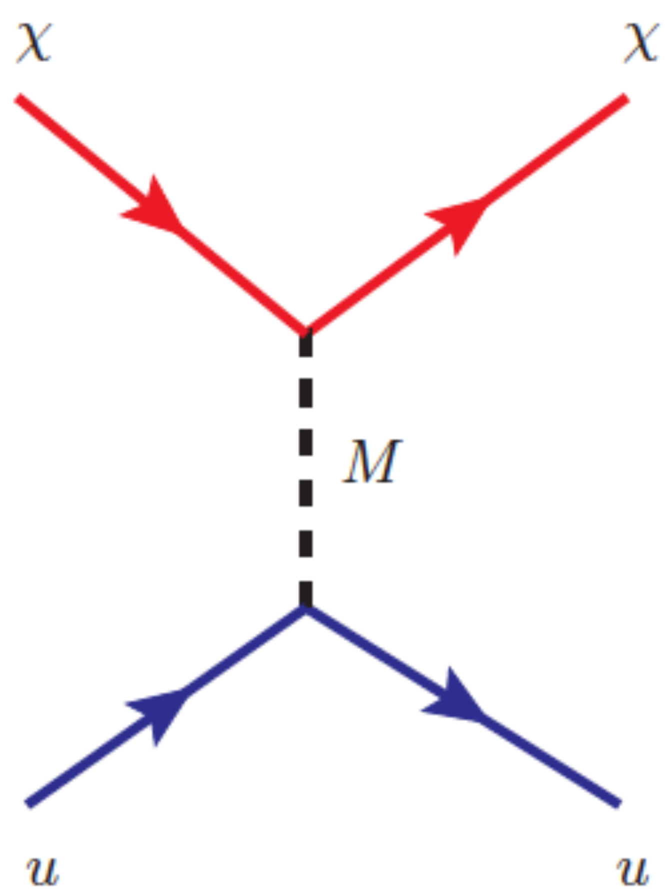


Assume a Maxwellian velocity distribution of the WIMPs outside the potential well of the Sun with a dispersion of v_d
Circular velocity of the Sun is assumed to be v_{SUN}=220km/s

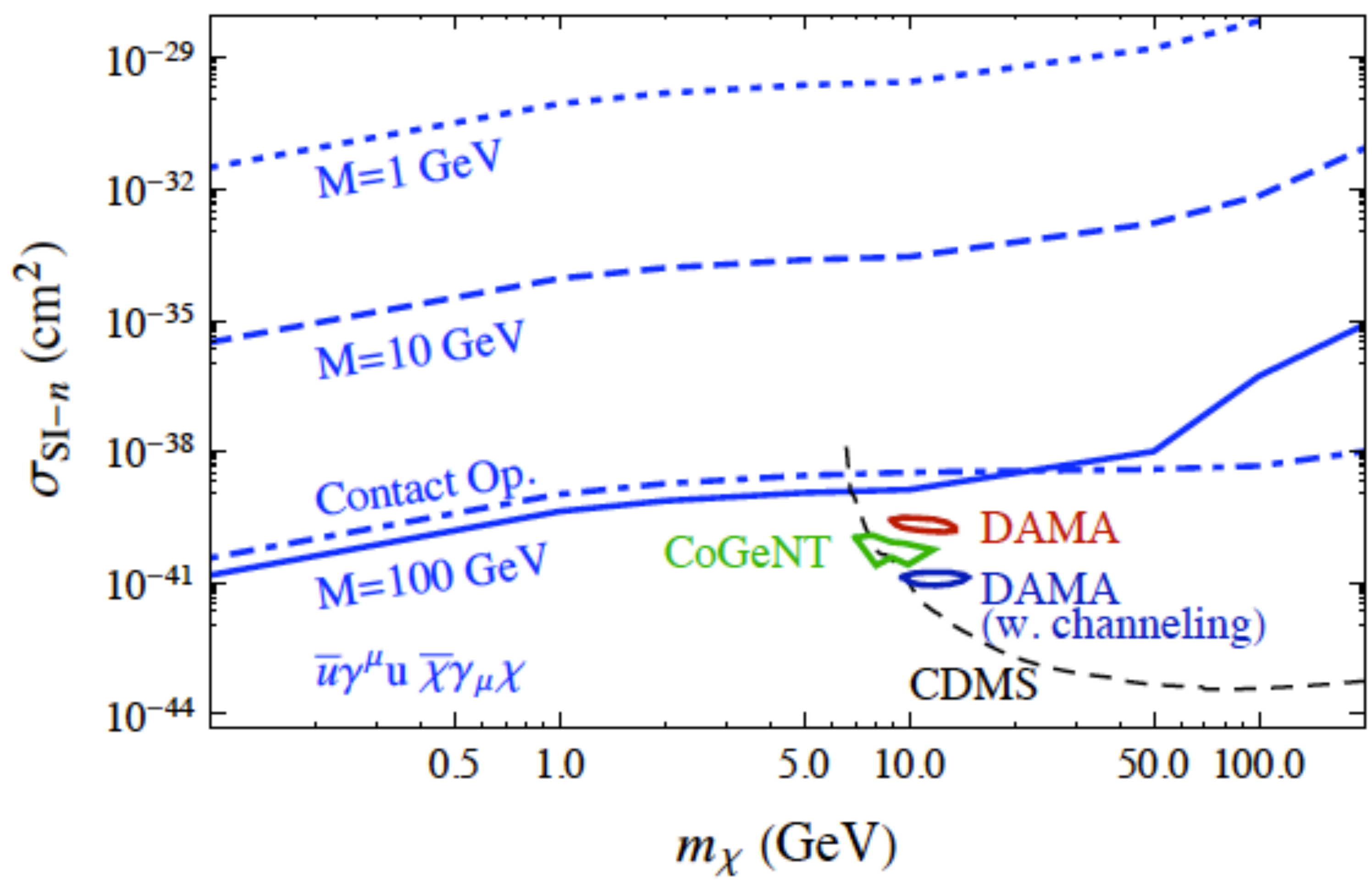
Uncertainty	WIMP Mass m_χ 10 GeV	100 GeV	1 TeV
Dark matter density	$^{+130\%}_{-17\%}$	$^{+130\%}_{-17\%}$	$^{+130\%}_{-17\%}$
Capture process (Planets)	$< 1\%$	$\sim 1\%$	$\pm 20\%$
Solar composition	$\sim 1\%$	$\sim 1\%$	$\sim 1\%$
Solar velocity	$\pm 6\%$	$\pm 15\%$	$\pm 18\%$
Velocity dispersion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

- 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

Accelerator Bounds



Bai et.al. JHEP1012

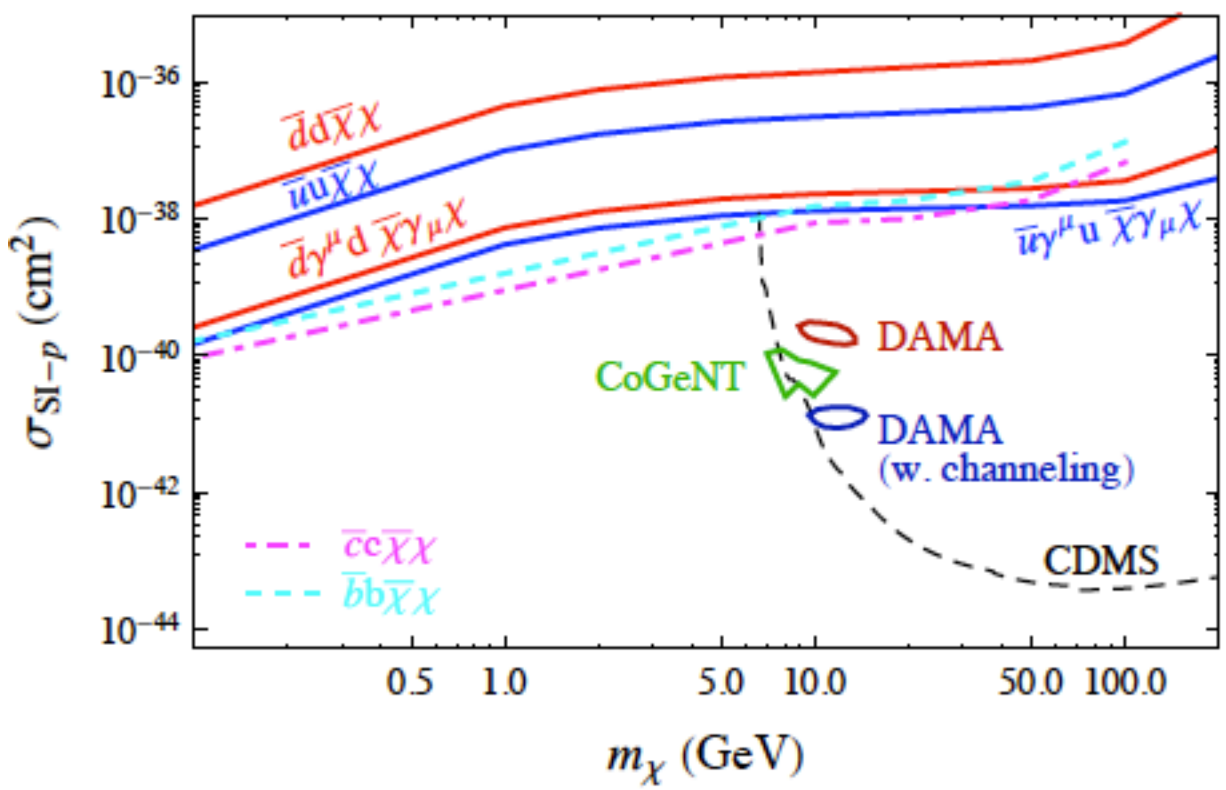


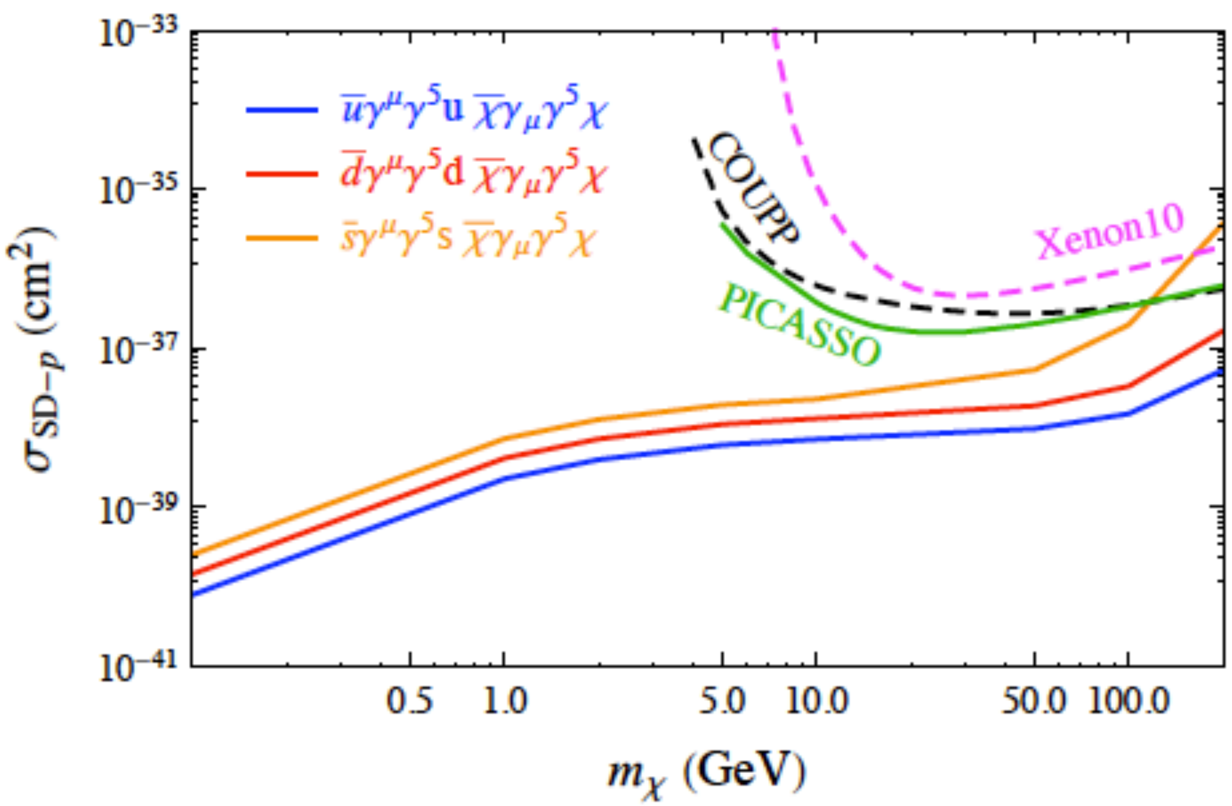
Direct detection enhanced over collider production if exchange has light mediator

$M < p_T(1\text{jet})$

Accelerator Bounds - Monojets

Bai et.al. JHEP1012





Paper analyzed implications of CDF monojet search in "direct detection" plane