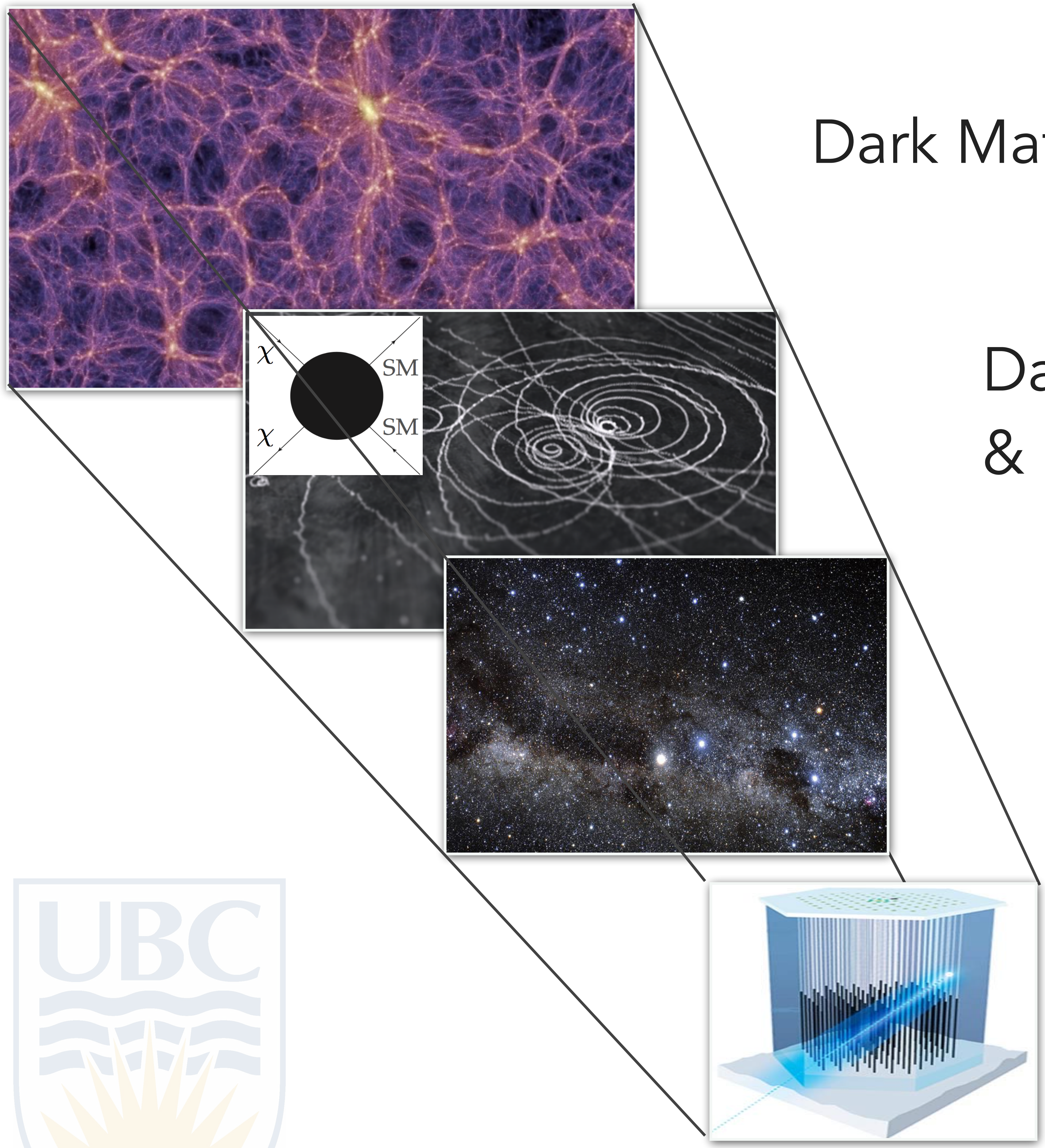
Review of indirect detection of dark matter with neutrinos

— DM@LHC 2017, University of California, Irvine —

Matthias Danninger, University of British Columbia

2017-04-03

In a nutshell



Dark Matter distributions

Dark Matter interactions
& Primary decay or annihilation products

Propagation

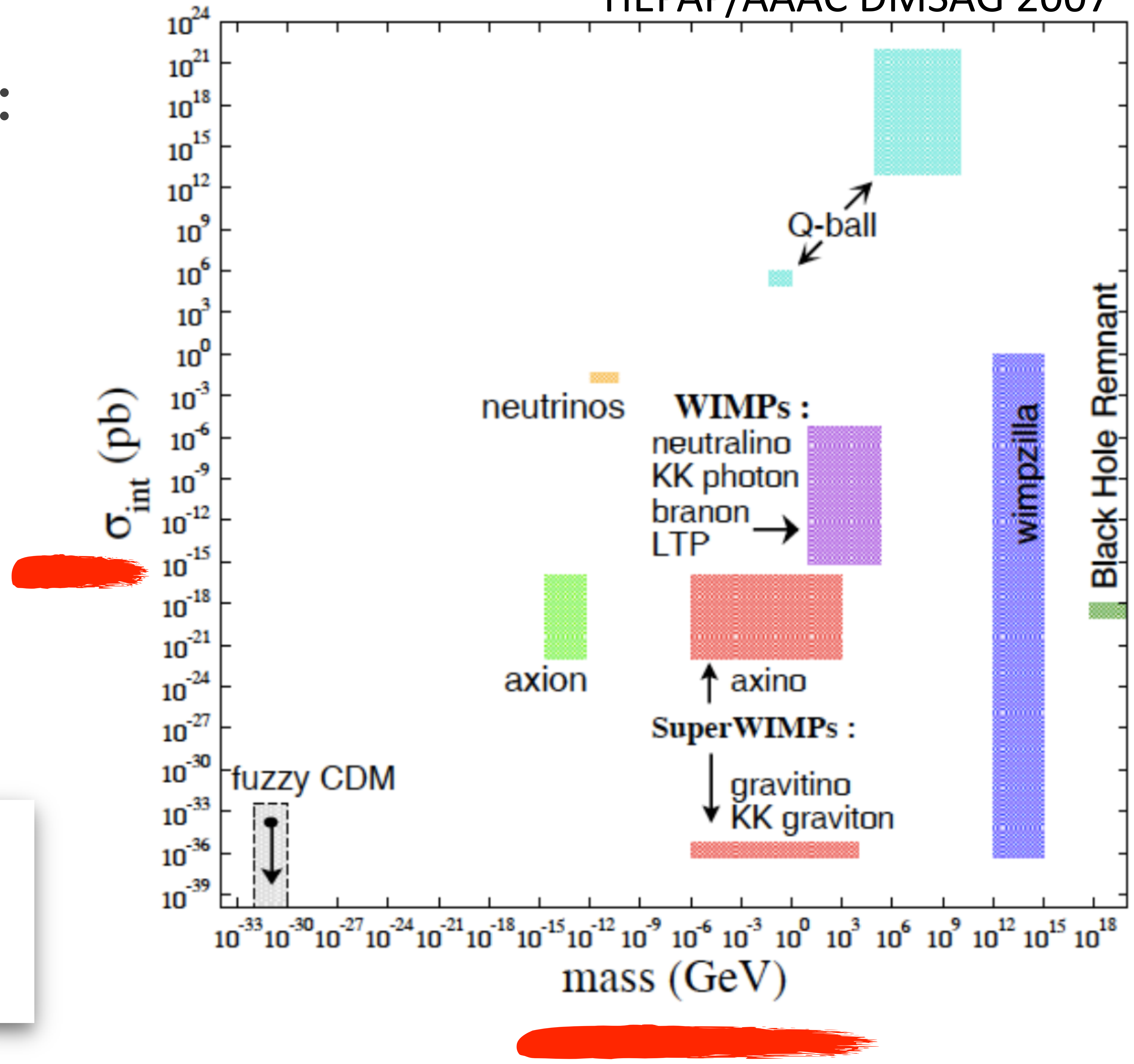
Detection

Interpretation:
- Testing beyond SM models
- Comparison between searches

Dark Matter Candidates — Why look at ν ?

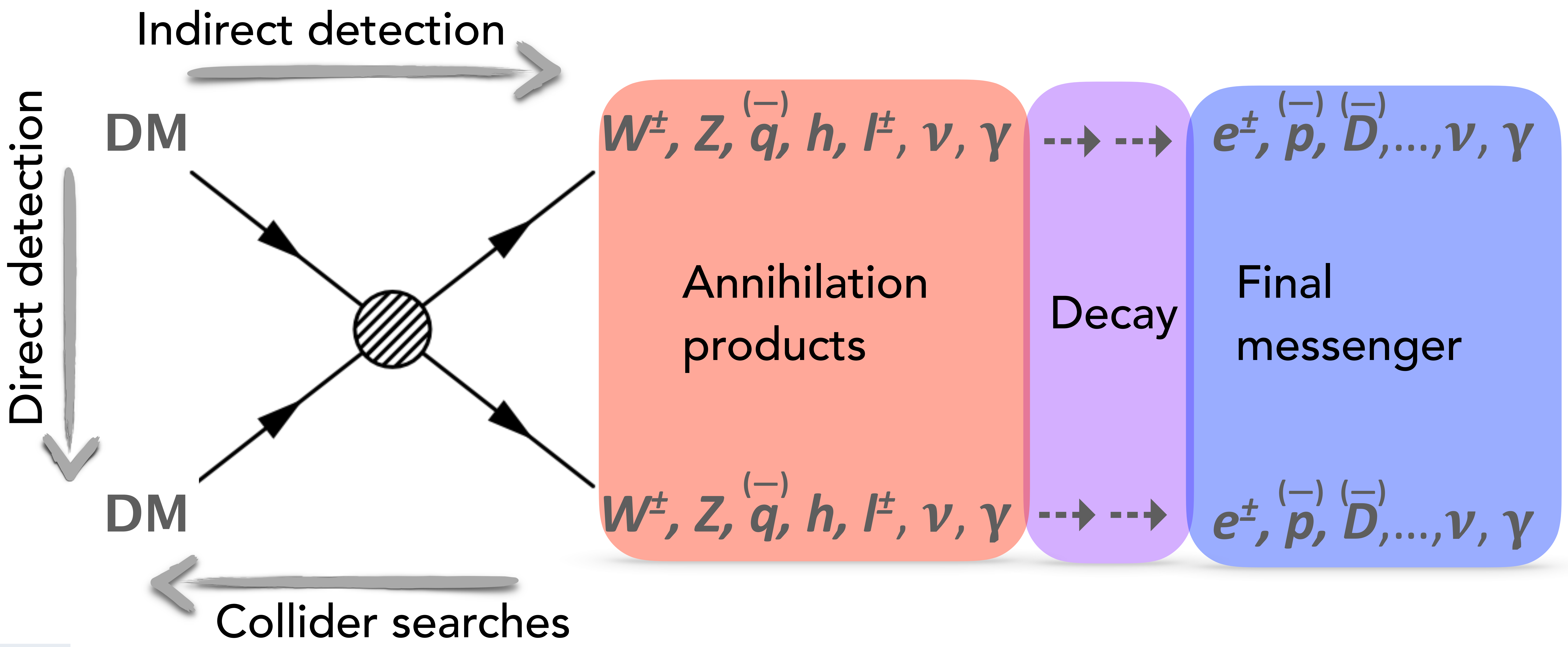
- Overwhelming evidence for particle dark matter
- Still very little knowledge about the properties:
    - Mass
    - Interaction cross-section with nuclei

HEPAP/AAAC DMSAG 2007



We can probe all these properties with neutrino telescopes!!

Neutrinos from Dark Matter

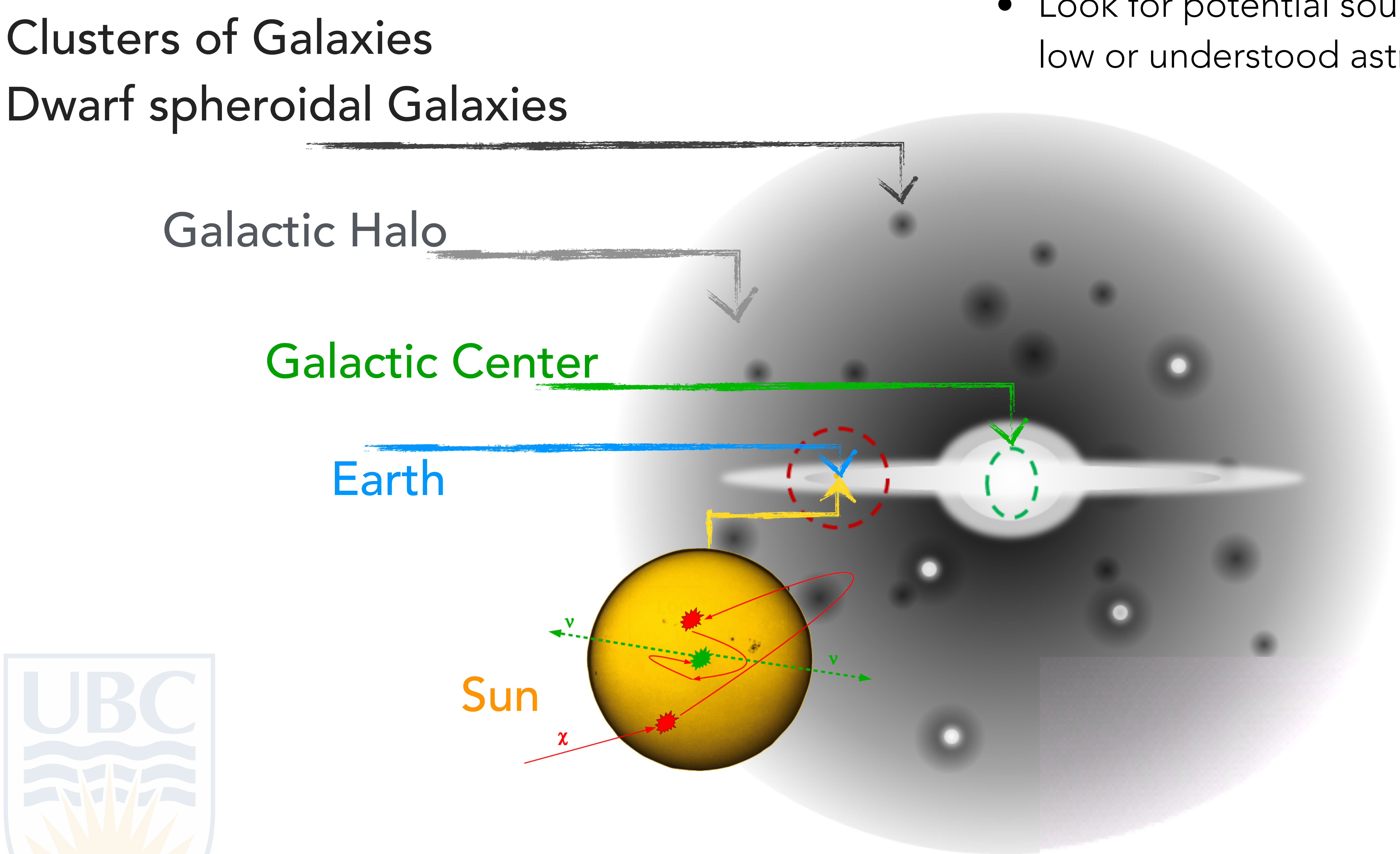


- Annihilation rate $\sim \rho^2$
- Decay rate $\sim \rho$

Indirect Dark Matter searches — Where to look?

(Image: M.Strassler)

- Look for potential sources that are well defined and have low or understood astrophysical backgrounds

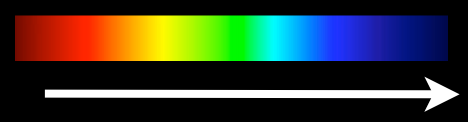


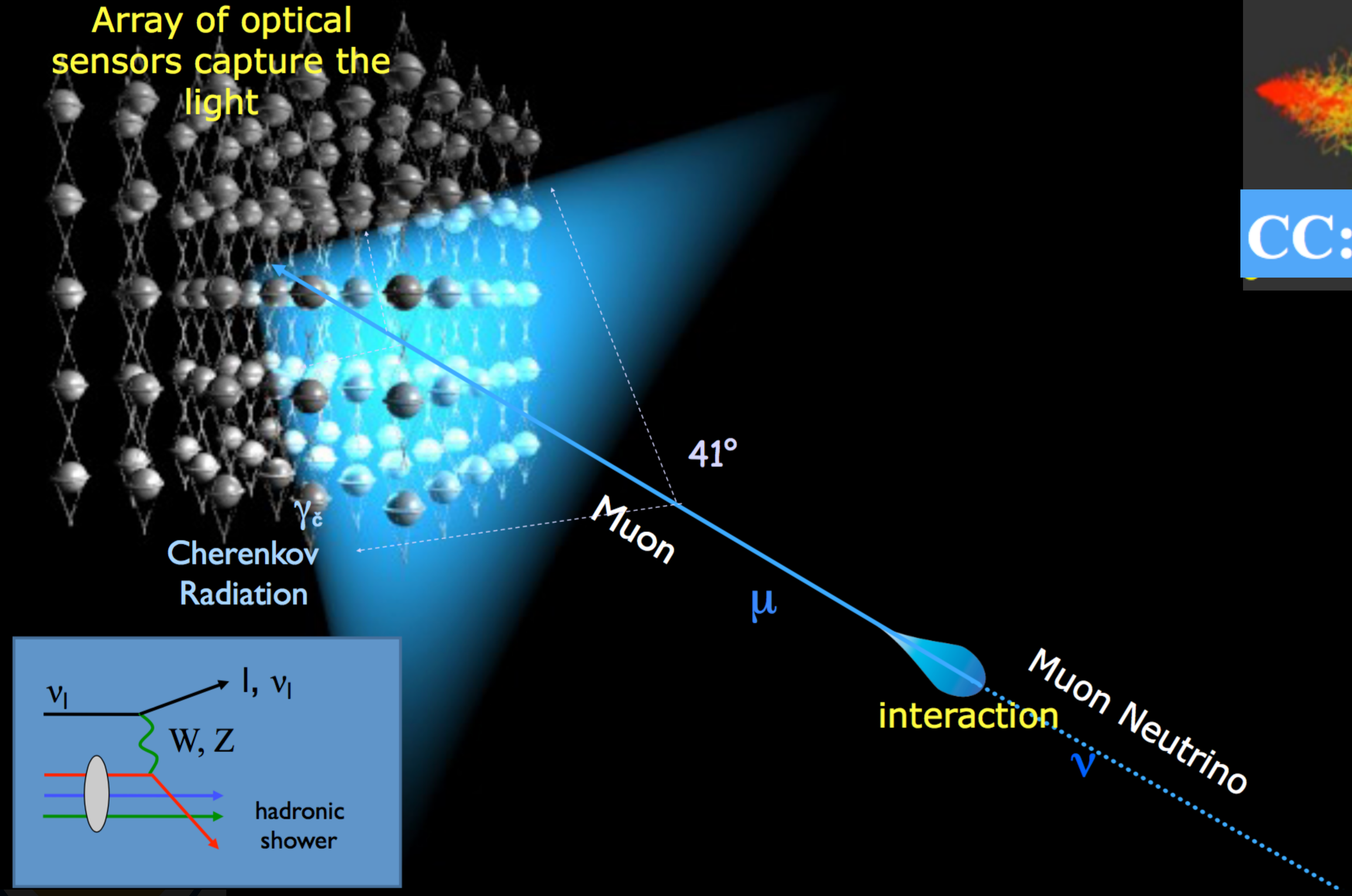
Analyses performed:

- Source stacking
- Point source analysis
- Large-scale anisotropy measurement
- Extended source searches

The experiments & analysis techniques

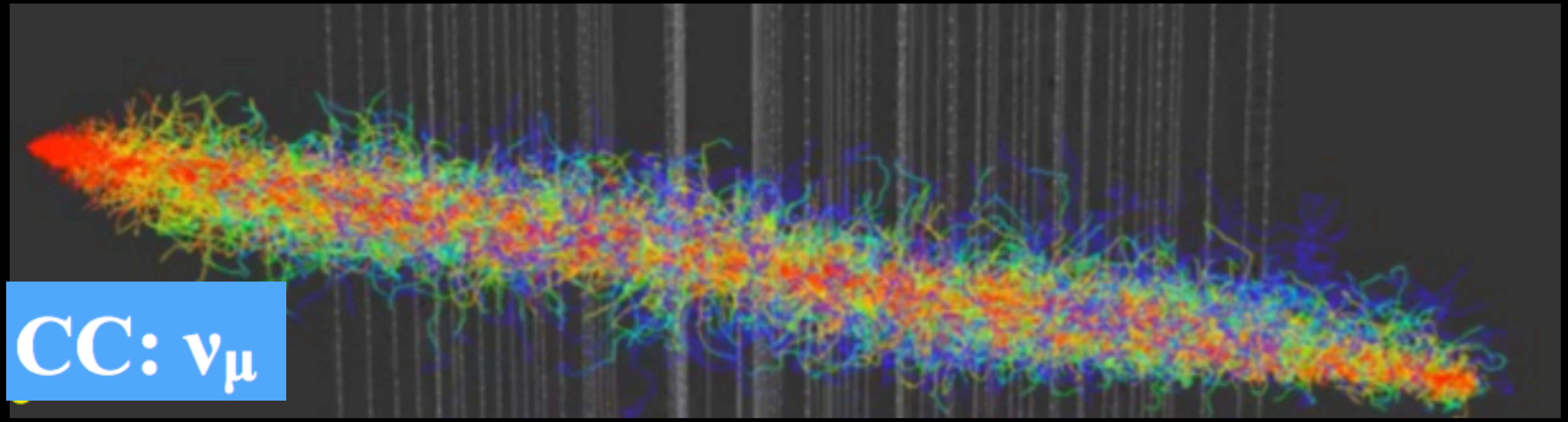
Detection principle & event topologies





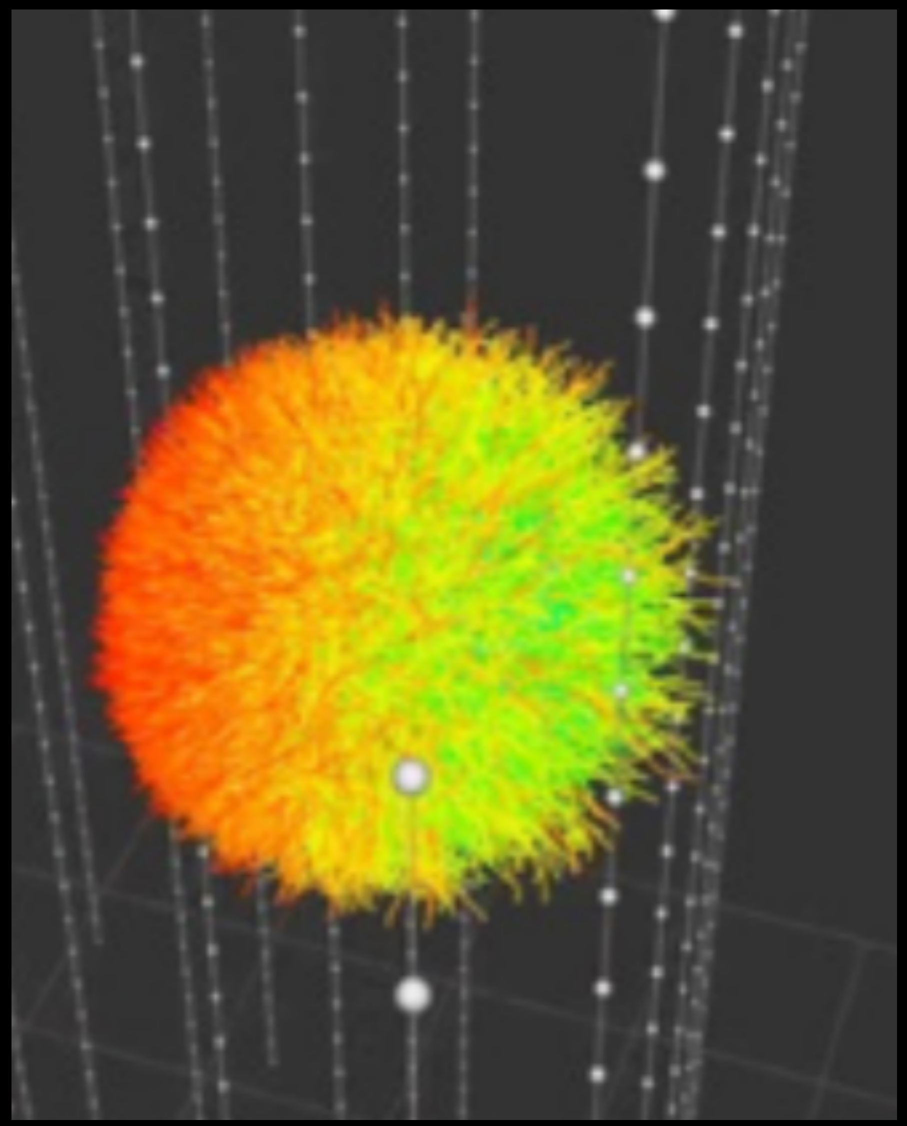
Track topology:

- good pointing
- Only lower bound on energy if not contained



Cascade topology:

- some pointing (~15°)
- Good energy resolution

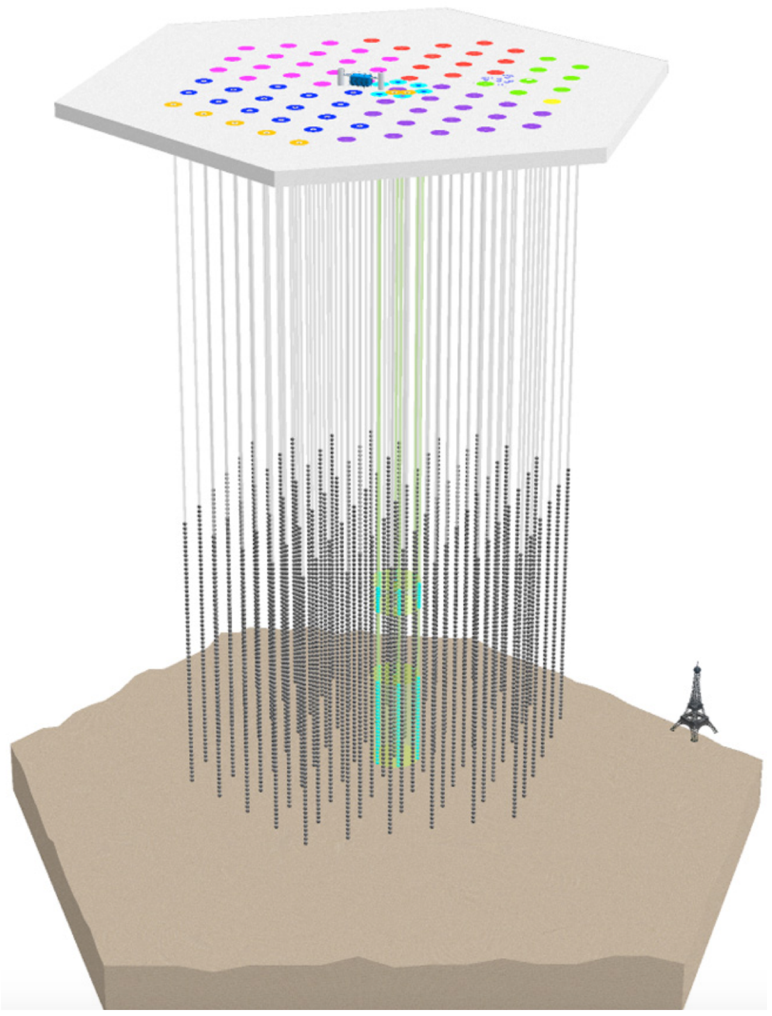


CC: ν_e ν_τ

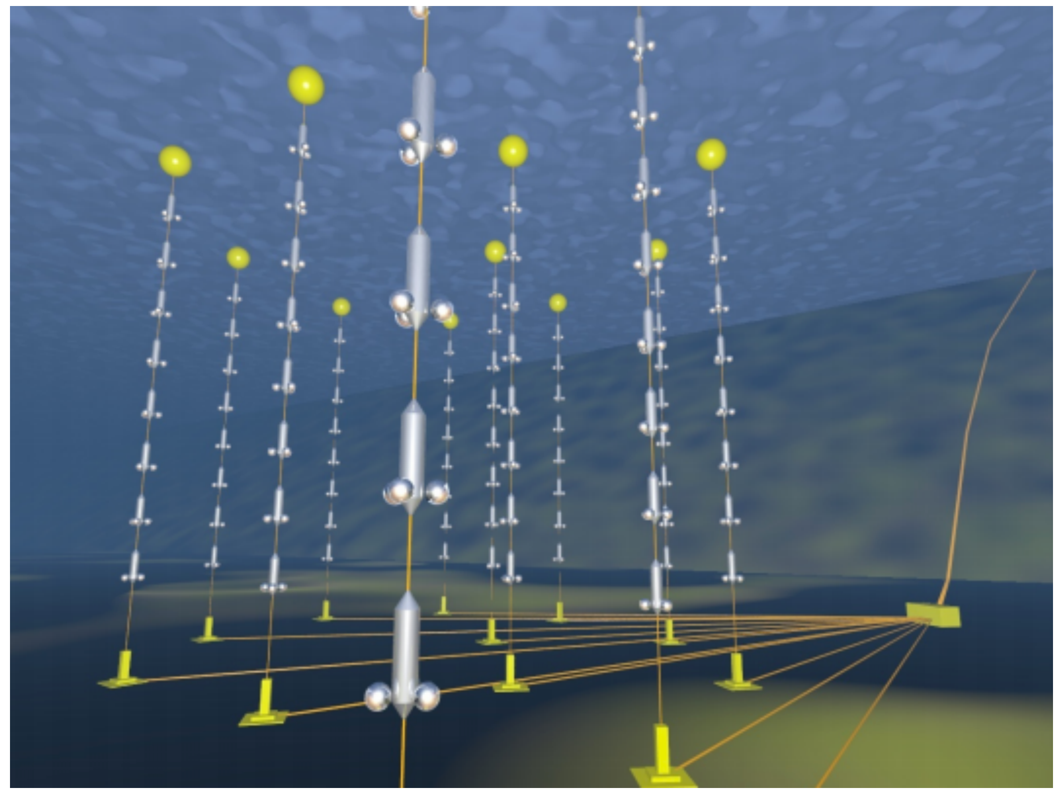
NC: ν_e ν_μ ν_τ

The Instruments

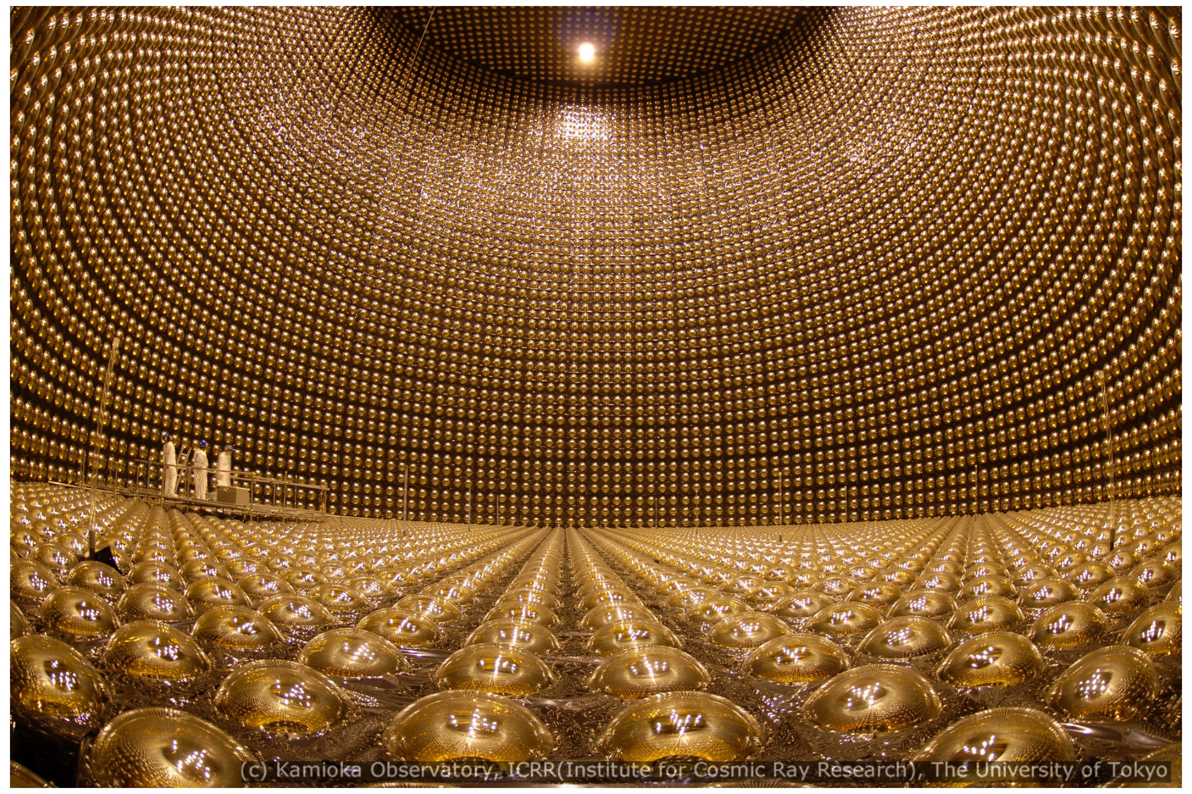
IceCube/DeepCore



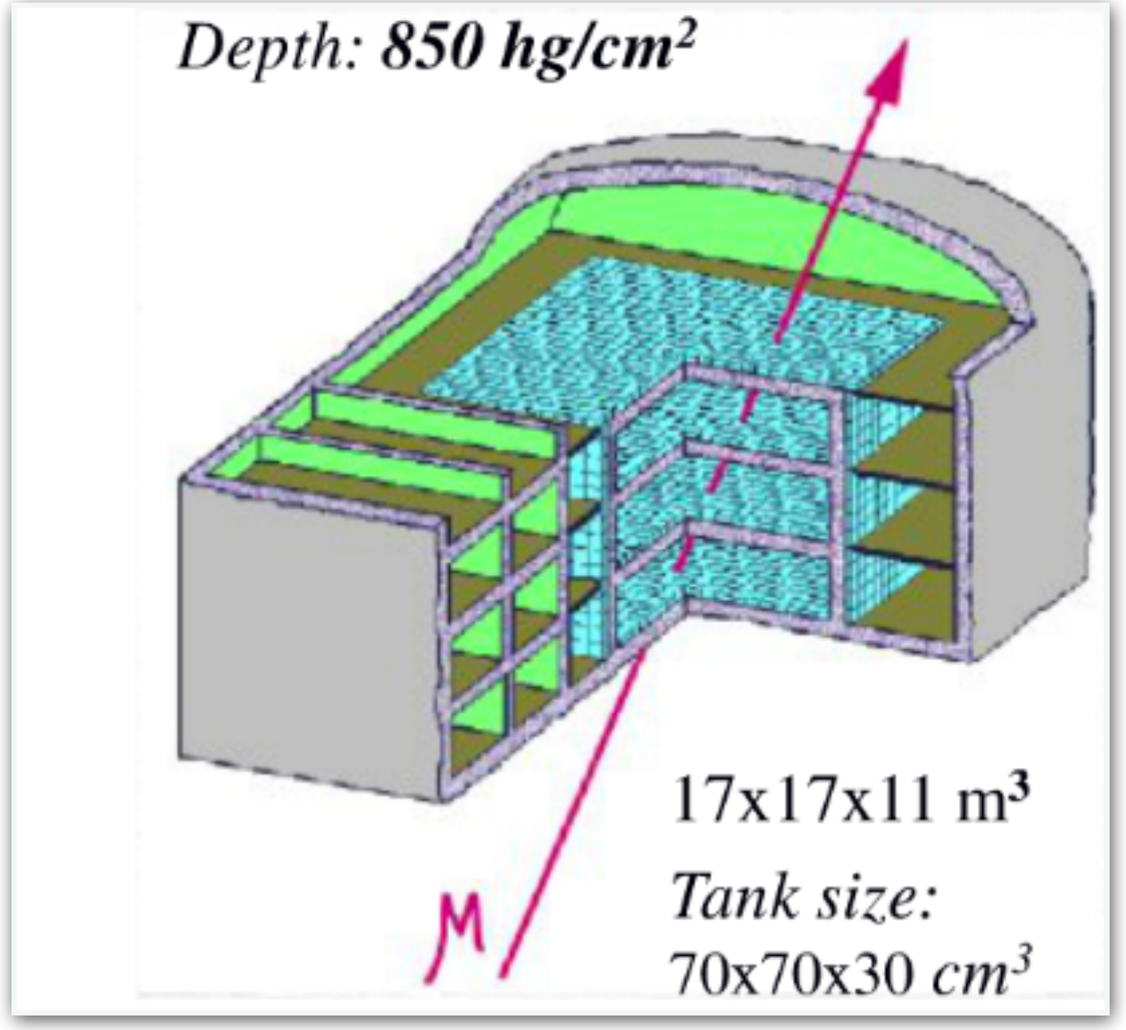
ANTARES



Super-K



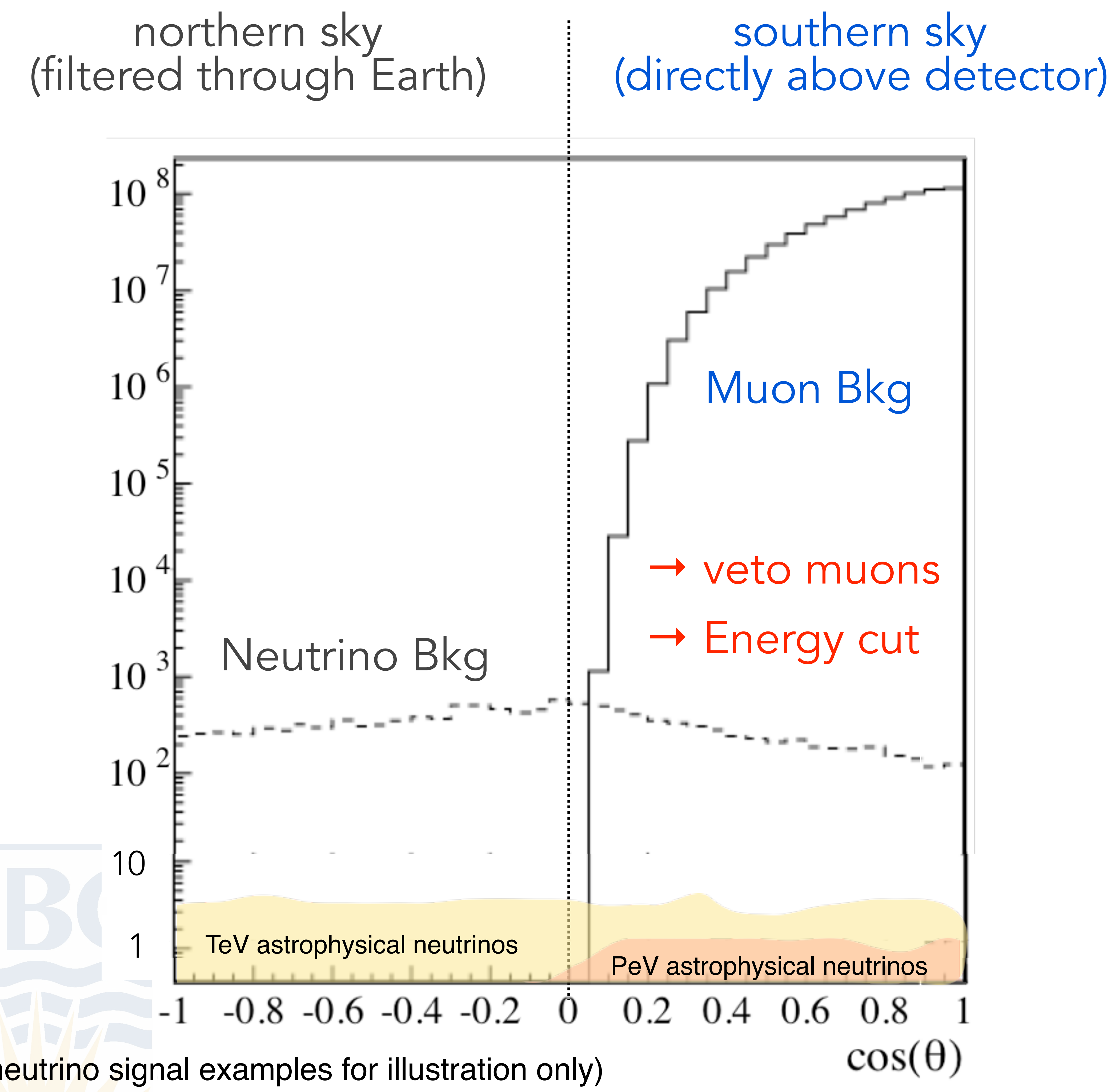
Baksan



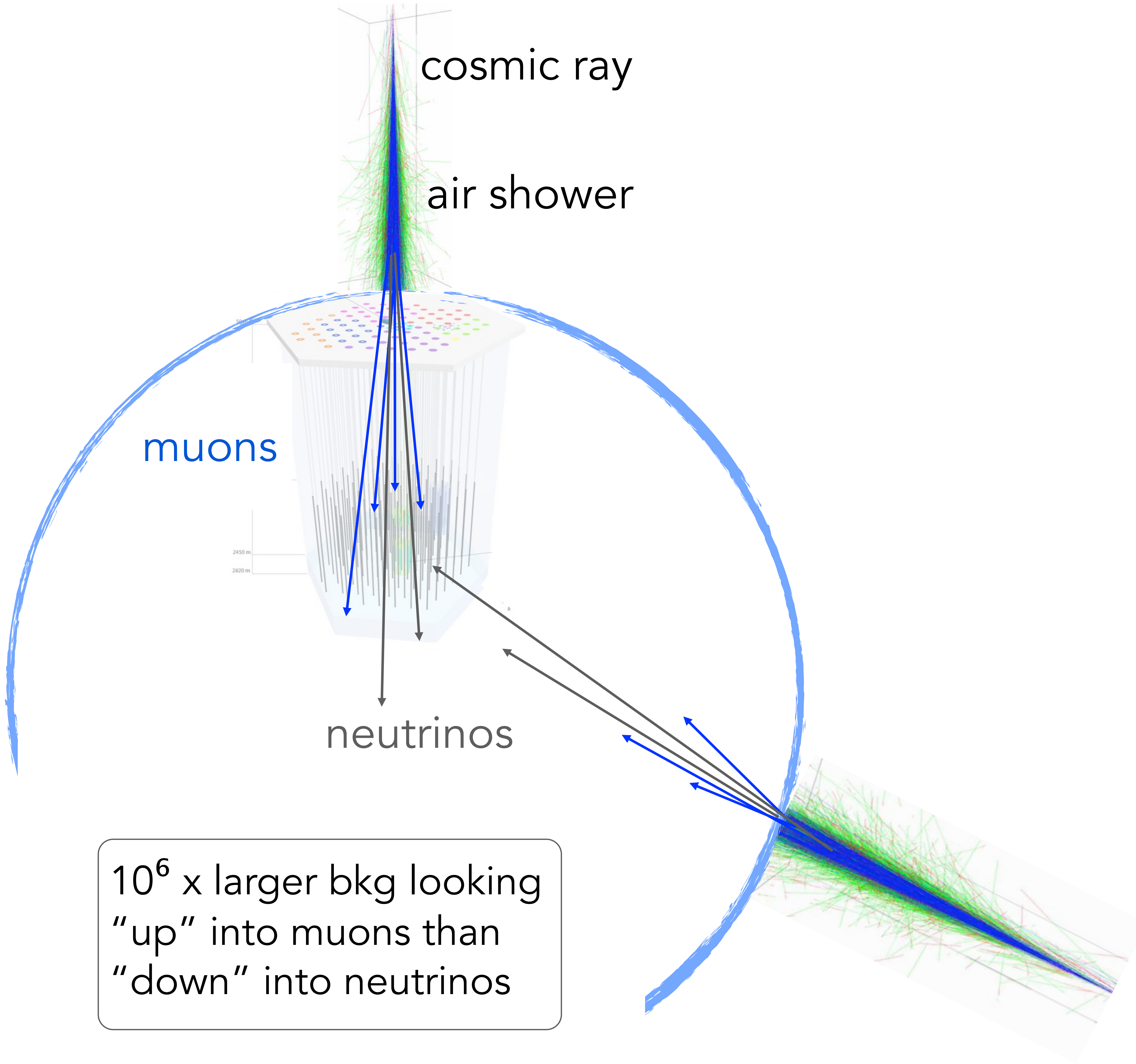
	E_ν-range (GeV)	Instrumented volume (ton)	$\overline{\Theta}$ (°) at E_ν 25 / 100 / 1000 GeV
IceCube	$\gtrsim 10^*$	~1 Gton	13 / 3.2 / 1.3
ANTARES	$\gtrsim 10$	~20 Mton	6 / 3.5 / 1.6
Super-K	$\gtrsim 0.1$	~50 kton	1-1.4‡
Baksan	$\gtrsim 1^\ddagger$	~3 kton	1.5‡ (tracks > 7 m)

‡ Values are given at muon level (E_μ); $\overline{\Theta}$ dominated by kinematic scattering angle.

Understanding the Cosmic Ray background



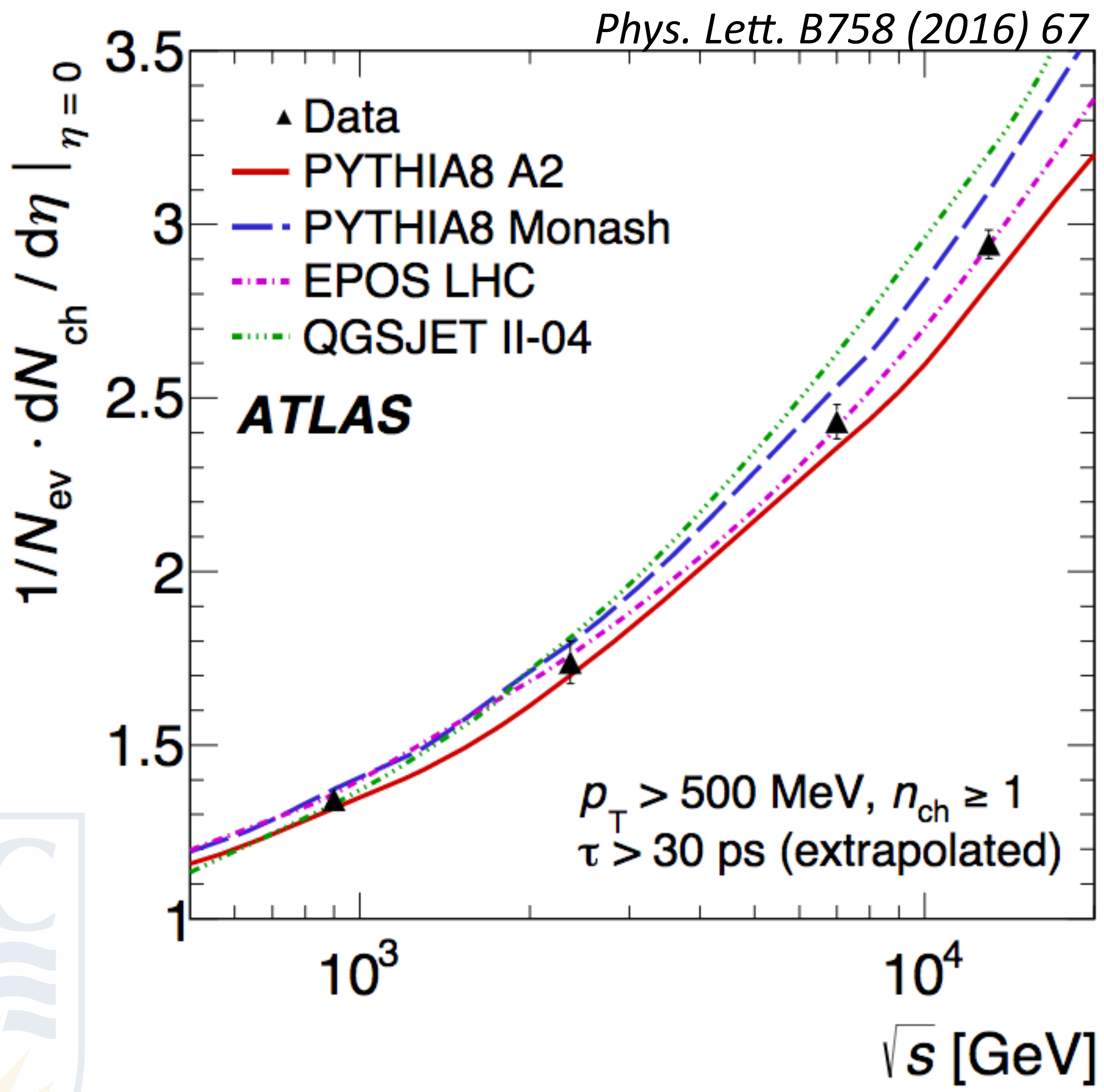
(neutrino signal examples for illustration only)

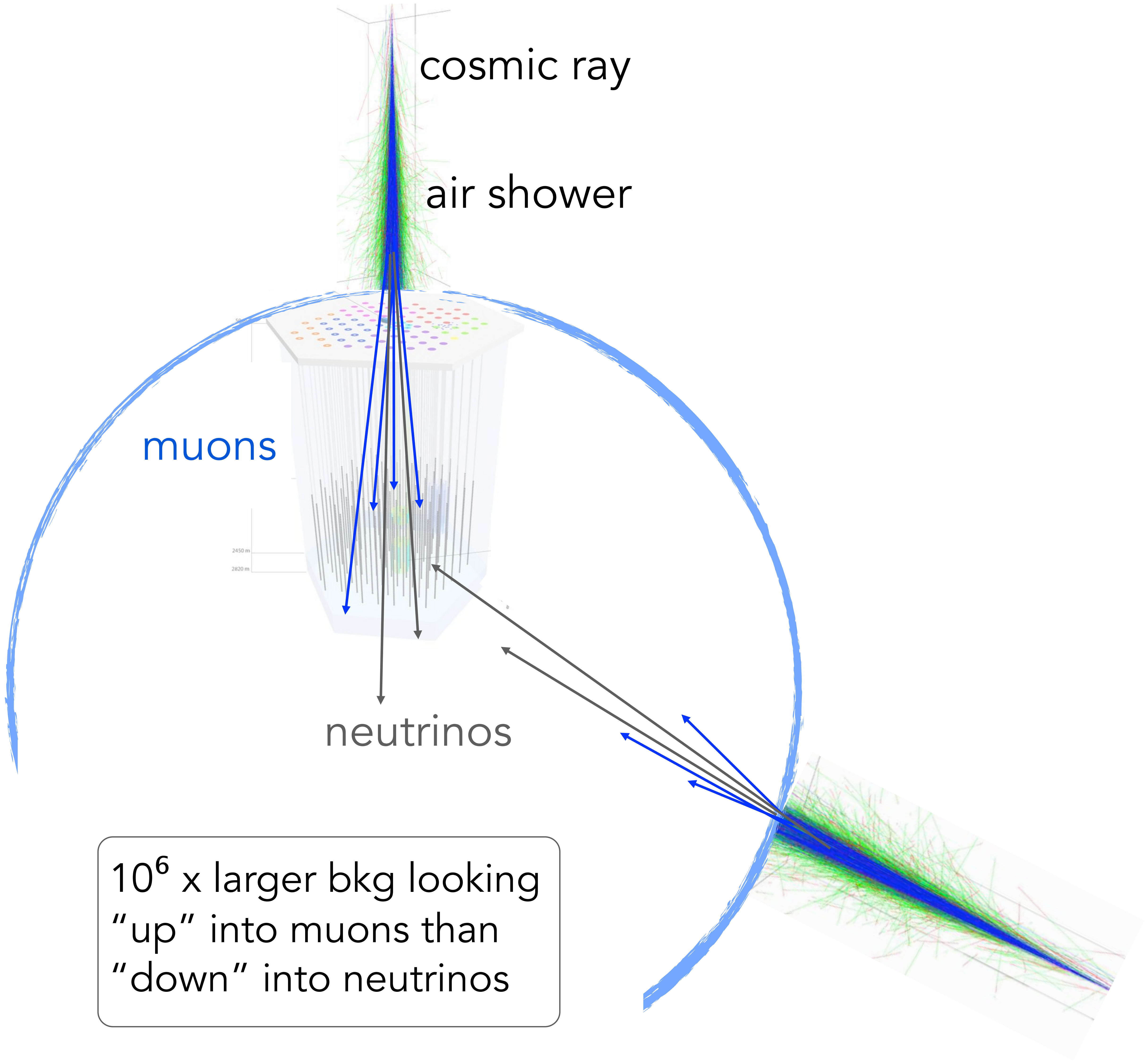


10^6 x larger bkg looking "up" into muons than "down" into neutrinos

Understanding the Cosmic Ray background

Average primary-charged-particle multiplicity in pp interactions





10^6 x larger bkg looking "up" into muons than "down" into neutrinos

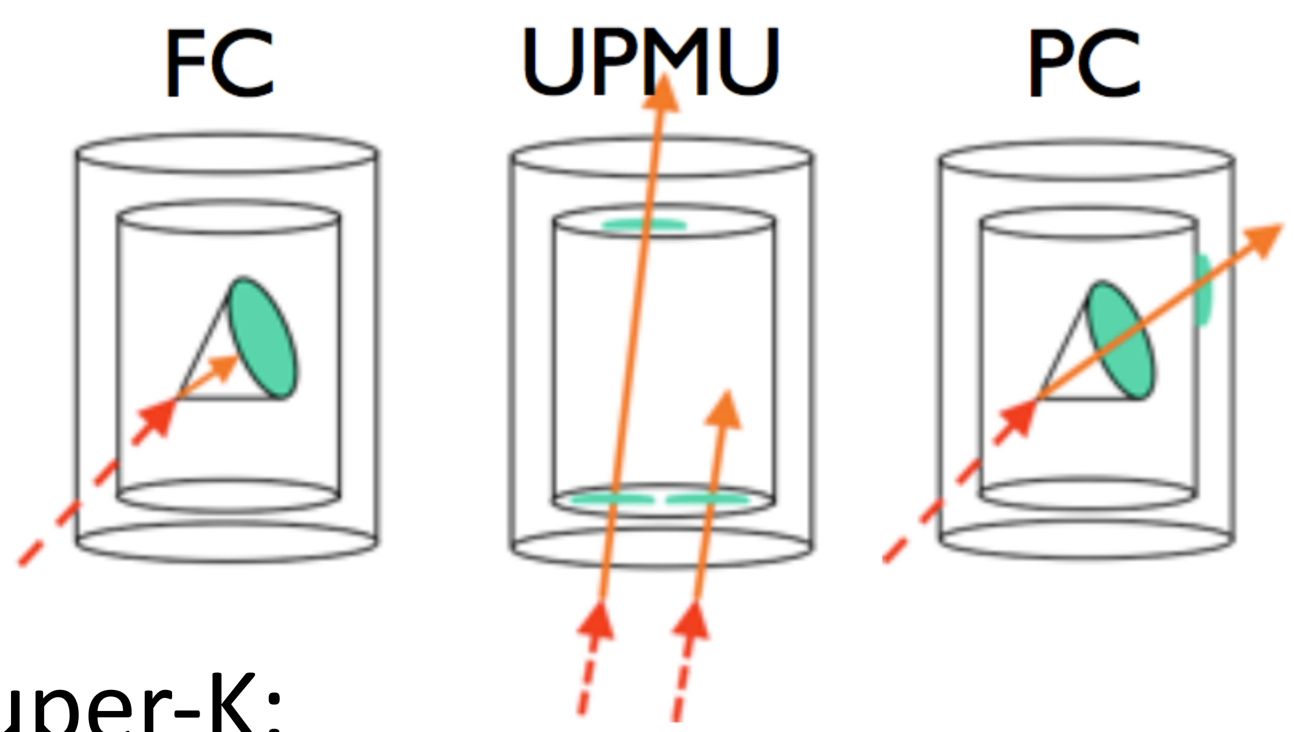
Improvements in analysis method and strategy

Few years back:

- Single region analyses using on/off-source counting method

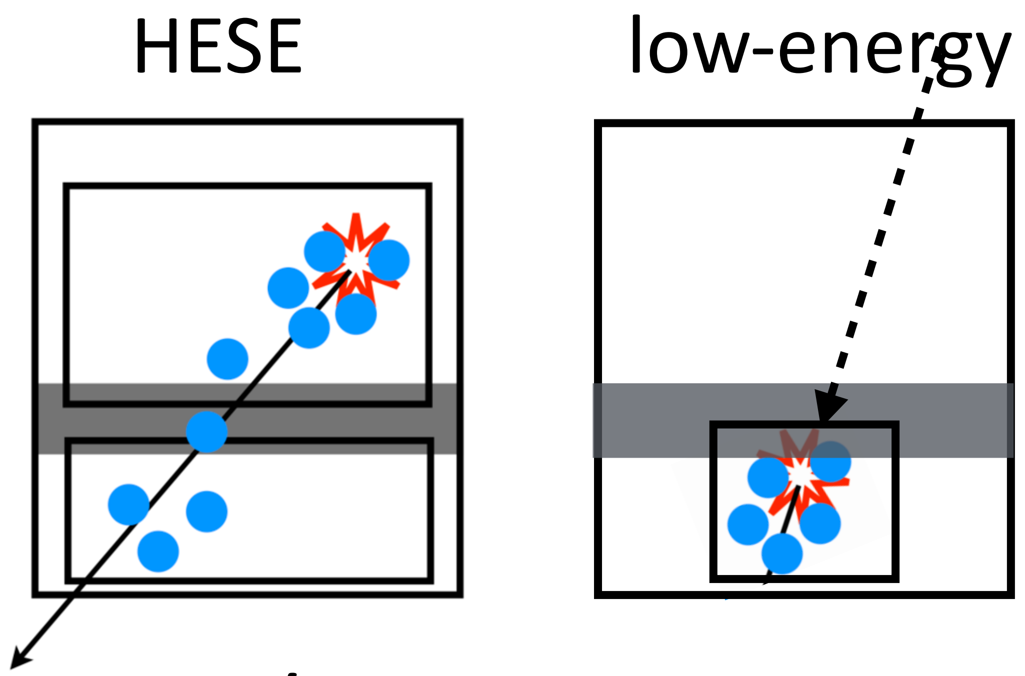
Today:

- Many topological event categories target wide range of DM masses
- Stringent $\mu_{atm.}$ vetoes allow down-going event selections
- Inclusion of ν_e channel —> particle identification
- Statistical analyses including directional and energy information
- Better understanding of systematic uncertainties



Super-K:

- Signal acceptance for *bb*-channel at 10 GeV increased by factor 47

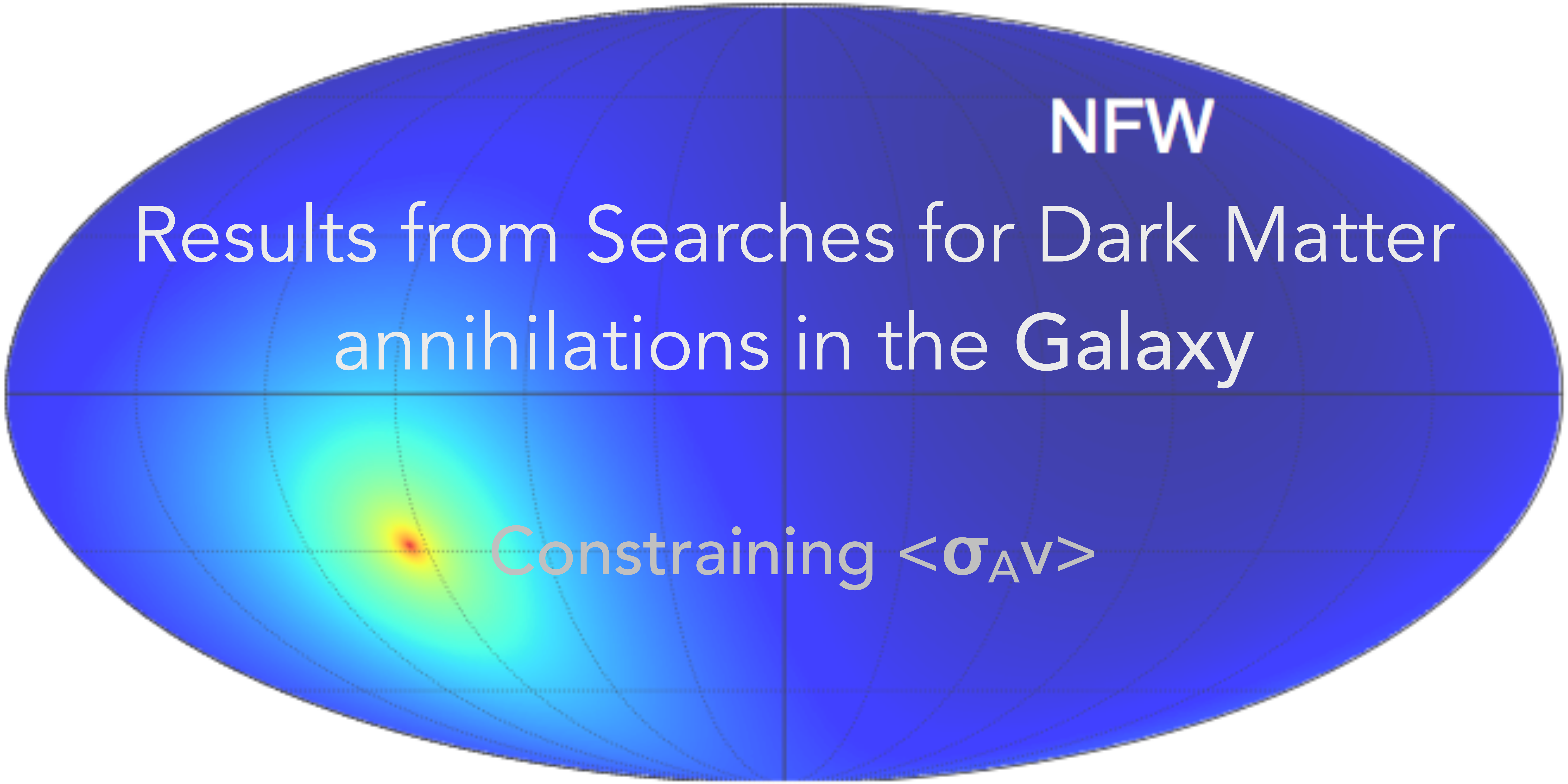


IceCube/DeepCore:

- Veto techniques make Galactic Centre searches possible

No excess over exp. background yet in ν:

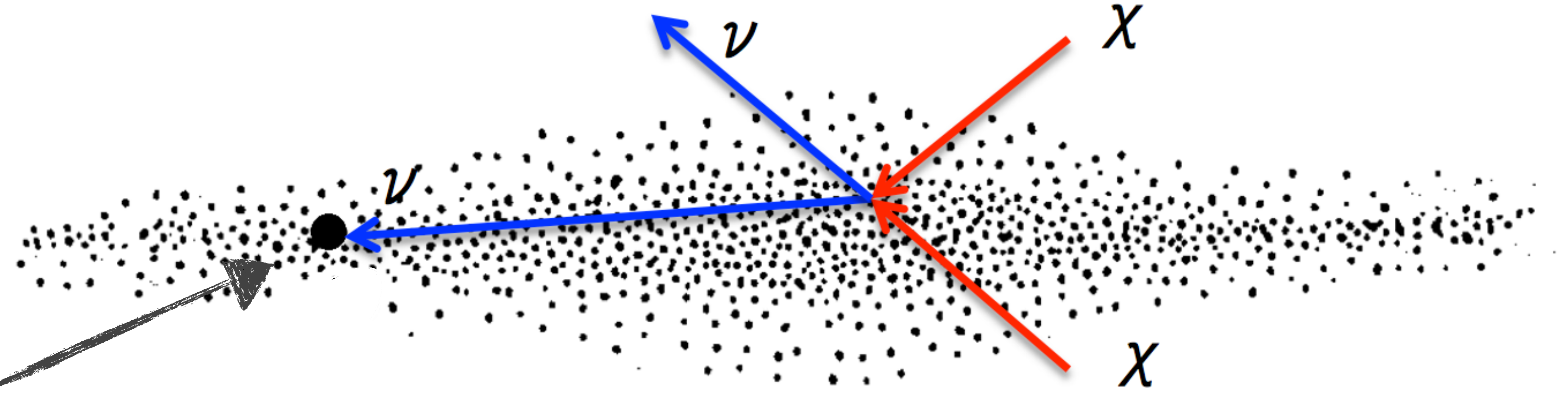
- All limits presented at the 90% CL



Results from Searches for Dark Matter annihilations in the Galaxy

Constraining $<\sigma_A v>$

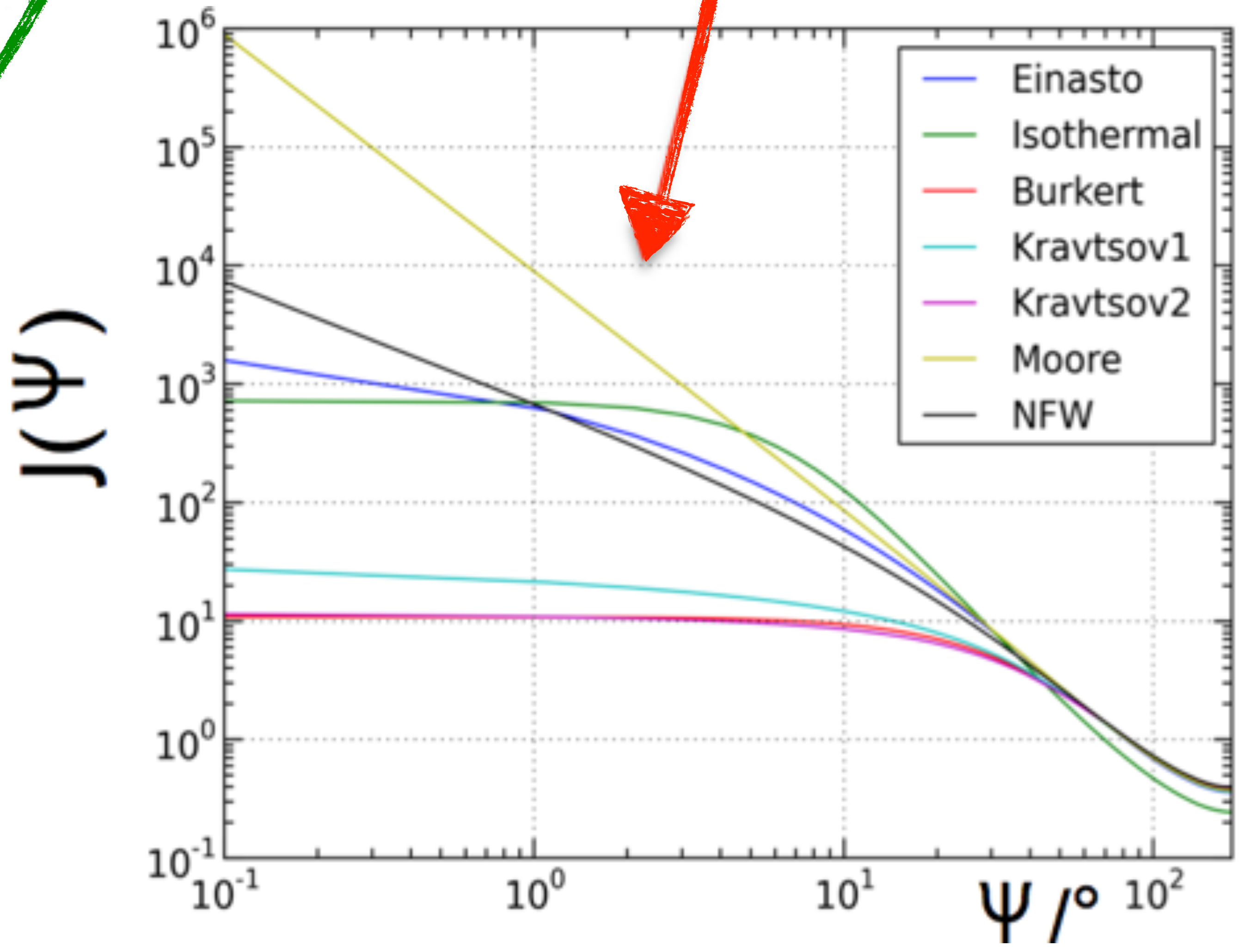
Neutrinos from Dark Matter annihilations

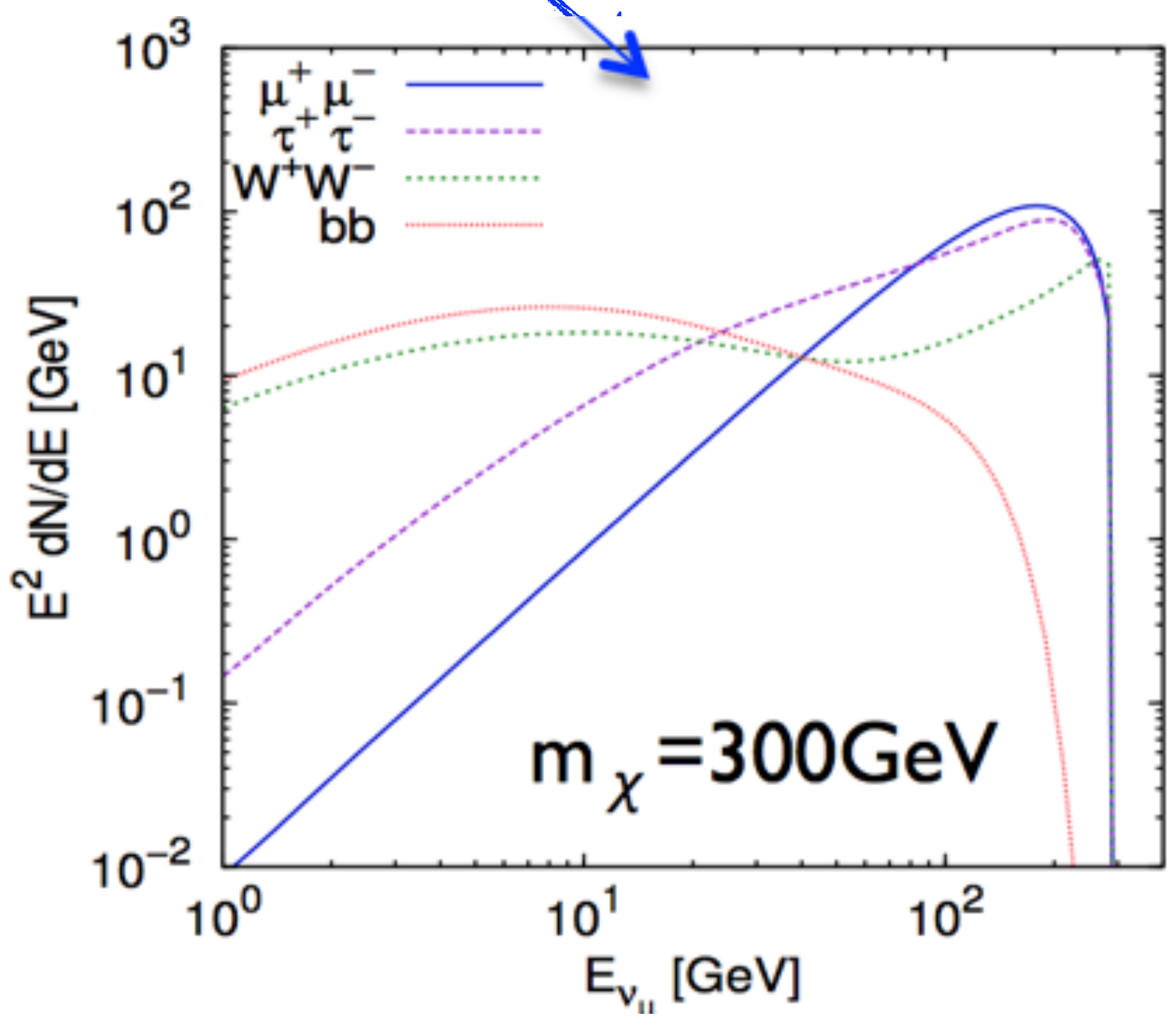


Flux measurement

$$\frac{d\phi_\nu}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{1}{4\pi m_\chi^2} J_a(\psi) \frac{dN_\nu}{dE}$$

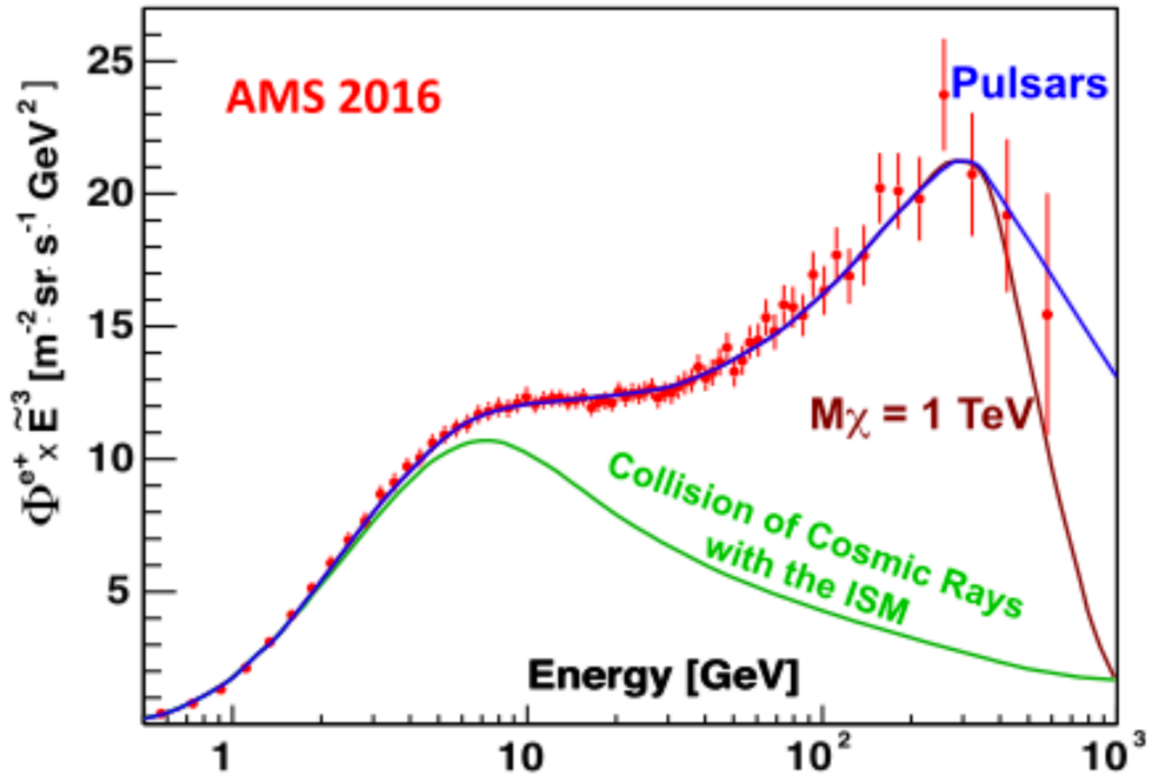
Parameter of Interest

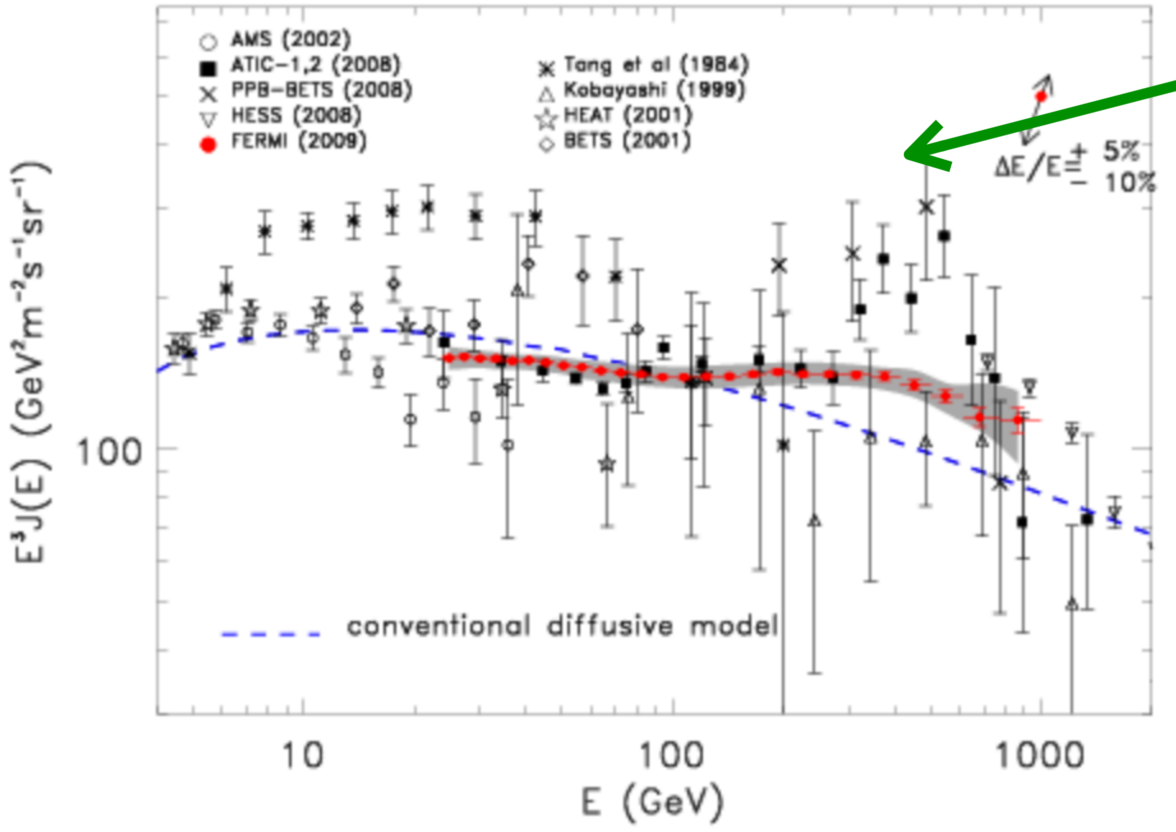


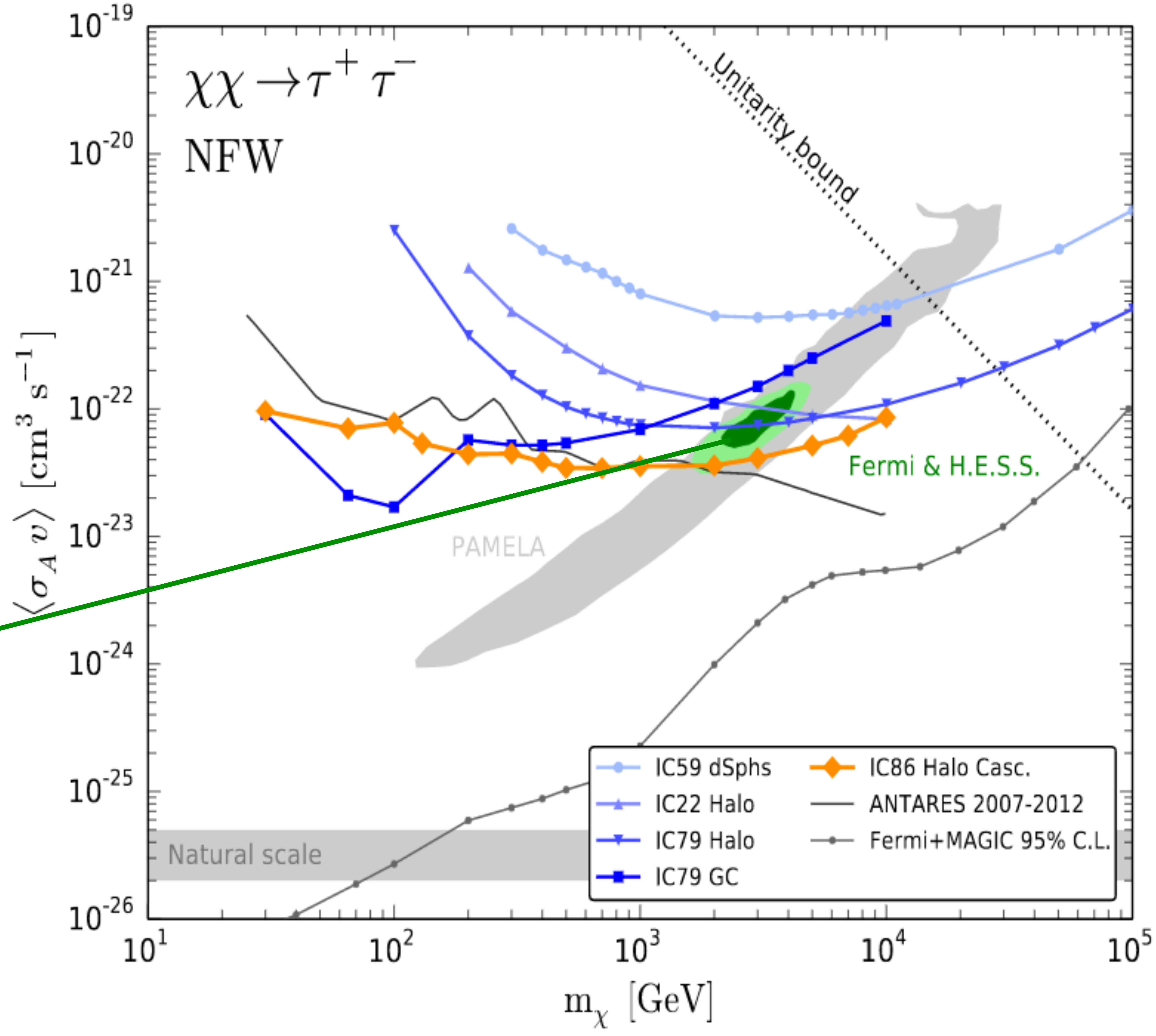


Limits on the annihilation cross-section

- Assume annihilation into $\boldsymbol{\nu\nu}$, $\boldsymbol{\tau\tau}$, $\boldsymbol{\mu\mu}$, ***bb***, ***WW***
- Models motivated by increase in positron fraction can be tested



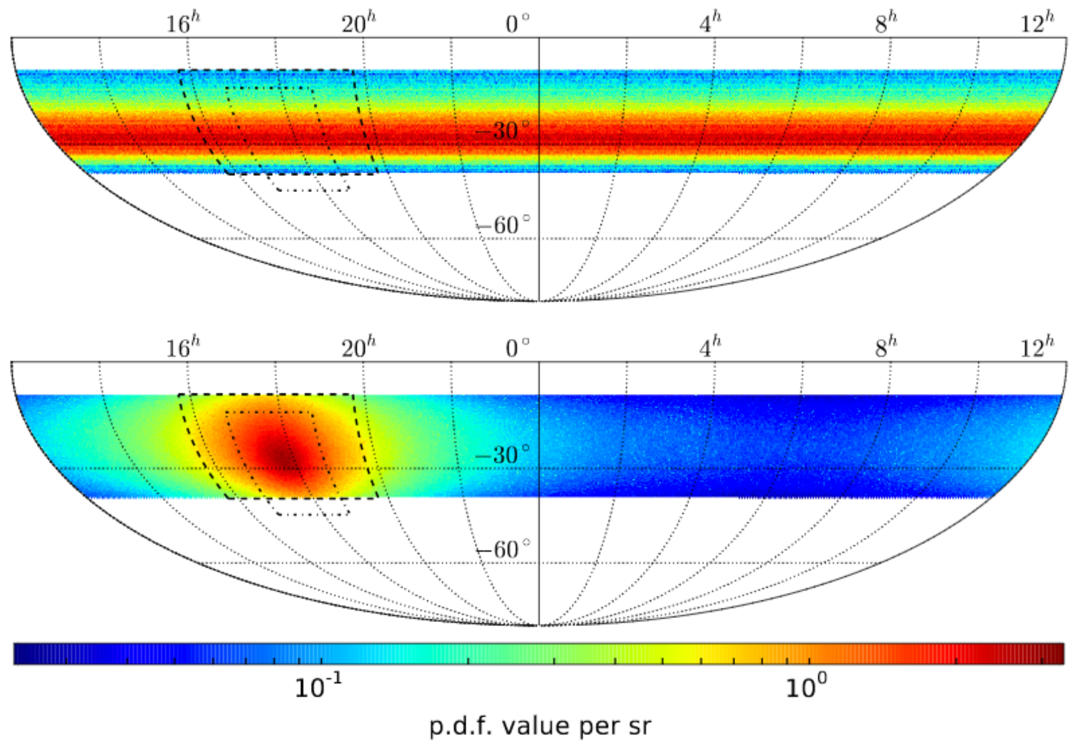




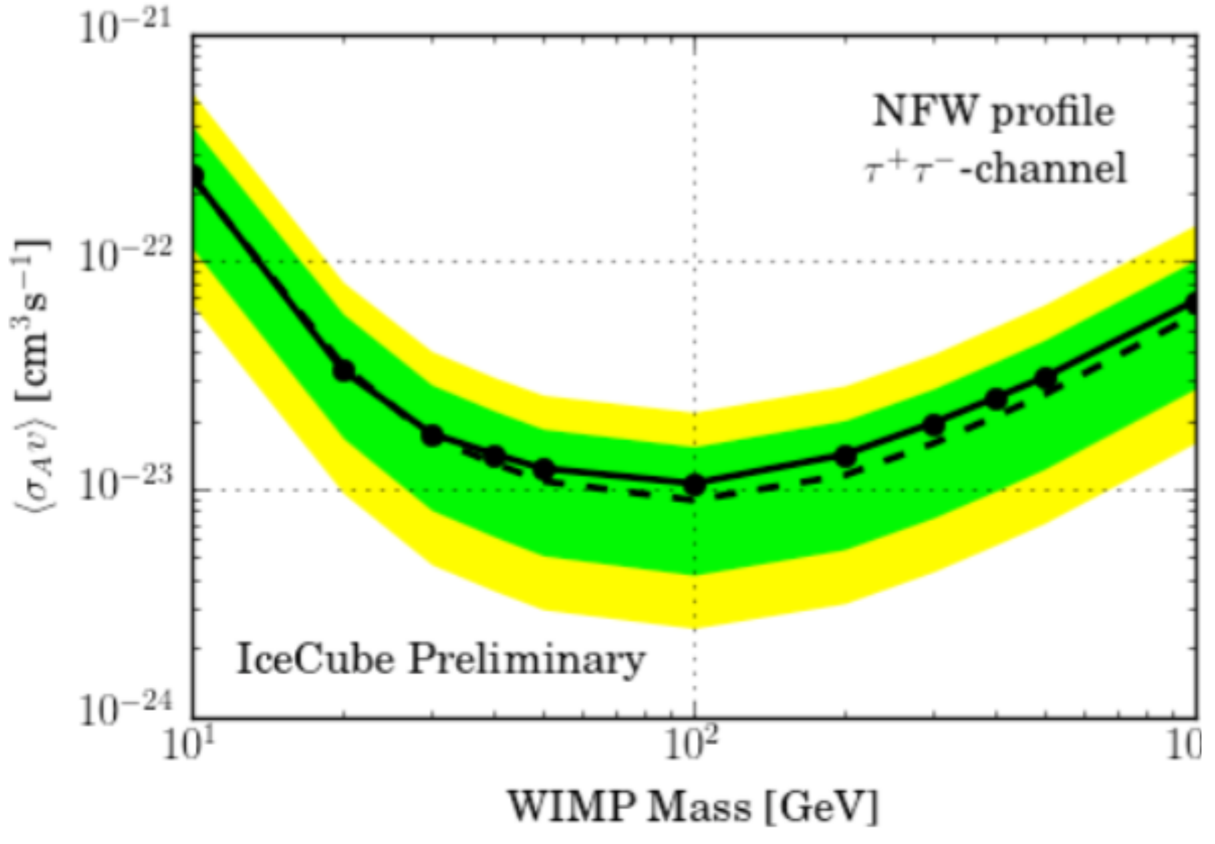
Limits on the annihilation cross-section

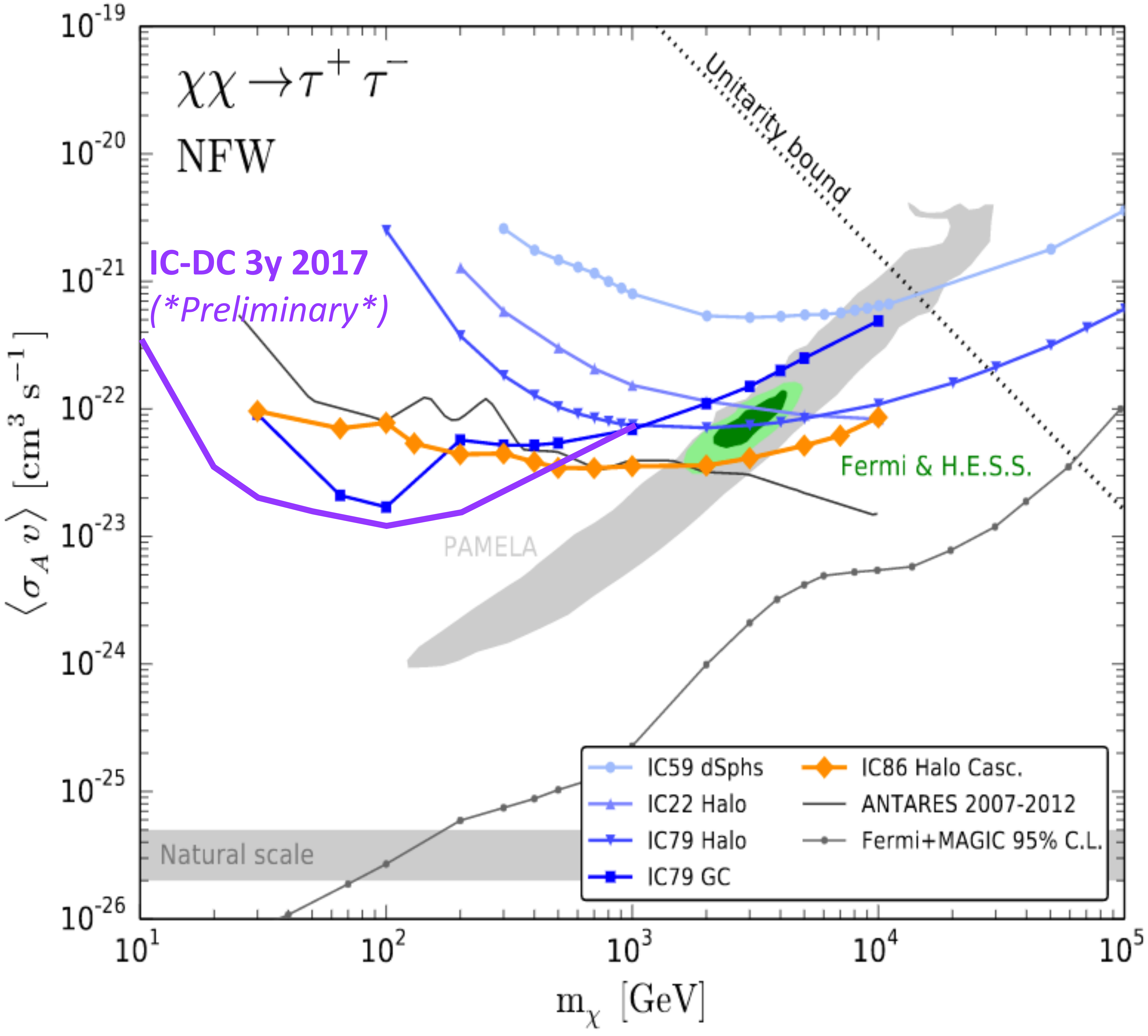
- Assume annihilation into
  νν, ***ττ***, ***μμ***, ***bb***, ***WW***
- Models motivated by increase in positron fraction can be tested
- IceCube: GC located above horizon

(equatorial coordinates)



Results from a search using 3 years IceCube-DeepCore data

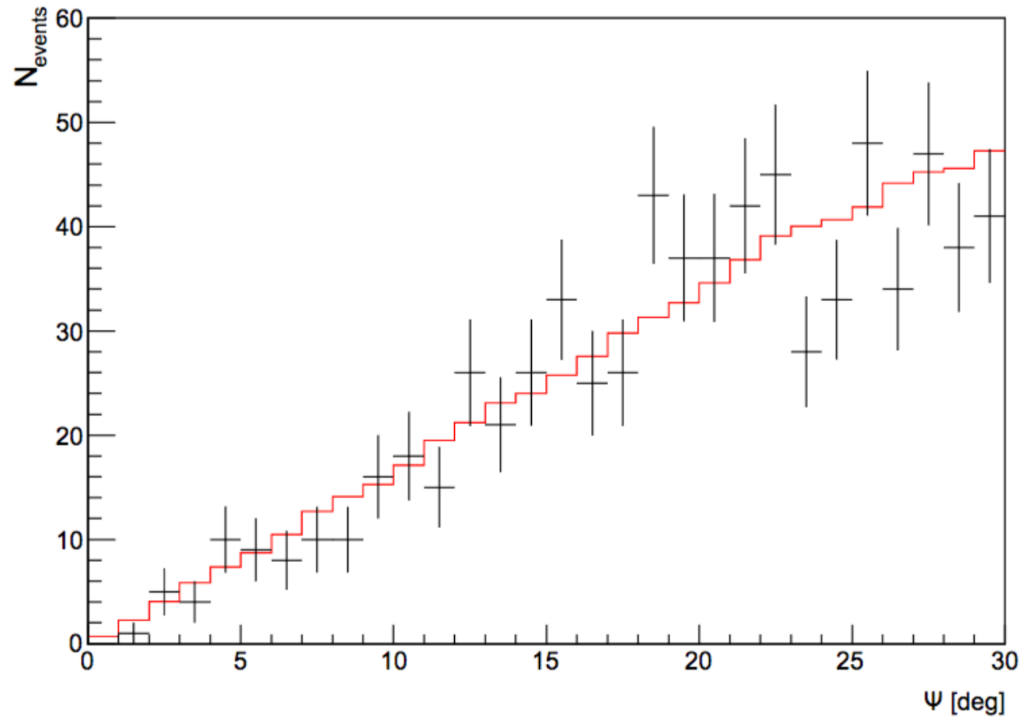


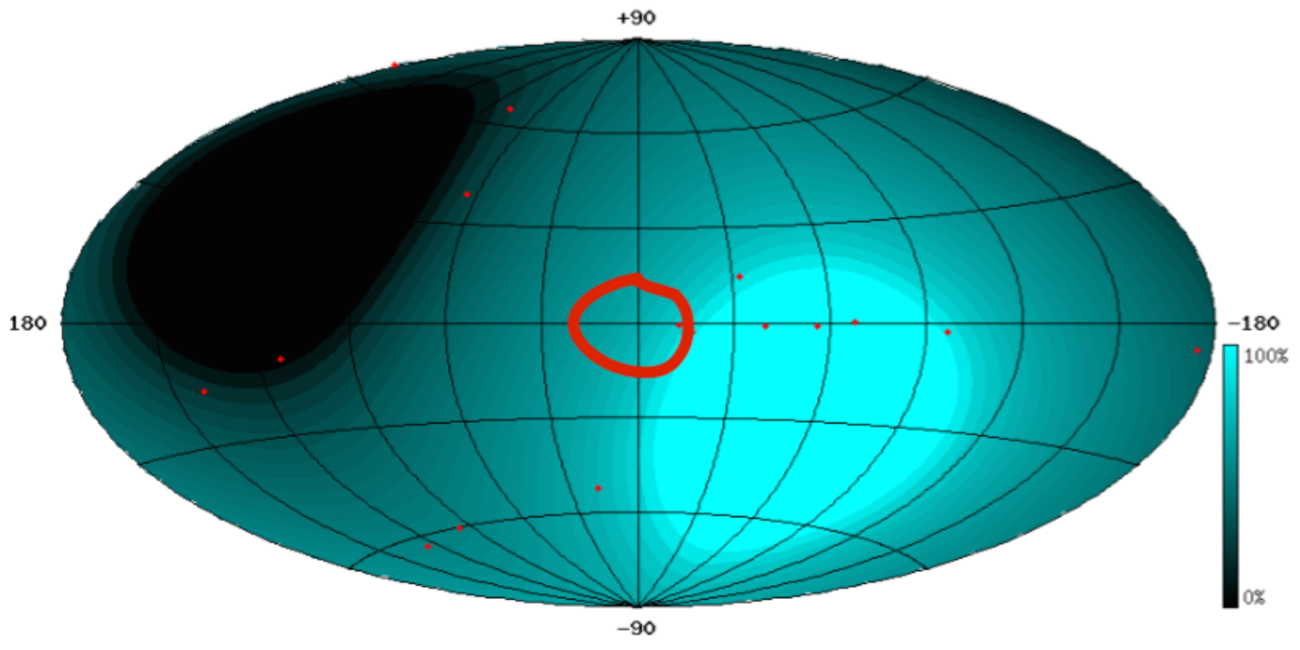


Limits on the annihilation cross-section

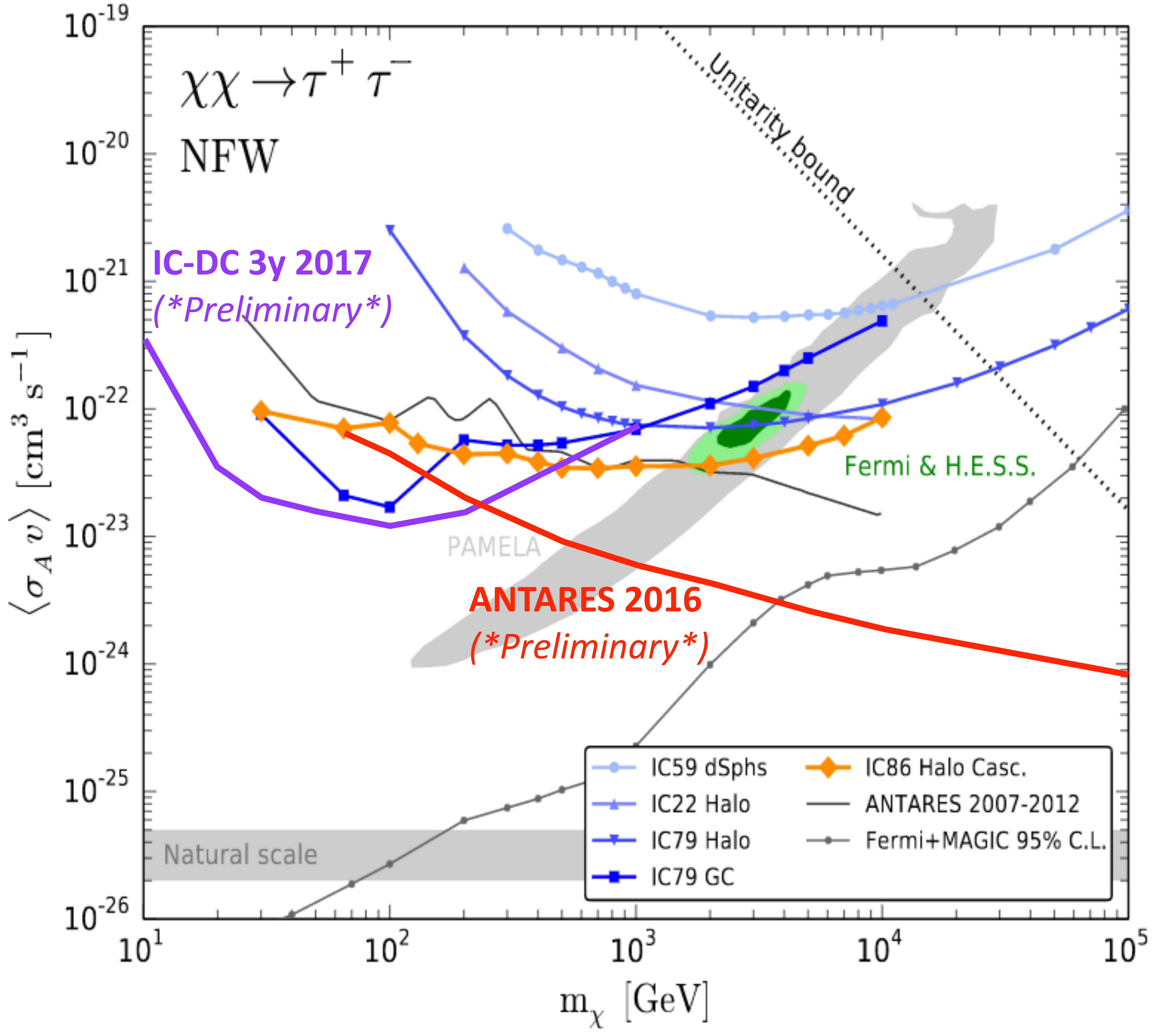
- Assume annihilation into
  νν, ***ττ***, ***μμ***, ***bb***, ***WW***
- Models motivated by increase in positron fraction can be tested
- IceCube: GC located above horizon
- ANTARES:
  ~60% of time below horizon

#events in cone close to GC



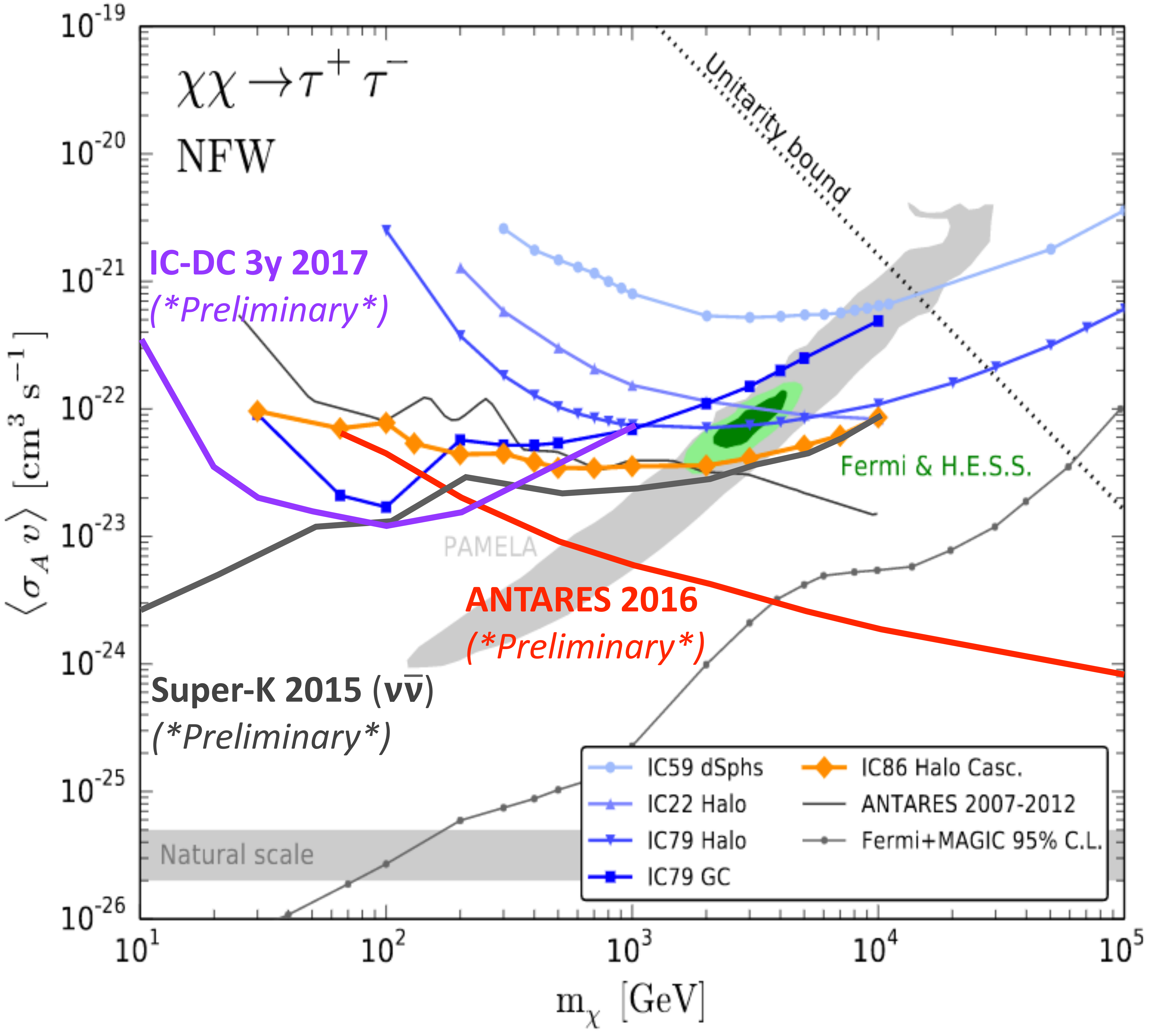


(galactic coordinates)



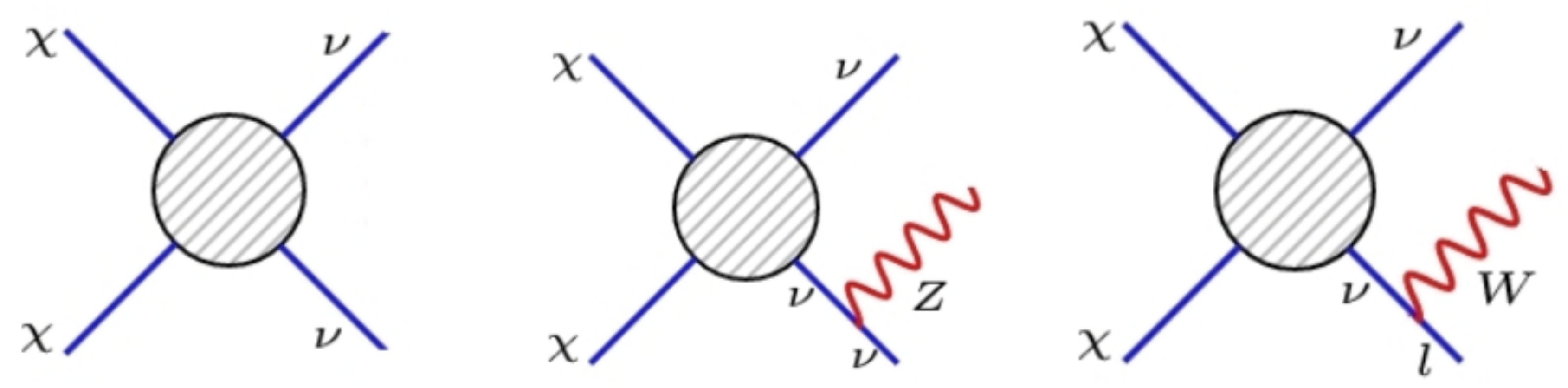
Limits on the annihilation cross-section

- Assume annihilation into
  νν, ***ττ***, ***μμ***, ***bb***, ***WW***
- Models motivated by increase in positron fraction can be tested
- IceCube: GC located above horizon
- ANTARES:
  ~60% of time below horizon
- Super-K extending to 1GeV in m_χ



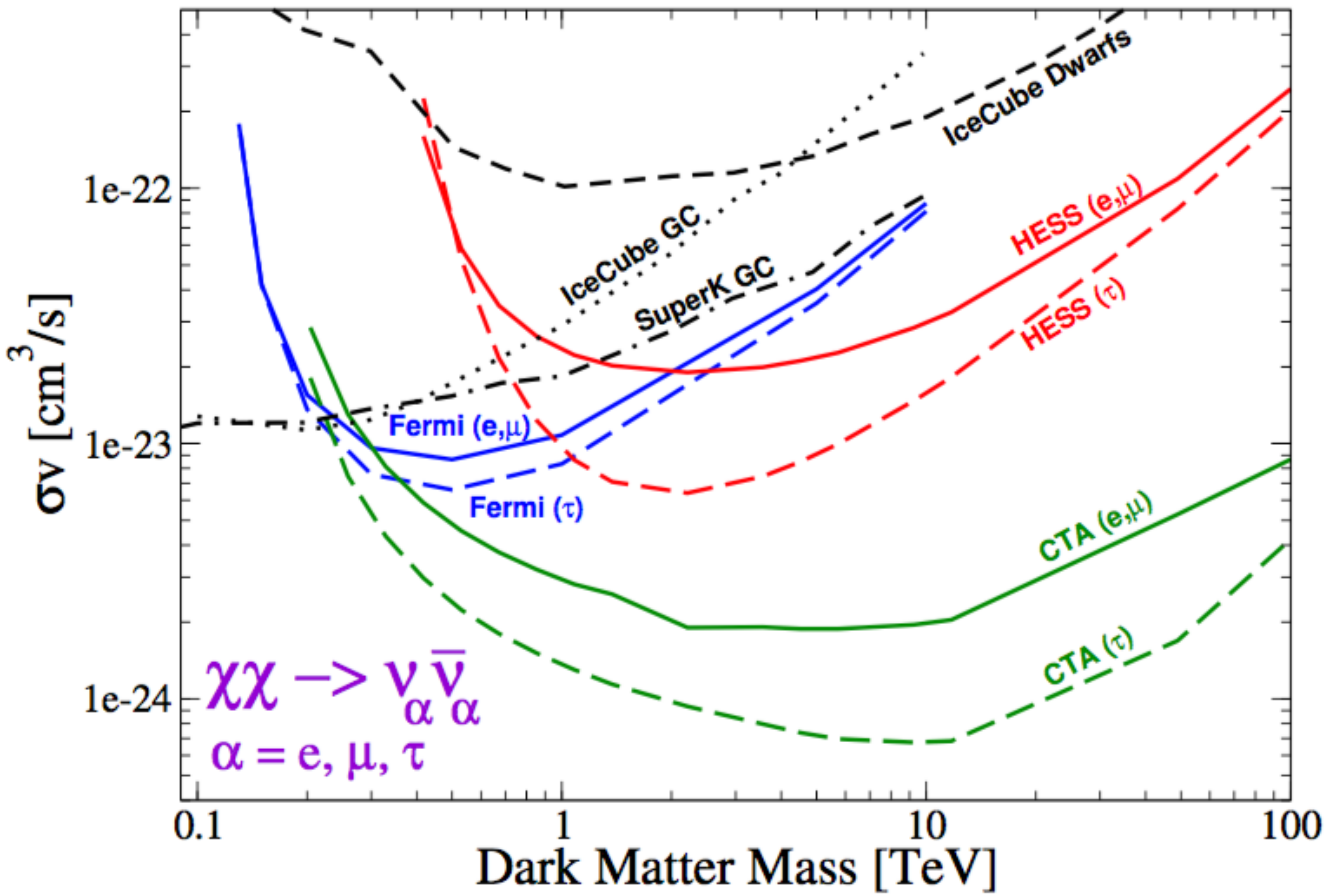
γ-Telescopes more sensitive to $\boldsymbol{\nu}$-signals?

Including weak corrections is important!



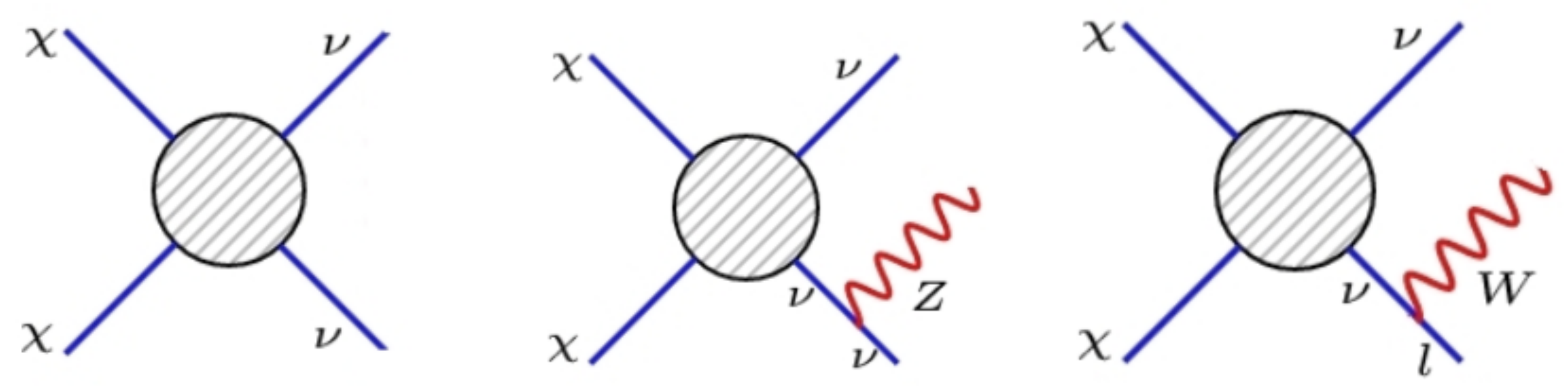
- $\boldsymbol{\nu}$ final states also give rise to a γ-ray emission
- More stringent limits for masses > 200 GeV
- Only $\boldsymbol{\nu}$-telescopes can "truly" discriminate a $\boldsymbol{\nu}$-line

JCAP 05 (2016) 050



γ-Telescopes more sensitive to $\boldsymbol{\nu}$-signals?

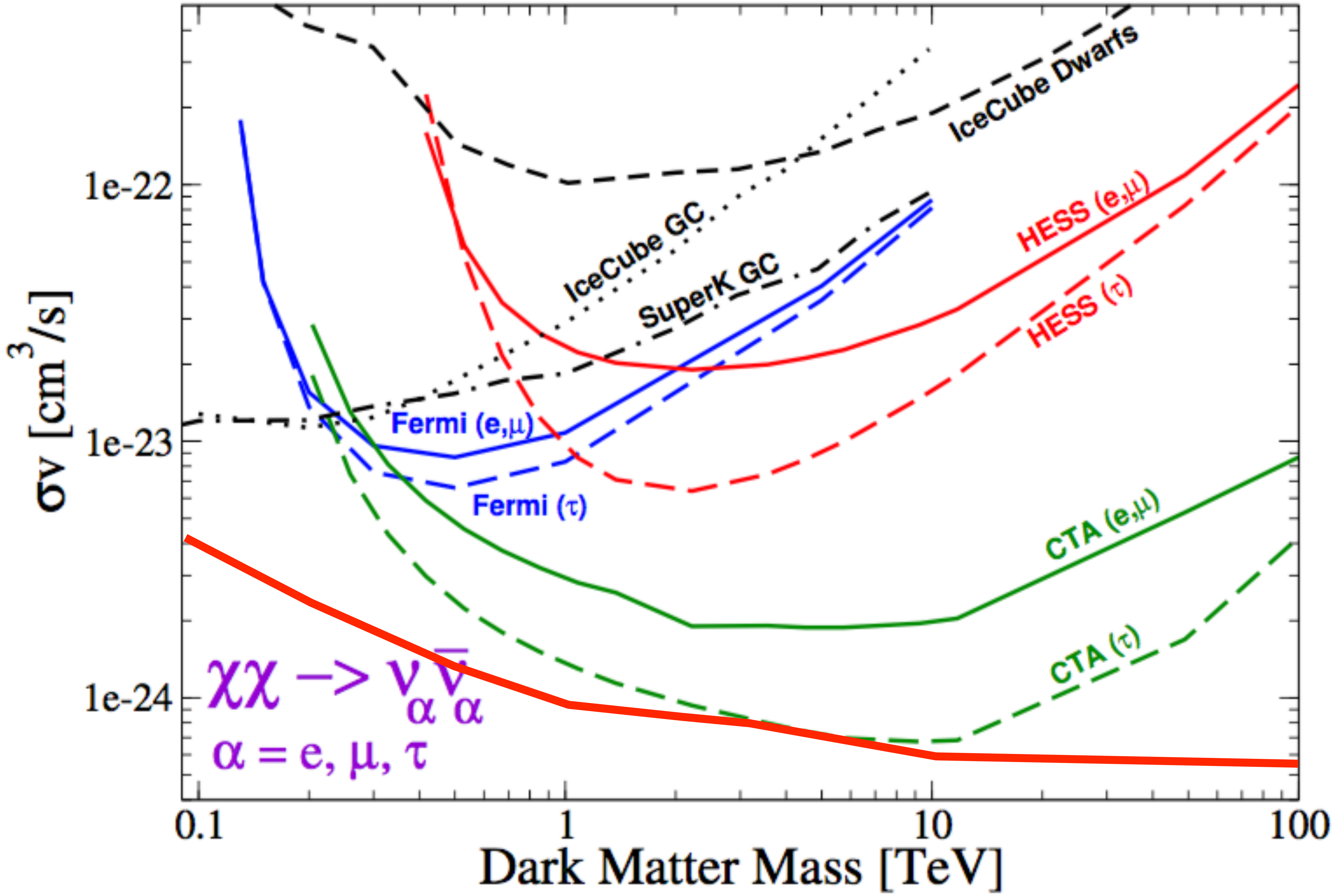
Including weak corrections is important!



- $\boldsymbol{\nu}$ final states also give rise to a γ-ray emission
- More stringent limits for masses > 200 GeV
- Only $\boldsymbol{\nu}$-telescopes can "truly" discriminate a $\boldsymbol{\nu}$-line

ANTARES 2016 $(\nu\nu)$
*(*Preliminary*)*

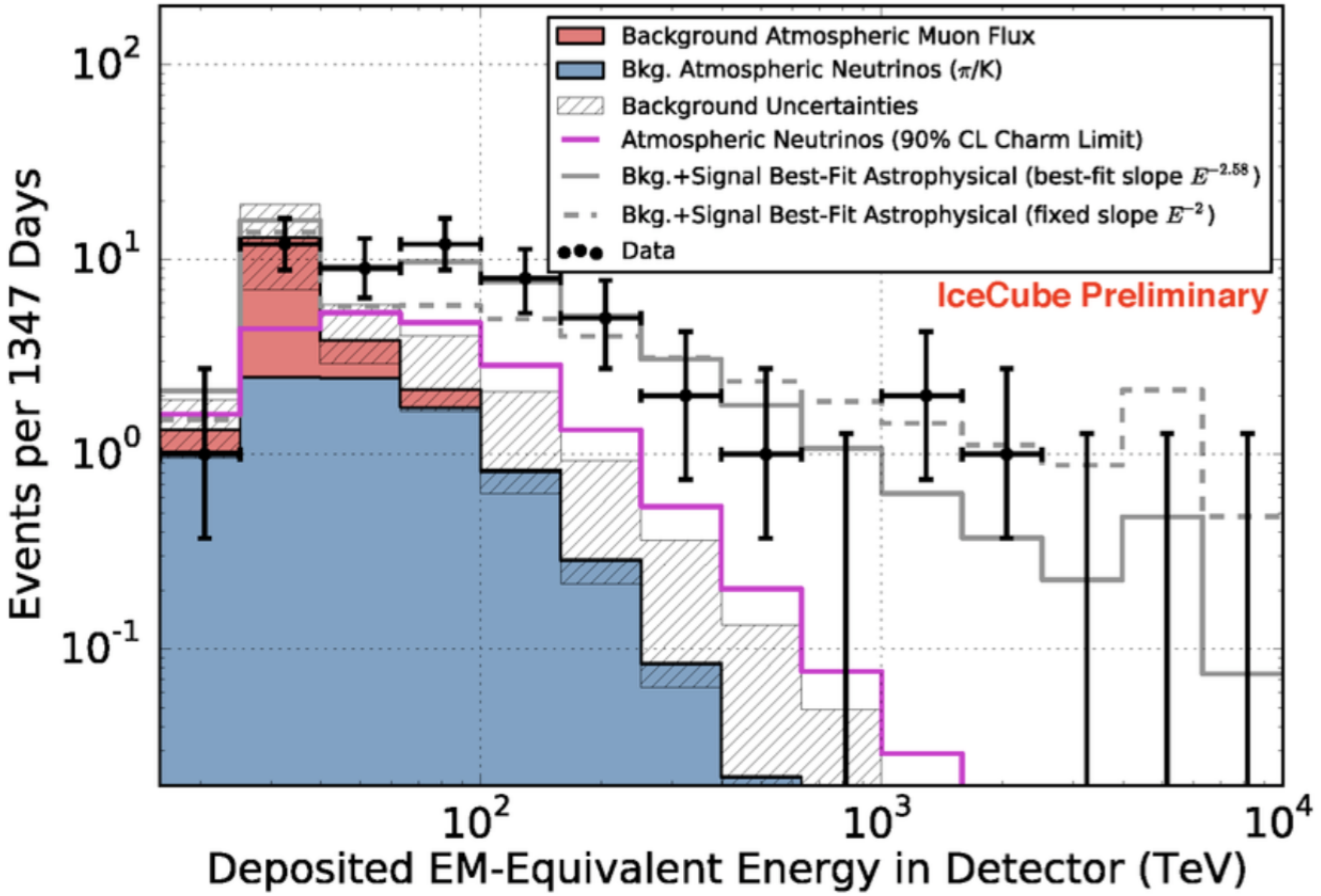
JCAP 05 (2016) 050



The picture might have changed again based on 2016 Antares results!

Heavy Dark Matter Decays

- Example of **DM → $\nu + \gamma$** (e.g. Gravitino)
- Using published IceCube data (*Atmospheric and astrophysical neutrinos above 1 TeV*)



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

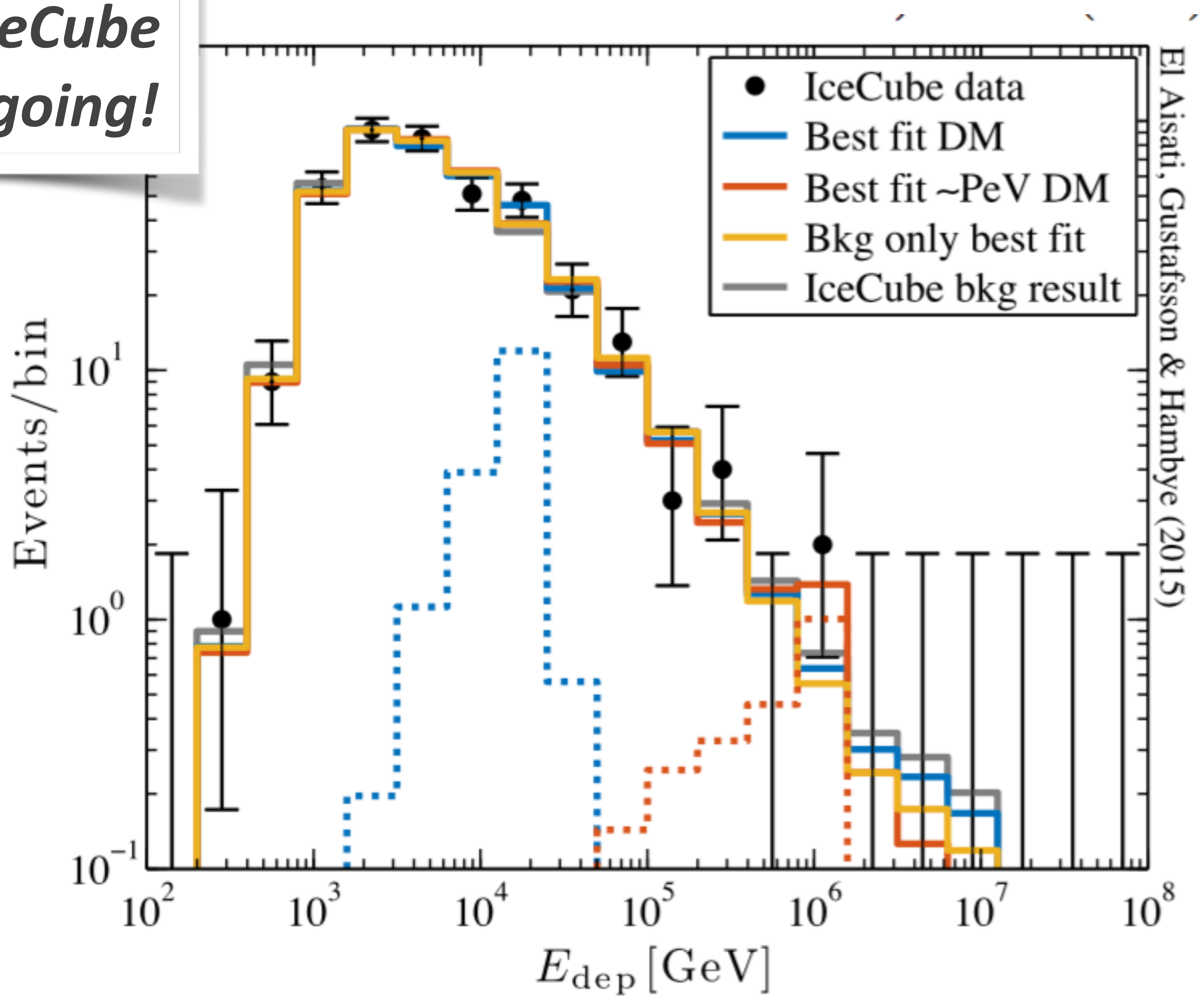
- 54 events observed (15 track-like, 39 shower-like)
- Expectation from conventional atm. muons and neutrinos ~21.6 events
- E^{-2} spectrum predicts too many neutrinos above 2PeV; Cutoff or steeper spectrum needed

Atmospheric-only hypothesis rejected by approx. 7 sigma

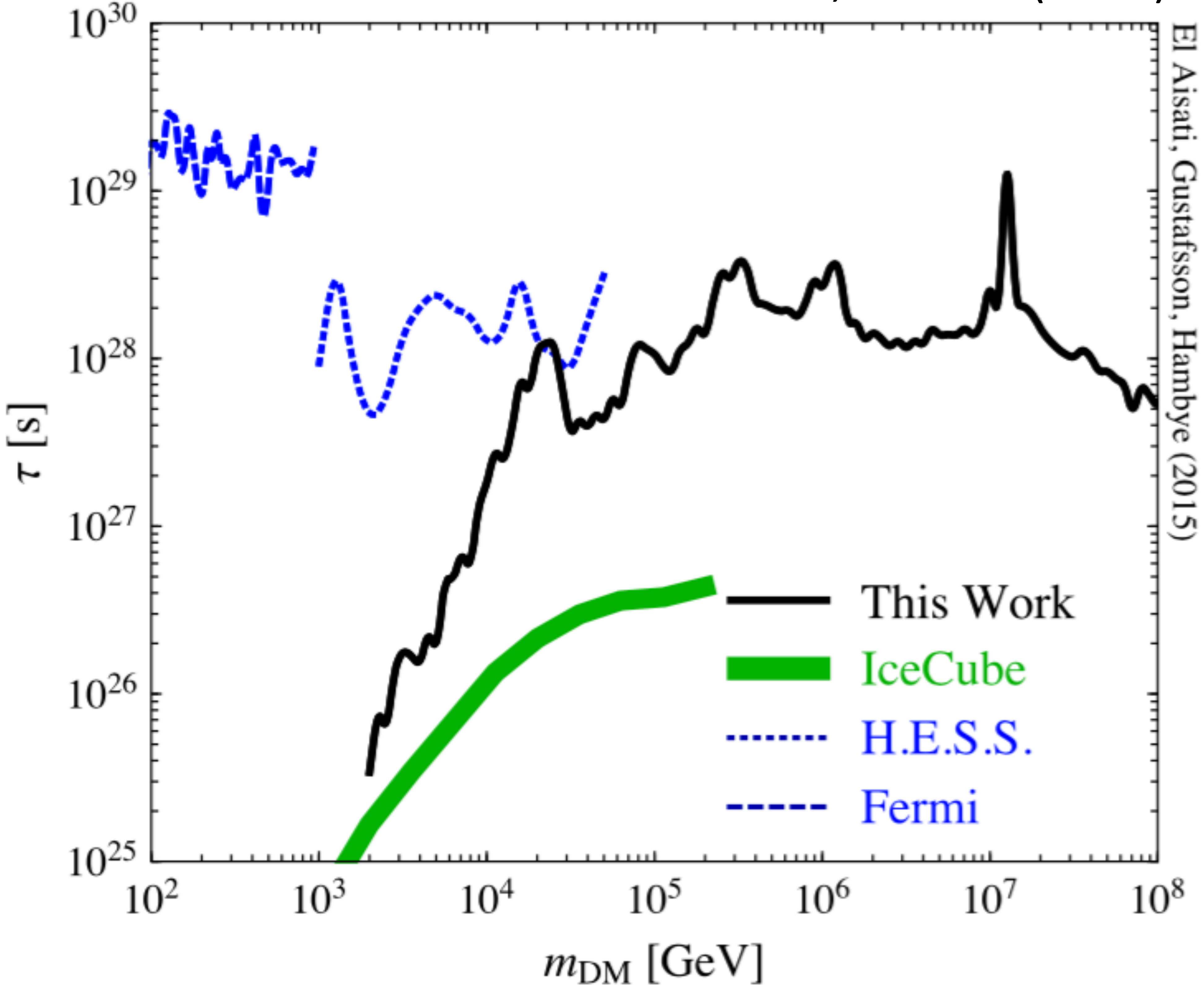
Heavy Dark Matter Decays

- Example of **DM → 𝝂+𝜸** (e.g. Gravitino)
- Using published IceCube data (*Atmospheric and astrophysical neutrinos above 1 TeV*)
- **𝝂**-telescopes remain the most promising instruments

Dedicated IceCube analysis on-going!

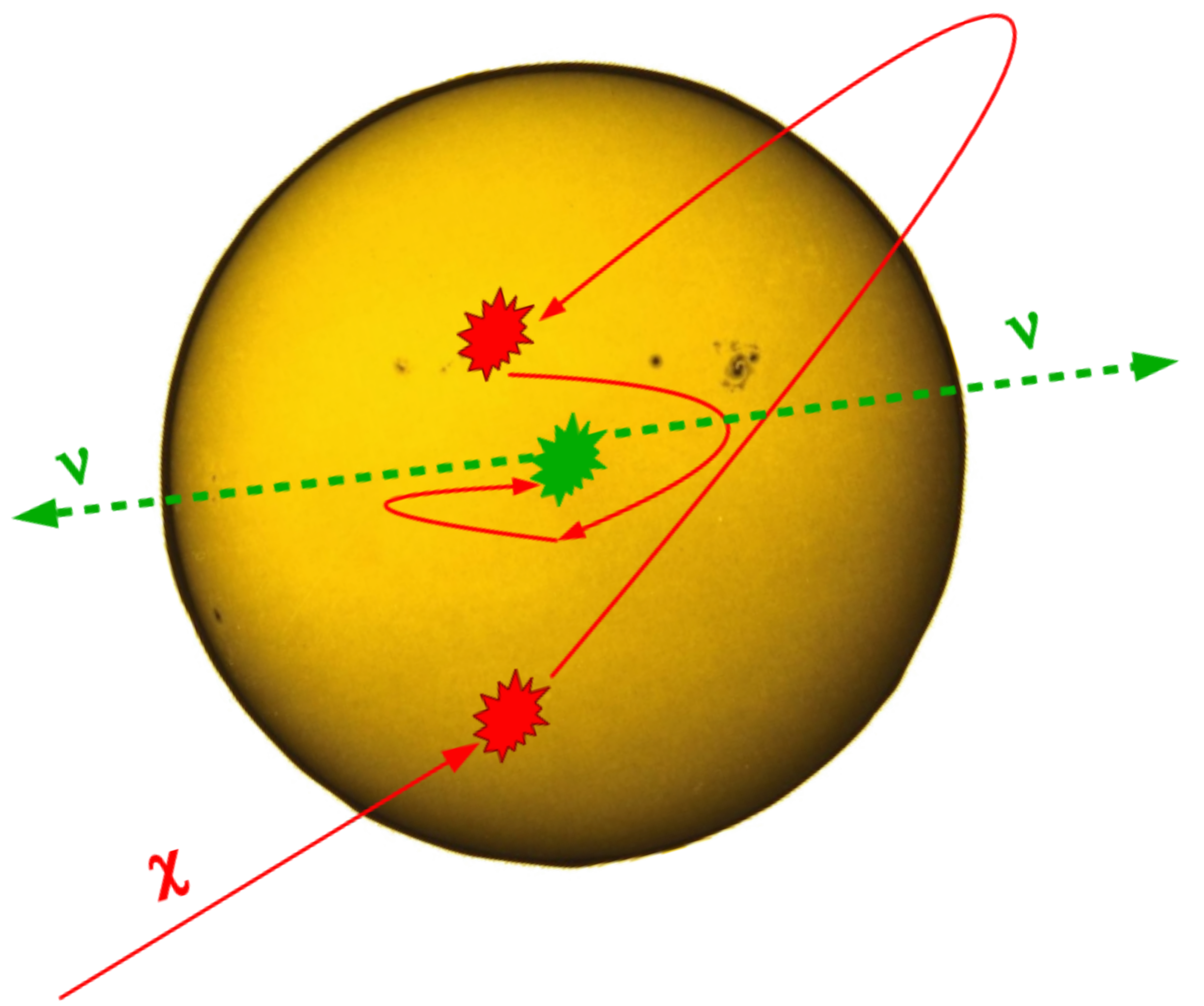


PRD 92, 123515 (2015)



Results from Searches for Dark Matter annihilations in the **Sun**

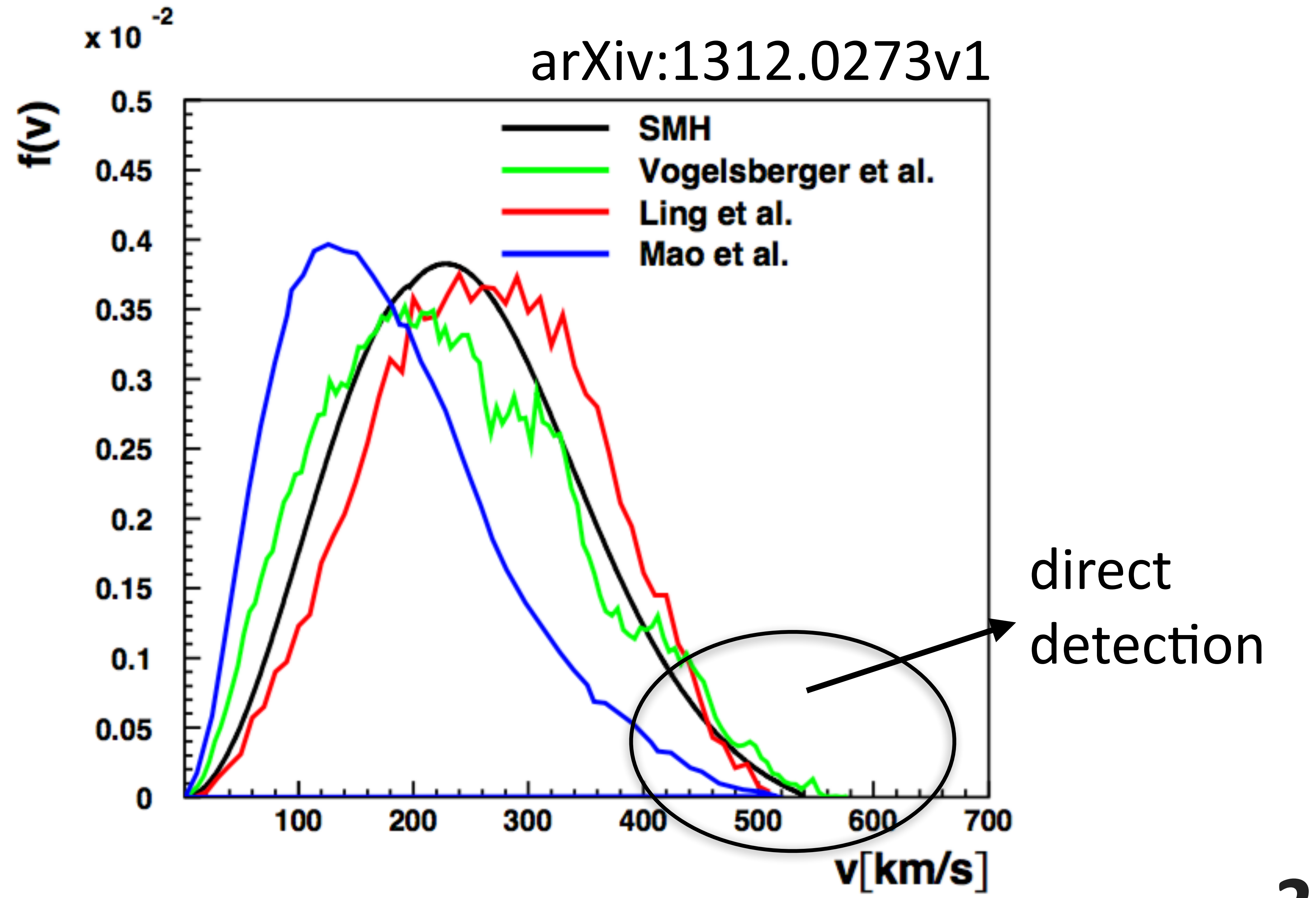
Solar Dark Matter searches



- All processes depend on WIMP mass
- Annihilation channel (branching ratios)
- At equilibrium ($\Gamma_A = 1/2\Gamma_C$) ν-flux does not depend on self-annihilation cross-section
- Capture (scattering) → Scattering cross-sections (SI & SD)

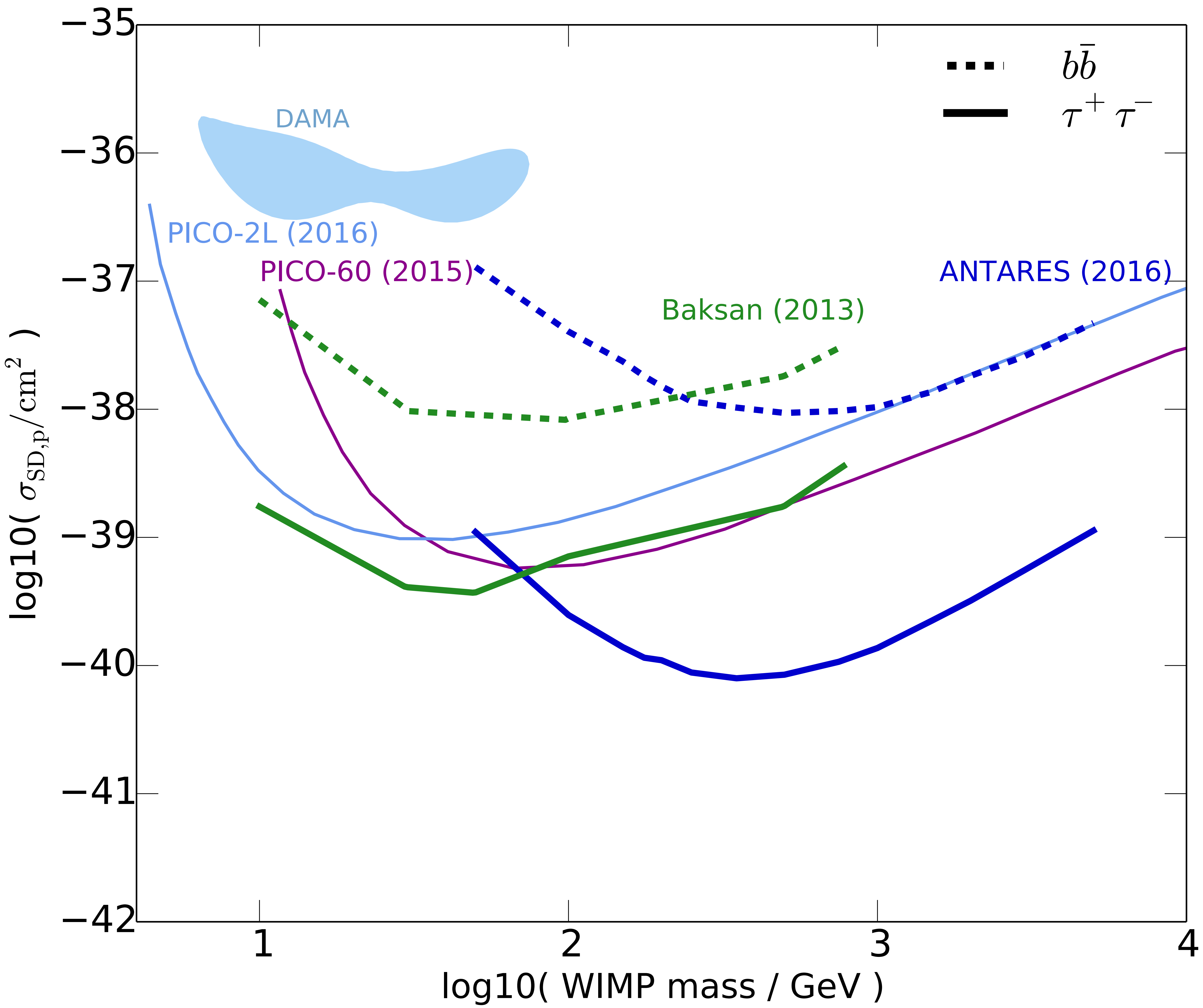
#WIMPs, Capture, Annihilation, Evaporation

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



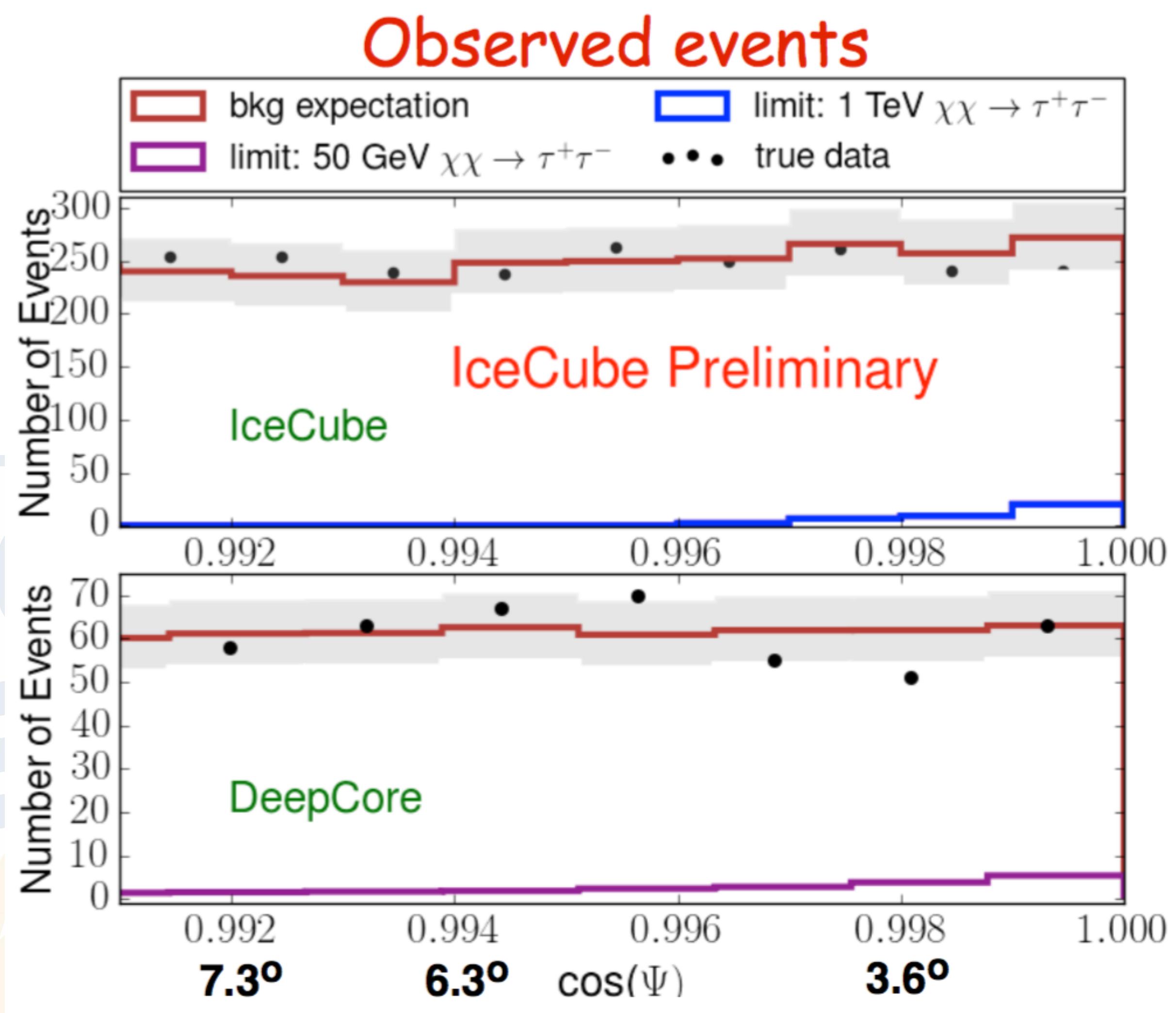
Limits on the interaction cross-section (SD)

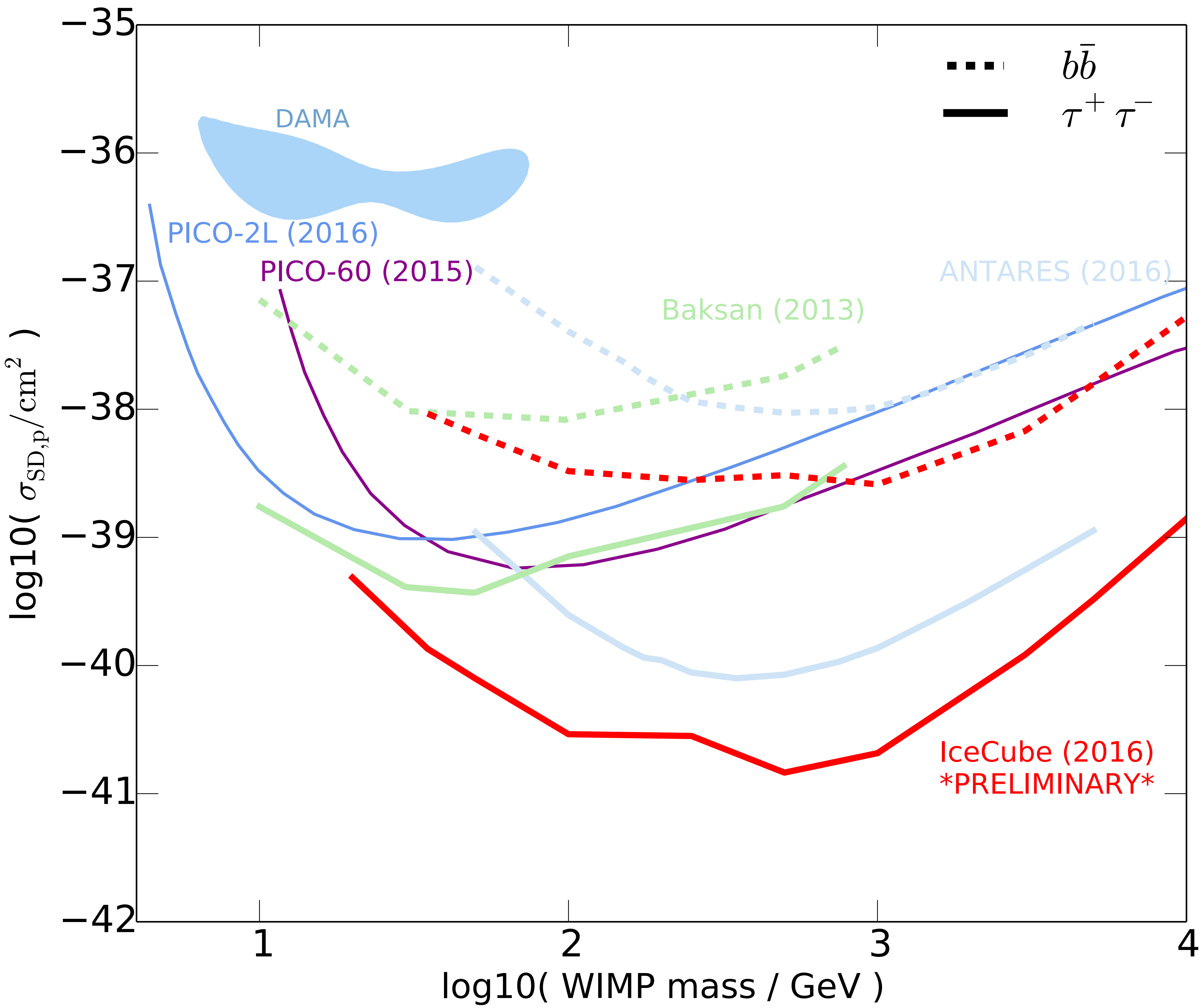
- Most stringent SD cross-section limit for most models
- Complementary to direct detection efforts
- Different astrophysical & nuclear form-factor uncertainties



Limits on the interaction cross-section (SD)

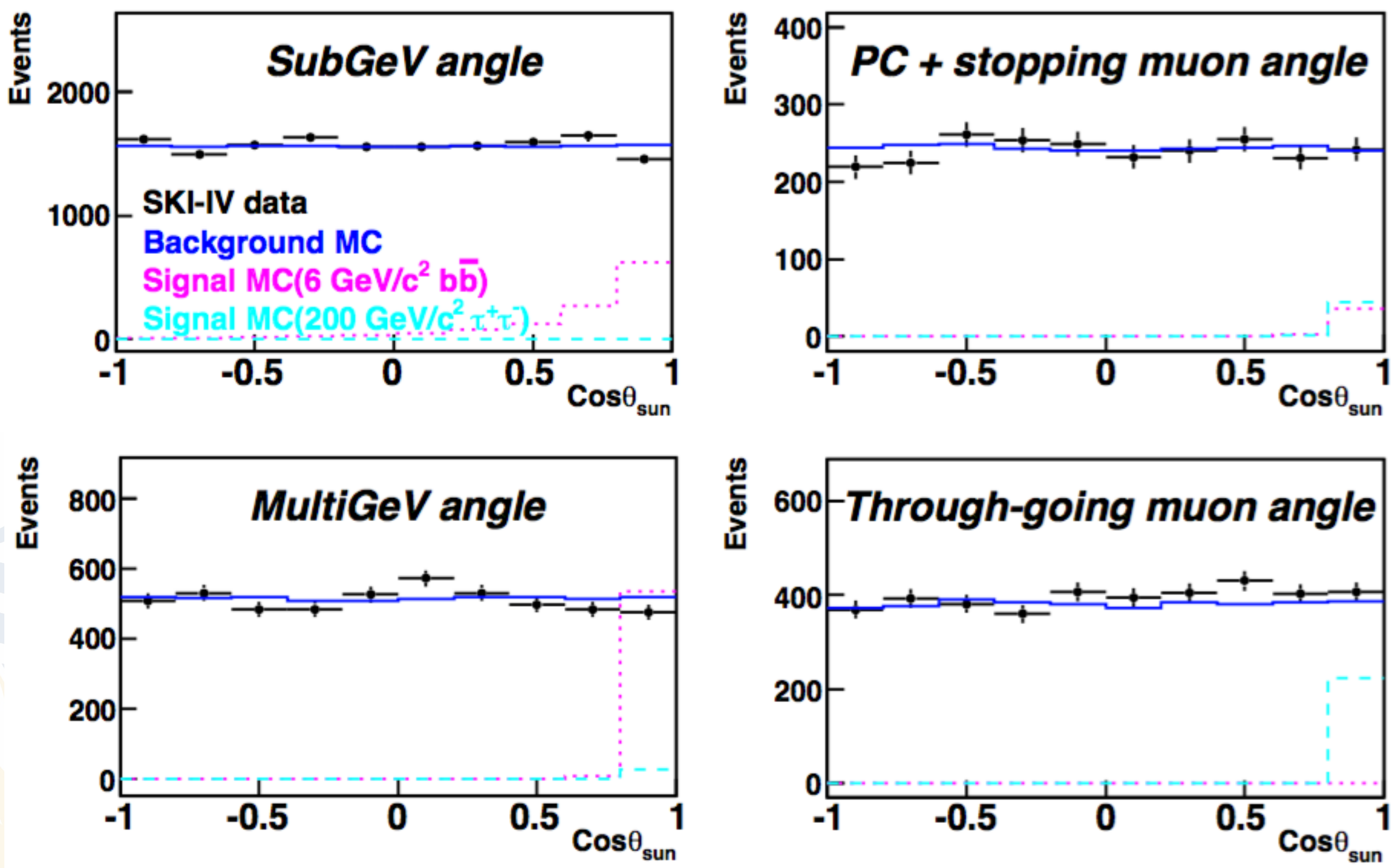
- Most stringent SD cross-section limit for most models
- Complementary to direct detection efforts
- Different astrophysical & nuclear form-factor uncertainties

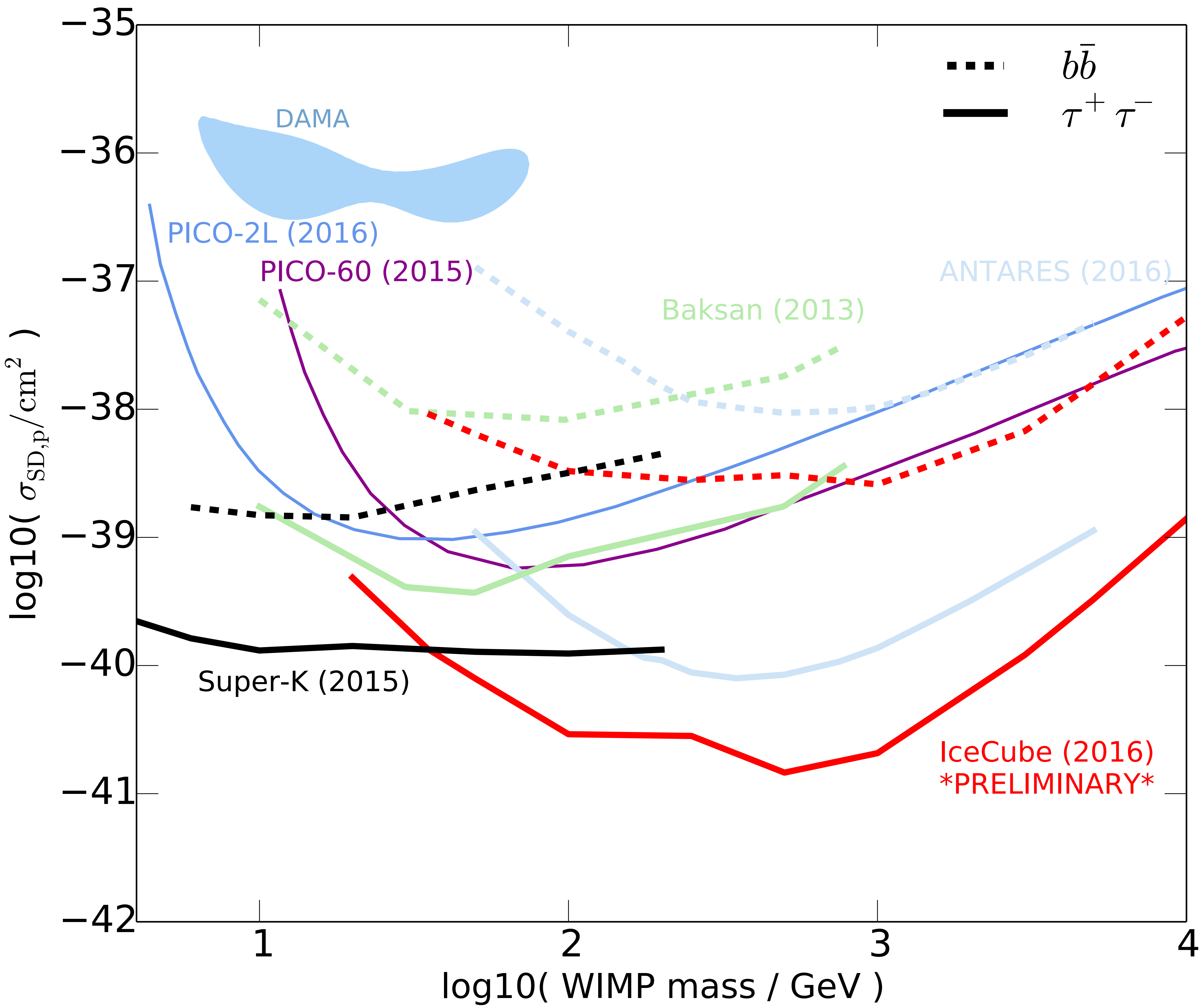




Limits on the interaction cross-section (SD)

- Most stringent SD cross-section limit for most models
- Complementary to direct detection efforts
- Different astrophysical & nuclear form-factor uncertainties

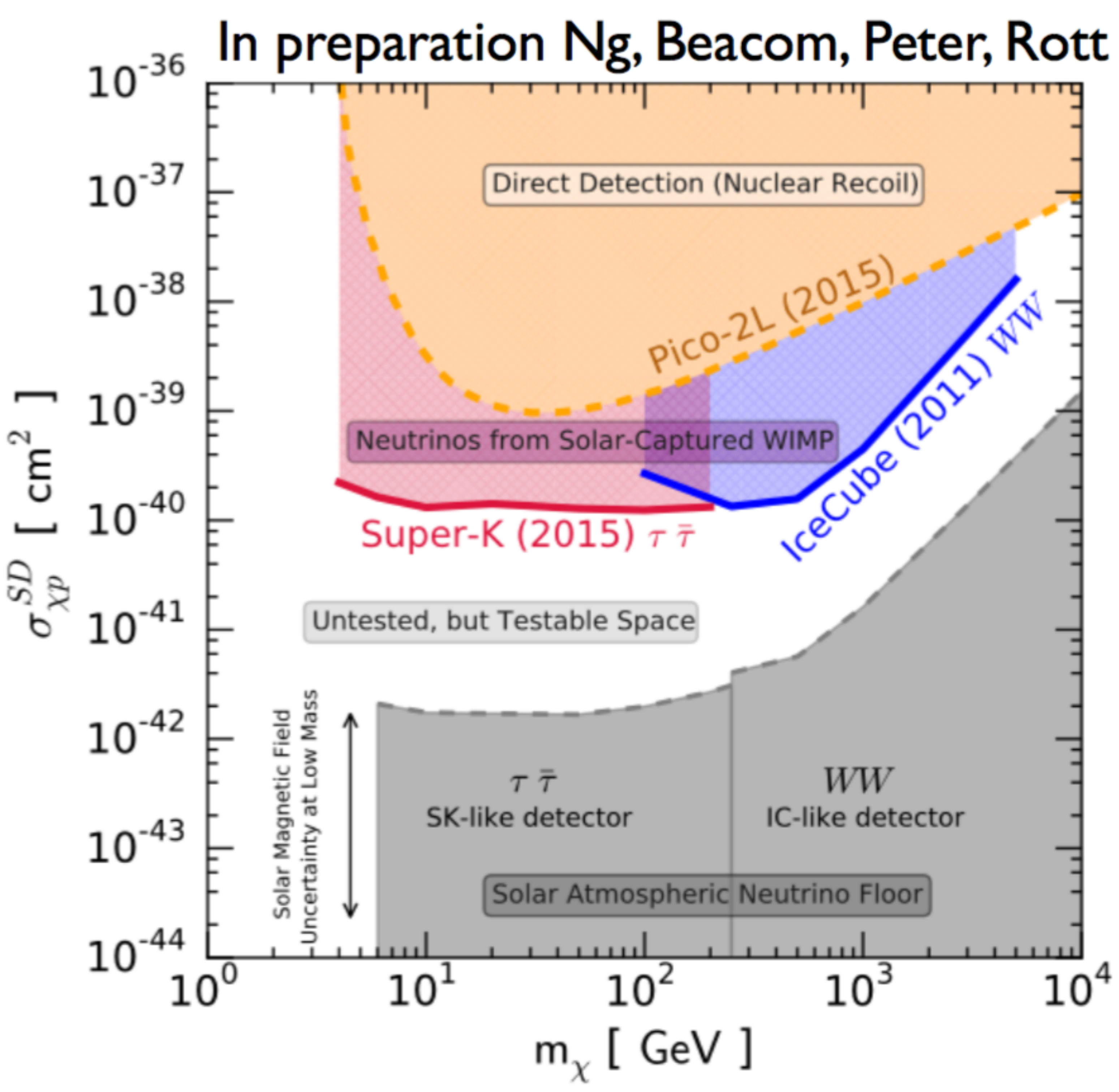


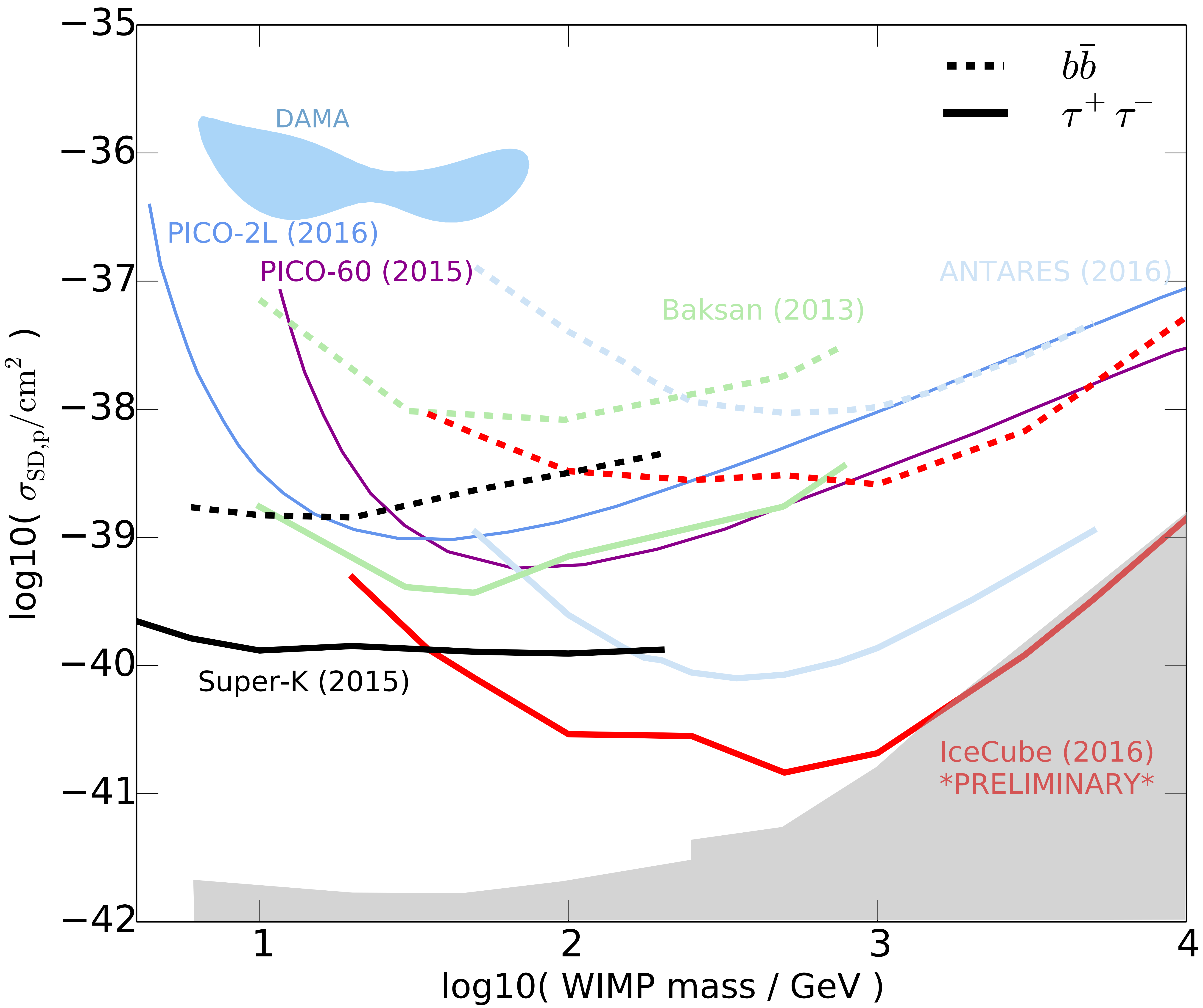


Limits on the interaction cross-section (SD)

Solar atmospheric background

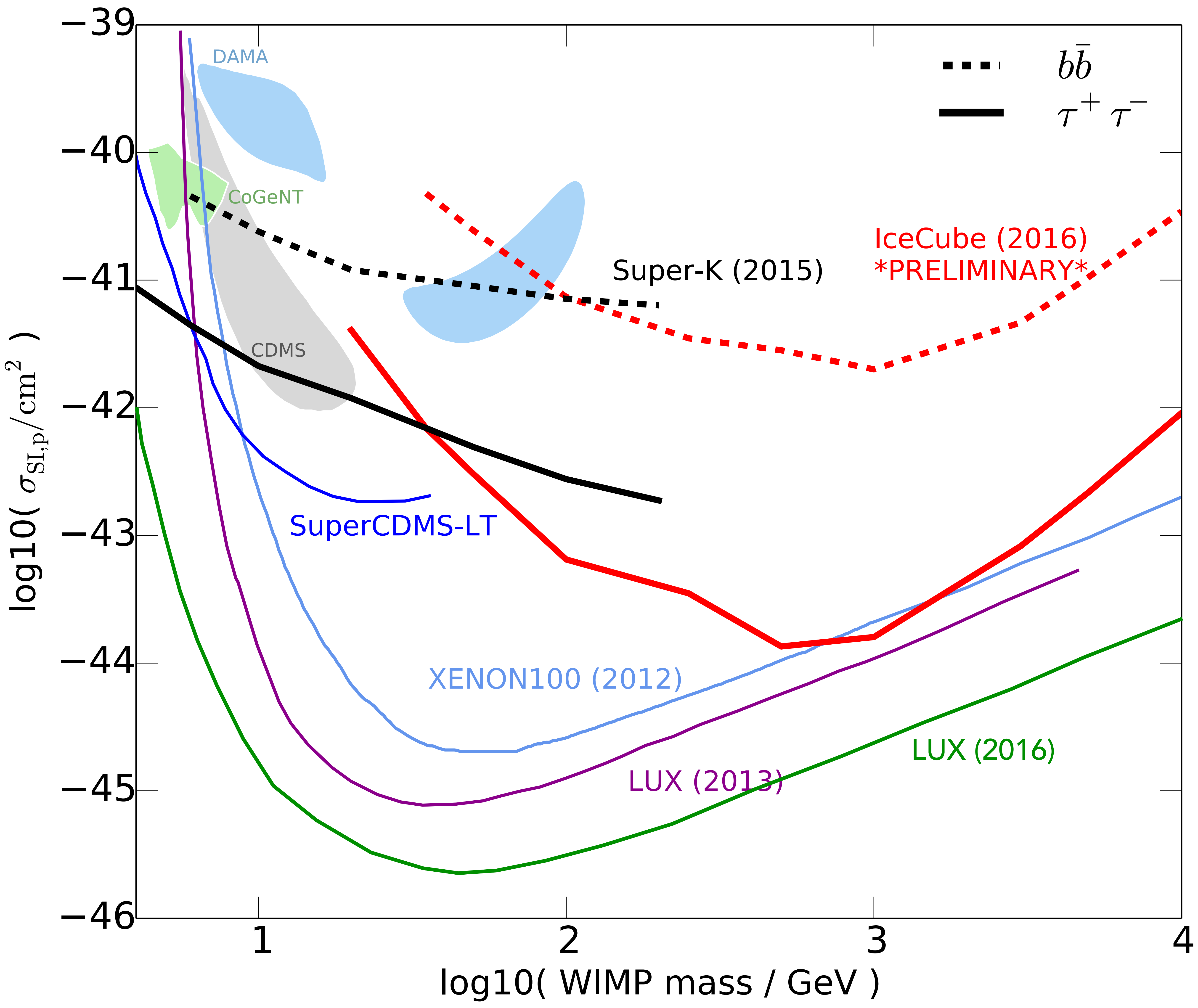
- Background that will be soon relevant
- First high-energy neutrino point source?





Limits on the interaction cross-section (SI)

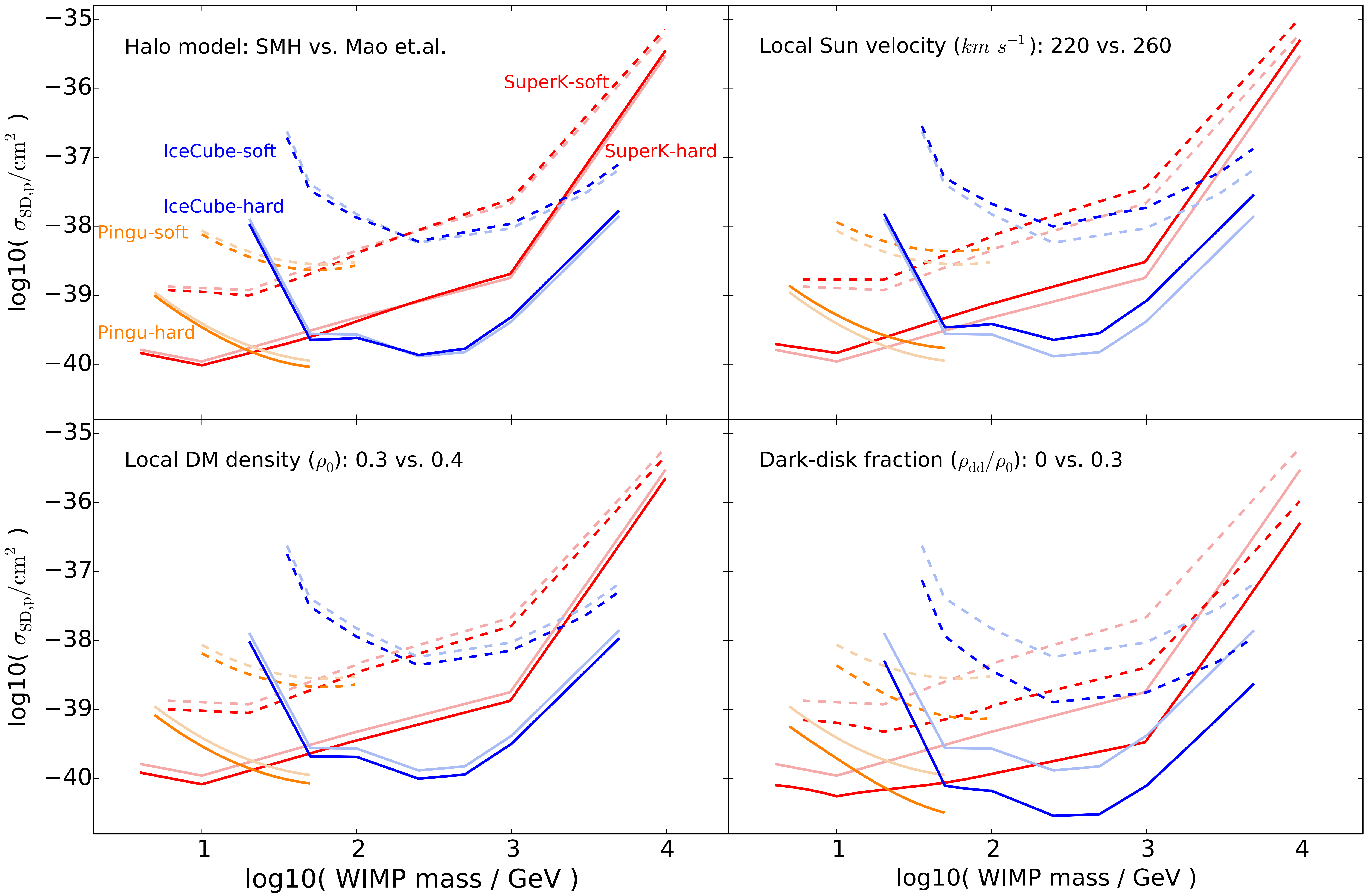
- SI cross-section limit dominated by direct detection
- Complementary but significantly weaker
- Different astrophysical & nuclear form-factor uncertainties



Impact of Astrophysical uncertainties

- Example for σ_{SD}
- IceCube results & PINGU sens. from **2014**
- **Not included:** Solar composition & nuclear form-factor uncertainties

Physics of the Dark Universe 5-6 (2014)



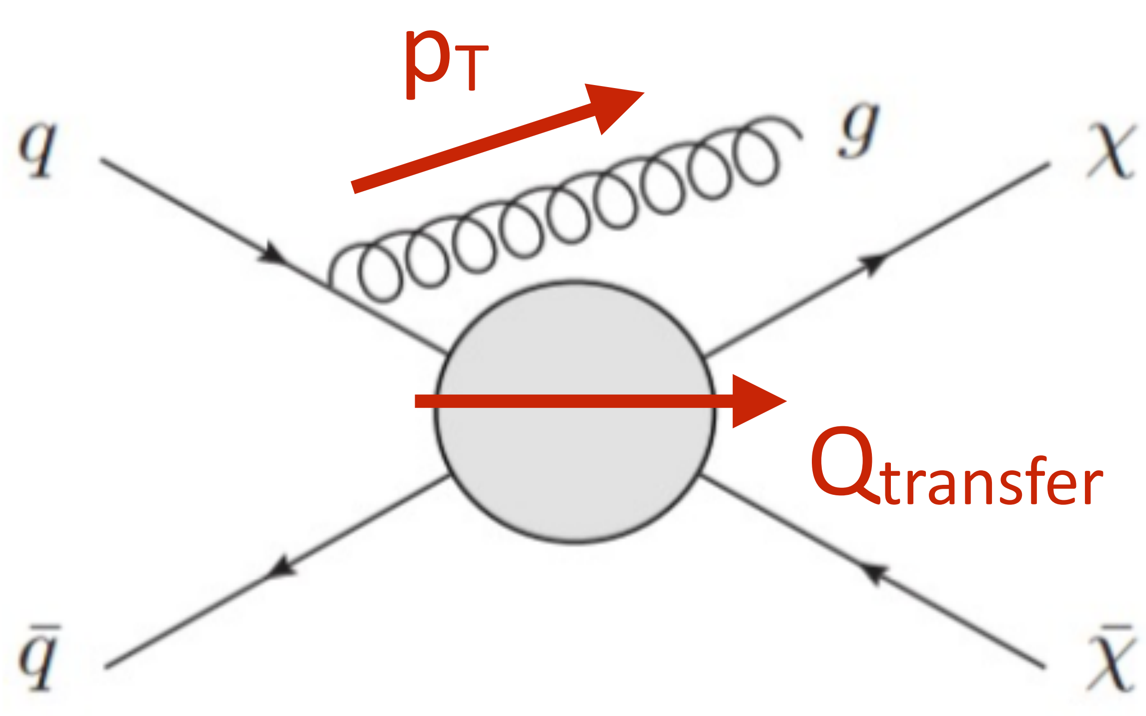
https://mdanning.web.cern.ch/mdanning/public/Interactive_figures/

Complementarity to Collider Searches

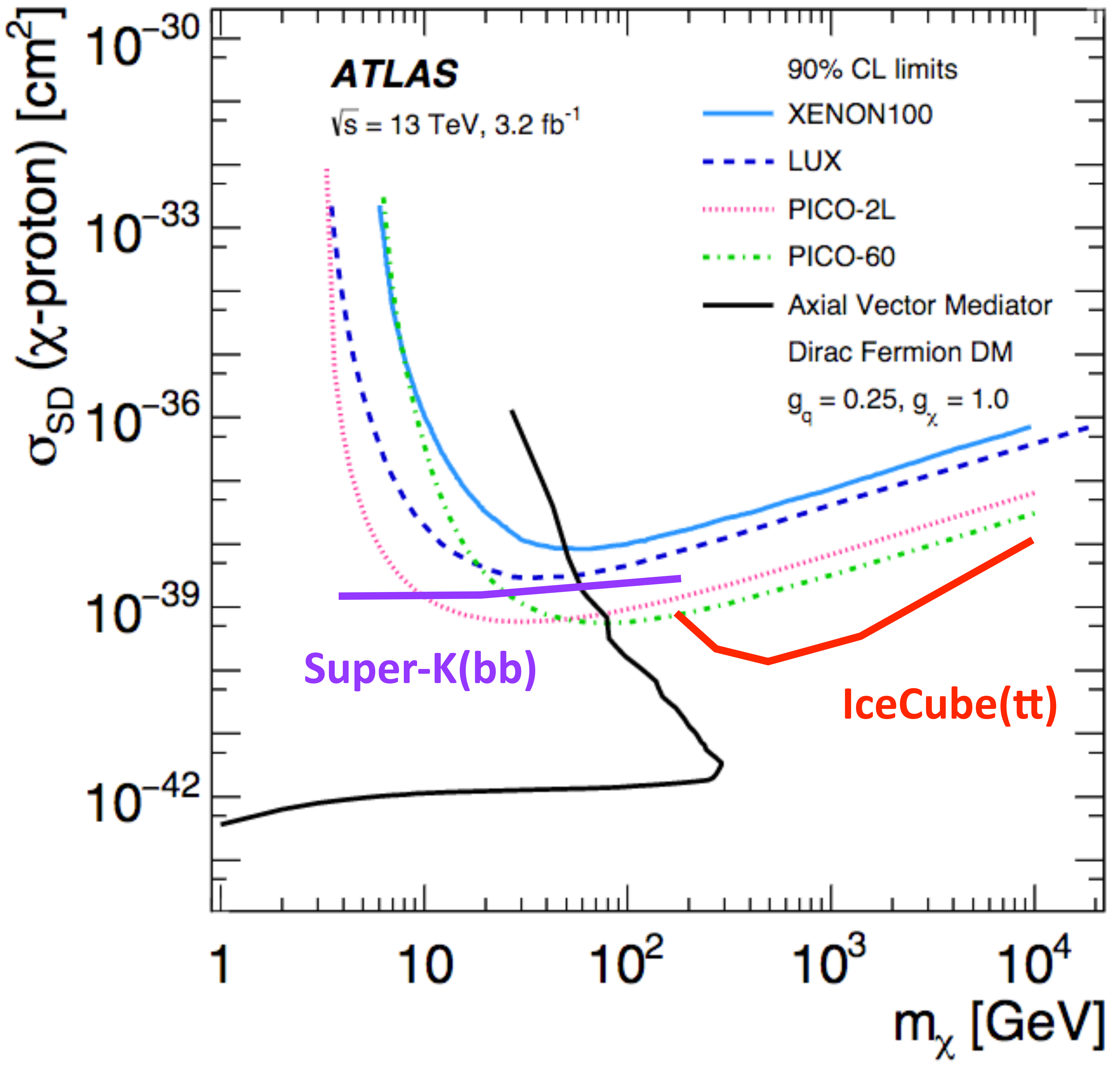
- DM is "stable" —> Missing energy at LHC
- Mono-X searches
  —> Rely on the detection of accompanying particles/jets
- Effective theory **(was)** typically assumed
- Move towards simplified models (still few parameters, but more assumptions)
  —> m_{DM}, m_{med}, 2 couplings

Atlas/CMS Dark Matter Forum Simplified models
arXiv/1507.00966

LHC DM WG Recommendations
arXiv/1603.04156



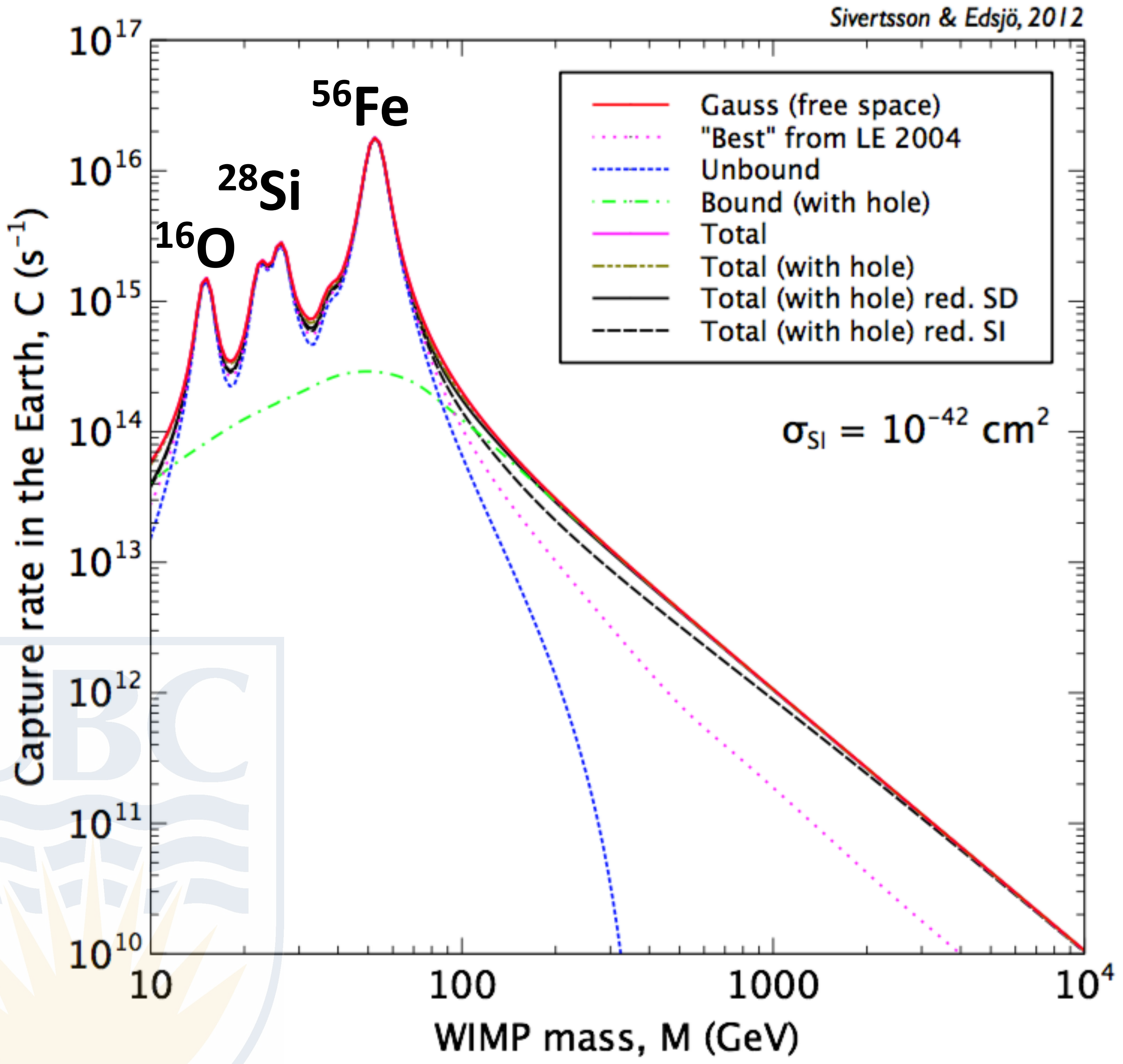
JHEP06(2016)059 (ATLAS Mono-photon search)
IceCube limits: JCAP 04 (2016) 022



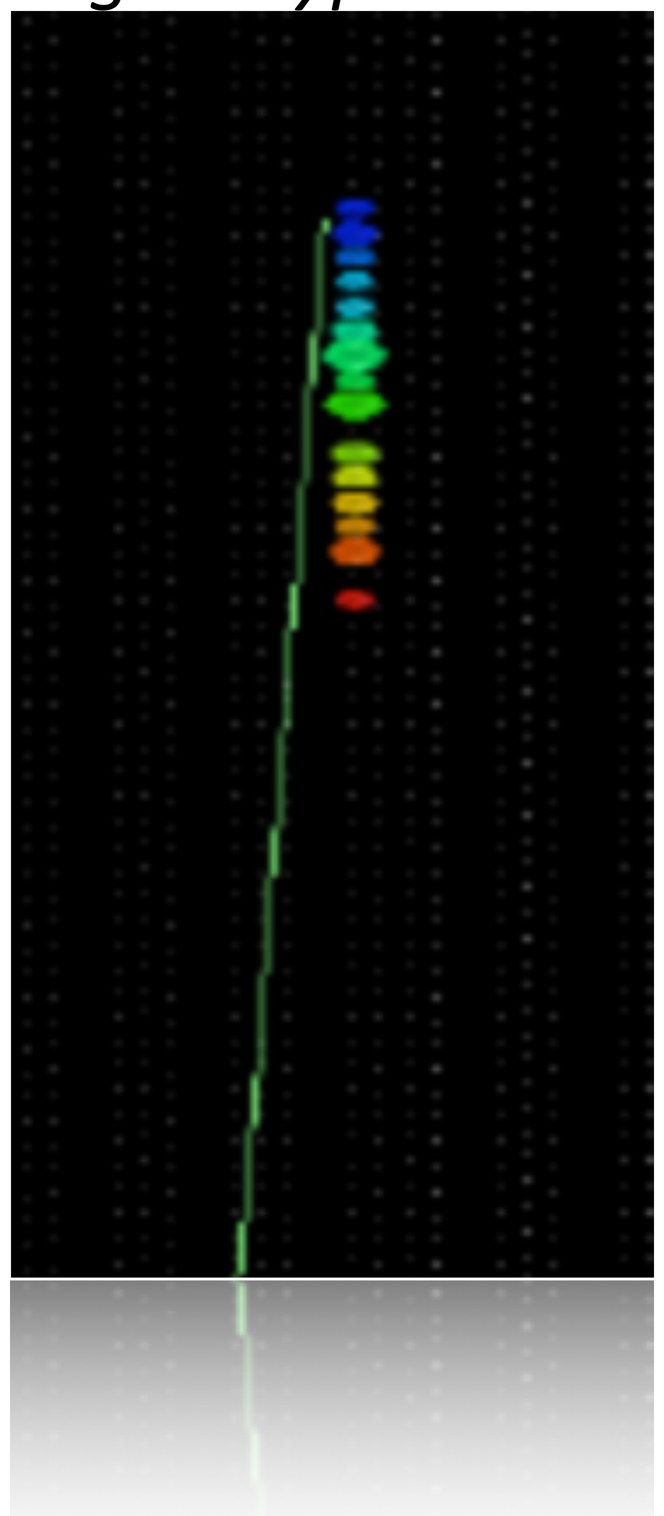
Results from Searches for Dark Matter annihilations in the **Earth**

Results for Dark Matter Searches from the Earth

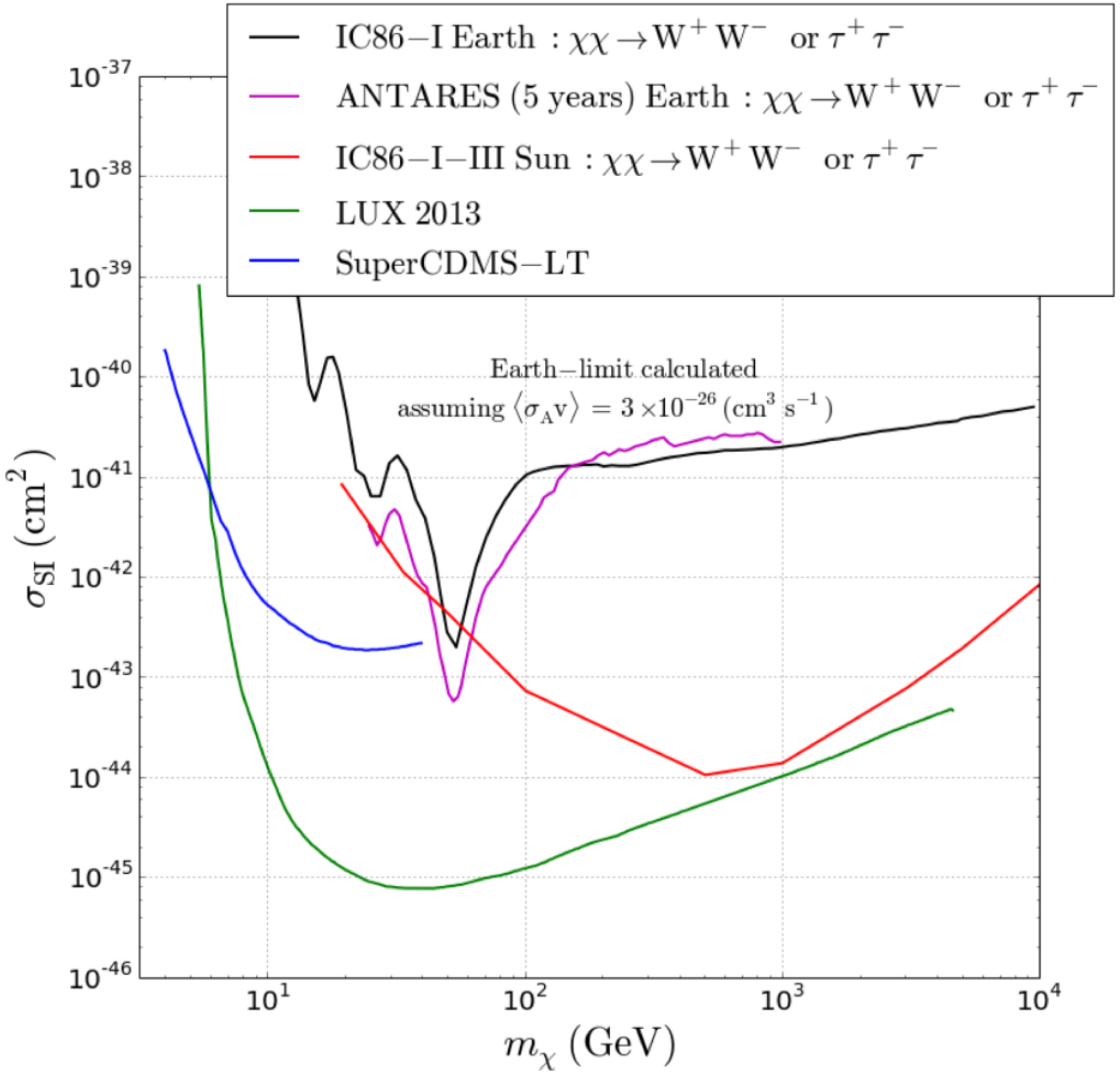
- Dark Matter could be captured in the Earth
- Signature: Vertically up-going excess **ν**-flux
- Experimentally challenging — no off-source data expectation



signal-type event



PhD thesis: J.Kunnen (VUB Oct.2015)

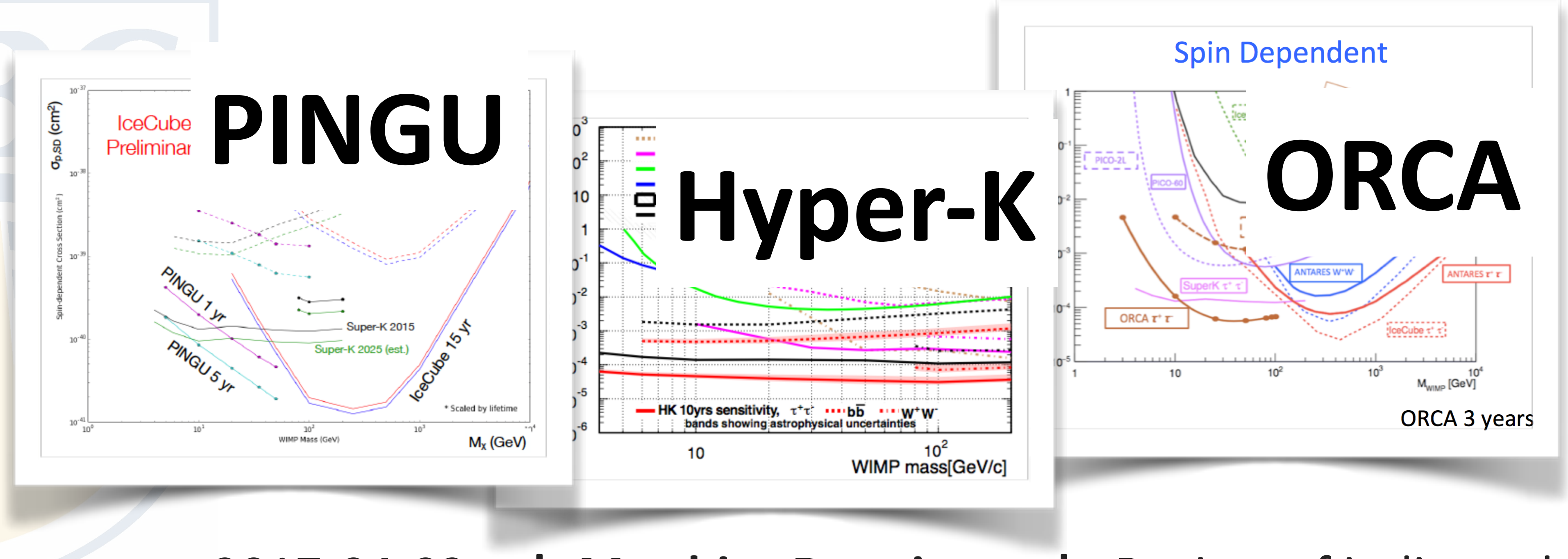


Future Prospects for neutrino telescopes & conclusions

Future prospects & Conclusions (1/2)

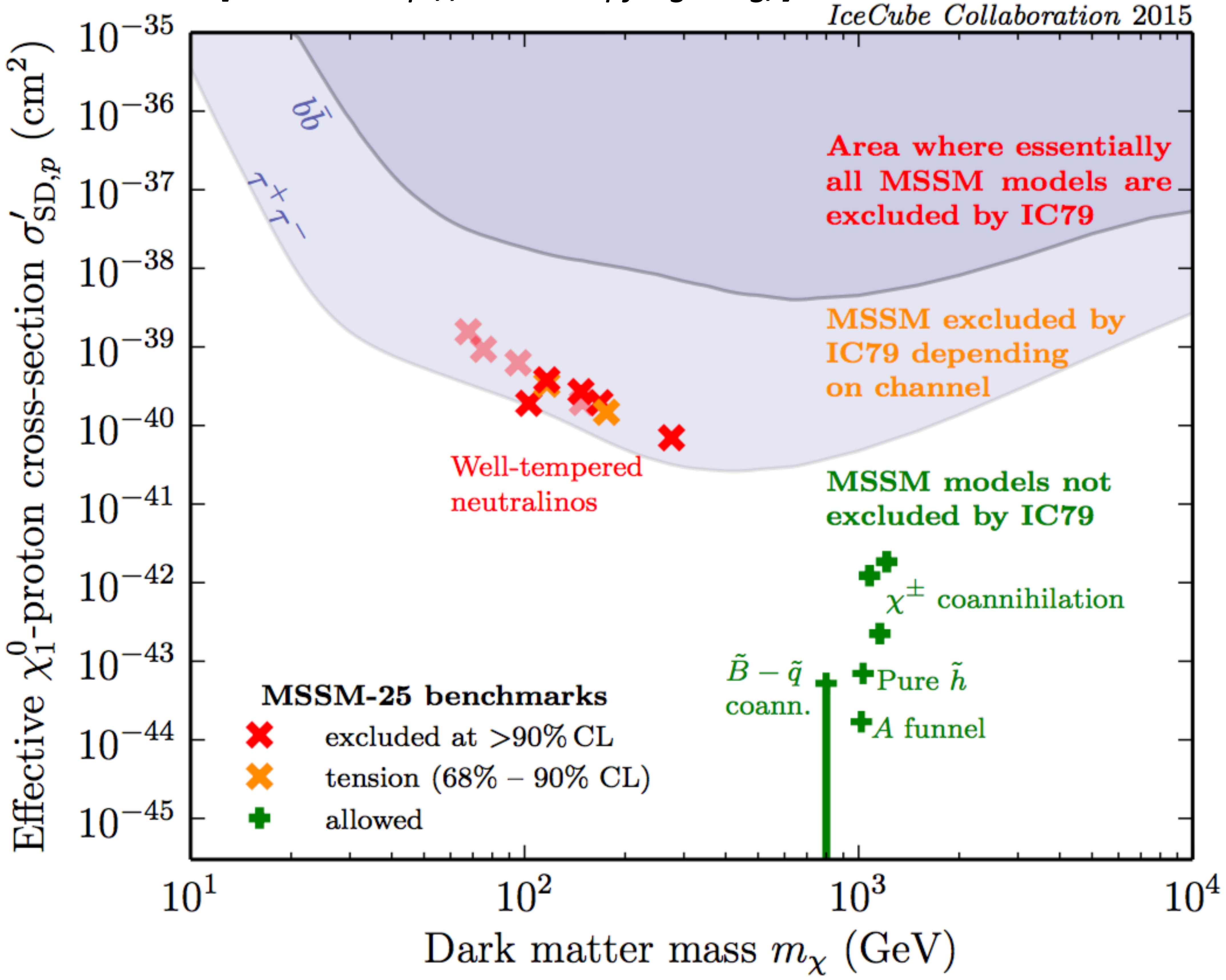
Dark Matter in the Sun

- Discovery channel for Dark Matter
- Most stringent SD cross-section limit for most models
- Sensitivity will continue to improve with current detectors — *Solar atm. background becomes important!*
- **Publishing data and detector responses is important!** —> allows inclusion into explicit model scans Future detectors will further improve limits at low DM masses
- Inclusion of cascade channel will further improve limits



JCAP 04 (2016) 022

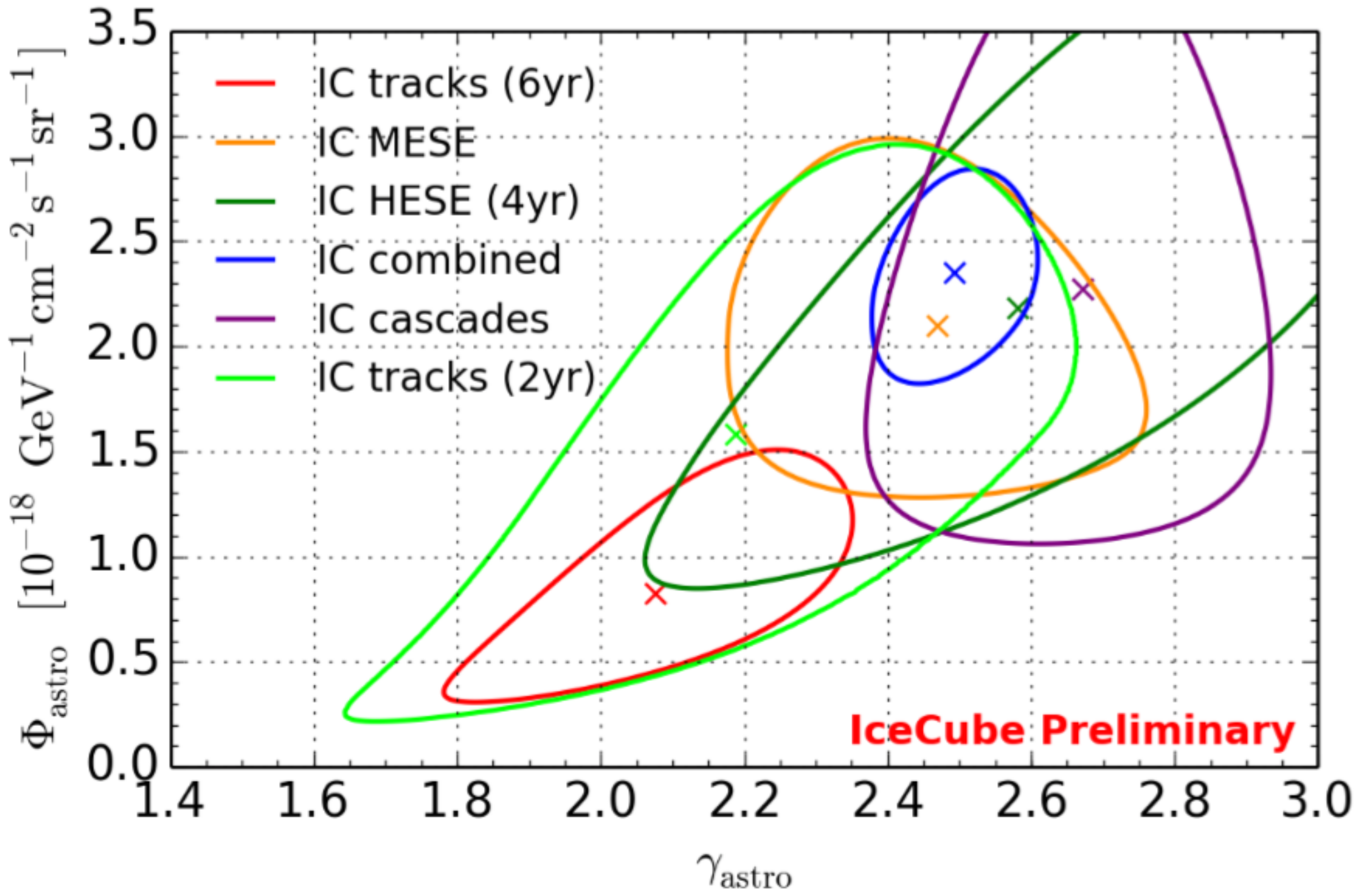
[code at: http://nulike.hepforge.org/]

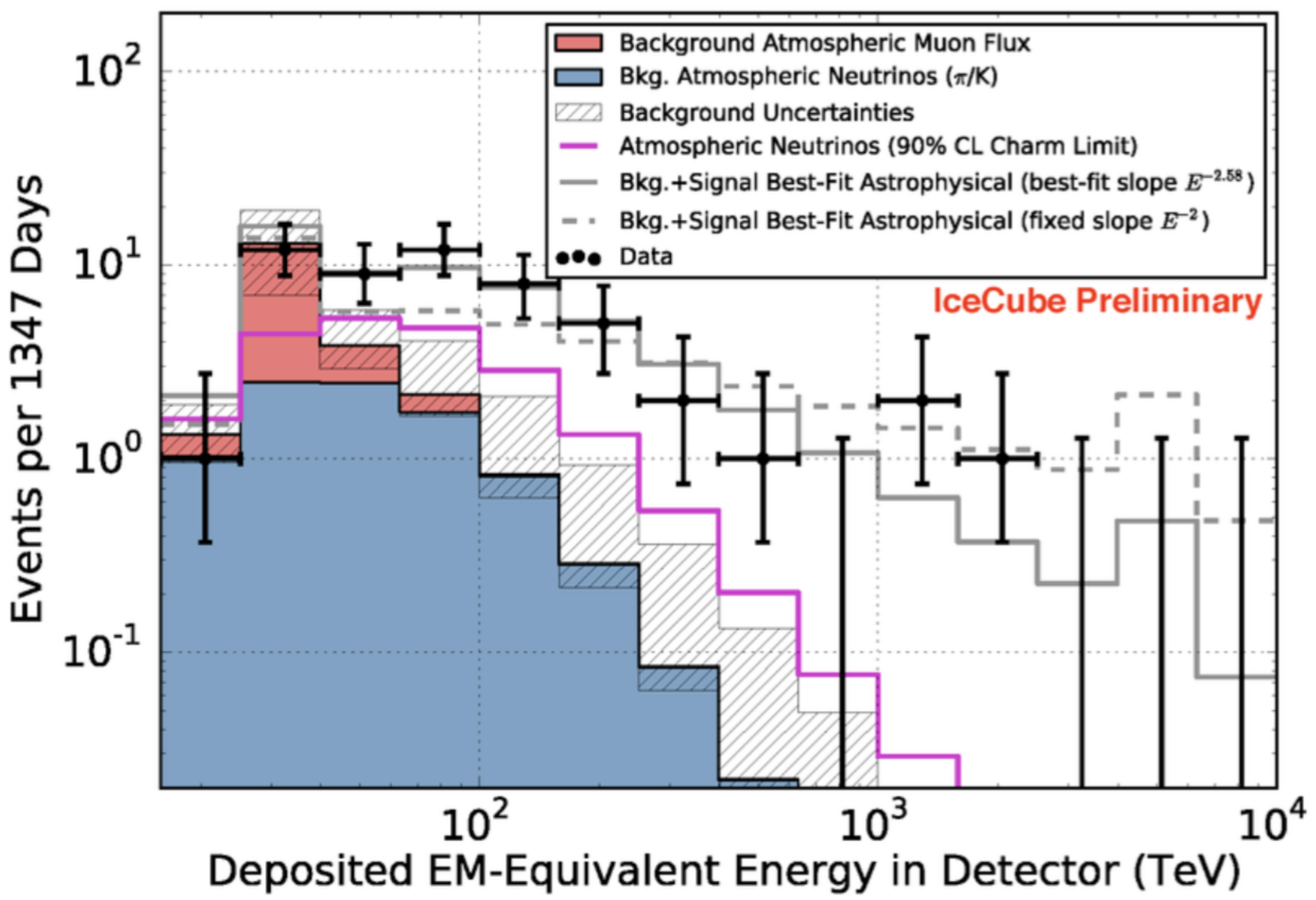


Future prospects & Conclusions (2/2)

Galactic halo, Galactic center, Dwarf spheriodals, Cluster of Galaxies, ...

- Gamma-rays much more competitive for low WIMP masses
- High masses (>1TeV) - neutrinos are more competitive than gamma-rays !
- Exciting prospects for ARCA and IceCube Gen2 high-energy extensions





Many models predict heavy Dark Matter!

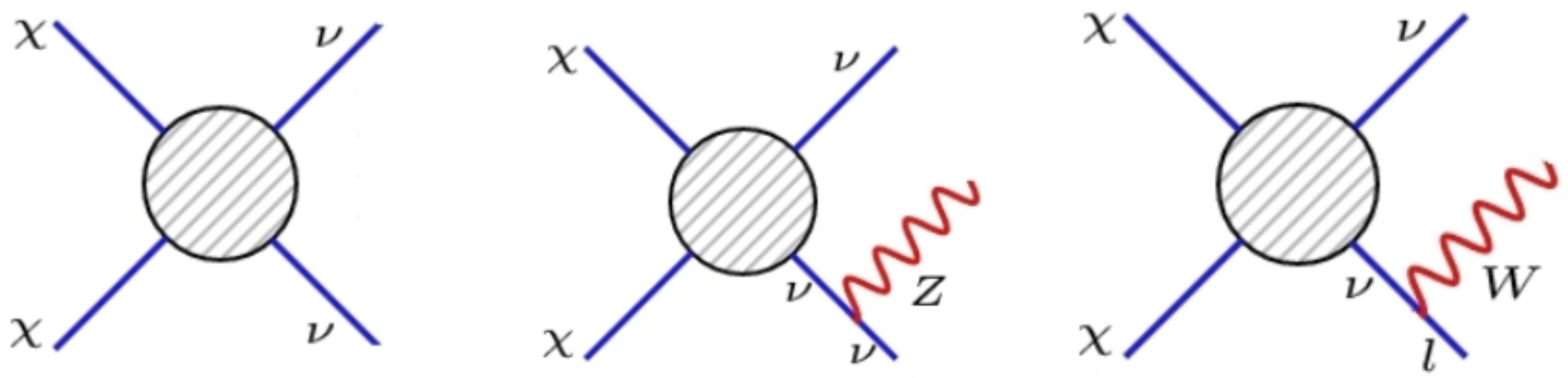
Intense interest in high-energy neutrino region

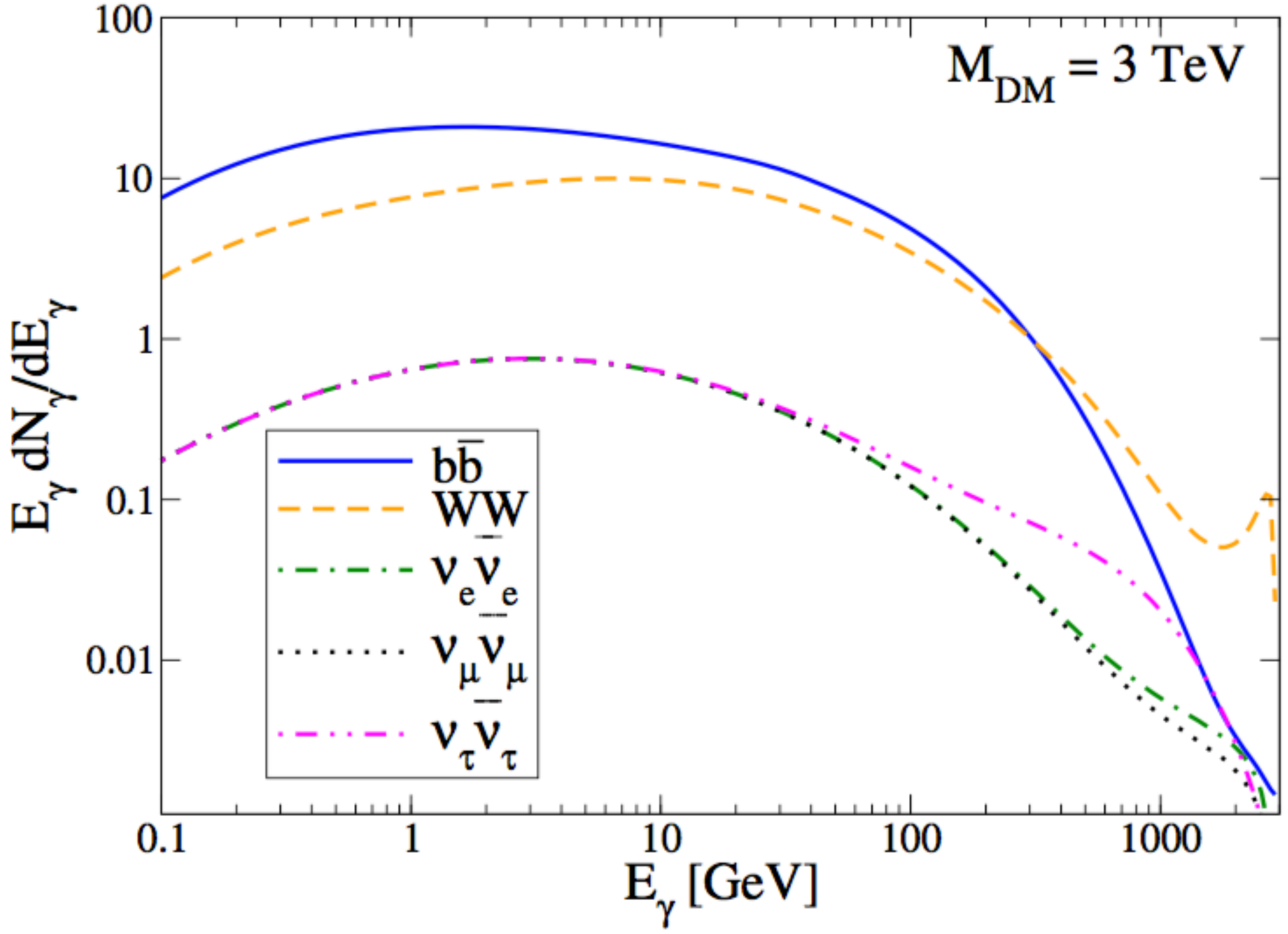
- Observations defy any simple explanation from a single generic source class
  - Multiple sources classes?
  - Hints of new physics?

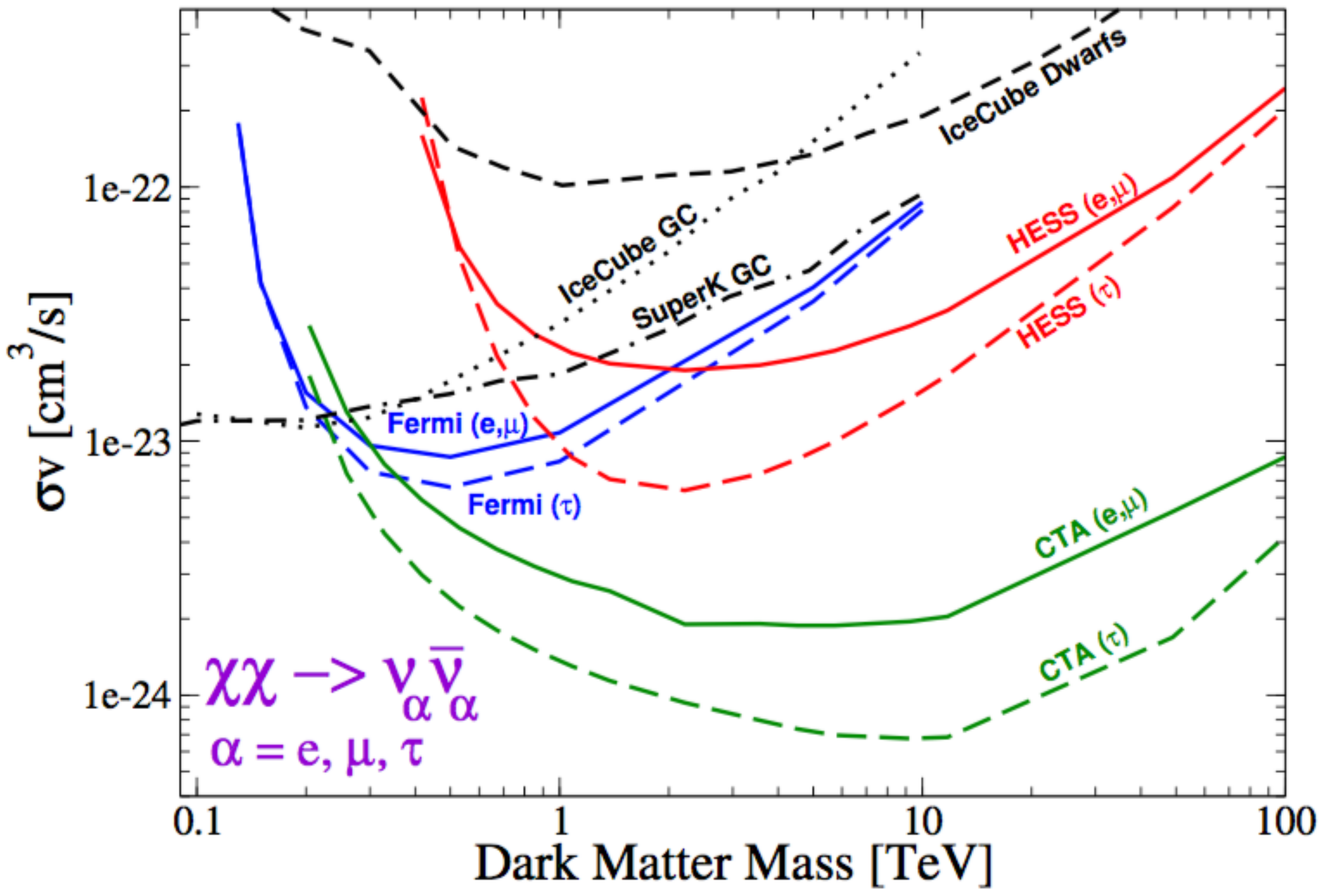
Thank you!!

Backup

Weak corrections for neutrino lines

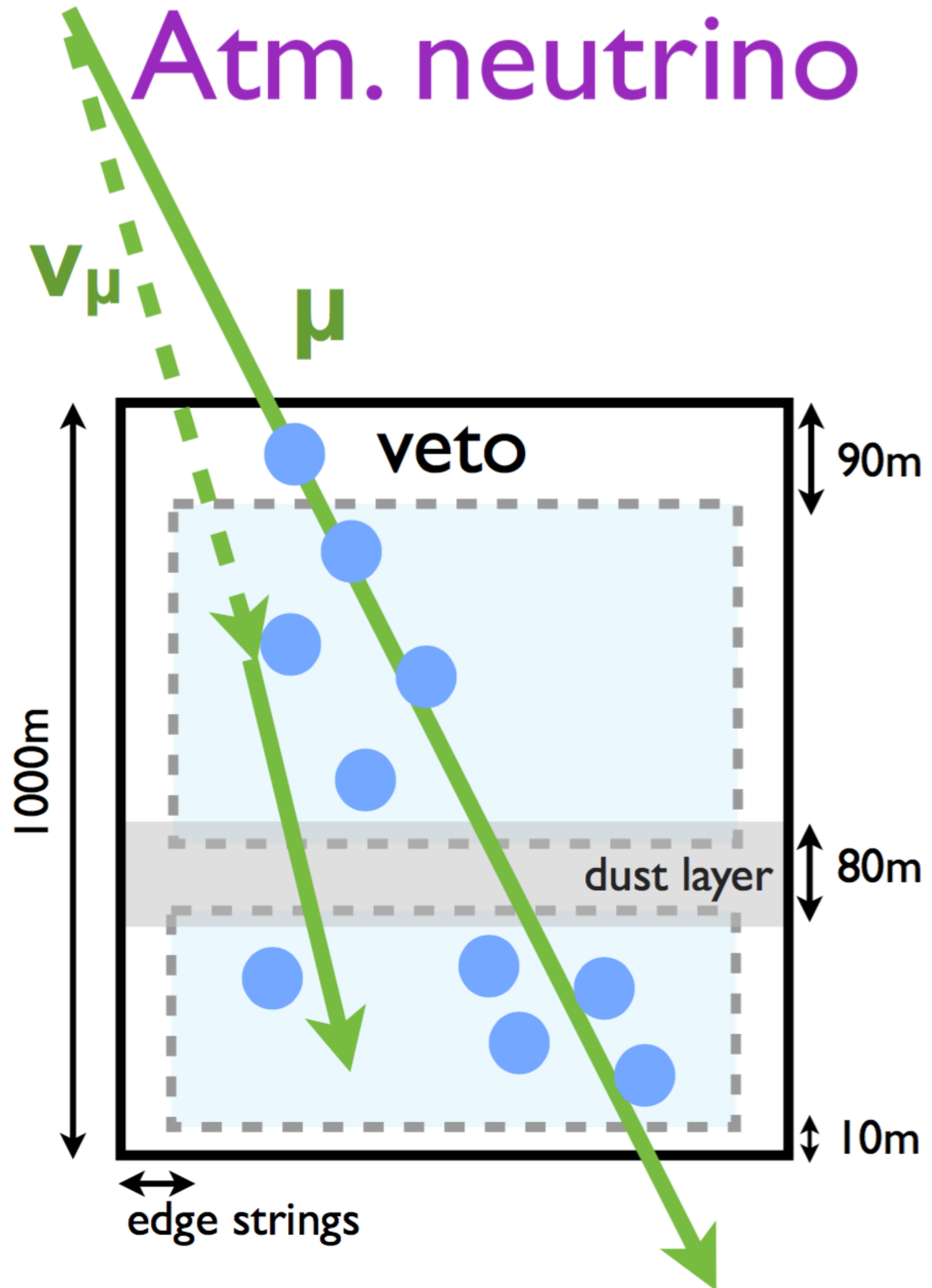






Veto and Self-veto

IceCube Collaboration **Phys.Rev. D91 (2015) no.2, 022001** (arxiv:1410.1749)



Down-going high-energy neutrinos can be nearly background free identified as astro-physical neutrinos