Solar Dark Matter Search with the IceCube Neutrino Observatory

Jeffrey Lazar for the IceCube Collaboration

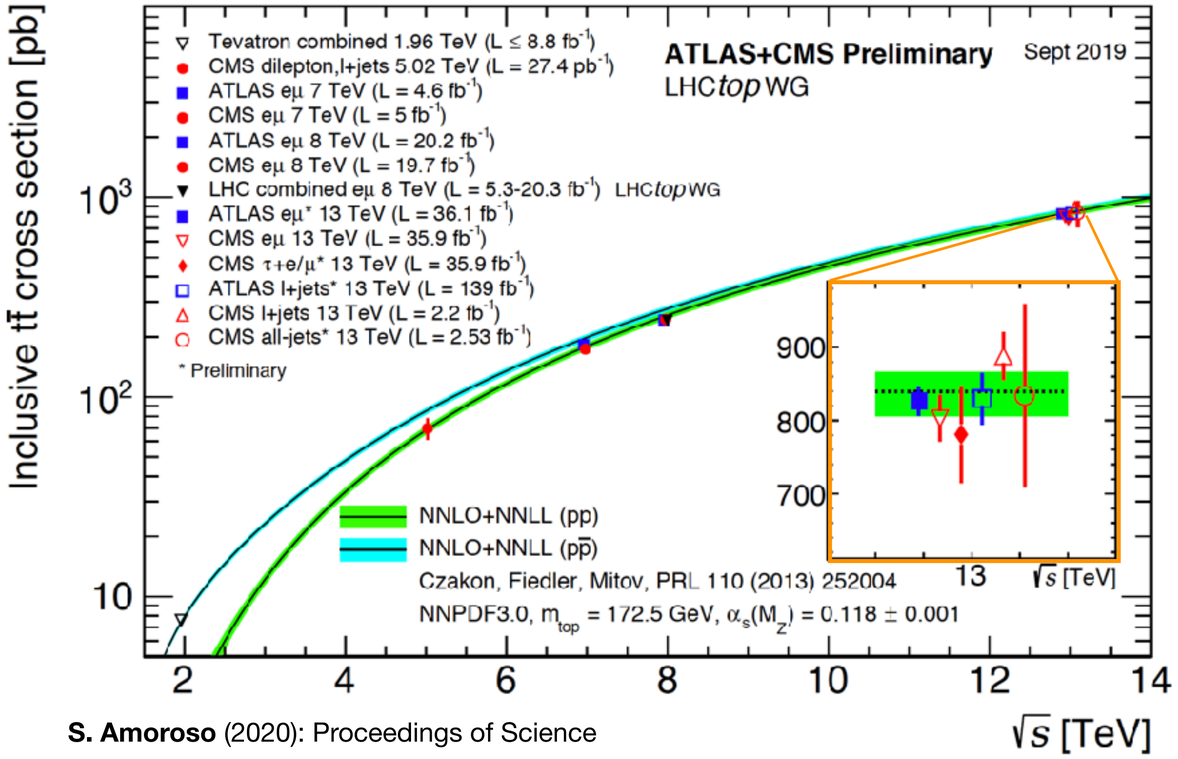
37th International Cosmic Ray Conference

Berlin, Germany (Virtual)

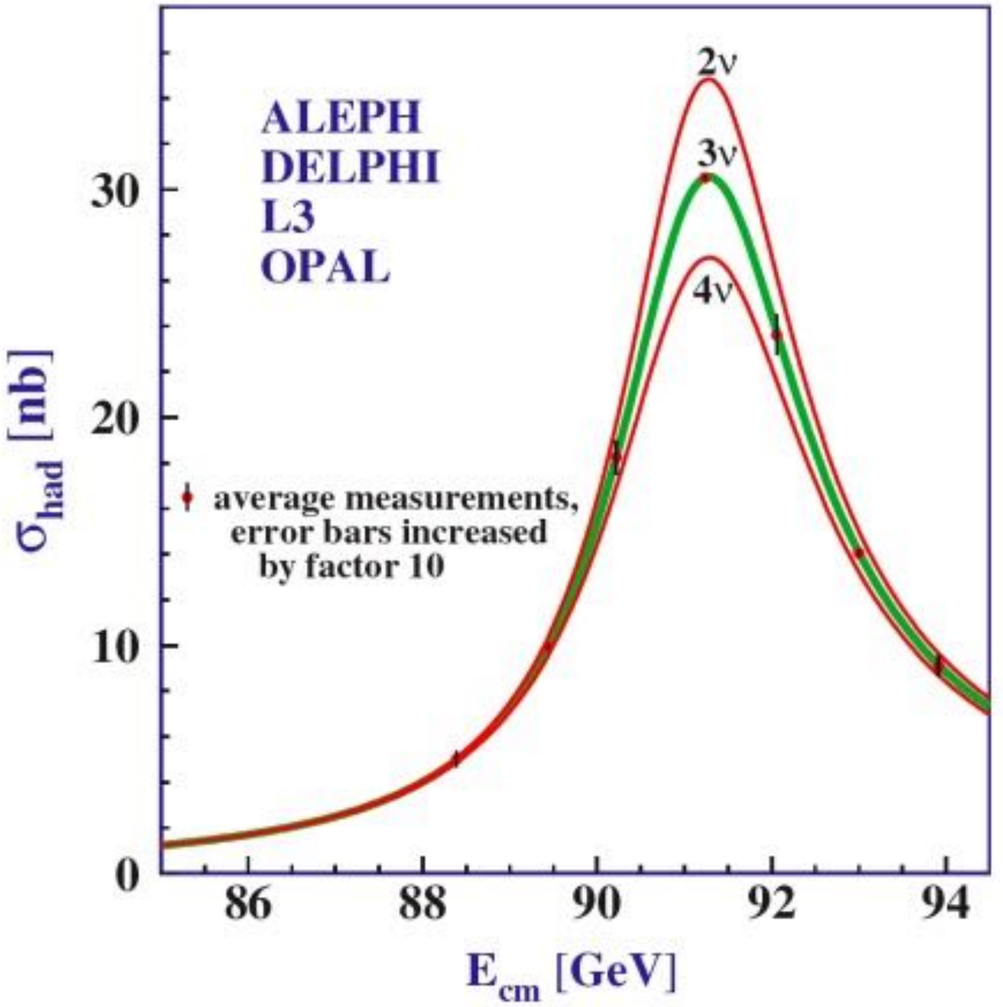
19 Jul., 2021

Triumphs of the Standard Model

The Standard Model (SM) has proved an incredibly precise, predictive theory



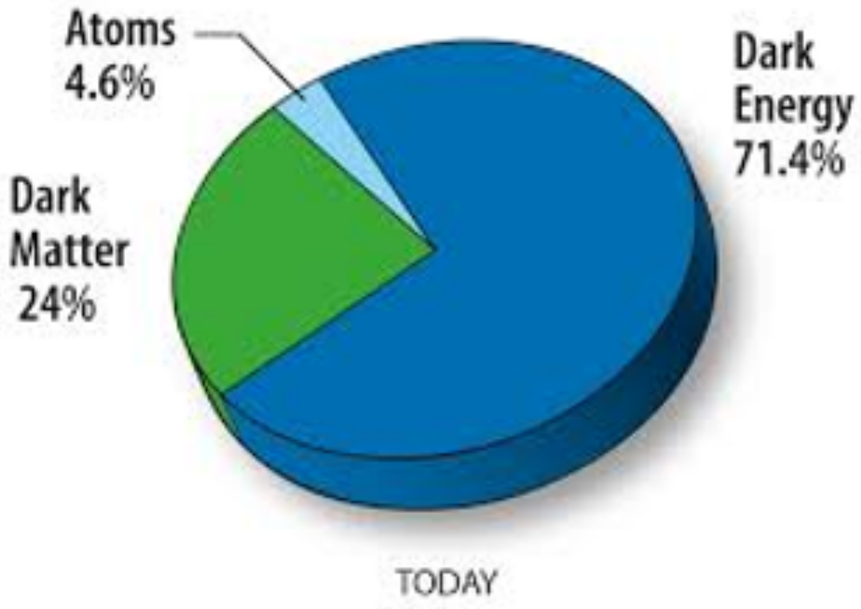
S. Amoroso (2020): Proceedings of Science



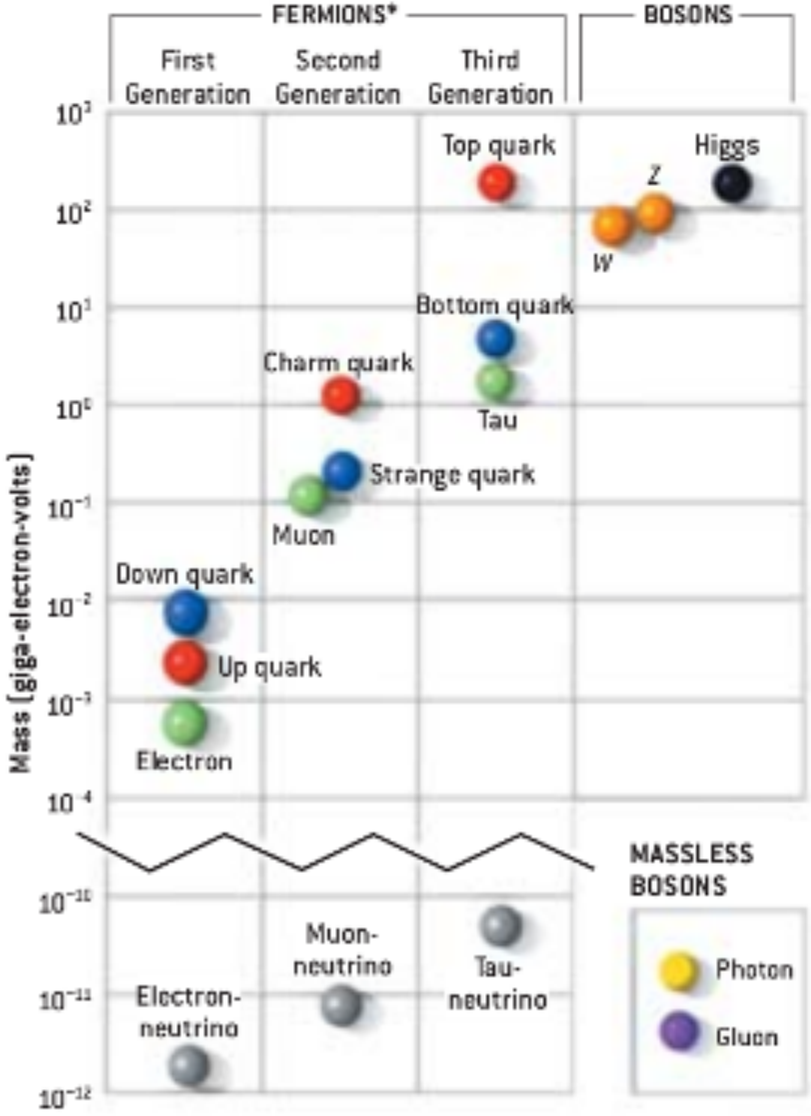
DELPHI (1989): Physical Letters B, **OPAL**: (1989): Physical Letters B
ALEPH: (1989): Physical Letters B, **L3**: (1990): Physical Letters B

But Something is Off

On large and small scales, something is amiss



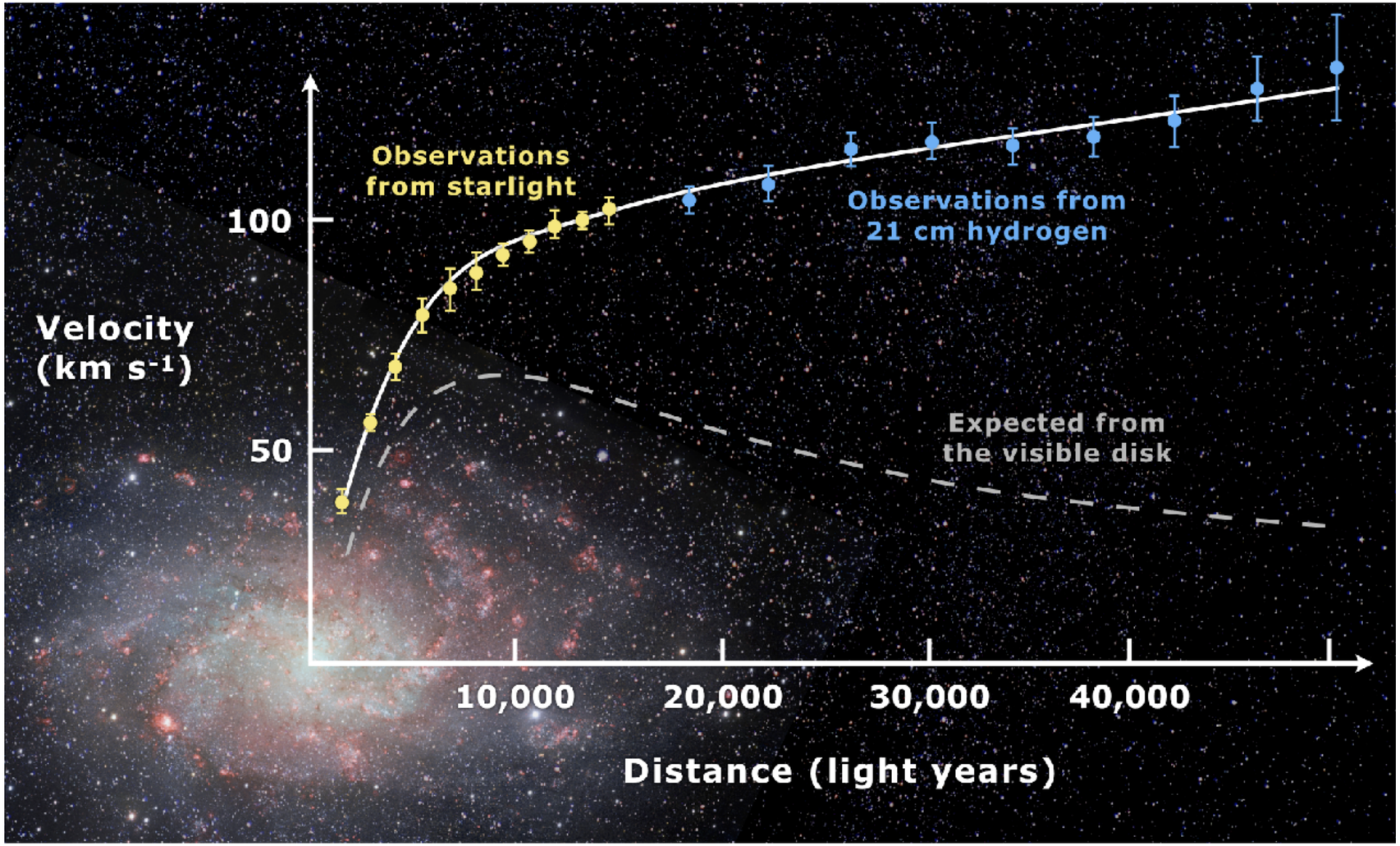
What is dark matter ?



How do neutrinos get mass ?

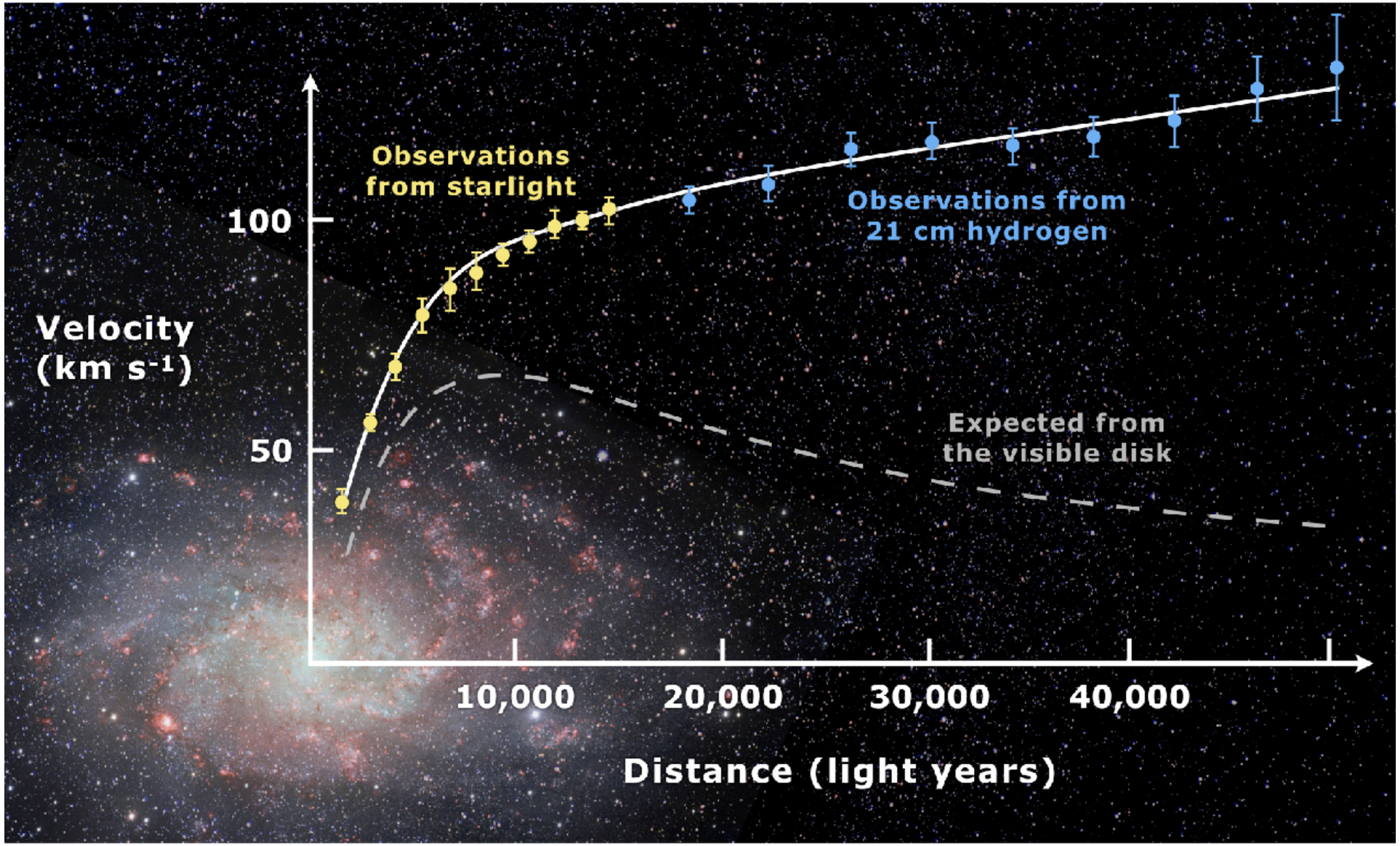
Why are they so small ?

Dark Matter: What do we Know



Dark Matter: What do we Know

- Evidence from numerous length scales



Dark Matter: Wha

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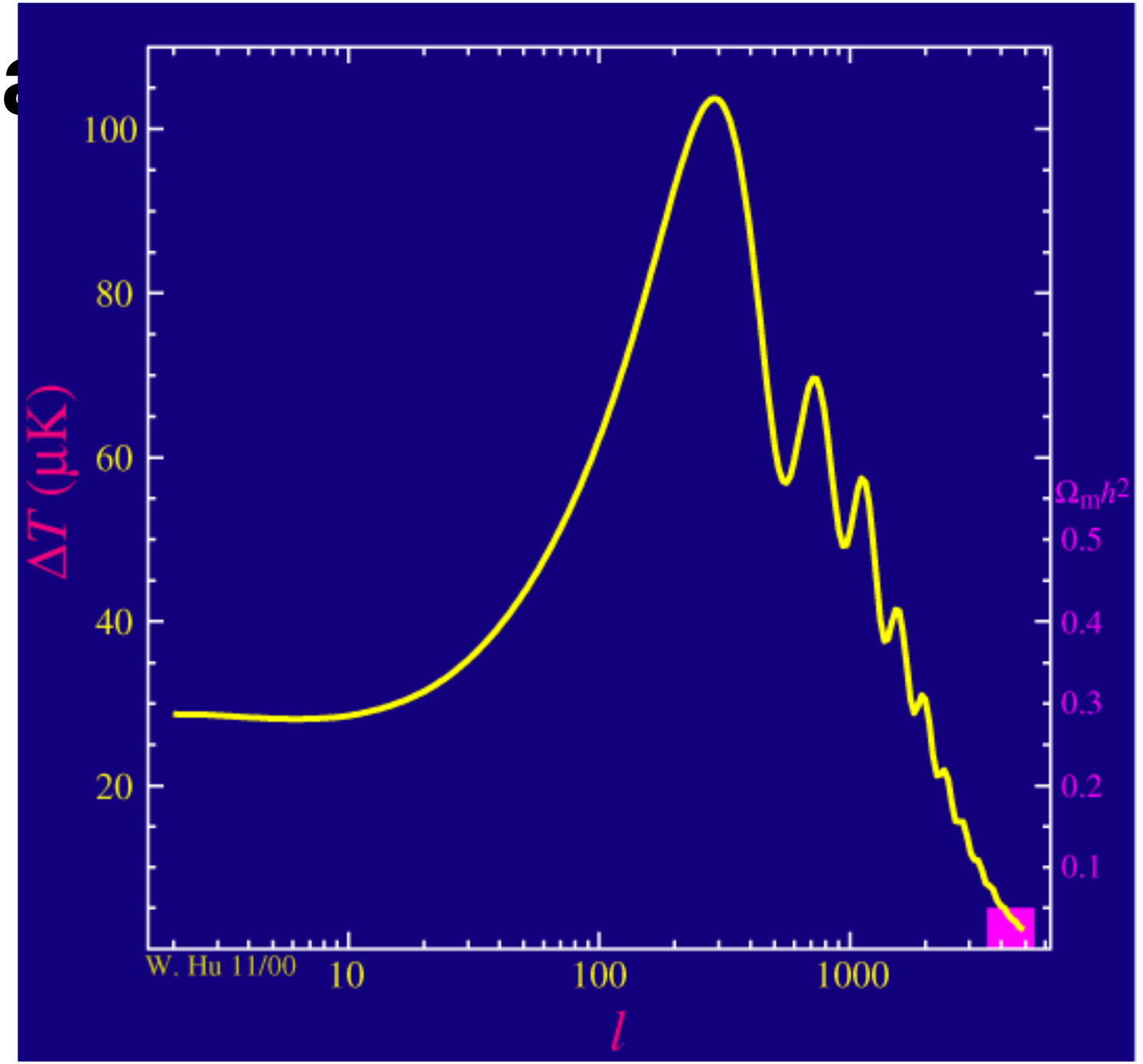
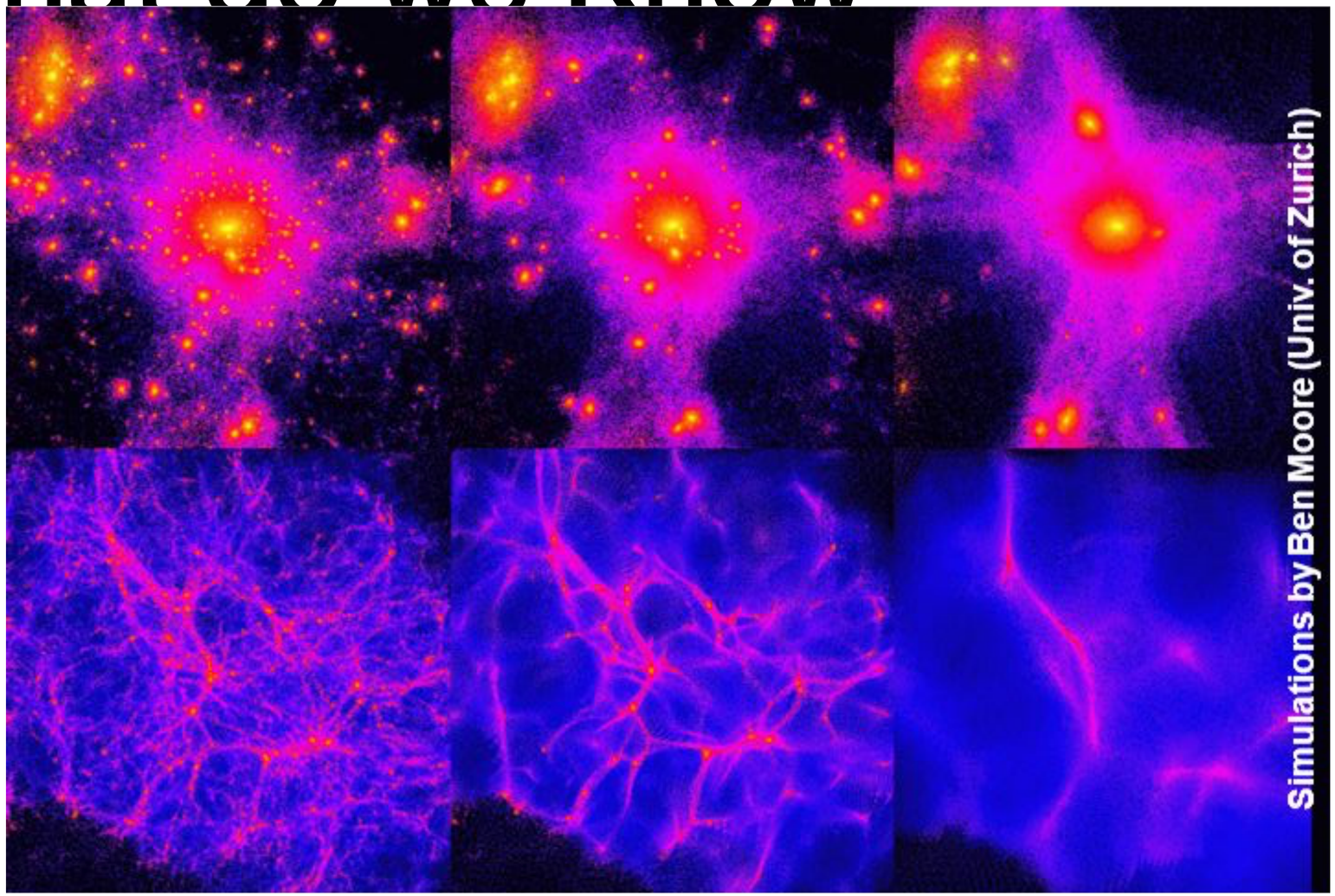


Gif courtesy of Wayne Hu

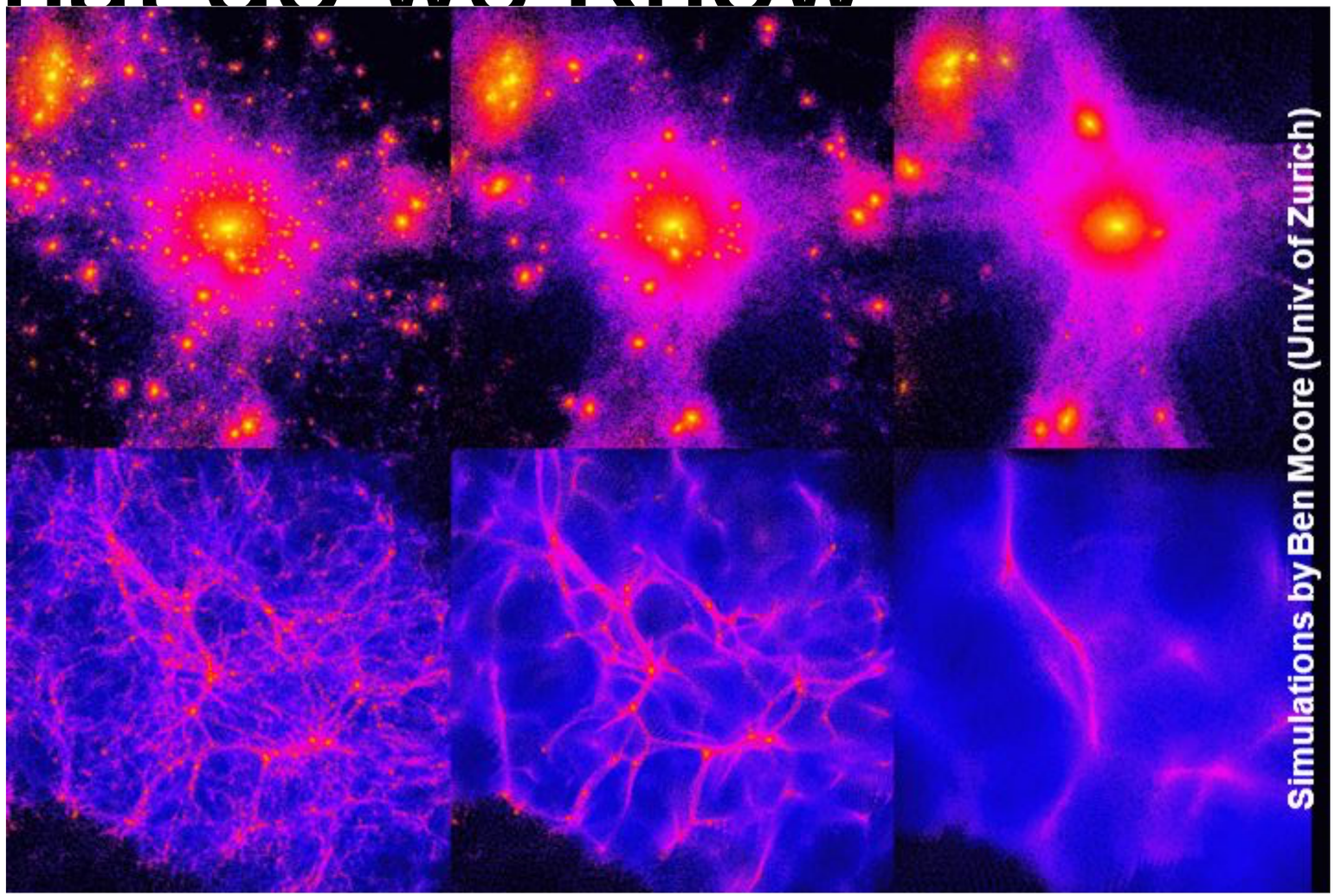
Dark Matter: What do we Know

- Evidence from numerous length scales
- Must be ‘cold,’ *i.e.* non-relativistic



Dark Matter: What do we Know

- Evidence from numerous length scales
- Must be ‘cold,’ *i.e.* non-relativistic
- Many candidates put forward but no evidence yet



Cold — Warm — Hot

Hints of Particle Dark Matter

- Observations hint that DM may be corpuscular in nature
- Bullet cluster suggests two populations of matter: one more strongly interacting than the other
- Blue is where matter is from lensing data, red from X-ray

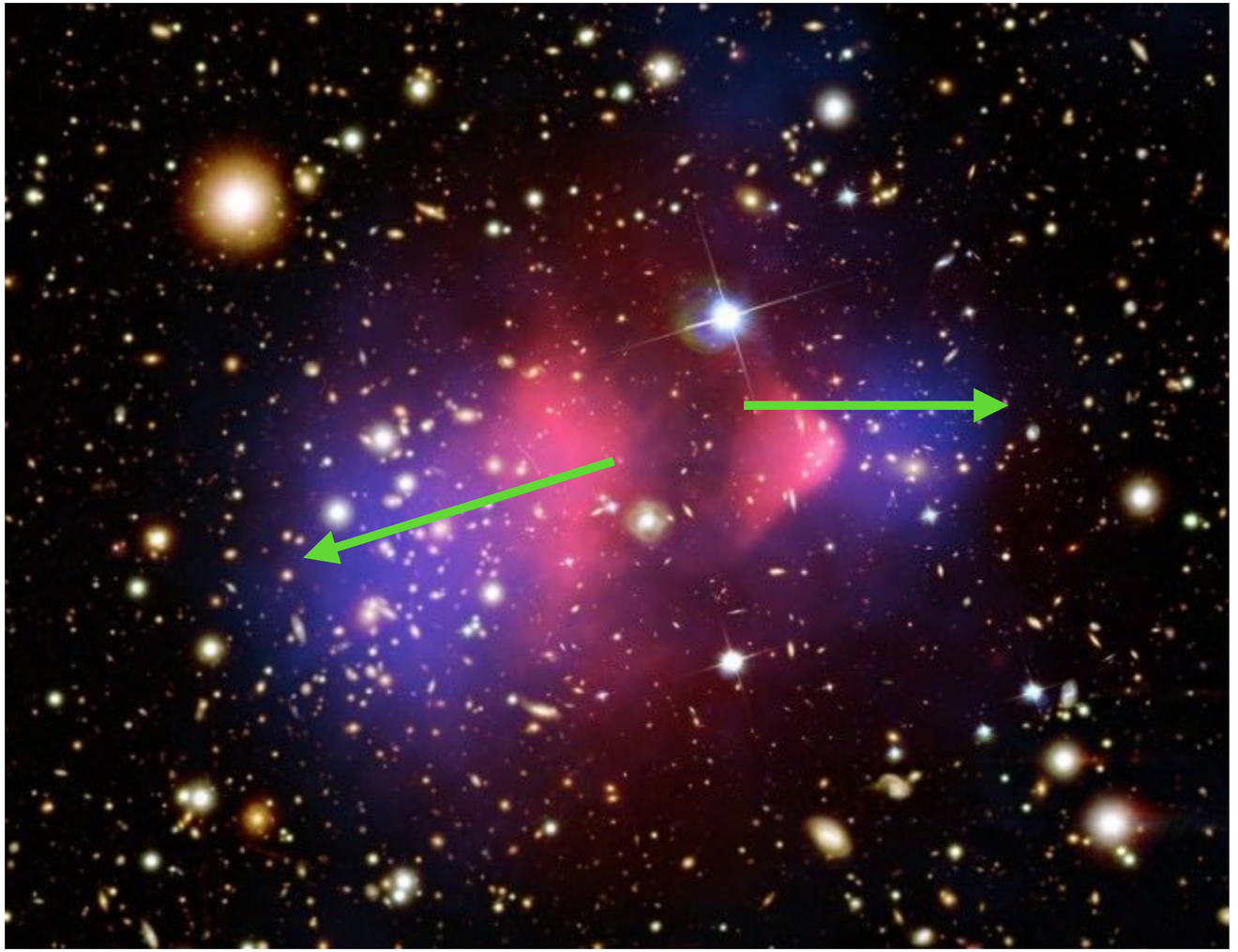
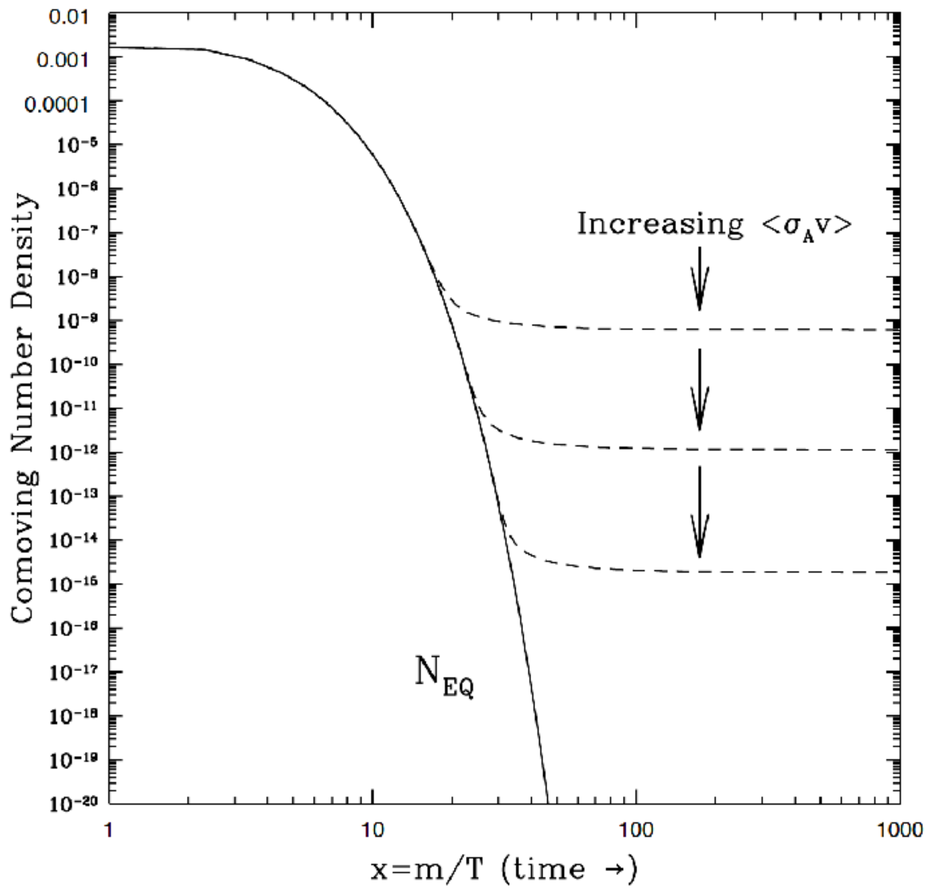


Image credit: X-ray: M.Markevitch et al.; Lensing Map/Optical: Magellan/U.Arizona/D.Clowe et al.

Theoretically Motivated Dark Matter

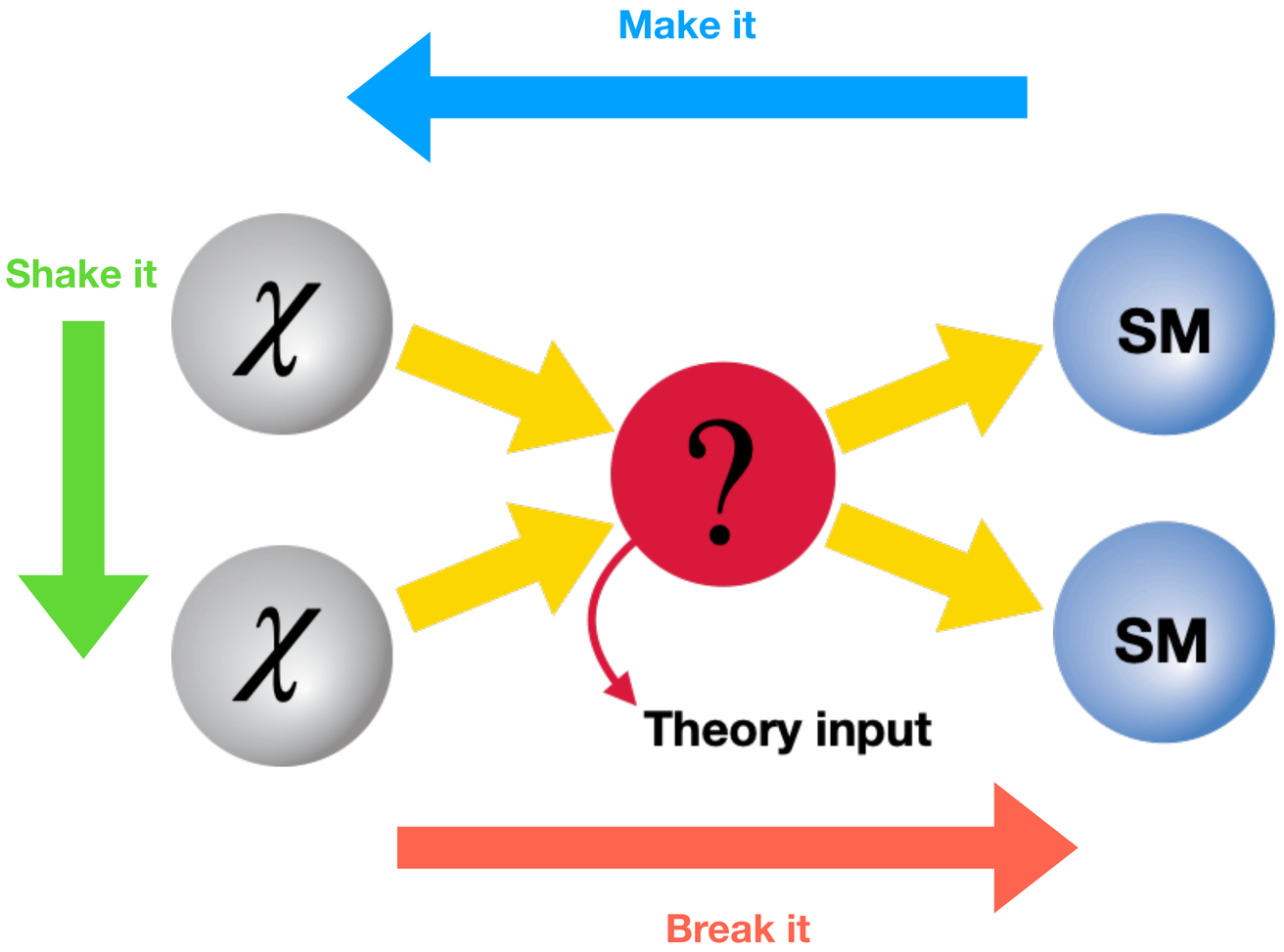
- Particle DM arises naturally in many theoretical frameworks meant to address other issues
- TeV-scale DM with weak-scale interactions produces the right relic abundance: WIMP miracle
- WIMPs occur in many models including scotogenic neutrino mass models and supersymmetric SM extensions



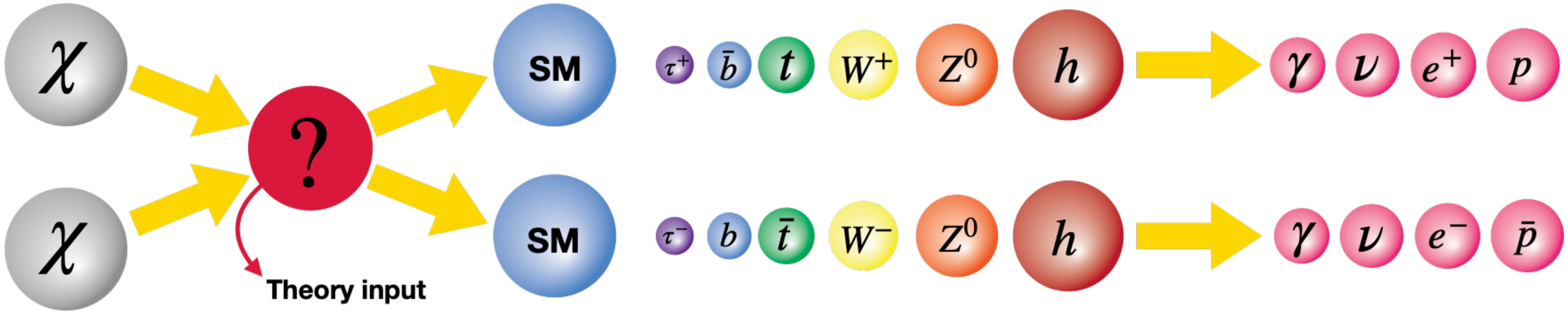
G. Jungman, M. Kamionkowski, and K. Griest: Physics Reports (1995)

Gateways to WIMP Detection

- Detection strategies fall into three brand classes
  - Production at colliders
  - Direct detection via calorimetry
  - Indirect detection of SM byproducts
- ‘Make it, shake it, break it’



WIMPs' Astrophysical Signatures



- Look for stable SM byproducts of WIMP annihilation or decay
- Neutrinos can escape dense astrophysical environments
- Look towards places where WIMPs are expected to accumulate

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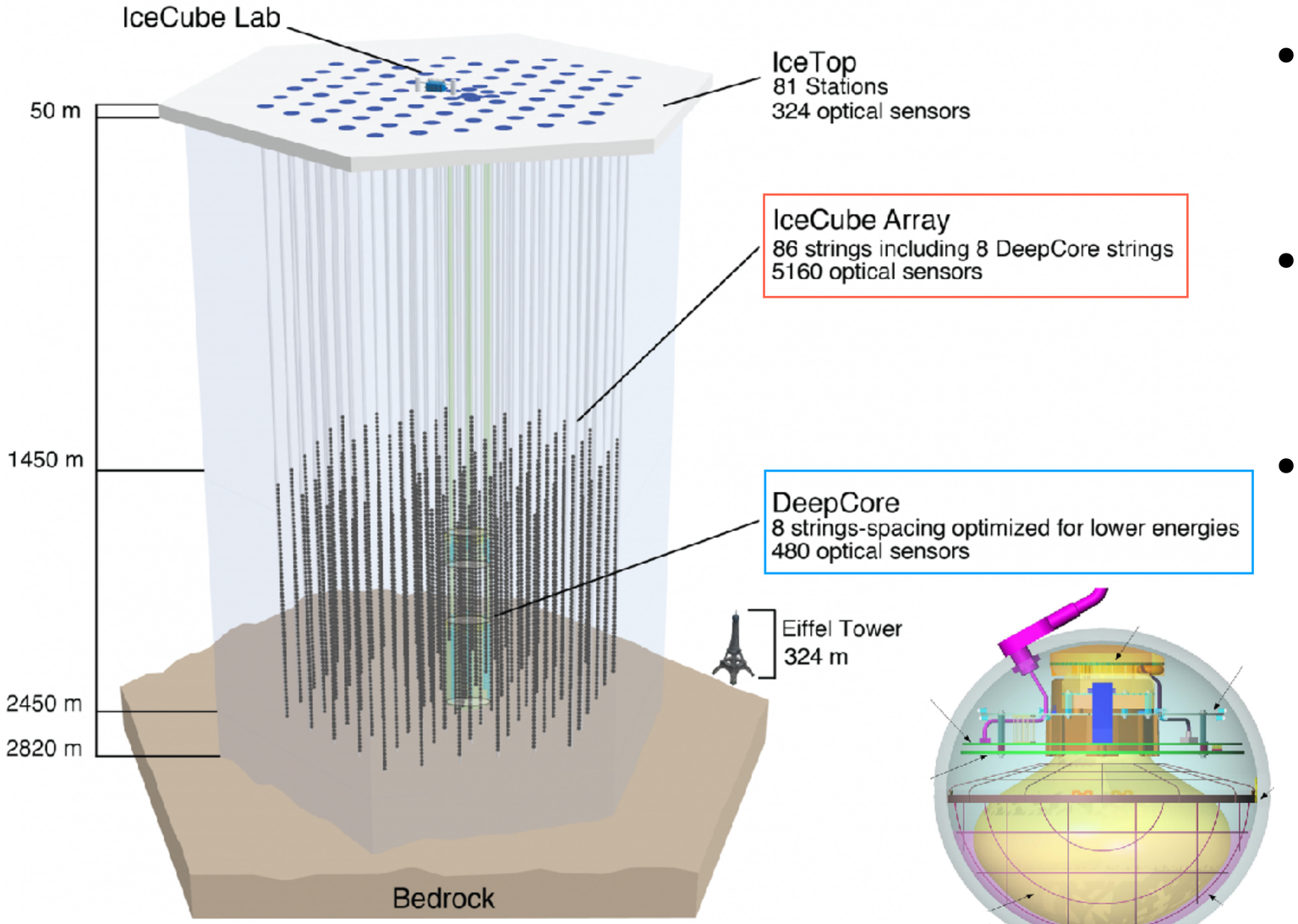
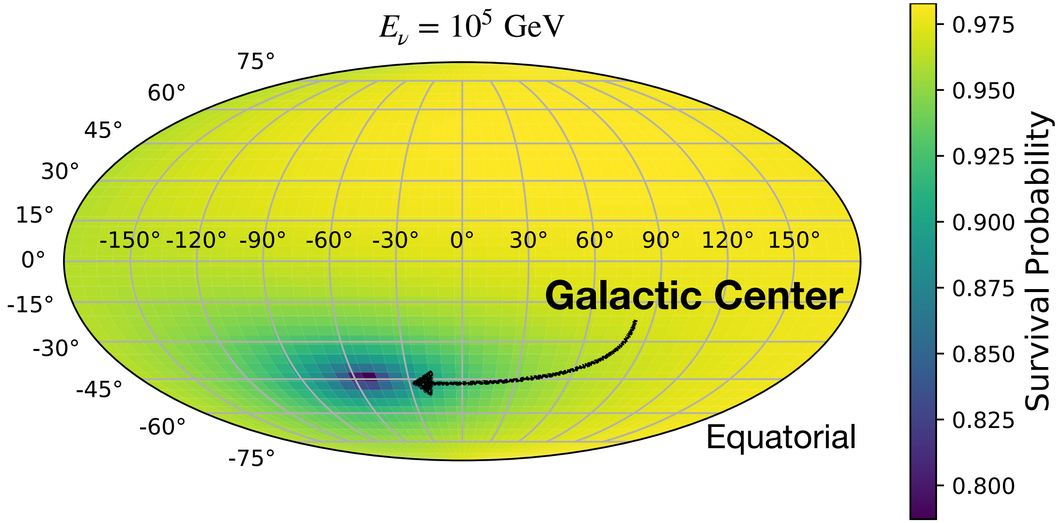
The IceCube Neutrino Observatory

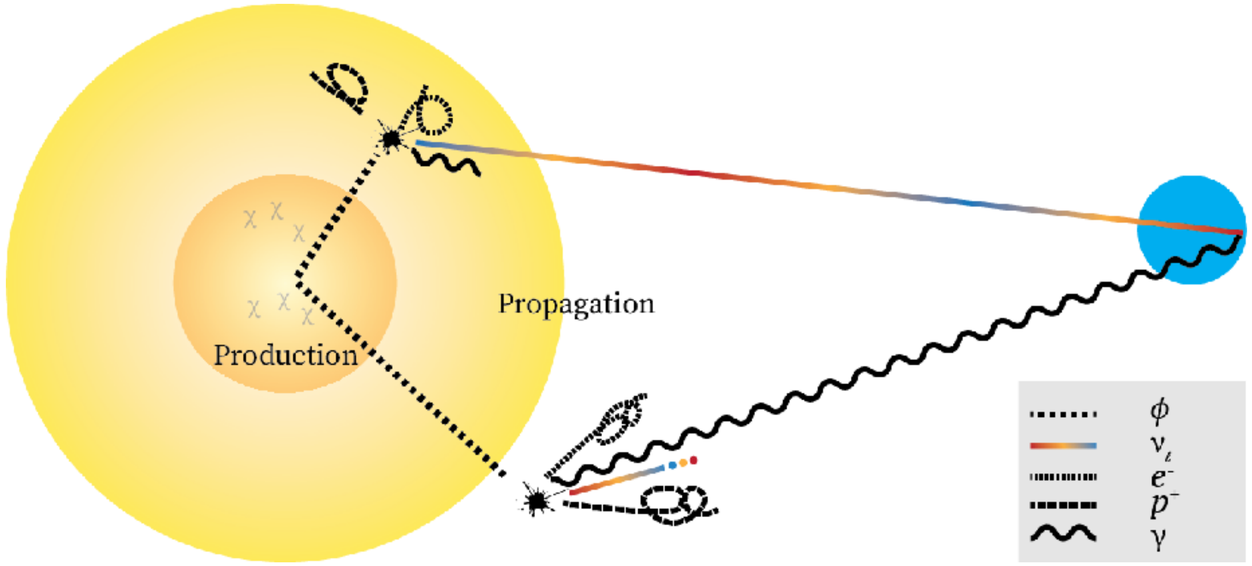


- Gigaton-scale neutrino observatory beneath the ice at the geographic South Pole
- IceCube and DeepCore sensitive to high- and low-energy neutrinos
- See highlight talk by M. Kowalski for more information about the detector and proposed future extensions (938)

IceCube Dark Matter Searches

- Multi-pronged strategy in the hunt for DM
  - WIMP scenarios (this talk)
  - Secluded dark matter
  - Dark matter-neutrino interactions
  - Non-relativistic, effective field theories





$$O_1 = \mathbb{1}_{\chi N} \qquad O_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\mathbb{1}_{\mathbb{N}}$$

$$O_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)\mathbb{1}_\chi \qquad O_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$

$$O_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N \qquad O_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$O_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)\mathbb{1}_{\mathbb{N}} \qquad O_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$

$$O_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right) \qquad O_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$

$$O_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_\chi \qquad O_{17} = i\frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_{\mathbb{N}}$$

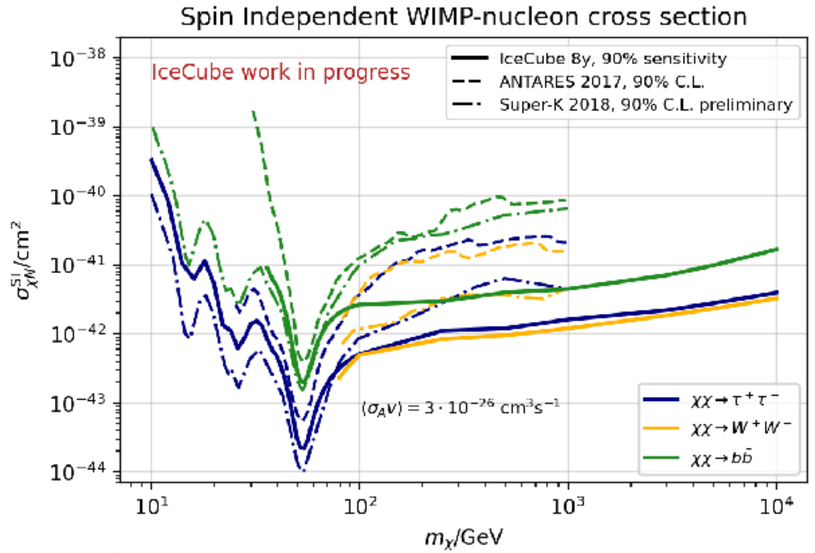
$$O_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_{\mathbb{N}} \qquad O_{18} = i\frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \hat{\mathbf{S}}_N$$

$$O_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right) \qquad O_{19} = \frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

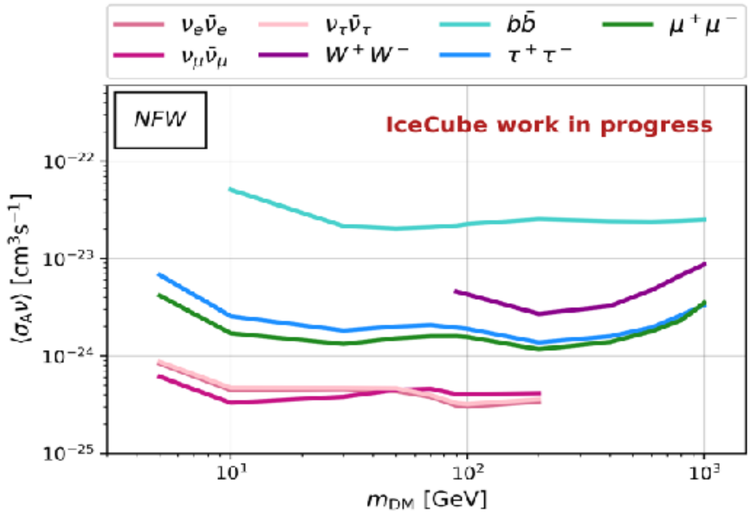
$$O_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\mathbb{1}_\chi \qquad O_{20} = \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right) \cdot \mathcal{S} \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

IceCube Dark Matter at ICRC

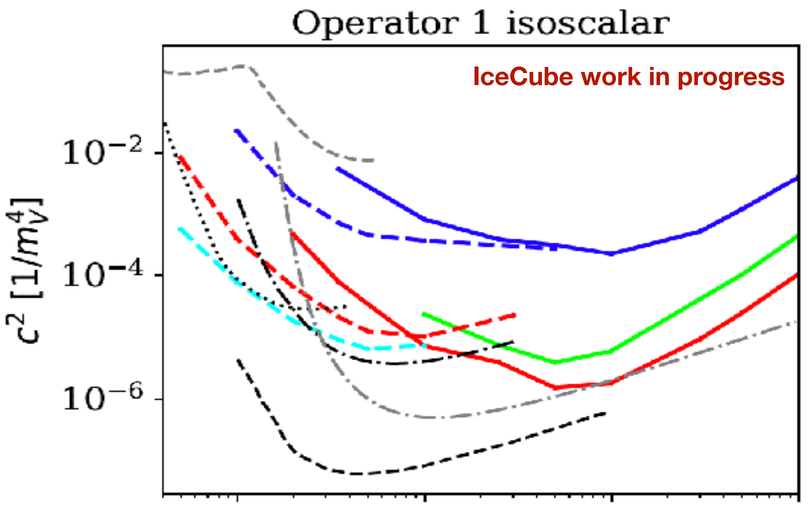
G. Renzi: 639



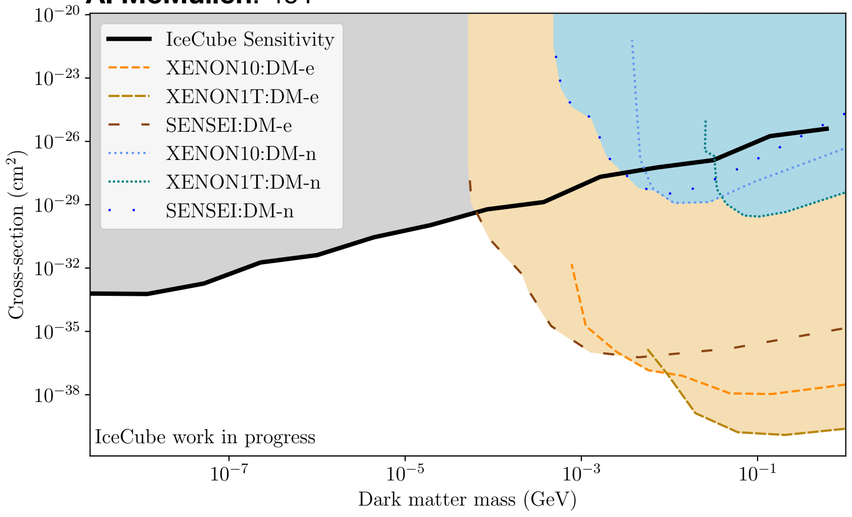
N. Iovine: 619



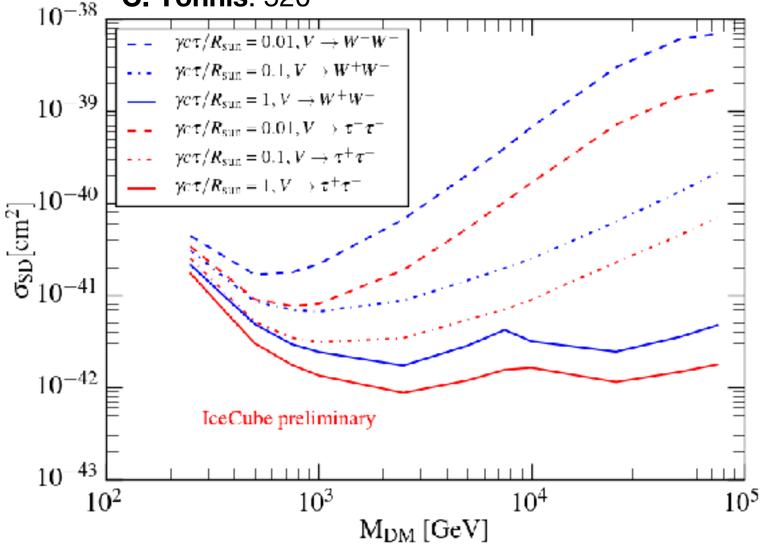
L. Peters: 522



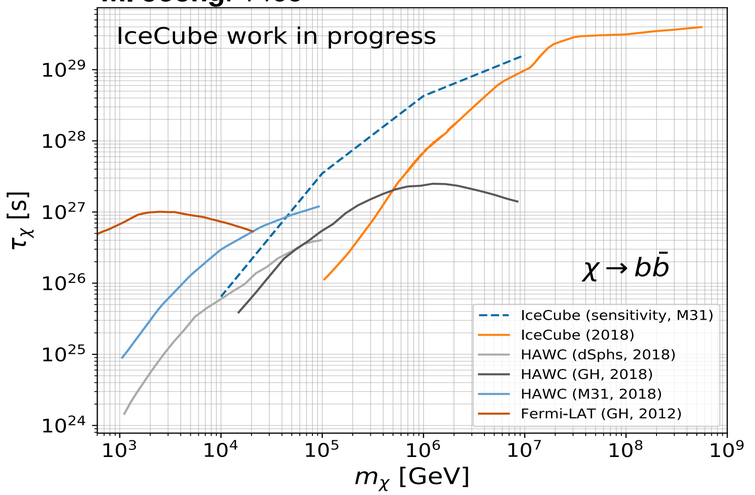
A. McMullen: 491



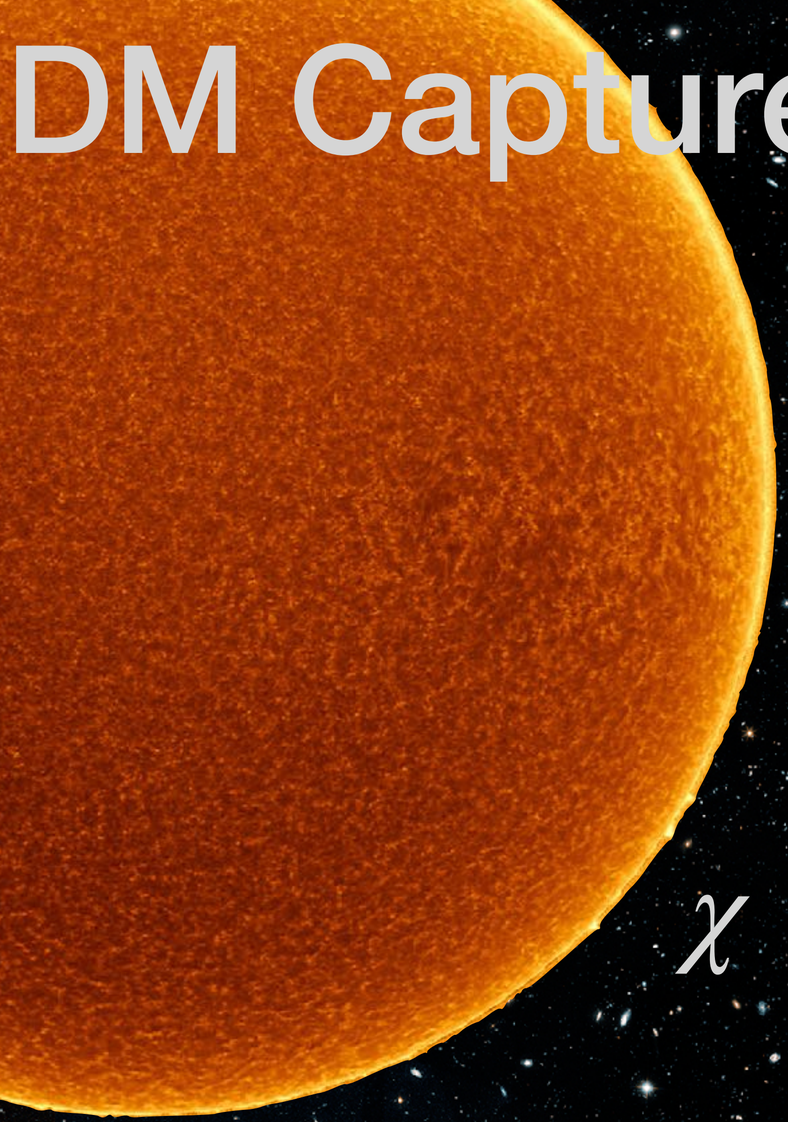
C. Tönnis: 520



M. Jeong: 1405



DM Capture and Indirect Detection



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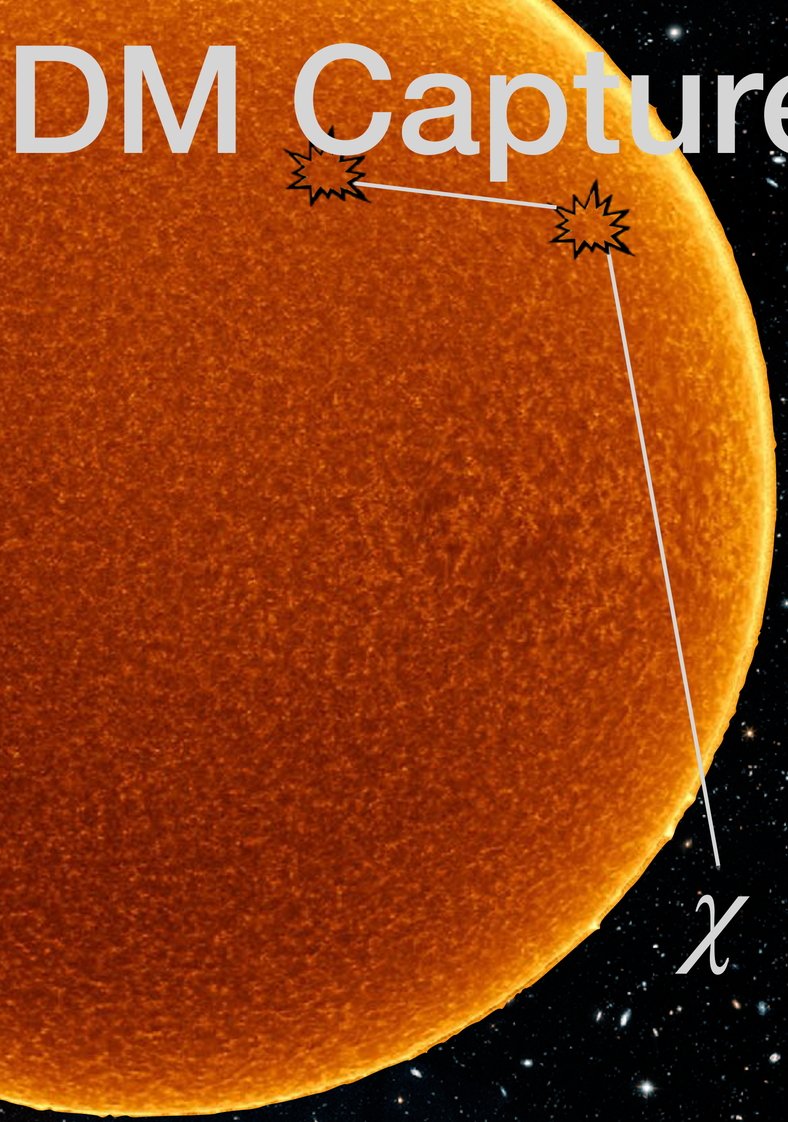

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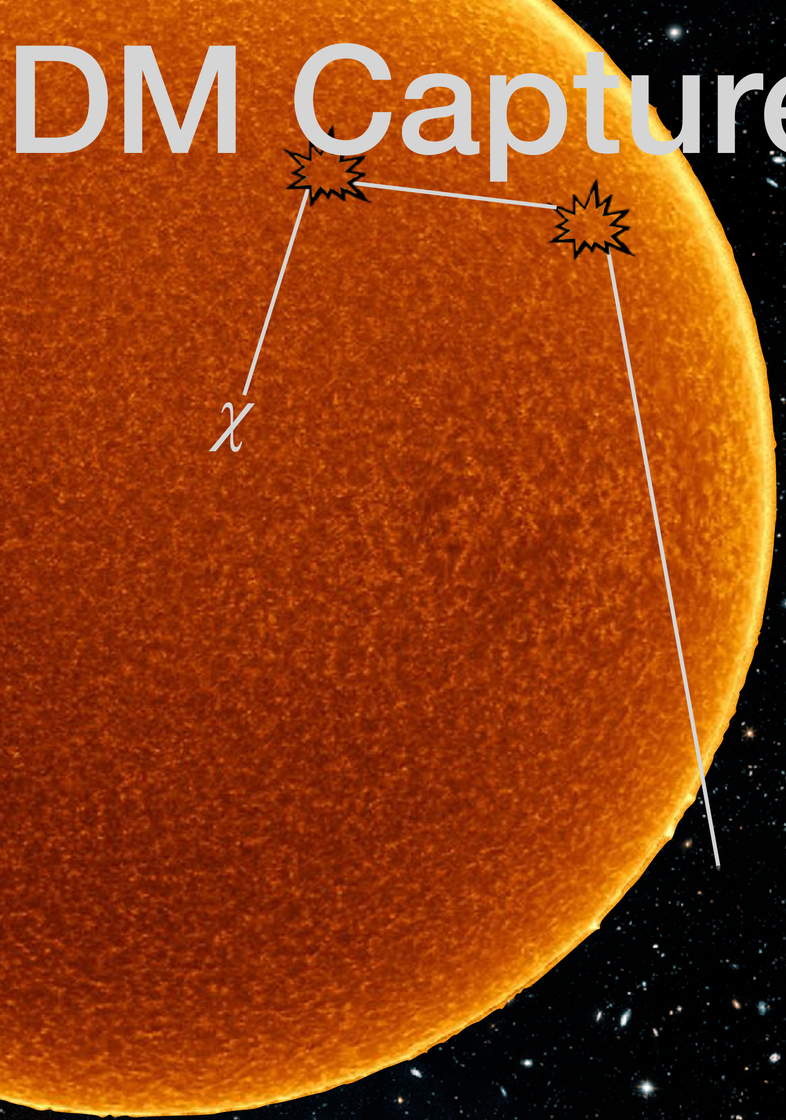

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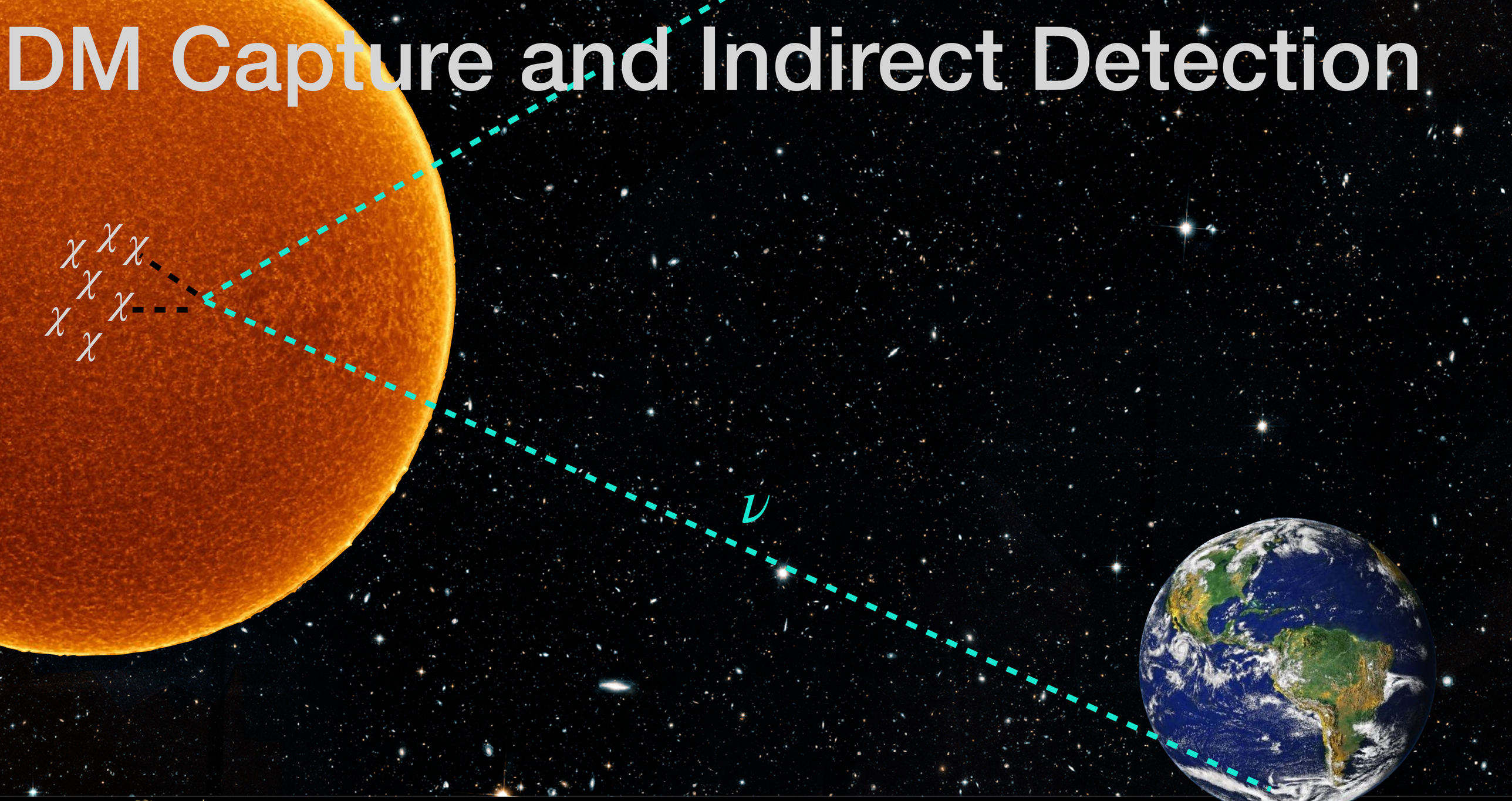
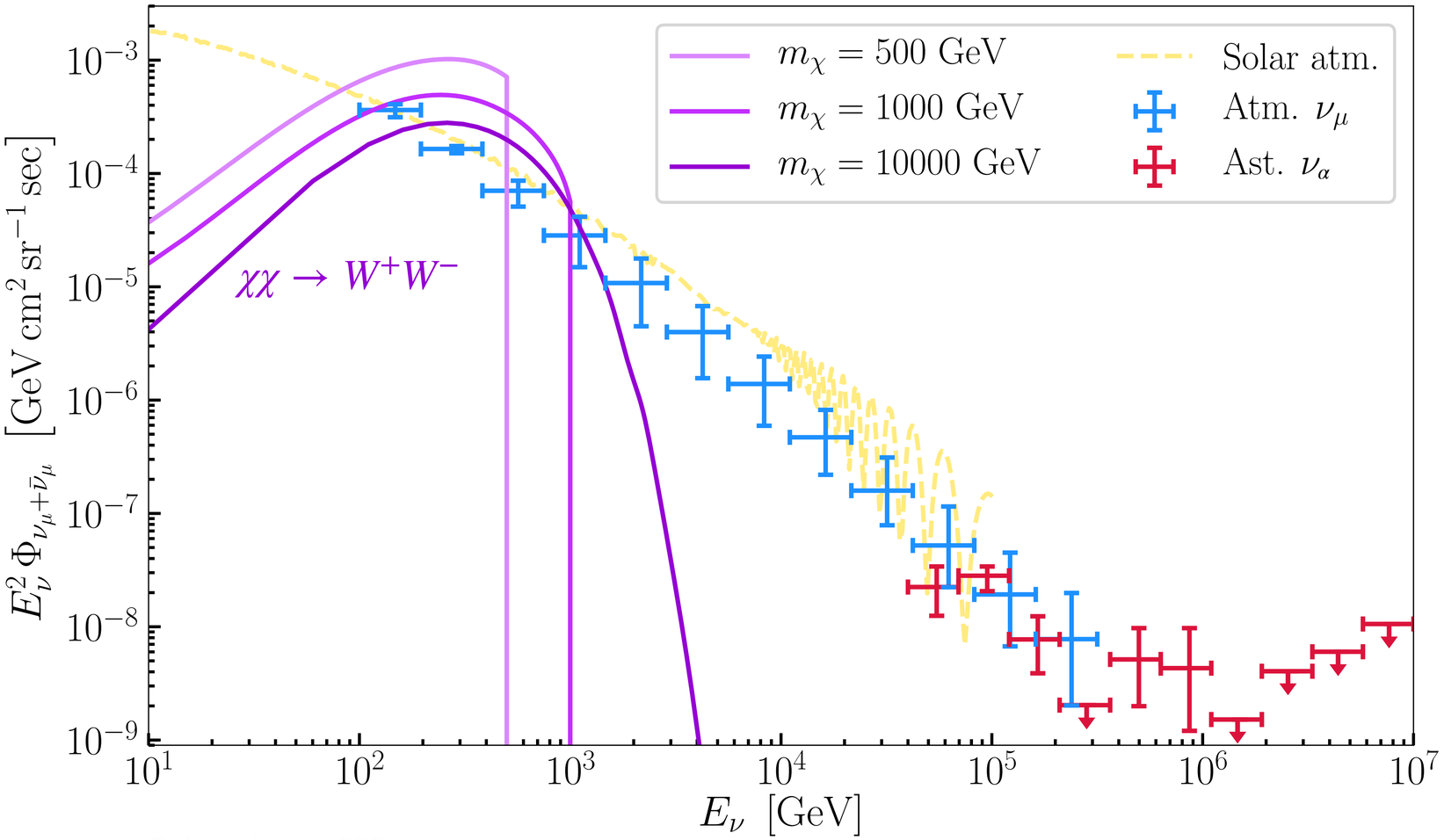


Backgrounds to this Analysis



R. Abbasi, *et al.*: PRD (2020)
T. Kajita: Adv. High Energy Phys. (2012)

- Backgrounds well-understood in direction of Sun
- Sun opaque to neutrinos above $E_\nu = 3$ TeV.
- Relevant backgrounds:
  - Atmospheric neutrinos
  - Atmospheric muons
  - Solar atmospheric neutrinos

WIMP Capture in the Sun

$$\dot{N} = C_C - C_A N^2 - C_E N$$

Capture rate: Proportional to $\sigma_{\chi N}$

Annihilation rate: Sets rate of WIMP conversion to neutrinos

Evaporation rate: Negligible for WIMP masses above a few GeV

- Solar WIMP ensemble in equilibrium
- Evaporation rate negligible above a few GeV
- Annihilation rate and capture rate in equilibrium
  →Annihilation rate proportional to $\sigma_{N\chi}$

G. Jungman, M. Kamionkowski, and K. Griest: Physics Reports (1995)

WIMP Capture in the Sun

$$\dot{N} = C_C - C_A N^2 - C_E N$$

($\dot{N} = 0$; $C_E N = 0$)

Capture rate: Proportional to $\sigma_{\chi N}$

Annihilation rate: Sets rate of WIMP conversion to neutrinos

Evaporation rate: Negligible for WIMP masses above a few GeV

$$\implies \frac{\Gamma_A}{2} = C_C \propto \sigma_{\chi N}$$

- Solar WIMP ensemble in equilibrium
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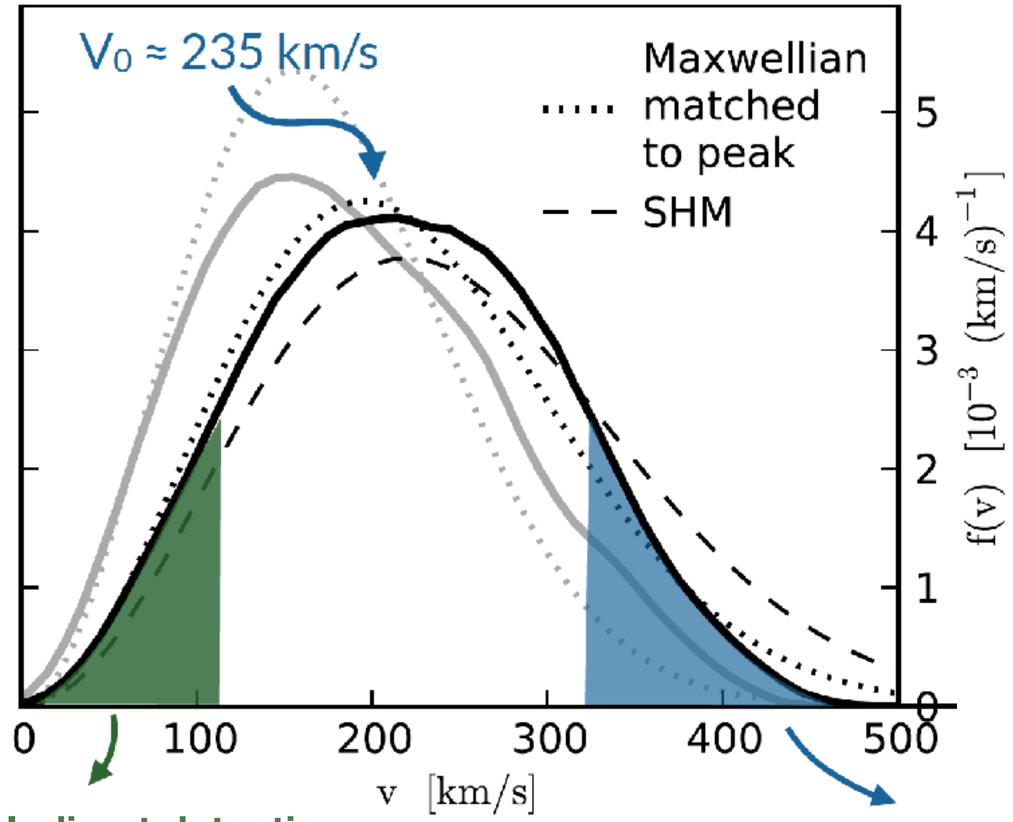
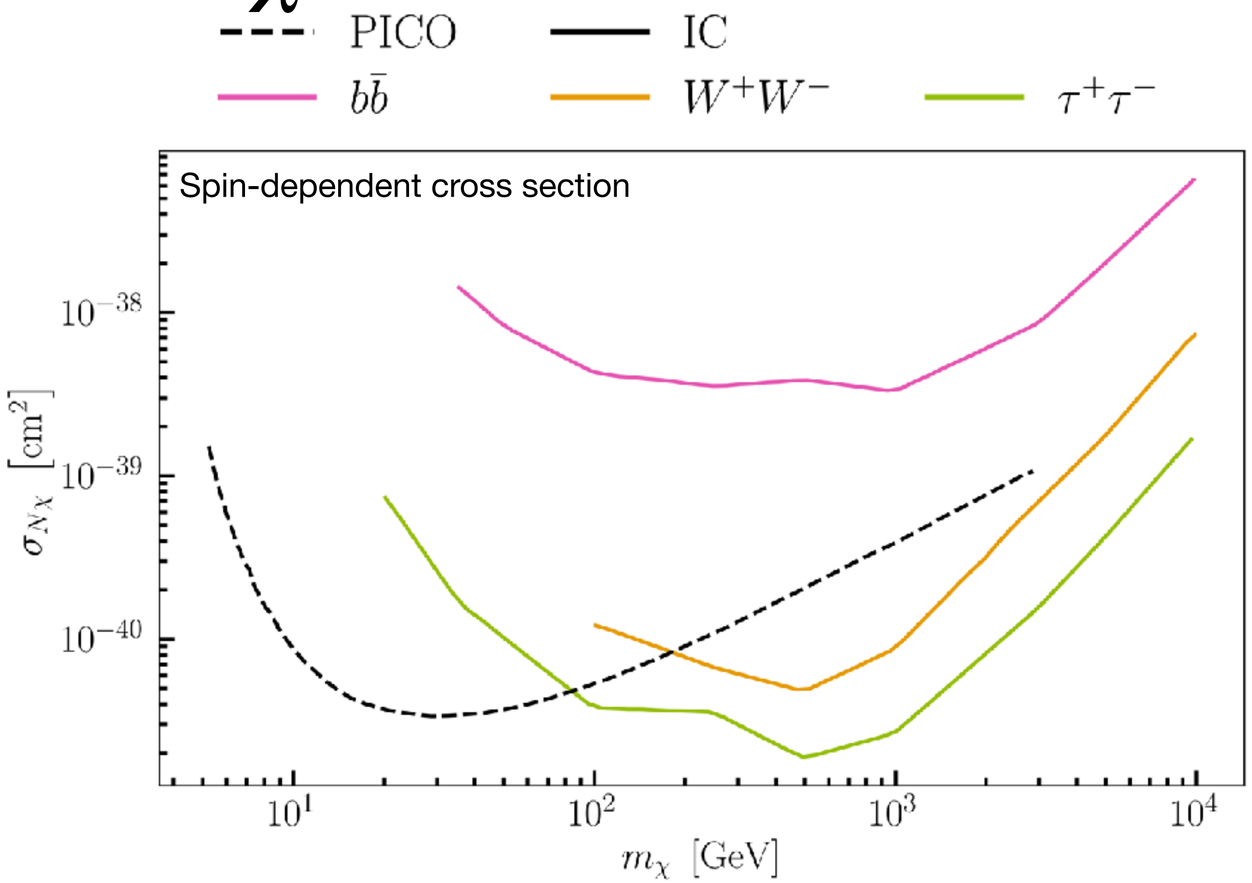
Two Ways to Probe $\sigma_{N\chi}$



Indirect detection

Direct detection

A. Pillepich, M. Kuhlen, J. Guedes, P. Madau: ApJ (2014)

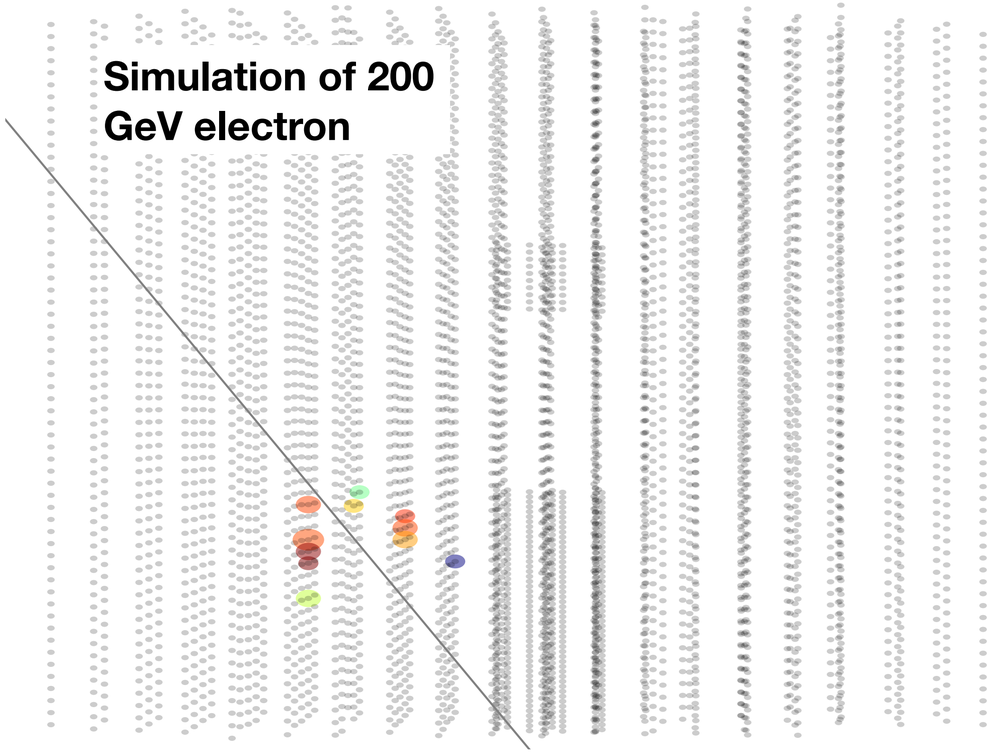


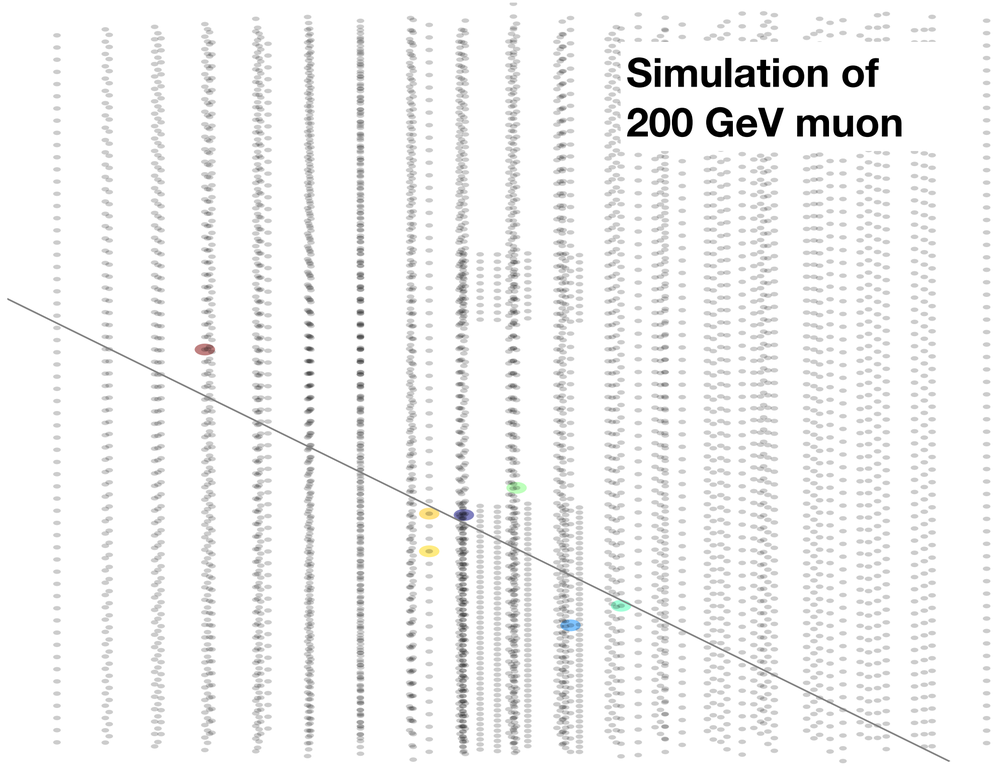
<u>Current limits</u> on WIMP-nucleon cross section from IceCube and PICO

M. G. Aarsten, *et al.*: EPJC (2016)
C. Amole, *et al.*: PRD (2019)

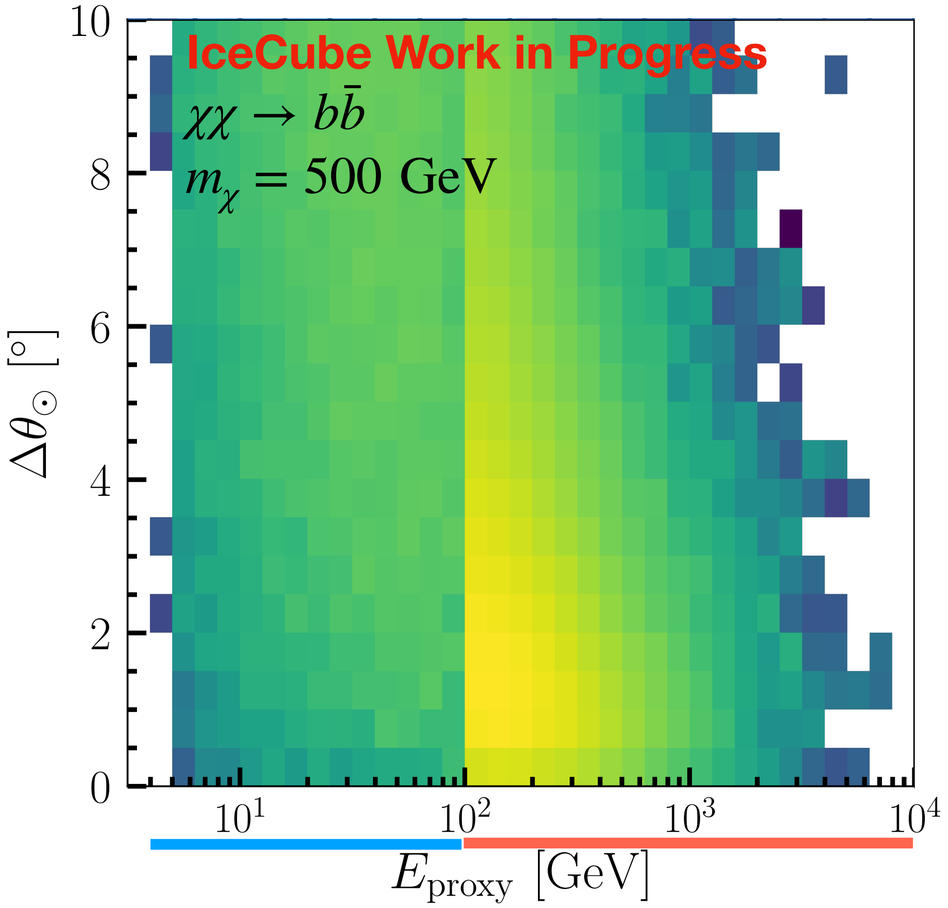
All-Energy, All-Flavor

- IceCube + DeepCore to cover WIMP mass range from 10 GeV to 10 TeV
- Directional reconstruction challenging at lower-energies
- Cascade channel signal-backgrounds 10x better→ Include all flavors in analysis





Analysis Event Distributions



- Combine low- and high-energy selections
- Expected event distribution for an example DM hypothesis
- HE events clustered towards the Sun
- LE events more spread due to worse angular resolution

Signal event distribution in reconstructed quantities. Expected number of events in low- and high-energy selections for $\chi\chi \to b\bar{b}$, $m_\chi = 500$ GeV

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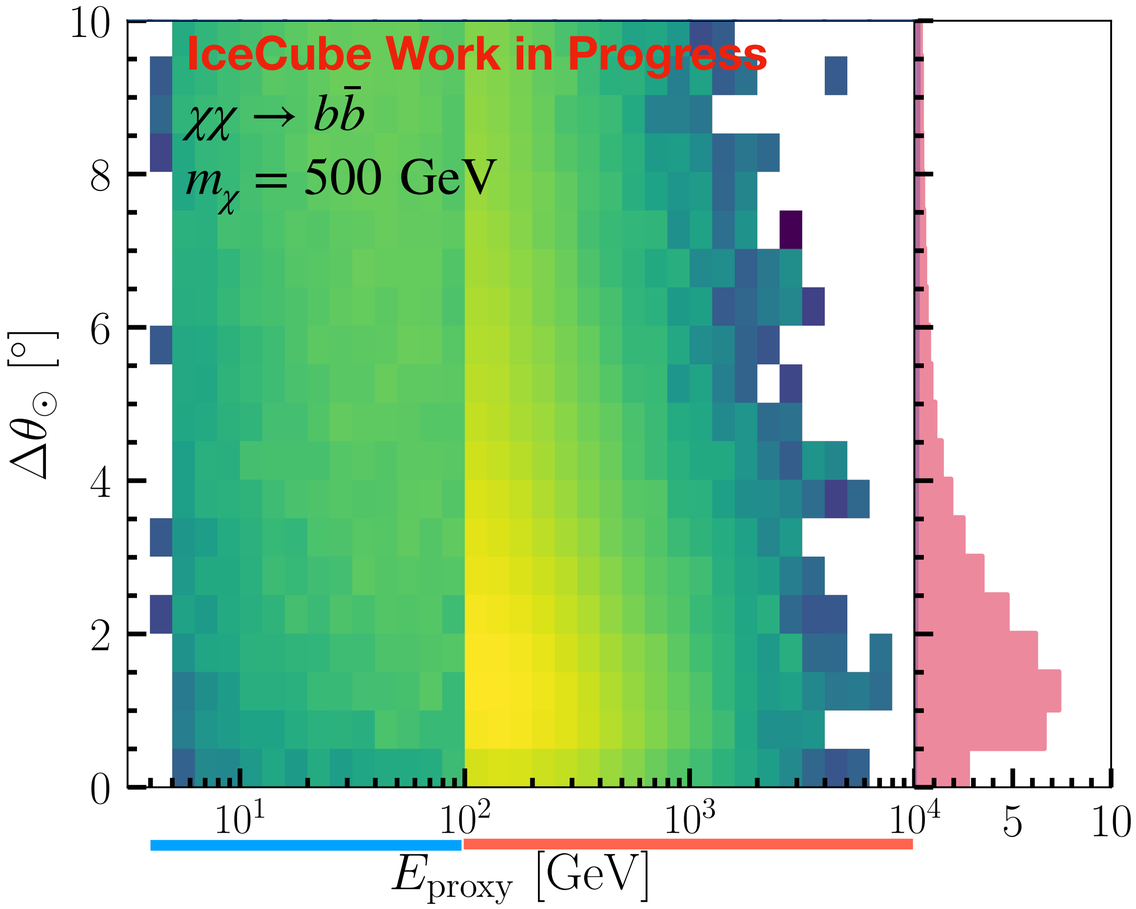

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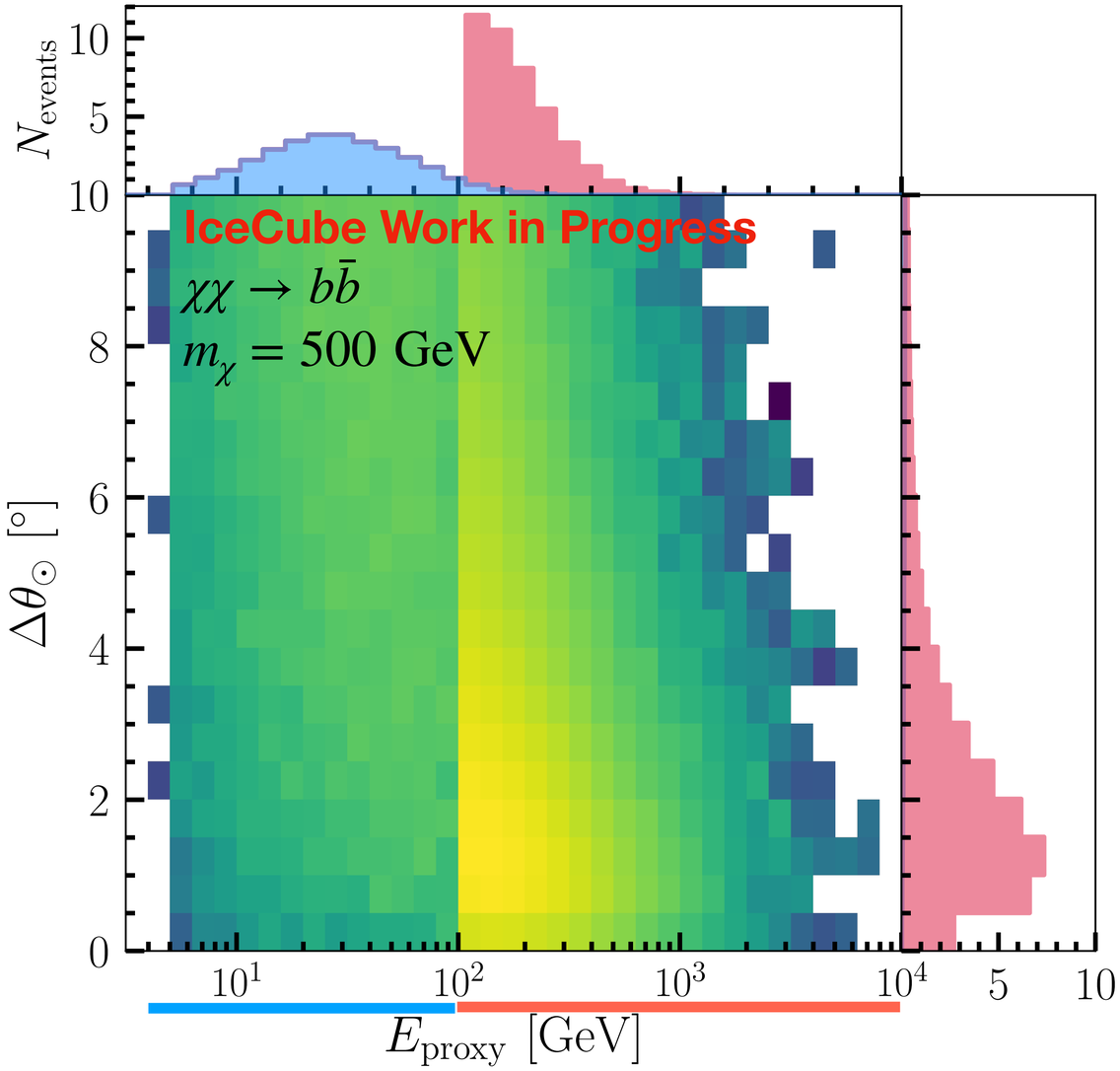

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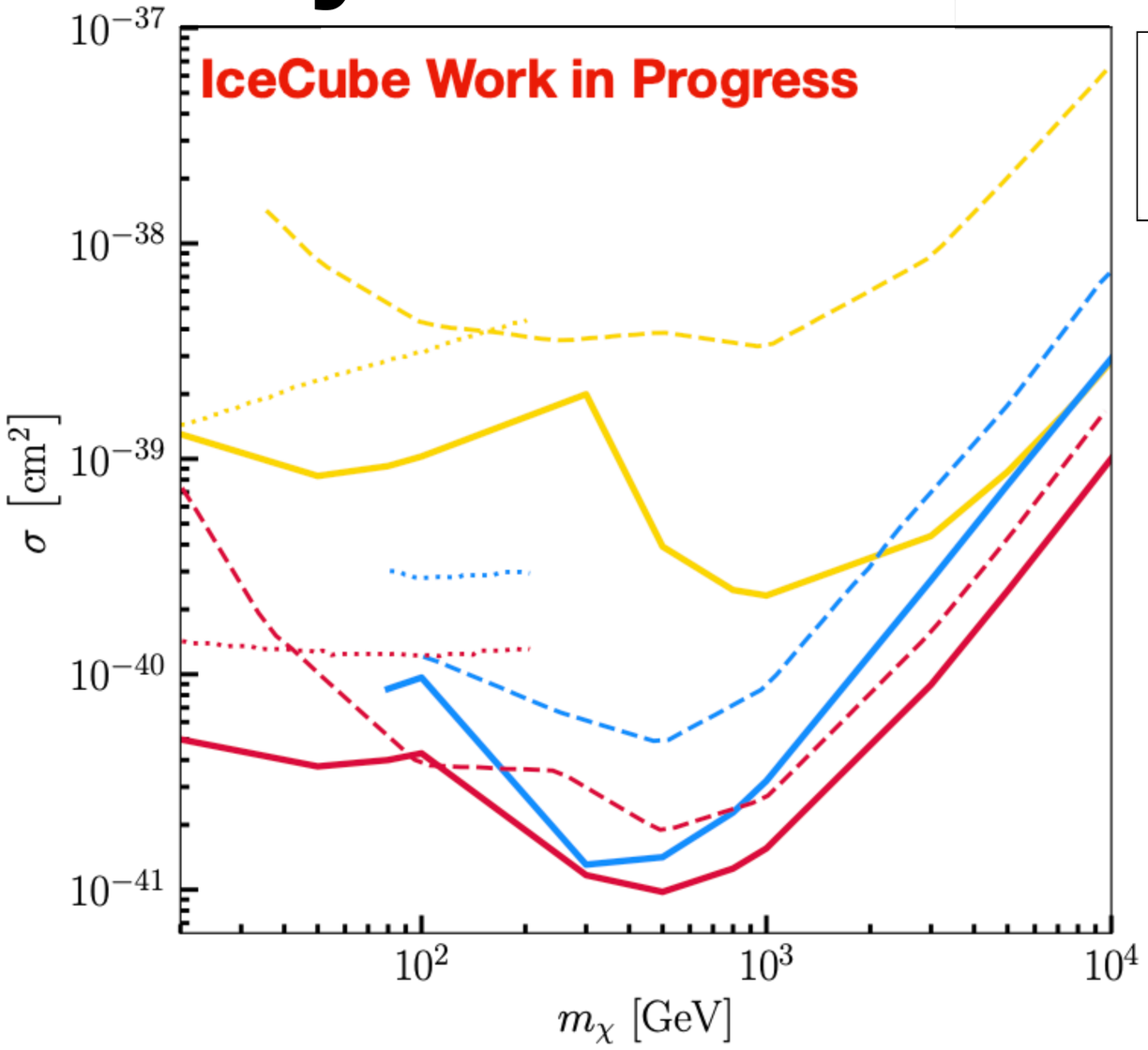
Analysis Sensitivities



- Current sensitivities with low- and high-energy selections compared to current limits
- World-leading sensitivities over range from 10 GeV to 10 TeV:

  <u>factor of 40 improvement in $b\bar{b}$</u>
- Large improvement in high-mass hadronic channels due to new EW calculation

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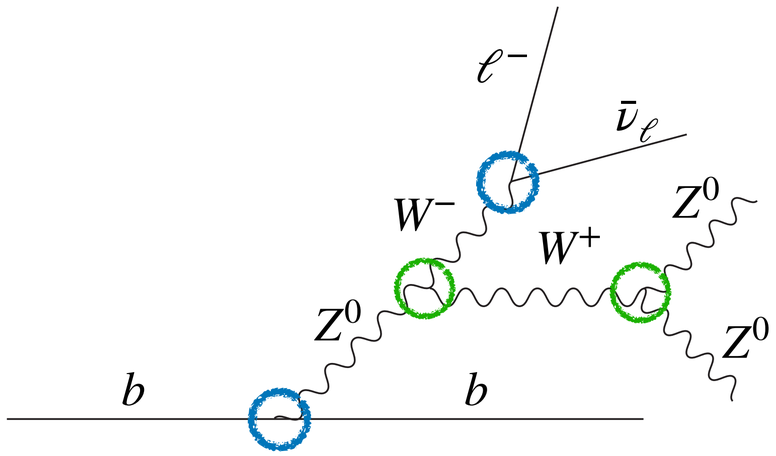
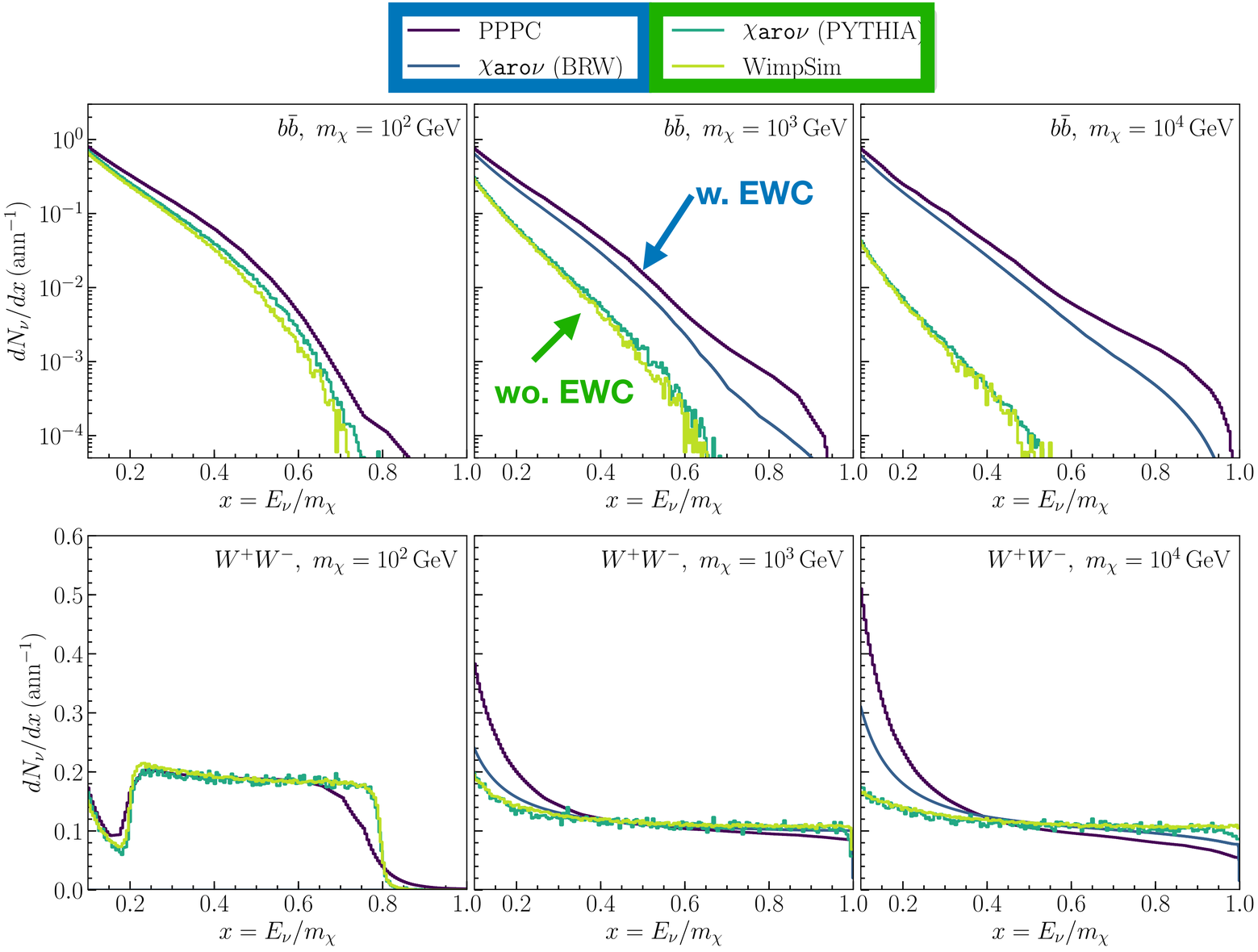
- Software package for calculating neutrino yields from DM annihilation/decay [1]
- Couples PYTHIA8 to an updated calculation of EW correction (BRW calculation) [2]
- Flexible python-based package allows for easy implementation of systematics and new fluxes
- See contribution 1141 for by Qinrui Liu more details on this work
- Source code at https://github.com/icecube/charon

[1] **Q. Liu, JL, C. A. Argüelles, A. Kheirandish**: JCAP (2020)
[2] C. W. Bauer, N. L. Rodd, B. R. Webber: JHEP (2020)

New Spectra

- Order of magnitude changes in $b\bar{b}$ spectra; spectra harder
- Moderate changes in W^+W^- and $\tau^+\tau^-$ channels lead to softer spectra

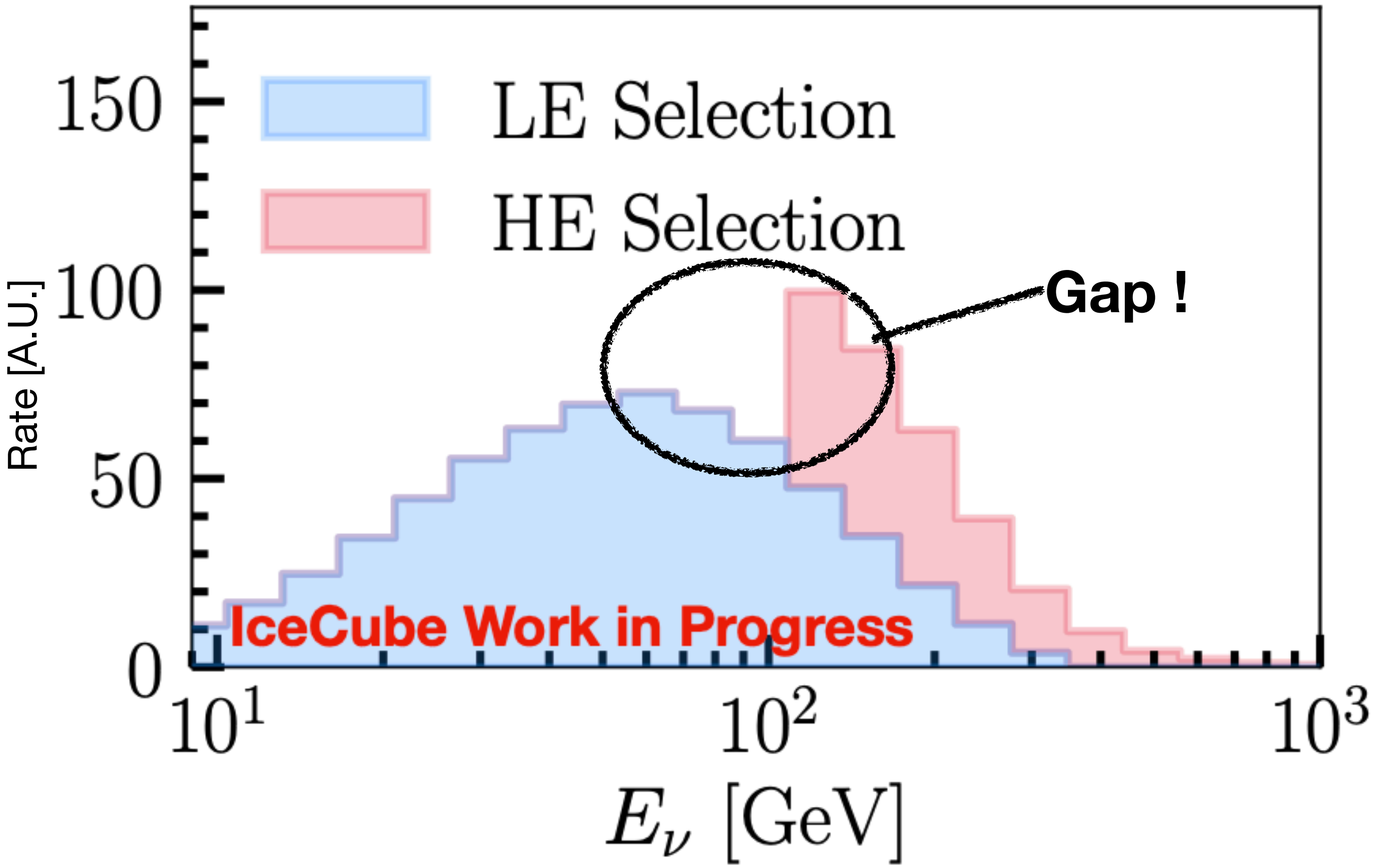




Q. Liu, JL, C. A. Argüelles, A. Kheirandish: JCAP (2020)

Augmented Selection

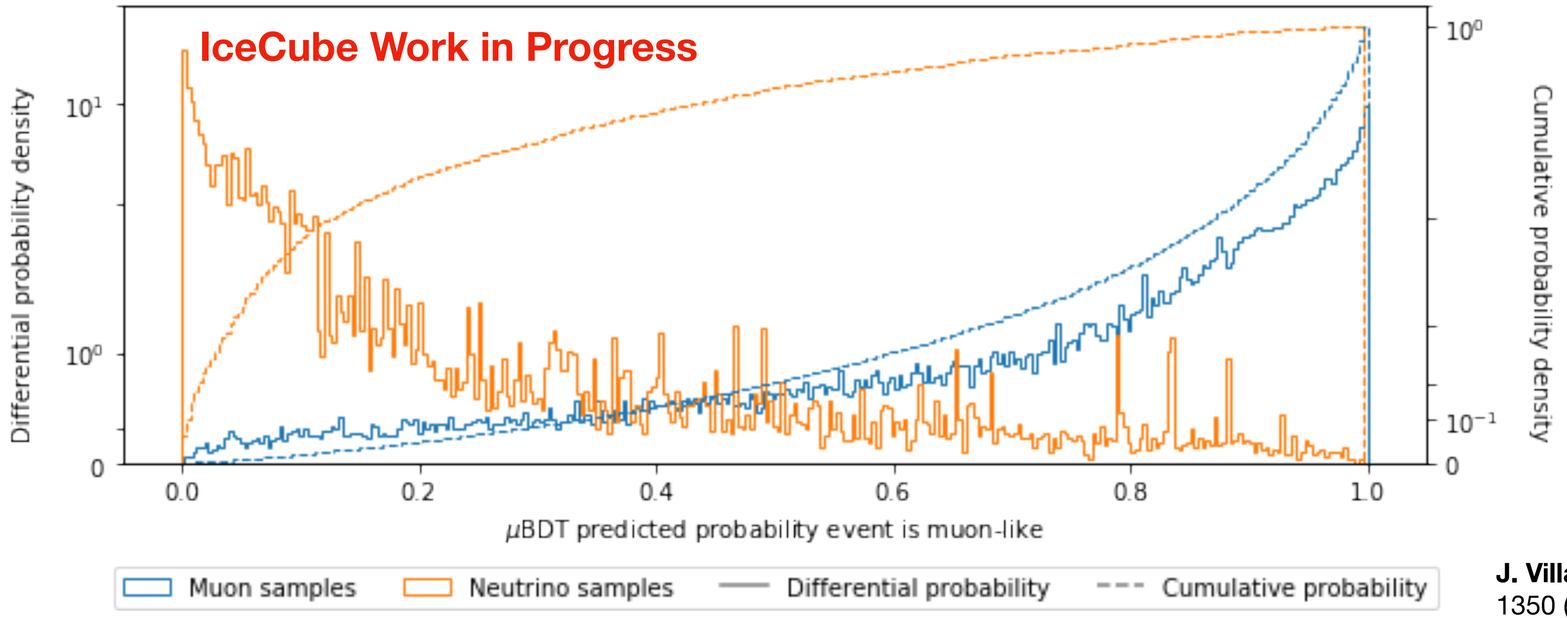
- Improve on current analysis by developing selection to target gap around 100 GeV
- Expected to fix loss of sensitivity around $m_\chi = 100$ GeV



Event rate vs. true neutrino energy. Event rate in arbitrary units in low- and high-energy selections for $\chi\chi \to b\bar{b}$, $m_\chi = 500$ GeV

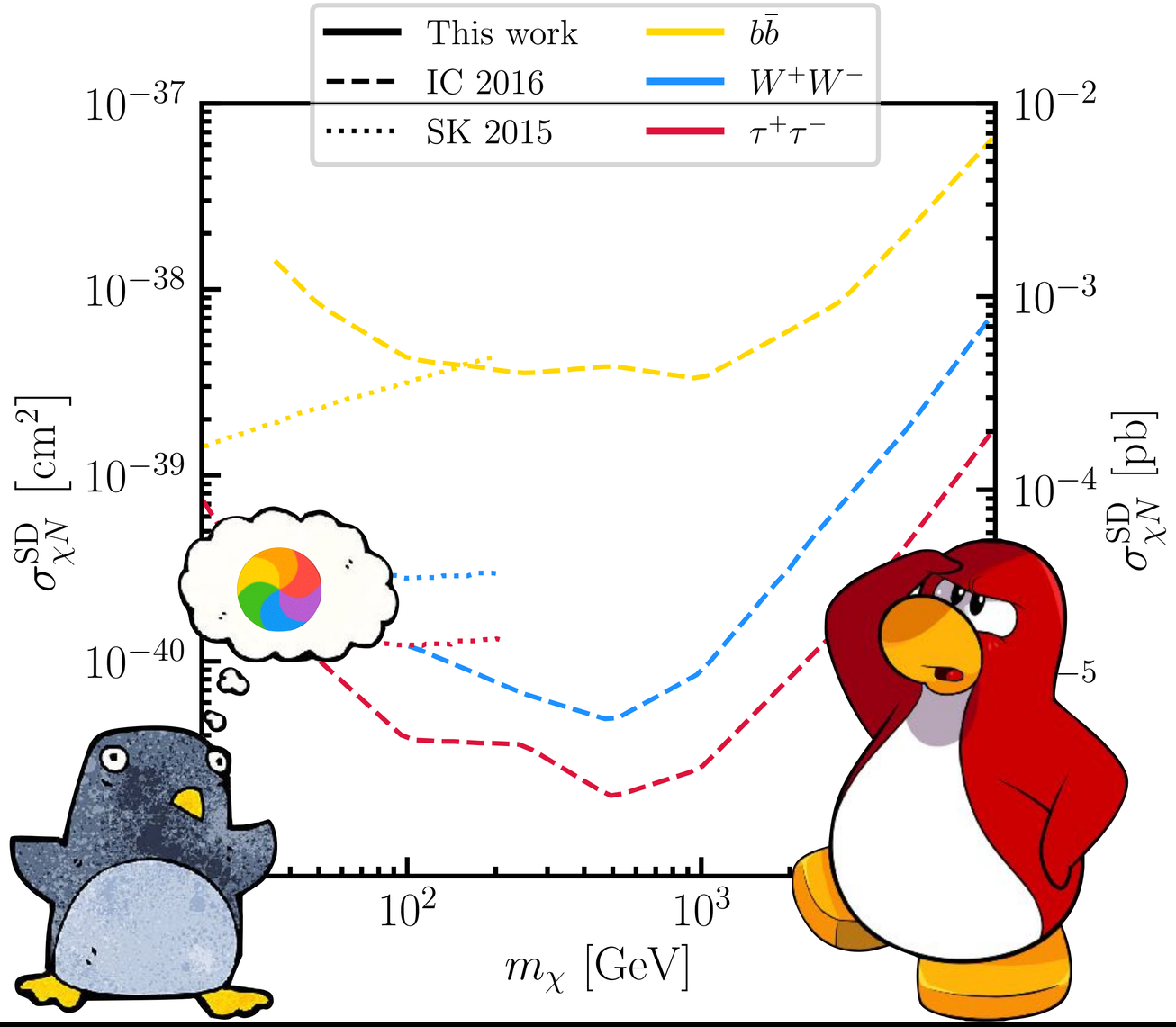
Towards a Medium-Energy Selection

- Developing an event selection to bridge low- and high-energy regimes
- Three-stage approach:
  - ✓ Target mid-energy events with filter designed for previous solar WIMP search
  - ✓ Filter out atmospheric muons with a branched decision tree (BDT)
  - ➡ Differentiate signal and background neutrinos with another BDT



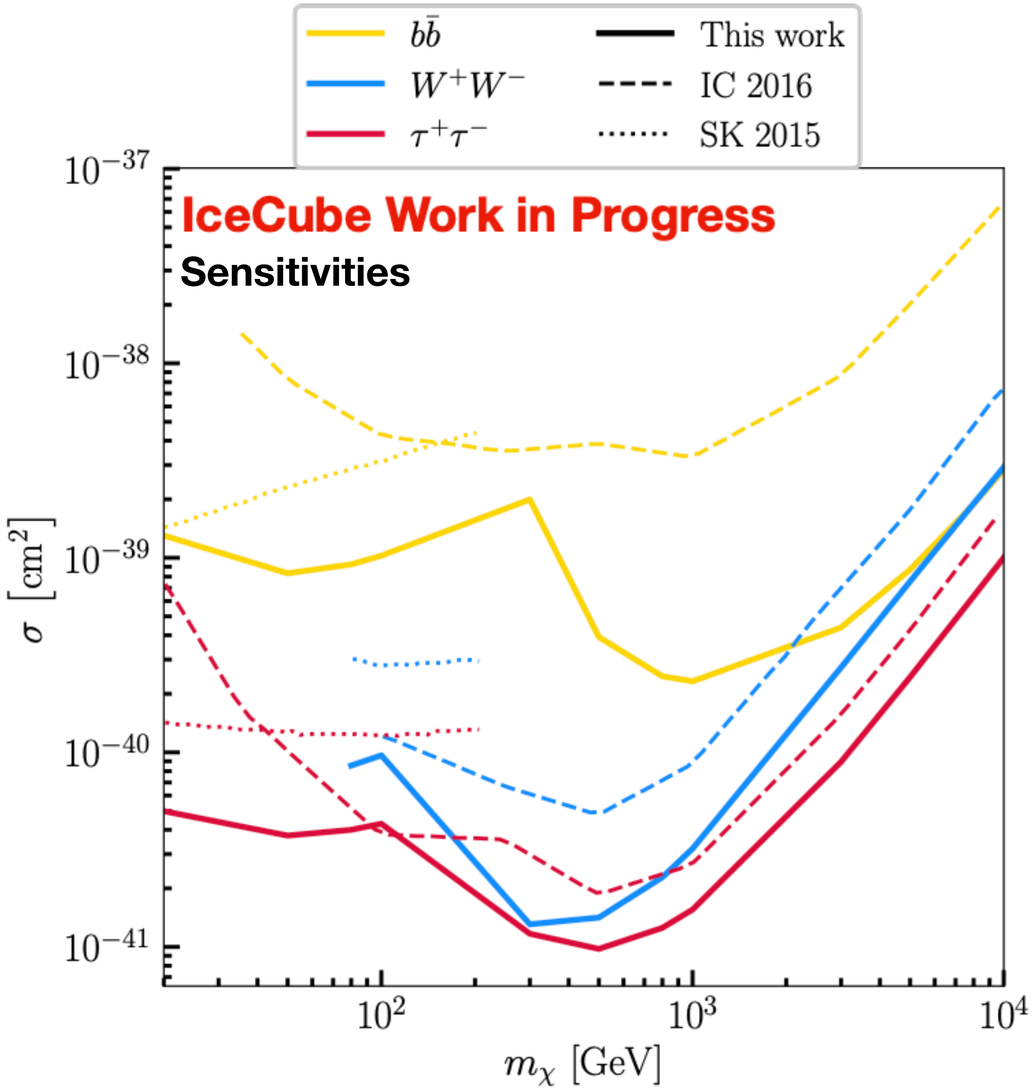
J. Villarreal, G. Roellinghoff, JL: ICRC PoS 1350 (2021)

Upcoming Results: Stay Tuned



Summary

- Many IceCube analyses underway to find dark matter
- New solar WIMP analysis has world leading sensitivities over 3 order of magnitude
  - New calculation of EW effect
  - Custom event selection
- Improved sensitivity to ~100 GeV region in progress
- **Results coming very soon**



Thank you for listening

Questions ?

Backups

Bullet Cluster Information