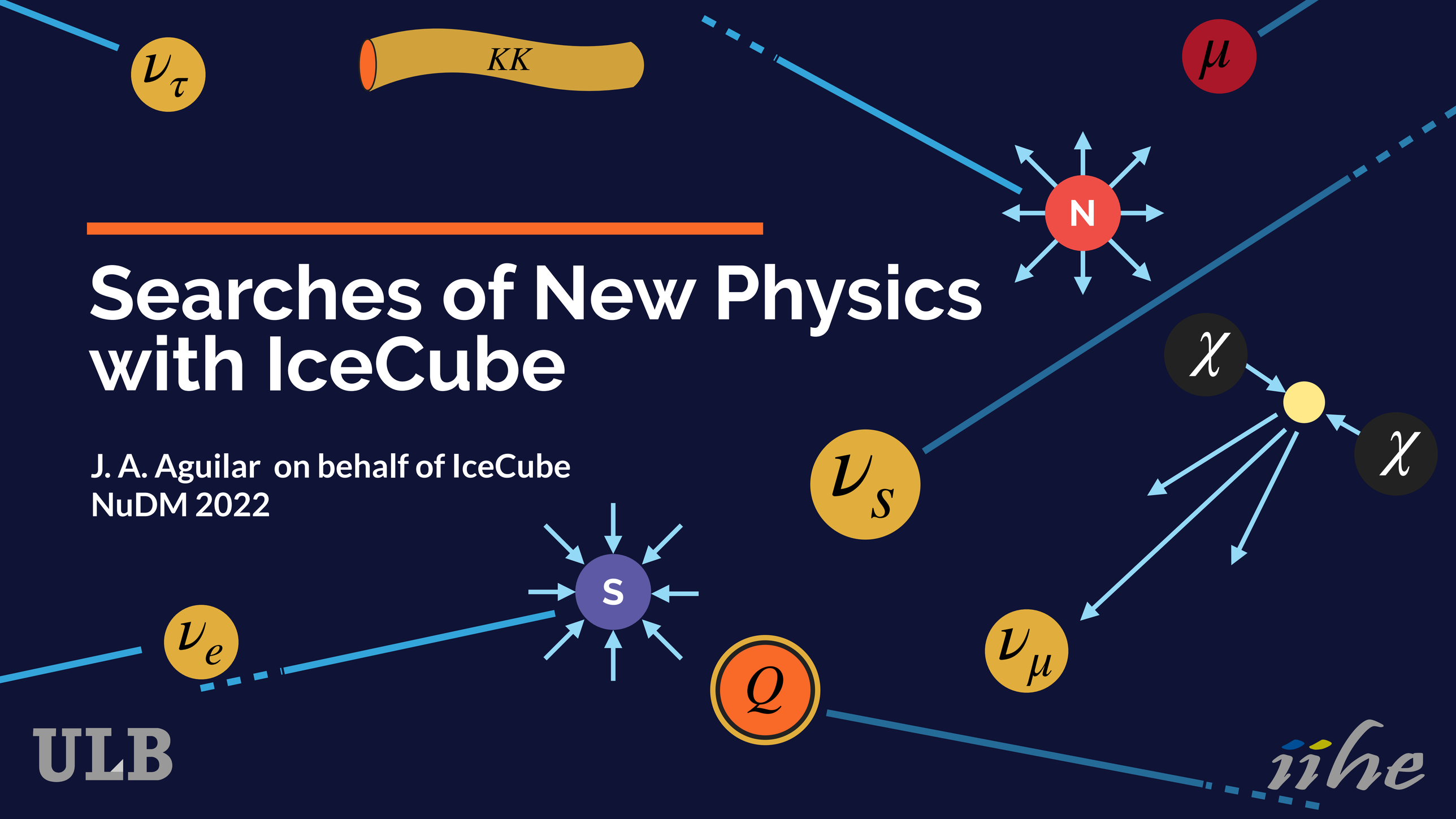

Searches of New Physics with IceCube

J. A. Aguilar on behalf of IceCube

NuDM 2022

ULB

iihe

Outline

- The IceCube Neutrino Telescope
- BSM searches with IceCube:
  - Dark Matter
  - Neutrinos
  - Exotics
- The Future

Outline

- The IceCube Neutrino Telescope
- BSM searches with IceCube:
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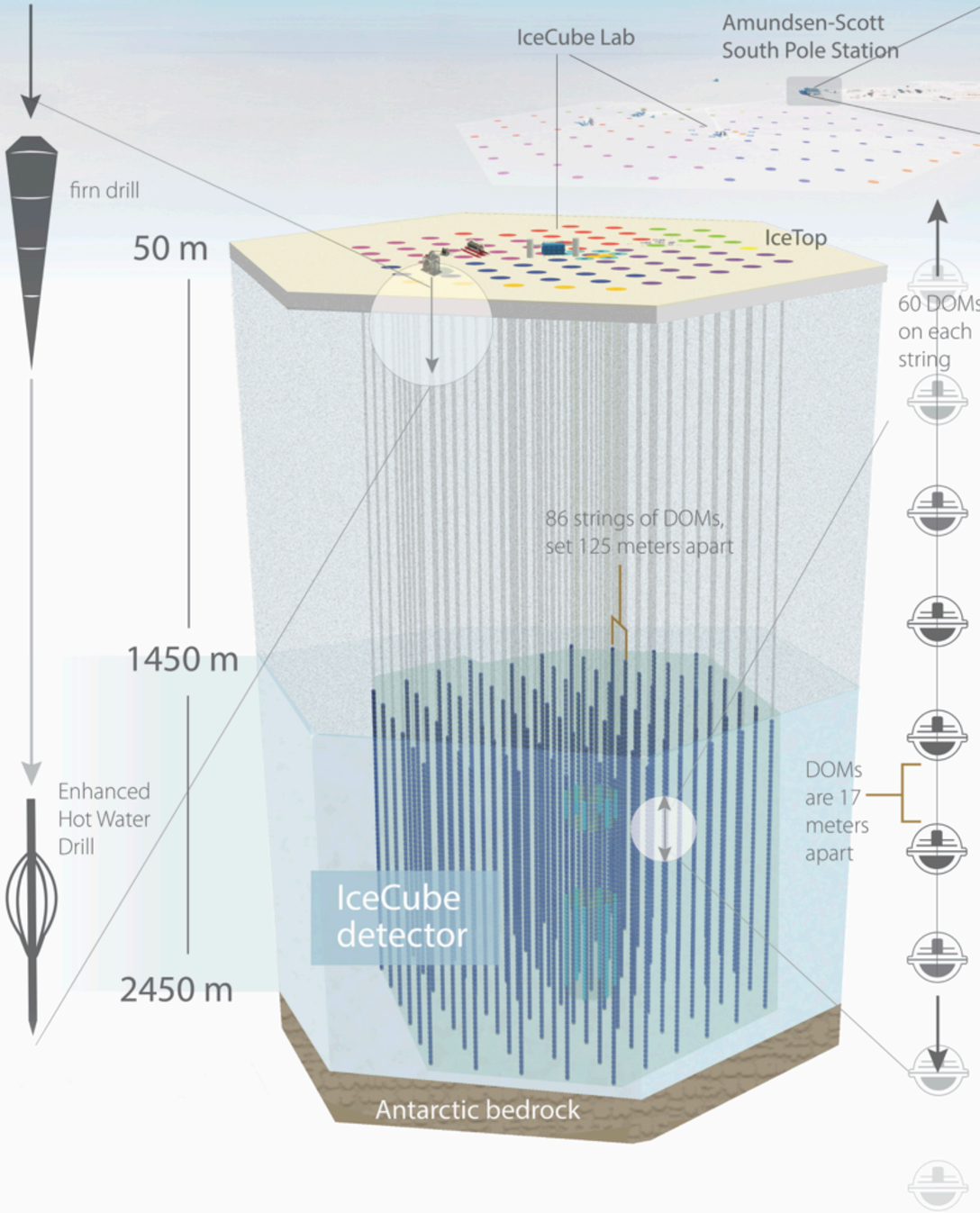
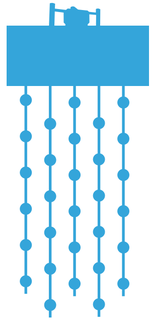
  - Neutrinos
  - Exotics
- The Future

Disclaimer: I will focus mostly on Dark Matter searches

IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)



86 string with 60 DOMs each

6 denser strings called **DeepCore**

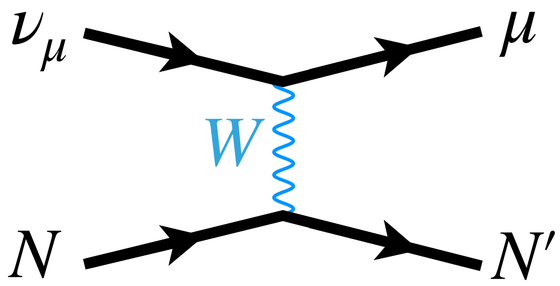
1 km^2 surface array with 324 DOMs: **IceTop**

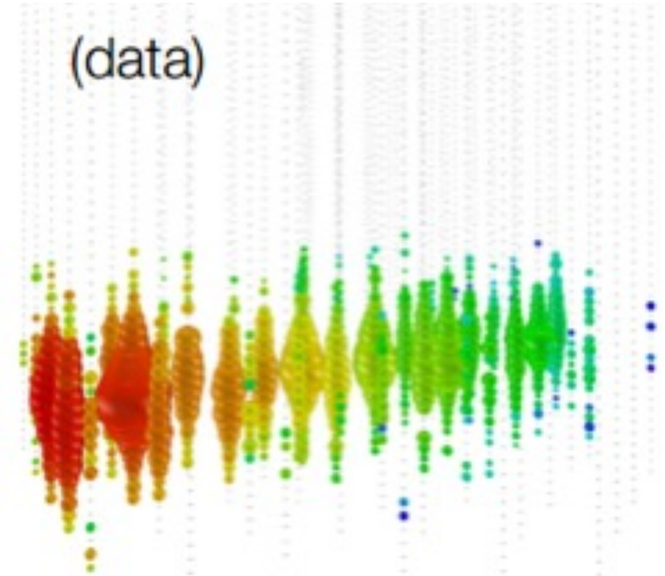
Completion in December 2010

In-Ice Signatures

Track topology

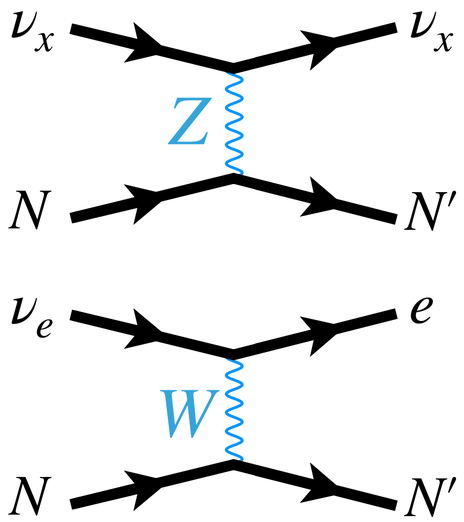
- Good angular resolution 0.1° - 1°:
  - **Neutrino Astronomy**
- Vertex can be outside the detector:
  - **Increased effective volume**
- Stochastic energy losses:
  - **Challenging energy estimation.**

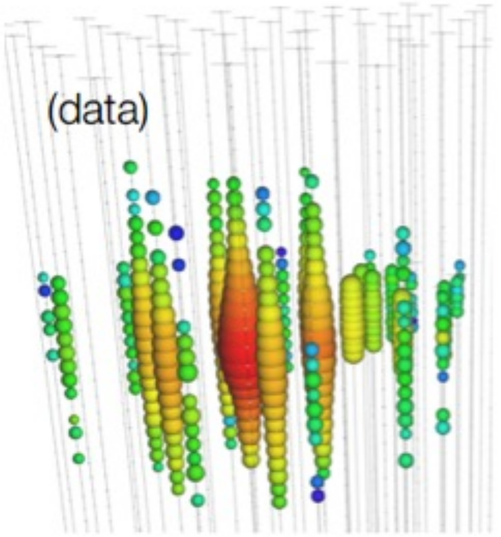


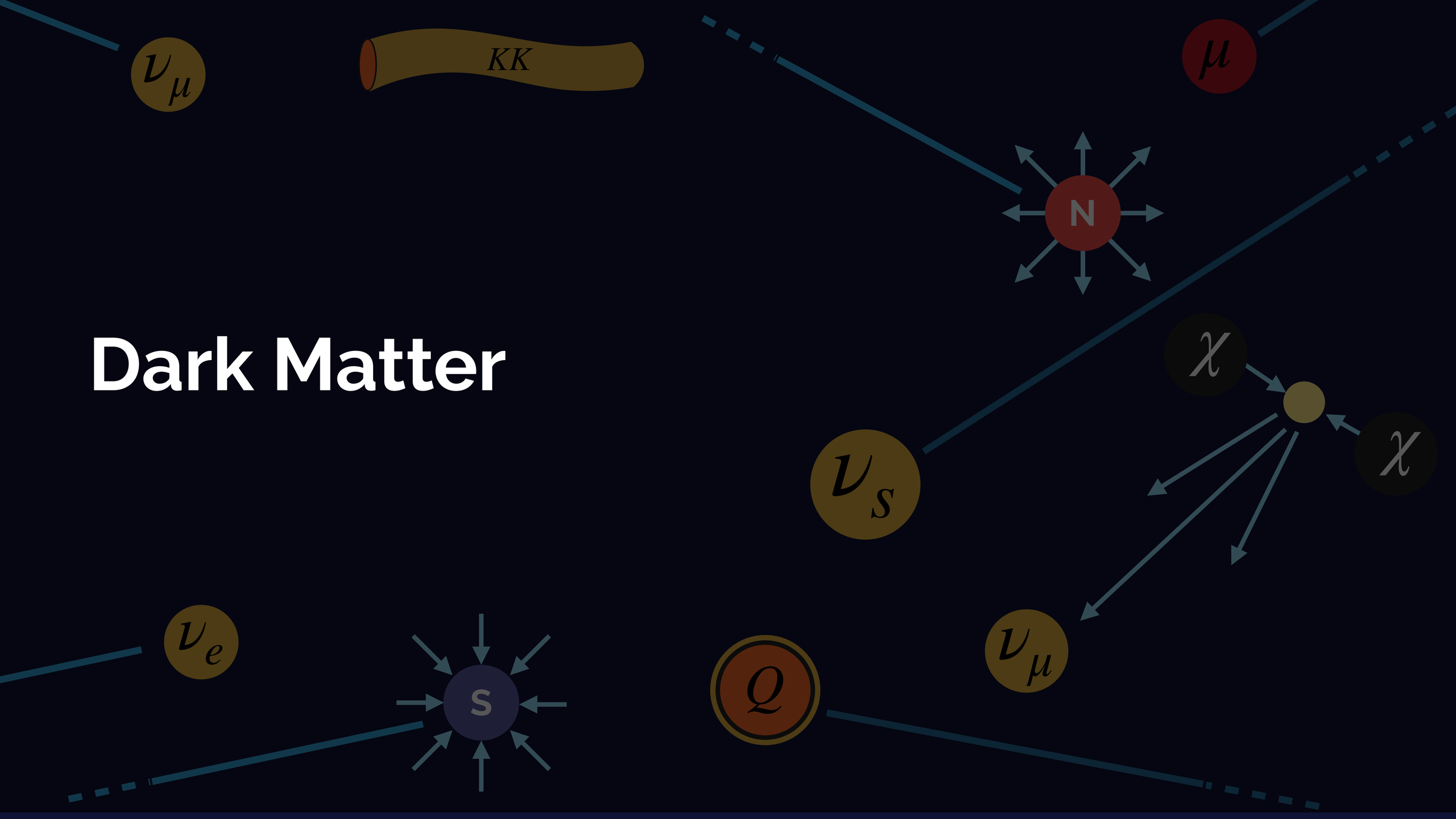


Cascade topology

- All flavors
- Fully active calorimeter:
  - **Energy resolution ±15%**
- Angular reconstruction possible:
  - **~10° @ E > 100 TeV**







Dark Matter

Dark Matter from the Galactic Halo (Case Study)

Flux from annihilation (very similar for decay):

$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_0^{\Delta\Omega}\mathrm{d}\Omega\int_{l.o.s.}\rho_\chi^2(r(s,\Psi,\theta))\mathrm{d}s$$

Dark Matter from the Galactic Halo (Case Study)

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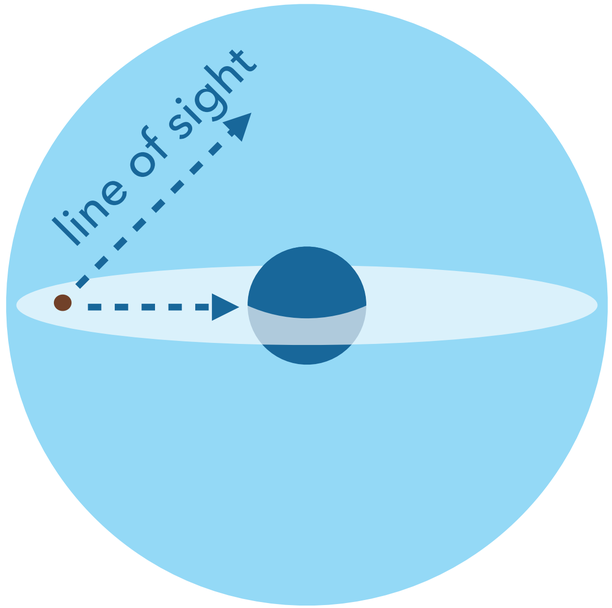
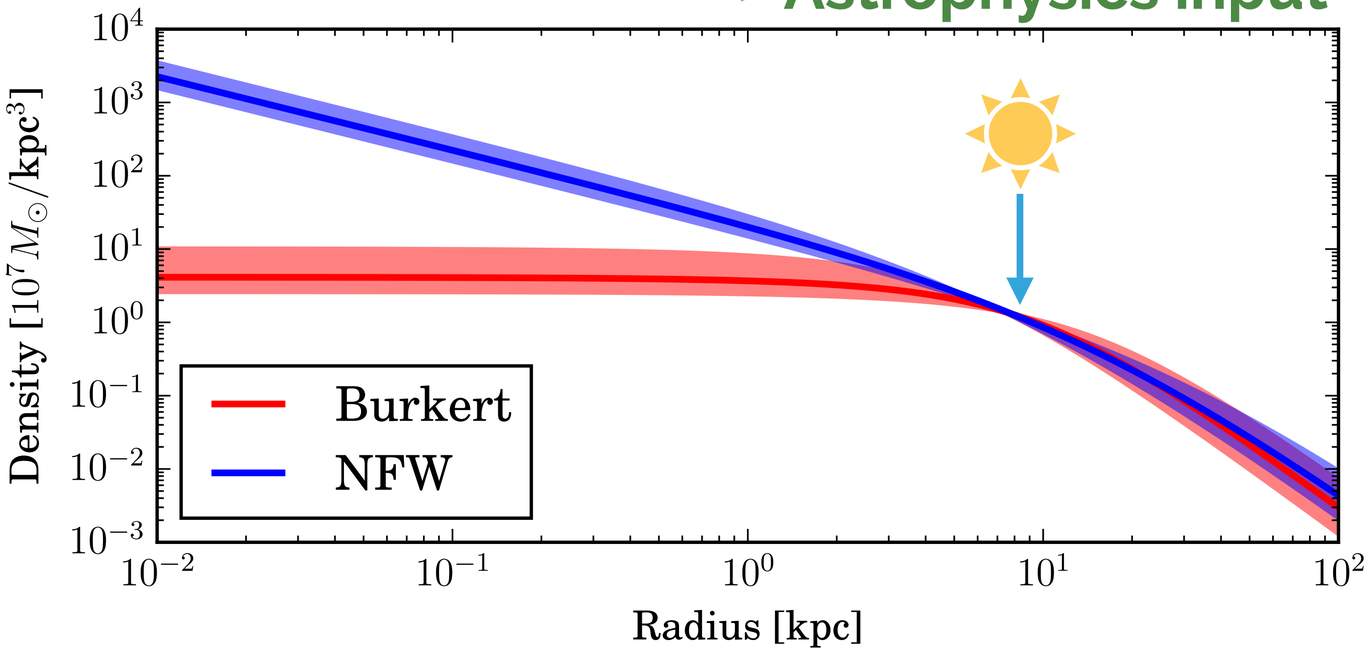
$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_0^{\Delta\Omega}\mathrm{d}\Omega\int_{l.o.s.}\rho_\chi^2(r(s,\Psi,\theta))\mathrm{d}s$$

Astrophysics input





The central cusps in dark matter halos: fact or fiction? [arXiv:1808.03088v2]

Dark Matter from the Galactic Halo (Case Study)

Flux from annihilation (very similar for decay):

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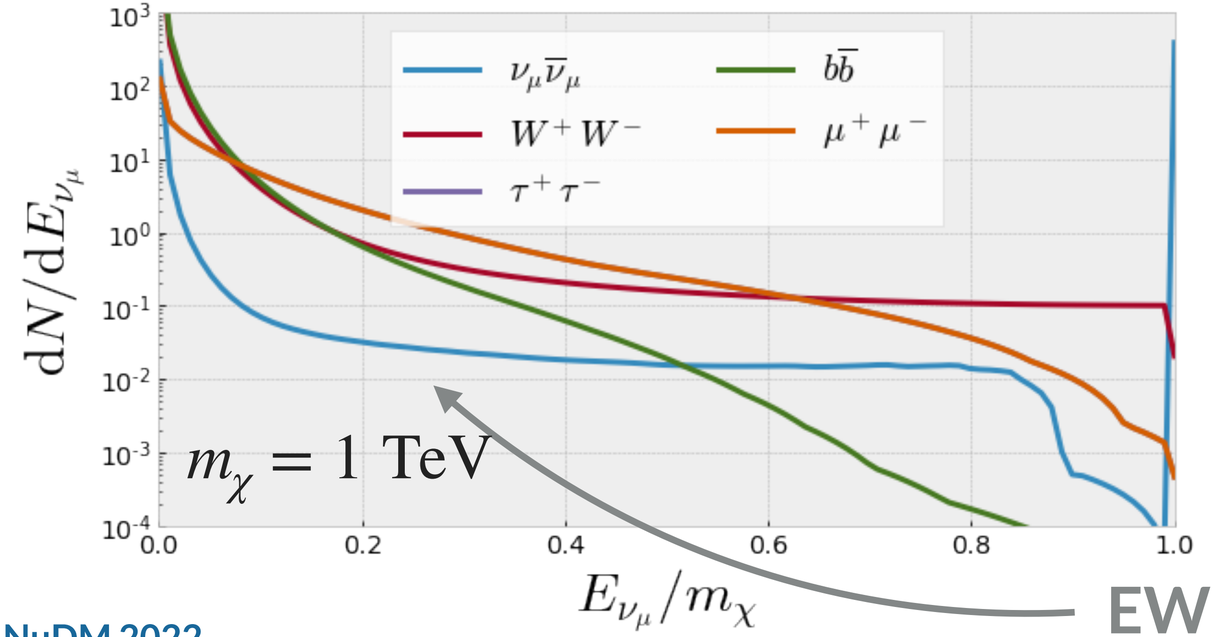
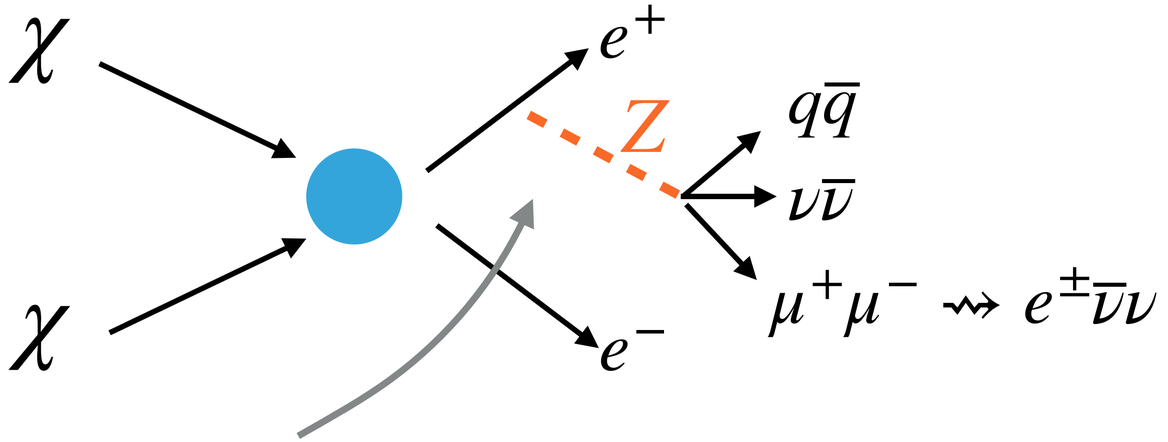
Particle Physics input

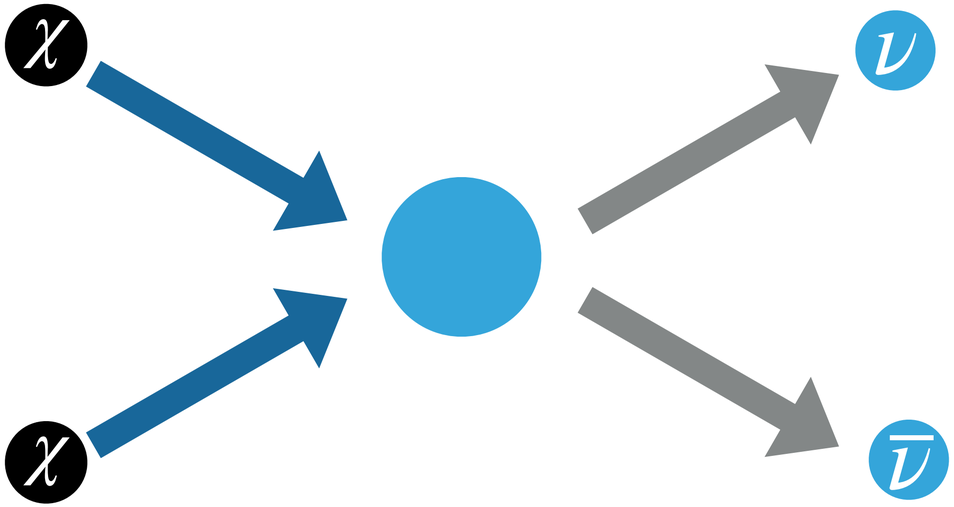


[arXiv:2007.15010, arXiv:1012.4515, arXiv:2007.1500]



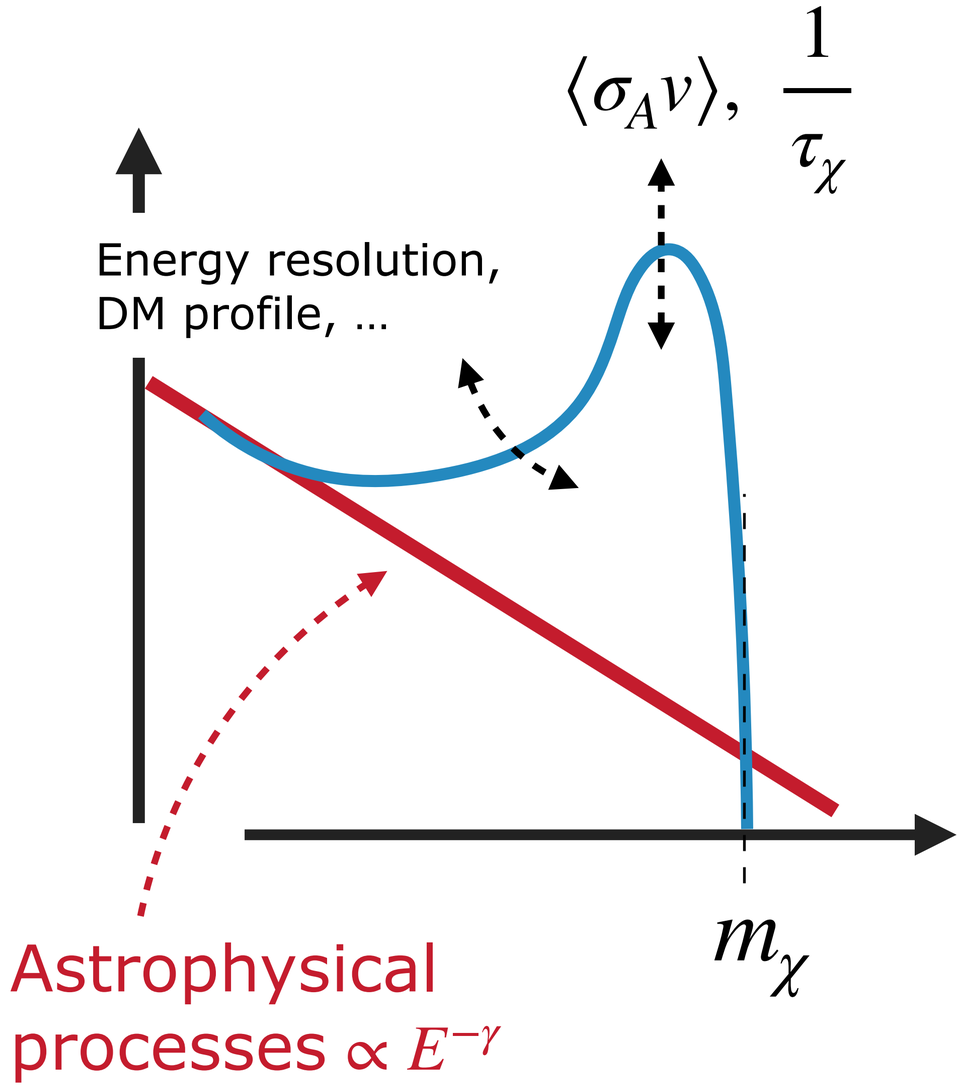
EW corrections are important

Dark Matter from the Galactic Halo: Neutrino Lines



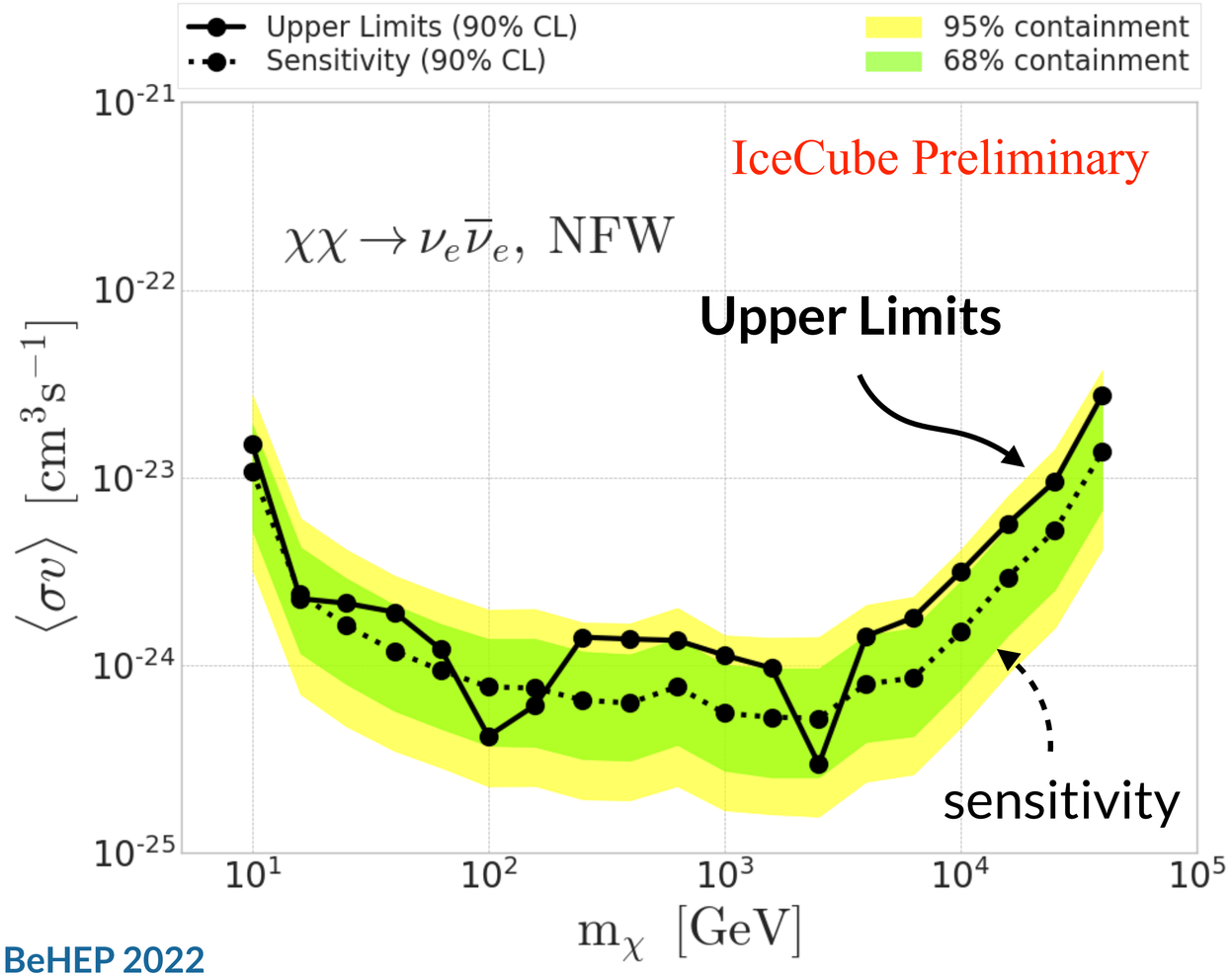
- Focusing on direct annihilation/decay to neutrinos.
- No astrophysical background:

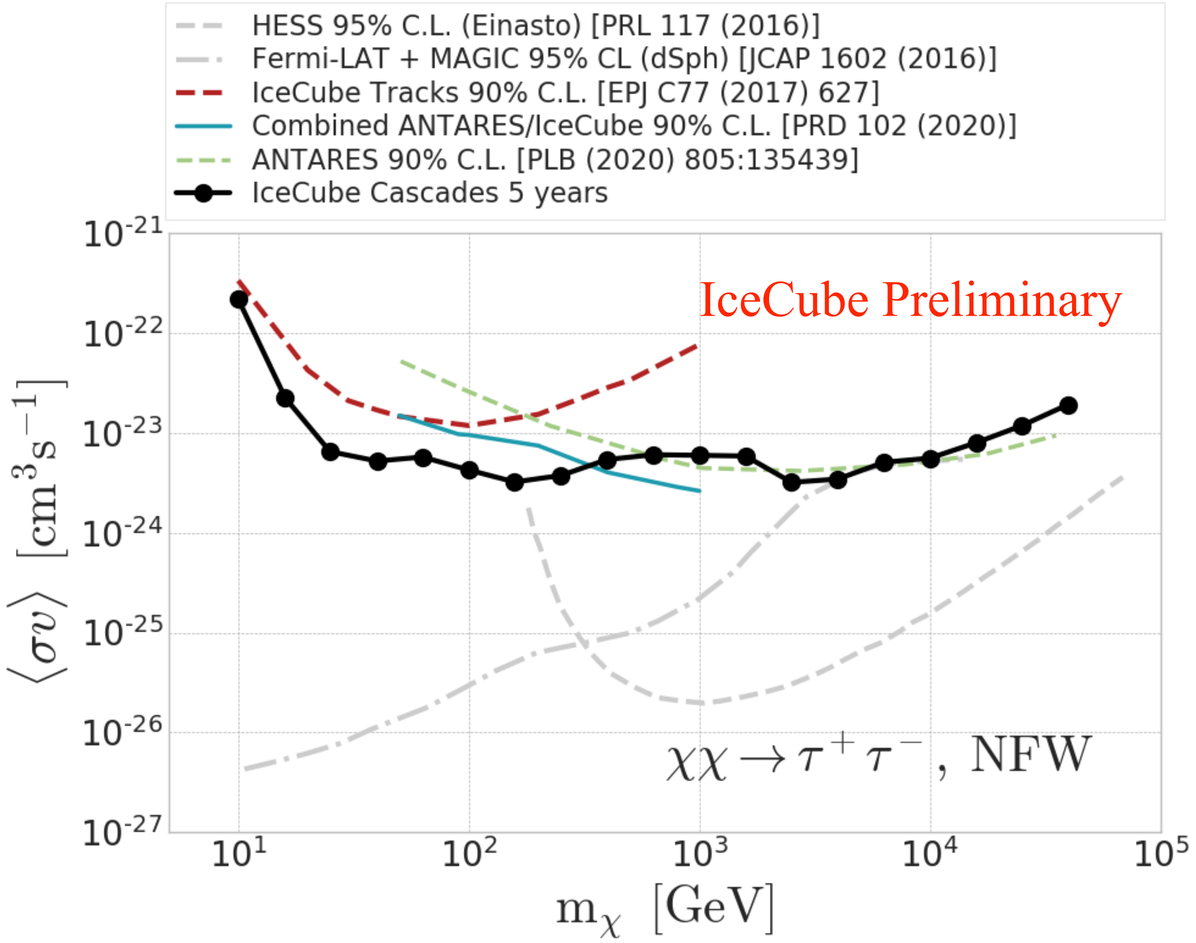
smoking gun signature of dark matter.



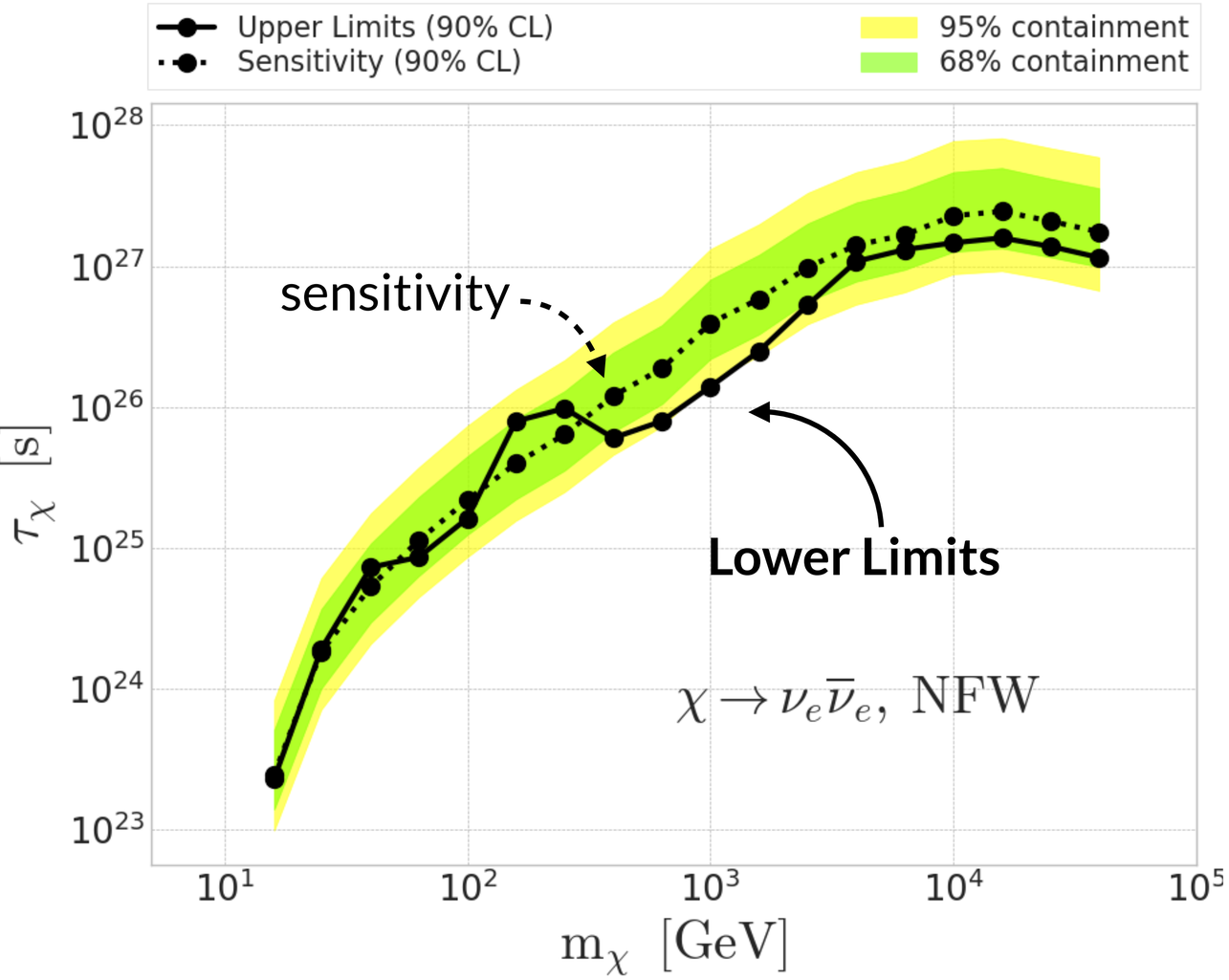
Dark Matter from the Galactic Halo: Neutrino Lines

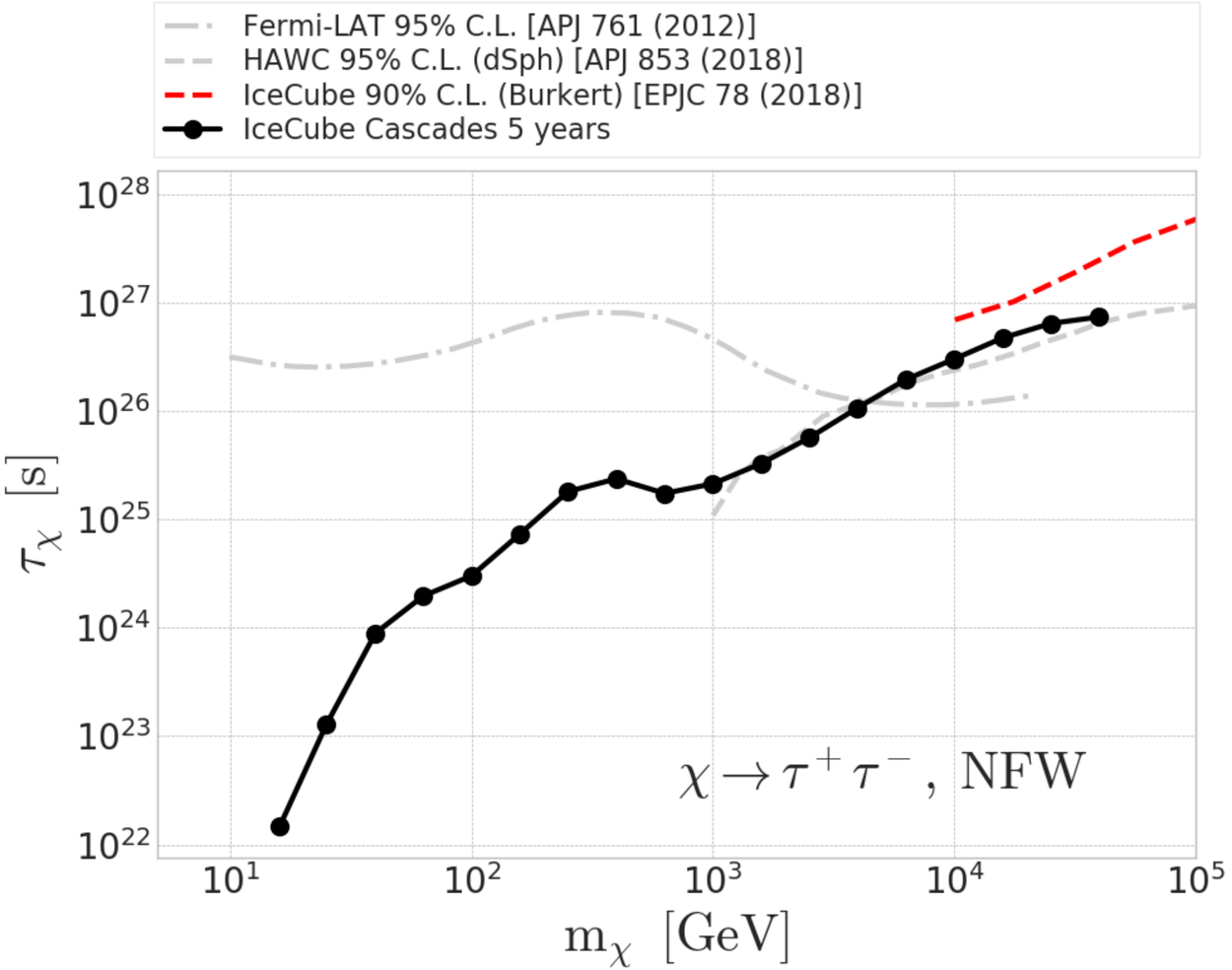
- 5 years of IceCube data: 2012 to 2016
- DeepCore data focusing on cascade events: Energy resolution $\sigma_{\log_{10} E_\nu} \sim 12\,\%$





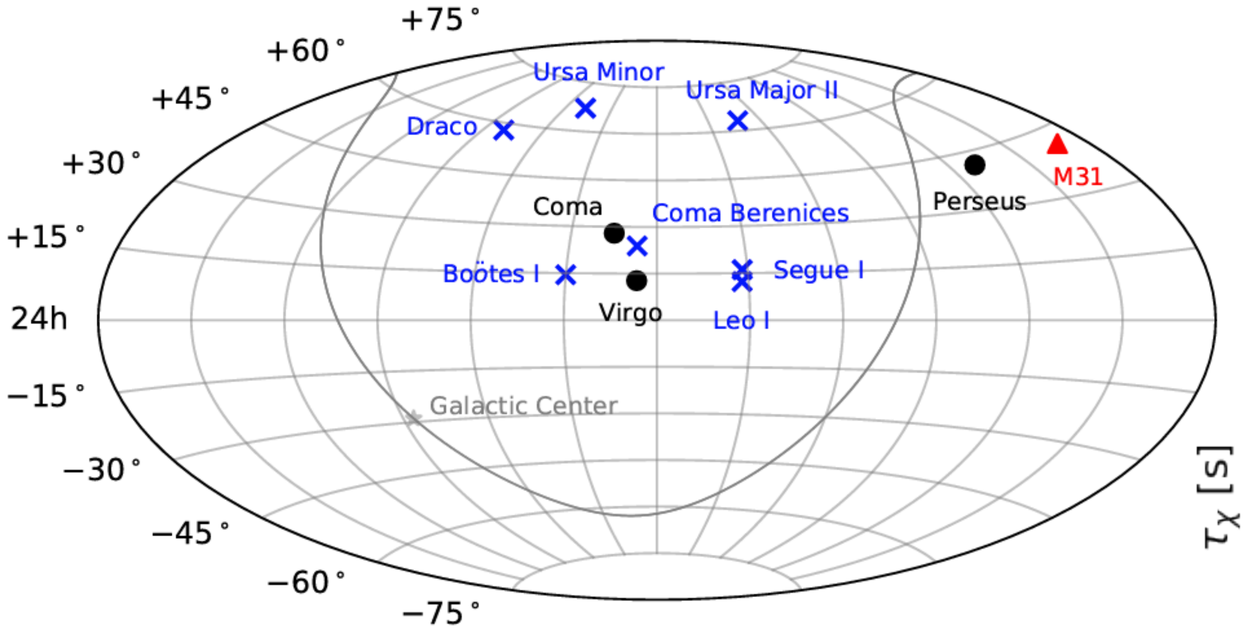
Dark Matter from the Galactic Halo: Neutrino Lines



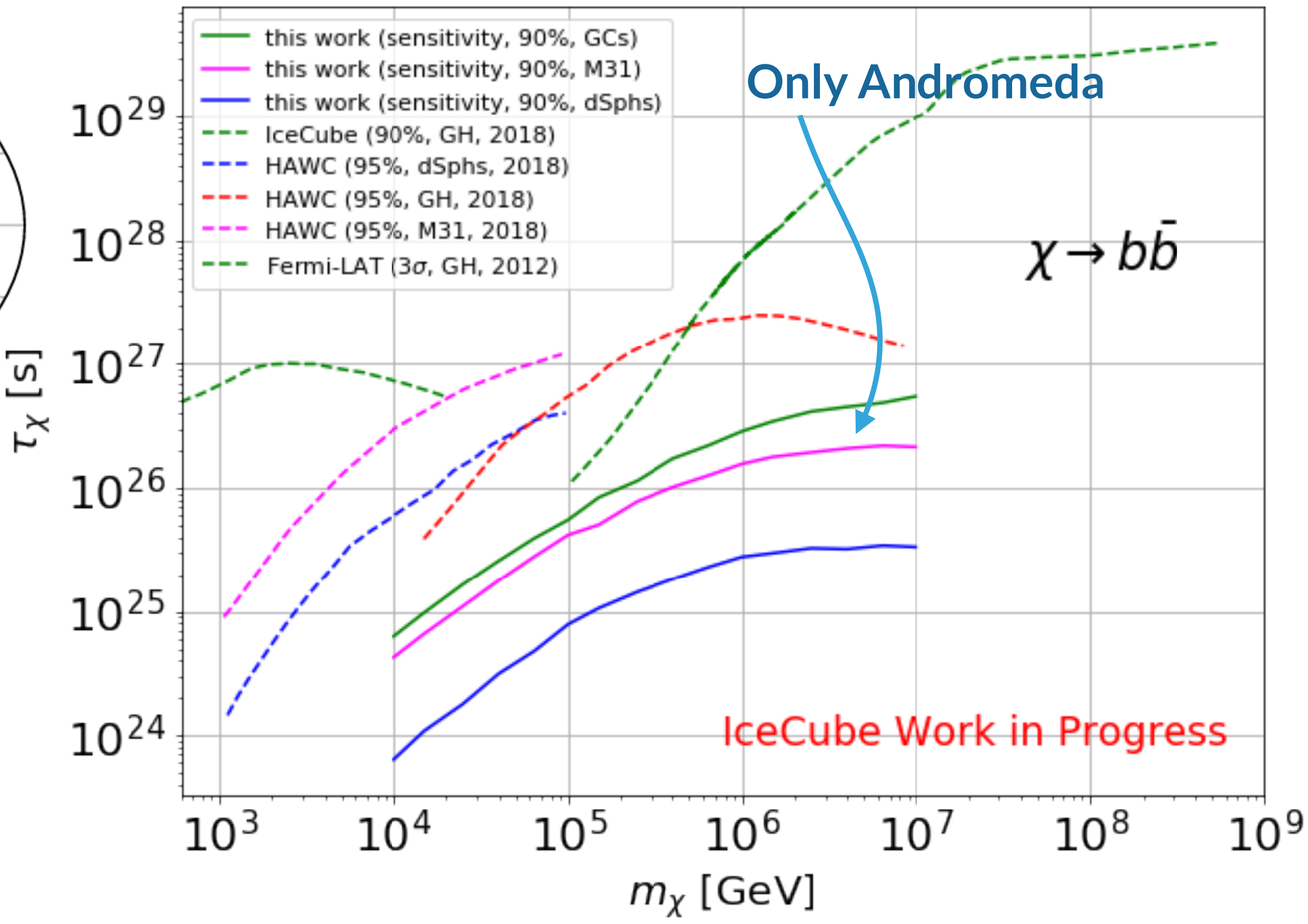


[publication in preparation]

Dark Matter from the Galaxy Clusters

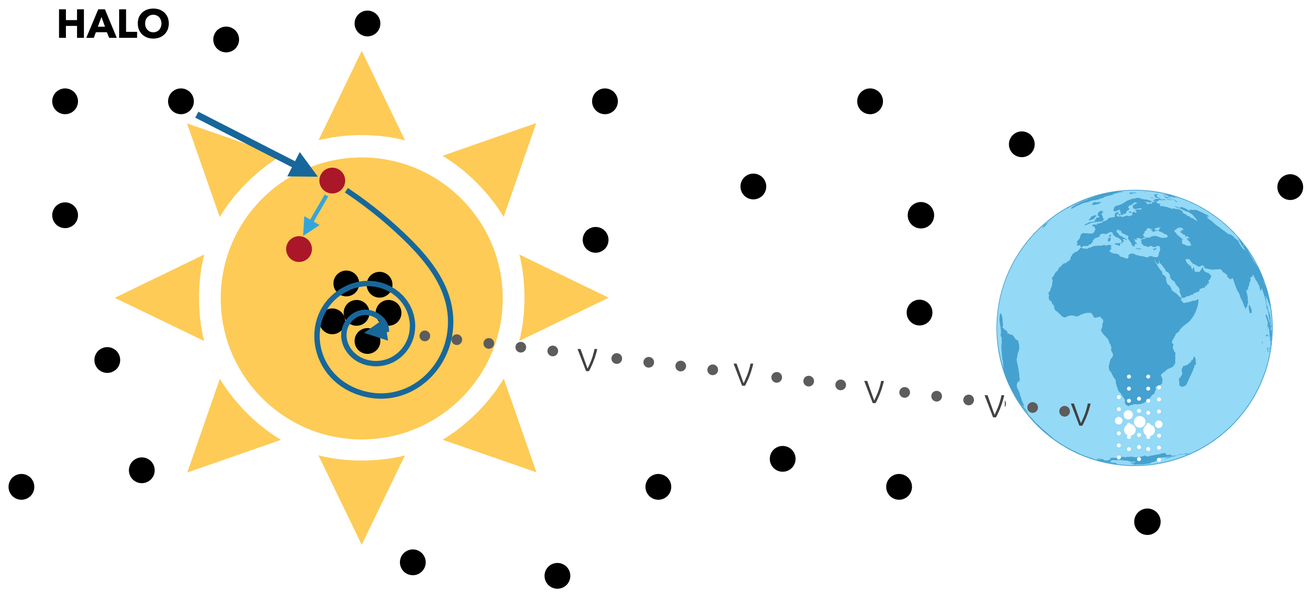


[PoS(ICRC2021)506]



- Stacking analysis on all main **Galaxy Clusters and Dwarf spheroidal galaxies** using a muon track selection (*à la point-source*).
- Targeting **heavy decaying dark matter**.

Dark Matter from Celestial Bodies



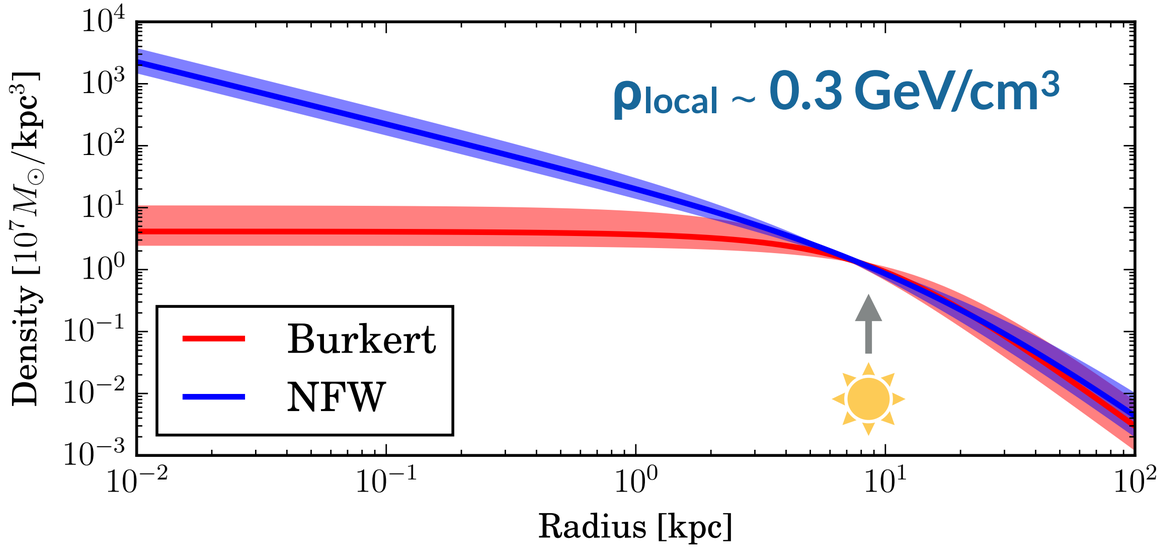
- Dark Matter can be **gravitationally trapped inside celestial bodies**
- Signal cannot be mis-interpreted as an astrophysical source (except for solar atm. neutrinos).
- Halo models agree in the Solar System.

$$\frac{\mathrm{d}N}{\mathrm{d}t} = C_c - C_A N^2 - C_E N$$

annihilation σ_A

capture $\sigma_{\chi-N}$

"evaporation"



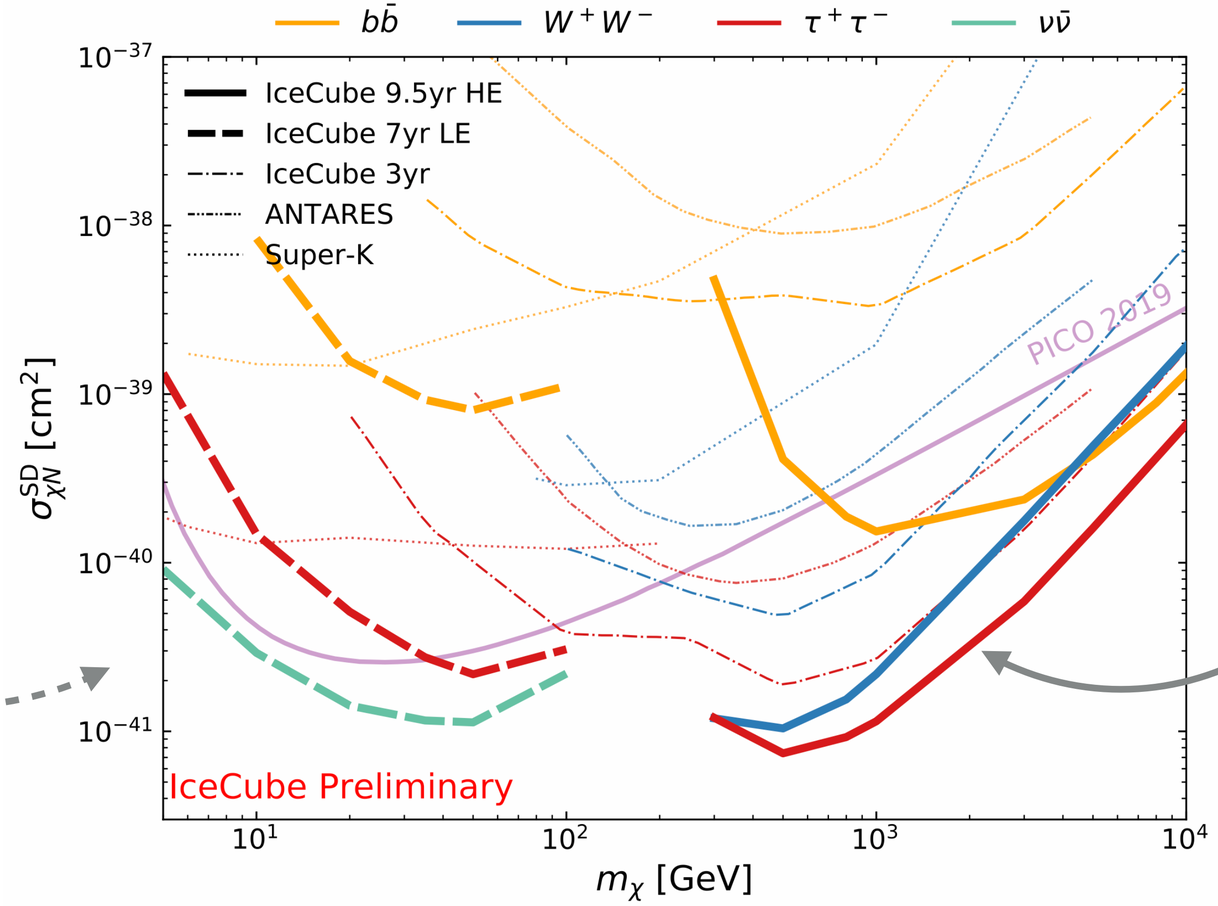
Celestial Bodies: The Sun

equilibrium!

$$\Phi_\nu \rightarrow C_A \Rightarrow C_c \rightarrow \sigma_{\chi N}$$

LE Analysis
[Phys. Rev. D 105, 062004]

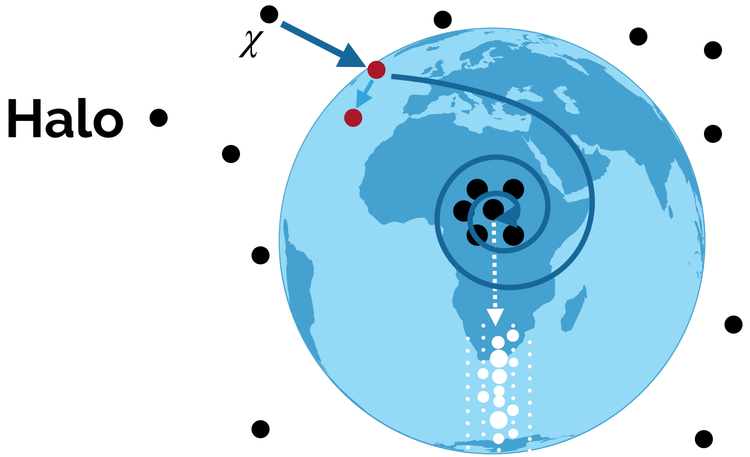
- 7 years of IceCube-DeepCore data (mostly cascades)



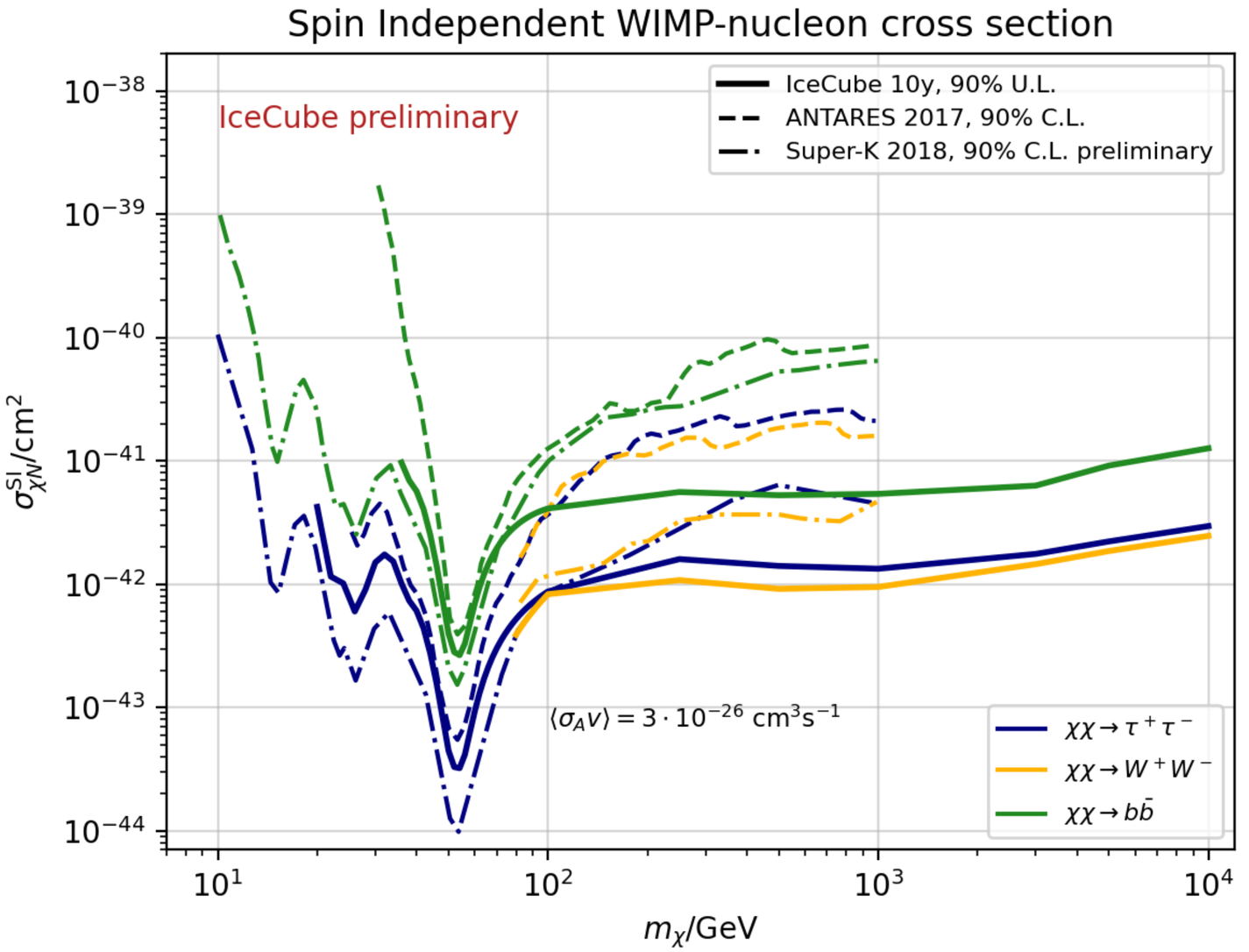
HE Analysis
[PoS(ICRC2021)020]

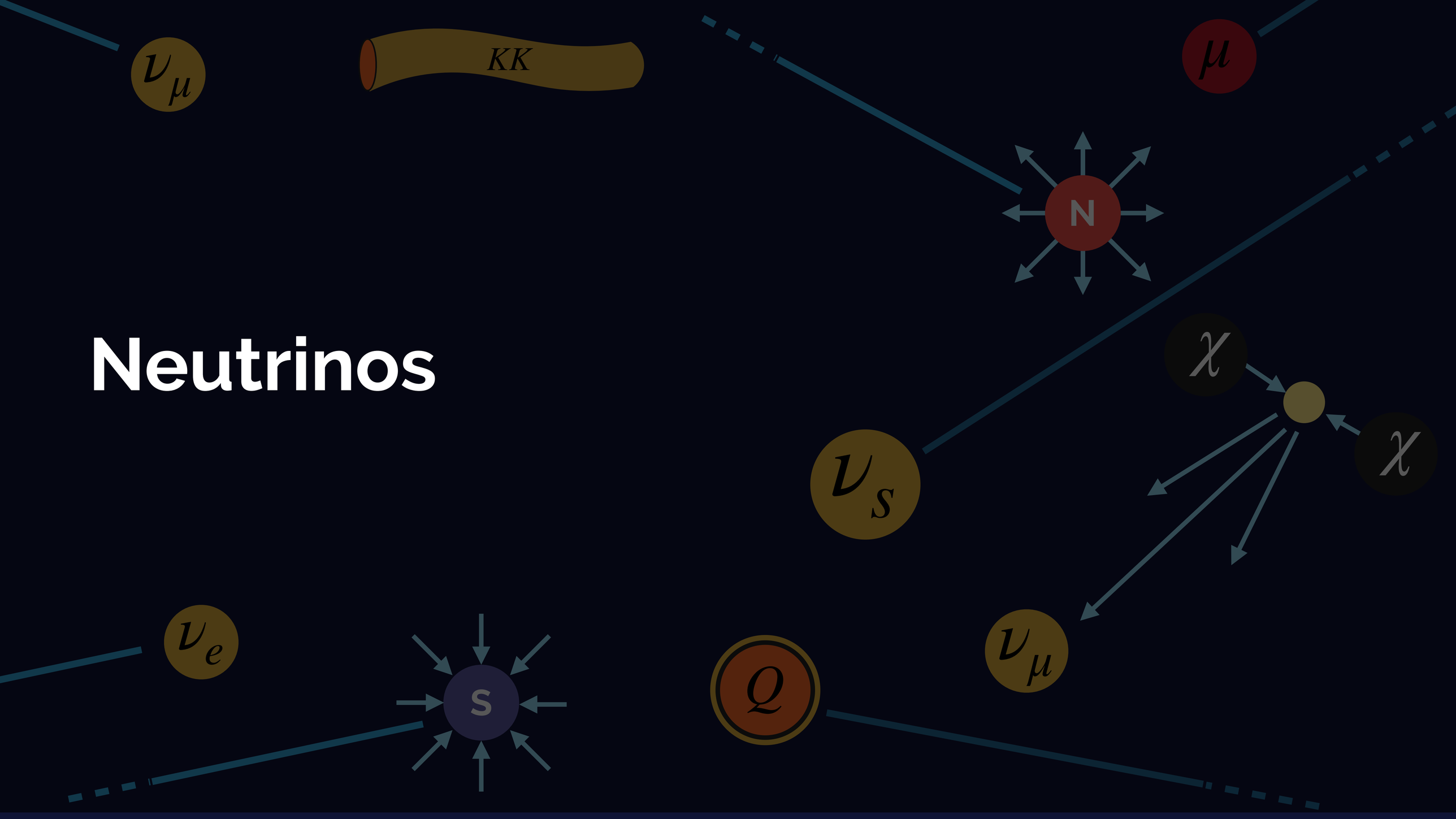
- 9 years of muon track data (HE)

Celestial Bodies Results from the Earth



- Analysis very sensitive to astrophysical uncertainties (dark disc, velocity distribution)
- Unique direction in the sky / control of systematics.
- **No thermal equilibrium**

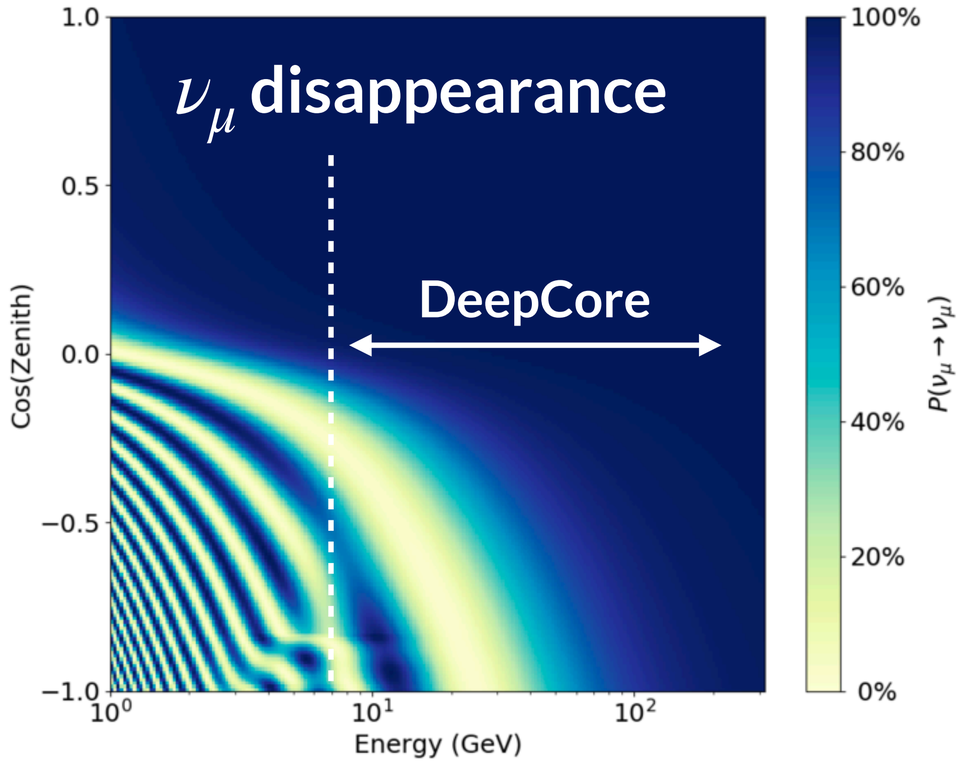


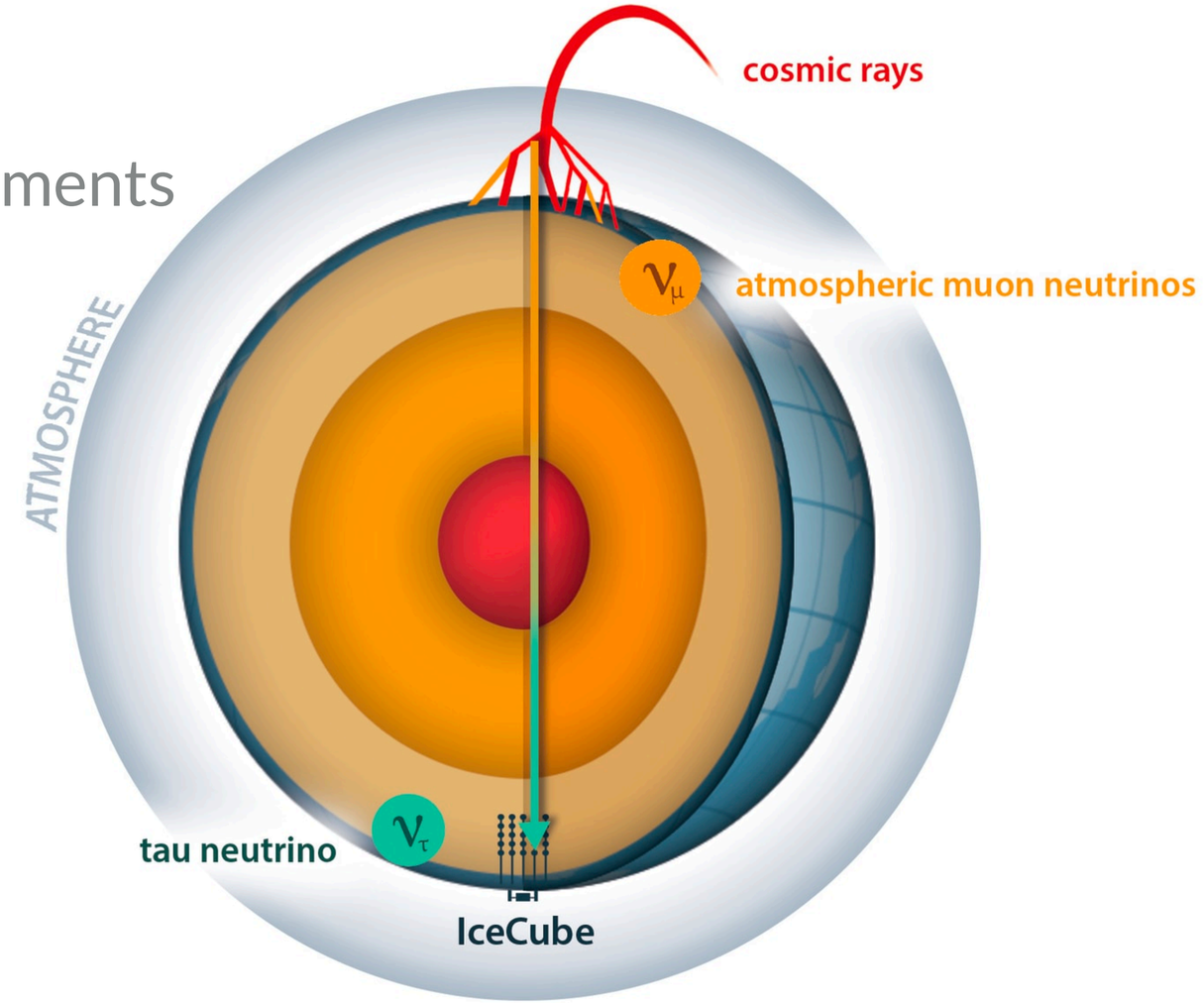


Neutrinos

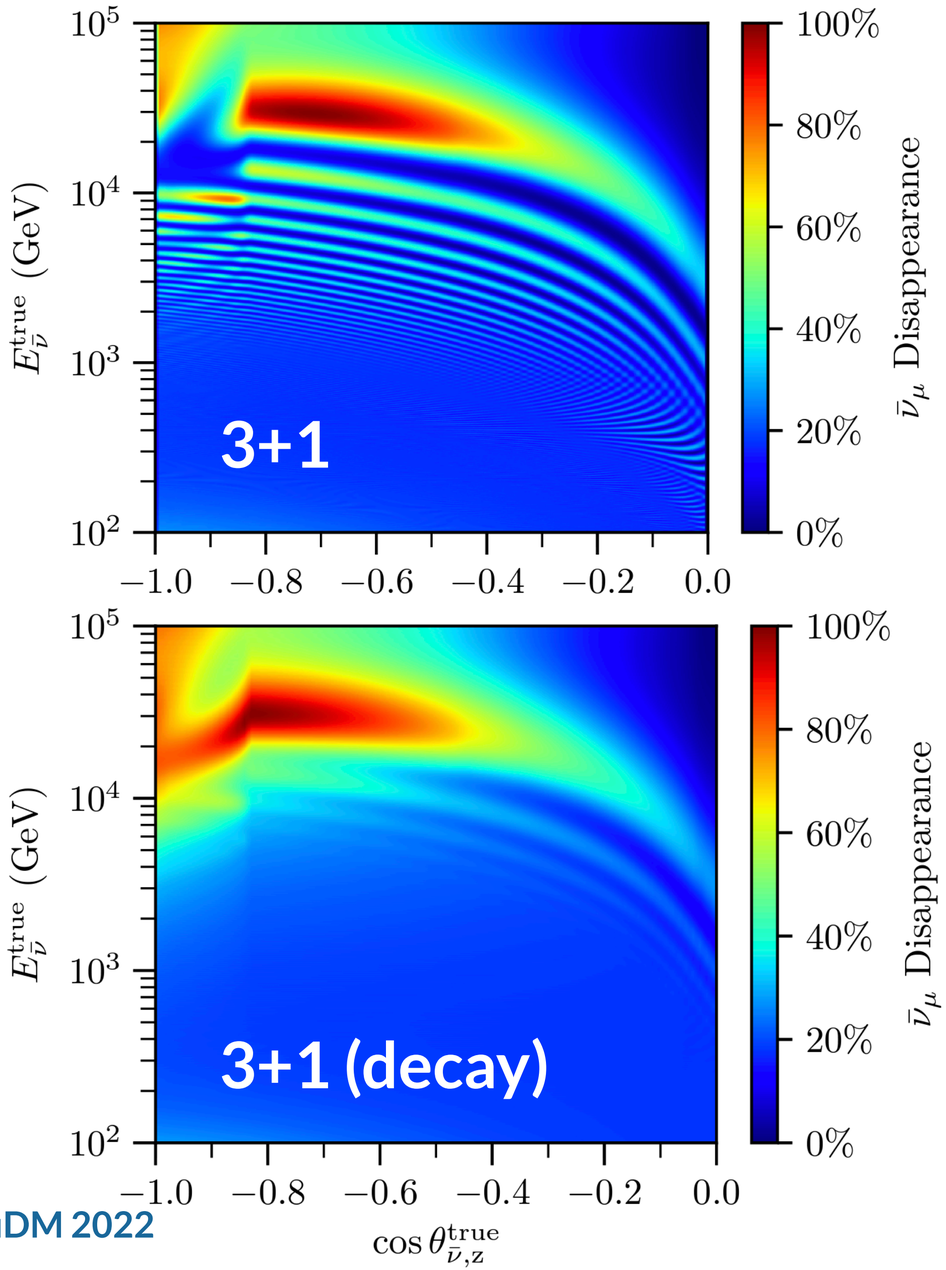
Neutrino Oscillations

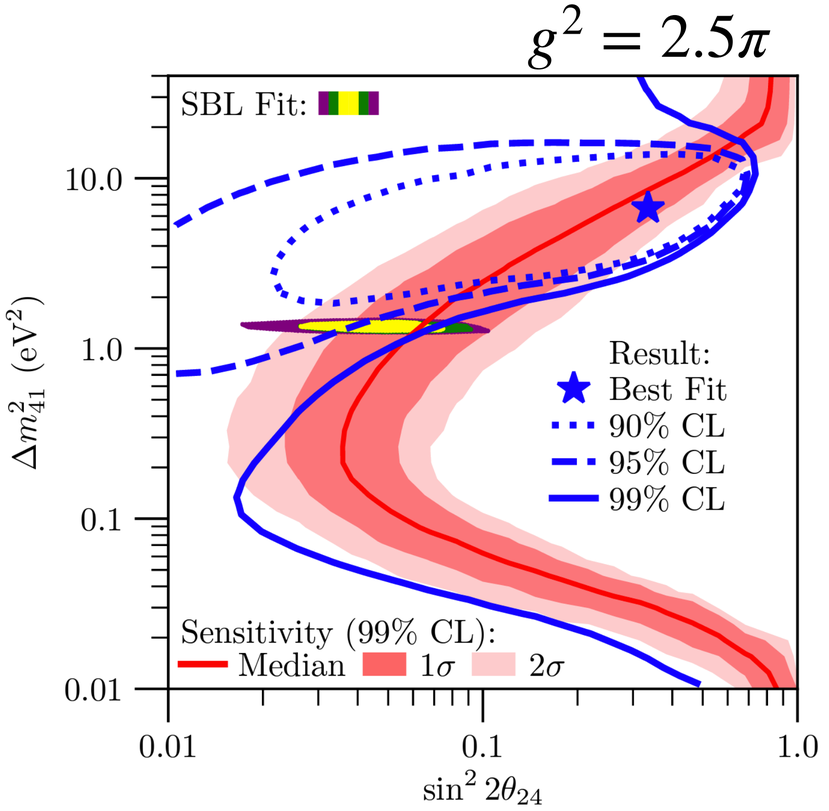
- Use of atmospheric ν_μ to study oscillations.
  - Zenith angle defines the baseline, L
  - DeepCore access same L/E as LBL experiments





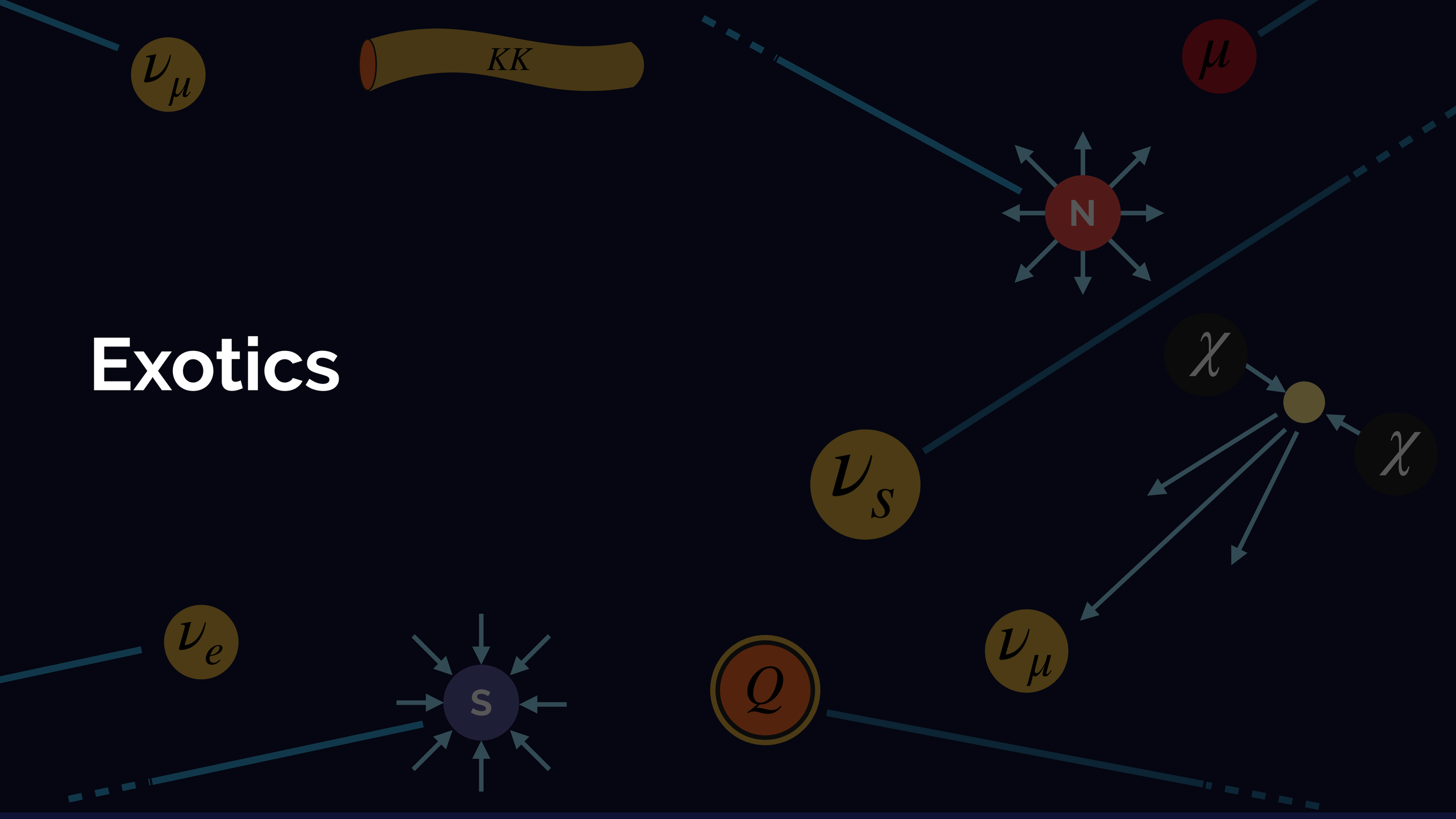
Neutrino Oscillations: Sterile Neutrinos with Decay





- Looking for eV-scale unstable sterile neutrino.
- Decay reduces the tension in 3+1 global fits.
- Both 3+1 and non-sterile model are disfavored w.r.t. to the 3+1 decay. But p-value of 3% is compatible with 3ν hypothesis.

[arxiv:2204.00612 accepted in PRL]



Exotics

Searching for Magnetic Monopoles

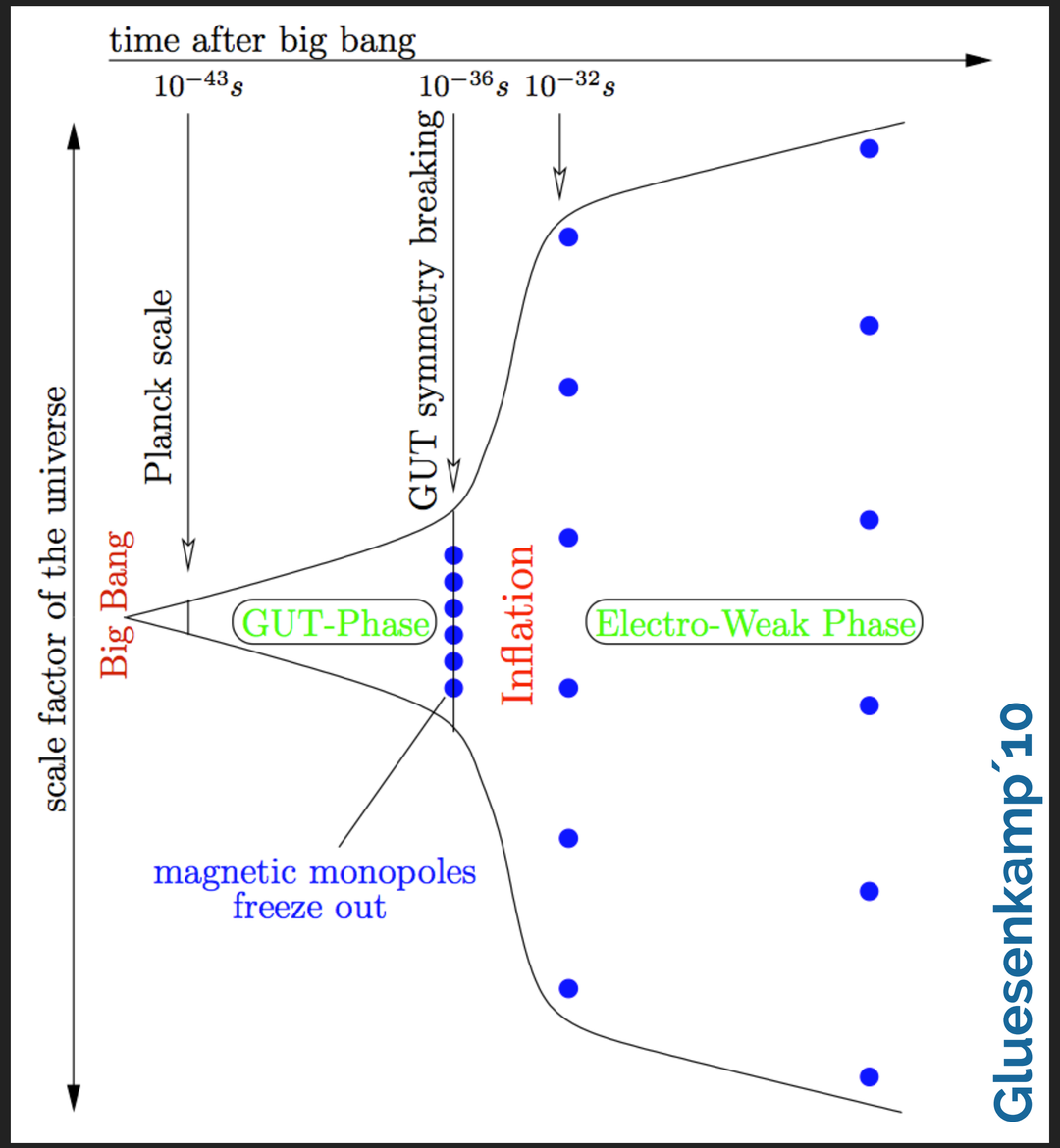
$$\vec{\nabla} \cdot \vec{B} = 4\pi\rho_M$$

$$-\vec{\nabla} \times \vec{E} = \frac{1}{c}\frac{\partial \vec{B}}{\partial t} + \frac{4\pi}{c}\vec{j}_m$$

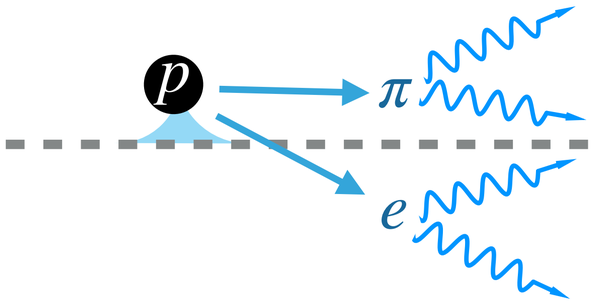
- Dirac monopoles can explain quantification of charge

$$g = \frac{2\pi\hbar}{\mu_0 e} n$$

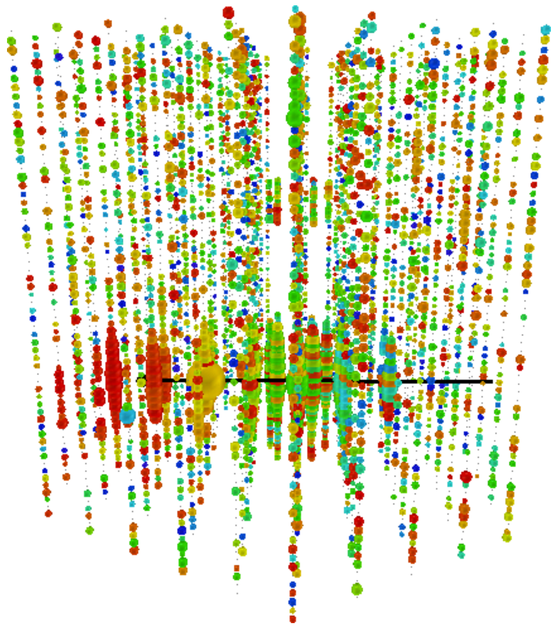
- GUT monopoles give a mass range:
  10^{13} GeV < M_{MM} < 10^{19} GeV
- GUT monopoles created before inflation and they are stable
- They are easily accelerated
  E_{kin} < 10^{15} GeV (M_{MM} < 10^{14} GeV)



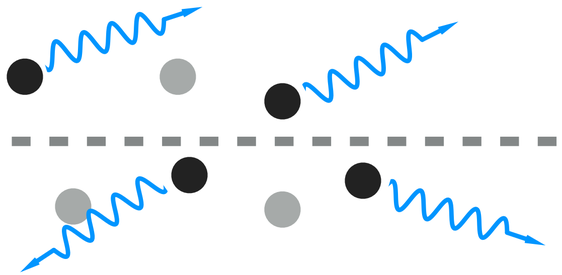
Searching for Monopoles Signatures



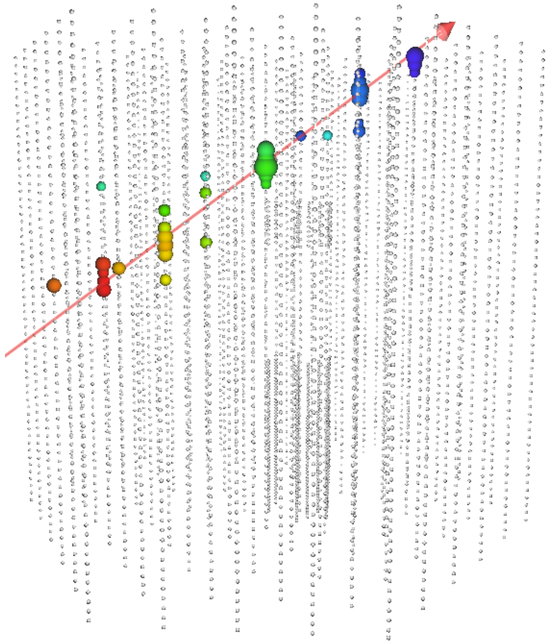
Catalysis of proton decay



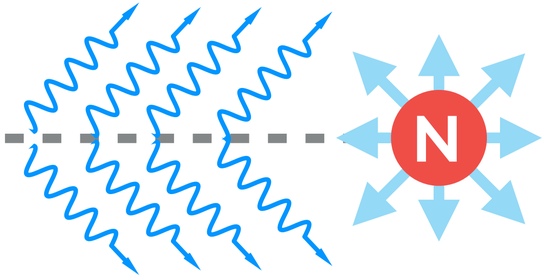
SLOW β < 0.1



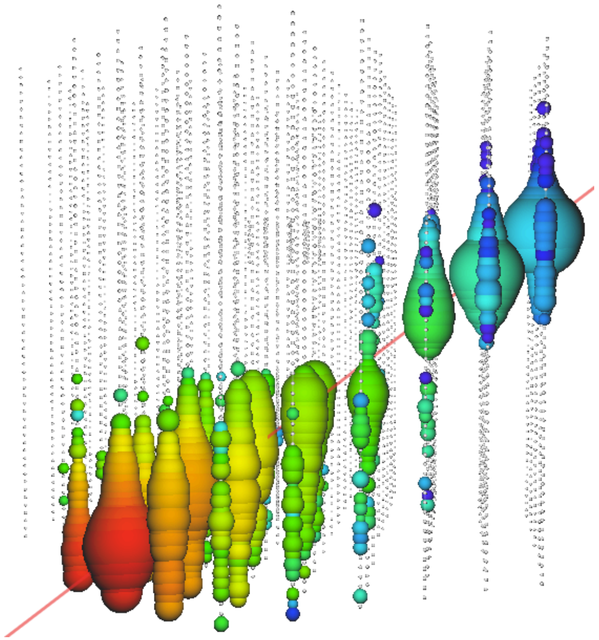
Luminescence



FAST 0.1 < β < 0.5

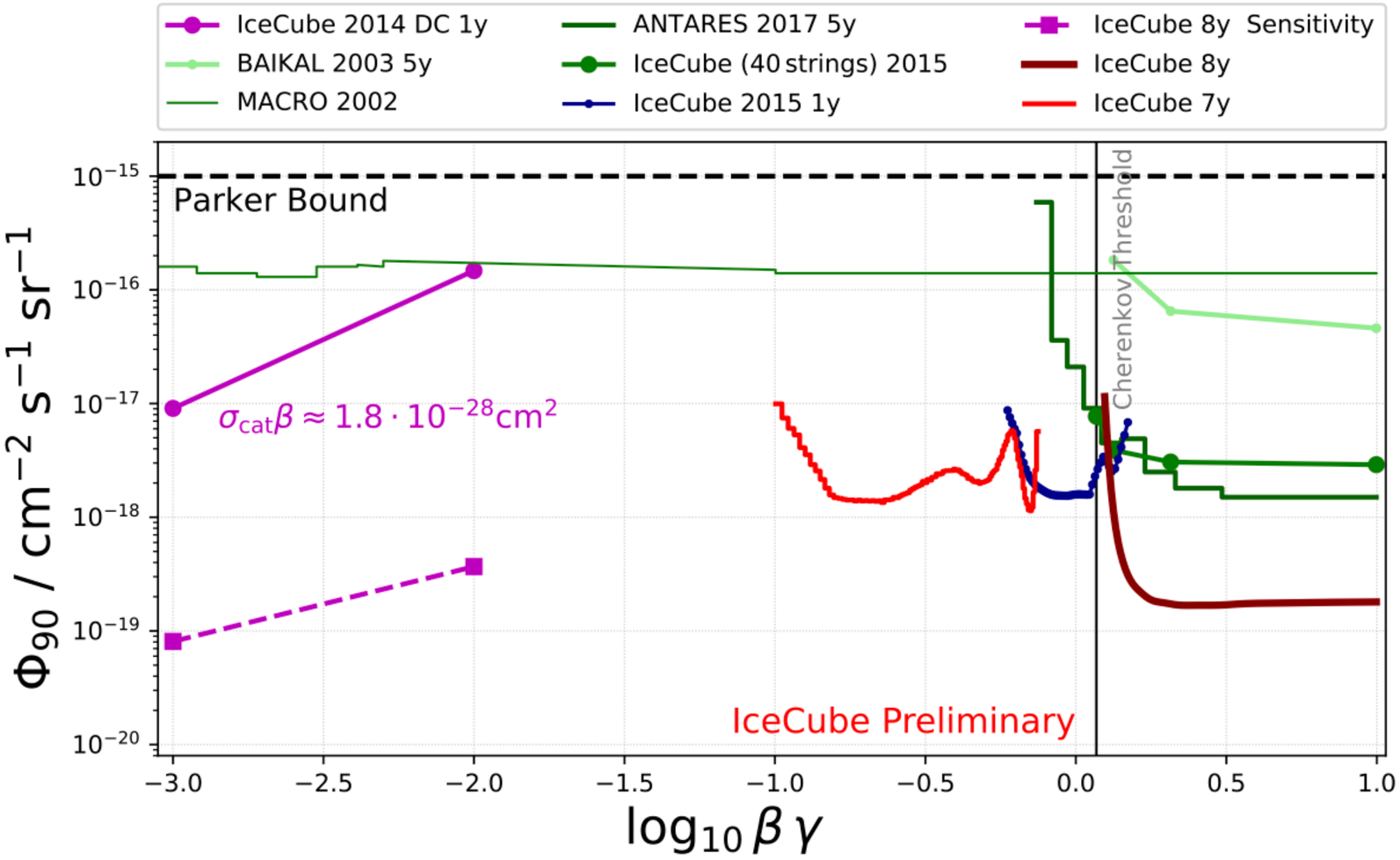


Direct/indirect Cherenkov



RELATIVISTIC β > 0.5

Monopole Searches: State of Art

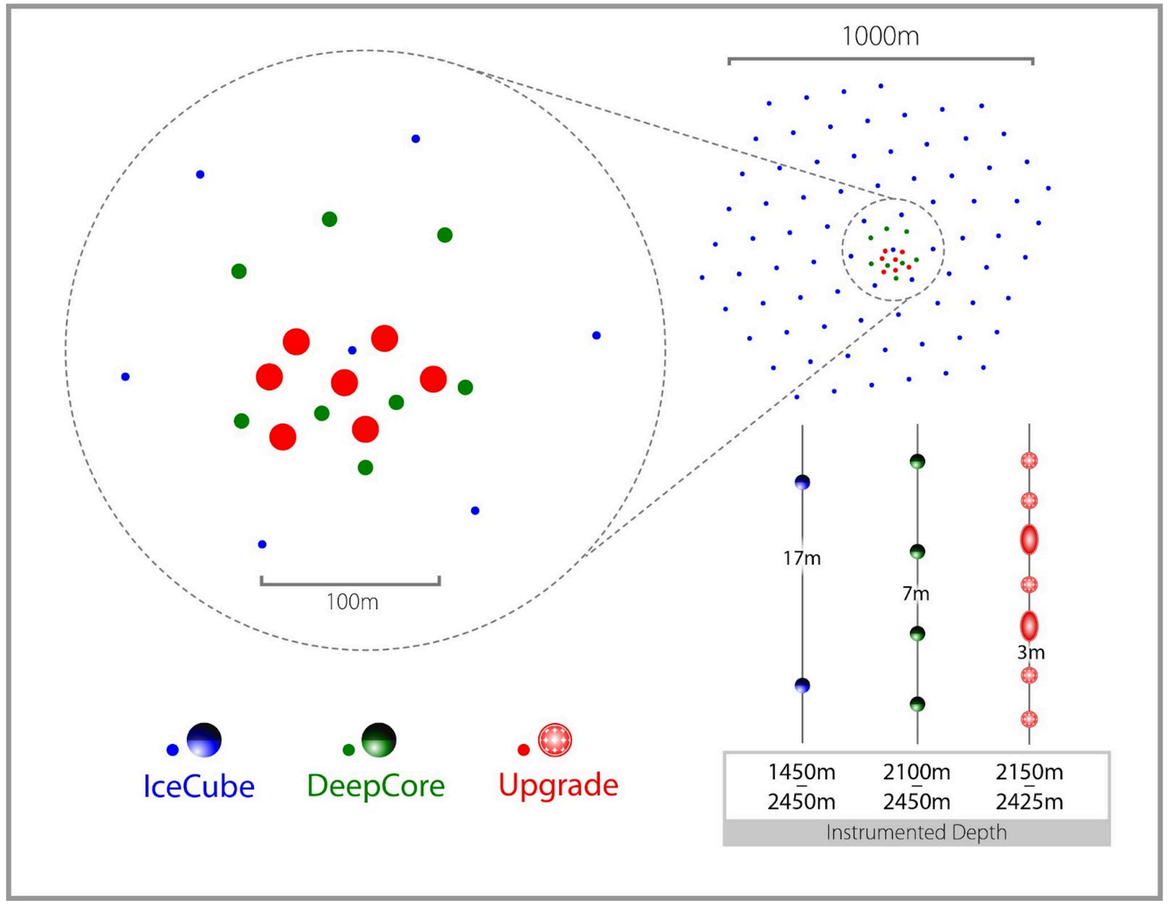


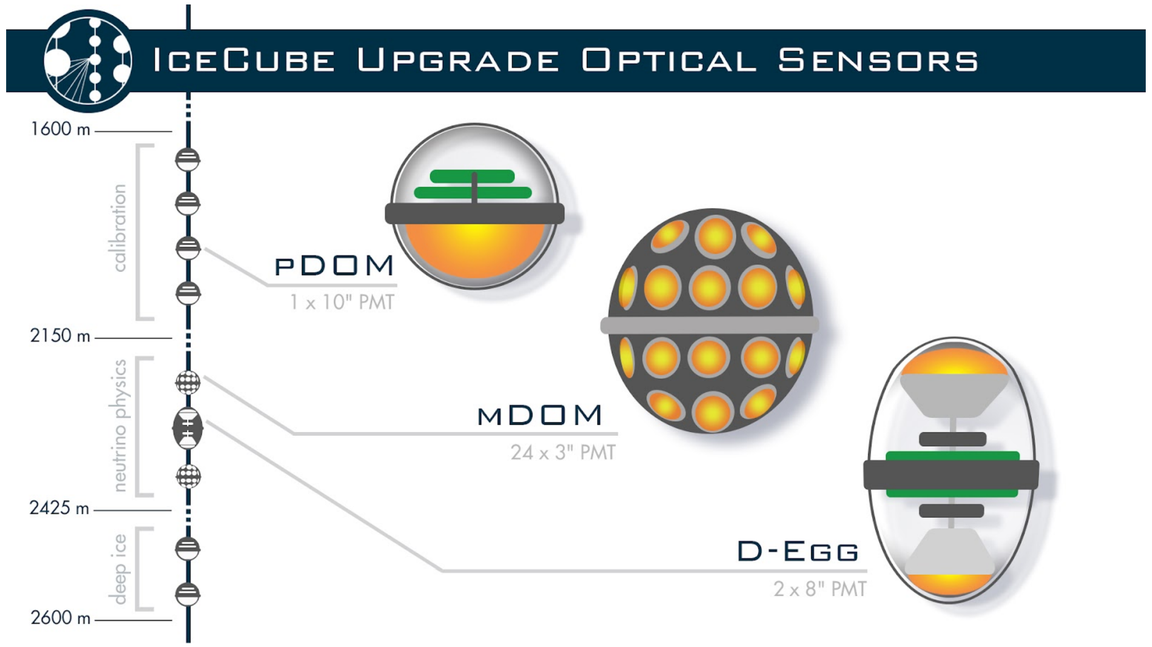
[Phys. Rev. Lett. 128, 051101 (2022)]

Catalysis | **Luminescence** | **Cherenkov light**

The Future: Lower Energies

IceCube Upgrade

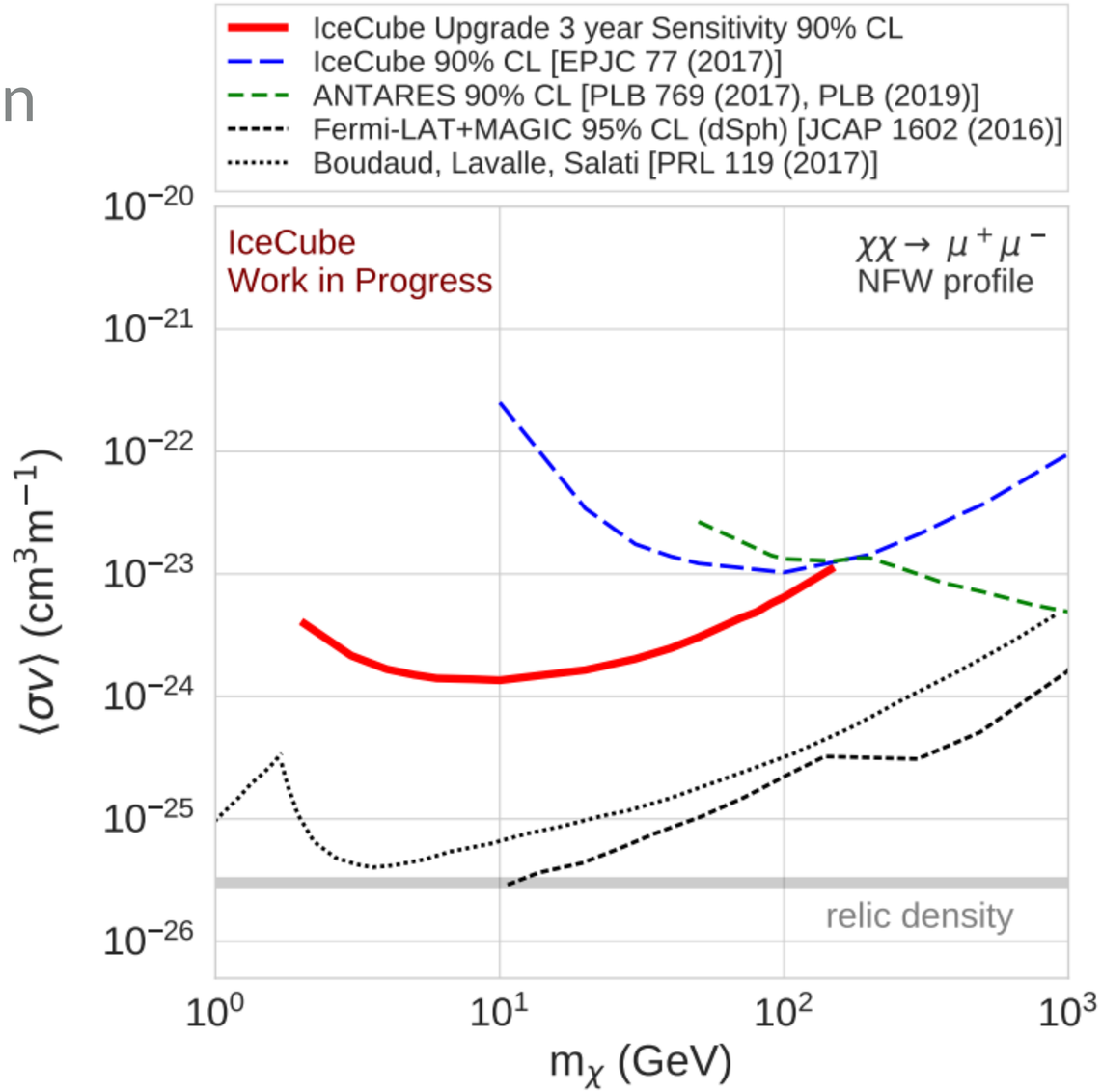




- Seven new in-filled strings
- Better efficiency and reconstruction at low energies
- Delayed due to Covid-19: deployment in 2025/26 season.

The Future: Dark Matter Halo Energies

- Better efficiency and reconstruction at low energies
- Detailed calibration of ice properties.
- Unprecedented sensitivity to atmospheric **neutrino mixing parameters and neutrino mass ordering**
- Expanding beyond the WIMP paradigm (**GeV dark matter**)



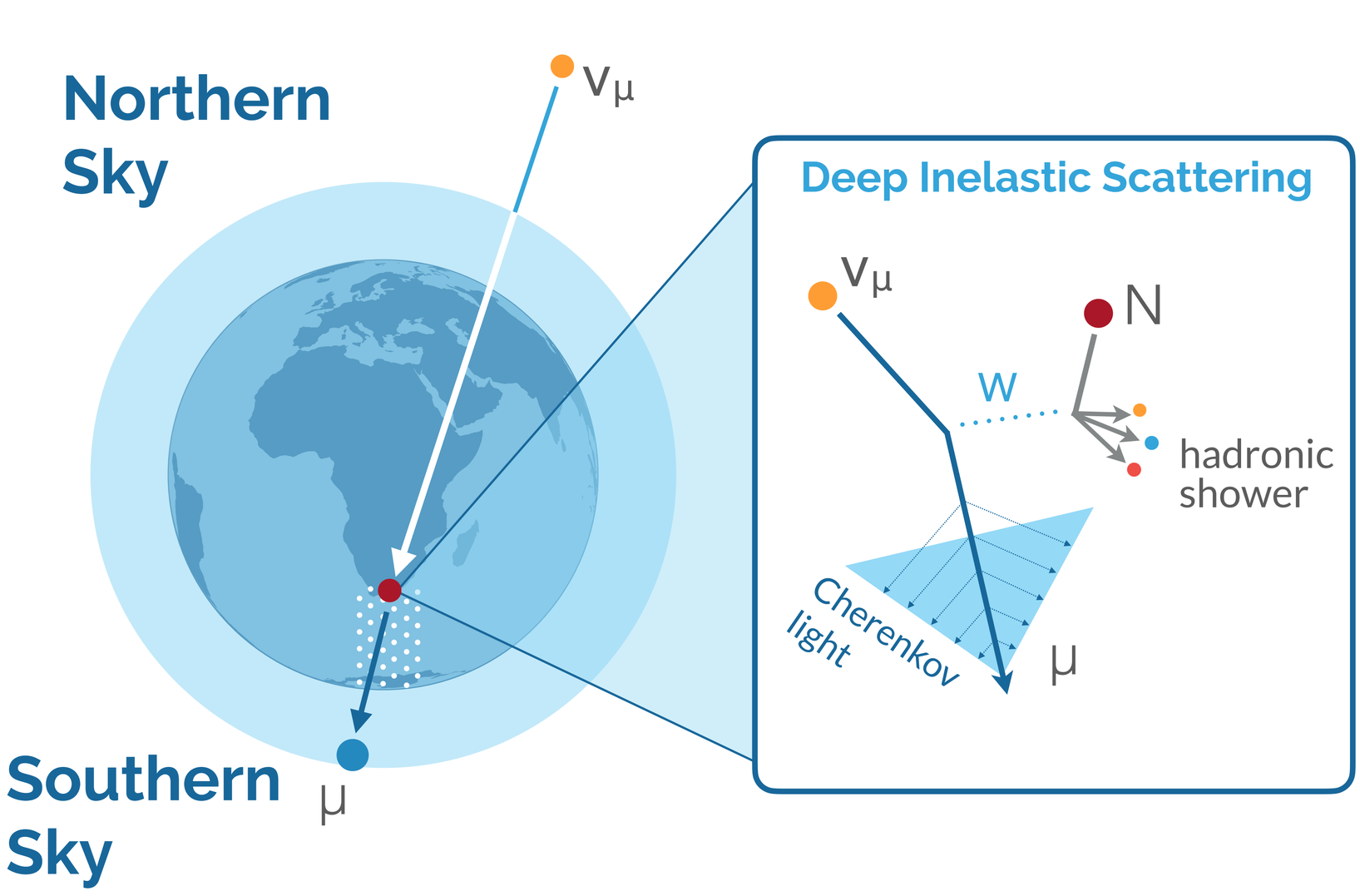
[PoS (ICRC2019) 506]

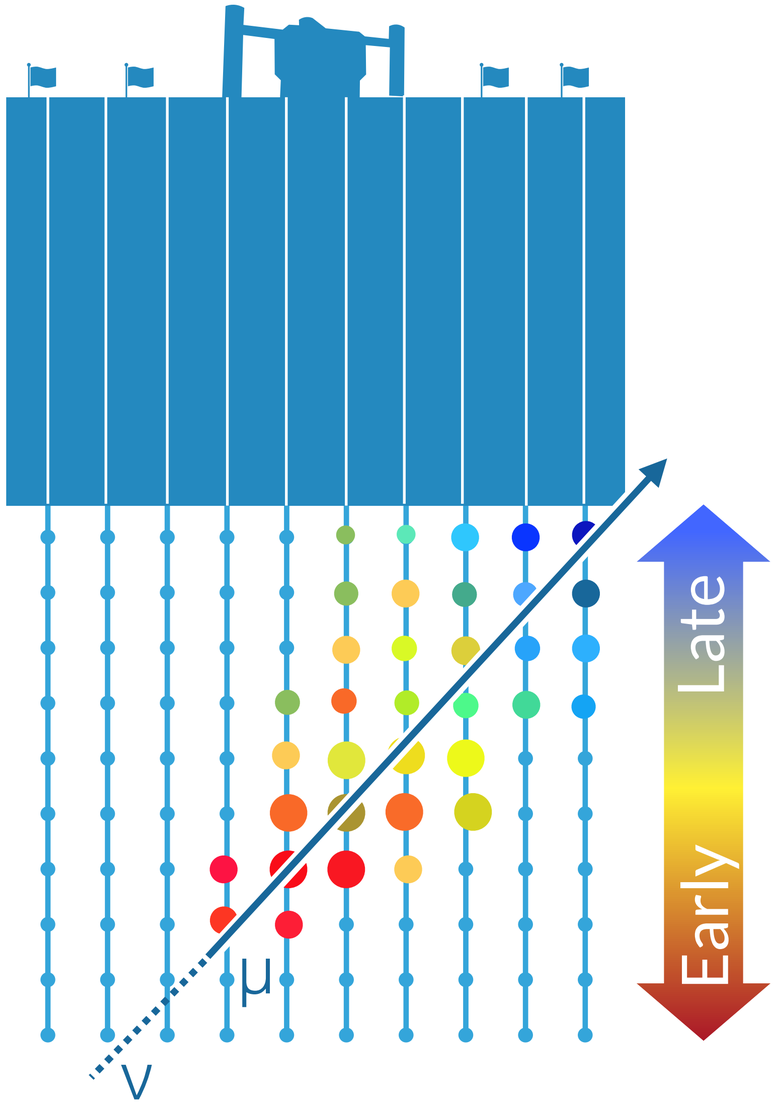
Conclusions

- The IceCube Neutrino Observatory is a **multipurpose experiment** with a rich program on **BSM and Dark Matter searches**:
  - Indirect detection of Dark Matter with neutrino telescopes provides complementarity to other techniques due to different backgrounds and systematics.
  - Atmospheric neutrinos fluxes can help to search for new physics in the oscillation patterns.
  - Neutrino telescopes can also provide a unique way to search for monopoles and exotic particles such as Q-balls.

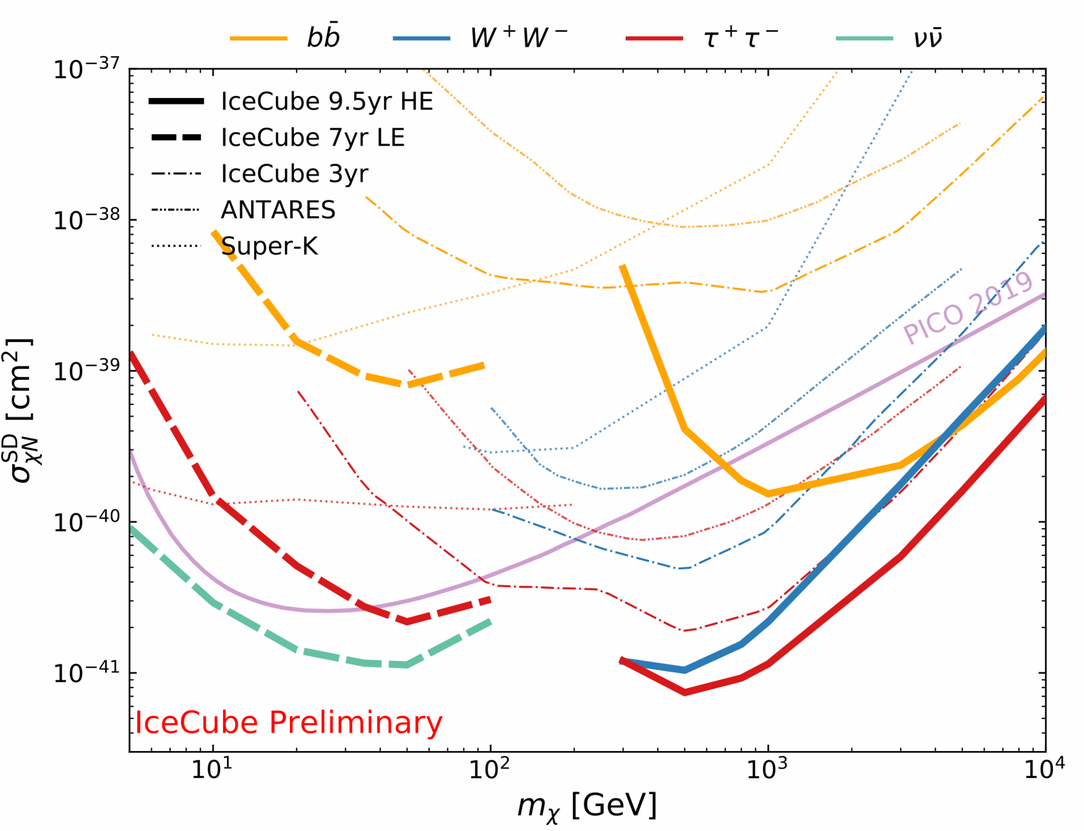
backups

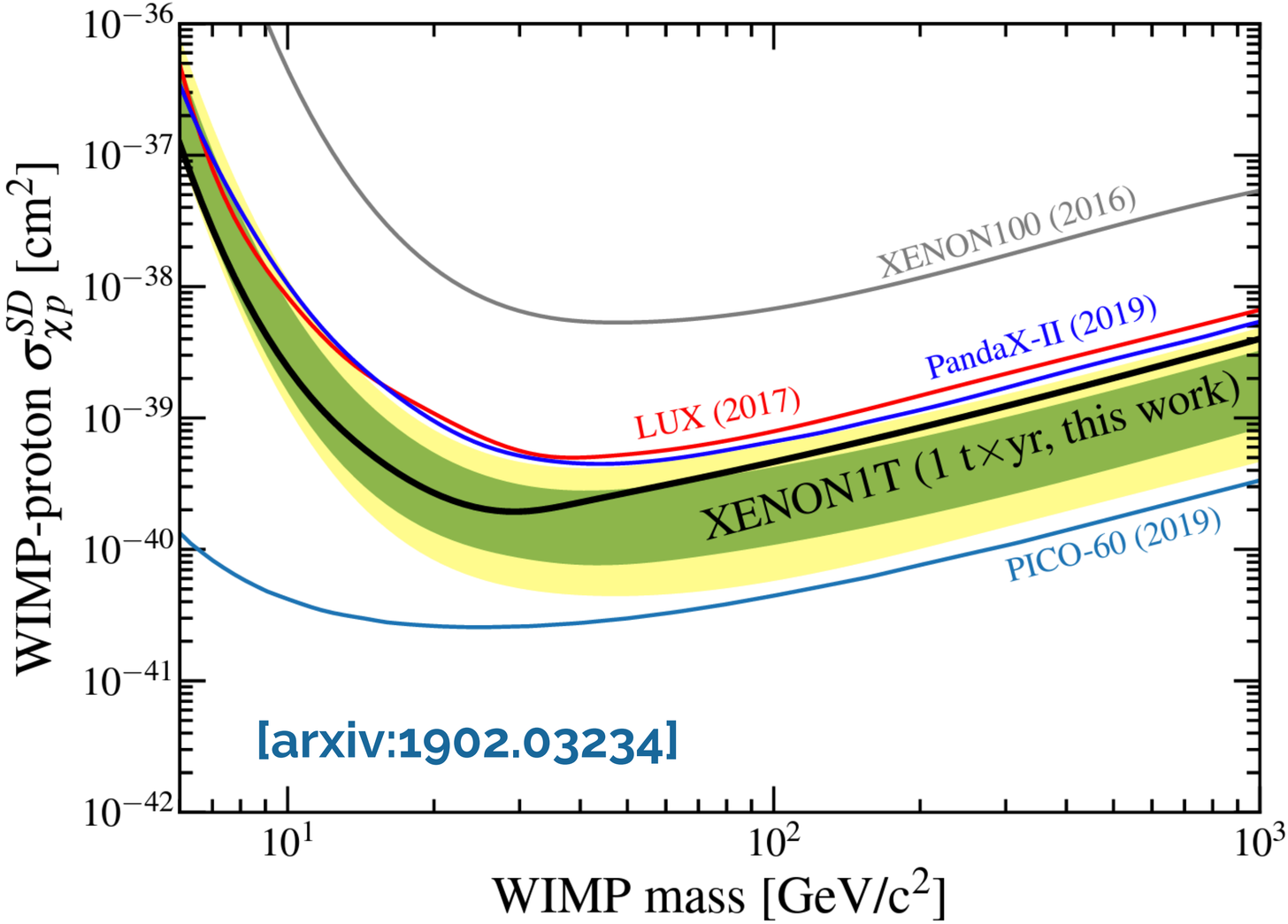
Detection Principle How Do We Detect Neutrinos?





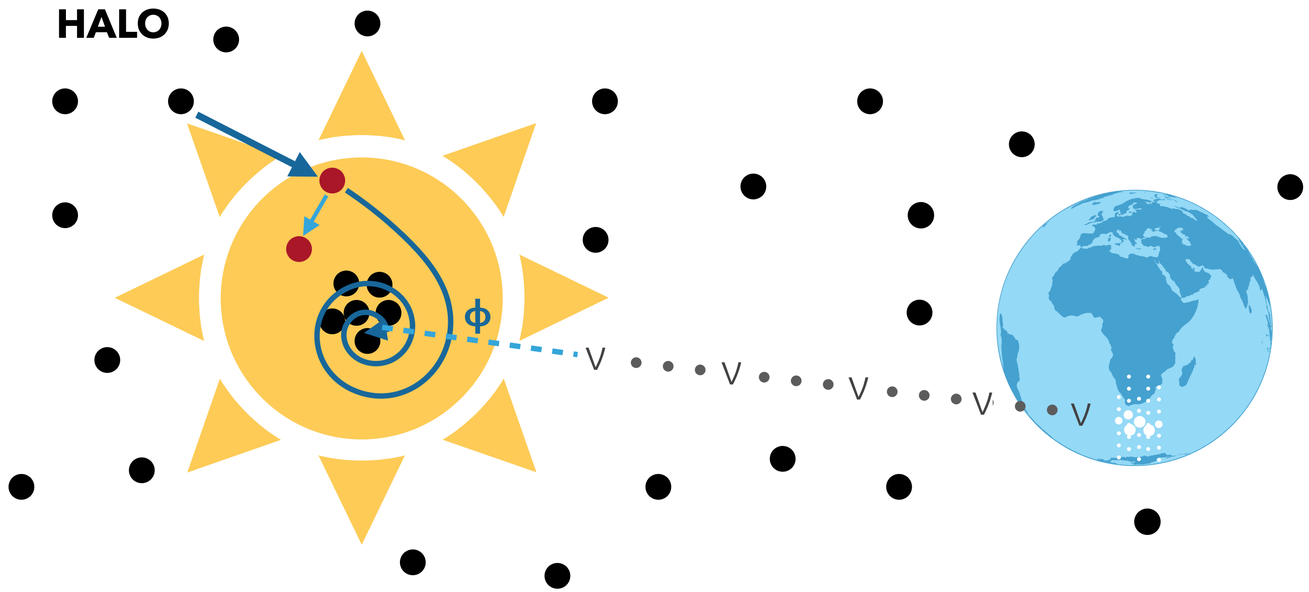
Celestial Bodies: The Sun

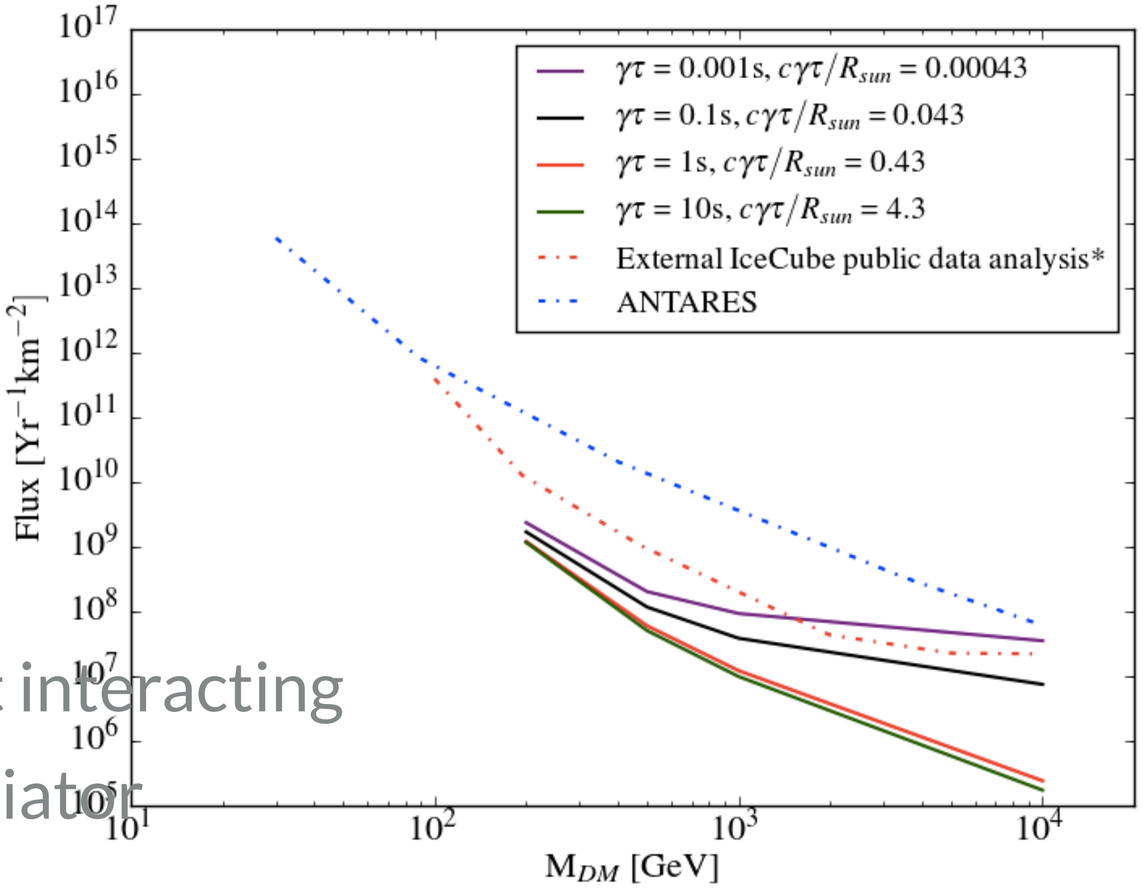




Strongest limits on the spin-dependent cross section

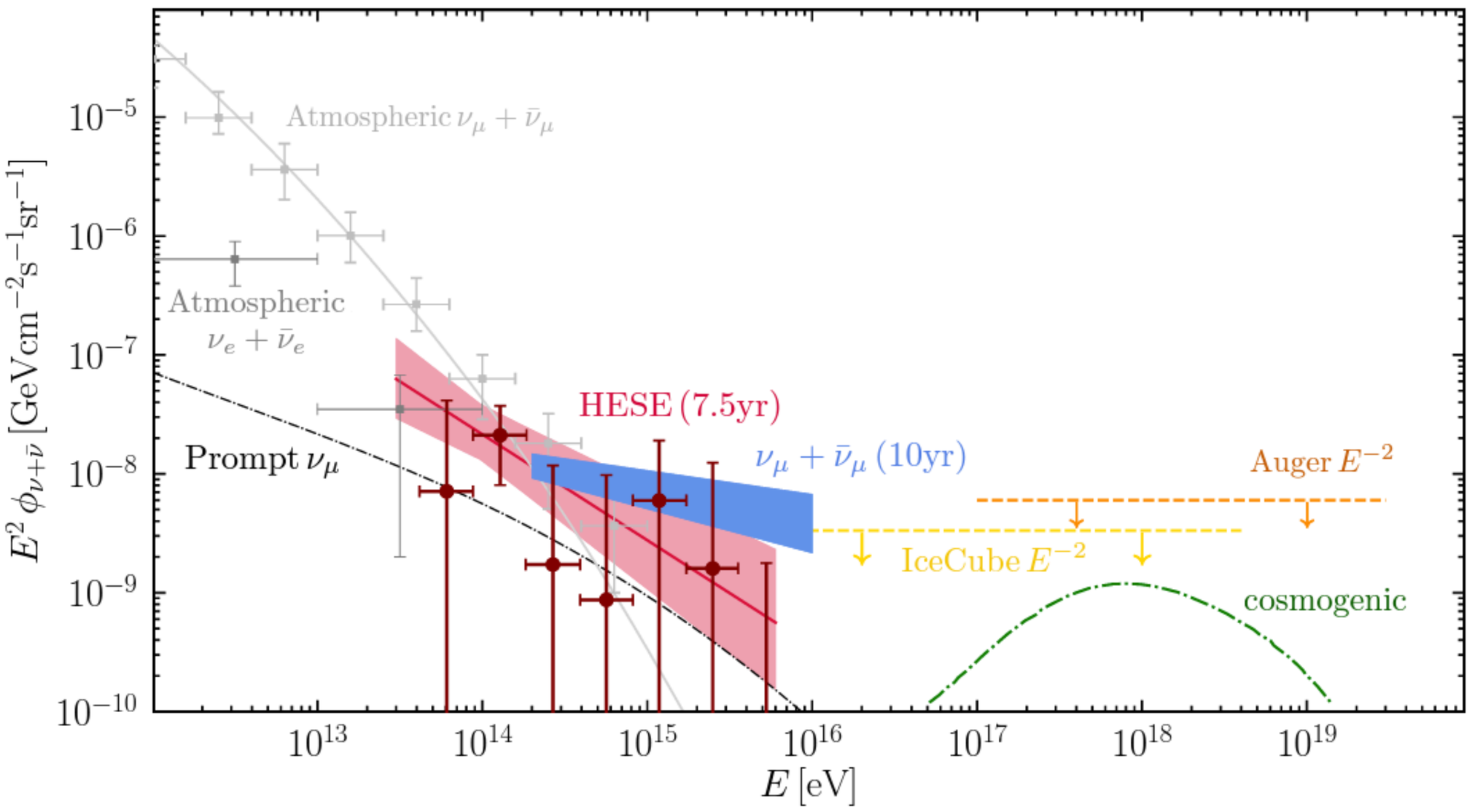
Celestial Bodies Secluded DM





- Dark matter annihilates in 2 mediators
- The mediator can escape the Sun without interacting
- Signal depends on the lifetime of the mediator

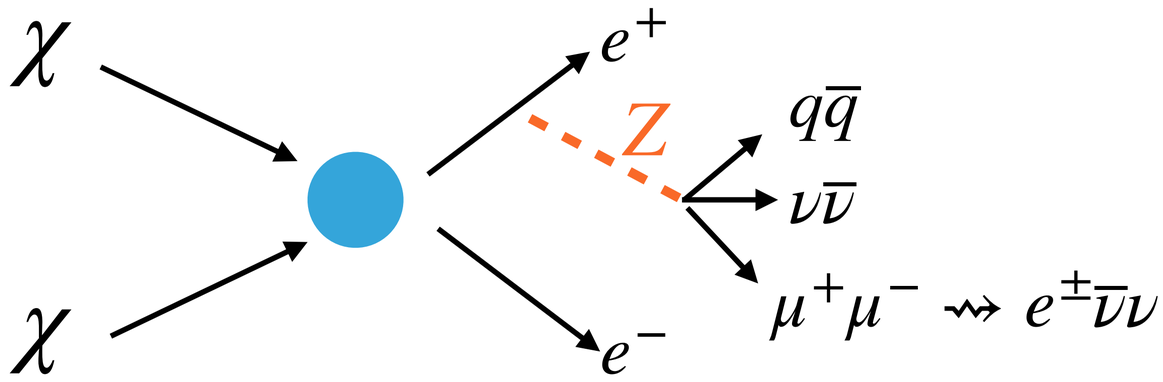
Astrophysical Neutrino Flux: State of Art

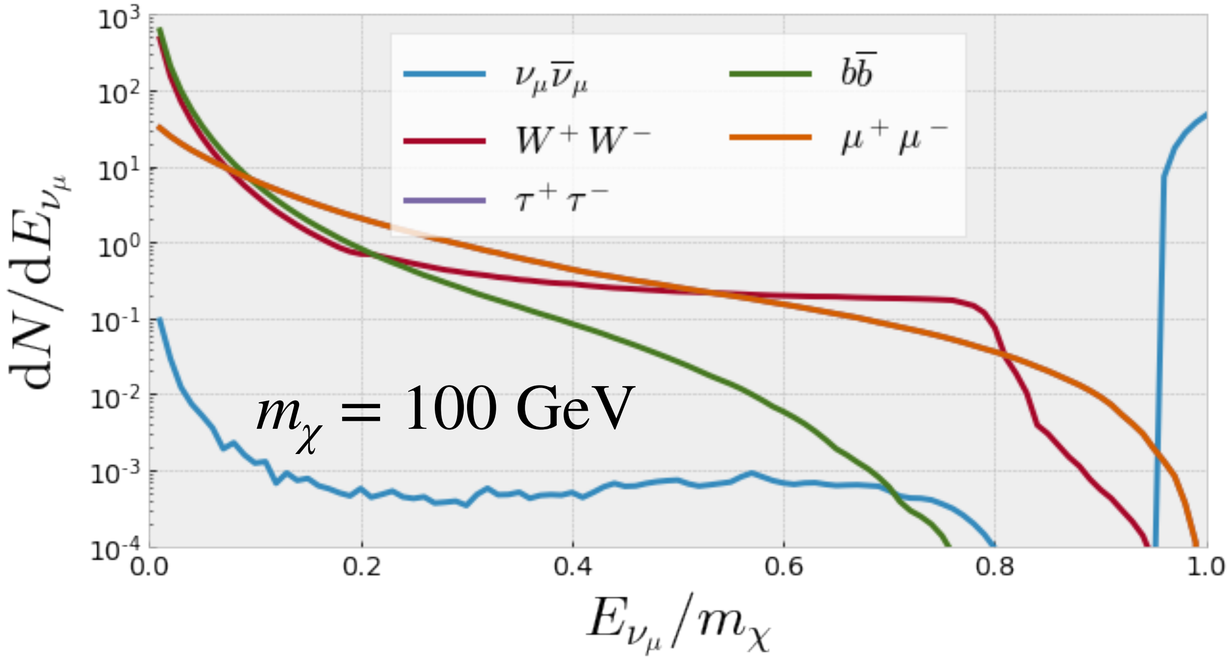


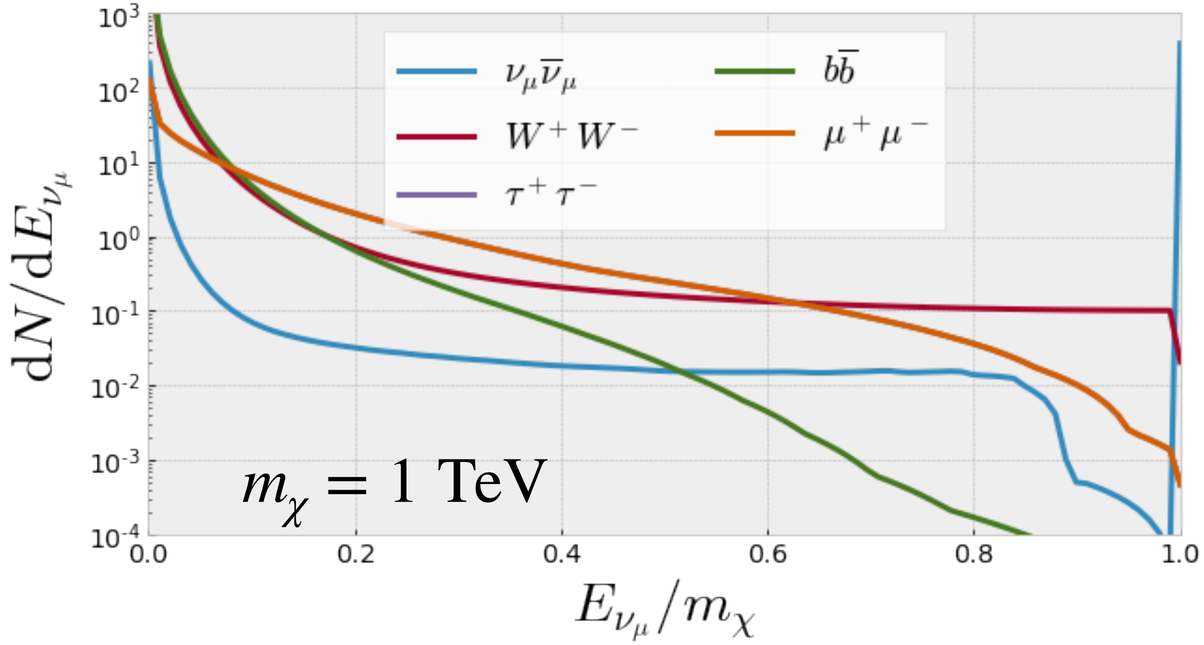
The Galactic Center The Particle Physics Input

- Neutrino Spectra from primary (neutrino lines) and secondary production ($W^+W^-, \tau^+\tau^-, \ldots$)

*https://arxiv.org/abs/1012.4515

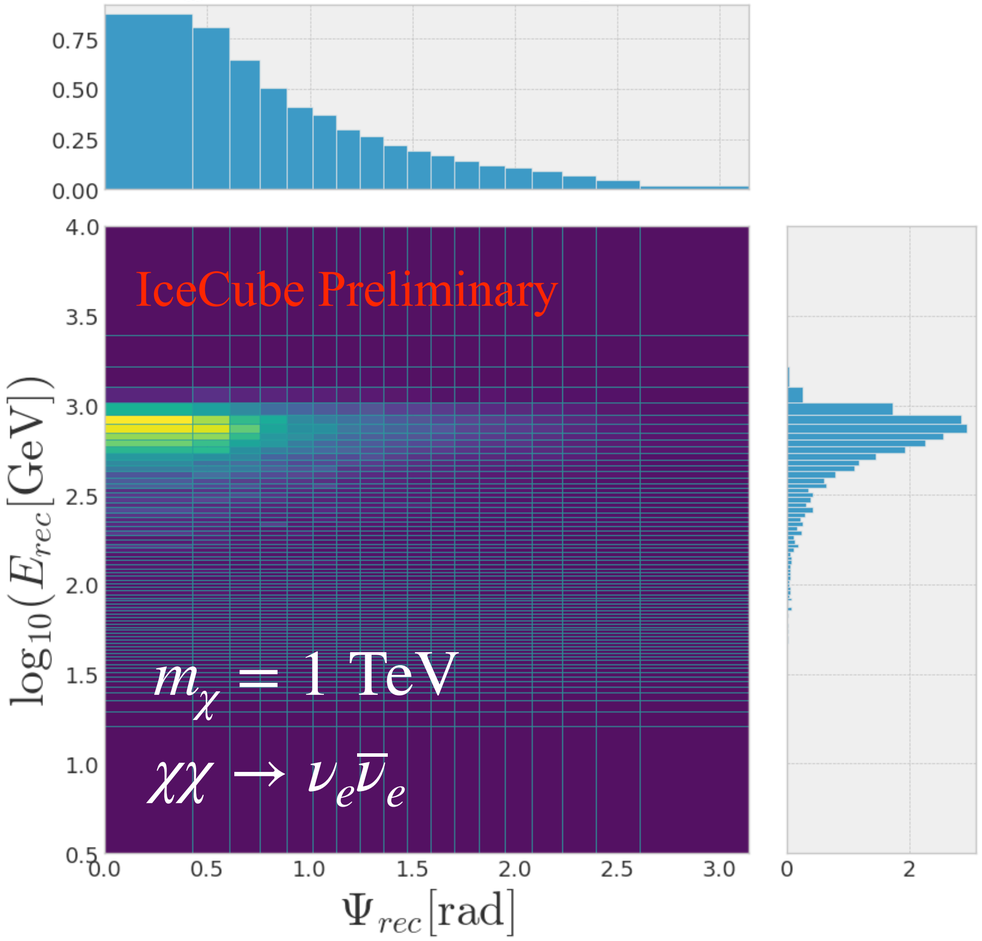




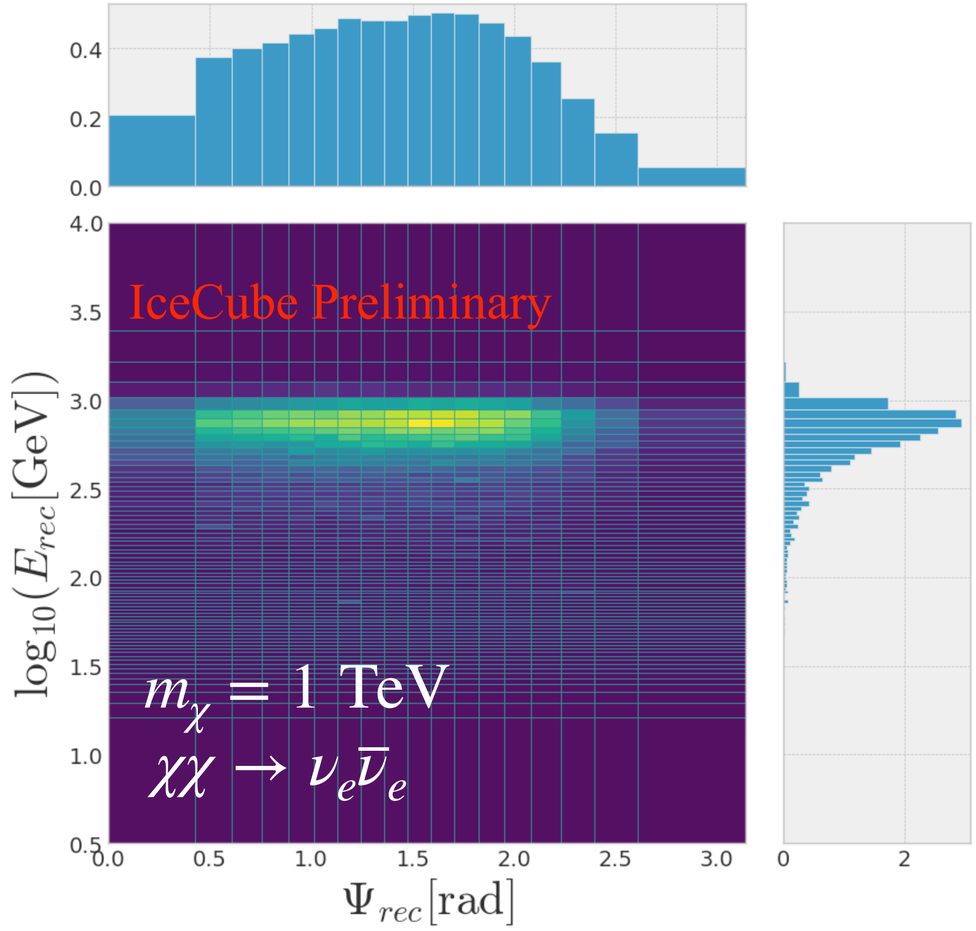


Analysis: Signal PDFs

Signal (HE sample)

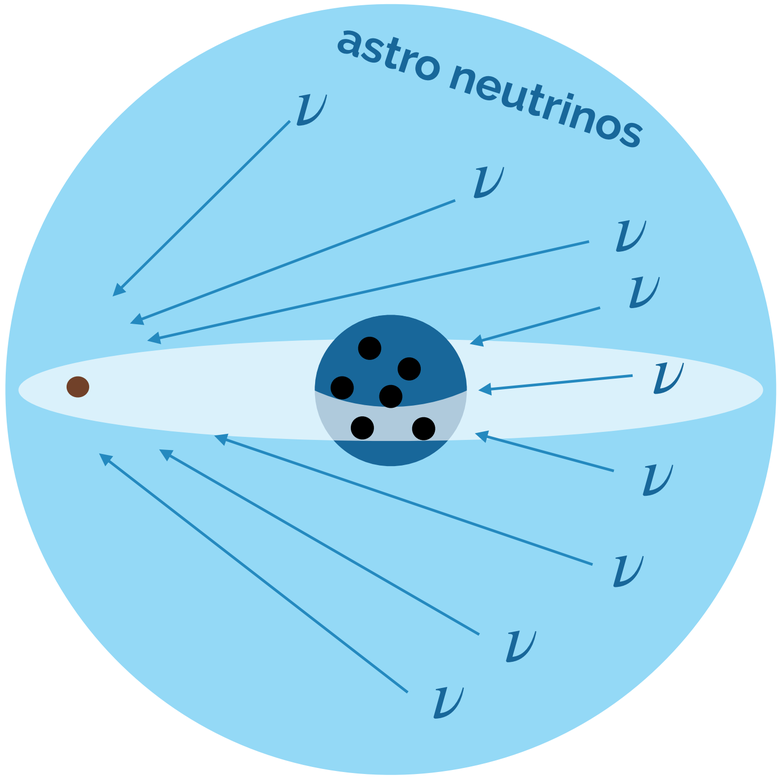


Scrambled Signal (HE sample)



- Binning follows the same binning as the background PDF.

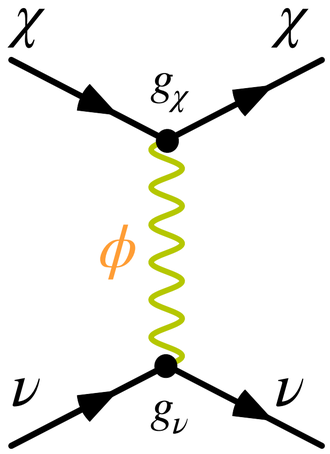
Neutrino-Dark Matter Scattering



- Astrophysical neutrinos assumed to be extra-Galactic:
  - **Isotropic distribution of arrival directions.**
- Scattering of high energy cosmic neutrinos on DM:
  - **Deficit in the direction of Galactic Center**
- Two simplified models tested:

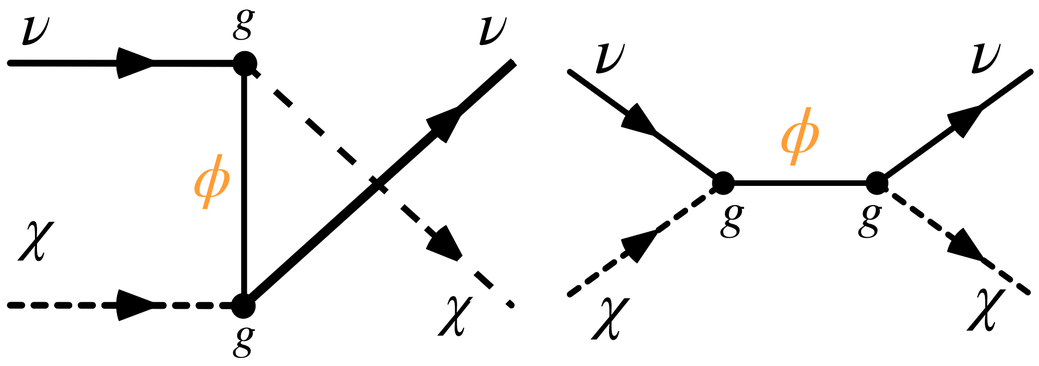
Fermion—vector

$(S_\chi, S_\phi) = (1/2,1)$



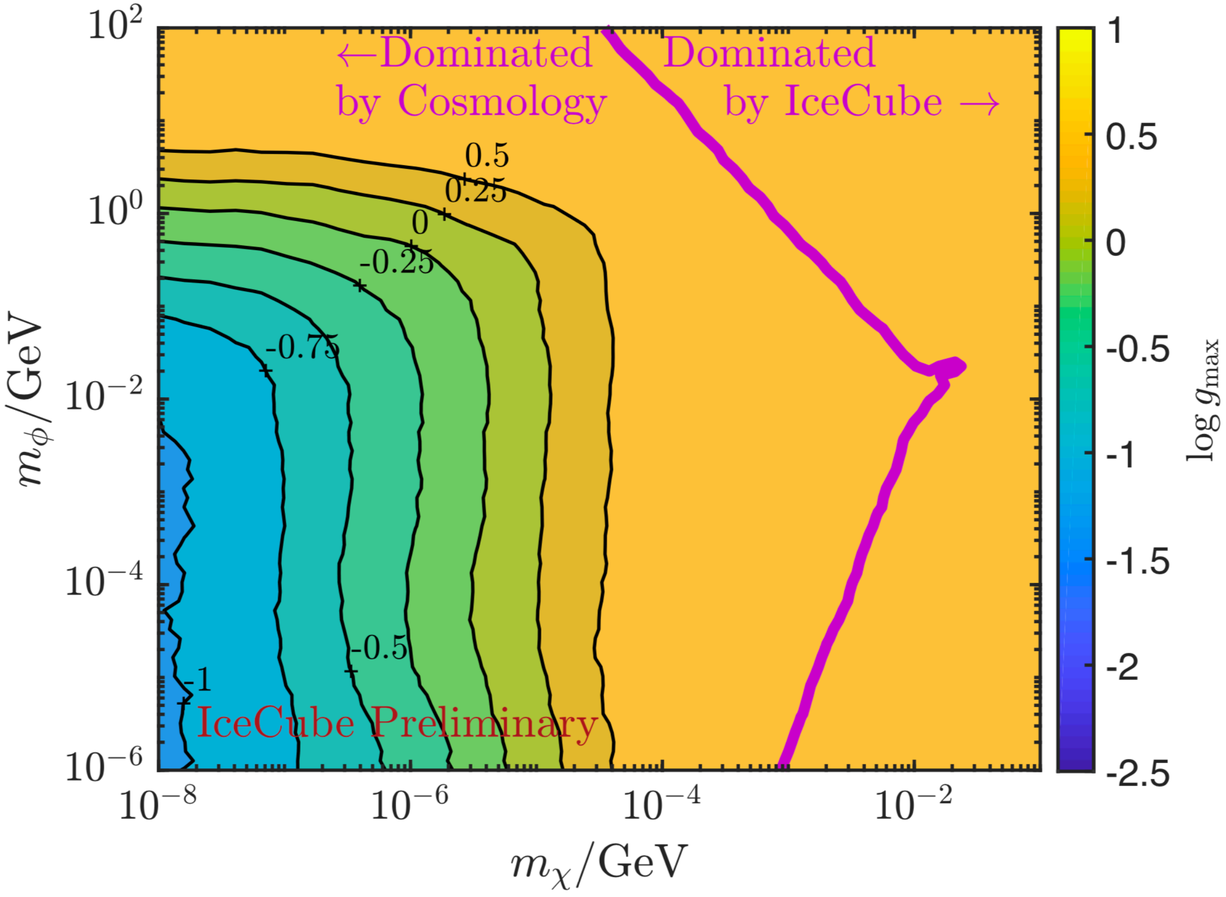
Scalar—Fermion

$(S_\chi, S_\phi) = (0,1/2)$

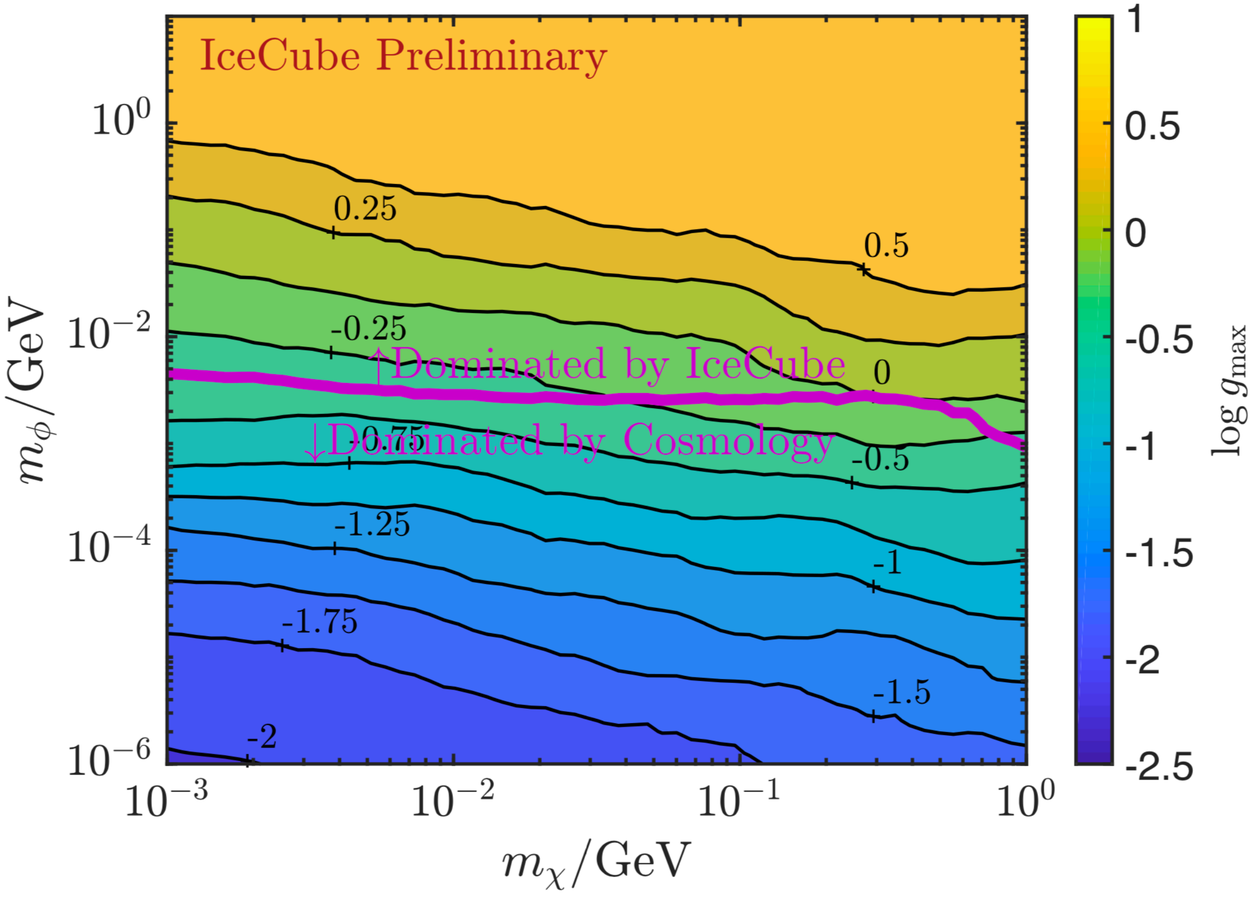


Neutrino-Dark Matter Scattering

Scalar—Fermion

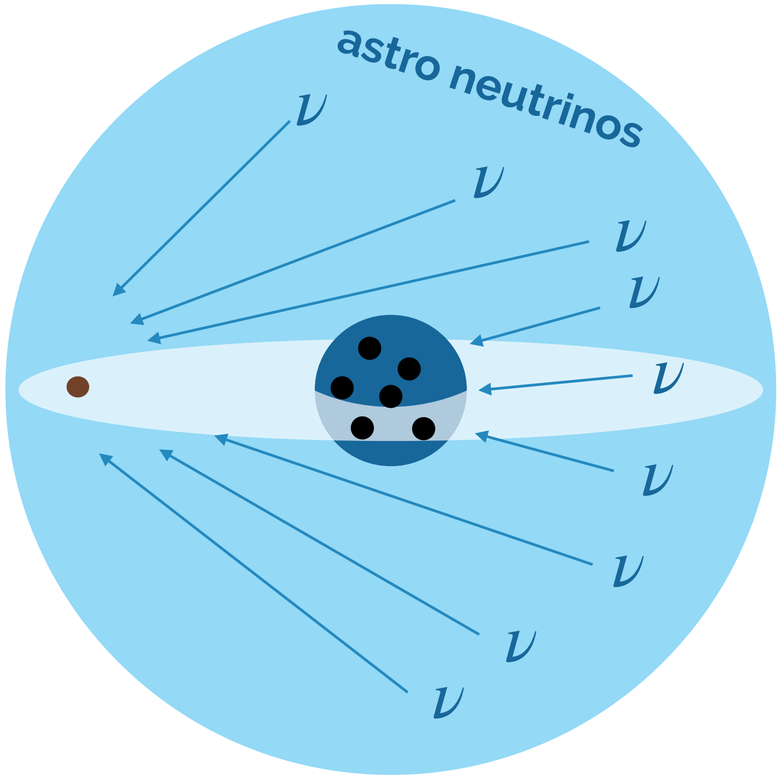


Fermion—vector

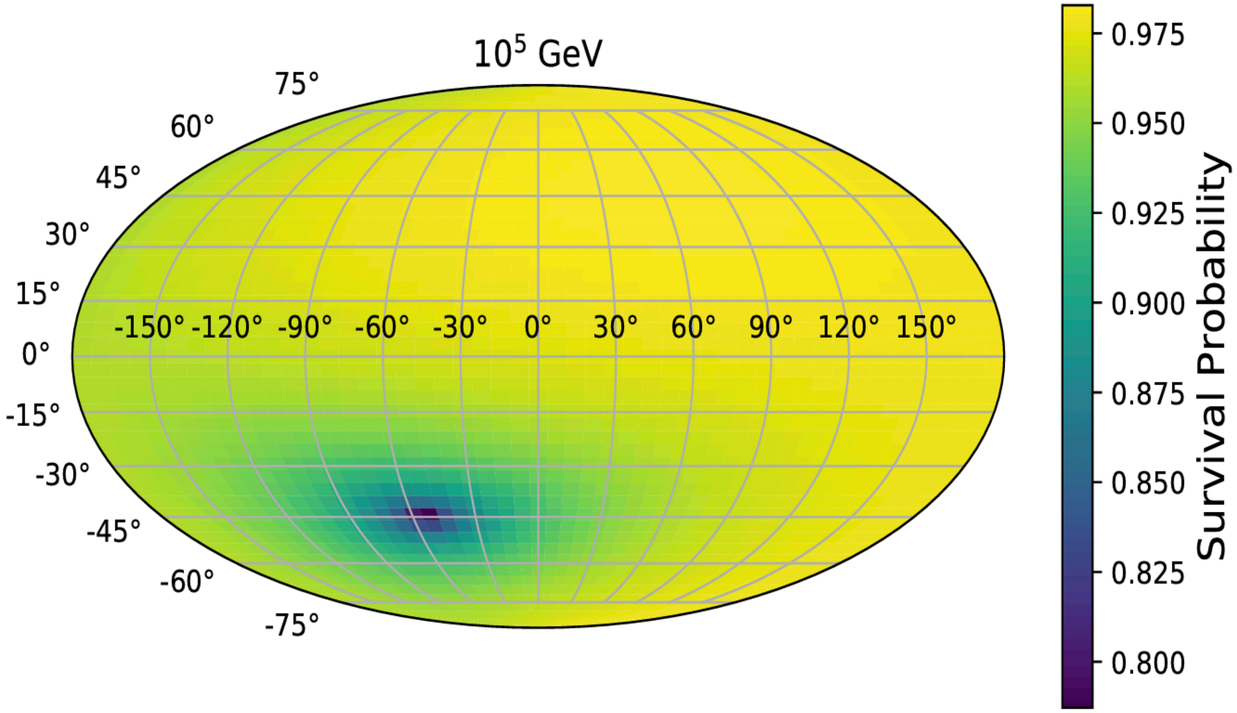


[Neutrino 2012, doi:10.5281/zenodo.1300506]

Neutrino-Dark Matter Scattering

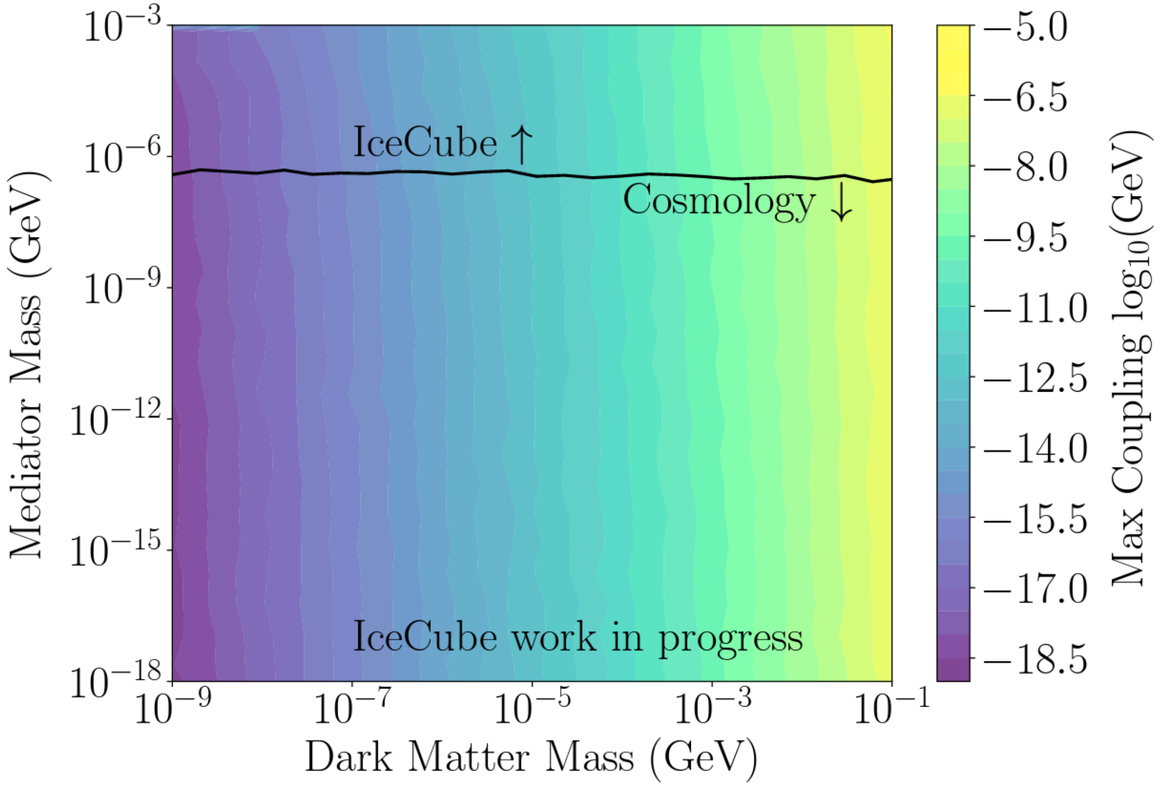


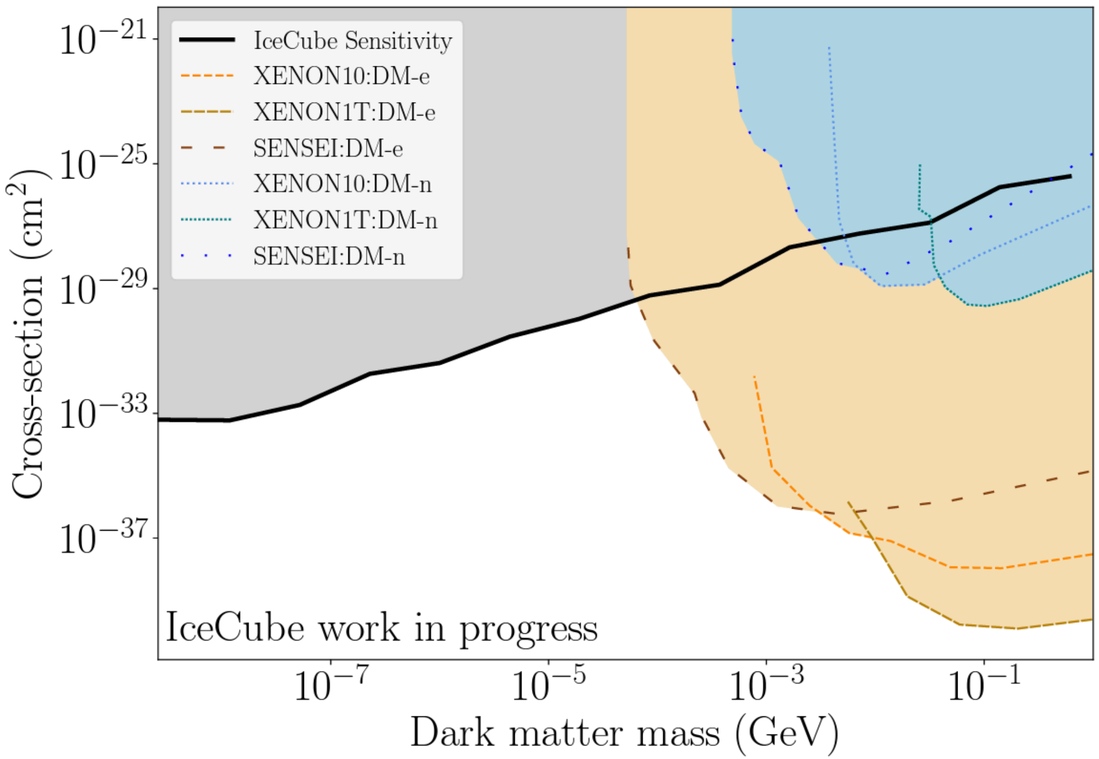
- Astrophysical neutrinos assumed to be extra-Galactic:
  - **Isotropic distribution of arrival directions.**
- Scattering of high energy cosmic neutrinos on DM:
  - **Deficit in the direction of Galactic Center**



Neutrino-Dark Matter Scattering

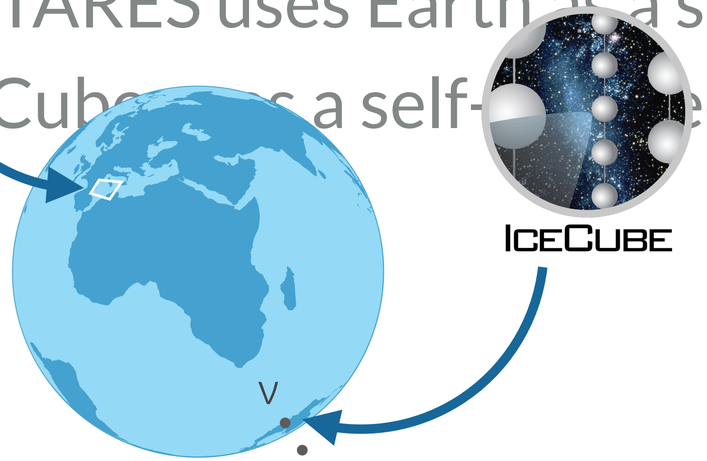
[PoS(ICRC2021)569]





Galactic Center ANTARES &

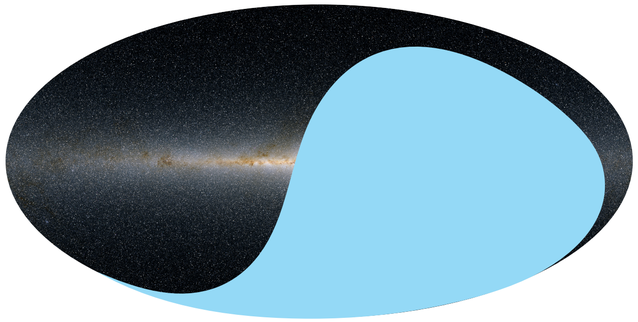
- rent best limits in neutrinos by ANTARES and IceCube
  - NTARES uses Earth as a shield/higher masses
  - IceCube s a self- echnique/lower masses



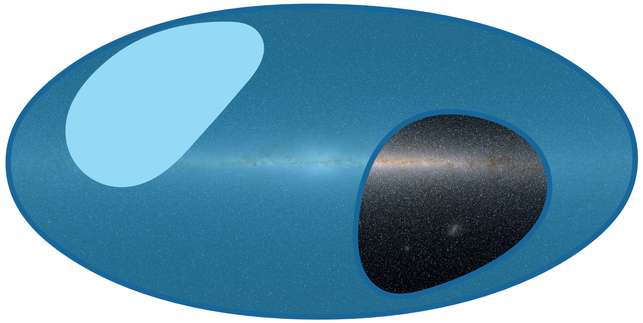
Galactic Center 30° above the horizon in IceCube field of view

Galactic Center

IceCube FoV



ANTARES FoV



The Astrophysical Input: J-factors, D-factors

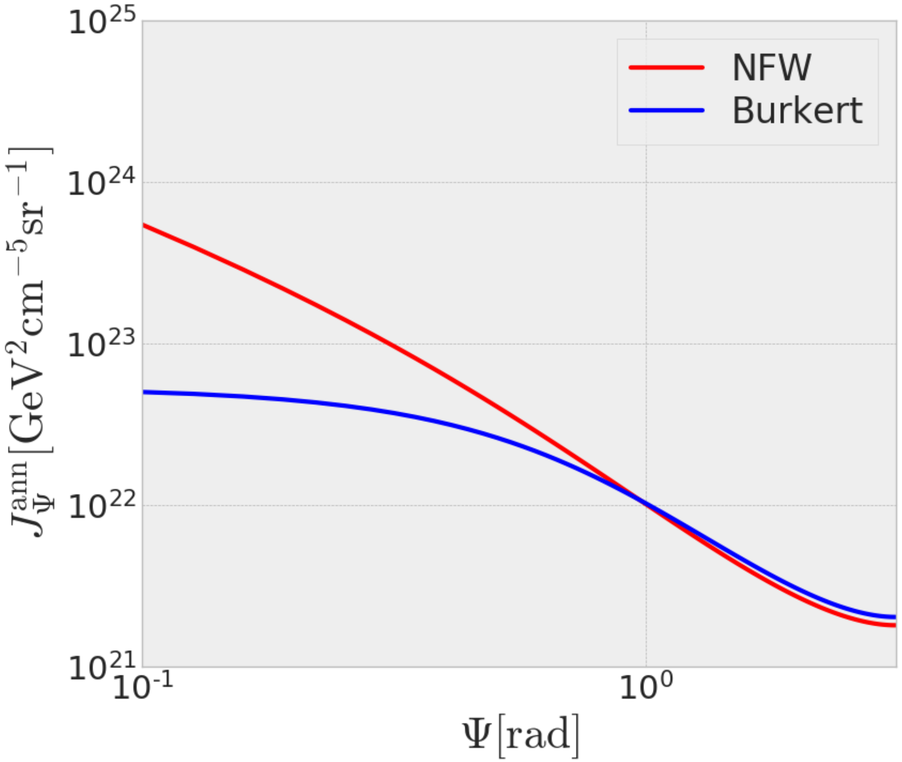
- Two archetypical density profile tested: NFW and Burkert

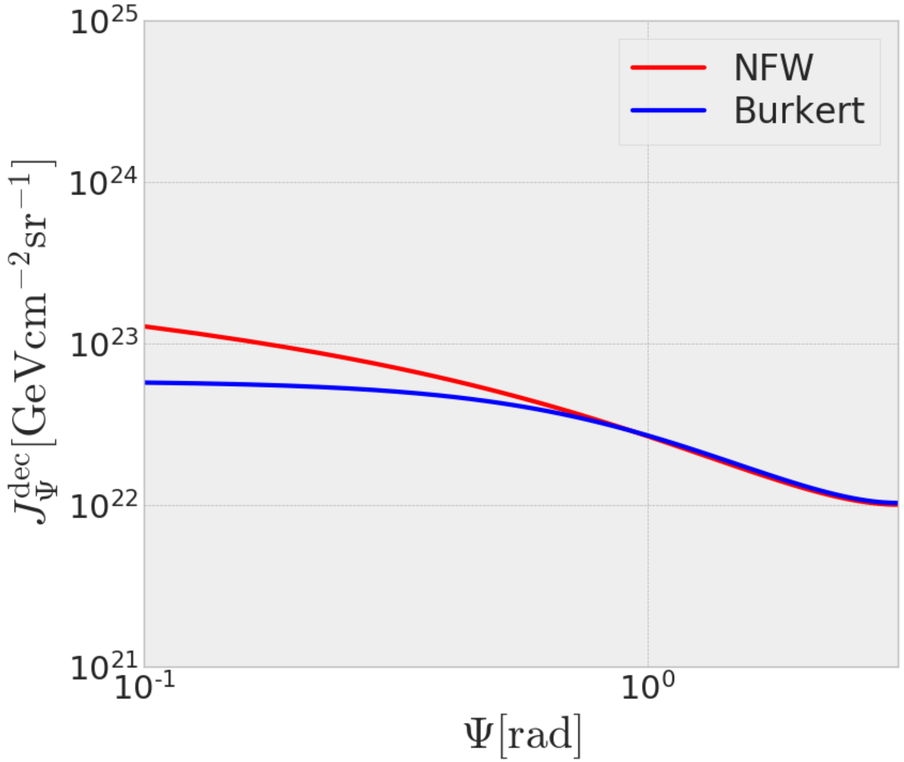
$$\rho_{Burkert}(r) = \frac{\rho_s}{(1 + r/r_s)(1 + (r/r_s)^2)}$$

$$\rho_{NFW}(r) = \rho_s \frac{r_s}{r}\left(1 + \frac{1}{r_s}\right)$$

Parameter	Units	Navarro-Frenk-White (NFW)	Burkert
ρ_0	$10^7\, M_\odot / kpc^3$	$1.40^{+2.9}_{-0.93}$	$4.13^{+6.2}_{-1.6}$
r_s	kpc	$16.1^{+17}_{-7.8}$	$9.26^{+5.6}_{-4.2}$

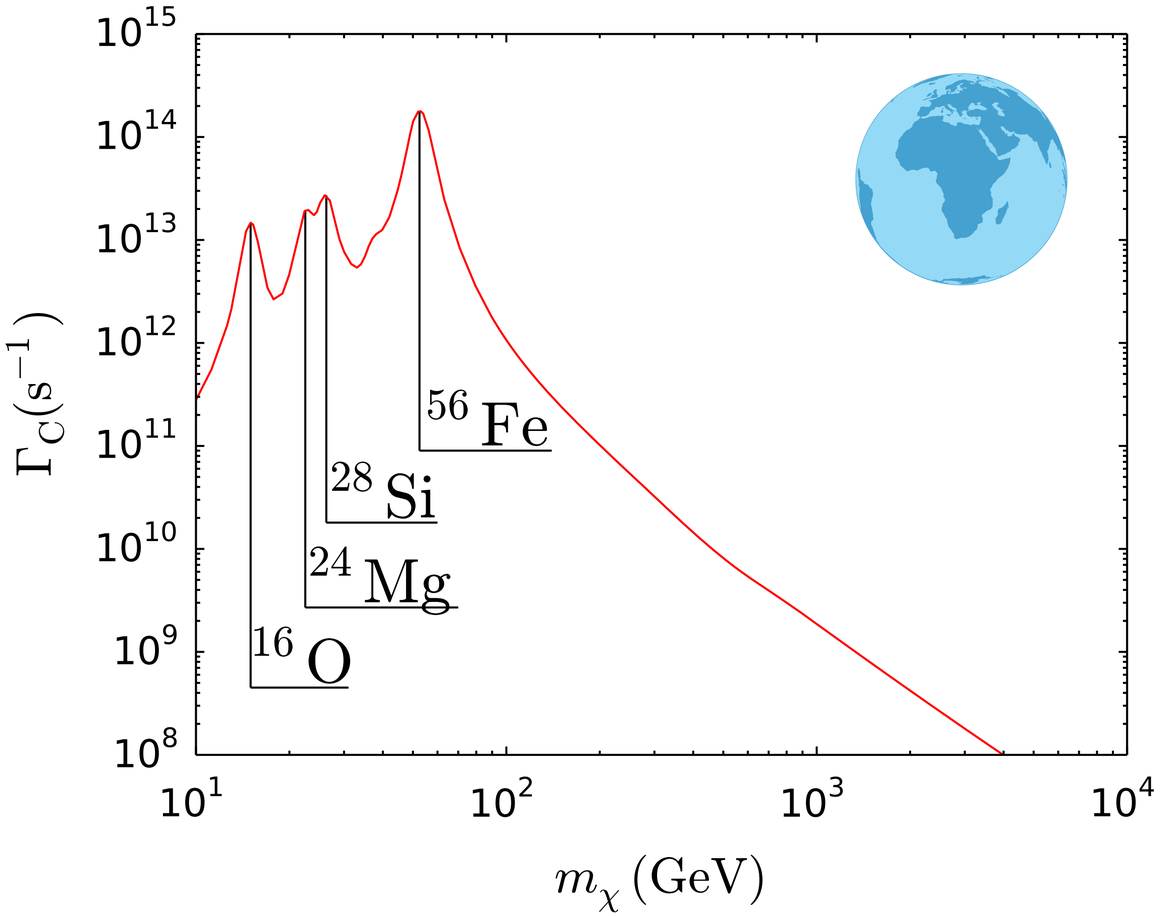
*values taken from arxiv:1304.5127





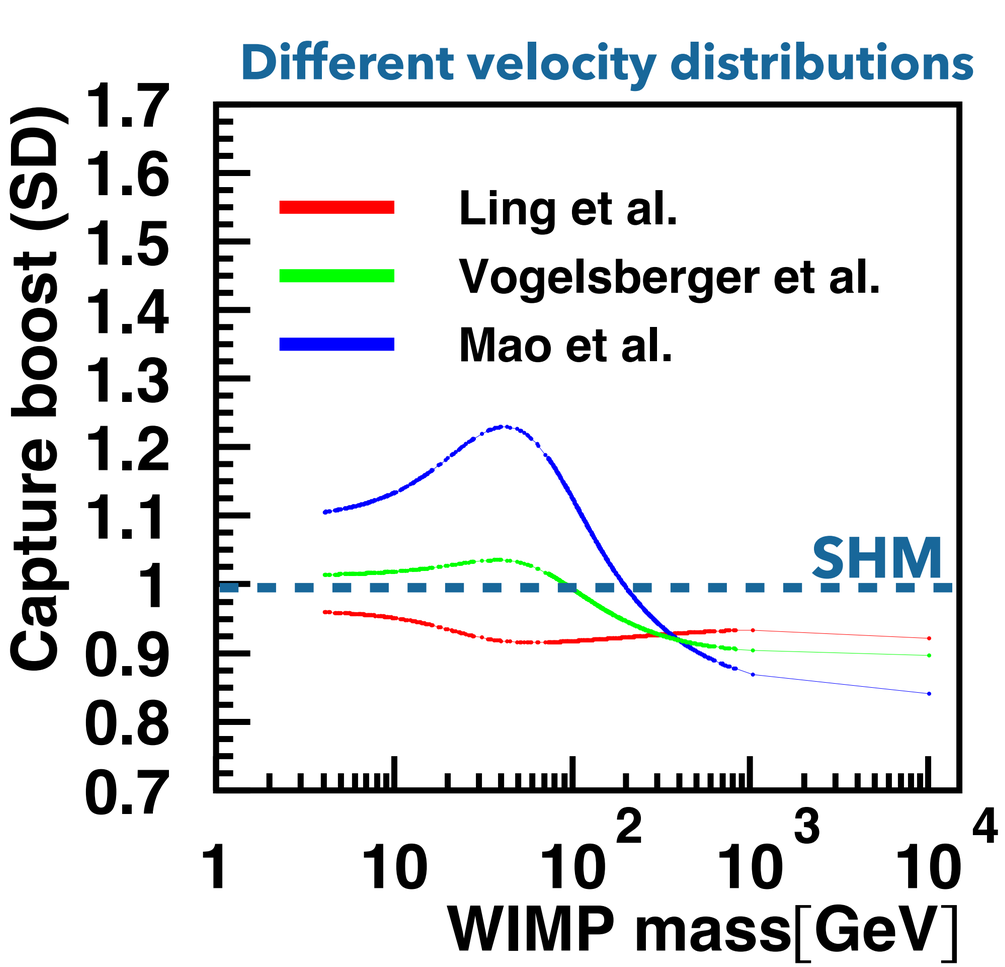
Local clumps not considered

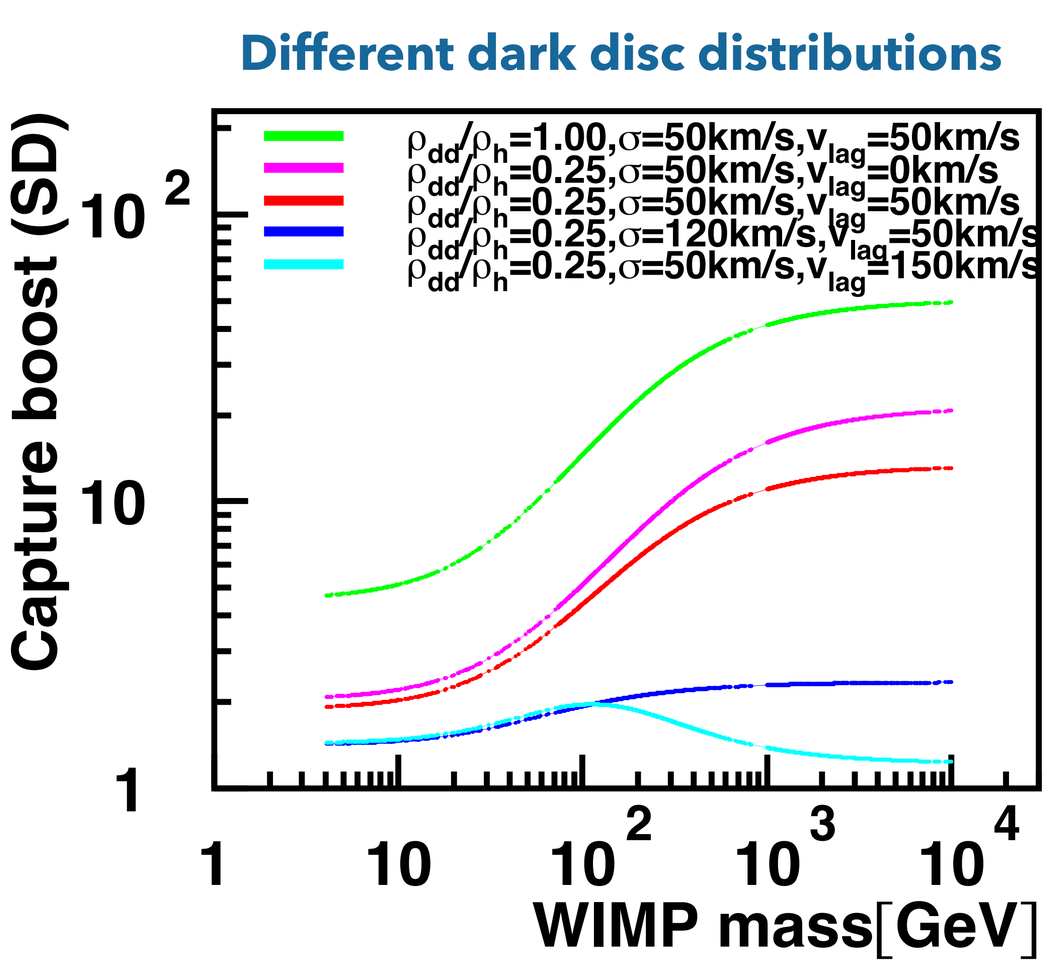
Capture Rate: Earth



CELESTIAL BODIES

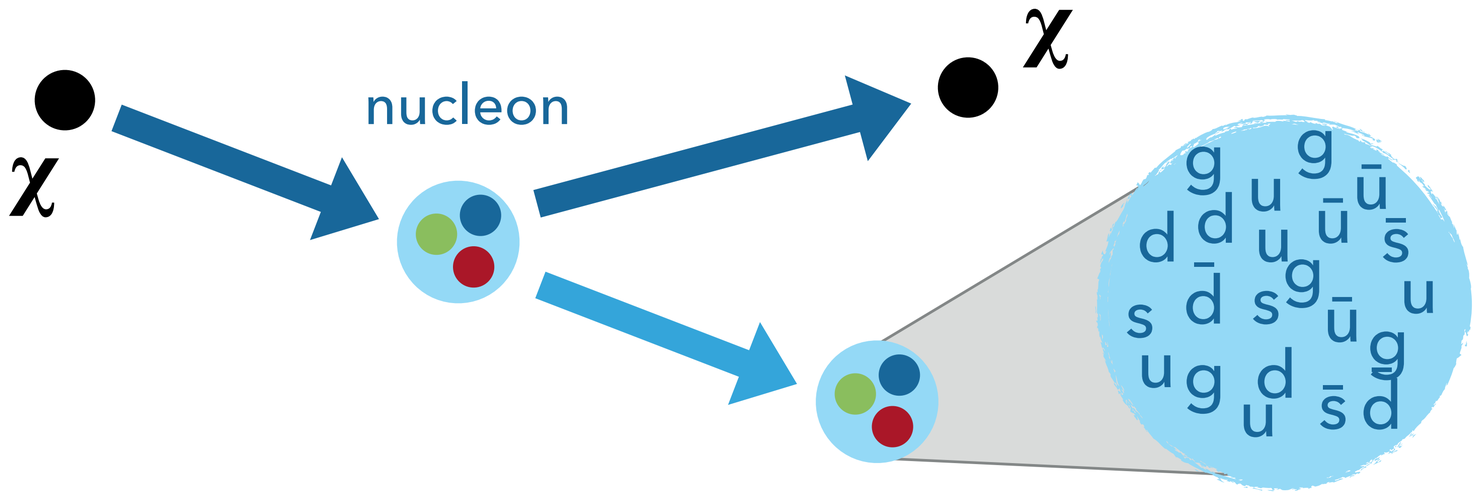
A **dark matter disc** will have a significant (good) impact on the capture rate for the Sun/Earth





Choi, Rott, Itow arXiv:1312.0273

CELESTIAL BODIES



Both direct detection and indirect detection (gravitational capture) depend on the WIMP-nucleon cross-section.

$$\sigma_{SI} \propto A^2$$

Spin independent → **Use heavy nuclei as target: Direct detection**

$$\sigma_{SD} \propto (a_p \langle S_p \rangle + a_n \langle S_n \rangle) \frac{J+1}{J} \frac{S(|\vec{q}|)}{S(0)}$$

Spin dependent → **Sun is full of protons: Indirect detection**

The nucleon structure plays an essential role in calculating observables

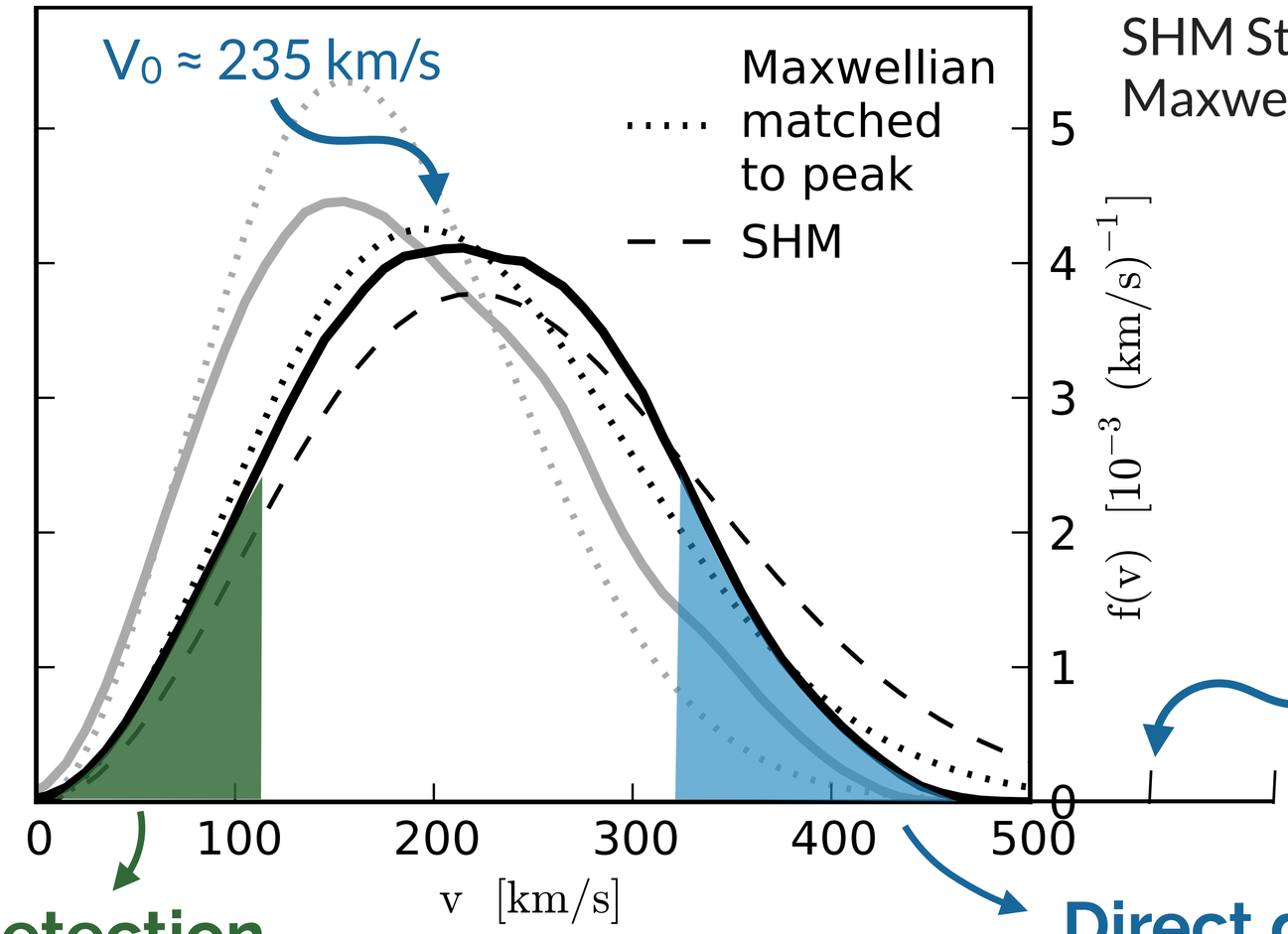
But it seems to affect more σ^{SI} than σ^{SD}

R. Ruiz, C. de los Heros arXiv:1307.6668

Celestial Bodies Velocity Distribution

Heavy dark matter particles can only be captured at low velocities

[arxiv:1308.1703]



SHM Standard Halo Model = Maxwellian with v_{esc}

$V_{esc} \approx 544$ km/s

Indirect detection

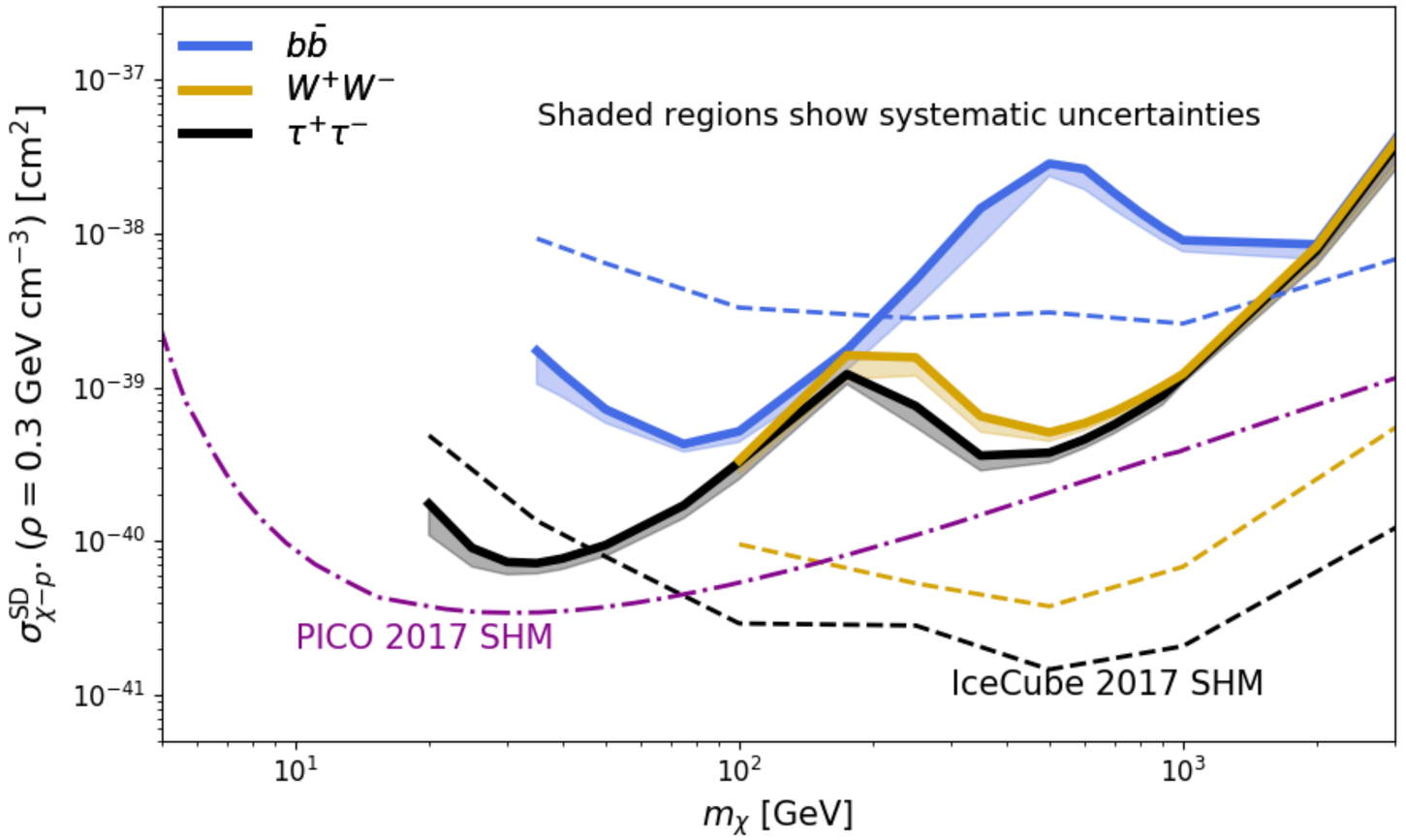
Direct detection

Velocity Independent PICO and IceCube

- IceCube has **best limits in** $\sigma_{SD}^{\chi-N}$ **at $m_\chi > 10^2$ GeV /** assuming a velocity distribution
- Combined limits with PICO assuming superposition of **streams with fixed velocity**.
- Only the velocity stream with the highest allowed scattering cross-section is selected / **Conservative limits**

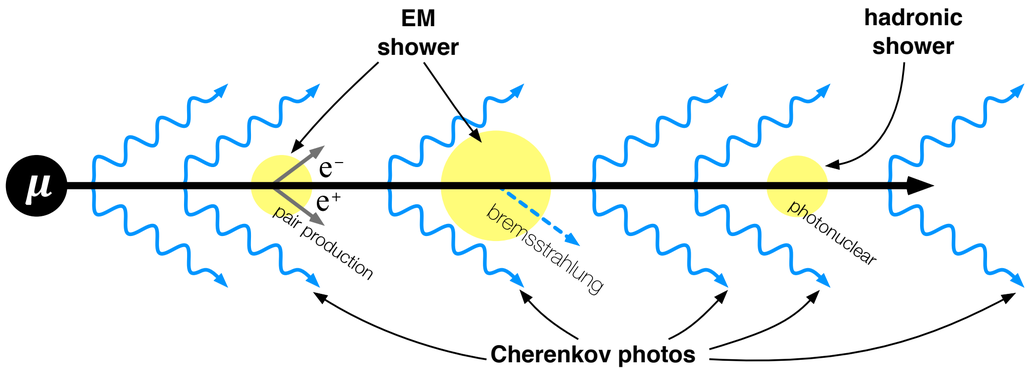
equilibrium!

$$\Phi_\nu \rightarrow C_A \Rightarrow C_c \rightarrow \sigma_{\chi N}$$

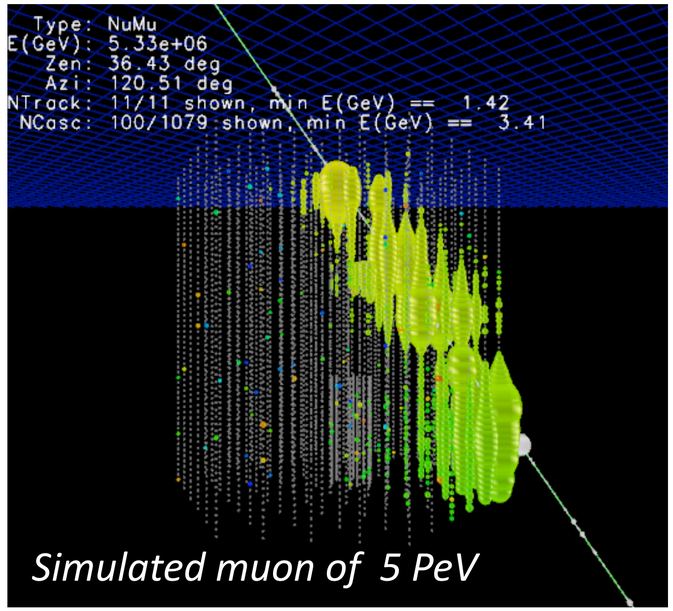


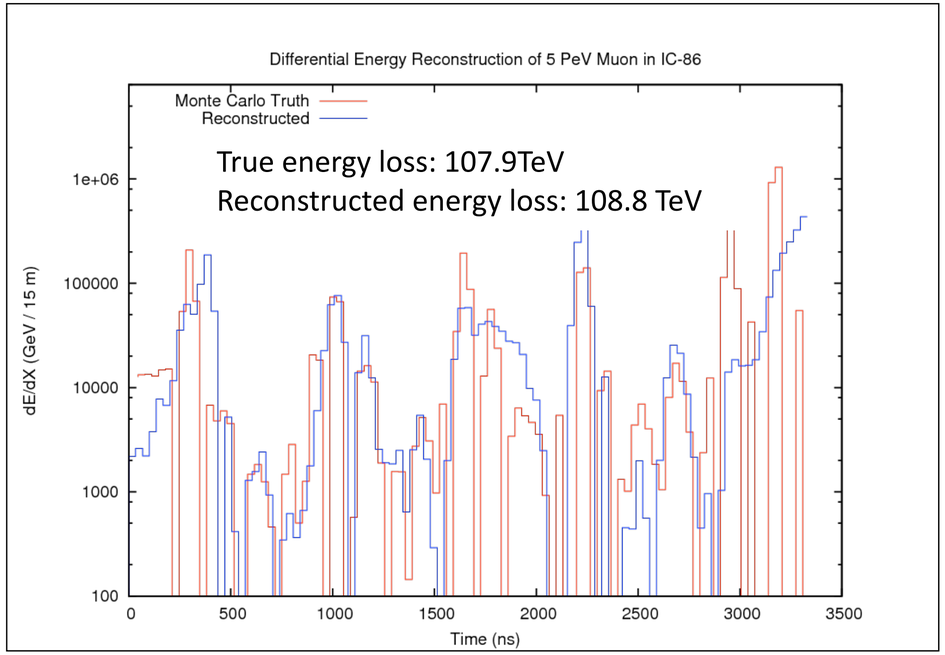
[Submitted to Eur. Phys. J. C, arXiv:1907.12509]

Muon energy reconstruction

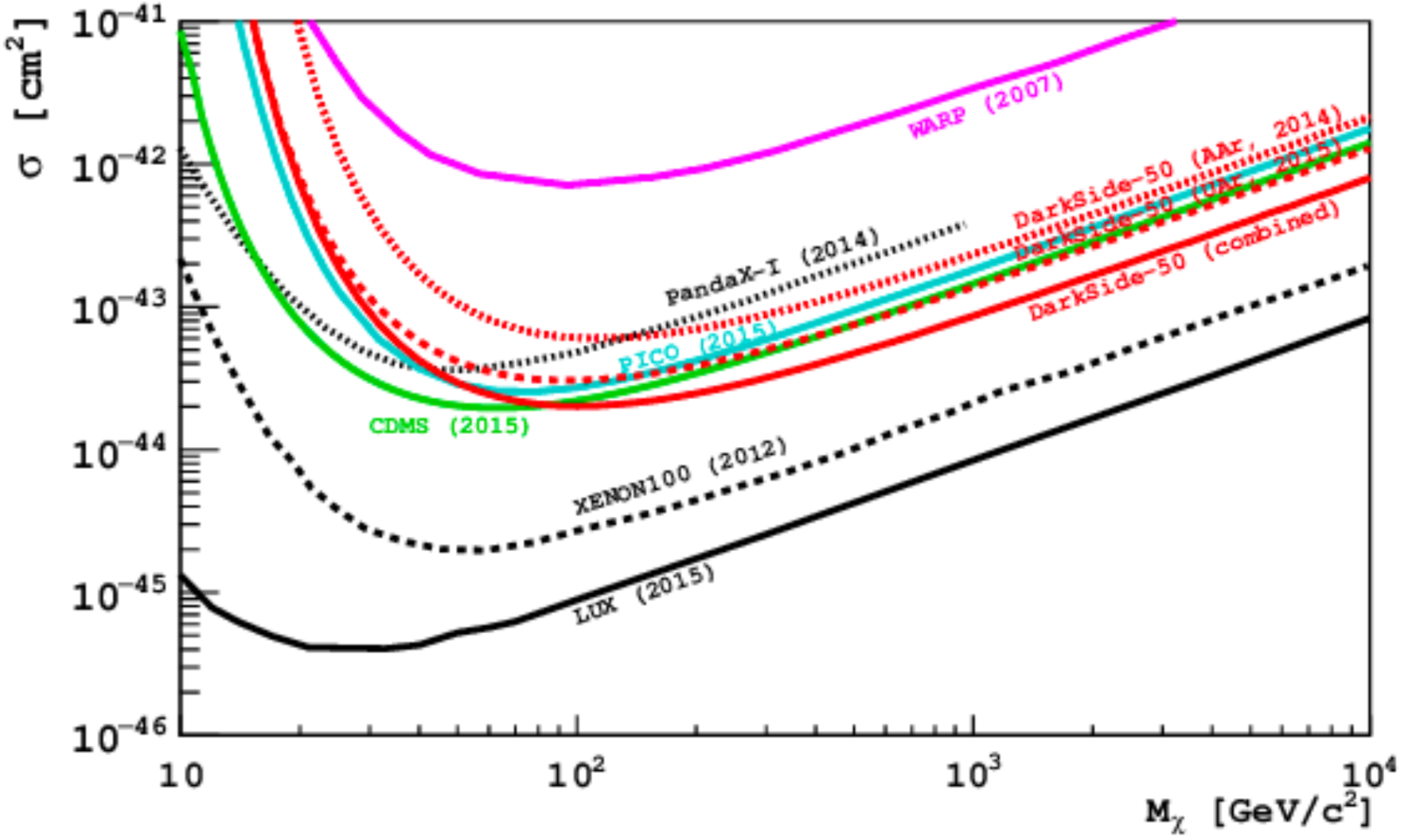


- Improved tools to resolve stochastic energy losses along the km long tracks.
- Energy deposited is a lower-bound of true energy.
- Muon energy resolution:
  - rms of $\log_{10}$ E: ~(30 -25) % (> 100 TeV)
- Limited by fluctuations in energy deposition.

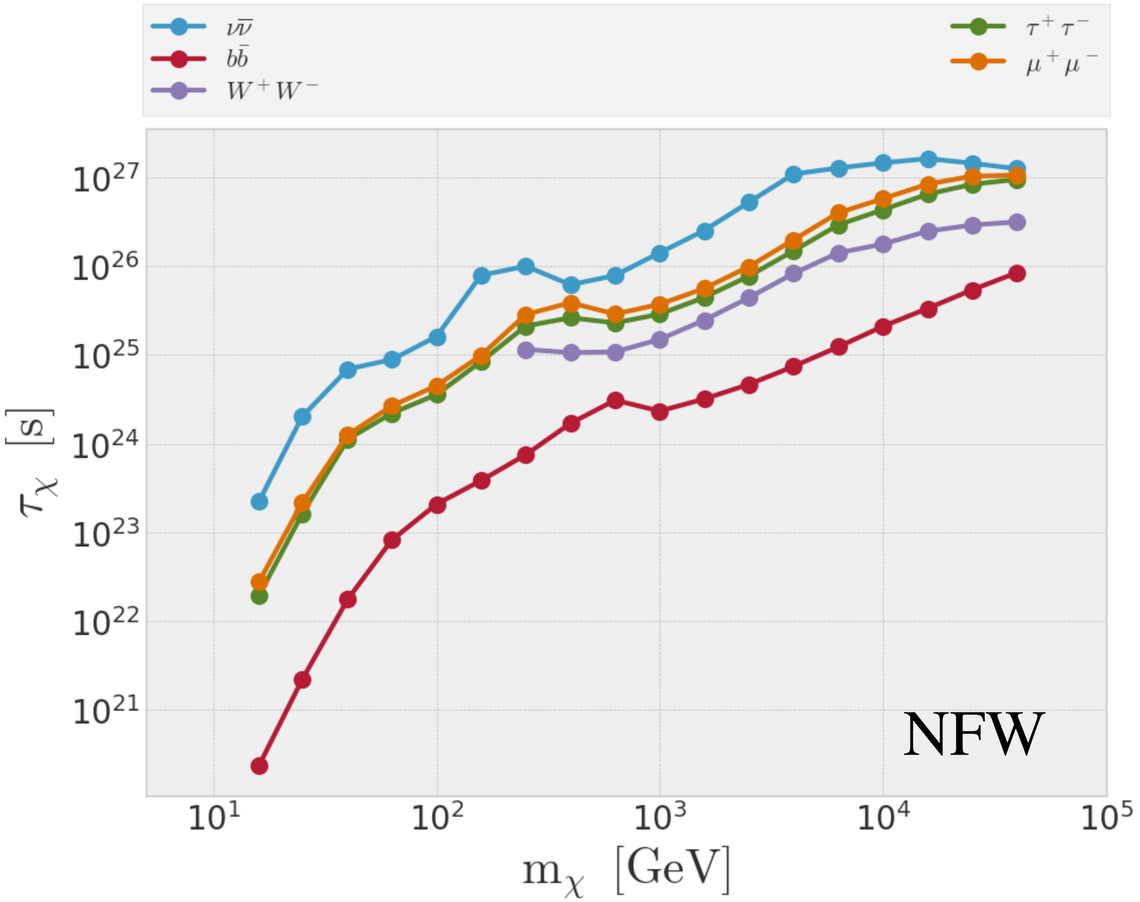


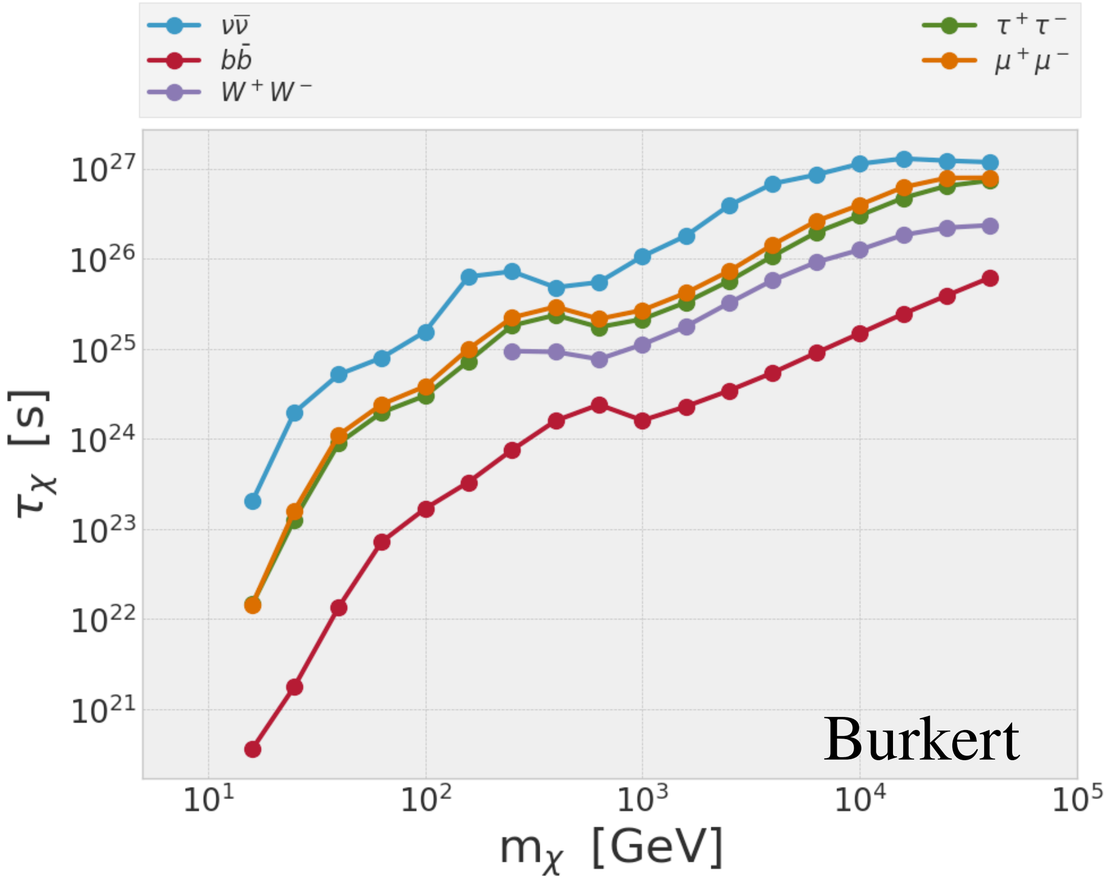


Spin Independent: Direct Detection

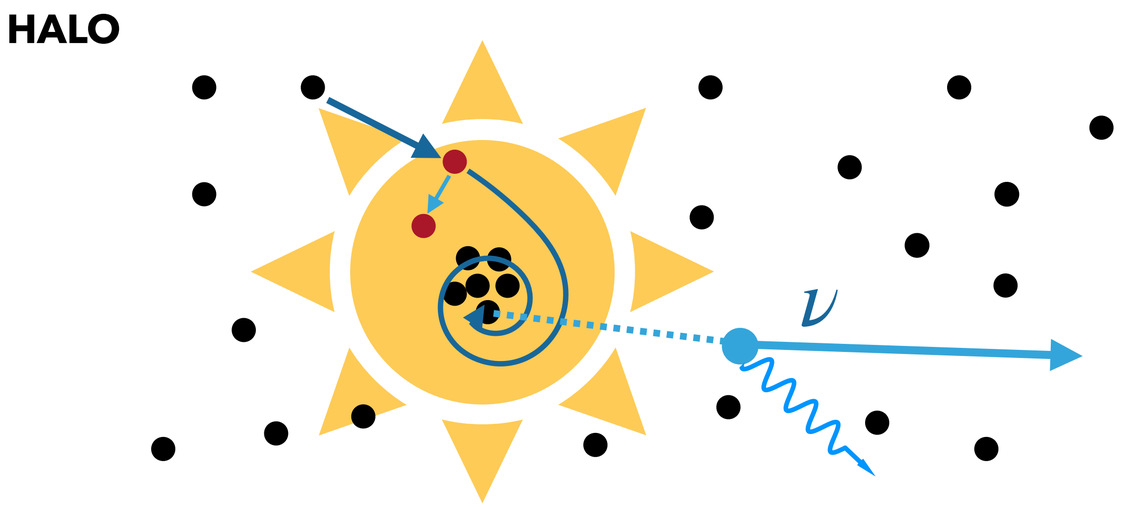


All Decay Channels

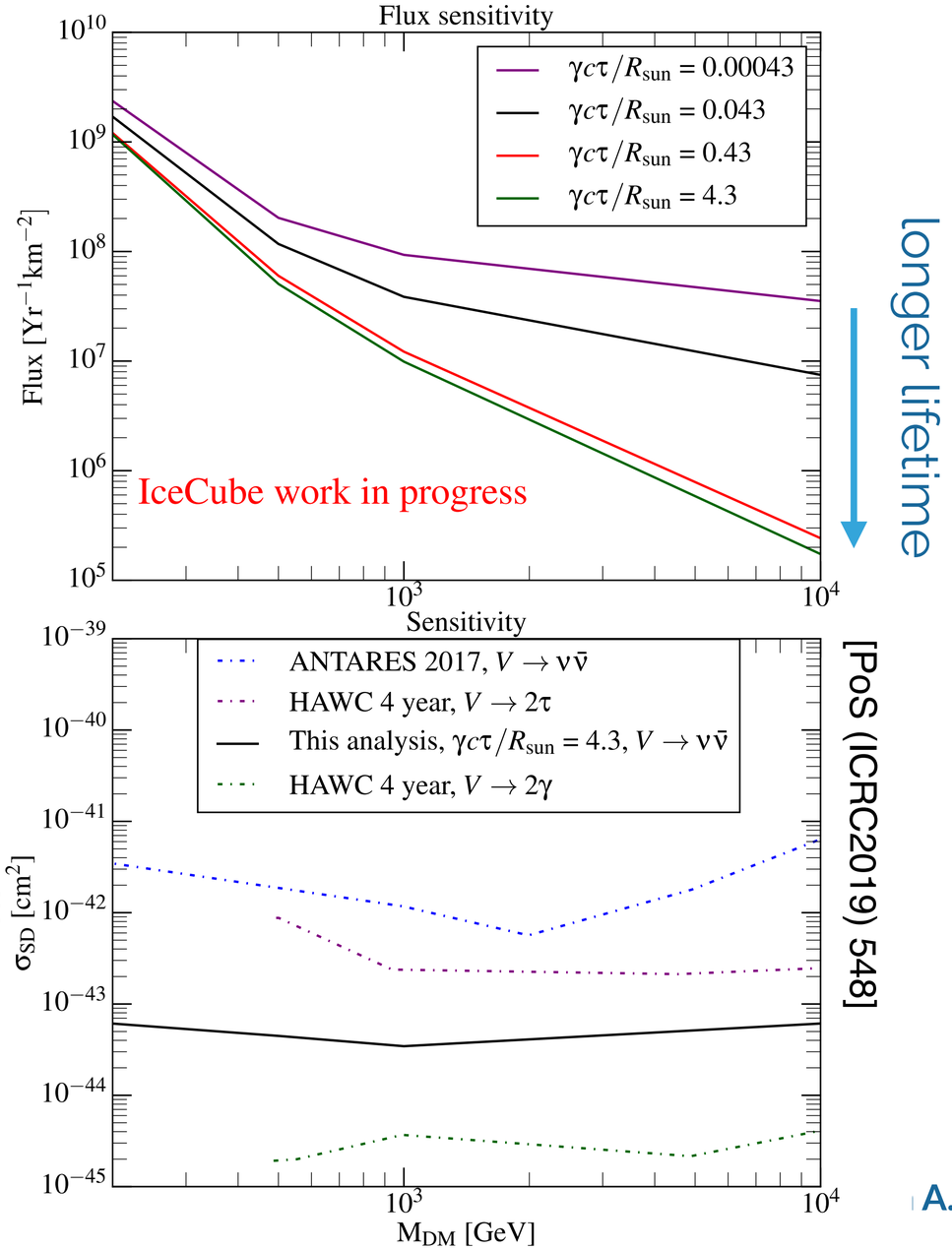


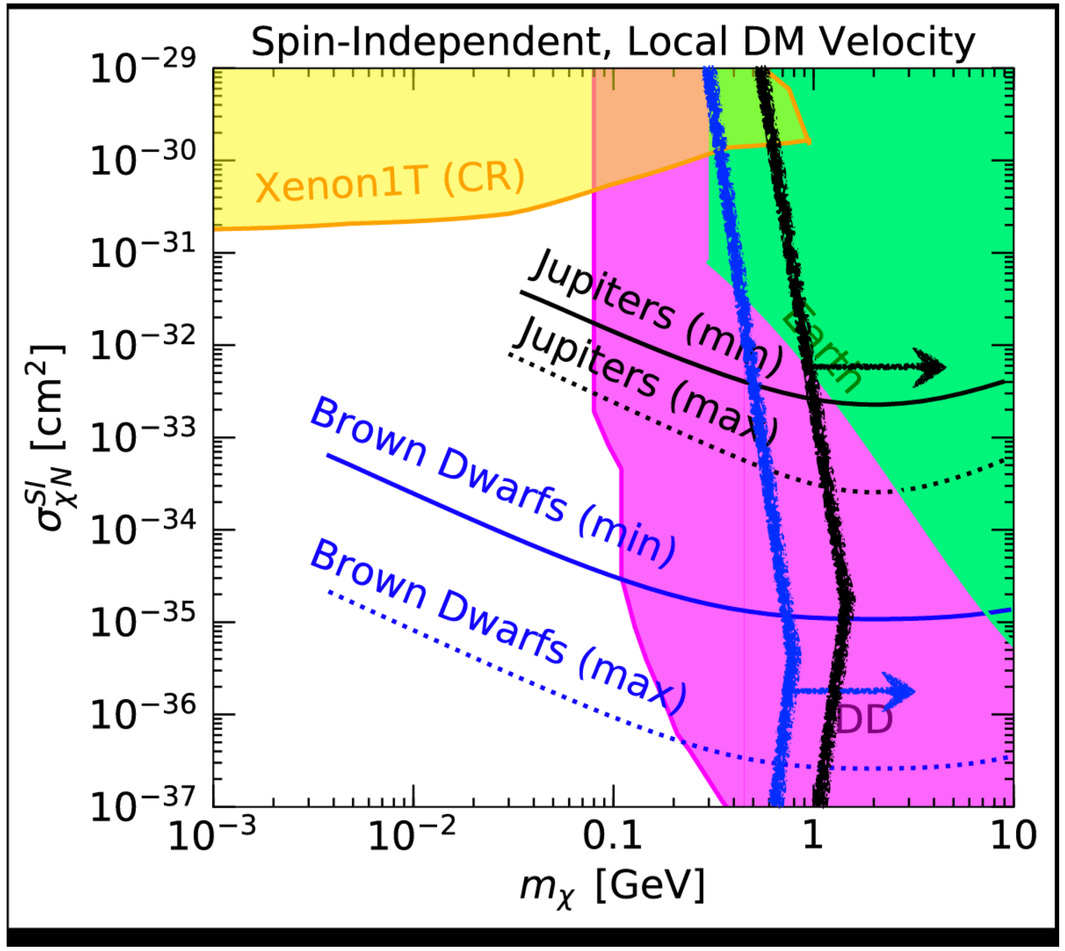


Secluded DM from the Sun



- Dark matter annihilates in a mediator outside
- Sensitivities depend on the mediator livetime.
- Mediator mass and livetime are additional free



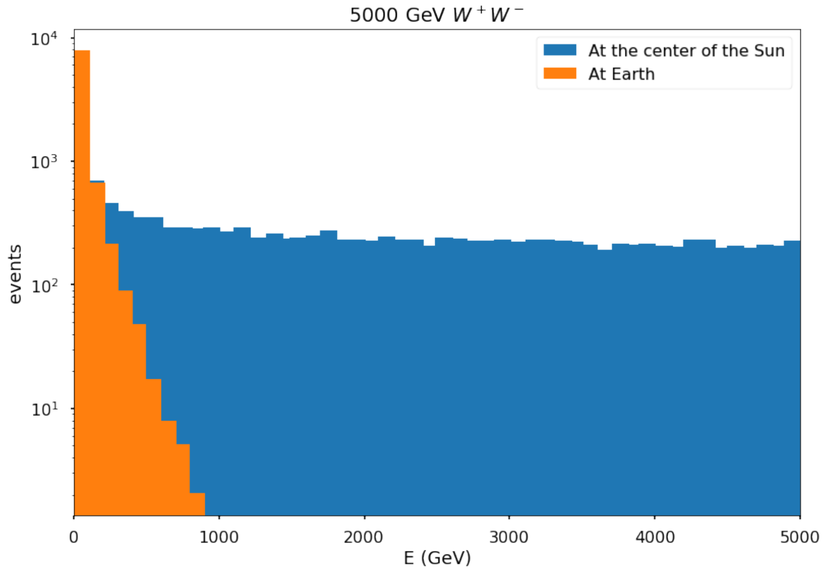


R. K. Leane and J. Smirnov, Phys. Rev. Lett. 126:161101, 2021

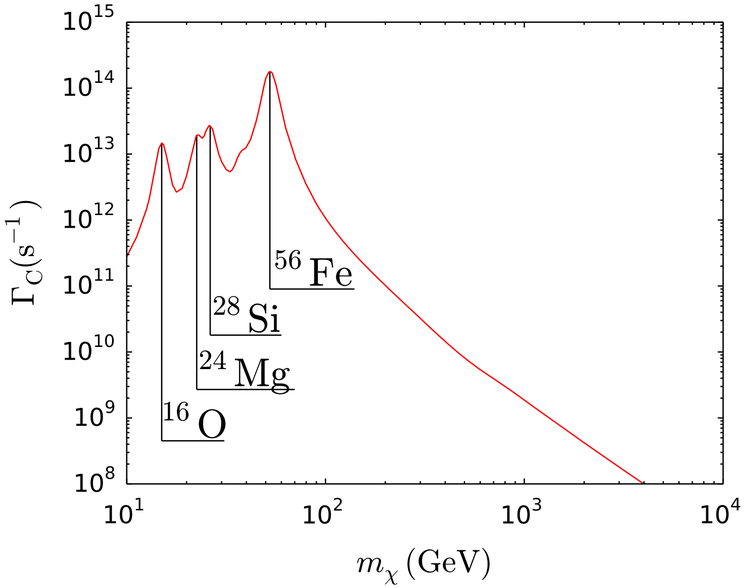
Dark Matter from Celestial

Differences between the Sun and the Earth

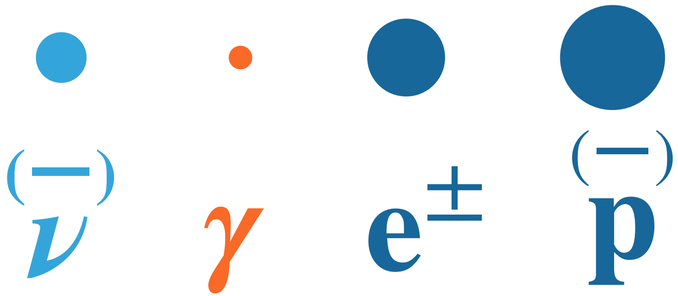
- Made of hydrogen:
  - **Capture rate driven by σ_{SD}**
- Very old and massive:
  - **Process in equilibrium $\frac{\mathrm{d}N}{\mathrm{d}t} = 0$**
- Very dense
  - **Only low energy neutrinos escape!**



- Small escape velocity:
  - **Not in equilibrium!**
- Only vertical up-going events:
  - **Need control of systematics.**
- Capture rate depends Earth abundance:
  - **Sensitivity driven by σ_{SI}**



Cosmic Messengers of Indirect Detection



Neutrinos

- Challenging detection
- Small signal expectations
- Some places only accessible via neutrinos
- Negligible astrophysical background (so far)

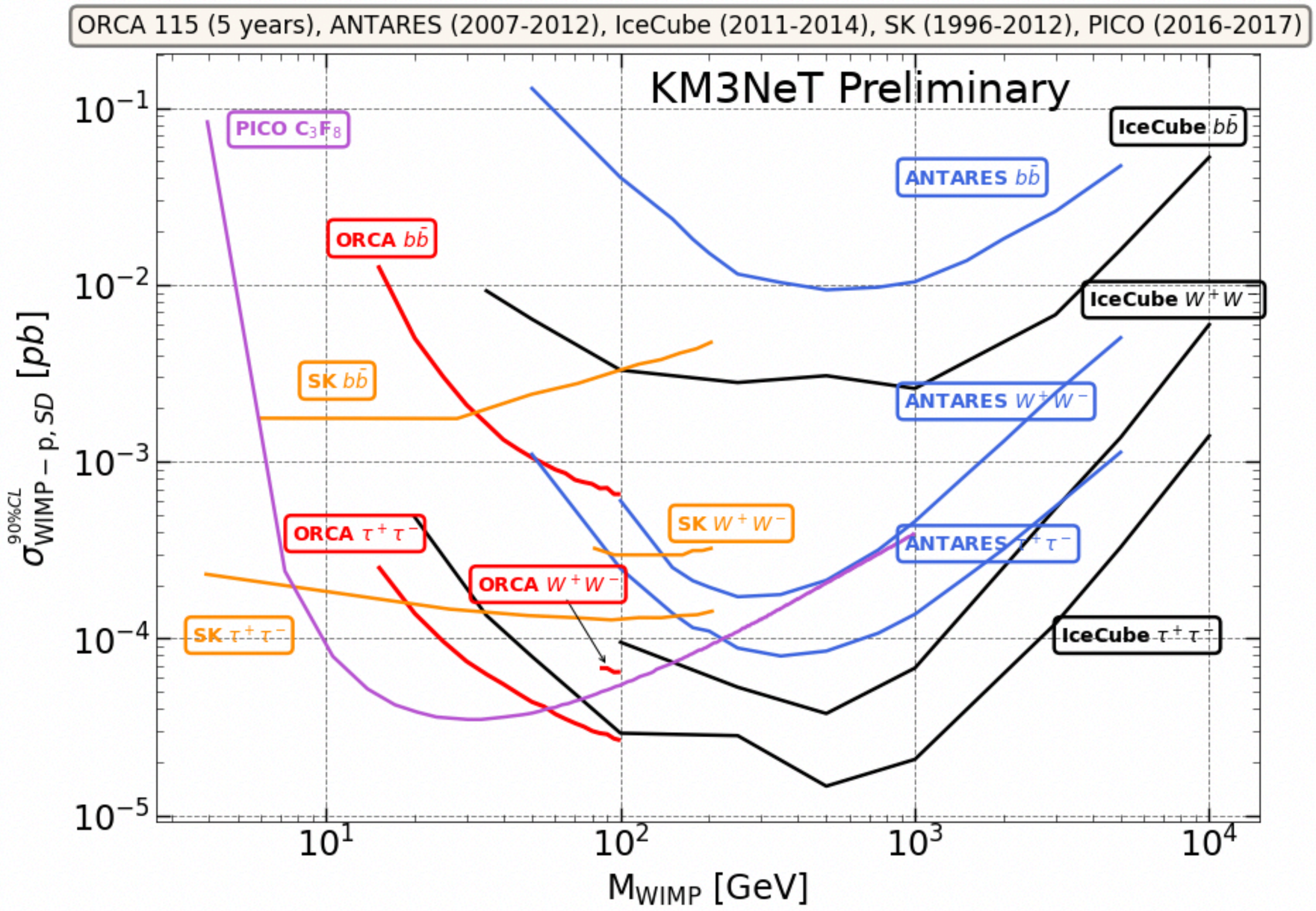
Gamma-rays

- Mature detection technique
- Large signal expectations
- Lots of astrophysical sources!
  - **Long standing "excess" in GeV**

Cosmic Rays

- Largest signal expectation
- Large uncertainties due to propagation (diffusion)
- Astrophysical background
  - **Long standing "excess" in $e^{\pm}$**
  - **"Excess" in $\overline{p}$**

Celestial Bodies: The Sun

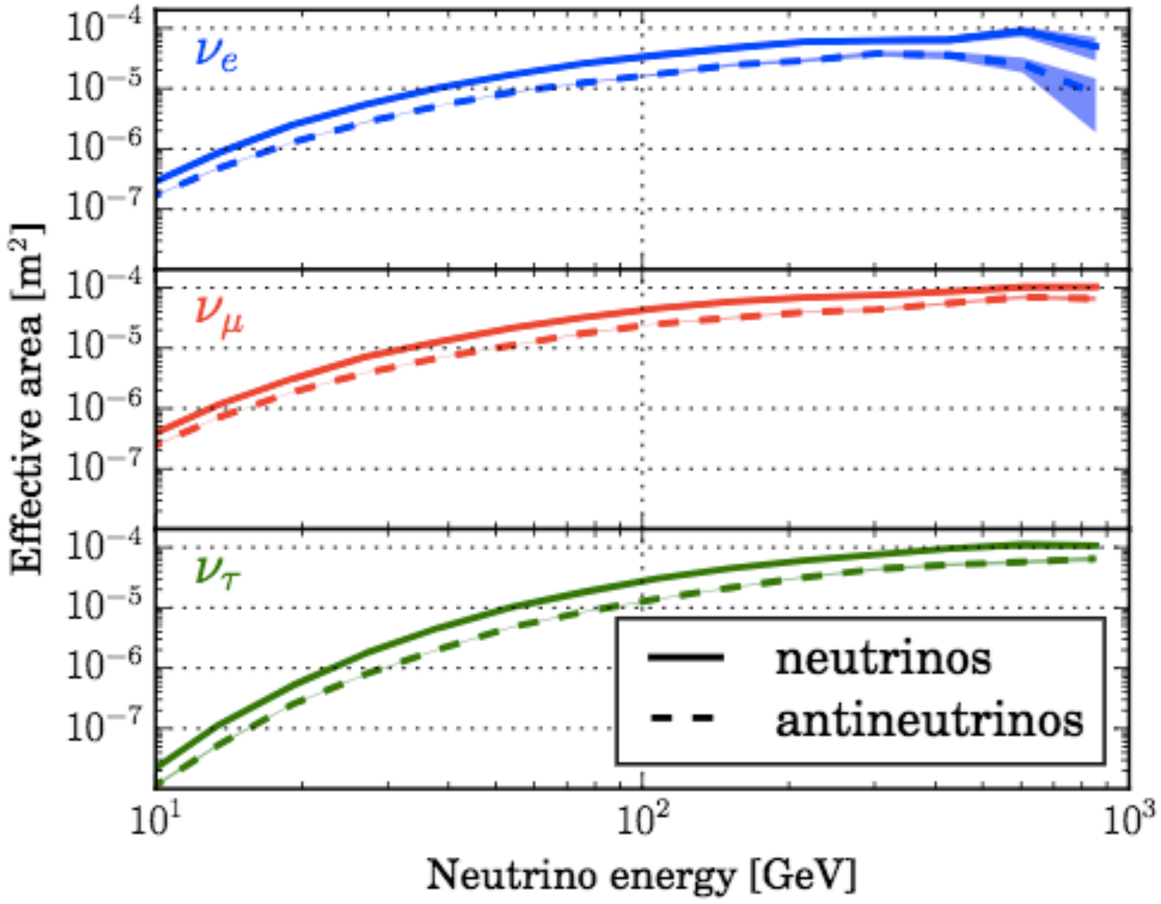


- **Red lines** are 5 years of ORCA simulated data
- Improve sensitivity below $m_\chi < 10^2$ GeV

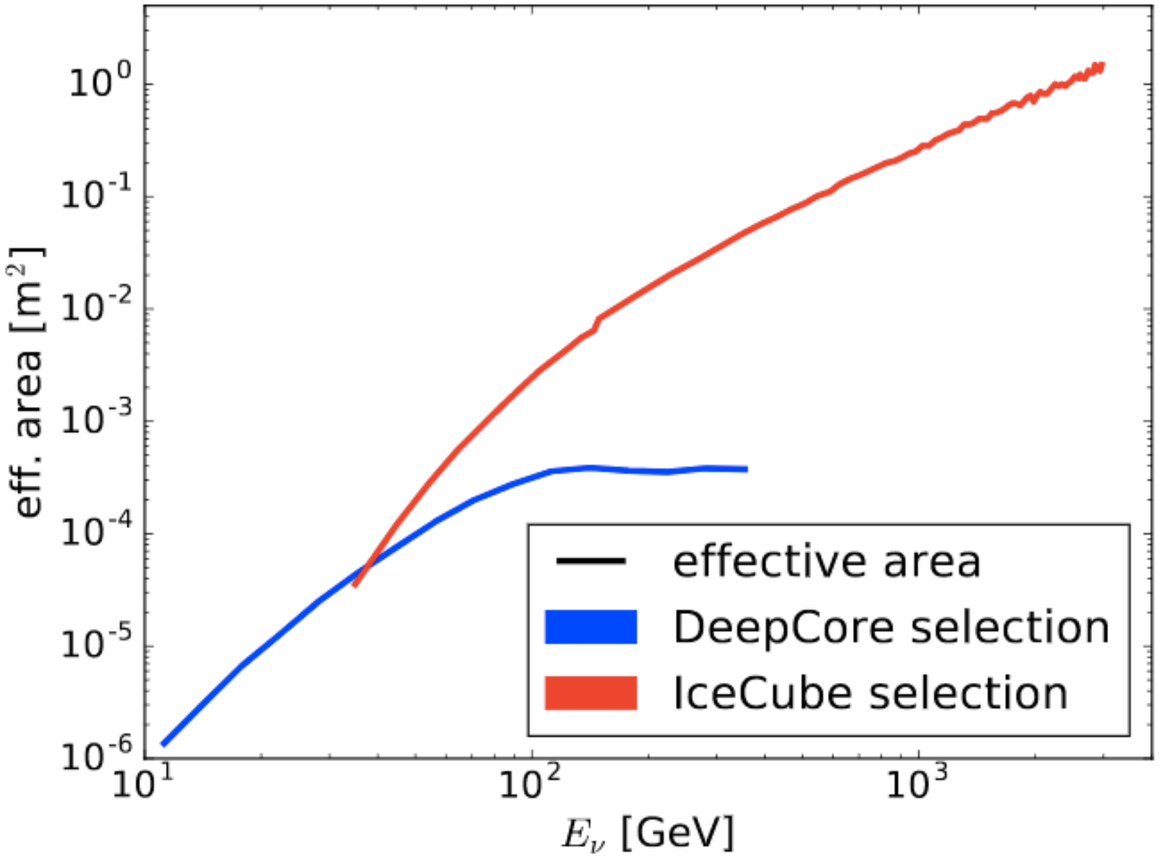
PoS(ICRC2019)536

Effective Areas

Galactic Center Aeff



Sun Aeff



ANITA Anomalous Events

- ANtarctic Impulsive Transient Antenna balloon-borne radio antenna, 4 one-month flights >2006
- Two very energetic (~ 0.5 EeV) upgoing air showers consistent with τ decay (type 4 above) from a CC of a ν_τ neutrino

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.[1]	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3°, 159.62 \pm 0.7°$	$-35.0 \pm 0.3°, 61.41 \pm 0.7°$
RA, Dec[2]	282.14064, +20.33043	50.78203, +38.65498
$E_{shower}^{(3)}$	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

[1] Latitude, Longitude of the estimated ground position of the event.
[2] Sky coordinates projected from event arrival angles at ANITA.
[3] For upward shower initiation at or near ice surface.

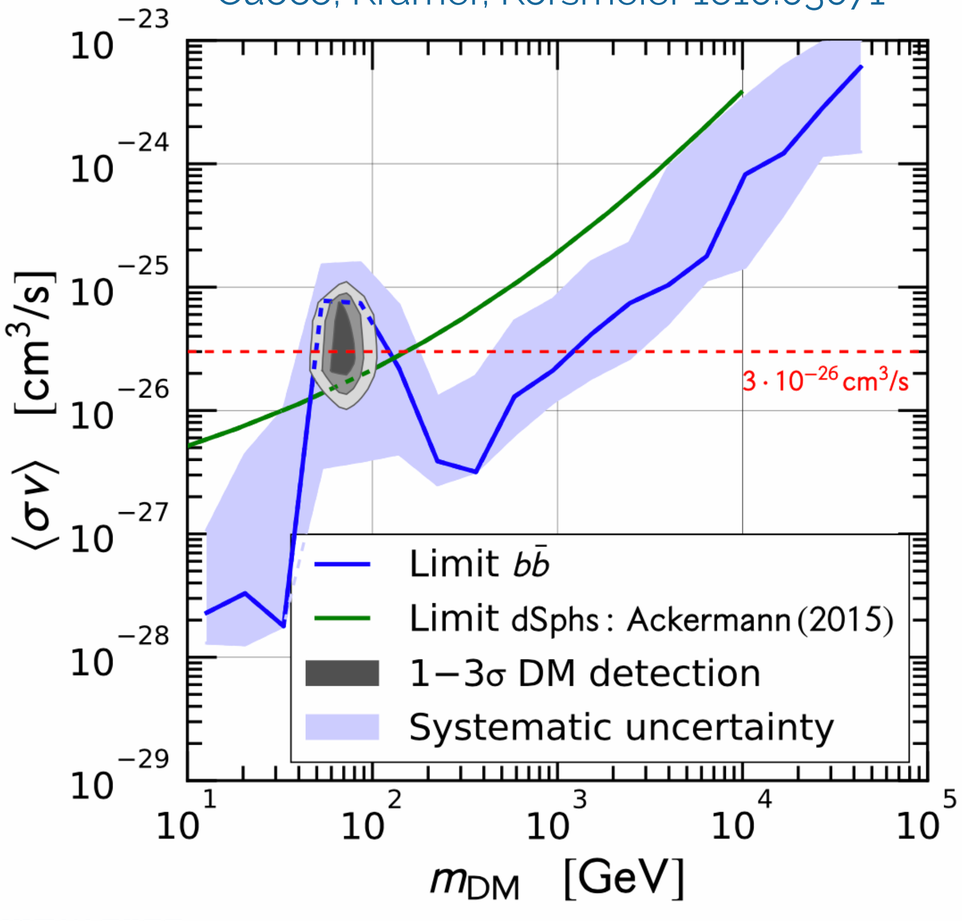
ANITA Anomalous Events

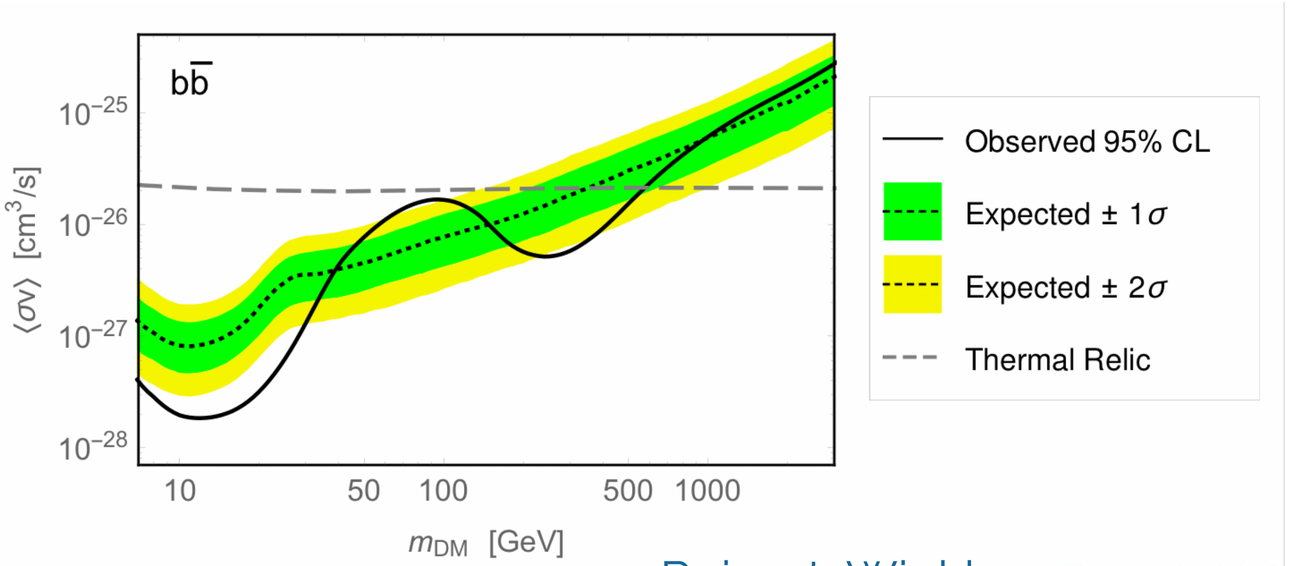
- ANtarctic Impulsive Transient Antenna balloon-borne radio antenna, 4 one-month flights >2006
- Two very energetic (~ 0.5 EeV) upgoing air showers consistent with τ decay (type 4 above) from a CC of a ν_τ neutrino
- But EeV ν_τ cannot cross the Earth (even with τ-regeneration). Also if astrophysical, they should more TeV neutrinos in from the same direction (IceCube saw 0).
- So? Dark Matter
- Or? Mis-qualified background (arXiv:1905.02846v1, arXiv:1903.08750)

Indirect detection CRs: $\bar{p}$

- "Excess" in anti-protons still there ($m_\chi = 80$ GeV, $b\bar{b}$) at the level of thermal cross-section (but significance $4.5\sigma \rightarrow \sim 1\sigma$)

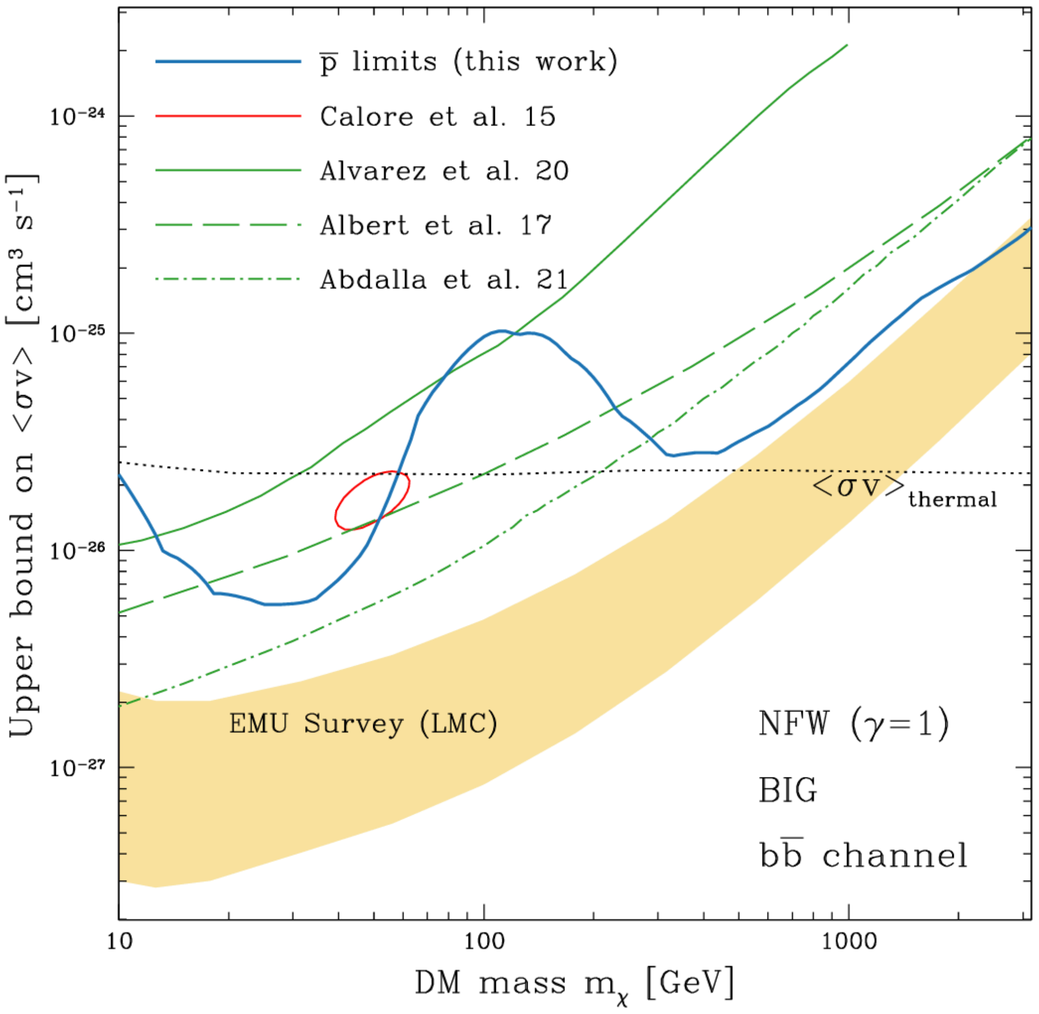
Cuoco, Krämer, Korsmeier 1610.03071





Reinert, Winkler 1712.00002

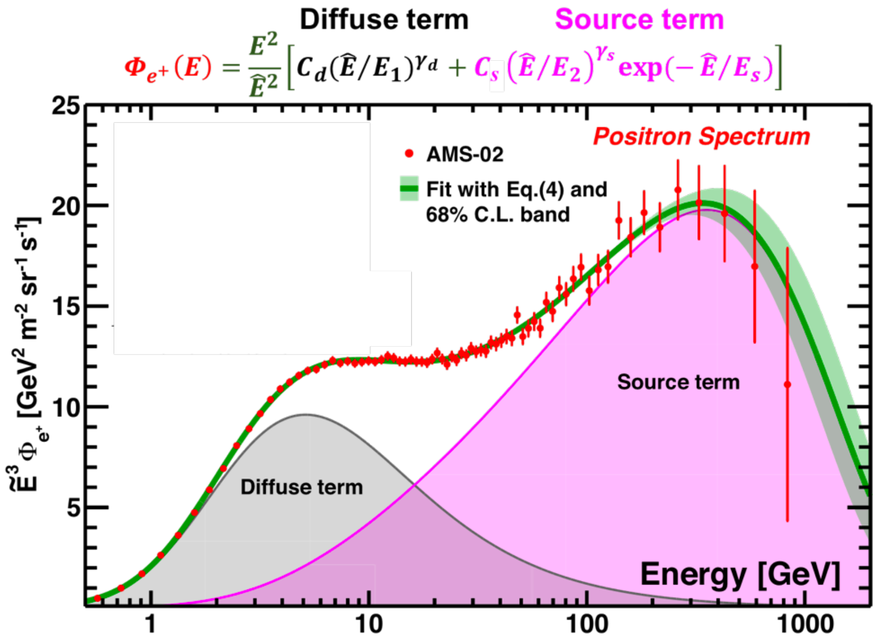
Indirect detection CRs: $\bar{p}$



- Using latest data from AMS
- Limits are weaker due to the "excess".
- Excess still there but not so significant.

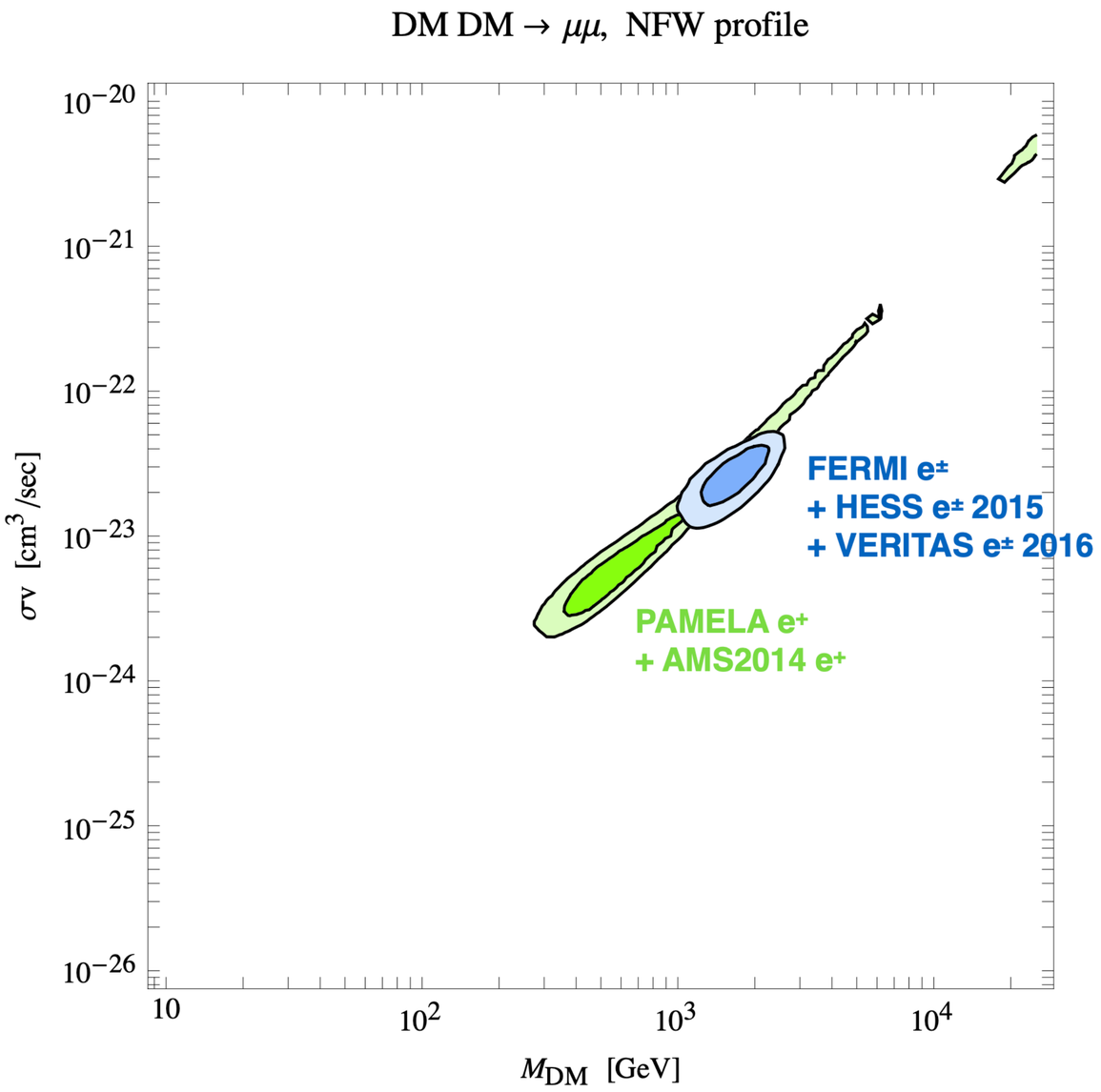
arXiv:2202.03076v2

Indirect detection CRs: $e^+/(e^- + e^+)$



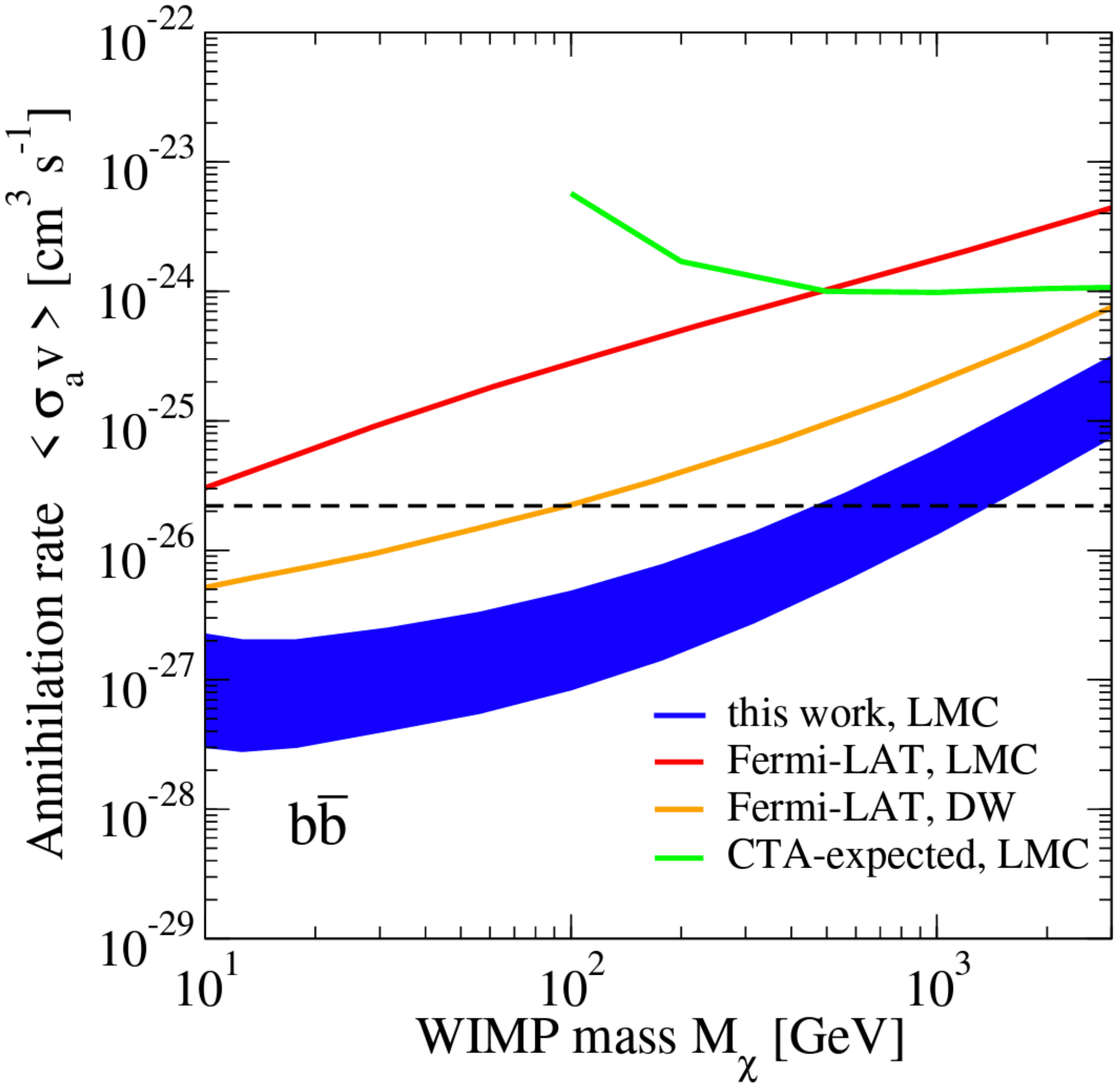
[PRL 113, 121102 (2014)]

- Leptophilic
- $m_\chi \sim 1$ TeV
- Annihilation cross-section >> thermal one
- Limits in tension with Gamma-rays limits, CMB etc.



Radio Emission from LMC

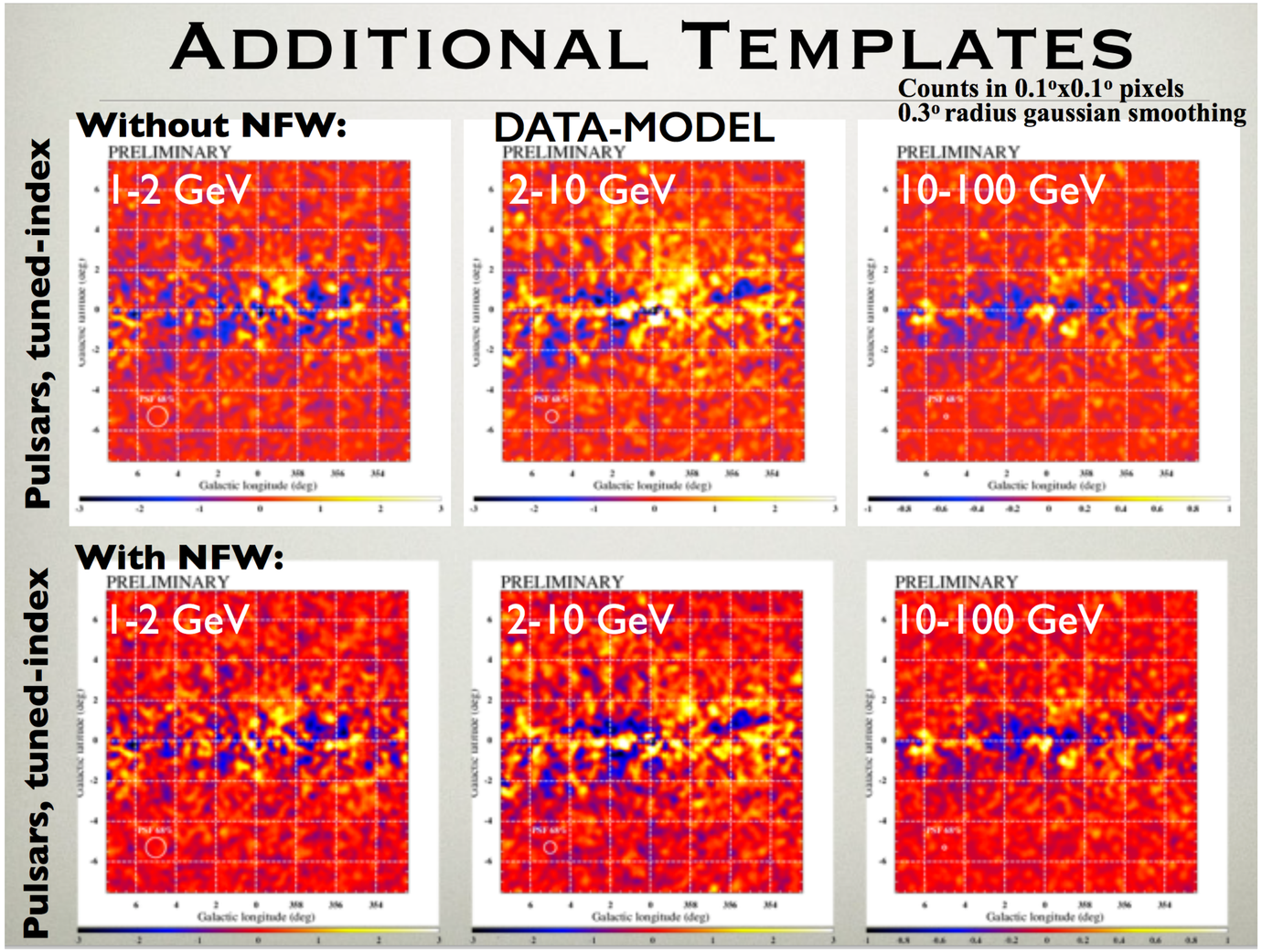
- Synchrotron emission can prove dark matter annihilation.
- Large Magellanic Cloud has high B-field and J-factor.
- Best limits for annihilation into quarks.



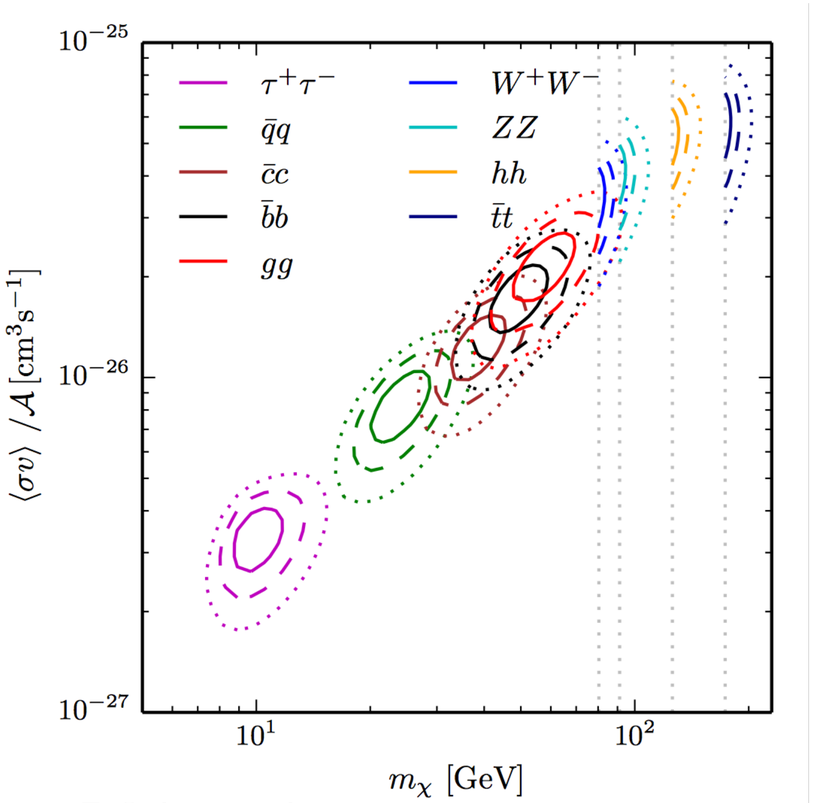
arXiv:2106.08025v2

Indirect detection Gamma-rays

- Persistent “excess” in GeV



S. Murgia for FERMI-LAT - ICRC 2015 T. Porter for FERMI-LAT - ICRC 2015 #815
Fermi coll. 1511.02938



F. Calore et al. 1411.4647