BEYOND STANDARD MODEL

IceCube

J. A. Aguilar on behalf of IceCube

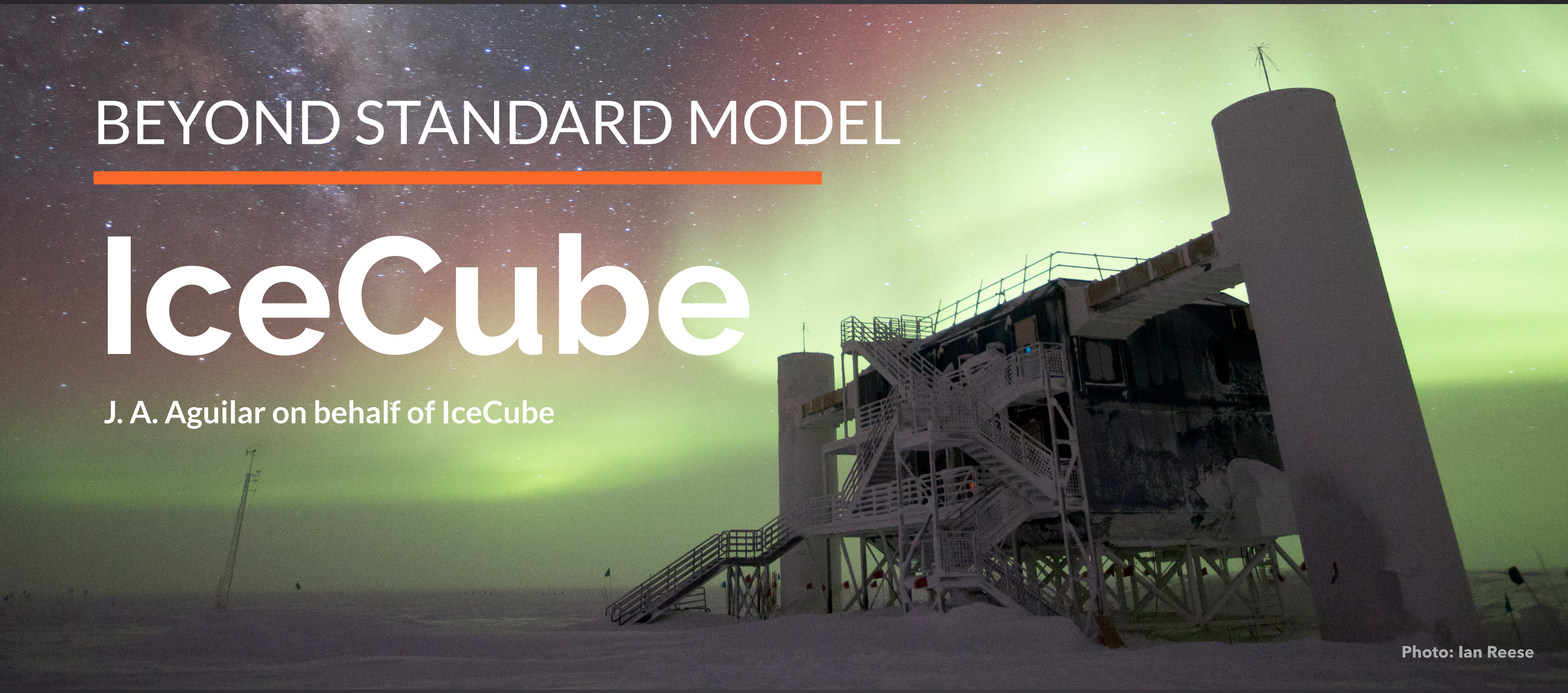


Photo: Ian Reese

ULB

NuFACT 2019

iihe

Outline

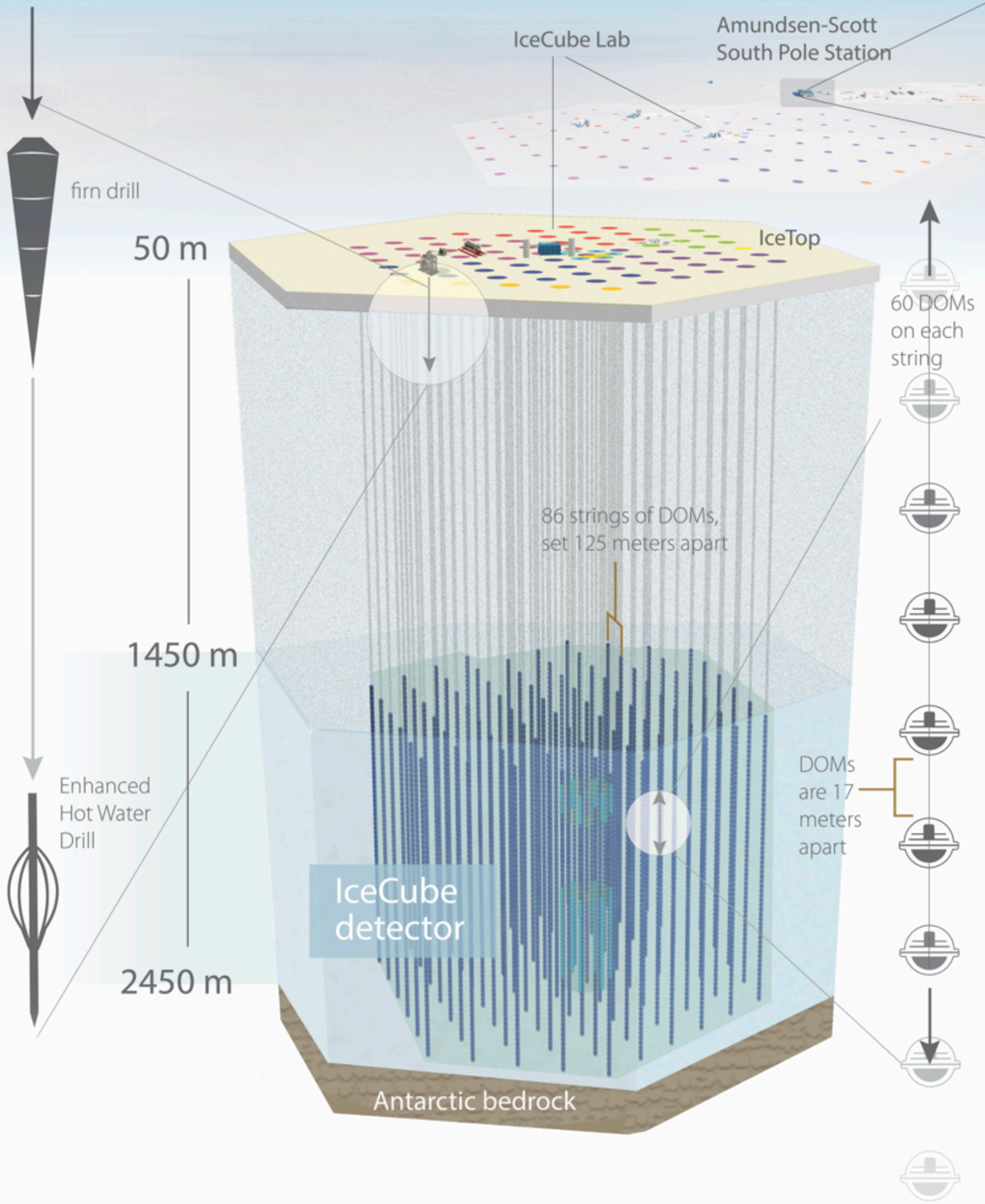
- IceCube
- Indirect Searches for Dark Matter
- Searches for BSM physics
- Conclusions

WG1 / Etienne Bourbeau / Latest Results on Neutrino Oscillation from the IceCube Neutrino Observatory

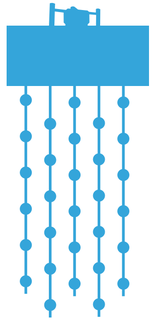
WG5 / Tom Stuttard / Neutrino oscillations and PMNS unitarity with IceCube/DeepCore and the IceCube Upgrade

WG1+5 / Joshua Hignight / Sterile Neutrino Searches with IceCube

IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)



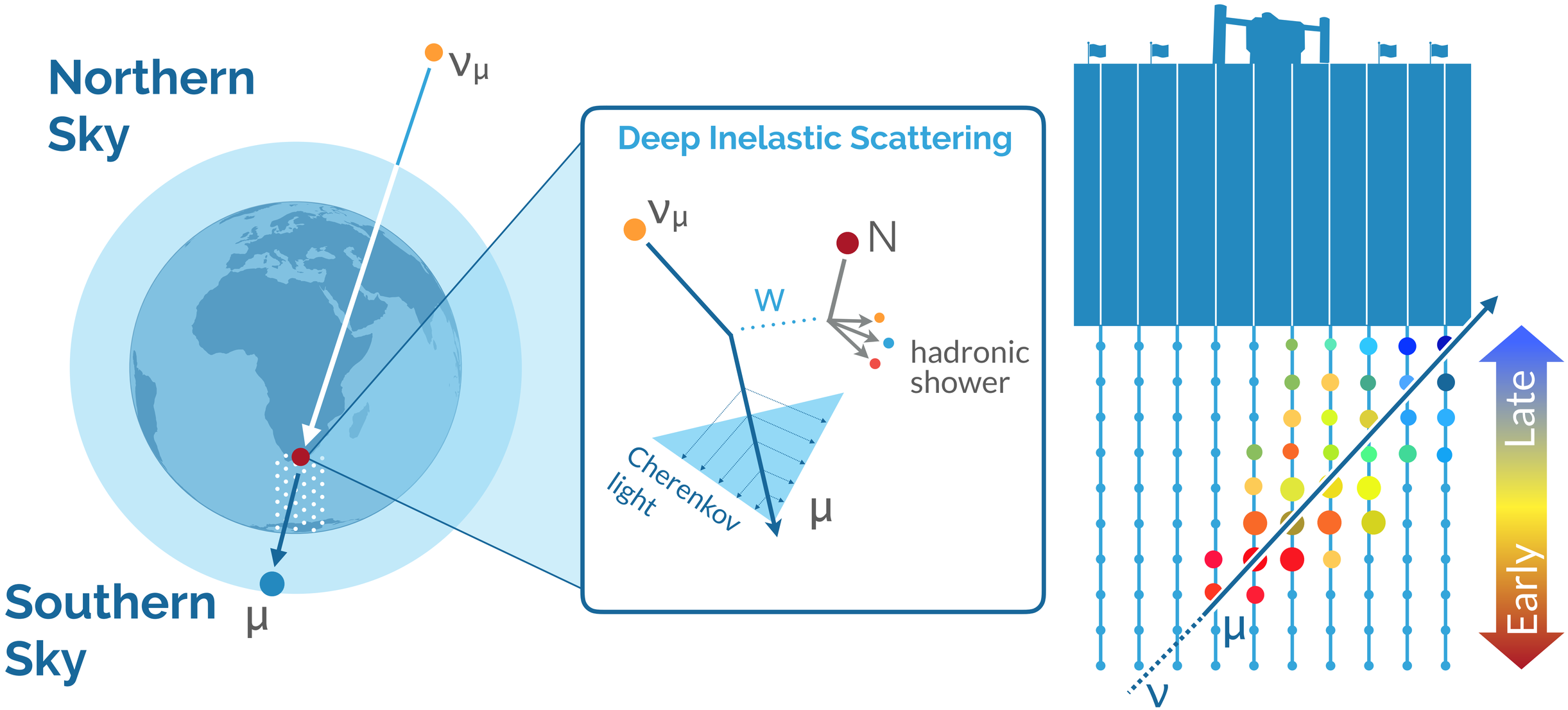
86 string with 60 DOMs each

6 denser strings called **DeepCore**

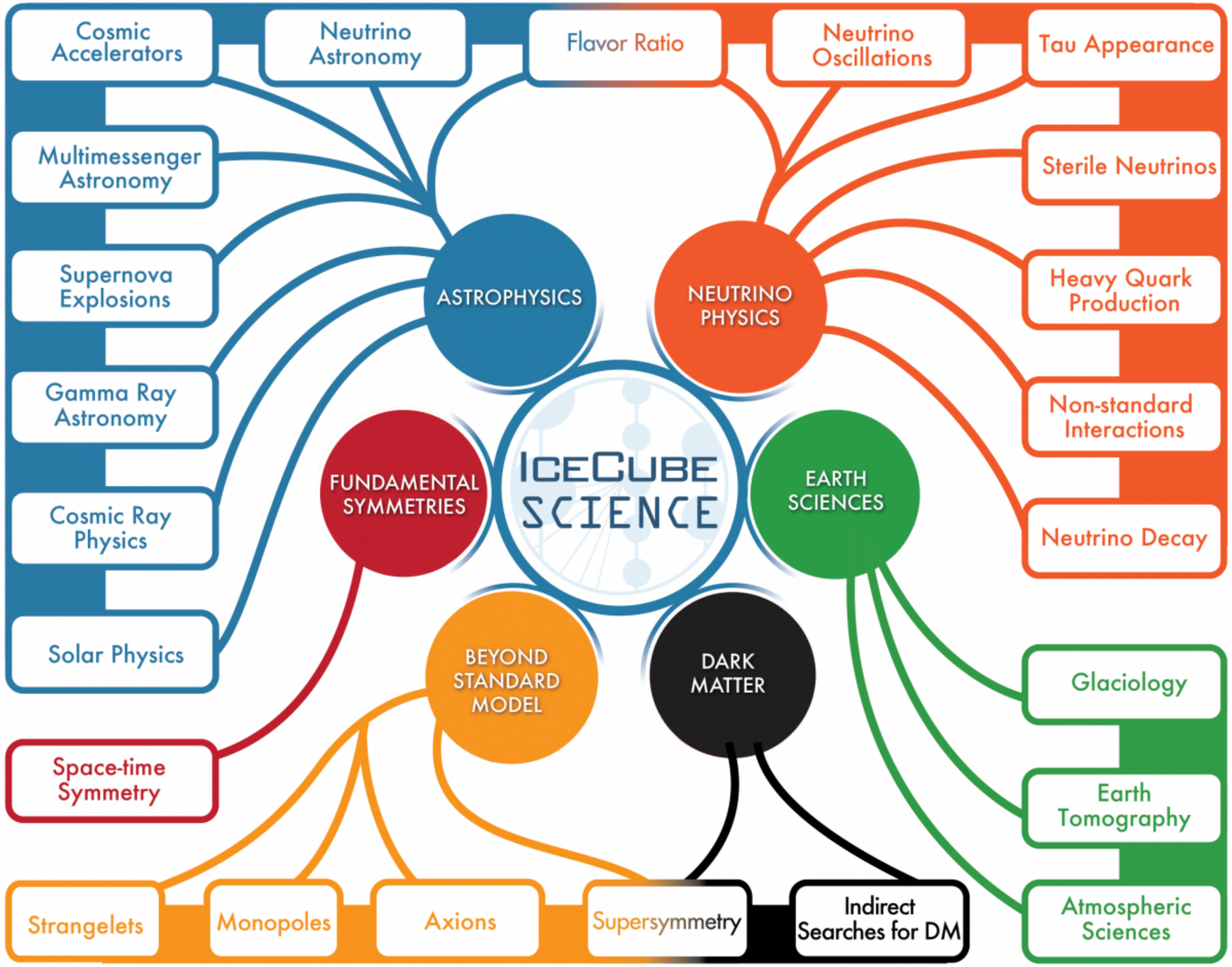
1 km^2 surface array with 324 DOMs: **IceTop**

Completion in December 2010

Detection Principle How Do We Detect Neutrinos?



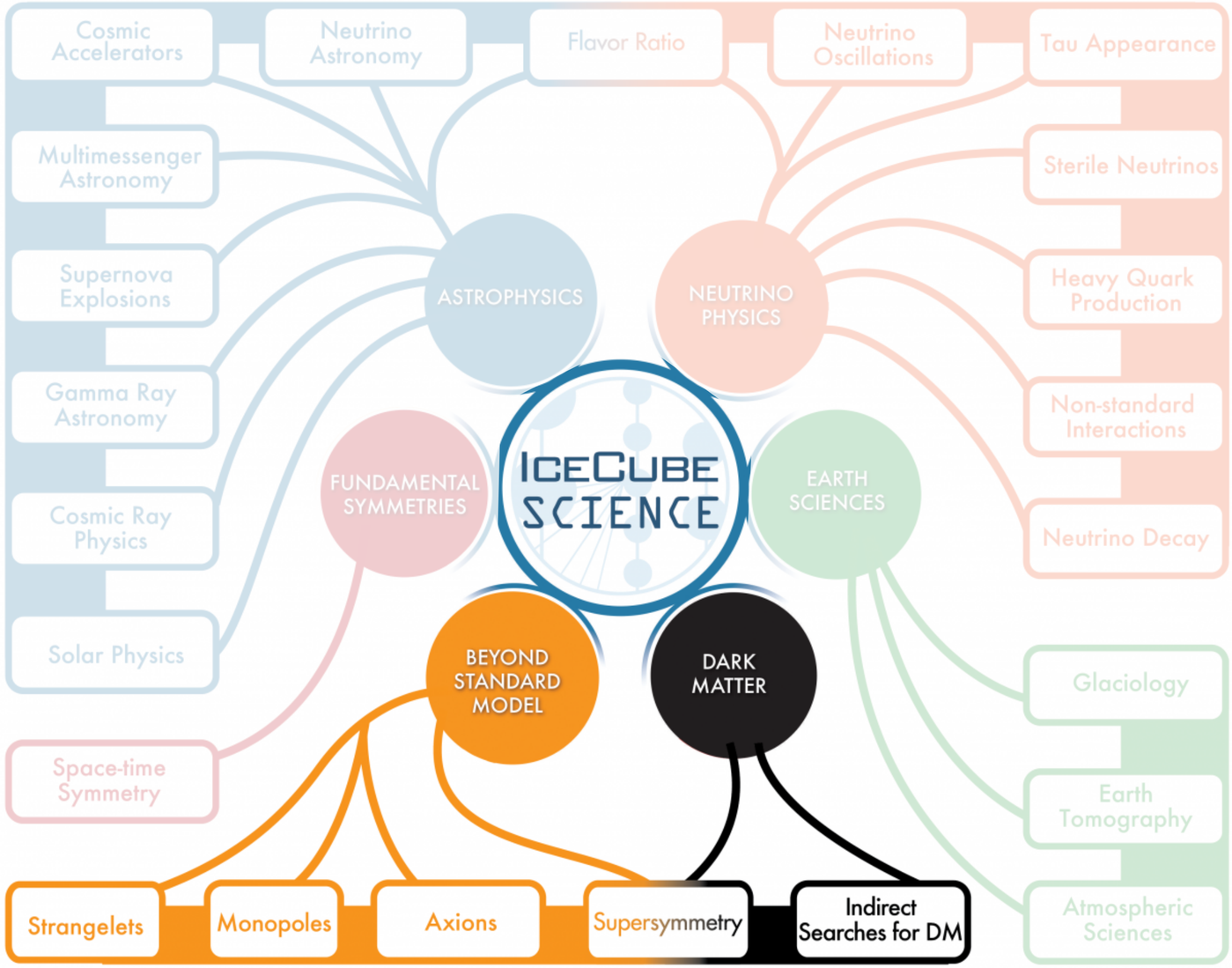
IceCube Science



Highlights

- In 2013 IceCube detected for the first time an astrophysical neutrinos flux. ***Physics World 2013 Breakthrough of the Year***.
- In July 2018 IceCube provided the ***first evidence for a known blazar as a source of high-energy neutrinos.***
- …

IceCube Science



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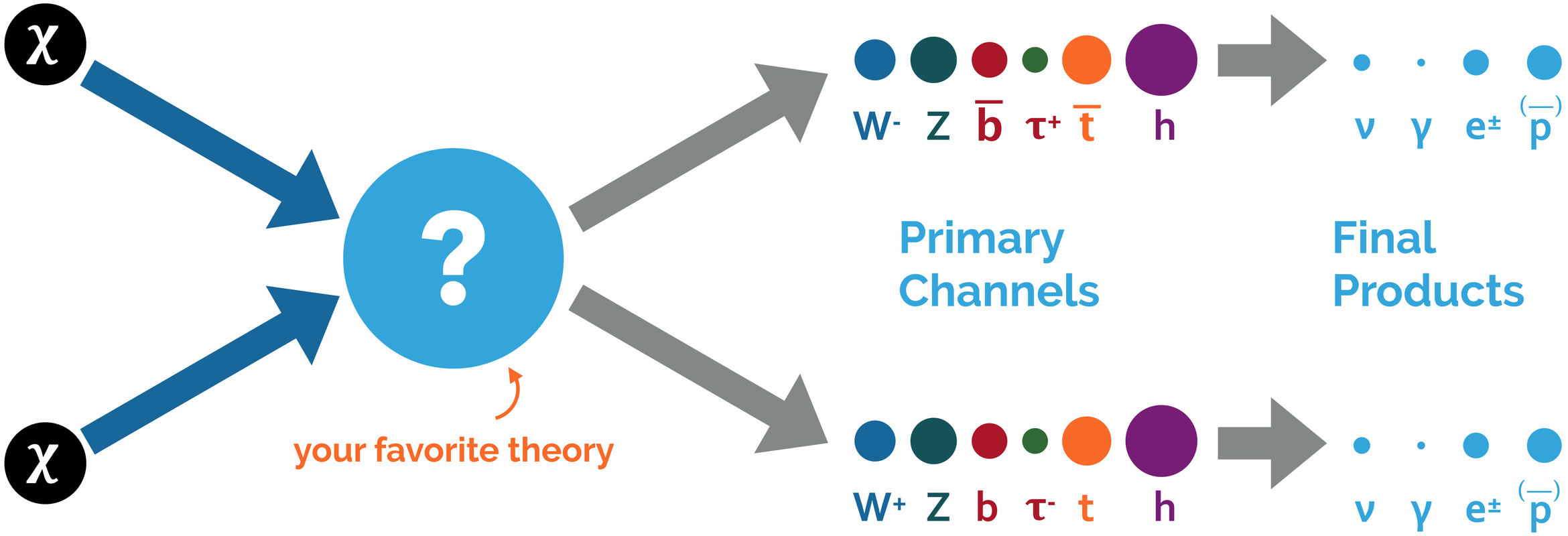
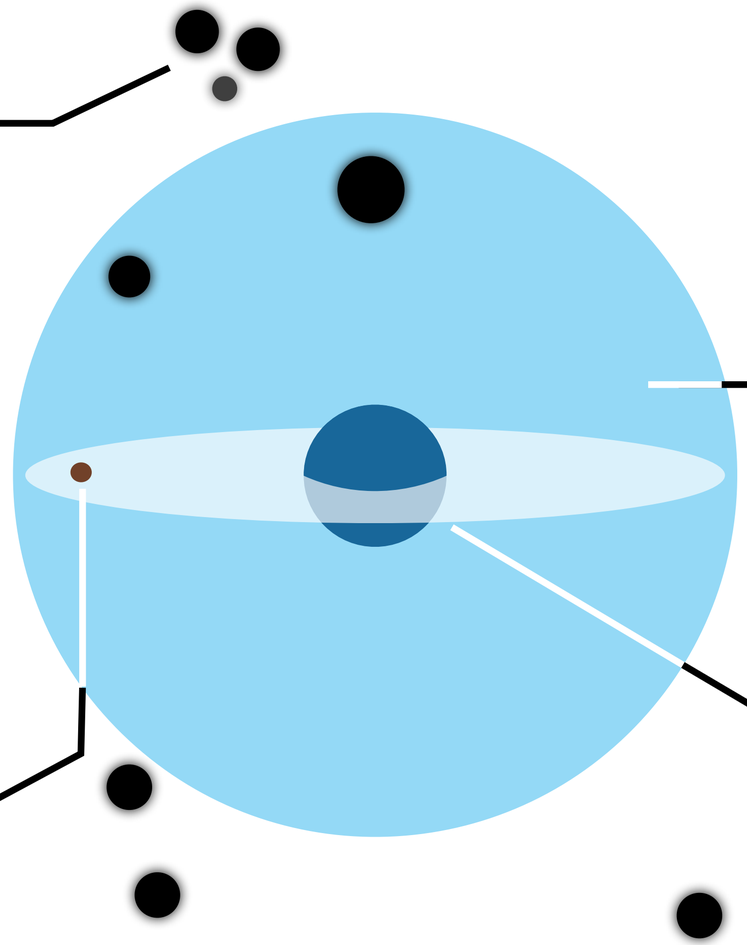
Indirect Detection of Dark Matter



- No need of specialized detectors: **Gamma-ray telescopes, neutrino detectors, CR-experiments**
- Search for products of dark matter annhilation processes: **Focus on large reservoirs of dark matter**

Dark Matter Searches with Neutrinos Where to Look?



Dwarf spheroidal Galaxies
Cluster of Galaxies

Probe velocity-averaged DM annihilation cross section $\langle v\sigma_A \rangle$

Galactic Halo

Probe velocity-averaged DM annihilation cross section $\langle v\sigma_A \rangle$

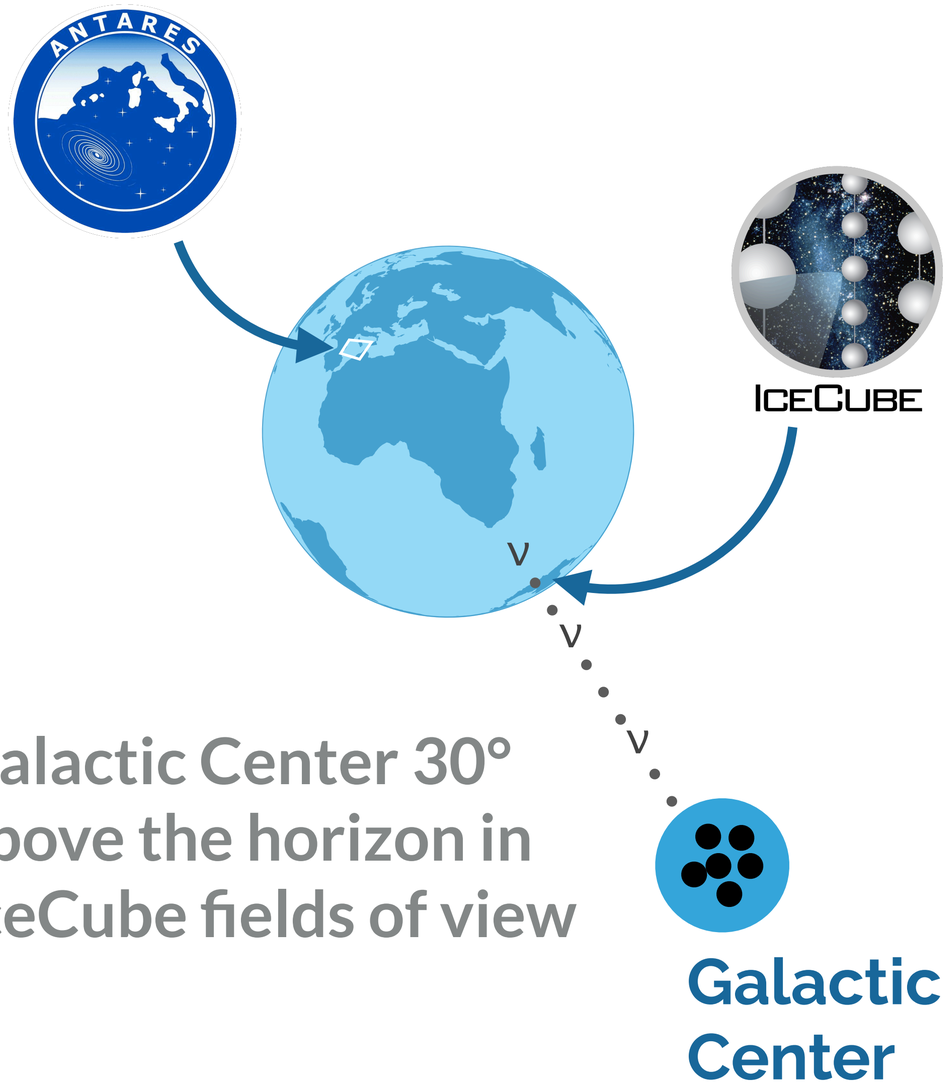
Galactic Center

Probe velocity-averaged DM annihilation cross section $\langle v\sigma_A \rangle$

Local Sources (Sun, Earth)

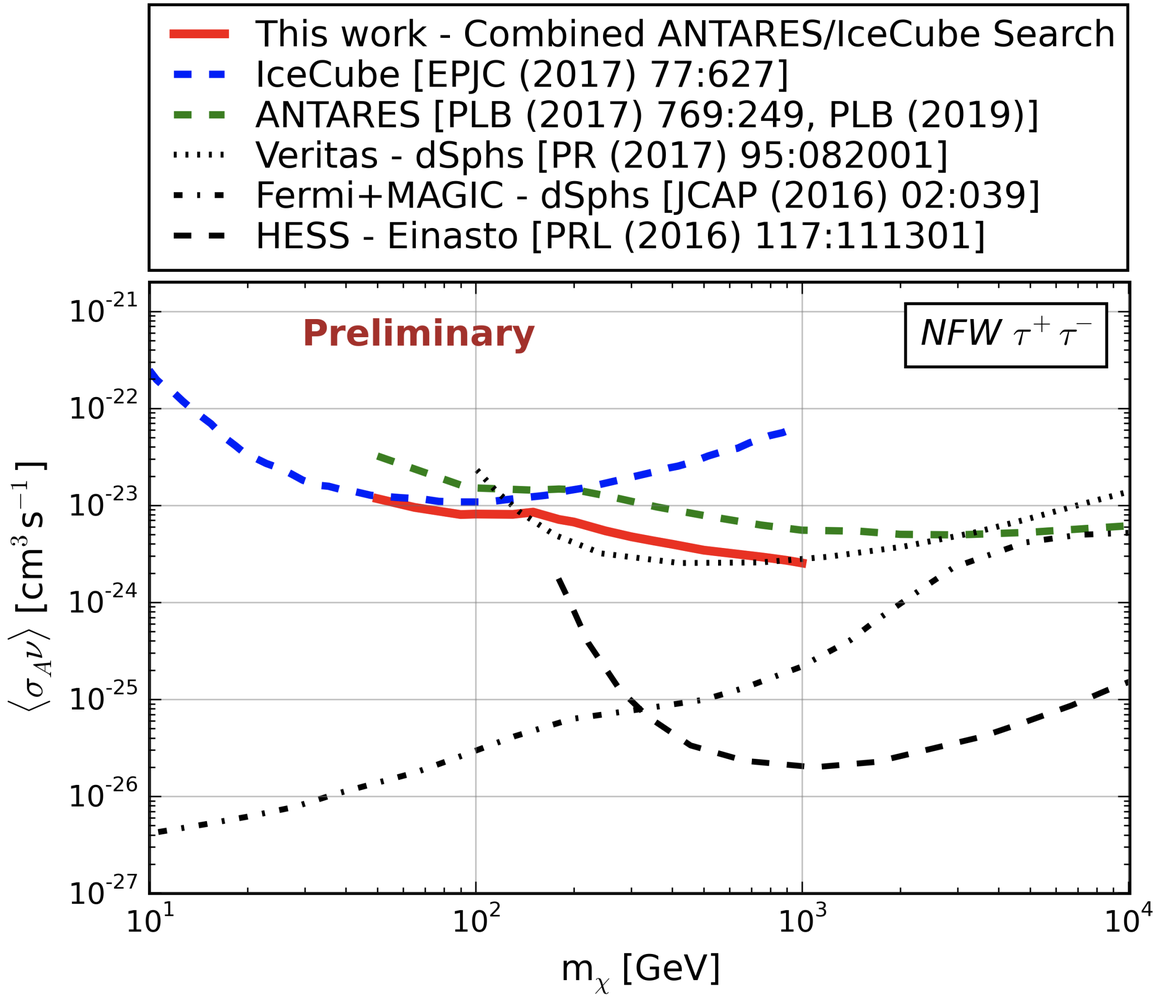
Only accessible with neutrinos
Under equilibrium they can probe σ_{SI} and σ_{SD}

Galactic Center ANTARES & IceCube



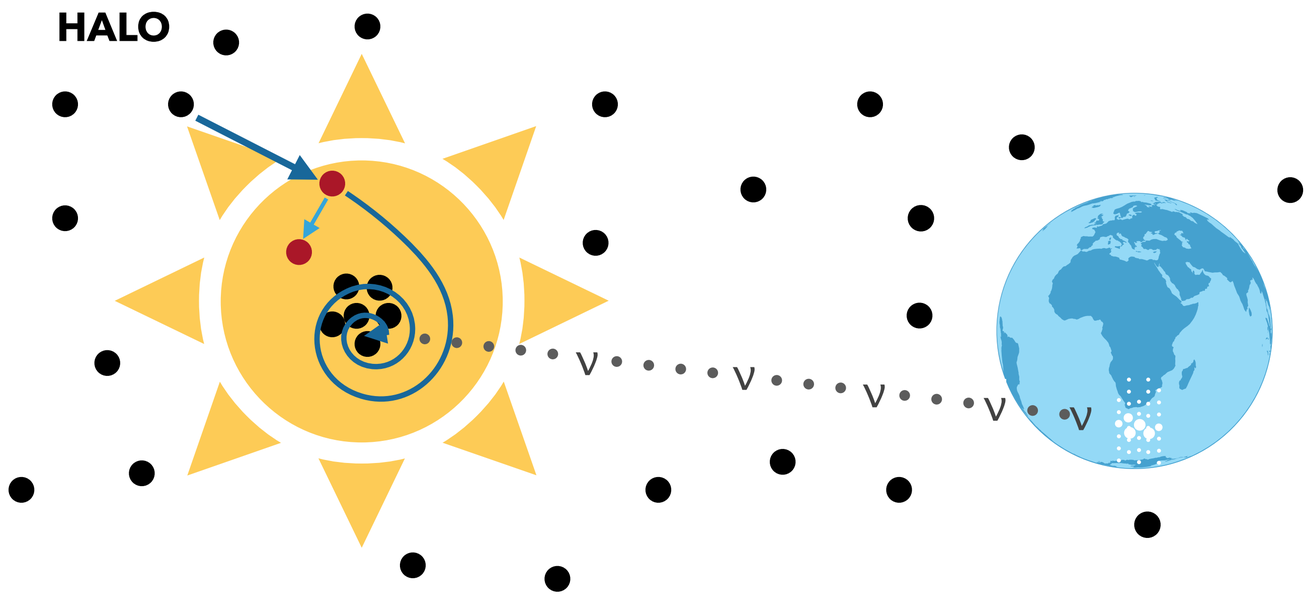
Galactic Center 30° above the horizon in IceCube fields of view

- ANTARES uses Earth as a shield/higher masses
- IceCube uses a self-veto technique/lower masses

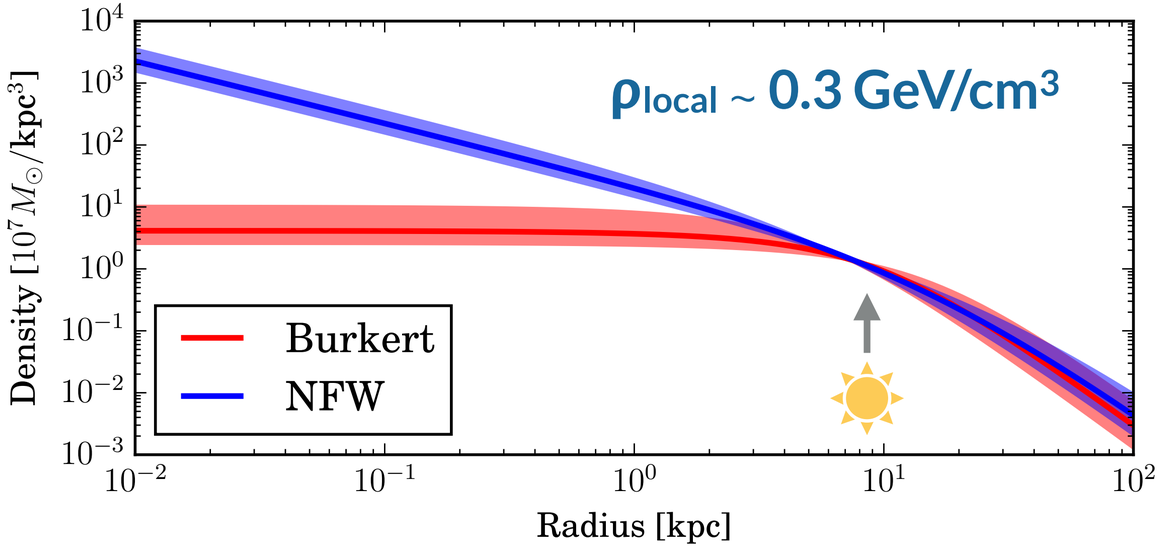


[ICRC2019 arXiv:1908.07300]

Dark Matter from Celestial Bodies



- Signal from the Sun or Earth in neutrinos cannot be mis-interpreted as an astrophysical source.
- Halo models agree in the Solar System.



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

annihilation σ_A

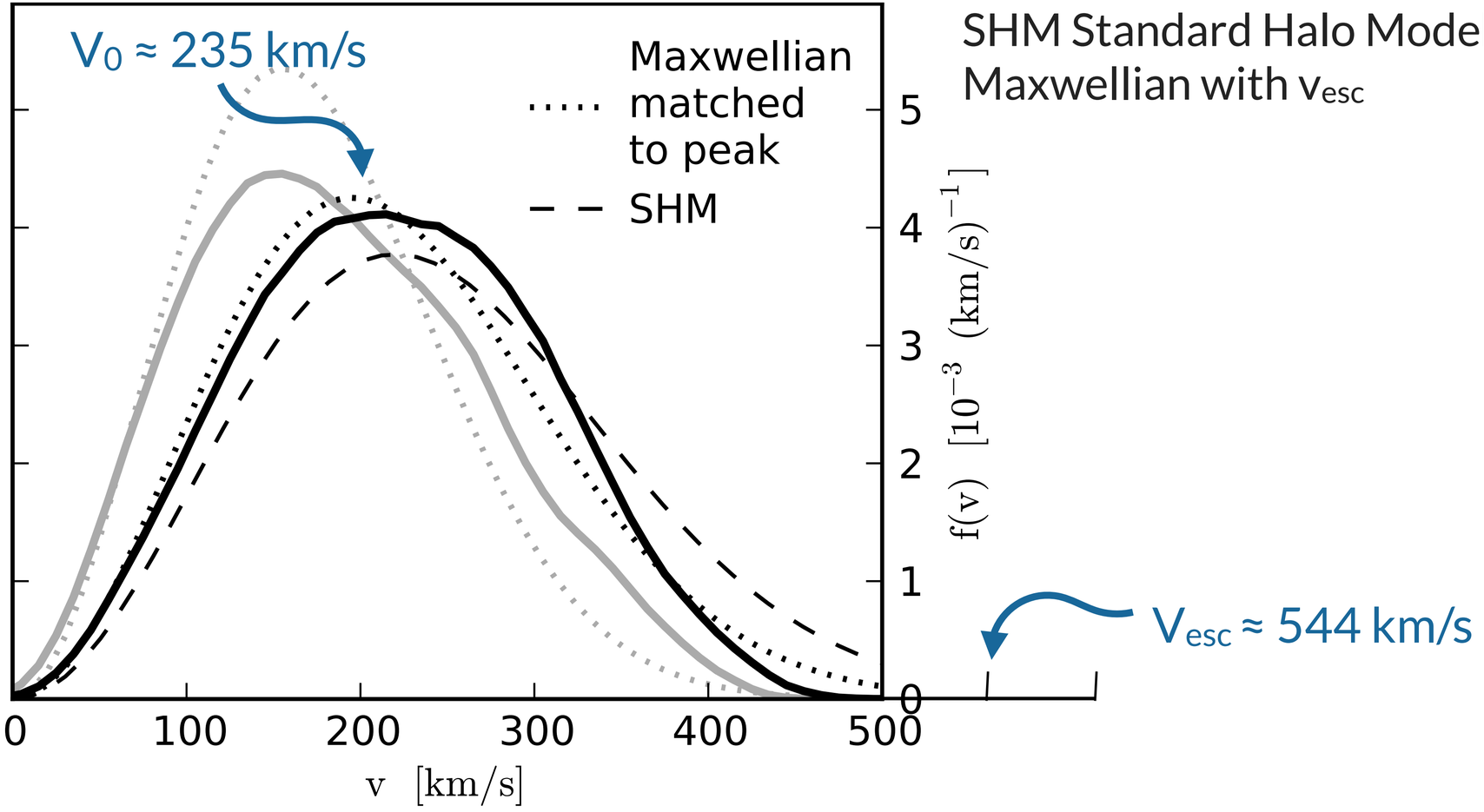
capture $\sigma_{\chi-N}$

Equilibrium $\frac{dN}{dt} = 0$ is assumed for the Sun, not for Earth

Celestial Bodies Velocity Distribution

Heavy dark matter particles can only be captured at low velocities

Figure from https://arxiv.org/pdf/1308.1703.pdf



SHM Standard Halo Model = Maxwellian with v_{esc}

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

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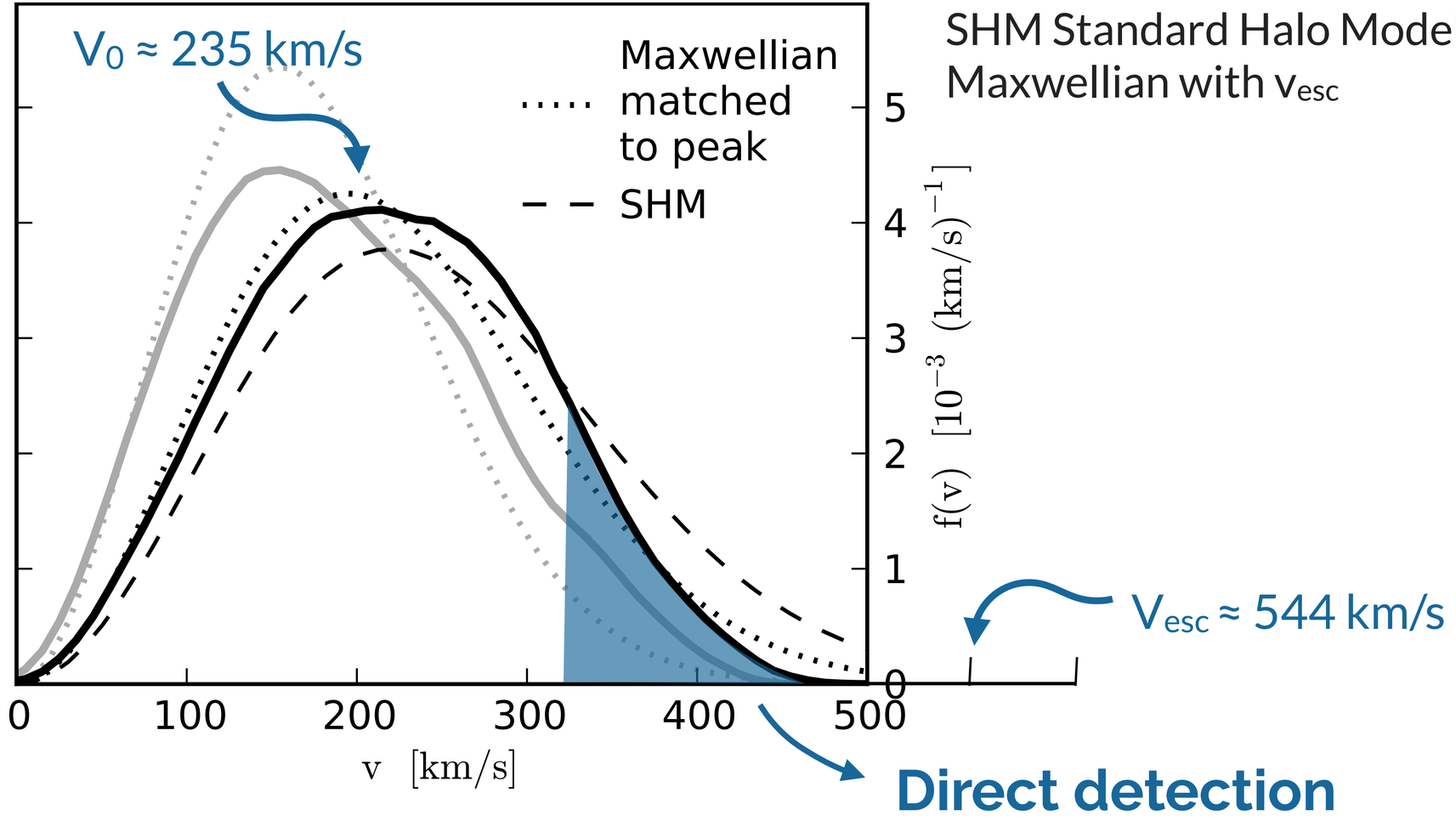

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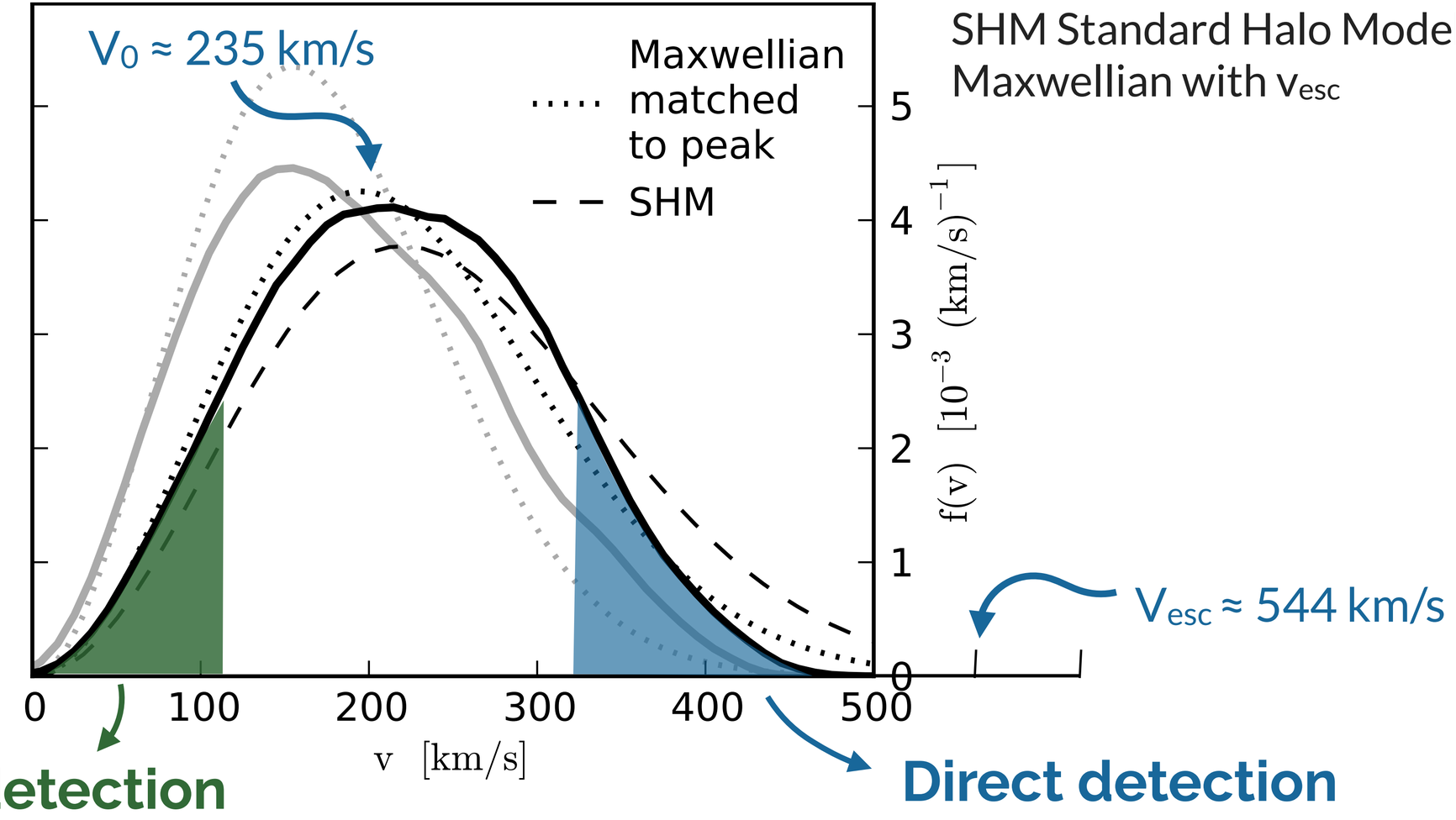


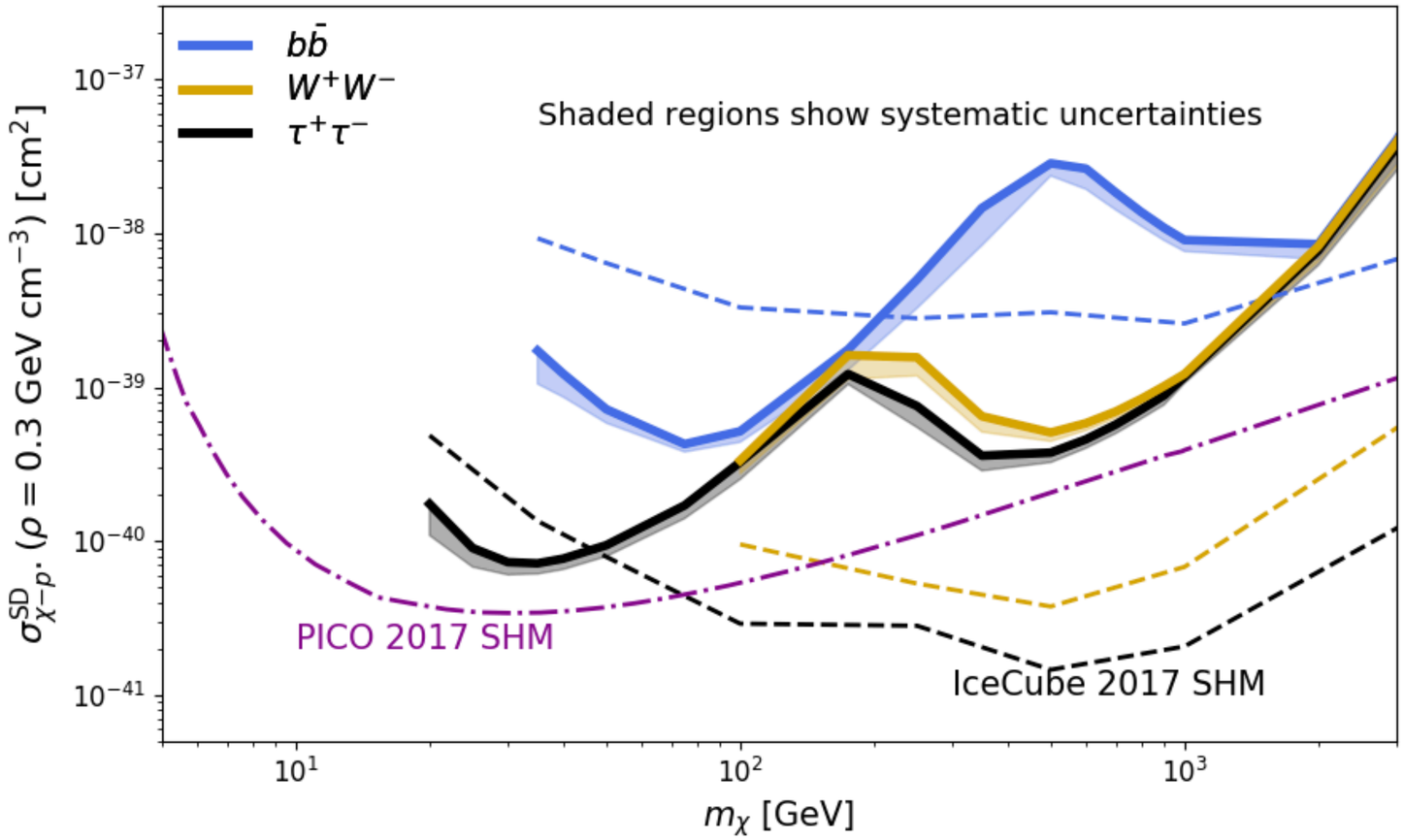
SHM Standard Halo Model = Maxwellian with v_{esc}

Velocity Independent PICO and IceCube

- **Deviations from the SHM** will affect spin-dependent limits.
- Construction of independent limits assuming as the superposition of **streams with fixed velocity**.
- **Conservative limits:** only the velocity stream with the highest allowed scattering cross-section is selected

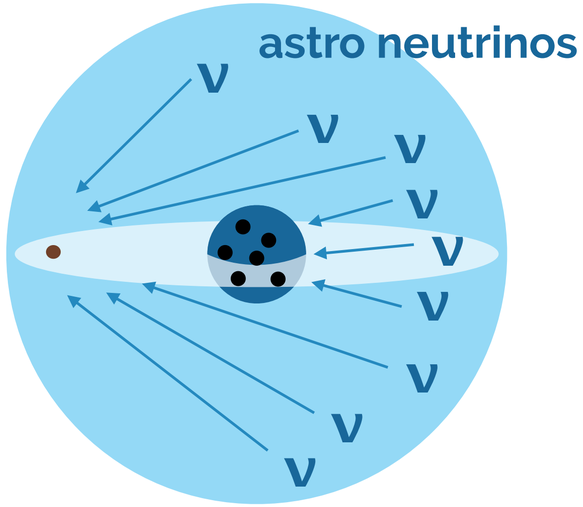
equilibrium!

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

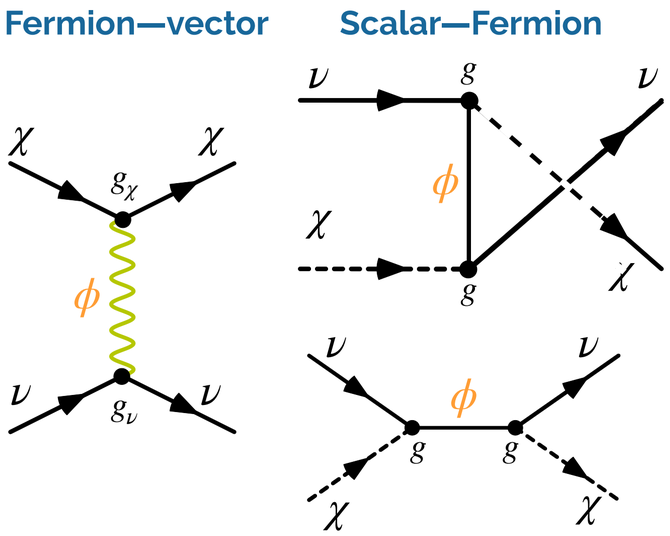


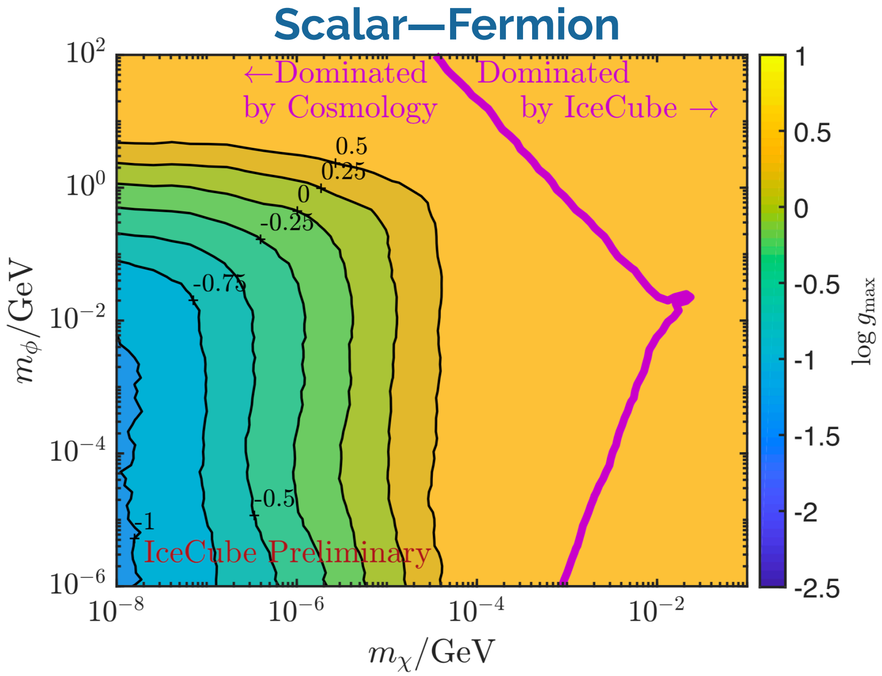
[Submitted to Eur. Phys. J. C, arXiv:1907.12509]

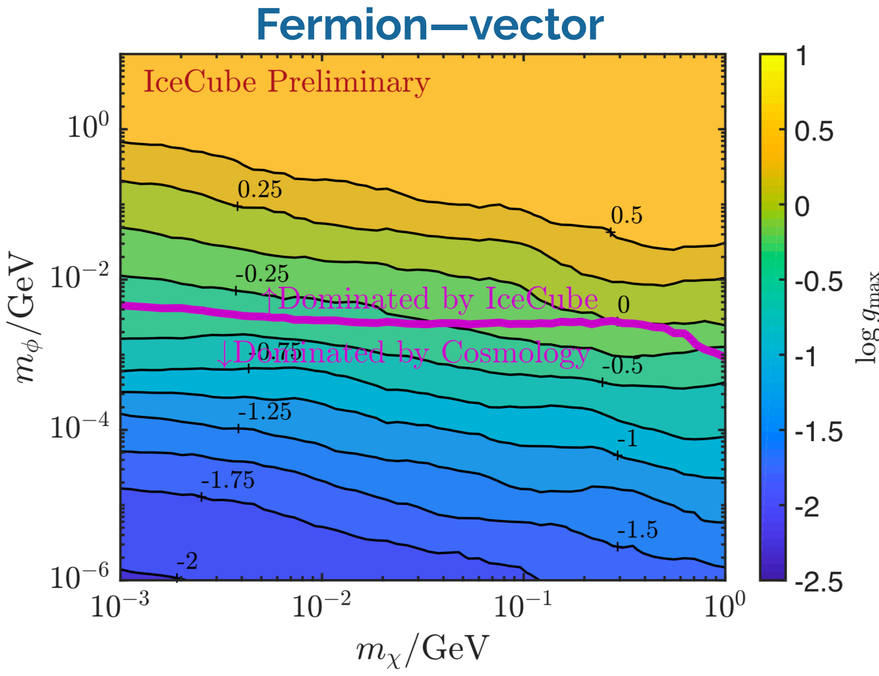
Neutrino Dark Matter Scattering



- Scattering of high energy cosmic neutrinos on DM in the halo can lead to a **deficit** in the direction of Galactic Center
- Look for a deficit on the **astrophysical neutrino flux**







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

Searching for Magnetic Monopoles

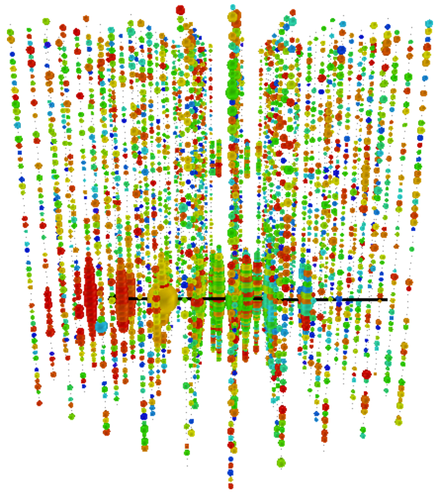
$$\vec{\nabla} \times \vec{B} = 4\pi\rho_M$$

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

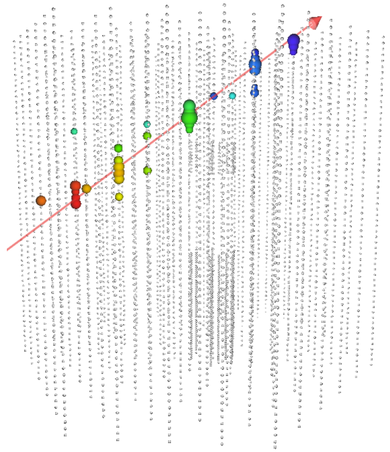
- Predicted by many GUT models
  10^{13} GeV < M_{MM} < 10^{19} GeV
- They can explain quantification of charge
  $$g = \frac{2\pi\hbar}{\mu_0 e} n$$
- They are stable
- They are easily accelerated
  E_{kin} < 10^{15} GeV (M_{MM} < 10^{14} GeV)

IceCube Signatures

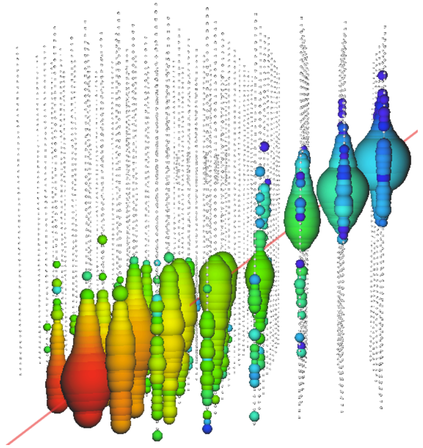
Slow monopoles	Low/Mildly relativistic	Relativistic
β < 0.1	0.1 < β < 0.5	β > 0.5



Catalysis of proton decay

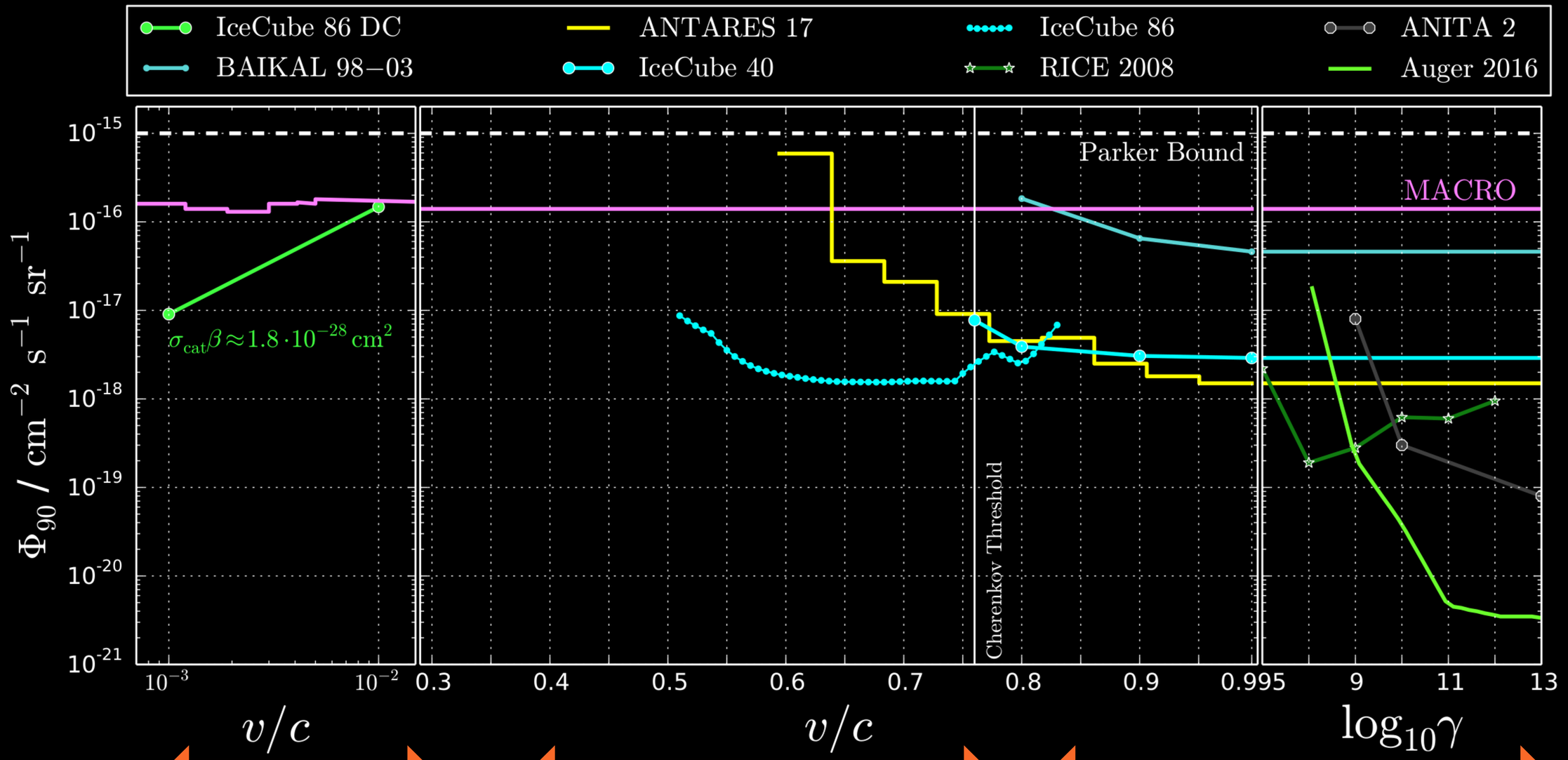


Luminescence



Direct/indirect Cherenkov

Monopoles Latest Results



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

New Physics from Astrophysical Neutrinos

Source 

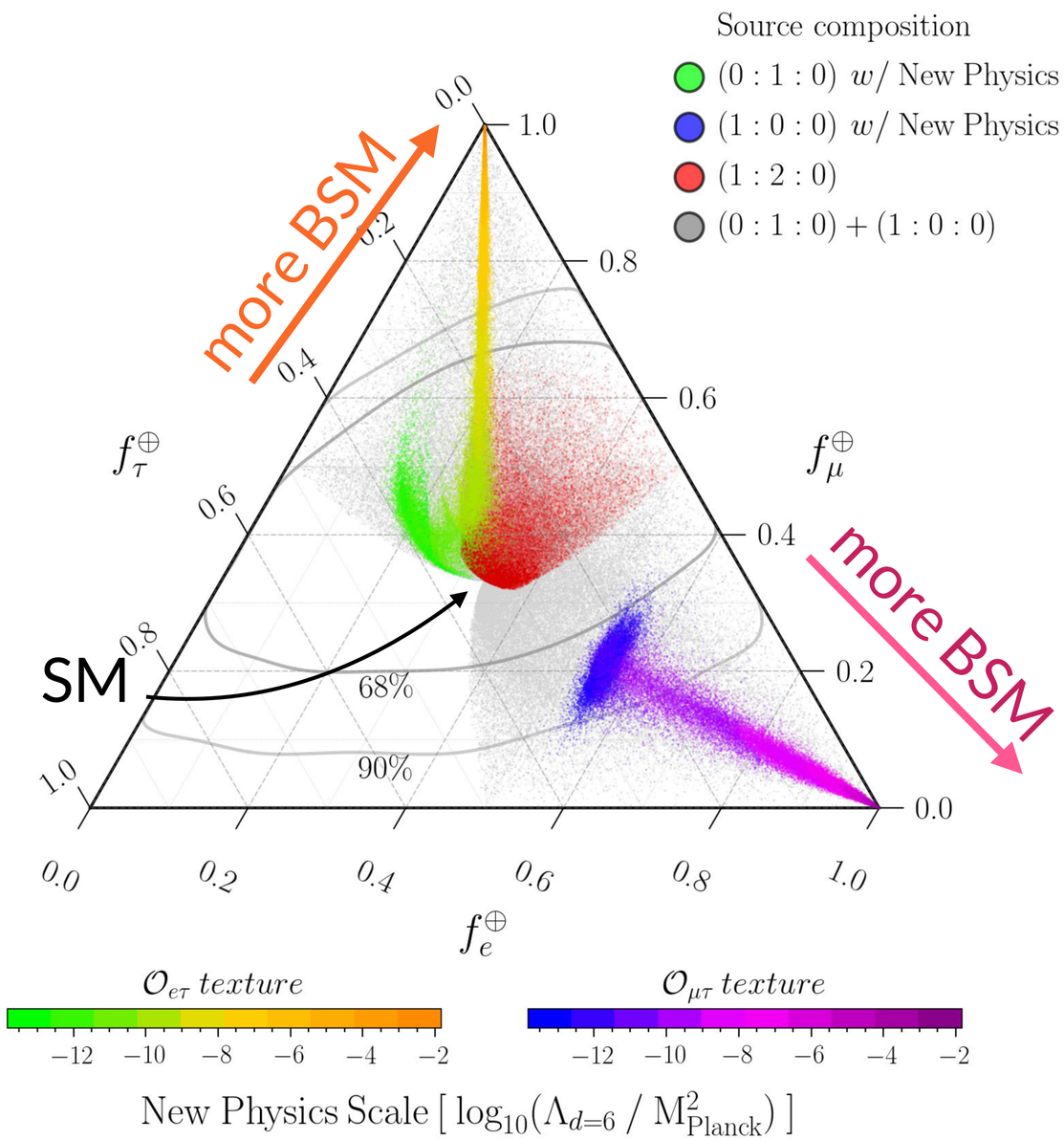
Earth

(1:0:0) neutron decay
(1:2:0) pion production → (1:1:1)
(0:1:0) muon dumped

- New physics can alter the 1:1:1 prediction.
- Parametrize new physics through a scale Λ_d and an operator O_d:

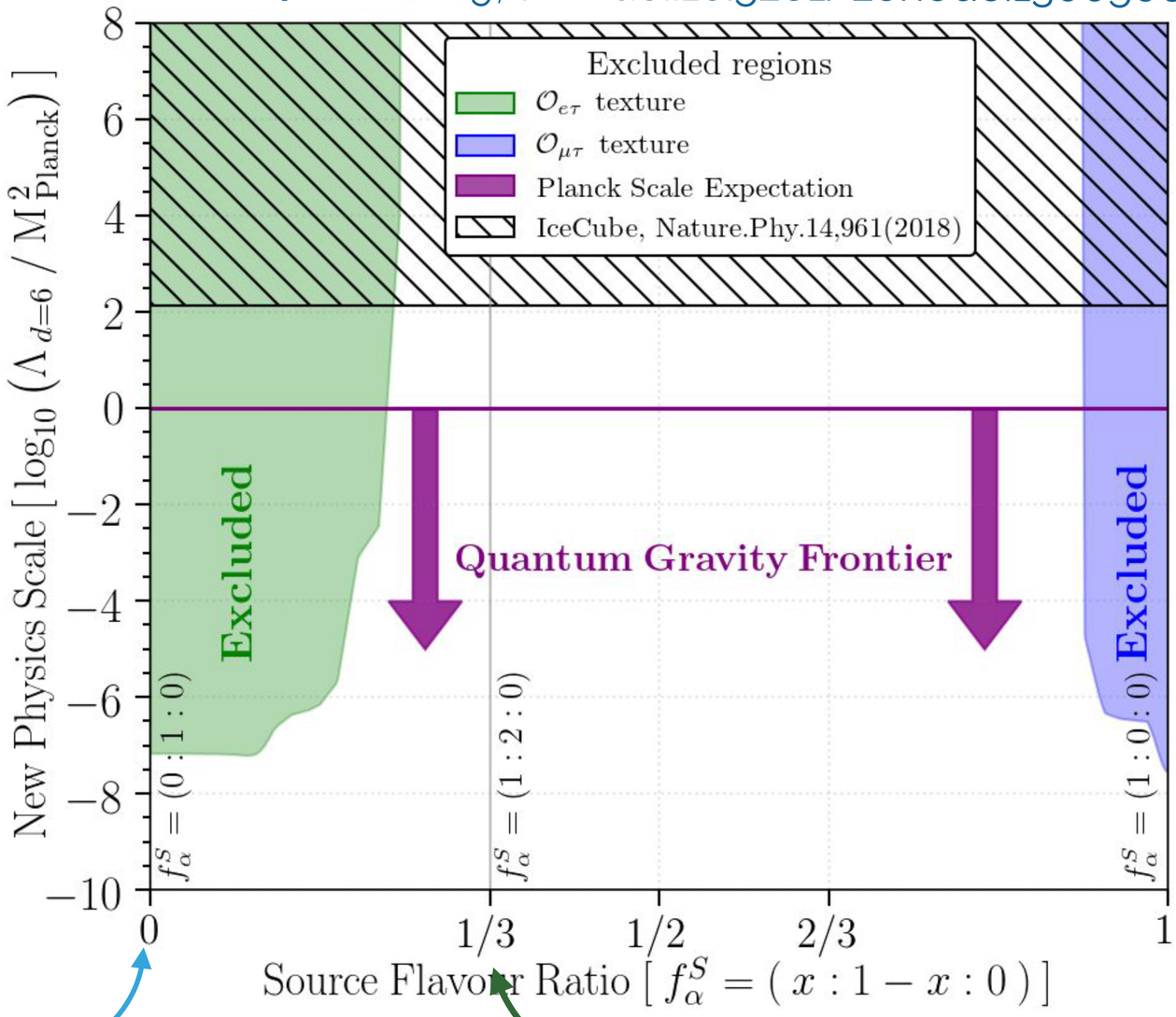
$$H_d = \frac{1}{2E} U M^2 U^\dagger + \frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger$$

standard oscillations — **new physics oscillations**



New Physics from Astrophysical Neutrinos Results

[ICRC 2019, arxivdoi:10.5281/zenodo.1300506]



muon dumped (0:1:0)

pion decay (1:2:0)

neutron decay (1:0:0)

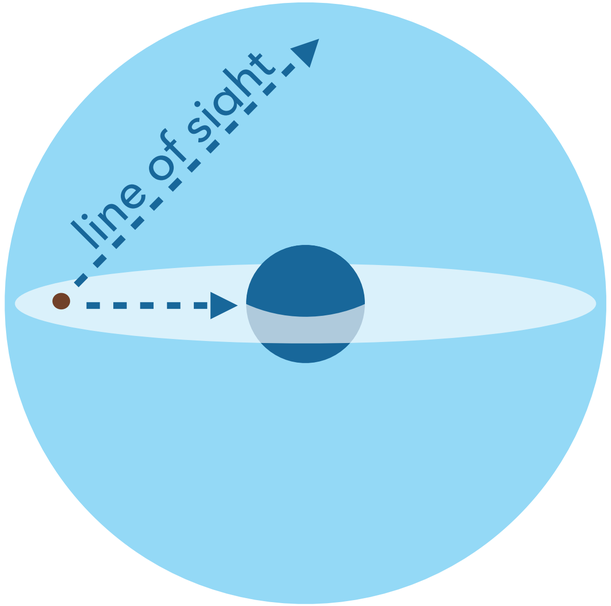
Conclusions

IceCube 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.
- IceCube has **world-best limits** on spin-dependent scattering cross-section.
- Neutrino telescopes can also provide a unique way to search for **monopoles and exotic particles** such as Q-balls.
- The detection of the **astrophysical neutrino flux** has open the opportunity to search for new physics

backups

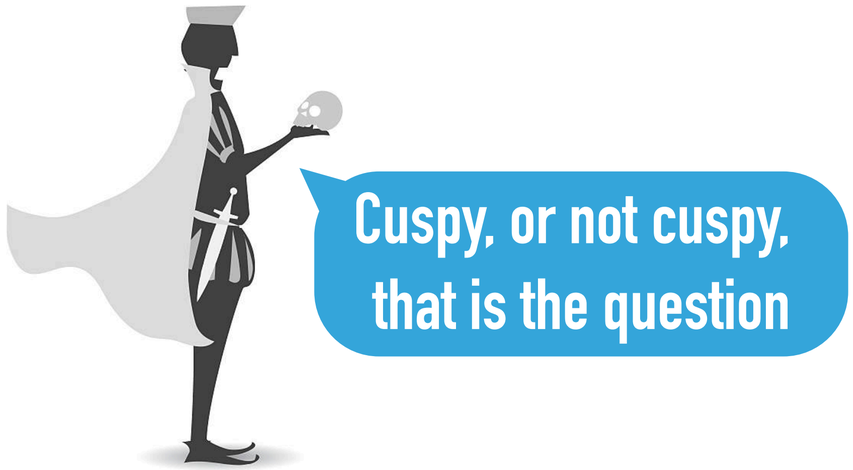
The Galactic Center The Astrophysical Input

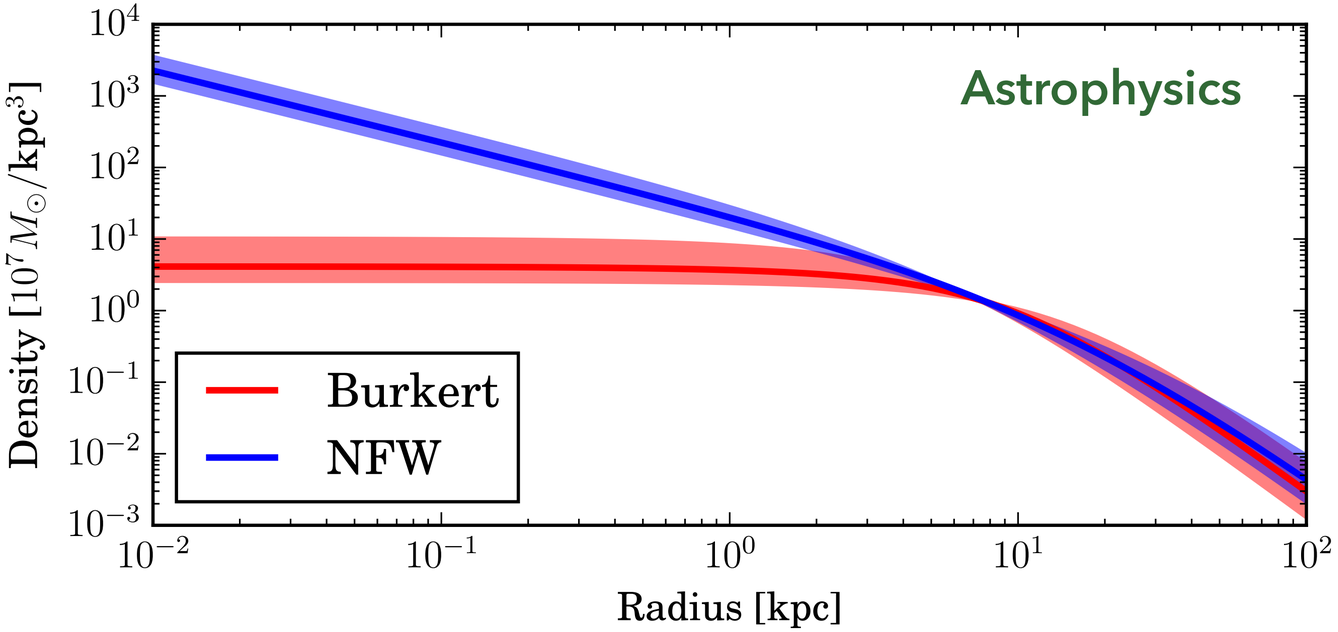


$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_0^{\Delta\Omega}\mathrm{d}\Omega\int_{l.o.s}\rho_\chi^2(r(s,\Psi,\theta))\mathrm{d}s$$

Particle physics

Astrophysics





Dark Matter Searches In a Nutshell

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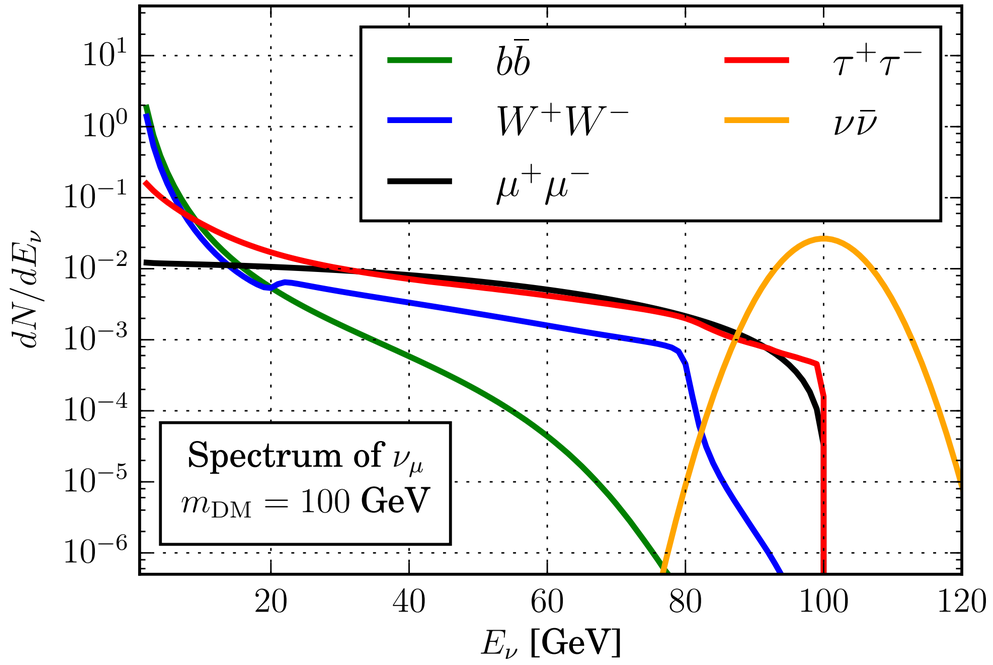
Theory input: SUSY?



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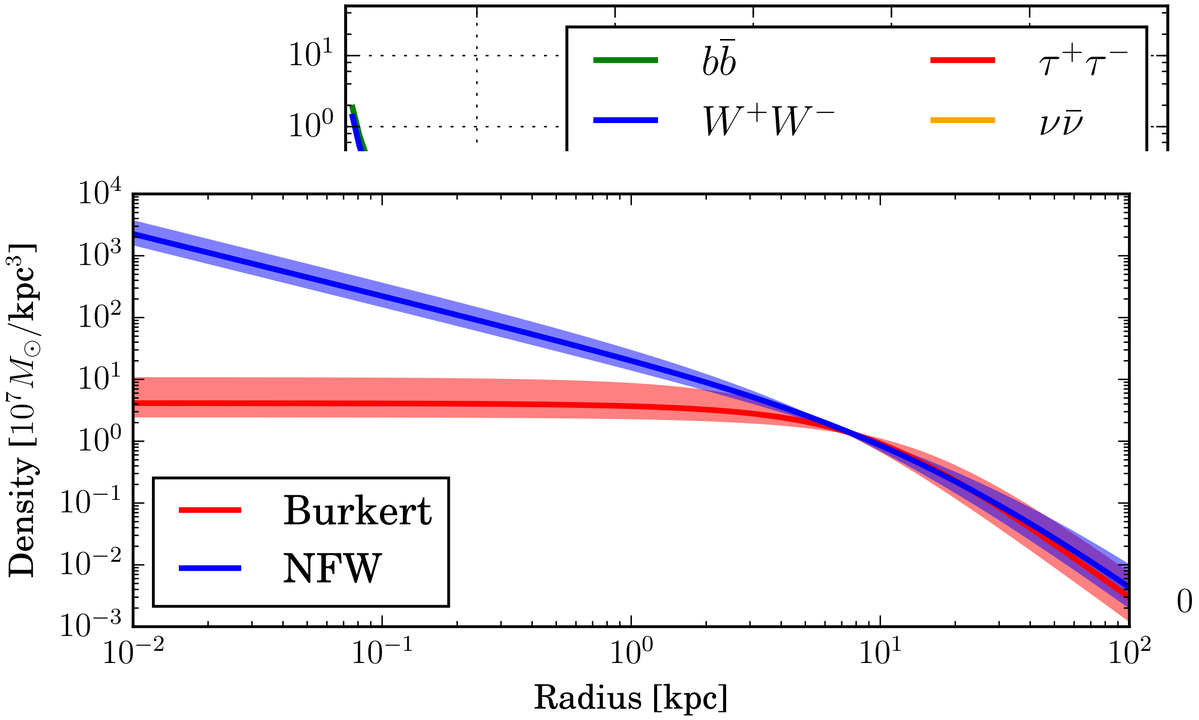

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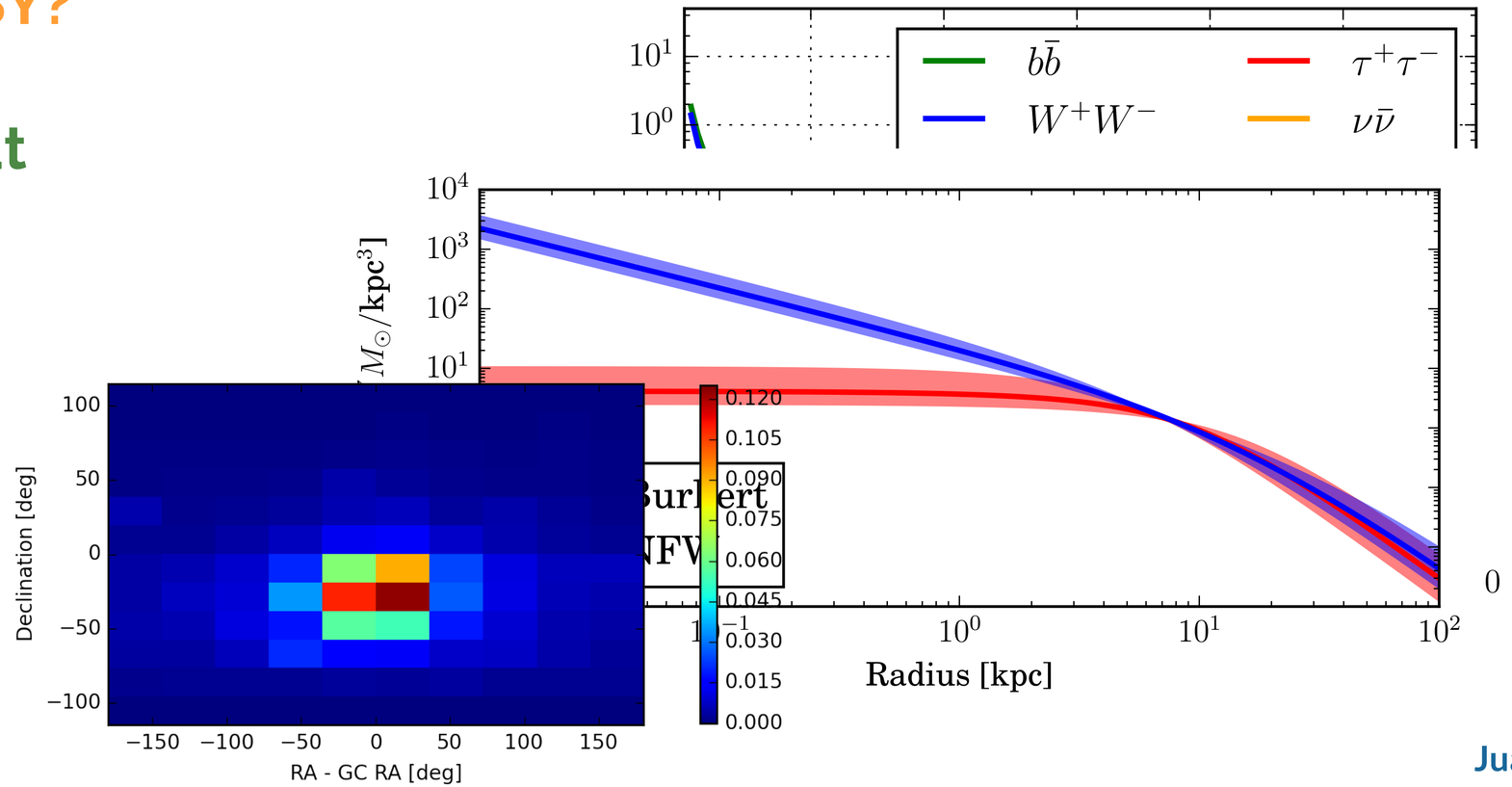
Measurement



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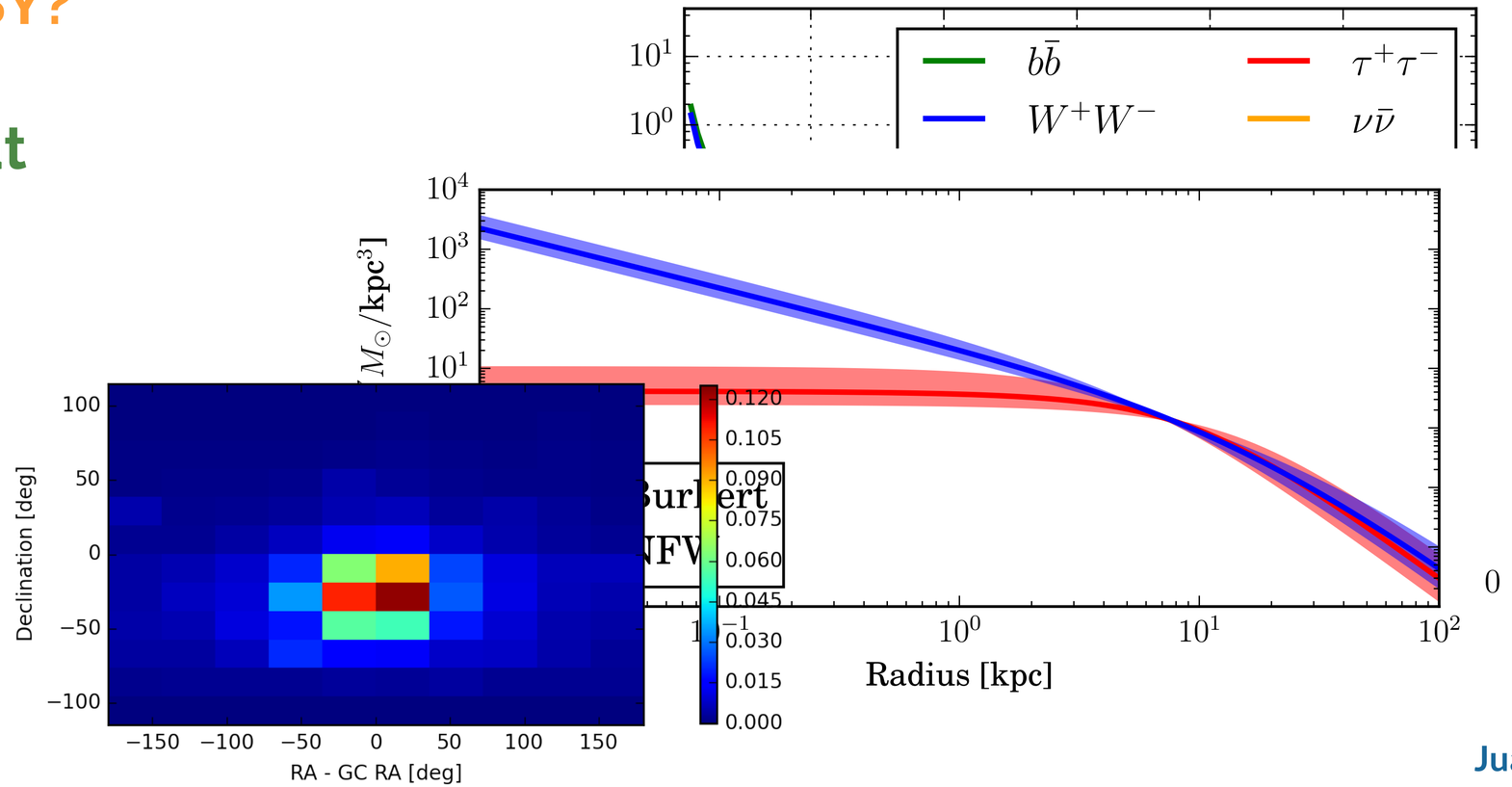
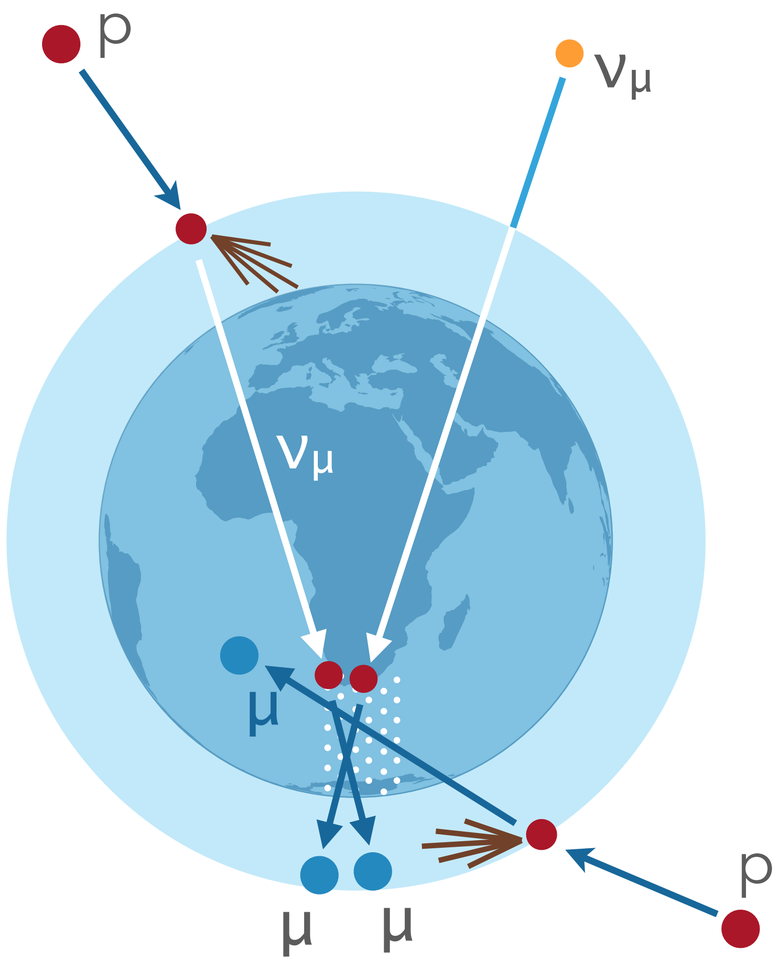
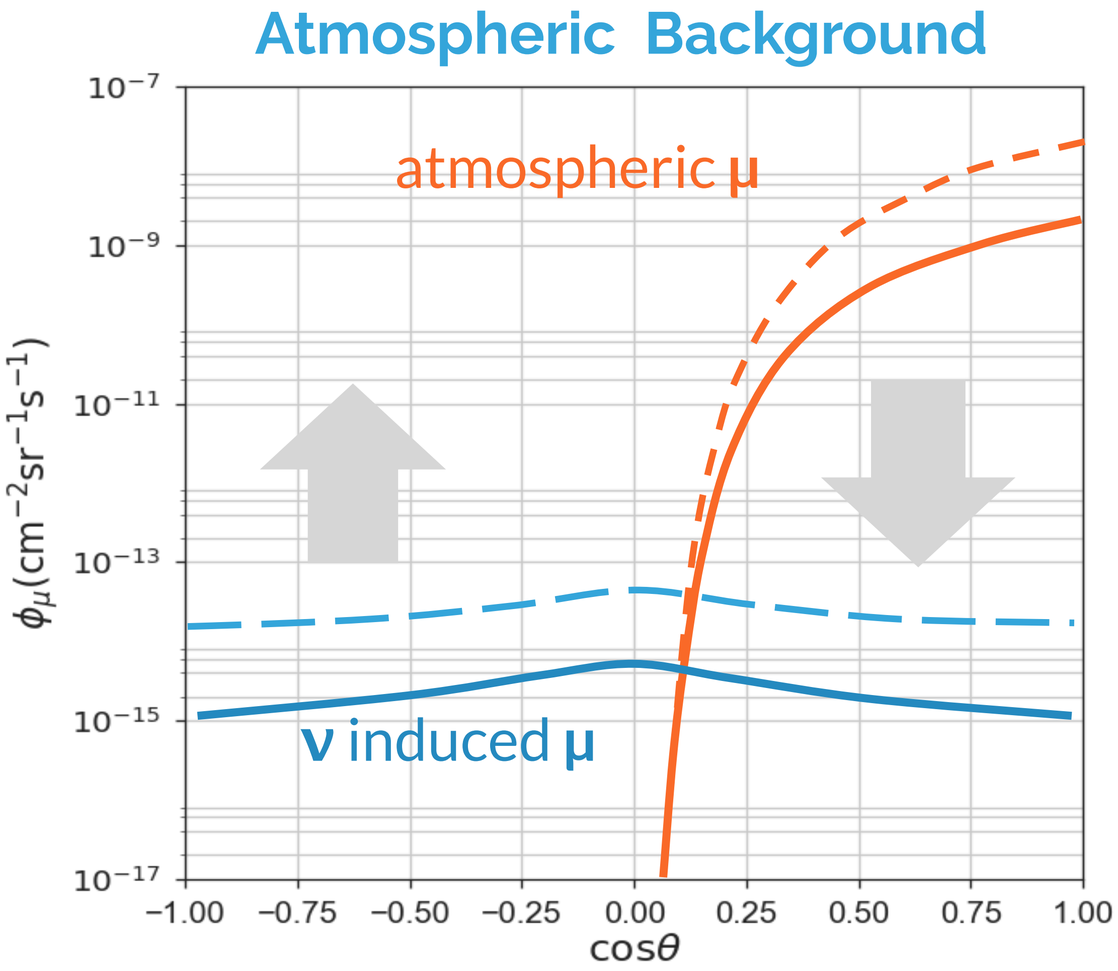
Measurement

Constrain!



Detection Principle Background



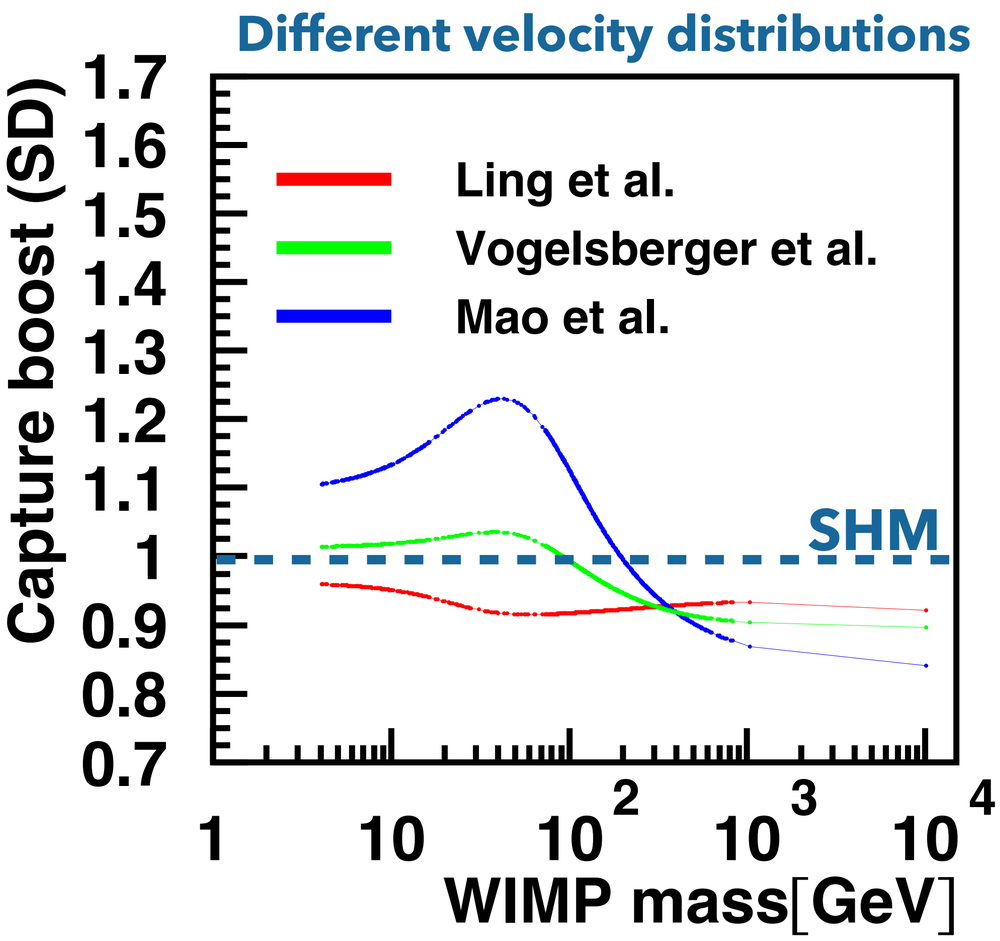


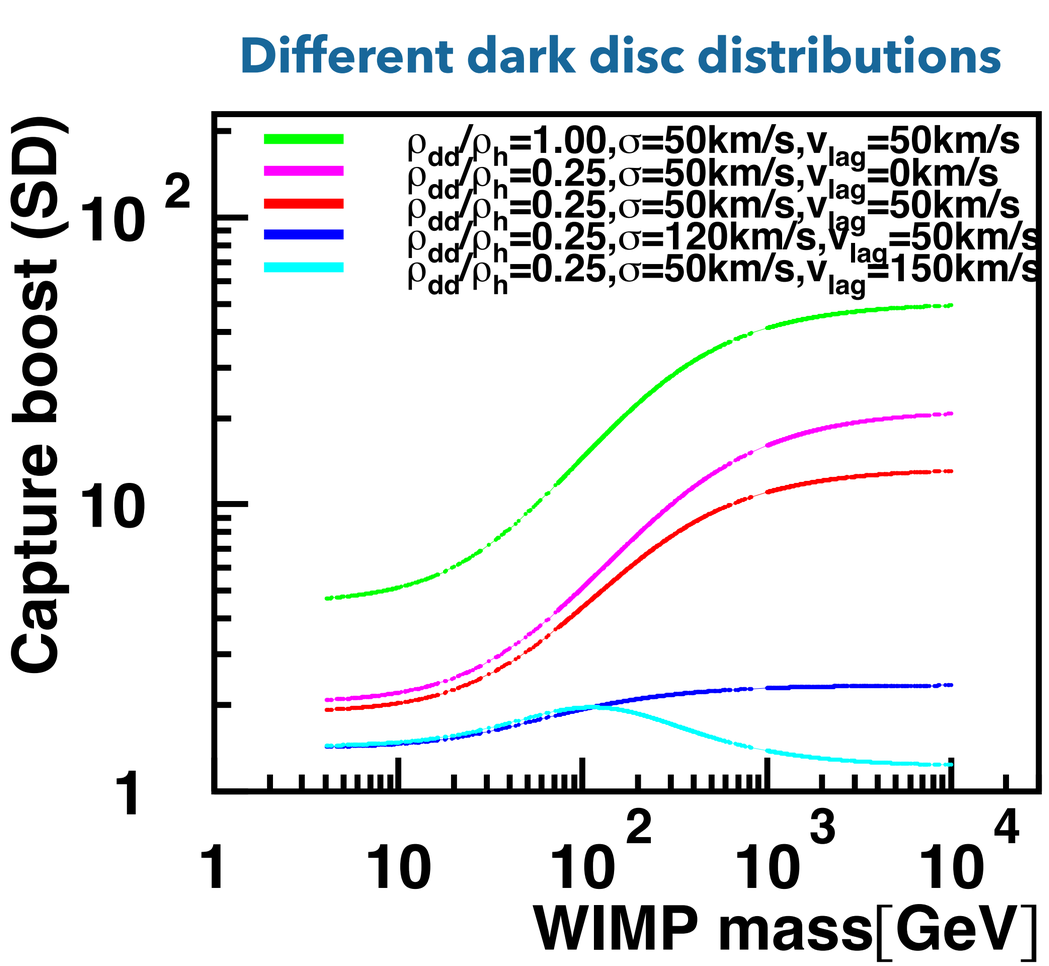
3kHz

2mHz

CELESTIAL BODIES: ASTROPHYSICAL INPUT

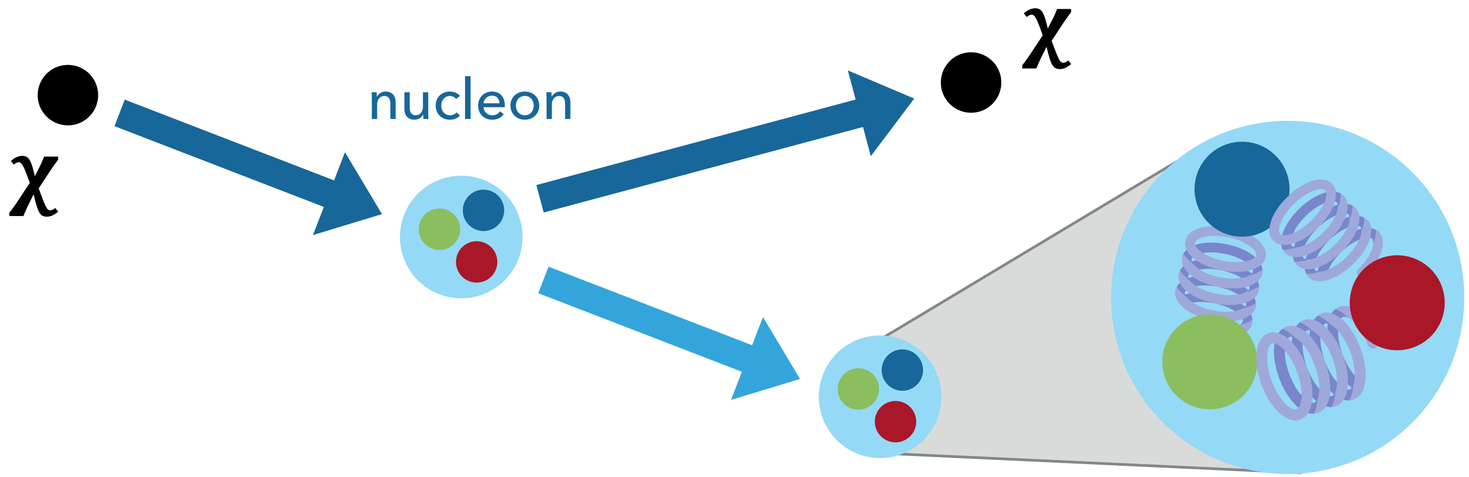
A **dark matter disc** will have a significant (good) impact on the capture rate for the Sun/Earh





Choi, Rott, Itow arXiv:1312.0273

CELESTIAL BODIES: PARTICLE



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

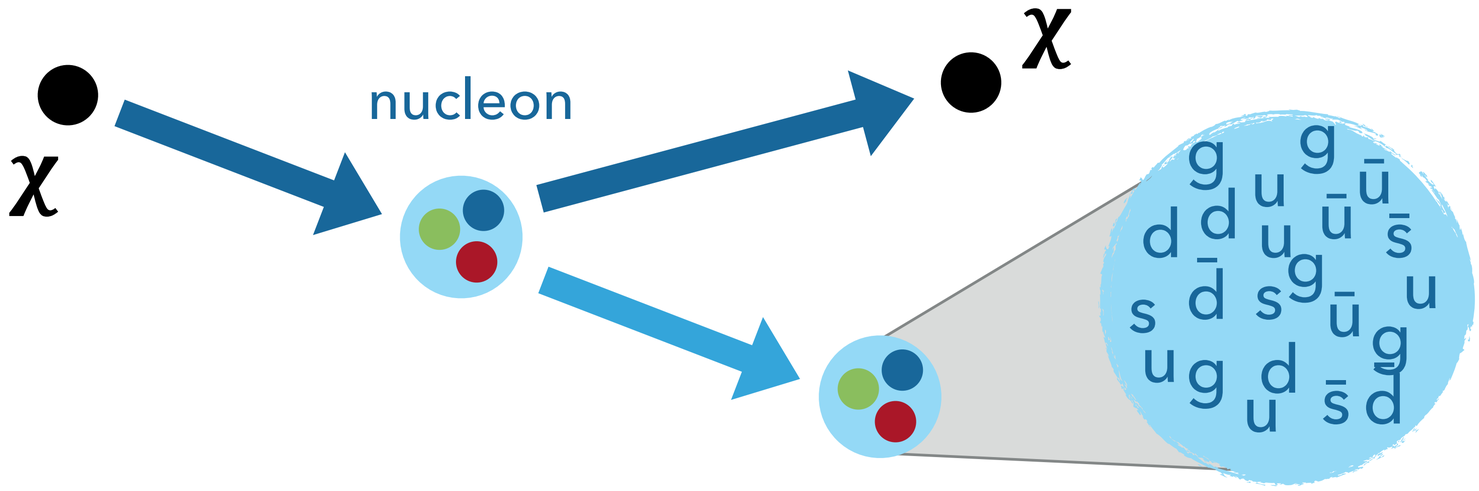
$$\sigma_{SI} \propto A^2$$

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**

CELESTIAL BODIES: PARTICLE



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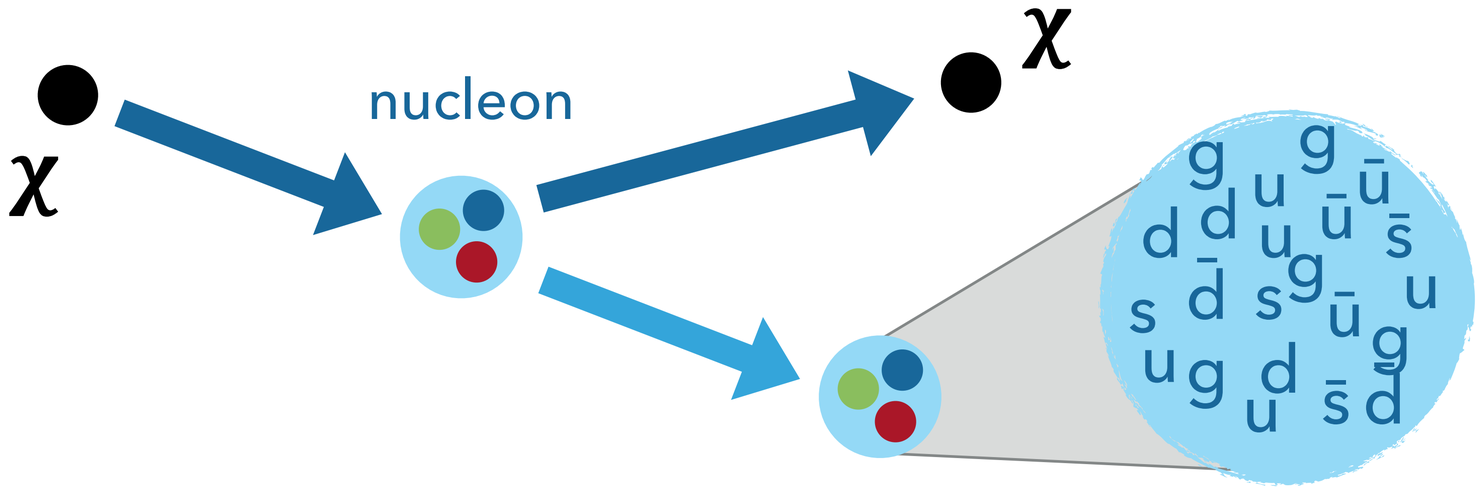

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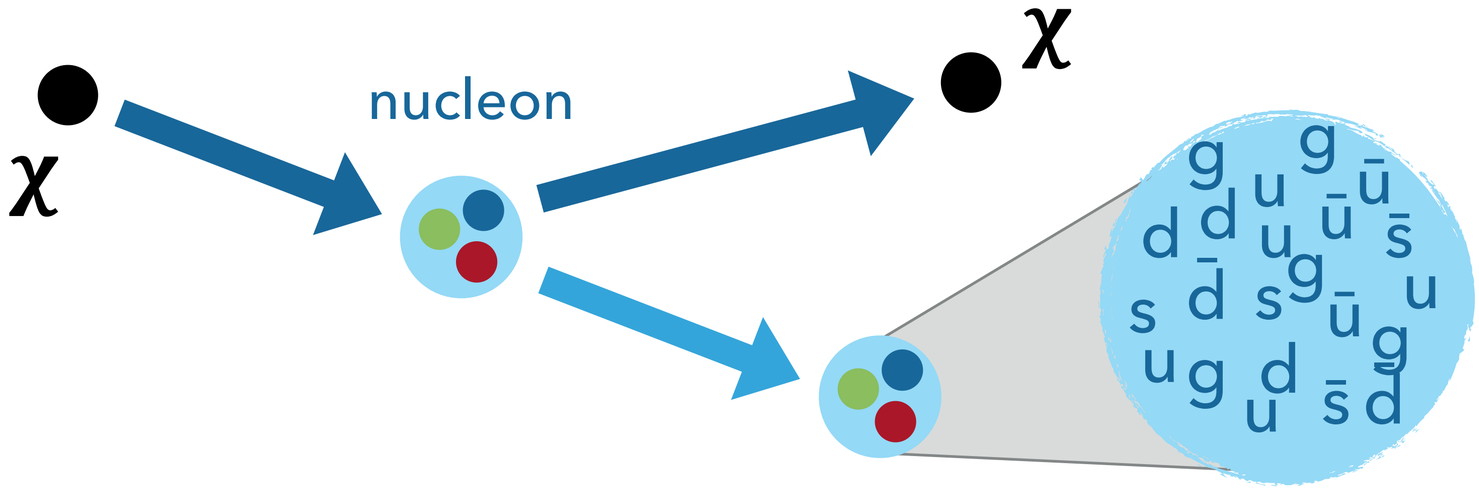
Spin dependent → **Sun is full of protons: Indirect detection**

The nucleon structure plays an essential role in calculating observables

CELESTIAL BODIES: PARTICLE



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

WIMP Searches From the Sun

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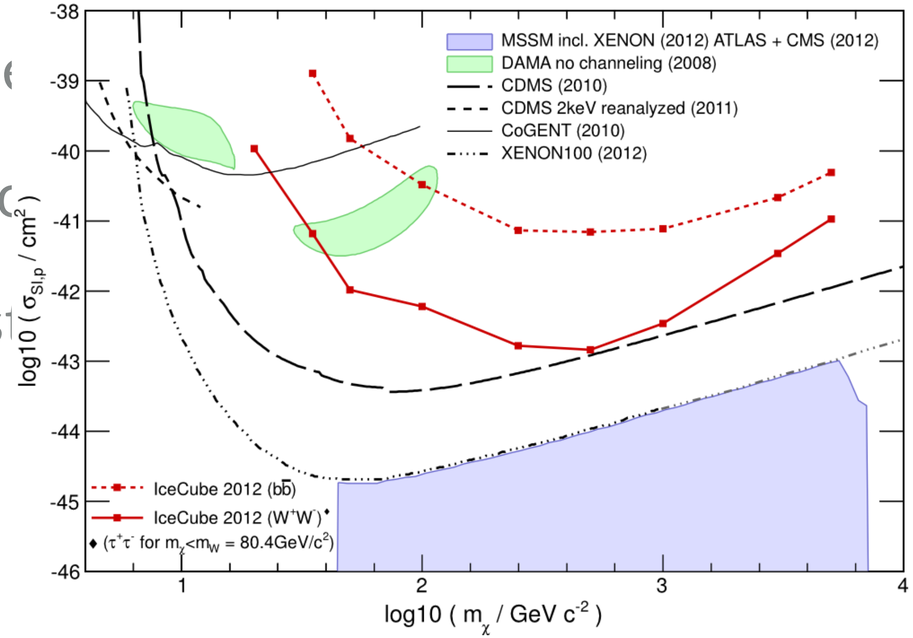
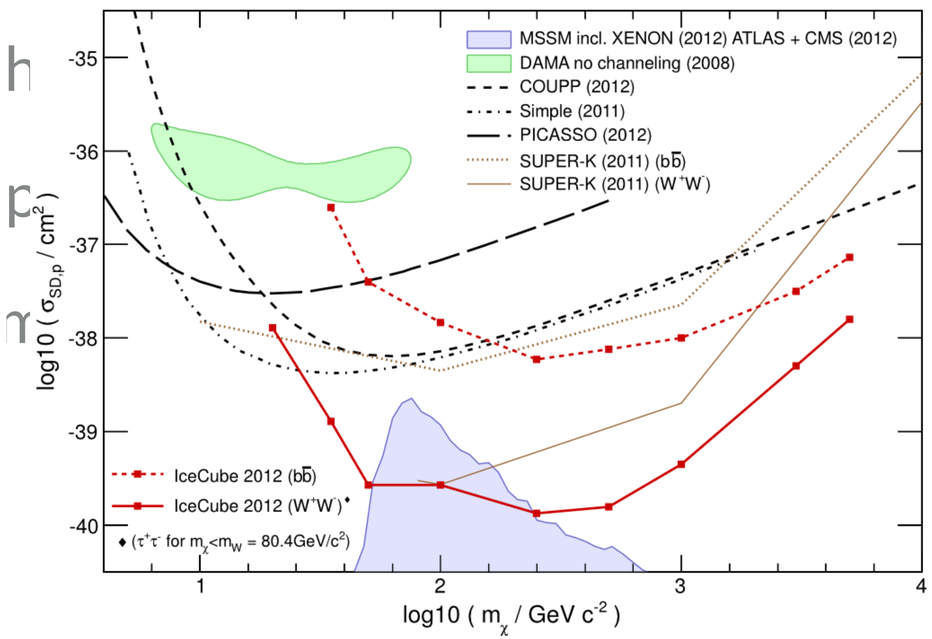
  - fills c
- Most st



90% CL χ-p cross-section (spin-independent)



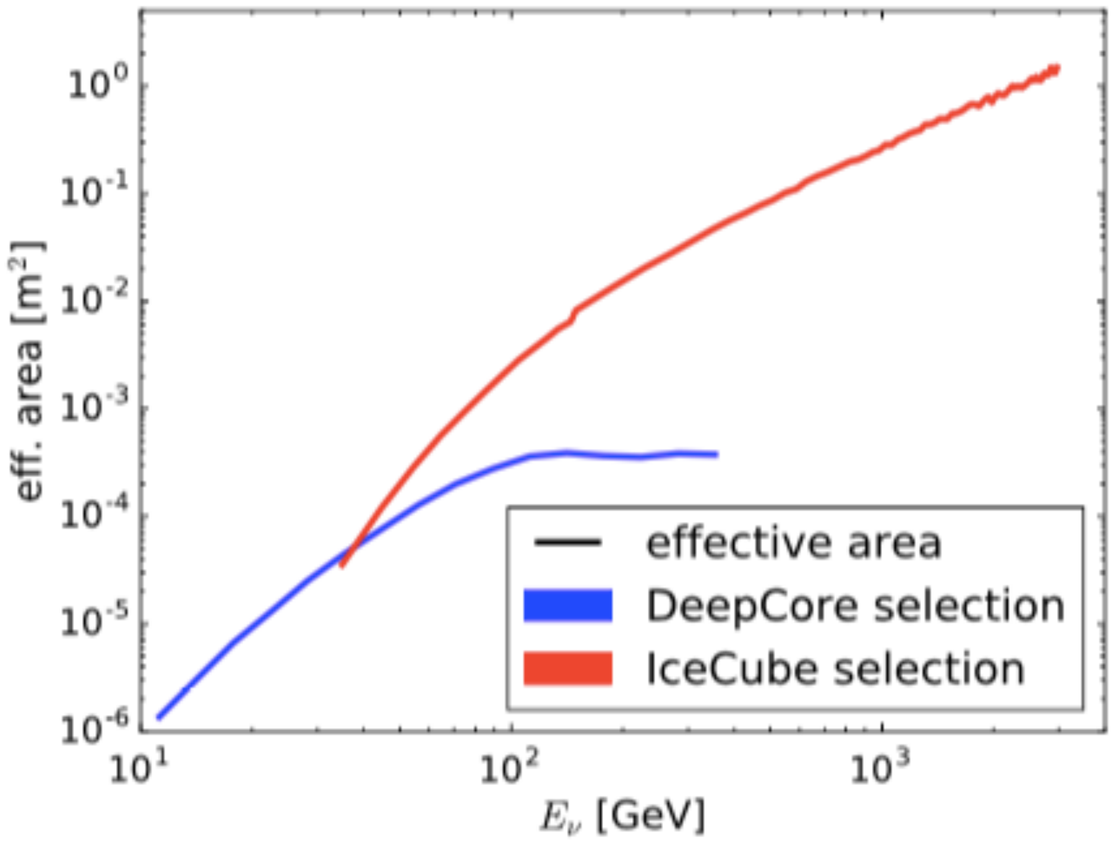
90% CL χ-p cross-section (spin-dependent)

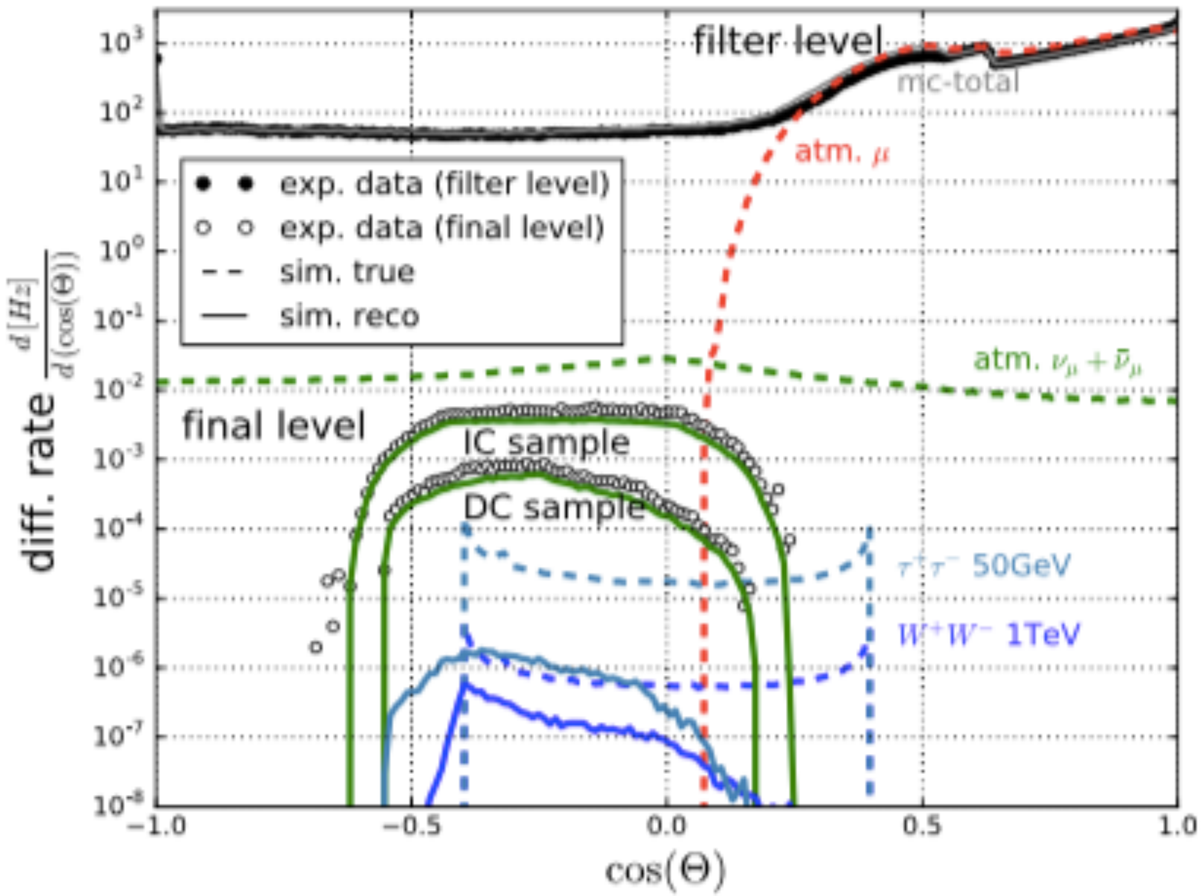
Complementary to direct detection search efforts

fills out WIMP picture by testing other properties

Most stringent SD cross-section limit for most models

Effective Areas Sun





Monopole light yield