Galactic WIMP search with the Super-Kamiokande detector

and group status in 2020

Piotr Mijakowski (BP3)

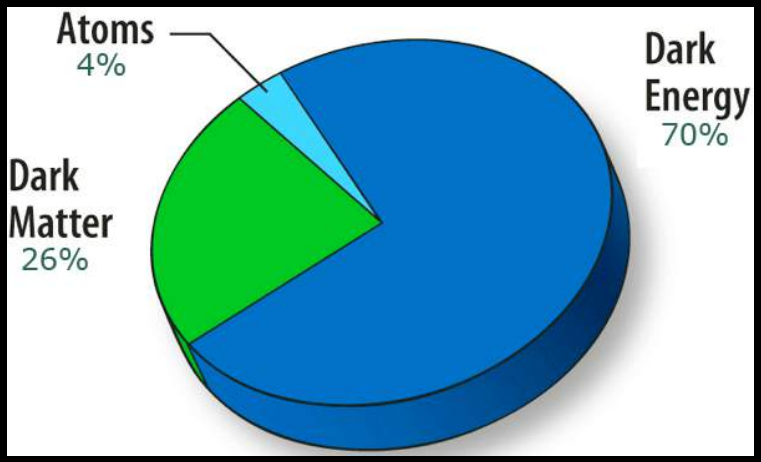
OUTLINE

1. KM3NeT

2. Super-Kamiokande

3. Achievement:

„Indirect Search for Dark Matter from the Galactic Center and Halo with the Super-Kamiokande Detector"
Phys. Rev. D 102 (2020) 072002



KM3NeT in 2020

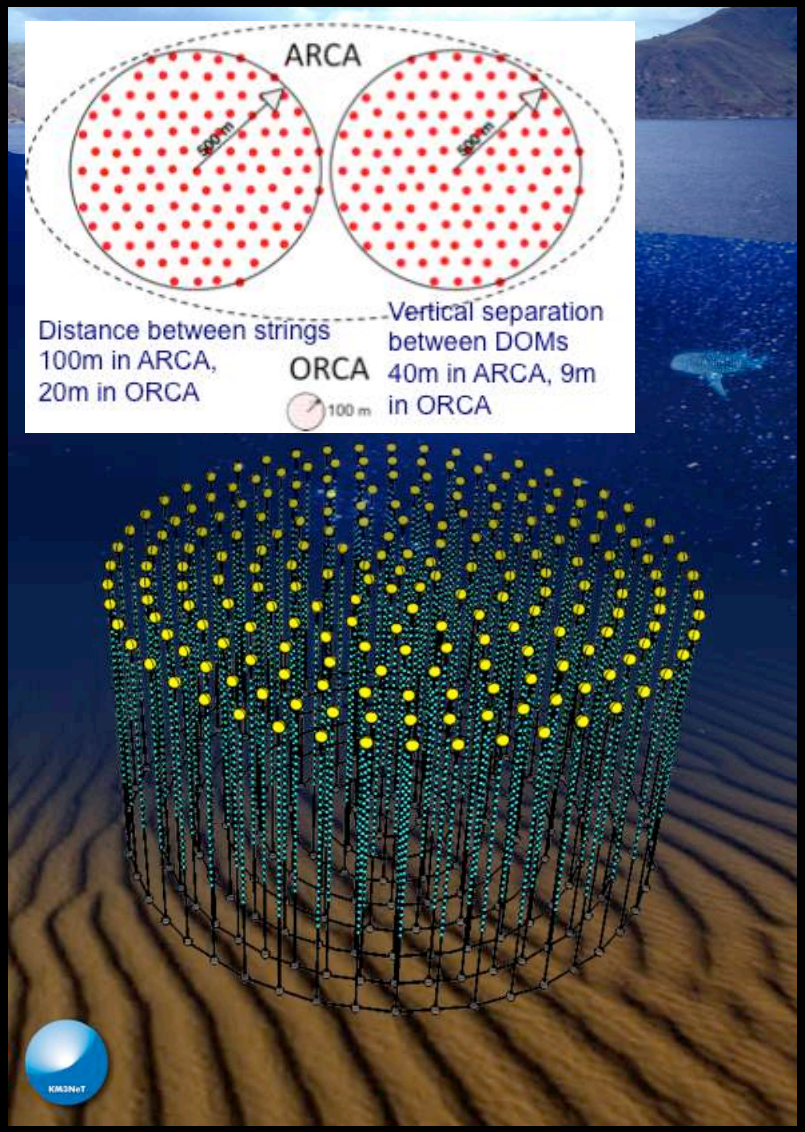
KM3NeT

Modular neutrino research infrastructure in the Mediterranean Sea

2 DETECTORS:

- **ORCA** (Oscillation Research with Cosmics in the Abyss),
  - Location: Toulon (FR), 6Mton, ~2.5km depth
  - Taking data: 6 strings now out of 115
  - Expected in 2025
- **ARCA** (Astroparticle Research with Cosmics in the Abyss)
  - Location: Capo Pasero (IT), ~1km^3, ~3.5km depth
  - Taking data: 1(2) strings now out of 2x115
  - Expected in 2027

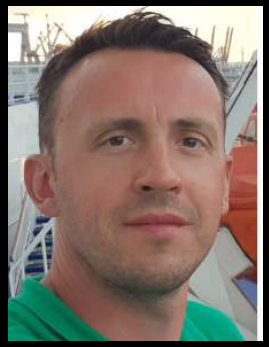
KM3NeT
Opens a new window on our universe



KM3NeT-PL GROUP (2020)

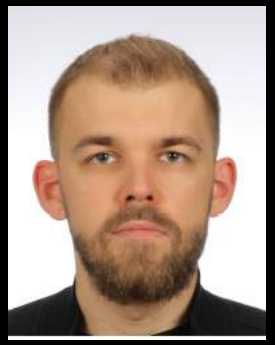
- Piotr Mijakowski – coordinator, SONATA-BIS

  Conference and Outreach Committee member, Institute Board and Review & Resources Board representative



- Rafał Wojaczyński, post-doc

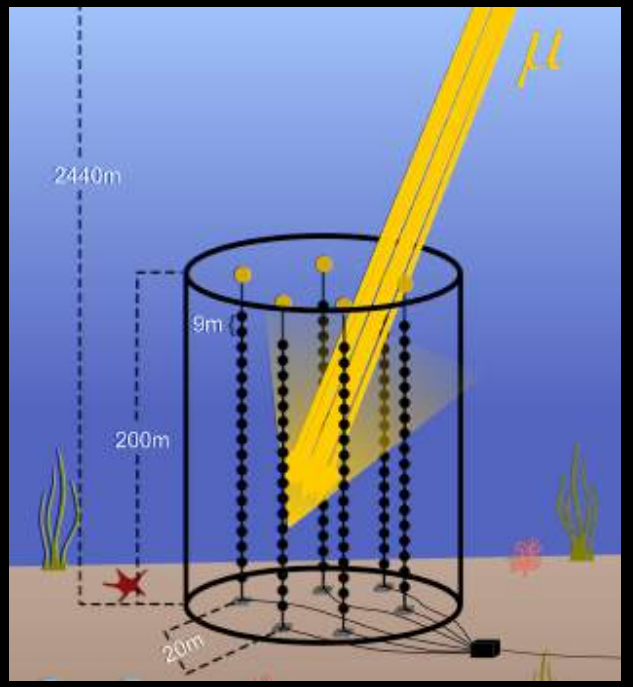
  GC WIMP search at ORCA (sensitivity), self-veto studies



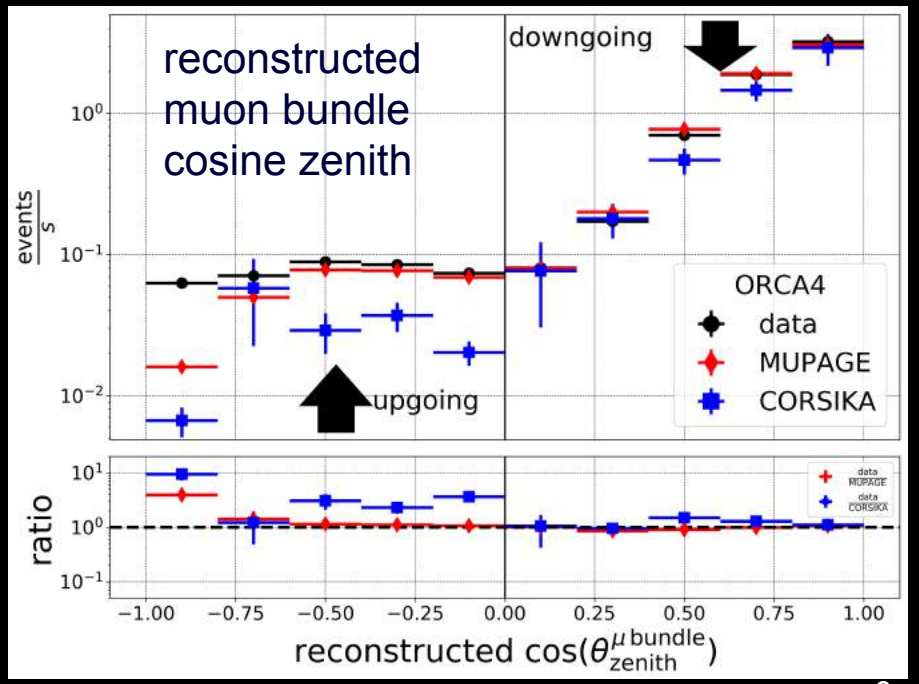
- Piotr Kalaczyński, PhD

  atm. ν/μ CORSIKA simulations & data comparisons, charm/prompt flux analysis

Cosmic ray muon studies



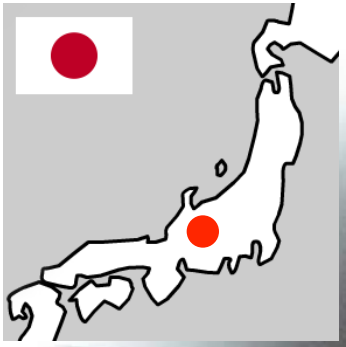
- First data available from KM3NeT-ORCA (4 strings) & KM3NeT-ARCA (2 strings)
- Comparison of data vs. Monte Carlo (CORSIKA) done by Piotr Kalaczyński
- Presented in 2020 at major conferences:
  - NEUTRINO 2020, Chicago (online) → poster
  - ICHEP 2020, Prague (online) → KM3NeT-ORCA talk in the name of collaboration (!!! for PhD student)

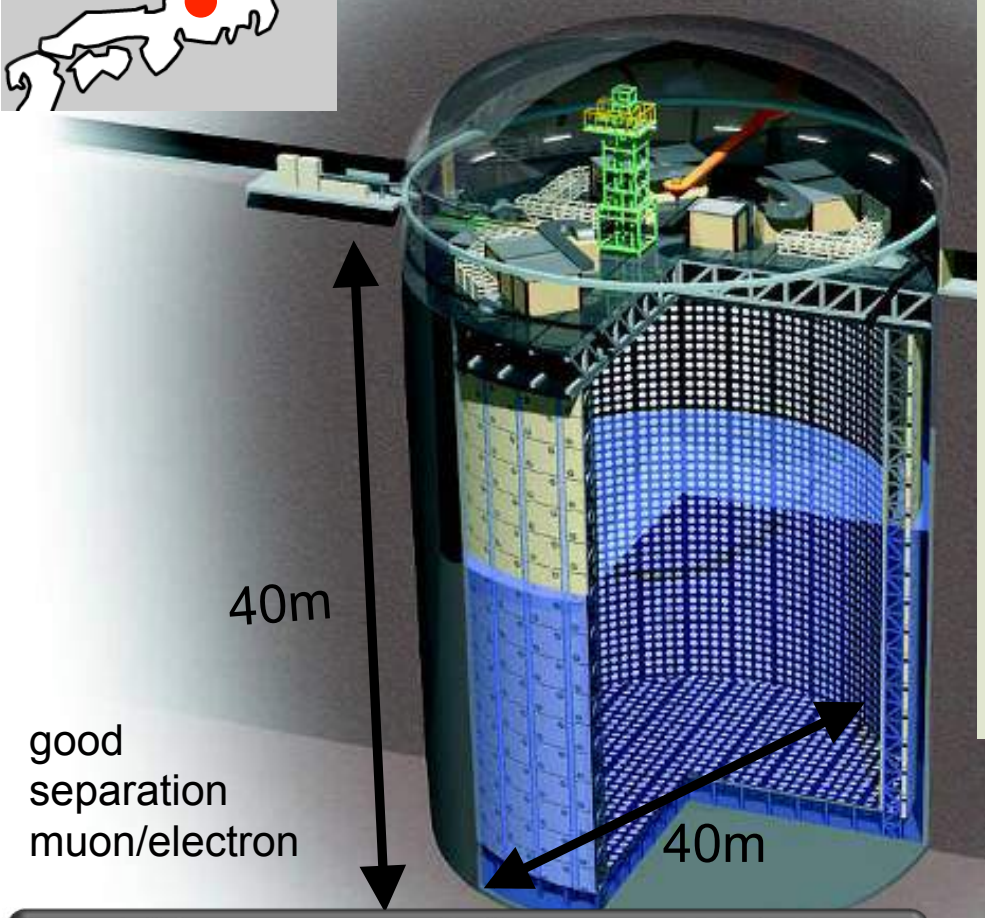


Super-Kamiokande

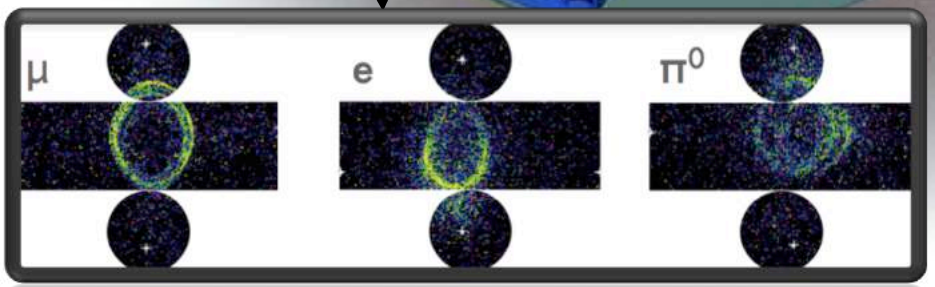
Super-Kamiokande

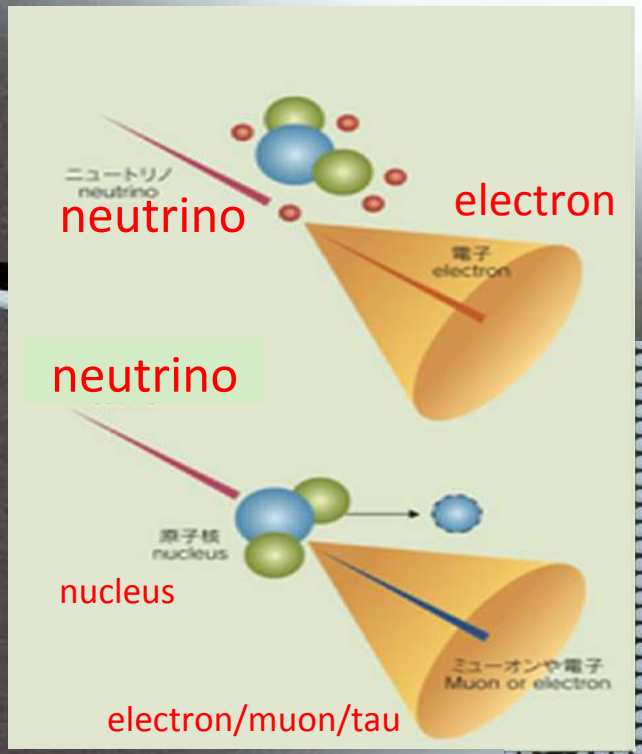
@ Kamioka Observatory (ICRR, University of Tokyo), Japan





good
separation
muon/electron





Super-Kamiokande PL

- Polish group expanded in 2020 thanks to new funds: Justyna Łagoda's SONATA-BIS
- Member status as of 2020 :
  - Piotr Mijakowski → country representative, dark matter

  5 new people this year:
  - Justyna Łagoda
  - Joanna Zalipska

  } atmospheric neutrinos, T2K-SK
  - Lakshmi Mohan
    new post-doc, reflectivity/detector calibration
  - Maitrayee Mandal
    PhD student, tau neutrino appearance analysis
  - Yashwanth Praphu
    PhD student, T2K-SK activities

„Indirect Search for Dark Matter
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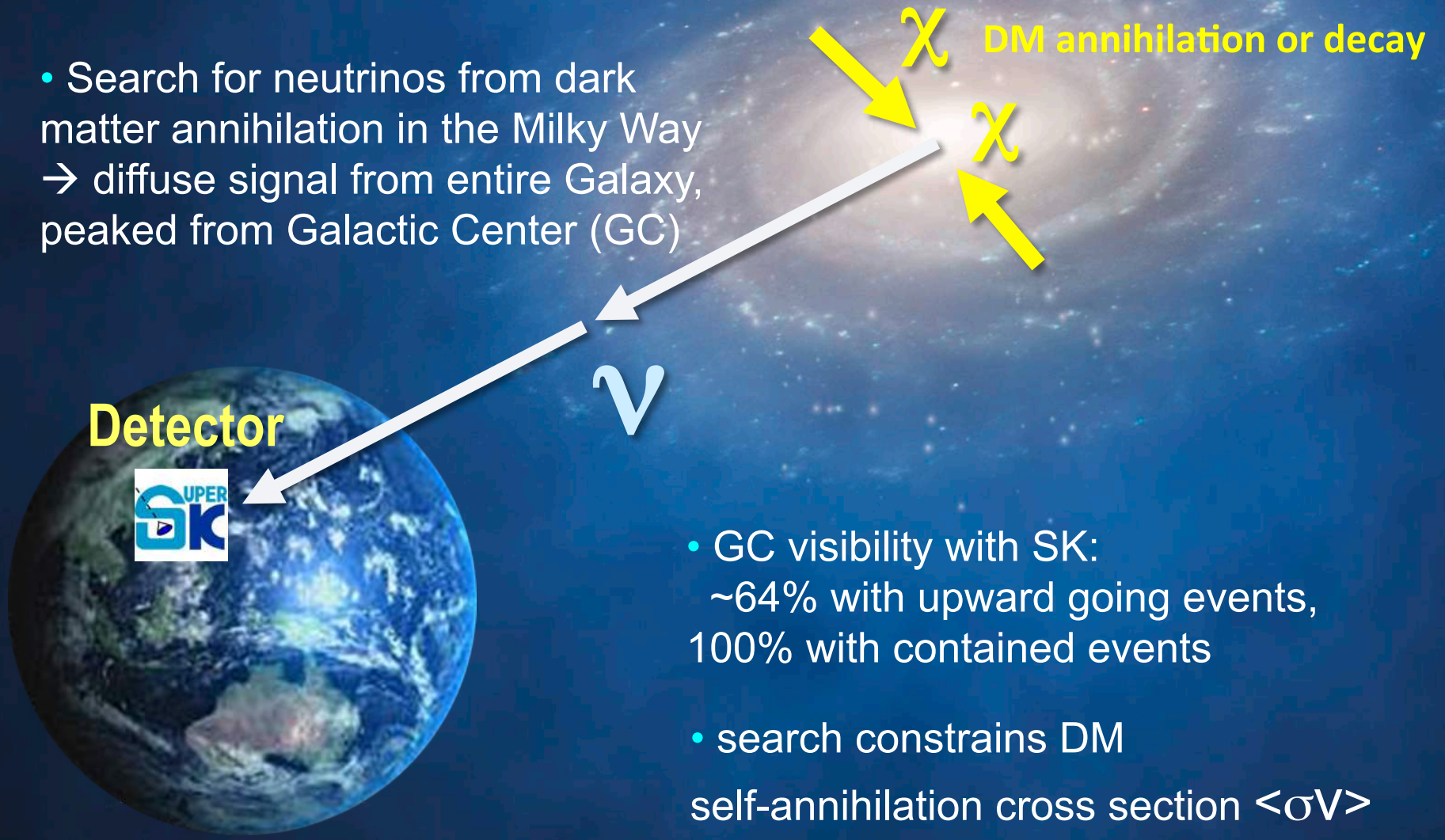
Phys. Rev. D 102 (2020) 072002

achievement

GALACTIC WIMP SEARCH IDEA

- Search for neutrinos from dark matter annihilation in the Milky Way → diffuse signal from entire Galaxy, peaked from Galactic Center (GC)



- GC visibility with SK: ~64% with upward going events, 100% with contained events
- search constrains DM self-annihilation cross section $\langle\sigma v\rangle$

GC WIMP SEARCH PAPER

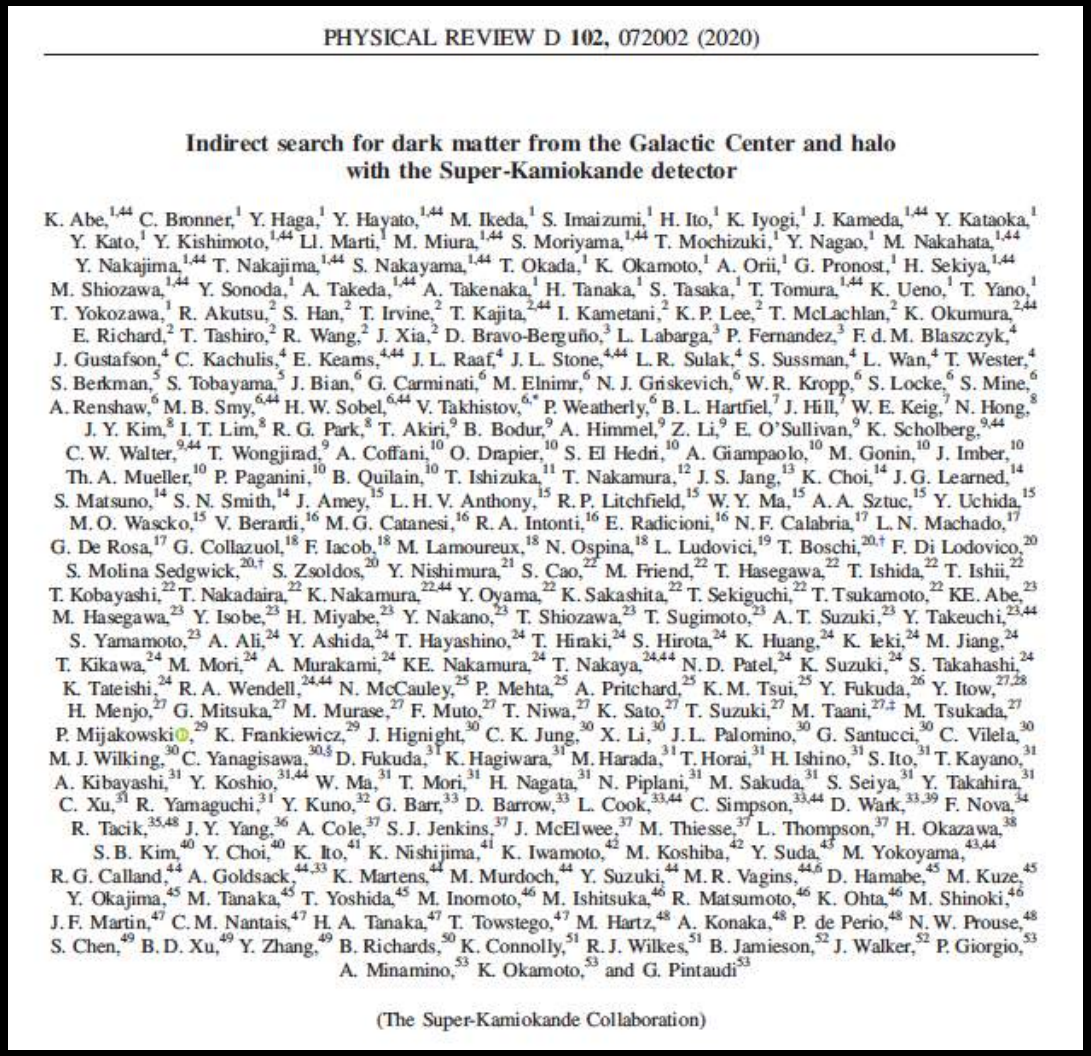
ANALYSIS PUBLISHED:

Phys. Rev. D 102 (2020) 072002

https://link.aps.org/doi/10.1103/PhysRevD.102.072002

NCBJ contribution is 100%:

- Main analysis by PM
- Cross check analysis by Katarzyna Frankiewicz (former PhD student)
- all plots in paper by PM/KF
- entire text by PM
- PM fully responsible for publication process (addressing referees, supplement etc)



PHYSICAL REVIEW D 102, 072002 (2020)

Indirect search for dark matter from the Galactic Center and halo with the Super-Kamiokande detector

K. Abe,[1,44] C. Bronner,[1] Y. Haga,[1] Y. Hayato,[1,44] M. Ikeda,[1] S. Imaizumi,[1] H. Ito,[1] K. Iyogi,[1] J. Kameda,[1,44] Y. Kataoka,[1] Y. Kato,[1] Y. Kishimoto,[1,44] Ll. Marti,[1] M. Miura,[1,44] S. Moriyama,[1,44] T. Mochizuki,[1] Y. Nagao,[1] M. Nakahata,[1,44] Y. Nakajima,[1,44] T. Nakajima,[1,44] S. Nakayama,[1,44] T. Okada,[1] K. Okamoto,[1] A. Orii,[1] G. Pronost,[1] H. Sekiya,[1,44] M. Shiozawa,[1,44] Y. Sonoda,[1] A. Takeda,[1,44] A. Takenaka,[1] H. Tanaka,[1] S. Tasaka,[1] T. Tomura,[1,44] K. Ueno,[1] T. Yano,[1] T. Yokozawa,[1] R. Akutsu,[2] S. Han,[2] T. Irvine,[2] T. Kajita,[2,44] I. Kametani,[2] K. P. Lee,[2] T. McLachlan,[2] K. Okumura,[2,44] E. Richard,[2] T. Tashiro,[2] R. Wang,[2] J. Xia,[2] D. Bravo-Berguño,[3] L. Labarga,[3] P. Fernandez,[3] F. d. M. Blaszczyk,[4] J. Gustafson,[4] C. Kachulis,[4] E. Kearns,[4,44] J. L. Raaf,[4] J. L. Stone,[4,44] L. R. Sulak,[4] S. Sussman,[4] L. Wan,[4] T. Wester,[4] S. Berkman,[5] S. Tobayama,[5] J. Bian,[6] G. Carminati,[6] M. Elnimr,[6] N. J. Griskevich,[6] W. R. Kropp,[6] S. Locke,[6] S. Mine,[6] A. Renshaw,[6] M. B. Smy,[6,44] H. W. Sobel,[6,44] V. Takhistov,[6,*] P. Weatherly,[6] B. L. Hartfiel,[7] J. Hill,[7] W. E. Keig,[7] N. Hong,[8] J. Y. Kim,[8] I. T. Lim,[8] R. G. Park,[8] T. Akiri,[9] B. Bodur,[9] A. Himmel,[9] Z. Li,[9] E. O'Sullivan,[9] K. Scholberg,[9,44] C. W. Walter,[9,44] T. Wongjirad,[9] A. Coffani,[10] O. Drapier,[10] S. El Hedri,[10] A. Giampaolo,[10] M. Gonin,[10] J. Imber,[10] Th. A. Mueller,[10] P. Paganini,[10] B. Quilain,[10] T. Ishizuka,[11] T. Nakamura,[12] J. S. Jang,[13] K. Choi,[14] J. G. Learned,[14] S. Matsuno,[14] S. N. Smith,[14] J. Amey,[15] L. H. V. Anthony,[15] R. P. Litchfield,[15] W. Y. Ma,[15] A. A. Sztuc,[15] Y. Uchida,[15] M. O. Wascko,[15] V. Berardi,[16] M. G. Catanesi,[16] R. A. Intonti,[16] E. Radicioni,[16] N. F. Calabria,[17] L. N. Machado,[17] G. De Rosa,[17] G. Collazuol,[18] F. Iacob,[18] M. Lamoureux,[18] N. Ospina,[18] L. Ludovici,[19] T. Boschi,[20,†] F. Di Lodovico,[20] S. Molina Sedgwick,[20,†] S. Zsoldos,[20] Y. Nishimura,[21] S. Cao,[22] M. Friend,[22] T. Hasegawa,[22] T. Ishida,[22] T. Ishii,[22] T. Kobayashi,[22] T. Nakadaira,[22] K. Nakamura,[22,44] Y. Oyama,[22] K. Sakashita,[22] T. Sekiguchi,[22] T. Tsukamoto,[22] KE. Abe,[23] M. Hasegawa,[23] Y. Isobe,[23] H. Miyabe,[23] Y. Nakano,[23] T. Shiozawa,[23] T. Sugimoto,[23] A. T. Suzuki,[23] Y. Takeuchi,[23,44] S. Yamamoto,[23] A. Ali,[24] Y. Ashida,[24] T. Hayashino,[24] T. Hiraki,[24] S. Hirota,[24] K. Huang,[24] K. Ieki,[24] M. Jiang,[24] T. Kikawa,[24] M. Mori,[24] A. Murakami,[24] KE. Nakamura,[24] T. Nakaya,[24,44] N. D. Patel,[24] K. Suzuki,[24] S. Takahashi,[24] K. Tateishi,[24] R. A. Wendell,[24,44] N. McCauley,[25] P. Mehta,[25] A. Pritchard,[25] K. M. Tsui,[25] Y. Fukuda,[26] Y. Itow,[27,28] H. Menjo,[27] G. Mitsuka,[27] M. Murase,[27] F. Muto,[27] T. Niwa,[27] K. Sato,[27] T. Suzuki,[27] M. Taani,[27,‡] M. Tsukada,[27] P. Mijakowski,[29] K. Frankiewicz,[29] J. Hignight,[30] C. K. Jung,[30] X. Li,[30] J. L. Palomino,[30] G. Santucci,[30] C. Vilela,[30] M. J. Wilking,[30] C. Yanagisawa,[30,§] D. Fukuda,[31] K. Hagiwara,[31] M. Harada,[31] T. Horai,[31] H. Ishino,[31] S. Ito,[31] T. Kayano,[31] A. Kibayashi,[31] Y. Koshio,[31,44] W. Ma,[31] T. Mori,[31] H. Nagata,[31] N. Piplani,[31] M. Sakuda,[31] S. Seiya,[31] Y. Takahira,[31] C. Xu,[31] R. Yamaguchi,[31] Y. Kuno,[32] G. Barr,[33] D. Barrow,[33] L. Cook,[33,44] C. Simpson,[33,44] D. Wark,[33,39] F. Nova,[34] R. Tacik,[35,48] J. Y. Yang,[36] A. Cole,[37] S. J. Jenkins,[37] J. McElwee,[37] M. Thiesse,[37] L. Thompson,[37] H. Okazawa,[38] S. B. Kim,[40] Y. Choi,[40] K. Ito,[41] K. Nishijima,[41] K. Iwamoto,[42] M. Koshiba,[42] Y. Suda,[43] M. Yokoyama,[43,44] R. G. Calland,[44] A. Goldsack,[44,33] K. Martens,[44] M. Murdoch,[44] Y. Suzuki,[44] M. R. Vagins,[44,6] D. Hamabe,[45] M. Kuze,[45] Y. Okajima,[45] M. Tanaka,[45] T. Yoshida,[45] M. Inomoto,[46] M. Ishitsuka,[46] R. Matsumoto,[46] K. Ohta,[46] M. Shinoki,[46] J. F. Martin,[47] C. M. Nantais,[47] H. A. Tanaka,[47] T. Towstego,[47] M. Hartz,[48] A. Konaka,[48] P. de Perio,[48] N. W. Prouse,[48] S. Chen,[49] B. D. Xu,[49] Y. Zhang,[49] B. Richards,[50] K. Connolly,[51] R. J. Wilkes,[51] B. Jamieson,[52] J. Walker,[52] P. Giorgio,[53] A. Minamino,[53] K. Okamoto,[53] and G. Pintaudi[53]

(The Super-Kamiokande Collaboration)

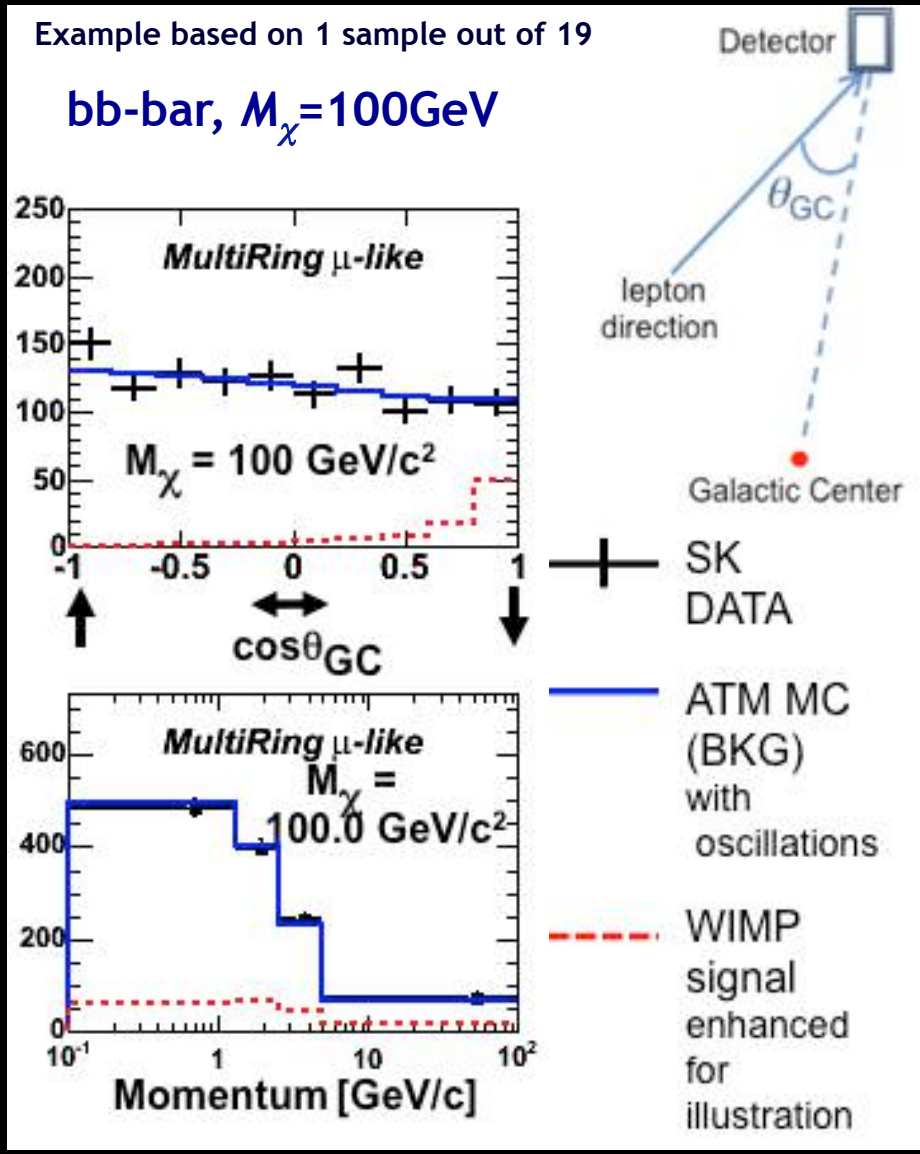
ANALYSIS IDEA - FIT

- Search for neutrinos from DM annihilation in the Milky way based on Super-Kamiokande data (1996-2014)

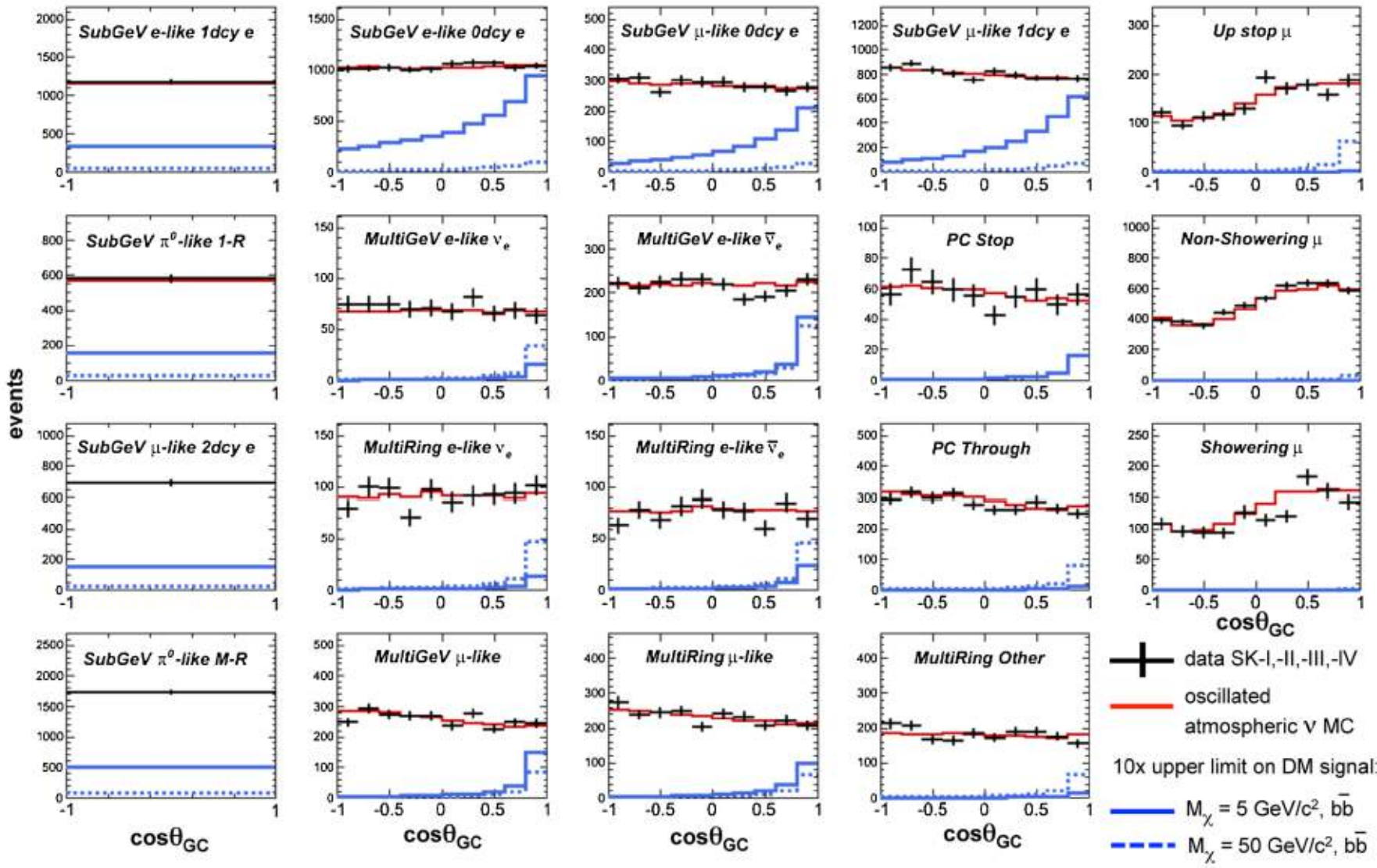
$$\chi\chi \to \nu\bar{\nu}, W^+W^-, b\bar{b}, \mu^+\mu^- \to \ldots \nu_{e/\mu/\tau}$$

- FIT: for each tested WIMP mass & ann. mode, find configuration of background and signal that would match DATA the best using reconstructed angular & momentum distributions

$$\text{DATA} \overset{?}{=} \text{SIGNAL} + \underbrace{\nu\ \text{ATM}}_{\text{Monte Carlo}}$$



DM-induced signal and atmospheric ν background



FIT RESULT

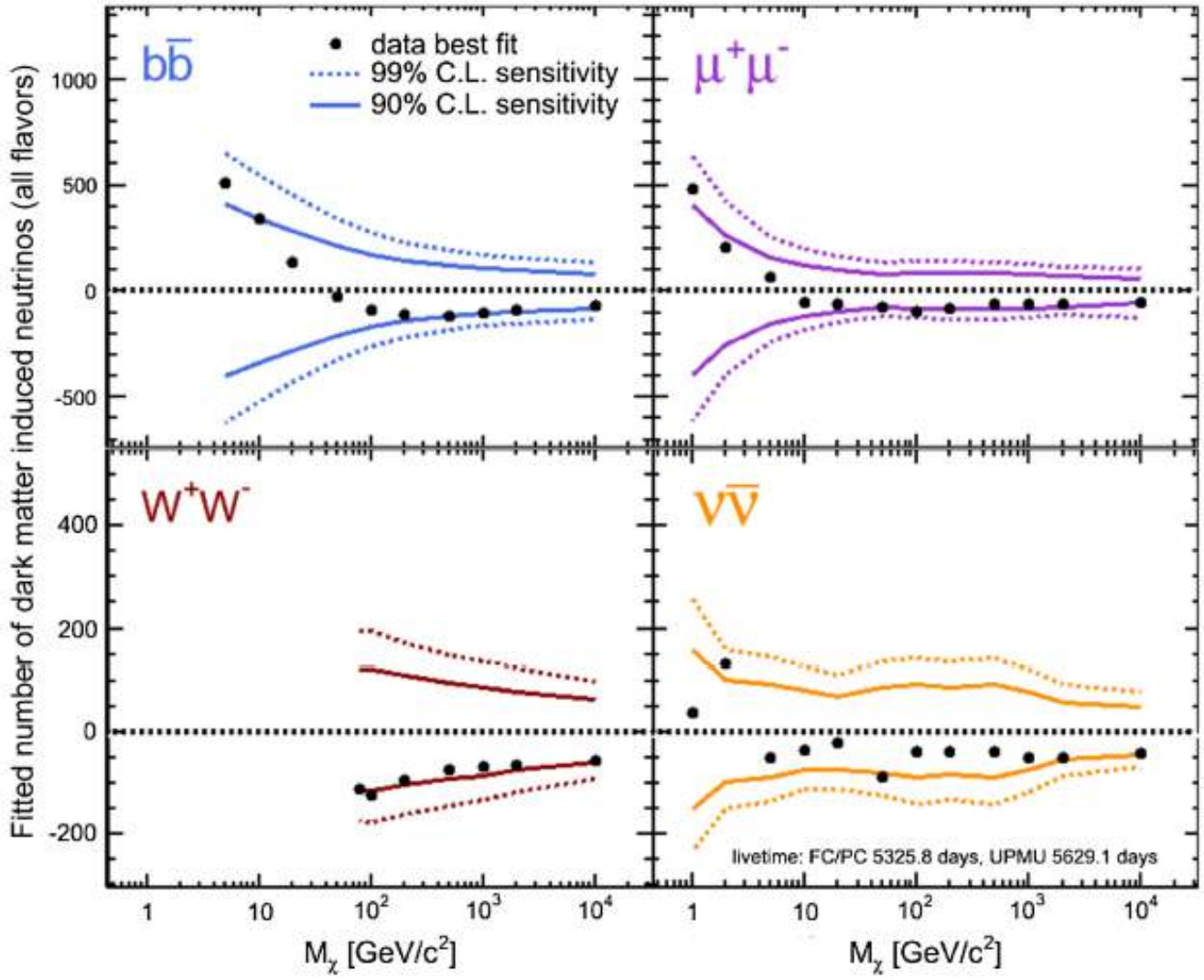


FIG. 5. Fitted number of DM-induced neutrinos of all flavors from annihilation into $b\bar{b}$, $\mu^+\mu^-$, W^+W^-, and $\nu\bar{\nu}$ as a function of the WIMP mass. Also shown are the expected sensitivities for the zero-signal case.

FIT RESULT – UPPER LIMITS

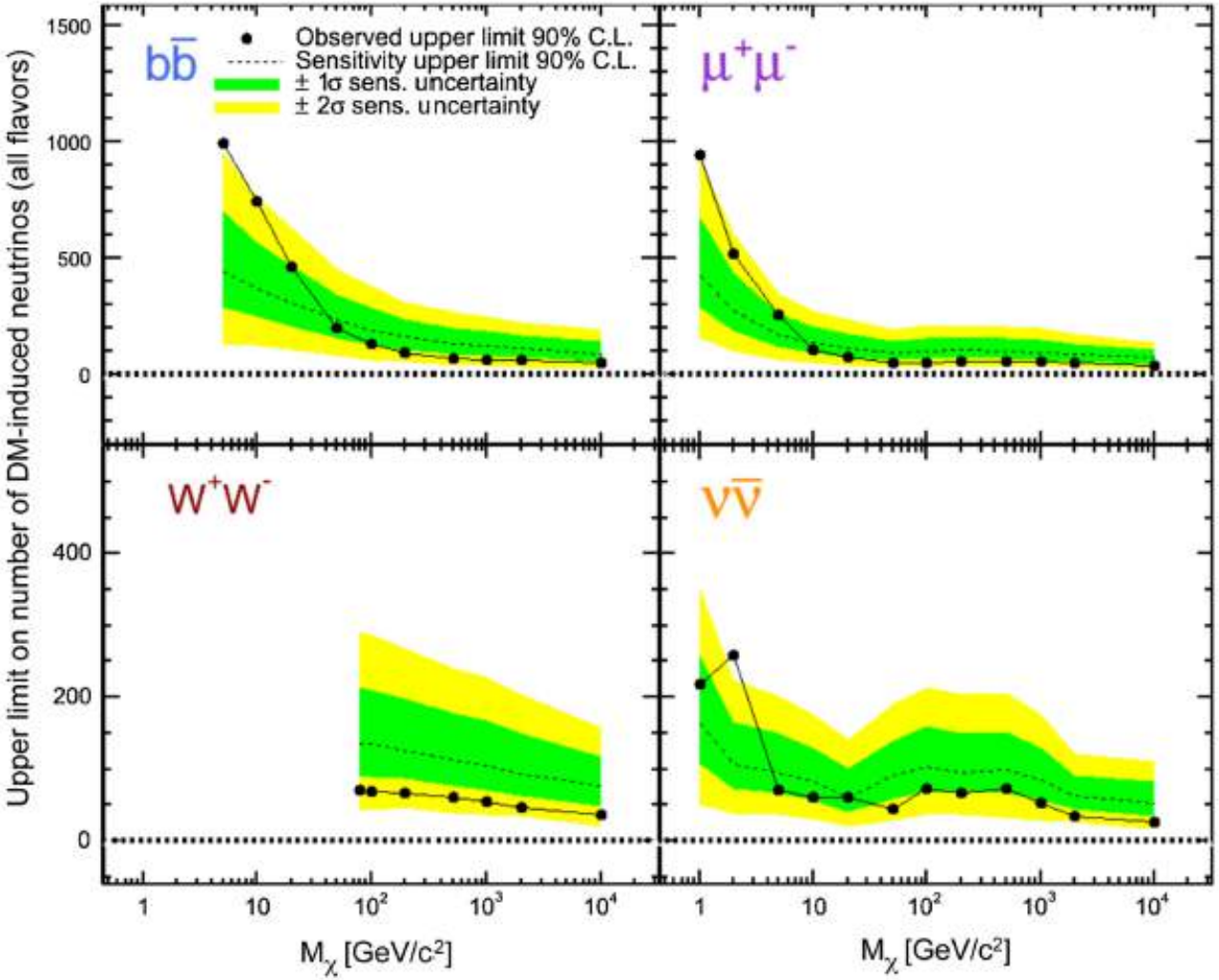
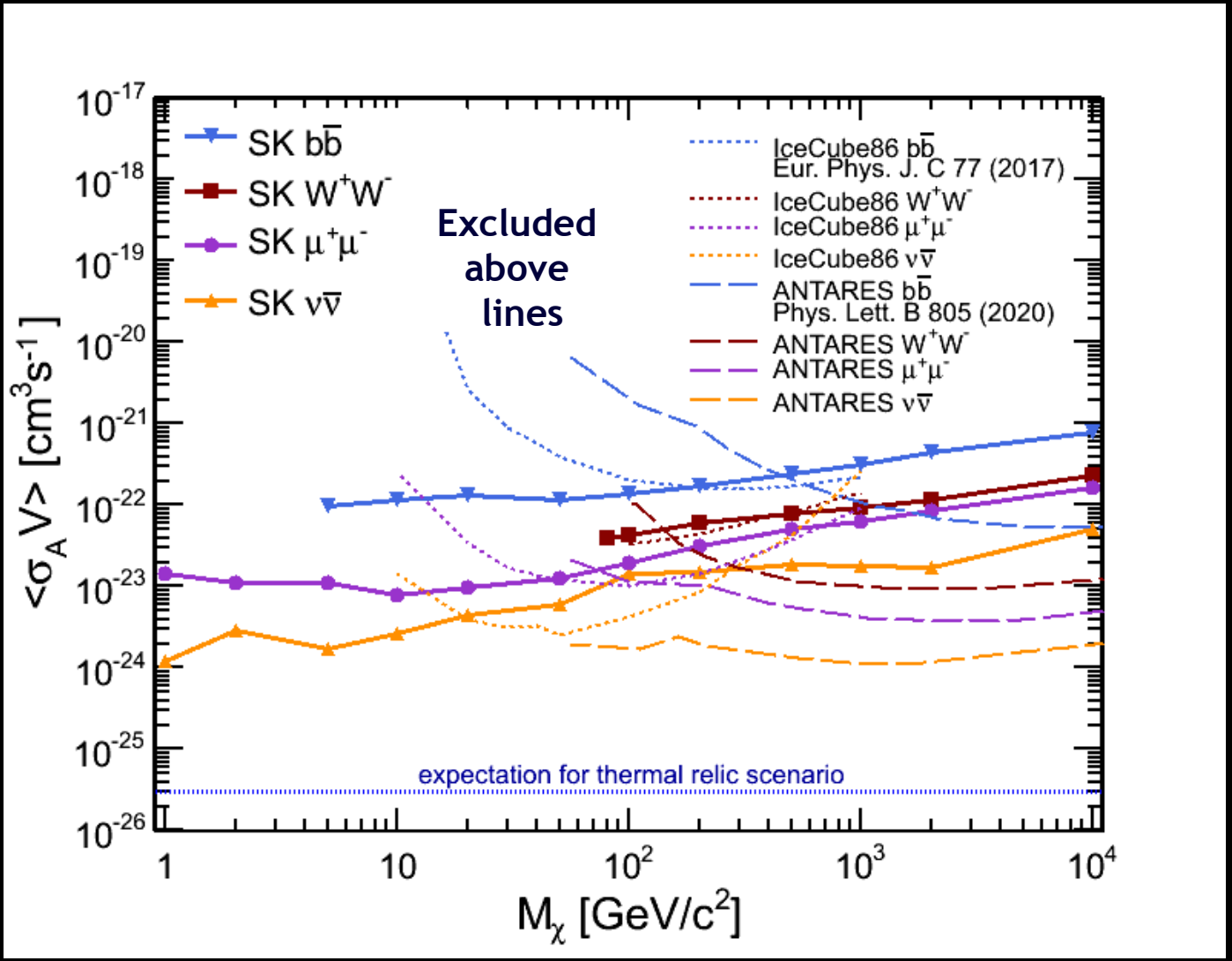


FIG. 6. Upper limit on the fitted number of DM-induced neutrinos of all flavors from annihilation into $b\bar{b}$, $\mu^+\mu^-$, W^+W^-, and $\nu\bar{\nu}$ as a function of the mass of the DM particles. The expected (median) limit assuming no signal is shown by the dashed line and the region containing 68.3% (95.5%) of the expected limits is shown by the green (yellow) band.

MAIN RESULT: WIMP ANNIHILATION CONSTRAINTS

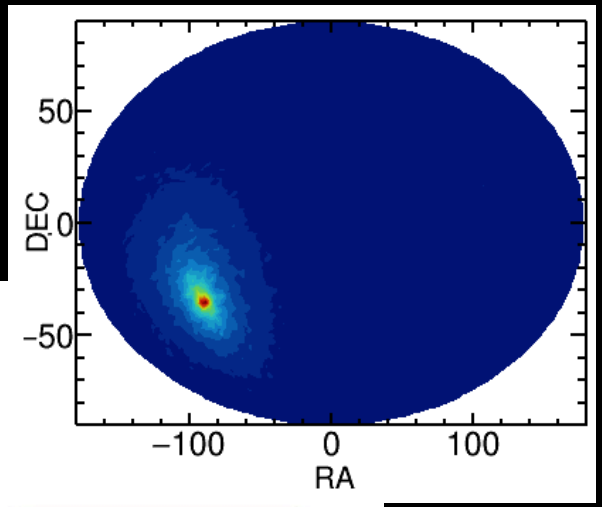


SK limits the best among all neutrino searches for WIMP masses below several tens of GeV (depeneding on the annihilation mode)

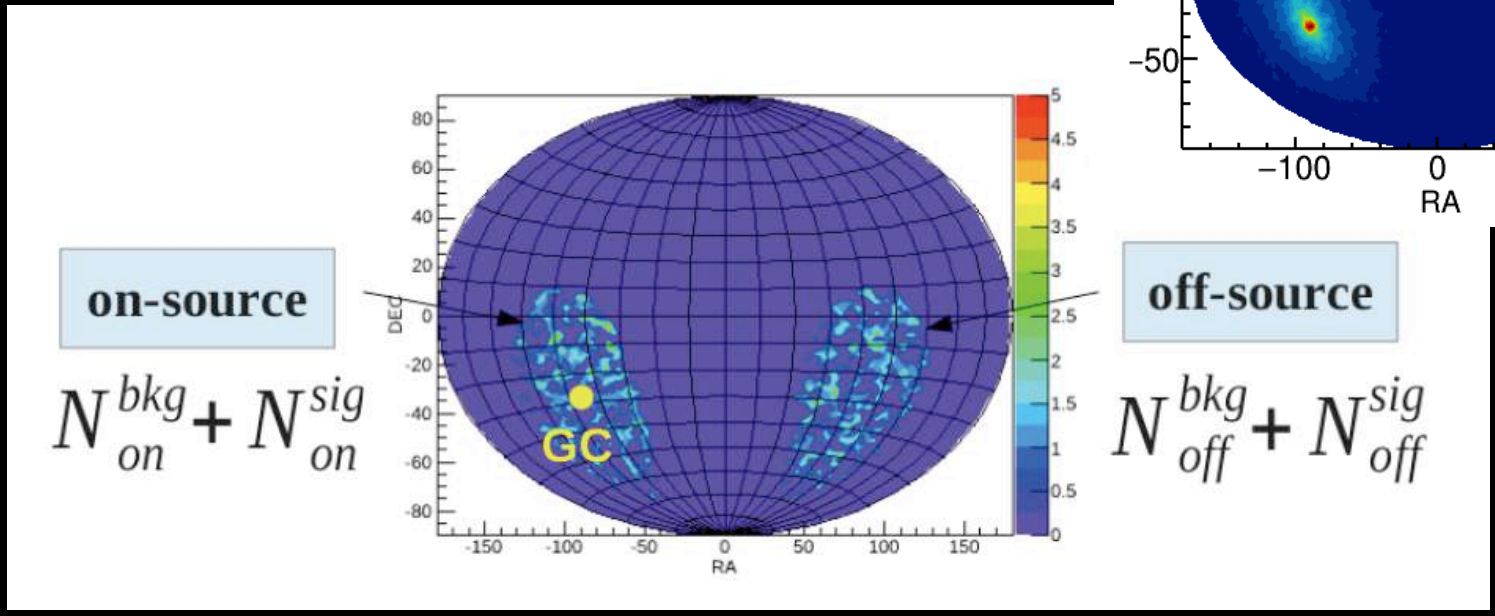
ON-/OFF-source analysis

- Cross check analysis performed by Kasia Frankiewicz and published in the same paper

expectation for DM-induced neutrinos

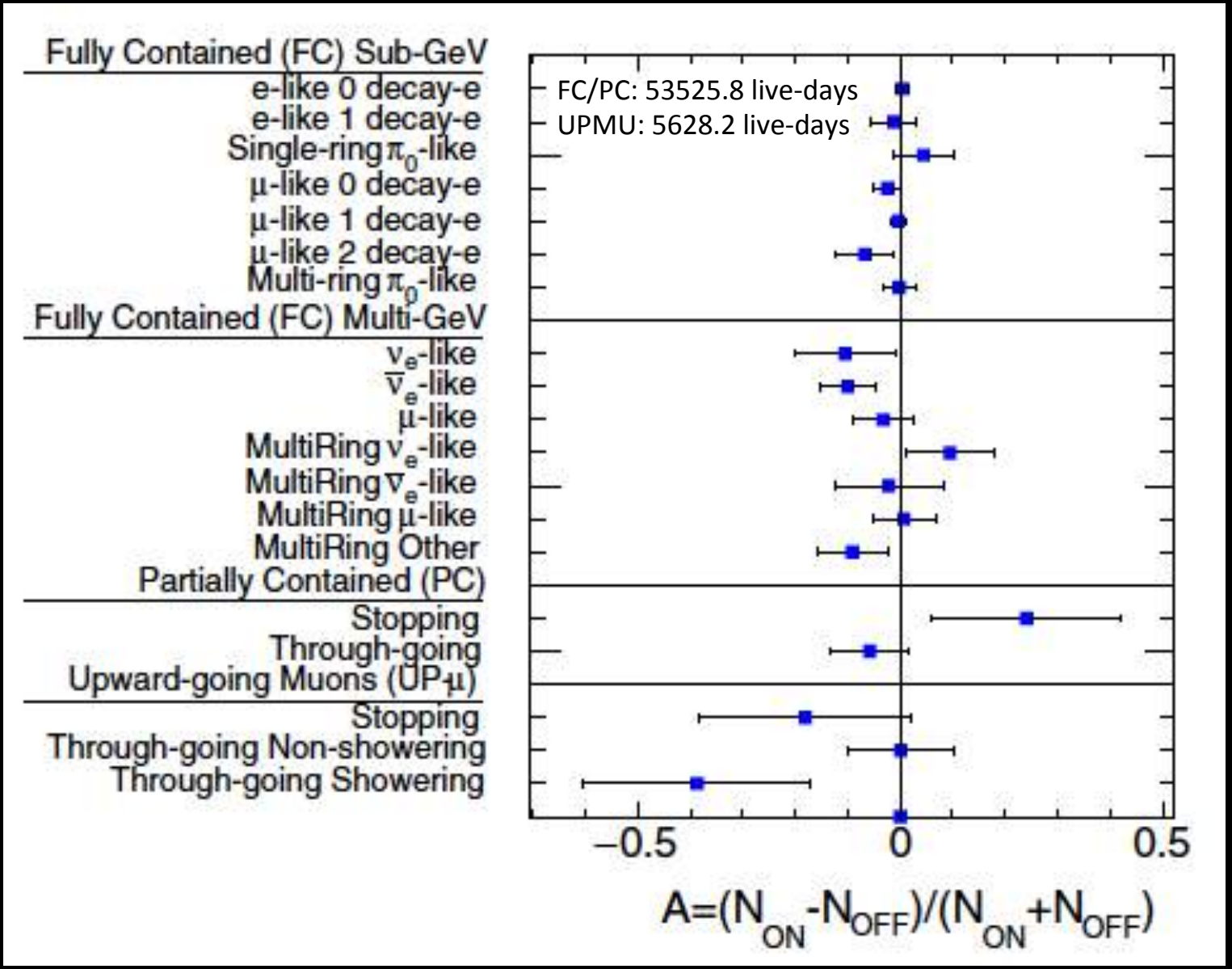


Search for large-scale anisotropy due to DM-induced ν's from Milky Way



- Simple idea but powerful estimate independent on any MC/syst. uncertainties

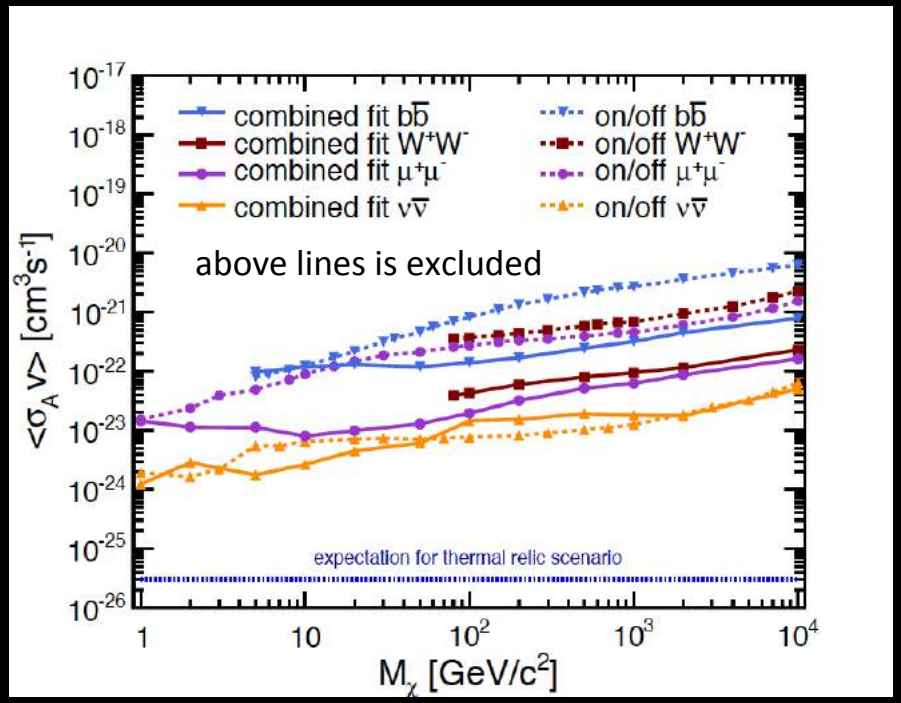
ON-/OFF-source result



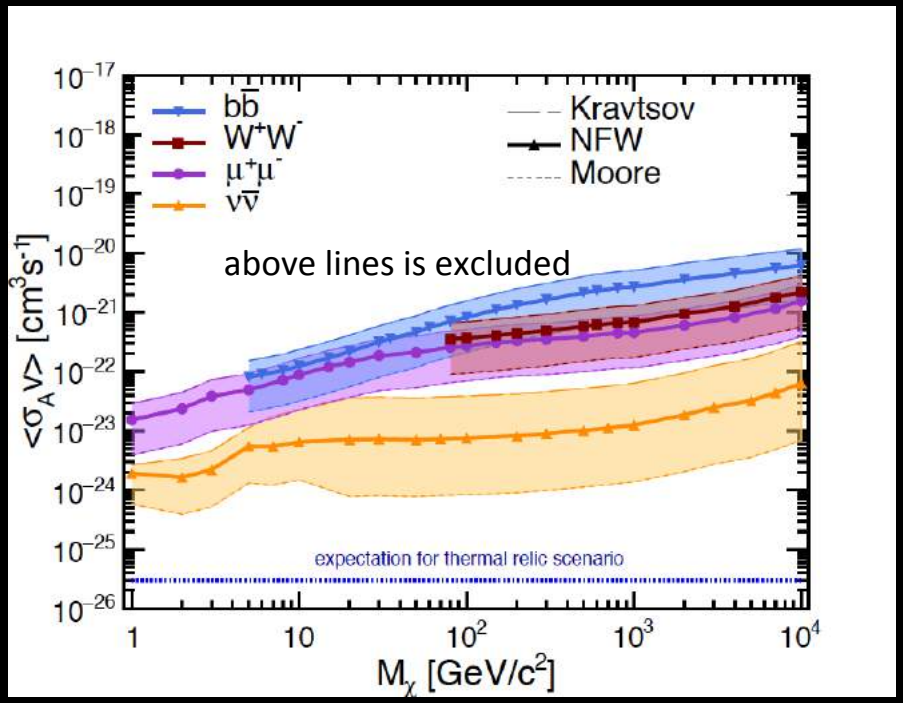
DATA is consistent with background, no asymmetry in neutrino flux observed

ON-/OFF-source result

Fit analysis gives stronger limits than ON-/OFF-source

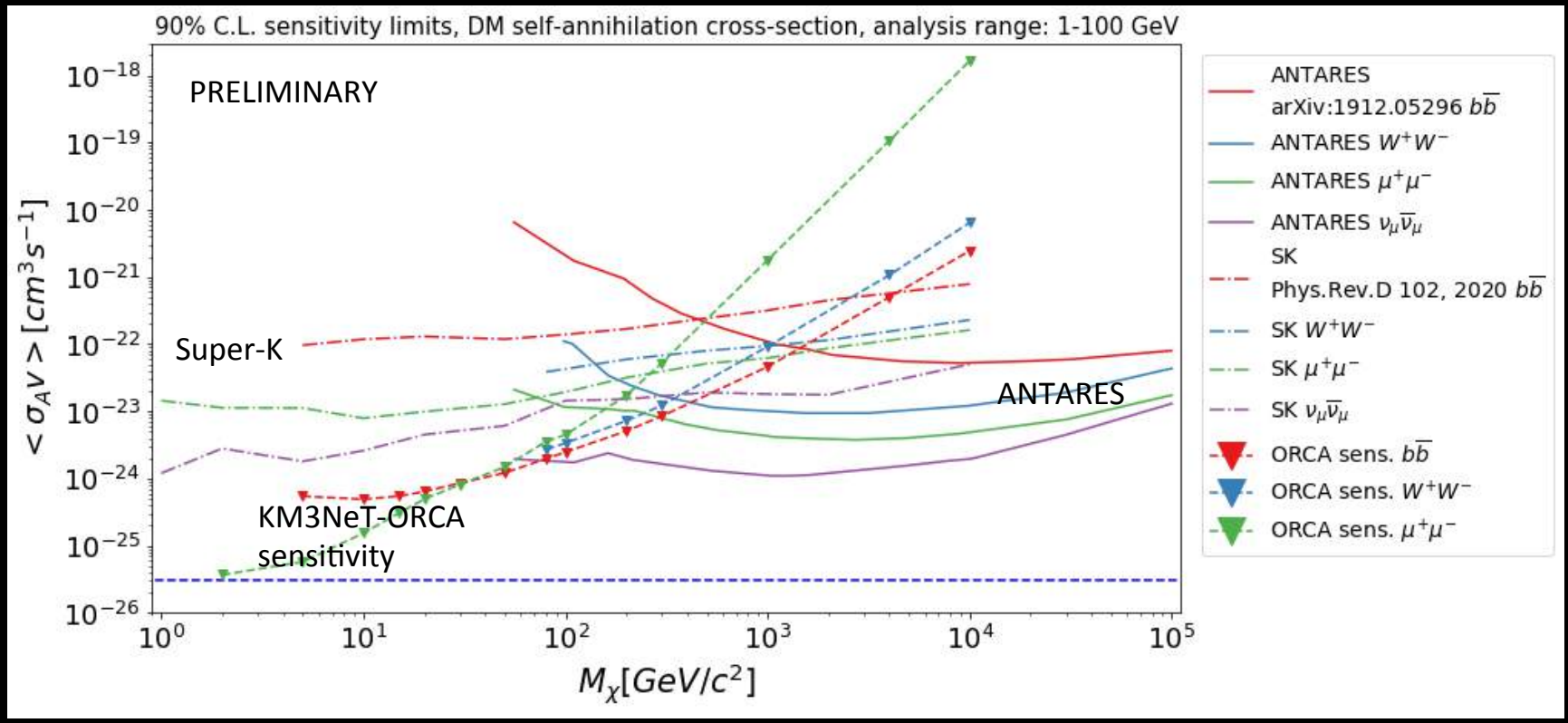


In ON-/OFF-source analysis we demonstrated impact of DM halo model choice



Future: ON-/OFF-source GC WIMP search at KM3NeT-ORCA

- ON-source / OFF-source analysis is also performed by Rafał Wojaczyński to estimate KM3NeT-ORCA performance
- Sensitivity expected for KM3NeT-ORCA full configuration (115 strings) within 1 year of operation

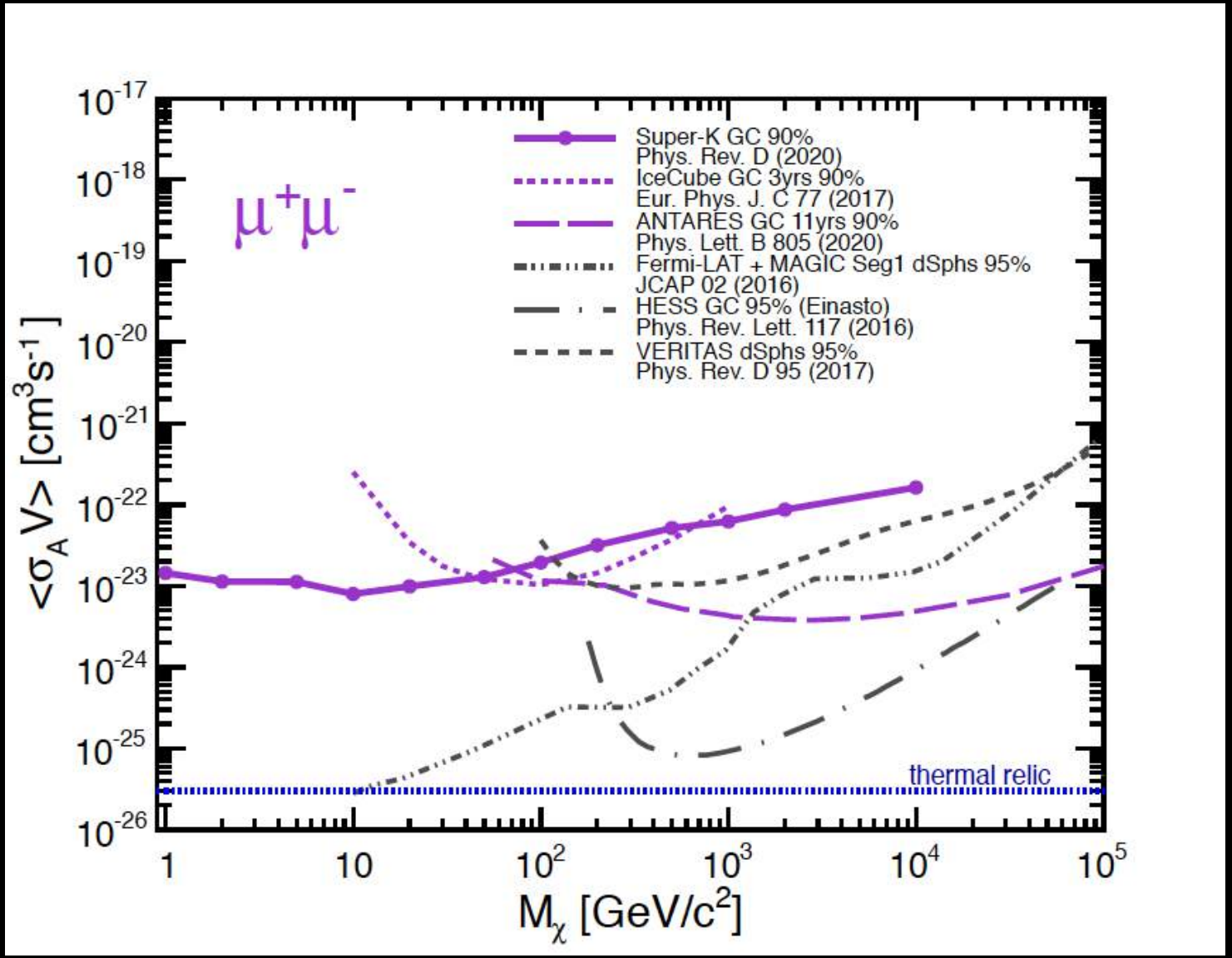


SUMMARY

- „Indirect Search for Dark Matter from the Galactic Center and Halo with the Super-Kamiokande Detector“, Phys. Rev. D 102 (2020) 072002
  - World best constraints on the value of dark matter self-annihilation cross section at neutrino telescopes for intermediate and low WIMP masses
  - Clear contribution → we are the only authors of presented analyses, authors of entire text and all plots shown in the paper
  - Results shown also at >15 international conferences by PM or K. Frankiewicz

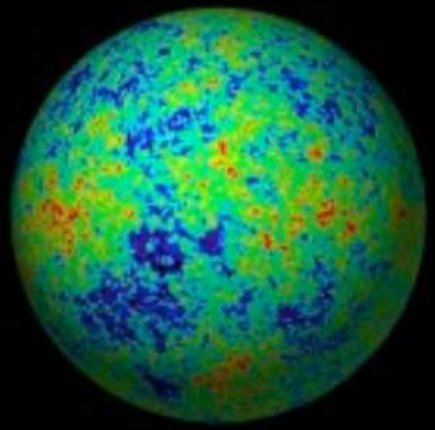
supplementary slides

COMPARISON WITH OTHER INDIRECT SEARCHES

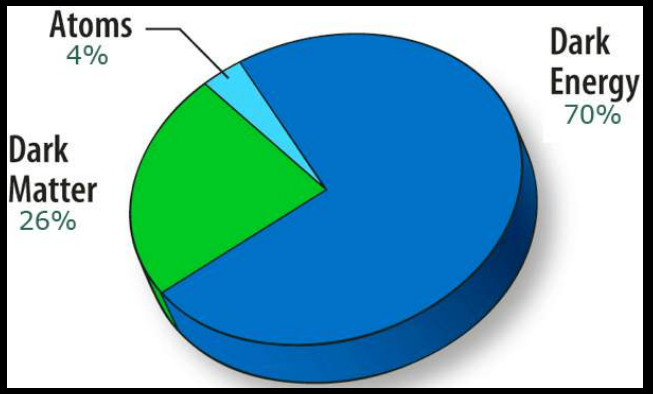


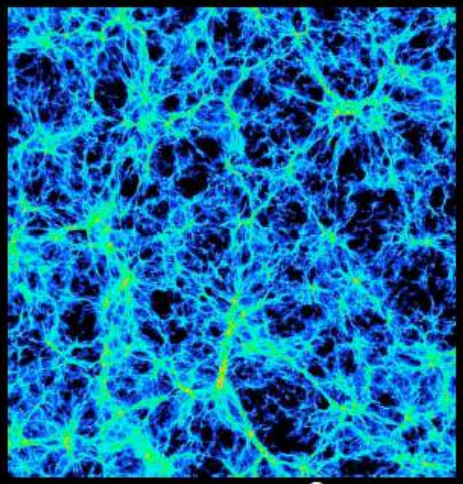
Dark Matter

CMB

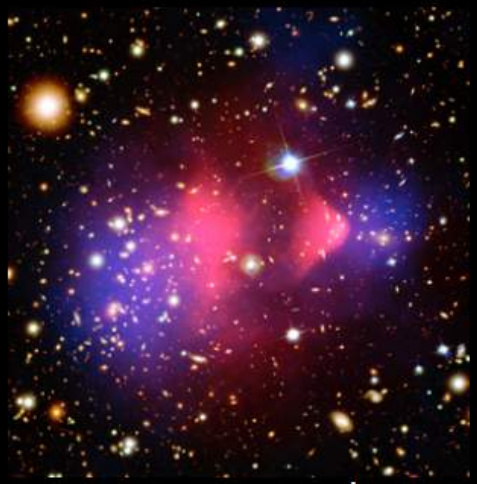


Supernova

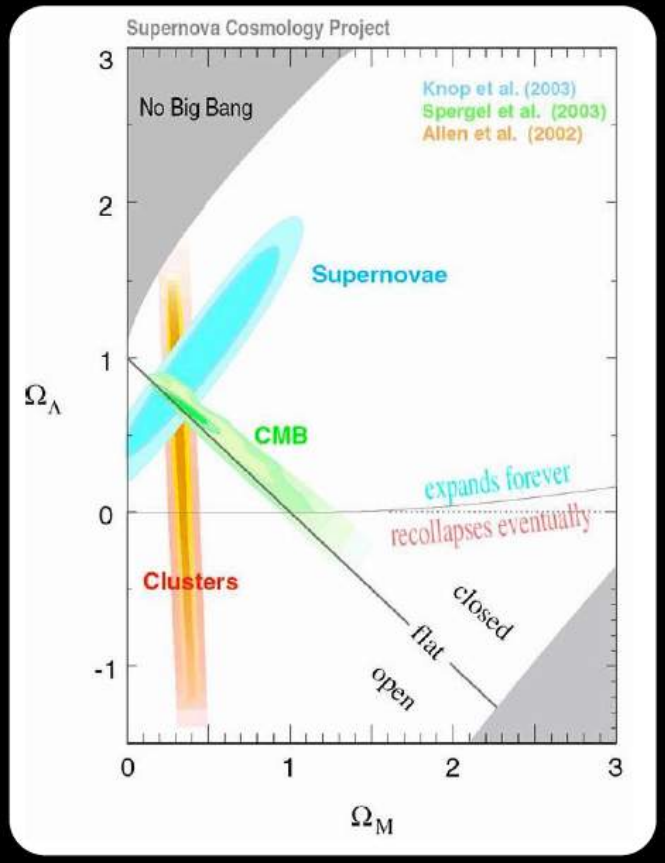




Structure



Lensing

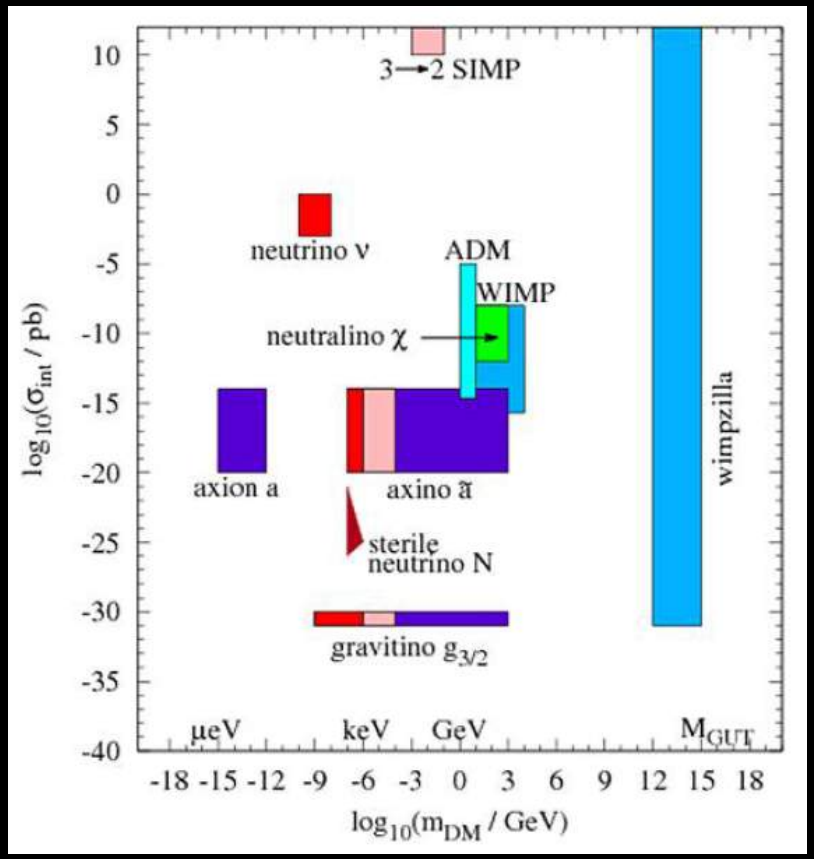


Dark Matter Candidates

Well motivated:

- ~~neutrino~~ – 'hot' DM
- WIMP
- neutralino χ
- gravitino $\tilde{G}$
- axion a
- axino $\tilde{a}$

still main candidate



WIMP (Weakly Interacting Massive Particle)

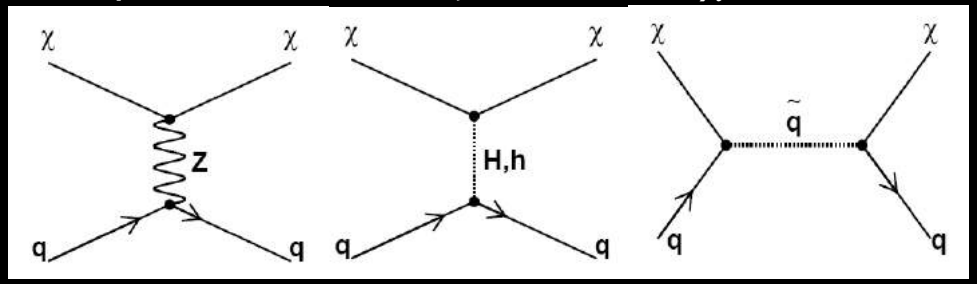
- neutral
- long livetime
- massive (GeV - TeV)
- weekly interacting with matter

Good WIMP candidate from SUSY → LSP

neutralino χ

$$\tilde{\chi} = a_1\tilde{\gamma} + a_2\tilde{Z} + a_3\tilde{H}_1 + a_4\tilde{H}_2$$

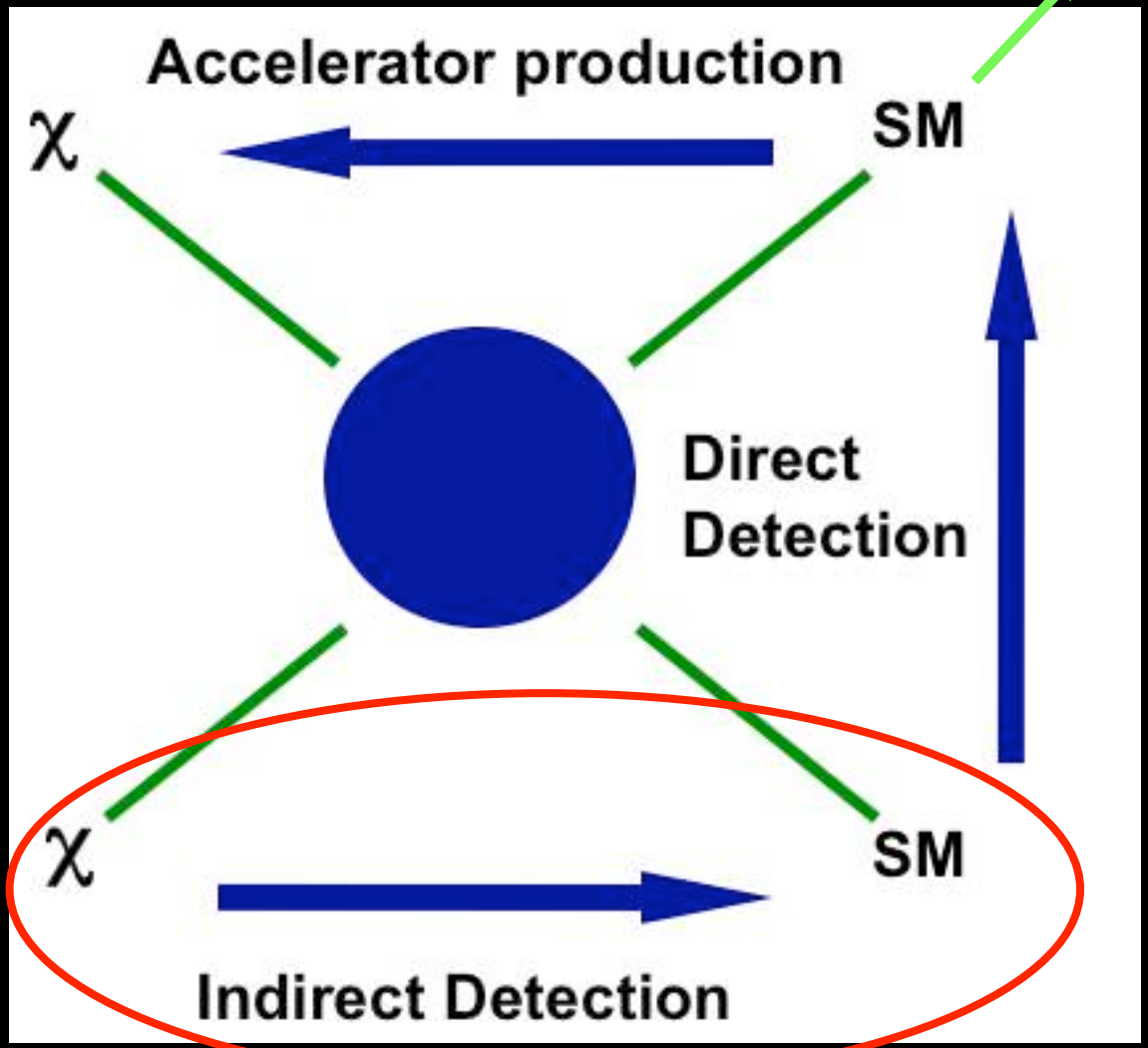
Example interactions of neutralino χ



Jungman, Kamionkowski, Griest, Phys. Rep., 267, 195 (1996)

WIMP searches

SM: Standard Model particle



χ: Dark Matter particle

Concept of indirect DM searches

» Indirect search = search for annihilation (or decay) products of DM

» PHOTONS

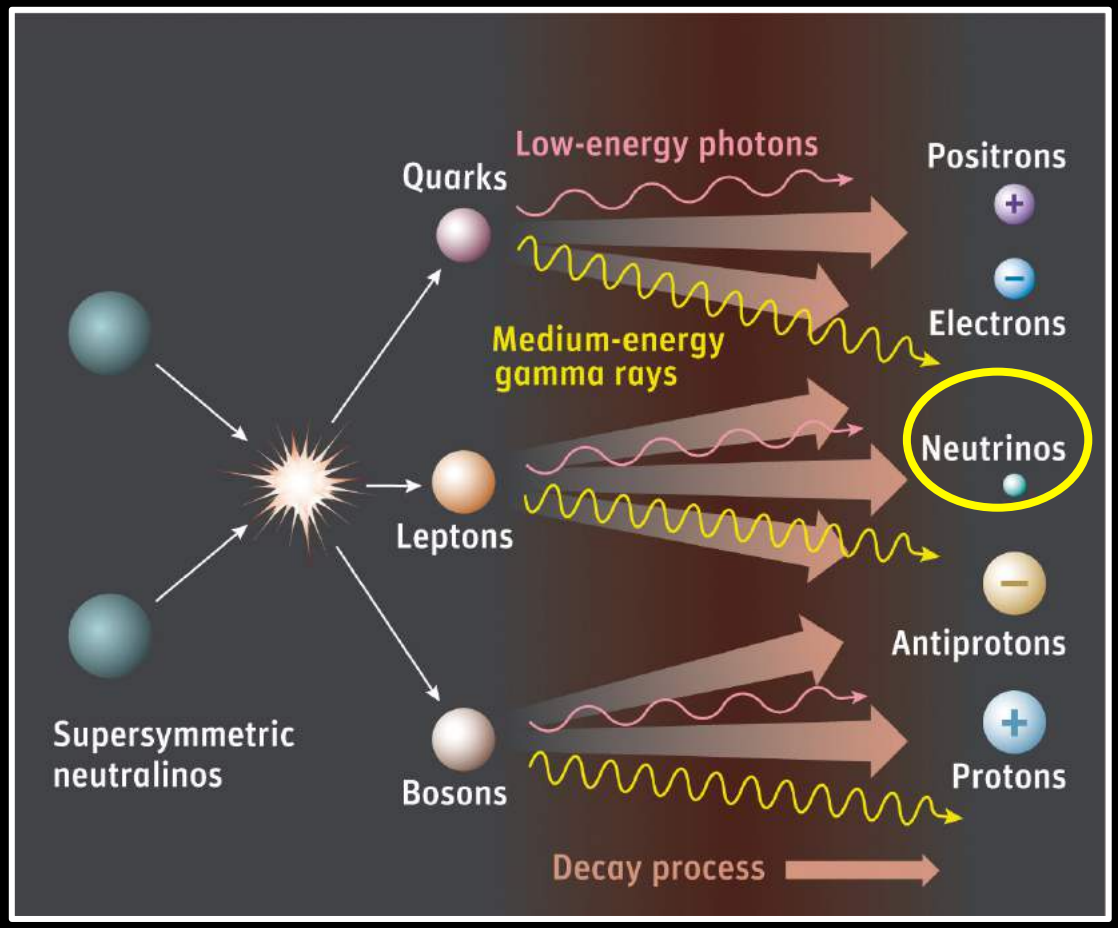
produced in most DM annihilation modes in π^0 decays,
E spectra not attenuated over galactic scales,

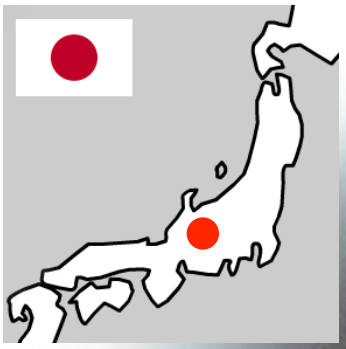
» ANTIMATTER

satellite or balloon-borne experiments, probe few kpc distances

» NEUTRINOS

excellent information on source (its direction, energy)
reach from dense regions like Sun, Galactic Center, core of Earth





Super-Kamiokande

@ Kamioka Observatory (ICRR, University of Tokyo), Japan

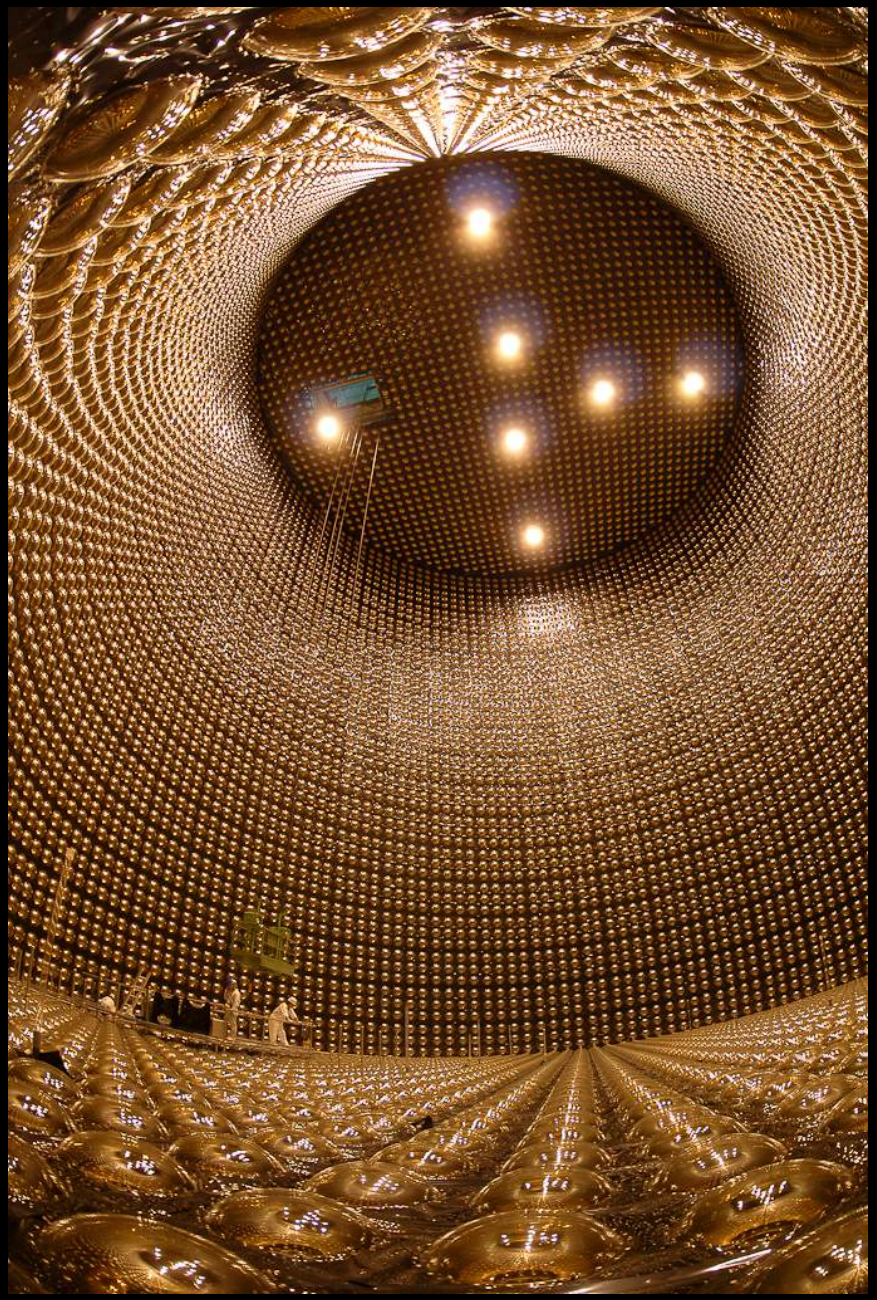
photomultipliers (PMTs) detect Cherenkov light

located 1km underground

40m

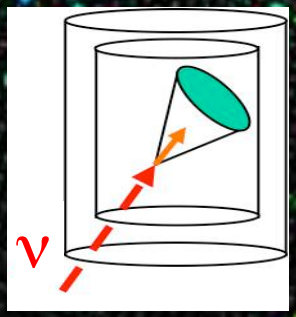
40m

- 50 kton of pure water (22.5 kton FV)
- inner (ID) & outer/veto (OD) detection regions
- SK runs from 1996
- measures solar, atmospheric, cosmic & accelerator neutrinos
- T.Kajita → Nobel Prize 2015



Detected Cherenkov light allows for reconstruction of:

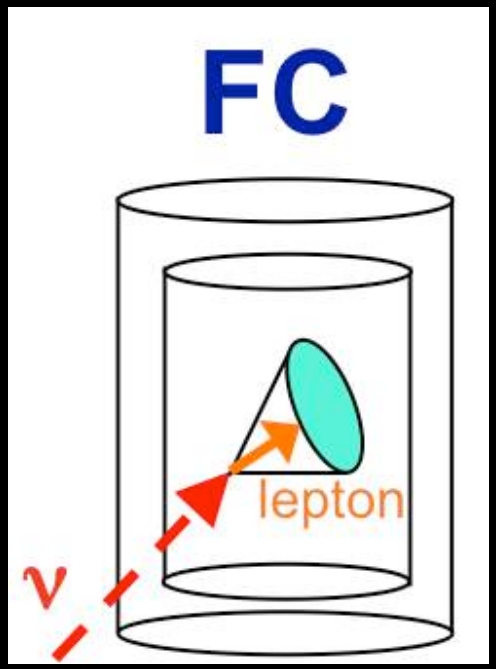
- lepton momentum (neutrino energy)
- lepton direction
- lepton flavor (e-like vs. μ-like, good separation possible)



$\nu_e + N \rightarrow e^- + N'$

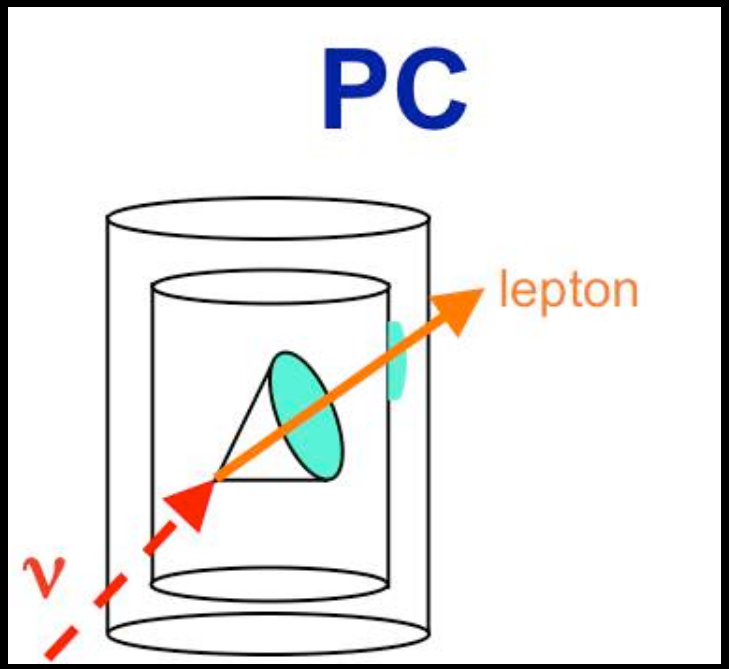
Super-K data samples

Fully-contained



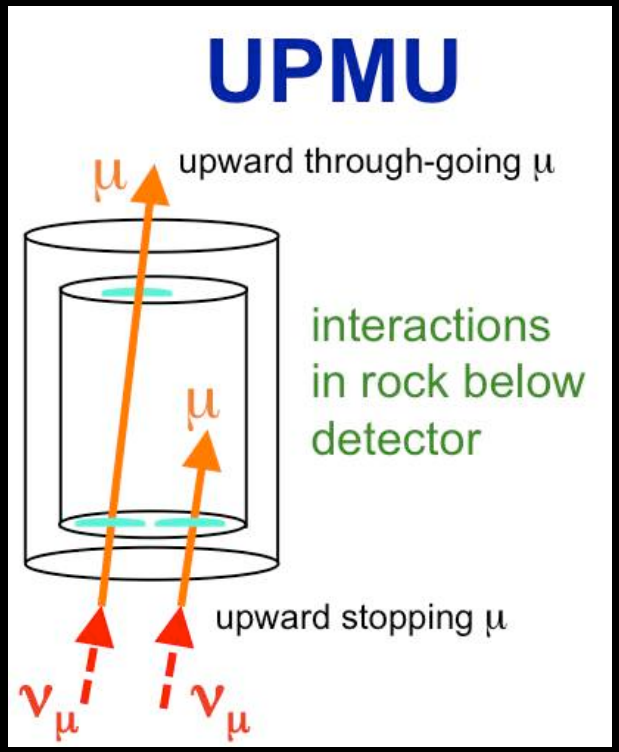
- ν energy reconstruction
- ν direction info
- e/μ identification possible

Partially-contained



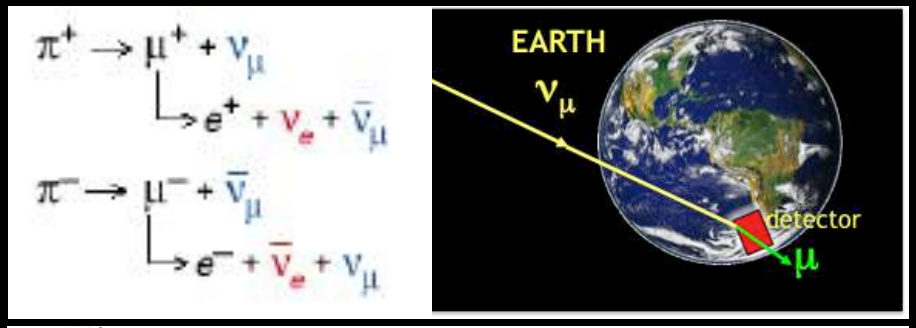
- partial E_ν info (lepton leaves detector)
- ν direction info

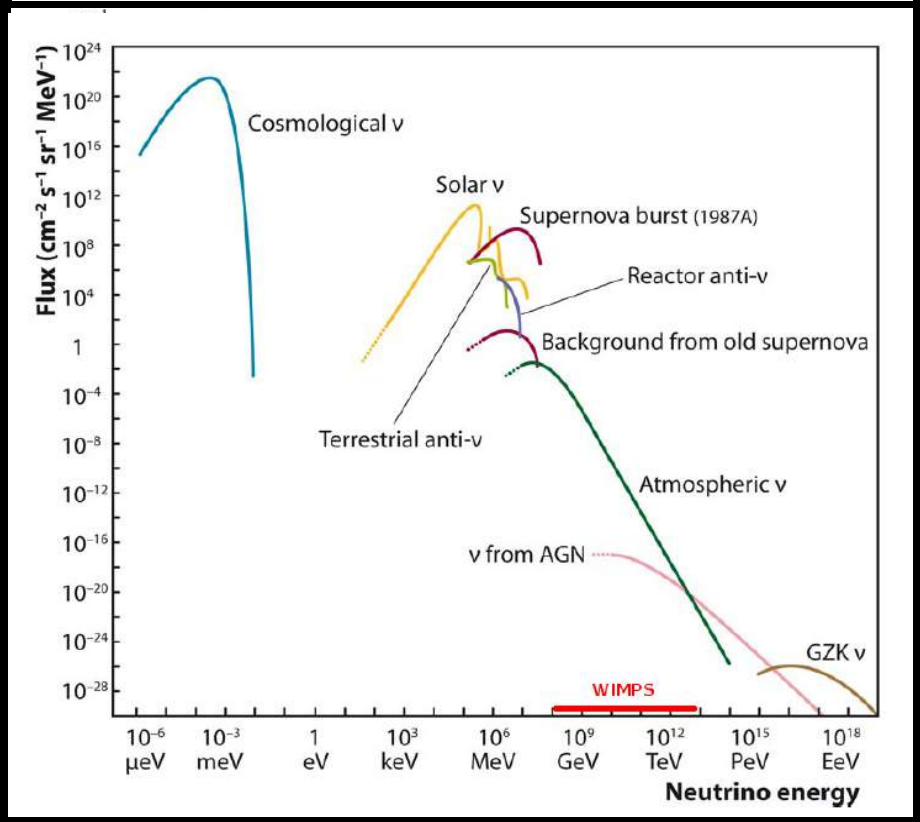
Upward-going muons



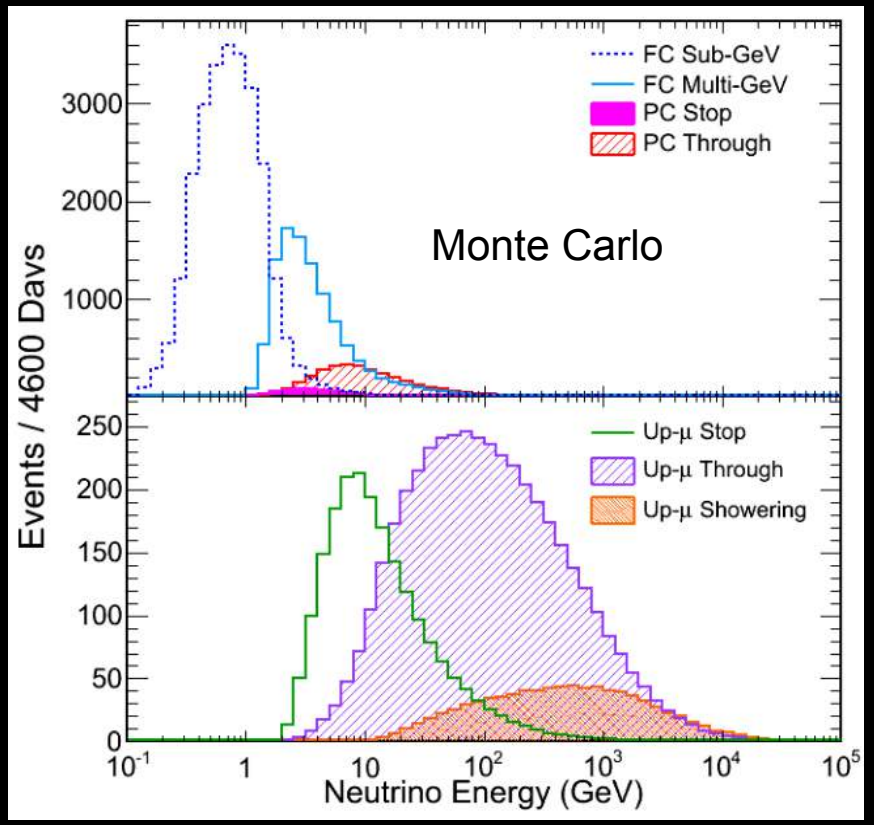
- no E_ν info
- excellent ν direction info
- downward-going muons are neglected (mainly cosmic ray μ)

Atmospheric neutrinos: main background in DM-induced ν searches



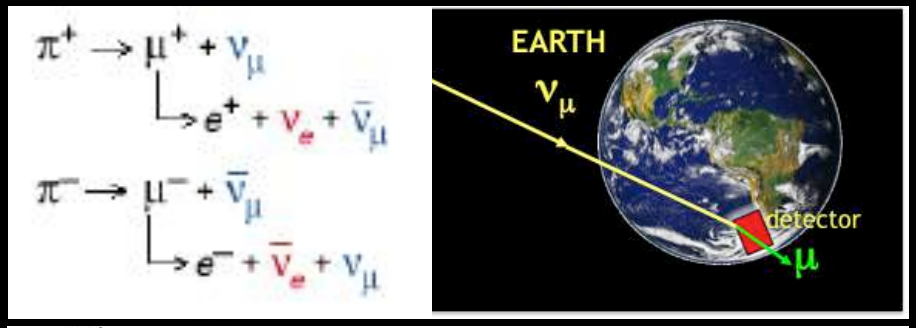


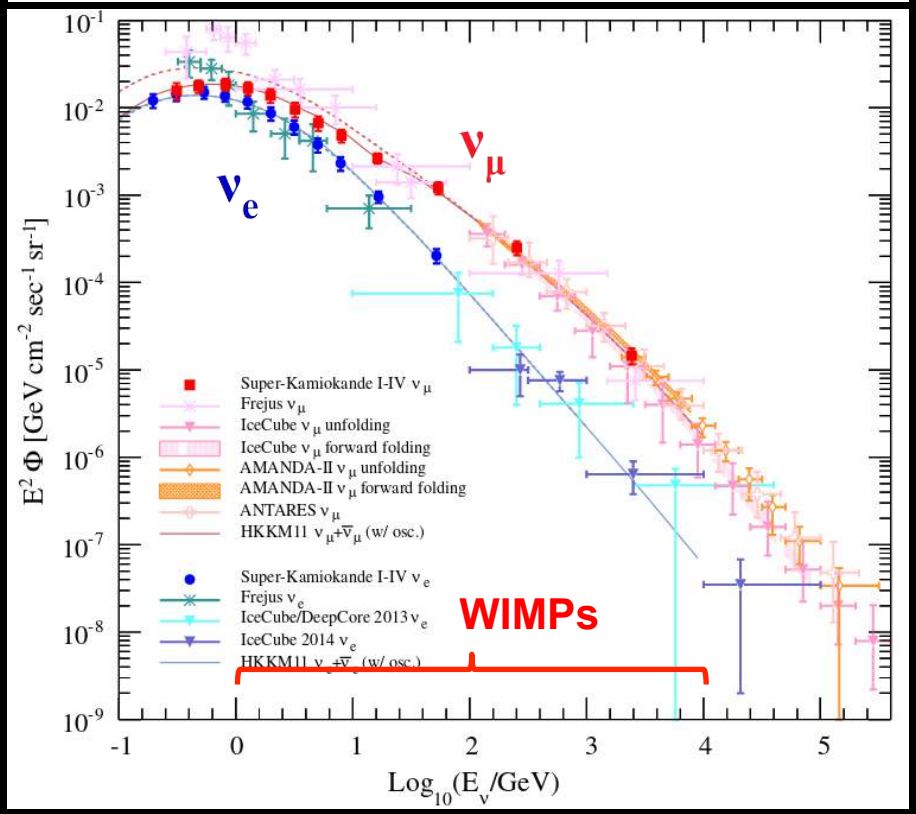
atmospheric neutrinos at SK



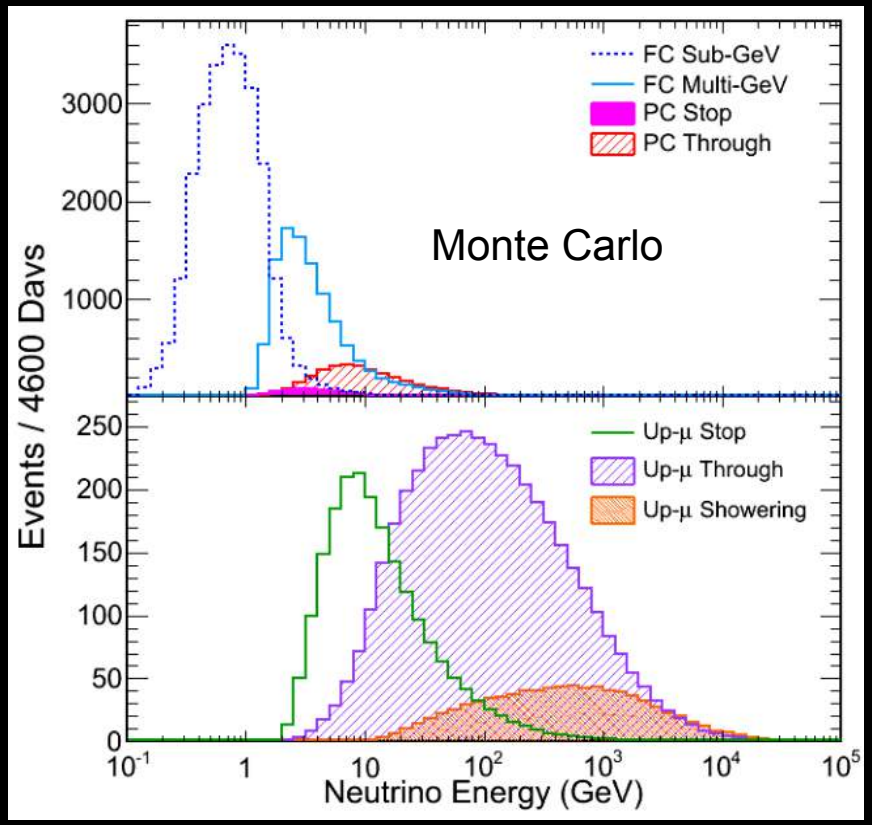
- ~10 events/day
- data period: 1996-2016
- ~50 000 events in total

Atmospheric neutrinos: main background in DM-induced ν searches





atmospheric neutrinos at SK

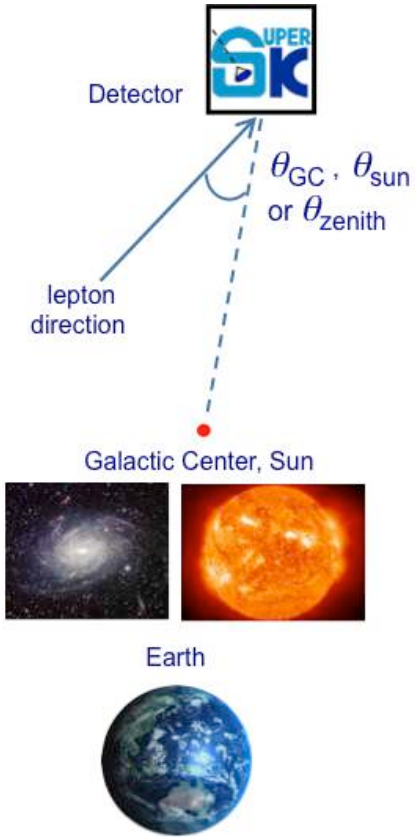


- ~10 events/day
- data period: 1996-2016
- ~50 000 events in total

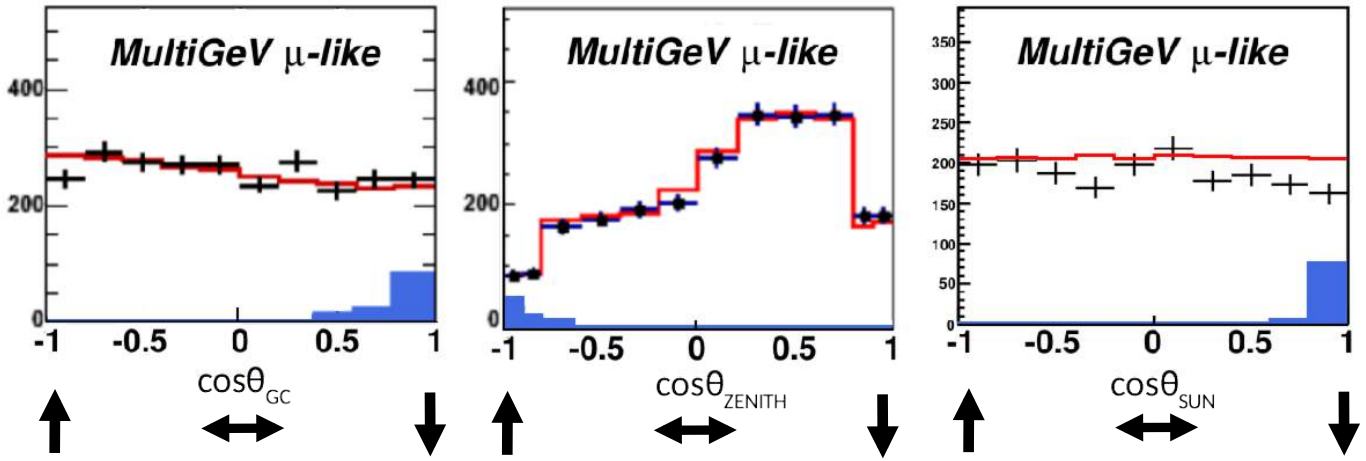
DM searches at Super-K using a fit method

- Search for excess of neutrinos form **Earth/Sun/Milky Way**
- **FIT:** for each tested WIMP mass & ann. mode, find configuration of ATM ν + DM signal that would match DATA the best using reconstructed angular & momentum distributions

$$\chi\chi \to \nu\bar{\nu}, W^+W^-, b\bar{b}, \mu^+\mu^- \to \ldots\nu_{e/\mu/\tau}$$



Galactic WIMP search | **Earth WIMP search** | **Solar WIMP search** point-like source



- In these coordinate systems signal is easy to distinguish from atmospheric neutrino background

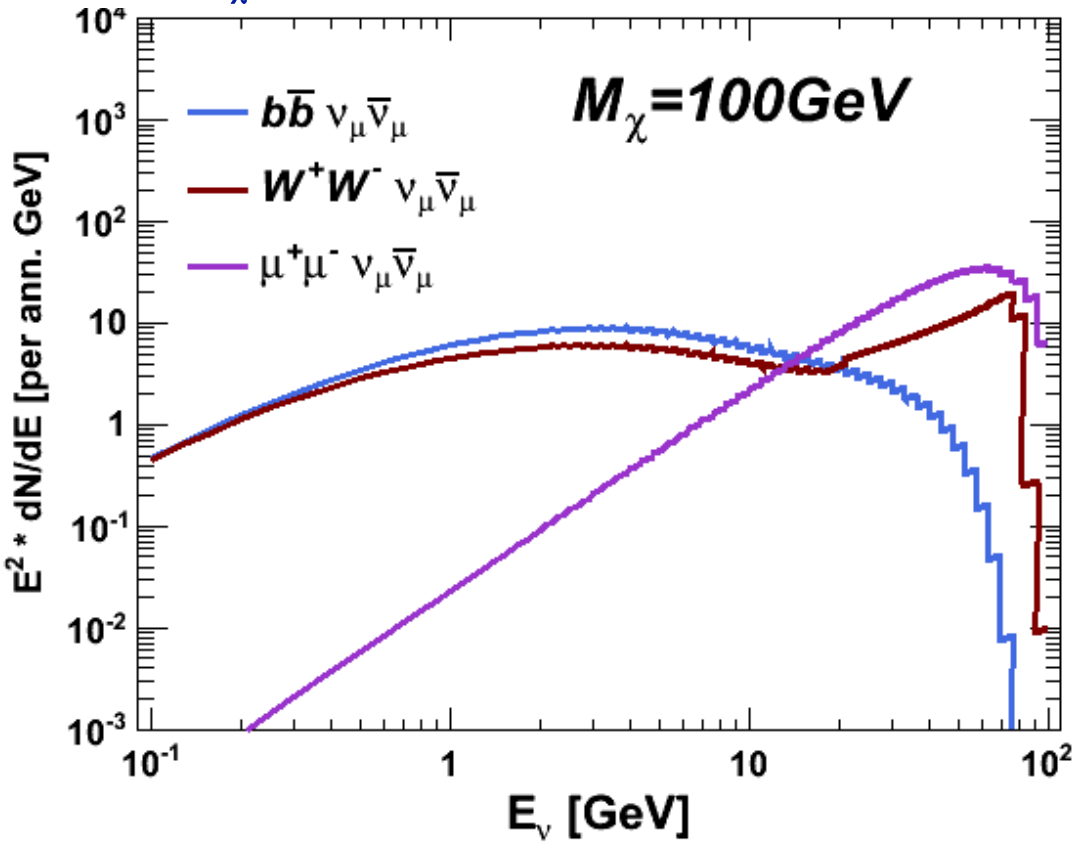
Galactic WIMP search: signal simulation

Simulate DM signal before detection
→DarkSUSY & WimpSim

P. Gondolo et al., JCAP 07, 008 (2004)
M. Blennow et al., arXiv: 0709.3898 (2008)

EXAMPLE: Galactic WIMP search

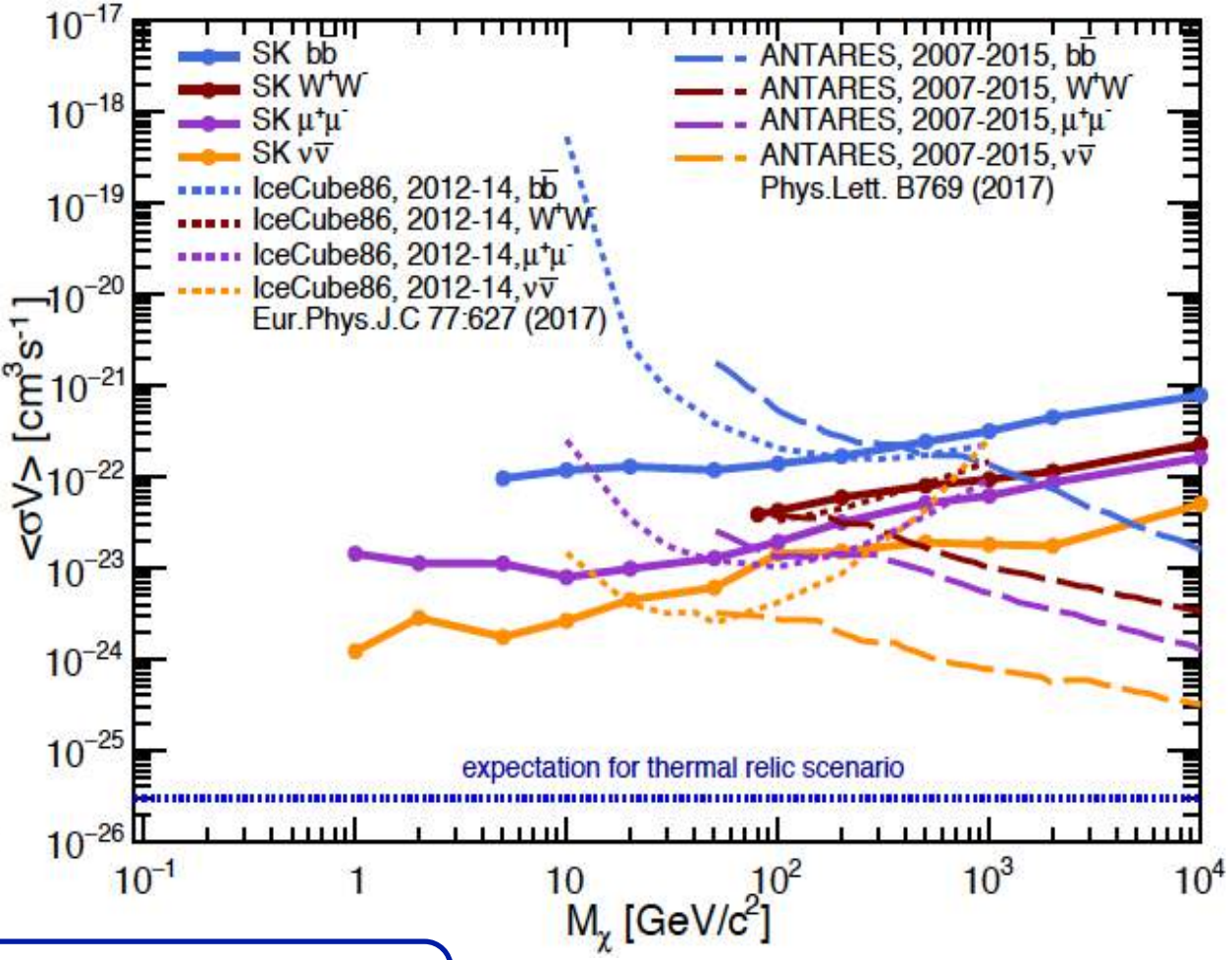
differential $\nu_\mu\nu_\mu$ energy spectra per DM annihilation for
M_χ=**100** GeV (oscillated throughout Galaxy)



Galactic WIMP search: DM self-annihilation cross section

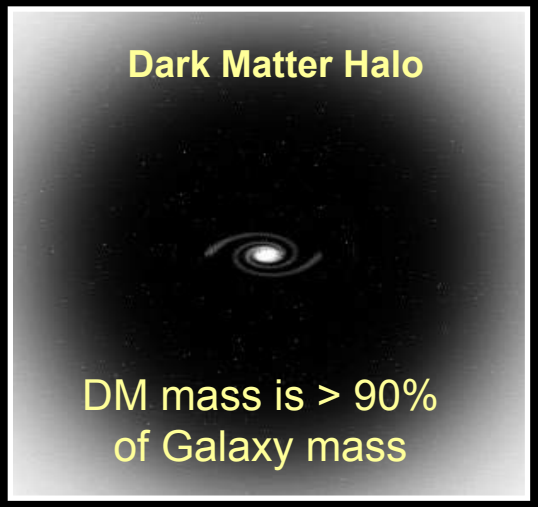
- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions, 5326-5629 live-days, 1996-2016
- NFW halo model assumed
- Fit results are consistent with null WIMP contribution
- 90% CL upper limit on DM self-annihilation cross section $\langle\sigma_A V\rangle$

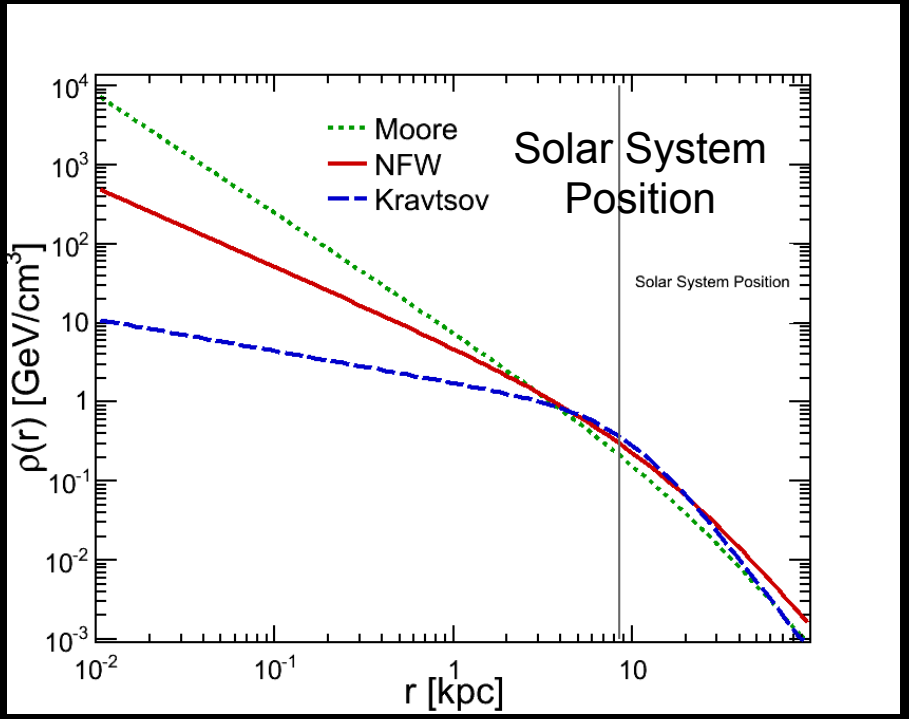
90% CL upper limit



$$\frac{d\phi_{\Delta\Omega}}{dE} = \frac{\langle \sigma_A \cdot V \rangle}{2} J_{\Delta\Omega} \frac{R_{sc}\rho_{sc}^2}{4\pi \cdot M_\chi^2} \frac{dN}{dE}$$

HALO MODELS

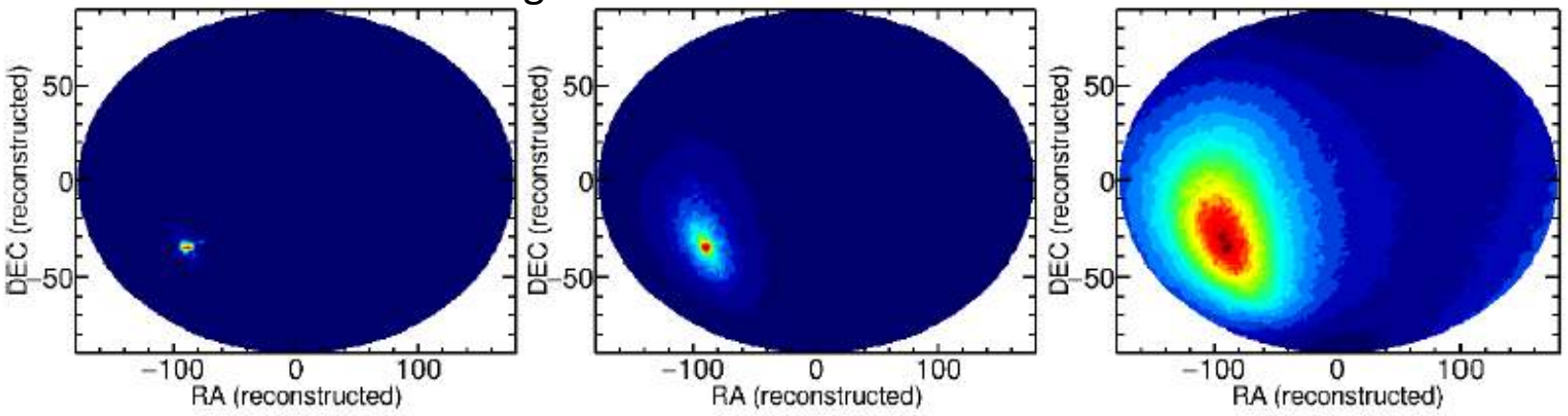




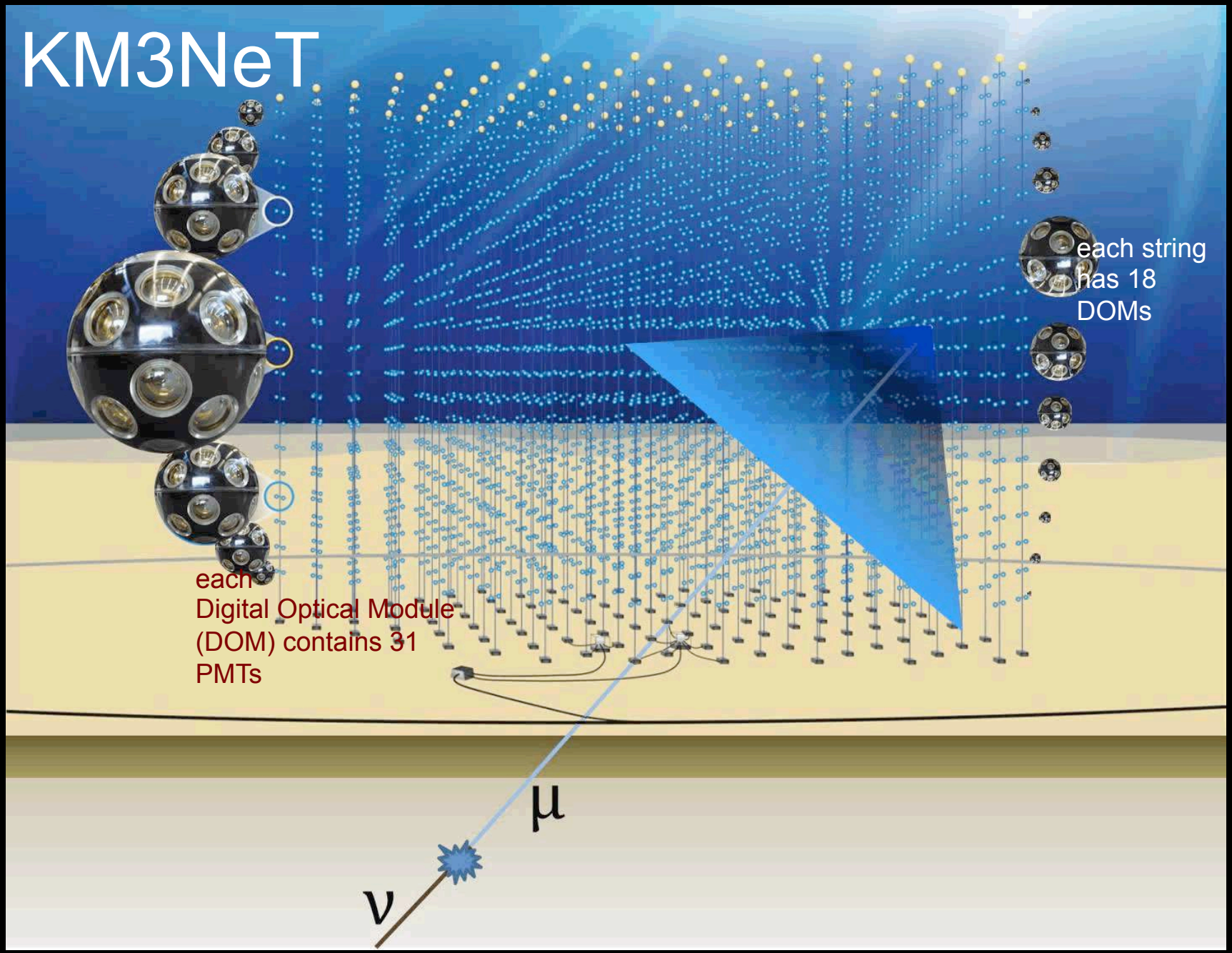
- NFW is our benchmark model
- Moore/Kravtsov: extreme cases

Moore **NFW** **Kravtsov**

simulated angular distributions of DM-induced neutrinos



KM3NeT


each string has 18 DOMs
each Digital Optical Module (DOM) contains 31 PMTs
μ
ν