DARK MATTER SEARCHES IN SUPER-KAMIOKANDE AND FUTURE WATER CHERENKOV DETECTORS

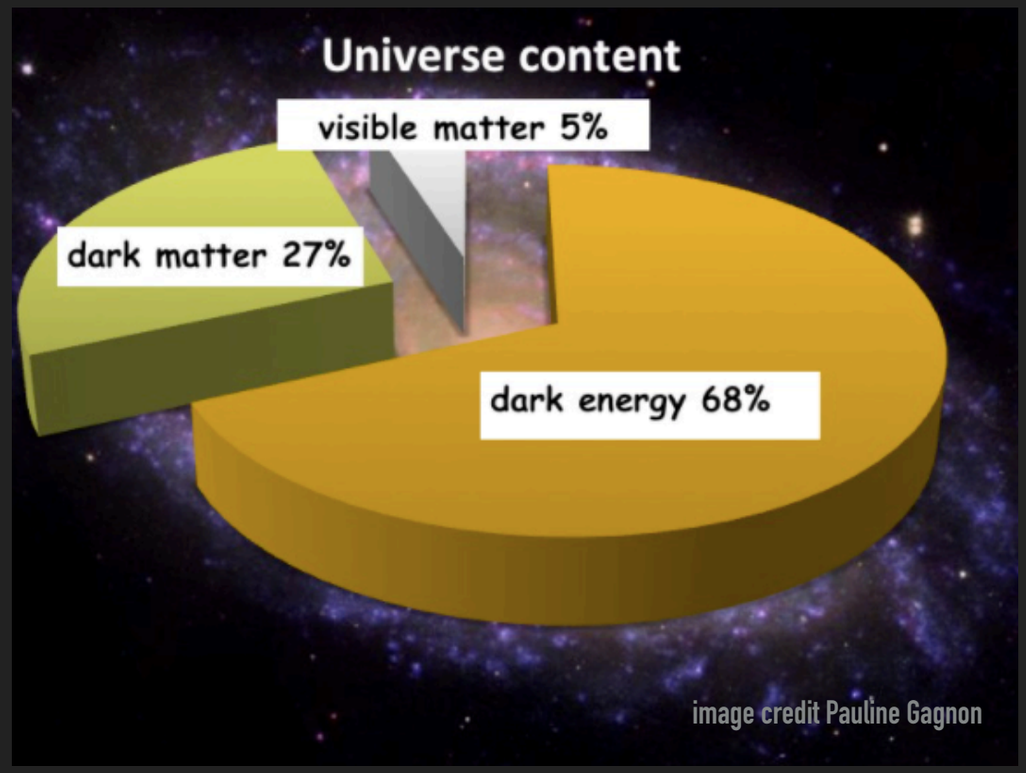
SAGA-YONSEI WORKSHOP, JANUARY 8TH 2021

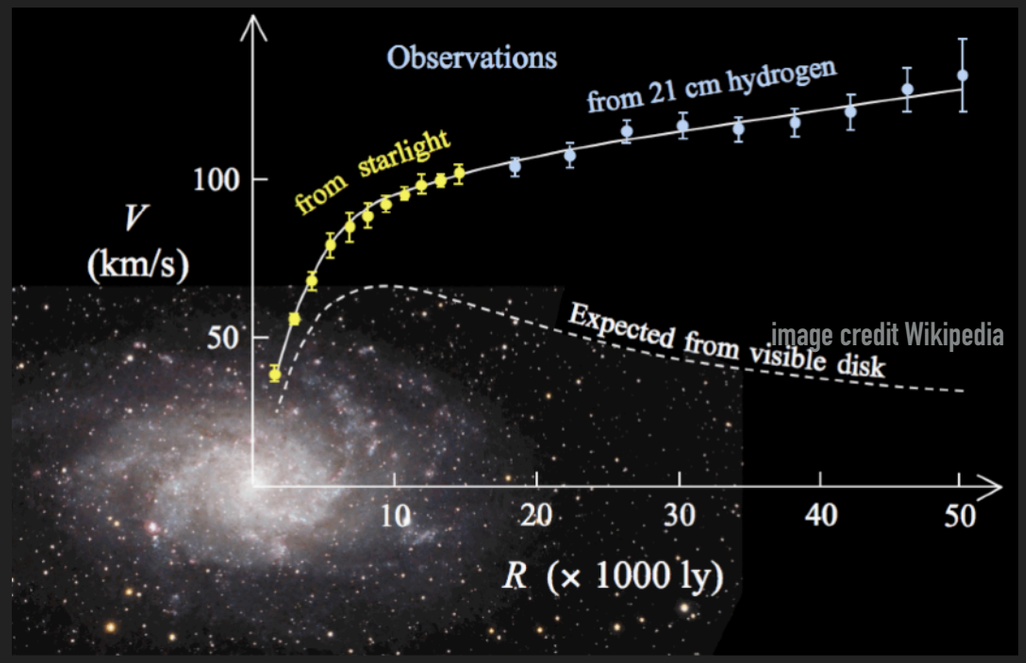
KOUN CHOI, SUNGKYUNKWAN UNIVERSITY

WHY DARK MATTER?

- Missing mass of the Universe
- Seed for structure formation in the Universe
- Missing part of understanding stellar motions in the Galaxy
- Missing knowledge of the stellar evolution, solar physics …

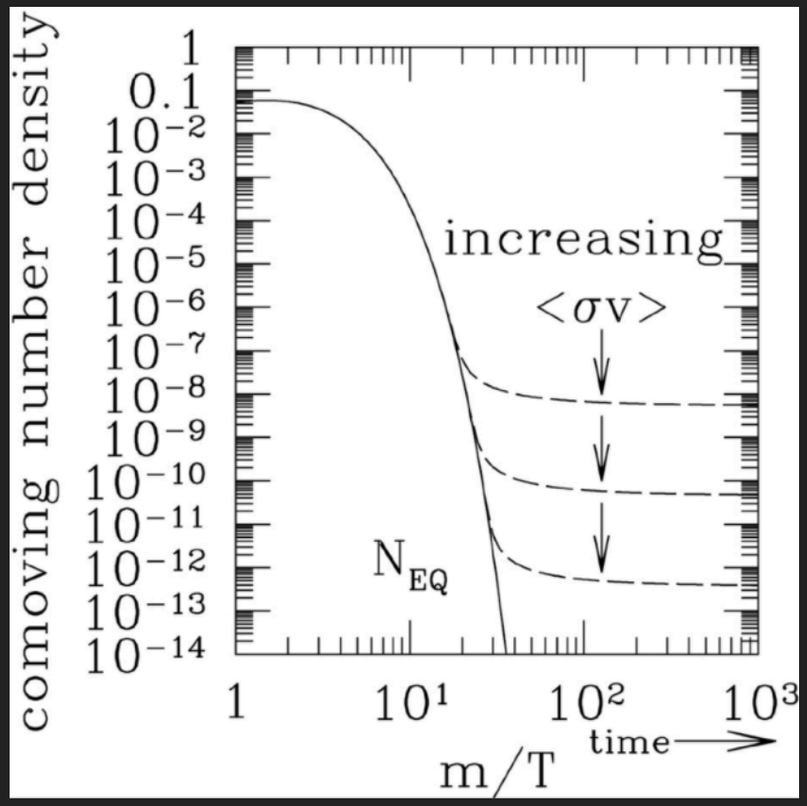
- above all, a window for new physics

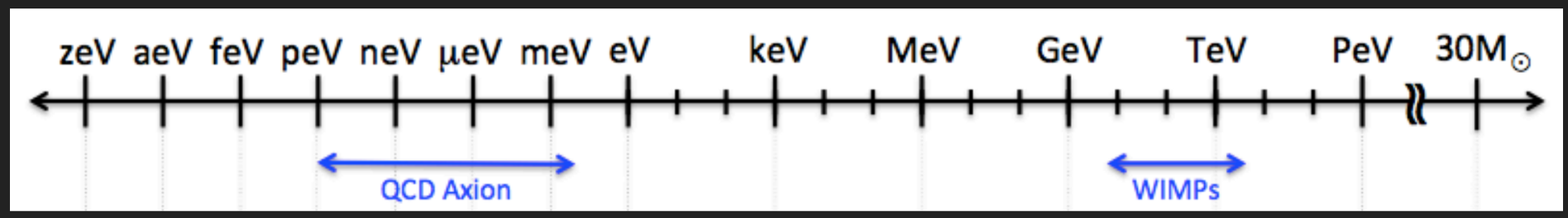




WHERE TO FIND?

- We know how much DM there is now
- The origin - “Freeze out” scenario (DM was produced with standard model particles in the early universe)
- As a minimal thermal relic candidate, “WIMP” is supported by particle physics modeling (“WIMP miracle”)





Large effort has been put to search for ‘WIMP’-like DM

HOW TO FIND?

- **Direct detection**

  Target: DM at rest in the Galactic halo

  Signal: DM-nucleon/electron scattering in the detector

- **Indirect detection** through cosmic particles

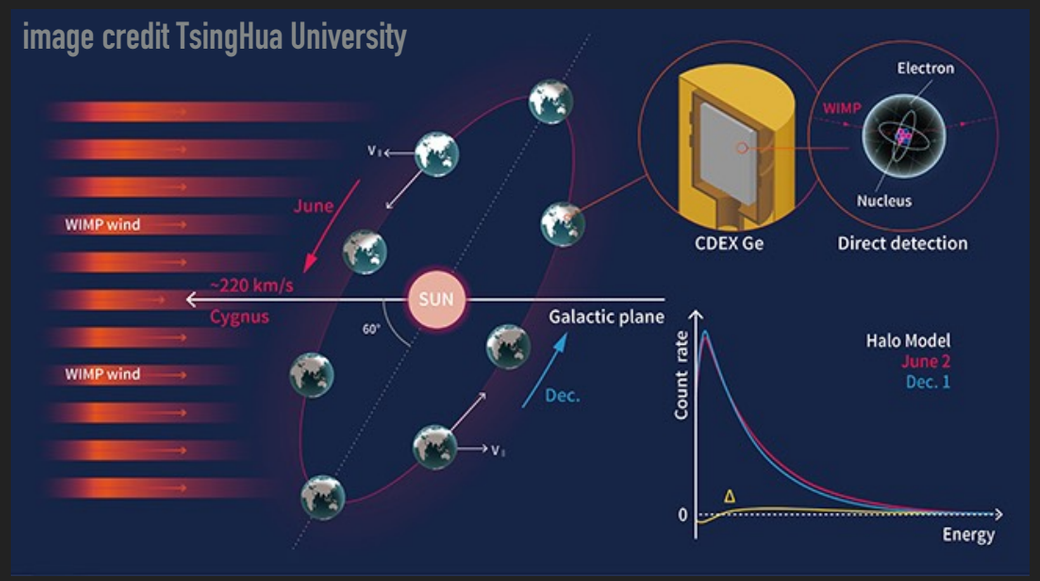
  Target: DM from the Galactic Center, dwarf galaxy, Sun …

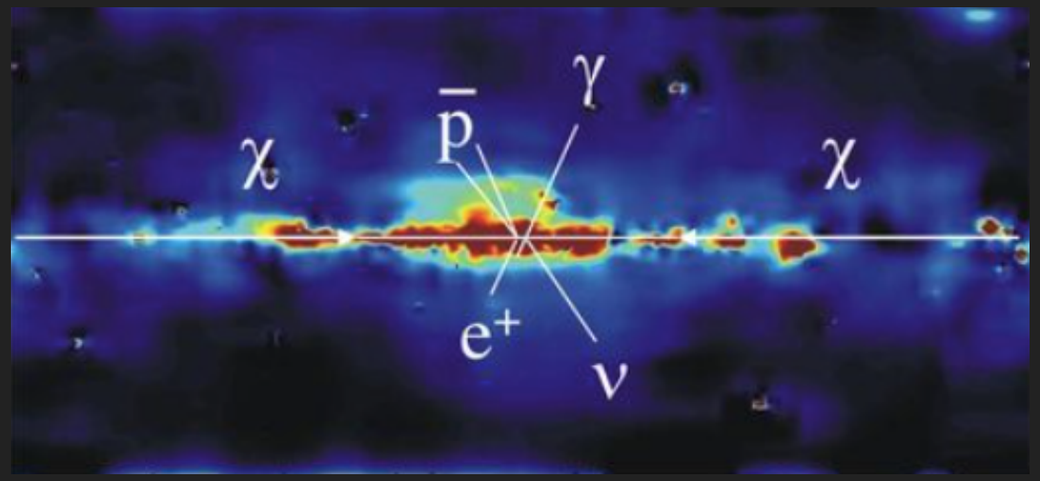
  Signal: gamma rays, charged particles, neutrinos

- **Accelerator**

  Target: DM produced by the particle beam

  Signal: missing energy & momentum





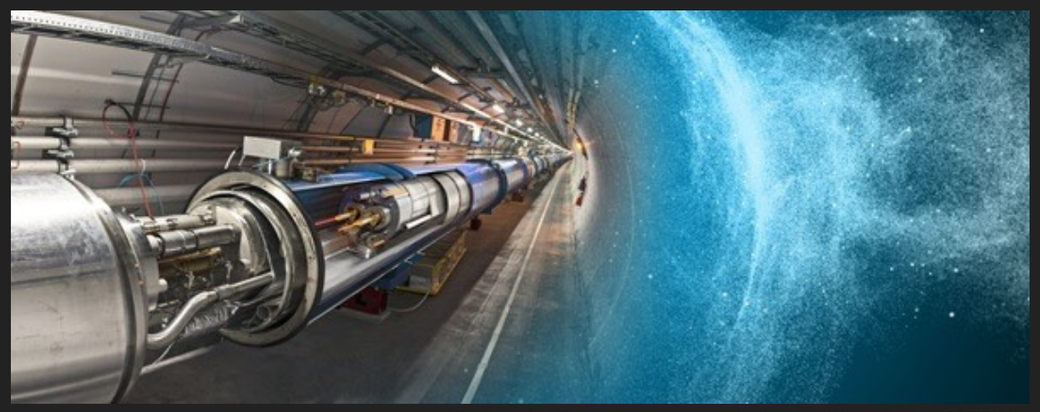
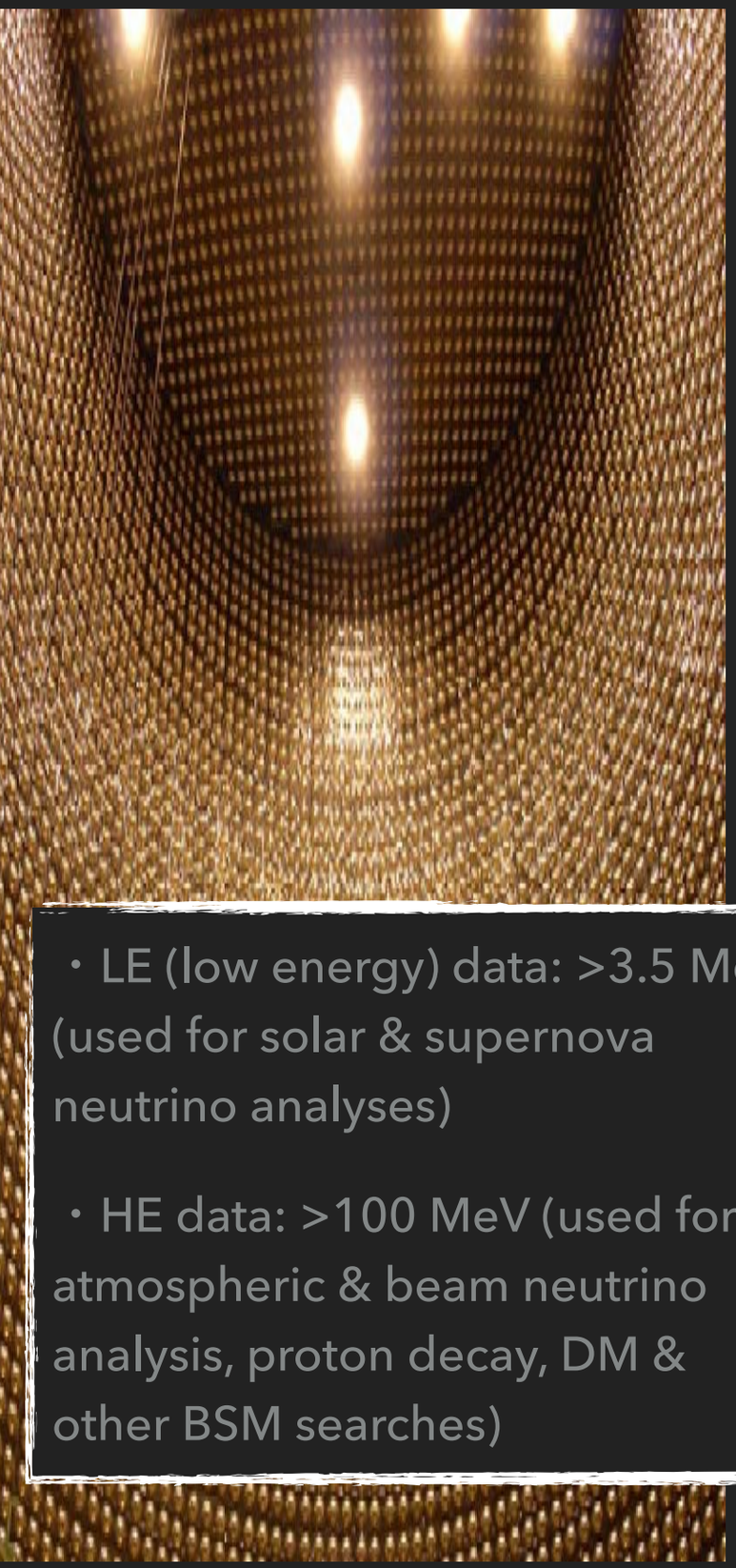


image credit Daniel Dominguez and Maximilien Brice/CERN



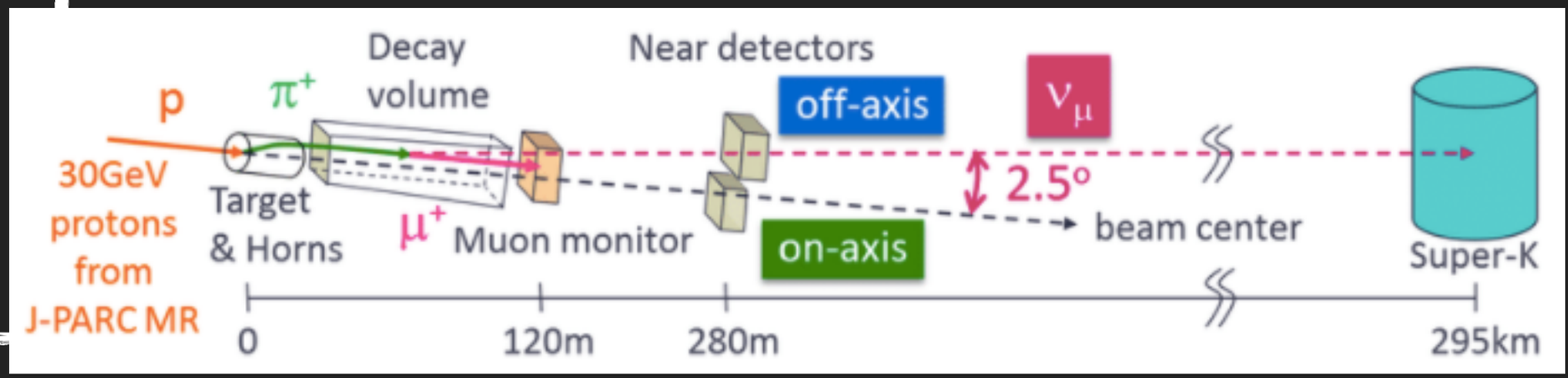
SUPER-KAMIOKANDE (SK)

- Water Cherenkov detector (WCD) built in Kamioka, Japan
- 50 ktons water (22.5 ktons fiducial volume)
- ID viewed by 11,000 20” photo-multiplier tubes (PMTs)
- ~2 m OD viewed by 8” PMTs
- Operating since 1996 (>20 years data accumulated)
- SK-Gd (0.02% Gadolinium doping in SK) phase started in 2020.8

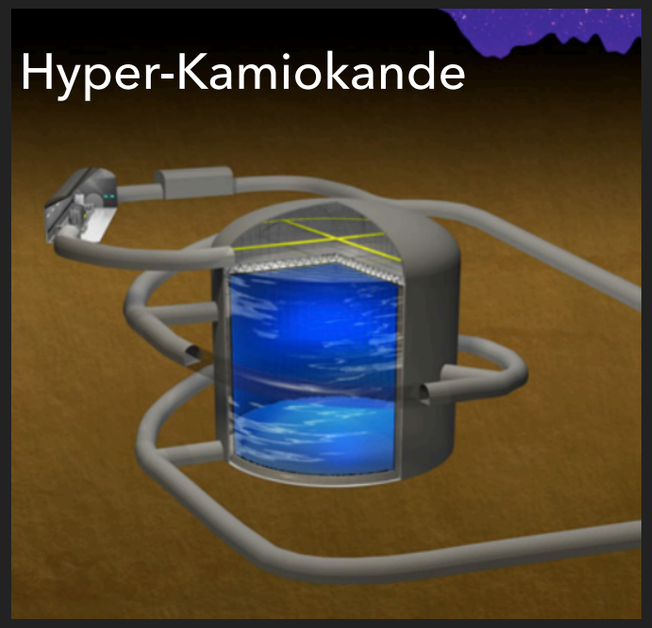
・LE (low energy) data: >3.5 MeV (used for solar & supernova neutrino analyses)

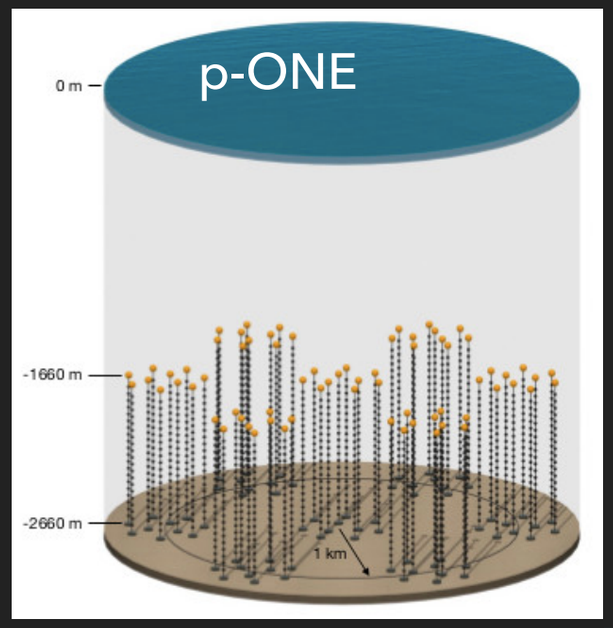
・HE data: >100 MeV (used for atmospheric & beam neutrino analysis, proton decay, DM & other BSM searches)

T2K (TOKAI TO KAMIOKA)

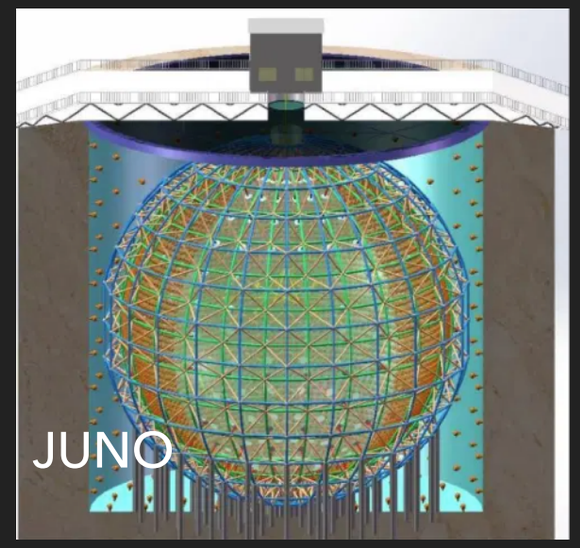


FUTURE NEUTRINO DETECTORS

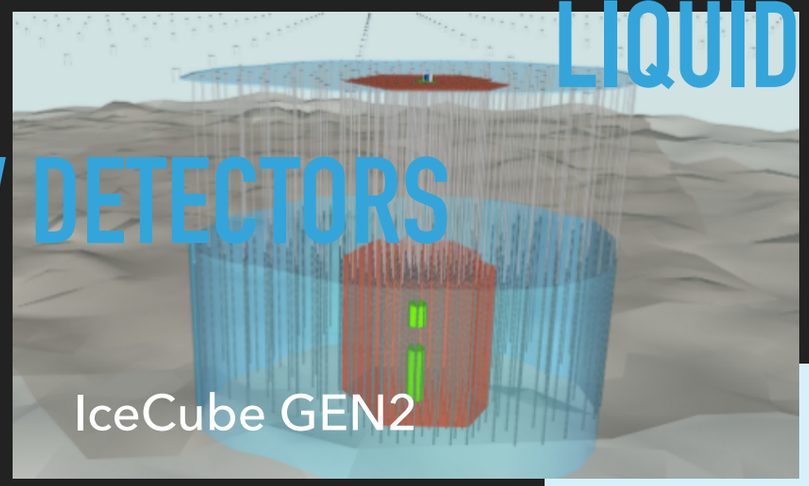




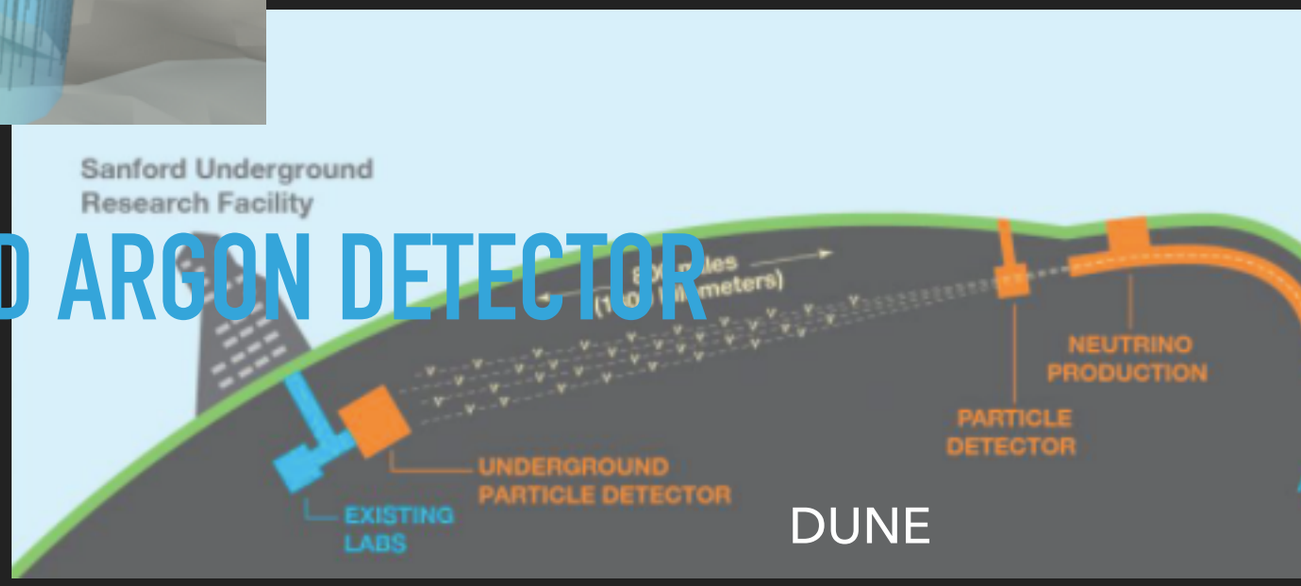
WbLS: THEIA, …



LIQUID SCINTILLATOR DETECTORS



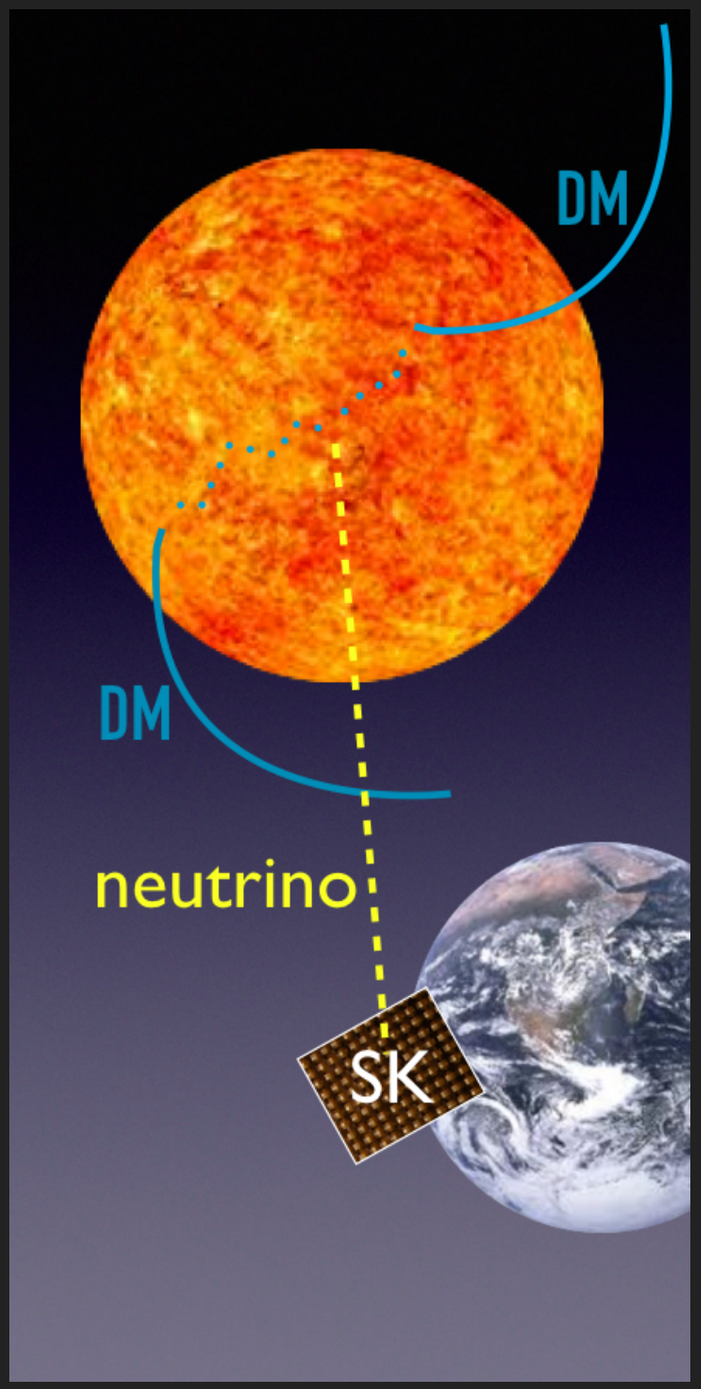
WATER CHERENKOV DETECTORS



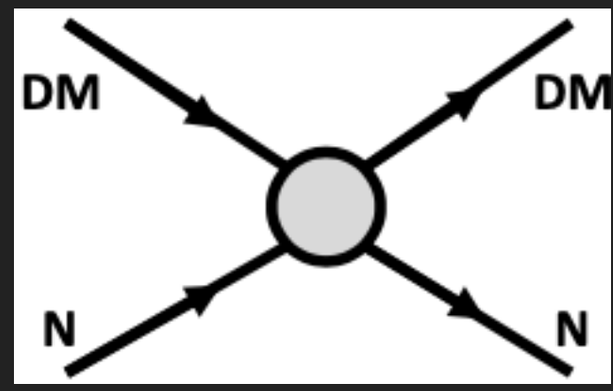
LIQUID ARGON DETECTOR

- Search for excess of neutrinos coming from some direction (“indirect detection”)

SOLAR DARK MATTER SEARCH

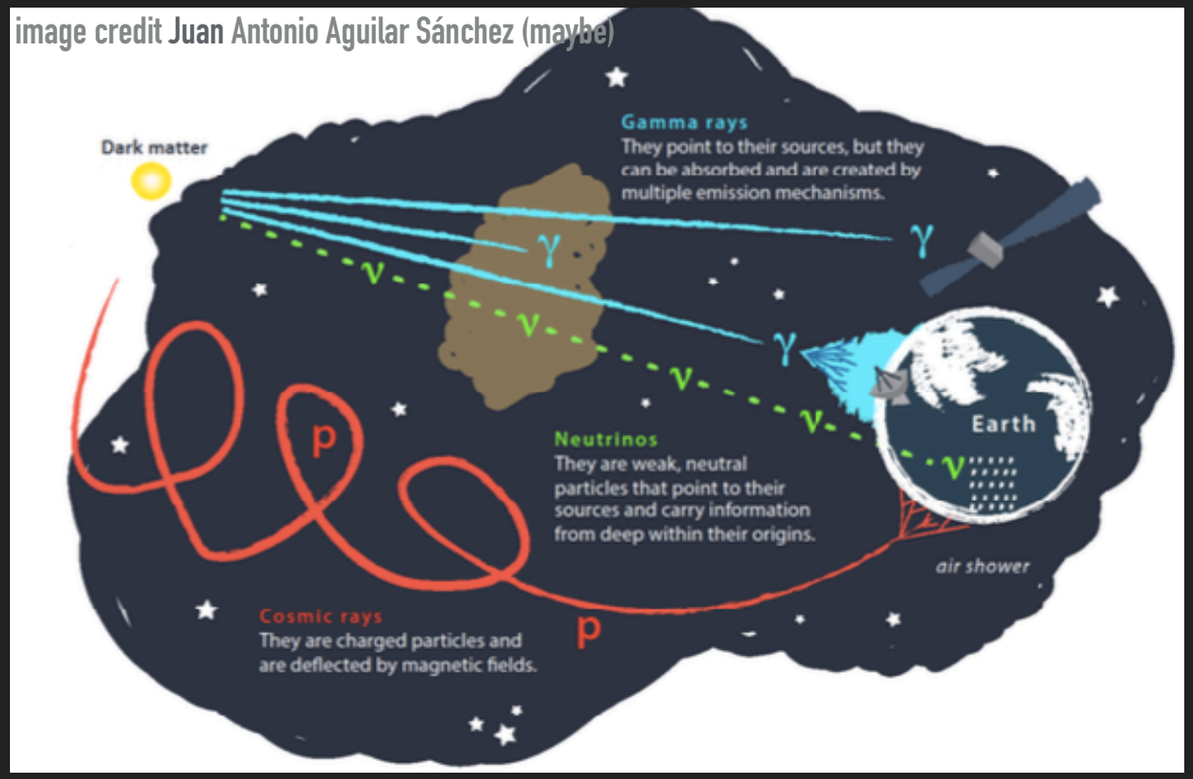


- Solar/Earth search - Neutrinos are only surviving annihilation yield
- Constrains DM-SM scattering cross-section (complementary to direct detection experiments)

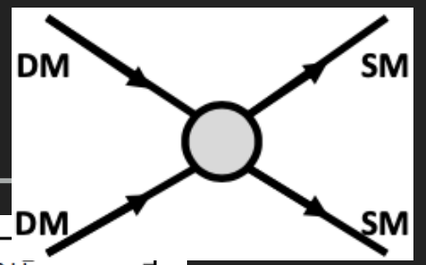


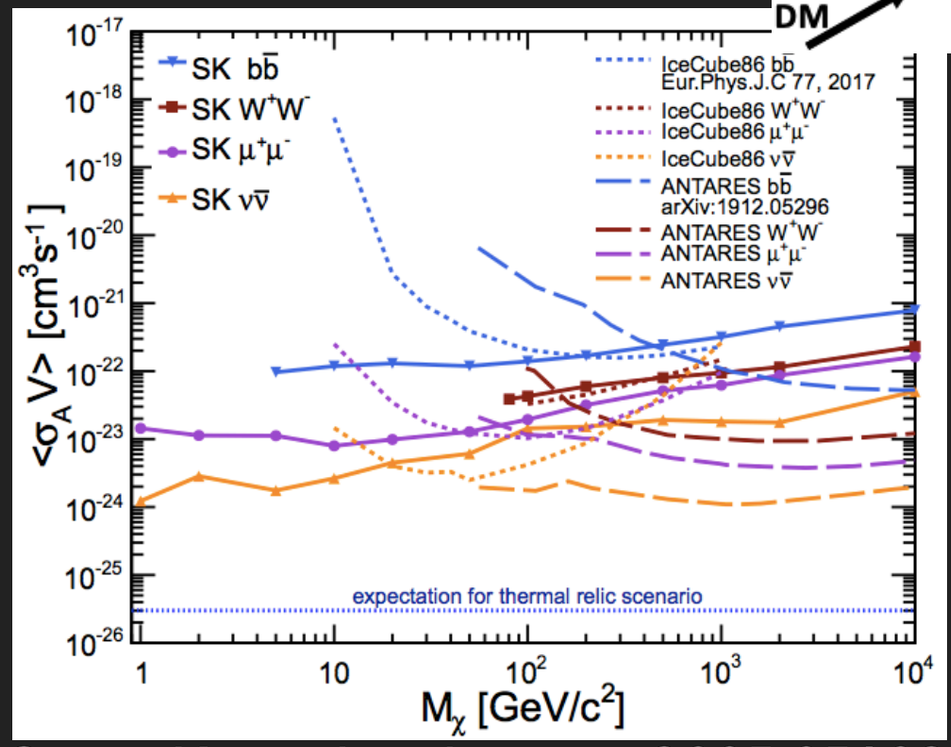
IceCube, arxiv:1612.05949

GALACTIC DARK MATTER SEARCHES

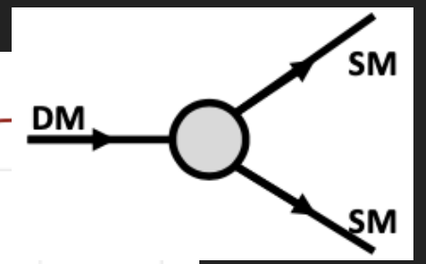


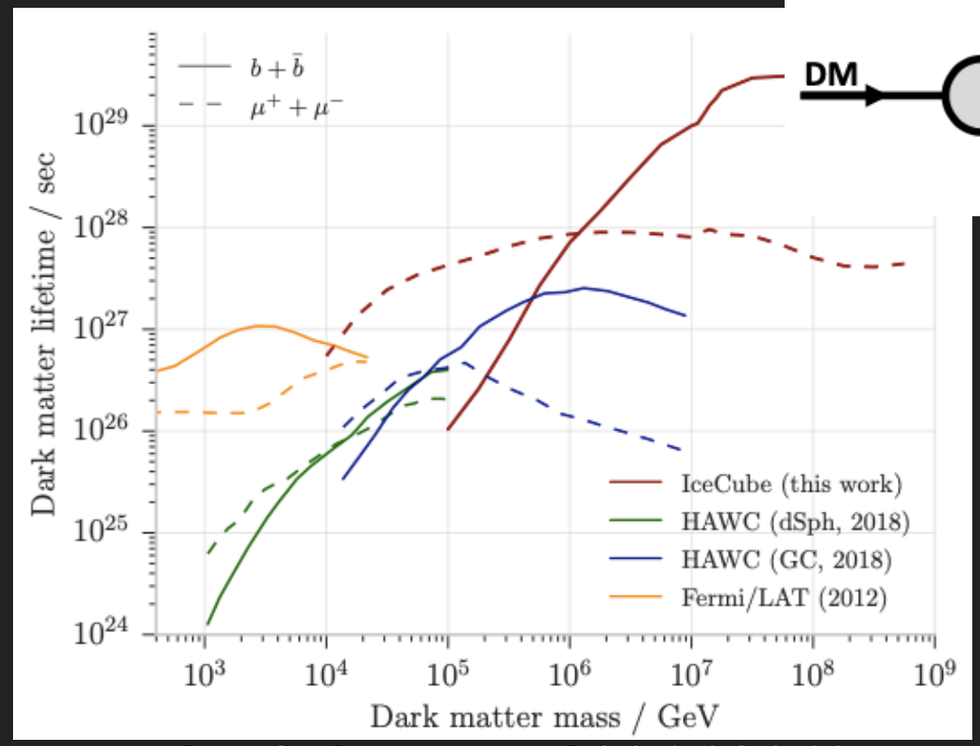
- Galactic halo/center search - Neutrinos keep directional information
- used to constrain DM annihilation cross-section / lifetime





Super-Kamiokande, arxiv:2005.05109





IceCube, axriv:1804.03848

DARK MATTER NOT FOUND

- A few anomalies but no consistent signal
- Dark matter may not be WIMP
- How the searches in the next decade should be?
  - persistently look in (WIMP parameter space not closed)
  - also look in every corner (open minded, experiment-driven strategy)

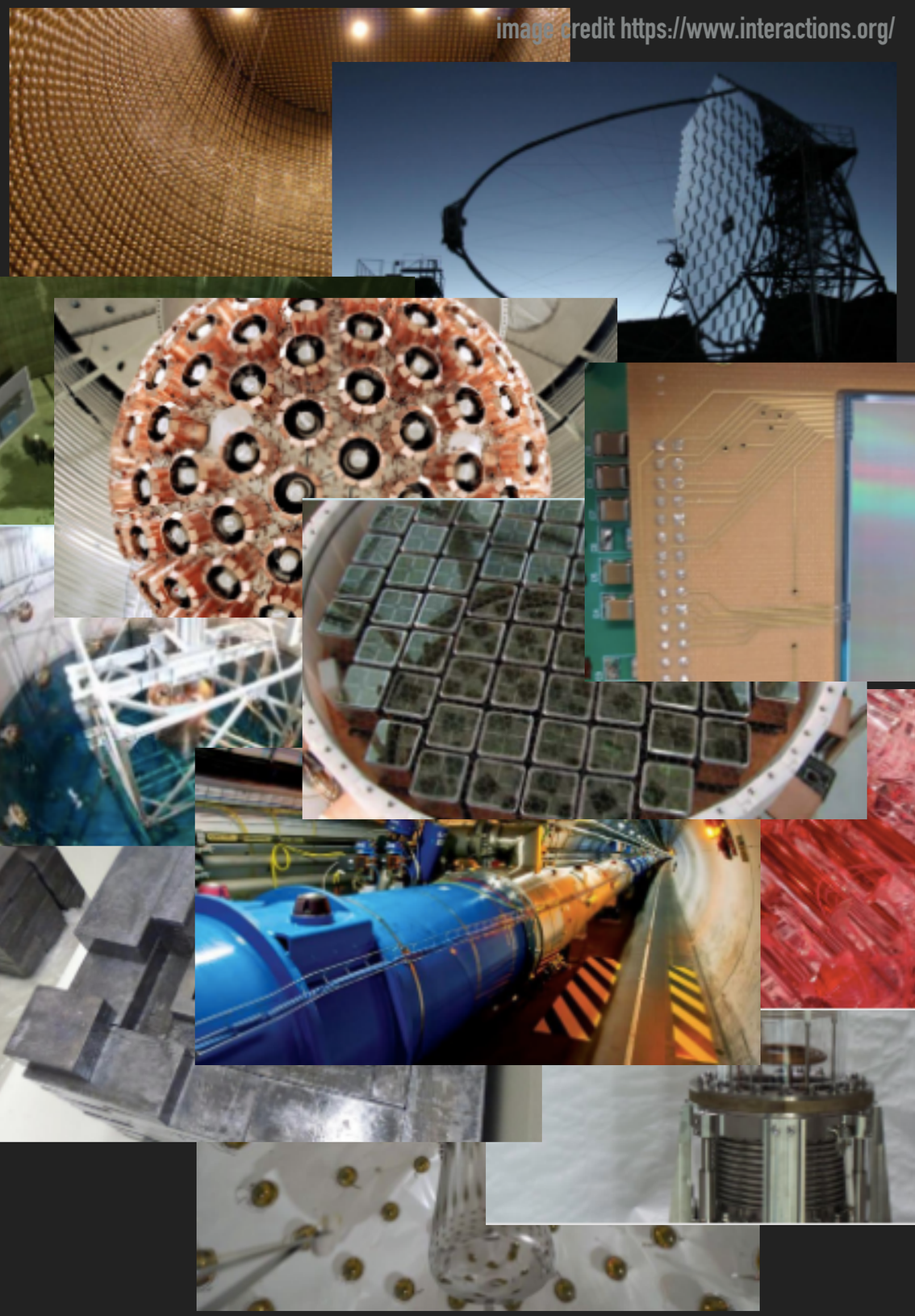


image credit https://www.interactions.org/

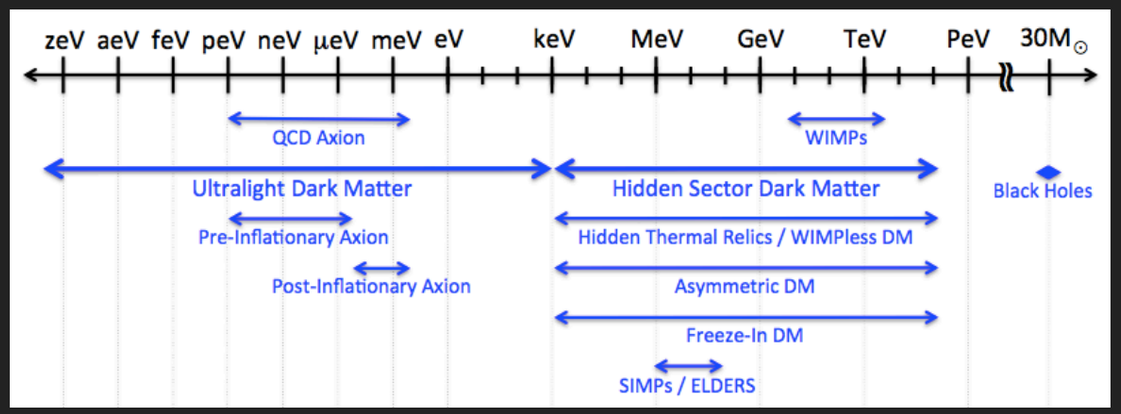


image credit US Cosmic Visions: New Ideas in Dark Matter 2017

NEW STRATEGY: GO TO SUB-GEV

- Sub-GeV DM is less searched because
  - "WIMP miracle" >2 GeV
  - direct detection experiments lose sensitivity

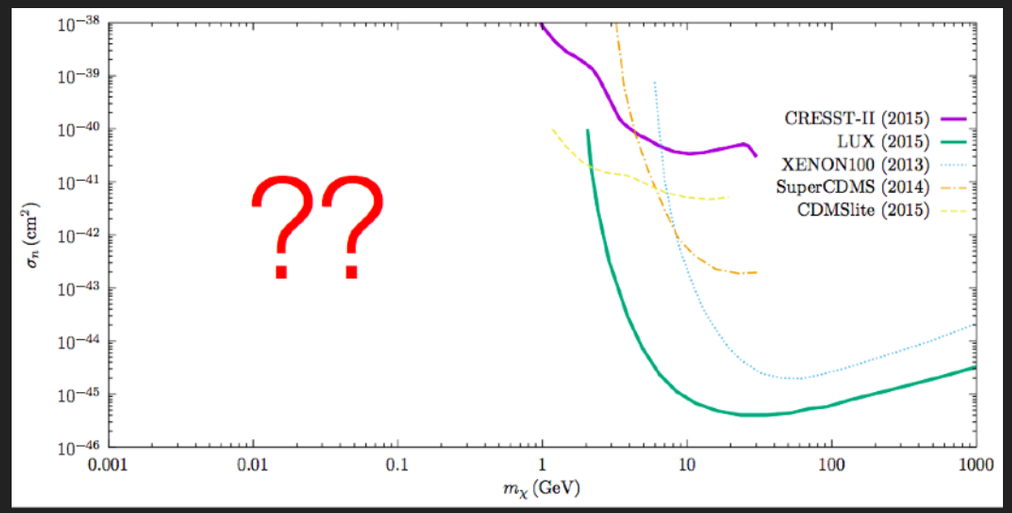
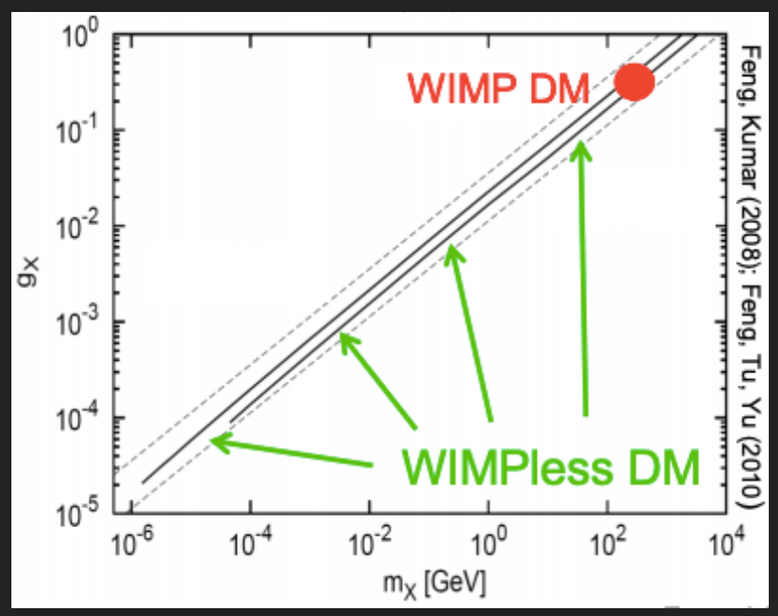


image credit: Josef Pradler

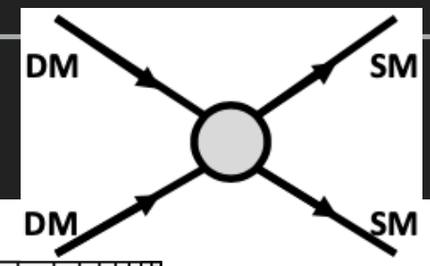


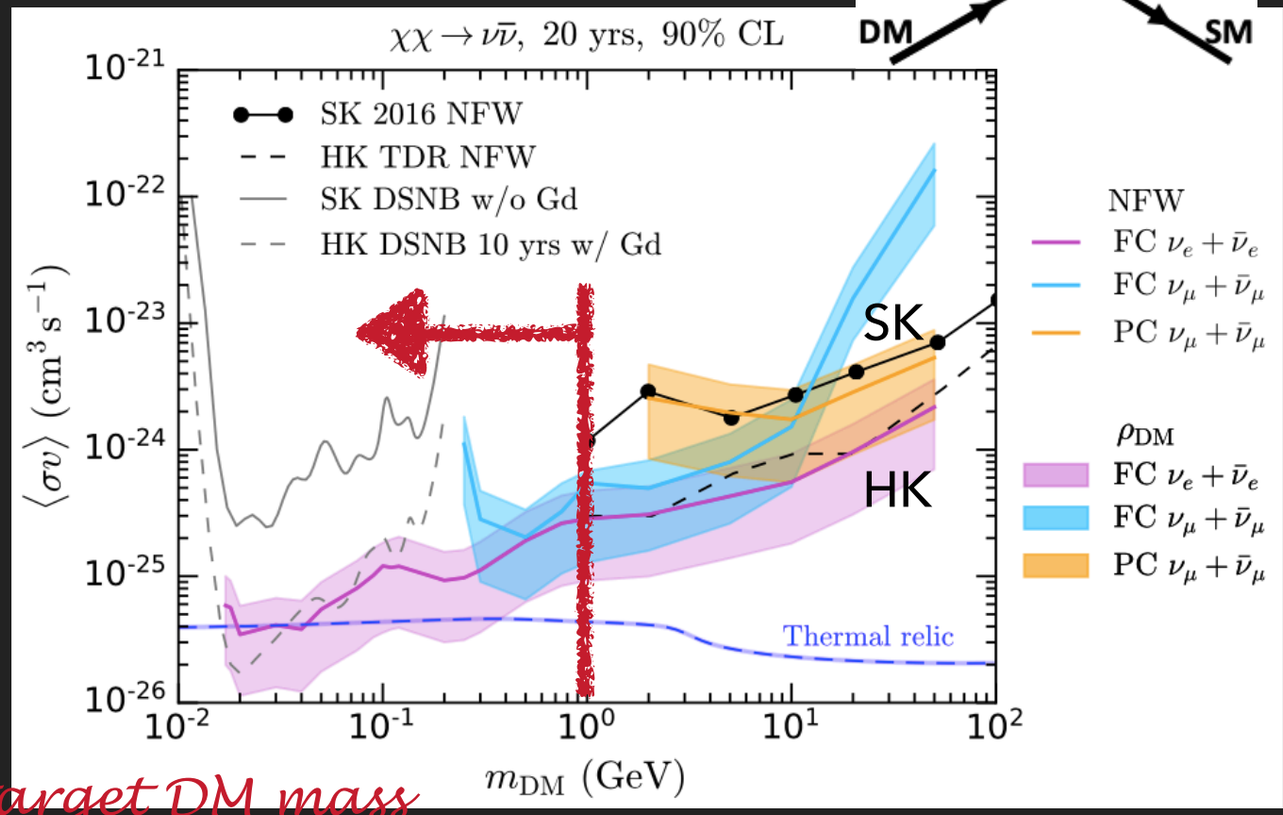
- However,
  Sub-GeV DM can also be a minimal thermal relic candidate &
  comes from wider modelings

- Current efforts in direct detection to detect sub-GeV signal (CRESST, DAMIC, SENSEI, CDMS, …)

SUB-GEV GALACTIC DARK MATTER SEARCH

- Sub-GeV dark matter annihilation from the Galactic Center & Halo
- Neutrino portal production scenarios
- use 20-yr SK low-energy data (<100MeV)
- neutron tagging in SK-Gd will help reducing IBD background





target DM mass region below 1 GeV N. F. Bell et al, arxiv:2005.01950

SK expected to be close to examine thermal relic scenarios for ~20 MeV DM (or at least prove HK can do so)

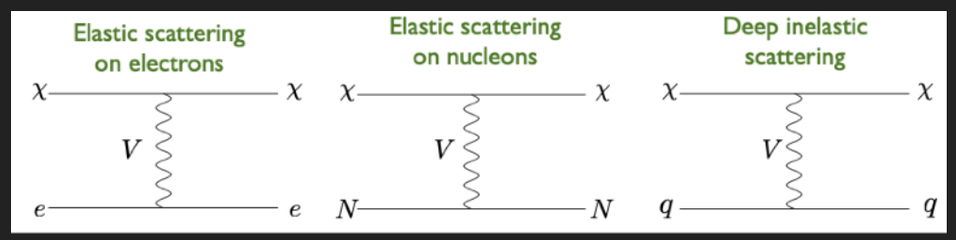
NEW STRATEGY: BOOSTED DARK MATTER (BDM)

Agashe et al., arxiv:1405.7370

Experiment	Volume (MTon)	$E_e^{\rm thresh}$ (GeV)	$\theta_e^{\rm res}$ (degree)	Refs.
Super-K	2.24×10^{-2}	0.01	3°	[69]
Hyper-K	0.56	0.01	3°	[81]
IceCube	10^3	100	30°	[82, 83]
PINGU	0.5	1	23°(at GeV scale)	[8]
MICA	5	0.01	30°(at 10 MeV scale)	[9, 84]

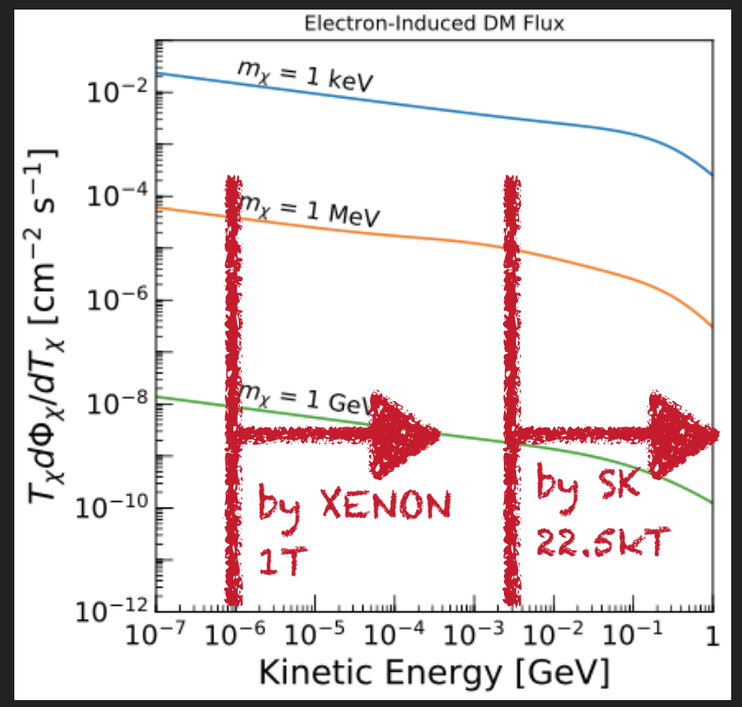
SK experimental threshold is ~3.5MeV for electron scattering (100GeV is HE analysis threshold)

- Too high energy threshold for thermal DM detection can be overcome if a boosting mechanism exists -> direct detection possible



- Usually Sees the high tail of the boosted DM spectrum - often examine same DM scenario with direct detection experiments - complementary observations

smaller signal acceptance of neutrino detector can be overcome by size (as always)

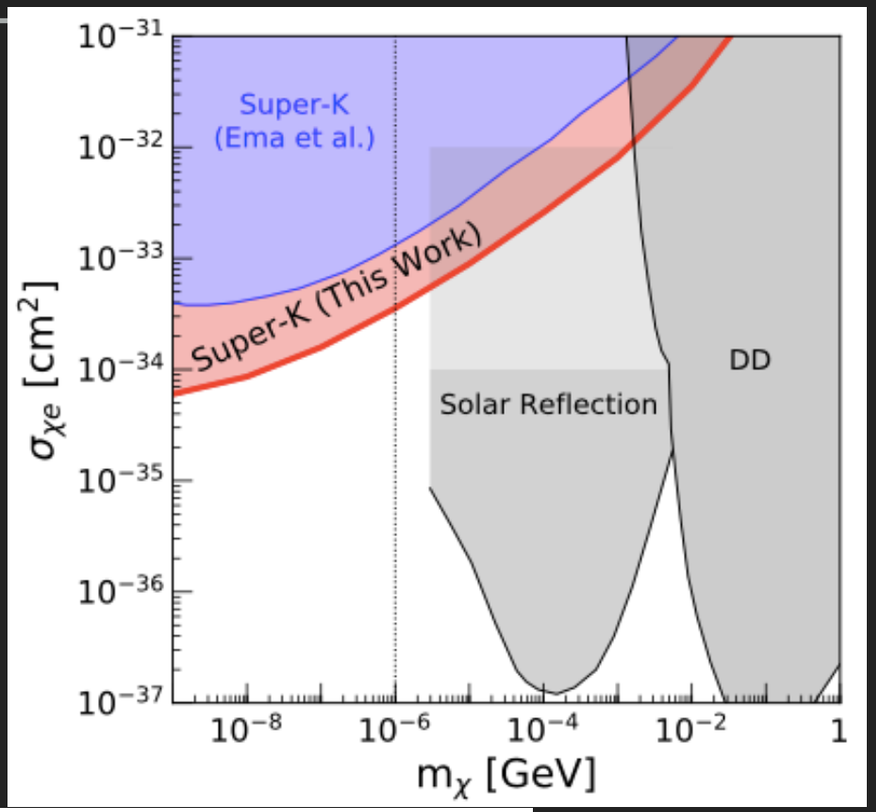


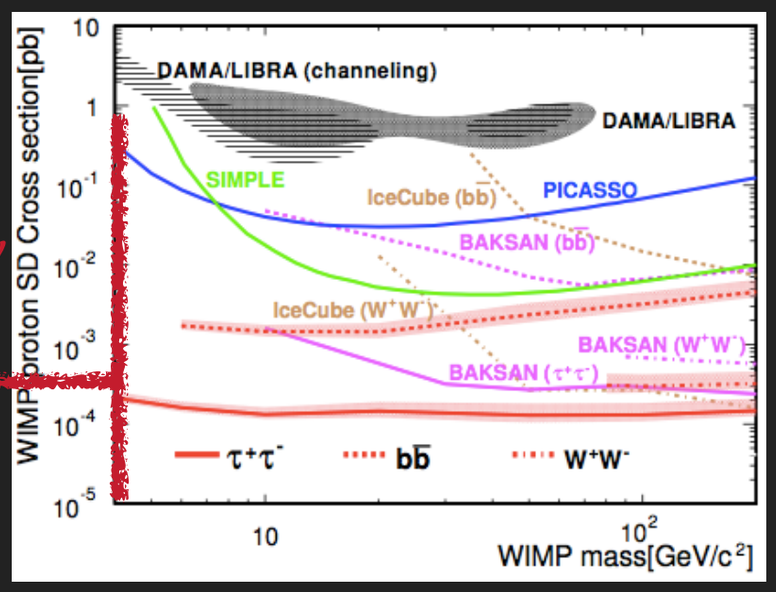
boosted spectrum by DM-electron scattering

Cappiello et al., arxiv:1906.11283

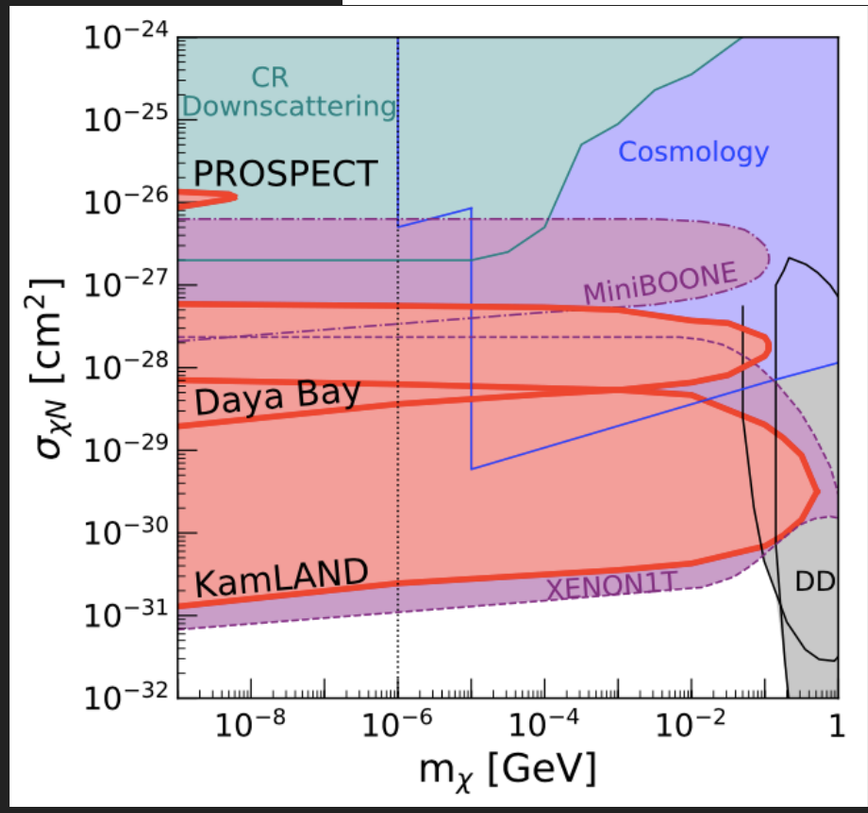
COSMIC-RAY BOOSTED DM SEARCH

- Cosmic rays can hit abundant DM and accelerate towards the Earth
- For X-p scattering, Minimal thermal relic scenario can be tested for new mass region (below 4 GeV)
  - Proton recoil Cherenkov threshold ~ 1.07 GeV narrows down the signal region & reconstruction of proton track is challenging (SK, arxiv:0901.1645)
  - Oxygen Neutral Current detection efficiency can be enhanced by SK-Gd neutron tagging





new target below 4 GeV

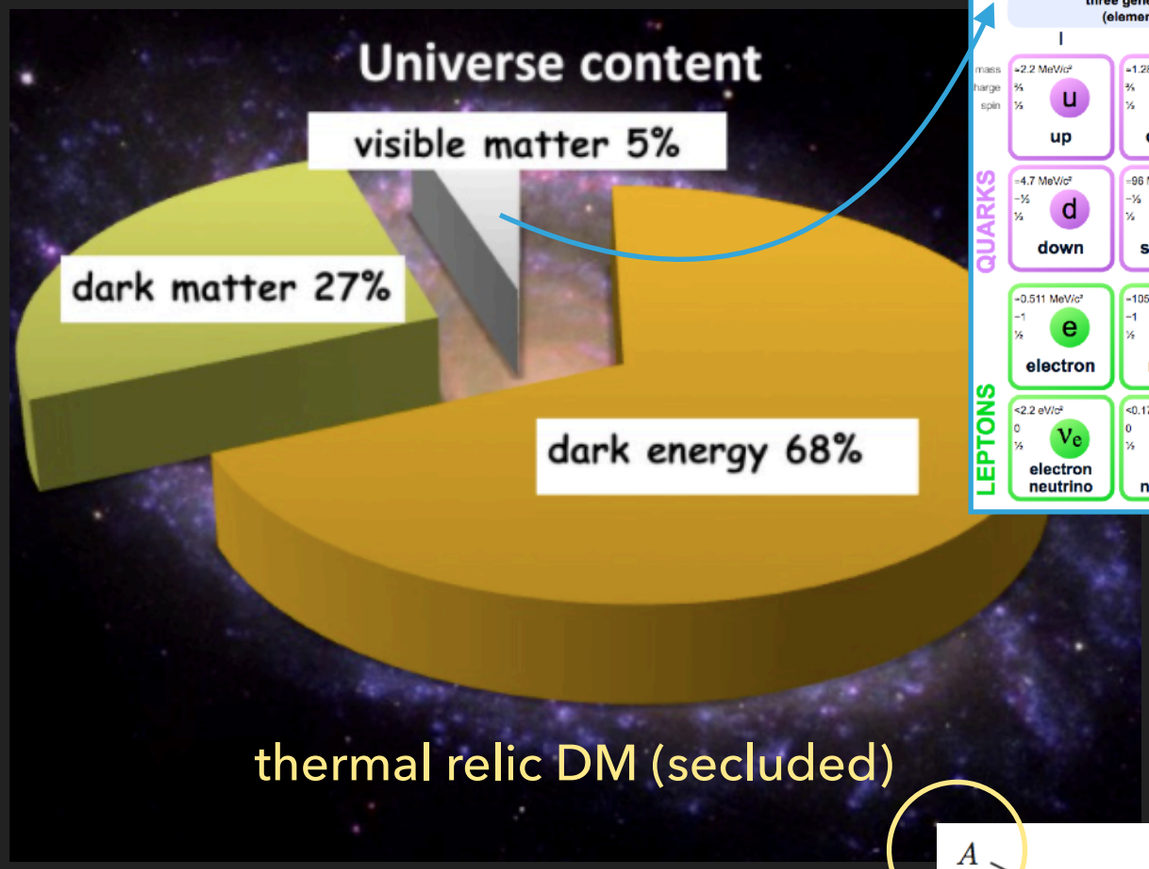


Cappiello et al., arxiv:1906.11283

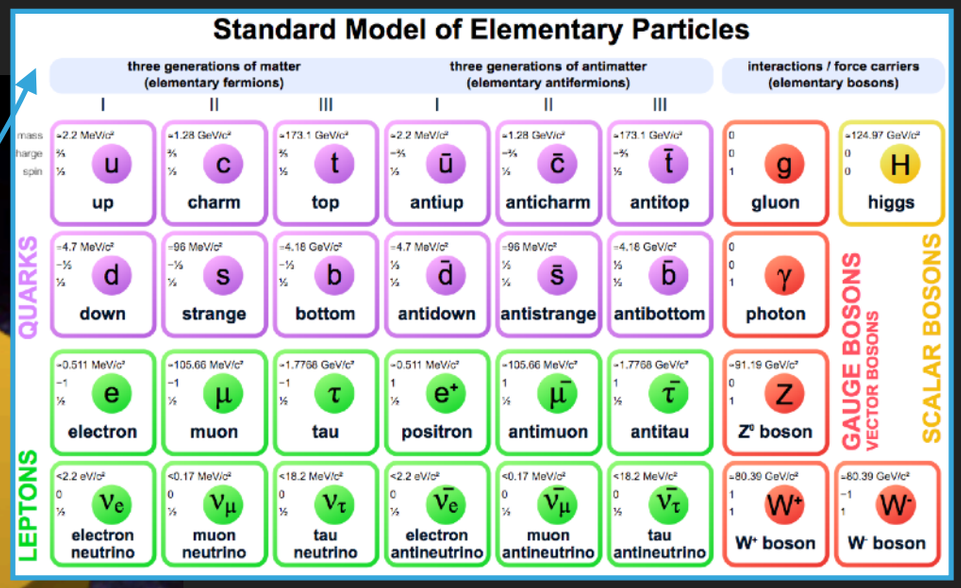
TWO-COMPONENT (NATURALLY BOOSTED) DARK MATTER SEARCH

IS IT NATURAL TO ASSUME SINGLE-COMPONENT DARK MATTER?

image credit Wikipedia

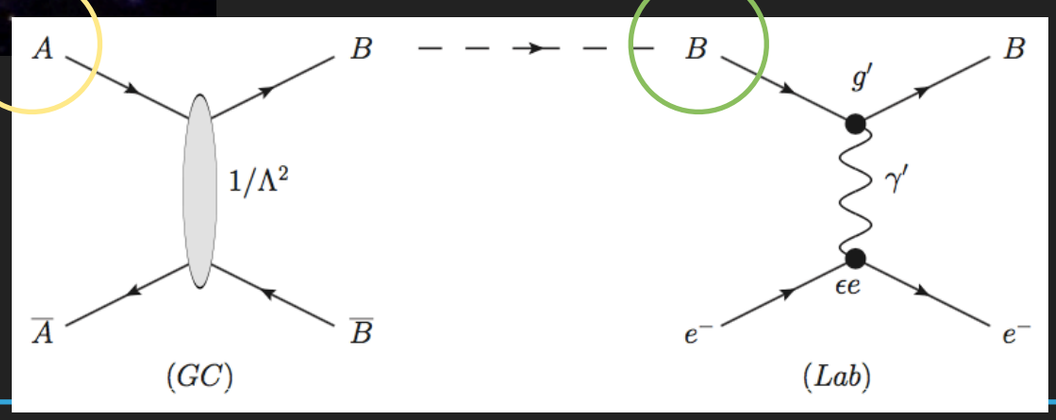


thermal relic DM (secluded)

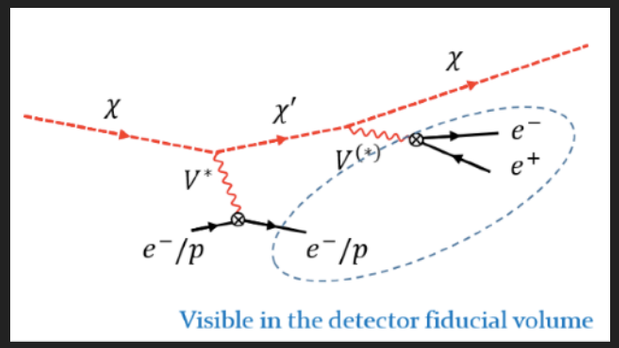


- In addition to DM at rest, there can be DM component with more energetic spectrum
- insight: sometimes it's easier to find "friend" of DM than DM itself (Agashe et al., arxiv:1405.7370)

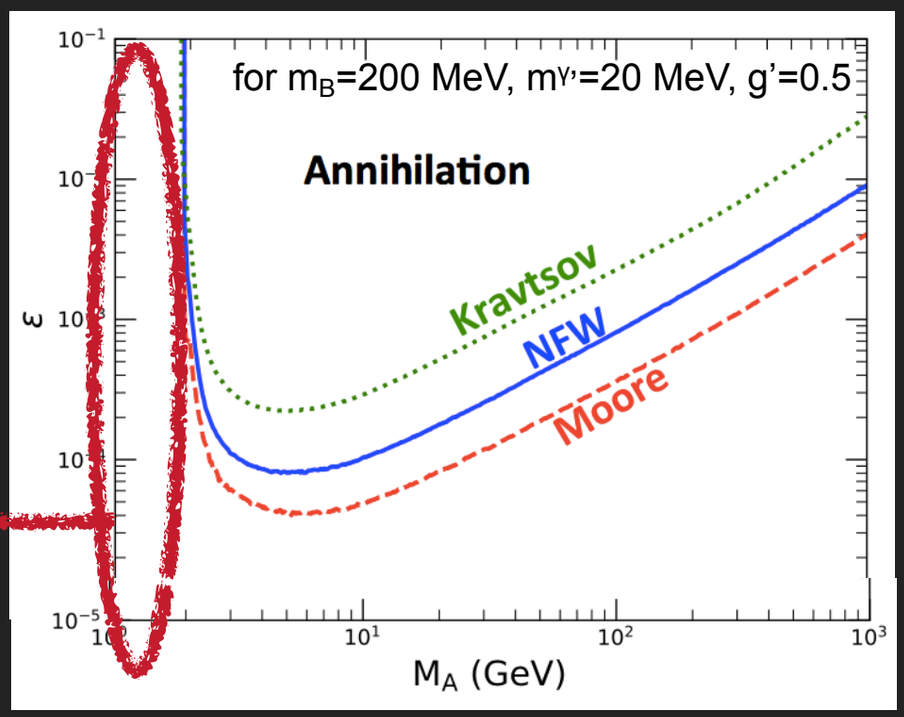
friend (detectable)



ELASTIC SIGNAL

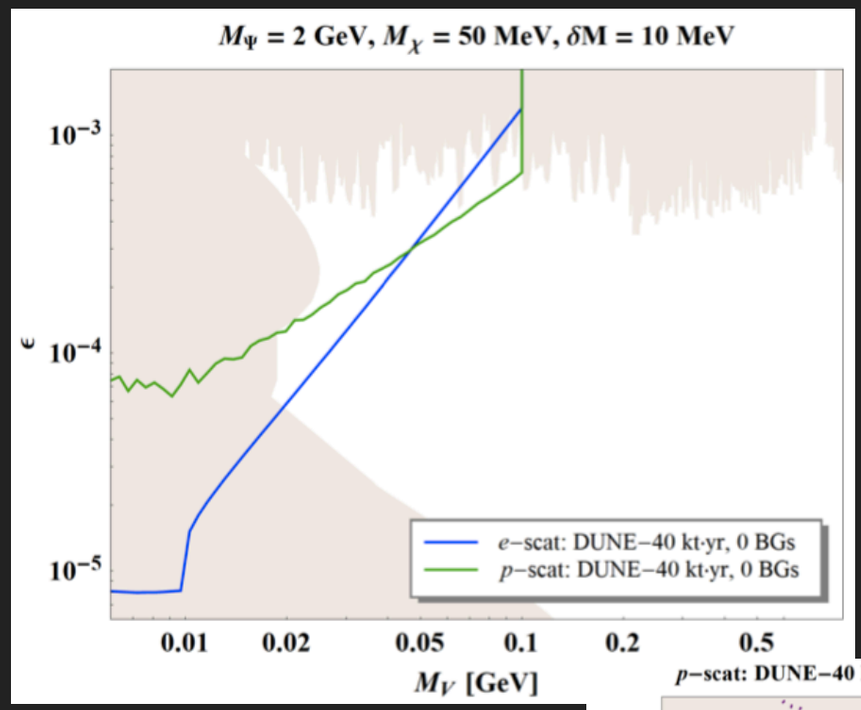


INELASTIC SIGNAL

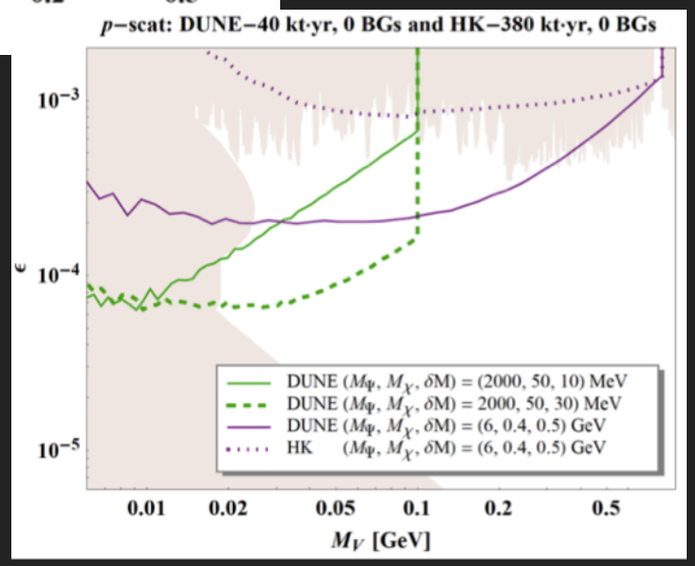


C. Kachulis for the Super-Kamiokande, Phys.Rev.Lett. 120 (2018) no.22, 221301

- Previous SK analysis done using the data above 100MeV
  - Adding low-energy (O(10) - 100MeV) data will allow to examine new (lower mass) parameter space and enhance sensitivity of existing limit

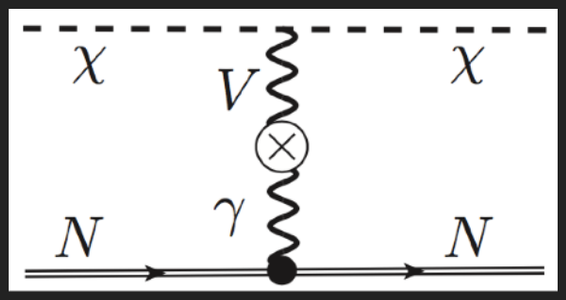


- DUNE threshold: 30MeV for p/e
- Good track separation



DUNE sensitivity, arxiv:2008.12769

DARK MATTER BEAM FROM INVISIBLE DECAY OF DARK PHOTON



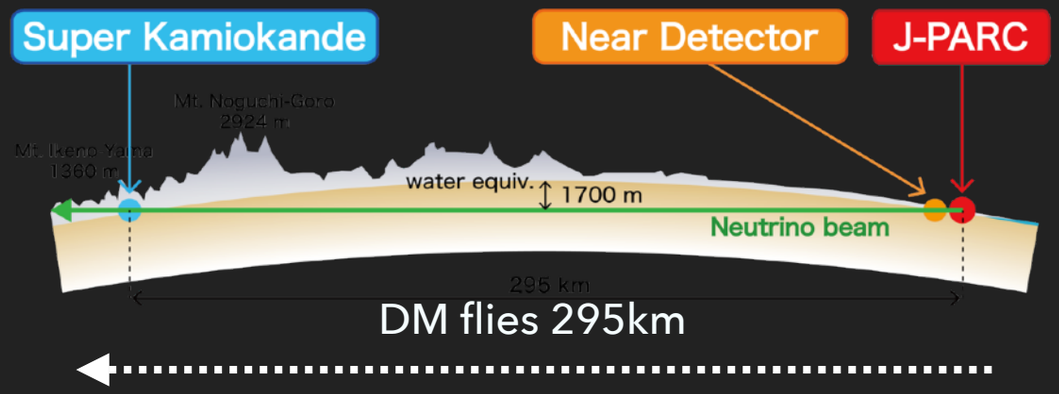
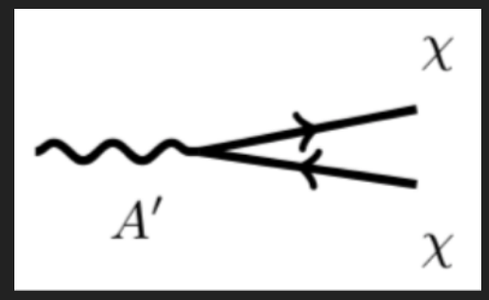
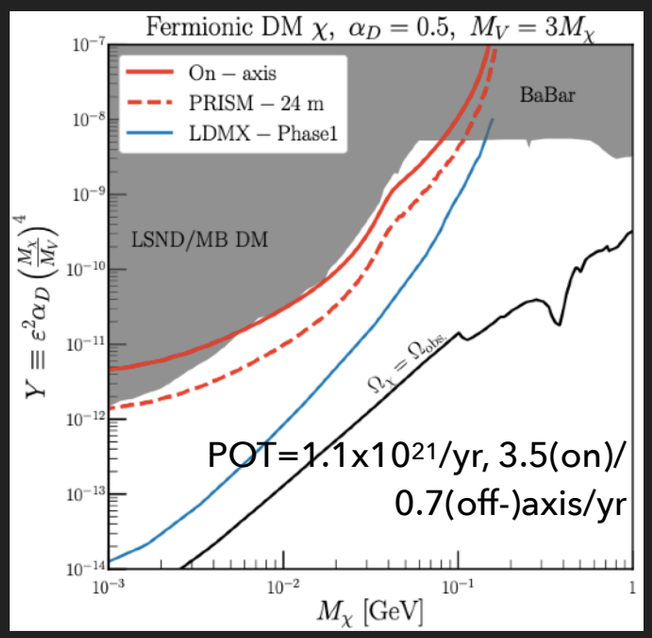


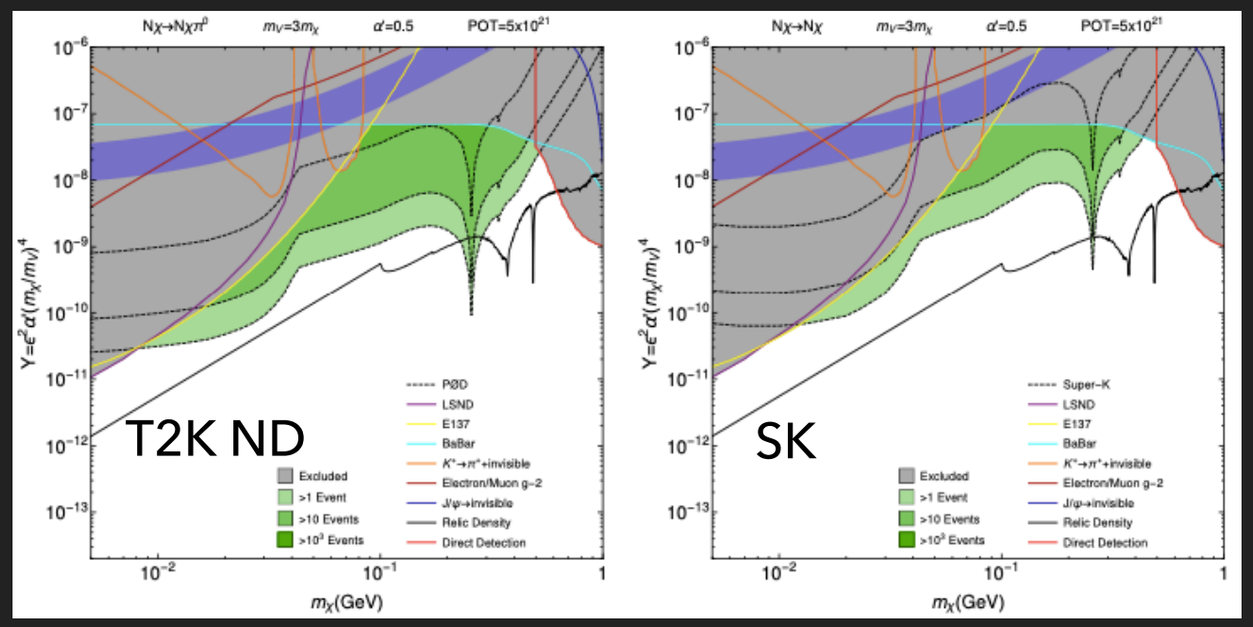
image credit www.ppd.stfc.ac.uk



- Directional search for DM produced by dark photon decay in J-PARC proton beam
- 2.5° off-axis, 295km distance
- Background reduction by time delay of DM beam to neutrino beam, different E spectrum
- Oxygen Neutral Current detection efficiency can be enhanced by SK-Gd neutron tagging

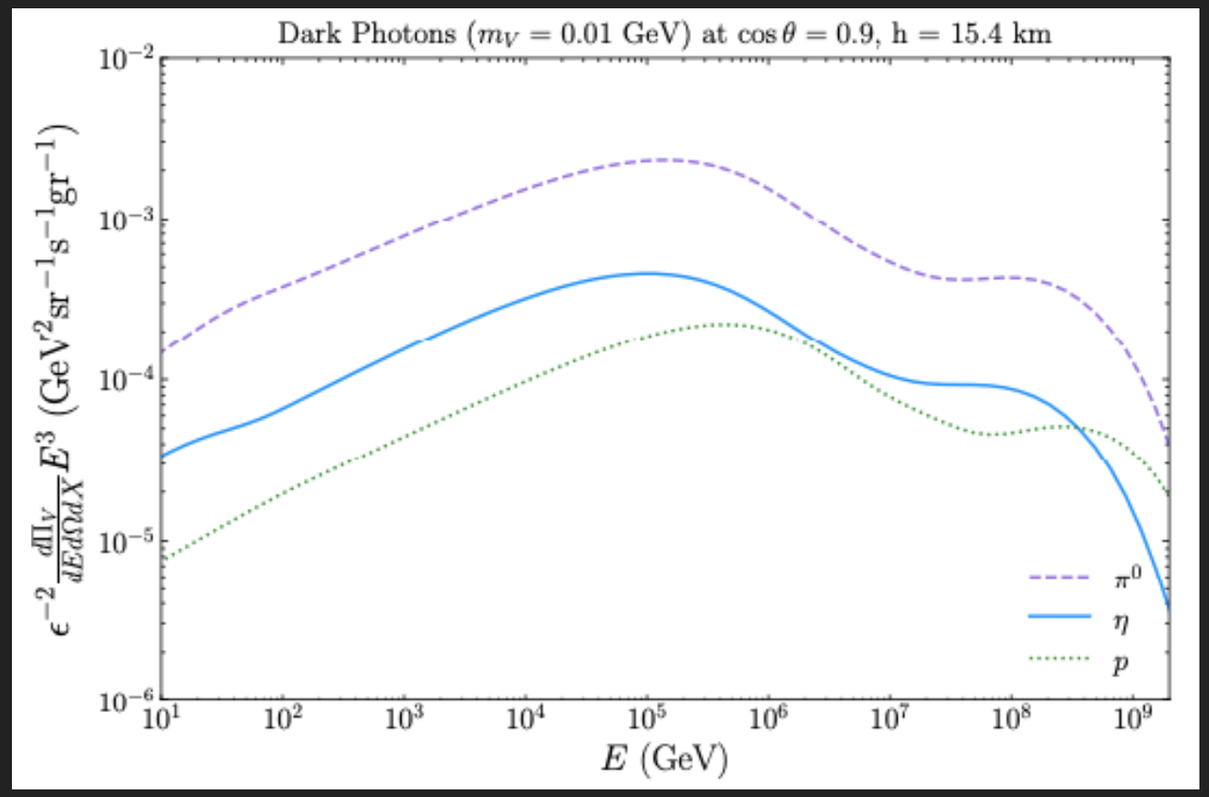


DUNE sensitivity, arxiv:2008.12769

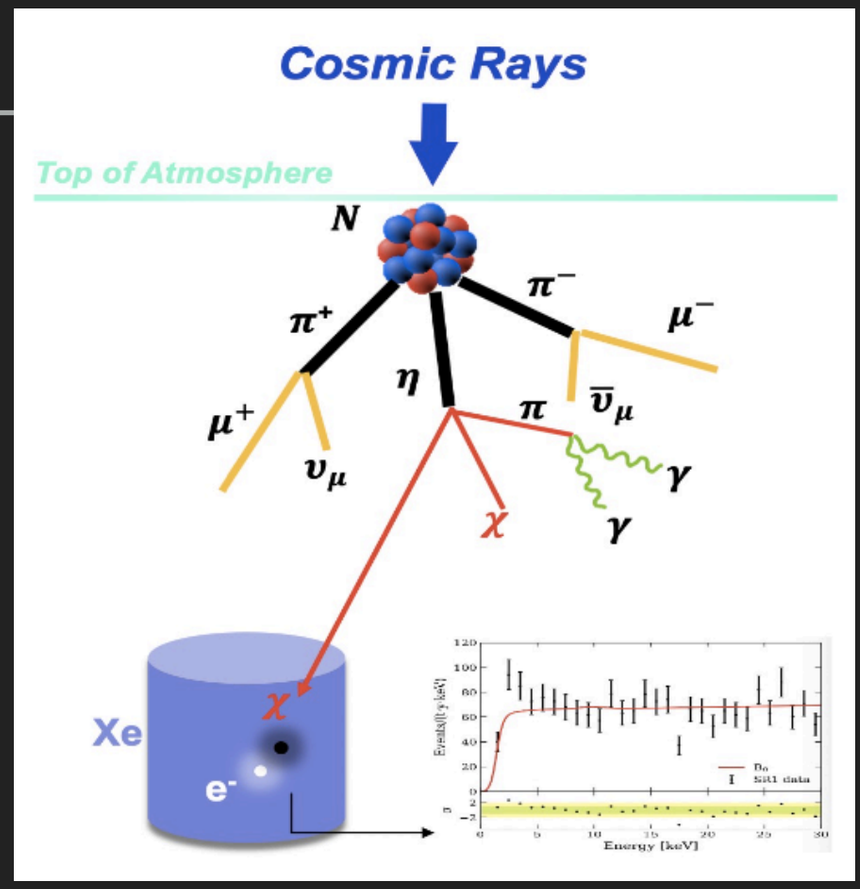


deNiverville et al, arxiv:1609.01770

DARK MATTER PRODUCTION IN AIR SHOWER



Argüelles et al., arxiv:1910.12839

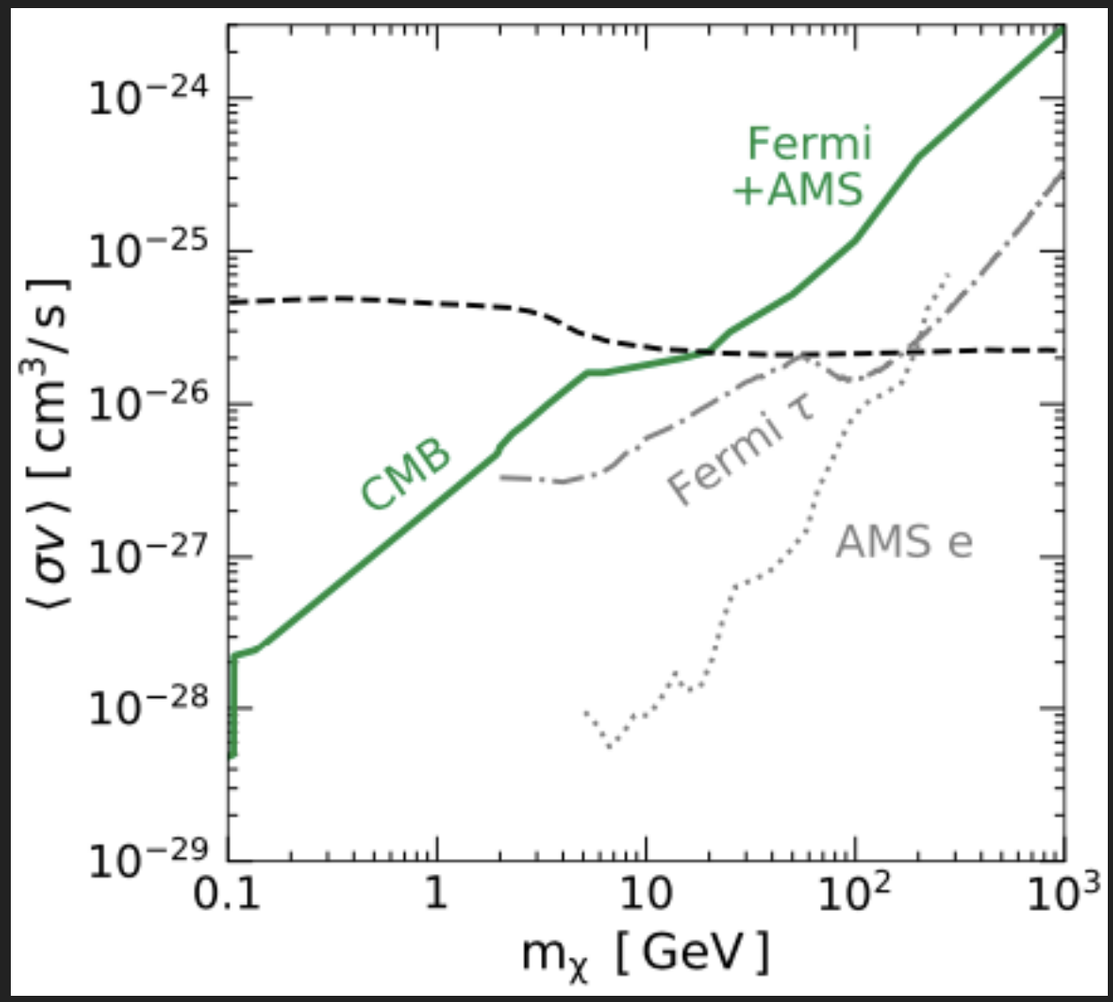


Su et al., arxiv:2006.11837

- How we discovered friendly particles in early days
- Cosmic-ray air shower can produce dark mediator such as dark photon, visible/ invisible decay products can be detected in the neutrino detector
- Dark photon production from meson decays is already severely constraint -> go beyond simple vector portal (arxiv:1910.12849, 1905.05776, 2006.11837, …)

WIMP IS NOT DEAD

- GeV-scale thermal WIMPs: Not even slightly ruled out (Leane et al, arxiv:1805.10305)
- Neutrino detectors will keep an effort in the GeV-TeV mass scale
- New search ideas, Be prepared for discovery (how to extract DM property, treat astrophysical uncertainty, model-independent analysis, …)



(Leane et al., arxiv:1805.10305)

SUMMARY

- Neutrino detector with sub-GeV threshold has a great potential for sub-GeV DM searches in both direct & indirect detections (GeV-TeV search still important)
- With 20-year data of SK, using the low-energy data (<100MeV) for DM searches for the first time, world-leading results are foreseen
- Multi-disciplinary DM searches collaborating with cosmic-ray, particle accelerator, theory, …
- Results can be extrapolated to bigger volume; can highlight future neutrino experiments (i.e. HK, KNO, DUNE, …) as multipurpose detector

THANK YOU FOR LISTENING