Dark Matter Searches

with Water Cherenkov Experiments

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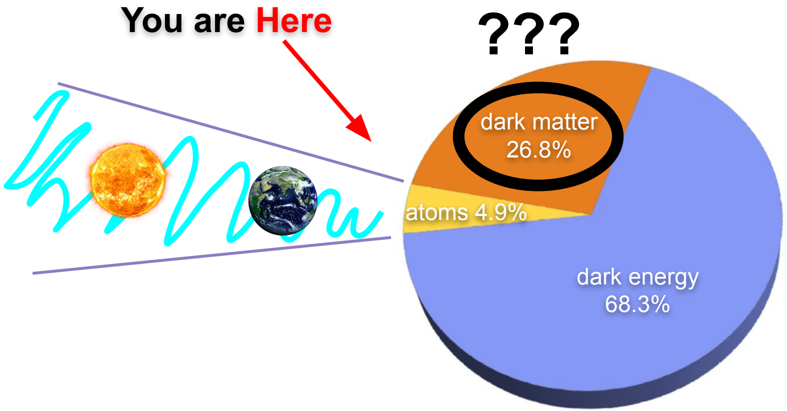
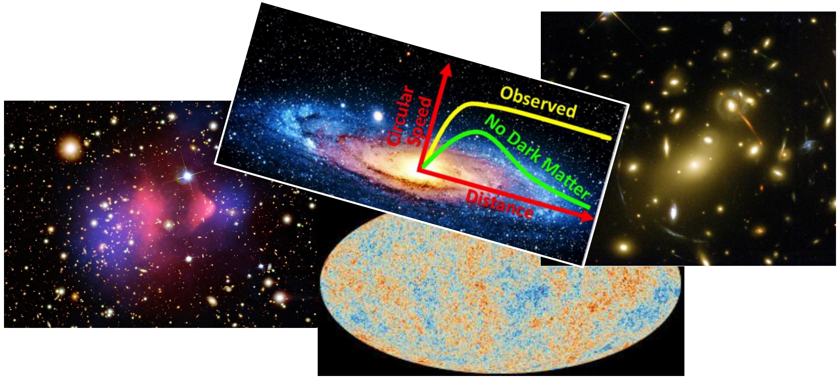
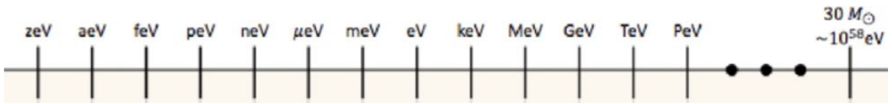
What is the Universe Made of? What's Dark Matter (DM)?





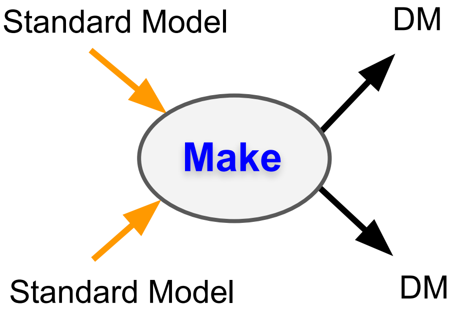


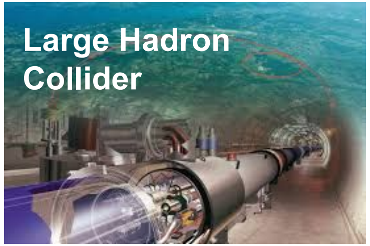
- ***All evidence astronomical***
- What is the origin? type and mass of particle(s)? interactions beyond gravity? …

→ **Myriad of possibilities:** ***Delve Deep, Search Wide*** (Snowmass-2021)

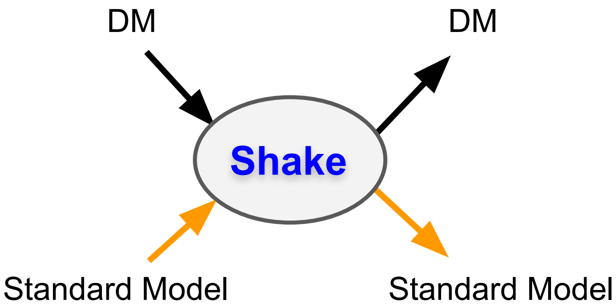
Traditional DM Searches: “Make, Shake, Break”

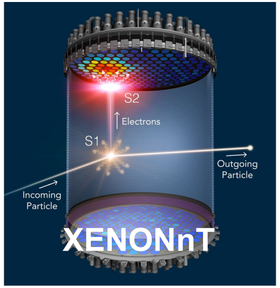
Production



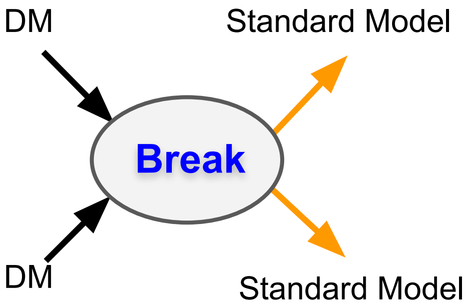


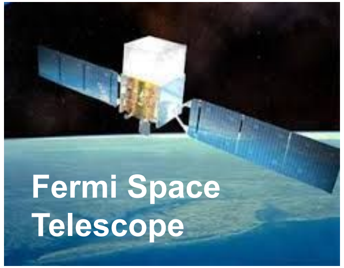
Direct Detection



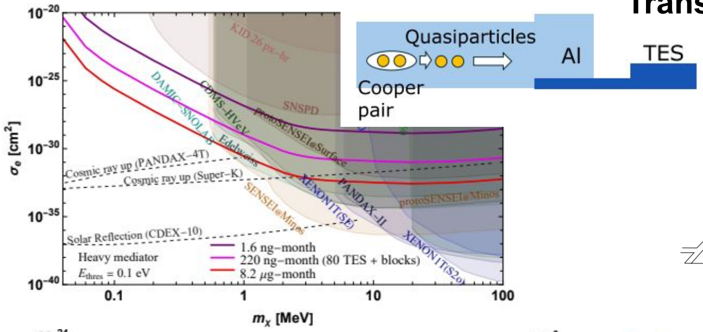


Indirect Detection



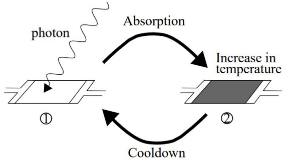


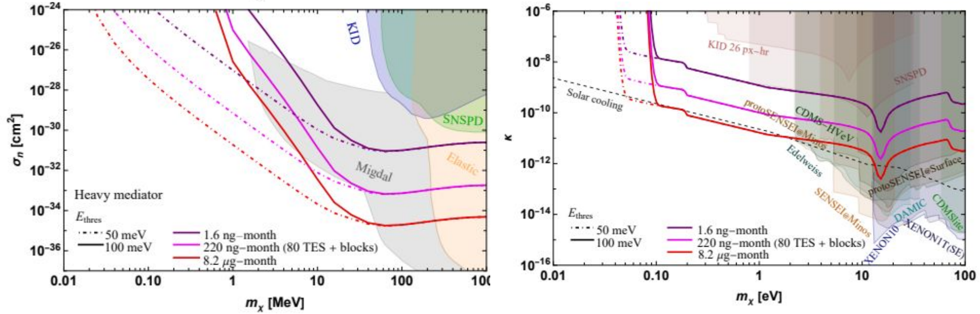
Many New Tech Ideas, Example: Sub-eV Quantum Sensors @ Kamioka



Transition-Edge Sensors (TES)

~0.1 eV TES threshold achieved in lab [Hattori+, 2022]





QUP-Kamioka DM Cryolab

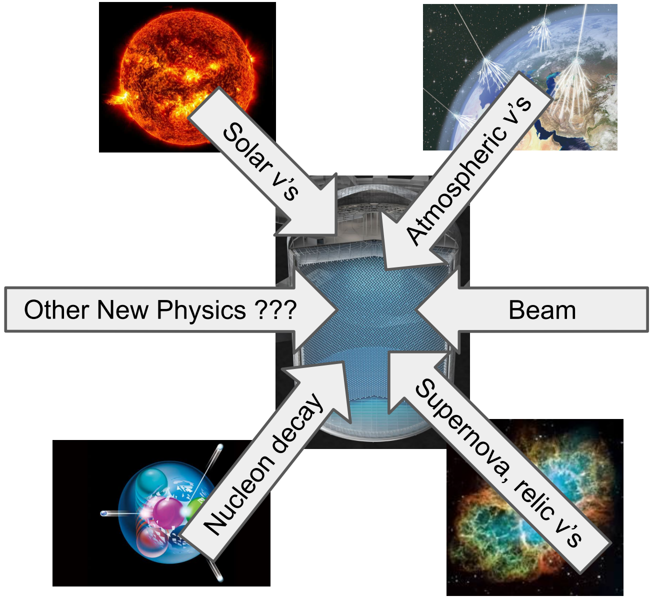
(partnership with Tohoku U. RCNS,
+ collab. LBNL, MIT …)

multiple upcoming experiments

- TES show excellent sensitivity for low-mass DM searches, sub-eV thresholds feasible
  → probe new parameter space w/ quantum sensors, multiple upcoming QUP experiments

[Chen, Takhistov, Nakayama, Hattori, (2025) 2506.10070]

Water Cherenkov (WC) Experiments as DM Discovery Machines

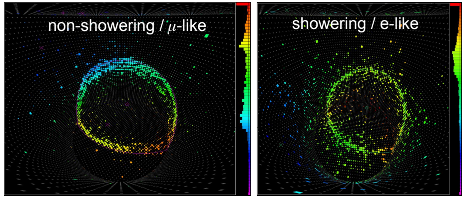


- **Super-K/SK (~50 kt):** >25 years of operation, leading neutrino physics and DM limits
- **Hyper-K/HK (~260 kt):** x8.4 SK fiducial mass, start 2028

→ ***spectacular multipurpose experiments***

- <u>Advantages of WC detectors for DM searches:</u>
  - Huge exposure compared to conventional direct DM detection, multi-megaton*year feasible
  - Low possible detection thresholds to ~ O(few x MeV)
  - Directional capabilities
  - Broad coverage of signatures

    → probe wide range of DM theories



Broad DM Program in WC Detectors: Selected Highlights

Dark Matter	Dark Matter Mass	(Super) Hyper-Kamiokande Signatures
PBH evaporation to ν (GC, halo)	$M_{\rm PBH} \lesssim 10^{15}$ g	ν scattering, diffuse ν background
Q-ball DM (catalysis)	$M_Q \gtrsim 10^{12} - 10^{16}$ GeV	catalyzed nucleon decay
Baryon-charged DM (e.g. hylogenesis)	$m_\chi \sim$ GeV–TeV	scattering-induced nucleon decay
DM annihilation (GC)	$m_\chi \sim 10$ MeV–100 GeV	ν scattering
DM annihilation (Earth, Sun, Jupiter capture)	$m_\chi \sim 1$ –10^3 GeV	ν scattering
Cosmic-ray upscattered (boosted) DM	$m_\chi \sim$ MeV–GeV	ν scattering
Millicharged DM (dark cosmic rays)	$m_\chi \sim 1$–10^3 GeV	ionization, ν-like e-scattering
Dark stars (powered by DM annihilation)	$m_\chi \sim 1$–10^5 GeV	energetic diffuse ν background

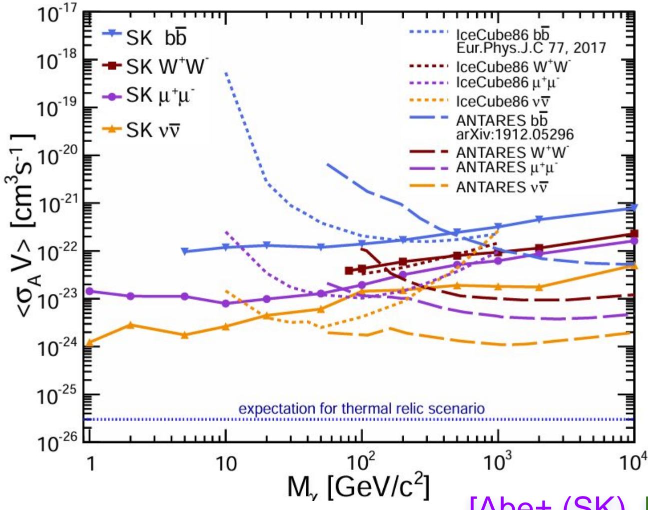
Galactic Center DM Annihilation

- For DM signals look where large DM concentration, prime is Galactic Center
- WIMP DM annihilation: $\chi\chi \rightarrow \nu\bar{\nu}, W^{+}W^{-}, b\bar{b}, \mu^{+}\mu^{-} \rightarrow ...\nu_{e/\mu/\tau}$

$$\frac{d\Phi_\nu}{dE} = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \frac{dN_\nu}{dE} J$$

$$J = \int_{\text{l.o.s.}} \rho_\chi^2(r)\, dr$$

J-factor



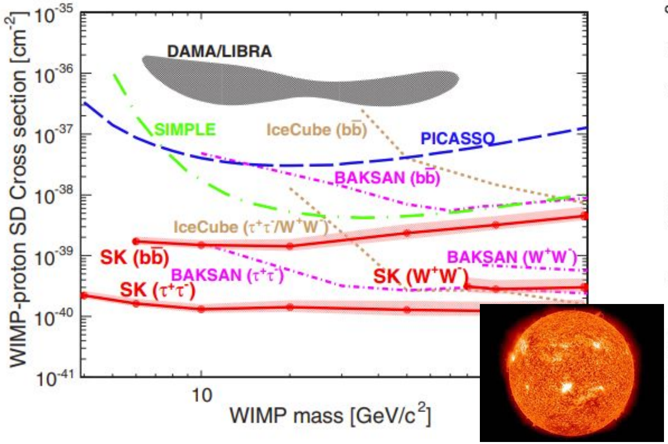
[Abe+ (SK), PRD '20]

- HK will improve over SK by factor x(few) for variety of channels, excellent sub-GeV DM reach e.g. [Bell+, 2020; ...], [Hernandez, Ramos, Martinez-Soler, Takhistov, in prep]

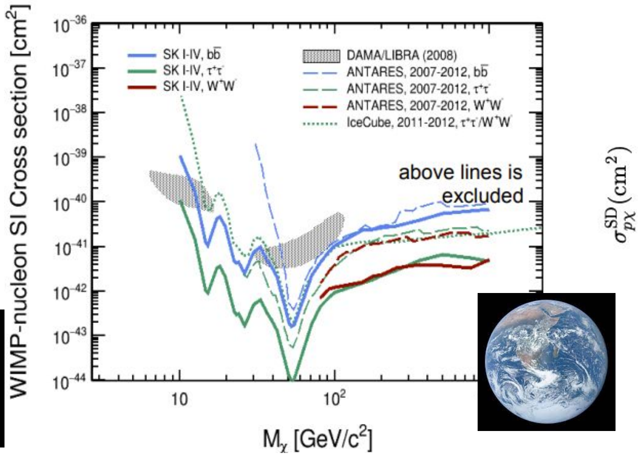
DM Capture and Annihilation in Celestial Bodies

- Halo DM can be captured by celestial bodies through interactions, observable signals then depend on capture–annihilation–evaporation dynamics (temperature, composition, grav.)

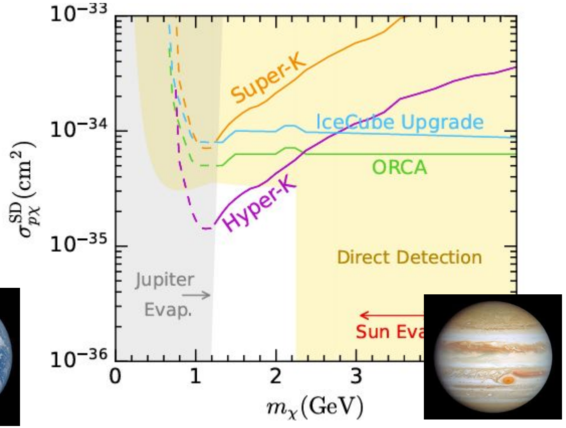
$$\Gamma_{\rm capt} \propto \sigma_{\rm scattering}\, \rho_{\rm DM}$$



[Choi+ (SK), PRL, (2015)]



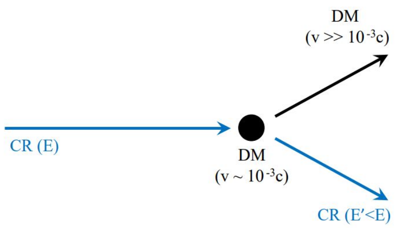
[Frankiewicz (SK), PhD Thesis, (2018)]

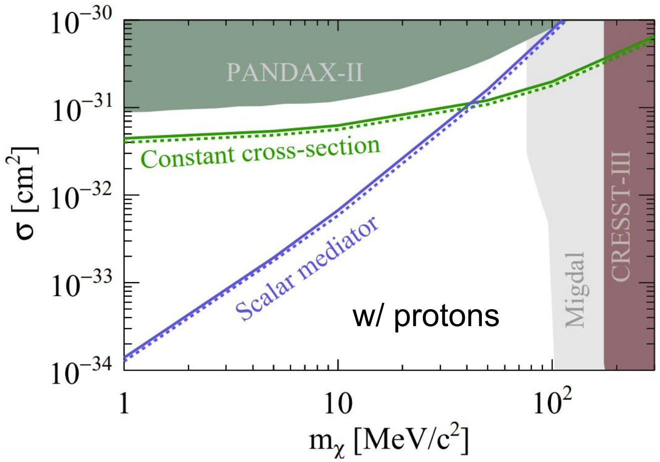


[Robles, Meighen-Berger, 2025]

Boosted DM and Cosmic-Ray Upscattering

- Cold DM (v ~ 10^{-3}) can be "boosted" to relativistic energies, probe new distinct regimes
- Prominent examples include
  - Galactic Center decays of heavy DM → light boosted DM [Agashe+, 2014]
  - Cosmic-ray DM upscattering [Beacom+, 2019; Pospelov+, 2019; ...]





DM Interaction with protons
→ same interaction in detector

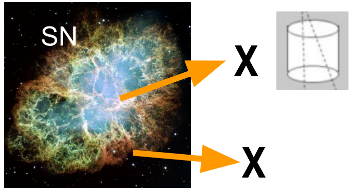
[Abe+ (SK), PRL, 2023]

- Various possibilities, such as blazar-boosted DM (assume DM "spike") [Granelli+, 2022]

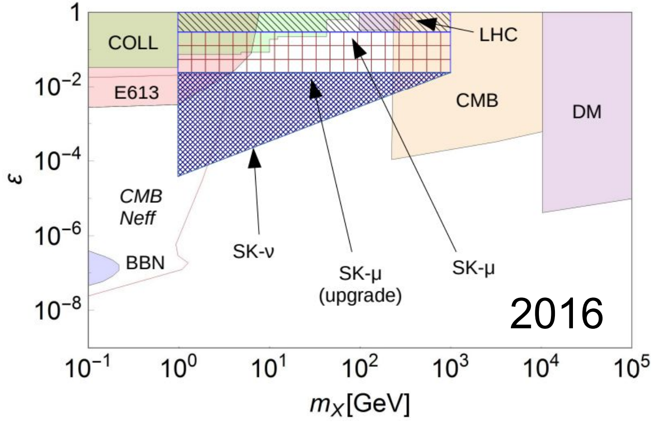
Millicharge DM and Dark Cosmic Rays

- DM with small (milli)charge can be accelerated in cosmic accelerators like cosmic rays
- First proposal to re-use DSNB analysis range for DM searches, many follow ups

cosmic accelerator



"astrophysical" DM flux $\sim E^{-\alpha}$



$\varepsilon \sim 1$ *muon-like*

$\varepsilon \ll 1$ *neutrino-like*

[Hu, Kusenko, Takhistov, PLB, (2016)] (also later [Dunsky+, 2019; Li, Lin, 2019])

*** *Can probe millicharges at SK/HK also from atmospheric collisions* [Plestid, Takhistov+, PRD, (2020)]

Macroscopic DM: Q-balls Catalyzing Nucleon Decay

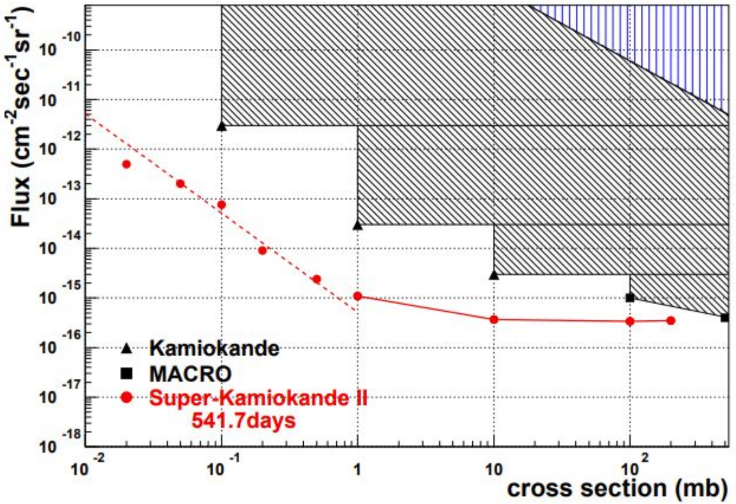
- Q-ball solitons can form naturally from scalar field instabilities in e.g. supersymmetric models
- If Q-balls carry baryon number (B), can catalyze nucleon decay–like events in exp., SK/HK

mass-radius relation depends on theory (potential), for gauge-mediated SUSY

$$M_Q = \frac{4\pi\sqrt{2}}{3} M_S Q^{\frac{3}{4}}$$

$$R_Q = \frac{1}{\sqrt{2}} {M_S}^{-1} Q^{\frac{1}{4}}$$

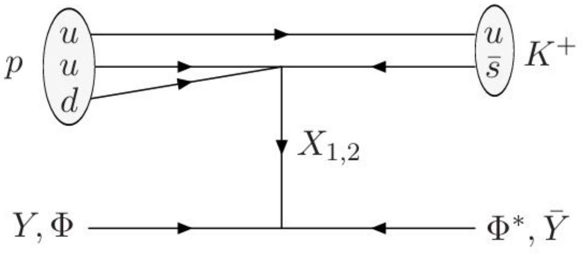
Q-ball DM flux ~ $\Phi_Q \sim \frac{\rho_{\rm DM}}{M_Q} v$



[Takenaga+ (SK), *PLB*, (2007)]

DM with Baryon (B) Charge

- DM with (anti-)B charge can naturally link visible and dark sectors
- Hylogenesis: DM carries B, visible and dark baryon asymmetries generated together
- DM can interact in detector and induce nucleon decays, with distinct kinematics



$$m_\Phi, m_Y \sim \text{few} \times \text{GeV}$$

Decay mode	$p_M^{\rm SND}$ (MeV)	$p_M^{\rm IND}$ (MeV)
$N \to \pi$	460	800 - 1400
$N \to K$	340	680 - 1360
$N \to \eta$	310	650 - 1340

[Davoudiasl+, PRL, 2010]

- Various other related proposals, e.g. mesogenesis: DM coupled to mesons and baryon asymmetry arises via baryon–meson–DM interactions [Berger, Ely, PRL, 2024]

New Broad Program of Non-Canonical Nucleon Decays

Test light new physics: axions, dark photons, sterile ν's, scalar DM …

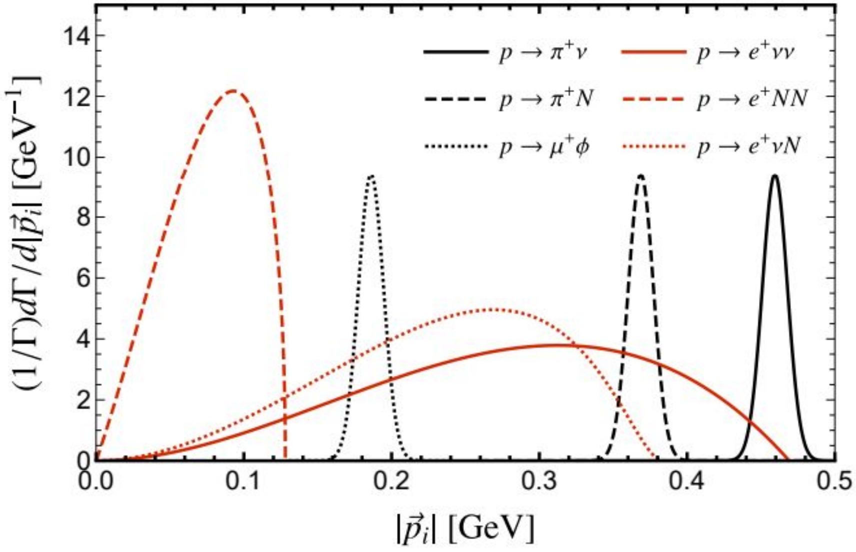
$\mathcal{O}$	Operator	$(\Delta B, \Delta L)$	Dim	Decay modes	New Field(s)
$\mathcal{O}_{d^2uN}$	$\epsilon^{abc}\,(d_a N)\,(d_b u_c)$	$(1,1)$	6	$p(n) \to \pi^{+(0)} N$	sterile neutrinos
$\mathcal{O}_{Dd^2u\bar{N}}$	$\epsilon^{abc}\,(d_a \sigma_\mu N^\dagger)\,(d_b D^\mu u_c)$	$(1,-1)$	7	$n \to N\gamma$ $p(n) \to \pi^{+(0)} N\gamma$	sterile neutrinos
$\mathcal{O}_{du^2e\phi}$	$\epsilon^{abc}\,(d_a u_b)\,(e u_c)\,\phi^\dagger$	$(1,1)$	7	$p \to e^+\phi$ $p(n) \to e^+\pi^{0(-)}\phi$	dark scalars, majorons
$\mathcal{O}_{d^2Q\bar{L}X}$	$\epsilon^{abc}\,(Q_a^i \sigma^\mu d_b)\,(d_c L_i^\dagger) X_\mu$	$(1,1)$	7	$n \to \nu X$ $p(n) \to \nu\pi^{+(0)} X$ $n \to e^+\pi^- X$	dark photons
$\mathcal{O}_{dQ^2\bar{L}\bar{H}\phi}$	$\epsilon^{abc}\,(Q_a^i Q_b^j)\,(L^\dagger{}_i d_c)\,H_j^\dagger \phi^\dagger$	$(1,1)$	8	$n \to \nu\phi$ $n \to e^+\pi^-\phi$	dark scalars, majorons
$\mathcal{O}_{Dd^2Q\bar{L}a}$	$\epsilon^{abc}(\partial^\mu a)\,(Q_a^i \sigma^\mu d_b)\,(d_c L_i^\dagger)$	$(1,1)$	8	$n \to \nu a$ $p(n) \to e^+\pi^{0(-)} a$ $p(n) \to e^+\pi^{0(-)} a$	axion-like particles
$\mathcal{O}_{Dd^2u\bar{N}a}$	$\epsilon^{abc}(\partial^\mu a)\,(d_a \sigma_\mu N^\dagger)\,(d_b u_c)$	$(1,-1)$	8	$n \to Na$ $p(n) \to \pi^{+(0)} Na$	axion-like particles with sterile neutrinos
$\mathcal{O}_{duQe\bar{L}\bar{N}}$	$\epsilon^{abc}\,(e u_a)\,(Q_b^i \sigma_\mu d_c)\,(N^\dagger \sigma^\mu L_i^\dagger)$	$(1,1)$	9	$p \to e^+\nu N$ $n \to e^+e^- N$	sterile neutrinos
$\mathcal{O}_{du^2eN^2}$	$\epsilon^{abc}\,(d_a u_b)\,(e u_c)\,(NN)$	$(1,3)$	9	$p \to e^+ NN$	sterile neutrino

** don't require external interactions like "induced" nucleon decays*

- Many novel possibilities mediated by motivated BSM particles
- Multi-nucleon decays possible
- Mixed scenarios possible (e.g. axion + sterile N, ν + dark photon → new minimal invisible mode)
- New tests of light new physics over decades in mass below ~ few GeV

[Fridell, Hati, Takhistov, PRD Lett. (2023), 2312.13740]

Unusual Kinematic Signatures, Many Opportunities



going beyond searches with just Standard Model final states

In SK thus far only: p → e(μ)X

[Takhistov+ (SK), PRL, (2015); + ongoing analysis]

Example: $m_N = 400$ MeV and dark scalar mass $m_\phi = 700$ MeV.

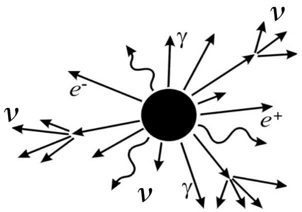
→ conventional searches can misinterpret or even completely miss

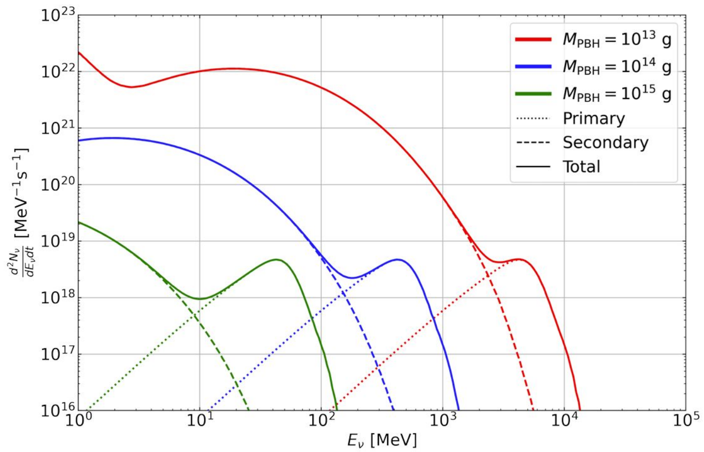
[Fridell, Hati, Takhistov, PRD Lett. (2023), 2312.13740]

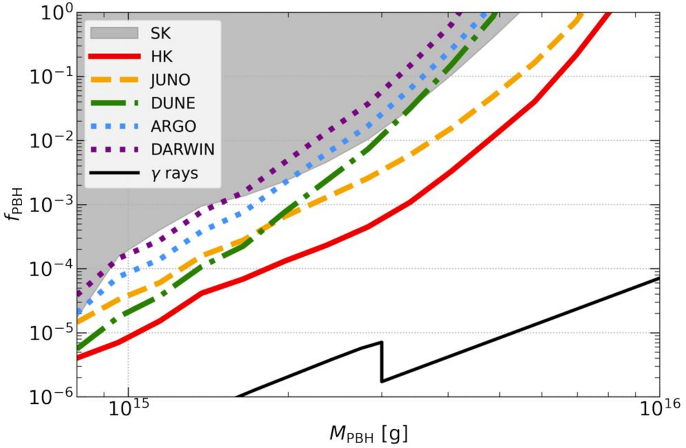
Evaporation of Primordial Black Hole (PBH) DM

- Black holes could have formed in early Universe and can contribute to DM
- PBHs $\lesssim 10^{15}$ g are efficiently undergoing Hawking evaporation today
- Neutrinos produced via primary, secondary emission
  → diffuse background and point-sources

$$T_{\rm PBH} \sim 1/M_{\rm PBH}$$



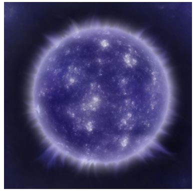




[Bernal+, 2022]

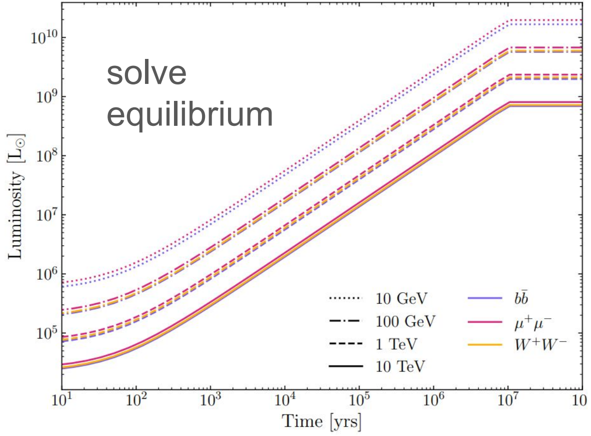
*** *Complementary to other PBH tests, e.g. interstellar gas heating* [Laha, Lu, Takhistov, PLB, 2021; Kim, 2020]

DM-powered Earliest (Dark) Stars

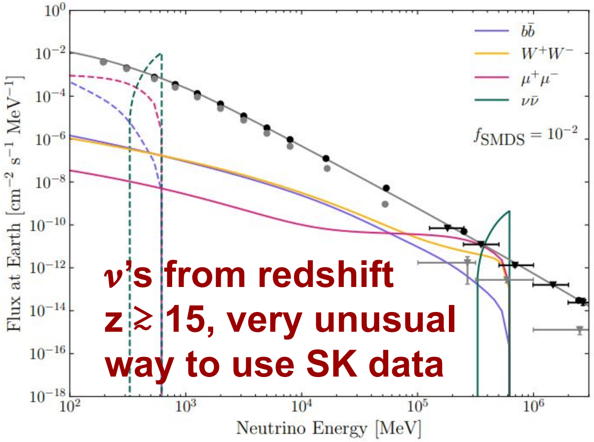


- Earliest stars could be "dark stars" fueled by DM annihilation heating instead of nuclear fusion [Spoylar, Freese, Gondolo, *PRL* (2008)]
- Dark stars can be significantly bigger ($\sim 10^6 M_\odot$) than Population III stars
- Upon collapse → early massive seeds for galactic supermassive black holes
- Possible candidates seen in JWST, redshifts z ~ 11-14 ? [Ilie, Paulin, Freese, *PNAS* (2023)]

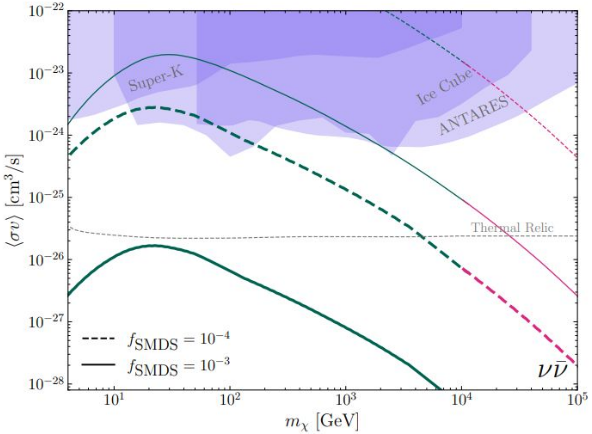
Dark Star Luminosity



SK Neutrino Flux



DM Annihilation



$$L_{\rm DM} \simeq (1-f_\nu)\int_0^R dr 4\pi r^2 \frac{\langle\sigma v\rangle \rho_\chi^2}{m_\chi}$$

[Schwemberger, Takhistov, *ApJ. Lett.* (2025), 2412.18654]

* *consistent with JWST*

Summary

• WC SK and HK are truly discovery machines: multipurpose detectors, unique DM sensitivity

• SK already set world-leading limits across diverse DM scenarios

• HK, with larger fiducial mass, low thresholds, etc. will broadly open new DM parameter space

→ annihilation sub-GeV DM, boosted DM, novel DM B-violation channels, PBH evaporation, diffuse signals from dark stars + much more….

• WC detectors provide a complementary and indispensable probe of DM — synergistic with conventional direct detection, colliders, astrophysical and emerging quantum-sensor approaches

• The coming decade can be transformative for DM searches with WC experiments