Probing very heavy dark matter through lunar radio observations of ultrahigh-energy neutrinos

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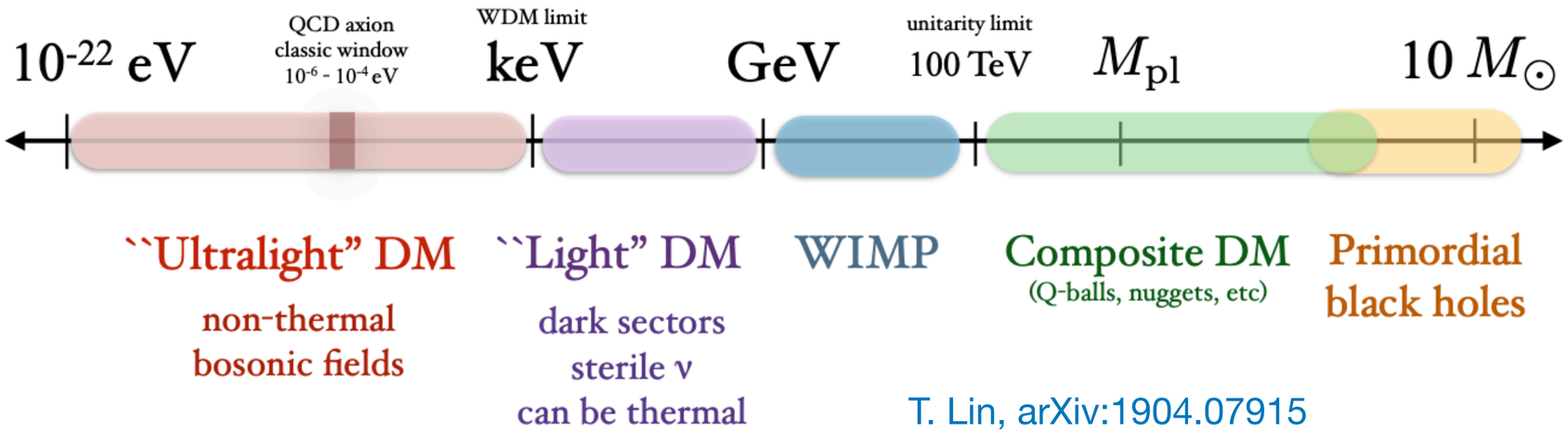
Based on arXiv:2405.06382

Why very heavy dark matter (VHDM)?

- Thermal DM relics are expected to have masses in the TeV range, e.g. WIMPS
- $m_{\rm DM} < 100$ TeV from unitarity bounds (e.g., Griest & Kamiokownski 1990, Harigaya et al. 2016)
- If DM is in **non-thermal** equilibrium and **cosmologically stable**, DM can be many orders of magnitude heavier than the weak scale (e.g. Chung et al. 1998)
- We will be working with $10^{12}\,\text{GeV} \leq m_{\rm DM} \leq 10^{18}\,\text{GeV}$



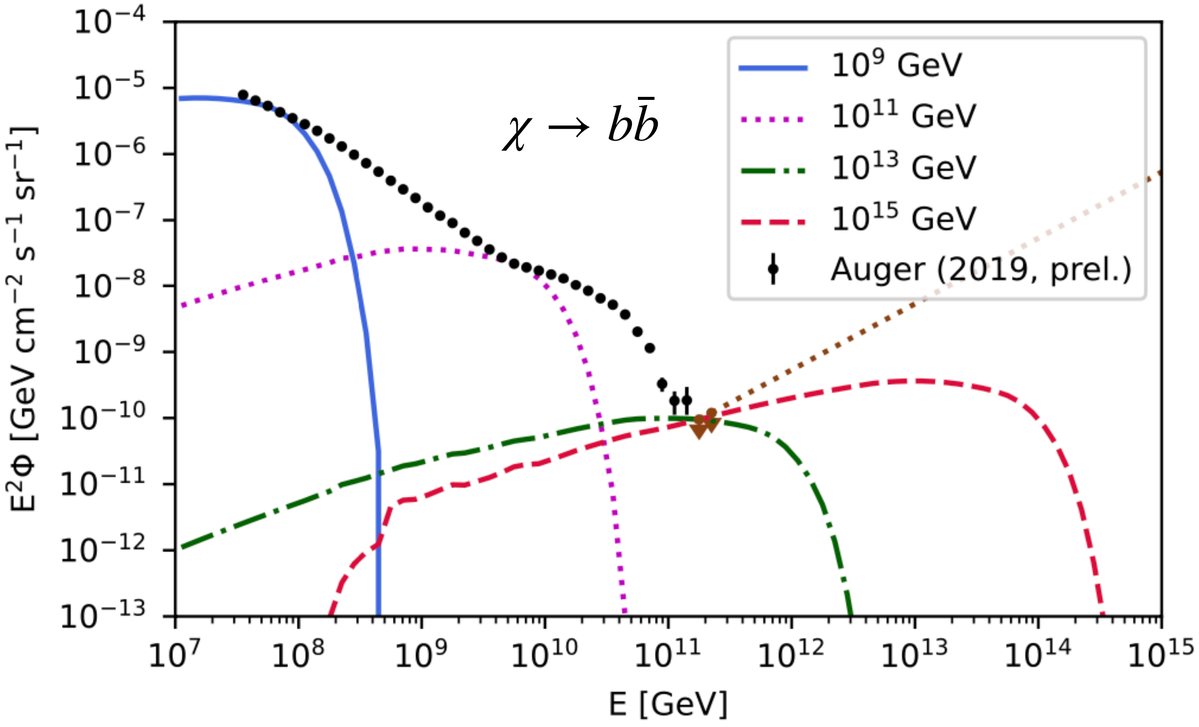
T. Lin, arXiv:1904.07915

Signatures of VHDM

DM annihilation and decay can produce a wide variety of particles: $p, \bar{p}, e^{\pm}, \gamma, \nu$

$p, \bar{p}$ would contribute to the ultrahigh energy cosmic ray (UHECR) spectrum

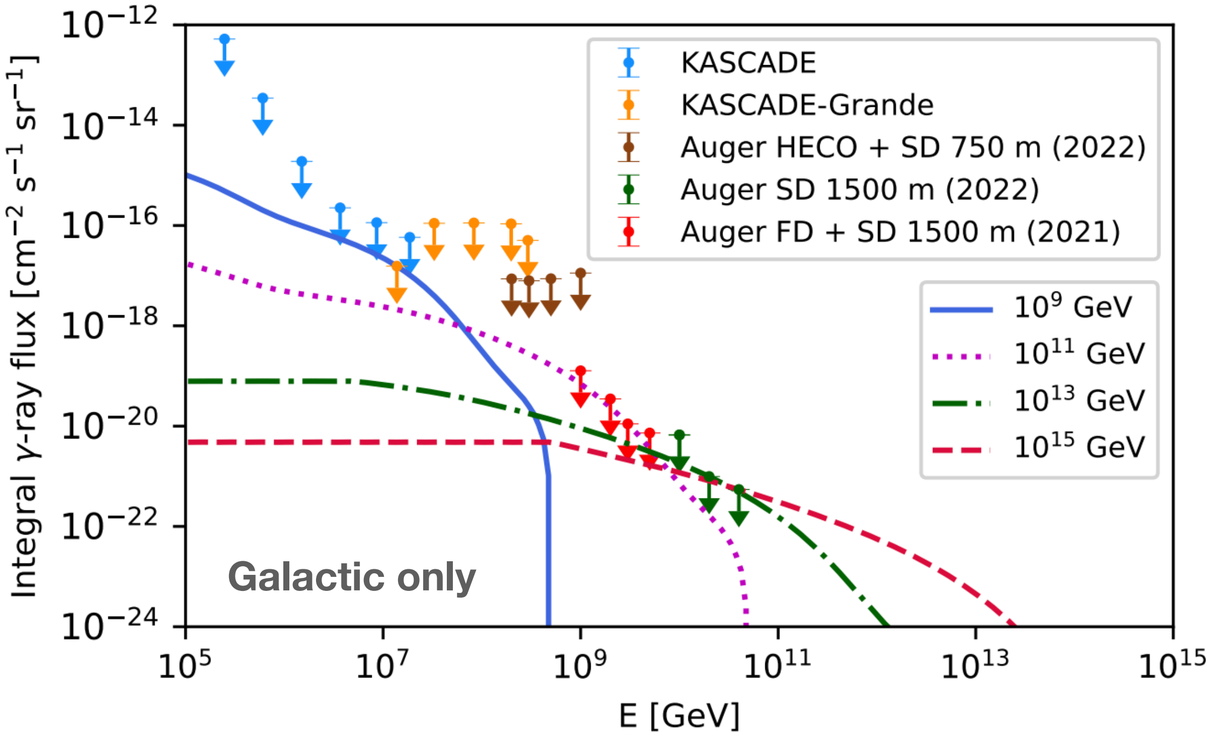
$z_{\max} \sim 2$



Das, Murase, Fujii 2023

γ-rays from Galactic DM produce atmospheric showers

Extragalactic γ cascade down to $\sim 1\,\mathrm{TeV}$

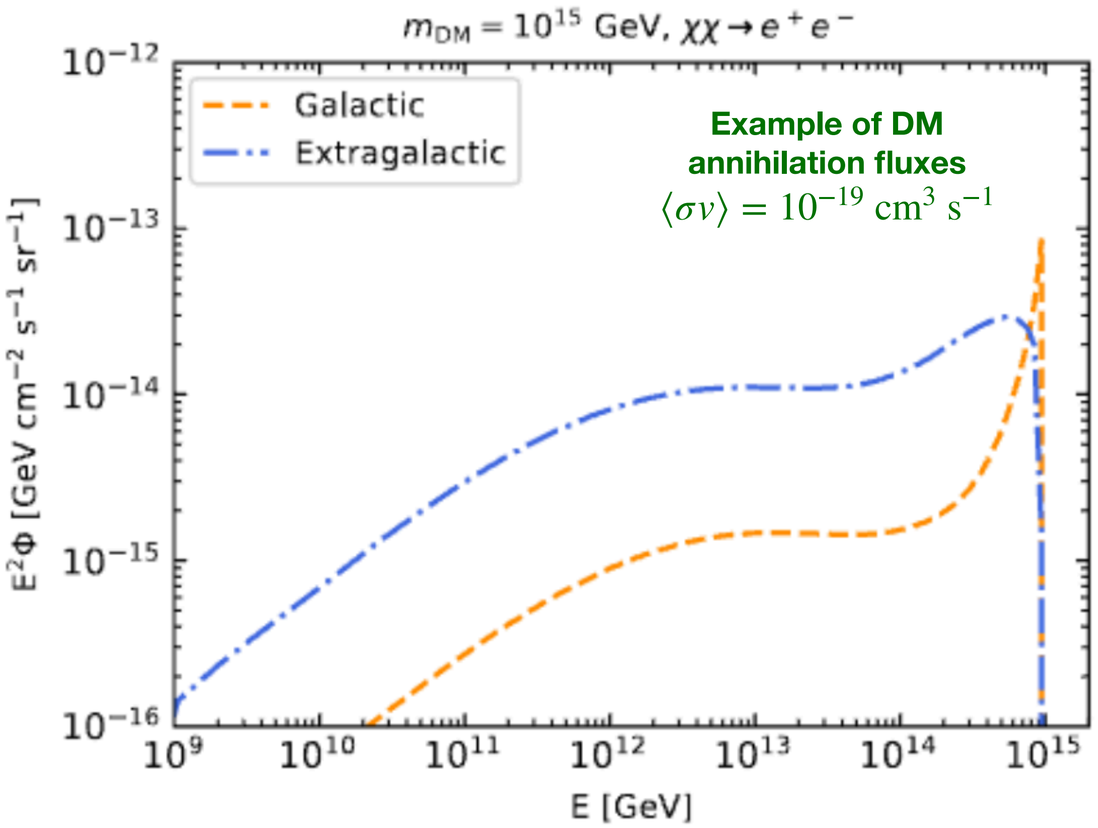


Neutrino signatures of VHDM

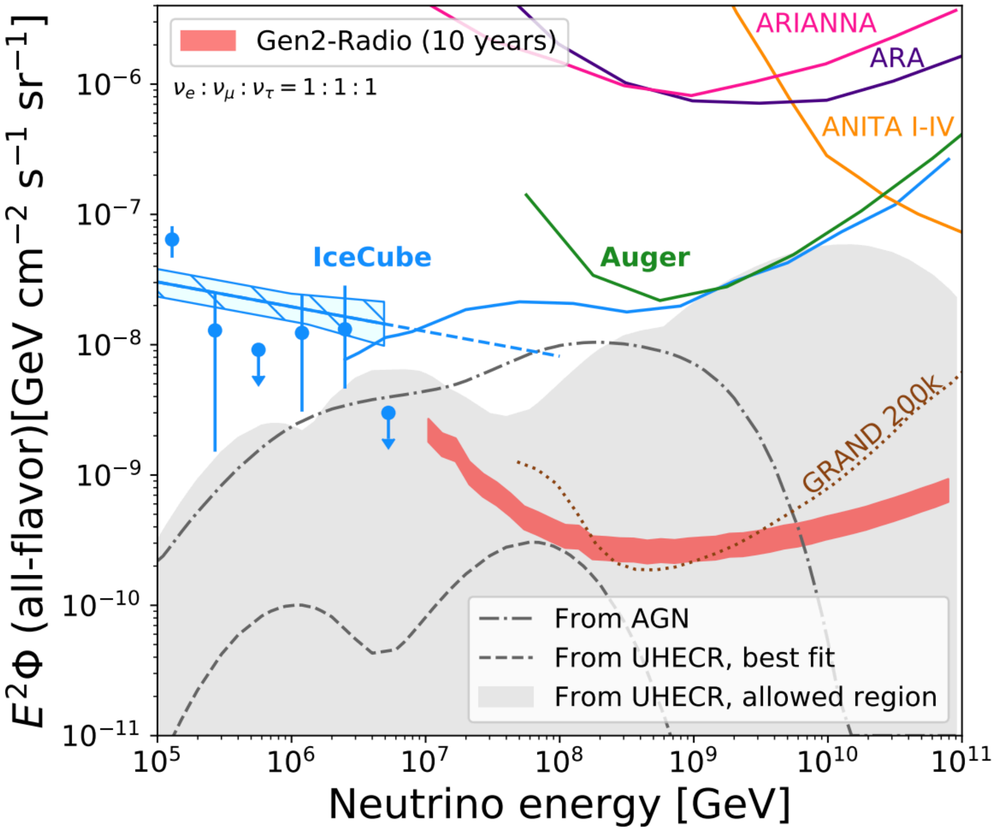
- Neutrinos travel very large distances, even at ultrahigh energies
- Horizon determined by $\nu + \nu_{C\nu B}$ interactions
- Galactic and extragalactic contributions to DM decay & annihilation

Main background is the CνB

UHECR interactions with CMB generate this $\sim$ EeV neutrino flux



Das, JC, Murase 2024



Aartsen et al. 2021

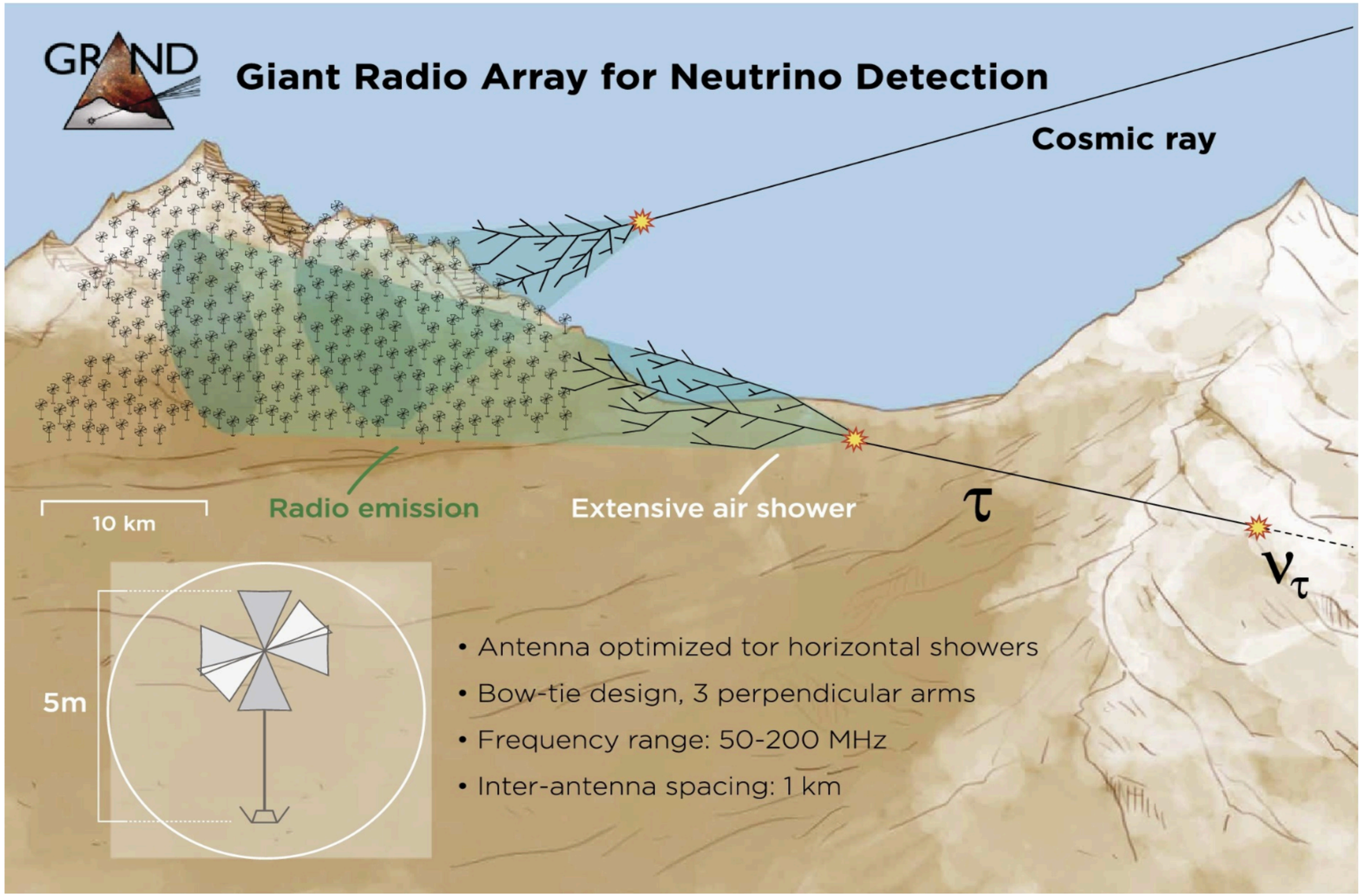
Detection of $E_\nu > 10^8$ GeV neutrinos

Detection via Askaryan effect from products of neutrino interactions

Large targets to trigger the interaction

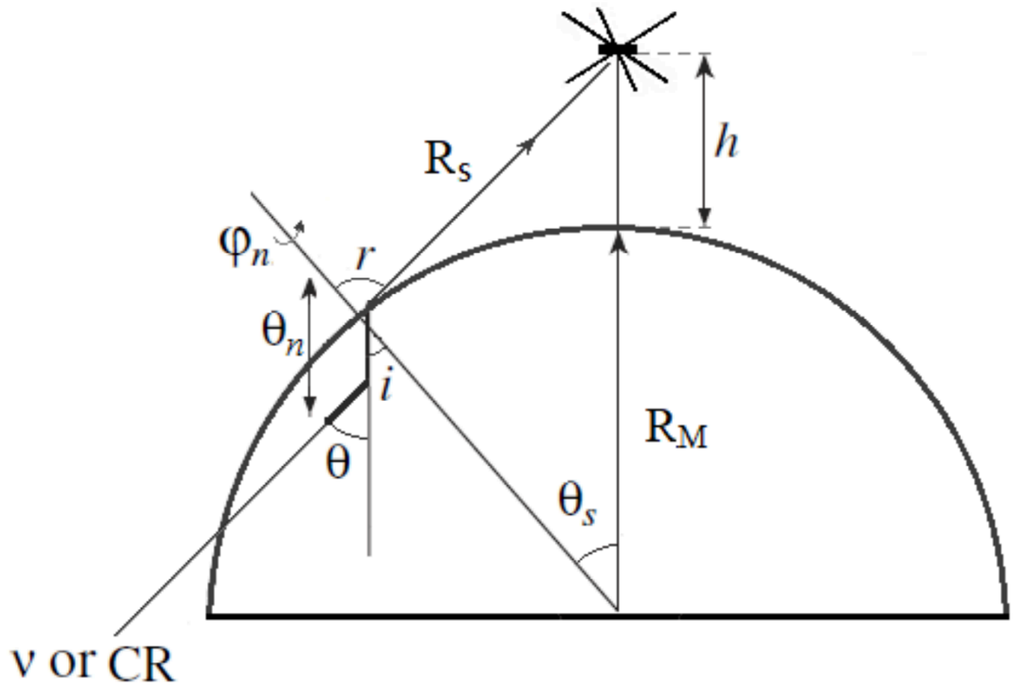
(but not too large!)

GRAND, IceCube-Gen2 radio
Target: Earth
Detector: Earth-based



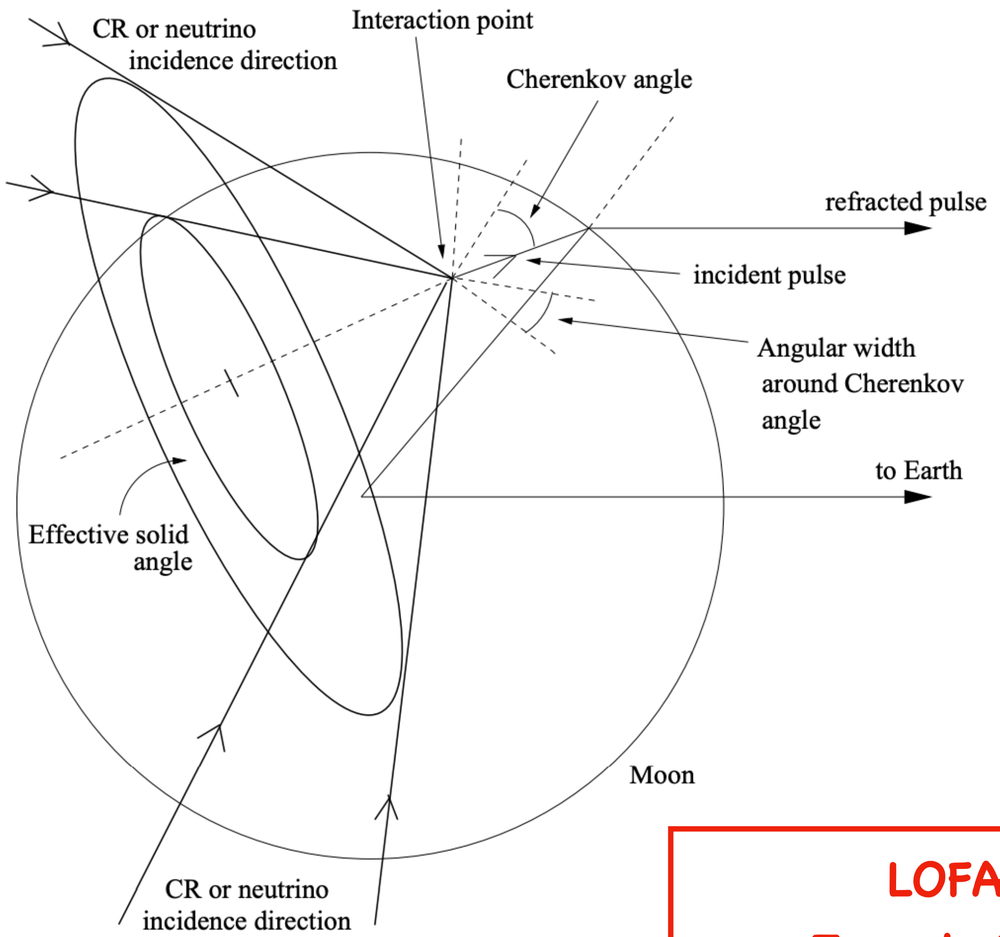
Detection of $E_\nu > 10^{12}$ GeV neutrinos

Ultra-long wavelength (ULW)
Target: Moon
Detector: Lunar-based



Detectors in lunar orbit

(Chen et al. 2023)



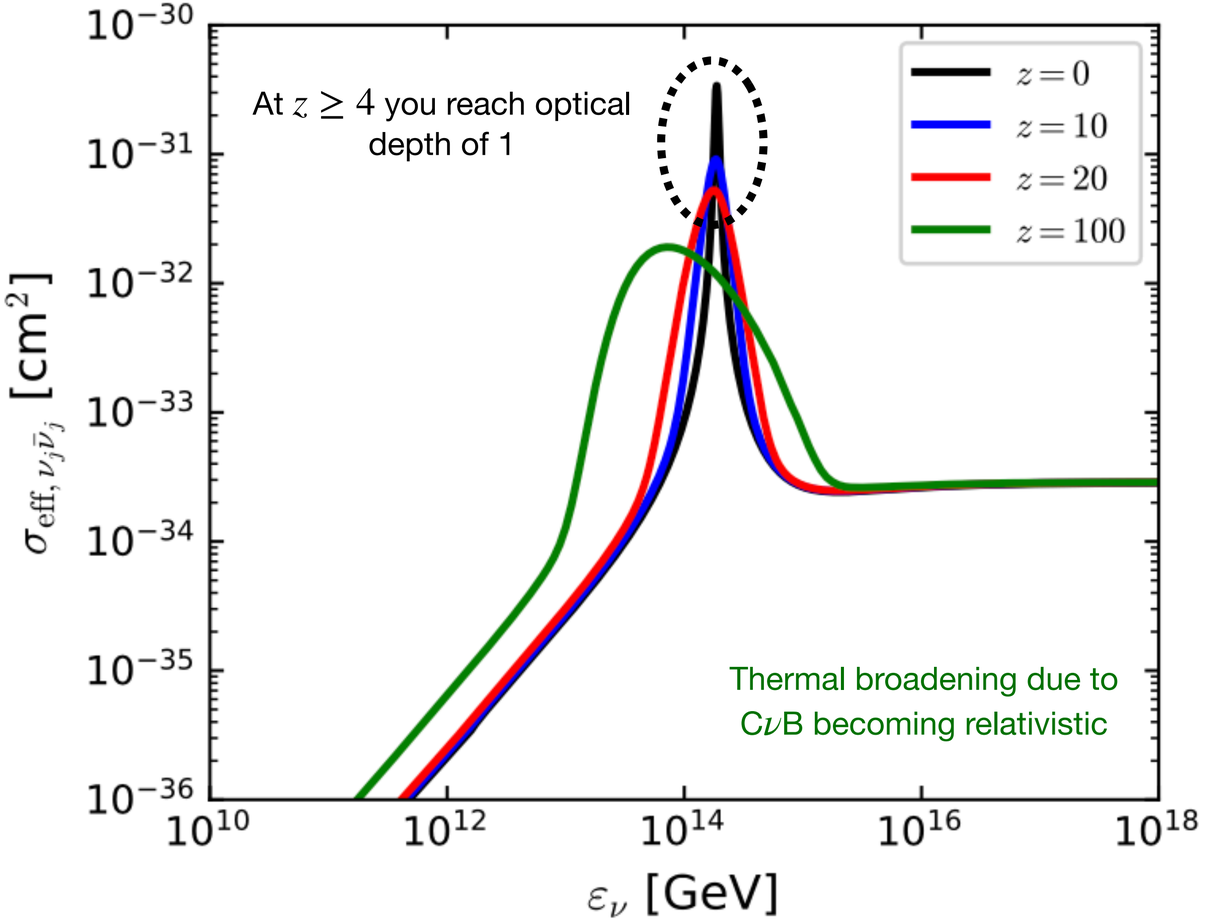
Radio detectors on Earth

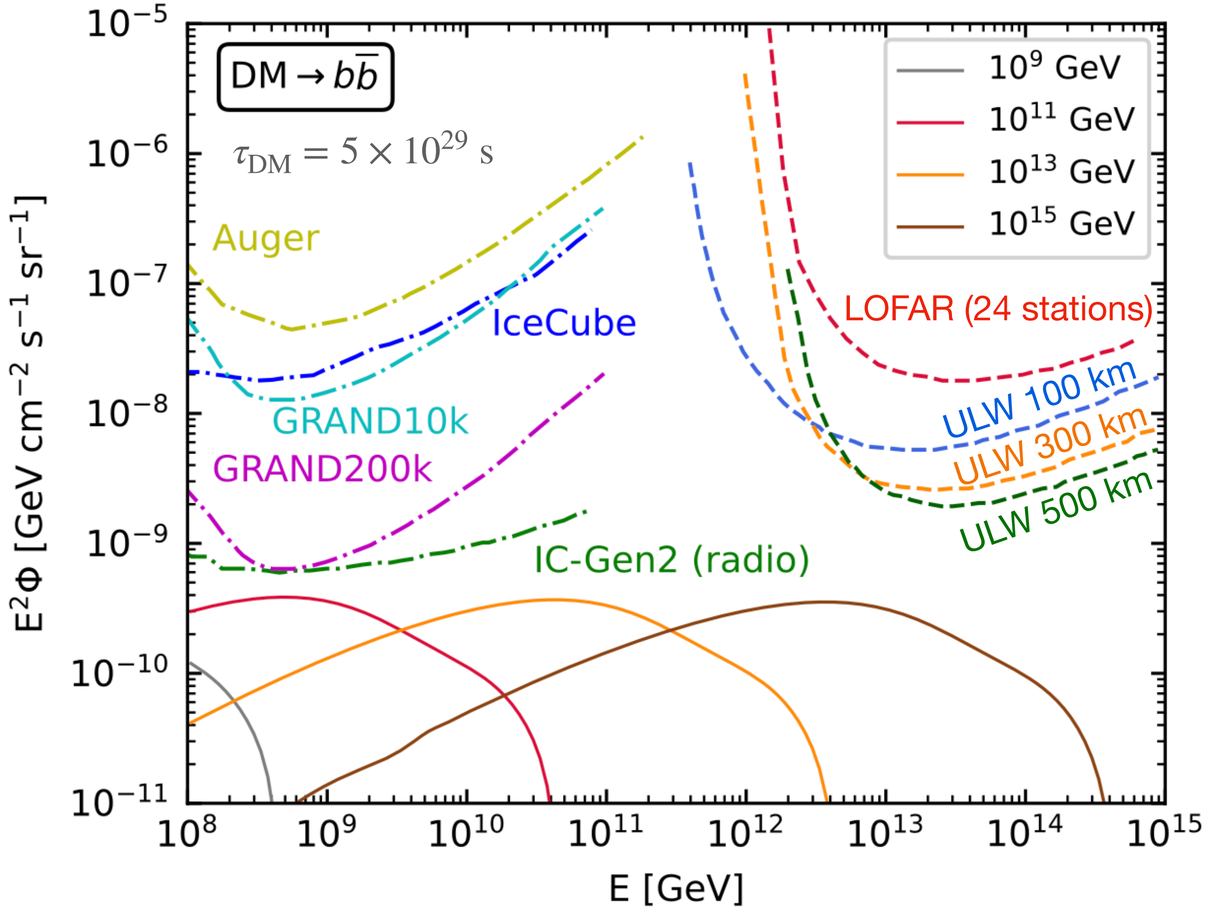
(J. Alvarez-Muñiz 2001)

LOFAR
Target: Moon
Detector: Earth-based

VHDM constraints

- Likelihood test based on total number of events up to $E_\nu = m_{\rm DM}/2$
- Use Galactic and extragalactic components
- Account for Z-boson production at large redshifts

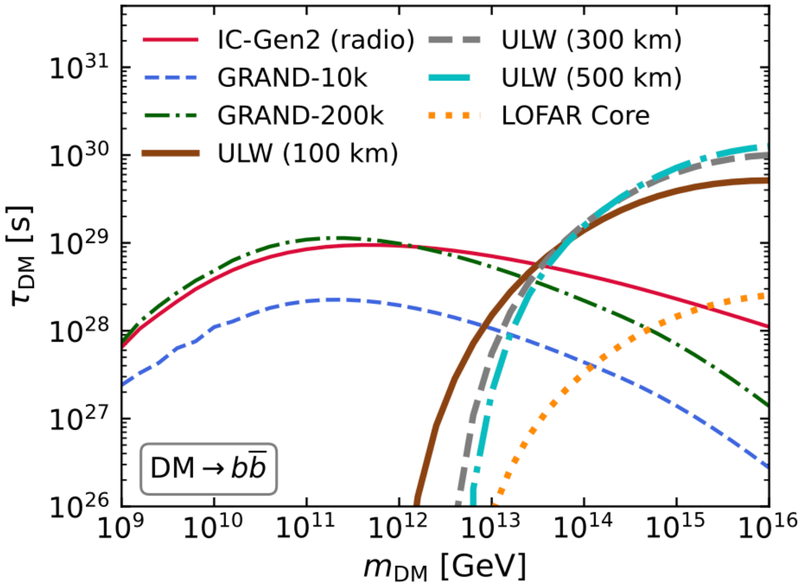


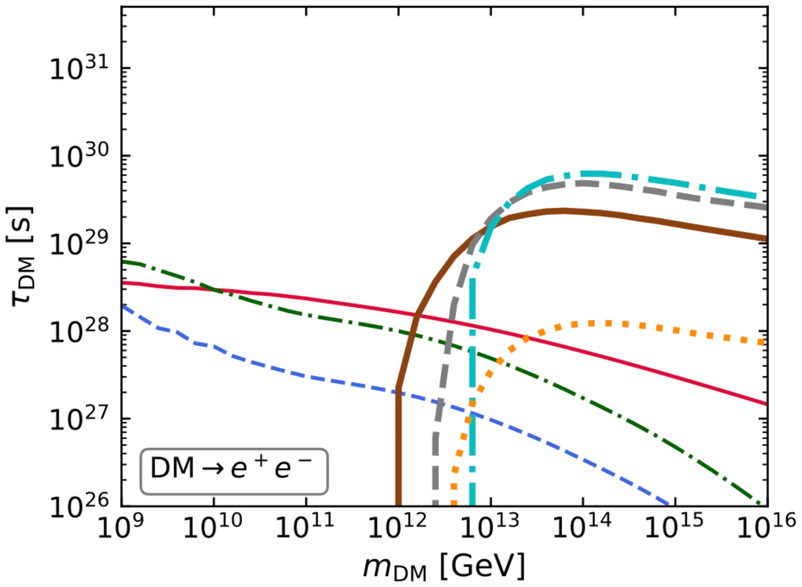


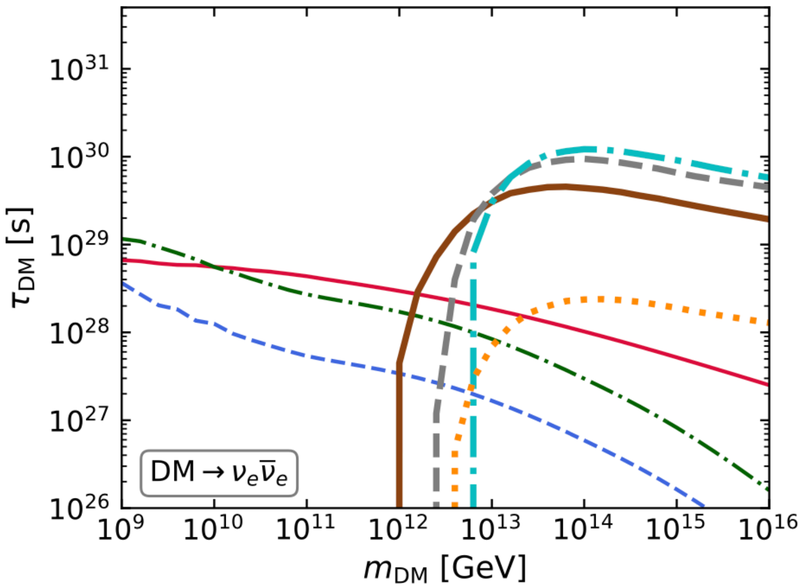
VHDM decay

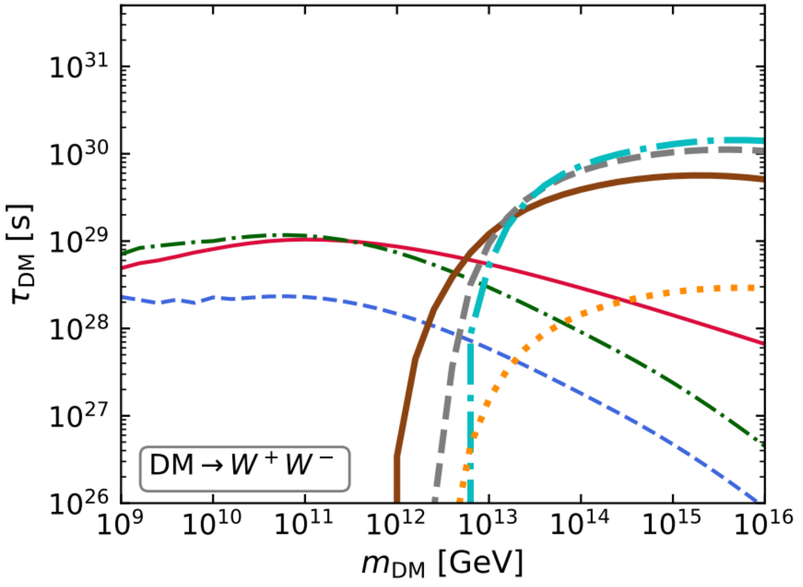
- ULW and LOFAR provide **more stringent** constraints than IC-Gen2 radio and GRAND at $m_{\rm DM} \gtrsim 10^{13}$ GeV
- Decay constraints with $m_{\rm DM} \sim 10^{13}$ GeV strongest for DM decay to leptons

IceCube-Gen2 radio, GRAND and ULW: 5 years of observation
LOFAR: 5000 hrs of observation





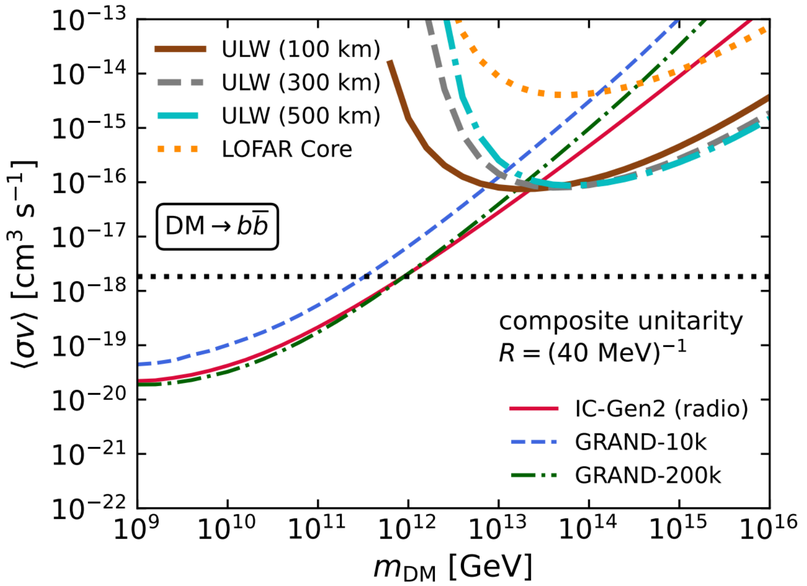


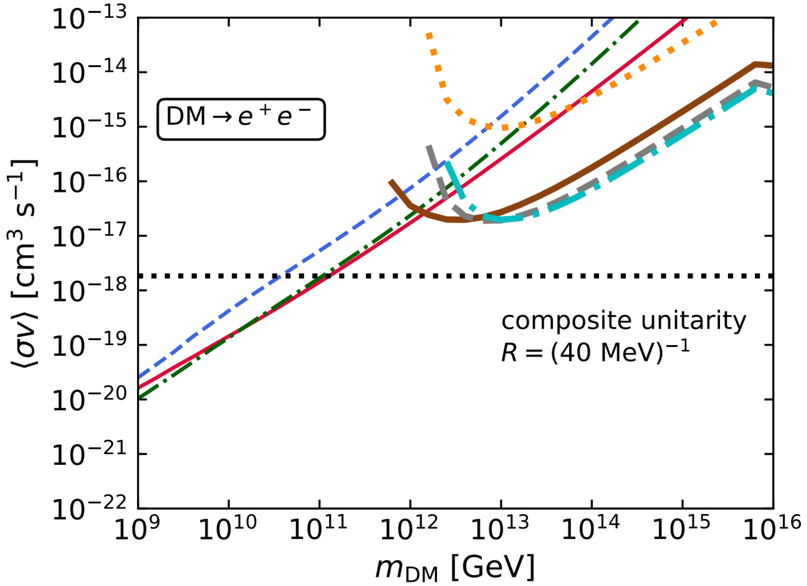


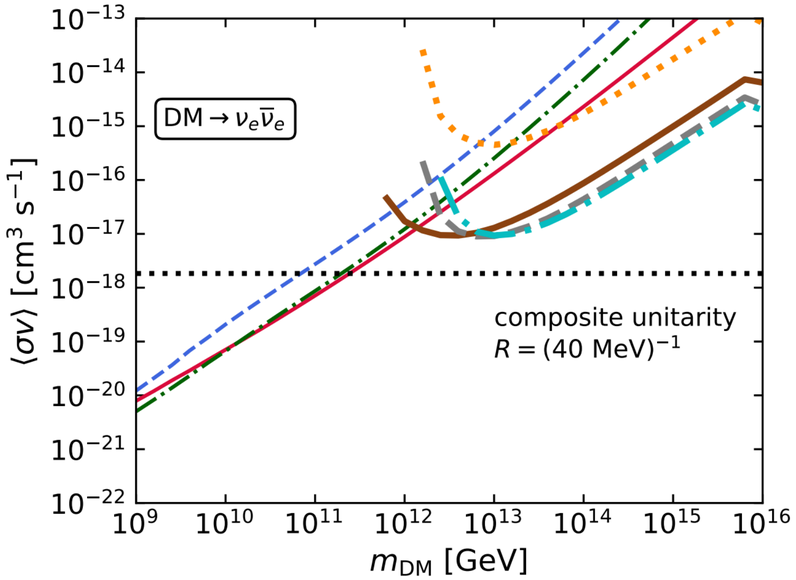
VHDM annihilation

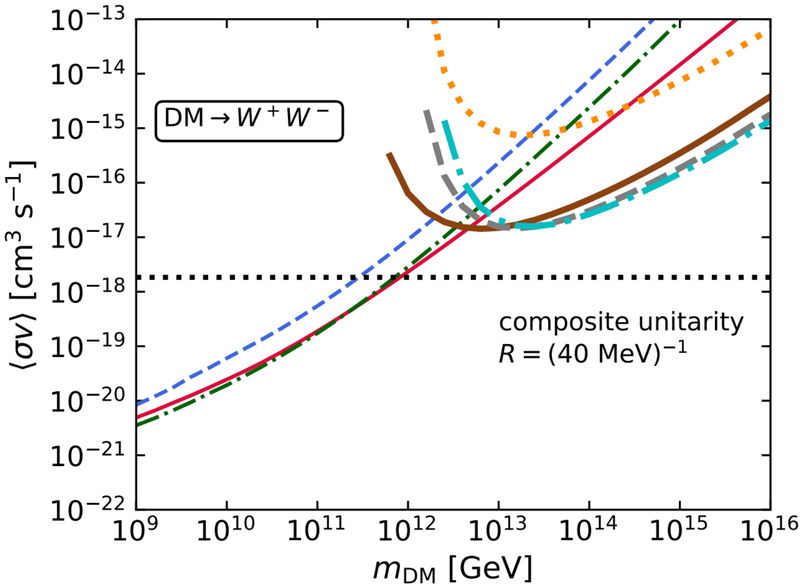
Similar trends observed for DM annihilation

IceCube-Gen2 radio, GRAND and ULW: 5 years of observation
LOFAR: 5000 hrs of observation









Summary

- Using the lunar regolith for neutrino interactions, we can observe signals from $\gtrsim 10^{12}$ GeV neutrinos
- DM decay limited to $\tau \gtrsim 10^{30}$ s at $m_{\rm DM} \gtrsim 10^{13}$ GeV
- DM annihilation limited to $\langle \sigma v \rangle \gtrsim 10^{-17}$ cm^3 s^{-1} at 10^{12} GeV $\lesssim m_{\rm DM} \lesssim 10^{14}$ GeV
- With lunar radio detections, neutrinos provide complementary bounds to UHECR measurements

Backup (aperture)