Time-delayed Neutrino Emission from Supernovae as a Probe of Dark Matter – Neutrino Interactions

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Motivation

- Self-interacting dark matter (DM) can alleviate problems in ΛCDM cosmology.
- It is possible for DM to interact with neutrinos via a new mediator, enabling neutrino self-interactions.
- Neutrino self-interactions are useful to alleviate the Hubble tension.
- We can use high-statistic neutrino events from a nearby supernova (SN) to probe for delayed neutrino signals from neutrino-DM interactions.

Model

We consider three particle physics models

$$\mathcal{L}_{\rm int} \supset g_\nu \bar{\nu}\gamma^\mu \nu V_\mu + g_\chi \bar{\chi}\gamma^\mu \chi V_\mu \quad \text{Fermion DM – Vector Mediator}$$

$$\mathcal{L}_{\rm int} \supset g_\nu \bar{\nu}\nu\phi + g_\chi \bar{\chi}\chi\phi \quad \text{Fermion DM – Scalar Mediator}$$

$$\mathcal{L}_{\rm int} \supset g_\nu \bar{\nu}\nu\phi + g_\chi \Lambda \chi^* \chi\phi \quad \text{Scalar DM – Scalar Mediator}$$

where the third Lagrangian assumes an energy scale $\Lambda = 100$ GeV. The couplings g_ν and g_χ are dimensionless. The angular distributions in the lab frame (DM at rest) are

$$\frac{d\sigma_{\nu\chi}}{d\cos\theta} = \frac{1}{32\pi m_\chi^2}\left(\frac{E'_\nu}{E_\nu}\right)^2 |\mathcal{M}|^2$$

where E'_ν is the scattered neutrino energy and $|\mathcal{M}|^2$ depends on the model. Total cross sections $\sigma_{\nu\chi}$ are proportional to $g_\chi^2 g_\nu^2$.

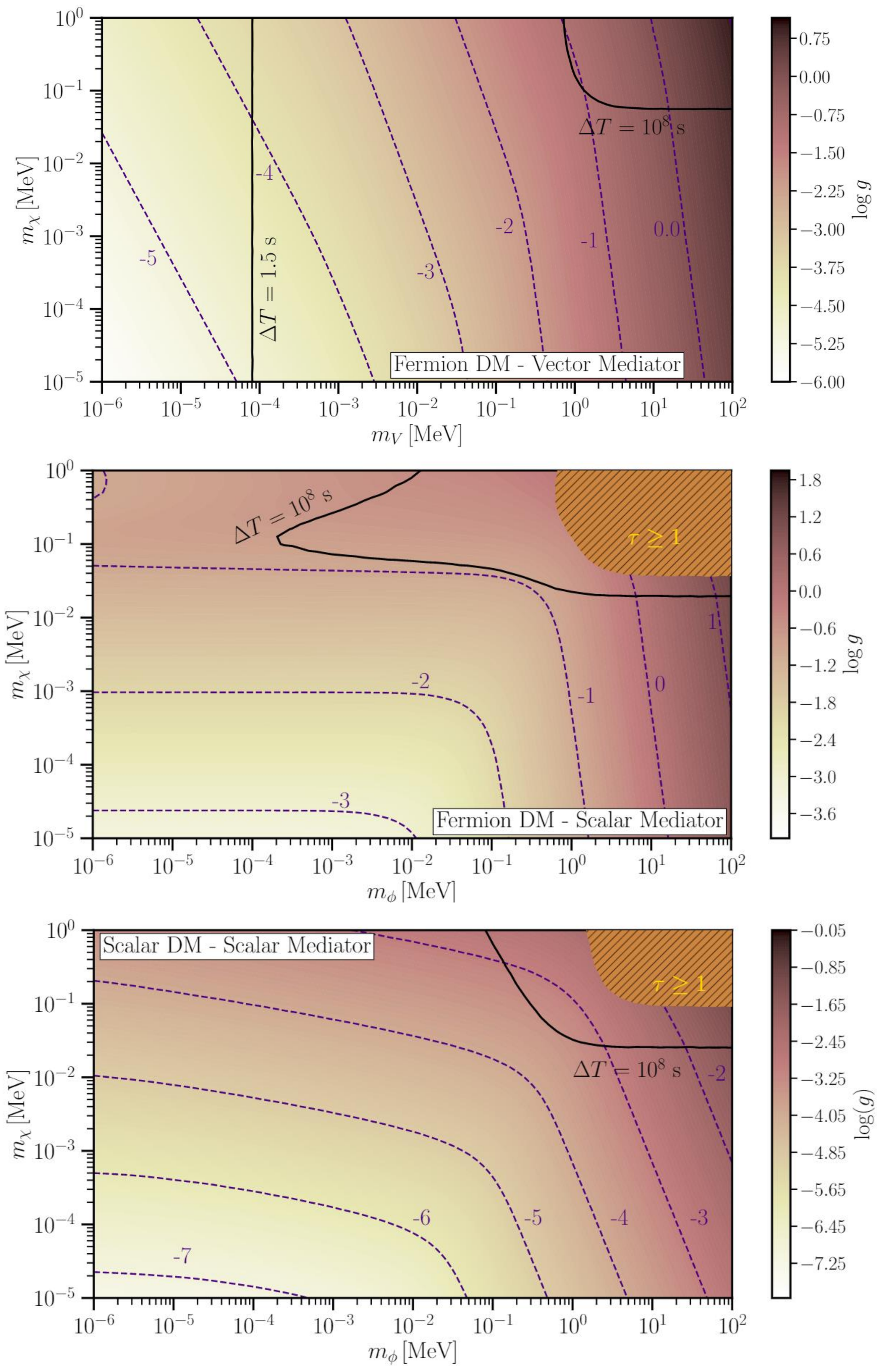

Figure 1: Limits on neutrino-dark matter coupling $g = \sqrt{g_\nu g_\chi}$. The time window ΔT is the time taken to enclose 50% of the signal. The region $\tau \geq 1$ can not be probed by our method.

Method

- Consider a supernova at a distance $D = 10$ kpc of duration $T_{\rm dur} = 1.5$ s.
- Expected ~ 44300 events at Hyper-Kamiokande[1].
- For an optical depth $\tau = n_\chi \sigma_{\nu\chi} D \ll 1$, neutrino-DM scattering occurs only once. The increased path length causes a time delay.

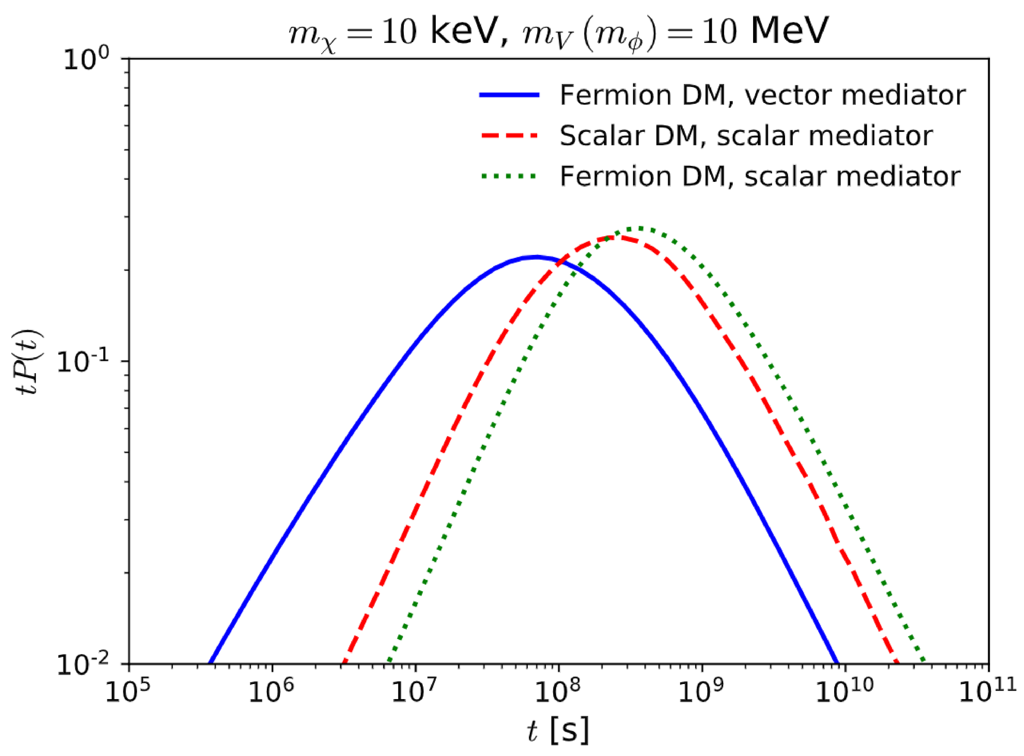

Figure 2: Time delay distribution of 15 MeV neutrinos for $m_\chi = 10$ keV and a 10 MeV mediator

- From the delay distribution $P(t)$, we can get the expected number of events in a given window after the initial burst.
- If no delayed signal is detected, we derive upper limits on the coupling.

Results

- Larger DM mass and heavier mediators lead to longer delays. Vector mediator has significantly shorter delays compared to the scalar mediator.
- For scalar mediators, there is a region that cannot be probed, denoted by $\tau \geq 1$. In this region, the bound on the number of delayed events is comparable or larger than the number of events from the neutrino burst.
- The delayed signal for $m_V \lesssim 100$ eV would overlap with the initial burst.

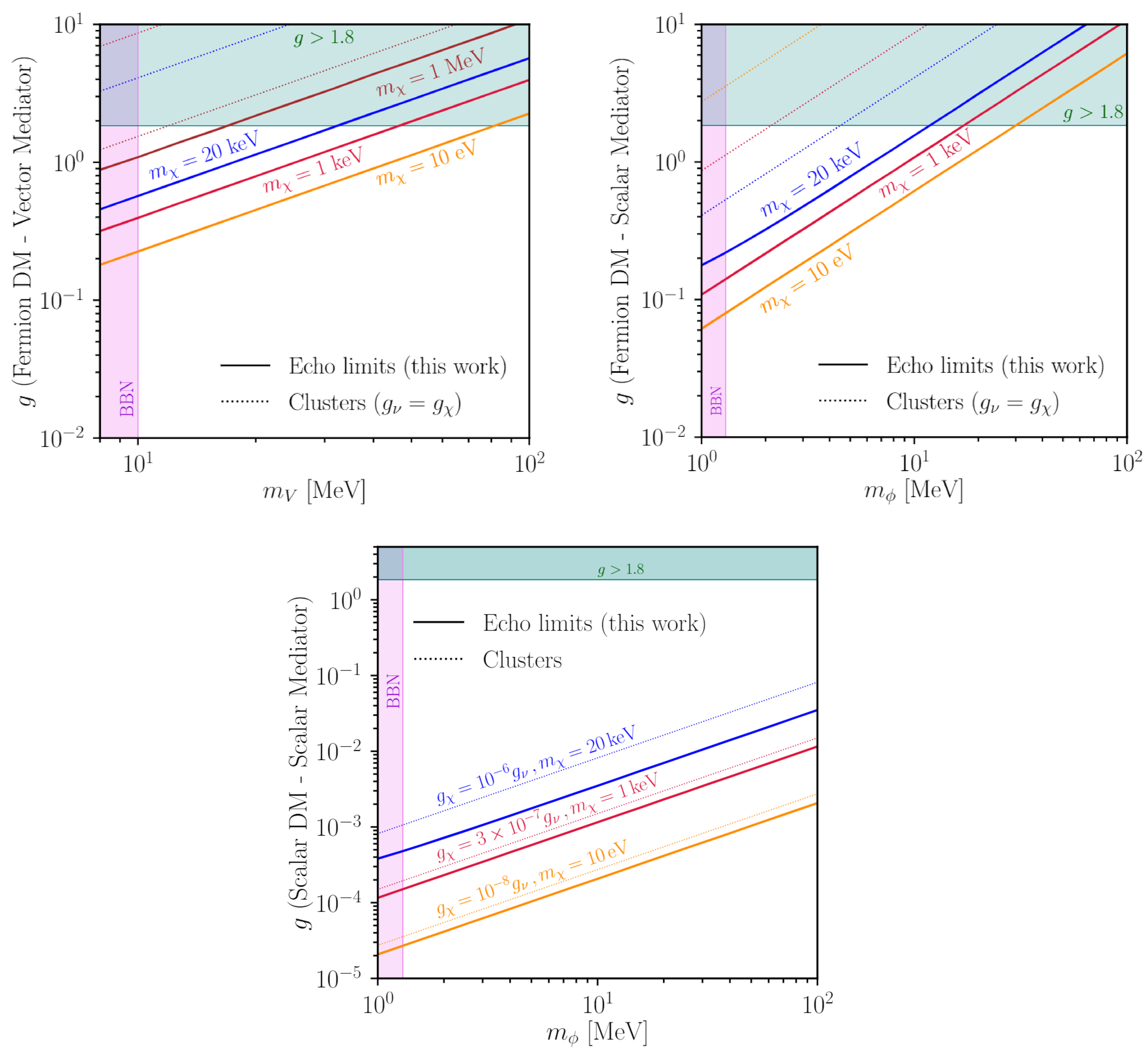

Figure 3: Constraints on $g = \sqrt{g_\nu g_\chi}$ for different DM masses. These are compared against Big Bang Nucleosynthesis (BBN) bounds and laboratory constraints[2].

- Our method is only sensitive to the effective coupling $g = \sqrt{g_\nu g_\chi}$.
- We can compare against DM self-interaction constraints from Galaxy clusters[3], $\sigma_{\chi\chi}/m_\chi \leq 0.1\ {\rm cm^2/g}$, by assuming a ratio g_ν/g_χ.

Conclusions

- The study provides a novel approach to study neutrino-DM interactions with MeV neutrinos from SNe.
- The echo method allows us to probe parameter space not accessible by other methods.
- Next-generation neutrino detectors would be able to explore the keV-MeV DM mass range due to increase statistic.

References

1. Hyper-Kamiokande collaboration, Astrophys. J. 916 (2021) 15.
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3. S. Tulin, H.-B. Yu and K.M. Zurek, Phys. Rev. D 87 (2013) 115007.