Transient Sources & the light curves of BSM-induced neutrino echoes

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High-energy neutrinos offer unique tool to explore physics BSM
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   → Probe physics at new energy scales
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4. Complementarity with cosmological & laboratory Measurements
High-Energy Neutrino Observables
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Direction & Time

IceCube Preliminary
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Neutrino energy

Deposited EM-equivalent

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Topology

- muon track
- shower

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IceCube Preliminary
Argüelles, Bustamante, AK, Palomares-Ruis, Vincent, 2019
Acts at production

- Heavy relics
- DM annihilation
- DM decay
- Sterile $\nu$
- Boosted DM
- NSI
- DM-$\nu$ interaction
- DE-$\nu$ interaction
- Lorentz+CPT violation
- Neutrino decay
- Long-range interactions
- Secret $\nu\nu$ interactions
- Supersymmetry
- Effective operators
- Leptoquarks
- Extra dimensions
- Superluminal $\nu$
- Monopoles

Argüelles, Bustamante, **AK**, Palomares-Ruis, Vincent, 2019
Note: P NotP anP exhaustiveP l ist

Argüelles, Bustamante, AK, Palomares-Ruis, Vincent, 2019
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DM annihilation,
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Acts at production

Acts during propagation

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Acts at detection

Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times

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DE-\( \nu \) interaction
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Neutrino decay
Time-Domain Neutrino Astrophysics

- Transient sources: primary candidates sources of high-energy neutrinos
- Recent progress in identification of cosmic neutrino sources demonstrated the feasibility of time-domain multimessenger astrophysics.

- **Blazar flares**
- **Tidal disruption events**
- **Long GRB**
- **Engine-driven Supernova**
- **Short GRB (NS merger)**

*Fig. Adopted Murase & Bartos 2019*
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**blazar flares**

IC 170922 coincident with TXS 0506+06

IceCube 2018

**tidal disruption events**

IC 191001 coincident with AT2019dsg

Stein+ 2020

**long GRB**

**engine-driven Supernova**

**short GRB** (NS merger)

Fig. Adopted Murase & Bartos 2019
BSM-induced Time Delay

- Identification of the origin of cosmic neutrinos offer new avenues to probe for new physics.
- SM induced delays due to the mass of neutrinos is negligible, much shorter than typical transients duration.
- Lorentz invariance and weak equivalence principle violation are examples of BSM scenarios that induce time-delay between neutrinos and gamma rays. [e.g. Ellis+2018, Laha 2018]
- Presence or absence of a delay between neutrinos and other cosmic messengers from a transient can be used to study non-standard neutrino interactions.

The time difference can be estimated by evaluating the extra distance neutrino has to travel, deduced from averaged scattering angle:

$$\langle (1 - \cos \theta) \rangle = \frac{1}{\sigma} \int d\Omega (1 - \cos \theta) \left( \frac{d\sigma}{d\Omega} \right)$$

Temporal profile follows differential cross section behavior!
Optical Depth for Secret $\nu$ Interactions

- The probability of high-energy neutrinos undergoing interaction as they propagate is given by:
  
  $$1 - \exp(-\tau_\nu)$$
Optical Depth for Secret $\nu$ Interactions

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Large Optical Depth Regime $\tau_\nu \gtrsim 1$

- Multiple scattering occurs
- Neutrinos cascade down
- Requires large statistics
- Limits depend on the primary spectrum
- Requires large coupling which might be limited by other measurements
- Cannot be applied to very short timescale for transients
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- Single scattering
- Neutrinos arrive at similar energies they were at the source
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- Time delay distribution reflects the differential cross section, generally inelastic.
- Background-free limits provides strong constraints
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Delay induced by Secret $\nu$-$\nu$ Interaction

- **Secret** self neutrino interactions
  - Can generate finite neutrino mass
  - Help alleviate cosmological tensions
- Interaction can be facilitated via scalar or vector mediator:
  \[
  \mathcal{L} \supset g_{ij} \bar{\nu}_i \nu_j \phi \\
  \mathcal{L} \supset g_{ij} \bar{\nu}_i (\gamma^\mu V_\mu) \nu_j
  \]
  \[
  \sigma_{\nu\nu}(E) = \frac{g^4}{16\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}
  \]
  Resonance at mediator mass $\frac{m_\phi^2}{2m_\nu}$
- Time-delay:
  \[\Delta t \approx \frac{1}{2} \frac{\langle \theta^2 \rangle}{4} D\]
  \[\approx 77 \text{ s} \left( \frac{D}{3 \text{ Gpc}} \right) C^2 \left( \frac{m_\nu}{0.1 \text{ eV}} \right) \left( \frac{0.1 \text{ PeV}}{E_\nu} \right)\]

![Graph showing delay vs. energy and distance](image)
Light Curves

Nonstandard $\nu$-$\nu$ interactions

The average time-delay for scalar and vector mediator are similar.
The Event distribution, i.e., the light curve differ!
**DM–ν Interactions**

- Neutrinos can provide the principal portal to DM
- Motivated by *Scotogenic* models (neutrino mass generation occurs via interactions with the dark sector)
- DM–ν interactions induce anisotropies and alter the spectrum of high-energy neutrinos [Argüelles, AK, Vincent, PRL 2017]
  - *competitive limits to cosmological studies*
    - *Limits from time-delay can be comparable and can probe weak coupling better!* [Murase & Shoemaker PRL 2019]

*time delay induced by DM–ν interaction with vector mediator (t-channel)*

\[ E_\nu = 100 \text{ TeV} \]
\[ D = 3 \text{ Gpc} \]
### Light Curves

- **ν-DM interactions**

![Time-delay PDF](image1.png)

**ν-DM t-channel** \(E_\nu = 100 \text{ TeV}, m_\chi = \text{MeV}, m_{\phi/V} = 5 \text{ MeV}\)

- Distinct behavior for scalar and vector mediator.
- A new window of opportunity to probe for sub-GeV DM.

![Light curve](image2.png)
In the absence of delay

Absence of time-delay in a multimessenger observation of a transient will provide upper limit on the strength of neutrino secret interactions

Murase & Shoemaker, PRL 2019

Carpio, AK, & Murase, in preparation
Summary

• High-energy neutrinos can expose the footprints of physics beyond the Standard Model and provide an insight unattainable by any other sectors.

• Neutrinos could present the key portal from Standard Model to the dark sector.

• Progress in multimessenger identification of the origin of cosmic neutrinos offers a unique opportunity to probe for physics BSM in the neutrino sector.

• Transient sources present primary candidates for the origin of high-energy cosmic neutrinos, and their identification is expected with high statistics in the next generation of neutrino telescopes.

• BSM-induced time-delays in the arrival of cosmic neutrinos offers a distinct feature to study secret neutrino interactions.
Thanks!
Back up Slides
Features in high-energy neutrino flux can reveal new physics phenomena. The upper limits on yet to be seen fluxes impose limits on BSM scenarios.