Resonant neutrino self-interactions in astrophysical spectra

Weak Interactions & Neutrinos Workshop, June 12, 2021

Jeff Hyde

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Work w/

Cyril Creque-Sarbinowski
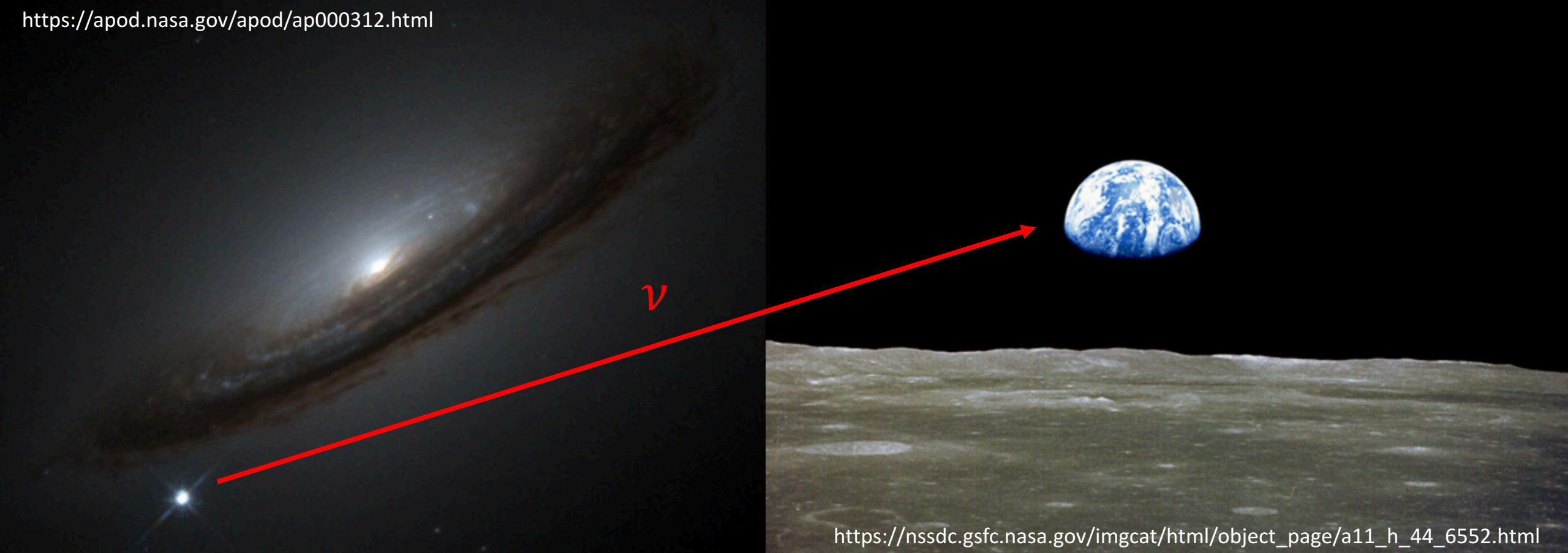
& Marc Kamionkowski

Motivations

- It's tough to constrain some neutrino properties (e.g. ν_τ interactions)

- Neutrino self-interactions are often considered (e.g. Hubble tension)

    e.g. Araki et al. 1409.4180 & 1508.07471, Barenboim et al. 1903.02036, Jones & Spitz 1911.06342,
    Ng & Beacom 1404.2288, Bustamante et al. 2001.04994, Blinov et al. 1905.02727,
    Mazumdar et al. 2011.13685, Carpio et al. 2104.15136, Das & Ghosh 2011.12315, Choudhury et al. 2012.07519

- Existing / upcoming neutrino experiments

    (Super-K, IceCube, POEMMA, …)

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  Here, we consider neutrino self-interactions mediated by a scalar, ϕ:

  $$\mathcal{L}_{int} = g_{ij}\phi\nu_i\nu_j$$
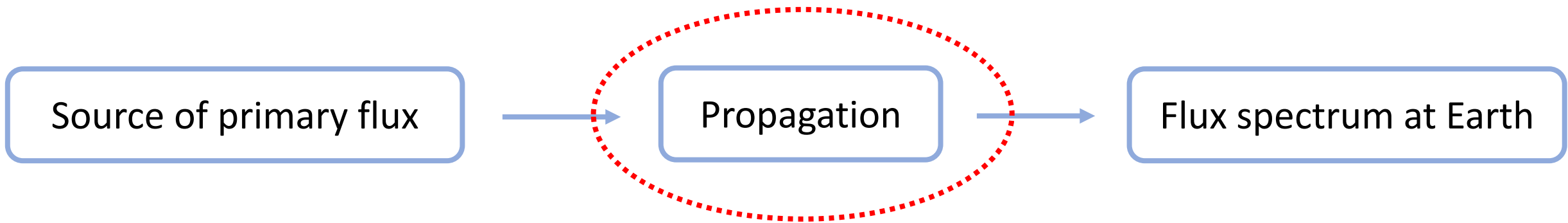
ν

Source of primary flux $\longrightarrow$ Propagation $\longrightarrow$ Flux spectrum at Earth

https://apod.nasa.gov/apod/ap000312.html

ν

https://nssdc.gsfc.nasa.gov/imgcat/html/object_page/a11_h_44_6552.html

| Source of primary flux | → | Propagation | → | Flux spectrum at Earth |

Possible scattering on CνB

SN 1987A: Kolb & Turner, PRD 36 (1987) 2895

Result for multiple flavors, arbitrary self-coupling matrix

Inputs:

Result:

Primary source term – depends on physics of source (e.g. supernova neutrinos)

Neutrino self-coupling matrix – depends on new physics model

Analytic calculation

Spectrum that arrives at Earth (Examples: supernova neutrinos at Super-K, high-energy neutrinos at IceCube)

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CCS, JH, MK, Phys. Rev. D 103, 023527, arXiv:2005.05332

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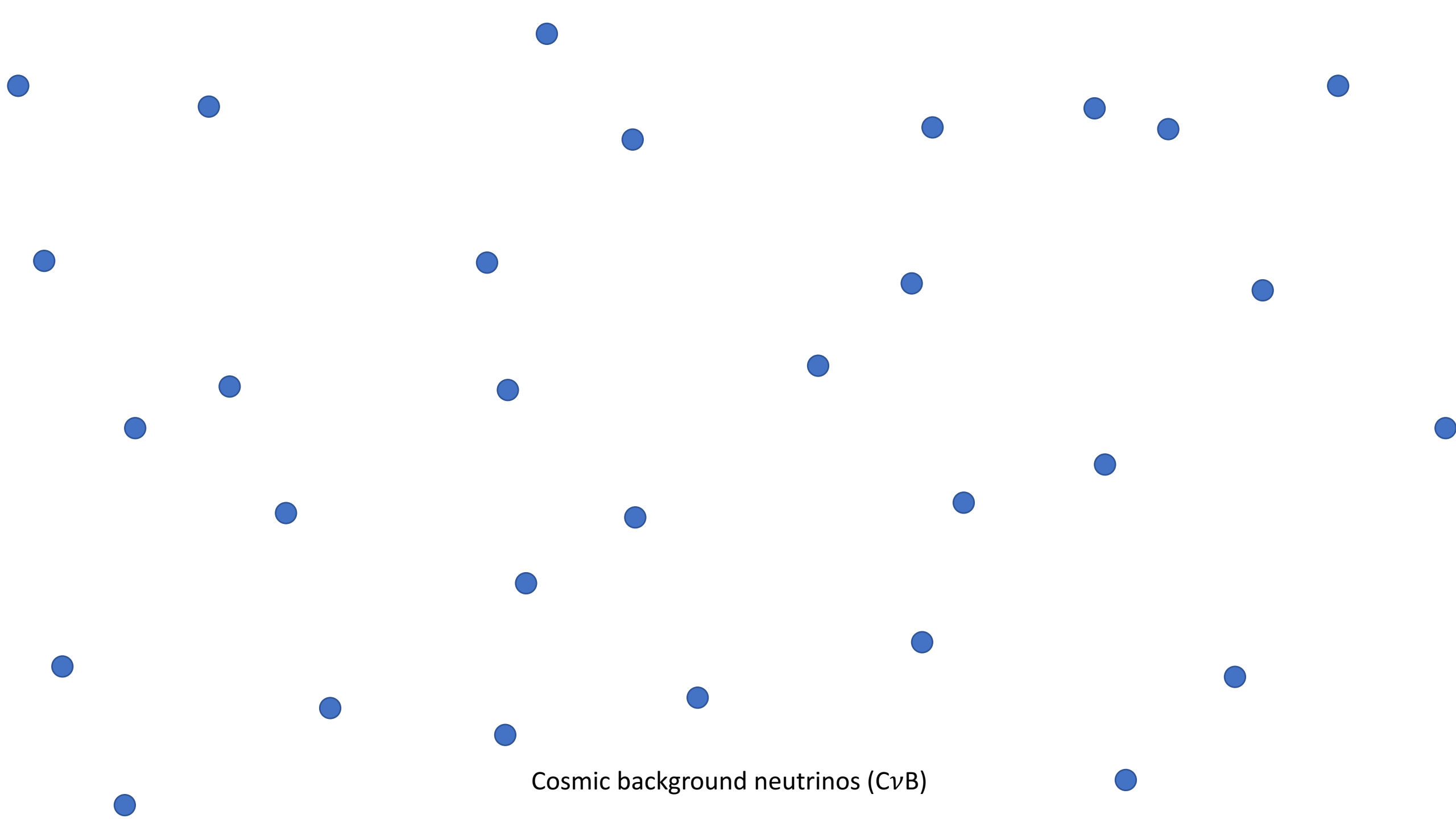Primary source term – depends on physics of source (e.g. supernova neutrinos)
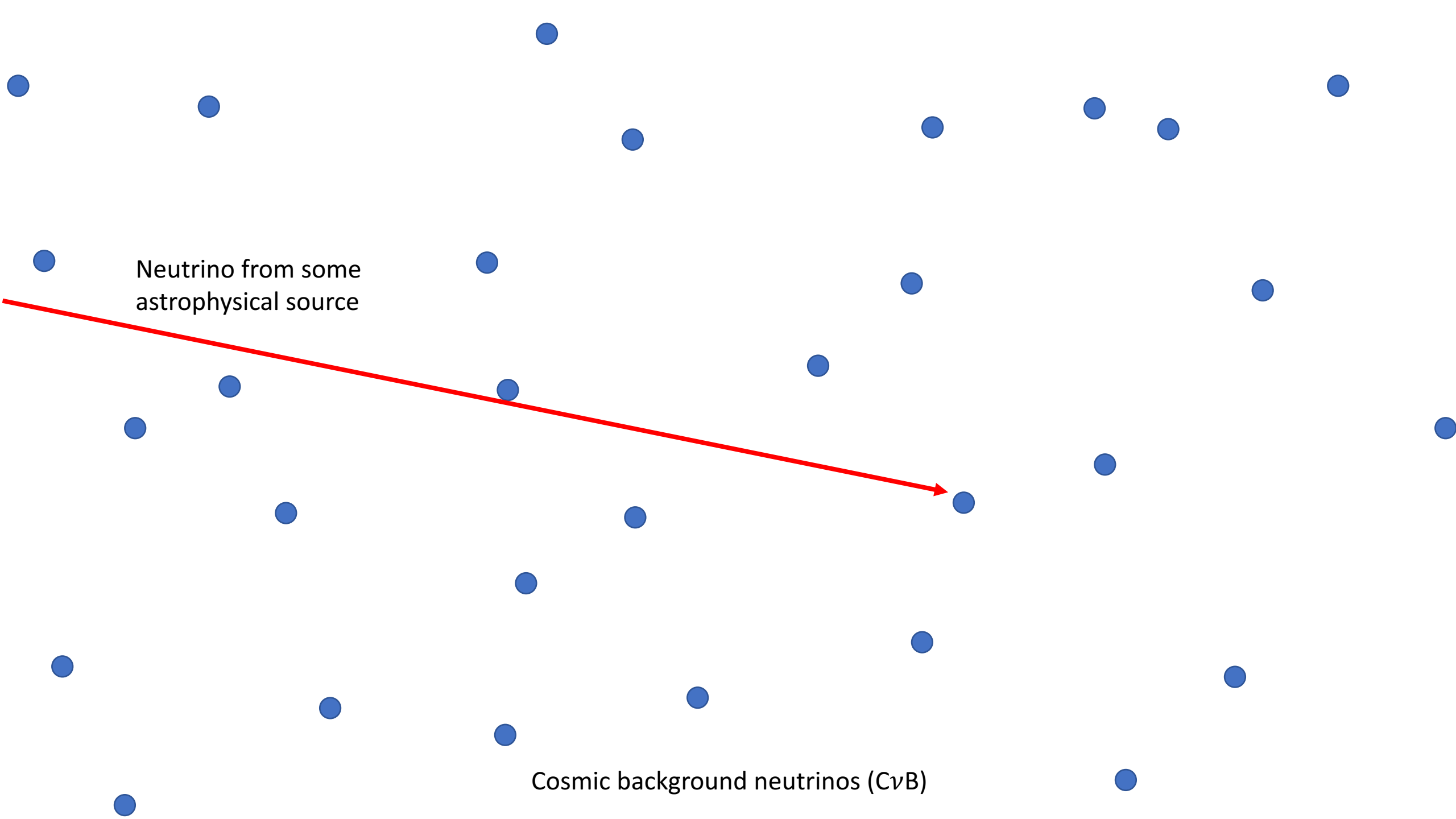
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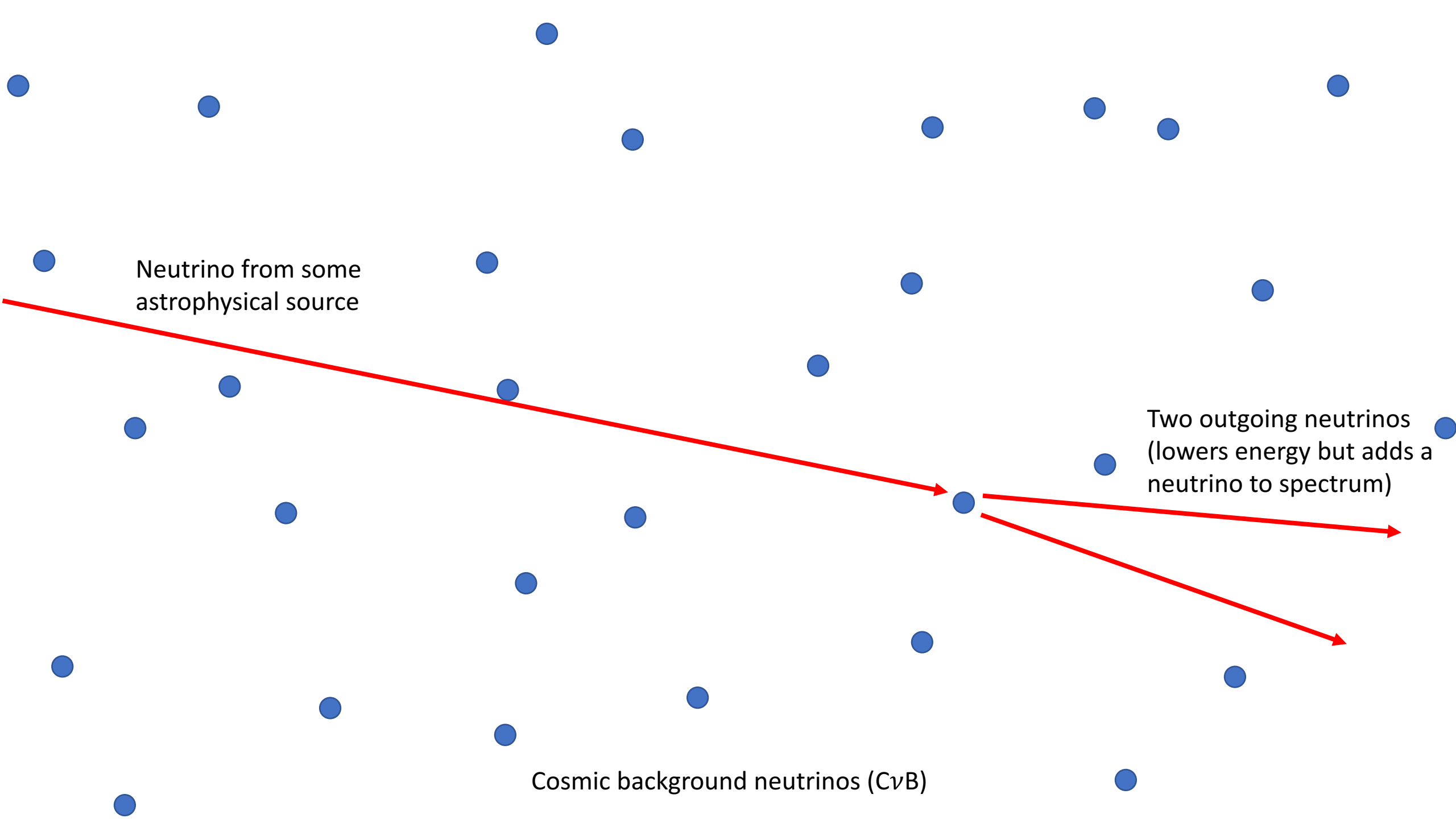Neutrino self-coupling matrix – depends on new physics model

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Cosmic background neutrinos (CνB)

Neutrino from some
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Neutrino from some astrophysical source

Two outgoing neutrinos
(lowers energy but adds a neutrino to spectrum)

Cosmic background neutrinos (CνB)

Also considered in:
Farzan & Palomares-Ruiz 1401.7019, Ibe &
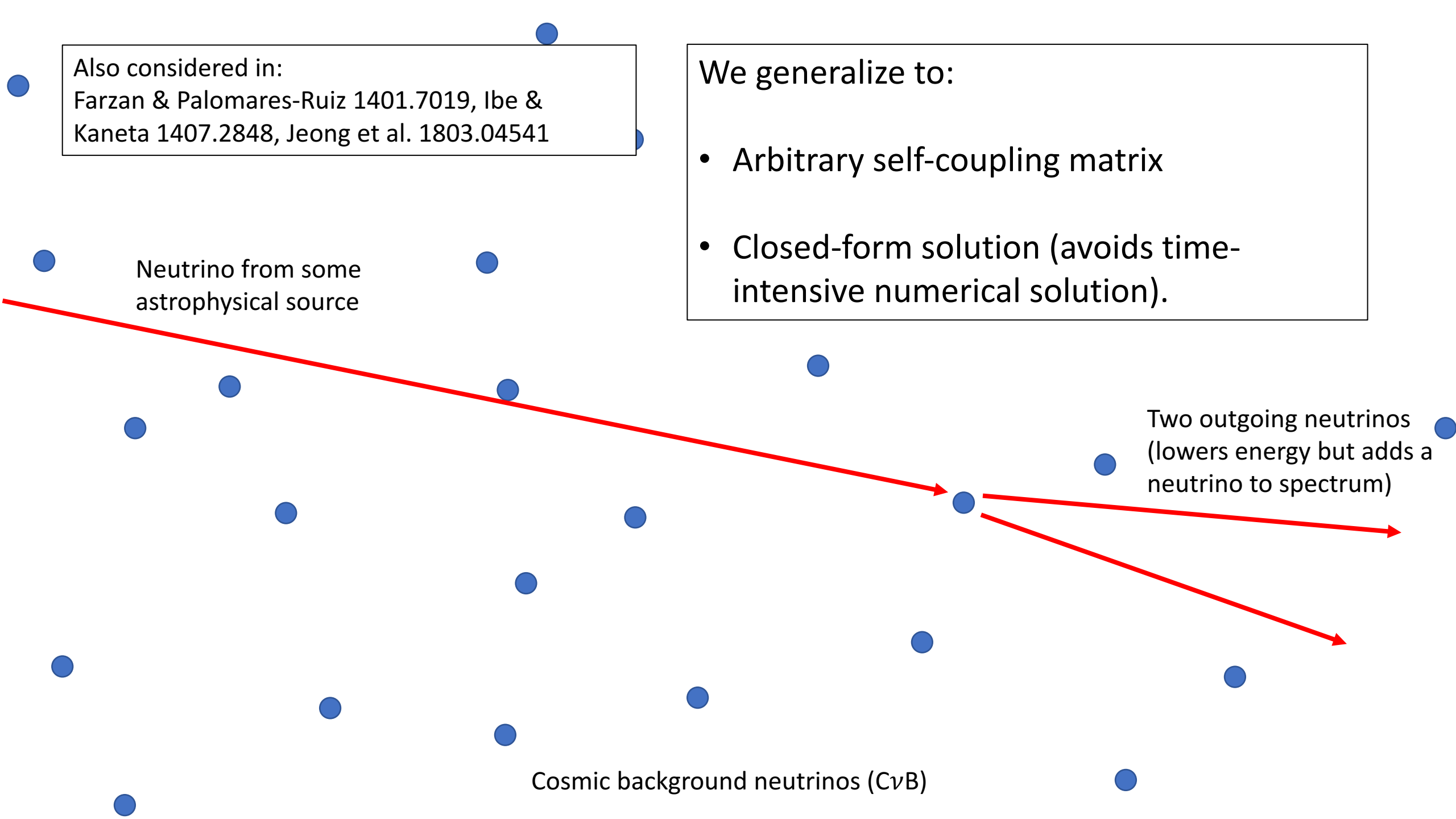Kaneta 1407.2848, Jeong et al. 1803.04541

We generalize to:

- Arbitrary self-coupling matrix

- Closed-form solution (avoids time-intensive numerical solution).

Neutrino from some astrophysical source

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Cosmic background neutrinos (CνB)

Boltzmann equations for evolution of neutrino flux

$$\frac{\partial \Phi_i}{\partial t} \; = \; H\Phi_i \; + \; HE\frac{\partial \Phi_i}{\partial E} \; + \; S_i(t, E)$$

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$\Phi_i(t, E)$ = specific flux of ν_i
(number per conformal time,
per comoving area, per energy)

Source term for
primary flux.

Boltzmann equations for evolution of neutrino flux

$$\frac{\partial \Phi_i}{\partial t} = H\Phi_i + HE\frac{\partial \Phi_i}{\partial E} + S_i(t,E) - \Gamma_i(t,E)\Phi_i$$

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Scattering events remove neutrinos from the primary spectrum. (Γ is rate.)

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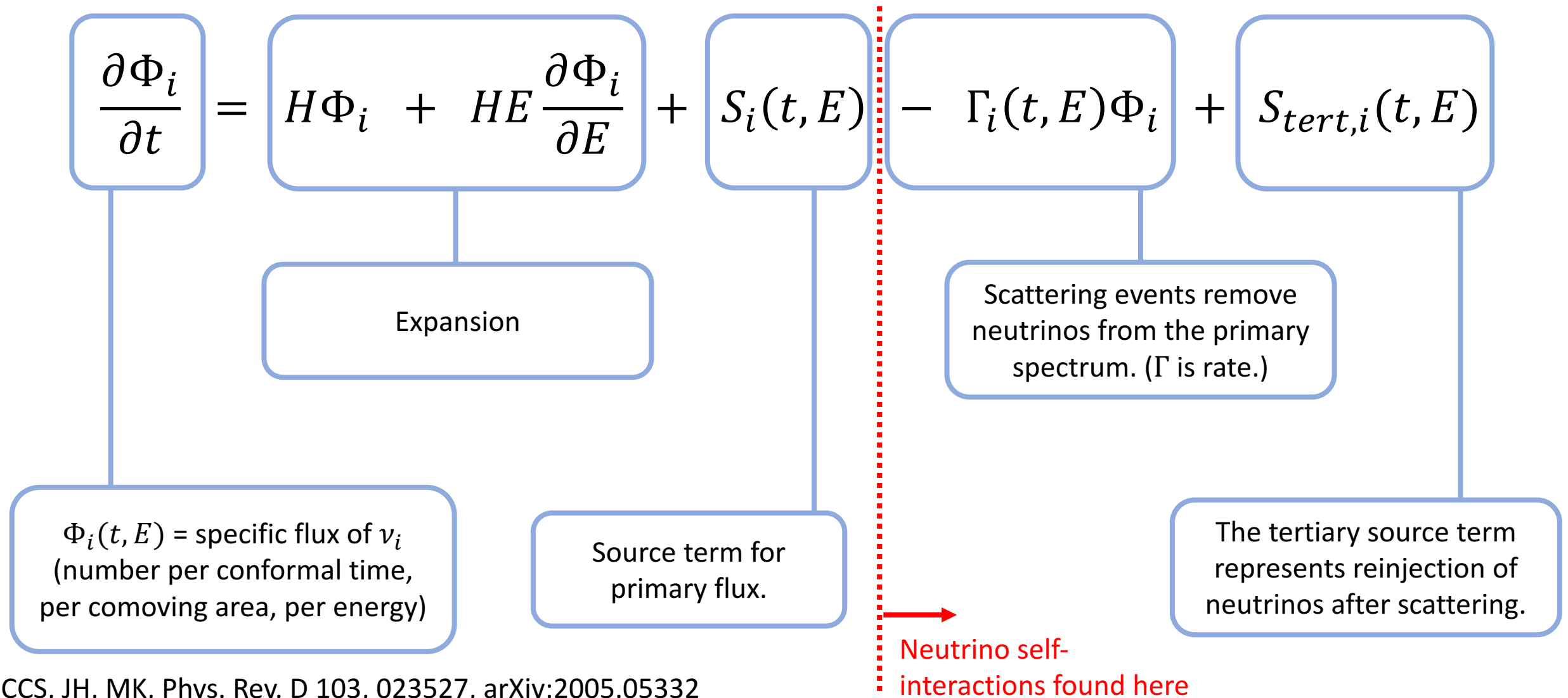$\Phi_i(t,E)$ = specific flux of ν_i (number per conformal time, per comoving area, per energy)

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Neutrino self-interactions found here

Resonant $\nu - \nu$ scattering

- Resonant scattering dominant – we take a Breit-Wigner form.

- In many cases, this can be well-approximated as a delta function at the resonant energy, $E_R = m_\phi^2 c^2 / 2m_\nu$.

Result for multiple flavors, arbitrary self-coupling matrix

$$\Phi_i(t,E) = \int_{-\infty}^{t} dt' \left(\frac{a(t)}{a(t')}\right) e^{-\tau_i(t',t,E)} \tilde{S}_i\left(t', \frac{a(t)}{a(t')}E\right)$$

Optical depth depends on form of neutrino self-coupling matrix...

$\tilde{S}_i = S_i + S_{tertiary}$,
w/ tertiary source dep. on self-coupling matrix, and $\tilde{S}_i$ evaluated at higher resonant energy, ...

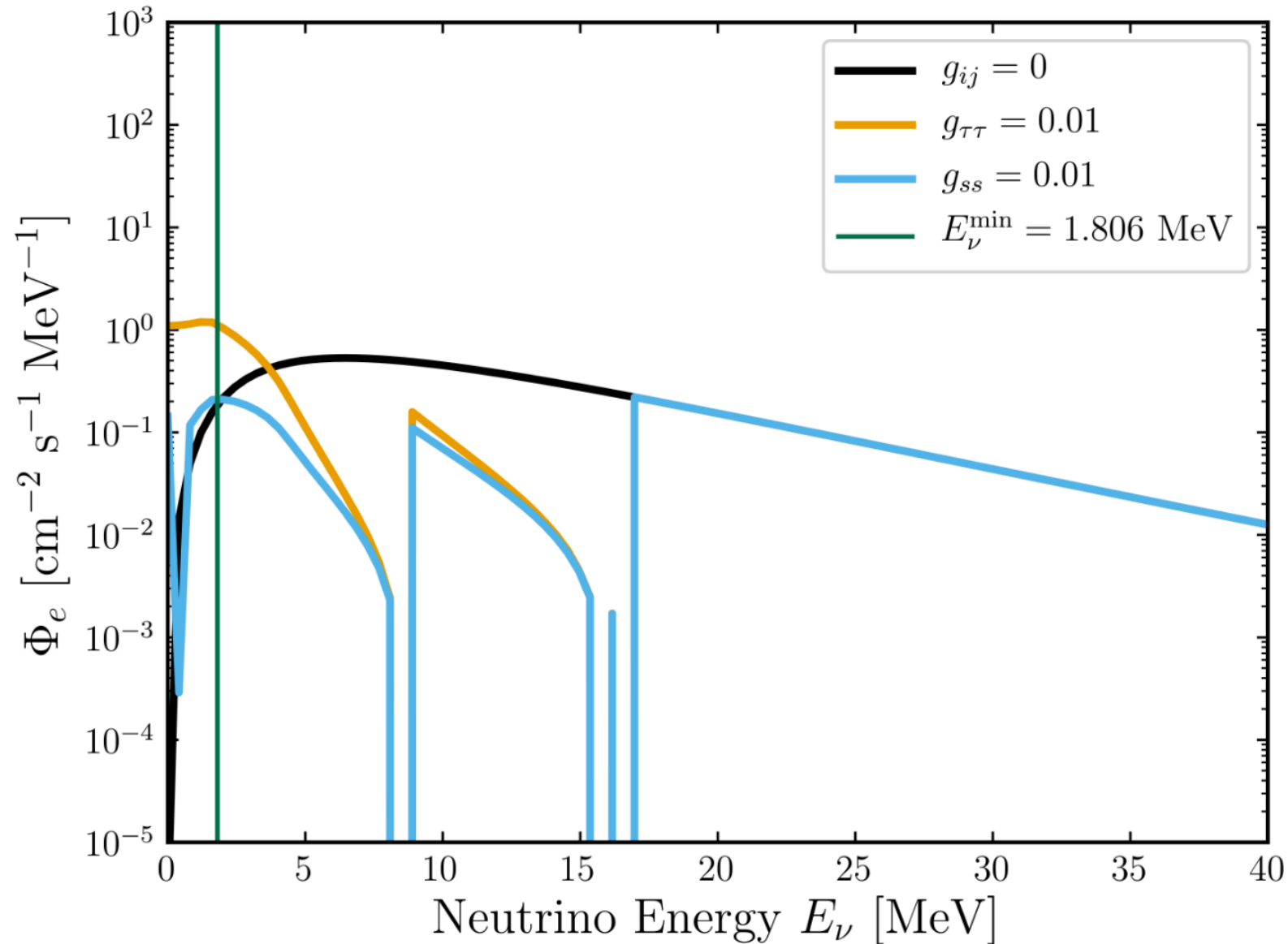## Result for multiple flavors, arbitrary self-coupling matrix

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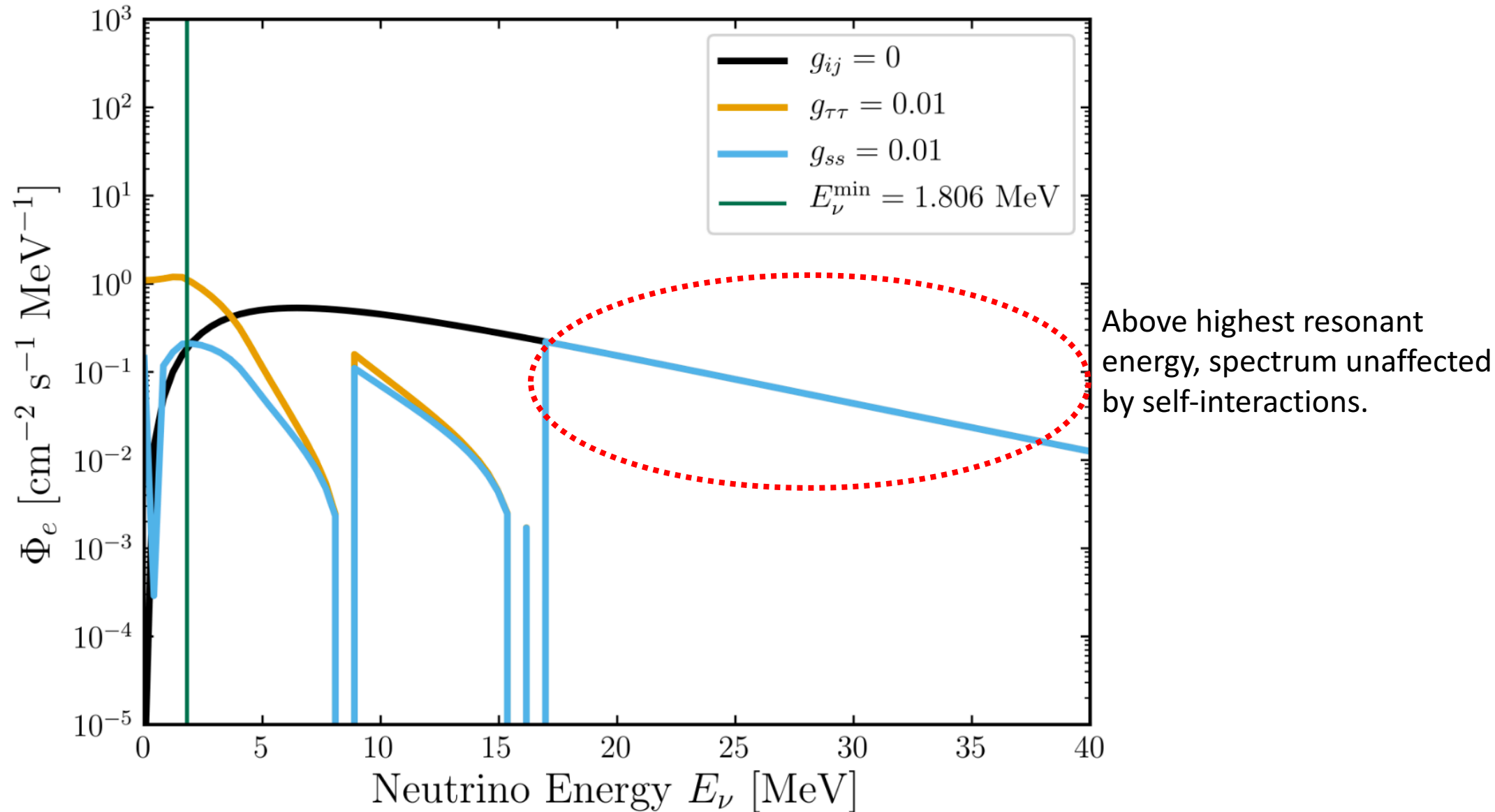Optical depth depends on form of neutrino self-coupling matrix...

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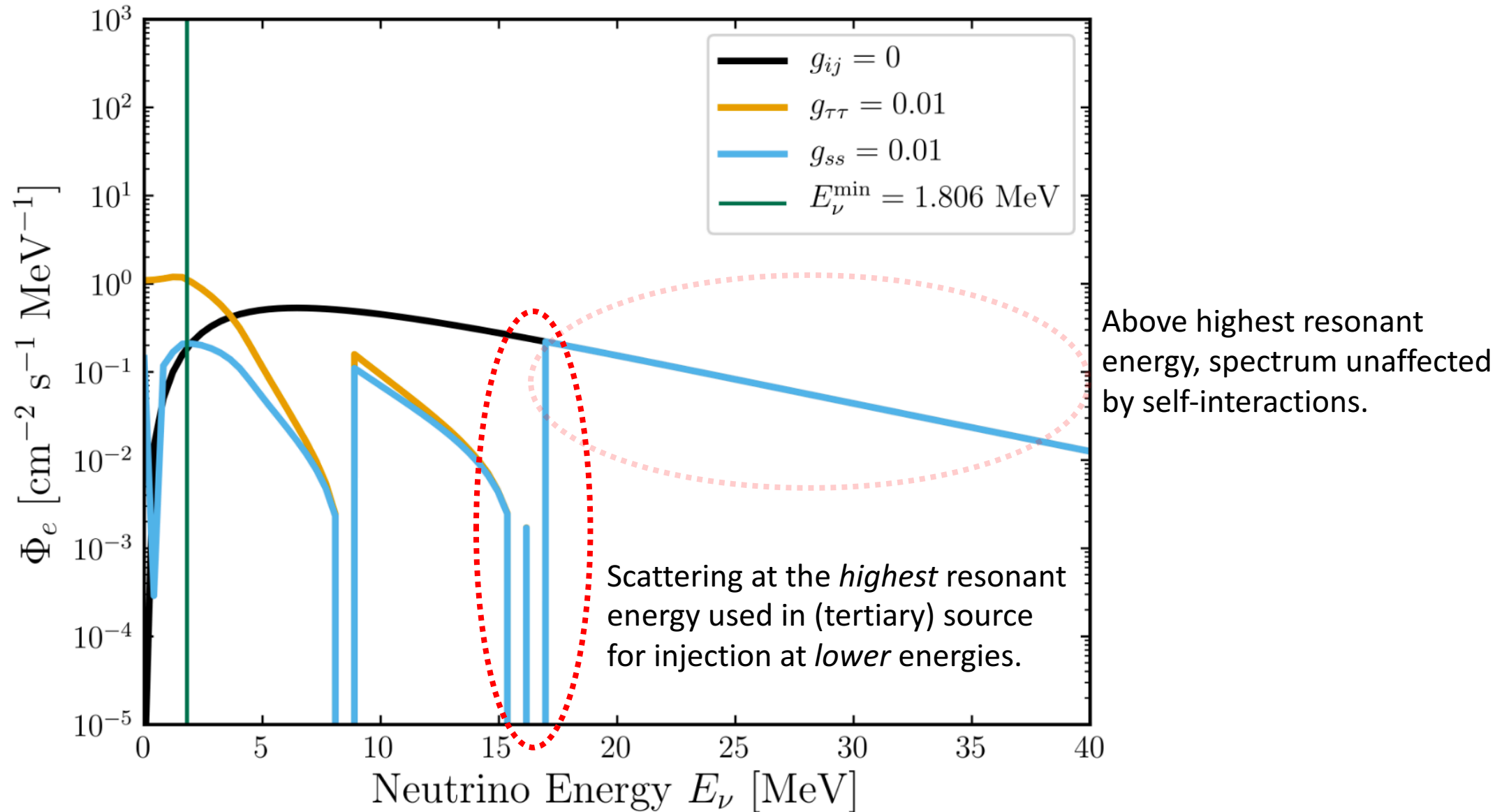Details here are pretty involved for such a short talk... See paper.

CCS, JH, MK, Phys. Rev. D 103, 023527, arXiv:2005.05332

Example: Diffuse Supernova Neutrino Background (DSNB)

CCS, JH, MK, Phys. Rev. D 103, 023527, arXiv:2005.05332

Above highest resonant energy, spectrum unaffected by self-interactions.

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Scattering at the *highest* resonant energy used in (tertiary) source for injection at *lower* energies.

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Example: Diffuse Supernova Neutrino Background (DSNB)

Neutrinos removed from spectrum at resonances, injected at lower energies.

Above highest resonant energy, spectrum unaffected by self-interactions.

Scattering at the *highest* resonant energy used in (tertiary) source for injection at *lower* energies.

Legend:
- $g_{ij} = 0$
- $g_{\tau\tau} = 0.01$
- $g_{ss} = 0.01$
- $E_\nu^{\min} = 1.806$ MeV

Axes: Φ_e [cm^{-2} s^{-1} MeV^{-1}] vs. Neutrino Energy E_ν [MeV]

CCS, JH, MK, Phys. Rev. D 103, 023527, arXiv:2005.05332

Event rates, +/- 1 sigma for 10 years at Super-K w/ gadolinium.

Comparison with expected spectrum at T = 8 MeV in absence of self-interactions.

Legend:
- $g_{ij} = 0$
- $g_{\tau\tau} = 0.01$
- $g_{ss} = 0.01$
- $(S/N)_+ = +1$
- $(S/N)_- = -1$

Axis labels: $N_{\text{events}}/(22.5\ \text{kton})$ vs Positron Energy E_{e^+} [MeV]

CCS, JH, MK, Phys. Rev. D 103, 023527, arXiv:2005.05332
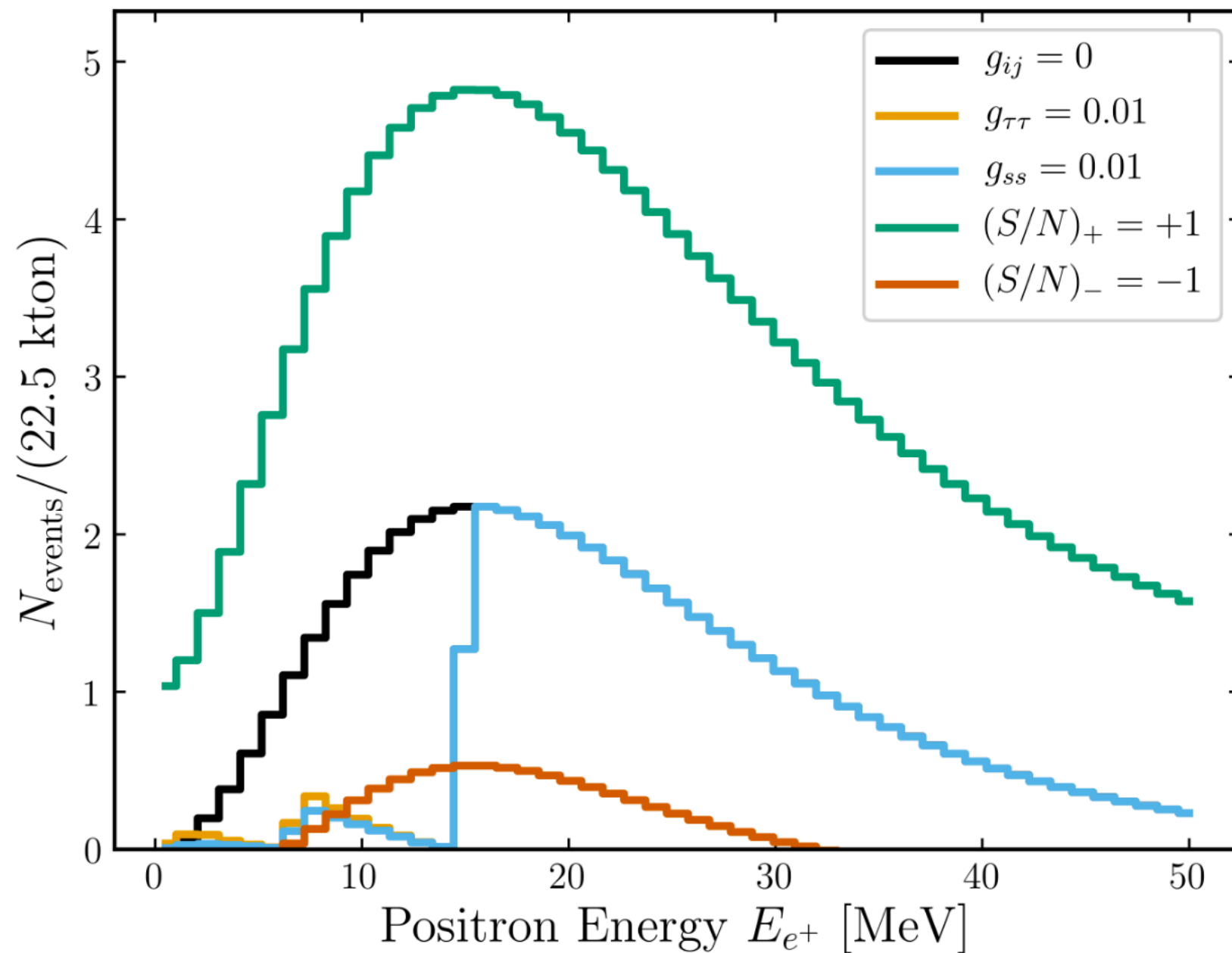
Forecasted 1-sigma constraints on coupling & scalar mediator, for 10 years at Super-K w/ gadolinium.

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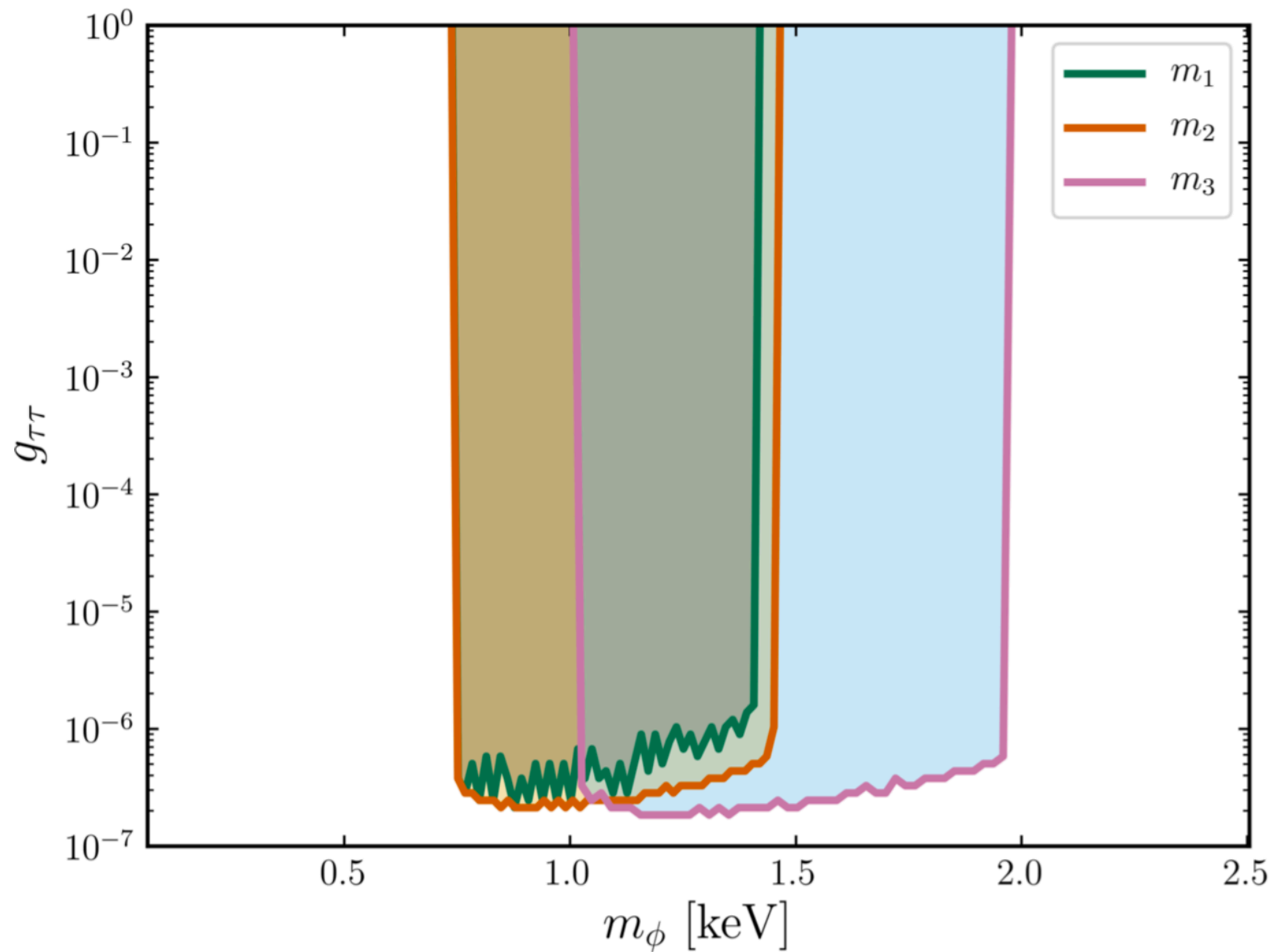
Example: High-Energy Astrophysical Neutrinos

Forecasted 1-sigma constraints on coupling & scalar mediator, for 988 days at IceCube.
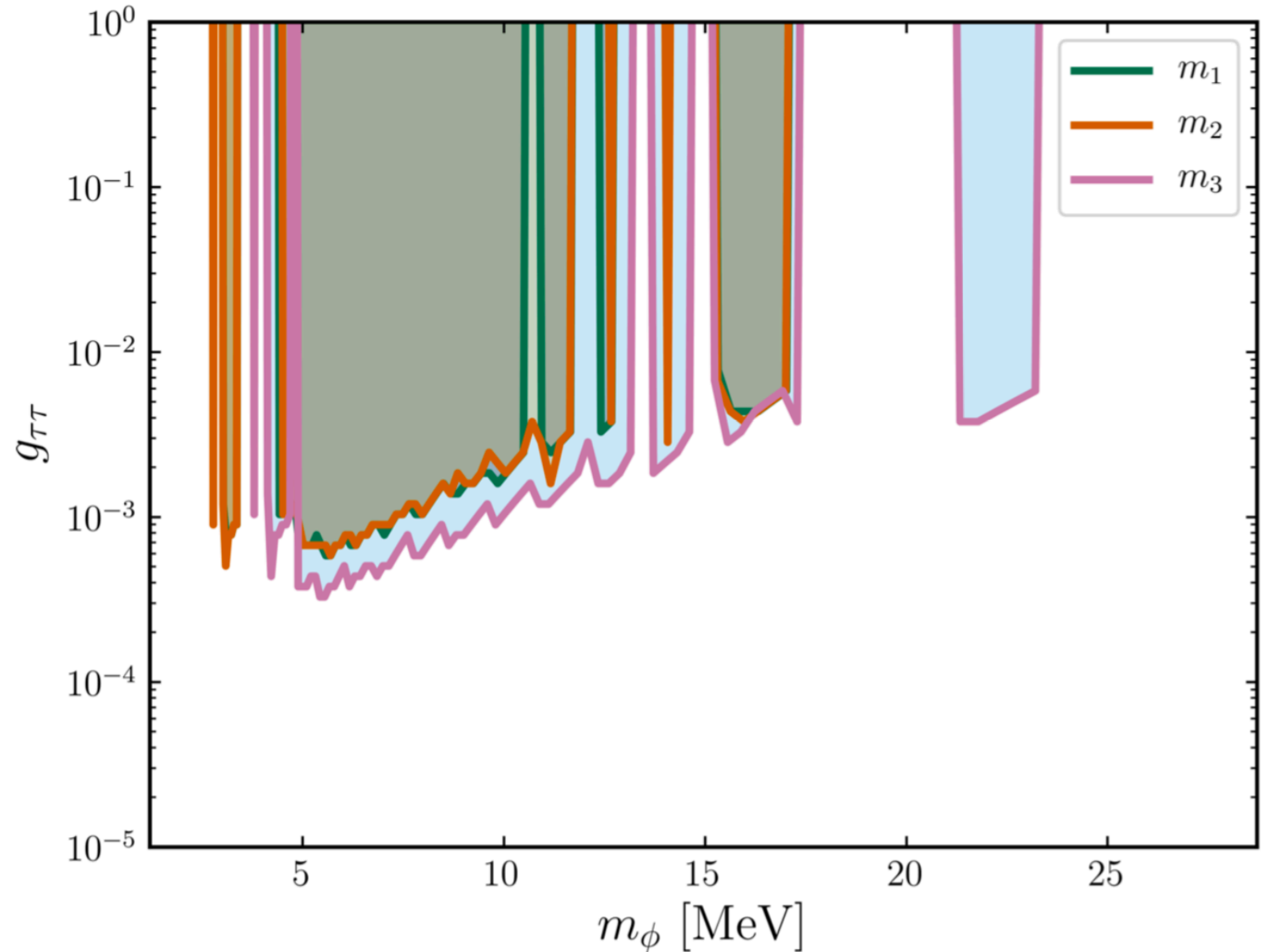
Summary

- Efficient way to calculate observed spectra, given a source and model of neutrino self-interactions.

- Observation of the DSNB by Super-K can constrain neutrino self-interactions with $\sim$ keV mass mediators.

- High-Energy Astrophysical Neutrinos at IceCube: can constrain $\sim$ MeV mediators.

Thank you!

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