Neutrino oscillations and decoherence: insights from microscopic models

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based on work in collaboration with
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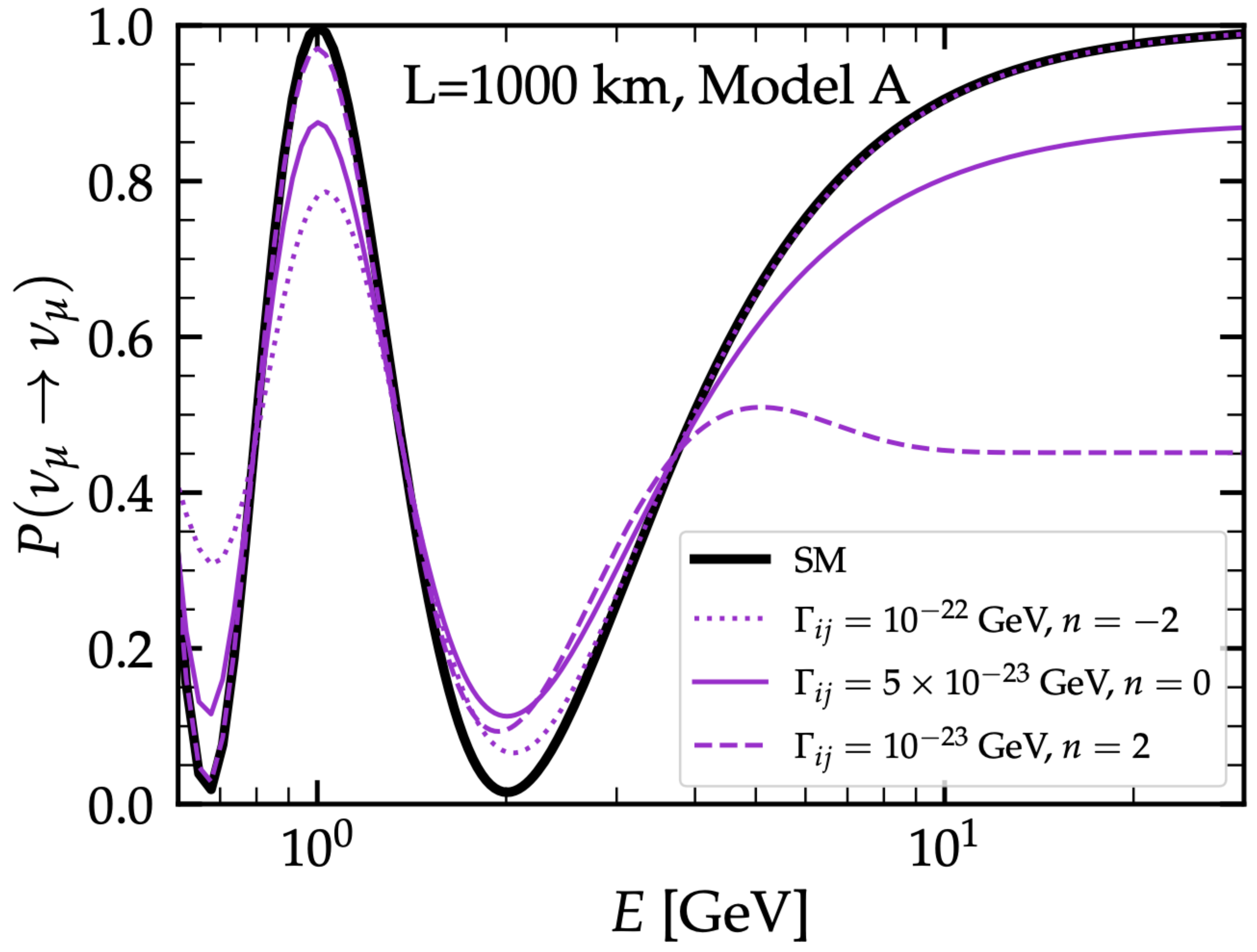
Friedrich-Alexander-Universität Erlangen-Nürnberg

KM3NeT

Erlangen Centre for Astroparticle Physics

Motivation

Precision era for decoherence in neutrino oscillations



[De Romeri, Giunti, Stuttard, Ternes 2306.14699 [hep-ph]]

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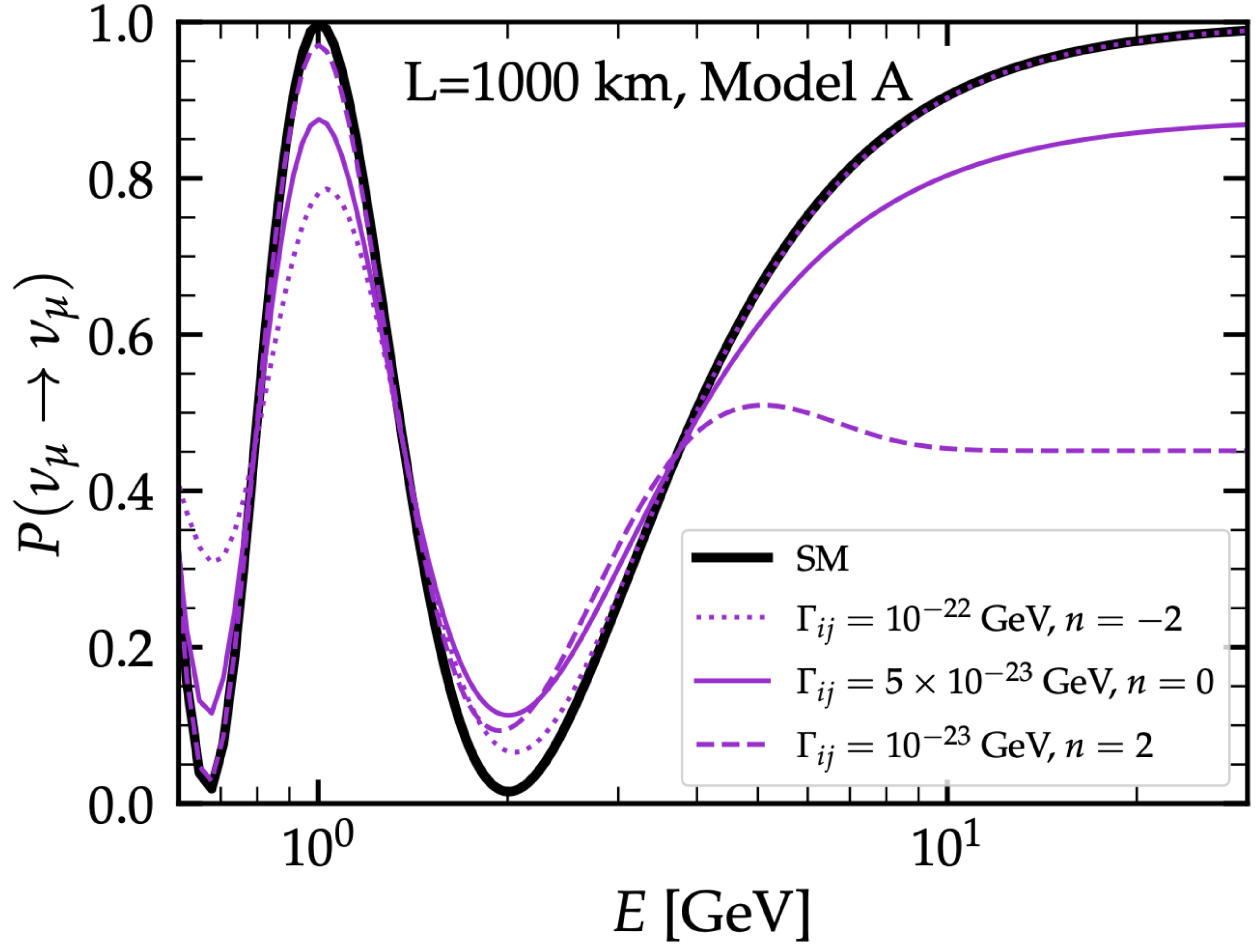

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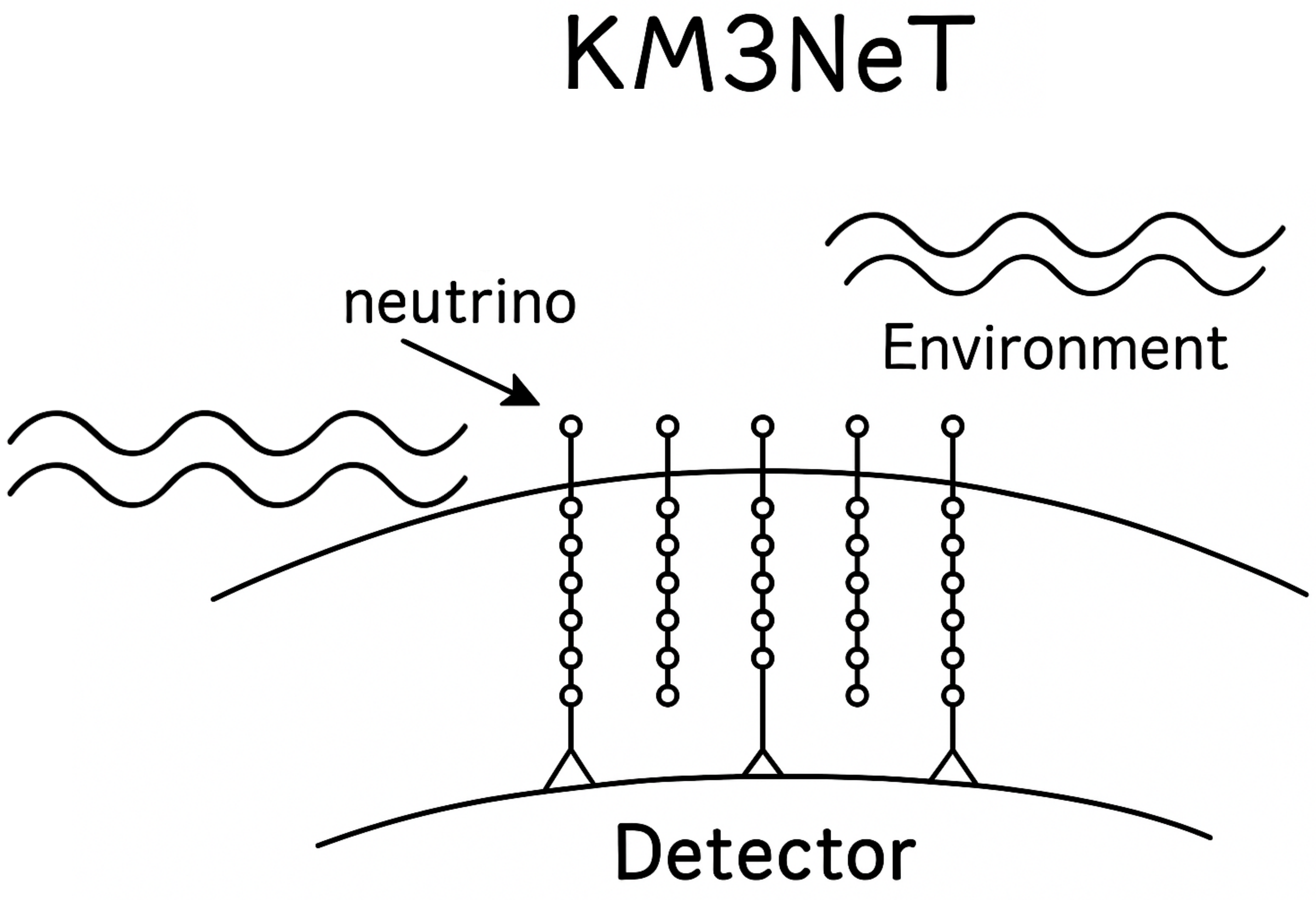

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Experiments

Microscopic models

Phenomenological models

neutrino physical interaction in the framework of open quantum systems

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Which is the underlying physics?

Maybe coupling to gravity $\longrightarrow$ signature for quantum gravity?

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Which is the underlying physics?
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Questions

Can one justify via theoretical models a given phenomenological ansatz?

Can a phenomenological model select a preferred microscopic model?

Phenomenological models $\xrightarrow{\text{typically used to explain}}$ Experiments

Experiments $\xrightarrow{\text{constrain pheno models}}$ Phenomenological models

Phenomenological models	typically used to explain → ← constrain pheno models	Experiments

However, there are still some open points:

energy dependence

shape of the dissipator

⟶ these choices can affect the oscillation probabilities

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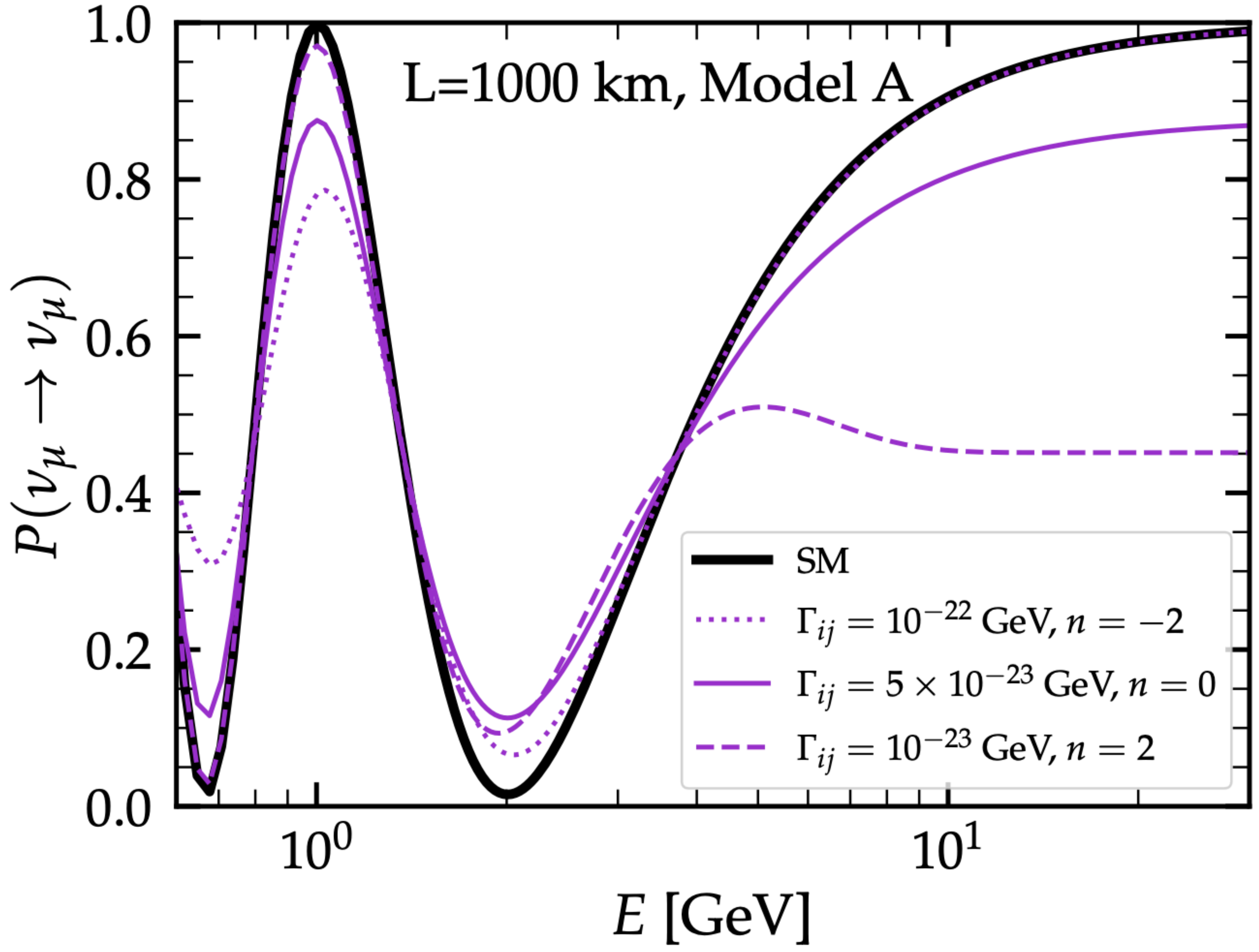
Microscopic models

Start from **open QFT** models: **underlying microscopic QM** model arises in the limit

⟶ the coupling between environment and system is given to us by the **action**

Phenomenological models



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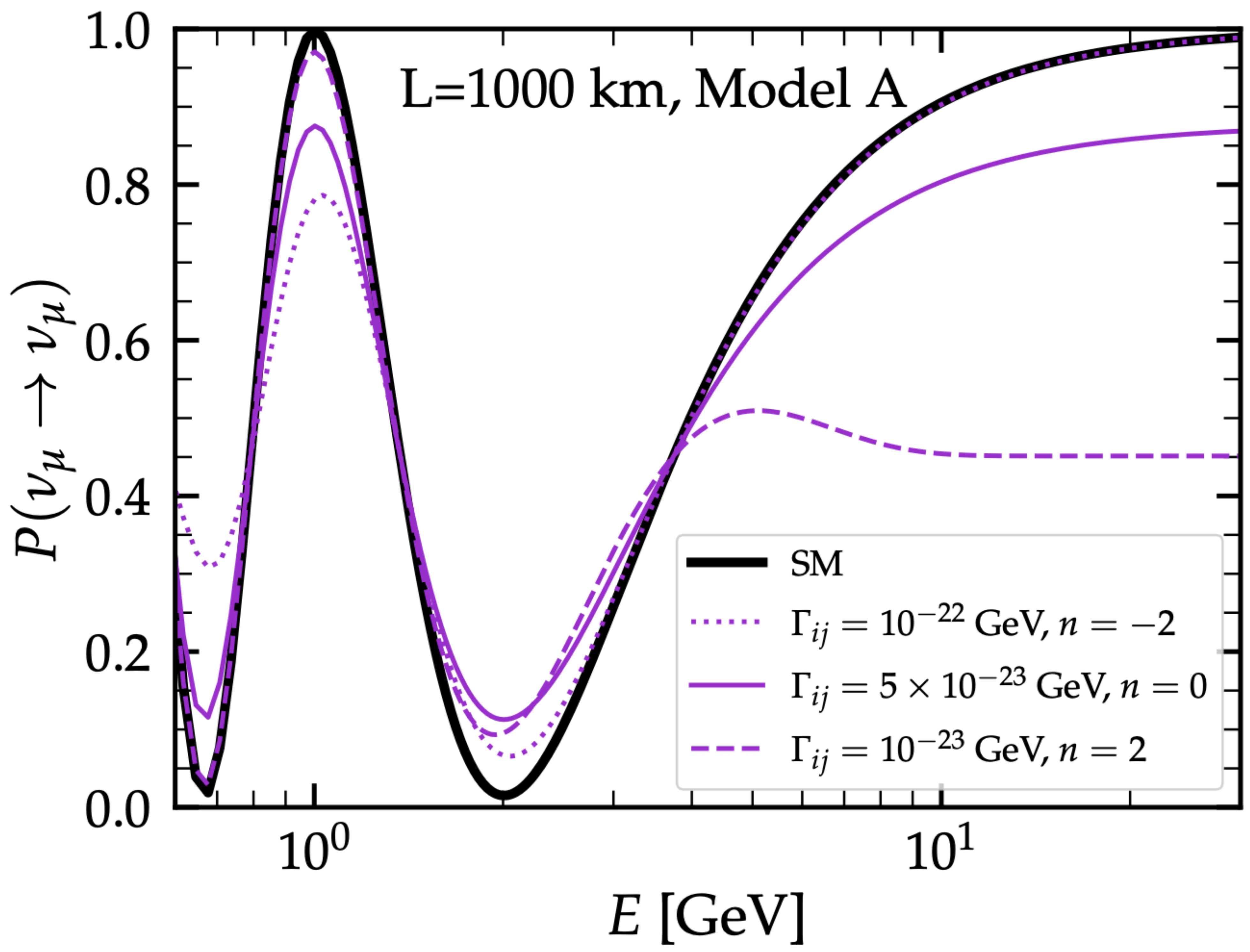

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from the **dissipator:** contains both decoherence & dissipation

$$\rho_{ij}(t) = \rho_{ij}(0) \cdot e^{-\frac{i}{\hbar}(H_i - H_j)t - \Gamma_{ij} t}$$

$$\Gamma_{ij} = \gamma_{ij} E^n, \qquad n \in [-2, 3]$$

E^n : energy dependence

γ_{ij} : shape of the dissipator

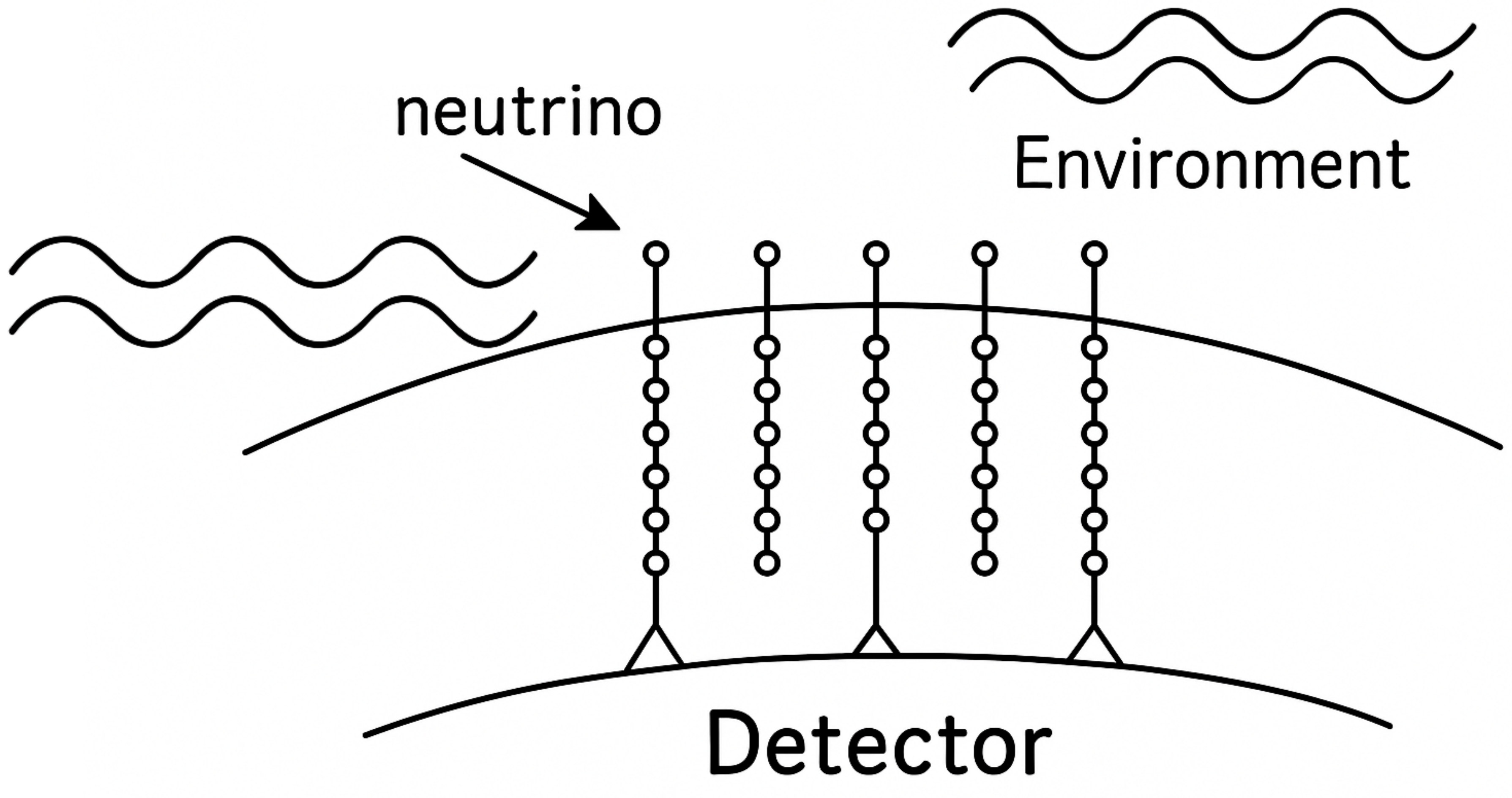
Microscopic
models

Microscopic models

QFT model → QM model:

Hamiltonian (environment + system + interaction)

$$\hat{H} = \hat{H}_S + \hat{H}_{\mathcal{E}} + \hat{H}_{\text{int}} \ , \quad \hat{H}_{\text{int}} = \hat{S} \otimes \sum_{i=1}^{N} g_i \hat{E}_i$$



Microscopic models $\longrightarrow$ Lindblad operator(s)

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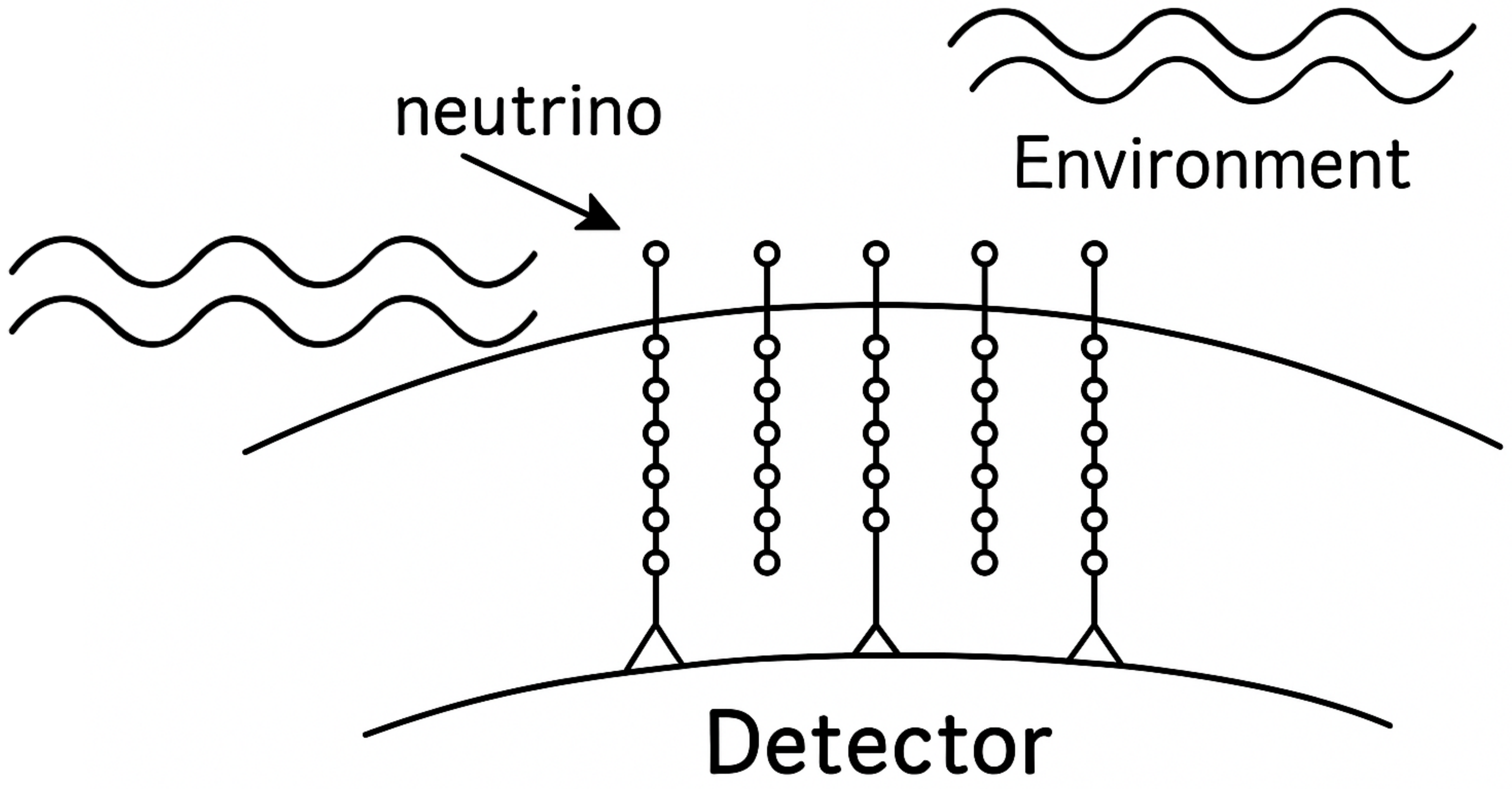

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Trace out environment dofs:
Lindblad master equation
(Lindblad operators)

$$\frac{d\hat{\rho}(t)}{dt} = -i[\hat{H}_S, \hat{\rho}(t)] + \underbrace{\frac{1}{2}\sum_j \left([\hat{A}_j, \hat{\rho}(t)\hat{A}_j^\dagger] + [\hat{A}_j\hat{\rho}(t), \hat{A}_j^\dagger] \right)}_{\textbf{dissipator}}$$

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Microscopic models → Lindblad operator(s) → Dissipator

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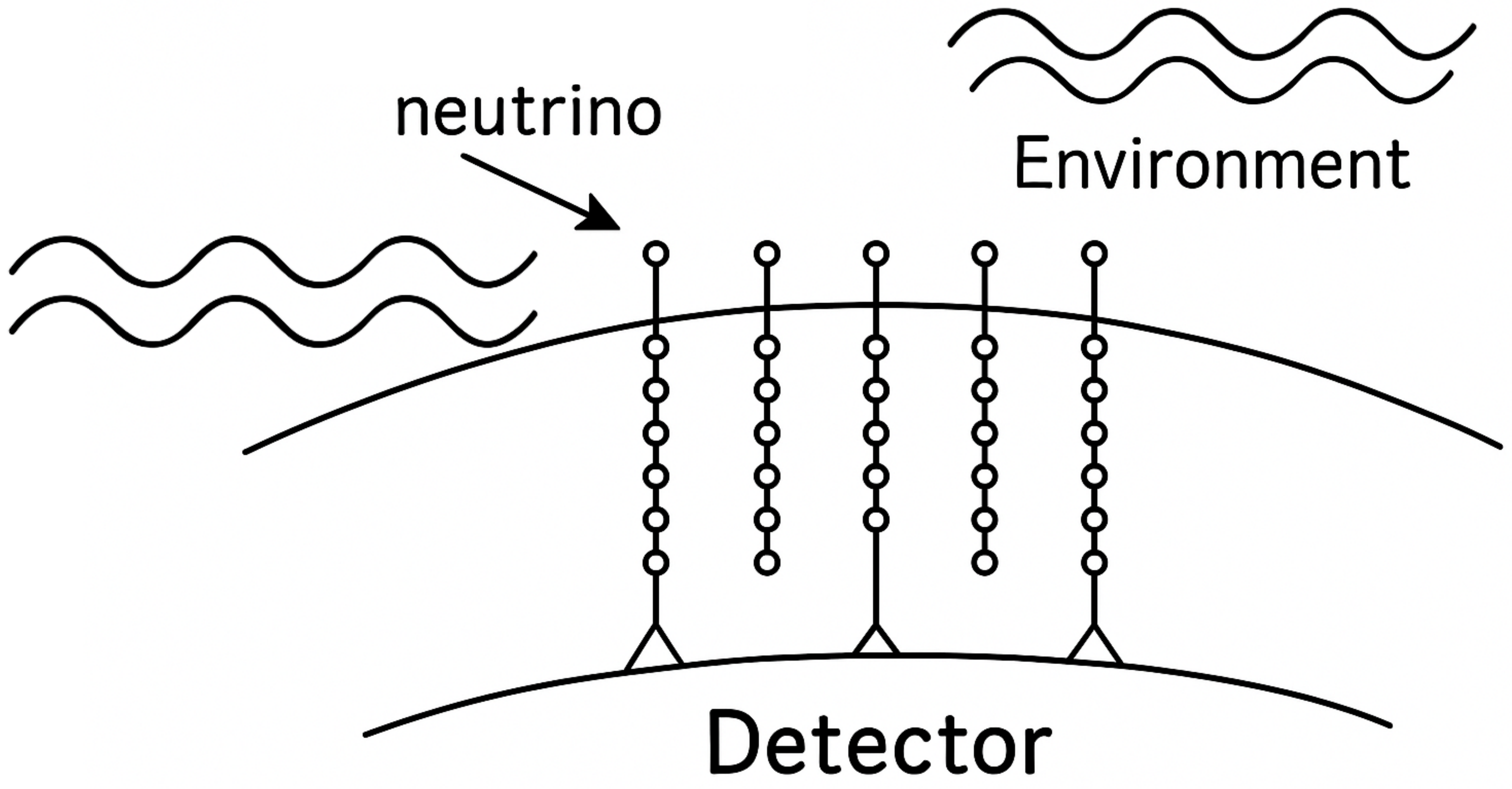

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Vectorize the master equation to write down **dissipator**

$$\frac{d}{dt}|\rho\rangle\rangle = \mathbb{L}|\rho\rangle\rangle$$

$$\frac{d}{dt}\rho_\alpha(t) = (h^\mu f_{\mu\nu\alpha} + D_{\nu\alpha})\,\rho^\nu(t)$$

Energy dependence

Rationale: positive powers, decoherence stronger at high E — high energy atmospheric

negative powers, decoherence stronger at low E — solar neutrinos, low energy atmospheric

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high energy atmospheric

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Consider for instance the QM model

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$$= \hat{H}_S + \frac{1}{2}\sum_{i=1}^{N}\left[\hat{p}_i^2 + \omega_i^2 \hat{q}_i^2\right] - \hat{H}_S \otimes \sum_{i=1}^{N} g_i \hat{q}_i$$

inspired by coupling via linearized gravity

[Blencowe, Xu 2005.02554 [quant-
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[Roman Kemper's talk]

[Domi, Eberl, Fahn, Giesel, Hennig, Katz, Kemper, Kobler 2403.03106 [gr-qc]]

$$\longrightarrow \begin{cases} \gamma_{ij} = \dfrac{\eta^2 c^8 k_B T}{\hbar^3}(\Delta m_{ij}^2)^2 \\ n = -2 \end{cases}$$

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Generalized model $\hat{H} = \hat{H}_S + \frac{1}{2}\sum_{i=1}^{N}\left[\hat{p}_i^2 + \omega_i^2 \hat{q}_i^2\right] - f(\hat{H}_S) \otimes \sum_{i=1}^{N} g_i \hat{q}_i$

Ansatz $f(\hat{H}_S) = \hat{H}_S^{k/2}, \qquad k \geq 1 \text{ and } k \in \mathbb{N} \qquad \longrightarrow \qquad \Gamma_{ij} \approx E^{k-4}\frac{k^2(\Delta m_{ij}^2)^2}{16} \propto E^{k-4}$

Energy dependence

If $f(\hat{H}_S) \sim \hat{H}_S^0 \longrightarrow$ no decoherence

If $f(\hat{H}_S) \sim \hat{H}_S^{1/2} \longrightarrow n = -3$

If $f(\hat{H}_S) \sim \hat{H}_S \longrightarrow n = -2$

If $f(\hat{H}_S) \sim \hat{H}_S^{3/2} \longrightarrow n = -1$

If $f(\hat{H}_S) \sim \hat{H}_S^2 \longrightarrow n = 0$

If $f(\hat{H}_S) \sim \hat{H}_S^{5/2} \longrightarrow n = 1$

If $f(\hat{H}_S) \sim \hat{H}_S^3 \longrightarrow n = 2$

$\vdots$

higher order

Energy dependence

If $f(\hat{H}_S) \sim \hat{H}_S^0 \longrightarrow$ no decoherence

different environments
(if at all specified),
different physics

If $f(\hat{H}_S) \sim \hat{H}_S^{1/2} \longrightarrow n = -3$

If $f(\hat{H}_S) \sim \hat{H}_S \longrightarrow n = -2$ Linearized gravity model, lightcone fluctuations [Studdard 2103.15313 [hep-ph]]

If $f(\hat{H}_S) \sim \hat{H}_S^{3/2} \longrightarrow n = -1$ Lorentz invariant model [Lisi, Marrone and Montanino hep-ph/0002053]

If $f(\hat{H}_S) \sim \hat{H}_S^2 \longrightarrow n = 0$ Energy independent

If $f(\hat{H}_S) \sim \hat{H}_S^{5/2} \longrightarrow n = 1$ Cross-section-like, quantum mechanics violation [Liu, Hu, and Ge, 1997]

If $f(\hat{H}_S) \sim \hat{H}_S^3 \longrightarrow n = 2$ String motivated model [Ellis, Lopez, Mavromatos, Nanopoulos, Winstanley, hep-ph/9505340, gr-qc/9602011]

$\vdots$
higher order

[D'Esposito, Gubitosi 2306.14778 [hep-ph]]

Energy dependence

Phenomenological models $\rightleftarrows$ Microscopic models

Energy dependence

select the interaction Hamiltonian coupling

within a class of

Phenomenological models

Microscopic models

Energy dependence

$$\begin{tikzcd}[column sep=huge] \boxed{\text{Phenomenological models}} \arrow[r, shift left, "\text{select the interaction Hamiltonian coupling}"] & \boxed{\text{Microscopic models}} \arrow[l, shift left, "\text{select a given energy dependence}"] \end{tikzcd}$$

within a class of

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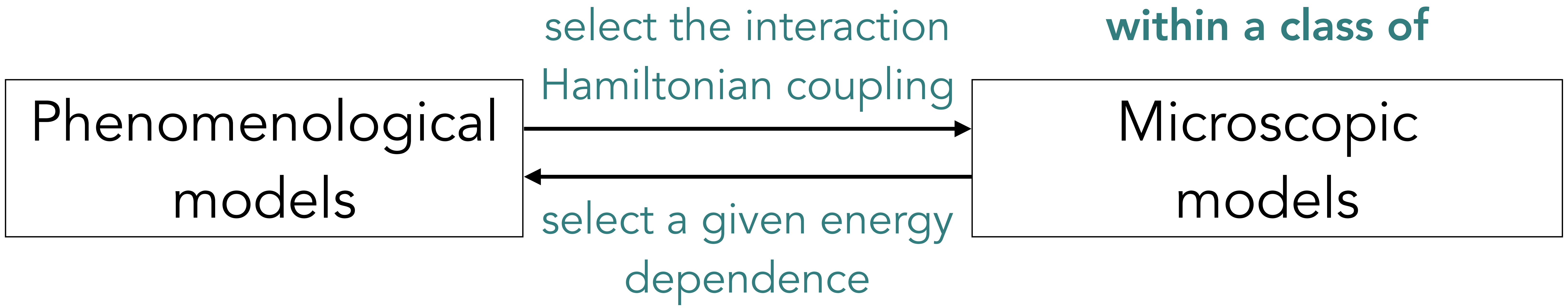

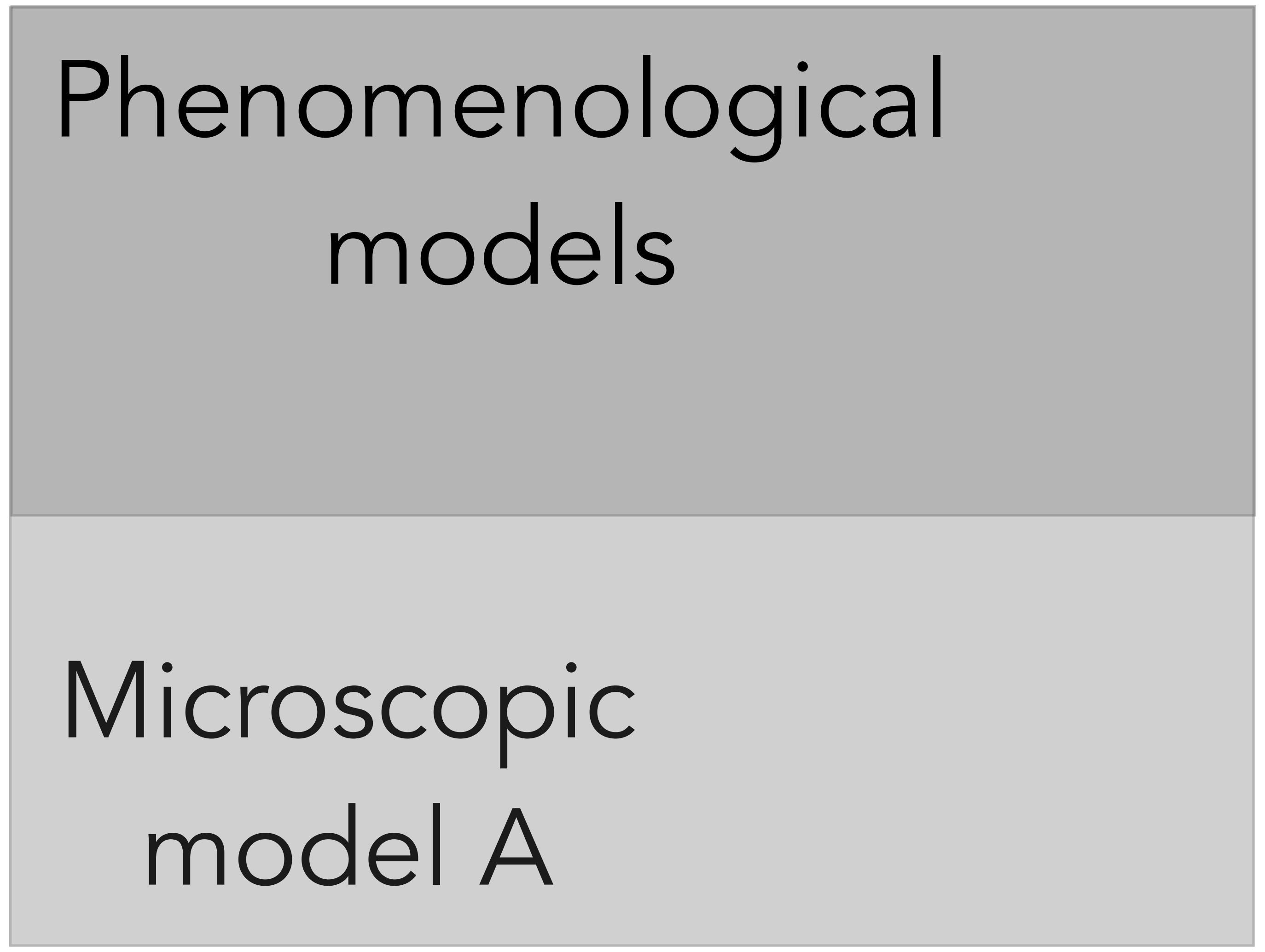

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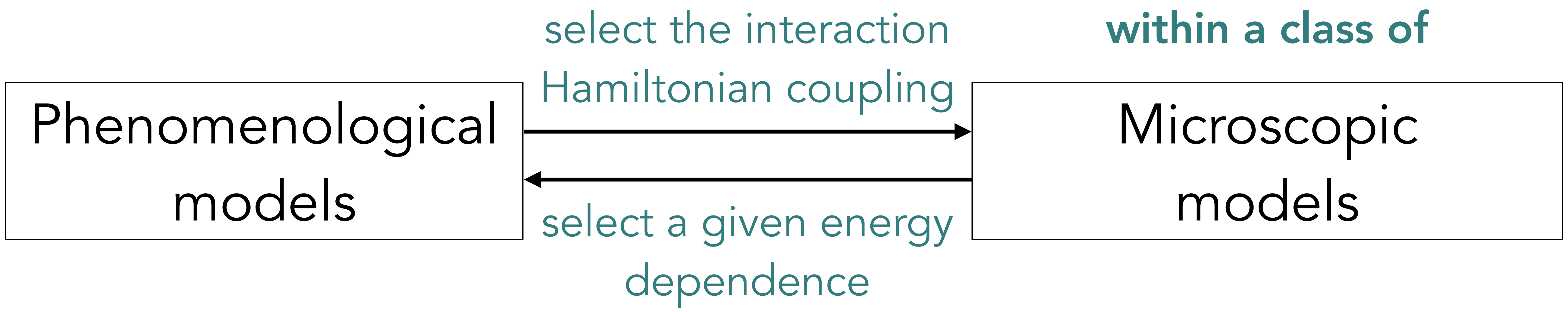

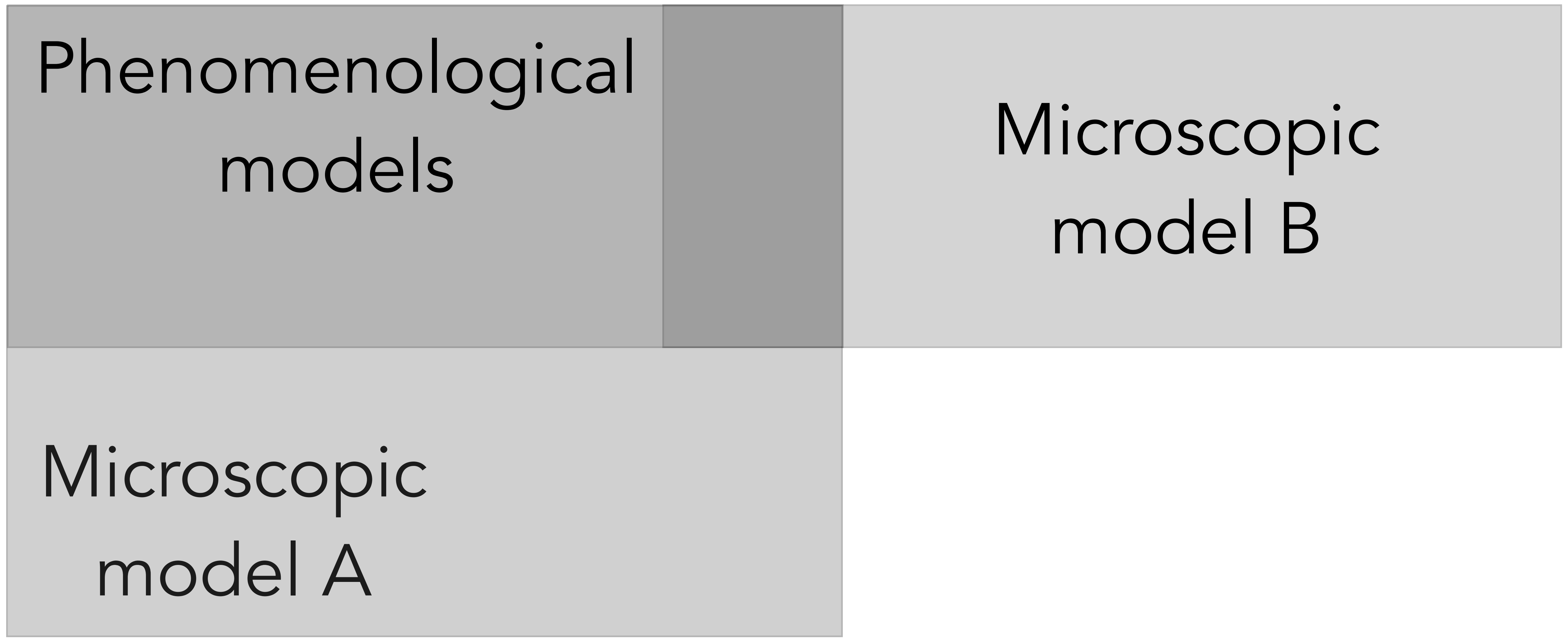

Shape of the dissipator

Rationale: Relaxation time (energy loss) $\gg$ Decoherence time

Expectation: solar and high energy atmospheric neutrinos' oscillations will "see" also dissipation

[Gomes, Gomes, Peres 2001.09250 [hep-ph]]

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In **vectorized** form

ansatz for the **dissipator**

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From the open quantum system perspective:

Microscopic models → Lindblad operator(s) → Dissipator

SU(2)

$$\hat{A}_S = \sum_{i=1}^{3} a_i \hat{\sigma}_i \longrightarrow D_{\mu\nu} = -\frac{1}{2}\begin{pmatrix} (a_2)^2 + (a_3)^2 & -a_1 a_2 & -a_1 a_3 \\ -a_1 a_2 & (a_1)^2 + (a_3)^2 & -a_2 a_3 \\ -a_1 a_3 & -a_2 a_3 & (a_1)^2 + (a_2)^2 \end{pmatrix}$$

Shape of the dissipator

Energy conservation: The dissipator is diagonal.

$$D_{\mu\nu} = diag(-\gamma, -\gamma, 0) \quad \text{two flavour case} \quad \text{SU}(2)$$

$$D_{\mu\nu} = diag(0, -\Gamma_{21}, -\Gamma_{21}, 0, -\Gamma_{31}, -\Gamma_{31}, -\Gamma_{32}, -\Gamma_{32}, 0) \quad \text{three flavour case} \quad \text{SU}(3)$$

depend on the Lindblad operator(s) $\hat{A}_S$ and on Γ

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Lindblad operators $\longrightarrow$ specific form of the dissipator with **related non-zero off-diagonal entries**

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Consider the ansatz $\boxed{D_{\mu\nu} = diag(-\gamma, -\gamma, -\chi)}$

[Oliveira 1603.08065 [hep-ph]]

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Which is then the underlying system-environment physics?

Take home message

The interaction environment-system determines the dissipator, energy dependence and shape of dissipator

$$\hat{H} = \hat{H}_S + \hat{H}_{\mathcal{E}} + \hat{H}_{\text{int}}$$

$$\hat{S} \otimes \sum_{i=1}^{N} g_i \hat{E}_i$$

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both affect the Lindblad operators, hence the shape of the dissipator

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both affect the decoherence rate, hence the energy dependence

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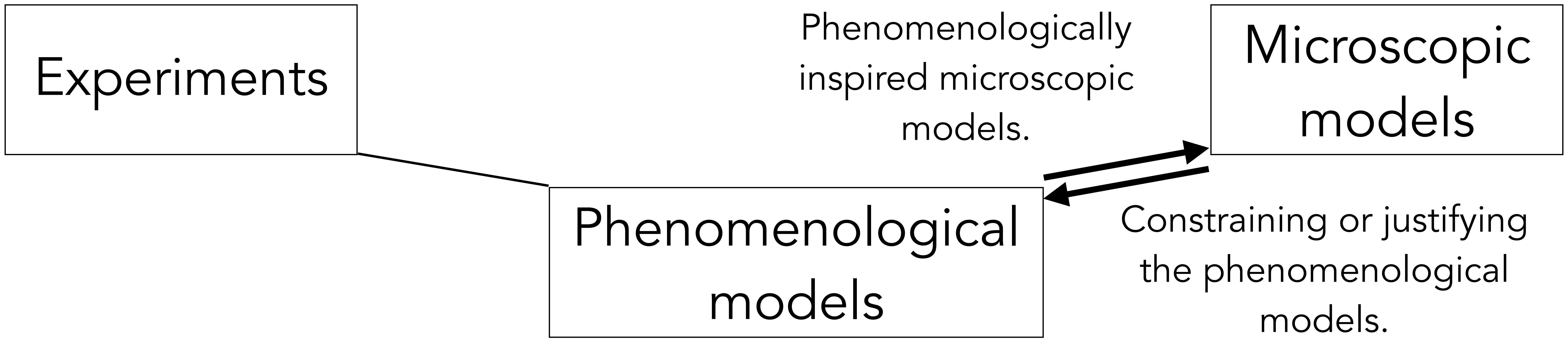
Conclusions

Precision era for decoherence in neutrino oscillations



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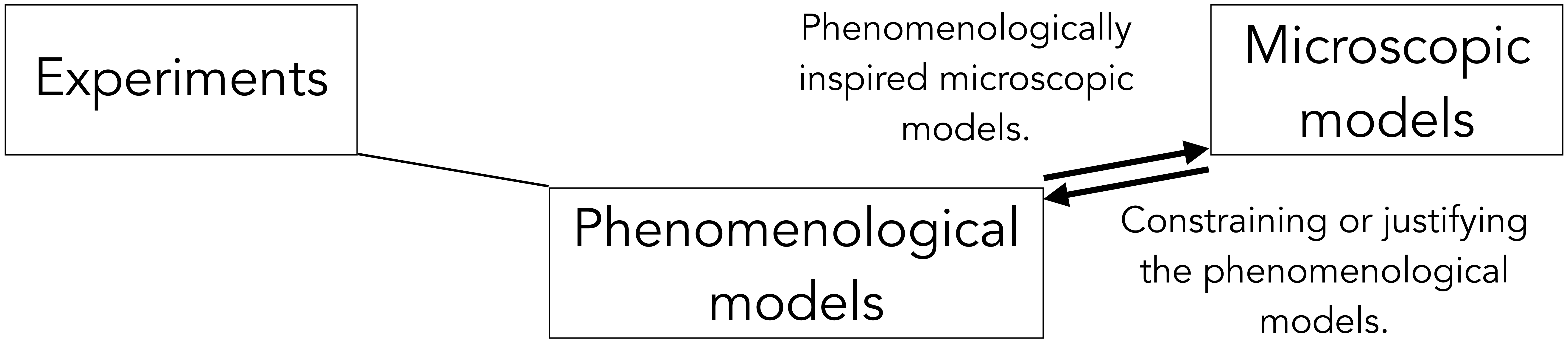


Understanding the underlying physics is important to interpret the data.

Conclusions

Precision era for
decoherence in neutrino oscillations

Experiments

Phenomenologically inspired microscopic models.

Microscopic models

Phenomenological models

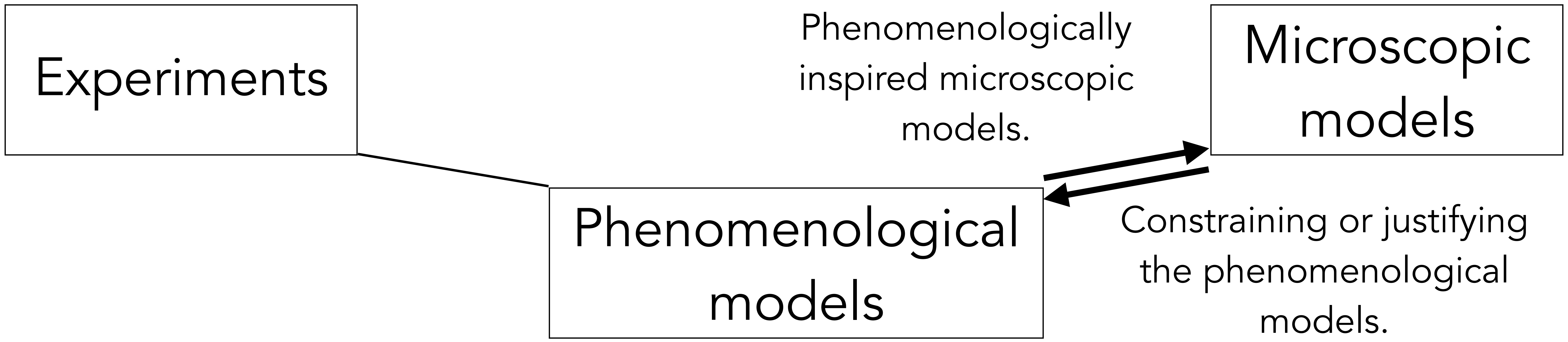
Constraining or justifying the phenomenological models.

Understanding the underlying physics is important to interpret the data.

Study of the **environment-system interaction** and mapping to pheno models $\longrightarrow$ energy dependence, shape of the dissipator

Conclusions

Precision era for decoherence in neutrino oscillations



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Study of the **environment-system interaction** and mapping to pheno models → energy dependence / shape of the dissipator

Thank you!