

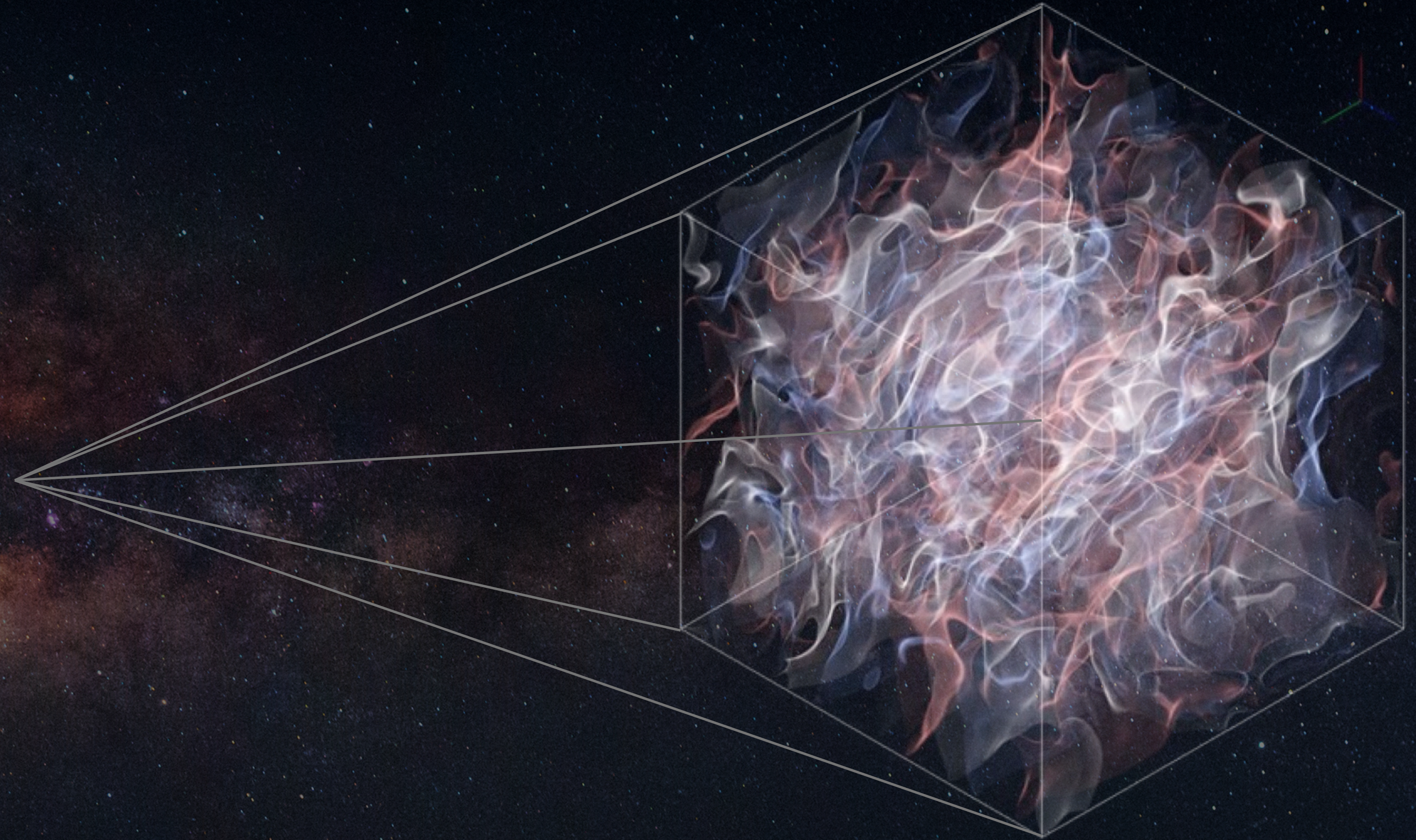
Supernova neutrinos on a quantum computer

Joachim Kopp

QuantHEP 2026

London, UK

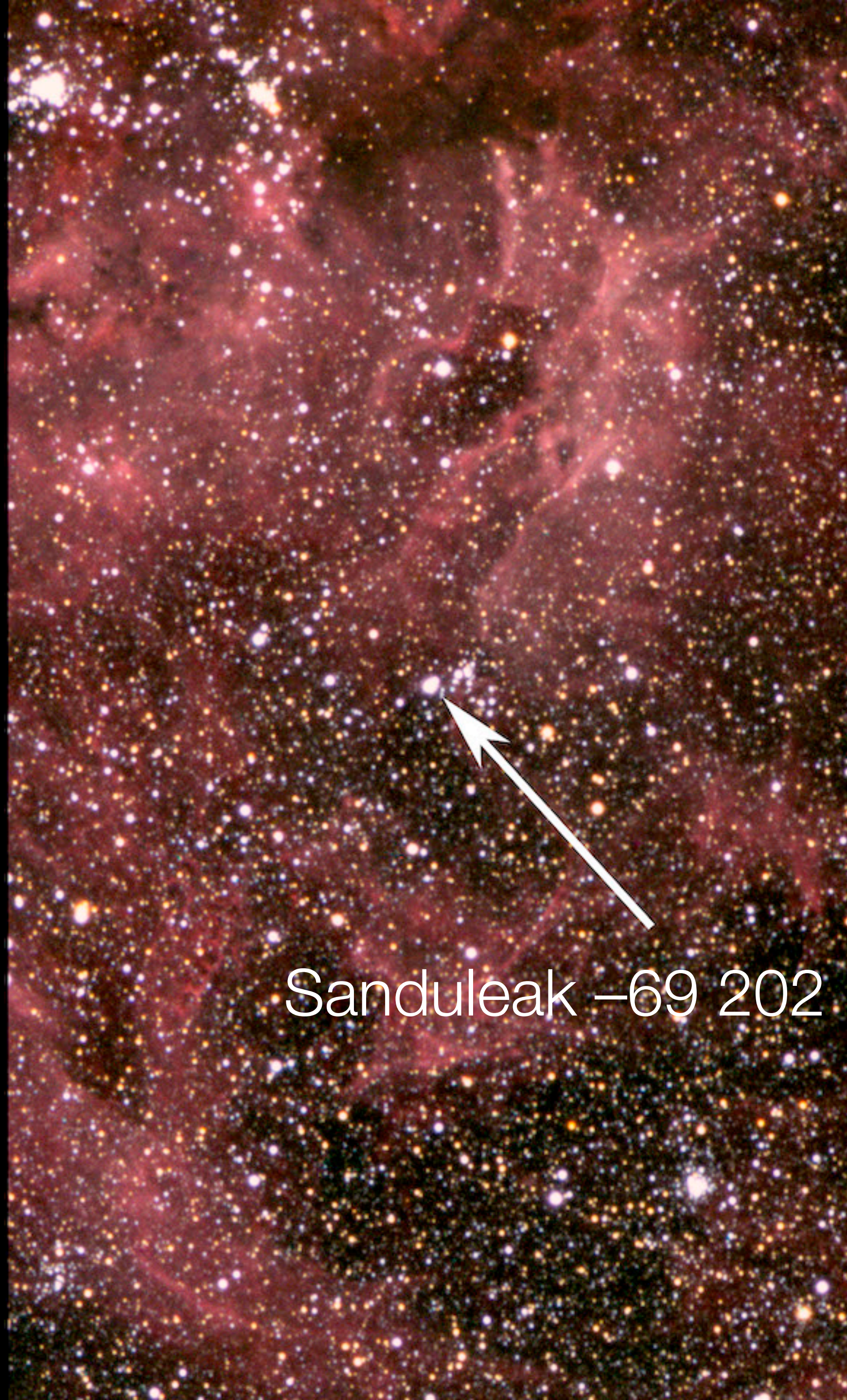
15 July 2026



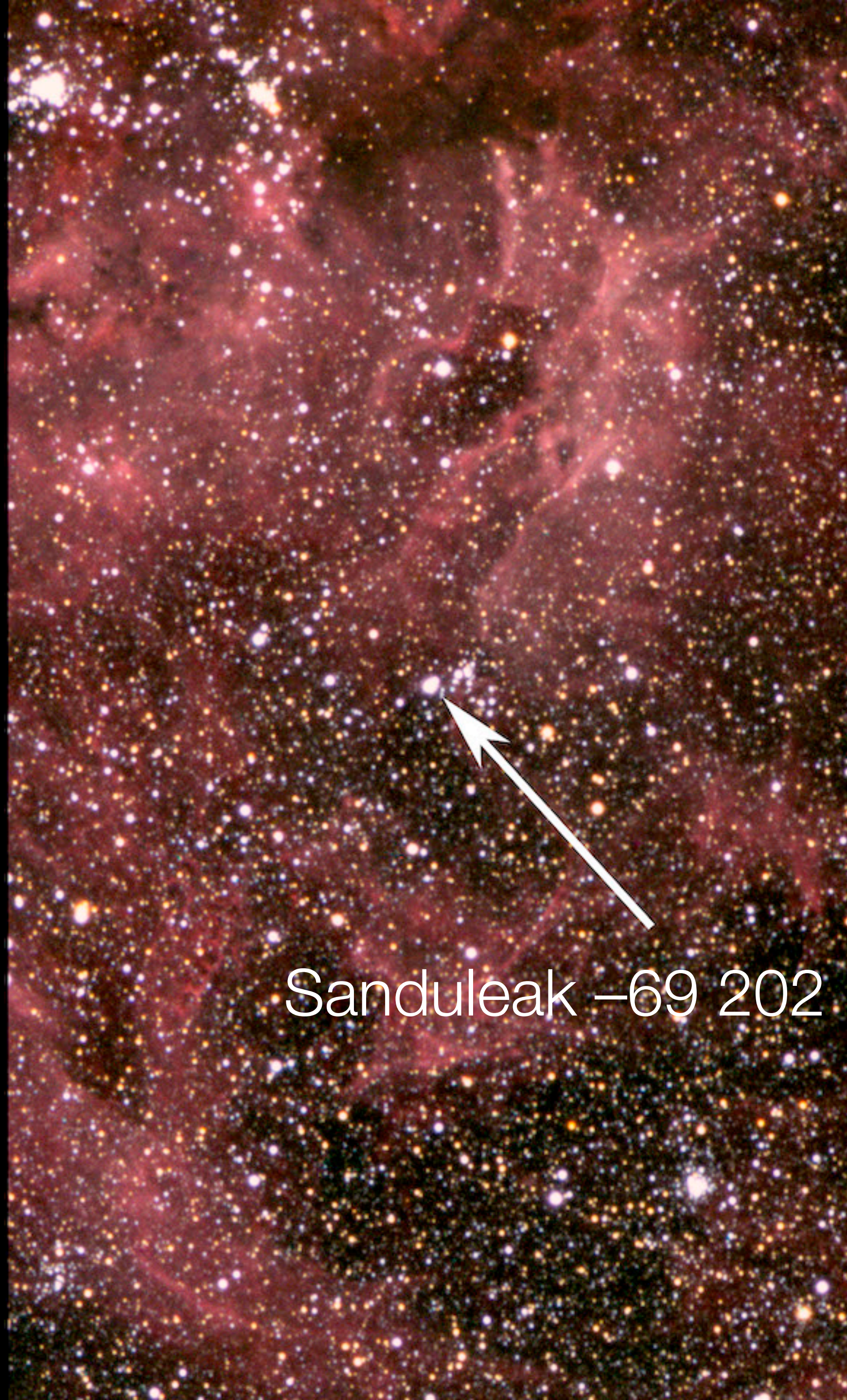
JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

in collaboration with **Katarina Bleau, Nikolina Ilic,**
Ushak Rahaman, XinYue (Theodore) Yu





Sanduleak -69 202



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SN 1987A

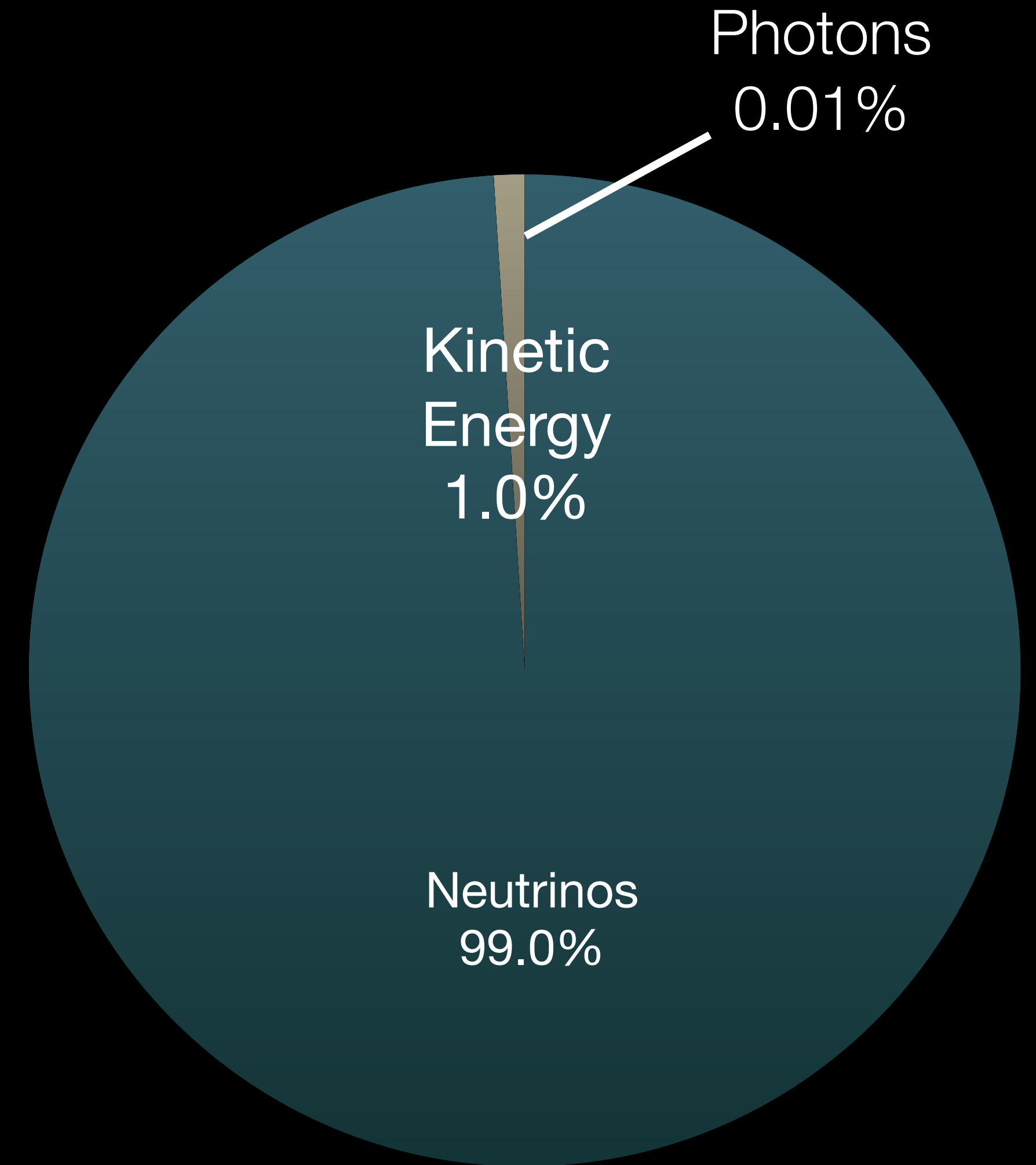
Core-Collapse Supernovae

- explosion of massive star ($\geq 8 M_{\odot}$)
that has run out of fuel
 - no more thermal pressure
 - core collapses
 - gigantic release of gravitational energy
- brighter than an entire galaxy
- $\sim 10\%$ of the star's mass converted to energy
 - 0.01% photons
 - 1% kinetic energy of explosion
 - 99% neutrinos



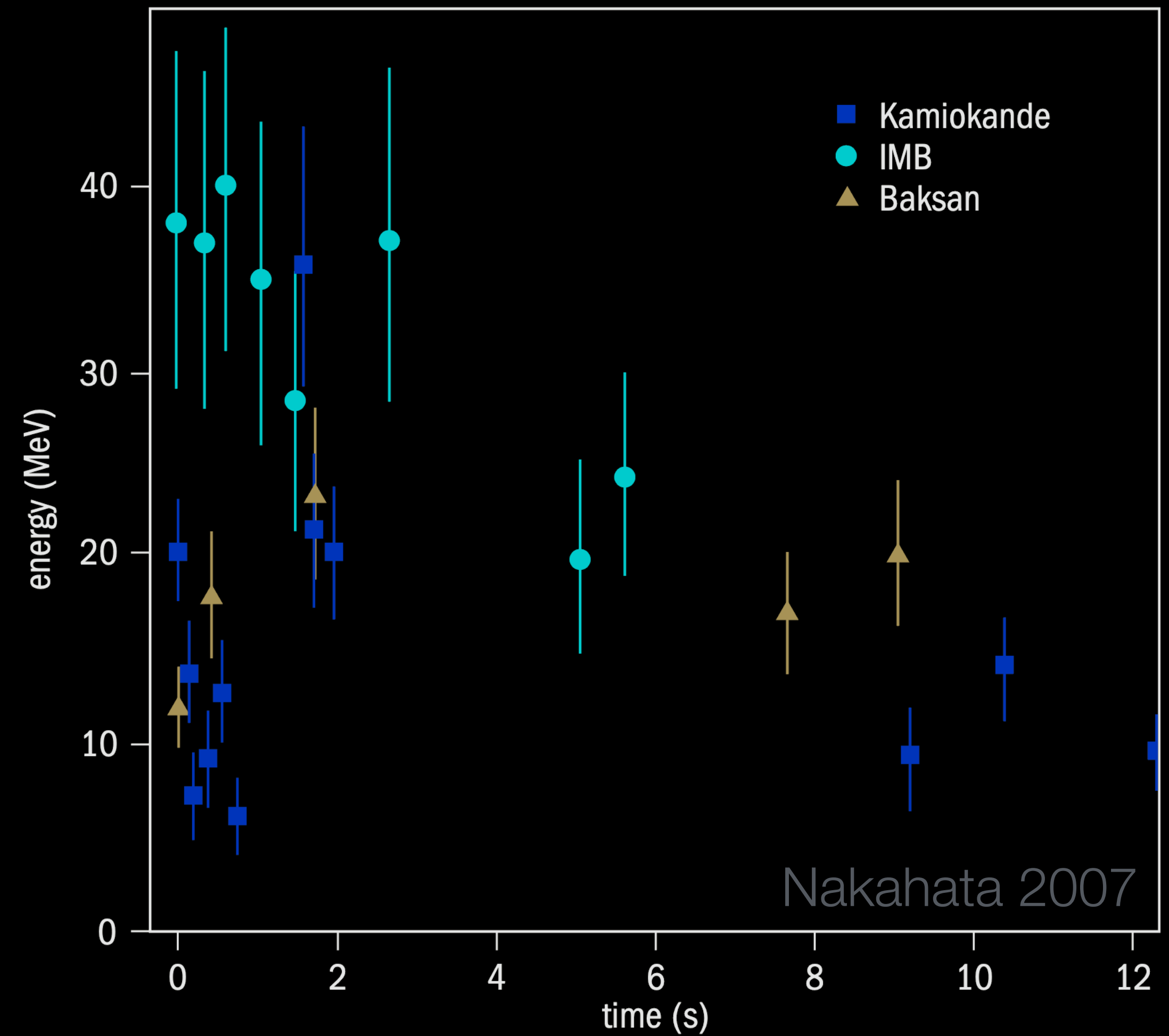
Core-Collapse Supernovae

- explosion of massive star ($\geq 8 M_{\odot}$) that has run out of fuel
 - no more thermal pressure
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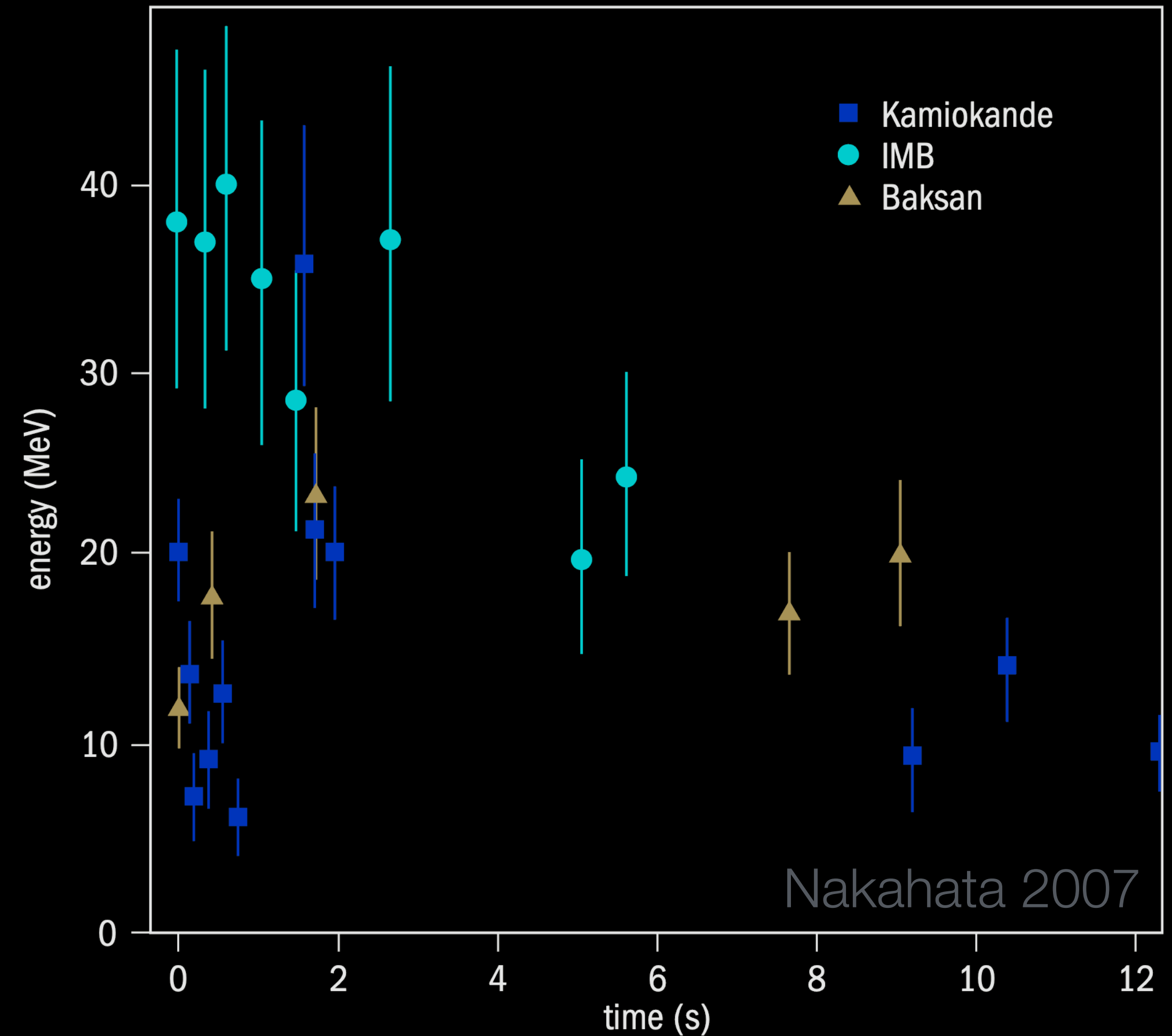
Neutrinos allow us to look
directly into the core of the exploding star

Supernova Neutrinos



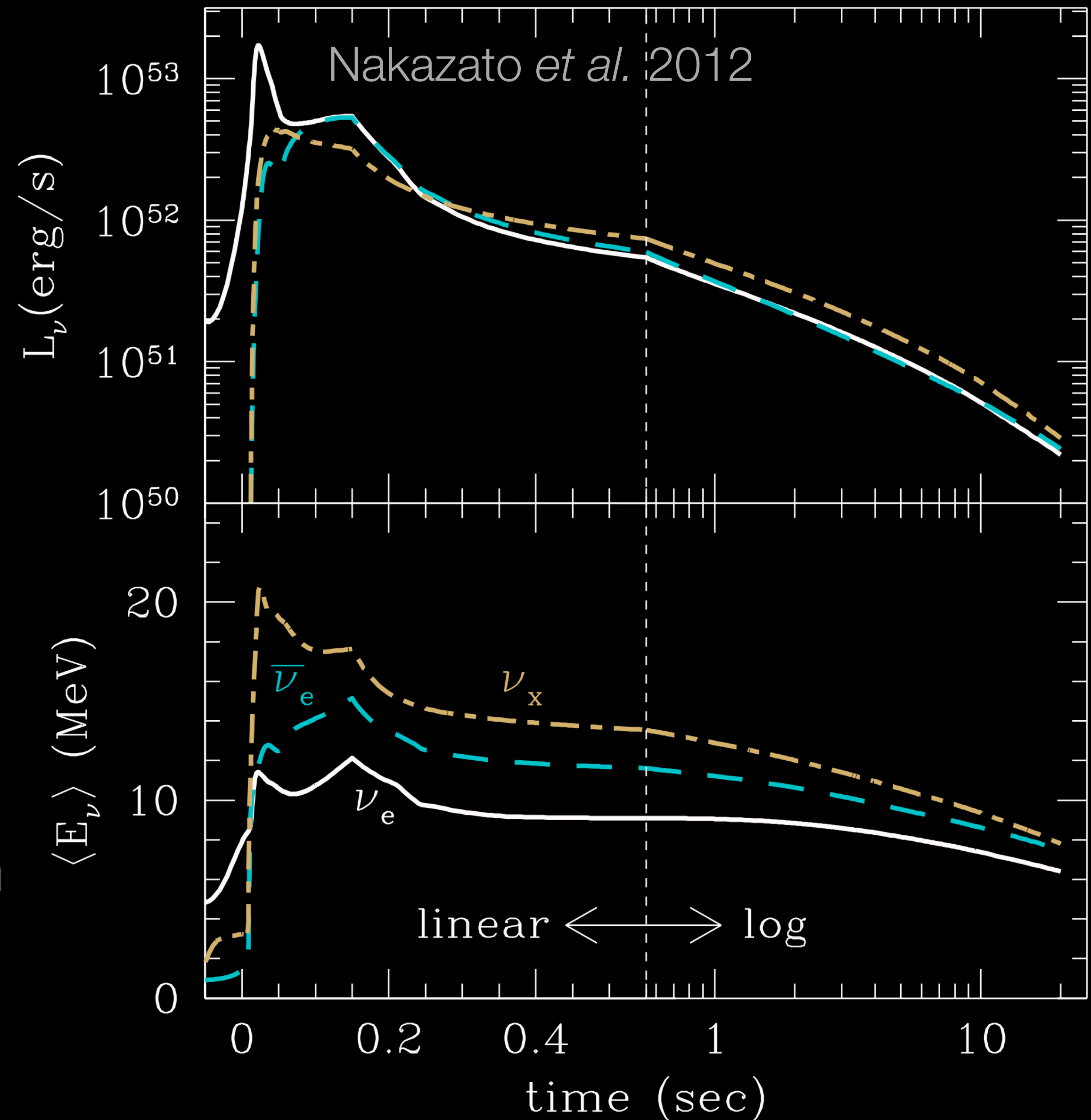
Supernova Neutrinos

- SN 1987A
 - 25 neutrino events



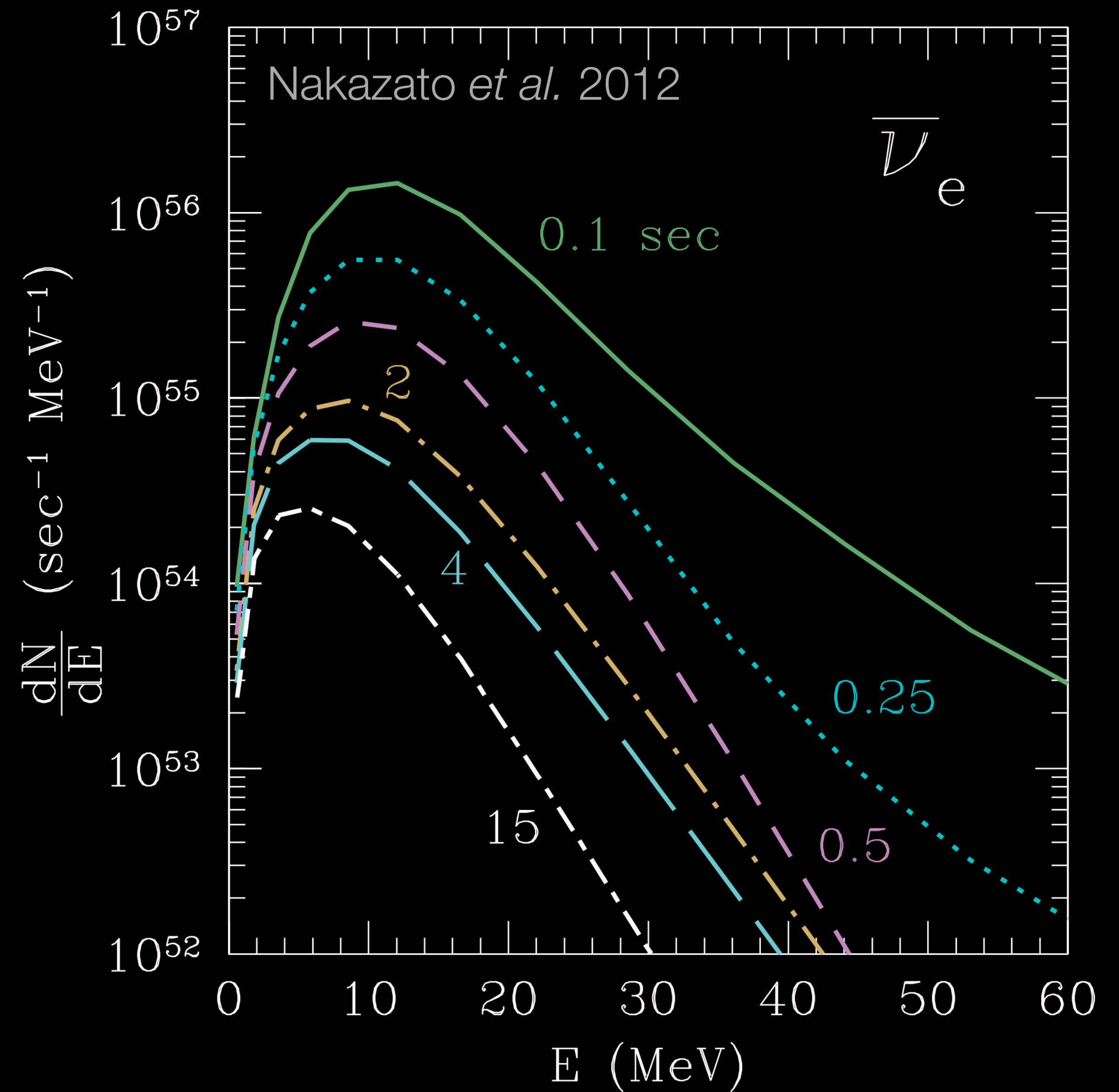
Supernova Neutrinos

- SN 1987A
 - 25 neutrino events
- the next galactic supernova
 - 10s of thousands of events
 - wealth of information on collapse dynamics, nucleosynthesis, ...
 - high-resolution “light” curves
 - detailed spectra
 - flavour composition
- need to relate observables at Earth to what is happening inside the SN



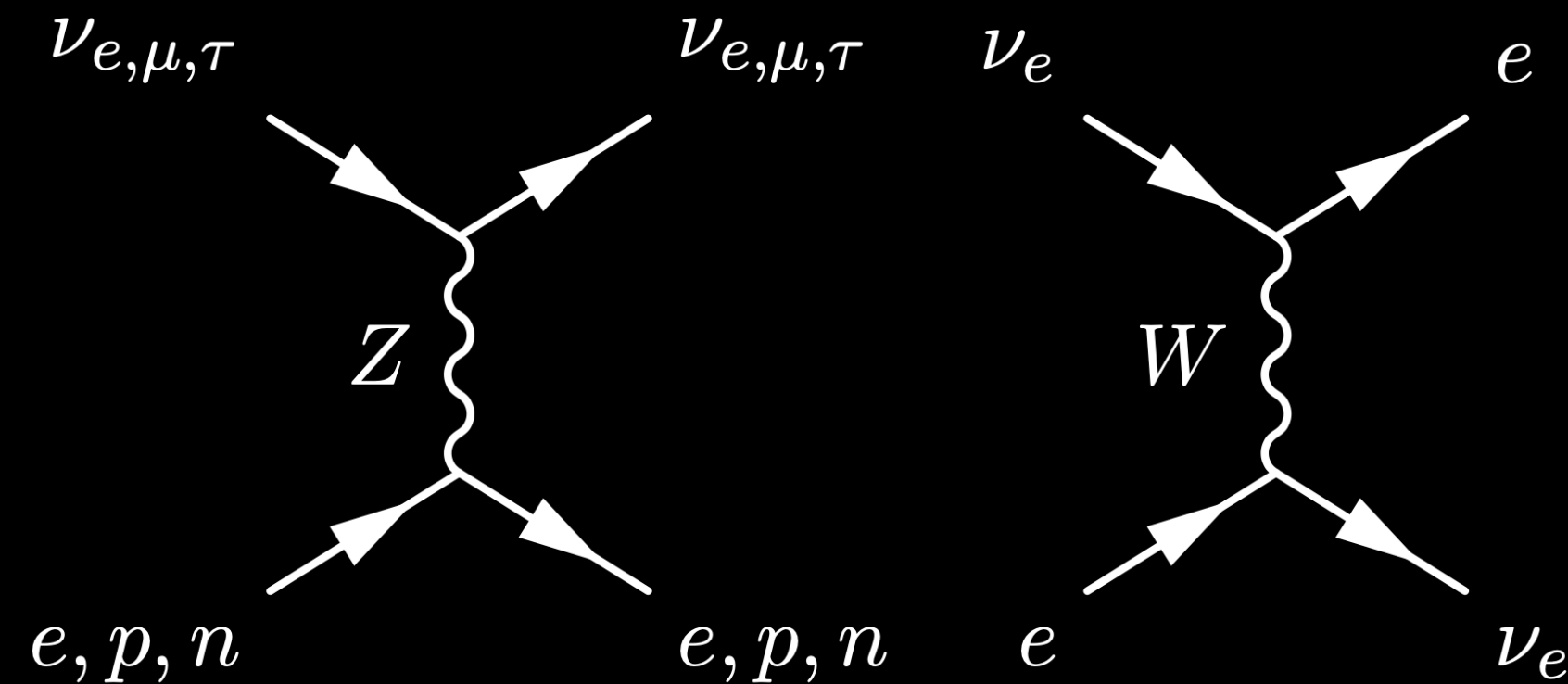
Supernova Neutrinos

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Neutrino Oscillations in Matter

- Neutrinos feel the presence of background matter



- coherent forward scattering:
 - exchange of force carrier without momentum change
 - contributions from all background particles add up *coherently* $\Rightarrow$ enhancement

$$i\mathcal{A} = \begin{array}{c} \text{---} \\ | \\ \text{wavy line} \\ | \\ \bullet \bullet \bullet \bullet \end{array} + \begin{array}{c} \text{---} \\ | \\ \text{wavy line} \\ | \\ \bullet \bullet \bullet \bullet \end{array} + \begin{array}{c} \text{---} \\ | \\ \text{wavy line} \\ | \\ \bullet \bullet \bullet \bullet \end{array} + \dots$$

Supernova Neutrinos

- neutrino density $> 10^{30} \text{ cm}^{-3}$
 - ▢ ➡ neutrinos induce matter effects for *themselves*
- flavour evolution in mean-field approximation:

$$i(\partial_t + \vec{v} \cdot \vec{\nabla}_{\vec{r}}) \rho_{\vec{r}, \vec{p}} = [H_{\text{vac}} + H_{\text{MSW}} + H_{\nu\nu}, \rho_{\vec{r}, \vec{p}}]$$

Supernova Neutrinos

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density matrix
 3 x 3 in flavour space

$$i(\partial_t + \vec{v} \cdot \vec{\nabla}_{\vec{r}}) \rho_{\vec{r}, \vec{p}} = [H_{\text{vac}} + H_{\text{MSW}} + H_{\nu\nu}, \rho_{\vec{r}, \vec{p}}]$$

vacuum oscillations

$$H_{\text{vac}} = \frac{1}{2E} U_{\text{PMNS}} M^2 U_{\text{PMNS}}^\dagger$$

matter effects

$$H_{\text{MSW}} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

self-interactions

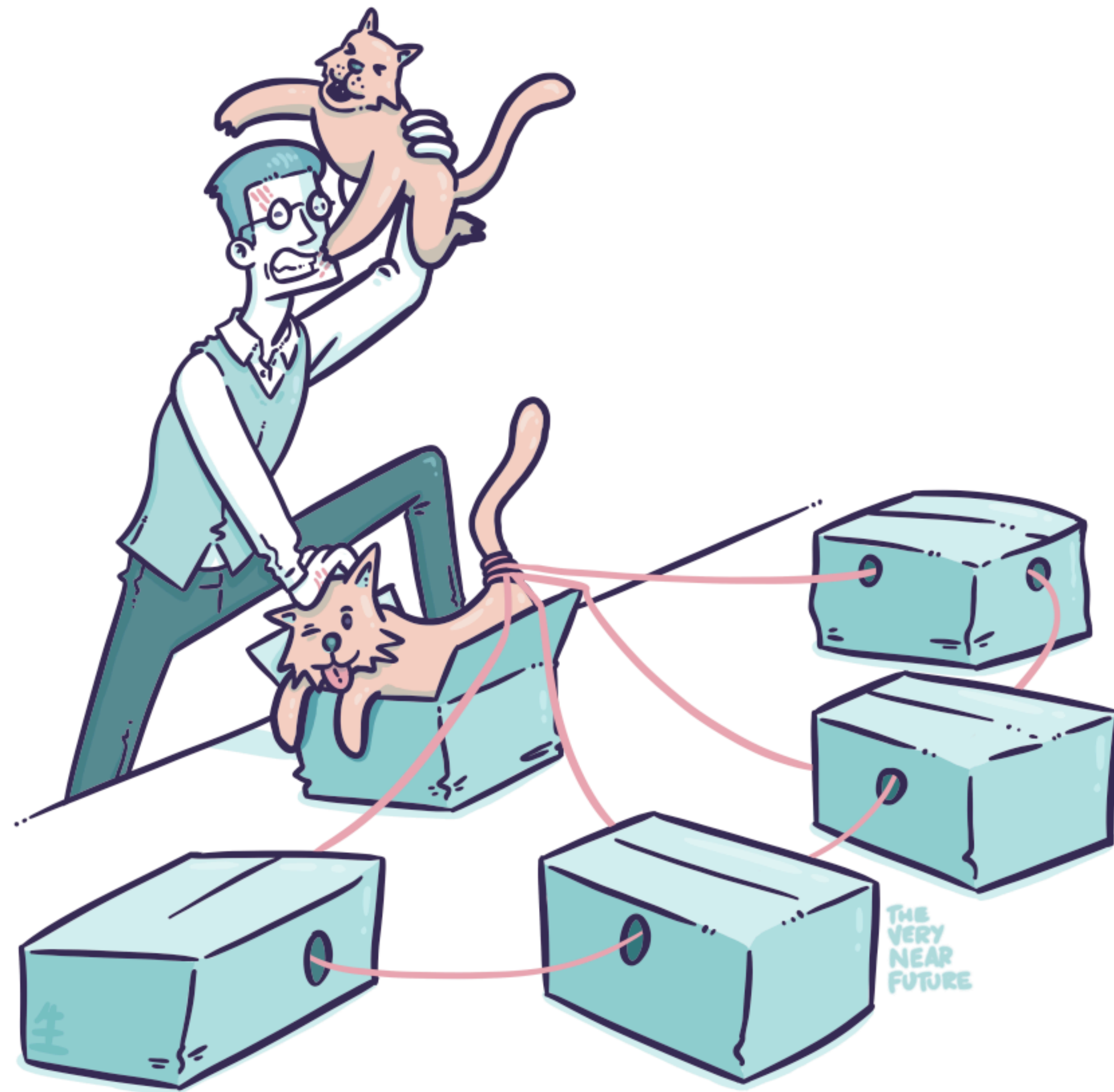
$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3 q}{(2\pi)^3} (1 - \cos \theta_{\vec{p}\vec{q}}) (\rho_{\vec{r}, \vec{q}} - \bar{\rho}_{\vec{r}, \vec{q}})$$

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- non-linear equation ▮▮▮▮▮ dynamics highly non-trivial
- computationally intractable so far
- a pure Standard Model problem
- solution will be crucial for understanding the next Galactic supernova
- possible quantum entanglement?



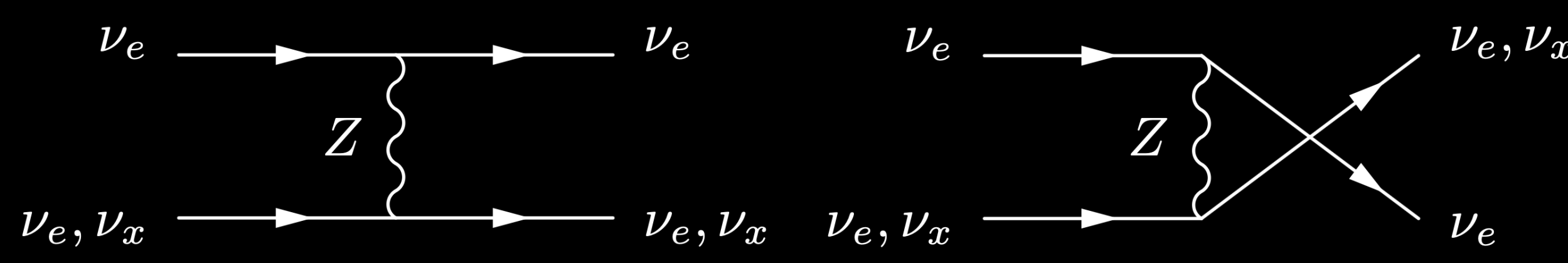
SCHRÖDINGER'S QUANTUM COMPUTER

Cartoon: Reddit u/TheVeryNearFuture

Supernova Neutrinos on a Quantum Computer

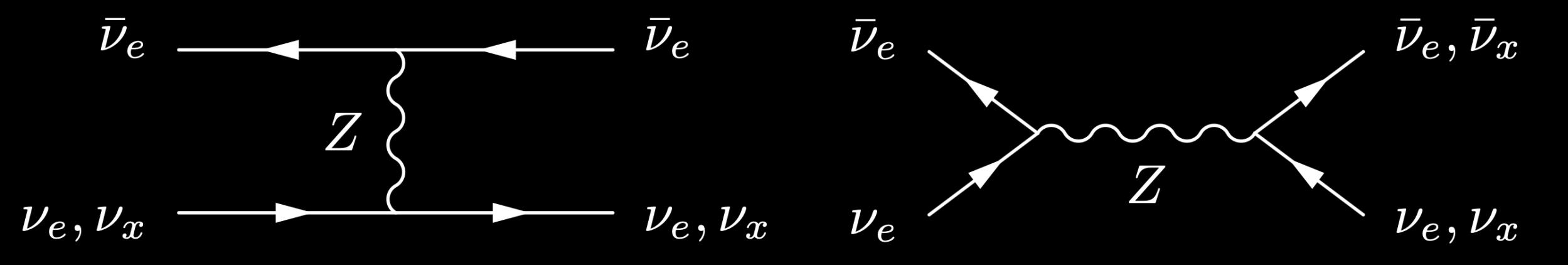
- highly entangled quantum system calls for simulation on a quantum system
- basic idea: flavour state of each neutrino mode represented by qubit q_i
(in 2-flavour approximation) Hall et al. 2021, Amitrano et al. 2022, Siwach et al. 2023
+ Alessandro Roggero's talk at this conference

neutrino–neutrino:



$$\Rightarrow H_{\nu\nu} = \sqrt{2}G_F n_\nu (1 - \cos \alpha) \begin{pmatrix} 2 & & & \\ & 1 & 1 & \\ & 1 & 1 & \\ & & & 2 \end{pmatrix} \begin{matrix} |\nu_e \nu_e\rangle \\ |\nu_e \nu_x\rangle \\ |\nu_x \nu_e\rangle \\ |\nu_x \nu_x\rangle \end{matrix}$$

neutrino–antineutrino:



$$\Rightarrow H_{\bar{\nu}\nu} = \sqrt{2}G_F n_\nu (1 - \cos \alpha) \begin{pmatrix} -2 & & -1 \\ & -1 & \\ & & -1 \\ -1 & & -2 \end{pmatrix} \begin{matrix} |\bar{\nu}_e \nu_e\rangle \\ |\bar{\nu}_e \nu_x\rangle \\ |\bar{\nu}_x \nu_e\rangle \\ |\bar{\nu}_x \nu_x\rangle \end{matrix}$$

Supernova Neutrinos on a Quantum Computer

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states:

$$|\psi\rangle = |q_1\rangle \otimes |q_2\rangle \otimes \dots \otimes |q_N\rangle$$

Hamiltonian:

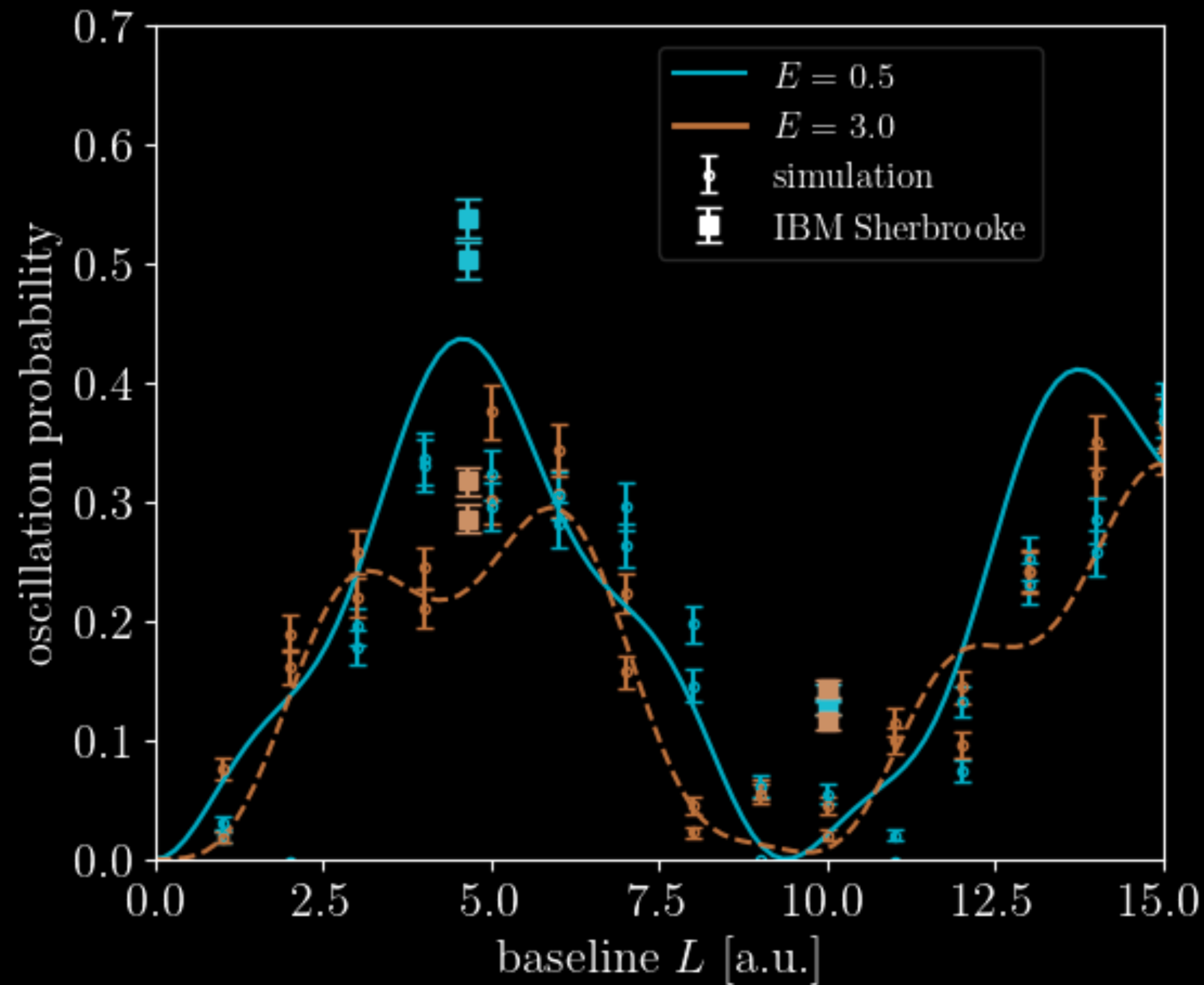
$$H = \sum_{k=1}^N \vec{b} \cdot \vec{\sigma}_k + \sum_{p < q}^N J_{pq} \vec{\sigma}_p \cdot \vec{\sigma}_q$$

- for $\nu\bar{\nu}$ interactions, use same Hamiltonian, but different state $\rightarrow$ qubit map

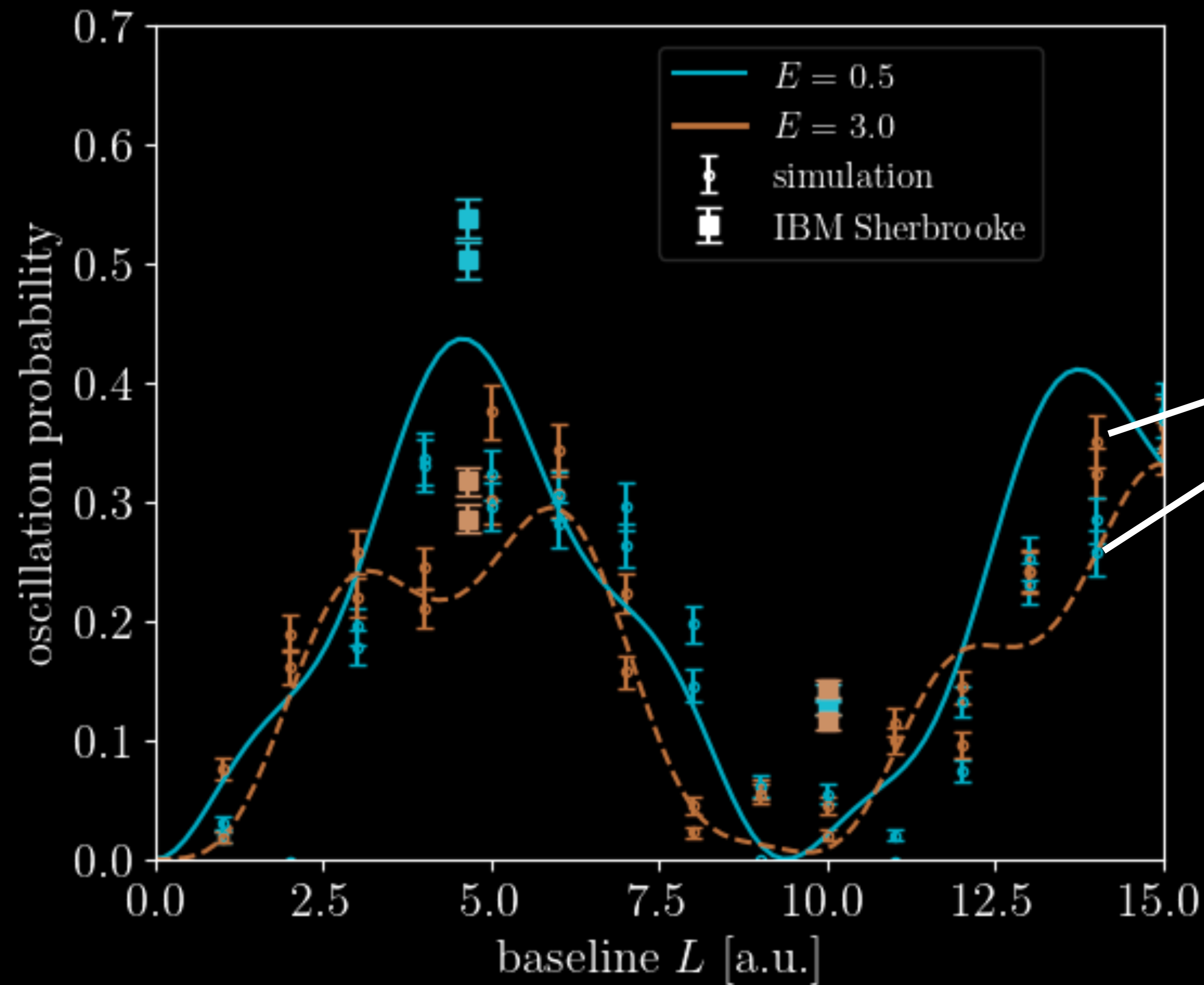
$$H_{q,\nu\bar{\nu}} = (\mathbb{1}_2 \otimes \hat{\sigma}_2) \cdot H_{q,\nu\nu} \cdot (\mathbb{1}_2 \otimes \hat{\sigma}_2)^\dagger$$

- time-evolution via Trotterization

Example: Synchronized Oscillations at High Density



Example: Synchronized Oscillations at High Density



neutrinos
of different energy
oscillate in unison
(unlike in vacuum)

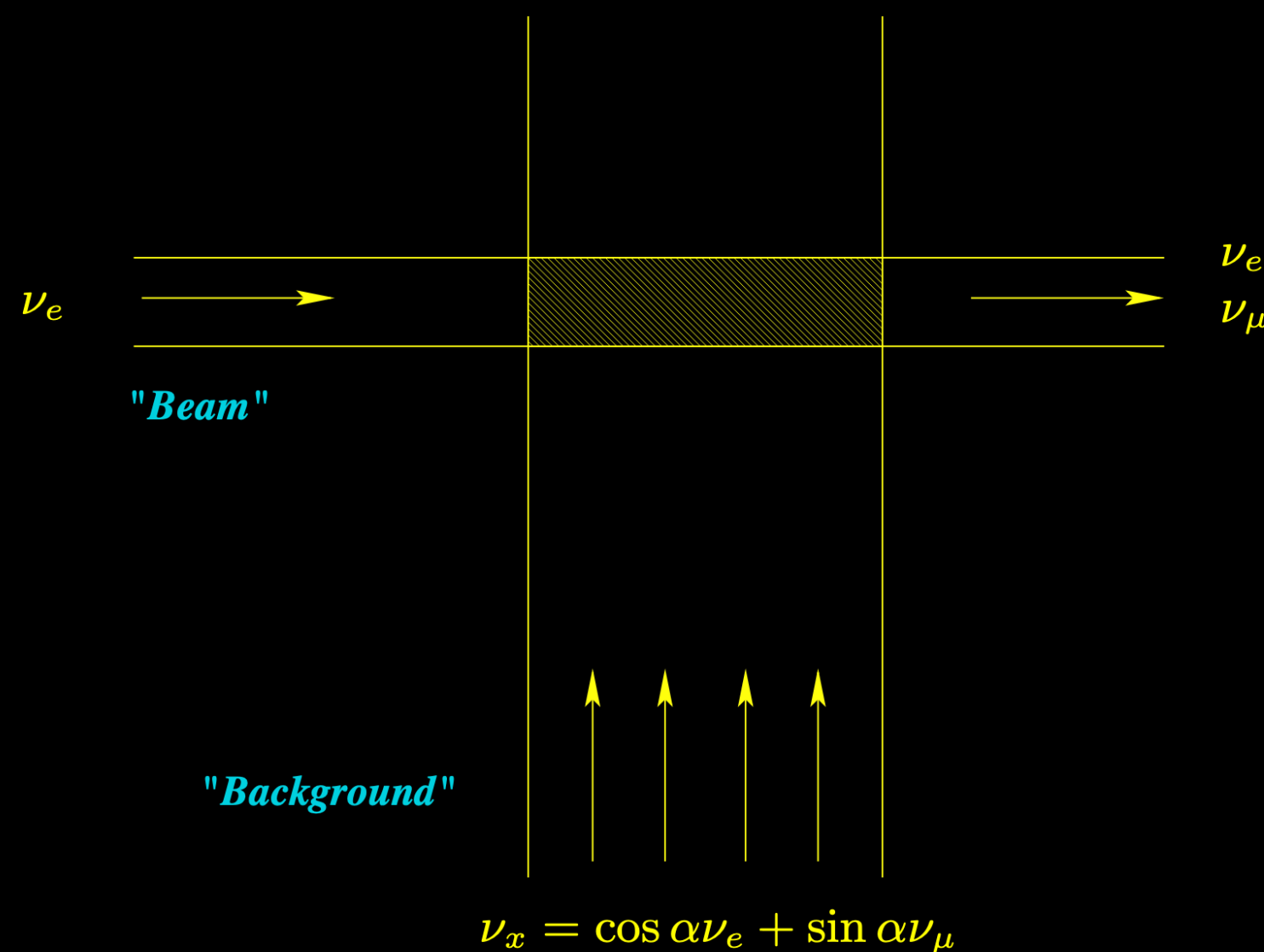
Emergence of the Mean Field Picture

When are quantum simulations needed?

- for simple toy systems, one can show analytically that mean-field behaviour emerges in the large- N limit

Friedland Lunardini 2003, Shalgar Tamborra 2023, Johns 2023
Bleau Ilic JK Rahaman Yu, *in preparation*

simple beam–background interaction



bipolar system

(equal + monoenergetic ν and $\bar{\nu}$ populations)

$$\nu_z = \cos \beta \nu_e + \sin \beta \nu_\mu$$

$$\bar{\nu}_x = \cos \alpha \bar{\nu}_e + \sin \alpha \bar{\nu}_\mu$$



$$|z'\rangle = |z\rangle - iaN_2 \left(\frac{1}{2} |\langle \bar{z} | \bar{x} \rangle|^2 |z\rangle + \langle \bar{z} | \bar{x} \rangle \langle \bar{x} | \bar{w} \rangle |w\rangle \right),$$

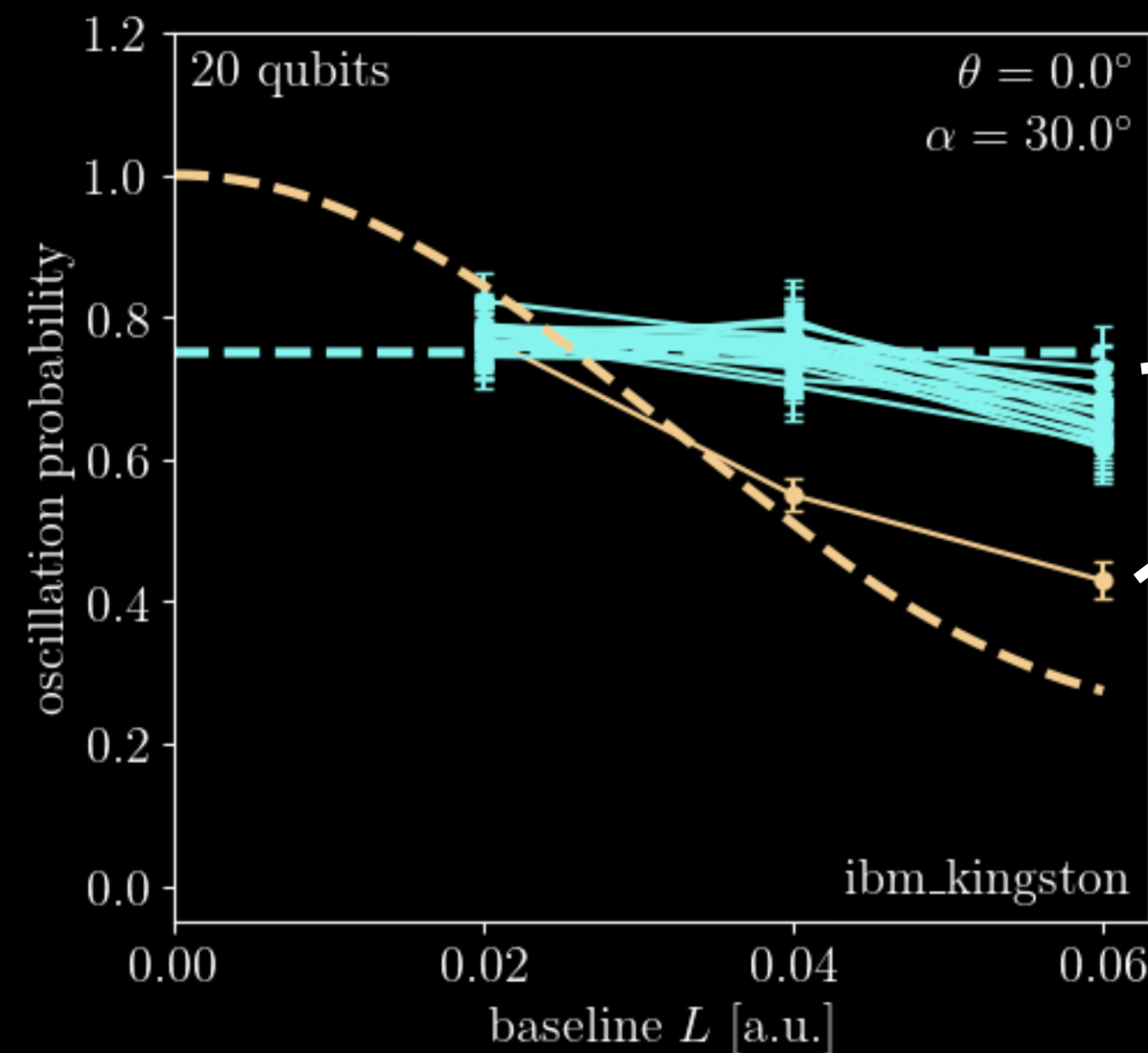
$$|\bar{x}'\rangle = |\bar{x}\rangle - iaN_1 \left(\frac{1}{2} |\langle \bar{z} | \bar{x} \rangle|^2 |\bar{x}\rangle + \langle \bar{z} | \bar{x} \rangle \langle \bar{y} | \bar{z} \rangle |\bar{y}\rangle \right)$$

Emergence of the Mean Field Picture

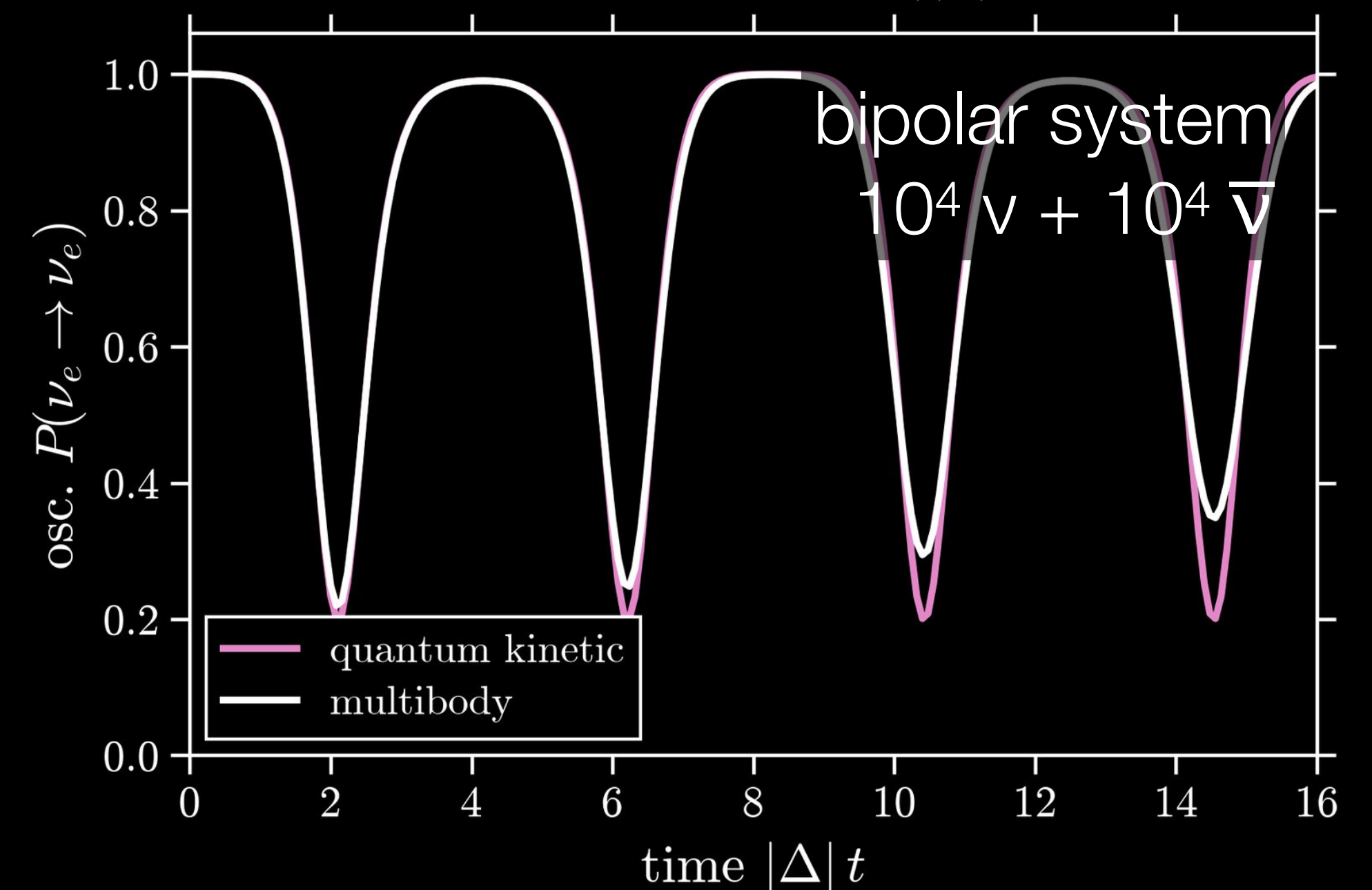
When are quantum simulations needed?

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- confirmed using quantum simulations

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quantum
simulation



Emergence of the Mean Field Picture

When are quantum simulations needed?

- for simple toy systems, one can show analytically that mean-field behaviour emerges in the large- N limit

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- confirmed using quantum simulations

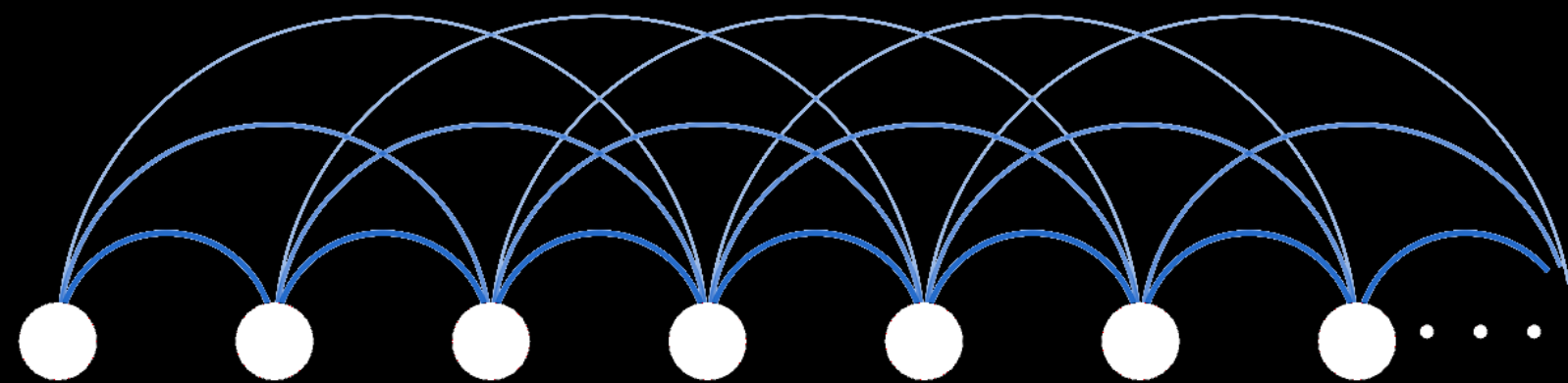
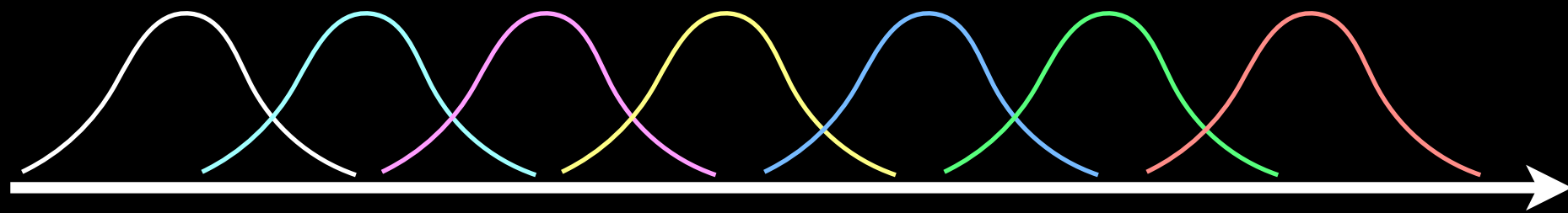
- all-to-all interactions assumed in most quantum simulations do not reflect situation in an actual supernova

- neutrinos stream away in all directions
- each neutrino pair gets at most one chance to interact (“once-in-a-lifetime encounters”)

Kost Johns Duan 2024

Possible Sources of Entanglement

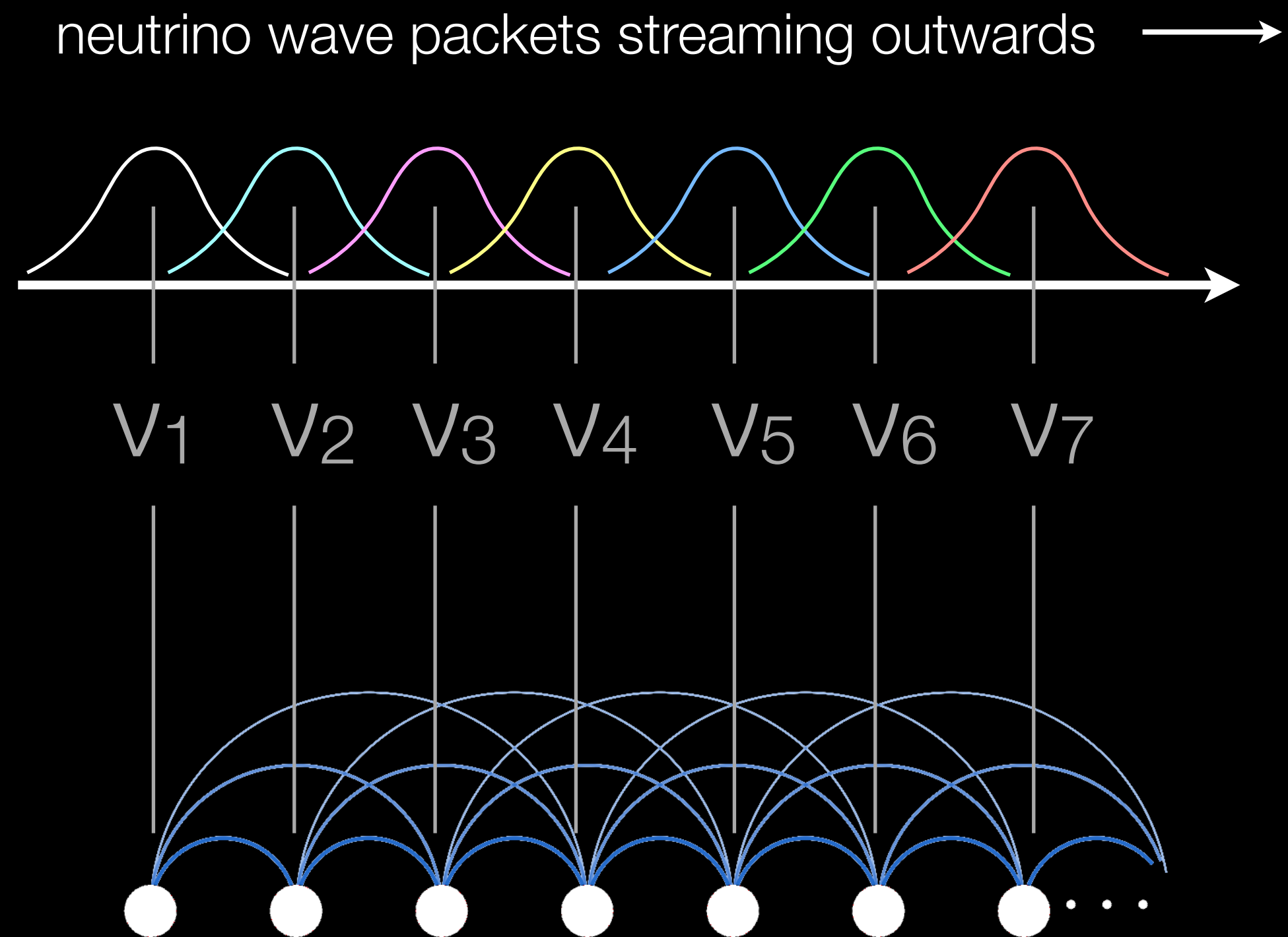
neutrino wave packets streaming outwards →



linear chain of qubits with nearest-neighbour interactions
(+ possibly next-to-nearest & next-to-next-to-nearest)

Bleau Ilic JK Rahaman Yu, *in preparation*

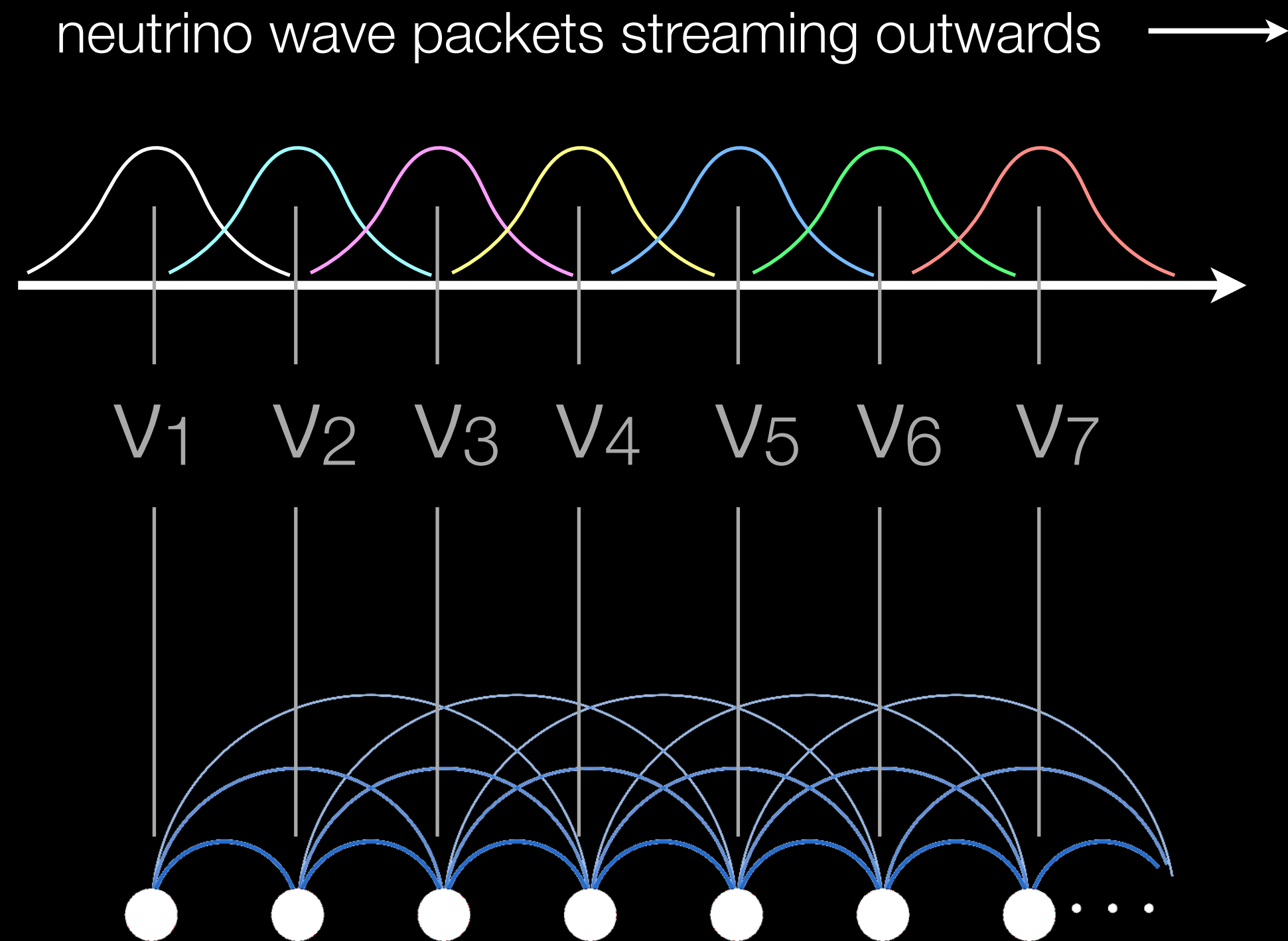
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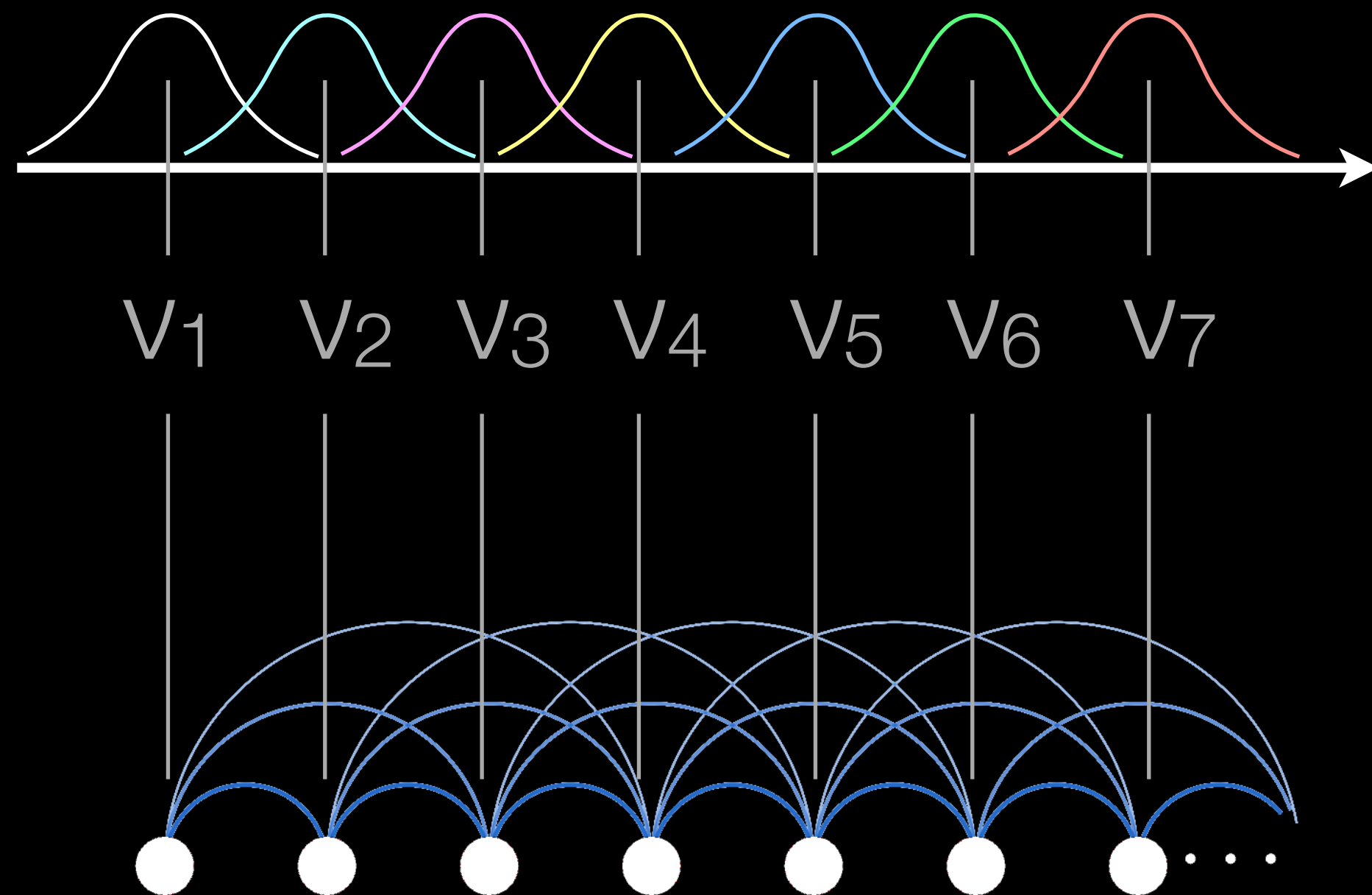
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Bleau Ilic JK Rahaman Yu, *in preparation*

- variations of Heisenberg model
- ▮ entanglement known to be relevant

Possible Sources of Entanglement

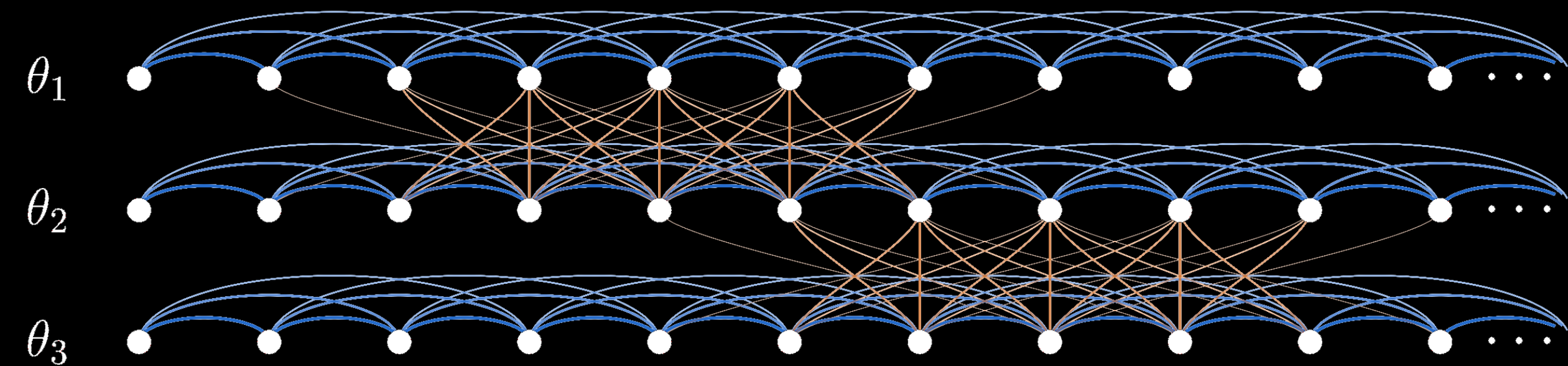
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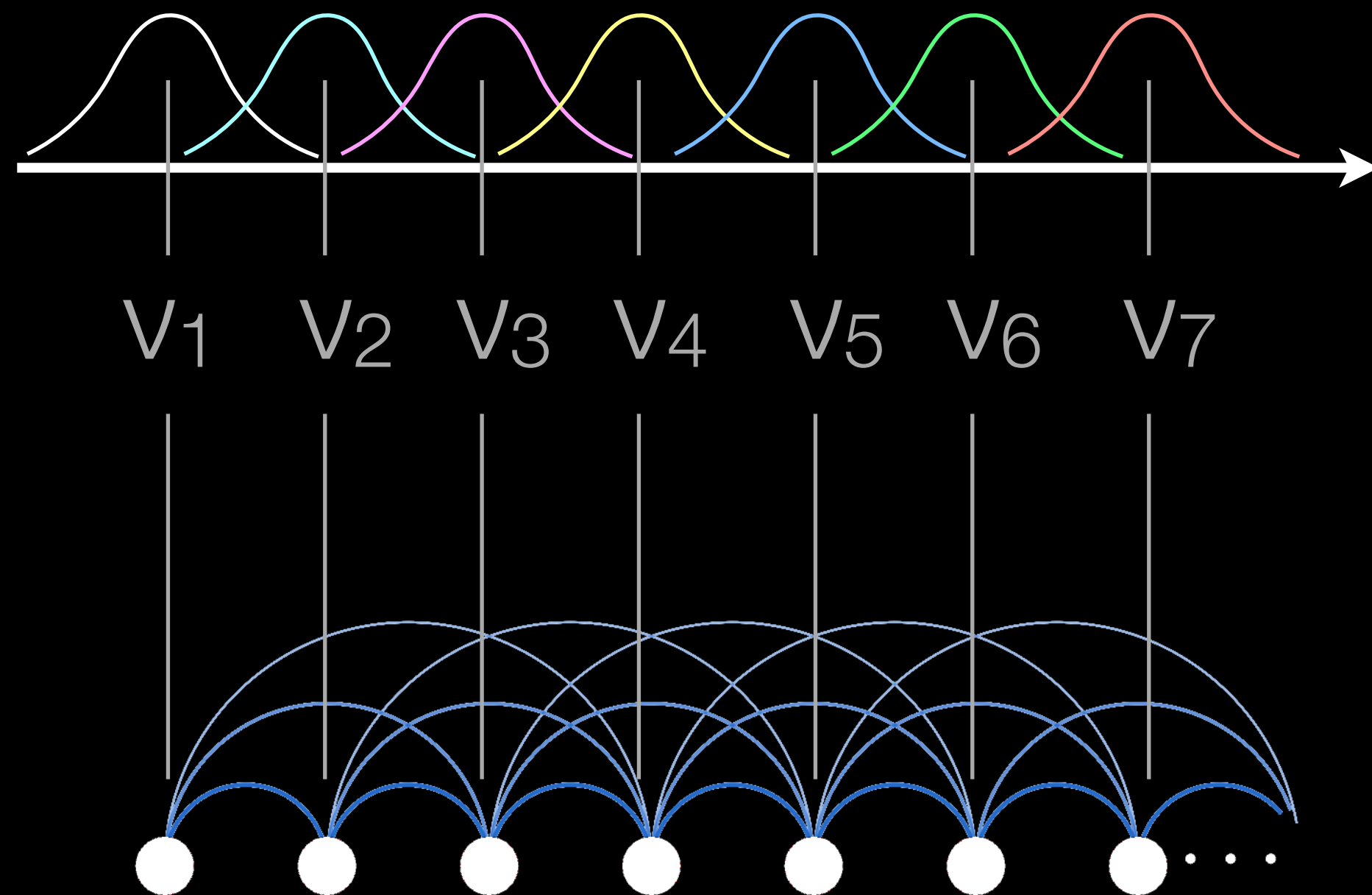
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generalisation: multiple beams at different angles



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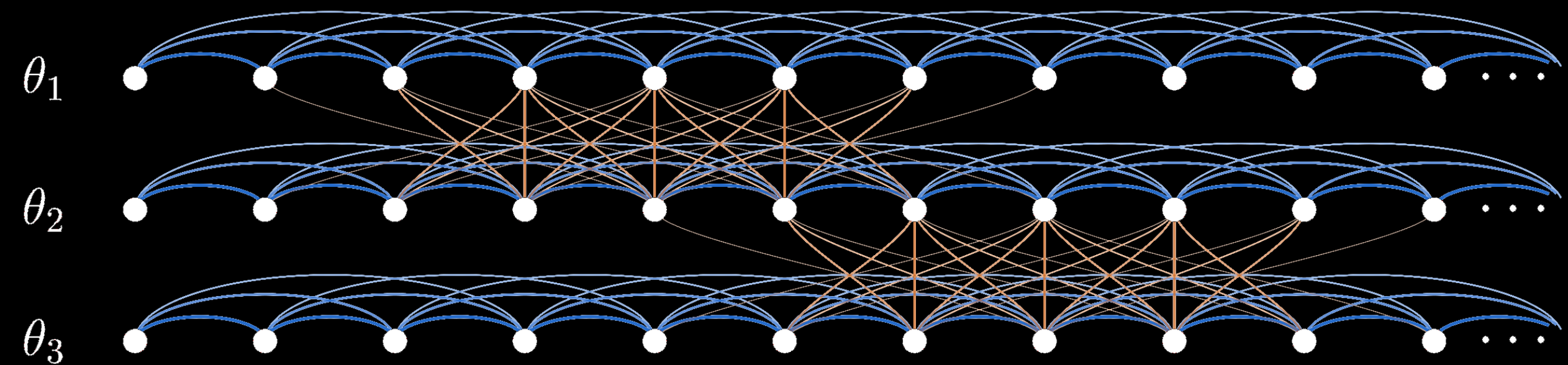
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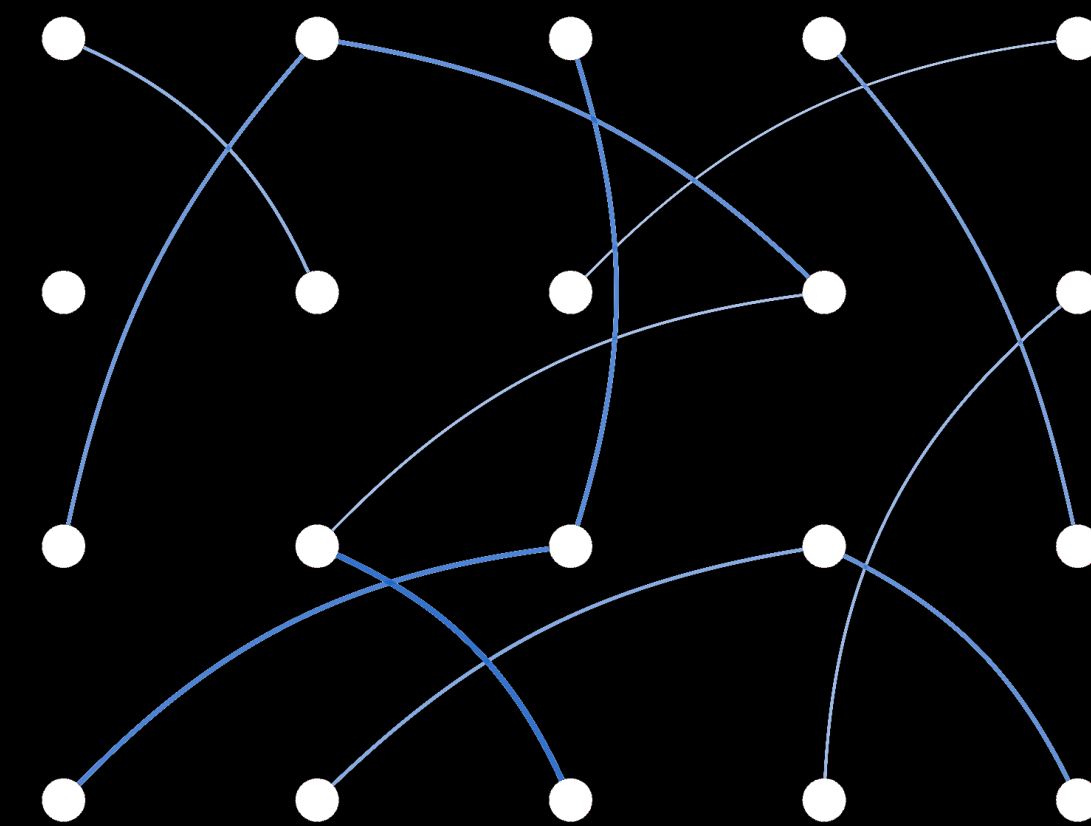
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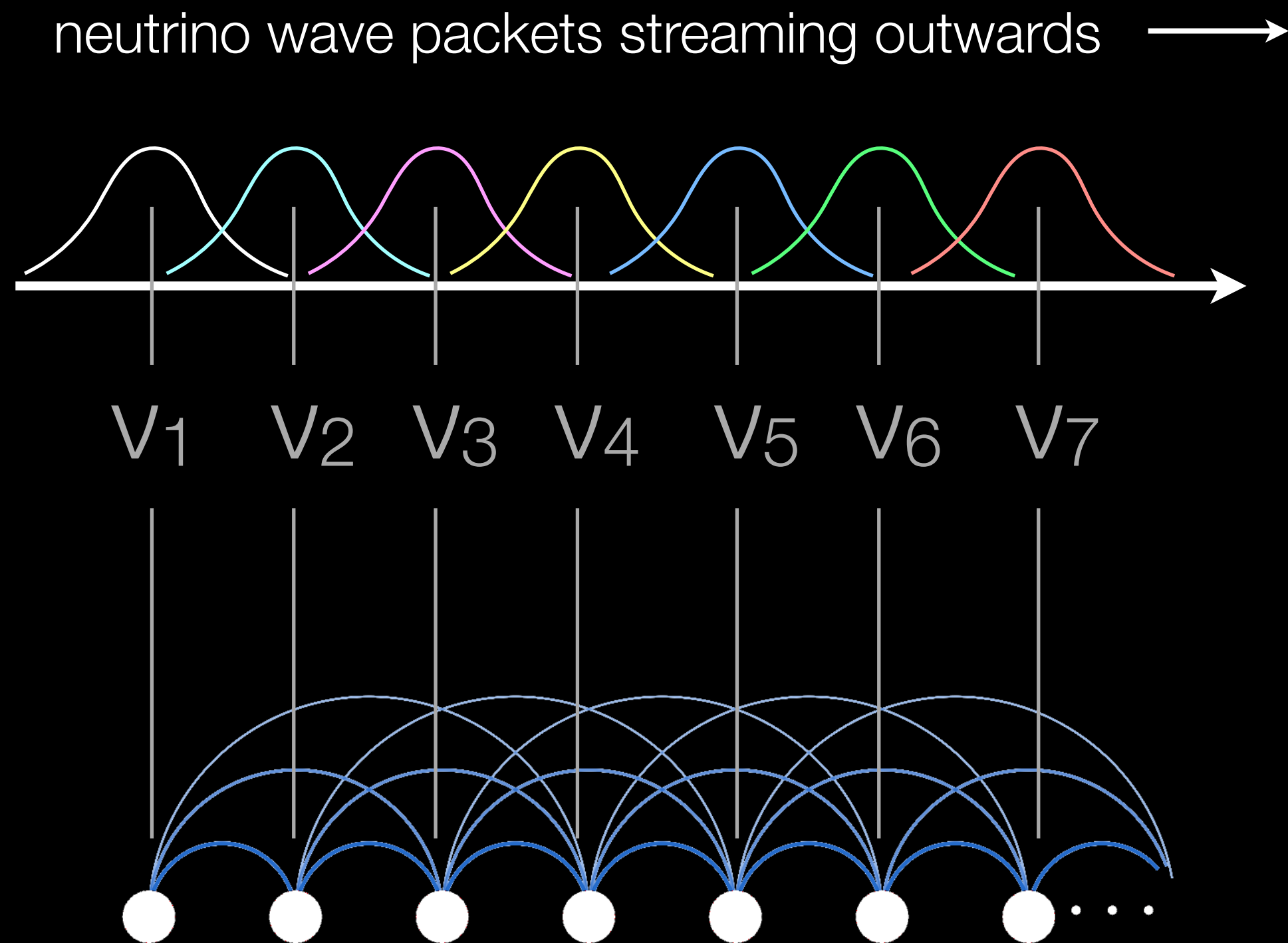
generalisation: multiple beams at different angles



generalisation: random walk



Possible Sources of Entanglement



linear chain of qubits with nearest-neighbour interactions
(+ possibly next-to-nearest & next-to-next-to-nearest)

Bleau Ilic JK Rahaman Yu, *in preparation*

- but in 3D environment:
 - neutrinos stream in all directions
 - wave packet size $\sim (1/n_\nu)^{1/3}$
 - no long-duration interactions
- build-up of entanglement questionable
- possibly way out:
magnetic fields
 - charged particles in spatially extended Landau states
 - neutrinos inherit large delocalisation

Implementation on Quantum Hardware

Symmetry of the Hamiltonian

$$H = \sum_{k=1}^N \vec{b} \cdot \vec{\sigma}_k + \sum_{p < q}^N J_{pq} \vec{\sigma}_p \cdot \vec{\sigma}_q$$

- If the $\vec{b}$ and J_{pq} are identical, H possess high degree of symmetry $\Rightarrow$ rewrite:

$$H_s = \vec{b} \cdot \vec{S}_{\text{tot}} + 2J \vec{S}_{\text{tot}}^2$$

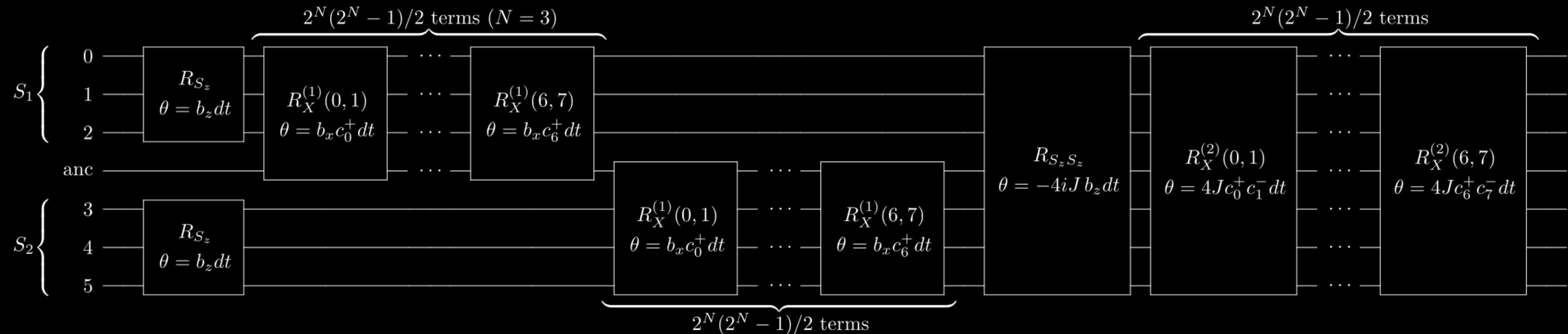
- N -qubit system: N coupled spin-1/2 particles
- H depends only on total spin S_{tot}
- Instead of N bits, need only $\log_2(N+1)$ bits
- encode orientation of S_{tot} as binary number

Bleau Ilic JK Rahaman Yu 2026

Simulation using Dicke States

- For two neutrino ensembles $\Rightarrow$ two quantum registers

$$H_s = \sum_{i=1,2} \vec{b}_i \cdot \vec{S}_i + 4J_{12} \vec{S}_1 \cdot \vec{S}_2$$

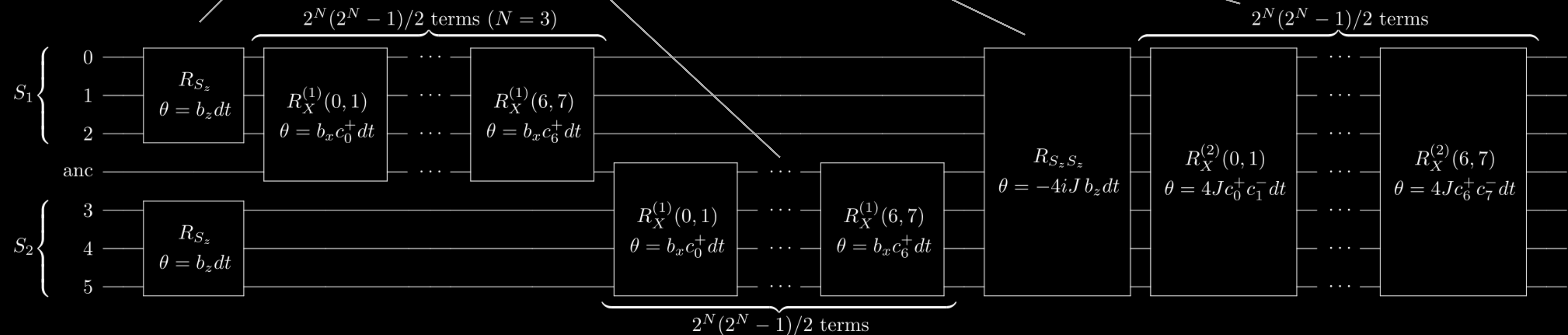


Bleau Ilic JK Rahaman Yu 2026 $\Rightarrow$ see paper for details on the implementation

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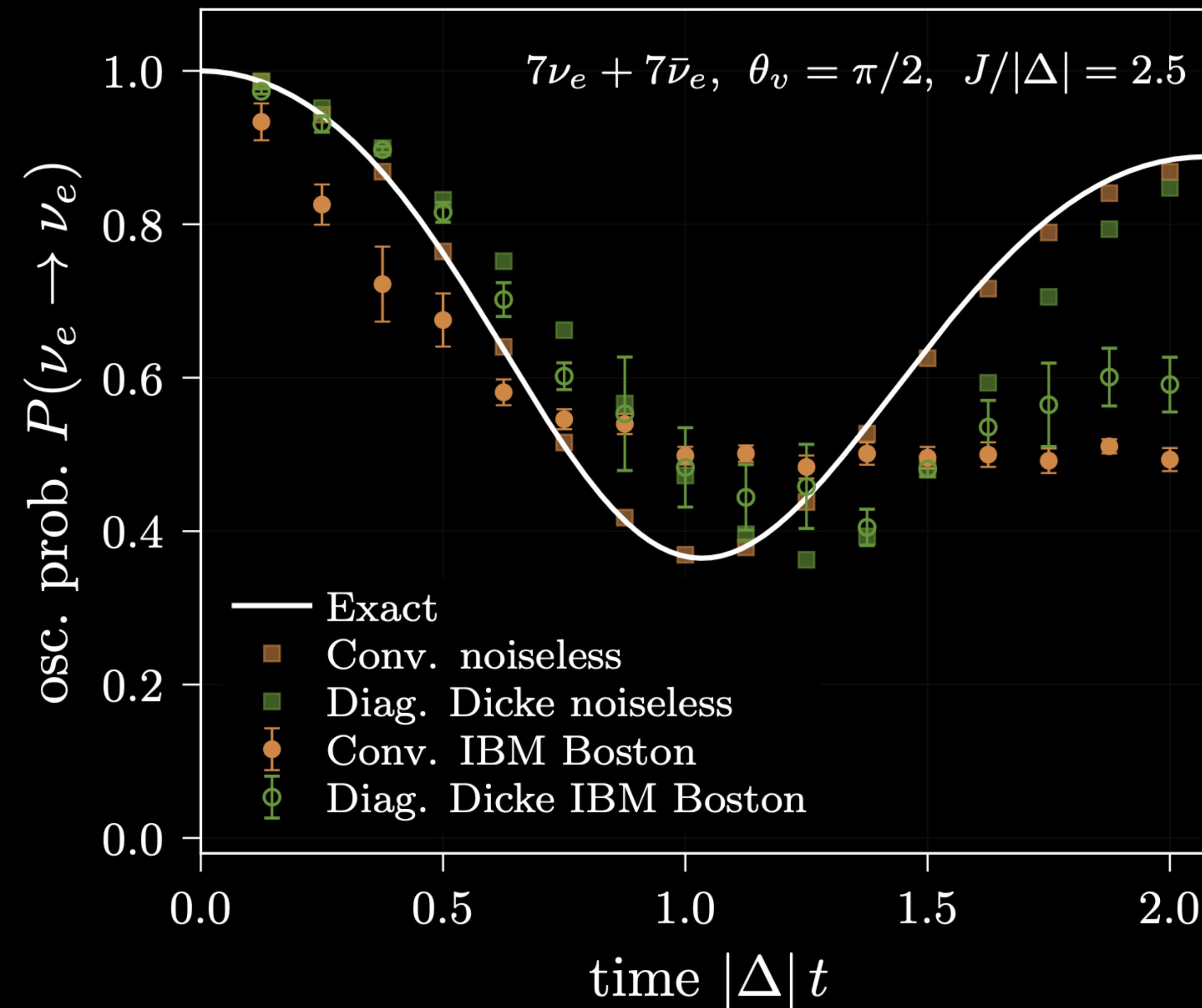
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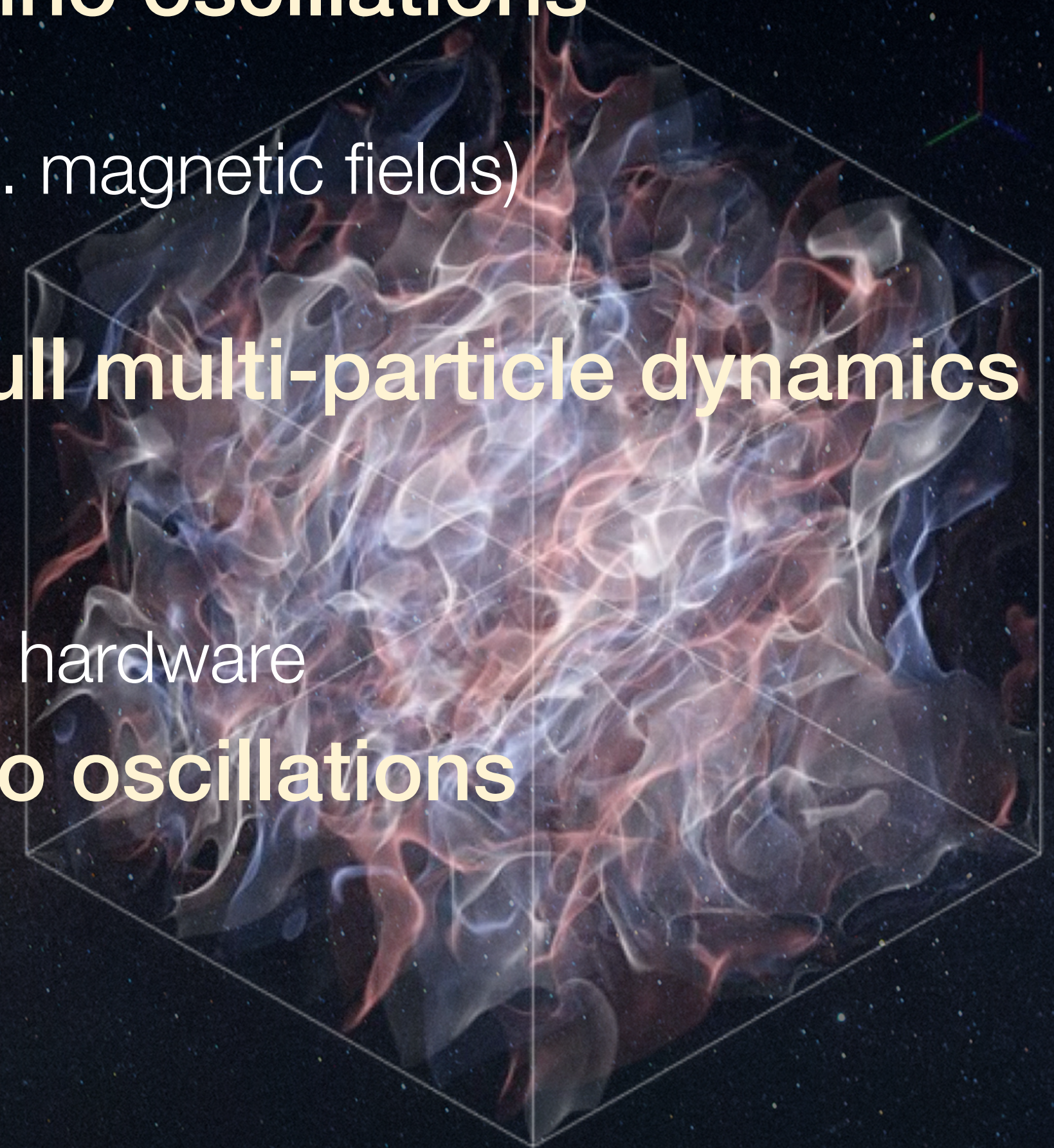
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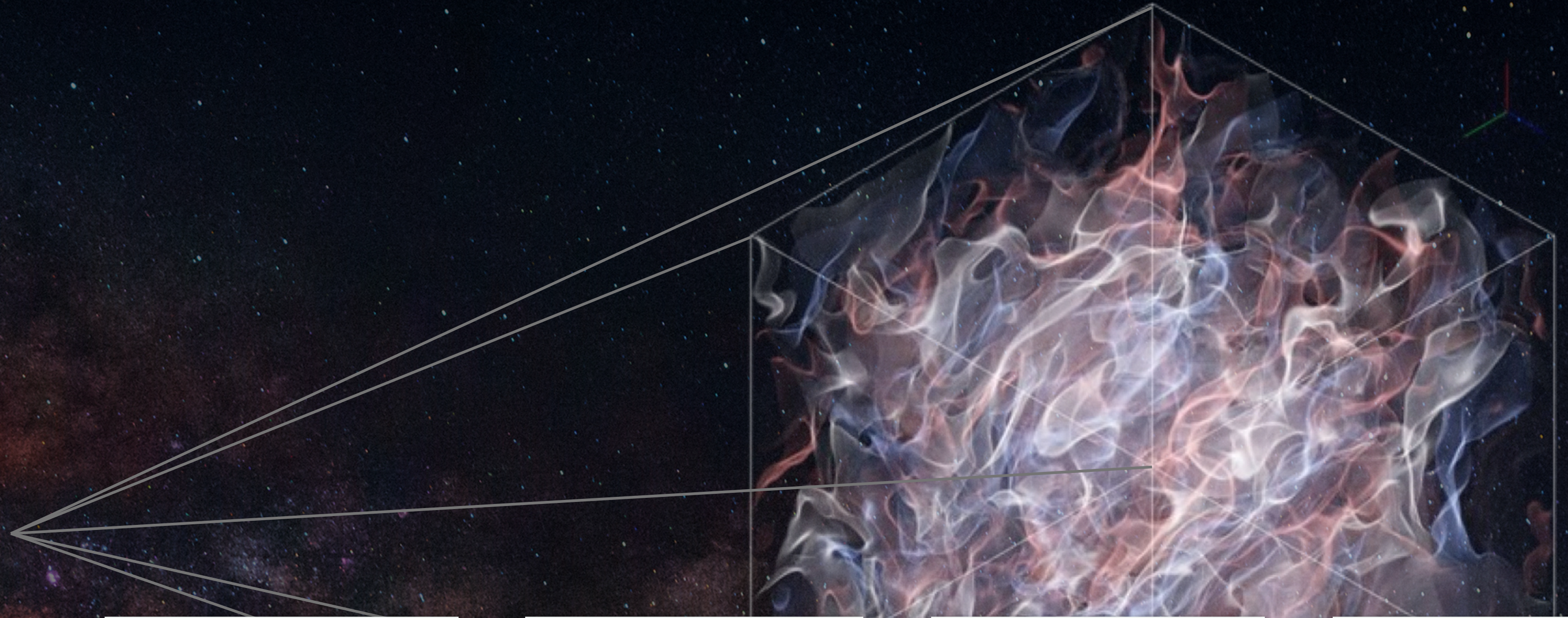


Take-Home Messages

- **quantum entanglement in supernova neutrino oscillations**
 - not a generic prediction
 - but possibly highly relevant in certain situations (e.g. magnetic fields)
 - ▮ use case for quantum computing
- **emergence of mean-field behaviour from full multi-particle dynamics at large N**
 - analytic results
 - explicit demonstration on both classical & quantum hardware
- **algorithms for simulating collective neutrino oscillations**
 - qubit-efficient encoding using Dicke states



Thank You!



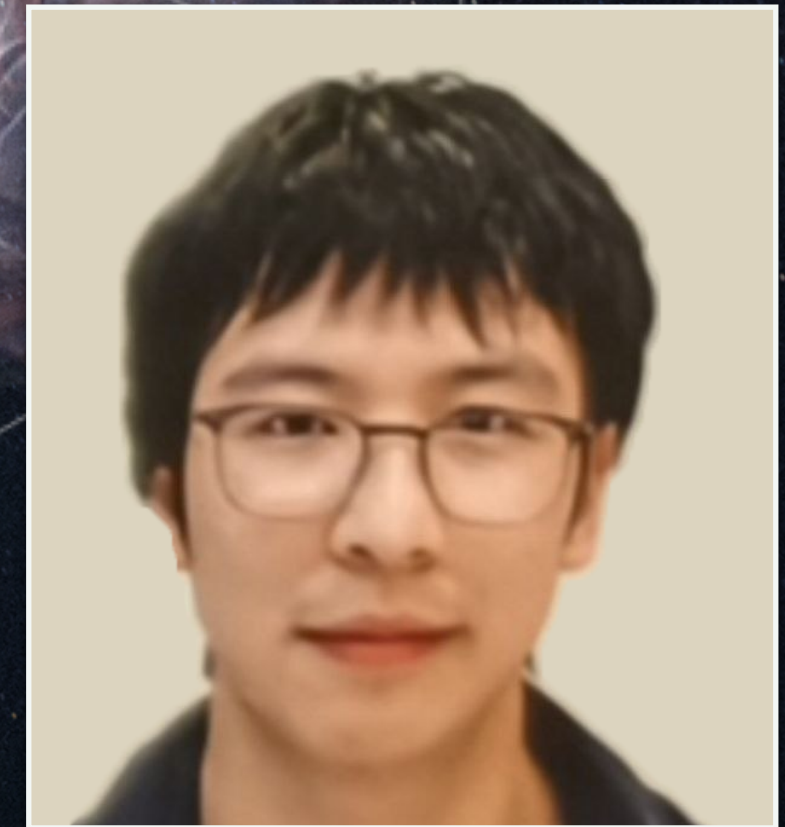
Katarina Bleau



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XinYue
(Theodore) Yu

