New Developments in Neutrino (Astro)Physics

Joachim Kopp (CERN & JGU Mainz)

PASCOS 2025 • Durham • 21 July 2025

CERN

Neutrino PLATFORM

QUANTUM TECHNOLOGY INITIATIVE

JOHANNES GUTENBERG UNIVERSITÄT MAINZ


DISCOVERY


DISCOVERY


PRECISION
DISCOVERY

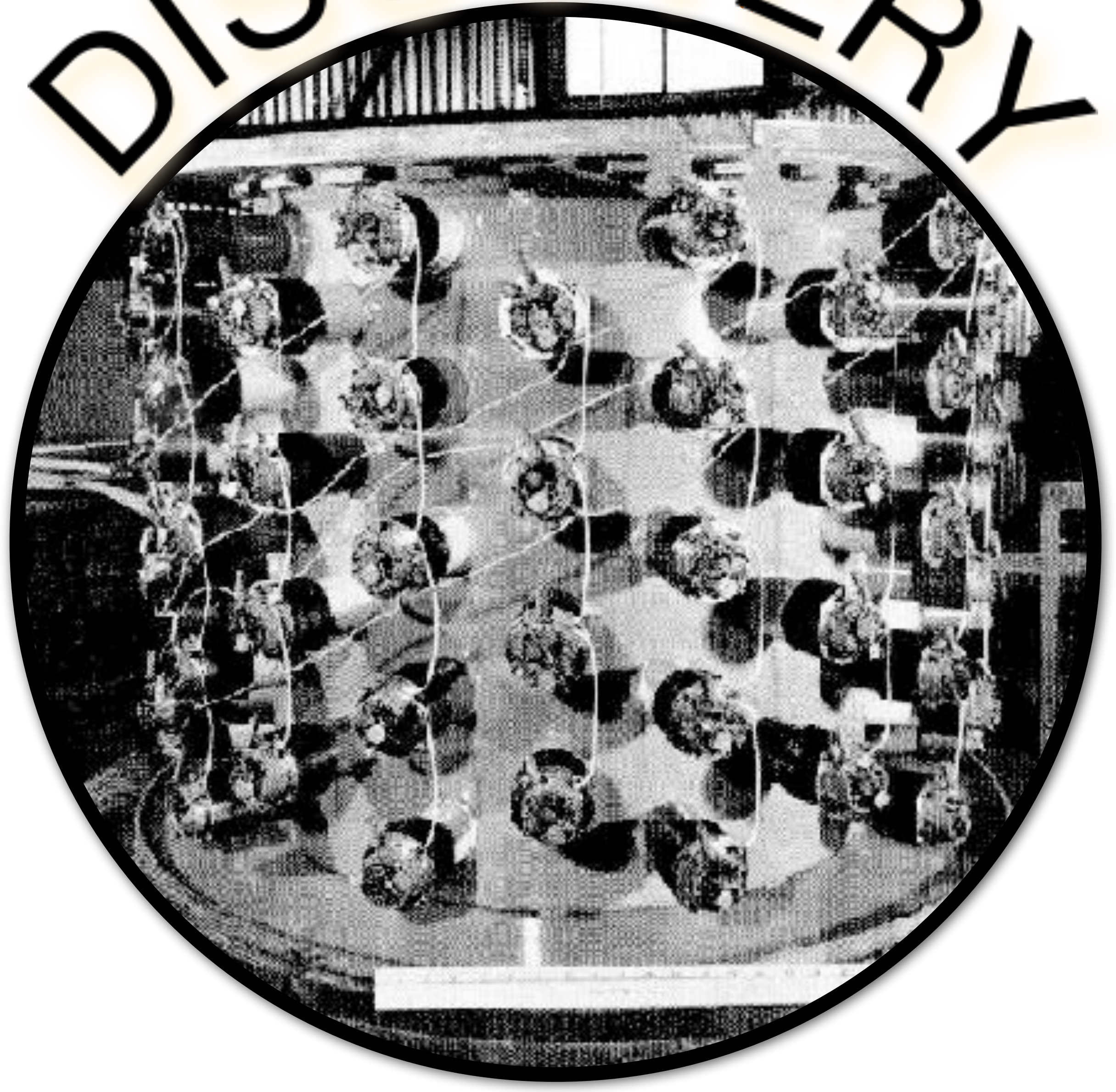

PRECISION
DISCOVERY


DISCOVERY
PRECISION
MESSENGER


DISCOVERY
PRECISION
MESSENGER

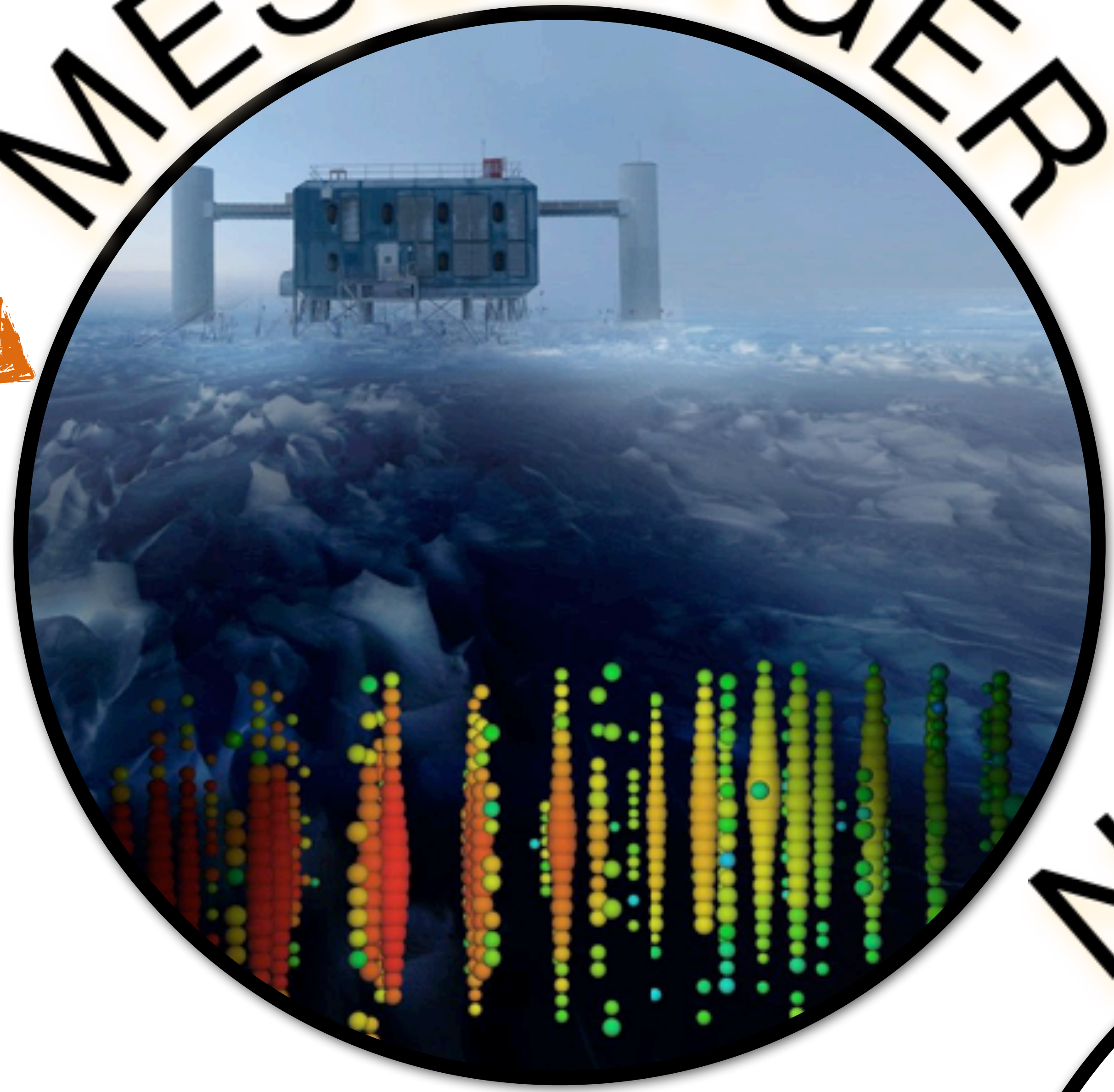

DISCOVERY
PRECISION
MESSENGER
NUISANCE

DISCOVERY

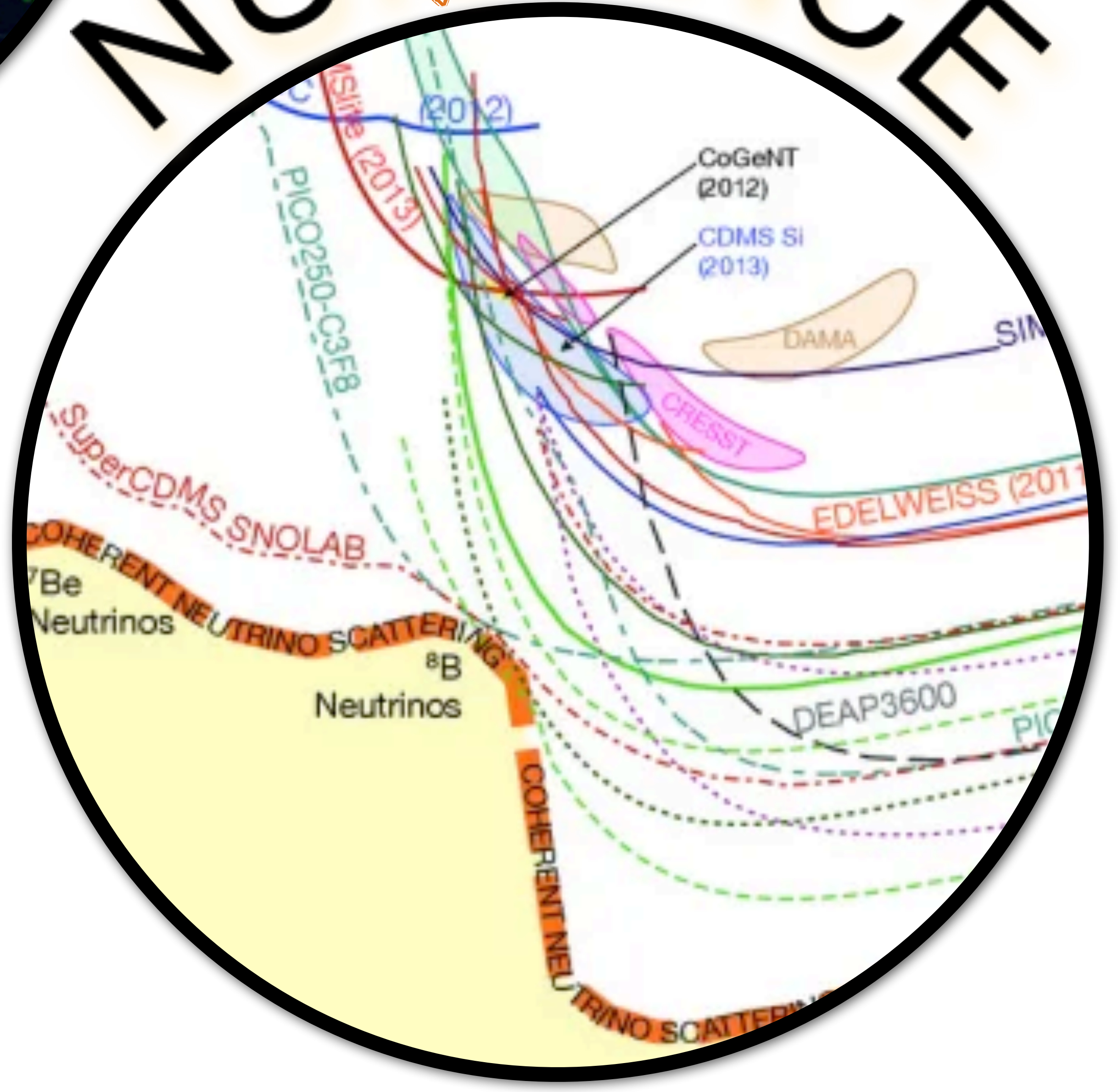


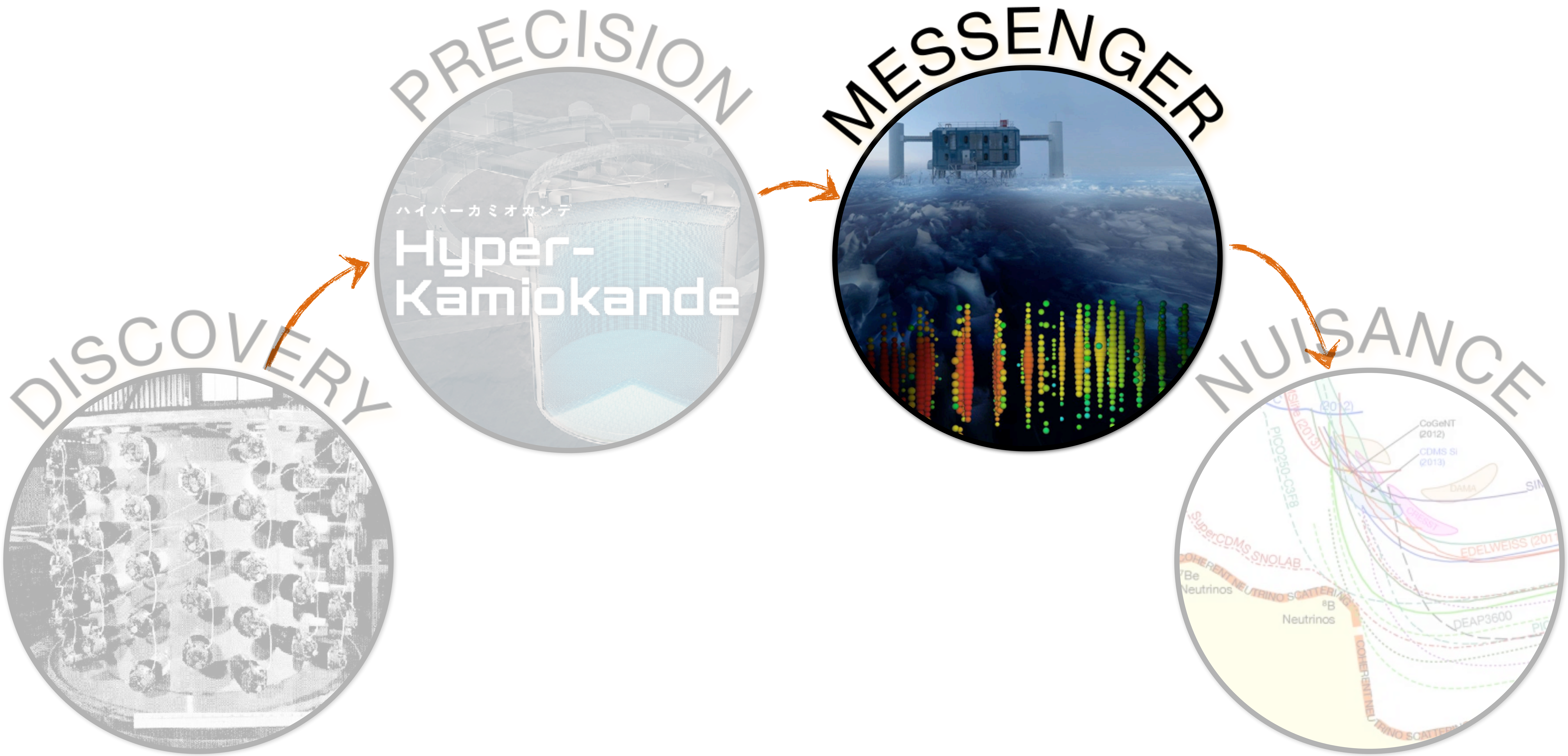
PRECISION

MESSENGER



NUISANCE




DISCOVERY
PRECISION
ハイパーカミオカンデ
Hyper-Kamiokande
MESSENGER
NUISANCE
CoGeNT (2012)
CDMS Si (2013)
DAMA
CRESST
EDELWEISS
PICO250-C3F8
SuperCDMS SNOLAB
COHERENT NEUTRINO SCATTERING
7Be Neutrinos
8B Neutrinos
DEAP3600

Neutrinos as Astrophysical Messengers

Neutrinos as Astrophysical Messengers

solar neutrinos

- ⋆ stellar evolution

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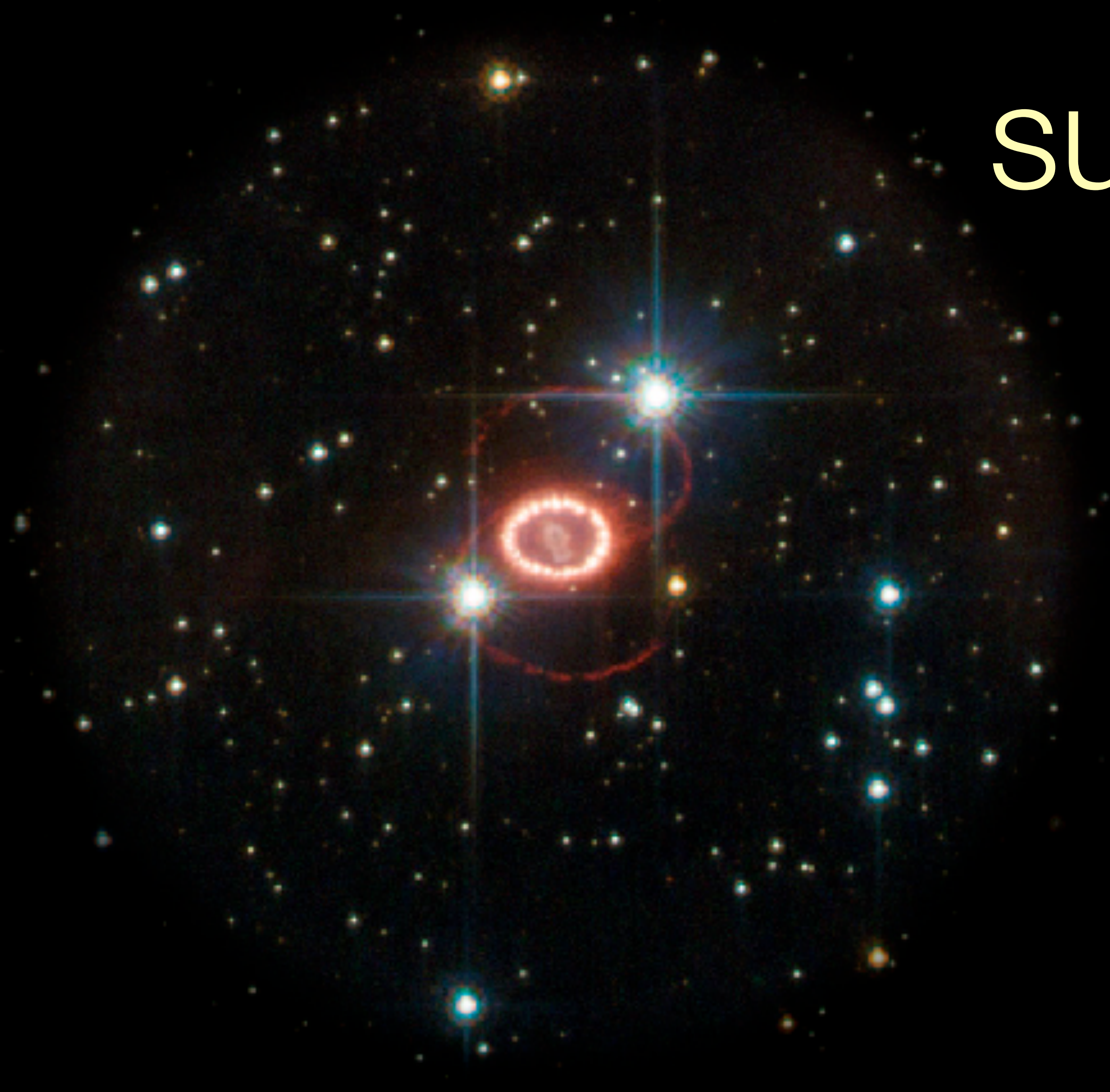
- ★ stellar evolution



supernova neutrinos

- ★ nucleosynthesis
- ★ matter under extreme conditions
- ★ stellar evolution

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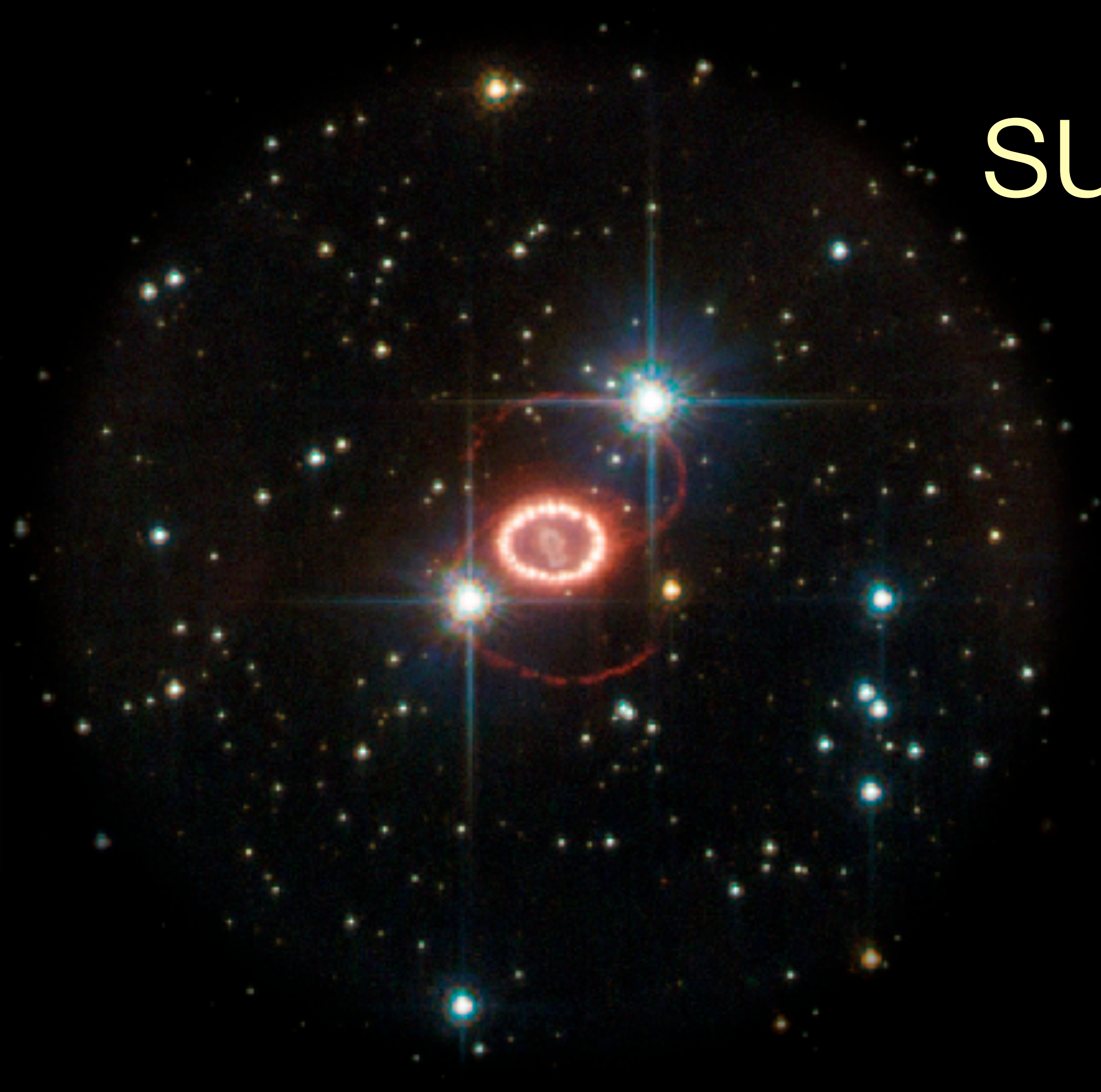

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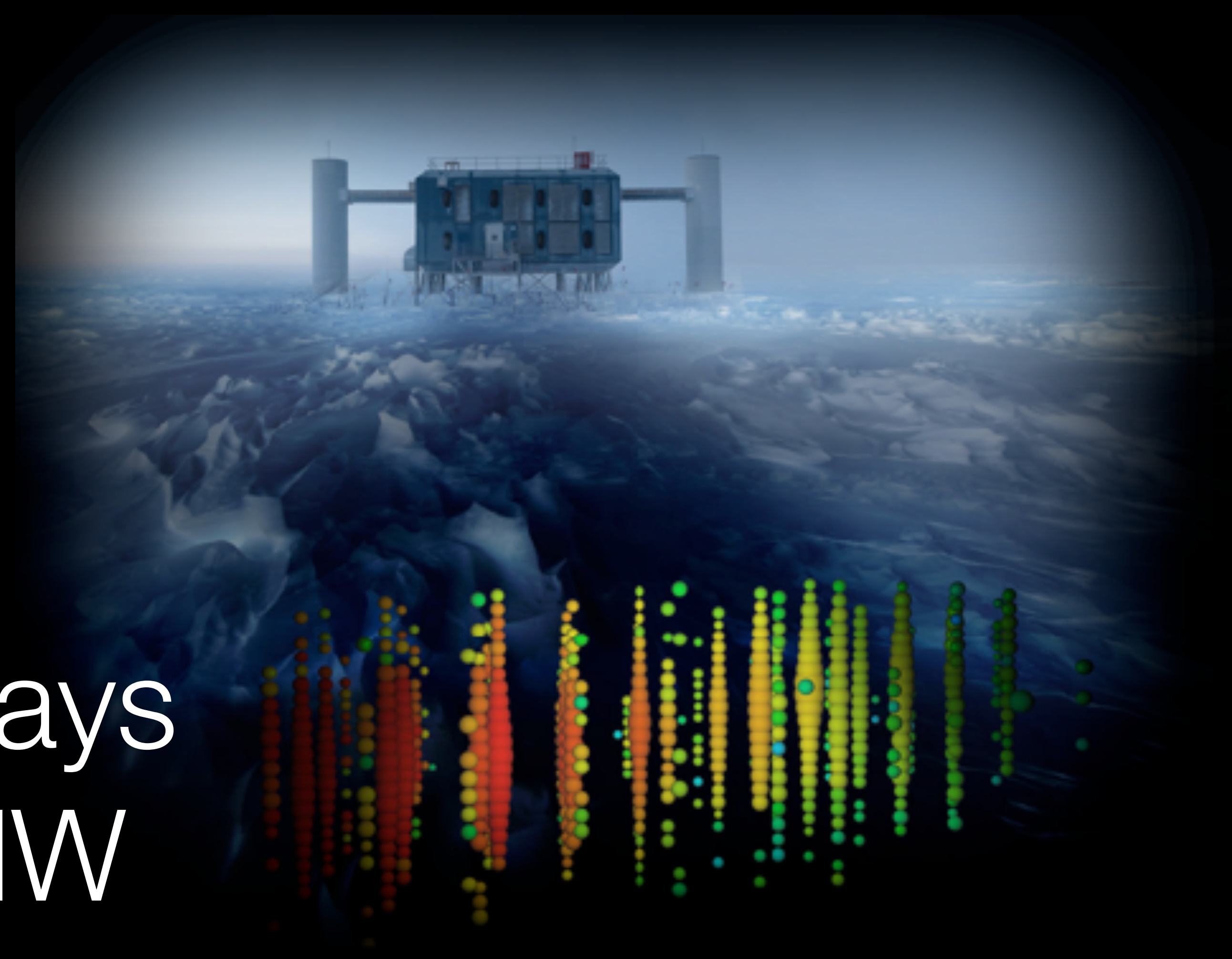
high-*E* neutrinos

- ⋆ origin of cosmic rays
- ⋆ AGNs, blazars, MW



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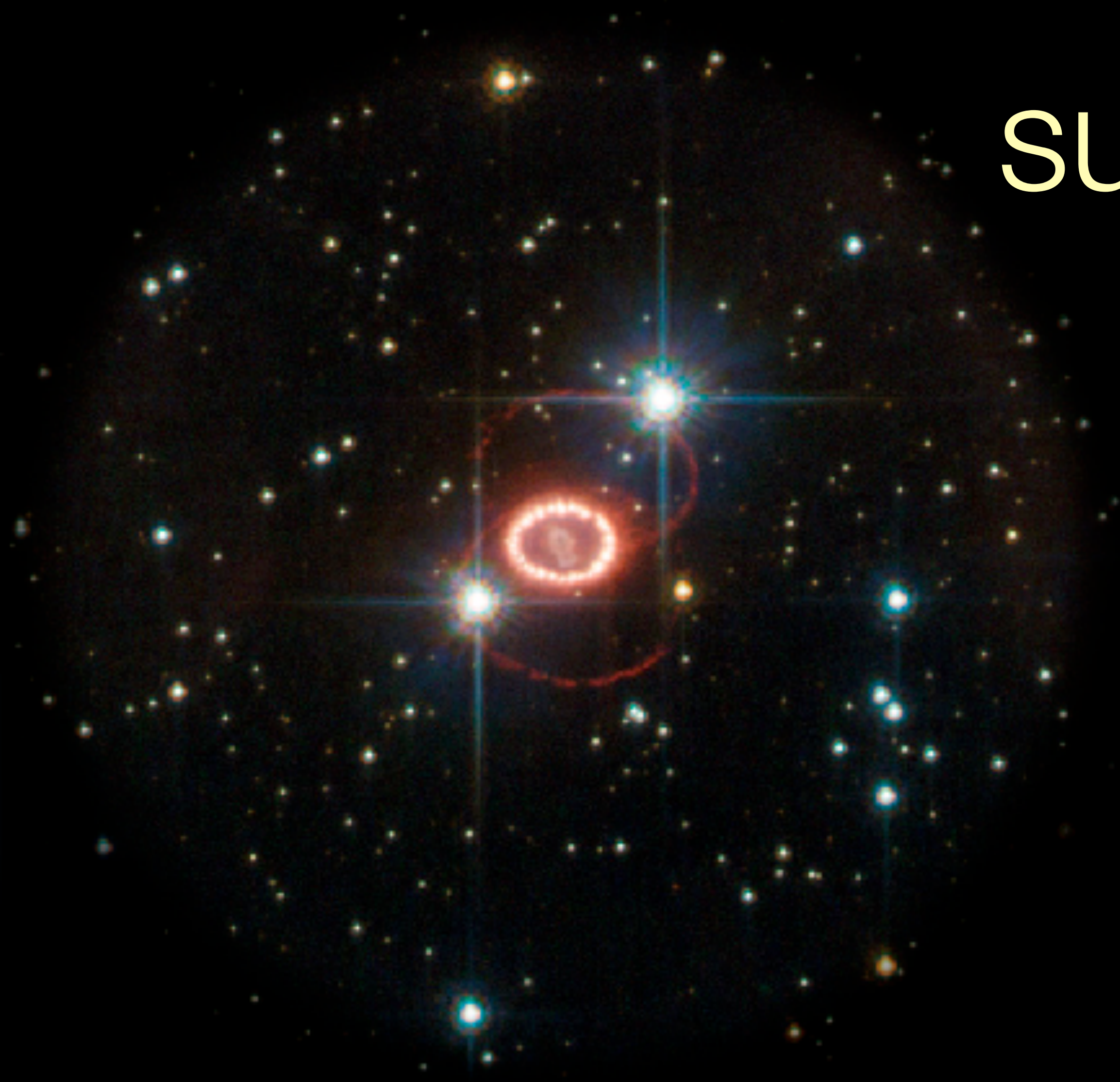

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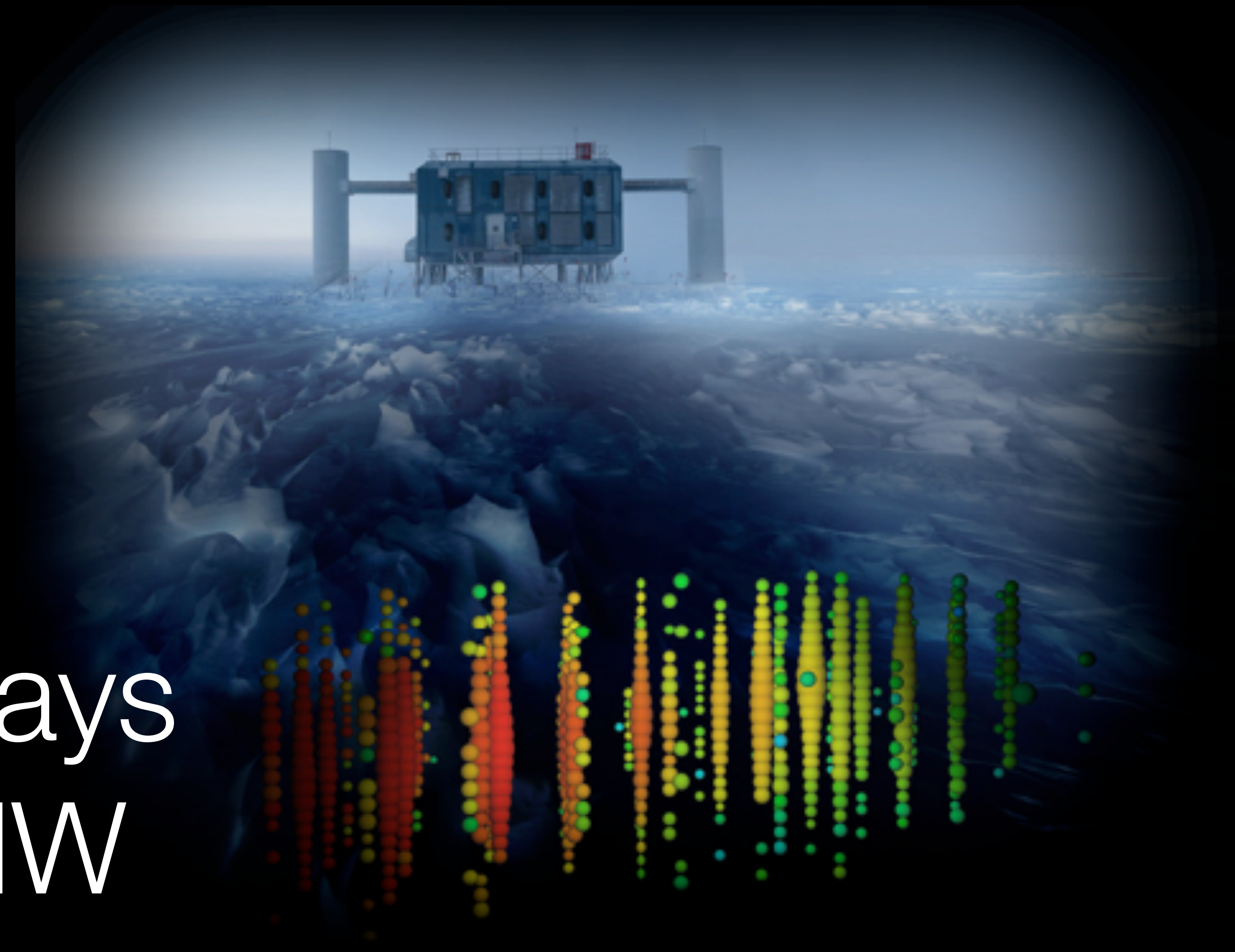

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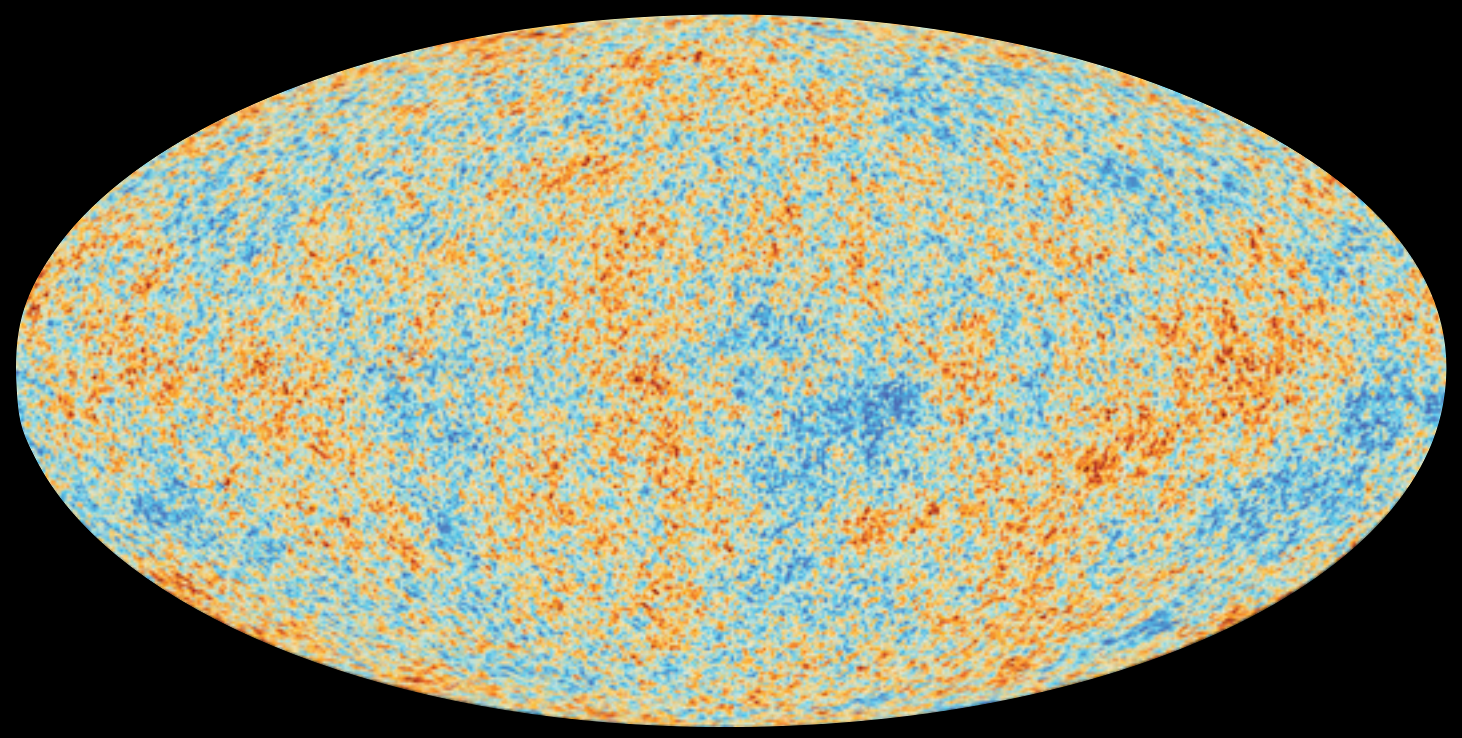


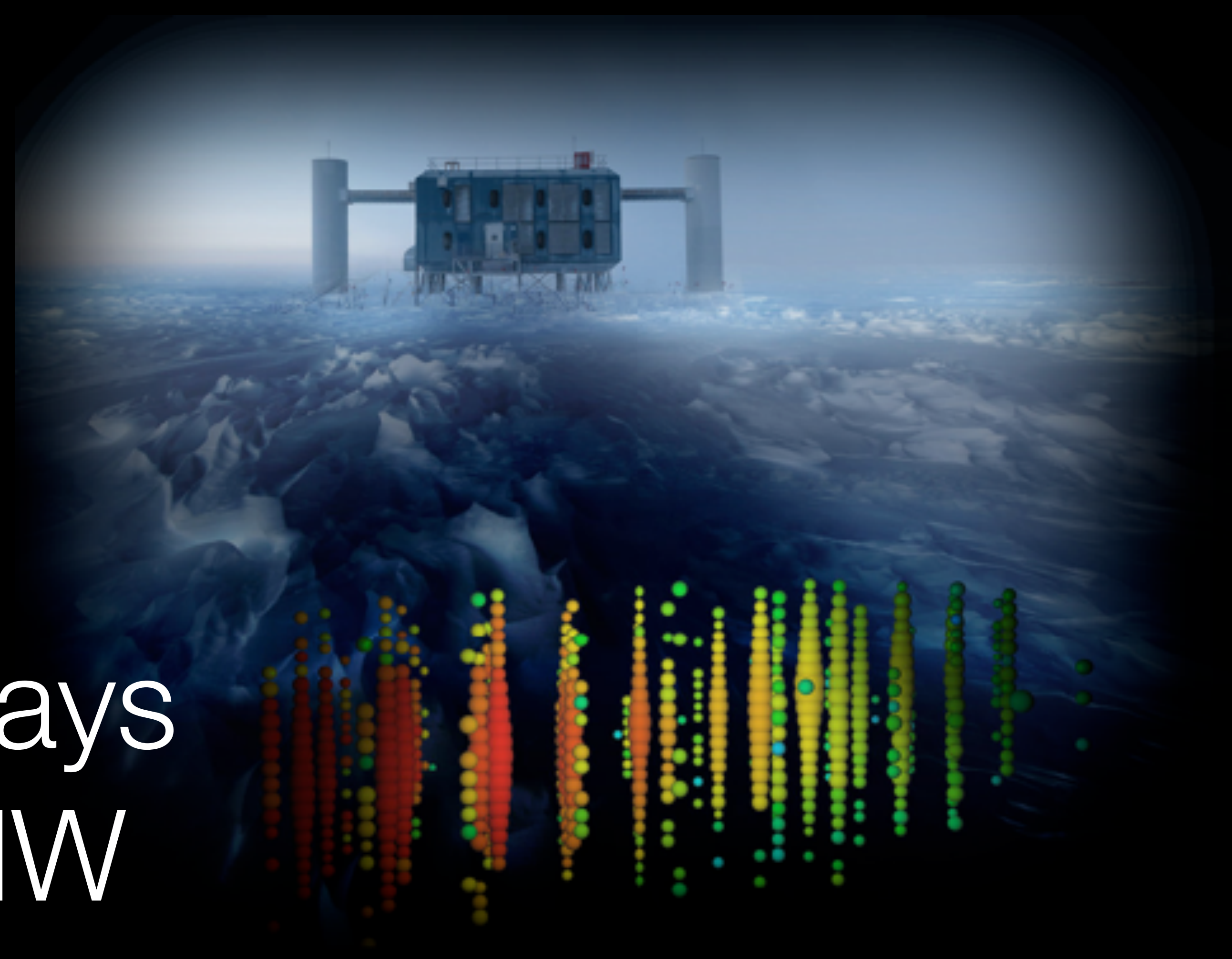
cosmology

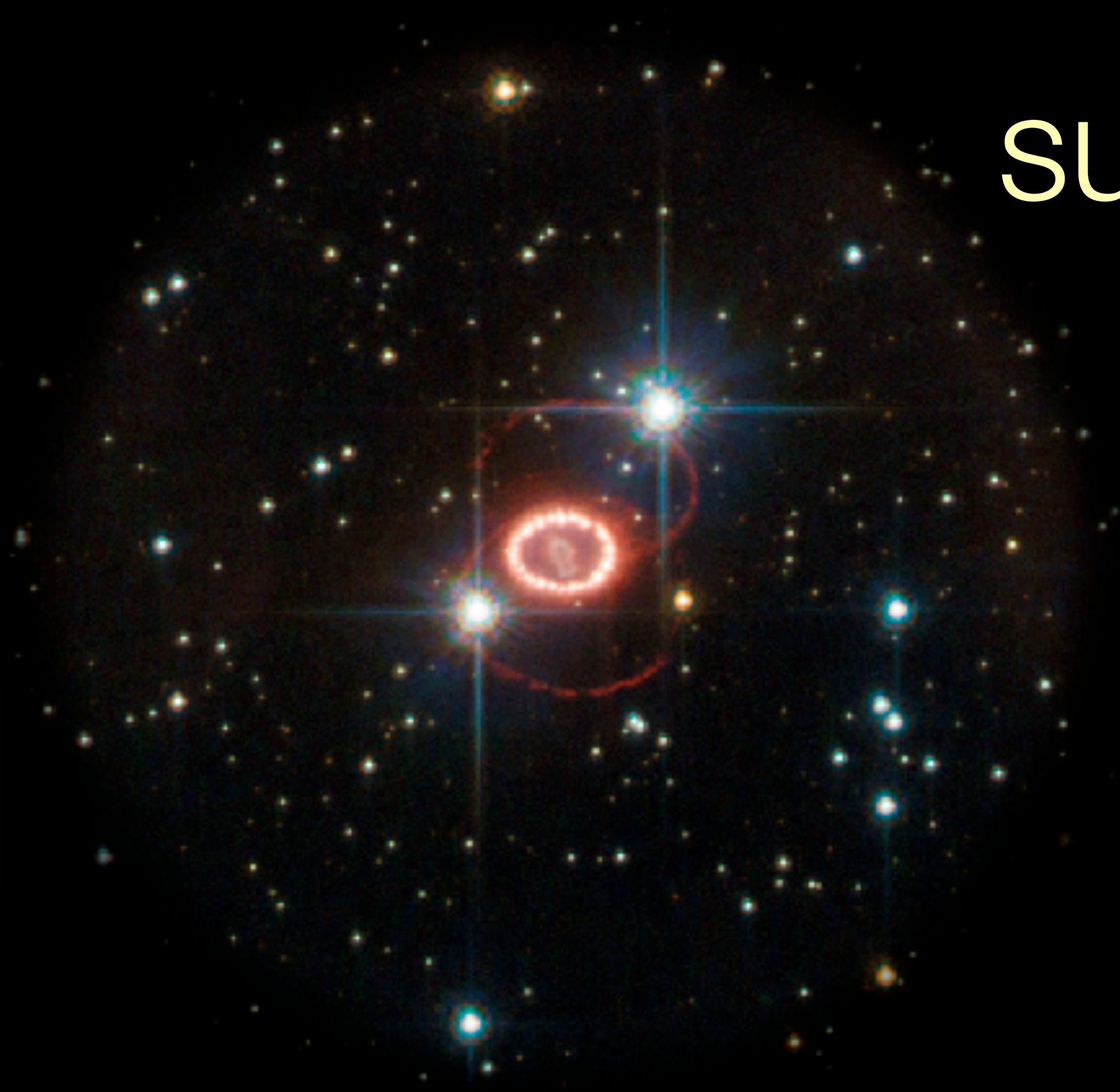
- ★ early Universe

Neutrinos as Astrophysical Messengers

solar neutrinos

- ⋆ stellar evolution





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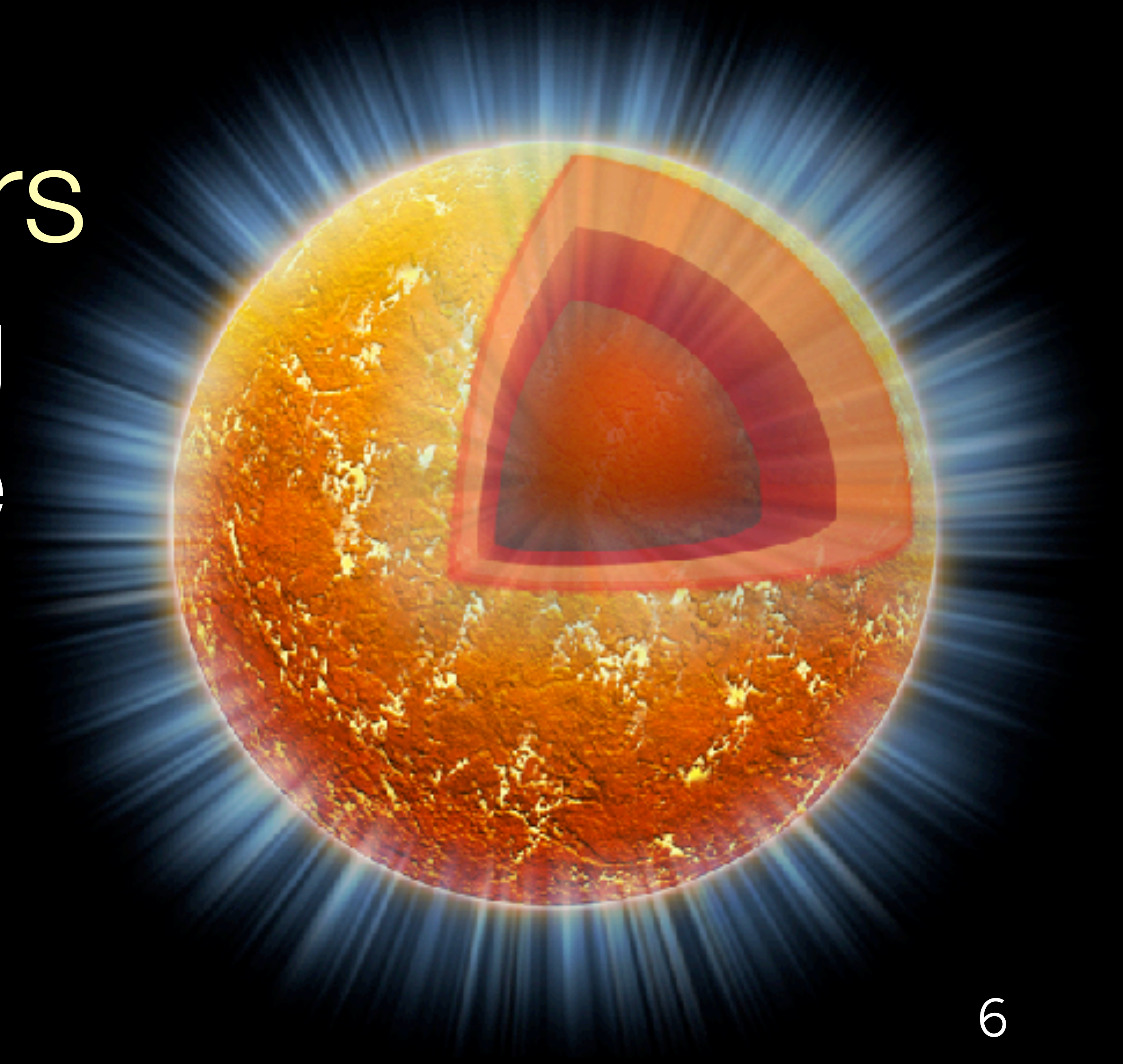
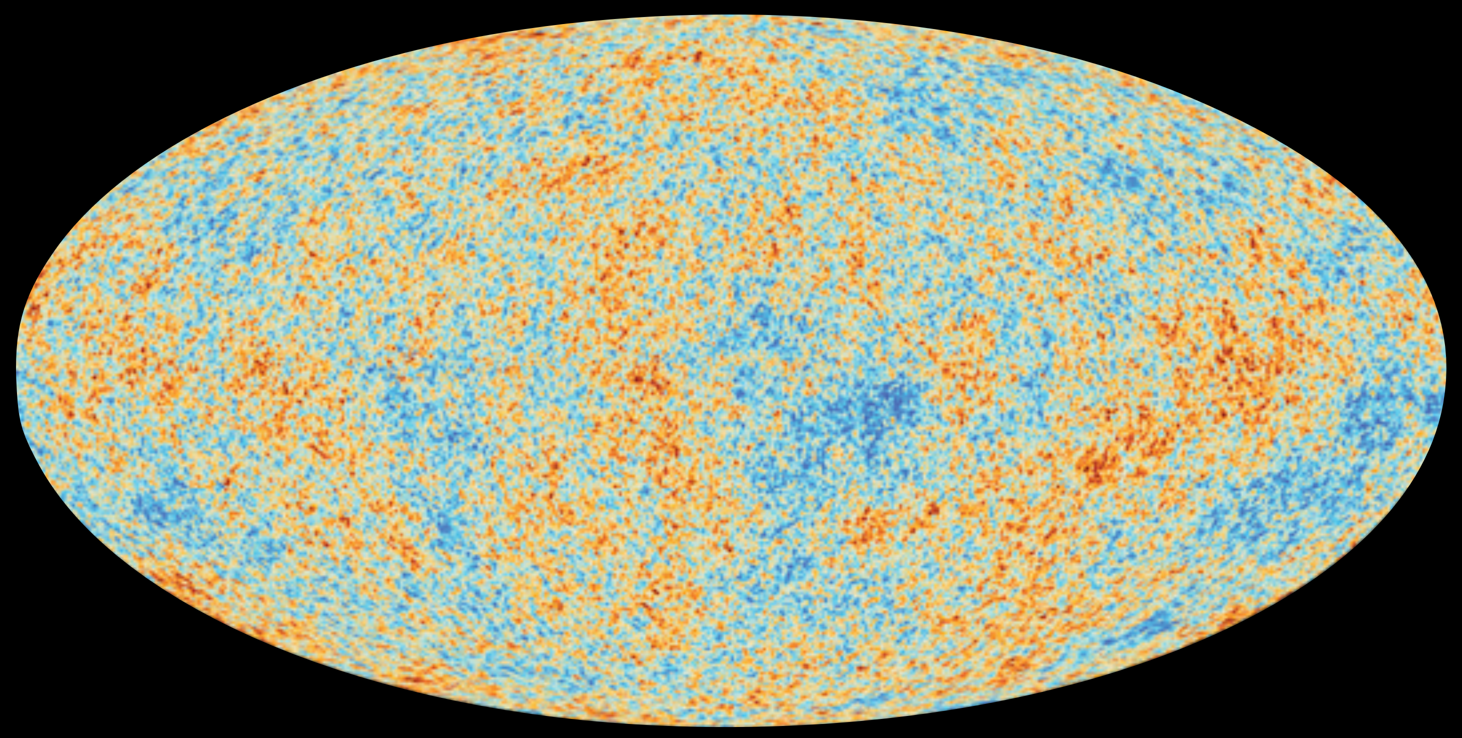
neutron stars

- ⋆ cooling
- ⋆ common-envelope systems





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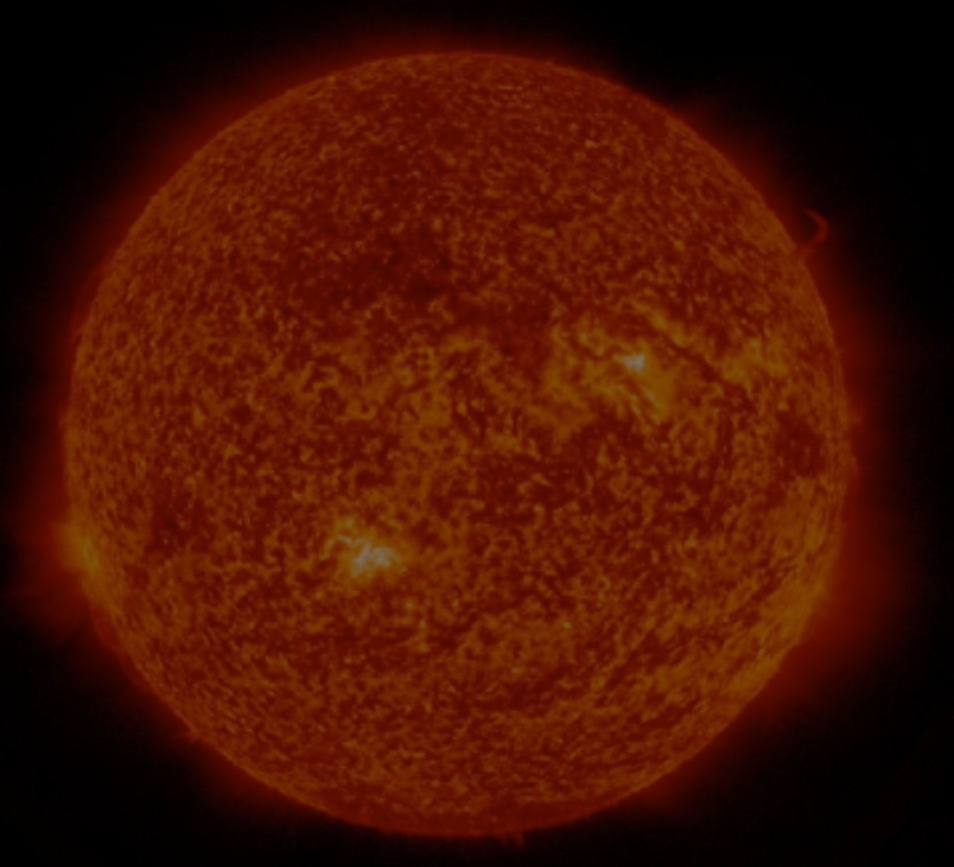

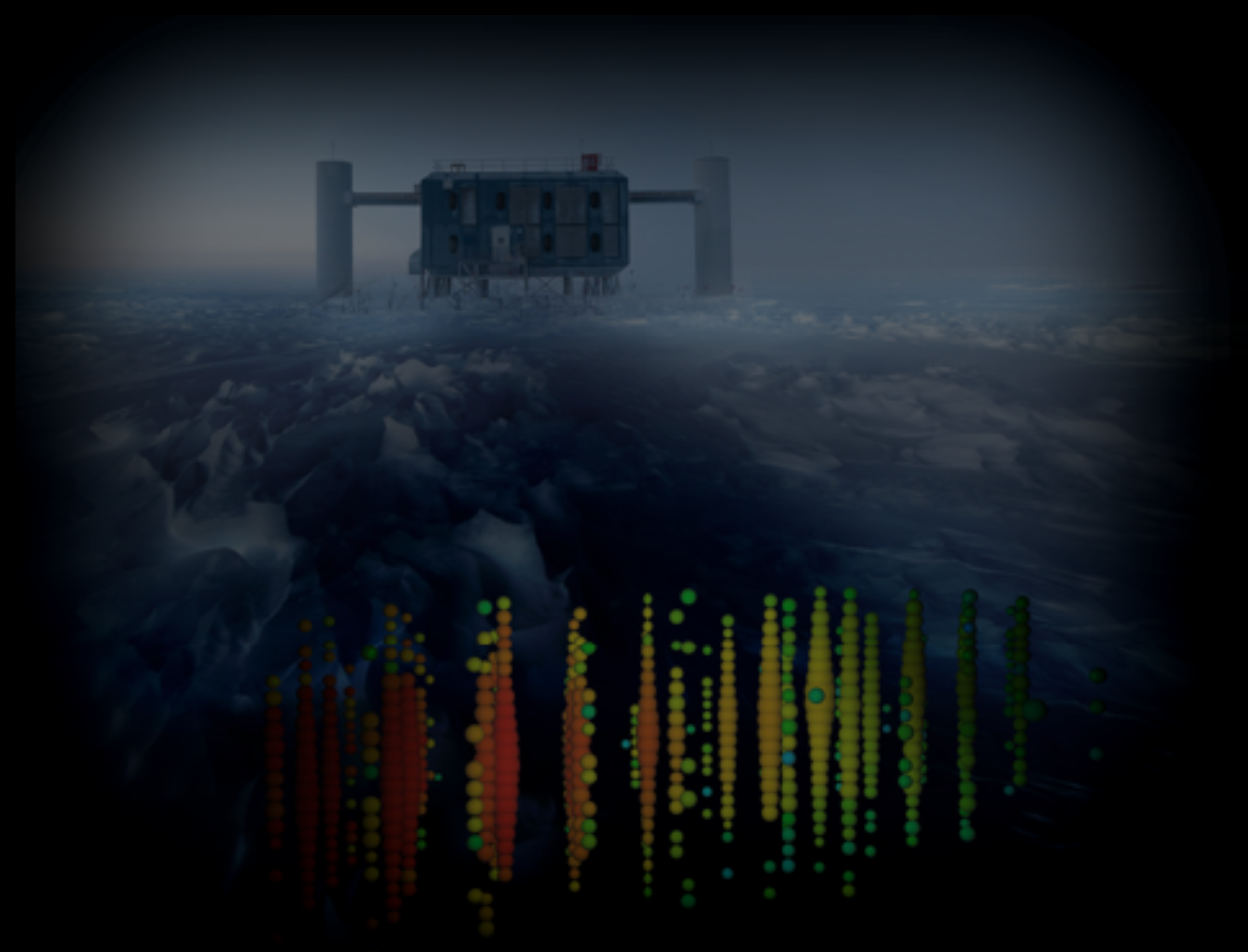

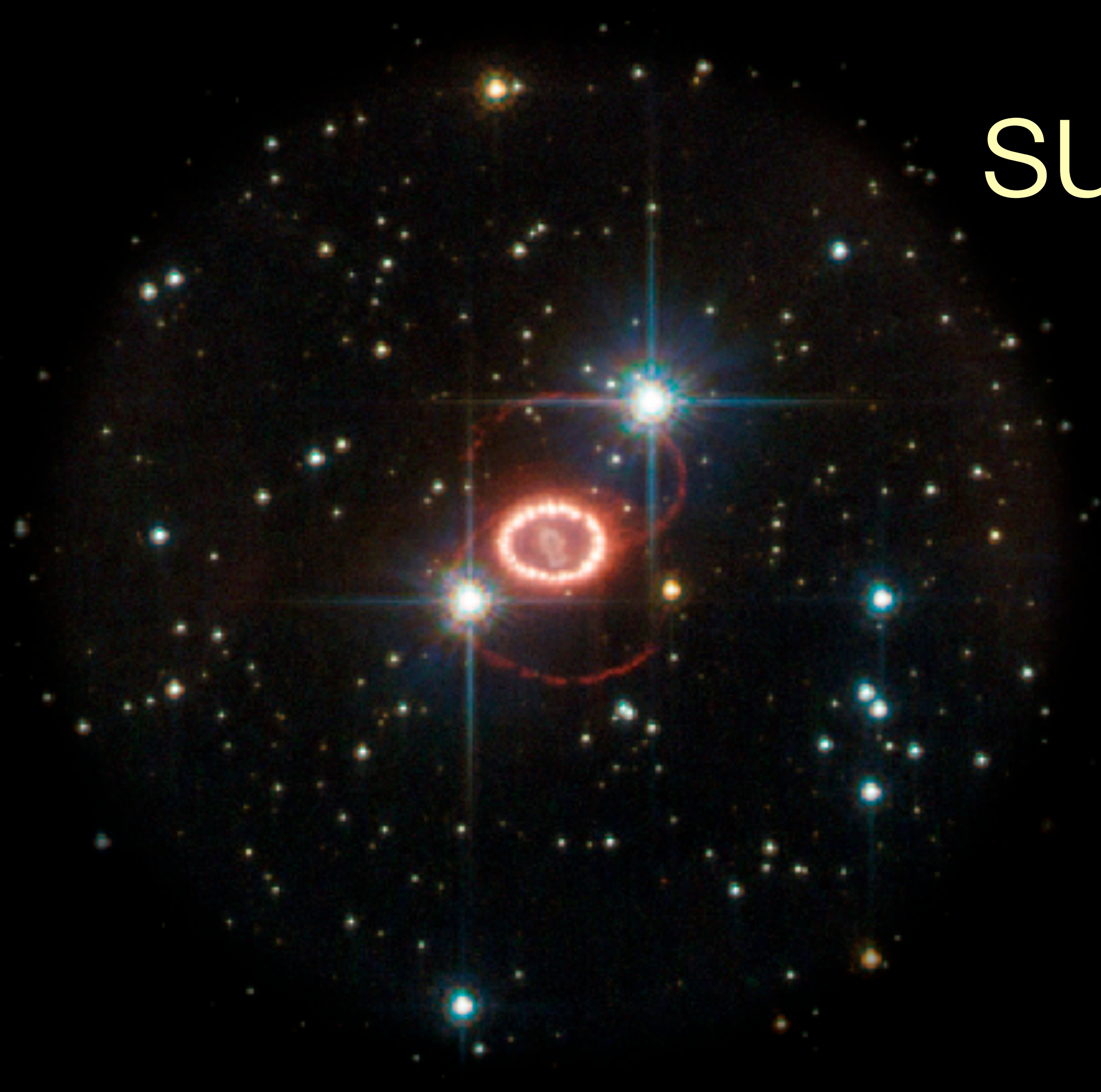

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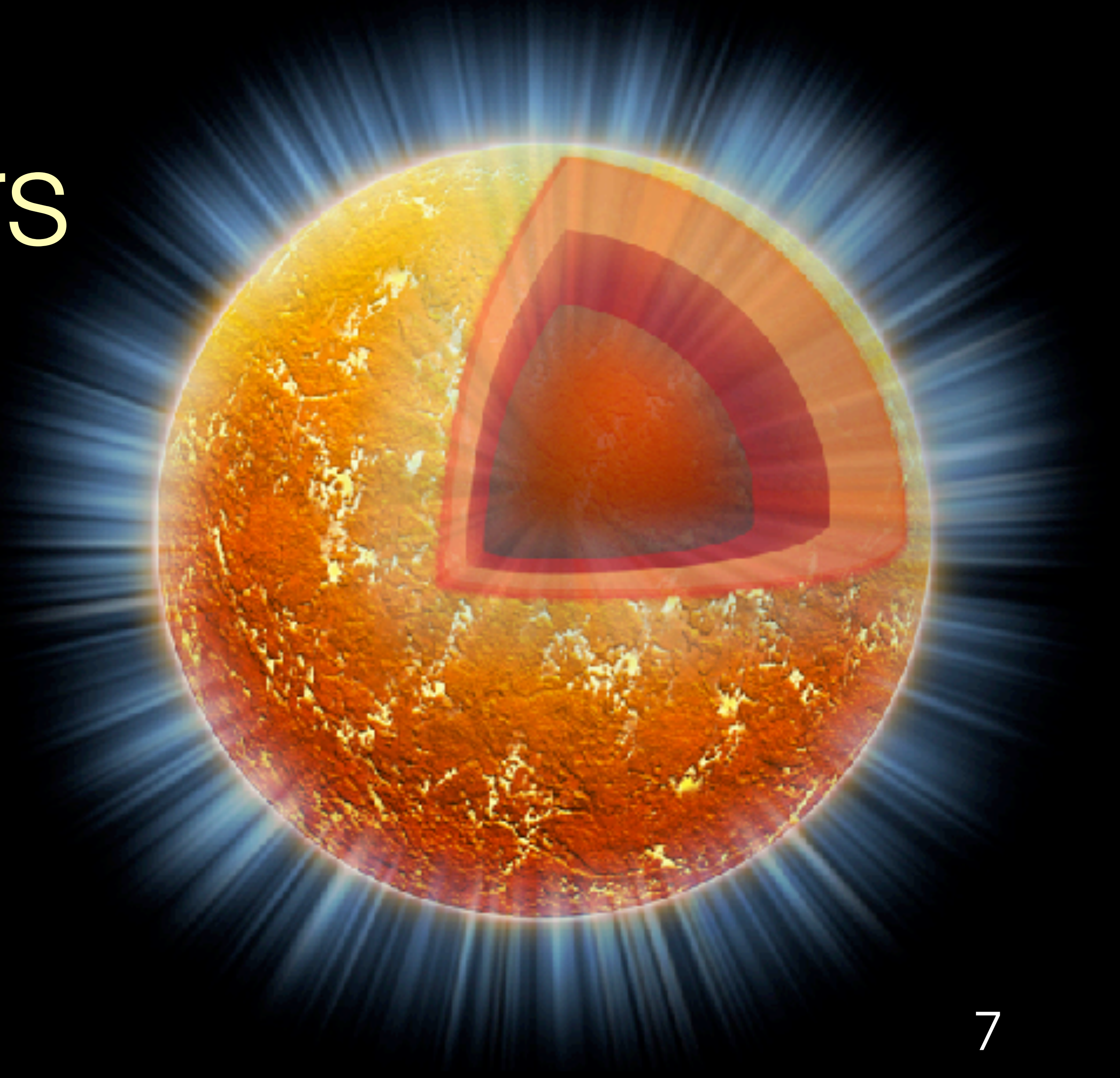
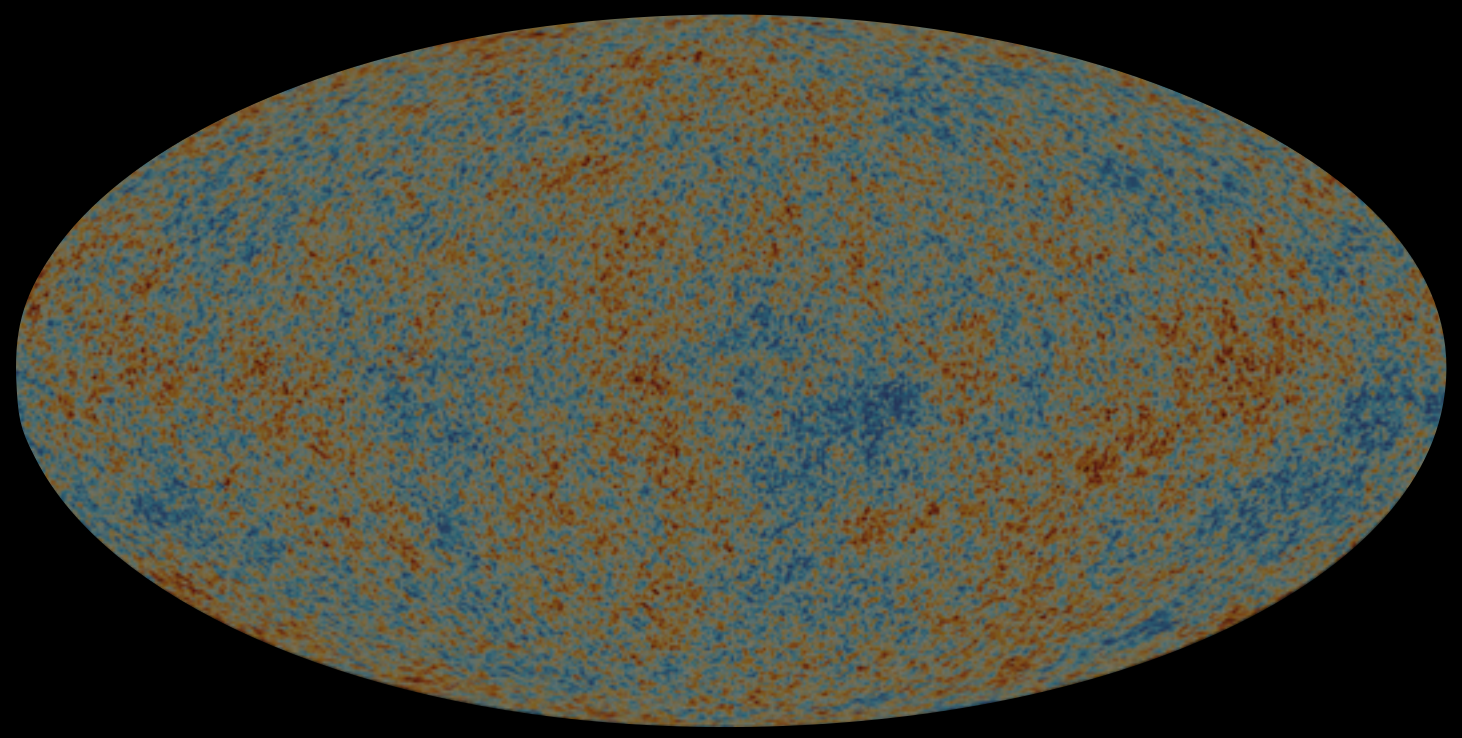
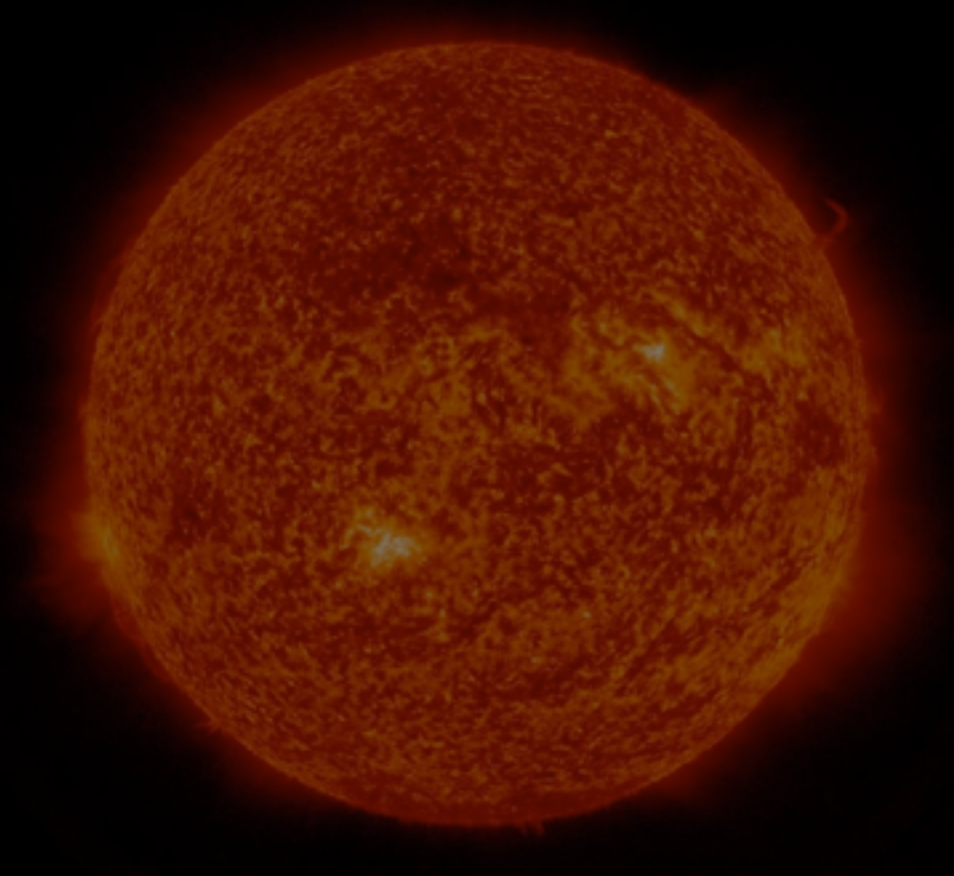
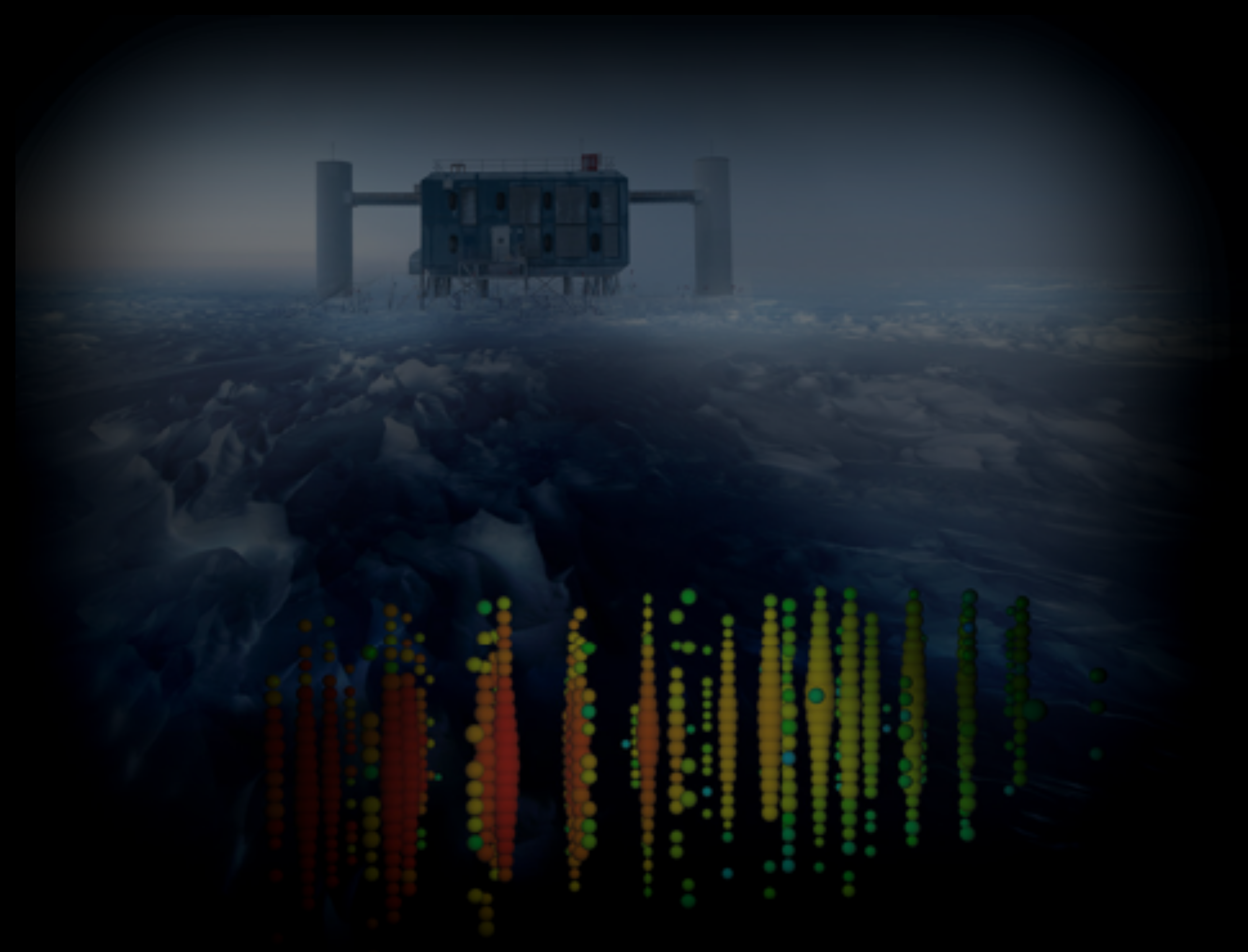
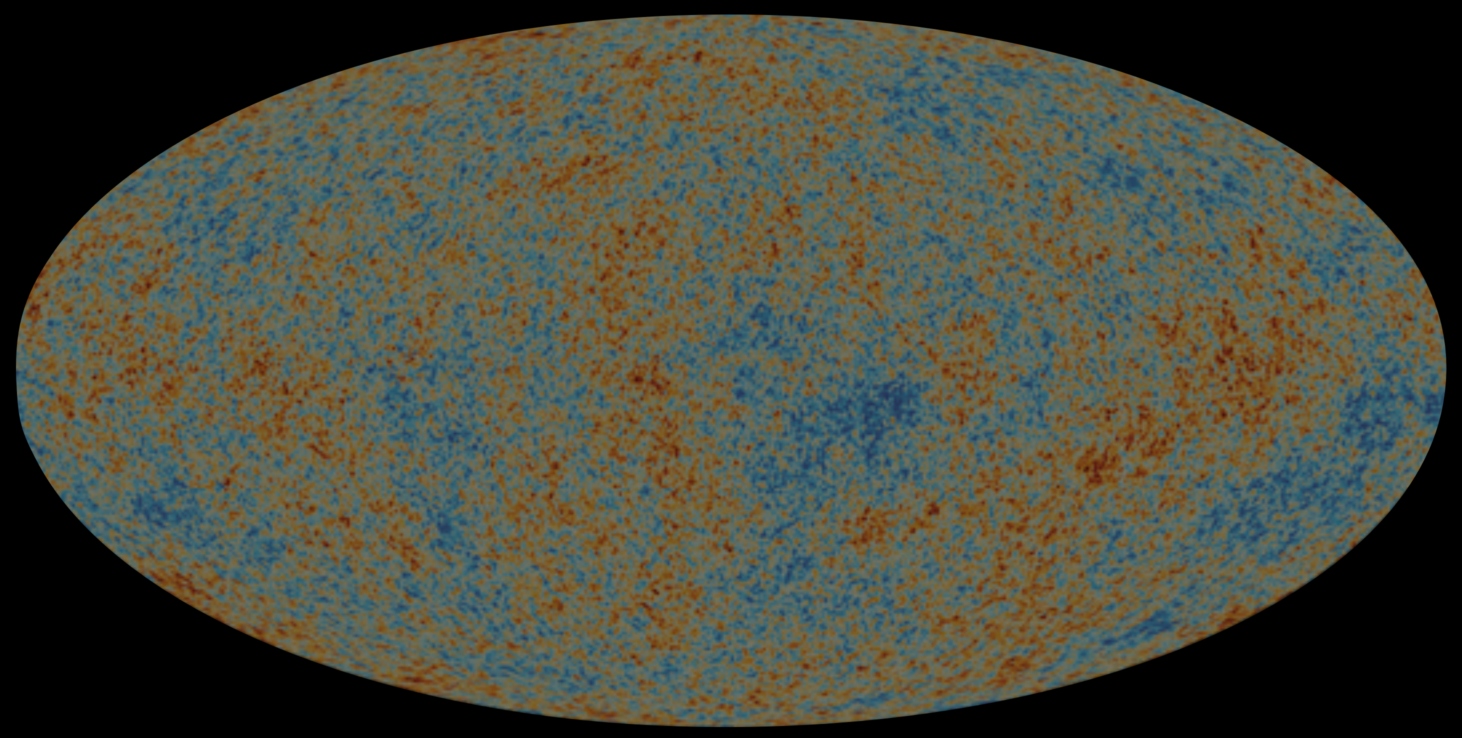




Neutrinos as Astrophysical Messengers







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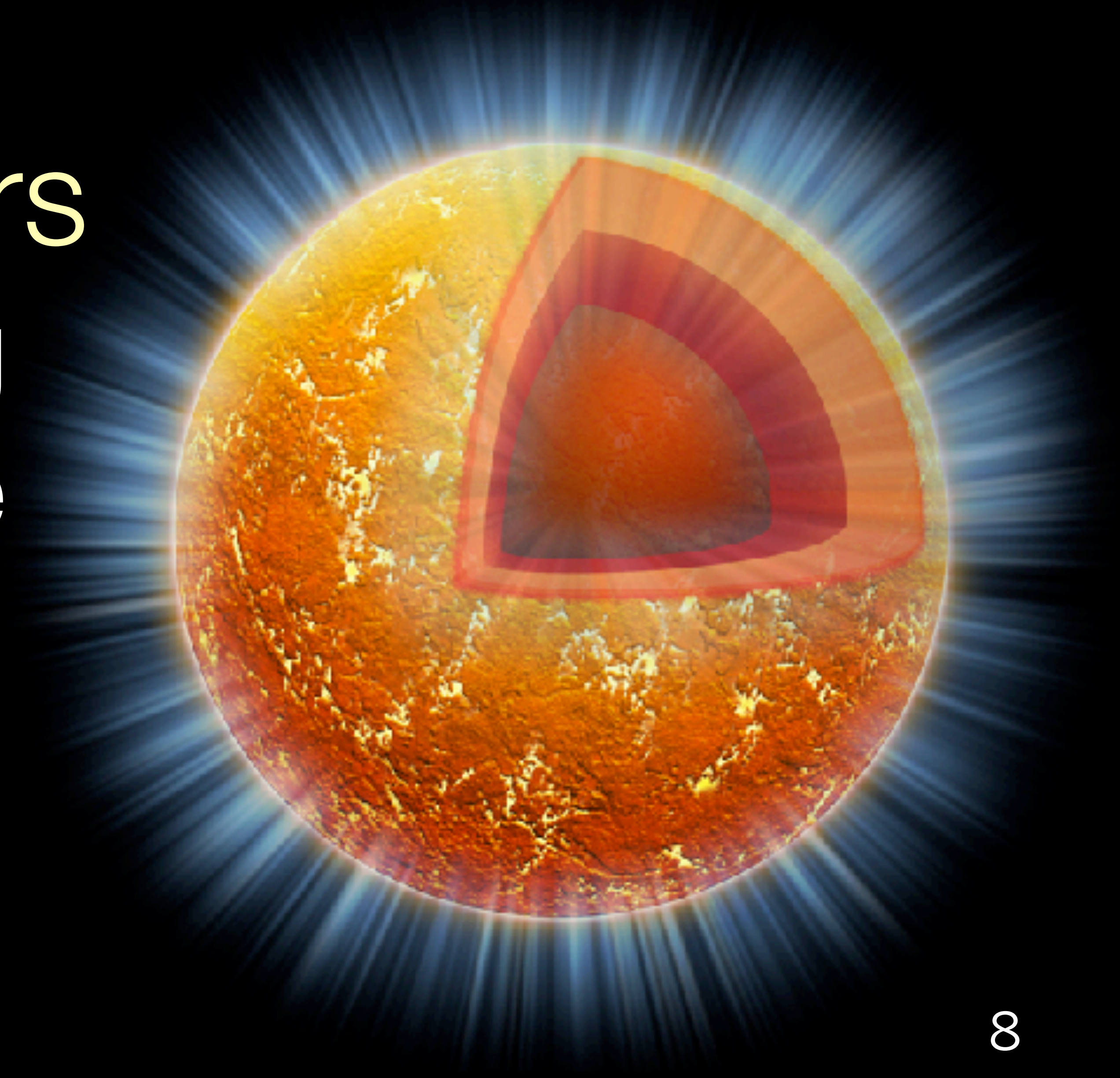


Neutron Stars

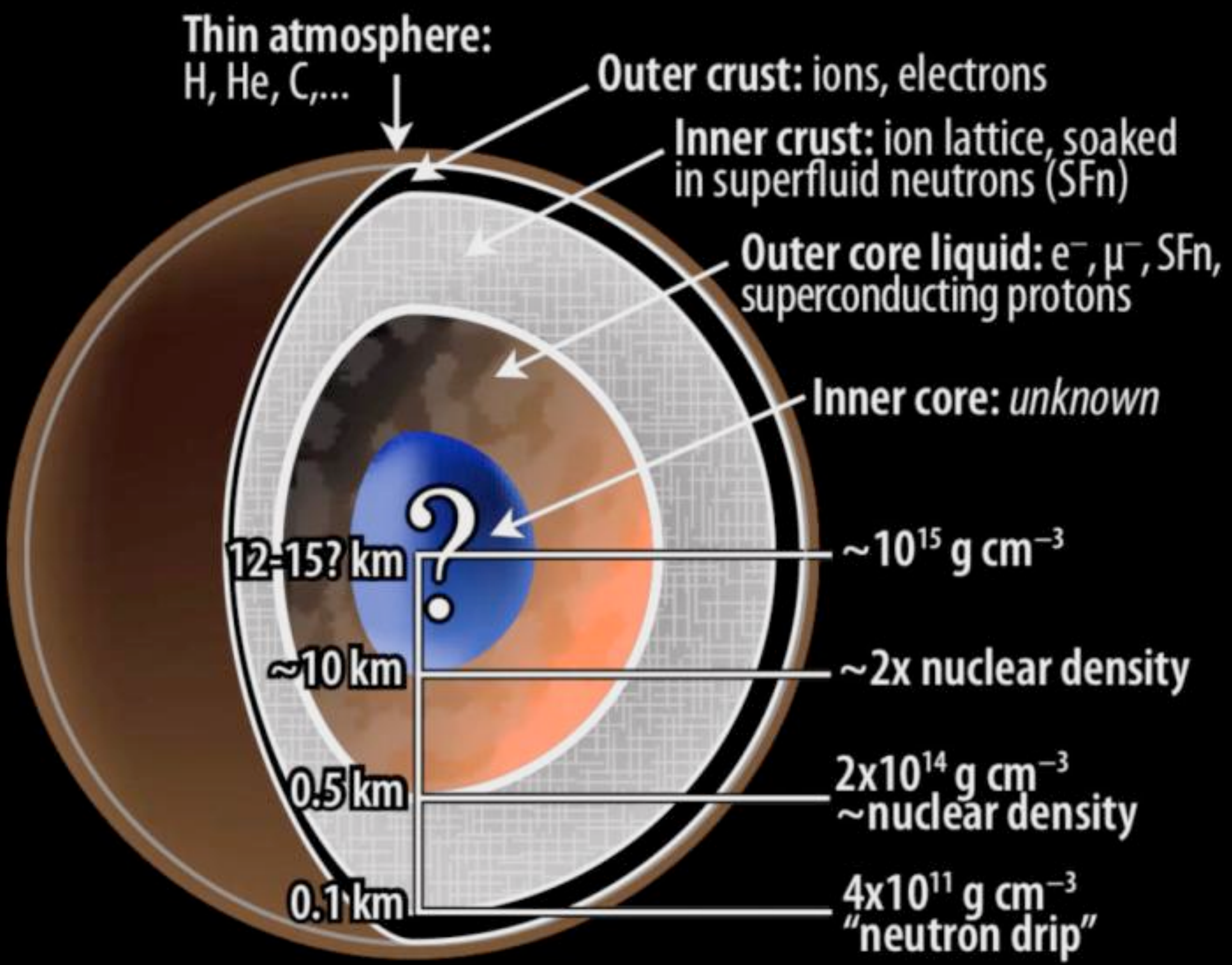
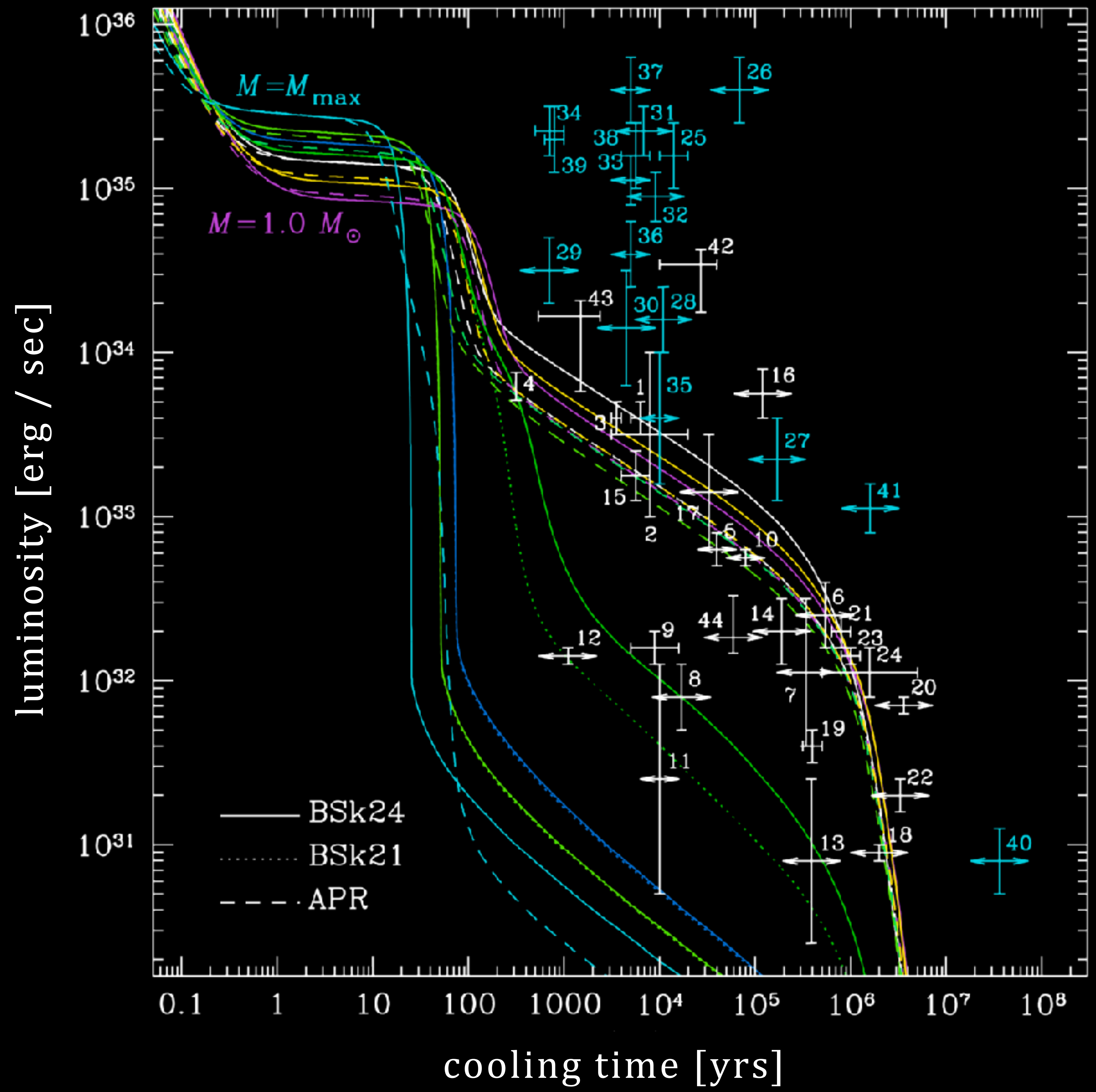
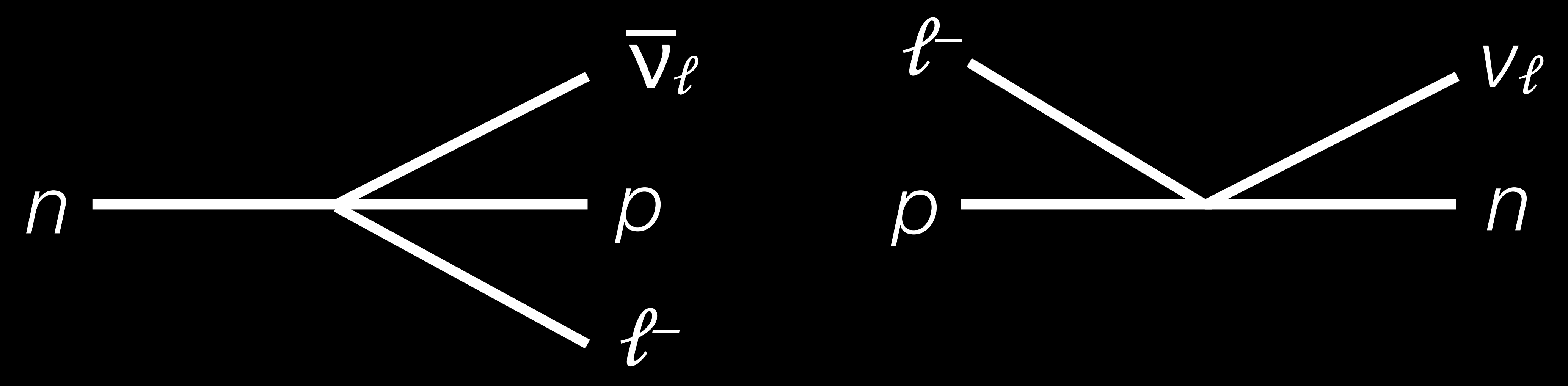


Image: Gendreau *et al.*

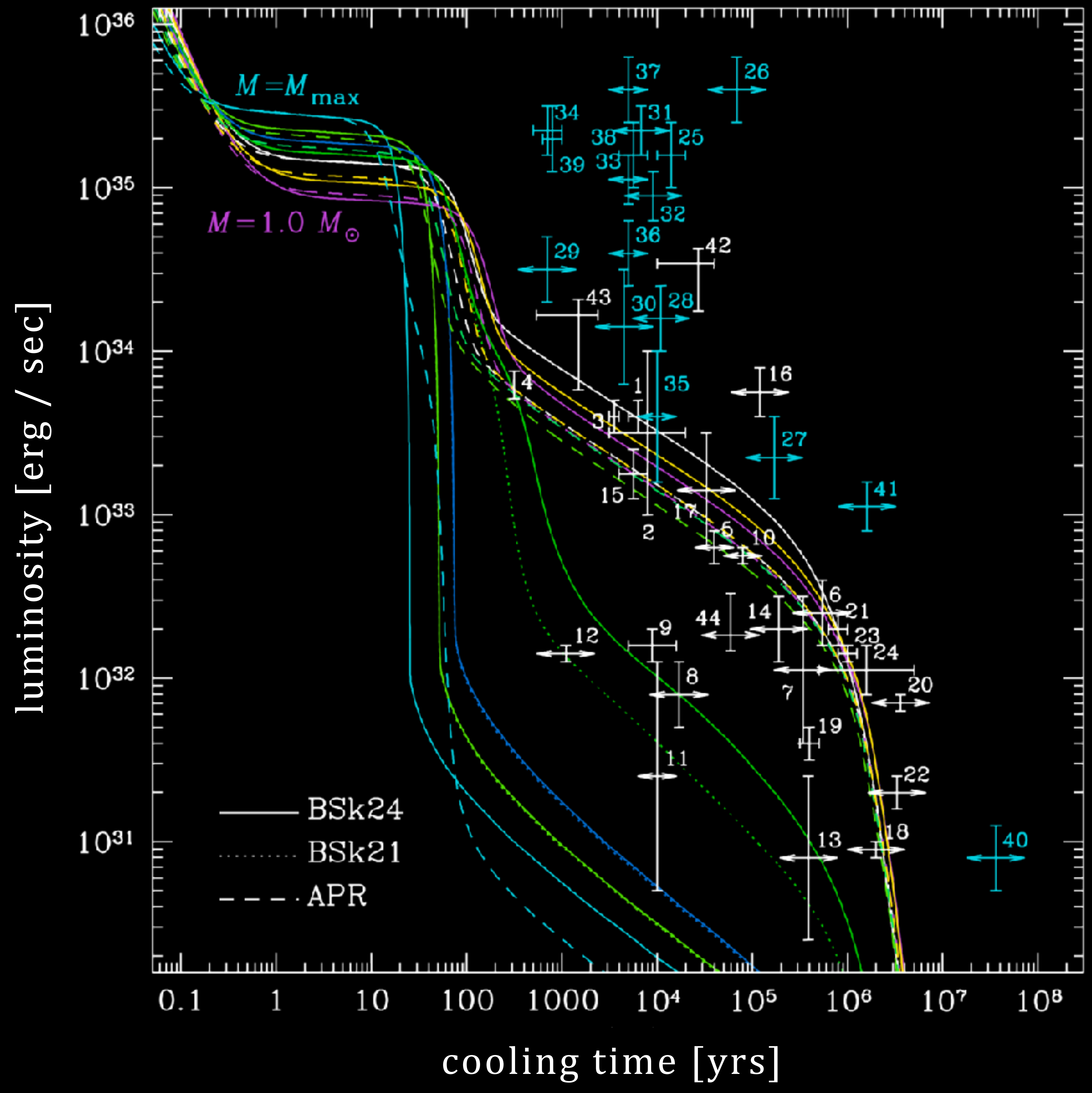


Neutrino Cooling

Direct Urca Processes



- kinematically forbidden except in the heaviest stars
- condition $p_{Fn} < p_{Fp} + p_{F\ell}$



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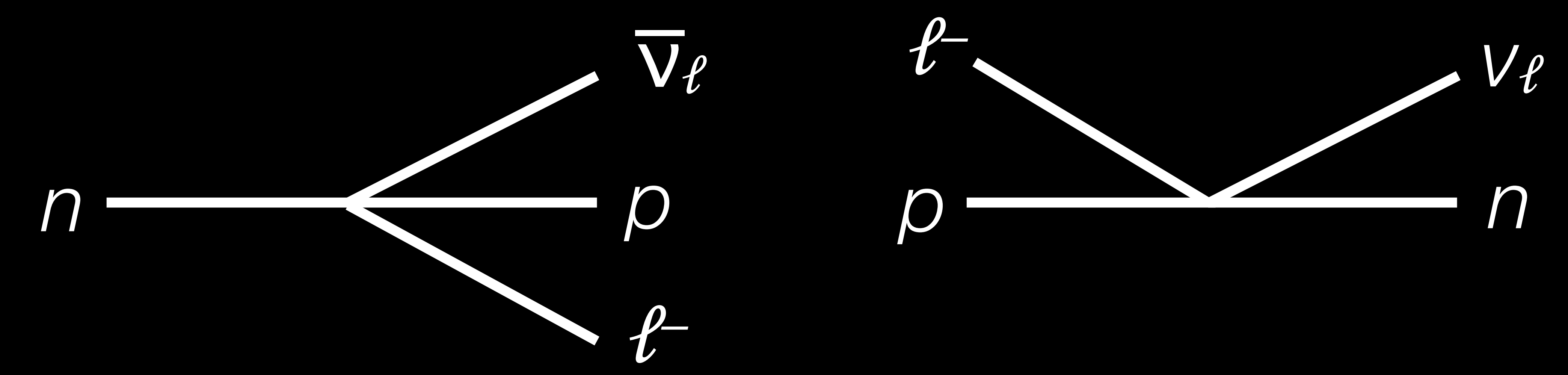

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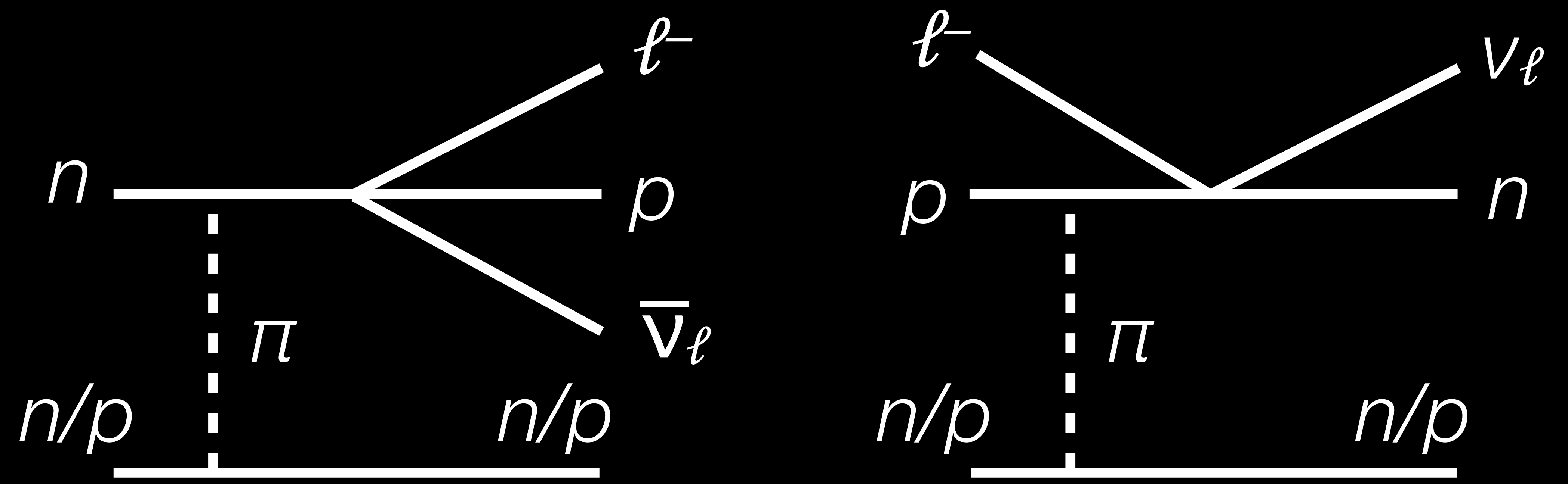
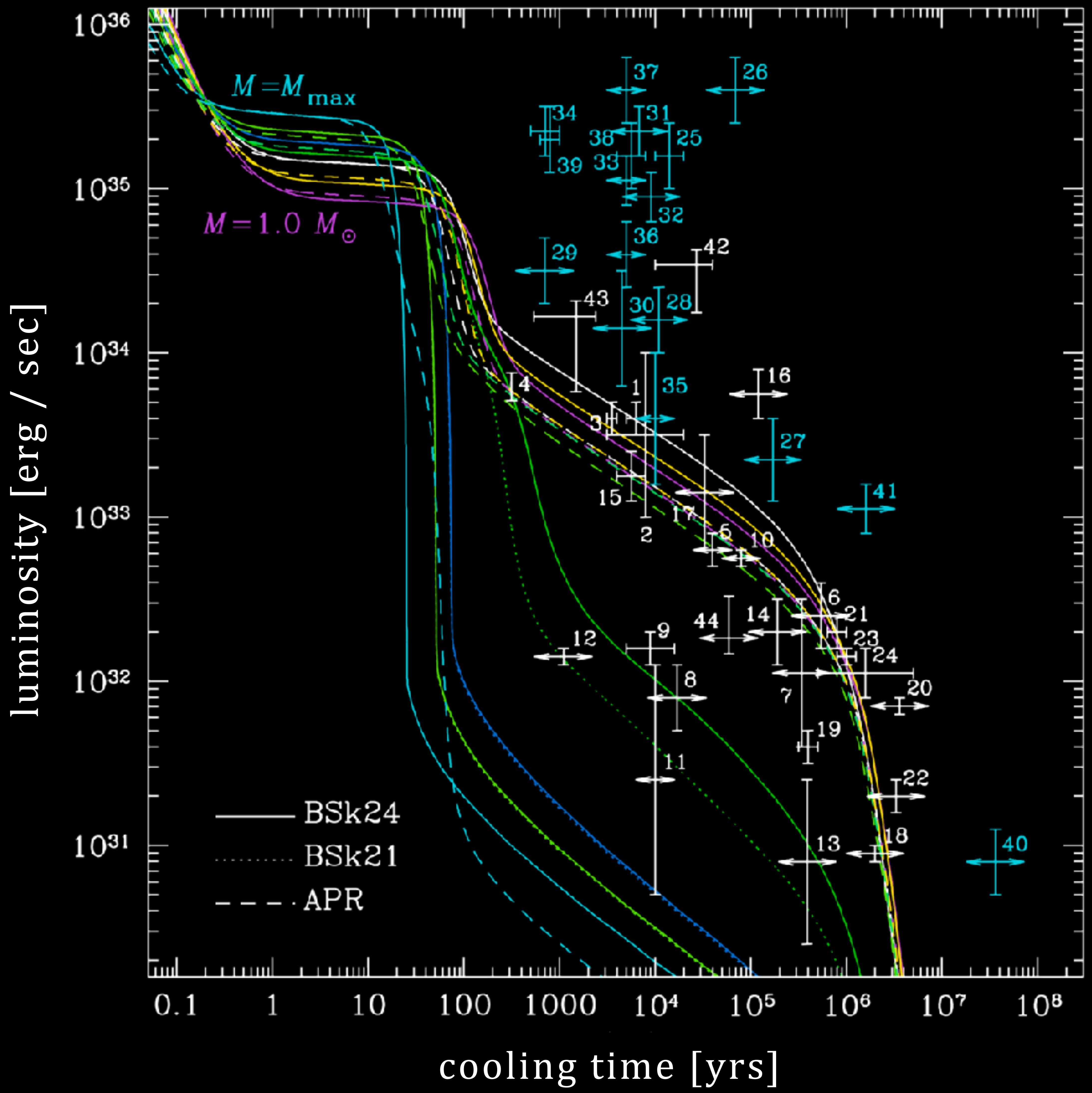
Modified Urca Processes



- allowed in all neutron stars



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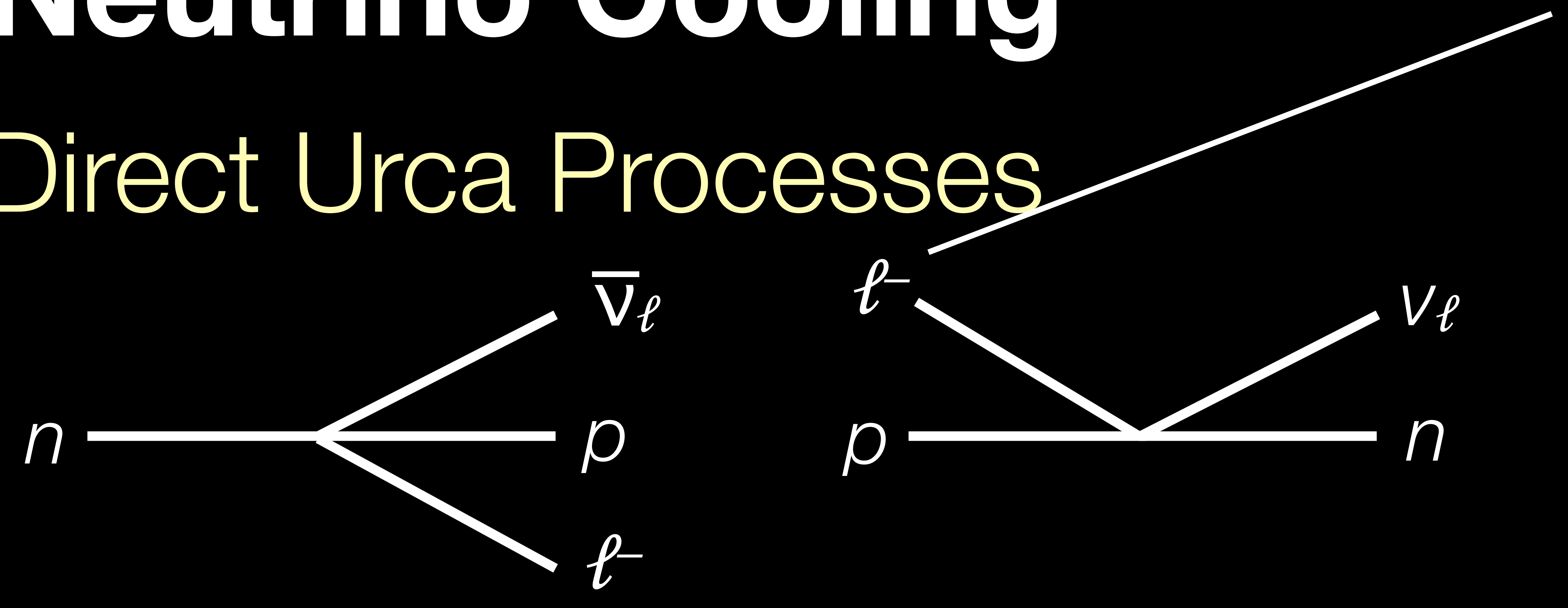

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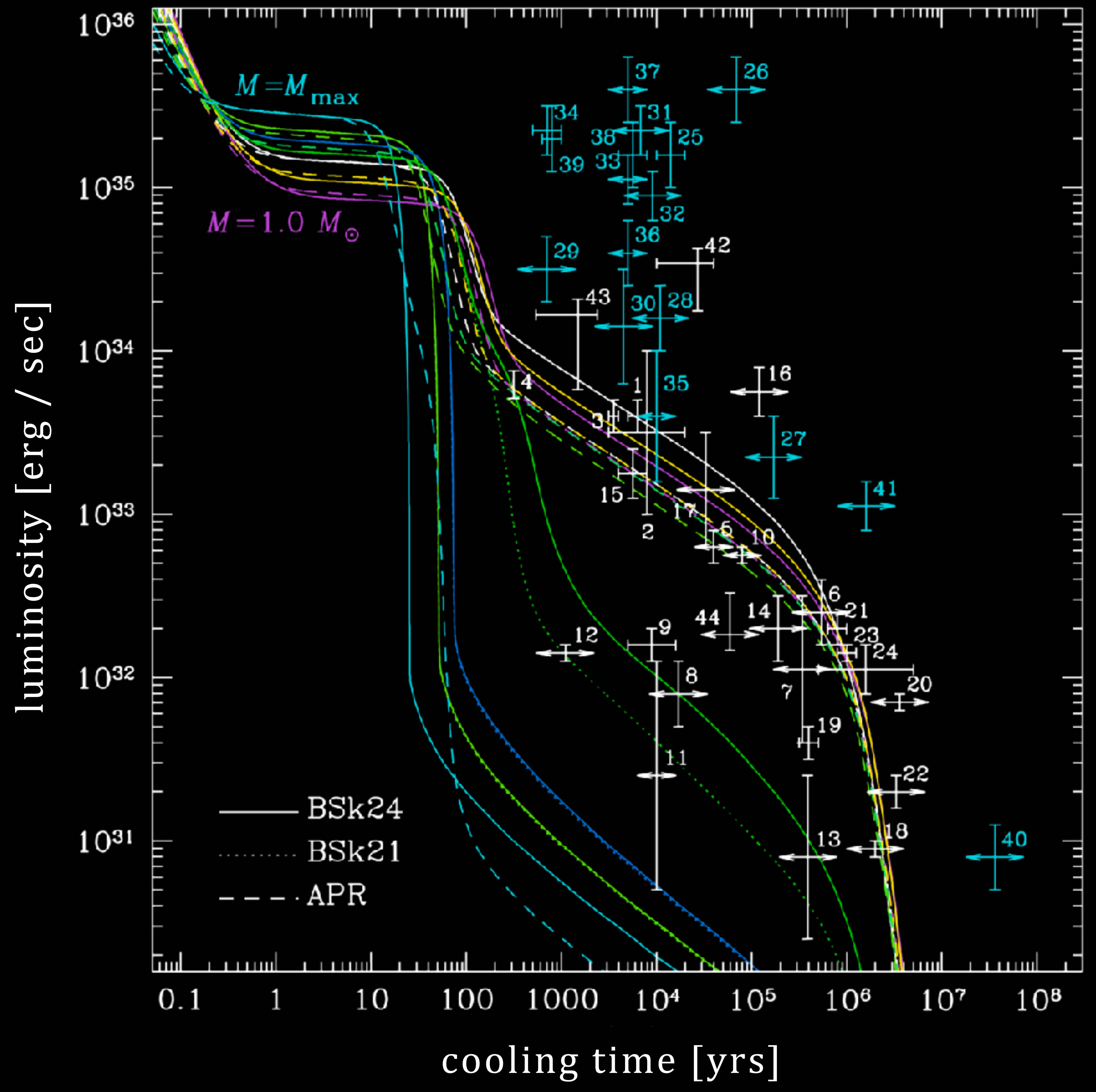

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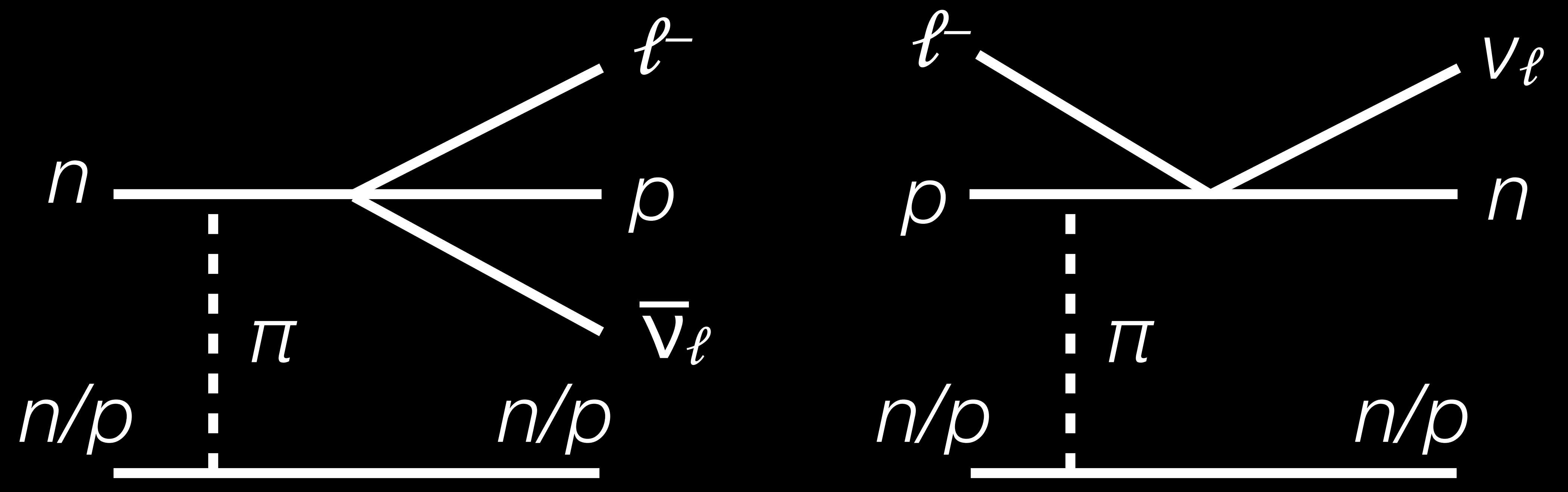
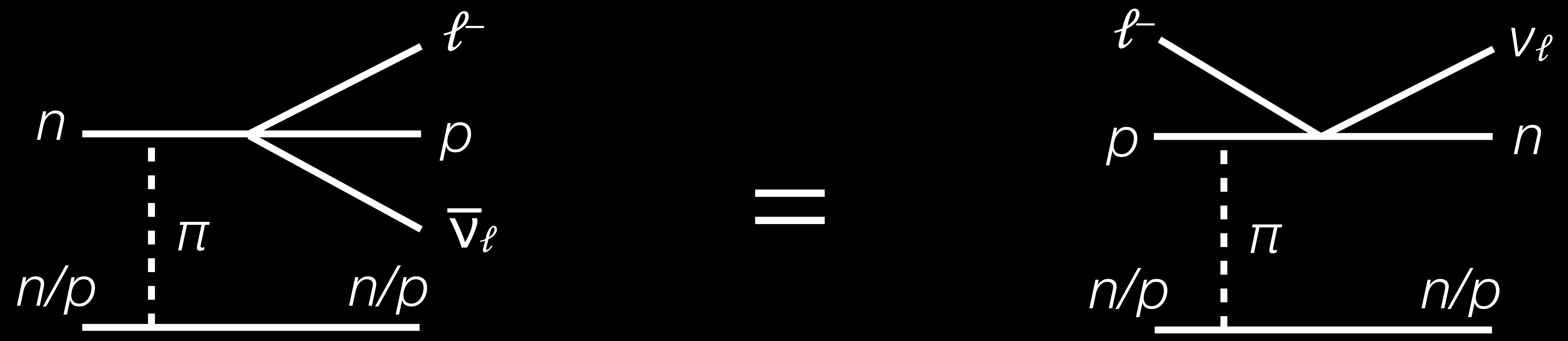


- allowed in all neutron stars

Neutrinos from Neutron Stars in Chemical Equilibrium



Regular modified Urca (in equilibrium)

- in young neutron stars (T ~ yrs): E_ν ~ 100 keV, $\phi \sim 10^{41}$ erg / sec
- at 10 kpc: **38 cm^{-2} sec^{-1}**
- for comparison: diffuse SN neutrinos: **~ 1 cm^{-2} sec^{-1}** at E_ν ~ MeV

➠ large flux, but low energy ➠ so far undetectable

Neutrinos from Neutron Stars

neutron stars evolve:

- spin-down / spin-up
- accretion
- expulsion of B-fields
- tidal deformation

Result:

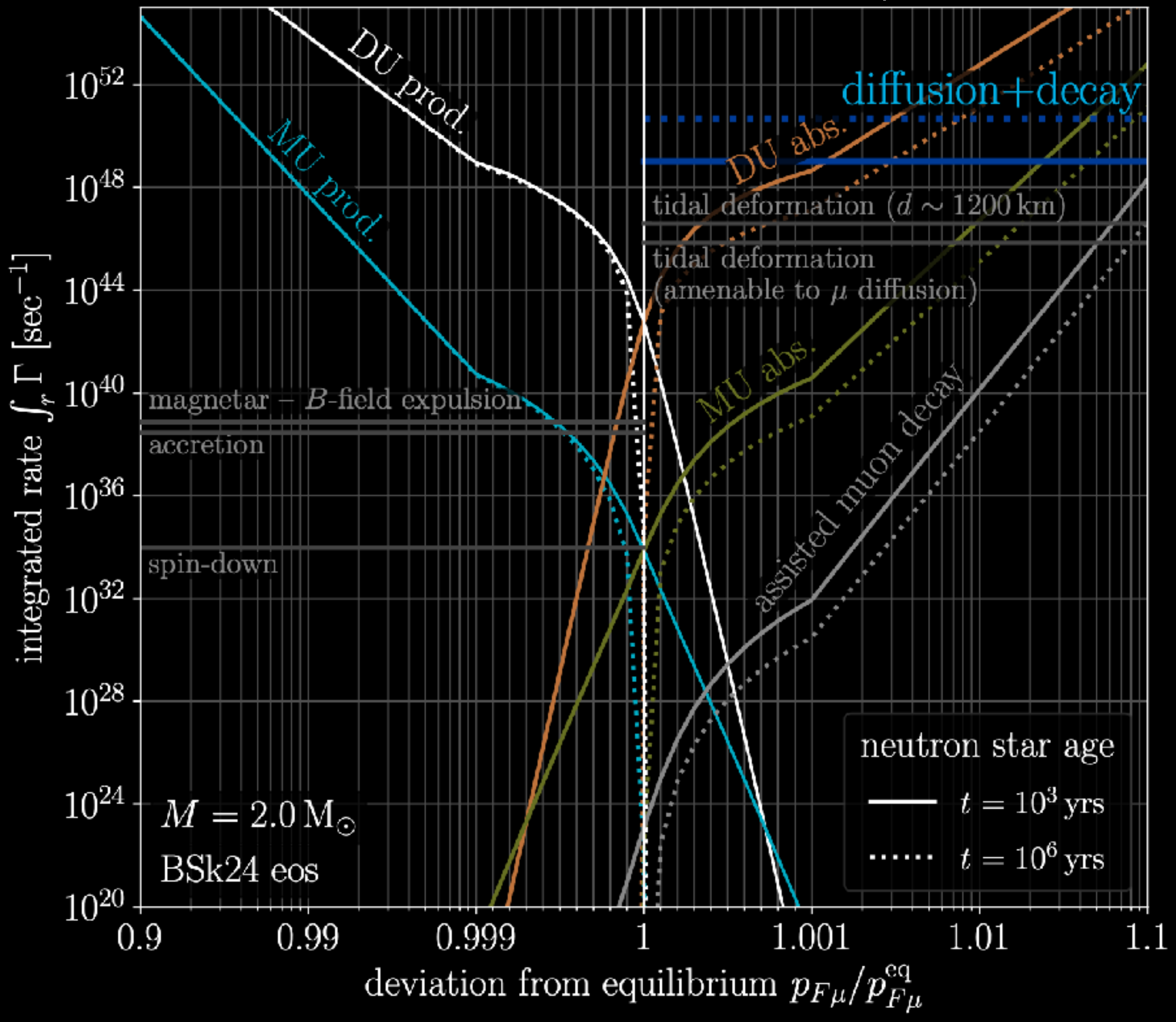
- out-of-equilibrium Urca processes
- extra neutrinos

JK Opferkuch arXiv:2312.08457

Neutron Stars Away from Thermal Equilibrium

- neutrino flux can be enhanced by several orders of magnitude
- but low energy still precludes detection so far
- opportunities for large low-threshold DM detectors?

JK Opferkuch 2023



Common-Envelope Evolution

- compact star (neutron star, black hole, white dwarf, …) enters companion star
- significant friction
- gigantic accretion rates (up to 0.1 $M_{\odot}$/yr for several months)
- outcome: Thorne–Żytkov object or explosion
- crucial for the formation of gravitational wave sources
- rare (0.01 / century – 1 / century in our galaxy)
- **never observed**

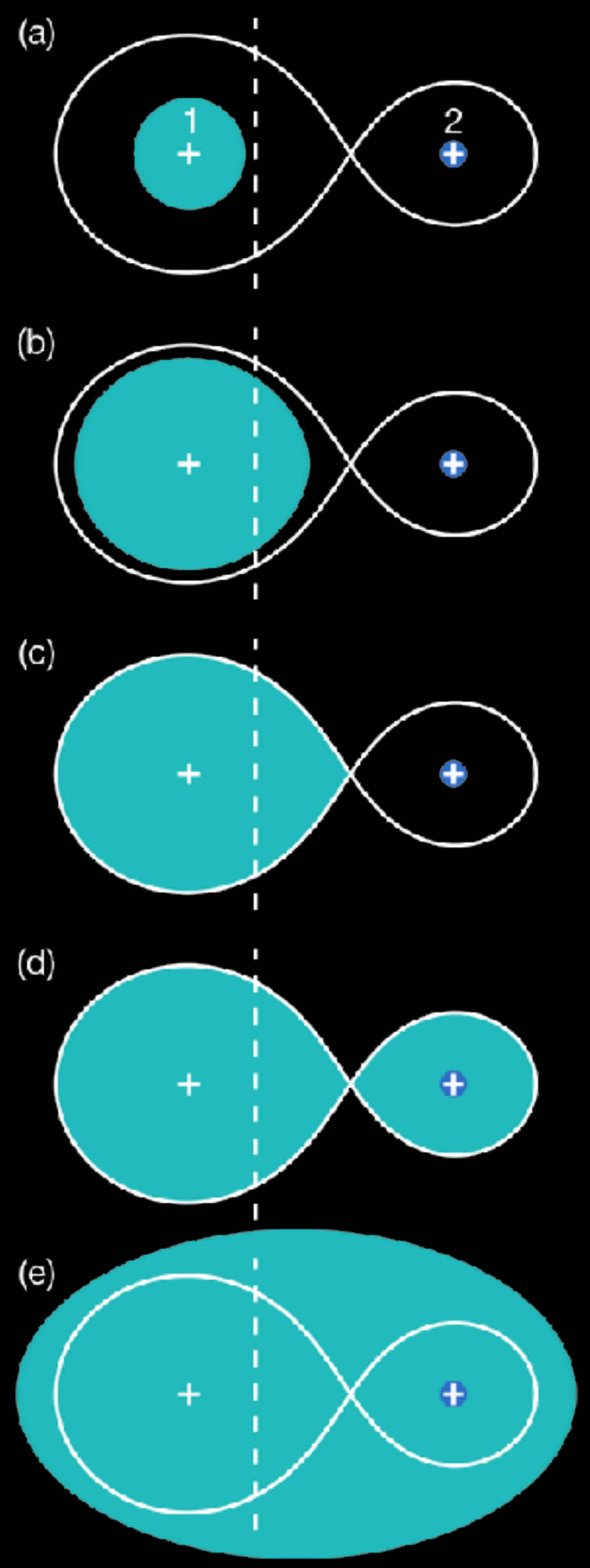


Image: Wikimedia Commons

Common-Envelope Evolution – Neutrino Emission

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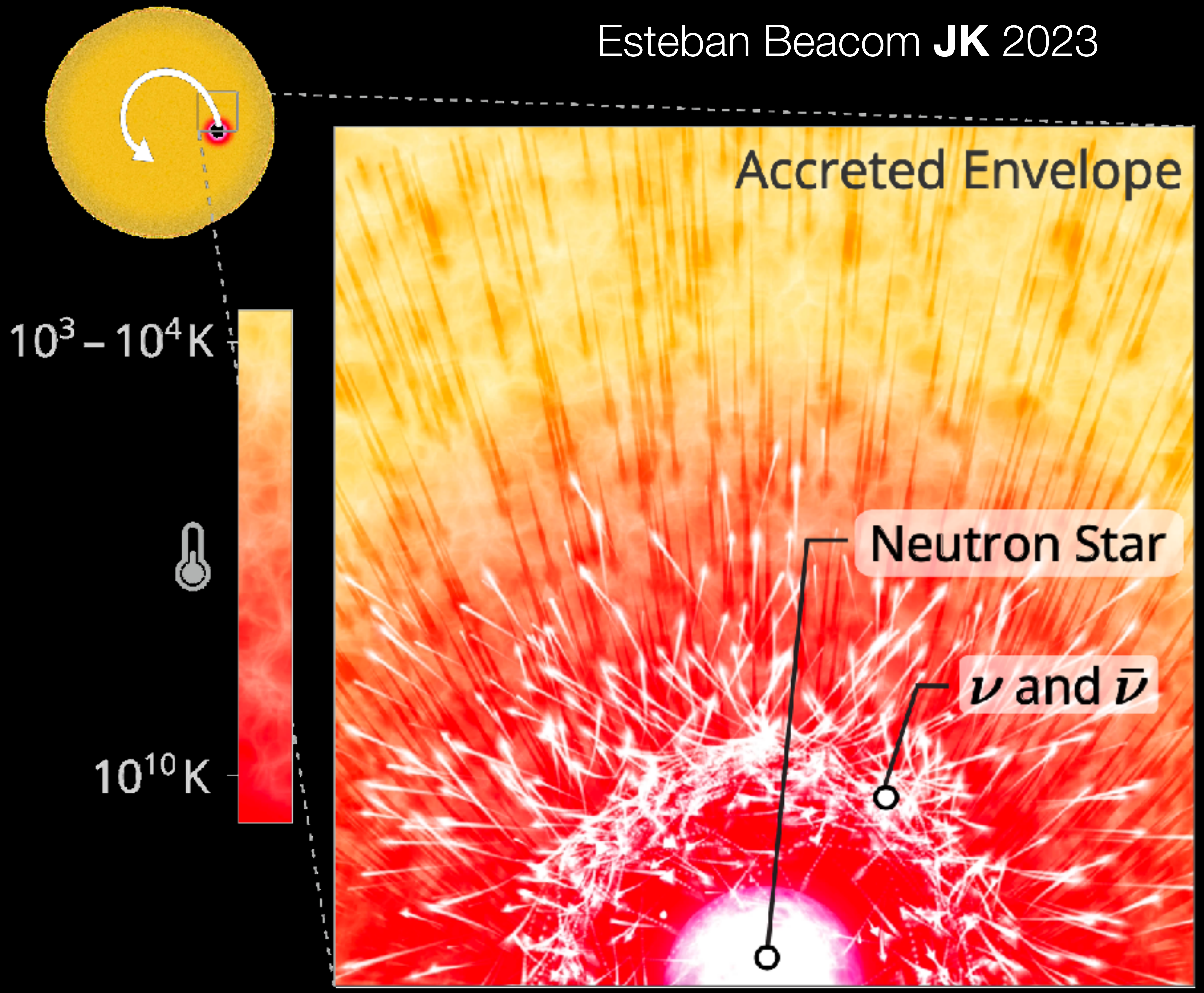

- gigantic accretion rates
- only cooling channel is via neutrinos

Common-Envelope Evolution – Neutrino Emission

temperature / density profile

- solve hydrodynamic equations with appropriate boundary conditions
  (accretion shock discontinuity)

$$\frac{1}{r^2}\frac{\mathrm{d}(r^2\rho v)}{\mathrm{d}r} = 0\,,$$

$$\frac{\mathrm{d}(\rho c^2 + e)}{\mathrm{d}r} - \frac{w}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r} = \frac{\varepsilon_{\mathrm{nuc}} - \mathcal{L}_\nu}{v}\,,$$

$$v\frac{\mathrm{d}v}{\mathrm{d}r} + \frac{GM_{\mathrm{NS}}}{r^2} + \frac{1}{w}\frac{\mathrm{d}P}{\mathrm{d}r}\left(v^2 + c^2 - \frac{2GM_{\mathrm{NS}}}{r}\right) = 0\,,$$

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continuity equation

energy conservation

Euler equation (in Schwarzschild background)

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Common-Envelope Evolution – Neutrino Emission

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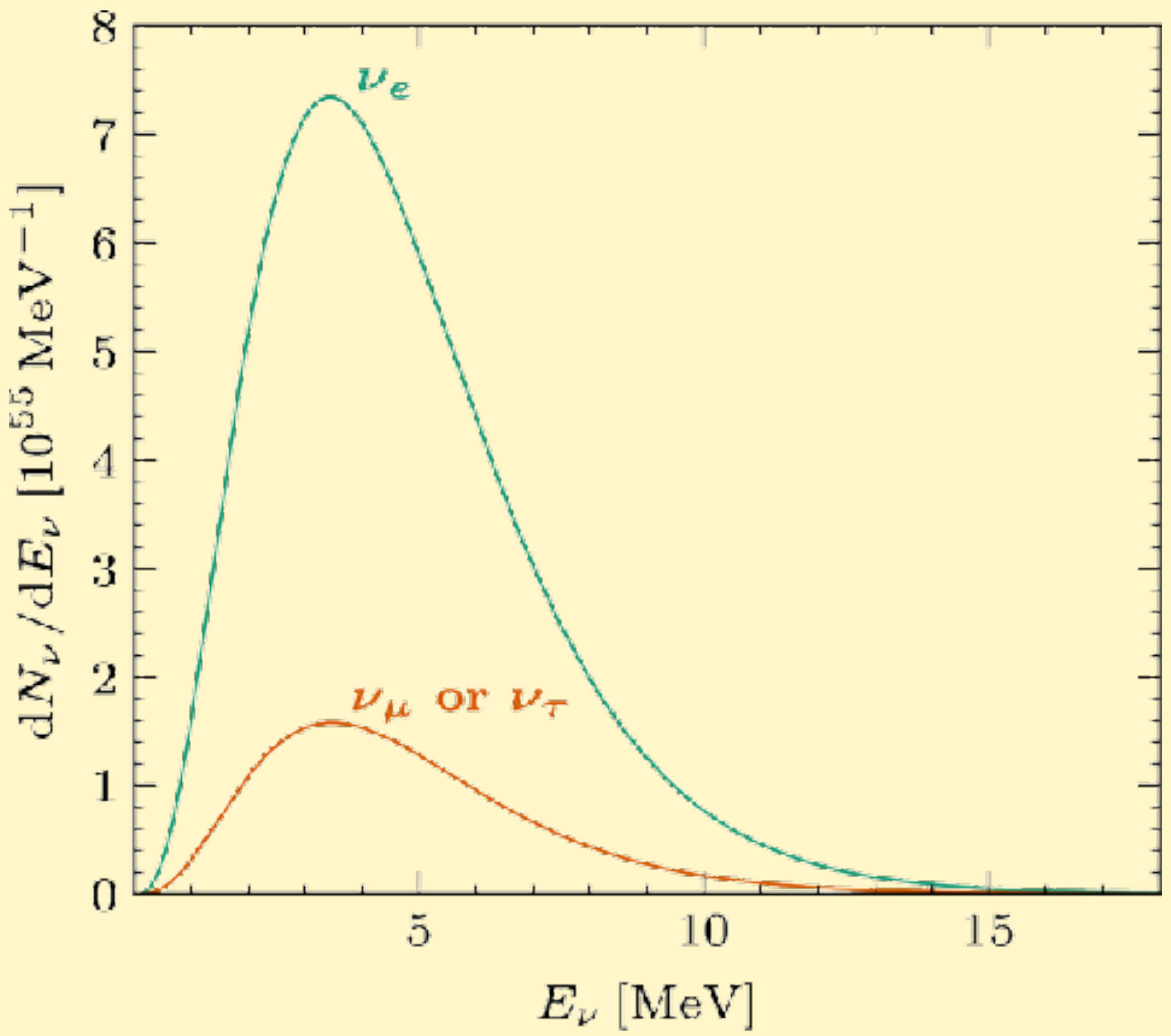
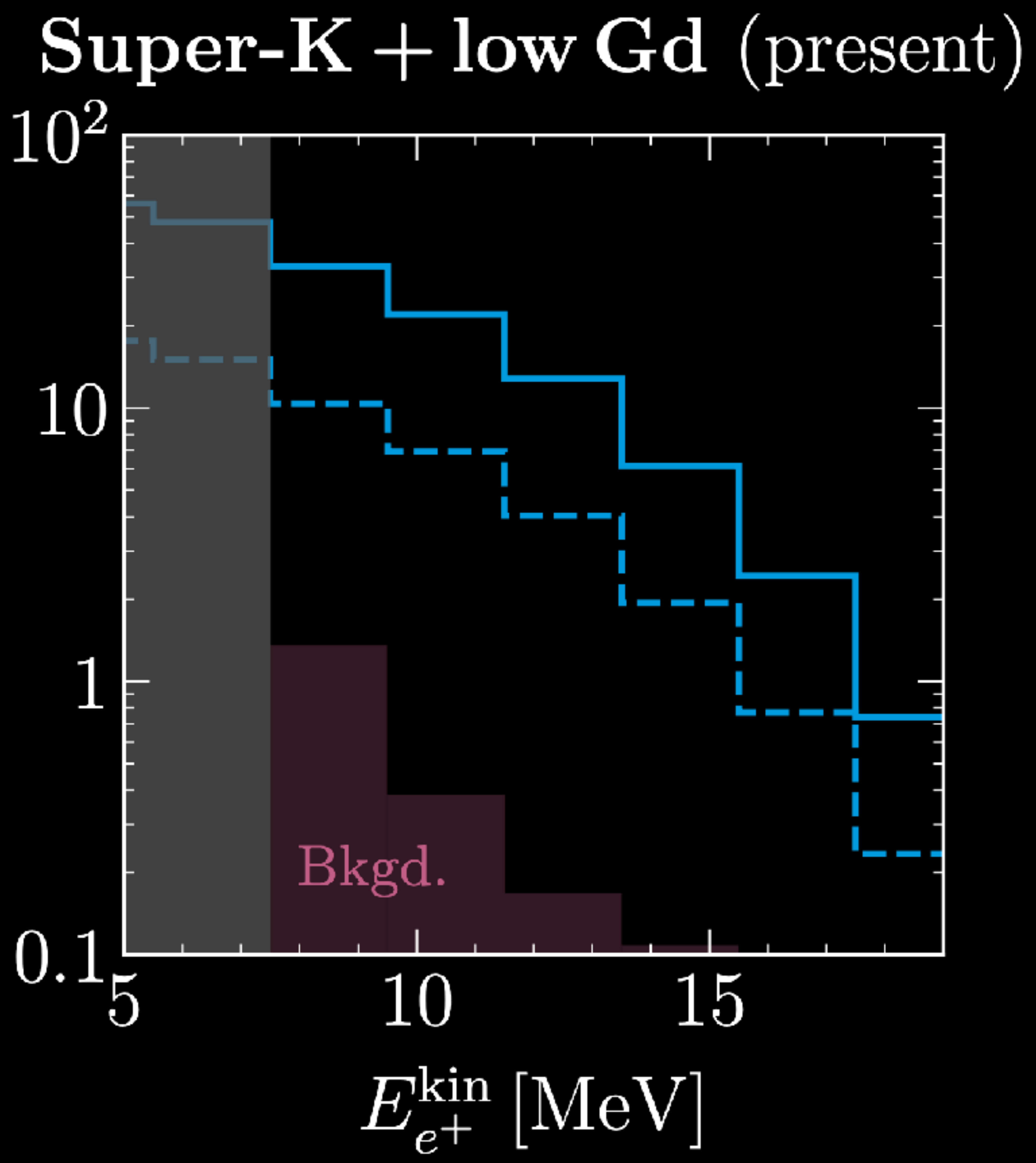
neutrino emission

- e^+e^- annihilation (dominant)
- plasmon decay (subdominant)



- neutrino oscillations

Common-Envelope Evolution



Main detection channel is IBD.

No directionality

Backgrounds:

- Accidental coincidences
- Li-9 from spallation
- NC interactions of atmospheric ν
- reactor ν, CC atmospheric

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Common-Envelope Evolution – Discovery Reach

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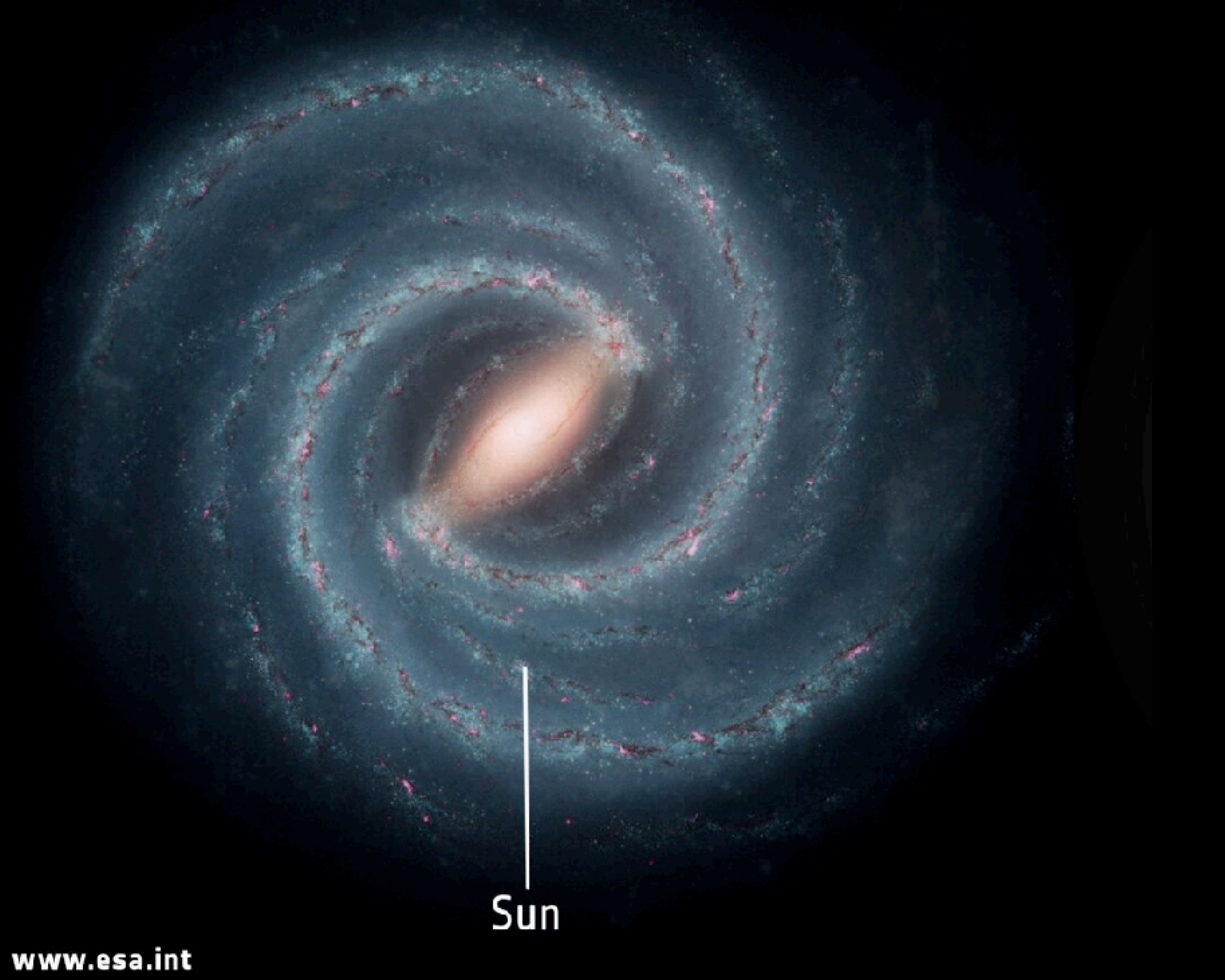

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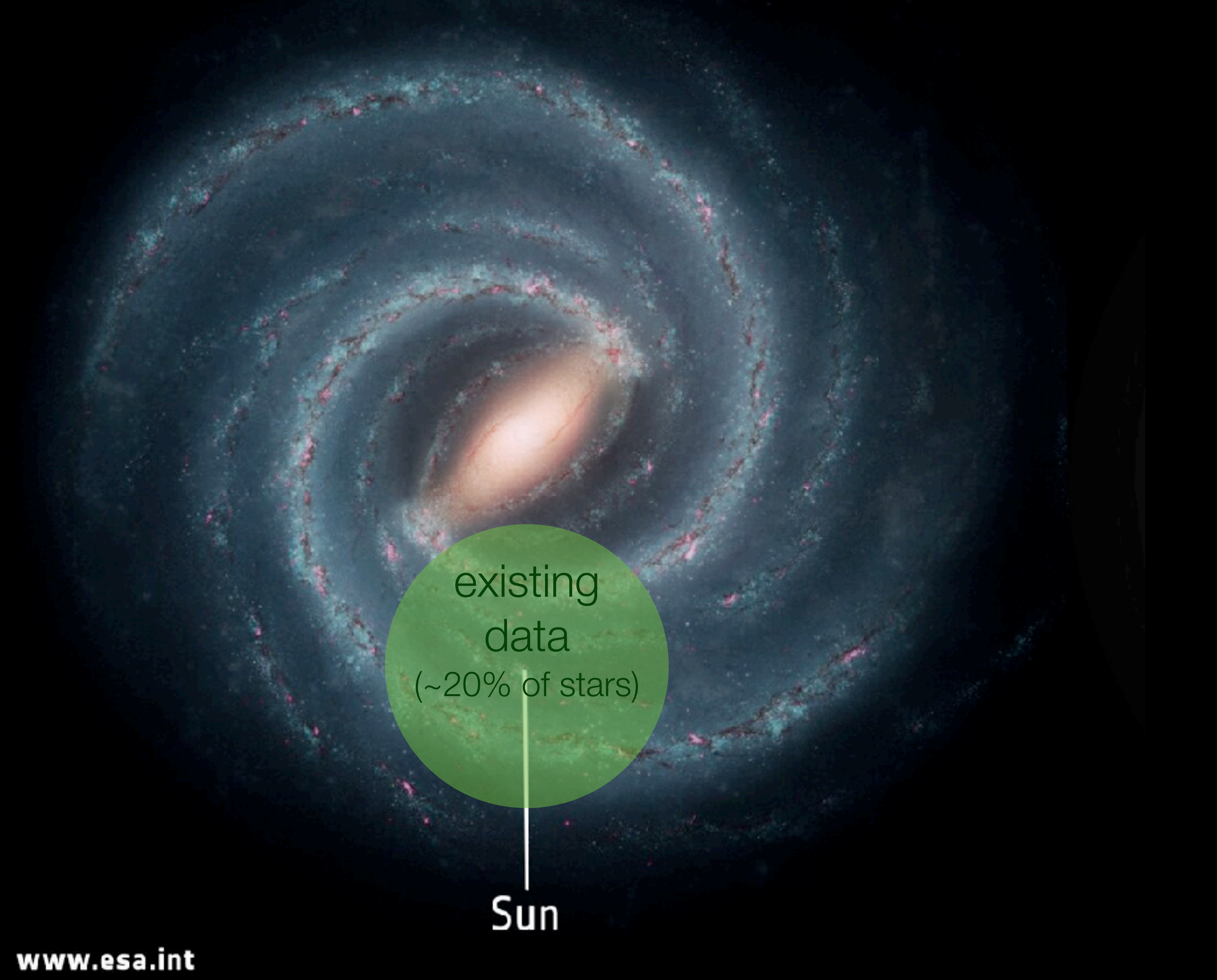

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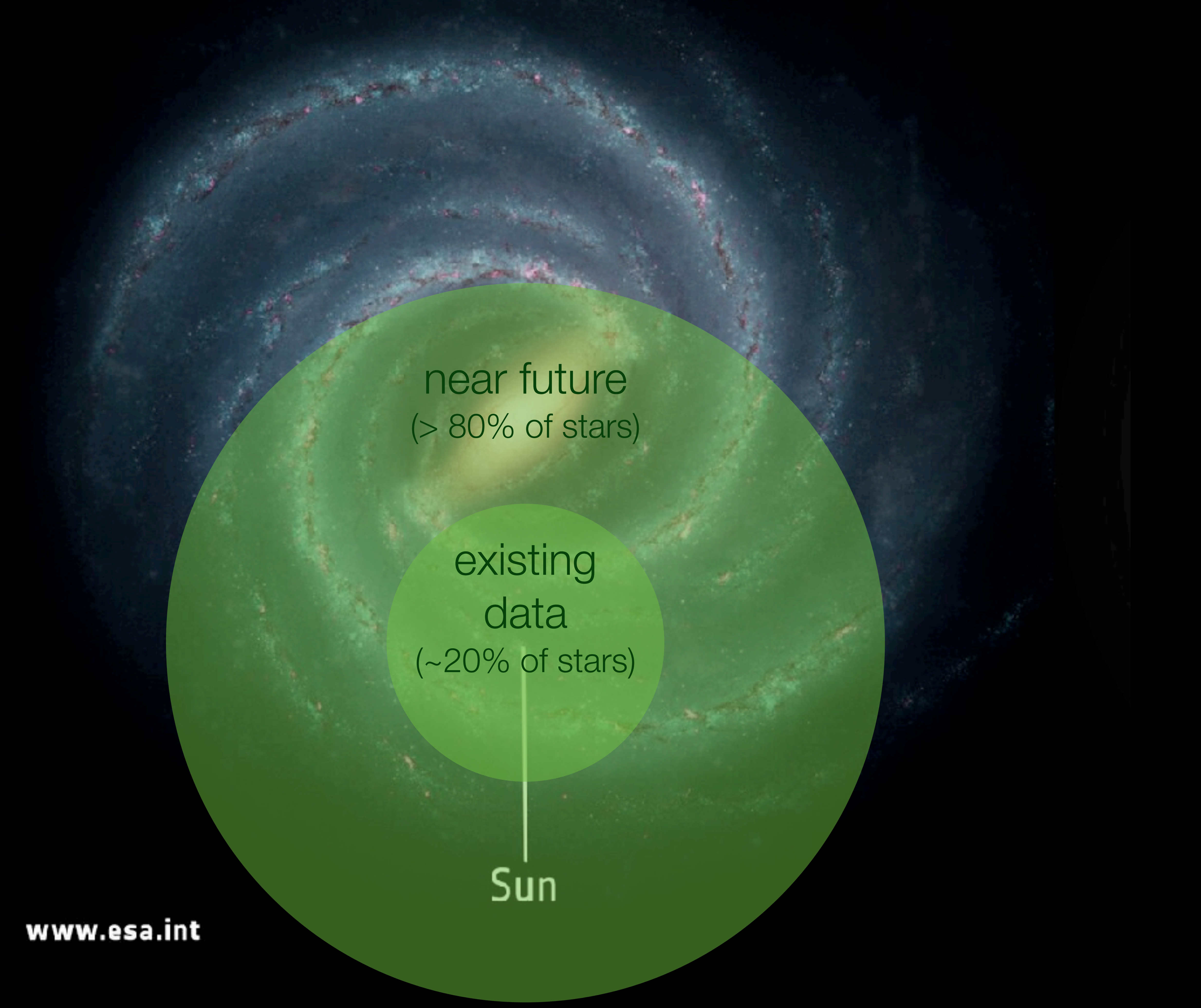

Common-Envelope Evolution – Discovery Reach

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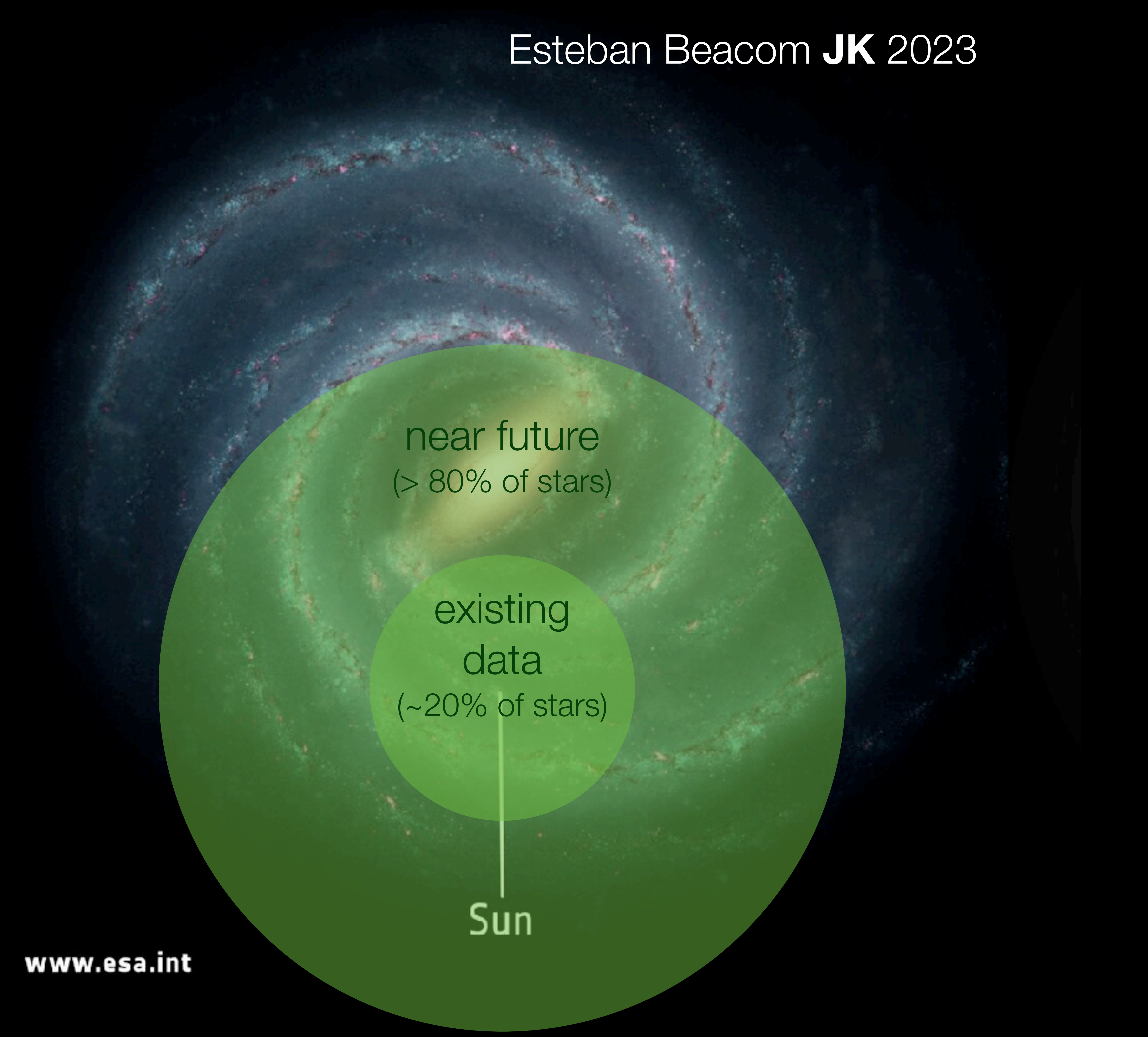
- CEE detectable almost anywhere in our galaxy
- novel astrophysical neutrino source
- opportunity for discovery



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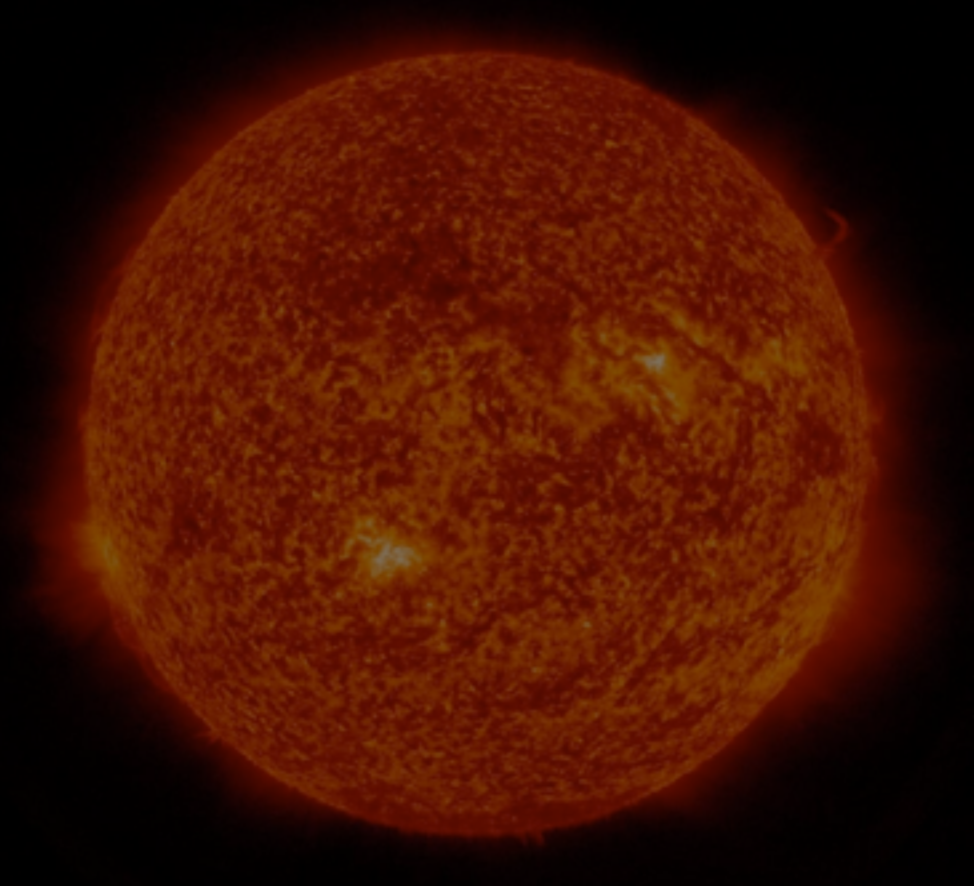

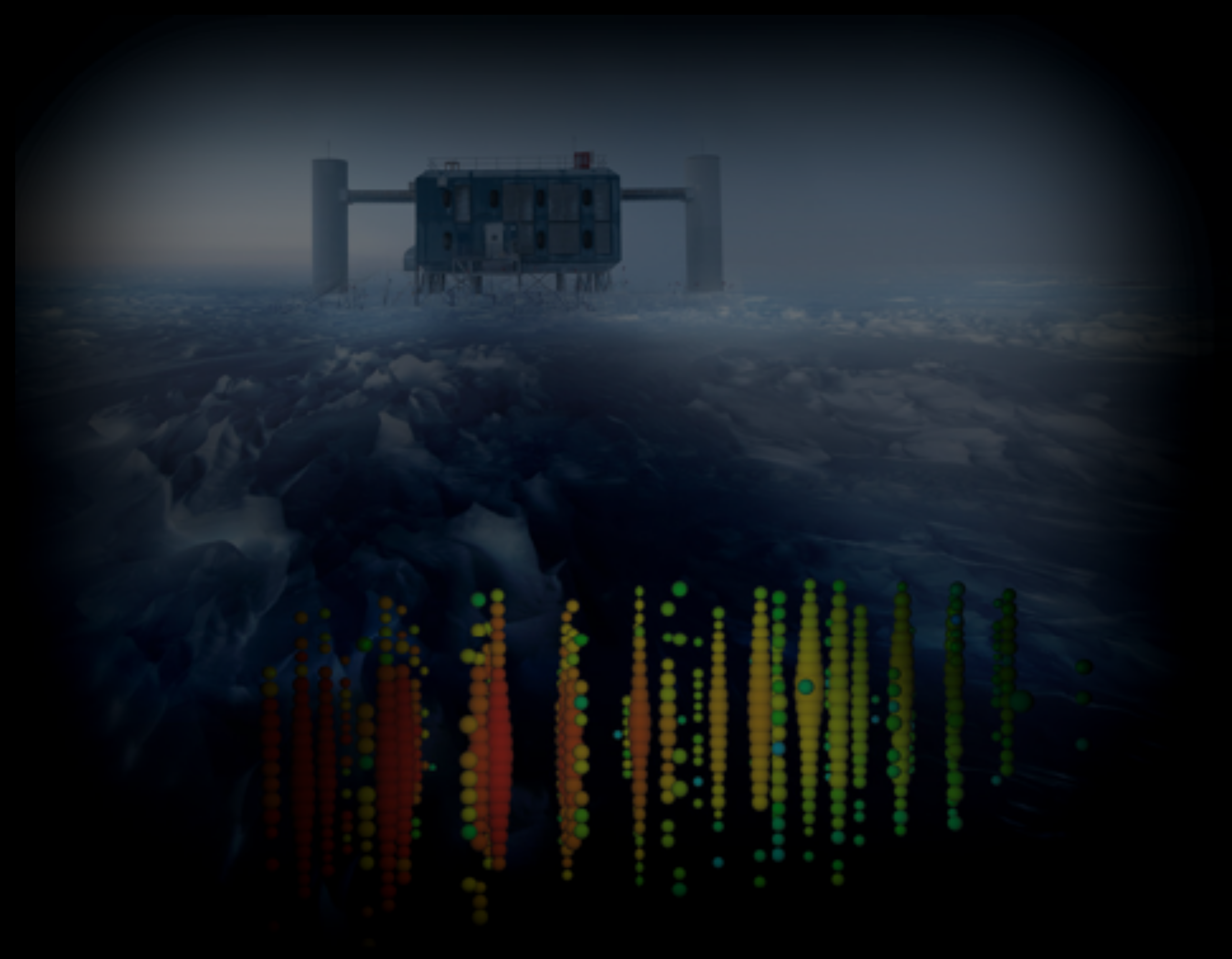

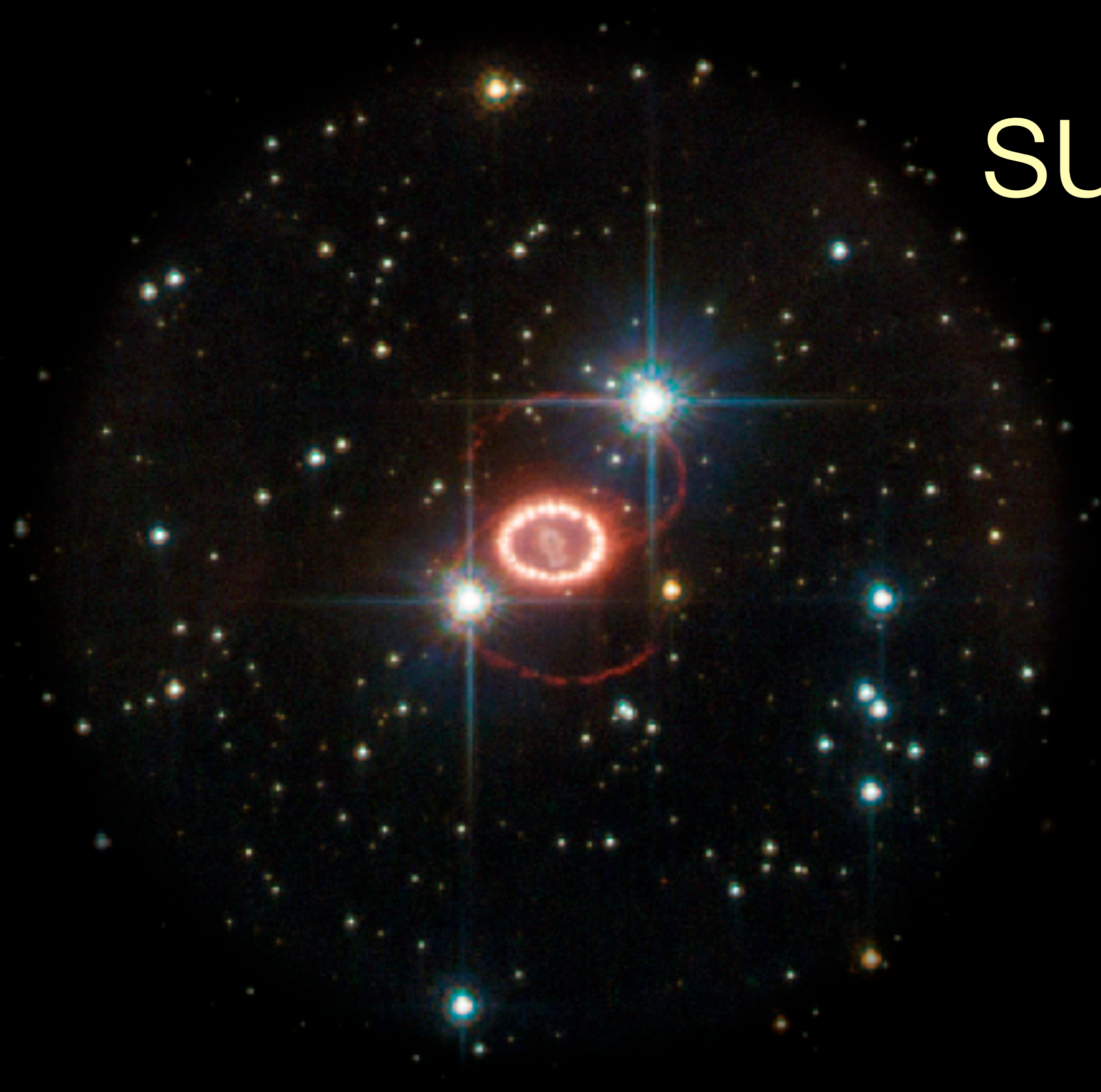

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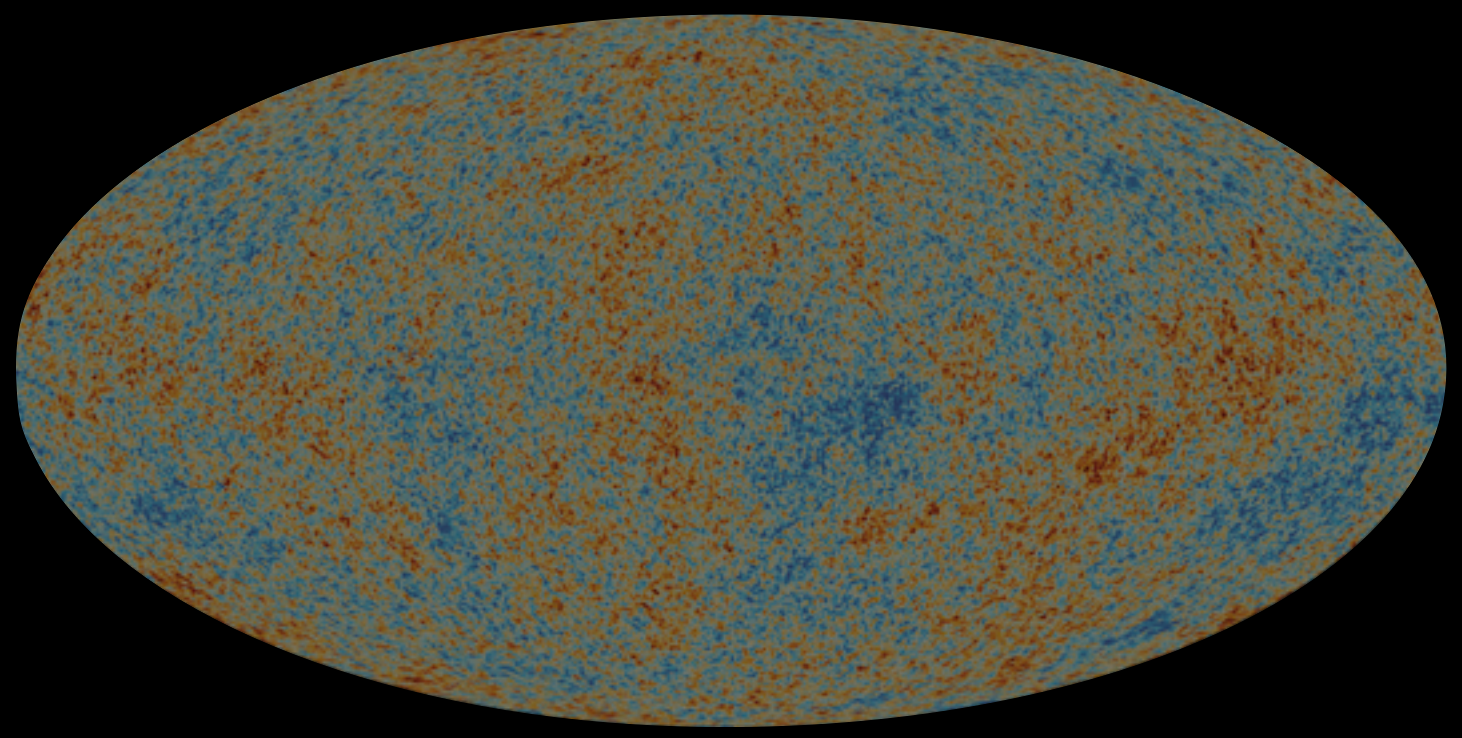
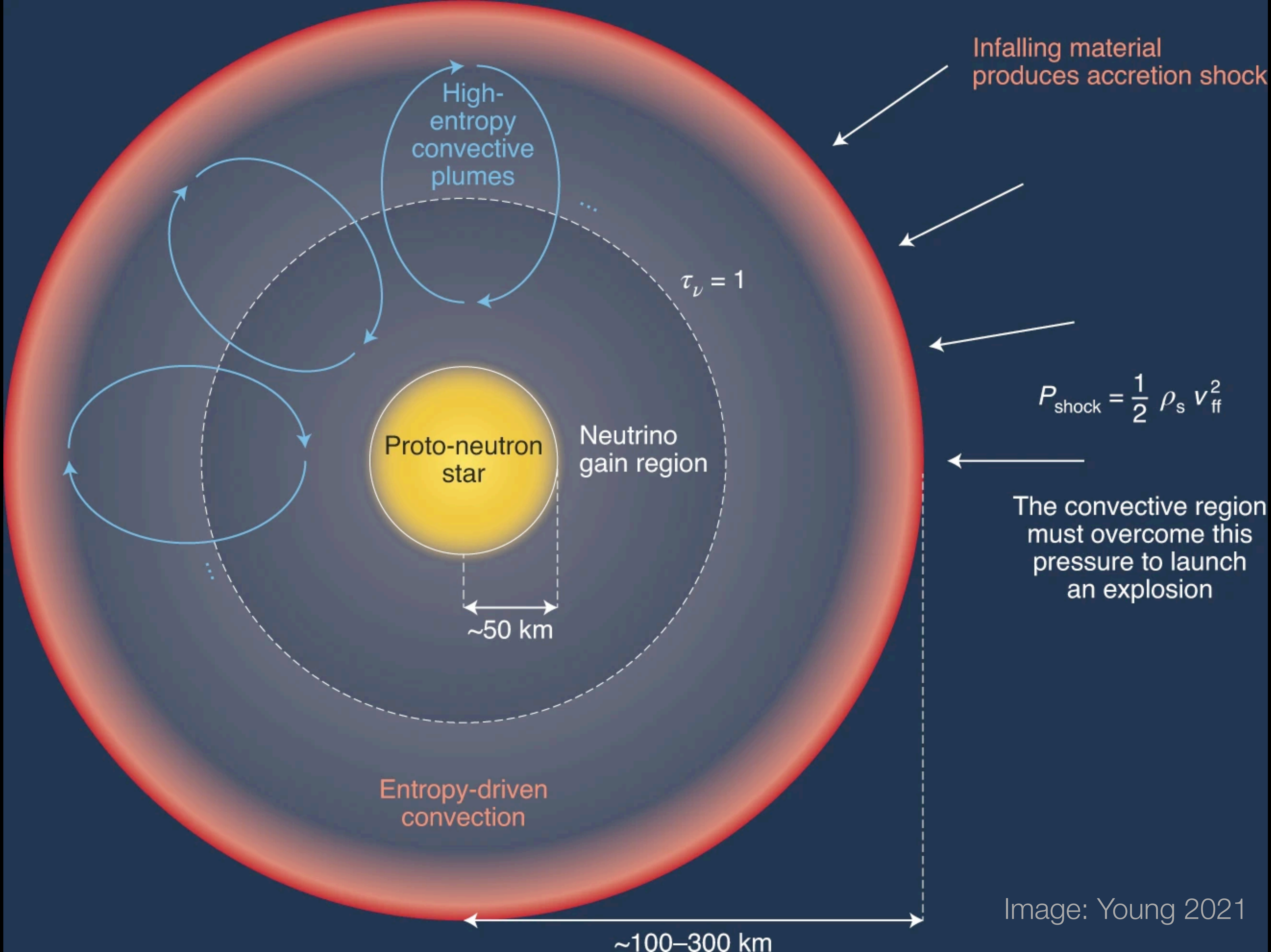




Infalling material
produces accretion shock
High-
entropy
convective
plumes
$\tau_\nu = 1$
Proto-neutron
star
Neutrino
gain region
~50 km
$P_{shock} = \frac{1}{2} \rho_s v_{ff}^2$
The convective region
must overcome this
pressure to launch
an explosion
Entropy-driven
convection
~100–300 km
Image: Young 2021

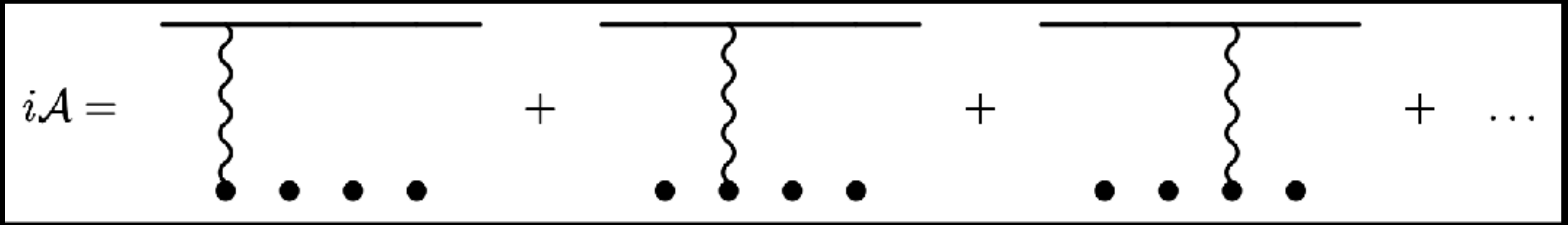
Melson Janka Marek 2015

Supernova Neutrinos

- neutrino density $> 10^{30}\,\mathrm{cm}^{-3}$

  ➠ each neutrino “feels" the presence of the other neutrinos

  (via coherent forward scattering)



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- flavour evolution described by von Neumann equation **(mean field approach)**

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

Supernova Neutrinos

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density matrix
in flavour space

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

vacuum oscillations

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

matter effects

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

self-interactions

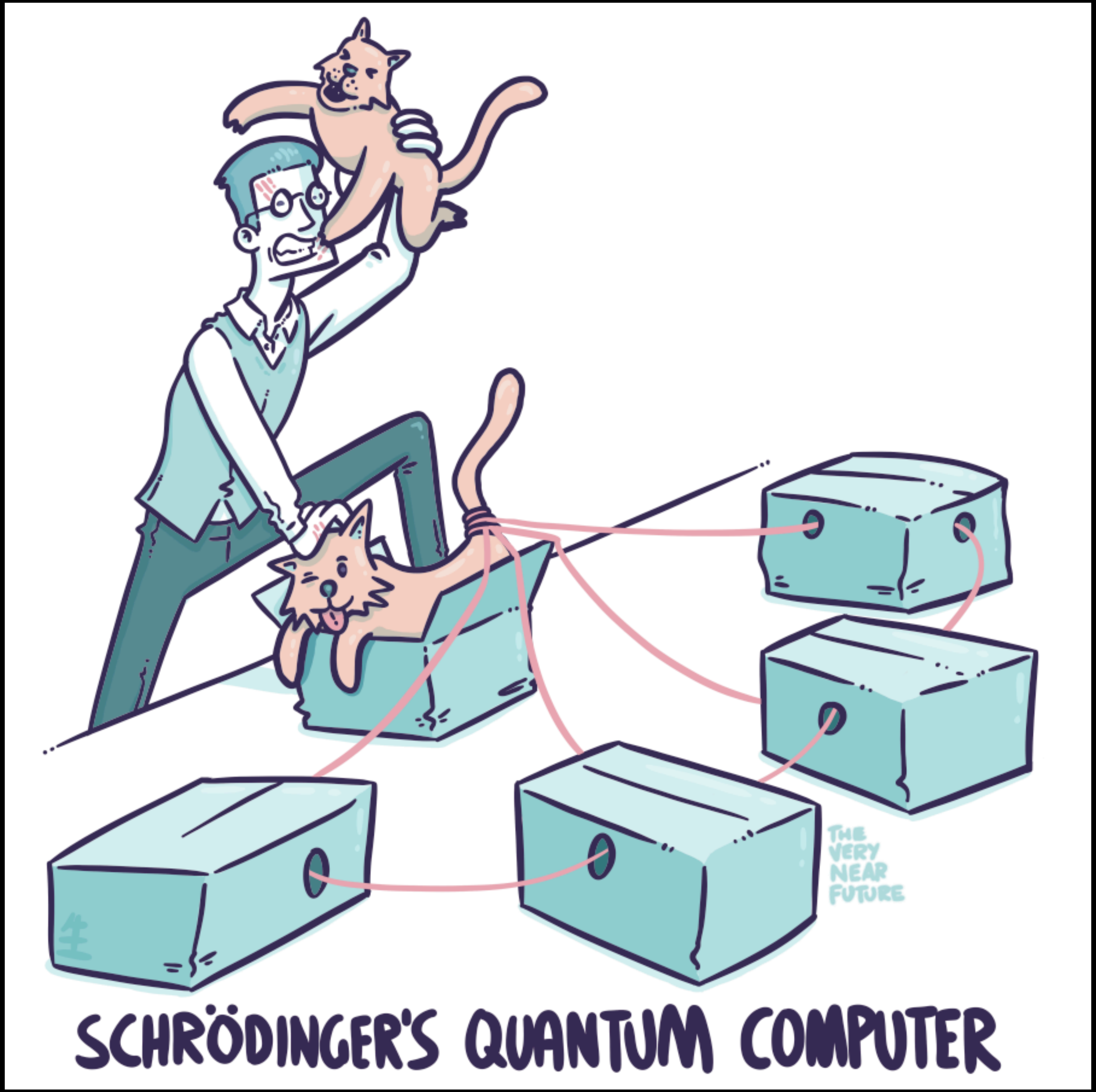
$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3q}{(2\pi)^3} (1 - \cos\theta_{\vec{p}\vec{q}})(\rho_{\vec{r},\vec{q}} - \bar{\rho}_{\vec{r},\vec{q}})$$

Supernova Neutrinos

- neutrino density $> 10^{30}\,\mathrm{cm}^{-3}$
  ➠ each neutrino “feels" the presence of the other neutrinos
- flavour evolution described by von Neumann equation **(mean field approach)**

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

- 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?



Cartoon: Reddit u/TheVeryNearFuture

Supernova Neutrinos on a Quantum Computer

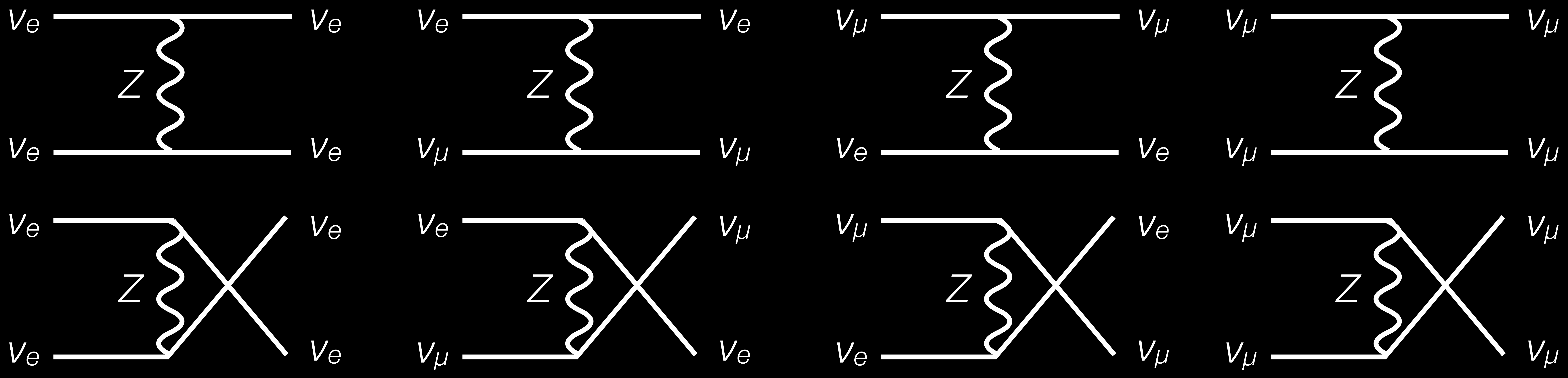
- highly entangled quantum system calls for simulation on a quantum system
- basic idea: flavour state of each neutrino mode represented by qubit q_i (in 2-flavour approximation)

  Hall et al. 2021, Amitrano et al. 2022, Siwach et al. 2023

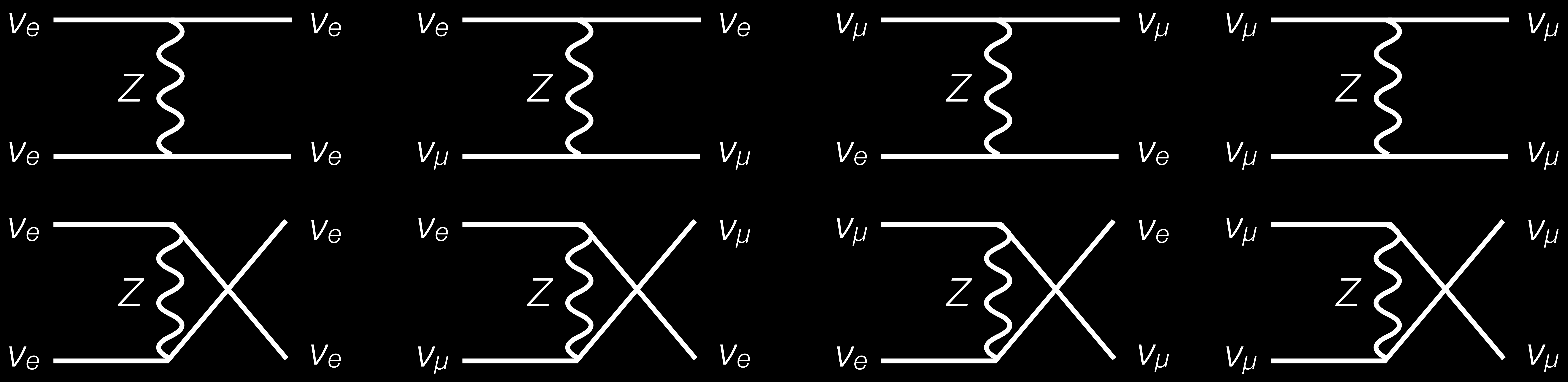
states: $$|\psi\rangle = |q_1\rangle \otimes |q_2\rangle \otimes \ldots \otimes |q_N\rangle$$

- time-evolution via Trotterization (discretisation in t + low-order expansion of $S = e^{i\hat{H}\delta t}$)
- However: in the large-N limit, fully entangled N-qubit system should reduce to the standard mean-field picture Friedland Lunardini 2003
- our goal here is to demonstrate this explicitly on a quantum computer

Neutrino Qubit Hamiltonian

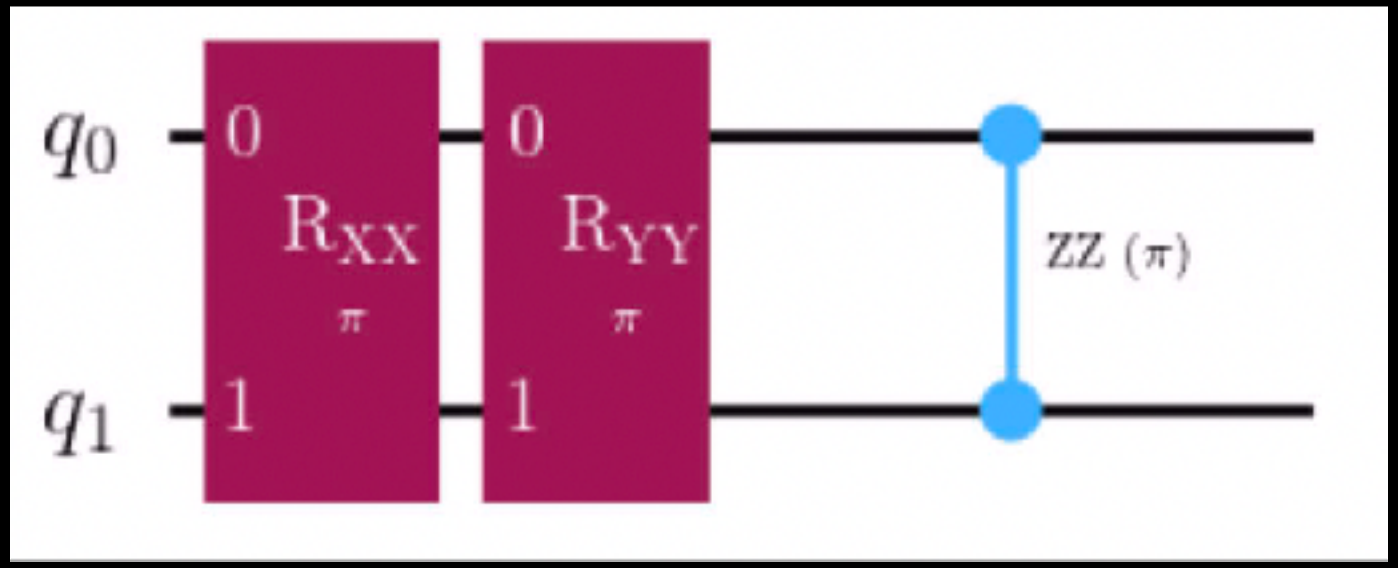


Neutrino Qubit Hamiltonian



$$H_{\text{int}} \propto \begin{pmatrix} 2 & & & \\ & 1 & 1 & \\ & 1 & 1 & \\ & & & 2 \end{pmatrix} \begin{array}{l} |\nu_e\nu_e\rangle \\ |\nu_e\nu_\mu\rangle \\ |\nu_\mu\nu_e\rangle \\ |\nu_\mu\nu_\mu\rangle \end{array}$$

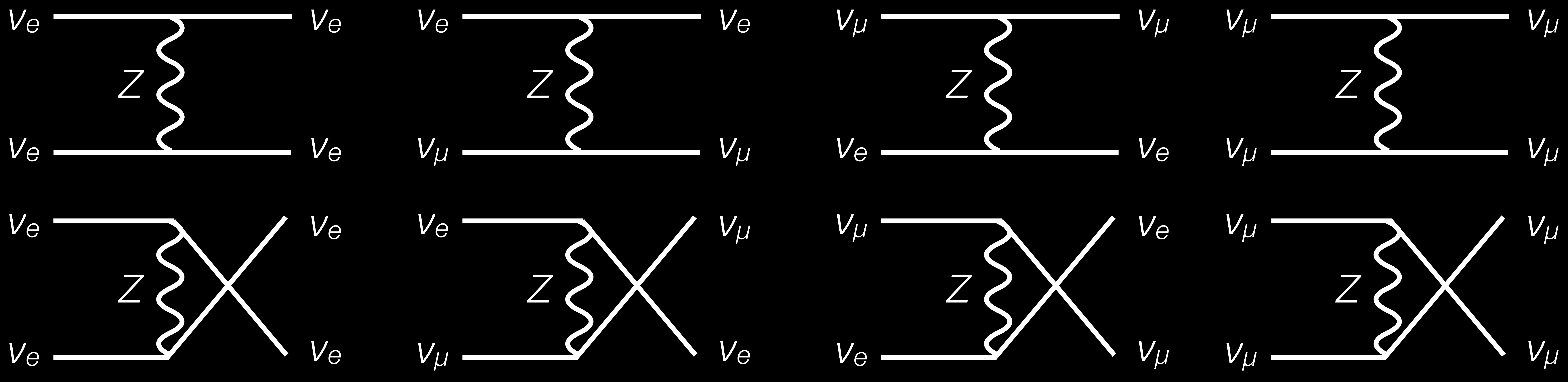
$\Leftrightarrow$



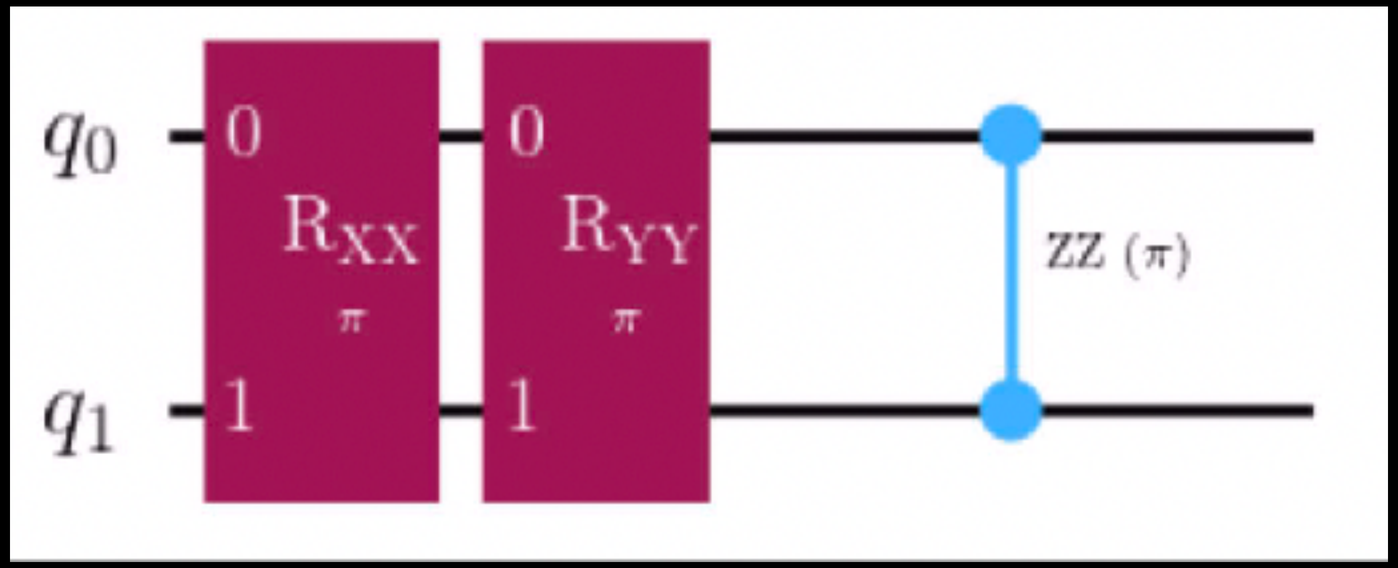
$\Leftrightarrow$

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

Neutrino Qubit Hamiltonian



$$H_{\text{int}} \propto \begin{array}{cc} \begin{pmatrix} 2 & & & \\ & 1 & 1 & \\ & 1 & 1 & \\ & & & 2 \end{pmatrix} & \begin{array}{c} |\nu_e\nu_e\rangle \\ |\nu_e\nu_\mu\rangle \\ |\nu_\mu\nu_e\rangle \\ |\nu_\mu\nu_\mu\rangle \end{array} \end{array} \Leftrightarrow$$



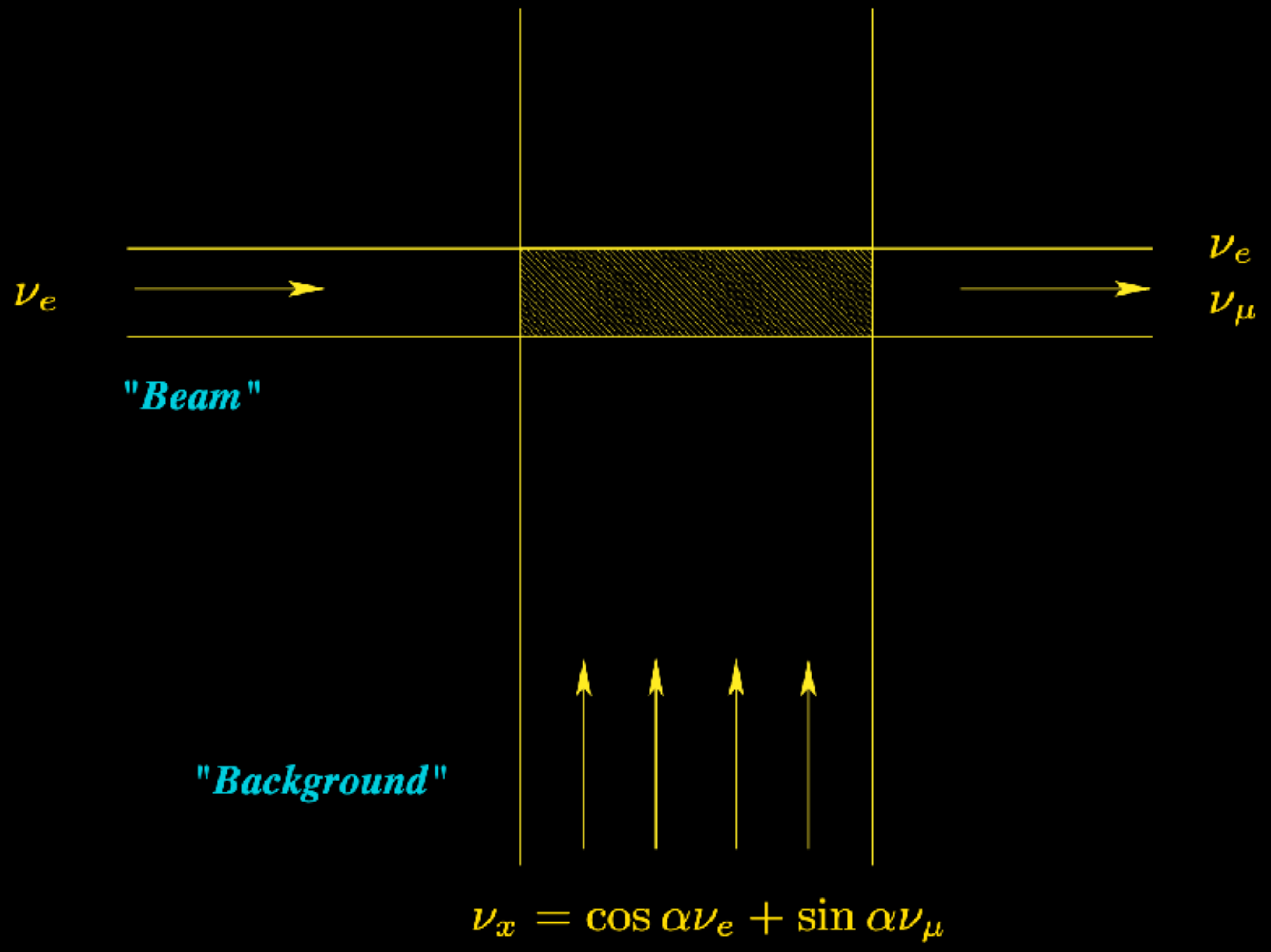
$$\Leftrightarrow \quad H = \sum_{k=1}^{N} \vec{b} \cdot \vec{\sigma}_k + \sum_{p<q}^{N} J_{pq} \vec{\sigma}_p \cdot \vec{\sigma}_q$$

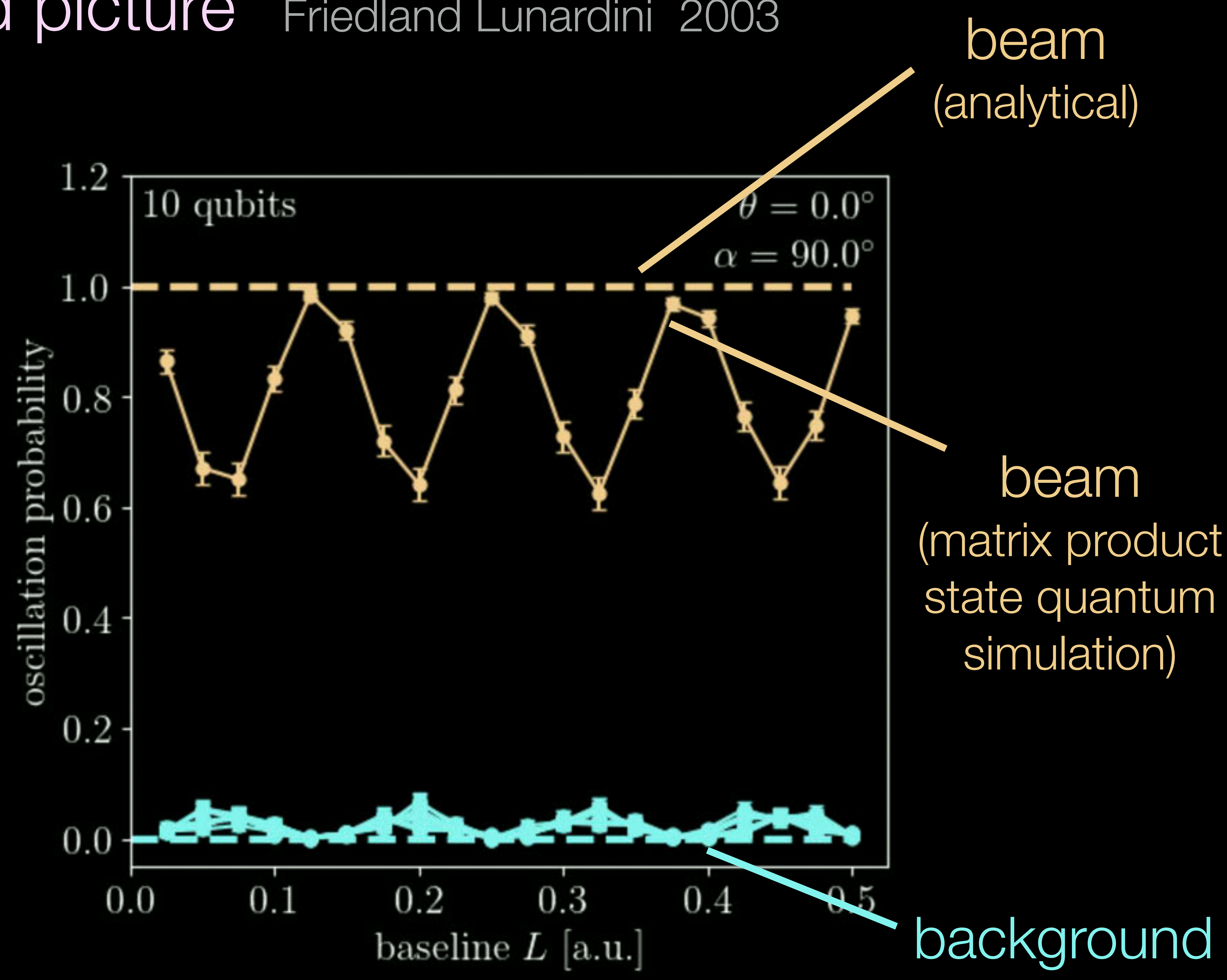
vacuum oscillations

self-interactions

Emergence of the Mean Field Picture

- in the large-N limit, fully entangled N-qubit system reduces to the standard mean-field picture   Friedland Lunardini 2003





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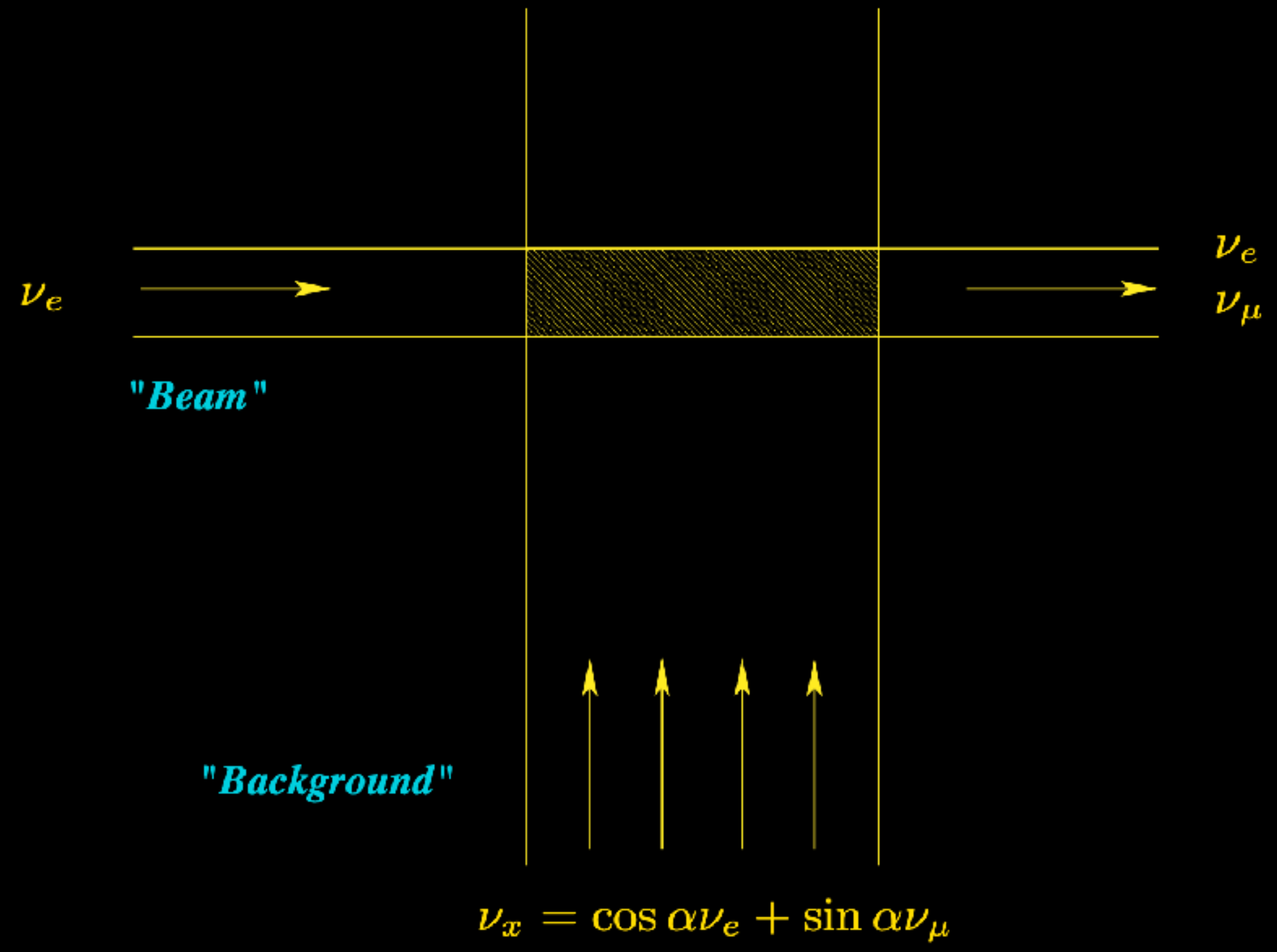
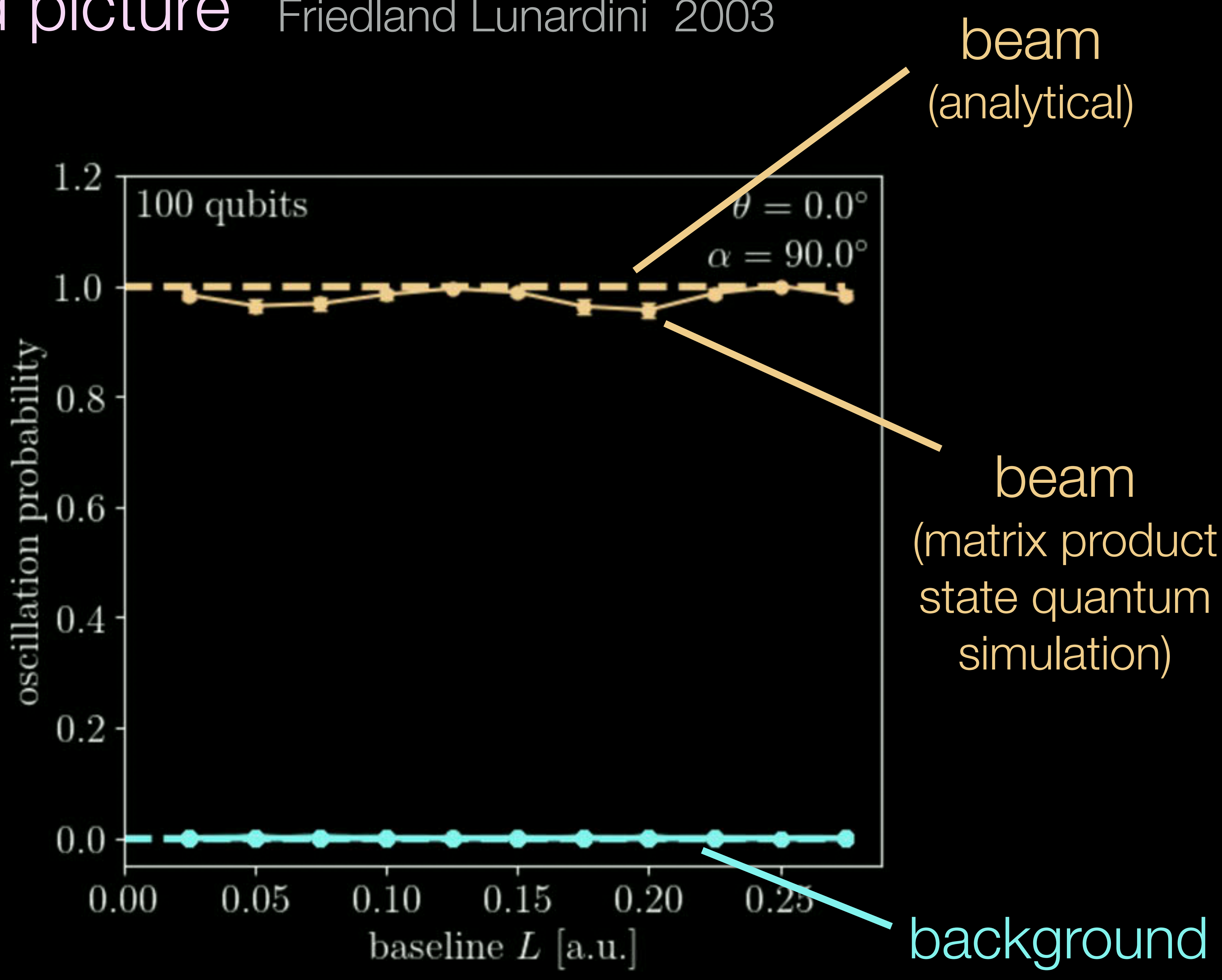
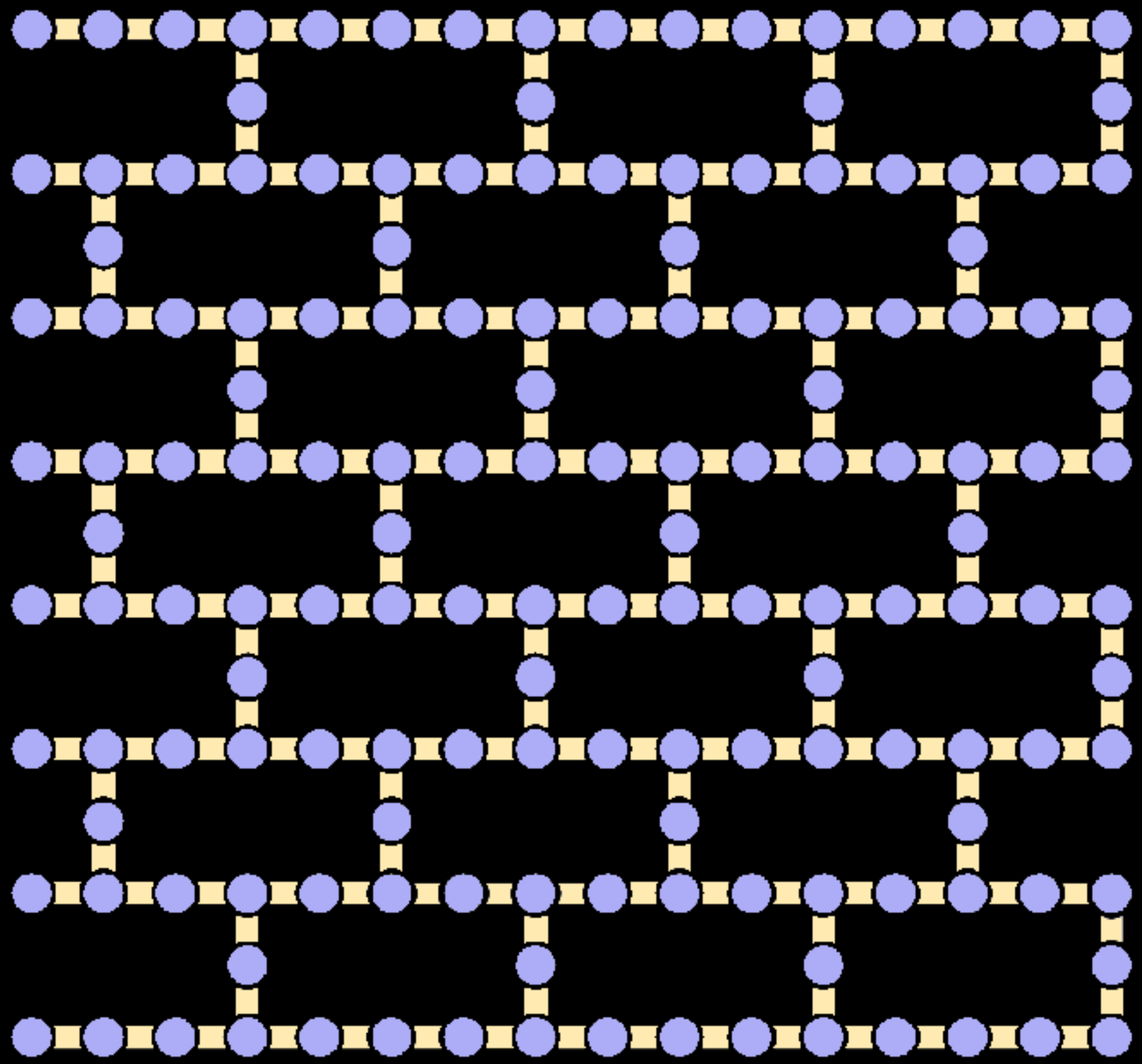




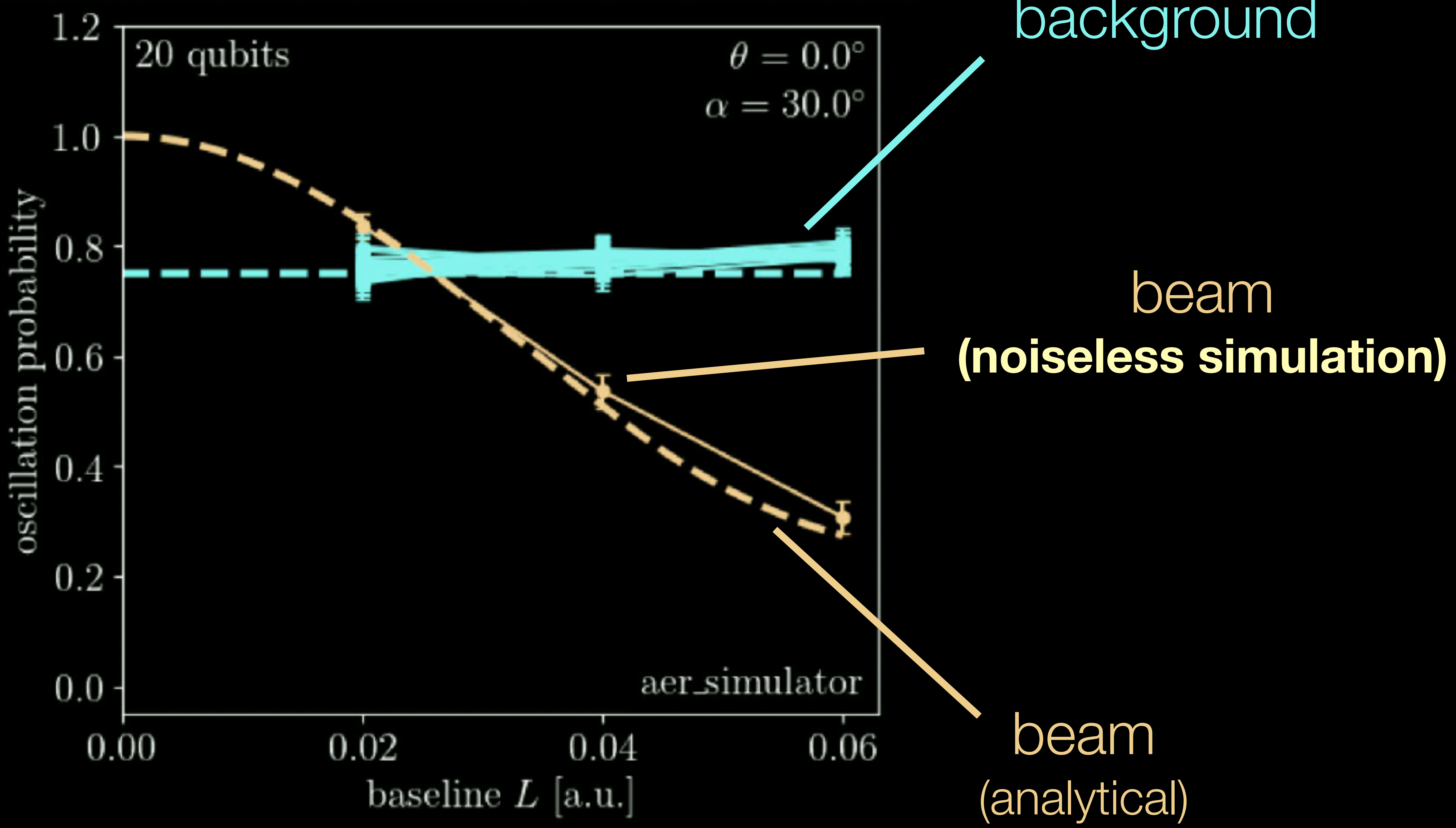
Implementation on Quantum Hardware

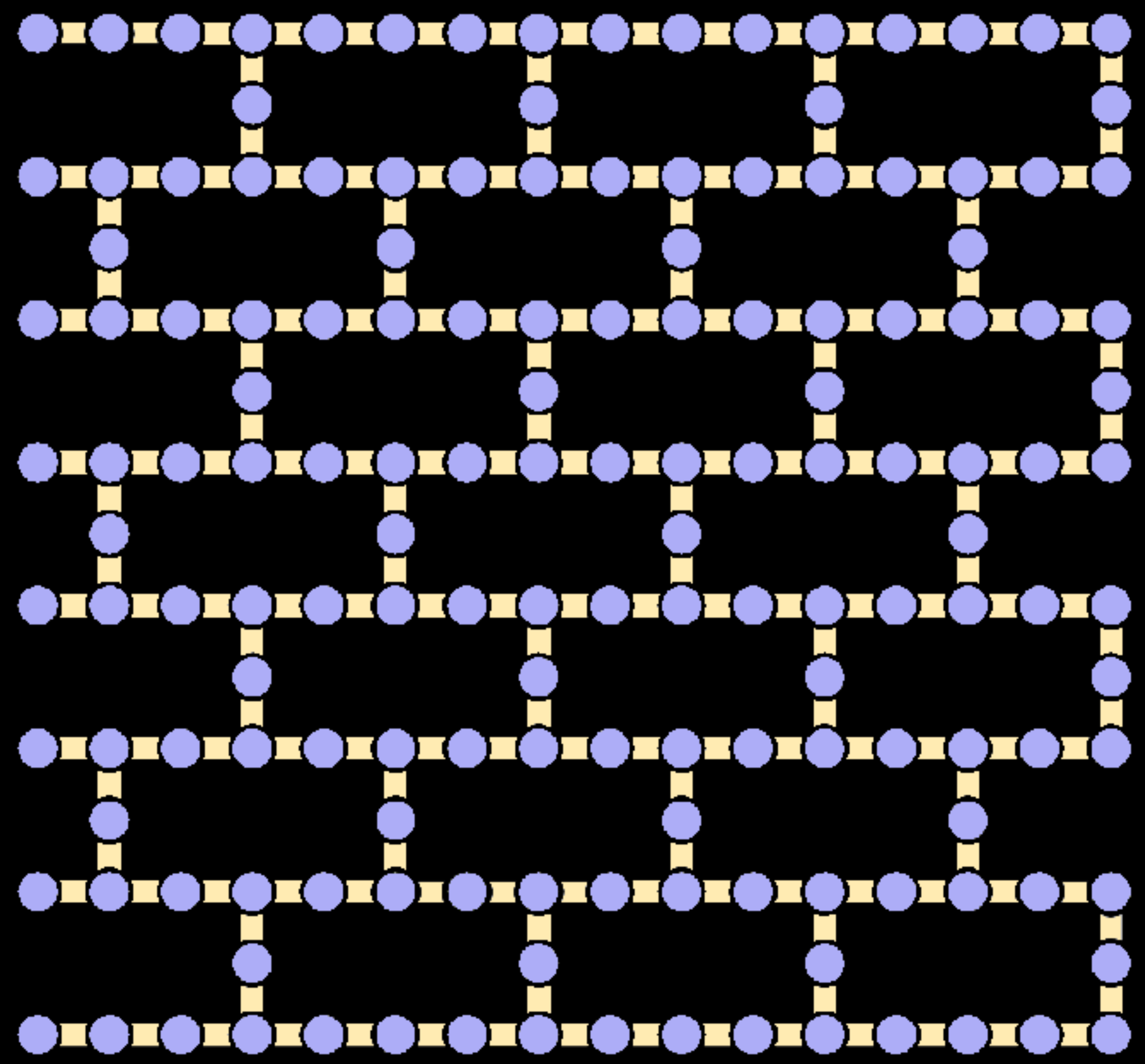
- deployment to IBM QPUs
  (superconducting transmons)
- severely noise-limited
  - more challenging than Heisenberg / Ising models due to all-to-all interactions
  - smart algorithm design allows implementation on linear qubit chain



IBM Heron r2 (156 qubits)

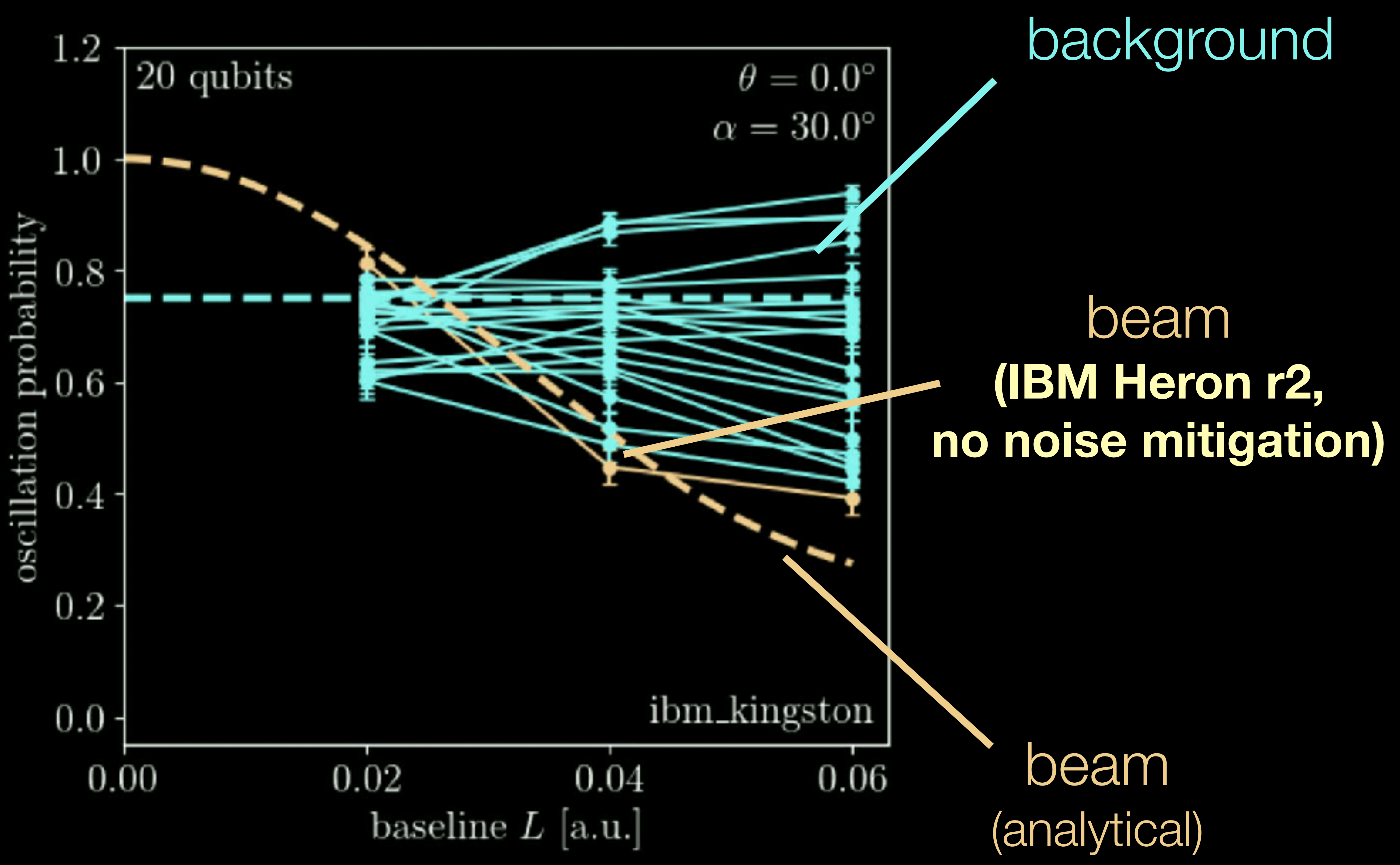
Capabilities of Current Quantum Hardware

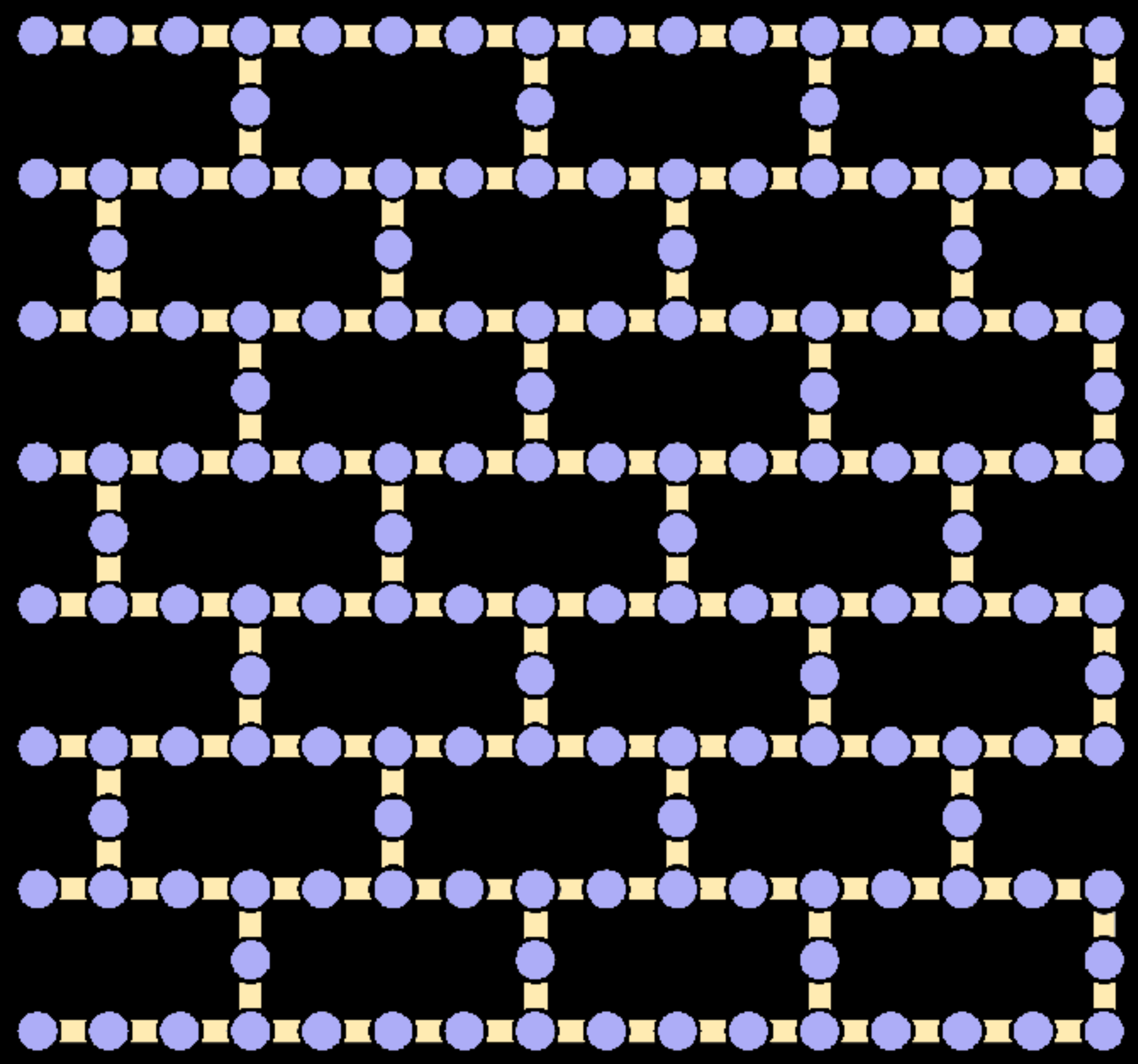




IBM Heron r2 (156 qubits)

Capabilities of Current Quantum Hardware





IBM Heron r2 (156 qubits)

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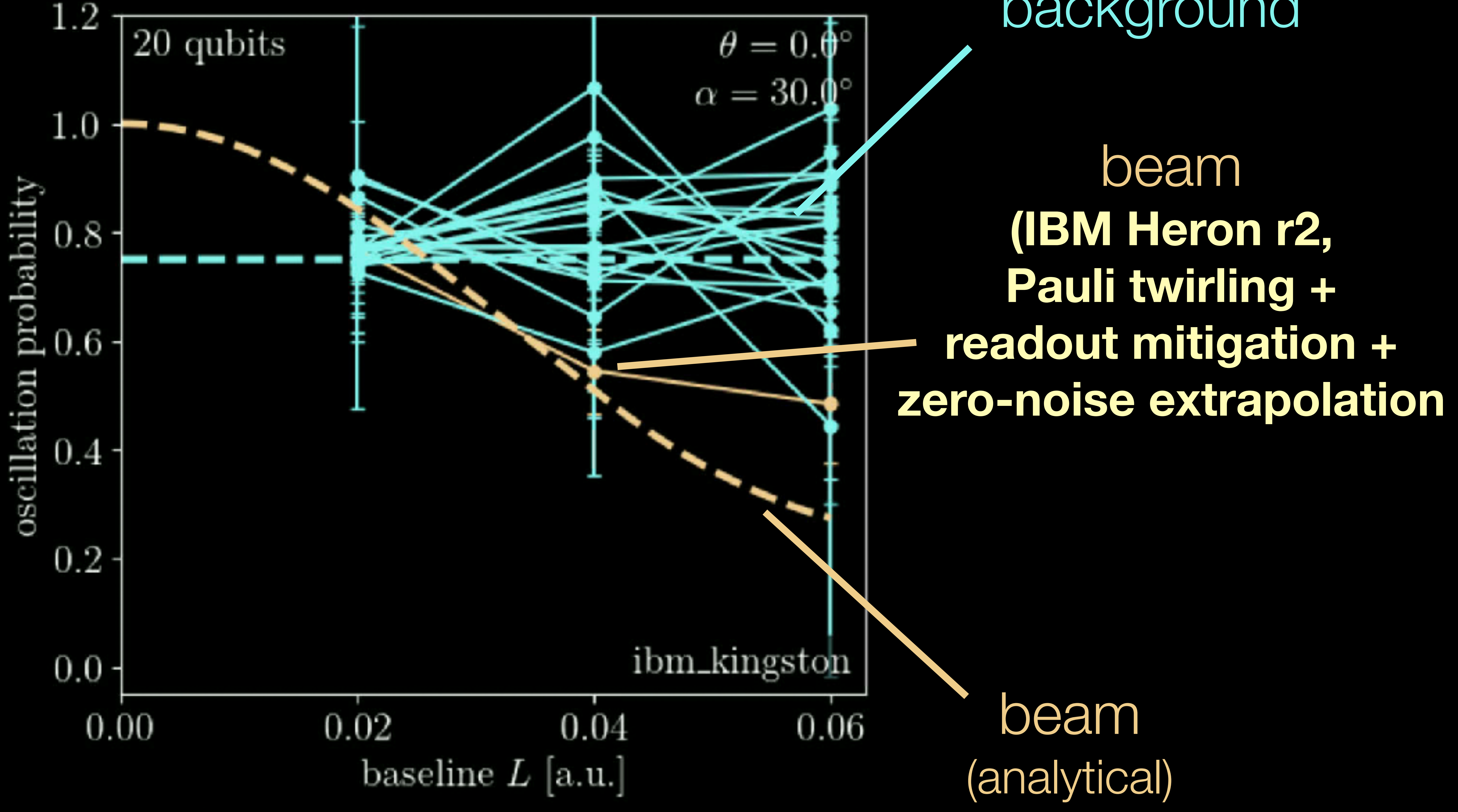

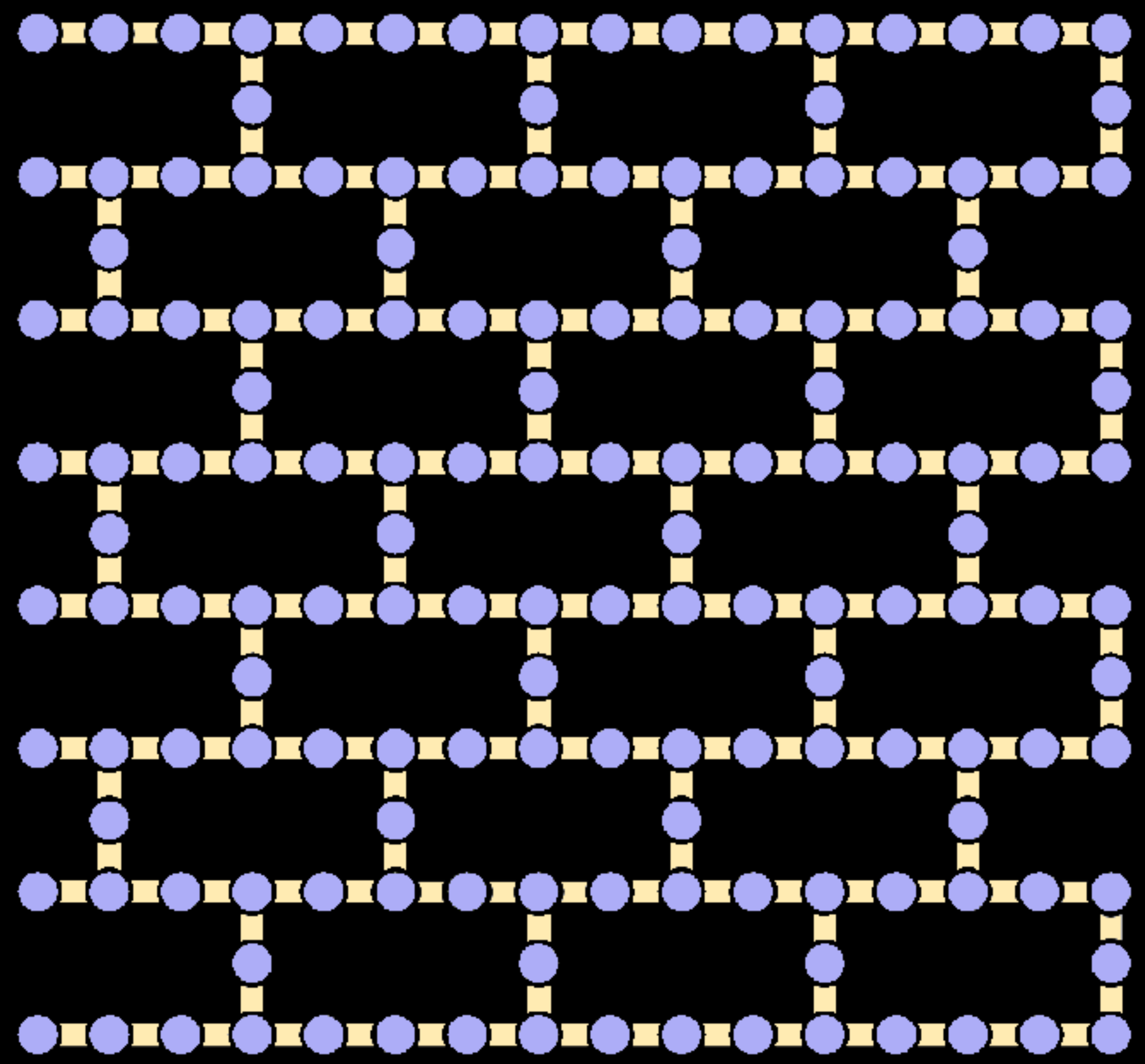

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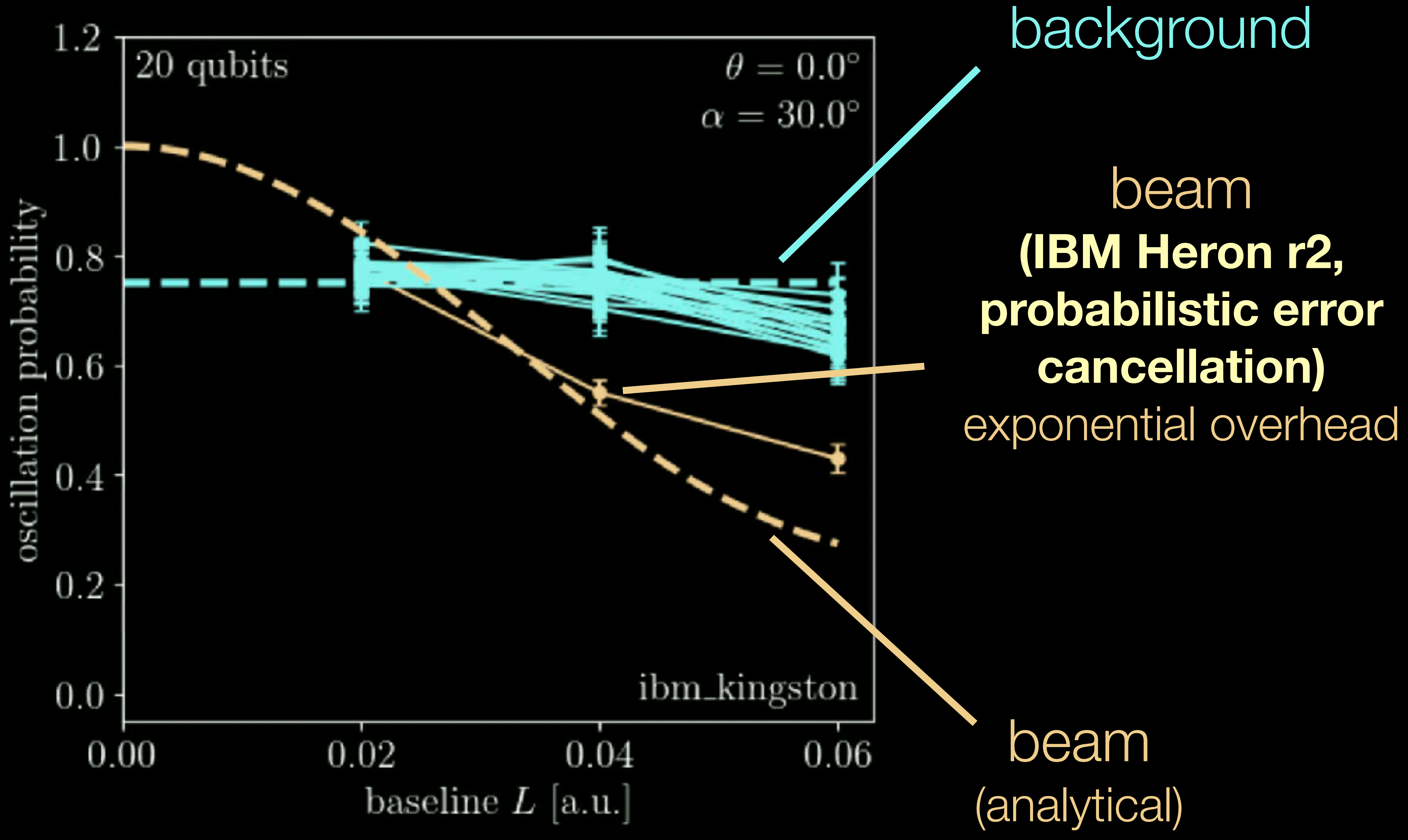
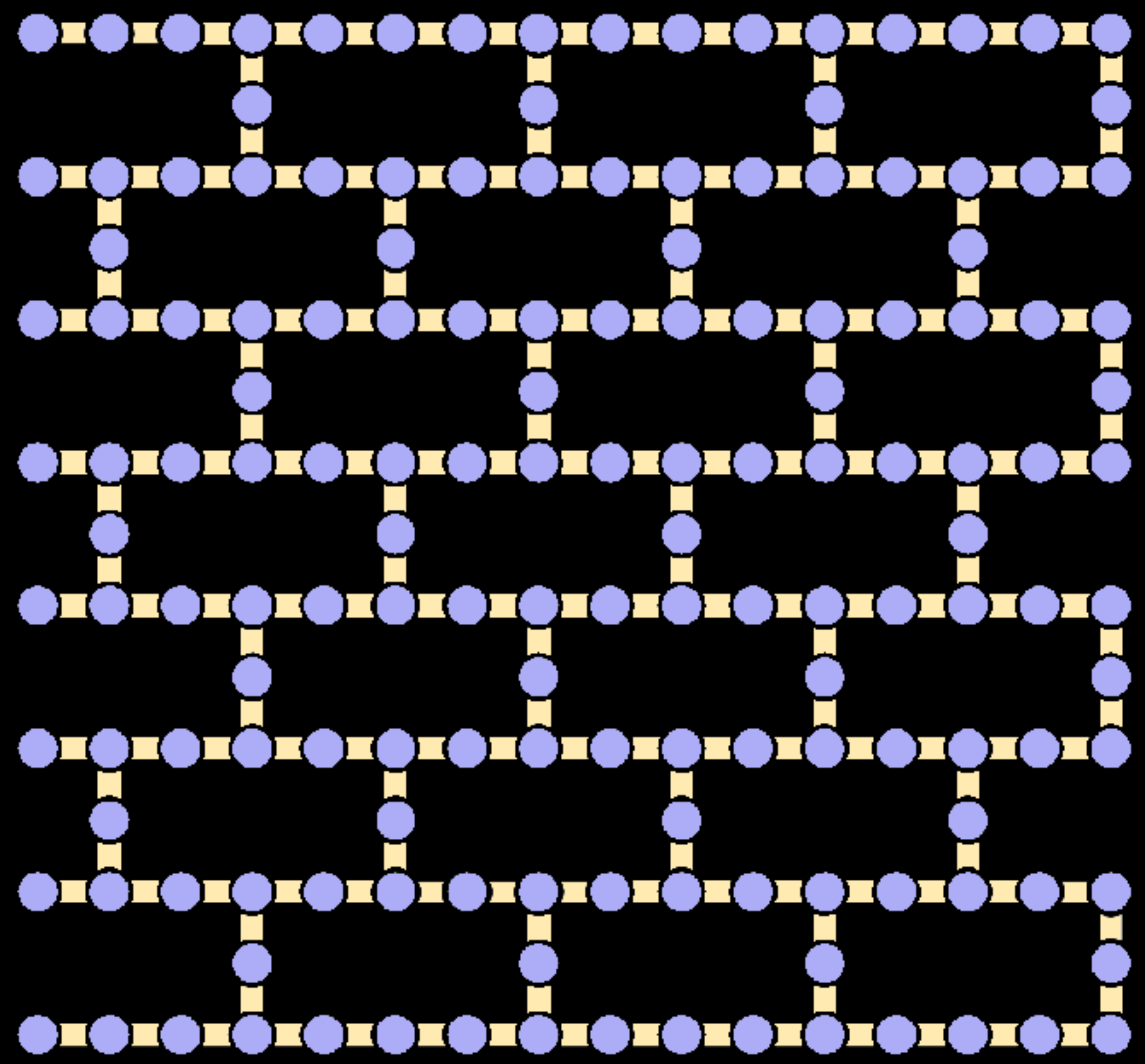
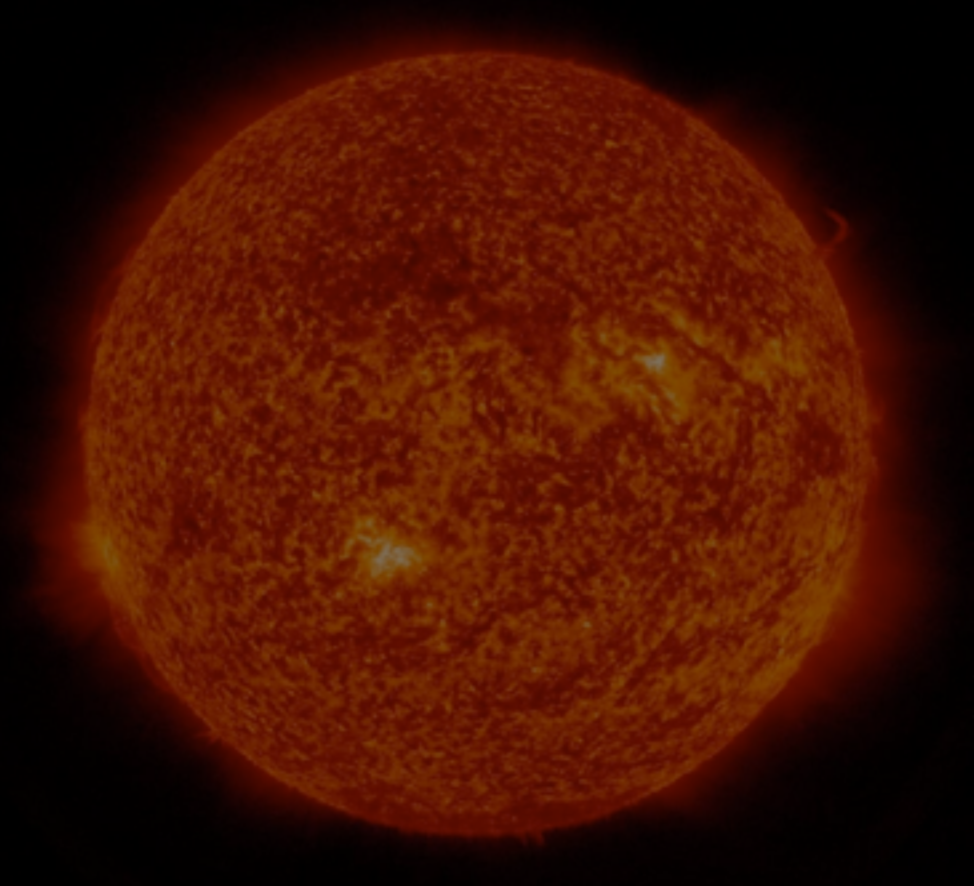
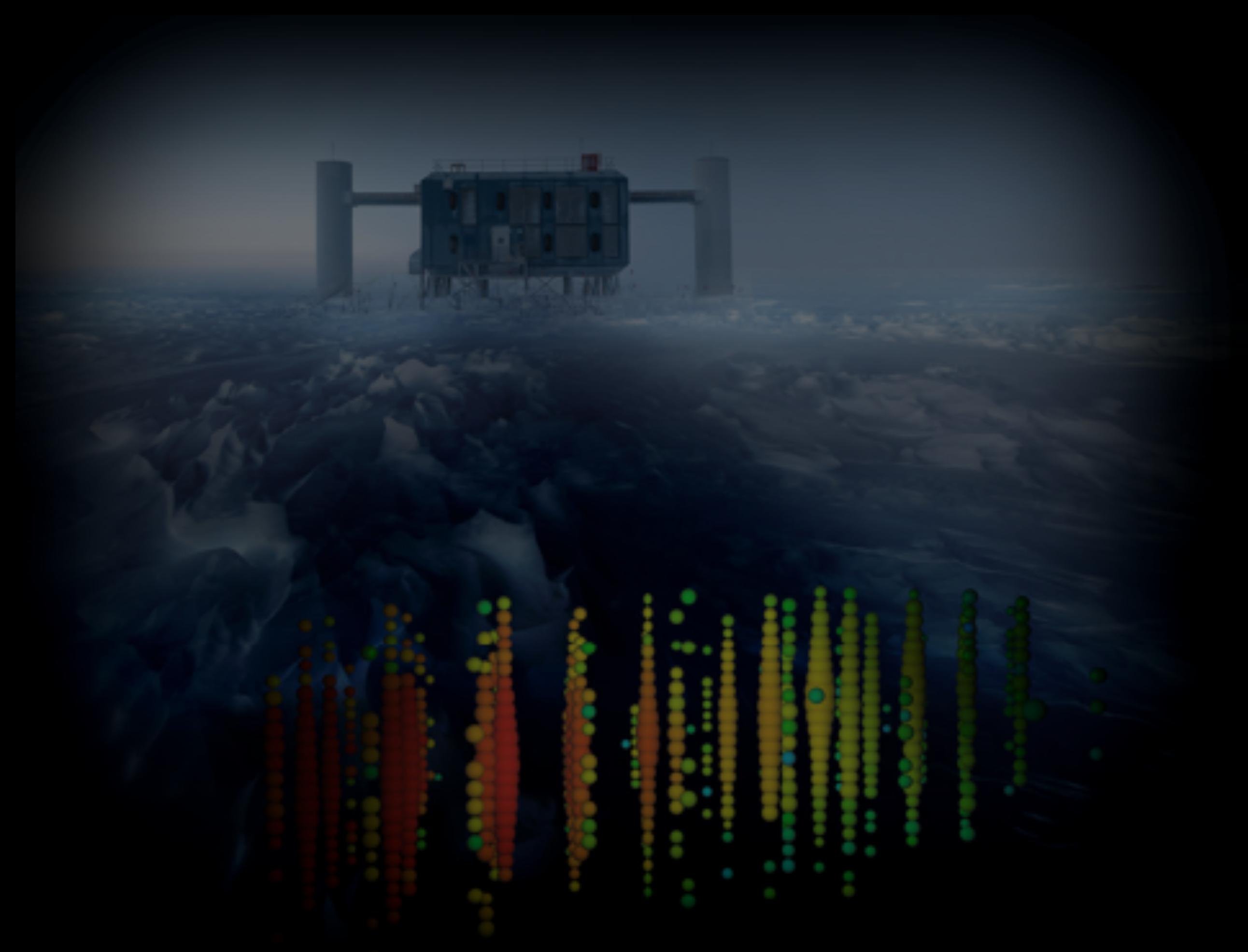


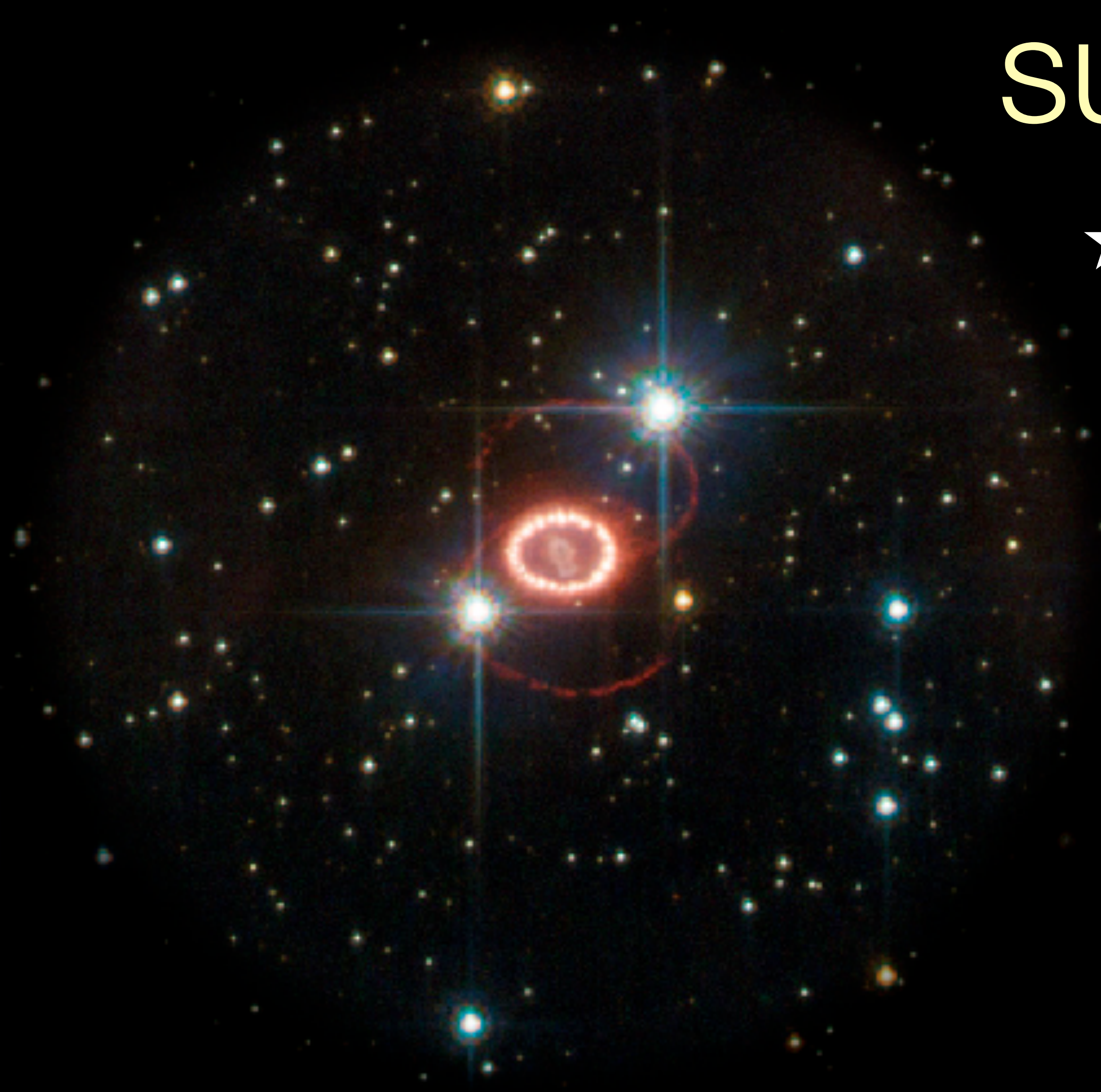


IBM Heron r2 (156 qubits)

Neutrinos as Astrophysical Messengers

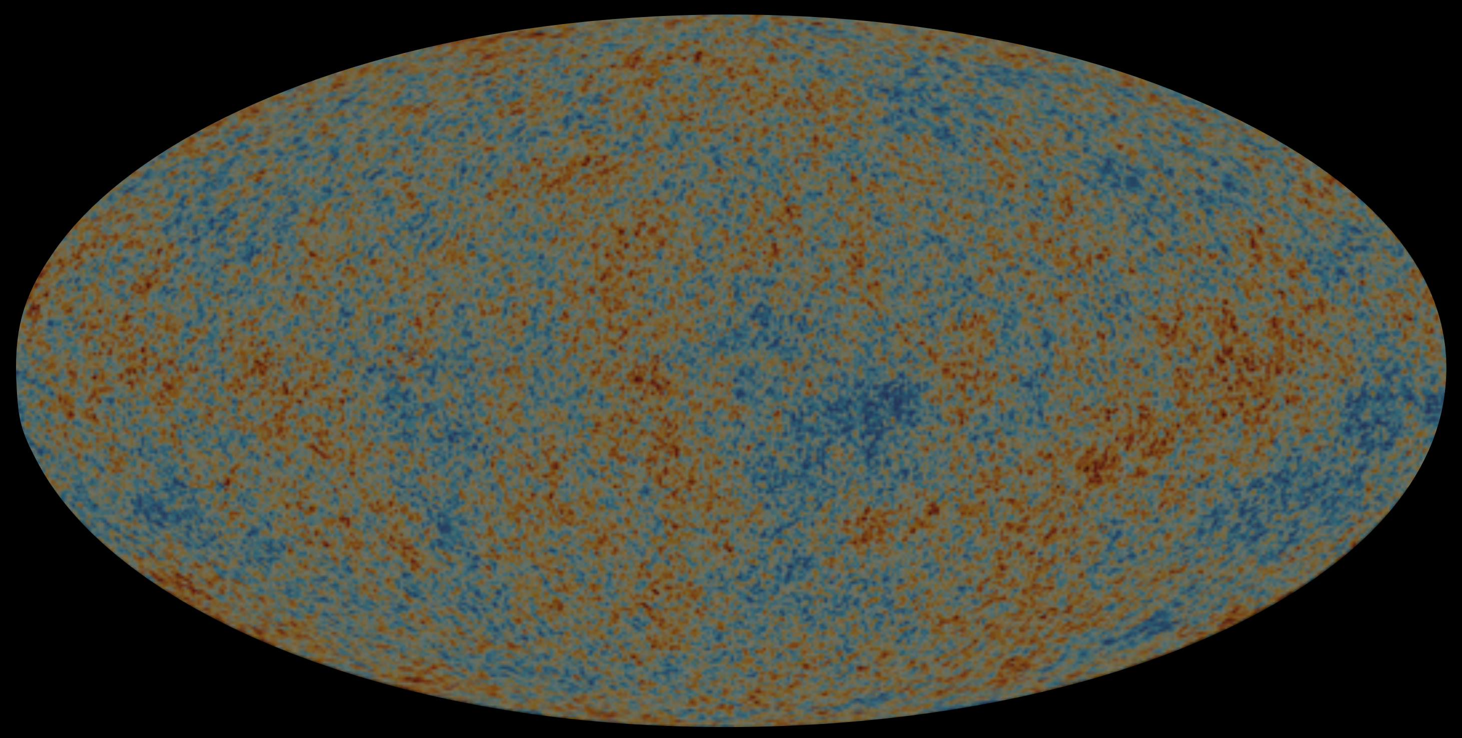






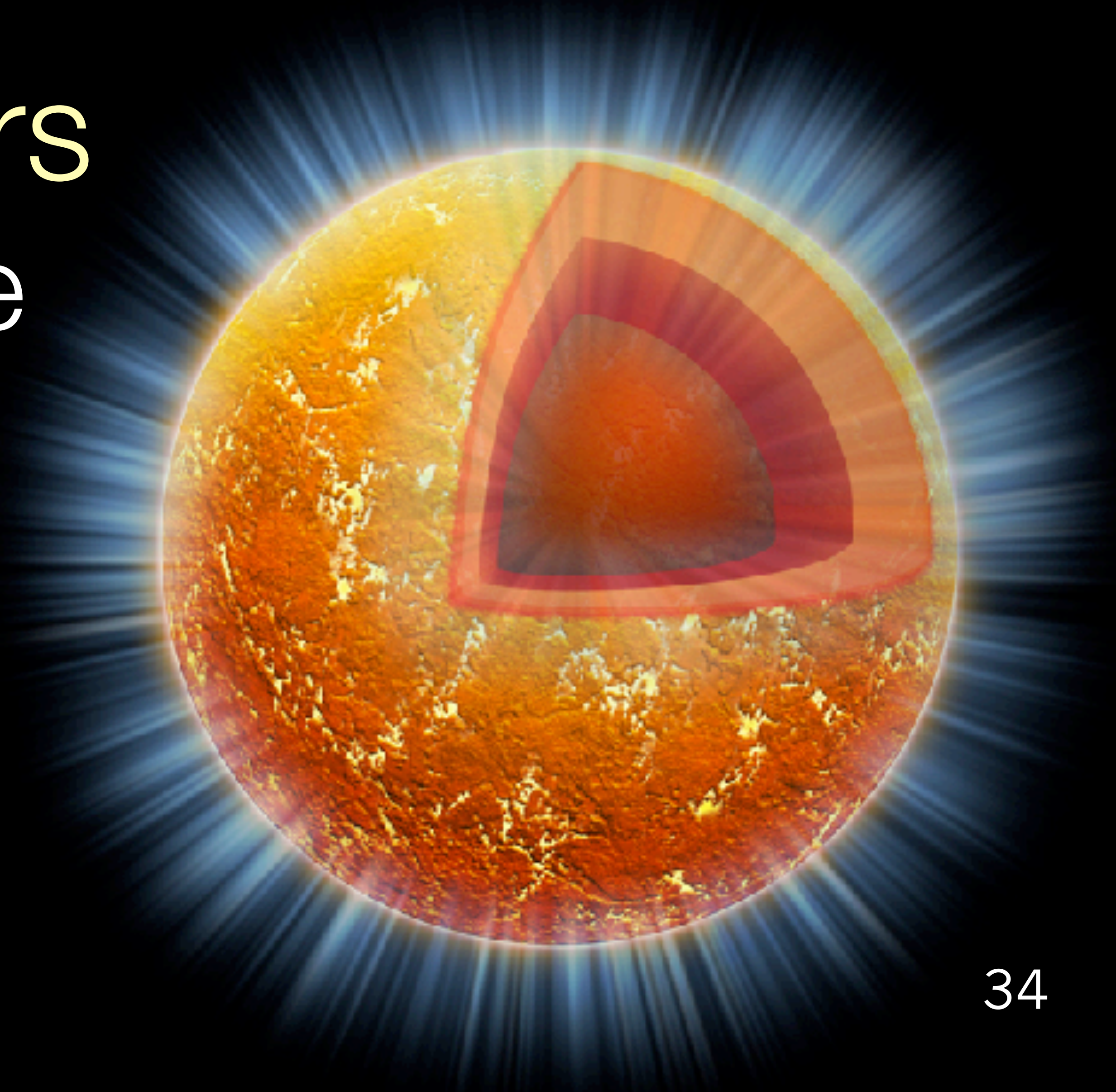
supernova neutrinos

- ★ oscillations of SN neutrinos poorly understood
- ★ playground for quantum computing



neutron stars

neutrinos may enable first discovery of common-envelope evolution



Thank You!

CERN

Neutrino PLATFORM

QUANTUM TECHNOLOGY INITIATIVE

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Bonus Slides

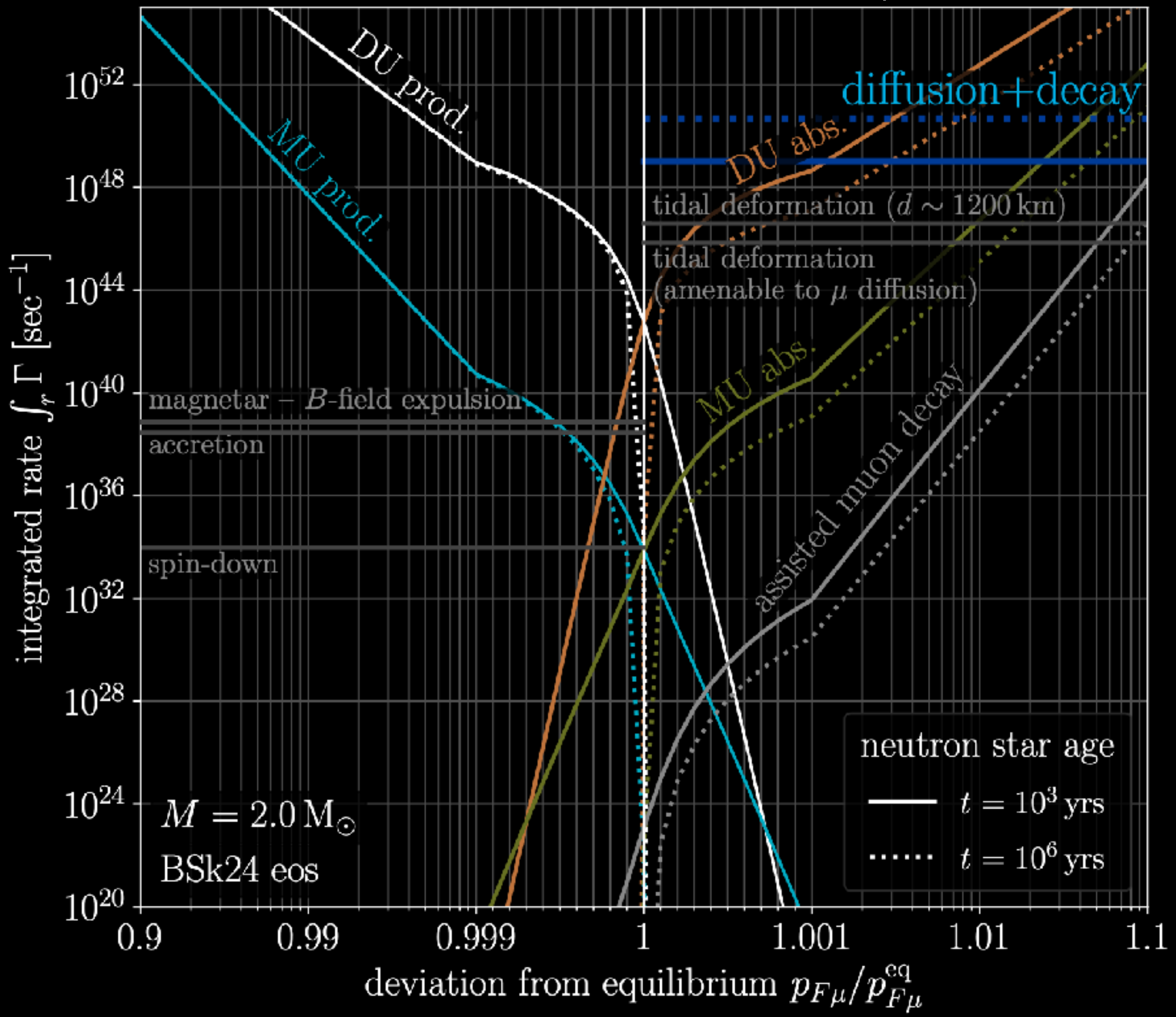
Departure from Equilibrium

Strategy for calculating rates

- ☐ apply Feynman rules + phase space integral + Pauli-blocking factors
- ☐ phenomenological parameterisation of nuclear matrix element
- ☐ neglect angular dependence of hadronic + leptonic matrix element
- ☐ treat nucleons as non-relativistic
- ☐ all momenta close to Fermi surfaces
- ☐ carry out angular integrals
- ☐ carry out energy integrals (multiple applications of residue theorem)

Friman Maxwell 1979
Yakovlev Levenfish 1995
Yakovlev Kaminker Gnedin Haensel 2000
Shapiro Teukolsky 1983

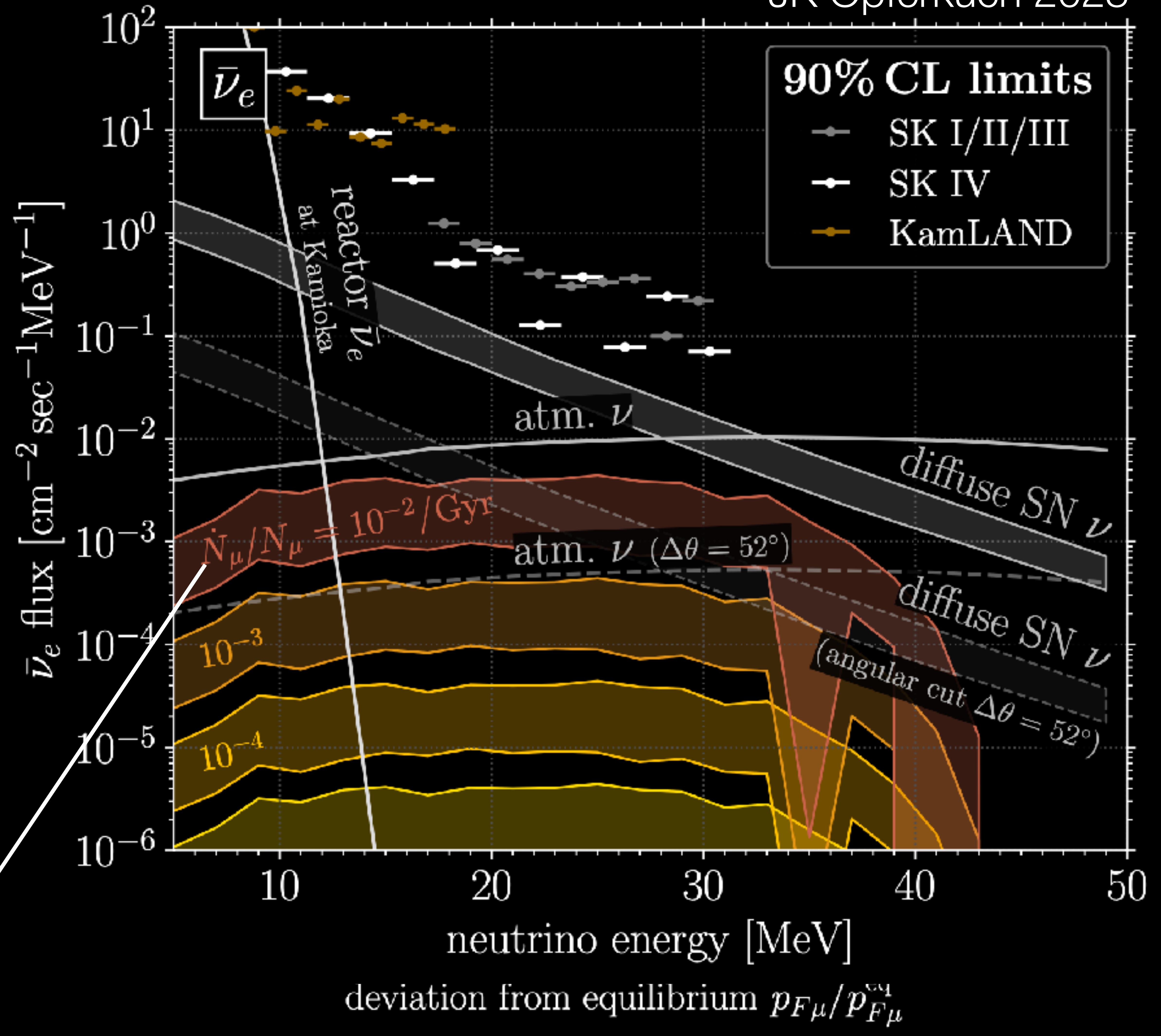
JK Opferkuch 2023



Neutron Stars Away from Thermal Equilibrium

- very strong dependence on departure from equilibrium and on *T*
- For muons:
  diffusion (over $\mathcal{O}$(yr) time scales) + decay
  - ➠ potential source of MeV neutrinos
  - ➠ would require a mechanisms that drives all NSs in the MW towards lower muon abundances
    (~1% over 10^9 yrs)
  - ➠ all mechanisms known to us do the opposite

JK Opferkuch 2023



no known mechanism that does this