Supernova Neutrino

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on HighEnergy Physics and Astrophysics

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OUTLINE

- Beyond SM
- Multi-messenger
- Core collapse supernova
- Standing Accretion Shock Instability (SASI)
- MSW effect
- Detector simulation
- What else can we add to simulation?
- Summary

Beyond Standard Model Physics

"Detectable" beyond SM physics

Neutrino physics

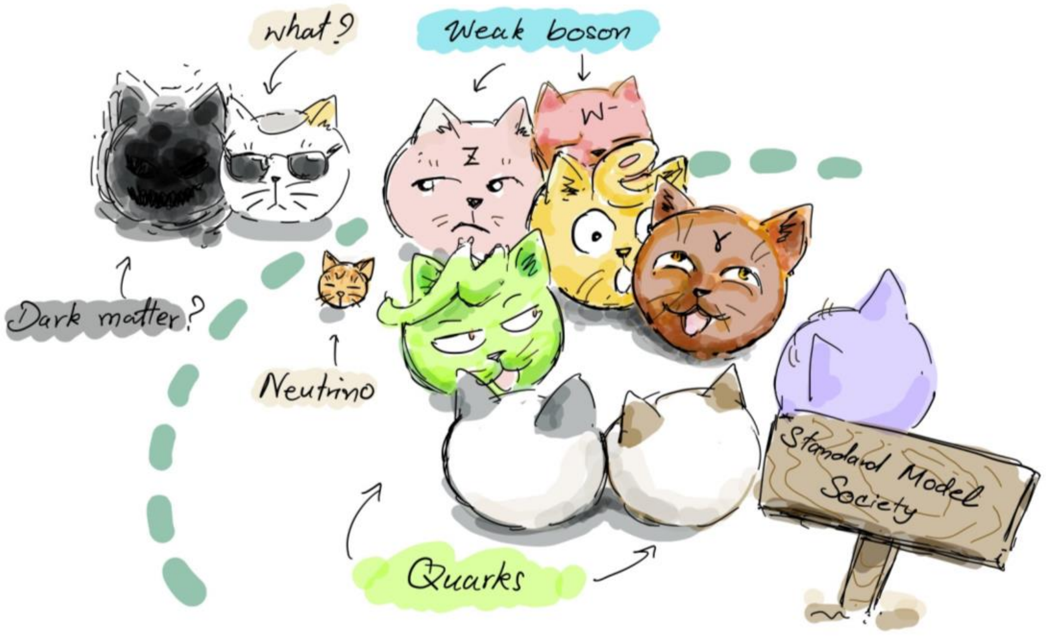
- CP-violation (CP-phase from oscillation parameter)
- Normal/inverse Hirachy
- Dirac vs Majorana (double beta decay)

UV theory – sterile neutrino

- See-saw mechanisms type I, II, III require new fundamental particles
- Theory with extra dimension also produce more particle

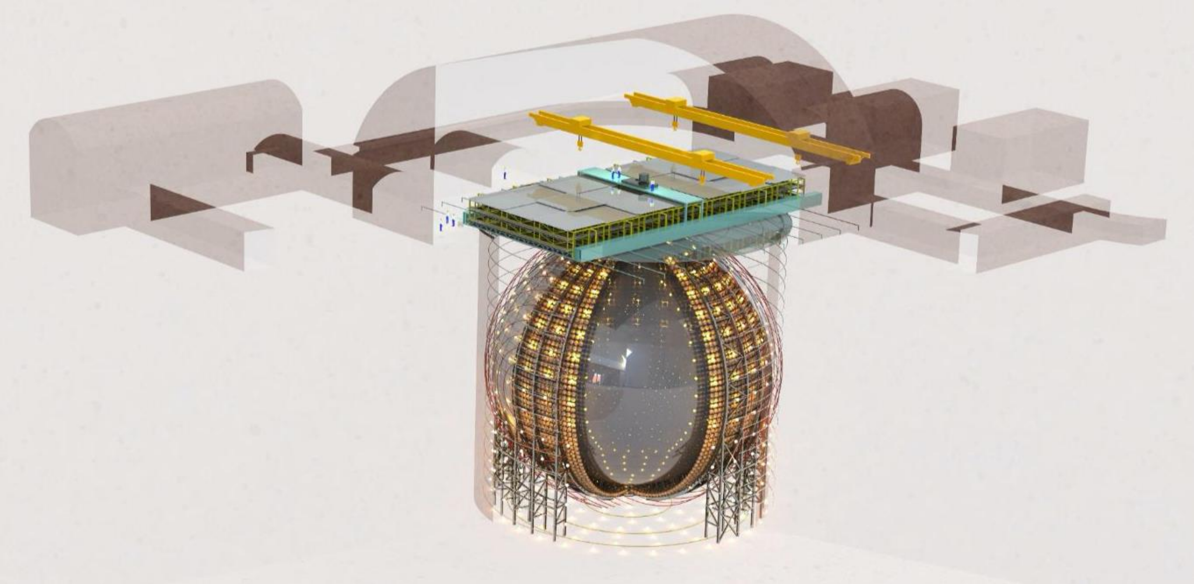
Dark matter

- WIMP produce neutrino



Multi-messenger detection

LIGO
Current detectable frequency range
10 Hz – 10kHz



Jiangmen underground neutrino observatory (JUNO)
Neutrino energy keV - GeV

The team working on this project

Core Collapse Supernova

Perfect target for multi-messenger astronomy

Turning the core into neutron star

- $E \sim \frac{3}{5}\frac{GM_N^2}{R_N} = 6.67 \times 10^{-11} \times \frac{1.4^2 M_\odot^2}{10\ km} \sim 10^{46}$ jules
- 99% goes to neutrino
- Energy up to around MeV

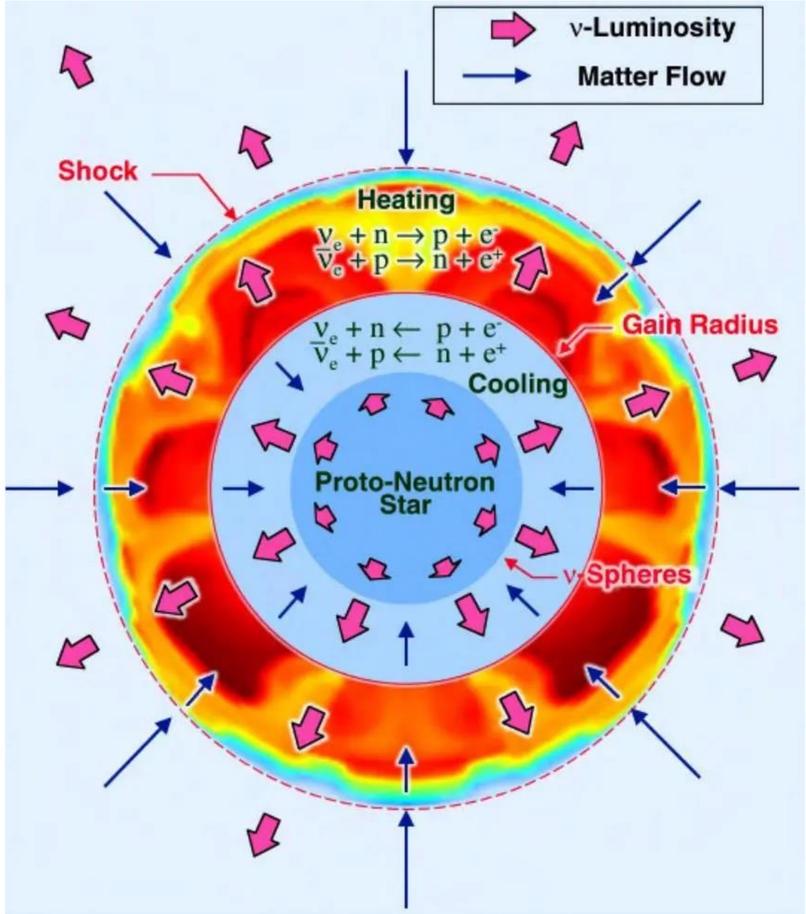
Neutrino heating

- Neutrino energy transfer to matter → drive the explosion

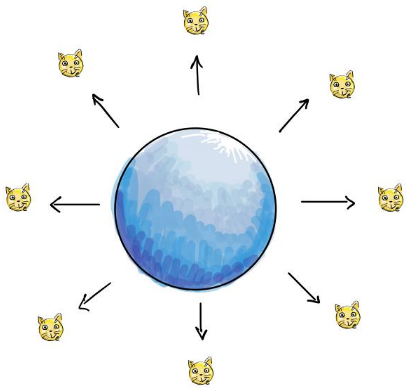
Expected gravitational wave emission

- Neutrino anisotropy

EM wave in various frequency bands i.e. gamma ray, radio, visible light etc.

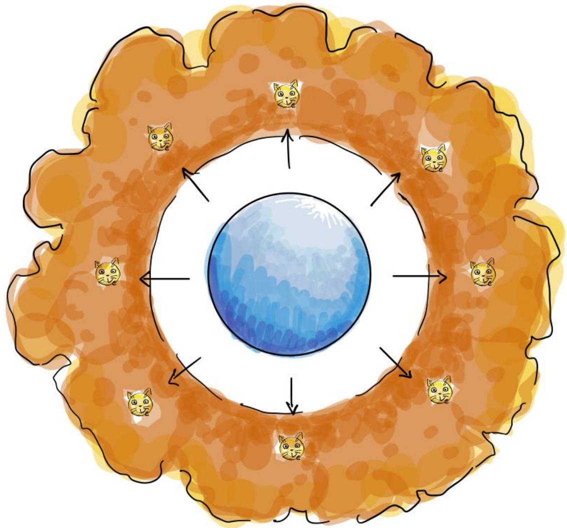


The explosion processes



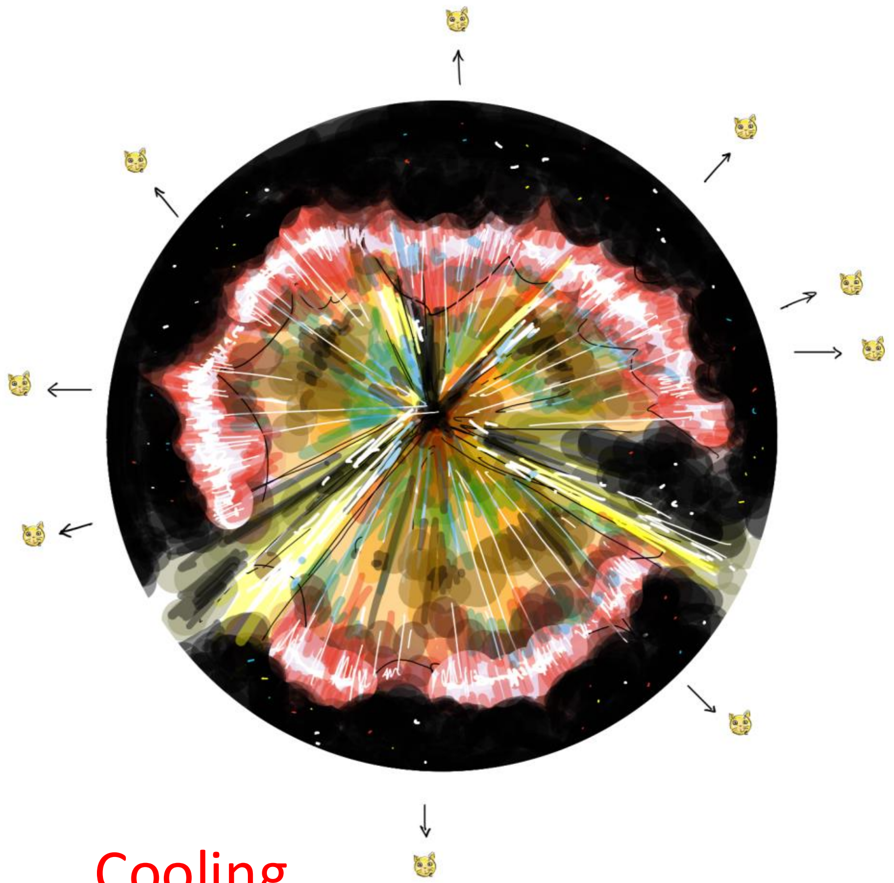
Neutronisation

- proto-neutron star (PNS) cooling
- Produce gianormous amount of neutrino from electron capture
- Emission is spherical symmetric due to intense gravitational force acting on PNS



Accretion

- Infalling matter stalling building up shock wave
- IBD and other processes, heating up the matter
- Leads to violent explosion



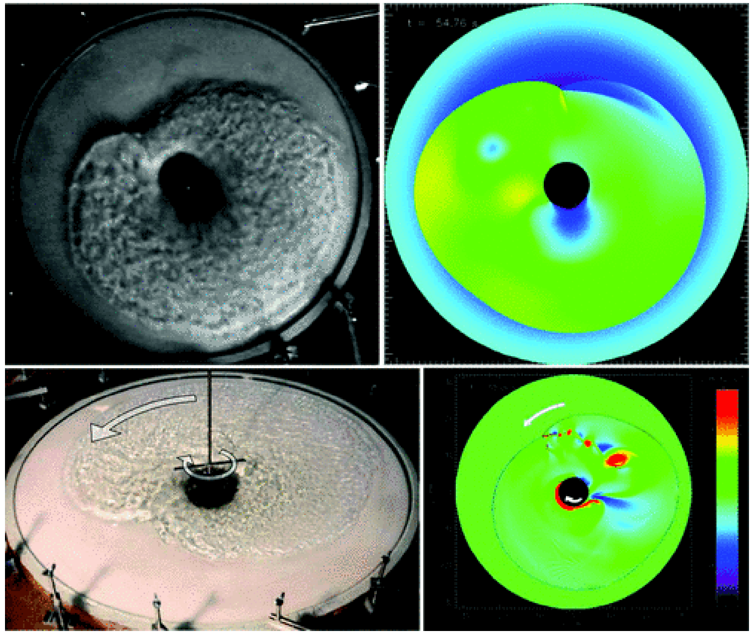
Cooling

- Single-flavour luminosity decay over time

Standing Accretion Shock Instability (SASI)

Hydrodynamics instability that is the key to SN explosion

- The infalling gas's speed is a lot faster than the speed of sound
- Create shock waves
- For standing spherical accretion shock, there is instability
- Relatively small perturbation can drive the instability
- Neutrino heating (neutrino transport)
- explosion



Phys. Rev. Lett. **108**, 051103 (2012)

Neutrino Dynamics

We will not discuss any further how SN explosion occur. Instead, we will focus on what we could learn about neutrinos.

Let us begin with Schrodinger equation

$$-i\frac{d\psi}{dt} = H\psi$$

The Hamiltonian $H = H_{vac} + H_{MSW} + H_{\nu\nu}$

- H_{vac} is free Hamiltonian
- H_{MSW} interaction of neutrino with matter
- $H_{\nu\nu}$ neutrino self-interaction

Fast Flavour Conversion

In neutrino dense environment: self-interaction

- Dominate in SN core

$$H_{\nu\nu} = \sqrt{2}G_F \int dv'(1 - v \cdot v')(\rho_{v'} - \bar{\rho}_{v'}),$$

  with

$$\rho_v \approx \begin{pmatrix} f_e(v) & S_v \\ S_v^* & f_X(v) \end{pmatrix},$$

  the perturbation S_v responsible for flavour conversion

- Fast Flavour conversion (FFC):
  solving the equation $S \sim e^{\Gamma t}$ where $\Gamma_{\max} \sim \sqrt{2} G_F n_\nu$
- Nonlinear interaction
- Flavour change in submillimeter scale

Neutrino Oscillation

Two mass eigenstate

$$i\frac{d}{dt}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = H\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \begin{pmatrix}\sqrt{p^2+m_1^2} & 0\\ 0 & \sqrt{p^2+m_2^2}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

Changing to flavour basis the equatin become

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_X\end{pmatrix} = U\,HU^{-1}\begin{pmatrix}\nu_e\\ \nu_X\end{pmatrix}$$, where

$$H_{vac} = U\,HU^{-1} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}p+\frac{1}{2}\frac{m_1^2}{p} & 0\\ 0 & p+\frac{1}{2}\frac{m_2^2}{p}\end{pmatrix}\begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix}$$

$$= p + \frac{\Delta m^2}{4E}\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix}$$

Neutrino Oscillation in Matter

If there is potential $V_e = \pm\sqrt{2}G_F N_e$

$$H_{vac} + H_{MSW}$$
$$= p + \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} V_e & 0 \\ 0 & 0 \end{pmatrix}$$

Substract what's not relavent to oscillation

$$H_M = \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \frac{1}{2}\begin{pmatrix} V_e & 0 \\ 0 & V_e \end{pmatrix}$$
$$= \frac{\Delta m^2_{eff}}{4E}\begin{pmatrix} -\cos 2\theta_{eff} & \sin 2\theta_{eff} \\ \sin 2\theta_{eff} & \cos 2\theta_{eff} \end{pmatrix}$$

Resonance

The eff parameter is given by

$$\cos 2\theta_{eff} = \frac{\left(\cos 2\theta - \frac{2EV_e}{\Delta m^2}\right)}{C}$$

$$\sin 2\theta_{eff} = \frac{\sin 2\theta}{C}$$

$$\Delta m^2_{eff} = C\Delta m^2$$

$$C = \sqrt{\left(\cos 2\theta - \frac{2EV_e}{\Delta m^2}\right)^2 + \sin^2 2\theta}$$

High and Low resonace

- Resonance occur when

$$\cos 2\theta - \frac{2EV_e}{\Delta m^2} = 0$$

Two possible resonance:

- Δm^2_{31} High resonance
- Δm^2_{21} Low resonance

Which particle undergoes resonace

- The sign of Δm^2_{12} is fixed,
- The sign of Δm^2_{13} will determine whether electron neutrino or antineutrino undergoes resonance

Positive:

$$F_{\nu_3} = F^0_{\nu_e}, \quad F_{\nu_2} = F^0_{\nu_X}, \quad F_{\nu_1} = F^0_{\nu_X}$$

$$F_{\overline{\nu}_3} = F^0_{\overline{\nu}_X}, \quad F_{\overline{\nu}_2} = F^0_{\overline{\nu}_X}, \quad F_{\nu_1} = F^0_{\overline{\nu}_e}$$

Negative:

$$F_{\nu_3} = F^0_{\nu_X}, \quad F_{\nu_2} = F^0_{\nu_e}, \quad F_{\nu_1} = F^0_{\nu_X}$$

$$F_{\overline{\nu}_3} = F^0_{\overline{\nu}_e}, \quad F_{\overline{\nu}_2} = F^0_{\overline{\nu}_X}, \quad F_{\nu_1} = F^0_{\overline{\nu}_X}$$

NMO and IMO

$$F_\alpha(E,t) = P_{\alpha\to\beta} F^0_\beta(E,t) = |U_{e1}|^2 F_{\nu_1} + |U_{e2}|^2 F_{\nu_2} + |U_{e3}|^2 F_{\nu_3}$$

Long distance → decoherence → $P_{\alpha\to\beta}$ is then only depent on U

Preserving the signature of MSW

- Normal Mass Ordering (NMO): $m_1 < m_2 < m_3$
- Inverse Mass Ordering (IMO): $m_3 < m_1 < m_2$

NMO

- $F_{\nu_e} \approx F^0_{\nu_X}$
- $F_{\bar{\nu}_e} = (1 - P_{\bar{\nu}_e\to\bar{\nu}_e}) F^0_{\bar{\nu}_e} + P_{\bar{\nu}_e\to\bar{\nu}_e} F^0_{\bar{\nu}_X}$
- $4F_{\nu_X} = F^0_{\nu_e} + P_{\nu_e\to\nu_e} F^0_{\bar{\nu}_e} + (3 - P_{\bar{\nu}_e\to\bar{\nu}_e})\, F^0_{\nu_X}$

IMO

- $F_{\nu_e} = P_{\nu_e\to\nu_e} F^0_{\nu_e} + (1 - P_{\nu_e\to\nu_e}) F^0_{\nu_X}$
- $F_{\bar{\nu}_e} \approx F^0_{\bar{\nu}_X}$
- $4F_{\nu_X} = (1 - P_{\nu_e\to\nu_e}) F^0_{\nu_e} + F^0_{\bar{\nu}_e} + (2 + P_{\nu_e\to\nu_e})\, F^0_{\nu_X}$

From the first run paper, JUNO seems to favor NMO, but this is only 2σ confidence level.

Supernova modeling

Both Pre-SN and SN event are very hard to simulate. It requires powerful computing power. JUNO software does not generate these event, but use the generated data existing in the literature to simulate detector signal.

Pre-SN

- Provide info of late state stellar evolution.
- Start emitting neutrino days before SN explosion
- Three different models are in used
  - Guo: pair process
  - Kato: pair process + weak interaction
  - Patton: pair + beta process

SN model

- Garching model (MPA)
  no neutrino anisotropy
- Nakazato model
- Fornax (Princeton group)

Include it into the framework:
neutrino anisotropy which produce gravitational wave

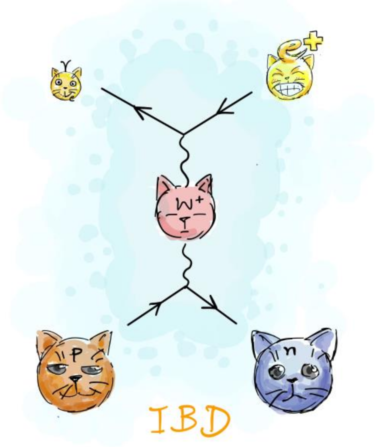
Simulated neutrino flux/energy from models

JUNO SN generator

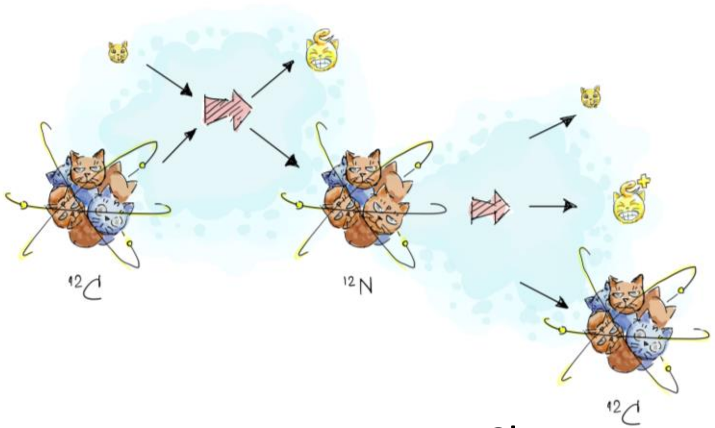
Signal in detector

The model in blue text already in used by JUNO

Expected signal in detector



Inverse beta decay



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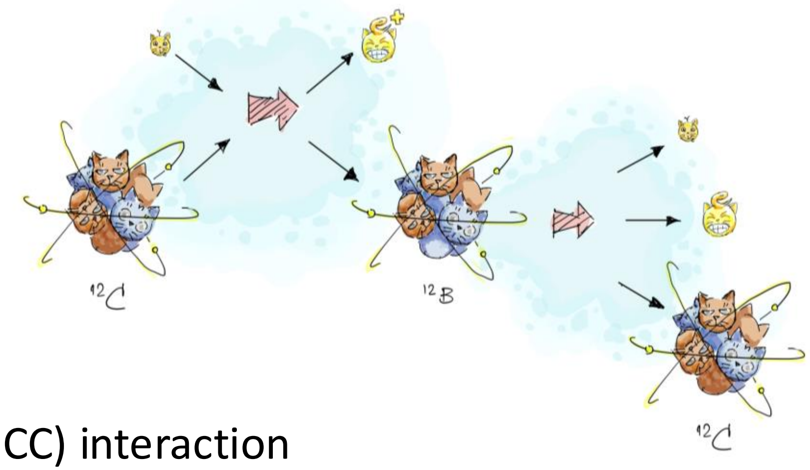
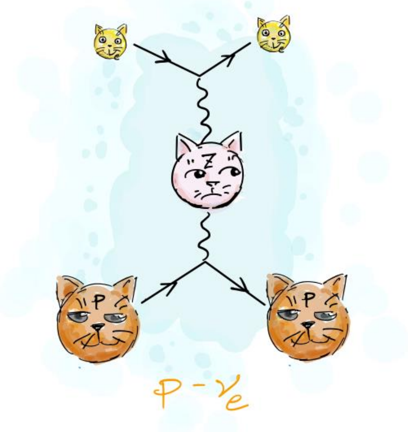
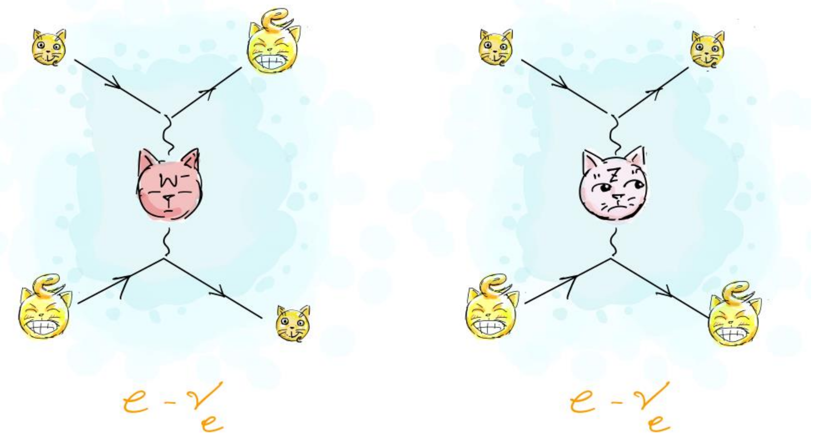


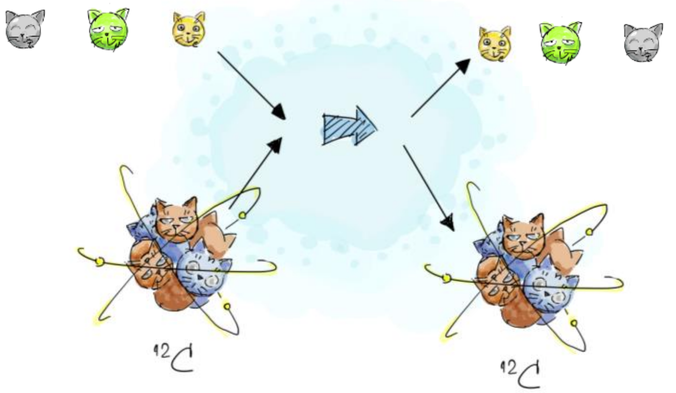
Charge current (CC) interaction with carbon-12



Neutrino – proton elastic scattering (*p*ES)

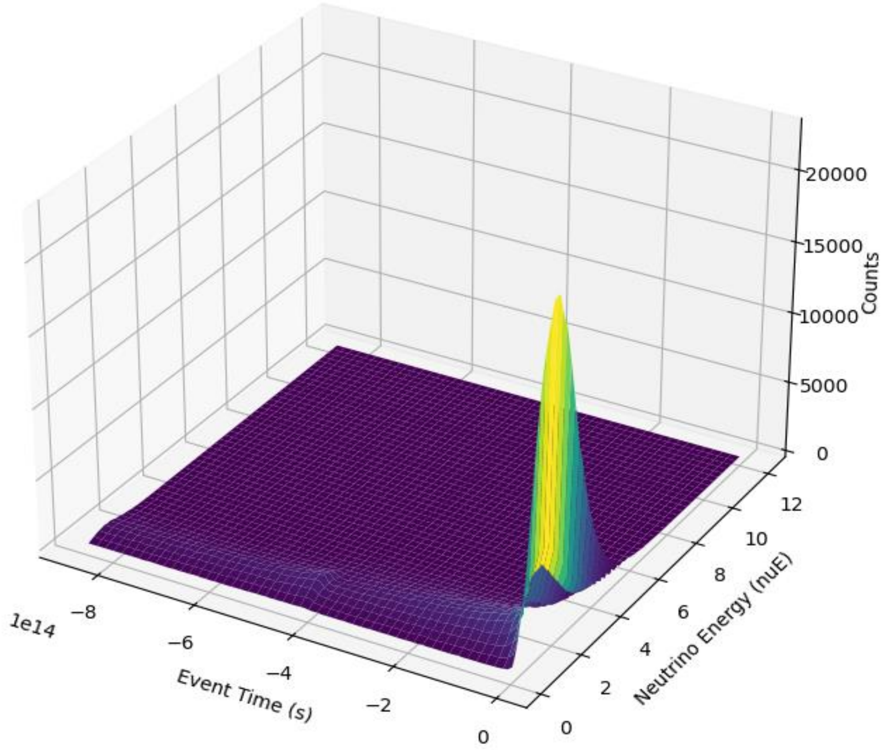


Neutrino – electron elastic scattering (*e*ES)



Neutral current (NC) interaction with carbon-12 (any neutrino)

Detector simulation for JUNO: pre-SN



Pre-SN 3D plot:
counts vs time, energy

Why interested in pre-SN

- Alert system
- To effectively provide an alert → MM trigger
- Clustering of neutrino signal

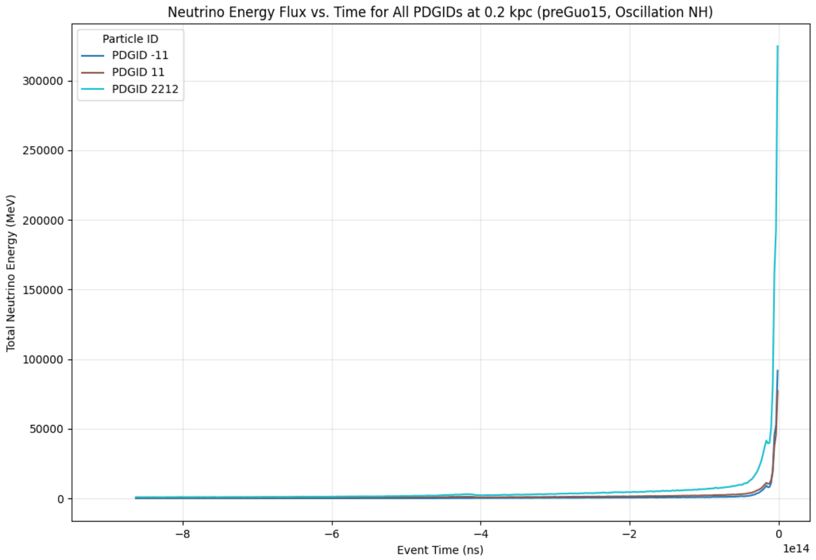
Simulated pre-SN

- 10 days before SN explosion
- Counts vs time and energy
- Normal & inverted hierarchy (NH, IH)

Note that this is a simulated plot. In reality this plot has to be reconstructed from detector data.

Detector simulation: Pre-SN

- JUNO Pre-SN generator produce signal that will be seen in the detector
- Interaction listed in the previous slide
- The plots on the right shown result from Guo, Kato and Patton for progenator of $15M_{\odot}$ distance 0.2 kpc



Guo model

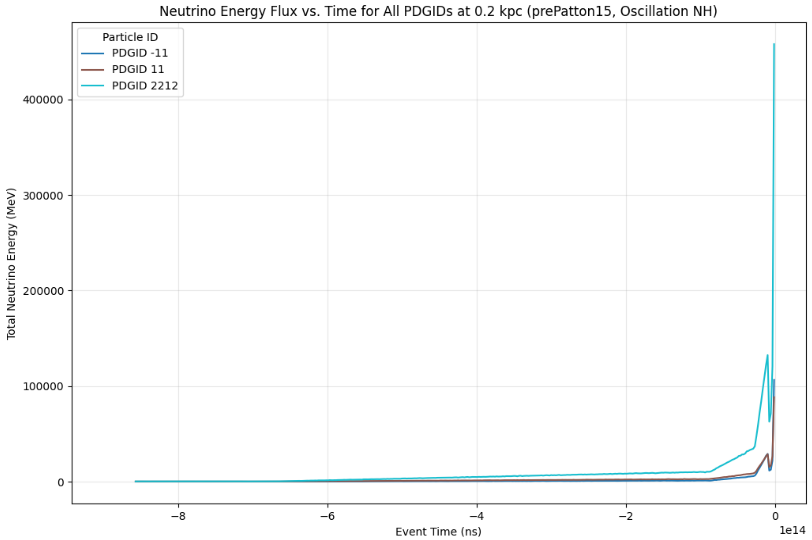
Particle ID:

electron (11) 

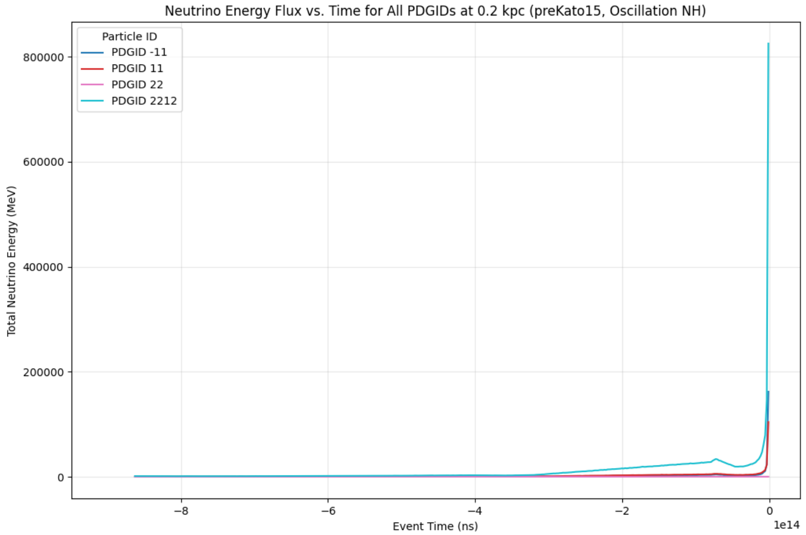
positron (-11) 

photon (22) 

proton (2212) 

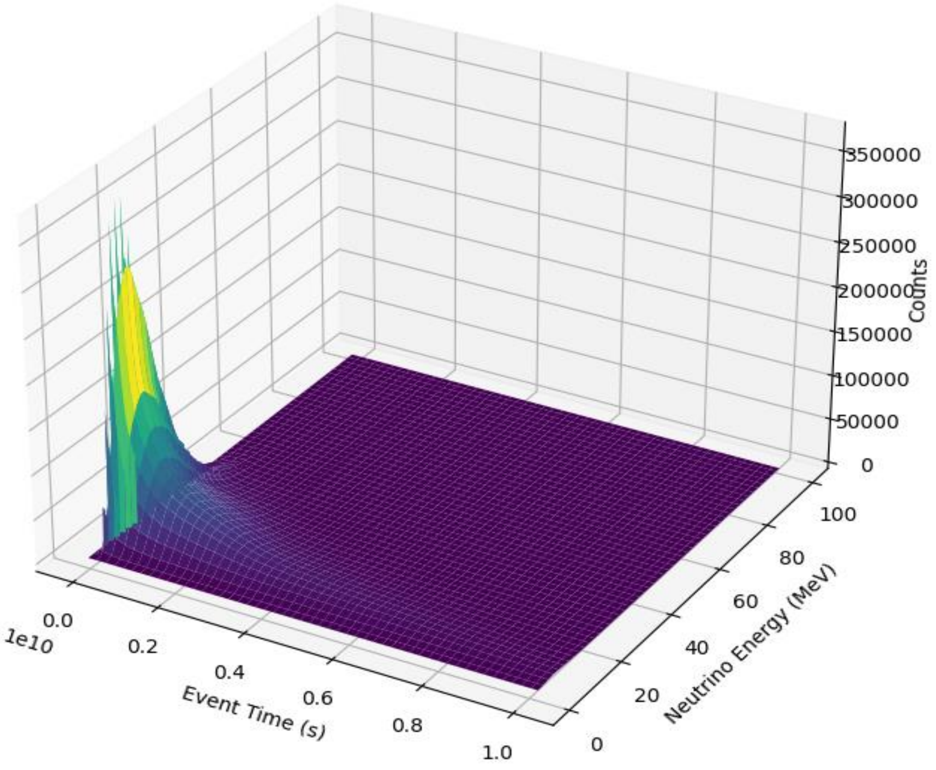


Patton model



Kato model

Detector simulation for JUNO: SN



Garching model SN 3D plot:
Conts vs time, energy

Data format

```
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1.00E+00 2.50E+00 1.255147E+44 0.000000E+00 0.000000E+00 5.027490E+38 0.000000E+00 0.000000E+00
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7.00E+00 1.00E+01 9.274068E+41 0.000000E+00 0.000000E+00 1.485891E+37 0.000000E+00 0.000000E+00
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```

$$
\begin{array}{llllllll}
t_0 & & & & & & & \\
E_0 & E_1 & \frac{\Delta N_{1,\nu_e}(t_0)}{\Delta E_1} & \frac{\Delta N_{1,\bar{\nu}_e}(t_0)}{\Delta E_1} & \frac{\Delta N_{1,\nu_x}(t_0)}{\Delta E_1} & \frac{\Delta L_{1,\nu_e}(t_0)}{\Delta E_1} & \frac{\Delta L_{1,\bar{\nu}_e}(t_0)}{\Delta E_1} & \frac{\Delta L_{1,\nu_x}(t_0)}{\Delta E_1} \\
E_1 & E_2 & \frac{\Delta N_{2,\nu_e}(t_0)}{\Delta E_2} & \frac{\Delta N_{2,\bar{\nu}_e}(t_0)}{\Delta E_2} & \frac{\Delta N_{2,\nu_x}(t_0)}{\Delta E_2} & \frac{\Delta L_{2,\nu_e}(t_0)}{\Delta E_2} & \frac{\Delta L_{2,\bar{\nu}_e}(t_0)}{\Delta E_2} & \frac{\Delta L_{2,\nu_x}(t_0)}{\Delta E_2} \\
\cdots & & & & & & & \\
E_{19} & E_{20} & \frac{\Delta N_{20,\nu_e}(t_0)}{\Delta E_{20}} & \frac{\Delta N_{20,\bar{\nu}_e}(t_0)}{\Delta E_{20}} & \frac{\Delta N_{20,\nu_x}(t_0)}{\Delta E_{20}} & \frac{\Delta L_{20,\nu_e}(t_0)}{\Delta E_{20}} & \frac{\Delta L_{20,\bar{\nu}_e}(t_0)}{\Delta E_{20}} & \frac{\Delta L_{20,\nu_x}(t_0)}{\Delta E_{20}}
\end{array}
$$

Detector simulation: SN

- JUNO SN generator produce signal that will be seen in the detector
- Interaction listed in the previous slide
- The plots on the right shown result from Garching Model
- Most of neutrino interactions result in IBD, and pES.
- NC is good for detect other neutrino species
- NH and IH yield different distributions

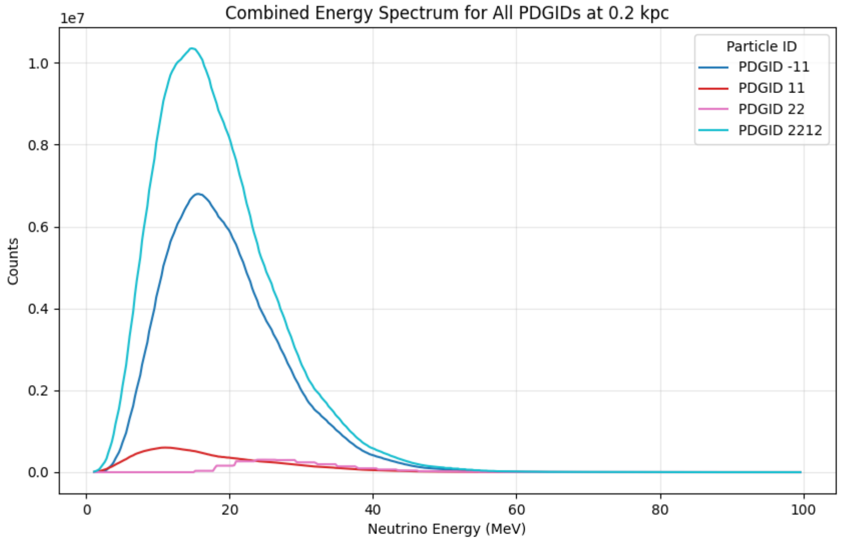
Particle ID:

electron (11) 

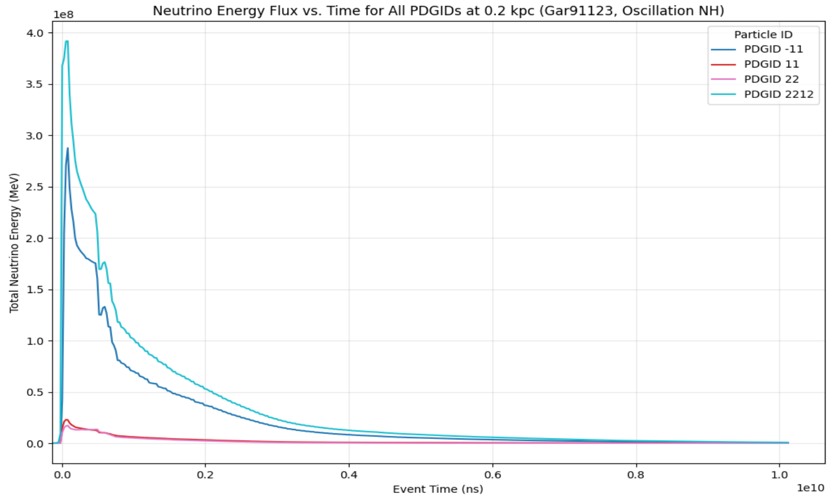
positron (-11) 

photon (22) 

proton (2212) 



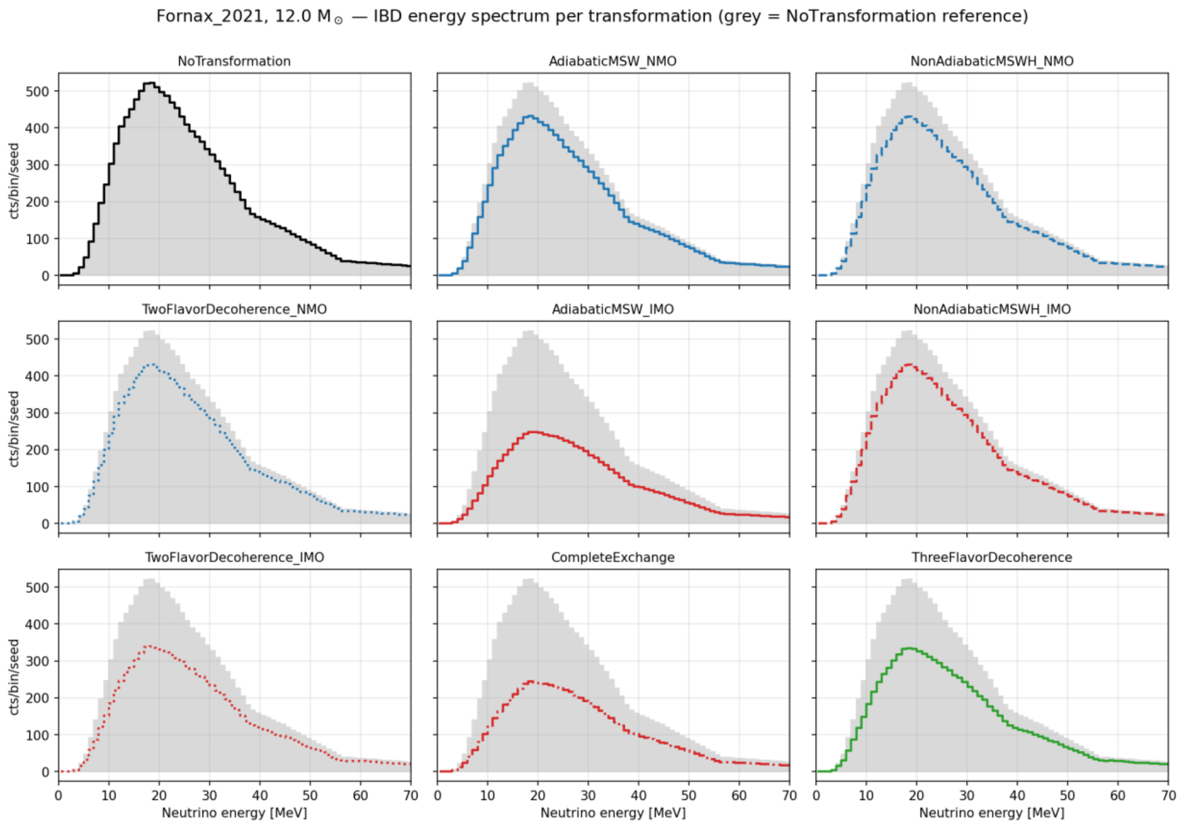
Energy spectrum of each particle

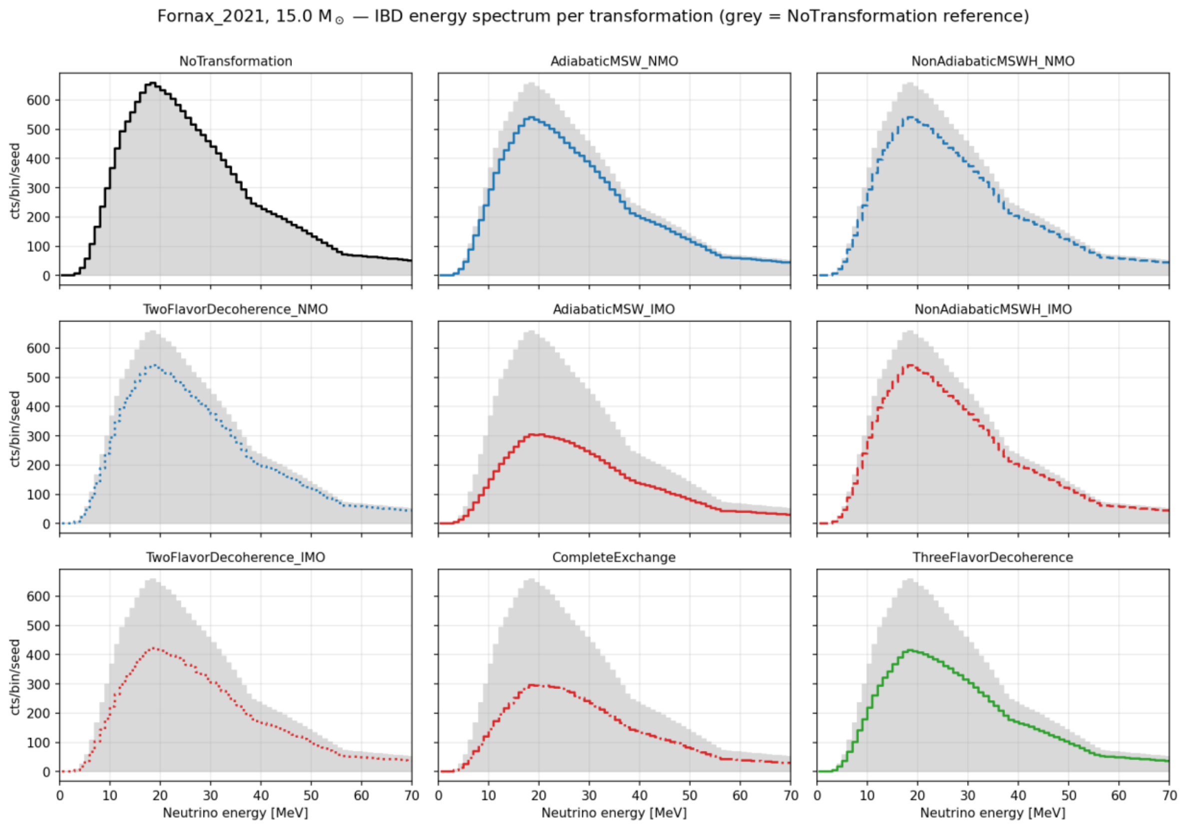


Total energy vs time for

SNEWPY

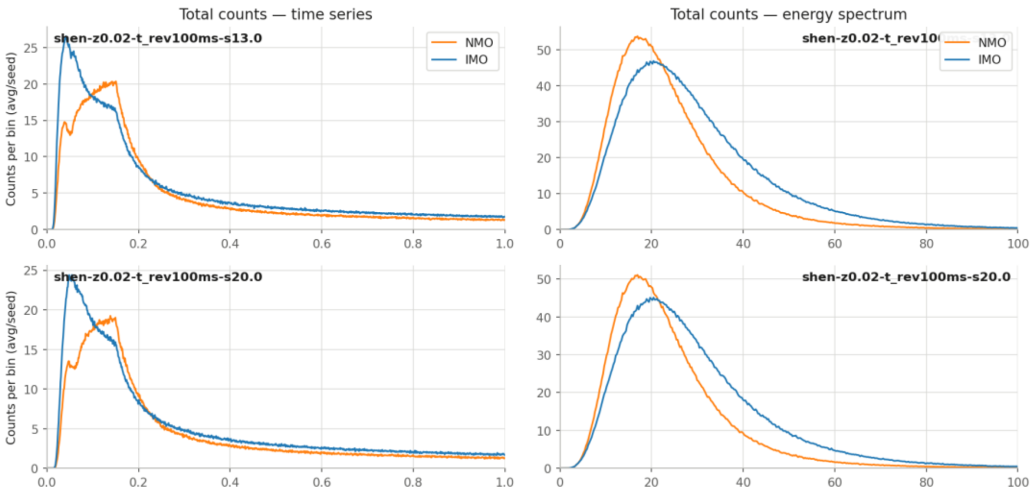
Include many models: FORNAX, Nakazato, Bolling etc.



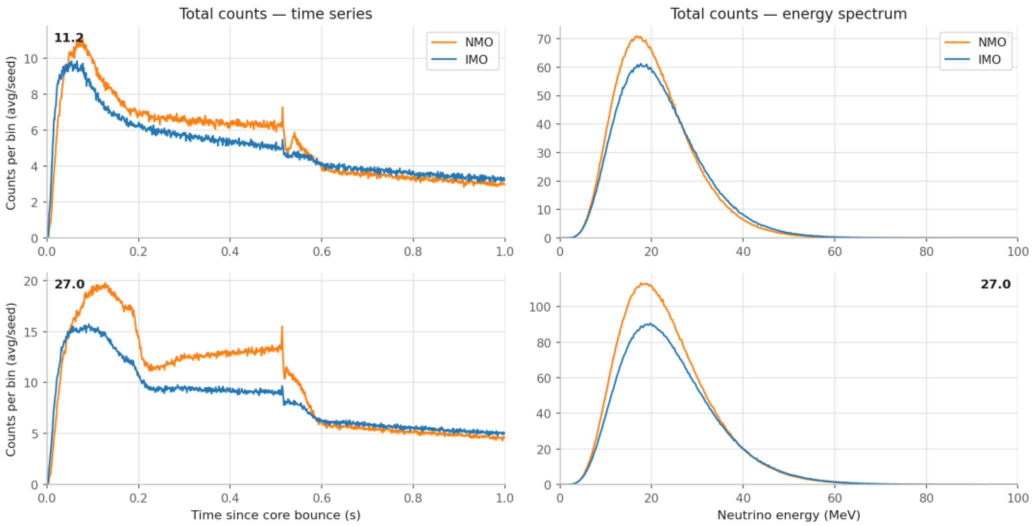


NMO vs IMO in different models

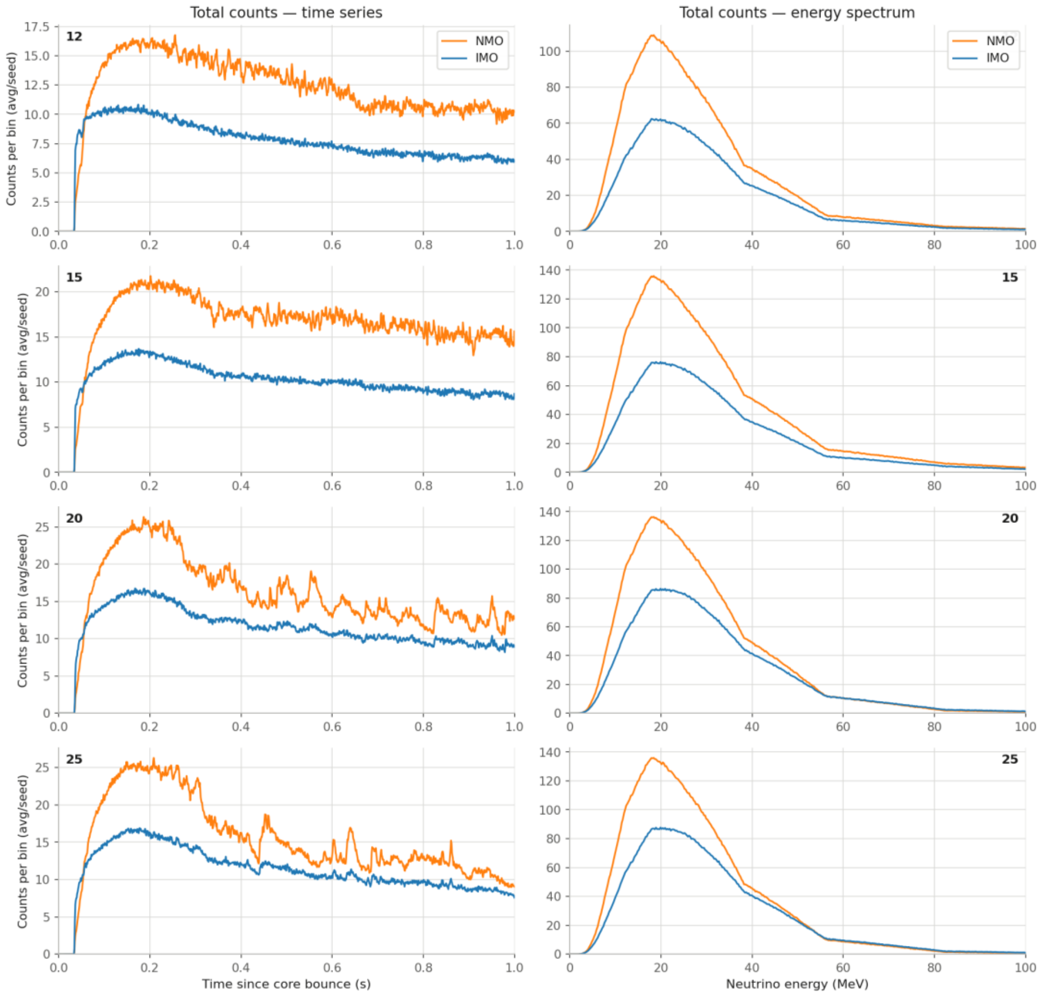
Nakazato 2013 · avg/seed, 500 seeds, 5 kpc



Bollig 2016 · avg/seed, 500 seeds, 5 kpc

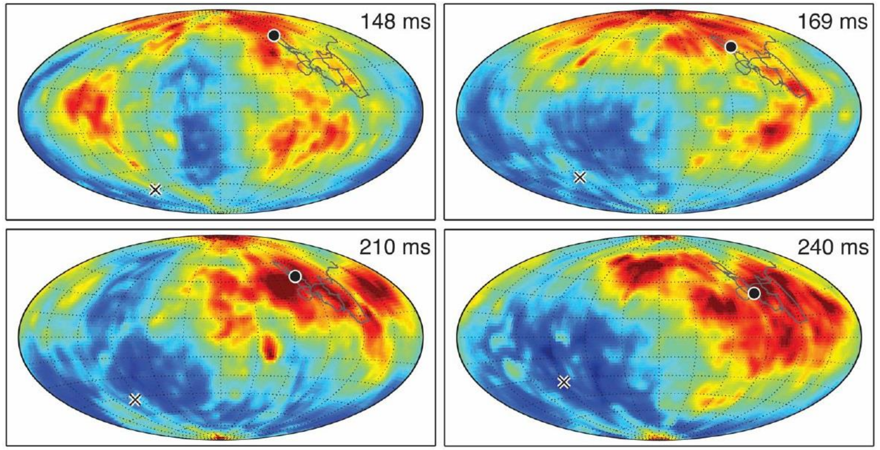


Fornax 2021 · avg/seed, 500 seeds, 5 kpc



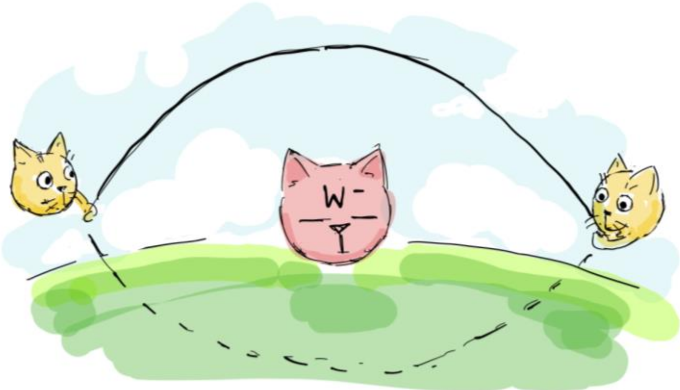
What else can we add to simulation?

- Neutrino anisotropy
  FORNAX 2025 version but not the current one available in SNEWPY

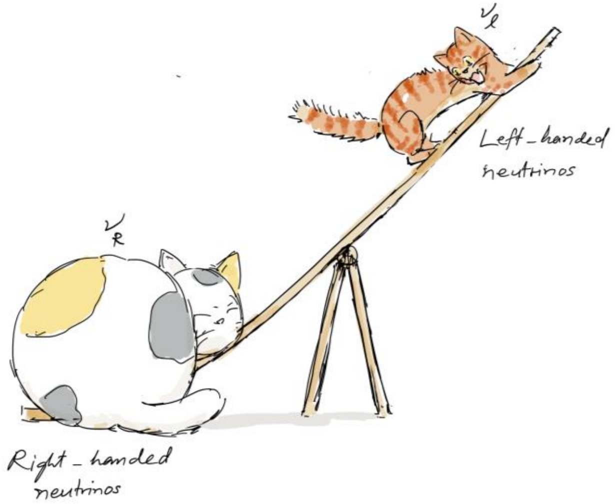


[Irene Tamborra et al. et 2014]

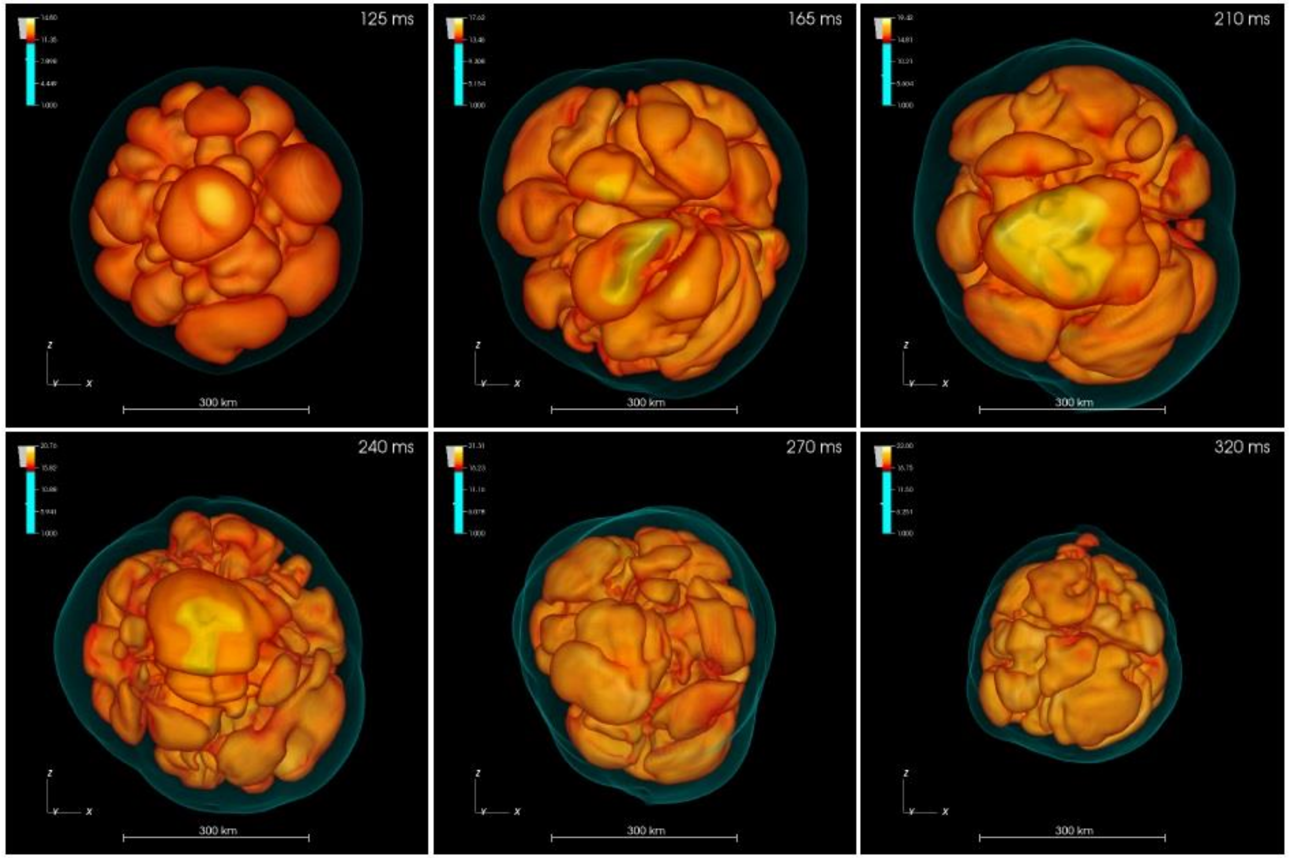
- Loop corrections
  Adding correction to classical theory



- Contribution from sterile neutrinos
  Including a heavier particle –> more interaction at loop level



Anisotropy



Simulation of boiling matter around newly form neutron star [Irene Tamborra et al. et 2014]

Neutrino transport

- Neutron star is spherically symmetric
- Neutrino – matter → anisotropy

Neutrino anisotropy

- Anisotropy from SASI activity
- Lepton-number emission self-sustained asymmetry (LESA)
- Updating SNEWPY
- JUNO SN generator?

Anisotropy → Gravitational

Gravitational wave driven by supernova

- Matter flow → GW (Garching)
- Neutrino anisotropy → GW 100 - 500 Hz (Fornax)
  - Angle dependent flux

$$\frac{dL_\nu}{d\Omega} = F_r(\theta,\phi,t) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} A_{l,m}(t) Y_{l,m}(\theta,\phi)$$

  - Gravitational wave amplitude for observor in z-axis

$$h_+ = \frac{4G}{c^4 D}\sqrt{\frac{8\pi}{15}}\int_{-\infty}^{t} dt' \left(A_{2,2}(t') + A_{2,-2}(t')\right)$$

$$h_\times = \frac{4G}{ic^4 D}\sqrt{\frac{8\pi}{15}}\int_{-\infty}^{t} dt' \left(A_{2,2}(t') - A_{2,-2}(t')\right)$$

If we detect GW during the explosion we know that neutrino emission is not spherical symmetric!

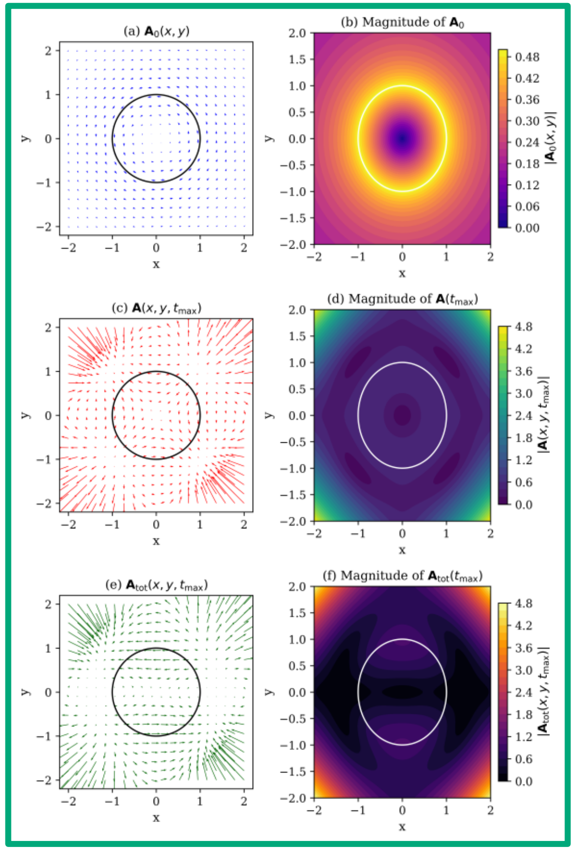
We can study the source of anisotropy which should originate from neutrino interaction with matter around the neutron star

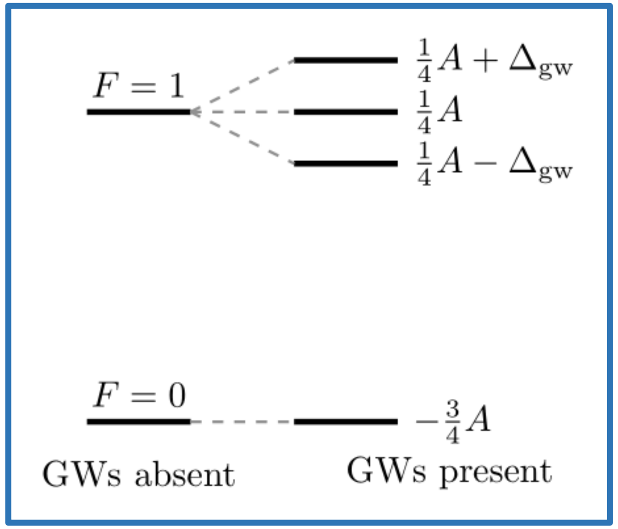
Gravitational waves effect on quantum systems

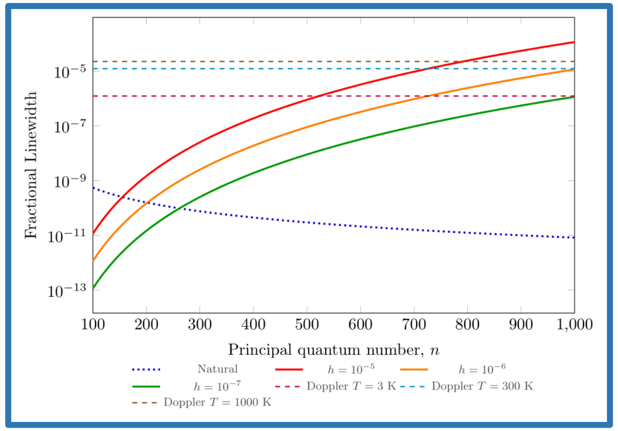
We are exploring GW interaction with systems that produces quantum effects e.g. Spectral broadening, Aharonov-Bohm effect

Goal → alternative GW detection

- GW – Spectral broadening in Rydberg atoms
- GW – Geometric phase of fermions
- GW – Rydberg EIT







Loop correction & Sterile neutrino

The distributioin in previous slides would have changed if:

- eV scale sterile neutrino e.g.

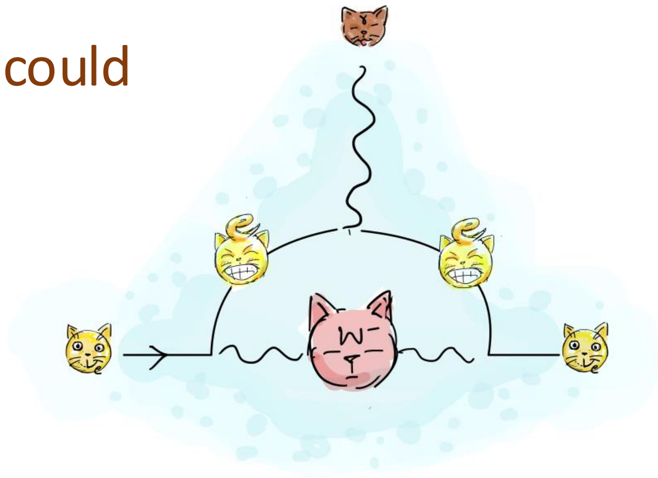
$$\mathcal{L}_{\text{type I}} = \mathcal{L}_{SM} + i\bar{N}\gamma^{\mu}\partial_{\mu}N - \left(\frac{1}{2}\overline{N^{c}}MN + \bar{l}Y_{\nu}\tilde{H}N + h.c.\right)$$

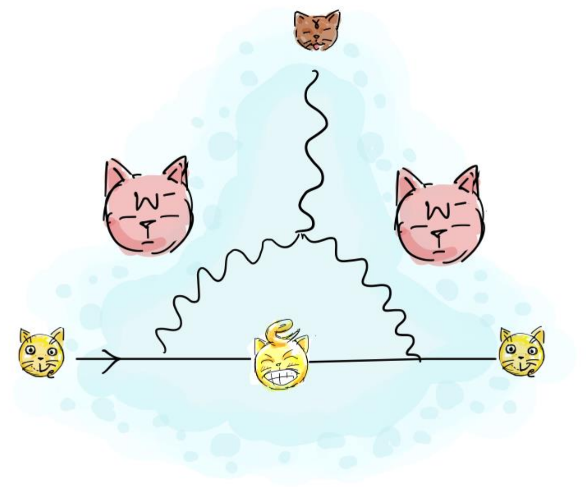
Compute effective action and include in simulation? A better constraint on sterile neutrino

- Some loop correction effect

matter around newly form neutron star could be highly magnetized

  - Electroweak Hall effect
  - Existence of sterile neutrino
    $\rightarrow$ μ_B/μ_p of neutrino larger could be measure in experiment
    [Carlo Giunti, et al. 2015]





Summary

- Supernova simulation is very hard to produce due to produce: need powerful computation power
- NMO and IMO can be infered from SN signal
- We can simulate pre-SN and SN signal in detectors using SNEWPY: using other people simulated data as well
- We plan to include more models into the JUNO framework
- Matching ν-signal & GW signal is interesting
- To include the effect of sterile neutrino … need to contact people that produce SN simulation

Reference

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Q&A