Long-term multi-messenger signal simulation of a supernova

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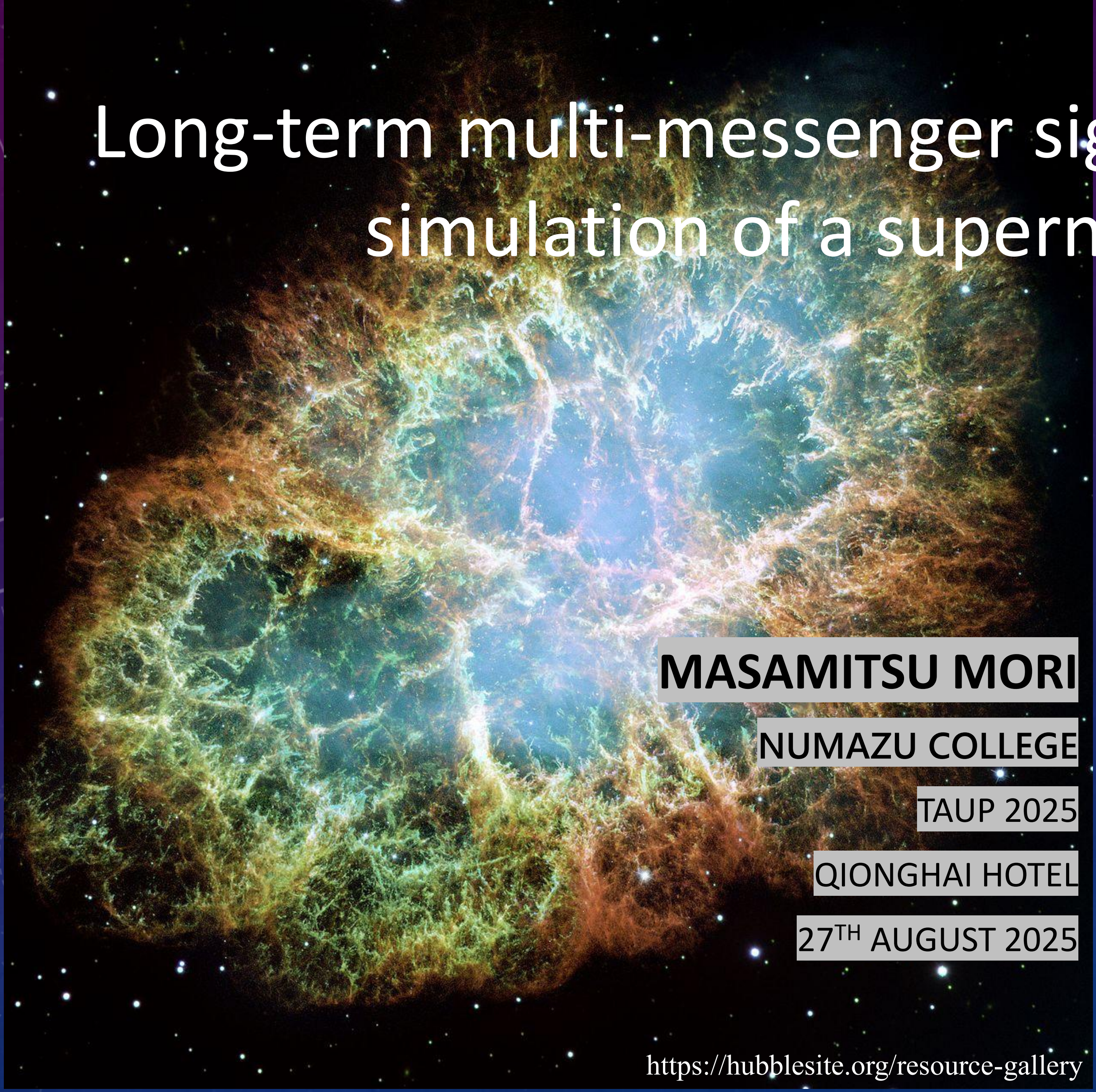


https://hubblesite.org/resource-gallery

Contents

1. Long-term simulation of supernova neutrino
2. Neutrino signals on earth
3. Gravitational waves
4. Supernova axions

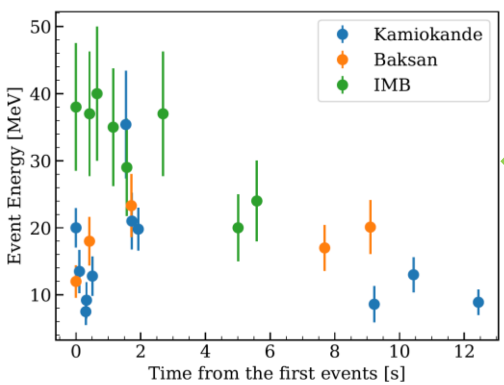
Keywords

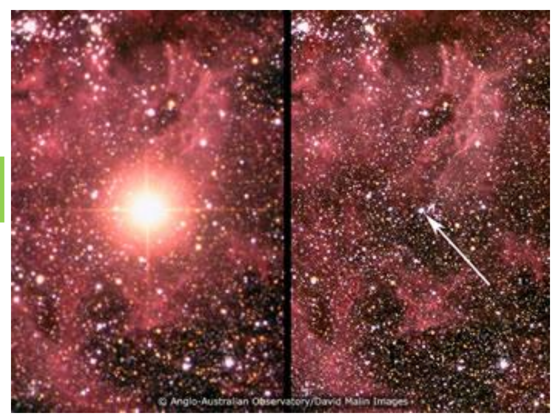
Supernova neutrino, Super-Kamiokande, Neutrino observation

Supernova and multi-messenger signals

- Huge explosion of heavy stars at their death
  - Most promising multi-messenger objects
- 99% of energy released as neutrinos
- Multi-Dimensional effects emit gravitational waves
- Possibility to produce beyond standard model particles.
  - Axions, sterile neutrinos.

Neutrinos





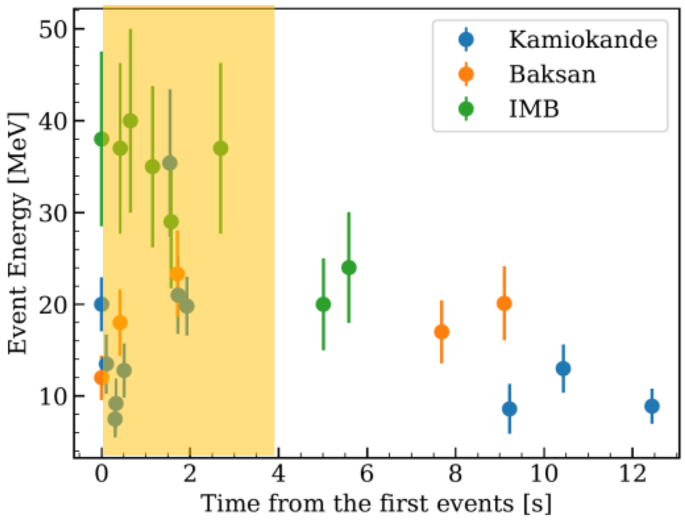
Axion?

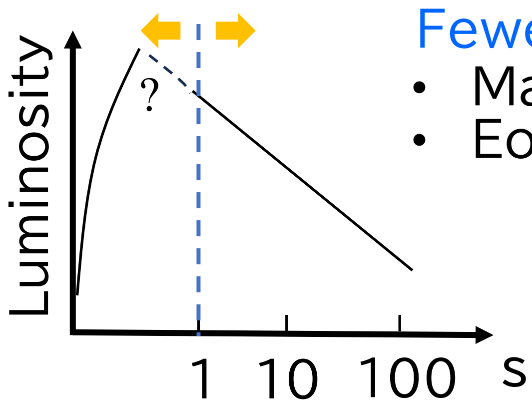
Gravitational waves

Why long-term simulation needed?

1. Observe neutrinos over 10 s from galactic supernovae
2. Clear signals in the late phase
3. Long-term includes short-term

Many Multi-D simulation



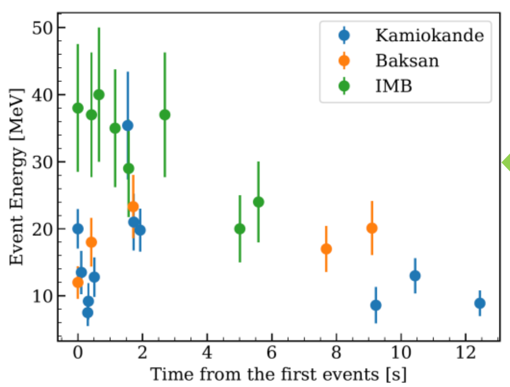


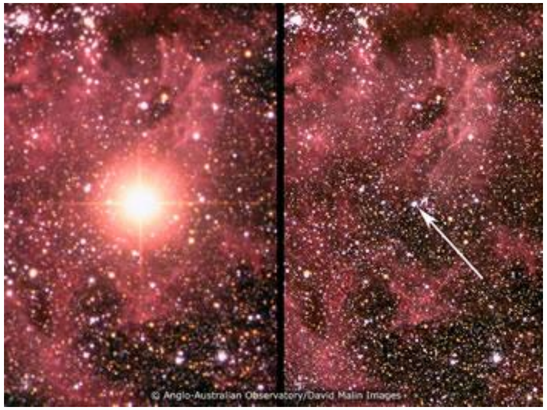
Fewer uncertainties (>1s)

- Mass
- EoS

Supernova and multi-messenger signals

Neutrinos





Axion?

Gravitational waves

Supernova simulation settings

- Simulator: GR1D
    1. General relativity
    2. Moment scheme
    3. 1D
- Progenitor
    - Mass 9.6Msun
    - Explode in 1D
- Equation of state
    - Based on Mean field theory

Neutrino interactions

Charged current reactions

$$\nu_e + n \leftrightarrow p + e^-$$

$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

$$\nu_e + (A,Z) \leftrightarrow (A,Z+1) + e^-$$

Neutral current reactions

$$\nu + e^- \longrightarrow \nu + e^-$$

$$\nu + \alpha \longrightarrow \nu + \alpha$$

$$\nu + p \longrightarrow \nu + p$$

$$\nu + n \longrightarrow \nu + n$$

$$\nu + (A,Z) \longrightarrow \nu + (A,Z)$$

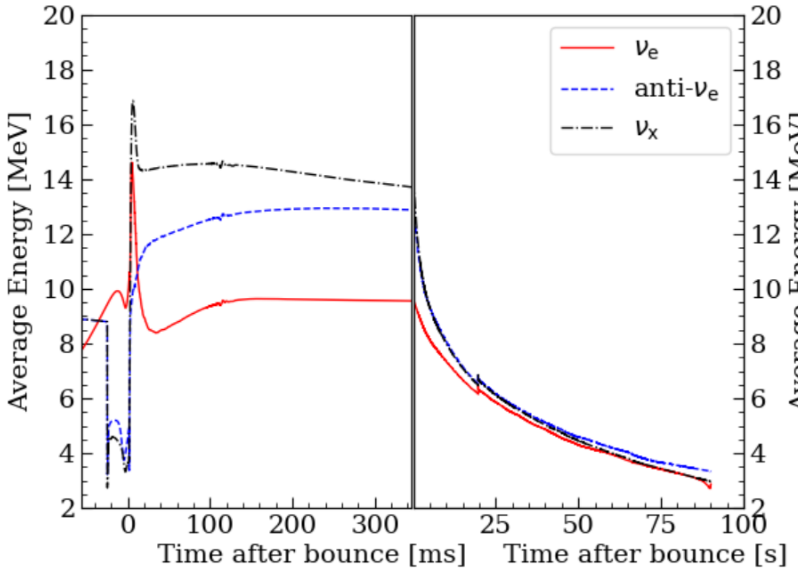
Thermal reactions

$$e^- + e^+ \longrightarrow \nu + \bar{\nu}$$

$$N + N \longrightarrow N + N + \nu + \bar{\nu}$$

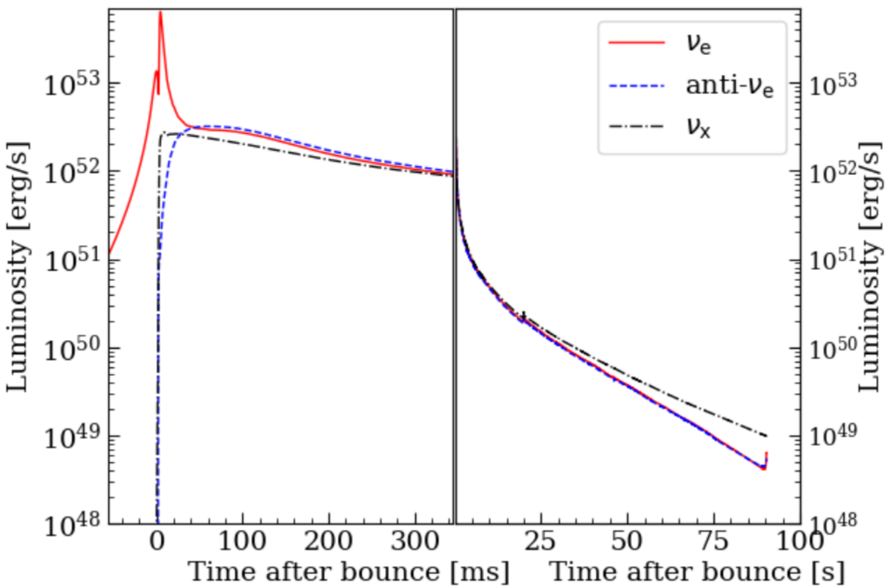
Long–term supernova neutrino simulaiton

Neutrino average energy



ν_x : μ and τ (anti) neutrinos

Neutrino luminosity

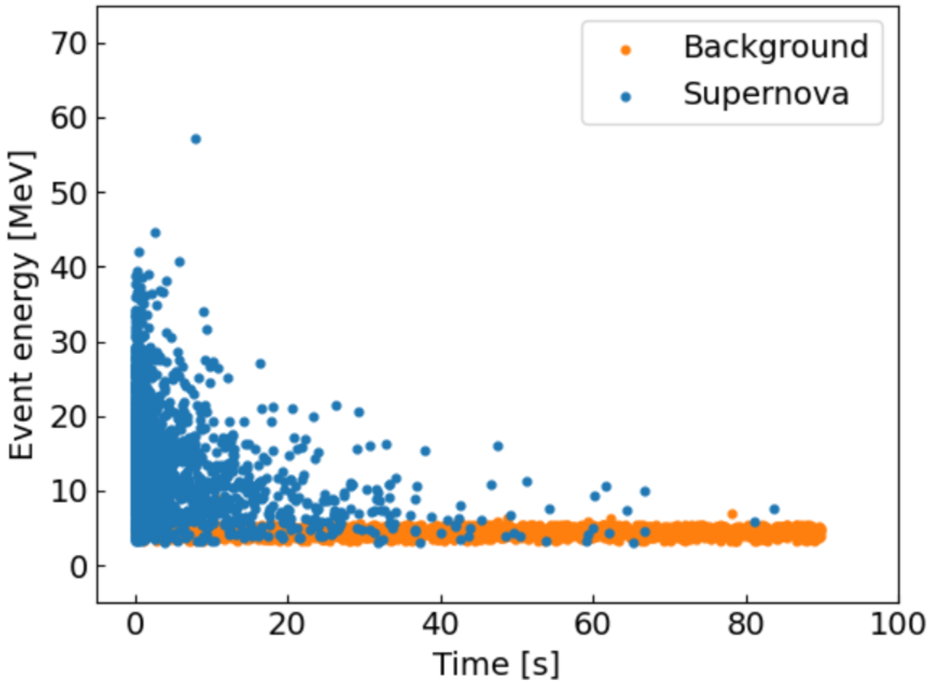


Mori et al. 2021

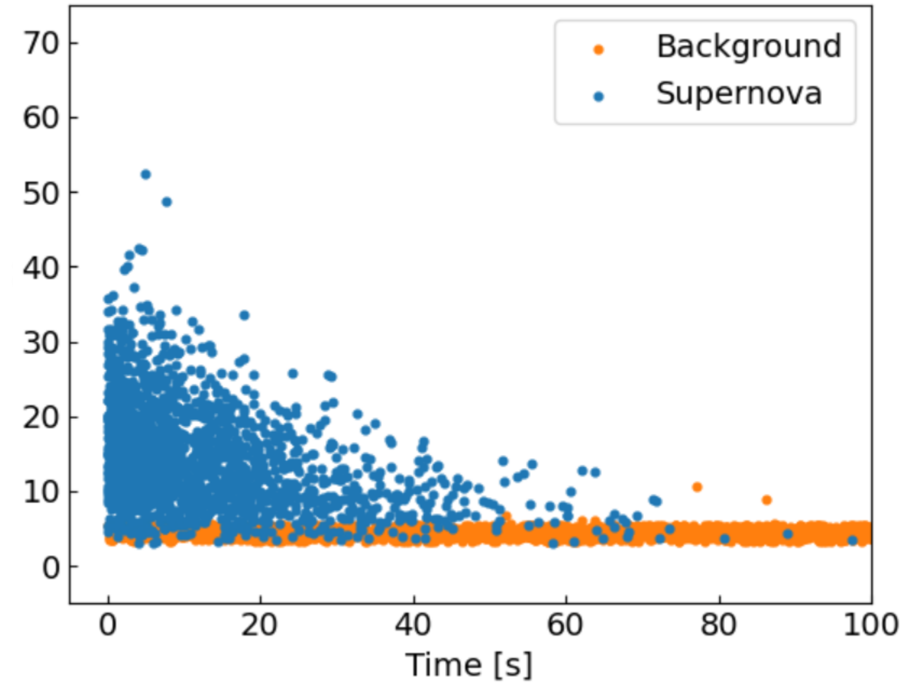
- Up to 90 seconds
  - Longest general relativistic neutrino radiation hydro simulation

Mock samples

Simulation



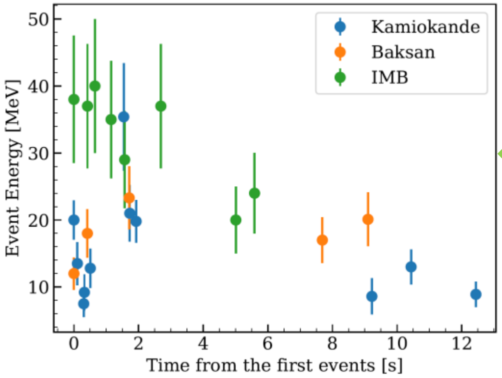
Analytic formula

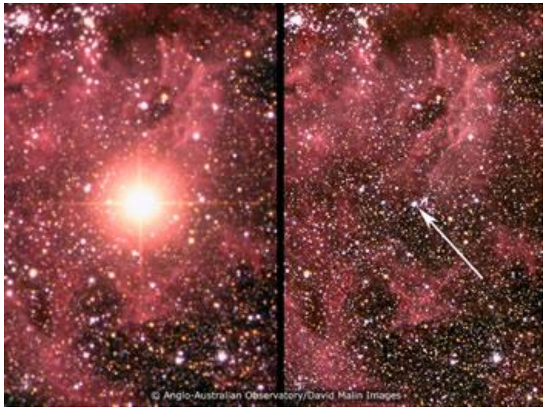


- Assumed a supernova occurs at 10 kpc away
  - Several events after 1 min.
- Analytic formula on the right
  - Suwa et al. (2021)
  - $R(t) = 720\mathrm{s}^{-1}\left(\frac{M_{\mathrm{det}}}{32.5\ \mathrm{kton}}\right)\left(\frac{D}{10\ \mathrm{kpc}}\right)^{-2}\left(\frac{M_{\mathrm{PNS}}}{1.4M_{\odot}}\right)^{15/2}\left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-8}\left(\frac{g\beta}{3}\right)^{5}\left(\frac{t+t_0}{100\ \mathrm{s}}\right)^{-15/2}$

Supernova and multi-messenger signals

Neutrinos





Axion?

Gravitational waves

Gravitational eigenmodes

- Supernovae also emit gravitational waves.
- Frequencies with the asteroseismology approach.
  - Used GREAT (https://www.uv.es/cerdupa/codes/GREAT/)
  - Torres-Forné et al (2018)
- Linear perturbation analysis both of fluid and metric.
- Use the 9.6$M_\odot$ result in post-process

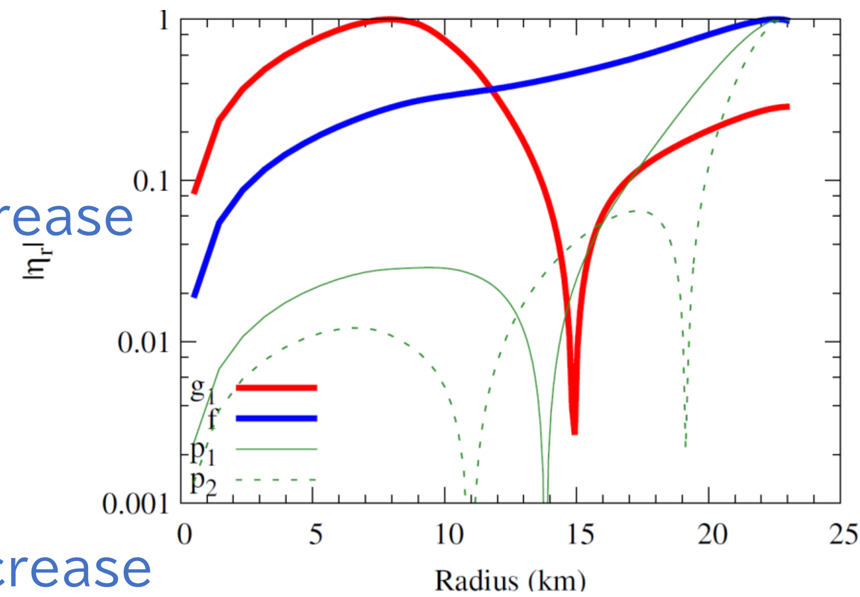
- Linear perturbation equations

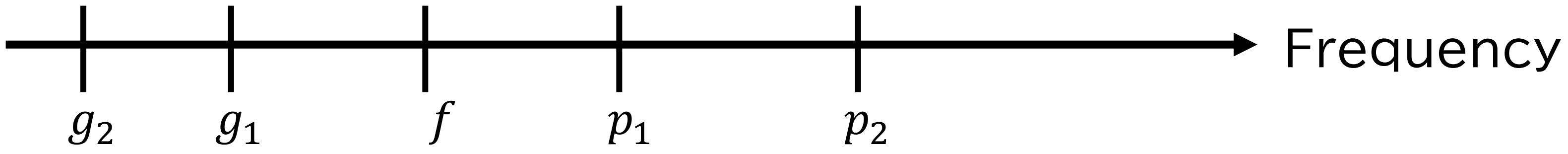
$$\partial_r \eta_r + \left[\frac{2}{r} + \frac{1}{\Gamma_1}\frac{\partial_r P}{P} + \frac{\partial_r \psi}{\psi}\right]\eta_r + \frac{\psi^4}{\alpha^2 c_s^2}\left(\sigma^2 - \mathcal{L}^2\right)\eta_\perp = \frac{1}{c_s^2}\frac{\delta\hat{Q}}{Q} - \left(6 + \frac{1}{c_s^2}\right)\frac{\delta\hat{\psi}}{\psi},$$

$$\partial_r \eta_\perp - \left(1 - \frac{\mathcal{N}^2}{\sigma^2}\right)\eta_r + \left[\partial_r \ln q - \mathcal{G}\left(1 + \frac{1}{c_s^2}\right)\right]\eta_\perp = \frac{\alpha^2}{\psi^4\sigma^2}\left[\partial_r(\ln\rho h)\left(1 + \frac{1}{c_s^2}\mathcal{G}\right)\right]\left(\frac{\delta\hat{Q}}{Q} - \frac{\delta\hat{\psi}}{\psi}\right),$$

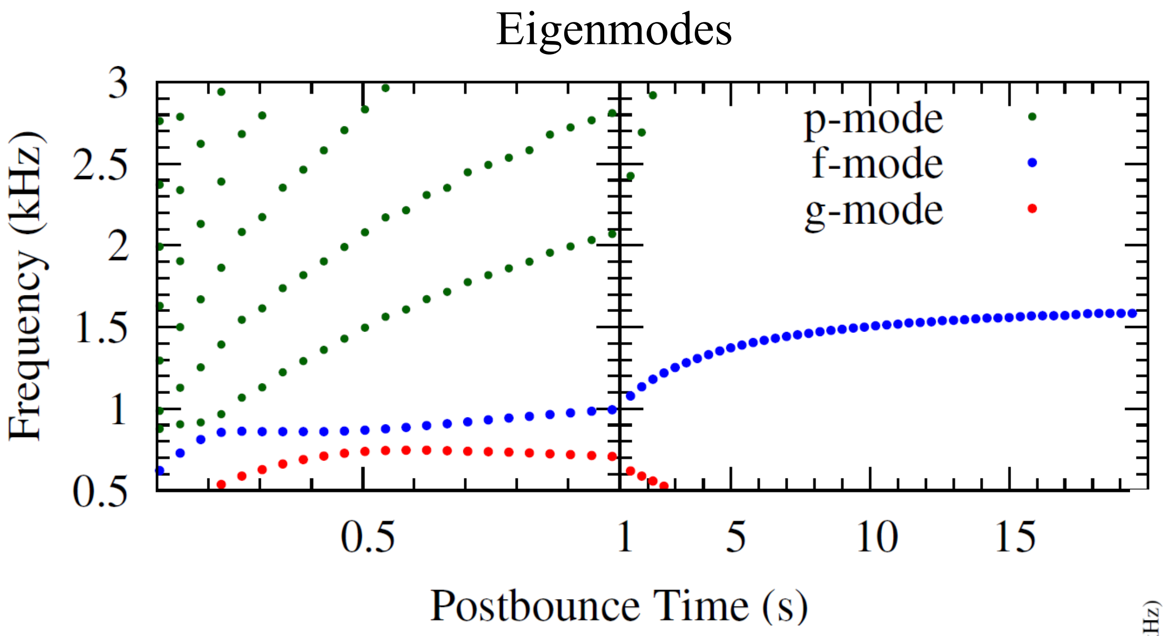
Types of oscillation modes

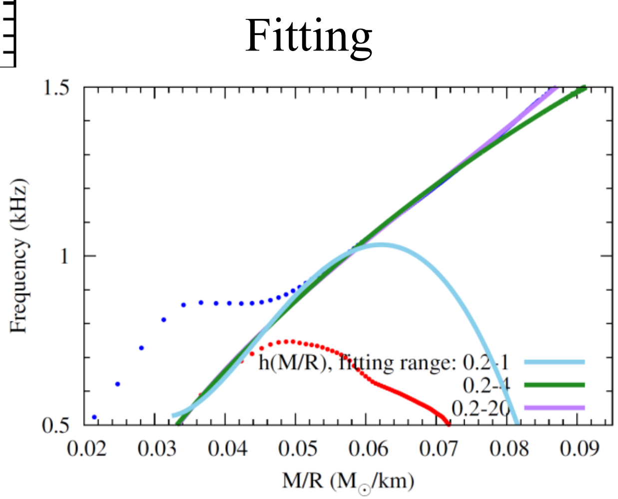
- p_i-mode
  - "i" is the number of nodes
  - Restoring force: pressure
  - Frequencies increase as nodes increase
- f-mode
  - Fundamental mode of the p-mode
- g_i-mode
  - Restoring force: buoyancy
  - Frequencies decrease as nodes increase





Gravitational wave frequency (Mori et al. Phys.Rev.D 107 (2023) 8, 083015)

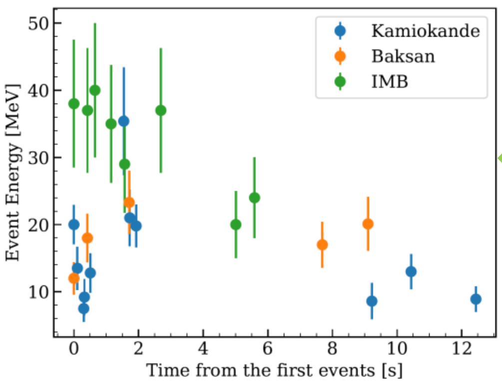


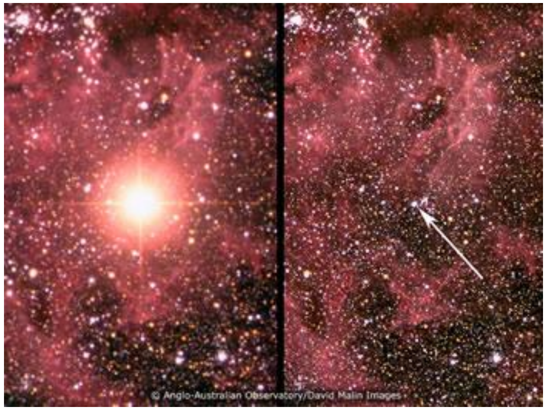


- Calculated eigenfrequencies up to 20 seconds.
- Differences of frequencies increase with time.
- We developed the fitting.

Supernova and multi-messenger signals

Neutrinos





Axion?

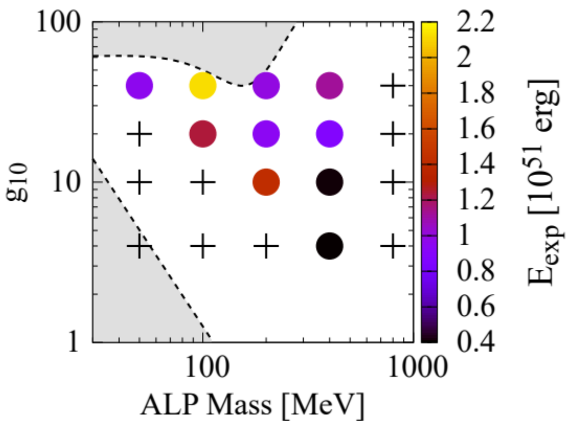
Gravitational waves

Supernova with Axions

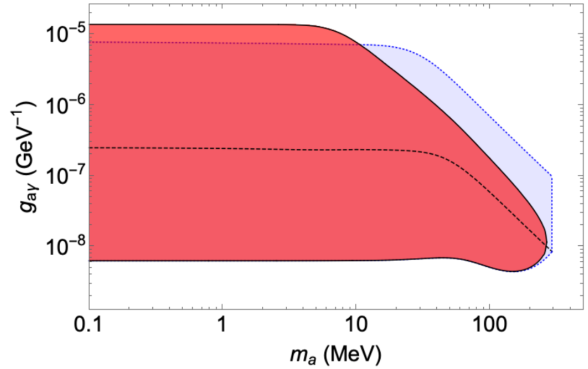
- Axions are a type of beyond standard model particles

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu}$$

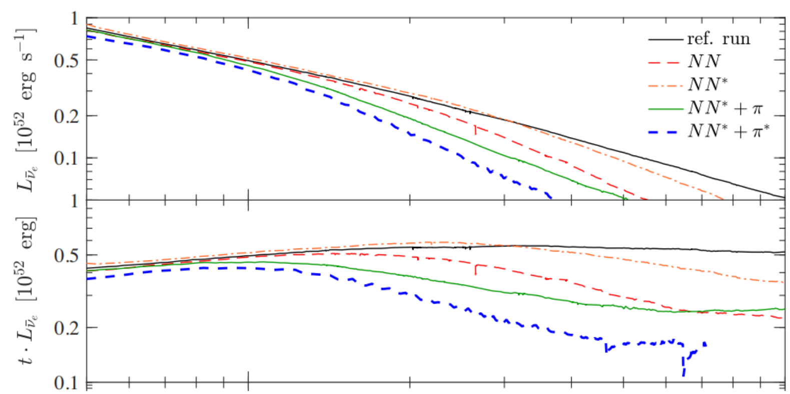
- Possibility to assist supernova explosions.
- Decrease neutrino emission



K.Mori et al. (2022)
Constraint due to explosion including axions



G. Lucente et al. (2020)
Constraint from SN1987A



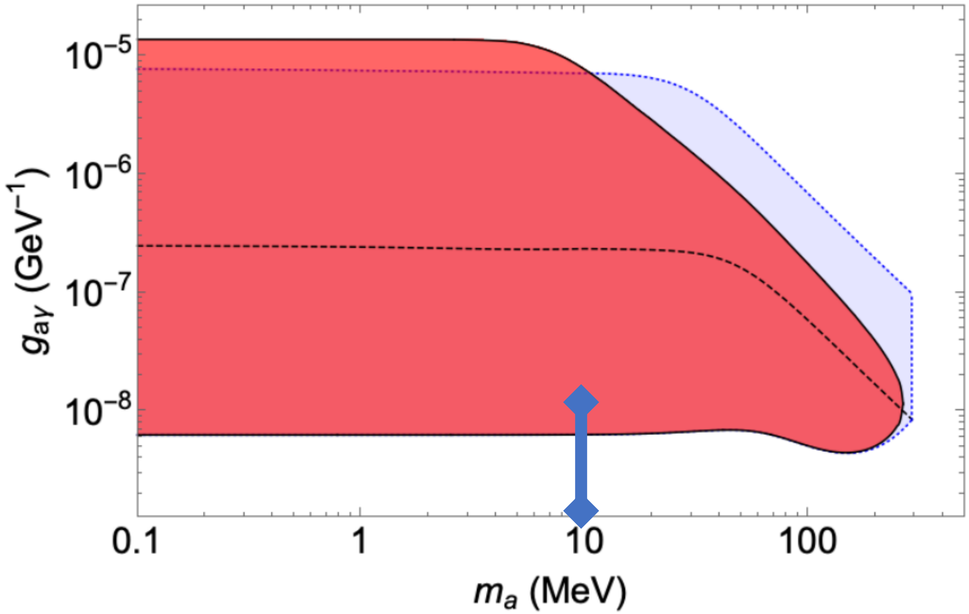
T. Fischer et al. (2021)
Long-term simulation

Axion setting

- Axions coupling with matter via photons

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu}$$

- Installed into the supernova simulation (GR1D)
- Mass:10MeV
- Coupling constant: $g_{a\gamma} = \frac{g_{10}}{10^{-10}} = 10 \sim 70\ [10^{-10}\mathrm{GeV}^{-1}]$



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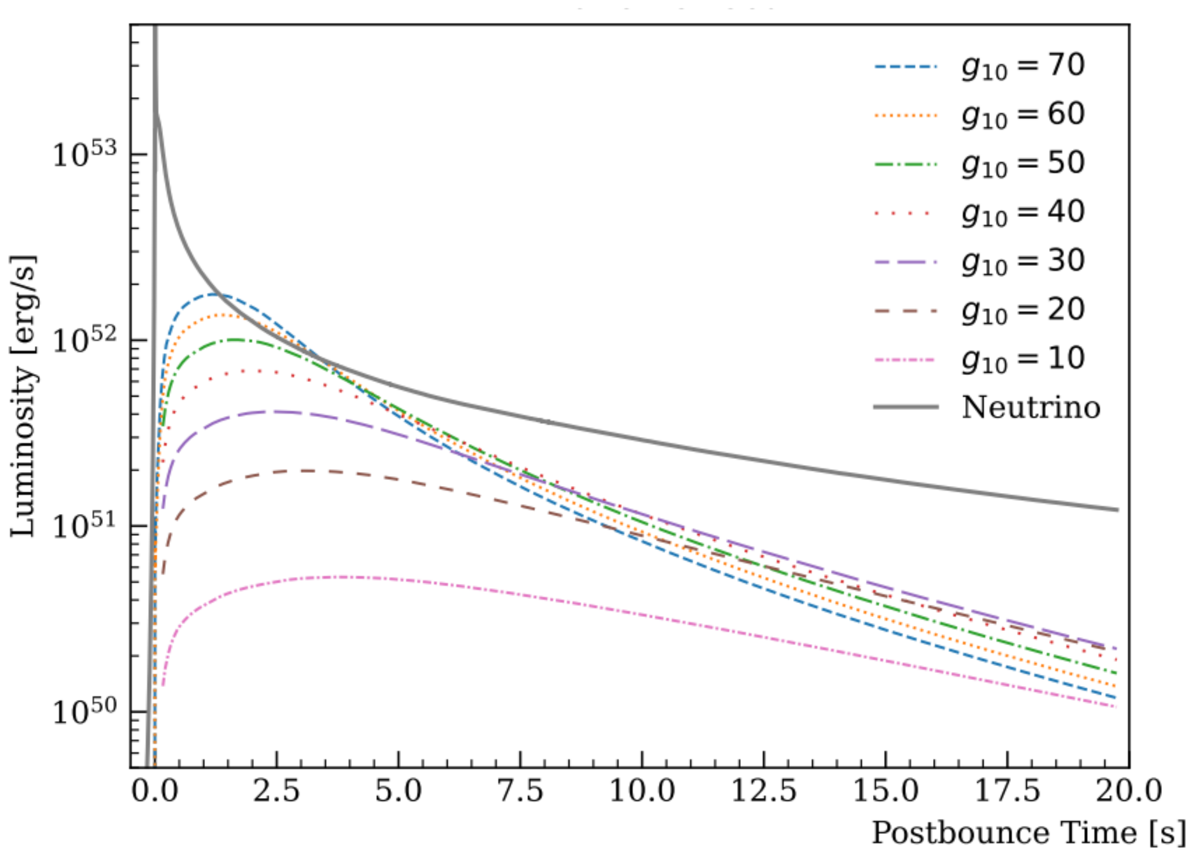
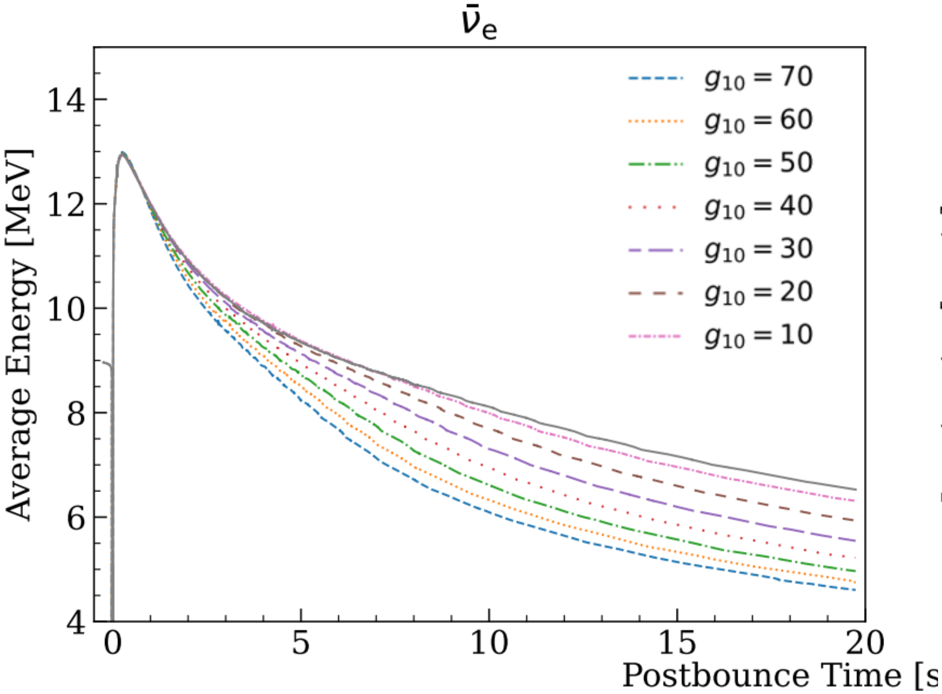
Axion Emission



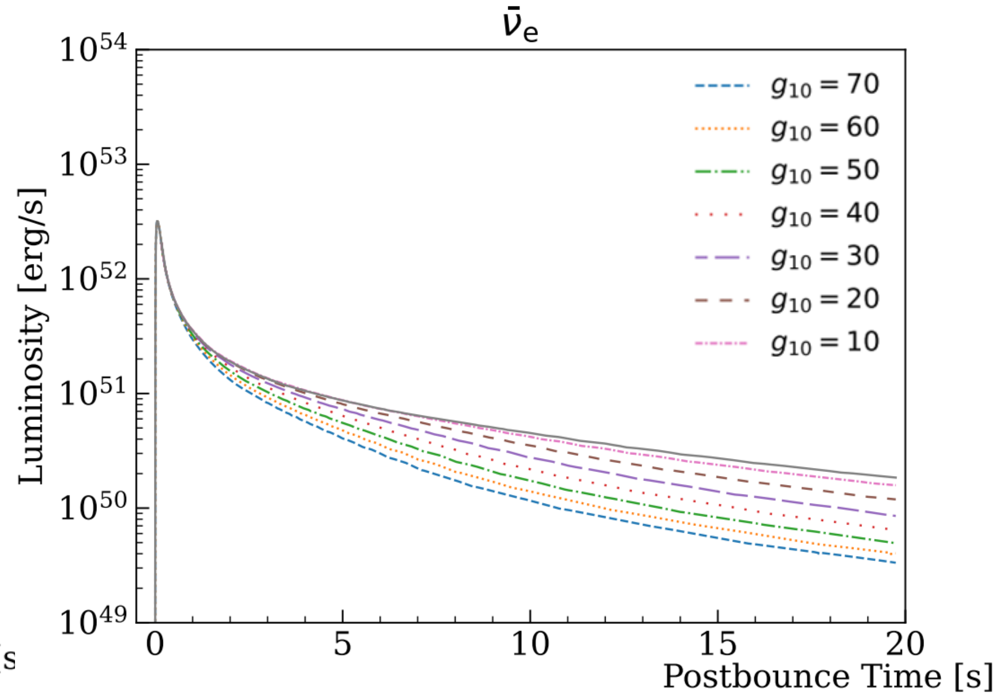
- 9.6 Msun
- Up to 20s
- Two axion models predicts higher axion luminosities than neutrinos

Neutrino emission with axions

Average Energy

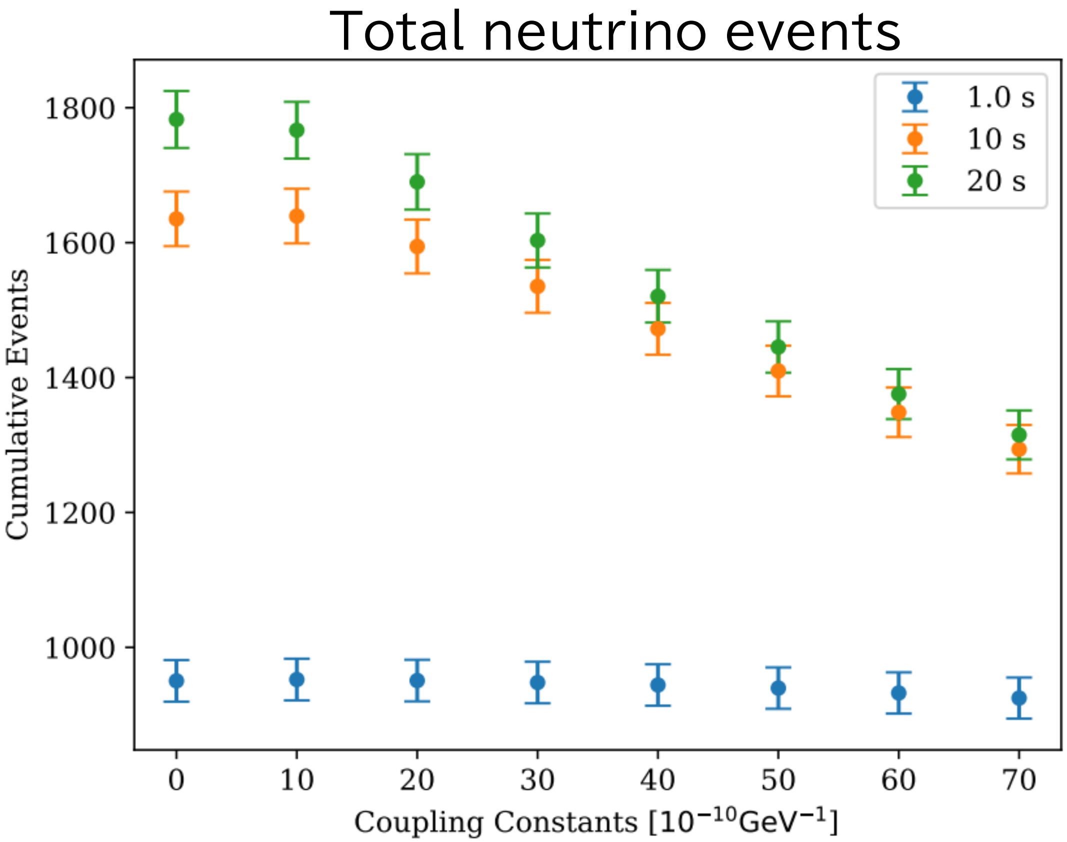


Luminosity



- Axions decrease neutrino energy
  - Implies that supernovae neutrinos provide axion information.

Axion search from supernova neutrinos

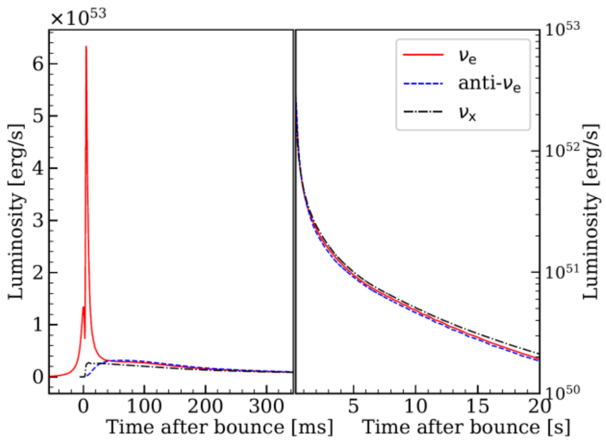


- 10kpc with Super-kamiokande
- Errorbars: 1σ
- At 1s, no difference
- After 10s, possibility to detect axions

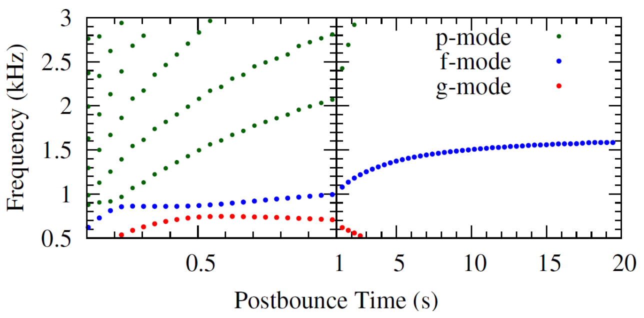
Summary

- Supernovae are promising multi-messenger targets.
- Established the long-term multi-messenger signals
  - Neutrinos
  - Gravitational waves
  - Axions

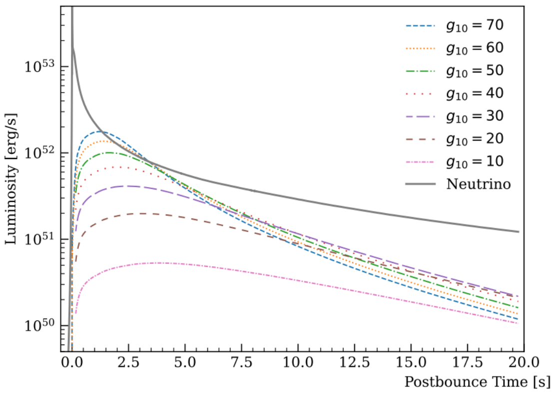
Neutrino



Gravitational waves



Axions

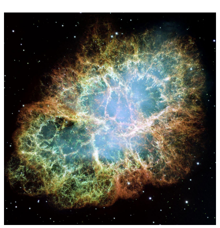


Neutrino signals on earth

Developing new software

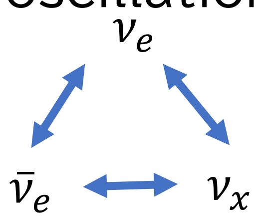
- FORcasting Events from Supernovae Theoretical modeling (FOREST)

- Simulates how signals of supernovae look like on earth
- Mock Samples are used for analysis practice and detector evaluation.

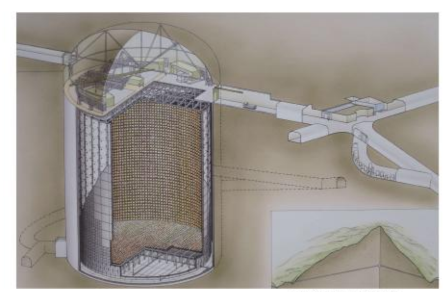


ν

Neutrino oscillation



Super-Kamiokande



Supernova evolution