Integrated strategic framework on supernova theory and their multi-messenger observations

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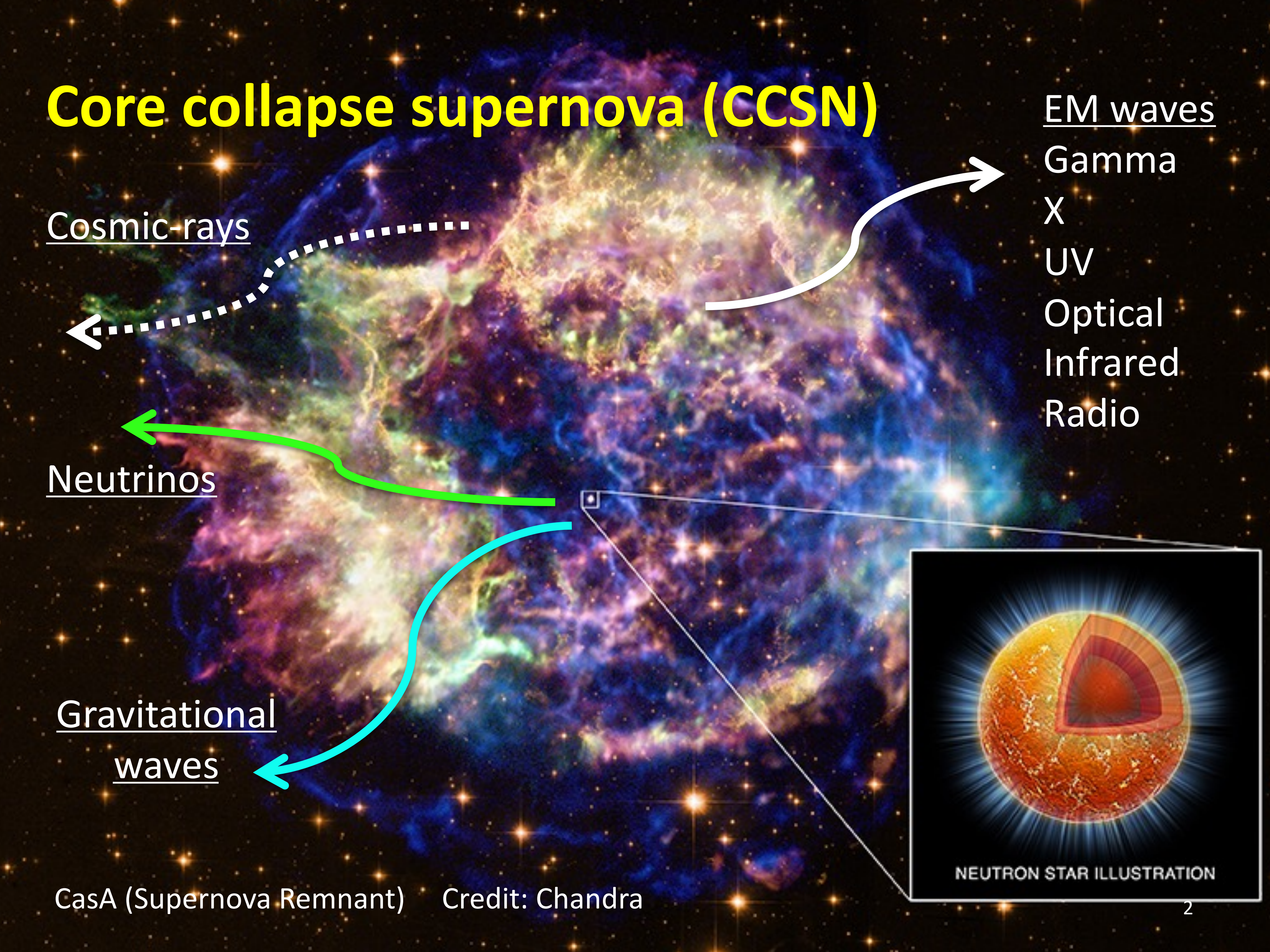
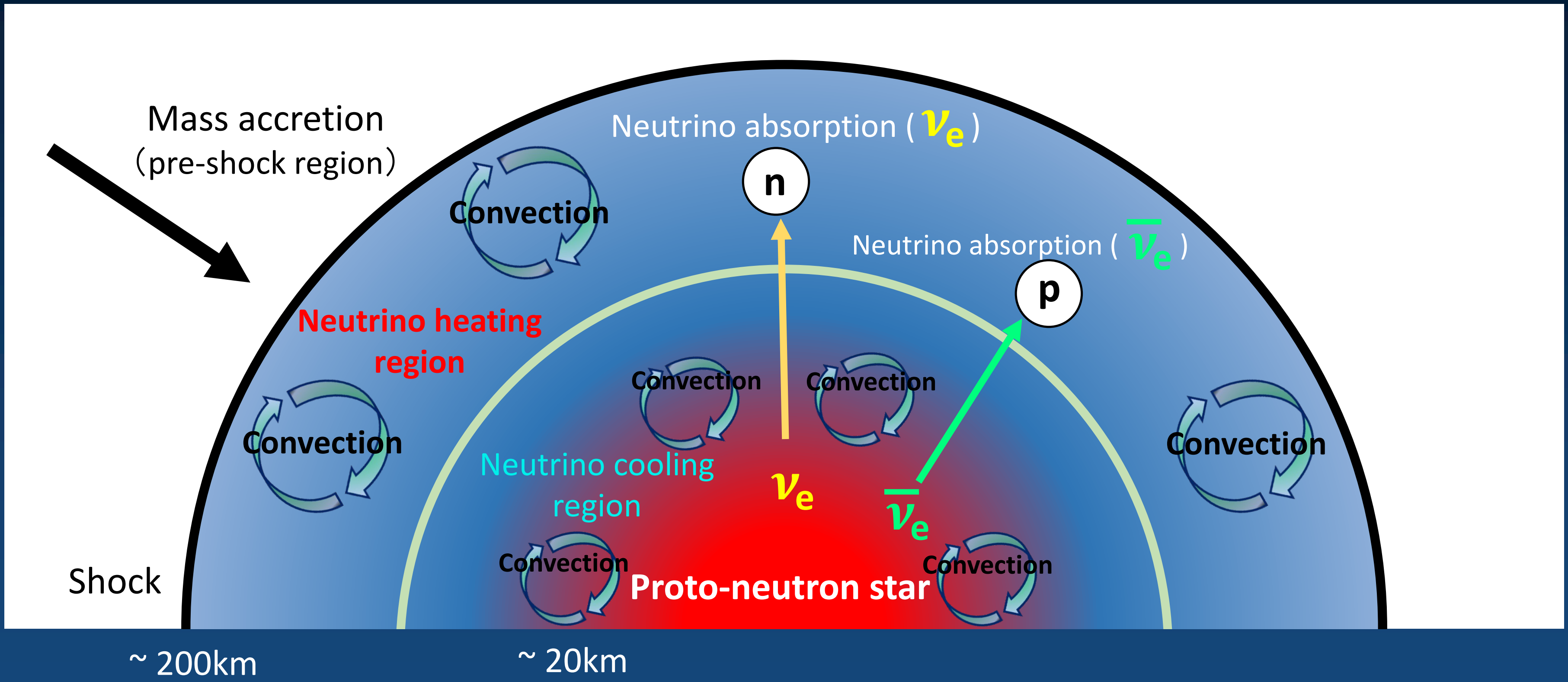
Core collapse supernova (CCSN)

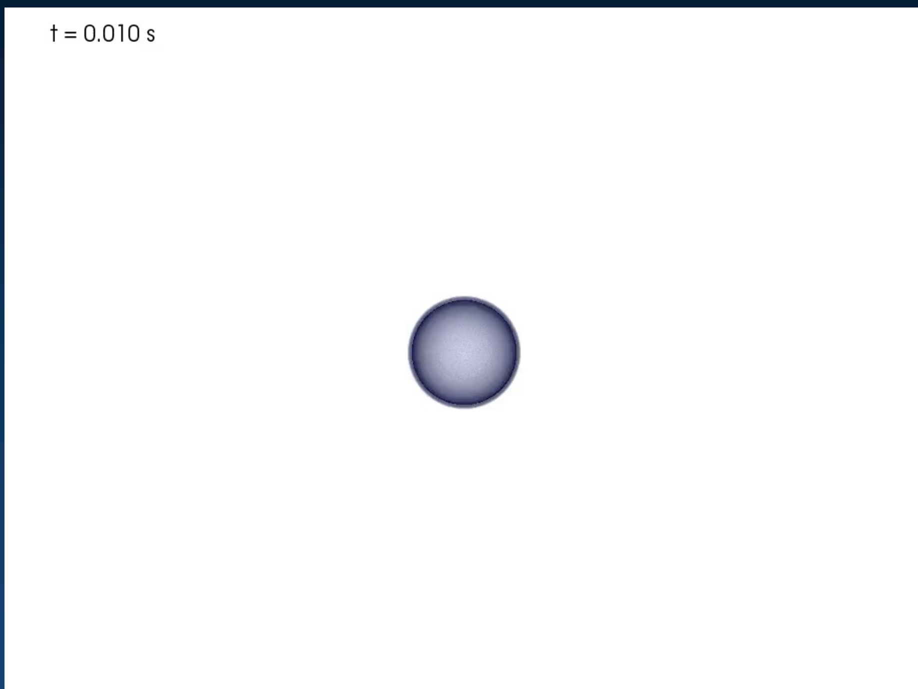


CasA (Supernova Remnant) Credit: Chandra

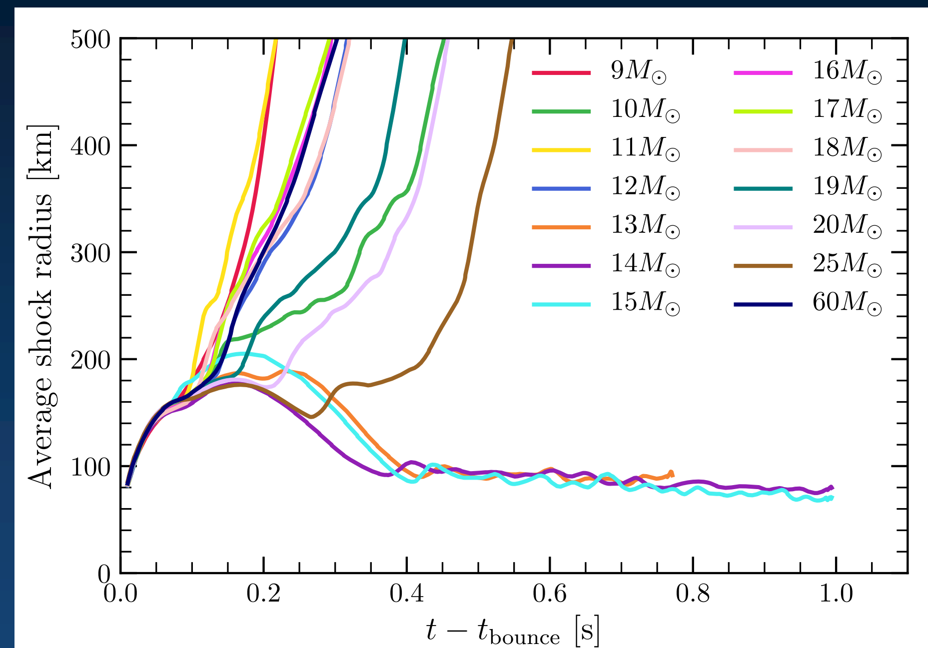
Neutrino-driven explosion mechanism
(aided by multi-dimensional fluid instabilities)



Explosions have been witnessed
more often than not in 3D CCSN simulations



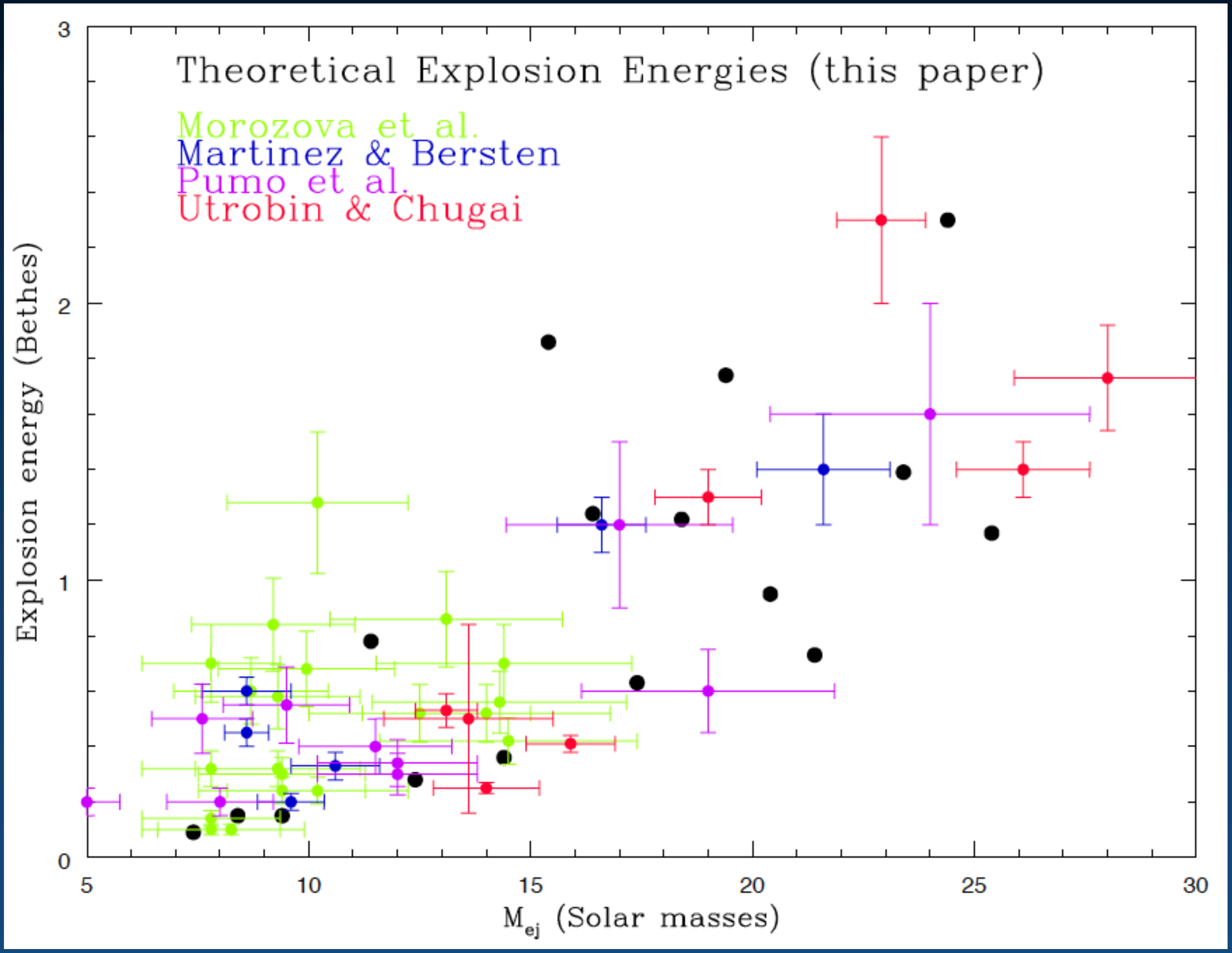
Nagakura et al. 2019



Burrows et al. 2020

Explosion energy

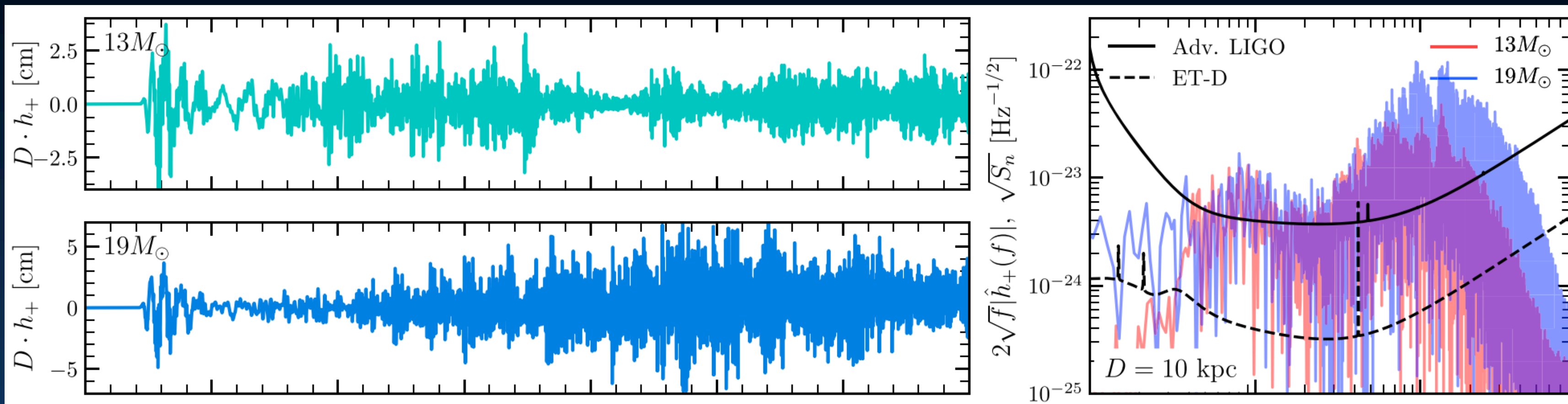
(comparing between multi-D CCSN simulations and observations)



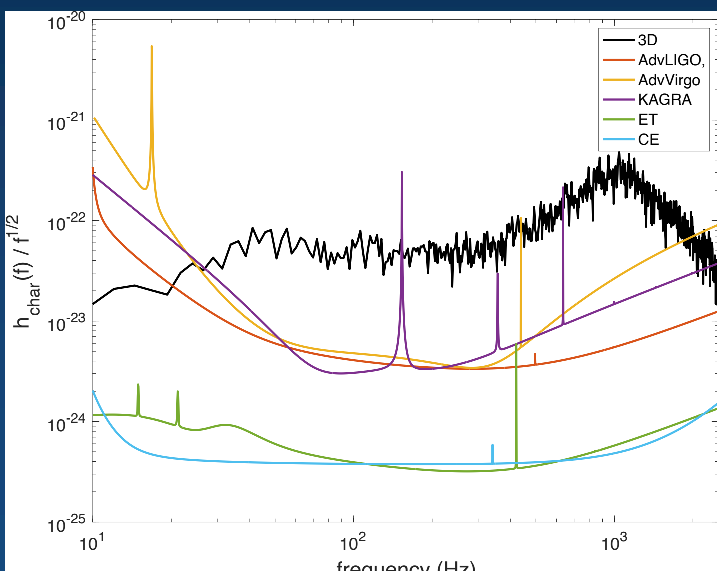
Burrows and Vartanyan 2021

Gravitational Waves

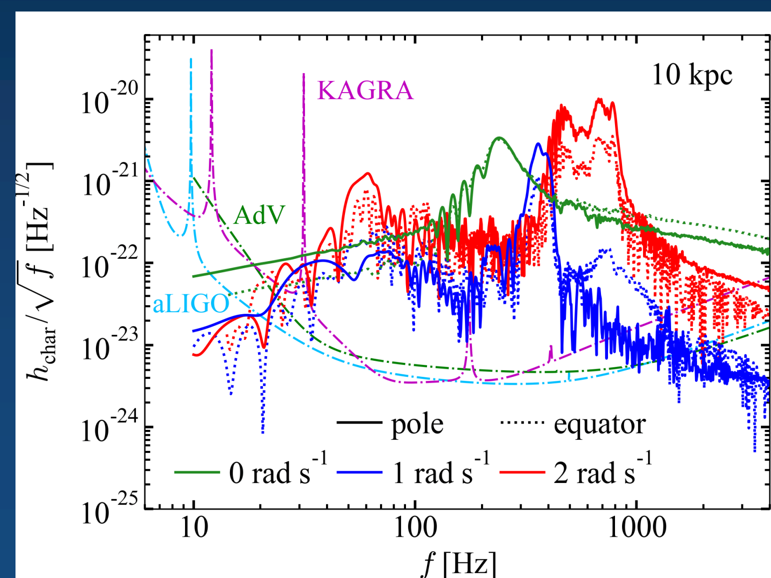
Radice et al. 2019



kHz



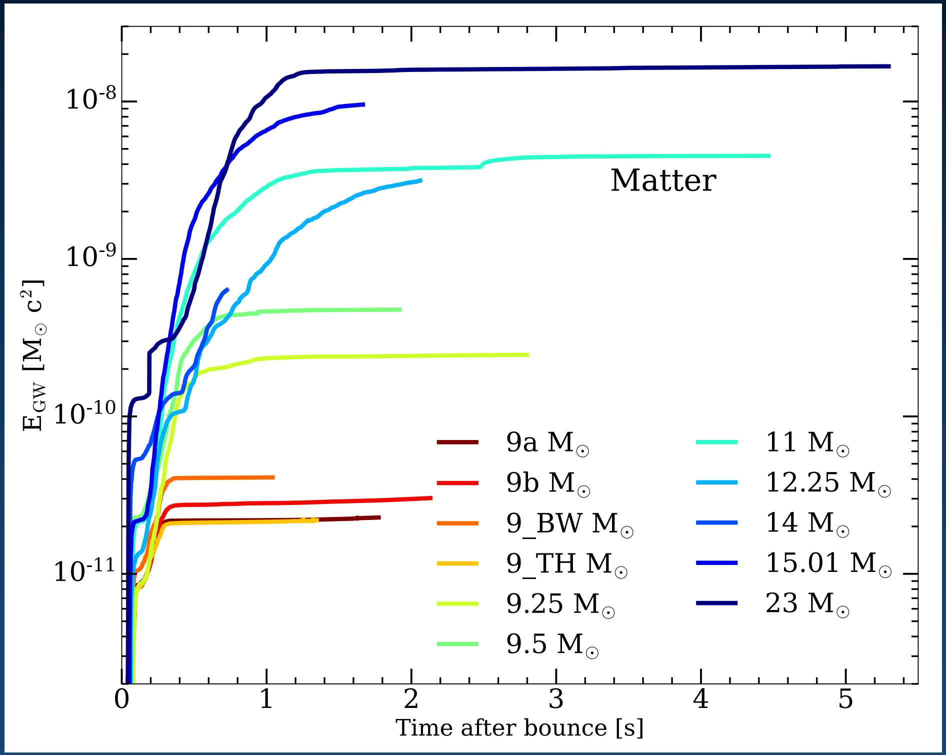
Mezzacappa et al. 2020



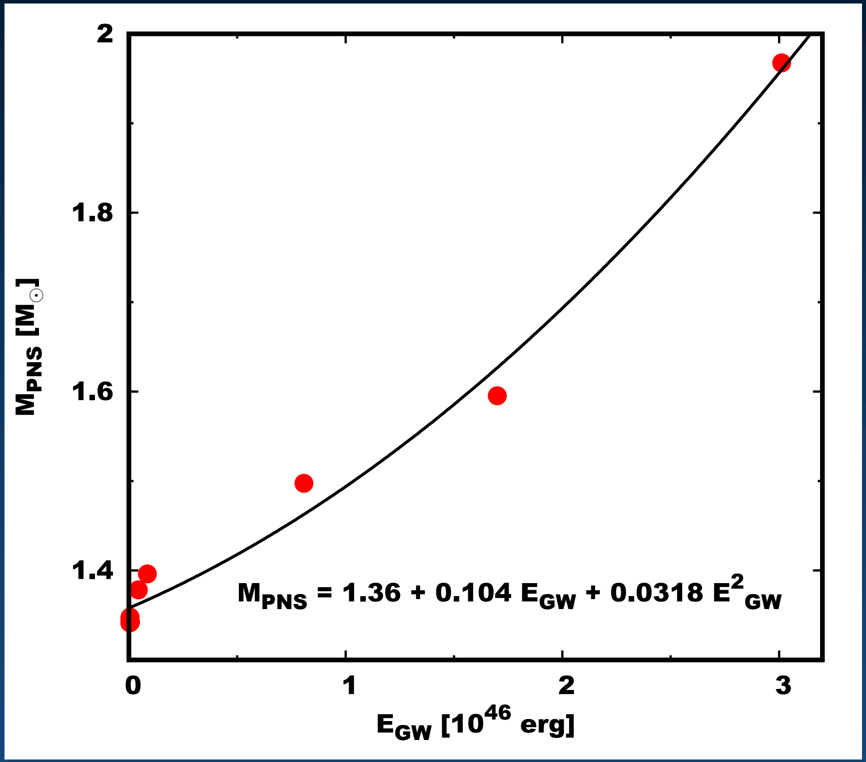
Shibagaki et al. 2021

Gravitational Waves

Strong correlation between GWs and Proto-neutron star mass

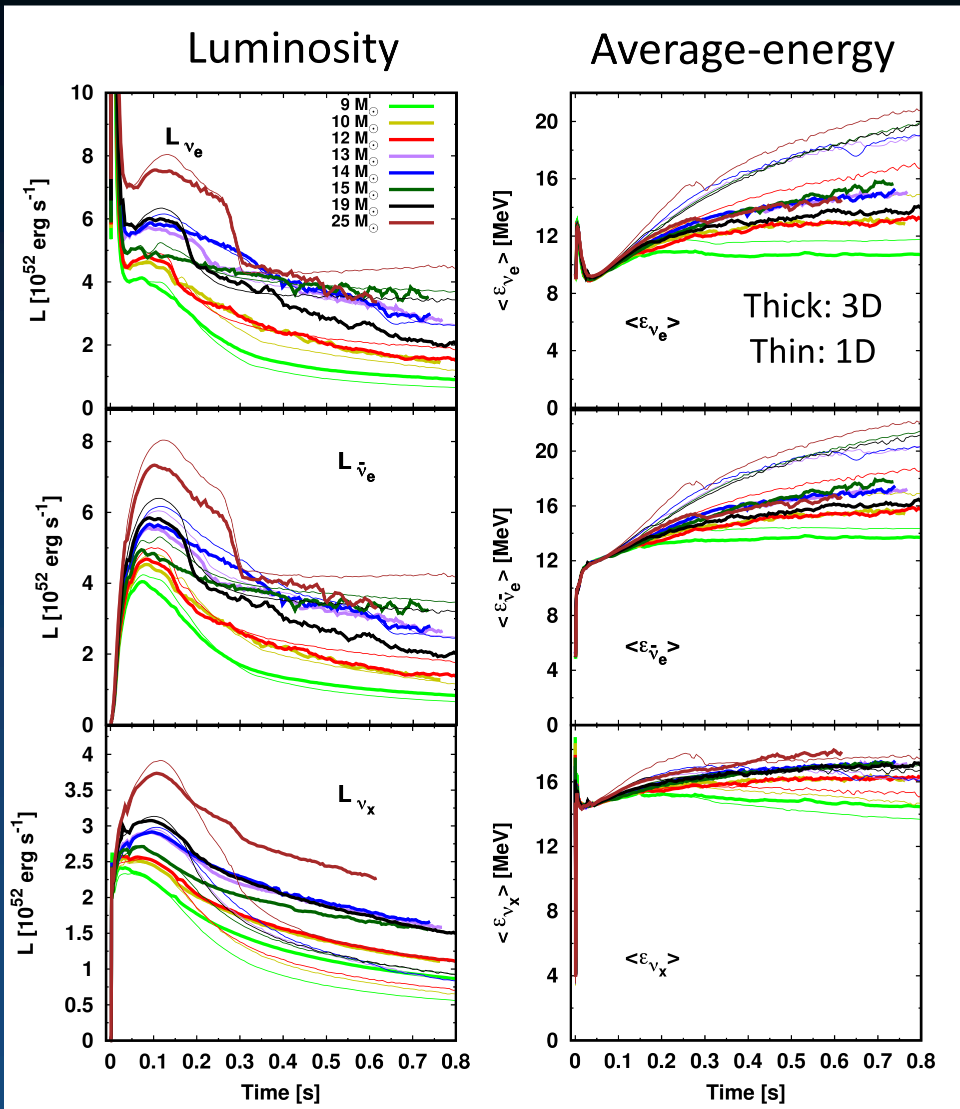


Vartanyan et al. 2023



Nagakura and Vartanyan 2023

Neutrino signals



Nagakura et al. 2021

Some new features emerge in 3D explosion models

1. Explosion models have low neutrino luminosity than those with non-explosions (due to weak mass accretion)

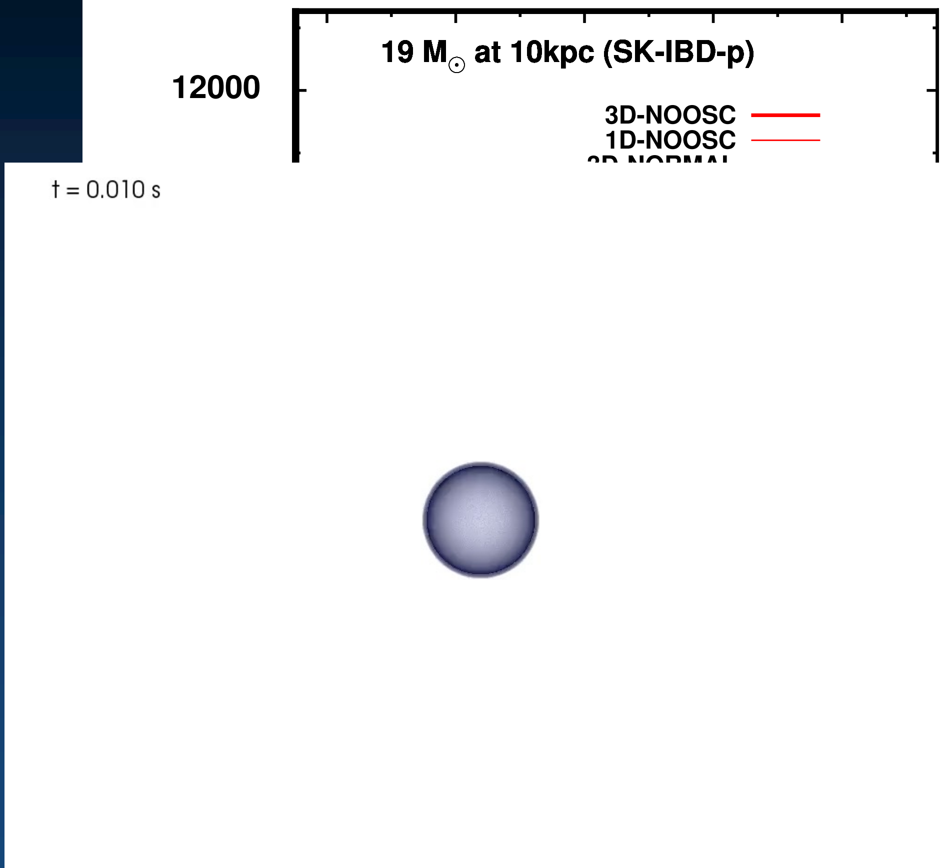
2. The average energy of electro-type neutrinos and their anti-partners are lower in 3D than 1D.

3. Neutrino luminosity of heavy-leptonic neutrinos are higher in 3D than 1D. (due to PNS convection)

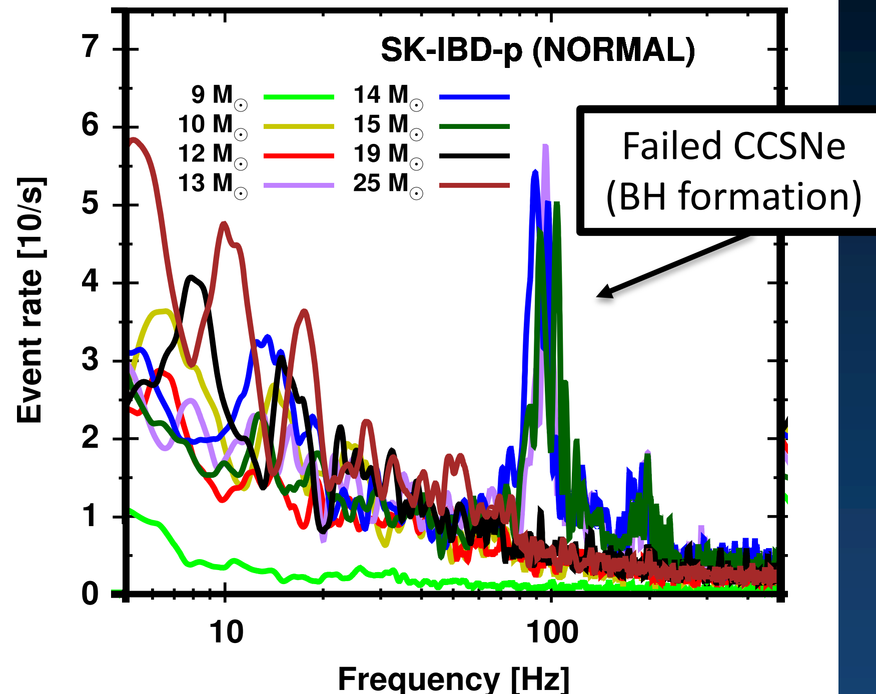
Useful formula: $$\frac{L_{\nu 3D}}{L_{\nu 1D}} \sim \frac{\mathrm{T}^4_{\nu 3D}\mathrm{R}^2_{\nu 3D}}{\mathrm{T}^4_{\nu 1D}\mathrm{R}^2_{\nu 1D}}$$

Detector simulations of neutrino signal for Super-K (Hyper-K)

Detection rate of neutrinos (SN@10kpc)



Fourier spectrum of time variability



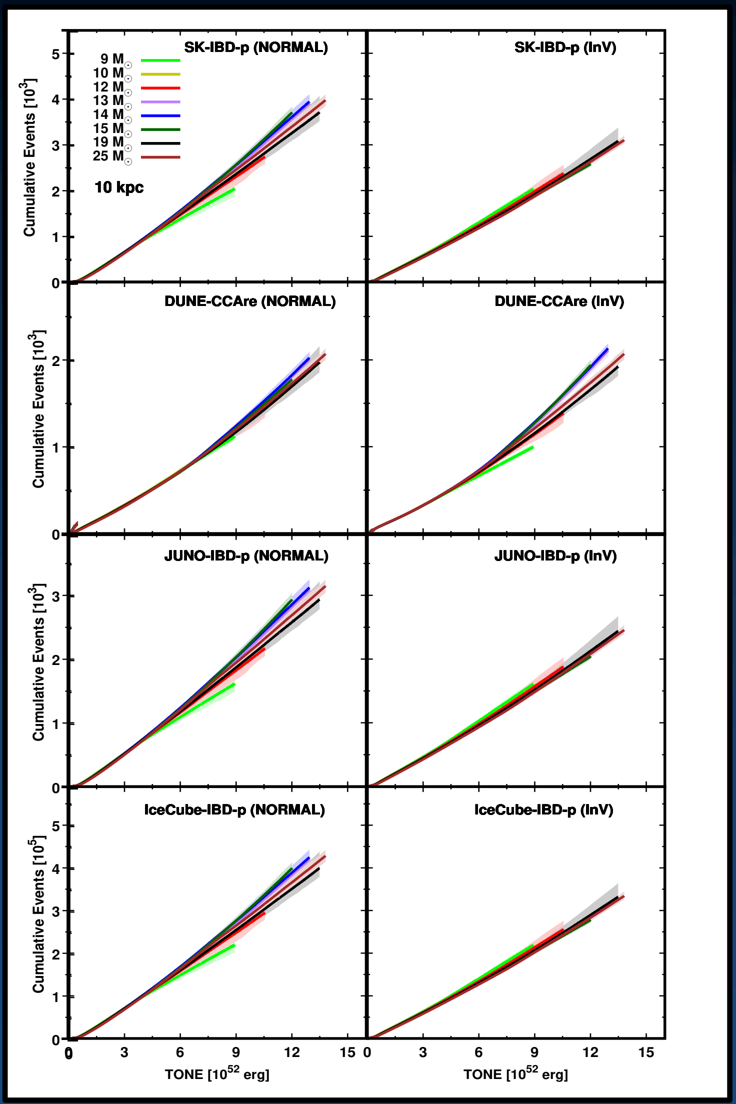
Nagakura et al. 2021

els is different from that in 1D.

2. The information of fluid instability in CCSN core is imprinted in neutrino signal as time variability.

Strong correlation between E_ν and N_{cum} in each detector

Nagakura et al. 2021



$$[\mathrm{SK-IBDp-NORMAL}]$$
$$N_{\mathrm{Cum}} = \left(220\,E_{52} + 5\,E_{52}^2 - 0.074\,E_{52}^3 + 0.0003\,E_{52}^4\right) \left(\frac{V}{32.5\,\mathrm{ktons}}\right)\left(\frac{d}{10\,\mathrm{kpc}}\right)^{-2},$$

$$[\mathrm{DUNE-CCAre-NORMAL}]$$
$$N_{\mathrm{Cum}} = \left(90\,E_{52} + 4.5\,E_{52}^2 - 0.062\,E_{52}^3 + 0.00028\,E_{52}^4\right) \left(\frac{V}{40\,\mathrm{ktons}}\right)\left(\frac{d}{10\,\mathrm{kpc}}\right)^{-2},$$

$$[\mathrm{JUNO-IBDp-NORMAL}]$$
$$N_{\mathrm{Cum}} = \left(165\,E_{52} + 5.1\,E_{52}^2 - 0.082\,E_{52}^3 + 0.00039\,E_{52}^4\right) \left(\frac{V}{20\,\mathrm{ktons}}\right)\left(\frac{d}{10\,\mathrm{kpc}}\right)^{-2},$$

$$[\mathrm{IceCube-IBDp-NORMAL}]$$
$$N_{\mathrm{Cum}} = \left(23000\,E_{52} + 600\,E_{52}^2 - 9\,E_{52}^3 + 0.04\,E_{52}^4\right) \left(\frac{V}{3.5\,\mathrm{Mtons}}\right)\left(\frac{d}{10\,\mathrm{kpc}}\right)^{-2},$$

E_ν has a strong correlation to M_{PNS}

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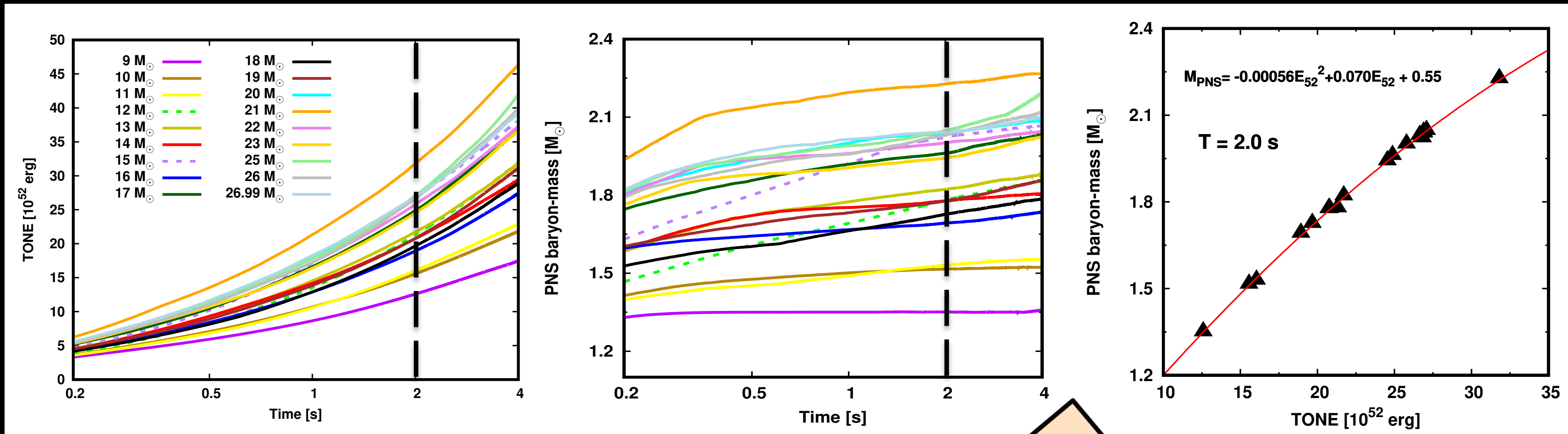
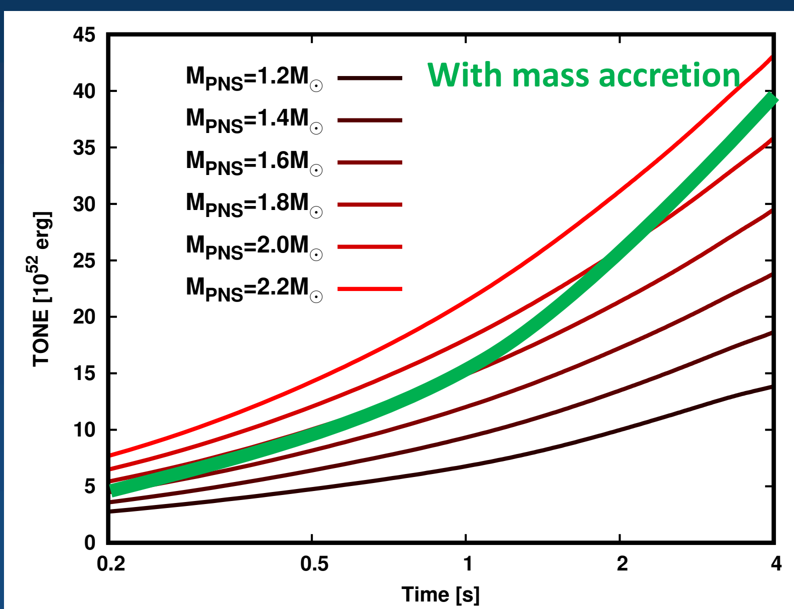
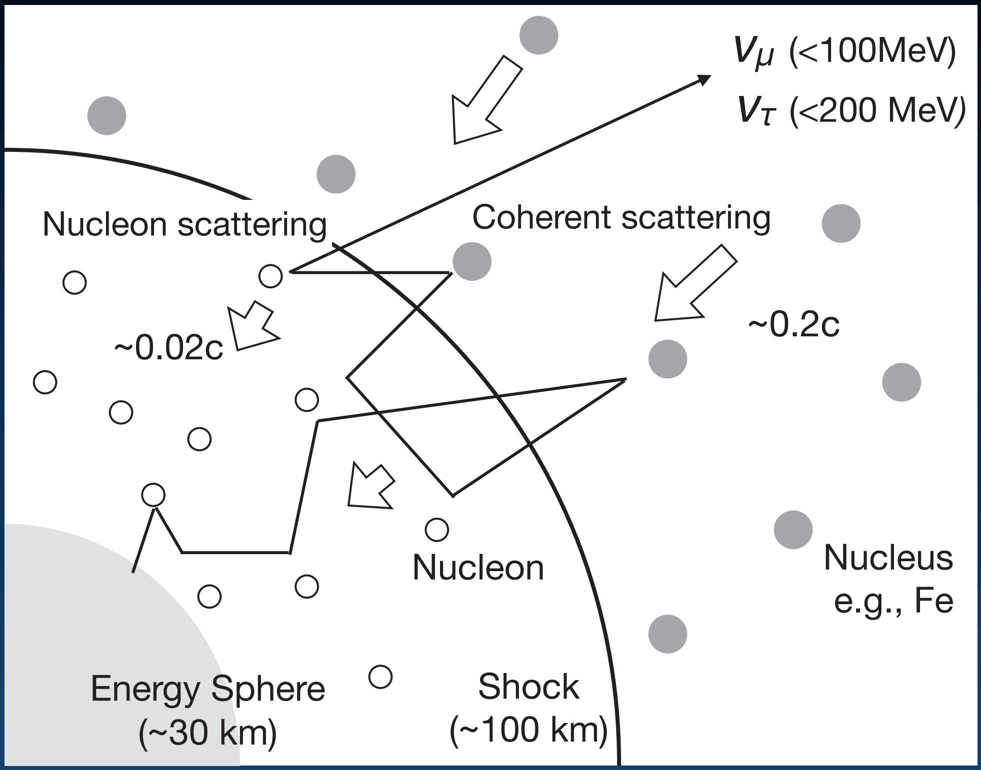


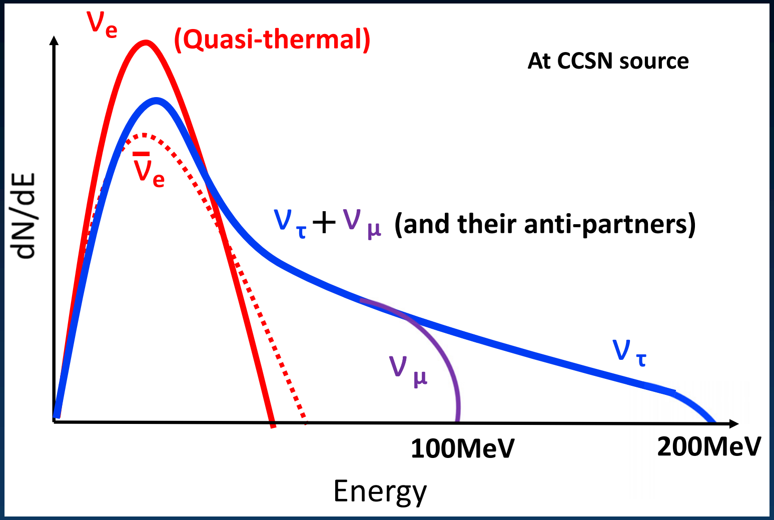


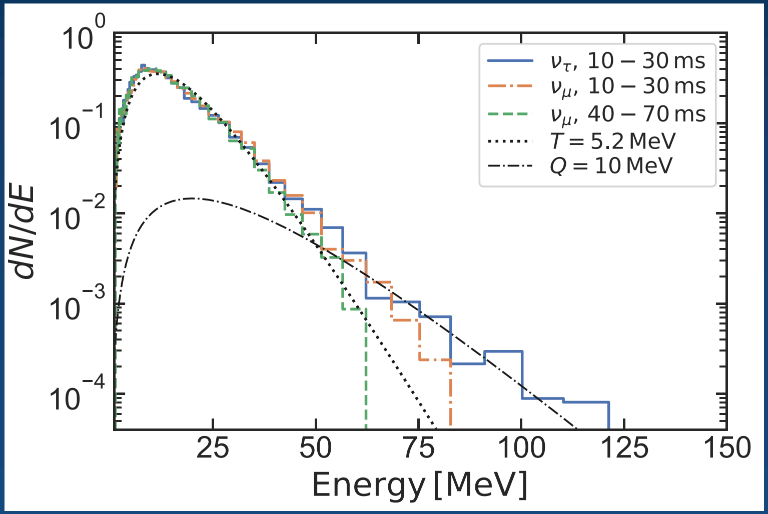
The time evolution of radiated energy of neutrinos is characterized by PNS mass

ν Neutrino shock acceleration in CCSNe

Nagakura and Hotokezaka 2021
(See also Kazanas and Ellison 1981, Giovanoni et al. 1989)







Non-thermal neutrinos is produced through Fermi acceleration.

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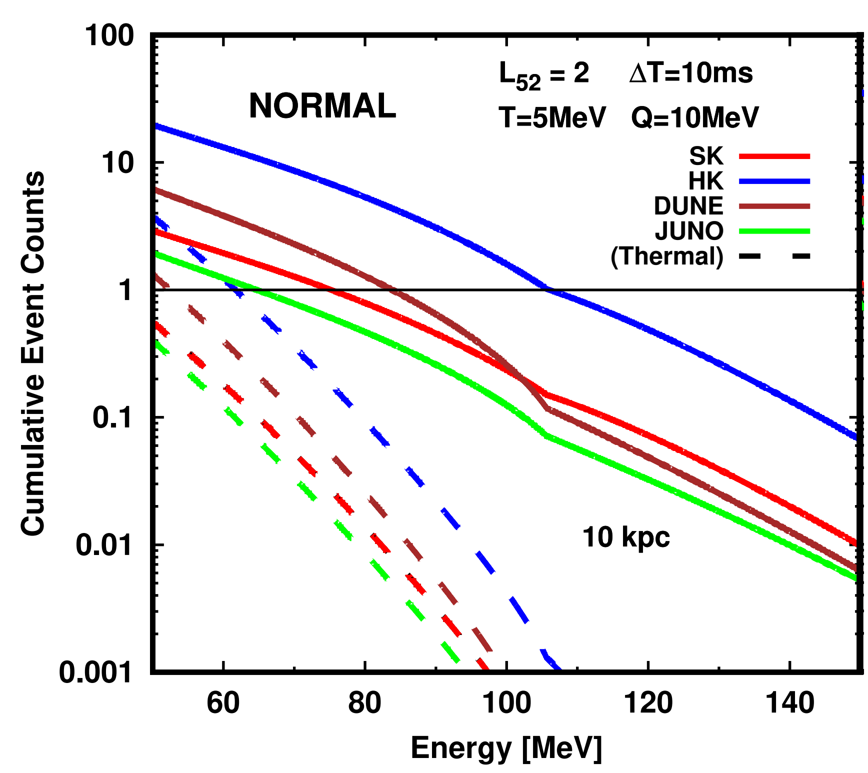
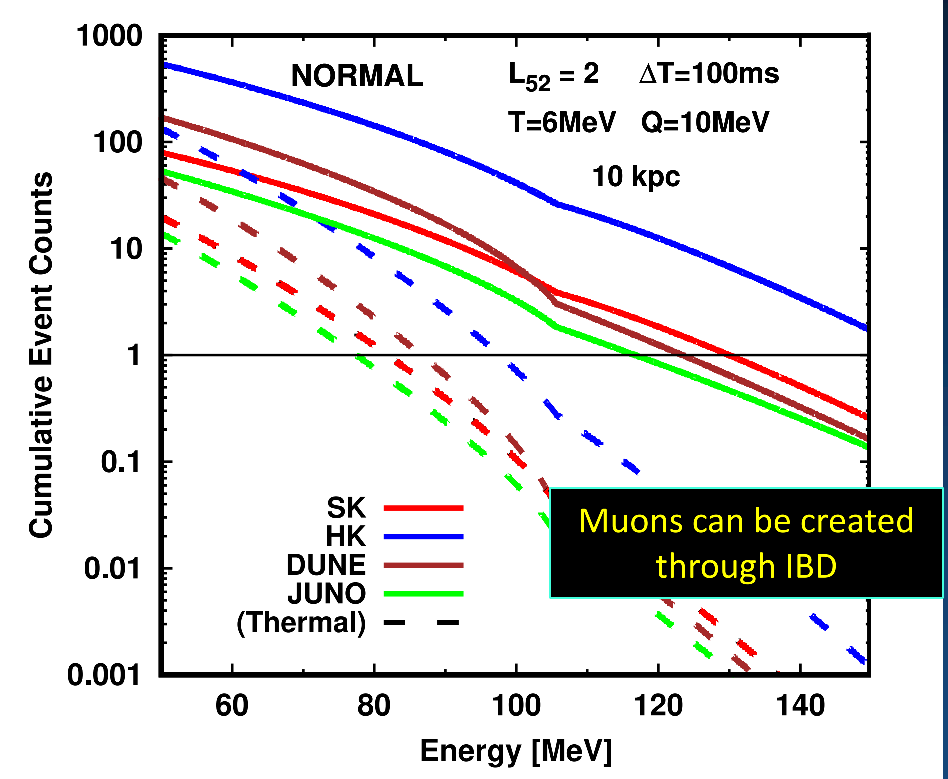
This leads to an interesting observational consequence in CCSN neutrinos.

Cumulative number of neutrino events at each detector

Early post-bounce phase < 30ms (all CCSN progenitors)



Late post-bounce phase (only cases with BH formation)



- How can we get rid of the uncertainty of neutrino flavor conversion in neutrino signal?

- Neutrino flavor conversion in CCSN core seems to be more complex than what we have considered so far, due to collective neutrino oscillations.

Neutrino oscillations induced by self-interactions

Pantalone 1992, Duan et al. 2006

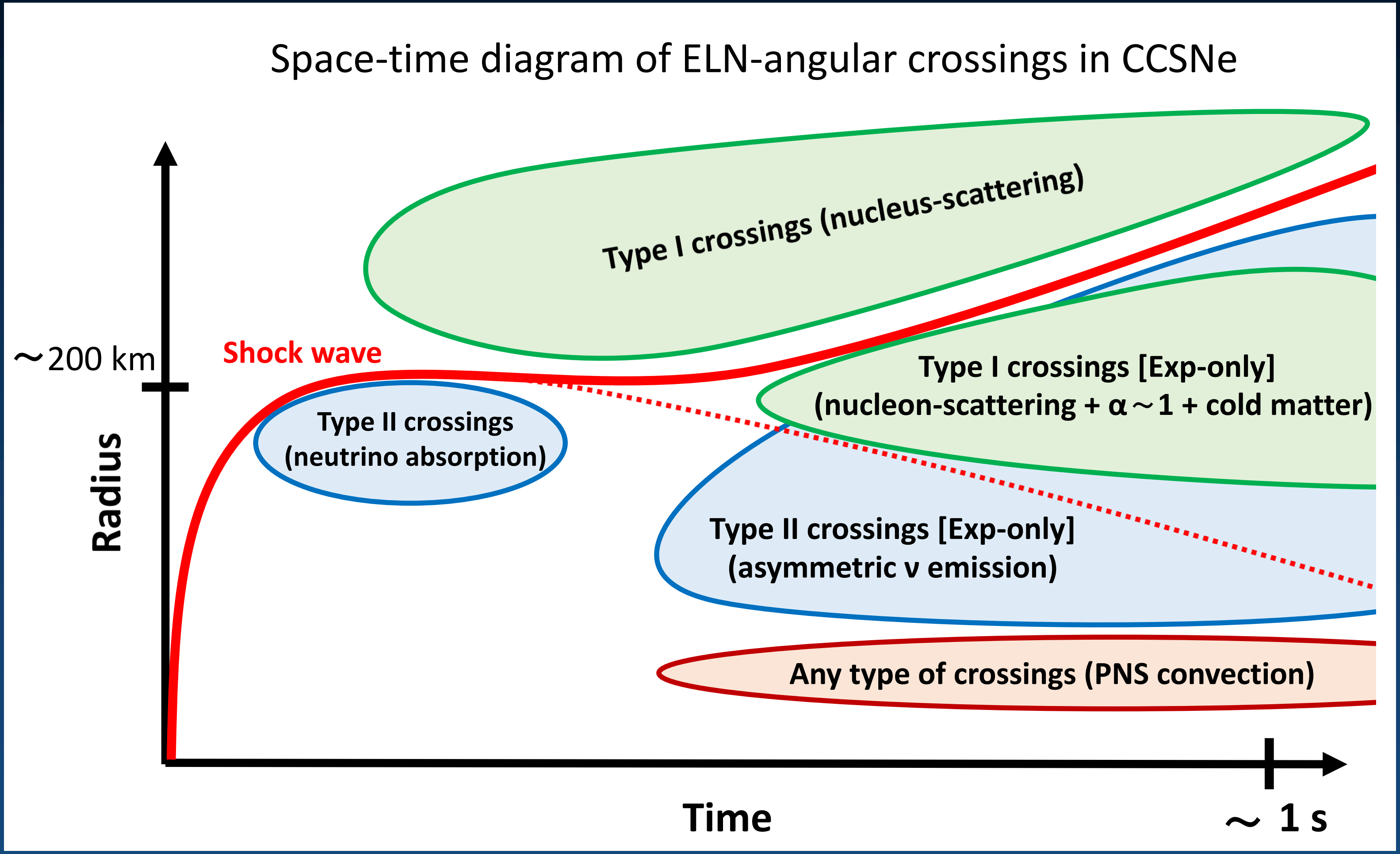
Sea of neutrinos

1. Refractions by self-interactions induce neutrino flavor conversions, which is analogy to matter effects (e.g., MSW resonance).

2. The oscillation timescale is much shorter than the global scale of CCSN/BNSM.

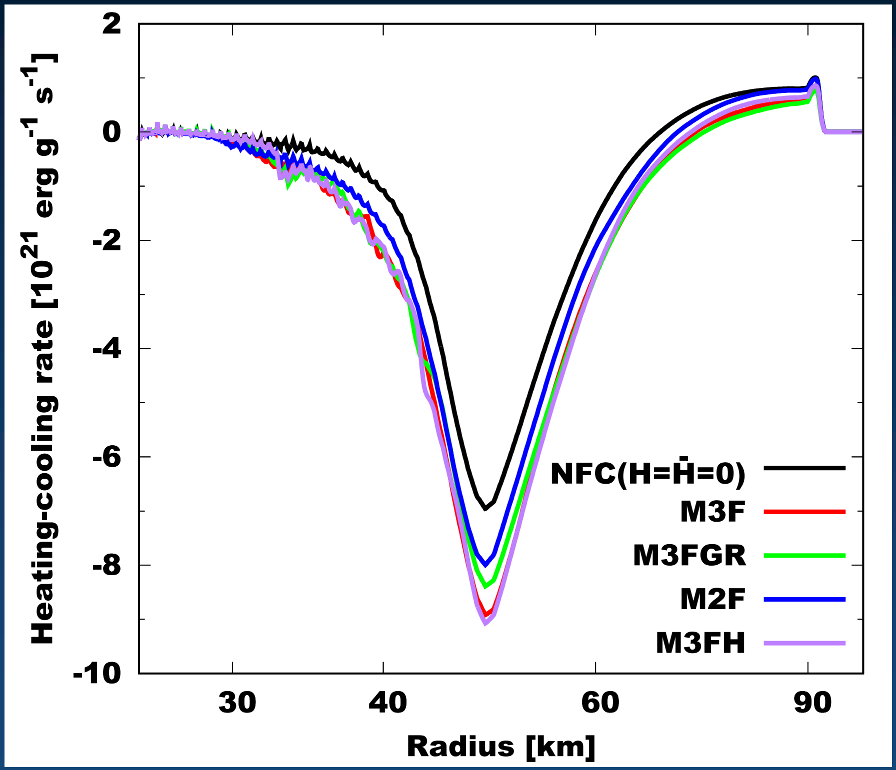
3. Collective neutrino oscillation induced by neutrino-self interactions commonly occurs in CCSNe and BNSM environments.

Collective neutrino oscillations ubiquitously occur in CCSN core

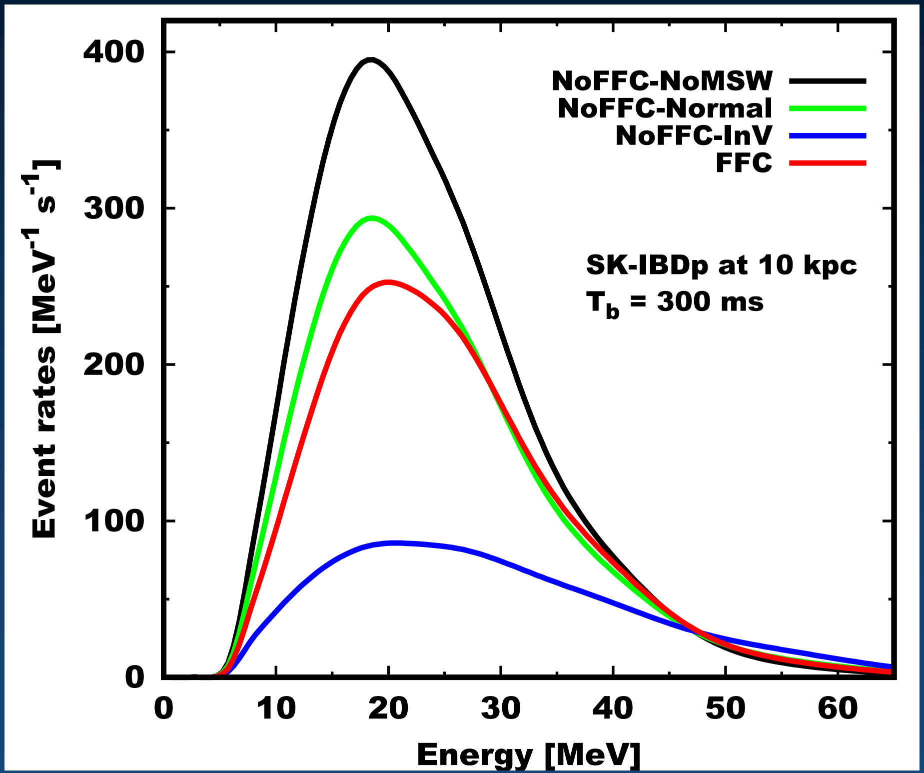


Nagakura et al. 2021

Collective neutrino oscillation potentially gives a significant impact on both CCSN dynamics and neutrino signal



Nagakura 2023 PRL

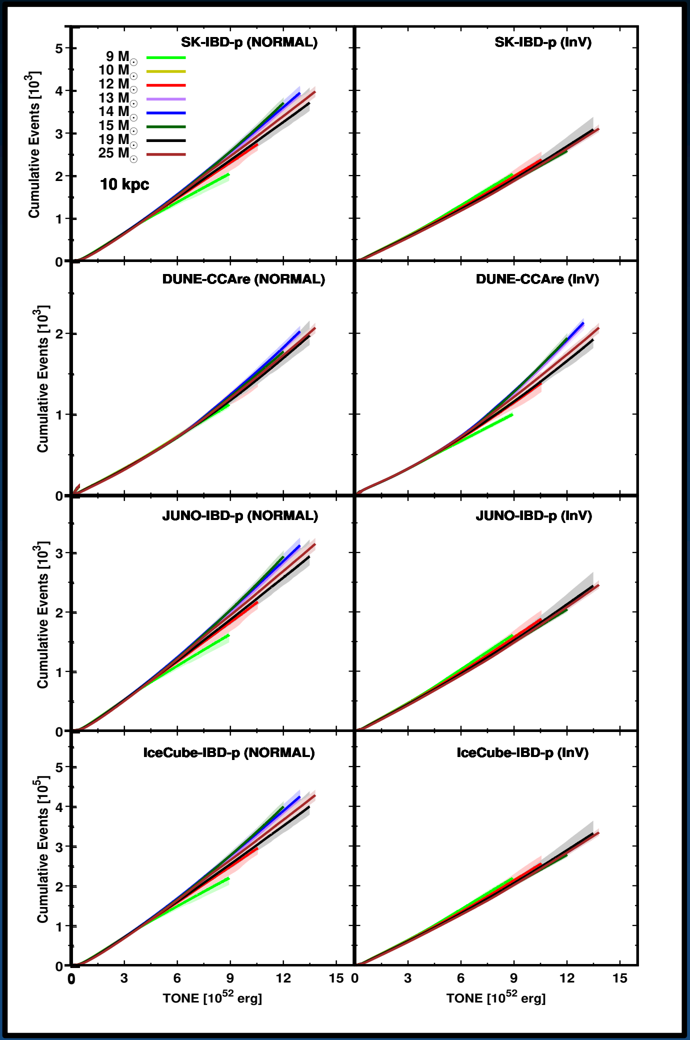


Nagakura and Zaizen (arXiv:2308.14800)

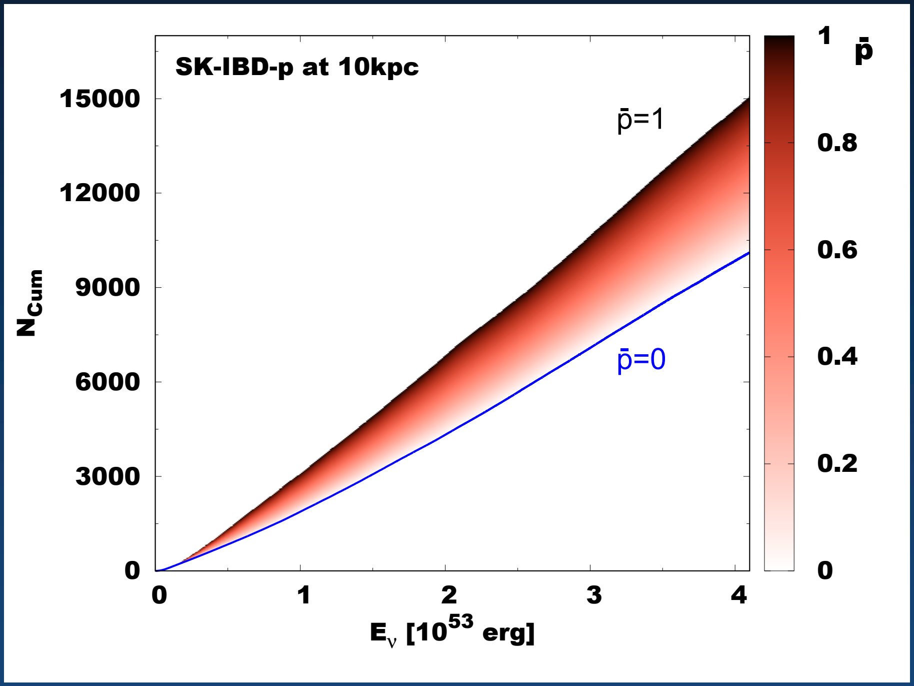
Correlation study of gravitational waves and neutrino signal

Nagakura and Vartanyan 2023

Weak progenitor dependence in neutrino radiated-energy vs. detection count

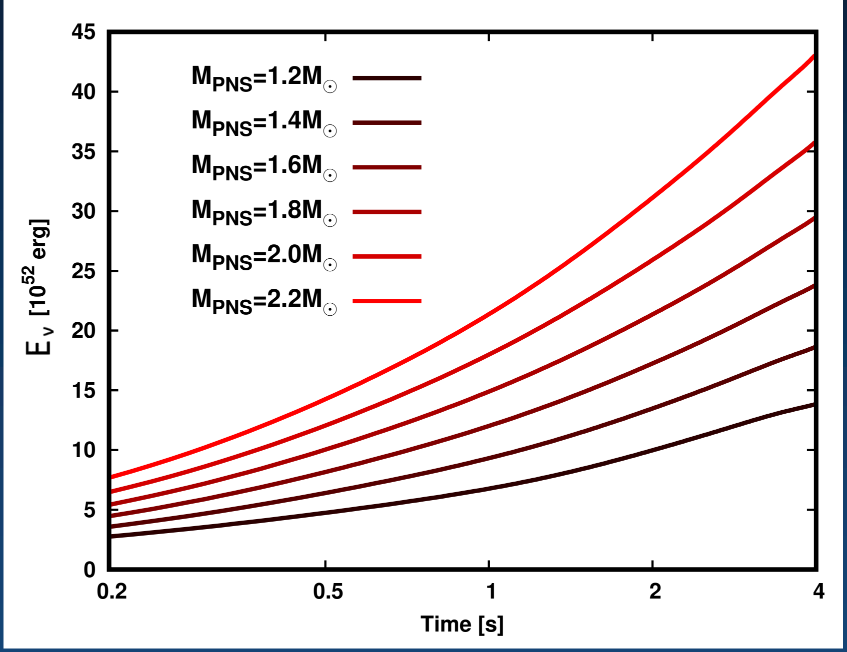


Event counts depend on neutrino flavor conversion



Proto neutron star (PNS) mass is a key ingredient to characterize GW and neutrino signal

Irradiated neutrino energy versus time



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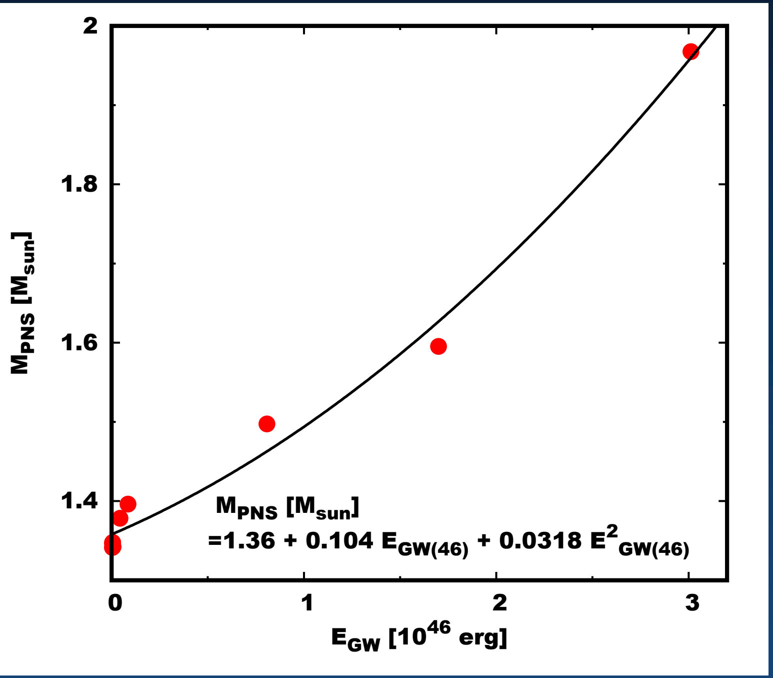
Irradiated GW energy vs. PNS mass



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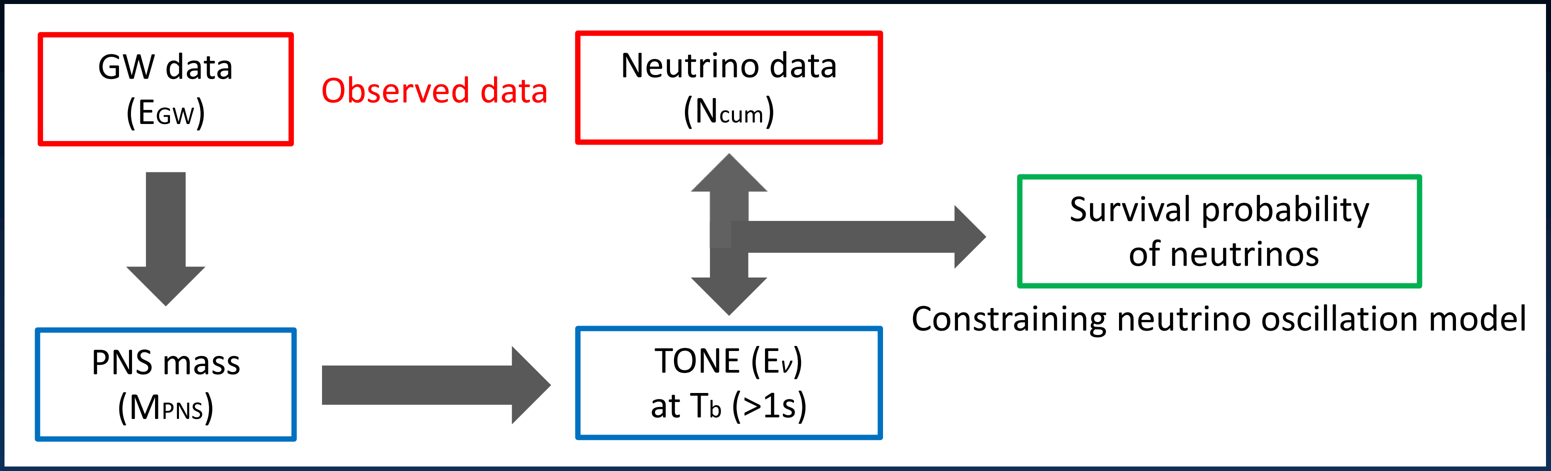
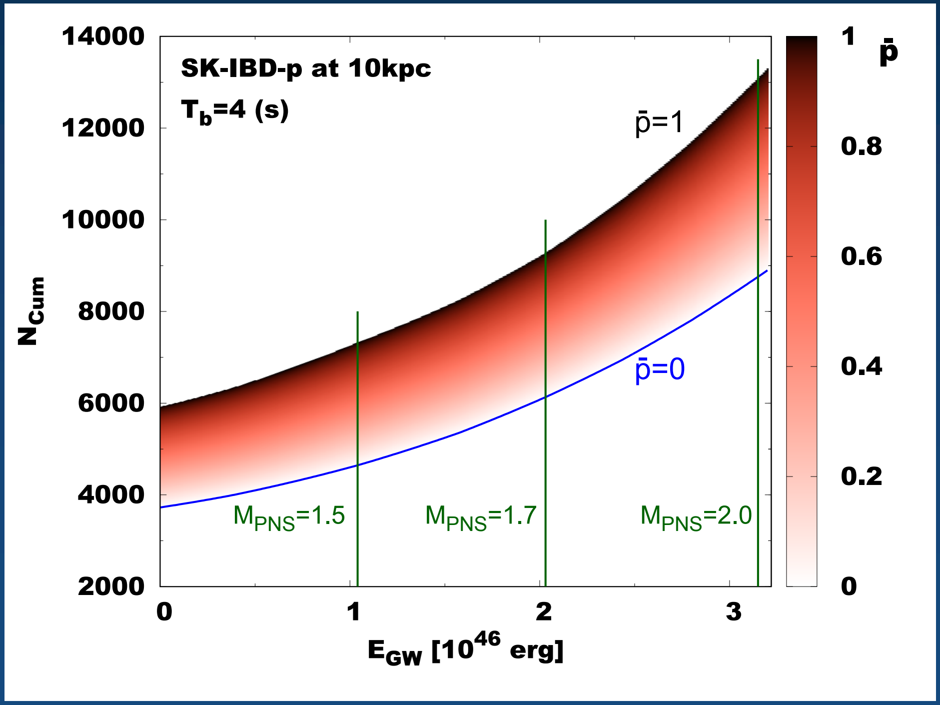
Flow chart: joint analysis for neutrinos and GW signals





Summary:

- Multi-D CCSN simulations can offer successful explosion models without artifices.
- Based on these simulations, we can consider what physical ingredients can be extracted from observable signals.
- Joint analysis of GWs and neutrinos can tell us about proto-neutron star evolution and place a constraint on neutrino oscillations in CCSNe.
- We are now extending our correlation study to include EM waves (stay tuned!).
- Information on complex physical processes inside CCSNe is imprinted in temporal variations and non-thermal spectra of neutrinos.