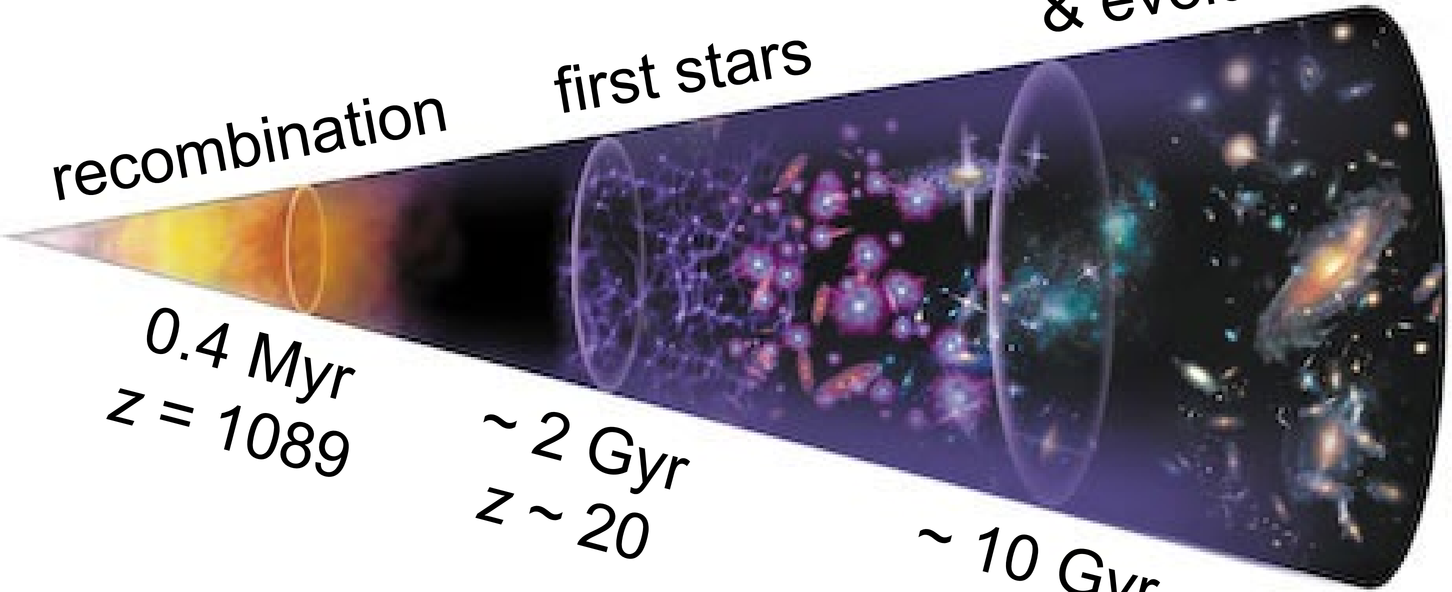
Overview of Astrophysical Uncertainties

Ken'ichiro Nakazato
(Fuculty of Arts & Science, Kyushu Univ.)

Towards the Detection of Diffuse Supernova Neutrinos:
What will we see? What can we learn?

History of Universe



Big Bang

recombination

first stars

galaxy formation & evolution

Now

0.4 Myr
z = 1089

~ 2 Gyr
z ~ 20

~ 10 Gyr
z ~ 5

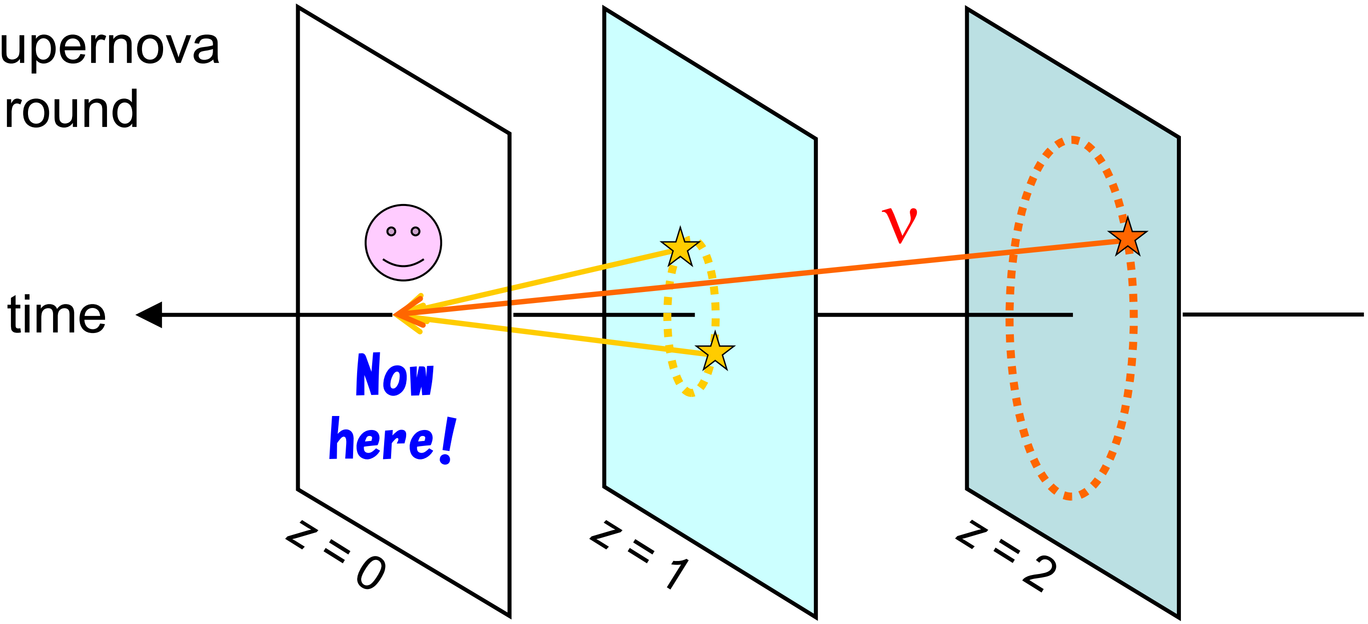
140 Gyr
z = 0

- The Universe is expanding!
- Cosmological redshift *z* denotes ``time”.

Many generations of stars have exploded!

Cosmic background neutrinos

a.k.a. Diffuse Supernova Neutrino Background (DSNB)



- Neutrinos emitted by all core-collapse SNe in the causally-reachable universe constitute diffuse background radiation.
- How significant would the DSNB flux be? What determines their flux and spectrum?

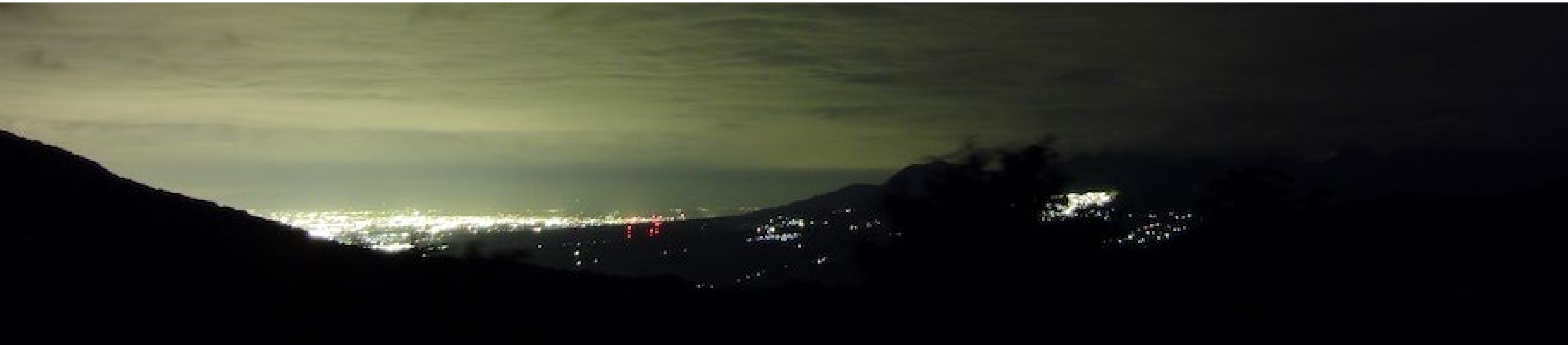
What determines BG luminosity?

⇓

Diffuse SN ν Background

- luminosity of a source → # of ν / SN (or BH)
- the source number
- distance to sources
  - cosmological redshift in the expanding universe
- also, neutrino oscillation parameters

} star formation history



Formulation

$$\left(\frac{dE'_\nu}{dE_\nu} = 1 + z\right)$$

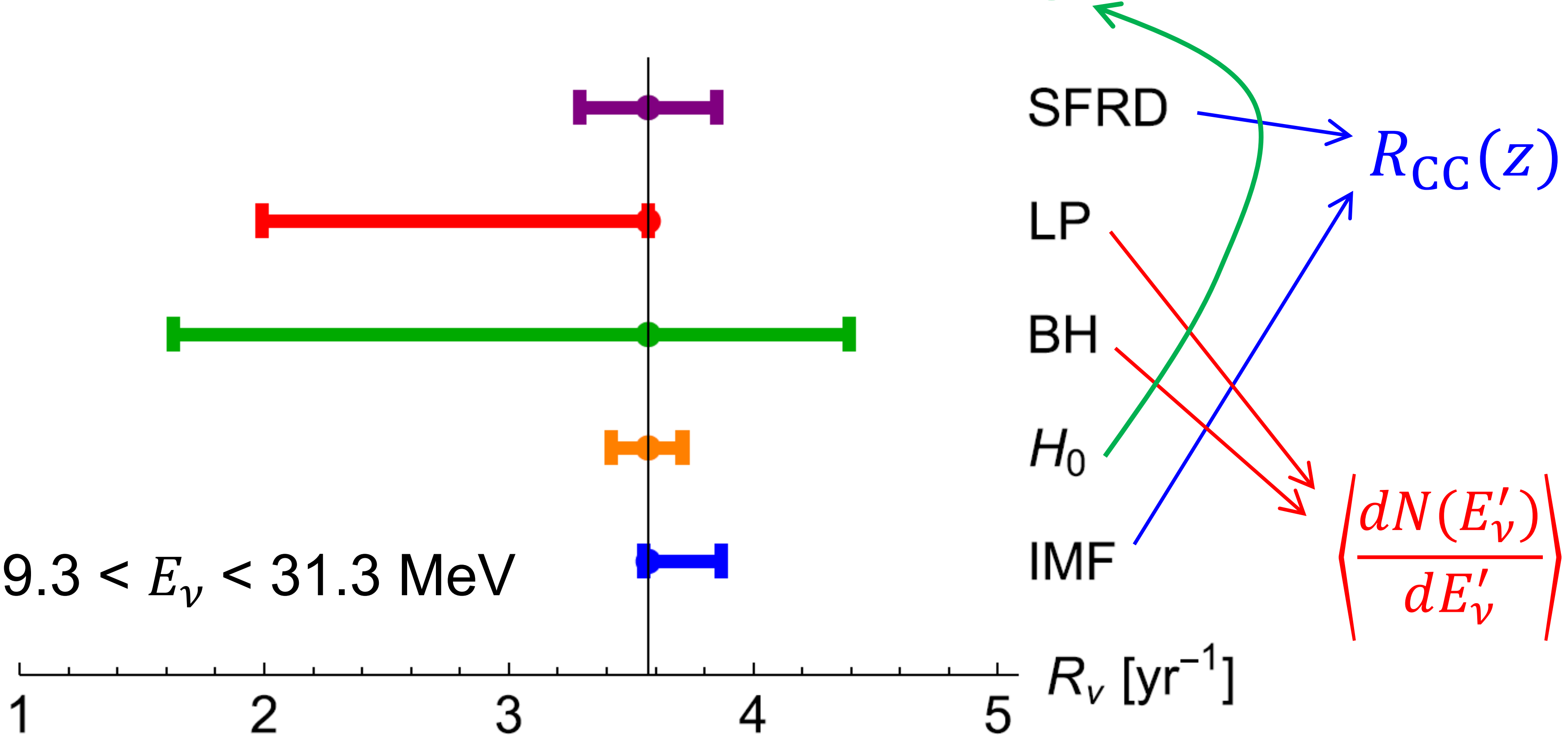
$$\frac{d\Phi(E_\nu)}{dE_\nu} = c\int_0^{z_{\max}} \underline{\underline{R_{\mathrm{CC}}(z)}}\,\boxed{\left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle} \frac{dz}{H_0\sqrt{\Omega_{\mathrm{m}}(1+z)^3+\Omega_\Lambda}}$$

- Cosmological parameters: $H_0,\ \Omega_{\mathrm{m}},\ \Omega_\Lambda$
- Spectrum of supernova neutrinos: $\left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle$
  - ➢ Property of proto-NS, Fraction of BH formation
- Core-collapse rate: $R_{\mathrm{CC}}(z)$
  - ➢ Star Formation Rate, Initial Mass Function

Uncertainties

Ekanger et al., PRD **109** (2024), arXiv:2310.15254

$$\frac{d\Phi(E_\nu)}{dE_\nu} = c\int_0^{z_{\max}} \underline{\underline{R_{\rm CC}(z)}}\,\boxed{\left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle} \frac{dz}{H_0\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}}$$

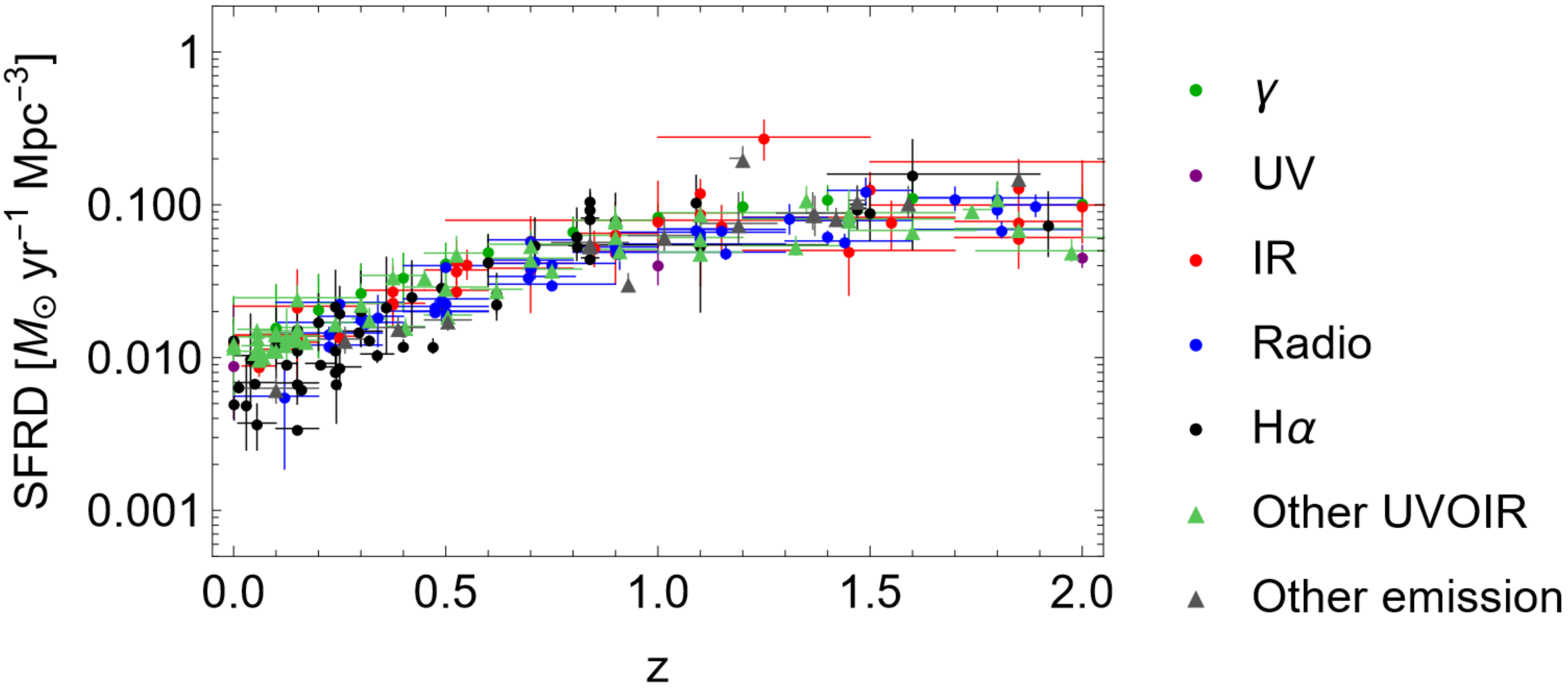


$9.3 < E_\nu < 31.3$ MeV

“LP” denotes late phase of neutrino emission

Star Formation Rate

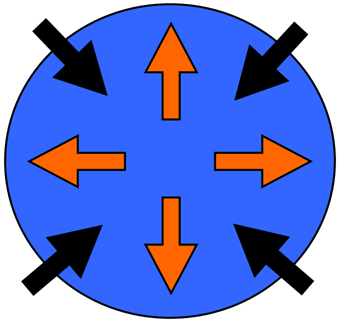
Ekanger et al., PRD **109** (2024), arXiv:2310.15254



- The measured values largely agree within uncertainties.

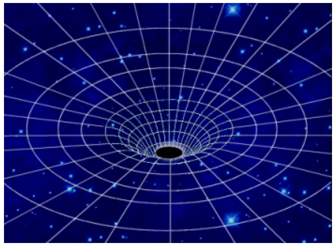
Neutron stars vs. Black holes

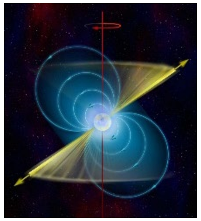
- Neutron stars sustain the self gravity by the nuclear repulsion.
- NS mass sustained by the nuclear repulsion has the upper limit.
- BH is formed beyond the upper limit.


self gravity

nuclear repulsion

Proto-neutron star

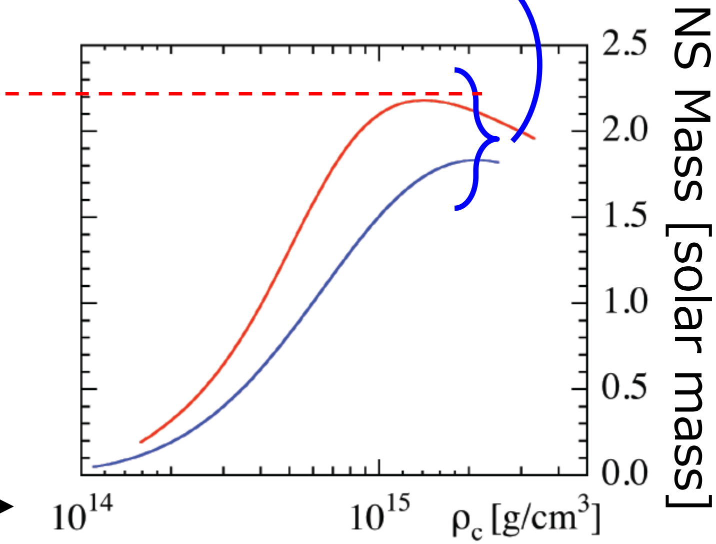

black hole


neutron star

threshold

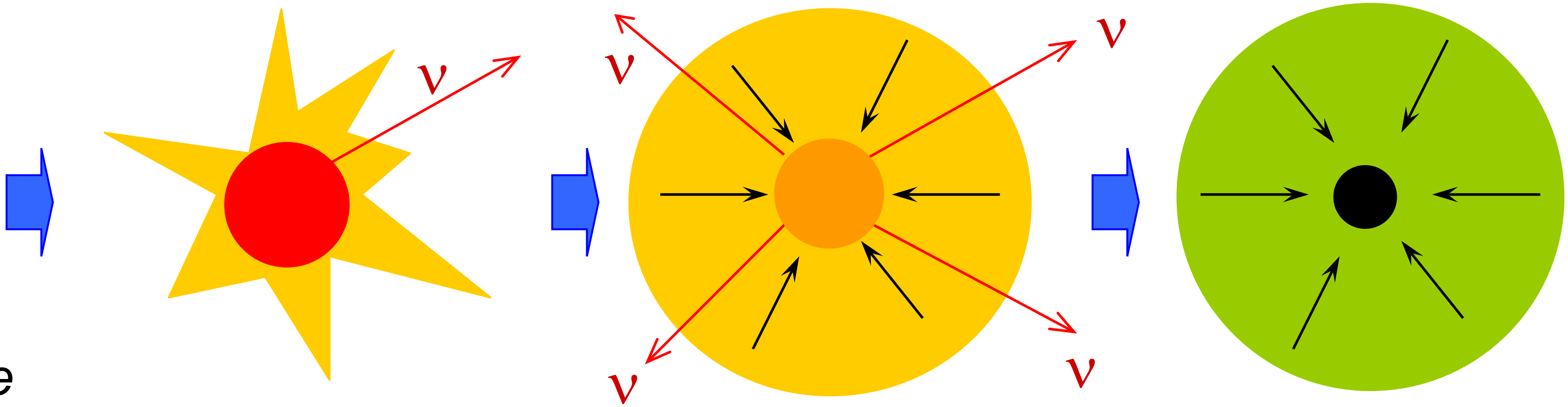
nuclear uncertainty

central density →



Failed supernova neutrinos

- Failed supernova progenitor makes bounce once and recollapse to the black hole.
- Therefore, mass accretion continues until the NS mass exceeds the limit.
  - The larger the maximum mass, the greater the total energy.



Massive star

Proto-neutron star

Black hole

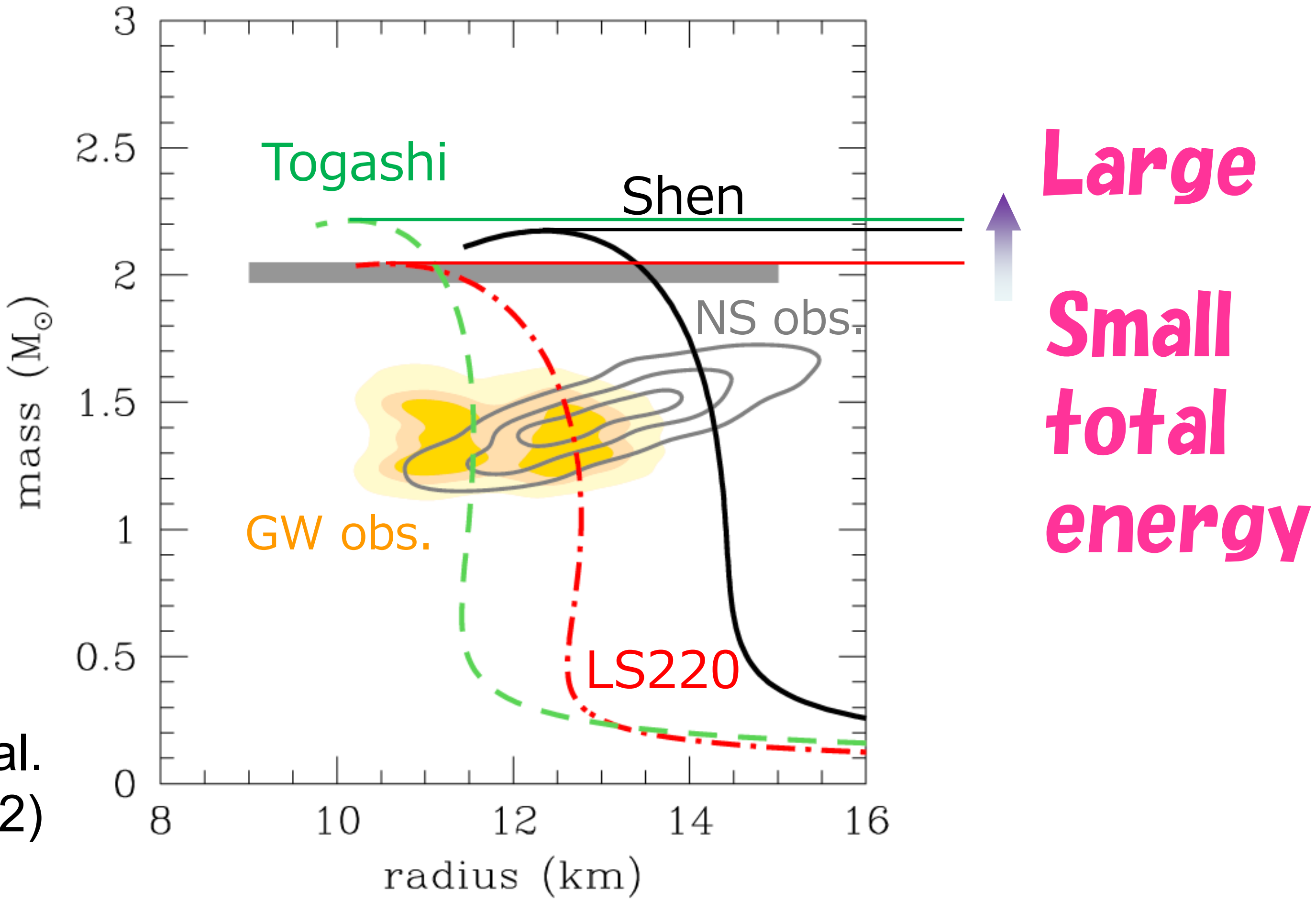
Core Collapse

Bounce

Mass accretion

Role of Nuclear EOS (BH)

- For BH formation, the maximum mass of remnant NS is determined by nuclear EOS.

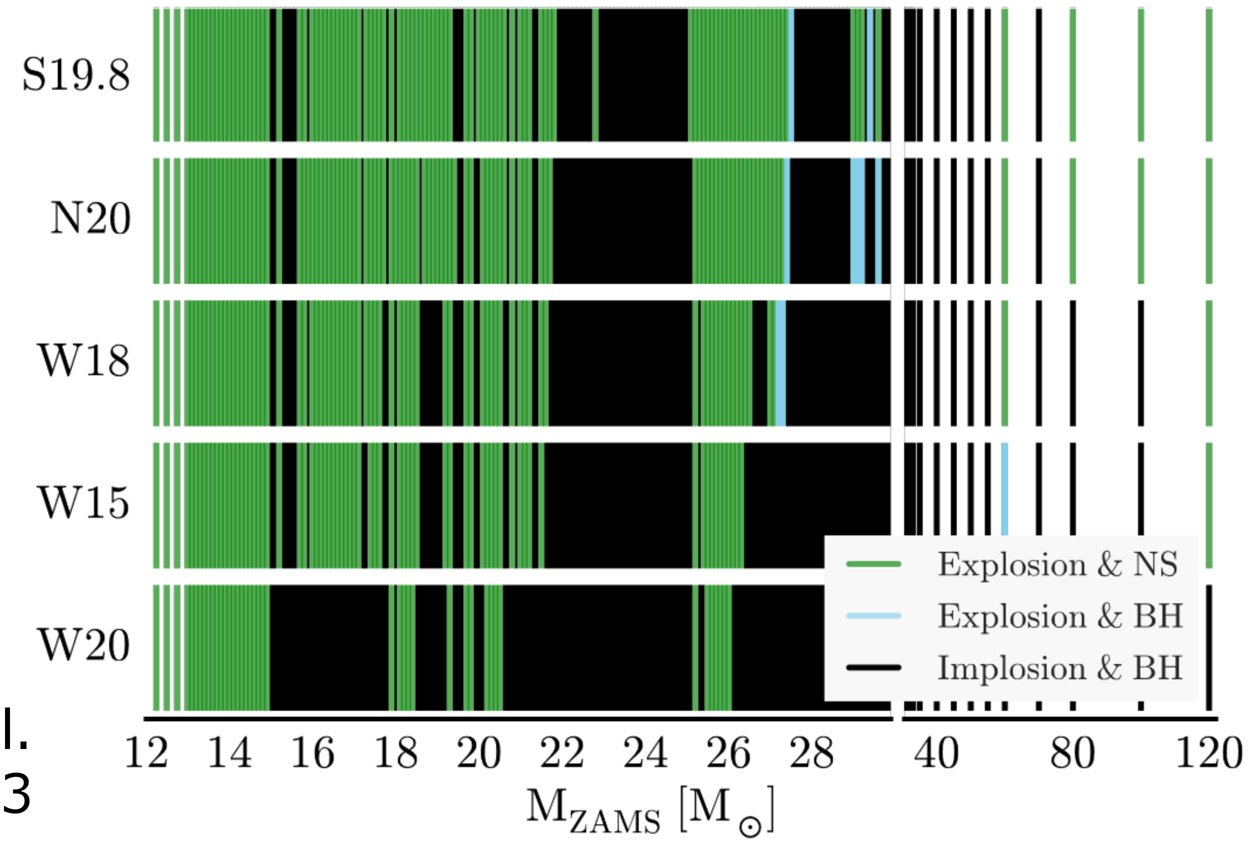


Nakazato et al.
ApJ. **925** (2022)

Progenitors of BH formation

- Whether the remnant becomes BH or NS depends on the progenitor mass.

→ Fraction of BHs has systematic uncertainty.



Sukhbold et al.
arXiv:1510.04643

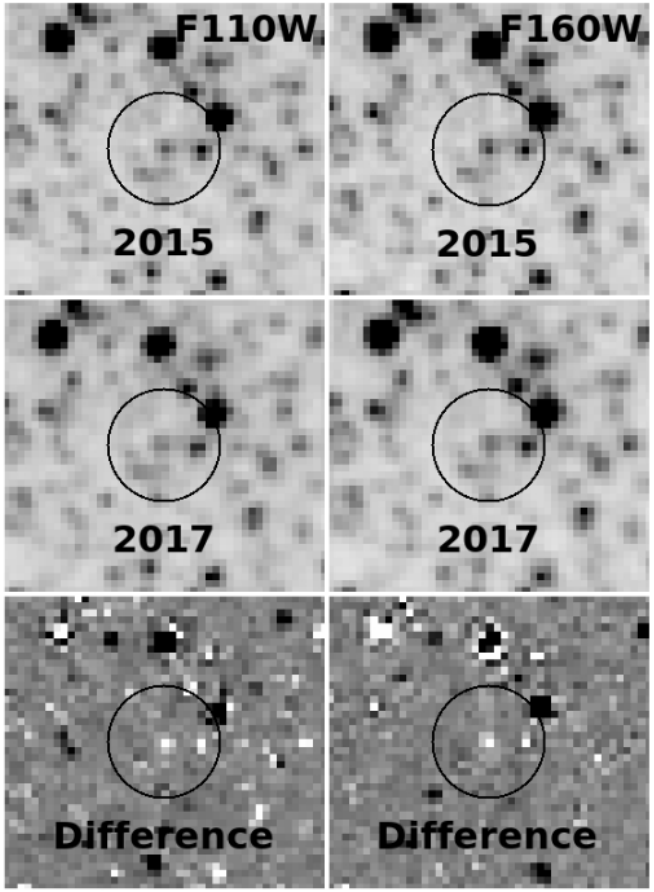
“Observing” BH formation

- Disappearance of a supergiant.
- Monitoring survey of them.

→ 2 candidates for BH formation and 8 supernovae

  - with $N_{\mathrm{FSN}} = 1$ and $N_{\mathrm{SN}} = 8$, $f_{\mathrm{BH}} = 4 - 39\%$

Basinger et al.
arXiv:2007.15658



Neustadt et al., arXiv:2104.03318

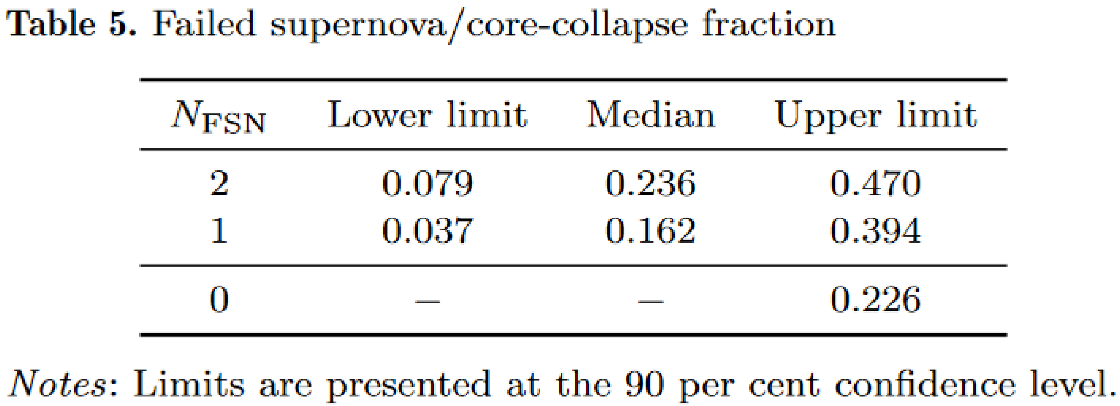


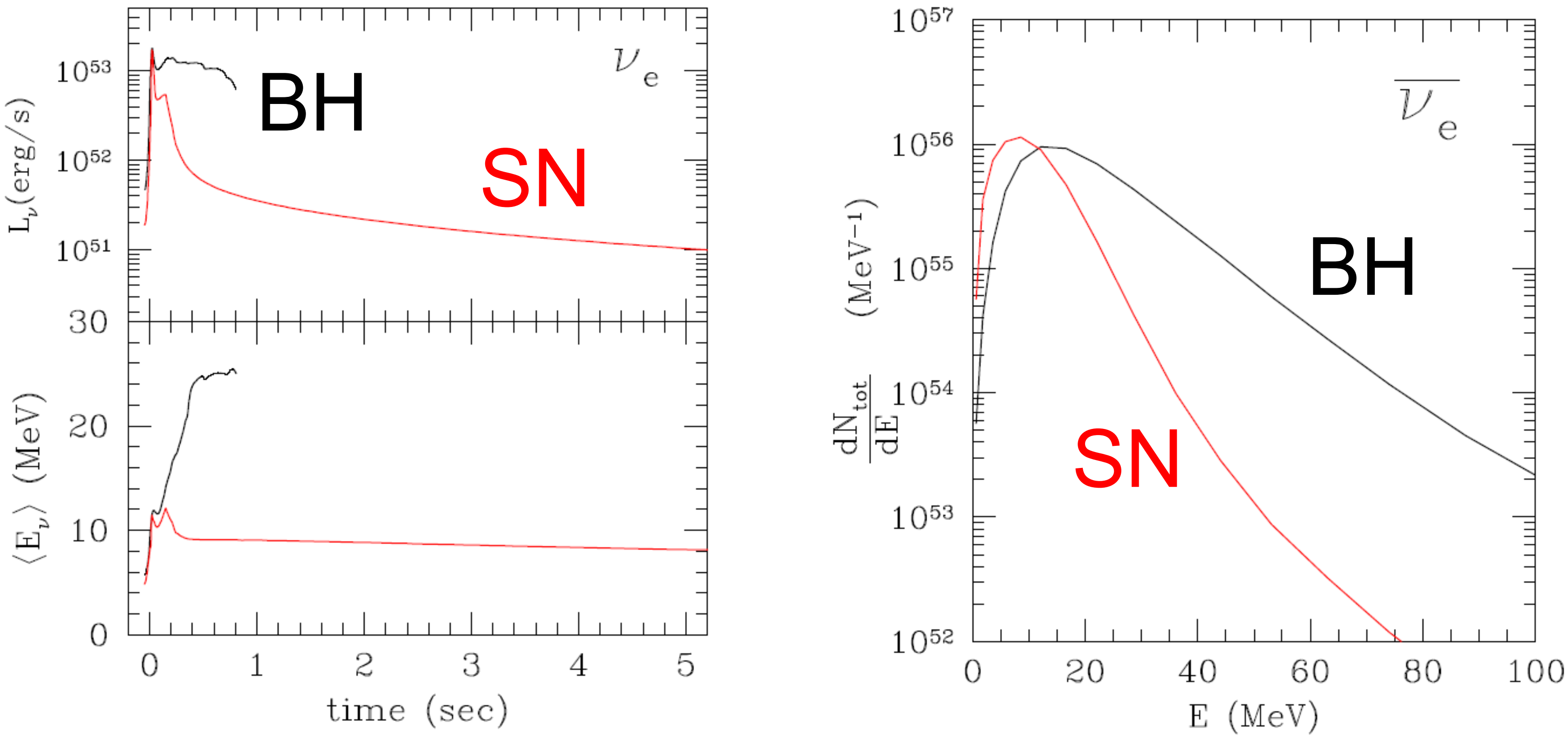
Table 5. Failed supernova/core-collapse fraction

N_{FSN}	Lower limit	Median	Upper limit
2	0.079	0.236	0.470
1	0.037	0.162	0.394
0	–	–	0.226

Notes: Limits are presented at the 90 per cent confidence level.

Neutrinos from BH formation

- Average energy of neutrinos is higher.
  - ➢ because the mass accretion continues until the BH formation and the PNS is heated.



Neutrino emissions from SN with NS formation and BH formation

Supernova neutrino energetics

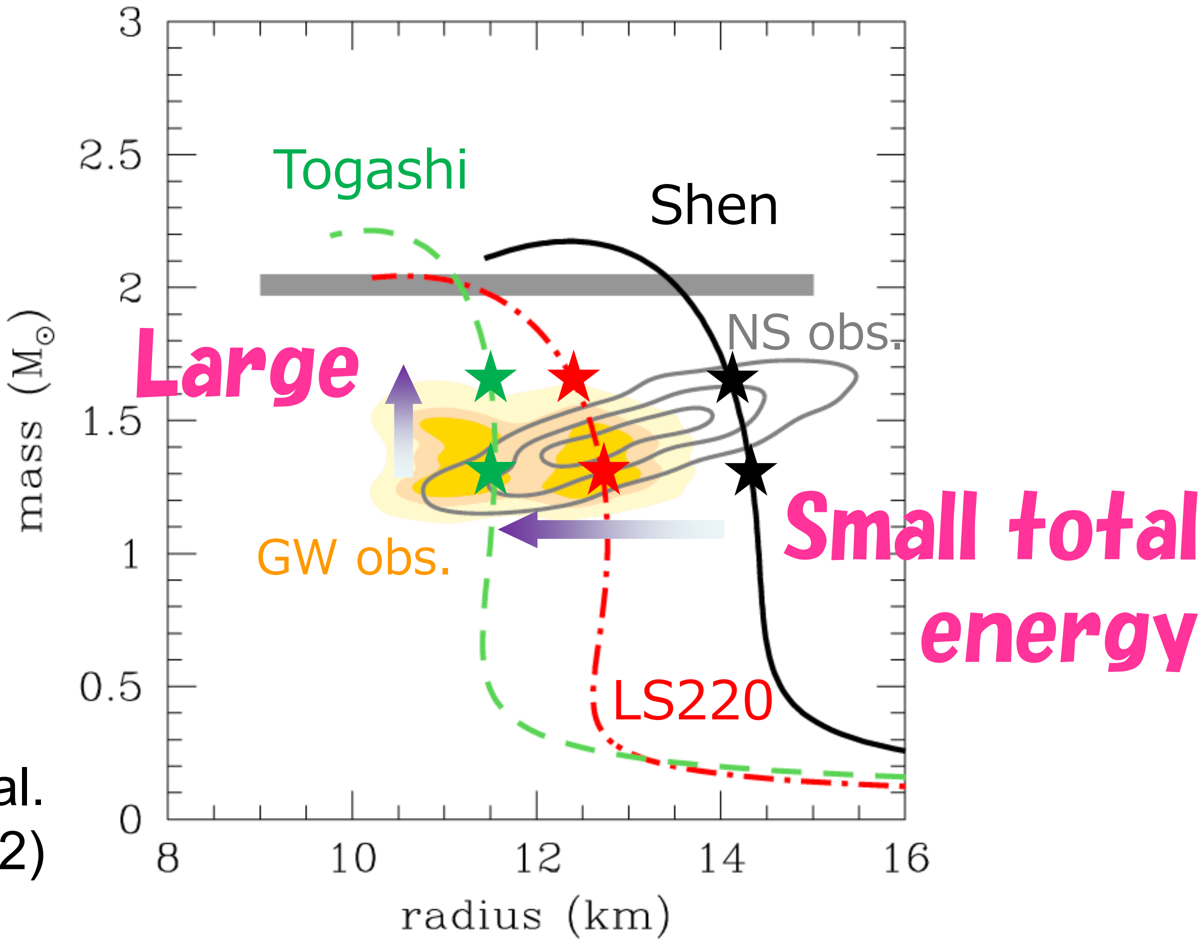
- Gravitational binding energy of remnant NS

$$E \sim \frac{GM_{\mathrm{NS}}^2}{R_{\mathrm{NS}}} \sim \underline{4 \times 10^{53}\ \mathrm{erg}} \left(\frac{M_{\mathrm{NS}}}{1.4 M_\odot}\right)^2 \left(\frac{R_{\mathrm{NS}}}{12\ \mathrm{km}}\right)^{-1}$$

- Energy partition
  - 99%, $O(10^{53}$ erg) : Neutrinos
  - 1%, $O(10^{51}$ erg) : Kinetic energy of explosion
  - 0.01%, $O(10^{49}$ erg) : Photons
- Therefore, the total energy is larger for the larger mass and the smaller radius.

Role of Nuclear EOS (SN)

- For successful SN explosion, the radius of remnant NS is determined by nuclear EOS.

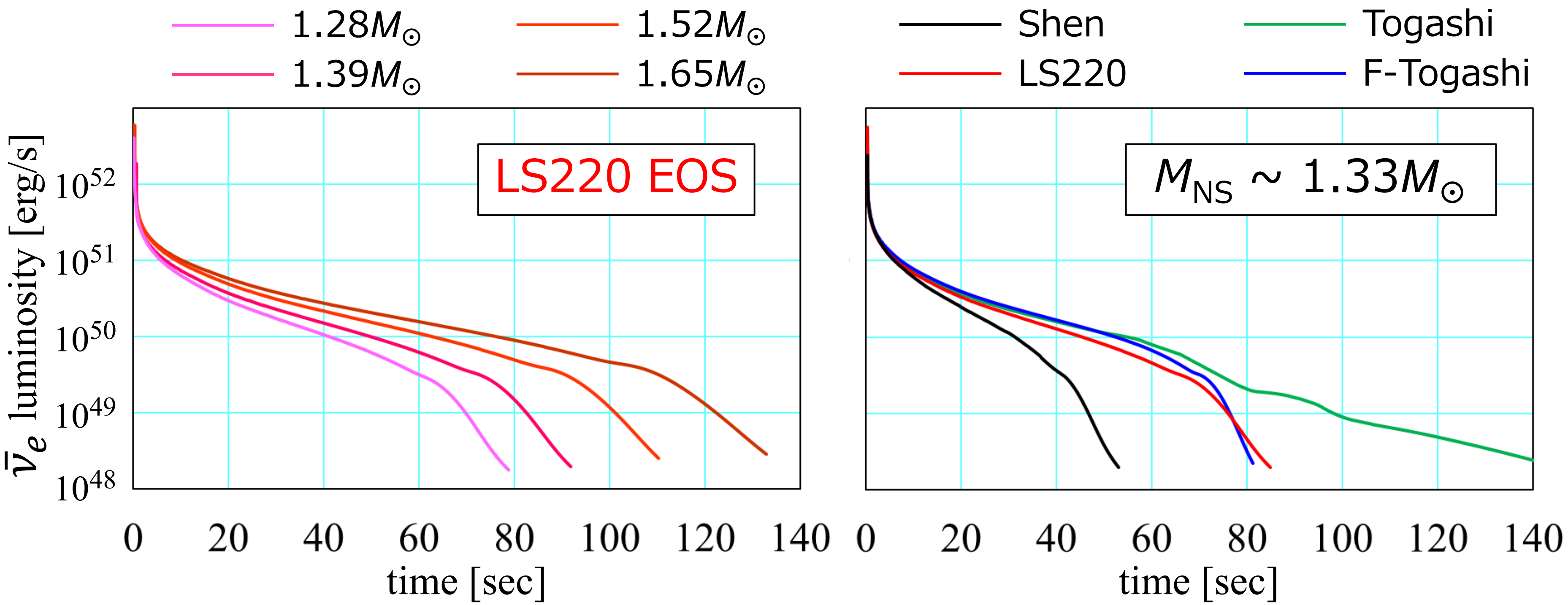


Nakazato et al.
ApJ. **925** (2022)

Neutrino light curve

Nakazato et al. (2022)
Sumiyoshi et al. (2023)

- Impact of NS mass and EOS persists into the late phase (LP).
  - Decay timescale of neutrino light curve is larger for NSs with larger mass and smaller radius.

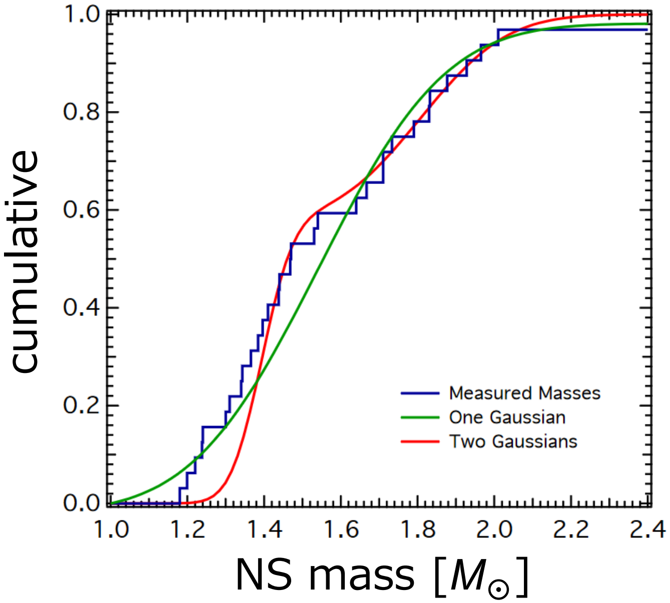


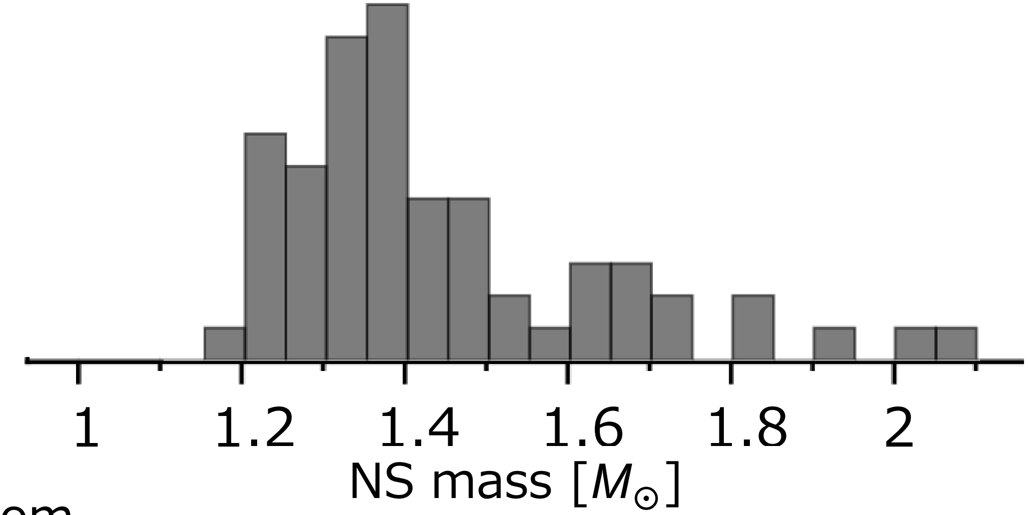
NS mass distribution

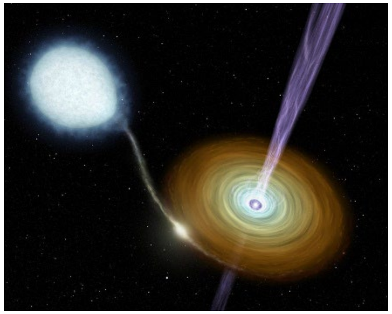
- Observationally, while it has a peak at ~ $1.35 M_\odot$, heavier NSs are also exist.

→ NS mass can get higher through mass accretion.

Antoniadis et al.
arXiv:1605.01665







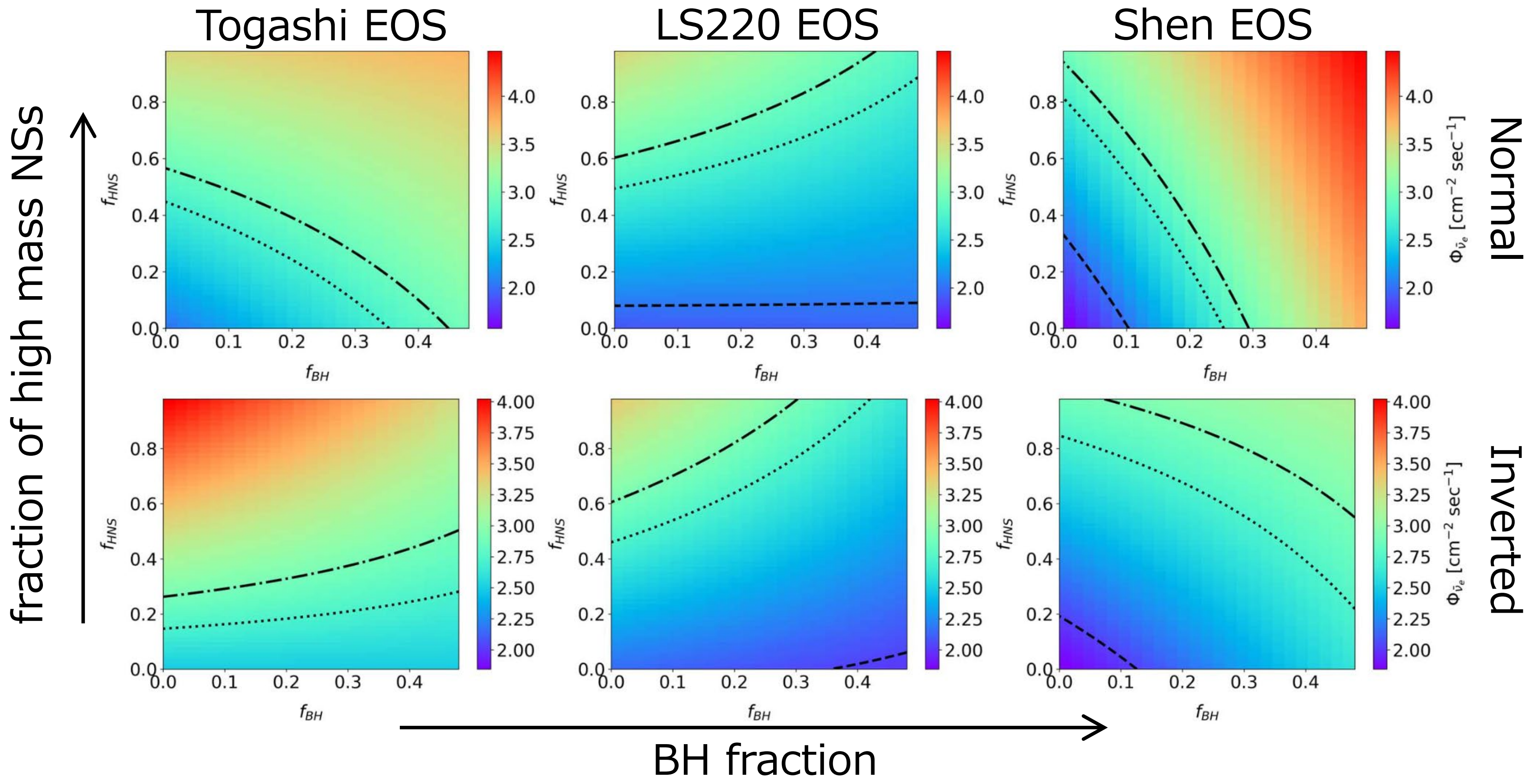
adapted from
https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

Diversity

Ashida & Nakazato, ApJ **937** (2022),
arXiv:2204.04880

- DSNB flux depends on EOS, BH fraction and NS mass distribution.

$13.3 < E_\nu < 31.3$ MeV



Togashi EOS

LS220 EOS

Shen EOS

Normal

Inverted

fraction of high mass NSs

BH fraction

Ashida, Nakazato & Tsujimoto,
ApJ 953 (2023),
arXiv:2305.13543

Formulation

$$\left(\frac{dE'_\nu}{dE_\nu} = 1 + z\right)$$

$$\frac{d\Phi(E_\nu)}{dE_\nu} = c\int_0^{z_{\max}} \underline{\underline{R_{\mathrm{CC}}(z)}}\,\boxed{\left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle} \frac{dz}{H_0\sqrt{\Omega_{\mathrm{m}}(1+z)^3 + \Omega_\Lambda}}$$

- Cosmological parameters:

$$H_0 = 67.7\ \mathrm{km/s/Mpc},\ \Omega_{\mathrm{m}} = 0.31,\ \Omega_\Lambda = 0.69$$

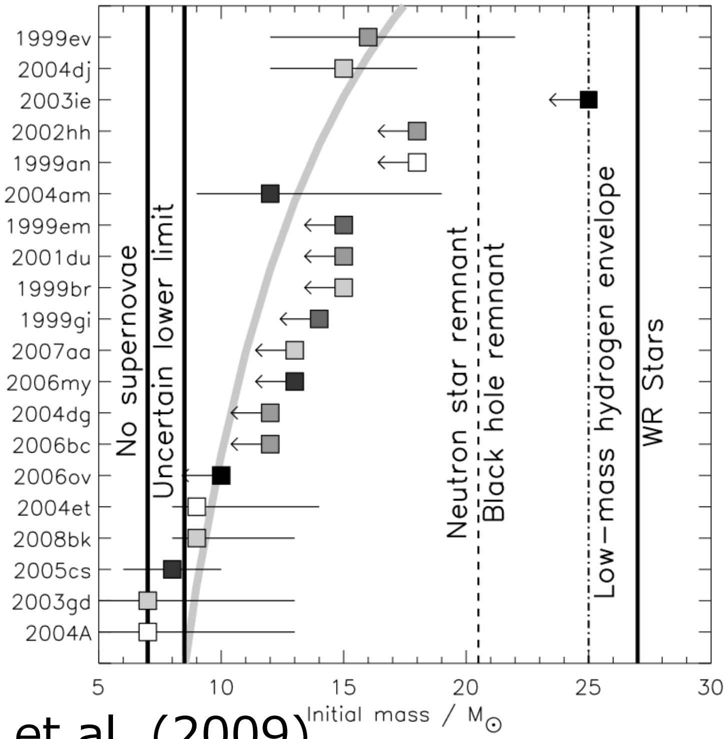
- Spectrum of supernova neutrinos: $\left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle$

- Core-collapse rate: $R_{\mathrm{CC}}(z)$

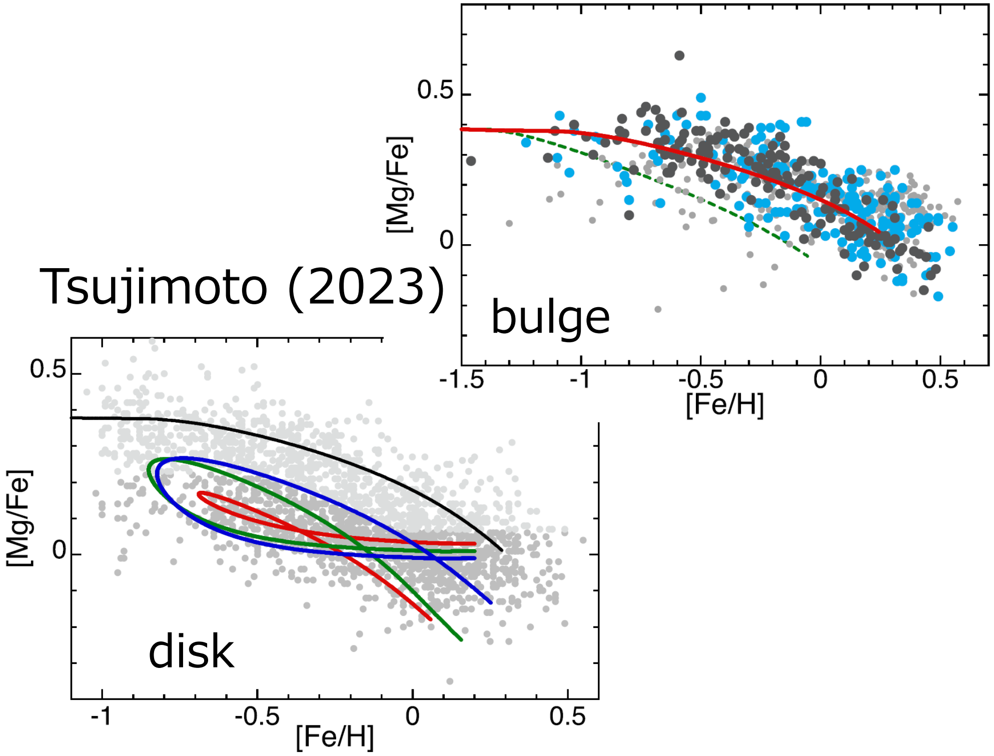
（from Tsujimoto, 2023）

According to Tsujimoto (2023)

- Galactic chemical evolution implies that:
  1. E/S0, Sab galaxies have flatter IMF
  2. Progenitors with ≥ 18$M_\odot$ becomes BH



Smartt et al. (2009)



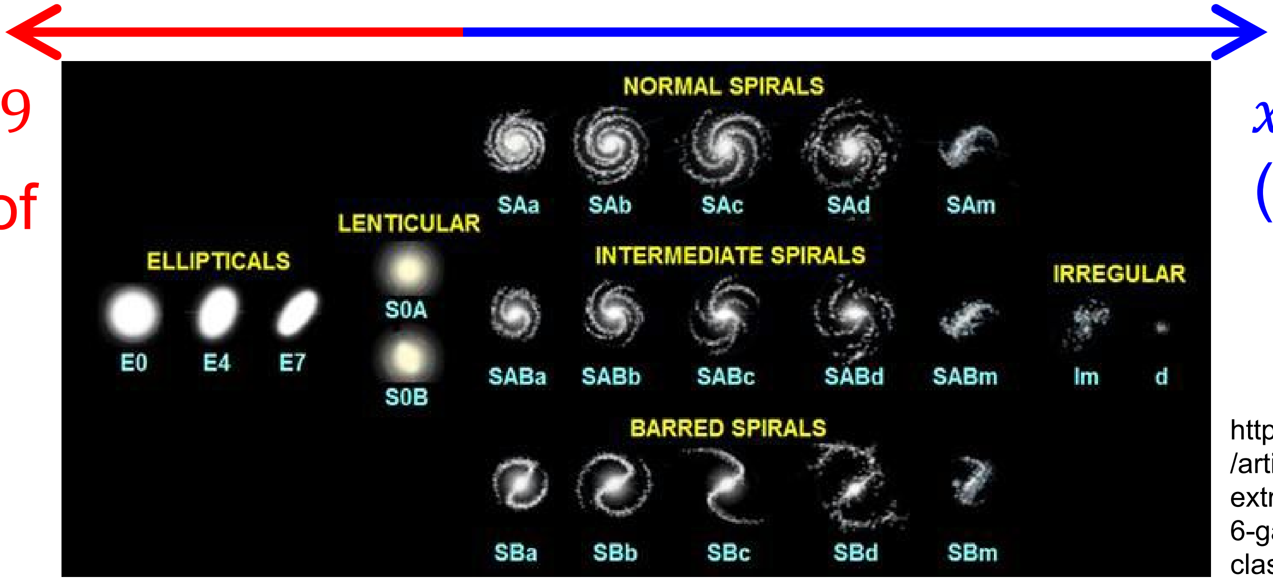
Tsujimoto (2023)

According to Tsujimoto (2023)

- Galactic chemical evolution implies that:
  1. E/S0, Sab galaxies have flatter IMF
  2. Progenitors with $\geq 18M_\odot$ becomes BH
- Initial mass function（IMF）: $\psi_{\mathrm{IMF}} = \frac{dN}{dM} \propto M^{x-1}$

$x = -0.9$

fraction of massive stars is higher



$x = -1.35$ (Salpeter)

https://www.cloudynights.com/articles/cat/articles/basic-extragalactic-astronomy-part-6-galaxies-discovery-and-classification-r3248

According to Tsujimoto (2023)

- Galactic chemical evolution implies that:
  1. E/S0, Sab galaxies have flatter IMF
  2. Progenitors with ≥ $18M_{\odot}$ becomes BH

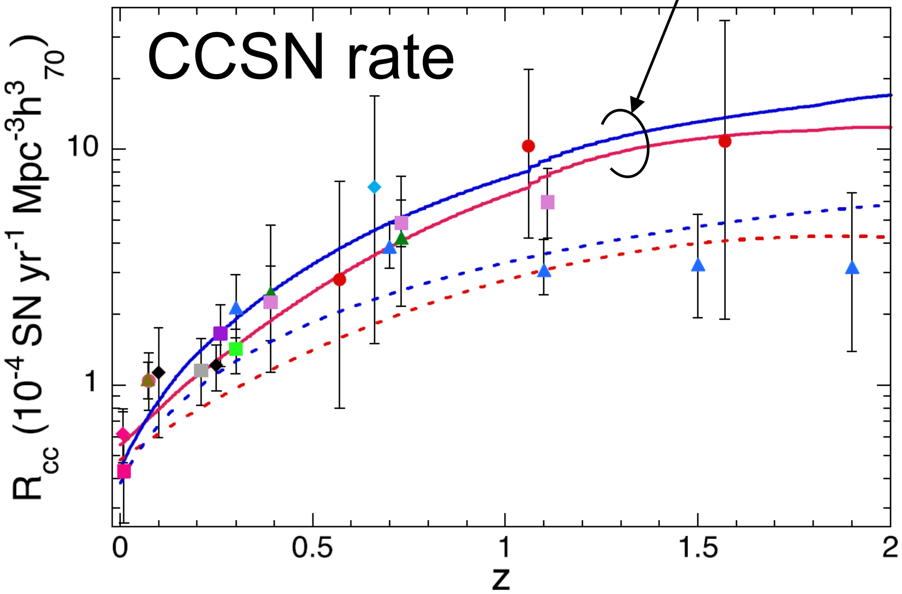
- CCSN rate: $\dot{\rho}_*(z) \times \frac{\int_{8M_{\odot}}^{18M_{\odot}} \psi_{\mathrm{IMF}}(M)dM}{\int_{0.1M_{\odot}}^{100M_{\odot}} M \cdot \psi_{\mathrm{IMF}}(M)dM}$
  - ➢ cosmic star formation rate, $\dot{\rho}_*(z)$, is from

Hopkins & Beacom (2006)

Madau & Dickinson (2014)

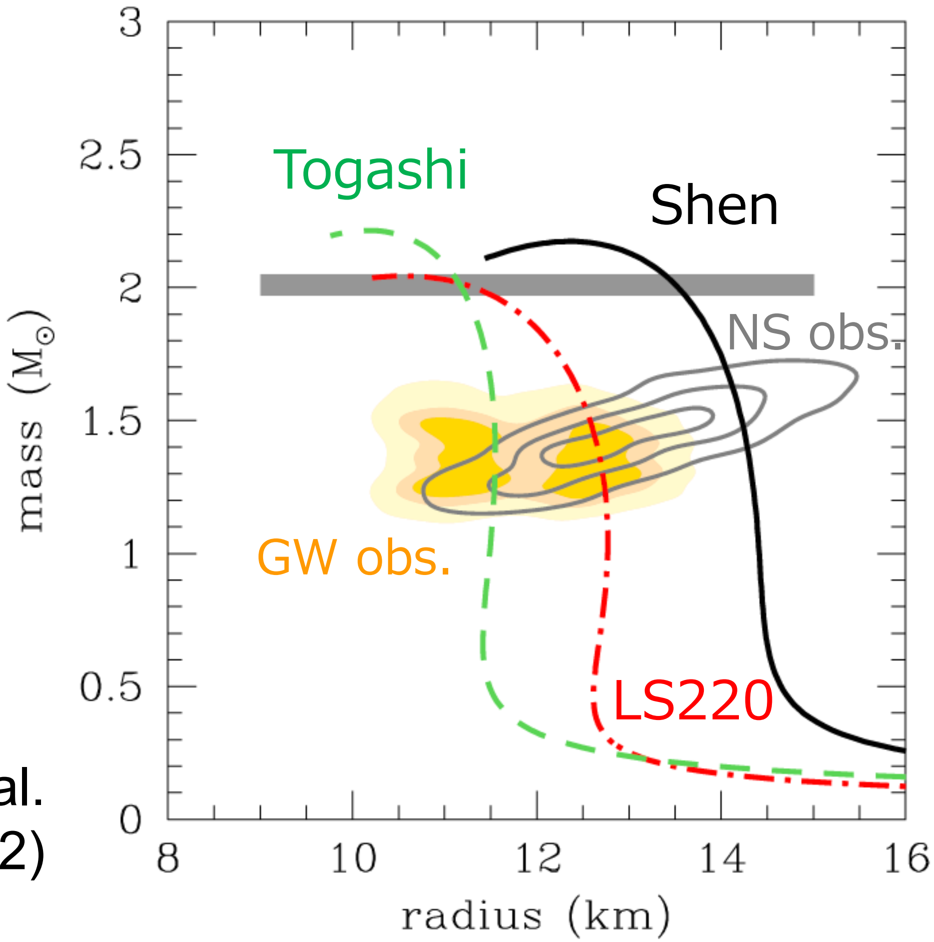
Tsujimoto, MNRAS **518** (2023)

flatter IMF for early type galaxies



Nuclear EOS and NS mass

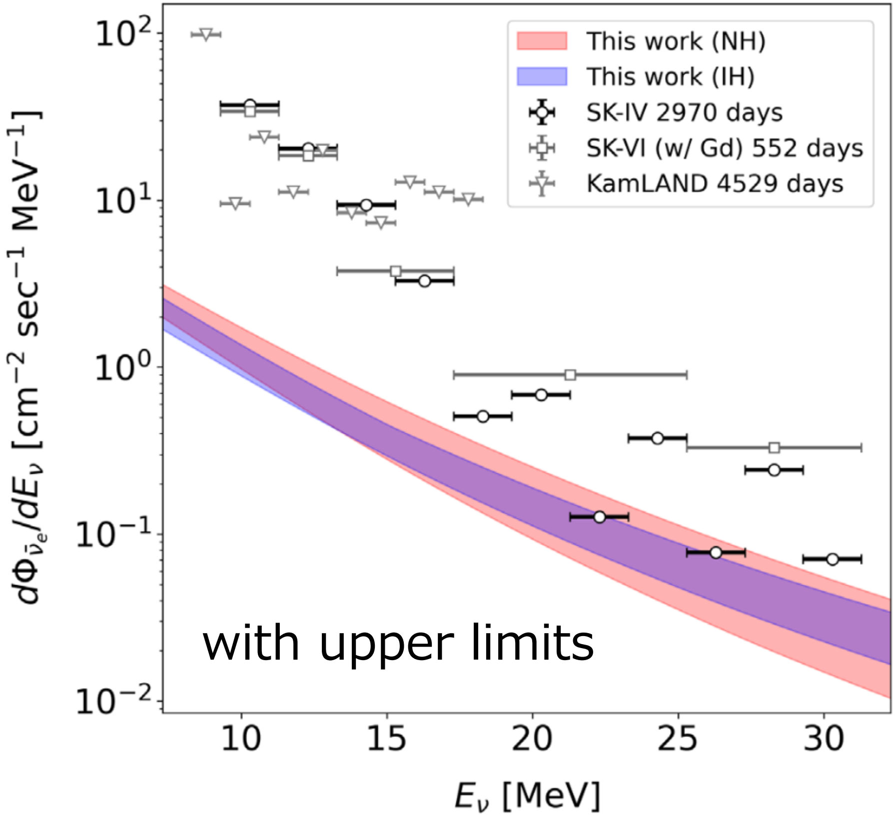
- We adopt 3 types of EOS in this study.
- We assume 1.35$M_\odot$ NS is formed.

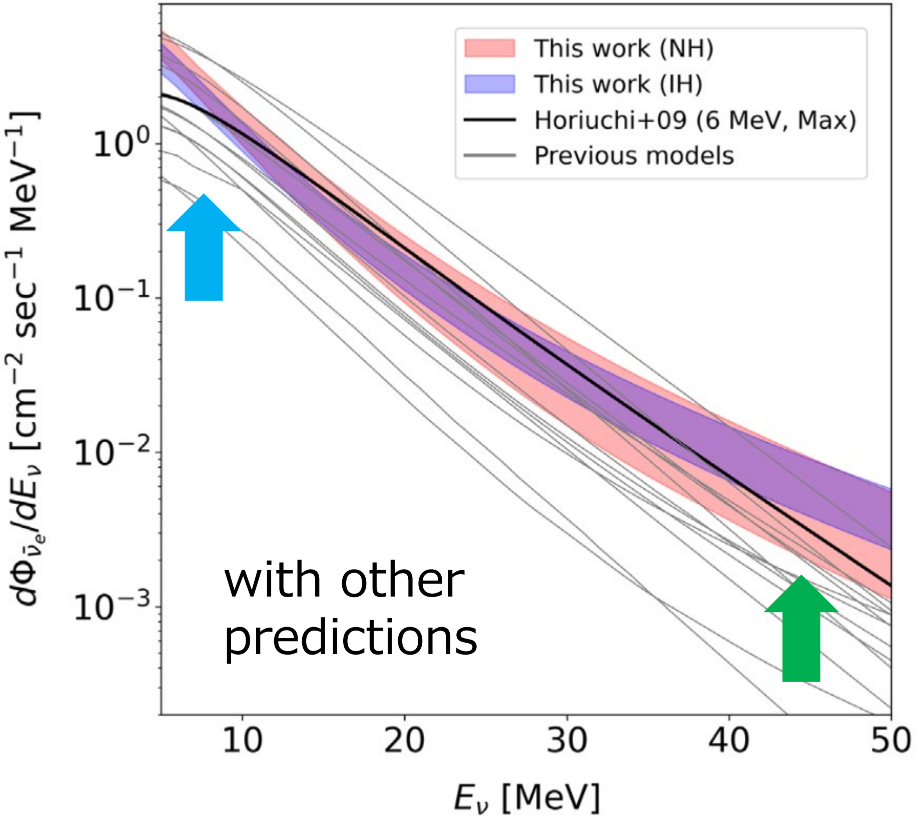


Nakazato et al.
ApJ. **925** (2022)

DSNB flux

Ashida, Nakazato & Tsujimoto,
ApJ **953** (2023), arXiv:2305.13543



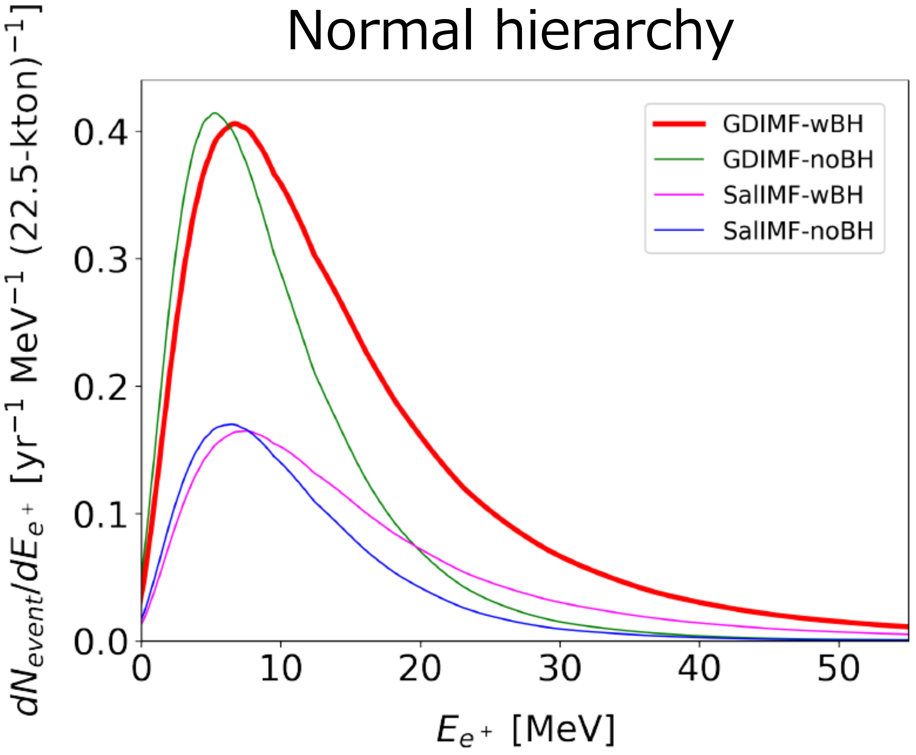


- Comparing with other work, enhancement at low ($\lesssim$10 MeV) and high ($\gtrsim$30 MeV) energies

→ due to high *z* and BH sources, respectively

Event spectra of DSNB

MD14 SFR, Togashi EOS,
Normal hierarchy



R: Galaxy-type dependent IMF,
$>18M_\odot \Rightarrow$ Black Hole

G: Galaxy-type dependent IMF,
$>18M_\odot \Rightarrow$ Neutron Star

P: Universal (Salpeter) IMF,
$>18M_\odot \Rightarrow$ Black Hole

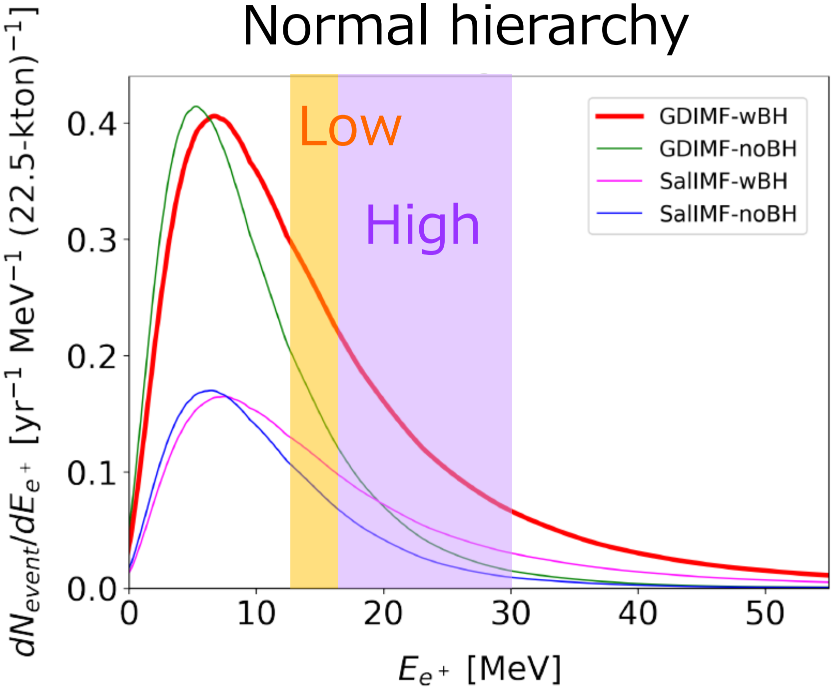
B: Universal (Salpeter) IMF,
$>18M_\odot \Rightarrow$ Neutron Star

- IMF determines total event rate.
- BH/NS determines spectral hardness.

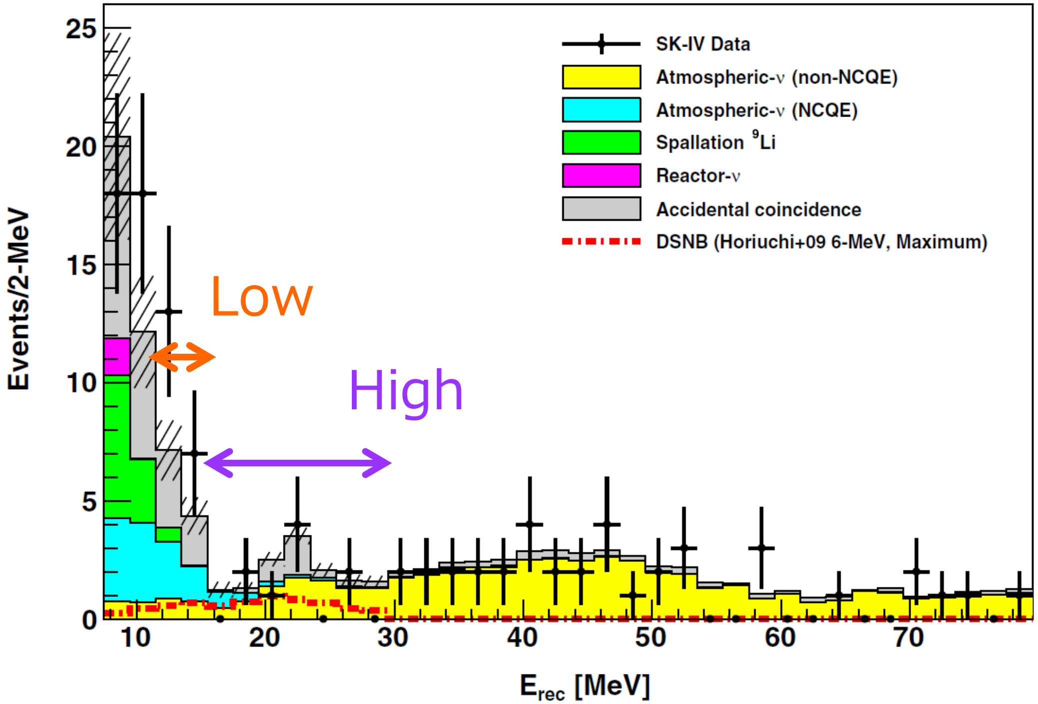
Spectral hardness

- Dividing the neutrinos into two energy bins
  - Low-energy bin: 13.3 < E_ν < 17.3 MeV
  - High-energy bin: 17.3 < E_ν < 31.3 MeV

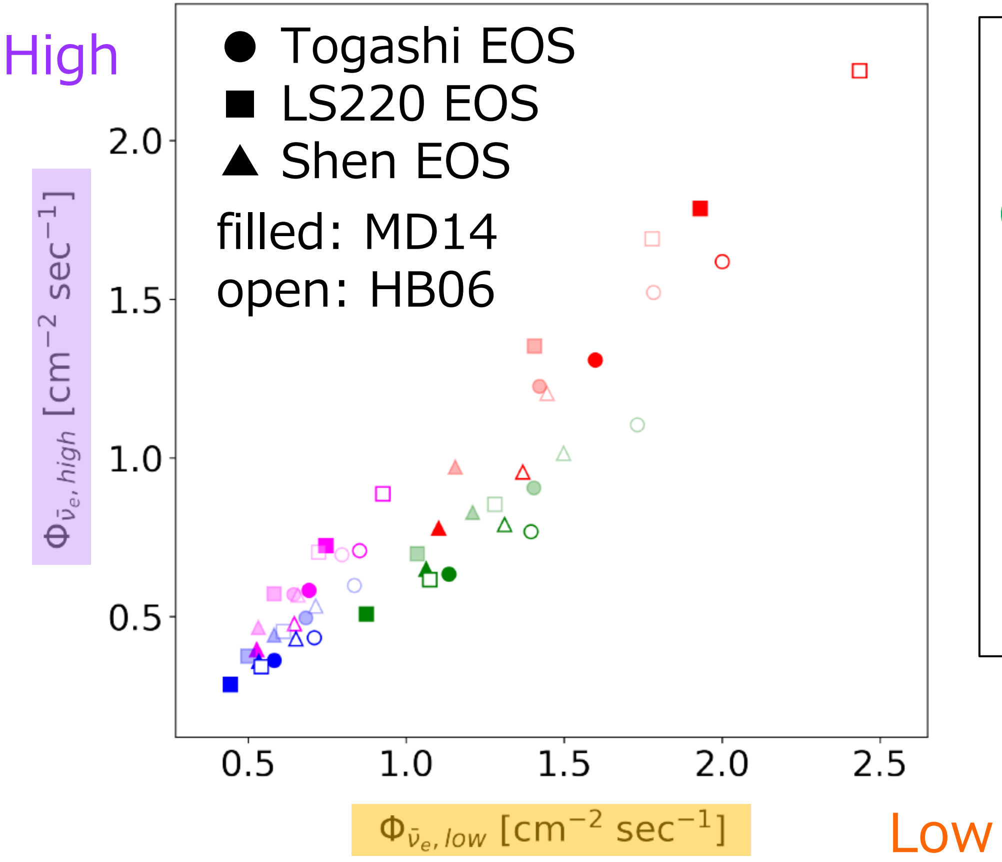
MD14 SFR, Togashi EOS,
Normal hierarchy



Abe et al.
Phys. Rev. D **104**, 122002 (2021)



High/Low energy flux



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thick symbol: Normal
thin symbol: Inverted

- Categorized by IMF and fate of stars $>18M_\odot$
  - Larger uncertainty than IMF, EOS, and mass hierarchy of neutrinos

Evaluation of signal significance

- Analysis based on Bayes' theorem

$$P(\text{model}|\text{obs}) = \frac{P(\text{obs}|\text{model}) \times P(\text{model})}{\sum_{\text{model}} P(\text{obs}|\text{model}) \times P(\text{model})}$$

- Observables are low （13.3 $< E_\nu <$ 17.3 MeV） and high （17.3 $< E_\nu <$ 31.3 MeV） energy event numbers： obs = $\{N_{\text{low}}, N_{\text{high}}\}$

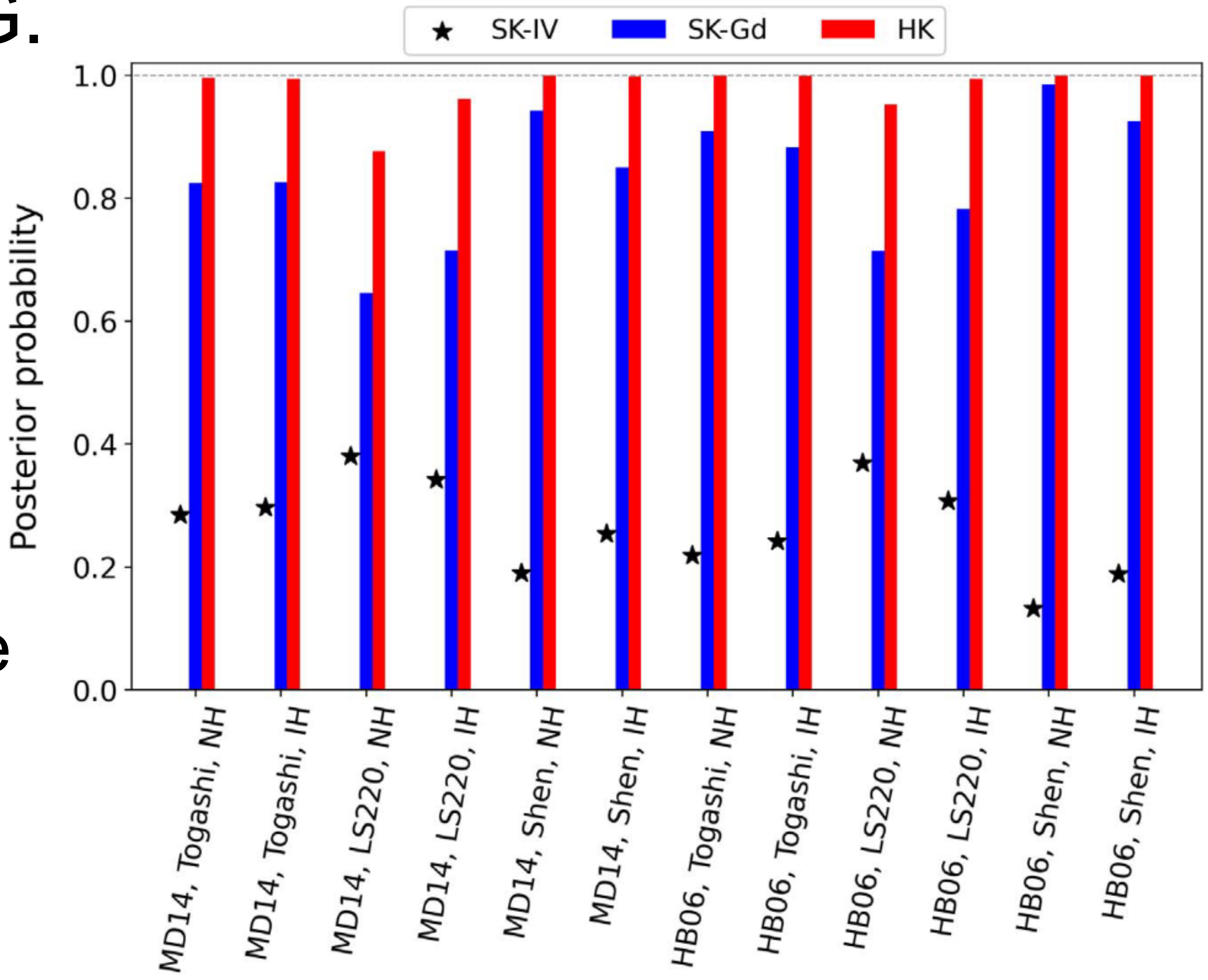
- Models with our DSNB + BG vs BG only
  - BG: non-NCQE, NCQE, accidental, Li9
  - Systematic and statistical errors are considered.

Results of signal significance

- Mostly, our signal models can be detected well over BG.

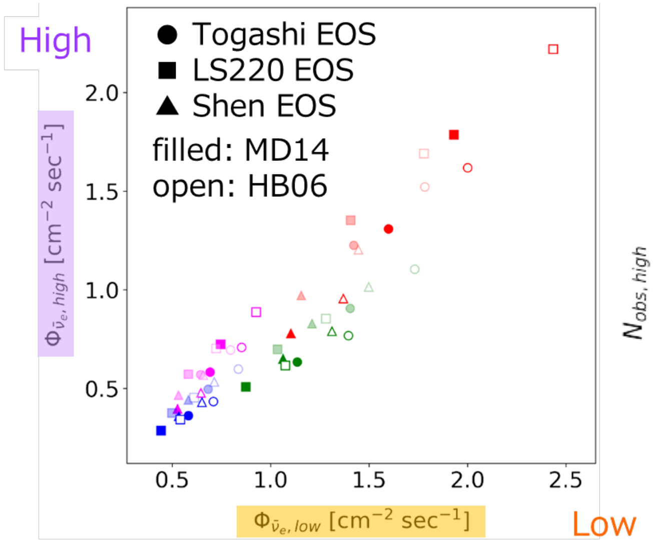
SK-Gd (10 yr):
70% neutron-tag efficiency

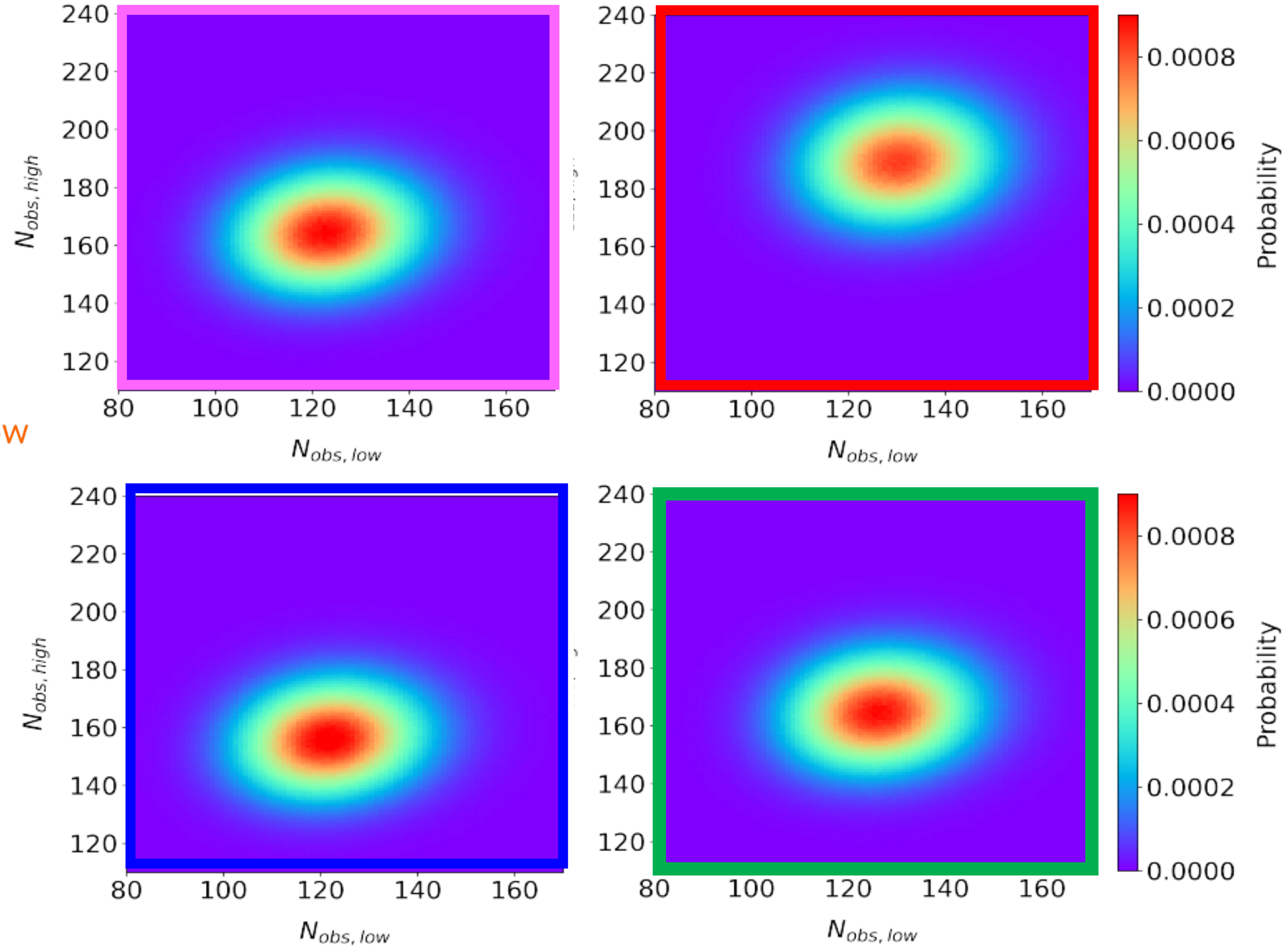
HK (10 yr):
neutron-tag efficiency same with SK-IV



Heatmap of N_{low} vs N_{high}

- Expected event count over 10 years in HK.

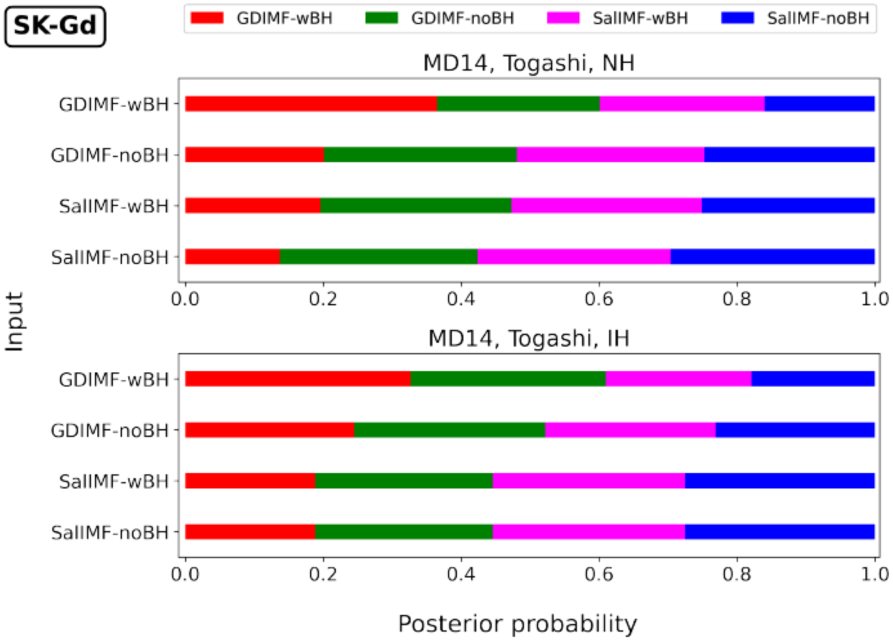


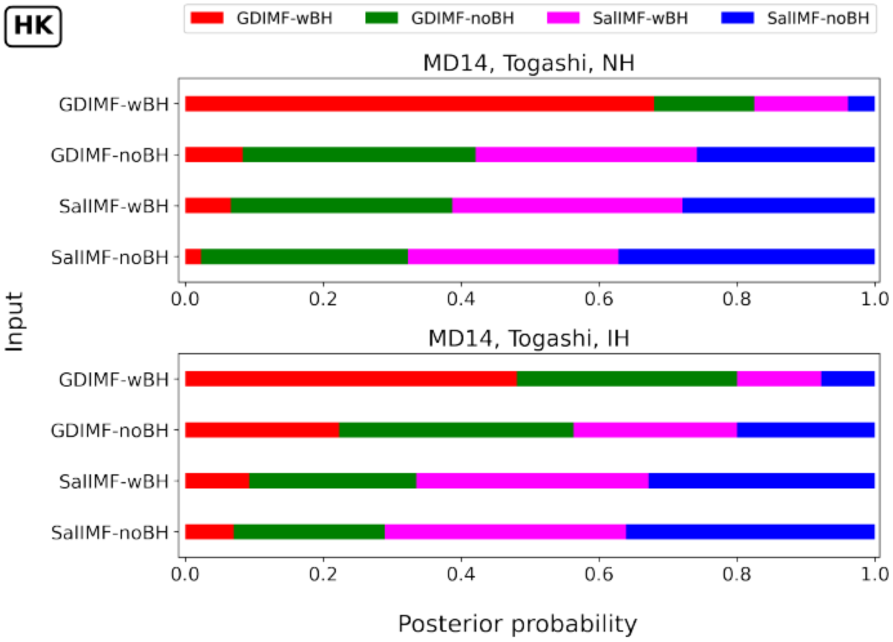


MD14 SFR,
Togashi EOS,
Normal hierarchy

Model discrimination

- Posterior resulting from each input model





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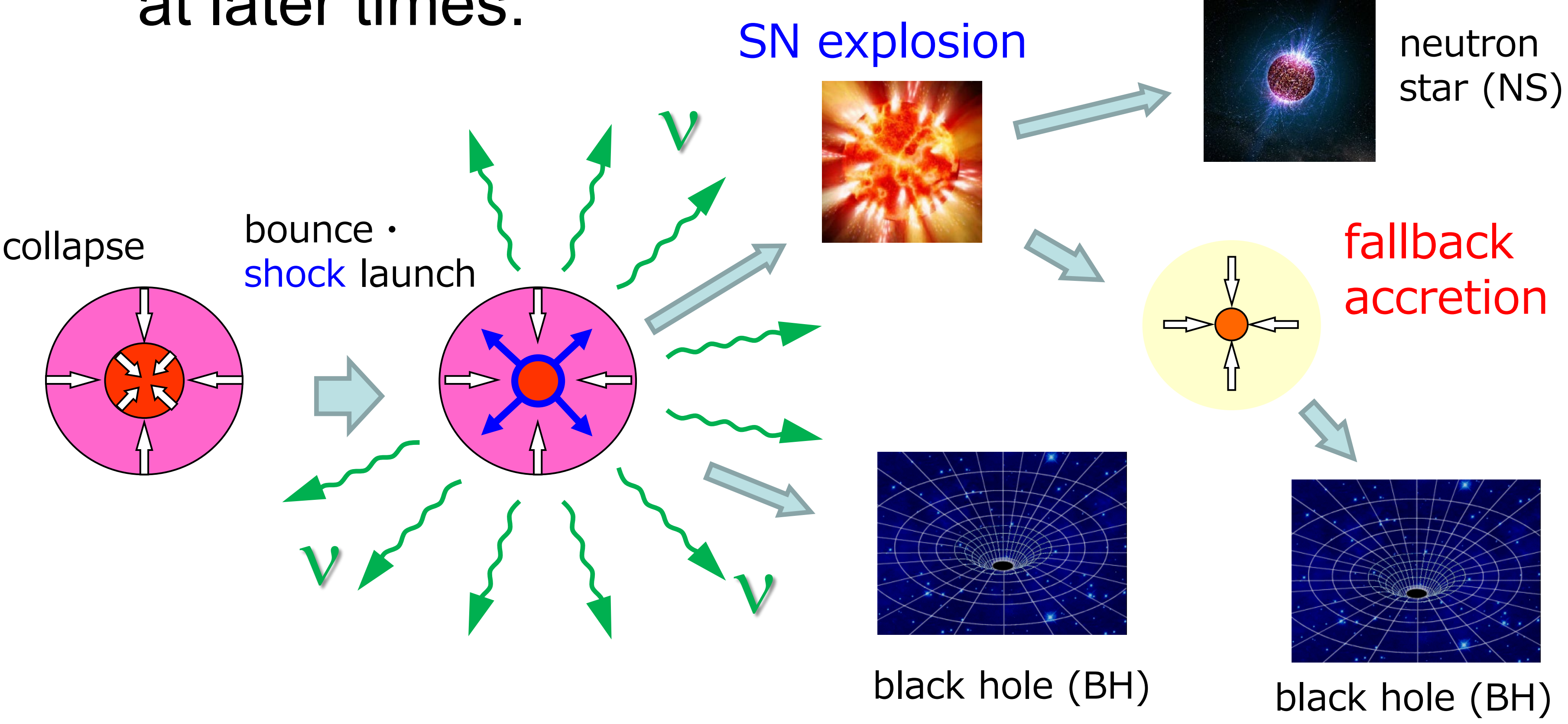
Nakazato, Akaho, Ashida & Tsujimoto,
ApJ in press,
arXiv:2406.13276

Another candidate

- Fallback accretion induced BH formation
    - ➢ Successful SN explosions accompanied by a substantial fallback that leads to a BH formation at later times.



collapse

bounce・
shock launch

ν

ν

ν

SN explosion

neutron
star (NS)

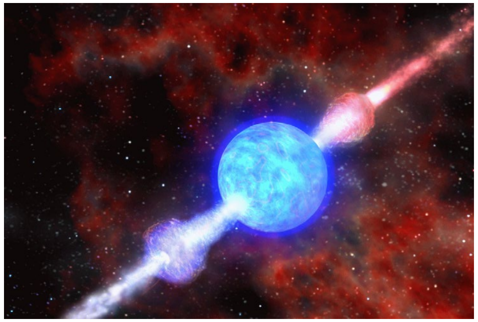
fallback
accretion

black hole (BH)

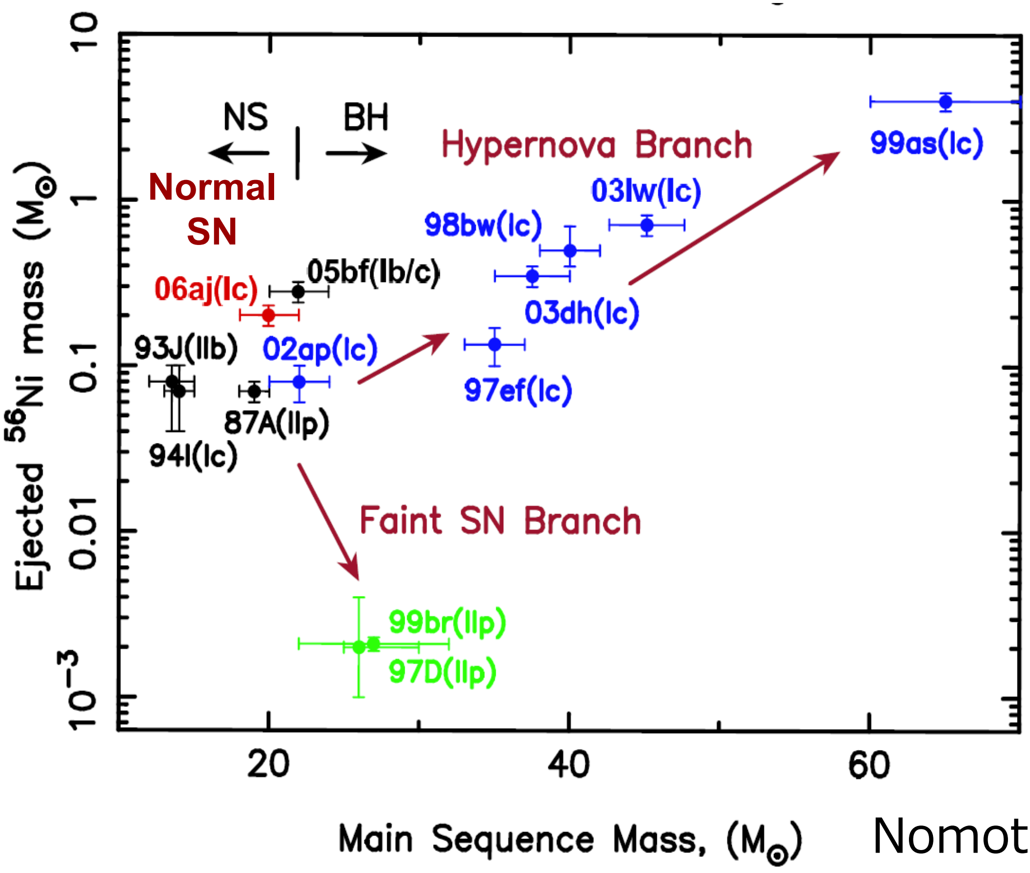
black hole (BH)

Why we study them?

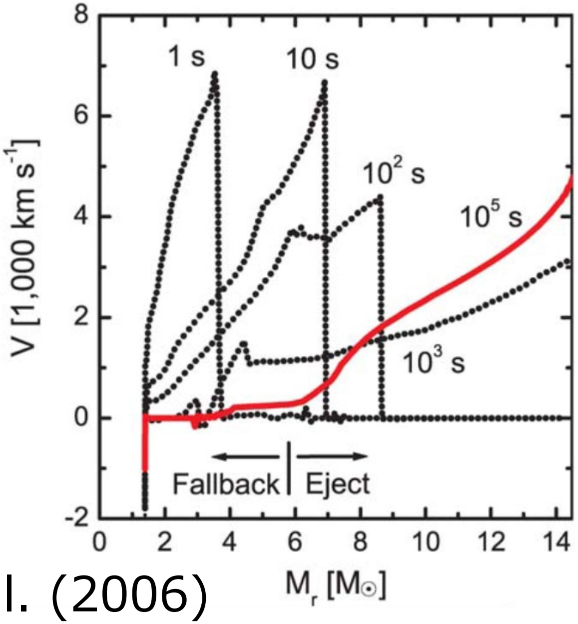
- Nucleosynthesis and chemical evolution
  - Hypernovae
  - Faint supernovae



GRB



fallback



Nomoto et al. (2006)

Why we study them?

- If exist, their impact is large.

  → The binding energy E_{bin} of maximum mass NS is fully converted to neutrinos.

  ➢ E_{bin} = (baryon mass − gravitational mass) c^2

- For example (in Togashi EOS):

  ➢ canonical mass ($1.32M_{\odot}$) NS

  $E_{\mathrm{bin}} = (1.47 - 1.32)M_{\odot}c^2 = 2.7\times10^{53}$ erg

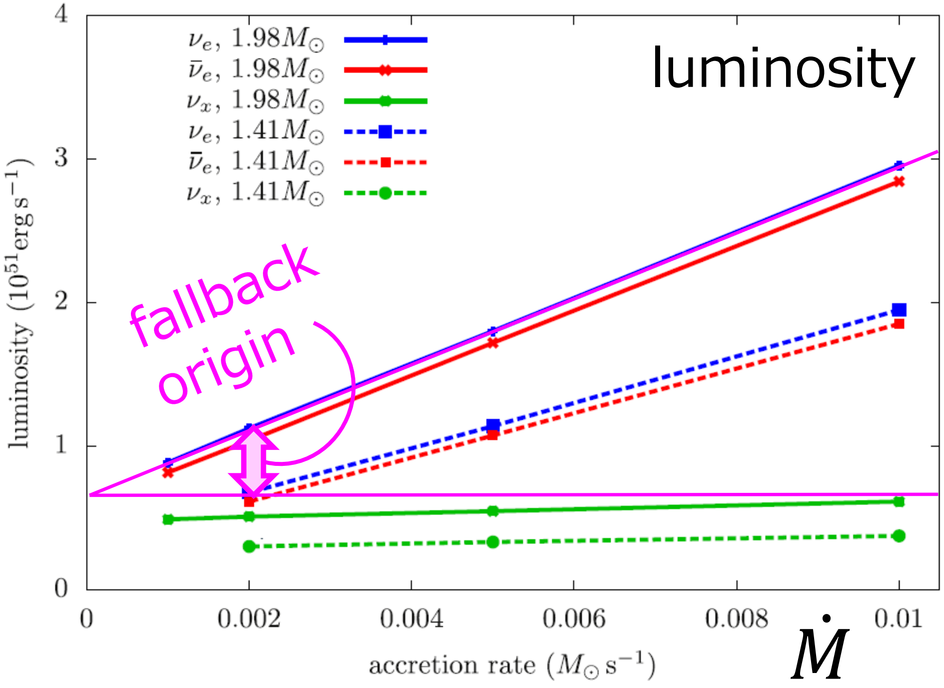
  ➢ maximum mass ($2.21M_{\odot}$) NS

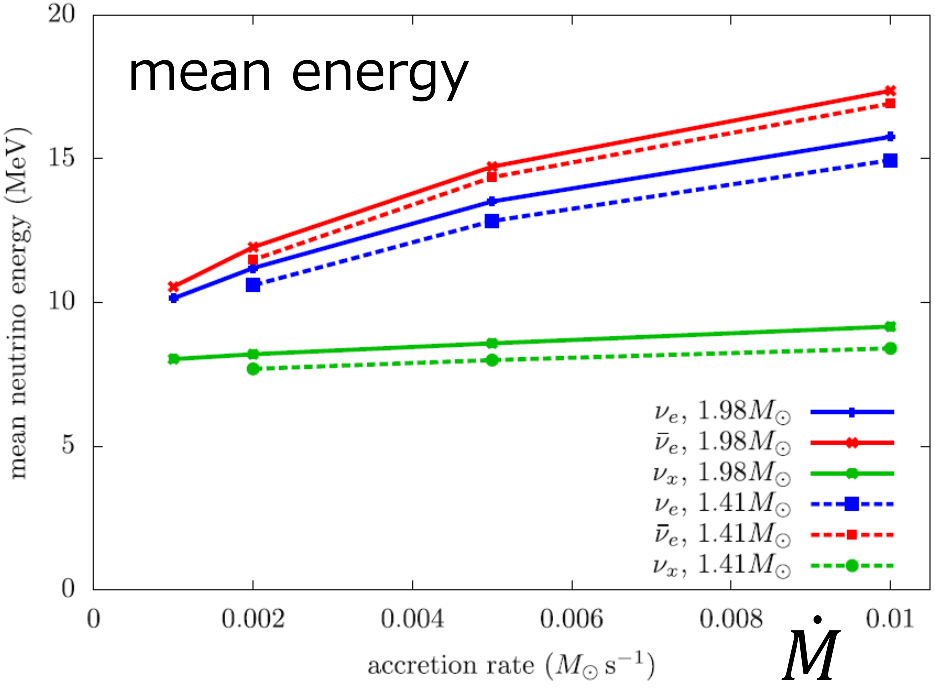
  $E_{\mathrm{bin}} = (2.70 - 2.21)M_{\odot}c^2 = 8.8\times10^{53}$ erg

Neutrinos from FB accretion

- Akaho, Nagakura & Foglizzo (2024)
  - ➢ Steady-state neutrino emission from fallback mass accretion onto PNS (1.41 and 1.98$M_\odot$)
    → M_g = 1.98$M_\odot$ corresponds to M_b = 2.35$M_\odot$
- Combining following 3 components:
  1. Core-collapse of massive star
  2. Cooling of 1.98$M_\odot$ proto-NS cooling
  3. Fallback accretion of 0.35$M_\odot$
     - ➢ Max. mass of NS is M_b = 2.70$M_\odot$ (Togashi).
     - ➢ We evaluate ν spectra emitted from fallback.

According to Akaho+ (2024)

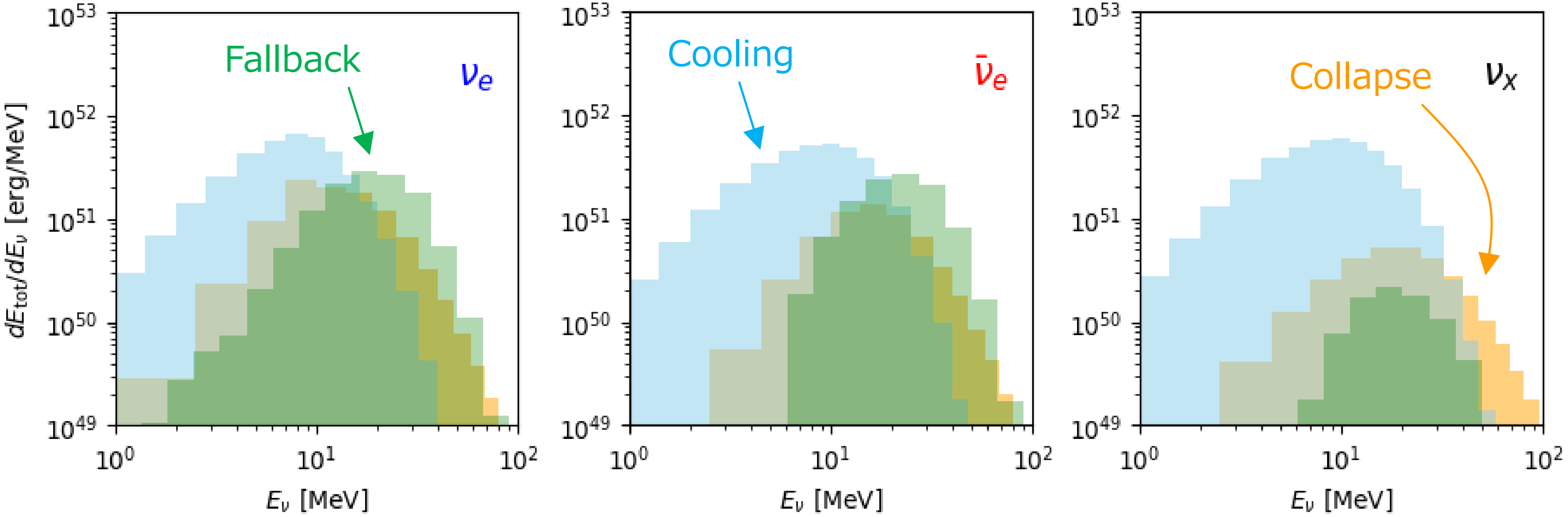




- Fallback produces high-energy ν_e and $\bar{\nu}_e$.
  - ➢ Their luminosity gets higher for larger $\dot{M}$.
- Emission of ν_x is from inside PNS.
  - ➢ Offsets of ν_e and $\bar{\nu}_e$ luminosities are as well.

Model description

- Neutrino spectra of individual component.



  - ➢ Resultant total emission energy: 8.7×10^{53} erg

- In this study, we assume that $f_{\rm BHSN}$ to be the fraction of SNe associating fallback induced BH formation among all CCSNe.

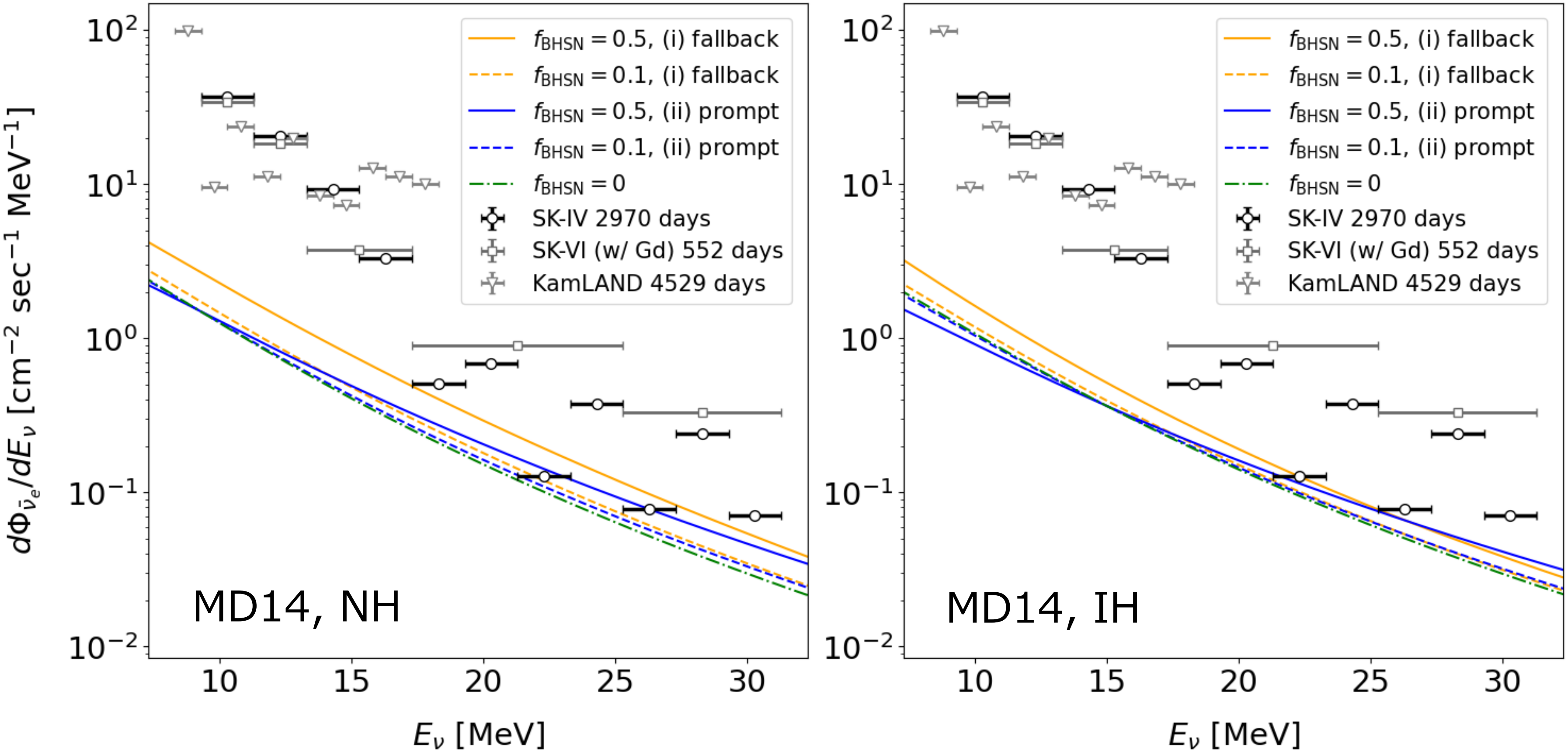
Two extremes

- The duration from bounce to BH formation determines the amount of emitted neutrinos.
  1. Fallback lasts for several tens of seconds.
     → Neutrinos corresponding to the binding energy of the maximum mass NS are released.
  2. Short duration similar with failed SNe.
     → The average energy is high but total energy is not exceedingly large.

Model	explosion	remnant	$\langle E_{\nu_e} \rangle$ (MeV)	$\langle E_{\bar{\nu}_e} \rangle$ (MeV)	$\langle E_{\nu_x} \rangle$ (MeV)	$E_{\nu_e,\mathrm{tot}}$ (10^{52} erg)	$E_{\bar{\nu}_e,\mathrm{tot}}$ (10^{52} erg)	$E_{\nu_x,\mathrm{tot}}$ (10^{52} erg)
Ordinary core-collapse SN	successful	NS	9.2	10.9	11.8	4.47	4.07	4.37
BH-forming SN, (i) fallback induced	successful	BH	11.8	13.6	10.9	19.48	18.50	12.07
BH-forming SN, (ii) prompt	successful	BH	16.1	20.4	23.4	6.85	5.33	2.89
Failed SN	failed	BH	16.1	20.4	23.4	6.85	5.33	2.89

DSNB flux

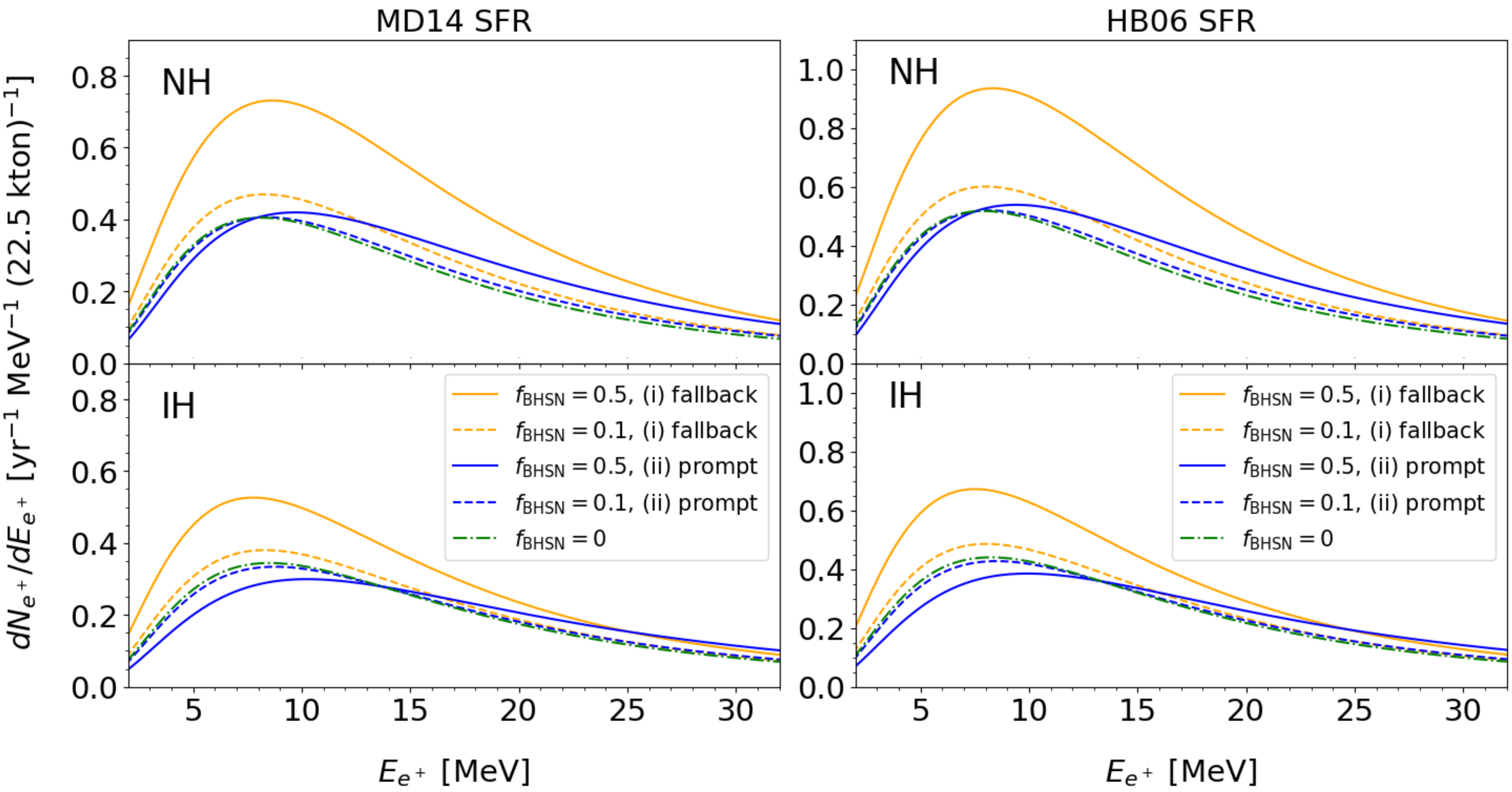
Nakazato et al., arXiv:2406.13276



- The impact is larger for NH case
  - ∵ The fallback accretion produce mainly ν_e and $\bar{\nu}_e$.
- NH, HB06, $f_{\rm BHSN}$ = 0.5 case is close to limits.

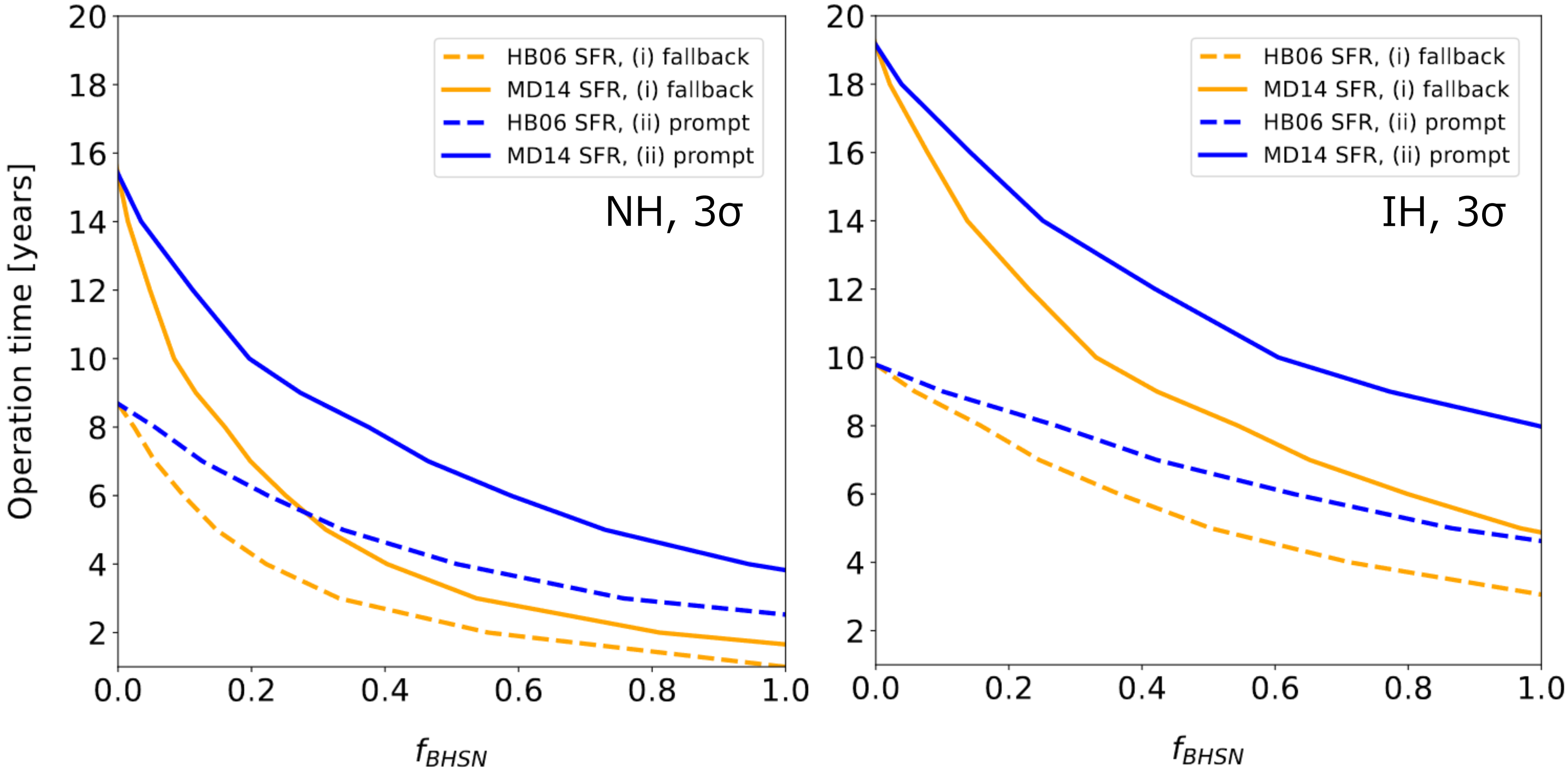
Event rate

Nakazato et al., arXiv:2406.13276



- For NH and f_{BHSN} = 0.5 case, event rate in the detectable range (16-30 MeV) gets twice.

Required operation time



- For NH and f_{BHSN} = 0.2 case, required time for 3σ detection at HK is shortened by half.

Conclusions

- The standard model of the DSNB flux, including its uncertainties, is becoming better understood.
- With extreme models considered, it could be as high as current observational limits.
  - ➢ With large fraction of failed SNe and BH-forming (successful) SNe
- In the coming years, SK-Gd, JUNO, and HK will likely exclude these extreme models.
  - ➢ Further effort would be required for model discrimination (counterarguments are welcome!)