ニュートリノで読み解くブラックホール形成

諏訪雄大（東大総文/京大基研）

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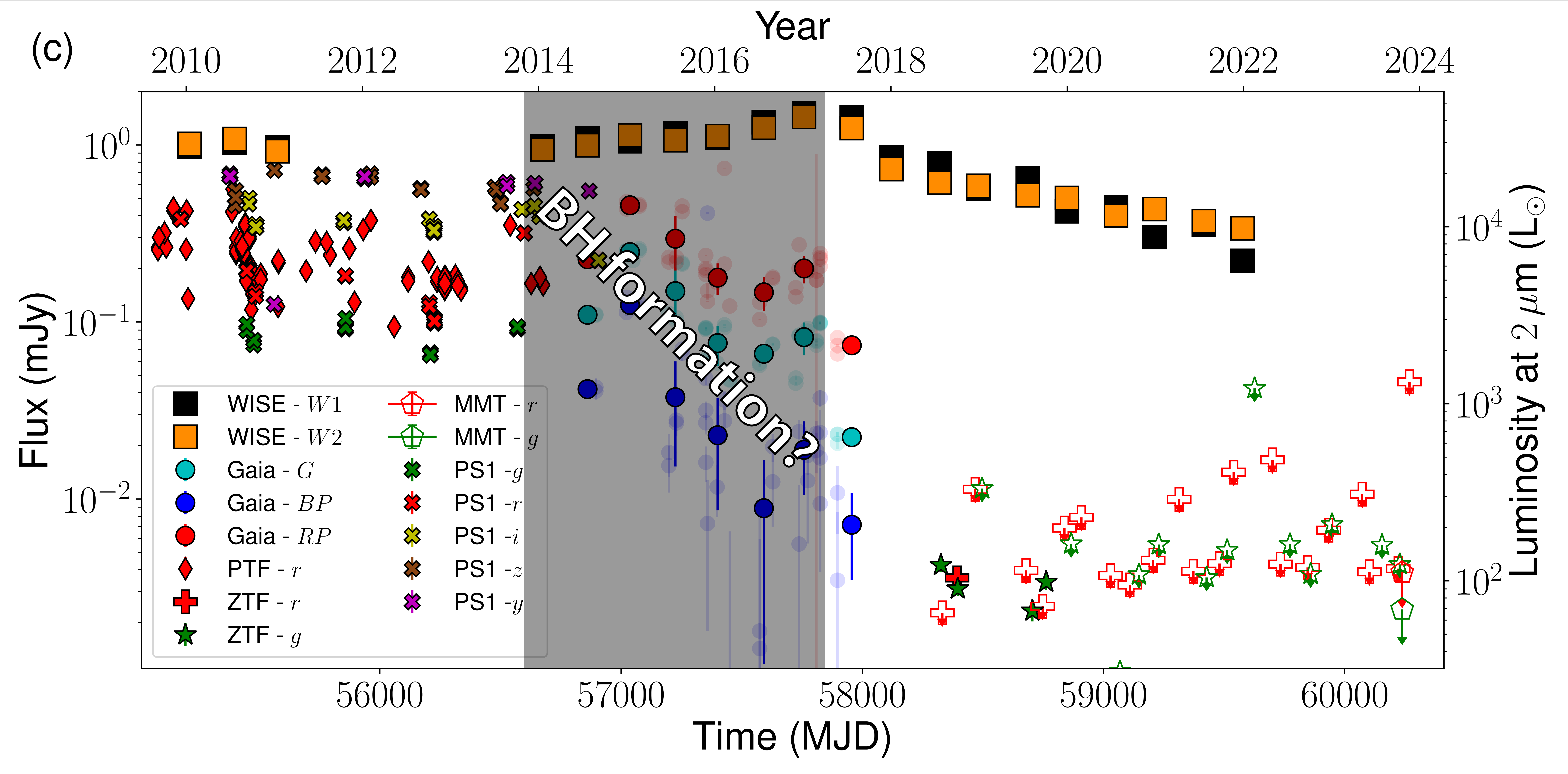
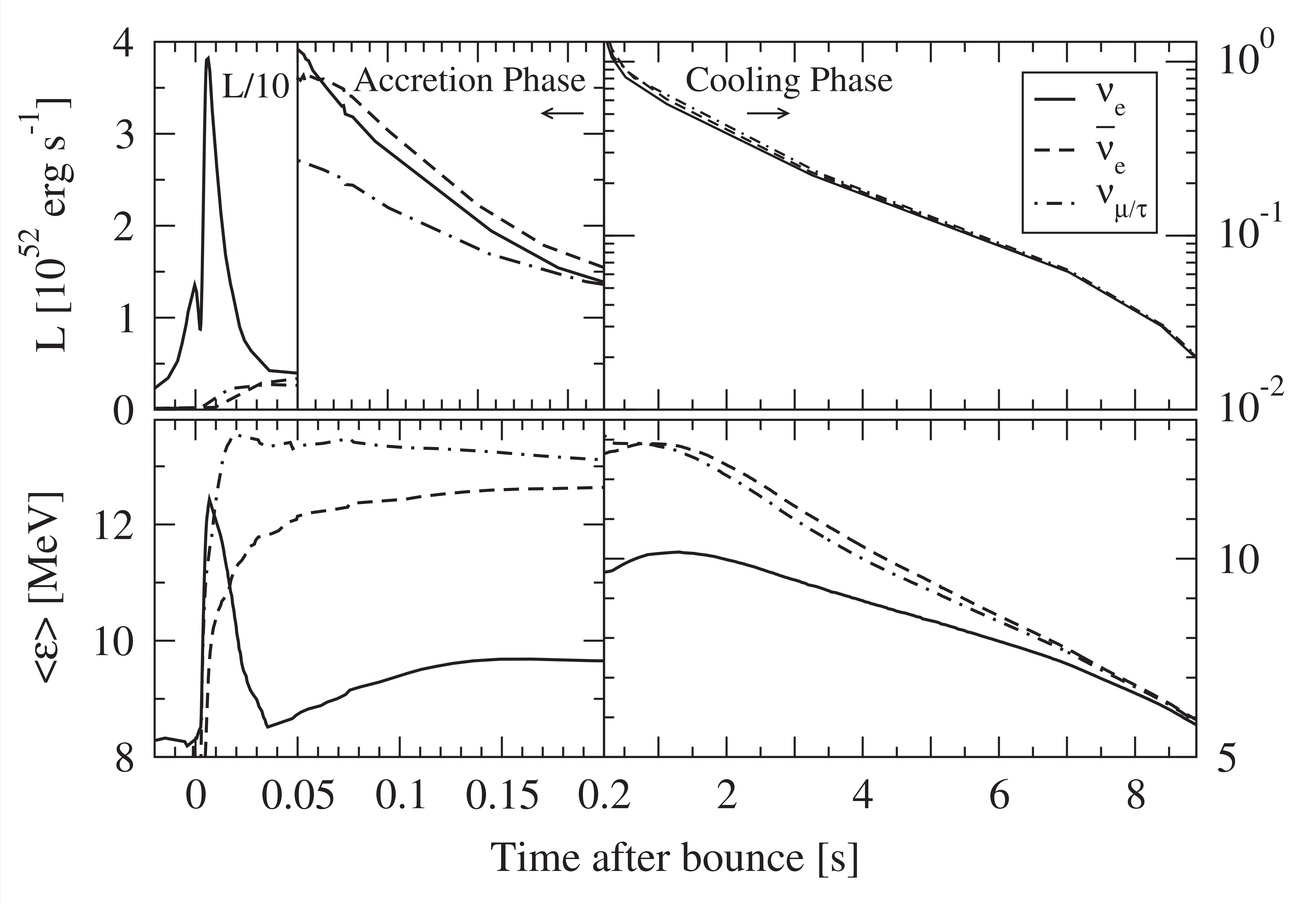
M31-2014-DS1 (D=770 kpc)

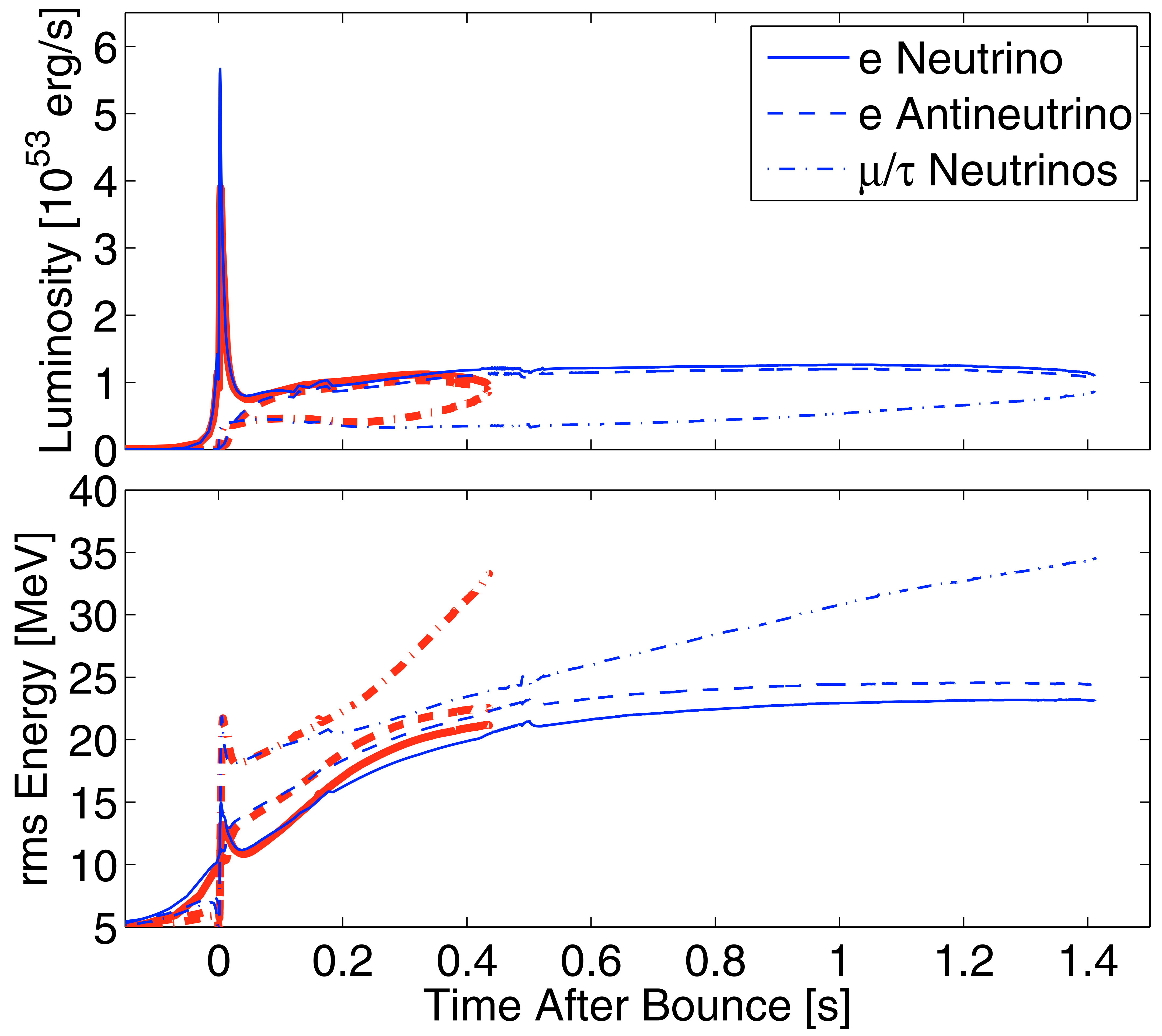


De+ 2024

Neutrino emissions in neutron star/black hole formation



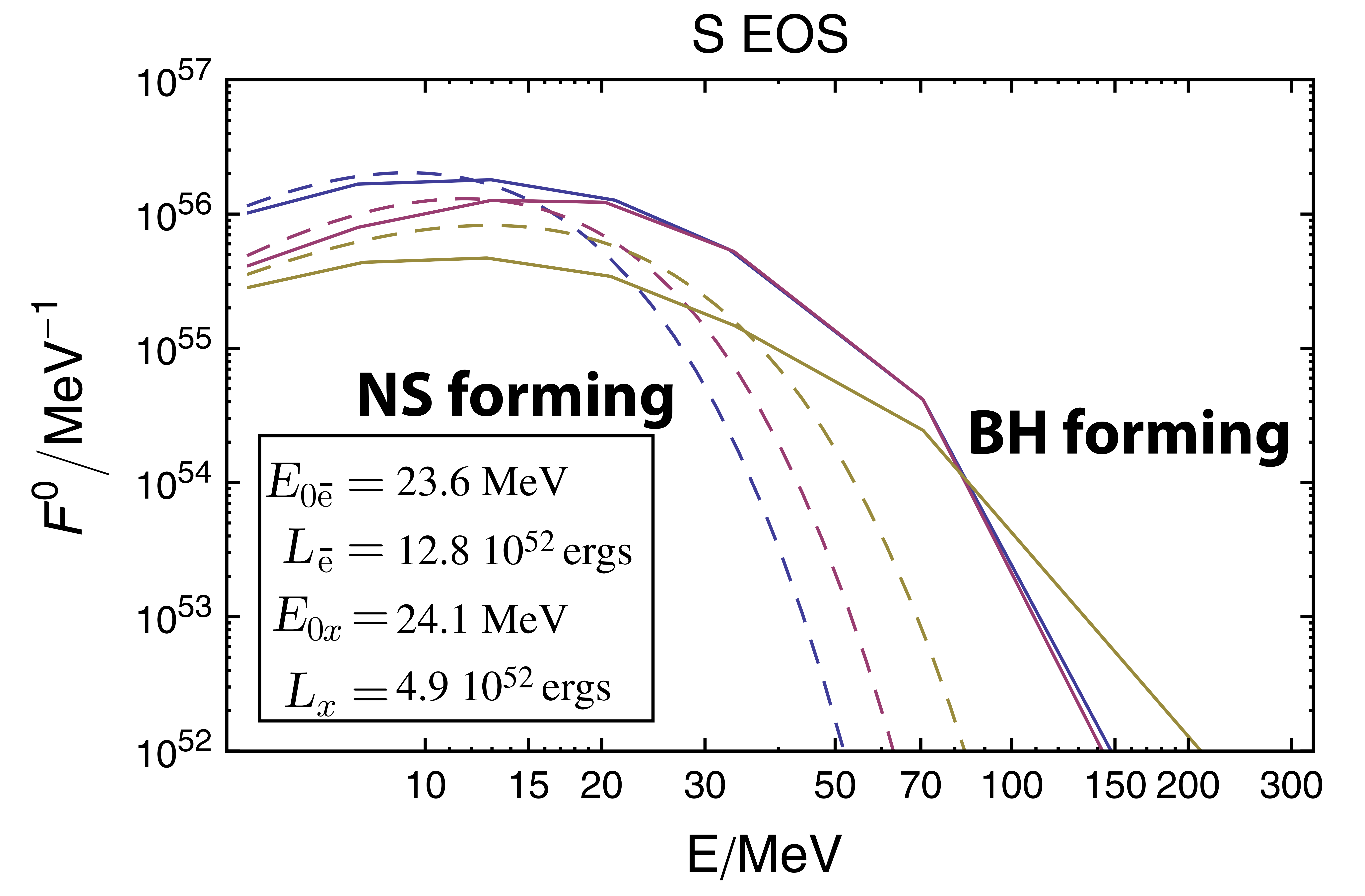
Hüdepohl+ 2010 (NS forming)



Fischer+ 2009 (BH forming)

Neutrino spectrum

Lunardini 2009



Expected neutrino numbers

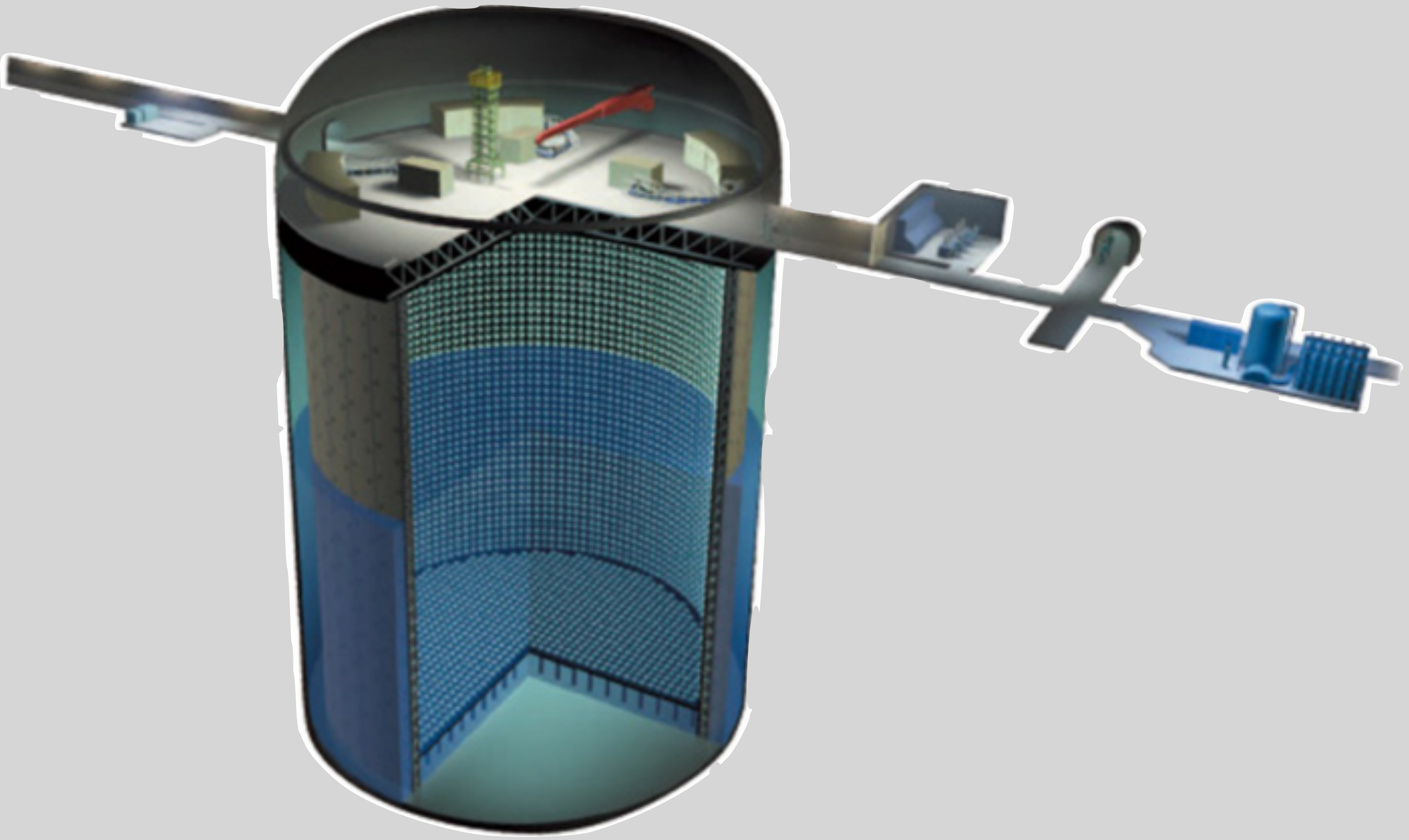
Inverse beta decay: $p + \bar{\nu}_e \rightarrow n + e^+$

$$N_\nu = \frac{2}{18}\frac{M_\mathrm{det}}{m}\frac{E_\nu}{4\pi D^2 \langle \epsilon_\nu \rangle}\langle \sigma \rangle$$

$$= 3.48 \left(\frac{D}{770\,\mathrm{kpc}}\right)^{-2} \left(\frac{\langle \epsilon_\nu \rangle}{15\,\mathrm{MeV}}\right) \left(\frac{E_\nu}{10^{53}\,\mathrm{erg}}\right)$$

average energy

total energy



http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/introduction.html

Constraints with Super-Kamiokande IV data

4.1. *Cluster Search*

Events surviving the pre-selection above are passed to a search algorithm that identifies clusters of events occurring within any of three specified time windows. The limits of these time windows are chosen based on the evolution of the neutrino flux during a supernova using criteria from the previous study (Ikeda et al. 2007). The 0.5 s window corresponds to the time between the initial collapse and subsequent bounce. The 2 s window covers the time until the shock is revived. The 10 s window corresponds to the neutron star cooling phase. In order to enhance the analysis efficiency, the event thresholds for these time windows are roughly half those used in the previous study, requiring at least 2, 2, and 4 events per cluster, respectively. The time windows are shown in Table 2. These criteria were analyzed to ensure they increased sensitivity without increasing the rate of background clusters. The number of events forming a cluster identified by the selection criteria is referred to as the cluster's multiplicity. See Section 5.1 for details.

Time window 1	$\geq$ 2 events in 0.5 [s]
Time window 2	$\geq$ 2 events in 2 [s]
Time window 3	$\geq$ 4 events in 10 [s]

Table 2. Time window settings.

Mori+ 2022

No event cluster found!

(Almost) complete simulation list

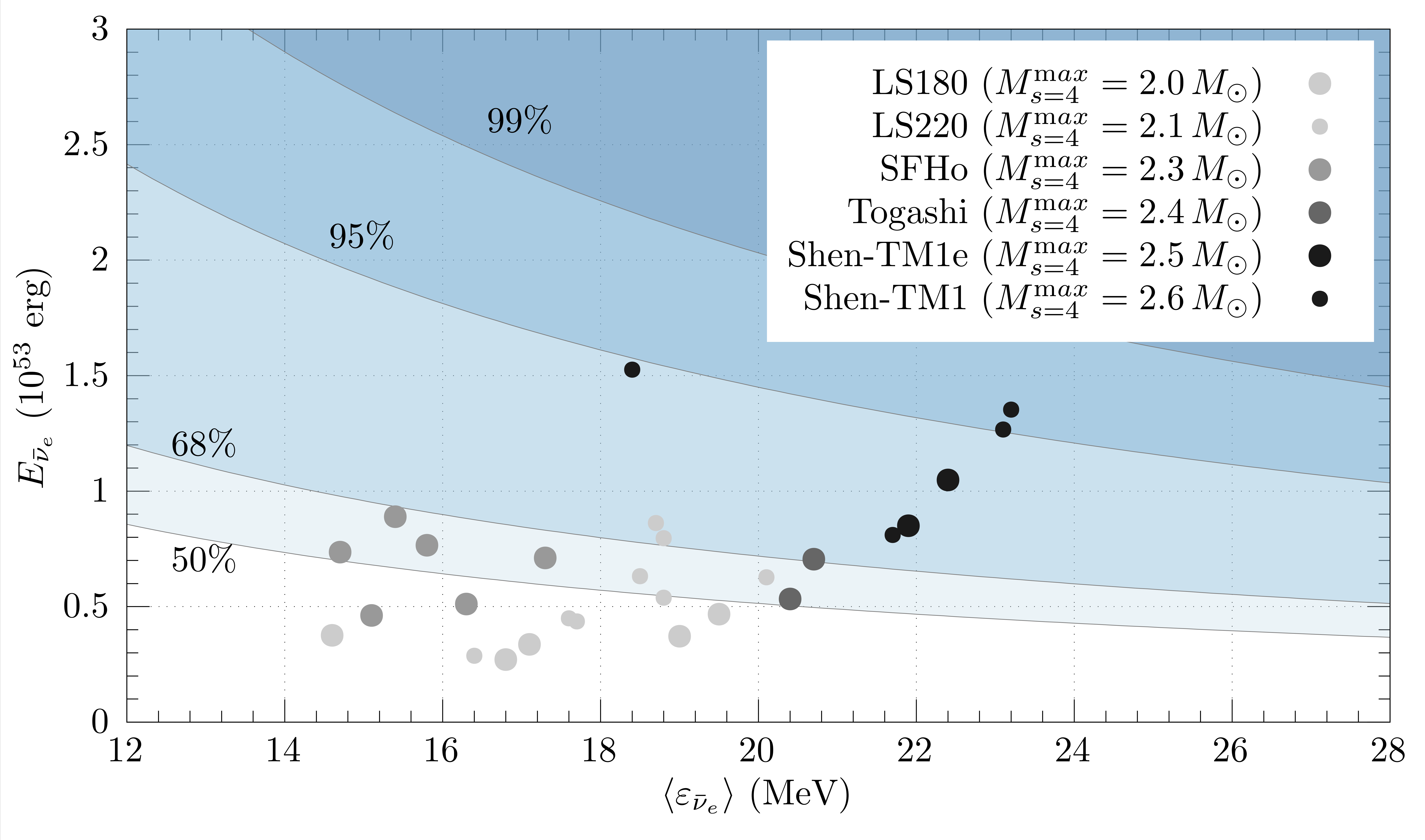
[Suwa, Akaho, Ashida, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, Zaizen, arXiv:2504.19510]

TABLE 1
Summary of Simulations

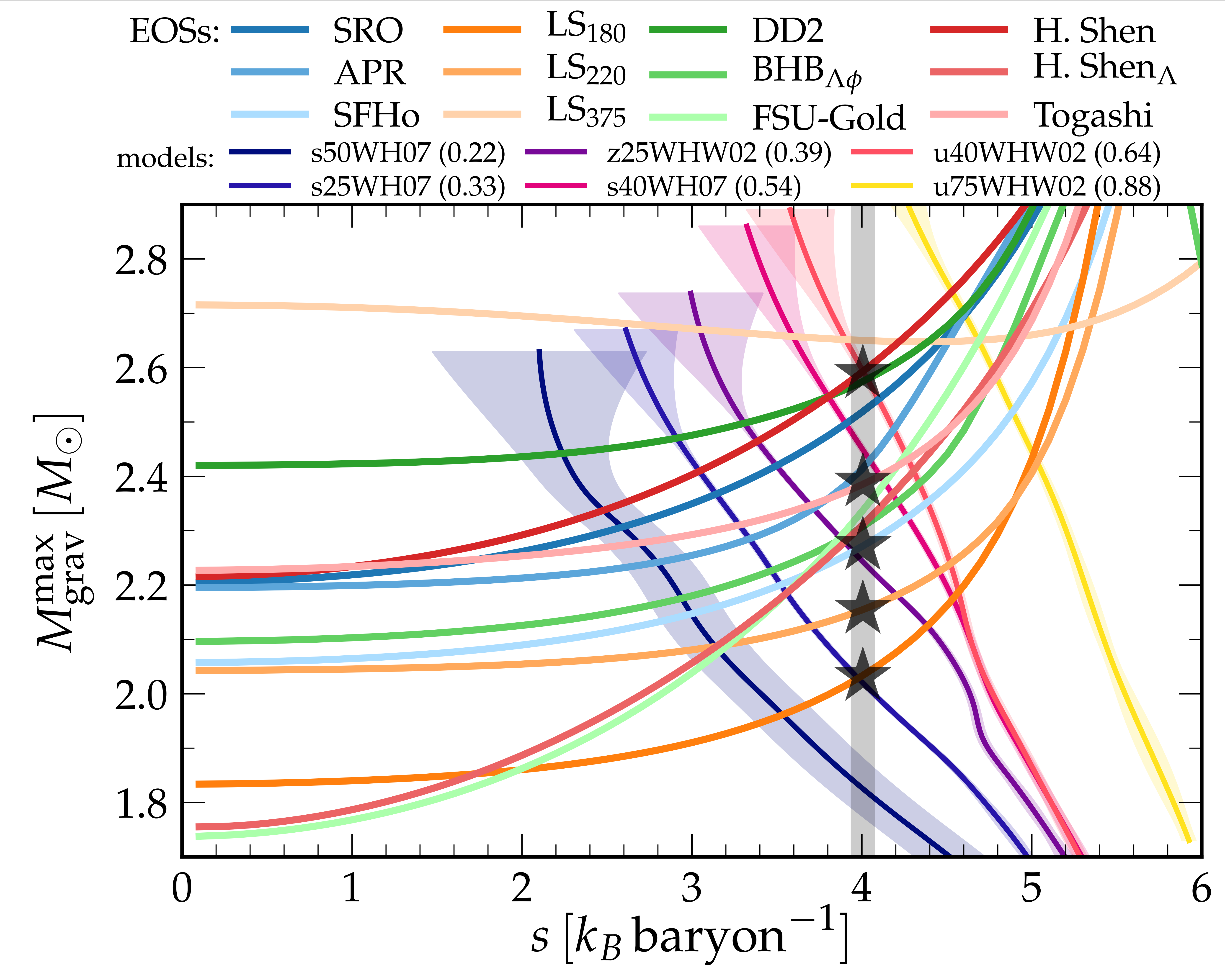
References[a]	Progenitor mass ($M_\odot$)	EOS	Gravity	$t_{\rm BH}$[b] (s)	E_{ν_e} (10^{53} erg)	$E_{\bar{\nu}_e}$ (10^{53} erg)	E_{ν_X} (10^{53} erg)	$\langle\varepsilon_{\nu_e}\rangle$ (MeV)	$\langle\varepsilon_{\bar{\nu}_e}\rangle$ (MeV)	$\langle\varepsilon_{\nu_X}\rangle$ (MeV)
Sumiyoshi et al. (2007)	40 (WW95[c])	LS180	fGR[d]	0.56	0.554	0.467	0.228	16.3	19.5	21.5
Sumiyoshi et al. (2007)	40 (WW95)	Shen-TM1	fGR	1.34	1.46	1.35	0.526	20.3	23.2	23.9
Sumiyoshi et al. (2008)	40 (H95[e])	LS180	fGR	0.36	0.334	0.271	0.160	13.5	16.8	21.9
Sumiyoshi et al. (2008)	50 (TUN07[f])	Shen-TM1	fGR	1.51	1.35	1.27	0.526	20.0	23.1	24.2
Sumiyoshi et al. (2008)	50 (TUN07)	LS180	fGR	0.507	0.450	0.372	0.191	15.7	19.0	21.2
Fischer et al. (2009)[g]	40 (WW95)	LS180	fGR	0.435	0.507	0.376	0.231	14.1	14.6	19.7
Fischer et al. (2009)	40 (WW95)	Shen-TM1	fGR	1.40	1.73	1.53	0.715	16.0	18.4	21.0
Nakazato et al. (2010)	40 (WW95)	LS220	fGR	0.780	0.729	0.627	0.382	17.3	20.1	24.1
Hüdepohl (2014)	40 (WW95)	LS180	eGR[h]	0.435	0.422	0.337	0.209	13.8	17.1	18.3
Hüdepohl (2014)	40 (WW95)	LS220	eGR	0.55	0.525	0.436	0.279	14.4	17.7	19.2
Hüdepohl (2014)	25 (WHW02[i])	LS220	eGR	1.225	0.696	0.632	0.331	15.3	18.5	17.7
Hüdepohl (2014)	40 (WHW02)	LS220	eGR	1.93	0.852	0.796	0.402	15.8	18.8	17.4
Sumiyoshi et al. (2019)	50 (TUN07)	Shen-TM1e	fGR	1.15	0.941	0.850	0.330	18.7	21.9	21.6
Sumiyoshi et al. (2019)	40 (WW95)	Shen-TM1e	fGR	1.103	1.15	1.05	0.422	19.3	22.4	23.1
Walk et al. (2020)	40 (WH07[j])	LS220	eGR	0.57	0.572	0.539	0.375	16.2	18.8	20.2
Nakazato et al. (2021)	30 (N13[k])	LS220	fGR	0.342	0.403	0.287	0.211	12.5	16.4	22.3
Nakazato et al. (2021)	30 (N13)	Togashi	fGR	0.533	0.685	0.533	0.289	16.1	20.4	23.4
Nakazato et al. (2021)	30 (N13)	Shen-TM1	fGR	0.842	0.949	0.81	0.400	17.5	21.7	23.4
Kresse et al. (2021)	40 (WW95)	LS220	eGR	0.57	0.938	0.862	0.483	15.7	18.7	17.6
Kresse et al. (2021)	40 (WHW02)	LS220	eGR	2.11	0.544	0.449	0.281	14.4	17.6	18.8
Choi et al. (2025)[l]	12.25 (S16&18[m])	SFHo	eGR	>2.09	0.563	0.511	0.297	13.9	16.3	15.5
Choi et al. (2025)	14 (S16&18)	SFHo	eGR	>2.82	0.768	0.711	0.393	15.0	17.3	15.9
Choi et al. (2025)	19.56 (S16&18)	SFHo	eGR	3.89	0.906	0.889	0.694	12.9	15.4	16.0
Choi et al. (2025)	23 (S16&18)	SFHo	eGR	6.23	0.776	0.736	0.609	12.4	14.7	14.8
Choi et al. (2025)	40 (S16&18)	SFHo	eGR	1.76	0.798	0.766	0.499	13.4	15.8	16.0
Choi et al. (2025)	100 (S16&18)	SFHo	eGR	0.44	0.529	0.462	0.246	12.9	15.1	17.1
unpublishded[n]	40 (WW95)	Togashi	fGR	0.927	0.824	0.705	0.471	18.1	20.7	25.7

Constraints

[Suwa, Akaho, Ashida, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, Zaizen, arXiv:2504.19510]



Nuclear equation of state and maximum mass of NS



Schneider+ 2020

Summary

* ニュートリノでブラックホール形成に迫る
* アンドロメダ銀河で見つかったM31-2014-DS1はその候補
* ブラックホール形成の数値シミュレーションによる予言：
  * 中性子星形成時と比較して、ニュートリノ光度と平均エネルギーが高い
  * 特に、中性子星の最大質量が大きい状態方程式ほど顕著
* Super-Kamiokande観測による制限：
  * 2個以上のイベントクラスターは発見されなかった
* これらを組み合わせることで、状態方程式に制限を与えた