超新星ニュートリノの理論研究

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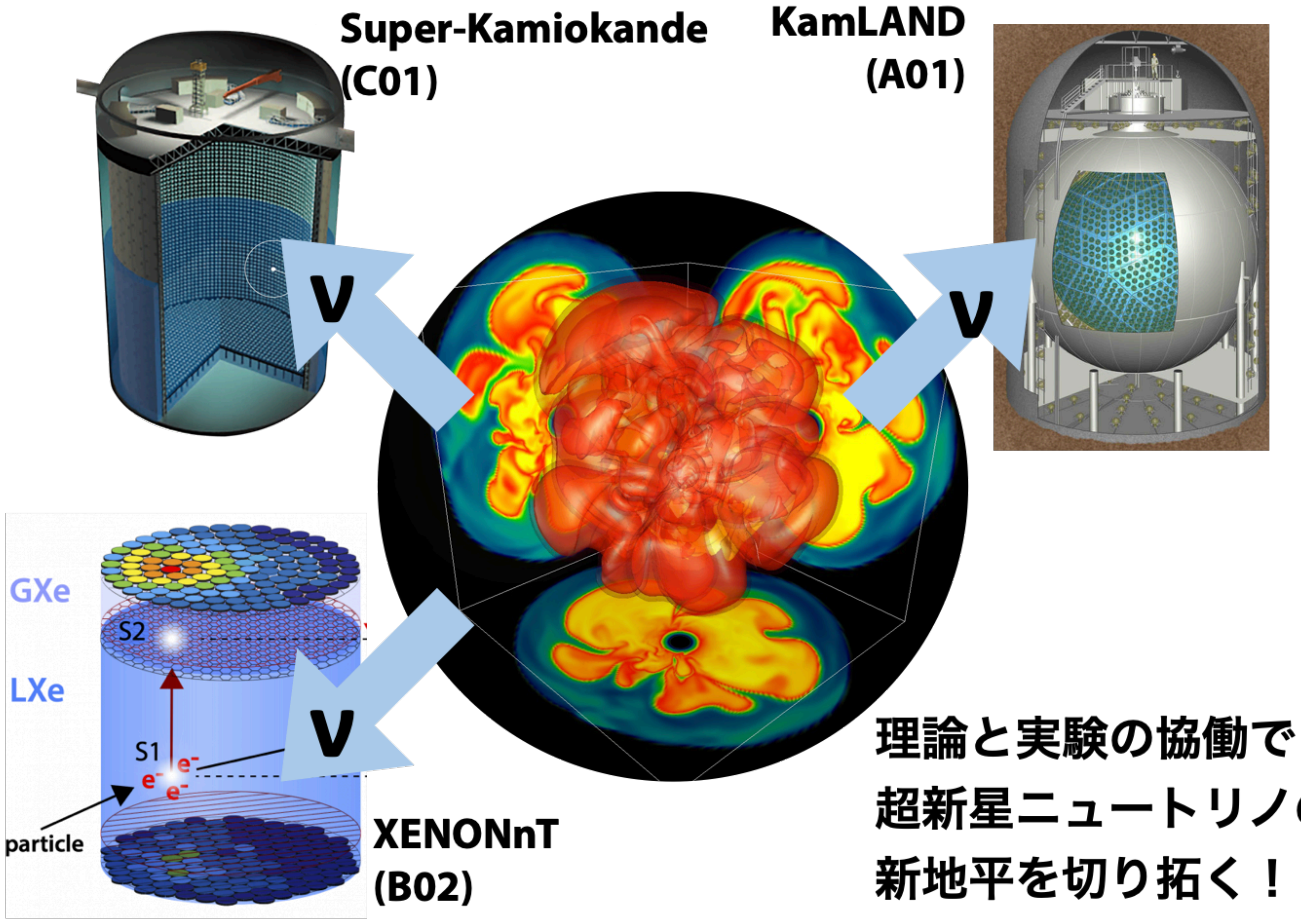
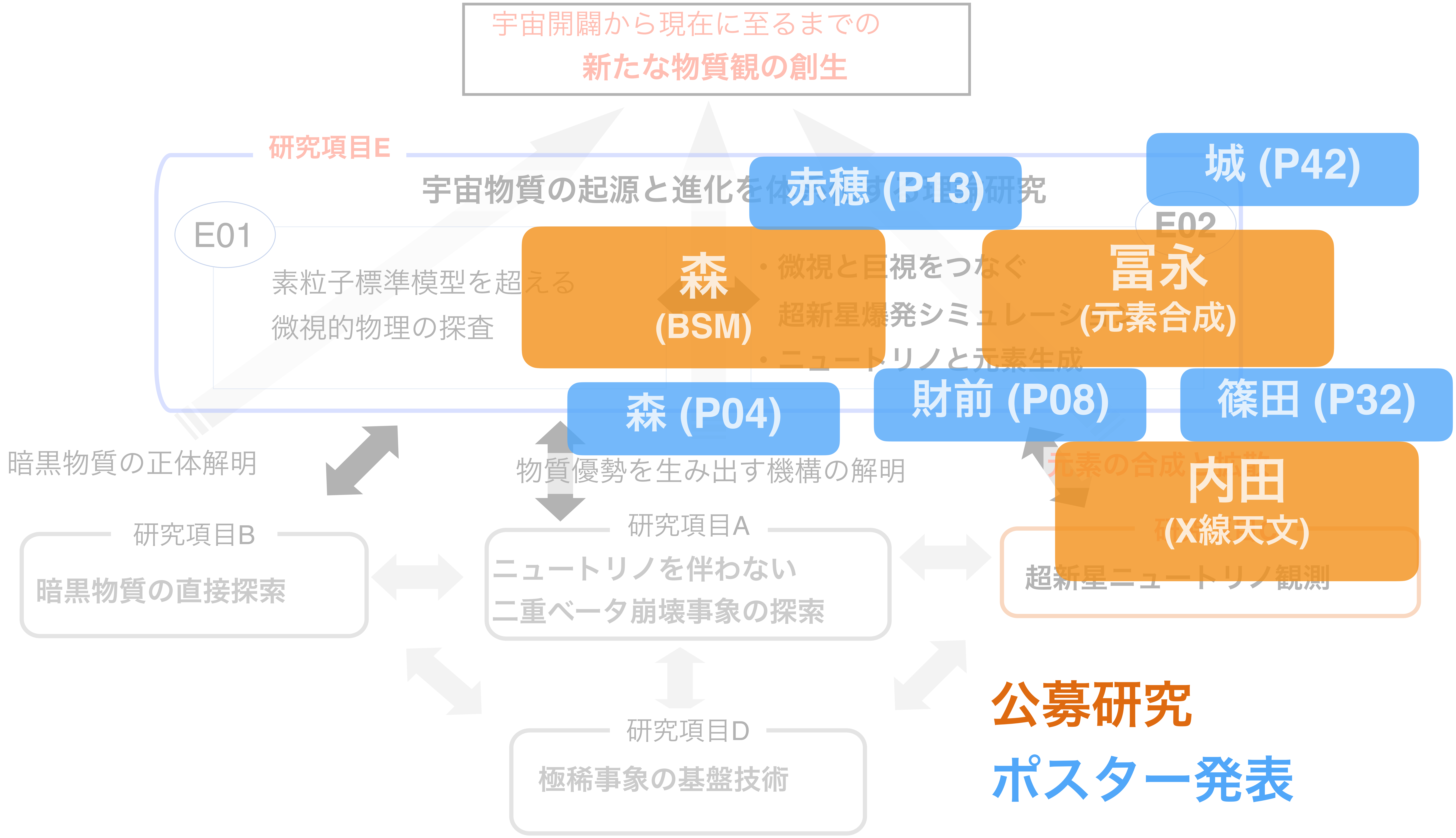
E02: 全ニュートリノフレーバーを用いた超新星ニュートリノの理論研究

- 重元素の起源＝超新星爆発
- 超新星爆発機構は宇宙物理学の最大の謎のひとつ
- **超新星ニュートリノの精密測定(A01/B02/C01)と詳細理論(E02)で中心に迫る**
- ミクロな新物理(E01)とマクロな天体現象(E02)を結ぶ

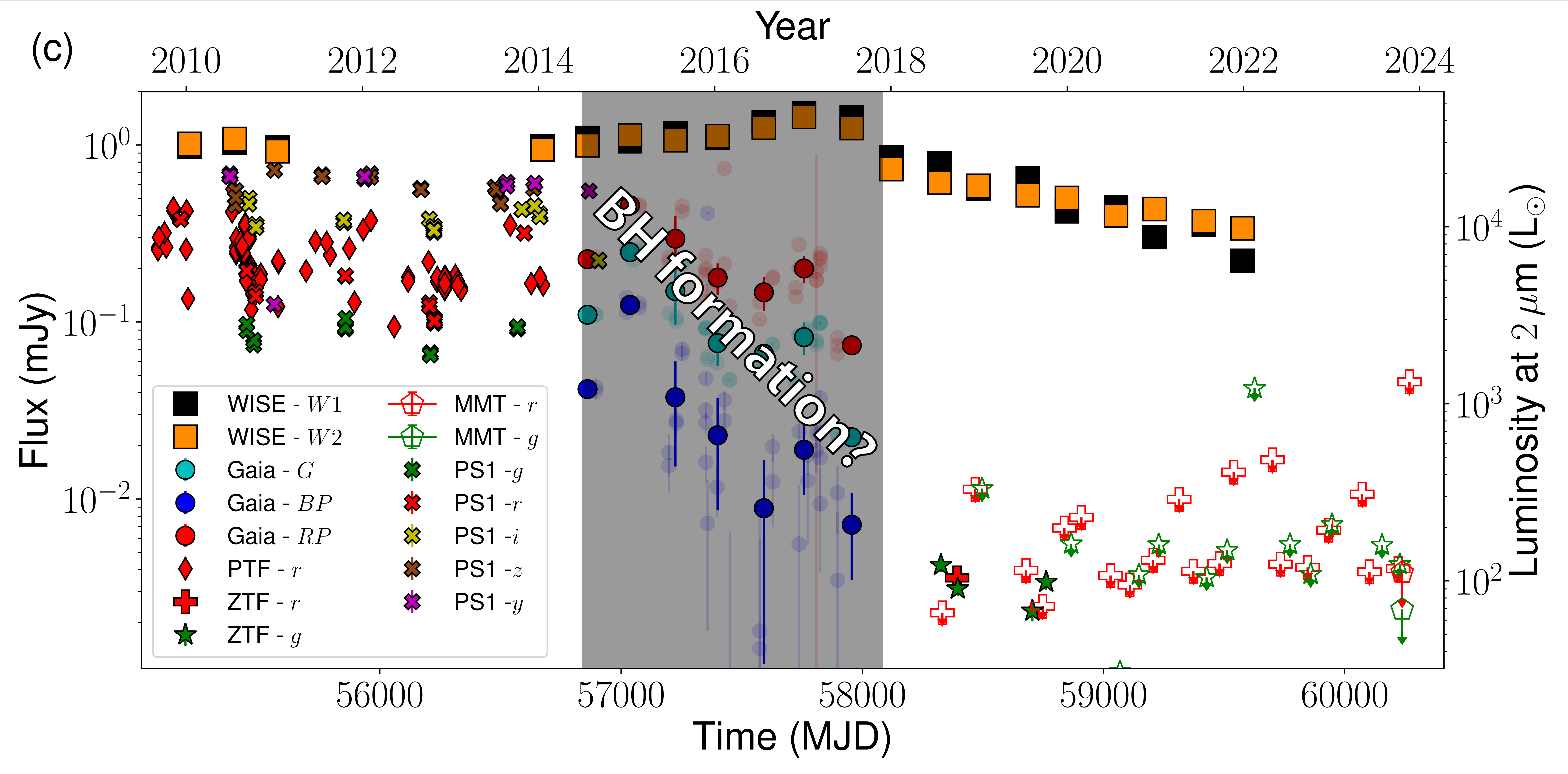


理論と実験の協働で
超新星ニュートリノの
新地平を切り拓く！



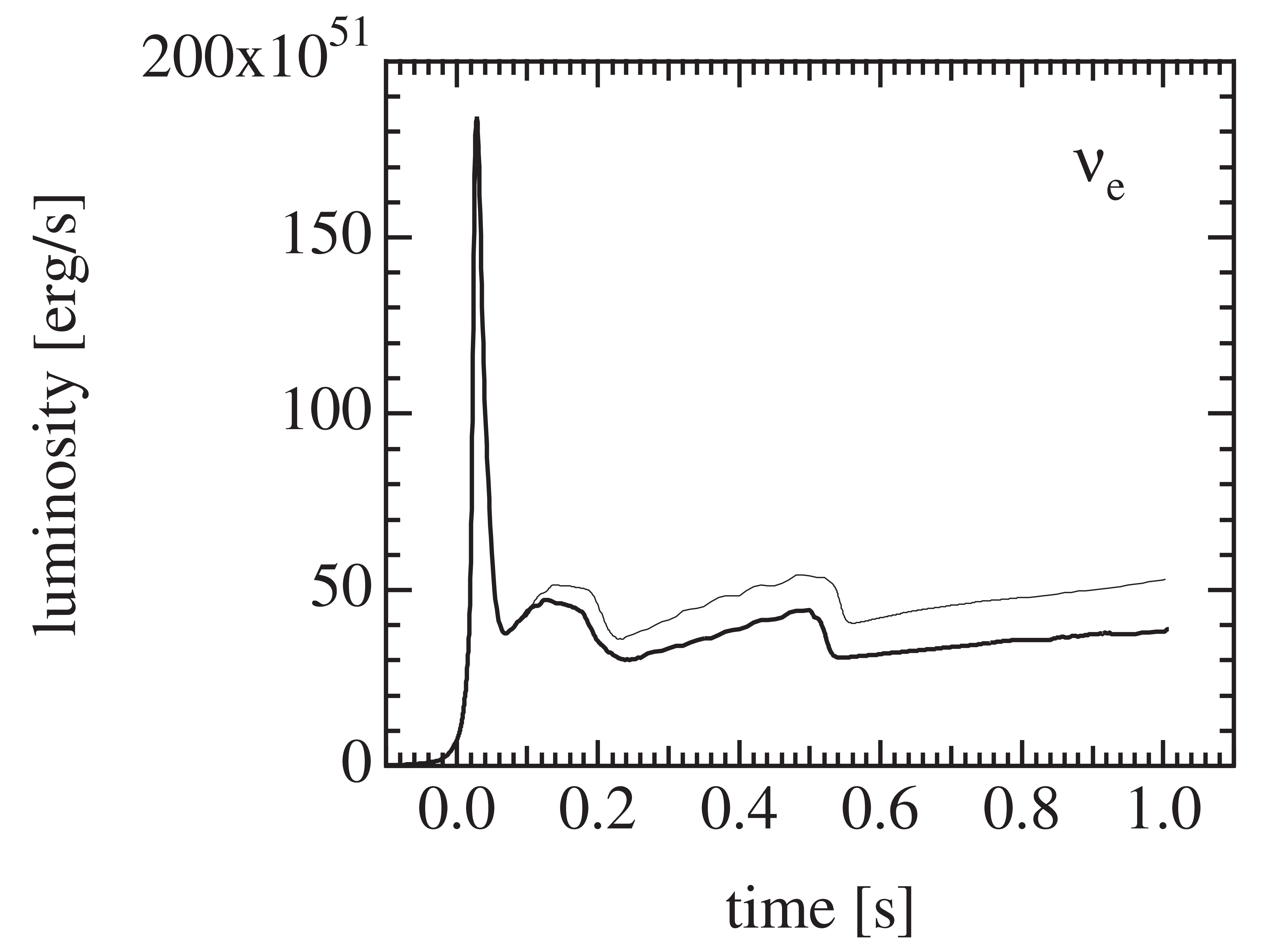
宇宙開闢から現在に至るまでの
新たな物質観の創生
研究項目E
宇宙物質の起源と進化を
研究
E01
素粒子標準模型を超える
微視的物理の探査
E02
・微視と巨視をつなぐ
超新星爆発シミュレーシ
・ニュートリノと元素生成
赤穂 (P13)
城 (P42)
森
(BSM)
冨永
(元素合成)
森 (P04)
財前 (P08)
篠田 (P32)
内田
(X線天文)
暗黒物質の正体解明
物質優勢を生み出す機構の解明
研究項目B
暗黒物質の直接探索
研究項目A
ニュートリノを伴わない
二重ベータ崩壊事象の探索
超新星ニュートリノ観測
研究項目D
極稀事象の基盤技術
公募研究
ポスター発表

M31-2014-DS1 (D=770 kpc)

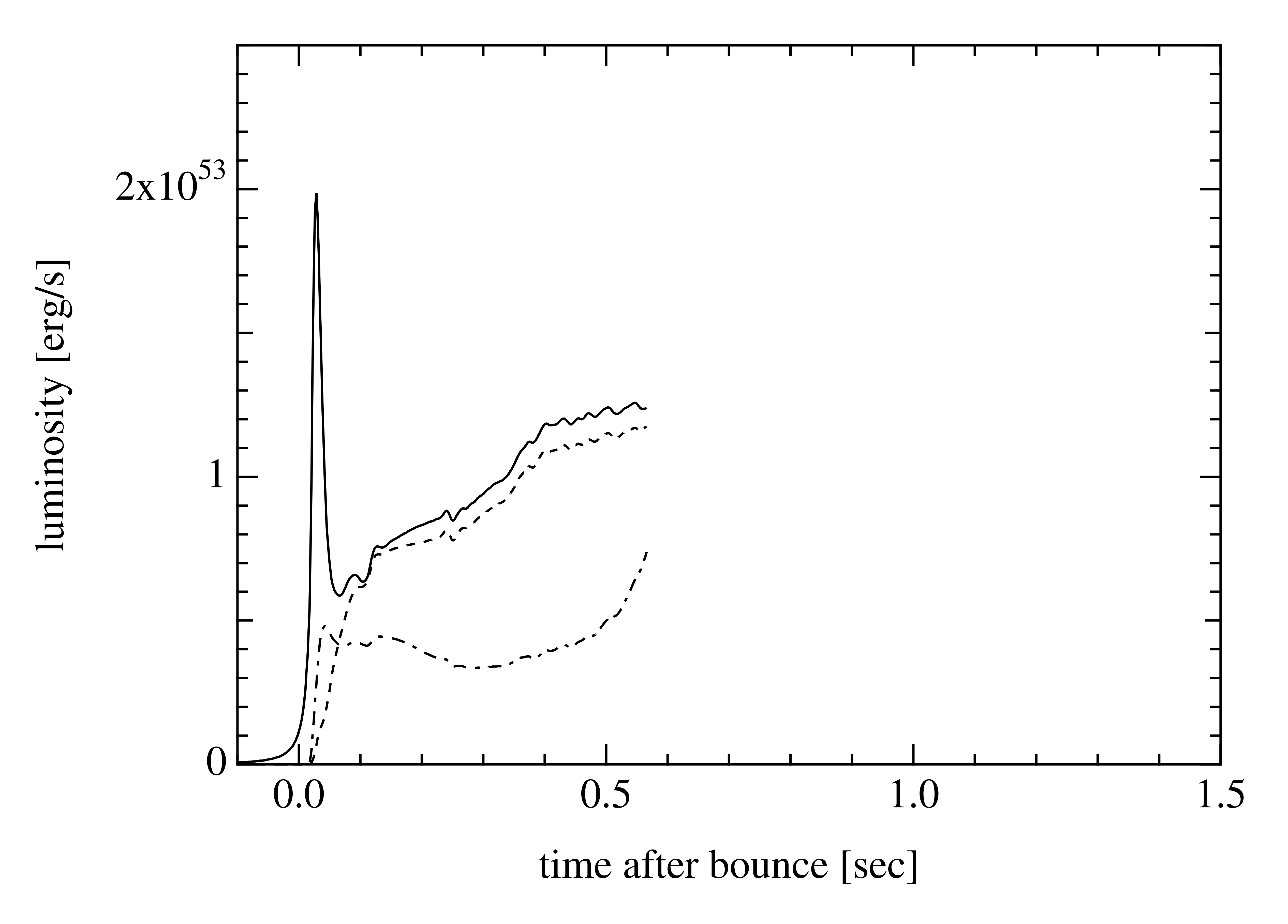


De+ 2024

BH forming simulations



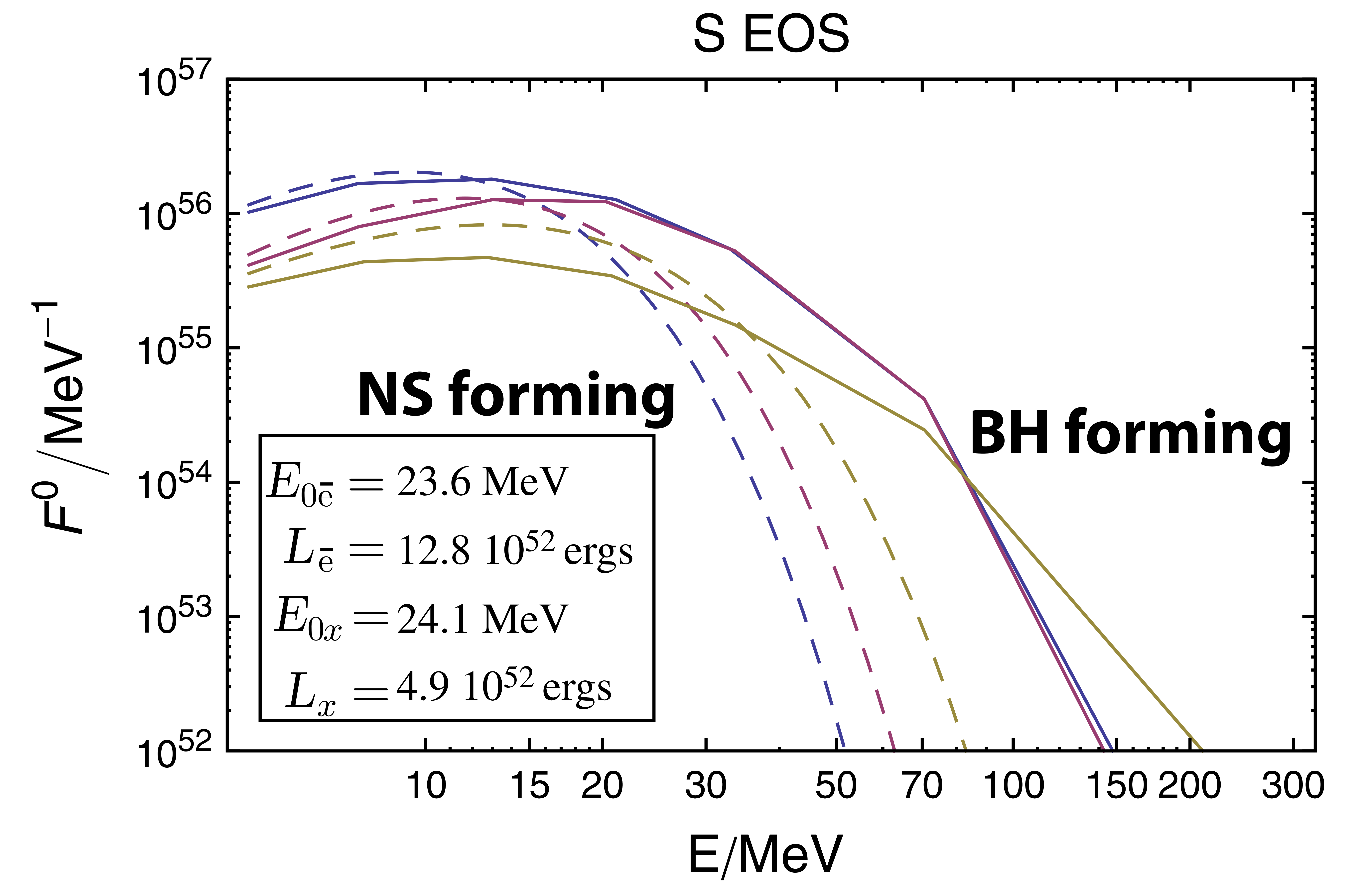
Sumiyoshi+ 2005 (NS forming)



Sumiyoshi+ 2007 (BH forming)

Neutrino spectrum

Lunardini 2009



Expected neutrino numbers

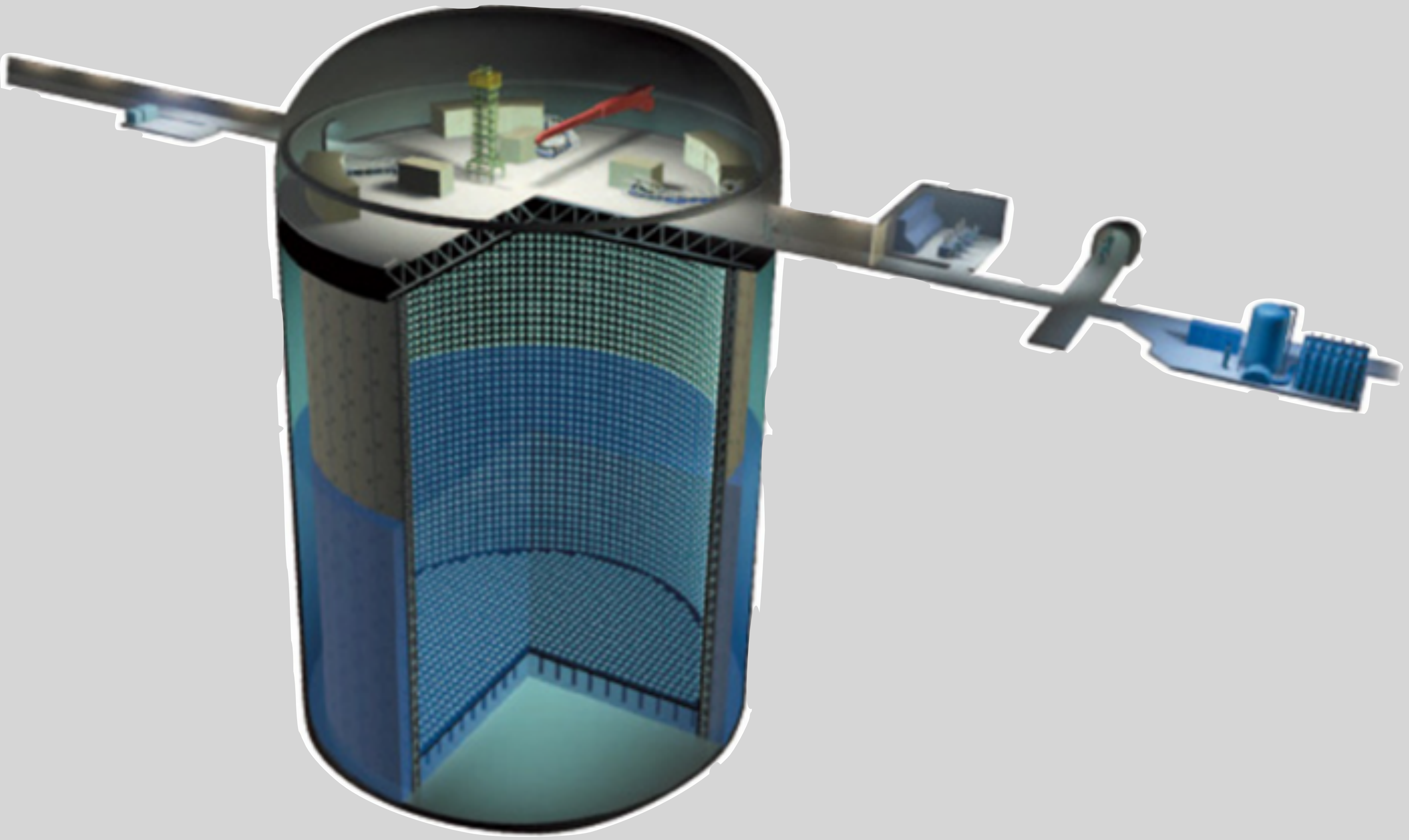
Inverse beta decay: $p + \bar{\nu}_e \rightarrow n + e^+$

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

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

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

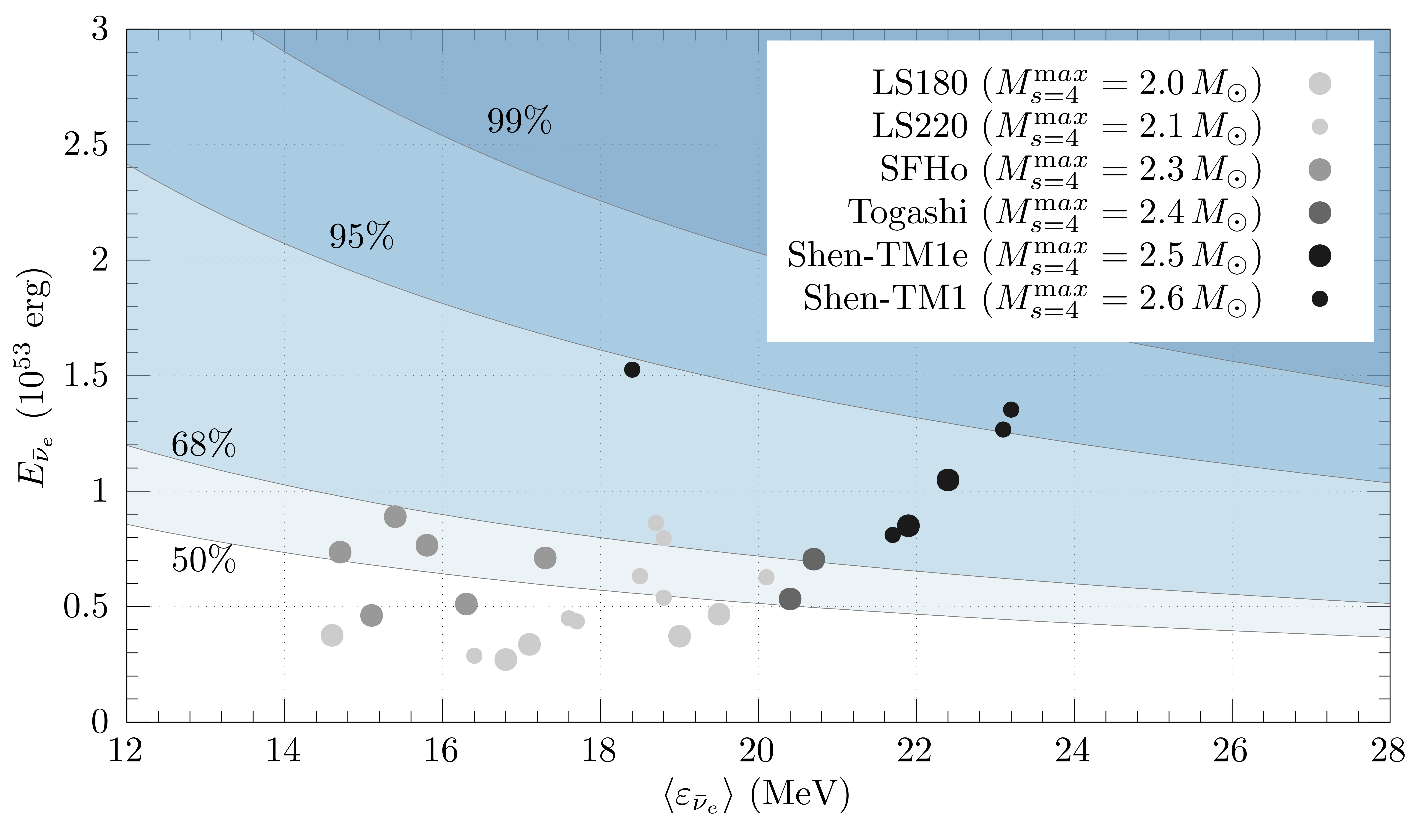
[Suwa, Akaho, Ashida, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, Zaizen, arXiv:2504.19510]

TABLE 1
SUMMARY OF SIMULATIONS

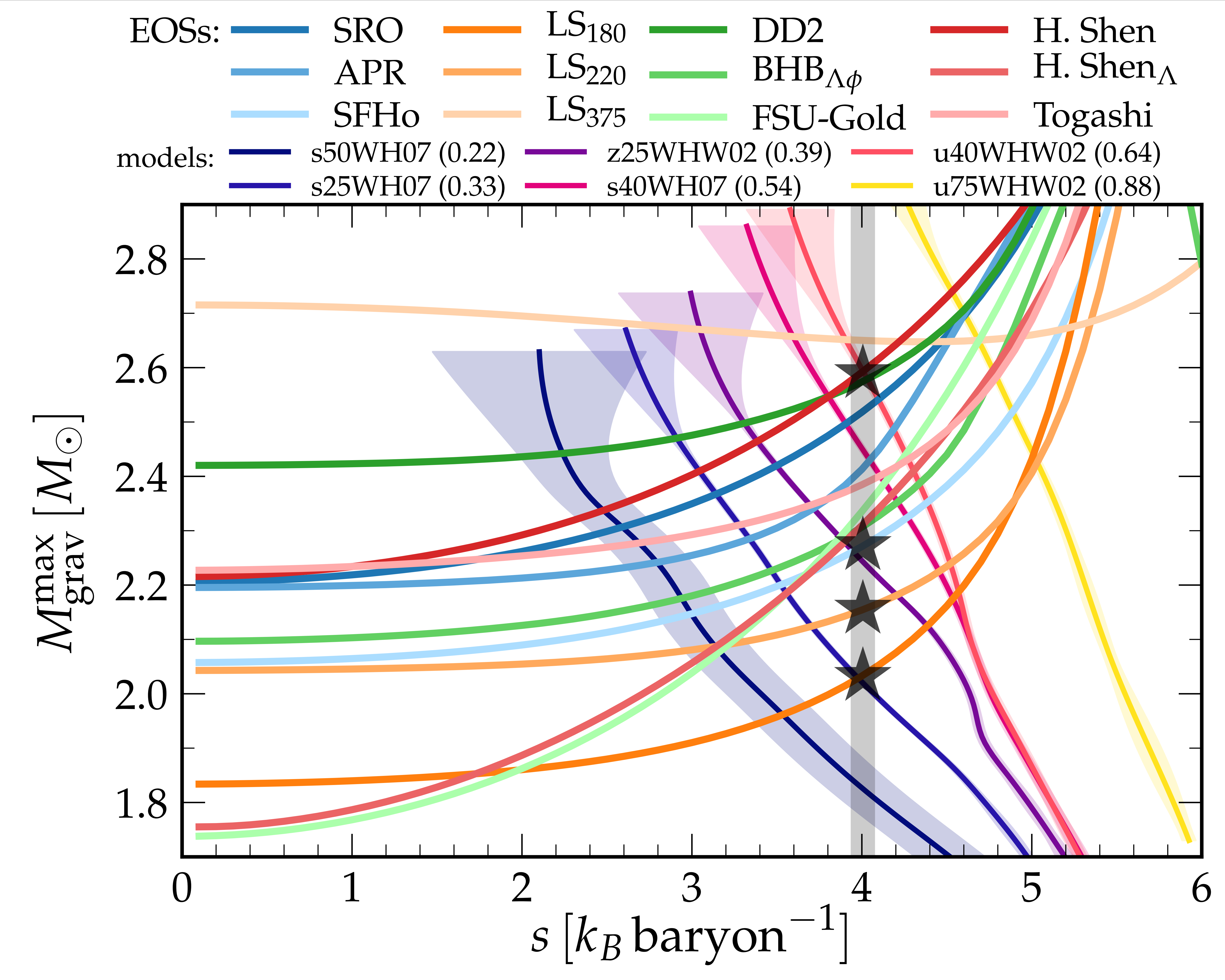
References[a]	Progenitor mass ($M_\odot$)	EOS	Gravity	$t_{\rm BH}$[b] (s)	E_{ν_e} (10^{53} erg)	$E_{\bar{\nu}_e}$ (10^{53} erg)	E_{ν_X} (10^{53} erg)	$\langle\varepsilon_{\nu_e}\rangle$ (MeV)	$\langle\varepsilon_{\bar{\nu}_e}\rangle$ (MeV)	$\langle\varepsilon_{\nu_X}\rangle$ (MeV)
Sumiyoshi et al. (2007)	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

* ニュートリノで星の中心に迫る
* 成功した超新星爆発だけではなく、失敗した超新星（ブラックホール形成）についても制限可能
* Super-Kamiokandeの未検出 → 核物質状態方程式
* 時間を絞ったデータ解析を行うとより定量的な制限が可能になる