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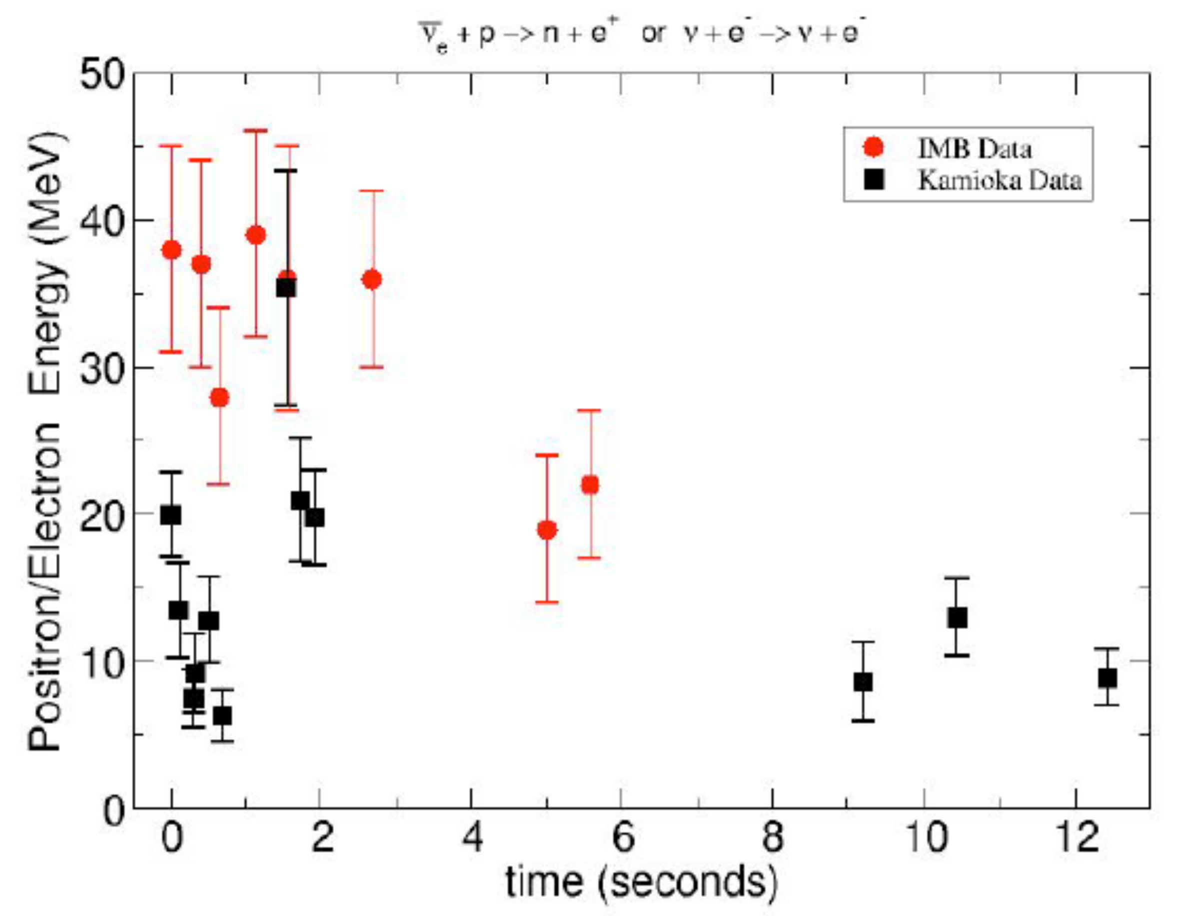
WHAT CAN THE FORTHCOMING LARGE NEUTRINO DETECTORS TELL US ABOUT FLAVOR TRANSITIONS OF GALACTIC SUPERNOVA NEUTRINOS?

K. C. Lai, Jason Leung, GLL, Phys. Rev. D 107 (2023) 4

EPS-HEP 2023

SUPERNOVA NEUTRINOS

- **Supernovae produced by the collapse of the core of massive star produce large fluxes of neutrinos**
- **99% of core collapse energies are carried out by neutrinos: $3x10^{53}$ ergs=10^{58}x20 MeV Neutrinos**



*SN 1987A: ~ 20 neutrinos

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

$$\nu + e^- \rightarrow \nu + e^-$$

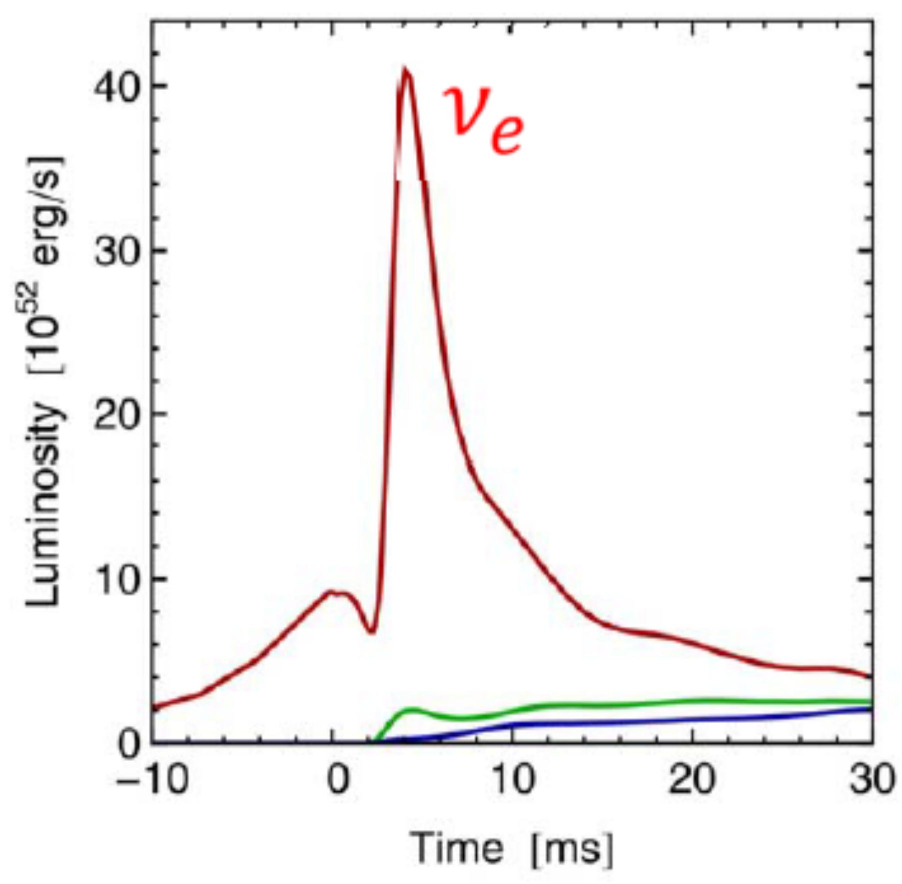
*In the future ~10,000 neutrinos can be detected from galactic supernova

THREE PHASES OF NEUTRINO EMISSIONS

T. Fischer, G. Martinez-Pinedo, M. Hempel, L. Huther, G. Ropke, S. Typel and A. Lohs, EPJ Web Conf. 109 (2016) 06002, arXiv:1512.00193.

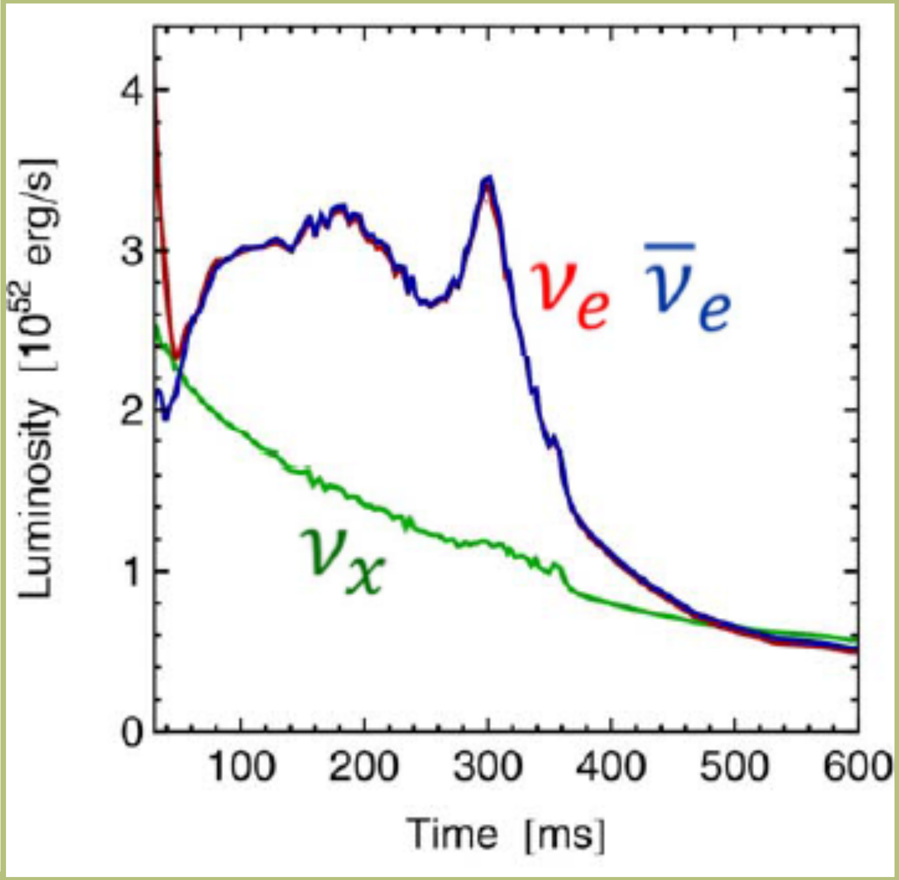
Prompt ν_e burst

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



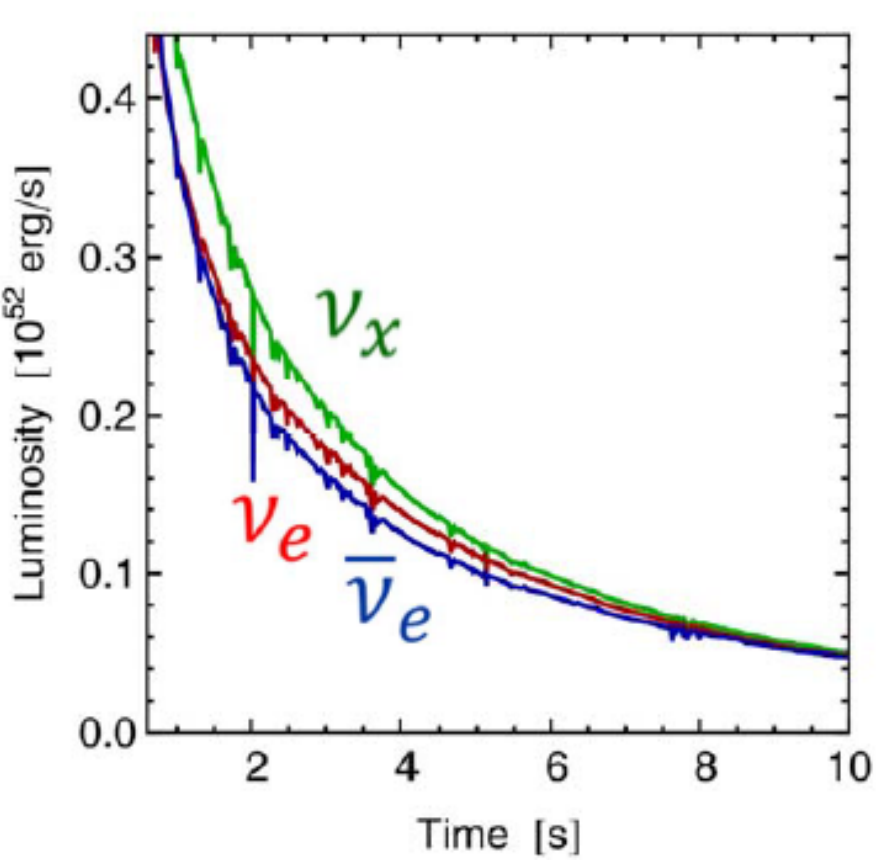
- Shock breakout
- De-leptonization of outer core layers

Accretion



- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling



- Cooling on neutrino diffusion time scale

WE FOCUS ON PROMPT ELECTRON-NEUTRINO BURST (NEUTRONIZATION BURST)

- We analyze $0 \leq t_{\rm pb} \leq 0.1{\rm s}$ as in

  P. D. Serpico, S. Chakraborty, T. Fischer, L. Hudepohl, H. T. Janka and A. Mirizzi, Phys. Rev. D 85 (2012) 085031

  In this period the main flavor transition mechanism is MSW

  S. Hannestad, G. G. Raffelt, G. Sigl, and Y. Y. Y. Wong, Phys. Rev. D 74, 105010 (2006); Erratum, Phys. Rev. D76, 029901(E) (2007).
- In accretion phase, both MSW and Self-Induced Oscillations need to be considered.

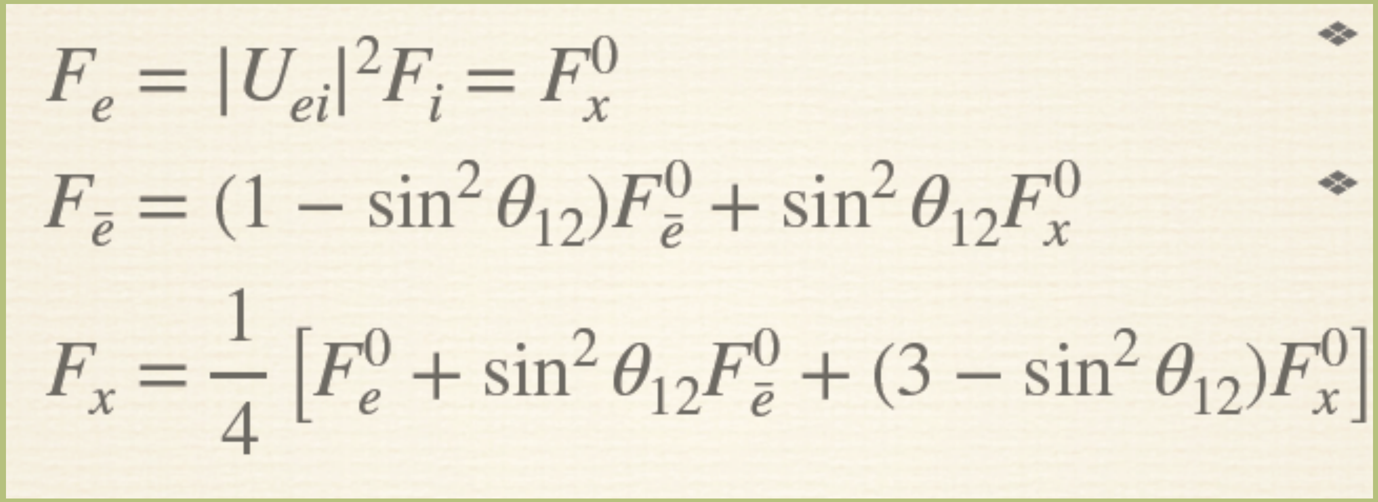
  B. Dasgupta and A. Mirizzi, Phys. Rev. D 92, 125030 (2015).
- In cooling phase, flavor transition effects are not important.

  A. Mirizzi, I. Tamborra, H.-T. Janka, N. Saviano, K.Scholberg, R. Bollig, L. Hudepohl, and S. Chakraborty, Riv. Nuovo Cimento 39, 1 (2016).

MSW FLAVOR TRANSITION MECHANISM VERSUS VACUUM FLAVOR TRANSITIONS (VFT)

- MSW effects

NO

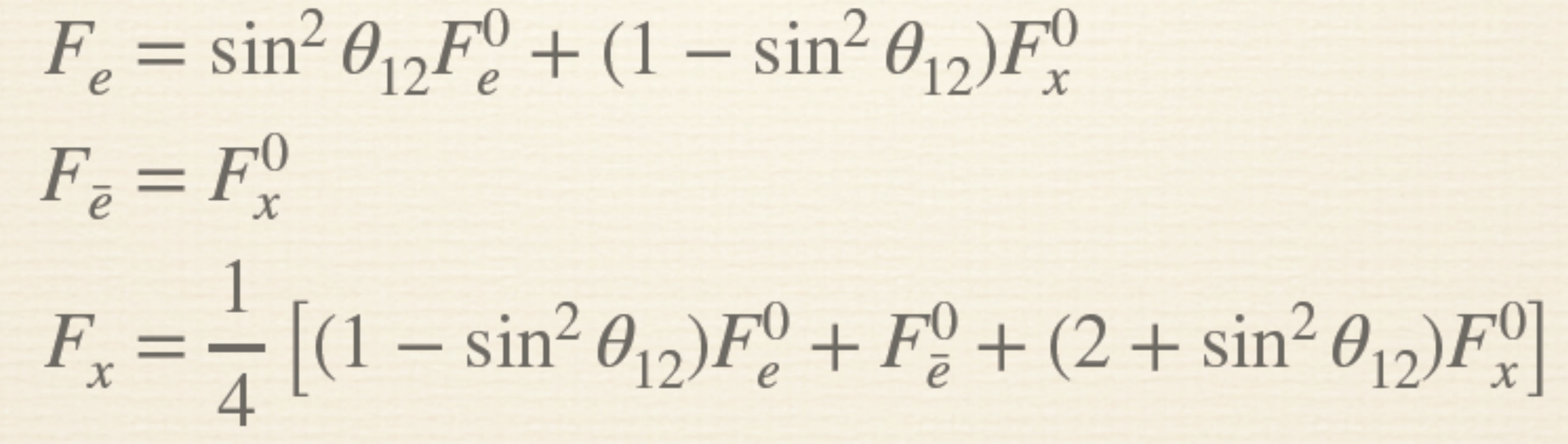


$$F_e = |U_{ei}|^2 F_i = F_x^0$$

$$F_{\bar{e}} = (1 - \sin^2\theta_{12}) F_{\bar{e}}^0 + \sin^2\theta_{12} F_x^0$$

$$F_x = \frac{1}{4}\left[F_e^0 + \sin^2\theta_{12} F_{\bar{e}}^0 + (3 - \sin^2\theta_{12}) F_x^0\right]$$

IO



$$F_e = \sin^2\theta_{12} F_e^0 + (1 - \sin^2\theta_{12}) F_x^0$$

$$F_{\bar{e}} = F_x^0$$

$$F_x = \frac{1}{4}\left[(1 - \sin^2\theta_{12}) F_e^0 + F_{\bar{e}}^0 + (2 + \sin^2\theta_{12}) F_x^0\right]$$

A. S. Dighe and A. Yu. Smirnov, Phys. Rev. D 62 (2000) 033007.

MSW FLAVOR TRANSITION MECHANISM VERSUS VACUUM FLAVOR TRANSITIONS (VFT)

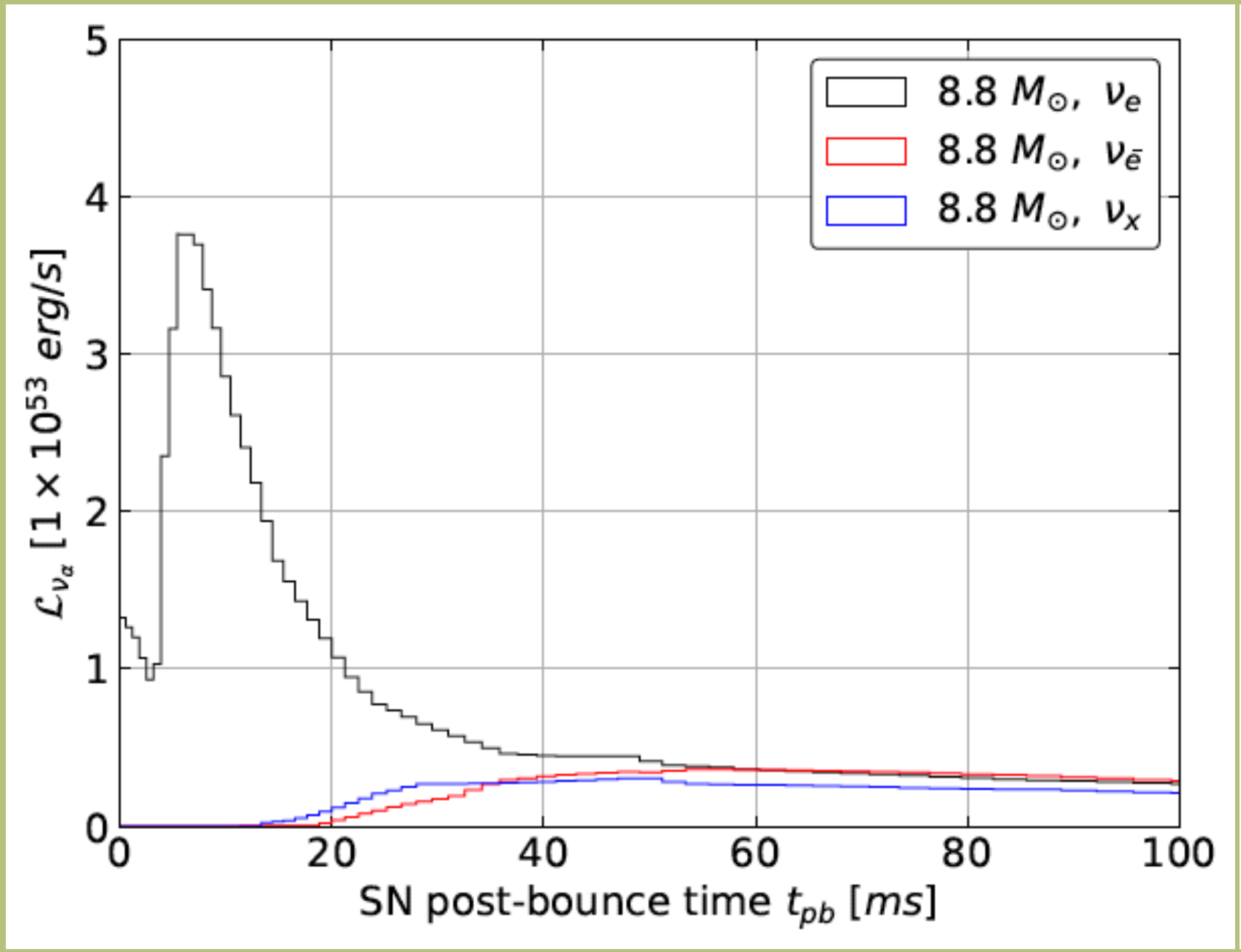
- Vacuum flavor transition

$$P_{\alpha\to\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 = \begin{pmatrix} 0.55 & 0.23 & 0.22 \\ 0.23 & 0.40 & 0.37 \\ 0.22 & 0.37 & 0.41 \end{pmatrix}$$

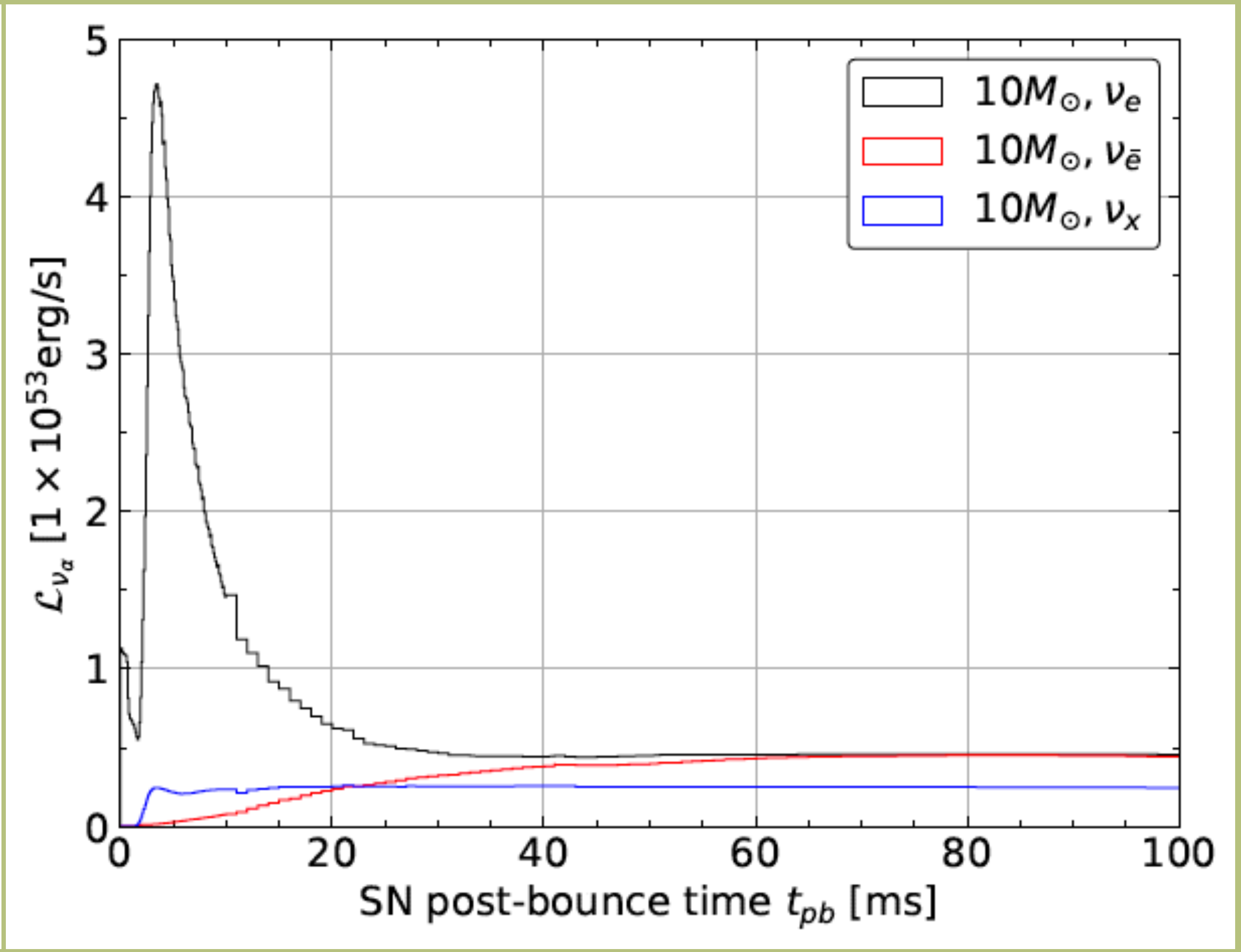
Classical transition probability for neutrinos traversing a vast distance

J. G. Learned and S. Pakvasa, Astropart. Phys. 3, 267-274 (1995)
H. Athar, M. Jezabek and O. Yasuda, Phys. Rev. D 62, 103007 (2000)
L. Bento, P. Keranen and J. Maalampi, Phys. Lett. B 476, 205-212 (2000)

SIMULATED SN LUMINOSITIES



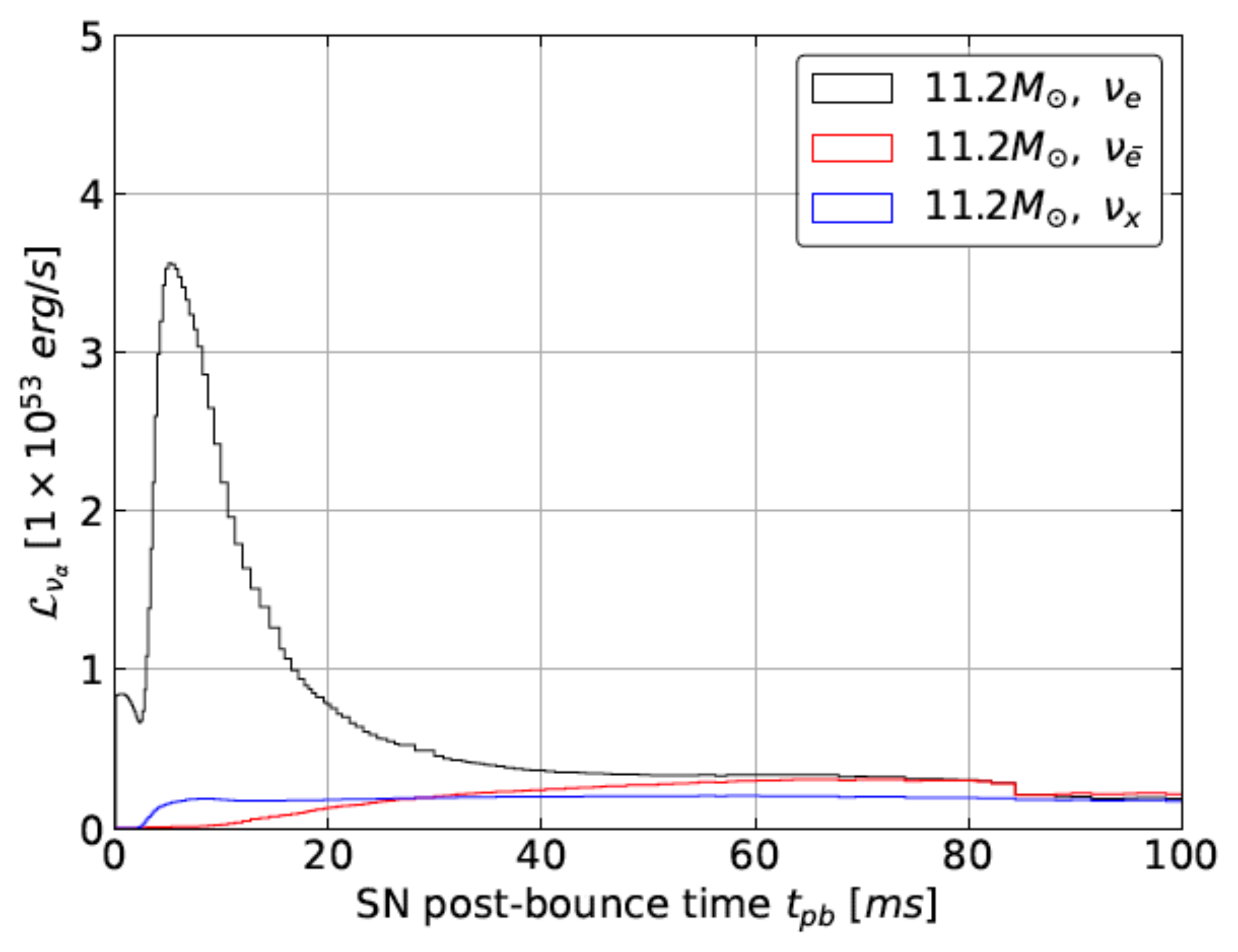
Simulation G



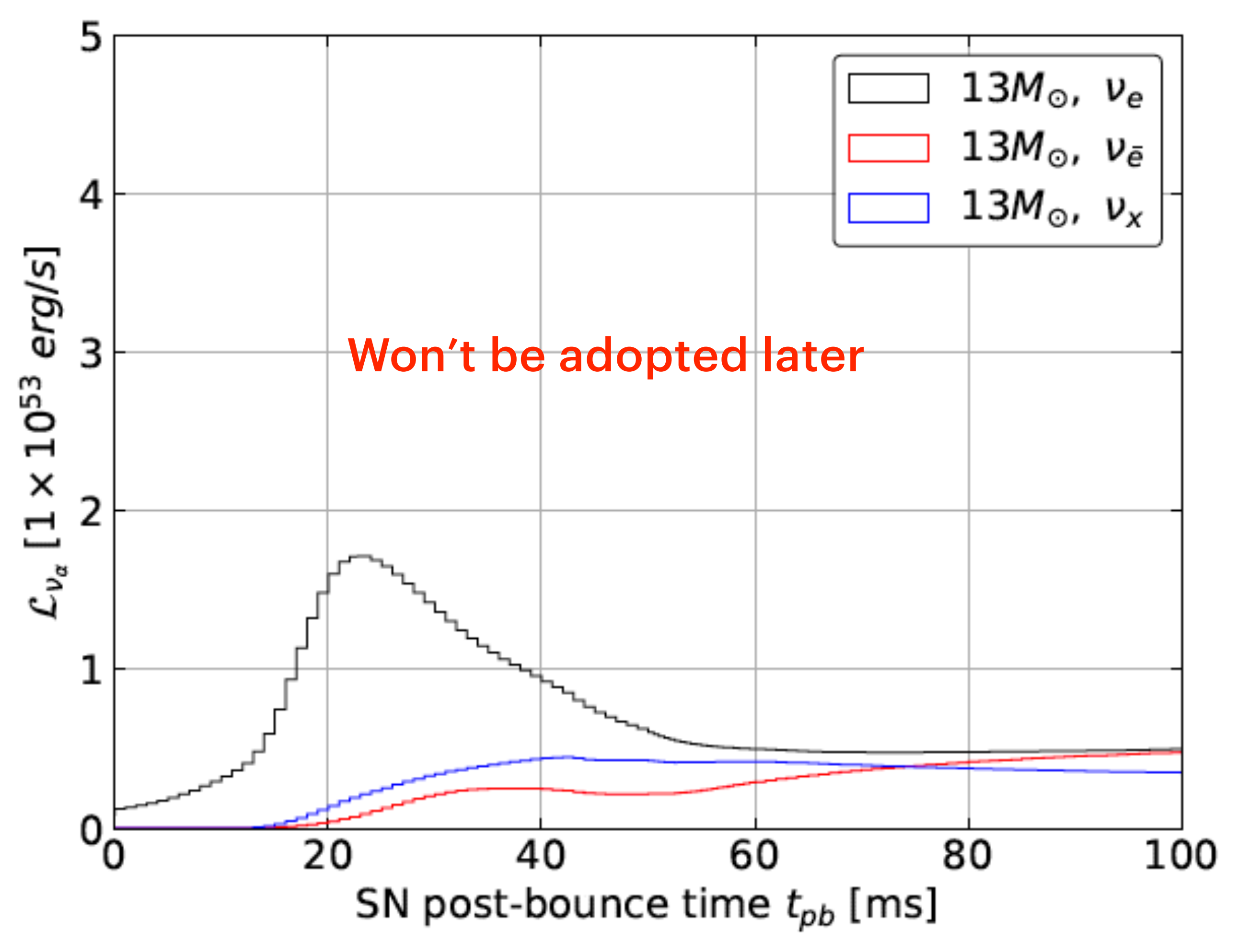
Simulation B

- L. Hudepohl, B. Muller, H.-T. Janka, A. Marek and G. G. Raelt, Phys. Rev. Lett. 104 (2010) 251101, Erratum: Phys. Rev. Lett. 105 (2010) 249901, arXiv:0912.0260.
- A. Burrows, D. Radice and D. Vartanyan, Mon. Not. Roy. Astron. Soc. 485 (2019) no.3, 3153, arXiv:1902.00547.

SIMULATED SN LUMINOSITIES



Simulation F



Won’t be adopted later

Simulation N

- T. Fischer, G. Martinez-Pinedo, M. Hempel, L. Huther, G. Ropke, S. Typel and A. Lohs, EPJ Web Conf. 109 (2016) 06002, arXiv:1512.00193.
- K. Nakazato, K. Sumiyoshi, H. Suzuki, T. Totani, H. Umeda and S. Yamada, Astrophys. J. Suppl. 205 (2013) 2, arXiv:1210.6841.

EVENT NUMBERS FOR 5 KPC DISTANCE GALACTIC SN IN JUNO AND DUNE FOR DIFFERENT FLAVOR TRANSITION SCENARIOS

$$\text{JUNO main detection channel}: \; \bar{\nu}_e + p \to e^+ + n$$

$$\text{DUNE main detection channel}: \; \nu_e +^{40} Ar \to e^- +^{40} K^*$$

The major detection channel of HyperK is also Inverse beta decay (IBD)

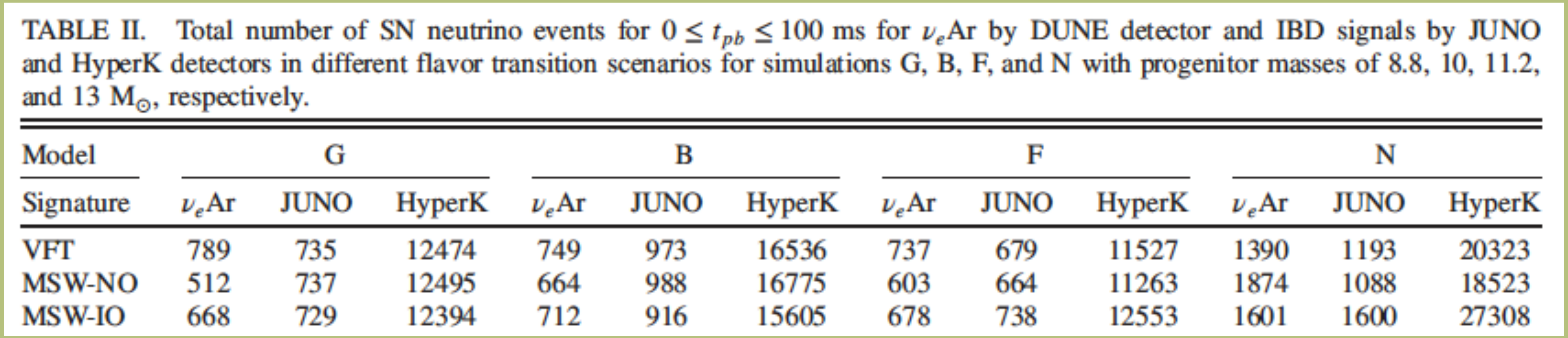
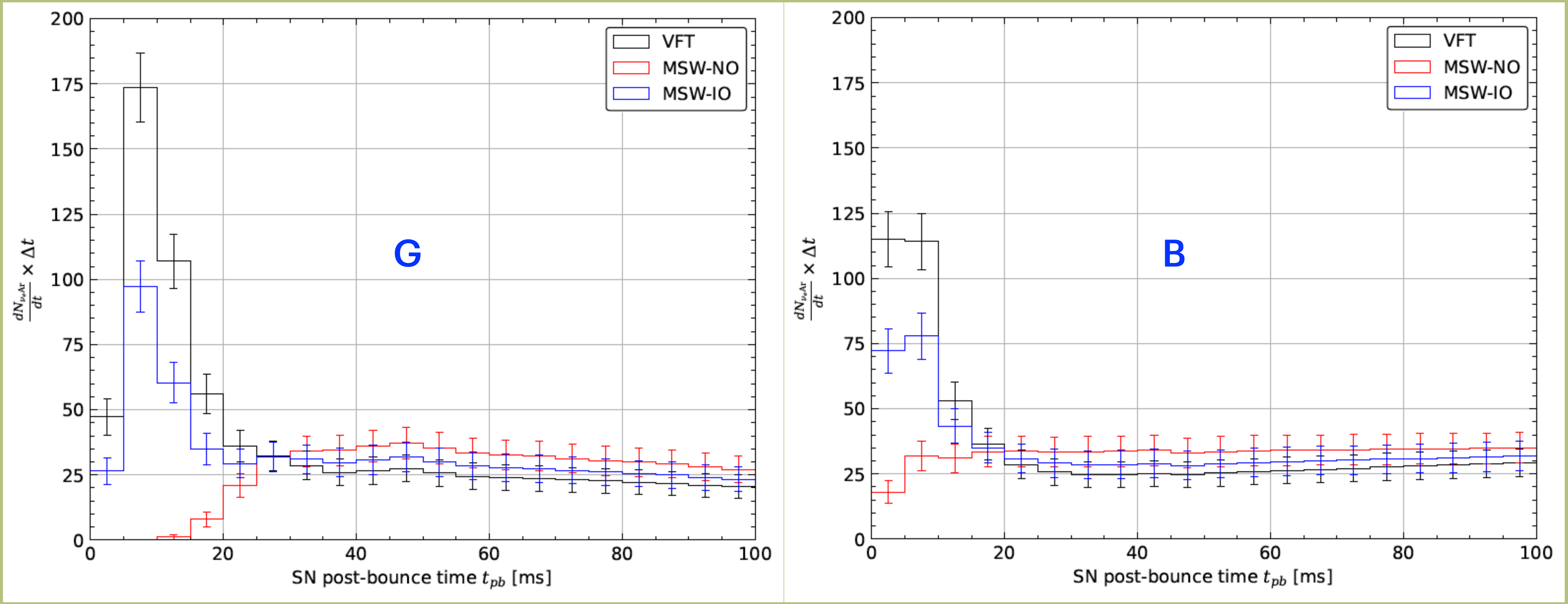


TABLE II. Total number of SN neutrino events for $0 \leq t_{pb} \leq 100$ ms for ν_eAr by DUNE detector and IBD signals by JUNO and HyperK detectors in different flavor transition scenarios for simulations G, B, F, and N with progenitor masses of 8.8, 10, 11.2, and 13 $M_\odot$, respectively.

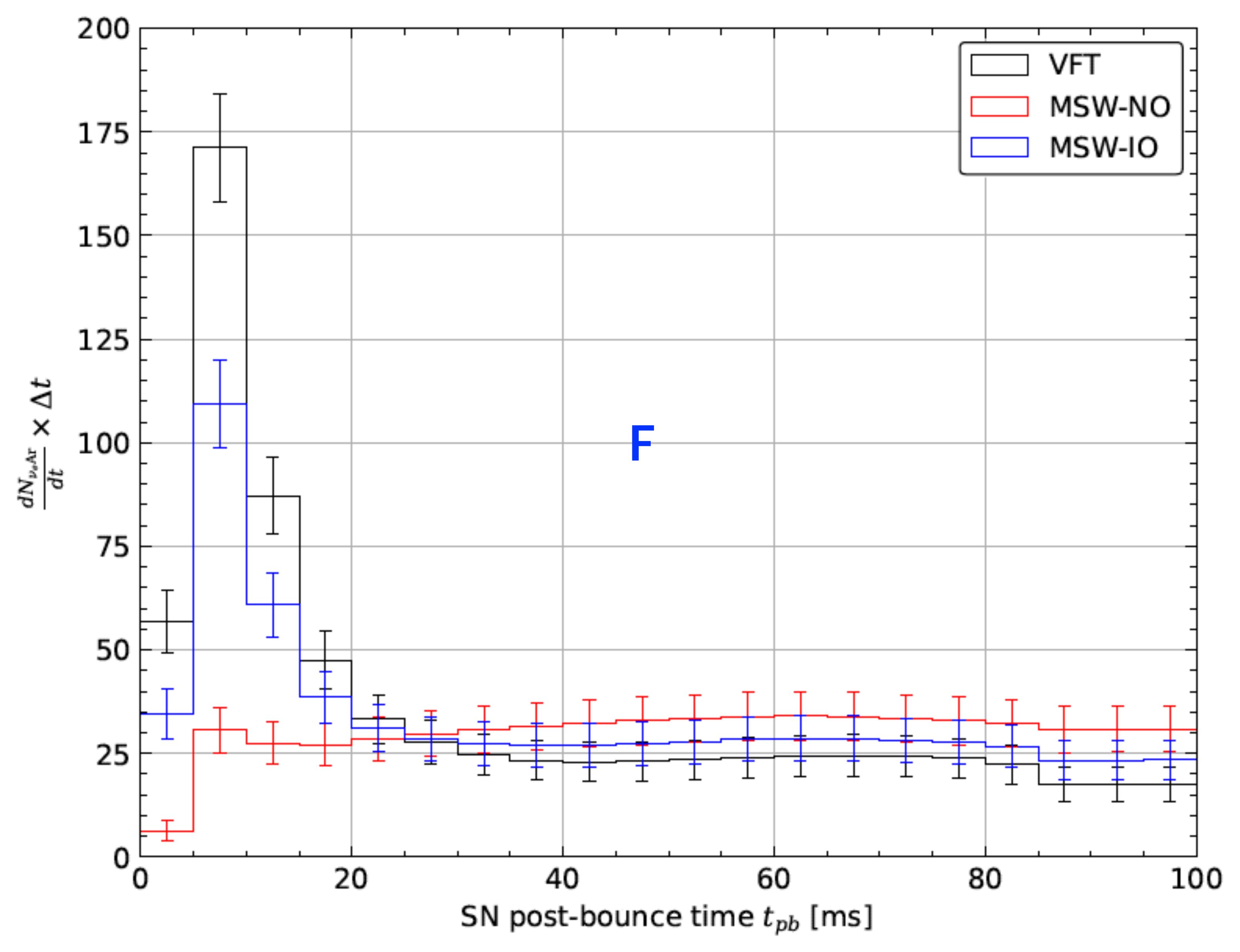
Model	G			B			F			N		
Signature	ν_eAr	JUNO	HyperK	ν_eAr	JUNO	HyperK	ν_eAr	JUNO	HyperK	ν_eAr	JUNO	HyperK
VFT	789	735	12474	749	973	16536	737	679	11527	1390	1193	20323
MSW-NO	512	737	12495	664	988	16775	603	664	11263	1874	1088	18523
MSW-IO	668	729	12394	712	916	15605	678	738	12553	1601	1600	27308

Need time distribution of events to discriminate various scenarios

EVENT TIME DISTRIBUTIONS FOR DUNE IN DIFFERENT SIMULATIONS AND FLAVOR TRANSITION SCENARIOS

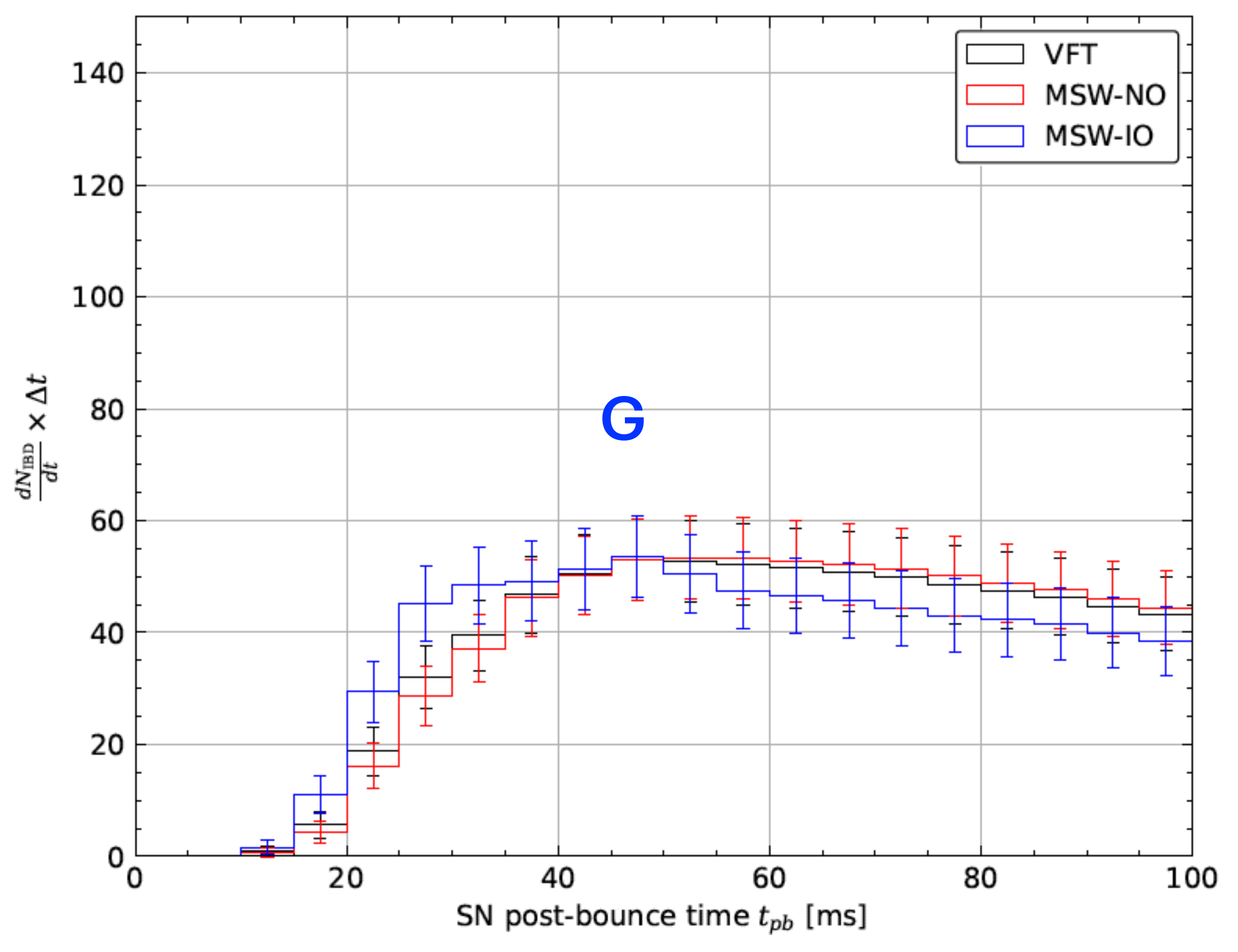


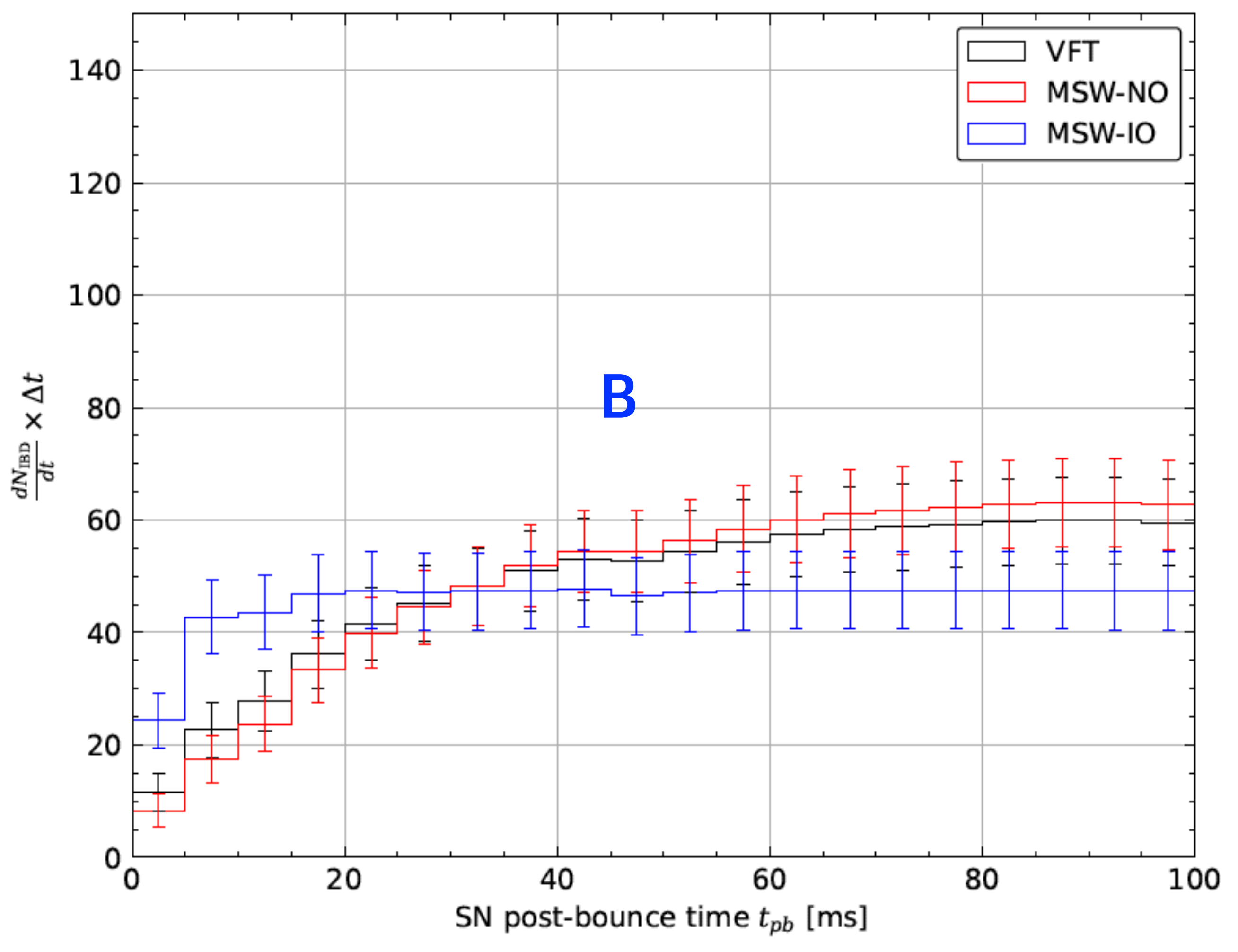
EVENT TIME DISTRIBUTIONS FOR DUNE IN DIFFERENT SIMULATIONS AND FLAVOR TRANSITION SCENARIOS



- Will not consider K. Nakazato *et al.* from this point on

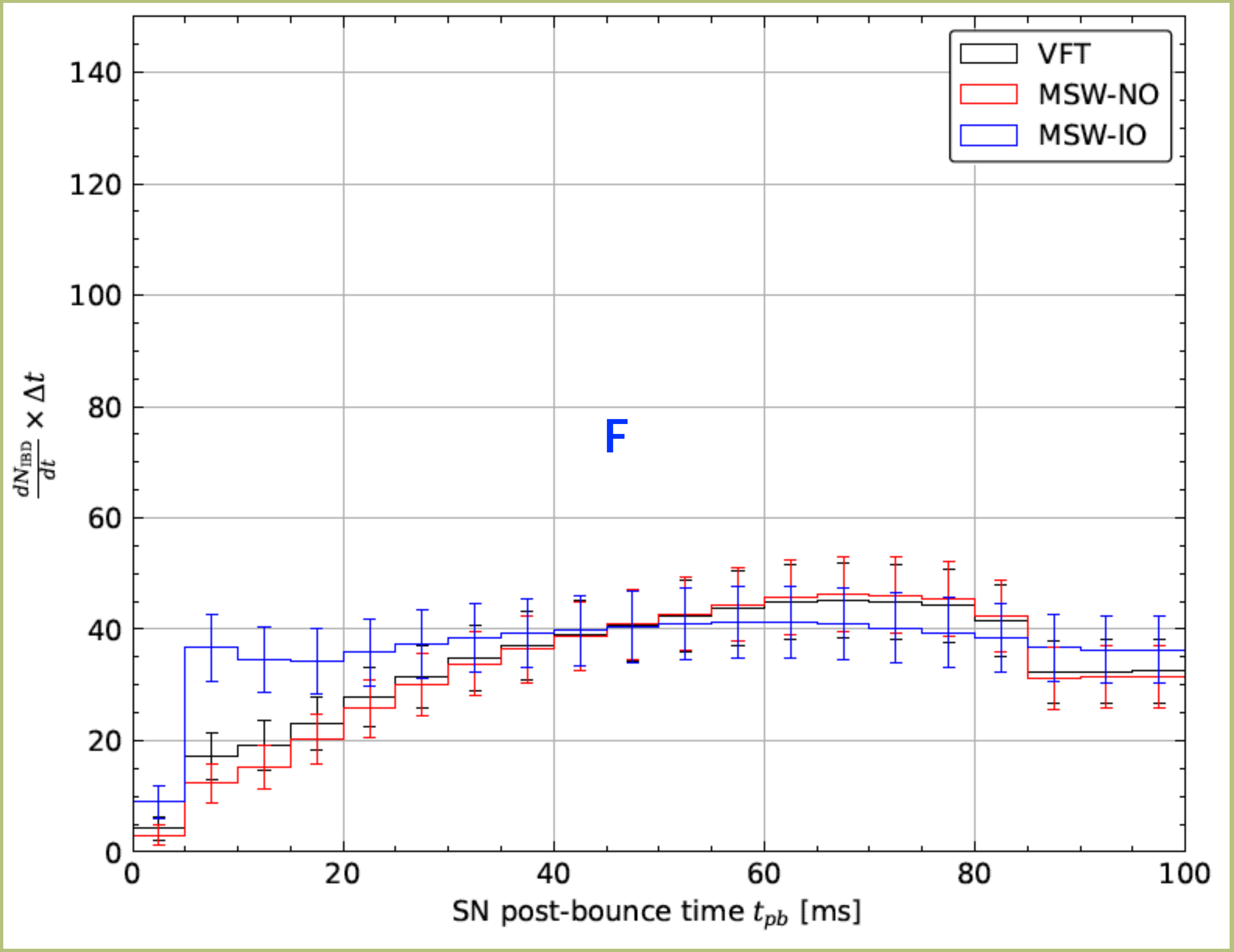
EVENT TIME DISTRIBUTIONS FOR **JUNO** IN DIFFERENT SIMULATIONS AND FLAVOR TRANSITION SCENARIOS





IBD events

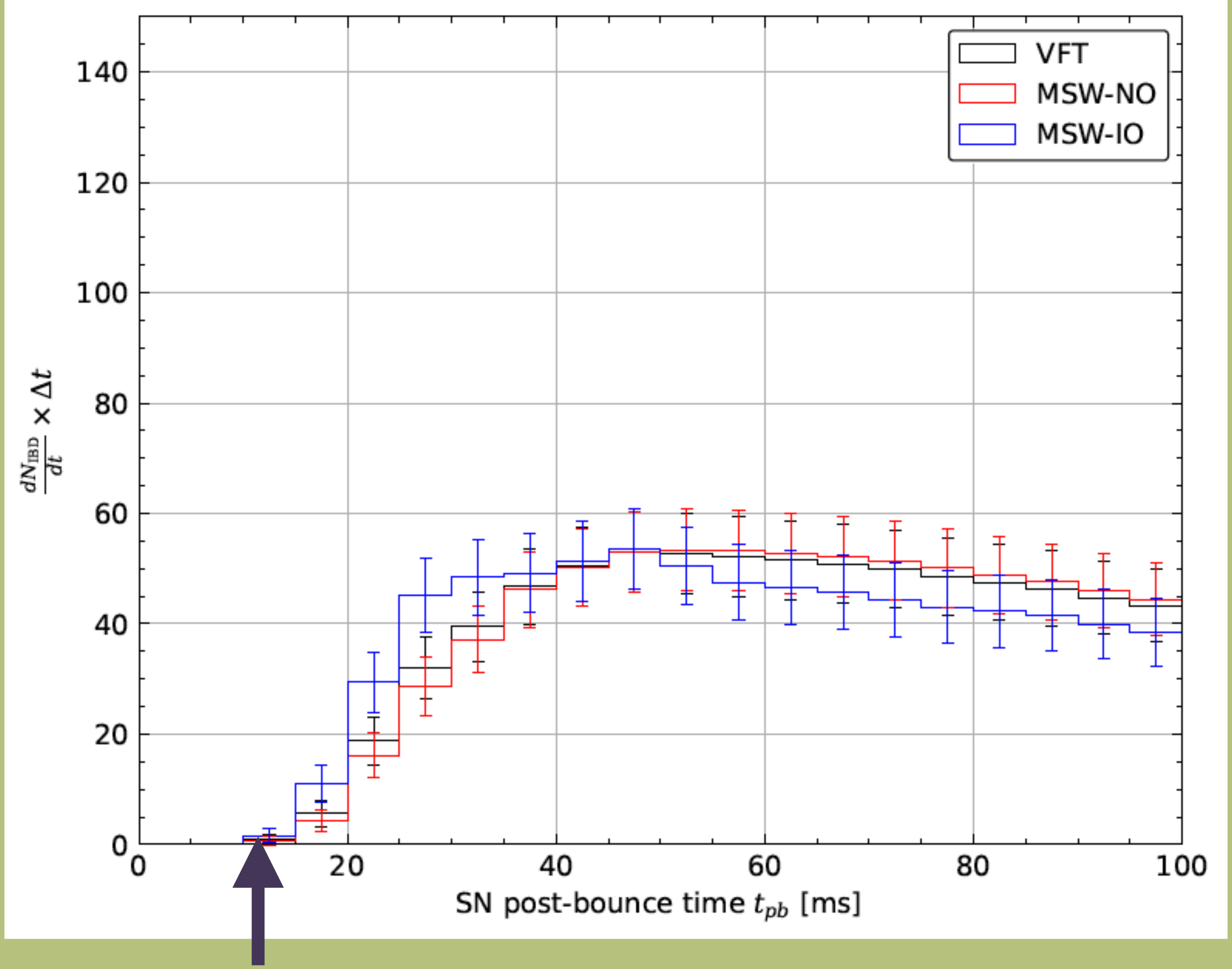
EVENT TIME DISTRIBUTIONS FOR JUNO IN DIFFERENT SIMULATIONS AND FLAVOR TRANSITION SCENARIOS



IBD events HyperK with smaller uncertainties

EVENT TIME DISTRIBUTIONS FOR IBD IN DIFFERENT SIMULATIONS AND FLAVOR TRANSITION SCENARIOS

- Garching simulation as an example



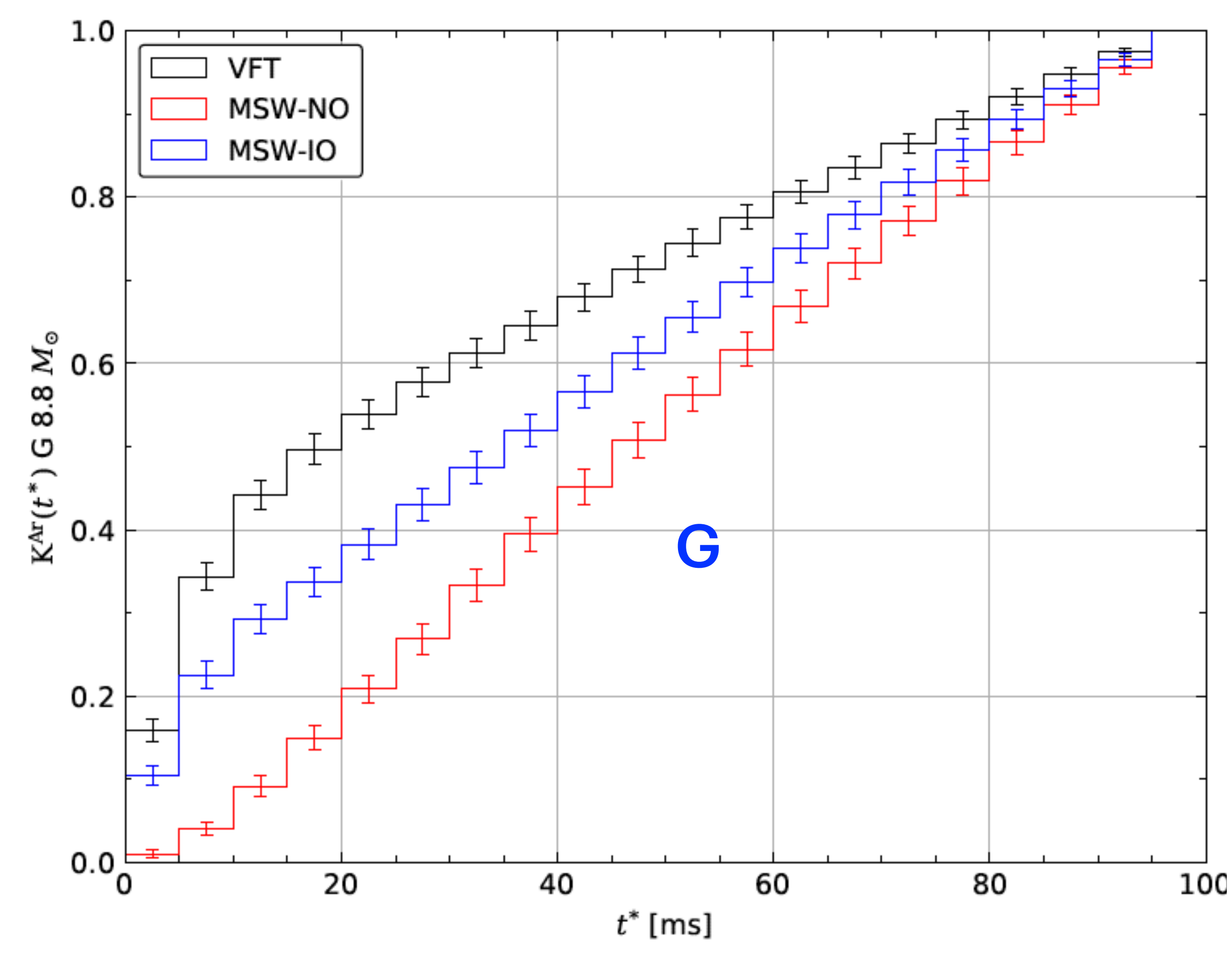
*t**=0

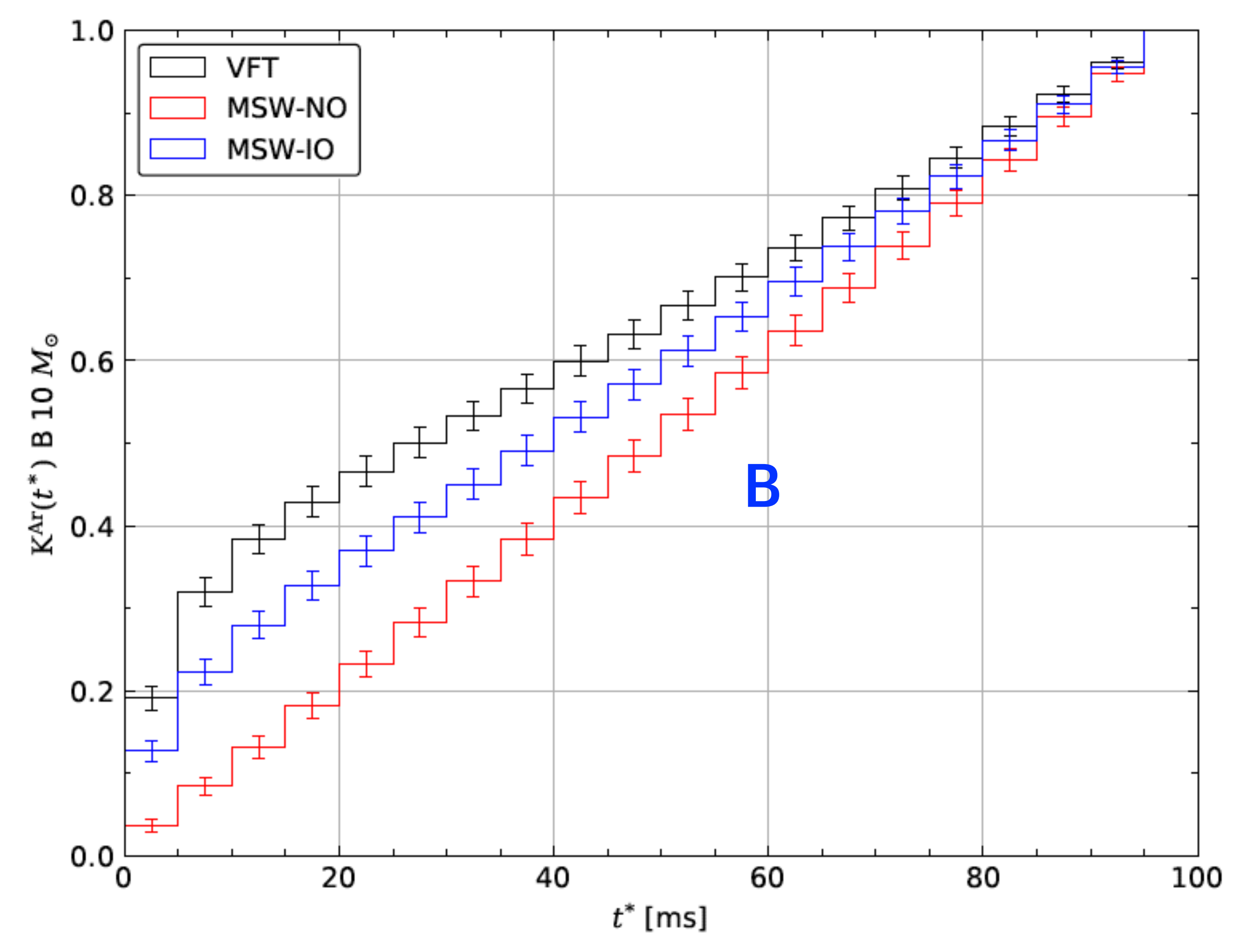
Choose the time origin according to actual measurement

CUMULATIVE TIME DISTRIBUTIONS OF DUNE EVENTS

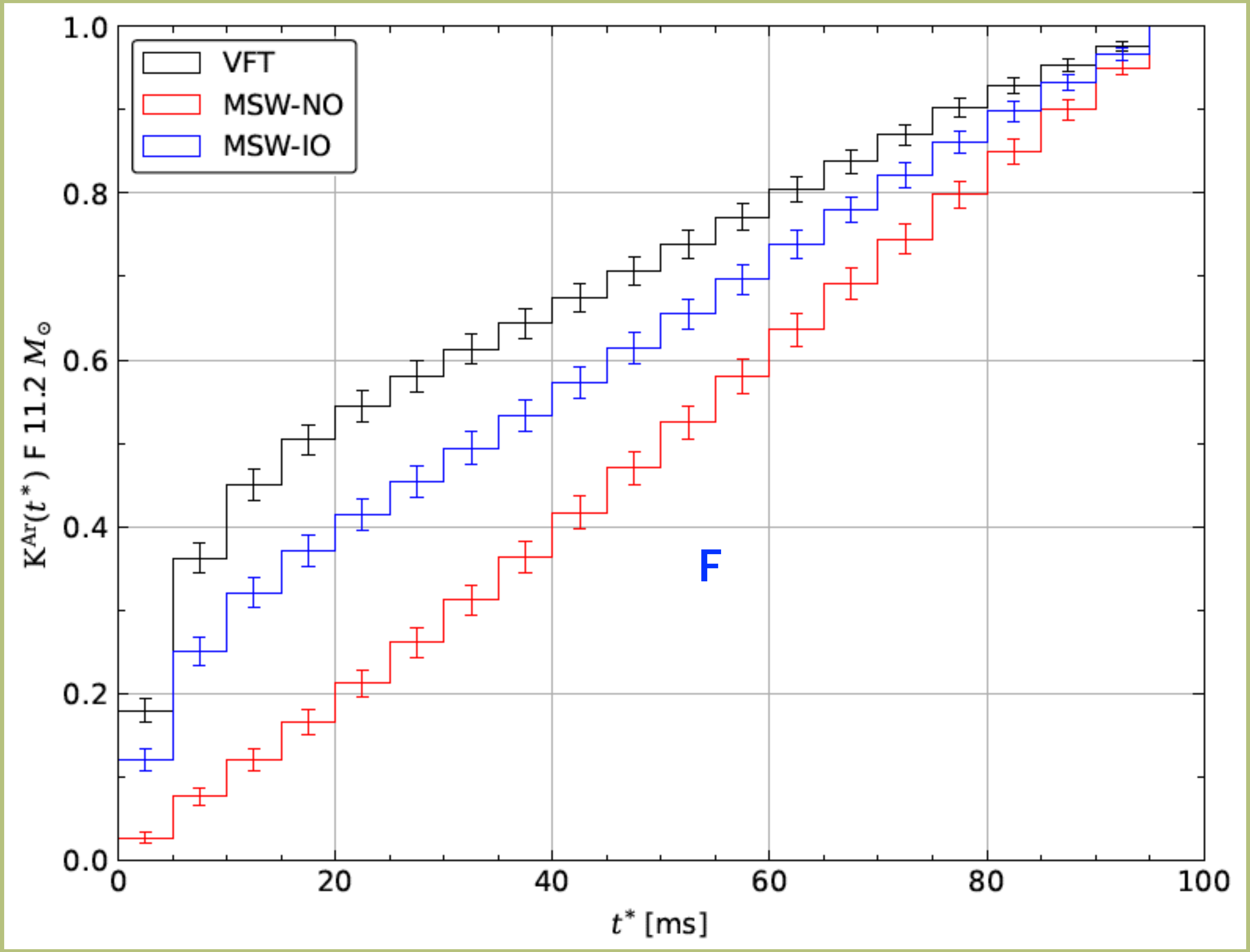
$$K^{i,\mathrm{Ar}}(t) = \frac{\int_0^t \frac{dN^i_{\mathrm{Ar}}}{dt'} dt'}{\int_0^{0.1\mathrm{s}} \frac{dN^i_{\mathrm{Ar}}}{dt'} dt'}$$

i = VFT, NO, IO





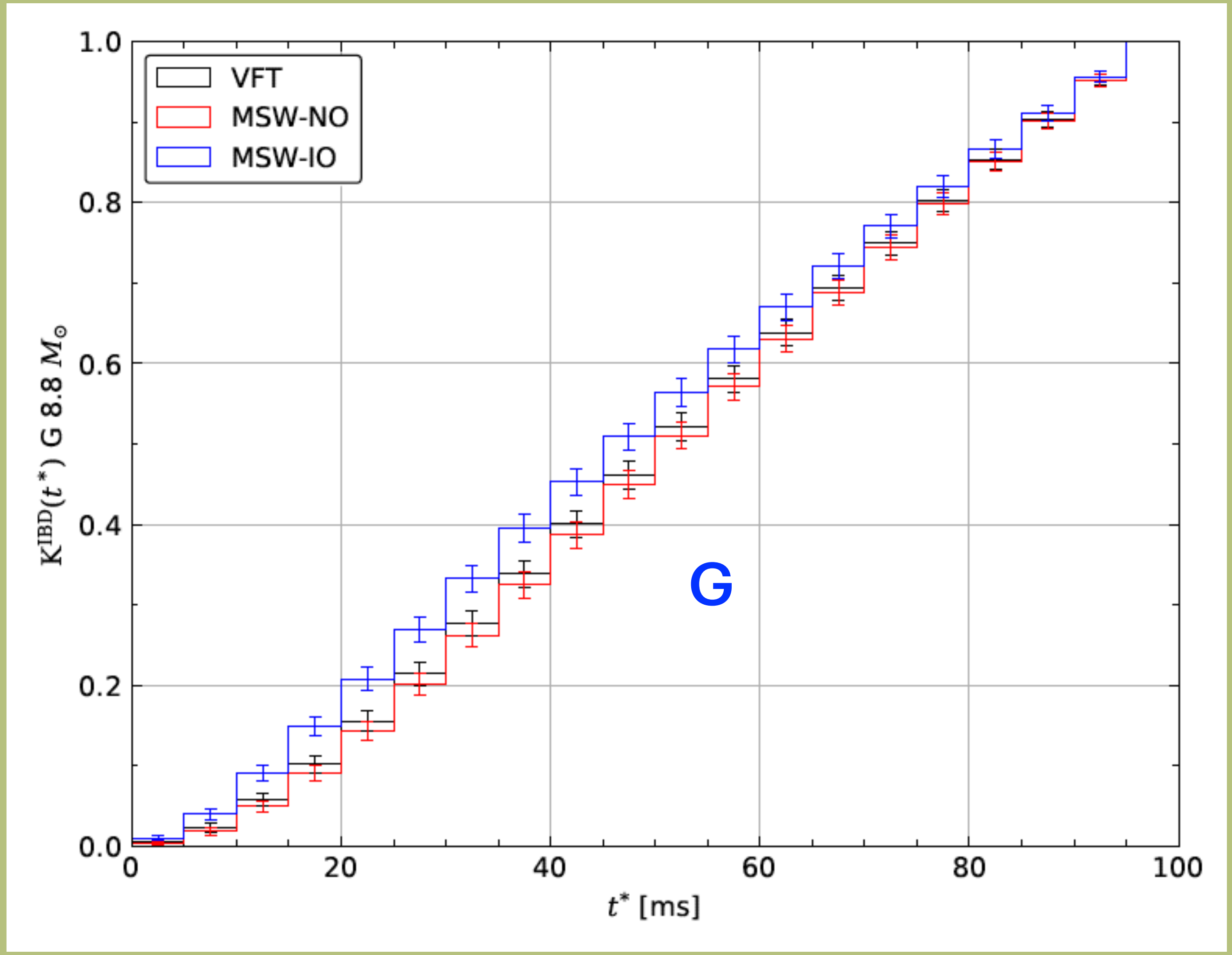
CUMULATIVE TIME DISTRIBUTIONS OF DUNE EVENTS

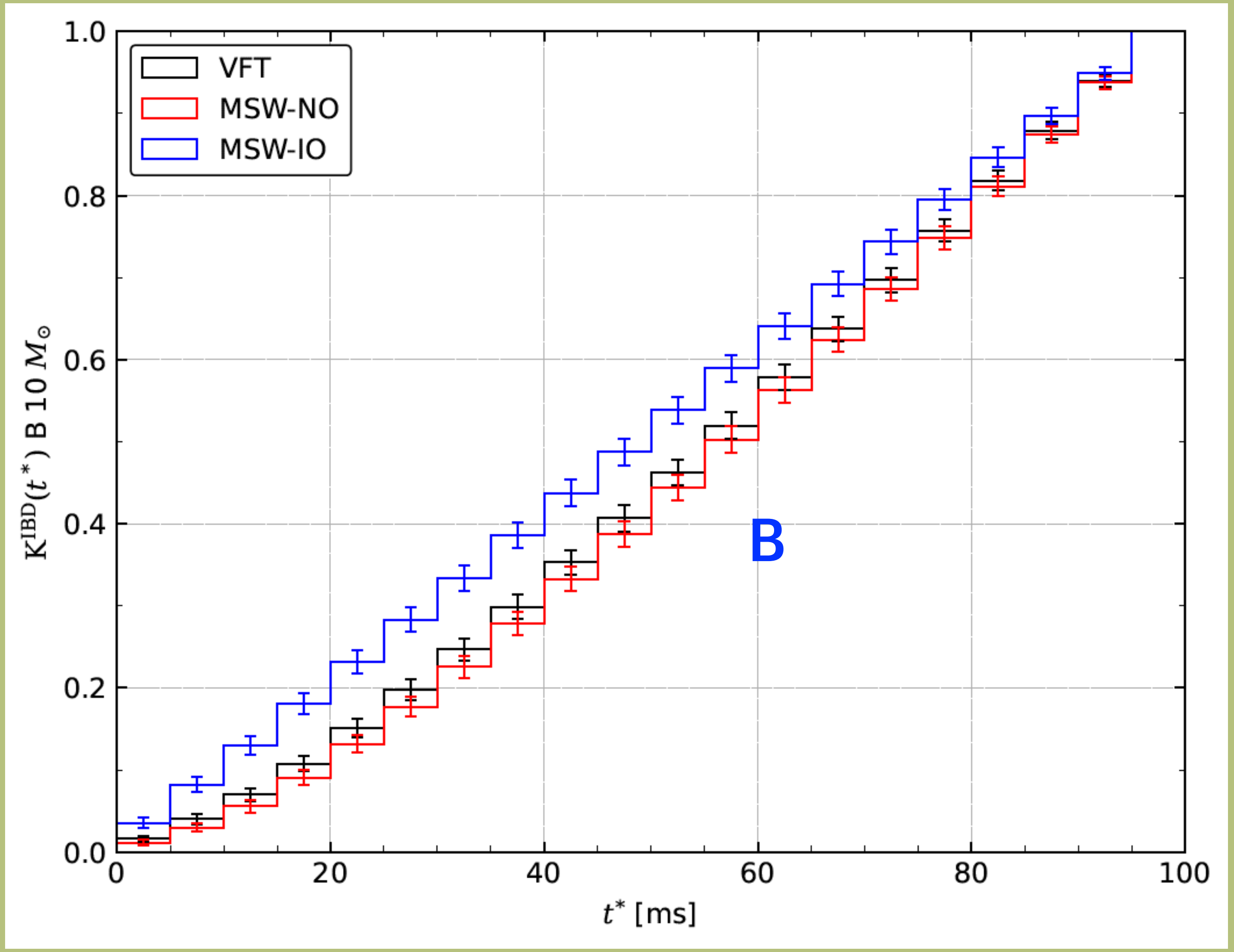


CUMULATIVE TIME DISTRIBUTIONS OF JUNO EVENTS

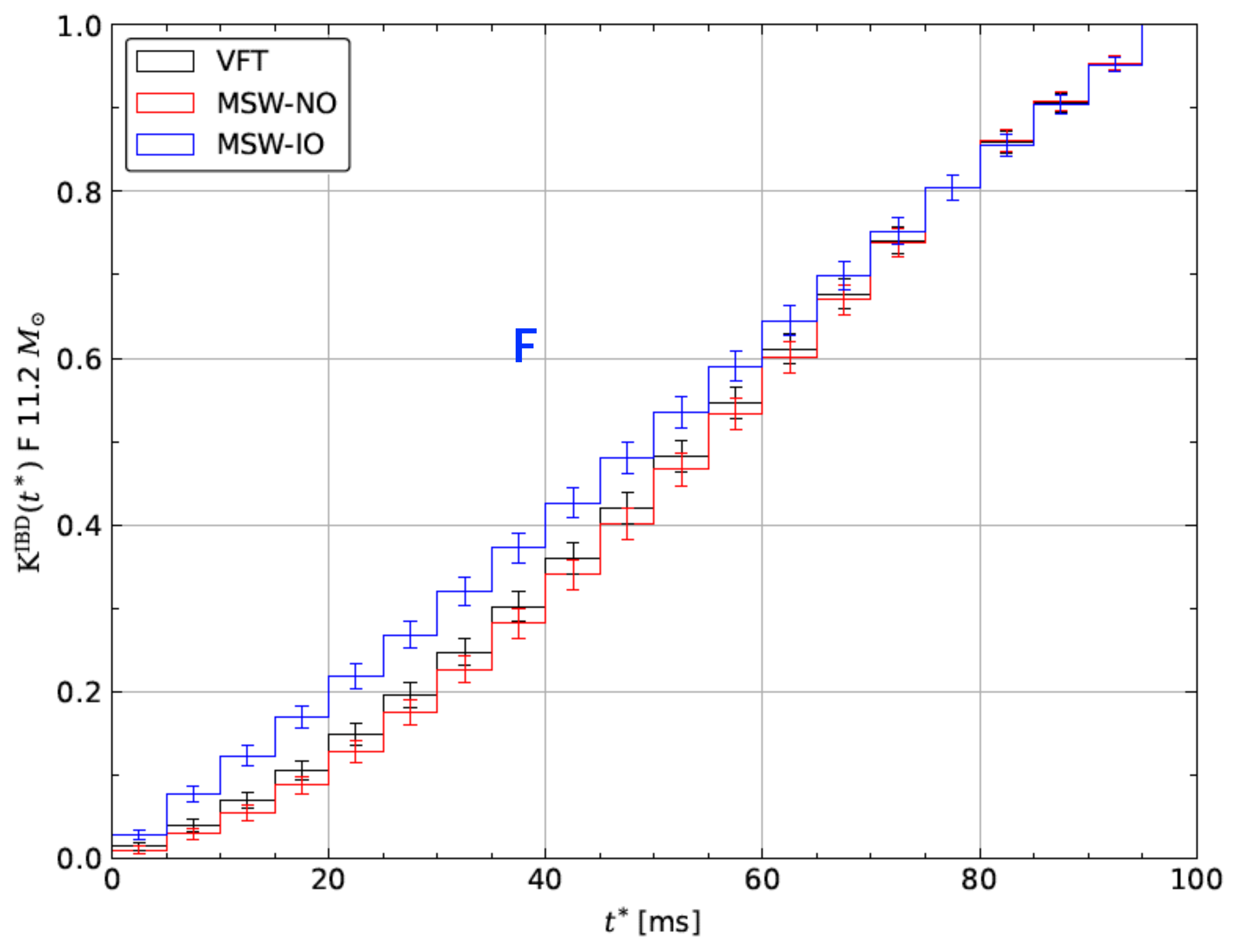
$$K^{i,\mathrm{IBD}}(t) = \frac{\int_0^t \frac{dN^i_{\mathrm{IBD}}}{dt'}dt'}{\int_0^{0.1\mathrm{s}} \frac{dN^i_{\mathrm{IBD}}}{dt'}dt'}$$

i = VFT, NO, IO





CUMULATIVE TIME DISTRIBUTIONS OF JUNO EVENTS



HyperK with smaller uncertainties

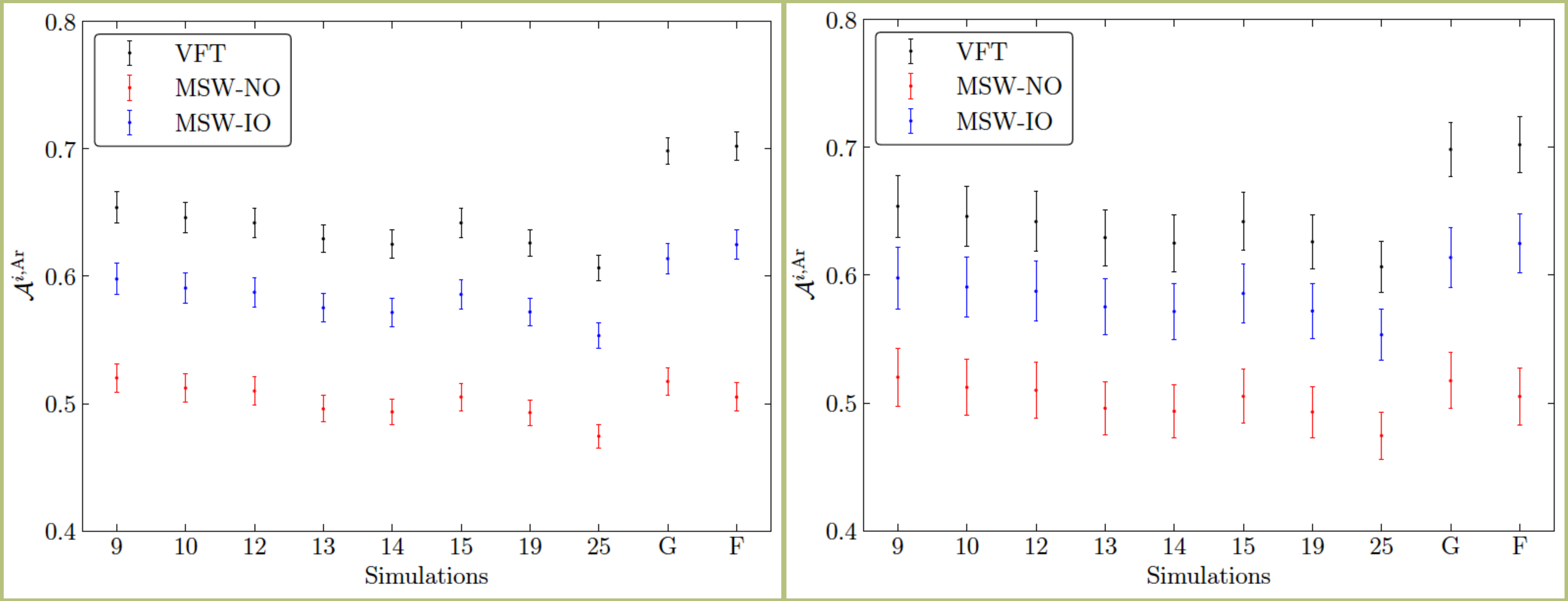
QUANTIFY THE SPECTRAL BEHAVIORS OF CUMULATIVE TIME DISTRIBUTIONS

$$\mathcal{A}^{i,\mathrm{Ar}} = \frac{1}{T}\int_0^T K^{i,\mathrm{Ar}}(t^*)dt^* \qquad T = 100\ \mathrm{ms}$$

$$\mathcal{A}^{i,\mathrm{IBD}} = \frac{1}{T}\int_0^T K^{i,\mathrm{IBD}}(t^*)dt^*$$

Replace a functional behavior by a number, the normalized area under the curve of cumulative time distribution, which indicates how fast the SN neutrino events accumulate!

THE NORMALIZED AREAS UNDER CUMULATIVE TIME DISTRIBUTIONS OF **DUNE** EVENTS



d=5 kpc

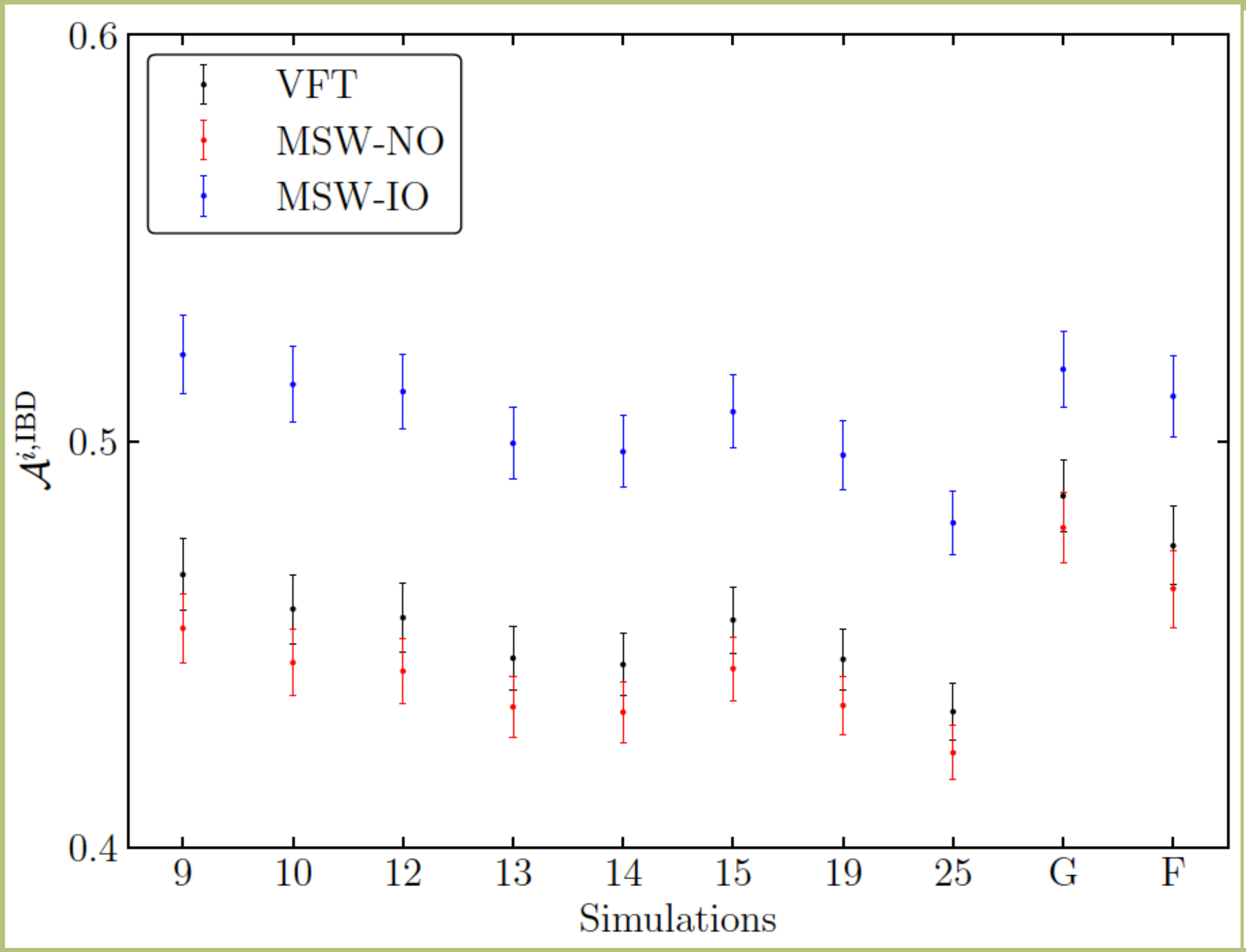
d=10 kpc

SHORT CONCLUSIONS FROM DUNE OBSERVATIONS

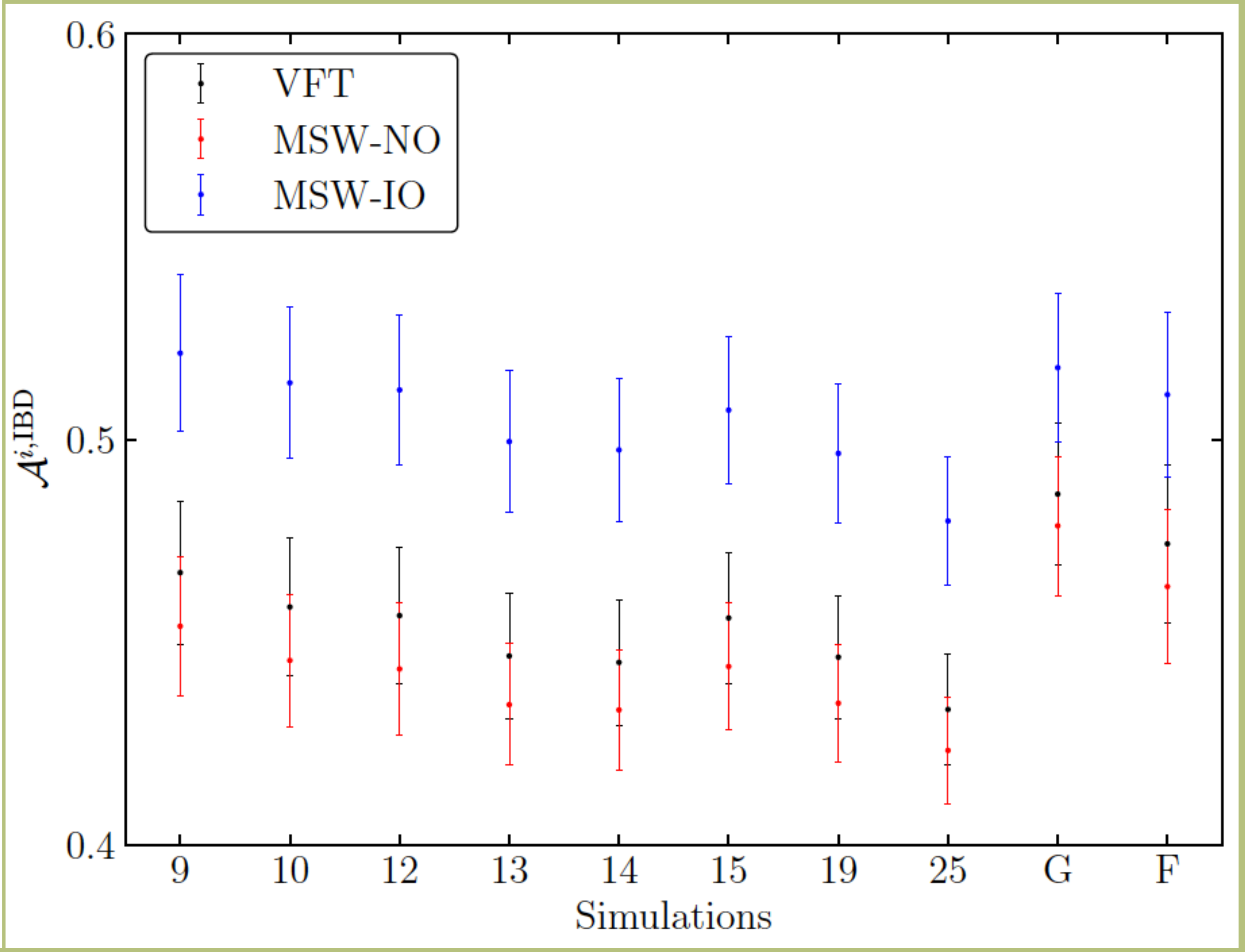
- At *d*=5kpc, MSW-NO can be distinguished from MSW-IO and VFT. On the other hand, the latter two are not separable.
- At *d*=10kpc, MSW-IO and MSW-NO slightly overlaps. However MSW-NO is still distinguishable from VFT.

THE NORMALIZED AREAS UNDER CUMULATIVE TIME DISTRIBUTIONS OF **JUNO** EVENTS

d=5 kpc



d=10 kpc



HyperK with smaller uncertainties

SHORT CONCLUSIONS FROM JUNO OBSERVATIONS

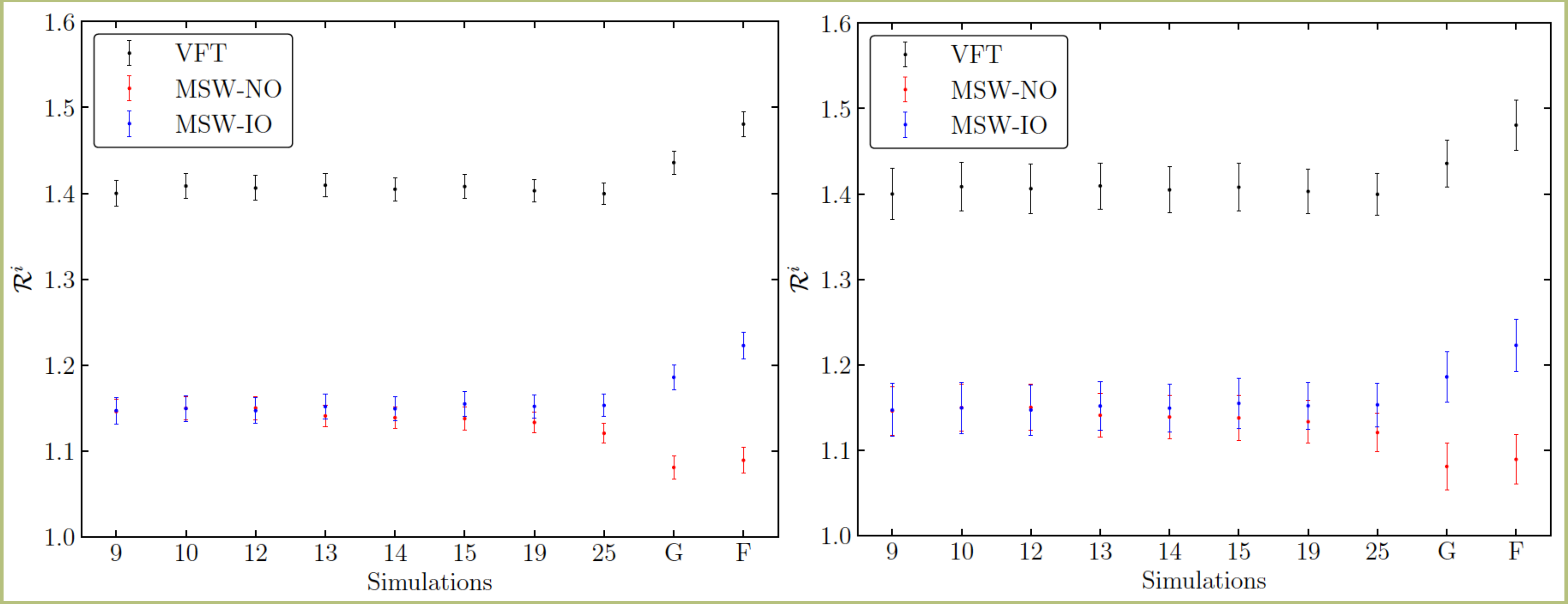
- JUNO (HyperK) IBD still cannot distinguish MSW-IO from VFT by itself. On the other hand, $\mathcal{A}^{\rm VFT,IBD} < \mathcal{A}^{\rm IO,IBD}$ in all simulations.
- Since $\mathcal{A}^{\rm VFT,Ar} > \mathcal{A}^{\rm IO,Ar}$, this motivates us to use the ratio $\mathcal{R}^i \equiv \mathcal{A}^{i,{\rm Ar}}/\mathcal{A}^{i,{\rm IBD}}$ with $i = {\rm NO,\ IO,\ and\ VFT}$ to distinguish various scenarios.

TAKING THE RATIO OF NORMALIZED AREAS IN DUNE AND JUNO MEASUREMENTS

$$\mathcal{R}^i = \mathcal{A}^{i,\mathrm{Ar}}/\mathcal{A}^{i,\mathrm{IBD}}$$

d=5 kpc

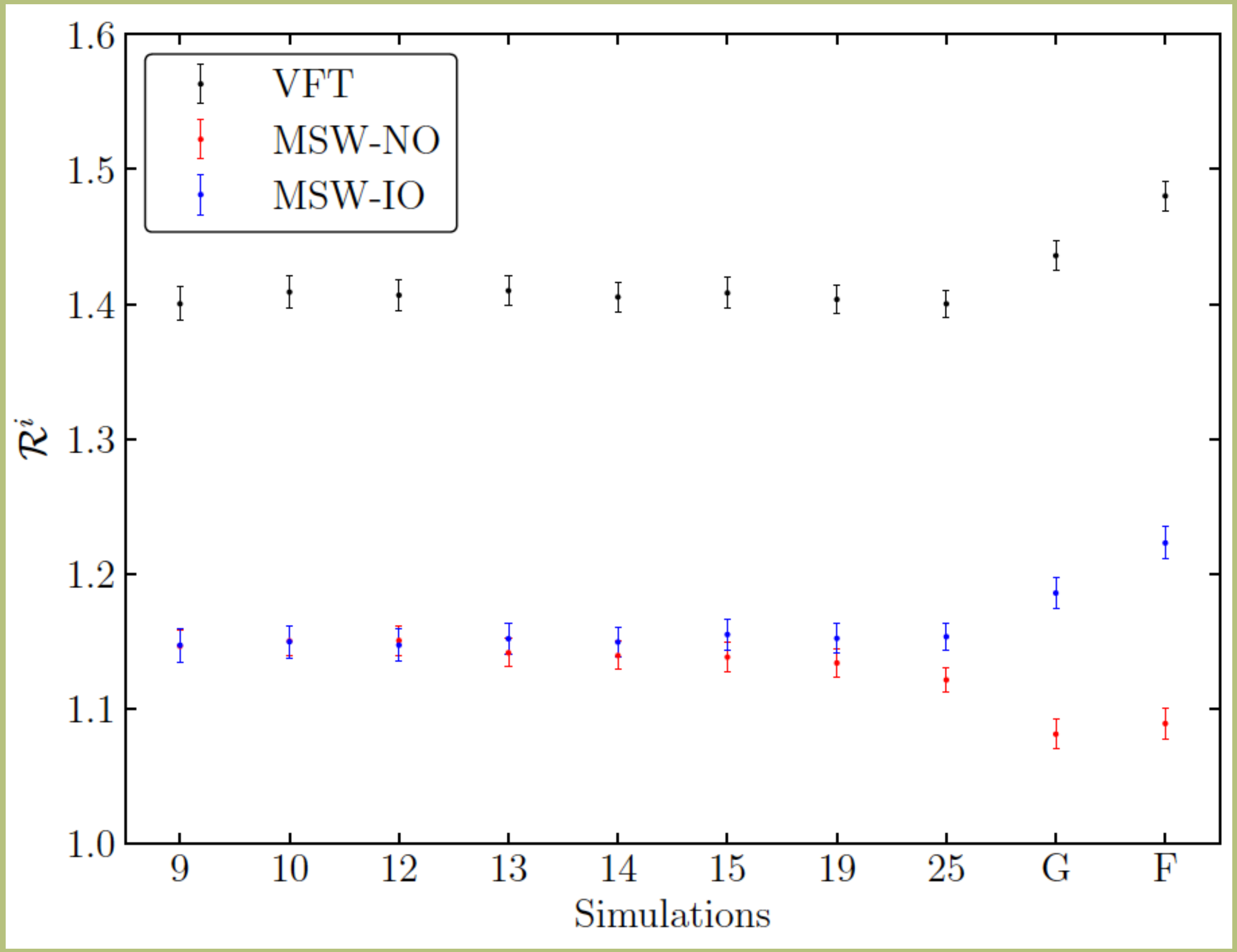
d=10 kpc



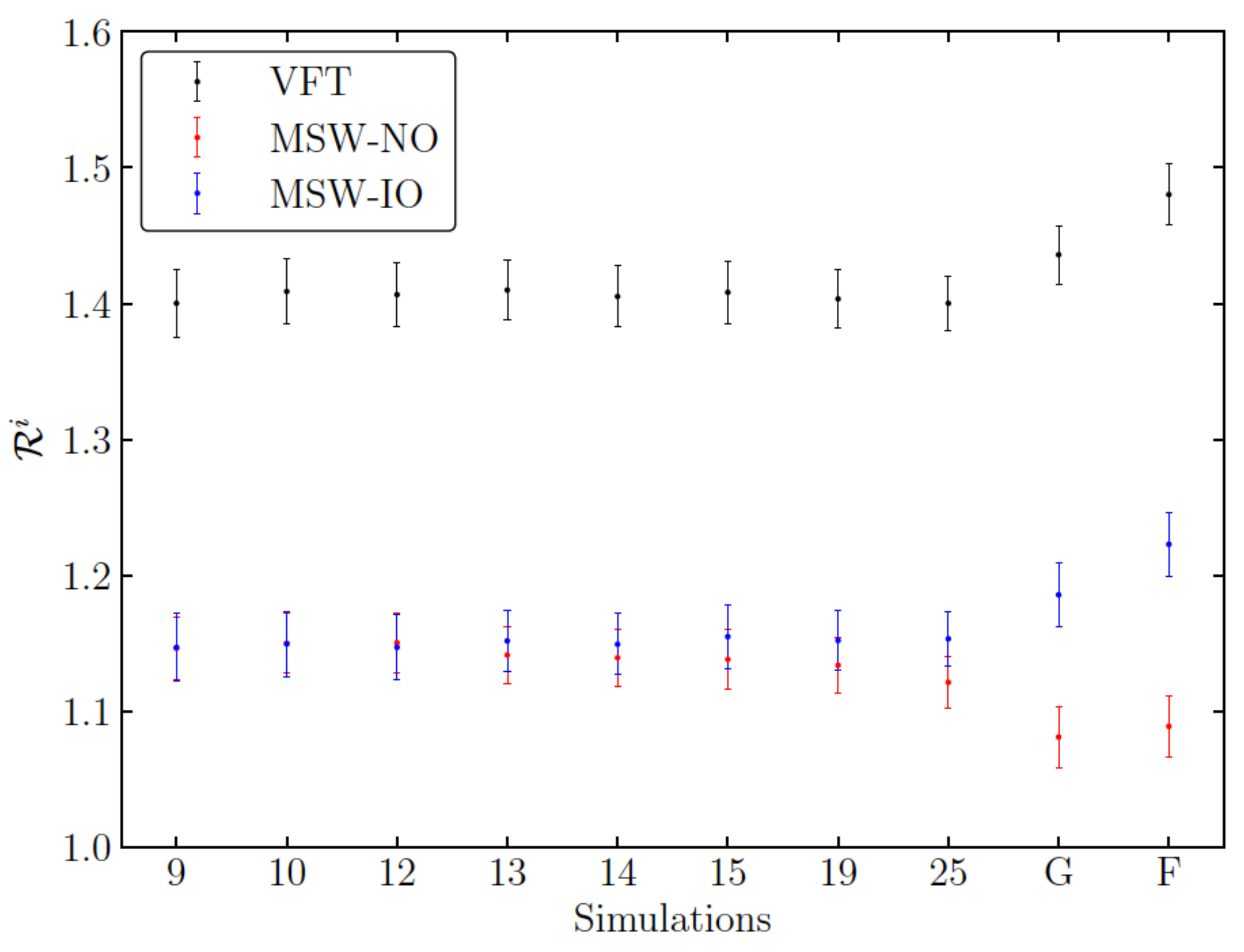
TAKING THE RATIO OF NORMALIZED AREAS IN DUNE AND HYPERK MEASUREMENTS

$$\mathcal{R}^i = \mathcal{A}^{i,\mathrm{Ar}} / \mathcal{A}^{i,\mathrm{IBD}}$$

d=5 kpc



d=10 kpc



SHORT CONCLUSIONS FROM THE RATIO DUNE/ JUNO, HYPERK

- At *d*=5 kpc, MSW-IO can be distinguished from VFT.
- At *d*=10 kpc, the above two scenarios remain distinguishable.

SUMMARY

- Galactic SN neutrinos can provide precious information on flavor transitions of neutrinos in dense medium.
- We propose to test MSW flavor transition mechanism in neutronization burst era of SN neutrino emissions. The non-MSW scenarios to be distinguished by the MSW one is vacuum flavor transition (VFT).
- Taking the SN distance to be 5 kpc and 10 kpc for illustrations, we find that simultaneous detections of ν_e (DUNE) and $\bar{\nu}_e$ (JUNO/HyperK) can distinguish between MSW and VFT.