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TESTING THE MSW EFFECT IN SUPERNOVA EXPLOSION WITH NEUTRINO EVENT RATES

THE VACUUM OSCILLATION AND THE MSW EFFECT

- **Vacuum Oscillation** : The neutrino flavour transition probabilities for a long distance traveling with the latest experimental data of those mixing angles[1]

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 \approx \begin{pmatrix} 0.550198 & 0.232905 & 0.216897 \\ 0.232905 & 0.394406 & 0.37269 \\ 0.216897 & 0.37269 & 0.410413 \end{pmatrix}$$

- **The MSW effect**[2] formula for small θ_{13}[3] :

Normal Mass Ordering (NH) :

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

Inverted Mass Ordering (IH) :

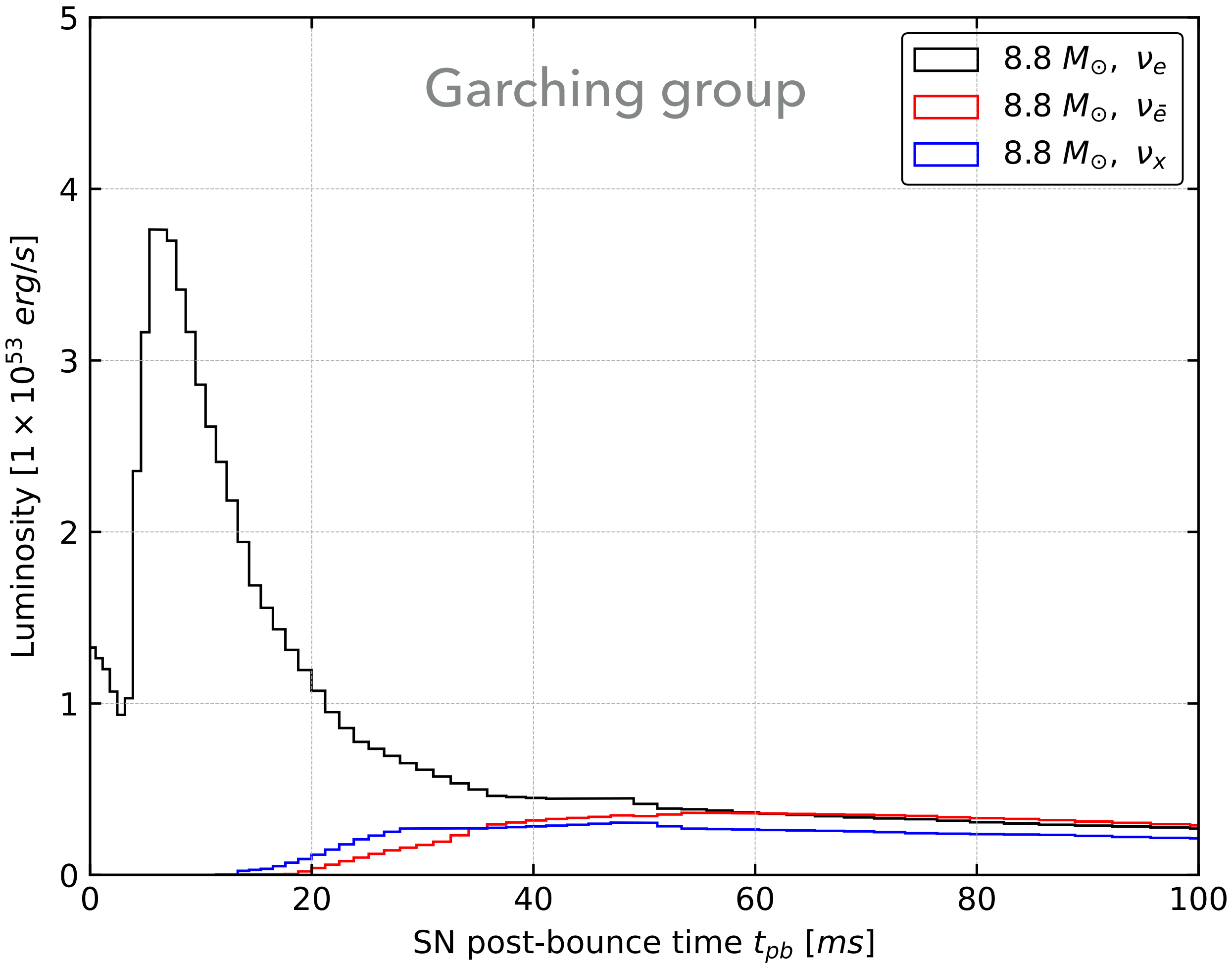
$$F_e = \sin^2\theta_{12}F_e^0 + (1-\sin^2\theta_{12})F_x^0$$
$$F_{\bar{e}} = F_x^0$$
$$F_x = \frac{1}{4}\left[(1-\sin^2\theta_{12})F_e^0 + F_{\bar{e}}^0 + (2+\sin^2\theta_{12})F_x^0\right]$$

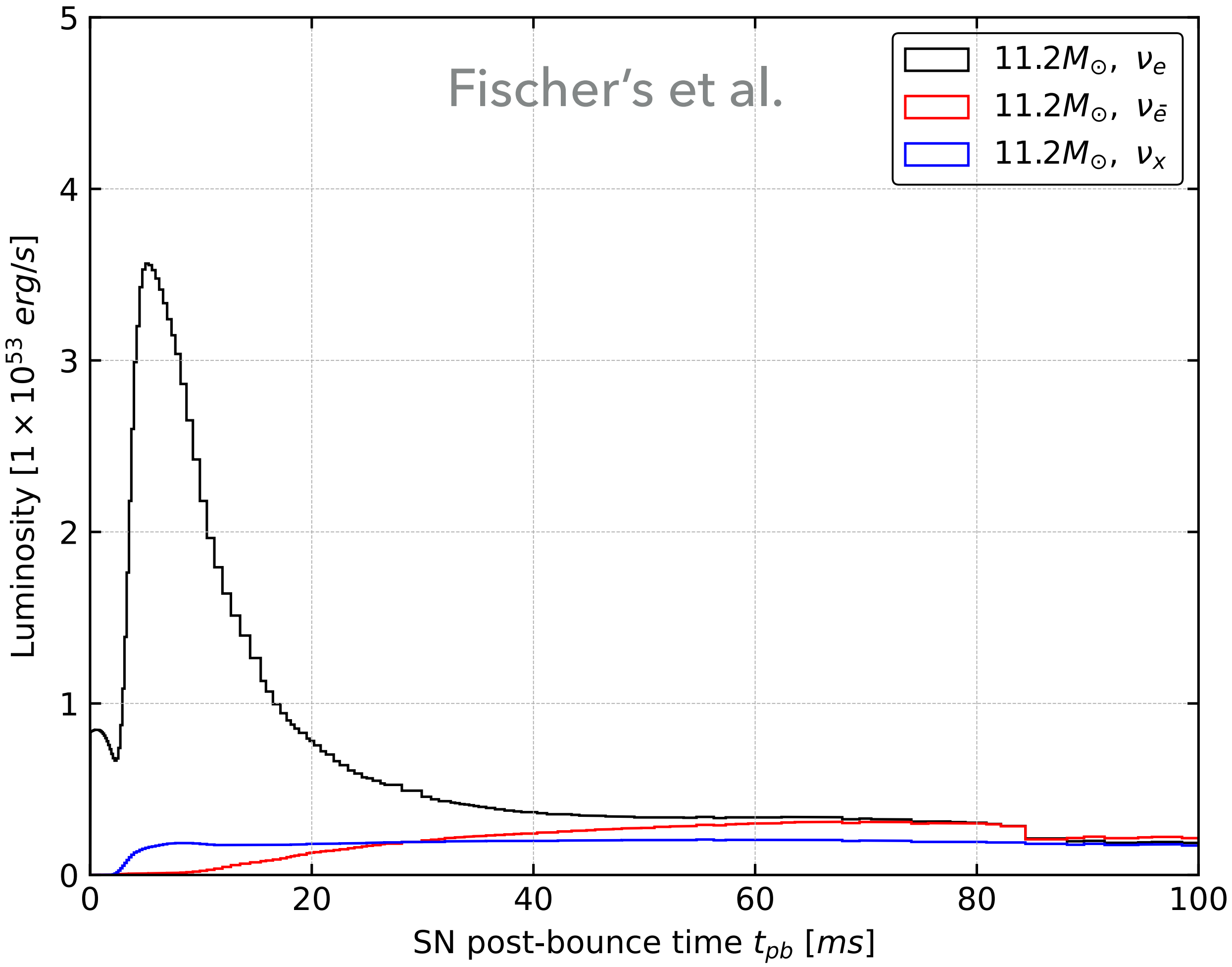
[1] P.A. Zyla et al. (Particle Data Group), to be published in Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

[2] L. Wolfenstein, “Neutrino oscillations in matter”, Phys. Rev. D 17, 2369 (1978)

[3] S. P. Mikheyev and A. Y. Smirnov, “Resonant Amplification of Oscillations in Matter and Solar-Neutrino Spectroscopy”, A.Y. Il Nuovo Cimento C 9 (1986) 17

THE SUPERNOVA NEUTRINO LUMINOSITY



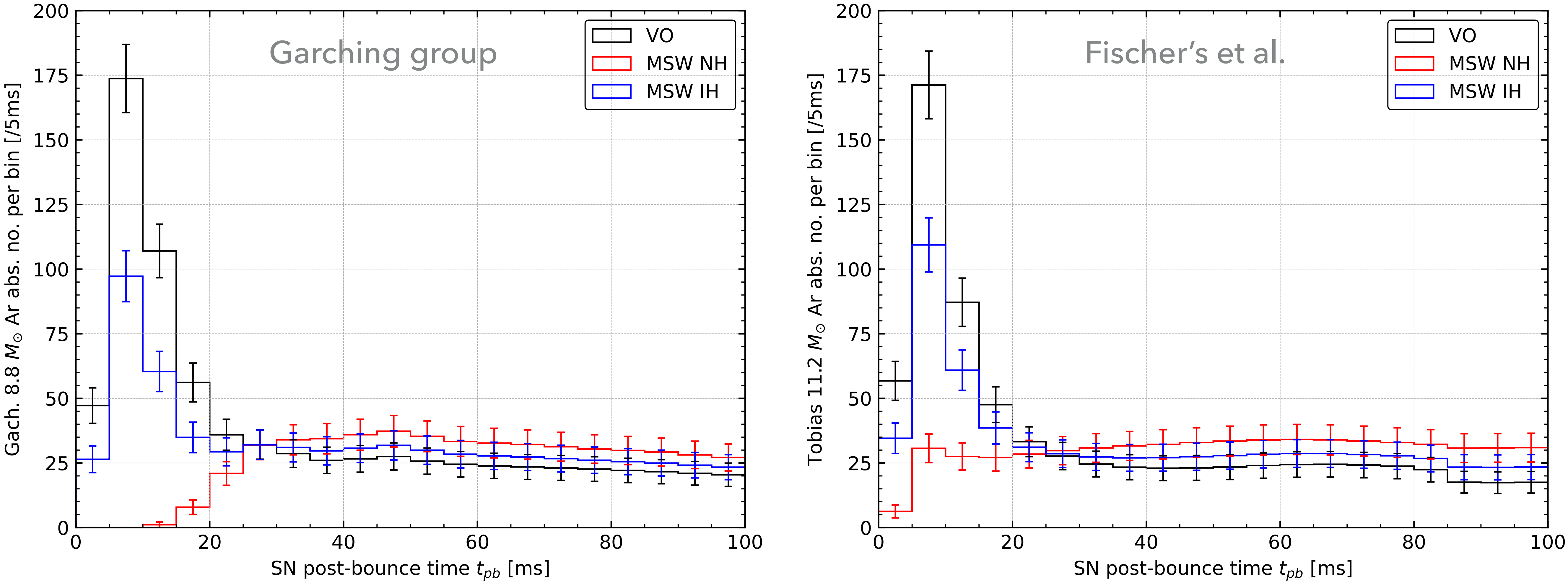


- These two simulations have a common time-evolution pattern
- A sharp peak emerges in the profile of ν_e primary emissions during the neutronization burst
- Note that a huge amount of ν_e is switched to other flavours according to the MSW oscillation formulas

[5]L. Hudepohl, B. Muller, H.-T. Janka, A. Marek and G. G. Raffelt, Phys. Rev. Lett. 104 (2010) 251101, Erratum: Phys. Rev. Lett. 105 (2010) 249901, arXiv:0912.0260

[6]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

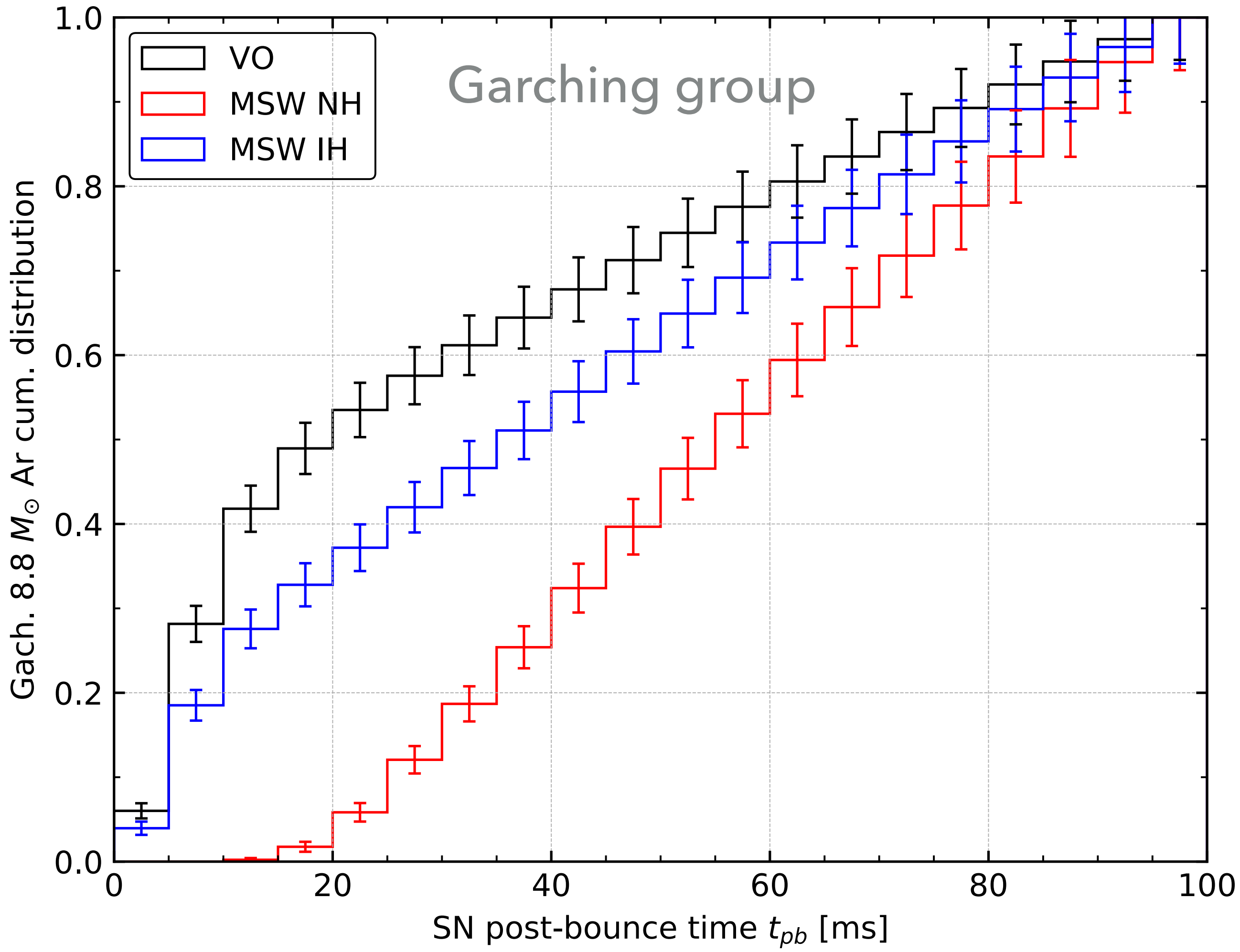
ARGON NEUTRINO ABSORPTION RATE IN DUNE[7] EXPERIMENT

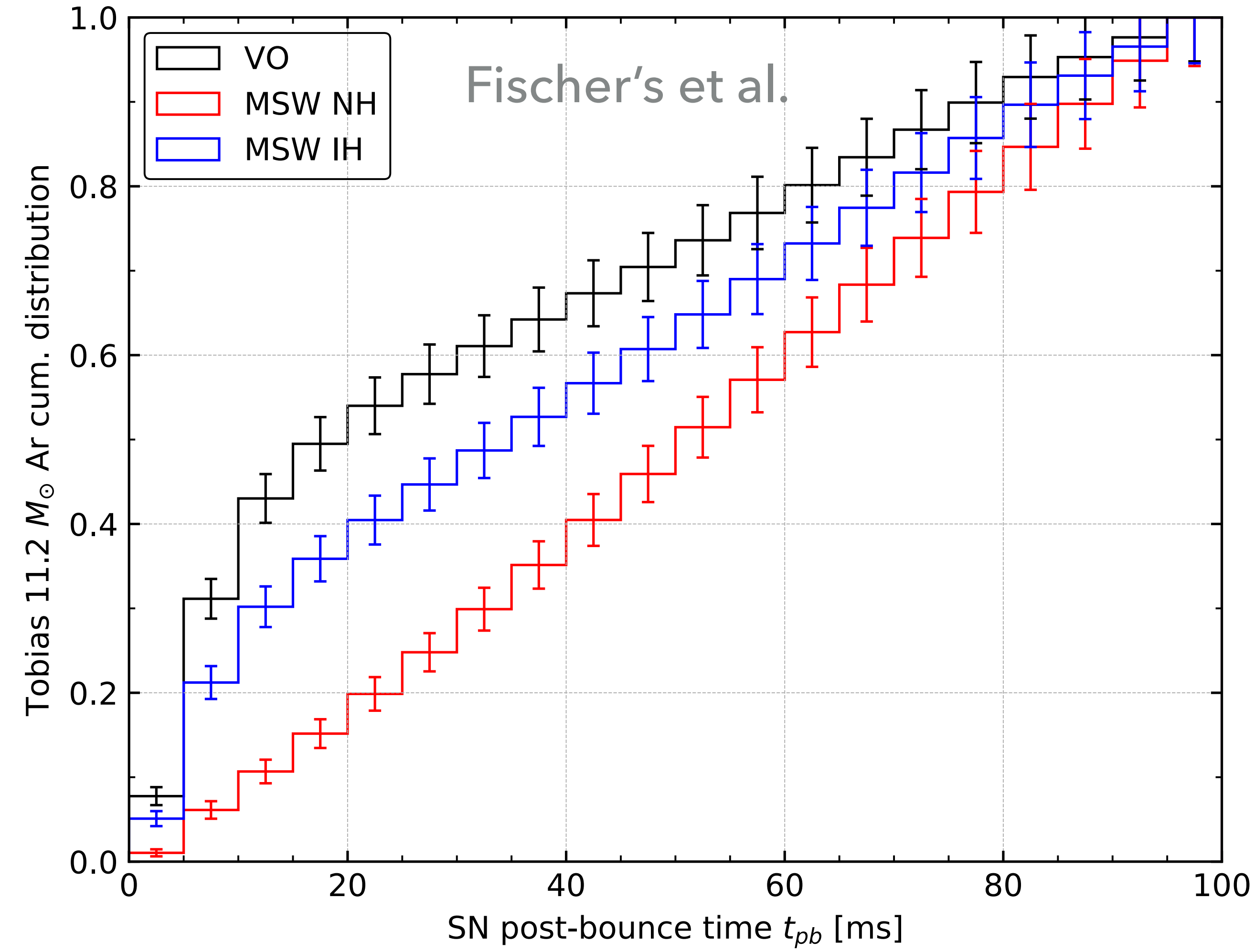


- A huge amount of ν_e is switched to other flavours in the MSW oscillation
- The sharp peak is retained only in VO (55%) and IH (30%) , but not in NH
- Argon neutrino absorption rate has a potential to discriminate the oscillation effect

[7]DUNE Conceptual Design Report, arXiv:1512.06148v2 [physics.ins-det]

CUMULATIVE DISTRIBUTION OF ARGON NEUTRINO ABSORPTION RATE

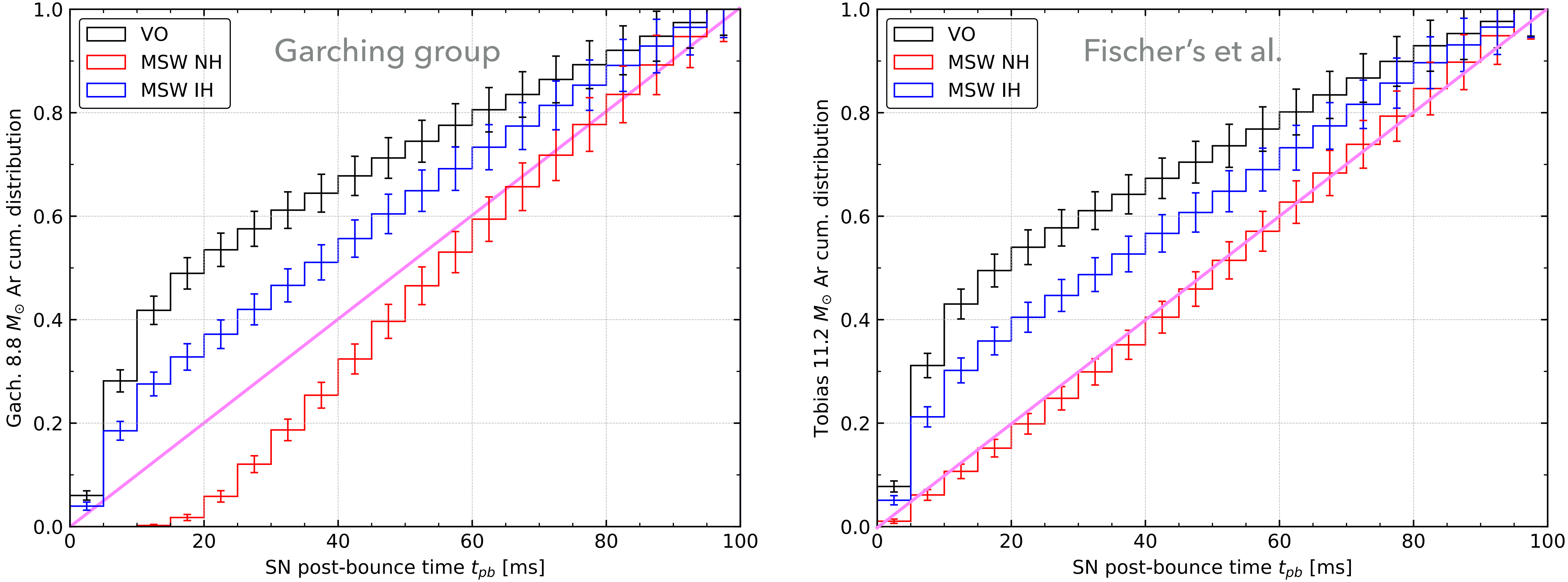




- Cumulative distribution $K(t) \equiv \int_0^t \frac{dN}{dt} dt \Big/ \int_0^{0.1s} \frac{dN}{dt} dt$[8]
- A way to look for common behaviour of SN neutrino among different models or simulations
- We can Perform a quantitative analysis by measuring the distance among models[8]
- We tend to construct a preliminary analysis by simple inspection on the time-evolution patterns

[8]P. D. Serpico, S. Chakraborty, T. Fischer, L. Hudepohl, H. T. Janka and A. Mirizzi, Phys.Rev. D 85 (2012) 085031, arXiv:1111.4483

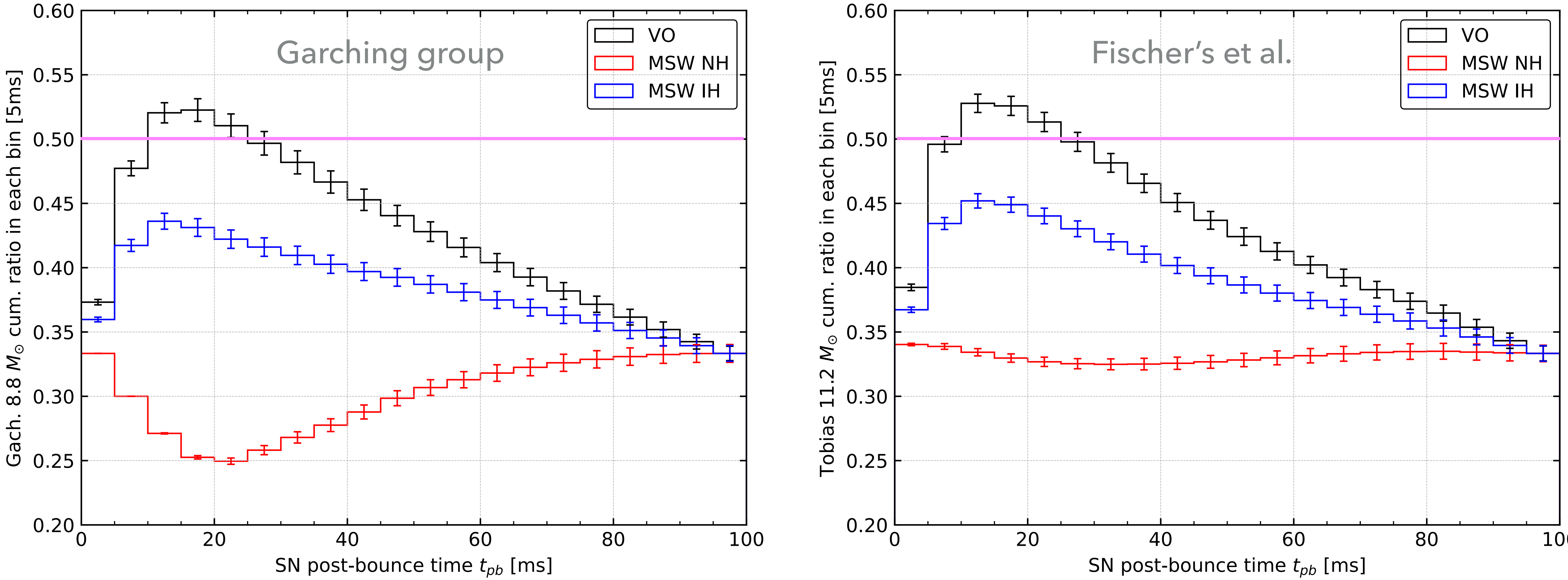
CUMULATIVE EVENT RATIO "$R_{\text{cum}}(K_{\text{Ar}}(t), N(t))$" [11]



- Wish to create some function which start and end with the same value
- Three patterns : concave, convex, straight line
- $R_{\text{cum}}(K_{\text{Ar}}(t), N(t)) \equiv \frac{2}{3}\left(\frac{1+K_{\text{Ar}}(t)}{1+N(t)}\right) - \frac{1}{3}$, $N(t)$ is a diagonal straight line in $K(t)$ plot

[11]Kwang-Chang Lai, C. S. Jason Leung and Guey-Lin Lin, arXiv:2001.08543 [astro-ph.HE]

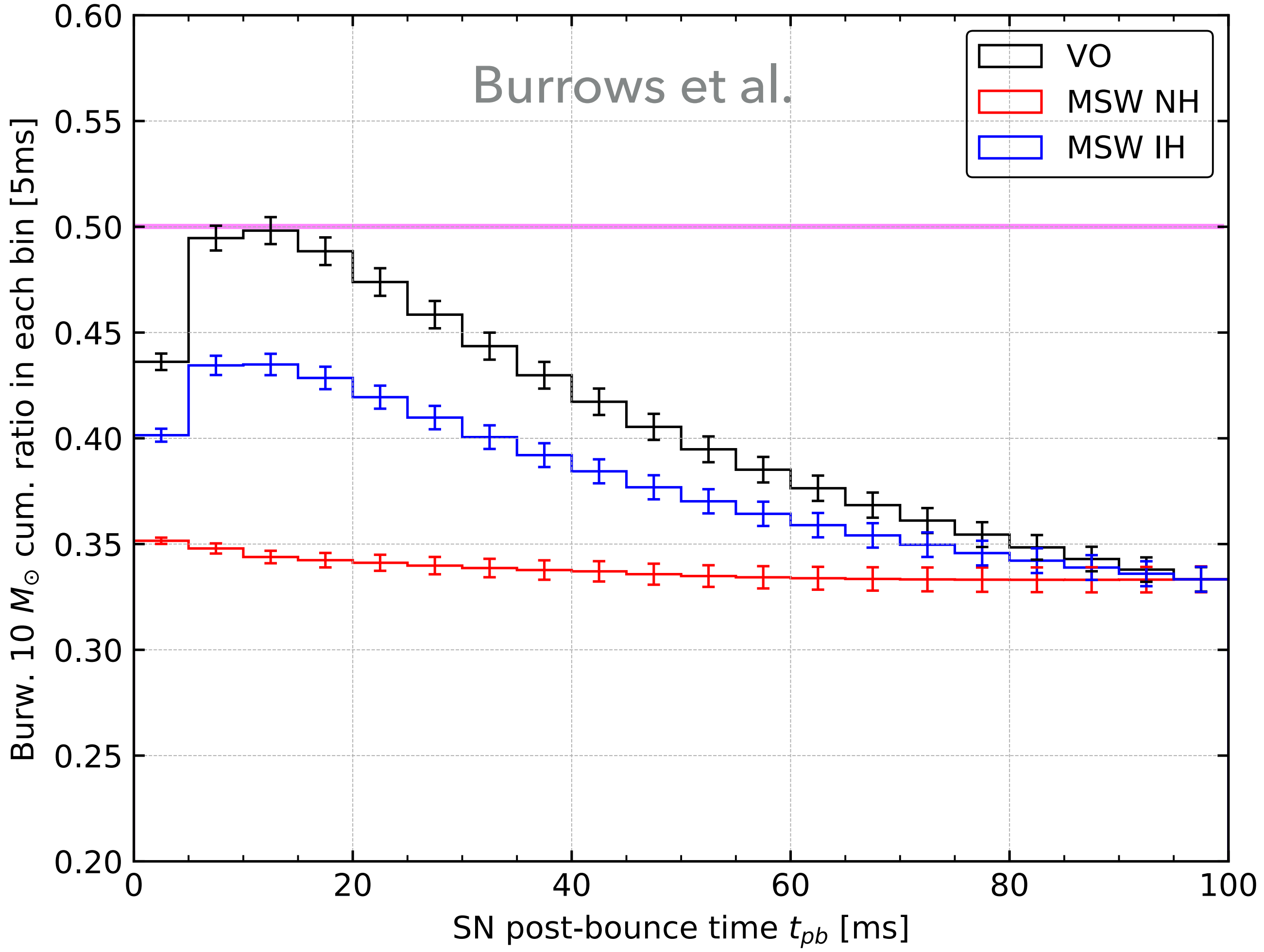
CUMULATIVE EVENT RATIO “$R_{\text{cum}}(K_{\text{Ar}}(t), N(t))$” [11]

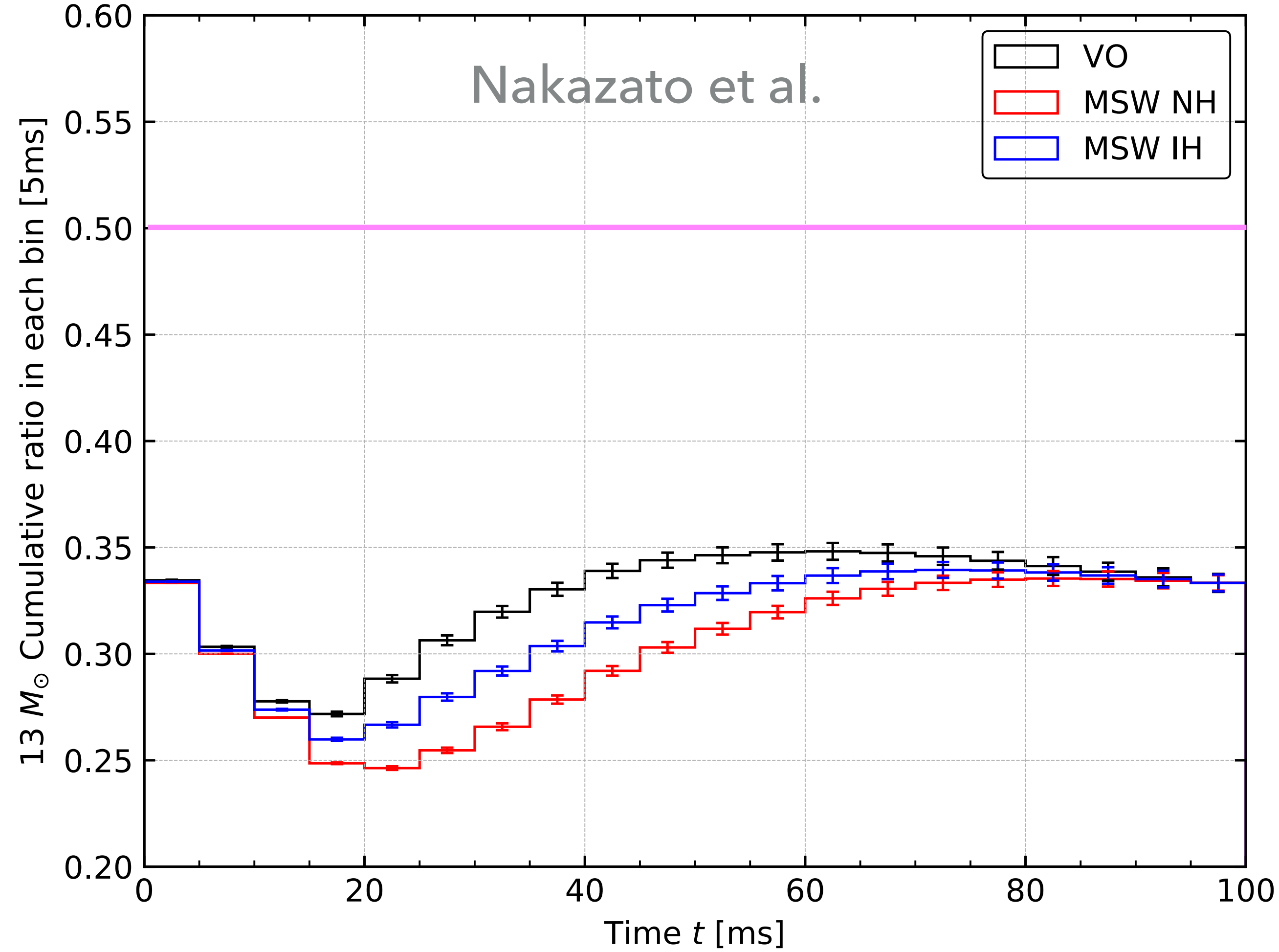


- $R_{\text{cum}}(K_{\text{Ar}}(t), N(t)) \equiv \frac{2}{3}\left(\frac{1+K_{\text{Ar}}(t)}{1+N(t)}\right) - \frac{1}{3}$, $N(t)$ is a diagonal straight line in $K(t)$ plot
- The maximum of $R^{\text{VO}}_{\text{cum}} \gtrsim 0.5$.
  This can be a criteria to separate the VO and the MSW oscillation (purple line), even if we do not have any simulation models to compare with

[11]Kwang-Chang Lai, C. S. Jason Leung and Guey-Lin Lin, arXiv:2001.08543 [astro-ph.HE]

CUMULATIVE EVENT RATIO "$R_{\mathrm{cum}}(K_{\mathrm{Ar}}(t), N(t))$" (OTHER MODELS)



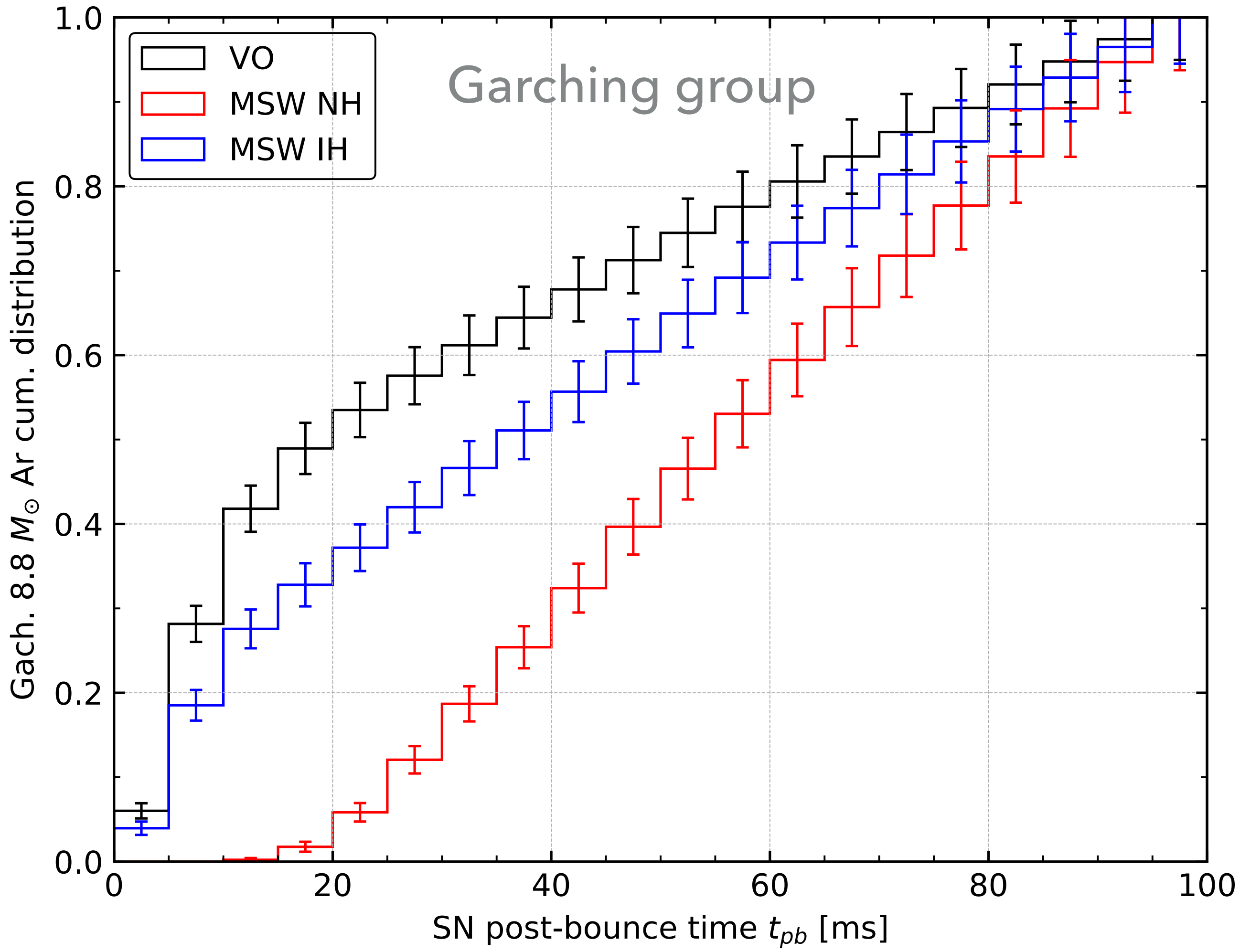


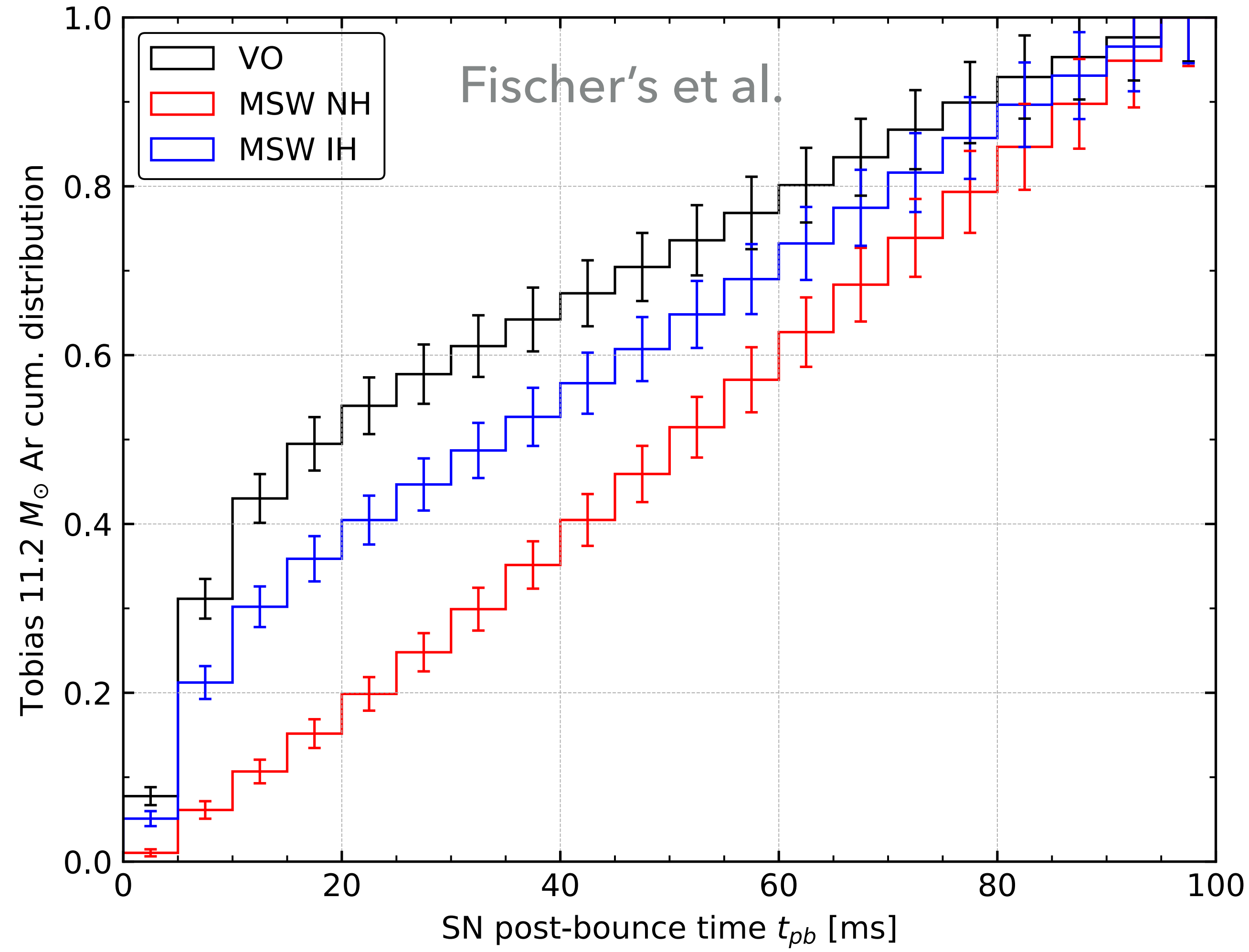
- Burrows'[9] (left penal) and Nakazato's[10] (right penal) SN simulation.
- This method is applicable in the series of Burrows' models as well
- Not suitable in the series of Nakazato's SN simulations

[9]A. Burrows, D. Radice and D. Vartanyan, Mon. Not. Roy. Astron. Soc. 485 (2019) no.3, 3153,arXiv:1902.00547

[10]K. Nakazato, K. Sumiyoshi, H. Suzuki, T. Totani, H. Umeda and S. Yamada, Astrophys. J.Suppl. 205 (2013) 2, arXiv:1210.6841

CUMULATIVE EVENT RATIO "$R_{\mathrm{cum}}(K_{\mathrm{Ar}}(t), K^s_{\mathrm{Ar,IH}}(t))$" [11]



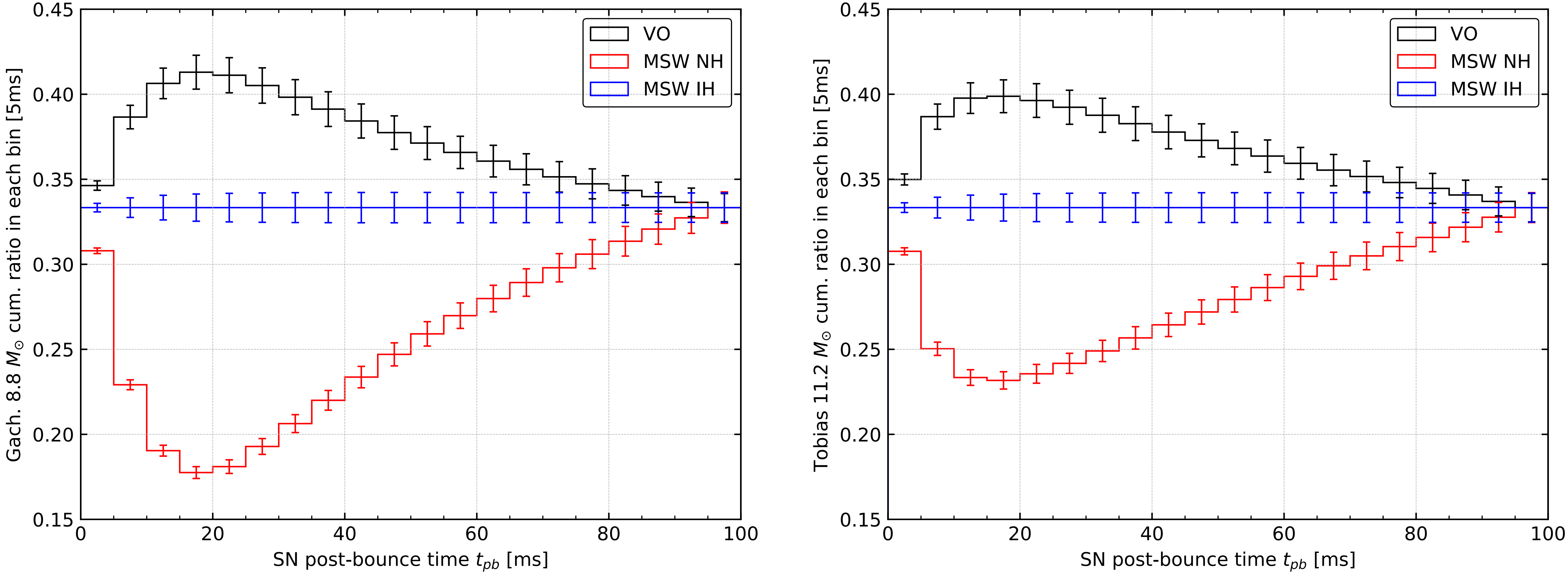


- $$R_{\mathrm{cum}}(K_{\mathrm{Ar}}(t), K^s_{\mathrm{Ar,IH}}(t)) \equiv \frac{2}{3}\left(\frac{1 + K_{\mathrm{Ar}}(t)}{1 + K^s_{\mathrm{Ar,IH}}(t)}\right) - \frac{1}{3}$$

  $K^s_{\mathrm{Ar,IH}}(t)$ is a set of $K_{\mathrm{IH}}(t)$ in our simulation pool

[11]Kwang-Chang Lai, C. S. Jason Leung and Guey-Lin Lin, arXiv:2001.08543 [astro-ph.HE]

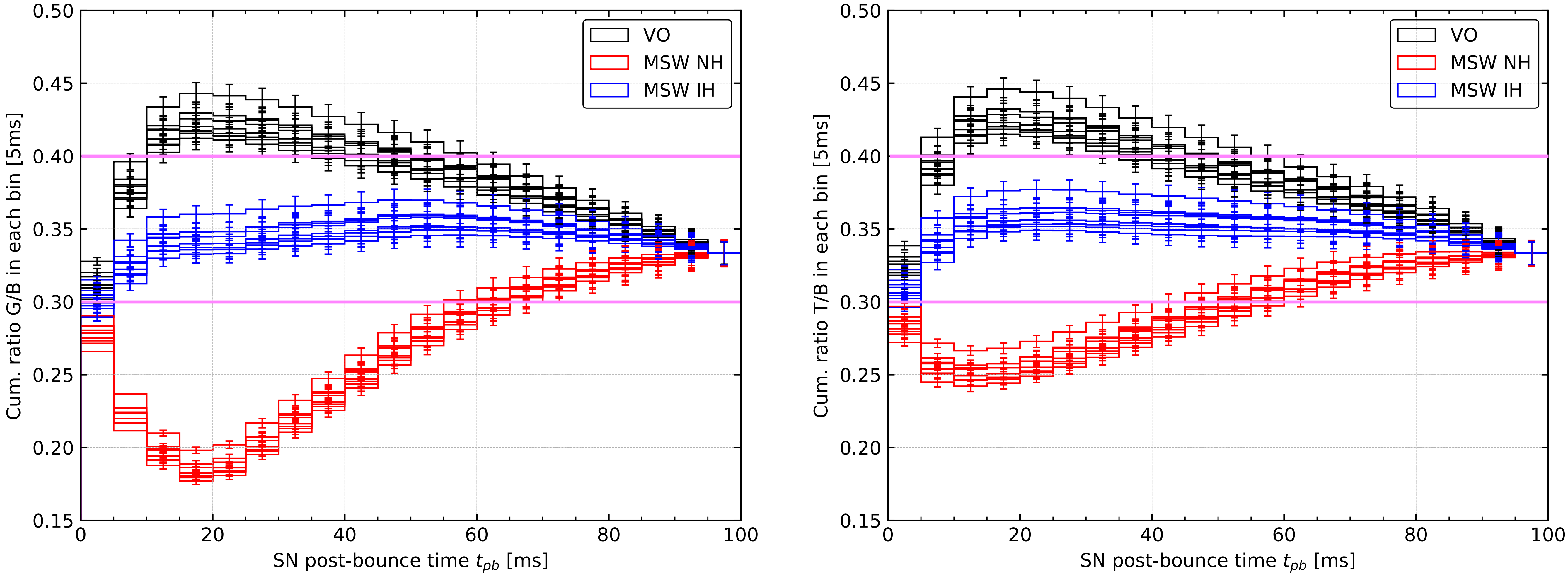
CUMULATIVE EVENT RATIO "$R_{\text{cum}}(K_{\text{Ar}}(t), K^s_{\text{Ar,IH}}(t))$" [11]



- $$R_{\text{cum}}(K_{\text{Ar}}(t), K^s_{\text{Ar,IH}}(t)) \equiv \frac{2}{3}\left(\frac{1+K_{\text{Ar}}(t)}{1+K^s_{\text{Ar,IH}}(t)}\right) - \frac{1}{3}$$
- Three patterns : concave (VO), convex (MSW NH), straight line (MSW IH)

[11] Kwang-Chang Lai, C. S. Jason Leung and Guey-Lin Lin, arXiv:2001.08543 [astro-ph.HE]

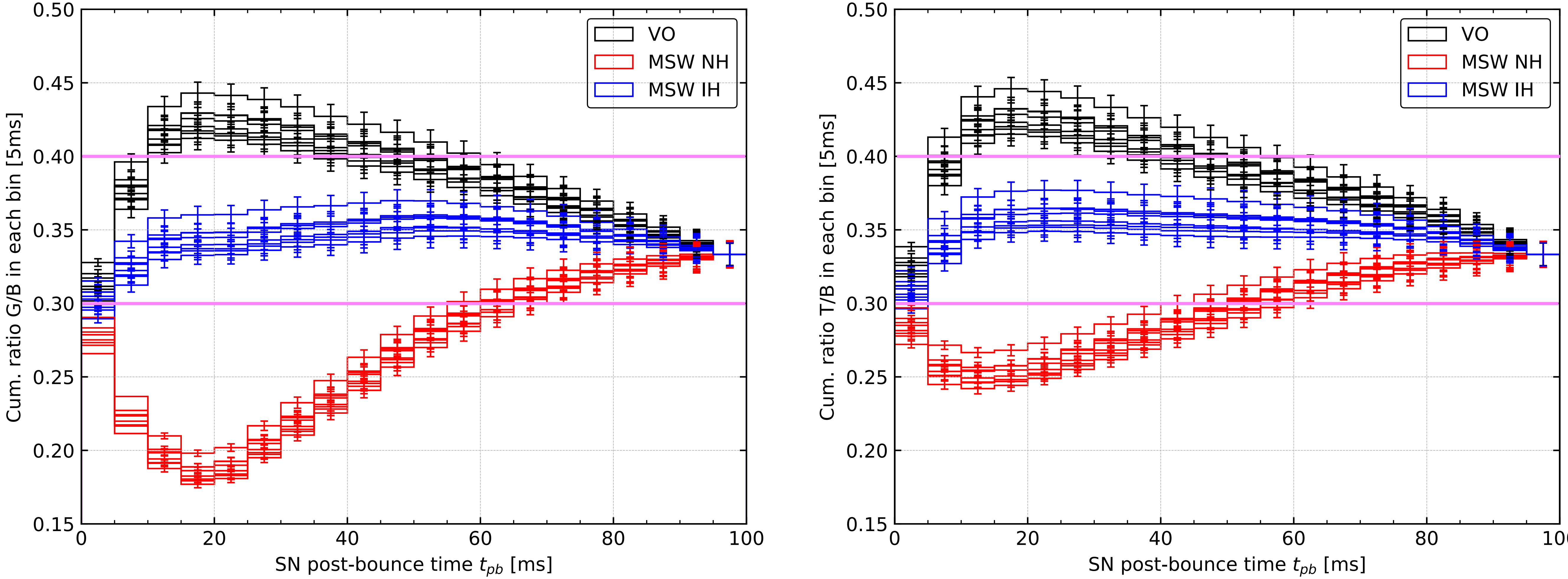
CUMULATIVE EVENT RATIO "$R_{\text{cum}}(K_{\text{Ar}}(t), K^s_{\text{Ar,IH}}(t))$" [11]



- $R_{\text{cum}}(K_{\text{Ar}}(t), K^s_{\text{Ar,IH}}(t)) \equiv \frac{2}{3}\left(\frac{1+K_{\text{Ar}}(t)}{1+K^s_{\text{Ar,IH}}(t)}\right) - \frac{1}{3}$
- Treat Garching and Fischer's SN neutrino simulation as an experimental data
- $K^s_{\text{Ar,IH}}(t)$ is a set of Burrows' SN neutrino simulations (use their simulation as the simulation pool)

[11]Kwang-Chang Lai, C. S. Jason Leung and Guey-Lin Lin, arXiv:2001.08543 [astro-ph.HE]

CUMULATIVE EVENT RATIO "$R_{\text{cum}}(K_{\text{Ar}}(t), K^{s}_{\text{Ar,IH}}(t))$" [11]



Criteria :

- There is a region in $R^{\text{VO}}_{\text{cum}} \gtrsim 0.4$
- $0.3 < R^{\text{IH}}_{\text{cum}} < 0.4$
- There is a region in $R^{\text{NH}}_{\text{cum}} < 0.3$

relies on the sharp peak in the ν_e primary emissions during the neutronization burst

[11]Kwang-Chang Lai, C. S. Jason Leung and Guey-Lin Lin, arXiv:2001.08543 [astro-ph.HE]

CONCLUSION

- We proposed a simple method to verify the MSW neutrino oscillation effect in SN
- Argon neutrino absorption rate has a huge potential to distinguish between the VO and the MSW oscillation
- Constructed two cumulative event ratios R_{cum}
- The time-evolution patterns of R_{cum} can be effective in determining whether the MSW effect occurs in SN neutrino propagation or not

REFERENCES

[1] P.A. Zyla et al. (Particle Data Group), to be published in Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

[2] L. Wolfenstein, "Neutrino oscillations in matter", Phys. Rev. D 17, 2369 (1978)

[3] S. P. Mikheyev and A. Y. Smirnov, "Resonant Amplification of Oscillations in Matter and Solar-Neutrino Spectroscopy", A.Y. Il Nuovo Cimento C 9 (1986) 17

[5]L. Hudepohl, B. Muller, H.-T. Janka, A. Marek and G. G. Raffelt, Phys. Rev. Lett. 104 (2010) 251101, Erratum: Phys. Rev. Lett. 105 (2010) 249901, arXiv:0912.0260

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