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Diagnosing the origin of dense circumstellar material in a multi-energy neutrino astronomical approach

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Based on the work published in The Astrophysical Journal 982, 93 (2025)

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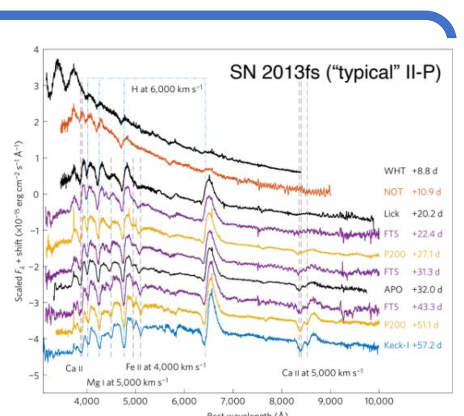
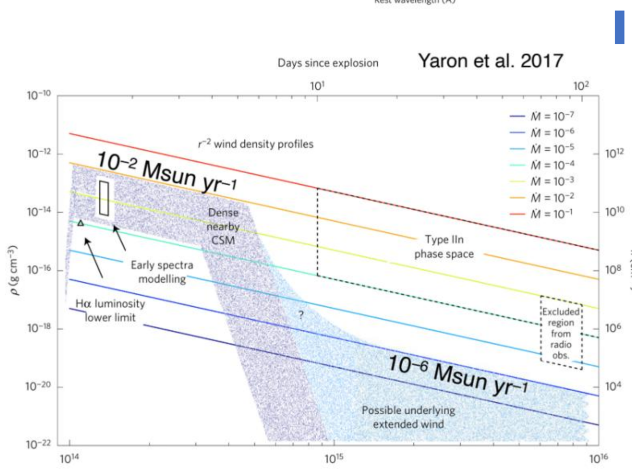
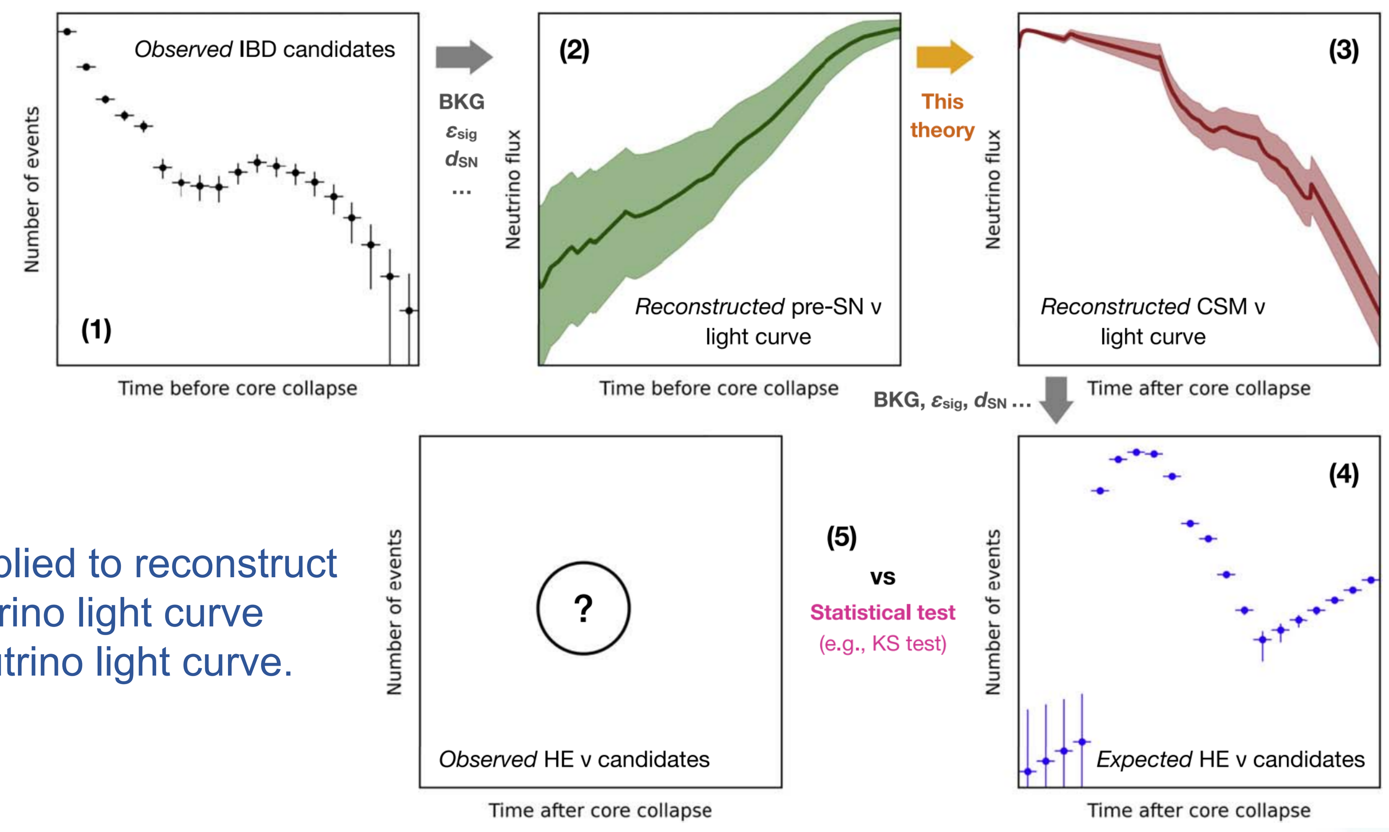
1. Introduction

- ❑ Origin of dense circumstellar material (**CSM**)??
  - Core convection
  - Binary star process
  - Pre-explosion activity
- ❑ Mass loss may be caused by a weaker gravitational binding due to pre-SN neutrino emission?
  - **Thermal MeV neutrinos** (pre-SN activity); e.g., C. Kato et al. ApJ 848, 48 (2017)
  - **Non-thermal high-energy neutrinos** (ejecta-CSM interactions); e.g., K. Murase PRD 97, 081301 (2018)
- ❑ Detecting multi-energy neutrinos could solve the mysterious origin of dense CSM.





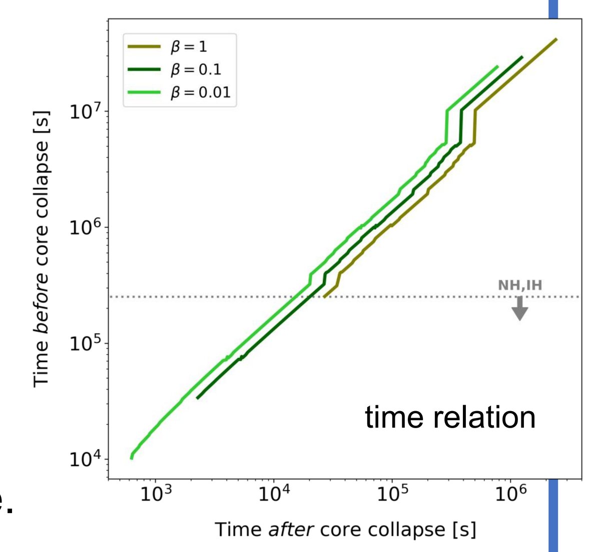
Approach

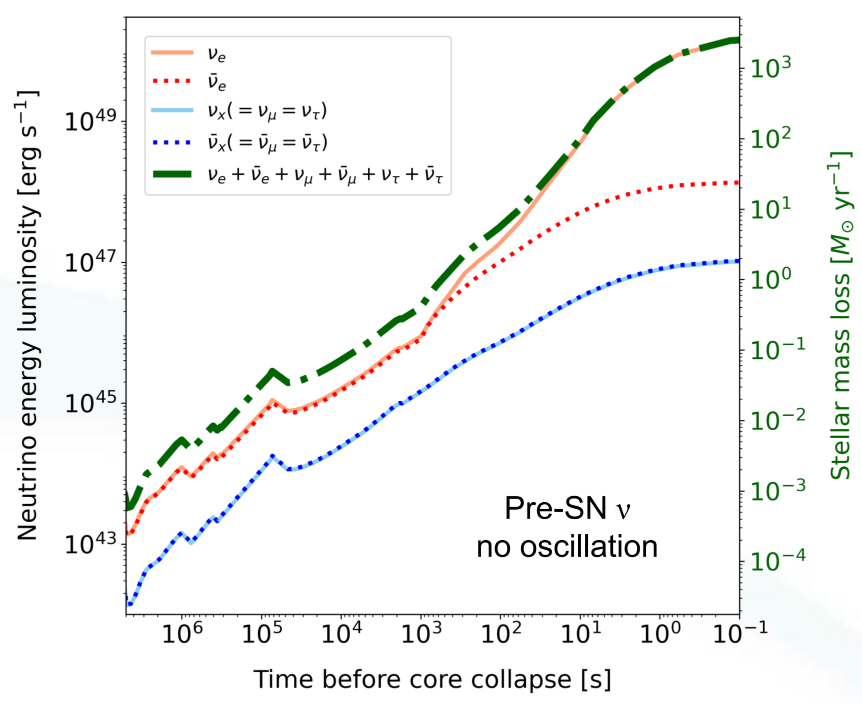


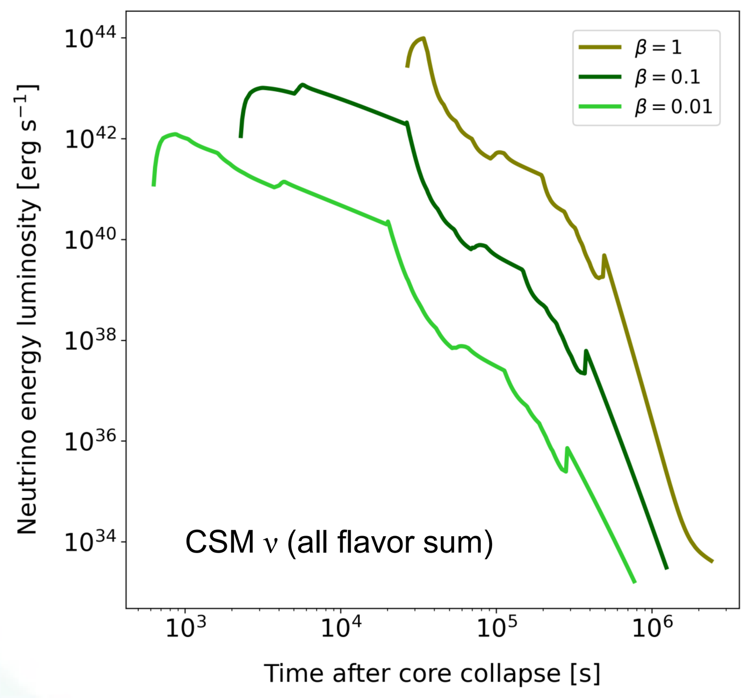
Our model is applied to reconstruct CSM-origin neutrino light curve from pre-SN neutrino light curve.

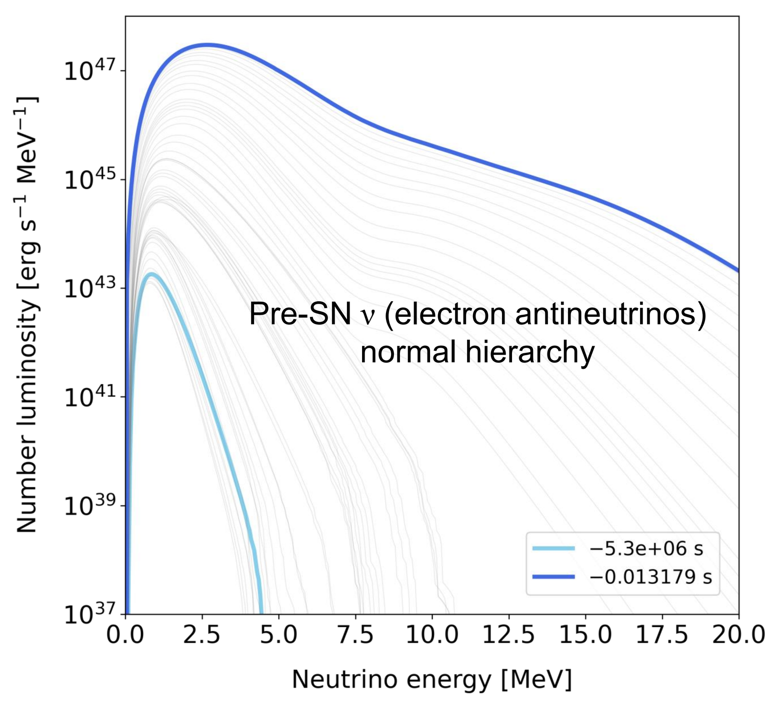
2. Model

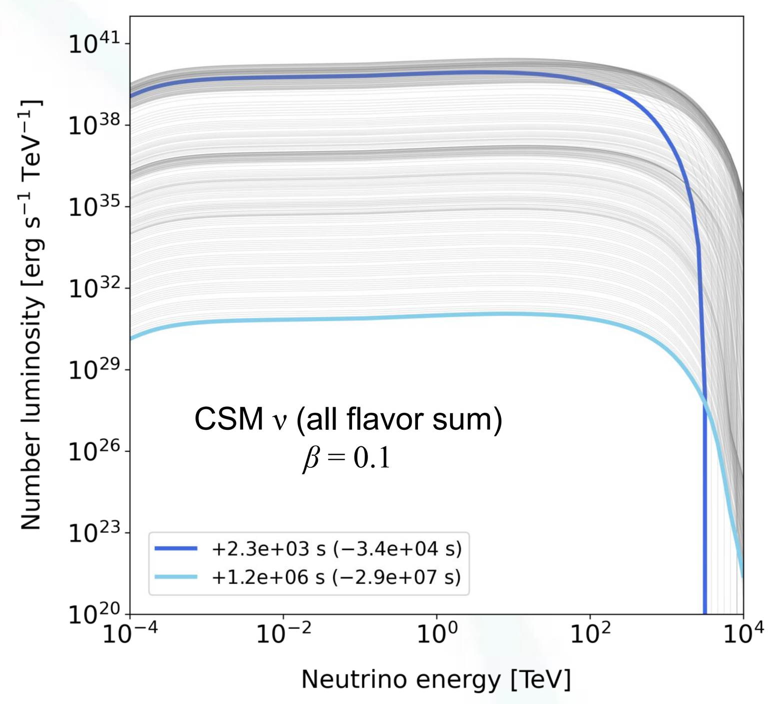
- ❑ Mass loss is assumed to originate from the neutrino release, resulting in CSM production. Core mass-loss rate is expressed as,
  - $\dot{M}_{\rm core} = \frac{L_{\rm pre-\nu}}{c^2} = 6.8 \times 10^{-3} \left(\frac{L_{\rm pre-\nu}}{10^{11} L_\odot}\right) M_\odot\ {\rm yr}^{-1}$
- ❑ CSM is reconstructed from pre-SN neutrinos. Mass-loss rate from the stellar surface is,
  - $\dot{M}_{\rm sur}(t) \approx \dot{M}_{\rm wind} + \beta \cdot \frac{L_{\rm pre-\nu}(t)}{c^2} \propto \rho_{\rm csm}(r,t)$
  - $\dot{M}_{\rm wind} = 10^{-6} M_\odot\ {\rm yr}^{-1}$ (steady-state wind mass-loss rate) $\ll \beta \dot{M}_{\rm core}$
  - β: mass-loss efficiency (considered 0.01~1.00)
- ❑ Ejecta-CSM interactions will produce high-energy neutrinos.
  - Roughly, $\rho_{\rm csm}(r,t) \propto \frac{L_{\rm pre-\nu}(t_{\rm csm})}{r^2}$
  - $t_{\rm csm} = t - \frac{r - R_{\rm sur}}{v_{\rm csm}}$, where $v_{\rm csm} = v_{\rm esc} = \sqrt{\frac{2GM_{\rm sur}}{R_{\rm sur}}}$
- ❑ The 'onset' time depends on CSM density.
  - When CSM is *shallow*, the collisionless shock wave is formed right after shock wave leaves a star.
  - When CSM is *dense*, timescale of the collisionless shock wave formation follows the photon escape time.





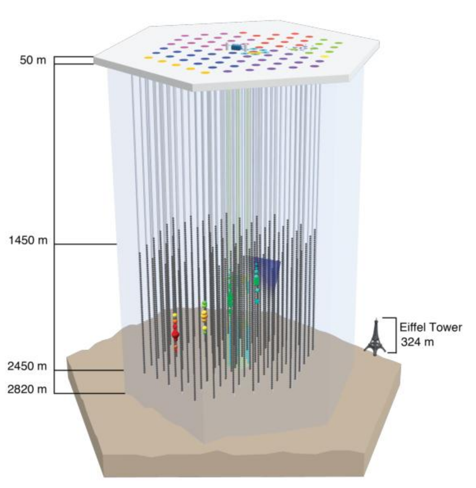


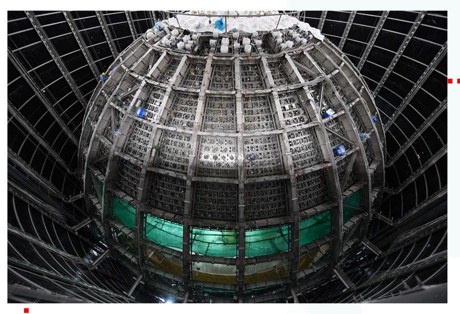




3. Demonstration

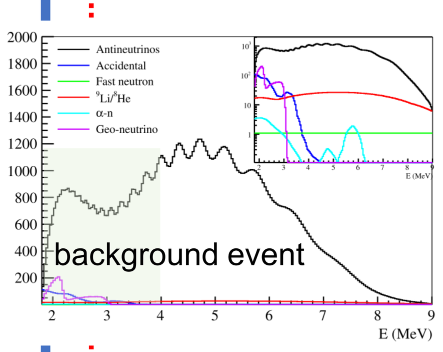
- ❑ **JUNO**: Based on J Phys. G 43, 030401 (2016); **1.8~4.0 MeV**
  - Detection channel: Inverse Beta Decay (IBD)
  - Background: reactor ν, geo ν, spallation, etc (~18 day^{-1} in total)
- ❑ **IceCube**: Based on HESE effective area; **10^1~10^3 TeV**
  - Detection channel: Deep Inelastic scattering (DIS)
  - Background: atmospheric ν (HAKKM2014), astrophysical ν (ESTES)
- ❑ **Synchronized detection**
  - JUNO: $N_{\rm sig}/\sqrt{N_{\rm sig} + N_{\rm bkg}} > 2$ and $N_{\rm sig} > 1$
  - IceCube: Converted via the time relation

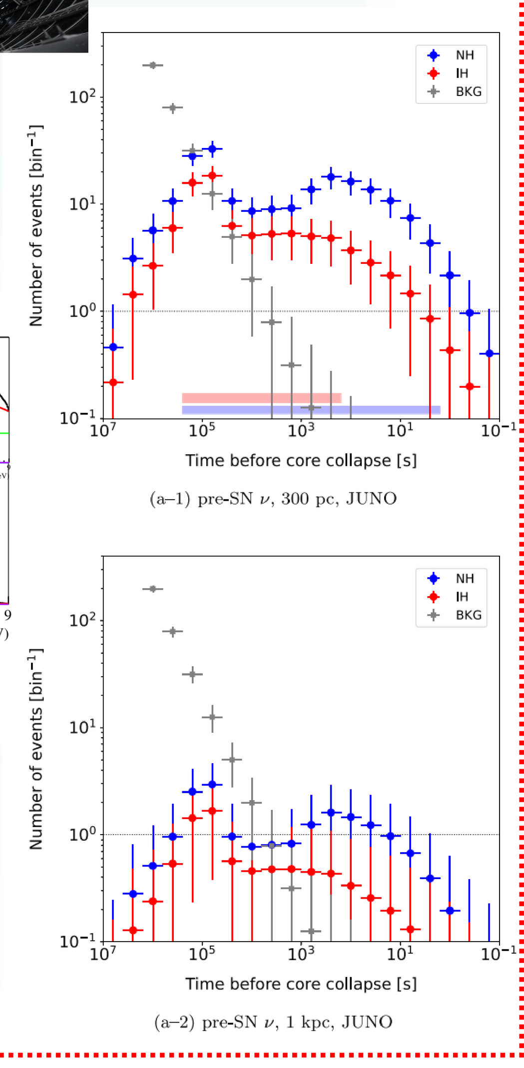




JUNO (China)

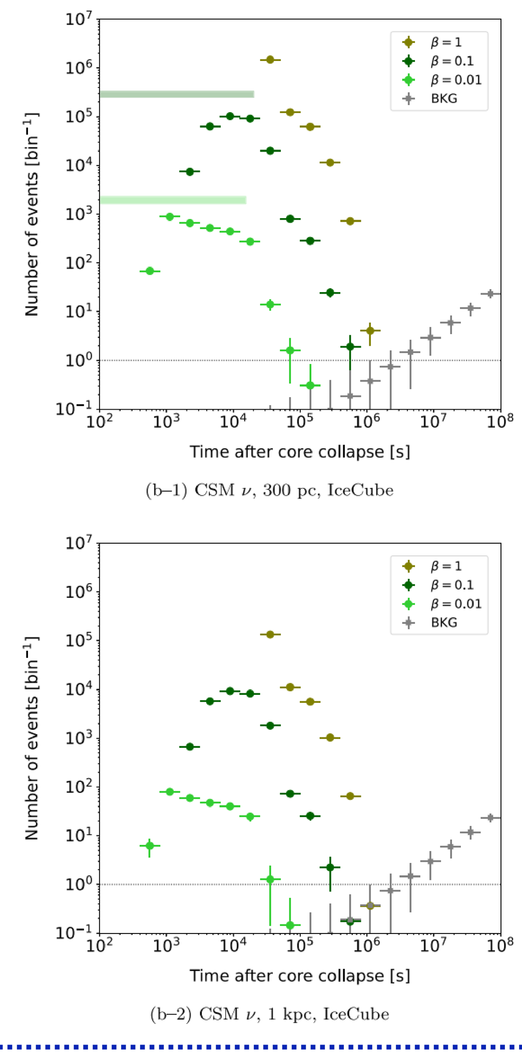
IceCube (South Pole)





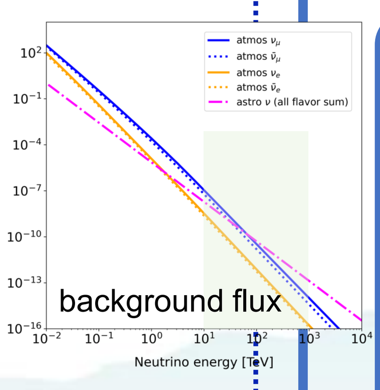
(a-1) pre-SN ν, 300 pc, JUNO

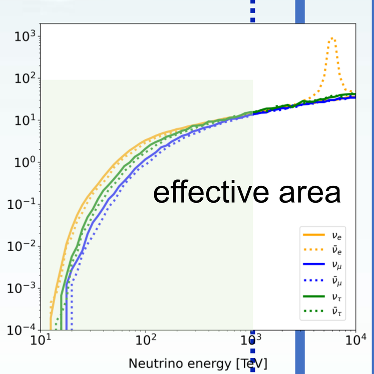
(a-2) pre-SN ν, 1 kpc, JUNO



(b-1) CSM ν, 300 pc, IceCube

(b-2) CSM ν, 1 kpc, IceCube





4. Conclusion & Discussion

- ❑ The proposed idea is applicable for the range up to **~500 pc**, which could be extended to **O(1) kpc**.
  - Analysis energy window in JUNO
  - Background reduction (especially reactor neutrinos…)
  - Combination with other detectors (e.g., SK-Gd, Hyper-K).
- ❑ Candidate Wolf-Rayet stars
  - A few within ~1 kpc; the closest is γ^2 Velorum (WR 11) at ~340 pc.
  - Increased to >10 within a few kpc.
- ❑ *Multi-energy neutrino astronomy era* is now explored!