３次元超新星モデルに基づく
非等方なニュートリノ放射と中性子星キック

-Anisotropic ν emission & NS kick-

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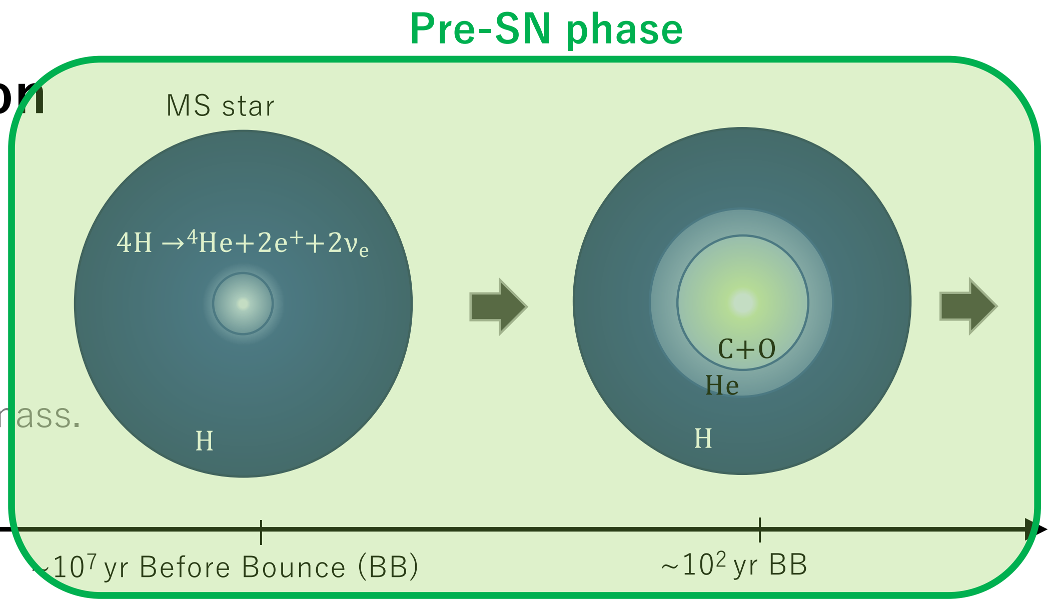
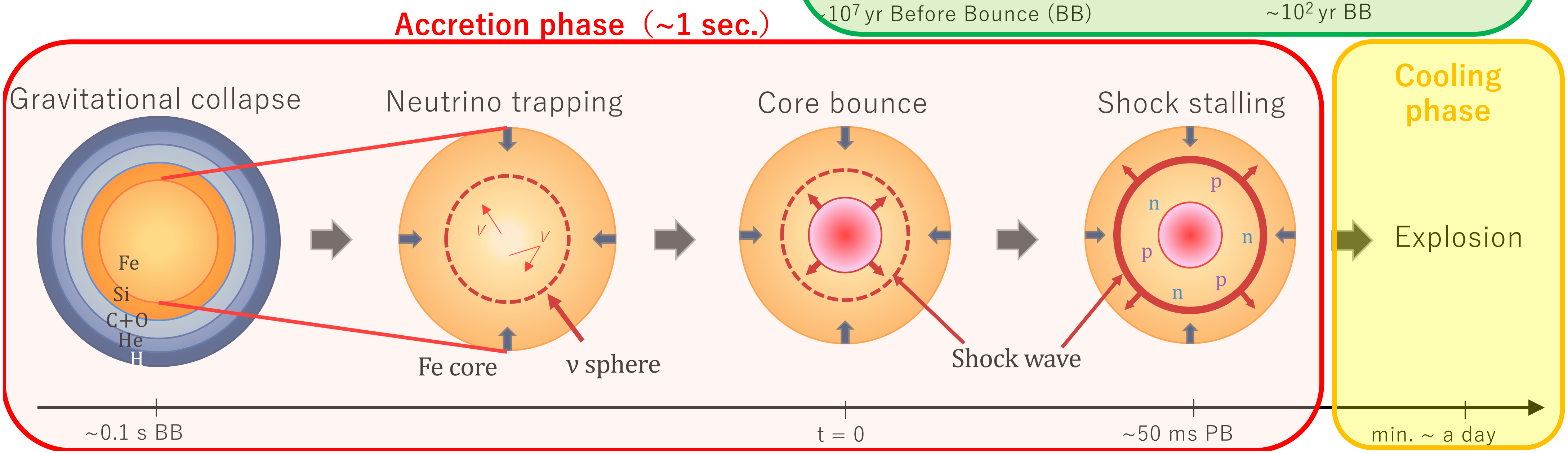
From a massive MS star to a CCSN

✓ The standard scenario toward explosion

A massive star forms iron core.
→ The core gravitationally collapses.
→ Shock stalls and revives via neutrino heating.
→ Finally, the shock breaks out the stellar surface.

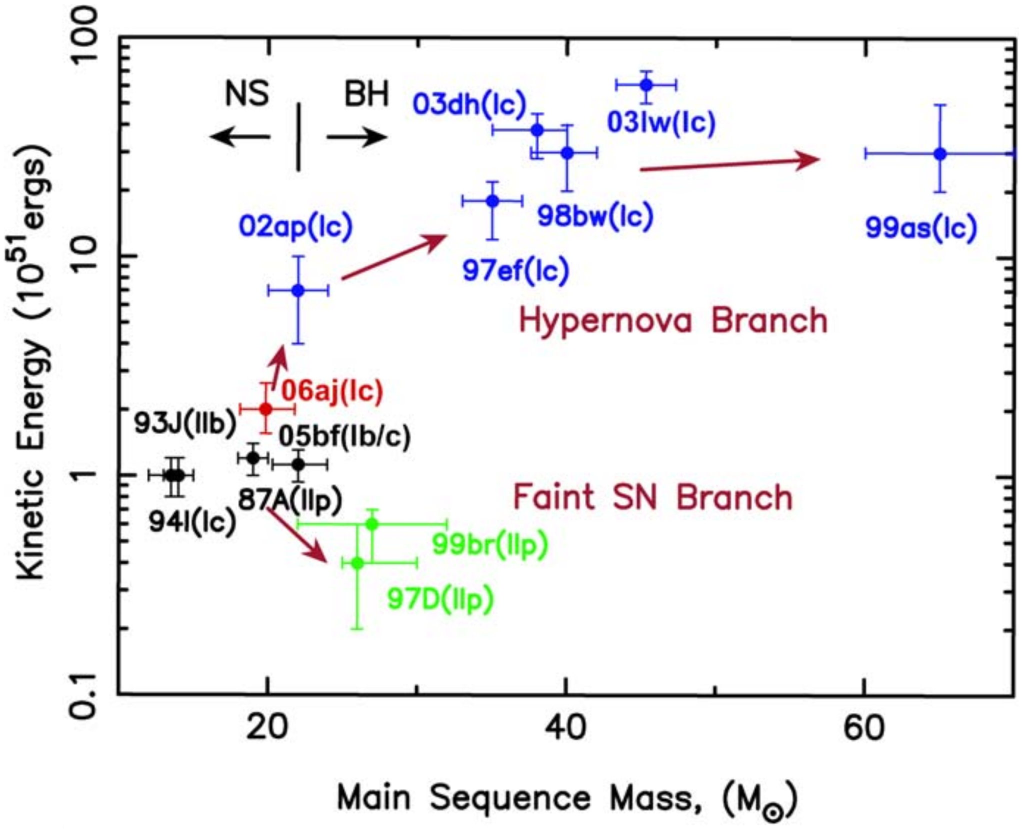
Note that the time scale of stellar evolution depends on its mass.
Shown is the case of a ~10 solar-mass star.

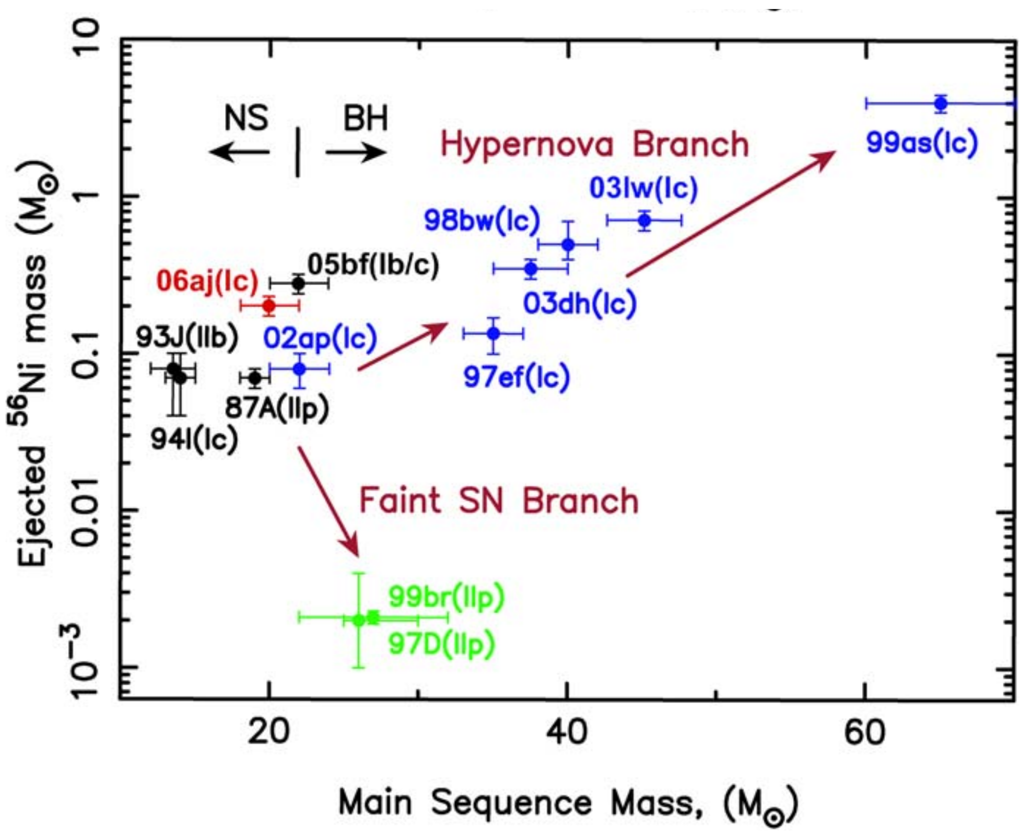




Diversity in CCSN properties

"Typical" explosion energy ($E_{\rm exp}$) ~ 10^{51} erg? Ni yelds ($M_{\rm Ni}$) ~ 0.07 $M_\odot$?





Nomoto et al. (2006)

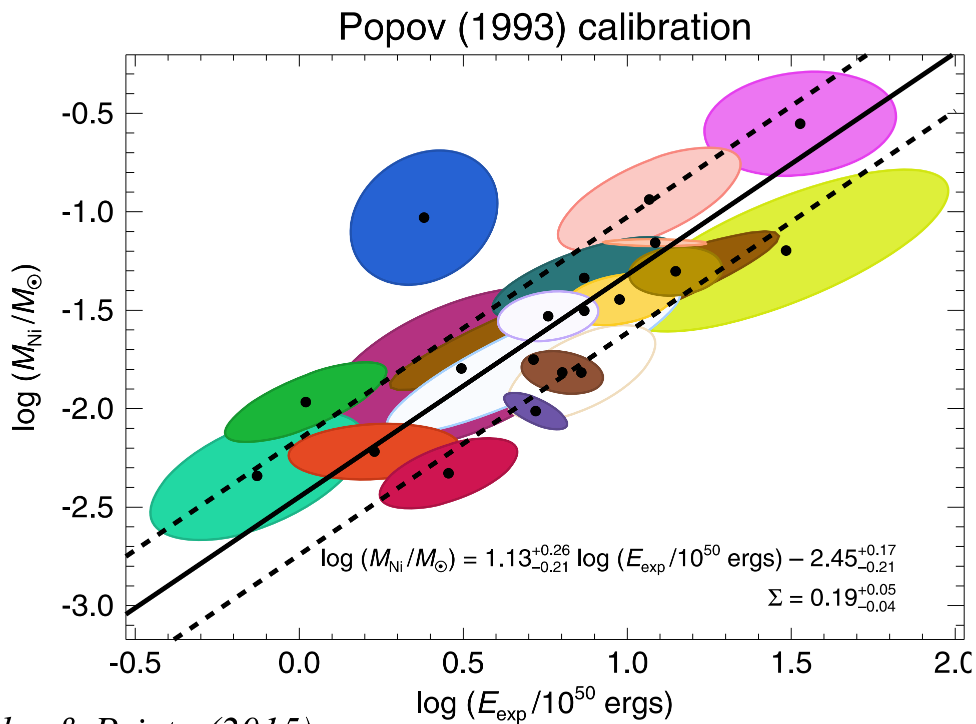
Diversity in CCSN properties

"Typical" explosion energy ($E_{\rm exp}$) ~ 10^{51} erg? Ni yelds ($M_{\rm Ni}$) ~ 0.07 $M_\odot$?

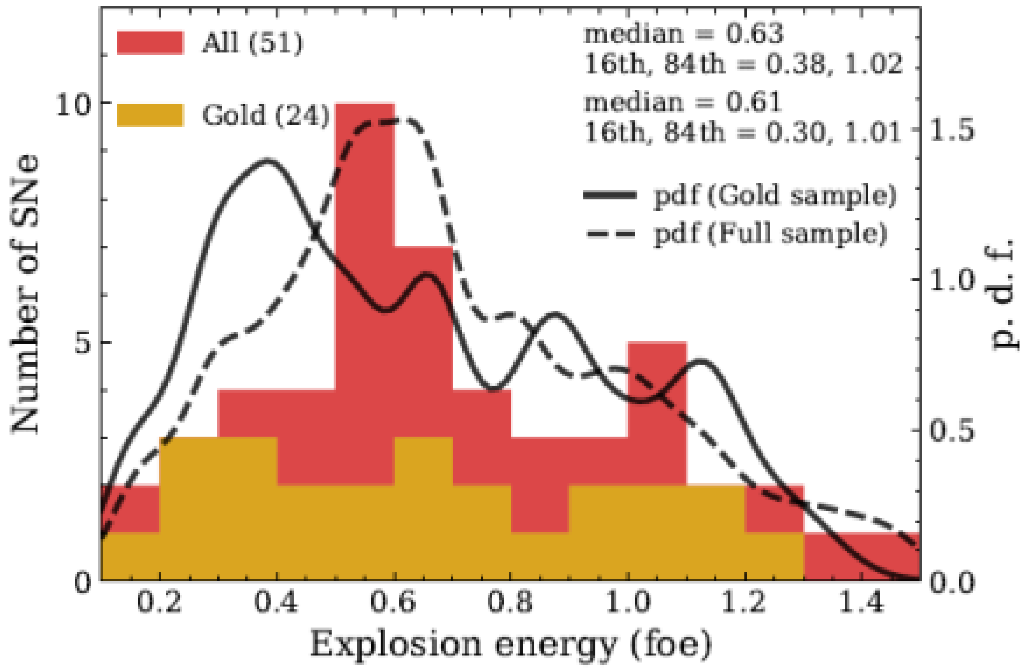
Recent observations suggest that $E_{\rm exp}$ & $M_{\rm Ni}$ is distributed over more than one order of magnitude.

What is the origin ?

→ **systematic study.**



Pejcha & Prieto (2015)



Martinez et al. (2022)

Systematic 3D MHD simulations of CCSNe - *KN+(2025), MNRAS, 536, 280*

✓ **3DnSNe_MHD** (*Matsumoto+'20*): 3-flavor ν-radiation (IDSA) MHD code + LS220 EoS.

✓ Progenitors : **9-24 $M_\odot$** non-rotating models from *Sukhbold+(2016)* (**16 models**).

✓ Fe core collapse to core bounce in 2D:

- B-field : $A_\phi = \frac{B_0}{2}\frac{r_0^3}{r^3 + r_0^3} r \sin\theta,$

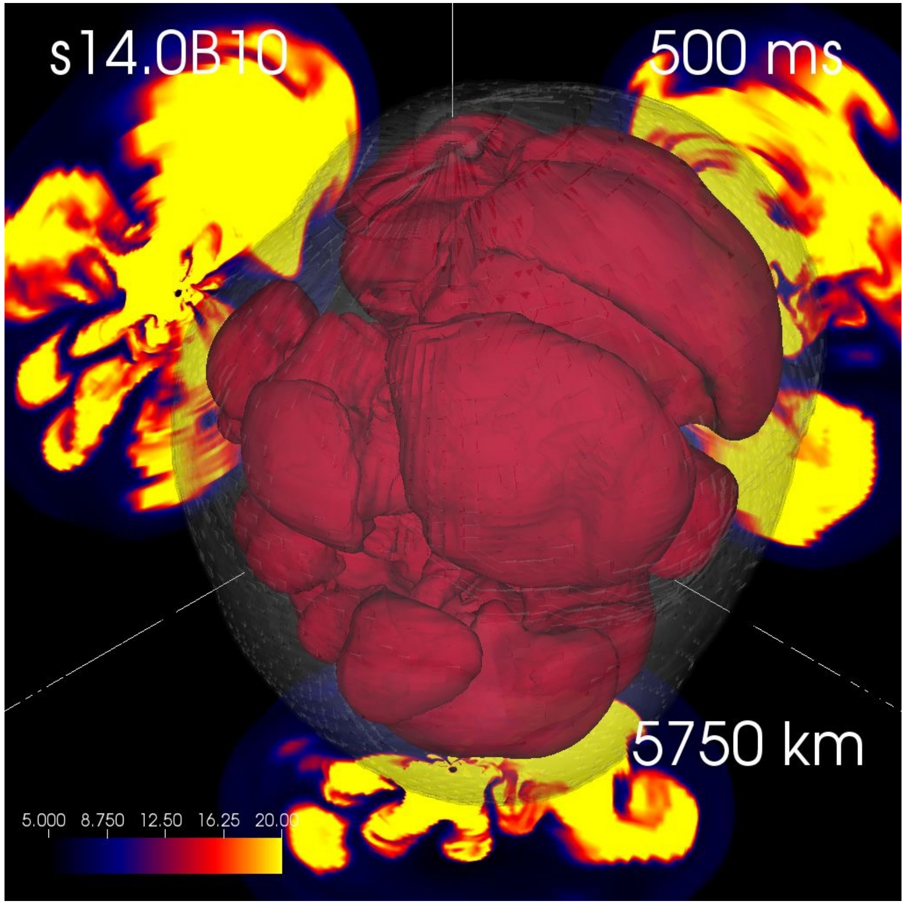
  $B_0 = 10^{10}$ [G], $r_0 = 10^3$ km (fixed).

- 600(r)x128(θ) grids
  ($0 \leqq R \leqq 10^4$ km, $0 \leqq \theta \leqq \pi$).

✓ 3D simulations after core bounce:

- Remap from 2D to 3D at 10 ms after bounce.

- 600(r)x64(θ)x128(ϕ) grids
  ($0 \leqq R \leqq 10^4$ km, $0 \leqq \theta \leqq \pi$, $0 \leqq \phi \leqq 2\pi$).

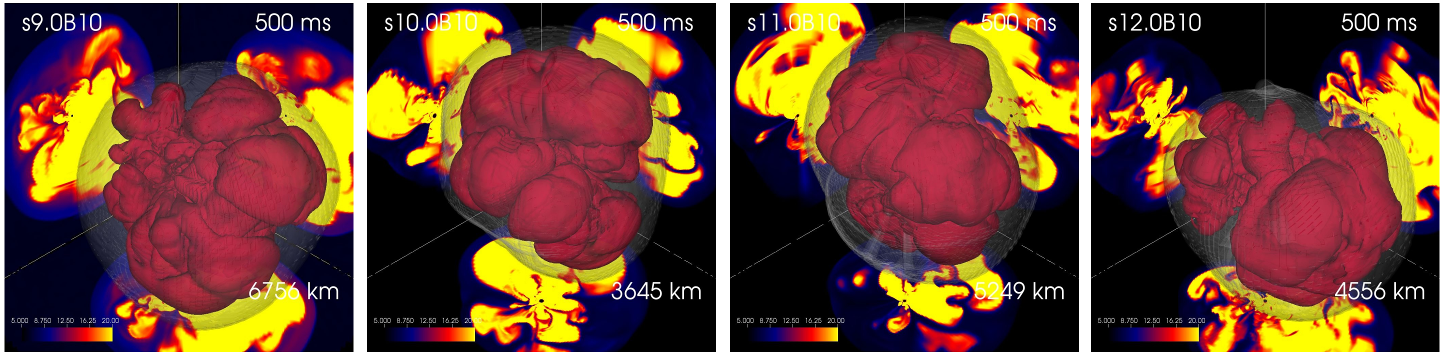


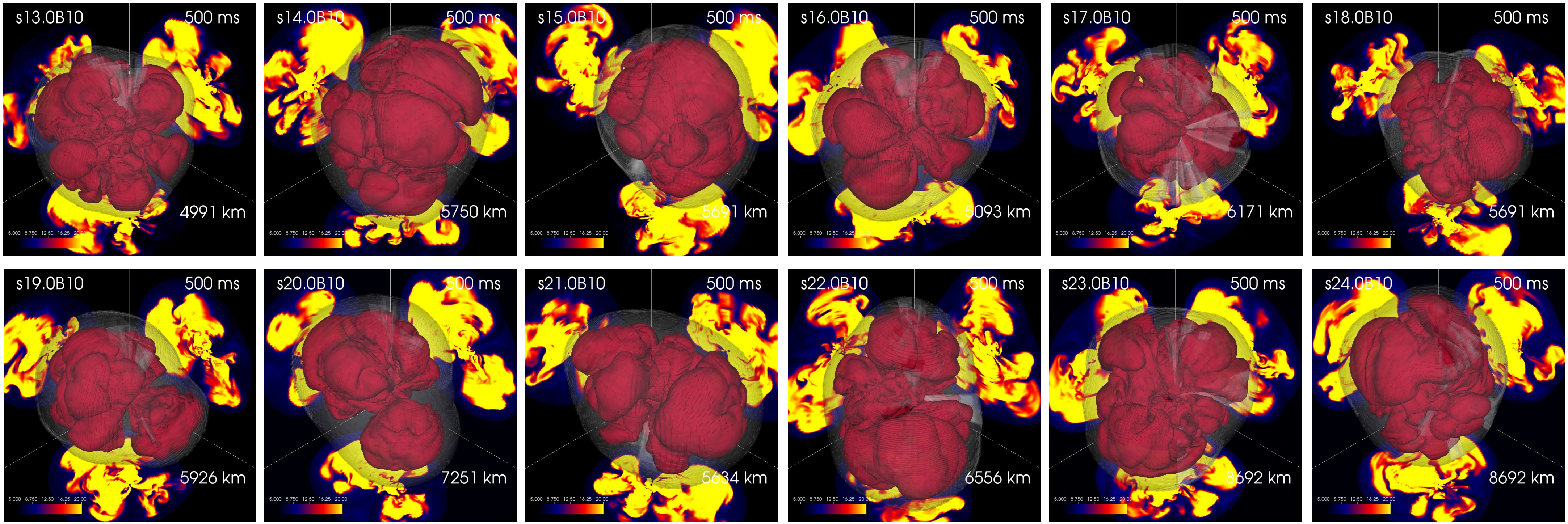
Systematic 3D MHD simulations of CCSNe - *KN+(2025), MNRAS, 536, 280*

- Movies (entropy map)

  M_{ZAMS} = 9-24 $M_{\odot}$,

  16 **EXPLODING** models.

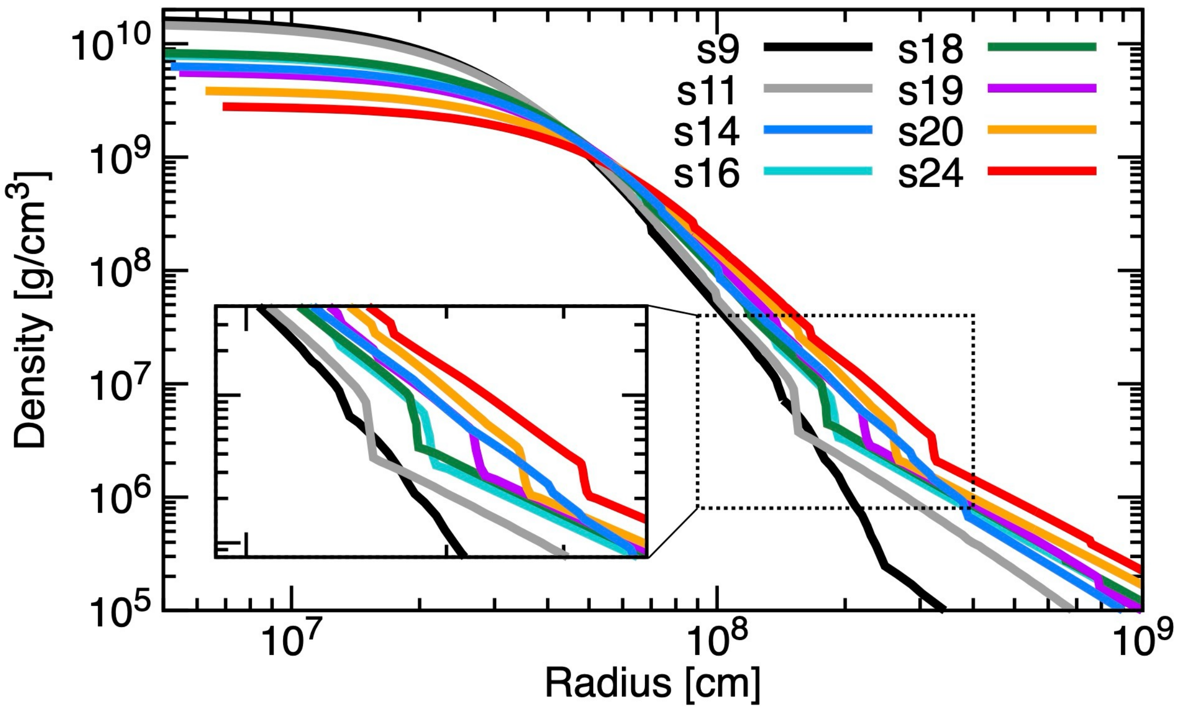


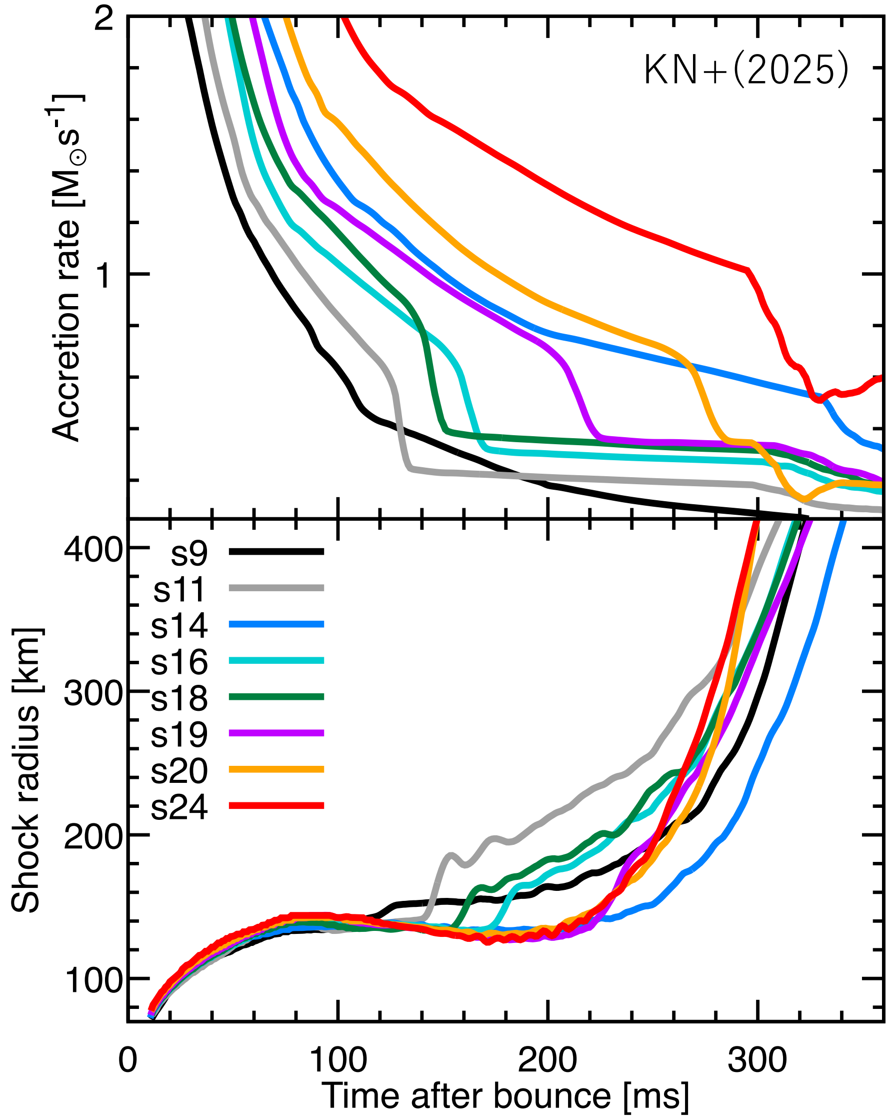


Progenitor structure and shock evolution

✓ Sukhbold et al. (2016) ApJ, 821, 38

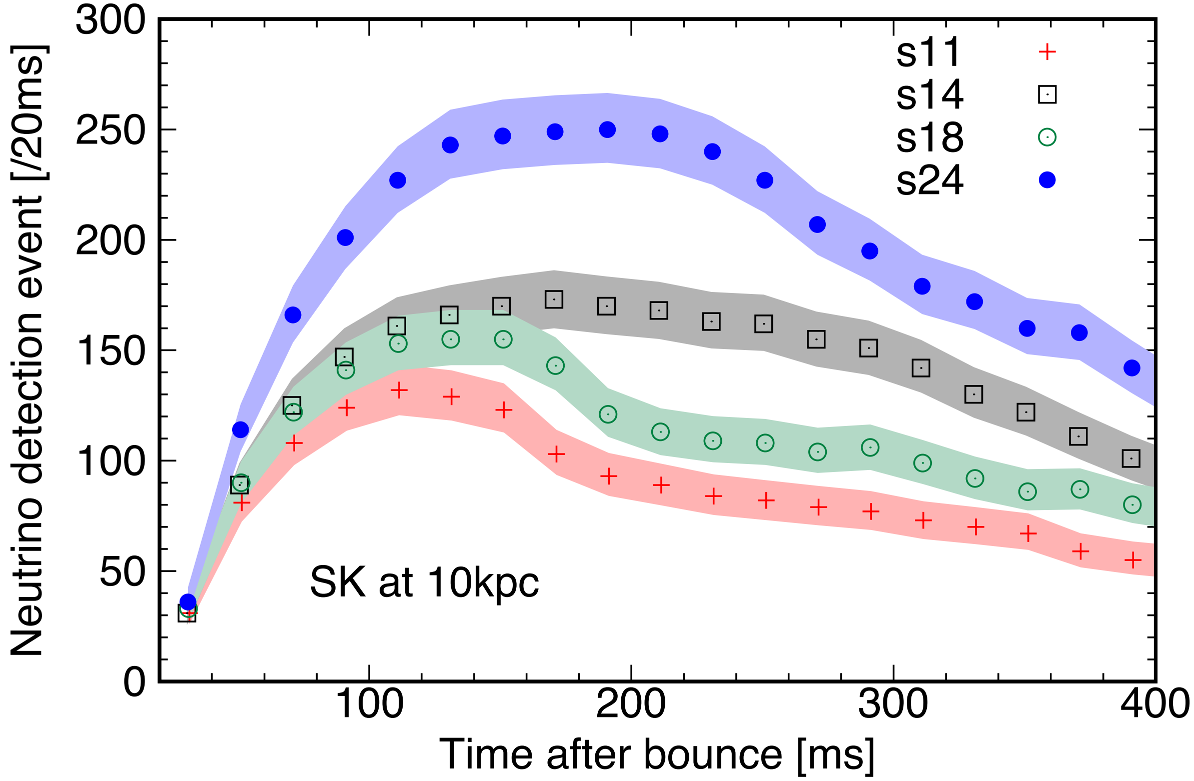
Density drops at the Si/O interface have a strong impact on shock evolution.





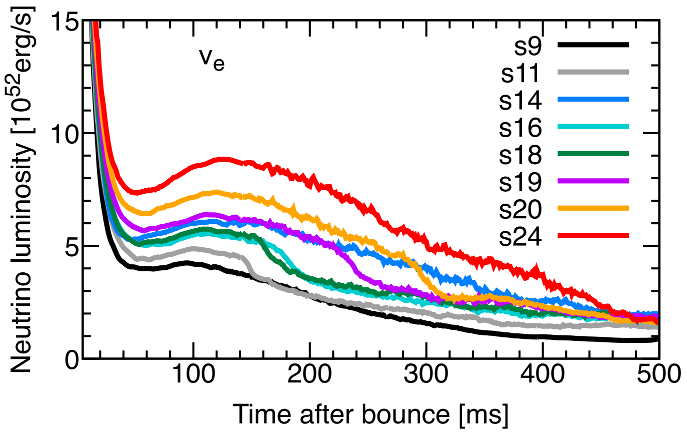
Neutrino detection event

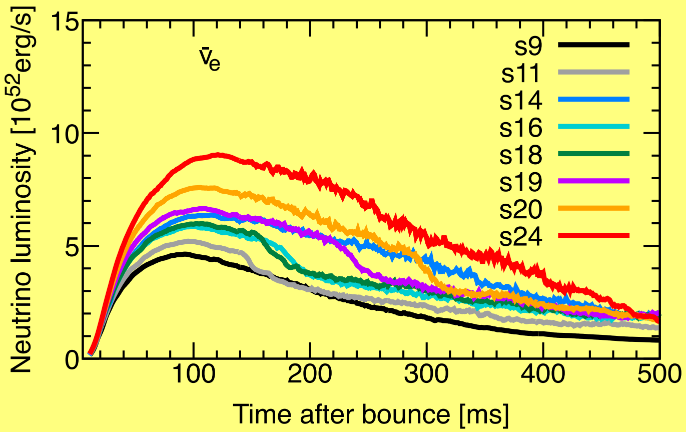
- ✓ Expected neutrino detection events by Super-Kamiokande (SK).
  Assuming the distance to the SN $D = 10$ kpc.
  SK: fiducial volume = 22.5 kton, threshold energy = 7 MeV.
  Only IBD is considered.
  The error bands are root-N Poisson.

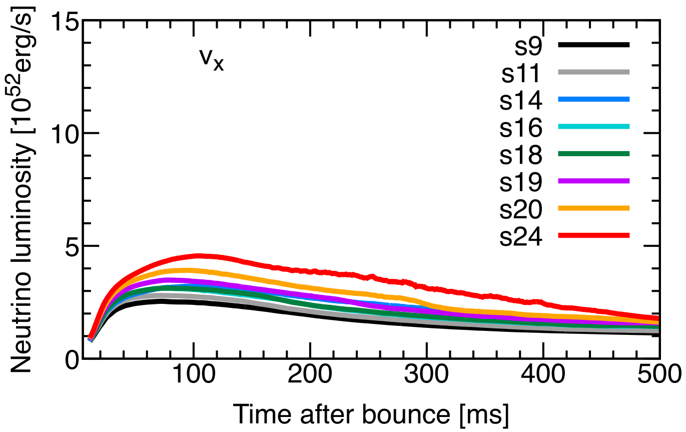


- ✓ In the very early phase (< 30ms) the detection number is almost identical.
- ✓ But it soon becomes distinguishable, reflecting the different accretion history.
- ✓ The sudden drops at ~150ms in the models s11 and s18 are marginally detectable.
- ✓ Caution! **No oscillation is considered here.**

Neutrino detection event

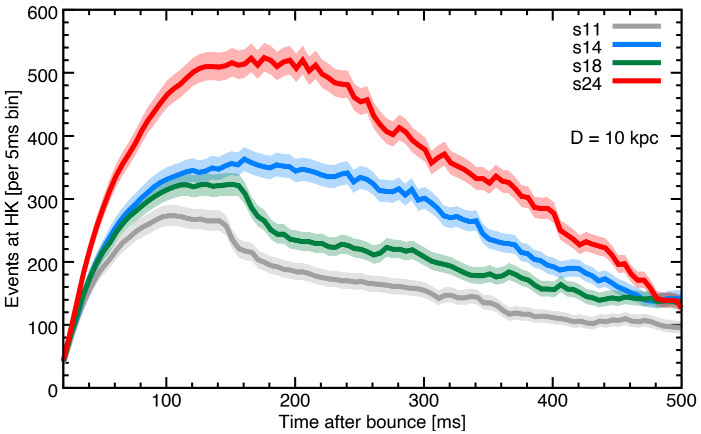




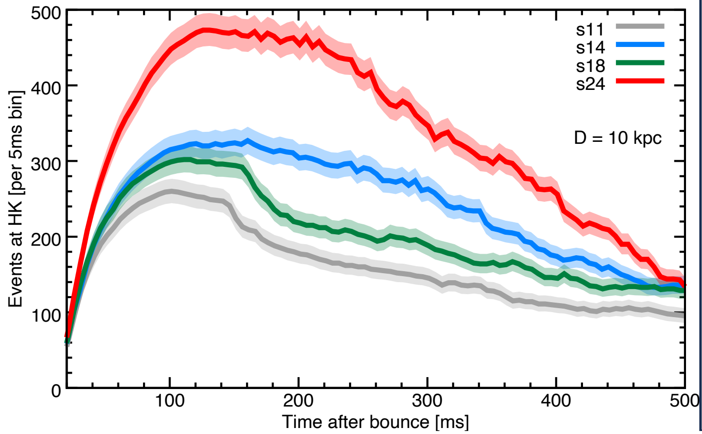


Neutrino detection events at HK via IBD ($\bar{\nu}_e$+p → n+e^+),
assuming D = 10 kpc and **isotropic nu emission.**

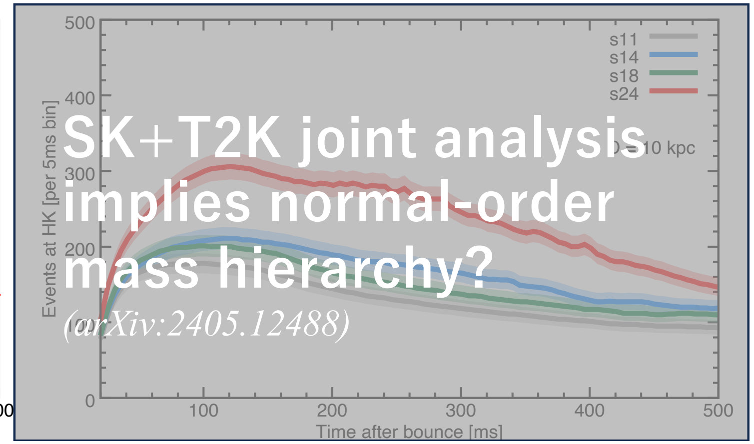
w/o oscillation



MSW(NO)



Full swap (IO)



SK+T2K joint analysis implies normal-order mass hierarchy?
(arXiv:2405.12488)

Angle-dependent neutrino luminosity *(Tamborra+2014)*

Given the neutrino intensity I, Neutrino flux F' and corresponding luminosity L' for an observer at distance D and angle γ is

$$L' = 4\pi D^2 F' = 4\pi \int I \, \mathrm{d}A' \ ,$$

where $\mathrm{d}A' = \cos\gamma \ \mathrm{d}A$ is a projected area on a sphere surrounding the neutrino source, and the corresponding solid angle $\mathrm{d}\Omega' = \cos\gamma \ \mathrm{d}A/D^2$.

We use the following simple relations in 1D neutrino transport *(Mueller,Janka,Annop+12;Tamborra+14)*:

$$I(\gamma) = aE + bF\cos\gamma, \quad F = fcE,$$

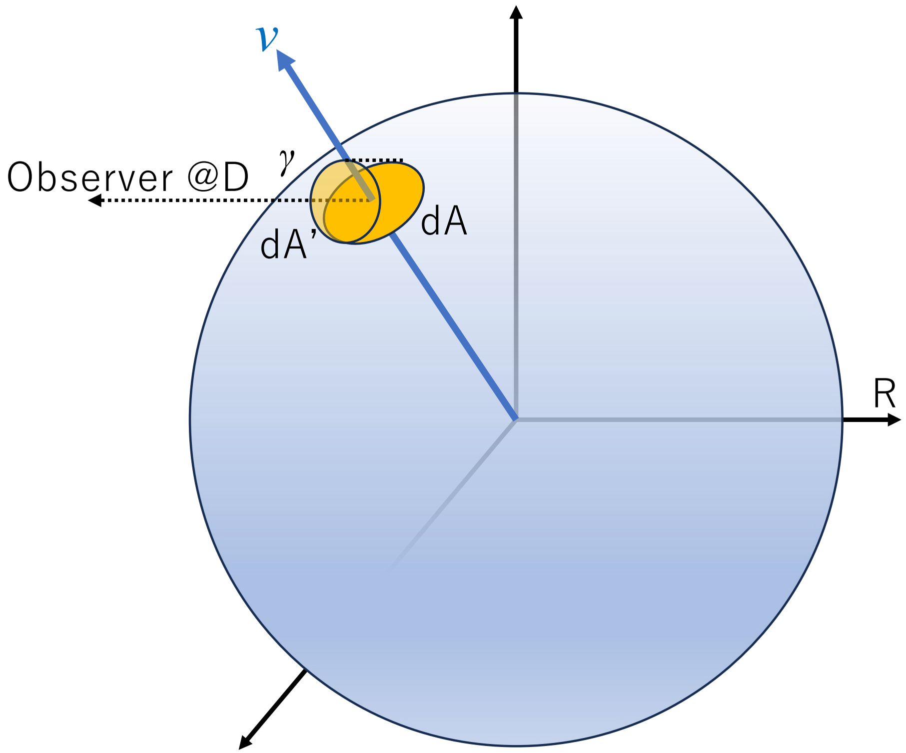
where E is energy density.

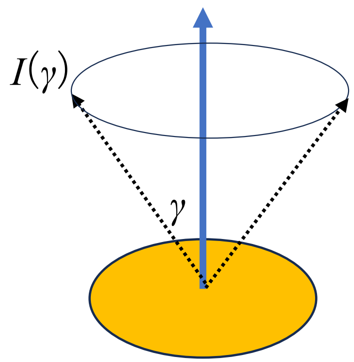
Simple algebra gives $a = \frac{c}{4\pi}, b = \frac{3}{4\pi}$, and $f = \frac{1}{2}$.

Then we have $I(\gamma) = \frac{1}{2\pi}\left(1 + \frac{3\cos\gamma}{2}\right)F$ and finally obtain

$$\boldsymbol{L'(\gamma) = 4\pi \int I\mathrm{d}A' = 2\int \left(1 + \frac{3\cos\gamma}{2}\right)\cos\gamma \, F\mathrm{d}A}$$

(Integrated over a semisphere).

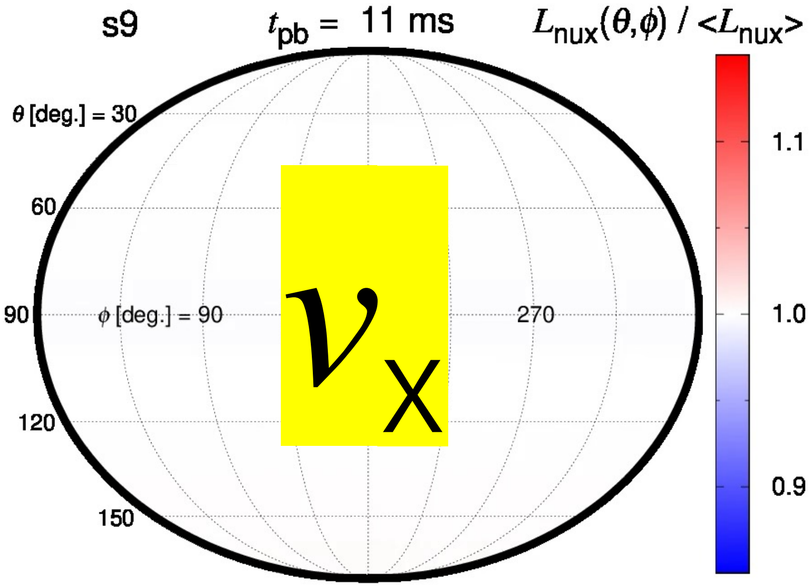


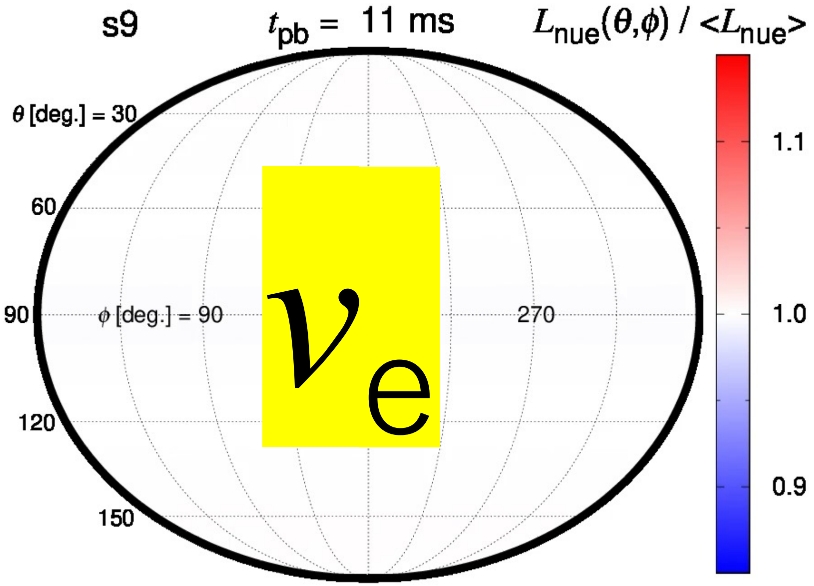


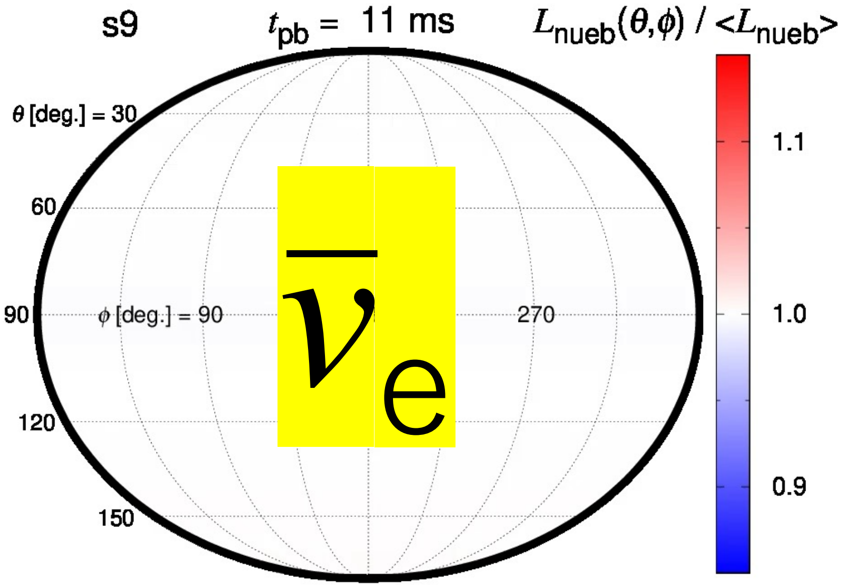
Angle-dependent neutrino luminosity - s9

An example of light progenitors (s9).

- >10%-level deviation after ~250 ms.
- Clear & stable anti-correlation between ν_e and $\bar{\nu}_e$.
- A small deviation in ν_x emission.



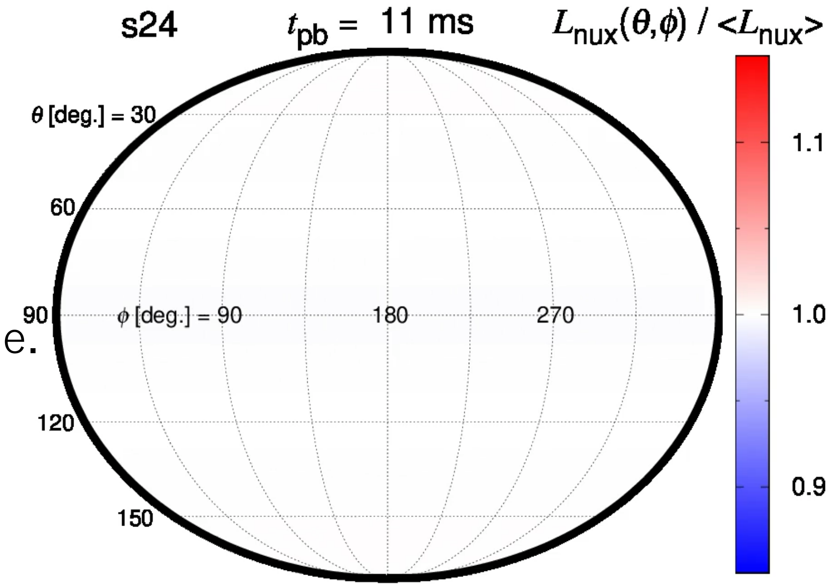


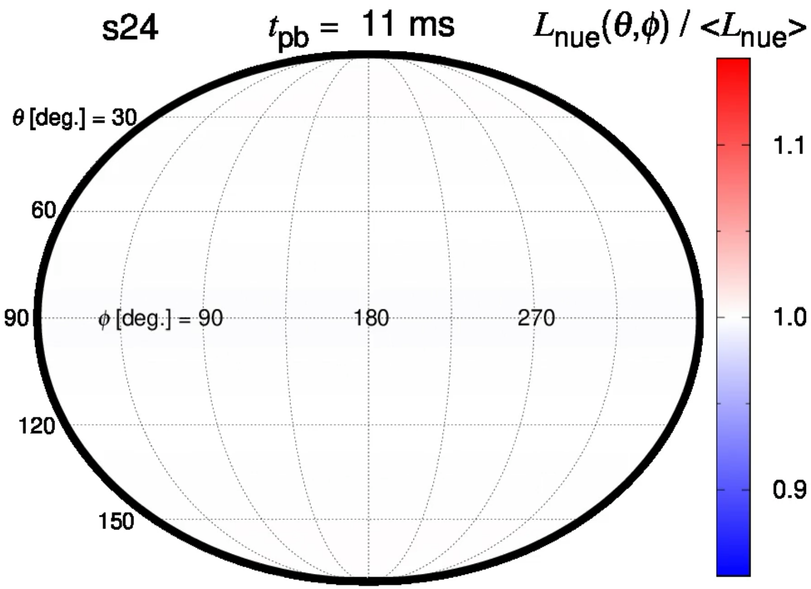


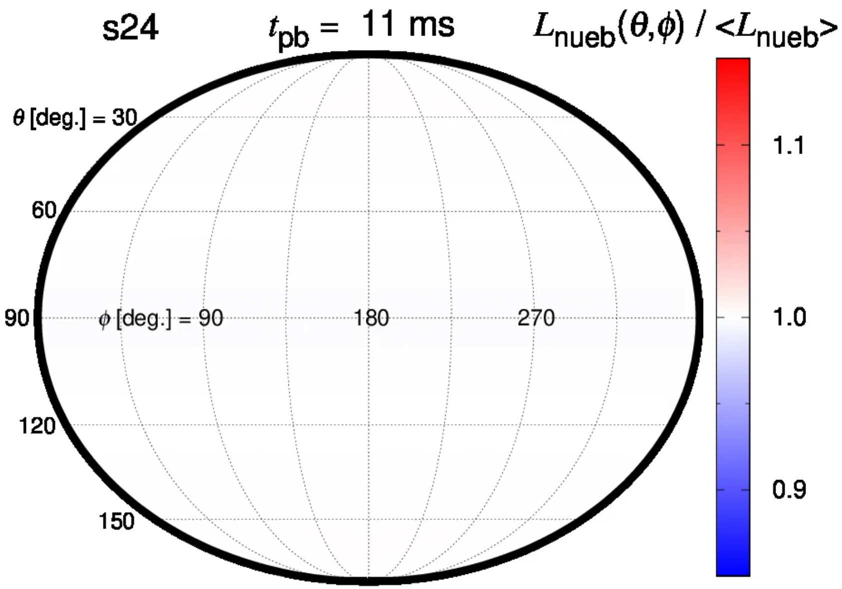
Angle-dependent neutrino luminosity - s24

An example of massive progenitors (s24).

- Almost uniform in the first ~130 ms.
- Possible anti-correlation between ν_e and $\bar{\nu}_e$, but unstable.
- A small deviation in ν_x emission, as in the model s9.

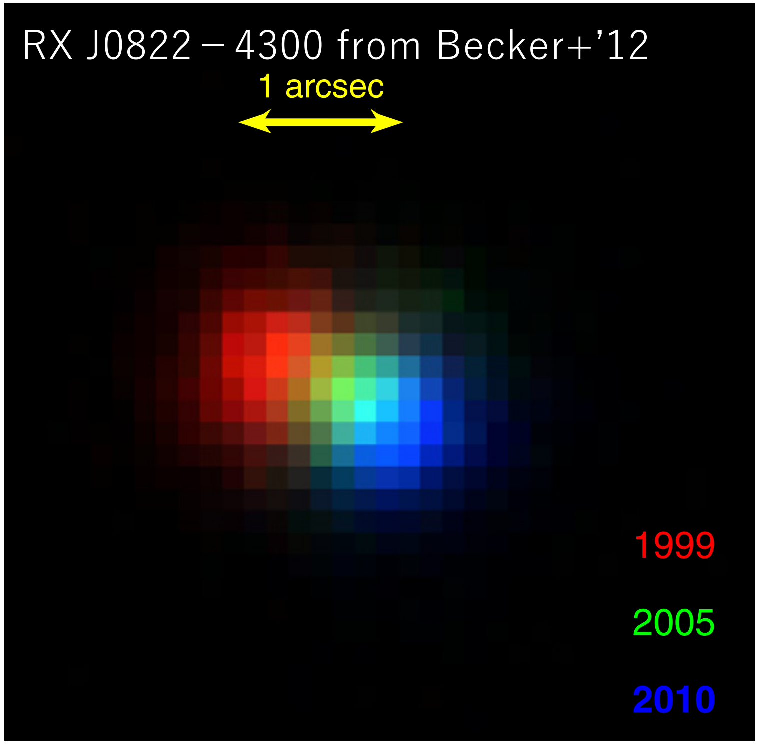


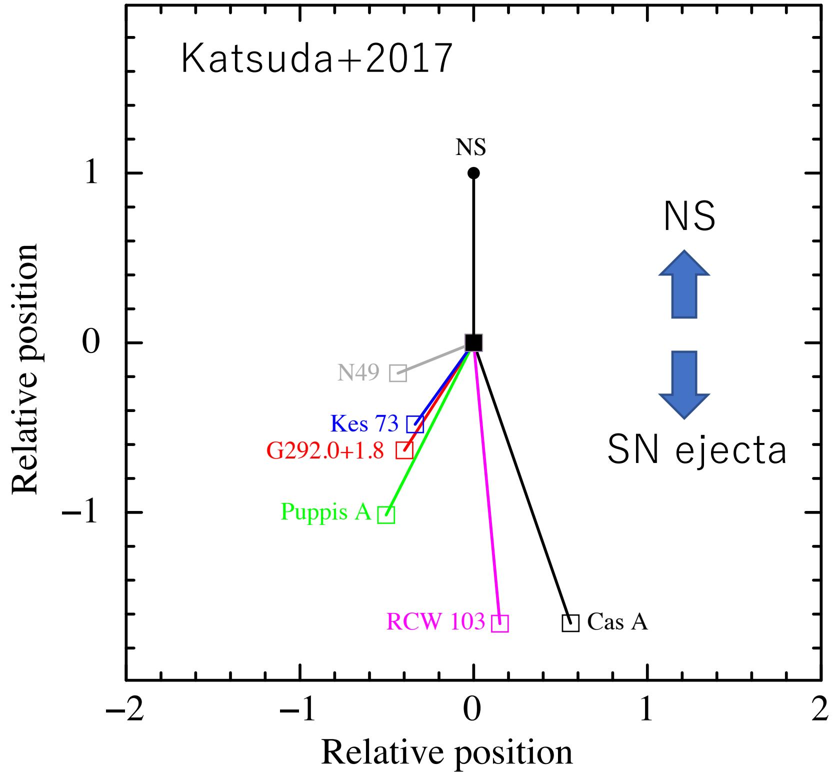




Neutron star kick

NSs are “kicked” at the explosion → correlated to anisotropic ejection of the matter and neutrino.





Neutron star kick

NSs are “kicked” at the explosion → correlated to anisotropic ejection of the matter and neutrino.

✓ Hydrodynamic kick.

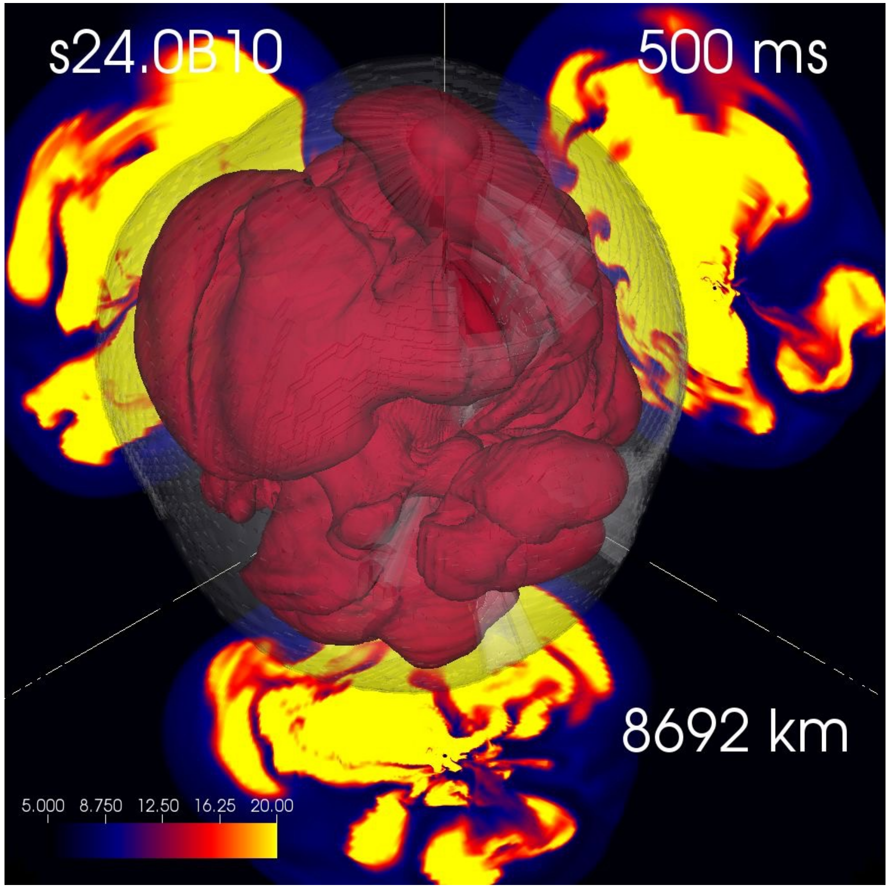
$$\mathbf{v}_{\mathrm{kick}}^{\mathrm{hydro}} = -\frac{1}{M_{\mathrm{PNS}}} \int_{\rho<10^{11}\,\mathrm{g\,cm^{-1}}} \mathbf{v}\rho \mathrm{dV},$$

assuming the conservation of the matter momentum.

✓ Neutrino-driven kick.

$$\dot{\mathbf{v}}_{\mathrm{kick}}^{\nu} = -\frac{1}{cM_{\mathrm{PNS}}} \int_S \left(\mathbf{F}^{\nu_e} + \mathbf{F}^{\bar{\nu}_e} + \mathbf{F}^{\nu_x}\right) \mathrm{dA},$$

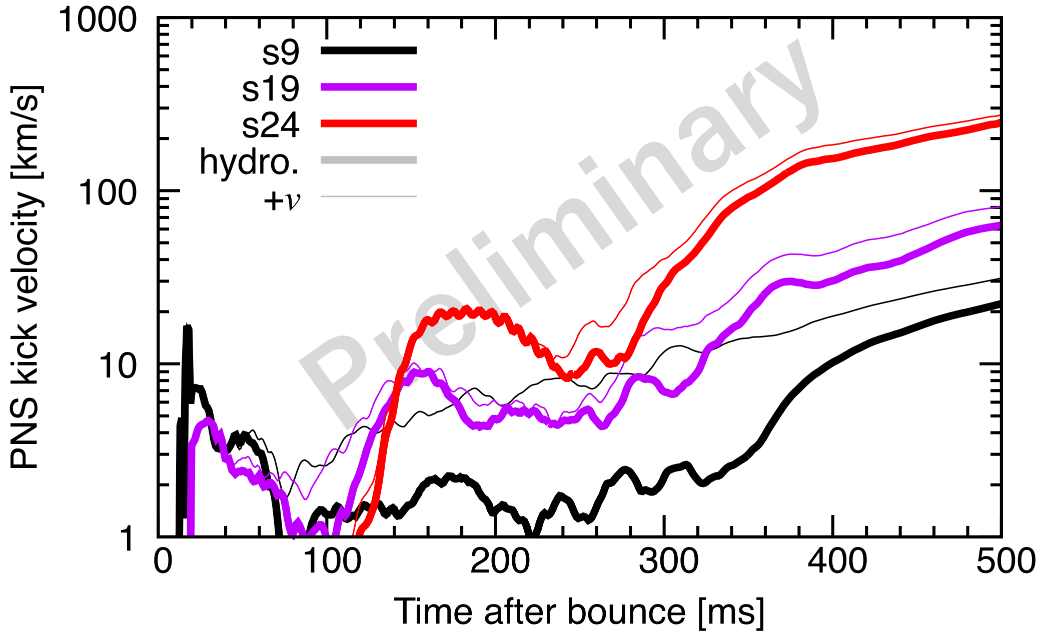
assuming ray-by-ray (only radial) transport of neutrino.



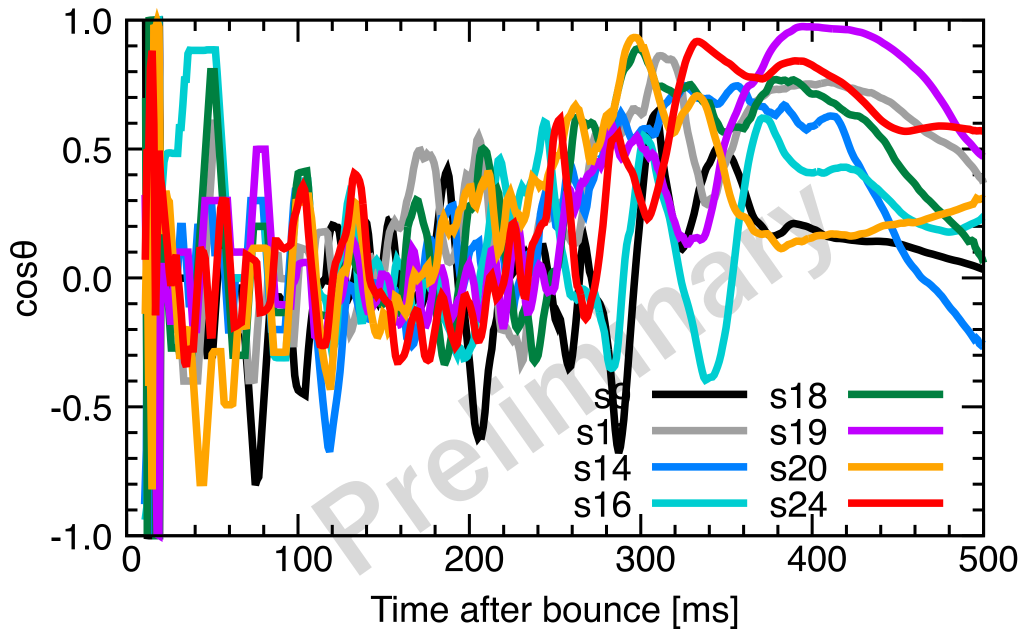
Neutron star kick

NSs are “kicked” at the explosion → correlated to anisotropic ejection of the matter and neutrino.

Time evolution of NS kick velocity

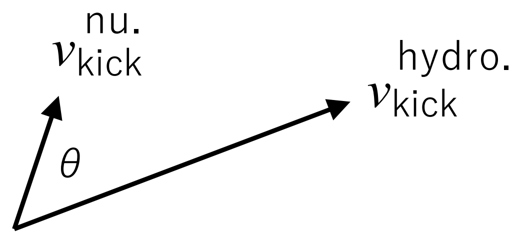


Angle between $v_{kick}^{hydro.}$ and $v_{kick}^{nu.}$



- NSs are accelerated after the shock revival (t_{pb} > 300ms).
- Nu-v_{kick} has a large fraction in small-mass models.
- Hydro-v_{kick} and nu-v_{kick} are roughly aligned.

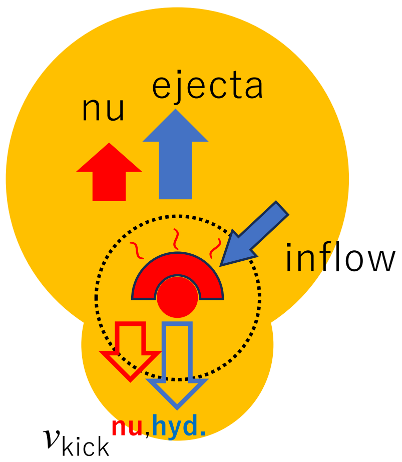
← What makes the anisotropy in nu emission?

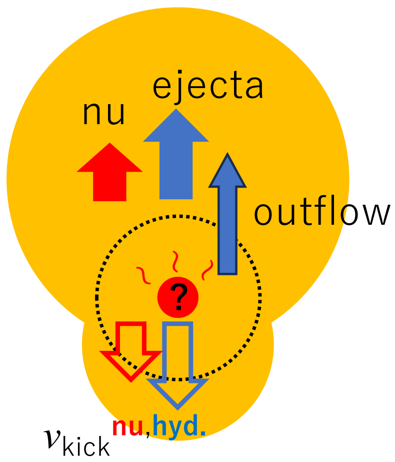


Origin(s) of the anisotropic neutrino emission

What makes the anisotropy in nu emission?

- Anisotropic inflows around the core?
- Or, another process in the core like PNS convection? (*Janka 2401.13817*)

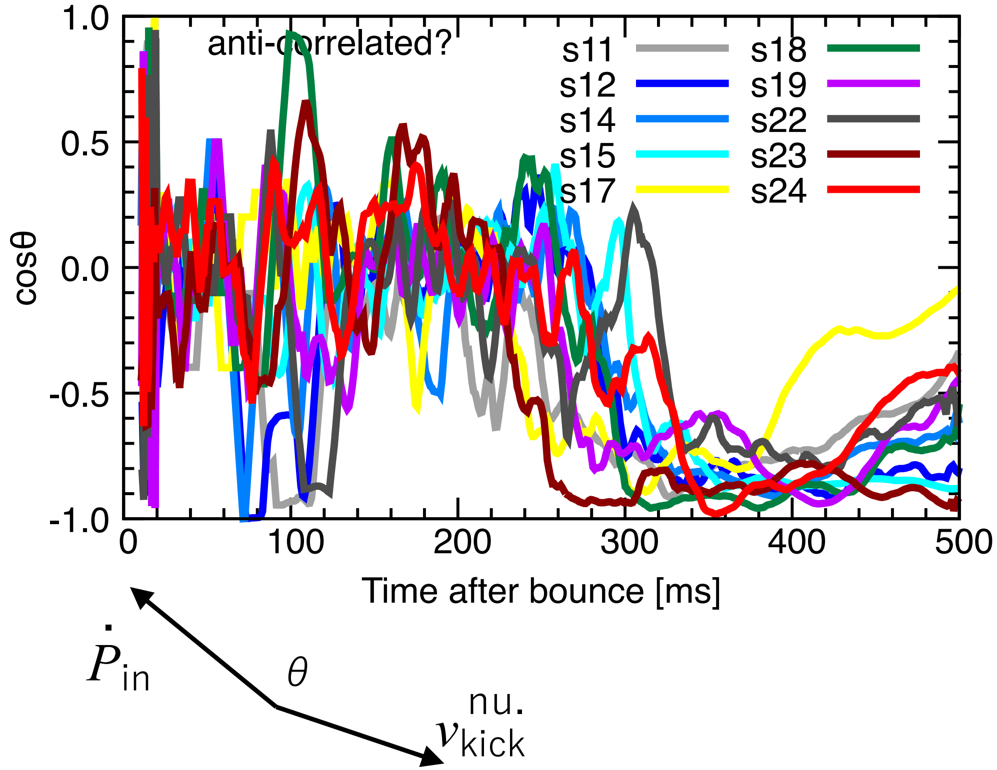




Momentum of in(out)-flow matter at r = 100 km:

$$\dot{\boldsymbol{P}}_{\rm in(out)} = \int_{r=100{\rm km}} \rho \boldsymbol{v} v_r r^2 {\rm d}\Omega \quad \text{for } v_r \lessgtr 0$$

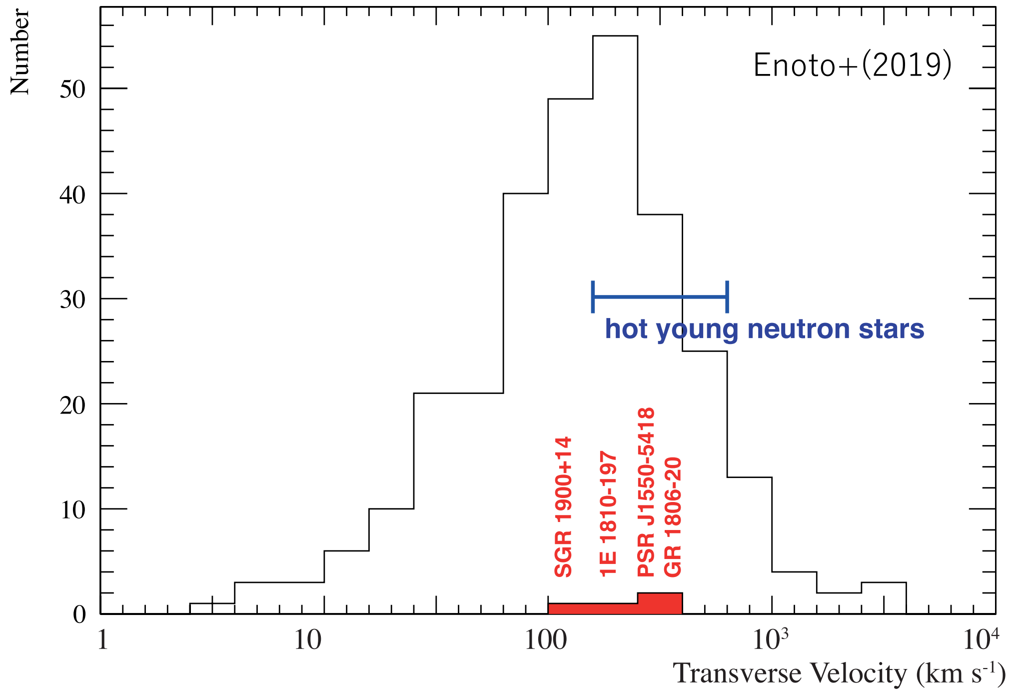
Angle between $\dot{P}_{\rm in}$ and $v_{\rm kick}^{\rm nu.}$



Long-term simulation is necessary!

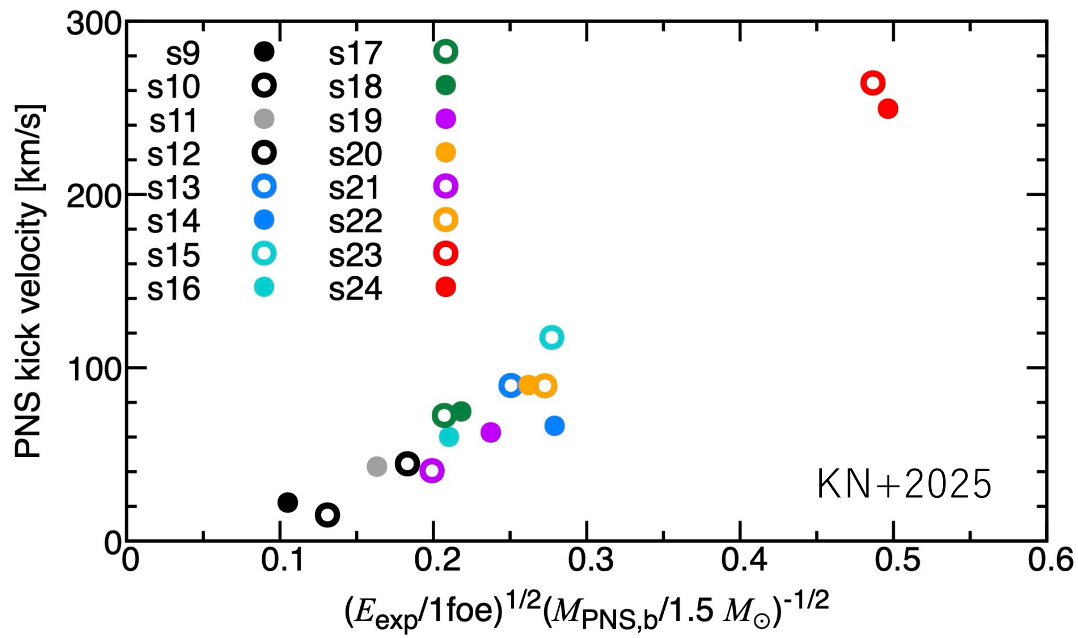
NSs are "kicked" at the explosion → correlated to anisotropic ejection of the matter and neutrino.

Observed NS v_{kick} distribution



Observations:
Typically **300-500 km/s**, some NSs > **1000 km/s**.

Correlation between $v_{PNS}^{hydro.}$ and $(E_{exp}/M_{PNS})^{1/2}$



Not yet converged at t_{pb} = 500ms.
→ long-term simulation is necessary.

Summary

✓ Systematic 3D simulations of CCSNe (Burrows+'20;'24, KN+'25).

✓ Neutrino detection event curve ~ mass accretion history ~ progenitor structure.

✓ Anisotropic neutrino emission:
(tpb < ~200ms) < a few %, no specific direction.
(later) > 10% in ν_e and ν_e luminosity.
Lepton-number emission self-sustained asymmetry (**LESA**)
at least in small-mass models.

✓ Diversity in neutrino detection number:
factor of ~2 from progenitor dependence,
~-40% from neutrino oscillation,
~±10% from anisotropic neutrino emission.

✓ Possible alignment between hydro-v_{kick} and nu-v_{kick} of NSs.