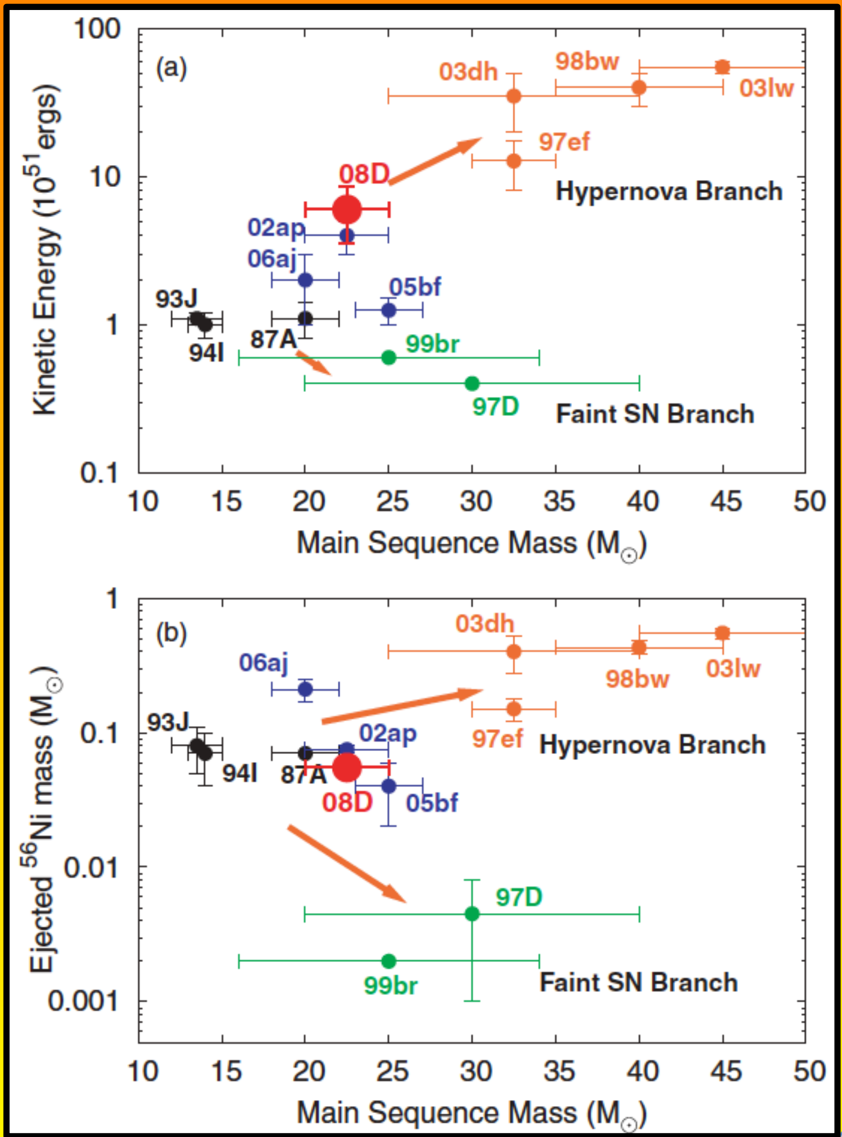
Toward BH forming CCSNe Simulation

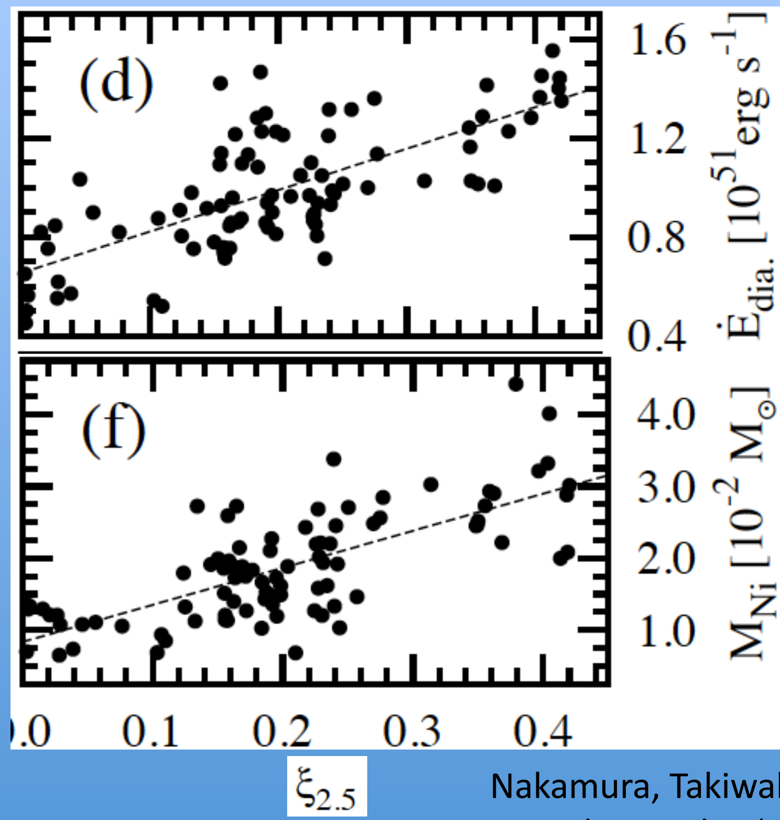
Takami Kuroda

Observations say



Tanaka+, '09

Our recent calculations suggest



Nakamura, Takiwaki, Kuroda, Kotake, '14

1. 2D axi-symmetric condition may be *too* favorable for the explosion
2. GR effects (e.g. BH) are ignored, thus the result would be different as "ξ" becomes higher and higher

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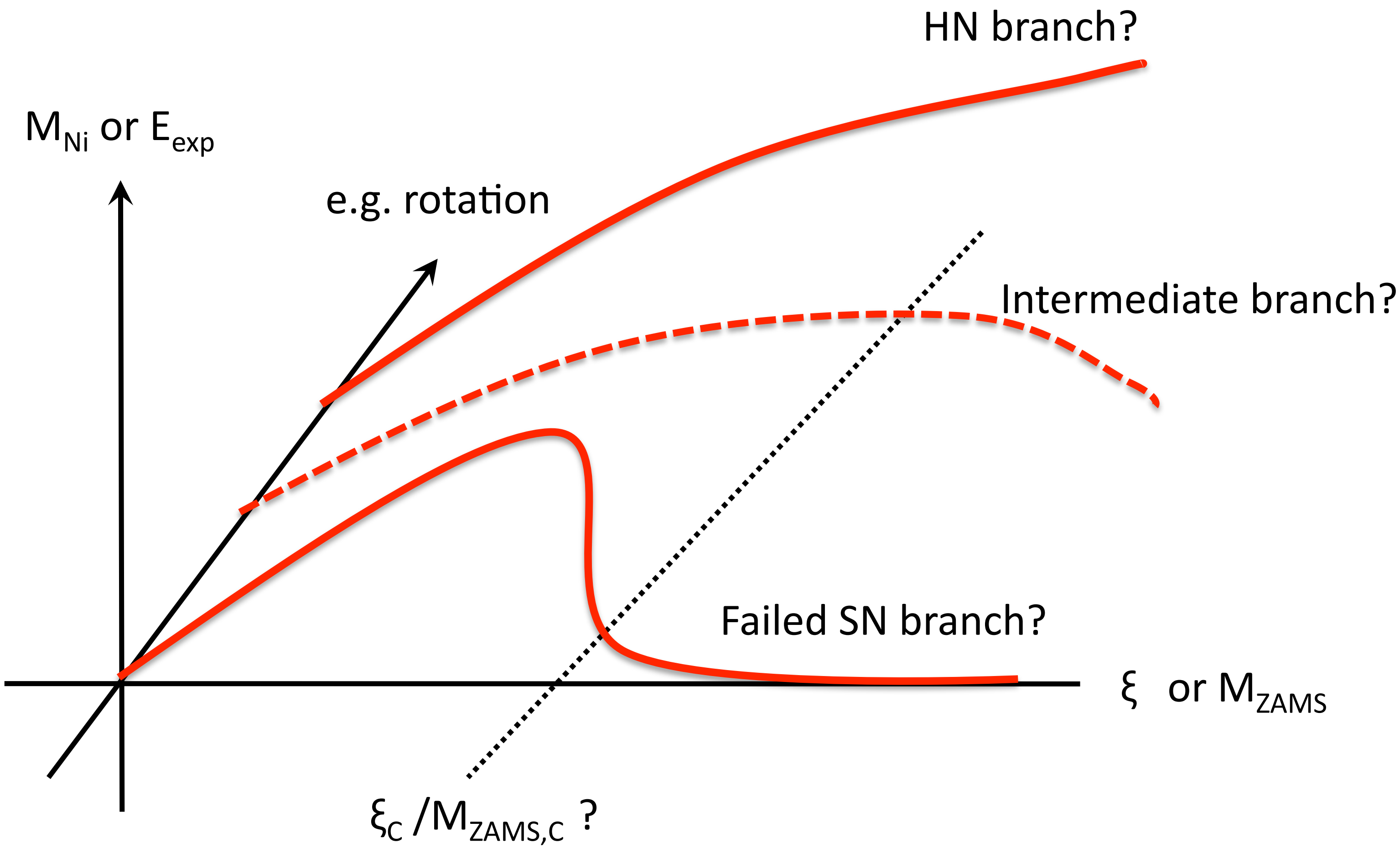


BSSN equations (17 variables)

$$
\begin{aligned}
(\partial_t - \mathcal{L}_\beta)\tilde{\gamma}_{ij} &= -2\alpha\tilde{A}_{ij} \\
(\partial_t - \mathcal{L}_\beta)\phi &= -\alpha K/6 \\
(\partial_t - \mathcal{L}_\beta)\tilde{A}_{ij} &= e^{-4\phi}\left[\alpha(R_{ij} - 8\pi(S_{ij} + P_{ij})) - D_i D_j \alpha\right]^{\mathrm{trf}} + \alpha(K\tilde{A}_{ij} - 2\tilde{A}_{ik}\tilde{\gamma}^{kl}\tilde{A}_{jl}) \\
(\partial_t - \mathcal{L}_\beta)K &= -\Delta\alpha + \alpha(\tilde{A}_{ij}\tilde{A}^{ij} + K^2/3) + 4\pi\alpha(S_0 e^{-6\phi} + E + \gamma^{ij}(S_{ij} + P_{ij})) \\
(\partial_t - \beta^k\partial_k)\Gamma^i &= -16\pi\tilde{\gamma}^{ij}(S_j e^{-6\phi} + F_j) \\
&\quad -2\alpha(\frac{2}{3}\tilde{\gamma}^{ij}K_{,j} - 6\tilde{A}^{ij}\phi_{,j} - \tilde{\Gamma}^i_{jk}\tilde{A}^{jk}) \\
&\quad +\tilde{\gamma}^{jk}\beta^i_{,jk} + \frac{1}{3}\tilde{\gamma}^{ij}\beta^k_{,kj} - \tilde{\Gamma}^j\beta^i_{,j} + \frac{2}{3}\tilde{\Gamma}^i\beta^j_{,j} + \beta^j\tilde{\Gamma}^i_{,j} - 2\tilde{A}^{ij}\alpha_{,j}
\end{aligned}
$$

Hydrodynamic equations (10+3 variables)

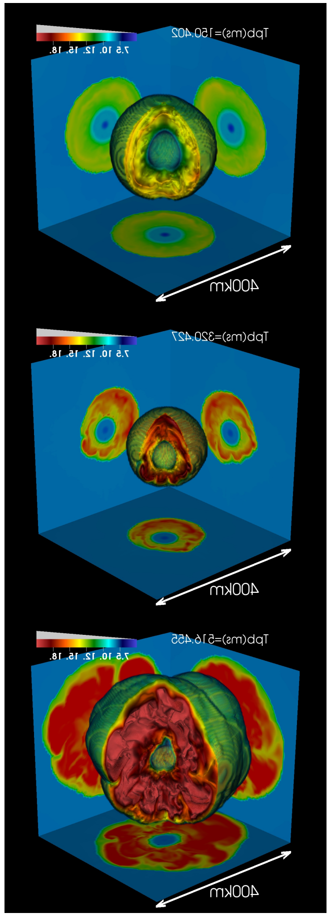
$$
\begin{aligned}
\partial_t\rho_* + \partial_i(\rho_* v^i) &= 0 \\
\partial_t S_i + \partial_j(S_i v^j + \alpha e^{6\phi}P_{\mathrm{tot}}\delta^j_i) &= -S_0\partial_i\alpha + S_k\partial_i\beta^k + 2\alpha e^{6\phi}S^k_k\partial_i\phi \\
&\quad -\alpha e^{2\phi}(S_{jk} - P_{\mathrm{tot}}\gamma_{jk})\partial_i\tilde{\gamma}^{jk}/2 - e^{6\phi}\alpha Q^\mu\gamma_{i\mu} \\
\partial_t\tau + \partial_i(S_0 v^i + e^{6\phi}P_{\mathrm{tot}}(v^i + \beta^i) - \rho_* v^i) &= \alpha e^{6\phi}K S^k_k/3 + \alpha e^{2\phi}(S_{ij} - P_{\mathrm{tot}}\gamma_{ij})\tilde{A}^{ij} - S_i D^i\alpha \\
&\quad +e^{6\phi}\alpha Q^\mu n_\mu \\
\partial_t(\rho_* Y_l) + \partial_i(\rho_* Y_l v^i) &= \rho_*\Gamma_l
\end{aligned}
$$

Neutrino Radiation equations (12x20 variables)

$$
\begin{aligned}
\partial_t(e^{6\phi}F_i) + \partial_j[e^{6\phi}(\alpha P^j_i - \beta^j F_i)] &= e^{6\phi}[-E\partial_i\alpha + F_j\partial_i\beta^j + (\alpha/2)P^{jk}\partial_i\gamma_{jk} + \alpha Q^\mu\gamma_{i\mu}] \\
\partial_t(e^{6\phi}E) + \partial_i[e^{6\phi}(\alpha F^i - \beta^i E)] &= e^{6\phi}(\alpha P^{ij}K_{ij} - F^i\partial_i\alpha - \alpha Q^\mu n_\mu)
\end{aligned}
$$

For the radiation part

(1) Single (gray) energy leakage scheme

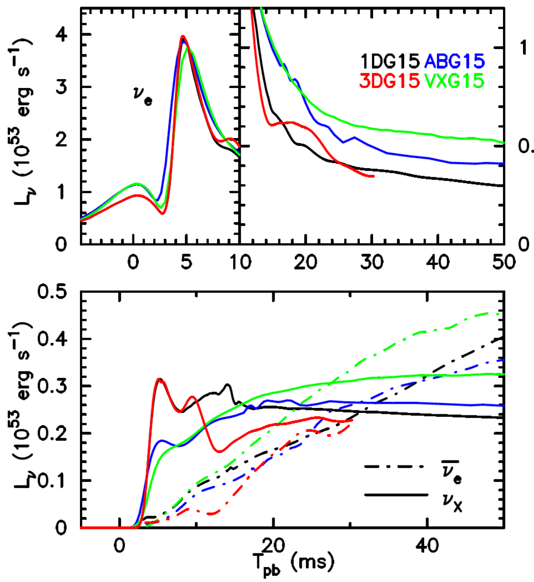


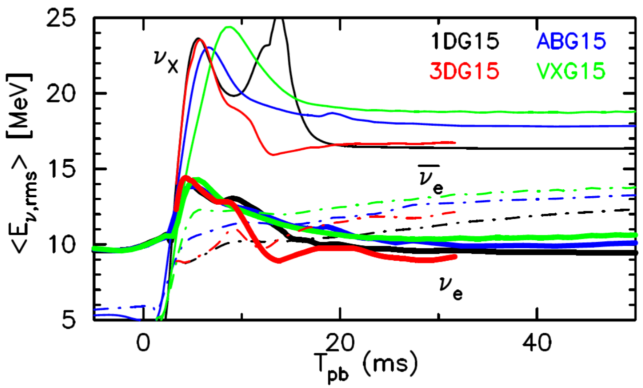
T_{pb}=150ms

T_{pb}=500ms

Calculations are not so numerically expensive
~20ms/1day with ~2000 cores.

(1) Multi energy neutrino transport





Neutrino luminosities and energies show consistent results with AGILE-Boltztran