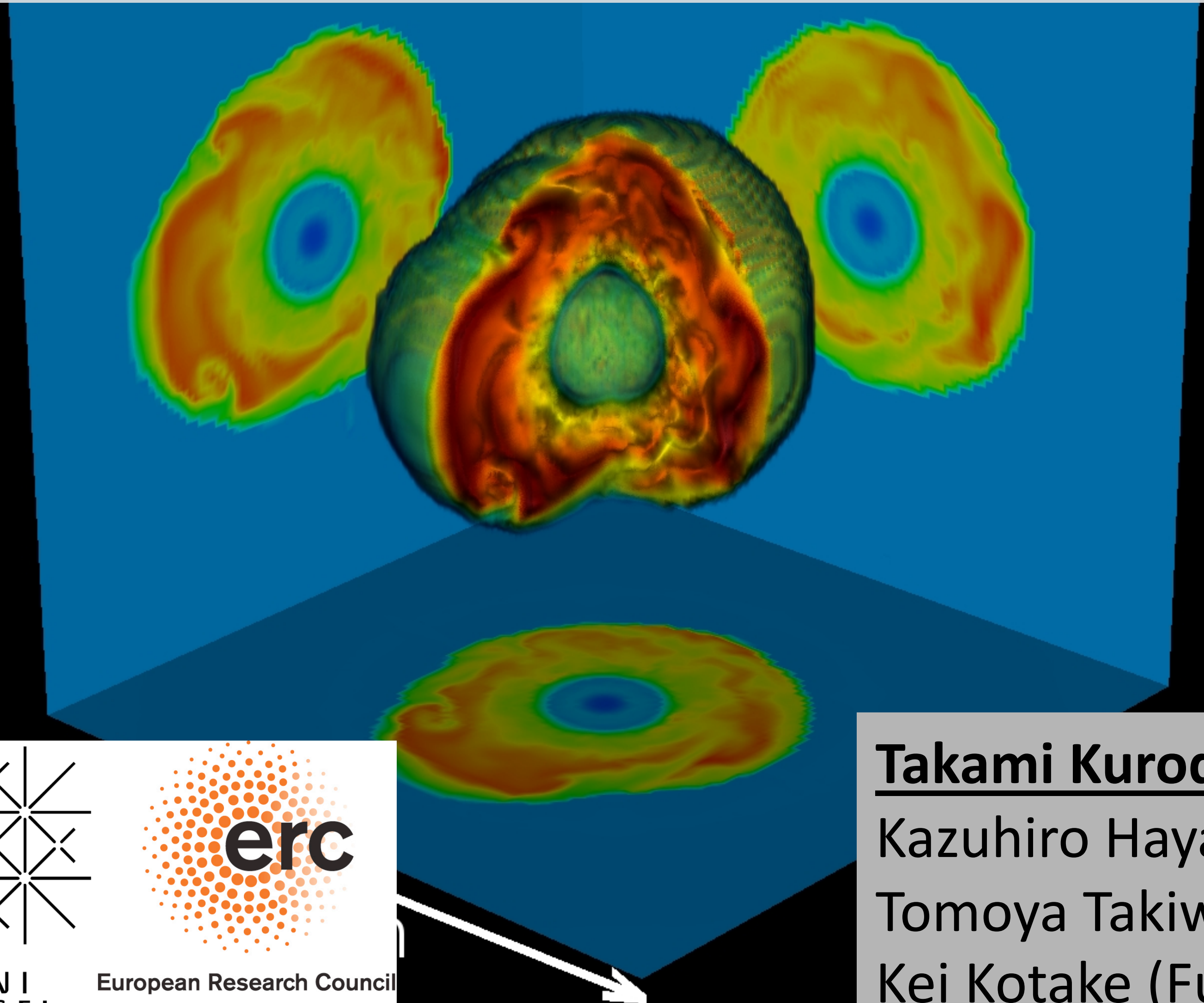
Deciphering signatures of EoSs/progenitor models imprinted in GW/neutrino signals emitted from SN cores

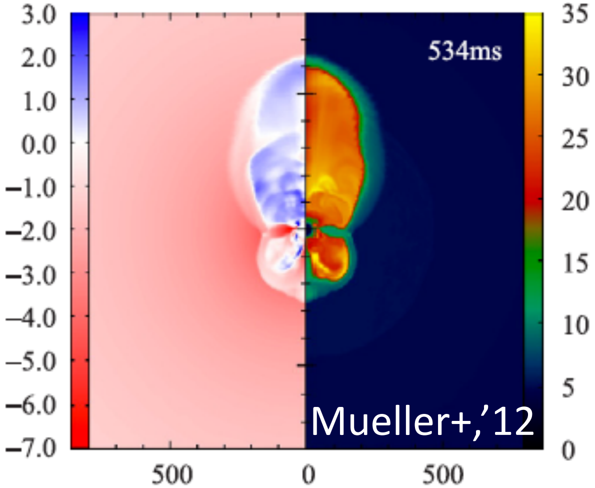


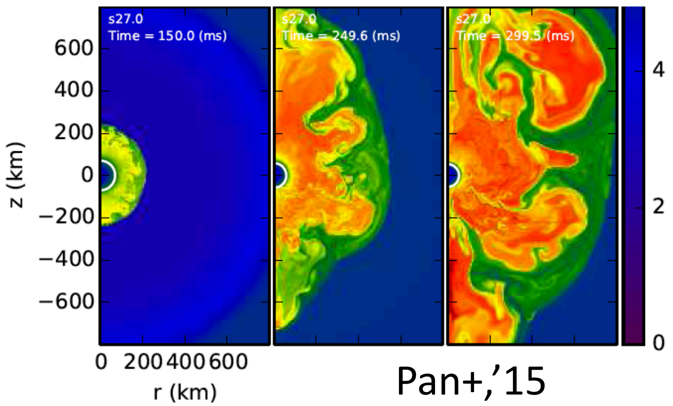
<u>Takami Kuroda</u> (Basel U.)
Kazuhiro Hayama (Osaka-city U.)
Tomoya Takiwaki (RIKEN)
Kei Kotake (Fukuoka U.)

UNI BASEL
European Research Council
Established by the European Commission

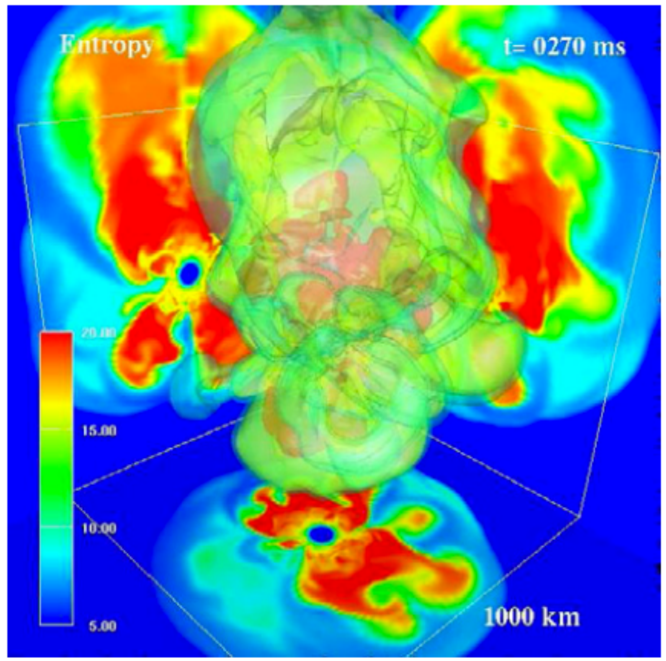
Three Keys for Successful Explosion

- Multi Dimension → (primarily affect on) Gain region (M_{gain}, τ_{gain})
- Progenitor profile → Mass accretion rate
- Nuclear EOS → Neutrino & Acoustic mode





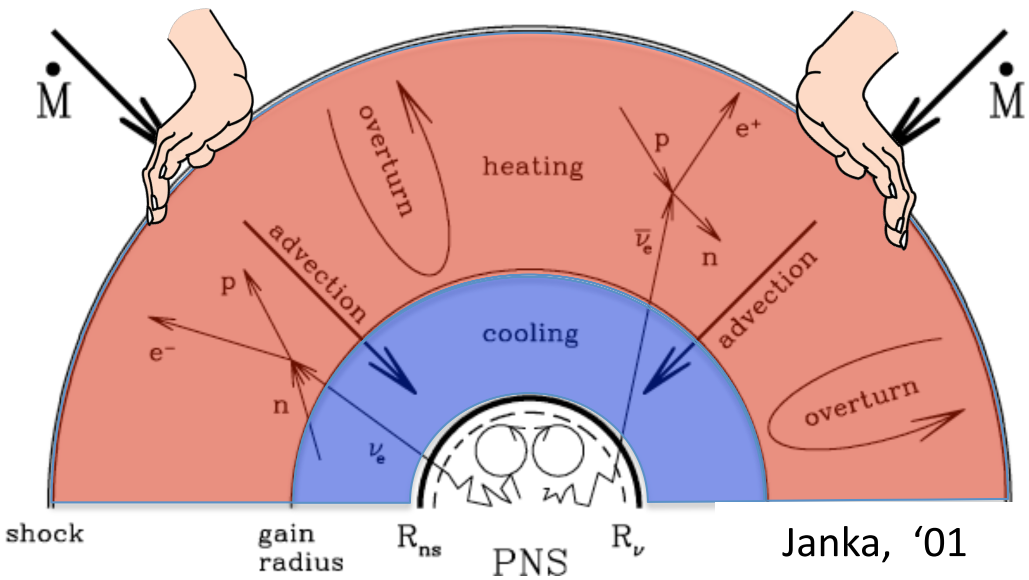
Pan+,'15



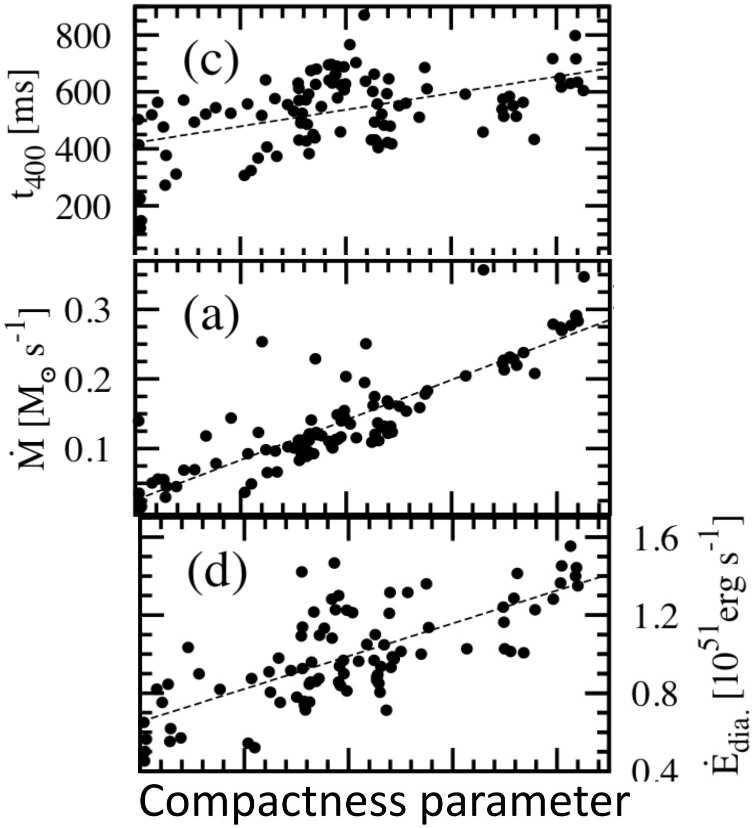
Takiwaki+,'14

Three Keys for Successful Explosion

- Multi Dimension → Gain region (M_{gain}, τ_{gain})
- Progenitor profile → Mass accretion rate
- Nuclear EOS → Neutrino & Acoustic mode



Janka, '01



Nakamura, Takiwaki, KT, Kotake,'14

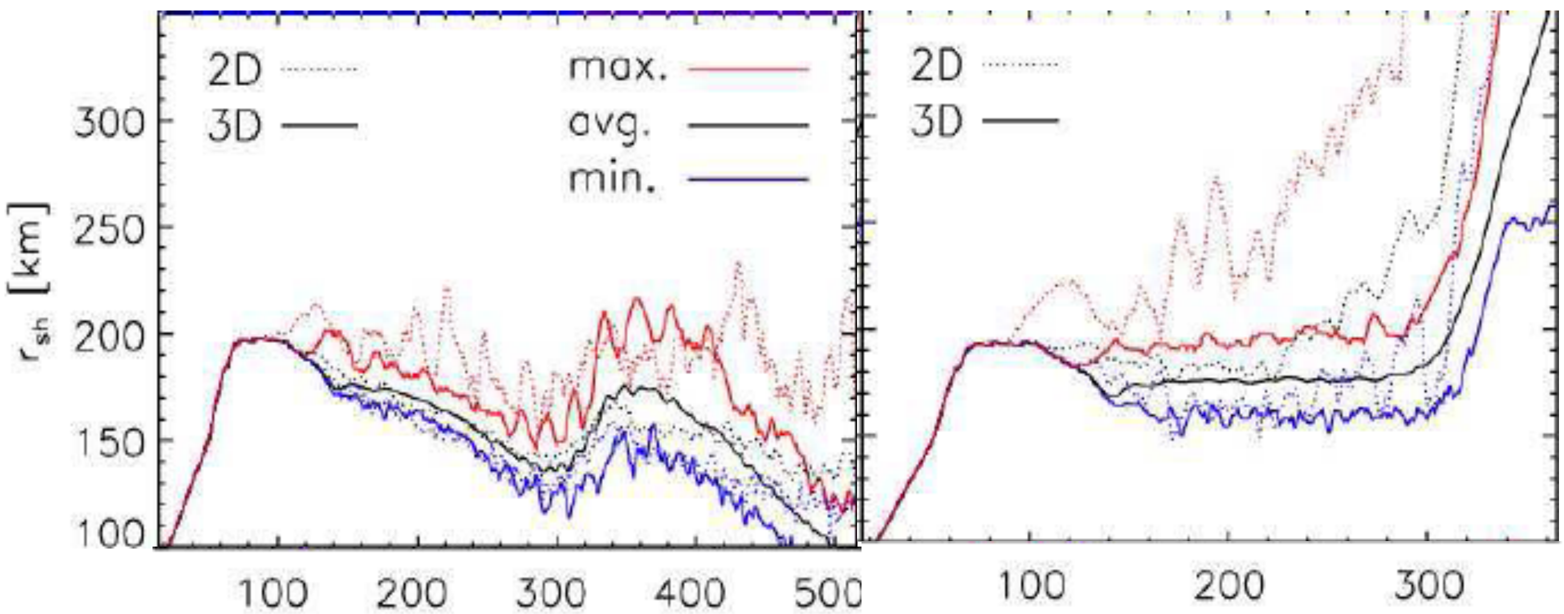
Both High and Low M_{dot} are OK.
(But not too high M_{dot} (→BH in GR))

Three Keys for Successful Explosion

- Multi Dimension → Gain region (M_{gain}, τ_{gain})
- Progenitor profile → Mass accretion rate
- Nuclear EOS → Neutrino Luminosity

"Soft" PNS is cinsidered to be more favorable
for the shock evolution in neutrino-driven explosion

Slow shrink (low luminosity) Rapid shrink (high luminosity)



Hanke+,'13

Aims of This Study

- Multi Dimension
- Progenitor profile
- Nuclear EOS

→

- SN core dynamics
- GW emissions
- Neutrino signals

We performed 3D full GR gray-neutrino transport simulations

$$\begin{cases} G^{\mu\nu} = 8\pi T^{\mu\nu} \\ \nabla_\alpha T^{\alpha\beta}_{(\mathrm{total})} = \nabla_\alpha T^{\alpha\beta}_{(\mathrm{fluid})} + \nabla_\alpha T^{\alpha\beta}_{(\nu)} = 0 \end{cases}$$

KT+,'12

BSSN equations (17 variables)

$$(\partial_t - \mathcal{L}_\beta)\tilde{\gamma}_{ij} = -2\alpha\tilde{A}_{ij}$$

$$(\partial_t - \mathcal{L}_\beta)\phi = -\alpha K/6$$

$$(\partial_t - \mathcal{L}_\beta)\tilde{A}_{ij} = e^{-4\phi}\left[\alpha(R_{ij} - 8\pi(S_{ij} + P_{ij})) - D_i D_j \alpha\right]^{\rm trf} + \alpha(K\tilde{A}_{ij} - 2\tilde{A}_{ik}\tilde{\gamma}^{kl}\tilde{A}_{jl})$$

$$(\partial_t - \mathcal{L}_\beta)K = -\Delta\alpha + \alpha(\tilde{A}_{ij}\tilde{A}^{ij} + K^2/3) + 4\pi\alpha(S_0 e^{-6\phi} + E + \gamma^{ij}(S_{ij} + P_{ij}))$$

$$\begin{aligned}(\partial_t - \beta^k\partial_k)\Gamma^i = & -16\pi\tilde{\gamma}^{ij}(S_j e^{-6\phi} + F_j) \\ & -2\alpha\left(\frac{2}{3}\tilde{\gamma}^{ij}K_{,j} - 6\tilde{A}^{ij}\phi_{,j} - \tilde{\Gamma}^i_{jk}\tilde{A}^{jk}\right) \\ & +\tilde{\gamma}^{jk}\beta^i_{,jk} + \frac{1}{3}\tilde{\gamma}^{ij}\beta^k_{,kj} - \tilde{\Gamma}^j\beta^i_{,j} + \frac{2}{3}\tilde{\Gamma}^i\beta^j_{,j} + \beta^j\tilde{\Gamma}^i_{,j} - 2\tilde{A}^{ij}\alpha_{,j}\end{aligned}$$

Hydrodynamic equations (10 variables)

$$\partial_t\rho_* + \partial_i(\rho_* v^i) = 0$$

$$\begin{aligned}\partial_t S_i + \partial_j(S_i v^j + \alpha e^{6\phi}P_{\rm tot}\delta^j_i) = & -S_0\partial_i\alpha + S_k\partial_i\beta^k + 2\alpha e^{6\phi}S^k_k\partial_i\phi \\ & -\alpha e^{2\phi}(S_{jk} - P_{\rm tot}\gamma_{jk})\partial_i\tilde{\gamma}^{jk}/2 - e^{6\phi}\alpha Q^\mu\gamma_{i\mu}\end{aligned}$$

$$\begin{aligned}\partial_t\tau + \partial_i(S_0 v^i + e^{6\phi}P_{\rm tot}(v^i + \beta^i) - \rho_* v^i) = & \alpha e^{6\phi}KS^k_k/3 + \alpha e^{2\phi}(S_{ij} - P_{\rm tot}\gamma_{ij})\tilde{A}^{ij} - S_i D^i\alpha \\ & + e^{6\phi}\alpha Q^\mu n_\mu\end{aligned}$$

$$\partial_t(\rho_* Y_l) + \partial_i(\rho_* Y_l v^i) = \rho_*\Gamma_l$$

Neutrino Radiation equations (12 variables)

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

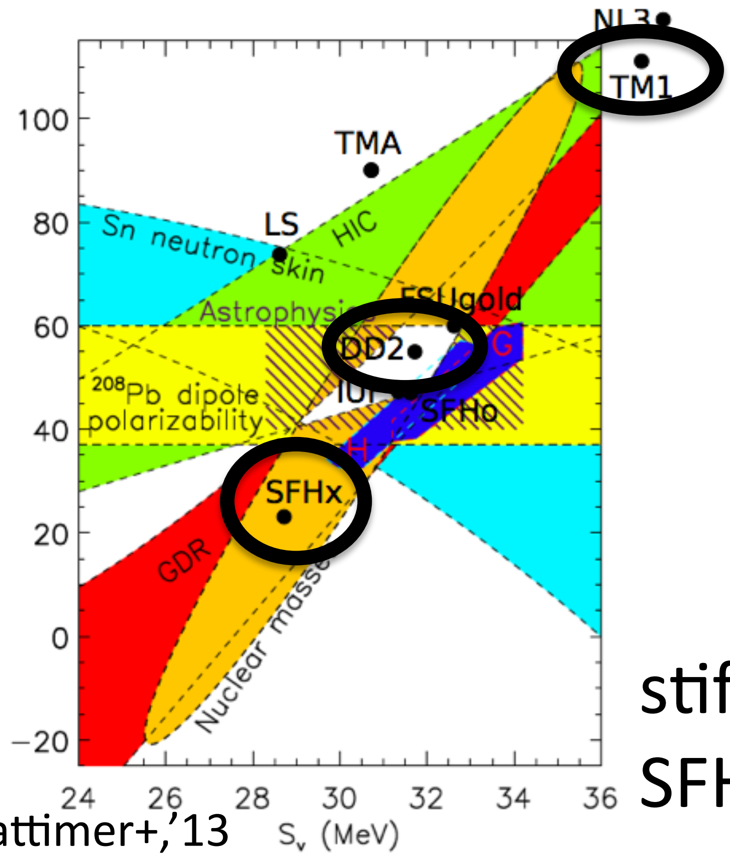
$$\partial_t(e^{6\phi}E) + \partial_i[e^{6\phi}(\alpha F^i - \beta^i E)] = e^{6\phi}(\alpha P^{ij}K_{ij} - F^i\partial_i\alpha - \alpha Q^\mu n_\mu)$$

Numerical Setups

✓Progenitor: 11.2, 40.0$M_\odot$ (WHW02) & 15.0$M_\odot$ (WW95)
(~0.3, 2.10 & 1.05 Xi@1.5Msun)

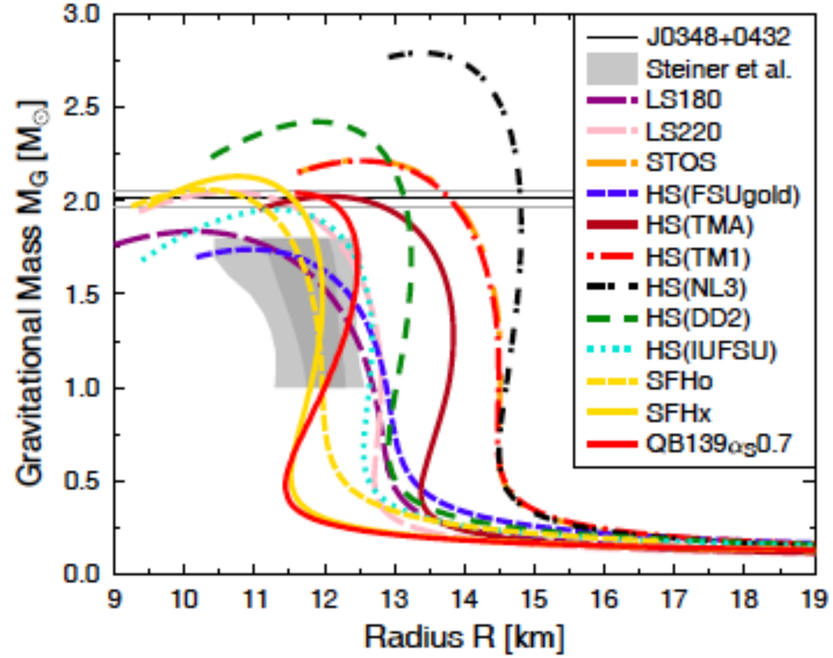
✓128^3cells*9 Level nested structure
({x,y,z}∈[-7500,7500]km, dx_{min}~450m)

✓EOS : SFHx, DD2 & TM1(Hempel+,'12 & Steiner+,'13)

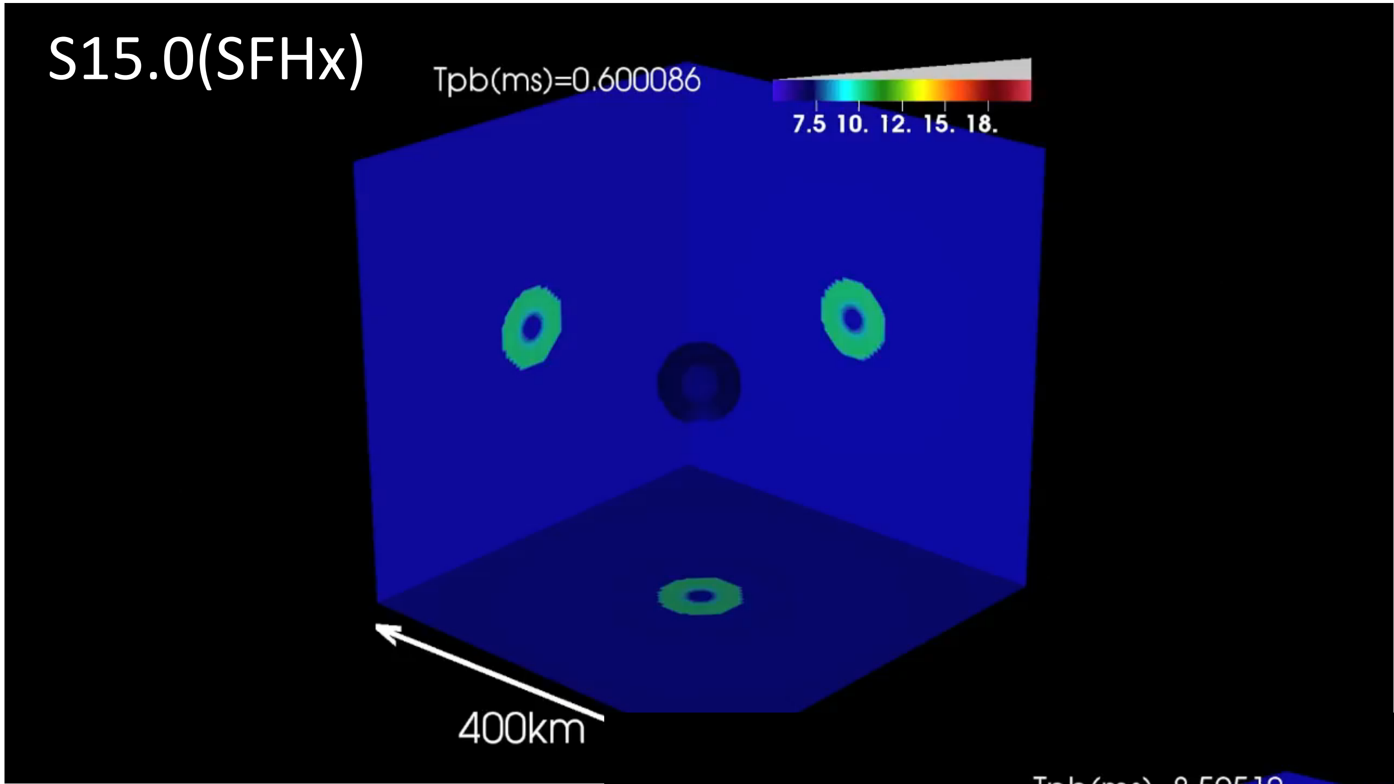


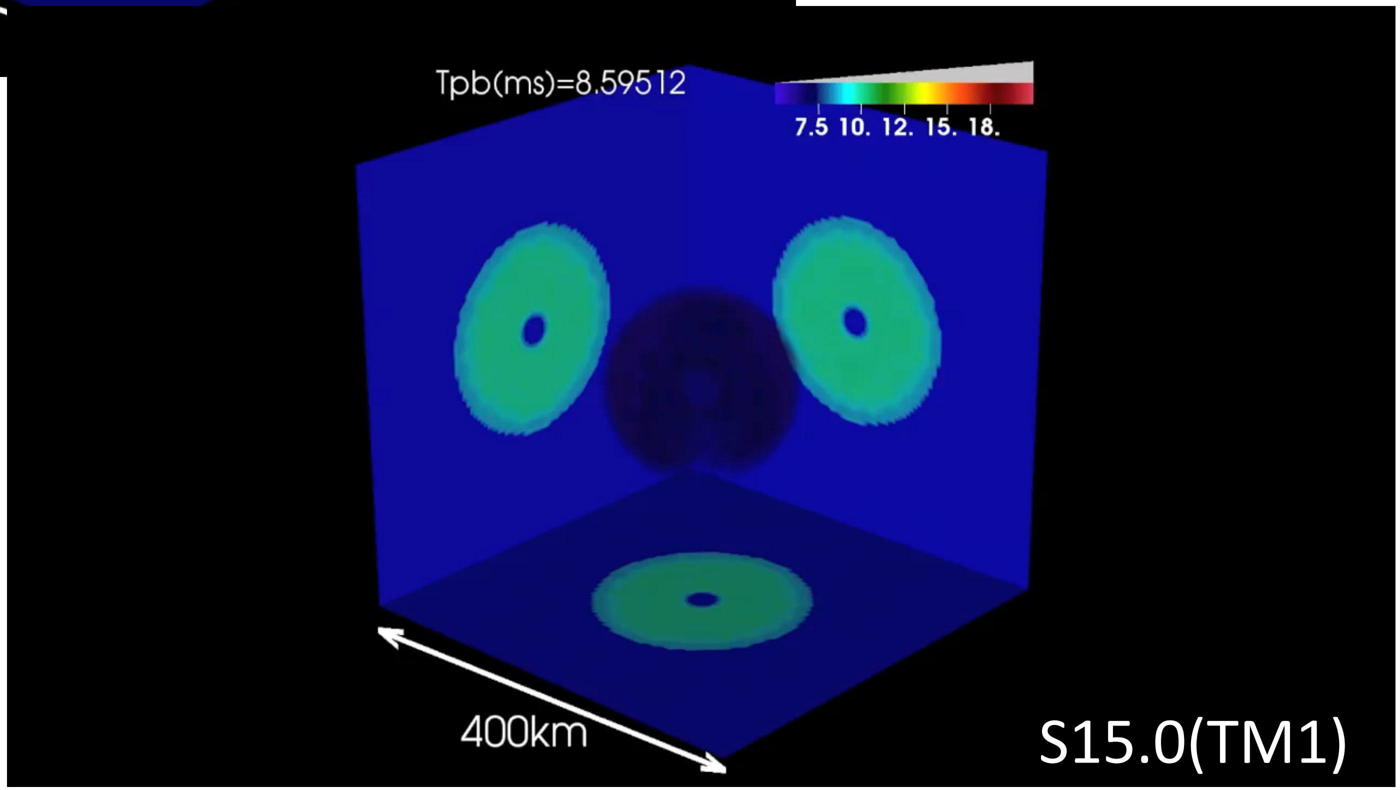
Lattimer+,'13

stiffness
SFHx<DD2<TM1

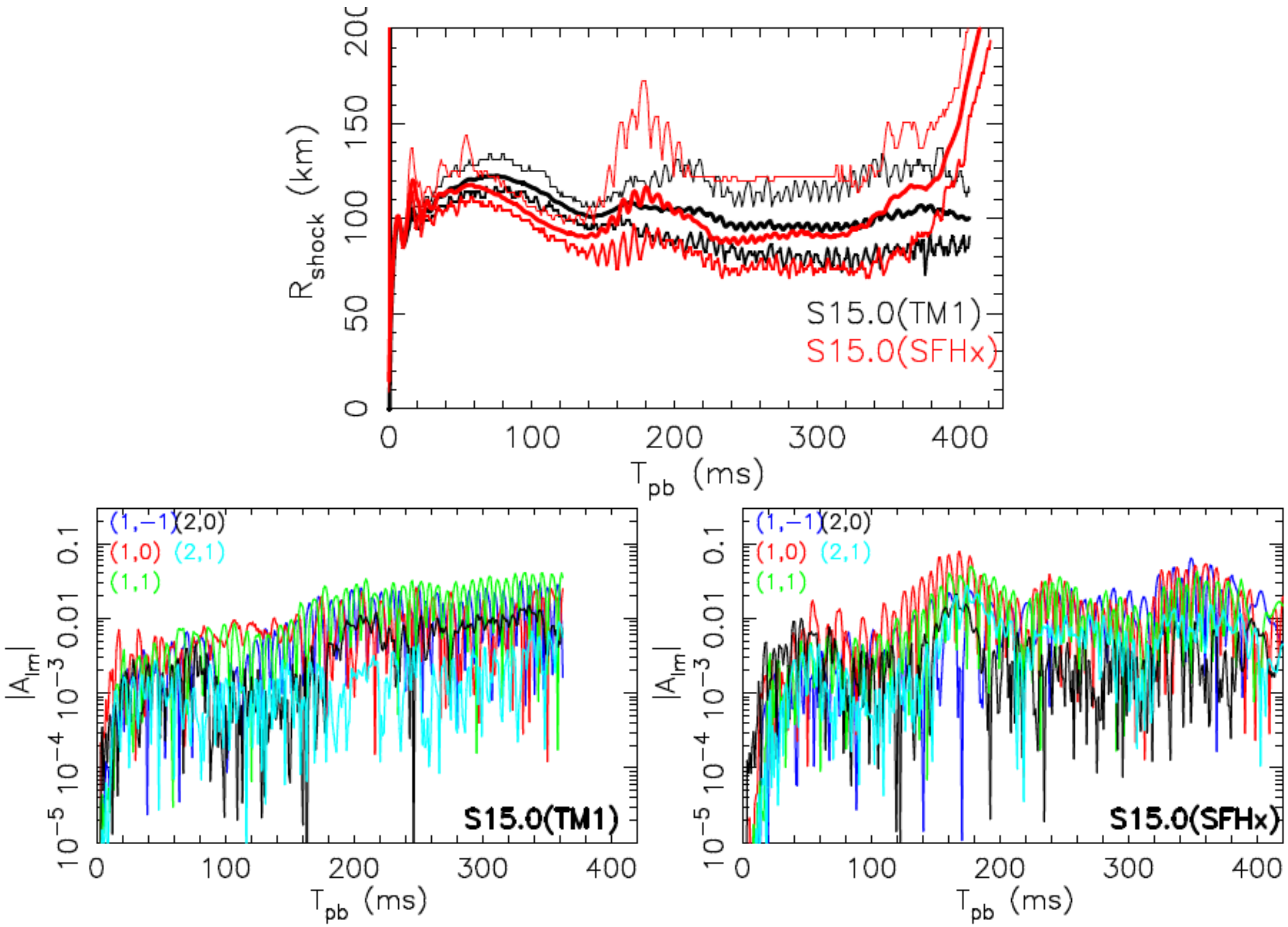


Fischer+,'14


S15.0(SFHx)
Tpb(ms)=0.600086
7.5 10. 12. 15. 18.
400km

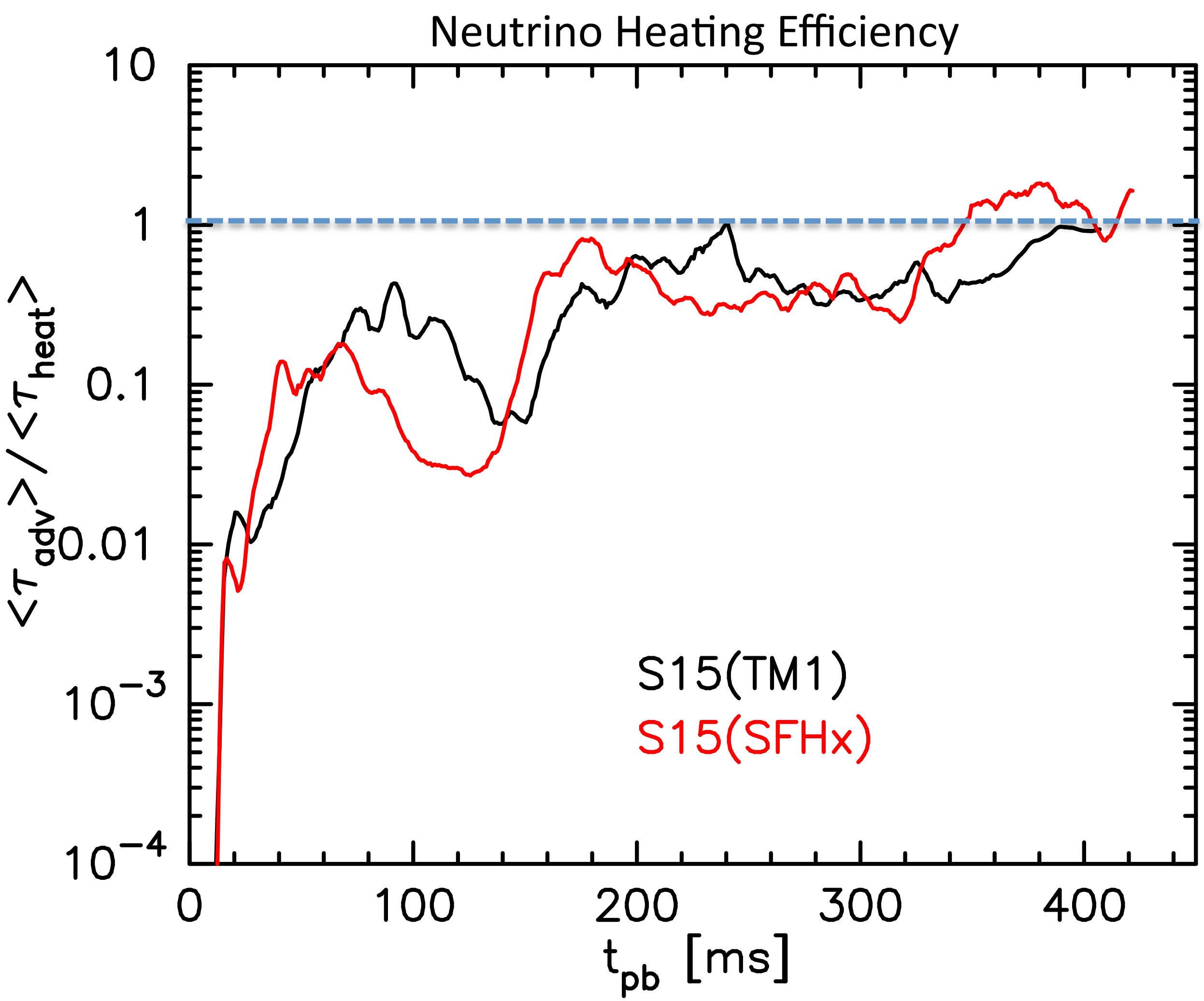

Tpb(ms)=8.59512
7.5 10. 12. 15. 18.
400km
S15.0(TM1)

EOS Dependence on SN dynamics



Vigorous SASI activity in the soft EOS model

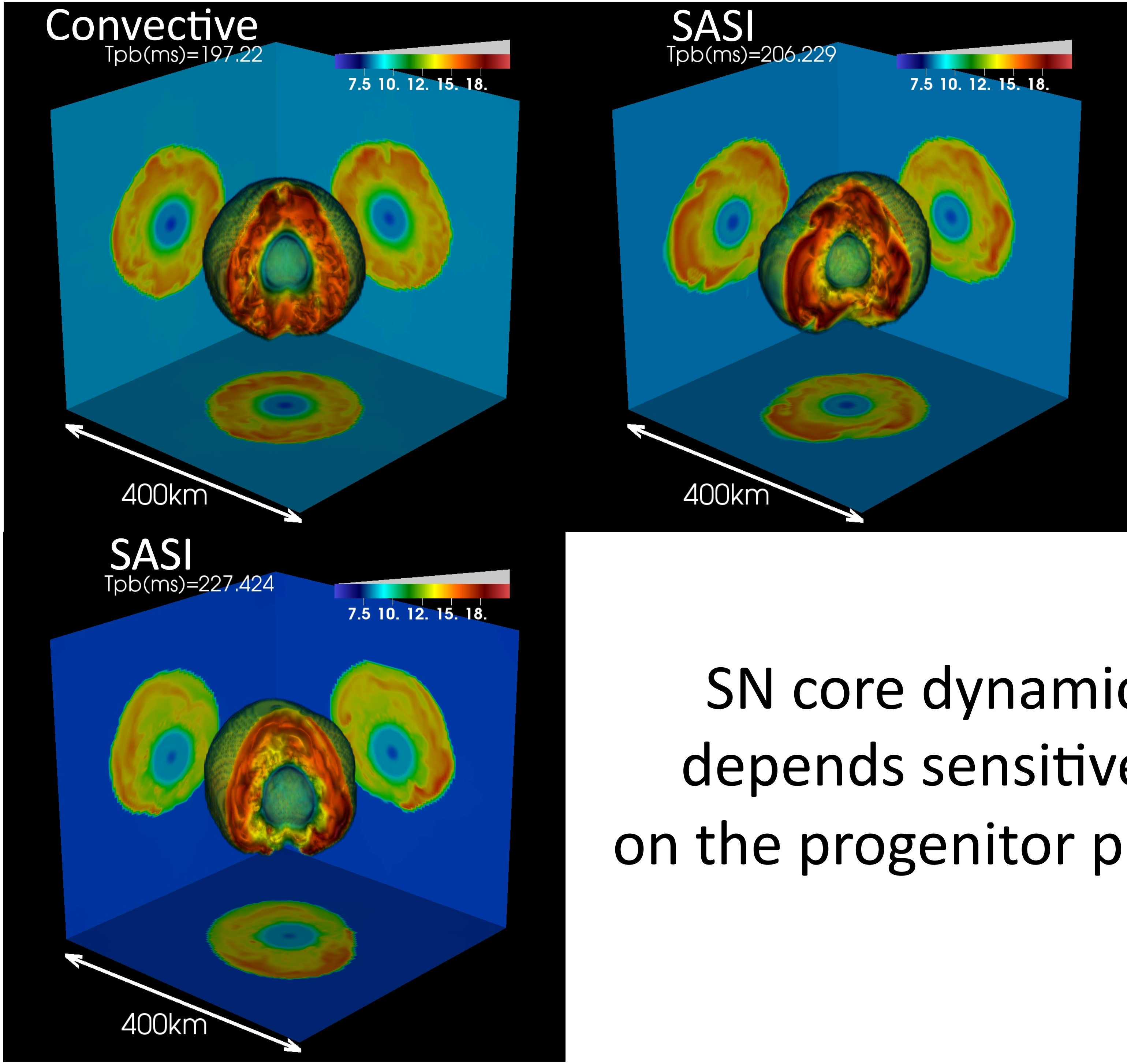
EOS Dependence on SN dynamics



The softer EOS model shows higher efficiency in the neutrino heating

S11.2

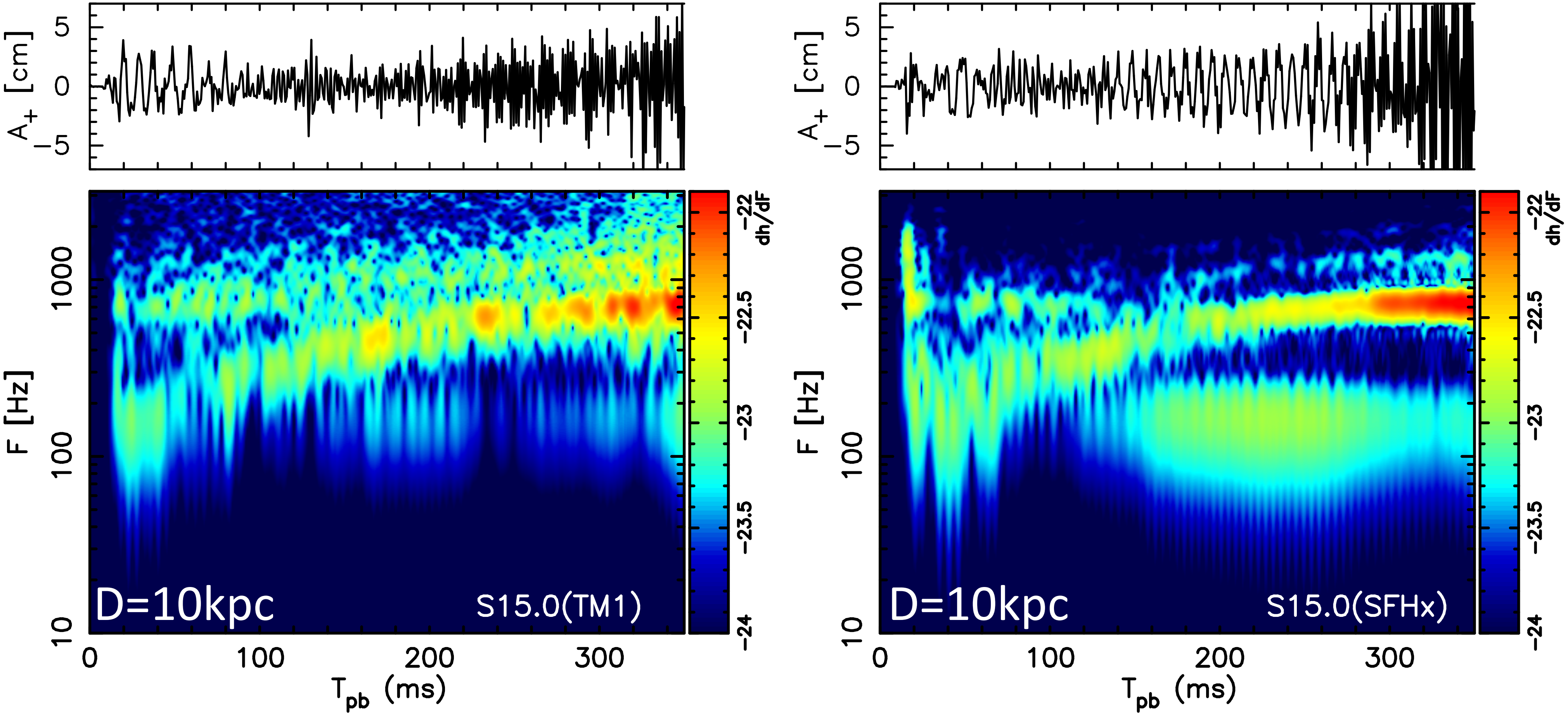
S15.0



S40.0

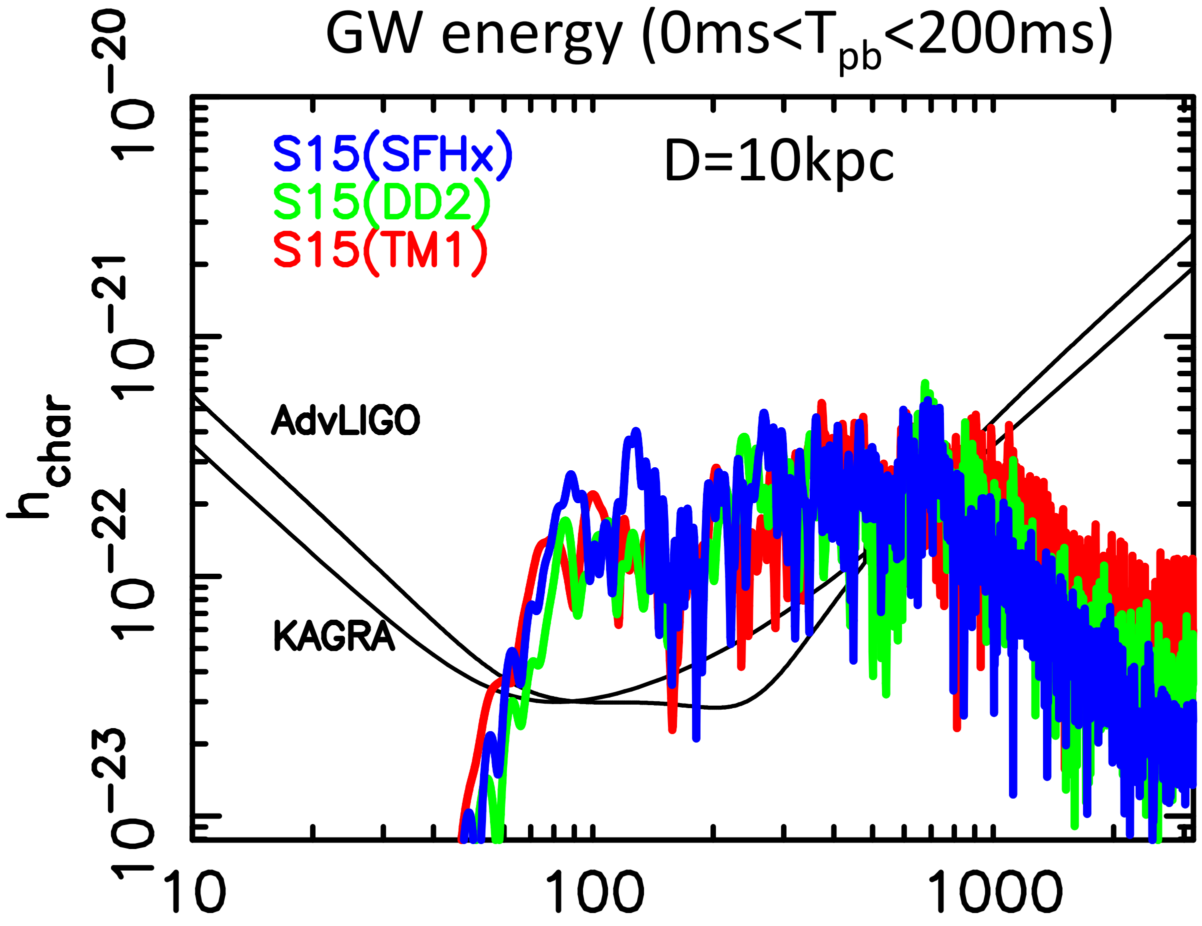
SN core dynamics depends sensitively on the progenitor profile

EOS Dependence on GW Emissions



EOS Dependence on GW Emissions

Spectra of cumulative
GW energy (0ms<T_{pb}<200ms)



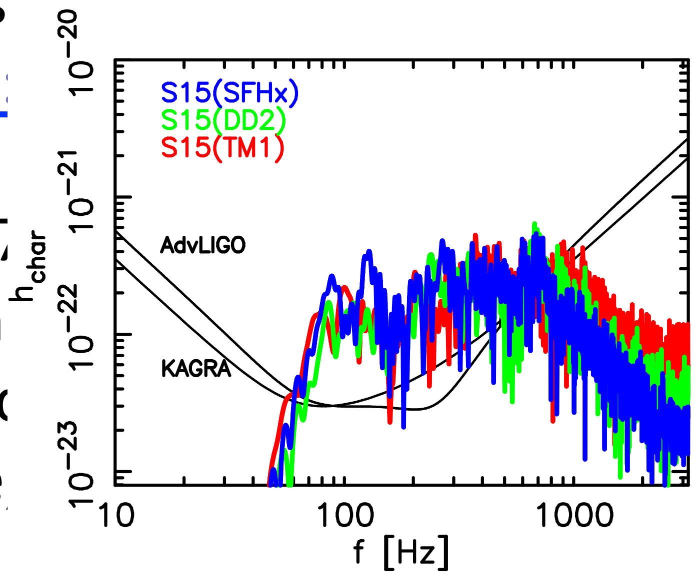
Strength of GWs

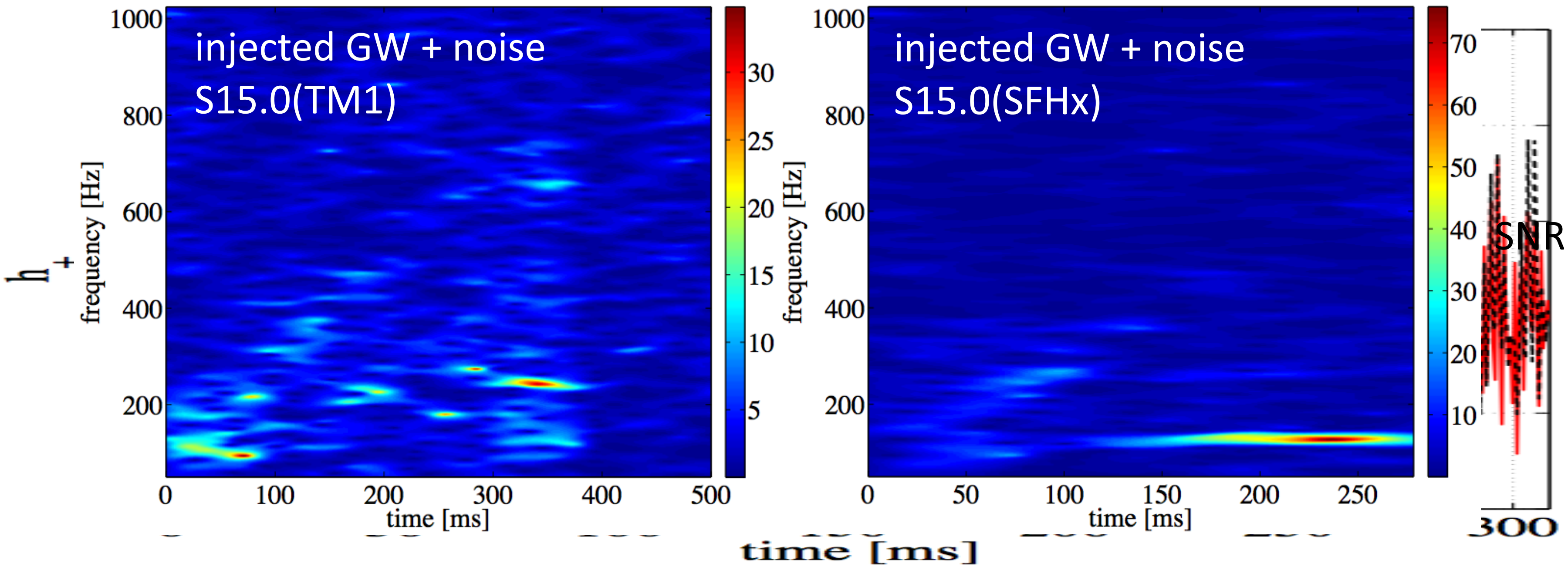
- @ higher tail → TM1>DD2>SFHx
- @ lower frequency → SFHx is the strongest

Coherent Network Analysis of GWs

We performed coherent network analysis
(Hayama, KT, Takiwaki & Kotake,’15, arXiv:

We used the RIDGE pipeline (Hayama+,’07
which takes full advantage of the global n
of LIGO-(H/L), VIRGO & KAGRA. We consic
detectors, sky-map position of the source

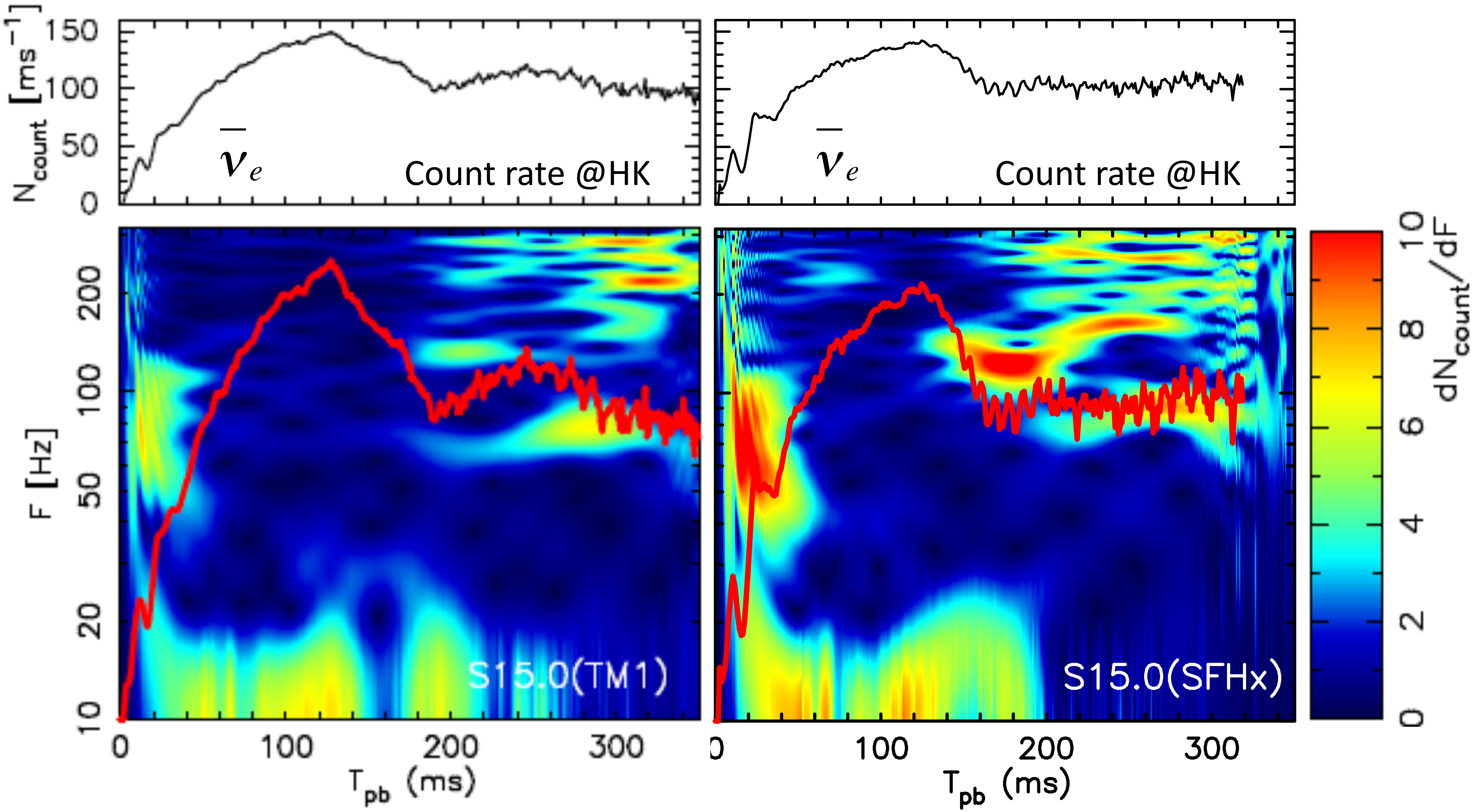




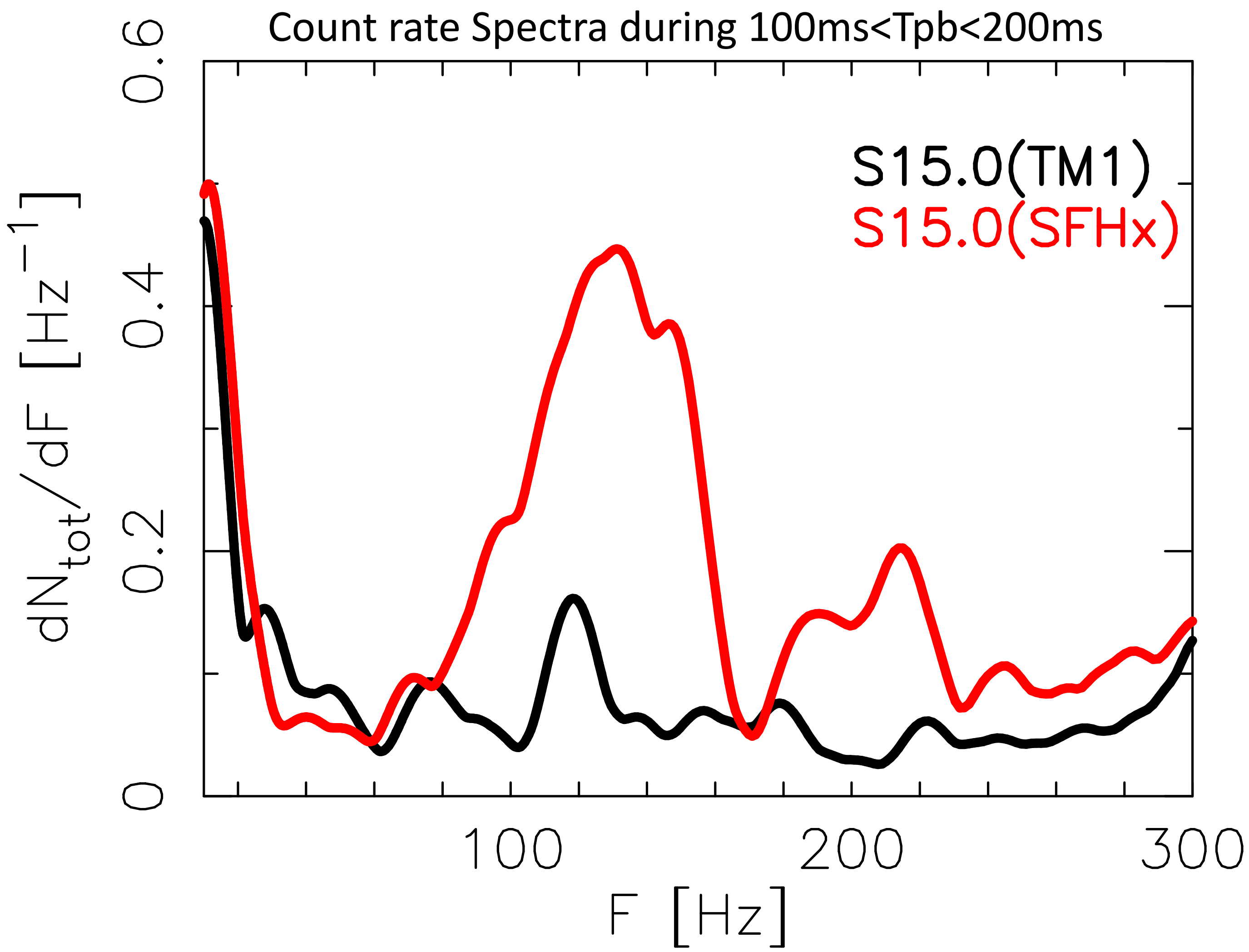
EOS Dependence on Neutrino Emissions

Tamborra+,'14

$$L(t) = 2 \int_{\mathrm{vis.hem.}} dA \, \cos\vartheta \, F_e(\mathbf{R}, t) \left(1 + \frac{3}{2}\cos\vartheta\right)$$

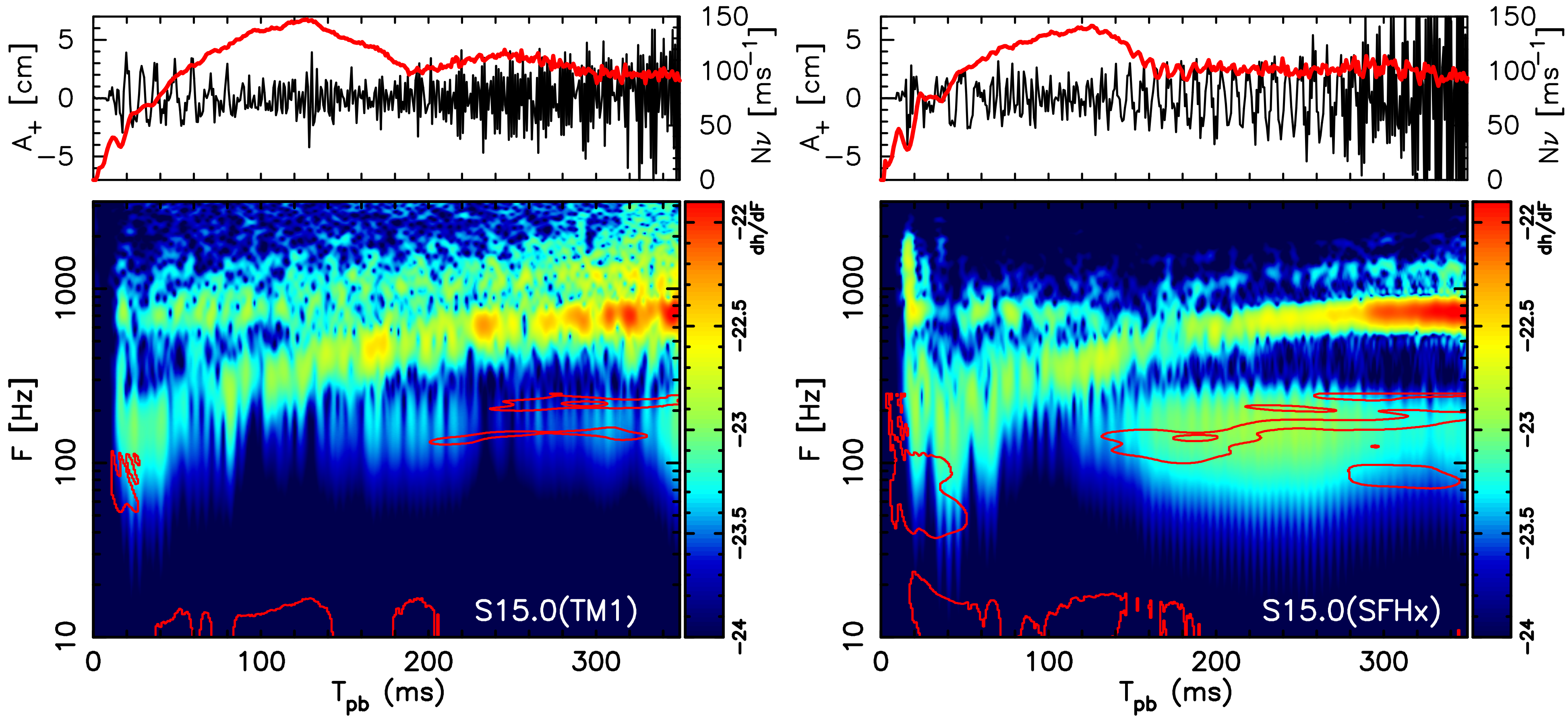


EOS Dependence on Neutrino Emissions



SASI modulation appears clearly at F~100Hz

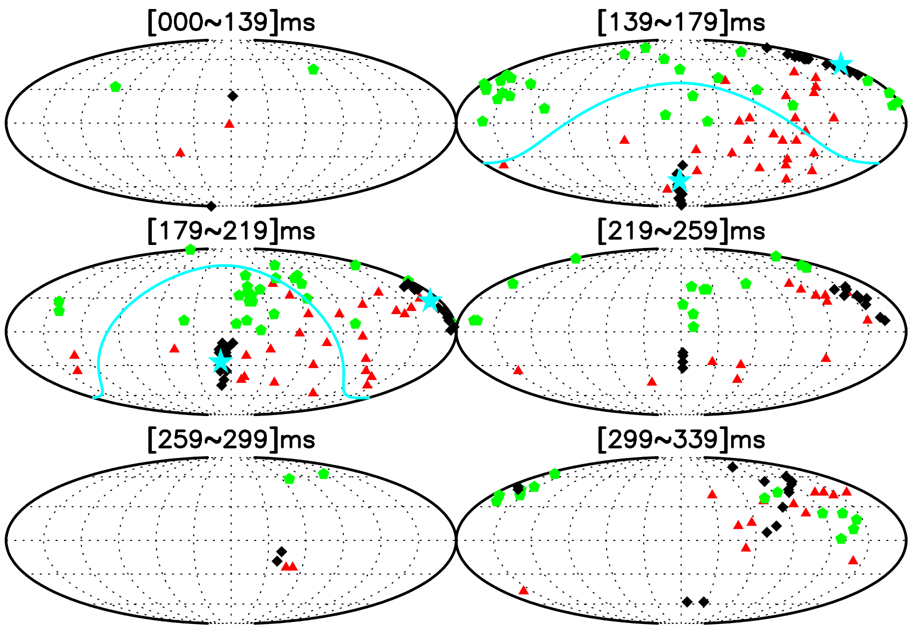
Coherence of GWs and Neutrinos associated with SASI modulation



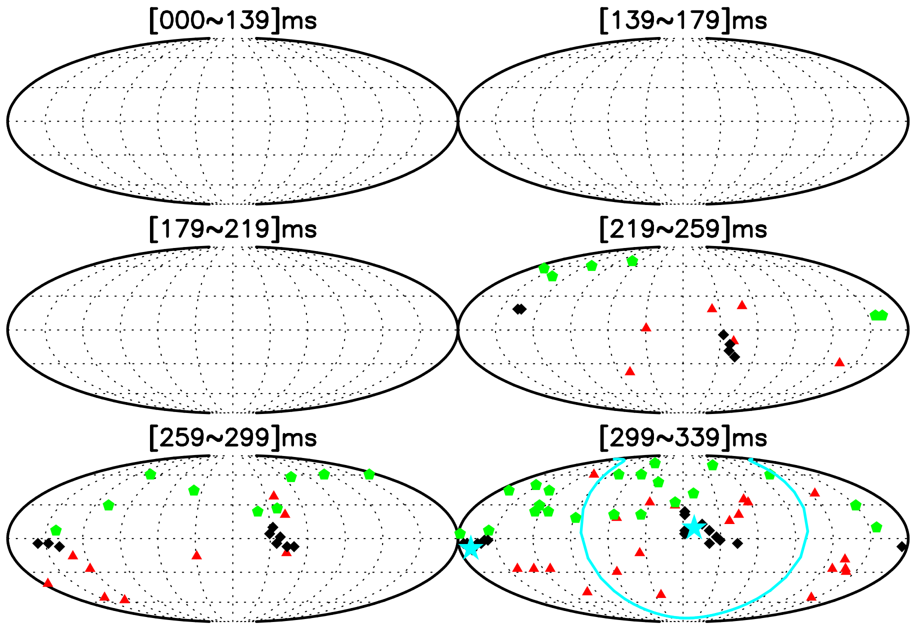
SASI activity can actually be imprinted in both GW and neutrino profiles

Directional dependence of SASI motion & GW/Neutrino emissions

S15.0(SFHx)



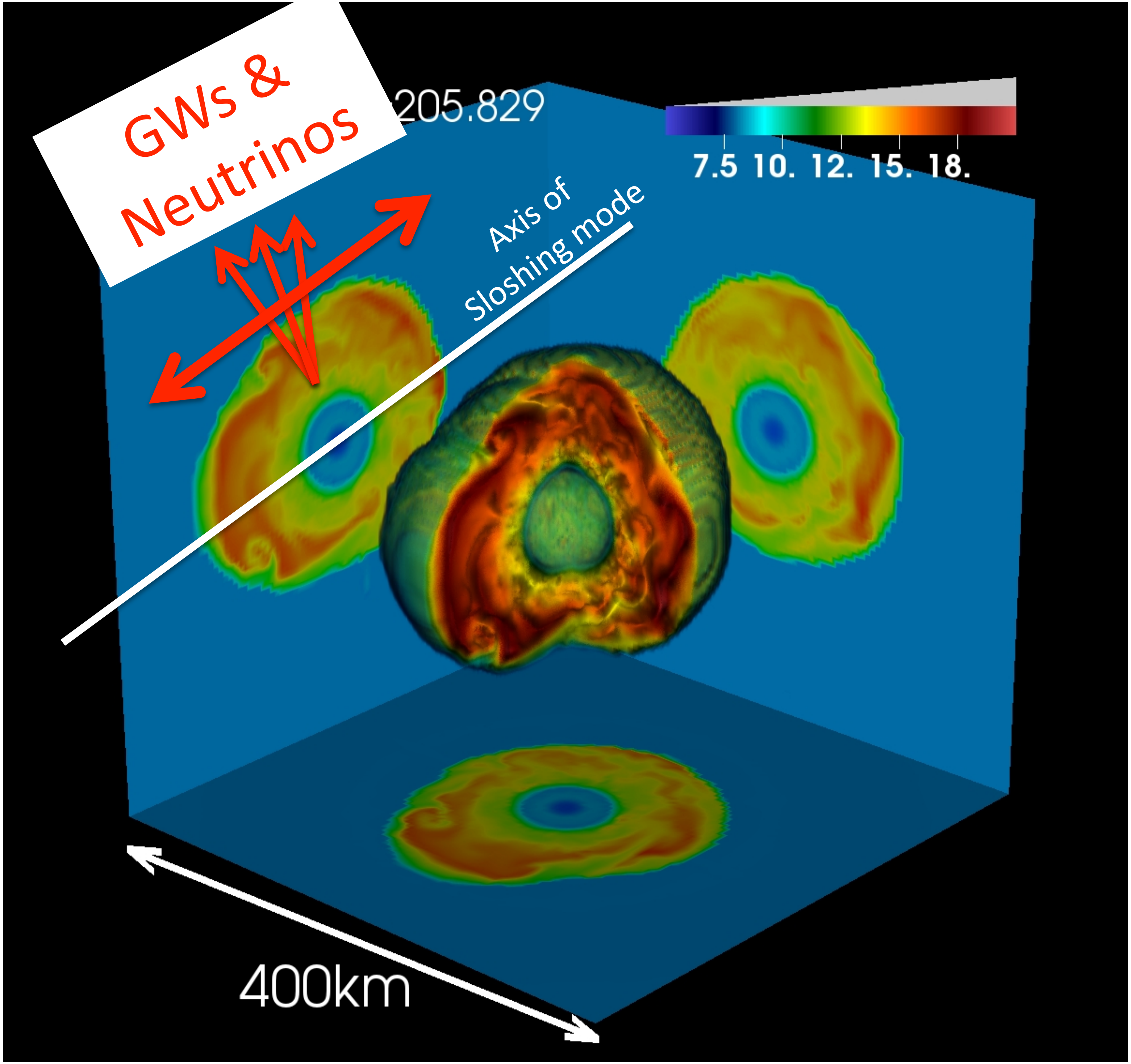
S15.0(TM1)



Black : Maximum shock position

Red : Strongest neutrino emission

Green : Strongest GW emission


GWs &
Neutrinos
205.829
7.5 10. 12. 15. 18.
Axis of
Sloshing mode
400km

Summary

•Softer EOS & more compact progenitor profile instigate SASI activity more efficiently
•SASI modulation is imprinted in both GW/Neutrino @~100Hz (@130Hz in S15.0(SFHx))
•From coherent network analysis, GW signals associated with SASI modulation, have SNR~70 (S15,SFHx) @D=10kpc.

Our next step is

To perform energy dependent neutrino transport
arXiv:1501.06330