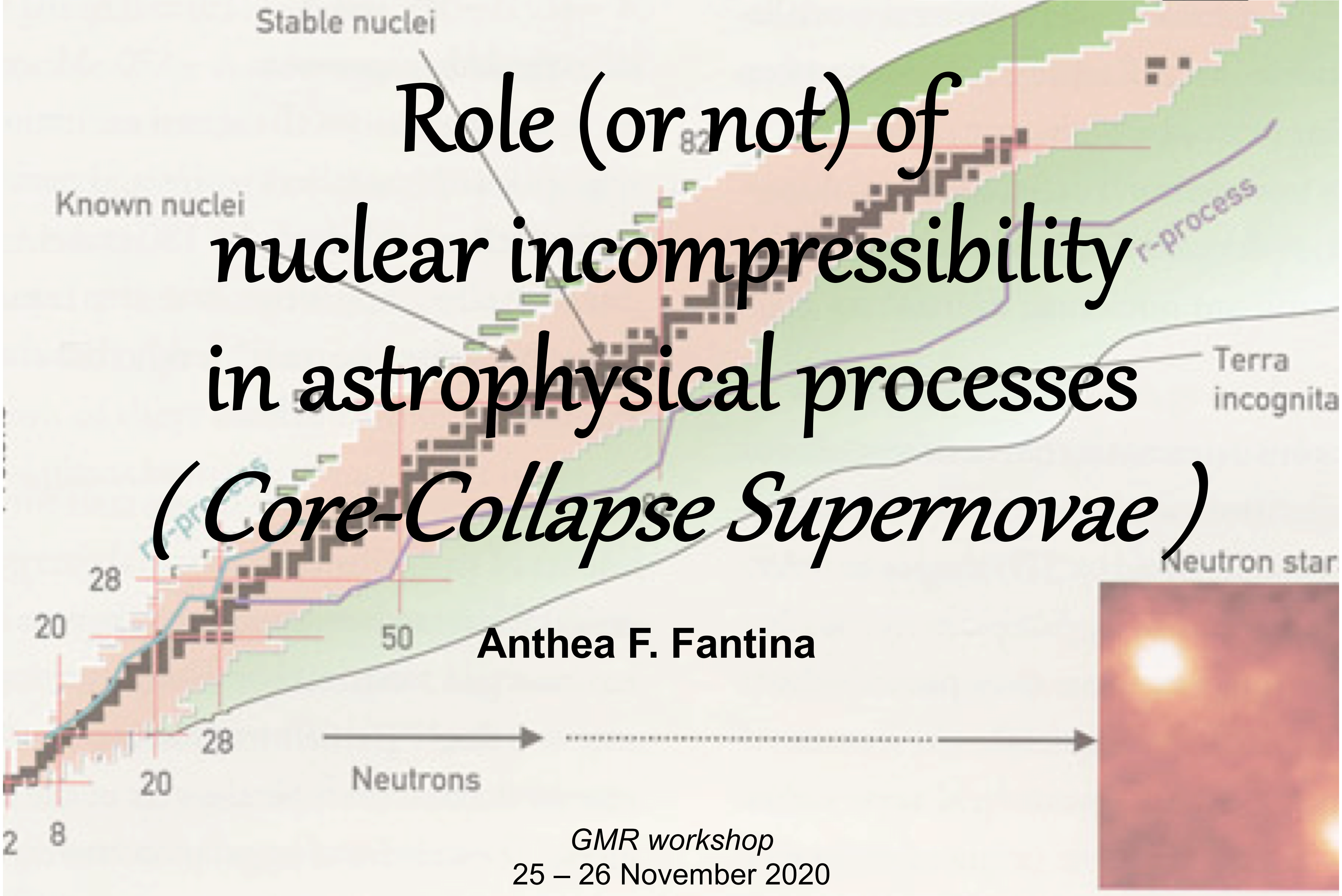


Role (or not) of nuclear incompressibility in astrophysical processes
(*Core-Collapse Supernovae*)

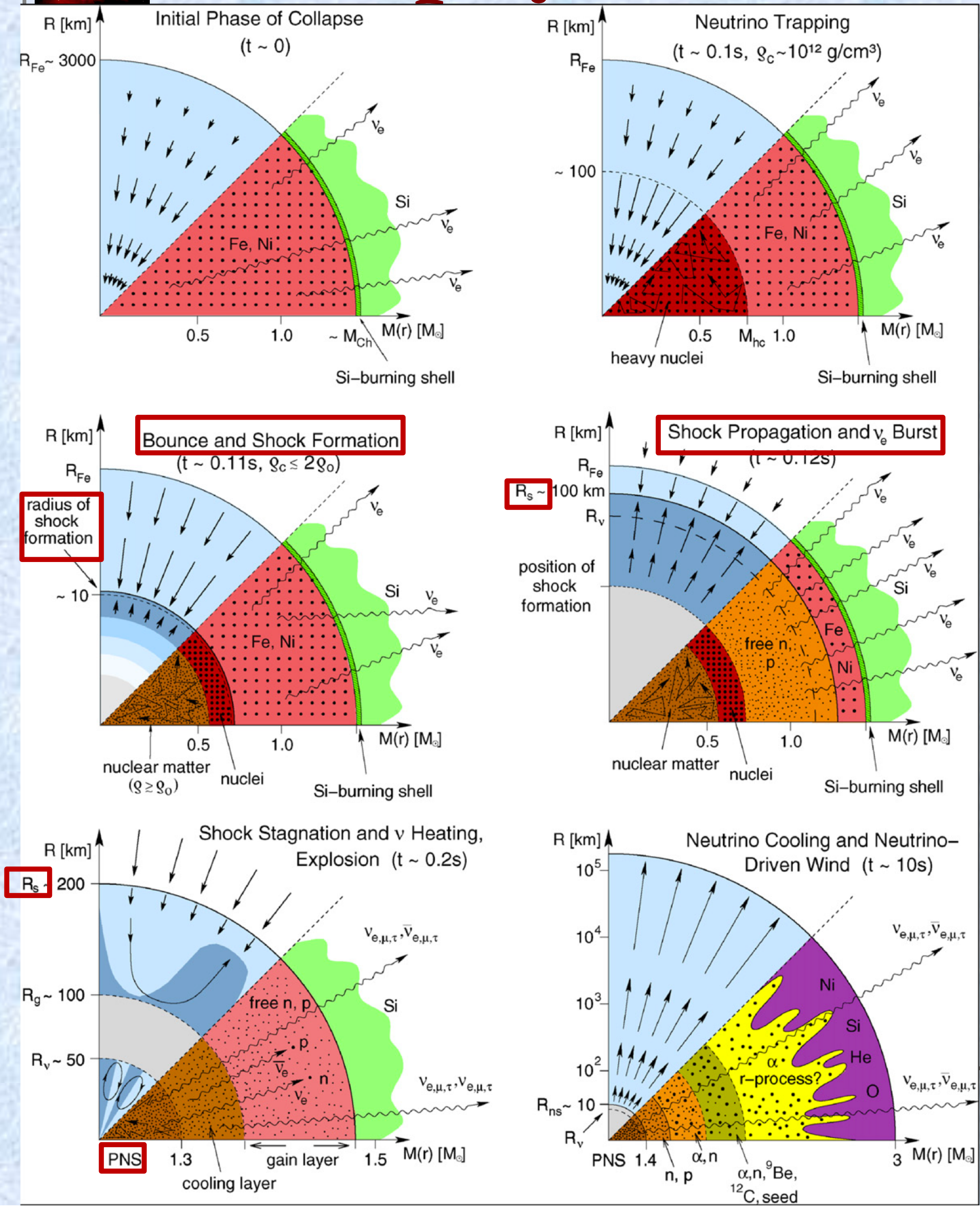
Anthea F. Fantina

GMR workshop
25 – 26 November 2020

Outline

- Introduction
  - Astrophysical context: core-collapse supernovae (CCSN)
  - Equation of state (EoS) in CCSN
- Role of the EoS
  - Role of nuclear incompressibility ($K \rightarrow K_{sat}$ or K_{inf})
- Conclusions & open questions

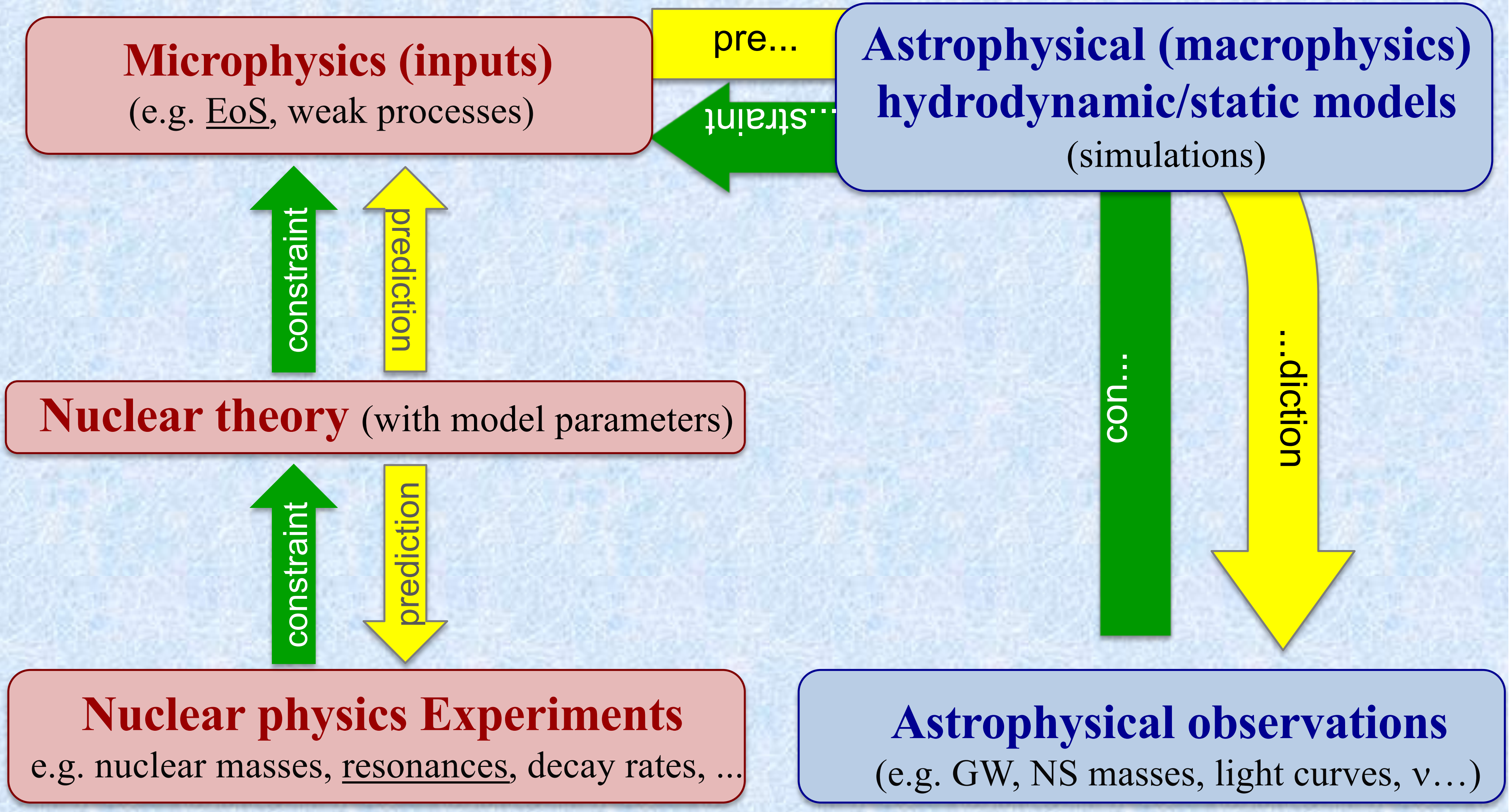
Astrophysical context : CCSN



1. **Infall epoch**
   → core collapse
2. **Bounce and shock propagation**
   → bounce formation
   → shock radius
3. **Explosion**
   → time of explosion

Janka et al., Phys. Rep. 442, 38 (2007)

Micro to macro: jumping across scales



EoS in CCSN simulations

Most used EoS (historically) in CCSN :

- **Hillebrandt & Wolff 1984** : NSE + SNA at higher density
  Skyrme (Ska) interaction for nucleons. $\boldsymbol{K_{sat}}$ **= 263 MeV**

- **Lattimer & Swesty (LS) 1991** : SNA, nuclei + α + free n,p + leptons
  CLDM and NR simplified Skyrme-like functional for nucleons, α Boltzmann gas
  $\boldsymbol{K_{sat}}$ **= 180, 220, 375 MeV**

- **Shen et al. 1998** : SNA, nuclei + α + free n,p + leptons
  TF approach, RMF (TM1) for nucleons, α Boltzmann gas
  $\boldsymbol{K_{sat}}$ **= 281 MeV**

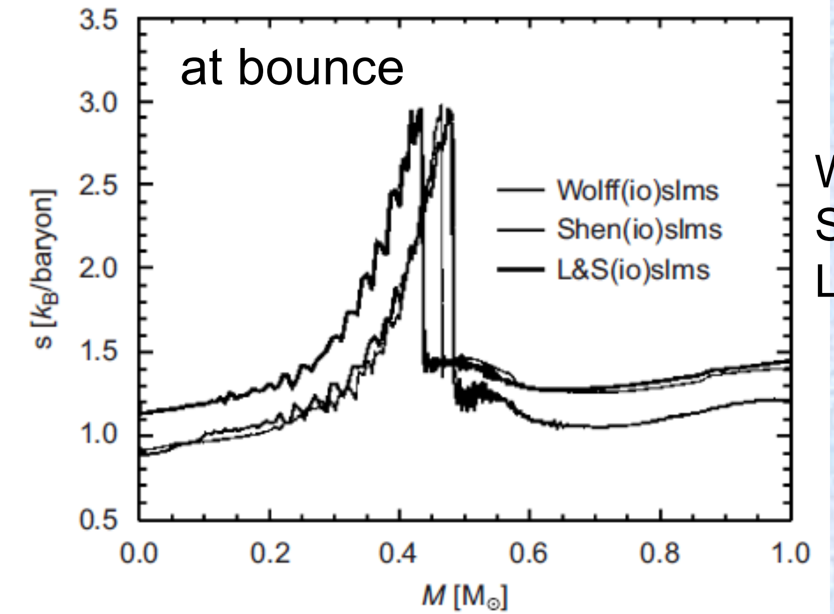
- **SHFo, SHFx 2013**: NSE, nuclei + α + free n,p + leptons
  RMF for nucleons
  $\boldsymbol{K_{sat}}$ ***= 245, 239 MeV*** (but also symmetry energy parameters differ…)

BUT :

- ❖ when comparing “incompressibility” → comparing different models !
- ❖ Mazurek’s law → complex interplay and feedback with hydro/transport

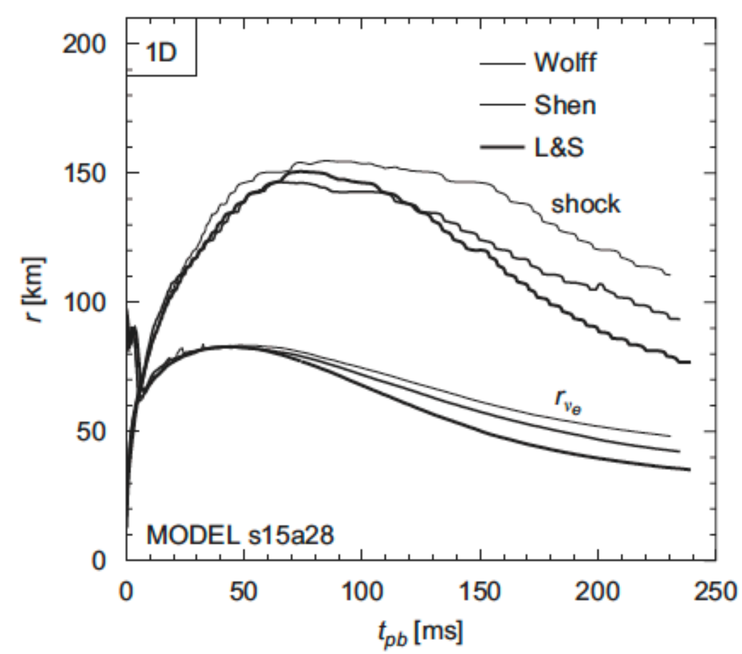
Hillebrandt & Wolff, in “Nucleosynthesis: challenges and new developments” (1985); Lattimer&Swesty, Nucl. Phys. A 535, 331 (1991); Shen et al., Nucl. Phys. A 637, 435 (1998); Steiner et al., ApJ 774, 17 (2013)
for a review: Oertel et al., Rev. Mod. Phys. 89, 015007 (2017), Burgio&Fantina, ASSL 457, 255 (Springer, 2018)

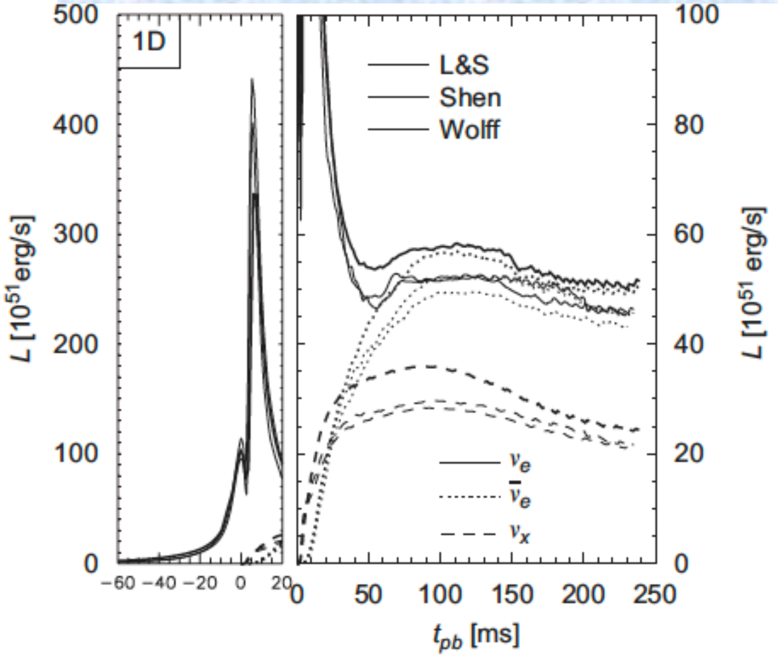
CCSN simulations: (post-)bounce



Wolff: K = 263 MeV
Shen: K = 281 MeV
LS: K = 180 MeV

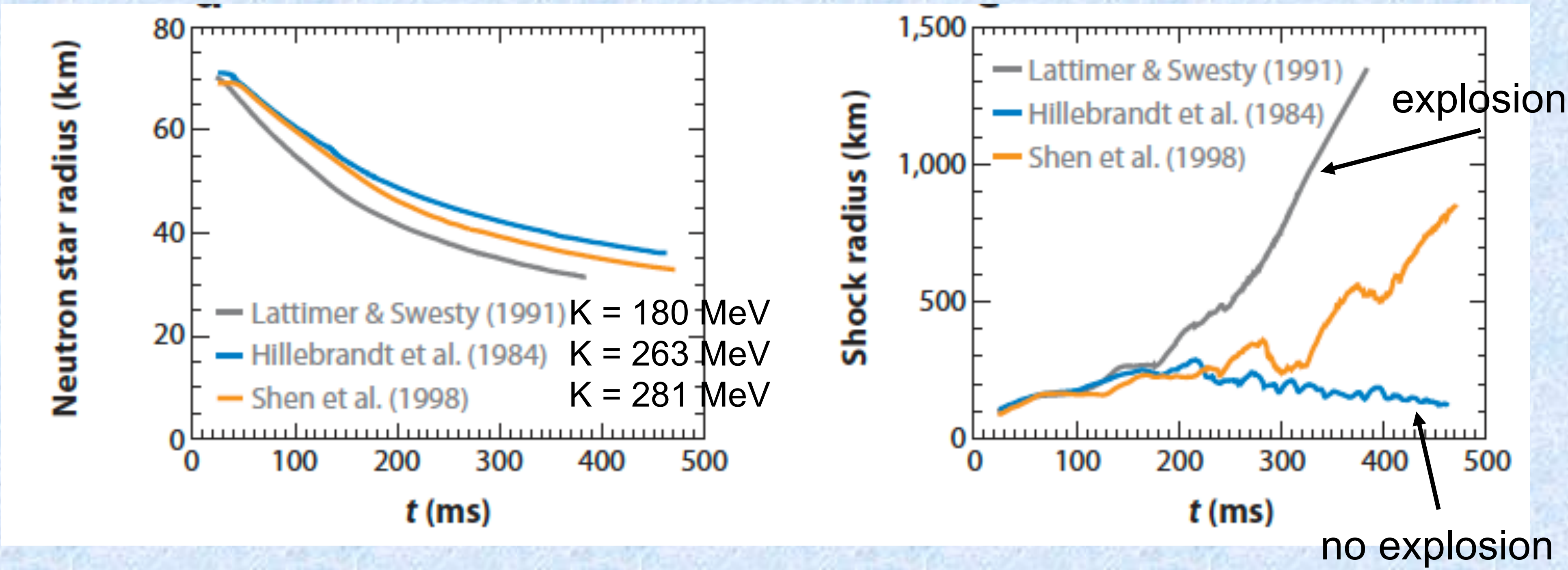
"softer" EoS → more compact PNS
→ higher ν luminosity





Janka et al., Phys. Rep. 442, 38 (2007) . 1D simulation, 15 M_{sun} progenitor, "ray-by-ray" ν treatment

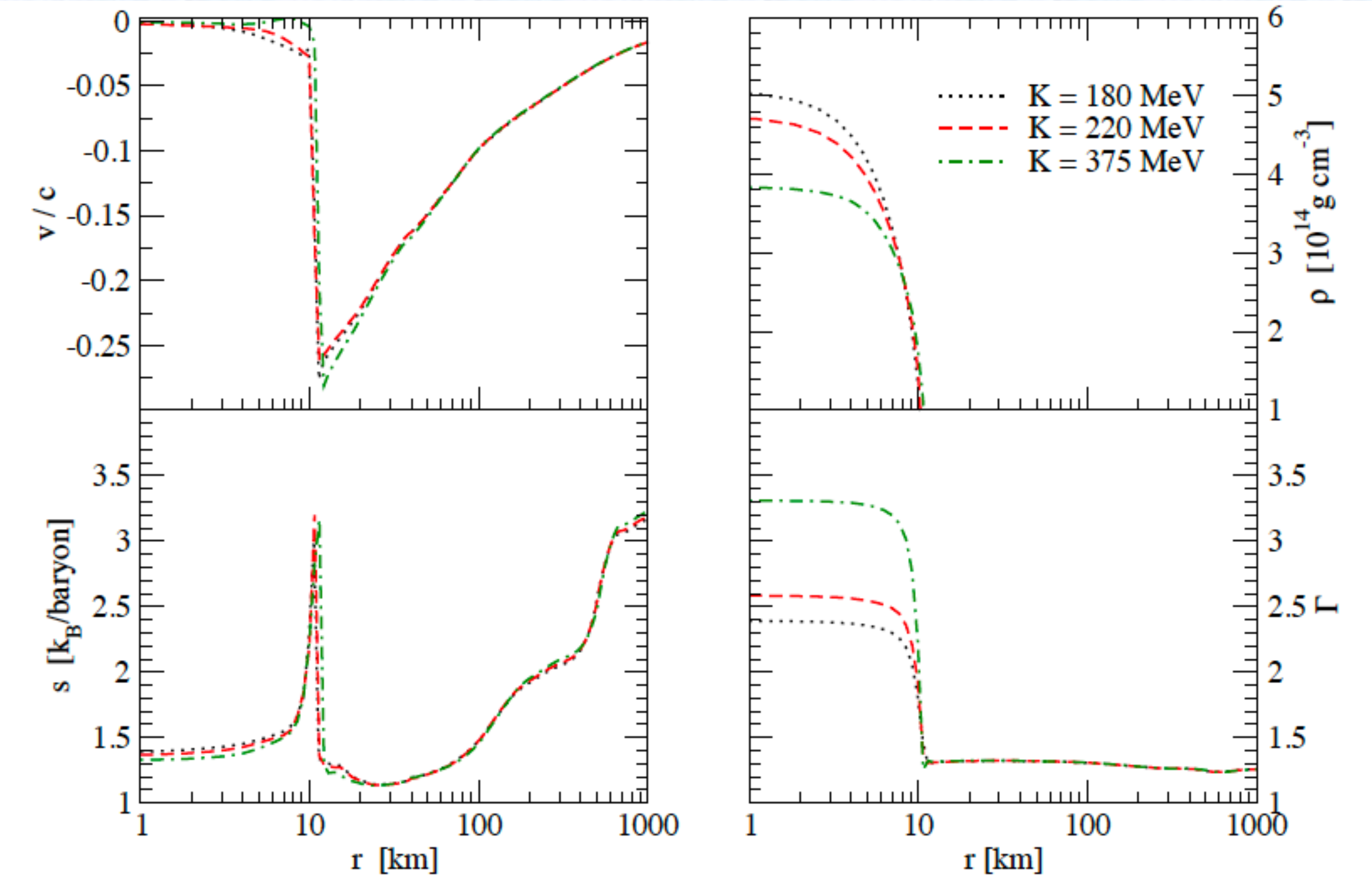
CCSN simulations: shock radius, PNS



Janka et al., Annu. Rev. Nucl. Part. Sci. 62, 407 (2012); see also Marek et al., A&A 496, 475 (2009)
2D simulations, Newtonian, 11.2 M_{sun} progenitor

“softer” EoS → more compact PNS
→ larger shock radius → explosion (?)

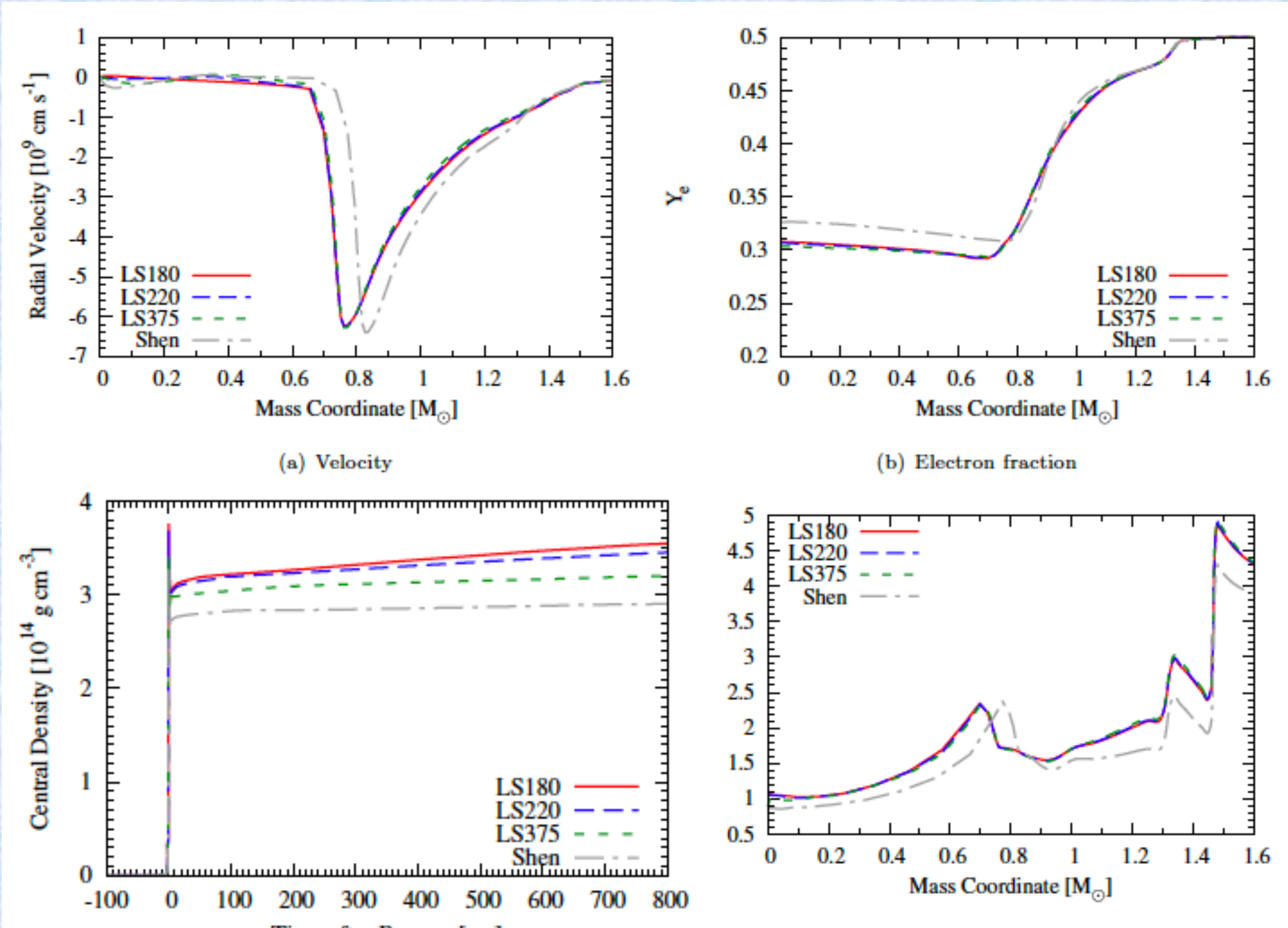
CCSN simulations: *K* and bounce



A. F. Fantina, PhD thesis (2010). 1D GR, Lattimer&Swesty EoS, neutrino leakage-type scheme. 15 M_{sun} progenitor

not great impact on dynamics at bounce, impact on matter properties

CCSN simulations: *K* and bounce



(a) Velocity

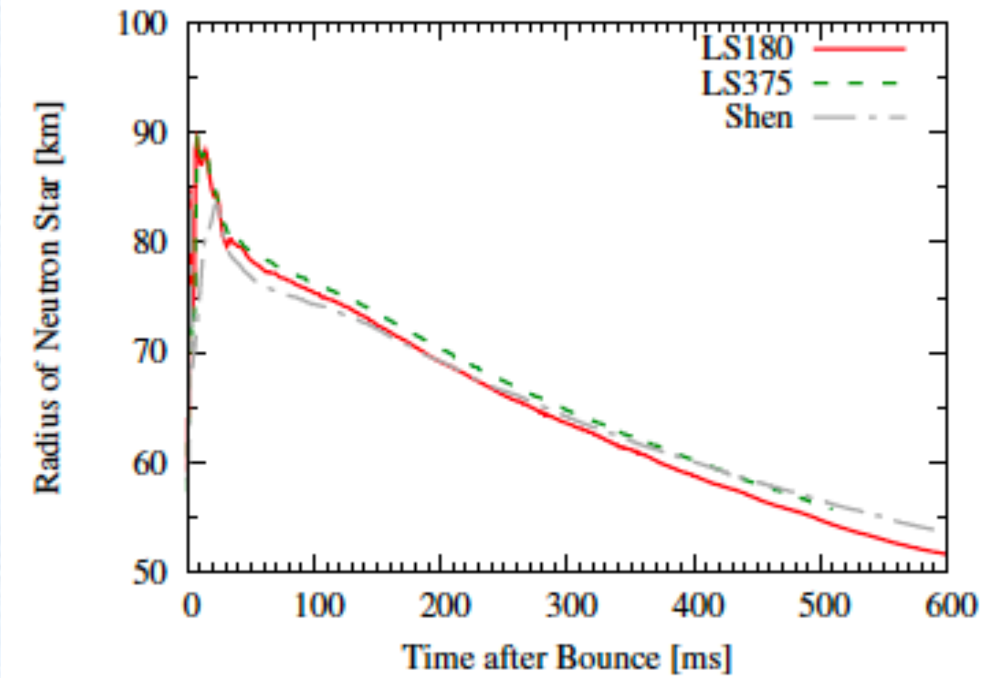
(b) Electron fraction

(d) Entropy per baryon

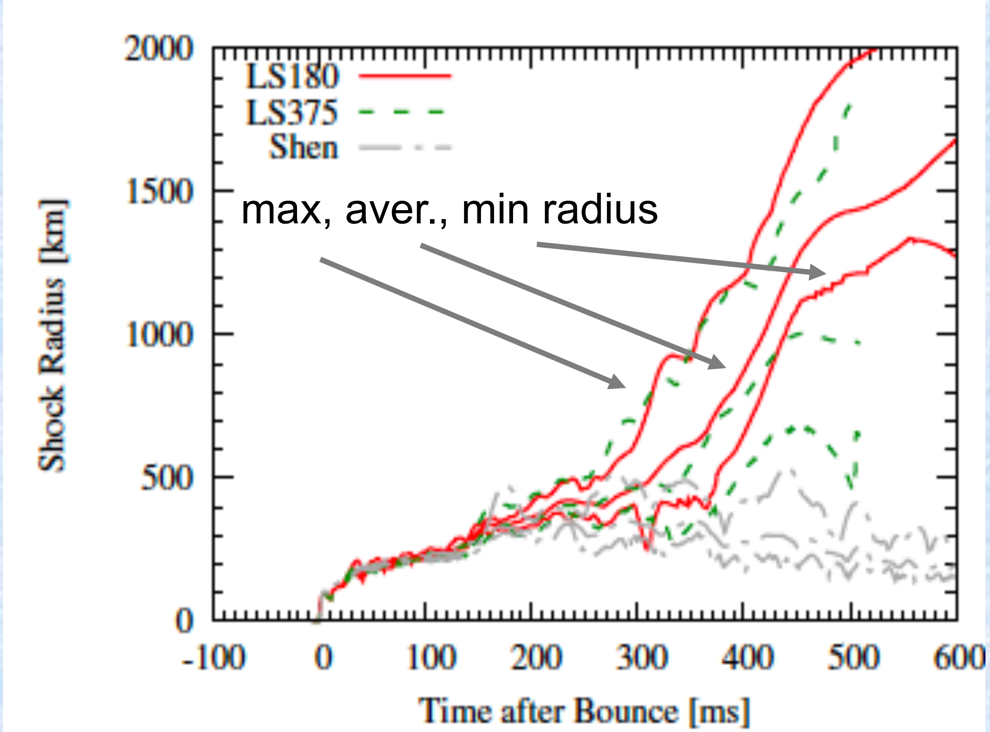
Suwa et al., ApJ 764, 99 (2013). 1D simulations, Newtonian, Lattimer&Swesty and Shen EoS, 15 M_{sun} progenitor, neutrinos treated in diffusion approximation scheme

➡ not great impact on dynamics at bounce within the same model

CCSN simulations: shock radius, PNS



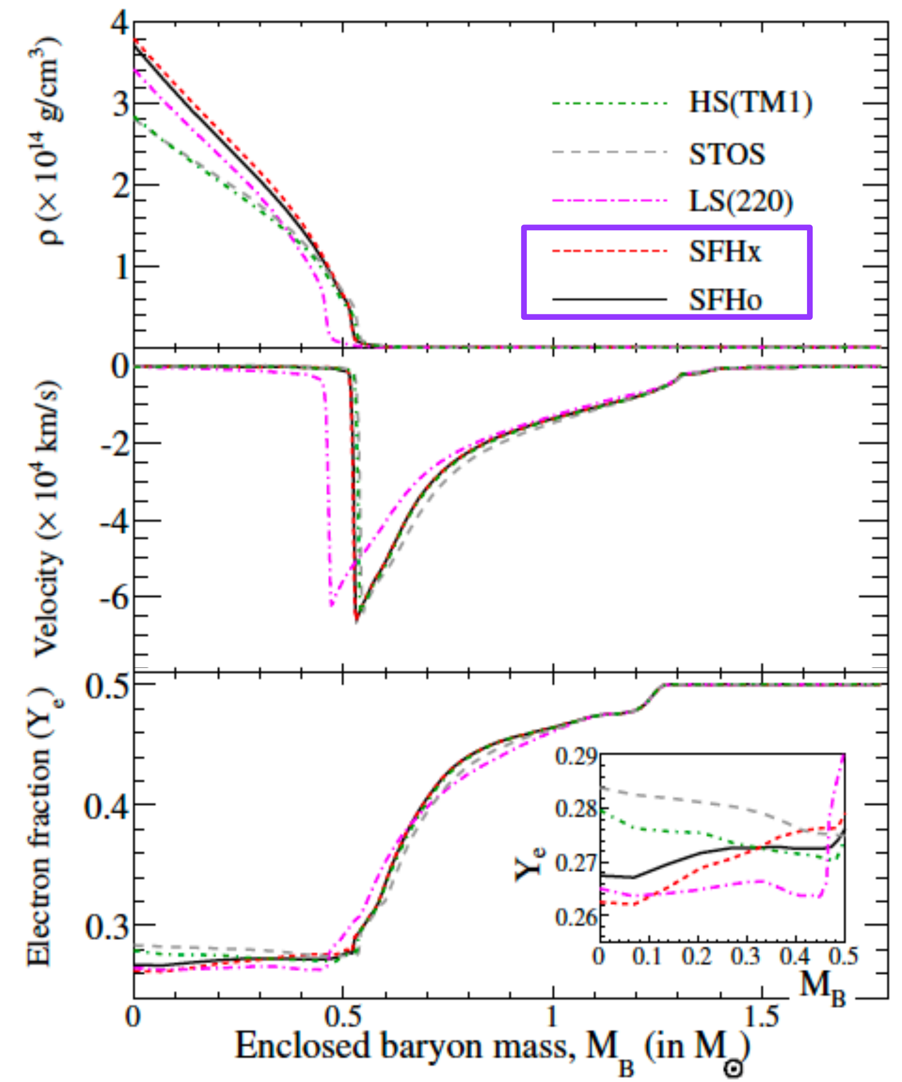
(d) Protoneutron star radii, determined at $\rho = 10^{11}$ g cm^{-3}.

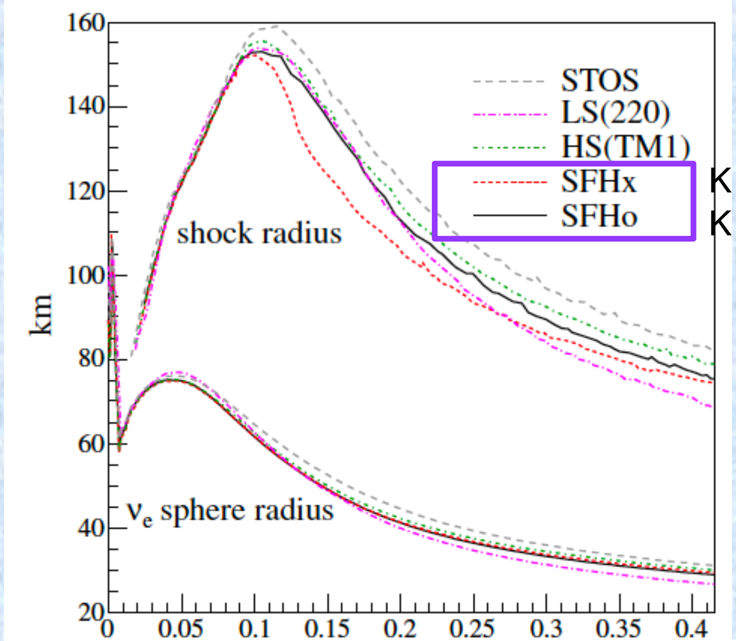


"softer" EoS :
→ larger shock radius → explosion (?)
→ more compact PNS
→ <u>but</u> : larger difference due to different models !

Suwa et al., ApJ 764, 99 (2013). 2D simulations, Newtonian,Lattimer&Swesty and Shen EoS, 15 M_{sun} progenitor, neutrinos treated in diffusion approximation scheme

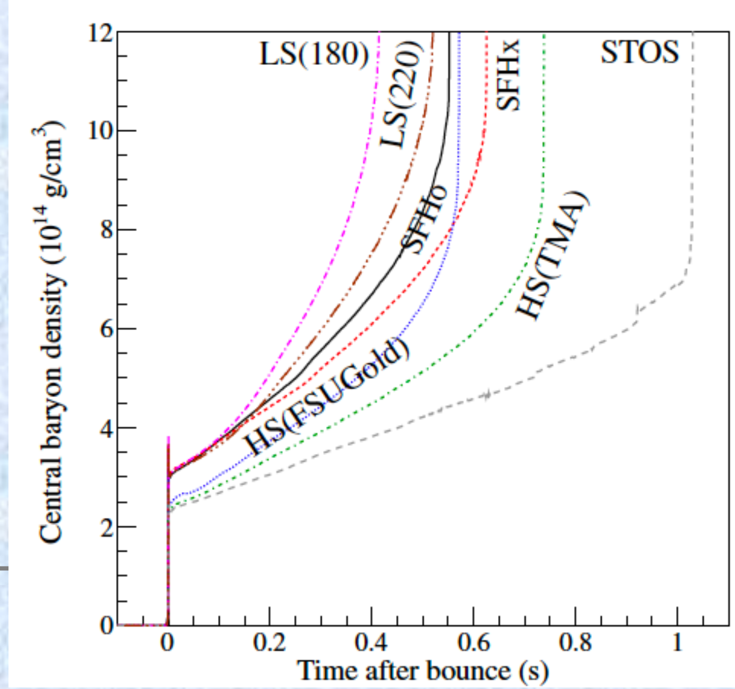
CCSN simulations: (post-)bounce





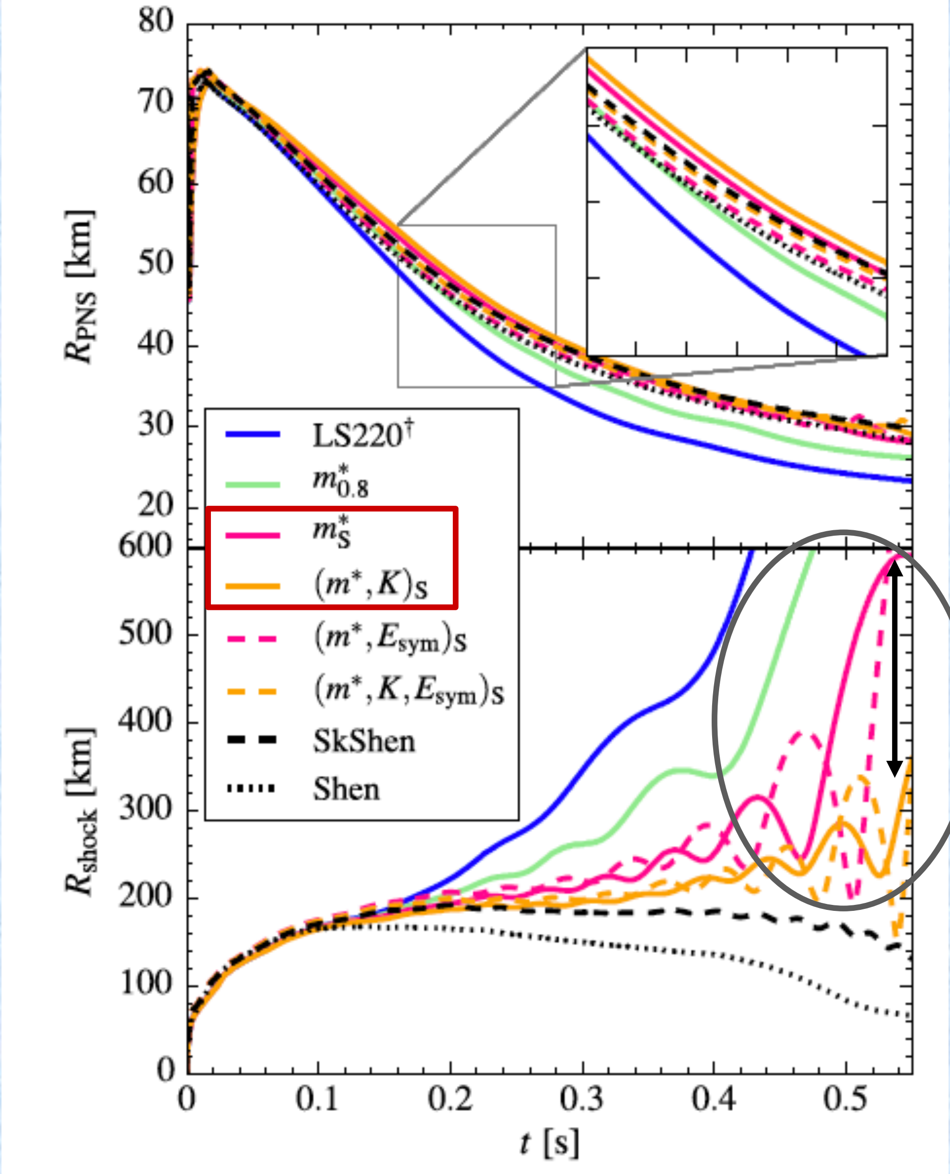
K = 239 MeV

K = 245 MeV

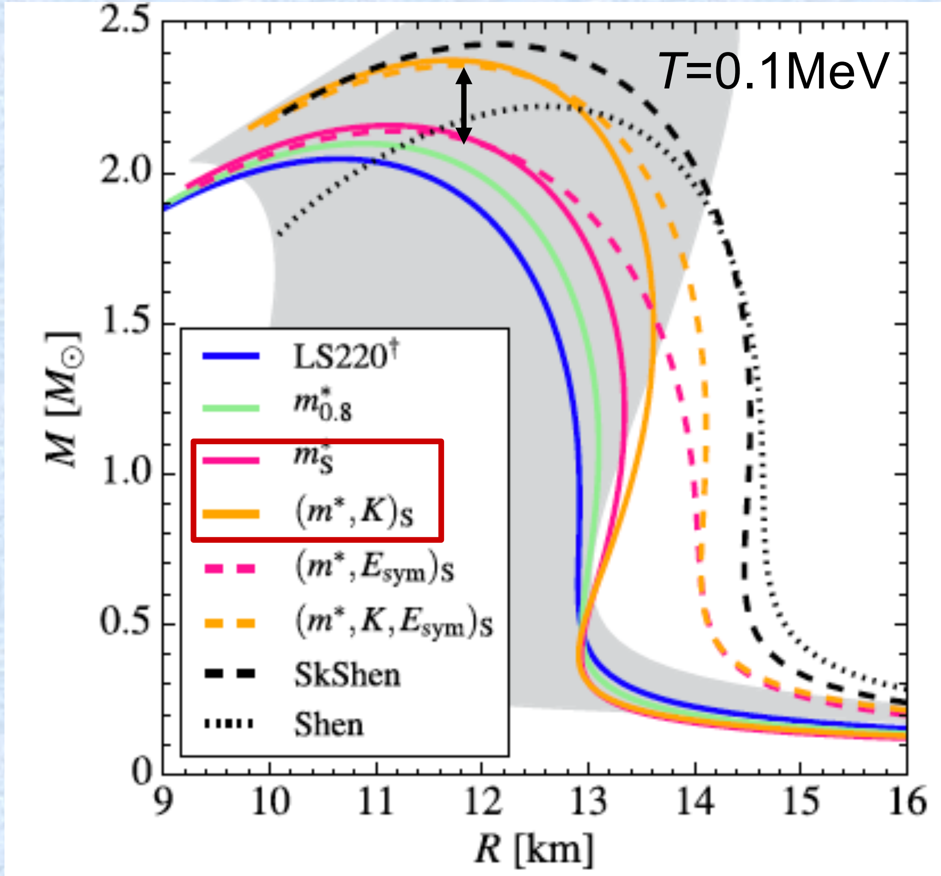


Steiner et al., ApJ 774, 17 (2013): 1D simulation GR, Boltzmann ν transport, 11.2 M_{sun} and 40 M_{sun} progenitors

CCSN simulations: shock radius, PNS

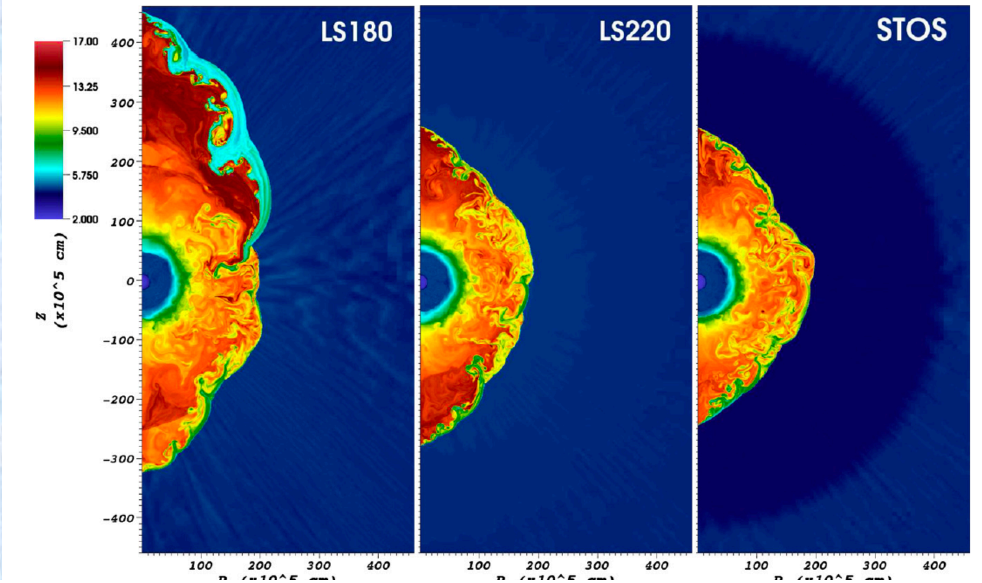


compare m^*_S to $(m^*,K)_S$
→ K changed from 220 to 281 MeV

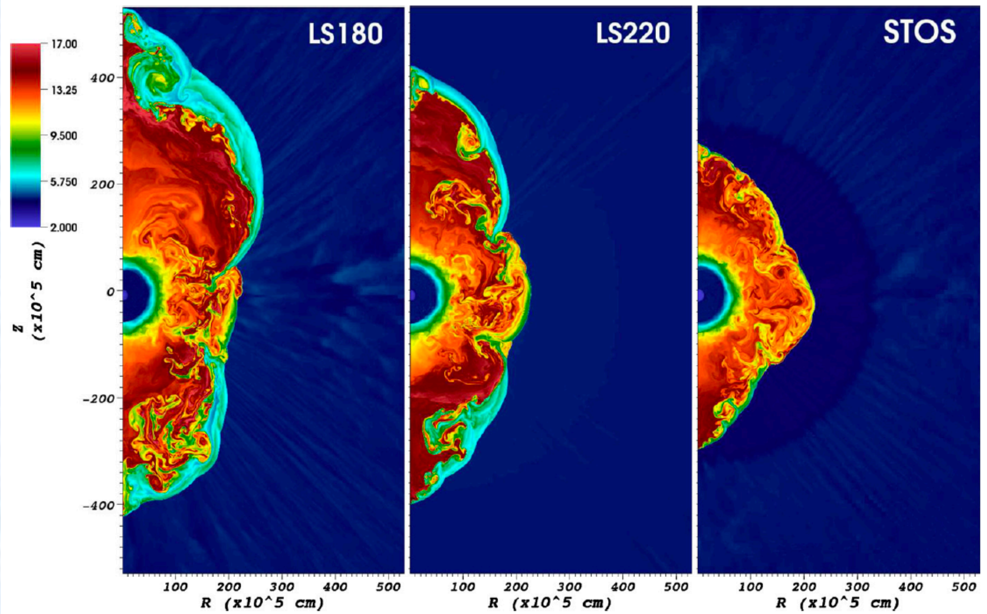


Yasin et al., PRL 124, 097701 (2020). 1D simulations, multi-species neutrino physics
15 M_{sun} progenitor

CCSN simulations: instabilities



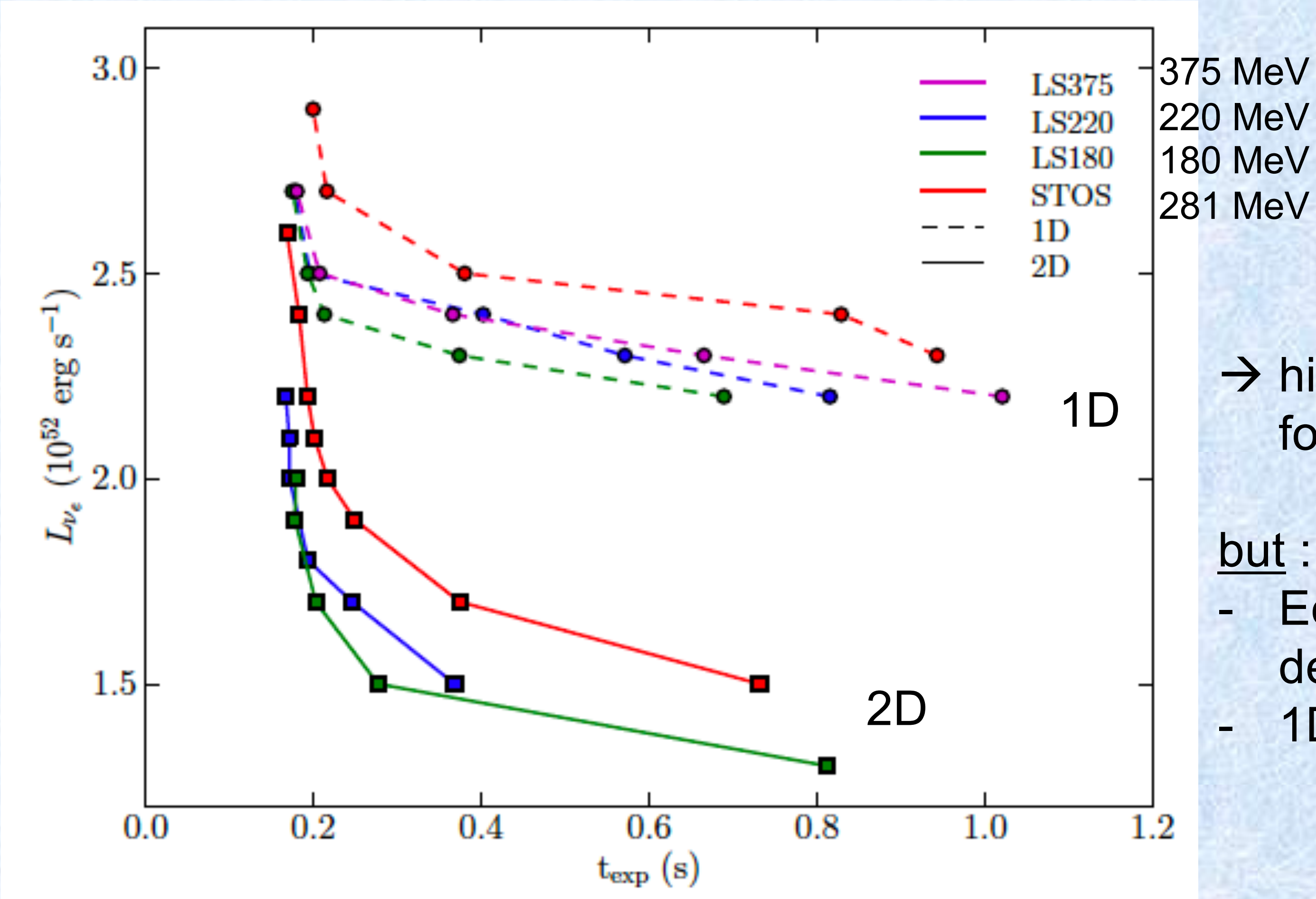
Entropy per baryon (colours)
300 ms after bounce
→ larger instabilities for lower K_{sat}



600 ms after bounce
→ Shock expansion for LS,
stationary for Shen et al. EoS

Couch, ApJ 765, 29 (2013). 2D simulations, simplified neutrino physics (fixed L_{ν})
15 M_{sun} progenitor

CCSN simulations: explosion time



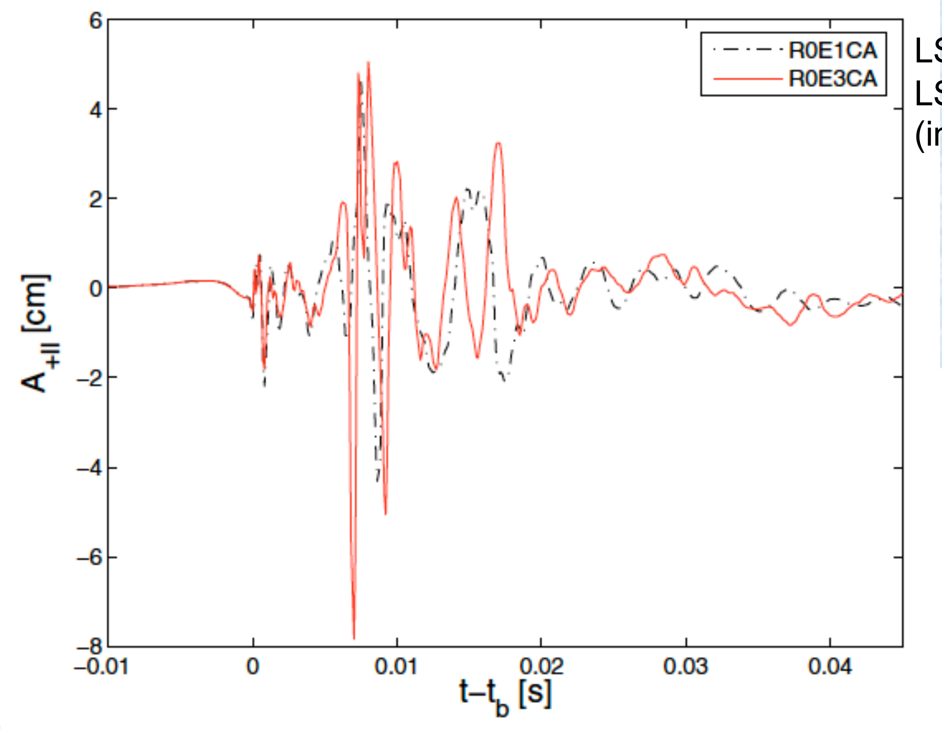
→ higher K_{sat}, later explosion for given L_ν if same model

but :

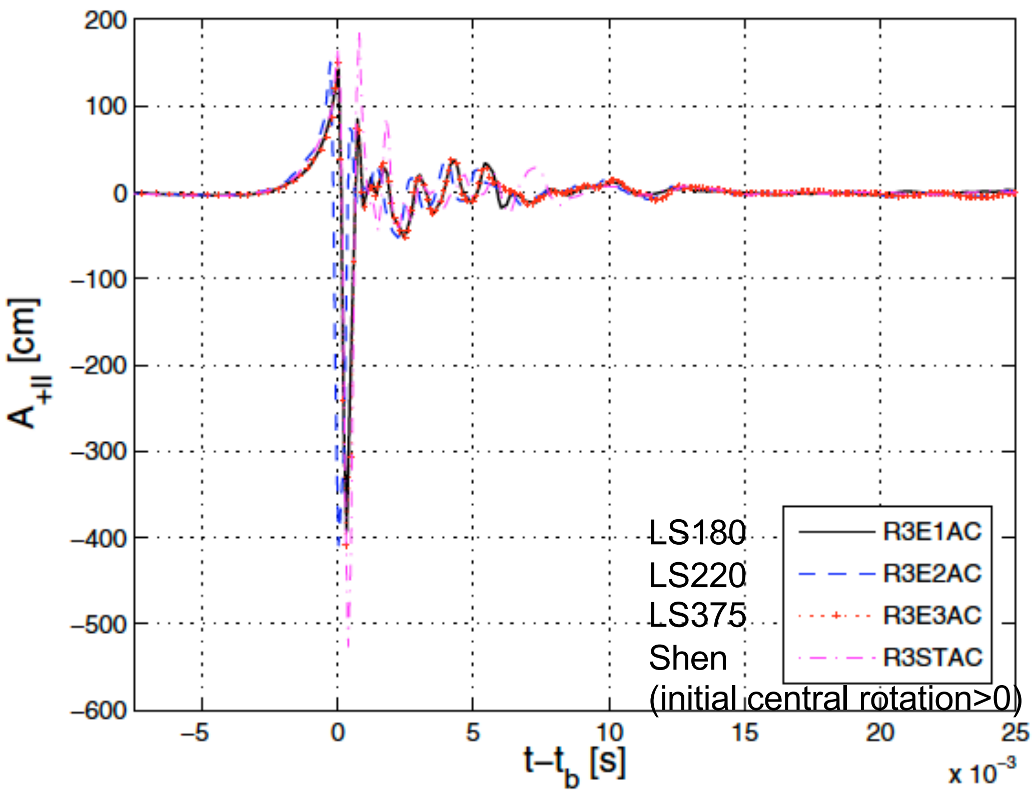
- EoS "stiffness" not only determined by K_{sat} !
- 1D vs 2D !

Couch, ApJ 765, 29 (2013). 1D and 2D simulations, simplified neutrino physics (fixed L_ν)
15 M_{sun} progenitor

CCSN simulations: GW signal



→ impact on GW signal (amplitude in equatorial plane) : hard to discriminate



Scheidegger et al., A&A 514, A51 (2010) 3D GR simulations with B field, Boltzmann transport, 15 M_{sun} progenitor

Conclusions and open questions

❖ Roughly speaking, "*softer*" EoS :

→ more compact and faster contracting PNS

→ higher ν luminosities

→ larger shock radii → more favourable to explosion

<u>but</u> :

❖Difficult to correlate single nuclear parameters in CC dynamics !

- EoS models differ from several aspects (nuclear theory, different parameters, …)
- spurious correlations among parameters

❖ Hydro vs micro effects

- effect of input parameters of simulation (progenitor, neutrino treatment,…)
- dimensionality of simulation

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❖ Hydro vs micro effects

- effect of input parameters of simulation (progenitor, neutrino treatment,…)
- dimensionality of simulation

✓ <u>NO</u> strong conclusive statements can be drawn

✓ K_{sat} not the only key parameter

✓ need of systematic studies / simulations


Thank you