重力崩壊型超新星の親星構造依存性

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  - Current status of Core-collapse supernova (CCSN) study
  - Detailed simulations for CCSN cores
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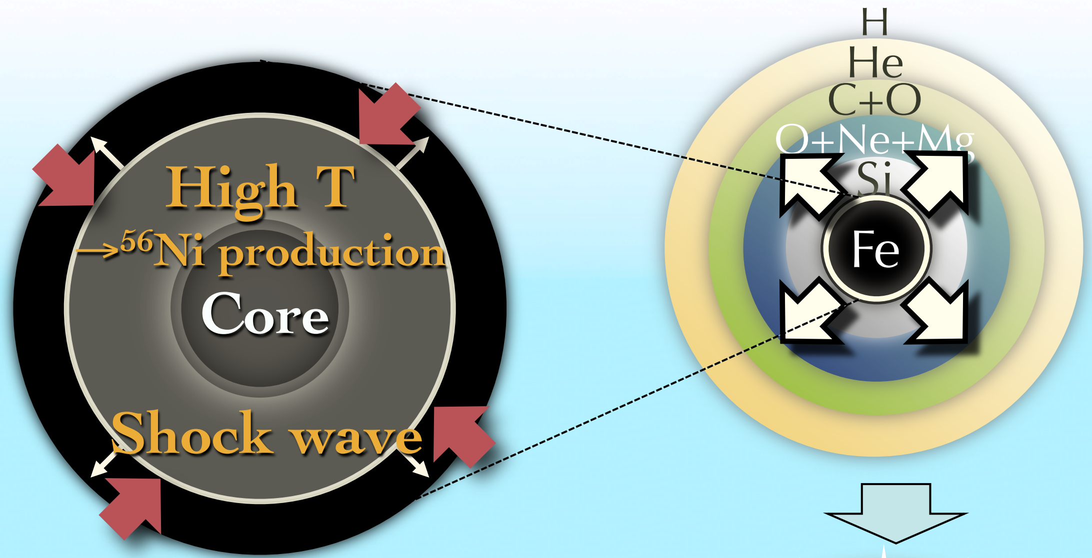
  - 2D self-consistent simulations of ~400 CCSNe
  - CCSN properties characterized by “compactness”
- Neutrino and GW signals from CCSNe
  - What can we learn from future detections?

Core-collapse Supernova mechanism

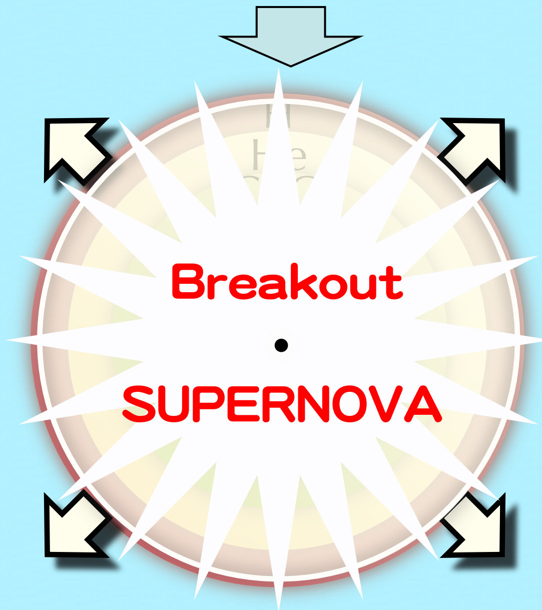
Collapse

Photo-disintegration and electron capture reactions remove pressure support.



Bounce

A shock wave is generated.
→ propagates outward, making radial velocity of accreting matter positive.



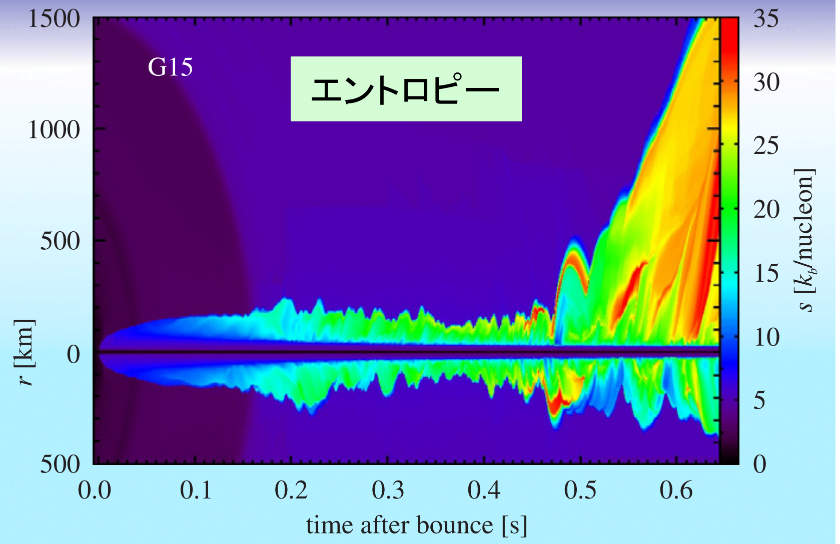
Sophisticated multi-D CCSN simulation (1)

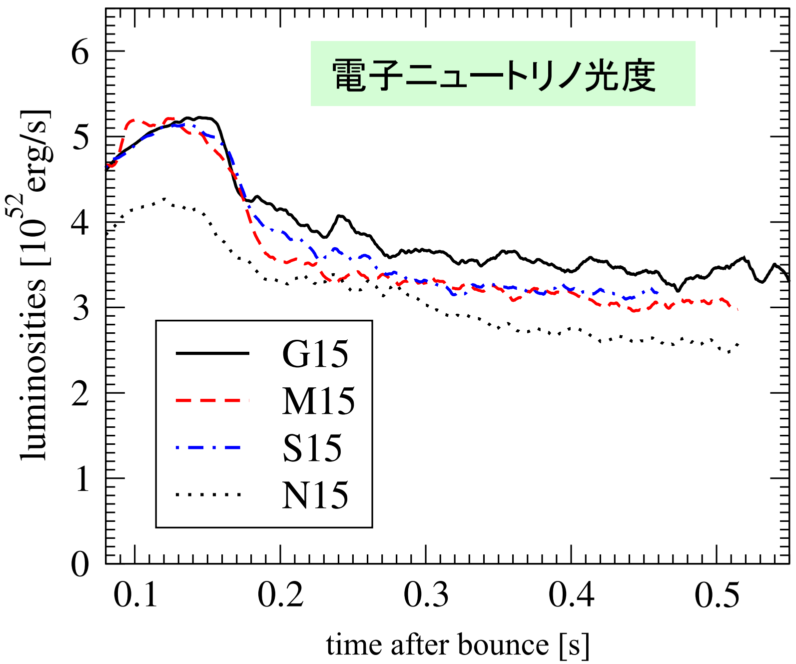
Mueller+ '12,'13,'14

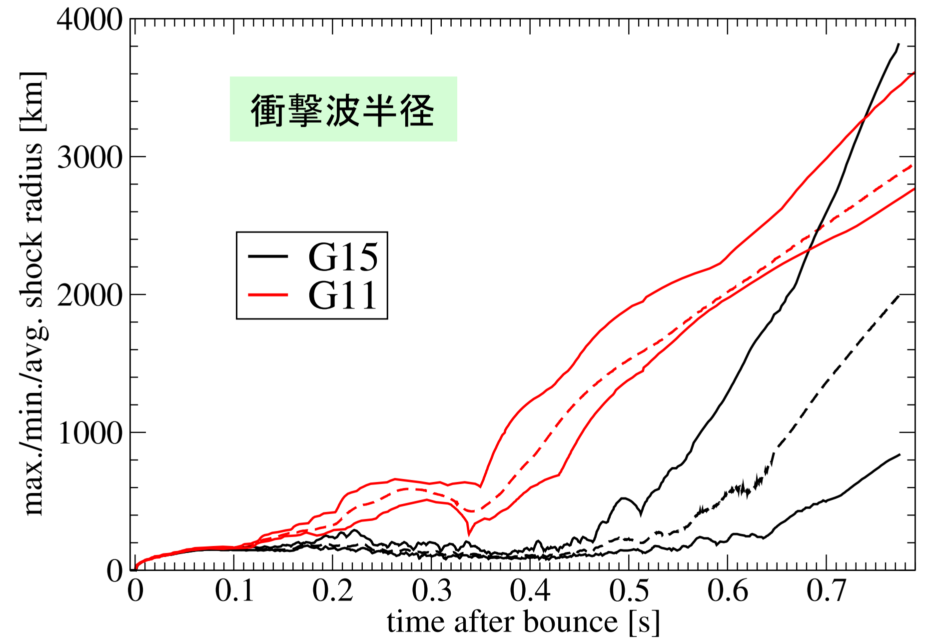
COCONUT-VERTEX

空間次元　: 2D (400*64)
　r<10,000km
N / GR　: GR
ニュートリノ : RbR+, VE
EOS　: LS91 (K=180,220MeV)
親星　: 8.1-27 Mo (WW95,WHW02,etc.)

GR効果によってニュートリノ光度・平均E ↑







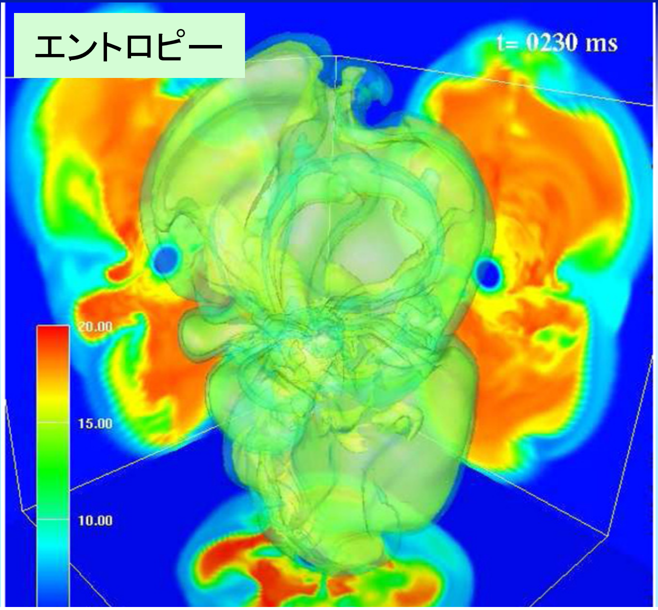
Sophisticated multi-D CCSN simulation (2)

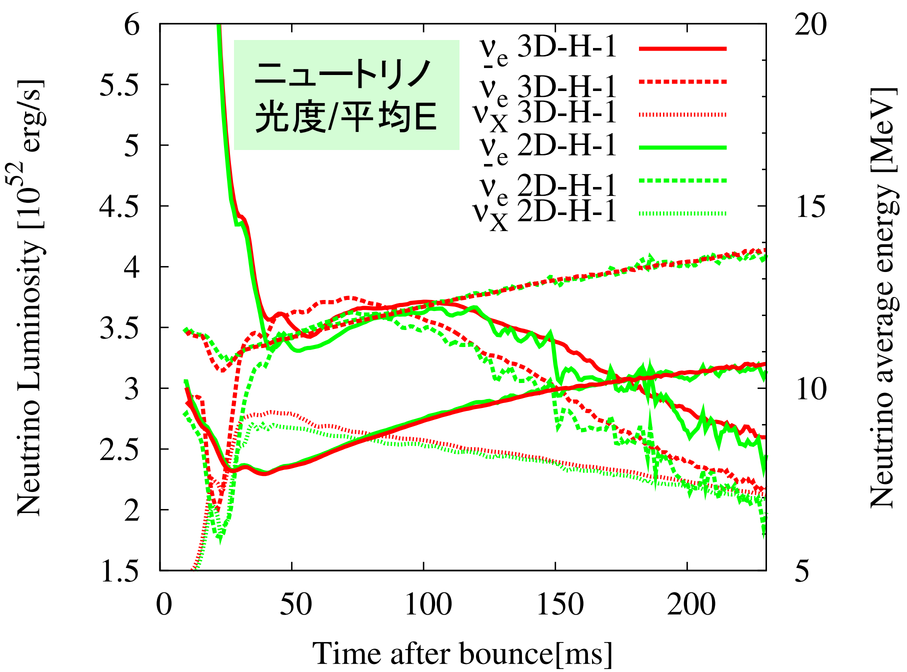
Takiwaki+ ’12,’14

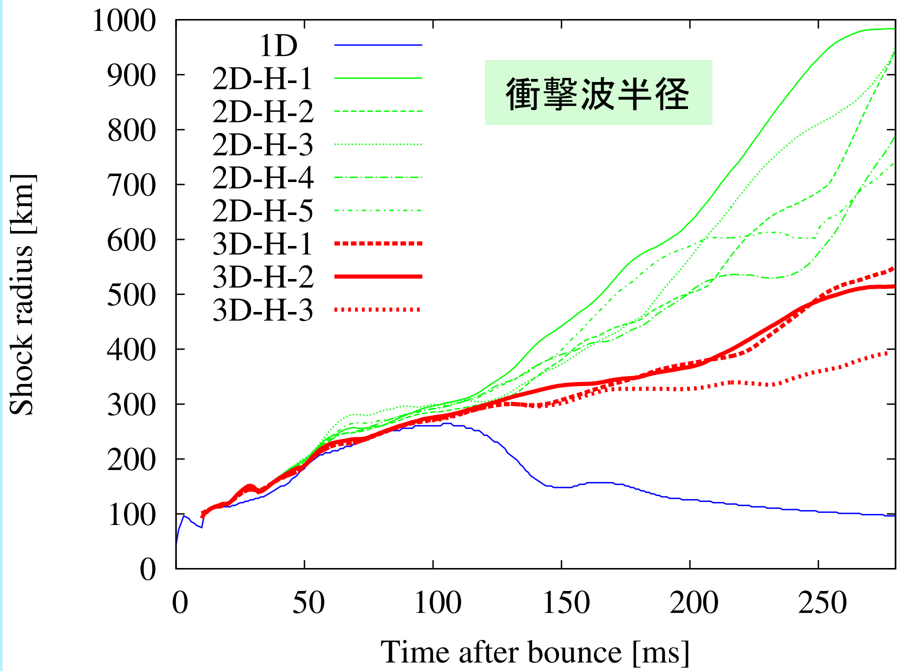
3DnSNE（仮称）

空間次元　：2D,3D (320*64*128)
　　　　　　r<5,000km
N / GR　　：Newtonian
ニュートリノ：RbR, IDSA
EOS　　　：LS91 (K=180MeV)
親星　　　：11.2 Mo (WHW02)

空間多次元性による衝撃波発達の違い（2D>3D>1D）







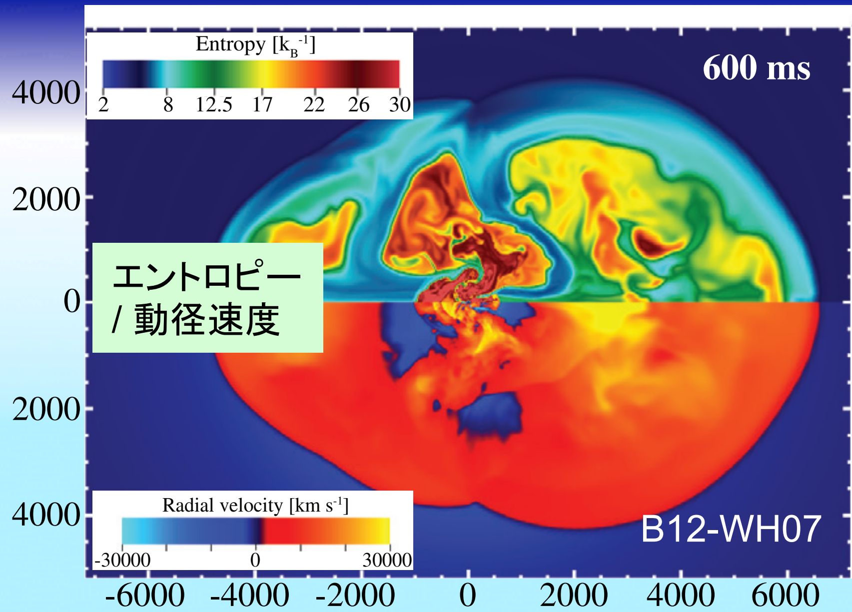
Sophisticated multi-D CCSN simulation (3)

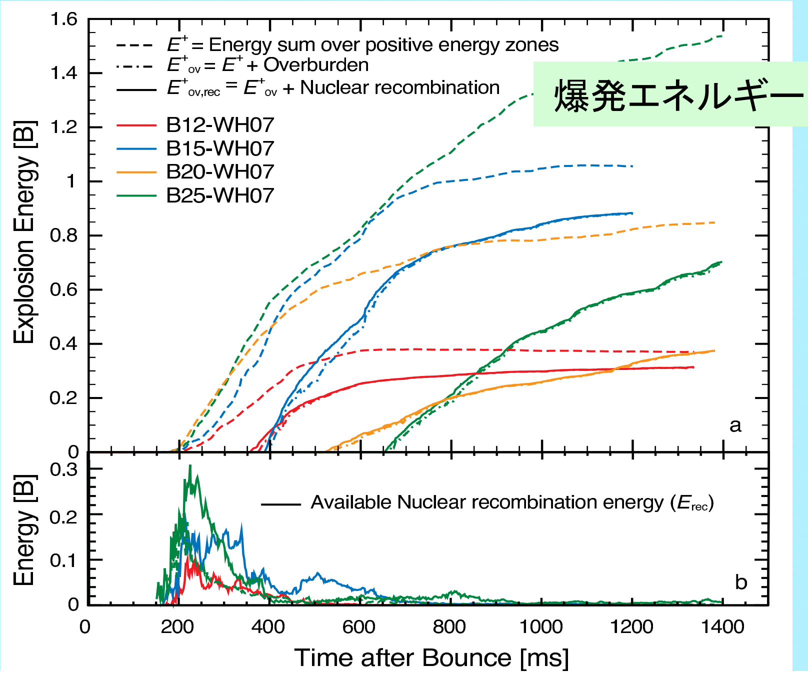
Bruenn+ '13,14

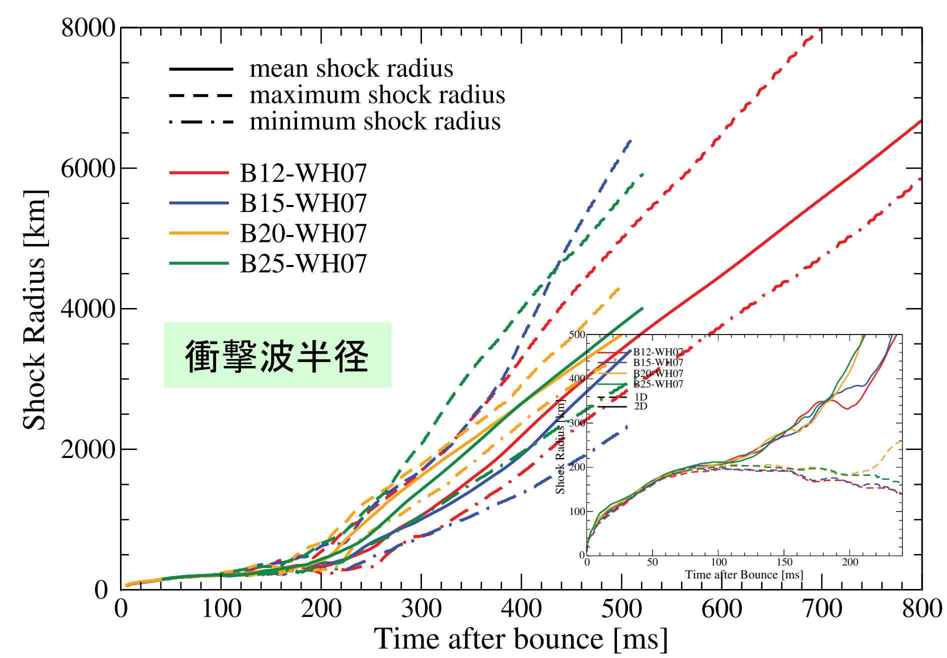
CHIMERA

空間次元　　: 2D
N / GR　　　: GR correction
ニュートリノ : RbR+, MGFLD
EOS　　　　: LS91 (K=220MeV), Cooperstein (1985), 14-alpha
親星　　　　: 12,15,20,25 Mo (WH07)

比較的長時間計算→爆発エネルギー収束？







Systematic CCSN study based on 1D simulation (1)

O’Connor & Ott ’11,’13

1DGR

空間次元　: 1D (1050 grids)
r<~10,000km, Δr=80m

N / GR　: GR

(2011)

ニュートリノ: Leakage + LB×f_{heat}

EOS　: LS180,220,375, HShen

親星　: WW95, WHW02, LC06, WH07
(M=~10-120Mo, Z=0-Zo)

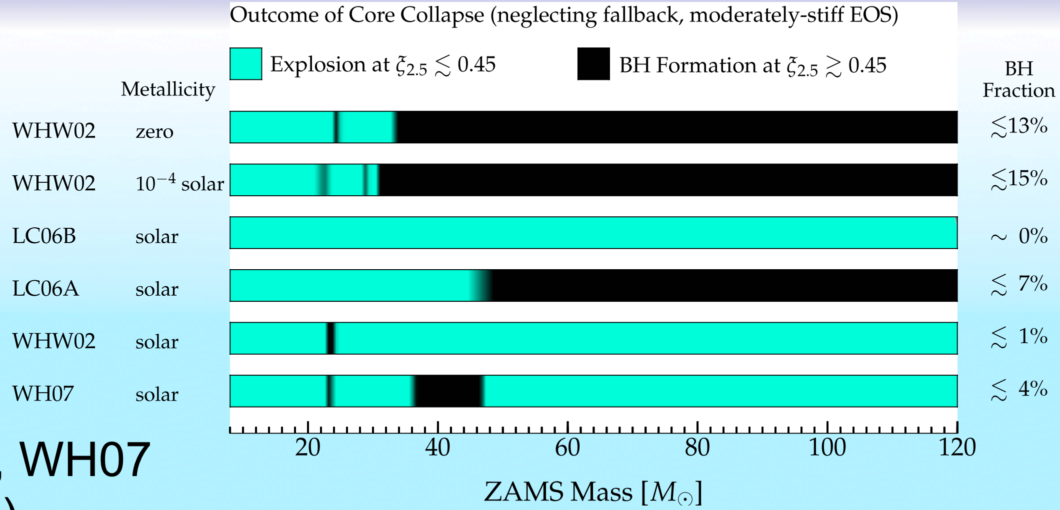
様々な質量・金属量・回転・EOSを網羅

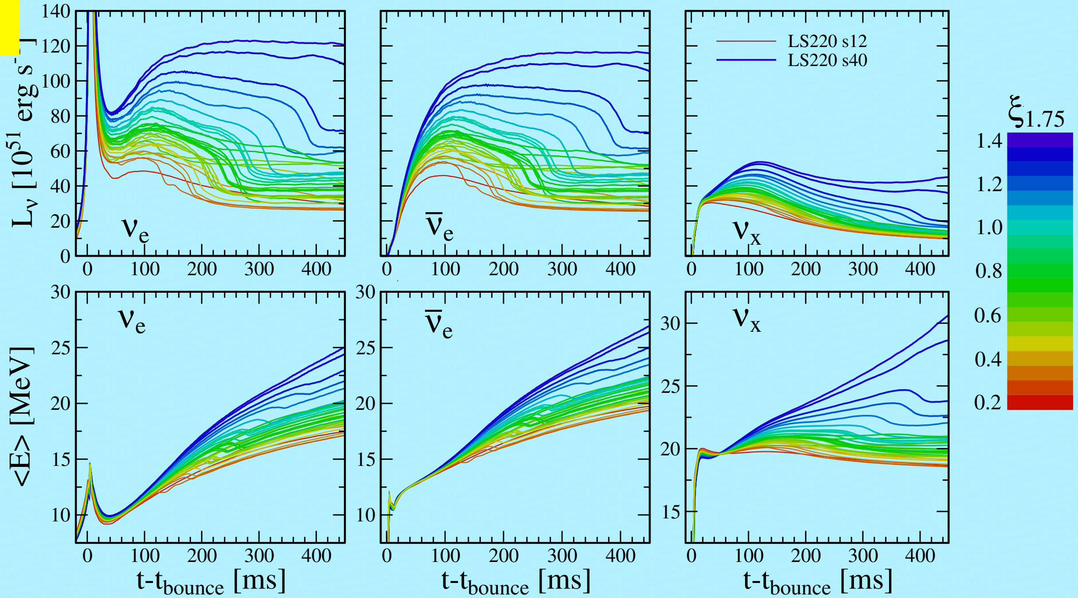
(2013)

ニュートリノ: M1

EOS　: LS220, HShen

親星　: WH07
(M=12-120Mo, Z=Zo)





ニュートリノ光度・エネルギーは *compactness*と相関

Systematic CCSN study
based on 1D simulation (2)

Ugliano+ ’12

PROMETHEUS-VERTEX

空間次元 : 1D
r<150,000km
N / GR : GR correction
ニュートリノ : gray
EOS : Janka & Mueller ’96,
Timmes & Swesty’00
親星 : 10.0-40 Mo (WHW02)

中心は解かずに簡単なモデル化:

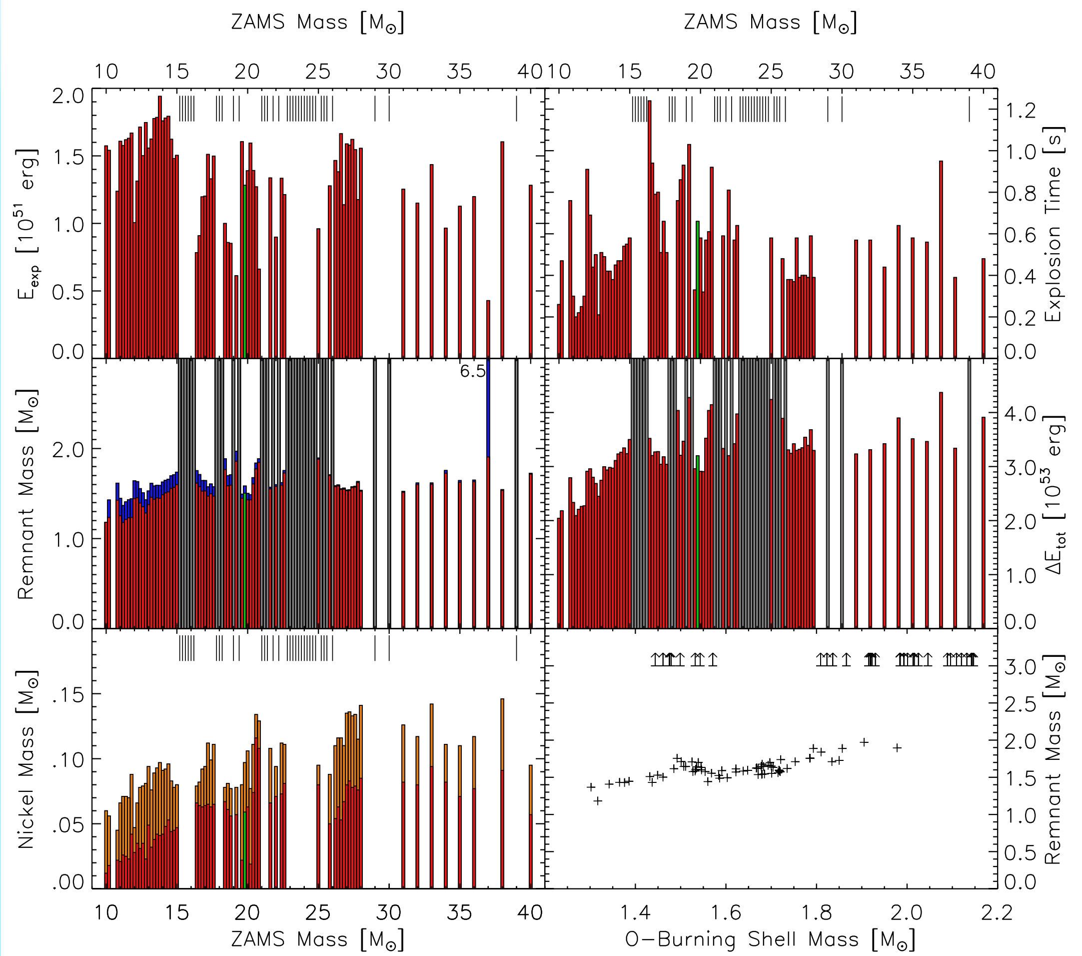
内部境界(PNS)半径

$$R_c(t) = R_{c,f} + (R_{c,i} - R_{c,f})/(1+t)^n$$

ニュートリノ光度

$$L_{\nu,c} = \frac{3\Gamma-4}{3(\Gamma-1)}(E_g+S)\frac{\dot{R}_c}{R_c} - \frac{\zeta}{3(\Gamma-1)}\frac{\delta E_{acc}}{\delta t}$$

太陽金属量の親星101モデルの1D爆発計算.
中心PNSを質点に置き換えることでfall-back
まで追いNS/BH質量・爆発エネルギー決定.



Two extremes

Mueller+'12,13,14; Takiwaki+'12,14; Bruenn+'13,14

- 空間2D/3D, ニュートリノ輸送解く.
- 空間スケール < ~ 10,000 km, 時間スケール < ~ 1sec.
- 親星モデル 数個

→ 衝撃波は復活するのか？中心からのニュートリノ/重力波信号？

Nakamura, Takiwaki, Kuroda, & Kotake

- 空間2D, ニュートリノ輸送解く.
- 空間スケール < 5,000 km, 時間スケール < 1.5 sec.
- 親星モデル ~400個

→ 超新星を特徴付ける物理量（E_{exp}, L_ν, E_ν, M_{PNS}, M_{Ni}, ..）vs. 親星

O'Connor & Ott '11,13; Ugliano+'12

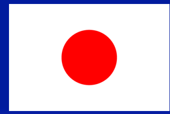
- 空間1D, 爆発するようにニュートリノ光度（加熱率）を手で操作.
- 空間スケール > 10,000 km, 時間スケール > 1 sec.
- 親星モデル > 100個

→ (爆発前提で) 親星依存性は？元素合成は？

(Piston / Thermal bomb model)

Systematic CCSN study
based on 2D self-consistent simulation!

Nakamura+’15



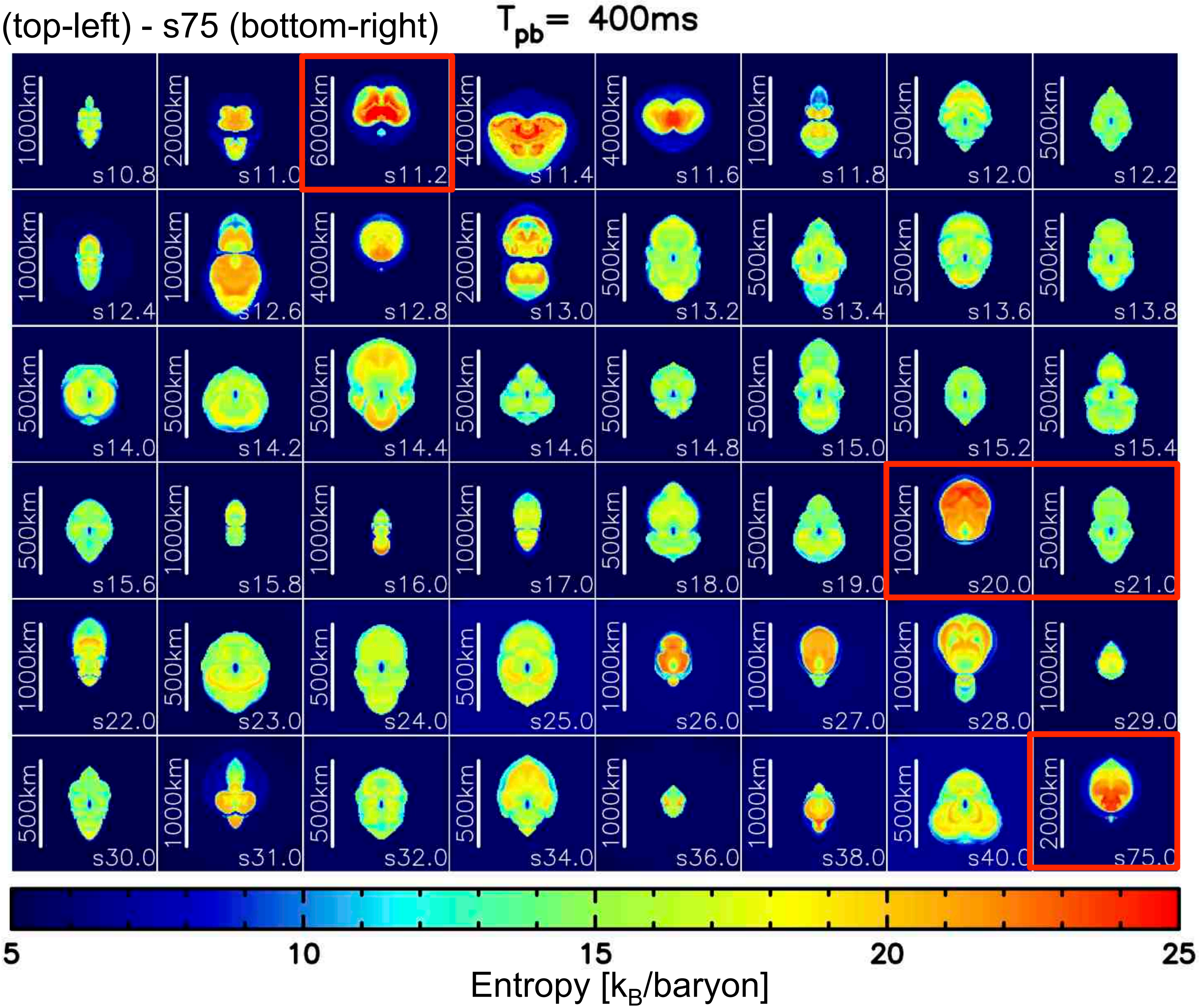
重力崩壊型超新星を起こす親星の**幅広い質量域を網羅**する大規模数値計算を実行し、超新星を特徴付ける**様々な物理量の系統的研究**を行う.

- 空間2次元→対流, SASI
- ニュートリノ輸送を解く→パラメータなしの self-consistent 計算

(cf. O’Connor & Ott’11,’13; Ugliano+’12)

- 輻射流体コード
  - Takiwaki+’12
  - 384(r)*128(θ) zones covering R=0-5000 km, θ=0-π
  - **IDSA** spectral transport (Liebendoerfer+’09) with 20 energy bins covering 3-300 MeV
- 状態方程式
  - Lattimer-Swesty (‘91) EoS (K=220 MeV)
- 親星
  - **101+247+30 = 378個** (Woosley, Heger, & Weaver ‘02)
  - M=10.8 ~ 75.0 Mo
  - Z = 0, 10^{-4}, 1 × Zo (s11.2 ← Z=Zo, M=11.2Mo)
- 計算には国立天文台の Cray XC30 を使用

48 solar-Z models
s11.2 (top-left) - s75 (bottom-right)

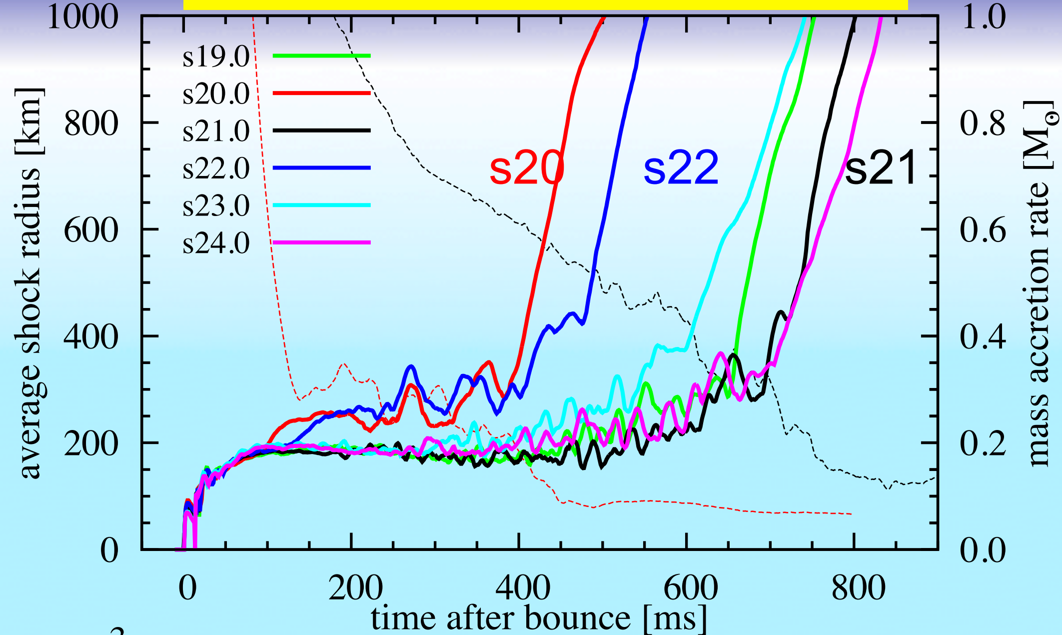


s19.0 - s24.0 models (1) *shock radius*

Model s21 (M=21Mo) takes a longer time to revive its shock than s22.

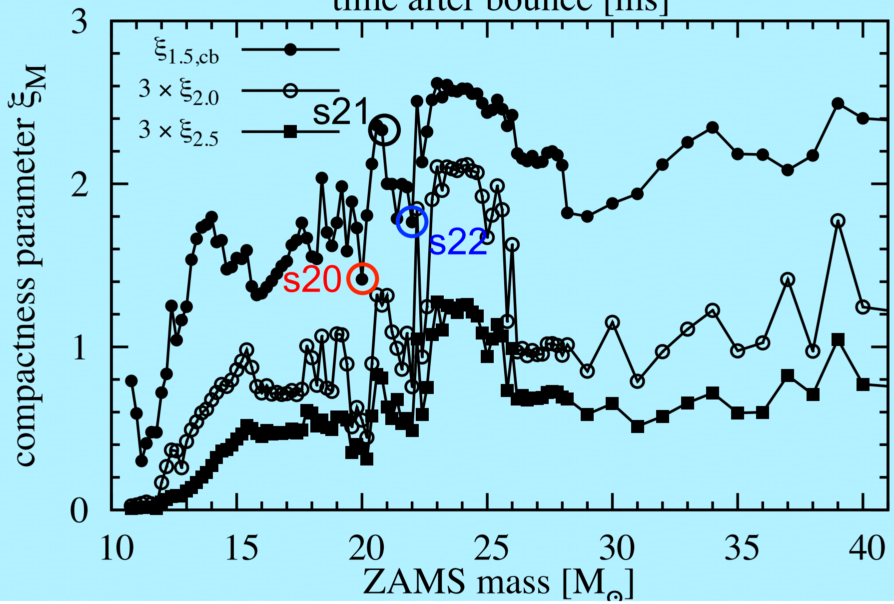
What determines the shock revival?
→ **mass accretion rate !**
（dotted lines）

Average shock radii (solid lines)



Compactness parameter
(O'Connor & Ott 2011)

$$\xi \equiv \frac{M/\ M_\odot}{R(M)/1000\mathrm{km}}$$

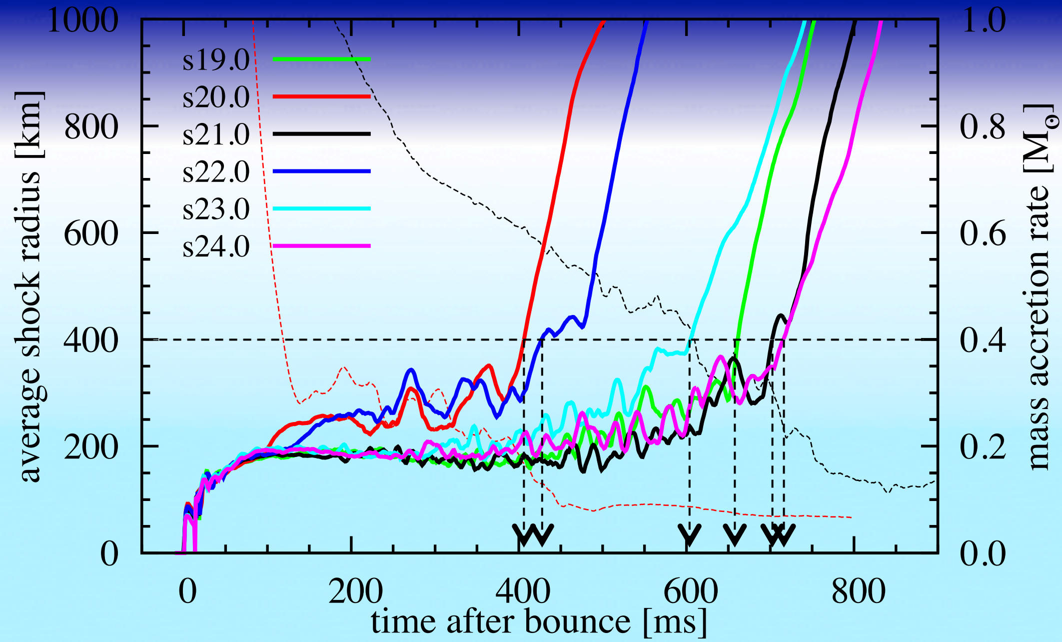


It characterizes density profile（≒mass accretion rate）within the mass coordinate M.

s21 > s20,s22

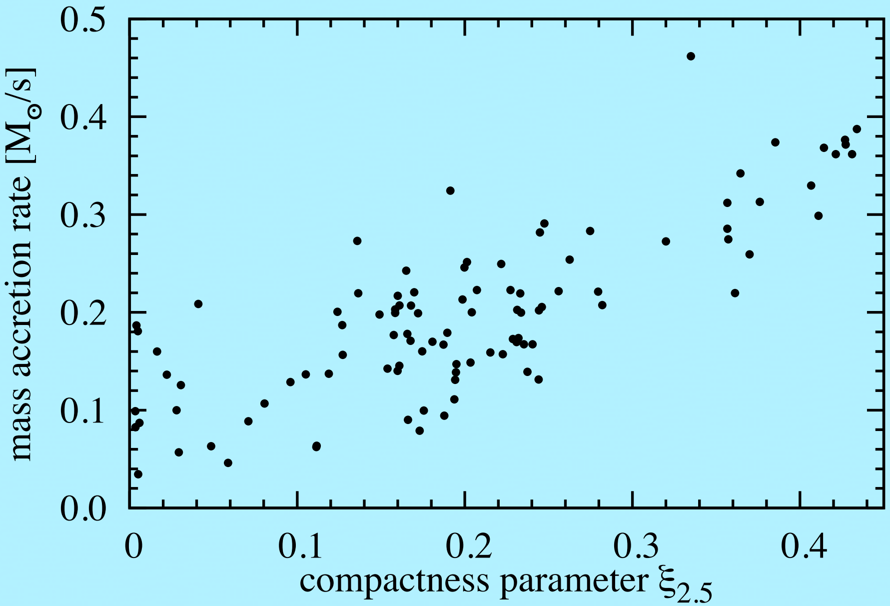
s19.0 - s24.0 models (2) *mass accretion*

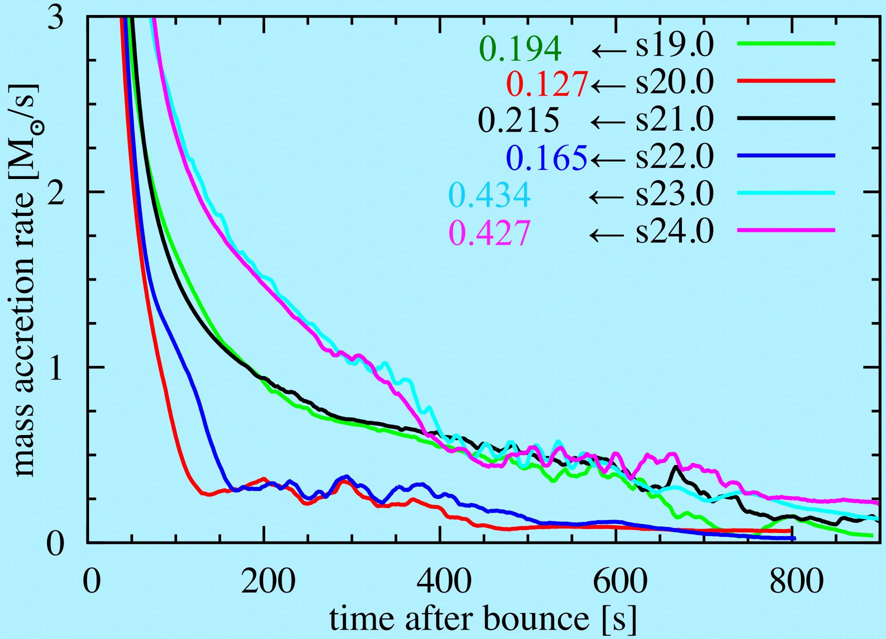
*t*400: the time when average shock radius arrive at 400km
（shock revival time; top-right）.



Mass accretion rate at *t*=*t*400
（bottom-left）.

It correlated with compactness ξ
（well fitted by a linear line）.



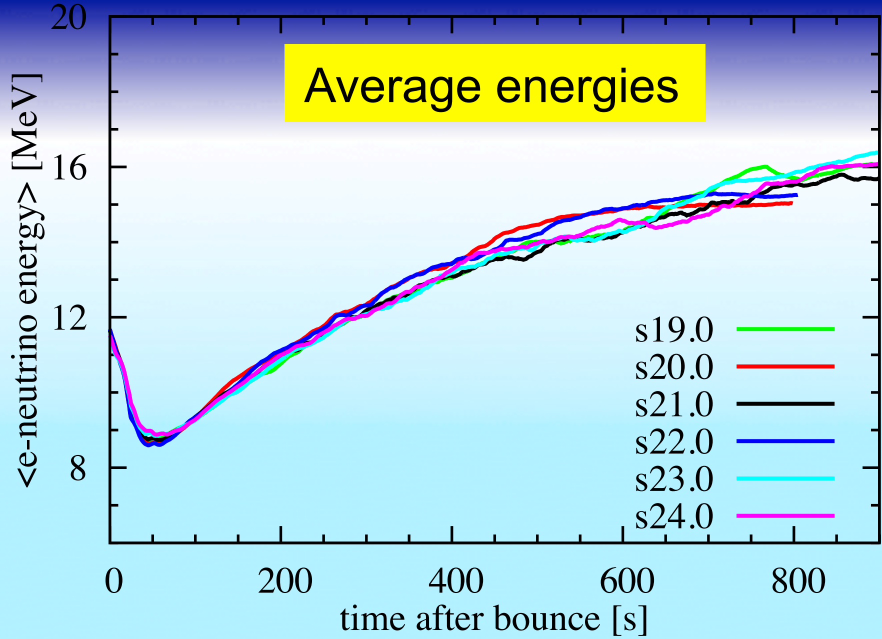


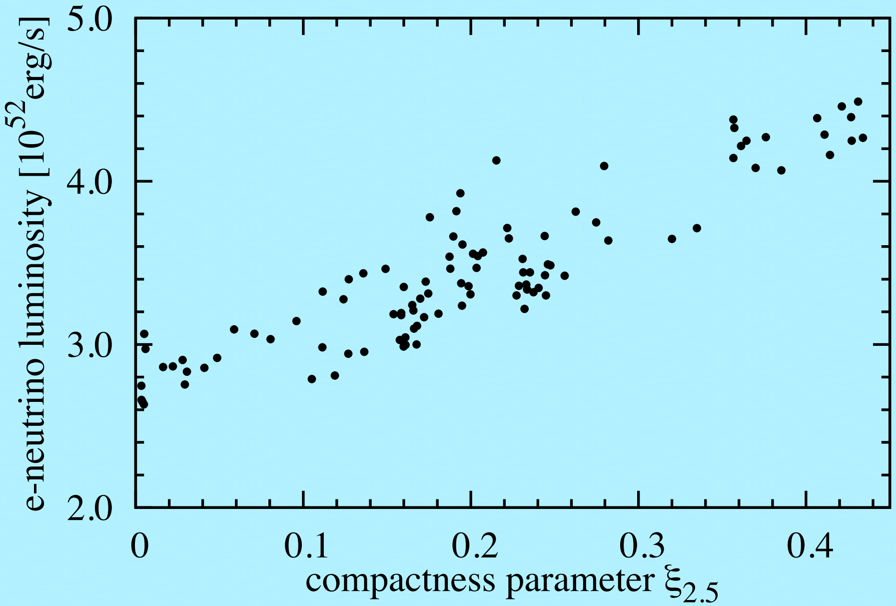
s19.0 - s24.0 models (3) *nu luminosity*

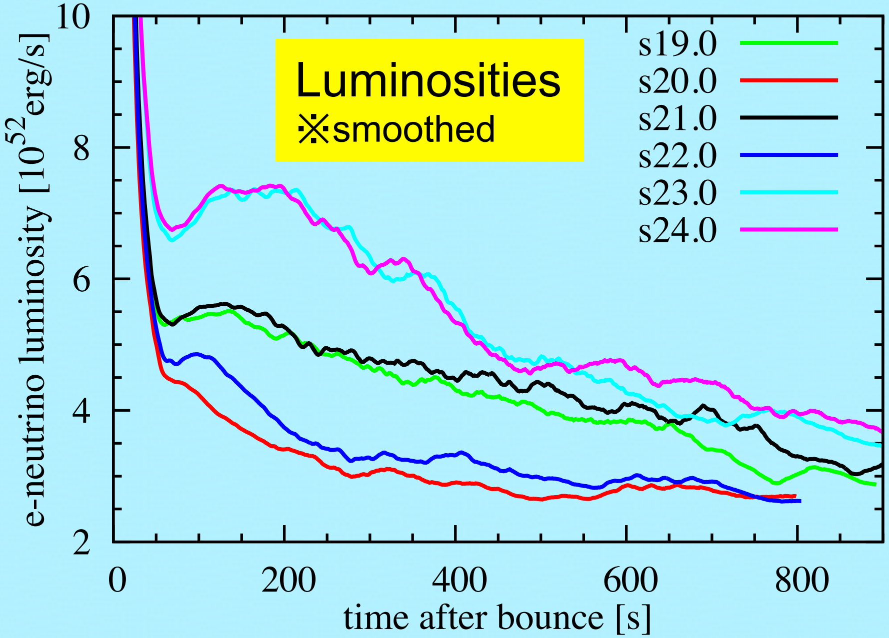
Shown are e^--neutrino energy (top) and luminosity (bottom-right).

The average energy evolves in essentially the same manner.

Large compactness (≒ large mass accretion rate) results in large neutrino luminosity.





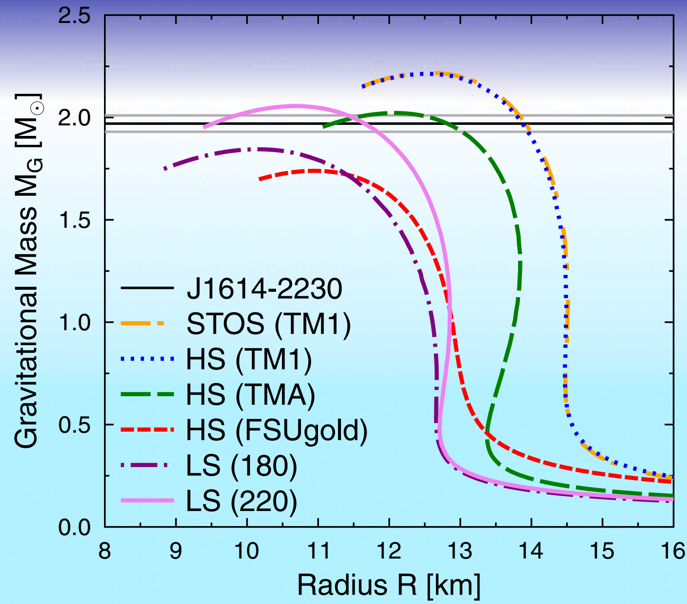


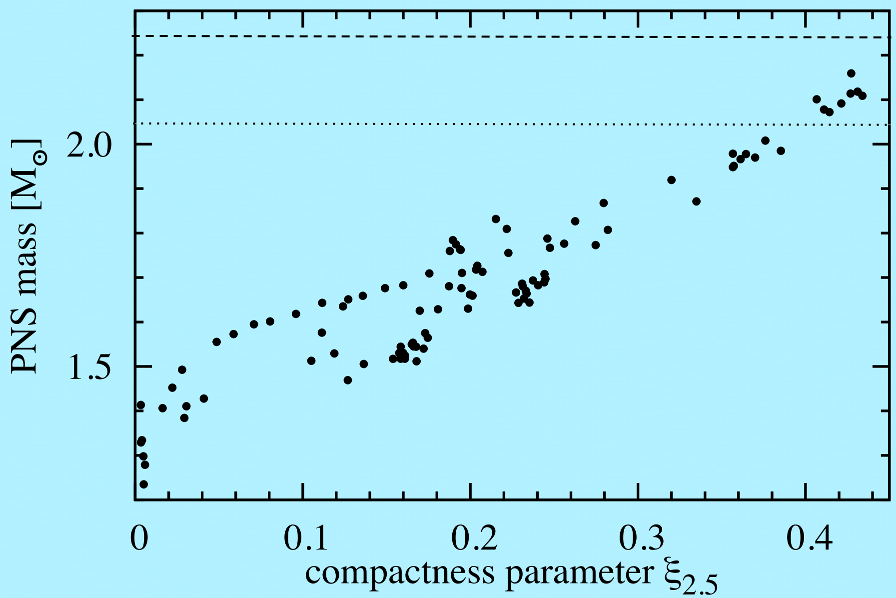
s19.0 - s24.0 models (4) *PNS mass*

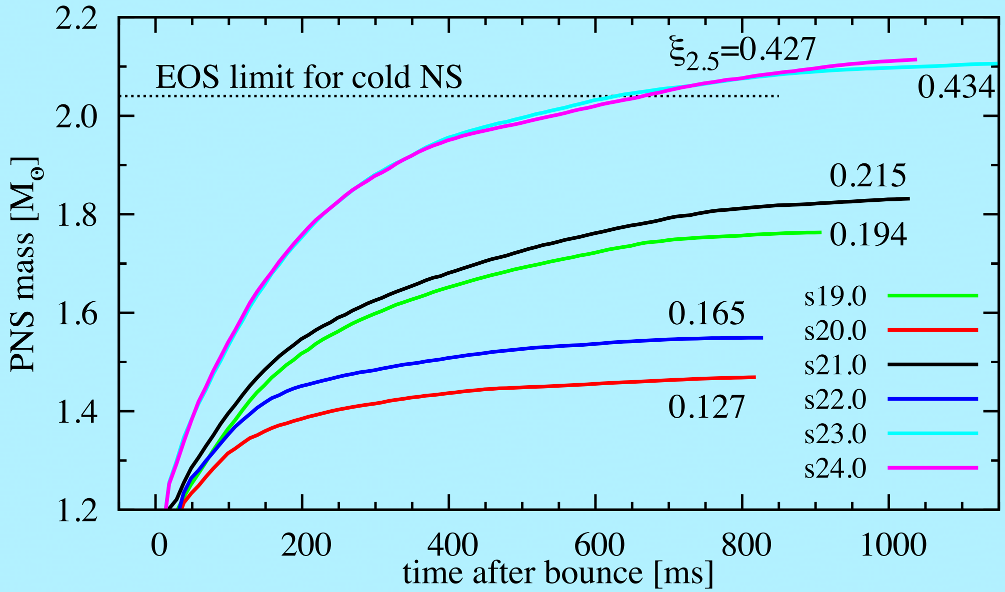
Gravitational mass of PNS（ρ > 10^{11} g/cc）.

Almost converged within our simulation time（t < 1.5 s, t_pb < ~1 s）.

CAUTION! Models with very high ξ exceed the PNS mass limit for LS220 EOS.
→ Out of our (Newtonian) study.







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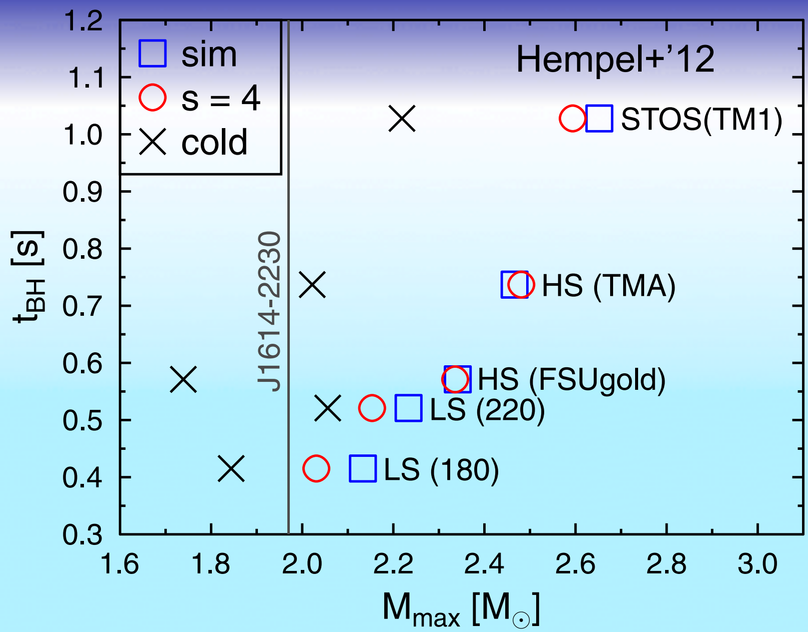
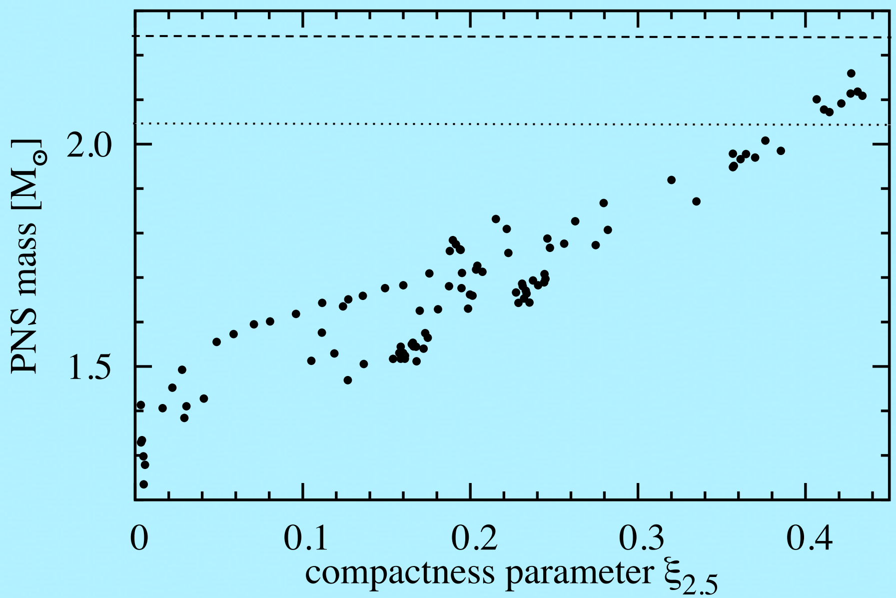
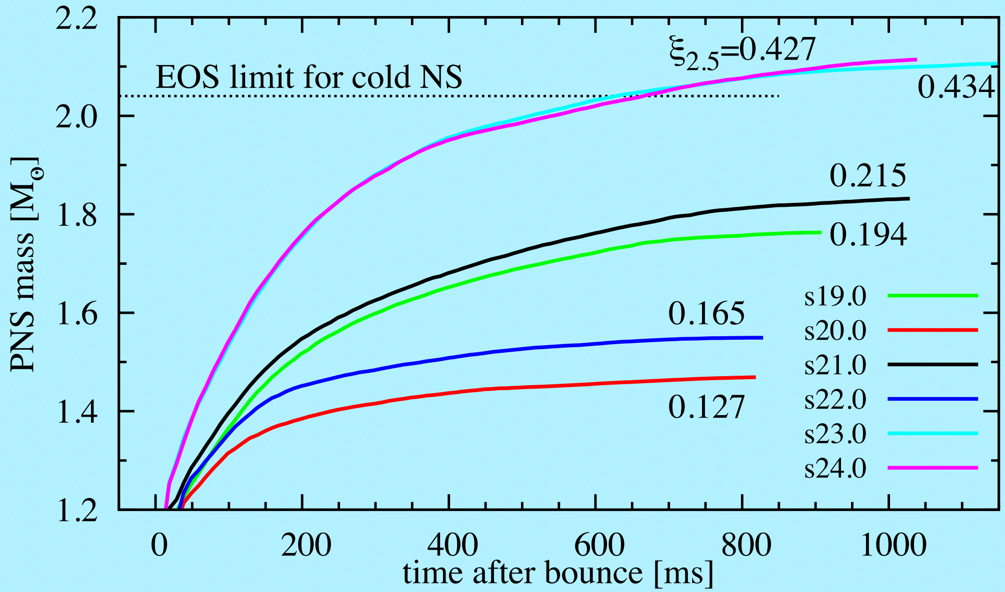
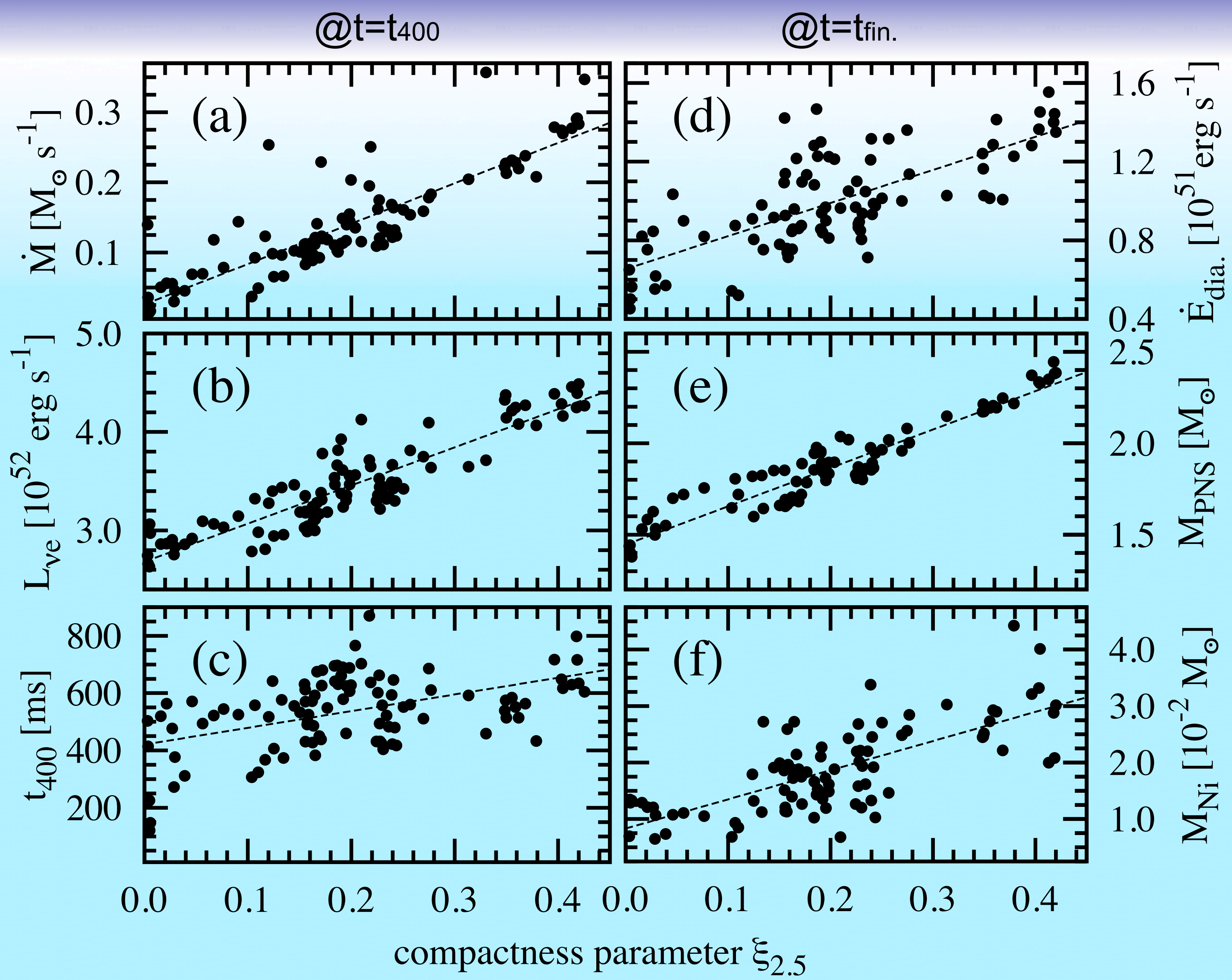






Compilation of CCSNe Simulations for 101 Solar-metallicity Progenitors



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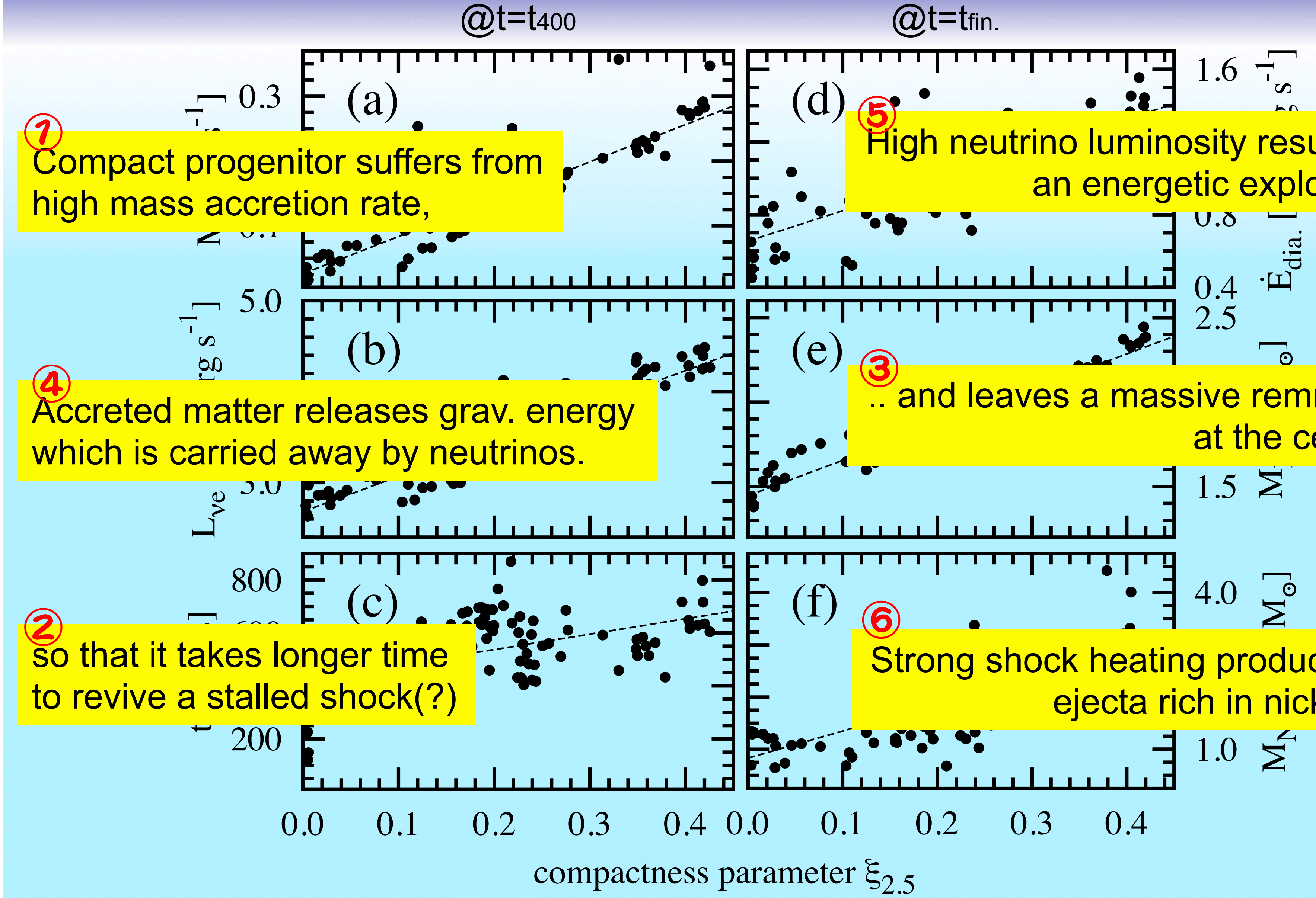
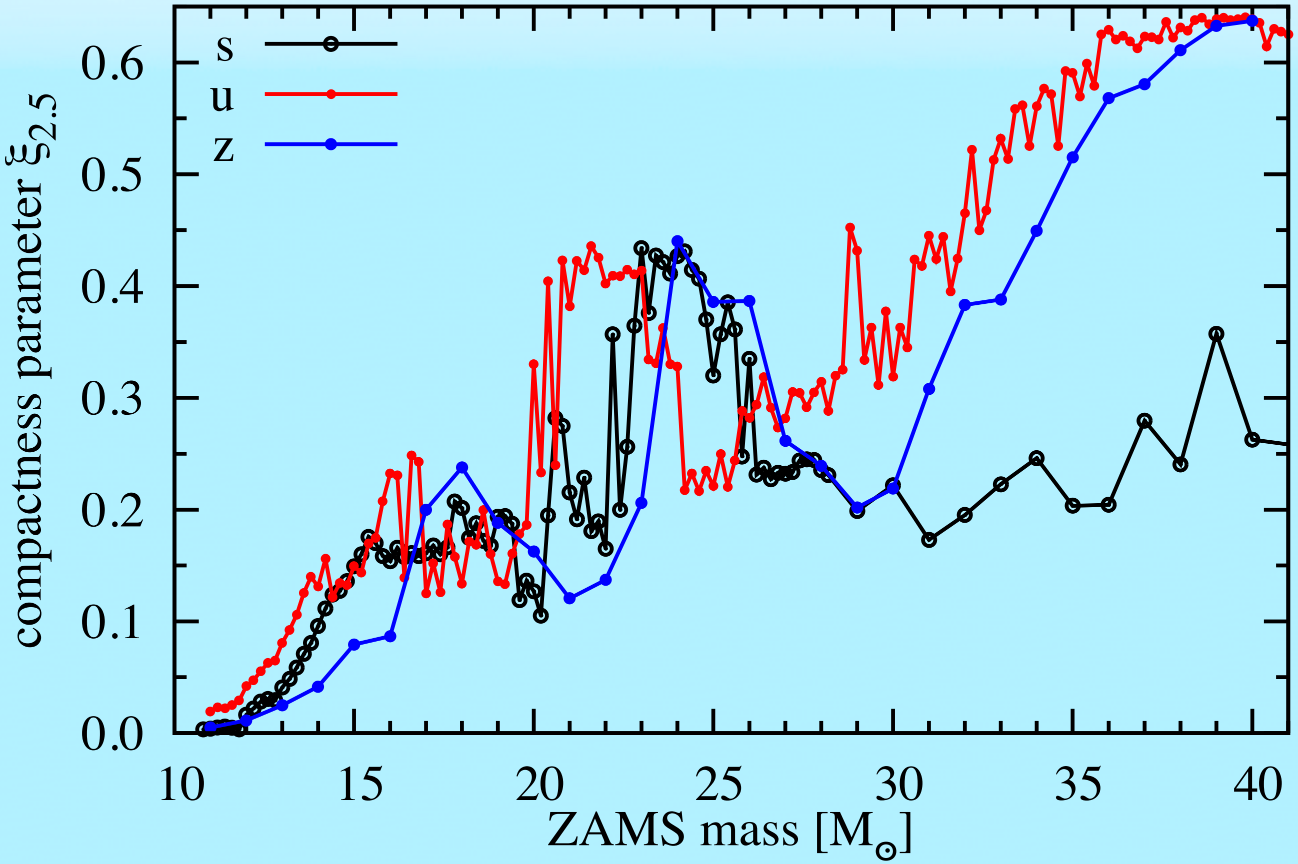


Metal-poor progenitors

- Solar-metallicity stars (s) : M_ZAMS = 10.8 - 40.0 Mo + 75.0 Mo (**101** models)
- UMP (Zsun/10000) stars (u) : M_ZAMS = 11.0 - 60.0 Mo + 75.0 Mo (**247** models)
- Zero-metallicity stars (z) : M_ZAMS = 11.0 - 40.0 Mo (**30** models)

Z = Zo
= 10^{-4} Zo
= 0



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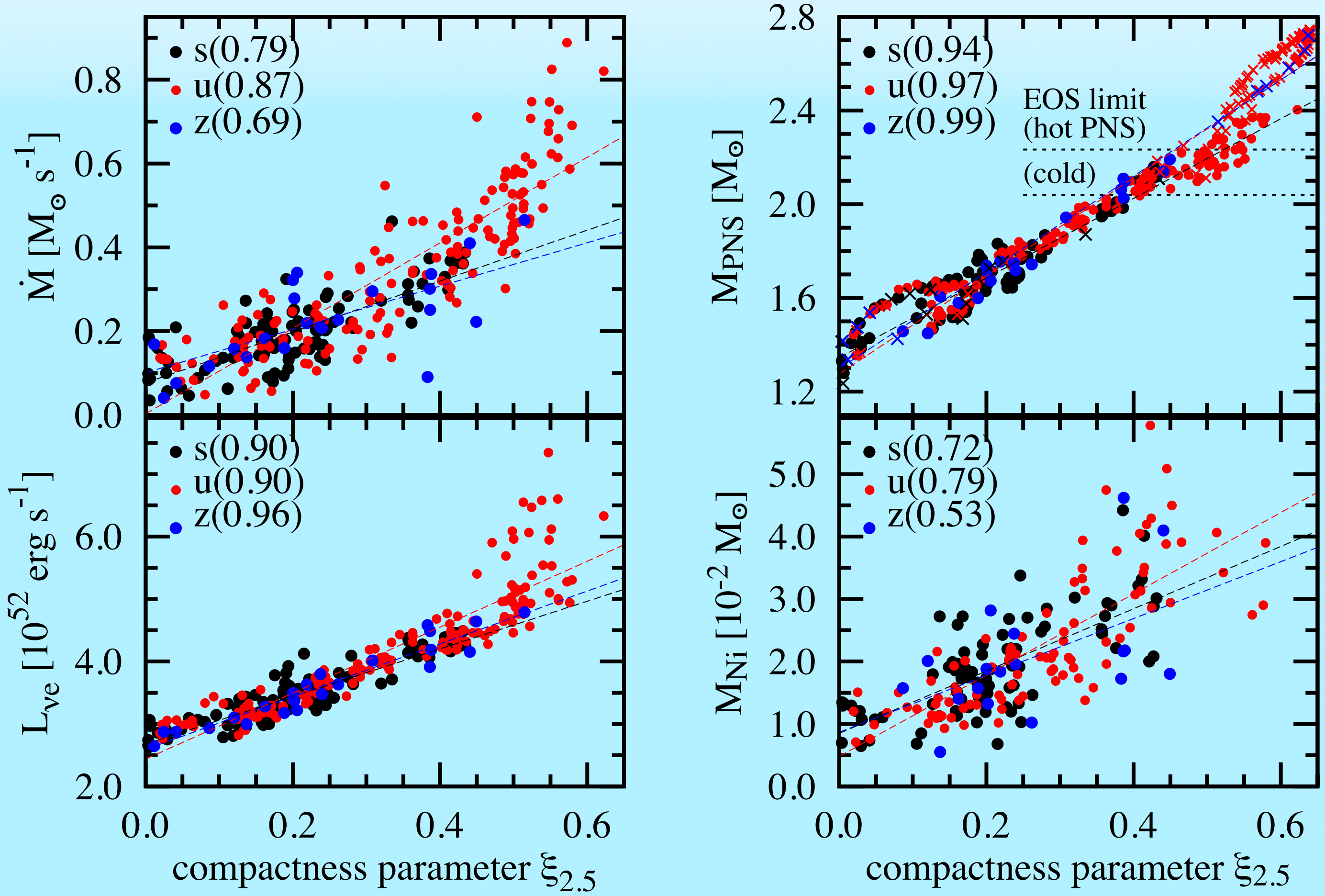
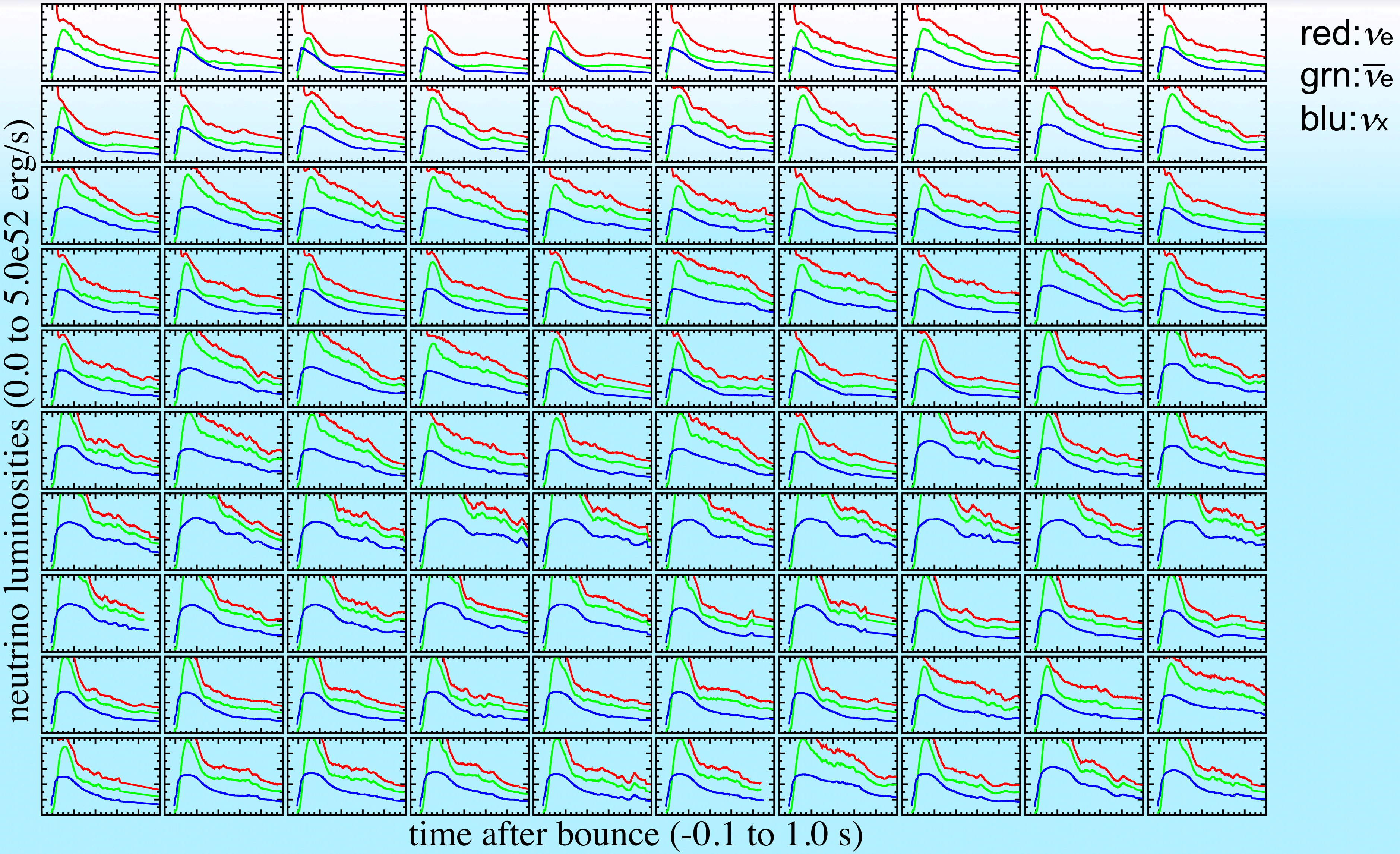
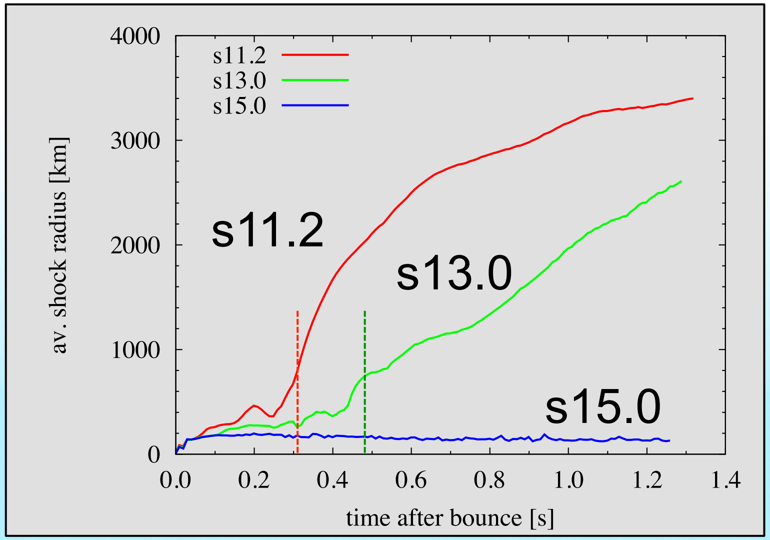
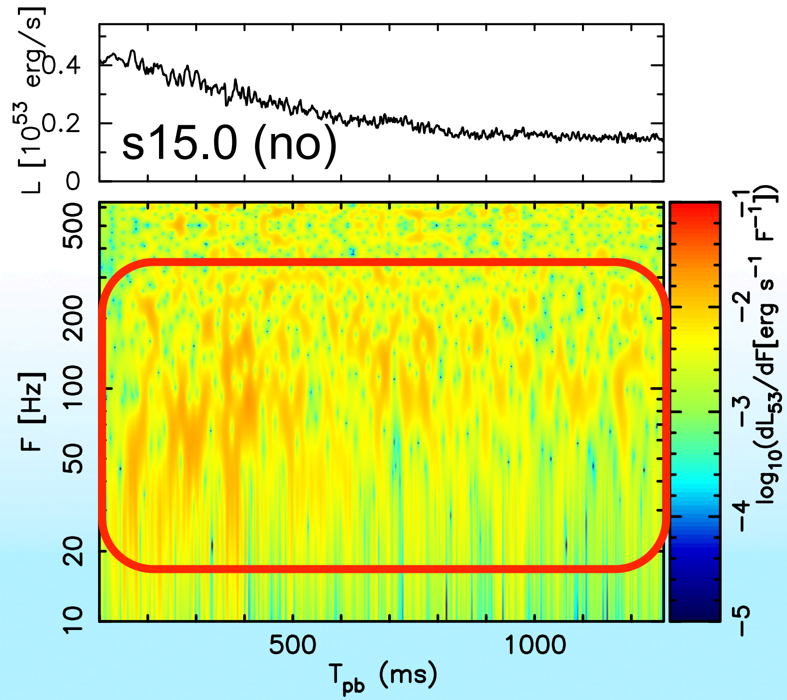


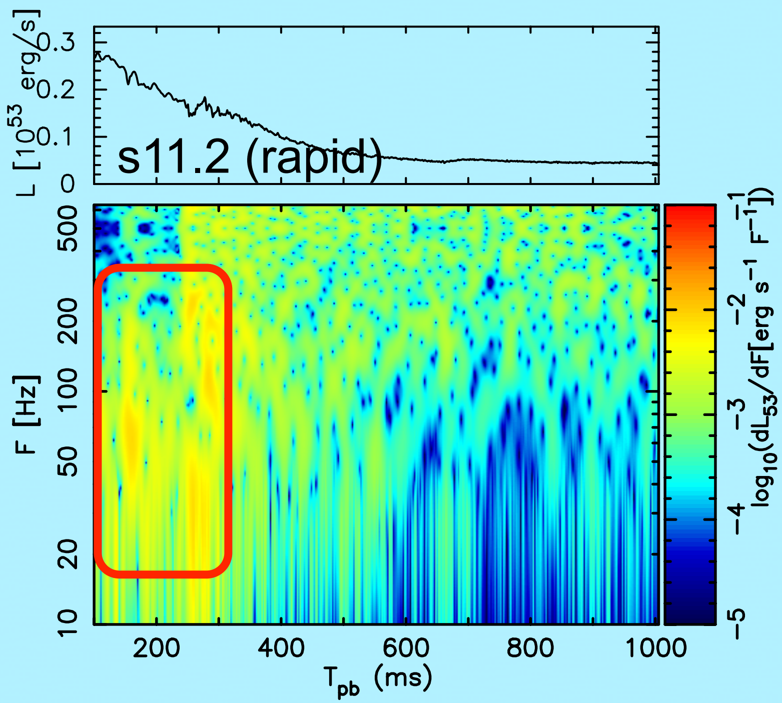
Neutrino Signals

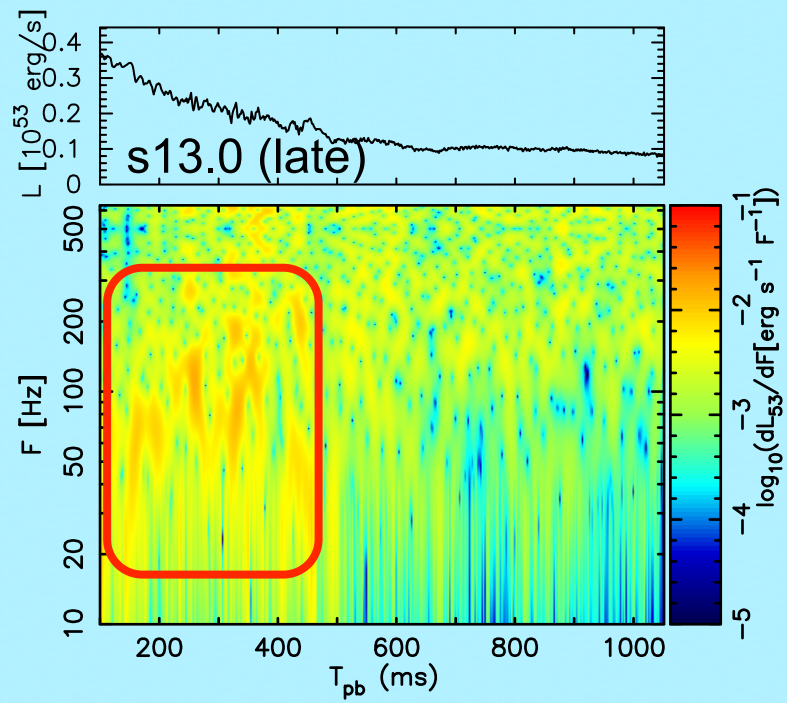


$\bar{\nu}_e$ luminosity









まとめ

- 約400個の超新星親星モデルに対して、2D CCSN数値計算を実行
  - 中心のPNS進化とニュートリノ輸送を考慮
  - 幅広い質量、金属量（将来的には回転と磁場も）
- 親星の構造を特徴付ける “compactness parameter”
  - O’Connor & Ott ’11　　　（$\xi = M / R$）
  - CCSNのPNS質量,ニュートリノ光度,爆発エネルギー,ニッケル生成量と相関
- 最終的な爆発エネルギーを得るには長時間/広範囲計算
  - 低温・低密度を含むEoSが必要
- CCSN as a multi-messenger
  - EM/GW/neutrino signals
  - GW/neutrino 信号には compactness による違い.
  - EMを算出するには長時間計算が必要.