超新星ニュートリノ加熱物質中の元素合成

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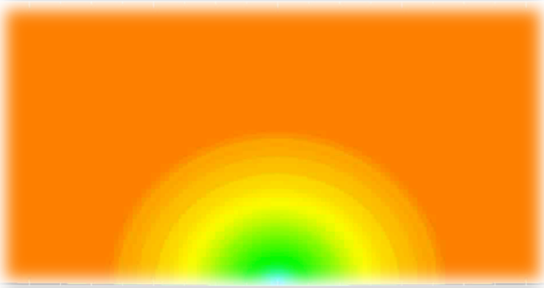
1. nucleosynthesis during the first 1 second;
   what do we see in the innermost SN ejecta?
   (Wanajo, Janka, Müller 2011, 2013, and in prep.)

2. nucleosynthesis during the next 10 seconds;
   do we see an r-process? (Wanajo 2013)

3. how close to successful supernova explosions?
   sensitivity to neutrino opacity (Melson+2015)

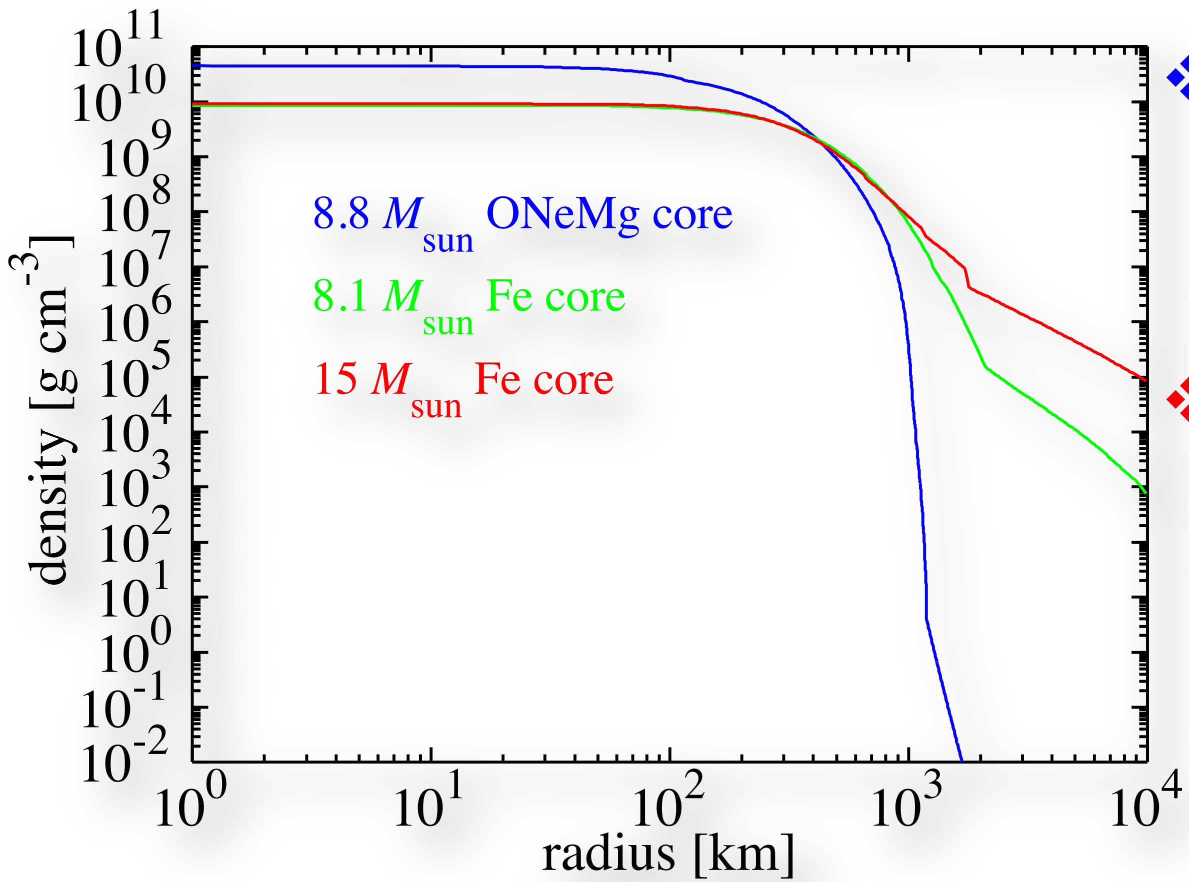


1. nucleosynthesis during the first 1 second; what do we see in the innermost SN ejecta? (Wanajo, Janka, Müller 2011, 2013, in prep.)

current status of SN simulations

	explosion (~ 10 $M_\odot$)	explosion (> 10 $M_\odot$)
1D	yes	no
2D	yes	yes
3D	yes	no

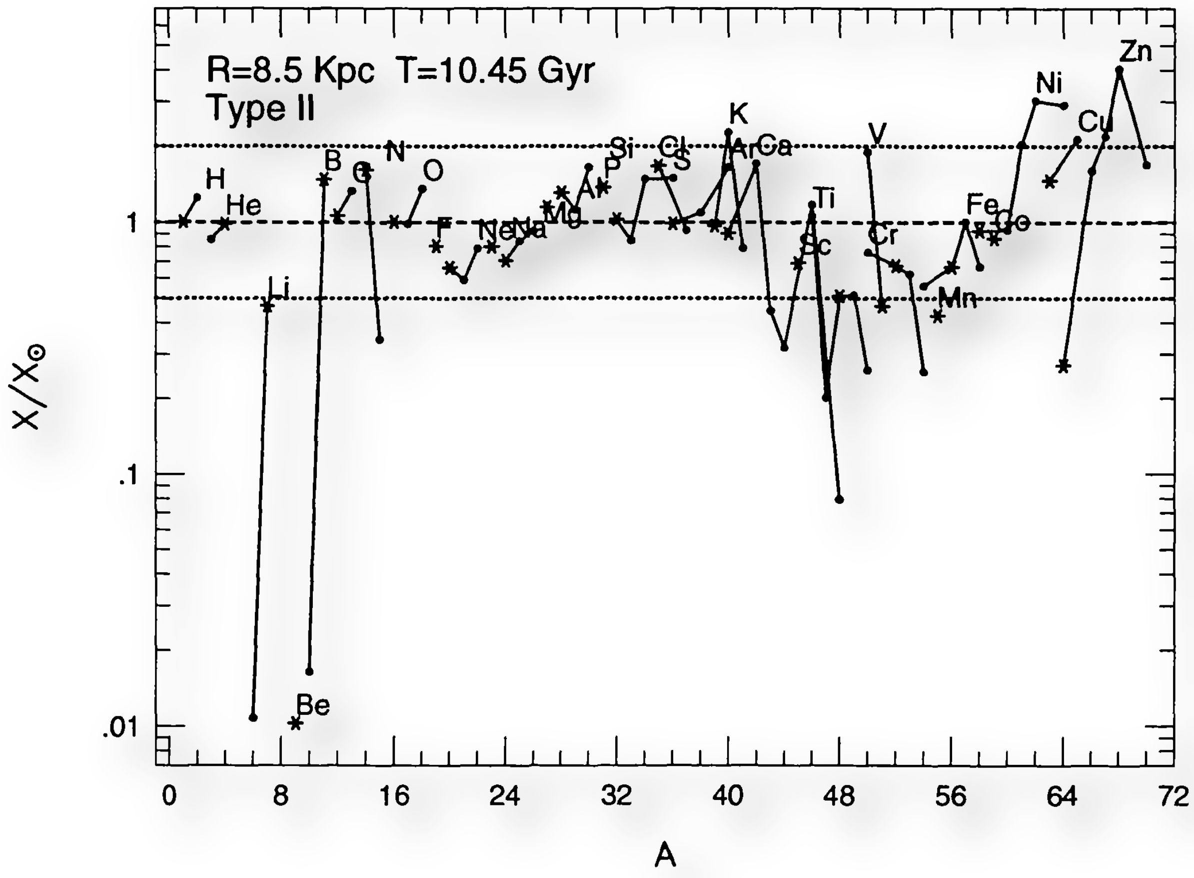
pre-SN core density profiles



- low-mass SNe (~ 8-10 $M_\odot$) diluted outer envelope makes explosion easy
- massive SNe (> 10 $M_\odot$) dense outer envelope makes explosion hard

known problems in SN nucleosynthesis

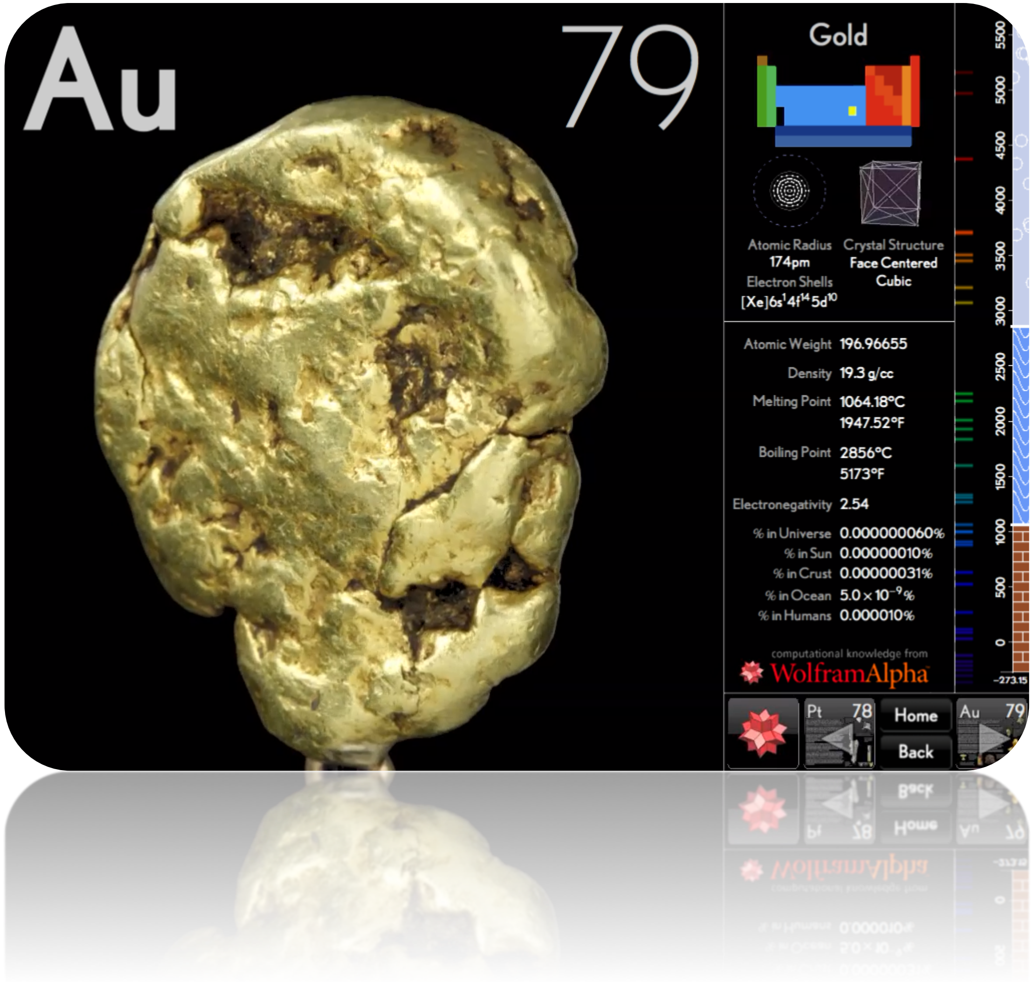
production factors from all SNe; Timmes+1995



previous SN nucleosynthesis based on parameterized 1D models

- no production of light trans-iron (Zn to Zr; *Z*=30-40, *A* = 64-90) nor r-process elements
- little production of ^{48}Ca (double magic), ^{64}Zn (main isotope), ^{92}Mo (p-isotope)

what crucial for nucleosynthesis are…

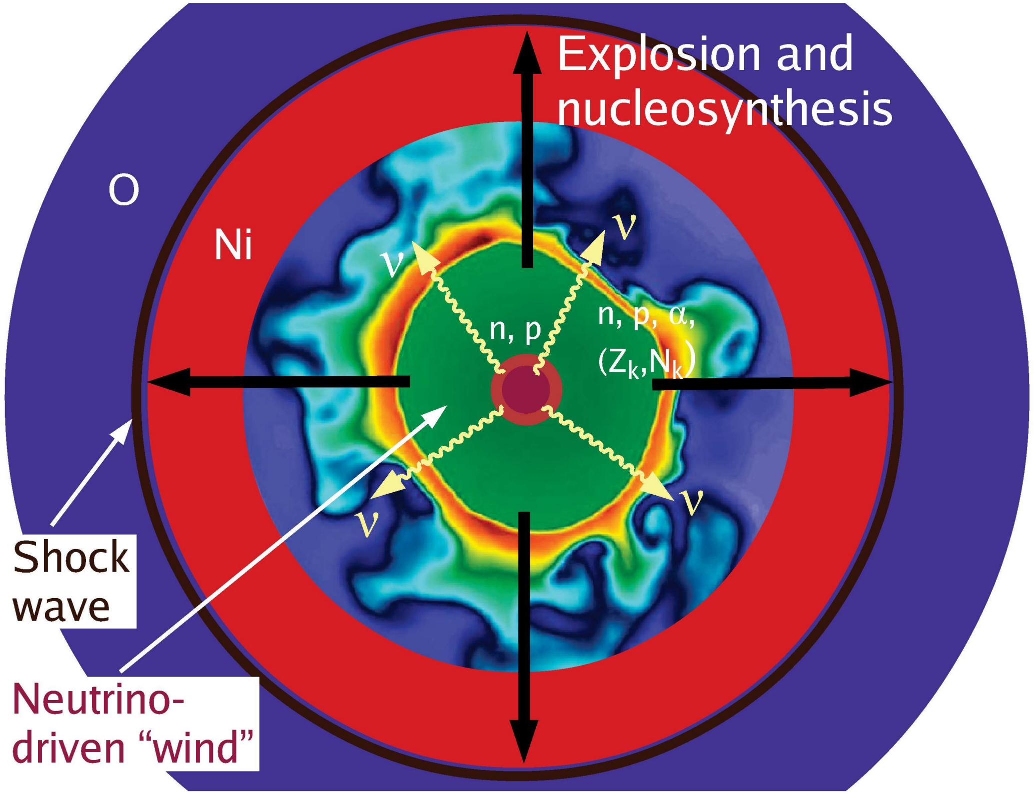


important physical parameters

- entropy; S ($\propto T^3/\rho$)
  controls n, p, α amounts
- expansion timescale; τ
  (e-folding time of T)
  controls n, p, α amounts
- electron fraction; Y_e
  (protons per nucleon)
  controls n/p ratios

innermost ejecta of SNe

Janka+2012



$$\nu_e + n \rightarrow p + e^-$$

$$\bar{\nu}_e + p \rightarrow n + e^+$$

- elements up to iron are formed in the outer layers
- (light) trans-iron elements likely to be formed in the innermost layers
- difficult to constrain Y_e from simulations because of its sensitivity to neutrino spectra

what determines Y_e ?

- Y_e is determined by

$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

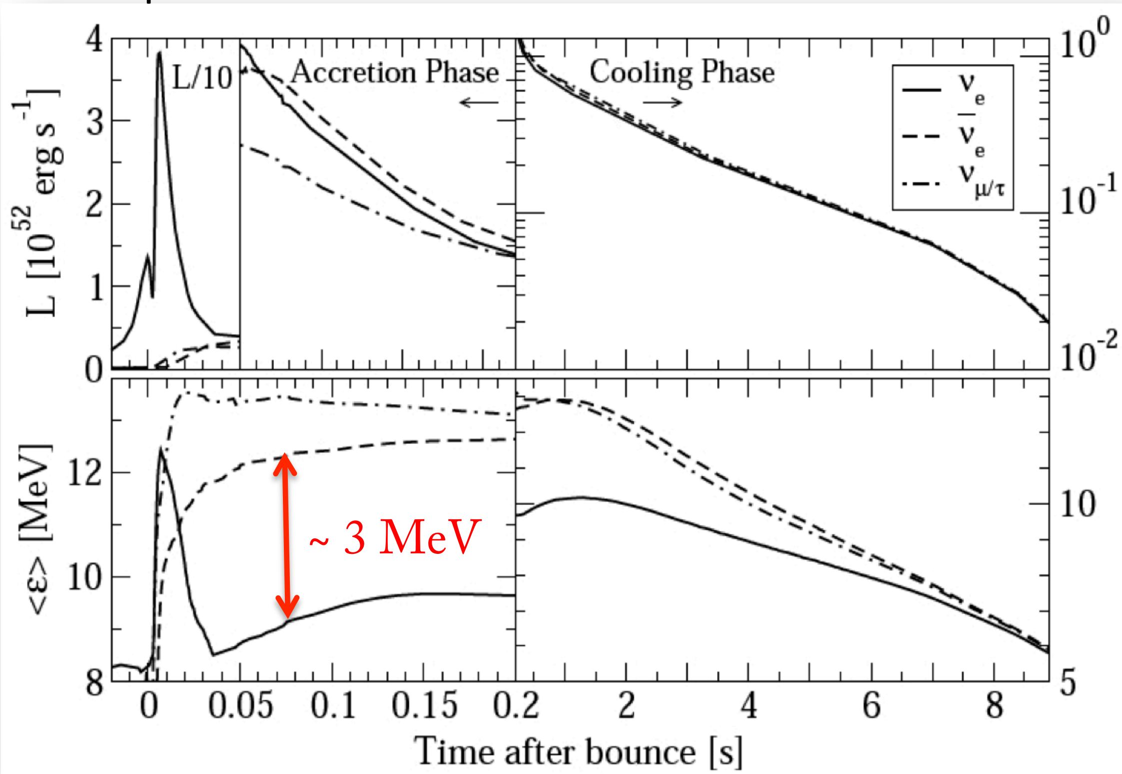
- equilibrium value is

$$Y_e \sim \left[1 + \frac{L_{\bar{\nu}e}}{L_{\nu e}} \frac{\varepsilon_{\bar{\nu}e} - 2\Delta}{\varepsilon_{\nu e} + 2\Delta}\right]^{-1},$$
$$\Delta = M_n - M_p \approx 1.29 \text{ MeV}$$

- for $Y_e < 0.5$ (i.e., n-rich)

$$\varepsilon_{\bar{\nu}e} - \varepsilon_{\nu e} > 4\Delta \sim 5 \text{ MeV}$$
$$\text{for } L_{\bar{\nu}e} \approx L_{\nu e}$$

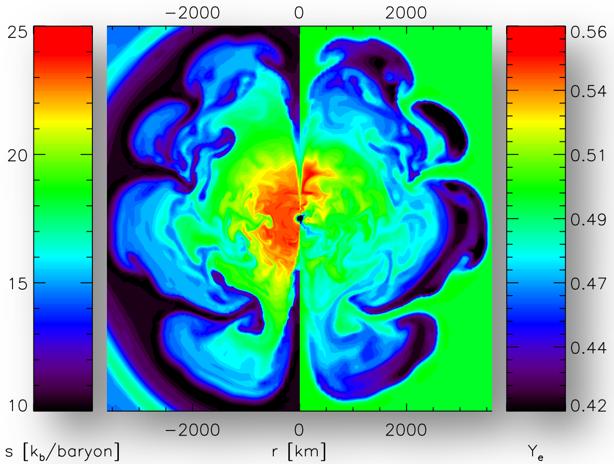
1D self-consistent explosion of a 9 $M_\odot$ star
Hüdepohl+2009



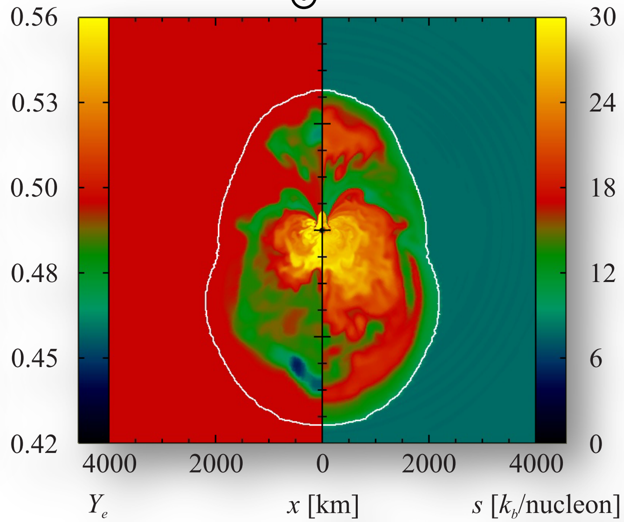
neutrino spectra in the early times are crucial for nucleosynthesis !!!

2D SN simulations with ν-transport

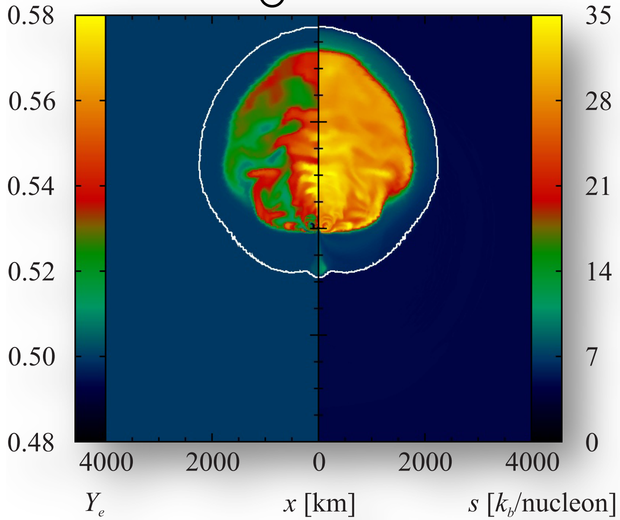
8.8 $M_\odot$ ECSN



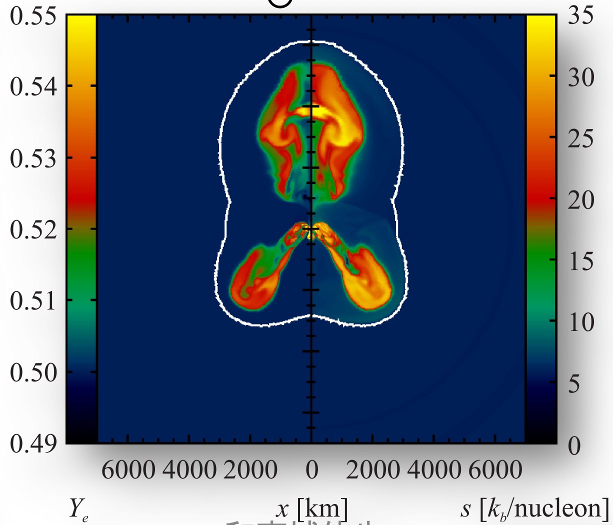
8.1 $M_\odot$ CCSN



15 $M_\odot$ CCSN



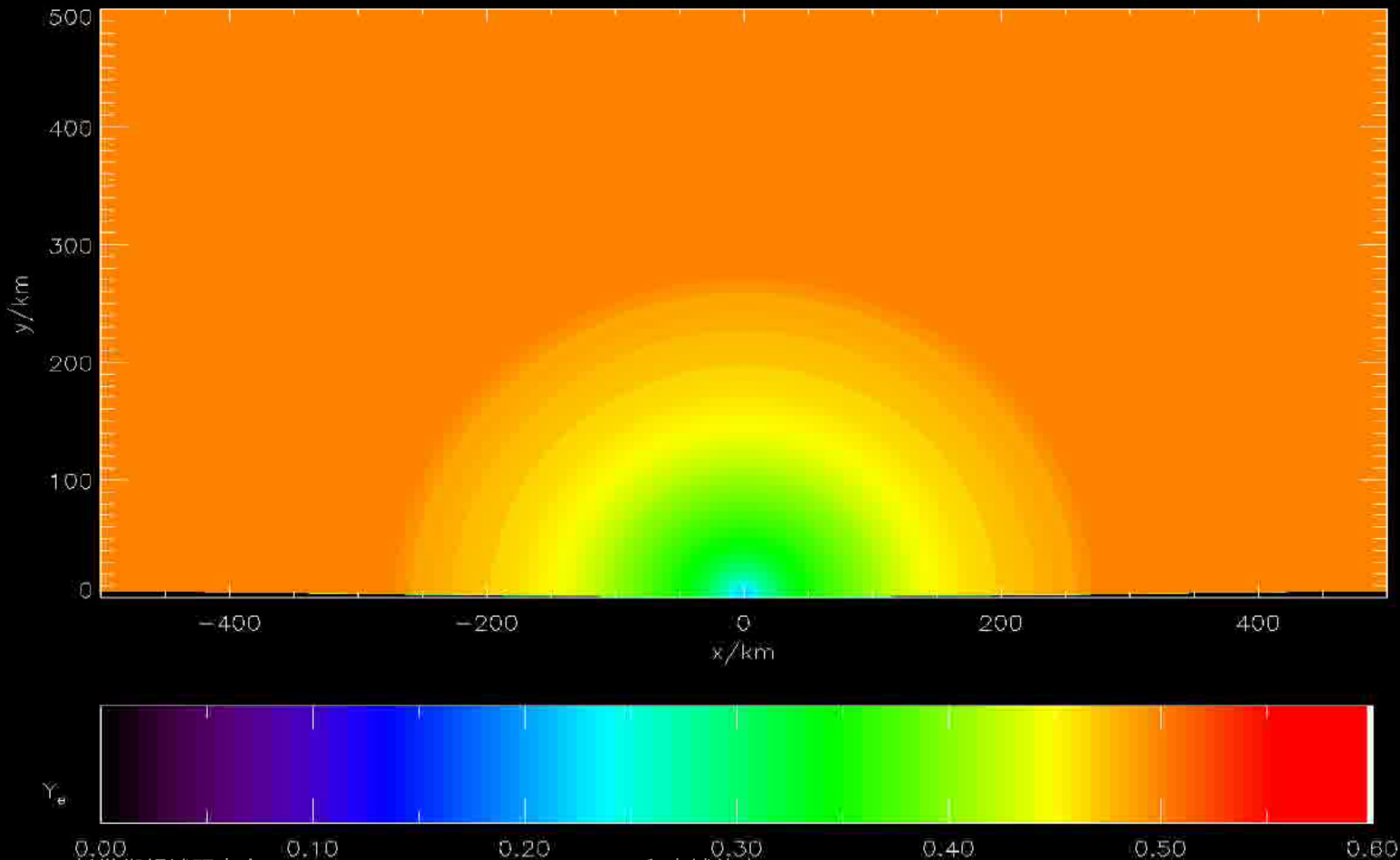
27 $M_\odot$ CCSN



- a number of self-consistent SN models with neutrino transport are now available
- very first result of SN nucleosynthesis with such models

8.8 $M_\odot$ self-consistently exploding ONeMg core supernova

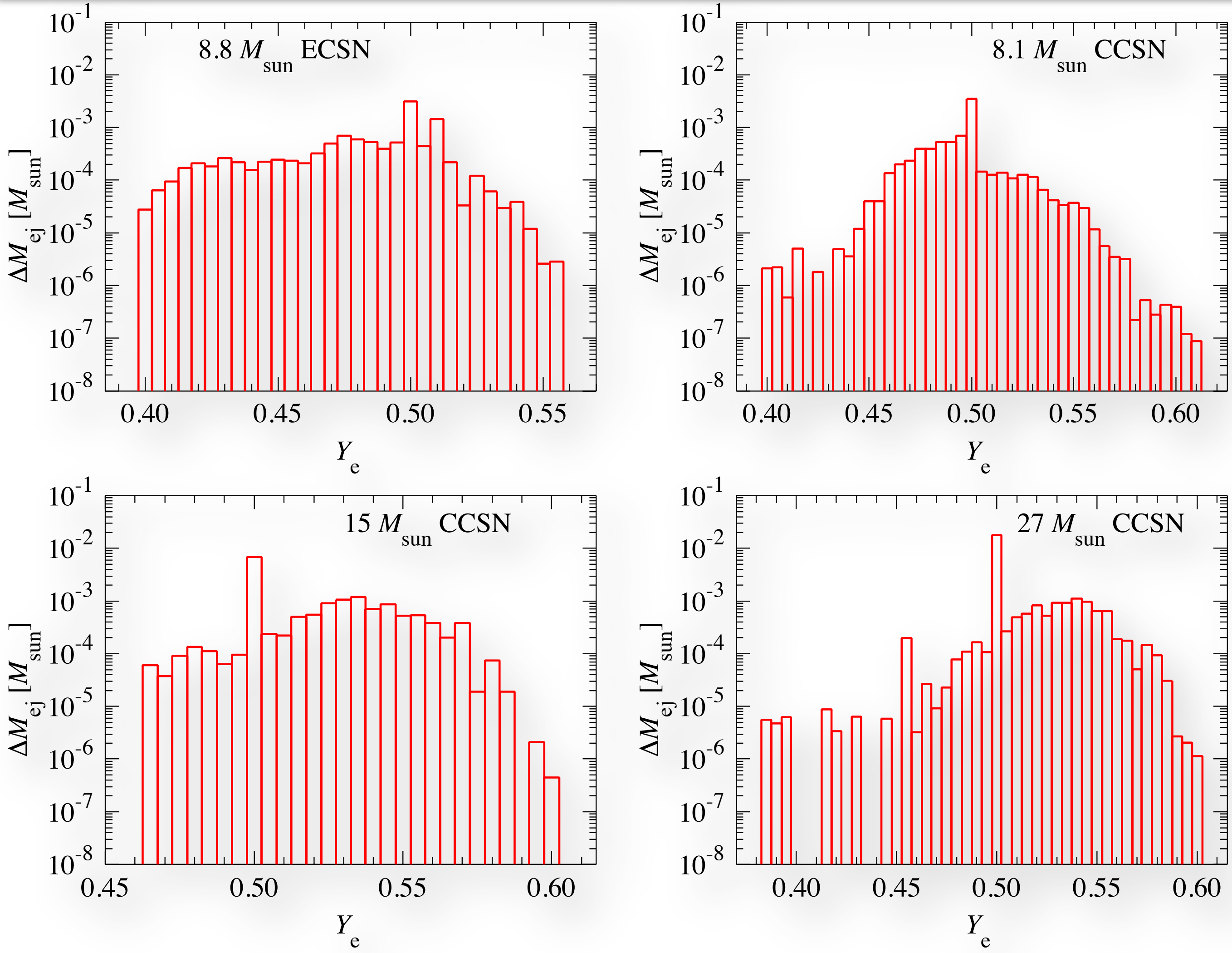
simulation by Bernhard Müller


500
400
300
200
100
0
y/km
-400
-200
0
200
400
x/km
Y_e
0.00
0.10
0.20
0.30
0.40
0.50
0.60

27 $M_{\odot}$ self-consistently exploding Fe core

simulation by Bernhard Müller

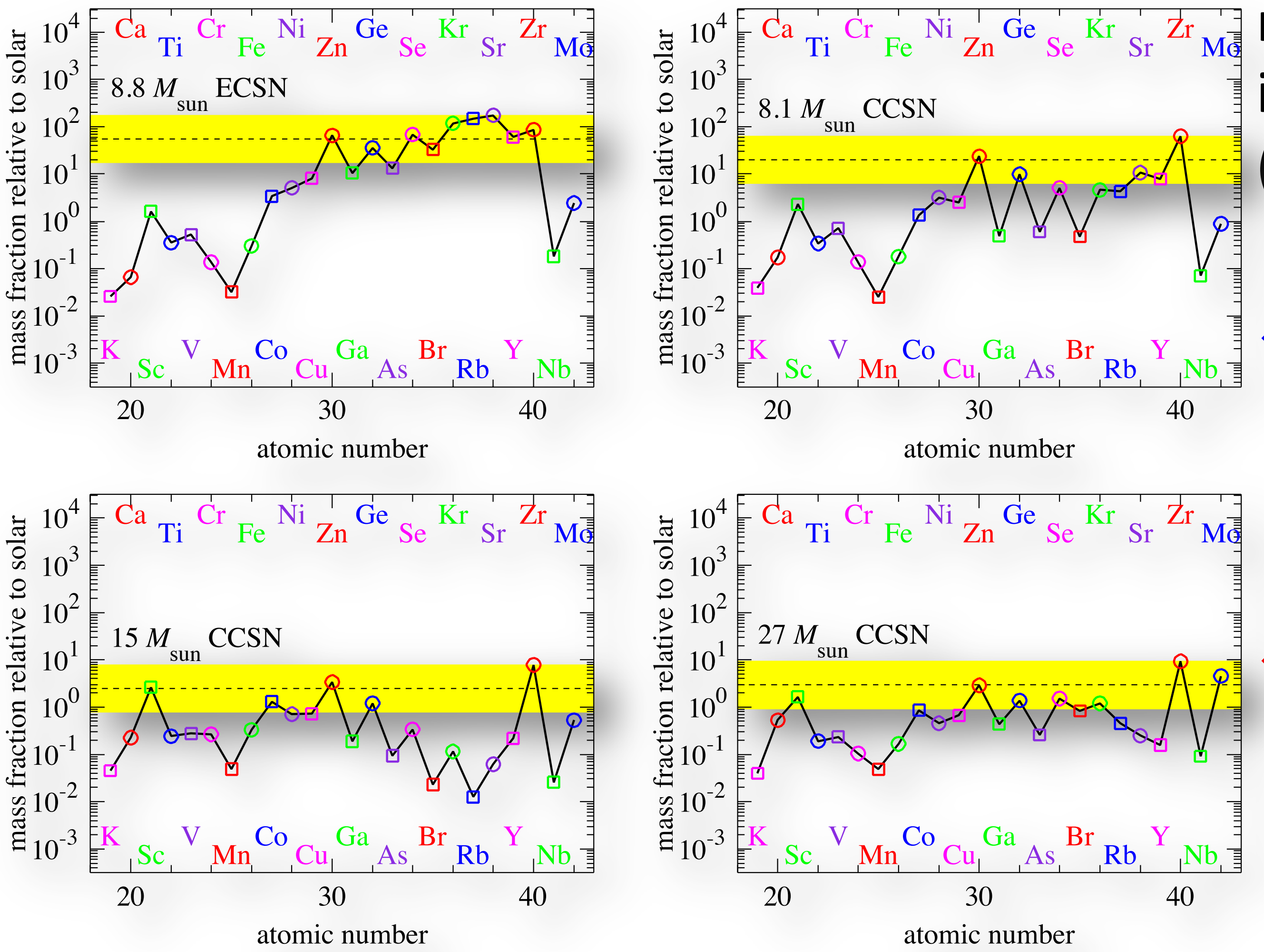
neutron-richness in the ejecta



Y_e distribution in the innermost ejecta (~ 0.01 $M_\odot$)

- light SNe have more n-rich ejecta (less neutrino-processed)
- massive SNe have more p-rich ejecta (more neutrino-processed)

elemental abundances for each SN



nucelosynthesis in the innermost ejecta (M_{ej} ~ 0.01 $M_{\odot}$)

- light SNe make more trans-iron elements (Zn to Zr)
- massive SNe make few trans-iron elements (mainly Zn and Zr)

Wanajo+2015, in prep.

a little bit more of ECSNe: ^{48}Ca

www.kadonis.org

^{42}Ti 199.00 ms	^{43}Ti 509.00 ms	^{44}Ti 59.99 a	^{45}Ti 3.08 h	^{46}Ti 8.25	^{47}Ti 7.44	^{48}Ti 73.72	^{49}Ti 5.41	^{50}Ti 5.18
^{41}Sc 596.00 ms	^{42}Sc 681.00 ms	^{43}Sc 3.89 h	^{44}Sc 3.97 h	^{45}Sc 100	^{46}Sc 83.79 d	^{47}Sc 3.35 d	^{48}Sc 1.82 d	^{49}Sc 57.20 m
^{40}Ca 96.94	^{41}Ca 102.01 ka	^{42}Ca 0.647	^{43}Ca 0.135	^{44}Ca 2.09	^{45}Ca 162.62 d	^{46}Ca 0.004	^{47}Ca 4.54 d	^{48}Ca 0.187
^{39}K 93.2581	^{40}K 1.25x10^{9} y	^{41}K 6.7302	^{42}K 12.32 h	^{43}K 22.30 h	^{44}K 22.13 m	^{45}K 17.30 m	^{46}K 1.75 m	^{47}K 17.50 s

^{48}Ca

- doubly magic (Z = 20, N = 28) n-rich isotope
- almost stable ($t_{1/2}$ = 1.9 × 10^{19} yr by double β-decay)
- origin is unknown; only suggested are hypothetical SNe Ia

a little bit more of ECSNe: ^{60}Fe

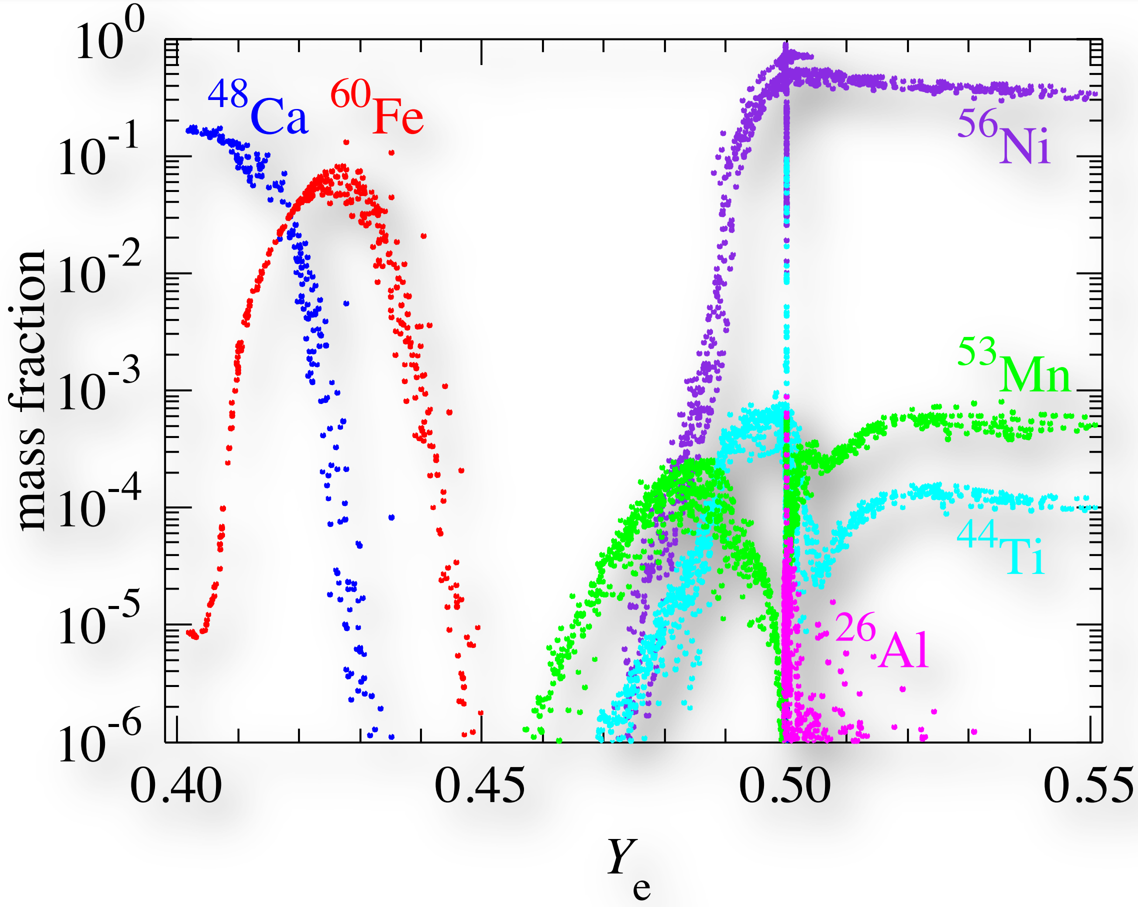
www.kadonis.org

^{56}Ni 6.08 d β^+	^{57}Ni 1.48 d β^+	^{58}Ni 68.077 38.7 mb	^{59}Ni 75.99 ka 87 mb, β^+	^{60}Ni 26.223 30 mb	^{61}Ni 1.14 82 mb	^{62}Ni 3.634 22.3 mb
^{55}Co 17.53 h β^+	^{56}Co 77.23 d β^+	^{57}Co 271.76 d β^+	^{58}Co 70.86 d β^+	^{59}Co 100 38 mb	^{60}Co 5.27 a β^-	^{61}Co 1.65 h β^-
^{54}Fe 5.845 27.6 mb	^{55}Fe 2.74 a 75 mb, β^+	^{56}Fe 91.754 11.7 mb	^{57}Fe 2.119 40 mb	^{58}Fe 0.282 12.1 mb	^{59}Fe 44.50 d β^-	^{60}Fe 1.50 Ma β^-

^{60}Fe

- n-rich radionuclide with $t_{1/2}$ = 2.62 × 10^6 yr (Rugel+2009)
- live ^{60}Fe in the early solar system (e.g., Tachibana+2003)
- live ^{60}Fe in the Milky Way Galaxy (e.g., Harris+2005)
- CCSNe (n-capture in He, O/Ne layers) can be the sources?

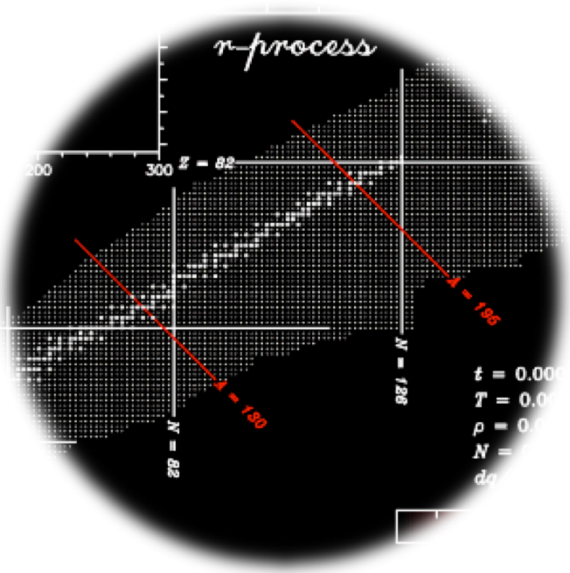
ECSNe make both ^{48}Ca and ^{60}Fe !



Wanajo+2013

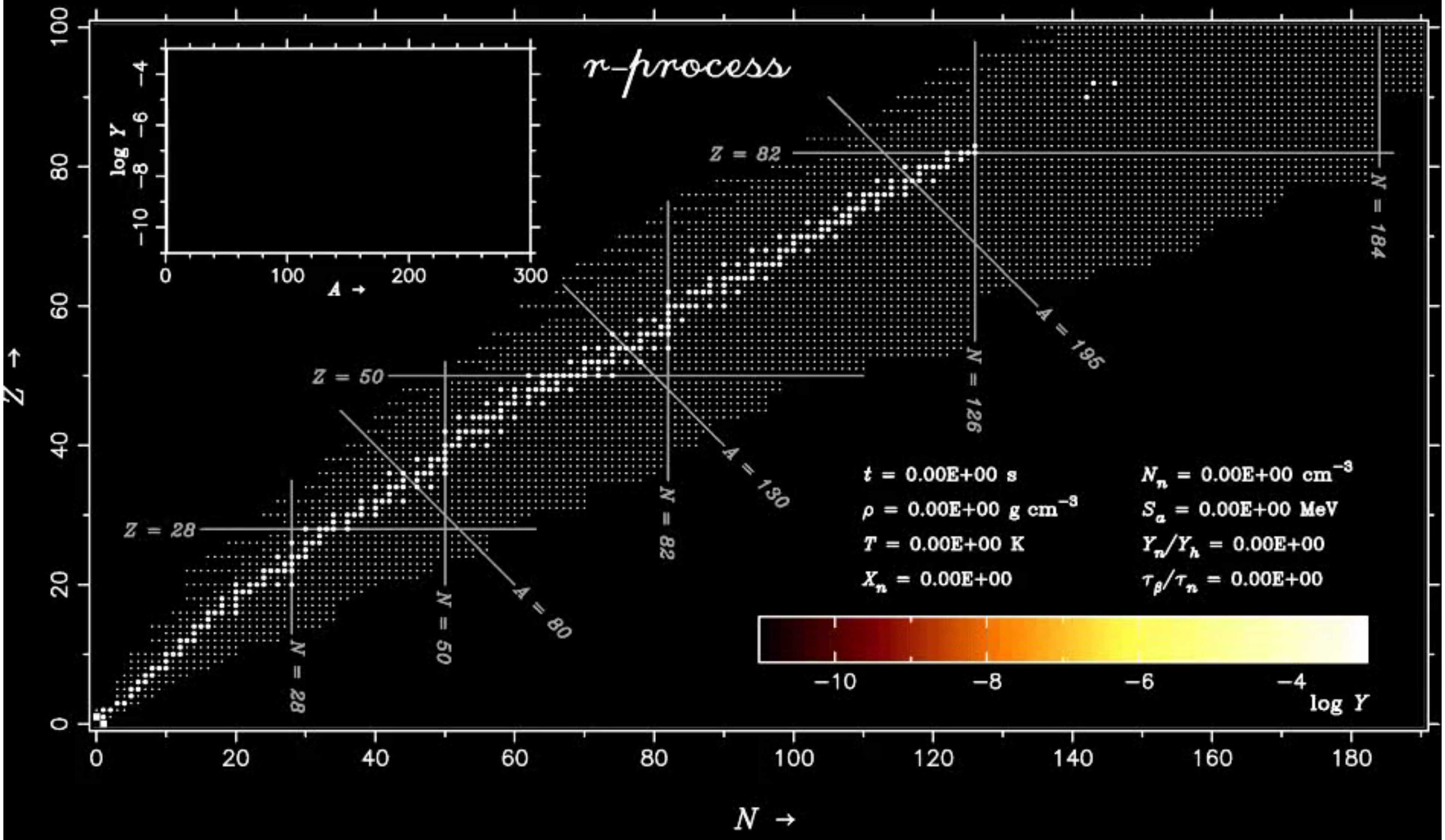
both are made in NSE-like conditions with Y_e = 0.40-0.45

- nucleosynthesis is extremely sensitive to Ye; a few percent level of accuracy is needed !!!

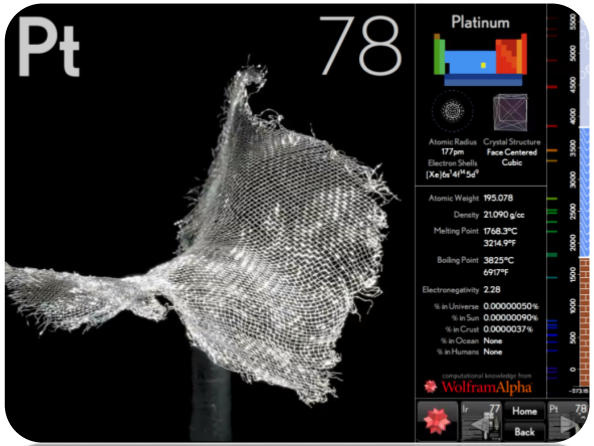


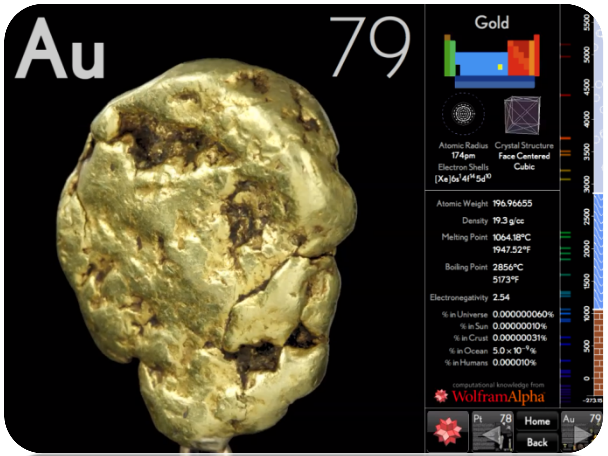
2. nucleosynthesis during the next 10 seconds;
   is the answer blowing in the wind?
   (Wanajo 2013)

do we find an r-process ?



how to make the 3rd peak and beyond

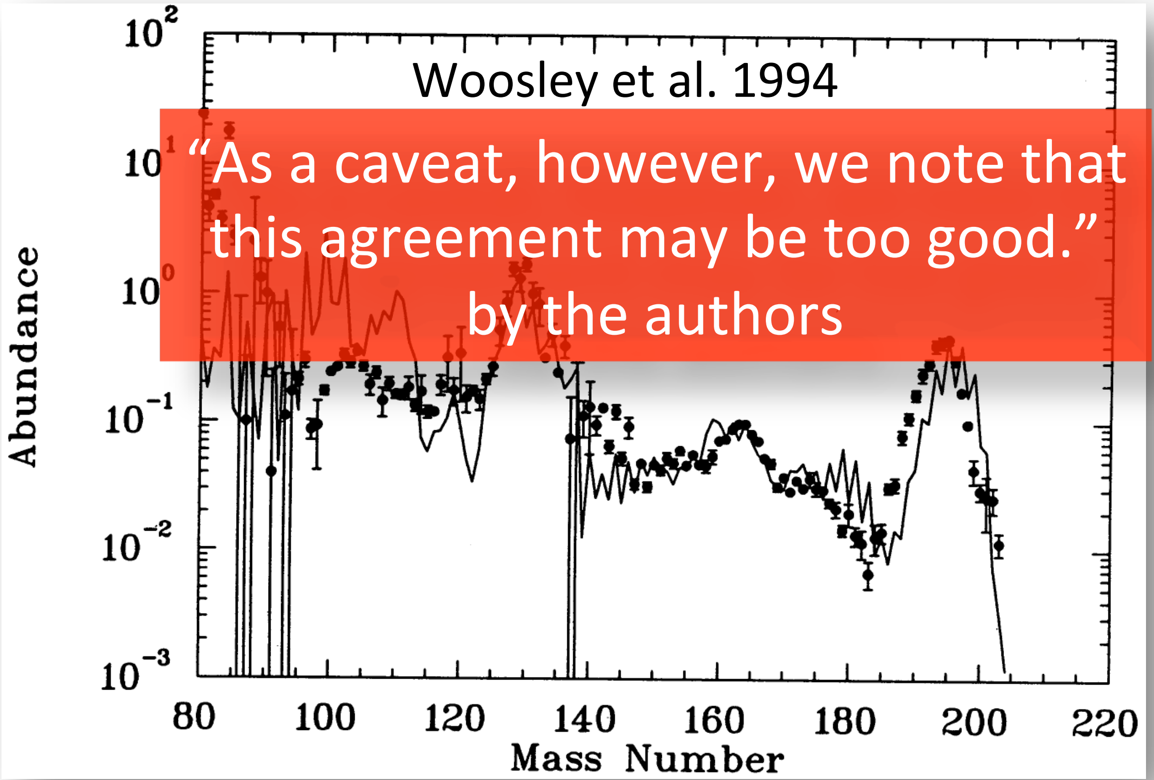




physical condition for making $A \geq 200$ (Hoffman+1997)

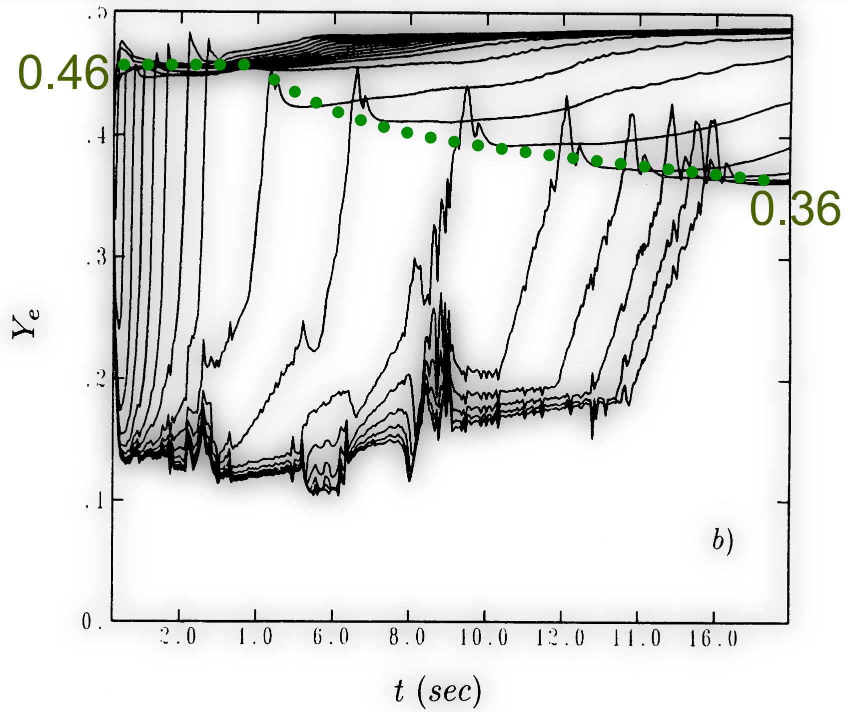
- high entropy scenario ($S > 100\ k_B\ \mathrm{nuc}^{-1}$)
  $f_{200} = (S / 230\ k_B\ \mathrm{nuc}^{-1})^3 / [(Y_e / 0.4)^3 (\tau / 20\ \mathrm{ms})] \geq 1$
- low entropy scenario ($S < 100\ k_B\ \mathrm{nuc}^{-1}$)
  $Y_e < 0.2$ with any S, τ

high-entropy SN neutrino-driven wind

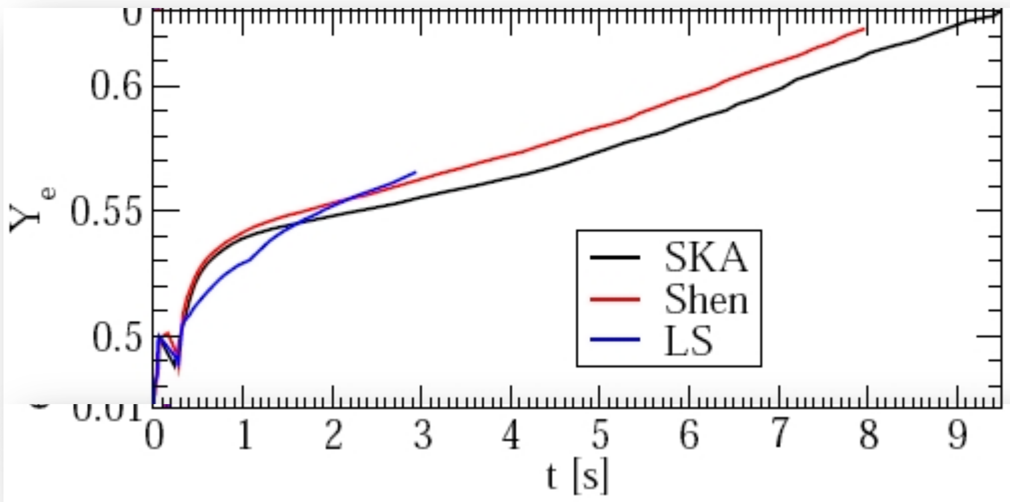


- ❖ successful r-process in the neutrino-driven winds of S_{rad}~400 k_B/nuc (1D hydro, 20 $M_\odot$ star; Meyer+1992; Woosley+1994)
- ❖ but such high entropy is unlikely (< 200 k_B/nuc; Takahashi+1994; Qian+1996; Otsuki+2000)

neutrino-driven wind is “proton-rich” ?



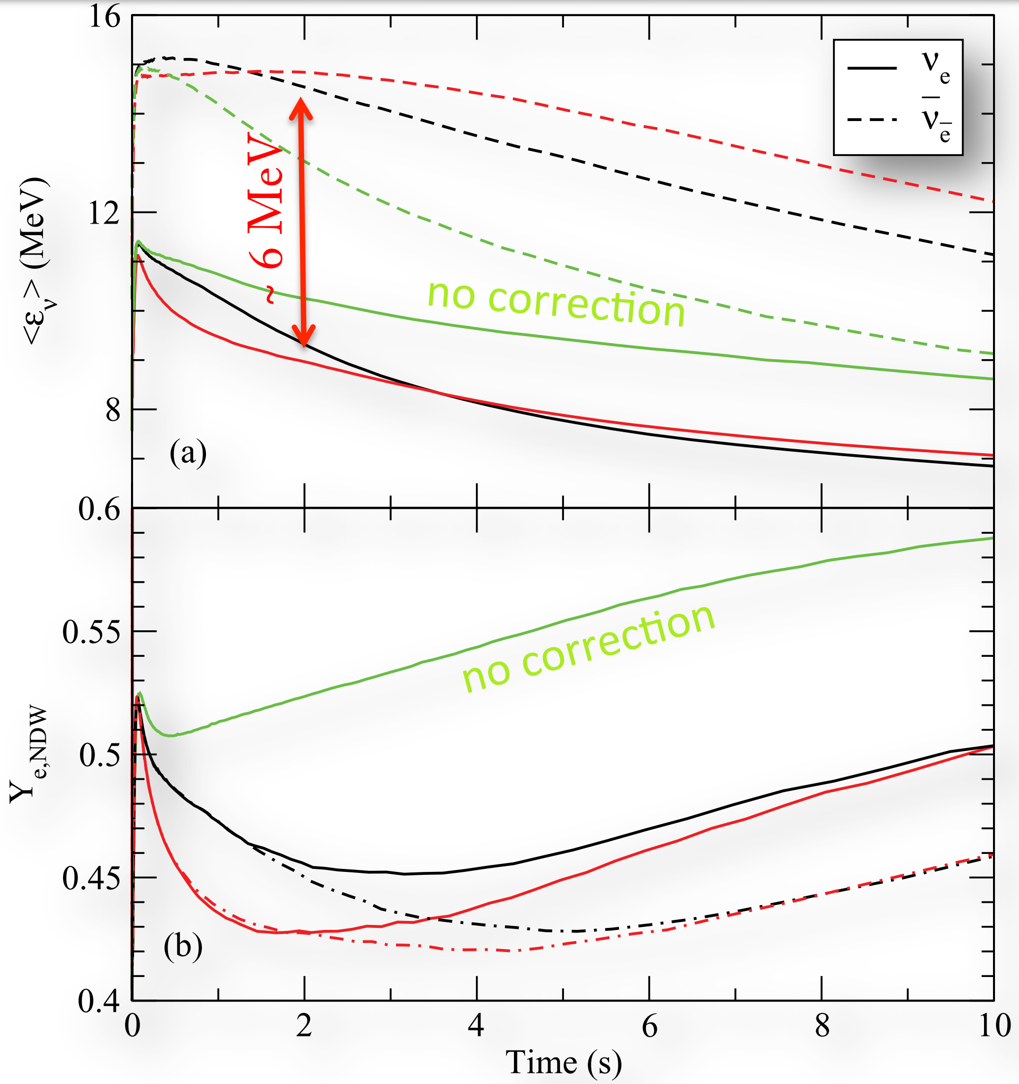
Woosley+1994



self-consistent explosion of a 9 $M_\odot$ star
Hüdepohl+2009

- $Y_e > 0.5$ in all recent neutrino-transport simulations because of similar neutrino energies and luminosities for all flavors (i.e., protons are favored due to the p-n-mass difference)
- no r-process is expected regardless of S or τ??

no, PNS wind is "slightly" n-rich!?

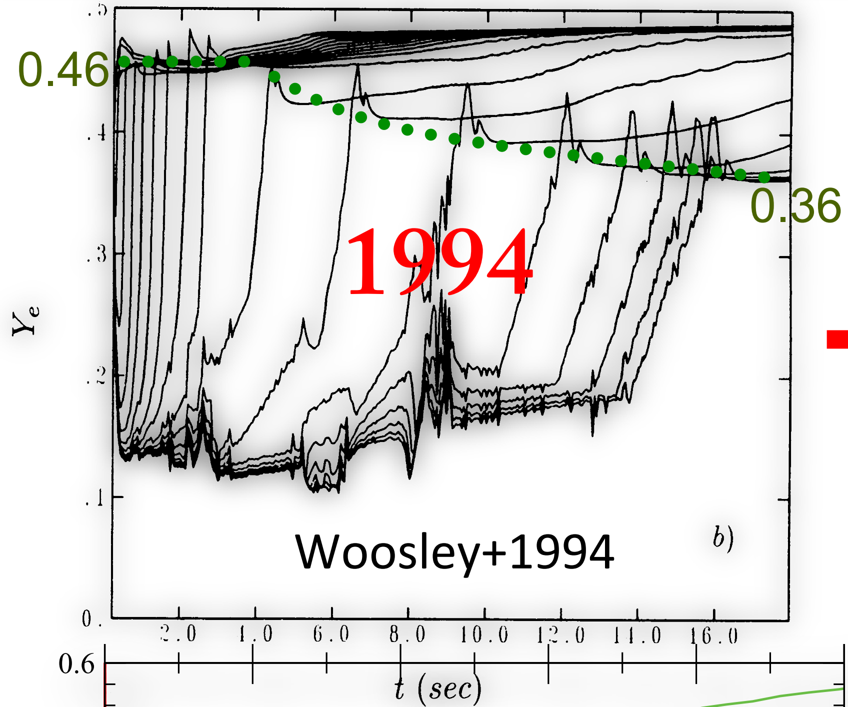


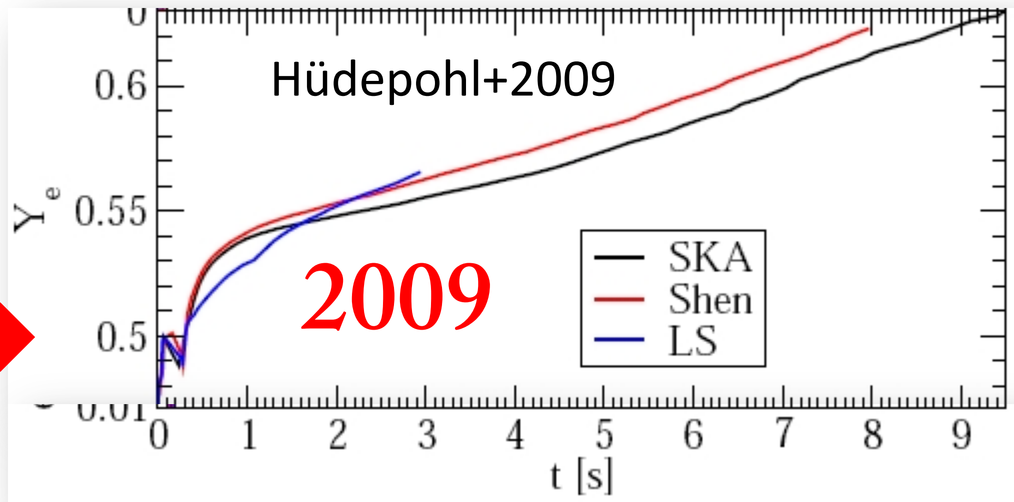
Roberts+2012

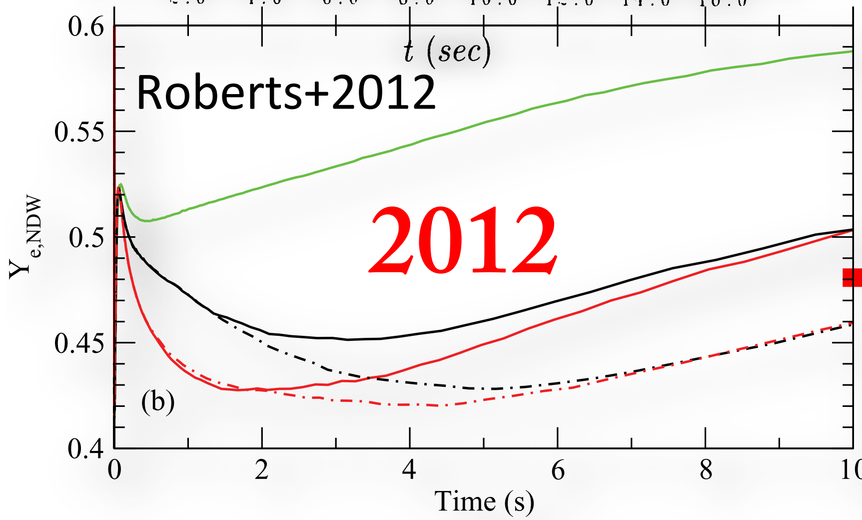
- for $\rho > 10^{13}$ g cm^{-3}, symmetry energy enhances ν_e + n and suppress $\bar{\nu}_e$ + p (Reddy+1998; Roberts +2012; M.-Pinedo+2012)

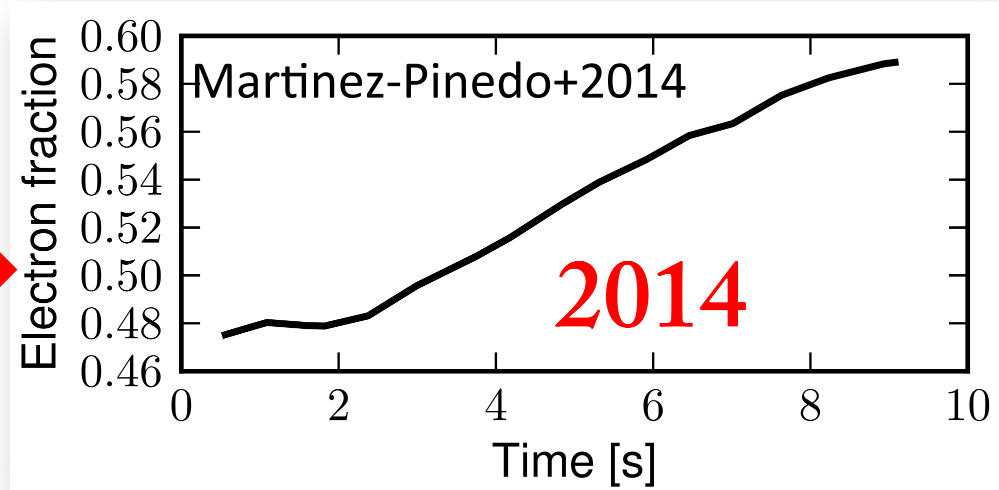
- proto-NS wind can be n-rich (down to Y_e ~ 0.4 ?) in the early phase, NOT in the late phase (Pauli-blocking for charged current reactions; Fischer +2012)

“history” of Y_e evolutions: who is right?

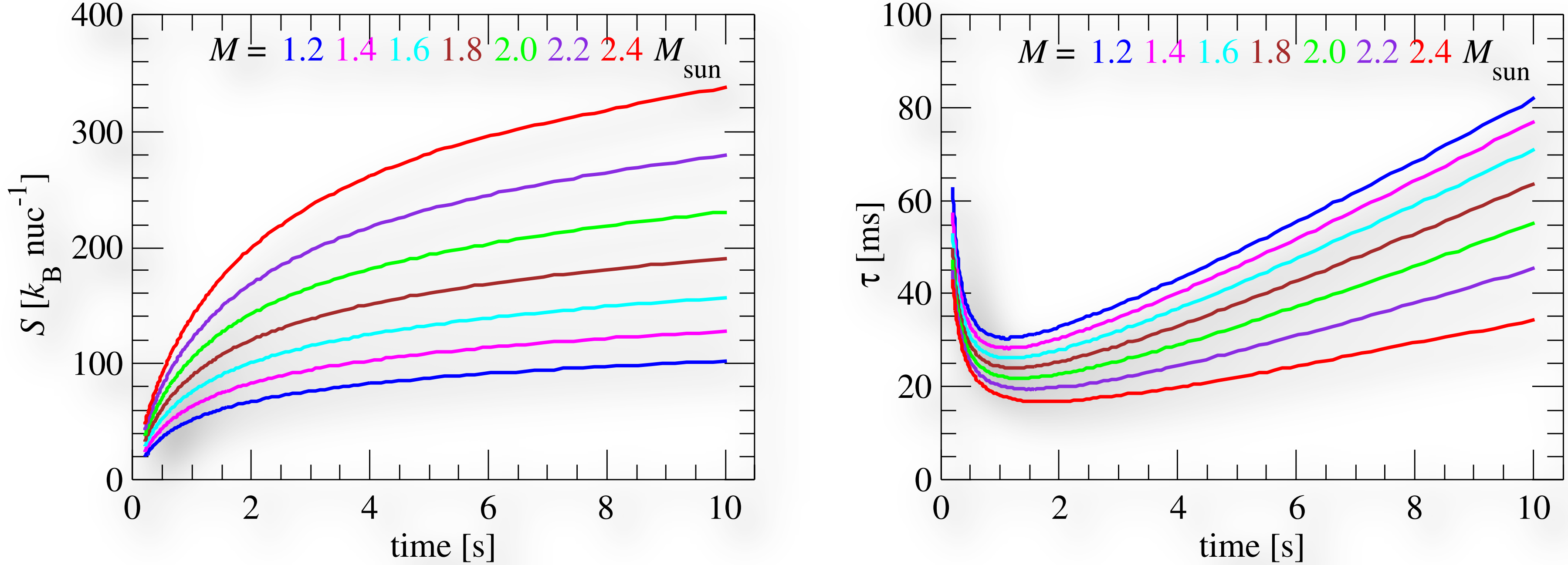








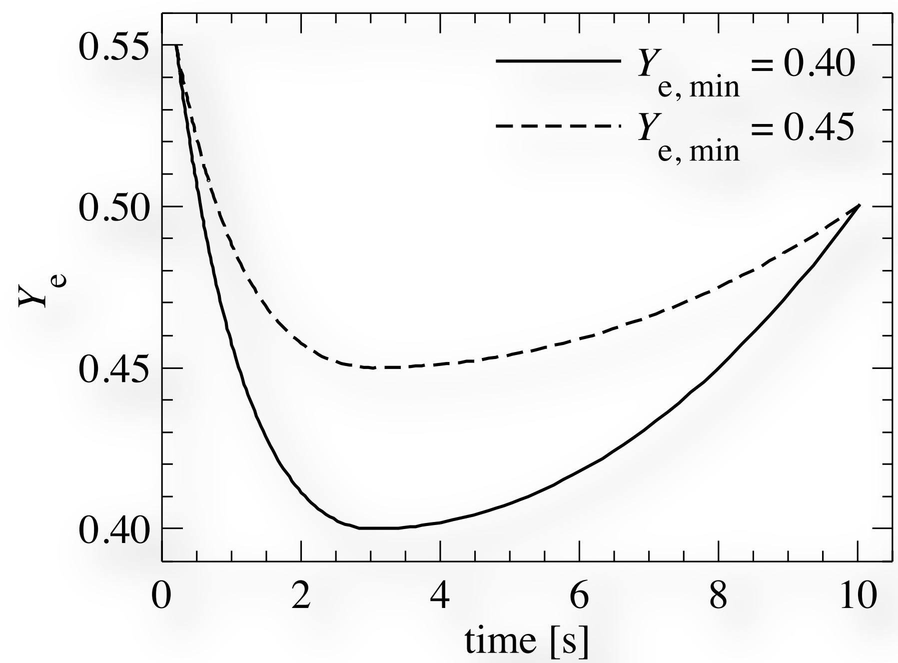
is the answer blowing in the wind?

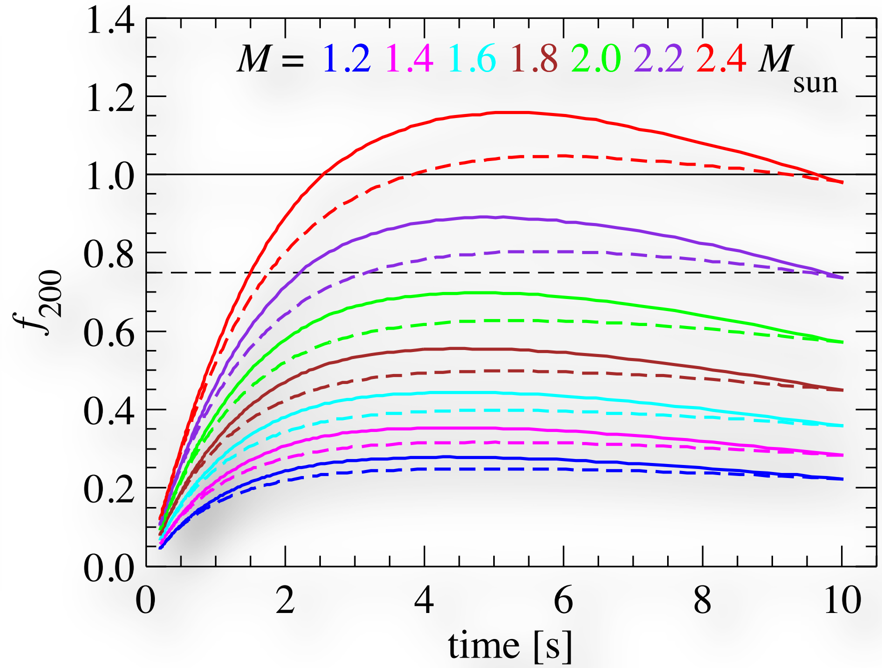


semi-analytic full-GR wind model (Wanajo 2013)

- ❖ $M_{\rm NS}$ = 1.2, 1.4, …, 2.4 [$M_\odot$]
- ❖ $R_{\rm NS}$ = 30 $(t/t_0)^{-1}$ + 10 [km]; t_0 = 0.2 ≤ t ≤ 10.2 [s]
- ❖ L_ν = 40 $(t/t_0)^{-1}$ [10^{51} erg s^{-1}] for all flavors
- ❖ $\langle\varepsilon_\nu\rangle$ = 12, 14, 14 [MeV] for ν_e, $\bar{\nu}_e$, and the others

is the answer blowing in the wind?

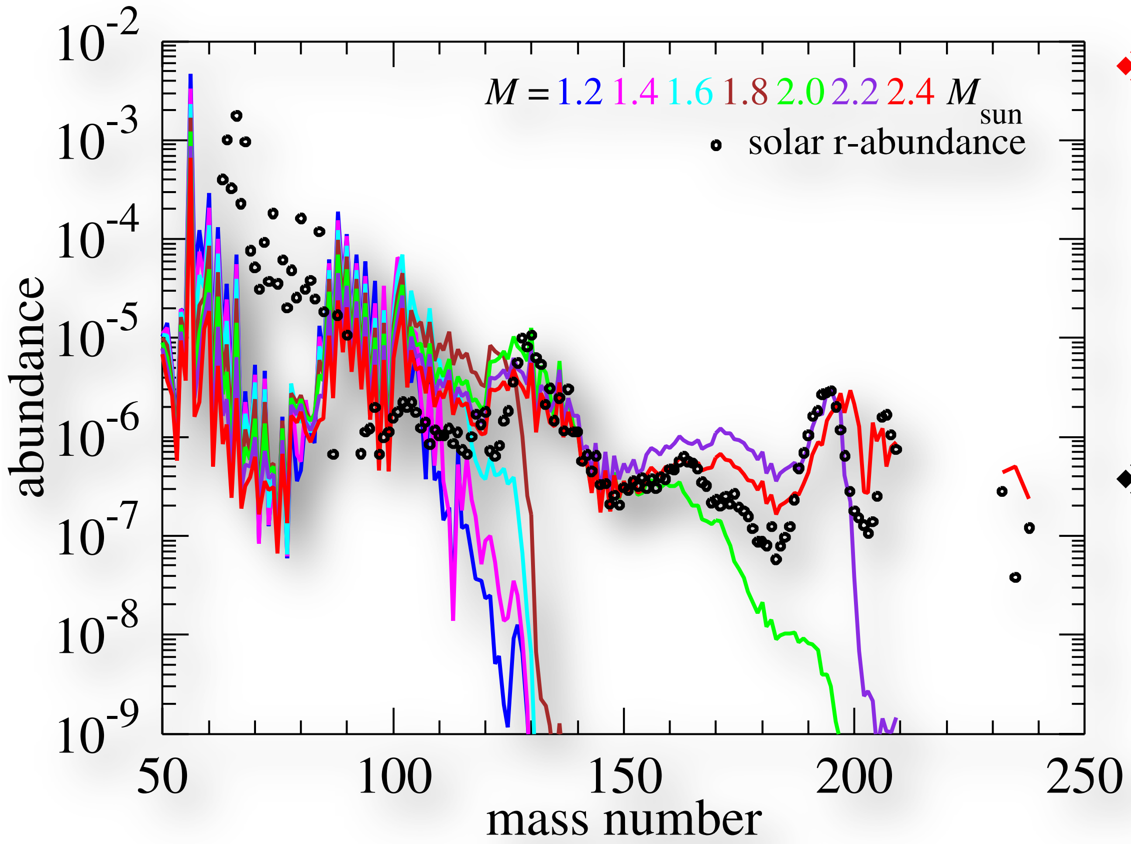




ad hoc Y_e evolution (to mimic Roberts+2012)

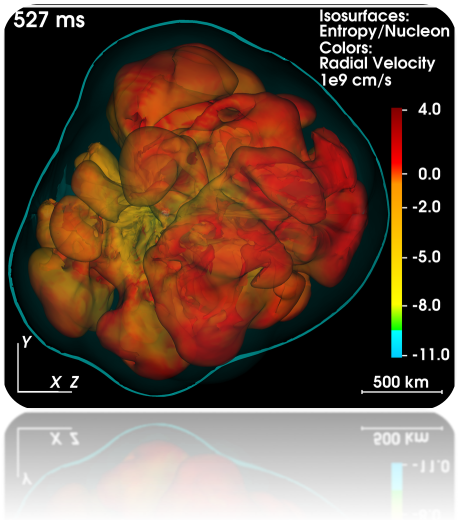
❖ only very massive proto-NSs (> 2.2 $M_\odot$) satisfy $f_{200} \geq 1$

is the answer blowing in the wind?



Wanajo 2013

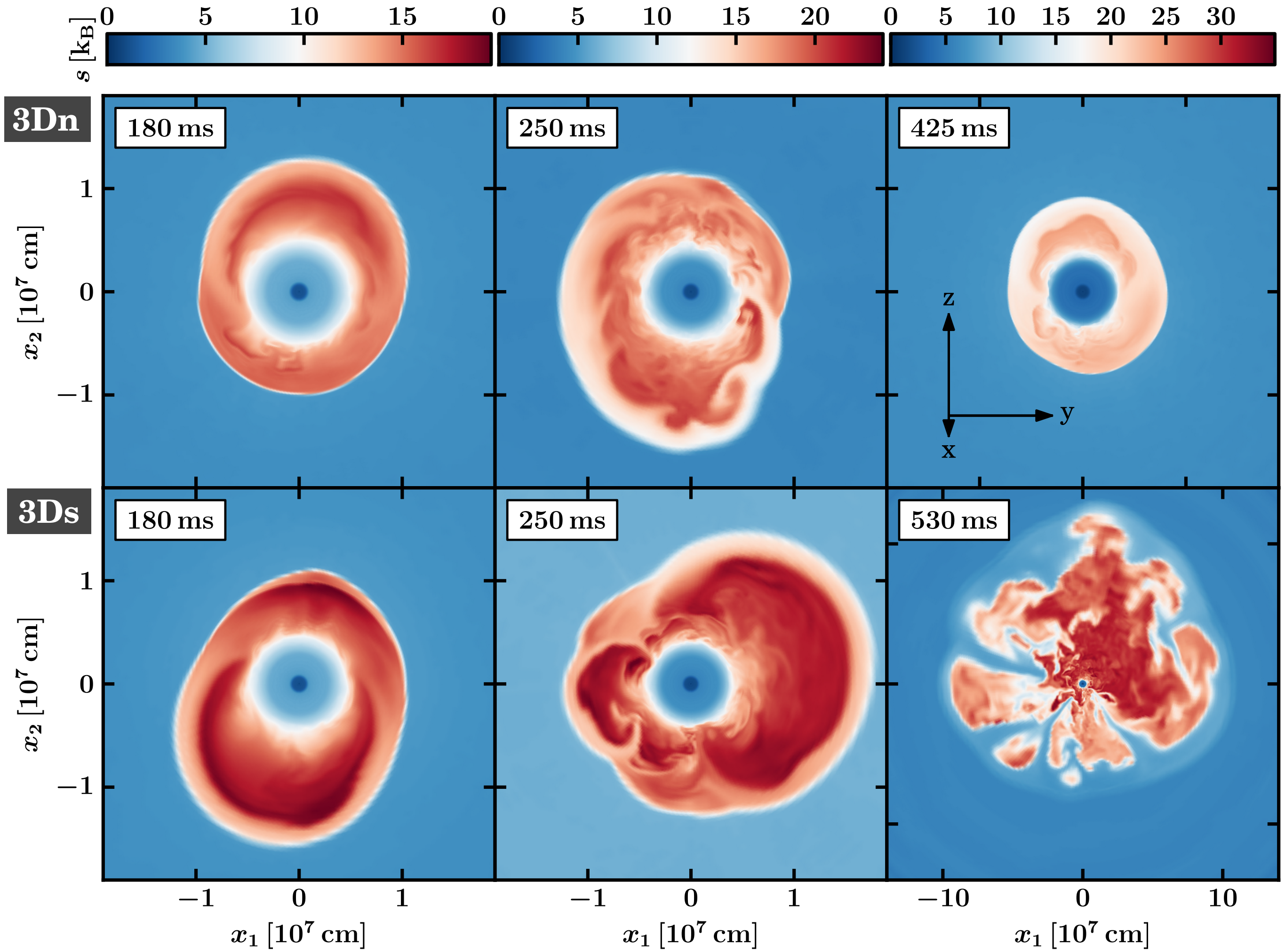
- only (unrealistically) massive proto-NSs ($> 2.2\ M_{\odot}$) make the heavy r-elements
- typical proto-NSs ($< 2.0\ M_{\odot}$) make weak r-elements ($A \sim 90 – 130$) only



3. how close to successful supernova explosions?
   sensitivity to neutrino opacity (Melson+2015)

strange quarks help the explosion?

Melson+2015



3D SN simulation
(20 $M_\odot$)

- without s
  ($g_a^s = 0$)
  explosion failed

- with s quarks
  ($g_a^s = -0.2$)
  explosion
  succeeded!!!

strange quarks help the explosion?

- lowest-order differential neutrino-nucleon scattering cross section

$$\frac{d\sigma_0}{d\Omega} = \frac{G_F^2 \epsilon^2}{4\pi^2} \left[c_v^2 (1 + \cos\theta) + c_a^2 (3 - \cos\theta) \right]$$

- strange quark contribution g_a^s (≤ 0)

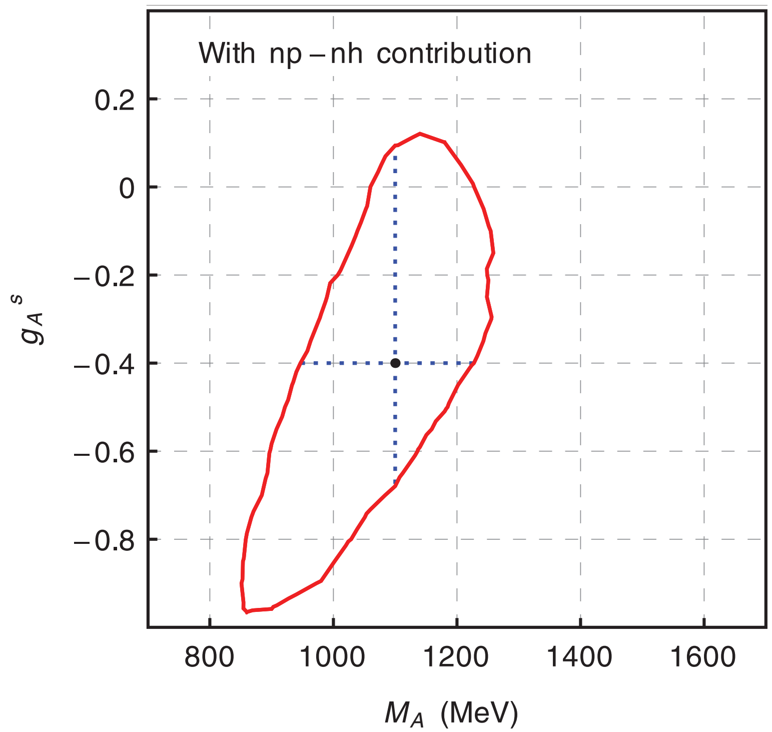
$$c_a = \frac{1}{2}(\pm g_a - g_a^s)$$ where the plus sign is for νp and the minus sign for νn

- c_a^2 decreases in the (n-rich) neutrinospheric region
  → ~10% reduction of neutral-current opacity ($g_a = 1.26$, $g_a^s = -0.2$)
  → ~10% increase of neutrino luminosities and mean energies
  → more efficient neutrino heating in the gain region

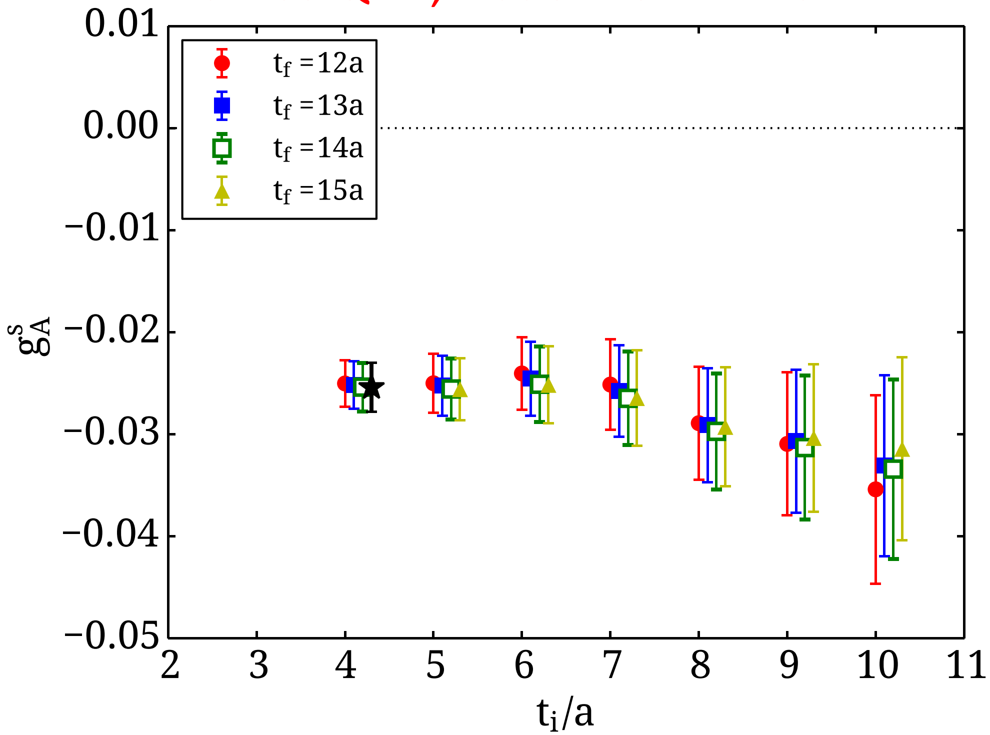
- only a 10% change of neutrino opacity can help the explosion !!!

strange quarks help the explosion?

MiniBooNE; Golan+2013



lattice QCD; Abdel-Rehim+2014



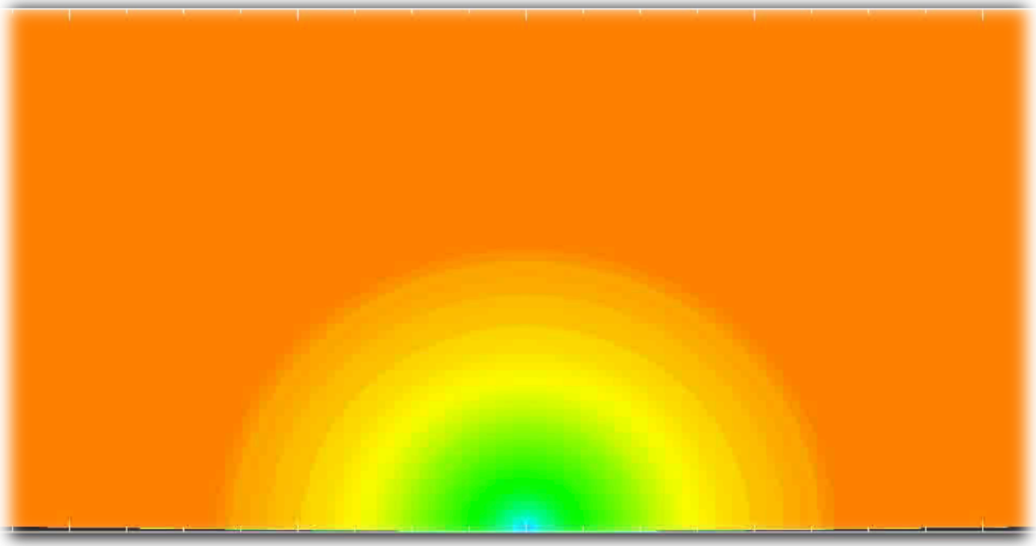
experiments

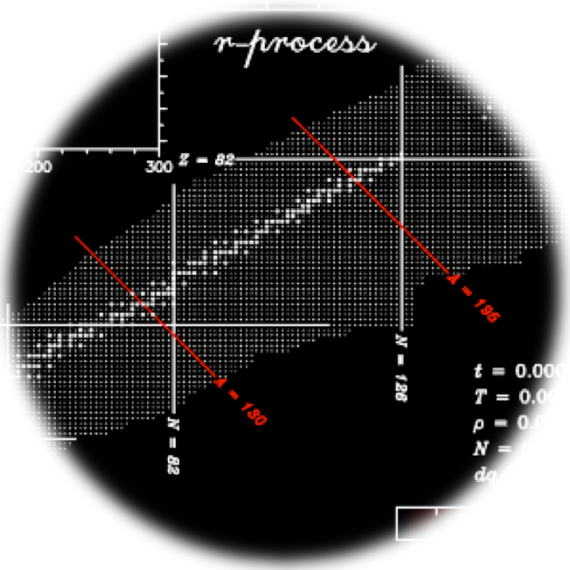
- ❖ large (negative) value with large errors: $g_a{}^s = -0.8$ to 0

theory

- ❖ small (negative) value with small errors: $g_a{}^s = -0.05$ to -0.02

summary





- core-collapse SNe can make light trans-iron elements (Zn to Zr) but r-process elements (see NS merger works; Wanajo+2014)
- nucleosynthesis in the innermost ejecta is higly sensitive to neutrino spectra; a few percent accuracy for Y_e is needed
- 10% change of neutrino opacity can help SN explosions