Asymmetric Nuclear Light Clusters in Supernova Matter

A.V. Yudin

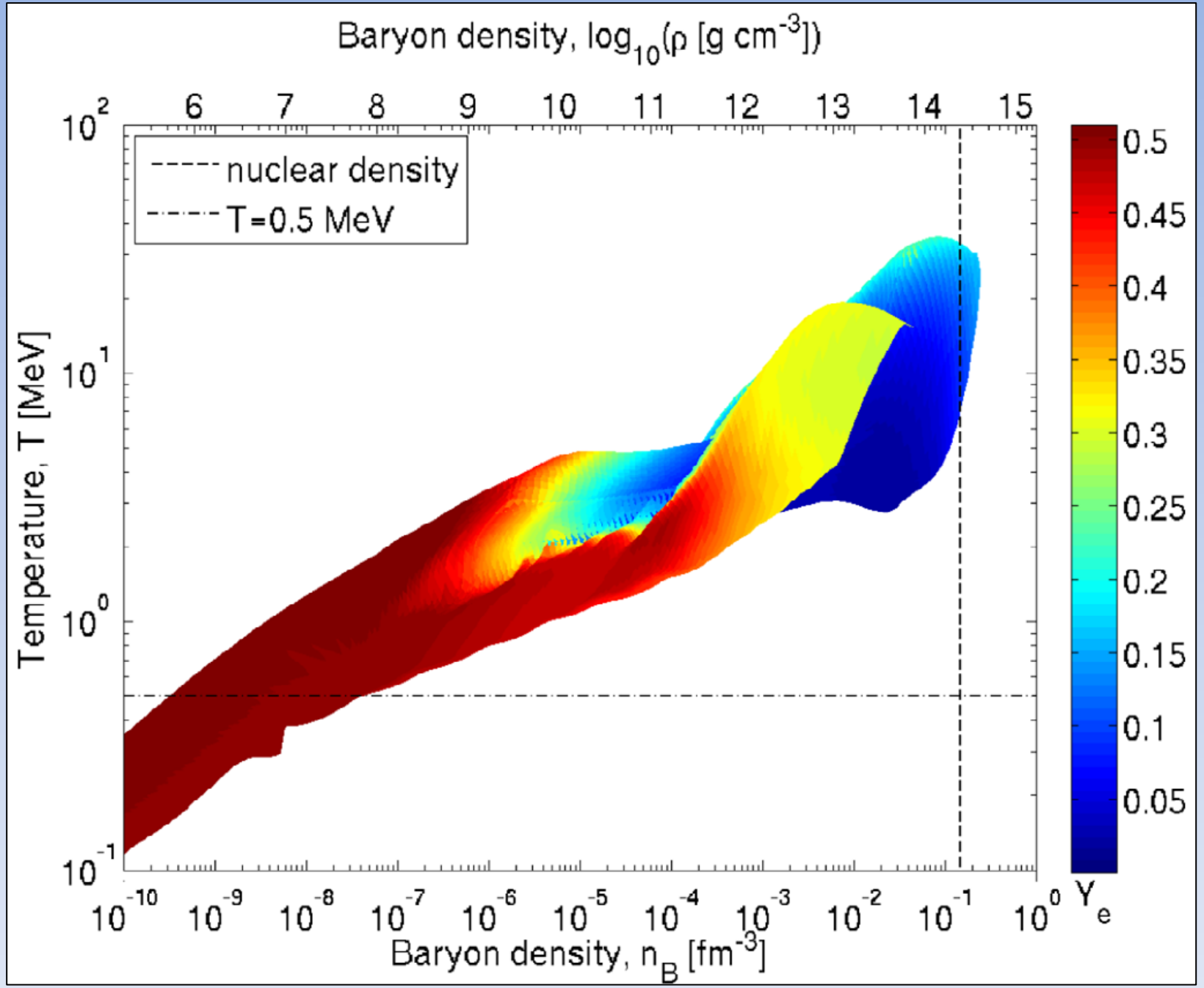
in collaboration with:

M. Hempel, S.I. Blinnikov,

D.K. Nadyozhin and I.V. Panov

“The Periodic Table through Space and Time’’

St.-Petersburg, 11.09.2019



From: T. Fischer, M. Hempel, I. Sagert, Y. Suwa, and J. Schaffner-Bielich, Eur. Phys. J. A (2014) 50: 46

Equation of state under Nuclear Statistical Equilibrium conditions

$$^{56}\mathrm{Fe} \rightleftharpoons 26\,\mathrm{p} + 30\,\mathrm{n}$$

$$(T-\rho-\theta)$$

$$Y_i = \frac{n_i m_u}{\rho}, \quad Y_e = \frac{1}{1+\theta}$$

$$\mu_{A,Z} = (A-Z)\mu_n + Z\mu_p$$

$$\begin{cases} Y_n + \sum_{A,Z}(A-Z)Y_{A,Z} = \dfrac{\theta}{1+\theta} \\ Y_p + \sum_{A,Z} Z\,Y_{A,Z} = \dfrac{1}{1+\theta} \end{cases}$$

$$Y_{A,Z} = \omega_{A,Z}\mu_{A,Z}^{3/2}\frac{m_u}{\rho\lambda_T^3}\exp\left[(A-Z)\psi_n + Z\psi_p + \frac{Q_{A,Z}}{kT}\right]$$

Nuclides taken into account

Z	A	I_{gs}	N_{ex}	Z	A	I_{gs}	N_{ex}
He 2	**4**	0	15	Fe 26	52,53,**54**	0, 3.5, 0	20, 21, 50
C 6	**12**	0	55		55,**56,57**	1.5, 0, 0.5	42, 111, 65
O 8	**16**	0	75		**58**,59,60	0, 1.5, 0	66, 40, 24
Ne 10	**20**	0	131		61,62	1.5, 0	4, 10
Mg 12	**24**	0	94	Co 27	55,56,57	3.5, 4, 3.5	72, 26, 94
Si 14	**28**	0	188		58,**59**,60	2, 3.5, 5	92, 73, 105
S 16	**32**	0	25		61,62,63	3.5, 2, 3.5	29, 15, 6
Ar 18	**36**	0	33		64,65	1, 3.5	8, 1
Ca 20	**40**,41,**42**	0, 3.5, 0	98, 28, 107	Ni 28	56,57,**58**	0, 1.5, 0	22, 2, 30
	43,44,45	3.5, 0, 3.5	73, 71, 41		59,**60,61**	1.5, 0, 1.5	68, 82, 76
	46,47,**48***	0, 3.5, 0	46, 15, 10		**62**,63,**64**	0, 0.5, 0	67, 12, 64
Sc 21	43,44,**45**	3.5, 2, 3.5	66, 56, 85		65,66	2.5, 0	10, 20
	46,47,48	4, 3.5, 6	96, 41, 46	Cu 29	61,62,**63**	1.5, 0, 1.5	58, 65, 80
	49	3.5	1		64,**65**,66	1, 1.5, 1	90, 19, 18
Ti 22	44,45,**46**	0, 3.5, 0	26, 24, 104		67,68,69	1.5, 1, 1.5	2, 3, 6
	47,48,49	2.5, 0, 3.5	66, 218, 35	Zn 30	**64**,65,**66**	0, 2.5, 0	101, 15, 98
	50,51	0, 1.5	39, 13		**67,68**,69	2.5, 0, 0.5	29, 50, 27
V 23	47,48,49	1.5, 4, 3.5	21, 52, 79		**70**	0	22
	50*,**51**,52	6, 3.5,3	65, 109, 30	Ga 31	**69,71**	1.5, 1.5	17, 15
	53	3.5	22	Ge 32	**70**,71,**72**	0, 0.5, 0	115, 58, 112
Cr 24	48,49,**50**	0, 2.5, 0	17, 11, 79		**73,74**,75	4.5, 0, 0.5	8, 137, 49
	51,**52,53**	3.5,0,1.5	100, 86, 65		**76***	0	68
	54,55,56	0,1.5,0	61, 31, 21	As 33	71,**75**	2.5, 1.5	24, 58
	57	1.5	1	Se 34	**74,76,78**	0, 0, 0	56, 91, 95
Mn 25	51,52,53	2.5, 6, 3.5	44, 41, 65		**80,82***,83	0, 0, 4.5	53, 18, 10
	54,**55**,56	3, 2.5, 3	52, 90, 78		84,85,86	0, 2.5, 0	20, 1, 1
	57,58,59	2.5, 1, 1.5	33, 17, 2		87,88,89	2.5, 0, 2.5	1, 1, 1
				Br 35	**79,81**	1.5, 1.5	53, 42
				Kr 36	**78,80,82**	0, 0, 0	53, 23, 28
					83,84,86	4.5, 0, 0	24, 31, 7

* Stable nuclides are in bold. Formally, the isotopes ^{48}Ca, ^{50}V, ^{76}Ge, and ^{82}Se are unstable. Their half-decay lives are 5.1×10^{19} y, 1.5×10^{17} y, 1.09×10^{21} y, and 1.21×10^{20} y, respectively.

https://www.nndc.bnl.gov/nudat2/

NuDat 2.7

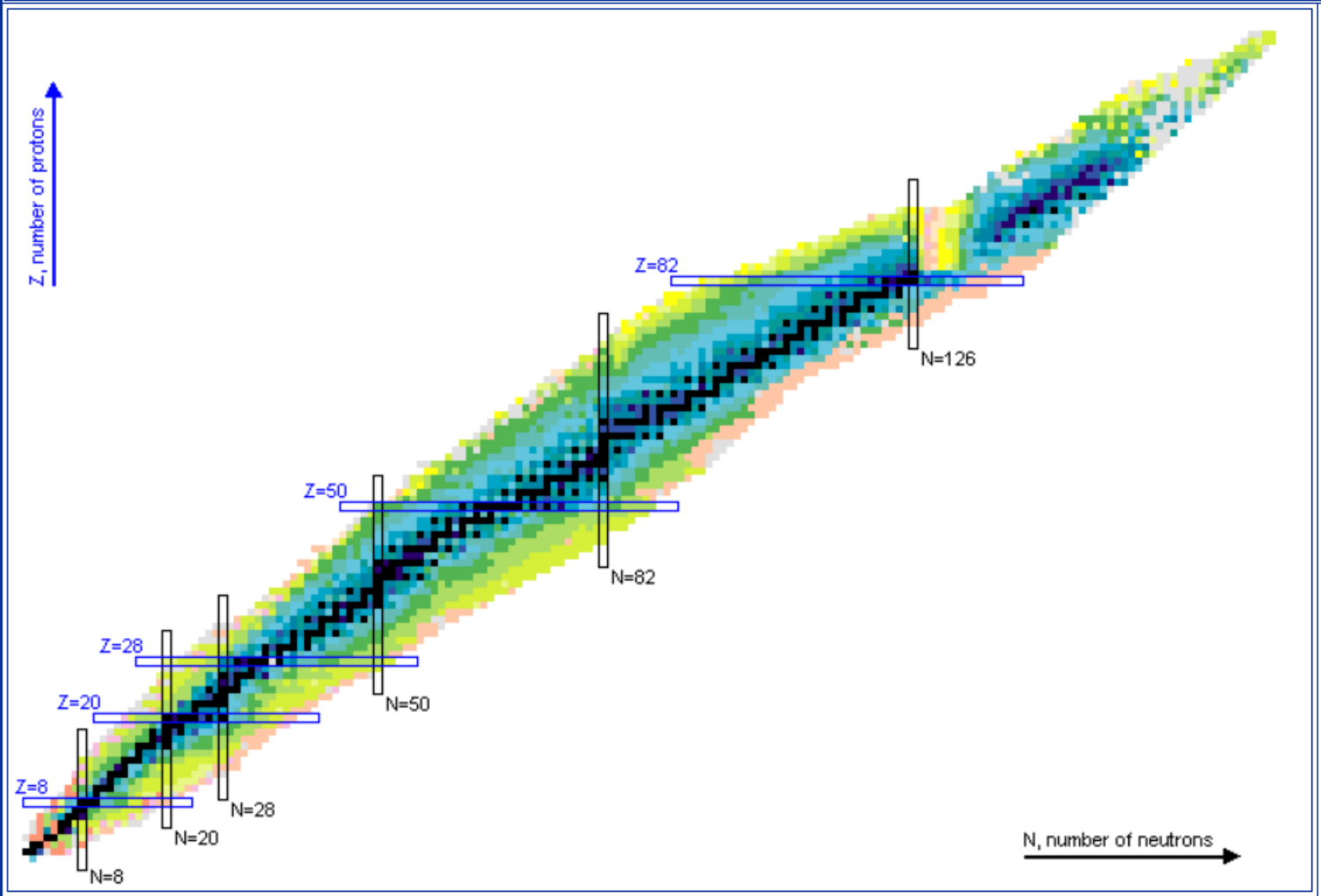
Search and plot nuclear structure and decay data interactively. More.

Levels and Gammas Search
Ground and excited states (energy, $T_{1/2}$, spin/parity, decay modes), gamma rays (energy, intensity, multipolarity, coinc.)

Nuclear Wallet Cards Search
Latest Ground and isomeric states properties

Decay Radiation Search
Radiation type, energy, intensity and dose following nuclear decay

Color code	Half-life	Decay Mode	$Q_{\beta-}$	Q_{EC}	$Q_{\beta+}$	S_n	S_p	Q_α	ΔQ_α	S_{2n}	S_{2p}	$Q_{2\beta-}$	Q_{2EC}	Q_{ECp}	$Q_{\beta-n}$
$Q_{\beta-2n}$	BE/A	(BE-LDM Fit)/A	Pair. gap	$E_{1st\ ex.\ st.}$	E_{2+}	E_{3-}	E_{4+}	E_{4+}/E_{2+}	β_2	$B(E2)_{42}/B(E2)_{20}$	$\sigma(n,\gamma)$	$\sigma(n,F)$	235U FY	239Pu FY	252Cf FY



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Zoom: 1 2 3 4 5 6 7

Uncertainty: NDS / Standard

Screen Size: Narrow / Wide

Nucleus: go

Seconds

> 10+15	10-01
10+10	10-02
10+07	10-03
10+05	10-04
10+04	10-05
10+03	10-06
10+02	10-07
10+01	10-15
10+00	< 10-15
unknown	

Interactive Chart of Nuclides
Click on a nucleus to obtain information

NNDC ENSDF NSR
Nuclear Wallet Cards

NuDat 2.7

Search and plot nuclear structure and decay data interactively. More.

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Ground and excited states (energy, $T_{1/2}$, spin/parity, decay modes), gamma rays (energy, intensity, multipolarity, coinc.)

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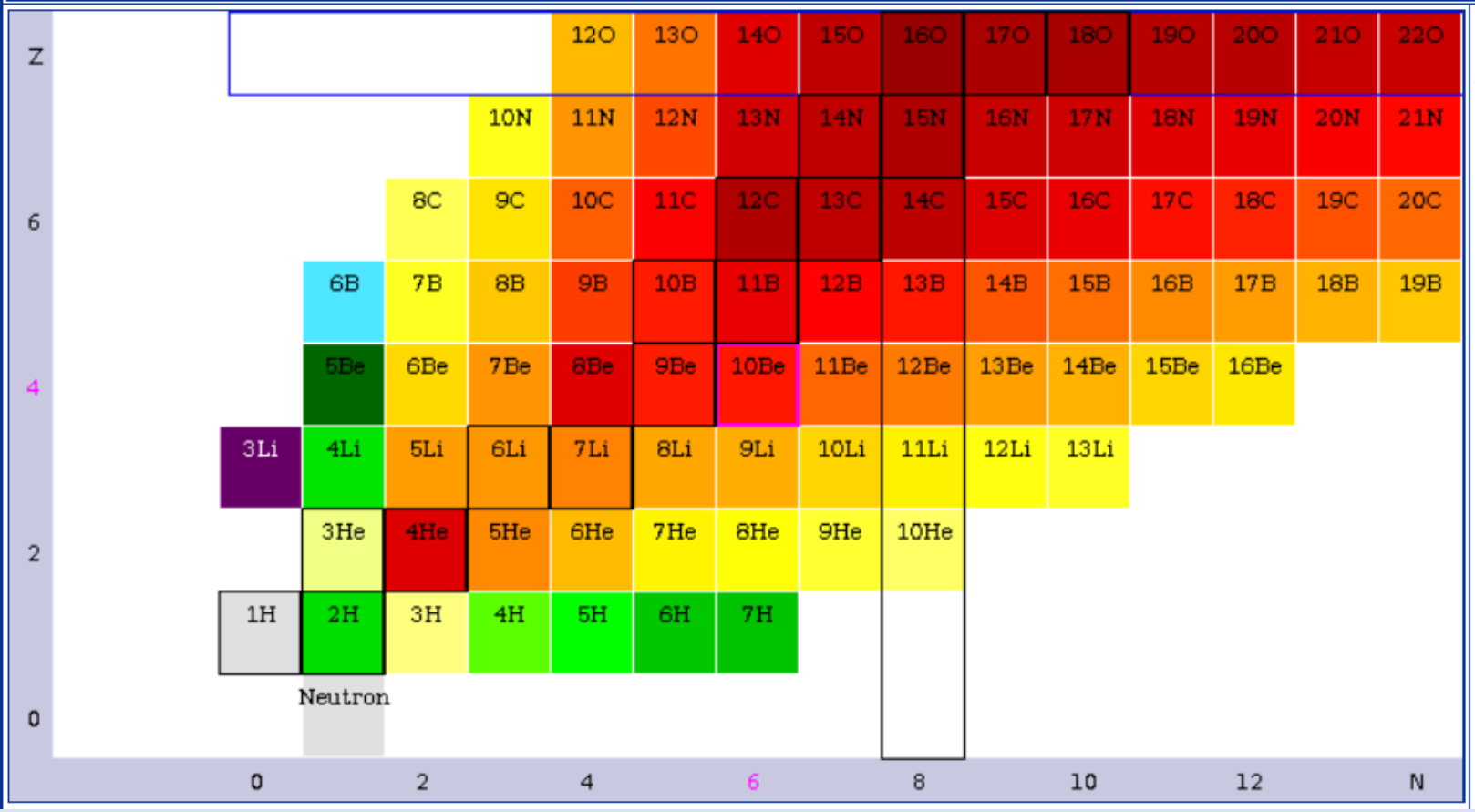
$Q_{\beta-2n}$	BE/A	(BE-LDM Fit)/A	Pair. gap	$E_{1st\ ex.\ st.}$	E_{2+}	E_{3-}	E_{4+}	E_{4+}/E_{2+}	β_2	$B(E2)_{42}/B(E2)_{20}$	$\sigma(n,\gamma)$	$\sigma(n,F)$	235U FY	239Pu FY	252Cf FY



Tooltips
On
Off

Zoom
1
2
3
4
5
6
7

Uncertainty
NDS
Standard

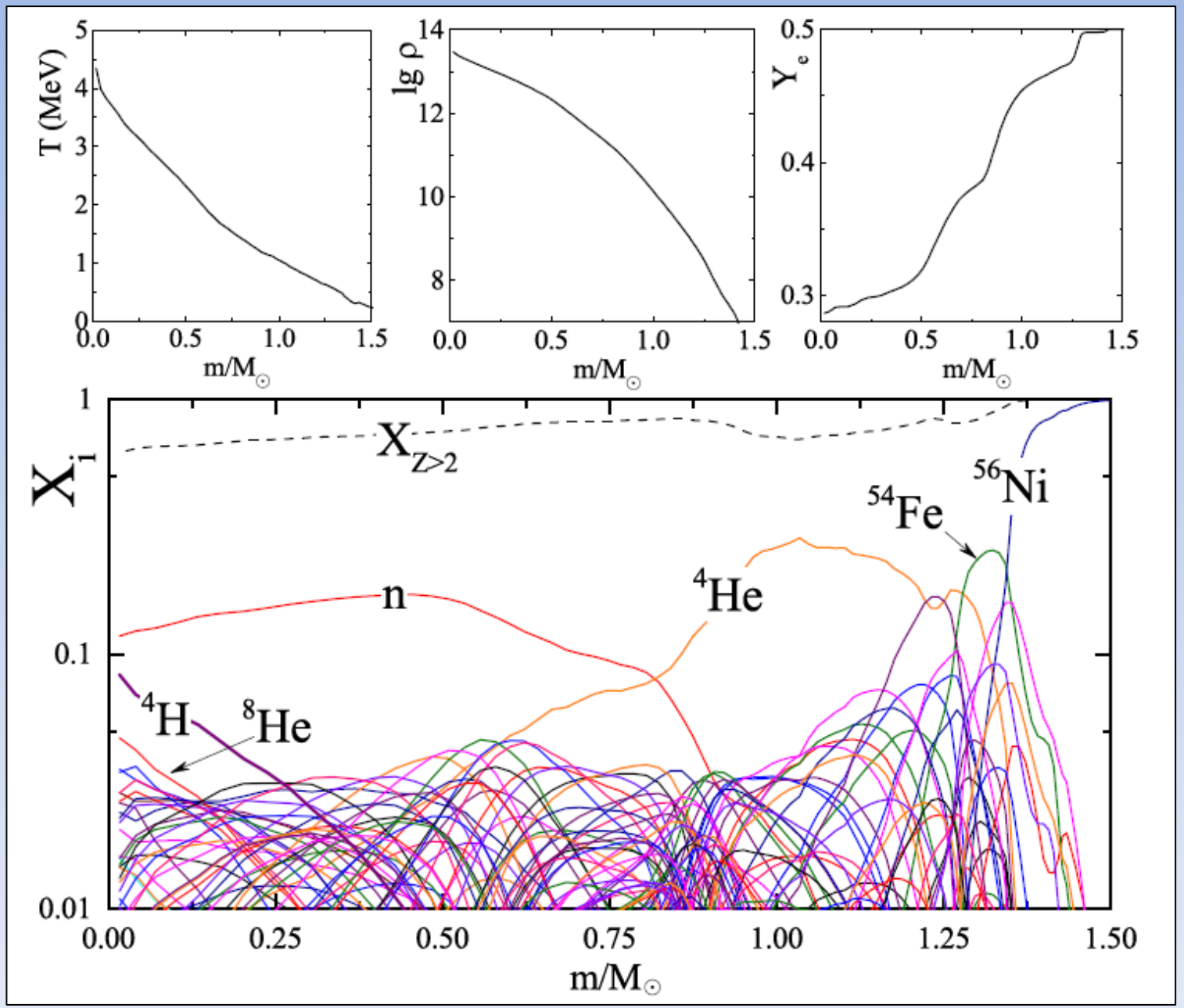
Screen Size
Narrow
Wide

Nucleus
go

keV

8.51E+3	3.12E+3
7.97E+3	2.58E+3
7.43E+3	2.04E+3
6.89E+3	1.50E+3
6.35E+3	9.67E+2
5.81E+3	4.28E+2
5.28E+3	-1.10E+2
4.74E+3	-6.49E+2

Infall Stage of Collapse



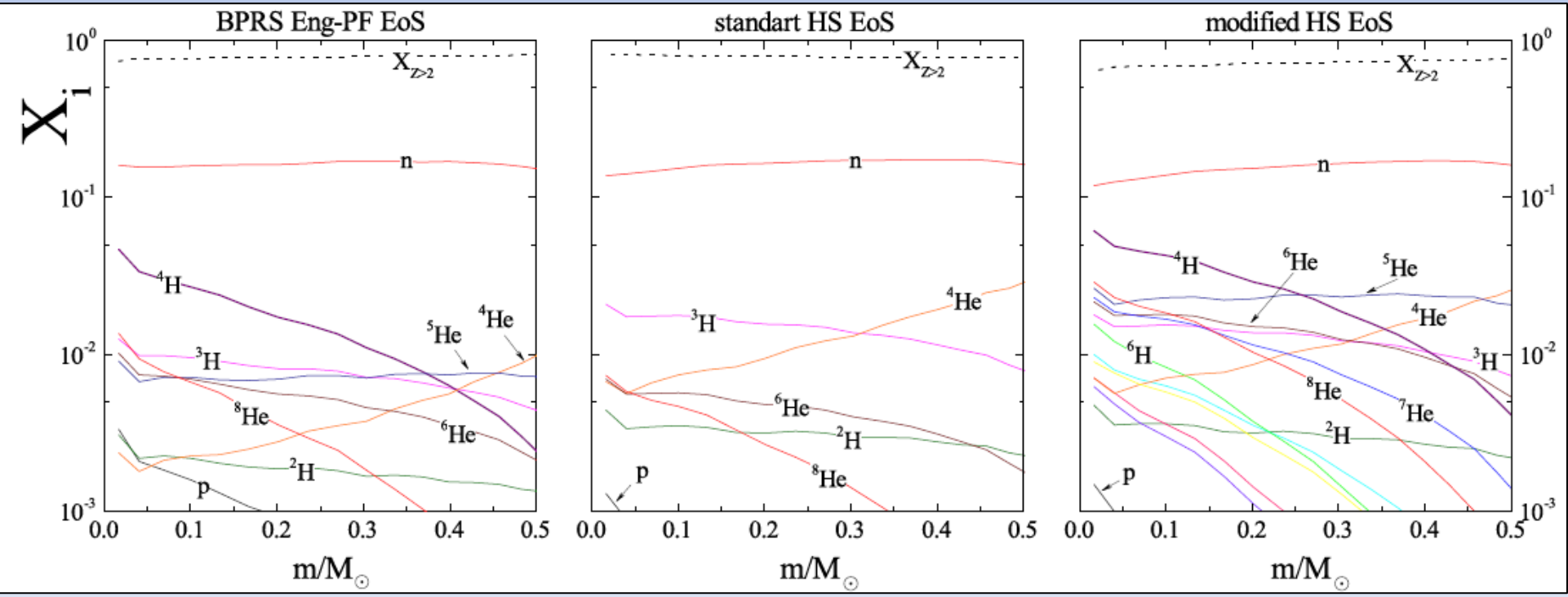
Comparison with other EoSs

The equation of state and composition of hot, dense matter in core-collapse supernovae

S. I. Blinnikov[1,2,3], I. V. Panov[2], M. A. Rudzsky[4], and K. Sumiyoshi[5,6]

A statistical model for a complete supernova equation of state

Matthias Hempel *, Jürgen Schaffner-Bielich



H4 properties

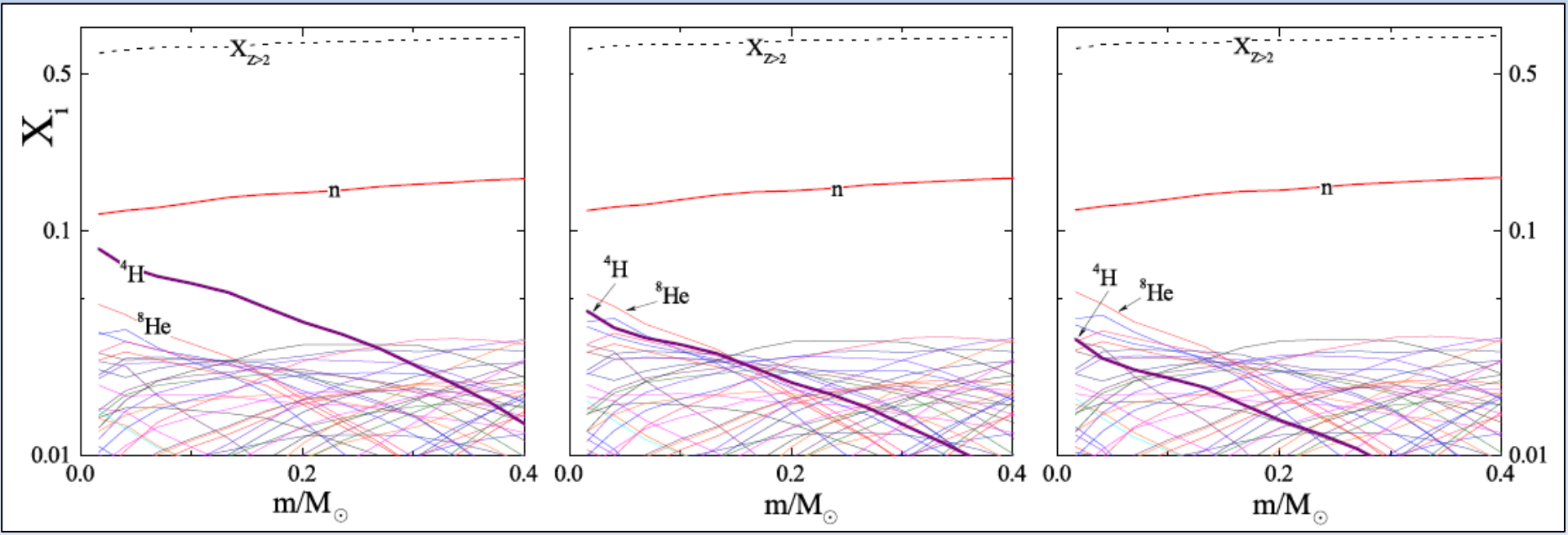
$^2\mathrm{H}(^3\mathrm{H}, p)^4\mathrm{H}$

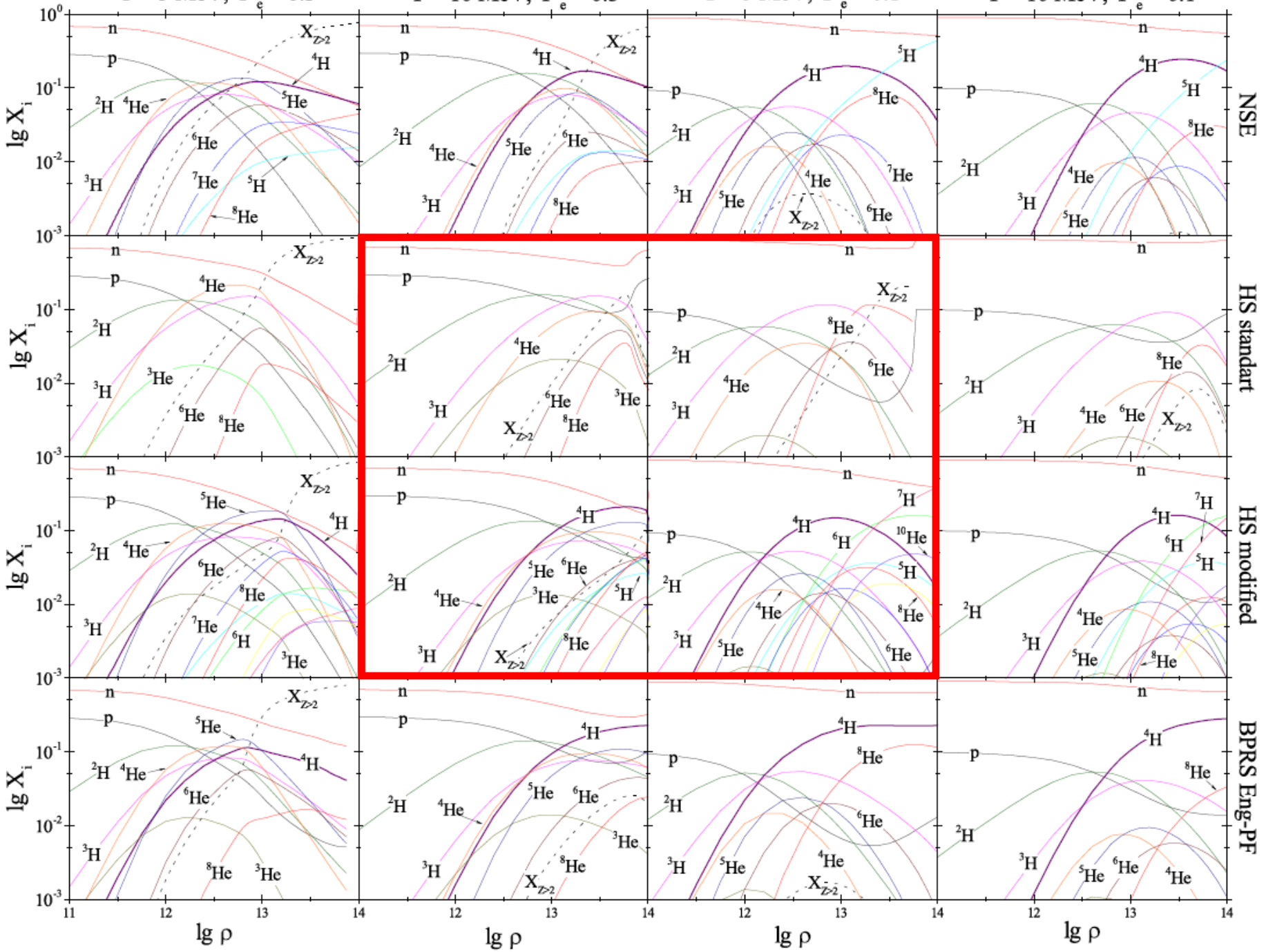
$n + {}^3\mathrm{H} \rightarrow {}^4\mathrm{H}$

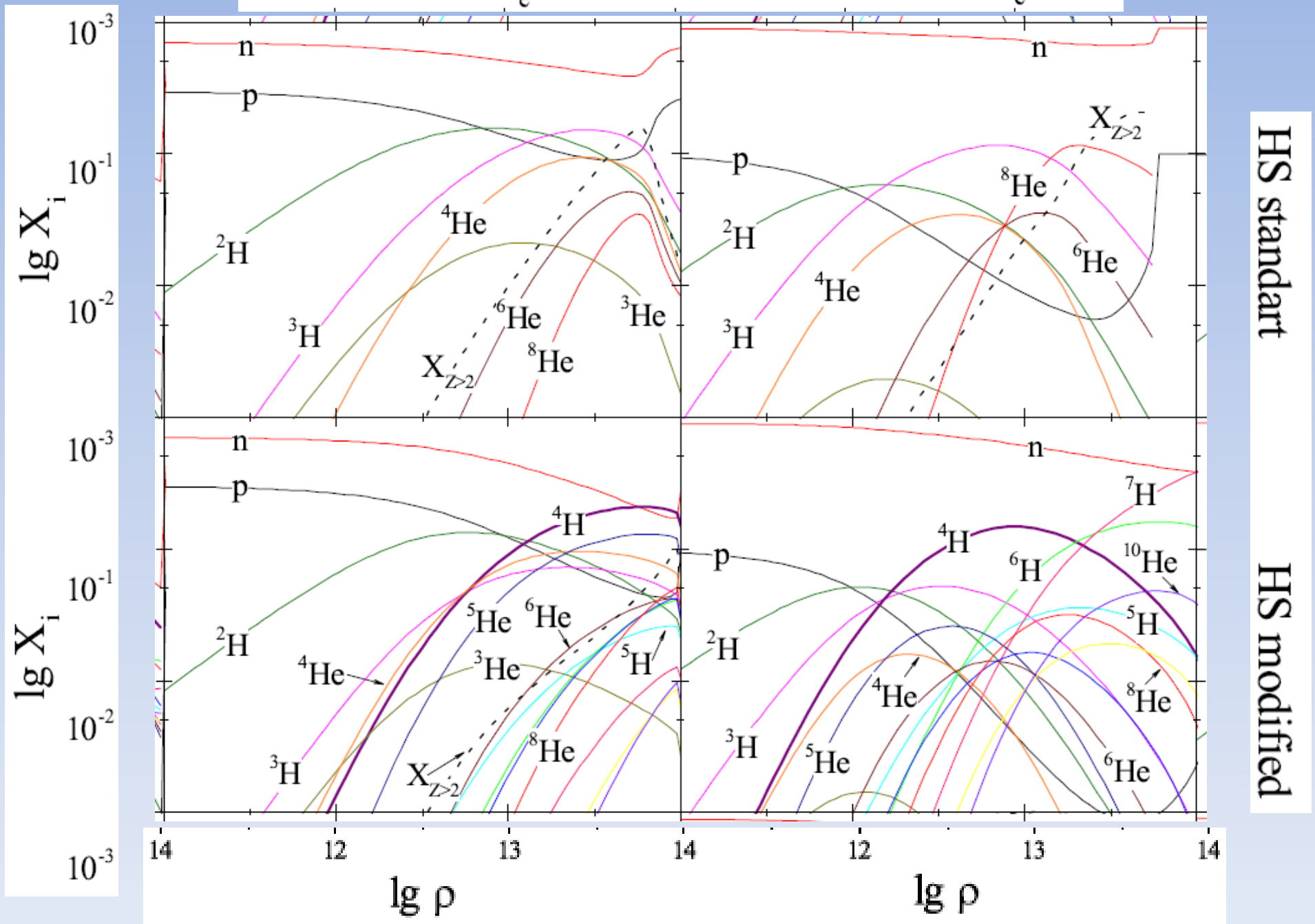
$^3\mathrm{H}(^3\mathrm{H}, {}^2\mathrm{H})^4\mathrm{H}$

E_{ex} (MeV)	Spin j	τ (10^{-22} sec)
0	2	1.43
0.31	1	0.98
2.08	0	0.74
2.83	1	0.51

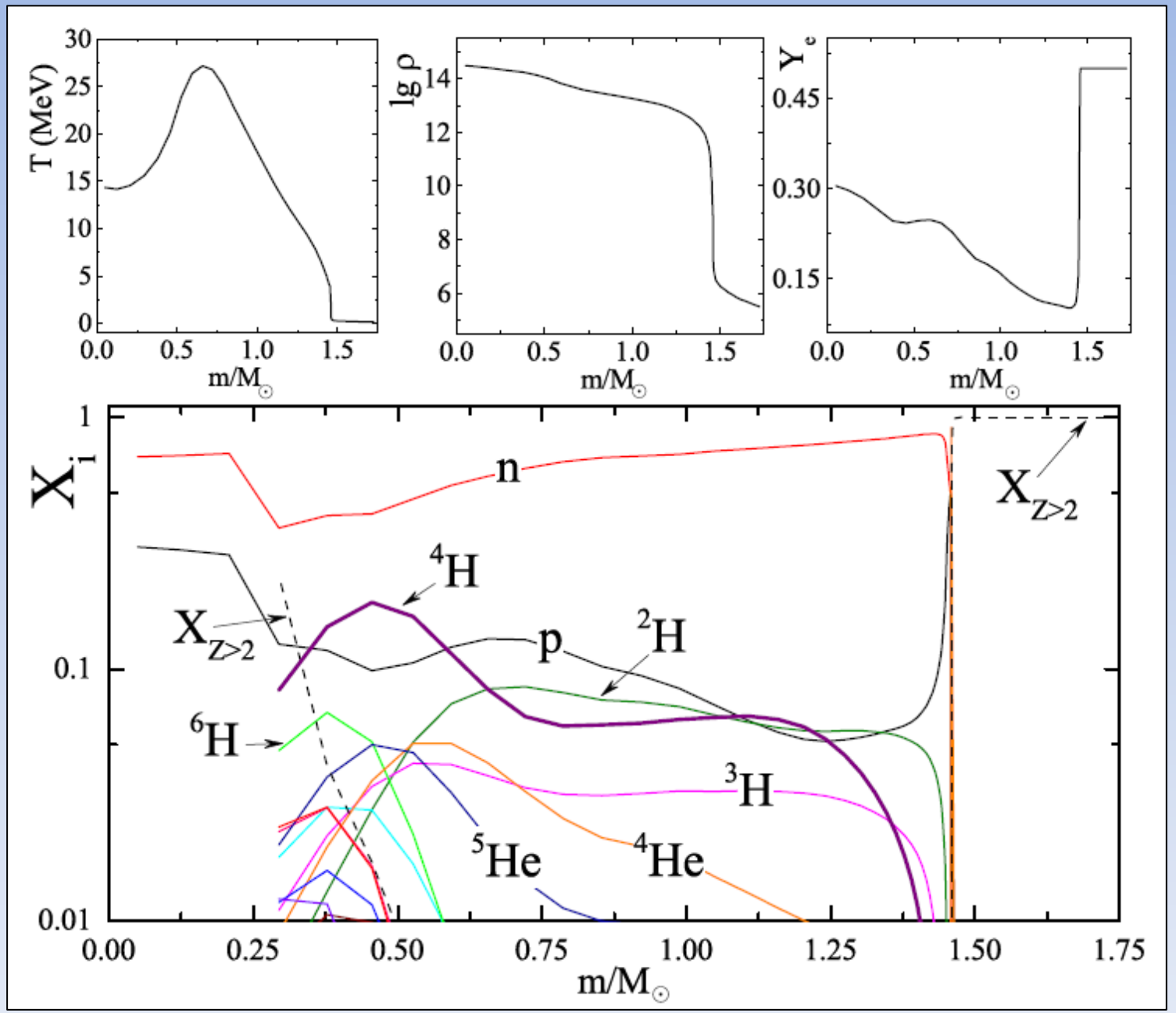
q=Q/A=1.72 MeV
(Audi et al 2015)
or
q=Q/A=1.394 MeV
(Audi and Wapstra 1995)



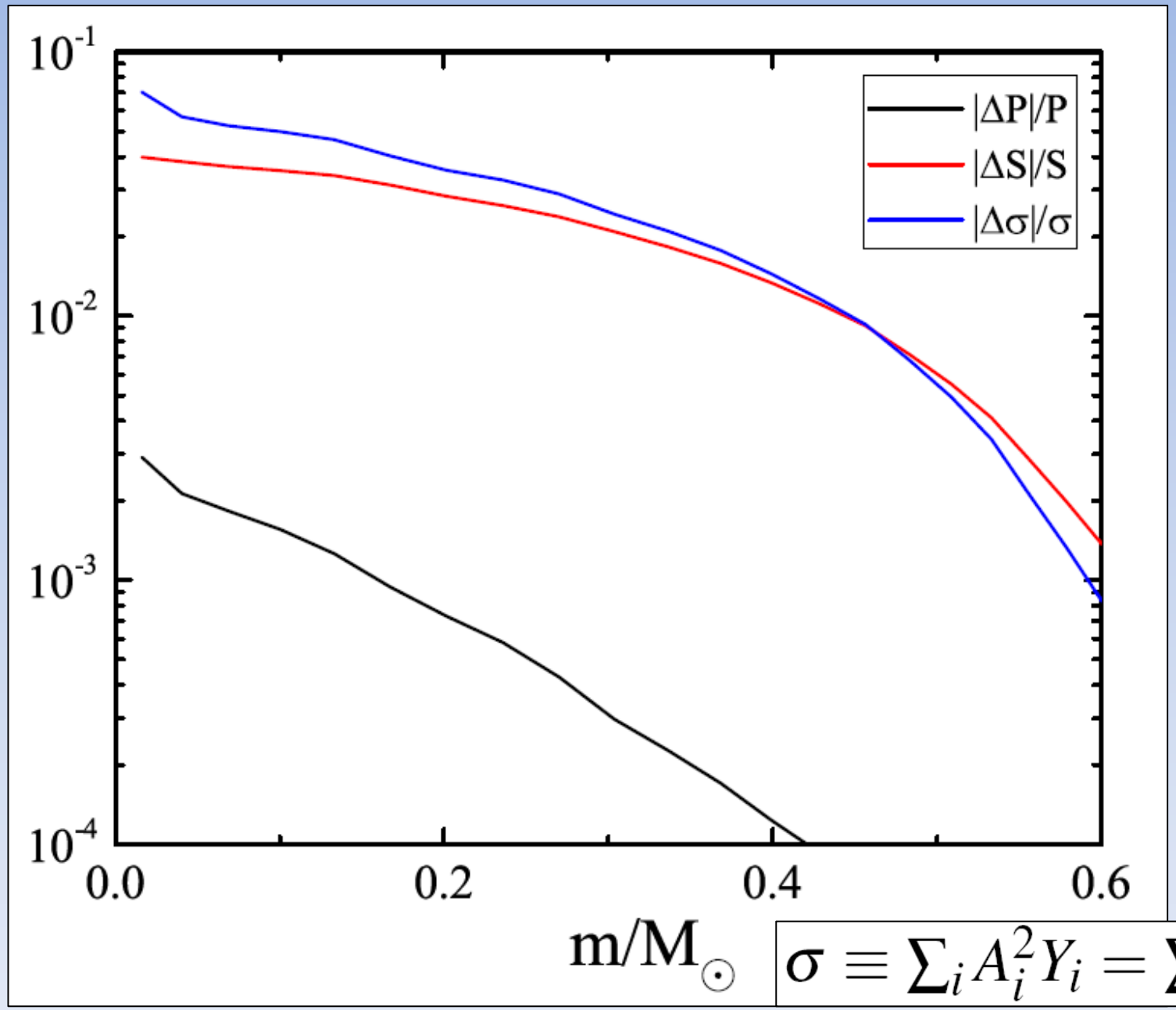

T = 5 MeV, Y_e = 0.3
T = 10 MeV, Y_e = 0.3
T = 5 MeV, Y_e = 0.1
T = 10 MeV, Y_e = 0.1
NSE
HS standart
HS modified
BPRS Eng-PF
lg X_i
lg ρ
X_Z>2


T = 10 MeV, Y e = 0.3
T = 5 MeV, Y e = 0.1
HS standart
HS modified
lg X i
lg ρ
n
p
2H
3H
4He
6He
3He
8He
X Z>2
5He
4H
5H
7H
6H
10He
14
12
13
10-3
10-1
10-2

Post-bounce stage



Importance of light clusters



$$\sigma \equiv \sum_i A_i^2 Y_i = \sum_i A_i X_i$$

Thank you!