Nucleosynthesis and Galactic Chemical Evolution

Yong-Zhong Qian
University of Minnesota

Third Santa Cruz School on Multi-Messenger Astrophysics
University of California, Santa Cruz
July16 & 17, 2024

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

Outline (7/16 & 7/17)

1. Overview of nucleosynthesis

2. Stellar Evolution & Nucleosynthesis

3. Cosmological Structure Formation

4. Galactic Chemical Evolution

Textbooks

Clayton: Principles of Stellar Evolution & Nucleosynthesis

Arnett: Supernovae & Nucleosynthesis

Pagel: Nucleosynthesis & Chemical Evolution of Galaxies

Periodic Table of Elements

Atomic # / Symbol / Name / Atomic Mass

C Solid — Hg Liquid — H Gas — Rf Unknown

Metals: Alkali metals; Alkaline earth metals; Lanthanoids; Actinoids; Transition metals; Poor metals

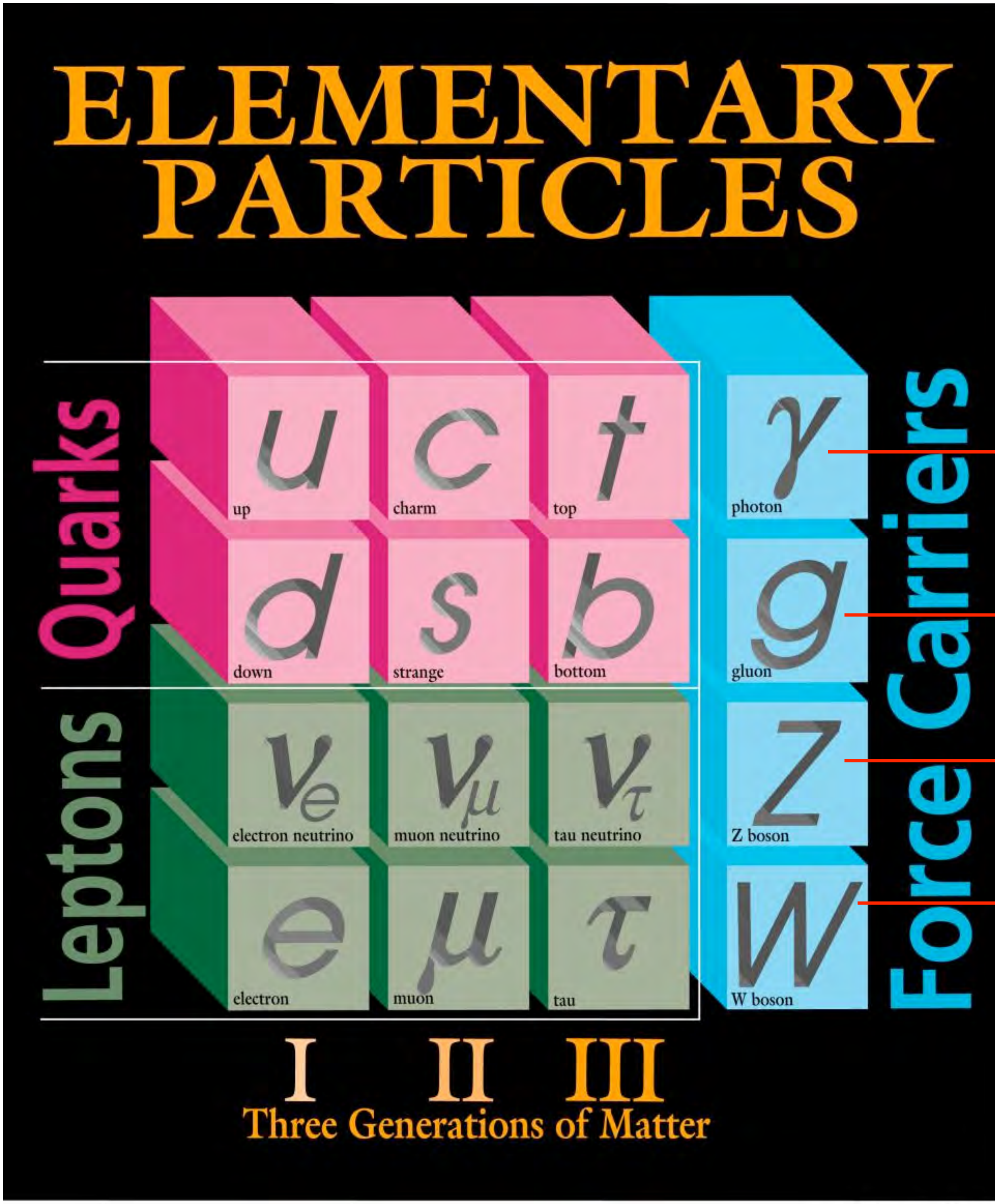
Nonmetals: Other nonmetals; Noble gases

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.00794																	2 He Helium 4.002602
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6	55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Ptable.com



Fermilab 95-759

Fundamental Interactions

Electromagnetic

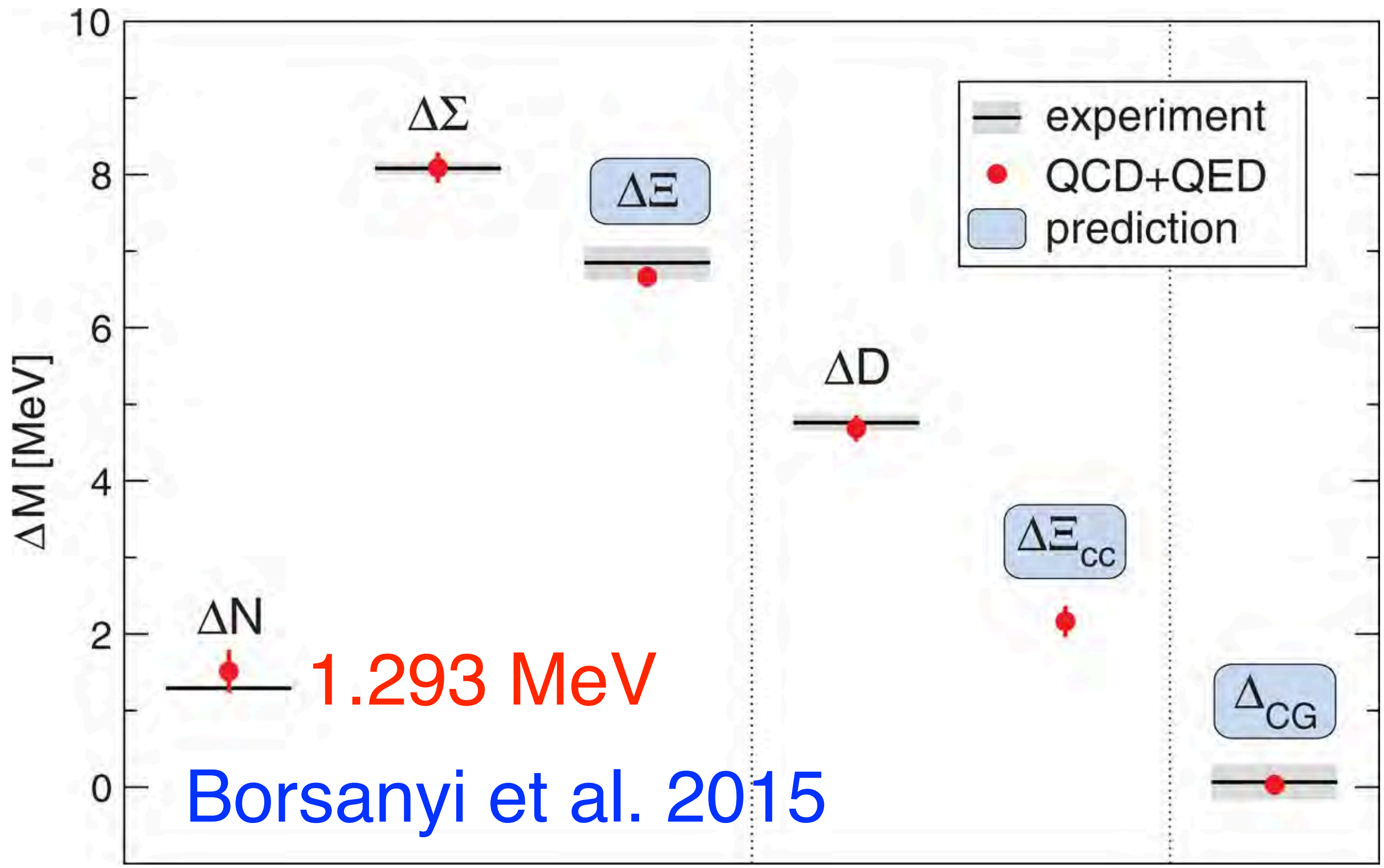
Strong

Weak (NC)

Weak (CC)

Gravitational

Standard Model of Particle Physics & Life of a Baryon: Big Bang Nucleosynthesis



$$\frac{n}{p} = \exp\left(-\frac{M_n - M_p}{T}\right) < 1$$

Big Bang:

75% H + 25% He
(by mass)

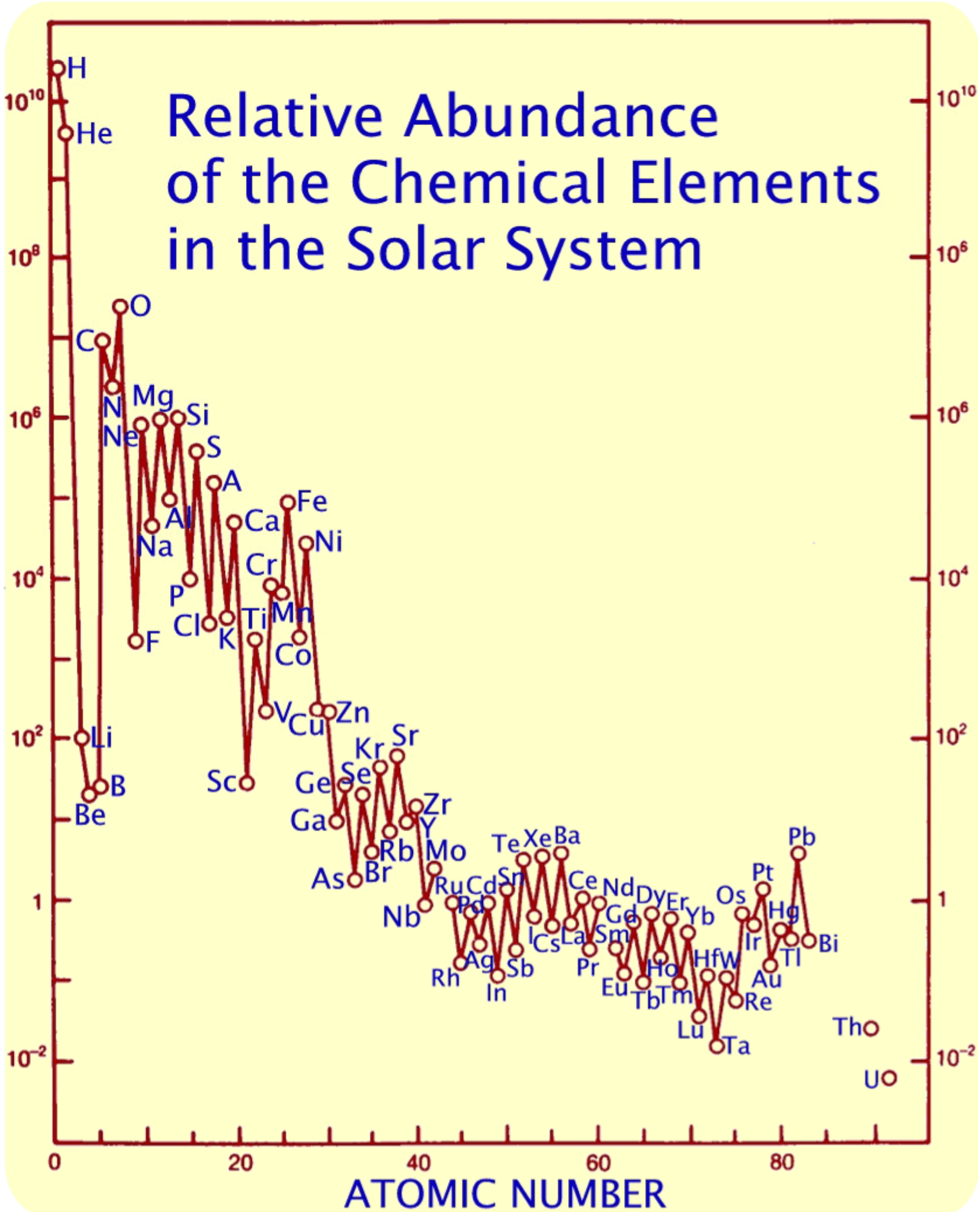
Sun:

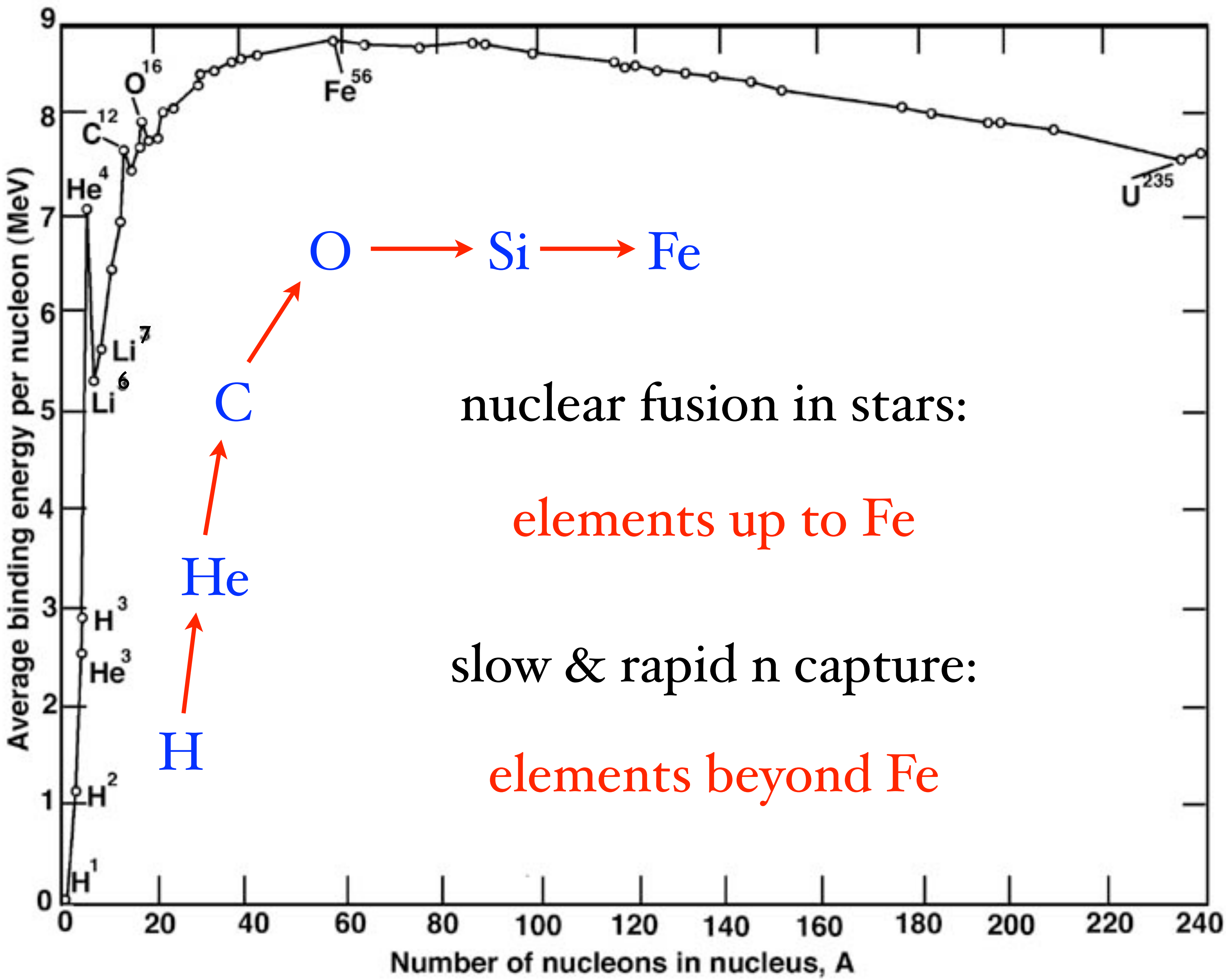
71.1% H + 27.4% He
+1.5% "Metals"

$$\text{“}p\text{”} \rightarrow \text{“}n\text{”} + e^+ + \nu_e$$

$$e^- + \text{“}p\text{”} \rightarrow \text{“}n\text{”} + \nu_e$$

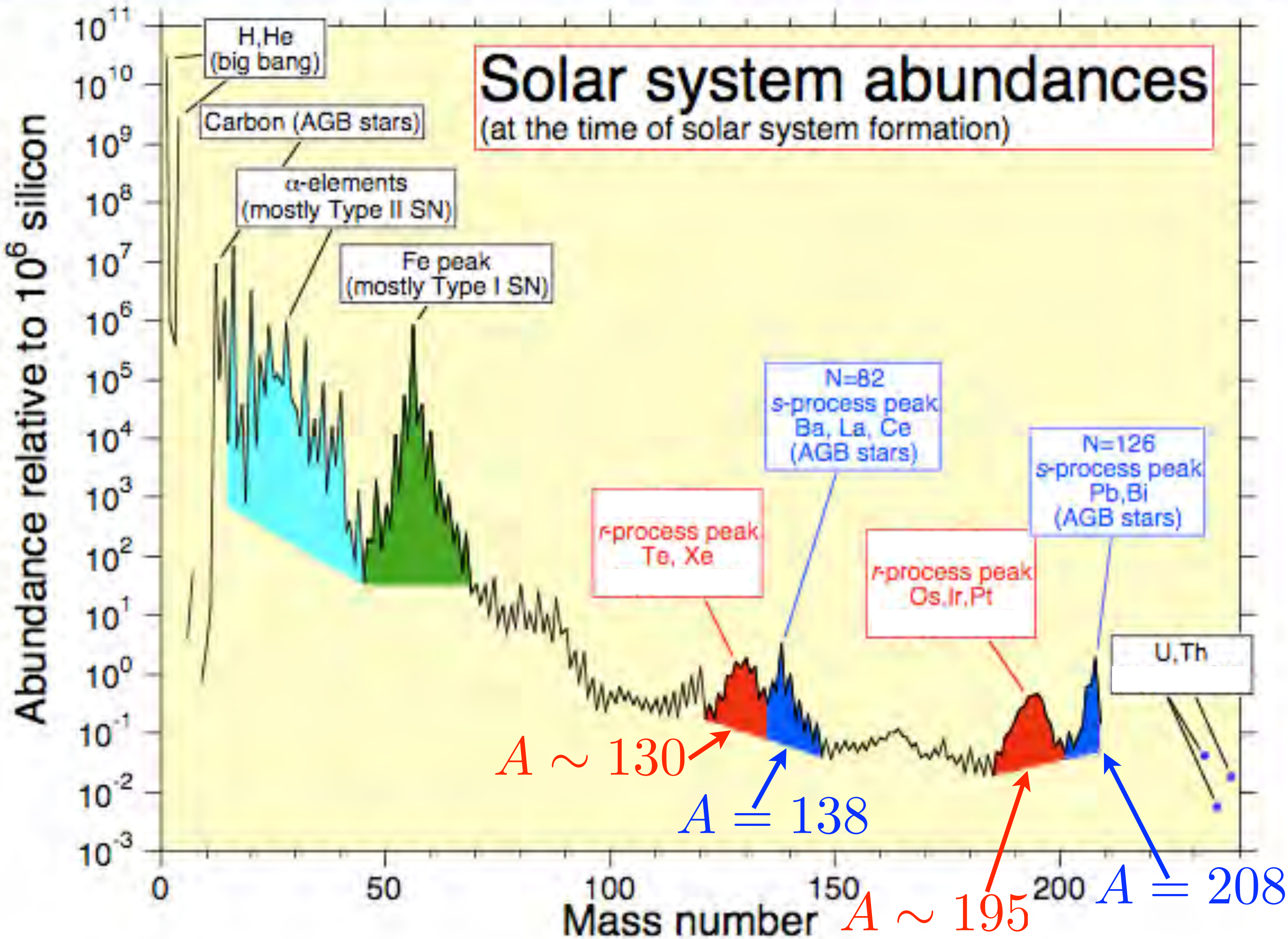
$$\bar{\nu}_e + \text{“}p\text{”} \rightarrow \text{“}n\text{”} + e^+$$



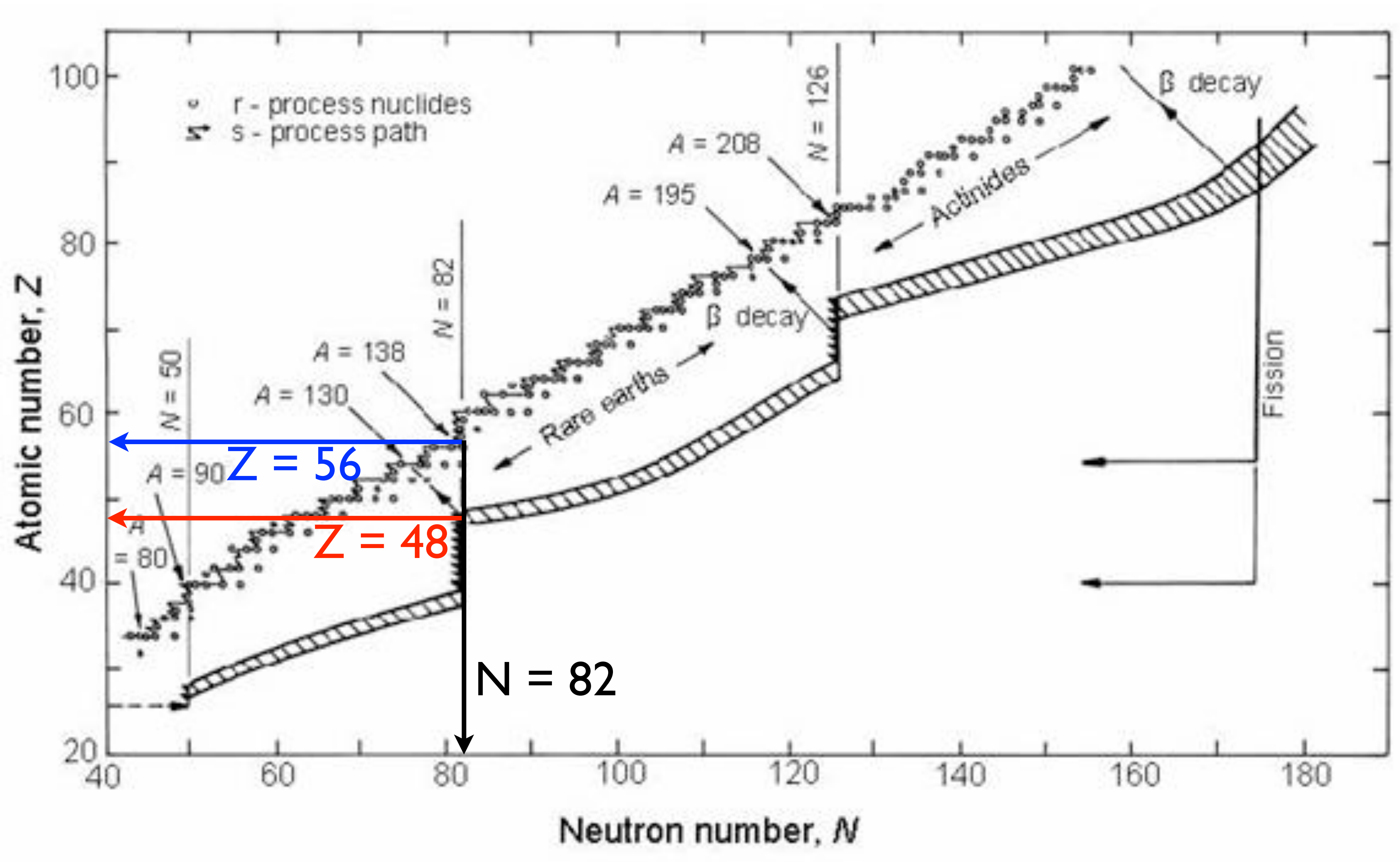


Average binding energy per nucleon (MeV)
Number of nucleons in nucleus, A
H1
H2
He3
H3
He4
Li6
Li7
C12
O16
Fe56
U235
H
He
C
O
Si
Fe
nuclear fusion in stars:
elements up to Fe
slow & rapid n capture:
elements beyond Fe

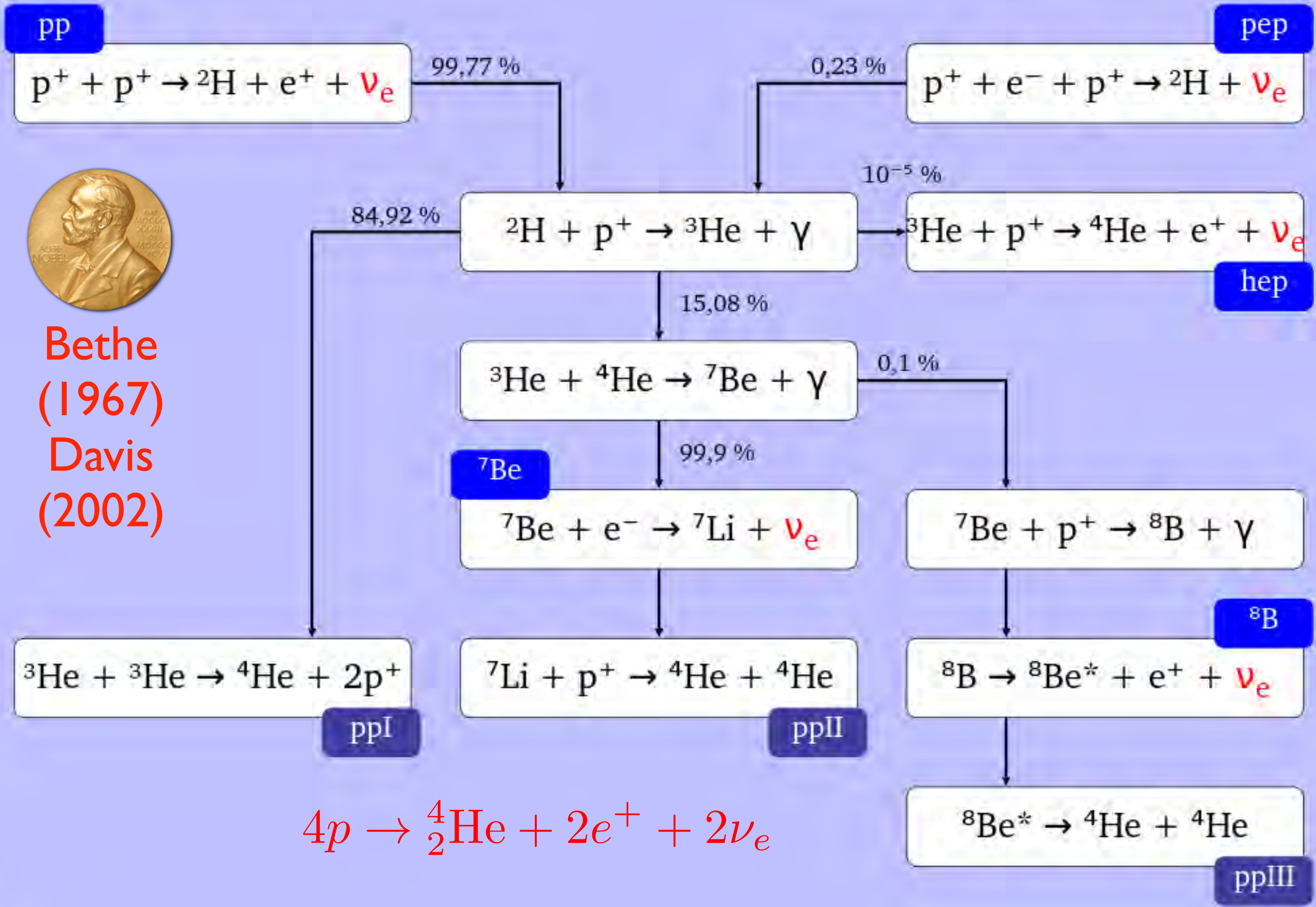
Cosmic Abundances



slow (s) and rapid (r) neutron capture processes



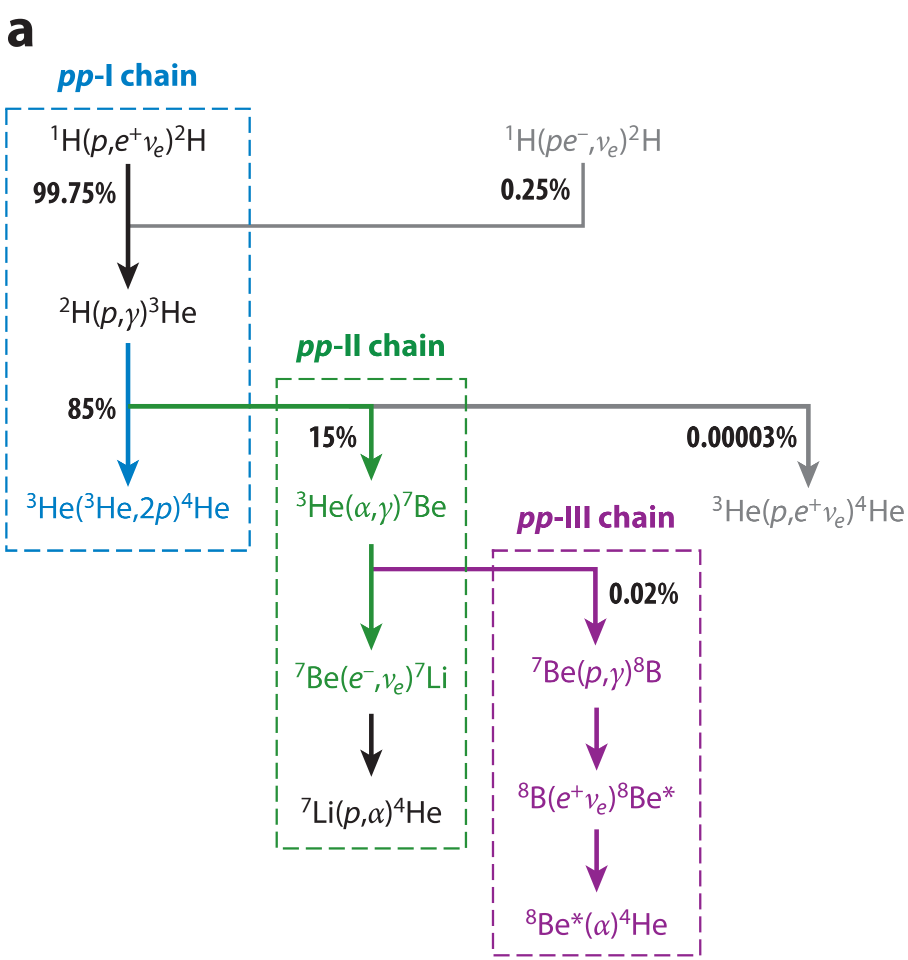
Solar Neutrinos (1)

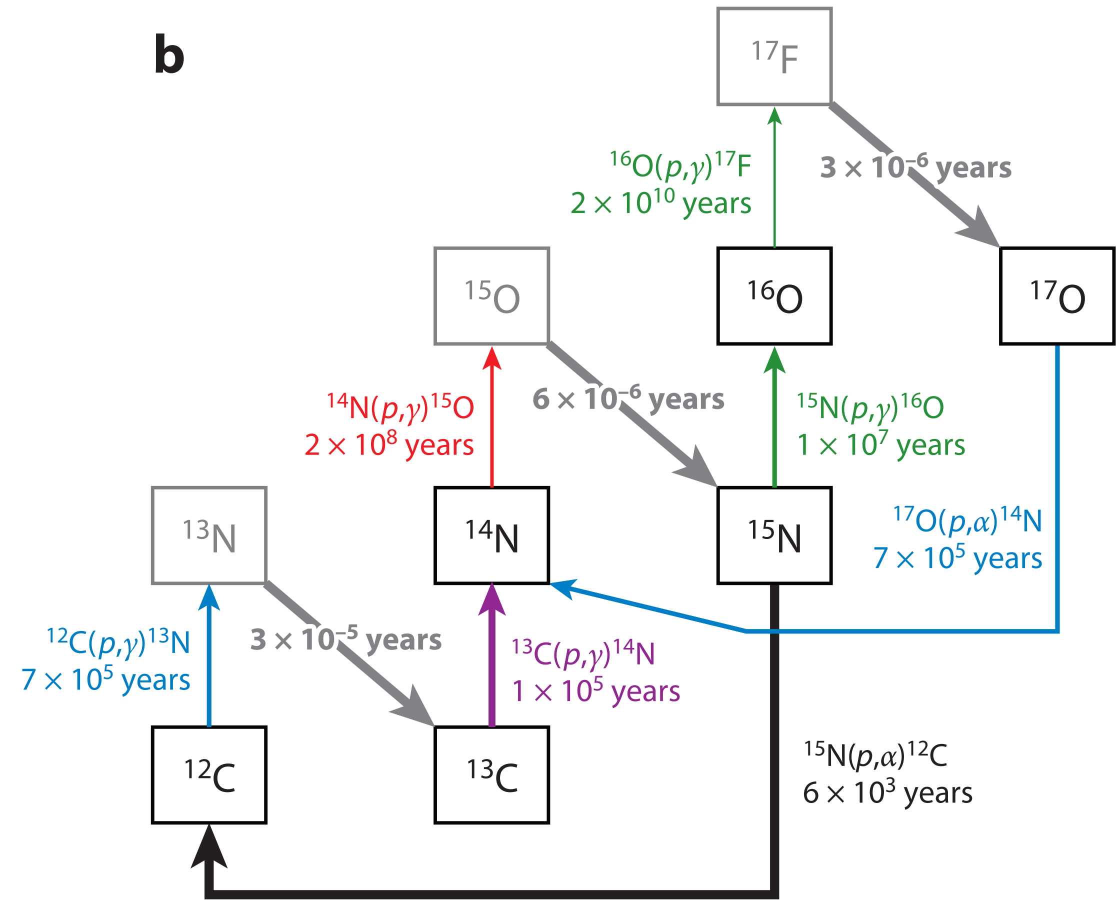


Bethe (1967)
Davis (2002)

$$4p \rightarrow {}^4_2\mathrm{He} + 2e^+ + 2\nu_e$$

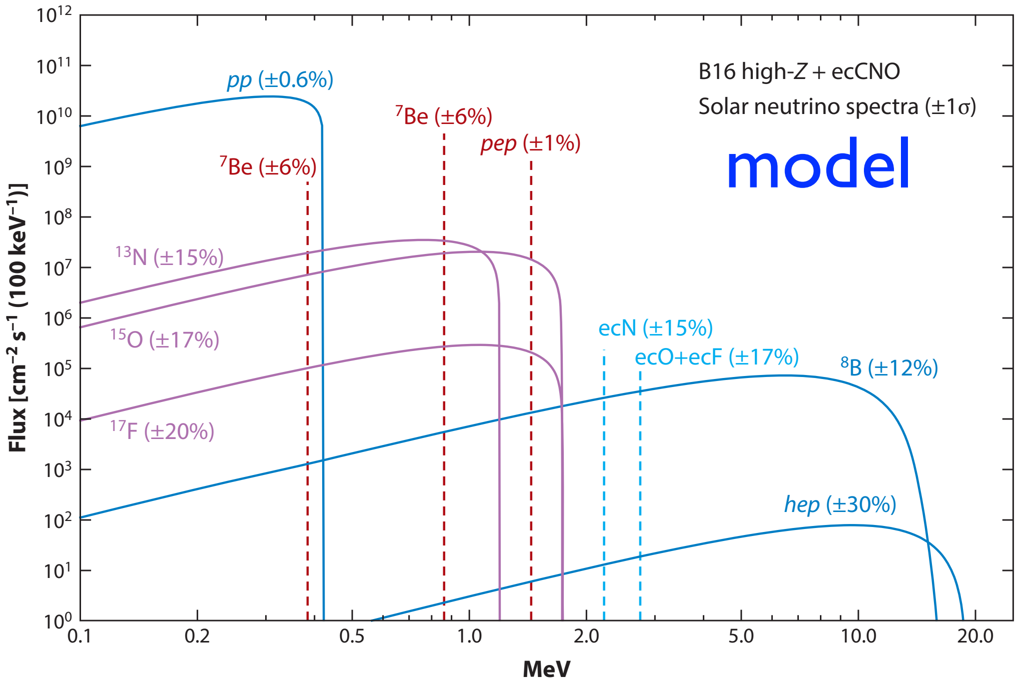
Solar Neutrinos (2)



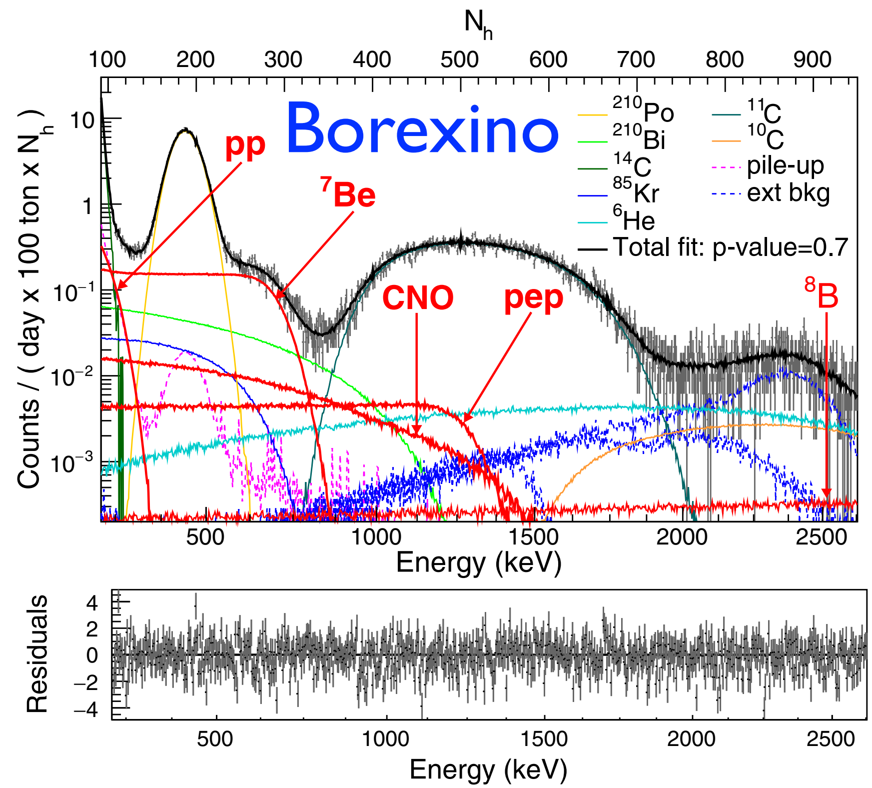


~99% of energy production

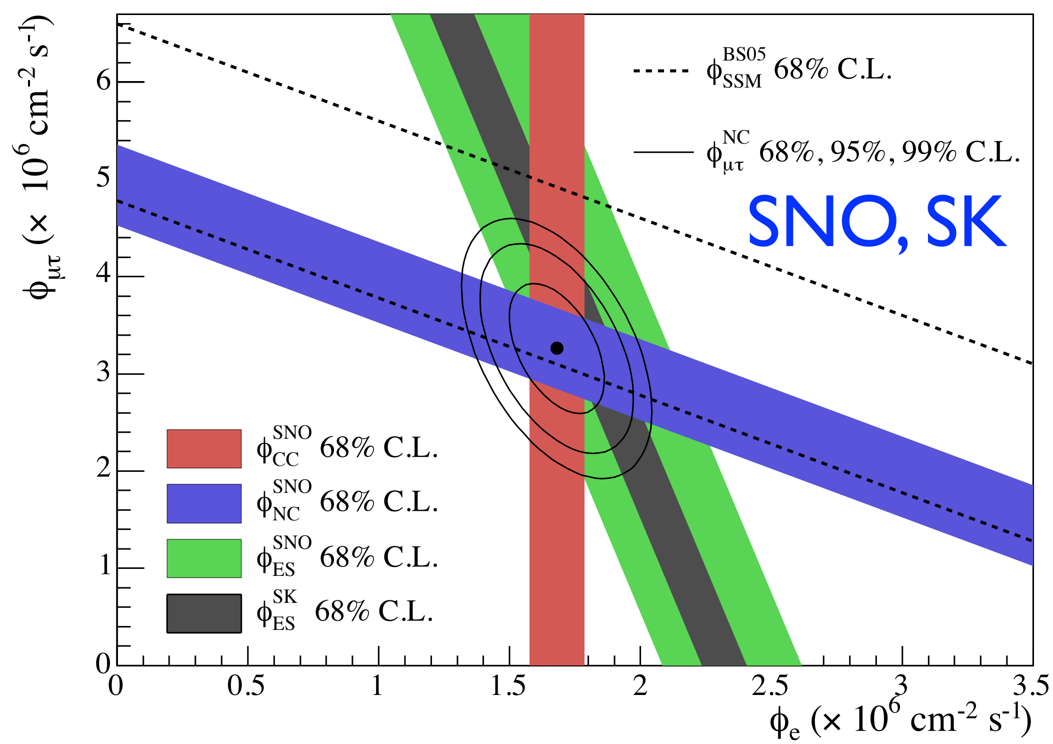
~1% of energy production



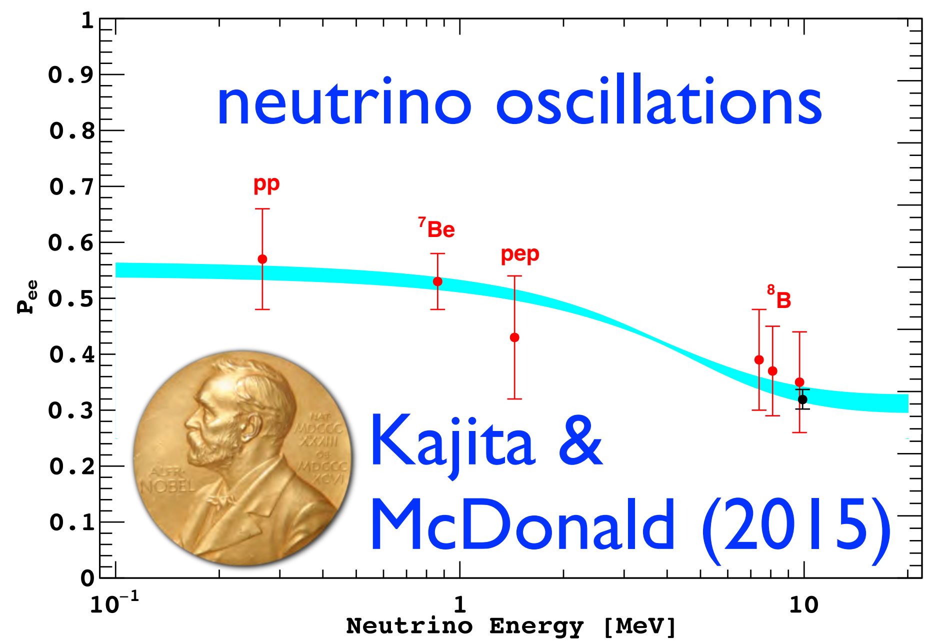
B16 high-Z + ecCNO
Solar neutrino spectra (±1σ)
model
pp (±0.6%)
7Be (±6%)
7Be (±6%)
pep (±1%)
13N (±15%)
15O (±17%)
17F (±20%)
ecN (±15%)
ecO+ecF (±17%)
8B (±12%)
hep (±30%)
Flux [cm-2 s-1 (100 keV-1)]
MeV



Borexino
Nh
pp
7Be
CNO
pep
8B
210Po
210Bi
14C
85Kr
6He
11C
10C
pile-up
ext bkg
Total fit: p-value=0.7
Counts / (day x 100 ton x Nh)
Energy (keV)
Residuals
Energy (keV)

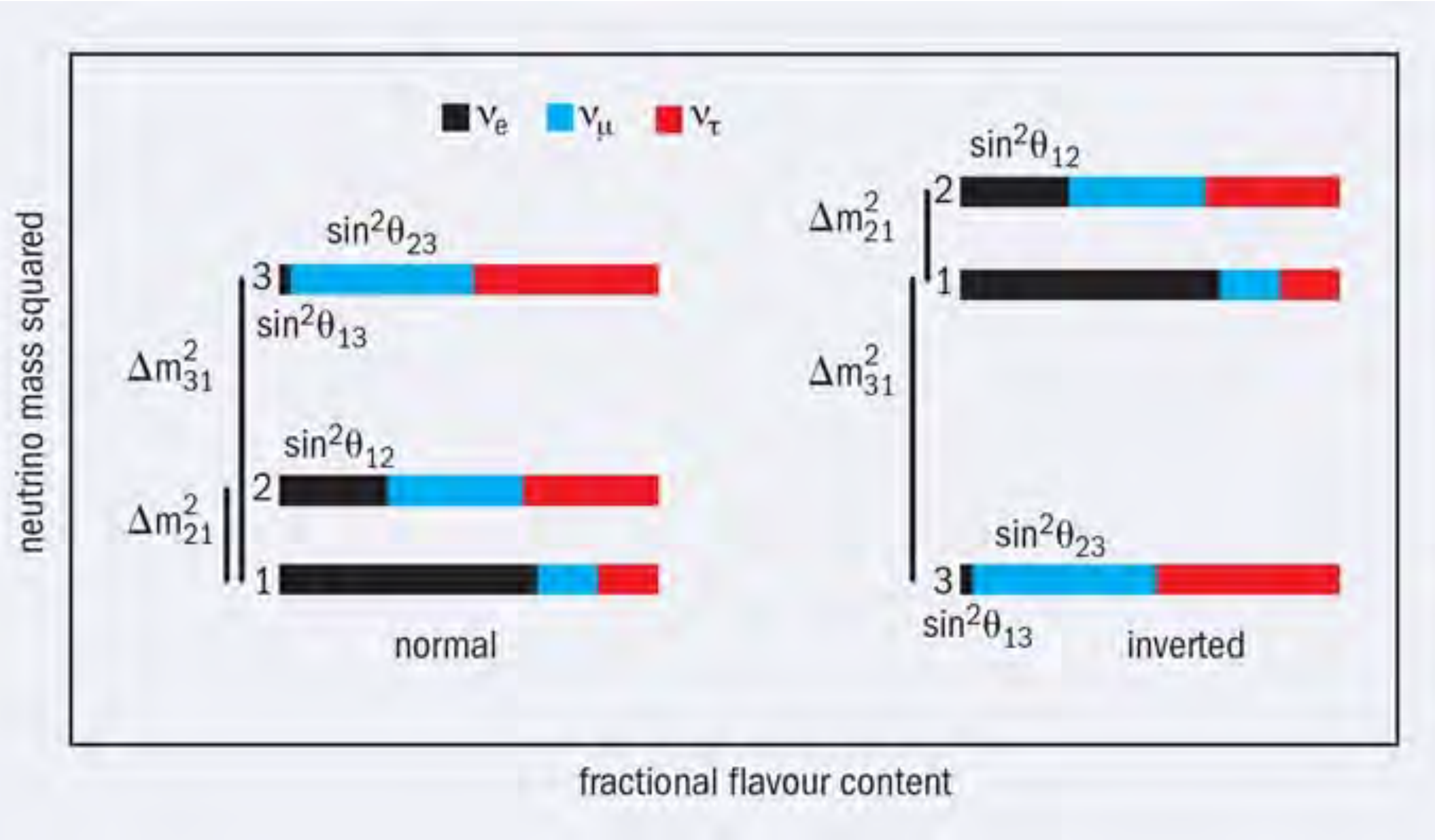


ϕ_{SSM}^{BS05} 68% C.L.
$\phi_{\mu\tau}^{NC}$ 68%, 95%, 99% C.L.
SNO, SK
ϕ_{CC}^{SNO} 68% C.L.
ϕ_{NC}^{SNO} 68% C.L.
ϕ_{ES}^{SNO} 68% C.L.
ϕ_{ES}^{SK} 68% C.L.
$\phi_{\mu\tau}$ ($\times 10^6$ cm^{-2} s^{-1})
ϕ_e ($\times 10^6$ cm^{-2} s^{-1})

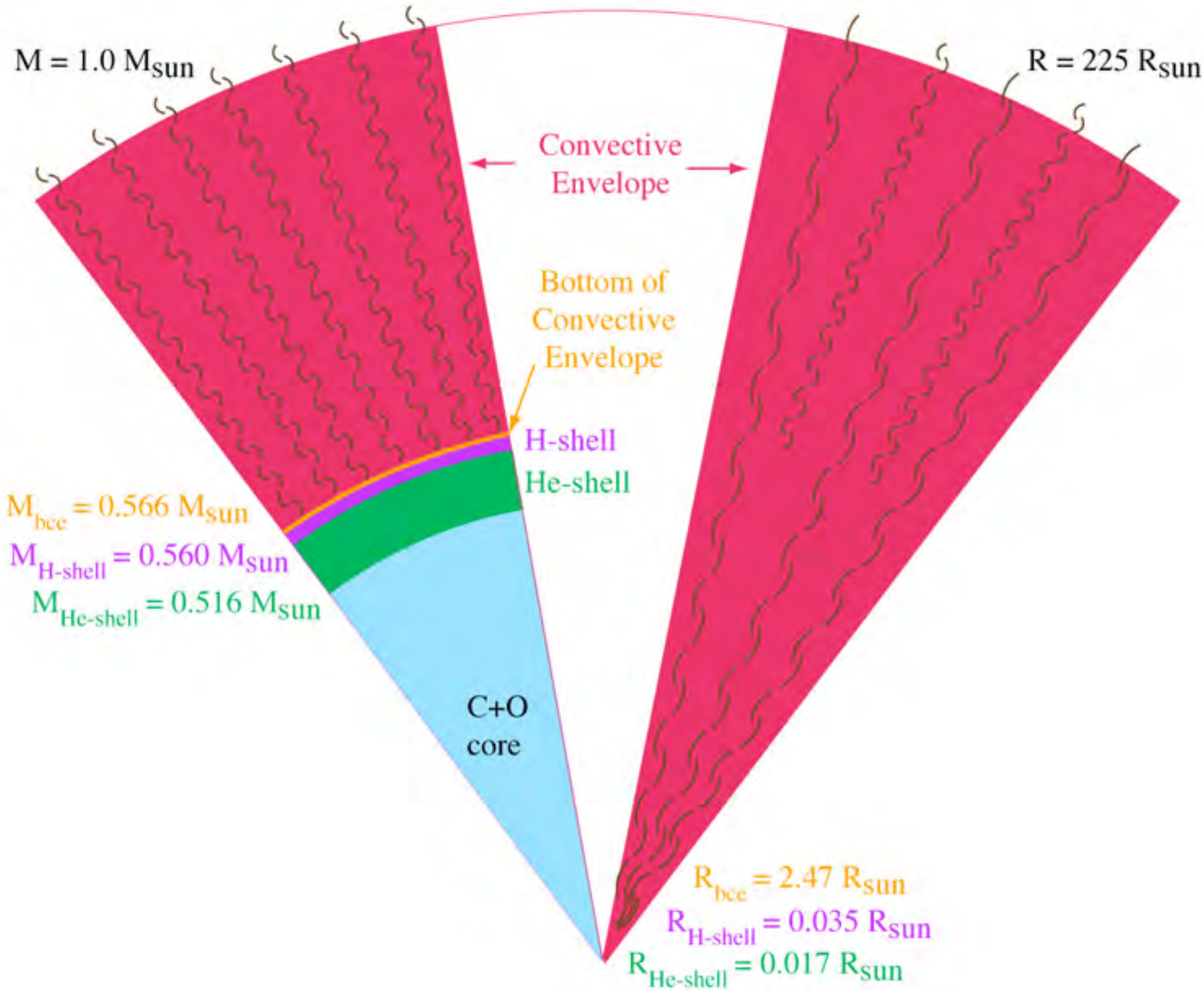


neutrino oscillations
pp
7Be
pep
8B
Pee
Kajita &
McDonald (2015)
Neutrino Energy [MeV]

Solar, atmospheric, reactor, & accelerator neutrino experiments



Structure of an Asymptotic Giant Branch star



s-process in low- & intermediate-mass stars

$$3\ {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

$${}^{12}\mathrm{C} + p \rightarrow {}^{13}\mathrm{N} + \gamma$$

$${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \nu_e$$

$${}^{13}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + n$$

$$n + {}^{56}\mathrm{Fe} \rightarrow s\text{-process nuclei}$$

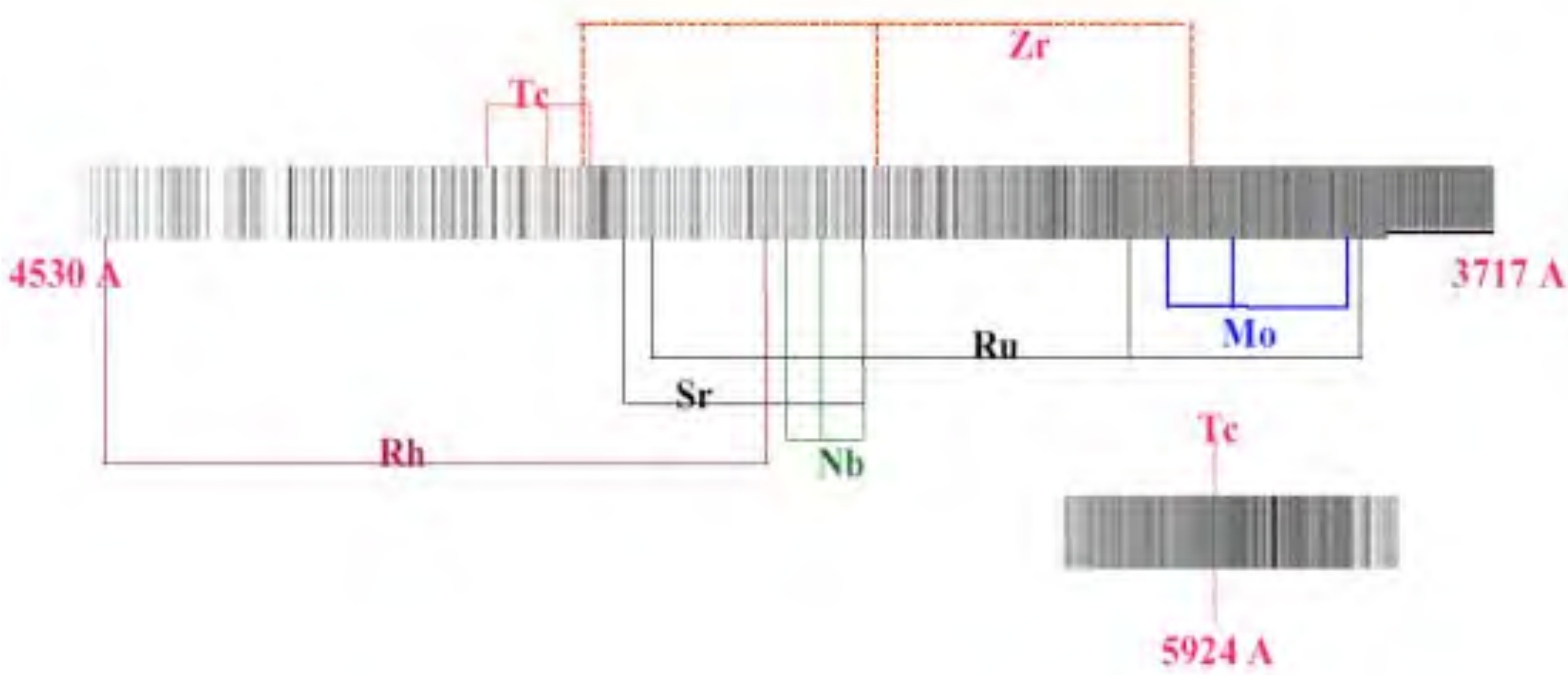
$$\boxed{4\ {}^{4}\mathrm{He} + p \rightarrow n + e^{+} + \nu_e + {}^{16}\mathrm{O}}$$

Evidence for Stellar s-Process Nucleosynthesis

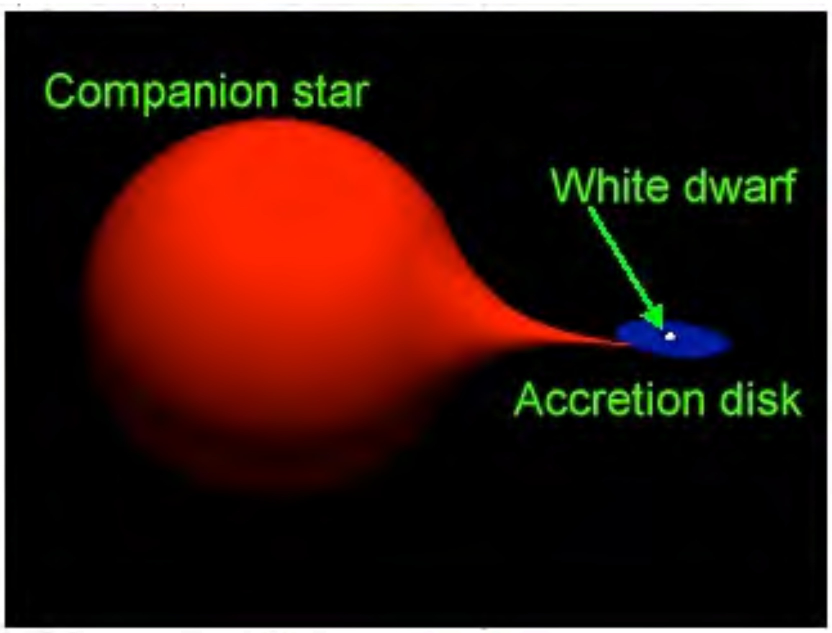
discovery of Tc spectral lines in stars by Merrill in 1952

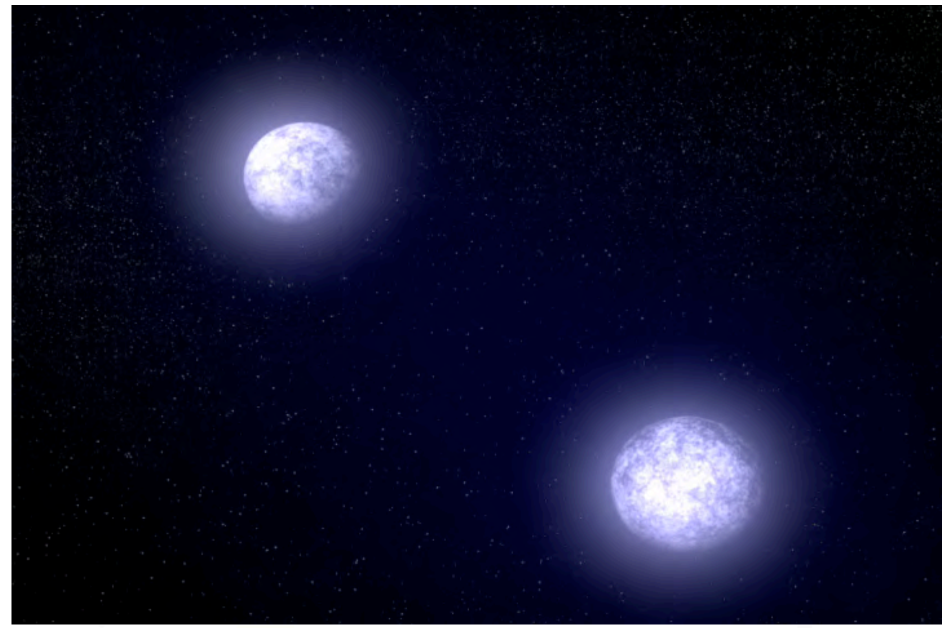
Tc has no stable isotopes; the half-lives of the longest-lived isotopes are:

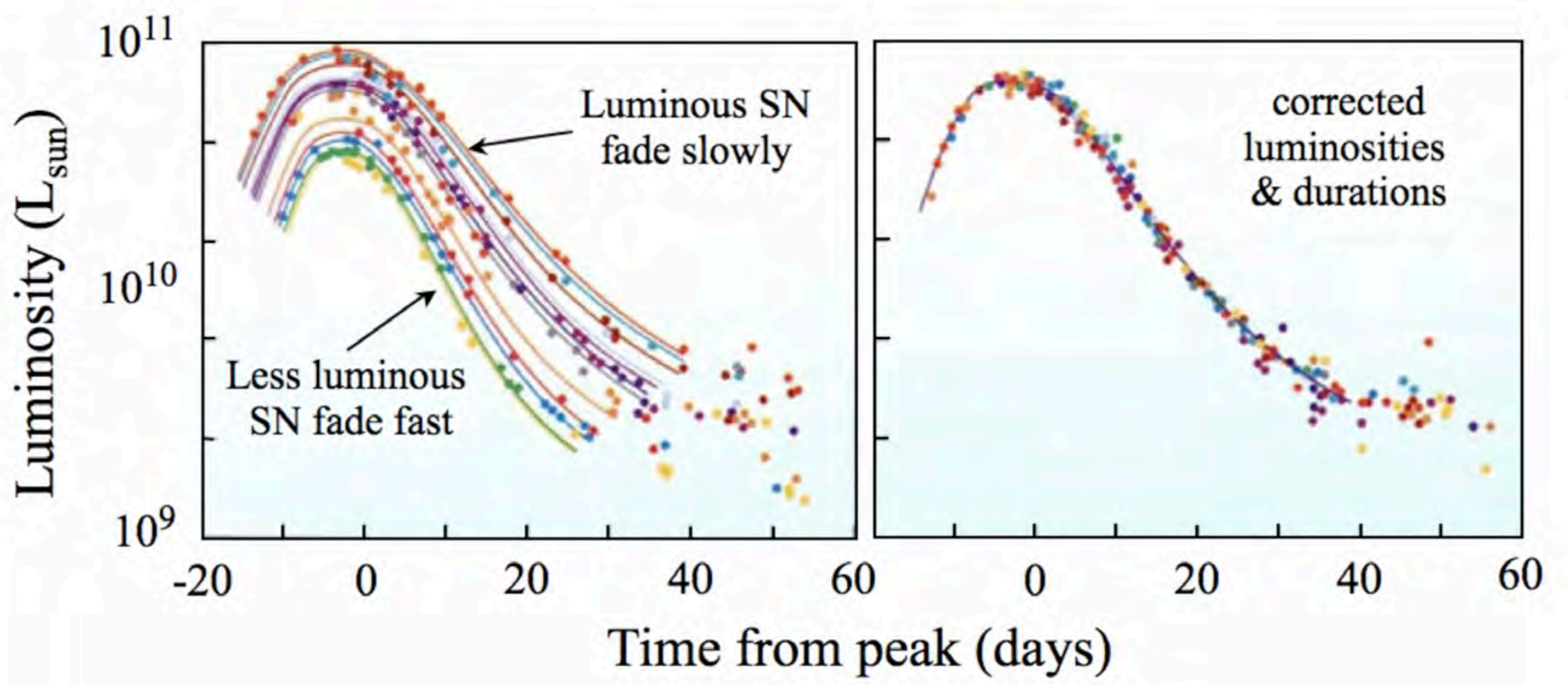
$$2.6 \times 10^6,\ 4.2 \times 10^6,\ 2.1 \times 10^5 \text{ yr for } {}^{97}\text{Tc},\ {}^{98}\text{Tc},\ {}^{99}\text{Tc}$$



Type Ia Supernovae: Accreting and Merging White Dwarfs







Simple description of stellar structure

$$\frac{dP}{dr} = -\frac{Gm(r)\rho(r)}{r^2}$$

$$\int_0^R \frac{dP}{dr} 4\pi r^3 dr = -\int_0^R \frac{Gm(r)\rho(r)}{r^2} 4\pi r^3 dr$$

$$-3\int_0^R P(r) 4\pi r^2 dr = -\int_0^R \frac{Gm(r)\rho(r)}{r} 4\pi r^2 dr$$

virial theorem

$$\boxed{-3(\gamma-1)E_K = E_G \Rightarrow E_K = -\frac{E_G}{3(\gamma-1)}}$$

$$P = (\gamma-1)\mathcal{E}_K = \begin{cases} (2/3)\mathcal{E}_K, & \gamma = 5/3 \text{ (NR)} \\ (1/3)\mathcal{E}_K, & \gamma = 4/3 \text{ (ER)} \end{cases}$$

$$E_{\rm tot} = E_K + E_G = \frac{3\gamma-4}{3(\gamma-1)} E_G$$

Virial theorem for a contracting gas cloud

$$T_c + \frac{\hbar^2}{2m_e d^2} \sim \frac{GMm_p}{R}, \quad \left(\frac{M}{m_p}\right) d^3 \sim R^3$$

$$T_c \sim \frac{GMm_p}{R} - \frac{\hbar^2}{2m_e}\left(\frac{M}{m_p}\right)^{2/3} \frac{1}{R^2} \Rightarrow T_{c,\mathrm{max}} \propto M^{4/3}$$

massive stars reach much higher temperatures during contraction

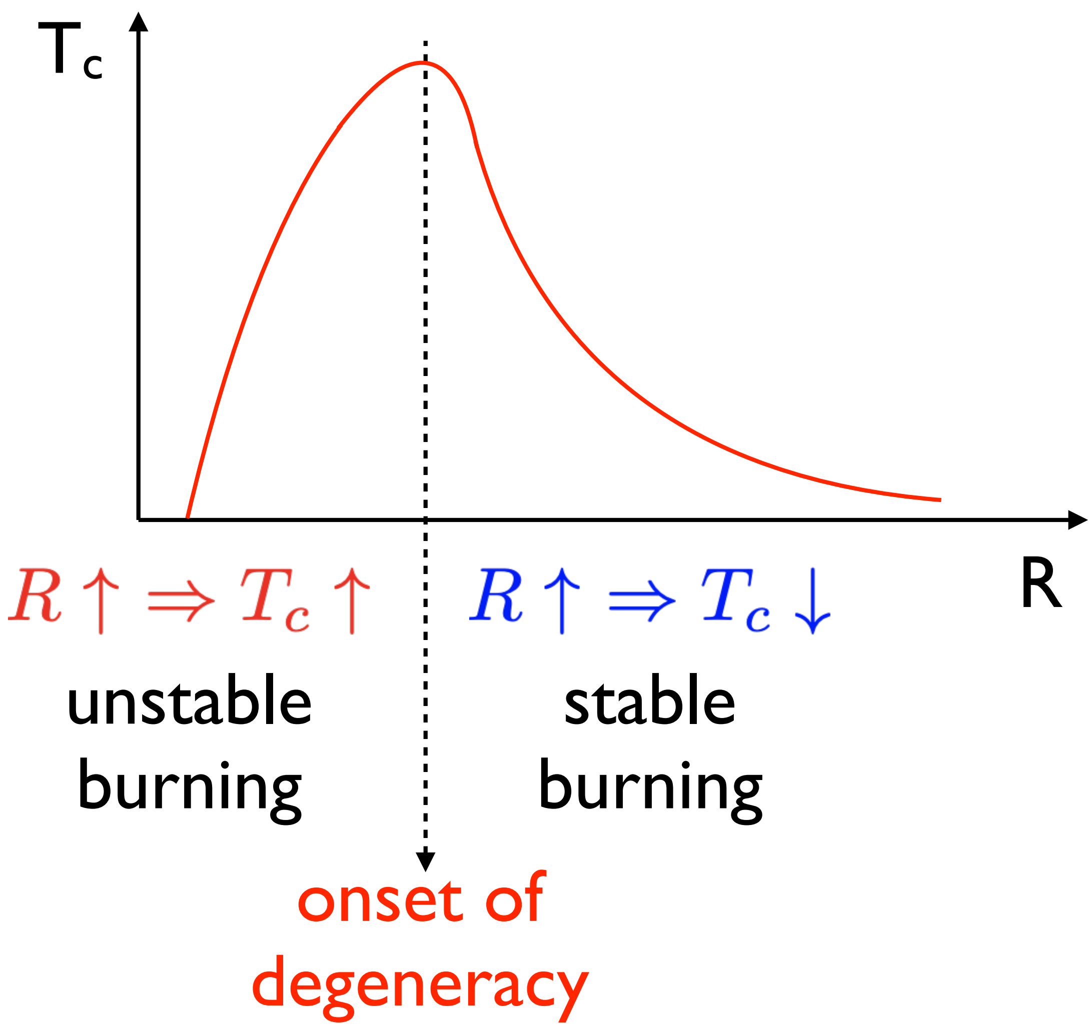
before degeneracy sets in: $T_c \propto \dfrac{M}{R}, \ \rho_c \propto \dfrac{M}{R^3} \Rightarrow \dfrac{T_c^3}{\rho_c} \propto M^2$

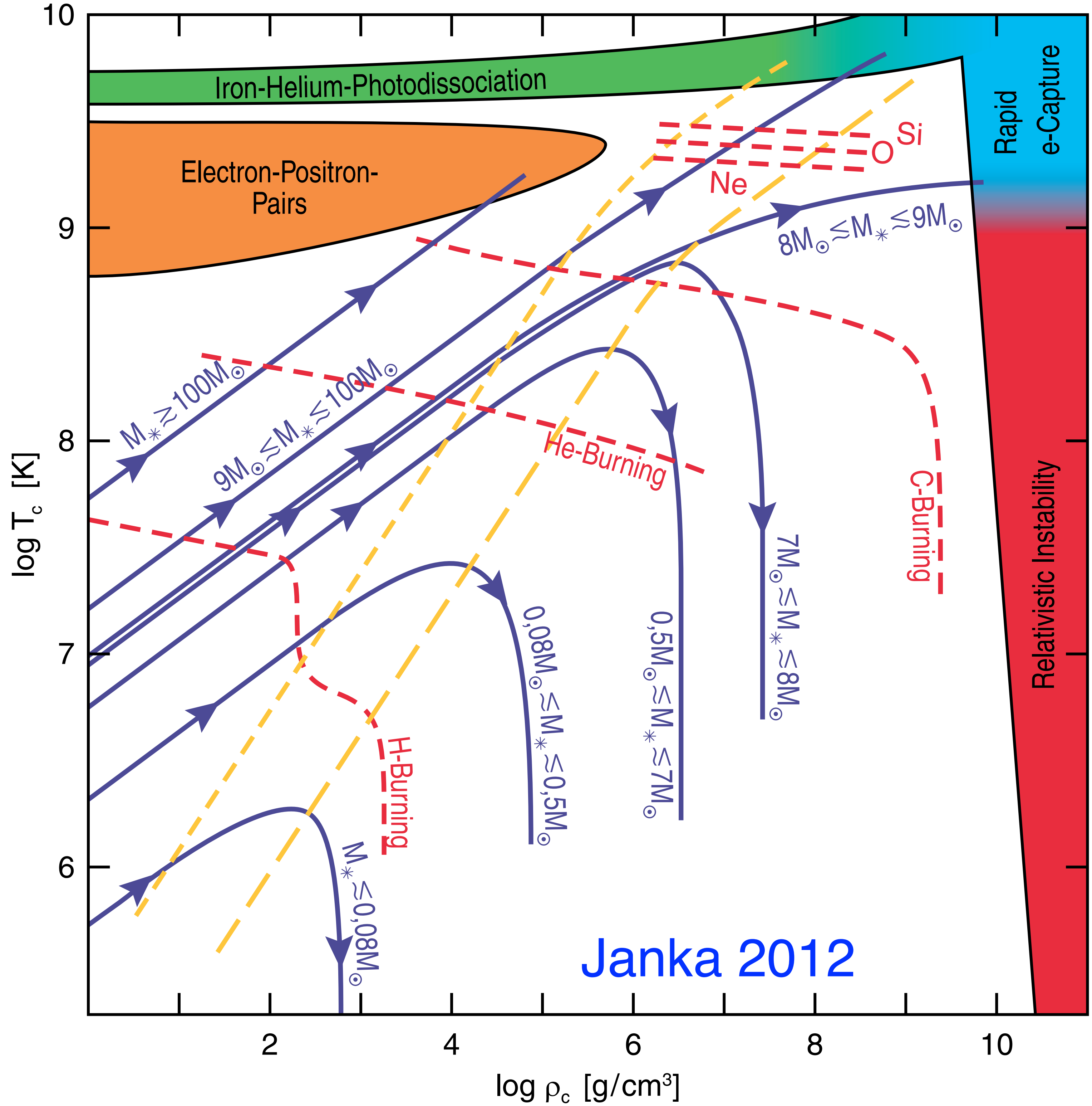
radiation pressure becomes important for $M \gtrsim 10\,M_\odot$

$$E_{\mathrm{tot}} = \frac{3\gamma - 4}{3(\gamma - 1)} E_G \sim -\frac{GM^2}{R} \quad \text{for } \gamma > \frac{4}{3}$$

Stability of nuclear burning

$$\text{fluctuation } \delta T_c > 0 \Rightarrow E_{\rm tot} \sim -\frac{GM^2}{R} \uparrow \Rightarrow R \uparrow$$





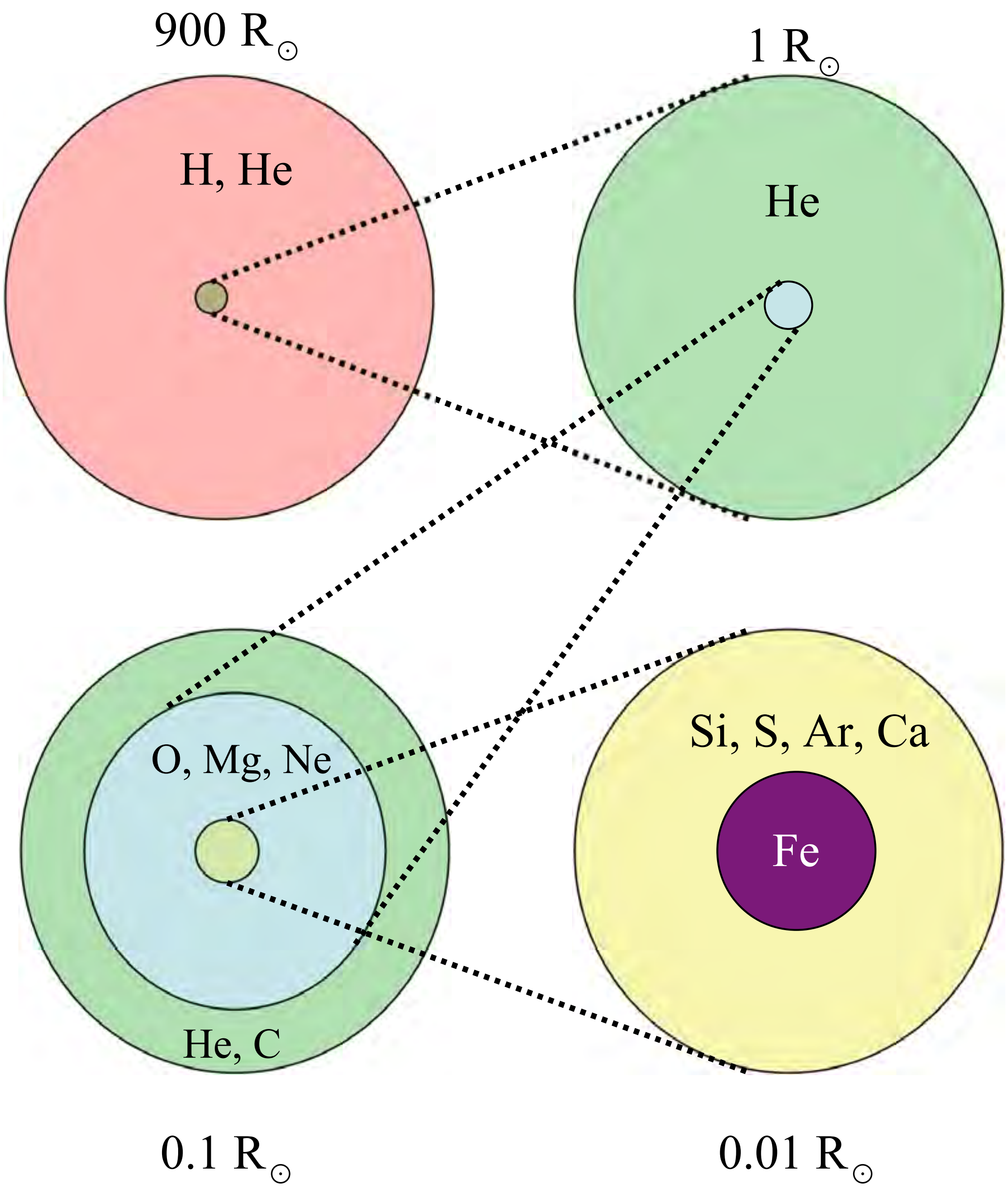
Iron-Helium-Photodissociation
Electron-Positron-Pairs
Rapid e-Capture
Relativistic Instability
Si
O
Ne
He-Burning
C-Burning
H-Burning
M∗≳100M⊙
9M⊙≲M∗≲100M⊙
8M⊙≲M∗≲9M⊙
7M⊙≲M∗≲8M⊙
0,5M⊙≲M∗≲7M⊙
0,08M⊙≲M∗≲0,5M⊙
M∗≲0,08M⊙
Janka 2012
log Tc [K]
log ρc [g/cm³]
10
9
8
7
6
2
4
6
8
10

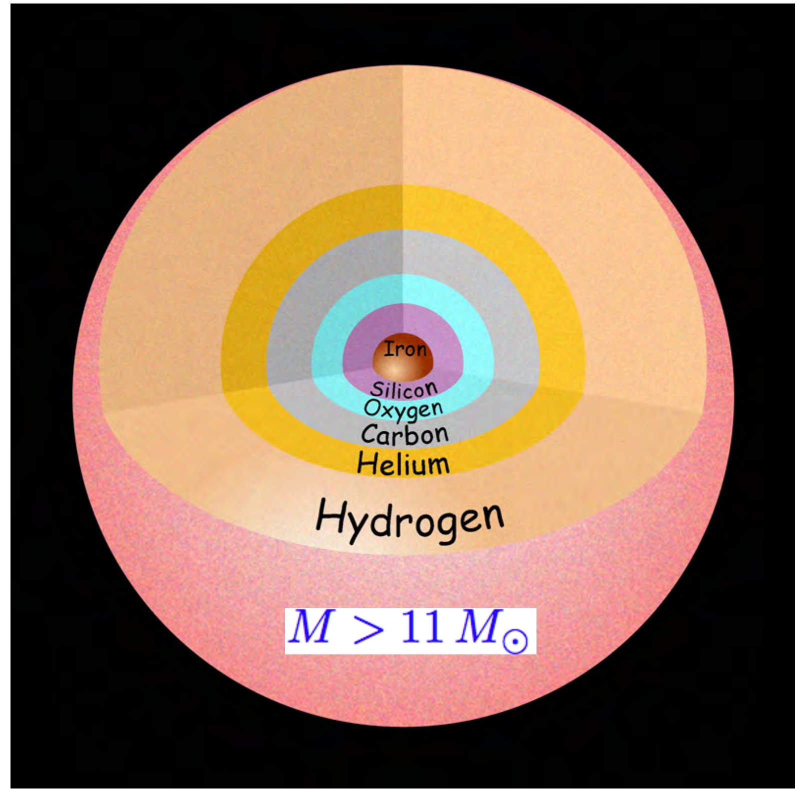
Nuclear burning stages

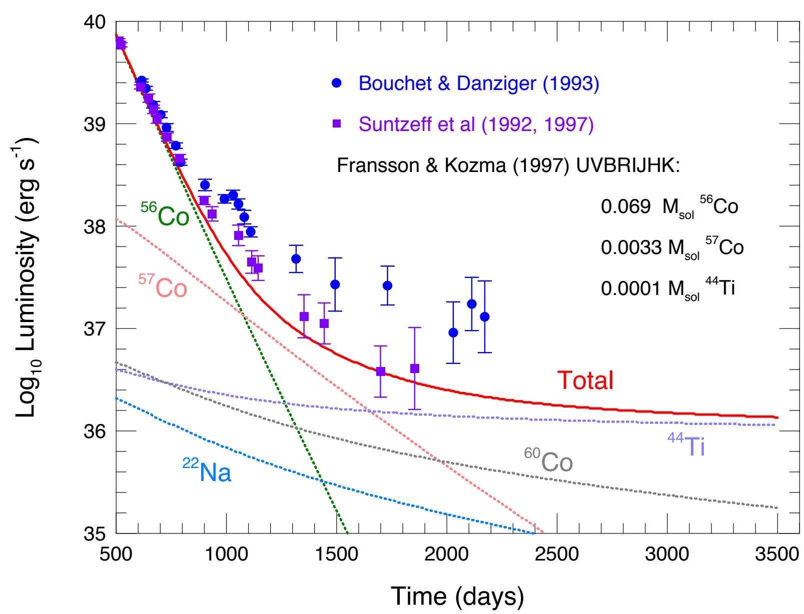
(20 $M_\odot$ stars)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$…

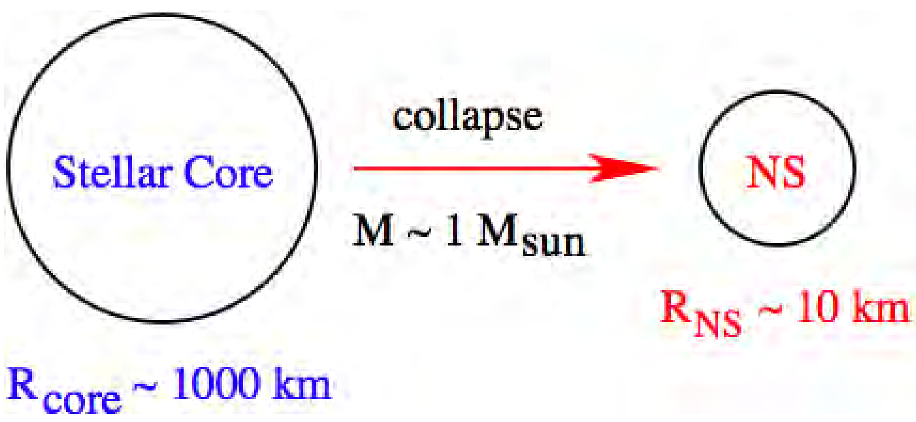
25 $M_\odot$ Presupernova Star







Supernovae as a neutrino phenomenon

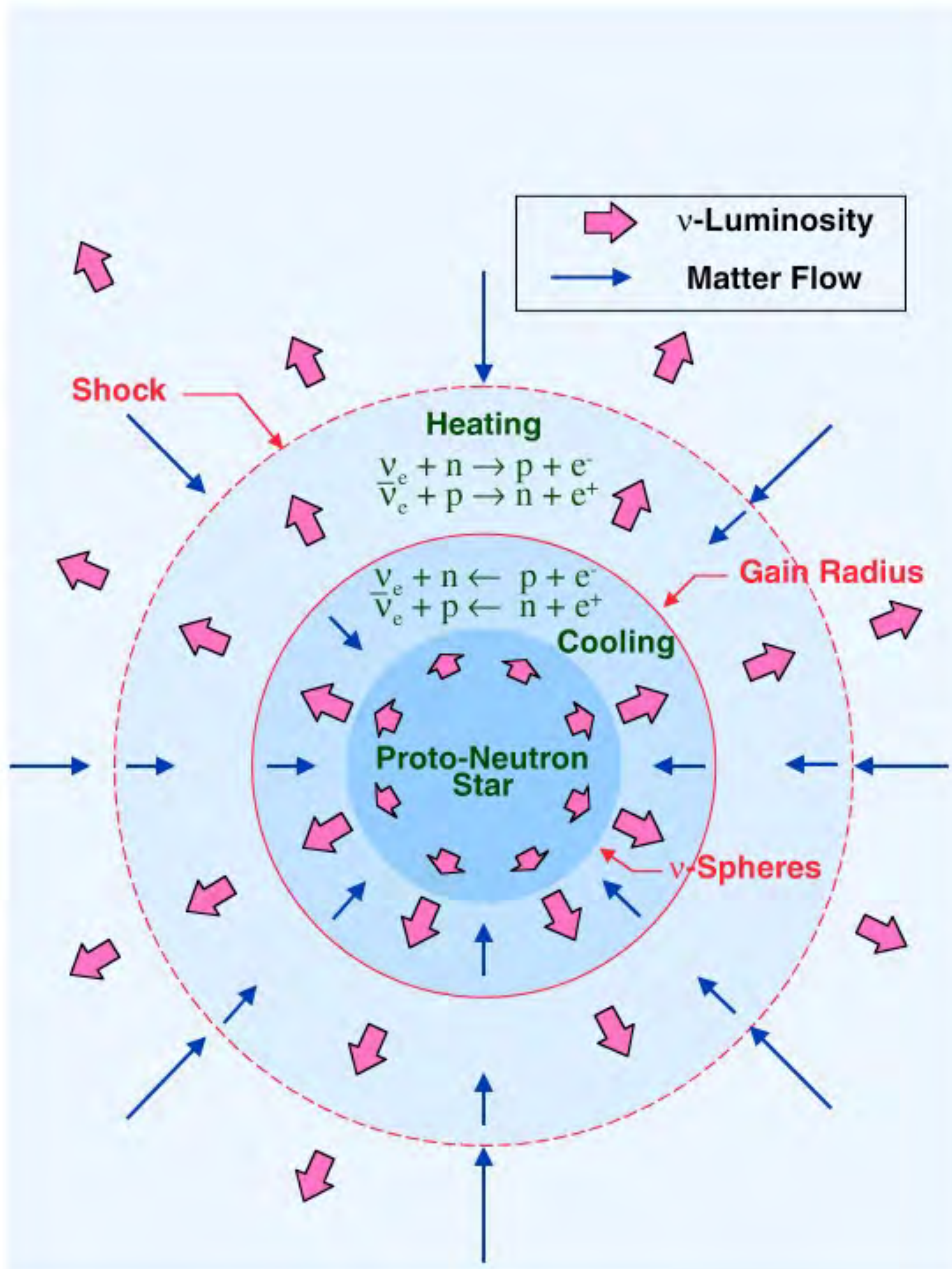


$$e^+ + e^- \to \nu + \bar{\nu}$$

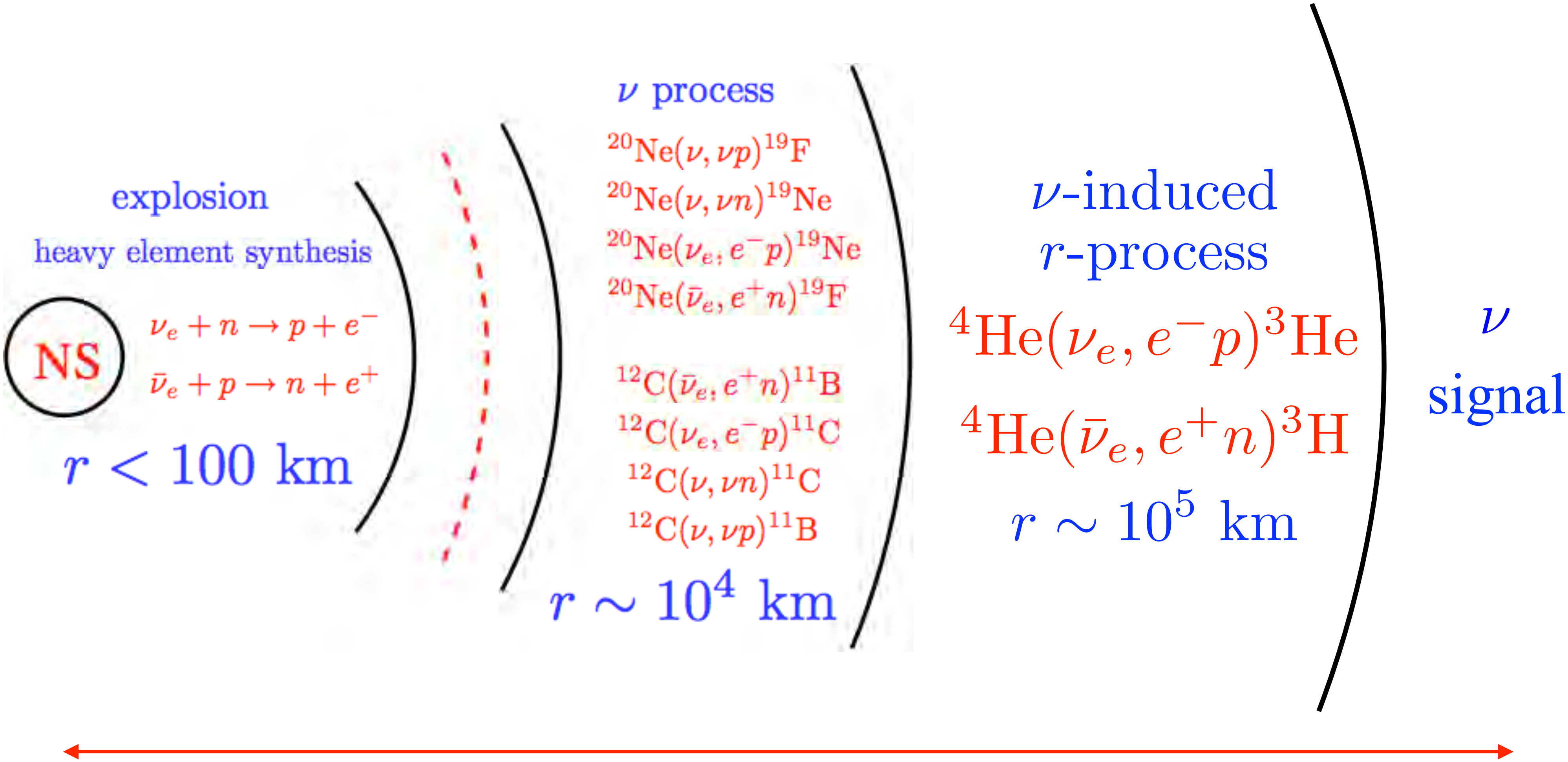
$$N + N \to N + N + \nu + \bar{\nu}$$

$$\frac{GM^2}{R_{\rm NS}} \sim 3 \times 10^{53}\ {\rm erg}$$

$$\Rightarrow \nu_e,\ \bar{\nu}_e,\ \nu_\mu,\ \bar{\nu}_\mu,\ \nu_\tau,\ \bar{\nu}_\tau$$

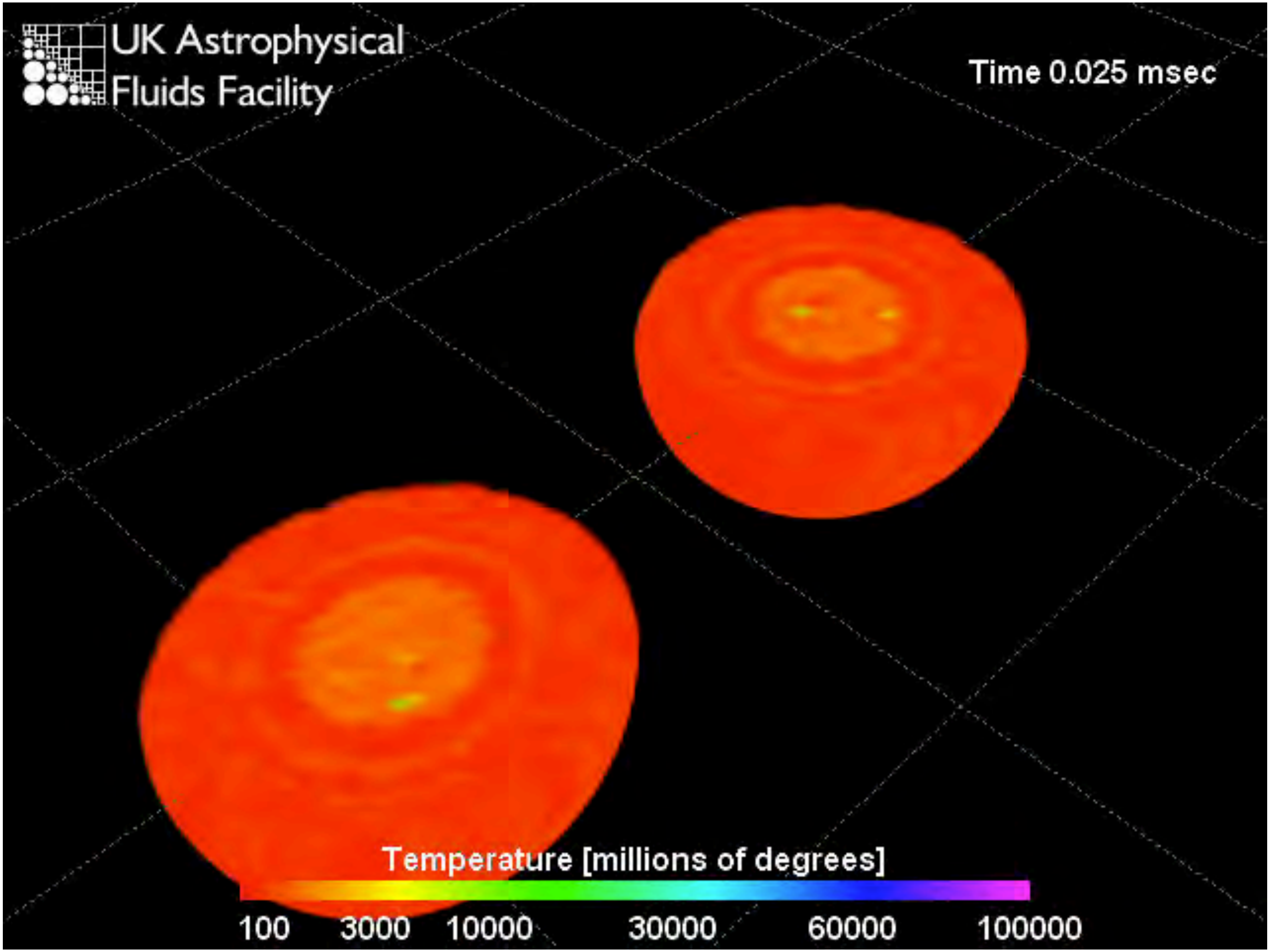


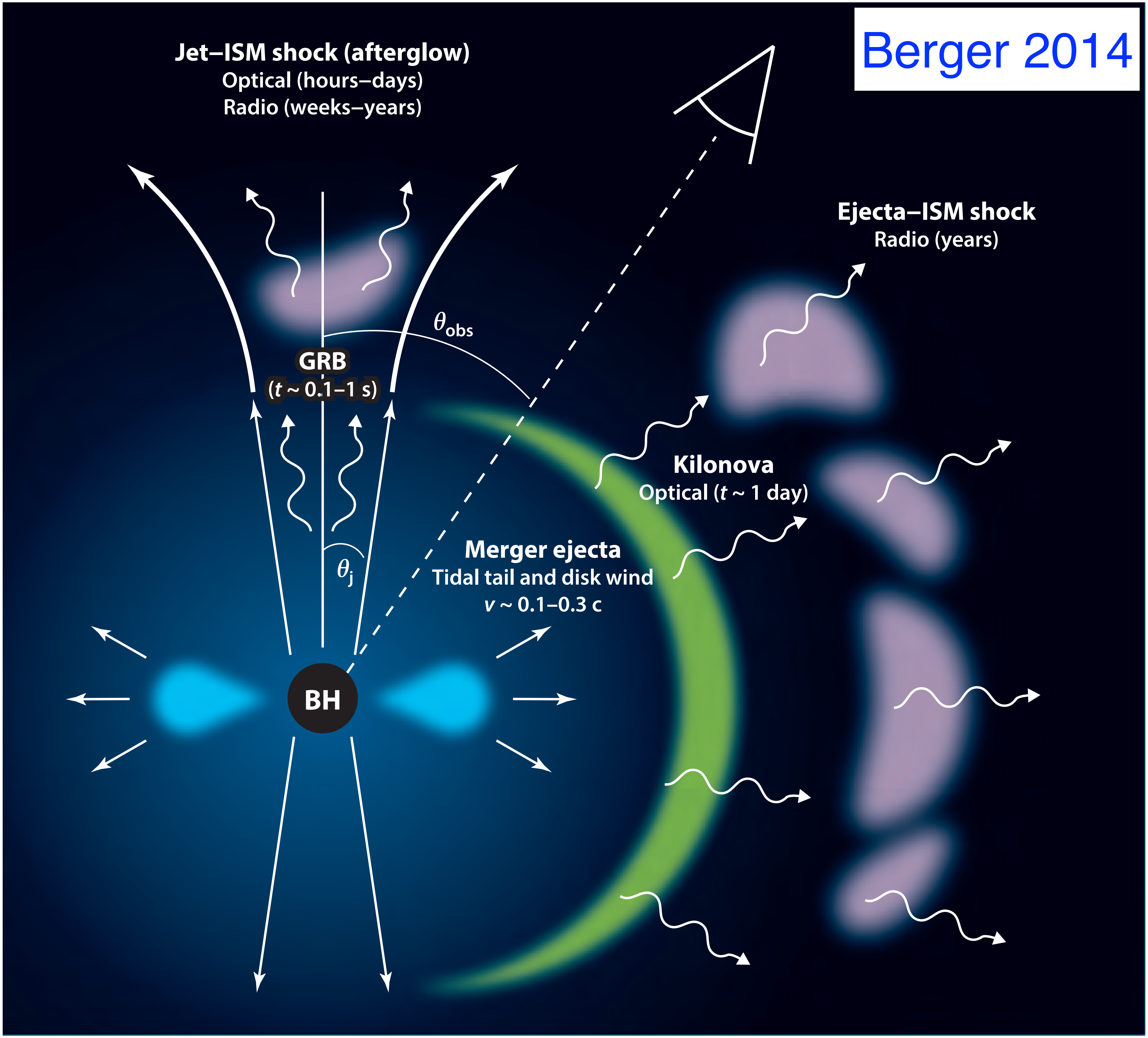
neutrino processes in typical core-collapse supernovae



neutrino interactions & oscillations

r-process in ejecta from neutron star merger




Berger 2014
Jet–ISM shock (afterglow)
Optical (hours–days)
Radio (weeks–years)
Ejecta–ISM shock
Radio (years)
θobs
GRB
(t ~ 0.1–1 s)
Kilonova
Optical (t ~ 1 day)
Merger ejecta
Tidal tail and disk wind
v ~ 0.1–0.3 c
θj
BH

Periodic Table of Elements

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.00794	Atomic # Symbol Name Atomic Mass																2 He Helium 4.002602
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6	55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

C Solid
Hg Liquid
H Gas
Rf Unknown

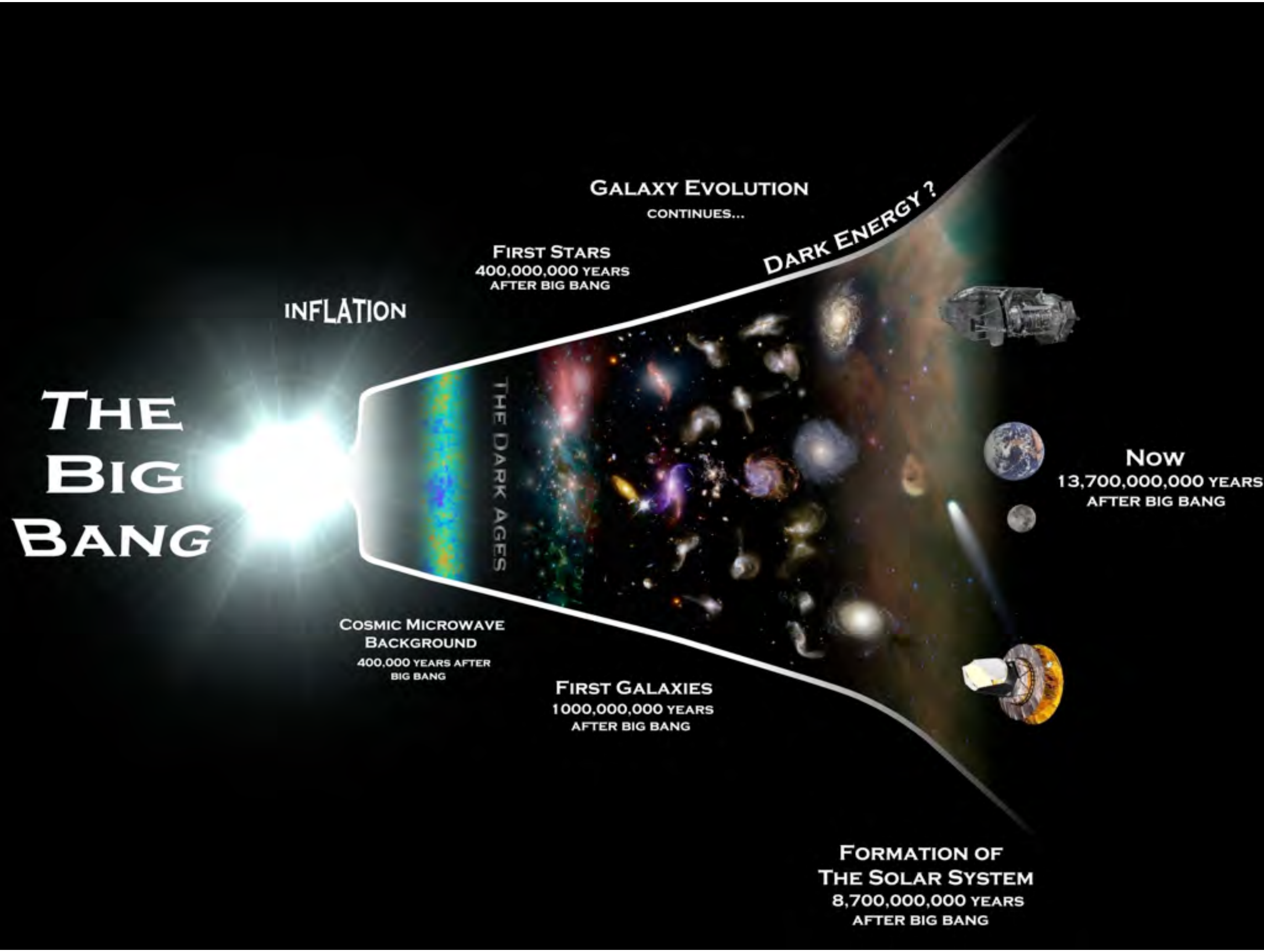
Metals: Alkali metals; Alkaline earth metals; Lanthanoids; Actinoids; Transition metals; Poor metals

Nonmetals: Other nonmetals; Noble gases

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

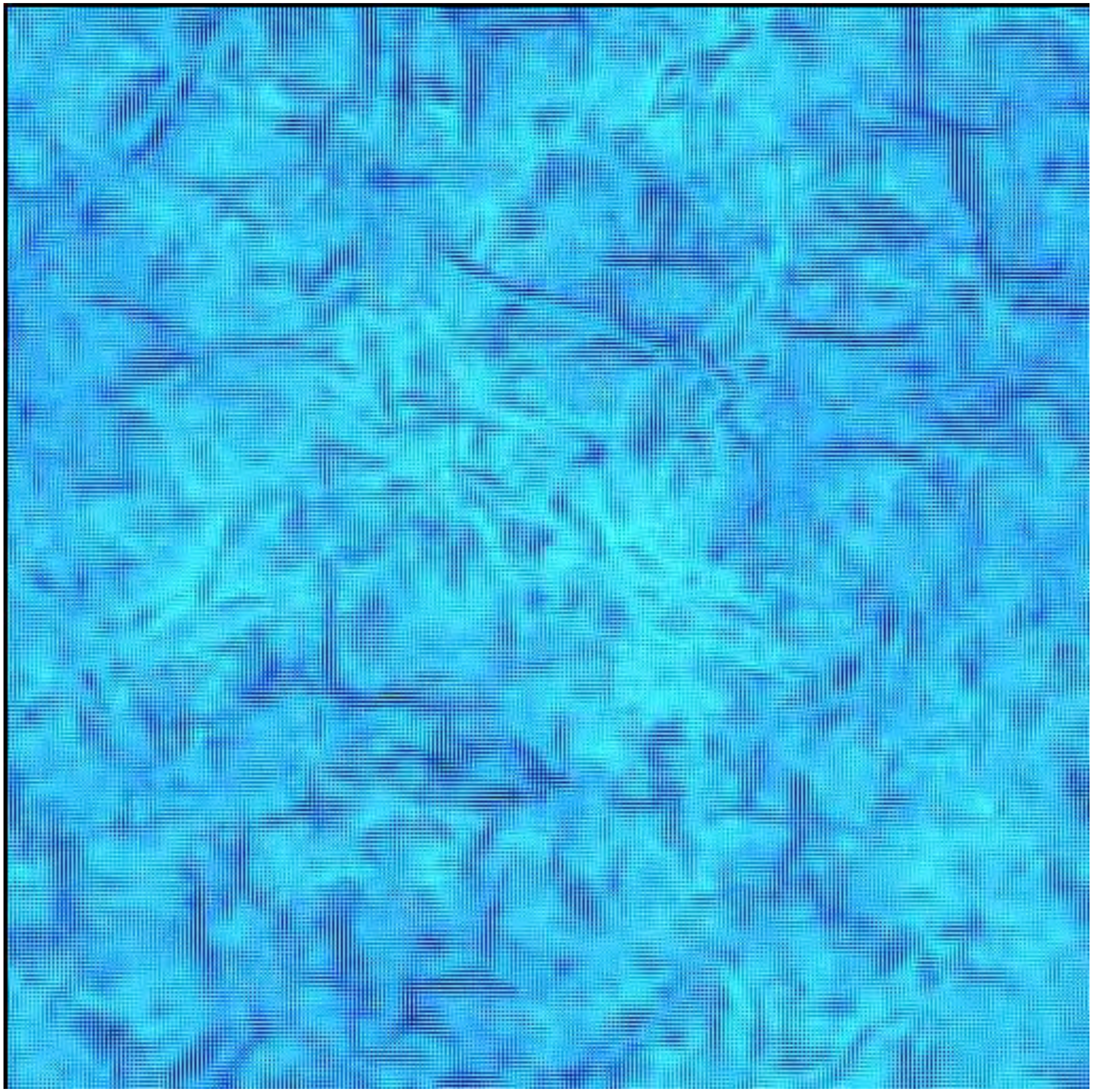
57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Ptable.com

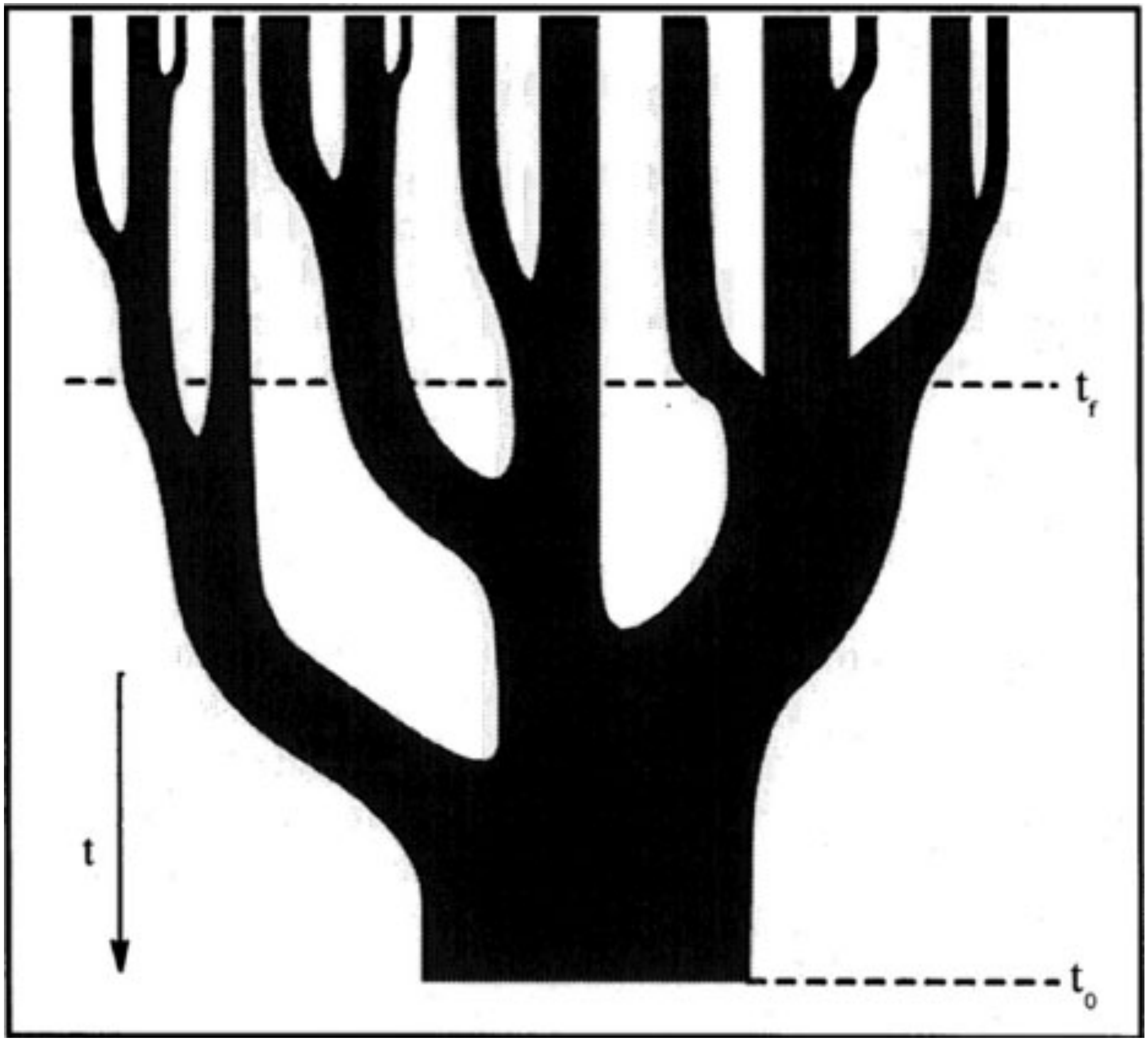


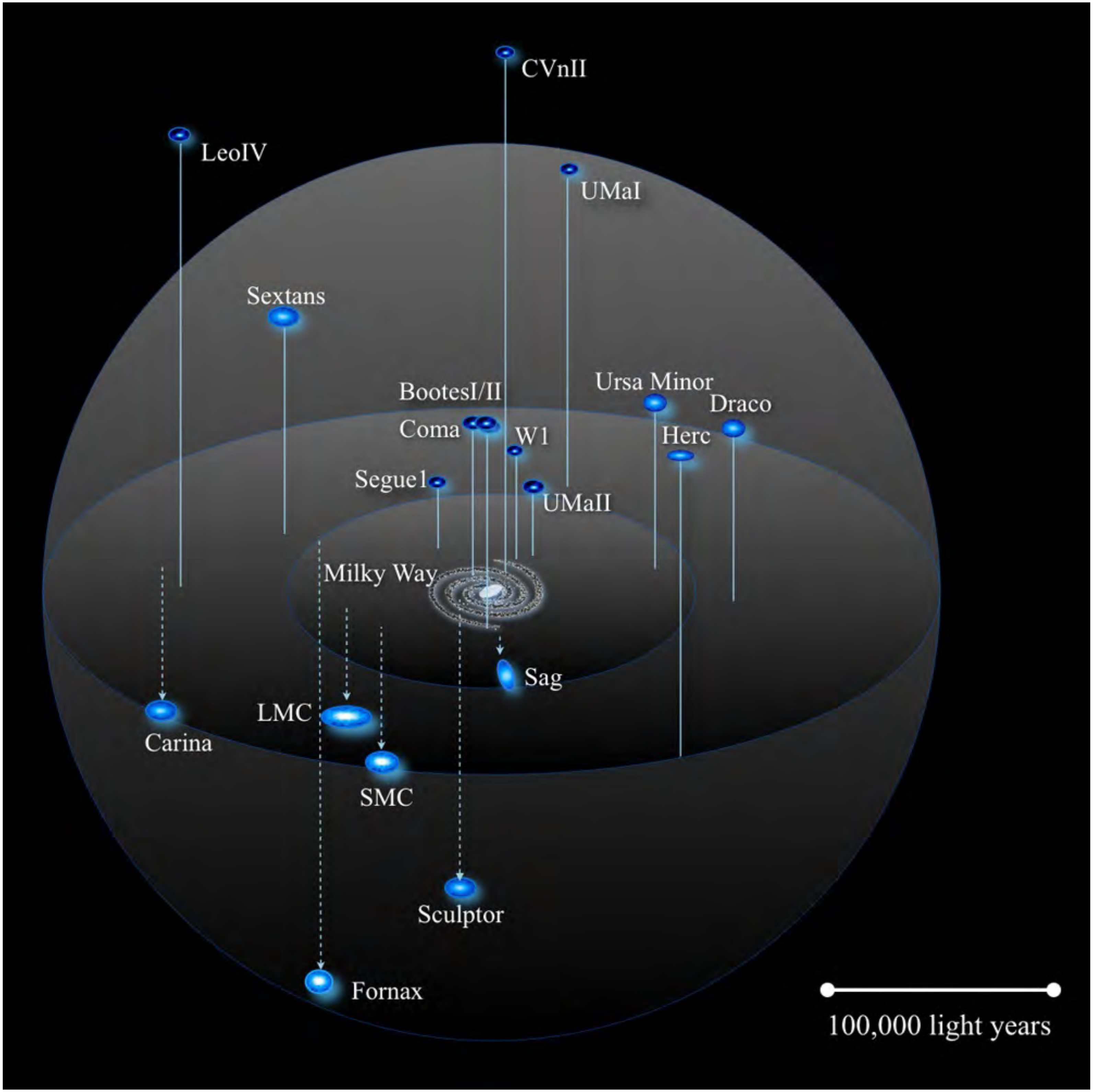
The Big Bang
Inflation
First Stars
400,000,000 years
after Big Bang
Galaxy Evolution
continues...
Dark Energy ?
The Dark Ages
Cosmic Microwave
Background
400,000 years after
Big Bang
First Galaxies
1000,000,000 years
after Big Bang
Now
13,700,000,000 years
after Big Bang
Formation of
The Solar System
8,700,000,000 years
after Big Bang

Hierarchical Structure Formation



Merger Tree

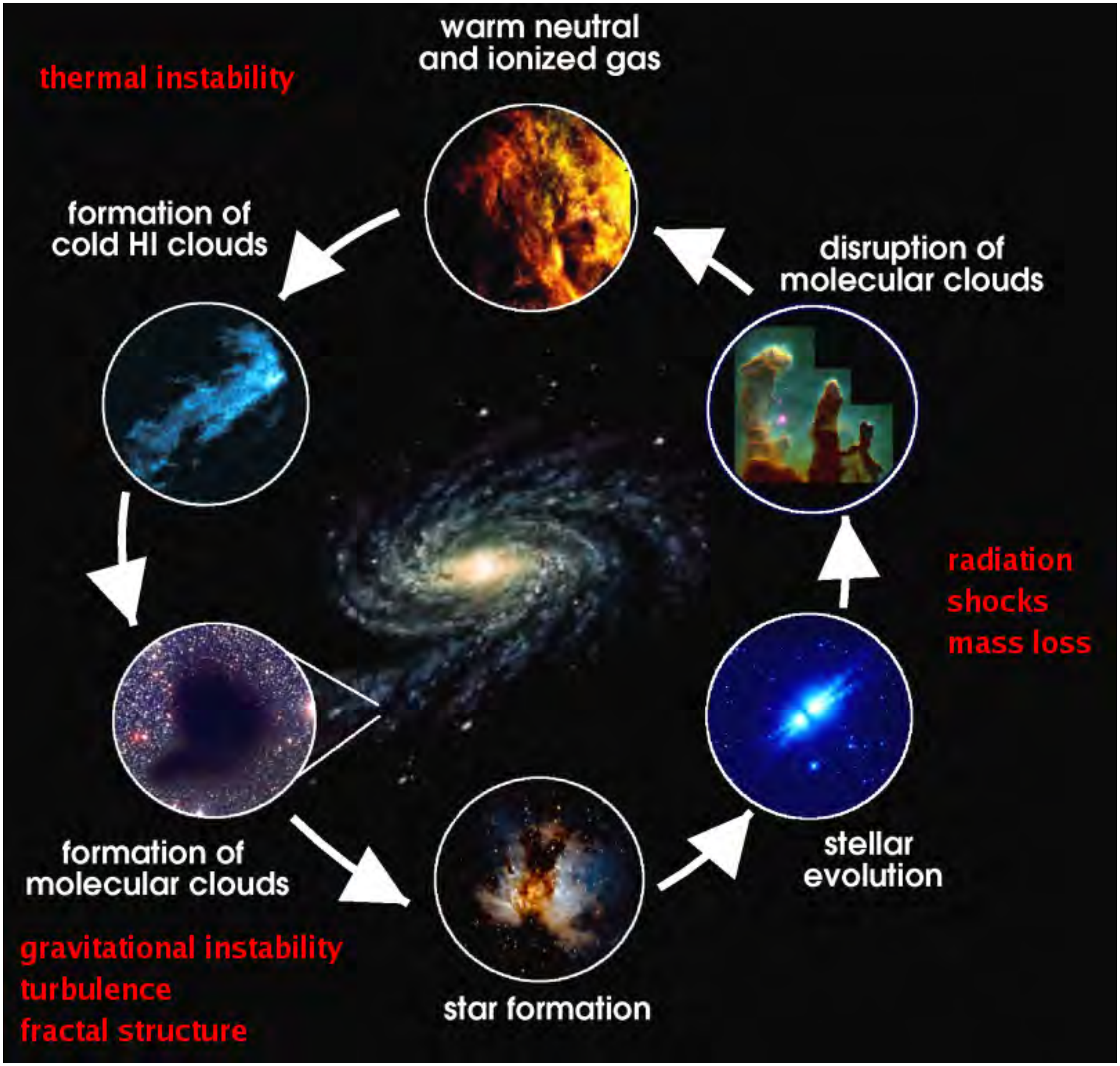




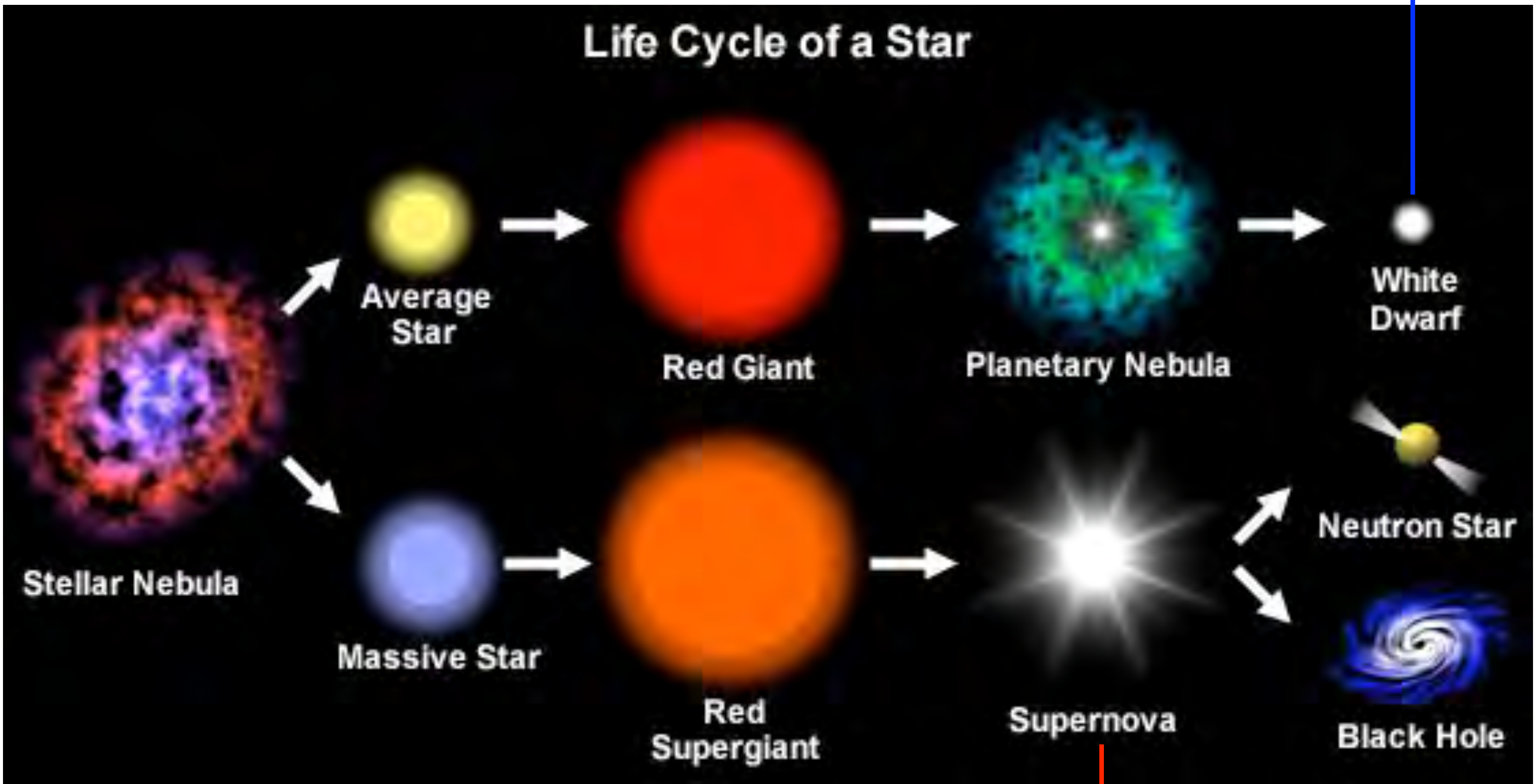
CVnII
LeoIV
UMaI
Sextans
BootesI/II
Ursa Minor
Draco
Coma
W1
Herc
Segue1
UMaII
Milky Way
Sag
LMC
Carina
SMC
Sculptor
Fornax
100,000 light years

Galaxy formation with gas dynamics

Life Cycle of Interstellar Medium



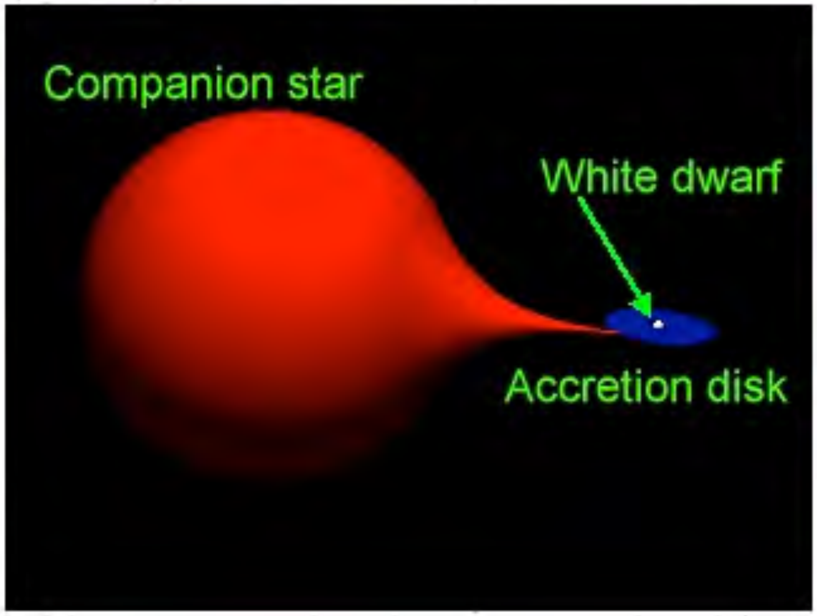
Type Ia SNe



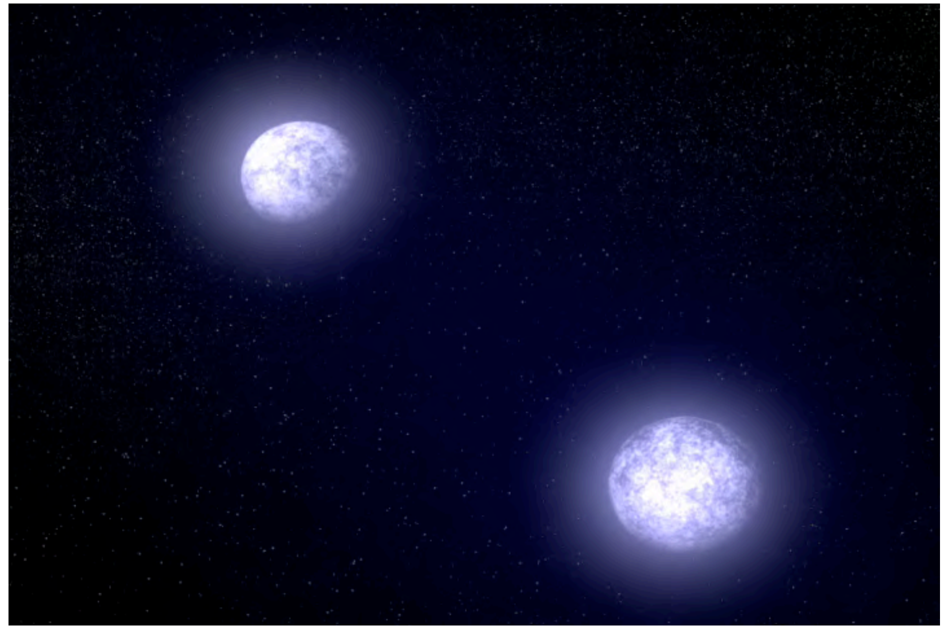
core-collapse SNe (mostly Type II)

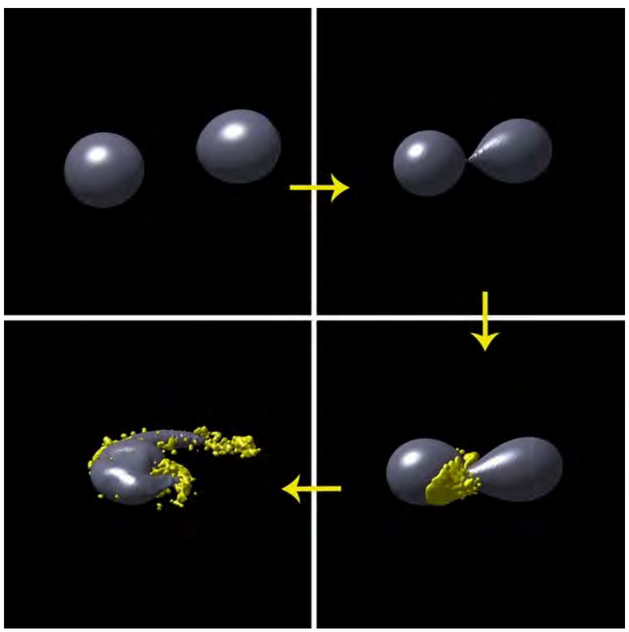
~ 10 Myr

SNe Ia: Accreting and Merging White Dwarfs



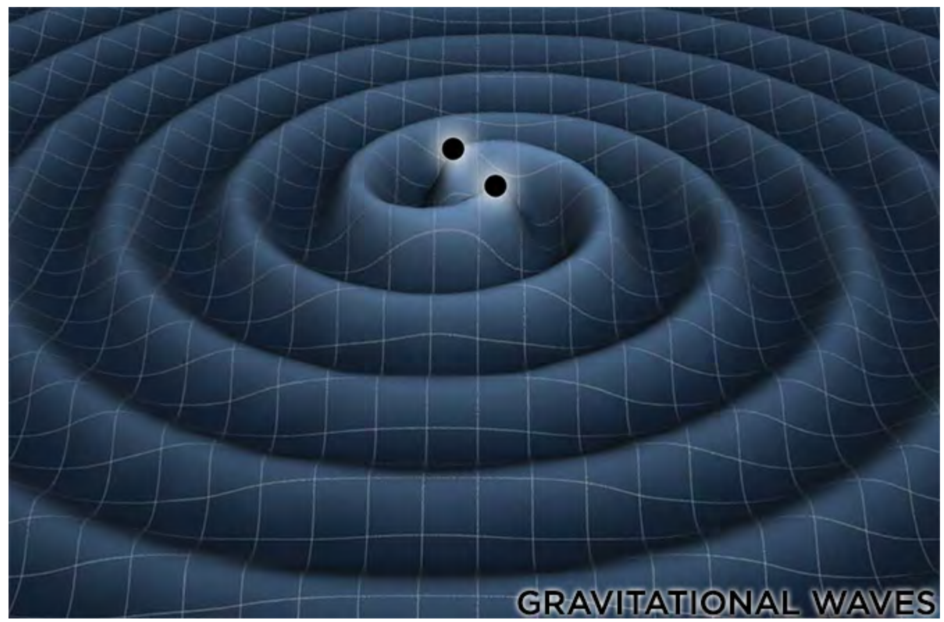
~1 Gyr



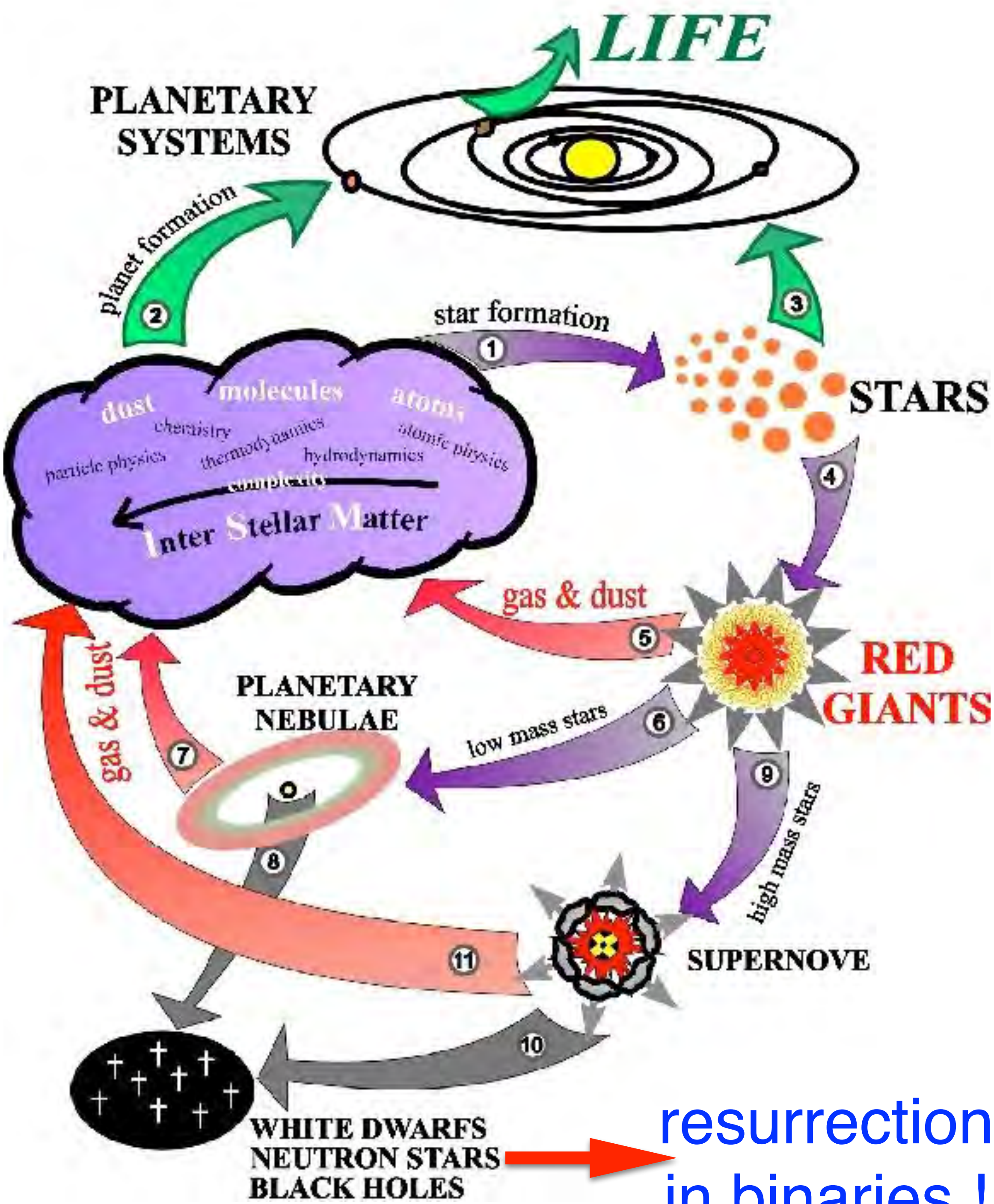


Neutron Star Mergers

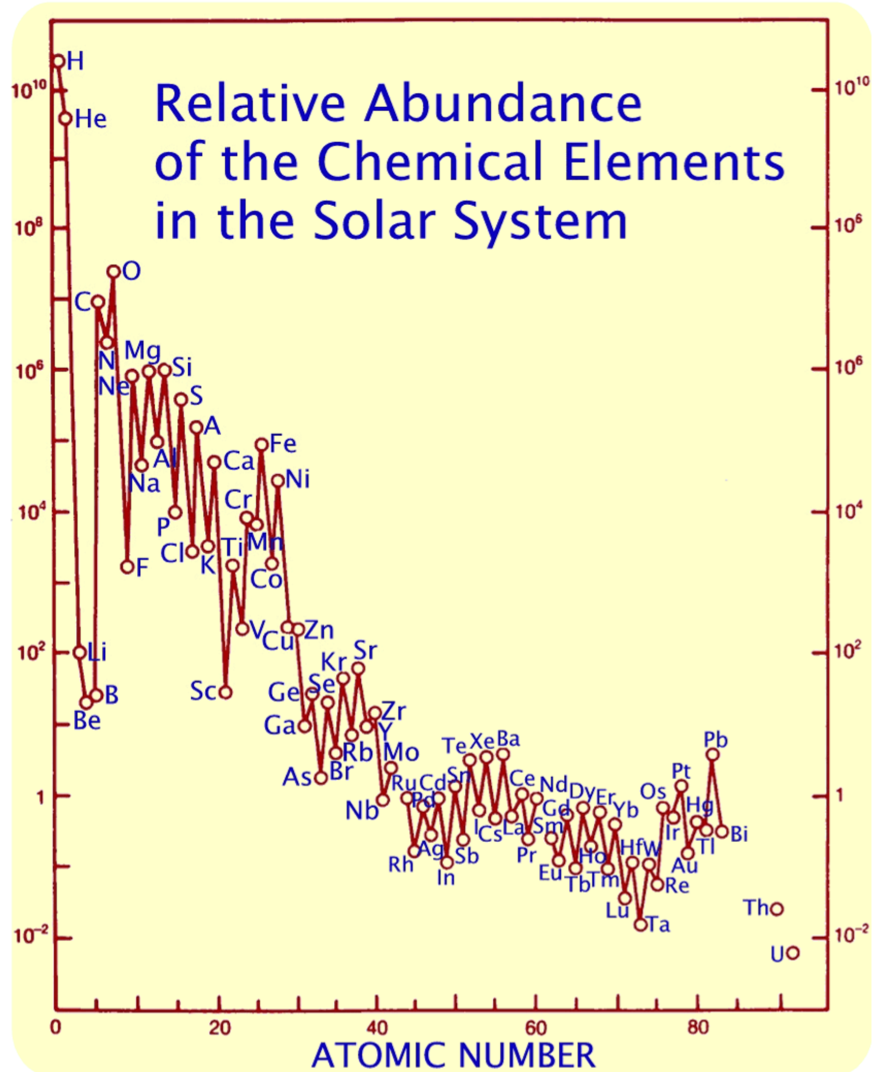
~100 Myr



Arise from the Ashes



resurrection in binaries !



Outline (7/16 & 7/17)

1. Overview of nucleosynthesis

2. Big Bang Nucleosynthesis

3. r-Process Nucleosynthesis

4. Neutrino-induced Nucleosynthesis

5. Cosmological Structure Formation

6. Galactic Chemical Evolution

Textbooks

Clayton: Principles of Stellar Evolution & Nucleosynthesis

Arnett: Supernovae & Nucleosynthesis

Pagel: Nucleosynthesis & Chemical Evolution of Galaxies

Basics of Big Bang Nucleosynthesis

initial state ($T > 1$ MeV): $n,\ p$

$$X_n + X_p = 1 \Rightarrow \text{need } n/p$$

rate of change in abundance:

$$\frac{dY_i}{dt} = P(t) - D(t)Y_i\,,\ Y_i = \frac{X_i}{A_i},\ n_i = \rho_b N_A Y_i$$

$$\left.\begin{array}{l} P(t):\ \text{production rate} \\ D(t):\ \text{destruction rate} \end{array}\right\}\ \text{both depend on } T(t) \text{ and } \rho_b(t)$$

$T(t)$ specified by dynamics of expansion

$\rho_b(t)$ specified by conservation of entropy per baryon

$$s \propto g^*_{\rm eff}(t)\frac{T^3}{\rho_b} \propto g^*_{\rm eff}(t)\frac{n_\gamma}{n_b} = \text{const.}$$

$$\text{baryon-to-photon ratio: } \eta = \frac{n_{b,0}}{n_{\gamma,0}} \Rightarrow s \approx \frac{3.6}{\eta}$$

entropy conservation $\Rightarrow$ evolution of $\rho_{\rm rel}$ at $100 > T > 1$ MeV

$$TS = E + PV - \mu N \Rightarrow S = \frac{E + PV - \mu N}{T}$$

fully relativistic: $S_{\rm rel} = \dfrac{\rho_{\rm rel} V + (\rho_{\rm rel}/3)V}{T} \propto g_{\rm eff} T(t)^3 R(t)^3$

$$g_{\rm eff} = \text{const.} \Rightarrow T(t) \propto R(t)^{-1},\ \dot{T}/T = -\dot{R}/R$$

$$\left(\frac{\dot{R}}{R}\right)^2 = \left(\frac{\dot{T}}{T}\right)^2 = \frac{8\pi}{3} G \rho_{\rm rel} = \left(\frac{8\pi}{3} G\right) g_{\rm eff} \frac{\pi^2}{15} T^4$$

$$T \to \infty \text{ as } t \to 0 \Rightarrow \frac{\dot{T}}{T} = -\sqrt{\frac{8\pi^3}{45} g_{\rm eff} G T^4}$$

$$t \approx \frac{1}{2}\sqrt{\frac{45}{8\pi^3}} \frac{1}{\sqrt{g_{\rm eff} G}} \frac{1}{T^2} = \frac{1.71}{\sqrt{g_{\rm eff}}} \left(\frac{\rm MeV}{T}\right)^2 \ {\rm s}$$

$$N_\nu = 3 \Rightarrow g_{\rm eff} = \frac{43}{8},\ t \approx 0.74 \left(\frac{\rm MeV}{T}\right)^2 \ {\rm s}$$

BBN and Neutrinos

freeze-out of n/p: $\nu_e + n \rightleftharpoons p + e^-$, $\bar{\nu}_e + p \rightleftharpoons n + e^+$

$$\sigma_{\nu_e n} \approx \frac{G_F^2}{\pi} \cos^2\theta_C (f^2 + 3g^2)(E_{\nu_e} + \Delta)^2$$

$$\sigma_{\bar{\nu}_e p} \approx \frac{G_F^2}{\pi} \cos^2\theta_C (f^2 + 3g^2)(E_{\bar{\nu}_e} - \Delta)^2$$

$$\cos^2\theta_C = 0.95,\ f = 1,\ g = 1.26,\ \Delta = M_n - M_p = 1.293 \text{ MeV}$$

$$\text{rate per nucleon: } \lambda_{\nu N} \approx \frac{4\pi}{(2\pi)^3} \int_0^\infty \frac{\sigma_{\nu N} E_\nu^2}{\exp(E_\nu/T) + 1} dE_\nu \approx 0.4 \left(\frac{T}{\text{MeV}}\right)^5 \text{s}^{-1}$$

$$\int_{t_{\text{FO}}}^\infty \lambda_{\nu N} dt \sim \int_0^{T_{\text{FO}}} 0.4 \left(\frac{T}{\text{MeV}}\right)^5 \times 2 \times 0.74 \left(\frac{\text{MeV}}{T}\right)^3 dT \sim 0.2 \left(\frac{T_{\text{FO}}}{\text{MeV}}\right)^3 \sim 1 \Rightarrow T_{\text{FO}} \sim 1.7 \text{ MeV}$$

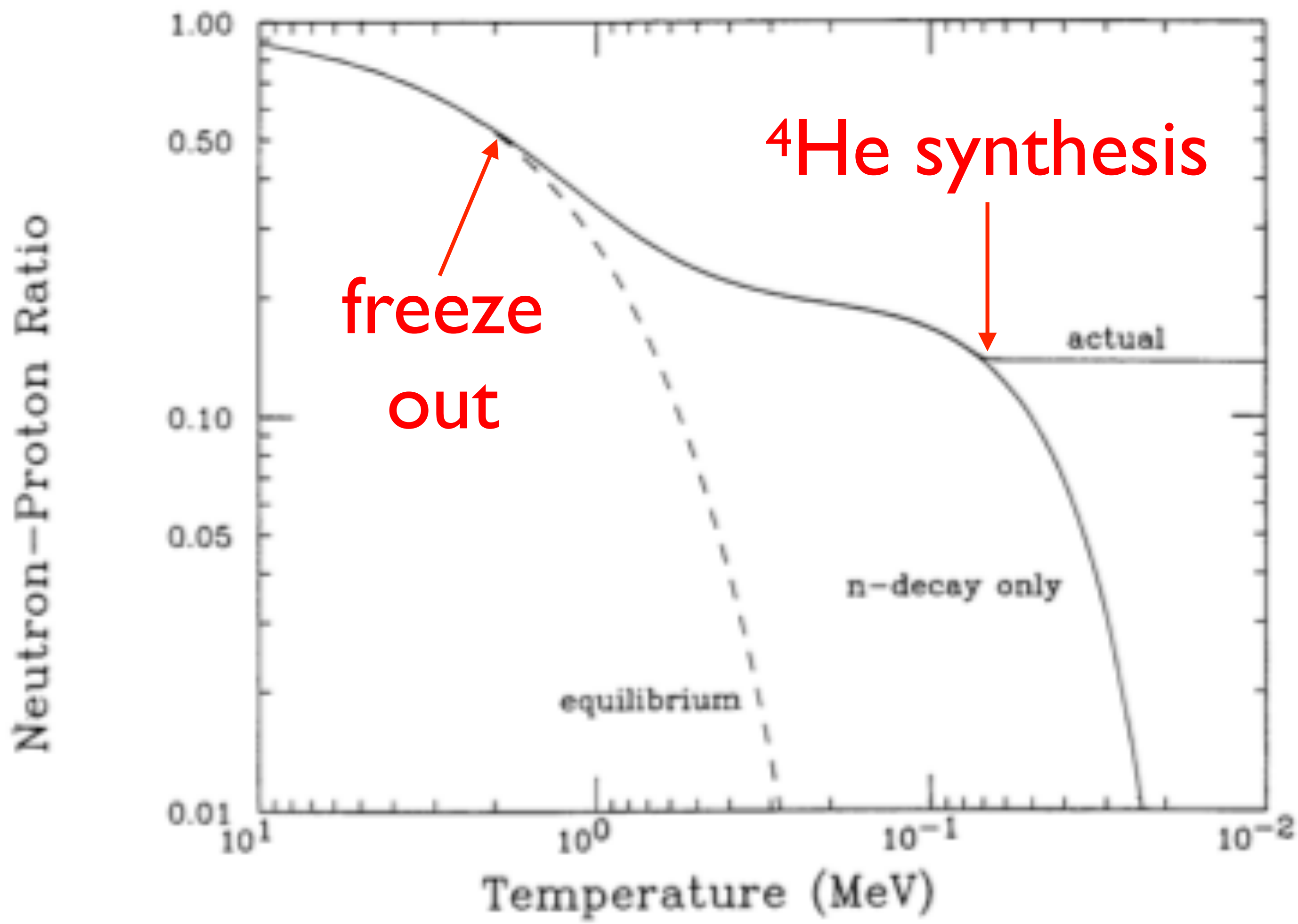


FIG. 1.—Evolution of the neutron-proton ratio with temperature. The NSE ratio is given by the dashed curve. If neutron decay is the only reaction (all other reactions are shut off), the n/p ratio follows the solid curve. The actual final value of the ratio is shown by the straight horizontal line.

$$\frac{n}{p} = \left(\frac{n}{p}\right)_{\mathrm{FO}} \exp\left(-\frac{t - t_{\mathrm{FO}}}{\tau_n}\right) \sim \exp\left(-\frac{\Delta}{T_{\mathrm{FO}}} - \frac{t - t_{\mathrm{FO}}}{\tau_n}\right)$$

$$\frac{n}{p} = \left(\frac{n}{p}\right)_{\rm FO} \exp\left(-\frac{t - t_{\rm FO}}{\tau_n}\right) \sim \exp\left(-\frac{\Delta}{T_{\rm FO}} - \frac{t - t_{\rm FO}}{\tau_n}\right)$$

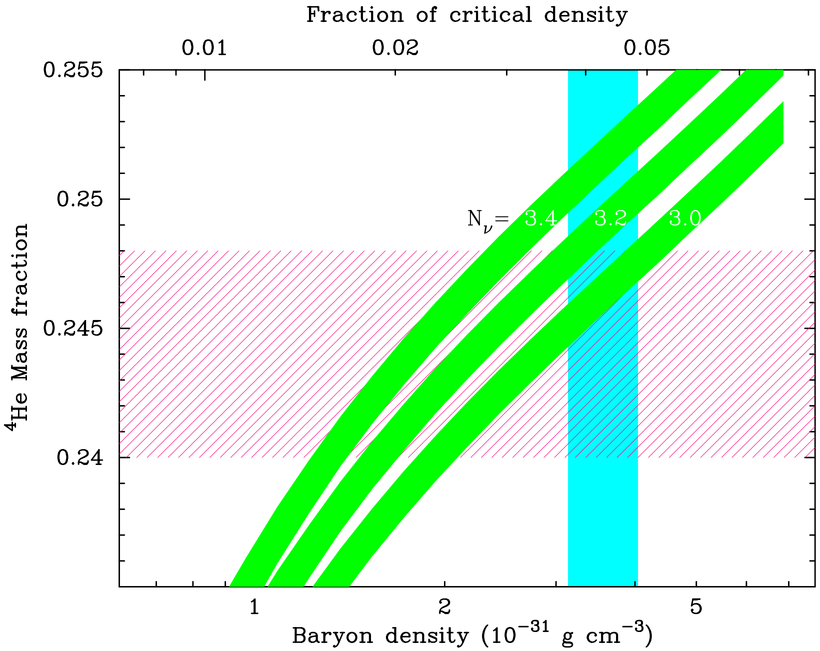
$$^4\text{He production: } X(^4\text{He}) \sim \frac{2n}{n+p} = \frac{2(n/p)}{(n/p)+1}$$

$$t \sim \frac{1}{\sqrt{a + bN_\nu}} \frac{1}{T^2}, \;\; \lambda_{\nu N} \propto T^5, \;\; \int_{t_{\rm FO}}^{\infty} \lambda_{\nu N} dt \propto \frac{T_{\rm FO}^3}{\sqrt{a + bN_\nu}} \sim \text{const.}$$

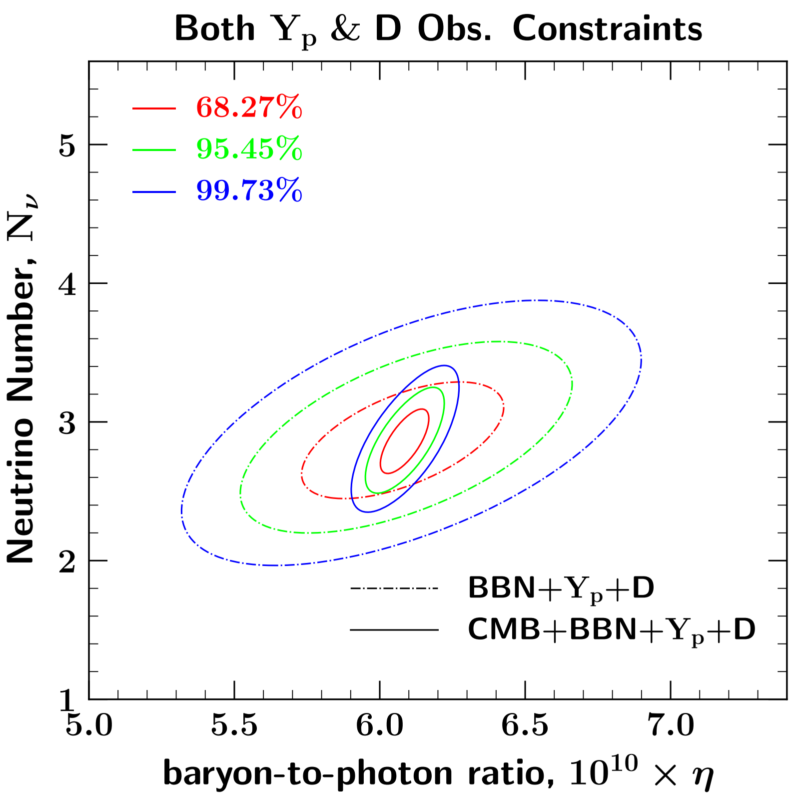
$$N_\nu \uparrow \Rightarrow T_{\rm FO} \uparrow \Rightarrow \left(\frac{n}{p}\right)_{\rm FO} \sim \exp\left(-\frac{\Delta}{T_{\rm FO}}\right) \uparrow$$

$$N_\nu \uparrow \Rightarrow t \downarrow \Rightarrow \frac{n}{p} = \left(\frac{n}{p}\right)_{\rm FO} \exp\left(-\frac{t - t_{\rm FO}}{\tau_n}\right) \uparrow$$

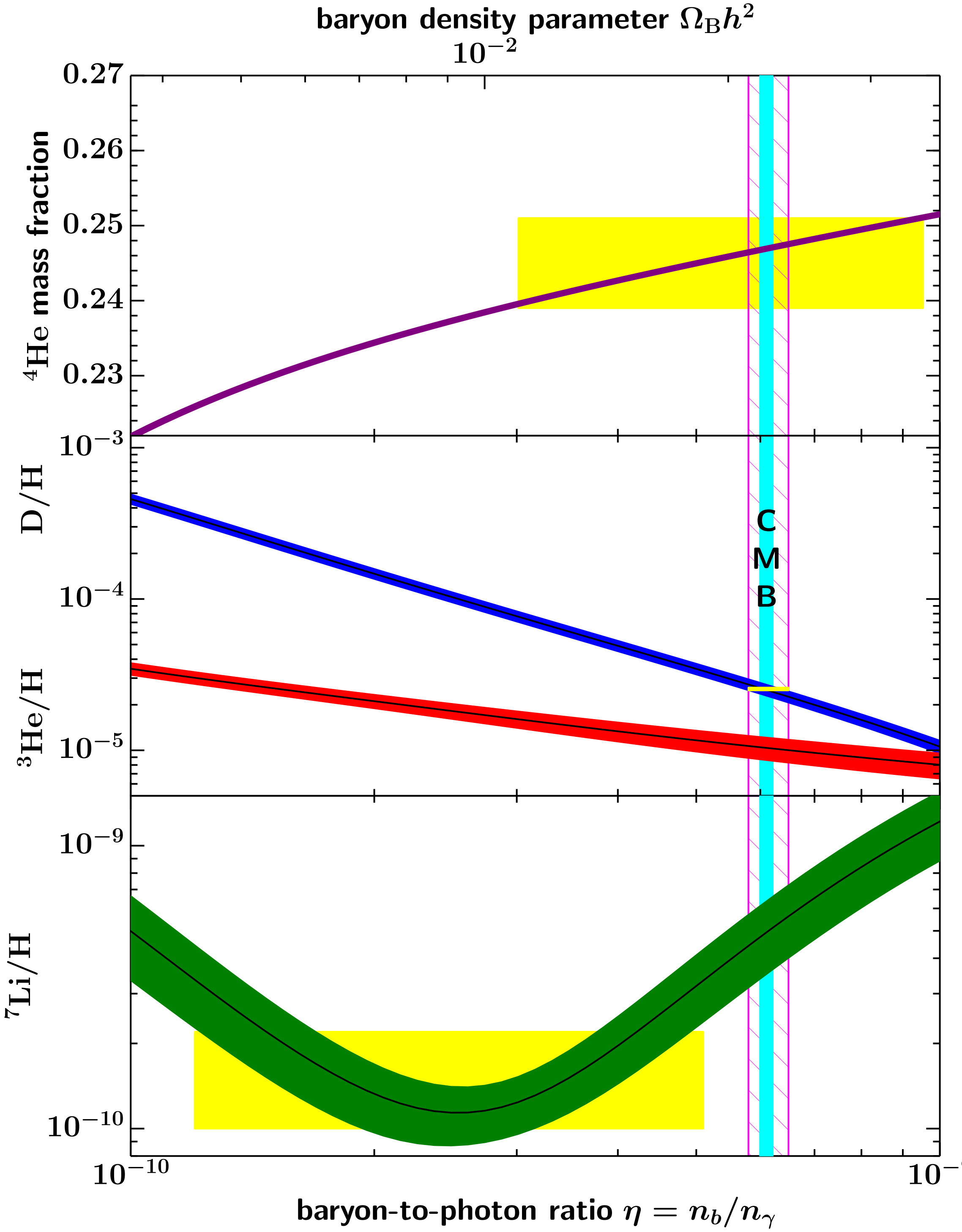
$$N_\nu \uparrow \Rightarrow \frac{n}{p} \uparrow \Rightarrow X(^4\text{He}) \uparrow$$



Fraction of critical density
0.01
0.02
0.05
0.255
0.25
0.245
0.24
^{4}He Mass fraction
N_ν= 3.4 3.2 3.0
1
2
5
Baryon density (10^{-31} g cm^{-3})



Both Y_p & D Obs. Constraints
68.27%
95.45%
99.73%
Neutrino Number, N_ν
1
2
3
4
5
BBN+Y_p+D
CMB+BBN+Y_p+D
5.0
5.5
6.0
6.5
7.0
baryon-to-photon ratio, $10^{10} \times \eta$



baryon density parameter $\Omega_B h^2$
10^{-2}
0.27
0.26
0.25
0.24
0.23
^{4}He mass fraction
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
C
M
B
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio $\eta = n_b/n_\gamma$

Nuclear Statistical Equilibrium (NSE)

$$Zp + (A-Z)n \rightleftharpoons (Z,A) + \gamma \Rightarrow Z\mu_p + (A-Z)\mu_n = \mu(Z,A)$$

considering excited states of nuclei:

$$n(Z,A) = \sum_i \frac{2J_i+1}{(2\pi)^3} \int_0^\infty \frac{4\pi p^2 dp}{\exp\{[(p^2/2M) + M + E_i - \mu]/T\}}$$

$$= G(Z,A)\left(\frac{MT}{2\pi}\right)^{3/2} \exp\left[\frac{\mu(Z,A) - M(Z,A)}{T}\right]$$

nuclear partition function: $G(Z,A) = \sum_i (2J_i+1)\exp\left(-\frac{E_i}{T}\right)$

$$\Rightarrow X(Z,A) = X_p^Z X_n^{A-Z} \frac{G(Z,A)}{2^A} A^{5/2}$$

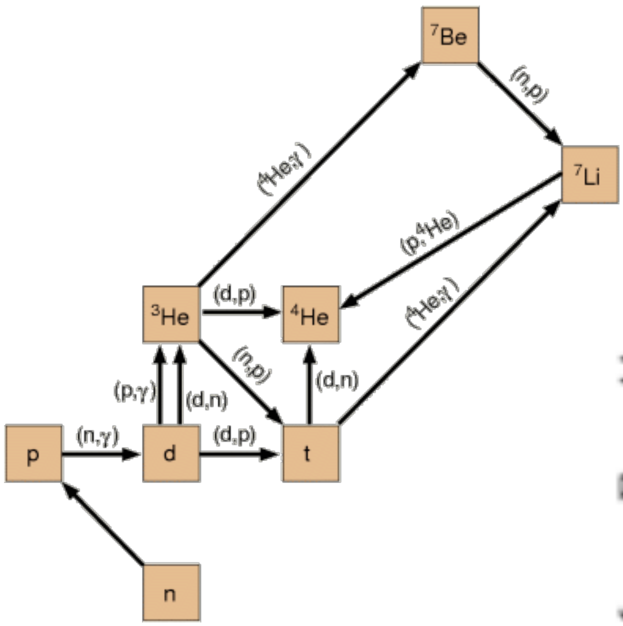
$$\times \left(\frac{\rho_b}{M_N}\right)^{A-1} \left(\frac{2\pi}{M_N T}\right)^{3(A-1)/2} \exp\left[\frac{B(Z,A)}{T}\right]$$

In NSE, no rates are needed to calculate abundances:

$$
\begin{aligned}
1 &= X_n + X_p + \sum_{(Z,A)} X(Z,A) \\
Y_e &= X_p + \sum_{(Z,A)} \frac{Z}{A} X(Z,A) \\
X(Z,A) &= X_p^Z X_n^{A-Z} \frac{G(Z,A)}{2^A} A^{5/2} \\
&\times \left(\frac{\rho_b}{M_N}\right)^{A-1} \left(\frac{2\pi}{M_N T}\right)^{3(A-1)/2} \exp\left[\frac{B(Z,A)}{T}\right]
\end{aligned}
$$

$$
\left[\eta \left(\frac{T}{M_N}\right)^{3/2}\right]^{A-1} \exp\left[\frac{B(Z,A)}{T}\right] \sim 1
$$

$\Rightarrow (Z,A)$ drops out of NSE at lower T



$$p(n,\gamma)d$$

$$d(d,n)^3\mathrm{He}$$

$$d(d,p)t$$

$$^3\mathrm{He}(d,p)^4\mathrm{He}$$

$$t(d,n)^4\mathrm{He}$$

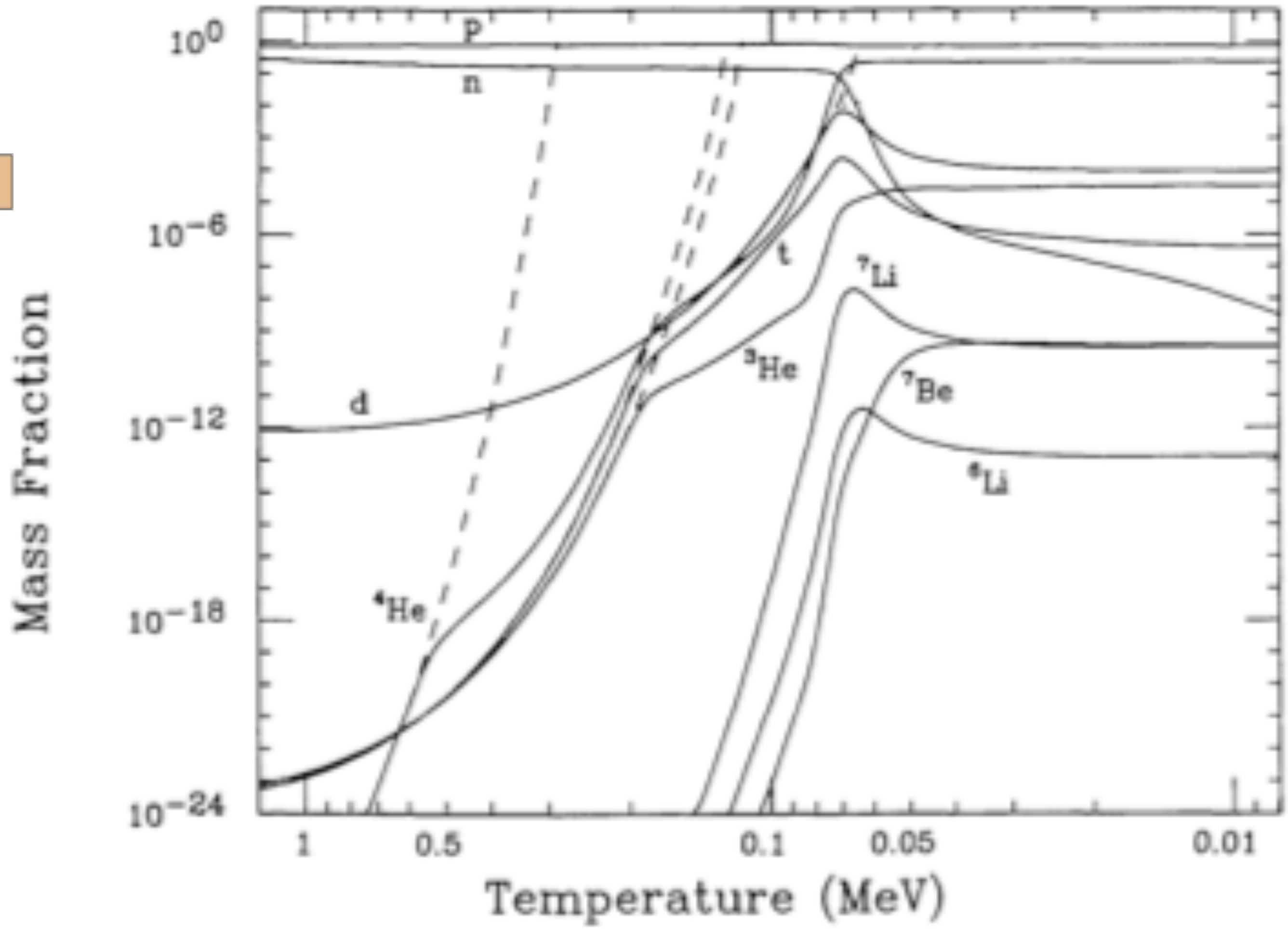
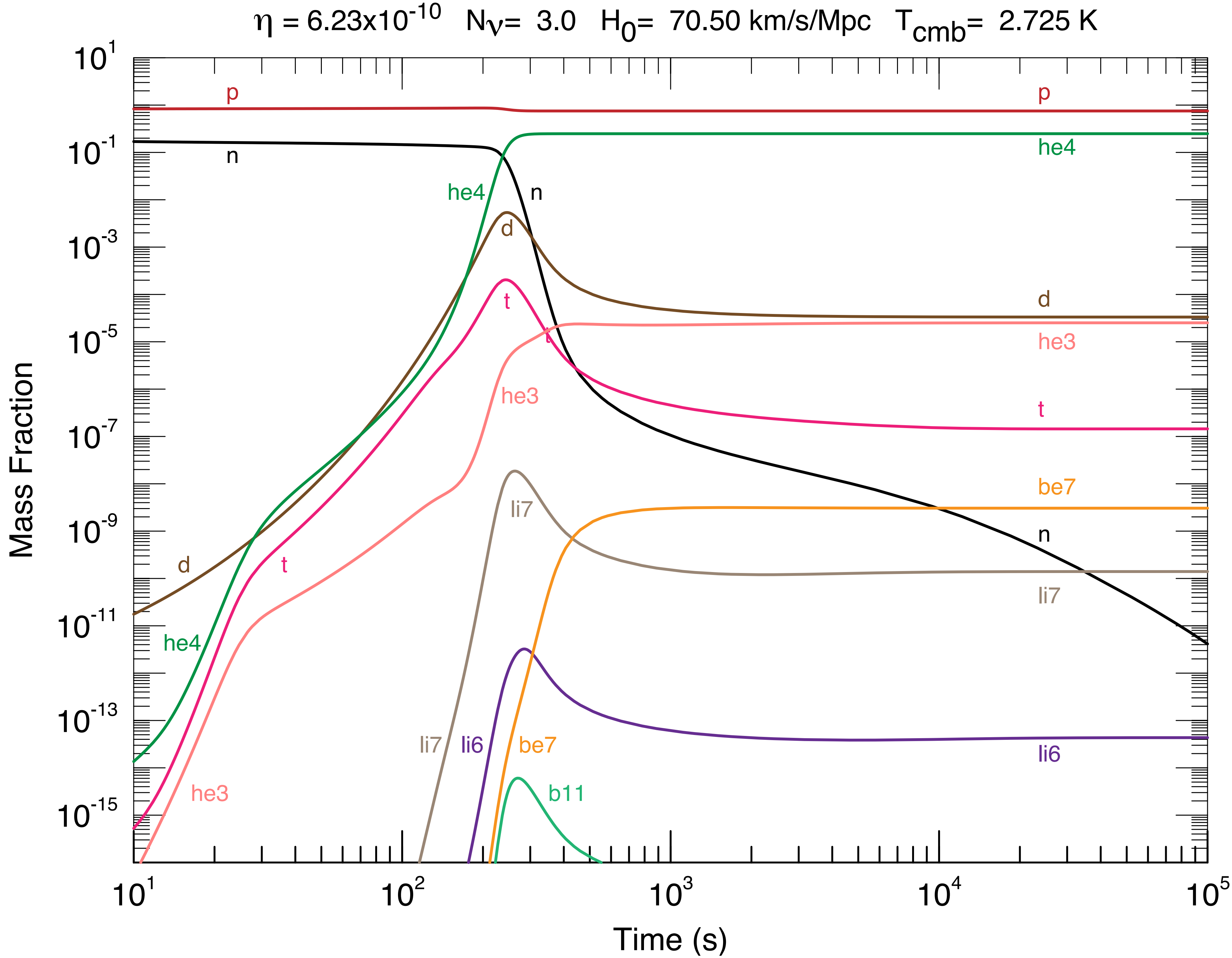


FIG. 2.—Evolution of light-element abundances with temperature, for a baryon-to-photon ratio $\eta_{10} = 3.16$. The dashed curves give the NSE curves of ^{4}He, t, ^{3}He, and d, respectively. The dotted curve is explained in the text.

$$T_{\rm NSE} \sim \frac{B(Z,A)/(A-1)}{\ln\eta^{-1} + (3/2)\ln(M_N/T)}$$



η = 6.23x10^{-10} N$_\nu$= 3.0 H$_0$= 70.50 km/s/Mpc T$_{cmb}$= 2.725 K
Mass Fraction
Time (s)
p
n
he4
d
t
he3
li7
li6
be7
b11

Expansion from high temperature & density

- nuclear statistical equilibrium (NSE)

all strong & electromagnetic reactions in equilibrium

$$(A-Z)n + Zp \rightleftharpoons (Z,A) + \gamma$$

- quasi-statistical equilibrium (QSE)

clusters of nuclei form & reactions involving n, p,
& light nuclei in equilibrium within each cluster

$$(n,\gamma), (p,\gamma), (n,p), (\alpha,\gamma), (\alpha,n), (\alpha,p)$$

- hot r-process

QSE within each isotopic chain only

$$(n,\gamma) \rightleftharpoons (\gamma,n) \text{ equilibrium}$$

quasi-statistical equilibrium (QSE)

typically QSE is achieved for $0.5 \gtrsim T \gtrsim 0.25$ MeV

$\alpha + \alpha + n \rightleftharpoons {}^{9}\mathrm{Be} + \gamma$

Q-value = 1.57 MeV

$n, \;\; p, \;\; \alpha$

light cluster

${}^{9}\mathrm{Be}(\alpha, n)^{12}\mathrm{C}$

${}^{12}\mathrm{C}$, etc.

heavier clusters

determination of neutron-to-seed ratio

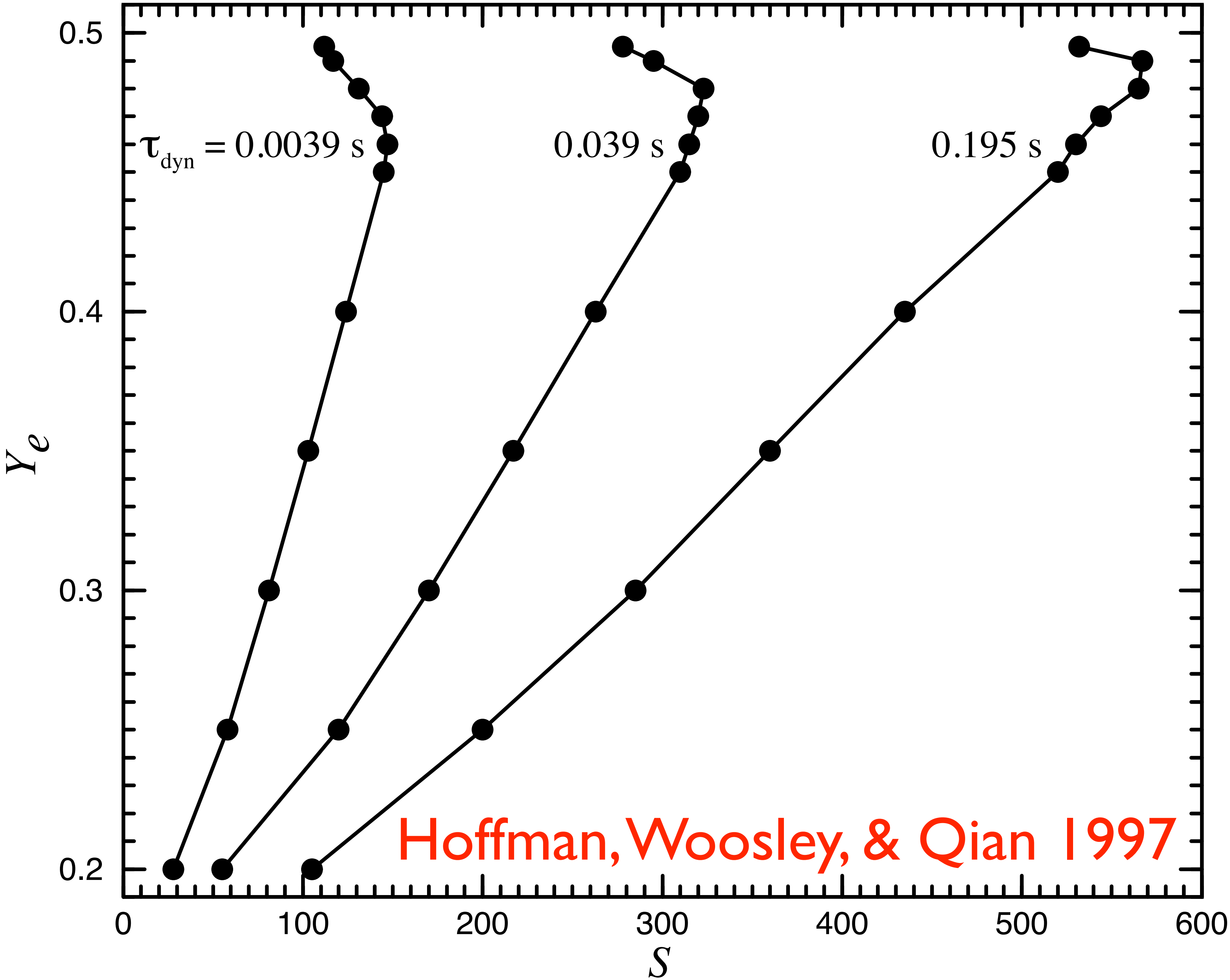
$Y_e \downarrow \Rightarrow$ more neutrons

entropy per baryon $S \propto (T^3/\rho) \uparrow \;\Rightarrow$

more photons capable of disintegrating ${}^{9}\mathrm{Be} \Rightarrow$ fewer seeds

$\tau_{\mathrm{dyn}} \downarrow \Rightarrow$ shorter time for producing seeds

conditions for producing r-nuclei with A~200



Hoffman, Woosley, & Qian 1997

$$(n,\gamma) \rightleftharpoons (\gamma,n) \text{ equilibrium: } n + (Z,A) \rightleftharpoons (Z,A+1) + \gamma$$

typically achieved for $0.25 \gtrsim T \gtrsim 0.1$ MeV

$$\frac{Y(Z,A+1)}{Y(Z,A)} = \frac{G(Z,A+1)}{G(Z,A)} \left(\frac{A+1}{A}\right)^{3/2}$$

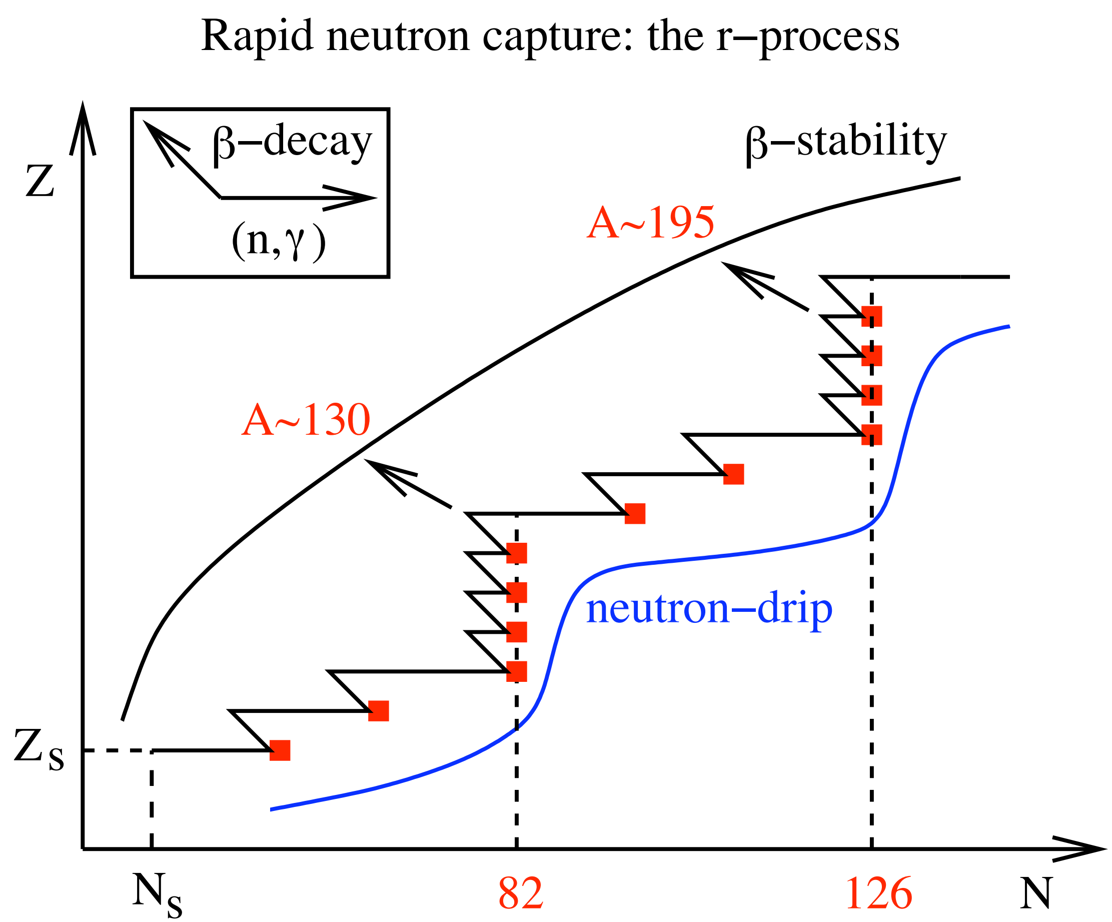
$$\times \boxed{\frac{n_n}{2} \left(\frac{2\pi}{M_N T}\right)^{3/2} \exp\left[\frac{S_n(Z,A+1)}{T}\right]}$$

$\sim 1 \Rightarrow$ waiting-point nuclei

$$S_n^{\mathrm{WP}} \sim T \ln\left[\frac{2}{n_n}\left(\frac{M_N T}{2\pi}\right)^{3/2}\right]$$

$$= T_9[2.79 + 0.198(1.5 \log T_9 - \log n_{n,20})] \text{ MeV}$$

steady β-flow in $(n,\gamma) \rightleftharpoons (\gamma,n)$ equilibrium



$$\frac{dY_{\rm WP}(Z+1)}{dt} = \lambda_\beta^{\rm WP}(Z) Y_{\rm WP}(Z) - \lambda_\beta^{\rm WP}(Z+1) Y_{\rm WP}(Z+1) = 0$$

$$\Rightarrow Y_{\rm WP}(Z) \propto 1/\lambda_\beta^{\rm WP}(Z)$$

$(n,\gamma) \rightleftharpoons (\gamma,n)$ equilibrium: $n + (Z,A) \rightleftharpoons (Z,A+1) + \gamma$

$$\frac{Y(Z,A+1)}{Y(Z,A)} = \frac{G(Z,A+1)}{2G(Z,A)} \left(\frac{A+1}{A}\right)^{3/2} \times n_n \left(\frac{2\pi}{M_N T}\right)^{3/2} \exp\left[\frac{S_n(Z,A+1)}{T}\right]$$

$$n_n \langle \sigma_{n,\gamma}(Z,A)v \rangle Y(Z,A) = \lambda_{\gamma,n}(Z,A+1) Y(Z,A+1)$$

$$\Rightarrow \lambda_{\gamma,n}(Z,A+1) = n_n \frac{Y(Z,A)}{Y(Z,A+1)} \langle \sigma_{n,\gamma}(Z,A)v \rangle = \frac{2G(Z,A)}{G(Z,A+1)} \left(\frac{A}{A+1}\right)^{3]2} \langle \sigma_{n,\gamma}(Z,A)v \rangle \times \left(\frac{M_N T}{2\pi}\right)^{3/2} \exp\left[-\frac{S_n(Z,A+1)}{T}\right]$$

typical nuclear properties of waiting-point nuclei with N = 82 & 126

$$S_n \sim 2\ \mathrm{MeV},\ \langle \sigma_{n,\gamma} v \rangle \sim 10^{-20}\ \mathrm{cm}^3\ \mathrm{s}^{-1},\ \lambda_\beta \sim 10\ \mathrm{s}^{-1}$$

$$n_n \langle \sigma_{n,\gamma} v \rangle \gg \lambda_\beta \Rightarrow n_n \gg 10^{21}\ \mathrm{cm}^{-3}$$

$$T_9 \sim 1 \Rightarrow \lambda_{\gamma,n} \sim 10^4\ \mathrm{s}^{-1} \gg \lambda_\beta$$

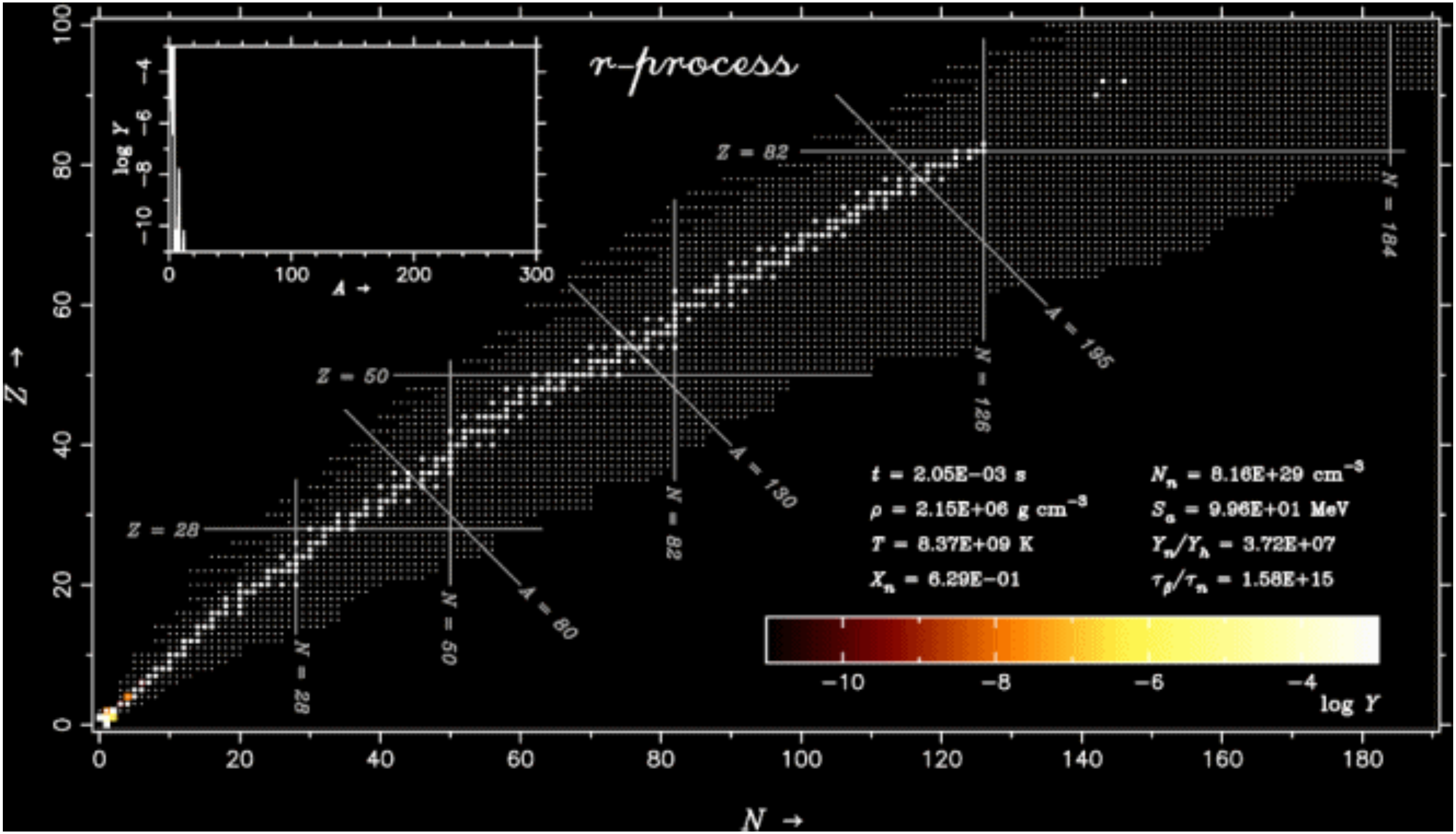
time for β-flow to go from seeds through $N = 82$ and 126

is $\lesssim 1$ s

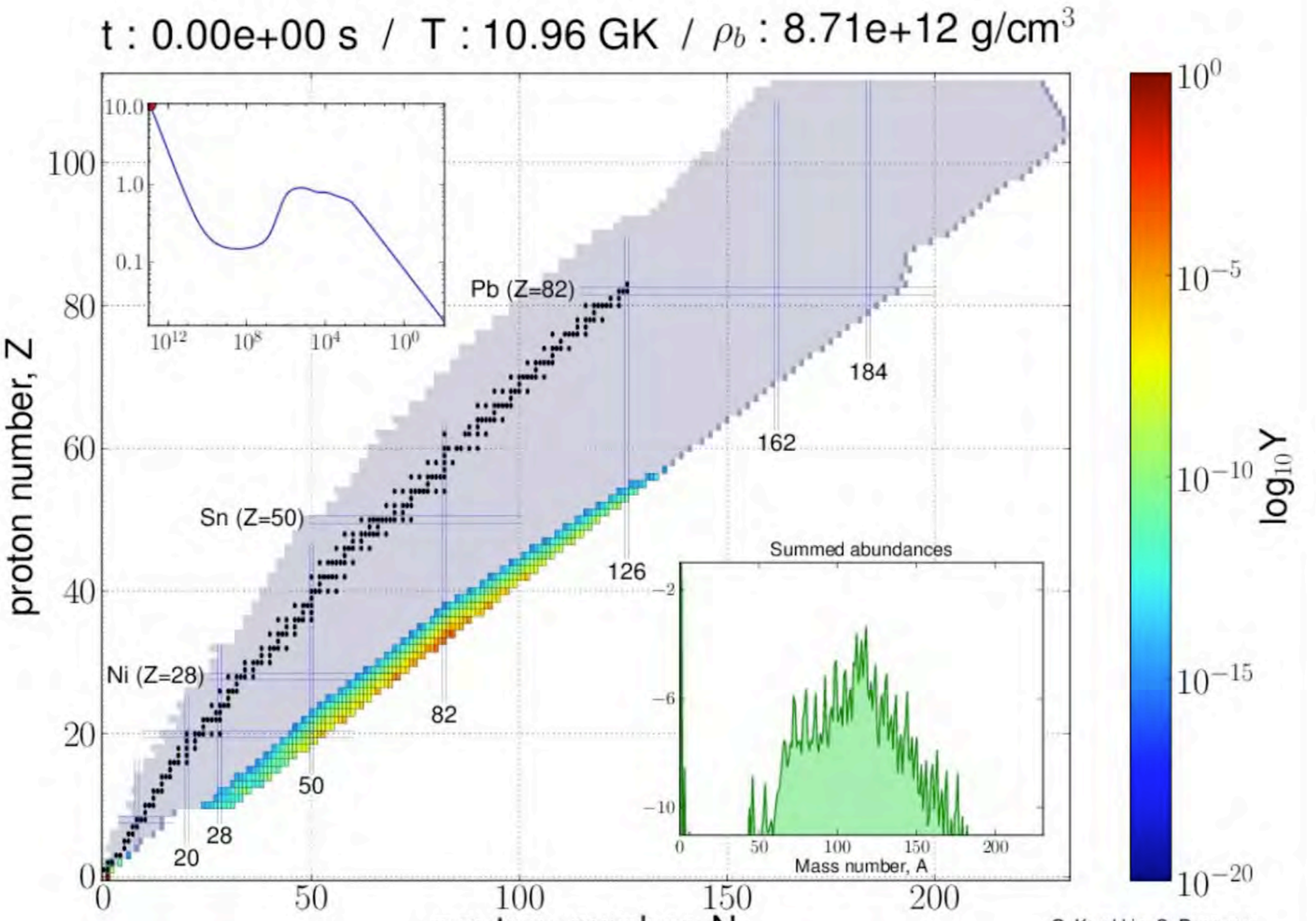
in contrast to a hot r-process, a cold r-process occurs
when photo-disintegration can be ignored

$$T_9 \ll 1 \ \Rightarrow \ \text{cold r-process}$$

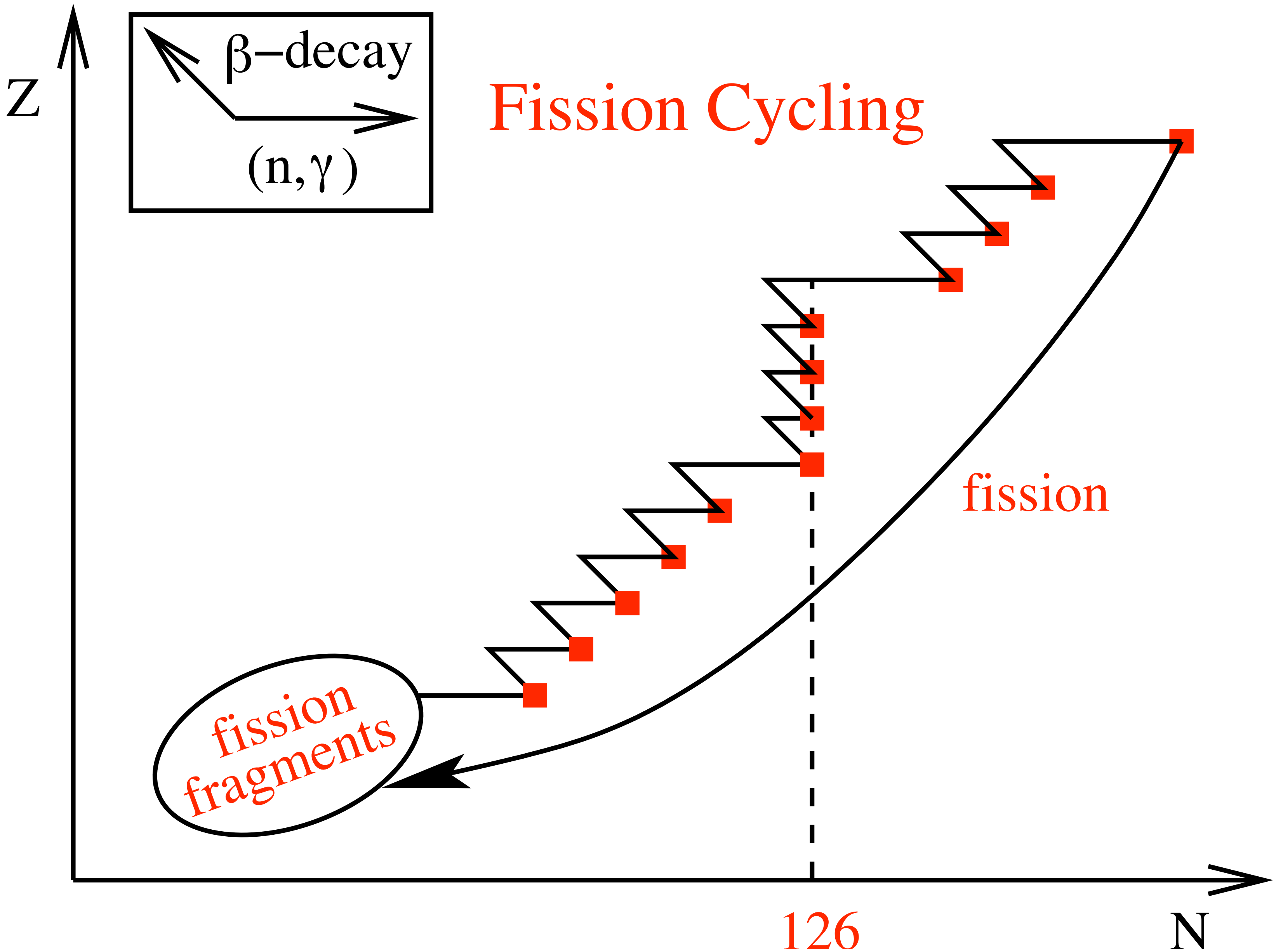
Hot r-process starting with free nucleons



Wanajo et al. 2004



O. Korobkin, S. Rosswog,
A. Arcones, C. Winteler,
arXiv:1206.2379

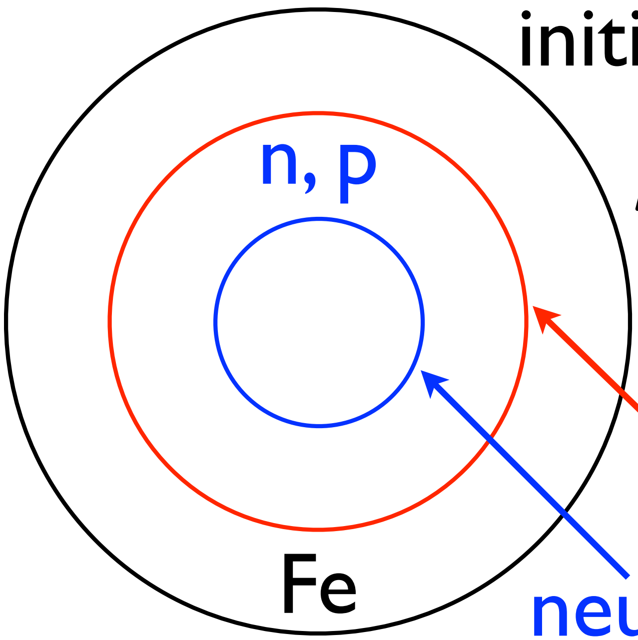

Z
β−decay
(n,γ)
Fission Cycling
fission
fission fragments
126
N

"neutronization" pulse at shock breakout

$$e^- + p \rightarrow n + \nu_e \Rightarrow \text{predominantly } \nu_e$$

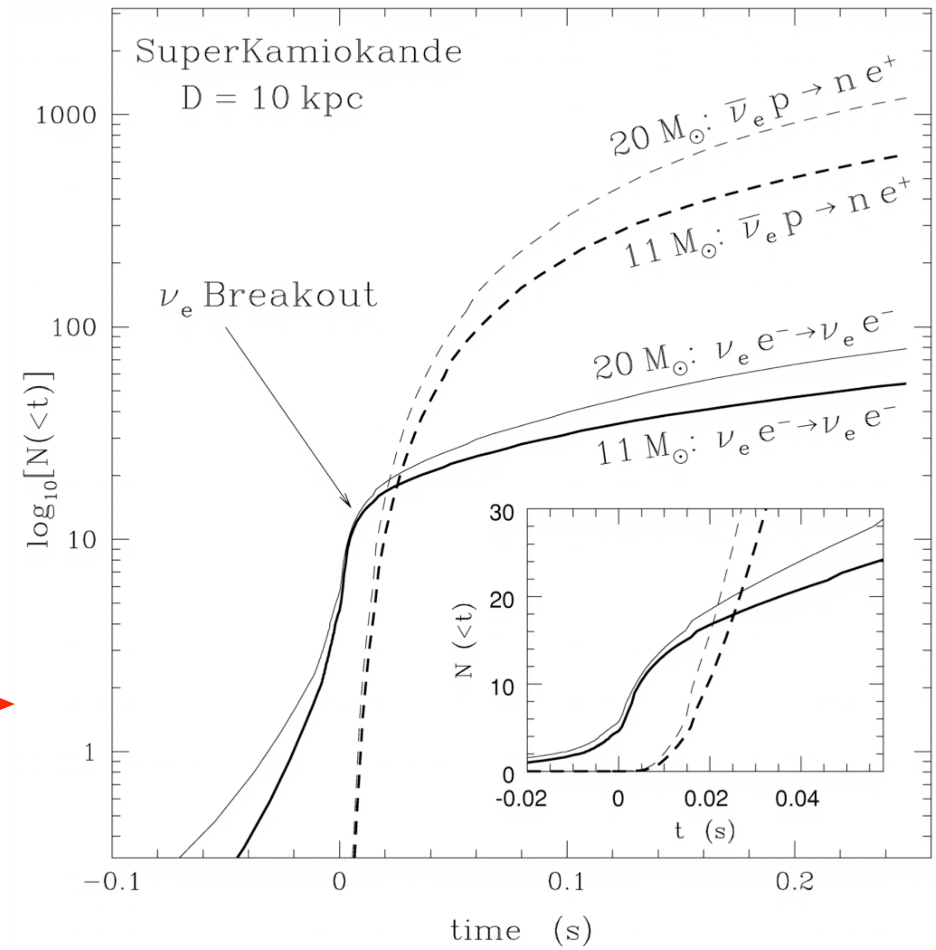
initial trapping surface

$\rho \sim 10^{11}$ g cm^{-3}

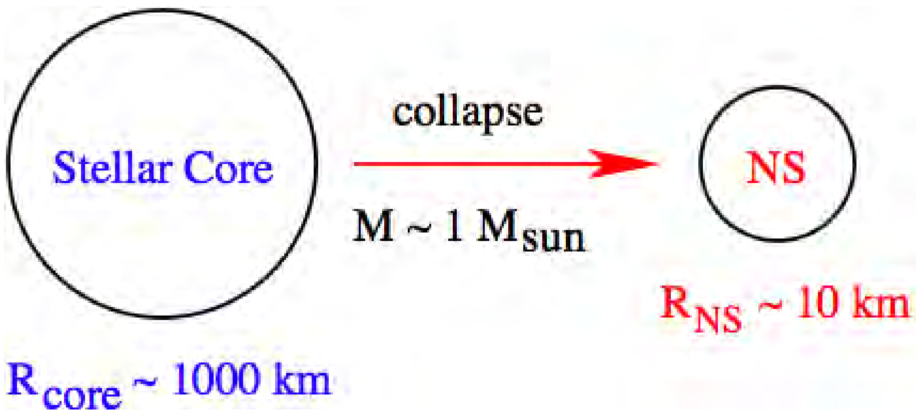


without oscillations

(Thompson et al. 2003)



Supernovae as a neutrino phenomenon

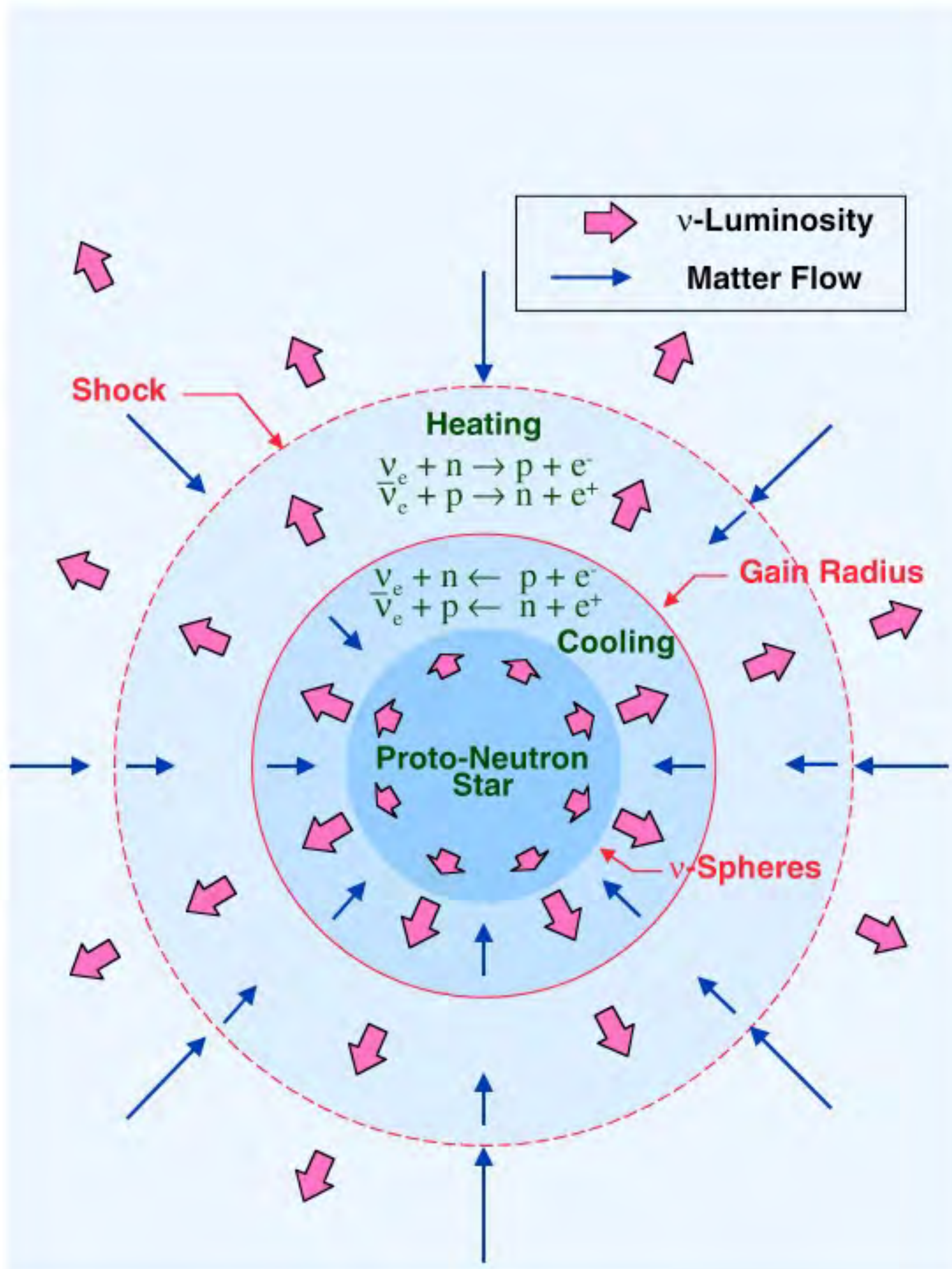


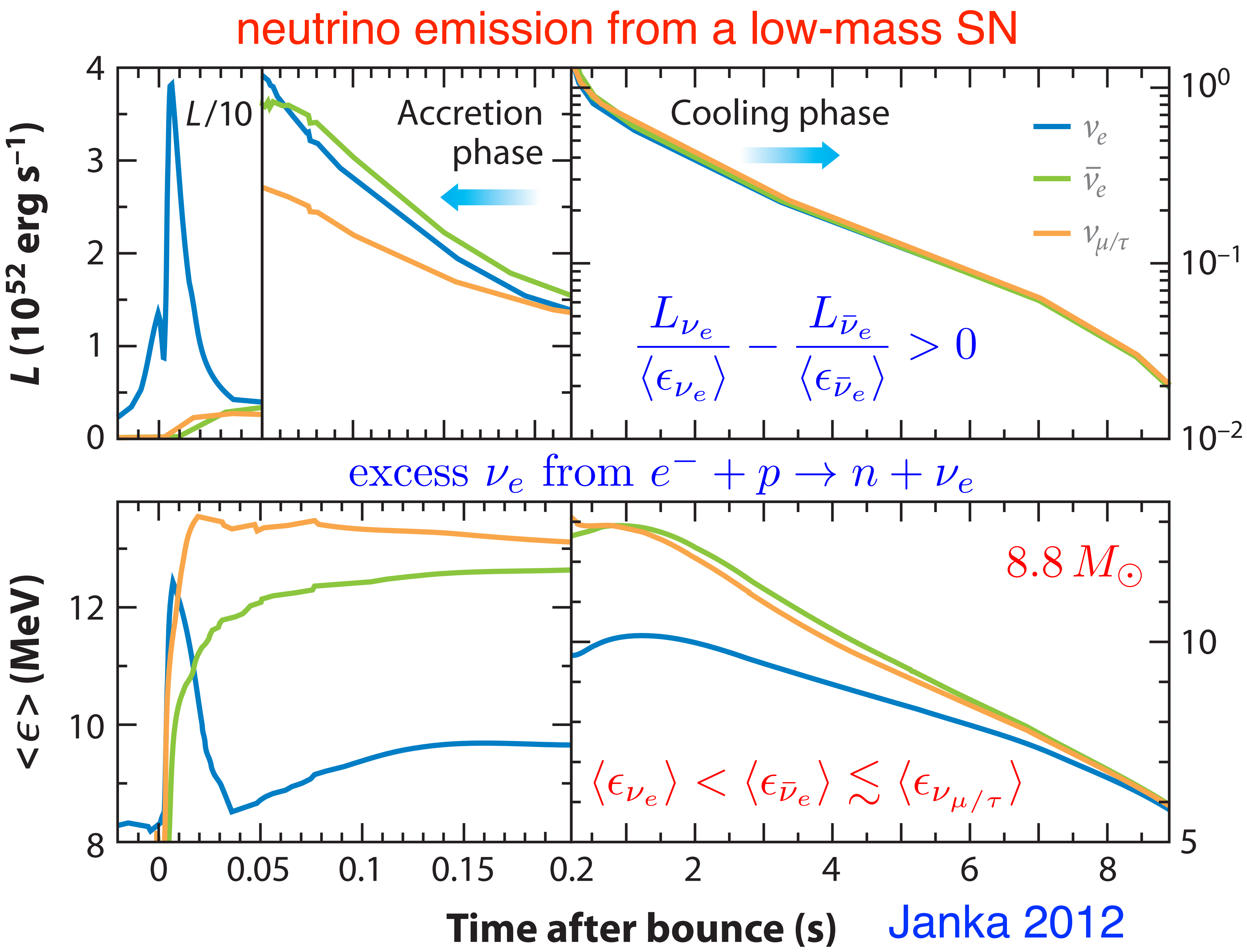
$$e^+ + e^- \rightarrow \nu + \bar{\nu}$$

$$N + N \rightarrow N + N + \nu + \bar{\nu}$$

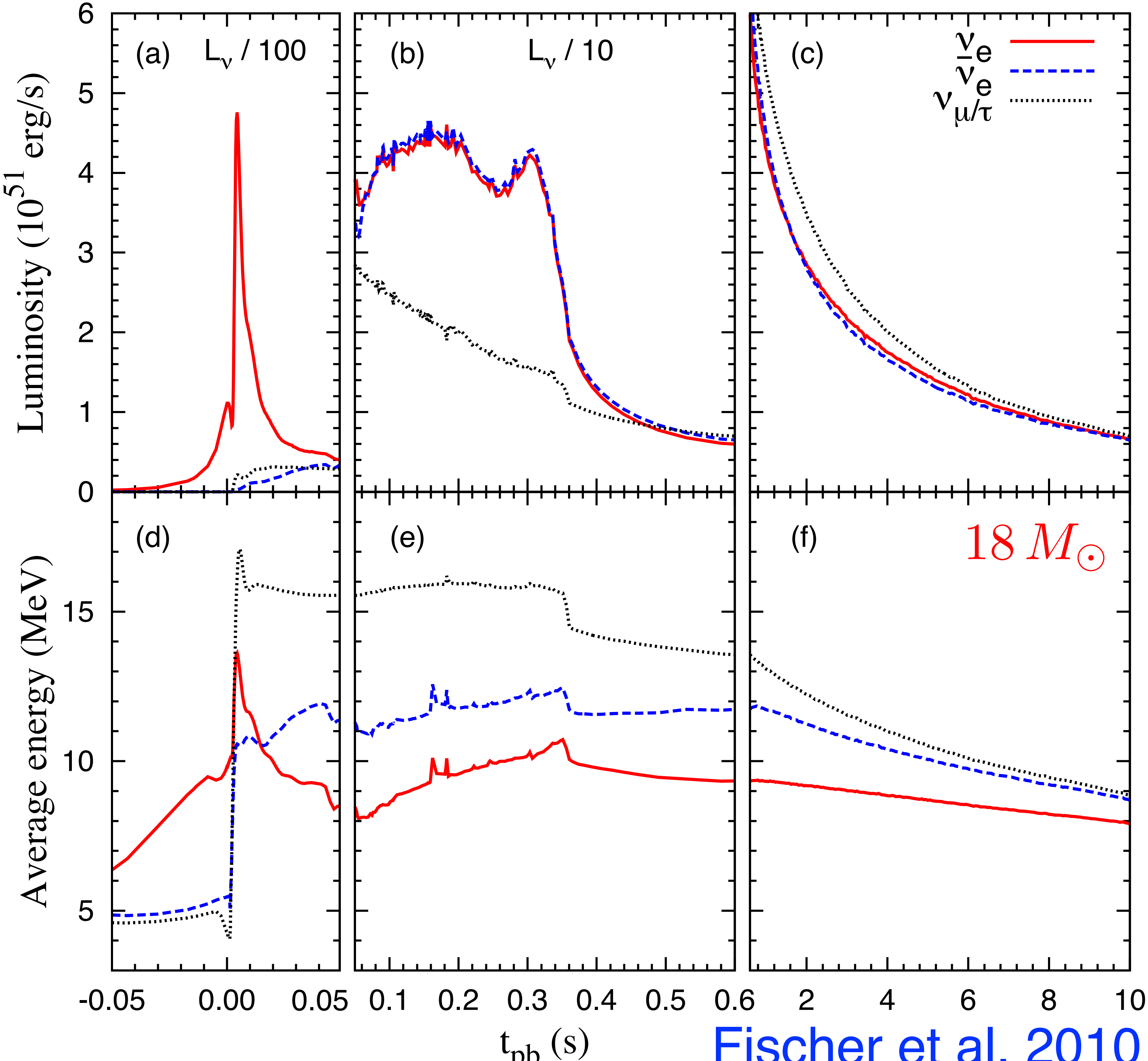
$$\frac{GM^2}{R_{\rm NS}} \sim 3 \times 10^{53}\ \text{erg}$$

$$\Rightarrow \nu_e,\ \bar{\nu}_e,\ \nu_\mu,\ \bar{\nu}_\mu,\ \nu_\tau,\ \bar{\nu}_\tau$$

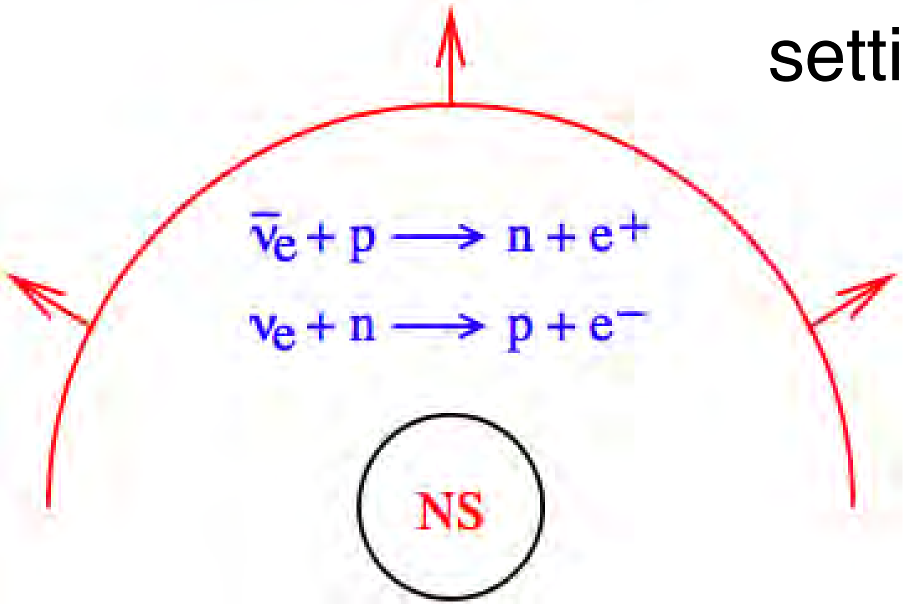




neutrino emission from a low-mass SN
L/10
Accretion phase
Cooling phase
ν_e
$\bar{\nu}_e$
$\nu_{\mu/\tau}$
$\frac{L_{\nu_e}}{\langle\epsilon_{\nu_e}\rangle} - \frac{L_{\bar{\nu}_e}}{\langle\epsilon_{\bar{\nu}_e}\rangle} > 0$
L (10^{52} erg s^{-1})
excess ν_e from $e^- + p \to n + \nu_e$
<ε> (MeV)
$8.8\,M_\odot$
$\langle\epsilon_{\nu_e}\rangle < \langle\epsilon_{\bar{\nu}_e}\rangle \lesssim \langle\epsilon_{\nu_{\mu/\tau}}\rangle$
Time after bounce (s)
Janka 2012



Fischer et al. 2010



setting n/p in the neutrino-driven wind

$$n/p > 1 \Rightarrow Y_e < 0.5$$

Qian et al. 1993
Qian & Woosley 1996
McLaughlin et al. 1996
Horowitz & Li 1999

$$\sigma_{\nu N} \propto (E_\nu \mp \Delta_{np})^2$$

$$\lambda_{\bar{\nu}_e p} = \frac{L_{\bar{\nu}_e}}{4\pi r^2} \frac{\langle \sigma_{\bar{\nu}_e p} \rangle}{\langle E_{\bar{\nu}_e} \rangle} \propto L_{\bar{\nu}_e} \left(\frac{\langle E^2_{\bar{\nu}_e} \rangle}{\langle E_{\bar{\nu}_e} \rangle} - 2\Delta_{np} \right)$$

$$\lambda_{\nu_e n} = \frac{L_{\nu_e}}{4\pi r^2} \frac{\langle \sigma_{\nu_e n} \rangle}{\langle E_{\nu_e} \rangle} \propto L_{\nu_e} \left(\frac{\langle E^2_{\nu_e} \rangle}{\langle E_{\nu_e} \rangle} + 2\Delta_{np} \right)$$

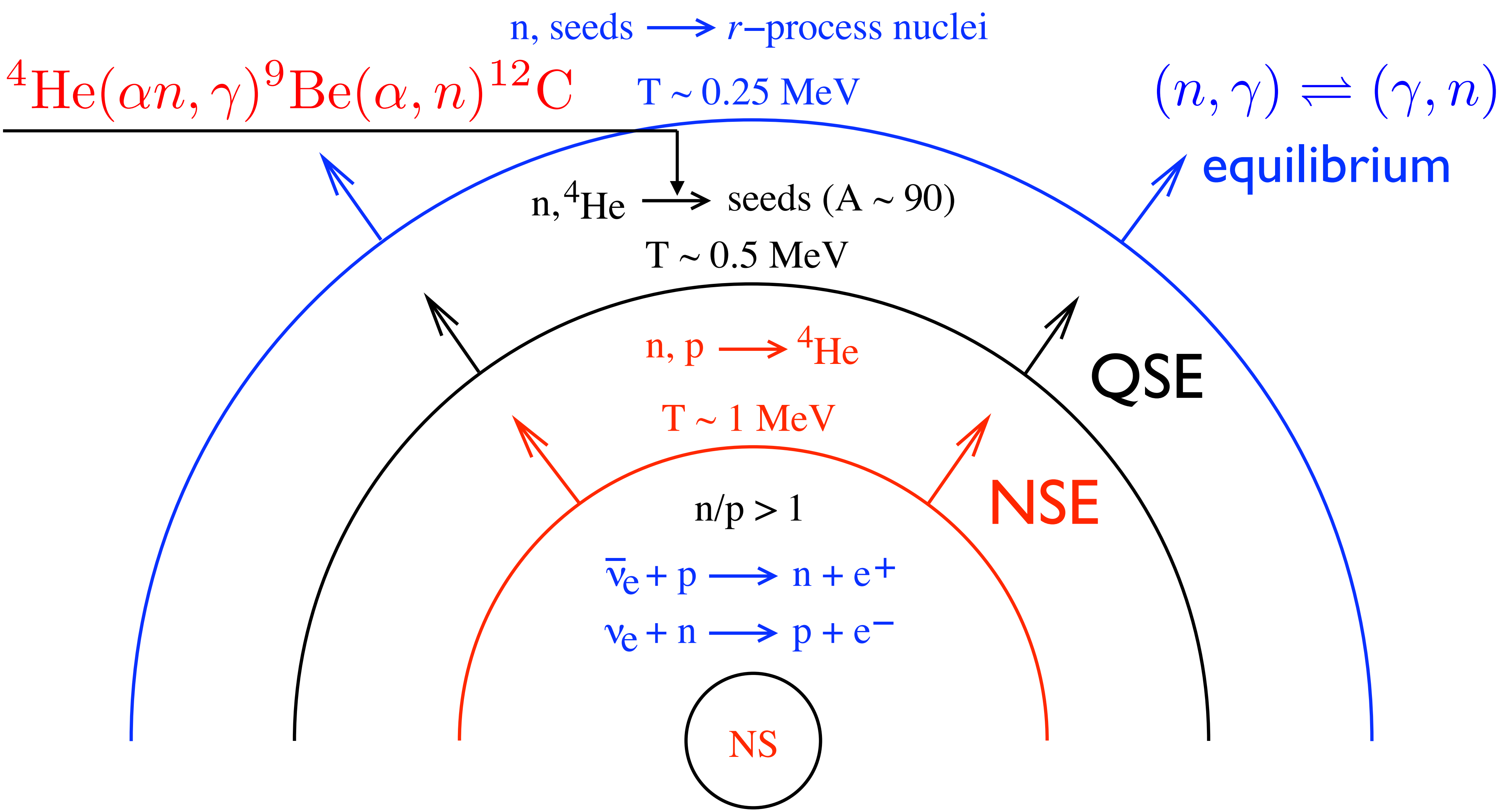
$$\frac{\langle E^2_{\bar{\nu}_e} \rangle}{\langle E_{\bar{\nu}_e} \rangle} - \frac{\langle E^2_{\nu_e} \rangle}{\langle E_{\nu_e} \rangle} > 4\Delta_{np} \approx 5.2 \text{ MeV} \Rightarrow \frac{n}{p} > 1$$

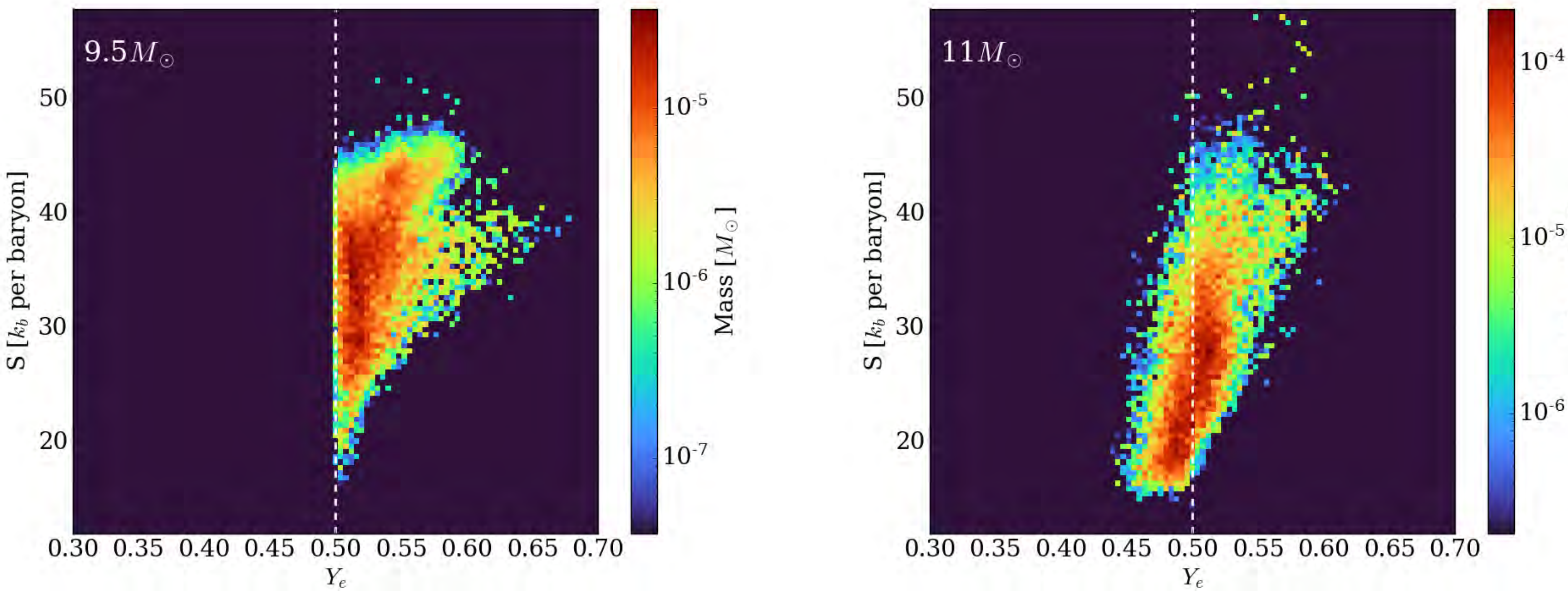
neutrino opacities!

Martinez-Pinedo et al. 2012; Roberts & Reddy 2012

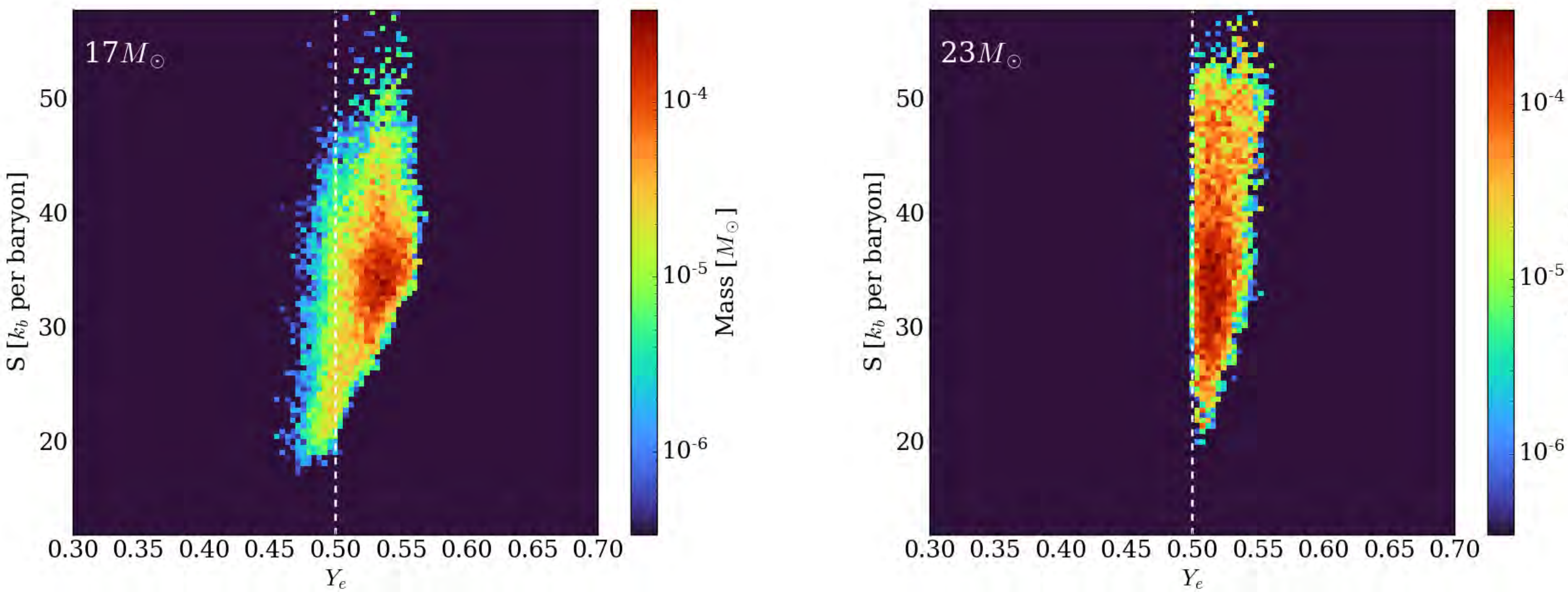
r–Process in Neutrino–driven Wind

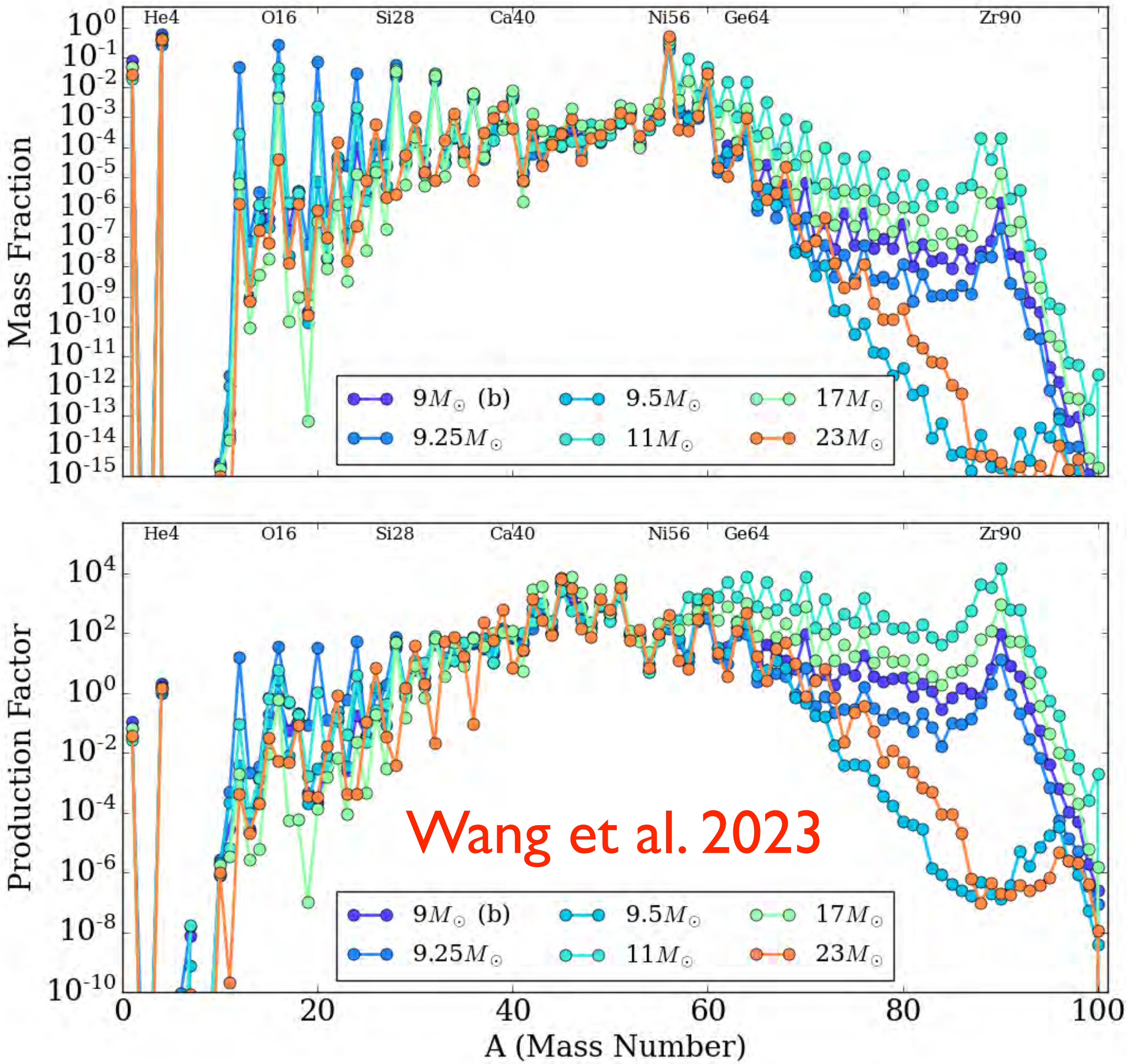
(e.g., Woosley & Baron 1992; Meyer et al. 1992; Woosley et al. 1994)





neutrino-driven winds in 3D models (Wang et al. 2023)





He4
O16
Si28
Ca40
Ni56
Ge64
Zr90
Mass Fraction
Production Factor
A (Mass Number)
9$M_\odot$ (b)
9.25$M_\odot$
9.5$M_\odot$
11$M_\odot$
17$M_\odot$
23$M_\odot$
Wang et al. 2023

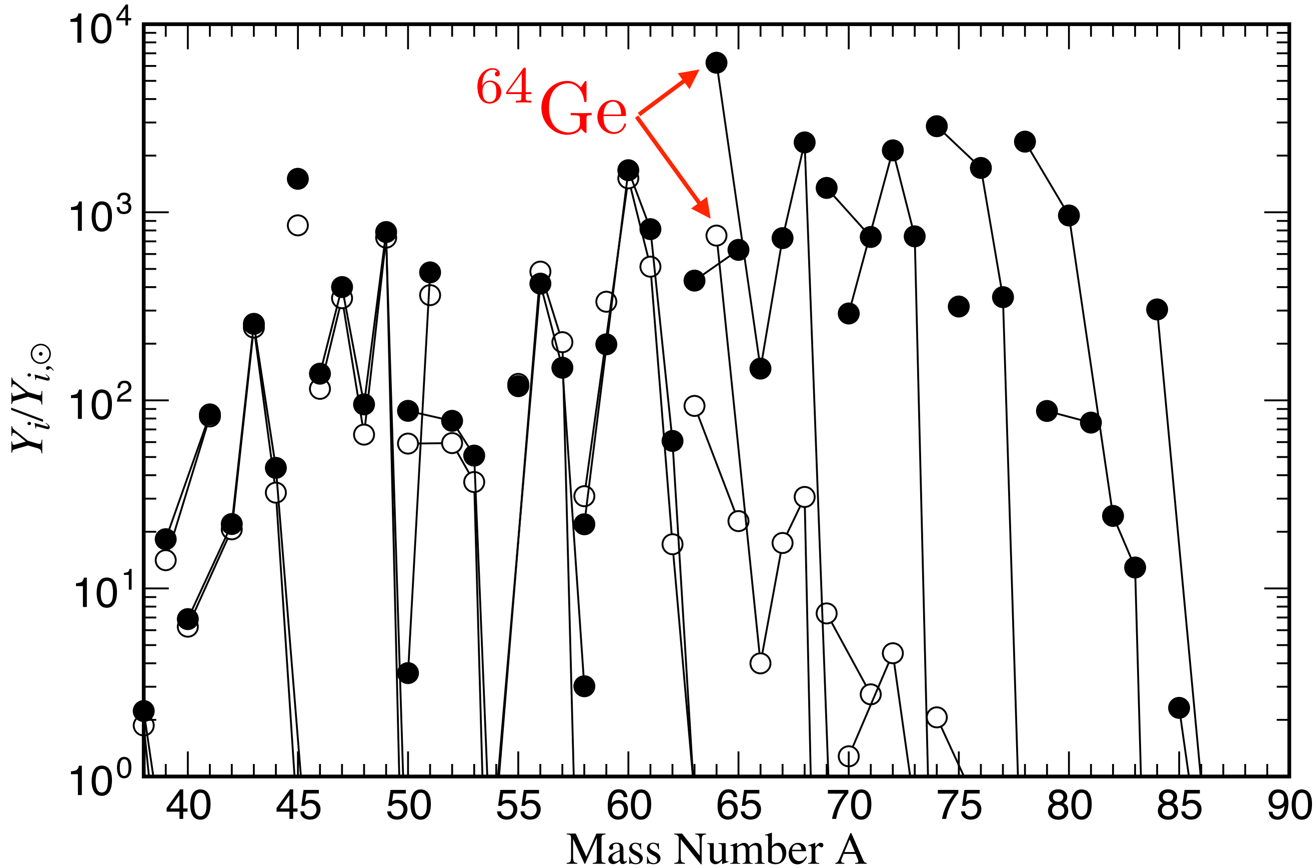
the νp-process in p-rich ν-driven winds

(Frohlich et al. 2006a,b; Pruet et al. 2005,2006)

$(p,\gamma) \rightleftharpoons (\gamma,p)$ equilibrium $\Rightarrow$ waiting point

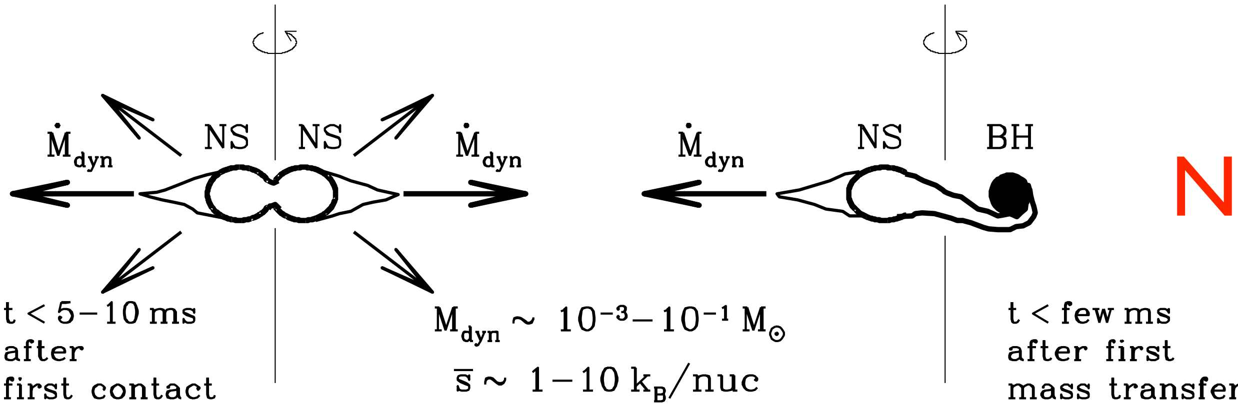
break through waiting-point nuclei with slow beta decay:

$$\bar{\nu}_e + p \to n + e^+,\ (Z,A) + n \to p + (Z-1,A)$$



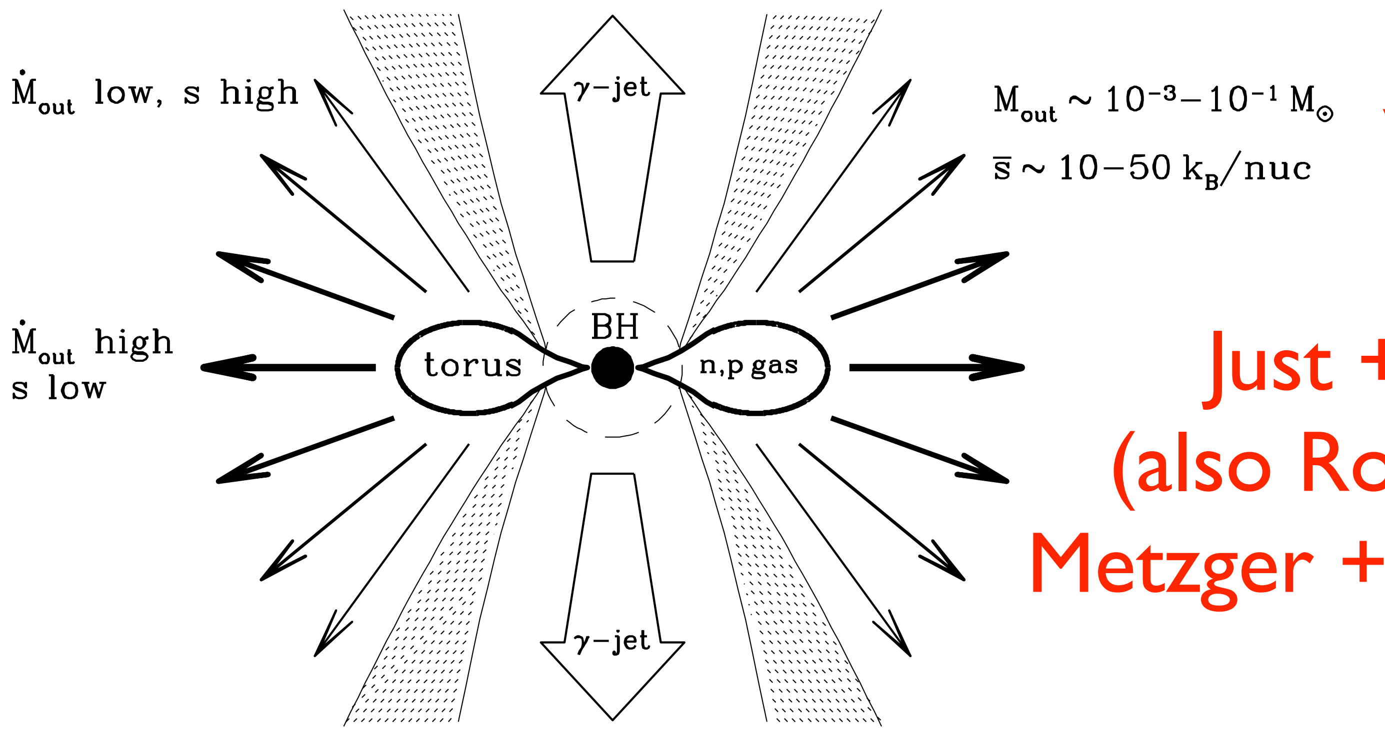
Mass Loss Phases During NS–NS and NS–BH Merging

Merger Phase: Prompt/dynamical ejecta
(due to dynamic binary interaction)



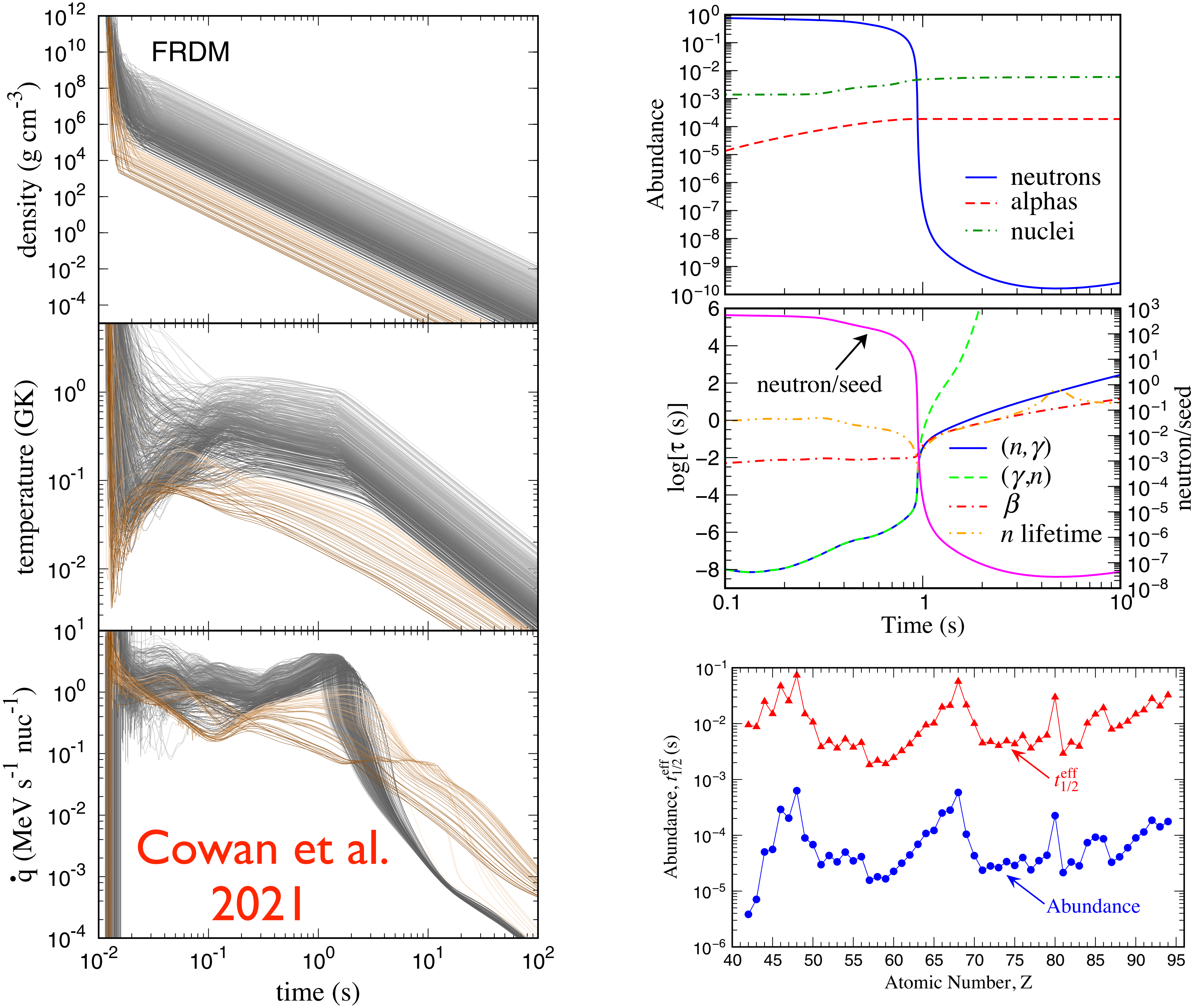
NS matter

BH–Torus Phase: Disk ejecta
(due to ν heating, viscosity/magn. fields, recombination)



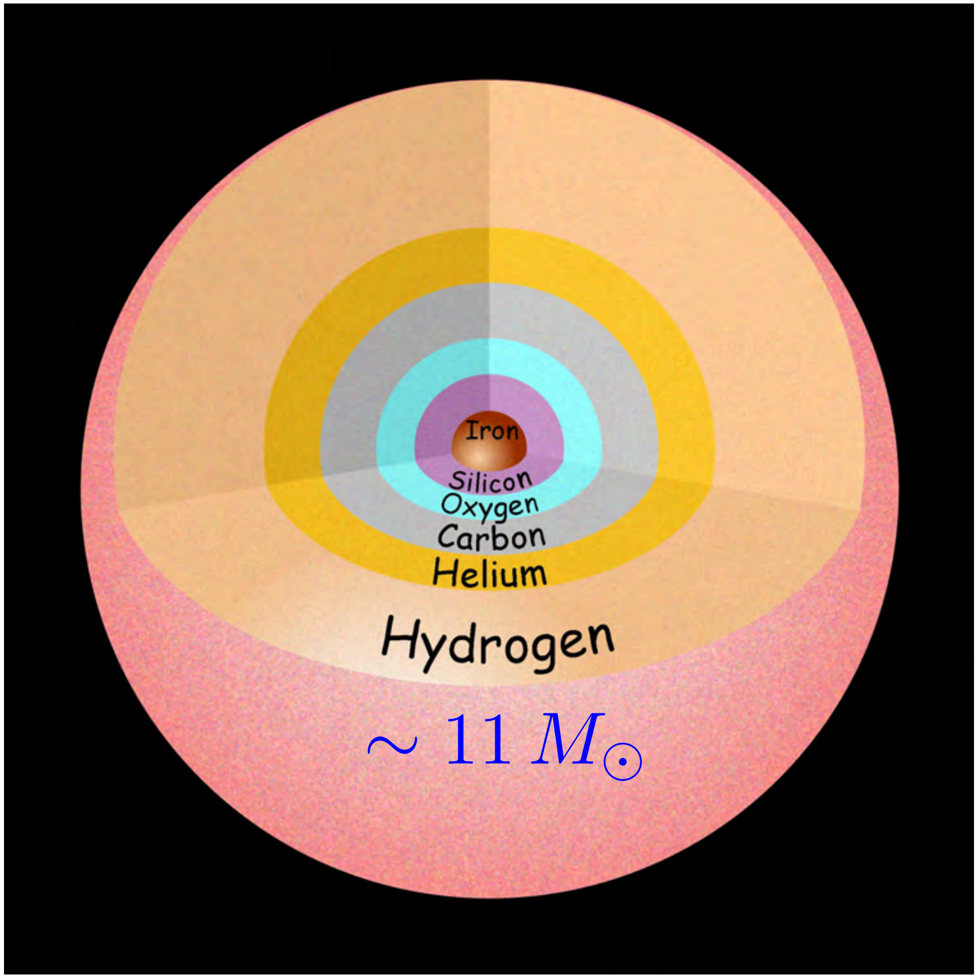
winds

Just + 2014
(also Rosswog +;
Metzger +; Wanajo +)



FRDM
density (g cm-3)
temperature (GK)
q̇ (MeV s-1 nuc-1)
time (s)
Cowan et al.
2021
Abundance
neutrons
alphas
nuclei
log[τ (s)]
neutron/seed
(n,γ)
(γ,n)
β
n lifetime
Time (s)
Abundance, t1/2eff (s)
t1/2eff
Abundance
Atomic Number, Z

Neutrino-Induced n Capture in He Shell of early SNe



neutron production by

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

Epstein, Colgate, & Haxton 1988

neutron capture by ^{56}Fe

high n_n requires few ^{56}Fe

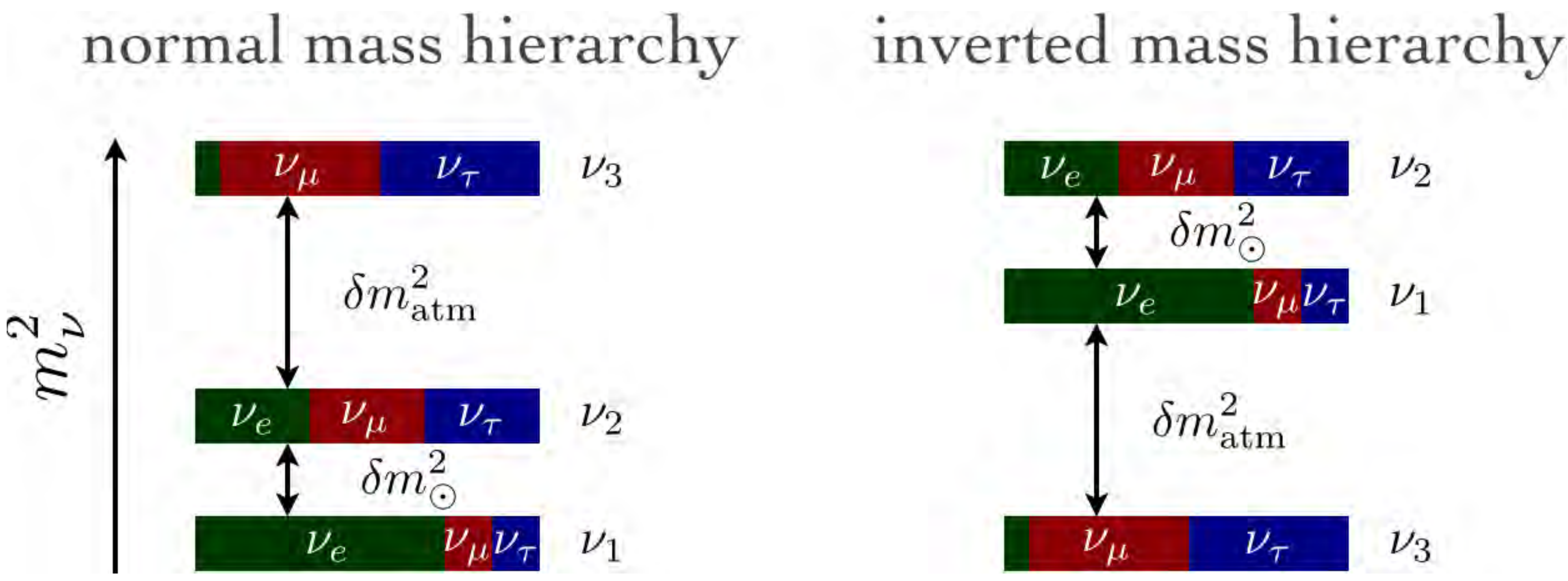
→ early SNe

$$\bar{\nu}_e + {}^4\mathrm{He} \rightarrow {}^3\mathrm{H} + n + e^+, \;\; \lambda_{\bar{\nu}_e\alpha,n} \propto T_{\bar{\nu}_e}^{5-6} \;!$$

Banerjee, Haxton, & Qian 2011

Neutrino Spectra & Flavor Oscillations

$T_{\nu_e} \sim 3\text{–}4$ MeV, $T_{\bar{\nu}_e} \sim 4\text{–}5$ MeV, $T_{\nu_{\mu,\tau}} = T_{\bar{\nu}_{\mu,\tau}} \sim 6\text{–}8$ MeV



in supernovae

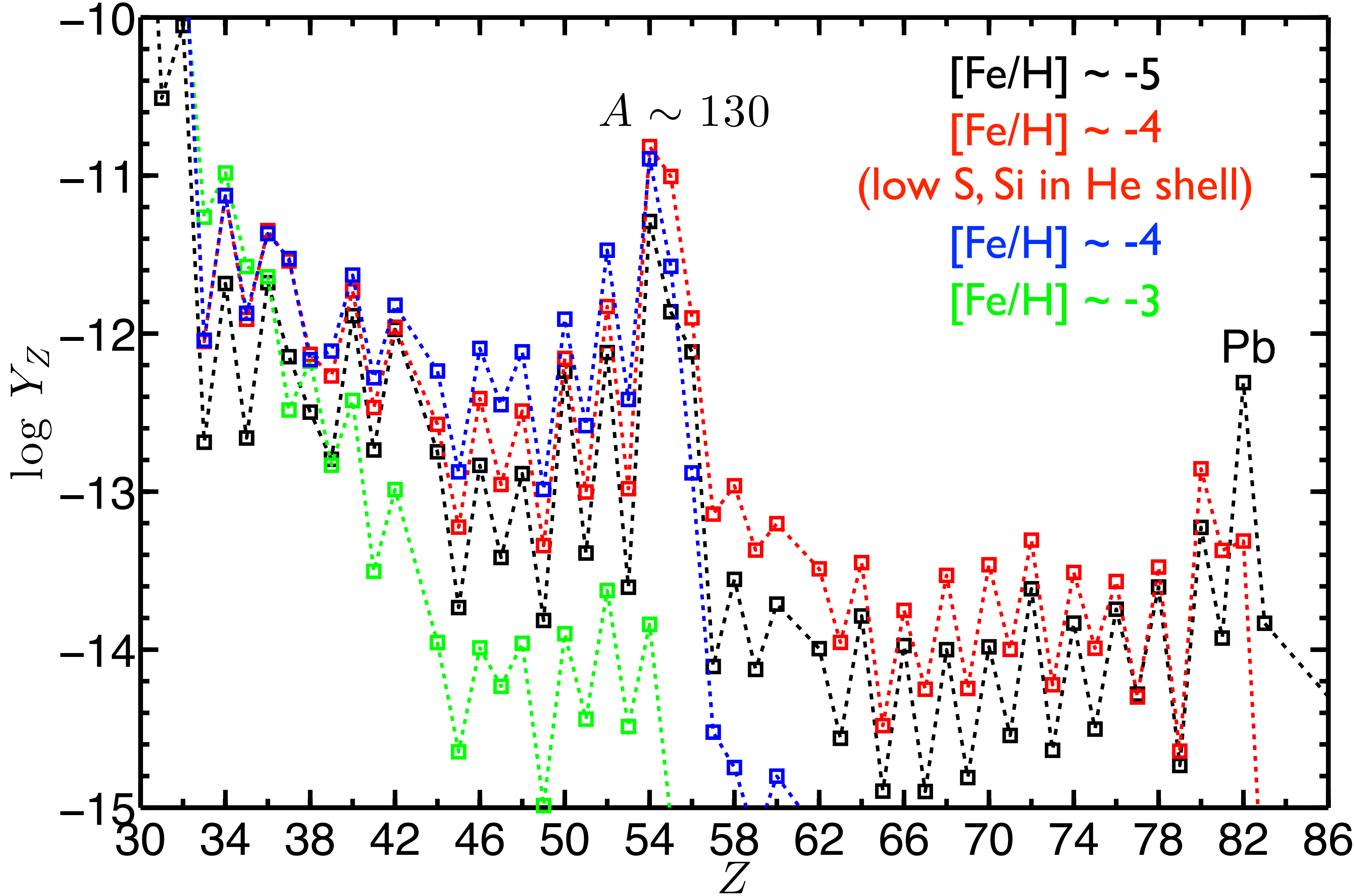
$\nu_e \rightleftharpoons \nu_{\mu,\tau}$

${}^4\mathrm{He}(\nu_e, e^- p)^3\mathrm{He}$

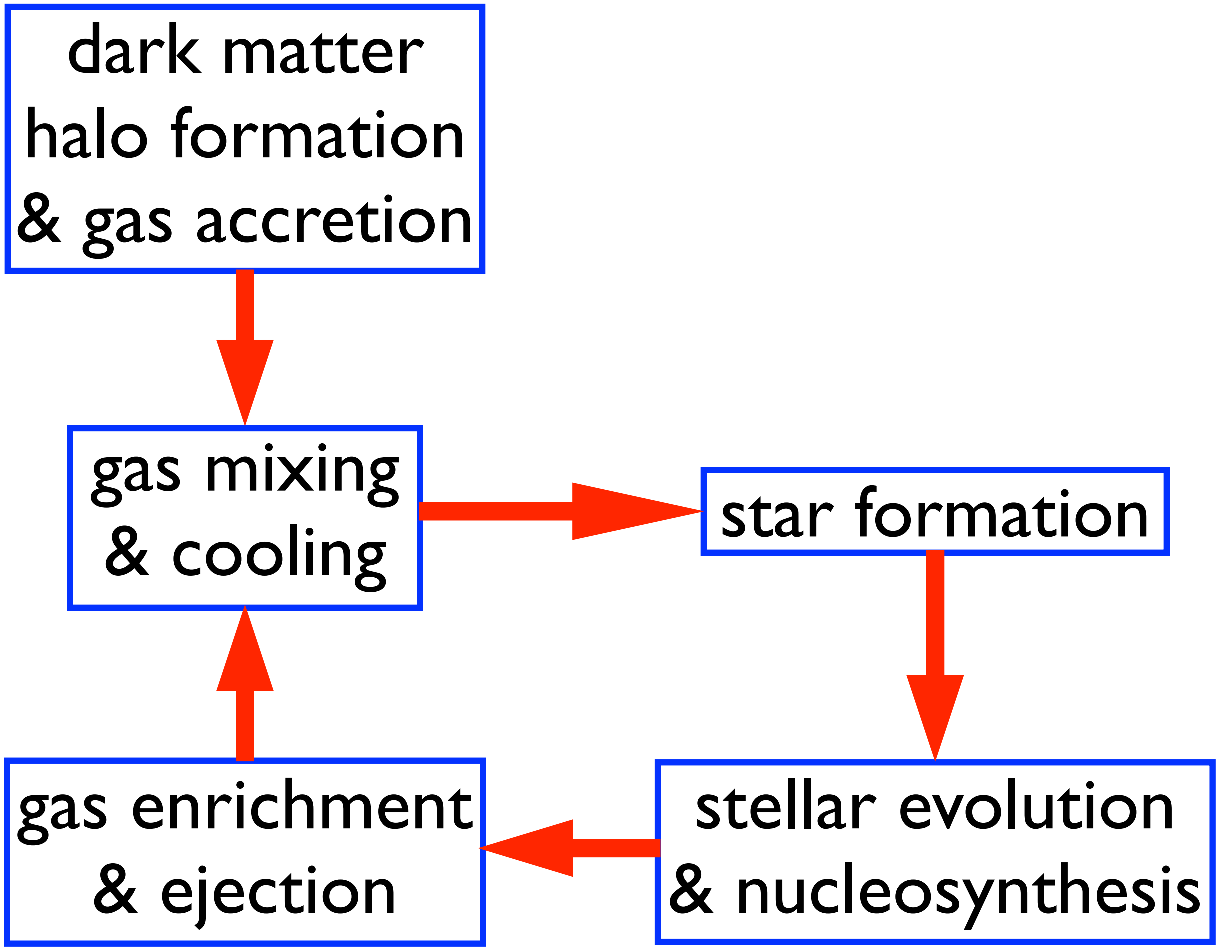
$\bar{\nu}_e \rightleftharpoons \bar{\nu}_{\mu,\tau}$

${}^4\mathrm{He}(\bar{\nu}_e, e^+ n)^3\mathrm{H}$

Banerjee, Qian, Heger, & Haxton 2016



Ab Initio Model of Chemical Evolution



Data-Driven Nuclear Forensics

nuclear input: masses; reaction rates, including beta-decay, n-capture, fission

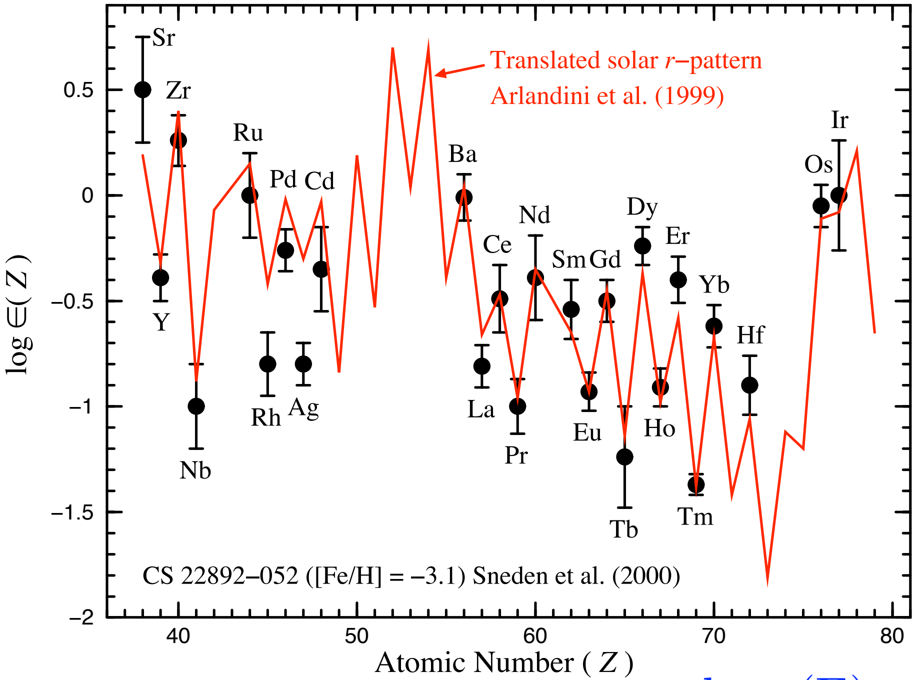
+

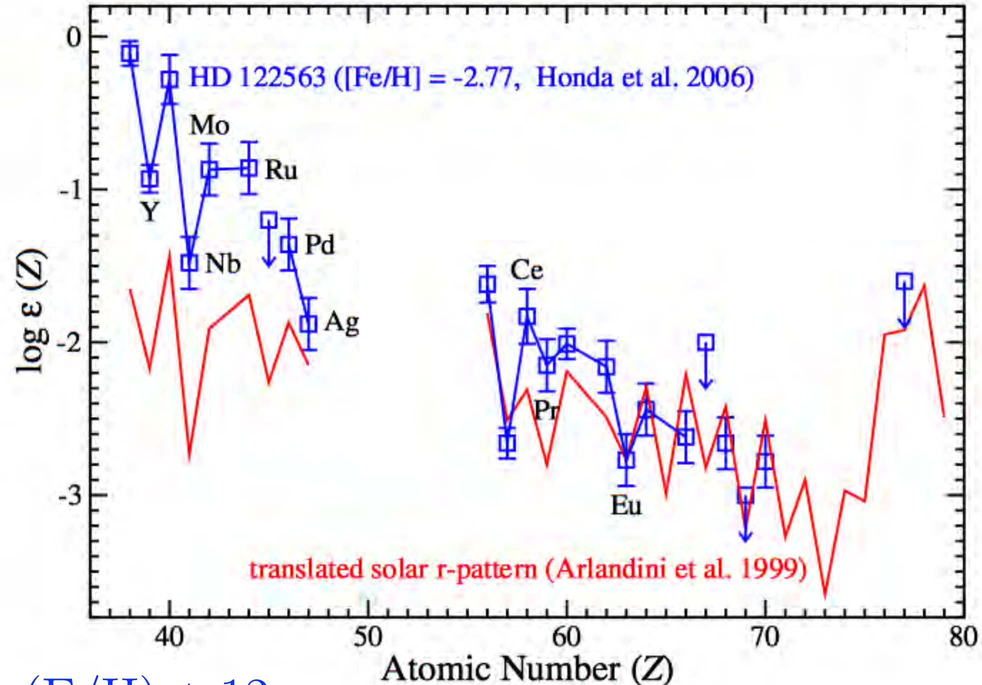
astrophysical input: electron fraction (Ye), entropy (S), expansion timescale (t_{exp})

production patterns $(E/Fe)_i$

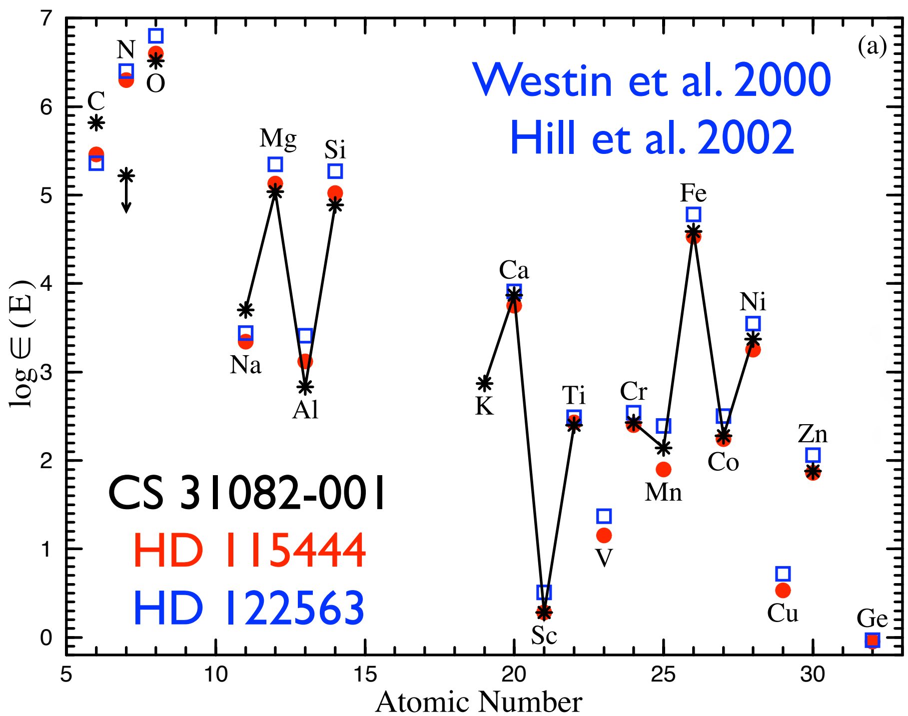
$$\left(\frac{\mathrm{E}}{\mathrm{Fe}}\right) = \sum_{i=1}^{n} x_i \left(\frac{\mathrm{E}}{\mathrm{Fe}}\right)_i , \quad \sum_{i=1}^{n} x_i = 1$$

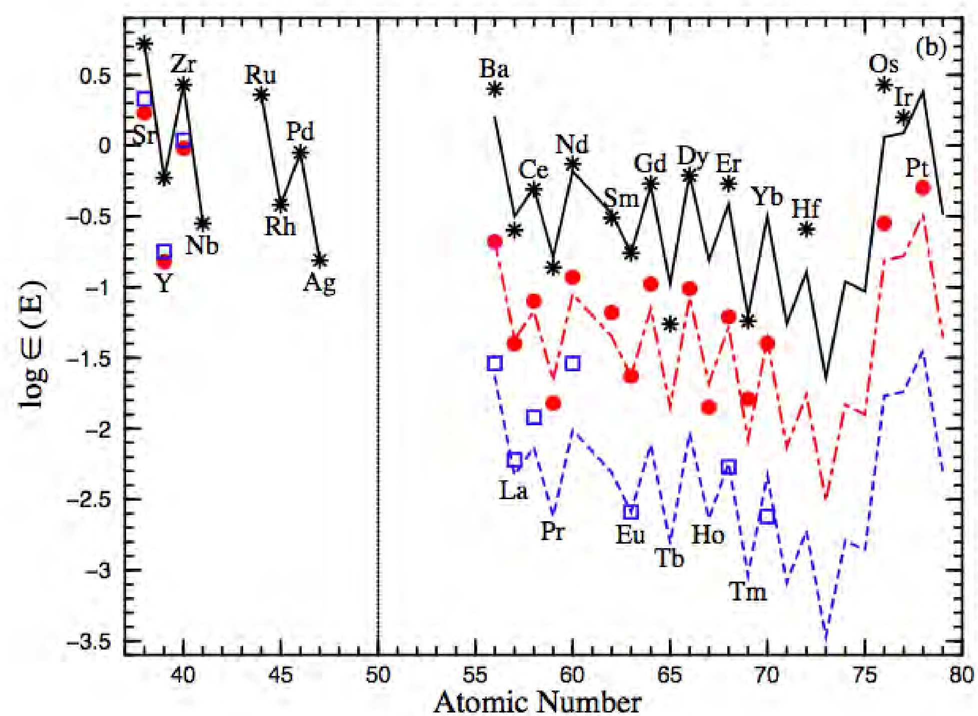
abundances in stars (E/Fe)





$$\log \epsilon(\mathrm{E}) = \log(\mathrm{E/H}) + 12$$





Early Chemical Evolution (~ First Gyr)

dominant sources: Core-Collapse SNe & NS Mergers

$$\left(\frac{\mathrm{E}}{\mathrm{Fe}}\right) = x\left(\frac{\mathrm{E}}{\mathrm{Fe}}\right)_1 + (1-x)\left(\frac{\mathrm{E}}{\mathrm{Fe}}\right)_2$$

R-Process Alliance search for r-process-enhanced stars in the Galactic Halo: data on (Sr/Fe), (Ba/Fe), (Eu/Fe) for 195 stars (Holmbeck et al. 2020)

$[\mathrm{E/Fe}] = \log(\mathrm{E/Fe}) - \log(\mathrm{E/Fe})_{sun}$

$[\mathrm{Sr/Fe}]_1 = -0.49$, $[\mathrm{Ba/Fe}]_1 = -3.00$, $[\mathrm{Eu/Fe}]_1 = -0.77$

$[\mathrm{Sr/Fe}]_2 = 0.90$, $[\mathrm{Ba/Fe}]_2 = 0.91$, $[\mathrm{Eu/Fe}]_2 = 1.30$

Gross, Xiong, & Qian 2023

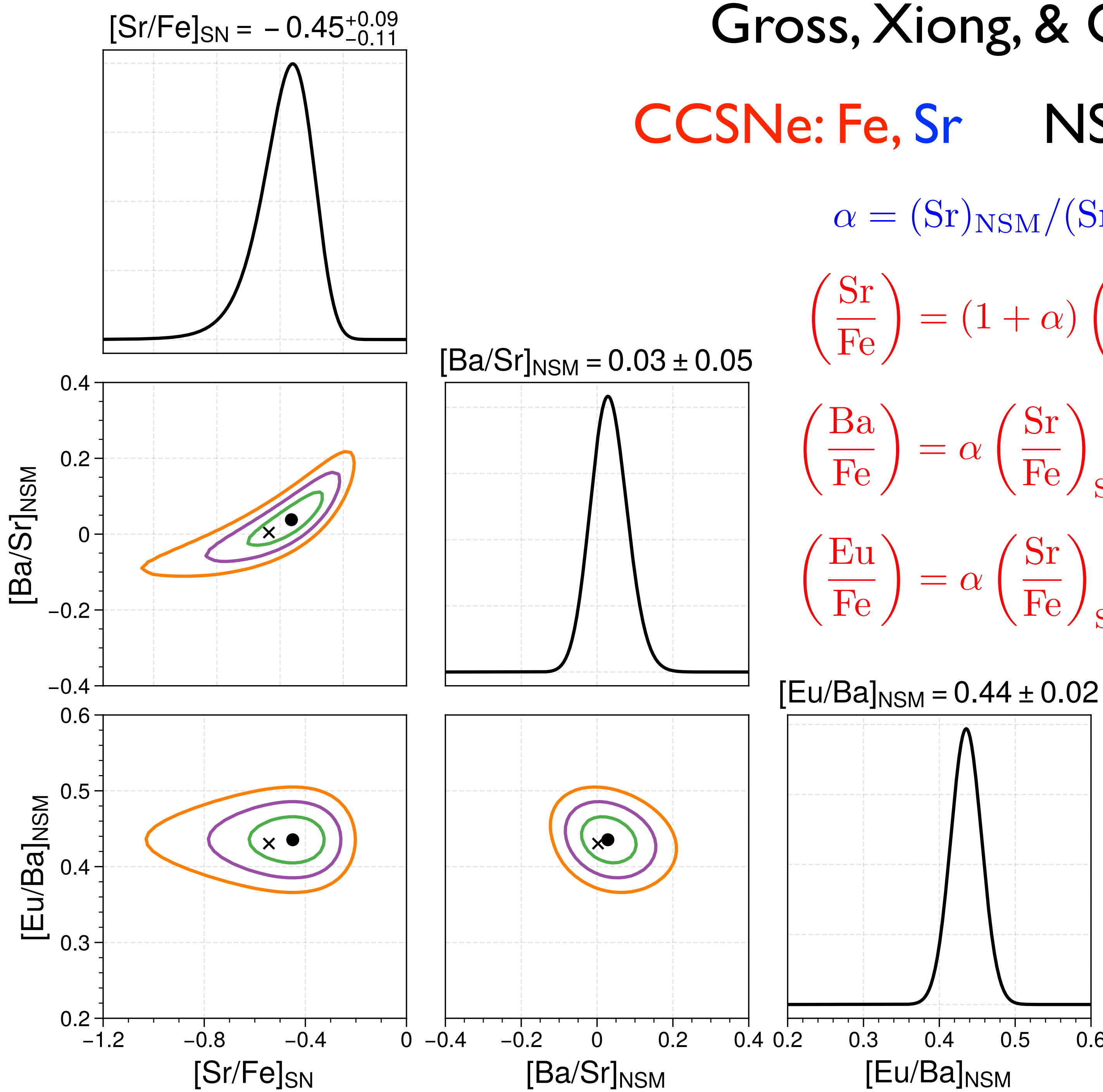
CCSNe: Fe, Sr **NSMs: Sr, Ba, Eu**

$$\alpha = (\mathrm{Sr})_{\mathrm{NSM}}/(\mathrm{Sr})_{\mathrm{SN}}$$

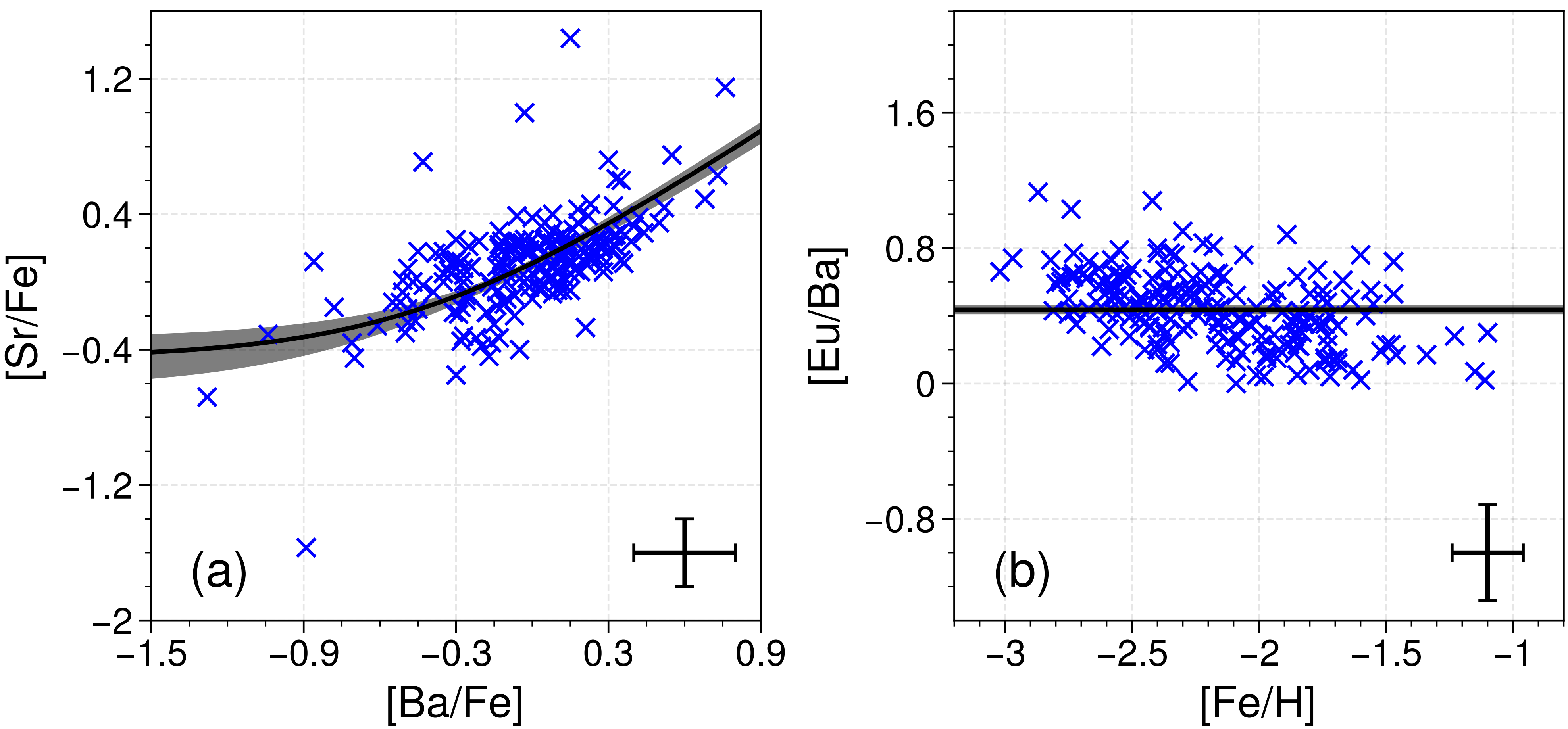
$$\left(\frac{\mathrm{Sr}}{\mathrm{Fe}}\right) = (1+\alpha)\left(\frac{\mathrm{Sr}}{\mathrm{Fe}}\right)_{\mathrm{SN}}$$

$$\left(\frac{\mathrm{Ba}}{\mathrm{Fe}}\right) = \alpha\left(\frac{\mathrm{Sr}}{\mathrm{Fe}}\right)_{\mathrm{SN}}\left(\frac{\mathrm{Ba}}{\mathrm{Sr}}\right)_{\mathrm{NSM}}$$

$$\left(\frac{\mathrm{Eu}}{\mathrm{Fe}}\right) = \alpha\left(\frac{\mathrm{Sr}}{\mathrm{Fe}}\right)_{\mathrm{SN}}\left(\frac{\mathrm{Ba}}{\mathrm{Sr}}\right)_{\mathrm{NSM}}\left(\frac{\mathrm{Eu}}{\mathrm{Ba}}\right)_{\mathrm{NSM}}$$

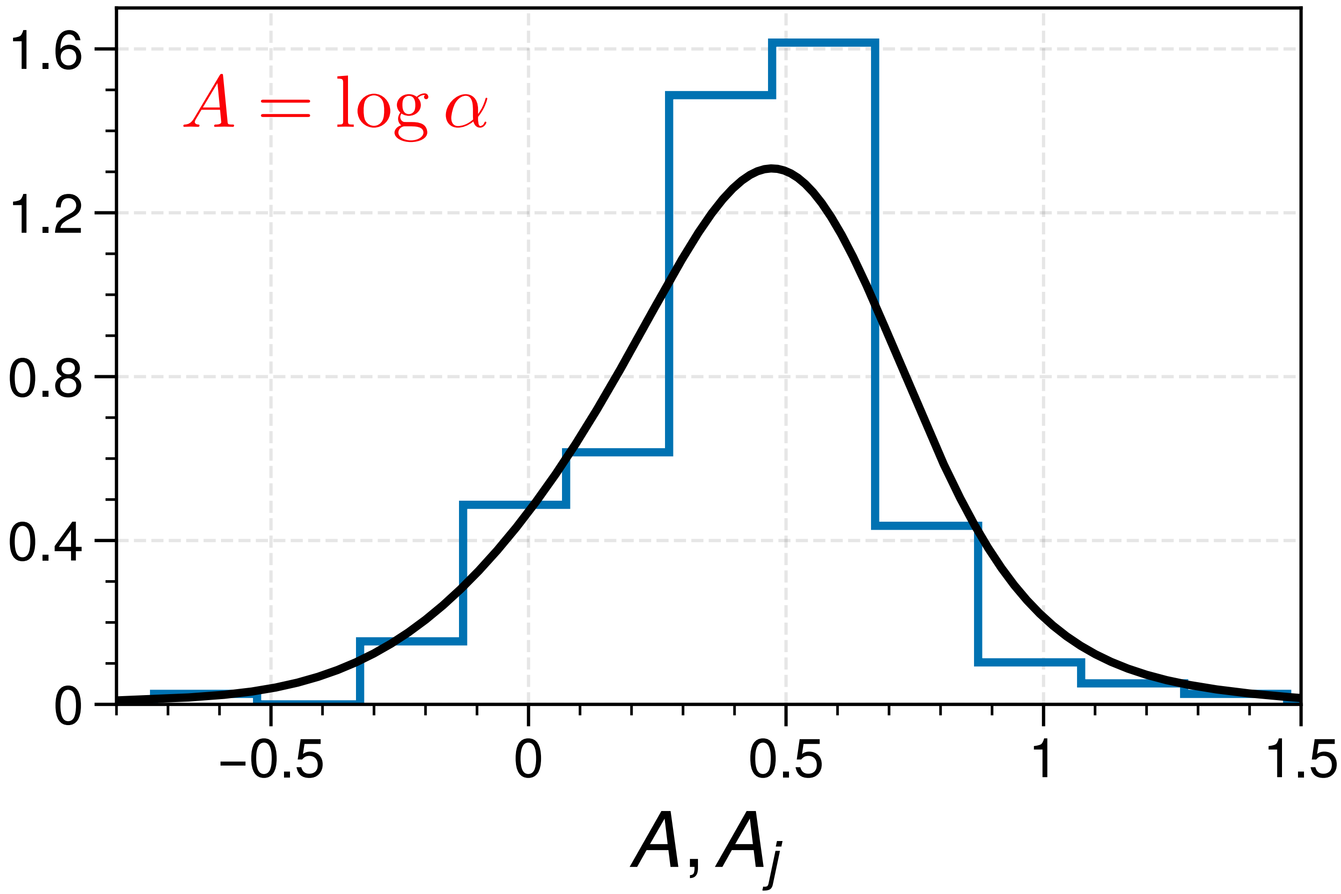


Gross, Xiong, & Qian 2023



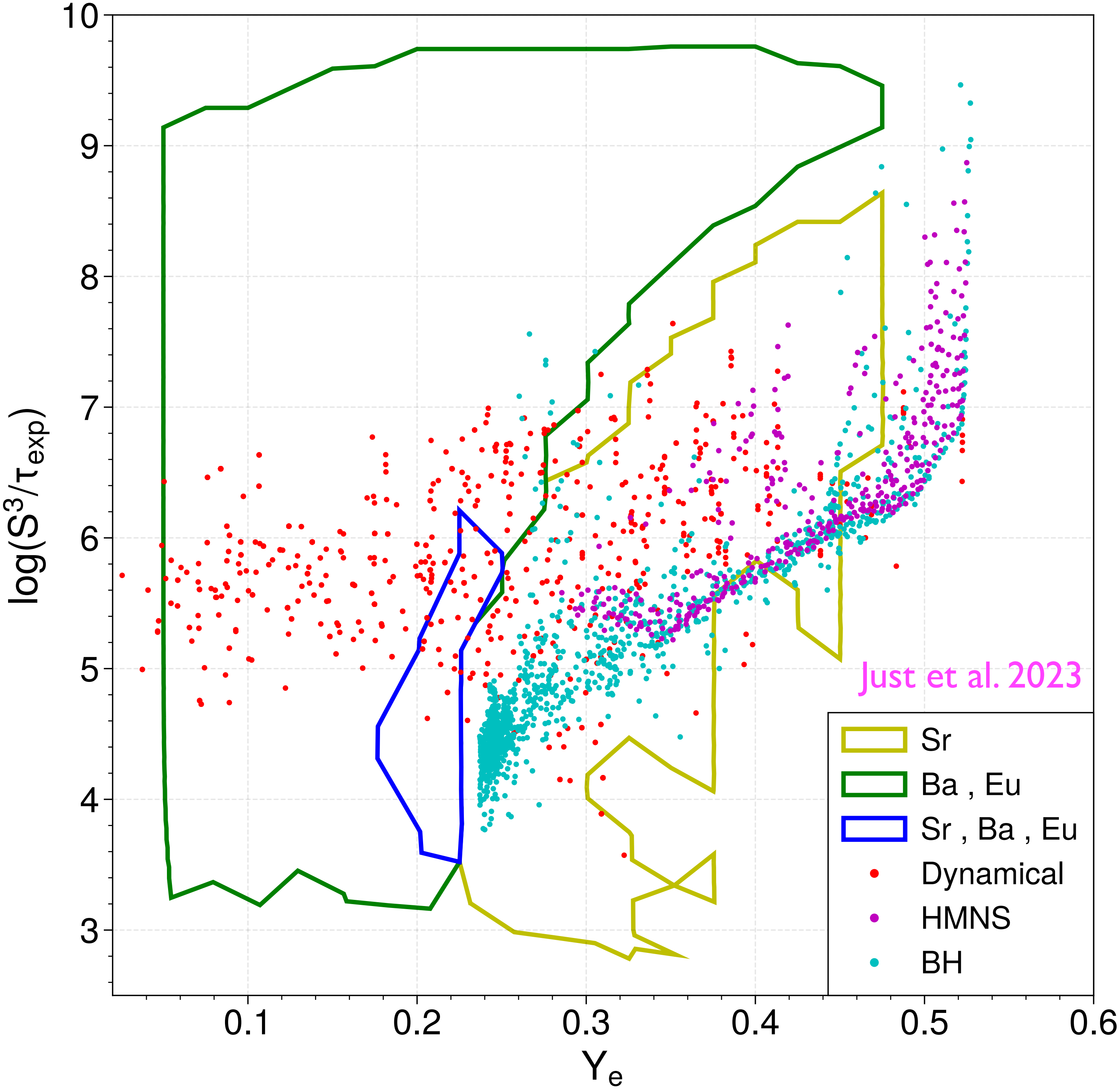
$$\left(\frac{\mathrm{Sr}}{\mathrm{Fe}}\right) = \left(\frac{\mathrm{Sr}}{\mathrm{Fe}}\right)_{\mathrm{SN}} + \left(\frac{\mathrm{Sr}}{\mathrm{Ba}}\right)_{\mathrm{NSM}} \left(\frac{\mathrm{Ba}}{\mathrm{Fe}}\right)$$

Gross, Xiong, & Qian 2023



$$\alpha_\odot \approx \frac{(\mathrm{Sr/Eu})_{\mathrm{NSM}}(\mathrm{Eu})_\odot}{(\mathrm{Sr/Fe})_{\mathrm{SN}}(\mathrm{Fe})_{\odot,\mathrm{SN}}} \approx 3 \Rightarrow (\mathrm{Fe})_{\odot,\mathrm{SN}} \approx (\mathrm{Fe})_\odot/3$$

Gross, Xiong, & Qian 2023



Gross, Xiong, & Qian 2023