Ph 203 L17

Neutron Capture Nucleosynthesis

He-burning stops @ Fe

Nuclei heavier than Fe requires n-capture processes

s-process (slow)	r-process (rapid)
n-capture time $\tau_{cap} \gtrsim 10-10^3$ yrs	$\tau_{cap} \lesssim 10$ ms
n density $\rho_n \gtrsim 10^{7-12}/cm^3$	$\rho_n > 10^{23}/cm^3$
multiple n-cap until: $\tau_{cap} \gtrsim \tau_\beta$	$\tau_{cap} \ll \tau_\beta$
$T_6 \sim 200$	$T_6 \gtrsim 1000$
⇒ Slow walk through Nucl. chart	Race to neutron dripline

S-Process

① n-capture on seed nuclei (e.g. Fe) until $\tau_\beta < \tau_{cap}$

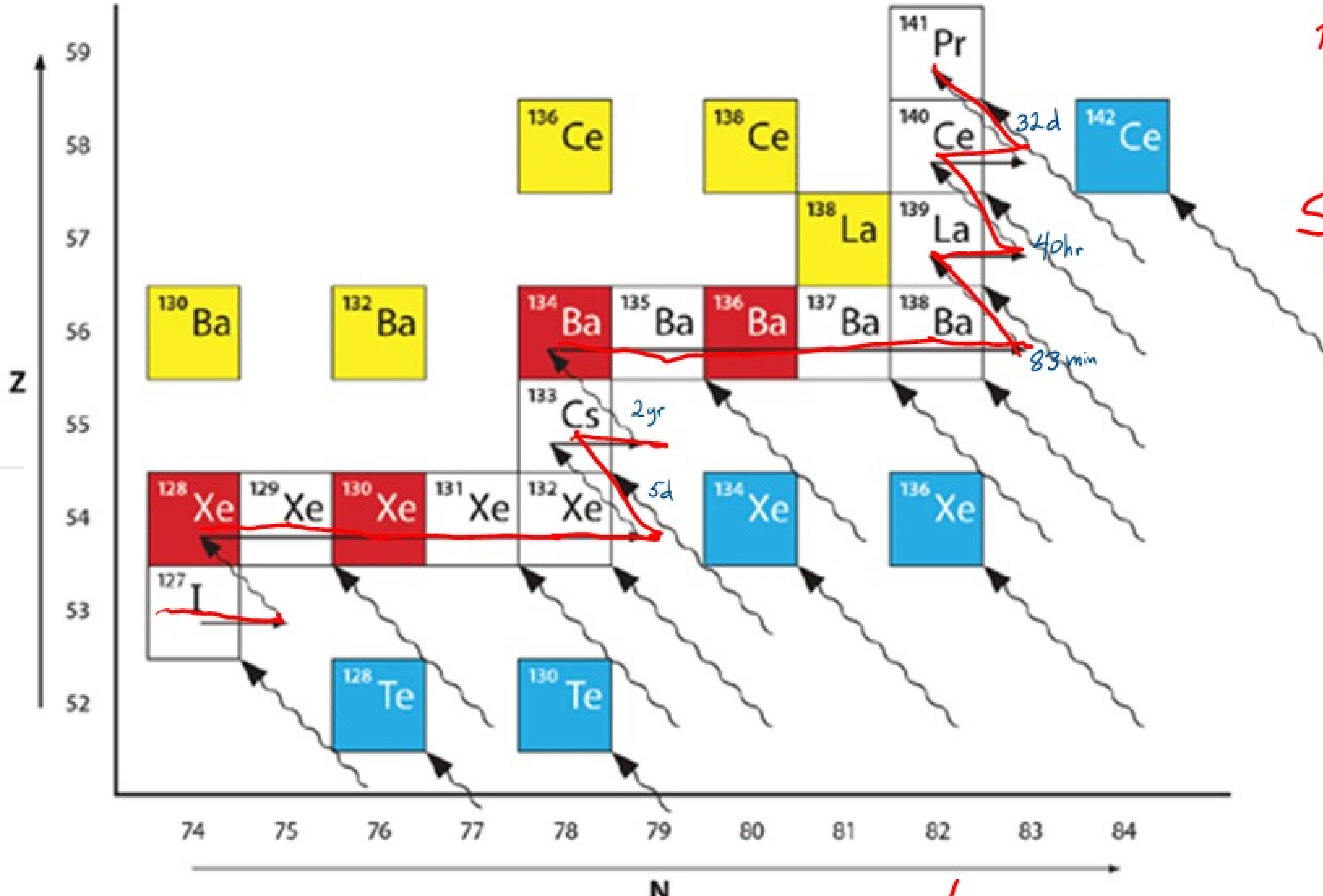
② β-decay to stable nucleus

③ go to ①

See diagram on next page:

S-Process

Z	Name	Symbol	Mass of Atom (u)	% Abundance
54	Xenon	^{124}Xe	123.905896	0.09
		^{126}Xe	125.904269	0.09
		^{128}Xe	127.903530	1.92
		^{129}Xe	128.904779	26.44
		^{130}Xe	129.903508	4.08
		^{131}Xe	130.905082	21.18
		^{132}Xe	131.904154	26.89
		^{134}Xe	133.905395	10.44
		^{136}Xe	135.907220	8.87
55	Cesium	^{133}Cs	132.905447	100
56	Barium	^{130}Ba	129.906310	0.106
		^{132}Ba	131.905056	0.101
		^{134}Ba	133.904503	2.417
		^{135}Ba	134.905683	6.592
		^{136}Ba	135.904570	7.854
		^{137}Ba	136.905821	11.232
		^{138}Ba	137.905241	71.698
57	Lanthanum	^{138}La	137.907107	0.090
		^{139}La	138.906348	99.910
58	Cerium	^{136}Ce	135.907144	0.185
		^{138}Ce	137.905986	0.251
		^{140}Ce	139.905434	88.450
		^{142}Ce	141.909240	11.114



All are stable

Red = s-process only

blue = r-process only

white = s/r process

Yellow = p or γ process

s-process

1. n-capture on stable nuclei (e.g. ^{56}Fe from He burning) until β-unstable nucleus
2. β-decay to stable nucleus
3. Go to (1) → Show Pic

where do n come from?

Separate reaction network using ^{12}C, ^{14}N

e.g. $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)^{16}O$

$^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$

↑ weak decay $p \to n$

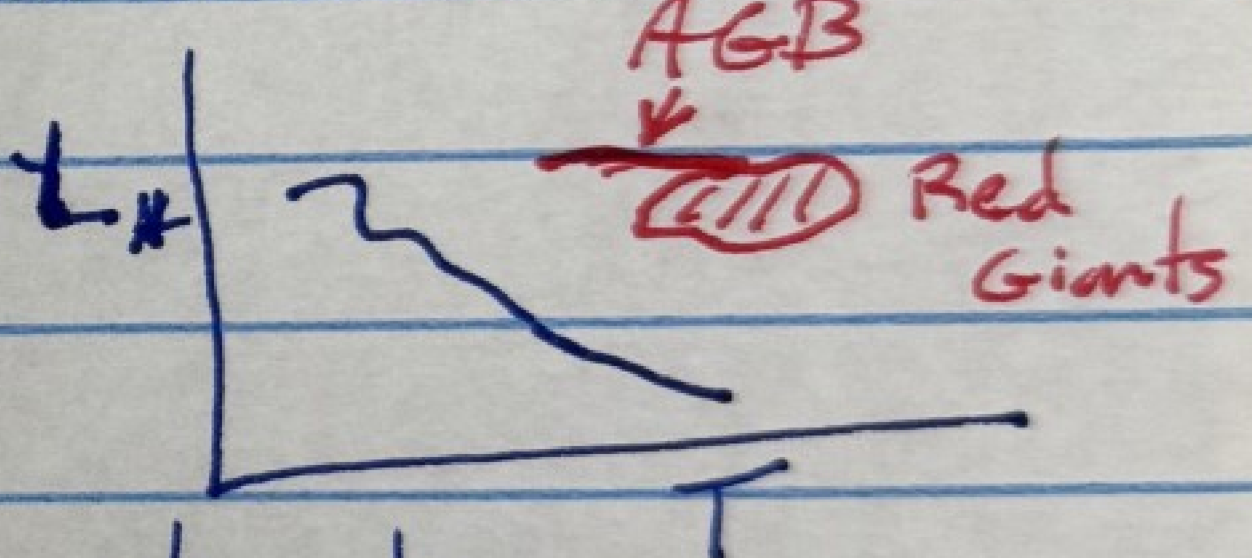
↳ works in He-burning ($T_6 \sim 200$)

s-process Origins:

1. lower Mass Stars $M < 10 M_\odot$ @ Red Giant, especially AGB stars $\sim 0.5-5 M_\odot$ (Asymptotic Giant Branch)

   use $^{12}C(p,\gamma)$...

   produces up to ^{208}Pb



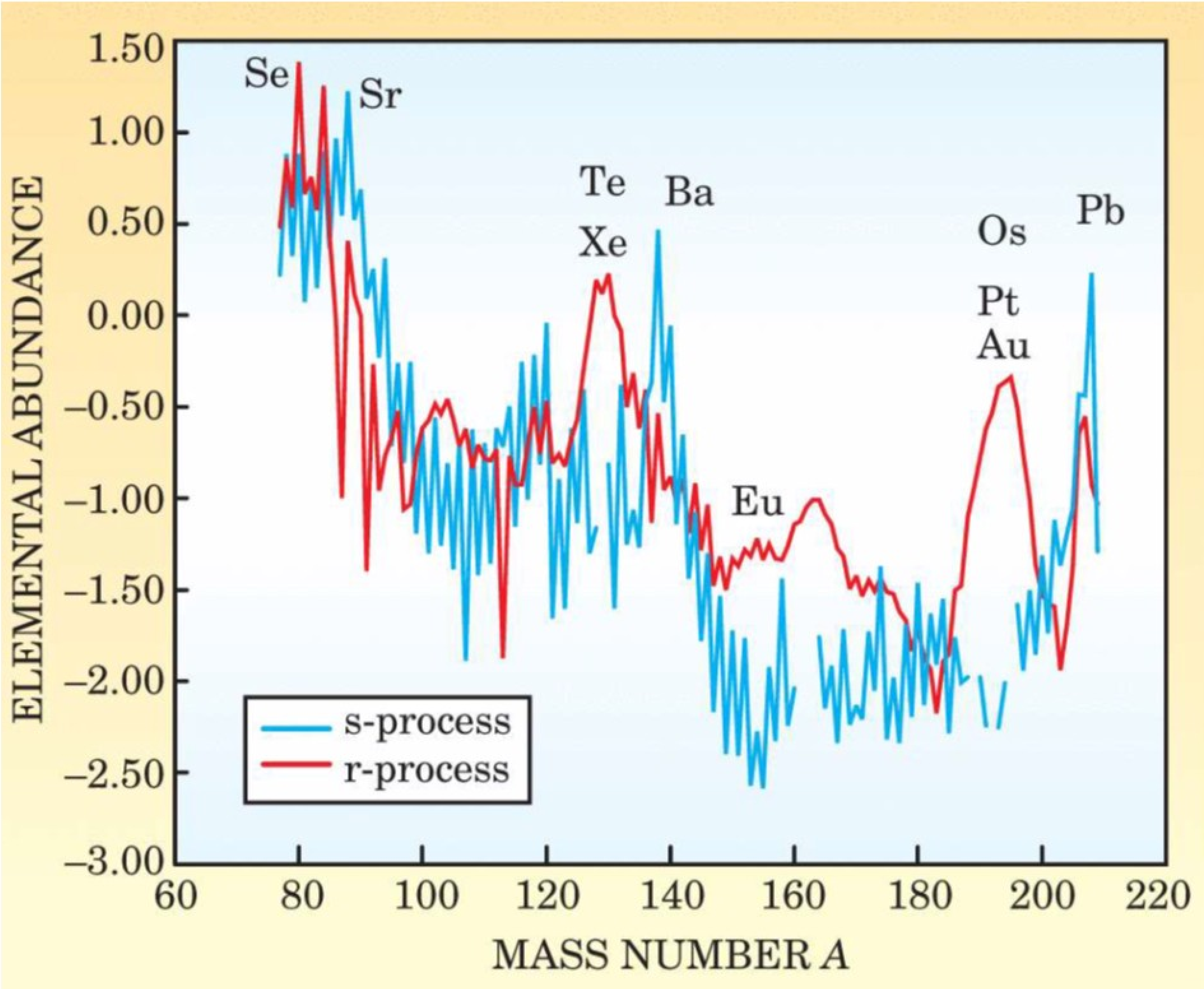
2. $M_* > 10 M_\odot$ use $^{14}N(p,\gamma)$ network

   ⟺ Produces up to ^{89}Y from SN remnants

⟺ Both give s-process peaks @ A≈85 & A≈140, 208

see Pic. next page

s/r-process abundance peaks



Direct confirmation of s-process

Merrill 1952 discovered Technetium on surface of stars (Red Giant) ↳ (Z = 52)

All Tc unstable ⇒ longest $\tau_{1/2} = 4.2$ Myrs

Must be produced via n-capture ≃ near surface

r-process

① Successive n-capture starting w Stable Nucleus Z

$_{Z}A \rightarrow {}_{Z}(A+1) \rightarrow {}_{Z}(A+2) \ldots$

② Stop @ dripline for β-decay(s)

$_{Z}A_{drip} \rightarrow {}_{Z+1}A_{drip} \rightarrow {}_{Z+2}A_{drip} \ldots$ till $\tau_\beta > \tau_{cap}$

③ Waiting points for β-decays

Major Stops @ n-shell closures = magic #'s 82, 126

④ Go to ①

↳ gives Peaks @ A ≃ 130, 195-208

↳ Entire process occurs in ~ 1-10 s from NP

↳ Suggests Cataclysmic Production...

Before we discuss r-process sites see...

Chart of Nuclei

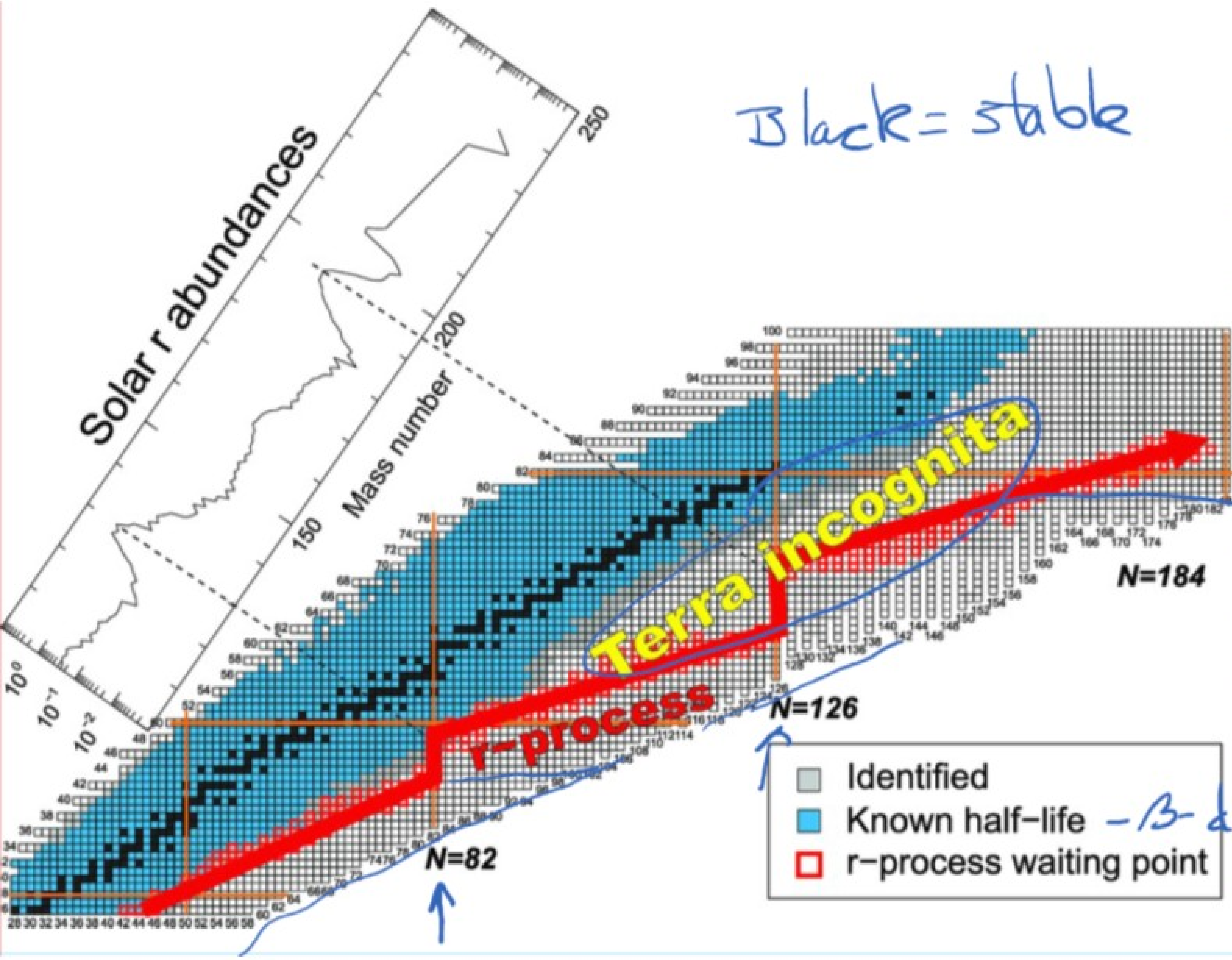
FRIB = Facility for Rare Isotope Beams

↳ (shhh! Radioactive!)

Summary of Element Production

PIC

Chart of Nuclei



Black = stable

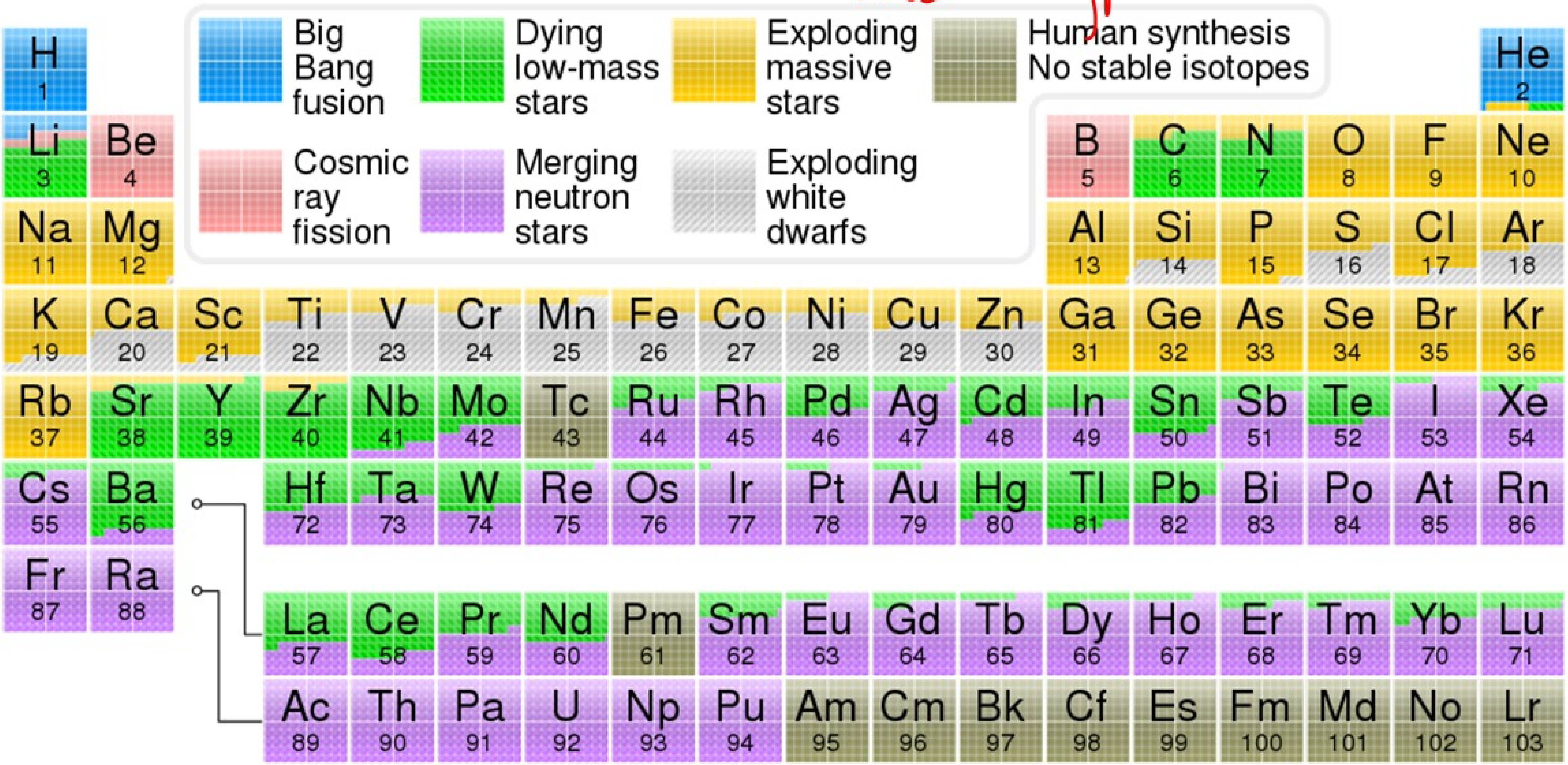
At n-magic # σ_{cap} is very small

for FRIB
MSU

– β-decay

Overview of Elemental Production

Green = Red Giant + p/γ process
Yel = Core Collapse SN (SN type II)
Red = Spallation
Purp = ns-ns mergers
White = Type 1a SN



PIC

Gr = Red Giant wind + P/γ process
Yel = Core Collapse SN II
Red = Spallation
Purp = n^*-n^* mergers
White = Type IA SN

⇒ Most stable nuclei can be accounted for via r/s process scenarios (ρ_n, T_6, σ_n, τ_β)

⇒ other odd balls ① few p-rich nuclei (e.g. $^{130,132}Ba^{56}$)
via p-process : (p, γ) . . .
or γ-process : (γ, n) . . .
② Light Nuclei not in pp chain (Be, B, ...)
via p + Air spallation

⇒ what about white Dwarf Nucleosyn ?
↳ how do nuclei escape ?

↳ WD-WD binaries
WD-RG binaries

Gravity pulls mass to denser star until "critical" mass & Star Explodes: Type IA SN

Rapid Hydrogen burning to ^{56}Ni $\tau_{1/2} = 6.1d$, $\tau_\beta = 8.8d$

$^{56}Ni (\beta^-)\, ^{56}Co (\beta^-)\, ^{56}Fe$

← $t^{1/2}_\beta = 77d$, $\tau_\beta = 111d$

↳ Powers remnant Light Curve

See Light Curve Pic

$\Delta M = \frac{L_1}{L_2} = 2.512^{\Delta m}$

$\Delta m = 3 \quad \frac{L_1}{L_2} = 16$

⇒ r-process sites:

(I) Core-Collapse SN (Type II SN)

$M_* > 10 M_\odot$: Gravity beats e^- degeneracy pressure & Core implodes to Neutron Star NS

each * small fraction of $M_\odot$ of r-process

(II) NS-NS Mergers (GW 170817)

optical remnant showed r-process nuclei up to $A \sim 200$

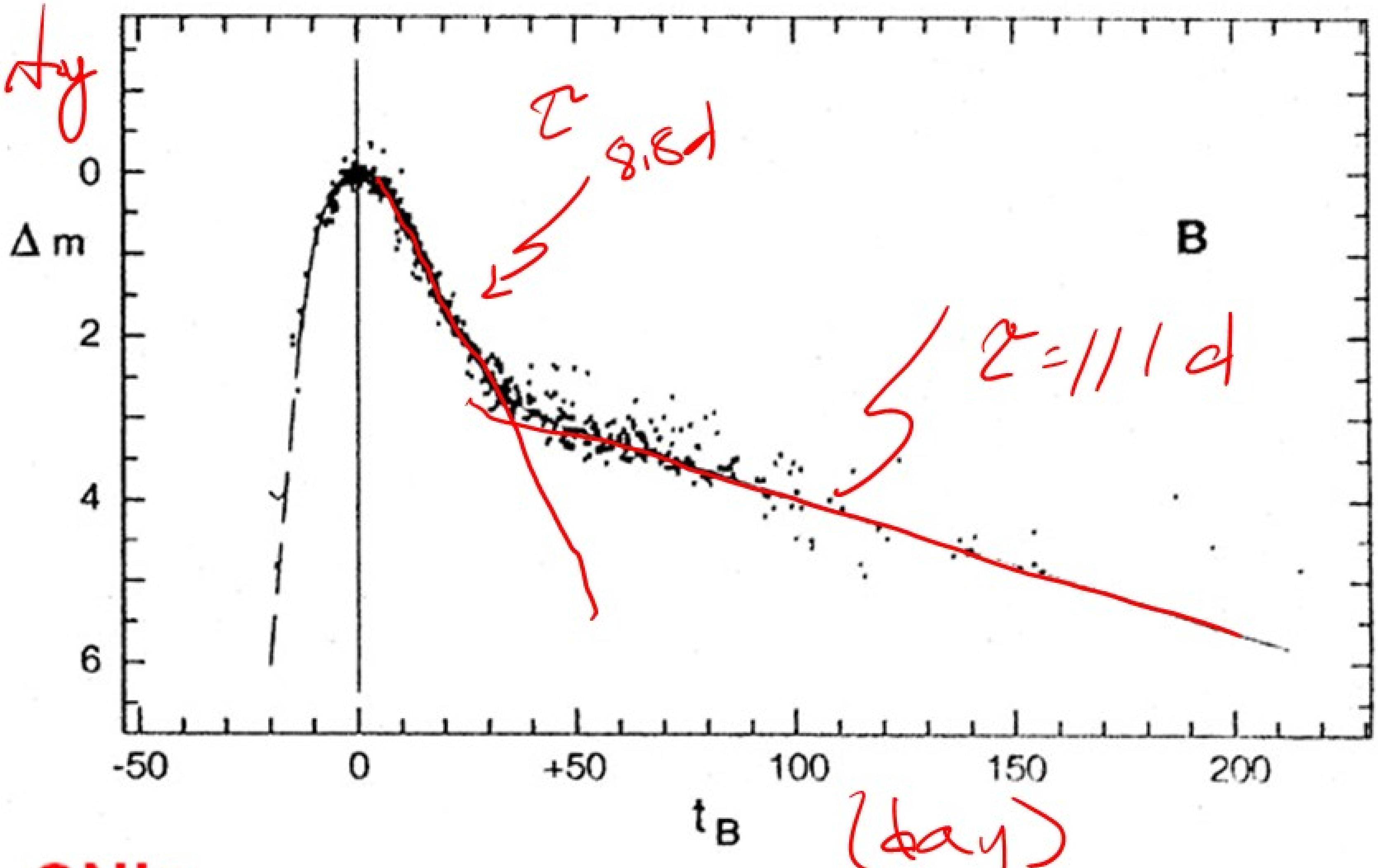
↳ up to $3 M_\odot$ of r-process each

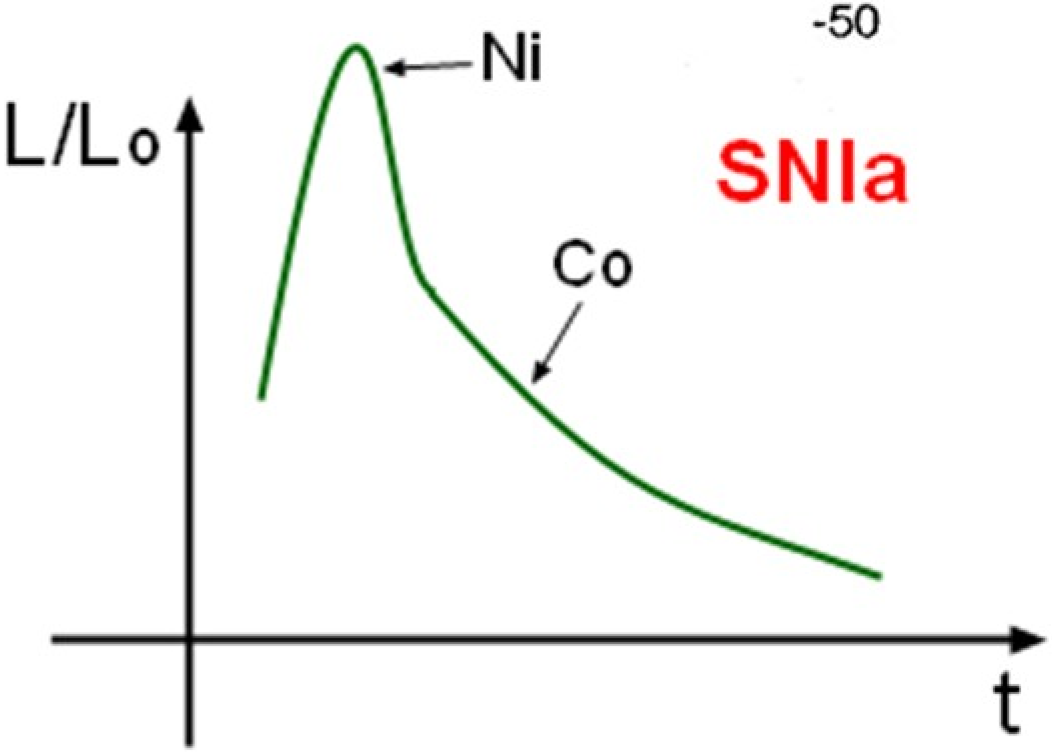
↳ Both contribute...

Type 1a SN

Luminosity

$$\frac{L_1}{L_2} = (2.512)^{\Delta m}$$





SNIa

Big-Bang Nucleosynthesis (BBN)

(production of d, ^3He, ^7Li)

⇒ Started @ $t_{BB} \sim 10s$ @ $kT = 100$ keV

$T_6 \simeq 1200$

⇒ Relies on Standard Model processes

⇒ lasted ~ 3 minutes

Nucleosyn. begins when n, p "condense" from quark-gluon soup @ $t_{BB} = 0.01\,s$: $kT = 5$ MeV when

$n + e^+ \rightleftarrows \bar{\nu}_e + p$
$n + \nu_e \rightleftarrows e^- + p$ } in equilibrium

as T↓

$$\frac{N_n}{N_H} = e^{-\frac{Q_{np}}{kT}}$$

← Boltzmann Factor

w/ $Q_{np} \simeq 1.3$ MeV $= M_n - M_p$

@ $T_F \lesssim 1$ MeV

"Freeze-out" = no chemical equilibrium

& $\frac{N_n}{N_H} = e^{-\frac{Q_{np}}{kT_F}} \simeq \frac{1}{6}$ & β decay

give $\frac{N_n}{N_H} \sim \frac{1}{7}$ then BBN begins @ $t_{BB} \simeq 10s - 50s$

& $p + n \rightarrow d + \gamma$ see BBN Network:

REVIEWS OF MODERN PHYSICS, VOLUME 88, JANUARY–MARCH 2016

Big bang nucleosynthesis: Present status

Richard H. Cyburt
Joint Institute for Nuclear Astrophysics (JINA), National Superconducting Cyclotron Laboratory (NSCL), Michigan State University, East Lansing, Michigan 48824, USA

Brian D. Fields
Departments of Astronomy and of Physics, University of Illinois, Urbana, Illinois 61801, USA

Keith A. Olive
William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA

Tsung-Han Yeh
Departments of Astronomy and of Physics, University of Illinois, Urbana, Illinois 61801, USA

ak interaction rates
ıd H is the Hubble

(3)

universe. G_F and G_N
pectively. Freeze-out

TABLE I. Reactions of relevance for BBN from the NACRE-II compilation.

$d(p,\gamma)^3$He	$d(d,\gamma)^4$He	$d(d,n)^3$He
$d(d,p)t$	$t(d,n)^4$He	^{3}He$(d,p)^4$He
$d(\alpha,\gamma)^6$Li	^{6}Li$(p,\gamma)^7$Be	^{6}Li$(p,\alpha)^3$He
^{7}Li$(p,\alpha)^4$He	^{7}Li$(p,\gamma)^8$Be[a]	

[a] ^{8}Be is not in our nuclear network; ^{8}Be is assumed to spontaneously decay into $2\,^4$He.

BBN cycle converts H to ^4He + d, ^3He, $^{6,7}Li$

ends @ $t_{BB} \simeq 1000$ s

see Abund vs. t / T pic

Final results of BBN is abundance vs baryon density today

$$\frac{n_B}{n_\gamma} \equiv \eta$$

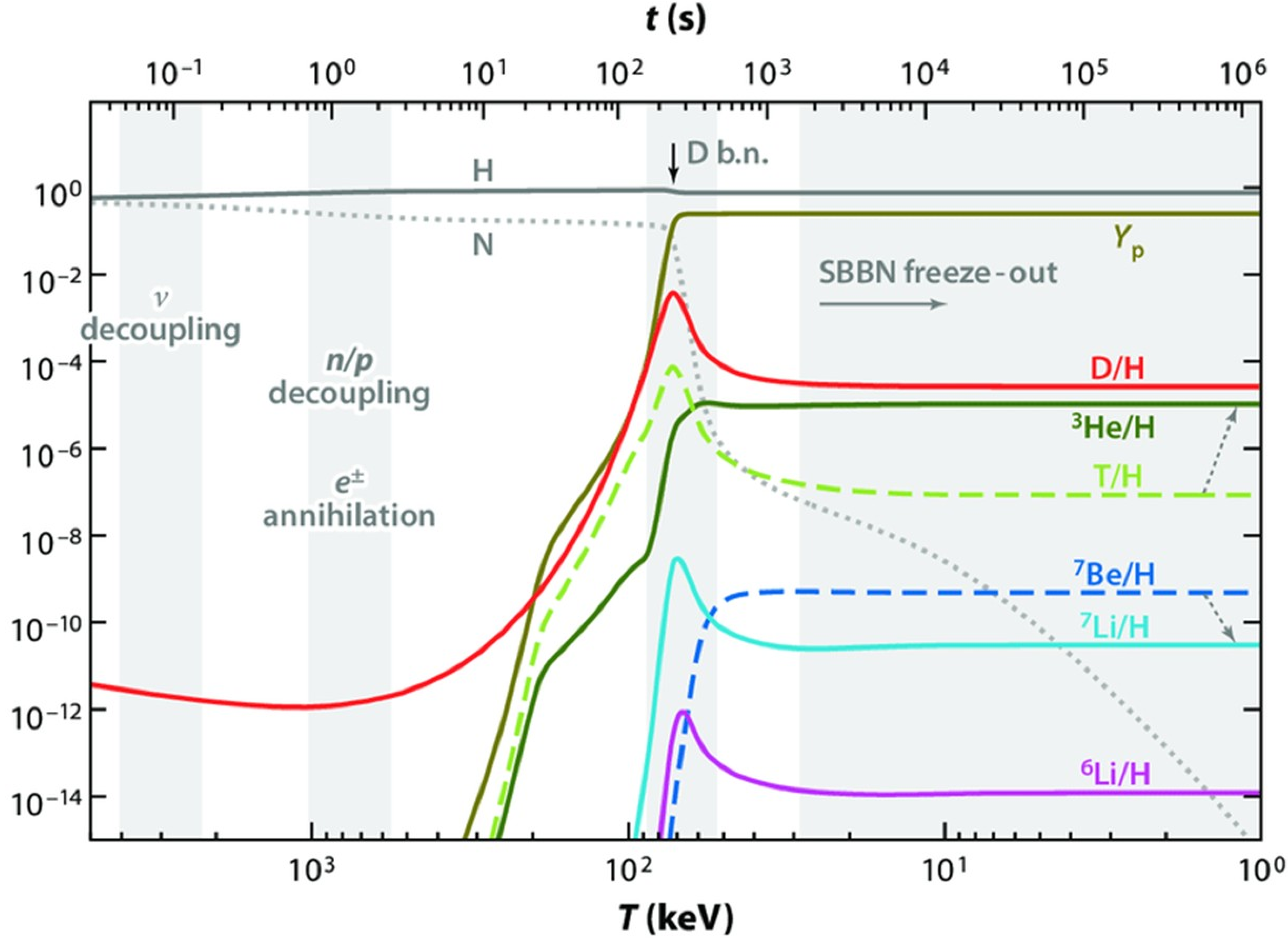
BBR density

Measure "Primordial" abund. in "Metal-poor" stars / regions / galaxies
→ low C, O, N, Fe

also Cosmic Microwave Bkgd (CMB) gives η precisely
(assuming "standard" CMB "clumping" predictions)

See Pic: ^4He good, d very good

^7Li problem see PDG for answers (mostly stellar destruction)


t (s)
10^−1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
D b.n.
H
N
Y_p
SBBN freeze-out
ν
decoupling
n/p
decoupling
e^±
annihilation
D/H
^3He/H
T/H
^7Be/H
^7Li/H
^6Li/H
10^0
10^−2
10^−4
10^−6
10^−8
10^−10
10^−12
10^−14
10^3
10^2
10^1
10^0
T (keV)

PDG 2025

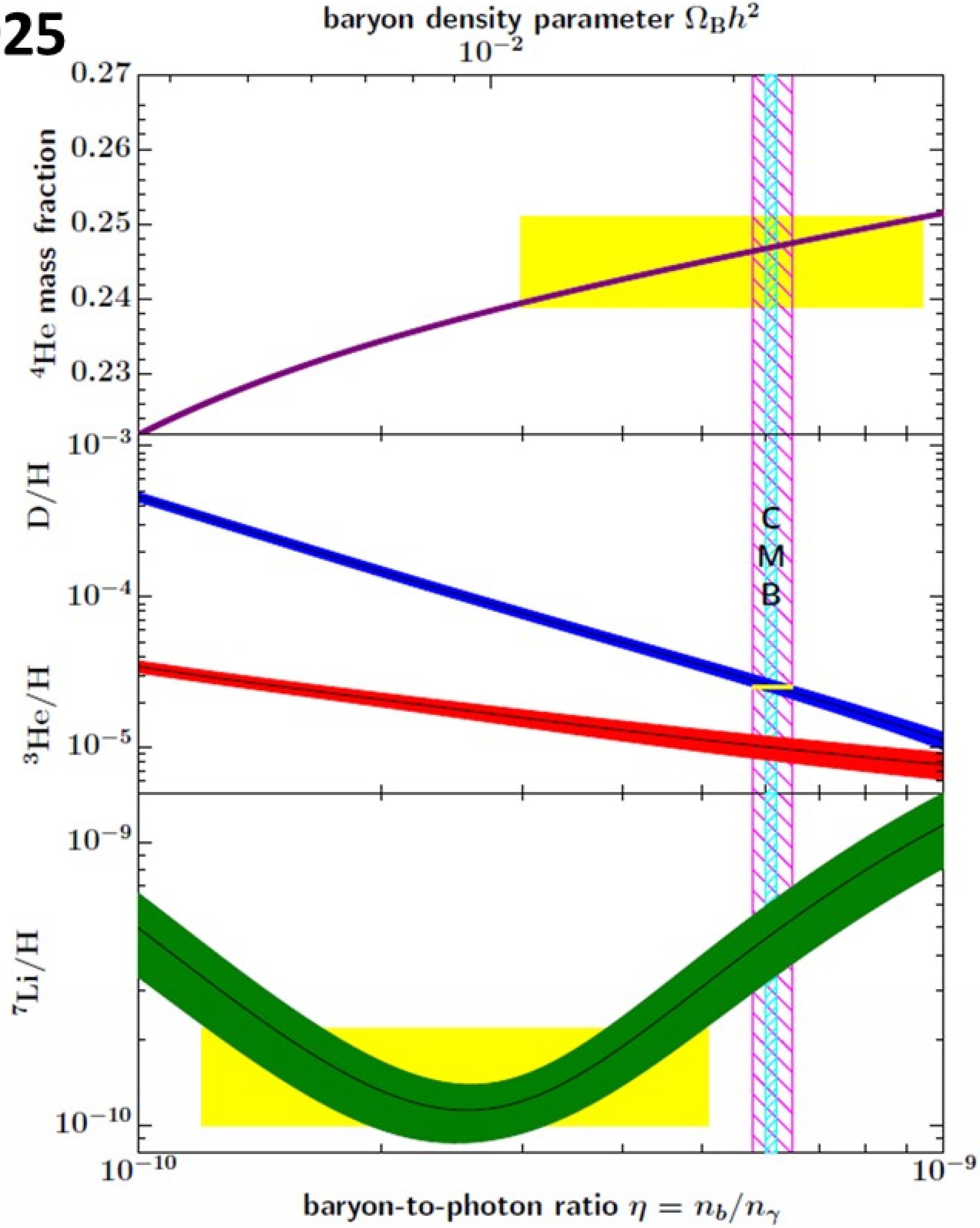


Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [47]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN D+^{4}He concordance range (both at 95% CL).