Heavy-Element Synthesis by Sources Associated with Massive Stars in Galactic History

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EMMI Rapid Reaction Task Force: The physics of neutron star mergers at GSI/FAIR

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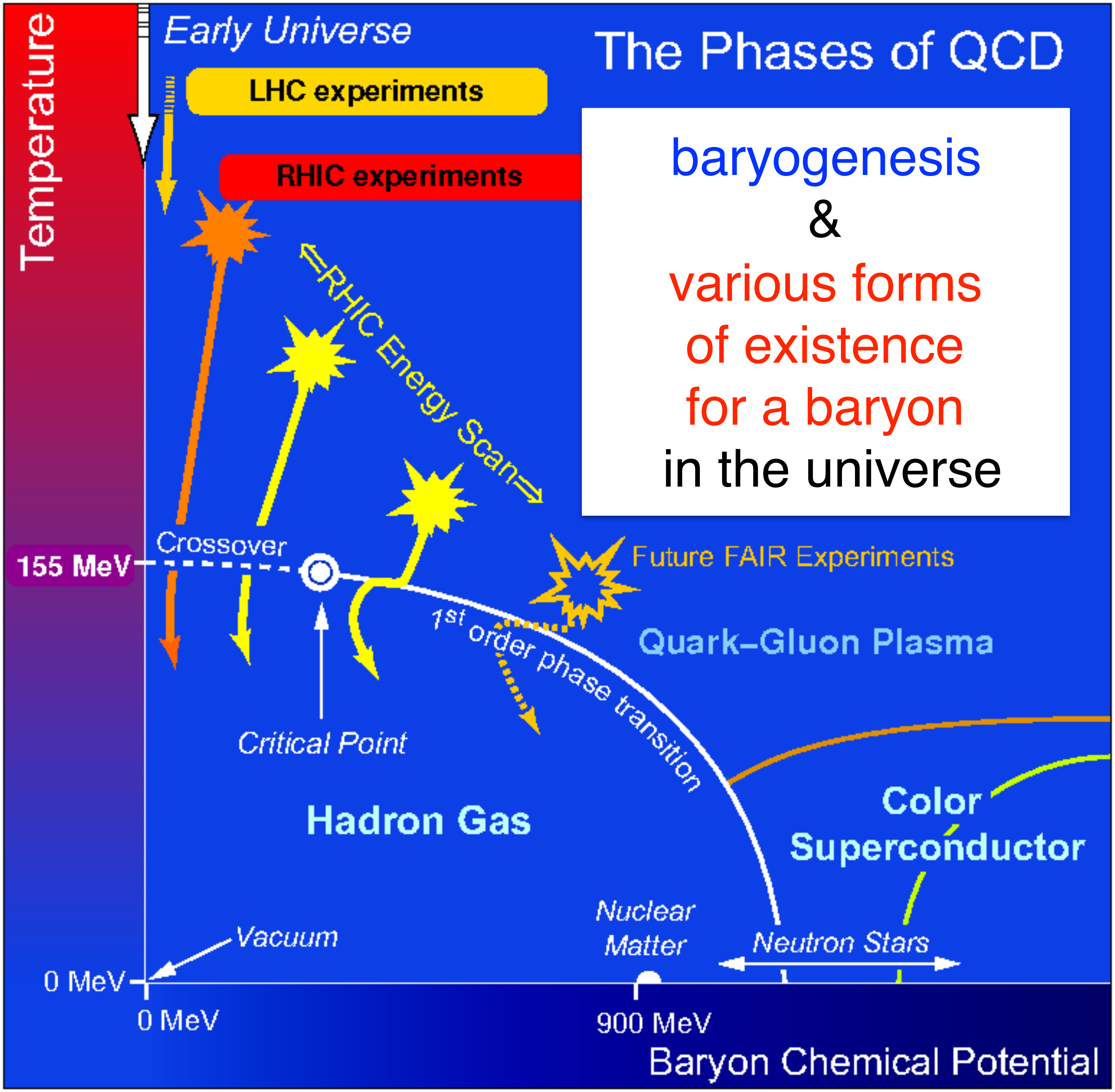
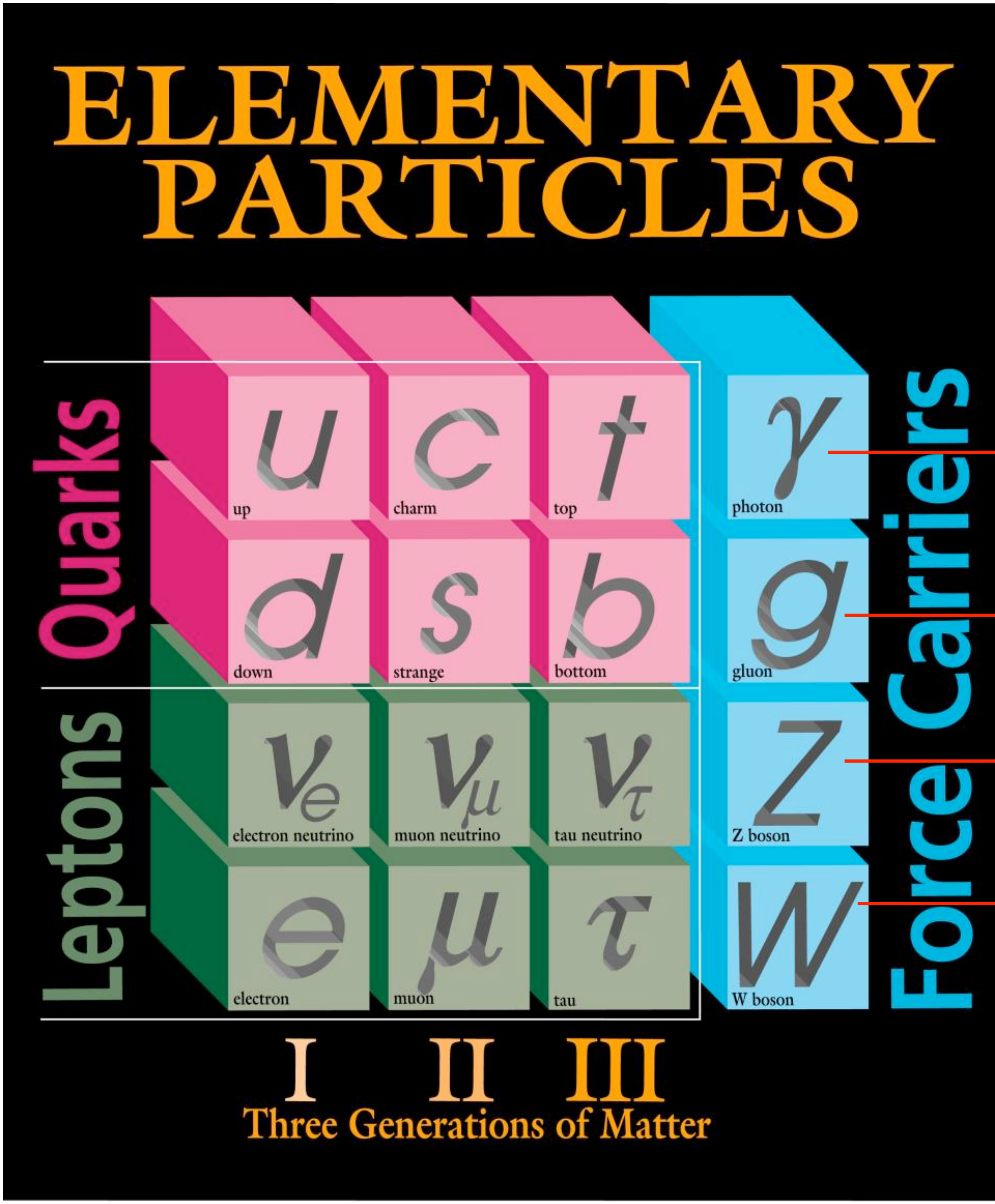

The Phases of QCD
baryogenesis
&
various forms
of existence
for a baryon
in the universe
Temperature
Early Universe
LHC experiments
RHIC experiments
⇐RHIC Energy Scan⇒
Future FAIR Experiments
Quark–Gluon Plasma
155 MeV
Crossover
Critical Point
1st order phase transition
Hadron Gas
Color Superconductor
Nuclear Matter
Neutron Stars
Vacuum
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential



Fermilab 95-759

Fundamental Interactions

Electromagnetic

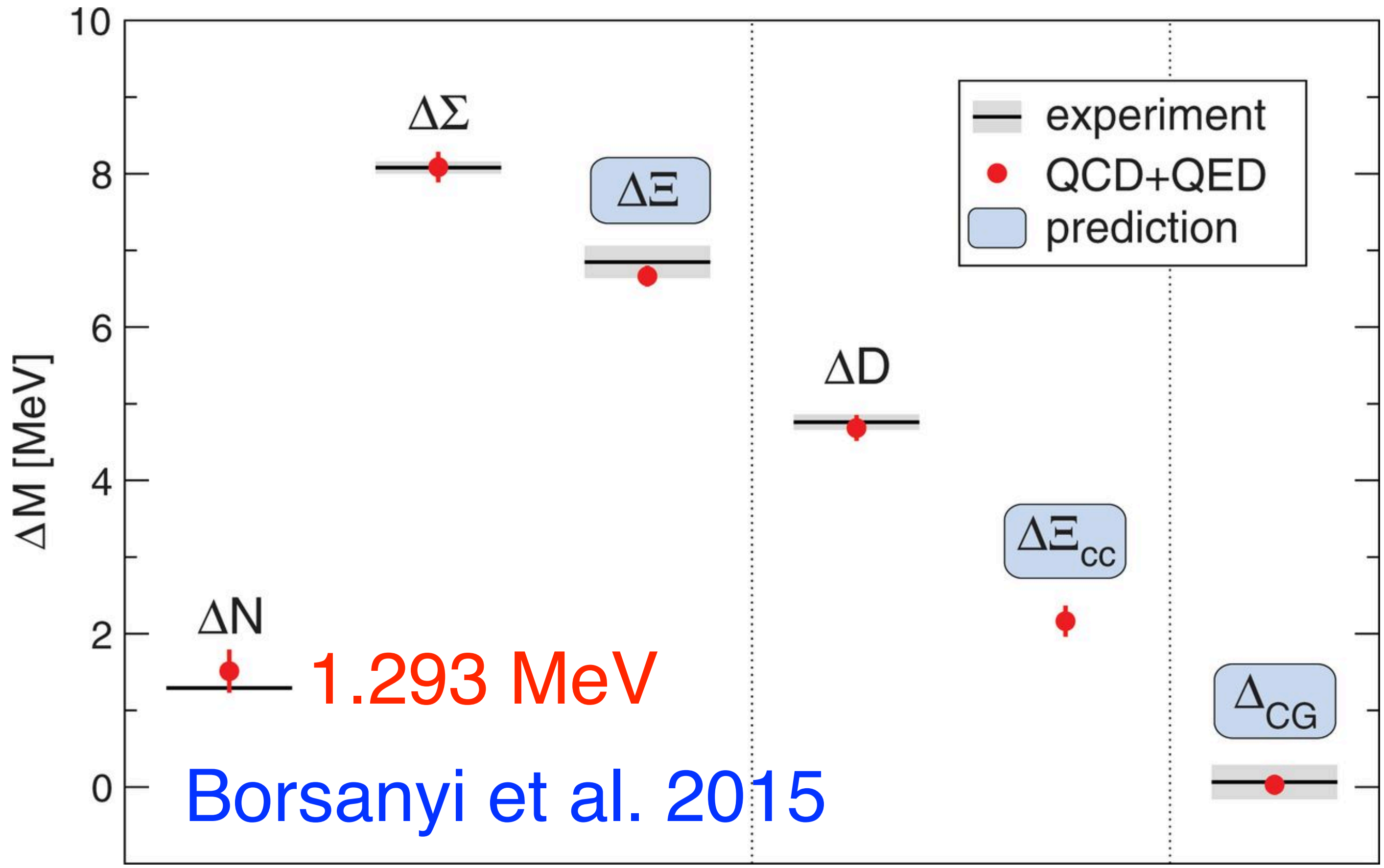
Strong

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:

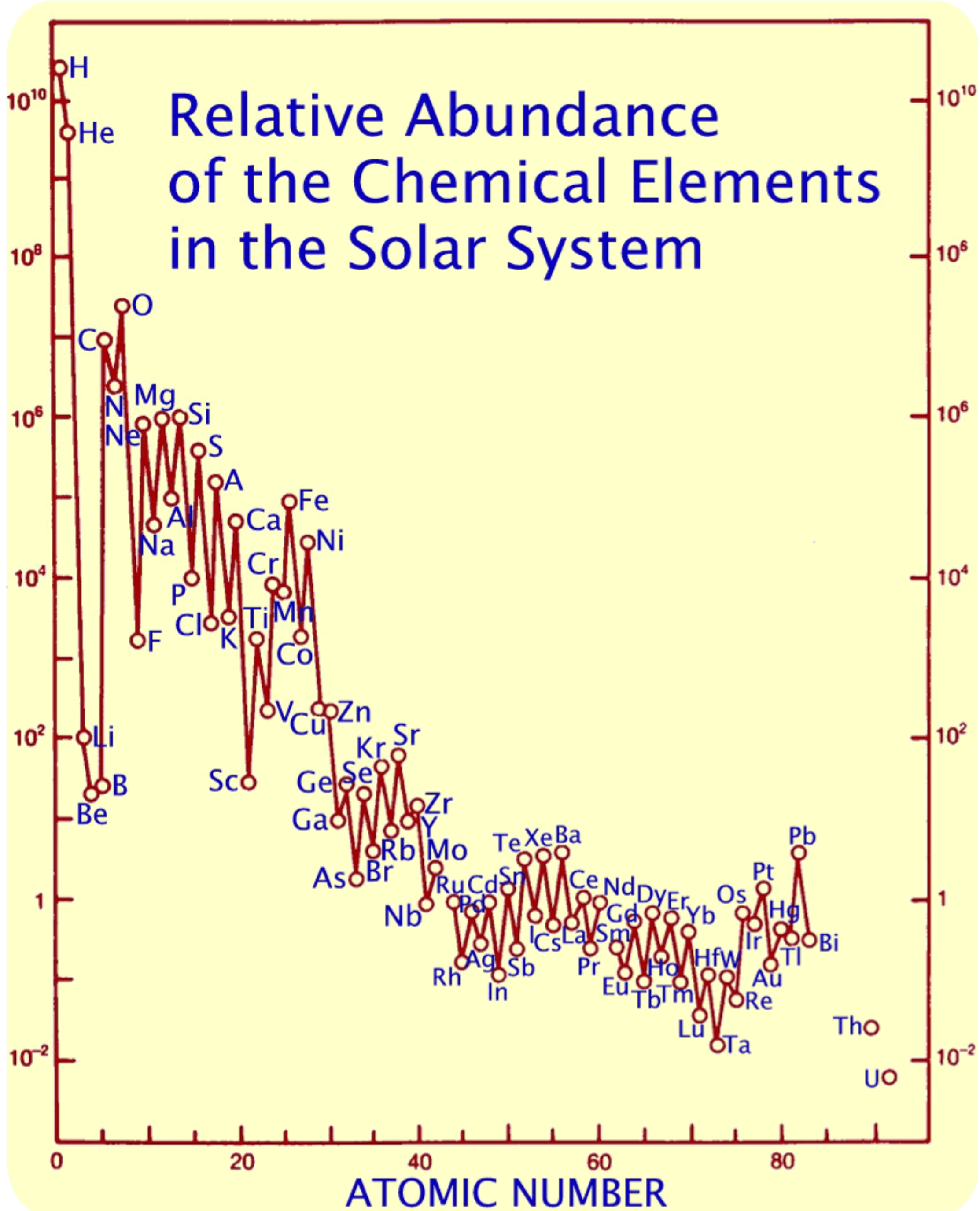
71.1% H + 27.4% He

+1.5% “Metals”

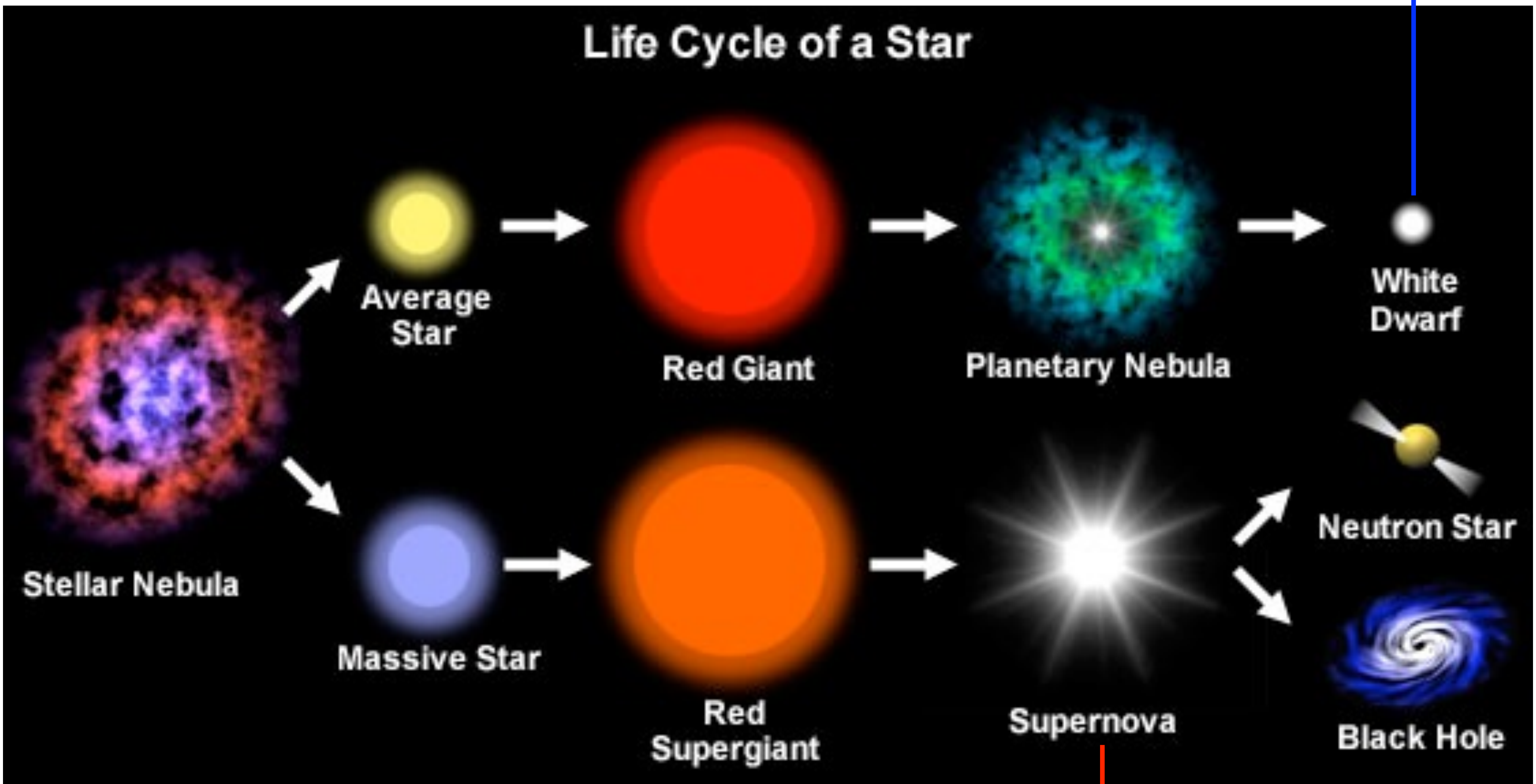
$$\text{“}p\text{”} \rightarrow \text{“}n\text{”} + e^{+} + \nu_e$$

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

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

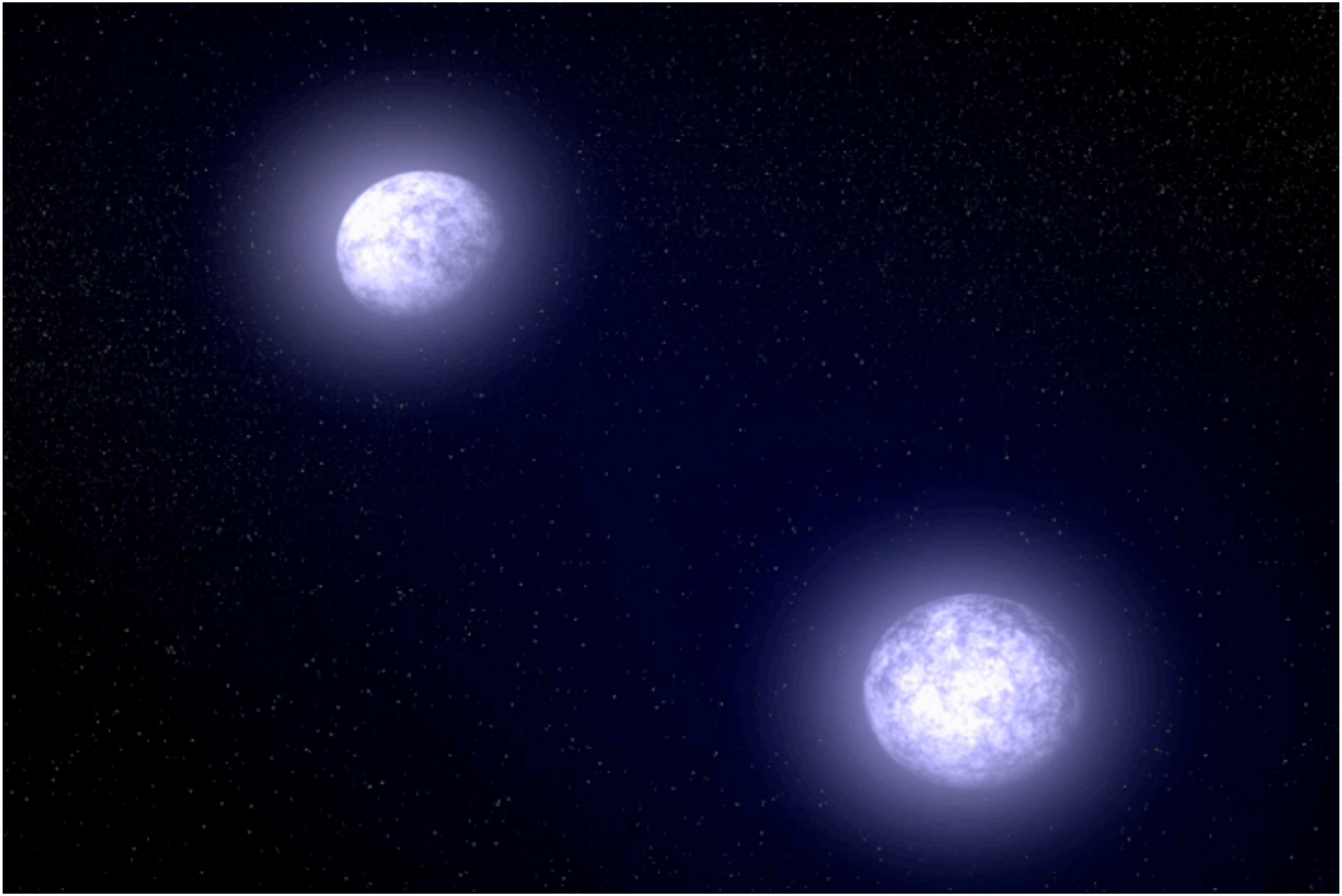


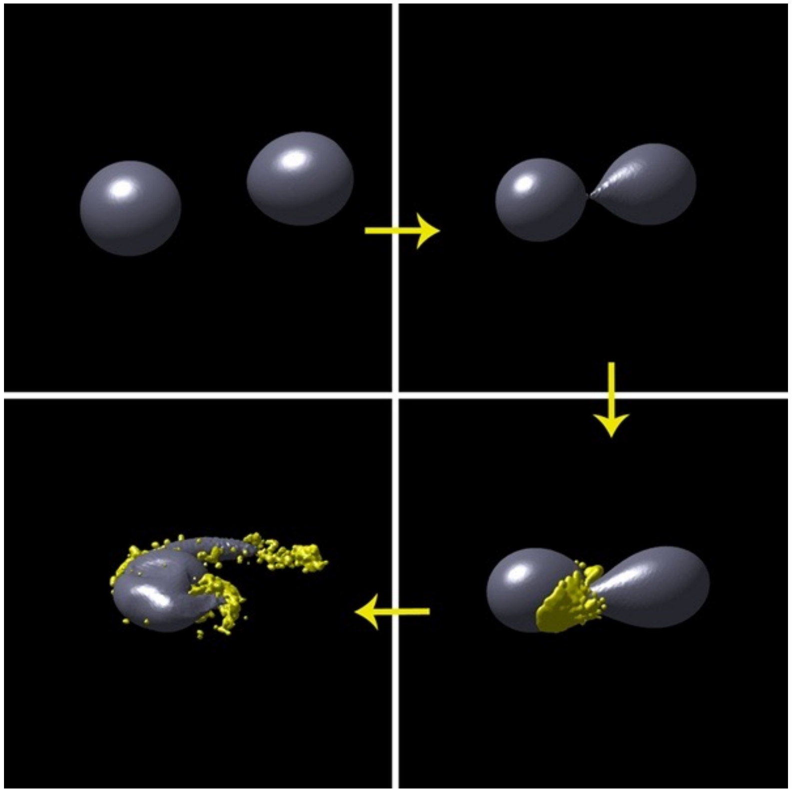
Type Ia SNe

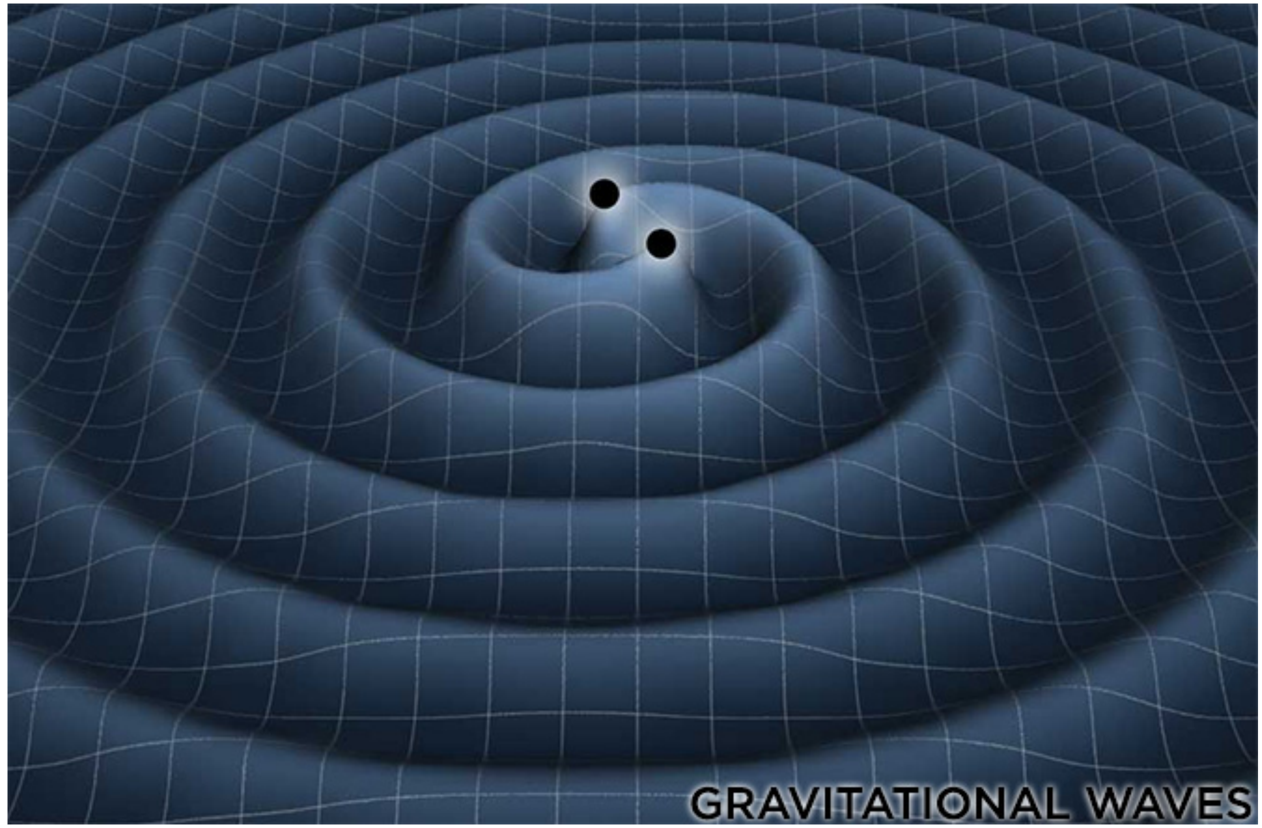


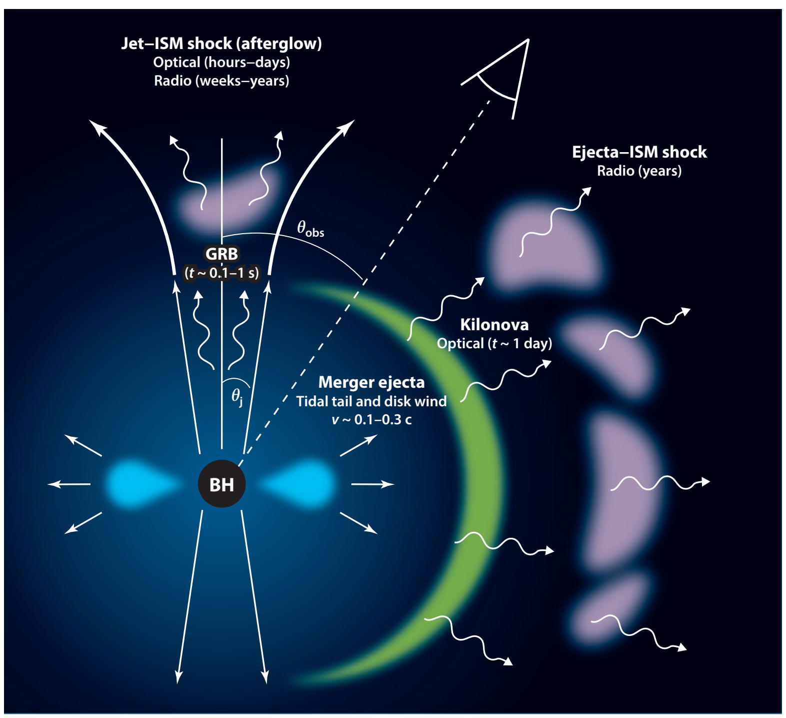
core-collapse SNe (mostly Type II)

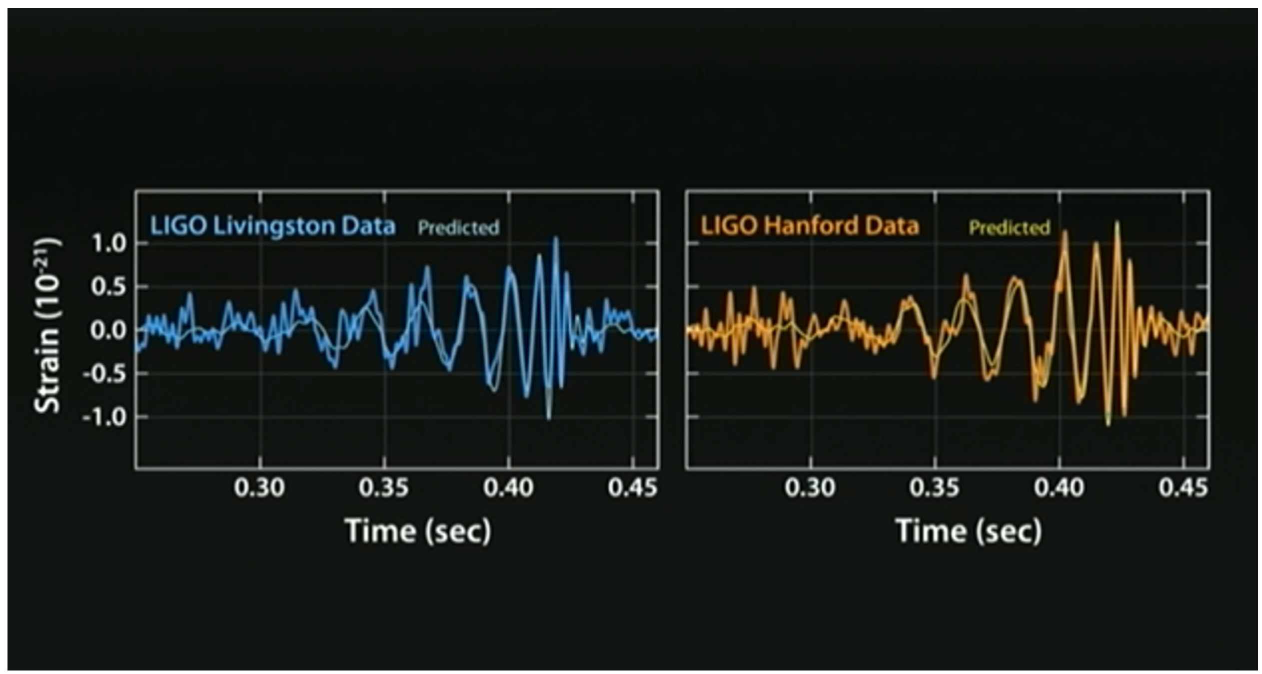
An SN Ia Scenario: White Dwarf Mergers



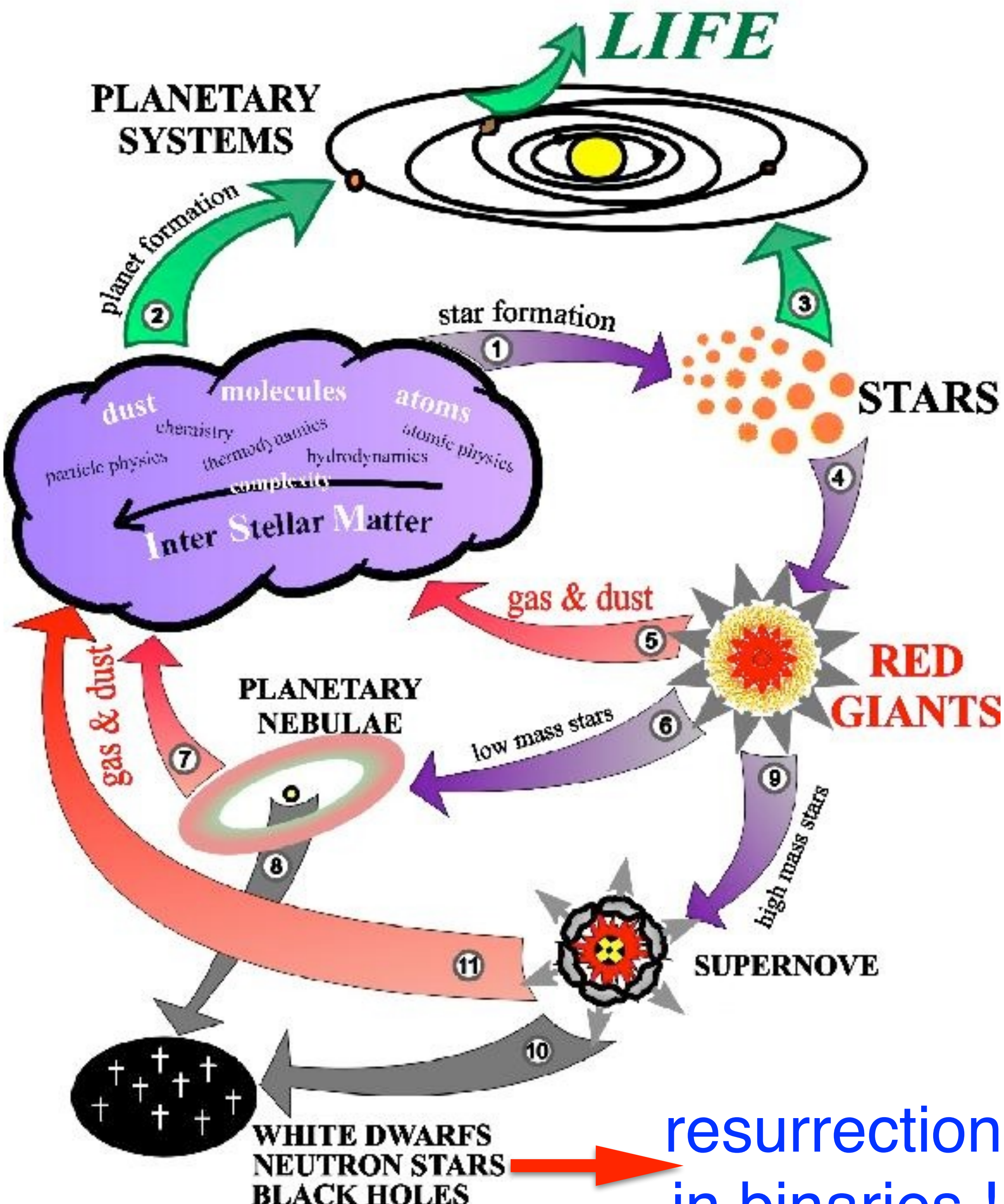



GRAVITATIONAL WAVES

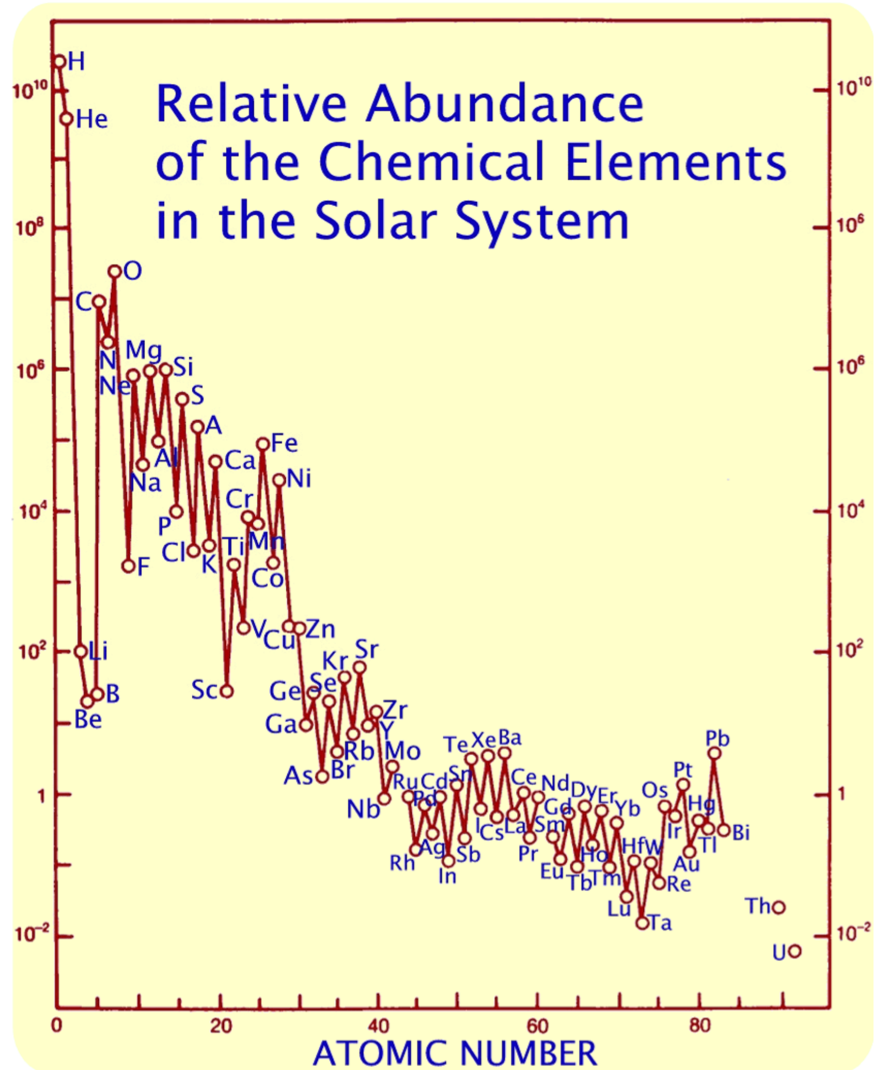

Jet–ISM shock (afterglow)
Optical (hours–days)
Radio (weeks–years)
Ejecta–ISM shock
Radio (years)
θ_{obs}
GRB
(t ~ 0.1–1 s)
Kilonova
Optical (t ~ 1 day)
Merger ejecta
Tidal tail and disk wind
v ~ 0.1–0.3 c
θ_j
BH


LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)

Arise from the Ashes



resurrection in binaries !



multiple processes & diverse astrophysical sources producing elements heavier than Fe

well-known: slow (s) & rapid (r) neutron capture, proton (p) capture

Burbidge, Burbidge, Fowler & Hoyle 1957 (B^2FH); Cameron 1957

main s-process: A > 88 (Sr & heavier)

AGB phase of intermediate-mass (~1-3 M_{sun}) stars

weak s-process: A < 88 (lighter than Sr)

He & C burning regions of massive (>10 M_{sun}) stars

γ-process: (γ, n) equivalent to (p, γ)

propagation of SN shock through envelope recently studied massive-star associated sources for elements heavier than Fe

1. n-rich & p-rich ν-driven winds from proto-NS
nuclei with A ~ 88 to 130

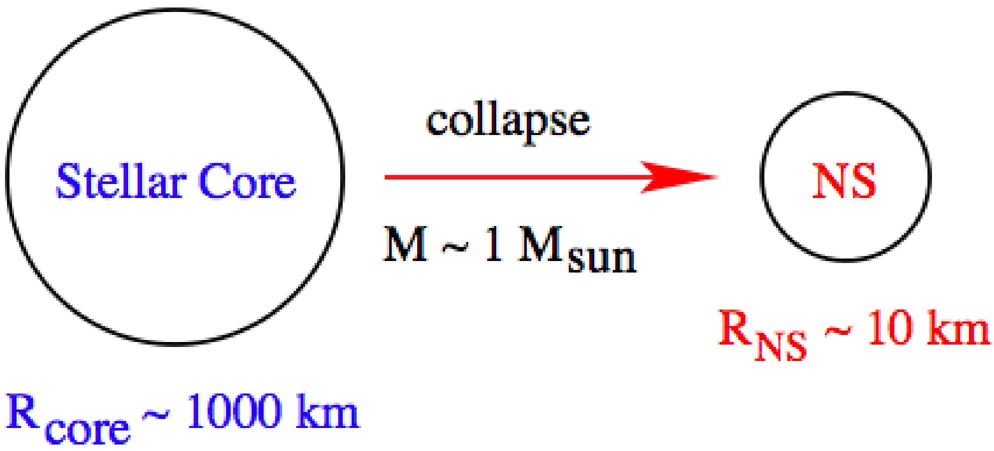
2. n-rich winds from accretion disks in NS mergers
nuclei with A ~ 88 to 130, r-process for A > 130

3. n-rich matter dynamically ejected from NSM
r-process for A > 130

4. n-rich matter dynamically ejected in SN
nuclei with A ~ 88 to 130, r-process for A > 130

5. n-capture during pre-SN evolution
nuclei with A > 56 (up to ~ 210)
intermediate (i) neutron capture &
carbon-enhanced weak s-process

Neutrino Emission from NS Formation



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

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

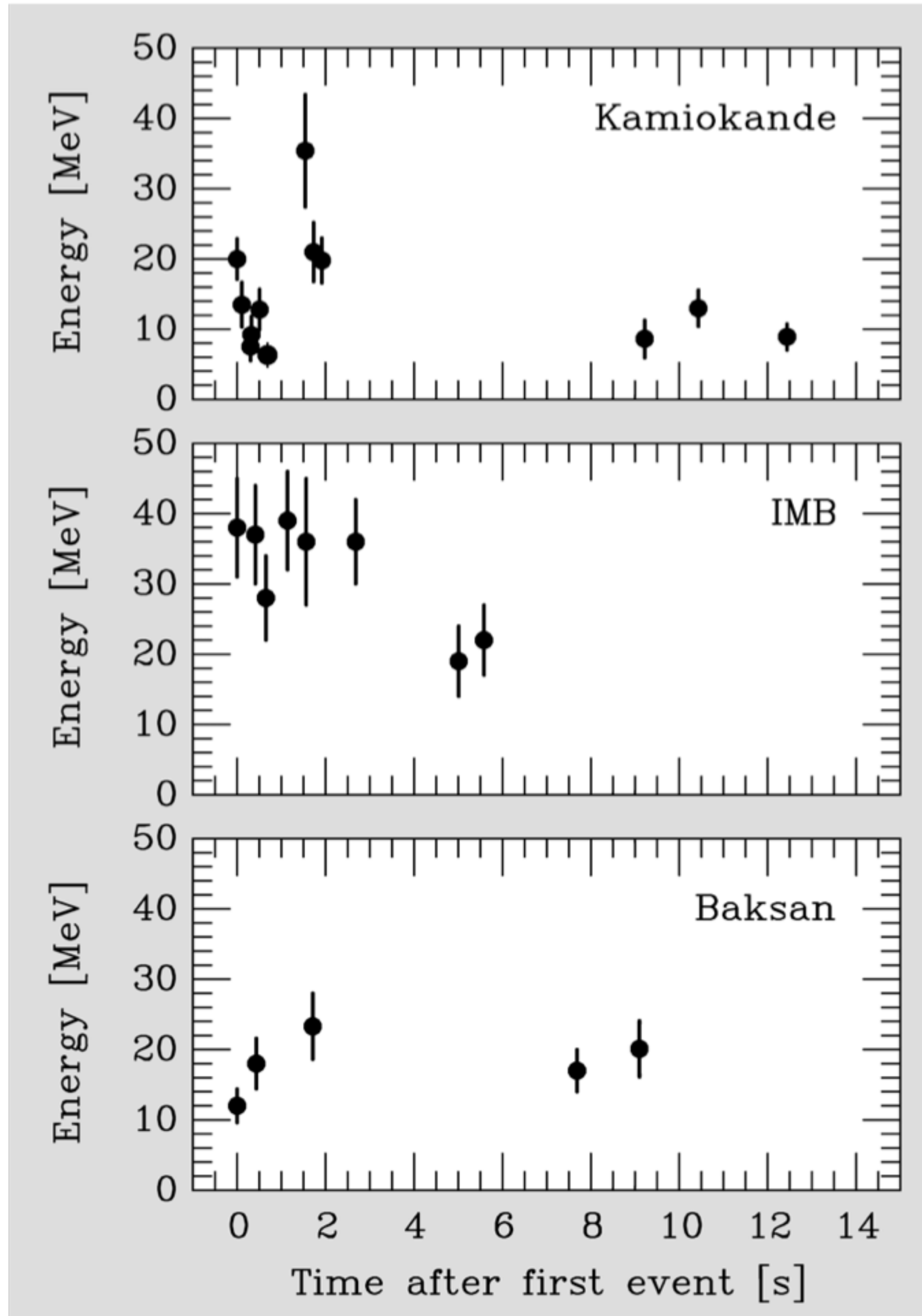
$$\frac{GM^2}{R_{\rm NS}} \sim 3 \times 10^{53}\ \text{erg}$$

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

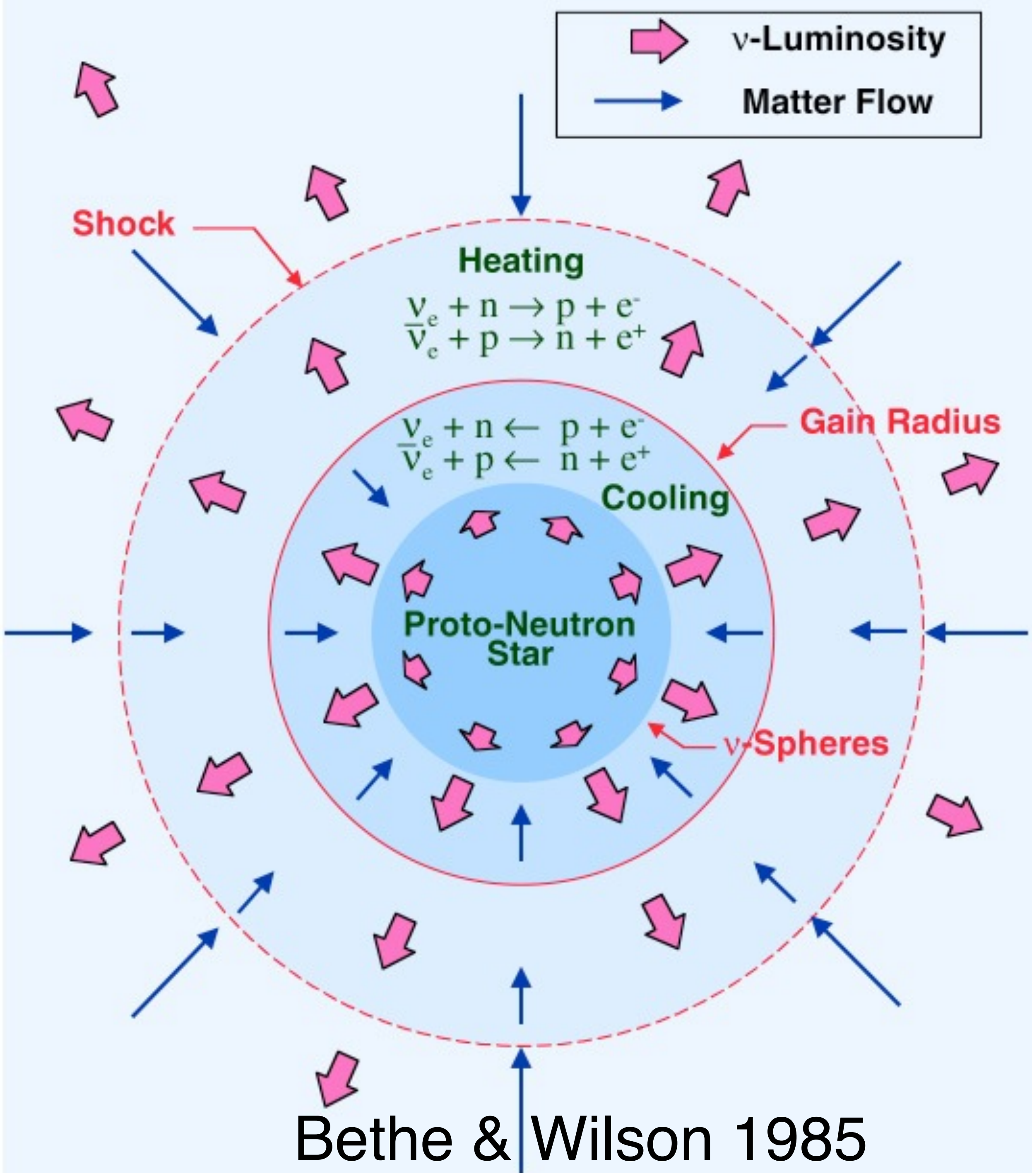
for a Galactic SN at ~10 kpc

~10^4 events due to

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

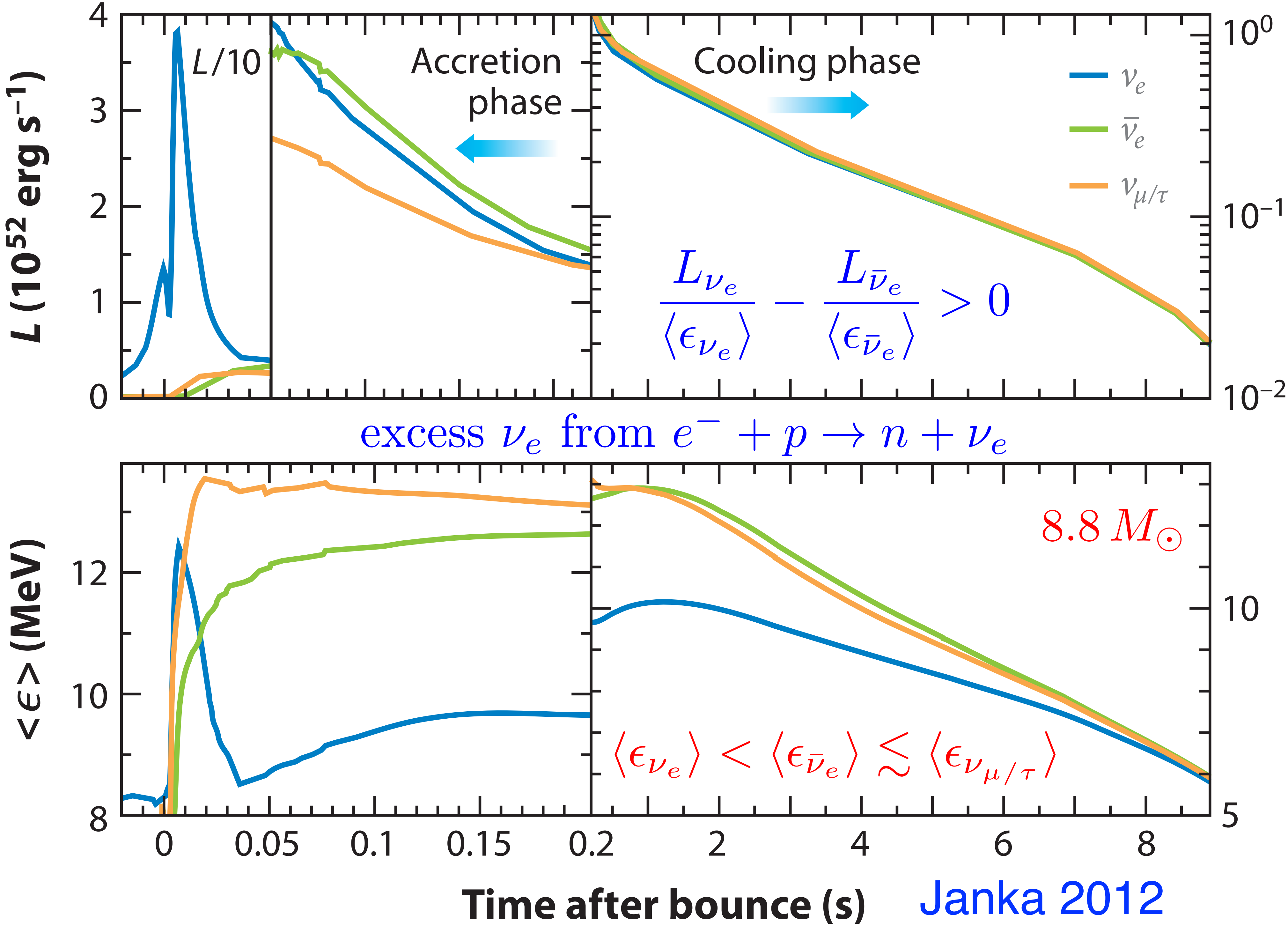


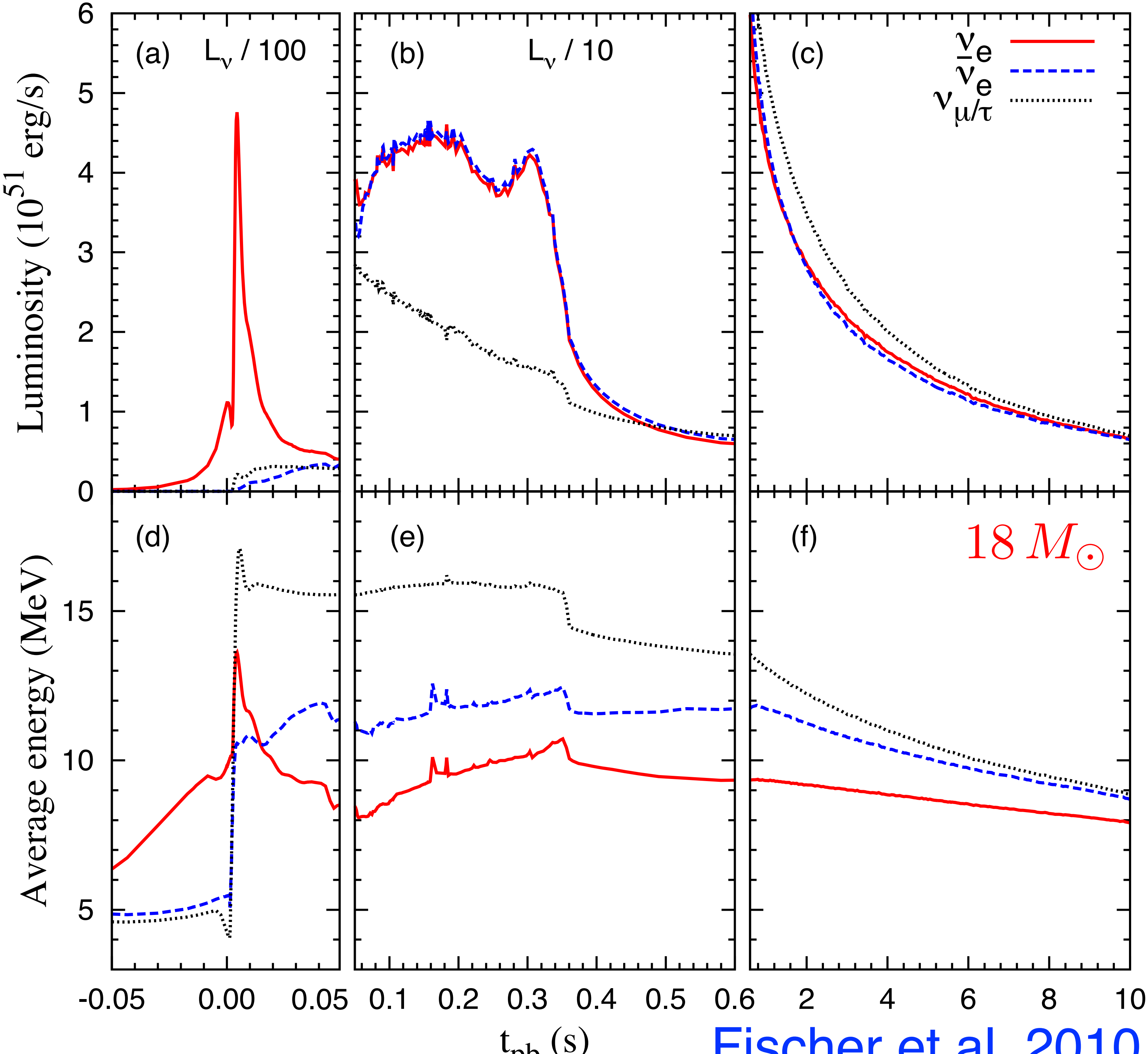
ν-Driven Core-Collapse Supernovae



Bethe & Wilson 1985

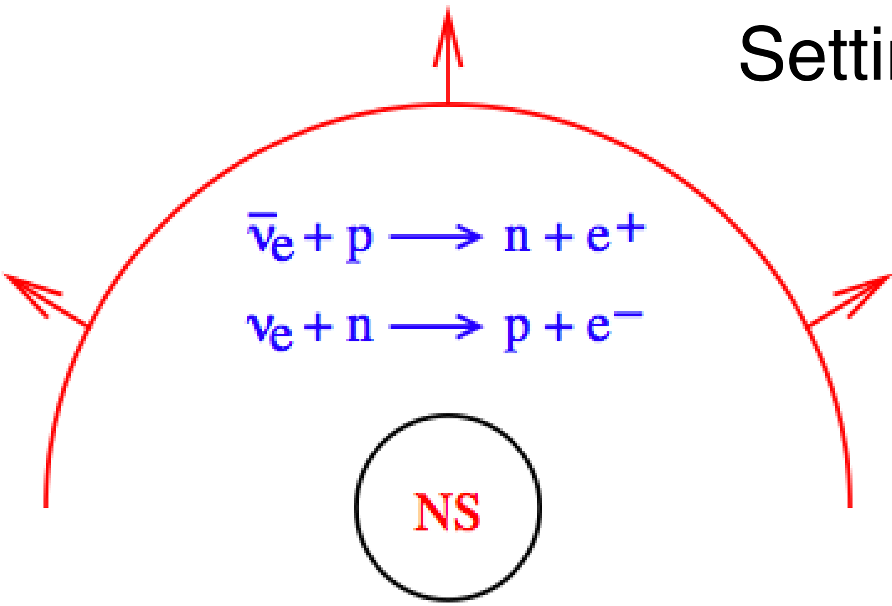
Neutrino Emission from a Low-Mass SN





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

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

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

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

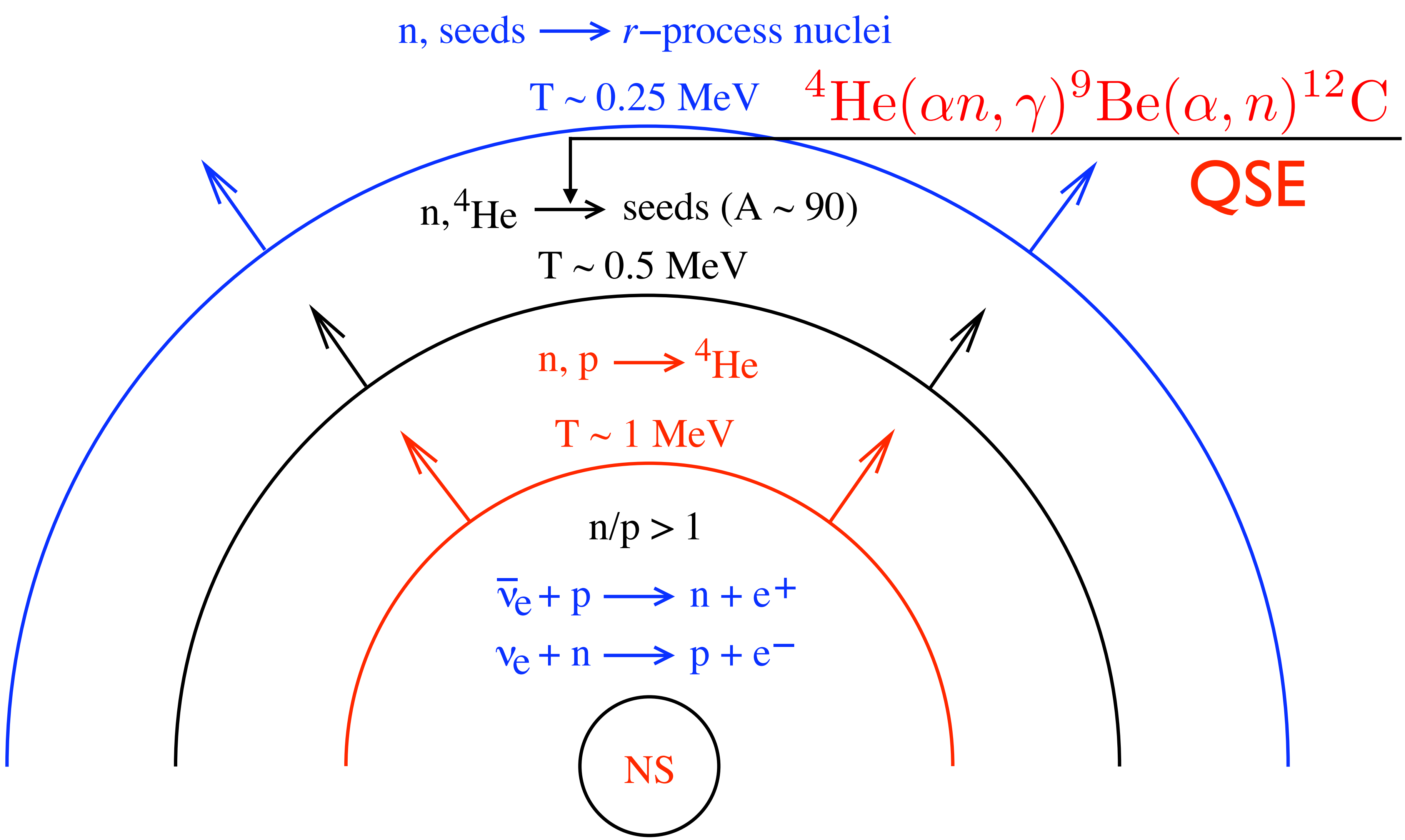
$$\frac{\langle E^2_{\bar{\nu}_e} \rangle}{\langle E_{\bar{\nu}_e} \rangle} - \frac{\langle E^2_{\nu_e} \rangle}{\langle E_{\nu_e} \rangle} > 4\Delta_{np} \approx 5.2 \text{ MeV} \Rightarrow \frac{n}{p} > 1$$

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)



$$Y_e\downarrow,\ S\uparrow,\ \tau_{\rm dyn}\downarrow \Rightarrow \text{heavier r-nuclei}$$

Conditions in the ν-driven wind

$Y_e \sim 0.4\text{–}0.5,\ \ S \sim 10\text{–}100,\ \ \tau_{\rm dyn} \sim 0.01\text{–}0.1\ {\rm s}$

(Witti et al. 1994; Qian & Woosley 1996; Wanajo et al. 2001; Thompson et al. 2001; Fischer et al. 2010; Roberts et al. 2010)

Sr, Y, Zr (A~90) readily produced in the ν-driven wind, up to Pd & Ag (A~110) likely, all by QSE

(Woosley & Hoffman 1992; Arcones & Montes 2011)

production of r-nuclei up to A~130 possible, but very hard to make A>130

(Hoffman et al. 1997; Wanajo 2013)

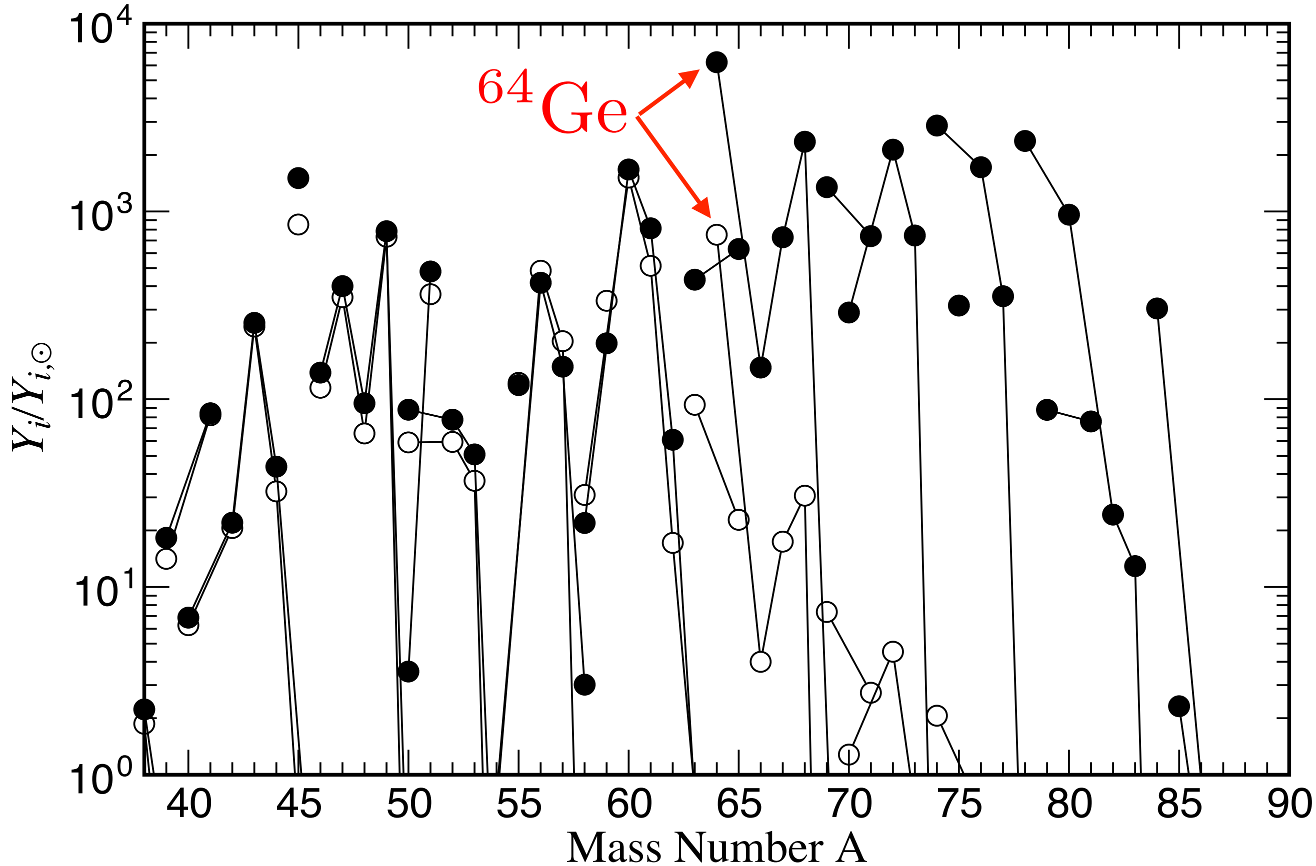
But see Metzger et al. 2007 for winds from rotating magnetized neutron stars

The νp-process in p-rich ν-driven winds
(Frohlich et al. 2006a,b; Pruet et al. 2005,2006)

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

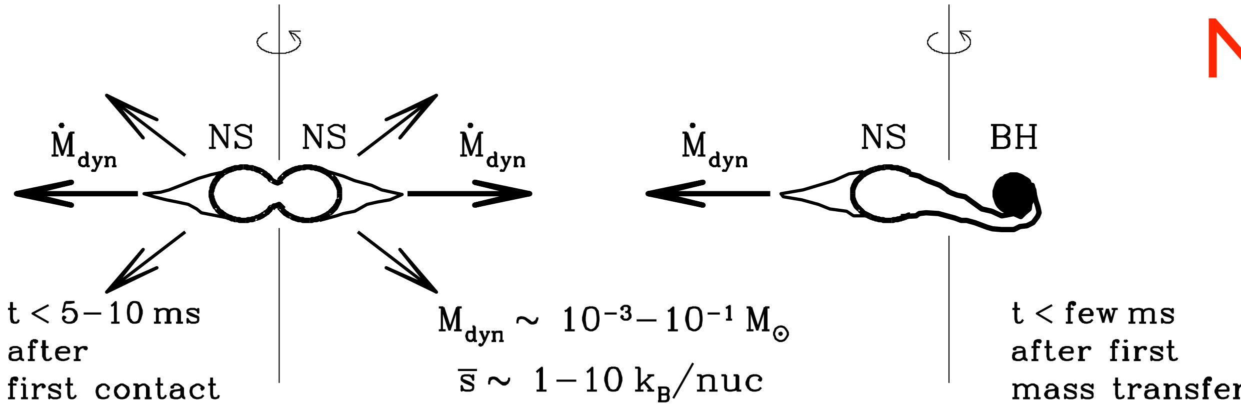
break through waiting-point nuclei with slow beta decay:

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



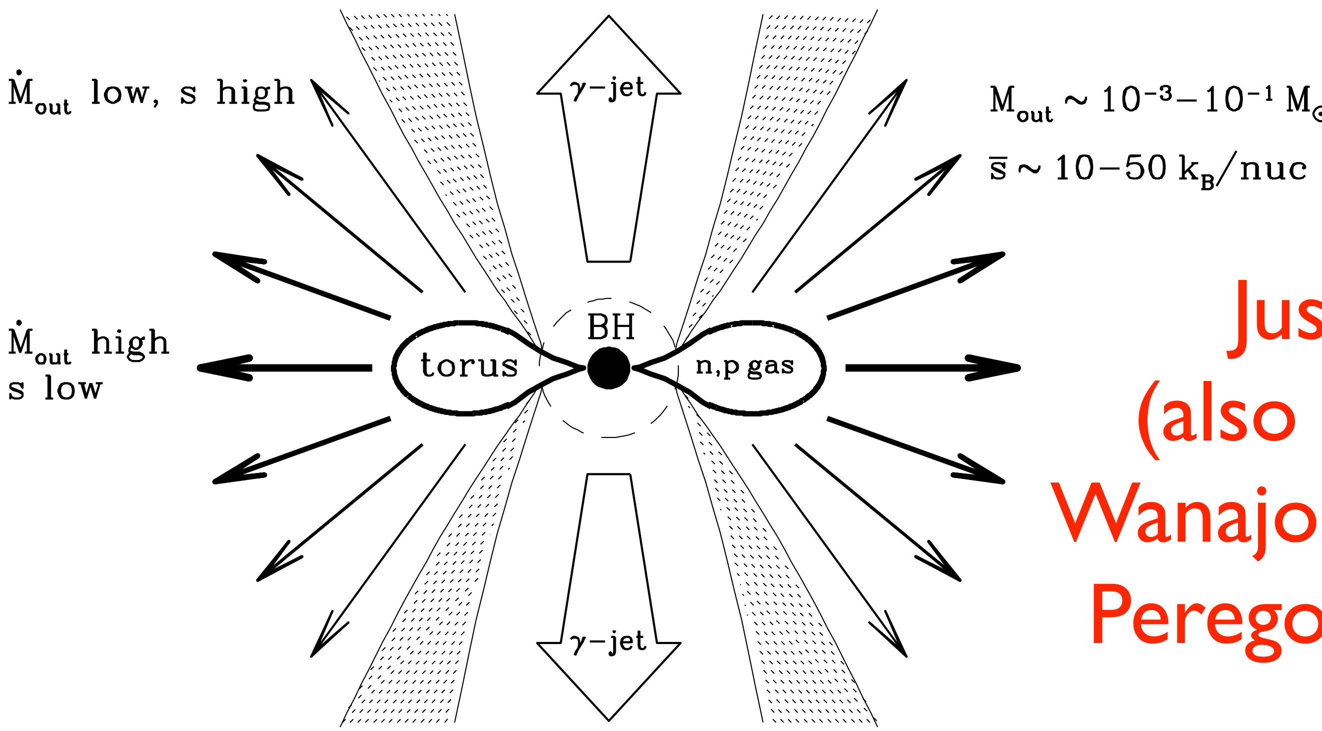
Mass Loss Phases During NS–NS and NS–BH Merging

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



NS matter
+ winds

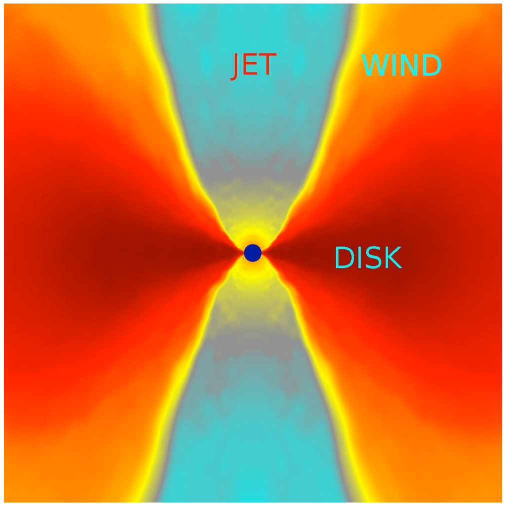
BH–Torus Phase: Disk ejecta
(due to ν heating, viscosity/magn. fields, recombination)



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

$Y_e \downarrow,\ S \uparrow,\ \tau_{\rm dyn} \downarrow\ \Rightarrow$ heavier r-nuclei

- winds from accretion disks of BHs



(Pruet et al. 2003;
Surman et al. 2006, 2008;
Wanajo & Janka 2012;
Fernandez & Metzger 2013)

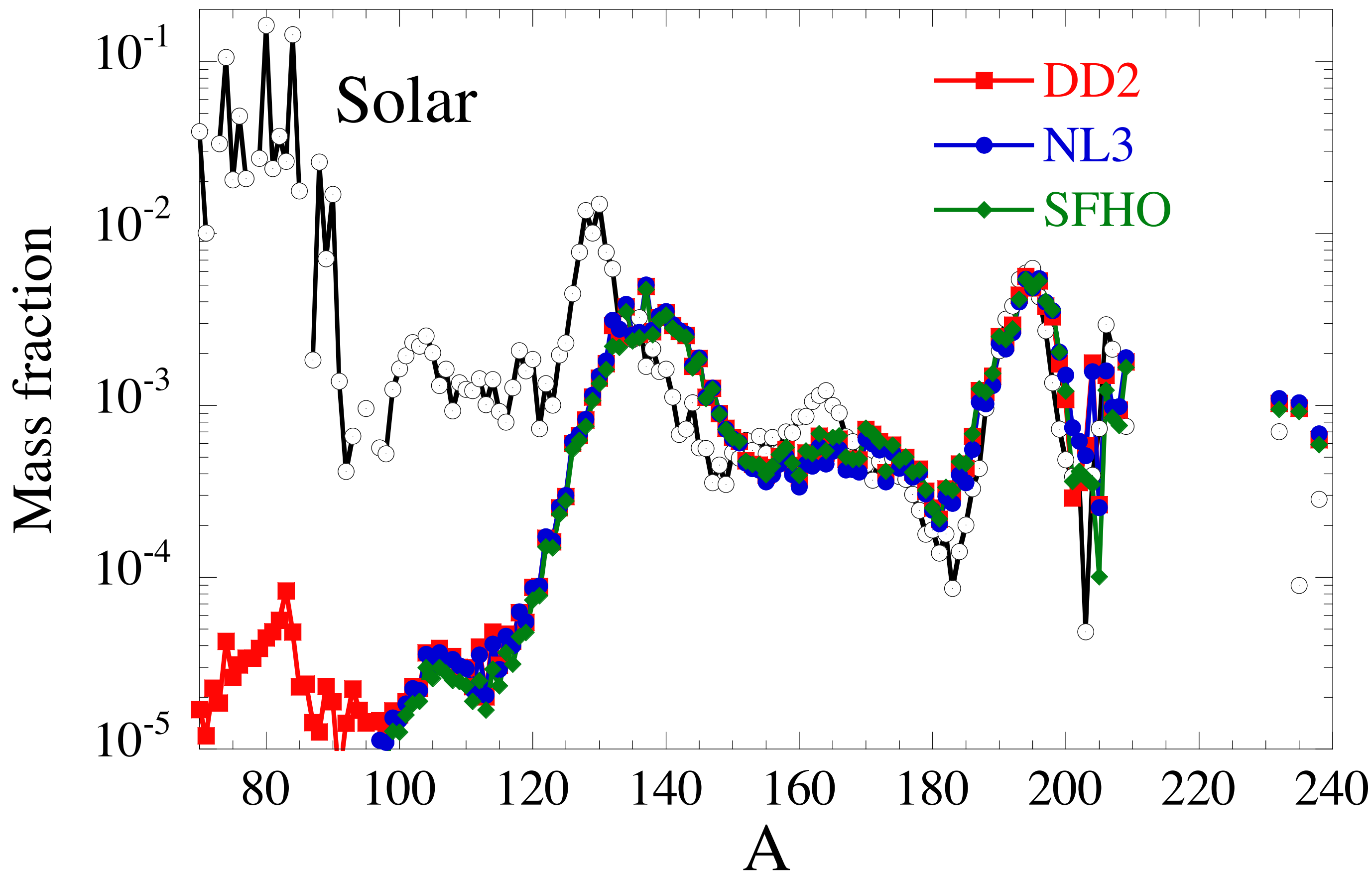
- fast expansion of shocked ejecta with neutron excess

(Ning, Qian, & Meyer 2007; Eichler et al. 2012)
but see Janka et al. 2008

- bubbles driven by convection

seen in low-mass SN models (Wanajo et al. 2011)

decompression of cold neutron star matter



(Goriely, Bauswein, & Janka 2011, 2013)

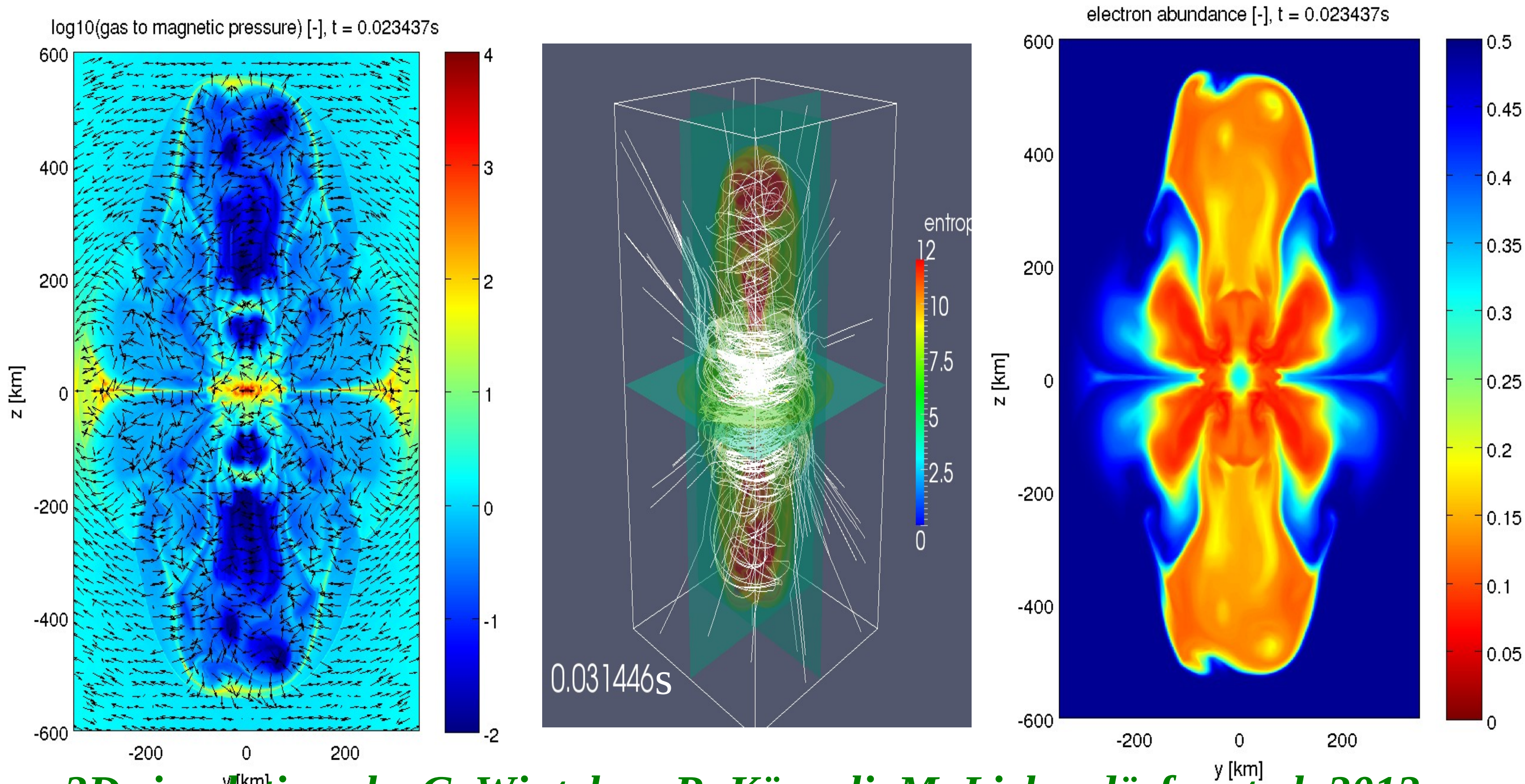
also Lattimer + 1977; Meyer 1989; Freiburghaus+1999; Korobkin + 2012; Mendoza-Temis + 2014; Eichler + 2014

- **jets** driven by rotation, magnetohydrodynamics, etc.

3D Collapse of Fast Rotator with Strong Magnetic Fields:

15 M_{sol} progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of 5 $x10^{12}$ Gauss,

results in 10^{15} Gauss neutron star



3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012
Eichler et al. 2013

(also Symbalisty + 1985; Nishimura + 2006; Fujimoto + 2007)

Generic features of astrophysical sites

Expansion of matter initially at high temperature & density consisting of free nucleons

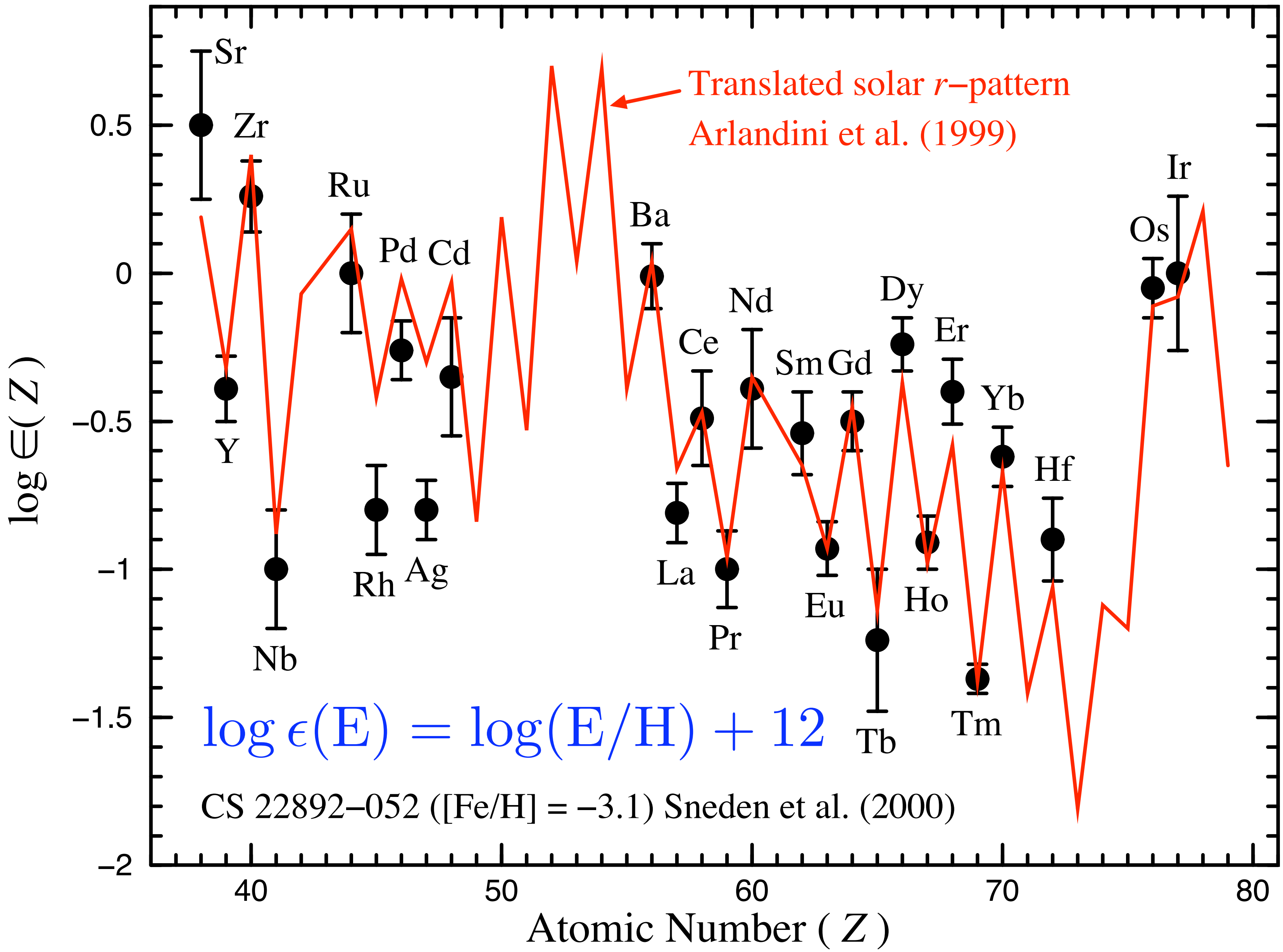
$Y_e, \ \tau_{\rm dyn}, \ S$

Ejection mechanism & effects of neutrinos: smaller for faster expansion

neutrino heating, convection, magnetohydrodynamics

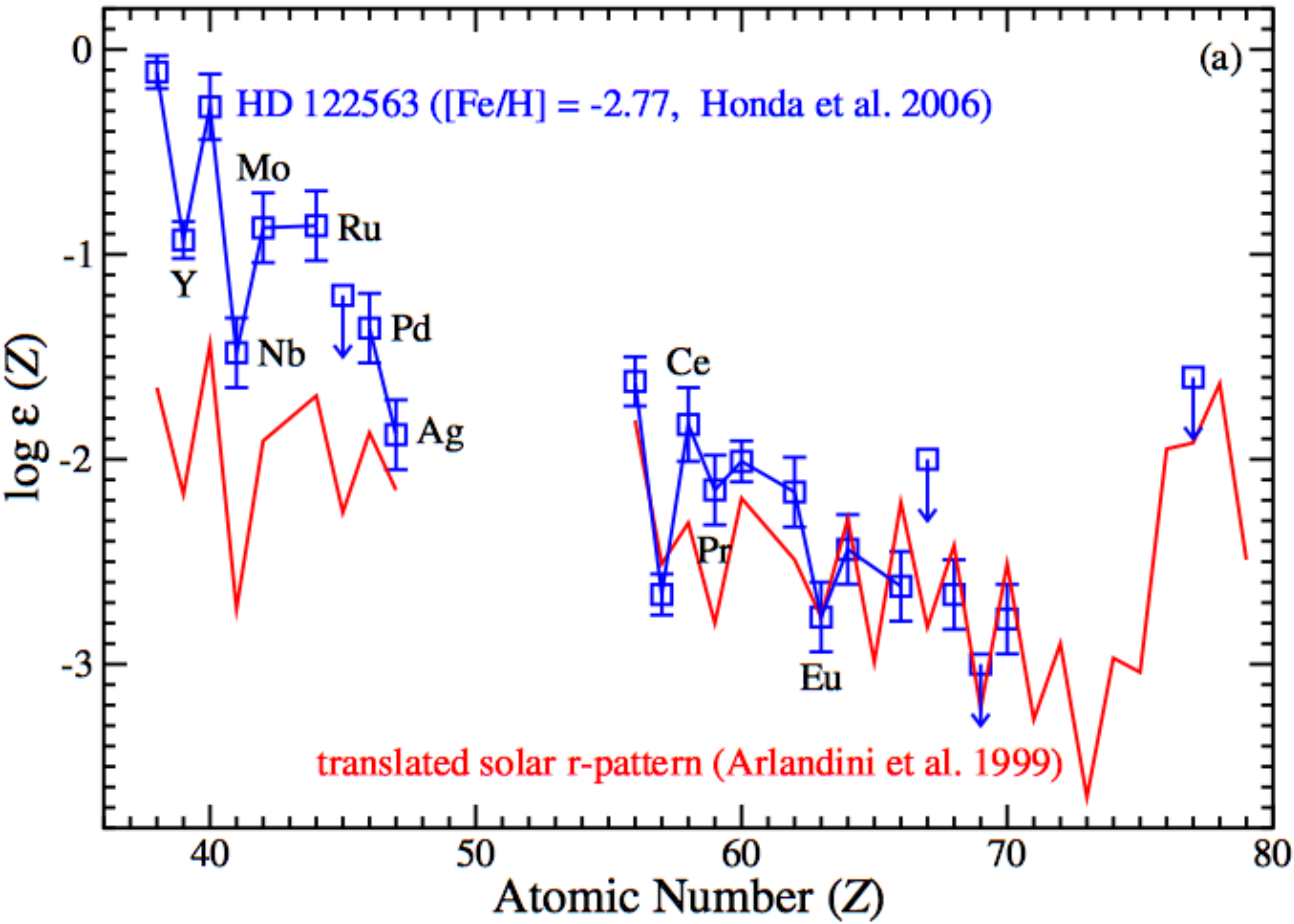
Fast ejection of extremely n-rich matter (Ye < 0.2): robust r-process producing A~195 & actinides

binary interaction during NS merger, MHD jet from NS



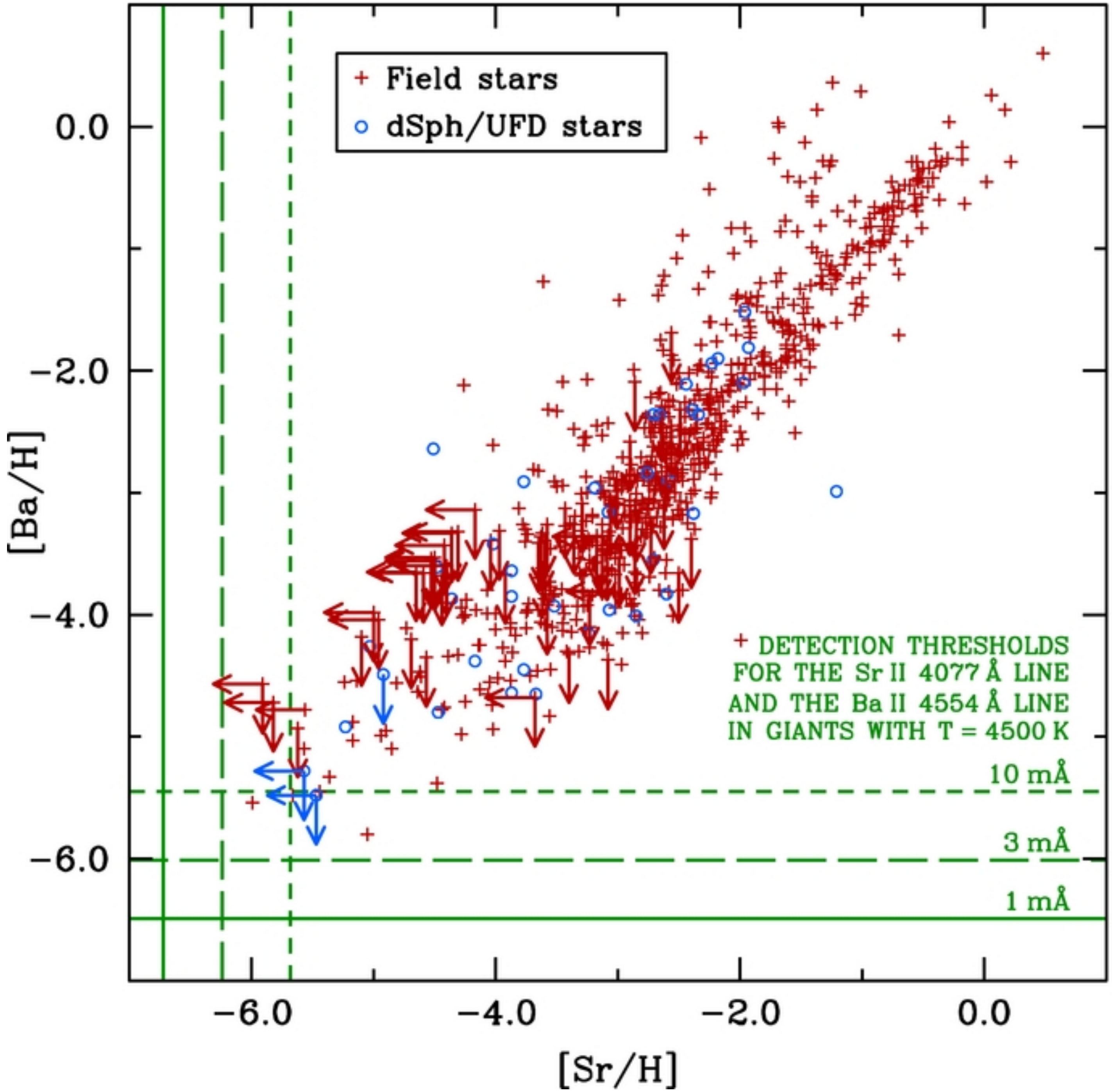
metal-poor star update:
Roederer +, Frebel +, Hansen +

meteoritic hints:
Wasserburg + 1996
Qian + 1998

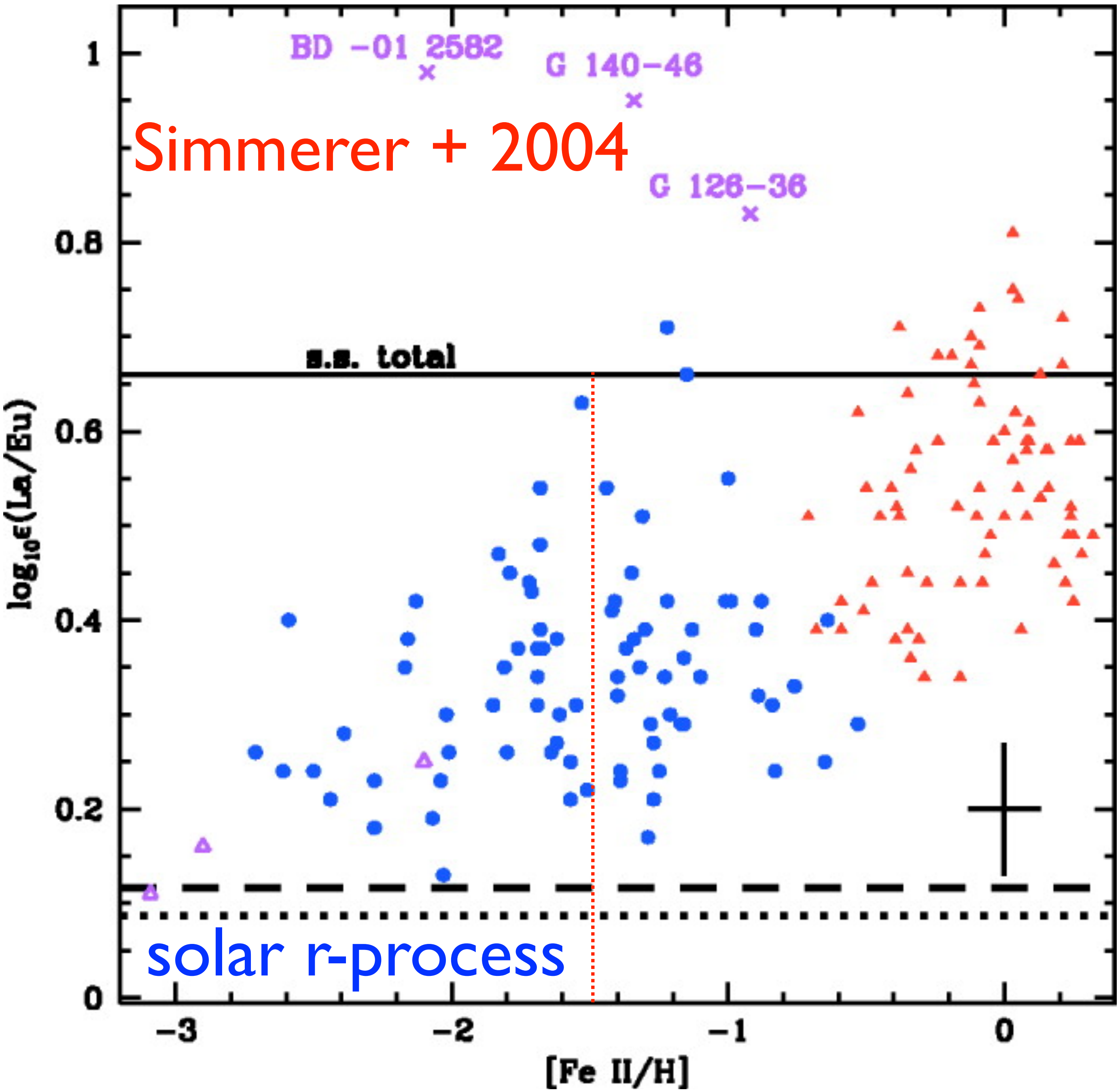


(a)
HD 122563 ([Fe/H] = -2.77, Honda et al. 2006)
Mo
Y
Ru
Nb
Pd
Ag
Ce
Pr
Eu
translated solar r-pattern (Arlandini et al. 1999)
log ε (Z)
Atomic Number (Z)
0
-1
-2
-3
40
50
60
70
80

Ubiquity of Sr and Ba (Roederer 2013)



Diversity of La/Eu: more than one n-capture process



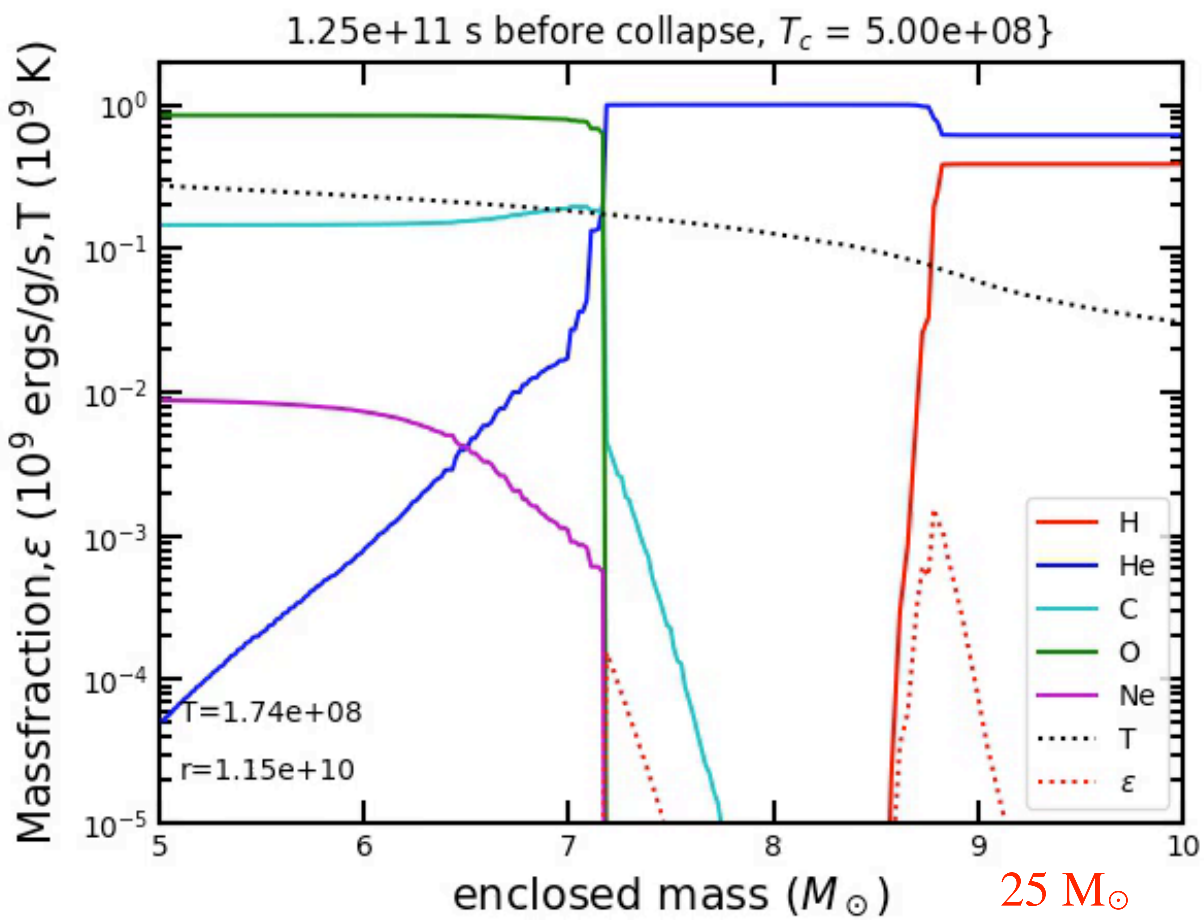
New Neutron-Capture Site in Massive Pop III and Pop II Stars as a Source for Heavy Elements in the Early Galaxy

Banerjee, Qian, & Heger, arXiv:1711.05964

Studies of similar process in other stellar environments:

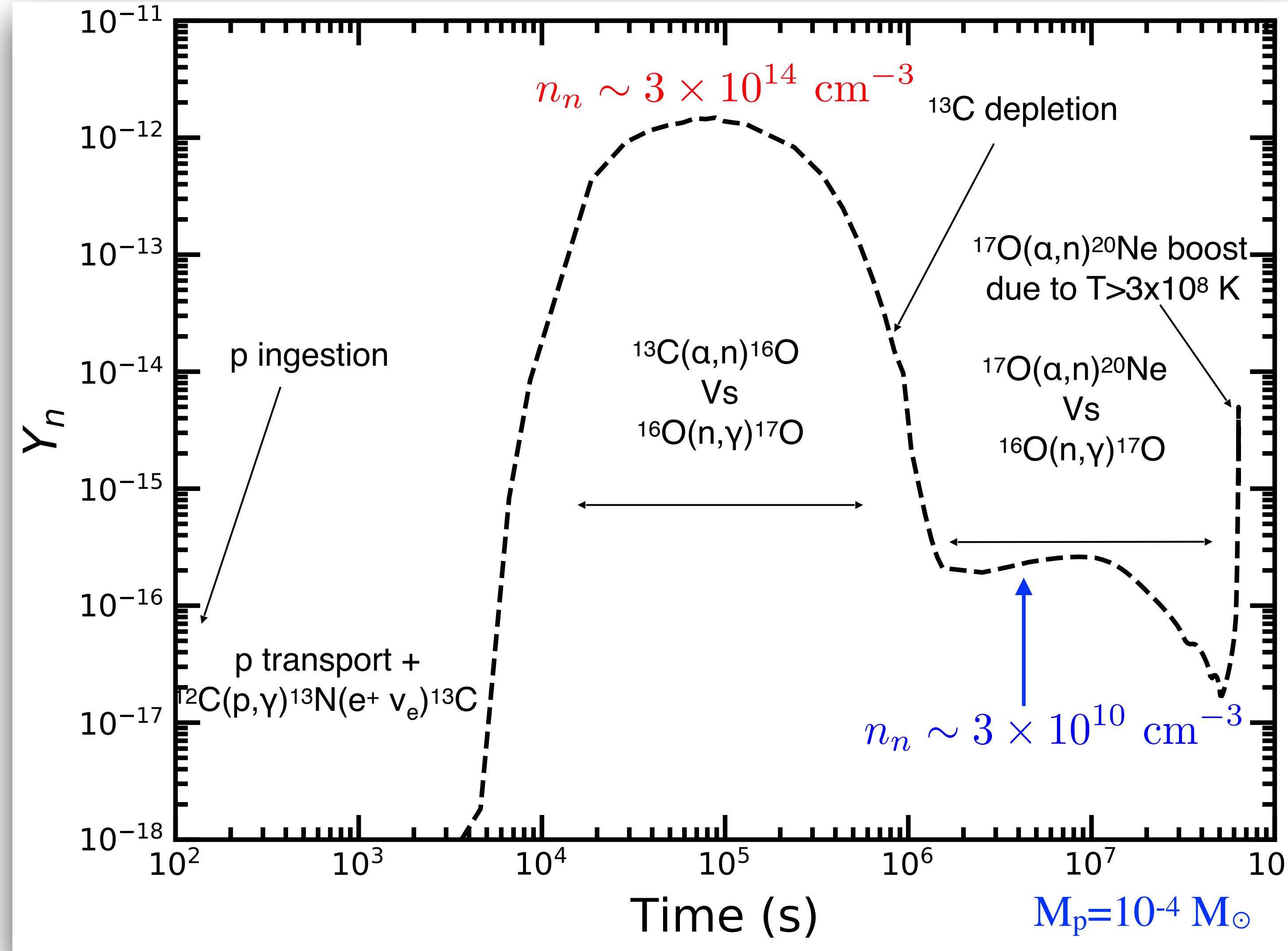
e.g., Campbell + 2010, Dardelet + 2014, Jones + 2016

Proton Ingestion



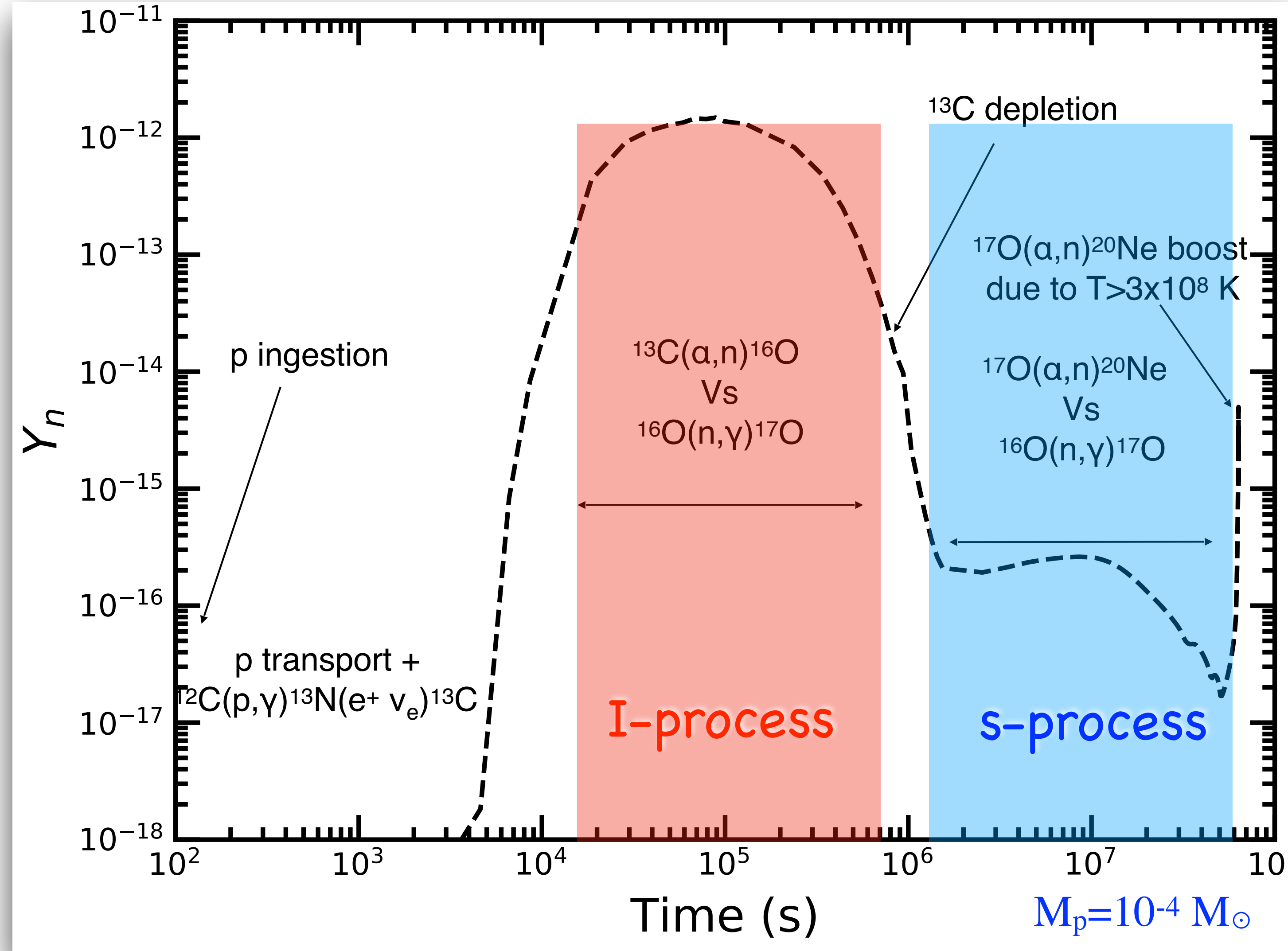
Growth of convective He shell.
Mixing can occur at the convective boundary.
Including overshoot leads to 10^{-3}–10^{-5} $M_\odot$ of proton ingestion.
Occurs for 20 $M_\odot \lesssim M \lesssim 30\ M_\odot$.

Free Neutrons from Protons



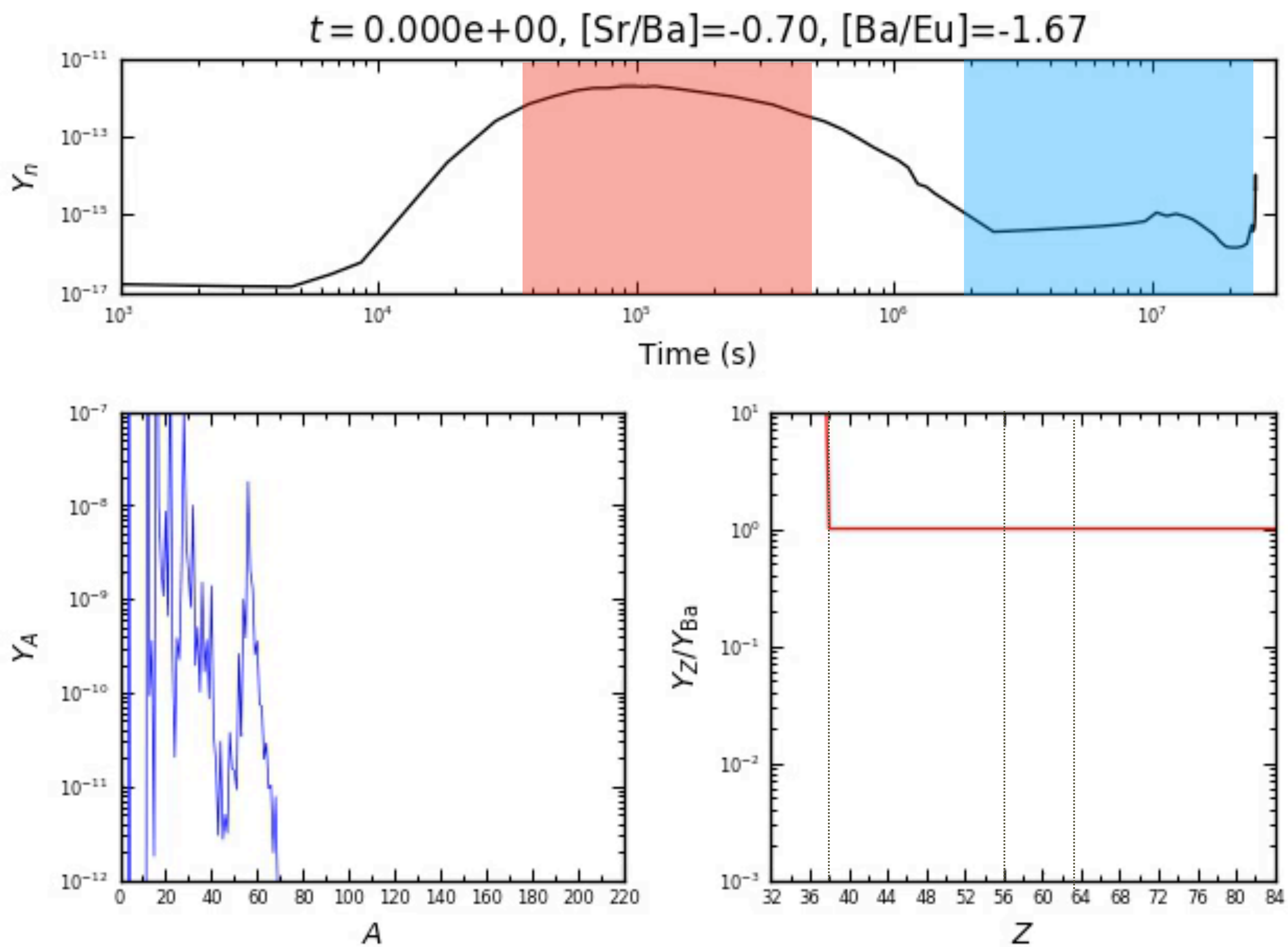
- Mixing timescale ~ 5×10^3 s.
- Initially Y_n increases on a timescale of ~ 10^4 s.
- Then Y_n decreases on a timescale of ~10^5 s.
- Most of the neutrons captured by ^{16}O.
- Primary neutron production

Free Neutrons from Protons



- Mixing timescale ~ $5x10^3$ s.
- Initially Y_n increases on a timescale of ~ 10^4 s.
- Then Y_n decreases on a timescale of ~10^5 s.
- Most of the neutrons captured by ^{16}O.
- Primary neutron production

Neutron Capture



$M_p = 10^{-4}\ M_\odot$

$25\ M_\odot$, $[Z]=-3$

- Most of the neutron capture occurs in the first ~10^6 s.
- Can result in both i-process and s-process.
- Final [Ba/Eu] depends on time available Δ for neutron capture.
- [Ba/Eu] can vary from ~0.25 to 1 with [Ba/Eu]<0.6 (>0.6) for $\Delta < 10^6$ s ($>10^6$ s)

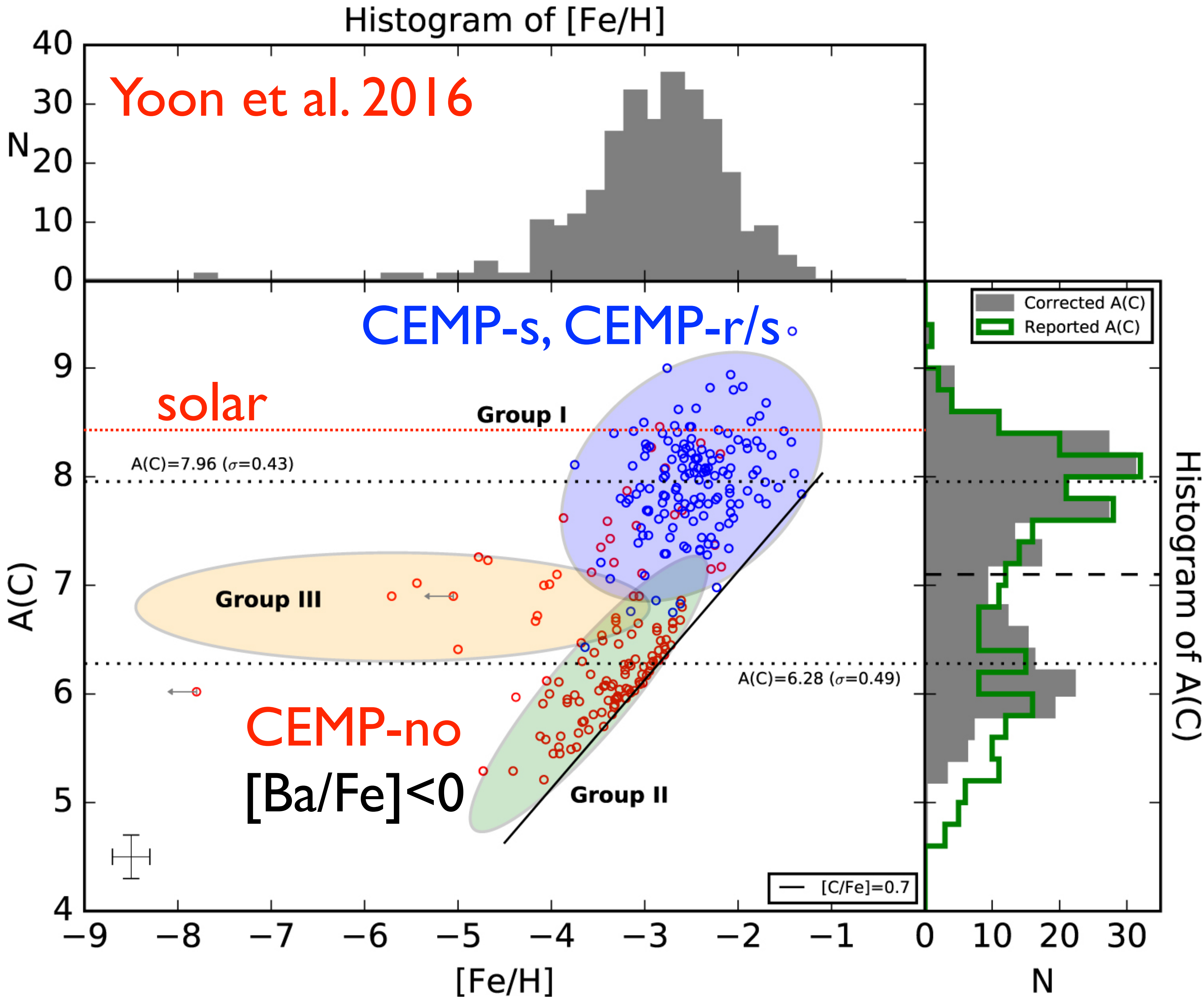
Key Parameters for n Capture from p Mixing

Amount of proton ingestion: neutron density

Time of proton ingestion: duration of neutron capture

Initial metallicity: seeds, absolute yields

Explosion energy: dilution mass



Histogram of [Fe/H]
Yoon et al. 2016
N
CEMP-s, CEMP-r/s
solar
Group I
A(C)=7.96 (σ=0.43)
Group III
A(C)=6.28 (σ=0.49)
CEMP-no
[Ba/Fe]<0
Group II
[C/Fe]=0.7
Corrected A(C)
Reported A(C)
Histogram of A(C)
A(C)
[Fe/H]
N

Binary of low & intermediate mass stars
formed at low metallicities

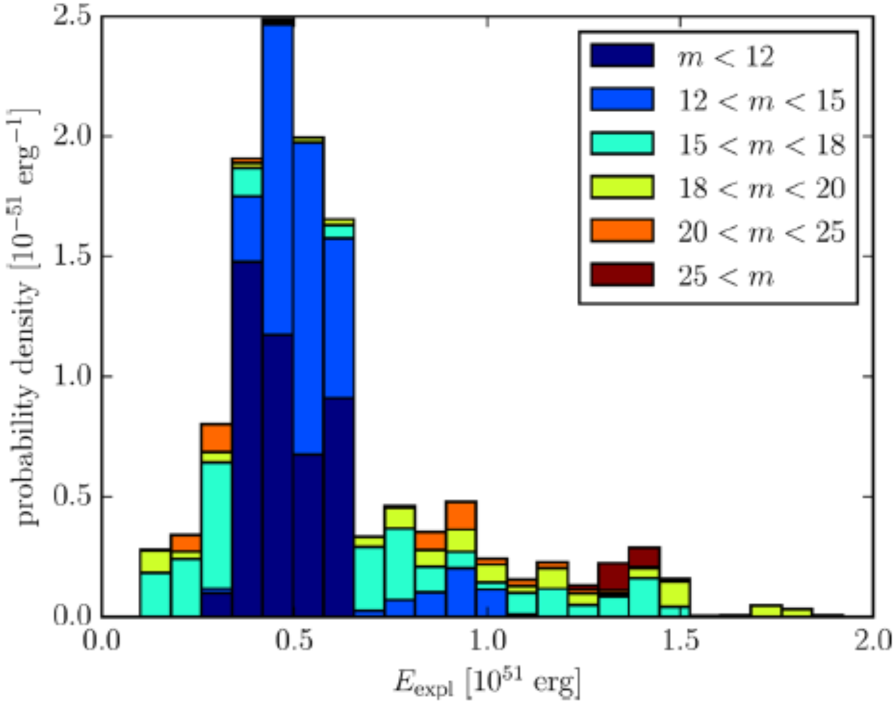
↓

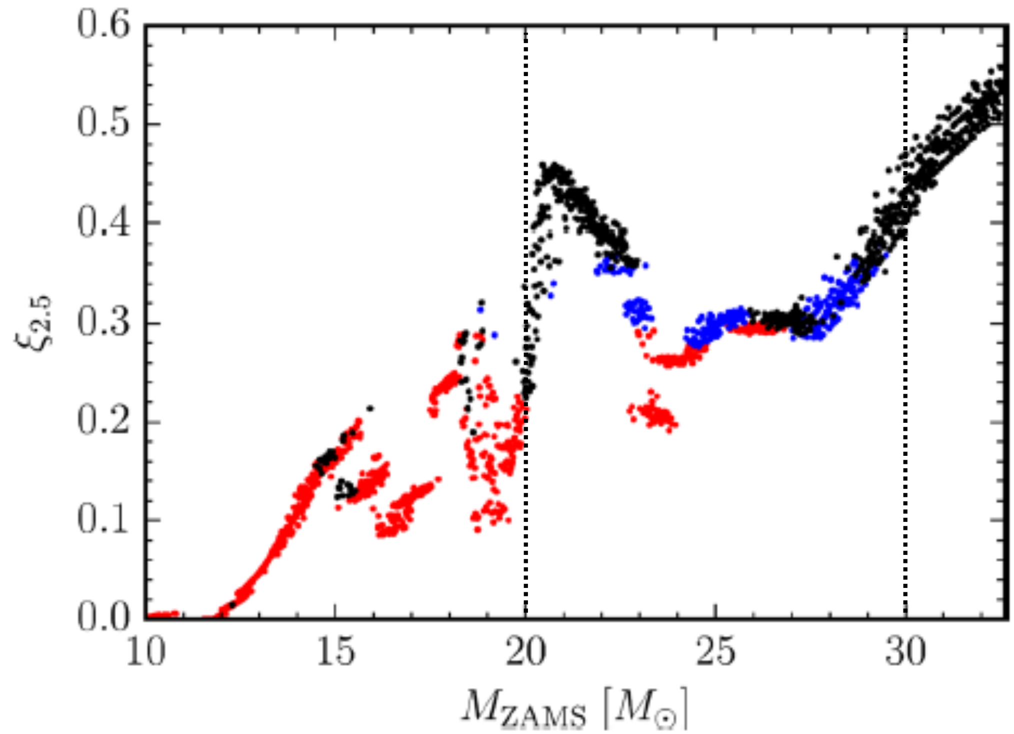
More massive member evolved through
AGB phase & dumped newly-synthesized
s-process products (along with C)
onto the companion

↓

Less massive member observed as C-Enhanced
Metal-Poor star with strong s-enrichment (CEMP-s)
in a binary (radial velocity variation)

C/Fe & Explodability of Core-Collapse Supernovae

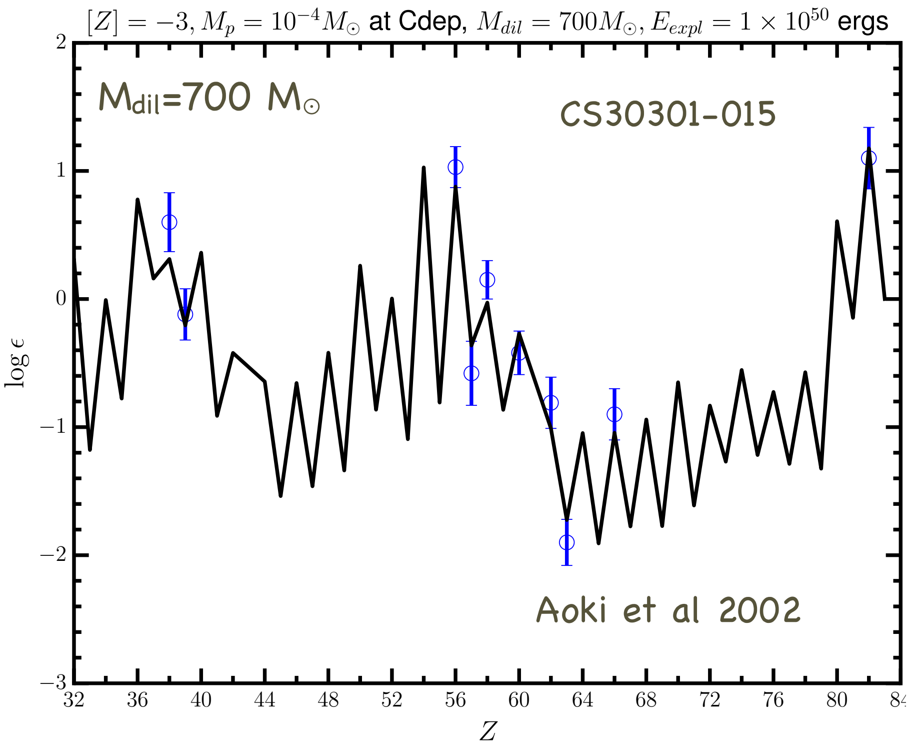




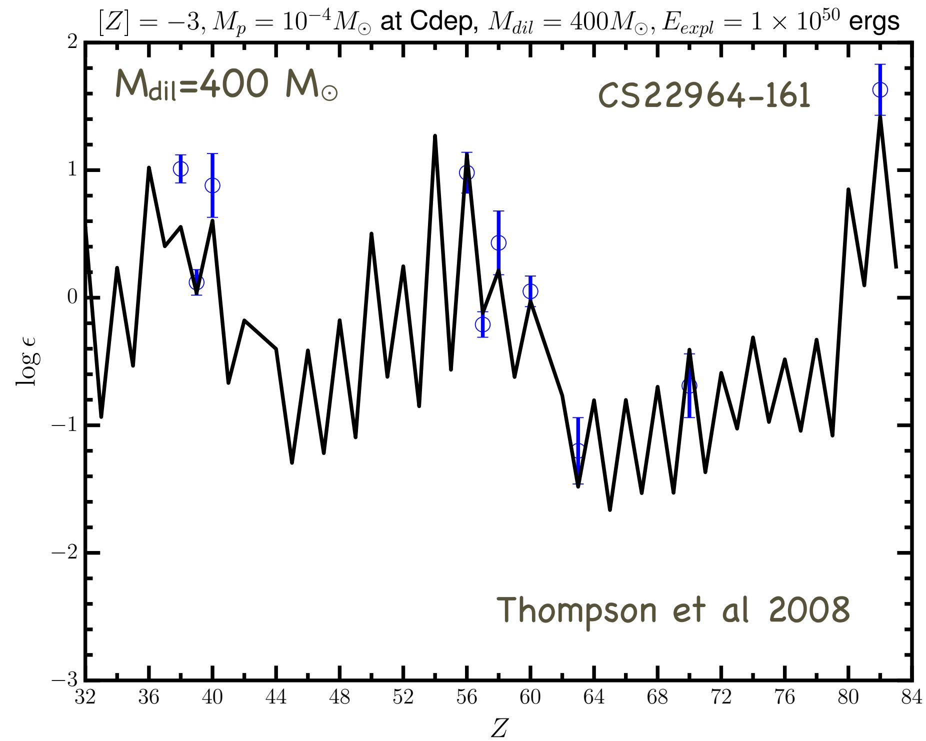
Muller et al 2016

Diversity: Comparison with Observations

Banerjee, Qian, & Heger, arXiv:1711.05964



Single CEMP-s star



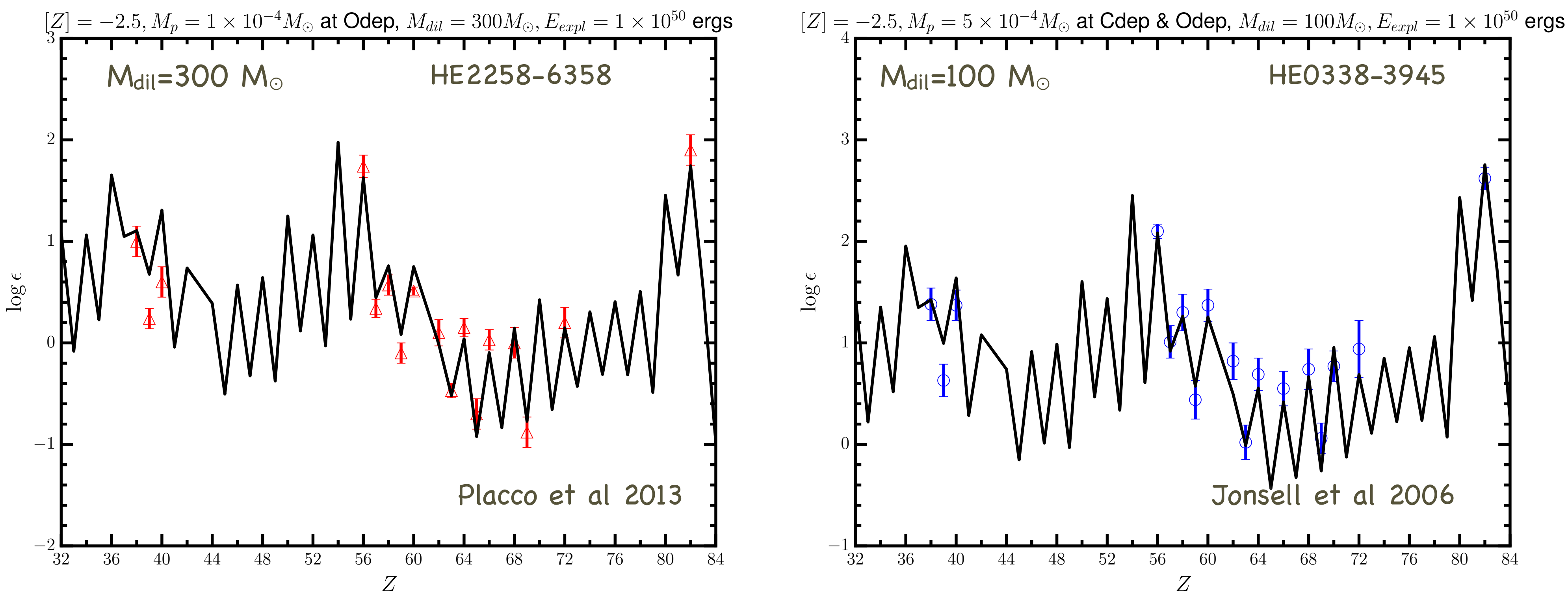
Binary system of CEMP-s star
No sign of third component

Proton ingestion $\gtrsim 10^6$ s before collapse

Low Dilution of $\lesssim 1000\ M_\odot$

Diversity: Comparison with Observations

Banerjee, Qian, & Heger, arXiv:1711.05964



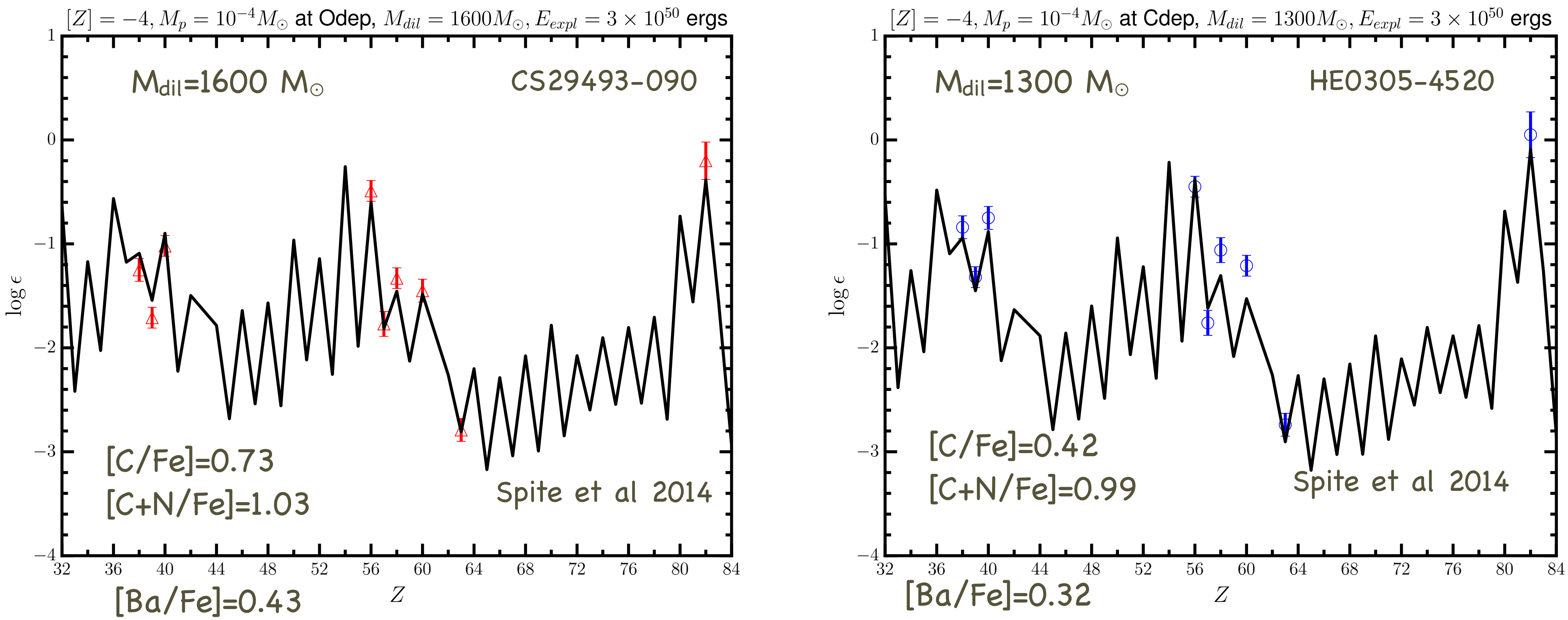
CEMP-r/s star

Proton ingestion $\lesssim 10^6$ s before collapse

Low Dilution of $\lesssim$ 1000 $M_\odot$

Diversity: Comparison with Observations

Banerjee, Qian, & Heger, arXiv:1711.05964



Low-s, r/s CEMP star, 0<[Ba/Fe]<1

No clear variation of radial velocity

Higher Dilution of $\gtrsim 1000\ M_\odot$

Natural consequence for this site

s-Process in Massive Carbon-Enhanced Metal-Poor Stars

Banerjee, Qian, & Heger, arXiv:1805.04306

Core H burning: initial CNO converted into ^{14}N

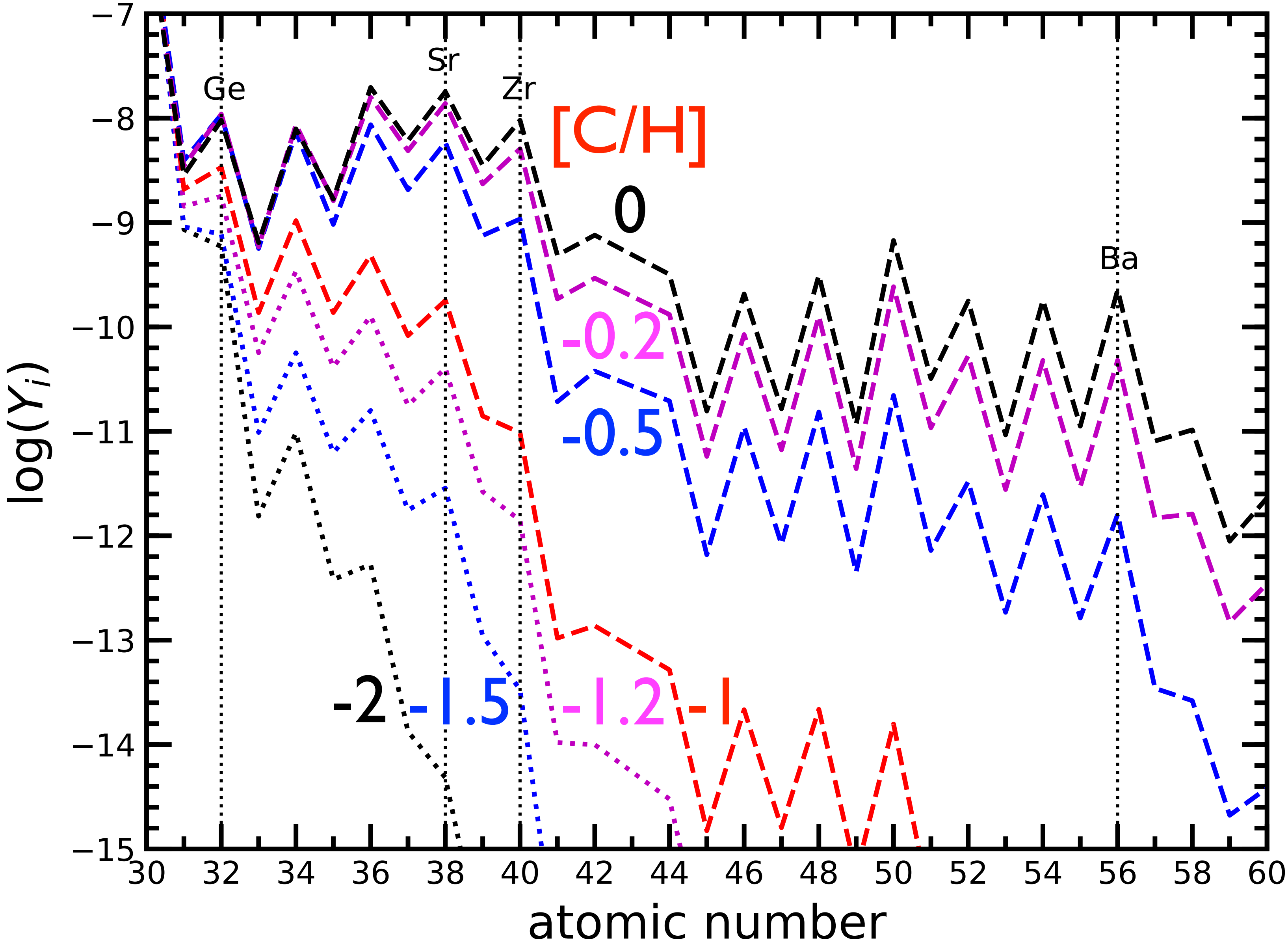
Core He burning: $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(e^+\nu_e)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$

Core He burning & subsequent evolution: $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$

Similar process in fast-rotating massive metal-poor stars:
e.g., Pignatari + 2008; Frischknecht + 2012, 2016

Banerjee, Qian, & Heger, arXiv:1805.04306

25M$_{sun}$, [Fe/H] = -3



Key Parameters for s-Process in Massive CEMP Stars

Initial C abundance : neutron production

Stellar mass: neutron production

Initial metallicity: seeds, absolute yields

Explosion energy: ejection & dilution mass

Summary

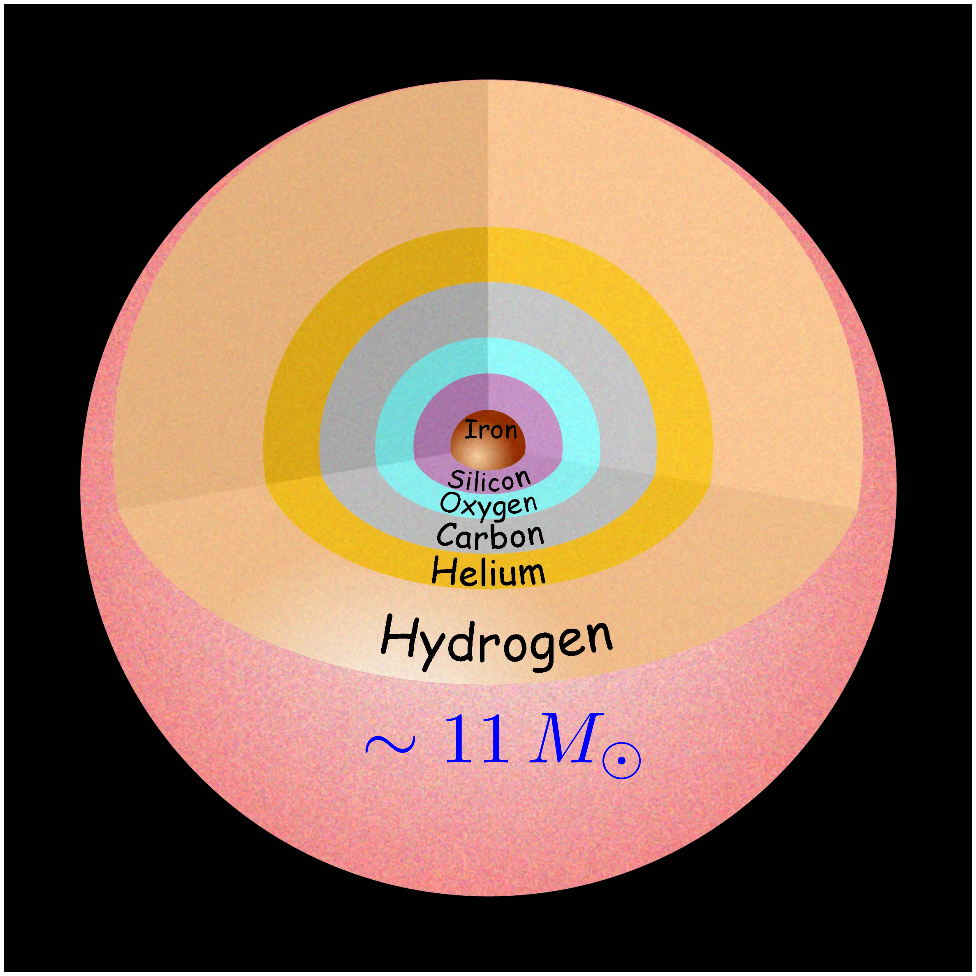
1. Ubiquity of Sr & Ba at low [Fe/H]
unlikely explained by NS-NS or NS-BH mergers
due to their rare occurrences

2. Diversity of La/Eu at low metallicities
requires more than one n-capture process

3. Most of CEMP-no & some CEMP-s stars are single
(Hansen et al. 2016a,b)
massive stellar sources likely required

4. n capture from p mixing during pre-supernova evolution
and the s-process in massive CEMP stars
can explain ubiquity of Sr & Ba + diversity of La/Eu at low [Fe/H]
the former also can explain CEMP-no,s,r/s stars
(Banerjee, Qian, & Heger, arXiv:1711.05964,1805.04306)

Neutrino-Induced r-Process 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

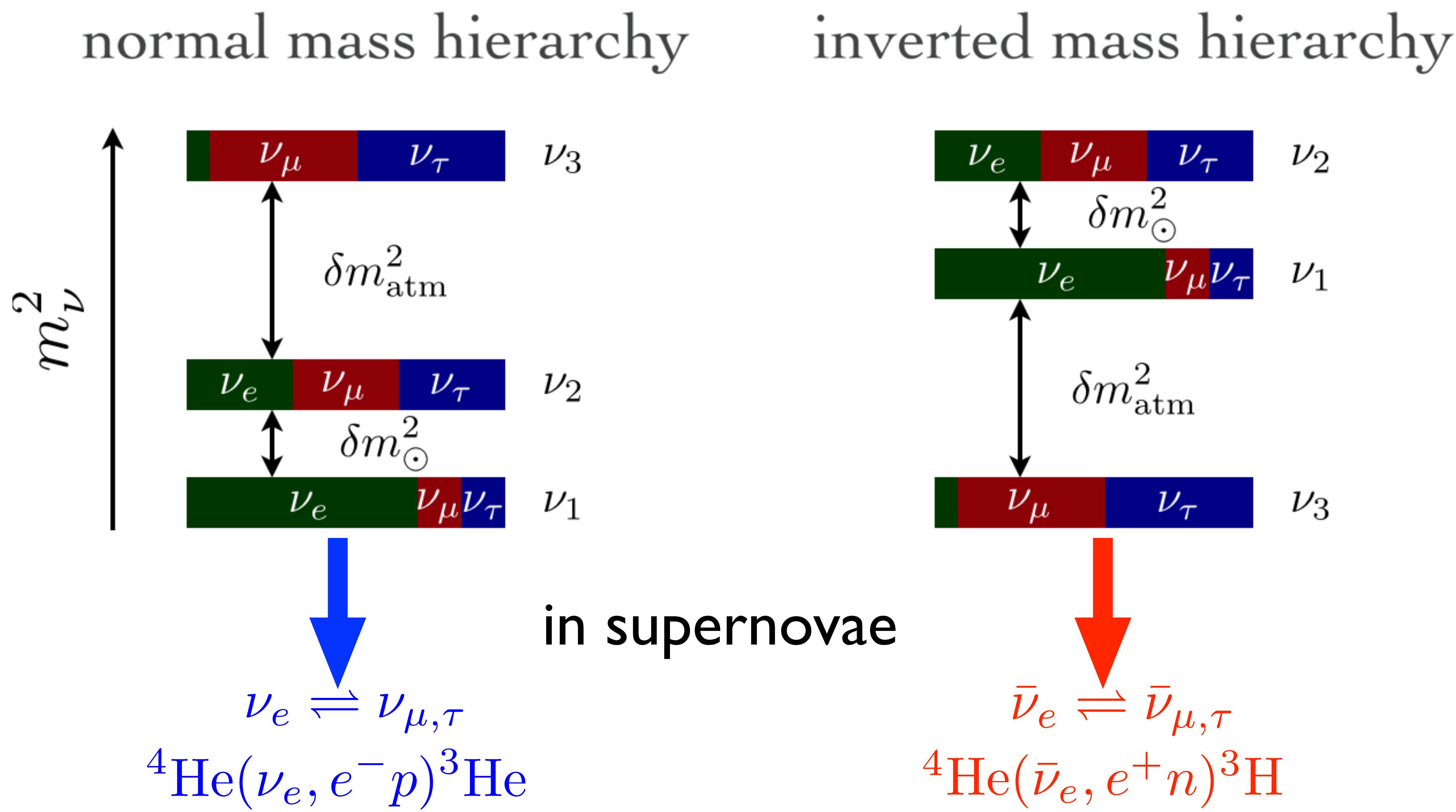
→ early SNe

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

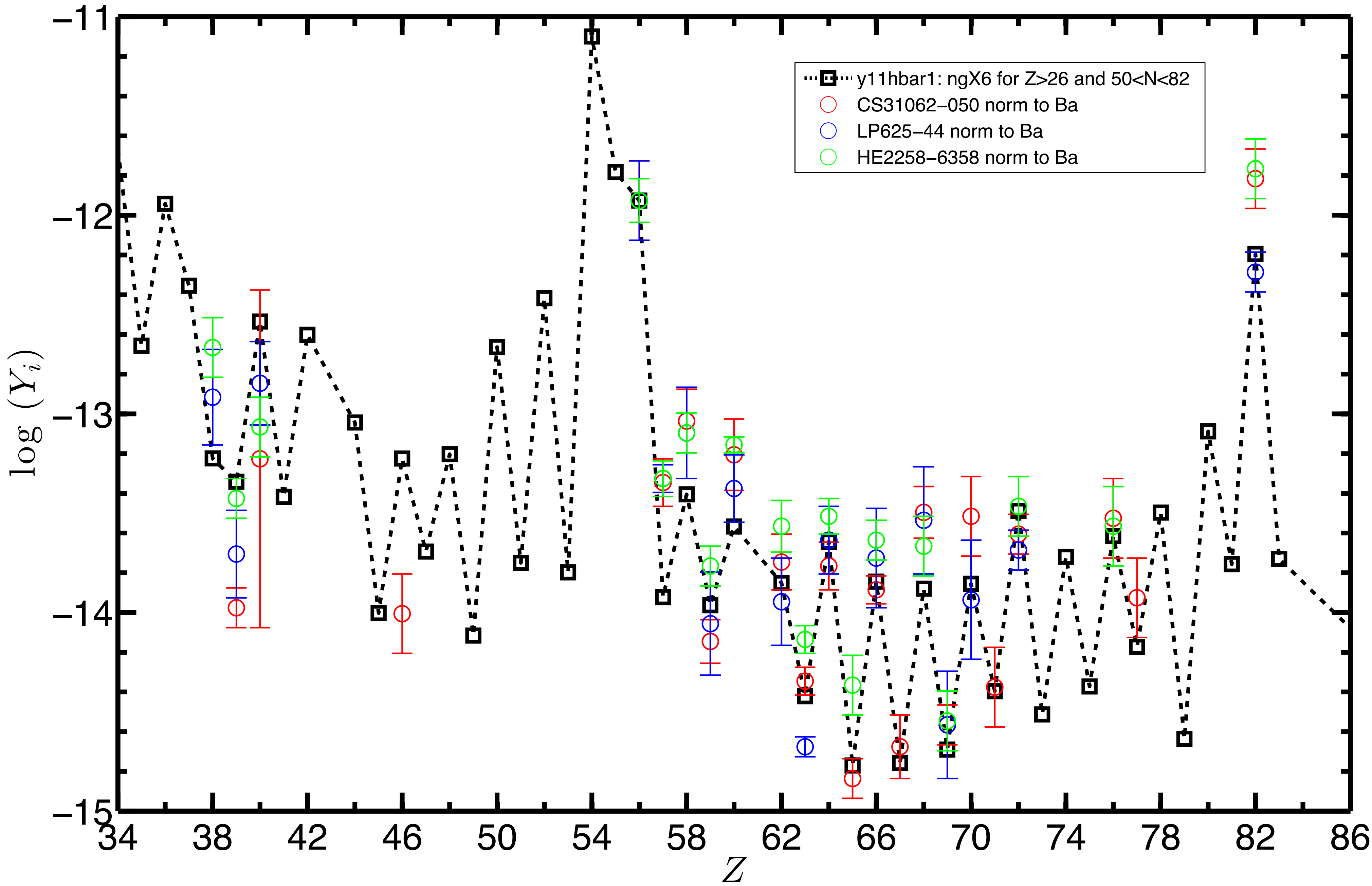
Banerjee, Haxton, & Qian 2011

Neutrino Spectra & Flavor Oscillations

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



Banerjee, Qian, Heger, & Haxton 201



How to Become a Star

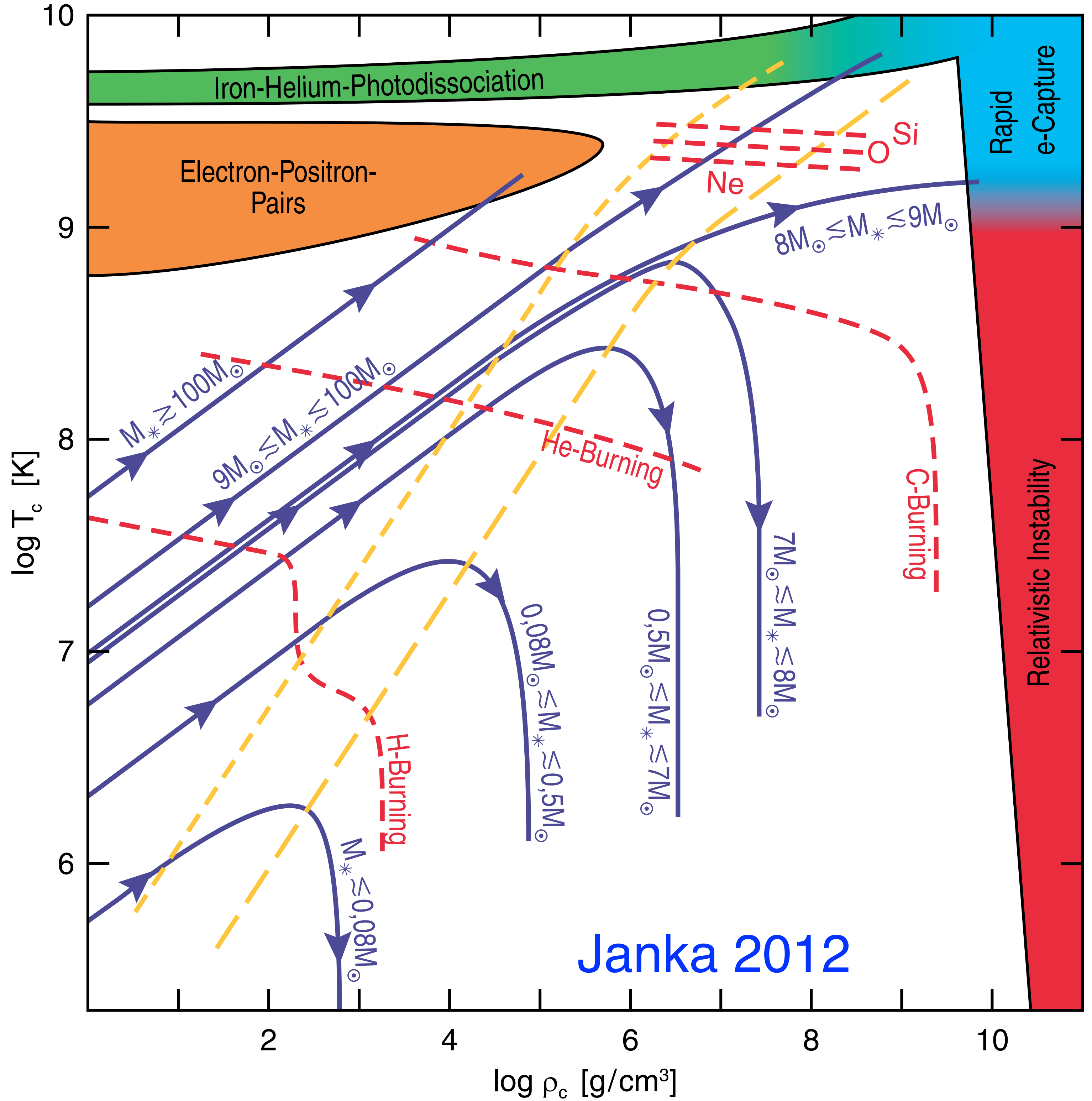
Virial theorem for a contracting gas cloud

$$T_c + \frac{\hbar^2}{2m_e d^2} \sim \frac{GMm_p}{R}$$

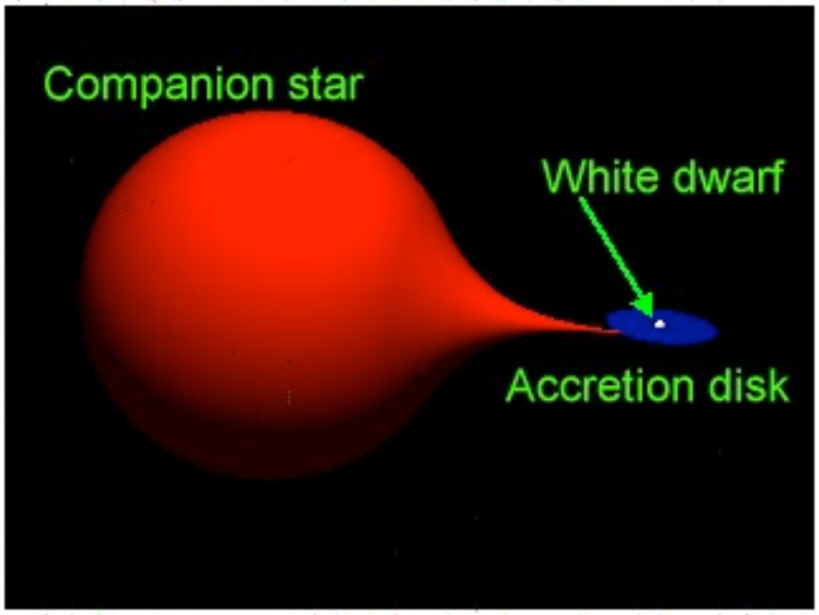
$$\left(\frac{M}{m_p}\right) d^3 \sim R^3 \Rightarrow$$

$$T_c \sim \frac{GMm_p}{R} - \frac{\hbar^2}{2m_e}\left(\frac{M}{m_p}\right)^{2/3}\frac{1}{R^2}$$

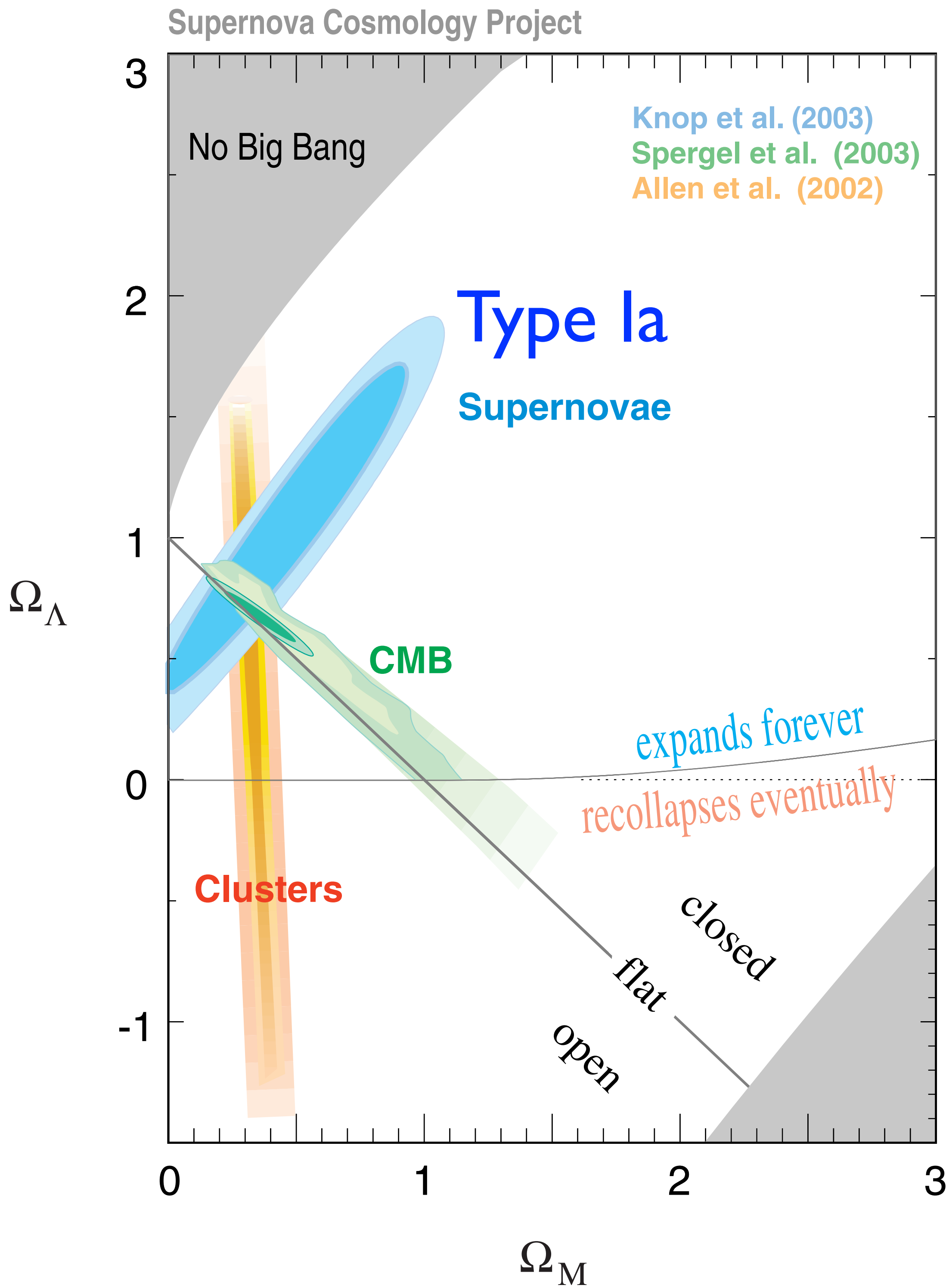
$$\Rightarrow T_{c,\mathrm{max}} \propto M^{4/3}$$



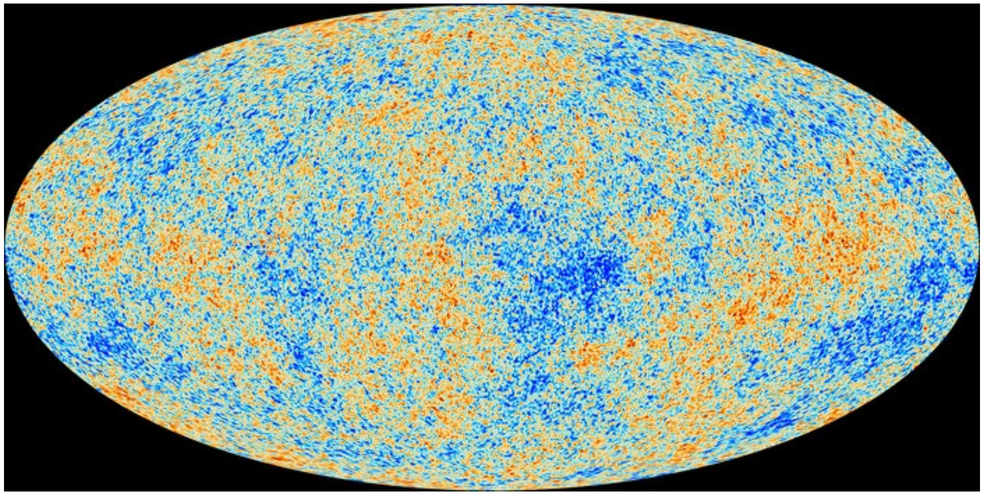
Iron-Helium-Photodissociation
Electron-Positron-
Pairs
Rapid
e-Capture
Relativistic Instability
Si
O
Ne
He-Burning
C-Burning
H-Burning
M* ≳ 100M⊙
9M⊙ ≲ M* ≲ 100M⊙
8M⊙ ≲ M* ≲ 9M⊙
7M⊙ ≤ M* ≤ 8M⊙
0,5M⊙ ≤ M* ≤ 7M⊙
0,08M⊙ ≤ M* ≤ 0,5M⊙
M* ≤ 0,08M⊙
log Tc [K]
log ρc [g/cm³]
10
9
8
7
6
2
4
6
8
10
Janka 2012

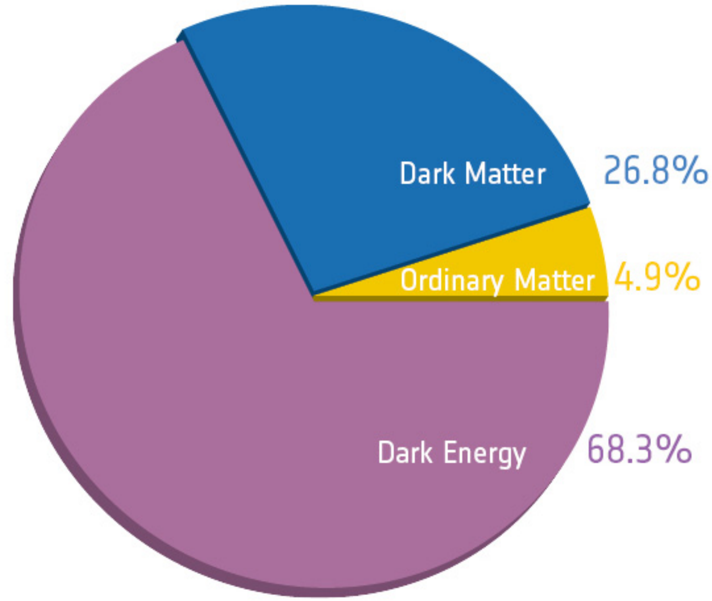


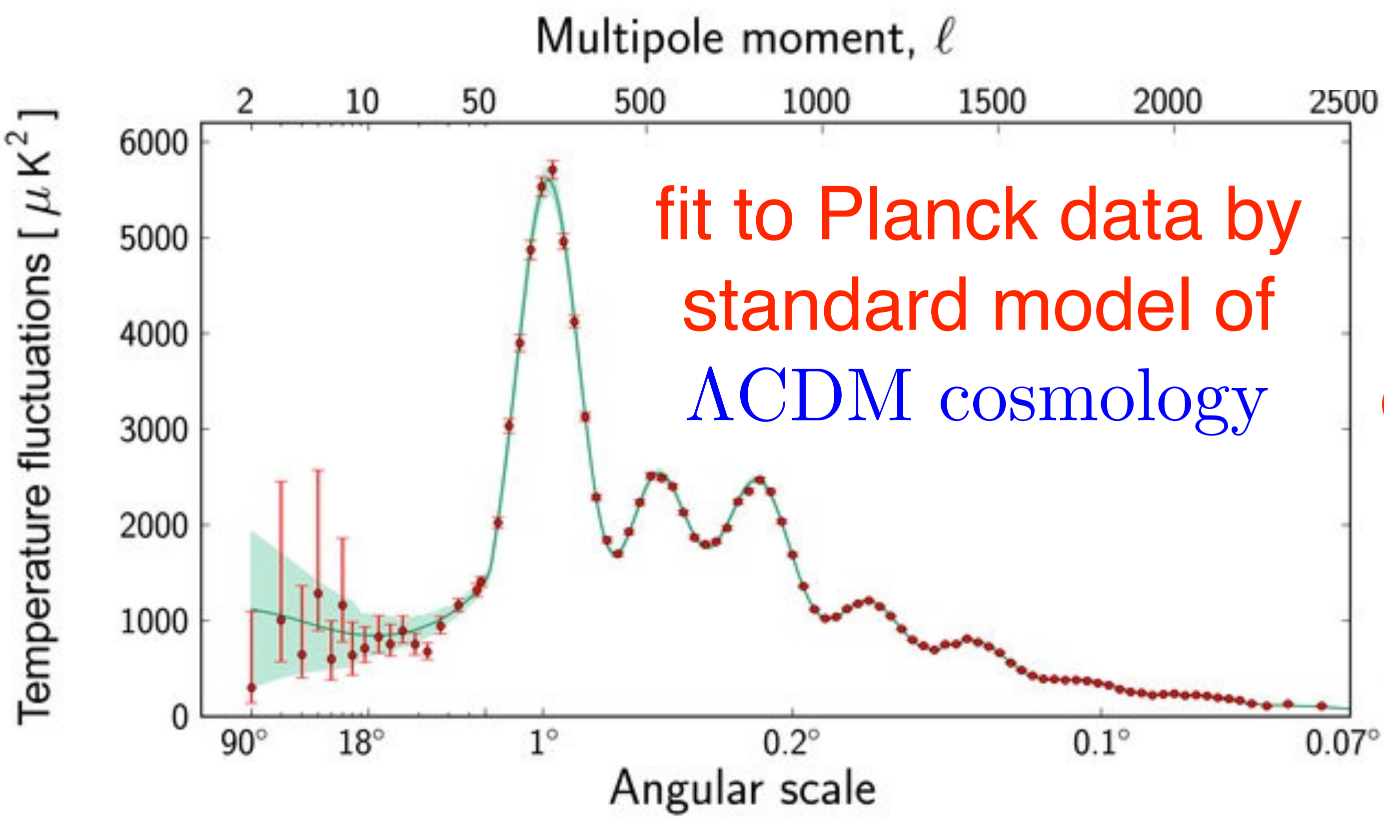
Nobel Prize 2011



Cosmic Microwave Background Experiments



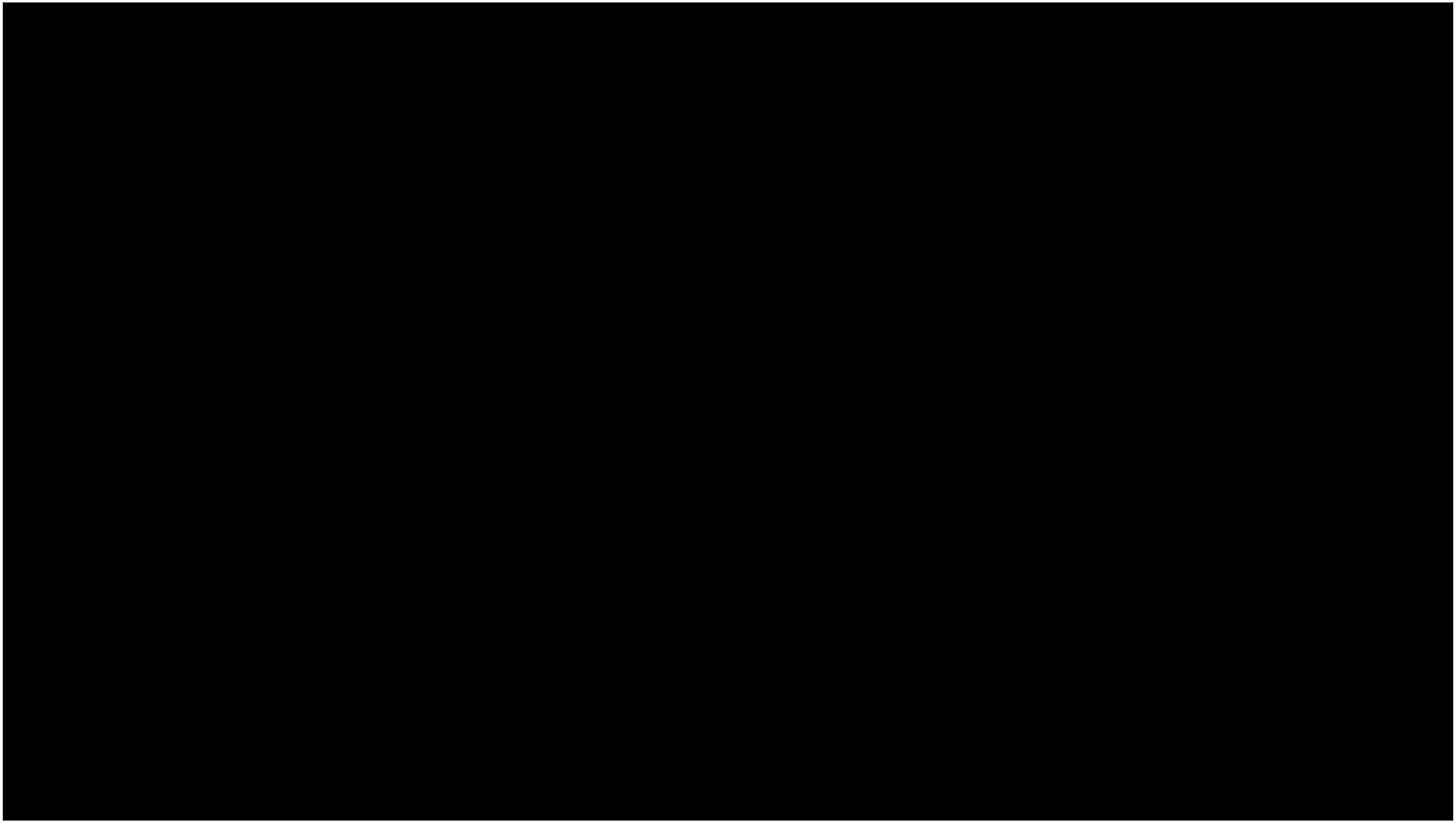




6 basic parameters

energy densities,
density fluctuations,
& probability of
scattering by
electrons

Galaxy and Star Formation



Life Cycle of Interstellar Medium