Stellar Sources and Chemical Evolution of the Early Universe

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INT Program on Astrophysical Neutrinos and the Origin of the Elements
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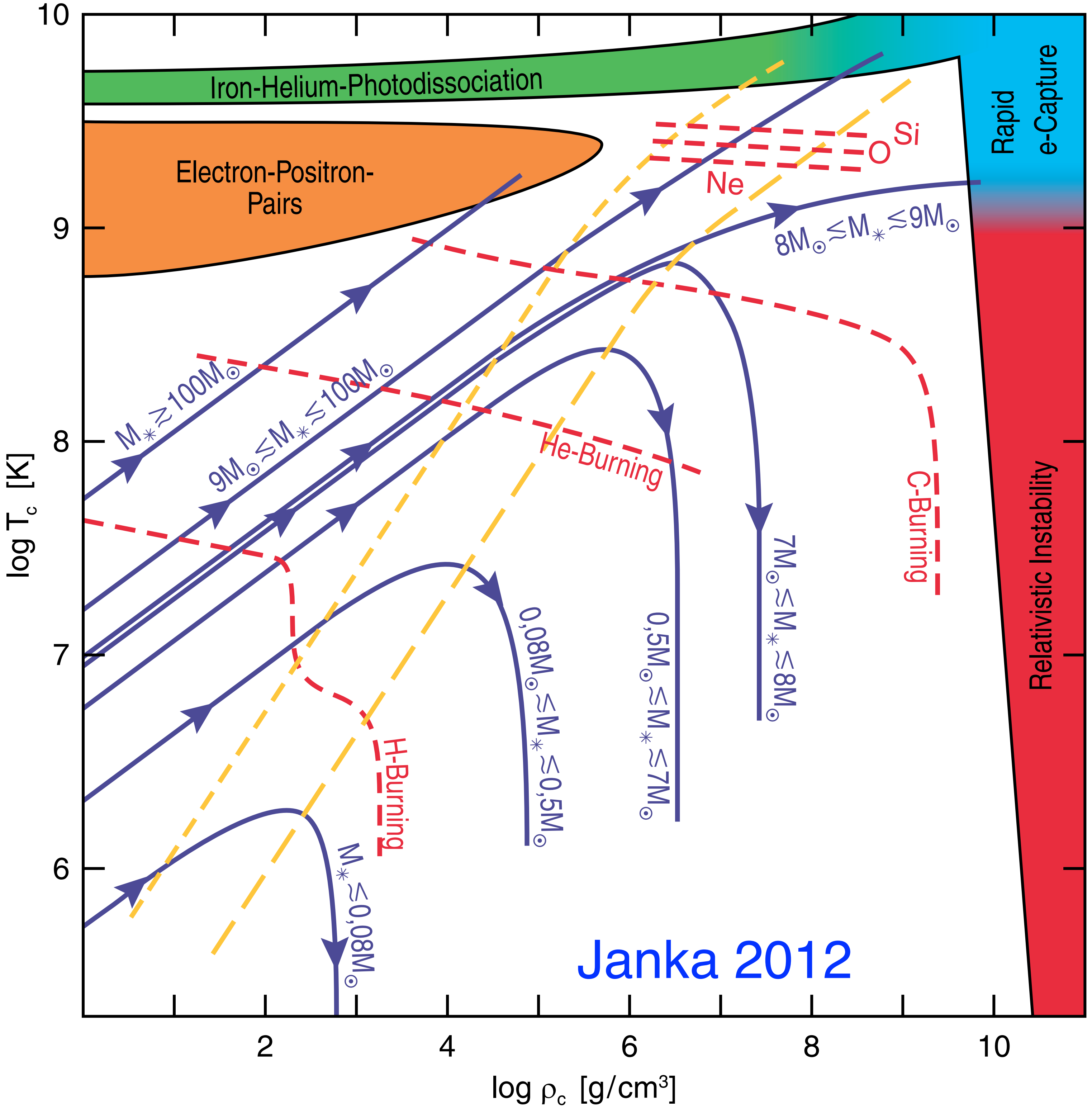
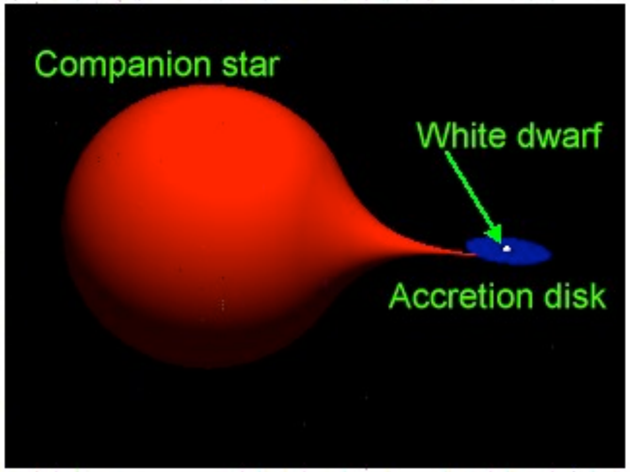
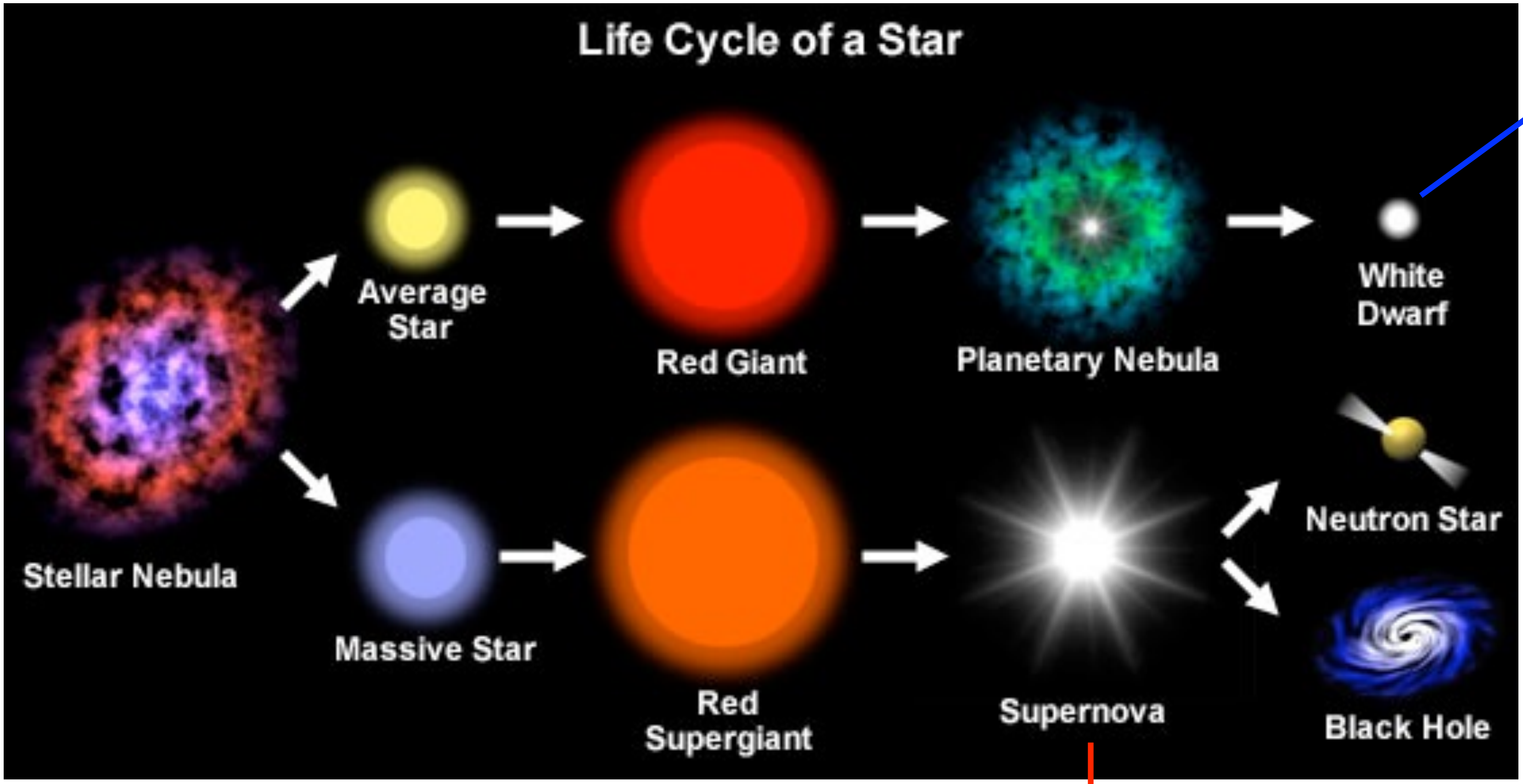
N3AS
Network for Neutrinos,
Nuclear Astrophysics,
and Symmetries
PHYSICS FRONTIER CENTER

NSF


Iron-Helium-Photodissociation
Electron-Positron-Pairs
Rapid e-Capture
Relativistic Instability
Si
O
Ne
He-Burning
C-Burning
H-Burning
$M_* \gtrsim 100 M_\odot$
$9M_\odot \lesssim M_* \lesssim 100 M_\odot$
$8M_\odot \lesssim M_* \lesssim 9 M_\odot$
$7M_\odot \lesssim M_* \lesssim 8 M_\odot$
$0{,}5M_\odot \lesssim M_* \lesssim 7 M_\odot$
$0{,}08M_\odot \lesssim M_* \lesssim 0{,}5 M_\odot$
$M_* \lesssim 0{,}08 M_\odot$
Janka 2012
10
9
8
7
6
log T_c [K]
2
4
6
8
10
log ρ_c [g/cm^3]

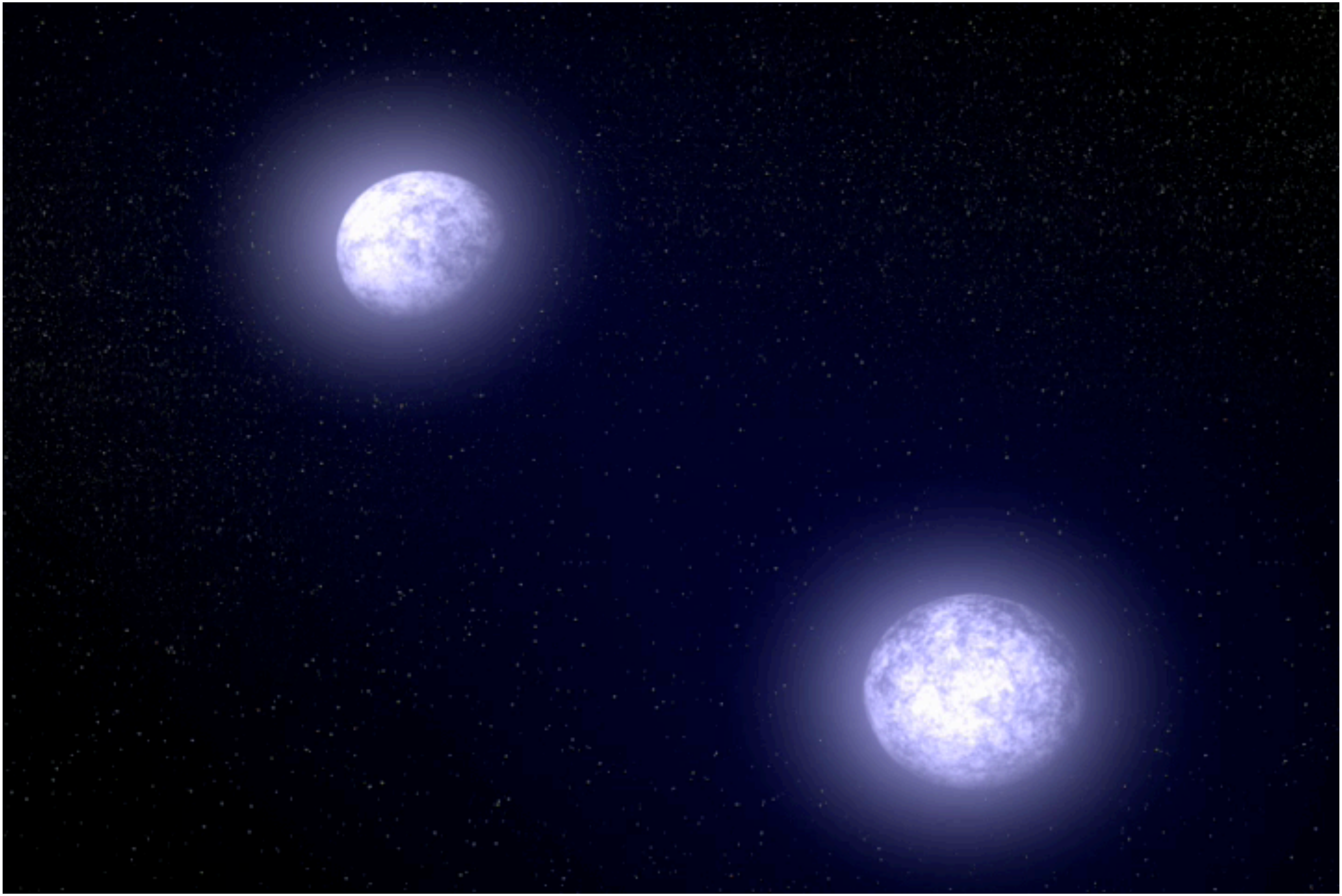


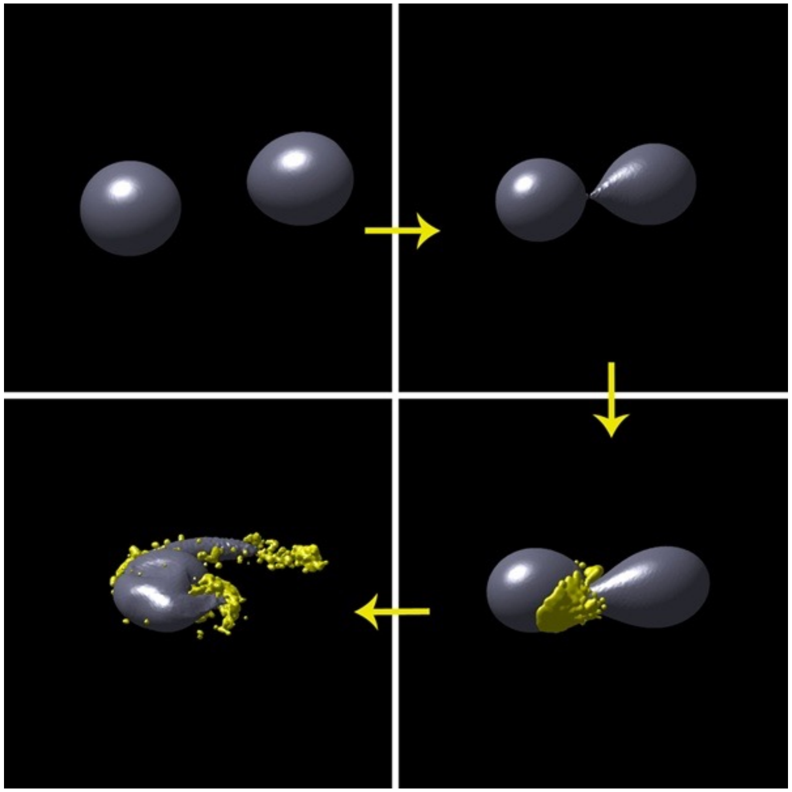
Type Ia SNe

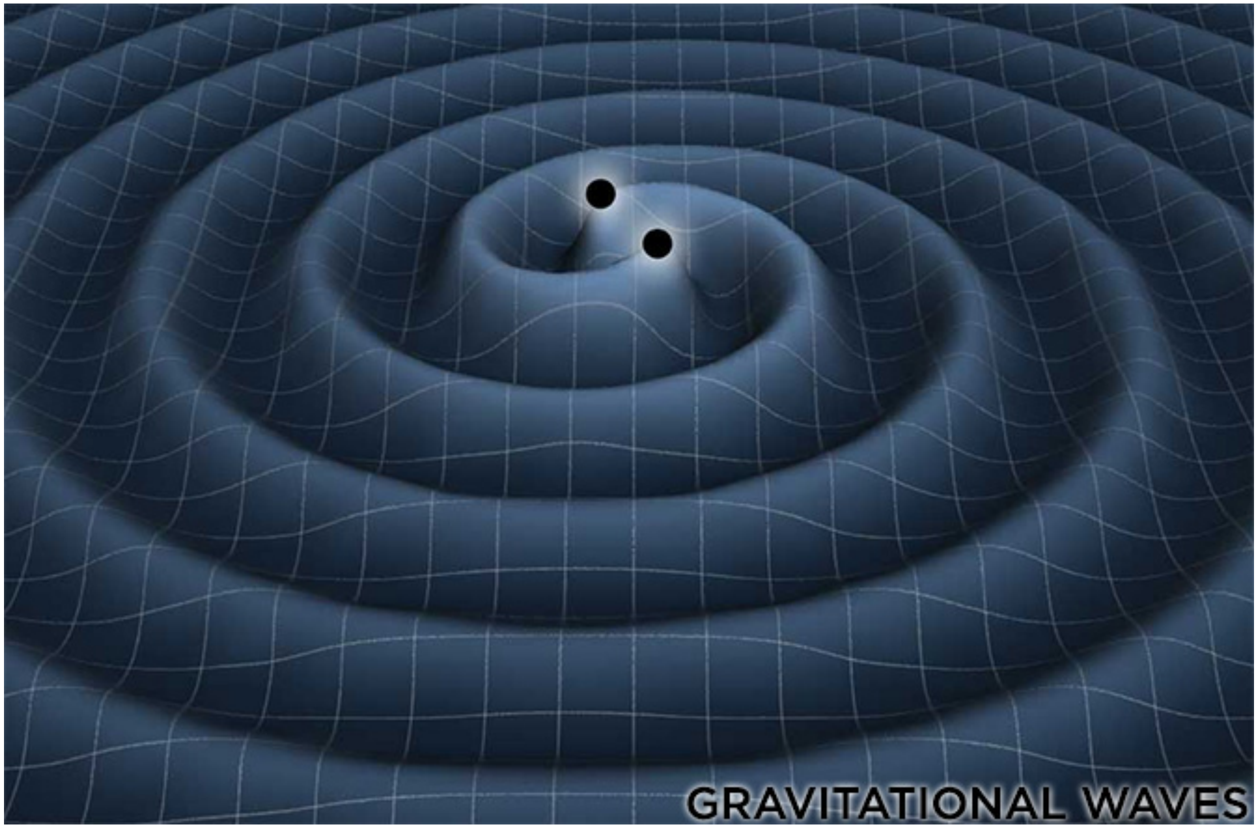


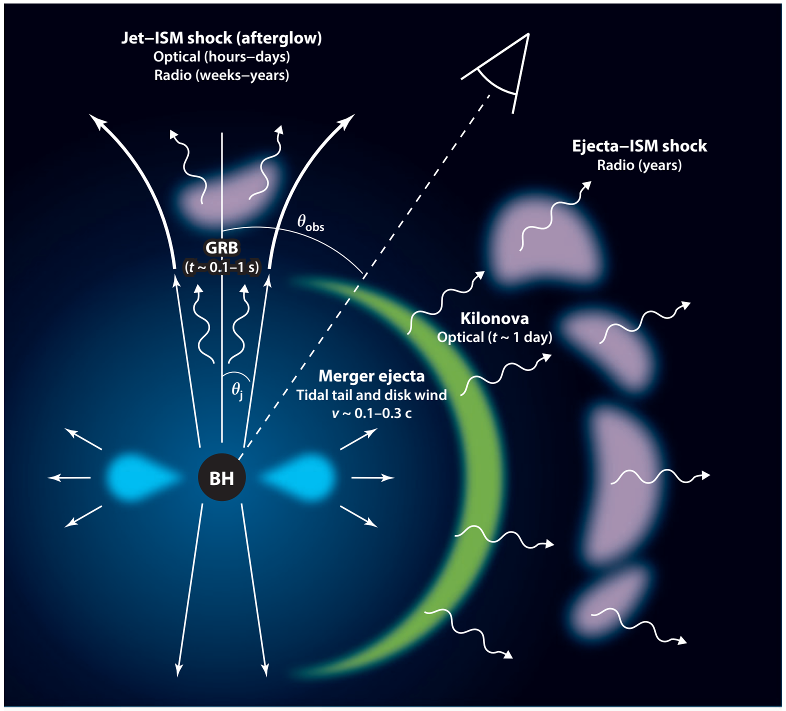
core-collapse SNe (mostly Type II)

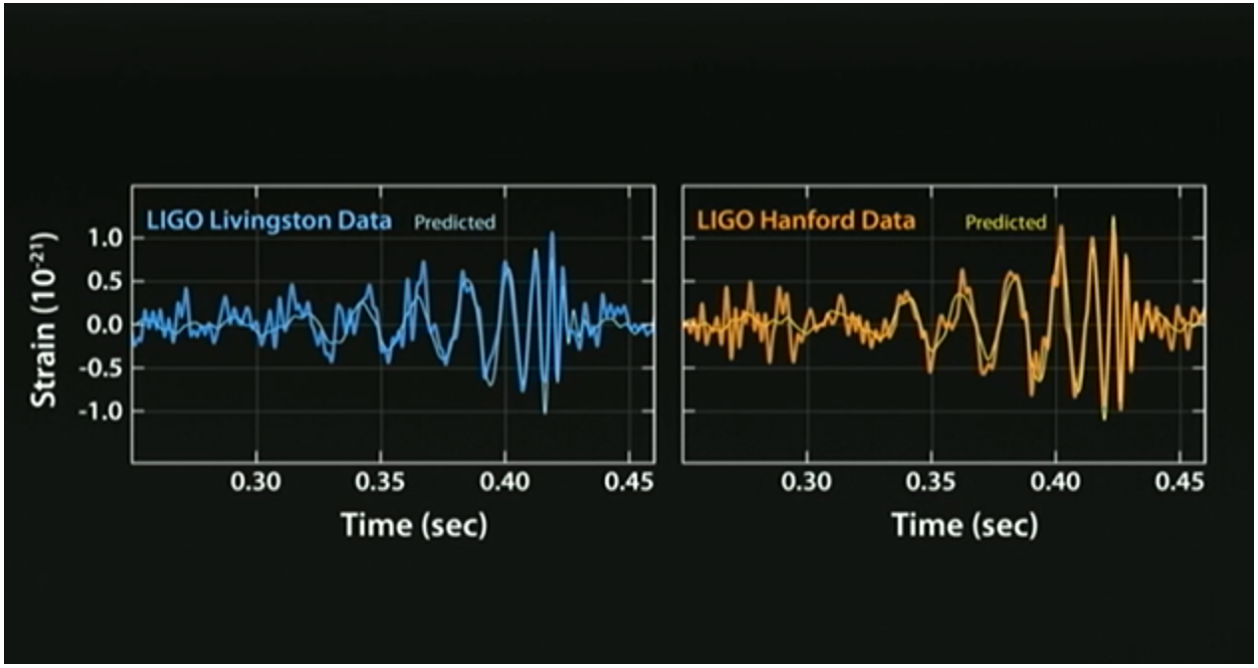
Another SN Ia Scenario: White Dwarf Mergers



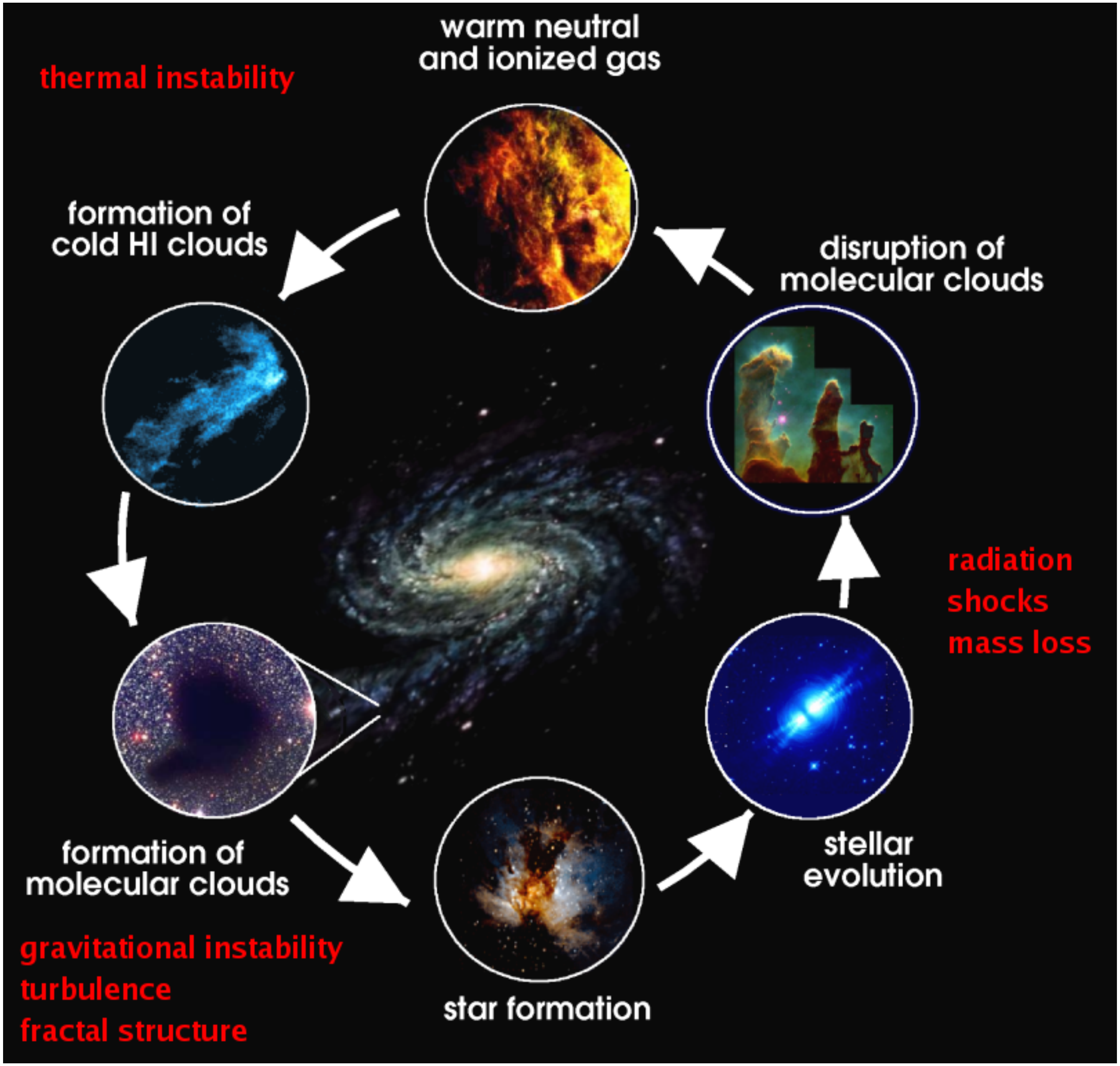



GRAVITATIONAL WAVES

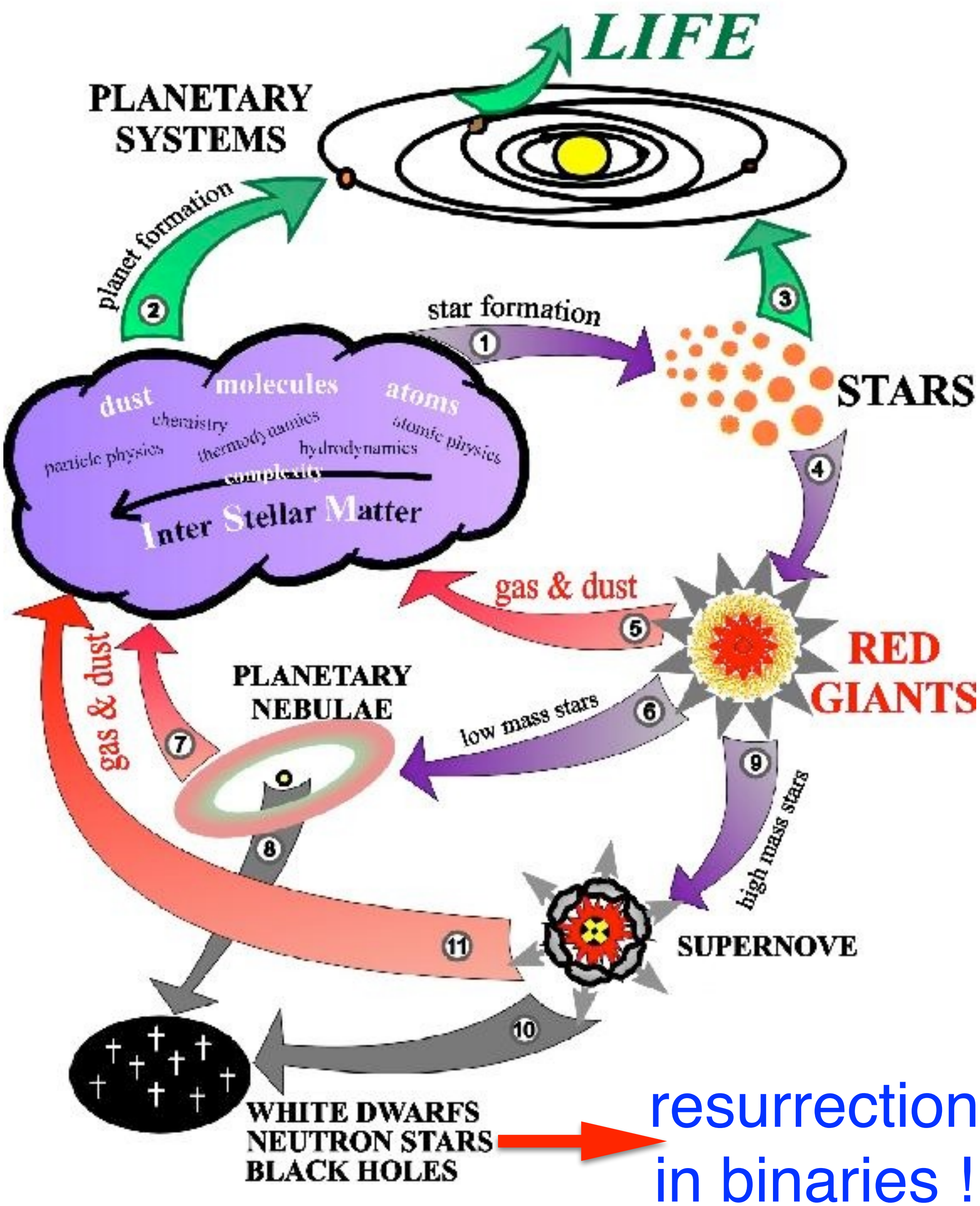

Jet–ISM shock (afterglow)
Optical (hours–days)
Radio (weeks–years)
Ejecta–ISM shock
Radio (years)
θ_{obs}
GRB
(t ~ 0.1–1 s)
Kilonova
Optical (t ~ 1 day)
Merger ejecta
Tidal tail and disk wind
v ~ 0.1–0.3 c
θ_j
BH


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)

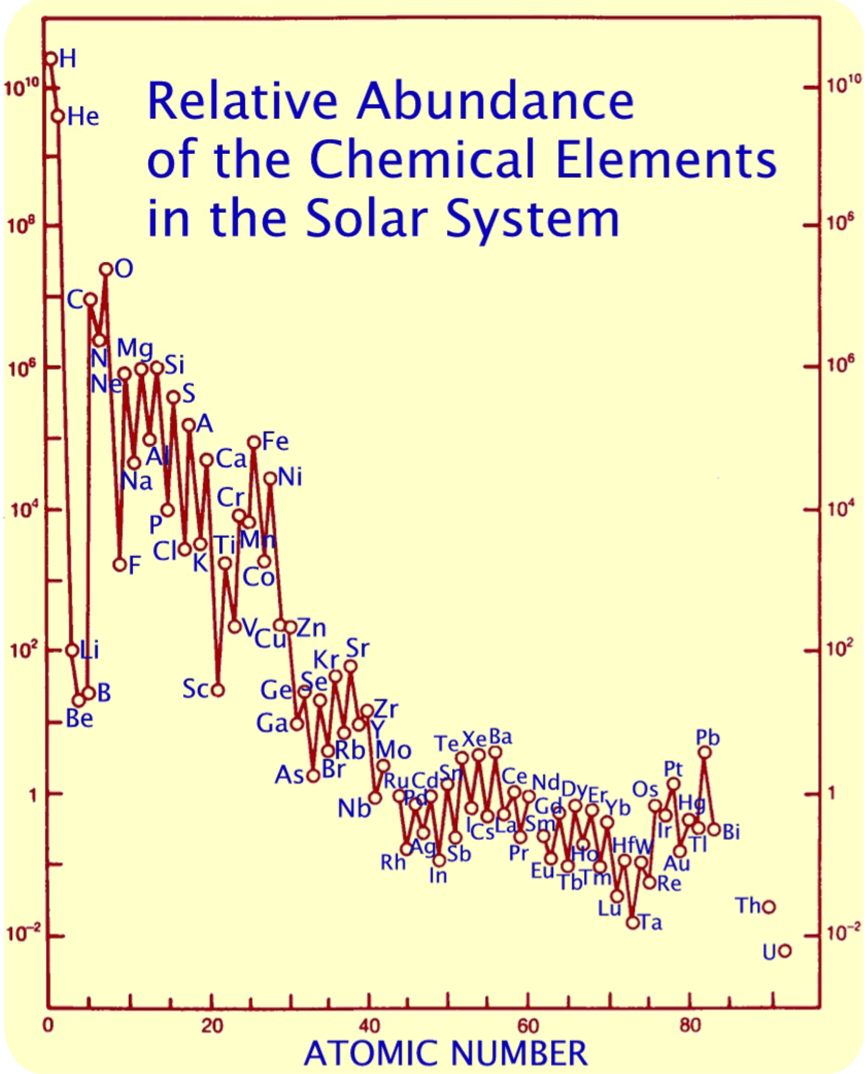
Life Cycle of Interstellar Medium



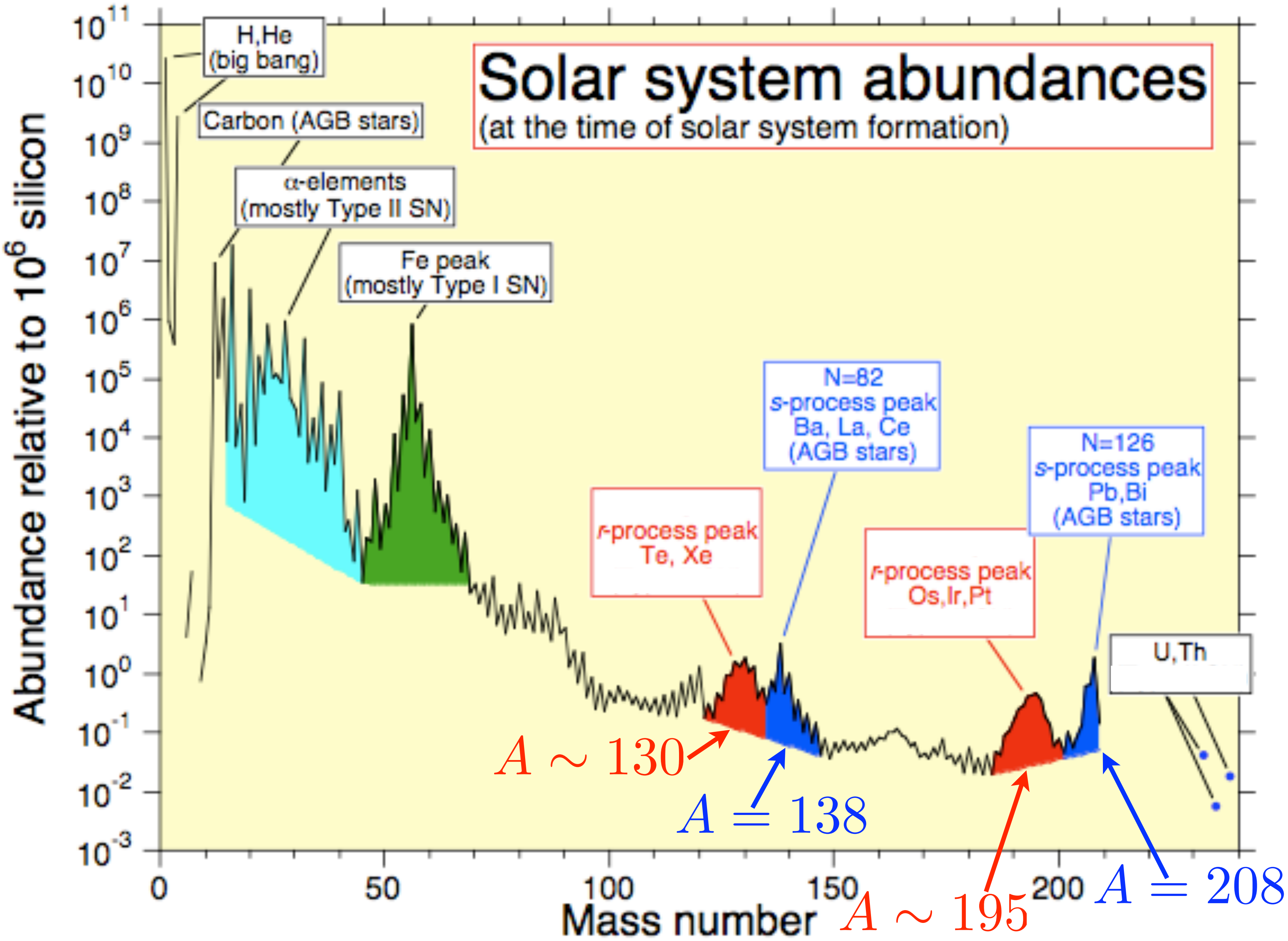
Arise from the Ashes



resurrection in binaries !



Cosmic Abundances



Simplifications for the early chemical evolution

Low-mass stars evolve on timescales of ~1 Gyr →

Fe from SNe Ia & s-process elements from AGB stars negligible during the first ~1 Gyr

Focus on massive stars & related sources: SNe II & NS mergers

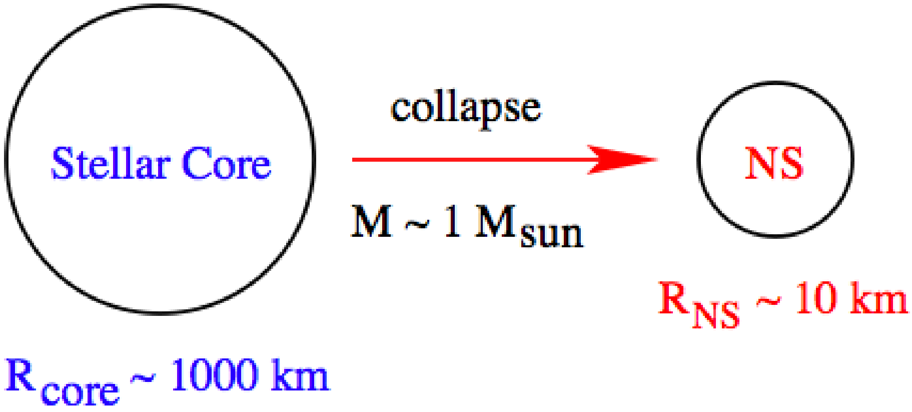
$$\text{SNe II produced} \sim \tfrac{1}{3}\left(\tfrac{\mathrm{Fe}}{\mathrm{H}}\right)_\odot \text{ over} \sim 10 \text{ Gyr} \rightarrow$$

$$\sim \tfrac{1}{30}\left(\tfrac{\mathrm{Fe}}{\mathrm{H}}\right)_\odot \text{ produced over} \sim 1 \text{ Gyr}$$

Stars formed during the first ~1 Gyr have

$$[\mathrm{Fe/H}] = \log\left(\mathrm{Fe/H}\right) - \log\left(\mathrm{Fe/H}\right)_\odot \lesssim -1.5$$

Supernova as a neutrino phenomenon

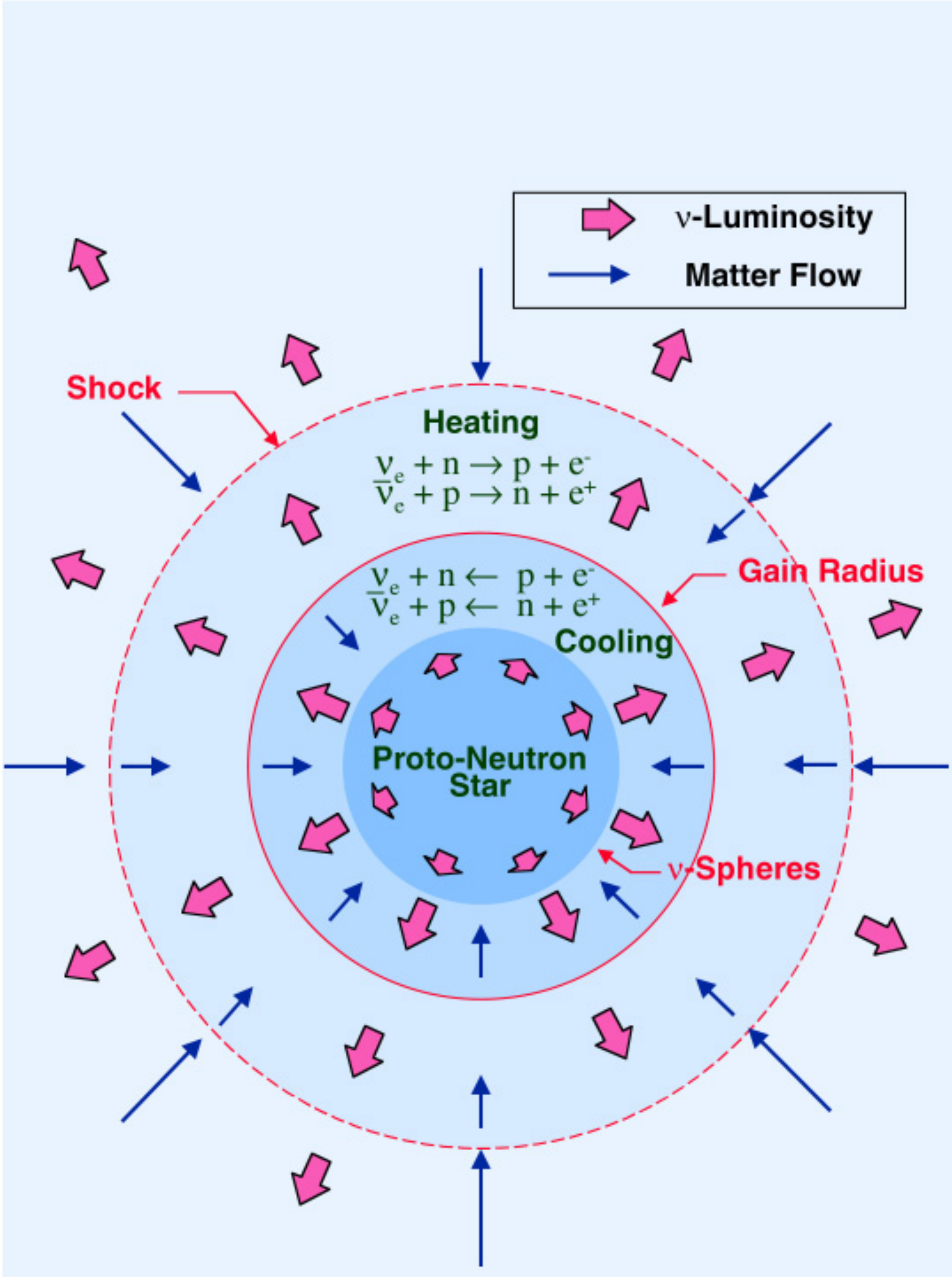


$$e^+ + e^- \to \nu + \bar{\nu}$$

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

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

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



Light Curve of SN 1987a

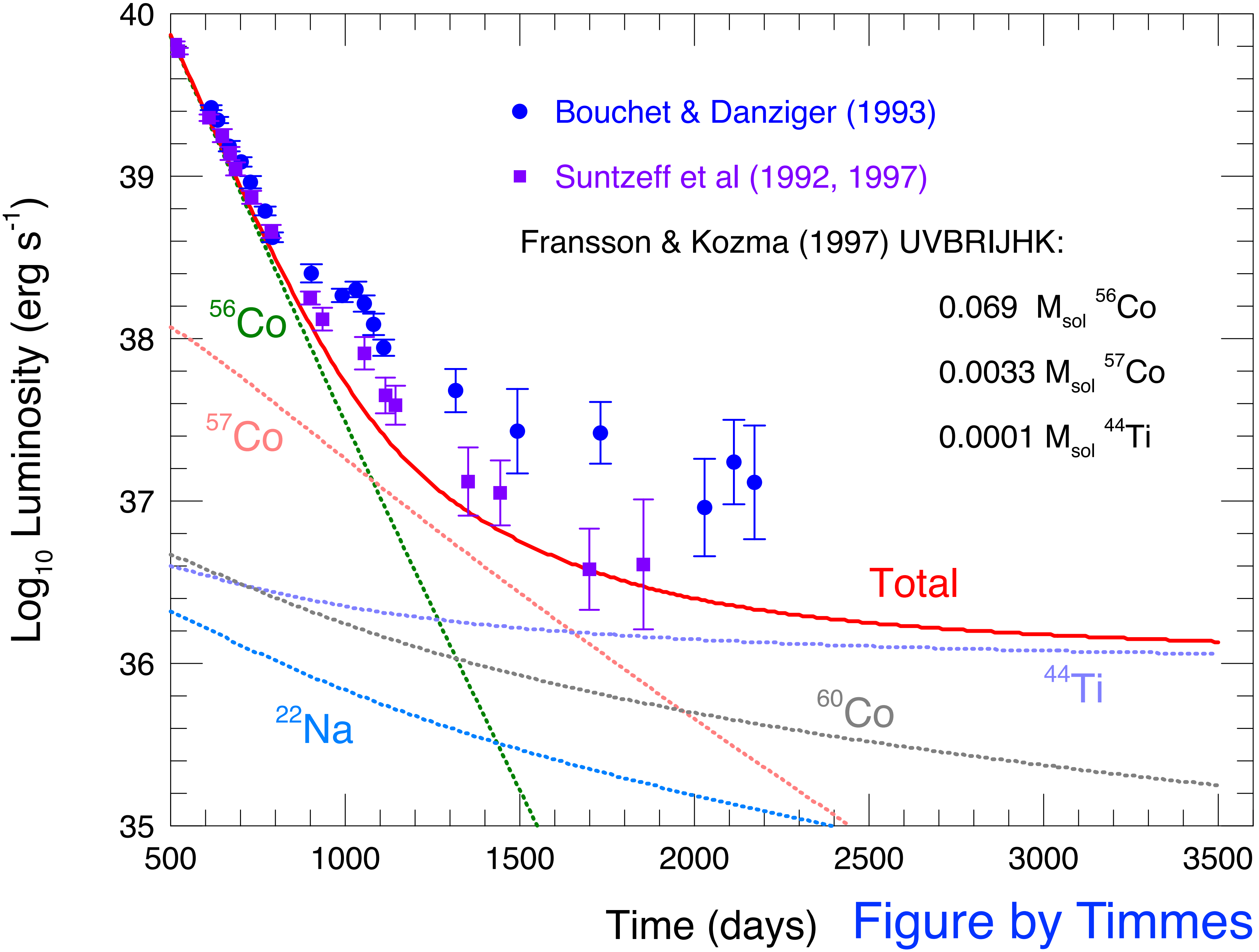
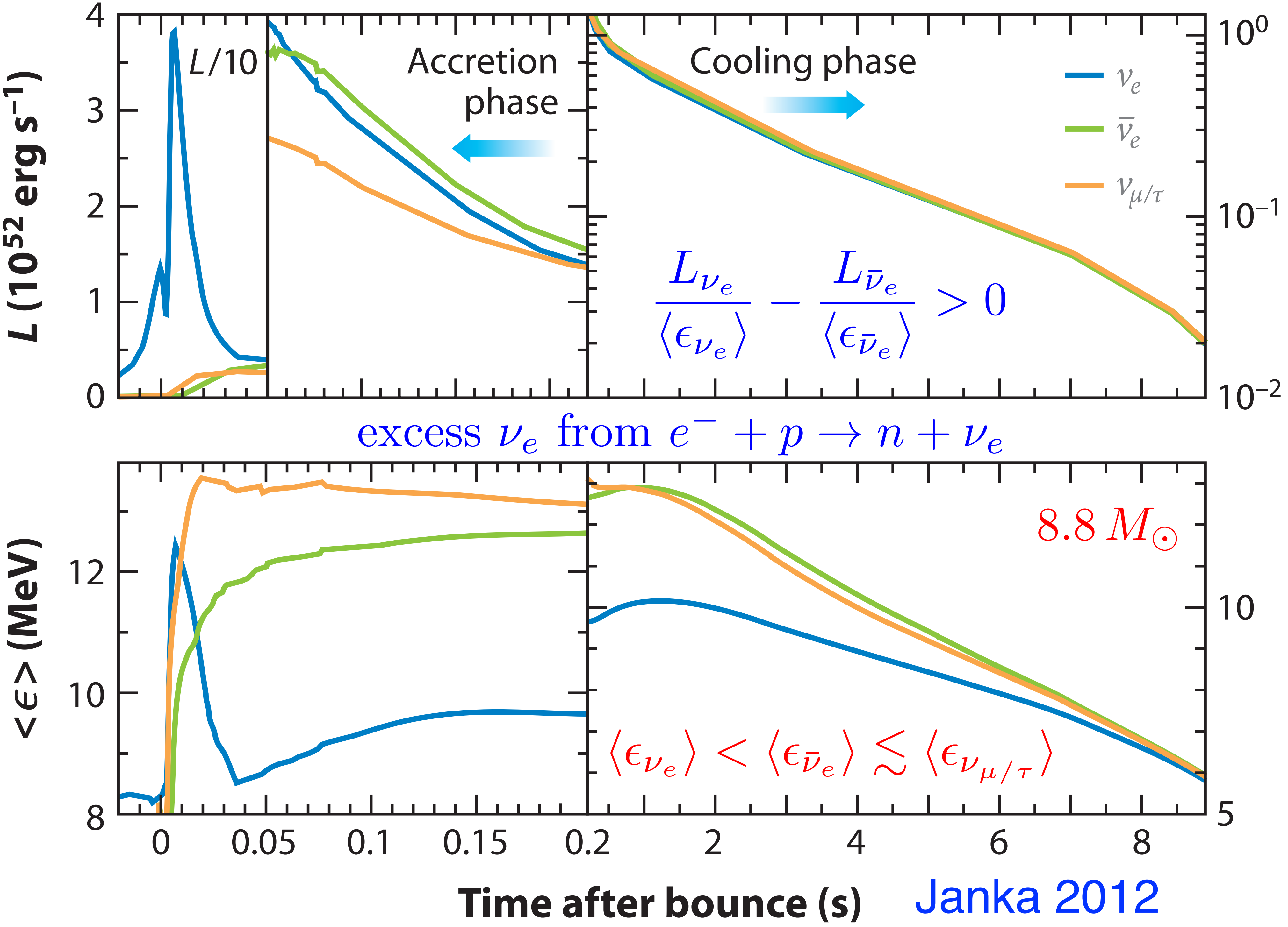


Figure by Timmes

Neutrino Emission from a Low-Mass SN



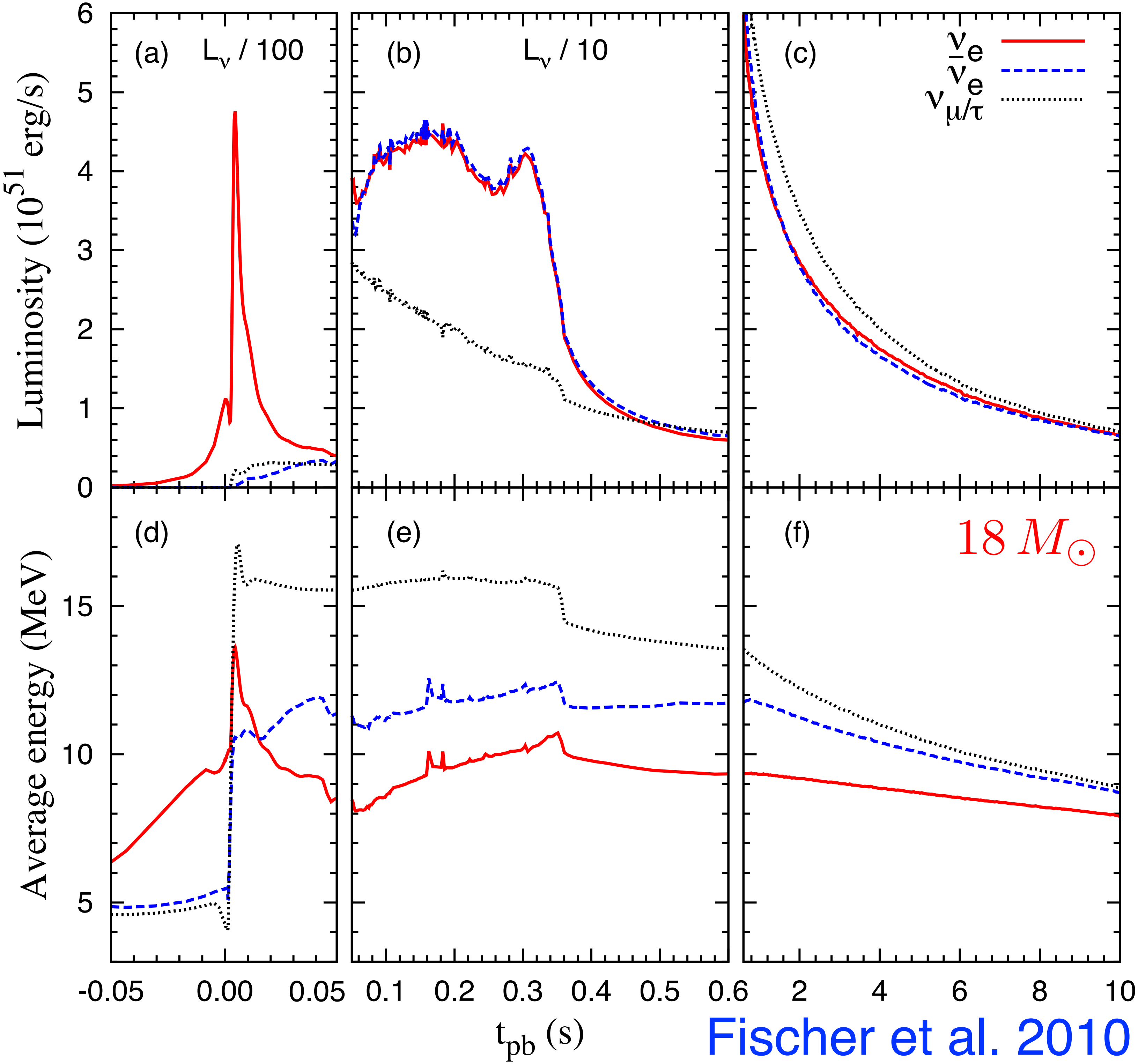
$$\frac{L_{\nu_e}}{\langle\epsilon_{\nu_e}\rangle} - \frac{L_{\bar\nu_e}}{\langle\epsilon_{\bar\nu_e}\rangle} > 0$$

excess ν_e from $e^- + p \to n + \nu_e$

$8.8\,M_\odot$

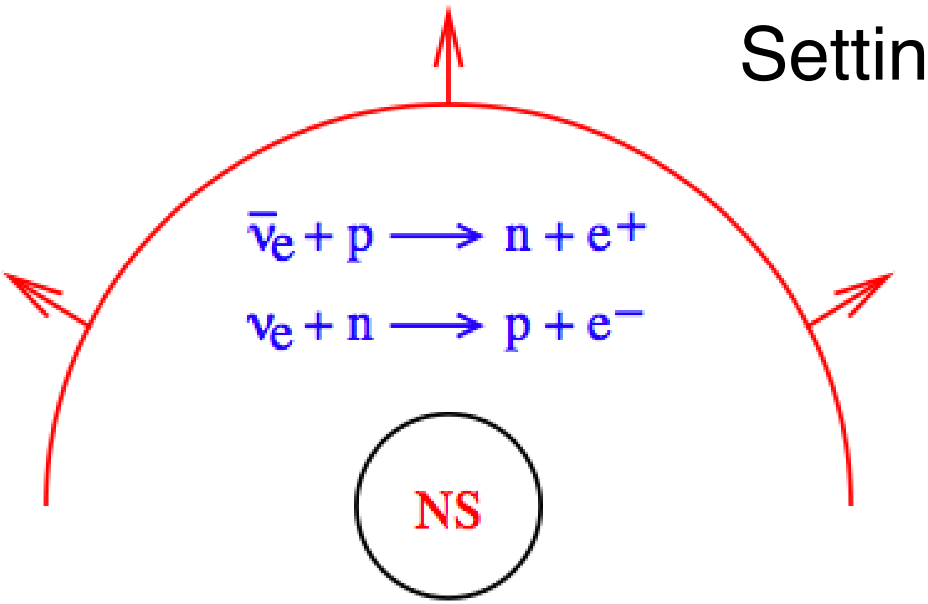
$$\langle\epsilon_{\nu_e}\rangle < \langle\epsilon_{\bar\nu_e}\rangle \lesssim \langle\epsilon_{\nu_{\mu/\tau}}\rangle$$

Janka 2012



Fischer et al. 2010

Setting n/p in the Neutrino-Driven Wind



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

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

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

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

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

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

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

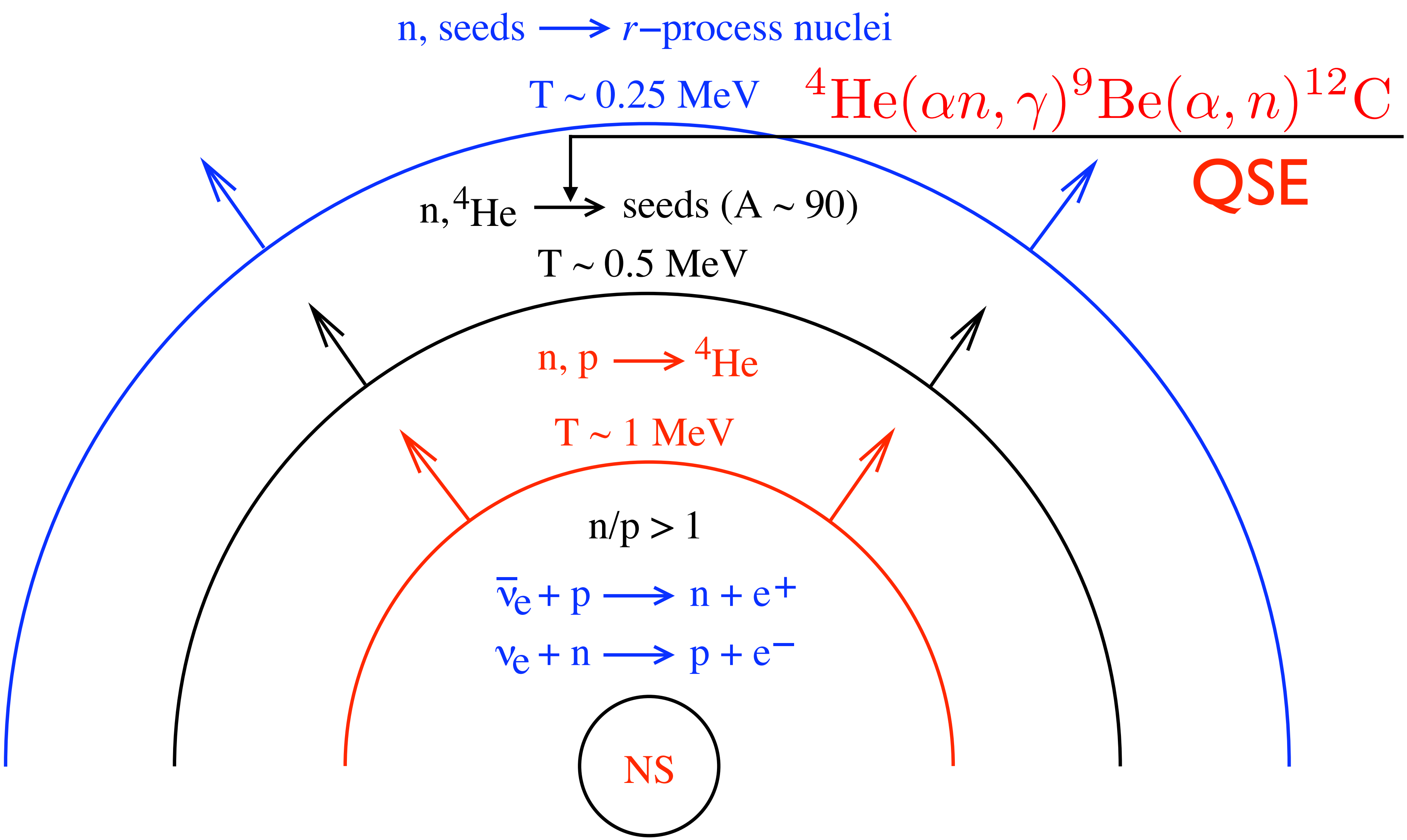
$$\frac{\langle E^2_{\bar{\nu}_e} \rangle}{\langle E_{\bar{\nu}_e} \rangle} - \frac{\langle E^2_{\nu_e} \rangle}{\langle E_{\nu_e} \rangle} > 4\Delta_{np} \approx 5.2 \text{ MeV} \Rightarrow \frac{n}{p} > 1$$

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)



n, seeds $\longrightarrow$ *r*–process nuclei

T ~ 0.25 MeV

$^{4}\mathrm{He}(\alpha n,\gamma)^{9}\mathrm{Be}(\alpha,n)^{12}\mathrm{C}$

QSE

n, ^{4}He $\longrightarrow$ seeds (A ~ 90)

T ~ 0.5 MeV

n, p $\longrightarrow$ ^{4}He

T ~ 1 MeV

n/p > 1

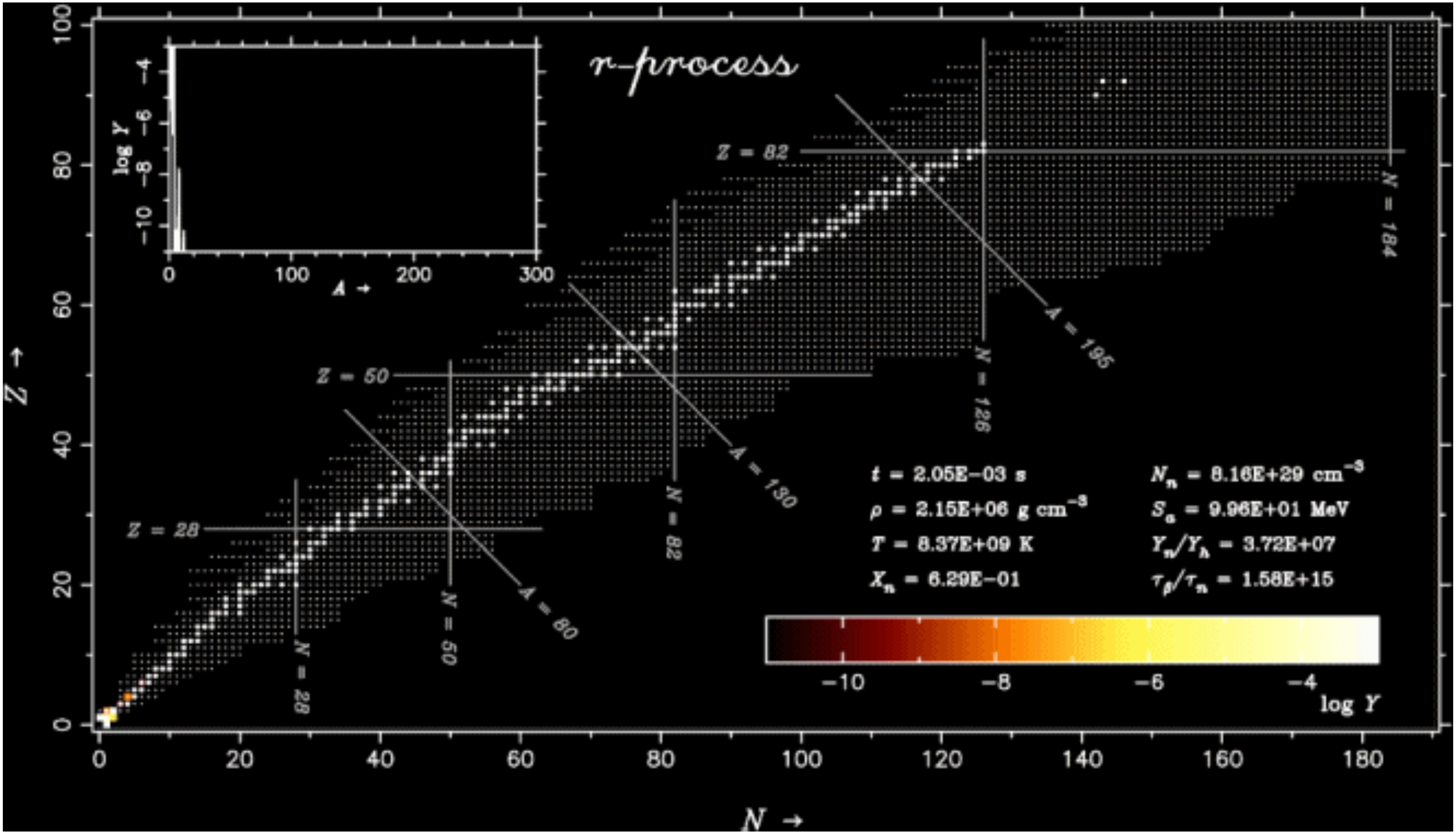
$\bar{\nu}_e + p \longrightarrow n + e^{+}$

$\nu_e + n \longrightarrow p + e^{-}$

NS

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

Rapid Neutron Capture: the r-Process



Wanajo et al. 2004

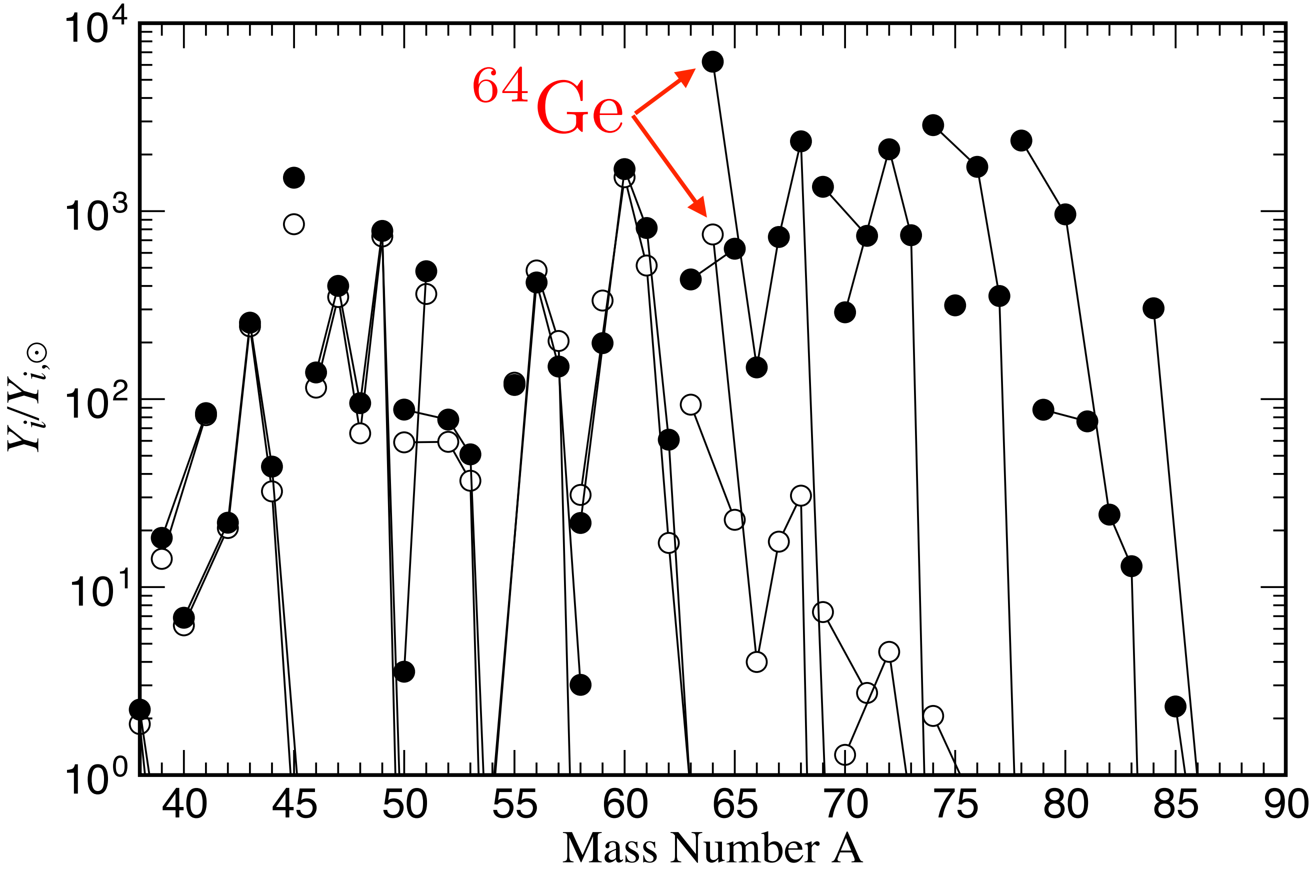
The νp-process in p-rich ν-driven winds

(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:

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

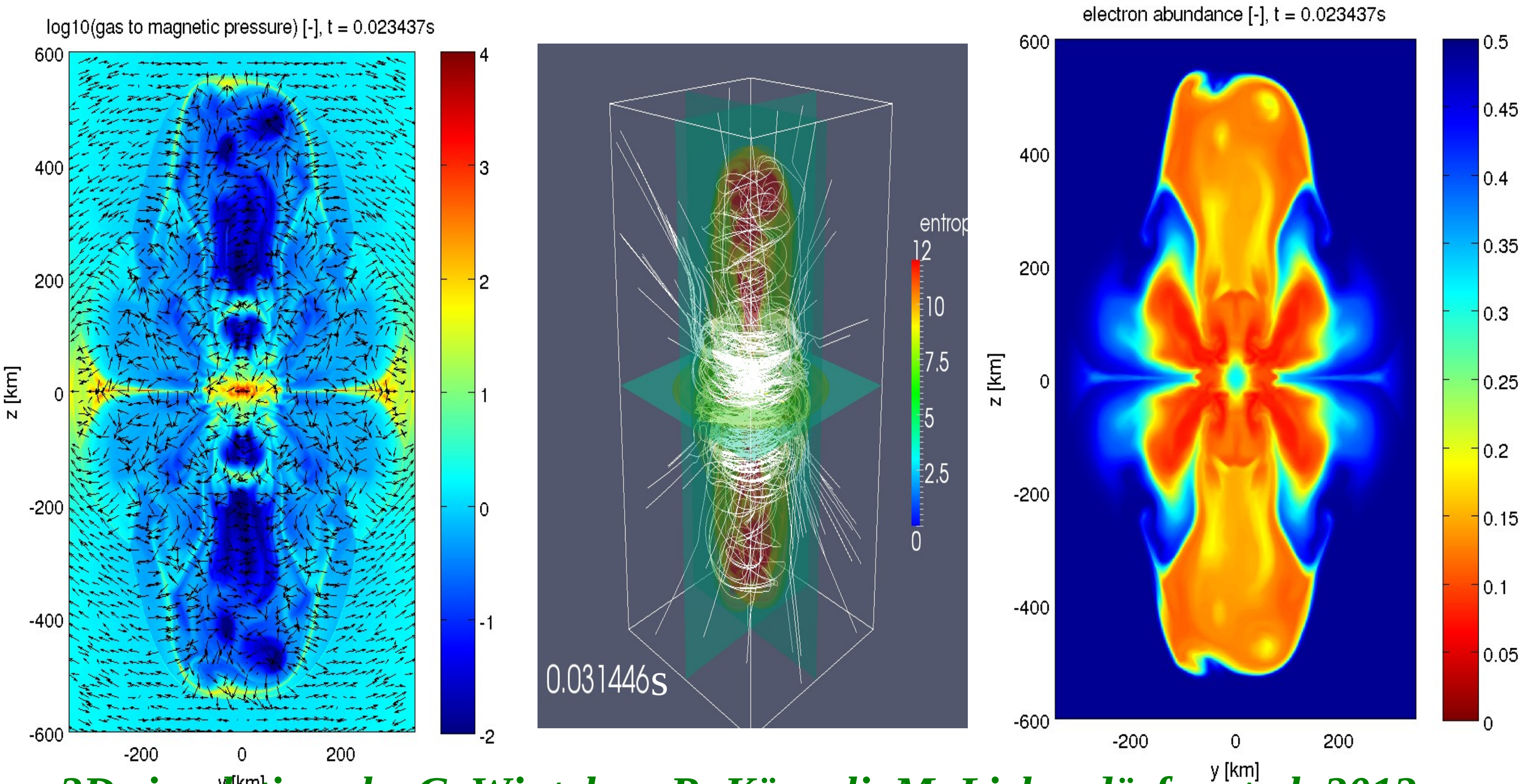


Jets driven by rotation, magnetohydrodynamics, etc.

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



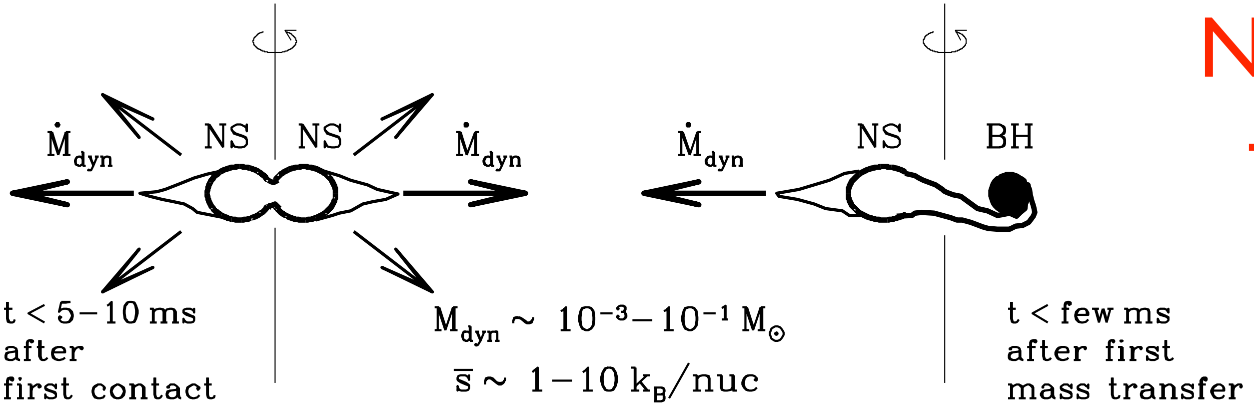
3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012
Eichler et al. 2013

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

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

Merger Phase: Prompt/dynamical ejecta

(due to dynamic binary interaction)



t < 5−10 ms
after
first contact

$M_{dyn} \sim 10^{-3}-10^{-1}\,M_\odot$

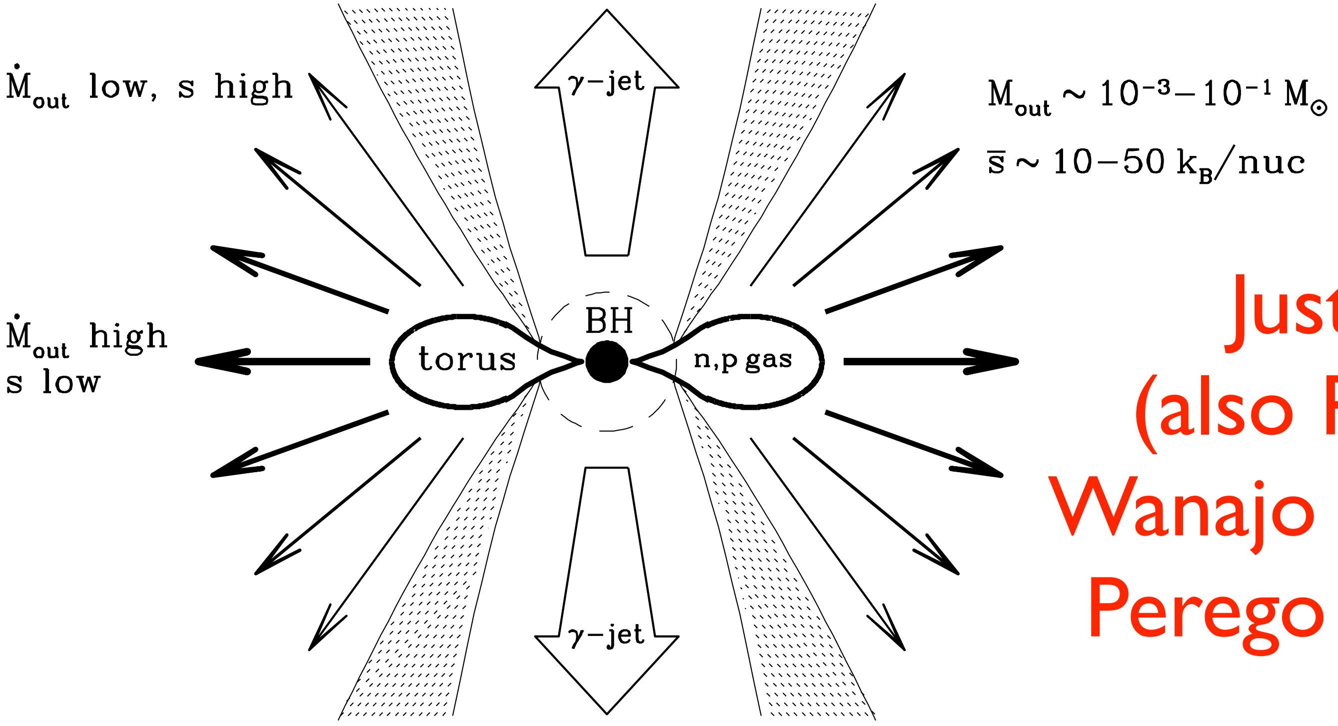
$\bar{s} \sim 1-10\,k_B/\mathrm{nuc}$

t < few ms
after first
mass transfer

NS matter
\+ winds

BH−Torus Phase: Disk ejecta

(due to ν heating, viscosity/magn. fields, recombination)



$\dot{M}_{out}$ low, s high

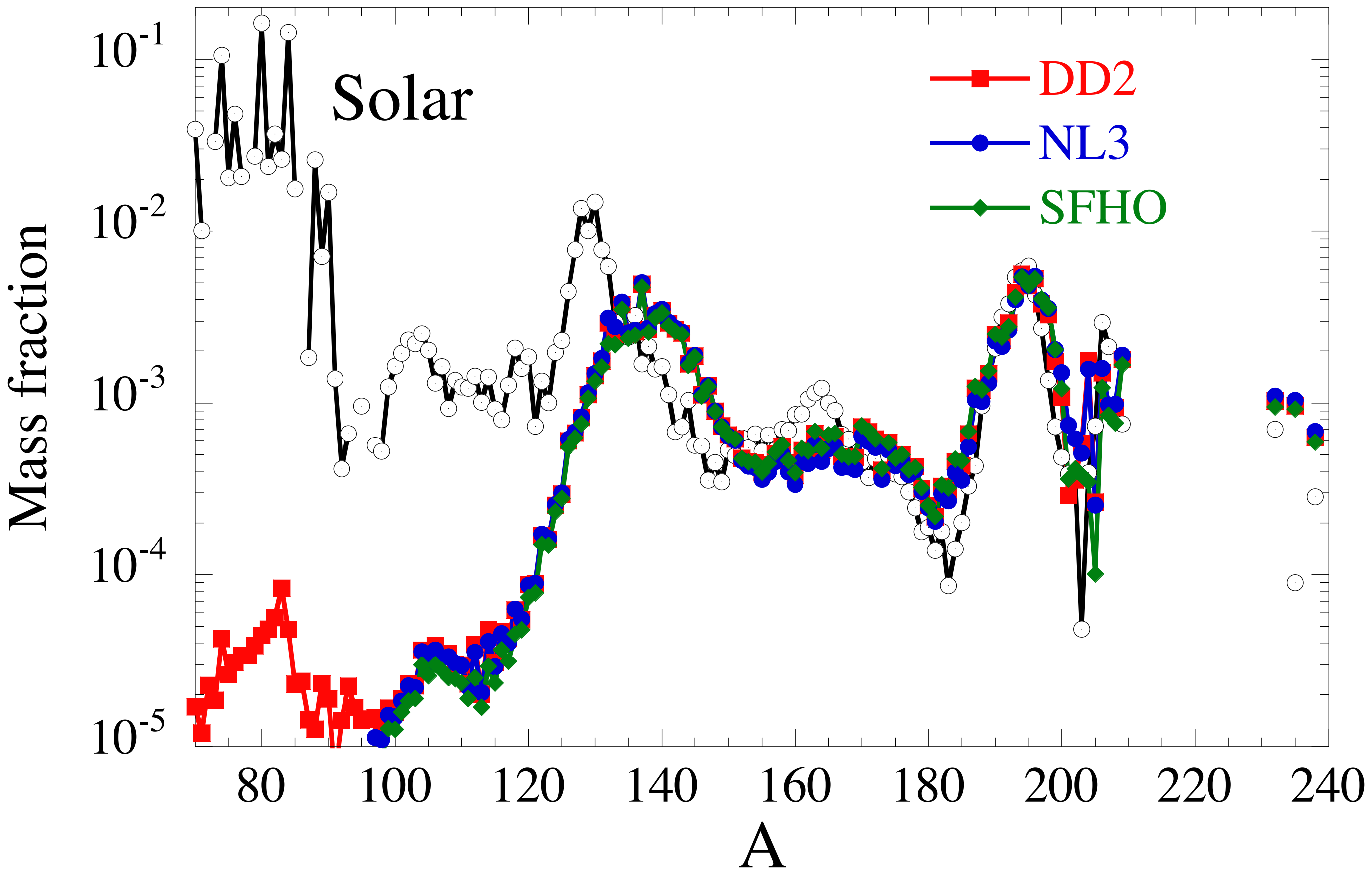
$\dot{M}_{out}$ high
s low

$M_{out} \sim 10^{-3}-10^{-1}\,M_\odot$

$\bar{s} \sim 10-50\,k_B/\mathrm{nuc}$

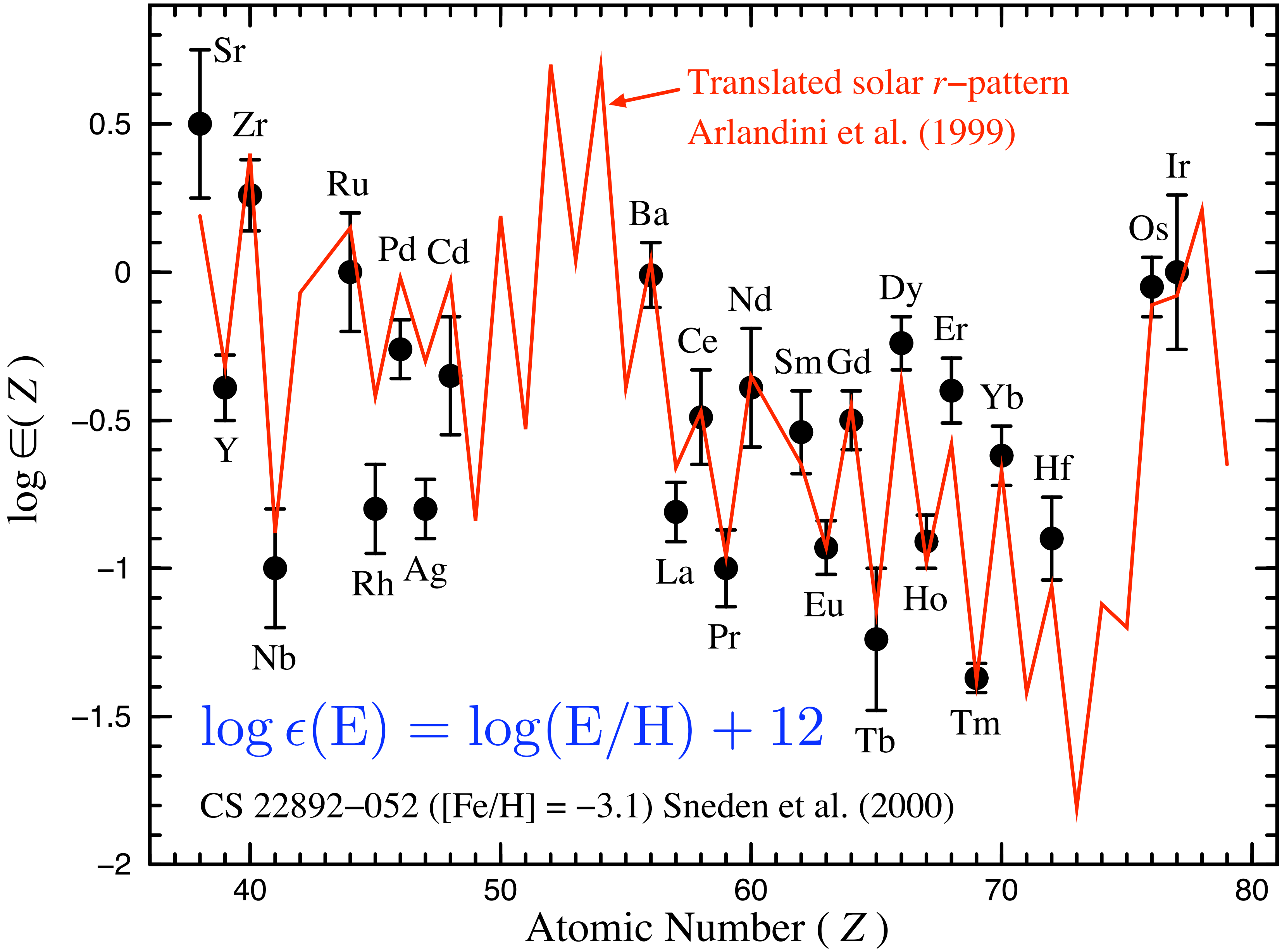
Just + 2014
(also Rosswog +;
Wanajo +; Metzger +;
Perego +; Martin +)

decompression of cold neutron star matter



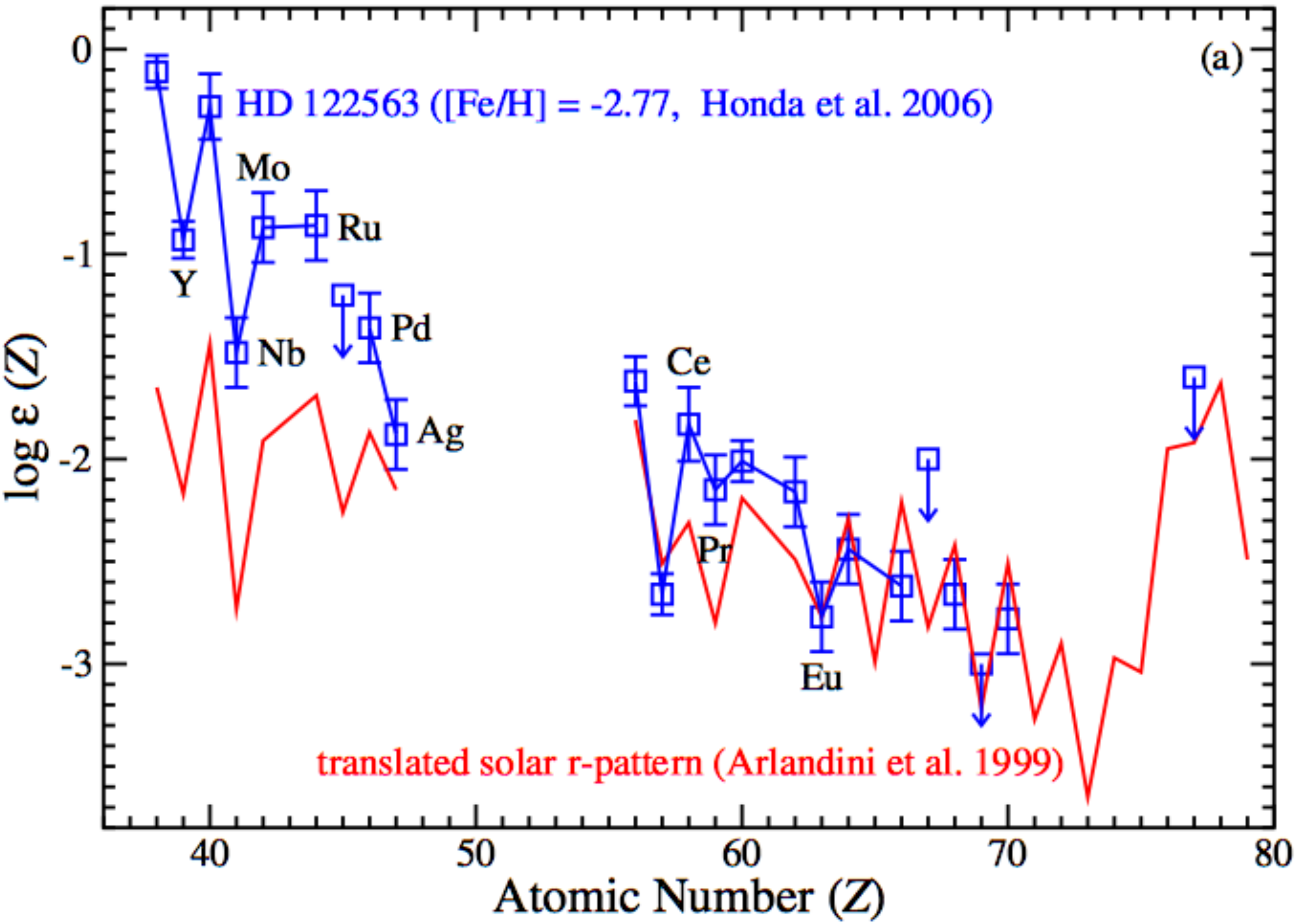
(Goriely, Bauswein, & Janka 2011, 2013)

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



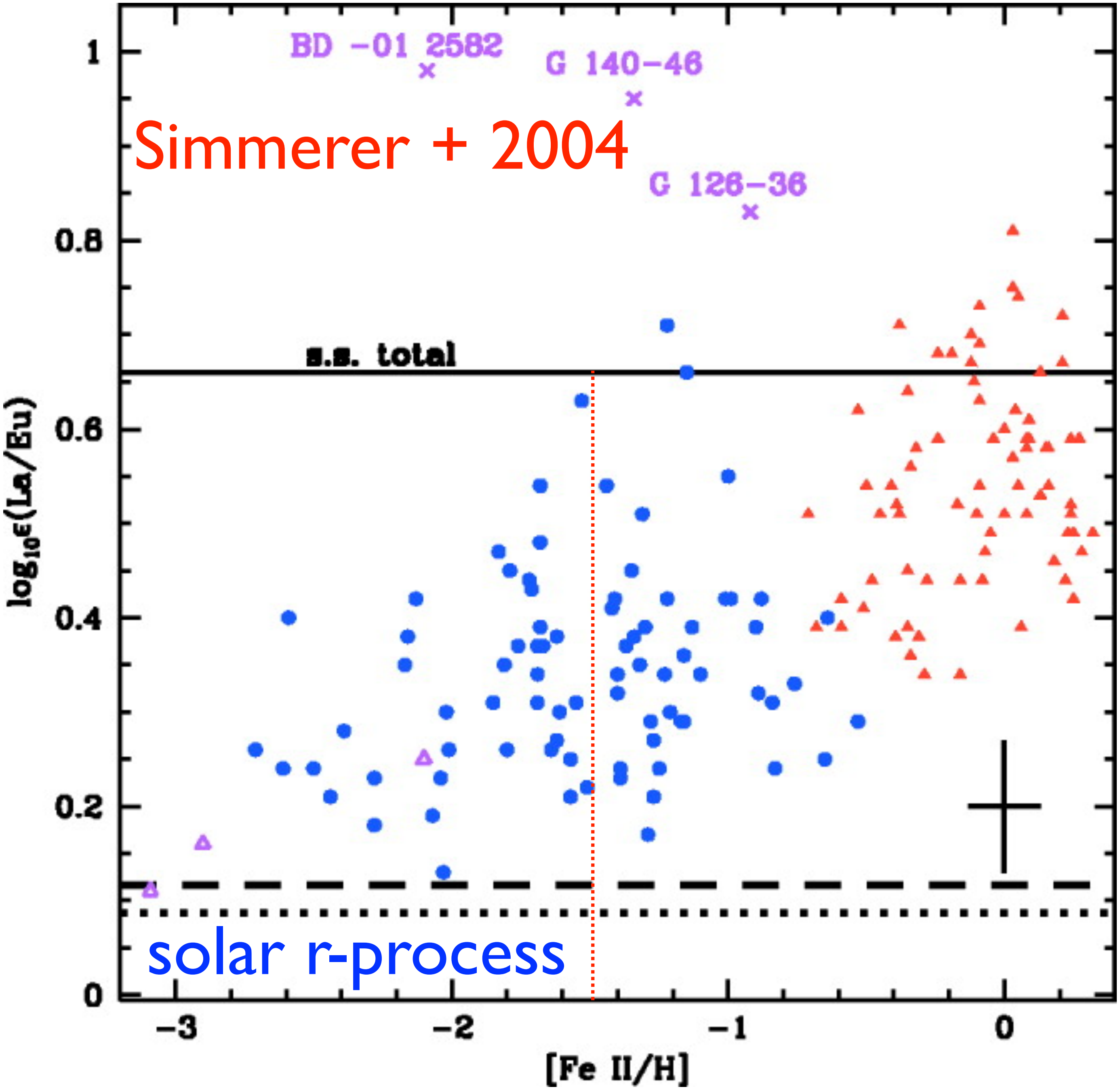
metal-poor star update:
Roederer +, Frebel +, Hansen +

meteoritic hints:
Wasserburg + 1996
Qian + 1998



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

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



Simmerer + 2004

solar r-process

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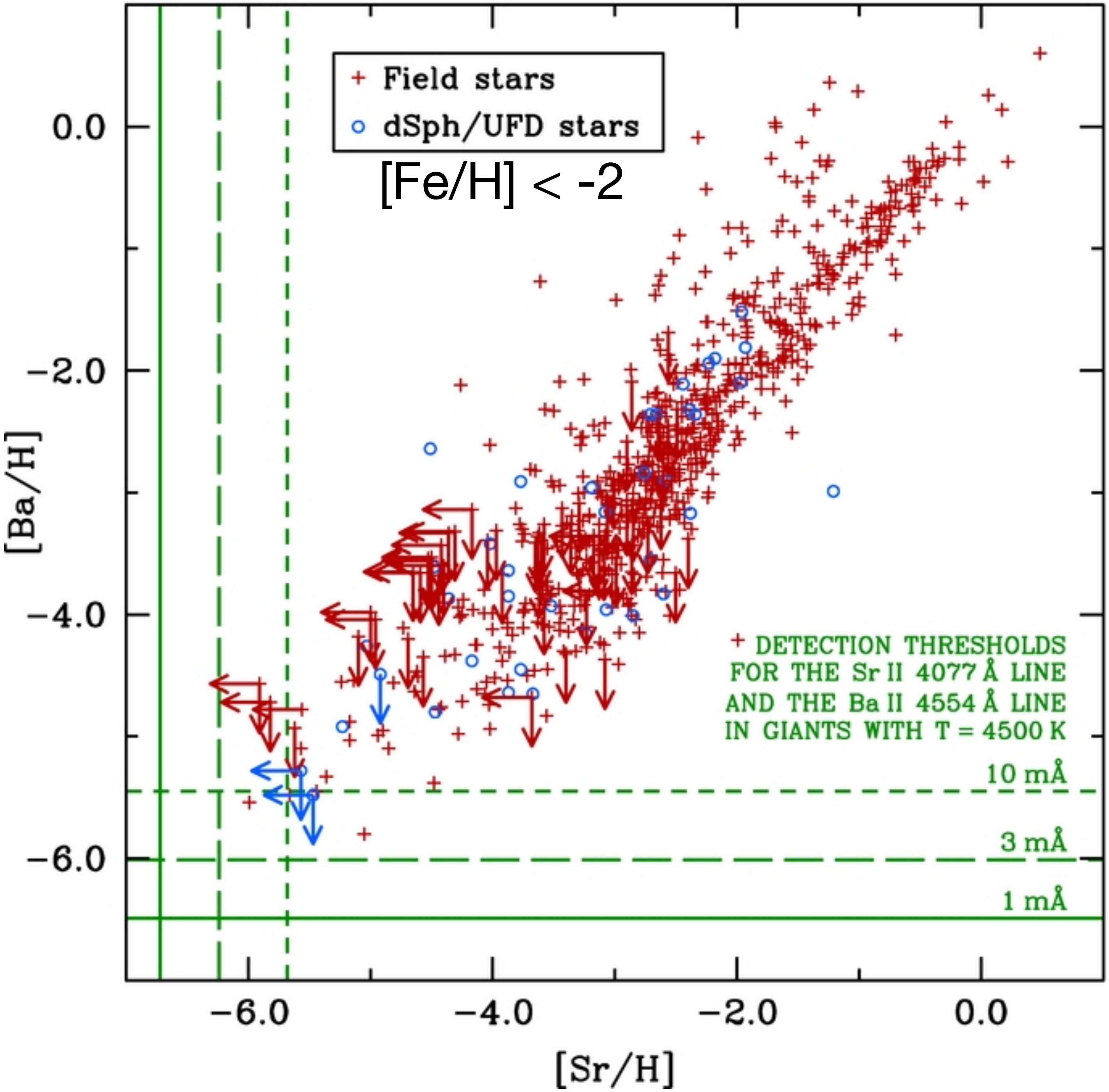
SNe II produced $\sim \frac{1}{3}\left(\frac{\mathrm{Fe}}{\mathrm{H}}\right)_{\odot}$ over ~ 10 Gyr →

$\sim \frac{1}{30}\left(\frac{\mathrm{Fe}}{\mathrm{H}}\right)_{\odot}$ produced over ~ 1 Gyr

Stars formed during the first ~1 Gyr have

$$[\mathrm{Fe/H}] = \log\left(\mathrm{Fe/H}\right) - \log\left(\mathrm{Fe/H}\right)_{\odot} \lesssim -1.5$$

Ubiquity of Sr and Ba (Roederer 2013)



Galaxy Formation

Summary

Early chemical evolution during the first ~1 Gyr dominated by SNe II & NS mergers

Low-mass stars formed during the first ~1 Gyr have $[\mathrm{Fe/H}] \lesssim -1.5$ & survive until the present

Neutron-capture elements Sr & Ba are ubiquitous in such metal-poor stars

The neutron-capture patterns vary greatly among such stars, reflecting mixtures of distinct sources