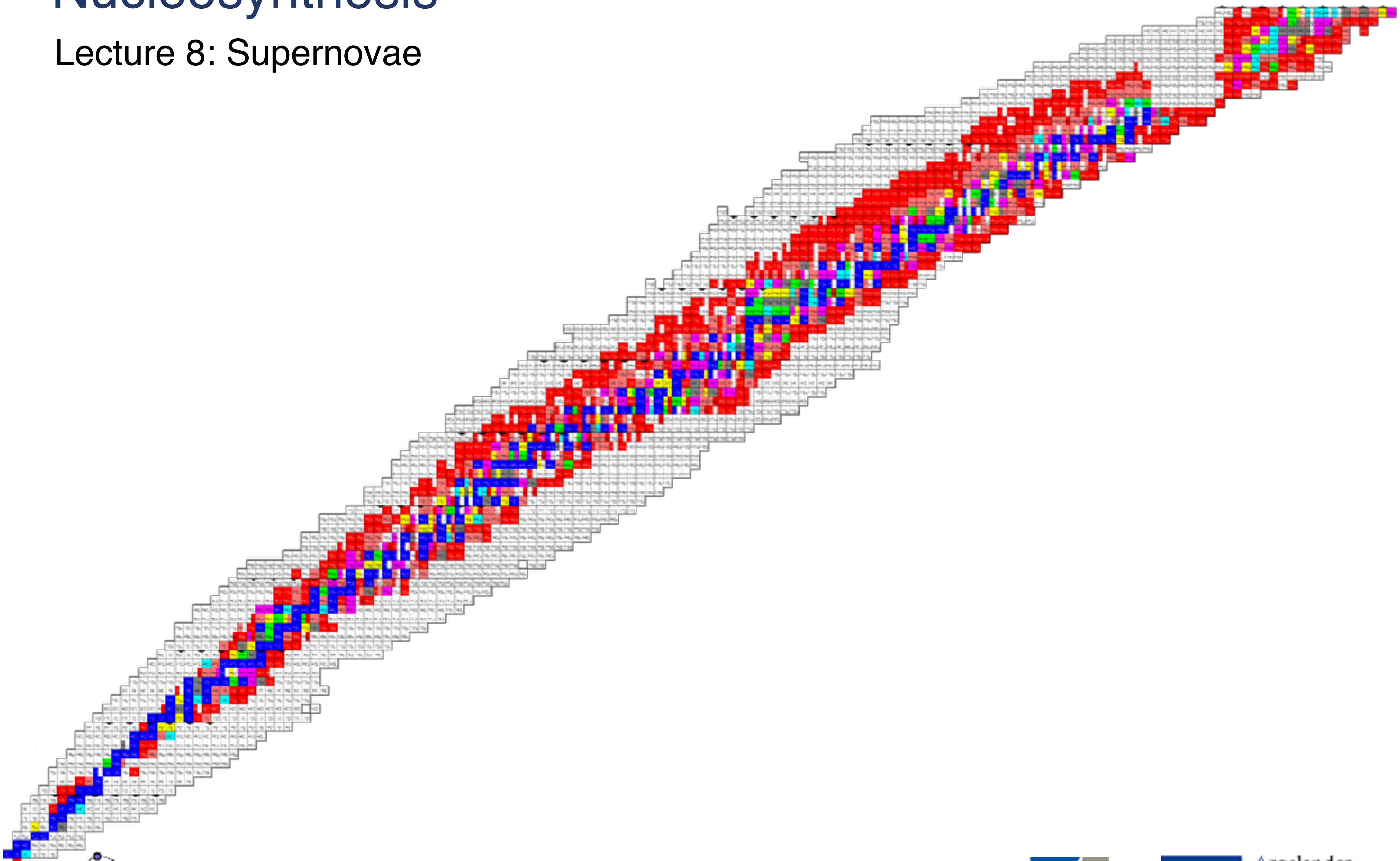
Nucleosynthesis

Lecture 8: Supernovae



Bonn-Cologne Graduate School of Physics and Astronomy

UNIVERSITÄT BONN

Argelander-Institut für Astronomie

Overview

- Lecture 1: Introduction & overview

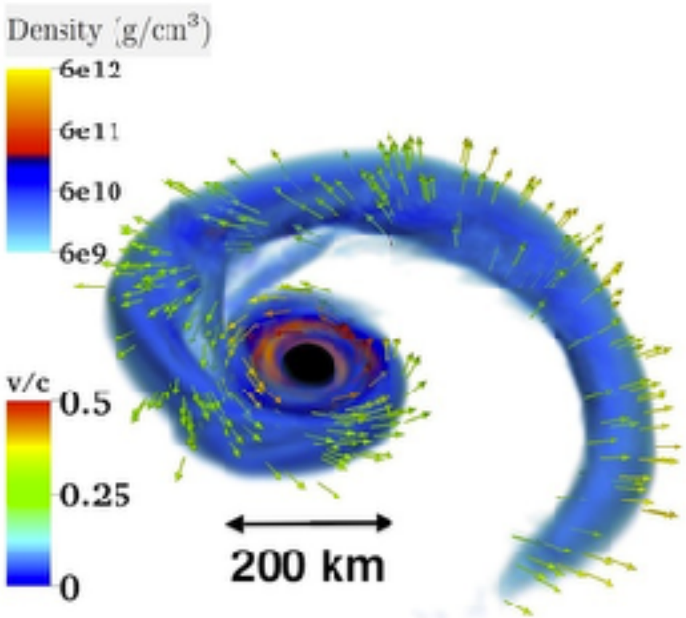
  Lecture 2: Thermonuclear reactions
- Lecture 3: Big-bang nucleosynthesis
- Lecture 4: Thermonuclear reactions inside stars — I (H-burning)
- Lecture 5: Thermonuclear reactions inside stars — II (advanced burning)
- Lecture 6: Neutron-capture and supernovae — I
- Lecture 7: Neutron-capture and supernovae — II
- Lecture 8: Thermonuclear supernovae
- Lecture 9: Li, Be and B
- Lecture 10: Galactic chemical evolution and relation to astrobiology

Paper presentations I	June 21
Paper presentations II	June 28

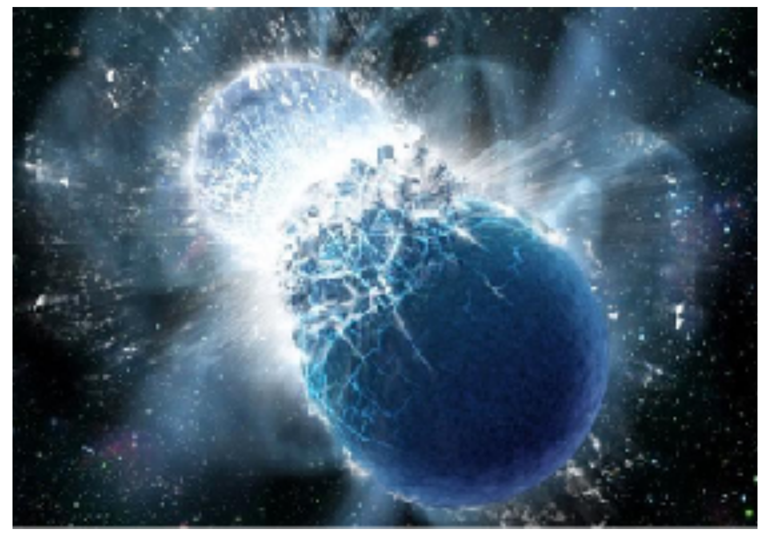
nucleosynthesis in neutron star mergers

Potential sources of ejecta in neutron star mergers

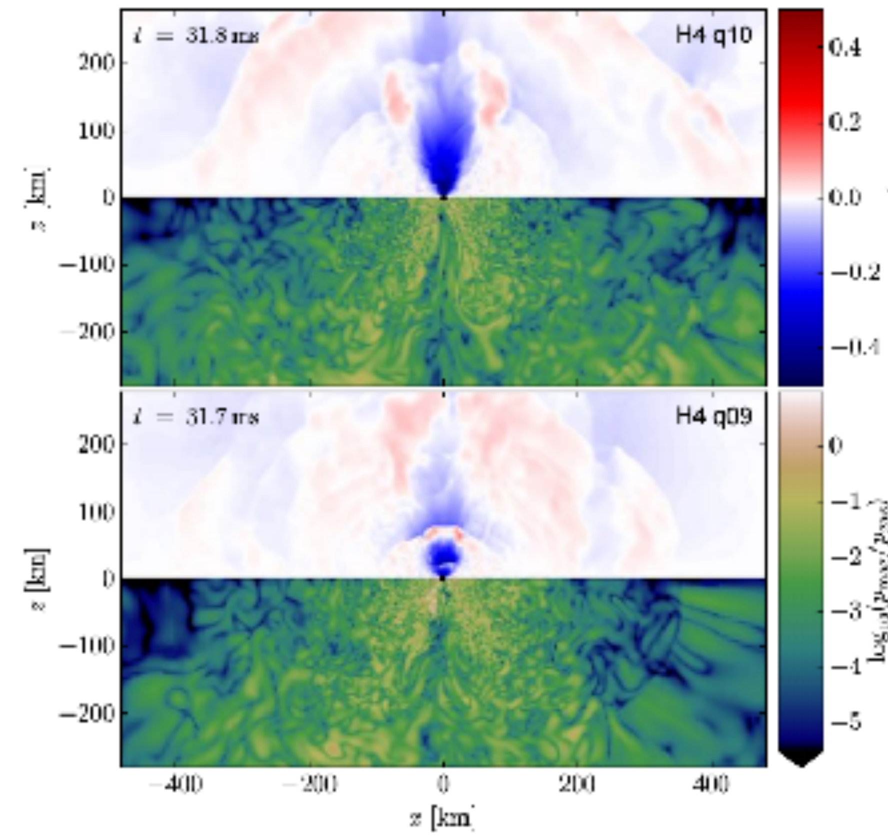
tidal ejecta



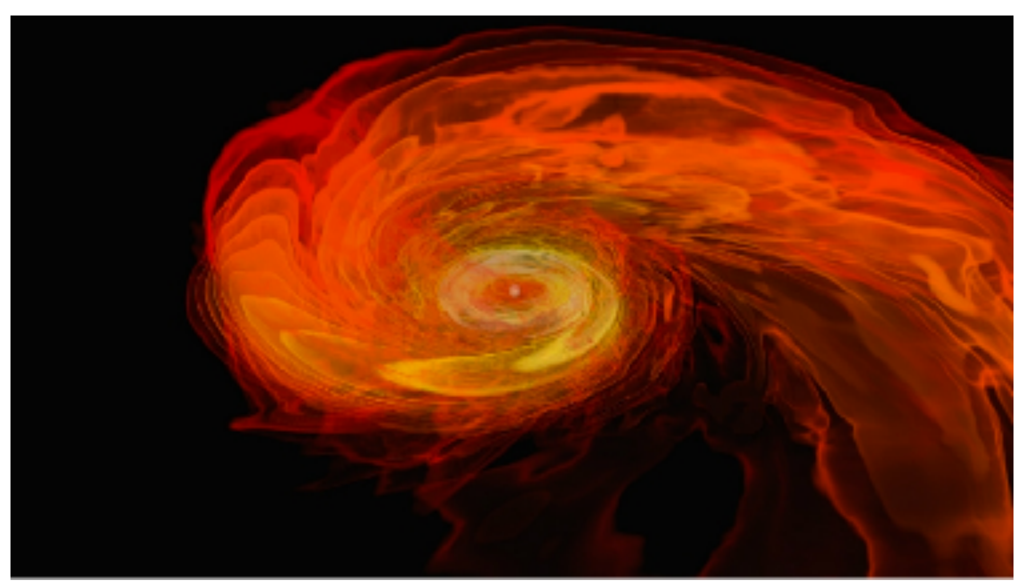
collision heated ejecta



ν- and B-driven winds

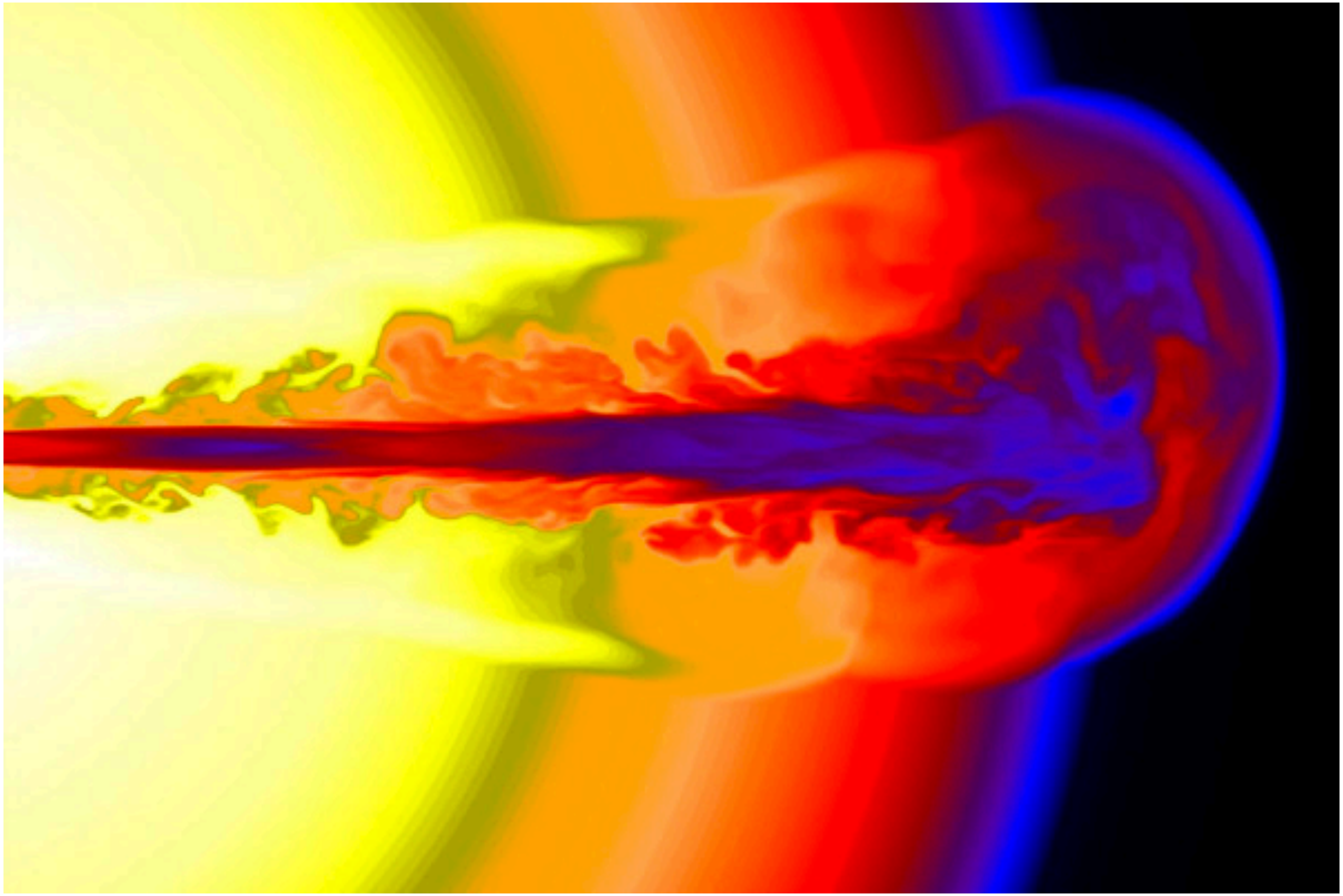


post-merger accretion disk



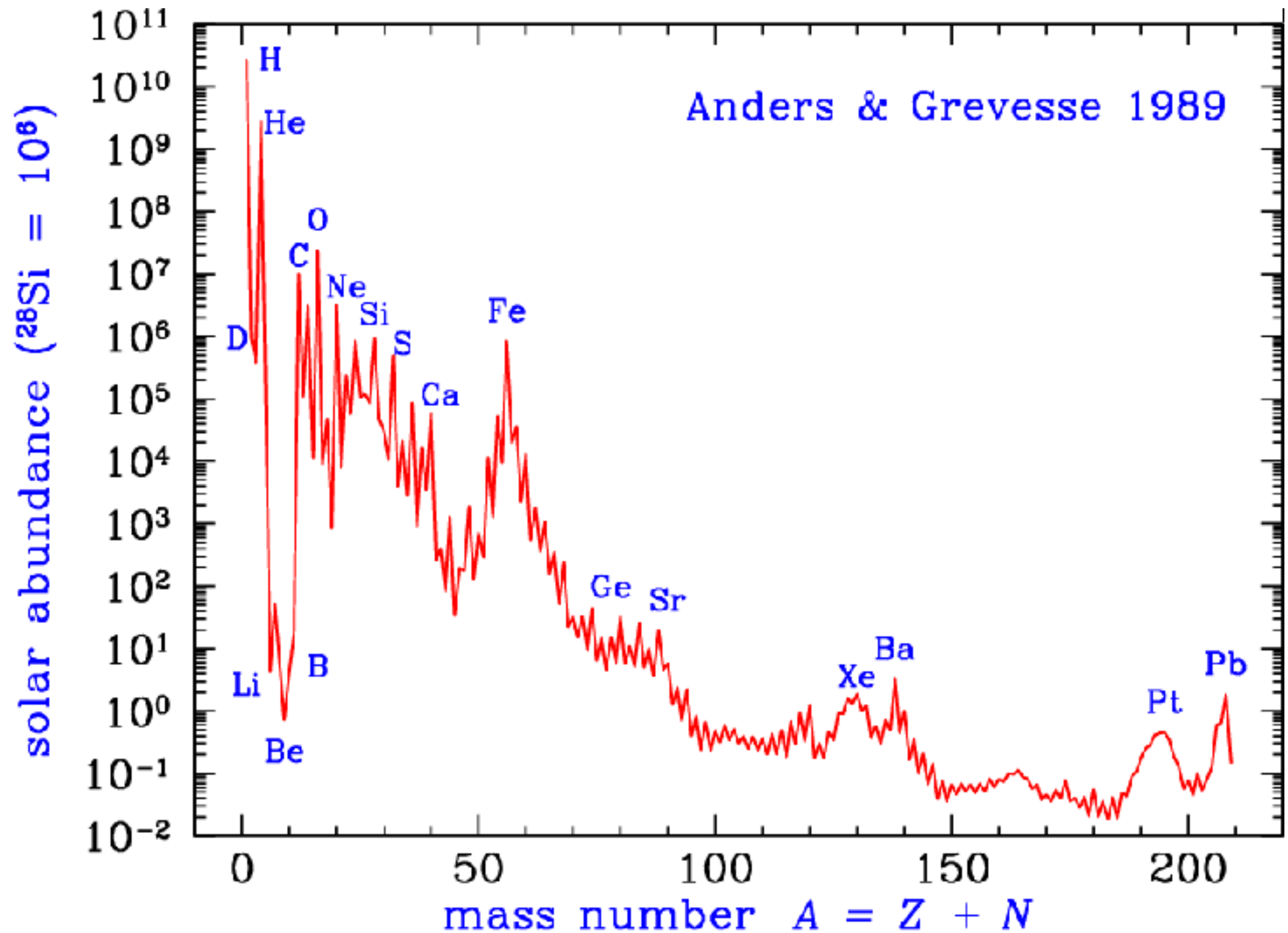
nucleosynthesis in neutron star mergers

Primary r-process elements are most likely created in “NS merger”-like collapsar accretion disks



nucleosynthesis in supernovae

Stellar explosions are the most important source of enrichment in galaxies



Supernovae

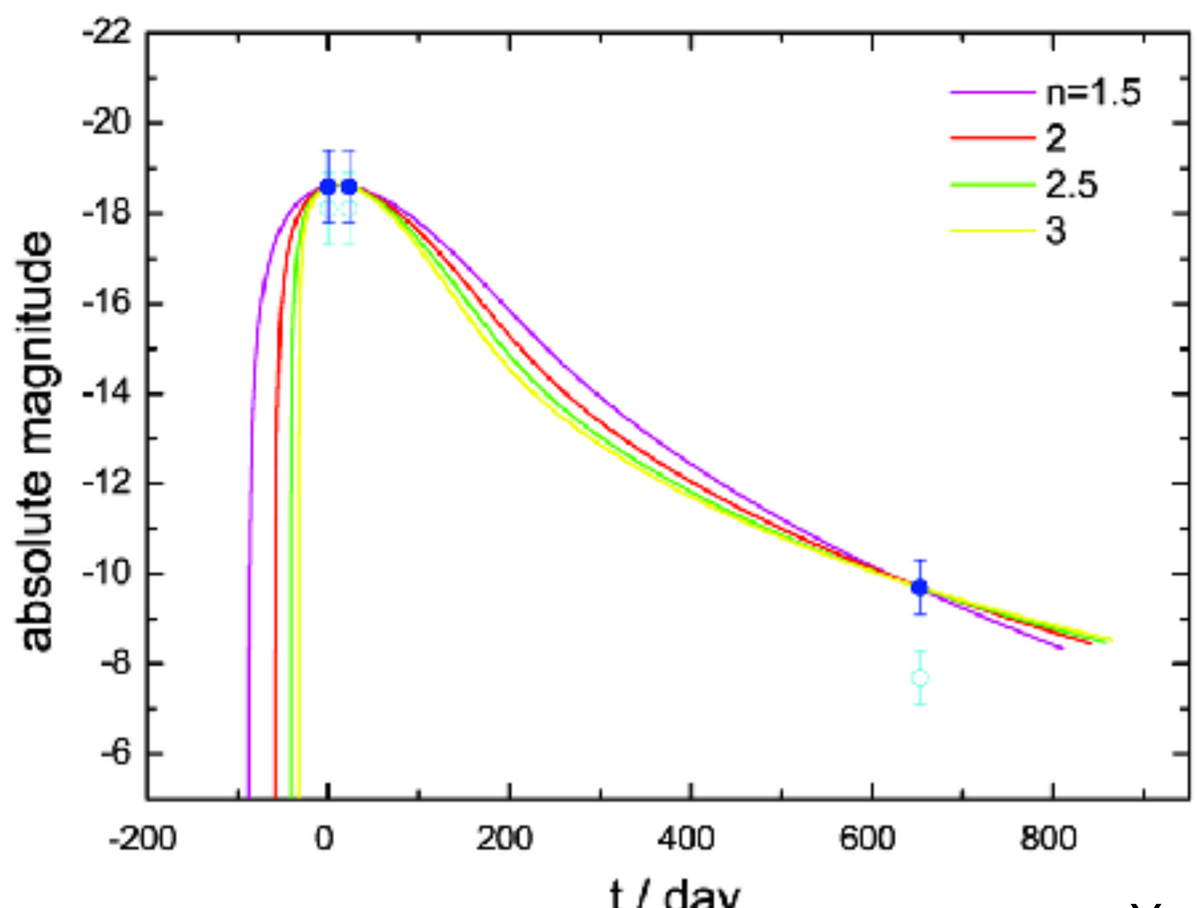
至和元年七月二十二日守將作監致仕楊惟德言伏覩客星出見其星上微有光彩黃色謹按黃帝掌握占云客星不犯畢明盛者主國有大賢乞付史館容百官稱賀詔送史館

嘉祐元年三月司天監言客星沒客去之兆也初至和元年五月晨出東方守天關晝見如太白芒角四出色赤白凡見二十三日

三月丁巳，詔禮部貢舉。辛未，司天監言：自至和元年五月，客星晨出東方守天關，至是沒。壬申，遣官謝天地、宗廟、社稷、寺觀、諸祠。癸酉，契丹遣使來謝。閏月癸未朔，以王舉正參知政事，程戡為樞密副使。詔前後殿間日視事。夏四月壬子朔，大塔河復決。丙辰，詔定補蔭選舉法。甲戌，錄繫囚。是月，大雨，水注安上門，門關折，壞官私廬舍數萬區。諸路言江、河決溢，河北尤甚。

宋史卷十二　仁宗四　二三九

明道元年六月乙巳，出東北方，近濁，有芒彩，至丁巳，凡十三日沒。至和元年五月己丑，出天關東南，可數寸，歲餘稍沒。熙寧二年六月丙辰，出箕度中，至七月丁卯，犯箕乃散。三年十一月丁未，出天囷。

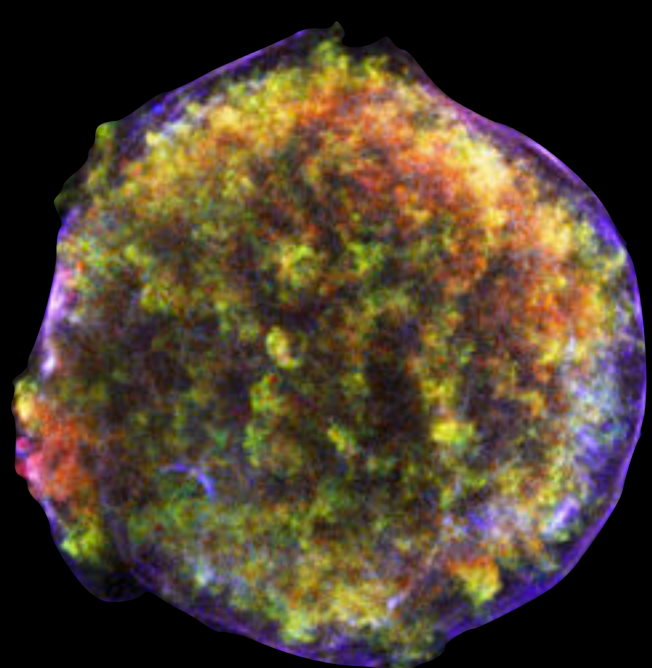


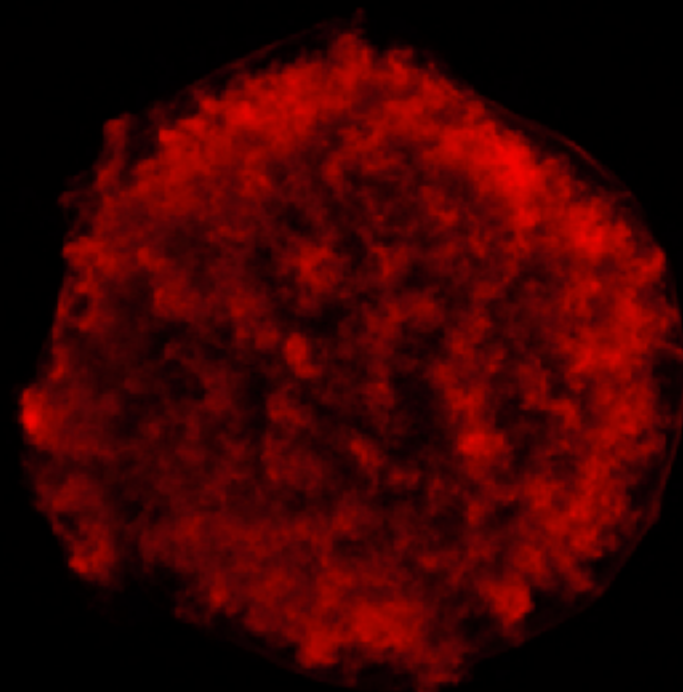
SN 1054

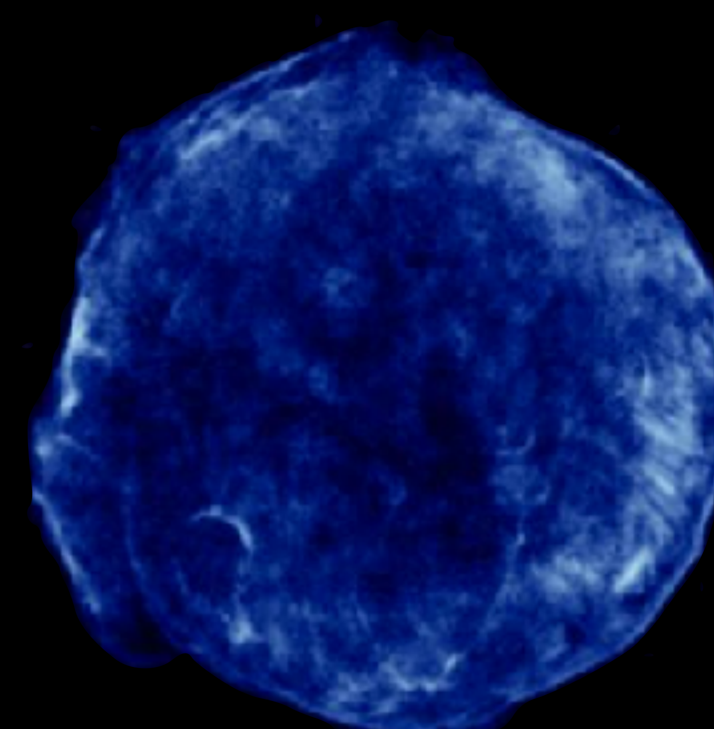
Yu et al. 2015

Supernovae

SN 1054



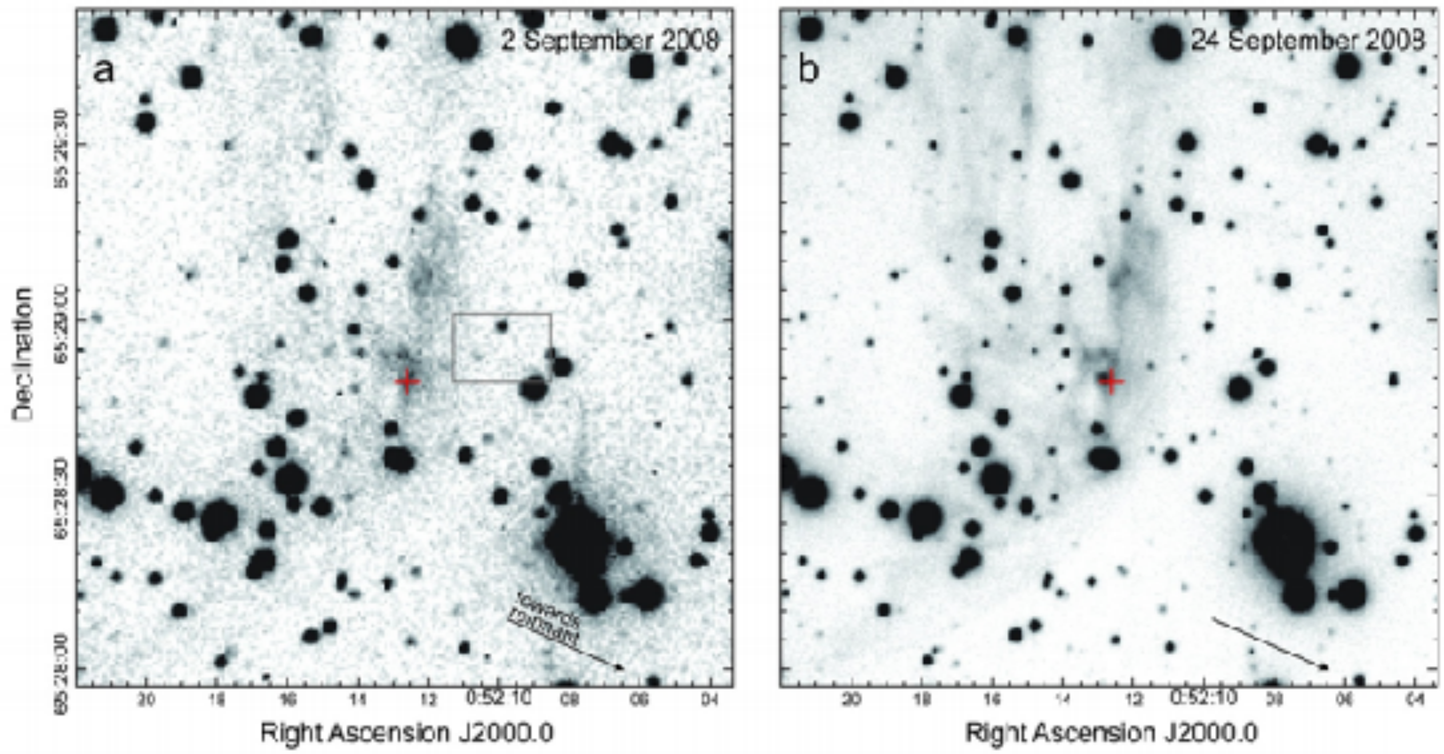


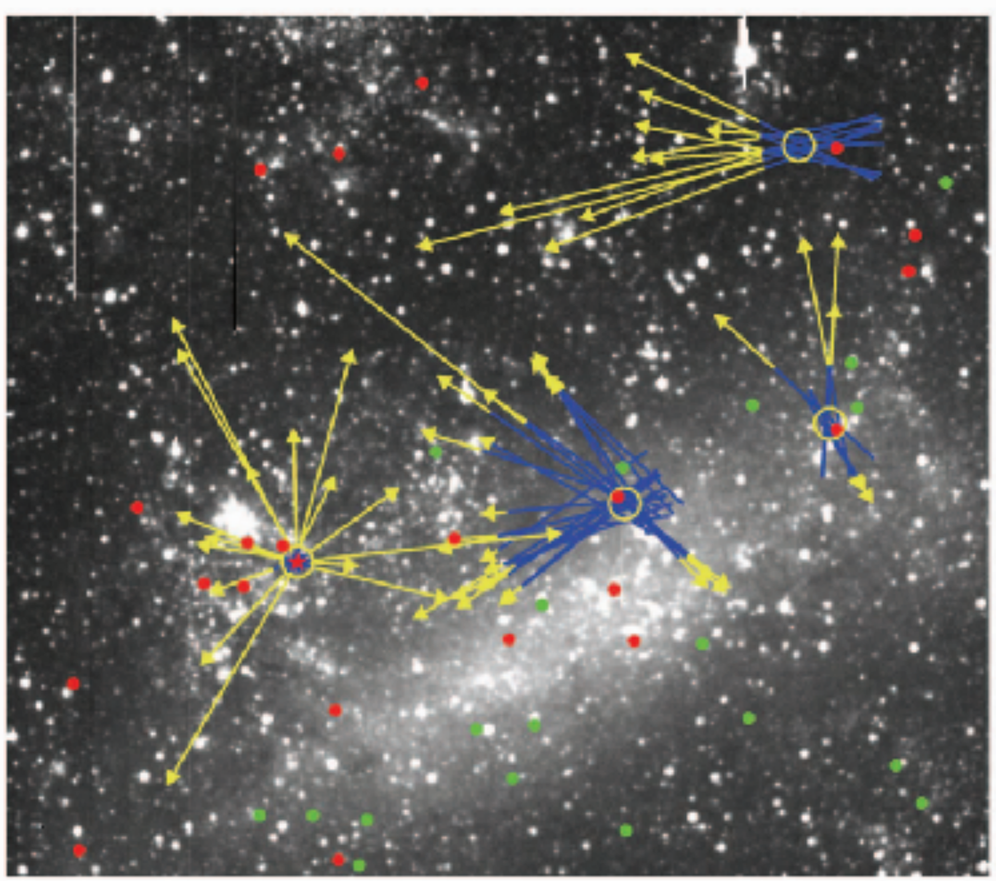


SN 1572

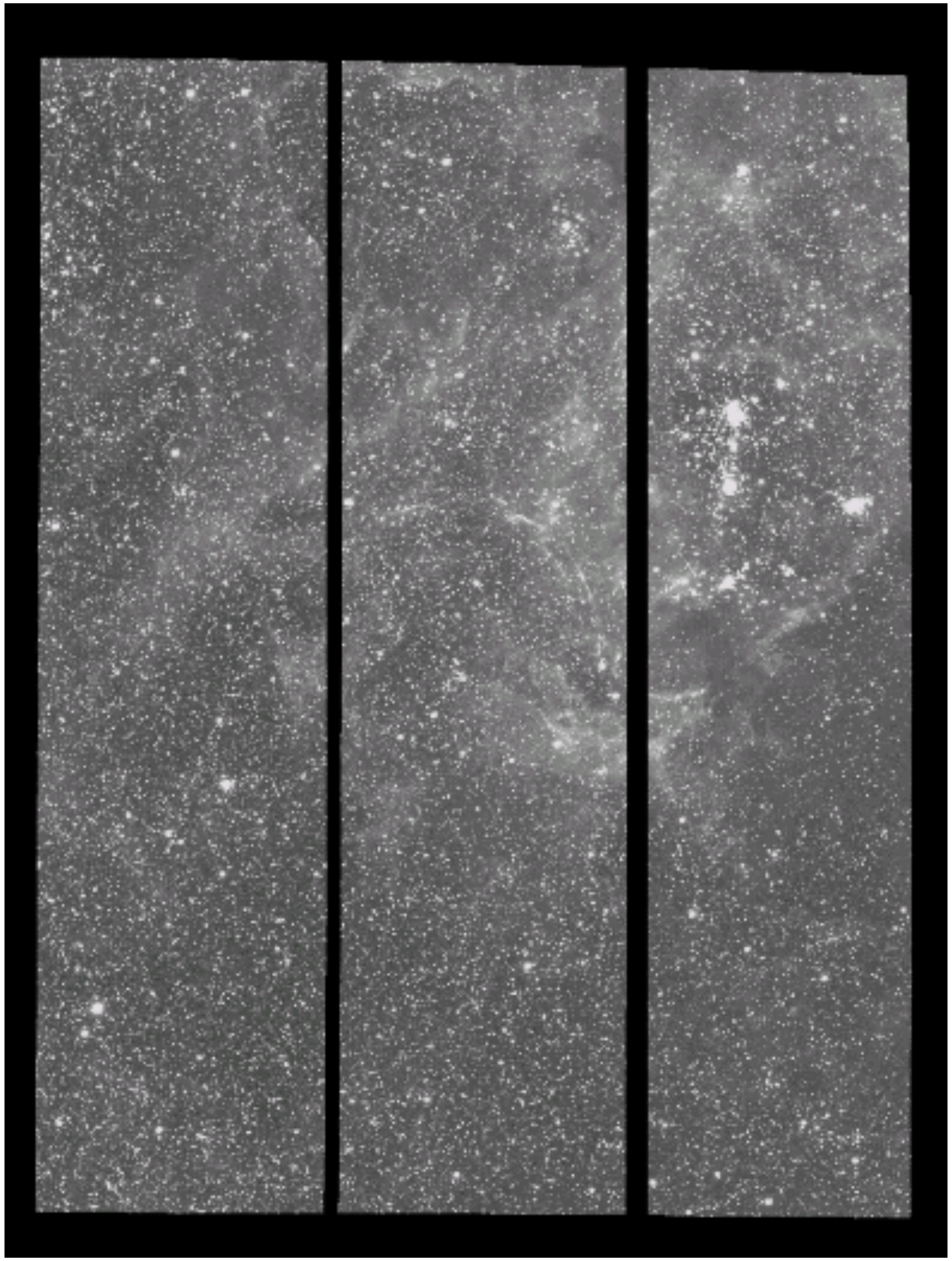
supernovae

Light echoes from SN 1572





Light echoes from SN 1987A



Krause et al. 2008, Rest et al. 2005

stellar explosions

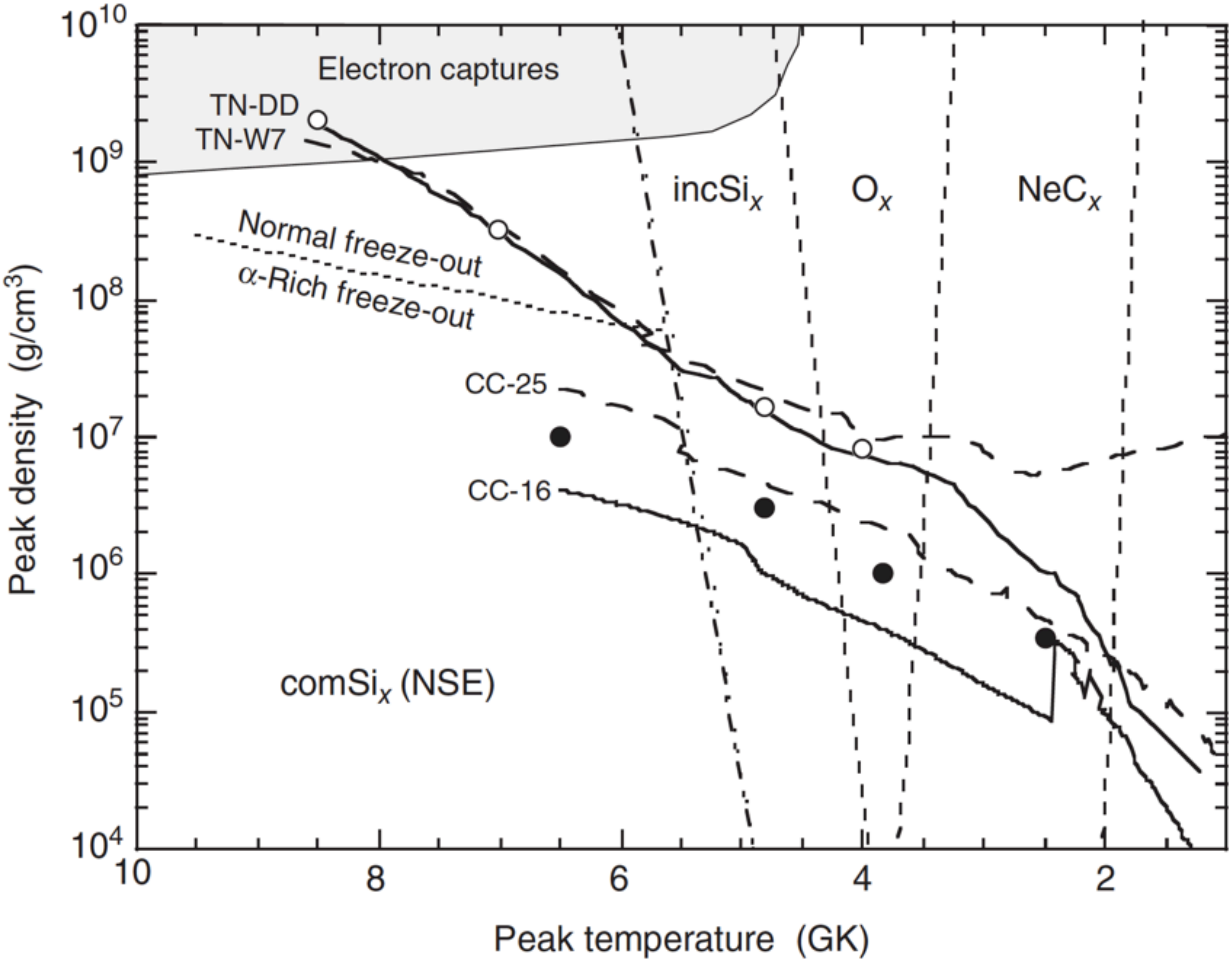
The simplest model for a supernova explosion is that of a conventional bomb

Large amount of energy on the verge of being released

+

trigger

Bombs often fail because they are not triggered in the right way.
So do most of our *model* supernova explosions!!!
Still not in a position to explain stellar explosions from first principles



Electron captures
TN-DD
TN-W7
Normal freeze-out
α-Rich freeze-out
incSi$_x$
O$_x$
NeC$_x$
CC-25
CC-16
comSi$_x$ (NSE)
Peak density (g/cm^3)
Peak temperature (GK)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10
8
6
4
2

nuclear statistical equilibrium

A system at *any temperature and density* will come into equilibrium, provided it is maintained for long enough

The nuclear statistical equilibrium most relevant for astrophysics is one in which strong and EM interactions participate. The abundance of each element is given in terms of its nuclear properties and the local plasma conditions

$$X_i(A_i, Z_i, T, \rho) = \frac{A}{N_A \rho} G(A, Z, T) \left(\frac{2\pi k T M(A_i, Z_i)}{h^2} \right)^{3/2} \exp \left[\frac{\mu(A_i, Z_i) + B(A_i, Z_i)}{kT} \right]$$

$$\mu(A_i, Z_i) = Z_i \mu_p + N_i \mu_n = Z_i \mu_p + (A_i - Z_i) \mu_n$$

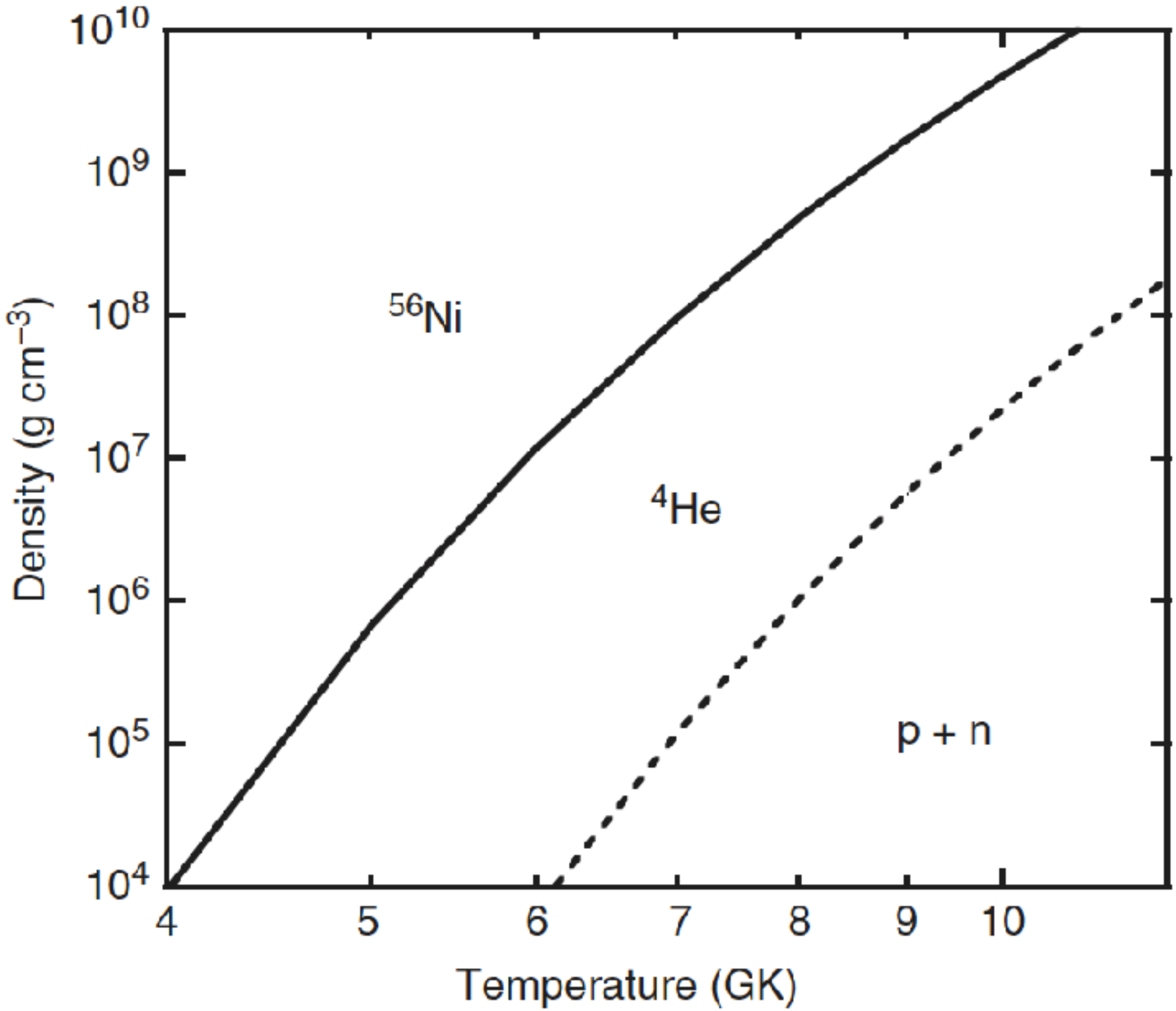
Mass (baryon number is conserved). Because weak interactions do not participate in the equilibrium, charge is also conserved (number of protons, neutrons)

$$\sum_i X_i = 1; \; Y_e = \sum \frac{Z_i}{A_i} X_i$$

With the above, each triplet (T, ρ, Y_e) yields a unique solution for (X_i, μ_p, μ_n)

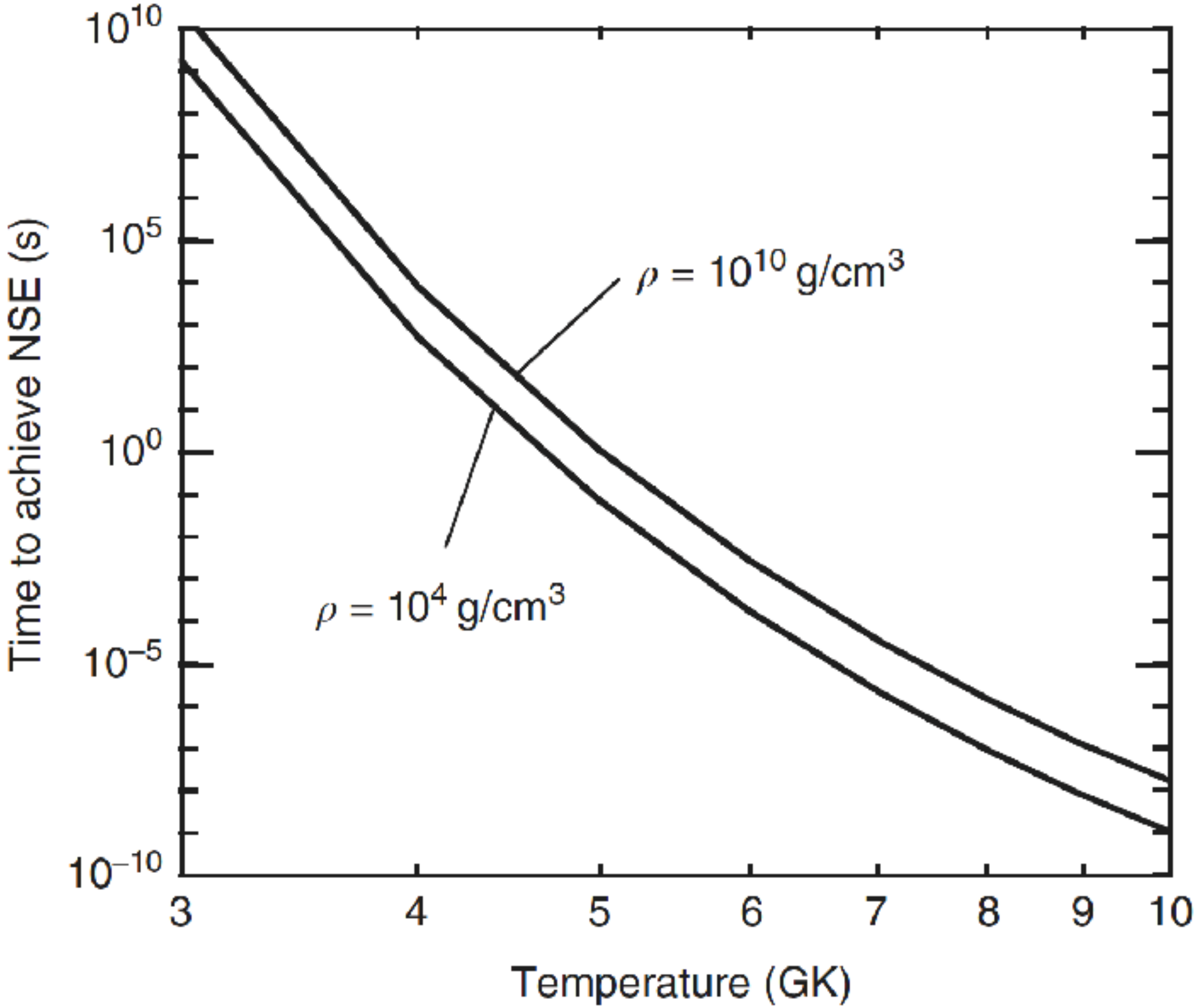
Blackboard

nuclear statistical equilibrium



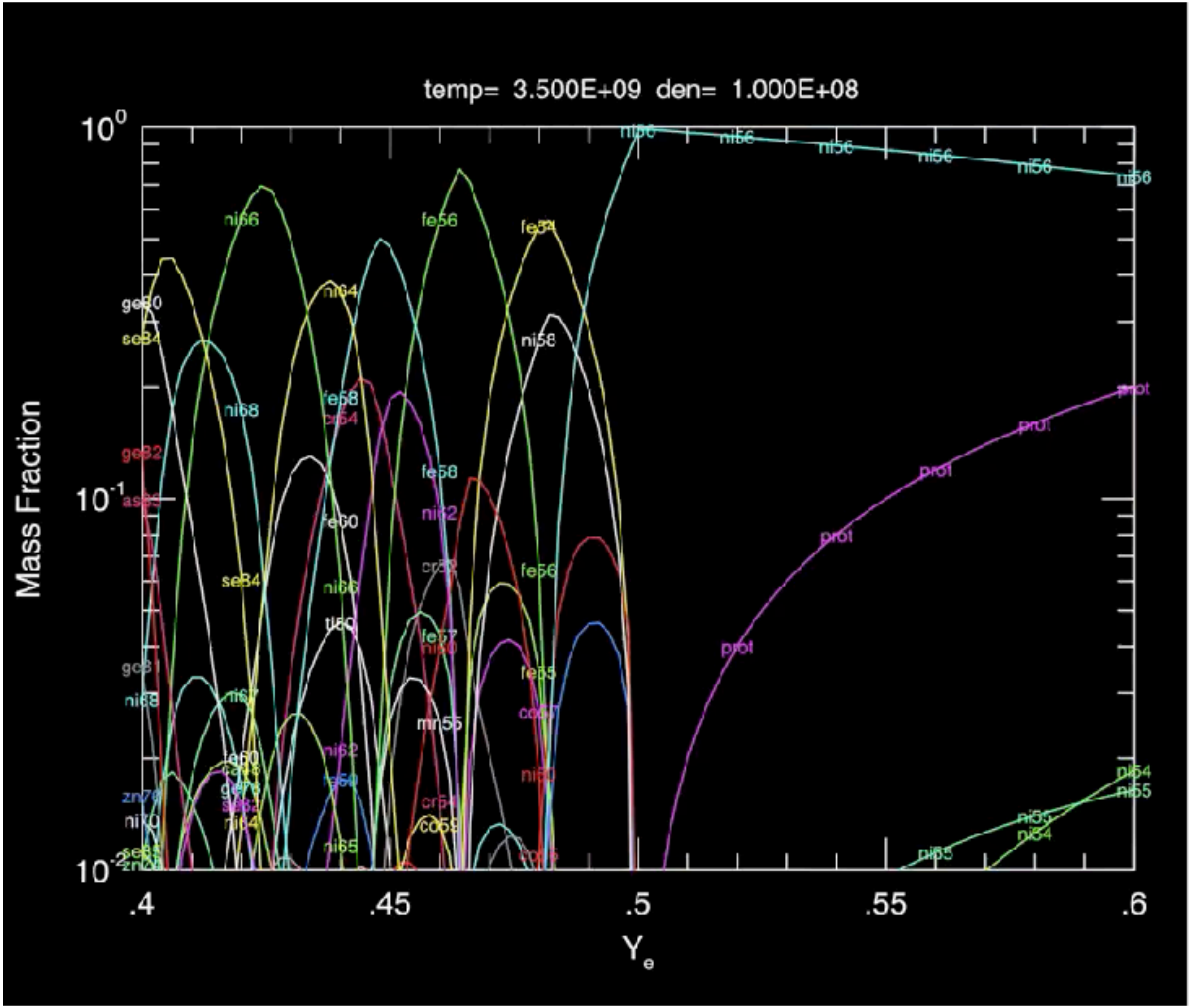
Credit: ILIADIS

nuclear statistical equilibrium



Credit: ILIADIS

nuclear statistical equilibrium



Credit: F. Timmes

SNe Ia

H- and He- deficient,
strong silicon lines

$10^{10\text{-}11}$ L_{sun}

$M_{56Ni} > 0.6$ M_{sun}

$v_{ej} > 10^3$ km/s

$E_{kin} \sim 10^{51}$ erg

in both elipticals+spiral

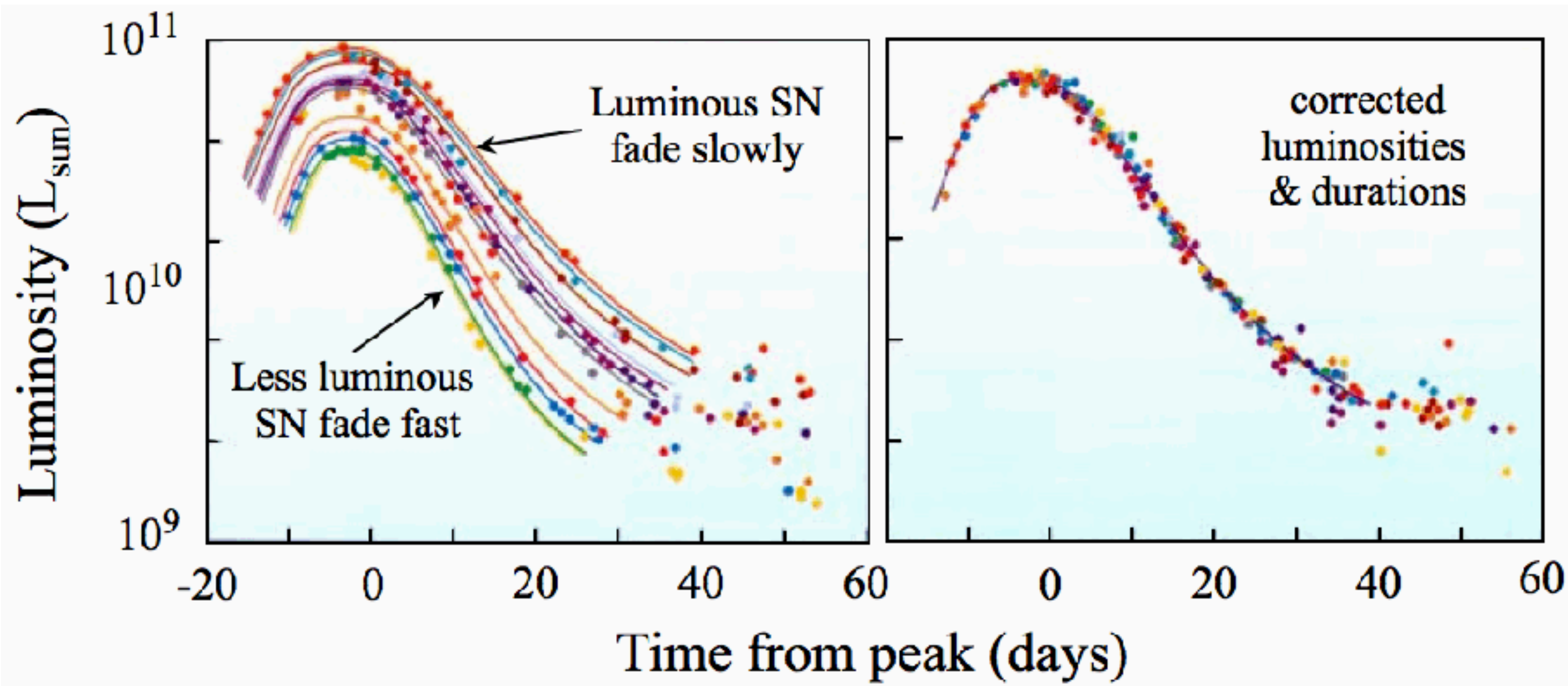
rate correlates with
star formation in spiral

similar peak L and
early spectra

SN 1994D; credit Nasa/HST

SNe Ia

Standardisable candles with high luminosities: can be used to measure cosmological distances (Phillips 1995)



SNe Ia models

The origin of SNe Ia is still debated! Most models include a CO white dwarf that somehow approaches the Chandrasekhar limit

Problem: stellar evolution makes CO white dwarfs with masses up to ~1.1 Msun
Somehow the white dwarf needs to gain ~0.2-0.3 M_{sun}

Three chief possibilities

single-degenerate model Chandrasekhar mass model
Mass accretion from a non-degenerate stellar companion until Chandrasekhar limit is reached. Carbon ignites in the centre due to compressional heating

single-degenerate model sub-Chandrasekhar mass model
Mass accretion from a non-degenerate stellar companion builds a thick He layer on top of CO core. Helium detonation leads to compression and carbon ignition

double degenerate model
Mass accretion in a merger

Each model has its own pros and cons. Still many aspects, including ignition and flame propagation are highly uncertain

SNe Ia: SD scenario

Accretion from a companion
if rate too high: common envelope
if rate too low: nova eruptions (mass likely decreases)
only seems possible for a small range accretion rates 10^{-7} M_{sun}/yr for billions of years
possibly visible as soft x-ray sources

SNe Ia: SD scenario

As the mass of the star increases due to accretion, so does the density/temperature in the core

$^{12}C + ^{12}C$ rate increases (highly screened!), at some point the energy generation rate becomes larger than the neutrino cooling rate —> **ignition**

Initially the extra energy drives convection which extends throughout the entire star —> **carbon shimmering**

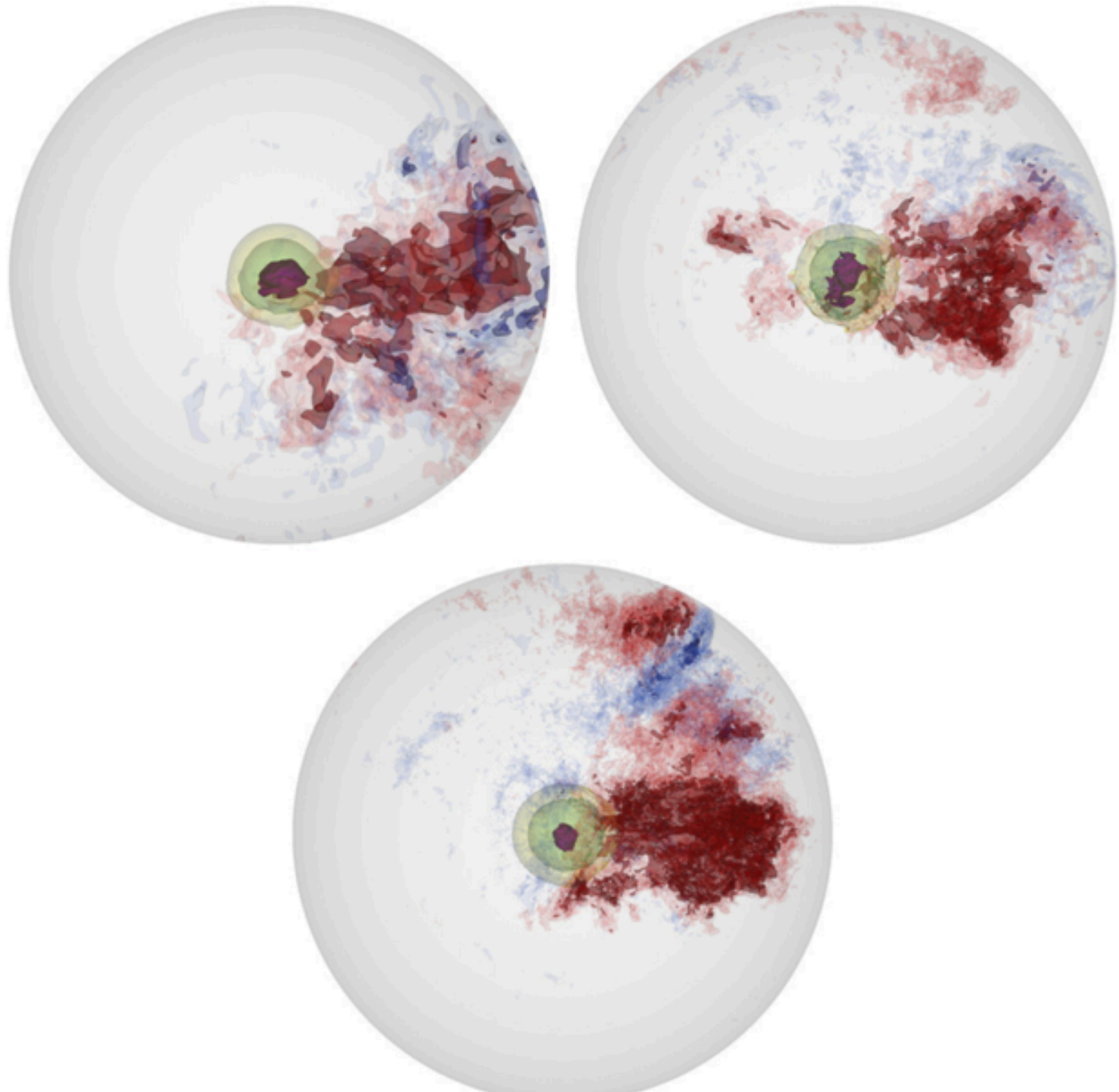
As temperature increases, there comes a point at which $\tau_{burn} \sim \tau_{conv}$

Runaway ensues! Burning becomes faster than the time it takes a sound wave to cross a pressure scale hight

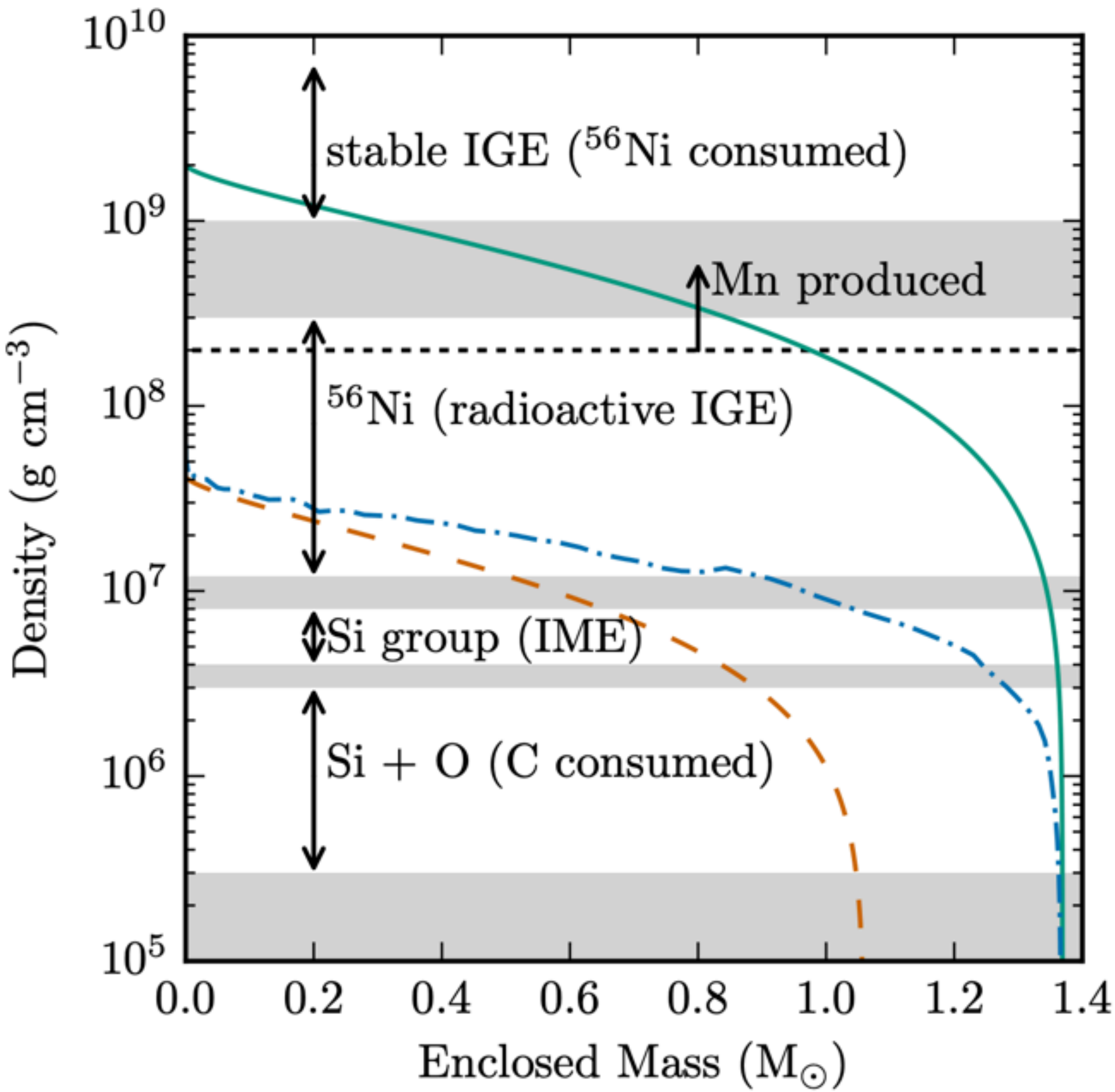
SNe Ia: SD scenario

Ignition may start off-centre and propagate inwards

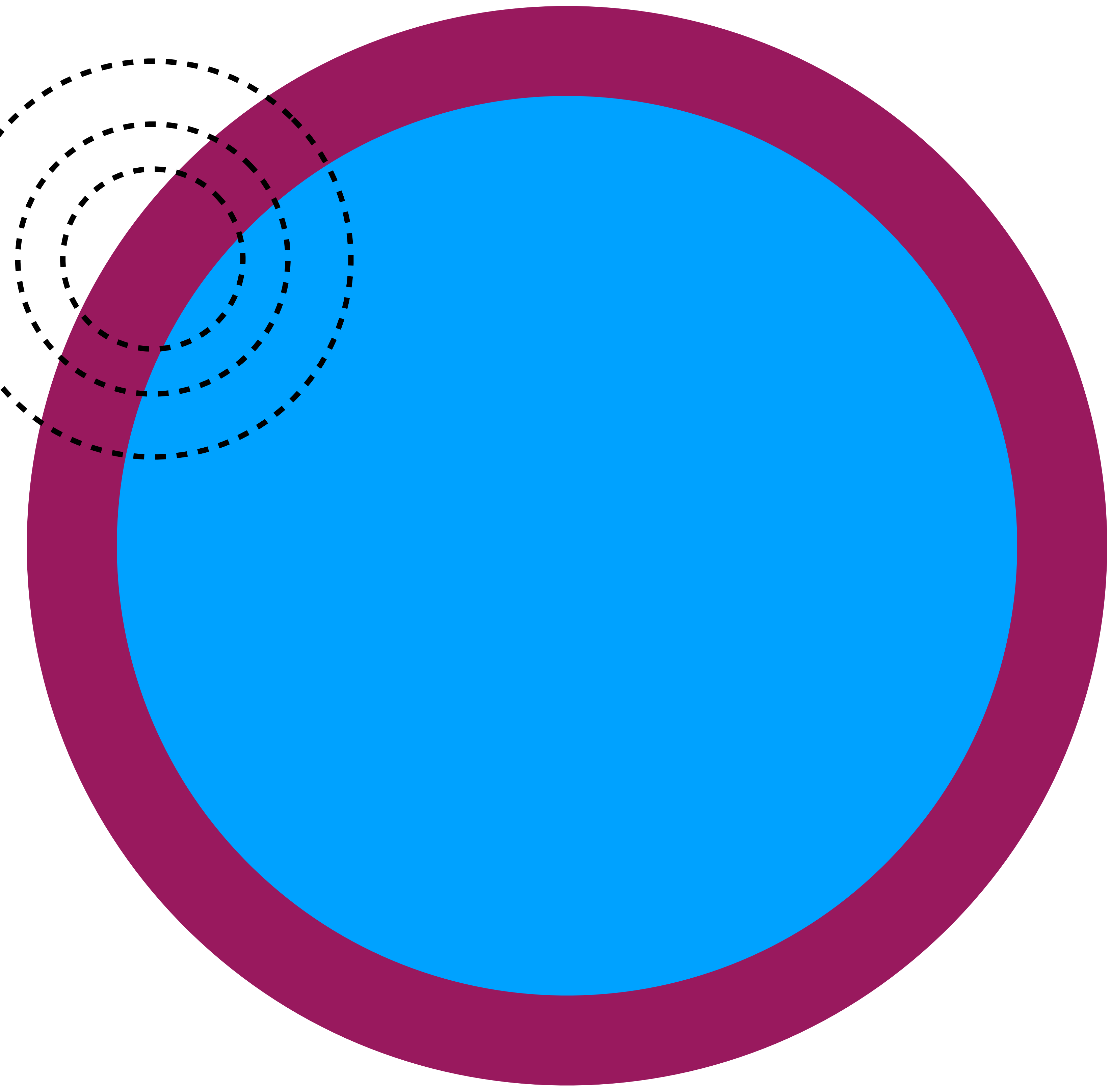
THE ASTROPHYSICAL JOURNAL, 745:73 (22pp), 2012 January 20 NONAKA ET AL.



SNe Ia: deflagration, detonation or both?



sub-Chandrasekhar mass models



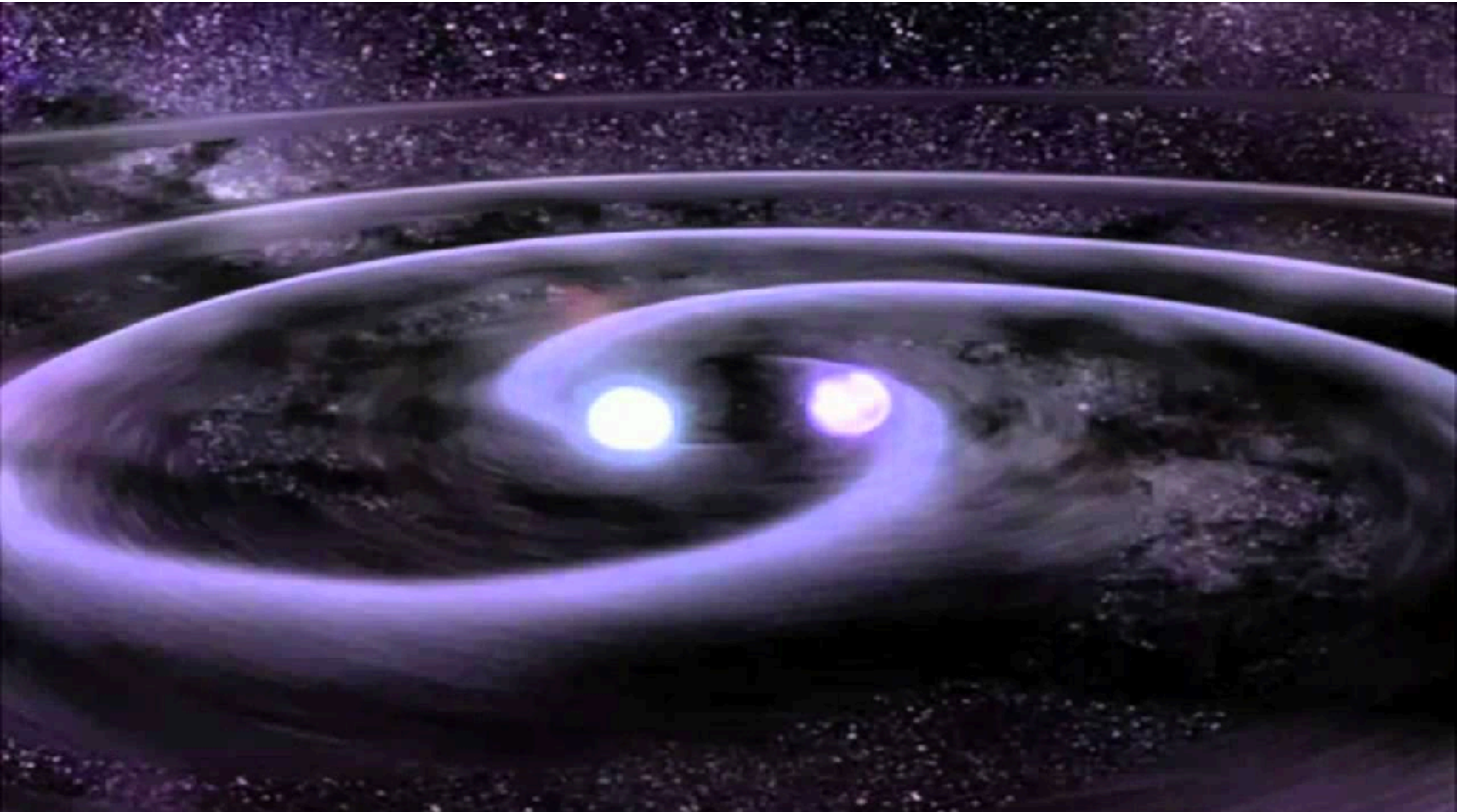
Helium layer should be thin enough to be invisible in the spectrum but thick enough to ignite (0.01-0.07 Msol)

Diversity of possible outcomes

Can have multiple ignition points

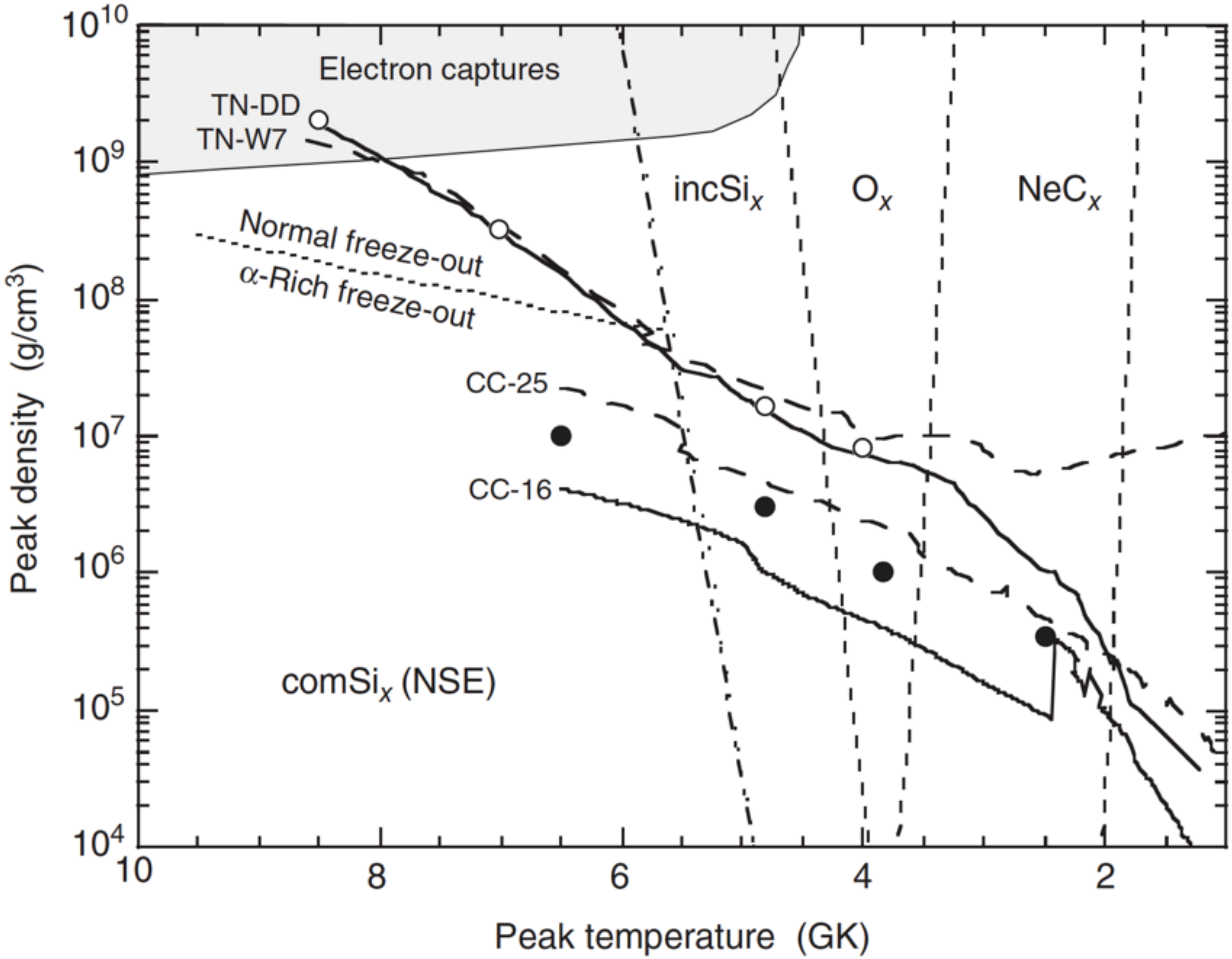
mergers

Wide range of possible outcomes ranging from prompt detonation to a stable configuration depending on initial masses and compositions



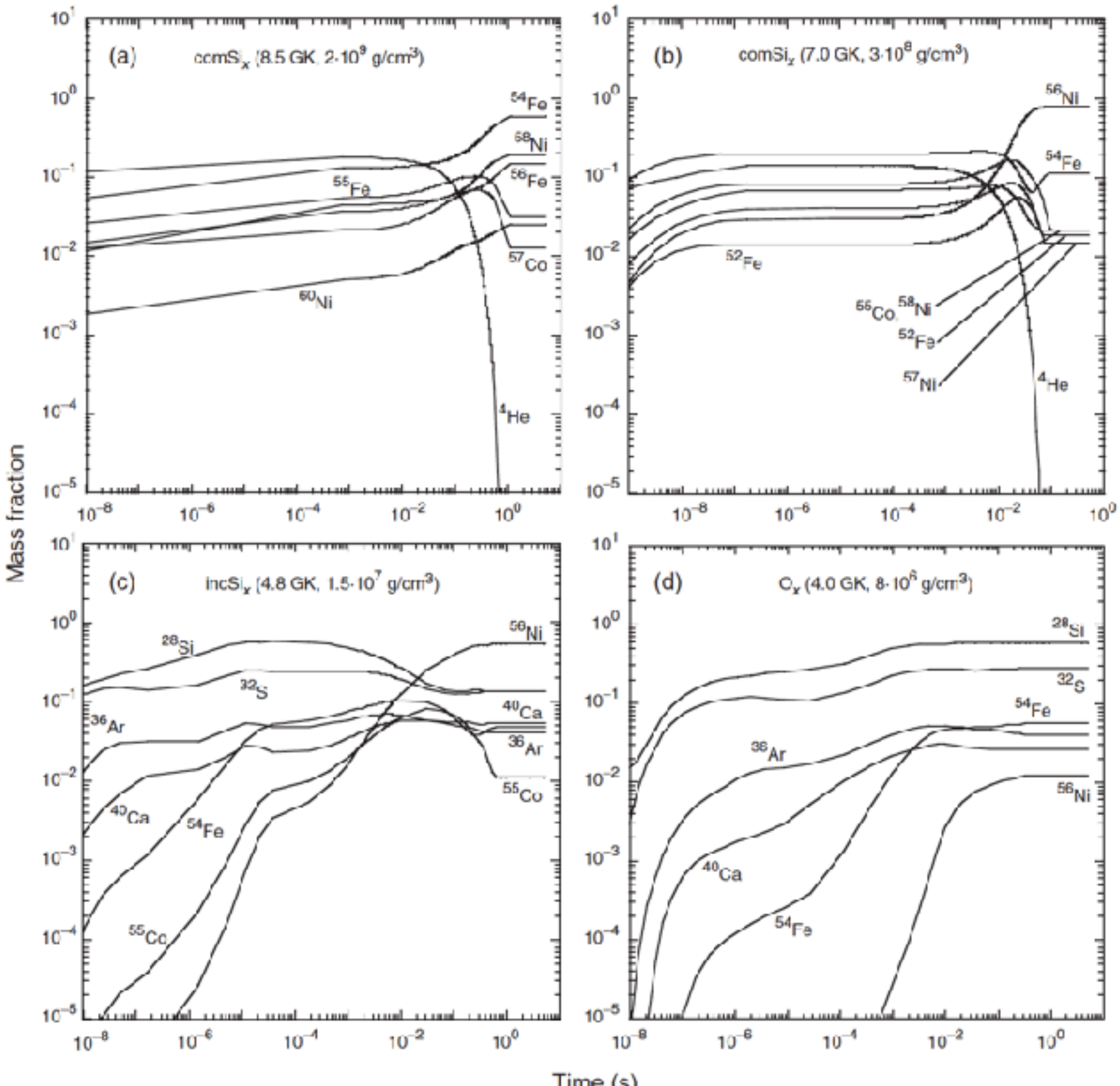
SNe Ia nucleosynthesis

Consider simple detonation model and post-shock adiabatic cooling



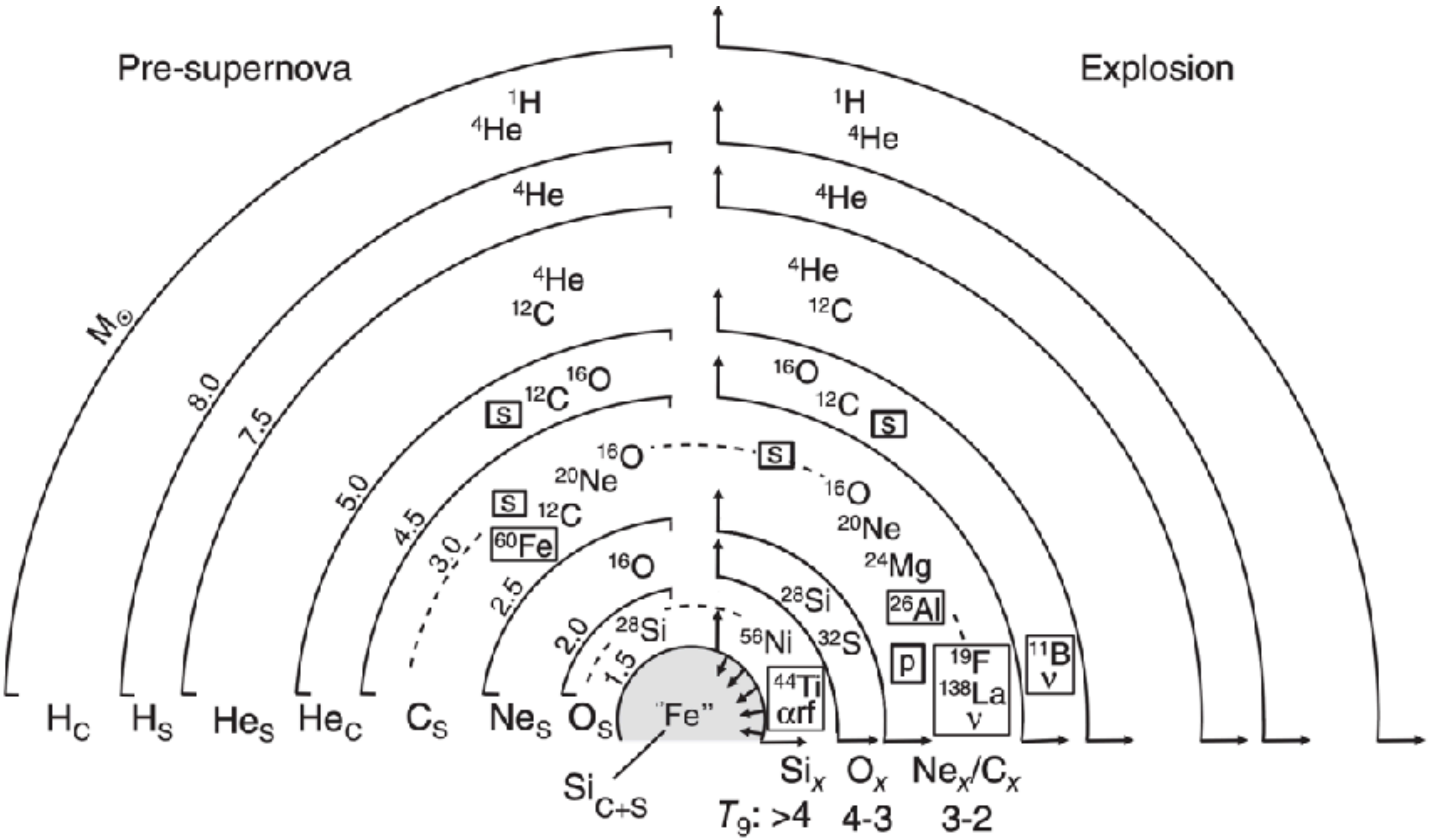
Credit: ILIADIS

SNe Ia nucleosynthesis



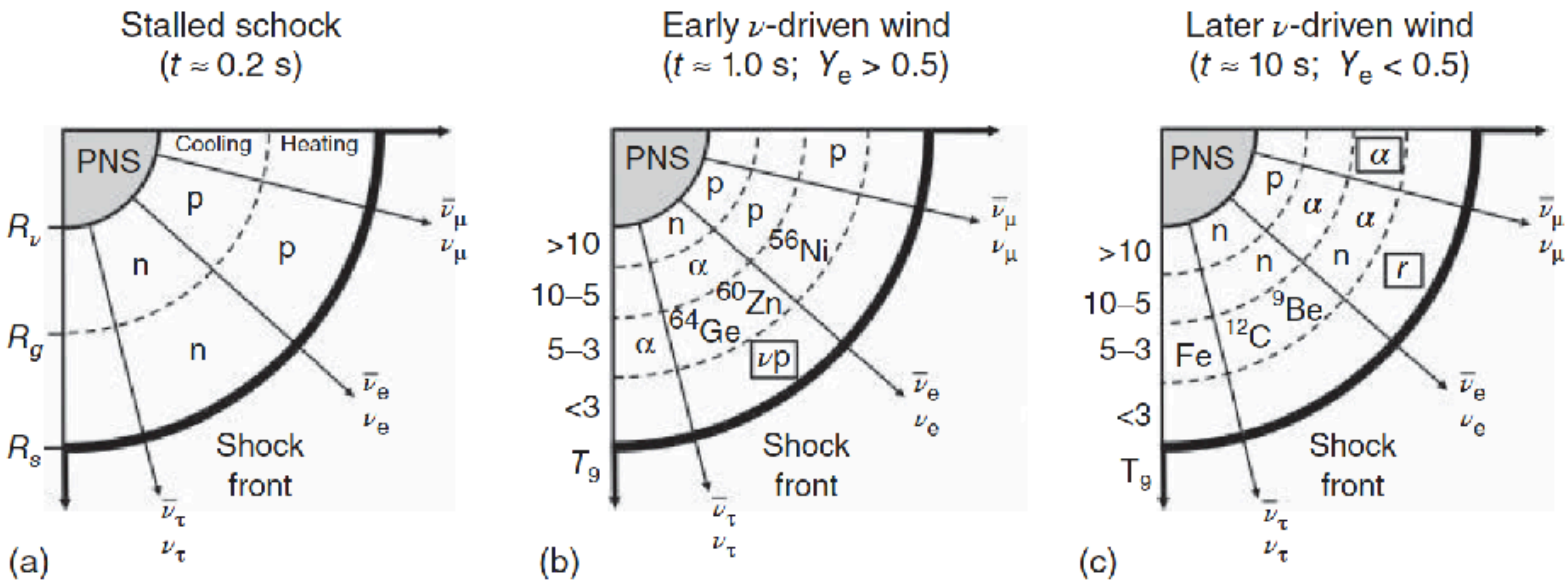
Credit: ILIADIS

Pre-supernova structure and core-collapse



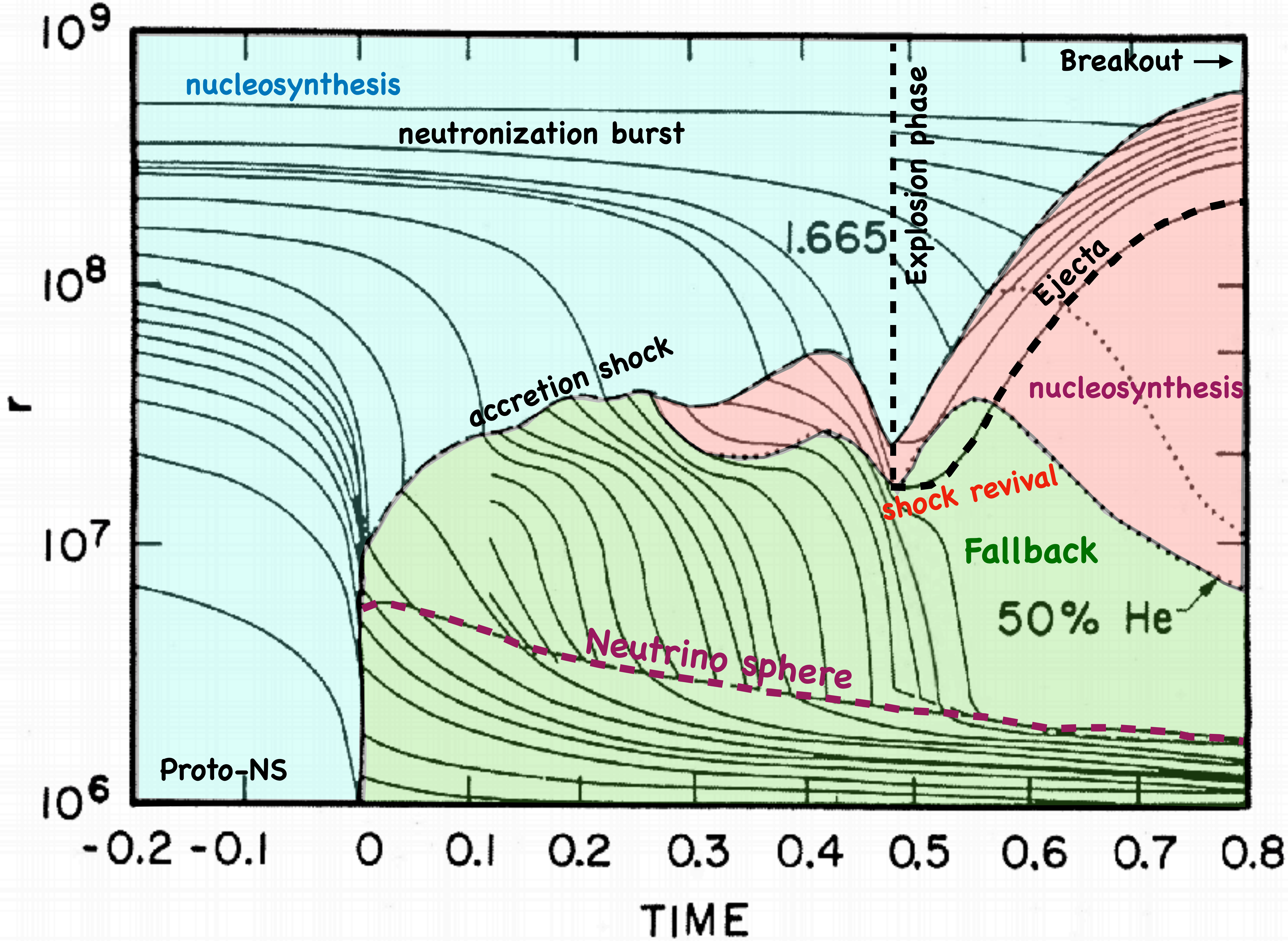
Credit: ILIADIS

Pre-supernova structure and core-collapse



Credit: ILIADIS

Core-collapse supernovae



Bethe & Wilson (1985)