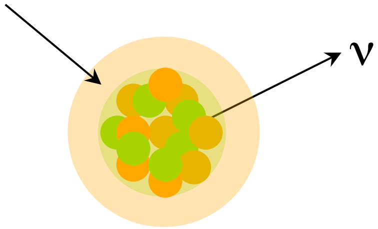
Physics of Core-Collapse Supernovae



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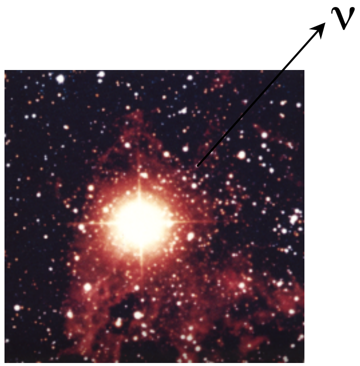


SN1987A

- Astrophysics: mechanism of supernova explosion
- Nuclear physics: matter at extreme conditions

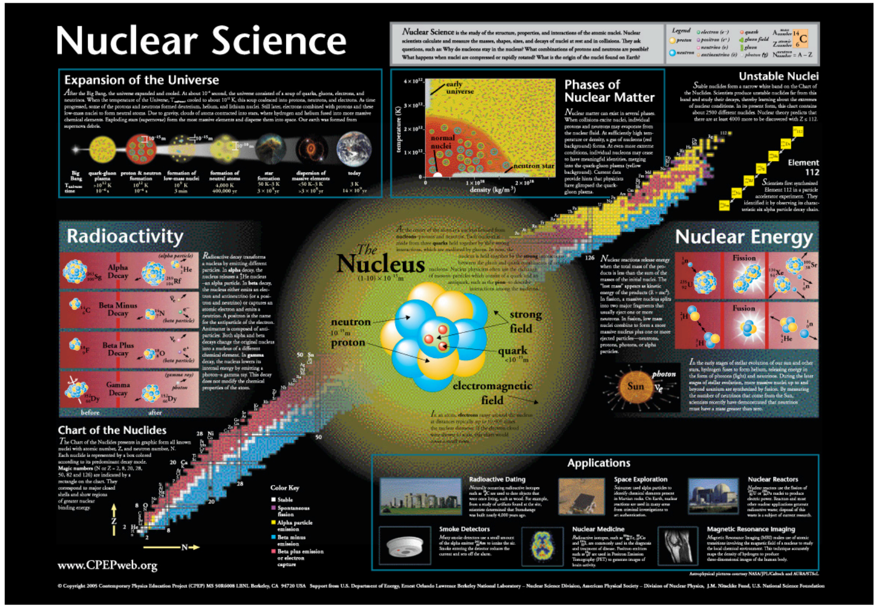
- Theory, Experiments, Observations, Supercomputers

Lecture at Osaka U., 2011. 7. 11

Focus of Lecture

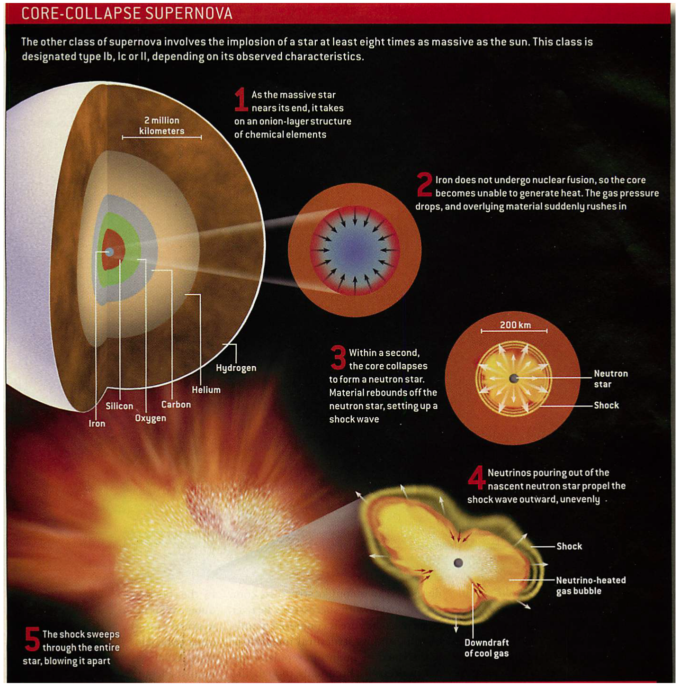
- Interplay of nuclear physics and astrophysics

Nuclei and matter



http://www.lbl.gov/abc/wallchart/index.html

Supernova explosions


CORE-COLLAPSE SUPERNOVA

The other class of supernova involves the implosion of a star at least eight times as massive as the sun. This class is designated type Ib, Ic or II, depending on its observed characteristics.

1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements

2 Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in

3 Within a second, the core collapses to form a neutron star. Material rebounds off the neutron star, setting up a shock wave

4 Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly

5 The shock sweeps through the entire star, blowing it apart

Scientific American (2006)

How are they related to each other?

Microphysics determines the outcome.

Items in this lecture

- What is “supernova explosion”?
  - Fate of massive star, evolution of the Universe
- Scenario of supernova explosion
  - Explosion energy from gravitational collapse?
- Nuclear physics in supernovae
  - Properties of dense matter, neutrino reactions
- Numerical simulations of supernovae
  - Needs of nuclear physics and difficulties

Collapse-driven supernovae

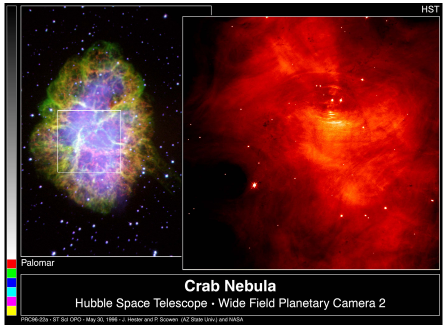
Bright display, origin of neutron stars and elements

Happening in core-collapse supernovae

– Birth of neutron stars and black holes

- Pulsars (1.4 solar mass in ~10km)
- Extremely dense: degenerate Fermions

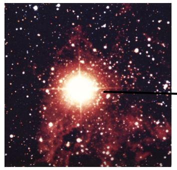
Crab Nebula (SN1054)



– Source of cosmic rays

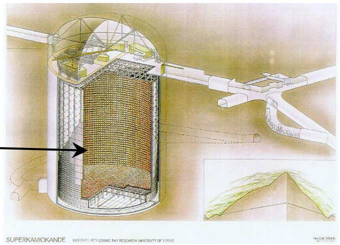
- Neutrino bursts: Nobel prize in Physics in 2002
- Evolution of matter & galaxies

SN1987A



ν

Kamiokande



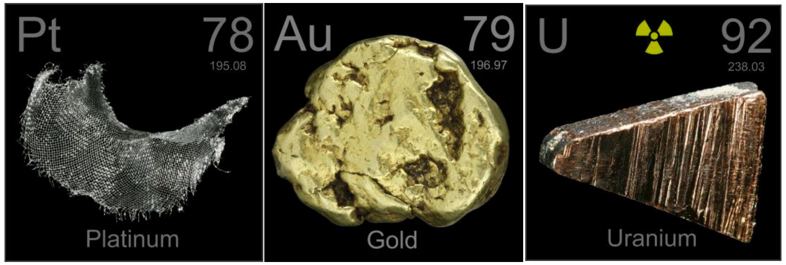
http://www-sk.icrr.u-tokyo.ac.jp/

Prof. Koshiba

http://nobelprize.org/

– Origin of heavy elements

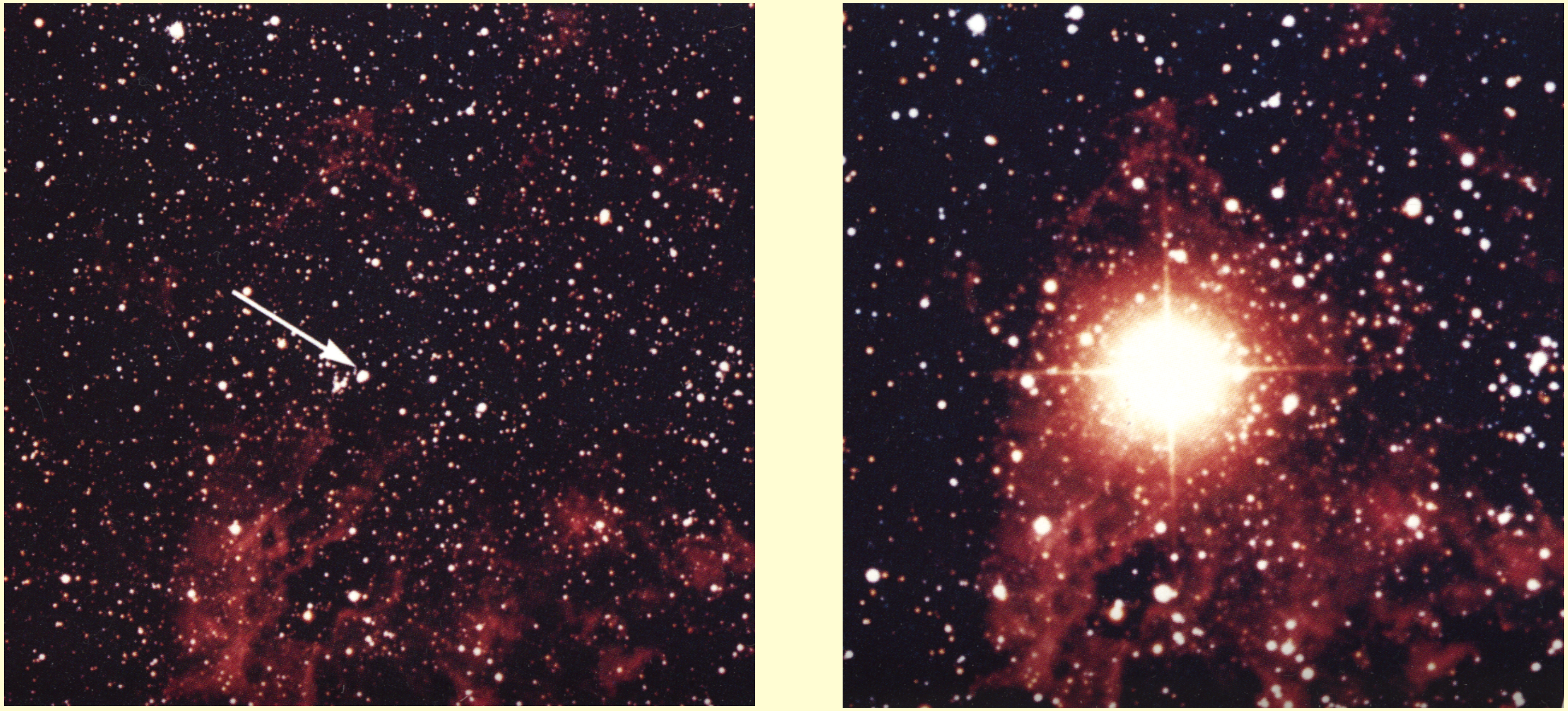
- Explosive nucleosynthesis
- Half of elements beyond Fe



http://periodictable.com/

Neutrino
+/- 1min

Supernova explosion: 23 February 1987, 7:35:35 (UT)



Before

After

At the end of life of massive star ~$20M_{solar}$

A.K.Mann "Shadow of a Star" (W.H. Freeman and Company, 1997)

Energy of supernova explosion

- Radiation energy: $E_{rad} \sim 10^{49}$ erg
  - Luminosity: $10^{41} \sim 10^{42}$ erg/s
- Explosion energy: $E_{kin} \sim 10^{51}$ erg
  - Kinetic energy of mass ejecta

- Total energy release of Sun for 4.5 billion years: $\sim 10^{51}$ erg
  - Solar luminosity: $4 \text{x} 10^{33}$ erg/s

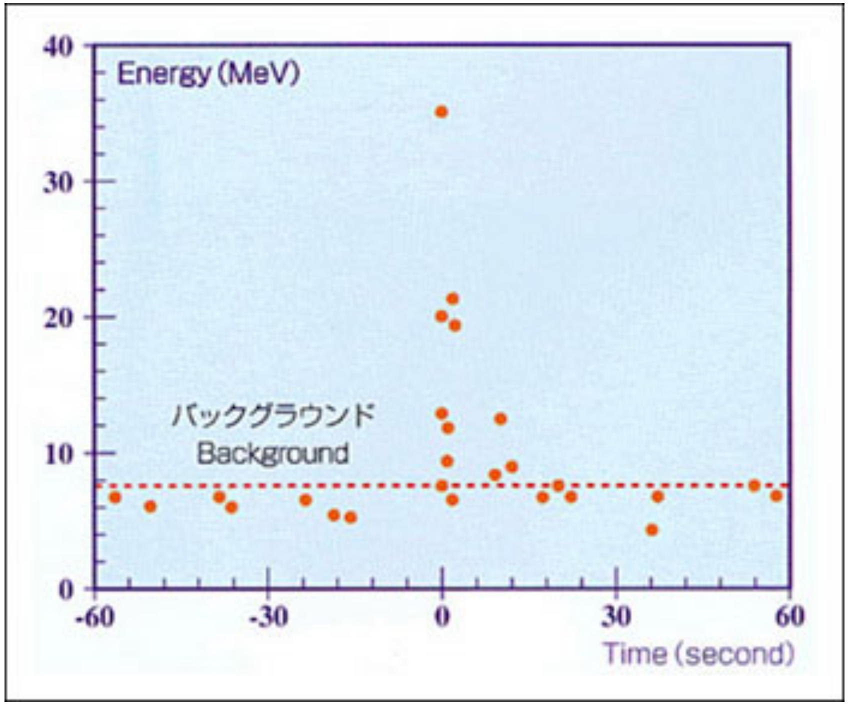
- Neutrino energy: $E_{\nu} \sim 10^{53}$ erg
  - Detection of neutrinos from SN1987A

Note: 1 J = 10^{7} erg

Neutrinos from SN1987A were detected

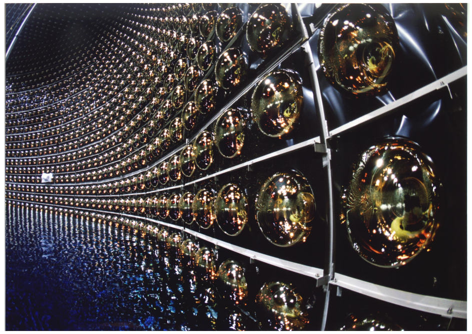
Research facilities for neutrino detections:

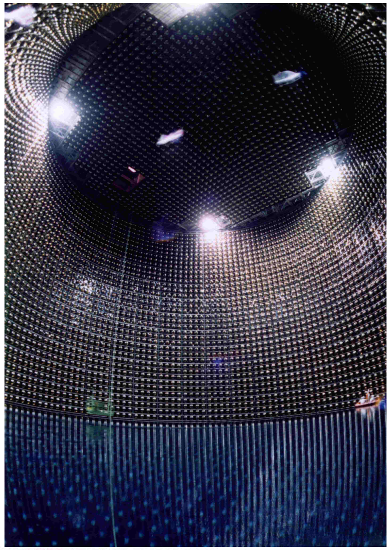
KAMIOKANDE-II (1983-1996)
Water tank 3000t + 1000 PMTs



~10^{16} neutrinos pass through the tank,
11 neutrinos are detected

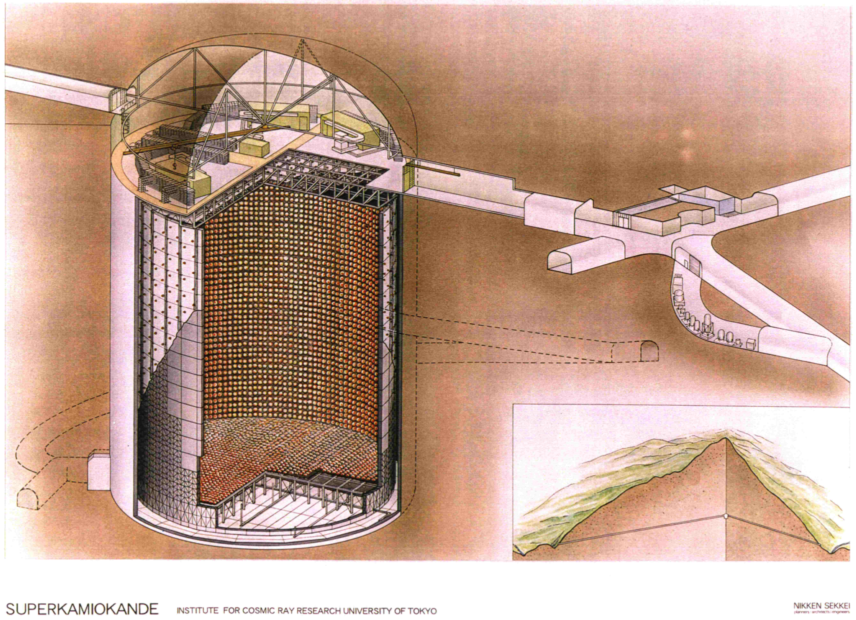
Average energy: E_ν ~10 MeV
Total energy: ~10^{53} erg





currently
SuperKamiokande

Kamioka, Gifu, Japan



http://www-sk.icrr.u-tokyo.ac.jp/

The Nobel Prize in Physics 2002

KUNGL.
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

English
French
German
Japanese (pdf)
Swedish

Press Release

8 October 2002

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize
2002 with one half jointly to

Raymond Davis Jr
Department of Physics and Astronomy, University of Pennsylvania, Philadelphi

Masatoshi Koshiba
International Center for Elementary Particle Physics, University of Tokyo, Japan

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

and the other half to

Riccardo Giacconi
Associated Universities Inc., Washington DC, USA

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources".

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小柴氏にノーベル賞

素粒子ニュートリノを観測

天体物理学を開拓

東大名誉教授

【ロンドン＝東海林一樹】スウェーデン王立科学アカデミーは八日、二〇〇二年のノーベル物理学賞を小柴昌俊東京大学名誉教授（76）と米ペンシルベニア大学物理・天文学科のレイモンド・デービス・ジュニア名誉教授（87）、米アソシエイテッド・ユニバーシティーズ社代表のリカルド・ジャコーニ氏（71）の三氏に授与すると発表した。小柴氏が宇宙から降り注ぐ素粒子ニュートリノの観測を通じて宇宙の進化や太陽内部のナゾを明らかにした業績を評価した。（関連記事3面、社会面に）

日本人、3年連続の受賞

日本人の受賞者は二〇〇〇年の白川英樹・筑波大学名誉教授（化学賞）、二〇〇一年の野依良治名古屋大学教授（化学賞）に次いで三年連続。ノーベル賞全体では十一人目。物理学賞は江崎玲於奈・芝浦工業大学学長が一九七三年に受賞して以来二十九年ぶり。

デービス名誉教授は一九六九年に太陽から飛来するニュートリノを初めて検出。太陽のエネルギーは中心部の核融合反応がもたらすことを証明。

小柴氏は岐阜県神岡町の地下千㍍に巨大な観測装置カミオカンデを建設、デービス名誉教授の成果を裏付けた。八七年には超新星爆発で放出されたニュートリノの検出に世界で初めて成功。ニュートリノ観測に基づく新たな天文学を育てた。

小柴氏の後を継いだ東

ノーベル賞受賞の喜びを語る小柴東大名誉教授（8日夜、東京都文京区の東大）

小柴昌俊氏（こしば・まさとし）　1926年9月19日豊橋市生まれ。51年東京大学理学部卒業。米ロチェスター大学、シカゴ大学で研究生活を送り、70年東大理学部教授。87年、超新星からのニュートリノを世界で初めて検出。97年文化勲章受章。東大退官後も独ハンブルク大学、東海大学で教べんをとる。2000年イスラエルのウルフ賞を、今回同時受賞した米国のデービス博士と共同で受賞している。現在、東京大学素粒子物理国際研究センター参与。76歳。

"Observation of elementary particle, neutrino. Pioneer of (neutrino) astrophysics."

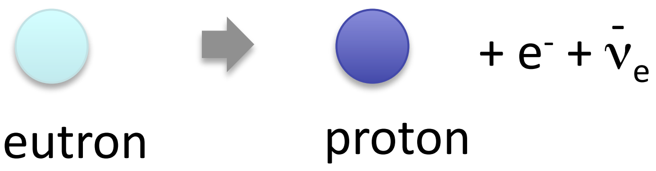
http://nobelprize.org

Neutrino: one of elementary particles

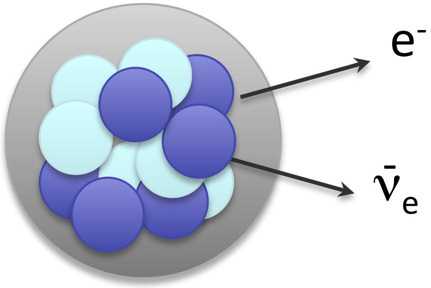
- Lepton: electron, muon, tau + 3 neutrinos
  - Electron-type: ν_e, mu-type ν_μ, tau-type ν_τ
  - (and their anti-particles)
  - Fermion: spin ½
  - Small mass, but not massless

e	μ	τ
ν_e	ν_μ	ν_τ

- Charge Neutral, Weak interaction
  - Very small cross section: $\sigma \sim 10^{-41}$ cm^2 (cf. 10^{-28} cm^2)



beta-decay of neutron



beta decay of nucleus

$^{14}C \rightarrow {}^{14}N + e^- + \bar{\nu}_e$

Supernova occurs ~1-2 times per century in a galaxy

- Observed so far

  5558 supernovae
- Recently

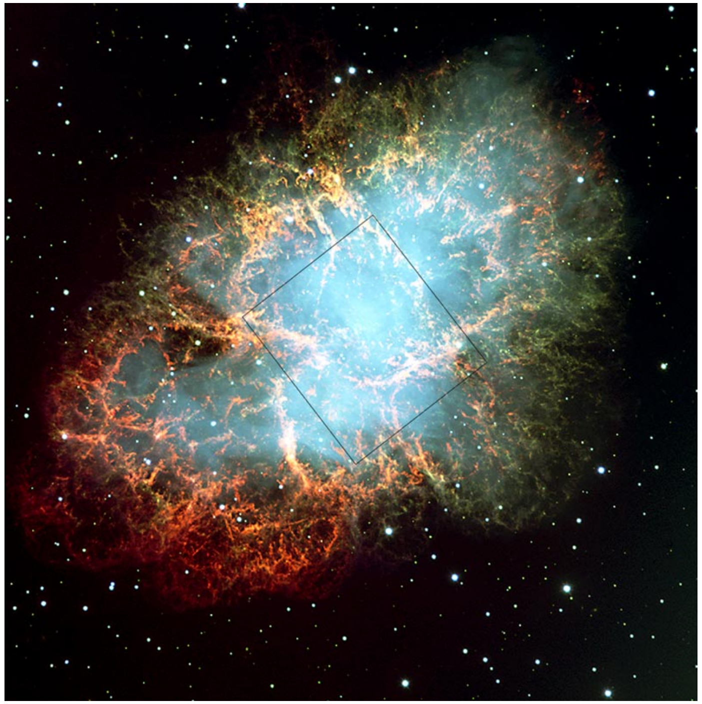
  2007: 573

  2008: 260

  2009: 390

  2010: 337

  2011: 26 (as of 7/9)



From http://hubblesite.org

Crab nebula: remnant of supernova in 1054

Supernova Catalog
http://www.sai.msu.su/sn/sncat/

d 6500 ly (2kpc)

Recorded in old Chinese and Japanese literatures

“Guest Star” in Sung Shih

Meigetsu-Ki by Teika, Fujiwara

凡十一日沒三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗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元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

The Crab Nebula (NGC 1952), the remains of the supernova of July 1054, an event observed and recorded at the Sung national observatory at K'ai-feng. In the intervening 900 years, the debris from the explosion has moved out about three lightyears; i.e., with a speed about 1/300 of that of light. In 1934 Walter Baade and Fritz Zwicky predicted that neutron stars should be produced in supernova explosions. Among the first half-dozen pulsars found in 1968 was one at the center of the Crab Nebula, pulsing 30 times per second, for which there is today no acceptable explanation other than a spinning neutron star. The Chinese historical record shown here lists unusual astronomical phenomena observed during the Northern Sung dynasty. It comes from the "Journal of Astronomy," part 9, chapter 56, of the *Sung History* (*Sung Shih*), first printed in the 1340's. The photograph of that standard record used in this montage is copyright by, and may not be reproduced without permission of, the Trustees of the British Museum.

From Gravitation by Misner, Thorn, Wheeler

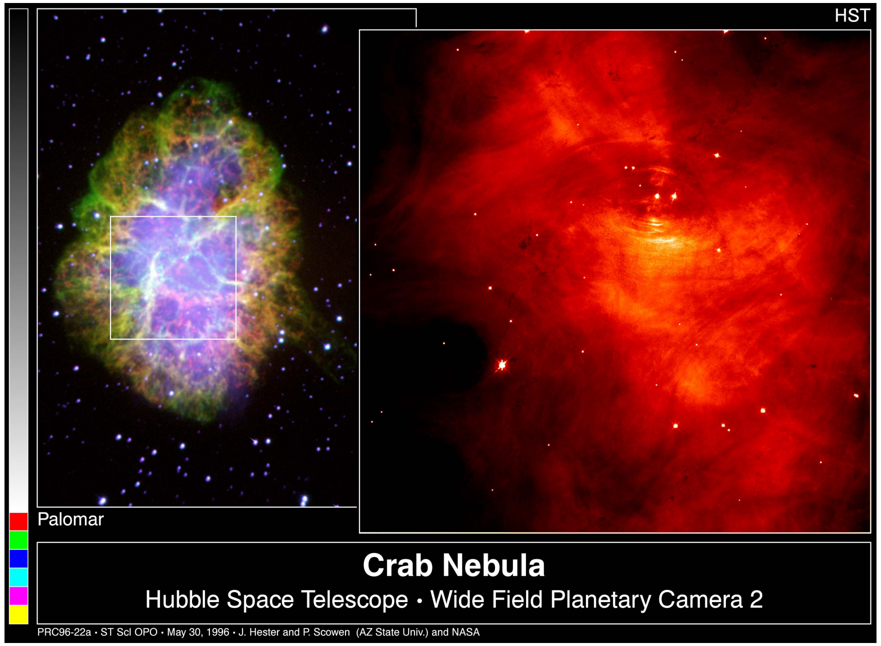
（上）『明月記』寛喜二年十一月八日条に記された「客星出現例」

（右）『定家図』（伝藤原信実筆、鎌倉時代）

（ともに冷泉家時雨亭文庫所蔵）

From Book by N. Itoh

Supernova leaves a neutron star (or black hole)



Crab pulsar:
rapidly rotating neutron star (P=33ms)

- Compact objects
  - Massive, Dense
  - Extreme condition

- Mass: $M_{NS} \sim 1.4 M_{solar}$
- Radius: $R_{NS} \sim 10$ km $= 10^6$ cm

  cf. Sun: $M_{solar} = 2 \times 10^{33}$ g,
  $R_{solar} = 7 \times 10^{10}$ cm

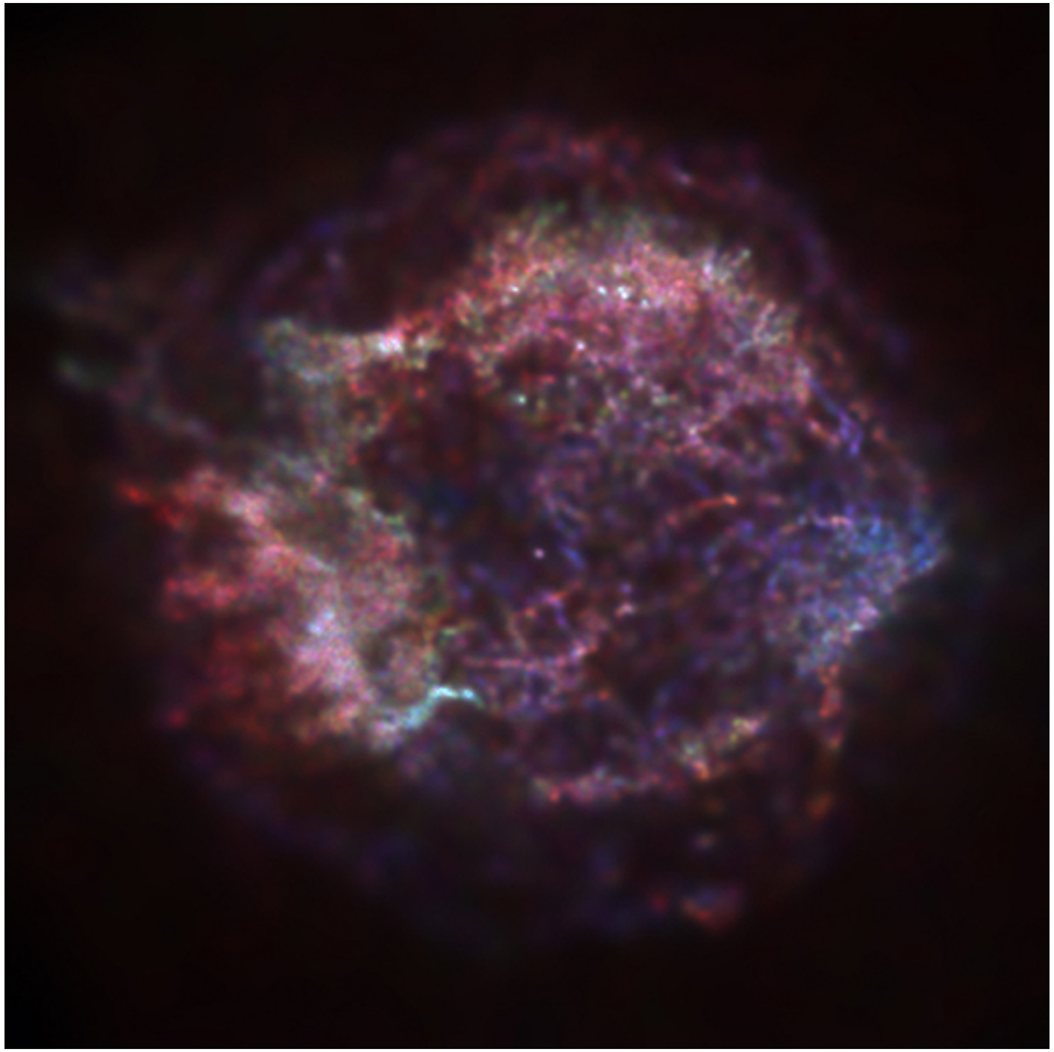
- Density:

$$\rho_{NS} = \frac{M_{NS}}{\frac{4\pi}{3} R_{NS}{}^3} = 6.7 \times 10^{14}\, g/cm^3$$

cf. Nuclear matter density:
$\rho = 3 \times 10^{14}$ g/cm^3 (0.17 fm^{-3})

Supernova produces heavy elements

Hallmark of
nucleosynthesis

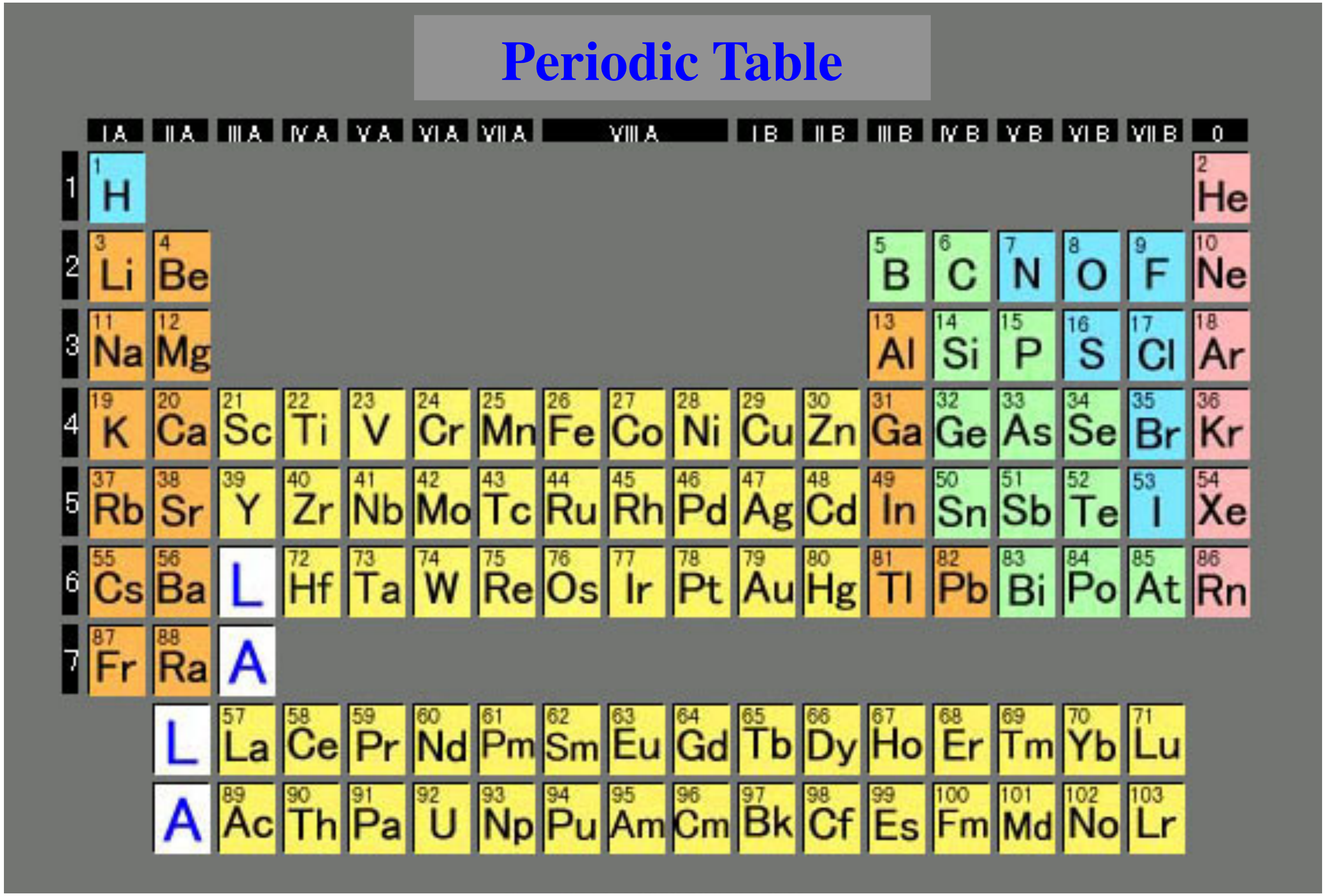


X-ray image
Red :Fe
White: Si, S

Cassiopeia A: remnant of supernova in ~1680

(type

Which elements are from supernovae?

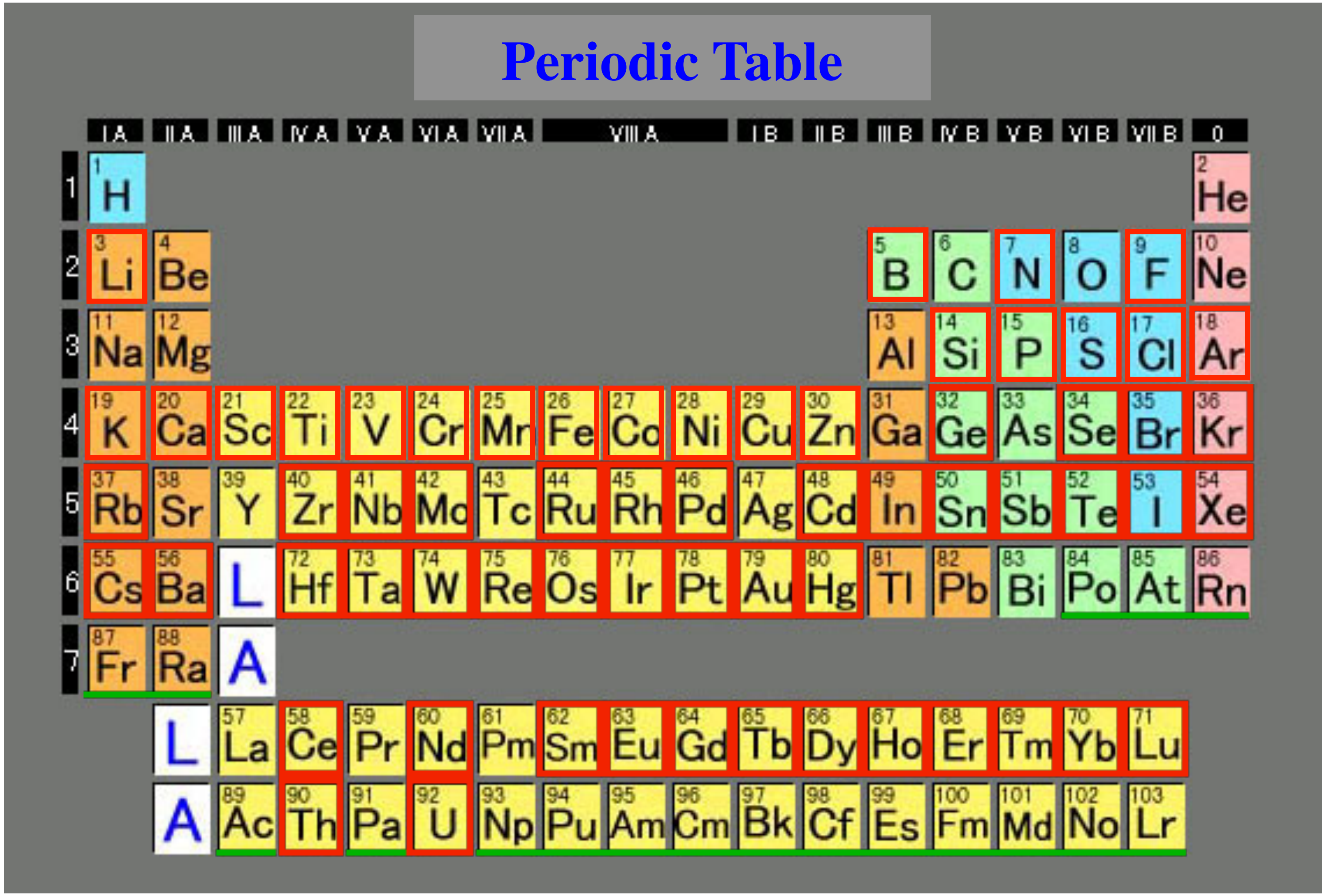


Periodic Table

	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	L	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	A															
		L	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		A	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

http://ccinfo.ims.ac.jp/periodic/indexj.html

Most of heavy elements are from supernovae



Periodic Table

	I A	II A	III A	IV A	V A	VI A	VII A	VIII A			I B	II B	III B	IV B	V B	VI B	VII B	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	L	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	A															
		L	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		A	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

http://ccinfo.ims.ac.jp/periodic/indexj.html

Woosley, Weaver (1995)   Seeger, Fowler, Clayton (1965)

> 50% r-process
Based on Seeger, Fowler, Clayton (1965)

Price of Gold & Platinum vs Iron

- Gold 1gram :

- Platinum 1gram :

150,000 ton found in the history for 6000 years
= Volume of Olympic swimming pool x 3

Precious (Expensive) because of **tiny abundance**

- Iron 1ton :

Solar abundance of elements

Relative ratio

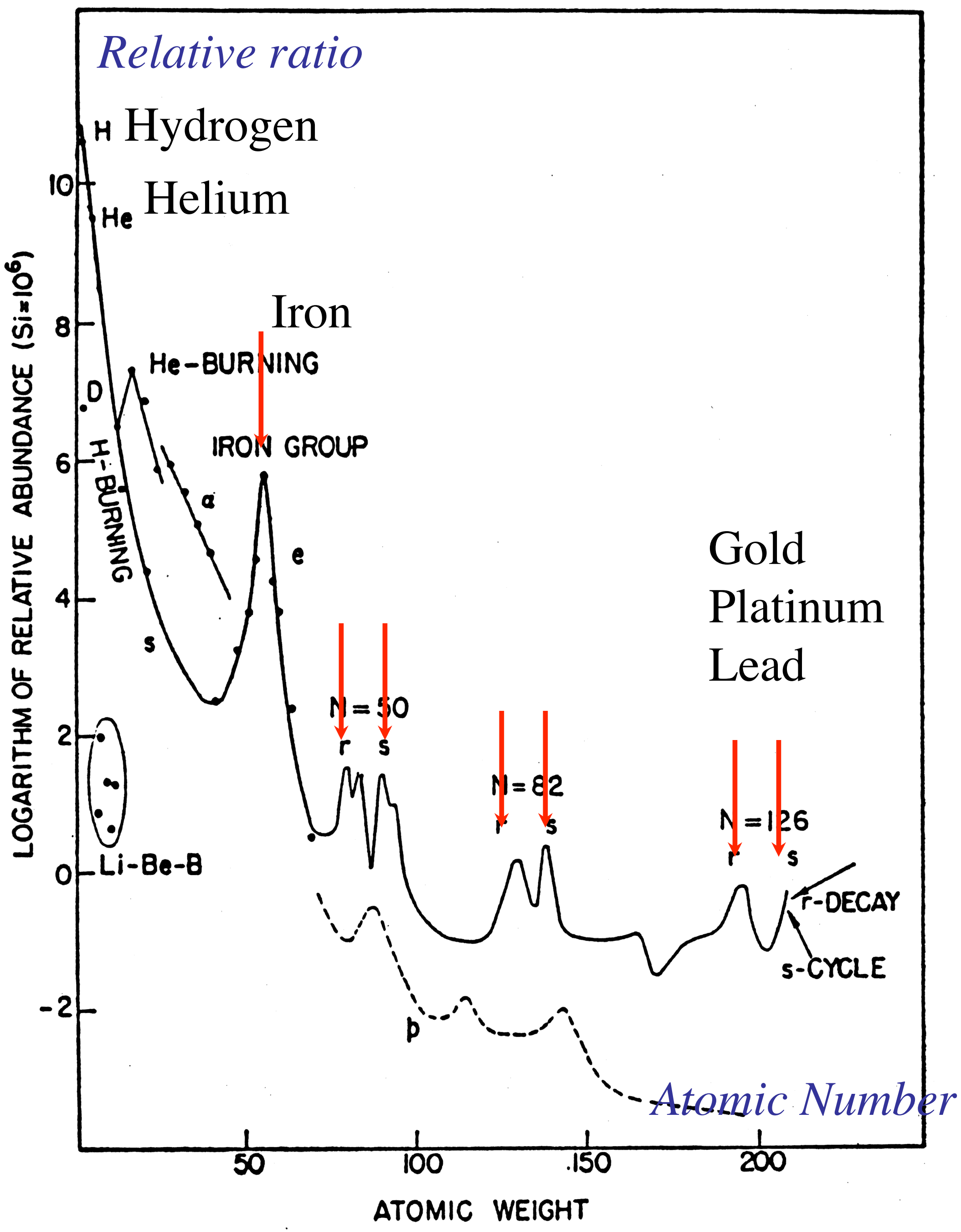
- H, He : 10^{12}
- Si, Fe, Ni : 10^{6}
- Au, Pt : 10^{0}

Abundance Peaks

- Fe group
- s-, r-process

Origin of heavy elements

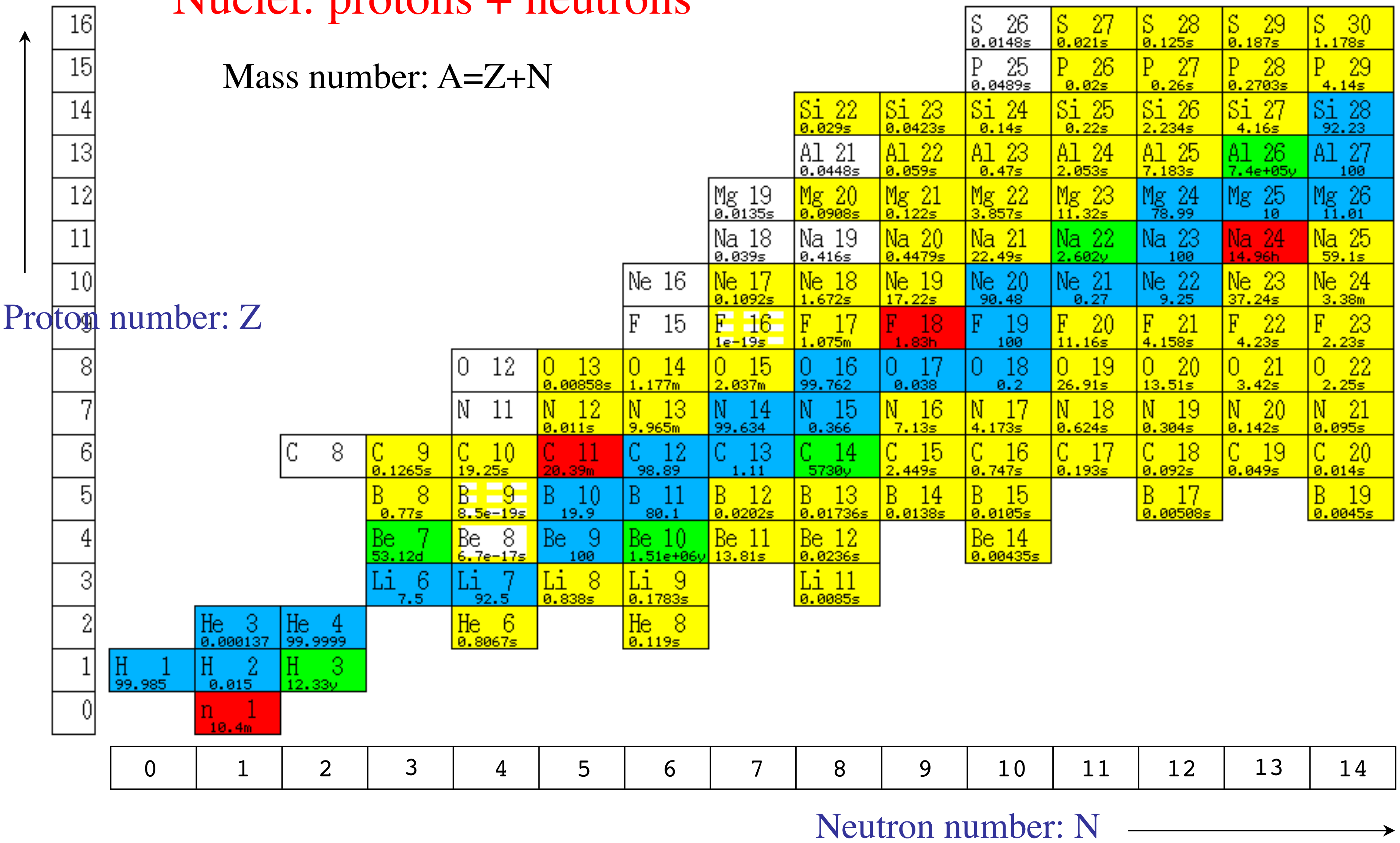
- Stellar evolution
- Supernova explosion



Nuclear Chart: species of nuclei

Nuclei: protons + neutrons

Mass number: A=Z+N

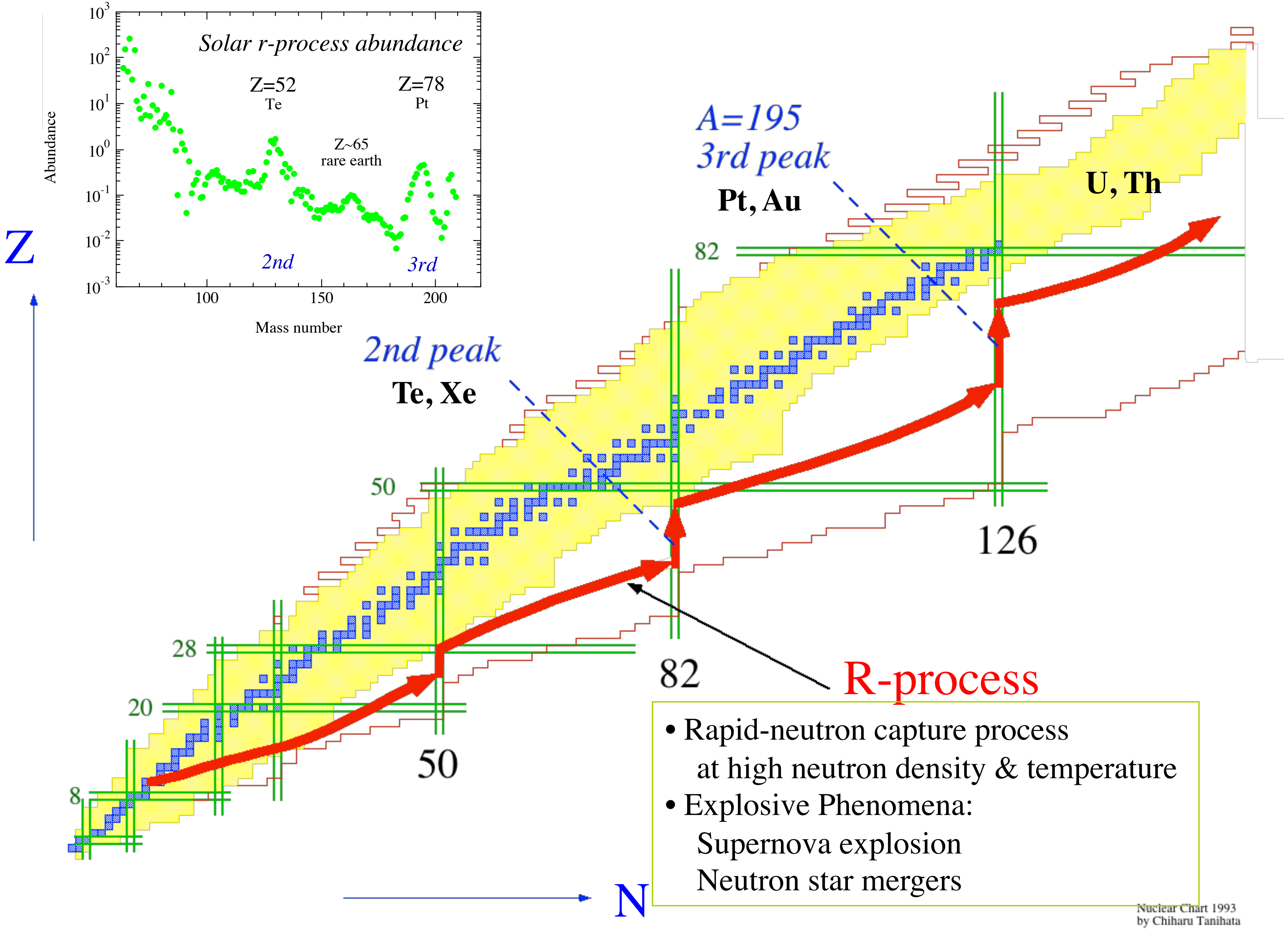


16											S 26 0.0148s	S 27 0.021s	S 28 0.125s	S 29 0.187s	S 30 1.178s
15											P 25 0.0489s	P 26 0.02s	P 27 0.26s	P 28 0.2703s	P 29 4.14s
14									Si 22 0.029s	Si 23 0.0423s	Si 24 0.14s	Si 25 0.22s	Si 26 2.234s	Si 27 4.16s	Si 28 92.23
13									Al 21 0.0448s	Al 22 0.059s	Al 23 0.47s	Al 24 2.053s	Al 25 7.183s	Al 26 7.4e+05y	Al 27 100
12								Mg 19 0.0135s	Mg 20 0.0908s	Mg 21 0.122s	Mg 22 3.857s	Mg 23 11.32s	Mg 24 78.99	Mg 25 10	Mg 26 11.01
11								Na 18 0.039s	Na 19 0.416s	Na 20 0.4479s	Na 21 22.49s	Na 22 2.602y	Na 23 100	Na 24 14.96h	Na 25 59.1s
10							Ne 16	Ne 17 0.1092s	Ne 18 1.672s	Ne 19 17.22s	Ne 20 90.48	Ne 21 0.27	Ne 22 9.25	Ne 23 37.24s	Ne 24 3.38m
9							F 15	F 16 1e-19s	F 17 1.075m	F 18 1.83h	F 19 100	F 20 11.16s	F 21 4.158s	F 22 4.23s	F 23 2.23s
8					O 12	O 13 0.00858s	O 14 1.177m	O 15 2.037m	O 16 99.762	O 17 0.038	O 18 0.2	O 19 26.91s	O 20 13.51s	O 21 3.42s	O 22 2.25s
7					N 11	N 12 0.011s	N 13 9.965m	N 14 99.634	N 15 0.366	N 16 7.13s	N 17 4.173s	N 18 0.624s	N 19 0.304s	N 20 0.142s	N 21 0.095s
6			C 8	C 9 0.1265s	C 10 19.25s	C 11 20.39m	C 12 98.89	C 13 1.11	C 14 5730y	C 15 2.449s	C 16 0.747s	C 17 0.193s	C 18 0.092s	C 19 0.049s	C 20 0.014s
5				B 8 0.77s	B 9 8.5e-19s	B 10 19.9	B 11 80.1	B 12 0.0202s	B 13 0.01736s	B 14 0.0138s	B 15 0.0105s		B 17 0.00508s		B 19 0.0045s
4				Be 7 53.12d	Be 8 6.7e-17s	Be 9 100	Be 10 1.51e+06y	Be 11 13.81s	Be 12 0.0236s		Be 14 0.00435s				
3				Li 6 7.5	Li 7 92.5	Li 8 0.838s	Li 9 0.1783s		Li 11 0.0085s						
2		He 3 0.000137	He 4 99.9999		He 6 0.8067s		He 8 0.119s								
1	H 1 99.985	H 2 0.015	H 3 12.33y												
0		n 1 10.4m													
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

Proton number: Z

Neutron number: N

Solar r-process abundance

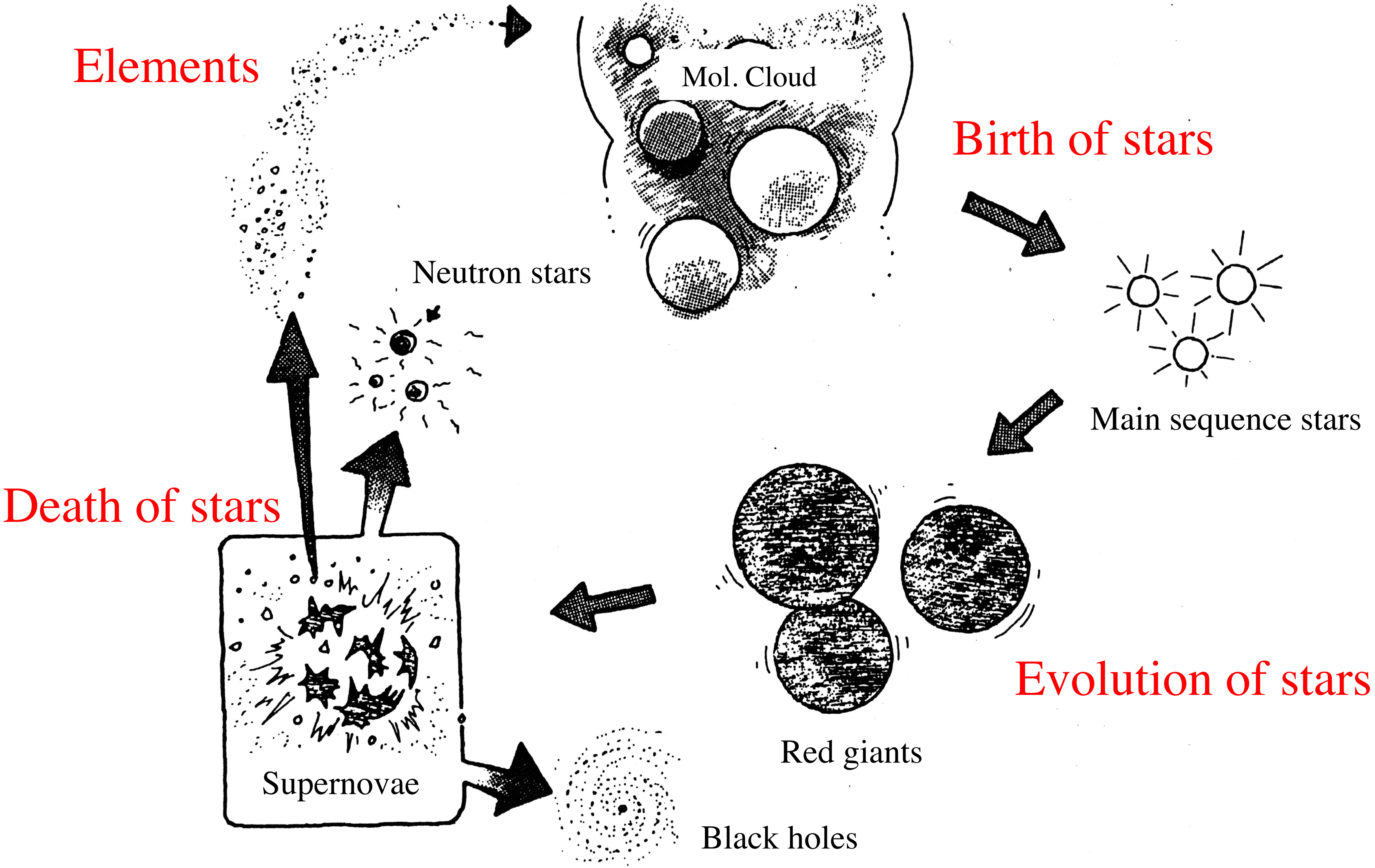


R-process

- Rapid-neutron capture process
  at high neutron density & temperature
- Explosive Phenomena:
  Supernova explosion
  Neutron star mergers

Nuclear Chart 1993
by Chiharu Tanihata

Cycle of stars and elements



Mol. Cloud

Birth of stars

Main sequence stars

Evolution of stars

Red giants

Death of stars

Supernovae

Elements

Neutron stars

Black holes

Role of supernova explosion

- Origin of elements
  - Create heavy elements, stuffs for next stars
- Origin of compact objects
  - Birth of neutron star or black hole
- Source of energy & particles
  - Cosmic rays (γ, X, ν,...), mass ejection,
- Evolution of Galaxy
  - Trigger of the birth of star

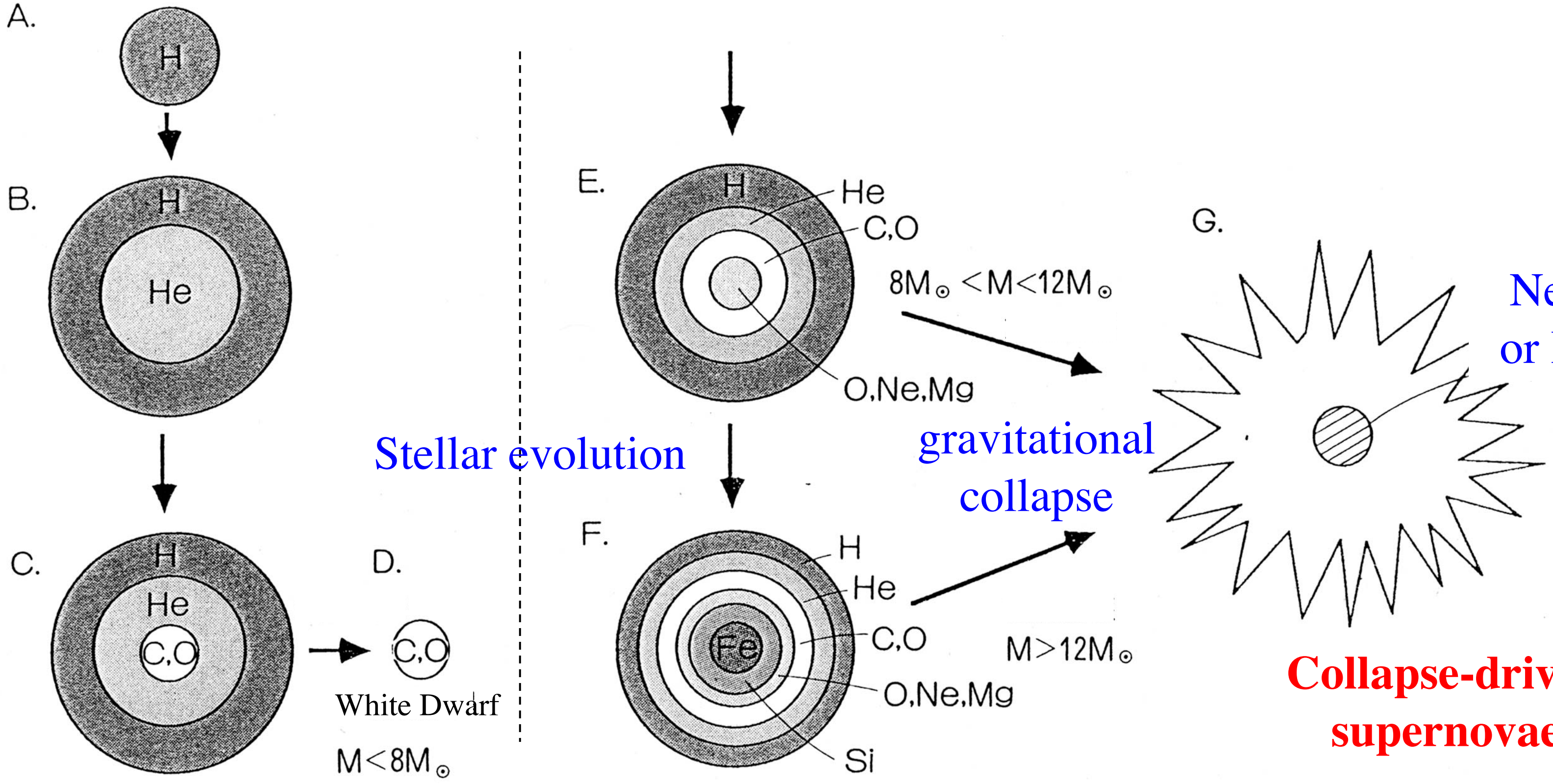
Scenario of supernova explosion

Release of energy from gravitational collapse of massive star

The end point of massive stars after stellar evolution

via stages of nuclear burning

Stars with ~20M_{sun}



White Dwarf

Stellar evolution

gravitational collapse

Neutron star or Black hole

Collapse-driven supernovae

Nuclear burning (fusion of alpha-particles)

H → ^{4}He → ^{12}C → ^{16}O → ^{20}Ne → ^{24}Mg → … → ^{56}Ni/^{56}Fe

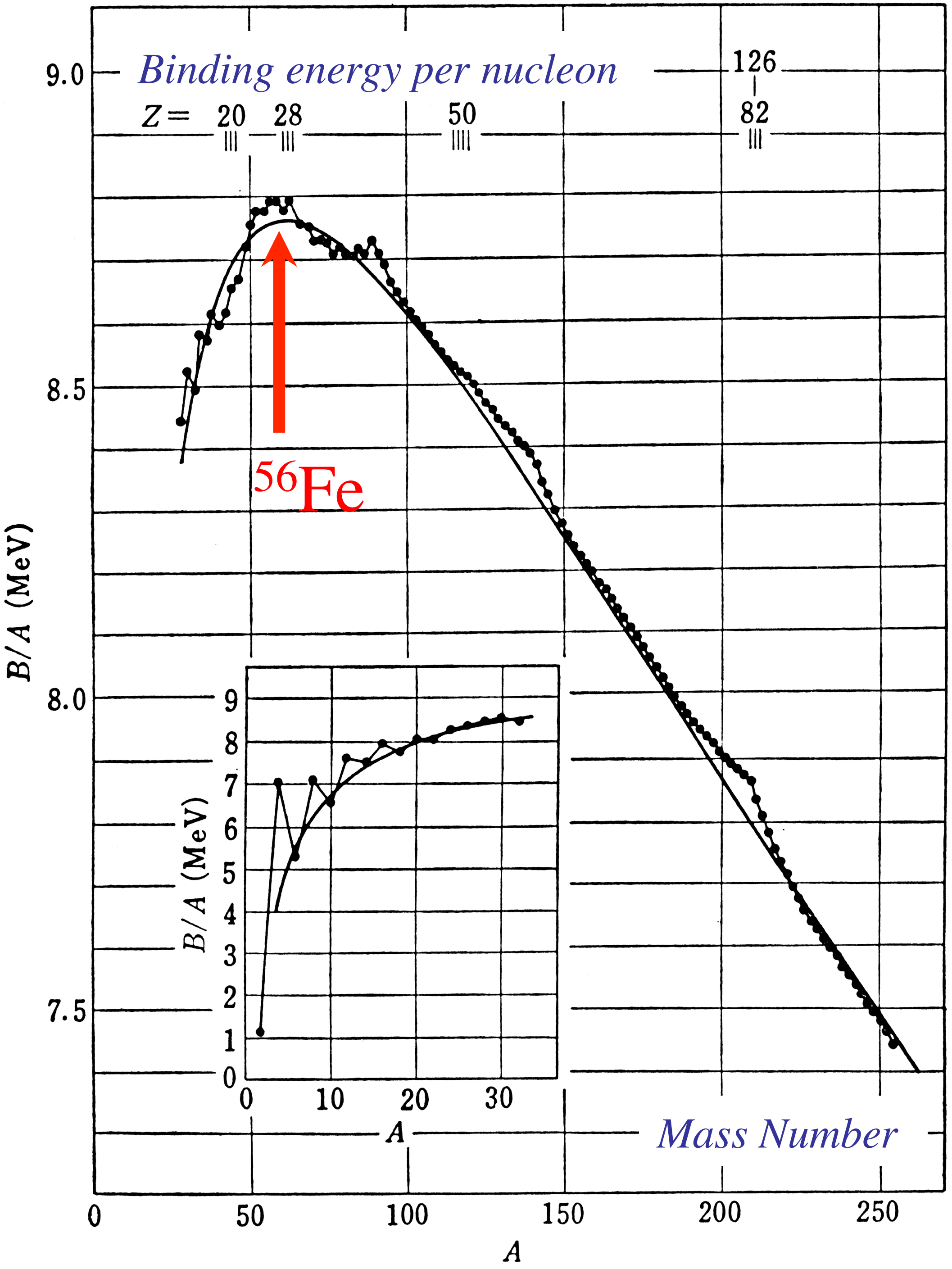
From H. Suzuki

Stability of nuclei

- Binding energy per nucleon
- Largest nuclei (Most stable) ^{56}Fe

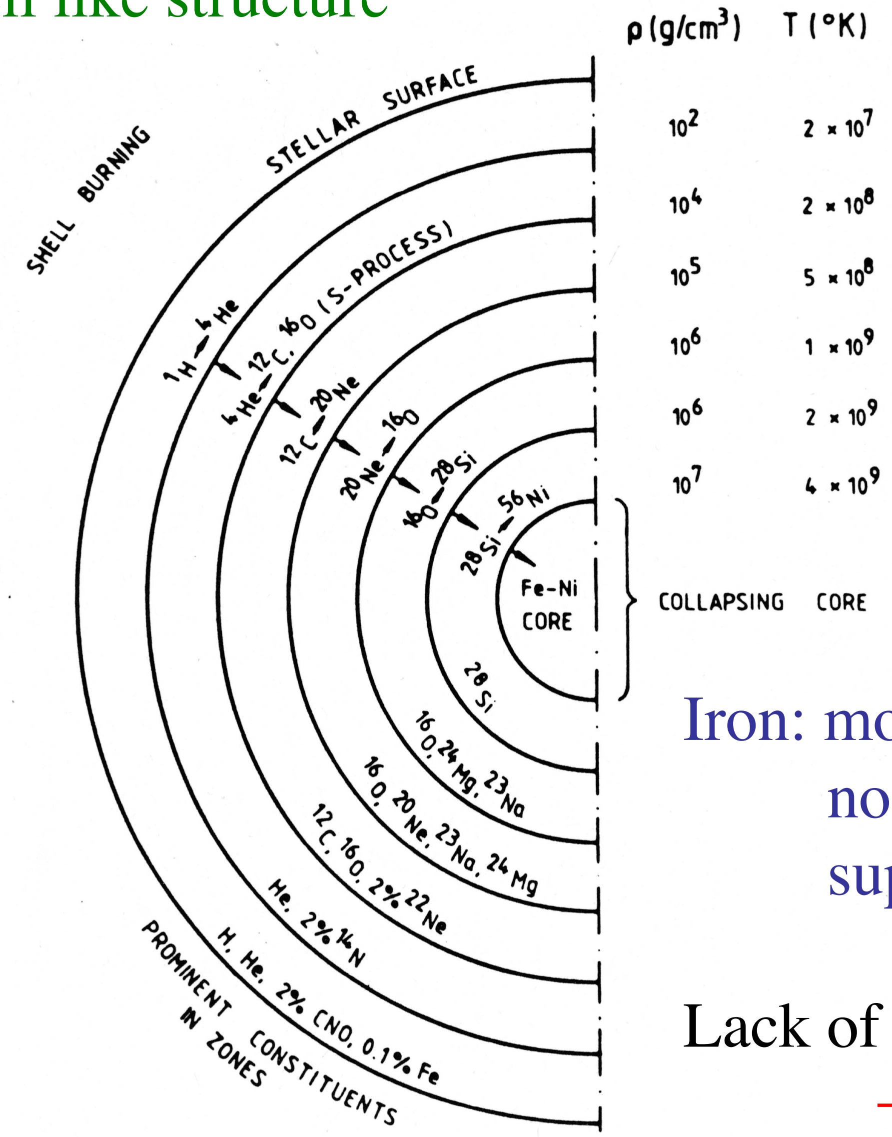
  B/A=8.6 MeV

- Stellar evolution ends up at ^{56}Fe



INNER STRUCTURE OF A PRESUPERNOVA STAR

Onion-shell like structure



ρ (g/cm³)	T (°K)
10^2	2×10^7
10^4	2×10^8
10^5	5×10^8
10^6	1×10^9
10^6	2×10^9
10^7	4×10^9

$R_* \sim 10^8$ km

$R_{Fe} \sim 10^3$ km

Iron core

Iron: most stable

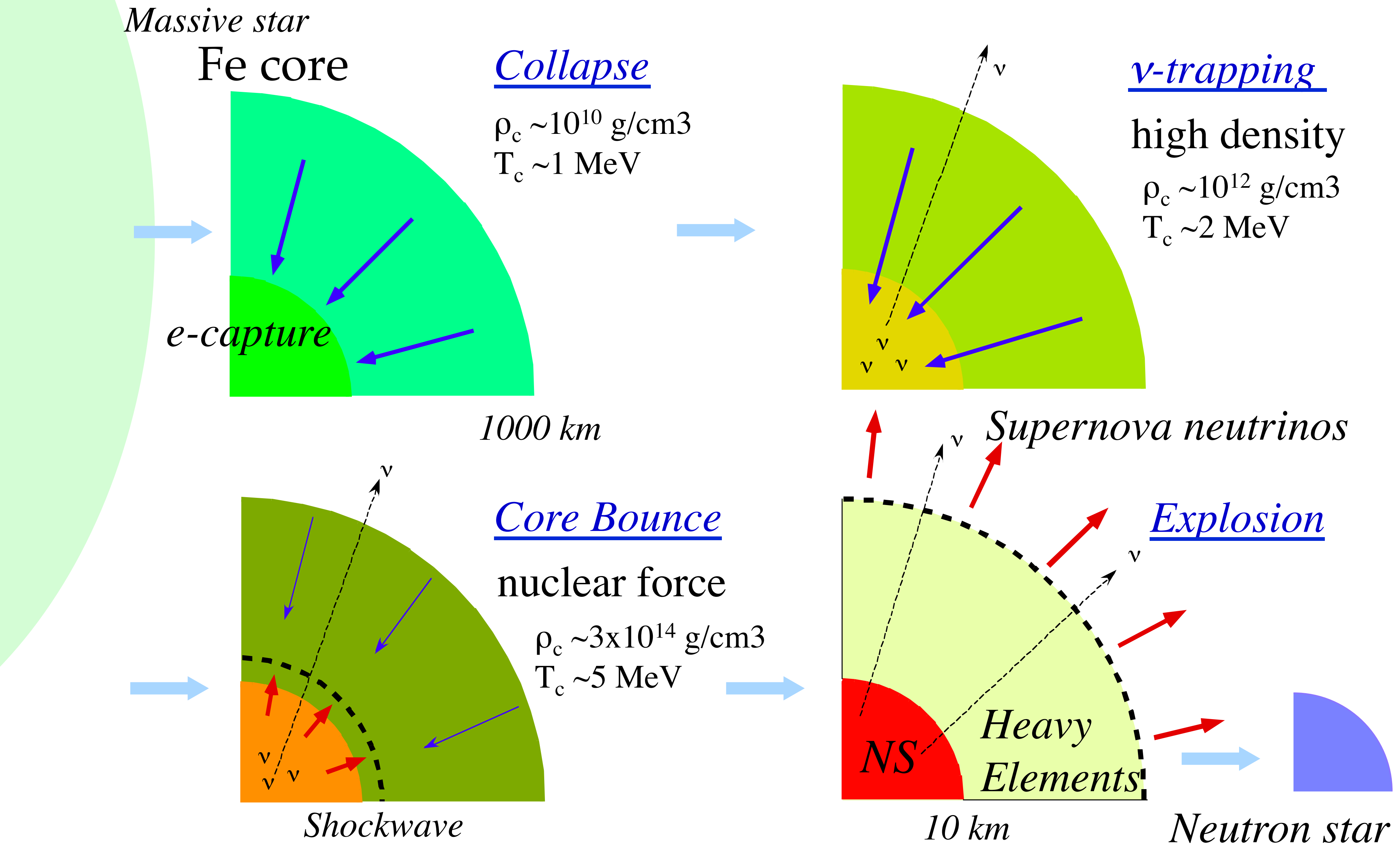
no more nuclear burning

supported by electron gas

Lack of pressure to support star

→ Gravitational collapse

Gravitational collapse, bounce and explosion



Massive star

Fe core

Collapse

$\rho_c \sim 10^{10}$ g/cm3
$T_c \sim 1$ MeV

e-capture

1000 km

ν-trapping

high density

$\rho_c \sim 10^{12}$ g/cm3
$T_c \sim 2$ MeV

Core Bounce

nuclear force

$\rho_c \sim 3\text{x}10^{14}$ g/cm3
$T_c \sim 5$ MeV

Shockwave

Supernova neutrinos

Explosion

NS

Heavy Elements

10 km

Neutron star

Energy budget of collapse and explosion

- Iron core to neutron star (M_{core}~$1.4M_{solar}$)
  - R_{Fe}~10^3 km → R_{NS}~10 km
  - ρ_c~10^9 g/cm^3 → ρ_c~10^{15} g/cm^3
- Gravitational energy released

$$\Delta E_{Grav} = -\left(\frac{GM^2}{R_{Fe}} - \frac{GM^2}{R_{NS}} \right) \sim 10^{53} erg$$

We want to explain this amount

- Explosion energy: $E_{exp} \sim 10^{51}$ erg
- Neutrino carries away: $E_\nu \sim 10^{53}$ erg

- Only ~1% is used for the explosion
- Neutrino-matter interaction is essential

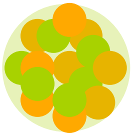
From nuclear physics to astrophysics

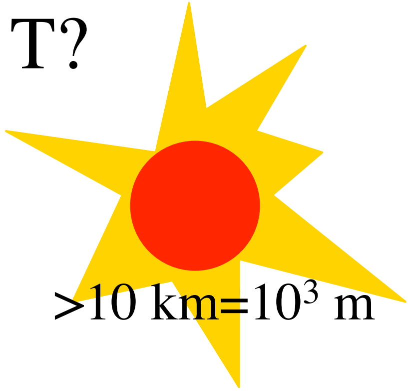
- Equation of state
- Neutrino reactions
- Nuclear data

- Hydrodynamics
- Neutrino transfer
- Stellar models

- Numerical simulations of core-collapse supernovae
  - Collapse and bounce, the birth of compact objects

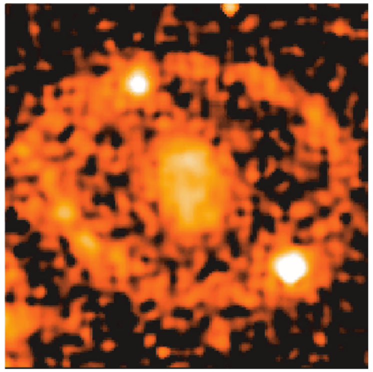
- Challenges:
  - Properties of dense matter at high ρ and T?
  - What is the explosion mechanism?
  - Observational signal from core?


~ fm=10^{-15} m

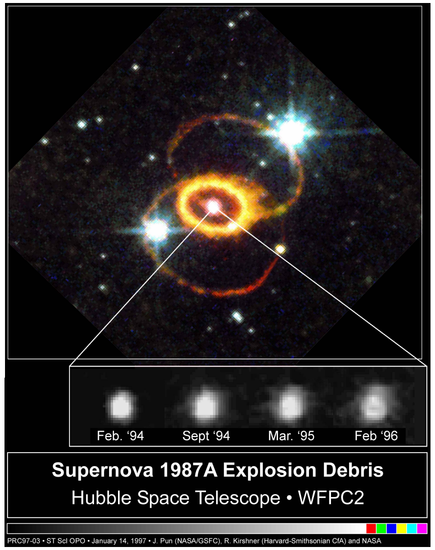

>10 km=10^3 m

Calculation of Hydrodynamics

- Supernova remnant
  - Shape, Polarization
  - Nucleosynthesis
  - Neutron star kick
- Multi-dimension
  - Spherical:1D
  - Axi-symmetric: 2D
  - Asymmetric: 3D
- Rotation
- Magnetic field
- Hydrodynamical Instability
  - Convection
  - Composition Mixing



Jun. 2000 Wang 2002



Jan. 1997

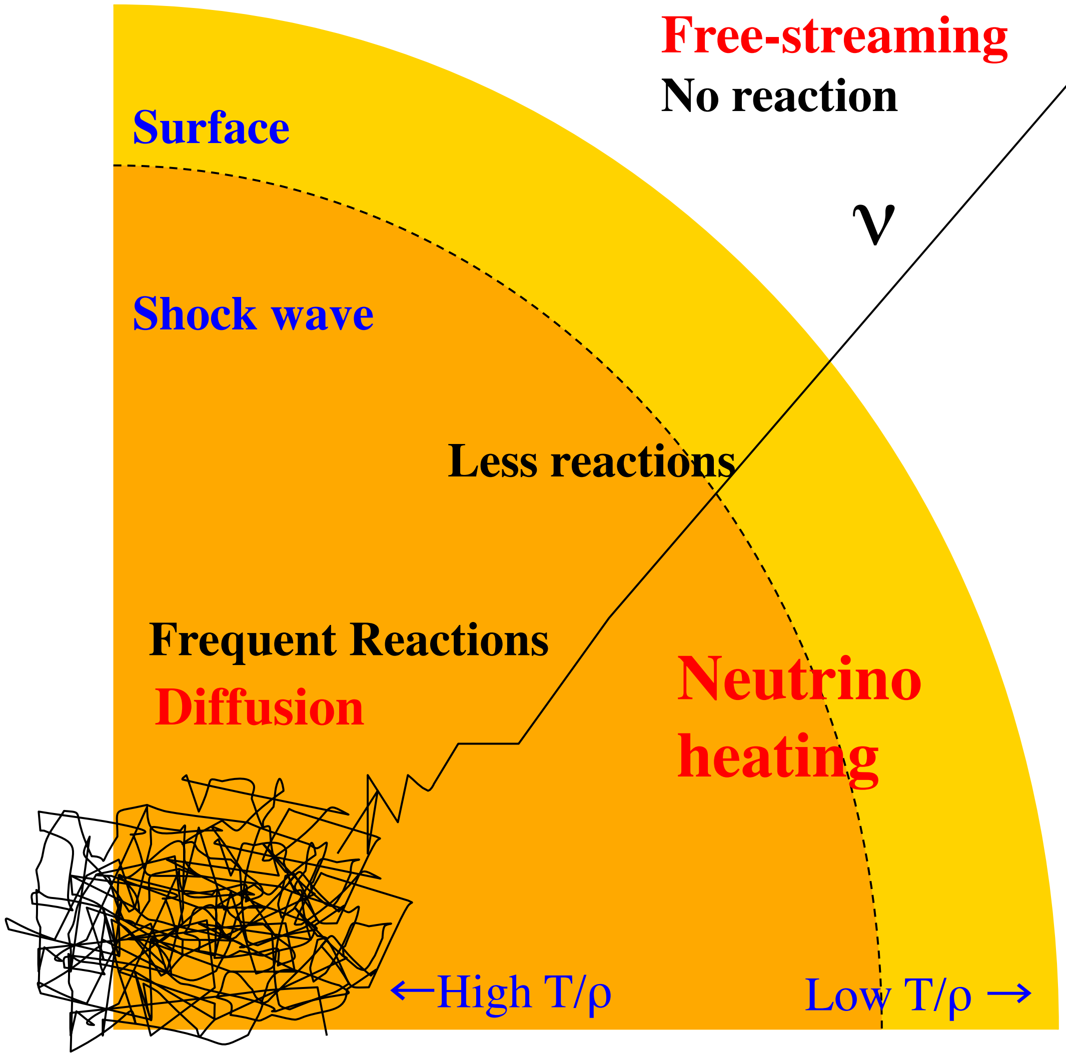
Example of hydro. simulation

A. Burrows (1995)

http://zenith.as.arizona.edu/~burrows/movies.html

Calculation of neutrino transfer

- Need to follow the neutrino reactions and its propagation
  - One cannot assume thermal & chemical equilibrium
  - Solve Boltzmann equation for neutrino distributions



Free-streaming

No reaction

Surface

ν

Shock wave

Less reactions

Frequent Reactions

Diffusion

Neutrino heating

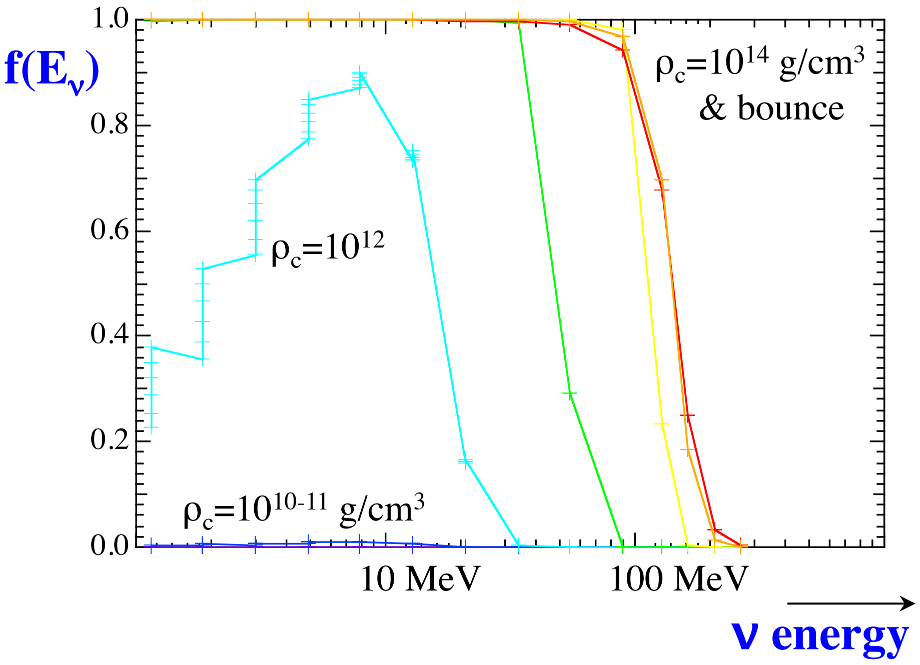
←High T/ρ

Low T/ρ →

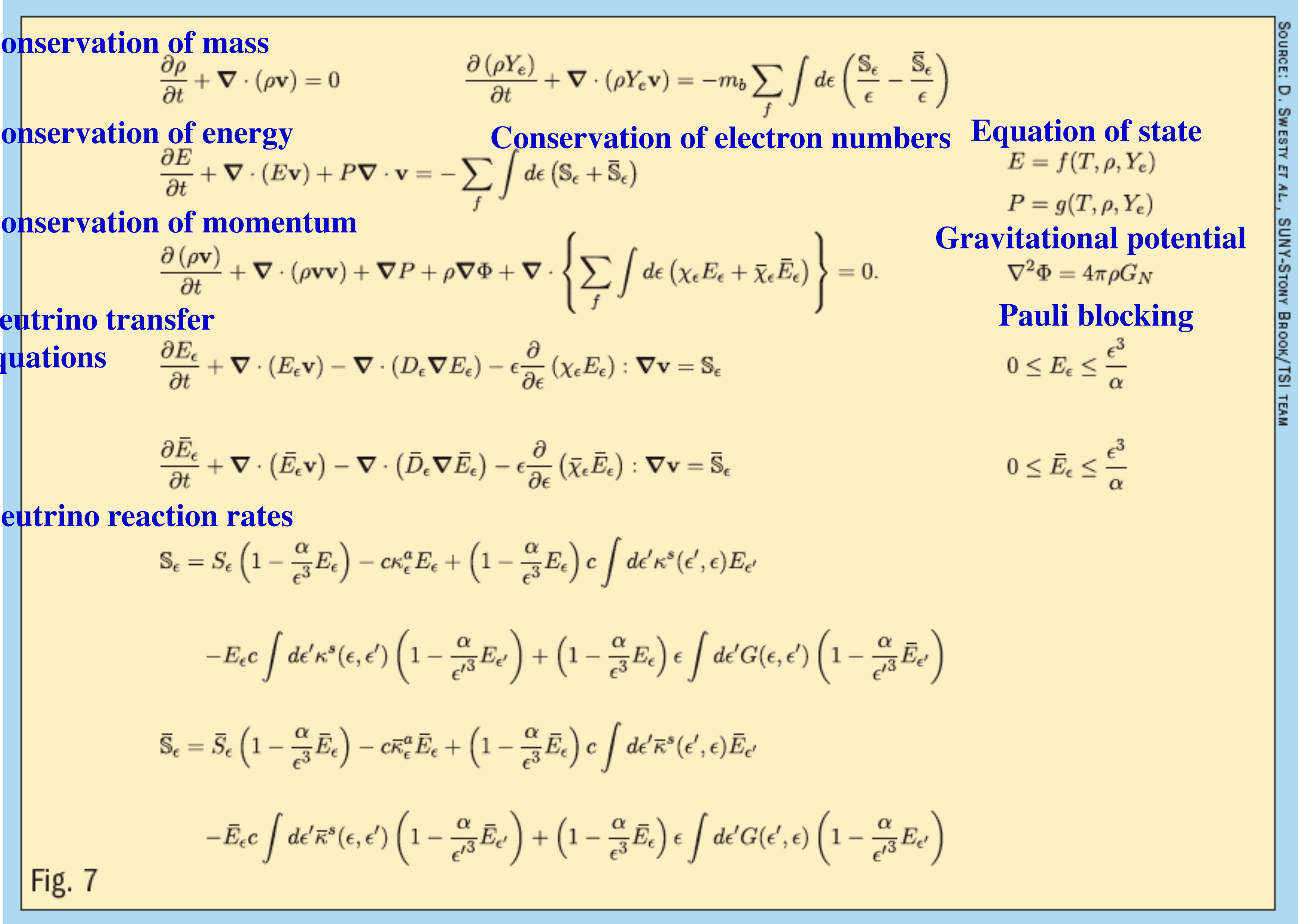
- Including all of neutrino reactions

  - scattering, emission, absorption

Neutrino distribution function (during collapse)



Basic equations



Conservation of mass

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \mathbf{v}) = 0 \qquad \frac{\partial (\rho Y_e)}{\partial t} + \boldsymbol{\nabla} \cdot (\rho Y_e \mathbf{v}) = -m_b \sum_f \int d\epsilon \left(\frac{\mathbb{S}_\epsilon}{\epsilon} - \frac{\bar{\mathbb{S}}_\epsilon}{\epsilon} \right)$$

Conservation of energy

Conservation of electron numbers

$$\frac{\partial E}{\partial t} + \boldsymbol{\nabla} \cdot (E\mathbf{v}) + P\boldsymbol{\nabla} \cdot \mathbf{v} = -\sum_f \int d\epsilon \left(\mathbb{S}_\epsilon + \bar{\mathbb{S}}_\epsilon \right)$$

Conservation of momentum

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \mathbf{v}\mathbf{v}) + \boldsymbol{\nabla} P + \rho \boldsymbol{\nabla} \Phi + \boldsymbol{\nabla} \cdot \left\{ \sum_f \int d\epsilon \left(\chi_\epsilon E_\epsilon + \bar{\chi}_\epsilon \bar{E}_\epsilon \right) \right\} = 0.$$

Neutrino transfer equations

$$\frac{\partial E_\epsilon}{\partial t} + \boldsymbol{\nabla} \cdot (E_\epsilon \mathbf{v}) - \boldsymbol{\nabla} \cdot (D_\epsilon \boldsymbol{\nabla} E_\epsilon) - \epsilon \frac{\partial}{\partial \epsilon} (\chi_\epsilon E_\epsilon) : \boldsymbol{\nabla} \mathbf{v} = \mathbb{S}_\epsilon$$

$$\frac{\partial \bar{E}_\epsilon}{\partial t} + \boldsymbol{\nabla} \cdot (\bar{E}_\epsilon \mathbf{v}) - \boldsymbol{\nabla} \cdot (\bar{D}_\epsilon \boldsymbol{\nabla} \bar{E}_\epsilon) - \epsilon \frac{\partial}{\partial \epsilon} (\bar{\chi}_\epsilon \bar{E}_\epsilon) : \boldsymbol{\nabla} \mathbf{v} = \bar{\mathbb{S}}_\epsilon$$

Neutrino reaction rates

$$\mathbb{S}_\epsilon = S_\epsilon \left(1 - \frac{\alpha}{\epsilon^3} E_\epsilon\right) - c\kappa^a_\epsilon E_\epsilon + \left(1 - \frac{\alpha}{\epsilon^3} E_\epsilon\right) c \int d\epsilon' \kappa^s(\epsilon', \epsilon) E_{\epsilon'}$$

$$-E_\epsilon c \int d\epsilon' \kappa^s(\epsilon, \epsilon') \left(1 - \frac{\alpha}{\epsilon'^3} E_{\epsilon'}\right) + \left(1 - \frac{\alpha}{\epsilon^3} E_\epsilon\right) \epsilon \int d\epsilon' G(\epsilon, \epsilon') \left(1 - \frac{\alpha}{\epsilon'^3} \bar{E}_{\epsilon'}\right)$$

$$\bar{\mathbb{S}}_\epsilon = \bar{S}_\epsilon \left(1 - \frac{\alpha}{\epsilon^3} \bar{E}_\epsilon\right) - c\bar{\kappa}^a_\epsilon \bar{E}_\epsilon + \left(1 - \frac{\alpha}{\epsilon^3} \bar{E}_\epsilon\right) c \int d\epsilon' \bar{\kappa}^s(\epsilon', \epsilon) \bar{E}_{\epsilon'}$$

$$-\bar{E}_\epsilon c \int d\epsilon' \bar{\kappa}^s(\epsilon, \epsilon') \left(1 - \frac{\alpha}{\epsilon'^3} \bar{E}_{\epsilon'}\right) + \left(1 - \frac{\alpha}{\epsilon^3} \bar{E}_\epsilon\right) \epsilon \int d\epsilon' G(\epsilon', \epsilon) \left(1 - \frac{\alpha}{\epsilon'^3} E_{\epsilon'}\right)$$

Equation of state

$$E = f(T, \rho, Y_e)$$

$$P = g(T, \rho, Y_e)$$

Gravitational potential

$$\nabla^2 \Phi = 4\pi \rho G_N$$

Pauli blocking

$$0 \le E_\epsilon \le \frac{\epsilon^3}{\alpha}$$

$$0 \le \bar{E}_\epsilon \le \frac{\epsilon^3}{\alpha}$$

Fig. 7

SOURCE: D. SWESTY ET AL., SUNY-STONY BROOK/TSI TEAM

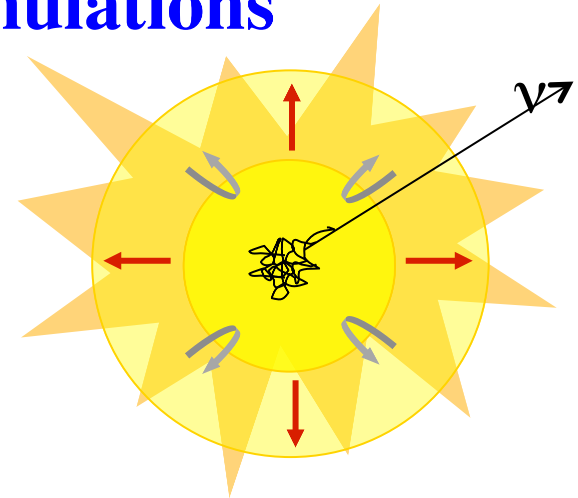
SciDAC Review Spring 2006

Physics at extreme condition

Properties of hot & dense matter and neutrino reactions

Properties of dense matter at extreme conditions

- **Necessary inputs for numerical simulations**



1. Pressure-Density
   - Stellar structure, Dynamics, Maximum Mass
2. Temperature (entropy)
3. Composition (proton, neutron, nuclei)
   - ν-energy distribution, ν-reaction

- **Equation of state (EOS) in supernova core**

- Dense more than nuclei: $\rho > \rho_0 = 3\text{x}10^{14}\text{g/cm}^3$

- Neutron-rich: $Y_p < Z/A = 0.46$ for ^{56}Fe

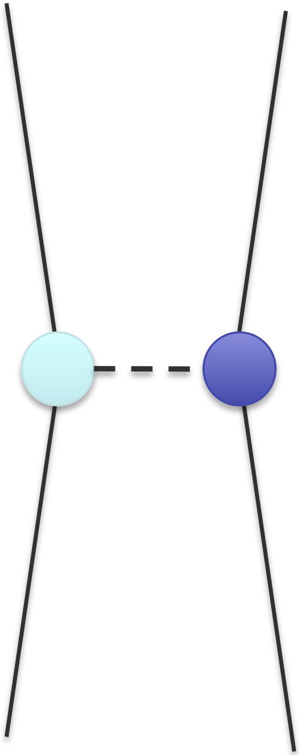
- Very Hot: $T > 10$ MeV ($\sim 10^{11}$ K)

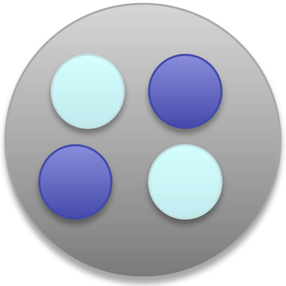
- Unified framework to cover wide range of ρ, Y_p, T
- Check by experimental data

Properties of nuclear matter

- Evaluate the energy when we put neutrons and protons in a box and compress the box
  - – Infinite matter: A, V→∞ with fixed density (n=A/V)

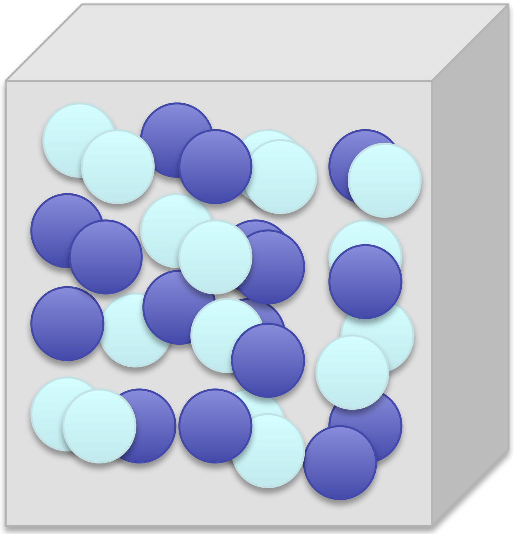
Nuclear force





Nucleus

A (=N+Z) nucleons
in volume V



Nuclear matter

Energy per nucleon of nuclear matter

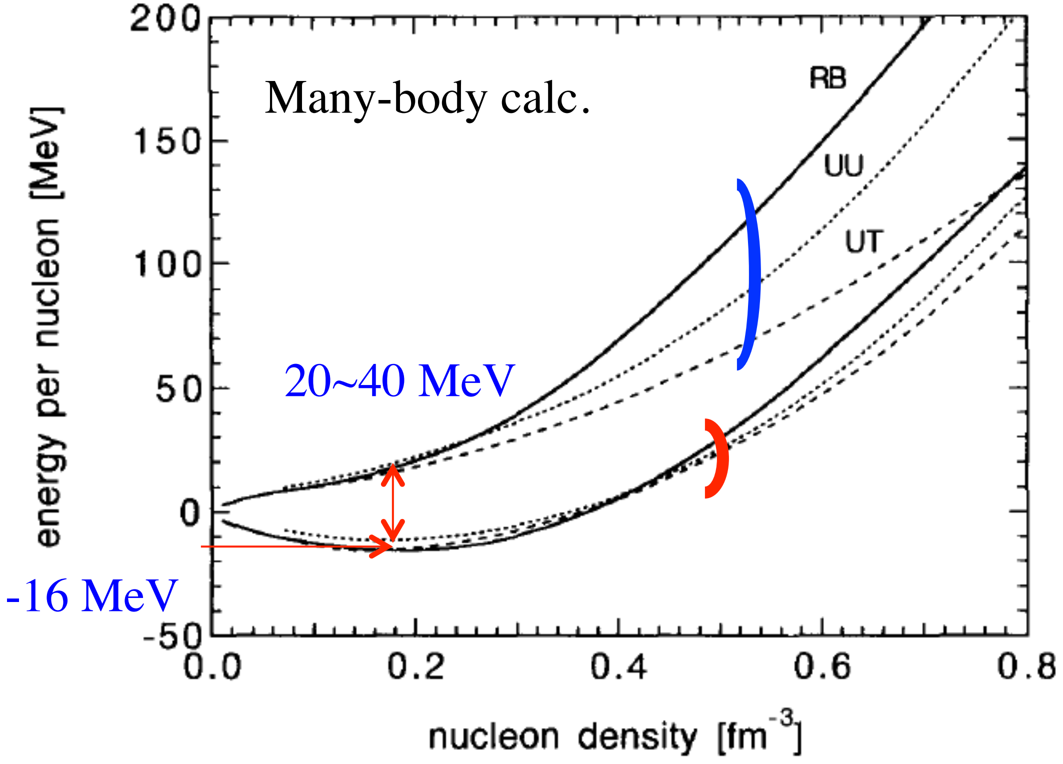
- Nuclear matter: neutrons and protons (Z=N, Y_p=Z/A=0.5)
  - Nuclear saturation: E/A=-16 MeV, n=0.17 fm^{-3} (Experiments)
- Neutron matter: only neutrons (Z=0, Y_p=0.0)
  - Symmetry energy: A_{sym}=20~40 MeV (Neutron-rich nuclei)

- Nuclear many body calculations to evaluate energy

- Nuclear interaction
  - Attraction, Repulision
- Pauli exclusion principle
  - Correlations, blocking
- Different from Fermi gas

ex. Non-relativistic
ideal Fermi gas

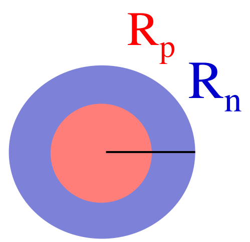
$$P = \frac{2}{3}E \propto n^{\frac{5}{3}}$$



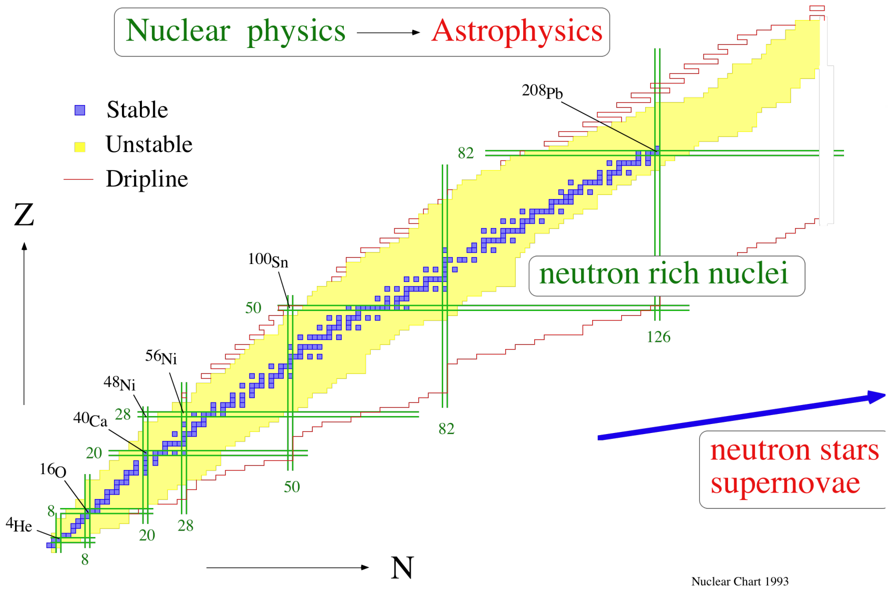
Sumiyoshi et al. NPA (‘95)

Supernova EOS by physics of unstable nuclei

- New data on neutron-rich nuclei (mass, radius,...)
  RI beam facilities since 1990

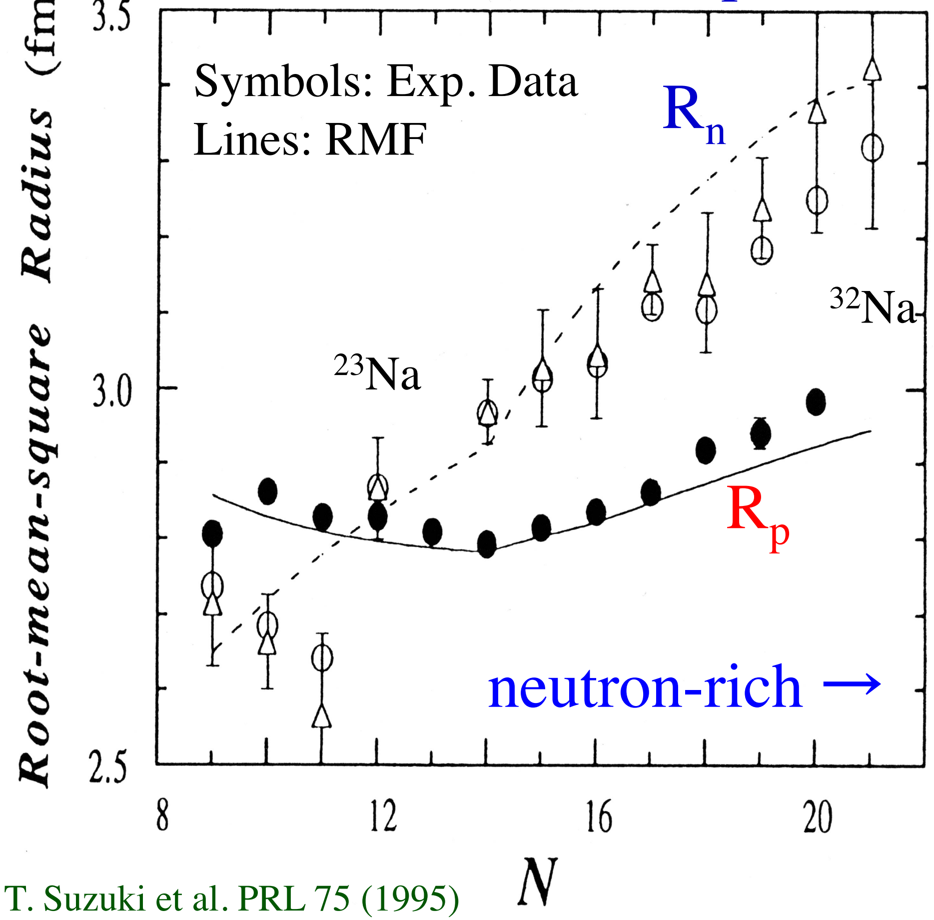


Neutron-rich nuclei
to constrain
Neutron-rich matter



Nuclear Chart 1993
by Chiharu Tanihata
65% for one page

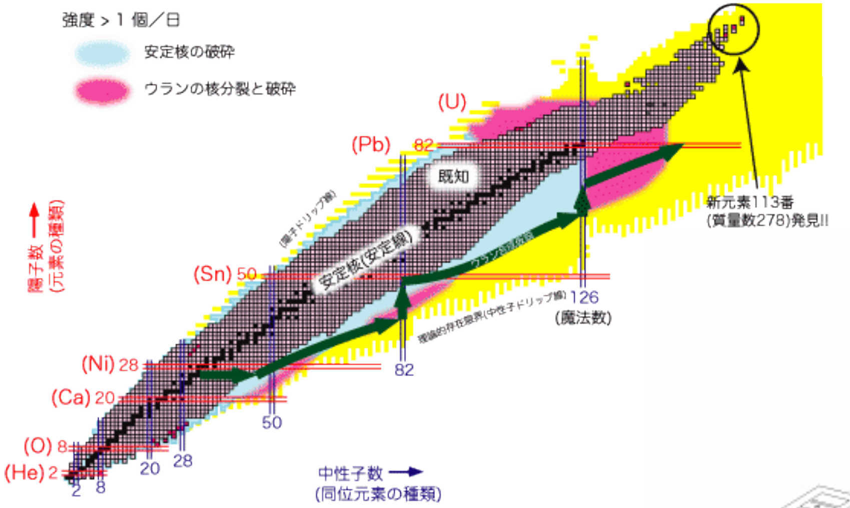
Radii of Na isotopes



T. Suzuki et al. PRL 75 (1995)

Accelerator facilities for nuclear physics

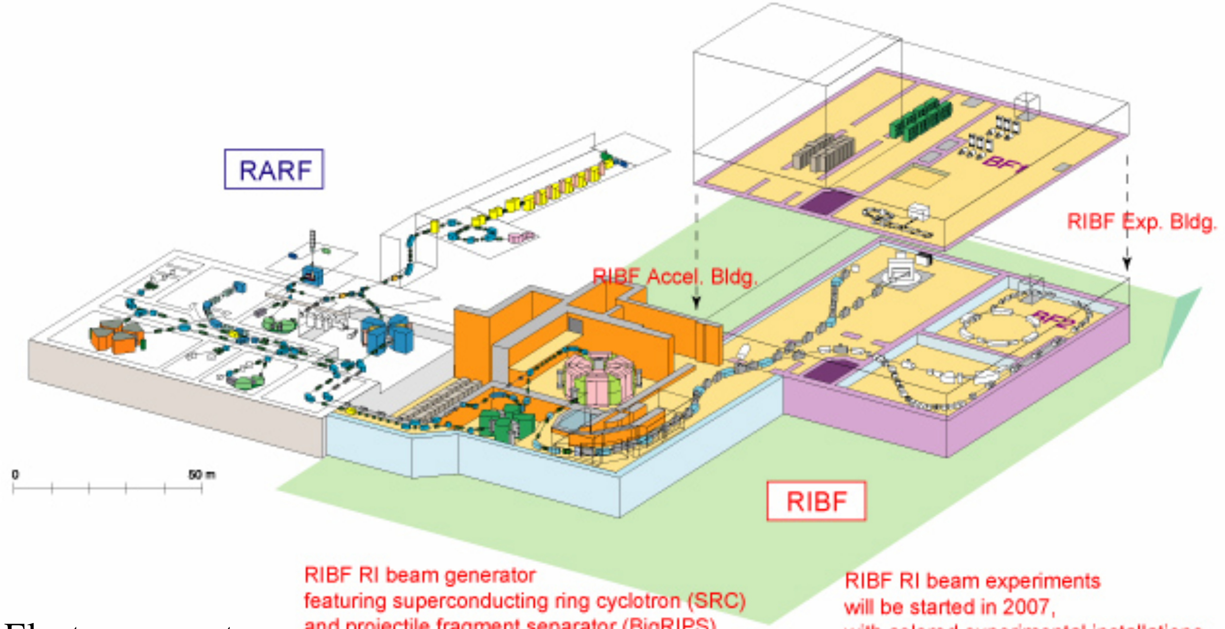
- Recent advance of radioactive nuclear beam facilities provides us with data on n-rich nuclei in Japan, US, Germany,…



ex. RI beam factory in RIKEN, Japan

Electro-magnet
8300 ton

Super-conducting Ring Cyclotron



RIBF RI beam generator
featuring superconducting ring cyclotron (SRC)
and projectile fragment separator (BigRIPS)
will be commissioned late in 2006.

RIBF RI beam experiments
will be started in 2007,
with colored experimental installations.

From www.rarf.riken.go.jp

Shen equation of state for supernovae

H. Shen, Toki, Oyamatsu & Sumiyoshi NPA, PTP(1998), arXiv:1105.1666 (2011)

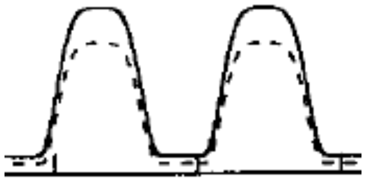
- Relativistic mean field theory+ local-density approx.
  - – Based on relativistic Brueckner Hartree-Fock (RBHF) theory
  - – Checked by exp. data of n-rich unstable nuclei: TM1
    - Nuclear structure: mass, charge radius, neutron skin,…

Covers wide range of

– Density:	$10^{5.1} \sim 10^{16}$ g/cm^3
– Proton fraction:	0 ~ 0.65
– Temperature:	0 ~ 400 MeV

Data table ~140 MB (110 x 66 x 92 points)

– Quantities: ε, p, S, μ_i, X_i, m*



Uniform and
non-uniform matter

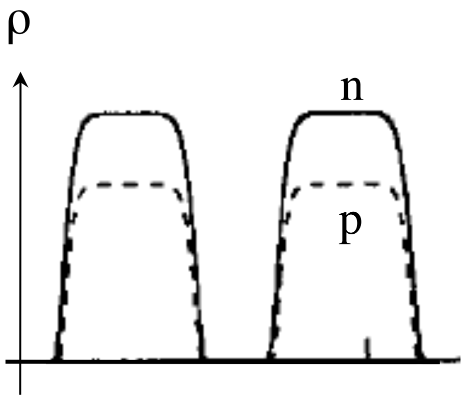
Shen-EOS

cf. Lattimer-Swesty EOS (1991)
- Extension of compressible liquid model

LS-EOS

Collapse

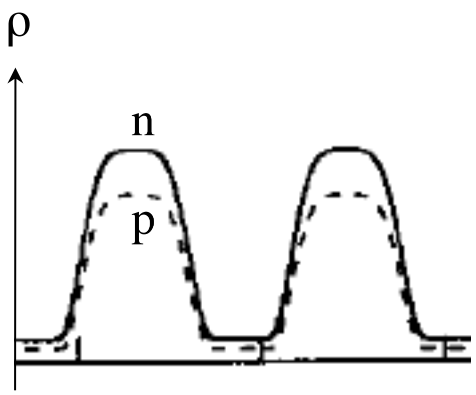
$\rho_c \sim 10^{10}$ g/cm^3
$T_c \sim 1$ MeV
$Y_e \sim 0.42$



Nuclei,
p, e^-

ν-trapping

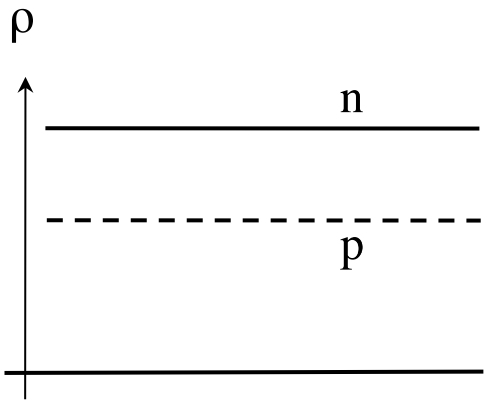
$\rho_c \sim 10^{12}$ g/cm^3
$T_c \sim 2$ MeV
$Y_e \sim 0.40$



Nuclei,
p, n, e^-, ν_e

Core-Bounce

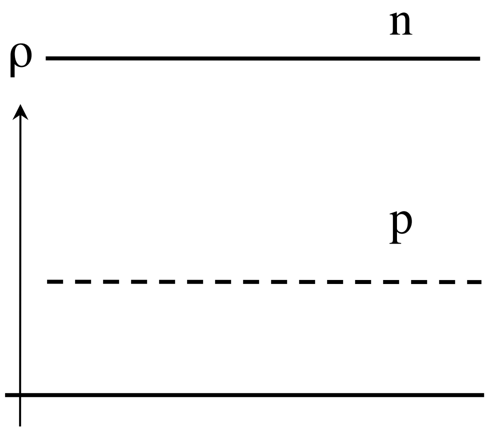
$\rho_c \sim 3\text{x}10^{14}$ g/cm^3
$T_c \sim 10$ MeV
$Y_e \sim 0.30$



p, n,
e^-, ν_e

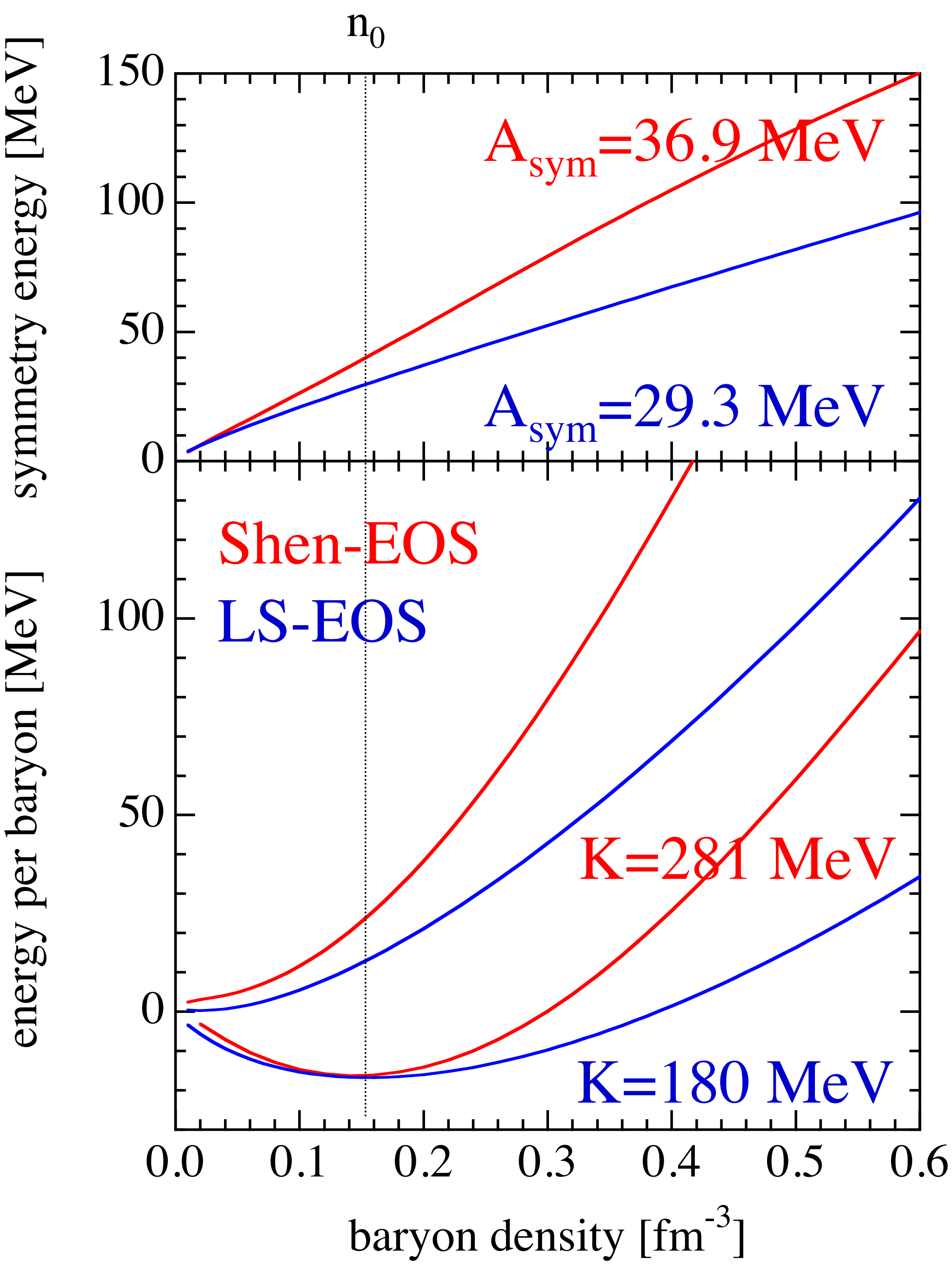
Explosion, Neutron stars

$\rho_c \sim 5\text{x}10^{14}$ g/cm^3
$T_c \sim 15$ MeV
$Y_e < 0.20$



p, n, (Λ, q)
e^-, ν_i, $\overline{\nu}_i$

Shen-EOS vs **LS-EOS**



Sumiyoshi et al. NPA730 (2004)

- **Stiff or Soft, that is a problem**

- EOS is stiff, IF:
  - Higher Energy, Steeper slope
- Affect supernova dynamics
  - Core bounce, Neutrino reactions

- Pressure: p

$$p = -\frac{\partial E}{\partial V} = n^2 \frac{\partial E}{\partial n}$$

- Incompressibility: K

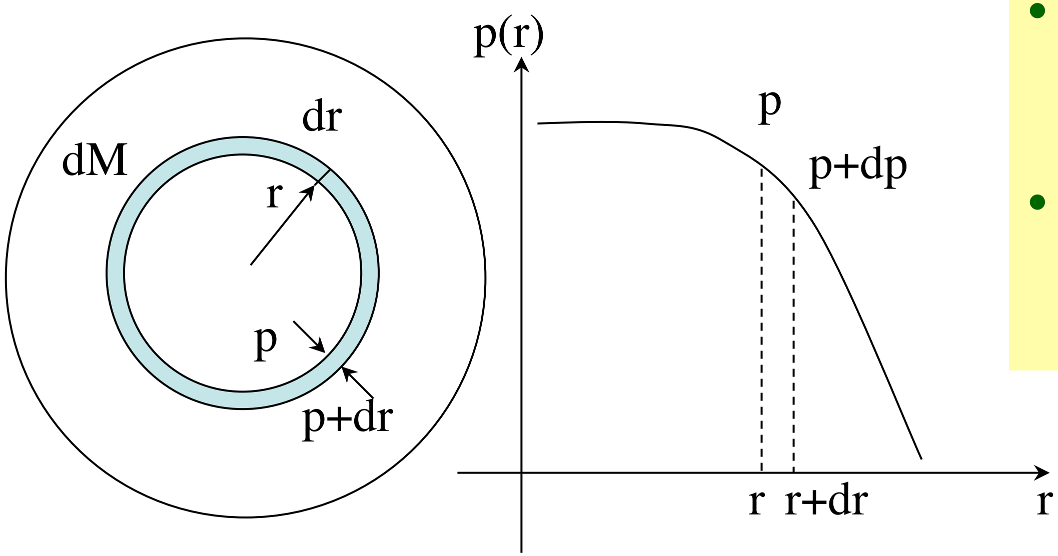
  Curvature at saturation

  Exp: K=200-300 MeV

$$K \equiv 9 \frac{dP}{dn}\Bigg|_{n=n_0} = 9 n_0^2 \frac{d^2 E}{dn^2}\Bigg|_{n=n_0}$$

Structure of neutron stars

Shen-EOS vs LS-EOS



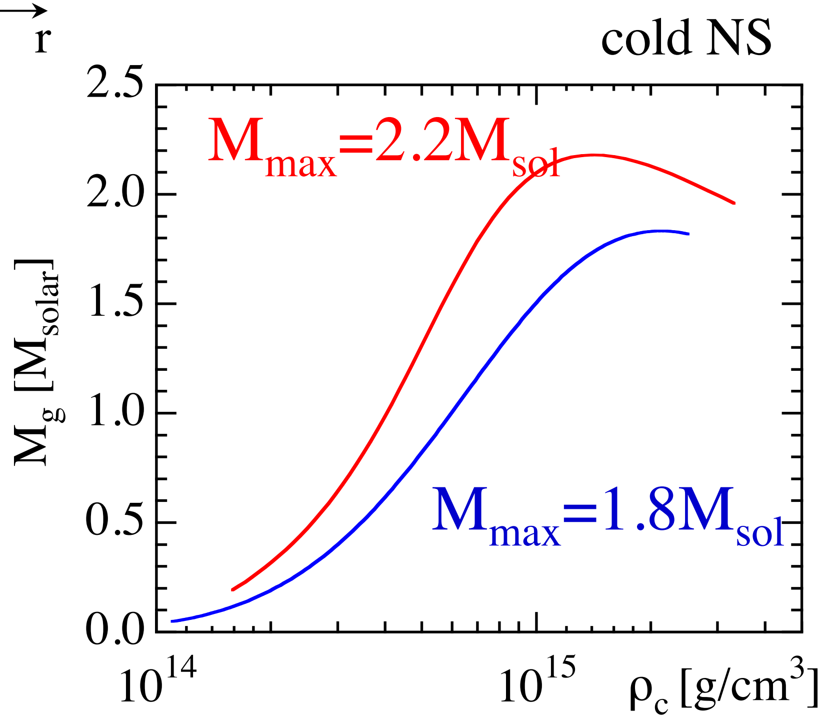
- Stiff EOS can support:
  - Massive neutron star
  - Less compact (large radius)
- Mass of neutron stars
  - observations (>1.4M_{sun})
  - critical mass for black hole

Balance between gravity and pressure gradient

$$\frac{dM}{dr} = 4\pi r^2 \rho$$

$$\frac{dp}{dr} = -\frac{GM\rho}{r^2}\frac{\left(1+\frac{p}{\rho}\right)\left(1+\frac{4\pi p r^3}{M}\right)}{\left(1-\frac{2GM}{r}\right)}$$

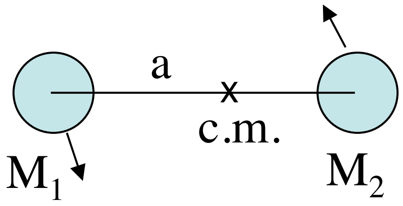
Tolman-Oppenheimer-Volkoff equation



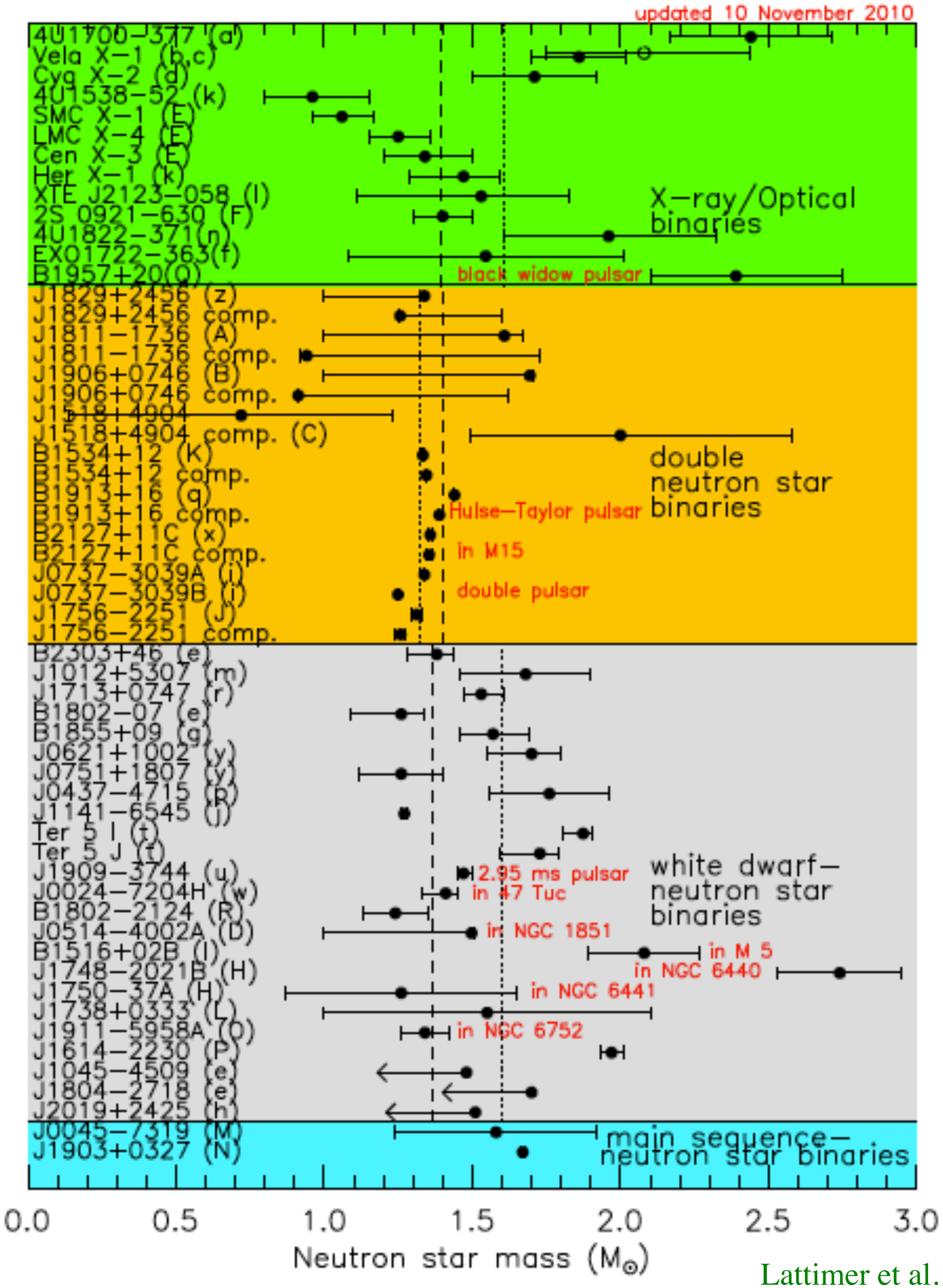
Sumiyoshi et al. NPA730 (2004)

Observation of neutron stars

- Mass of neutron stars
- Motion of binary system
  - orbital period P
  - Doppler shift v
  - Kepler's law:
  - $G(M_1+M_2)P^2=4\pi^2a^3$



- Binary pulsar
  - Hulse-Taylor binary pulsar
  - $M_{PSR}=1.4411\pm0.0003M_{solar}$



Lattimer et al.

ν reactions with matter in supernova core

ν number, energy change → heating/cooling of matter

- Difficult experiments
- Dependence on energy, nuclei
- Various nuclei appear

- Cross section: $\sigma \sim 10^{-41}$ cm^2
- Interaction: $\sigma \sim E_\nu^2$
- Nucleus: $\sigma \sim A^2$

- Emission/absorption:

$e^- + p \leftrightarrow \nu_e + n$　　　$e^- + A \leftrightarrow \nu_e + A'$

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

- Scattering:

$\nu_i + N \leftrightarrow \nu_i + N$　　　$\nu_i + A \leftrightarrow \nu_i + A$

$\nu_i + e \leftrightarrow \nu_i + e$

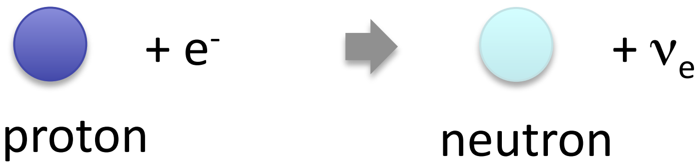
- Pair creation/annhilation:

$e^- + e^+ \leftrightarrow \nu_i + \bar{\nu}_i$　　　$\gamma^* \leftrightarrow \nu_i + \bar{\nu}_i$

$N + N \leftrightarrow N + N + \nu_i + \bar{\nu}_i$　　　$i = e, \mu, \tau$

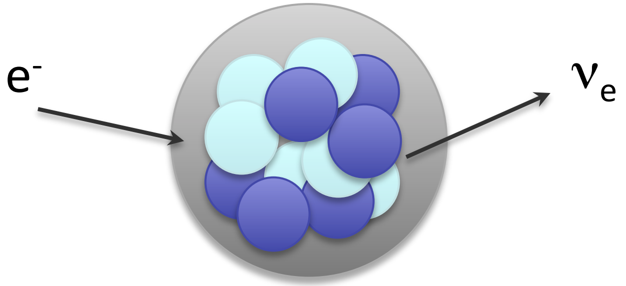
Neutrino process during the collapse I

- Neutrino production through electron capture
  - Fermi energy of electrons
    $\mu_e \sim (3\pi^2 n_e)^{1/3} = 11.1$ MeV at 10^{10} g/cm^3
  - Decrease of electron pressure as $\rho \uparrow$, $\mu_e \uparrow$
  - Neutrino emission (and trapping)
  - Amount of leptons in central core
    - electrons and neutrinos



electron capture of proton

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



electron capture on nuclei

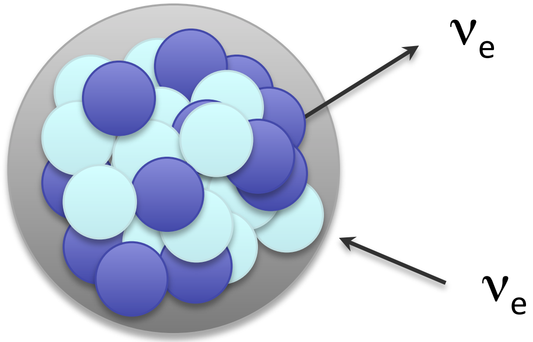
$^{56}\mathrm{Fe} + e^- \rightarrow {}^{56}\mathrm{Mn} + \nu_e$

Neutrino process during the collapse II

- Neutrino trapping by neutrino scattering
- ν-mean free path (λ_ν) vs core radius (R_{core})

$$\lambda_\nu = \frac{1}{\sigma_{\nu A} n_A} = 1 \times 10^7 cm \left(\frac{\rho}{3 \times 10^{10} g/cm^3} \right)^{-\frac{5}{3}} \left(\frac{A}{56} \right)^{-1}$$

For $\rho > 3 \mathrm{x} 10^{10}$ g/cm^3 ,
$\lambda_\nu \leq R_{core}$: **ν cannot escape**



neutrino scattering on nuclei

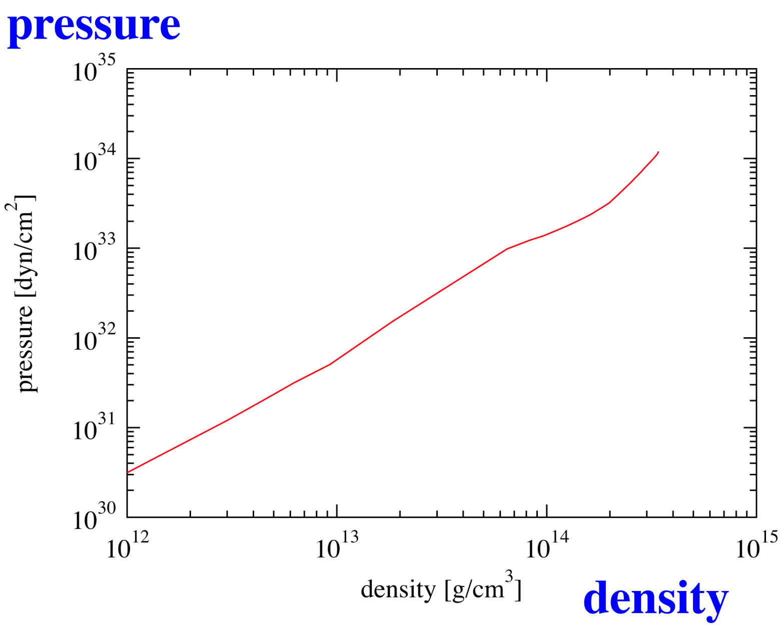
$^{100}Zr + \nu_e \rightarrow {}^{100}Zr + \nu_e$

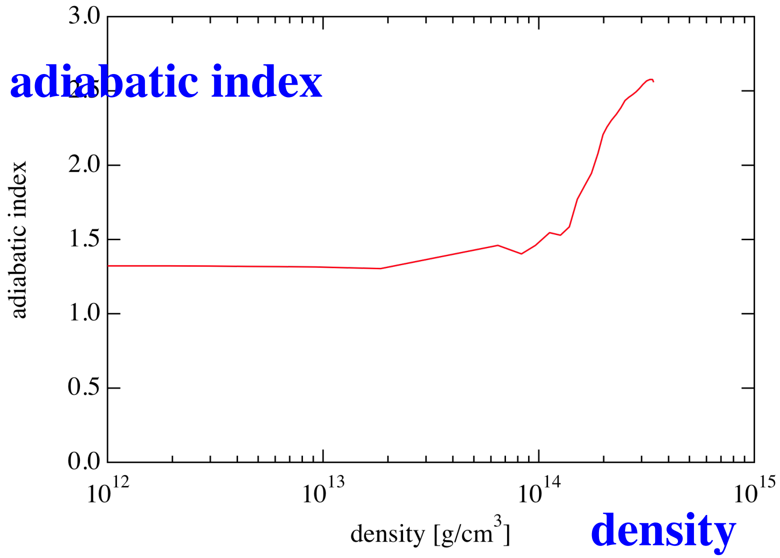
- Diffusion time scale

$$\tau_{diffusion} = \frac{3R_{core}^2}{c\lambda_\nu} = 7 \times 10^{-3} \sec \left(\frac{\rho}{3 \times 10^{10} g/cm^3} \right) \left(\frac{A}{56} \right)$$

For $\rho \geq 10^{11}$ g/cm^3 ,
$\tau_{dyn} \leq \tau_{diffusion}$: **ν are trapped**

Role of EOS at core bounce



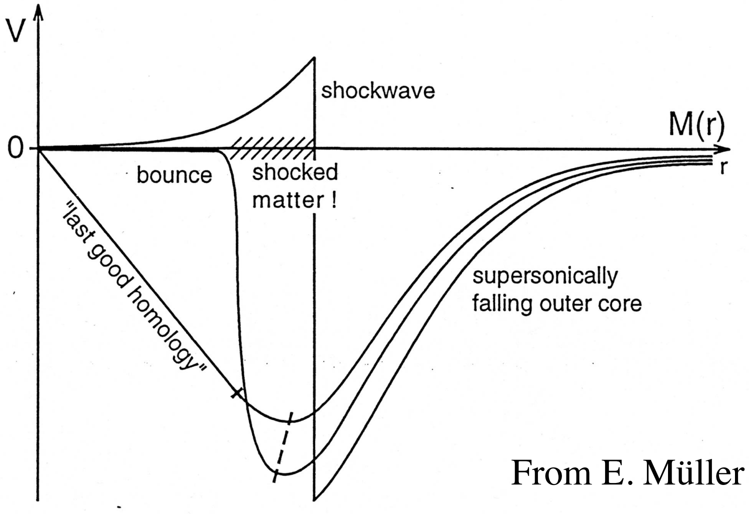


- Matter becomes stiff

Adiabatic Index $$\Gamma = \left.\frac{d\log P}{d\log \rho}\right|_S$$

above $\rho \sim 3\text{x}10^{14}$ g/cm^3 ,

- Repulsion of nuclear force
- Halts the collapse and core bounce
- Produces shock wave



From E. Müller

Studies of Explosion Mechanism

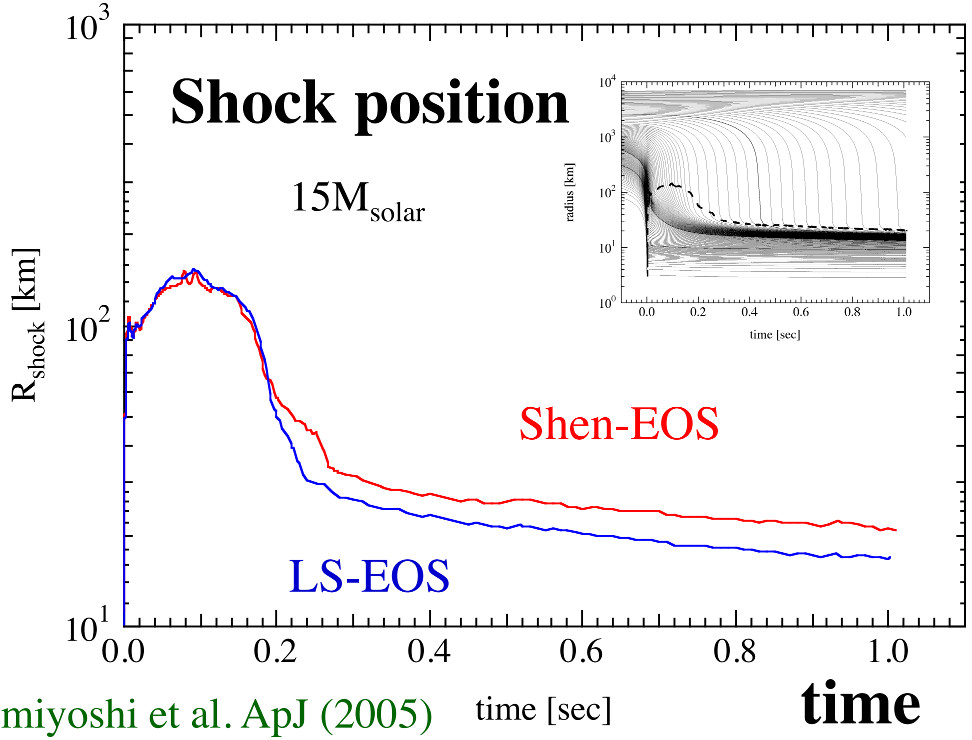
Delicate balance of counter-effects

No explosion in 1D simulations

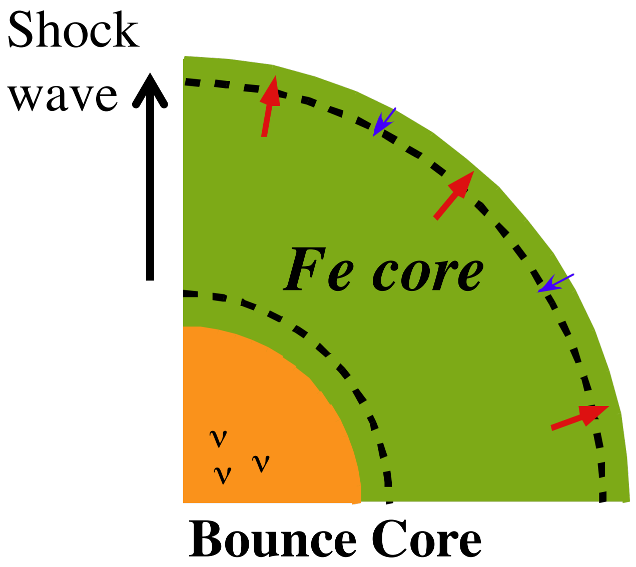
spherical

US, Germany, Japan (2001-)

First principle calculation: ν-radiation hydrodynamics



Sumiyoshi et al. ApJ (2005)



Shock wave stalls on the way

Initial shock energy

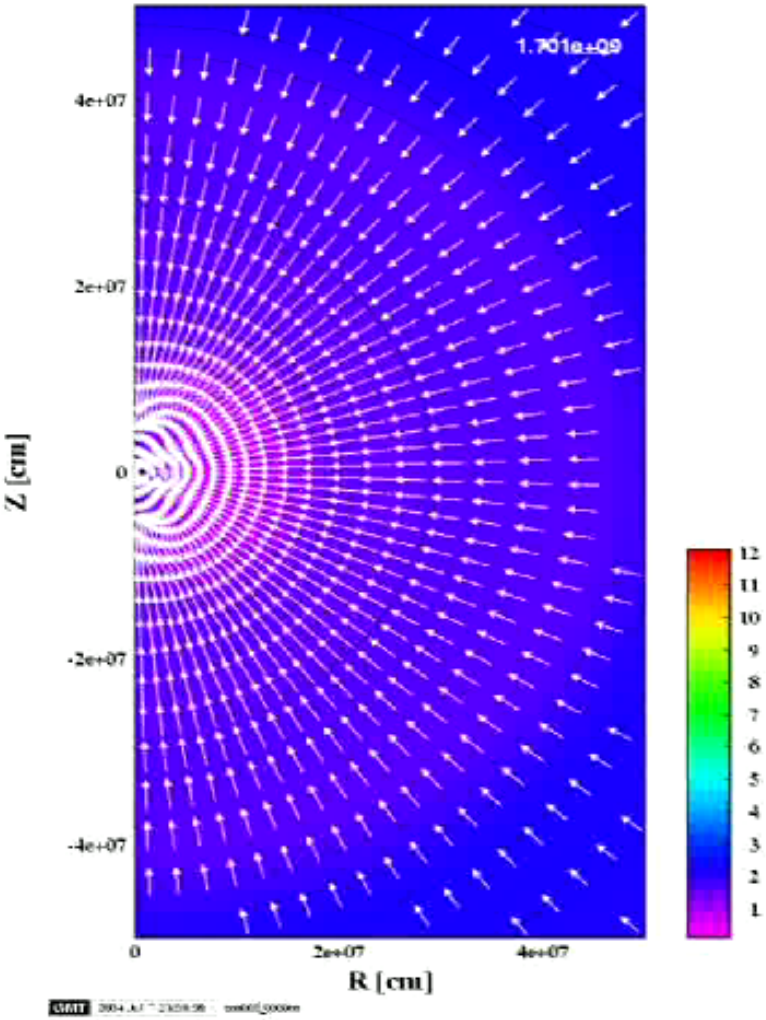
$$E_{shock} \sim \frac{GM_{inner}^2}{R_{inner}} = several \times 10^{51} erg$$

Energy loss due to Fe dissociation

$$E_{loss} \sim -1.6 \times 10^{51} \left(\frac{M_{outer}}{0.1 M_{solar}} \right) erg$$

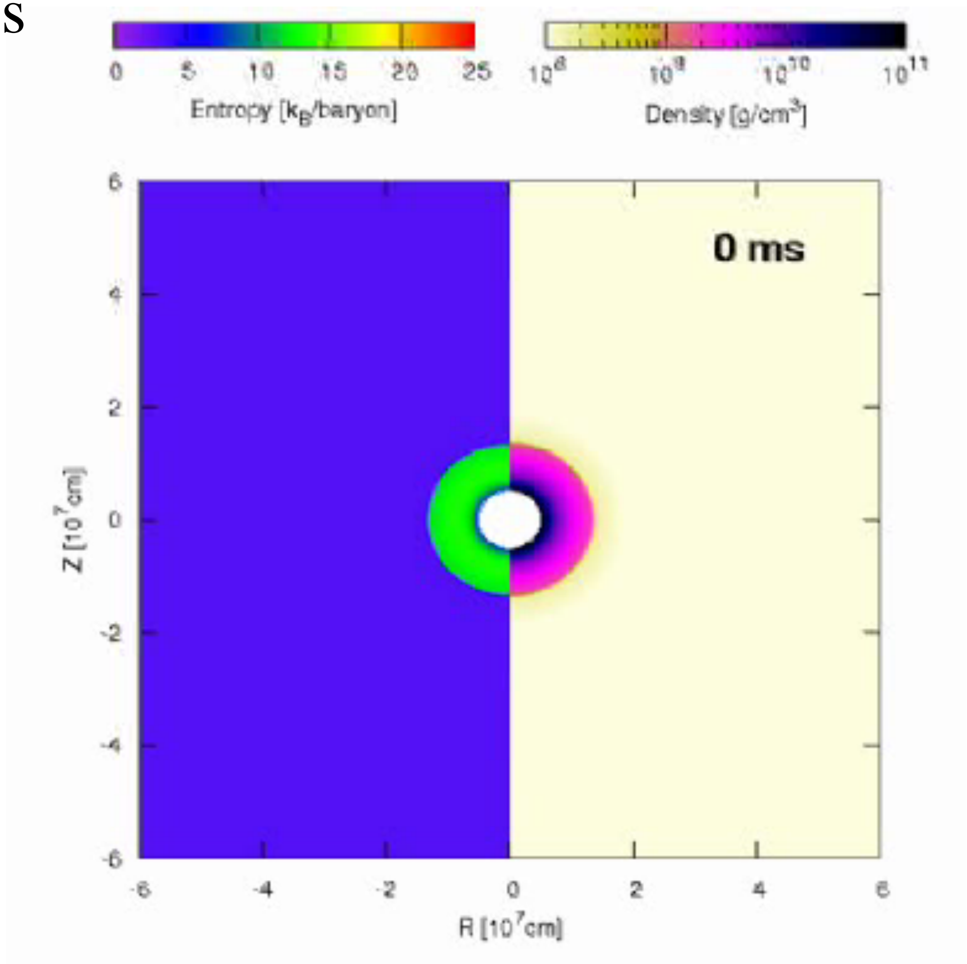
Role of asymmetry: multi-D simulations

Approx. neutrino + hydrodynamics



- Convection, rotation

Kotake et al. ApJ 2003



- Up-down asymmetric instbility

(Standing Accretion Shock Instability, **SASI**)

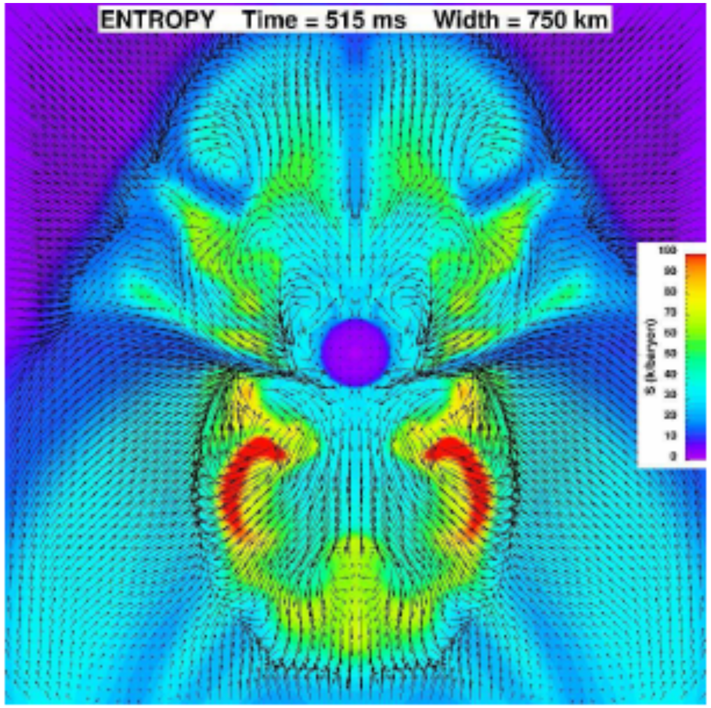
N. Ohnishi et al. ApJ 2007

A handful of successful explosion: remains elusive

Explosions after ~500ms

Acoustic Powered

Burrows et al. ApJ 640 (2006) 878

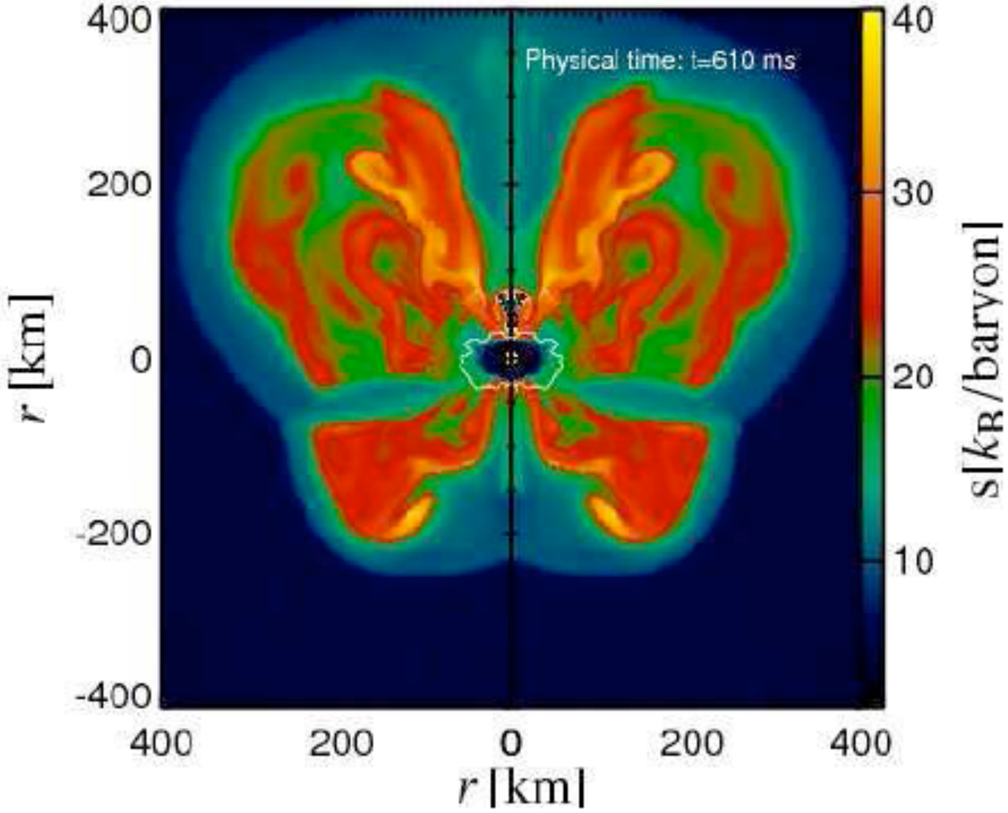


11M_{solar} without rotation Shen-EOS

Flux-limited diffusion method

SASI + Neutrino-heating

Marek-Janka, astro-ph/0708.3372



15M_{solar} with rotation LS-EOS

Ray-by-ray method

Not settled yet: different method, microphysics, stellar models

Neutrino heating mechanism

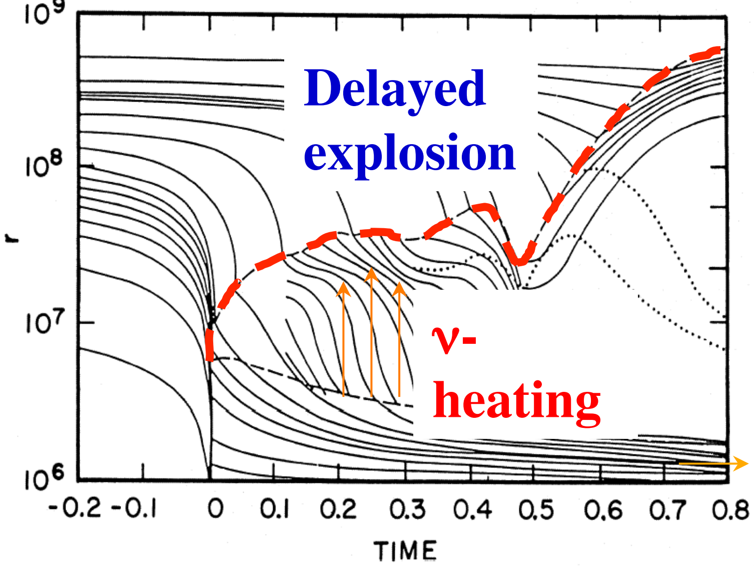
Bethe & Wilson ApJ (1985)

Heating of material by neutrino absorption

Transfer of energy from ν

$$E_{\nu-heat} \sim 2.2\times10^{51}\left(\frac{\Delta M}{0.1M_{solar}}\right)\left(\frac{\Delta t}{0.1s}\right)erg$$

Legend of Wilson's simulation (1985)

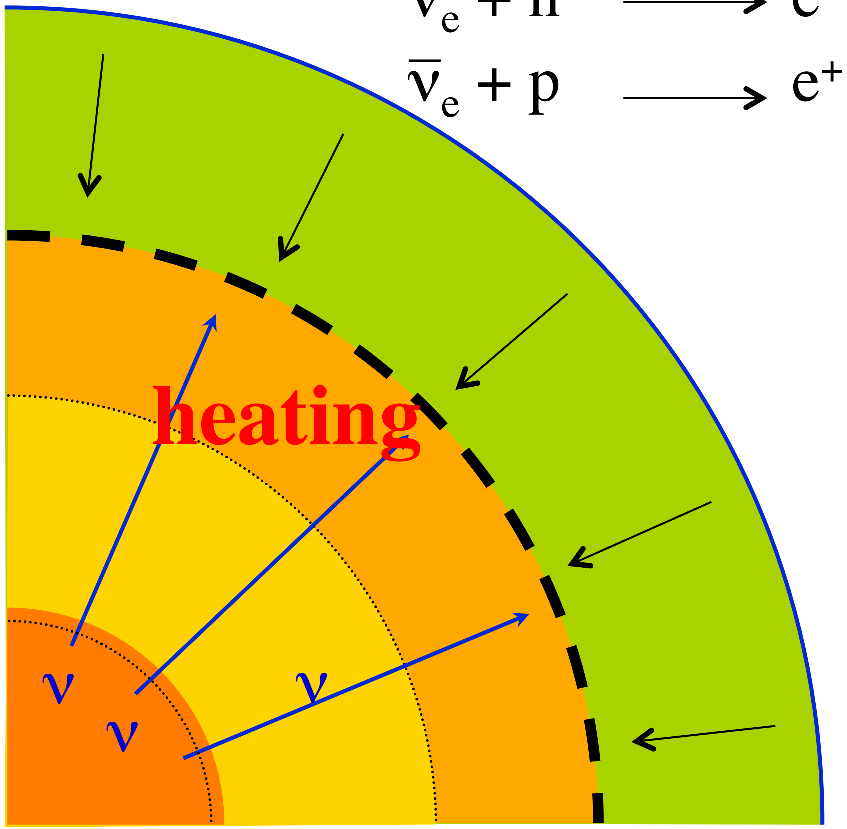


Delayed explosion

ν-heating

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

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



heating

ν

ν

ν

Proto-NS

Shock
~200km

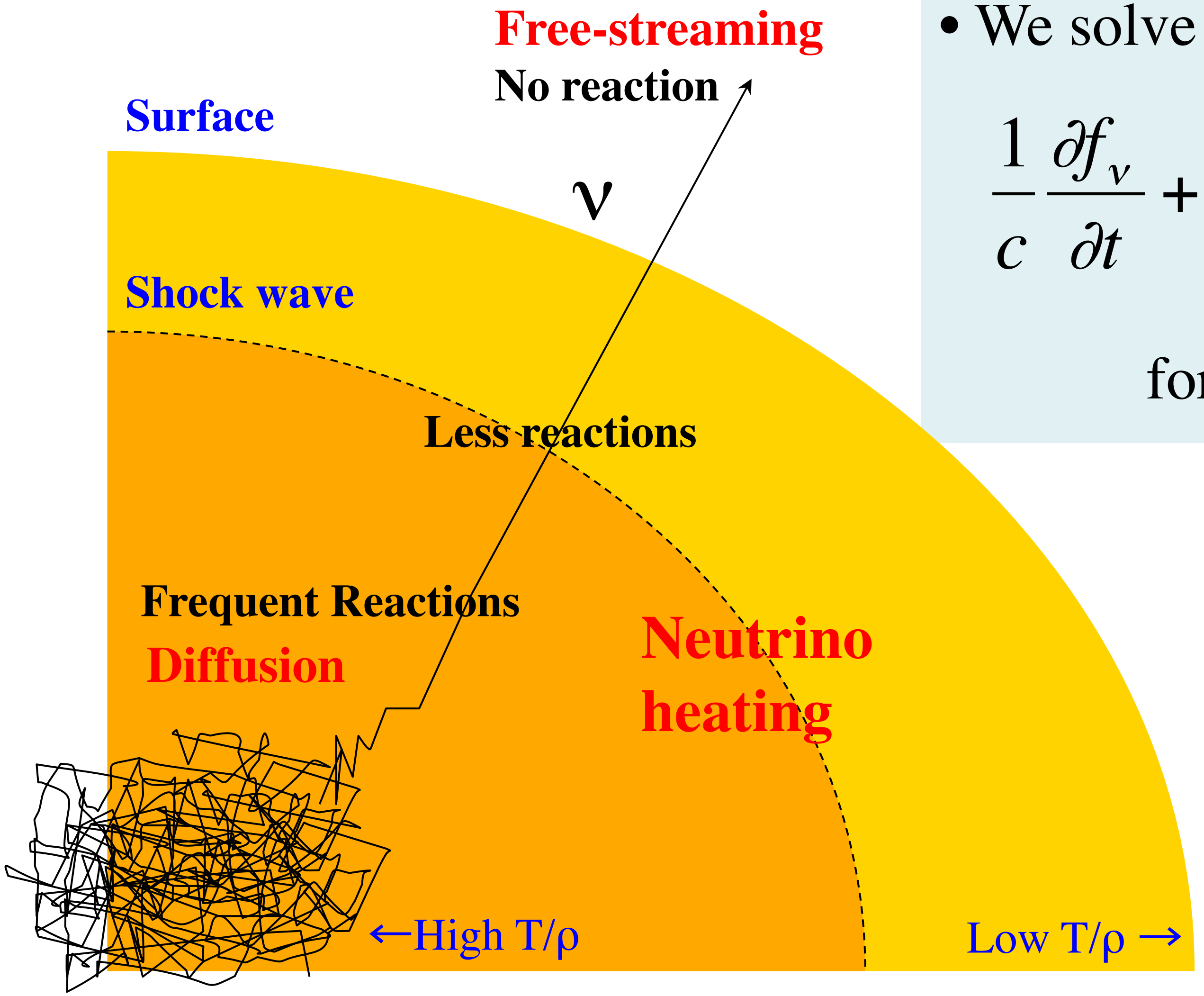
Fe core
surface

Depends on neutrino energy, flux, target material, time

Calculation of ν-radiation transfer

- Neutrino propagation from supernova core to outside

- Neutrino heating occurs in intermediate regime



- We solve Boltzmann eq. for neutrinos

$$\frac{1}{c}\frac{\partial f_\nu}{\partial t}+\vec{n}\cdot\vec{\nabla}f_\nu=\frac{1}{c}\left(\frac{\delta f_\nu}{\delta t}\right)_{collision}$$

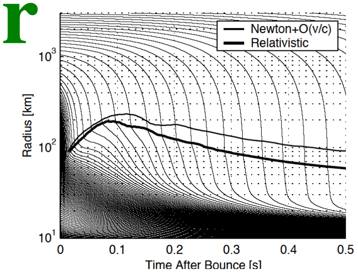
for $f(t,x,y,z,p_x,p_y,p_z)$

- in 6 dimension
  - 3D space, 3-p_ν
- with all ν-reactions

Status of calculation of neutrino transfer

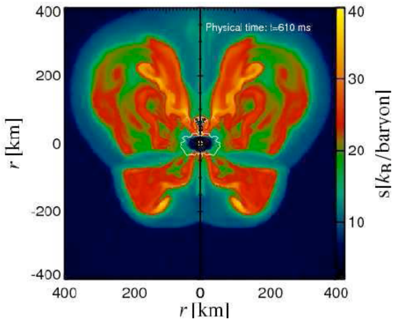
- 1D: first principle calculations
  - Examine Microphysics, Systematics (2000~)

Liebendoerfer, Sumiyoshi-Yamada-Nakazato



- 2D: approximate treatment
  - State-of-the-art calculations (recent)

Ott (S_n-method), Burrows, Marek-Janka, Suwa-Kotake



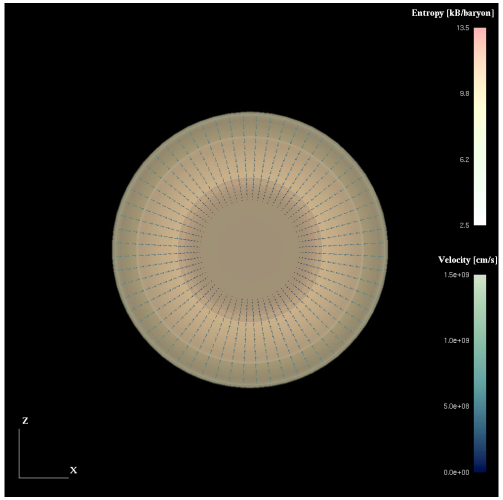
- 3D: simple treatment
  - Explore hydrodynamical instabilities

Blonding-Mezzacappa, Iwakami-Ohnishi-Kotake

Need full 3D calculations:

To establish the supernova mechanism

Hydro instabilities to have more time for ν-heating

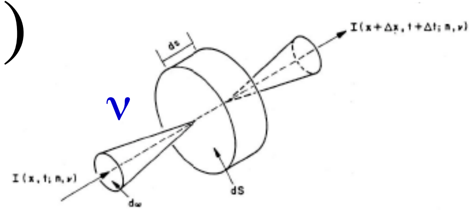


Iwakami

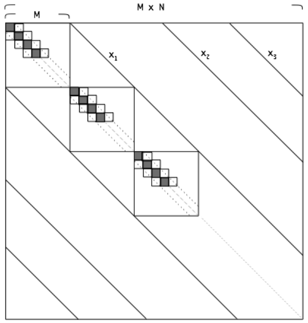
Project on ν-radiation transfer in 3D

Sumiyoshi, Yamada (2011) submitted to ApJ

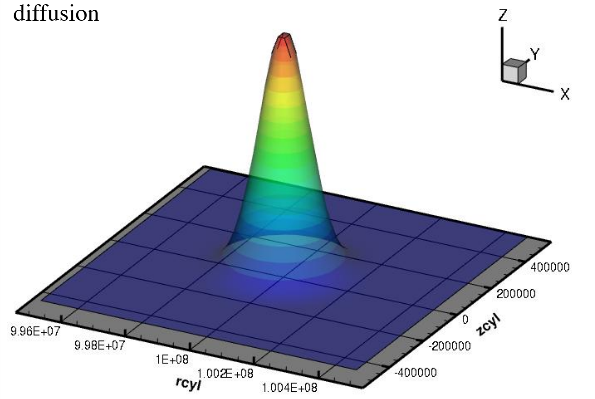
- New numerical code to solve Boltzmann equation in 3D
  - Neutrino distribution in 6D $(r, \theta, \phi, \theta_\nu, \phi_\nu, \varepsilon)$
  - EOS table and neutrino reactions

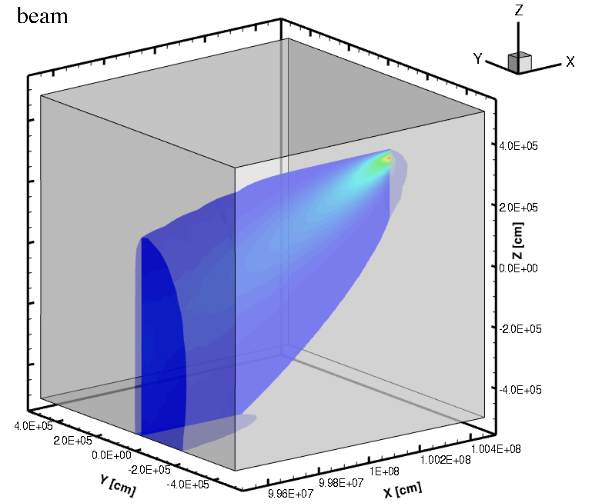


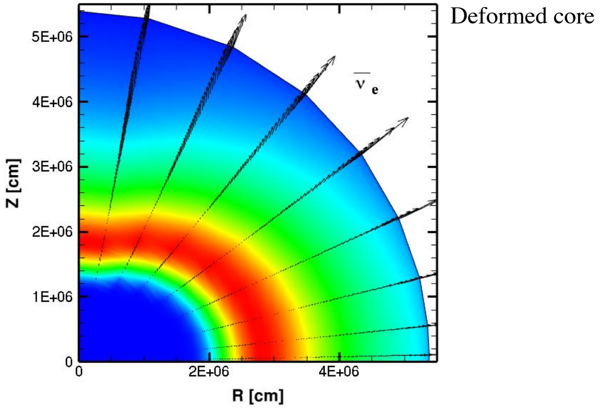
- Computational challenge
  - Large sparse-block matrix (implicit method)
    - Parallel algorithm, matrix solver



- Validated code: applied to supernova cores







Computational challenge

- Maximum tests done up to now:
  - – 900GB memory on 8cpu at SX9/Osaka Univ.
    - Gaussian packet: 75x72x72, 12x12x4
- Expected spec requirement at least (1^{st} stage)
  - – Large block matrix: ~6TB
  - – Neutrino distribution: ~25GB / species
  - – Computations: ~100T floating operations / step
- Need top supercomputers:
  - – K-supercomputer

    ~10Pflops

Fujitsu

Summary

- **Core-collapse supernovae**
  - Origin and evolution of elements, stars, galaxies
  - Not solved yet even after researches for > 4 decades
- **Mechanism of core-collapse supernovae**
  - Interplay of nuclear physics and astrophysics
  - The fate of massive stars: collapse & bounce
- **Physics of extreme conditions**
  - Properties of hot and dense matter
  - Neutrino interaction in supernova core
- **Numerical challenge on supercomputers**
  - Detailed counter effects to obtain the explosions
  - Hydrodynamics and neutrino transport in 3D

This project is done in collaboration with

- Supernova research
  - S. Yamada
  - K. Nakazato
  - H. Suzuki
- RMF-EOS table
  - H. Shen
  - K. Oyamatsu
  - H. Toki
  - A. Ohnishi
  - C. Ishizuka
- Supercomputing
  - S. Hashimoto
  - H. Matsufuru
  - T. Sakurai
- Numerical simulations
  - K. Kotake
  - T. Takiwaki
  - H. Nagakura
  - S. Furusawa

Category 5: Origin and structure of matter and universe
Subject 3: Supernova explosion & Black hole


HPCI Strategic Program Field 5
'The origin of matter and the universe"

10Pflops supercomputer at AICS, Kobe

K computer

ranking 1st position in top 500, June 20, 2011