Recent studies on supernova nucleosynthesis with X-ray observations of supernova remnants

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Self introduction

Affiliation: The Institute of Physical and Chemical Research (RIKEN)

Position: Special Postdoctoral Researcher

Research interests:

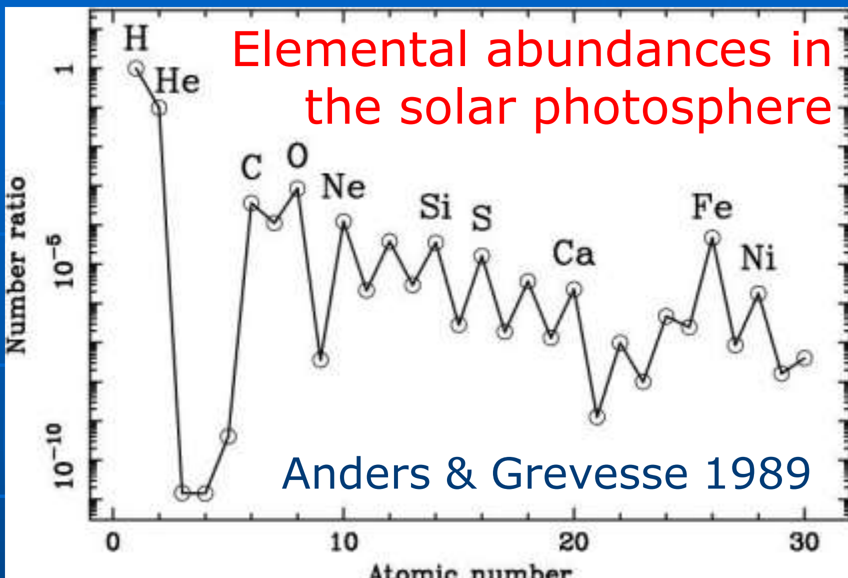
- X-ray studies of supernova remnants
- X-ray instrument development

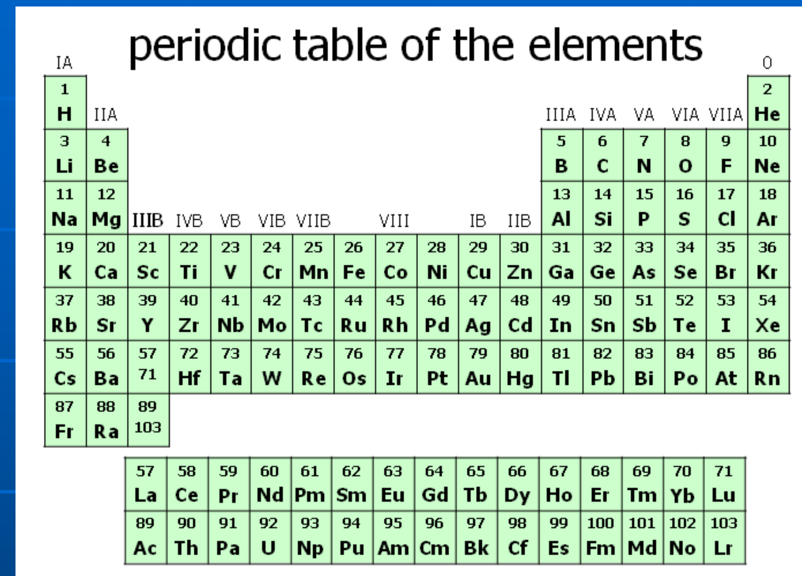
Talk Plan

- Introduction
  - Supernova (SN) and nucleosynthesis
  - Supernova remnant (SNR)
- X-ray observation
  - What information can we obtain from observation?
  - Current X-ray missions and their characteristics
- Observation results on Type Ia SNRs
  - Layered composition structure of SN ejecta
  - Detection of low-abundance elements (Cr, Mn, and Ni)
- Conclusion

Motivation for observation of SNRs

As origins of heavy elements





Immediately after the beginning of the universe : only H and He

Present universe : various heavy elements exist abundantly
  Synthesized in stars and ejected by supernova explosion
  Nucleosynthesis (nuclear fusion) is performed actively
  just at the moment of SN explosion as well

Details of stellar and SN nucleosynthesis are very important
 to understand chemical evolution of the universe

Motivation for observation of SNRs

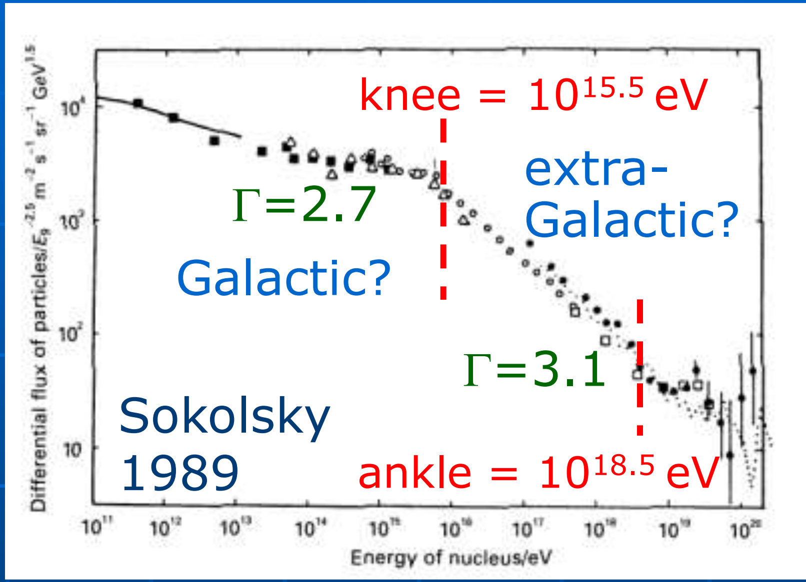
As origins of cosmic-rays

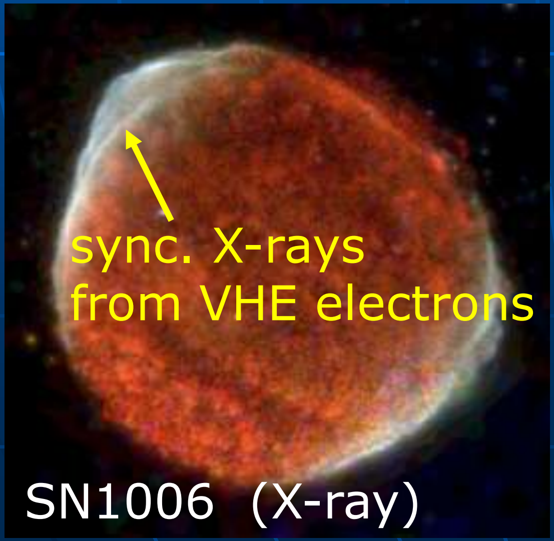
Very high energy particle (up to 10^{21} eV)

Energy density u_{CR} ~ 1eV/cc

c.f.	stellar light	< 0.3eV/cc
	magnetic field	0.3eV/cc
	CMB	0.3eV/cc
	thermal energy	0.01eV/cc

Major component of the Galaxy





- The origin and acceleration mechanism had been unknown since the discovery
- CR (E < $10^{15.5}$ eV) are believed to be accelerated at shock front of SNRs

Maximum energy?
Detailed mechanism of acceleration?

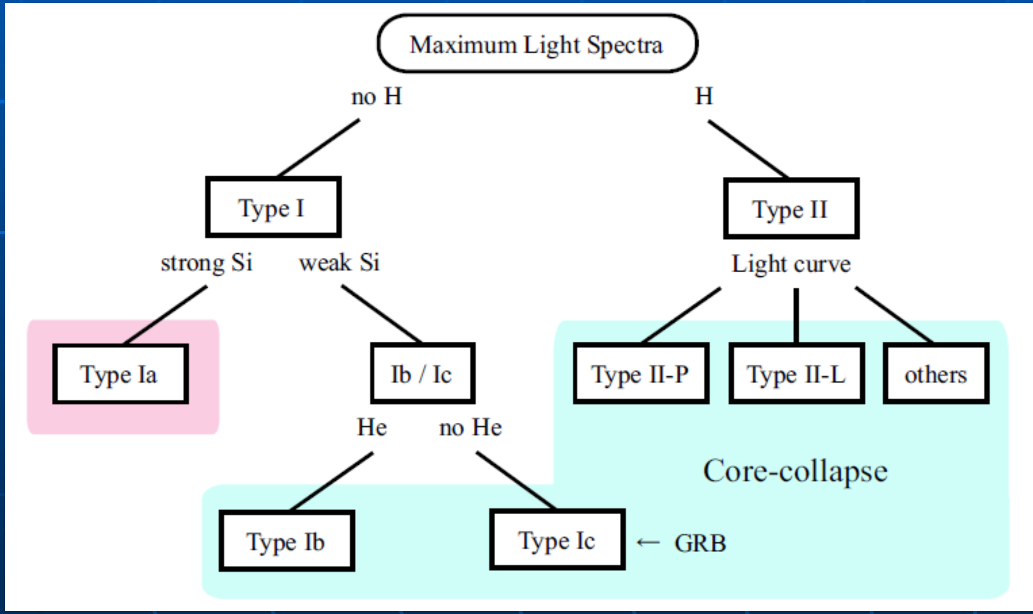
Supernovae and their progenitors

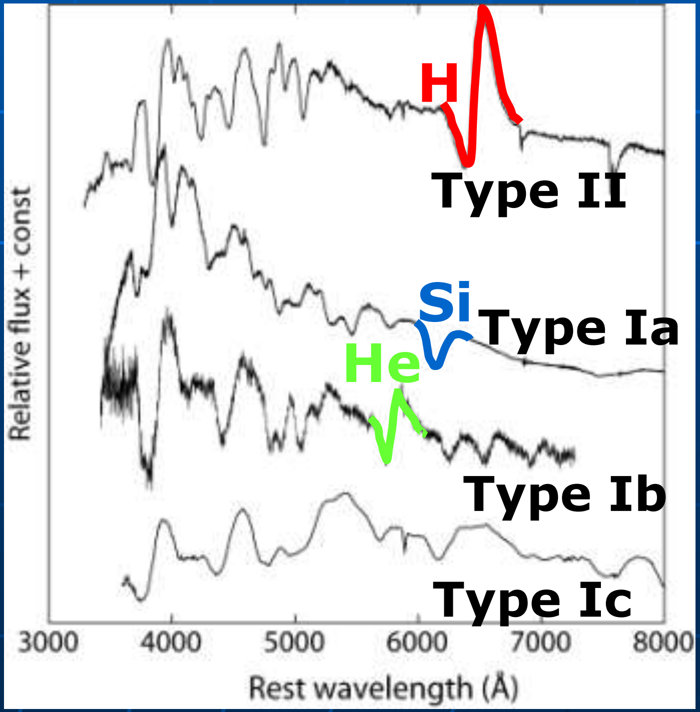
Supernovae

Explosion of stars at the end of their lifetime
Occur every ~30yrs in our Galaxy

Classification

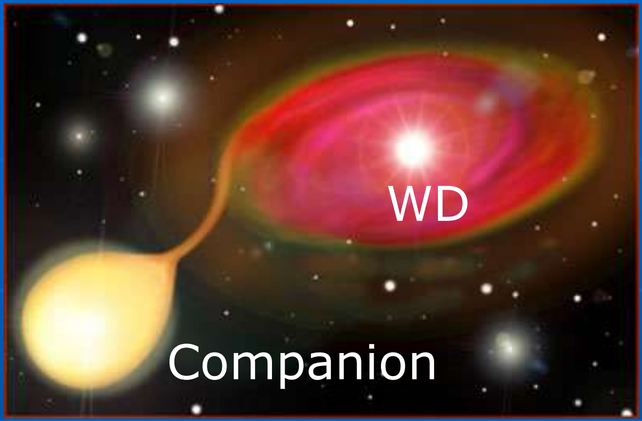
Traditionally based on their optical spectra near maximum light and light curves





But, not reflect differences in progenitors

Supernovae and their progenitors



Nuclear reaction energy
~ 10^{51} ergs

① Type Ia SNe

- Observed in all types of galaxies
- Not concentrated in spiral arms

Thermonuclear explosion of C+O white dwarf in binary system ($M=3\sim8M_\odot$ @main seq.)

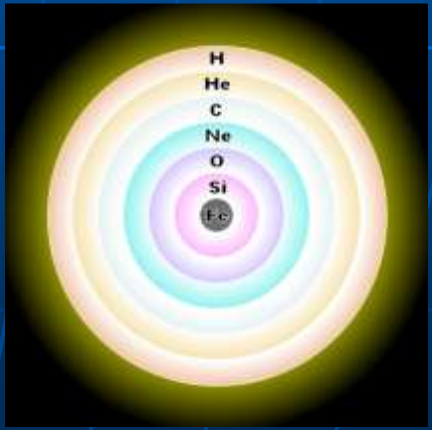
- Mass accretion from companion increases the WD mass to Chandrasekhar limit
- Carbon burning is ignited at the core
- Nuclear fusion advances explosively

② Type II/Ib/Ic SNe

- Observed in arms of spiral galaxies

Core-collapse of massive star ($M>8M_\odot$) with onion-like abundance structure

- Photo-disintegration of Fe-core leads to gravitational collapse
- Stellar remnant (NS or BH) is left



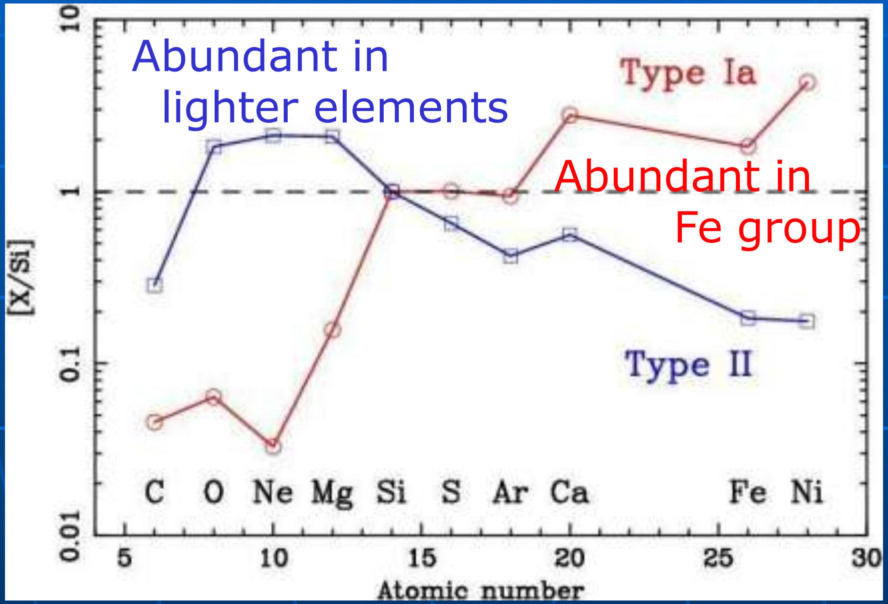
Gravitational energy ~ 10^{53} ergs (99% neutrino, 1% kinetic energy)

Expected nucleosynthesis yield

Abundance ratio of heavy elements has been calculated numerically

But a lot of problems still remain since the details of explosion mechanisms have not been solved.

Abundance ratio relative to solar



Examples of theoretical calculation

Type Ia (W7 model): Nomoto+84
Type II ($25M_\odot$): Thielemann+96

- Distribution of ejecta?
- explosion velocity of ejecta?

- Mixing effect due to instability during the explosion or progenitor's metallicity affect the abundance or distribution of ejecta?

- Origin of Au, Ag, U ?

Observations would help us to solve these problems!

How can we investigate nucleosynthesis yield?

① Optical observation of SN explosion

Many SN events can be observed

- Inside is optically thick due to a high density
- Have to observe many times to obtain information of deeper region

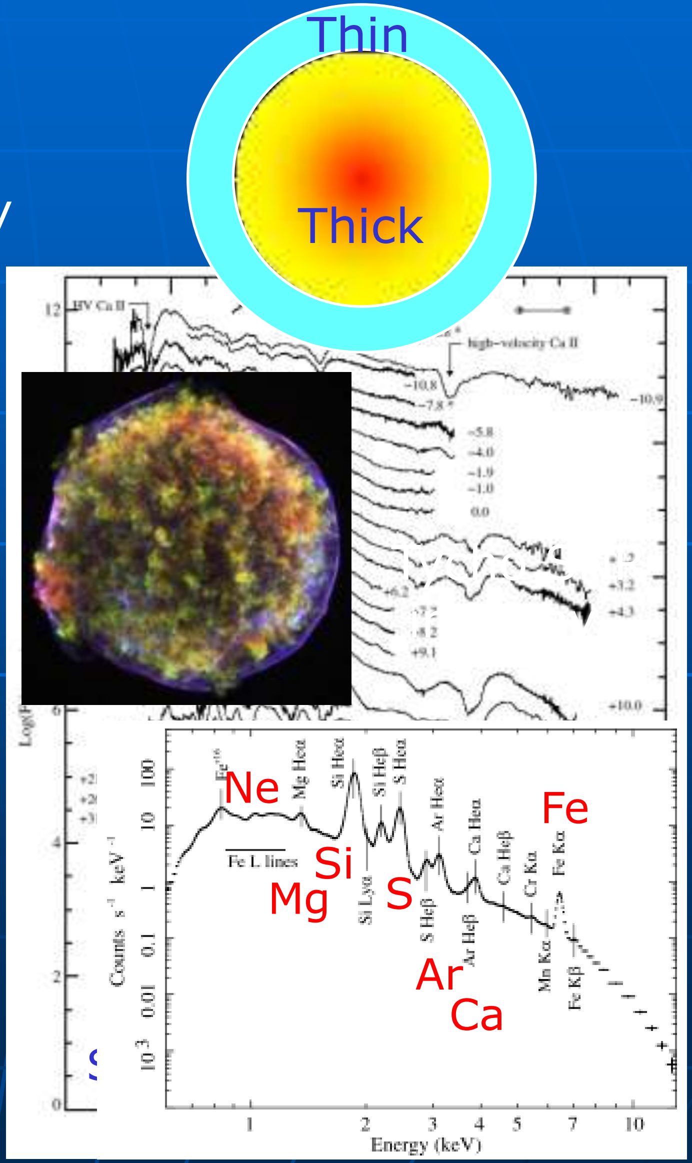
② X-ray observation of SN remnant (SNR)

Hot (~10^7 K) thin (<$1\,\mathrm{cm}^{-3}$) thermal plasma

- Ejecta in entire SNR can be directly observed in X-ray at one time
- K-shell emissions from major heavy elements are included in X-ray band

Young SNRs
= "SN explosion magnified by microscope"
3D information (asymmetry)

- Provide X-rays for >10^4 yrs after explosion



Supernova remnants and X-ray emission

Ejecta expand supersonically and form shock wave by interacting with ISM

Shock heating = energy conversion
from kinetic energy to thermal energy

$$(3/16)\times(\mu V^2/2) = k_B T$$

kT ~ 10^7 K ~ 1keV for V ~ 1000km/s

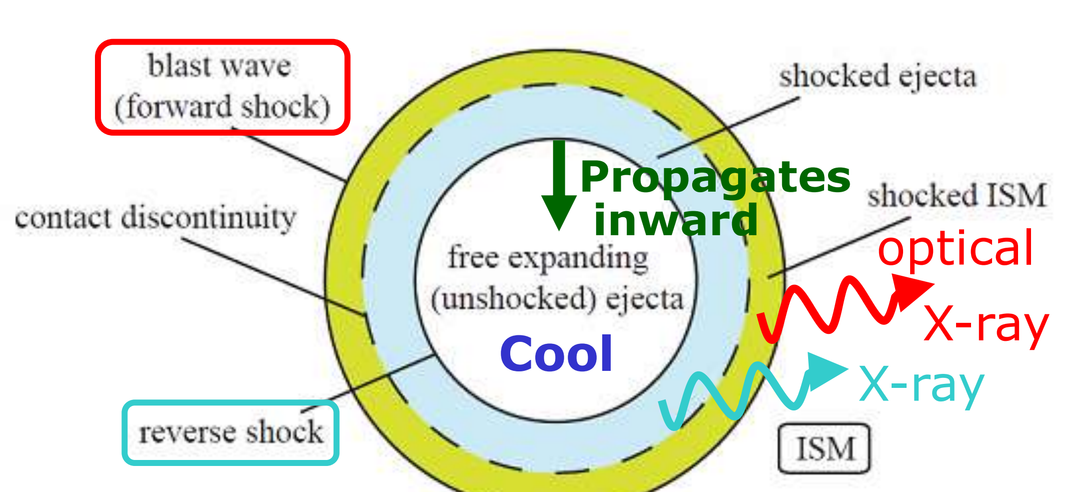
Forward shock sweeps up ISM
Reverse shock compresses ejecta

Matter is hot enough to emit X-ray
between the two shock waves

Cassiopeia A

Optical (DSS)
usually faint

X-ray (Chandra)
very bright



Schematic view of young SNRs

SNR E0102-72 @SMC

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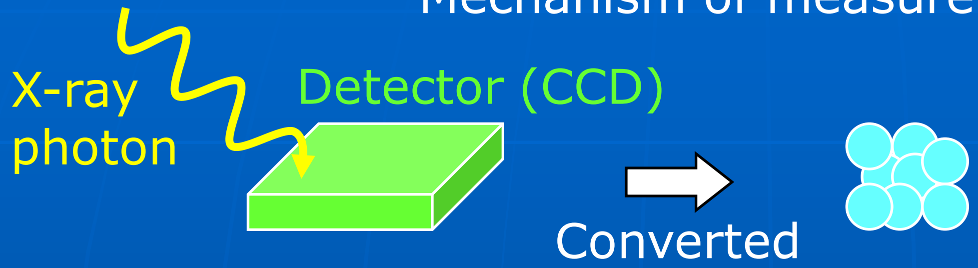
What can we measure with X-ray?

Mechanism of measurement

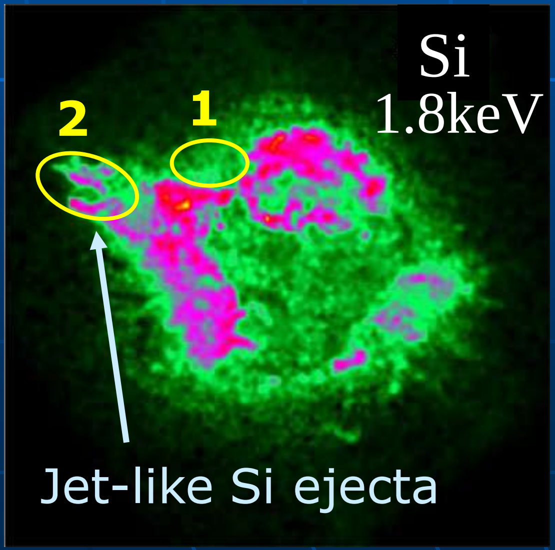


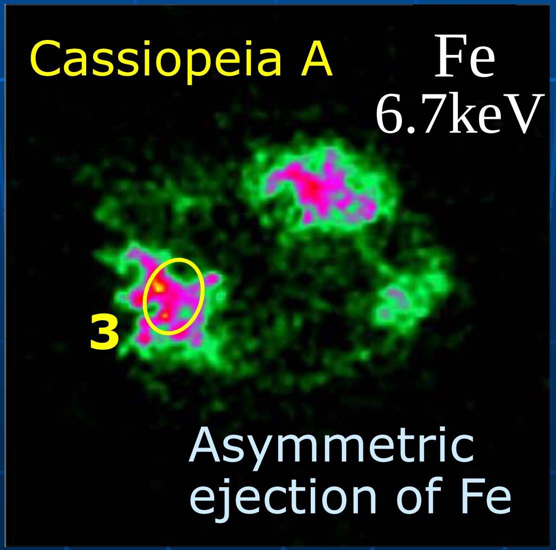
Number of electrons is proportional to the incident X-ray energy

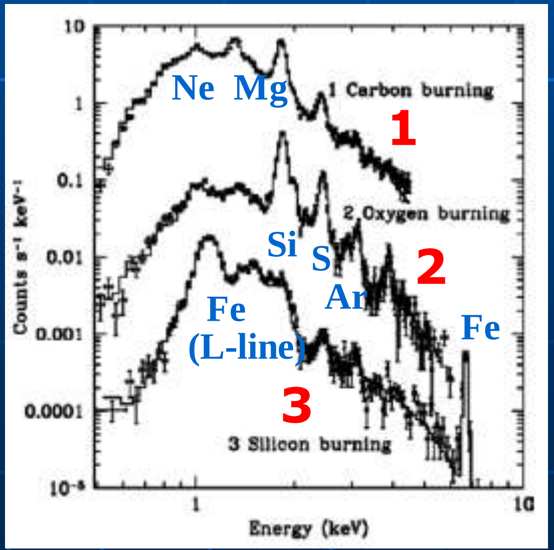
- Time ⇒ Light curve
- Position ⇒ Image
- Energy ⇒ Spectrum

"Images of specific energies" and/or "Spectra of specific regions" are available

Chandra images and spectra of Type II SNR Cassiopeia A (Vink+04)







Current X-ray missions and their performances

BAD ← Imaging → GOOD!

GOOD! ← Spectroscopy → BAD

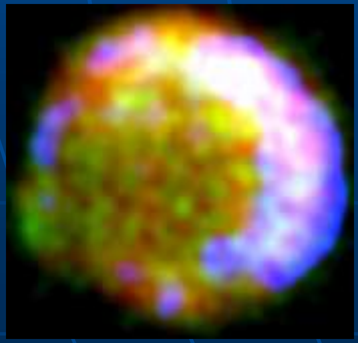
Satellite	Energy resolution (eV) @6keV	Effective area (cm^2) @1.5 keV	Energy band (keV)	Angular resolution (arcmin)	Instrumental background level or noise
Suzaku	140	1100	0.2-12	110	Low, stable
XMM	140	2200	0.5-12	15	High, unstable
Chandra	180	660	0.5-12	0.5	High, unstable

Current X-ray missions and their performances

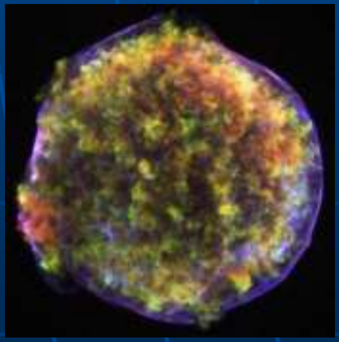
BAD ← Imaging → GOOD!

GOOD! ← Spectroscopy → BAD

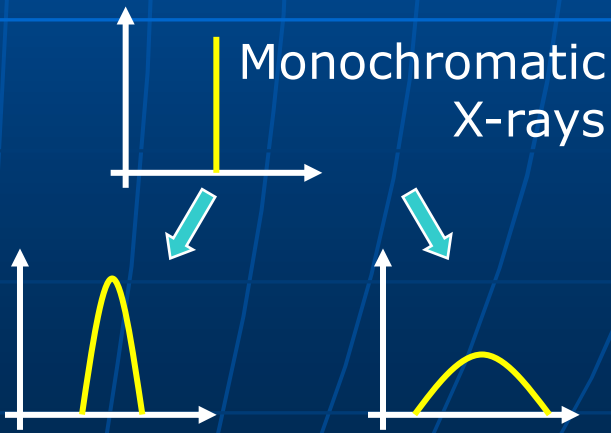
Tycho SNR



Suzaku



Chandra



Suzaku

Chandra

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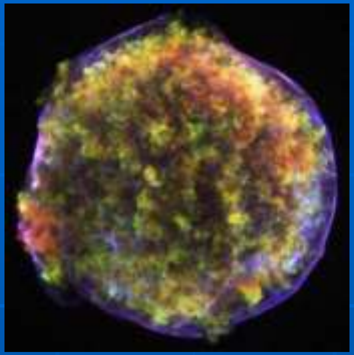
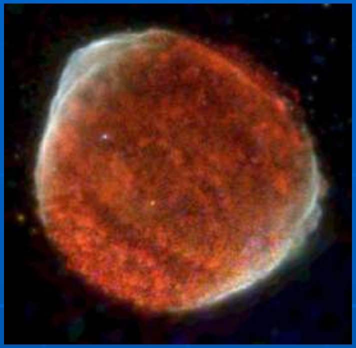
X-ray images of Type Ia SNRs

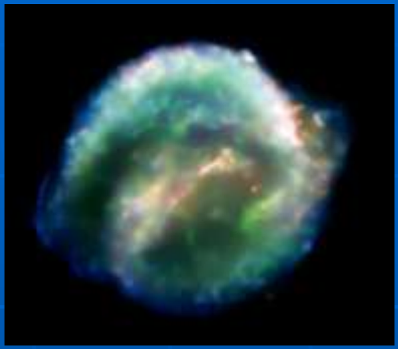
Our Galaxy



Tycho

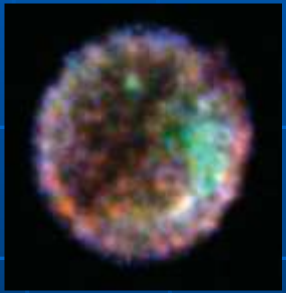


SN1006



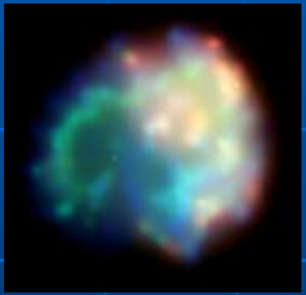
Kepler

LMC

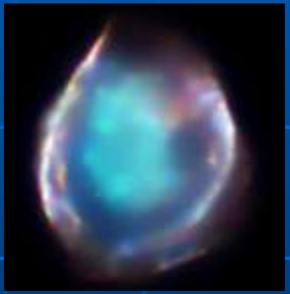


0509-67.5

0519-69.0



N103B



DEM L 71

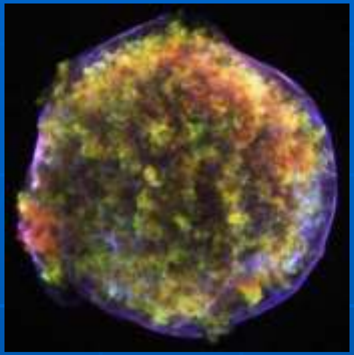
SMC

IKT25 (candidate)

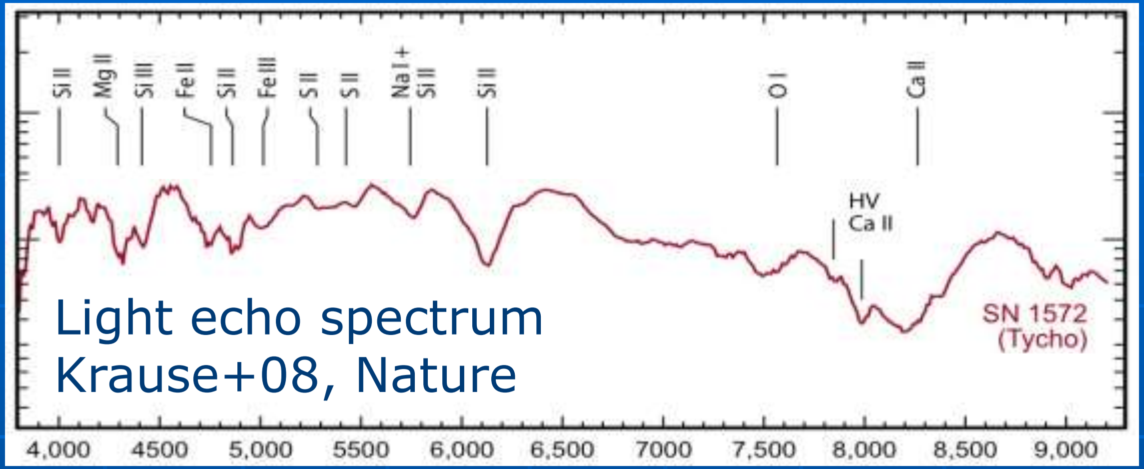
Tend to have smooth circular shape

Some exceptions are probably due to contrast of ISM densities

Tycho's SNR (SN 1572)



Chandra image
(Warren+06)



Discovered by Tycho Brahe
Brightness : m_V = -4.0~-4.5mag

Light echo spectroscopy
"normal" Type Ia SN
Absolute brightness: M_V ~-19mag
(extinction A_V = 1.9mag)
⇒ Distance = 3.8 (2.9-5.3) kpc

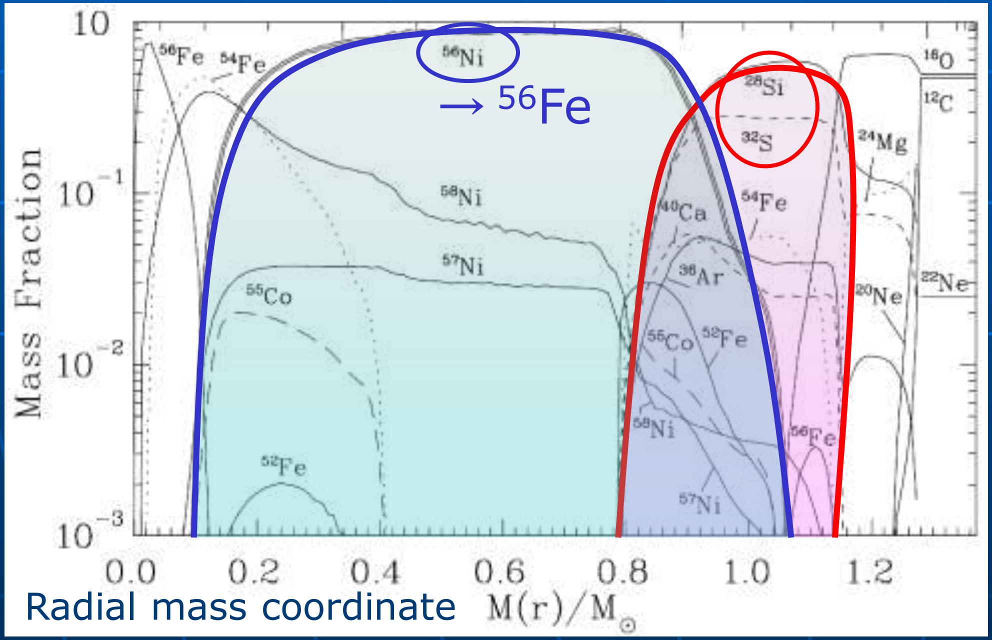
Ejecta distribution in Tycho's SNR

XMM-Newton (Decourchelle+01)

Evidence of layered composition structure

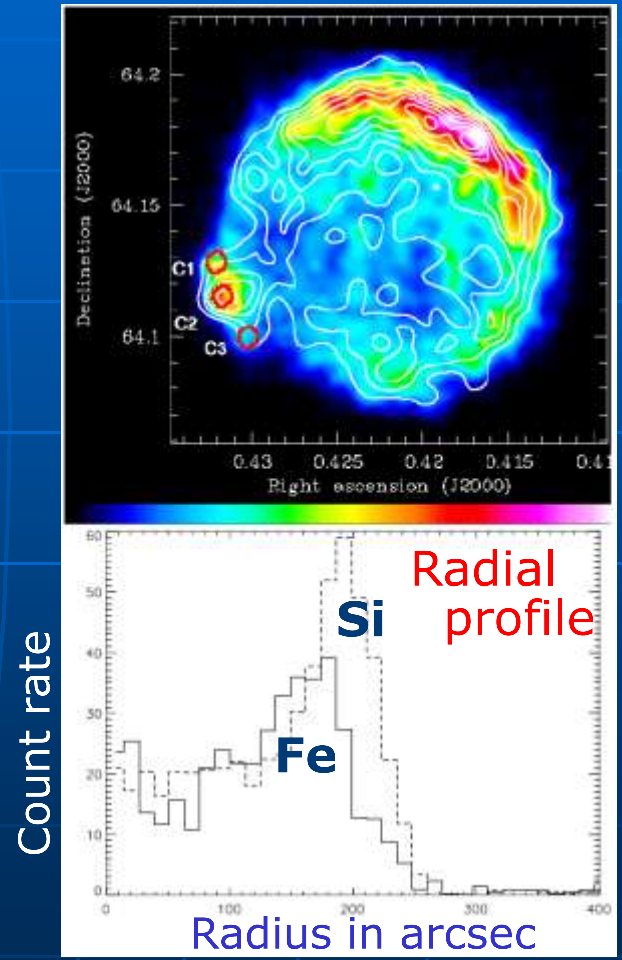
Fe (high-Z) is stratified toward SNR center with respect to Si and S (lower-Z element)

W7 model for SN Ia (Iwamoto+99)



Qualitatively consistent with theoretical model although it is derived from an 1D simulation

Color: Si, S
Contour: Fe

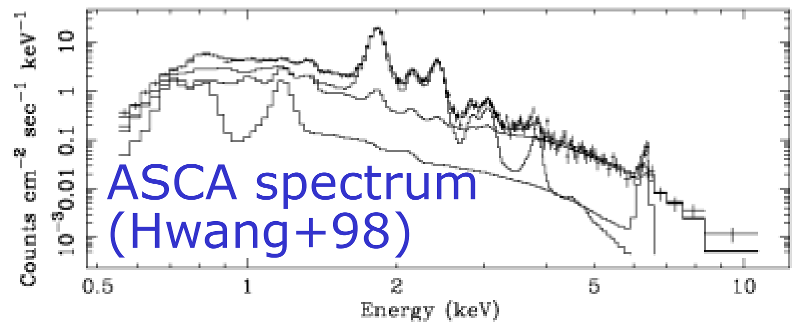


Decourchelle+01

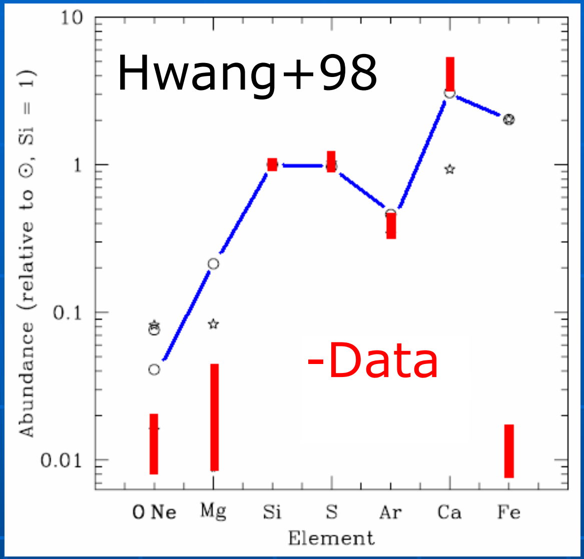
Relative abundances

Relative abundances determined from X-ray spectrum of entire SNR (Hwang+98):

- O, Ne, Si, S, Ar, Ca are broadly consistent with the theoretical model
- Fe is far below the predicted value

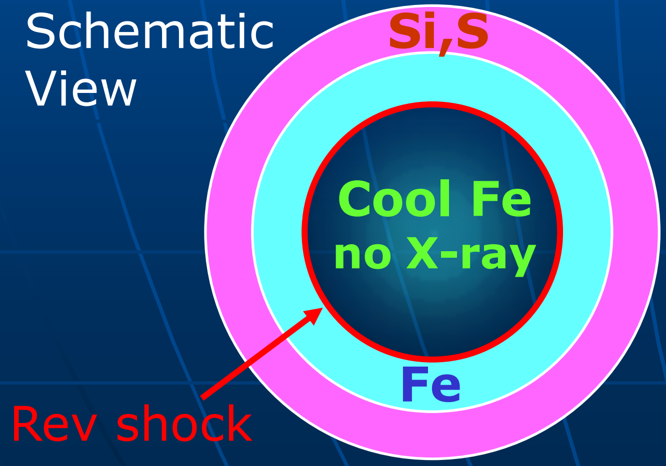


Relative abundance



Solid line:
W7 model (Nomoto+84)

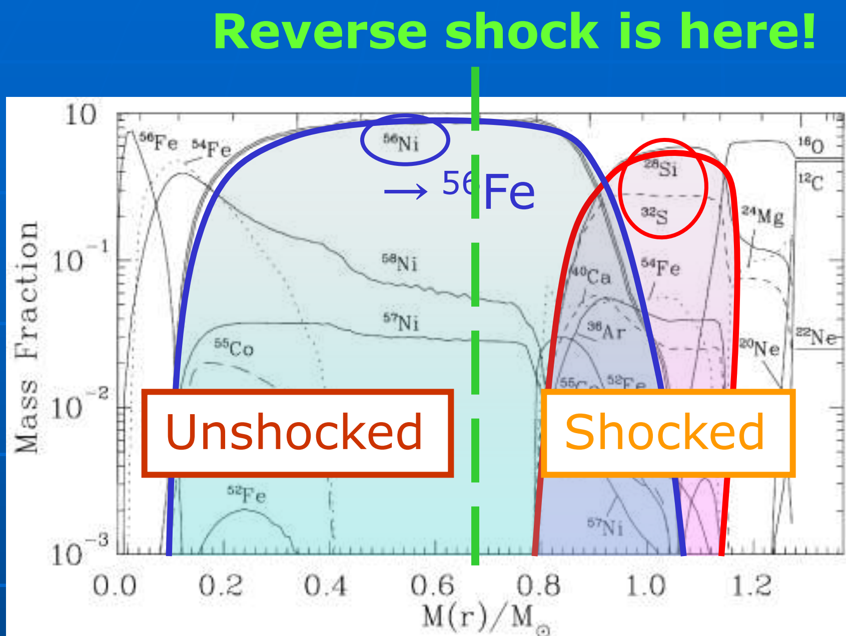
Schematic View



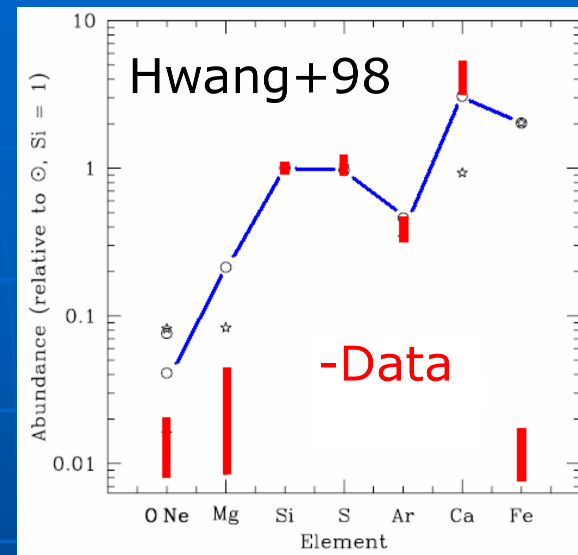
This discrepancy (b/w data and model) would be due to the fact that the rev shock has not propagated enough into the SNR to shock all of the Fe

Most of the Fe ejecta are too cool to provide enough X-ray emission

Relative abundances



Relative abundance



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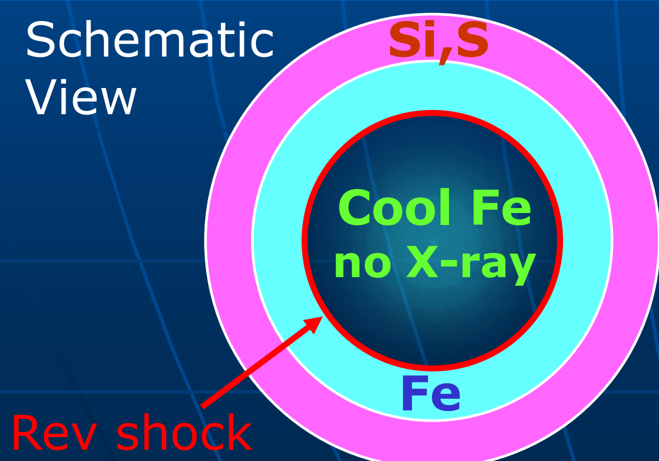

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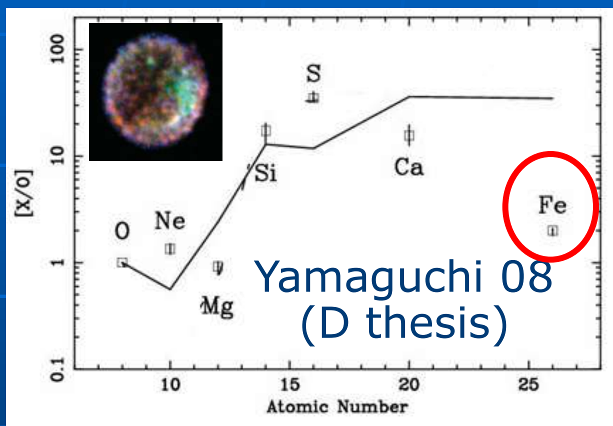
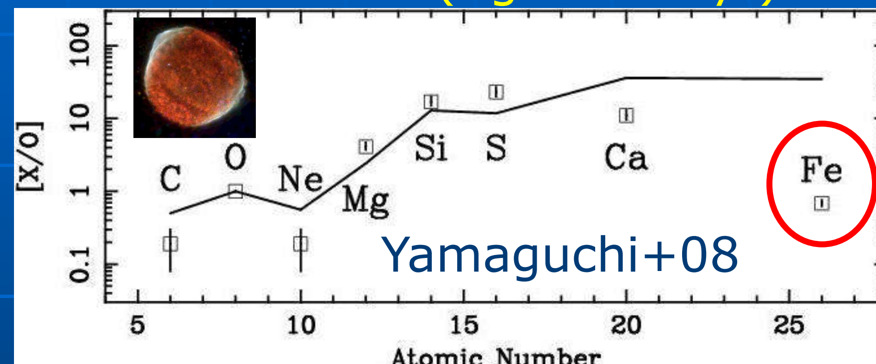
Abundances in the other Type Ia SNRs

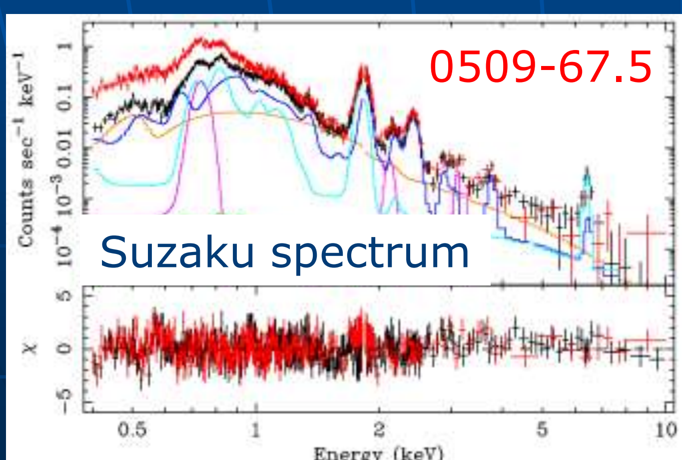
- Similar evidence for unshocked Fe ejecta is commonly found in the other young Type Ia SNRs
- Fe yield are much low compared to those of Type Ia models

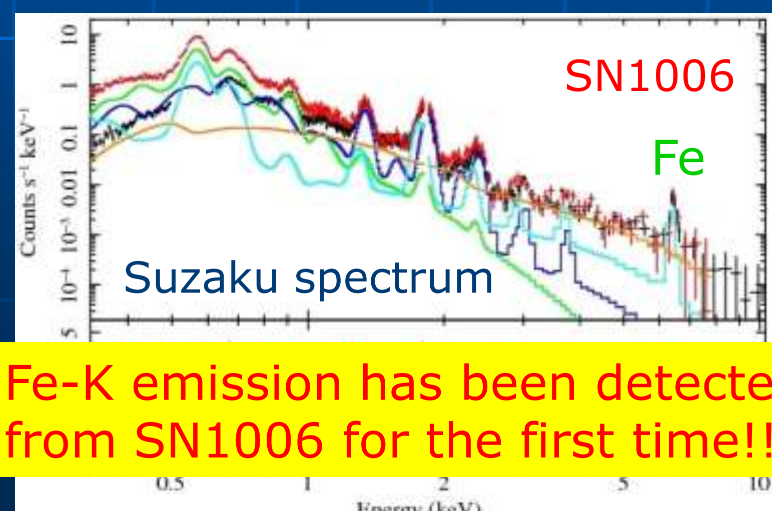
0509-67.5 (Age~800yr)



SN1006 (Age~1000yr)







Fe-K emission has been detected from SN1006 for the first time!!

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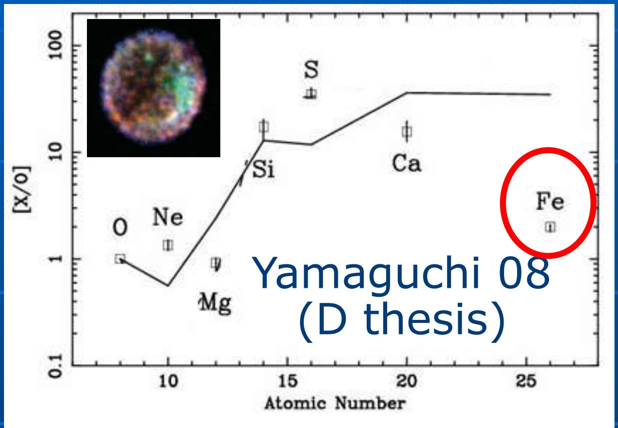
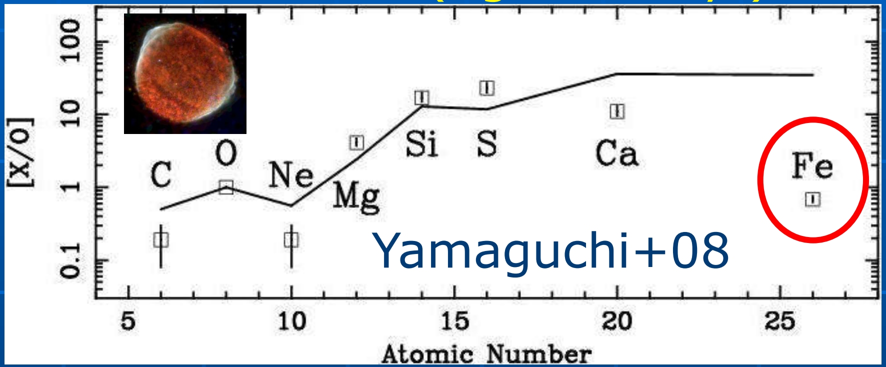
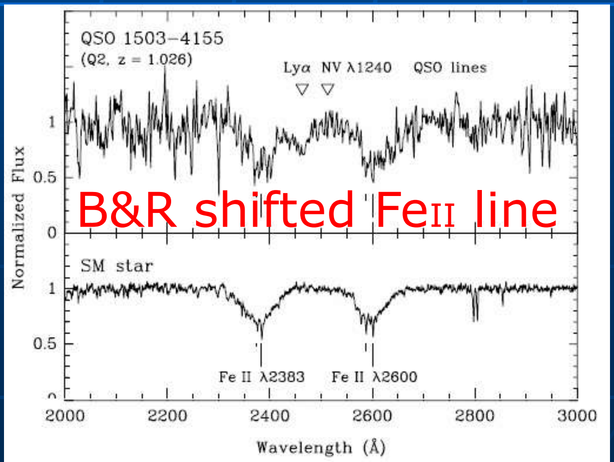


SN1006 (Age~1000yr)



UV observation shows the evidence of cold Fe ejecta

FeII absorption lines were detected in the spectra of bgd stars (e.g., Winkler+05)

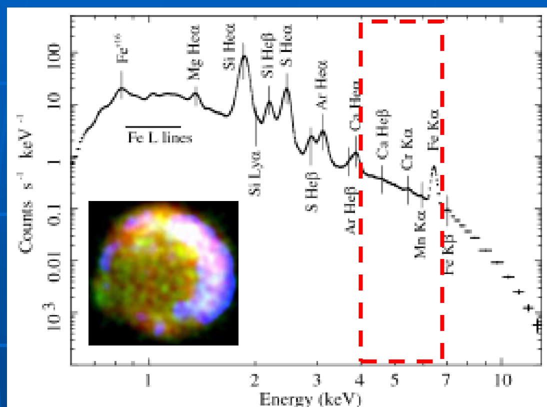


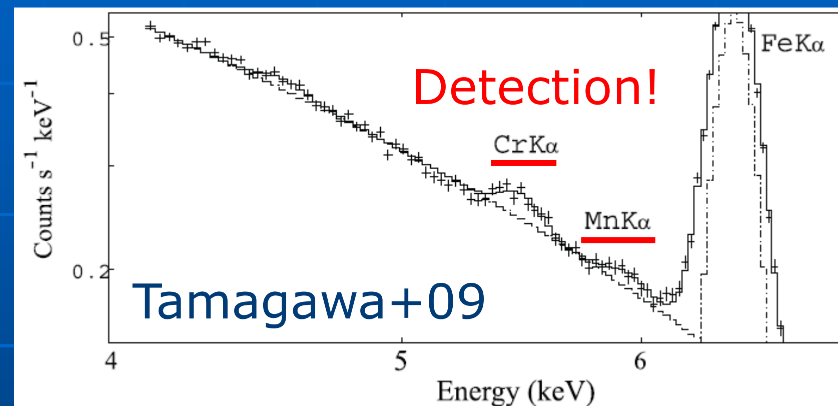
Recent Suzaku result on Tycho's SNR

Suzaku (Tamagawa+09)

Good energy resolution and high sensitivity

The first discovery of Cr and Mn lines from Type Ia SNRs





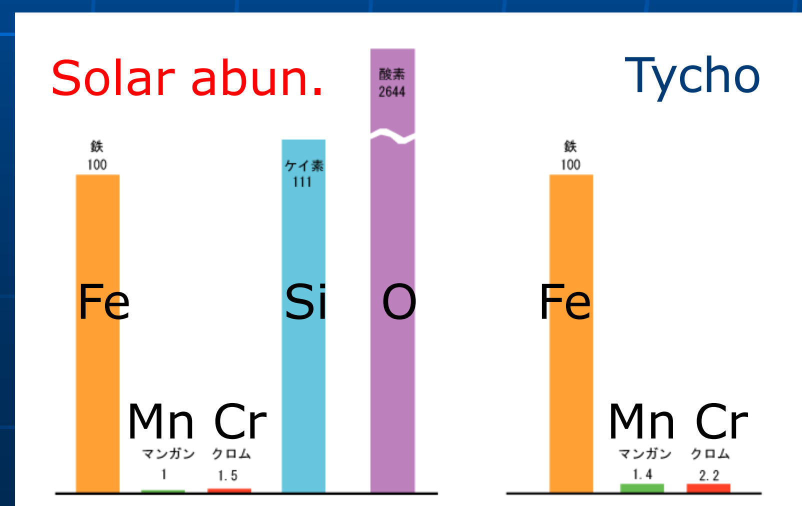
Cr and Mn

very low abundant elements

Cr/Fe ~ Mn/Fe ~ 0.01, in solar

Cr/Fe = 0.022

Mn/Fe = 0.014 in Tycho's SNR



Neutron-rich element in Type Ia SNRs

Cr: ^{52}Fe (Z=26) → ^{52}Mn (Z=25) → ^{52}Cr (Z=24)
Mn: ^{55}Co (Z=27) → ^{55}Fe (Z=26) → ^{55}Mn (Z=25)

23	24	25	26	27	28
V	Cr	Mn	Fe	Co	Ni

↑
Parent nuclides synthesized in the explosion

Heavy elements which have been detected from Type Ia SNR so far

	O	Ne	Mg	Si	S	Ar	Ca	Cr	Mn	Fe
								Fe	Co	Ni
Proton	8	10	12	14	16	18	20	26	27	28
Neutron	8	10	12	14	16	18	20	26	28	28

Unequal numbers of protons and neutrons (neutron excess) !

To synthesize such elements, progenitor should be rich with neutron
But, Type Ia progenitor consists mainly of ^{12}C (Z=6) and ^{16}O (Z=8)

How did the neutron excess in the progenitor originate?

⇒ Found in processes during the progenitor's evolution!!

Neutron excess in Type Ia progenitor

- During the progenitor's main seq., C, N, and O which act as catalysts for CNO cycle pile up into ^{14}N

- ^{14}N is converted to ^{22}Ne in He-burning phase through the reactions
$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^+,\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$$

Elements in Type Ia progenitor (WD)

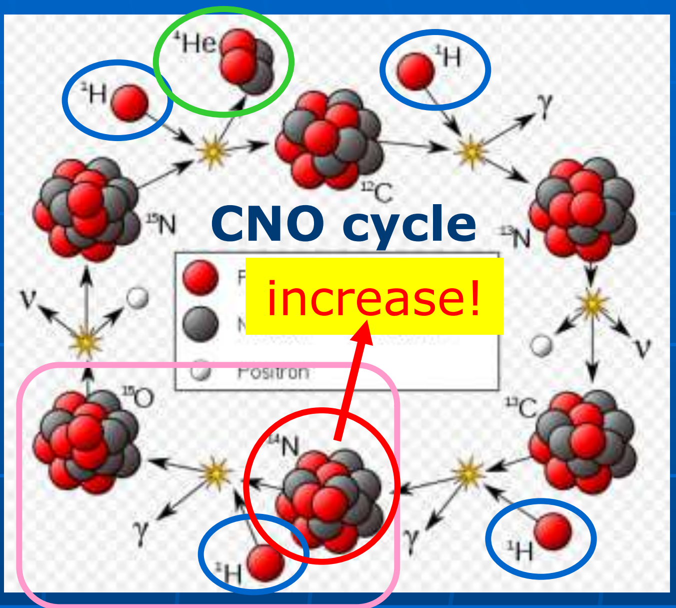
	C	O	Ne
Proton	6	8	10
Neutron	6	8	12

Increases the neutron excess

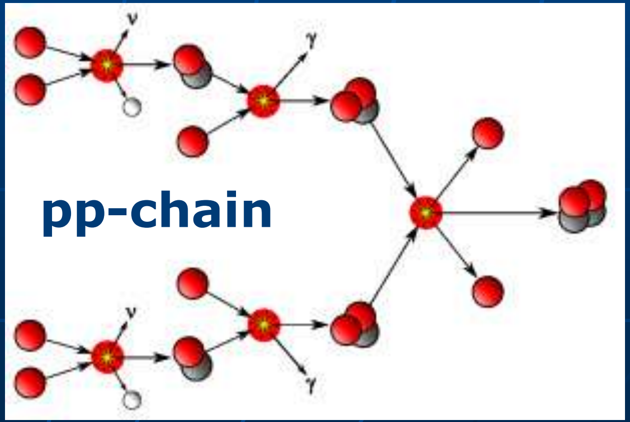
- CNO cycle takes place efficiently when C, N, and O are abundant

⇒ Neutron excess (abundance of ^{22}Ne) becomes larger when the progenitor's metallicity (initial CNO abundances) is high

H-burning: ^{4}He is eventually synthesized from 4 protons



Slowest reaction

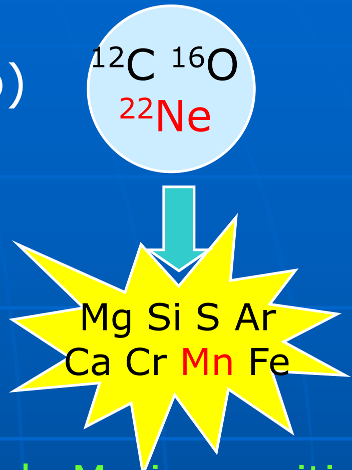


Mn/Cr ratio as an initial metallicity tracer

During Type Ia SN explosion:

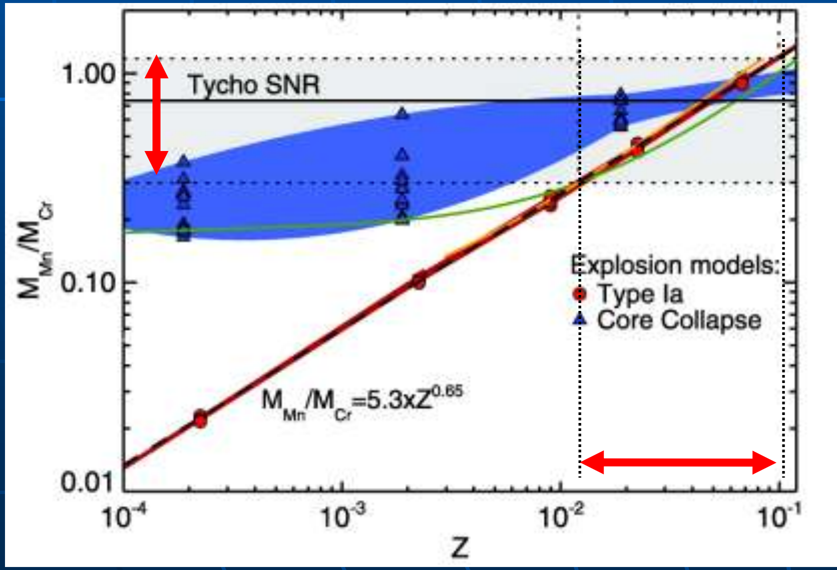
^{52}Cr and ^{55}Mn are synthesized together (as ^{52}Fe and ^{55}Co) in incomplete Si burning layer (e.g., Iwamoto+99)

- The yield of ^{55}Mn (neutron-rich nuclide) would be sensitive to the neutron excess due to ^{22}Ne
- ^{52}Cr is NOT sensitive to neutron excess



Only Mn is sensitive to neutron excess!!

Mn/Cr ratio is an good tracer of the initial progenitor's metallicity!



Badenes+08 noted a correlation b/w Mn/Cr mass ratio and metallicity Z

$$M_{Mn}/M_{Cr} = 5.3 \times Z^{0.65}$$

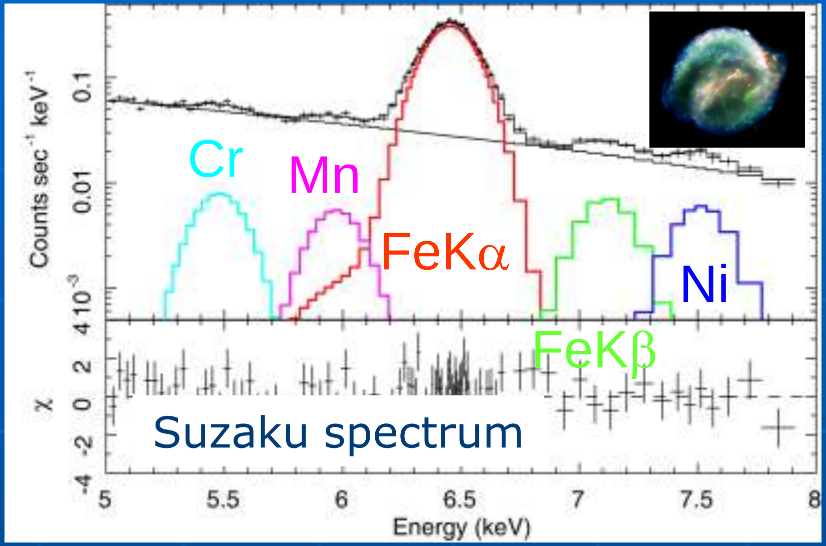
For the progenitor of Tycho's SN, ($M_{Mn}/M_{Cr} = 0.74 \pm 0.47$) yields a supersolar metallicity

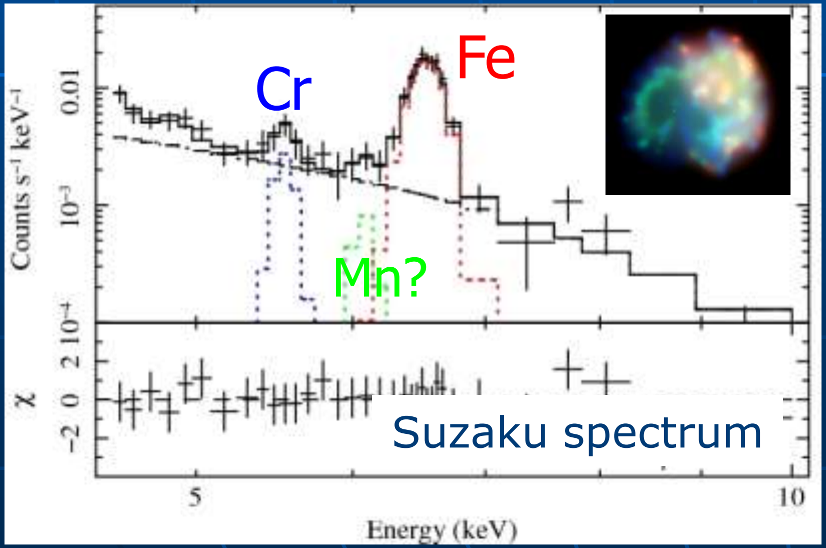
- $Z = 0.048$ (0.012−0.099)
- Large uncertainty, but definitely not subsolar ($Z<0.01$)

Low-abundance element in the other Type Ia SNRs

Kepler's SNR (Tamagawa+, in prep.)

- Suzaku Detected ^{52}Cr, ^{55}Mn, and ^{58}Ni, for the first time!
- M_{Mn}/M_{Cr} = 1.7±0.9
- Z = 0.17 (0.9-2.6)
- Higher metallicity than Tycho's SNR
- ^{58}Ni is also neutron-excess element





N103B (Yamaguchi+, in prep.)

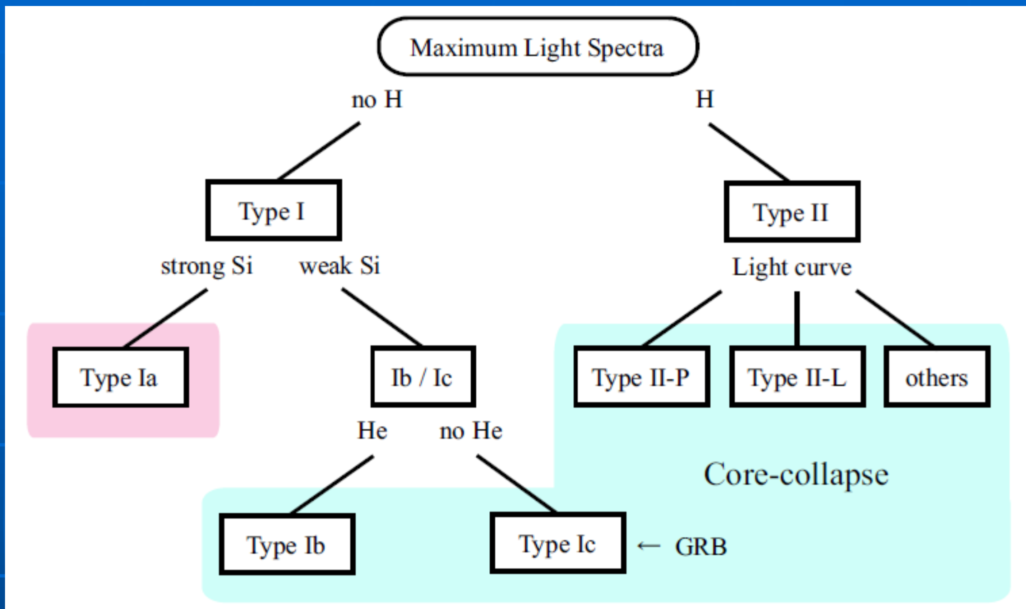
- SNR in the LMC
- First detection of Cr emission from an extra-Galactic SNR!
- Marginal detection of Mn
- LMC metallicity is ~ 1/3 of the solar
  ⇒ Low value of Mn/Cr is expected
- Follow up observation is coming soon!

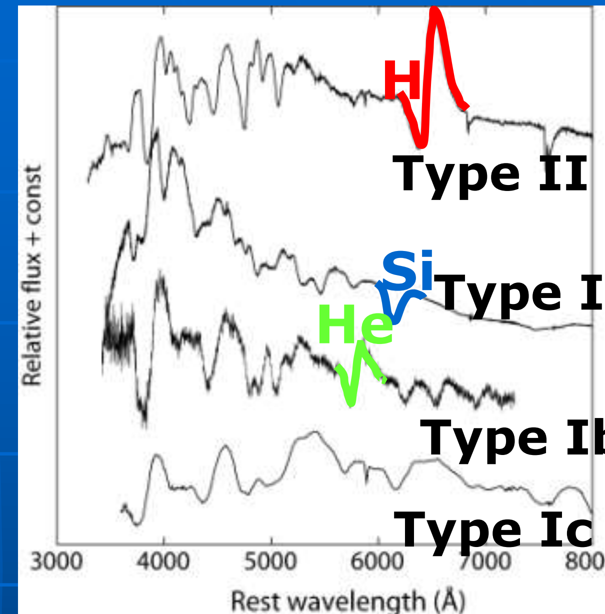
Conclusion

- X-ray observations of SNR is ideal method to study the supernova nucleosynthesis
- In Type Ia SNR, Fe is more concentrated toward SNR center with respect to Si and S, suggesting that heavier elements had been synthesized at deeper region in the progenitor
- Most of Fe ejecta in young Type Ia SNR has not been heated by reverse shock
- Recently, Suzaku has successfully detected low-abundance elements (Mn, Cr, Ni) from several Type Ia SNRs
- Mn/Cr mass ratio is useful as a progenitor's metallicity tracer
  - Tycho: $Z = 0.048$ (0.012−0.099), higher than the solar
  - Kepler: $Z = 0.17$ (0.9-2.6), higher than Tycho

Appendix

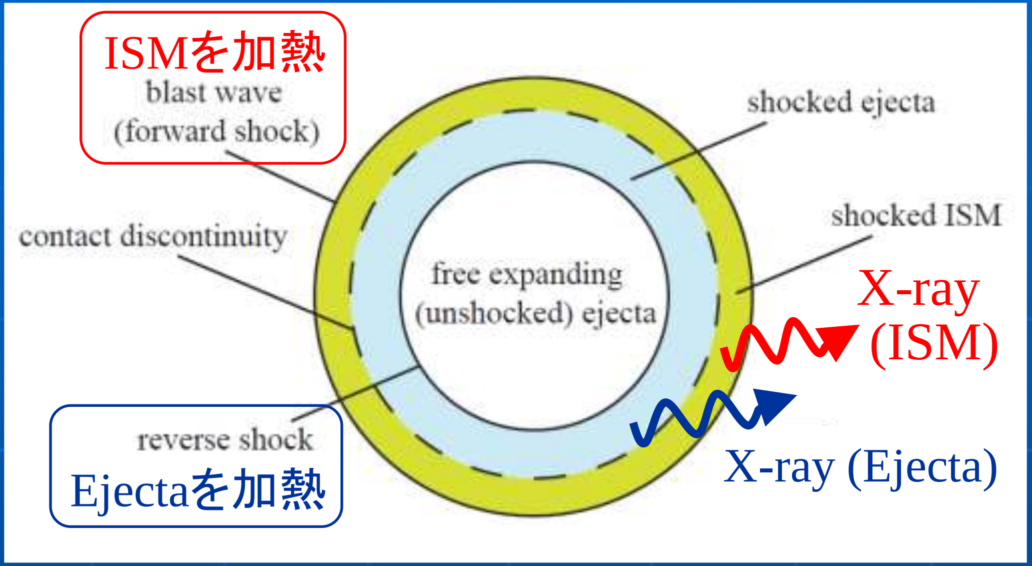
Classification of supernovae





If a optical spectrum lacks absorption lines of H Balmer series, the SN is classified as Type I. Type I SNe are sub-classified according to the presence or absence of the strong SiII absorption at 6150A. Type Ib spectrum contains He lines, while Type Ic has no He lines. Subclasses of Type II SNe are distinguished by the shape of their LC. Ia progenitor is believed to be Chandrasekhar mass WD. The others are massive stars. Type Ib are thought to be massive stars that have lost their H envelope by stellar wind. Wolf-Rayet stars are the possible progenitors.

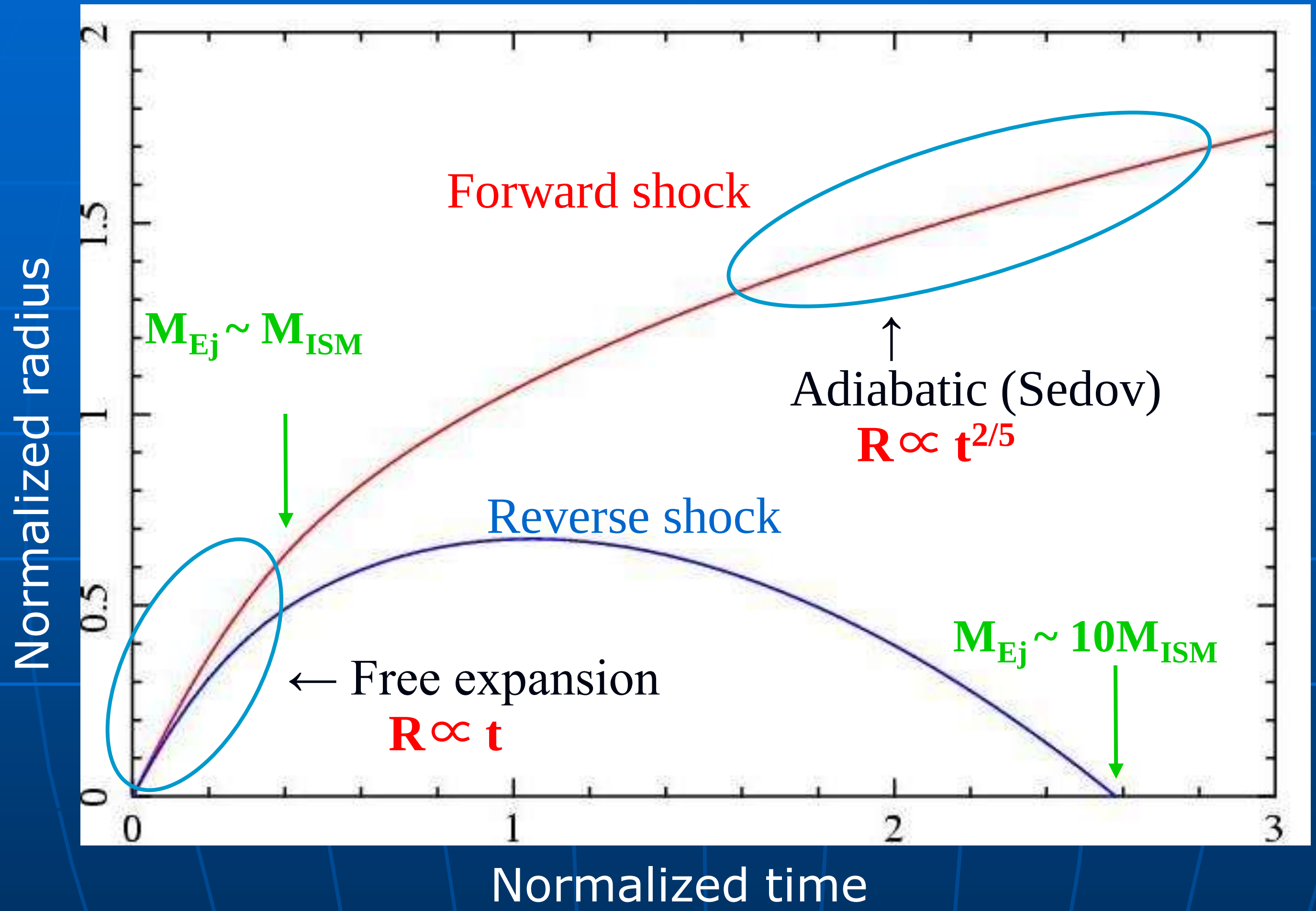
Shock wave in young SNRs



In the transition phase b/w free exp. and adiabatic phases, interaction with ISM cannot be ignored. The swept-up ISM pushes back on the ejecta. Thus ejecta are decelerated. It causes another shock wave to propagate inward through the ejecta, called as "reverse shock". The ejecta are compressed and heated by the rev shock. The boundary b/w the ISM and ejecta is called "contact discontinuity".

Only b/w the two shock waves, the material is hot enough to emit X-rays, and this forms the bright shell of young SNRs. In the central region, ejecta is not hot and still freely expanding. Such ejecta cannot emit X-rays, and hence its information cannot been received directly.

Shock wave in young SNRs



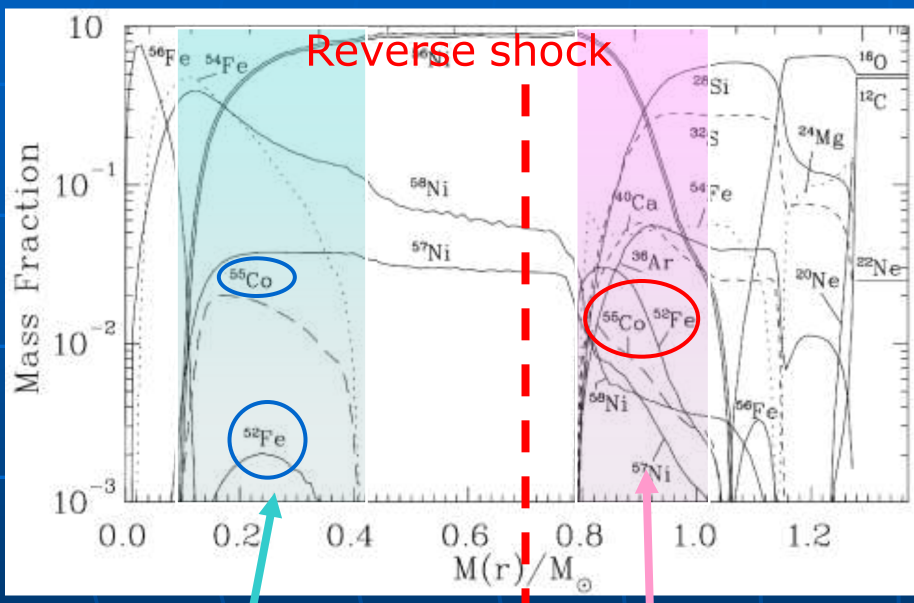
As shown the figure, not only fwd shock but also rev shock initially propagate out ward (as seen by an outside observer). After M_{ISM} becomes greater than M_{Ej}, the reverse shock propagates back to the centre.

Mn/Cr ratio as an initial metallicity tracer

The yield of ^{55}Mn (neutron-rich nuclide) is sensitive to the neutron excess

^{52}Cr and ^{55}Mn are synthesized together (as ^{52}Fe and ^{55}Co)

W7 model for SN Ia (Iwamoto+99)



Cool, no X-ray

Hot, emit X-ray

Incomplete Si burning

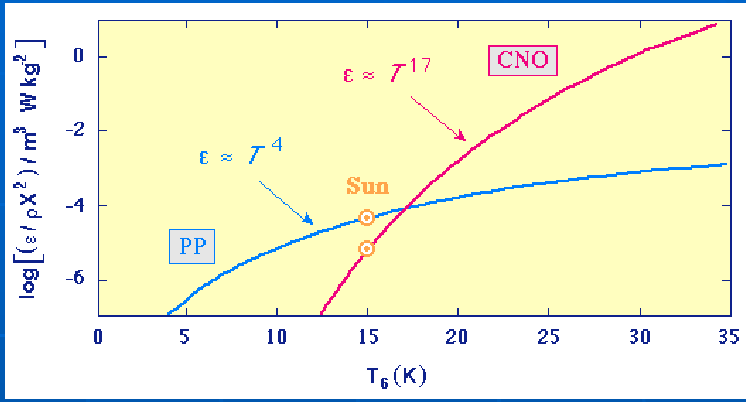
Electron captures taking place in the central layers

^{55}Co is synthesized at deeper layer. In this region, electron capture can take place during the explosion. (neutron-rich NSE: Brachwitz+00) But, in the most of young Ia SNR, rev shock have not reached into this deeper region. Electron captures are too slow to change the original neutron excess except in the innermost <0.3Mo.

The relation by Badenes+08 removes the inner neutron-rich NSE material. It is also important that the relation is not sensitive to C/O mass ratio of the progenitor.

CNO cycle

- During the progenitor's main seq., C, N, and O act as catalysts for CNO cycle
- The slowest step in the hydrogen-burning CNO cycle is proton capture on to 14N
- This results in all the CNO catalysts piling up into 14N when H-burning is completed



The rate of CNO cycle depends on the temperature and CNO abundances.

Because 14N is the nucleus most resistant to destruction, it will become most abundant as the cycle proceed. If the CNO cycle is in a steady state, the rate of energy release is

$$\varepsilon_{CNO} \propto \rho X_H X_{CNO} T_6^{-2/3} \exp(-152/T_6^{1/3}),$$

where X_{CNO} is the mass fraction of all isotopes of C,N,O (Arnett 1973)

- The beta+ decay of 18F during He-burning increases the neutron excess of the WD material, definded as η = 1-<Z_A/A>, resulting in a linear scaling of η with metallicity: $\eta = 0.101 \times Z$ (Timmes+03).

Production of ^{22}Ne

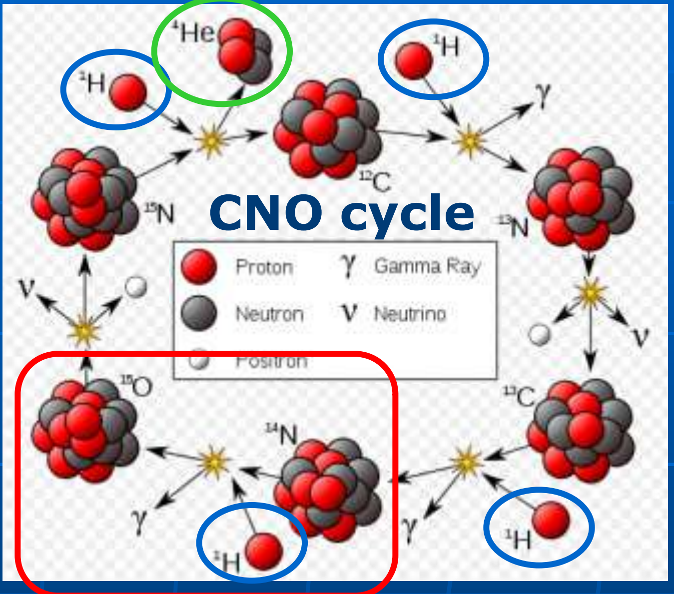
- During the progenitor's main seq., C, N, and O which act as catalysts for CNO cycle pile up into ^{14}N

- ^{14}N is converted to ^{22}Ne in He-burning phase through the reactions $^{14}N(\alpha, \gamma)^{18}F(\beta^{+}, \nu)^{18}O(\alpha, \gamma)^{22}Ne$, which increase the neutron excess of WD

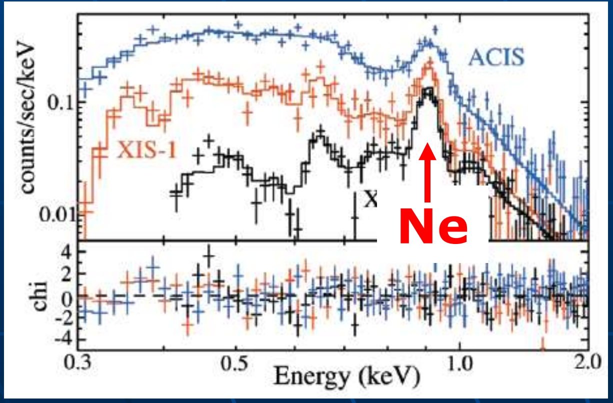
Main processes in He-burning phase

$$3\,^{4}He \rightarrow {}^{12}C$$
$$^{12}C + {}^{4}He \rightarrow {}^{16}O$$

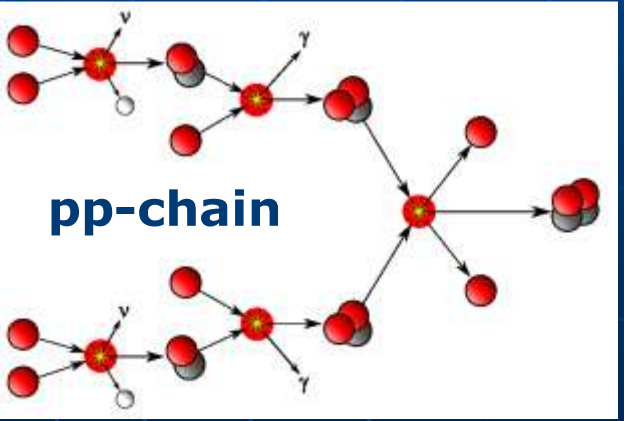
H-burning: ^{4}He is eventually synthesized from 4 protons



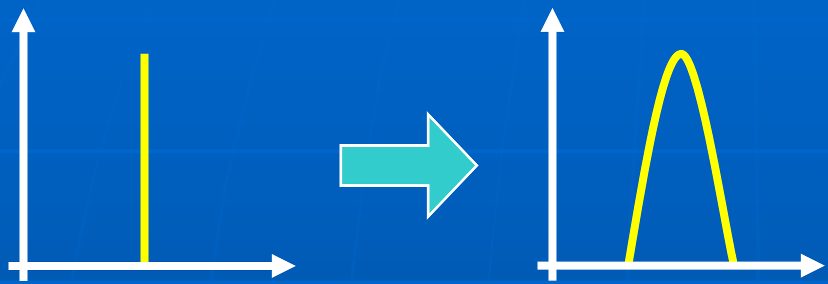
Slowest step



Emission line from ^{22}Ne in planetary nebula BD+30 3639 (Murashima+06)



Spectrum

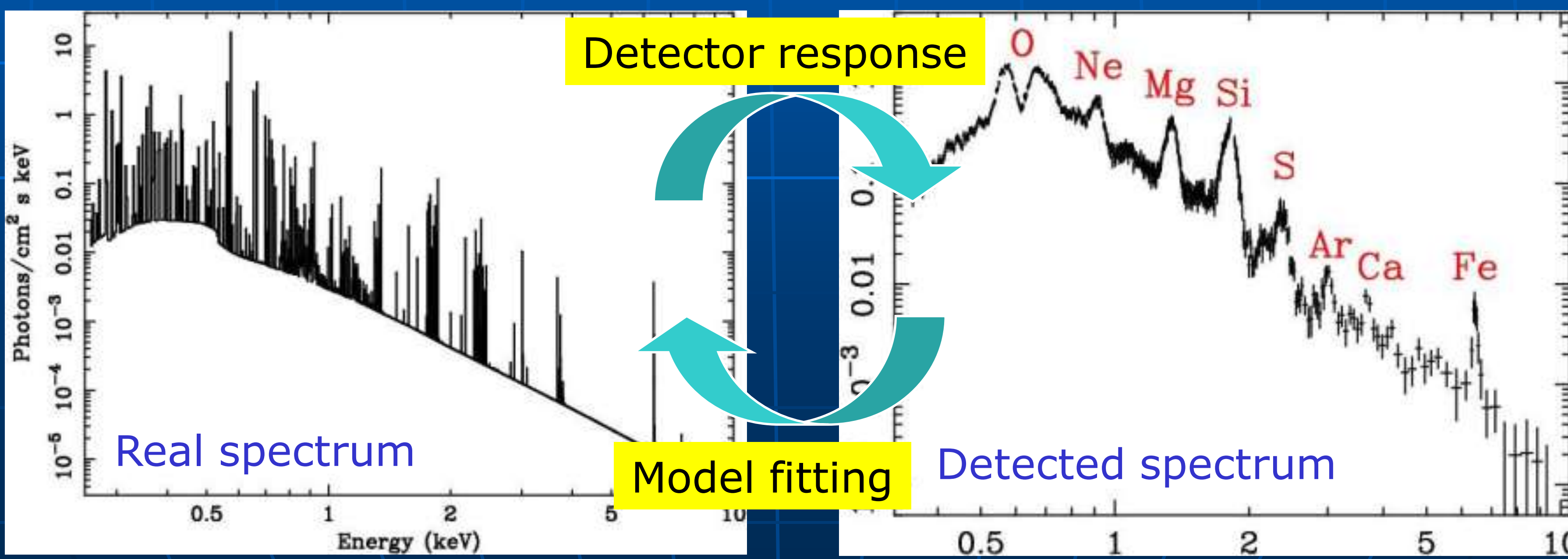


Monochrome X-rays

Gaussian

Energy resolution is limited…

Width of Gauss is determined by Poisson distribution (statistical) and electric noise (systematic)



	^{1}H	^{1}H
H burning (main seq.)	pp-chain	CNO cycle (need C, N, O to work)
	⇩	⇩
	^{4}He	^{4}He ^{14}N
He burning	↘ ↙	⇩
Type Ia progenitor	^{12}C ^{16}O	^{22}Ne (neutron excess!)

^{14}N is converted to ^{22}Ne in He burning phase through the reaction

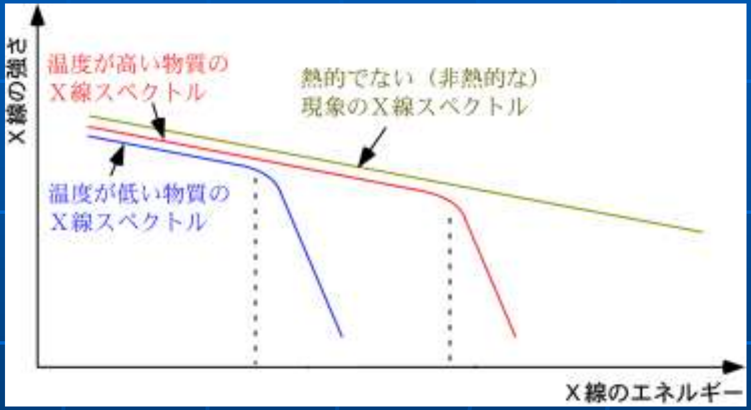
$$^{14}N(\alpha, \gamma)^{18}F(\beta^{+}, \nu)^{18}O(\alpha, \gamma)^{22}Ne$$

放射過程

超新星残骸からのX線放射過程はとても単純です

- 熱的プラズマ (optically thin)
  - 制動輻射（連続スペクトル）
  - 特性X線（輝線スペクトル）
- 非熱的(non-Maxwellian)電子
  - シンクロトロンX線（連続）

連続スペクトル
熱的 or 非熱的電子の
エネルギー分布がわかる



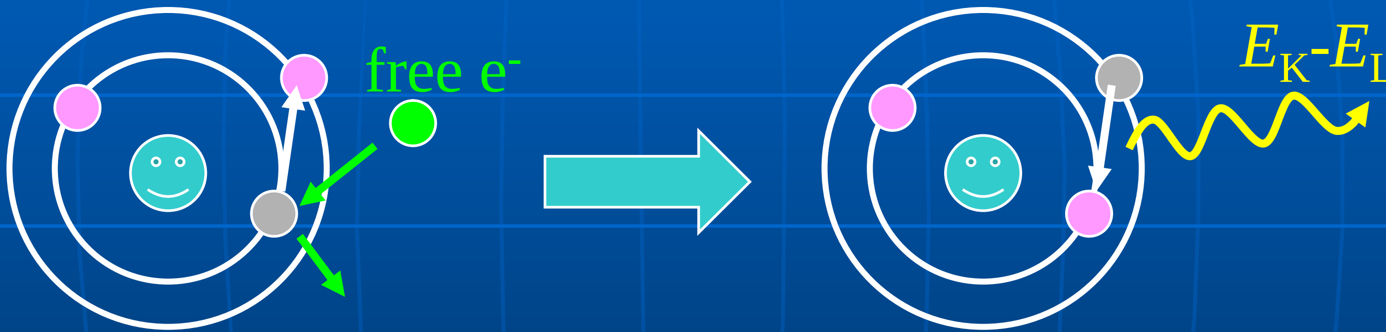
制動放射

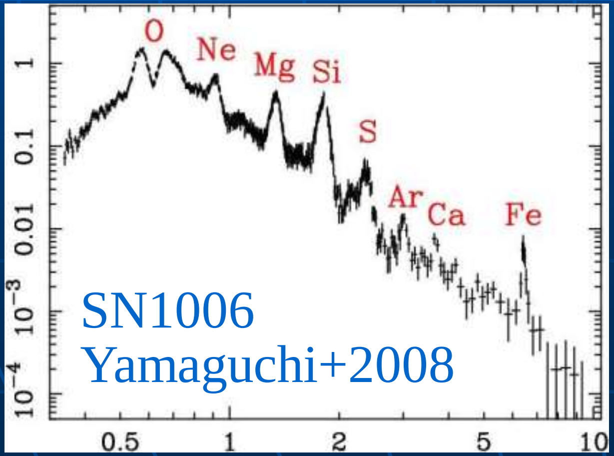
放射過程

超新星残骸からのX線放射過程はとても単純です

・熱的プラズマ (optically thin) 制動輻射（連続スペクトル）
特性X線（輝線スペクトル）

・非熱的(non-Maxwellian)電子 シンクロトロンX線（連続）



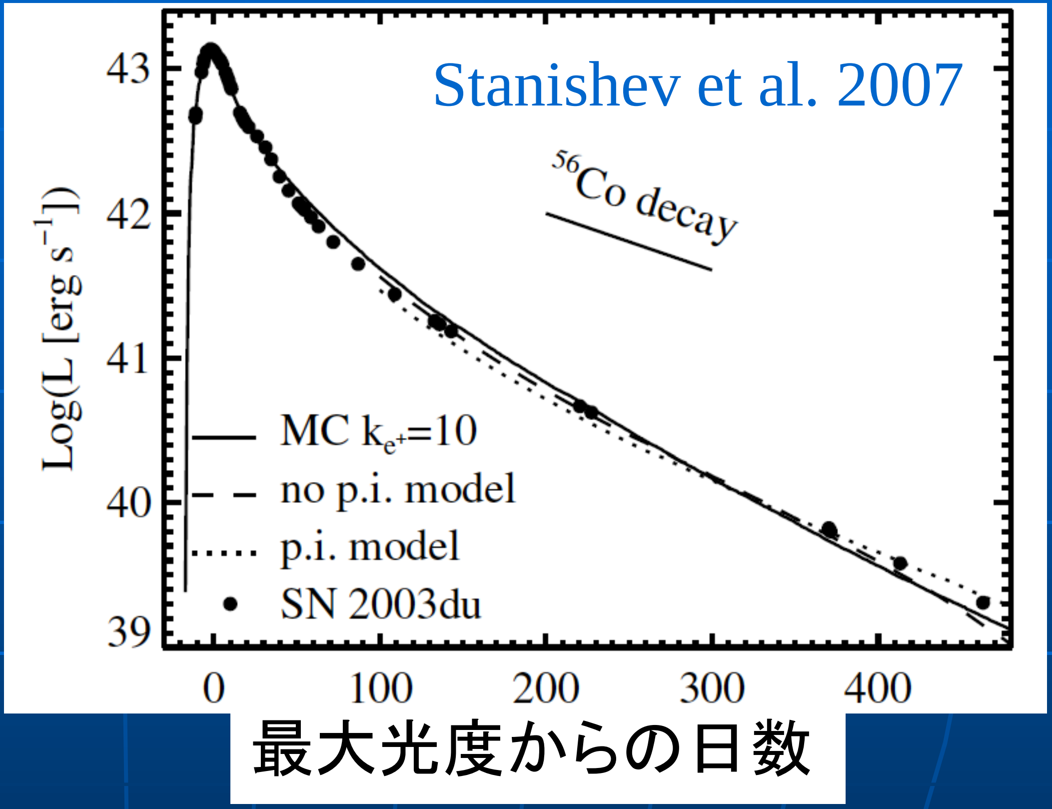


輝線スペクトル
プラズマに含まれる元素の
種類と量がわかる

光度曲線

超新星の熱源は ^{56}Ni
(e.g., Arnett 1979)

^{56}Ni
8.8日 γ線 (E.C.)
^{56}Co
111日 γ線 (E.C.)
e^+ (β^+ decay)
^{56}Fe



ほとんどのエネルギーを可視光で放射

Ia型超新星：明るさ（絶対光度）はどれもほぼ同じ
^{56}Ni = 0.6-0.8 $M_{\odot}$（重力崩壊型より多量）