

超新星元素合成の基礎： 観測データの理解を視野に入れて

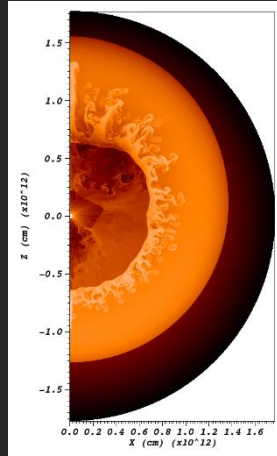
前田 啓一

京都大学 宇宙物理学教室

Theoretical Astrophysics

Nuclear Theory & Experiments

Stellar Evolution
Explosion Dynamics

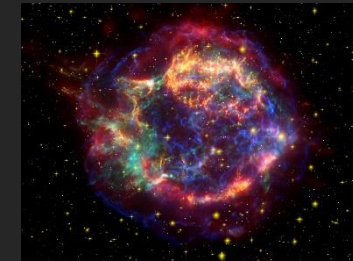


Reaction Rates
Equation of States
Opacities

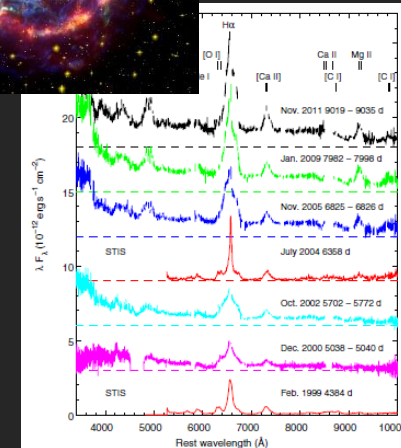
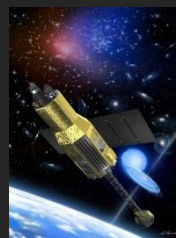
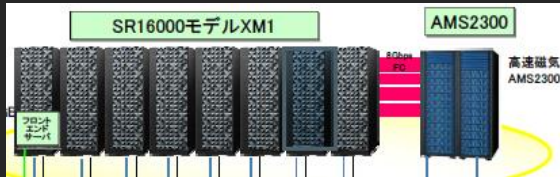
Astrophysical Models

Nucleosynthesis
Radiation Transfer

Imaging Spectroscopy



Observational Astronomy



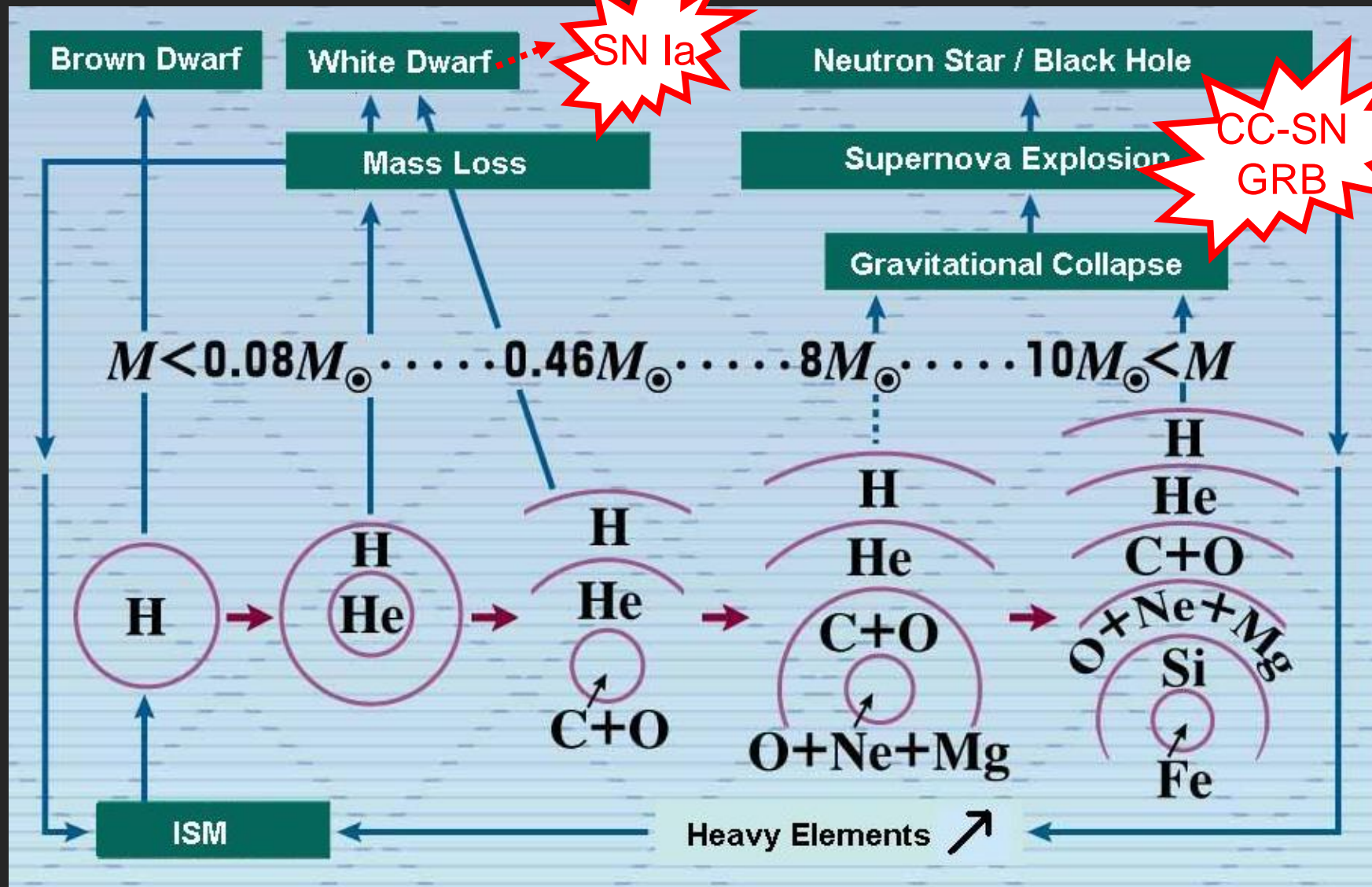
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 - Stellar evolution and Supernovae.
 - Explosion Mechanism.
- Explosive Nucleosynthesis:
 - Thermonuclear reaction basics.
 - Shock propagation and explosive nucleosynthesis.
- Examples of Observations:
 - Supernova Remnants.
 - SN 1987A.
 - Extragalactic Supernovae.

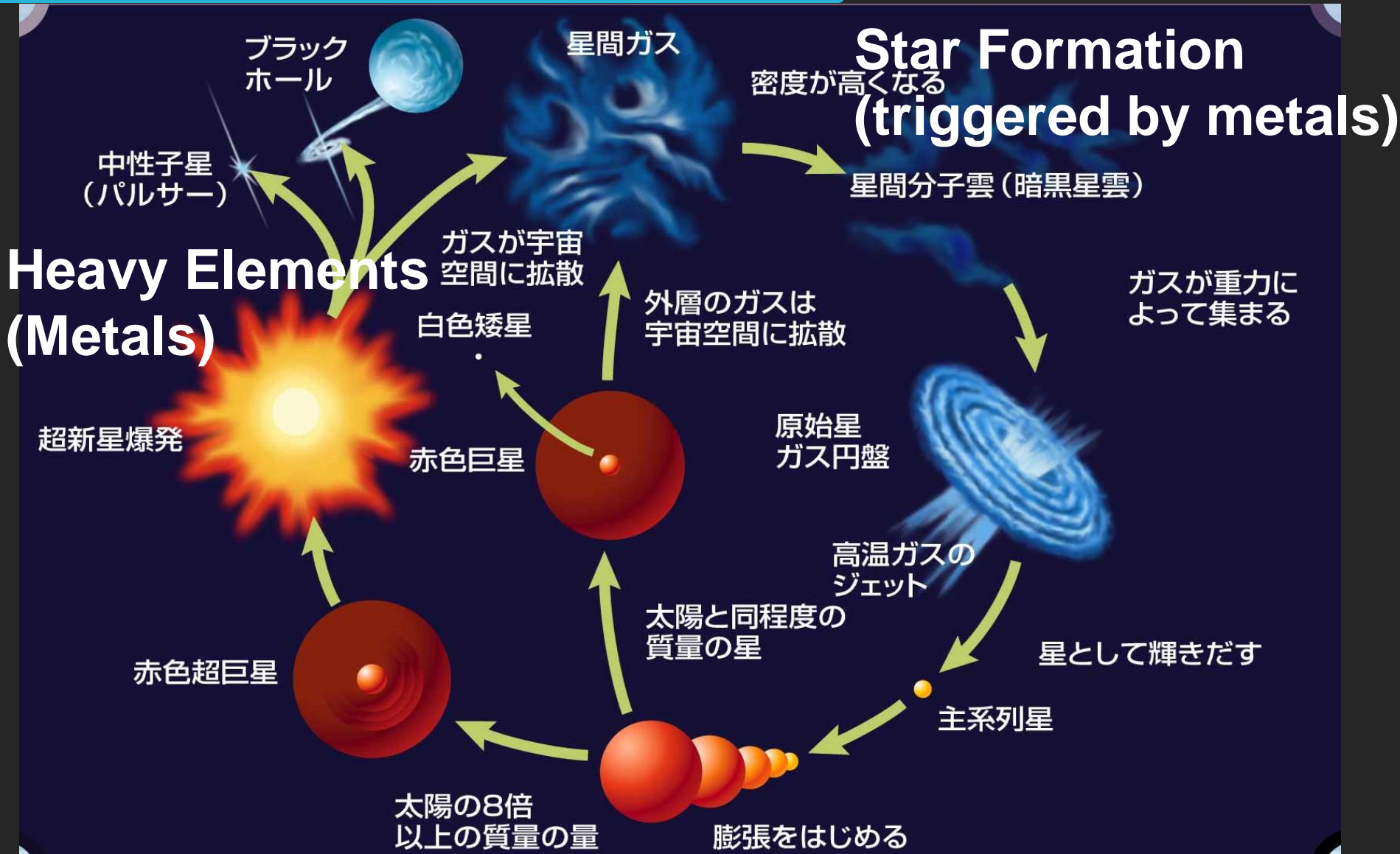
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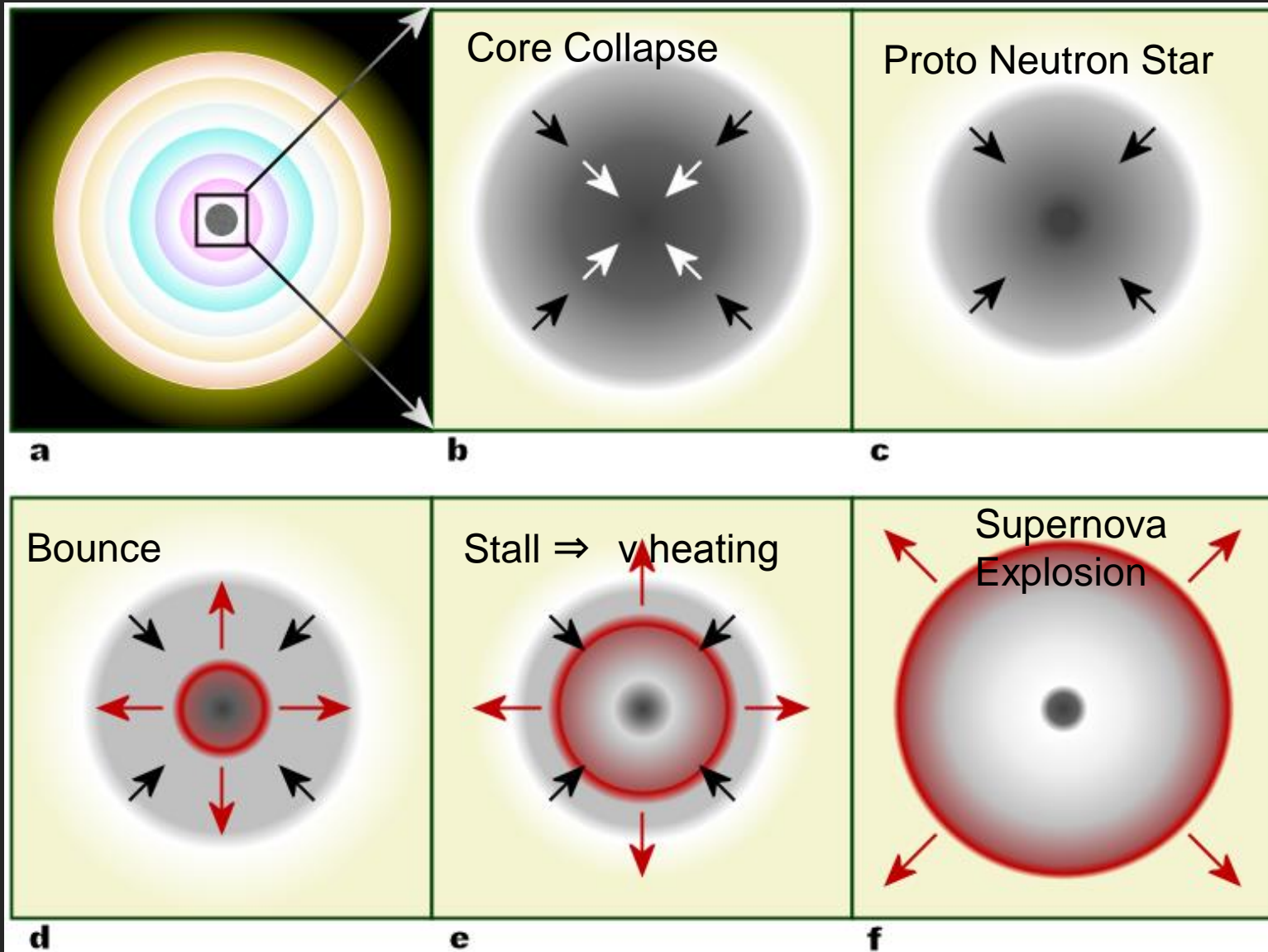
Stellar Evolution and Supernovae (SNe)



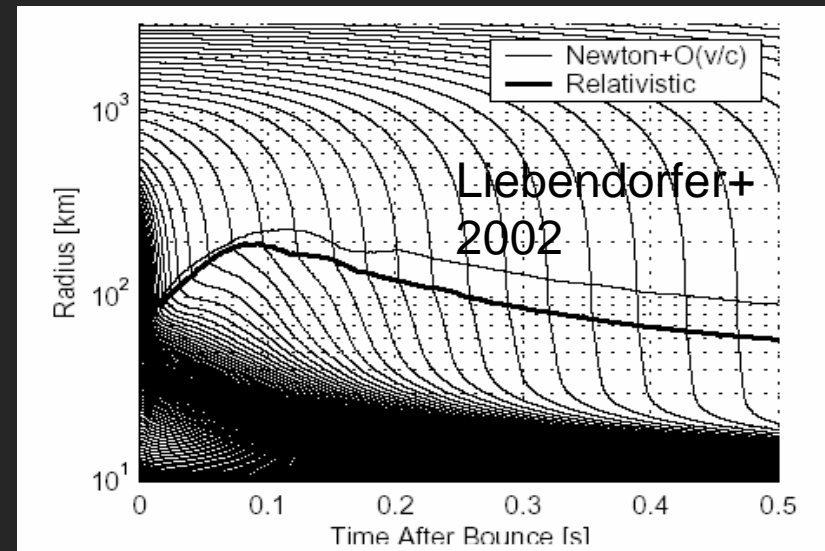
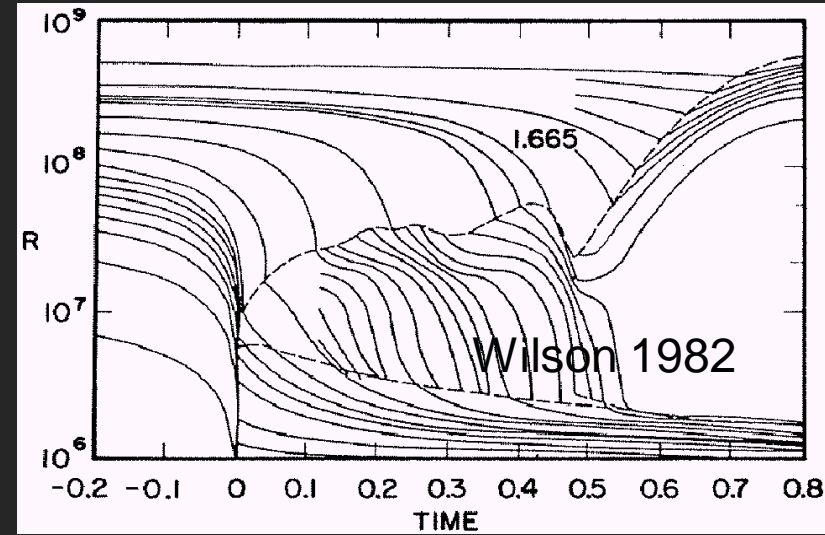
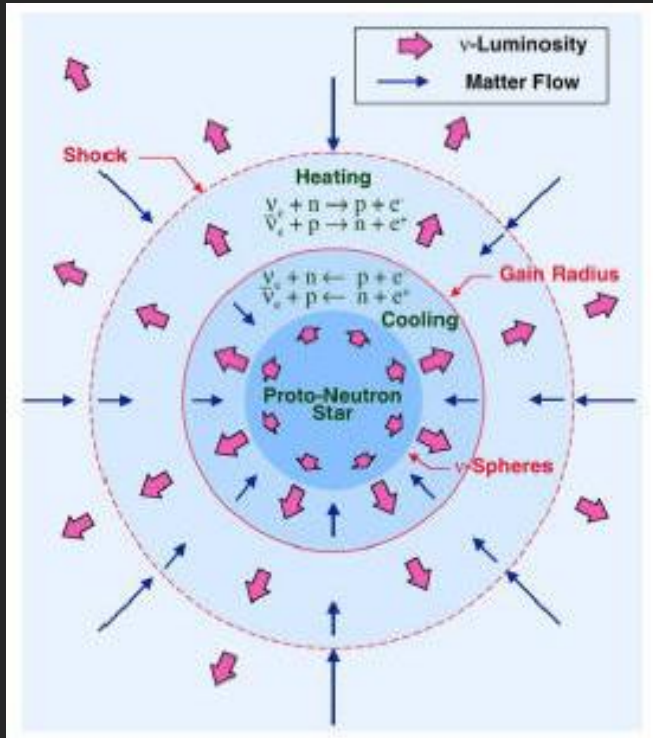
Supernovae = A key in the cosmic cycle



Core-Collapse Supernovae ($> 10M_{\odot}$)



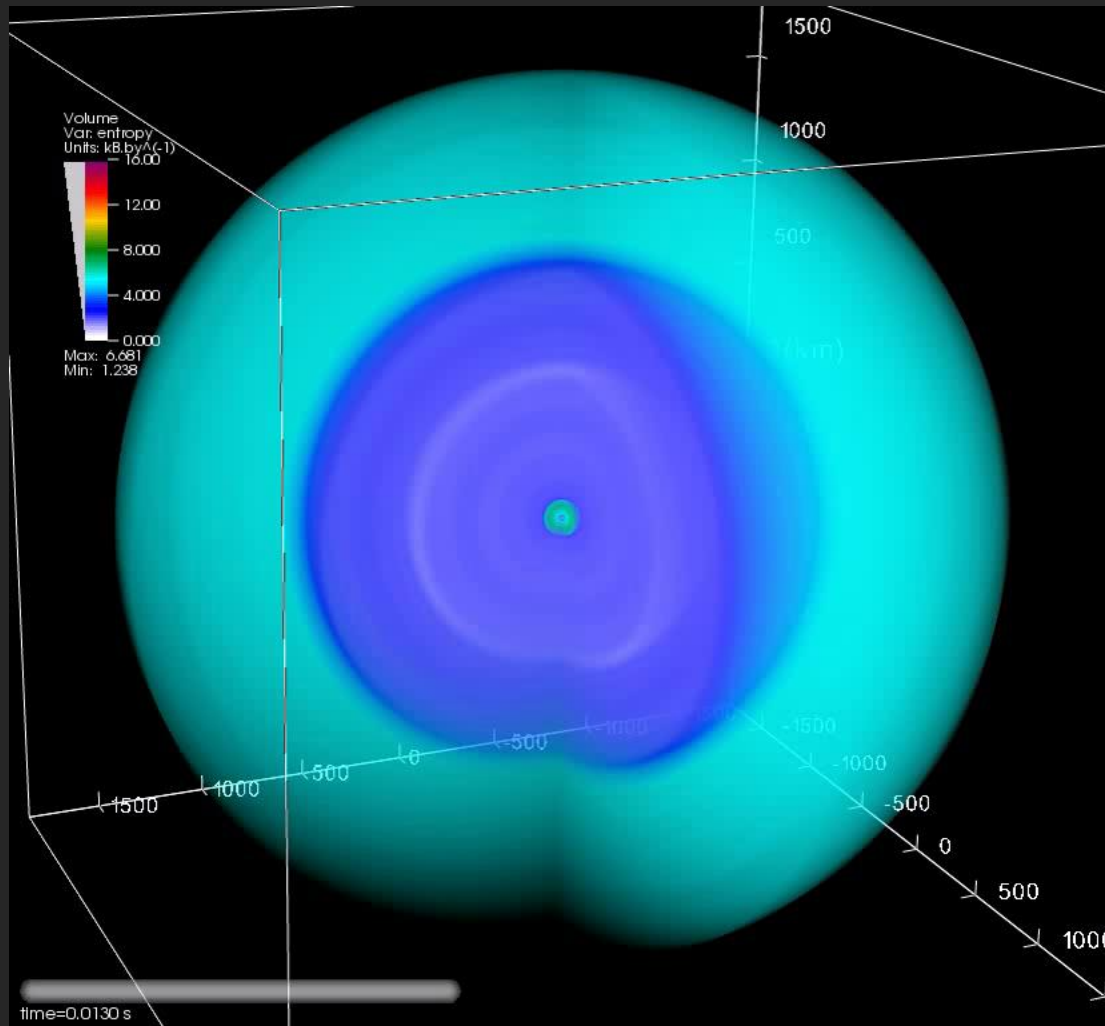
Neutrino heating (+ explosion?)



$$E_g = \frac{GM^2}{R} \sim 3 \times 10^{53} \text{ erg} \left(\frac{M}{M_{\text{sun}}} \right)^2 \left(\frac{R}{10 \text{ km}} \right)^{-1}$$

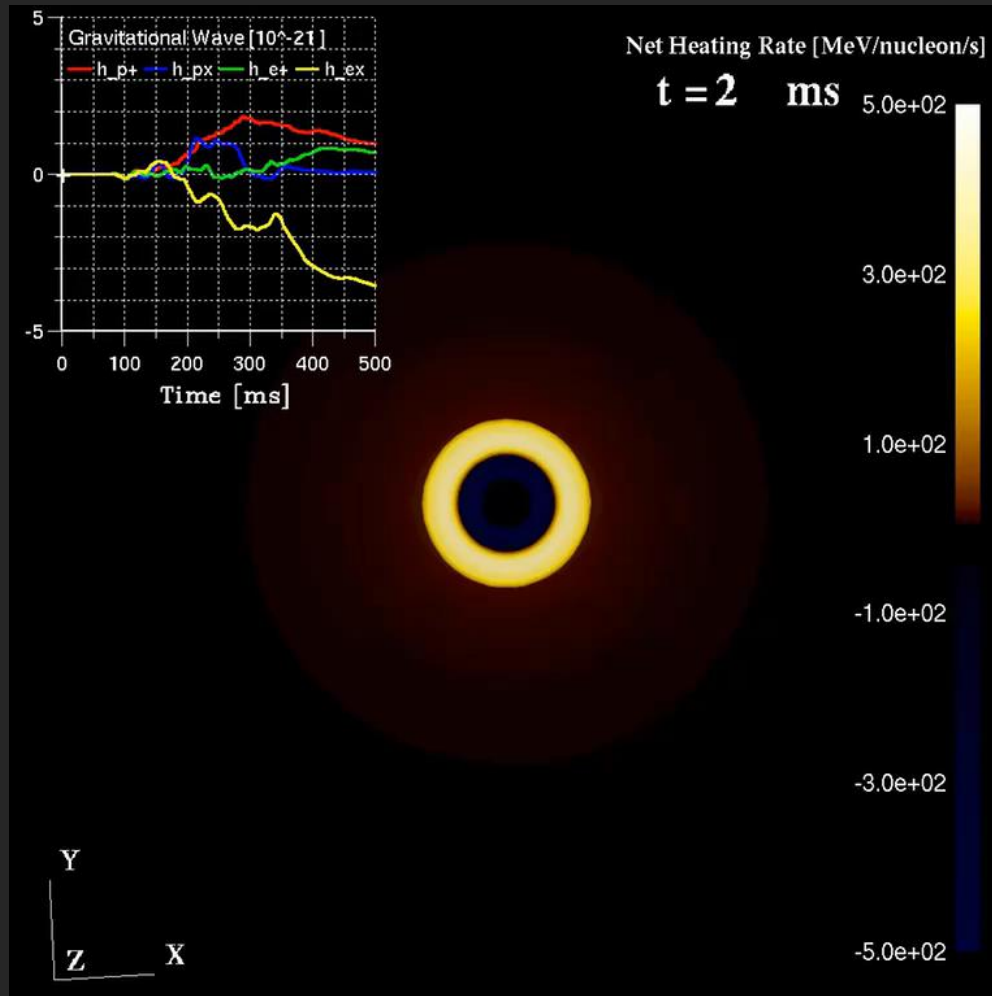
If, $\sim 1\%$ of $E_{\nu} \Rightarrow$ Kinetic Energy
 “Delayed Neutrino Explosion”
 Consensus: Does not work in 1D.

Neutrino heating in multi-D



Buras, Marek , Janka (MPA)

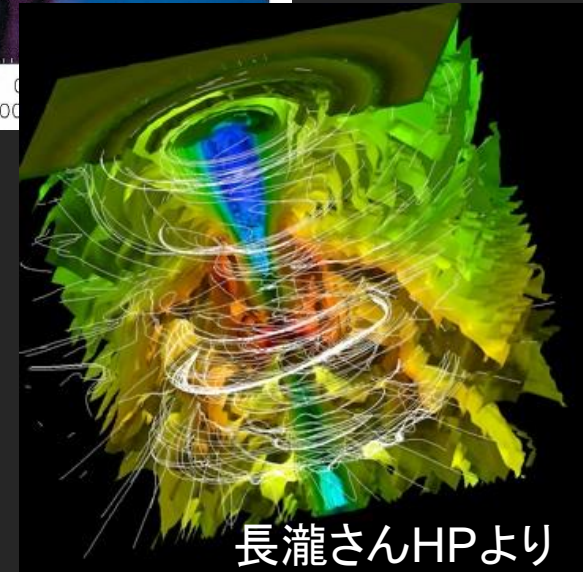
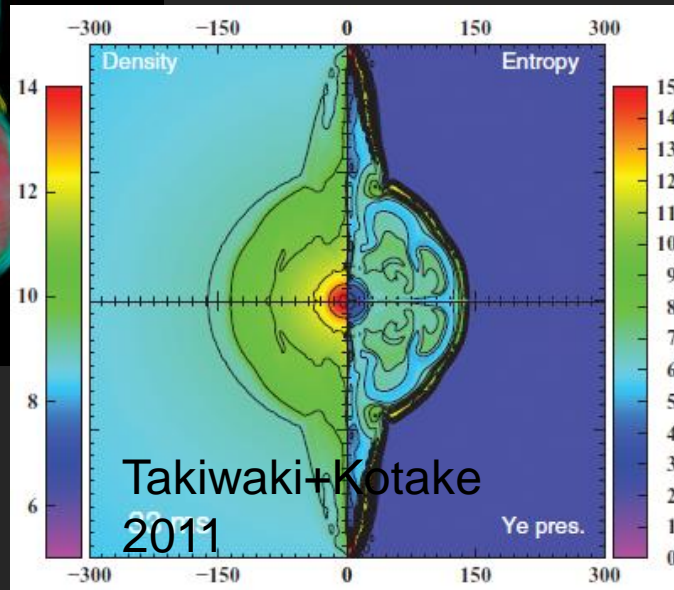
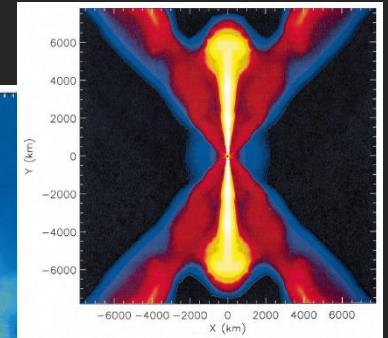
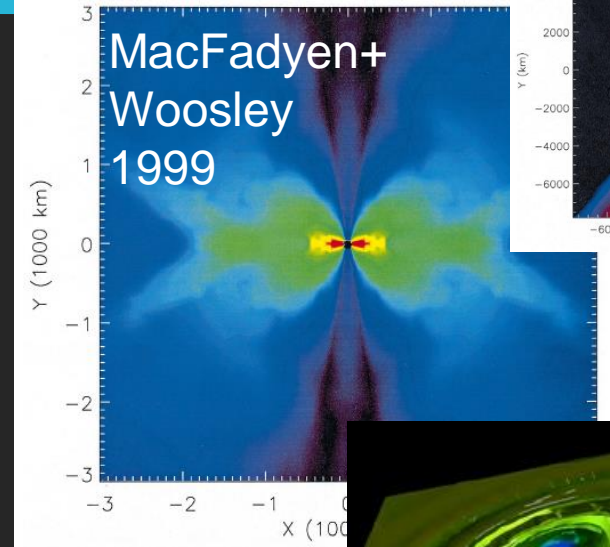
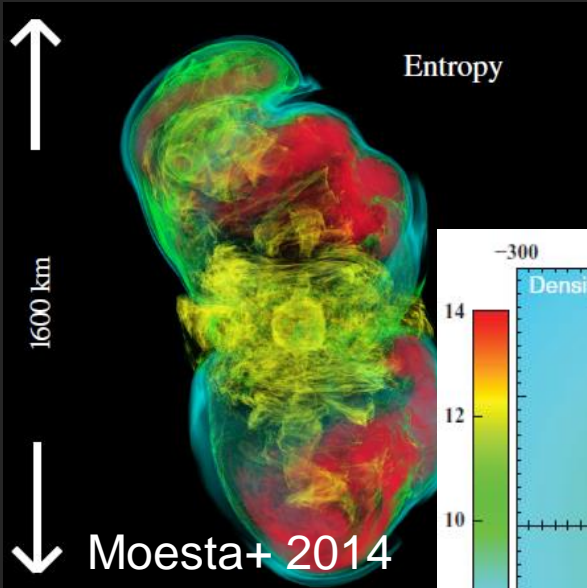
Neutrino Heating in Multi-D



“Collapser” (ν /MHD+Rotation, $> 25M_{\odot}$?) (Black Hole Formation)

Other Scenarios

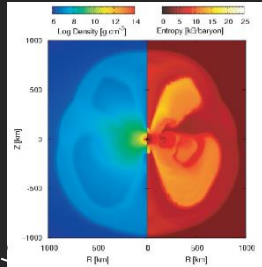
MHD+Rotation (Magnetar Formation)



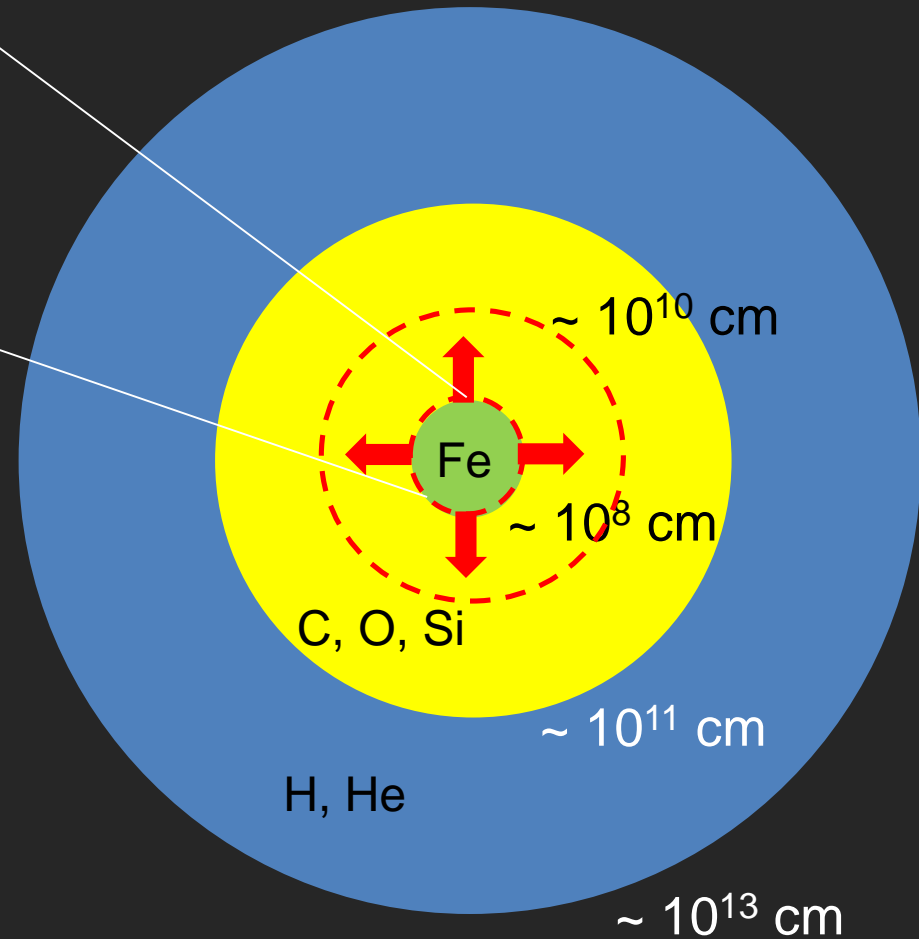
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Explosive Nucleosynthesis above Fe core



Once the shock is launched, the high temperature there induces explosive nucleosynthesis above the Fe core.



Dynamics $[\rho(r,t), T(r,t)]$
 \Rightarrow Nuclear reactions $[X_i(r, t)]$

Stellar and SN Nucleosynthesis

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Supernova nucleosynthesis

From Wikipedia, the free encyclopedia

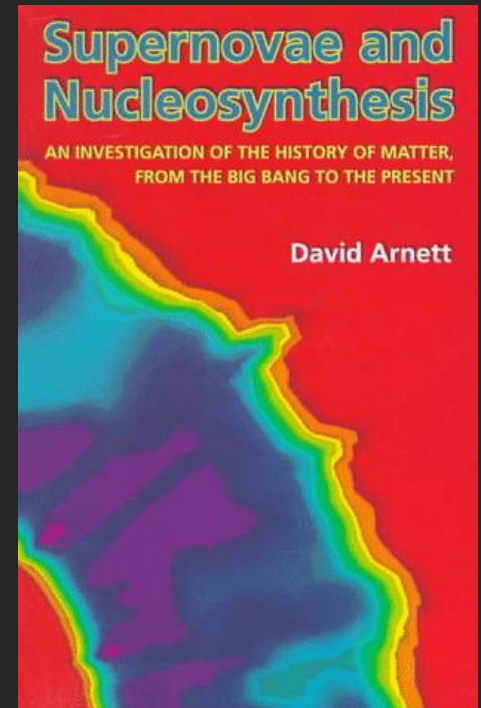
Supernova nucleosynthesis is the production of new **chemical elements** inside **supernovae**, a picture due to Fred Hoyle.^[1] It occurs primarily due to explosive **nucleosynthesis** during explosive oxygen burning and silicon burning.^[2] Those fusion reactions create the elements **silicon, sulfur, chlorine, argon, sodium, potassium, calcium, scandium, titanium** and **iron peak** elements: **vanadium, chromium, manganese, iron, cobalt, and nickel**. These are called "primary elements", in that they can be fused from pure hydrogen and helium in massive stars. As a result of their ejection from supernovae, their abundances increase within the interstellar medium. Elements heavier than nickel are created primarily by a rapid capture of **neutrons** in a process called the **r-process**. However, these are much less abundant than the primary chemical elements. Other processes thought to be responsible for some of the **nucleosynthesis** of underabundant heavy elements, notably a **proton** capture process known as the **rp-process** and a **photodisintegration** process known as the **gamma (or p) process**. The latter synthesizes the lightest, most neutron-poor, isotopes of the heavy elements.

References [edit]

- [↑] "Synthesis of the elements from carbon to nickel" *Astrophys. J. Suppl.* 1, 121 (1954)
- [↑] Woosley, S.E., W. D. Arnett and D. D. Clayton (1973). "Explosive burning of oxygen and silicon" *Astrophys. J.* 183, 315-333
- [↑] P. A. Seeger, W.A. Fowler, D. D. Clayton (1965). "Nucleosynthesis of heavy elements from carbon in cool stars. I. Carbon, oxygen, neon, magnesium and silicon" *Astrophys. J.* 147, 310-330

Other reading [edit]

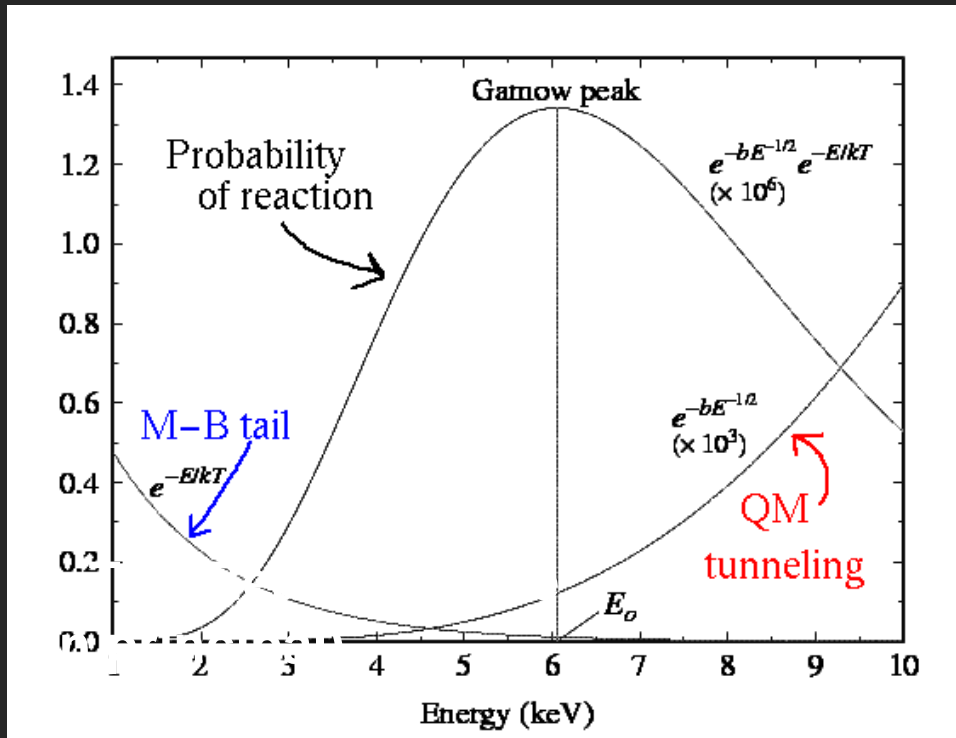
- E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, *Synthesis of the Elements from Hydrogen and Helium*, Wiley-Interscience, 1957
- D. D. Clayton, "Handbook of Isotopes in the Cosmos", Cambridge University Press, 1988



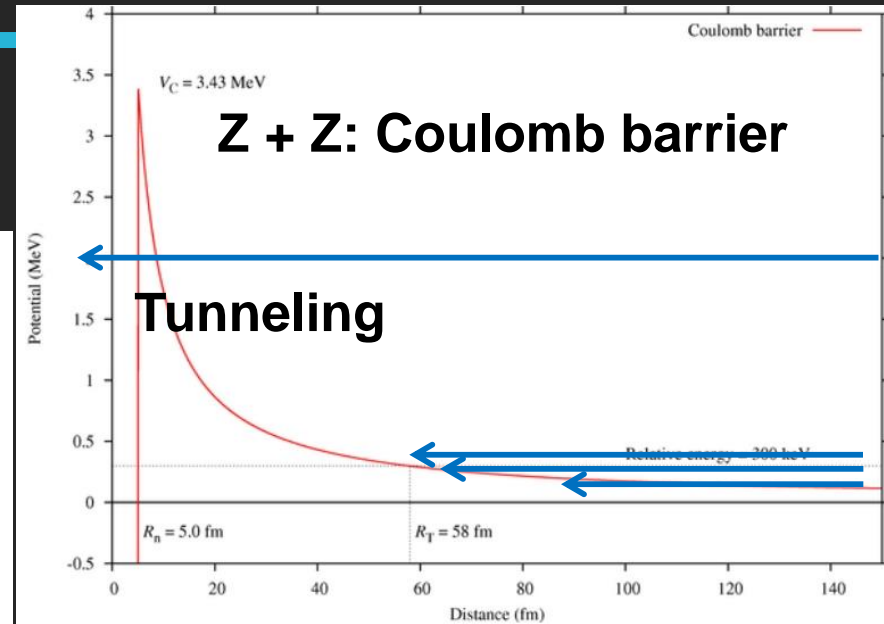
Pioneering works by many "big names" since 1950's. (e.g., B2FH paper).

Thermonuclear Reactions

Gamov Peak



核力による反応が共鳴を待たない場合 (クーロン障壁を超えた後の反応率がエネルギーにほとんど依存しない場合)。



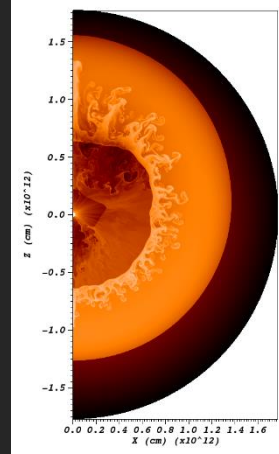
High T
 \Rightarrow Particles w/ high energy

$$r = N_x N_y \langle \sigma v \rangle$$

$$\langle \sigma v \rangle = \left(\frac{8}{\mu\pi} \right)^{\frac{1}{2}} \frac{1}{(kT)^{\frac{3}{2}}} \int_0^{\infty} \sigma(E) P(E) dE$$

$$\sigma(E) = \frac{1}{E} \exp(-2\pi\eta) S(E)$$

Reaction Rates



Reaction Rates
Equation of States
Opacities

Astrophysical Models

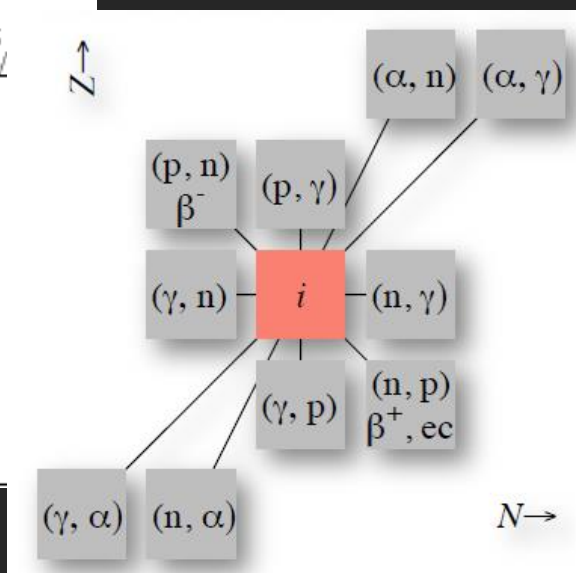
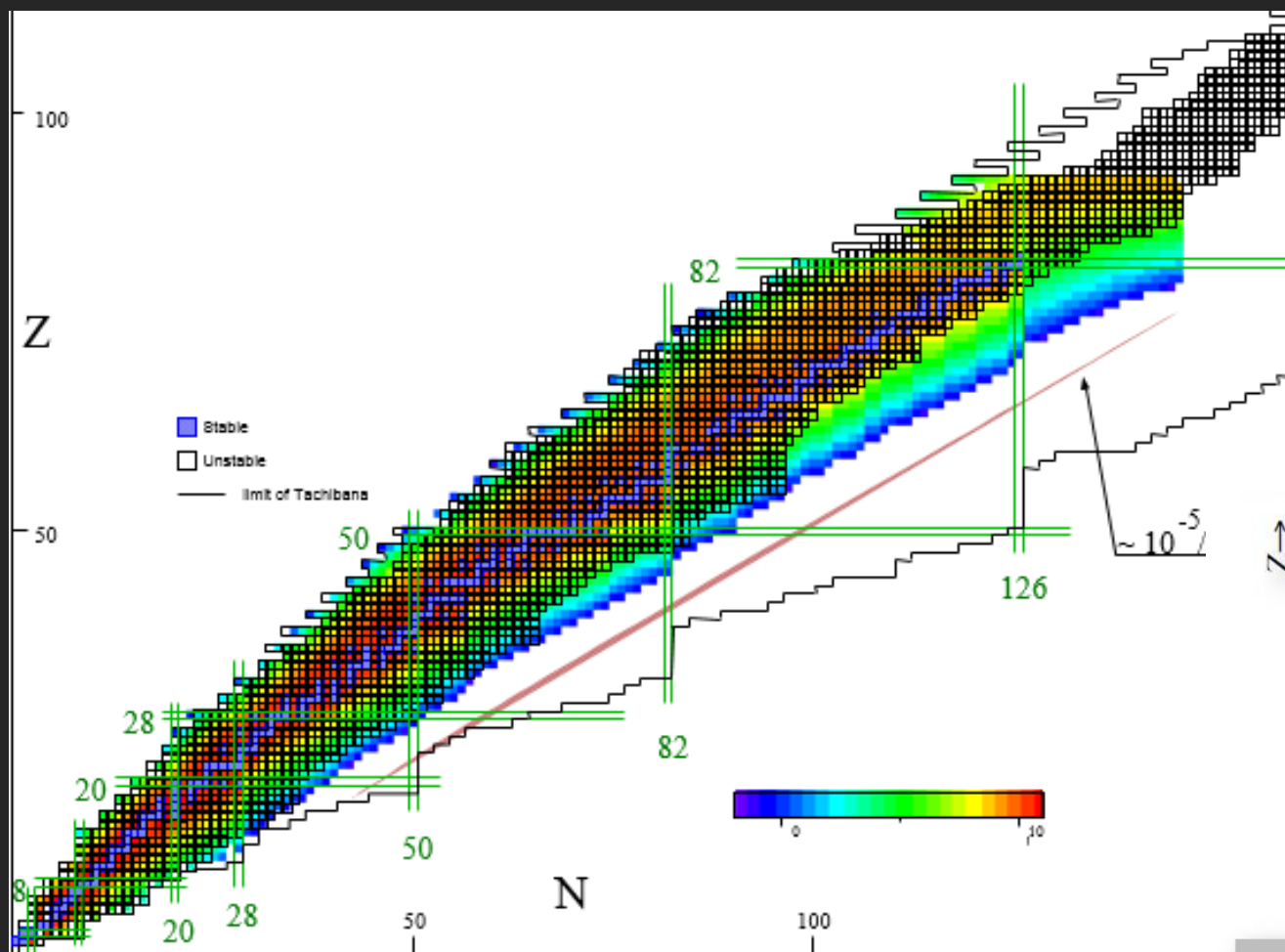
(Most) Astrophysics thermonuclear reactions can be treated within the statistical Hauser-Feshbach model of nuclear reactions (compound nucleus reactions by averaging over resonances):

Nuclear Ingredients from nuclear experiments & theory

(mass, shell energy, energy levels, resonances, ...)

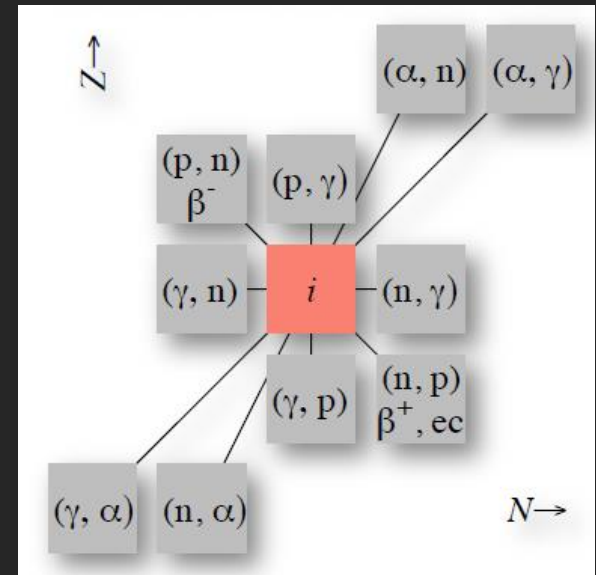
⇒ Cross section calculations

Reaction Network



Reaction Network

$$Y_i = \frac{X_i}{A_i} = \frac{n_i}{\rho N_A}$$



$$\dot{Y}_i = \sum_j C_j R_j Y_j + \sum_{jk} \frac{C_i}{C_j! C_k!} R_{jk} Y_j Y_k + \sum_{jkl} \frac{C_i}{C_j! C_k! C_l!} R_{jkl} Y_j Y_k Y_l$$

decay
 photodisintegration
 e/e+ capture
 v-induced

two-body

three-body
 (e.g., 3α)

C_i : Relative numbers of particles in the reaction.
 R_i : Reaction rate

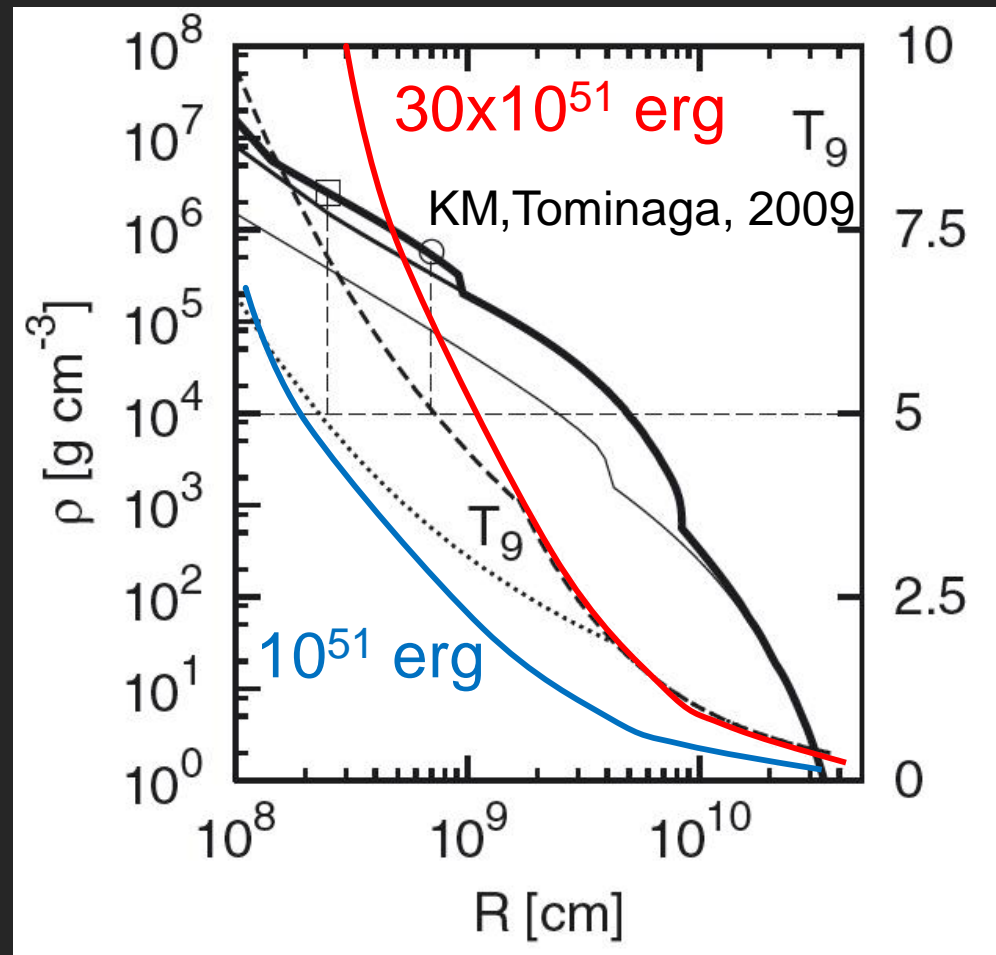
Thermal conditions behind the shock

$T_9 = T/10^9\text{K}$ at the passage of the shock (i.e., peak T)

Fe/Si Si/O O/He

Rrough estimate:

- $E_K \sim (4\pi/3) R^3 \rho T^4$
↓
- $T \propto (E_K/R^3)^{1/4}$
- **> 10^9K , up to O core.**
- **Higher T for inner.**



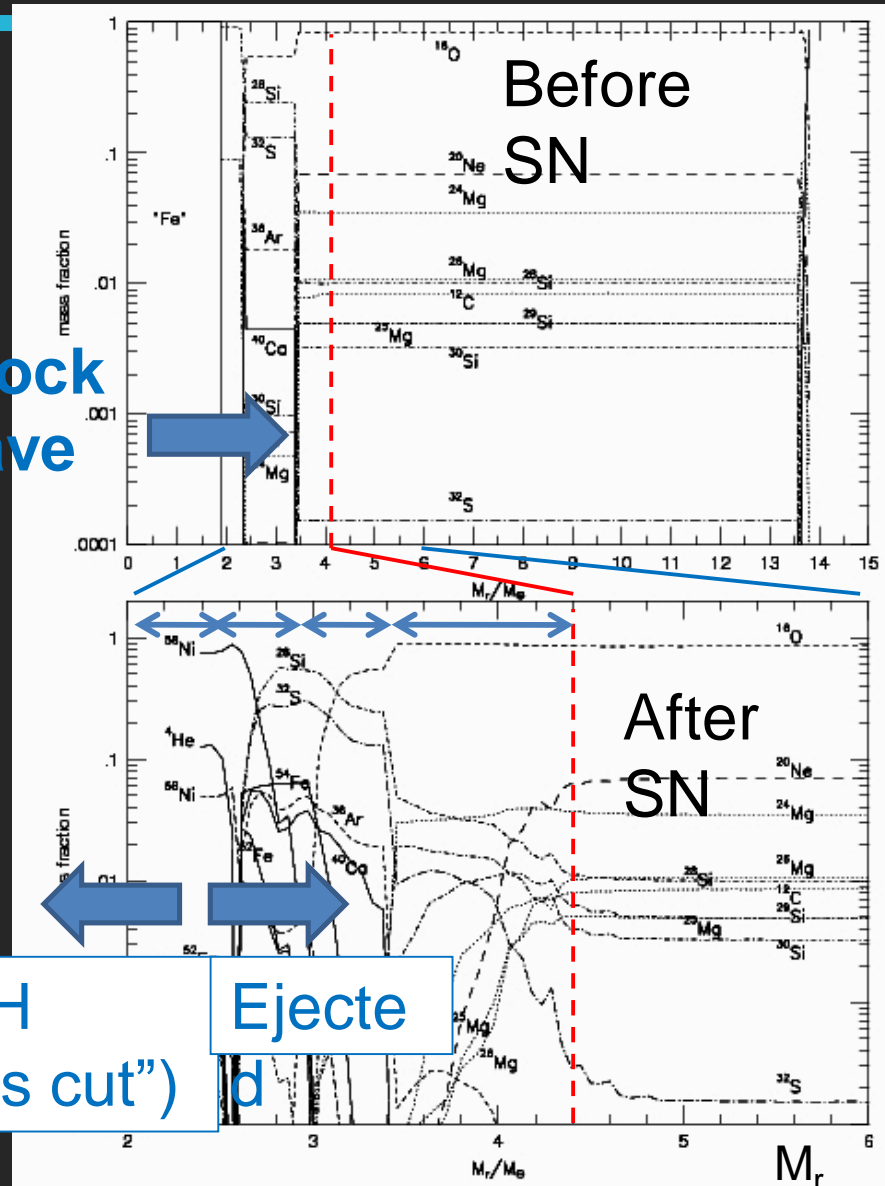
CC-SN Nucleosynthesis

- Explosive burning.

- $T \propto (E_K/R^3)^{1/4}$

- $T_9 = T/10^9\text{K} > 5$: Si-burn.
 ^{56}Ni , He, Fe-peak
- $T_9 = 4-5$: incomplete Si-burn.
Si, S, Fe, Ar, Ca, Fe-peak
- $T_9 = 3-4$: O-burn.
O, Si, S, Ar, Ca
- $T_9 = 2-3$: C,Ne-burn.
O, Mg, Si, Ne

Fe core
Si core
O core

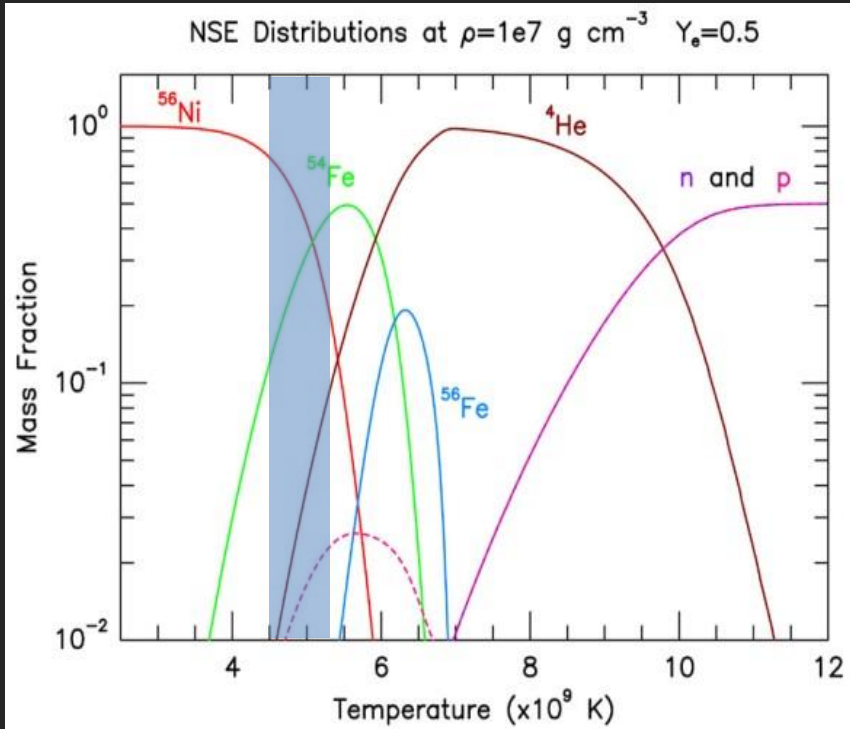


$T > 5 \times 10^9 \text{ K}$: Equilibrium

- Weak interactions are decoupled.
- Nuclear reactions:
 - **NSE ($> 5 \times 10^9 \text{ K}$): Nuclear Statistical Equilibrium**
 - $A \leftrightarrow B \leftrightarrow C \leftrightarrow D \leftrightarrow E \leftrightarrow F \leftrightarrow G \dots$
 - At any moment, ALL isotopic composition described by T , ρ , Y_e (p/n ratio) at given time t .
 - History enters in weak interaction (Y_e change) and timing of the freezeout (when reactions decoupled).

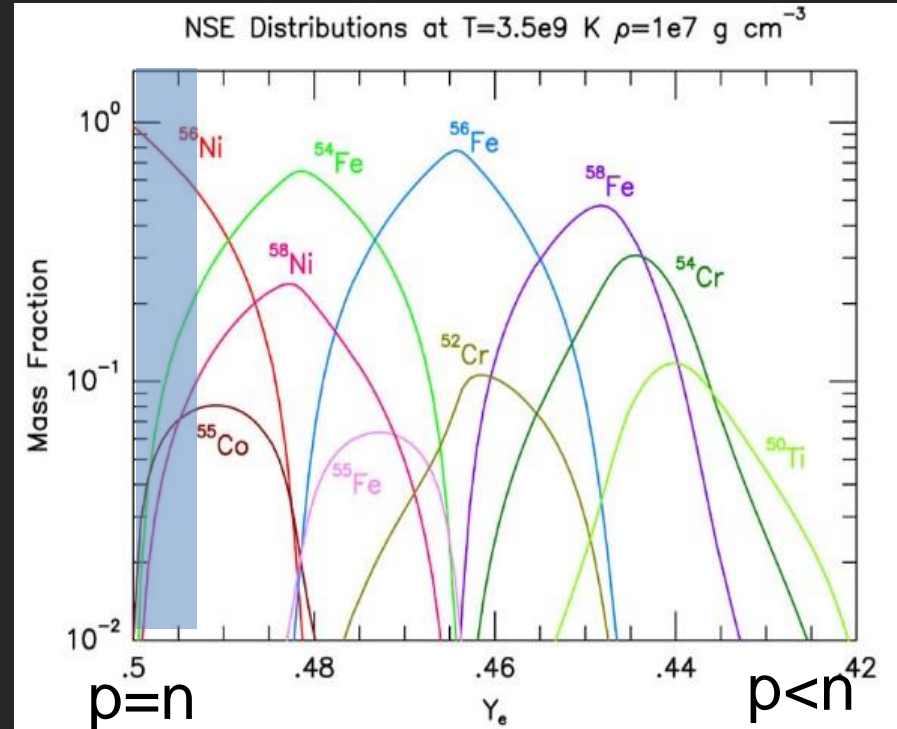
NSE

$\chi_i(T)$ for given ρ , $Y_e (=0.5)$



Temperature given by
explosion dynamics

$\chi_i(Y_e)$ for given ρ , $T (=3.5\text{GK})$



Y_e given by
(1) Progenitor (before exp.)
(2) weak interaction (dur. exp.)

^{56}Ni in SN explosive nucleosynthesis

- Why ^{56}Ni most abundant? (for initial $Y_e \sim 0.5$)
 - NSE \Rightarrow Forms most stable isotope.
 - Fe-peaks (for $T \sim 5 \times 10^9$ K).
 - Electron capture is slow. p/n ratio ~ 1 .
 - ^{56}Ni has equal number of protons and neutrons in it.

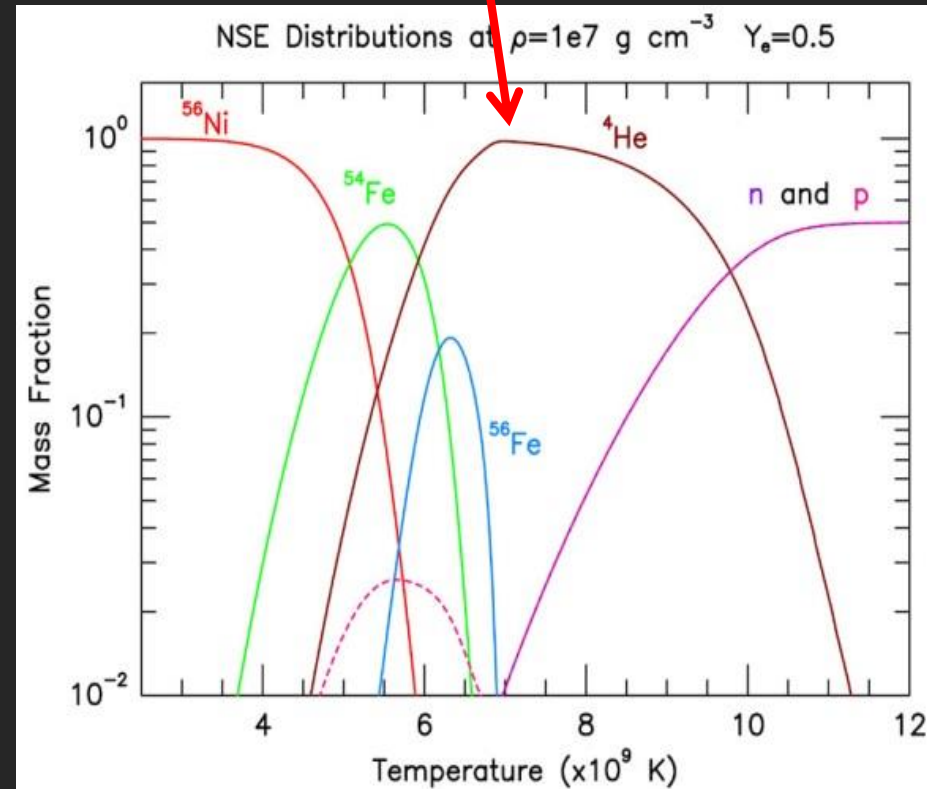
α -rich freezeout (higher T)

- For high entropy (or high T), triple- α decouples.
 - NSE (Fe-peaks) + α left after the “freezeout”.

- α eventually captured by heavy (NSE) elements.



...



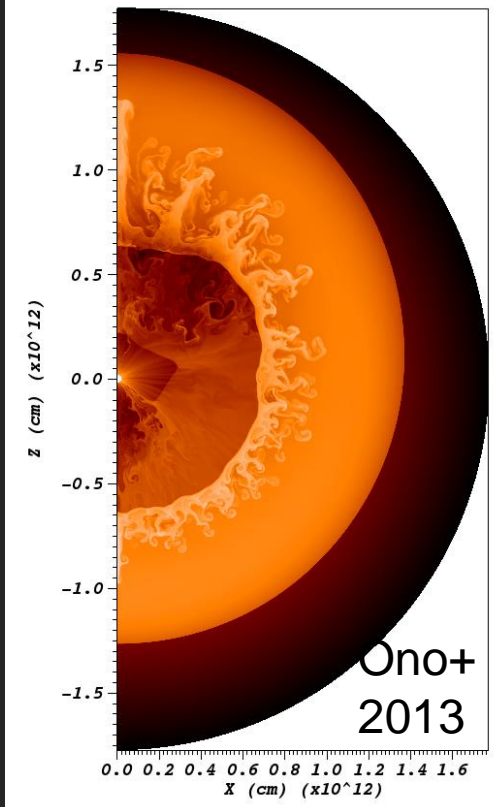
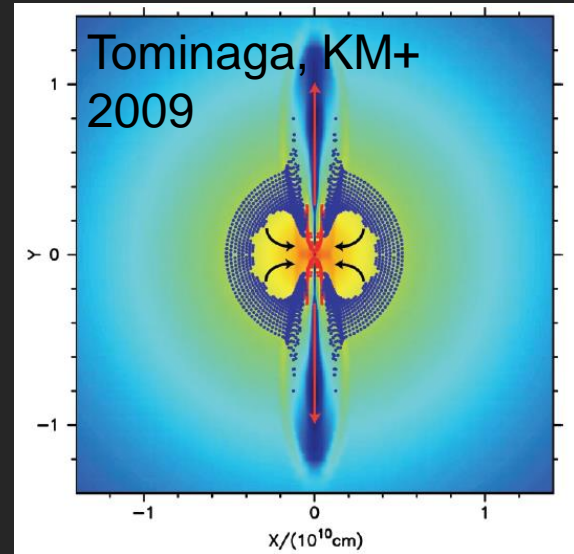
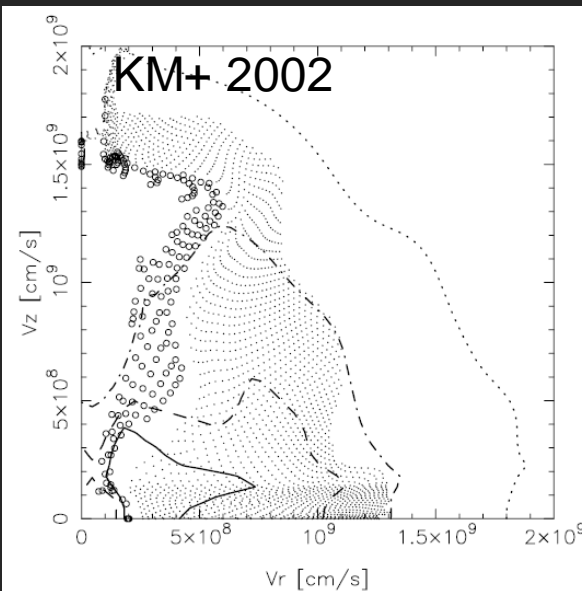
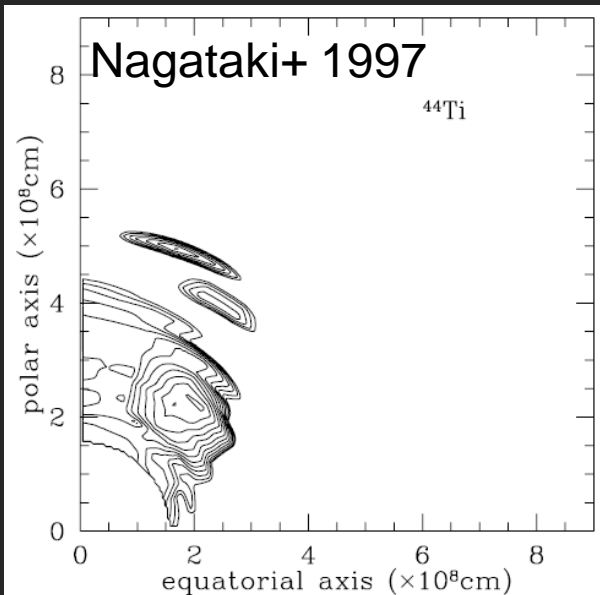
In practice

- Hydrodynamic simulation to get thermal history.
 - Core-collapse SNe.
 - Decent first-principal explosion model only exist for “ONeMg” explosion (weak SN, $\sim 8M_{\text{sun}}$).
 - Mimic the collapse-explosion by a parameterization, then follow the shock in the Si/O/He/H layer.
 - SNe Ia.
 - State-of-the-art simulations give decent “explosion” and thermal history for nucleosynthesis.
- “Small” reaction network for major isotopes.
- Postprocess “Large” network calculation to get the composition for each hydro elements.

Bipolar/2D Models

Most intensively studied multi-D models in SN nucleosynthesis study.

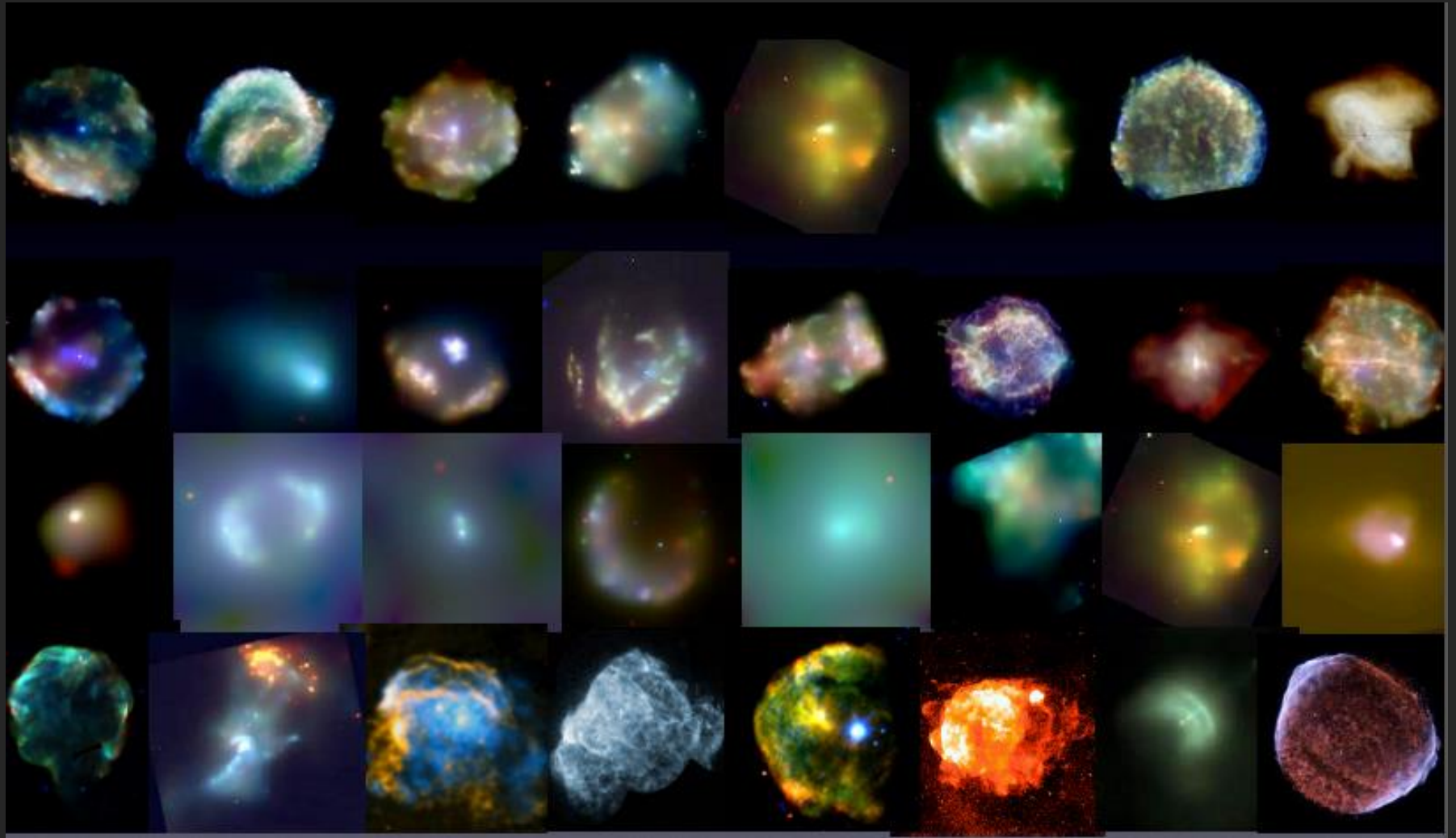
Relatively simple, but may catch the main global property of the SN explosion(s).



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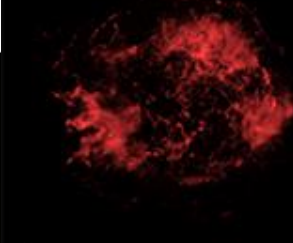
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Supernova Remnants



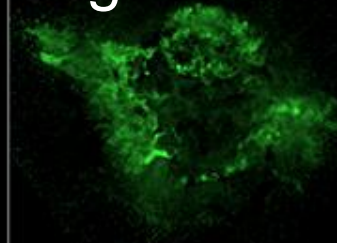
Distribution of radioactive isotopes

Fe (\leftarrow ^{56}Ni)



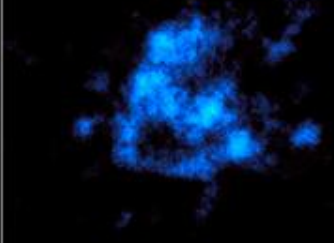
鉄

Mg



ケイ素/マグネシウム

^{44}Ti



チタン-44

広報活動

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報道発表資料

2014年2月20日

独立行政法人理化学研究所

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いいね! 42 ツイート 82

超新星「カシオペア座A」は非対称に爆発した

— 高エネルギーX線宇宙望遠鏡でチタンの鮮明な天体写真を撮影 —

この発表資料を分かりやすく解説した「[60秒でわかるプレスリリース](#)」もぜひご覧ください。

ポイント

- 高エネルギーX線の集光撮影で元素の量や位置を直接観測可能に
- 超新星爆発で飛び散った放射性チタンの非対称な空間分布を発見
- 重力崩壊型の超新星爆発のメカニズムを理解するうえで貴重な観測結果

広報活動

[プレスリリース\(研究成果\)](#)

2014

2013

2012

2011

2010

2009

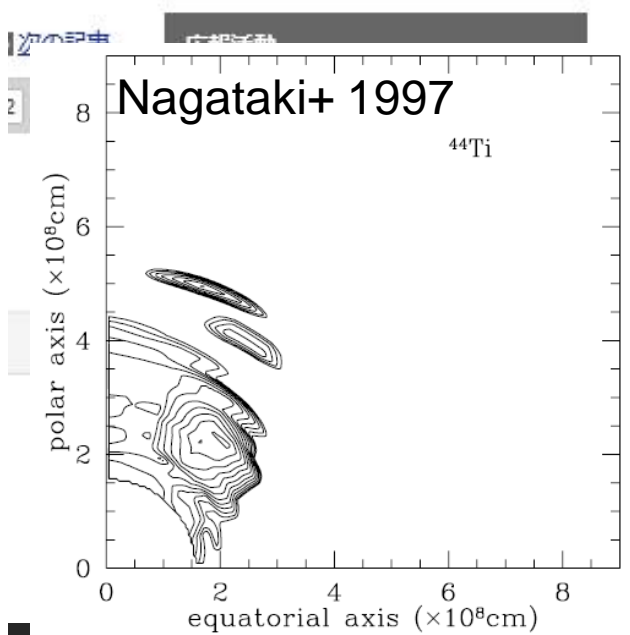
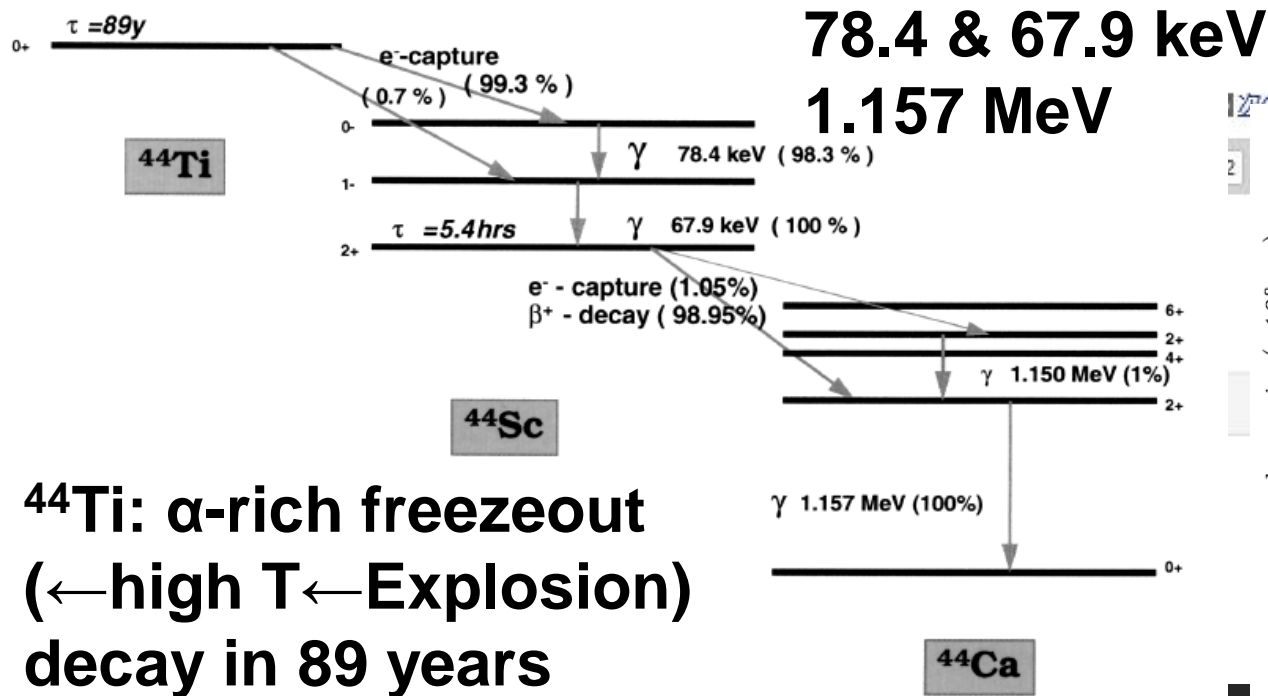
2008

2007

2006

2005

Distribution of radioactive isotopes



Distribution of elements



Kyoto University

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刊行物・資料請求
お問合せ
アクセス・マップ
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ホーム
* 概要
● 教育

藤原定家の超新星は非対称爆発をした - X線天文衛星「すざく」が明らかにした標準光源の「ゆがんだ」形状 -

2013年7月2日

内田裕之 日本学術振興会特別研究員（理学研究科）、小山勝二 同名誉教授、山口弘一 東京大学・スミソニアン天体物理学センター研究員らのグループの共同研究で、1006年に「明月記」に記録した超新星SN1006が非対称にゆがんだ爆発をしたことが明らかになりました。

この研究成果は米国の科学雑誌「アストロフィジカル・ジャーナル」（771号：2013年7月15日発行）に掲載されました。




左から小山名誉教授、内田特別研究員

藤原定家は1006年に超新星爆発があったことを「明月記」に記録として残しました。その記録と現在の研究から、この超新星は有史上最も明るく輝いた核星走型超新星といわれています。この型の超新星はIa（いちイー）型と呼ばれ、明るさが一定の標準光源として宇宙の加速膨張の発見に寄与してきました。明るさが一定の標準光源であるためには、爆発が対称に行わなければならないと考えられてきましたが、藤原定家の超新星SN1006は、鉄などの元素がある方向に偏った非対称



北
東—西
南

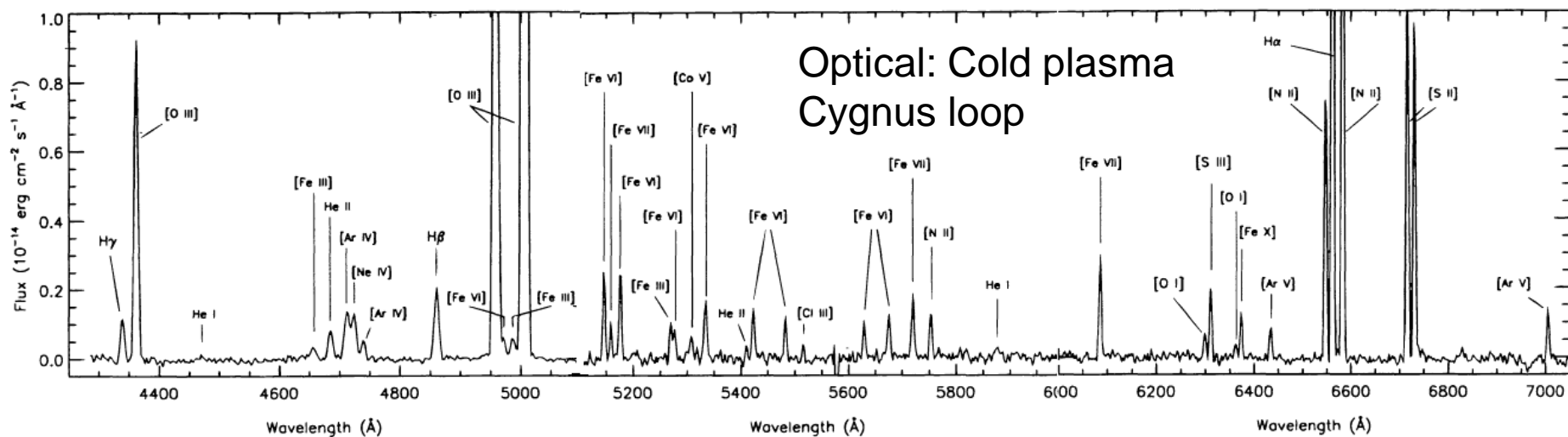
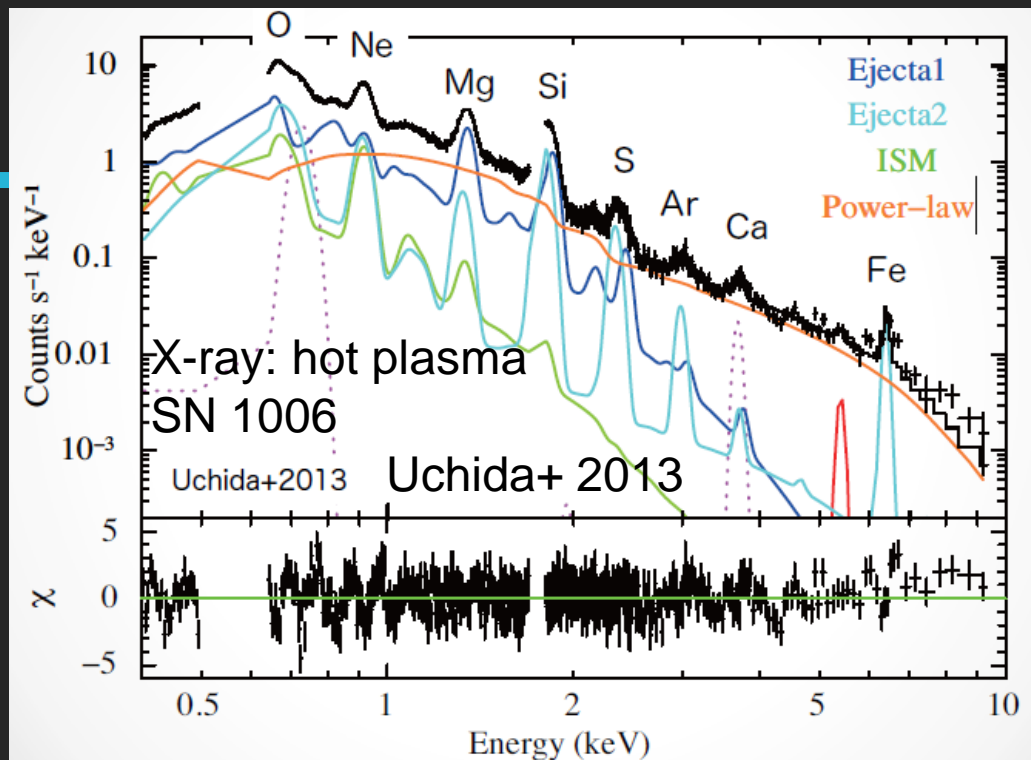
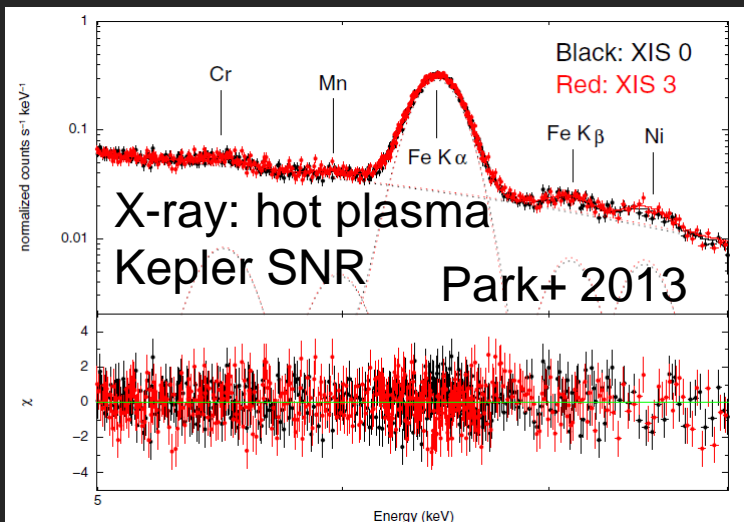
SN1006



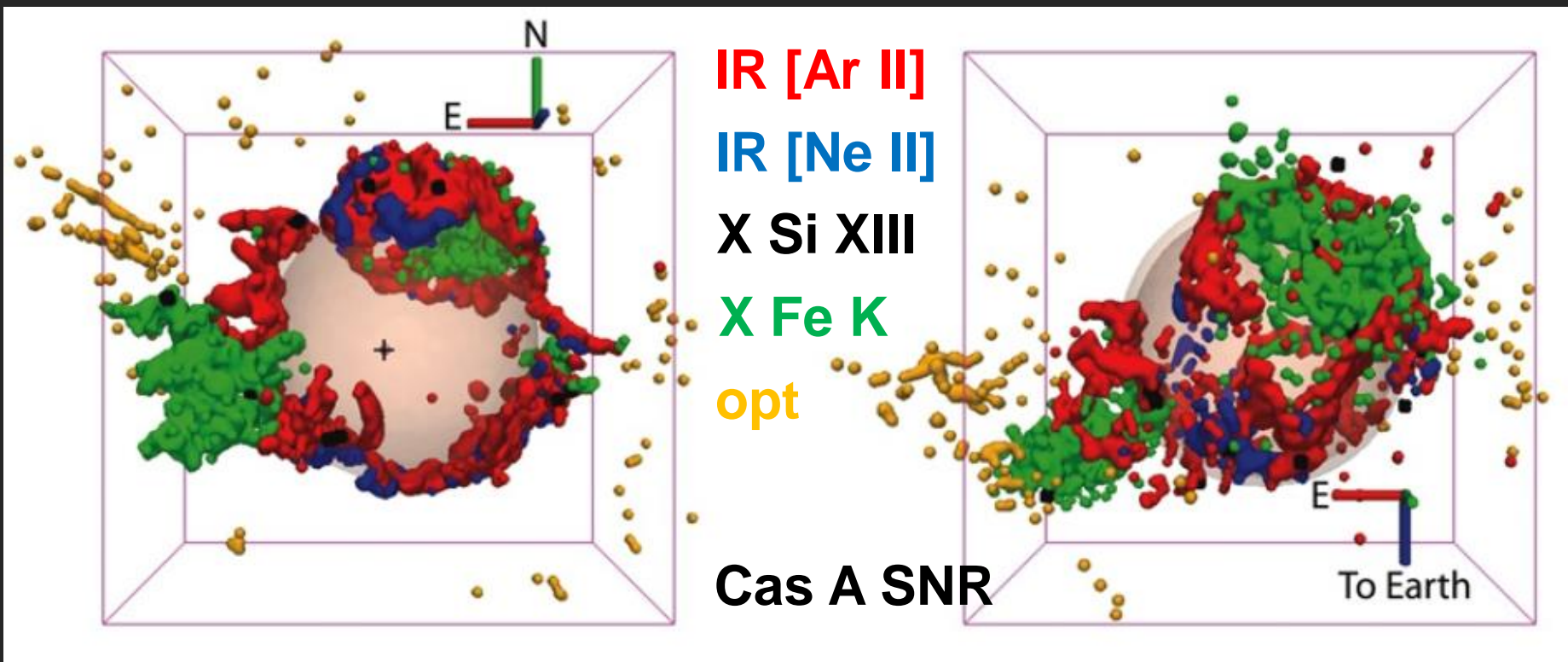
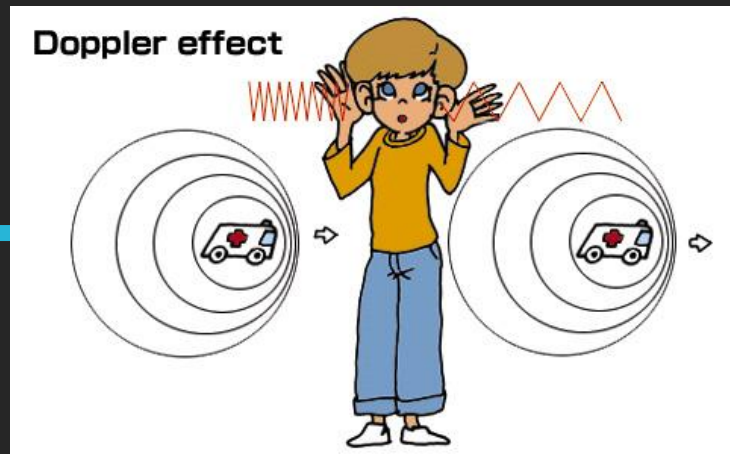
爆発中心
↓
+

ケイ素は南東(左下)に多く分布

Abundance diagnostics



Abundance + 3D kinematics



2D Spatial image + Doppler shift @ each point

Delaney+ 2010

Beyond Galactic Supernova Remnants

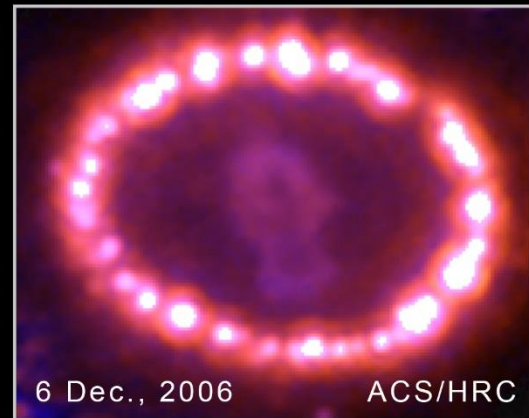
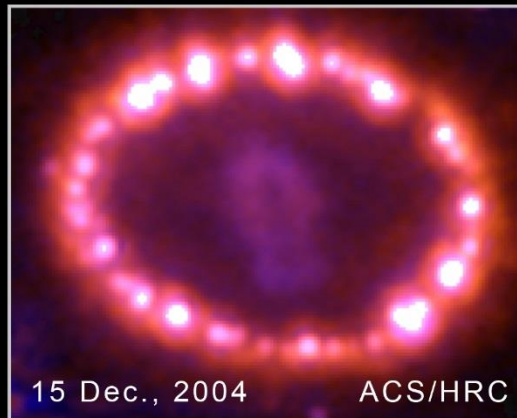
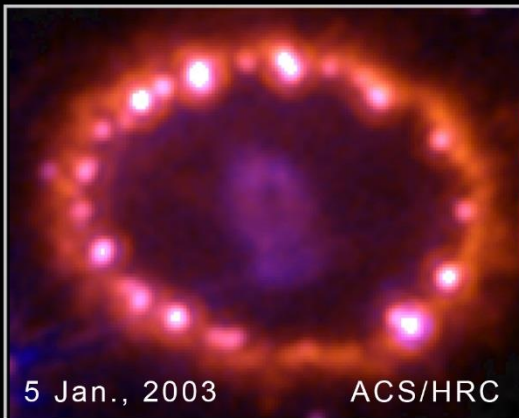
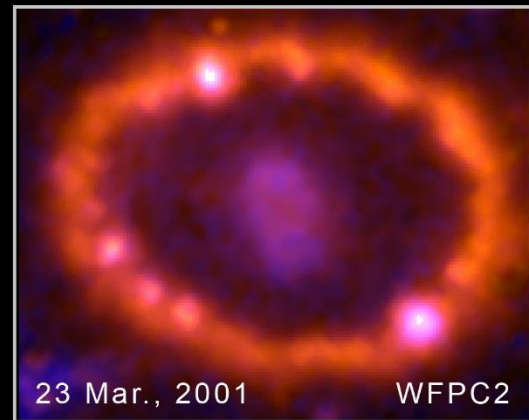
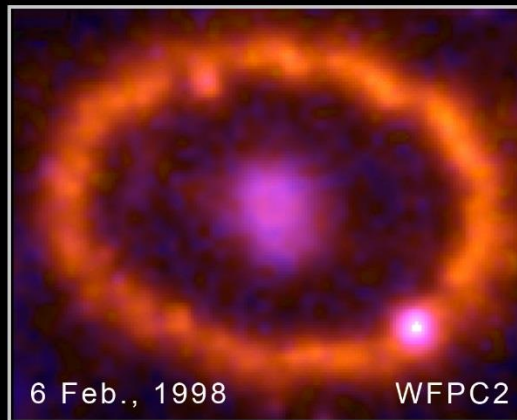
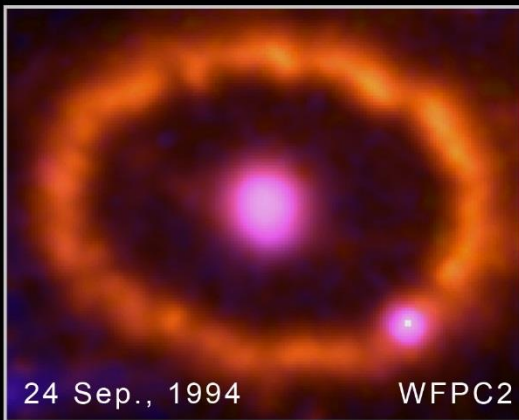
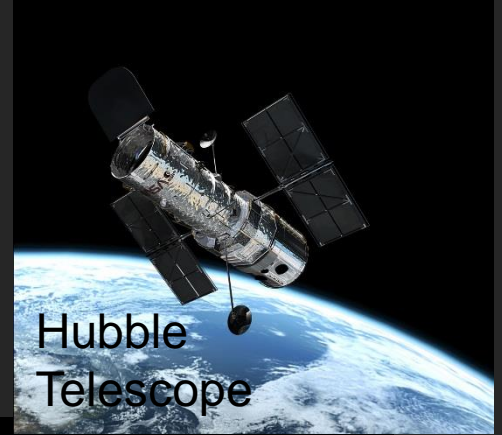
主な超新星 [編集]

Wikipediaより抜粋

超新星	年	星座	銀河	距離	最大光度	型	残骸・別名	備考
SN 185	185年	ケンタウルス座	銀河系	3,300光年	-8		RCW 86	最古の観測記録
SN 393	393年	さそり座	銀河系		-1		RX J1713.7-3946 ?	
SN 1006	1006年	おおかみ座	銀河系	7,200光年	-9	I		
SN 1054	1054年	おうし座	銀河系	7,000光年	-6	II?	かに星雲	
SN 1181	1181年	カシオペア座	銀河系	> 26,000光年	0	II	3C 58	
SN 1572	1572年	カシオペア座	銀河系	8,000~9,800光年	-4	I	チコの星	
SN 1604	1604年	へびつかい座	銀河系	20,000光年以内	-2.5	I	ケプラーの星	銀河系で最後
SN 1885A	1885年	アンドロメダ座	アンドロメダ銀河	254万光年	5.8	Ia	アンドロメダ座S星	他銀河で初の発見
SN 1987A	1987年	かじき座	大マゼラン雲	157,000光年	2.9	II		肉眼で見えた最後

No SN discovery in our Galaxy after SN 1604.

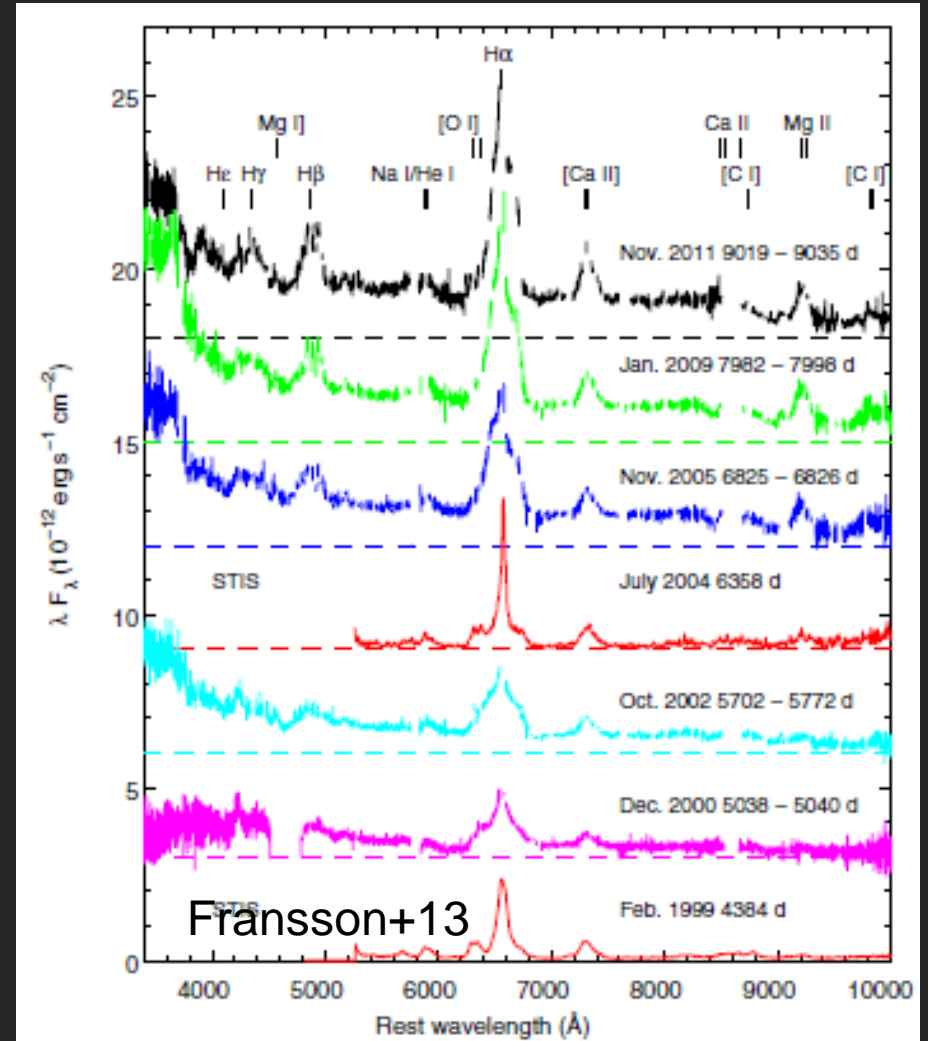
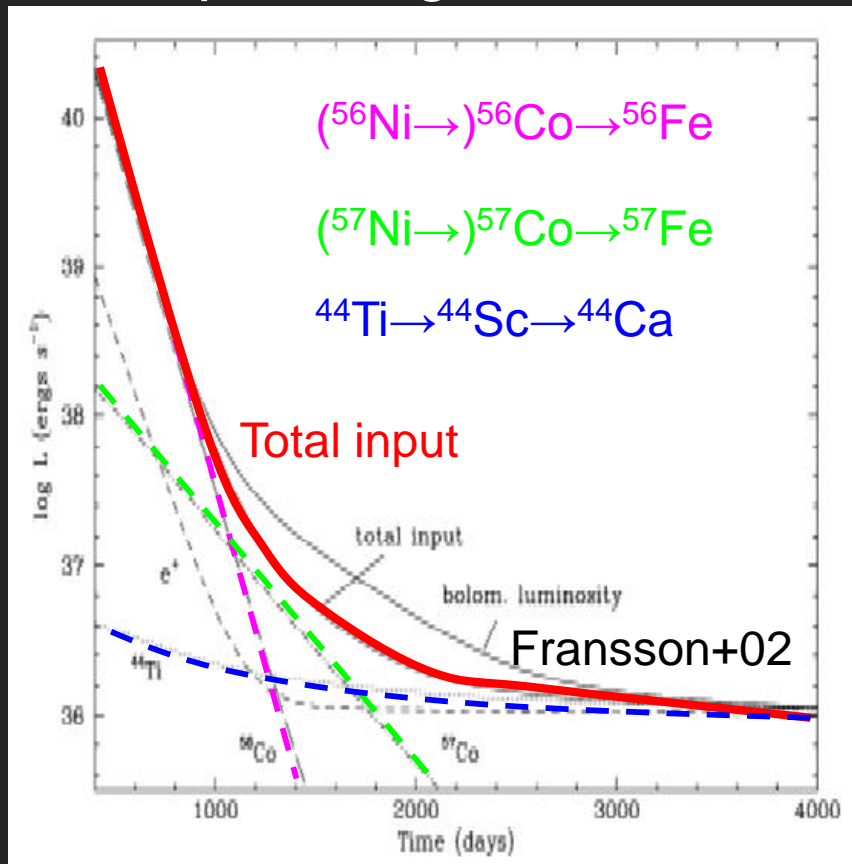
“SNR” 1987A



Early bright phase : Spatially unresolved

Metal emission/absorption lines in optical

Radioactivities
⇒ Optical Light Curve



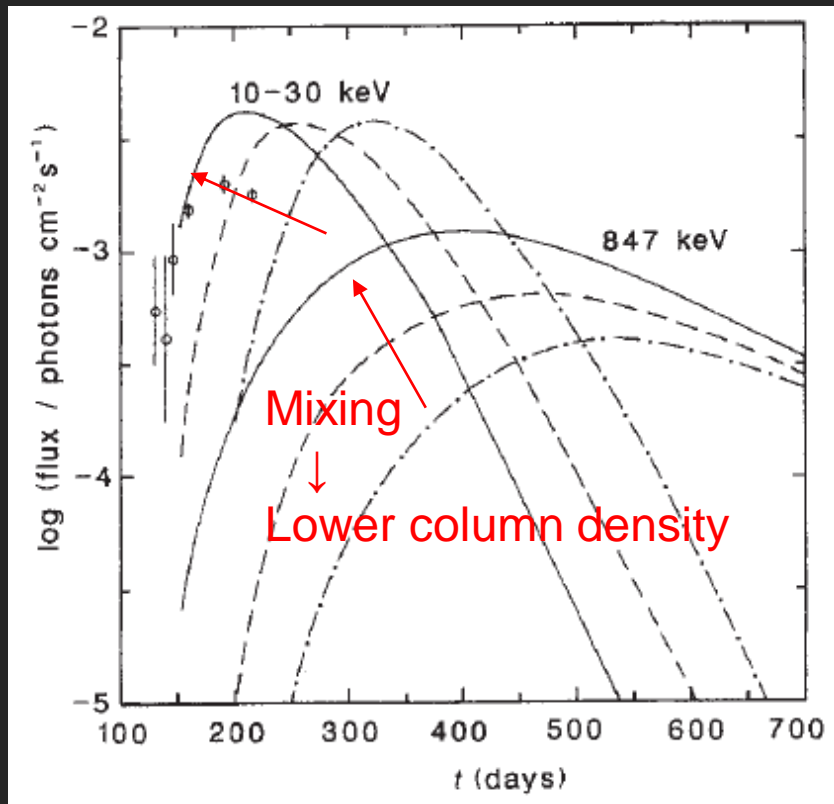


Radioactivities at high energy

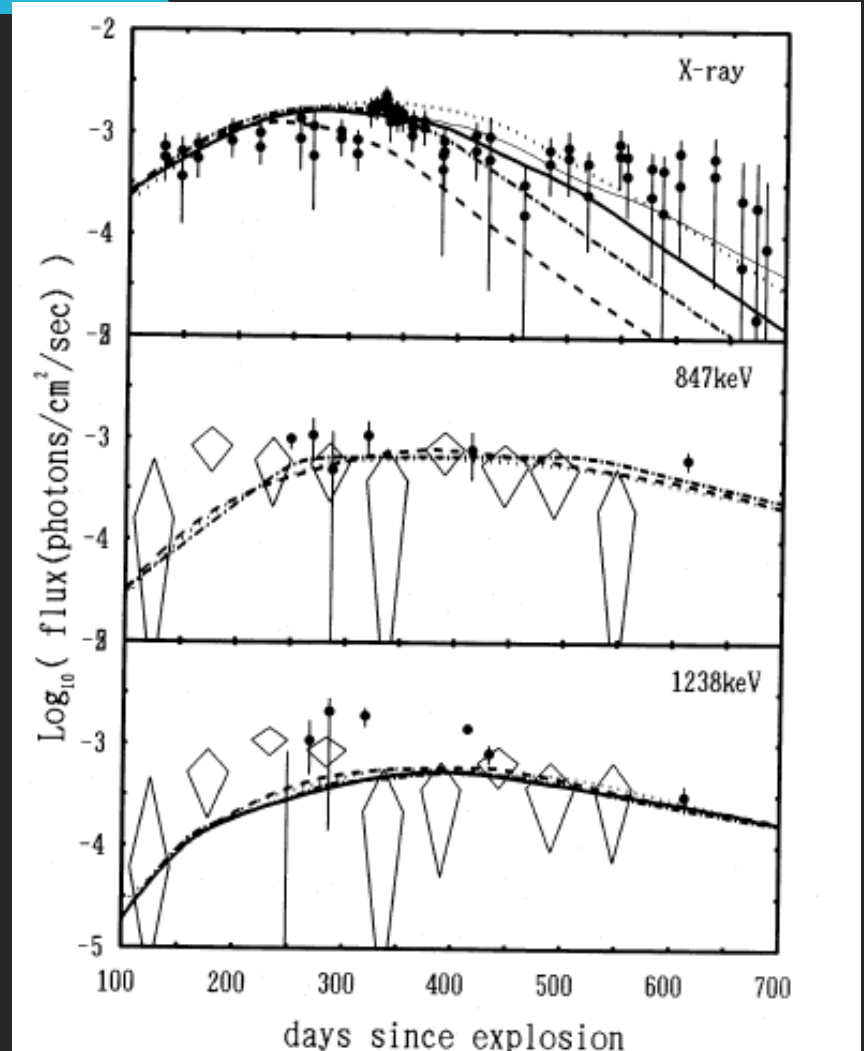
SN 1987A:

Prediction: X-ray after 1 yr

Observation: X-ray at 0.5 yr

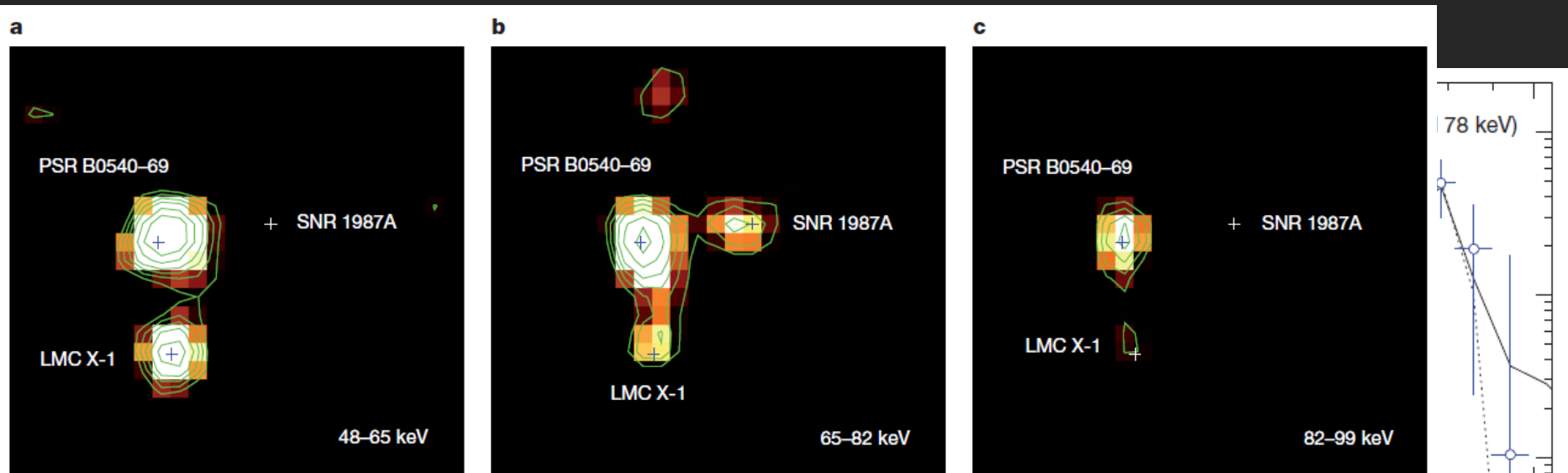


Itoh+ 1987

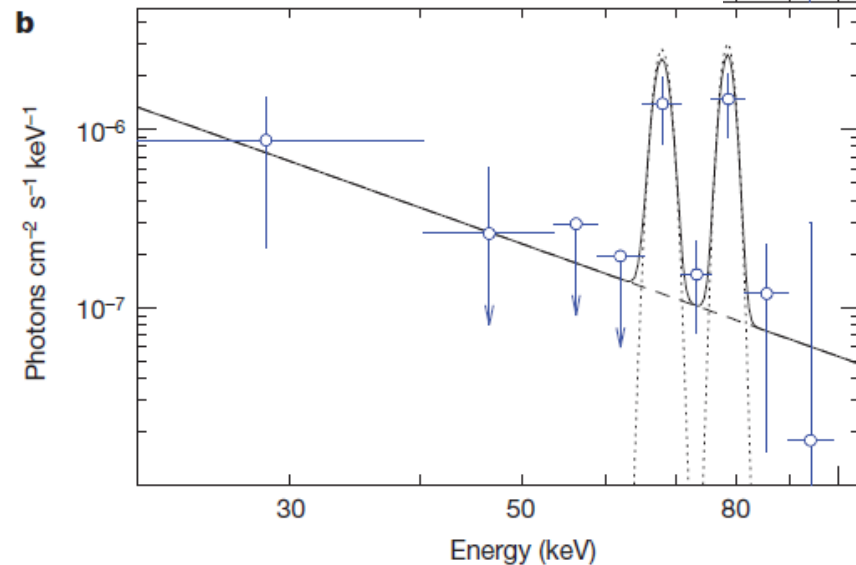
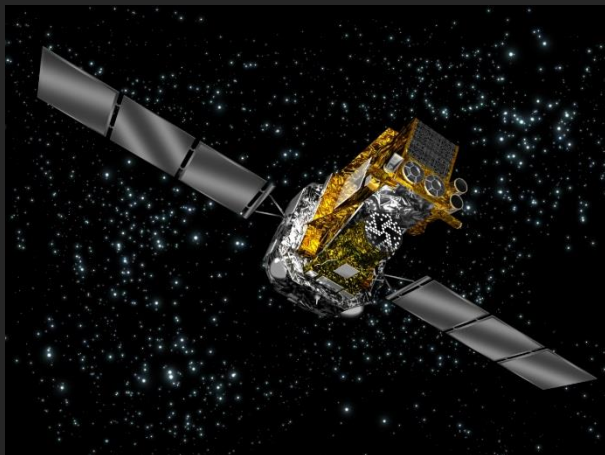


Kumagai+ 1988

Radioactive ^{44}Ti in SN 1987A



^{44}Ti (INTEGRAL)



Extragalactic Supernovae



Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)

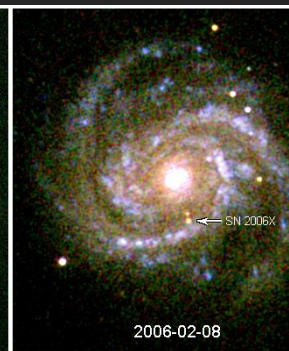
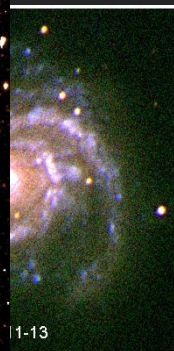
(as seen from Hubble Space Telescope)

3 Weeks Before

Supernova Discovery

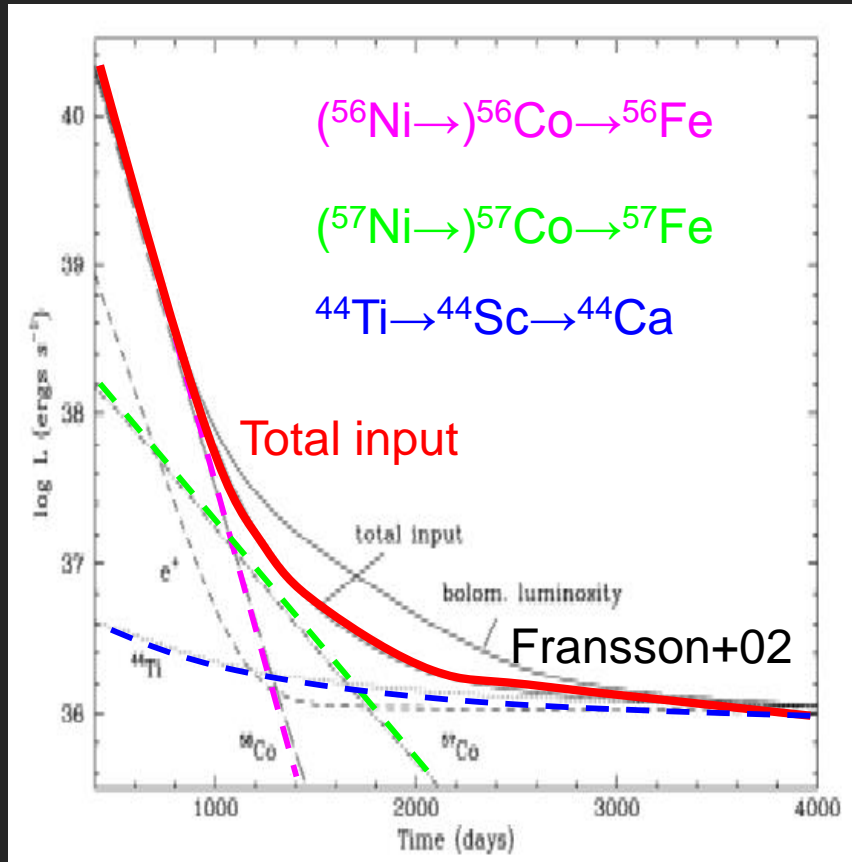
Difference

(as seen from telescopes on Earth)



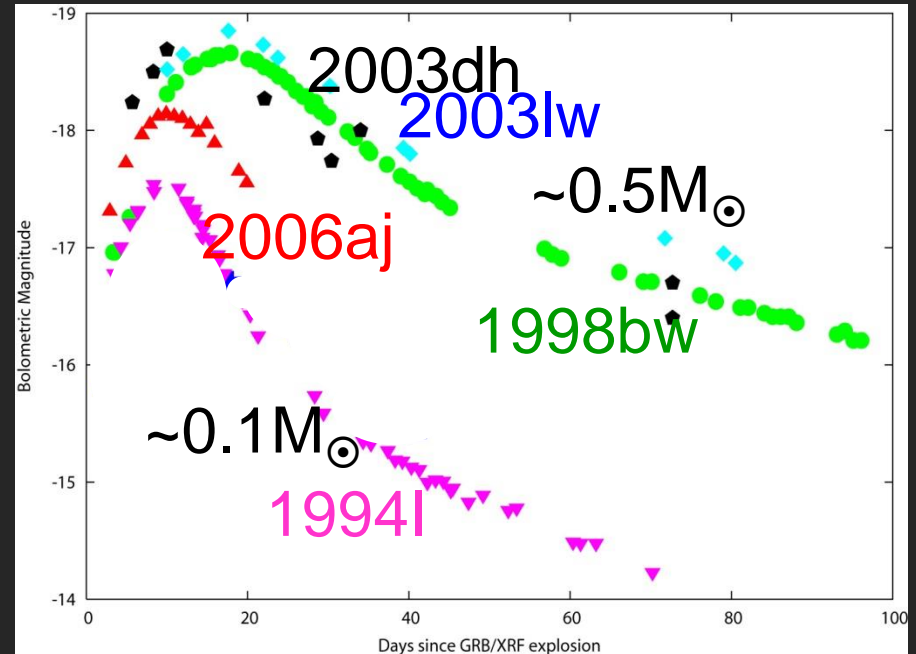
Radioactivity as a power source (mostly ^{56}Ni)

Radioactivities
 \Rightarrow Optical Light Curve



Optical luminosity \leftrightarrow $M(^{56}\text{Ni})$

Bolometric (UBVRI)



0

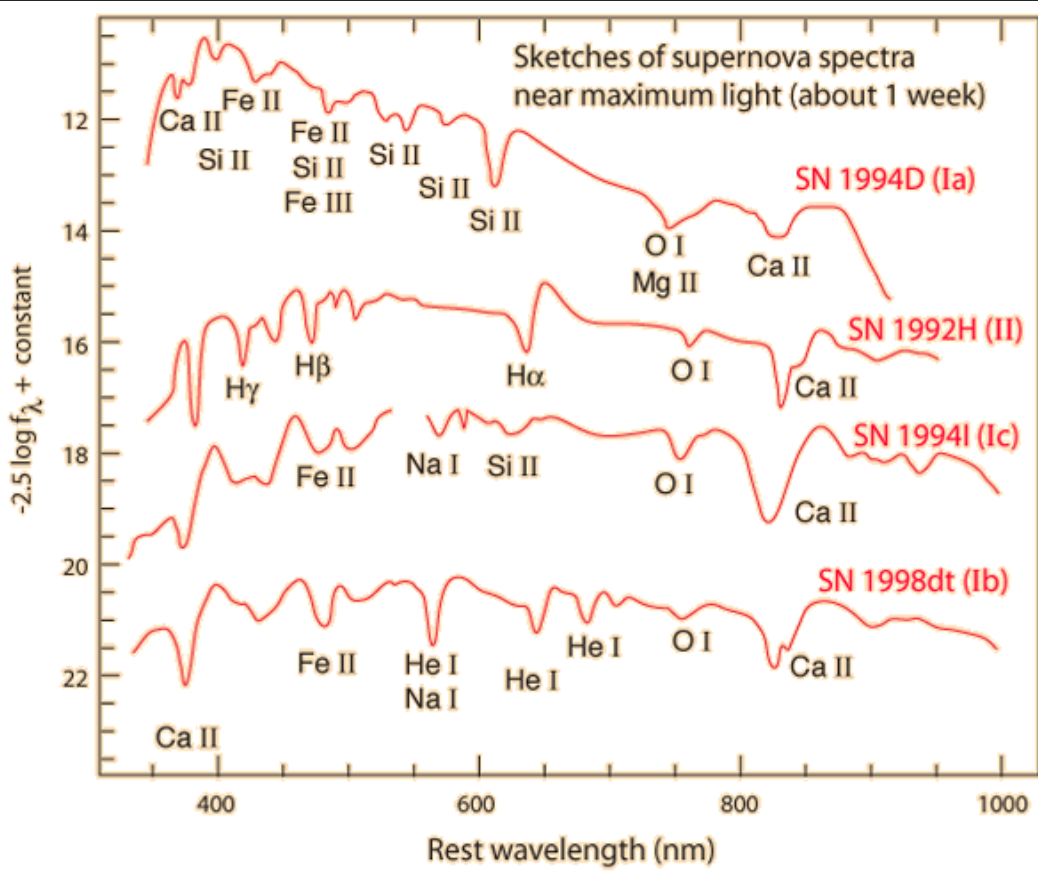
40

80

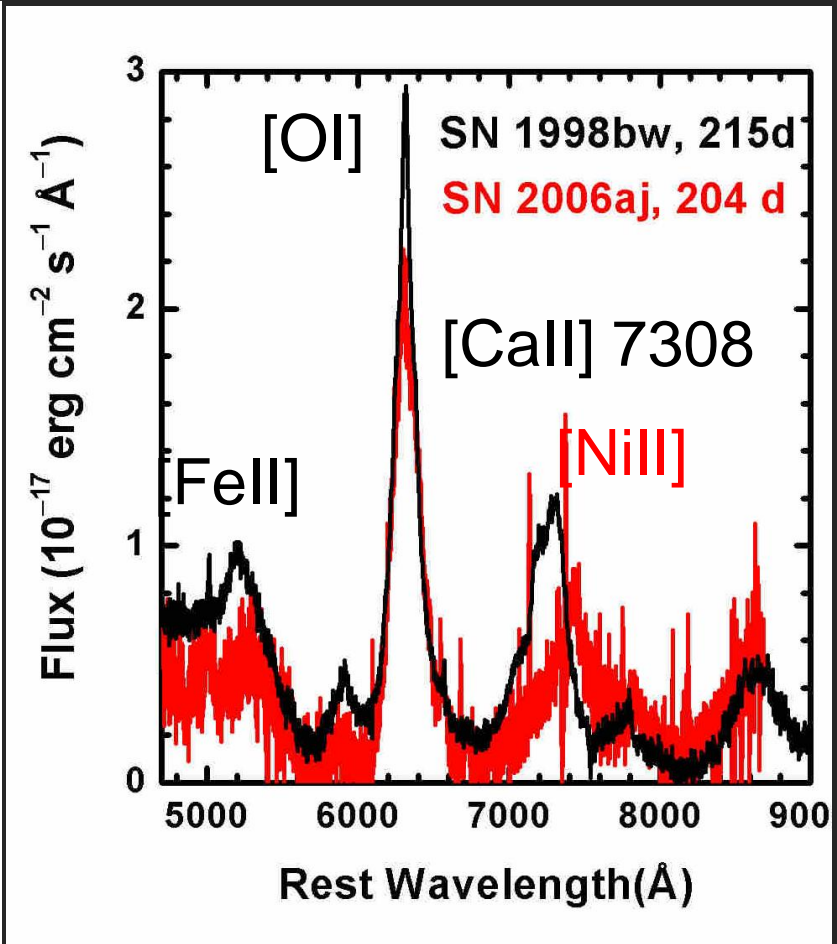
Time (day)

Metal Absorption/Emission Lines

爆発直後(高密): 表面組成 ⇒ 膨張 ⇒ 1年後(低密): 内側 (explosive)



Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.



Global properties

Light curve + spectral modeling

⇒ Progenitor mass
Explosion energy

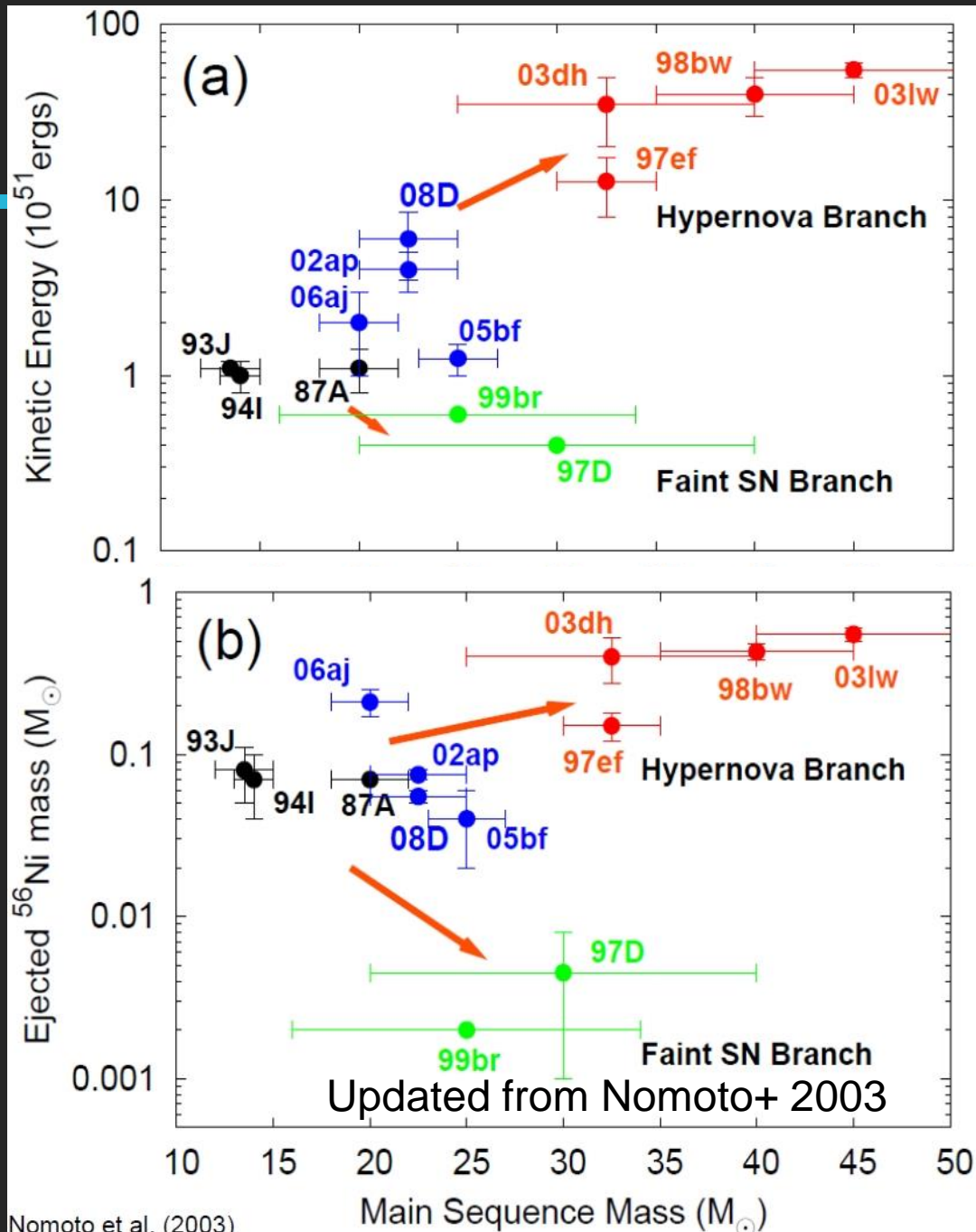
Luminosity

⇒ $M(^{56}\text{Ni})$

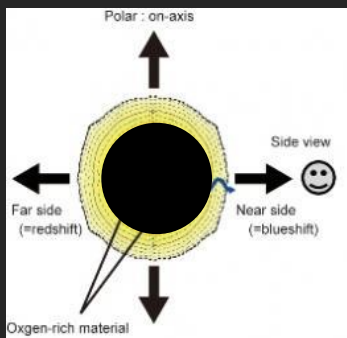
Environment, host galaxy

⇒ Age

Metallicity

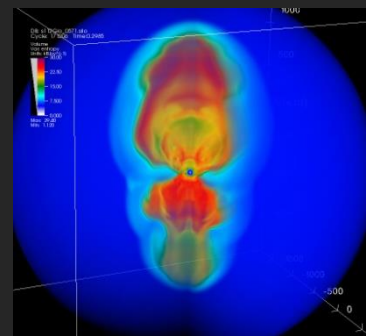
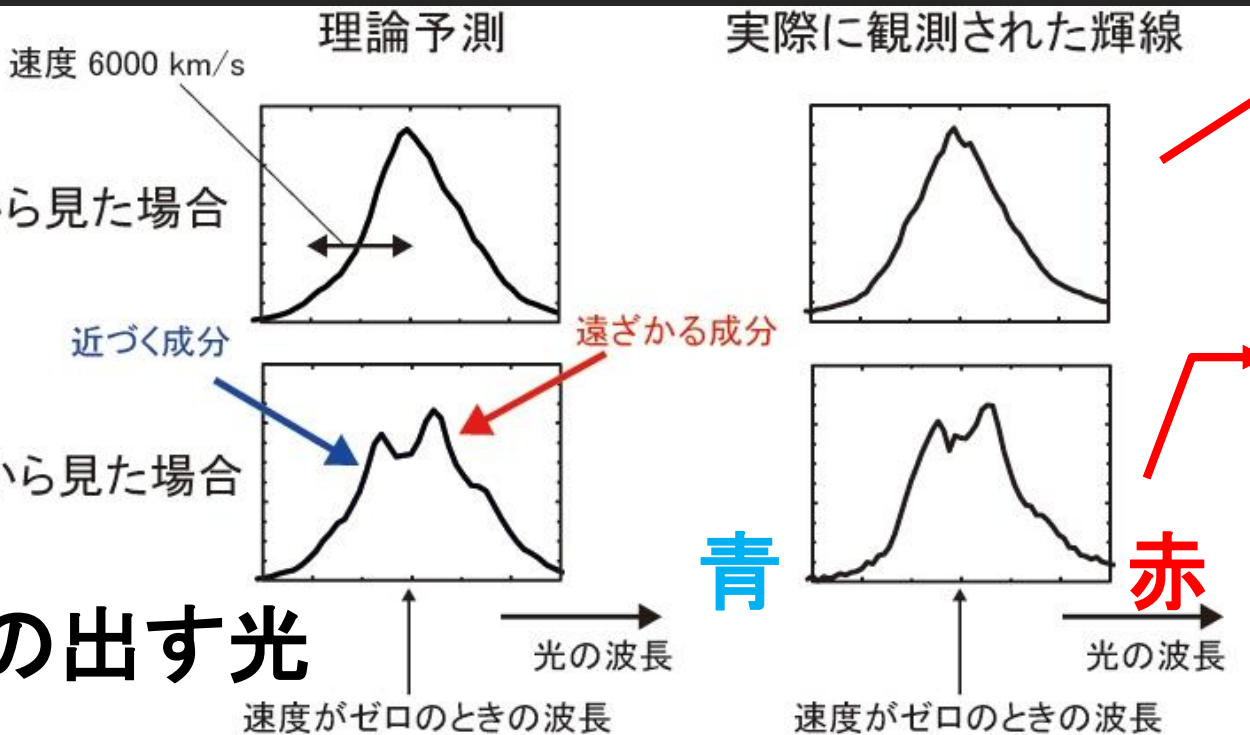
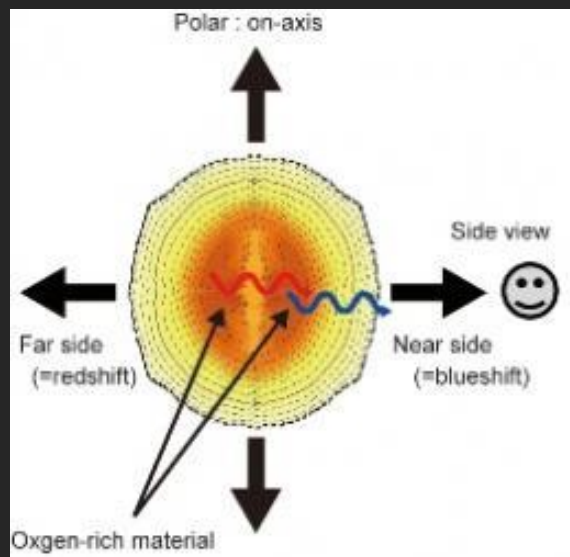


Kinematics



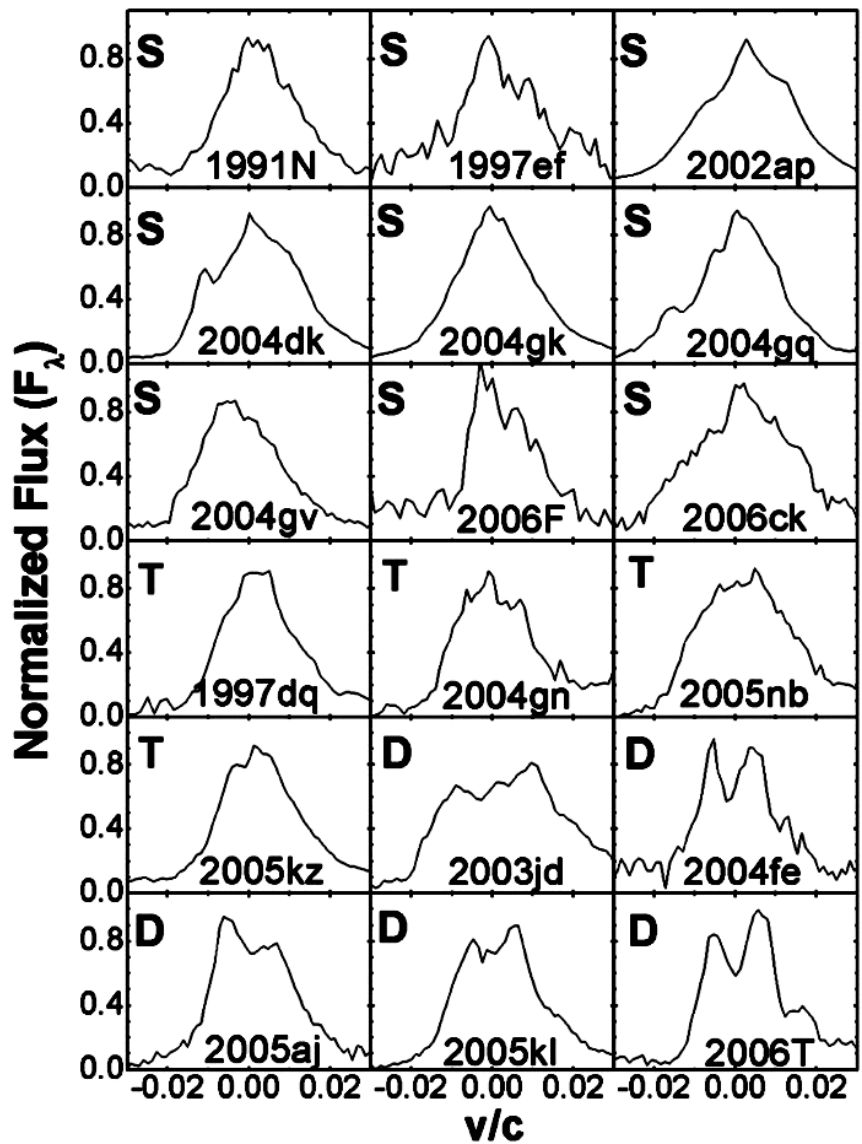
~1年

すかすかになって、
内側まで見通せる



重力崩壊
型超新星
の理論

前田、川端他、2008, Science



酸素の出す光

速度がゼロのときの波長

光の波長

青

赤

速度がゼロのときの波長

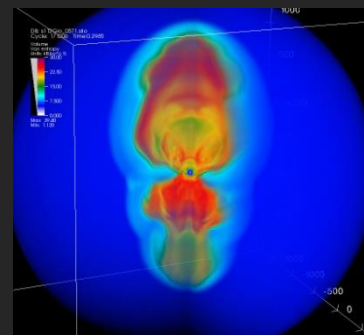
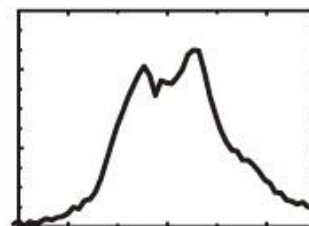
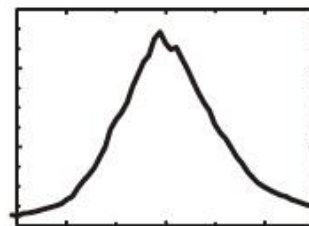
光の波長

成分



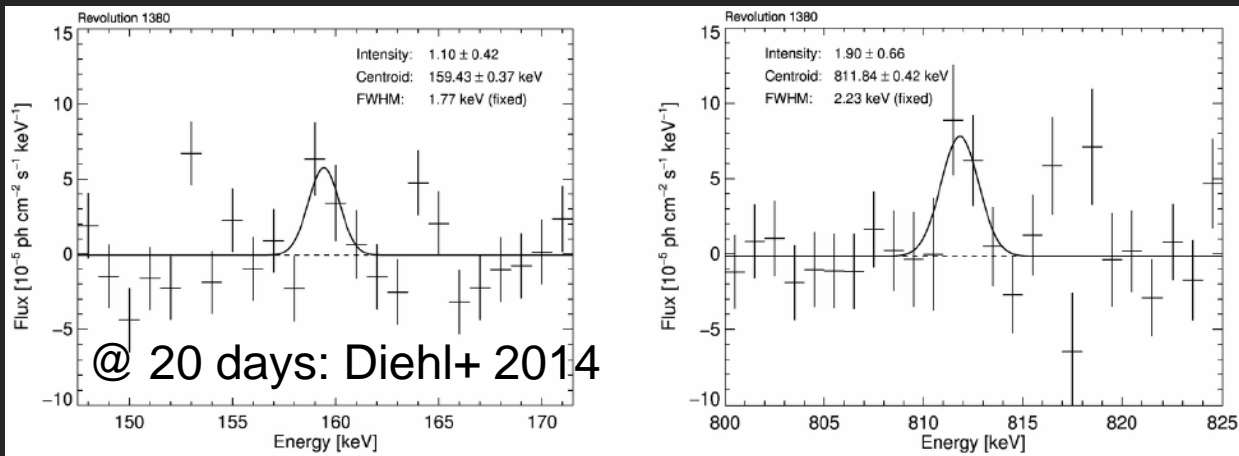
すばる望遠鏡

実際に観測された輝線



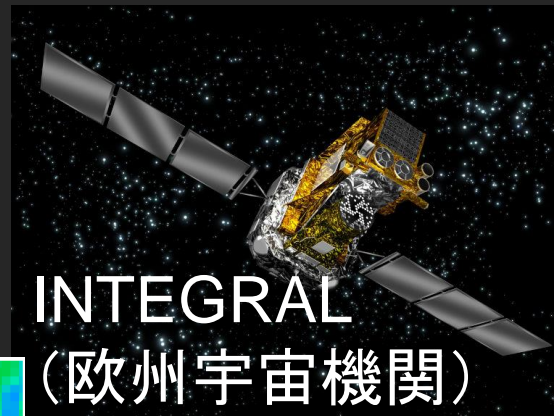
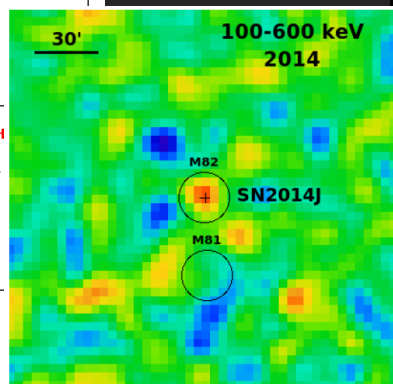
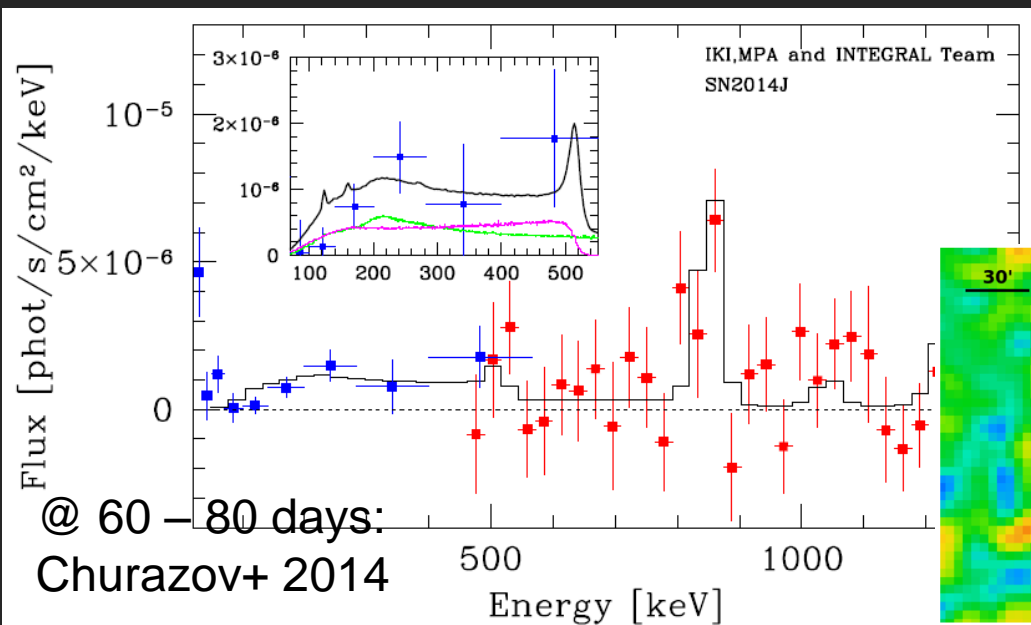
重力崩壊型超新星の理論

Radioactivity: Direct detection



@ 20 days: Diehl+ 2014

SN Ia 2014J @M82
1986年以來もっとも近くで
発生したIa型超新星



Ia型超新星からの
核ガンマ線検出。
これまでは1987A(
重い星)のみ。

Summary: List of contents

- Introduction:
 - Stellar evolution and Supernovae.
 - Explosion Mechanism.
- Explosive Nucleosynthesis:
 - Thermonuclear reaction basics.
 - Shock propagation and explosive nucleosynthesis.
- Examples of Observations:
 - Supernova Remnants.
 - SN 1987A.
 - Extragalactic Supernovae.