

核燃焼型超新星にまつわる 最近の話題

Ia型超新星親星問題



Single Degenerate (SD)



Double Degenerate (DD)

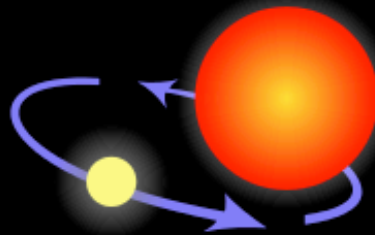
山口 弘悦 (NASA/GSFC, Univ of MD)

第30回 理論懇シンポジウム 「**星の物理**の新地平」

The progenitor of a Type Ia supernova



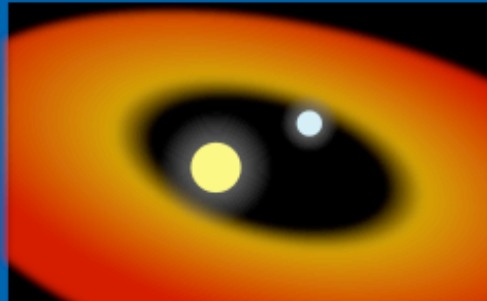
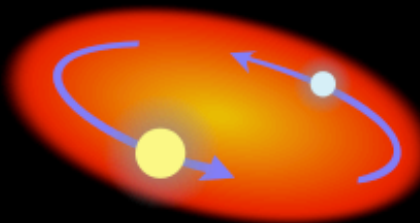
Two normal stars are in a binary pair.



The more massive star becomes a giant...



...which spills gas onto the secondary star, causing it to expand and become engulfed.



The remaining core of the giant collapses and becomes a white dwarf.

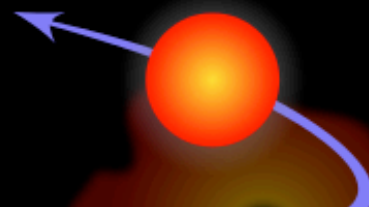
このへんのお話をします
(今日の後半)



The aging companion star starts swelling, spilling gas onto the white dwarf.



The white dwarf's mass increases until it reaches a critical mass and explodes...



...causing the companion star to be ejected away.

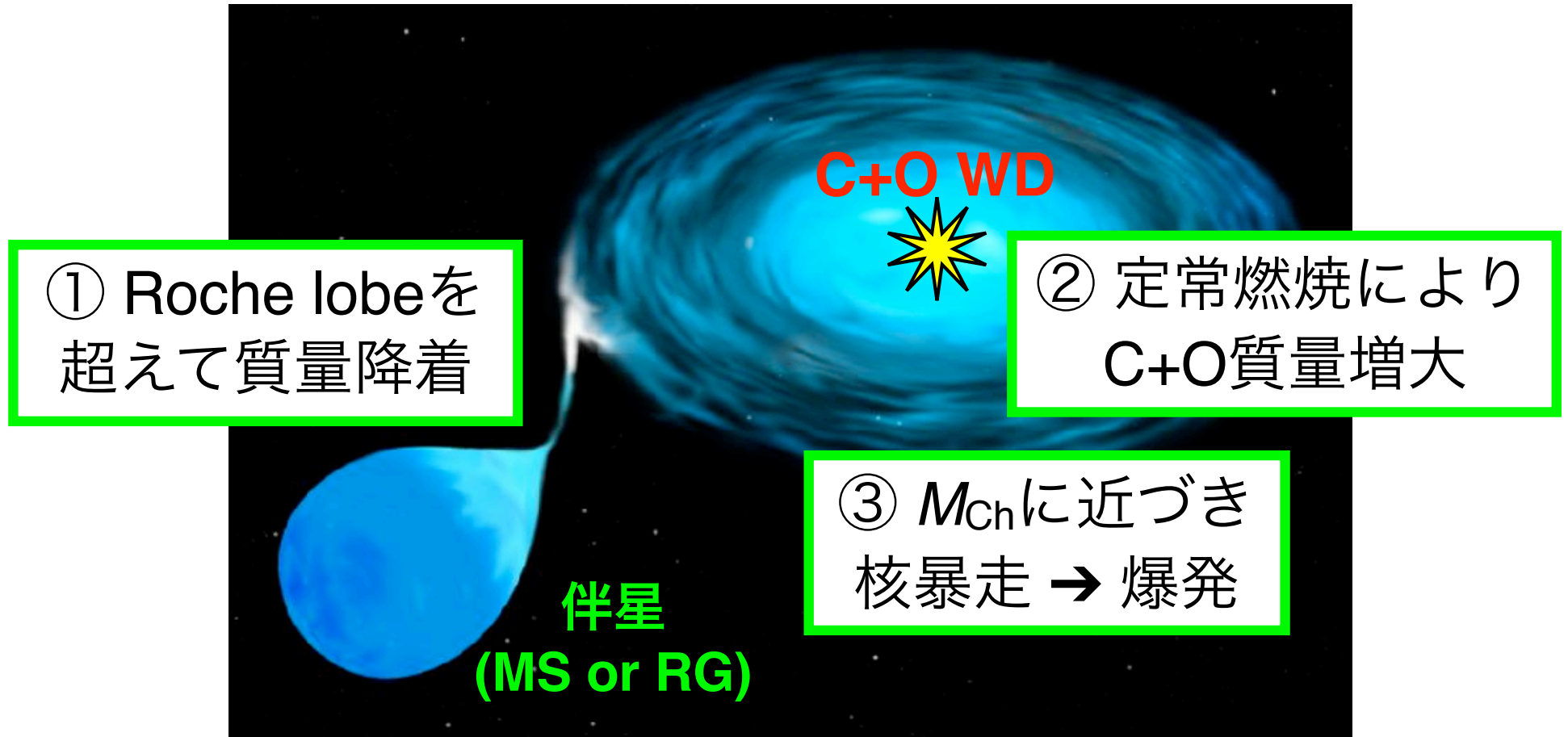
Outline

Ia型超新星 ここ10年の進展と混迷

SD vs DD 仁義なき戦い

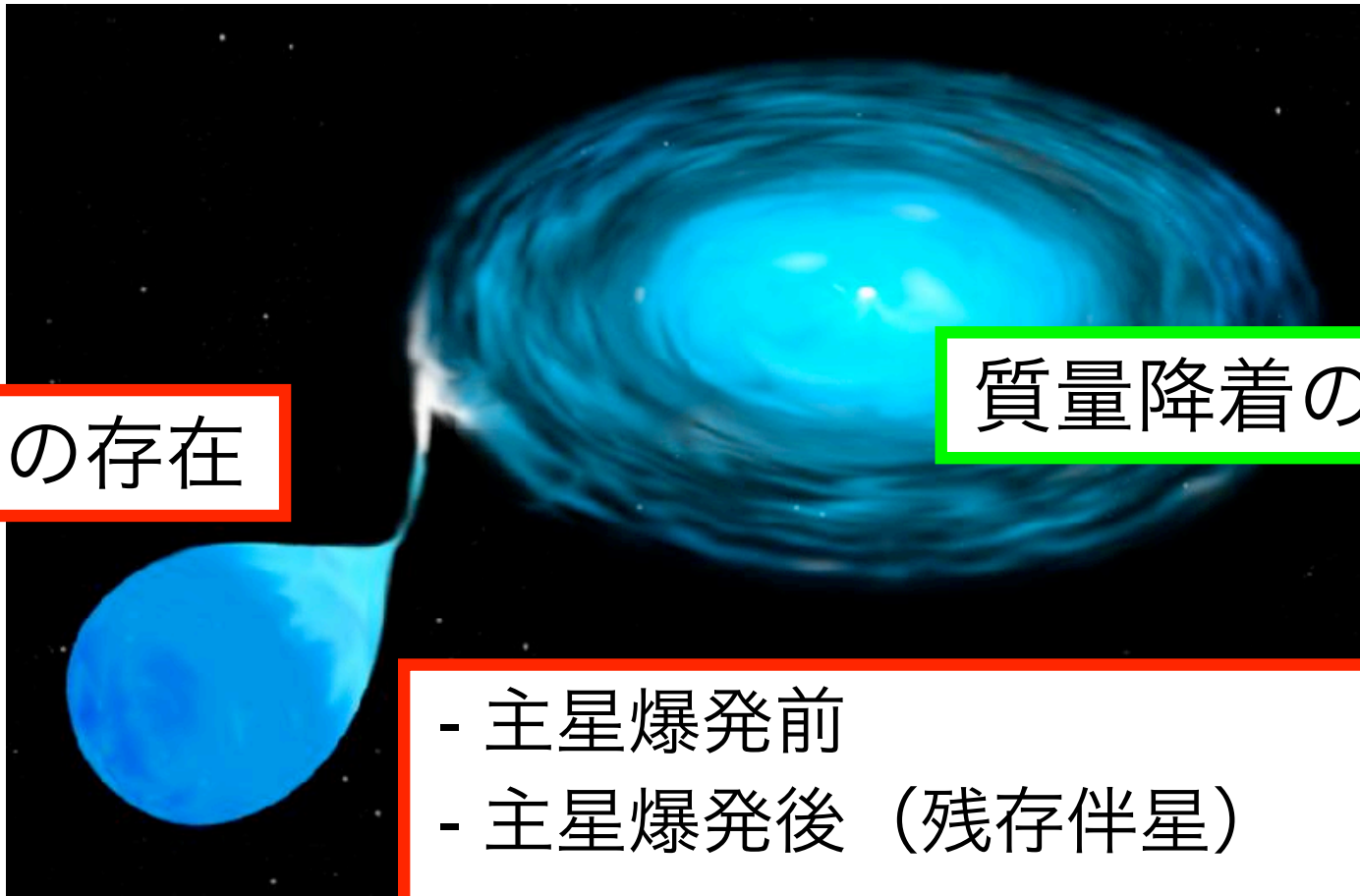
- **DD派の攻勢：強気の原因**
- **SD派の逆襲？：発展の予感**
「星の物理」の観点から、研究紹介を兼ねて
- **平和的解決案と将来への展望**
- Type Iax, He-shell detonation, etc...
(次の機会に)

Single degenerate (SD) モデル



四面楚歌

SDの痕跡が見つからない



伴星の存在

質量降着の名残り

- 主星爆発前
- 主星爆発後（残存伴星）
- 衝突に伴う熱放射
- 衝突に伴う外層の“剥ぎ取り”

主星爆発前の伴星探査

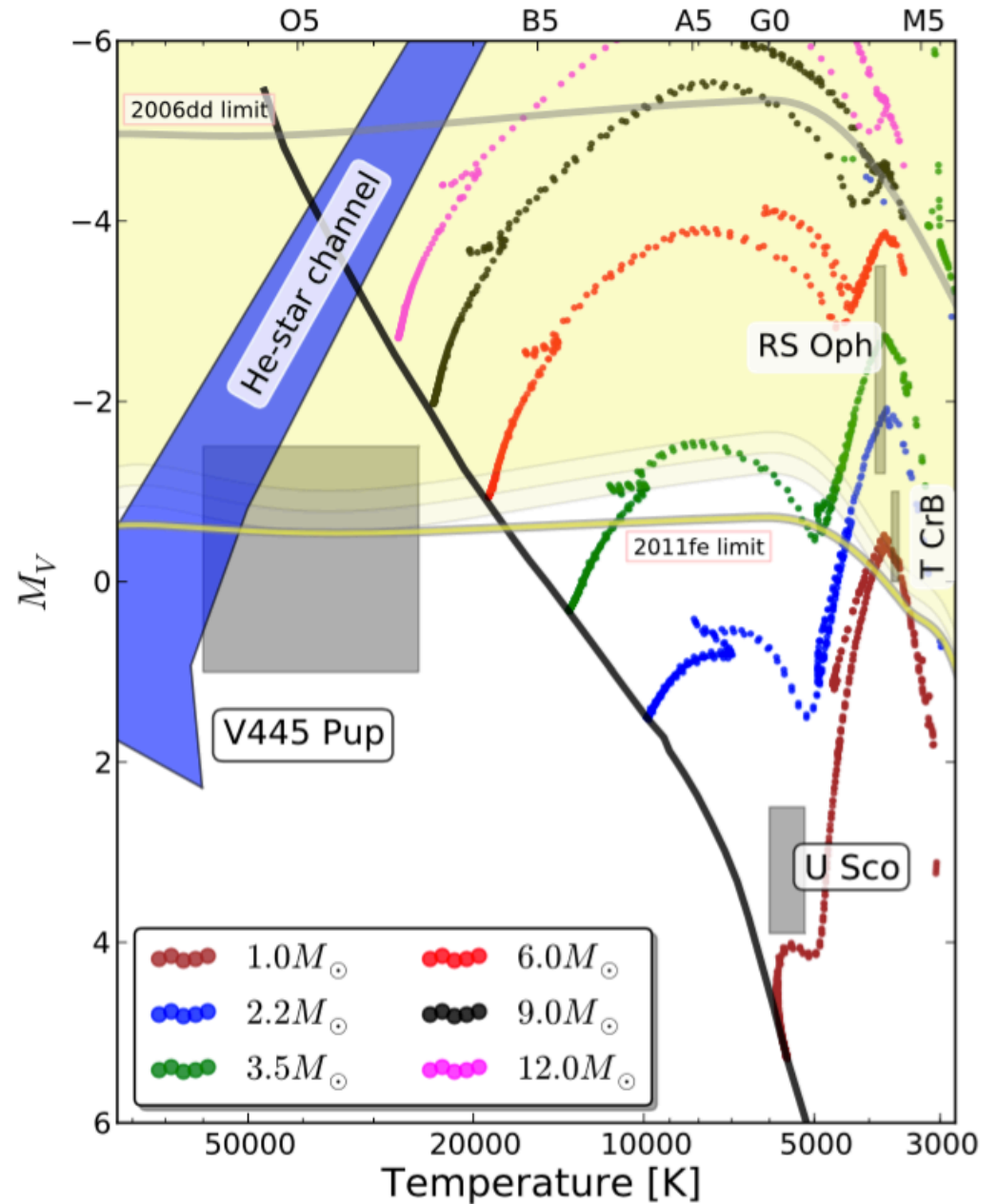
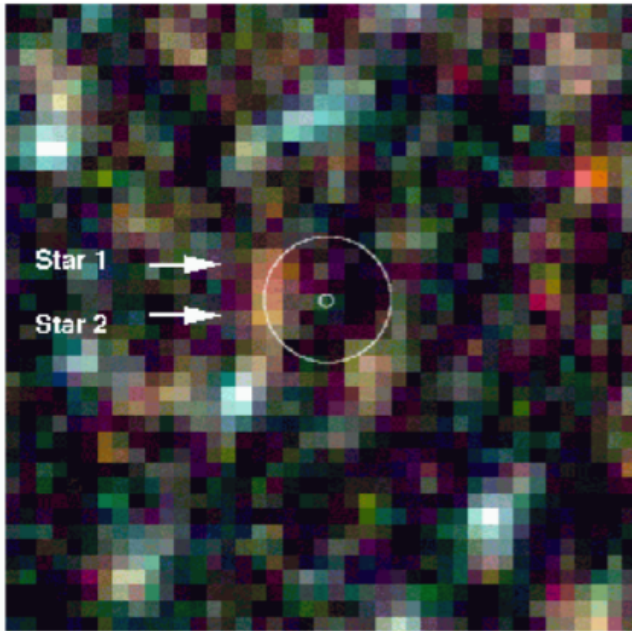
SN 2011fe (M101: 6.4 Mpc)



主星爆発前の伴星探査

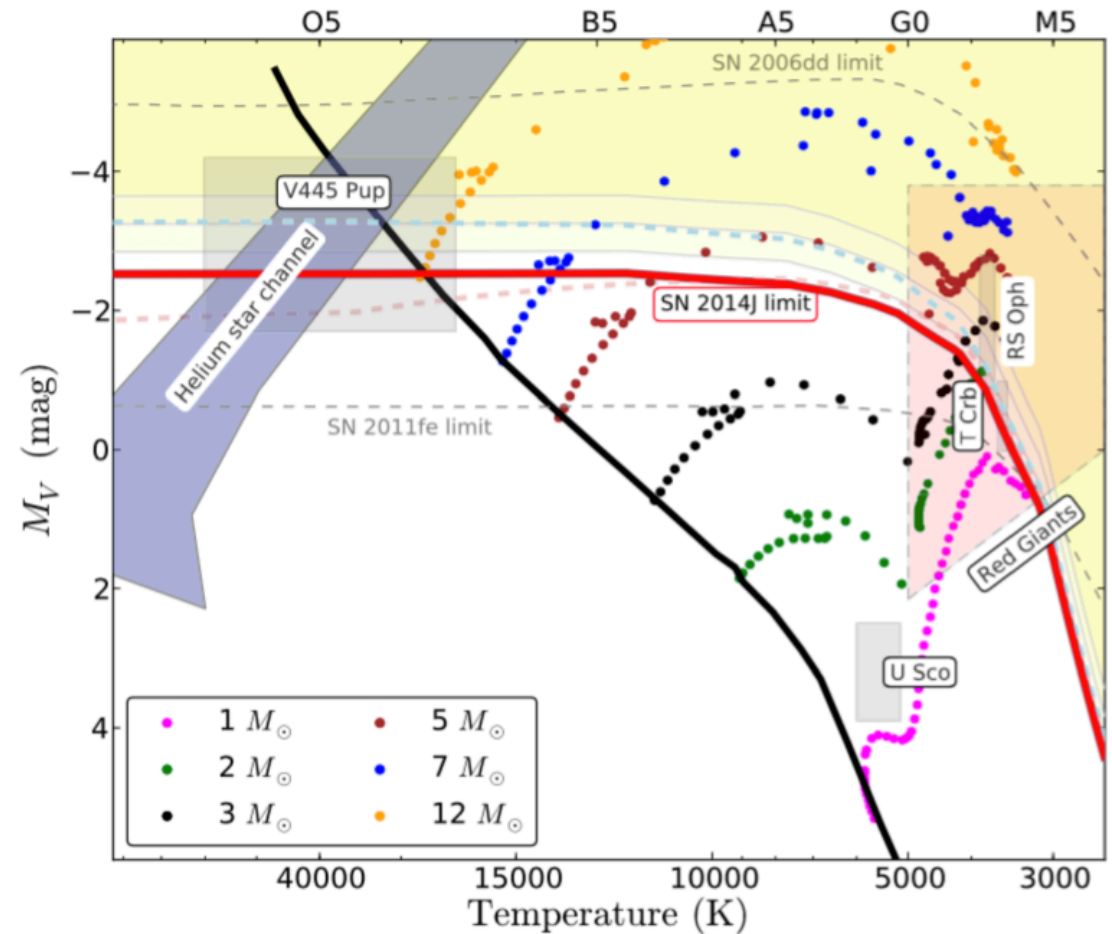
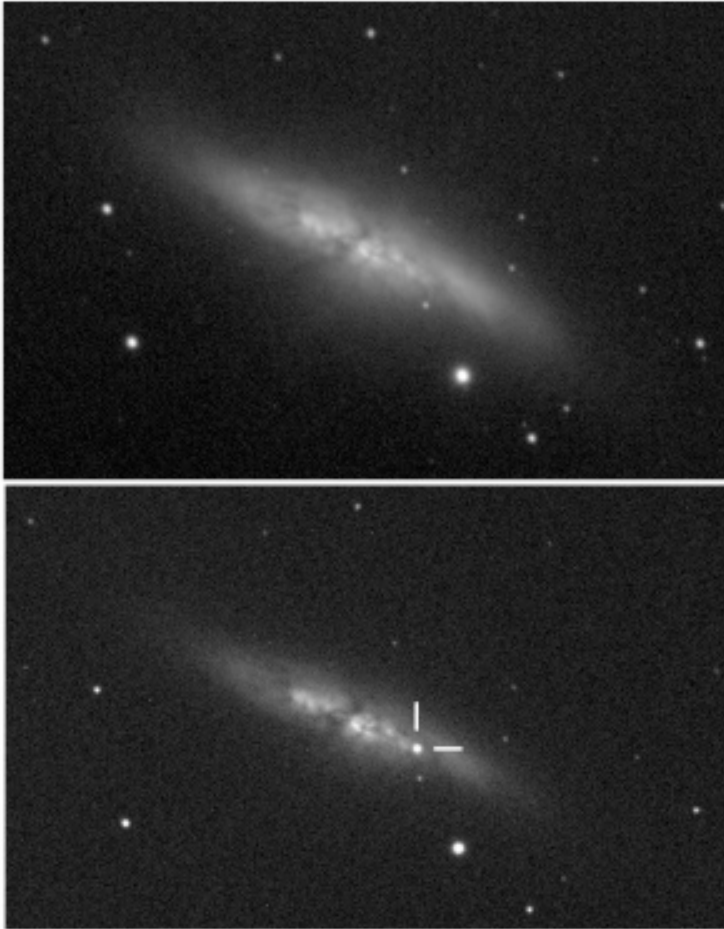
SN 2011fe:

赤色巨星および
> $3.5M_{\odot}$ の主系列星を
棄却 (Li+2011)



主星爆発前の伴星探査

SN 2014J (M82: 3.5 Mpc)

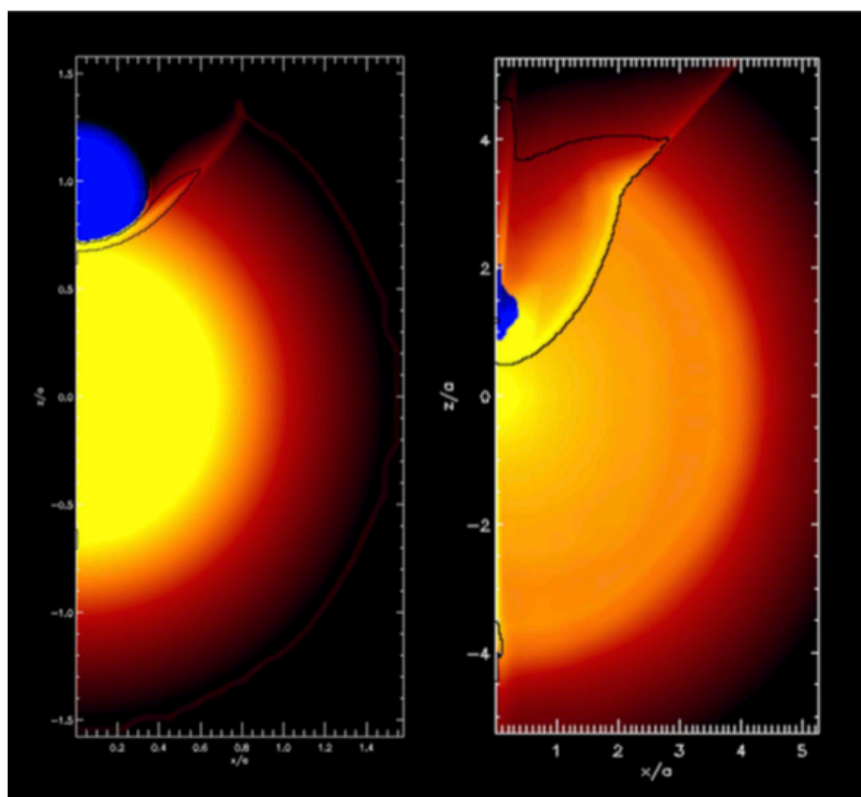


赤色巨星の大半を棄却 (Kelly+2014)

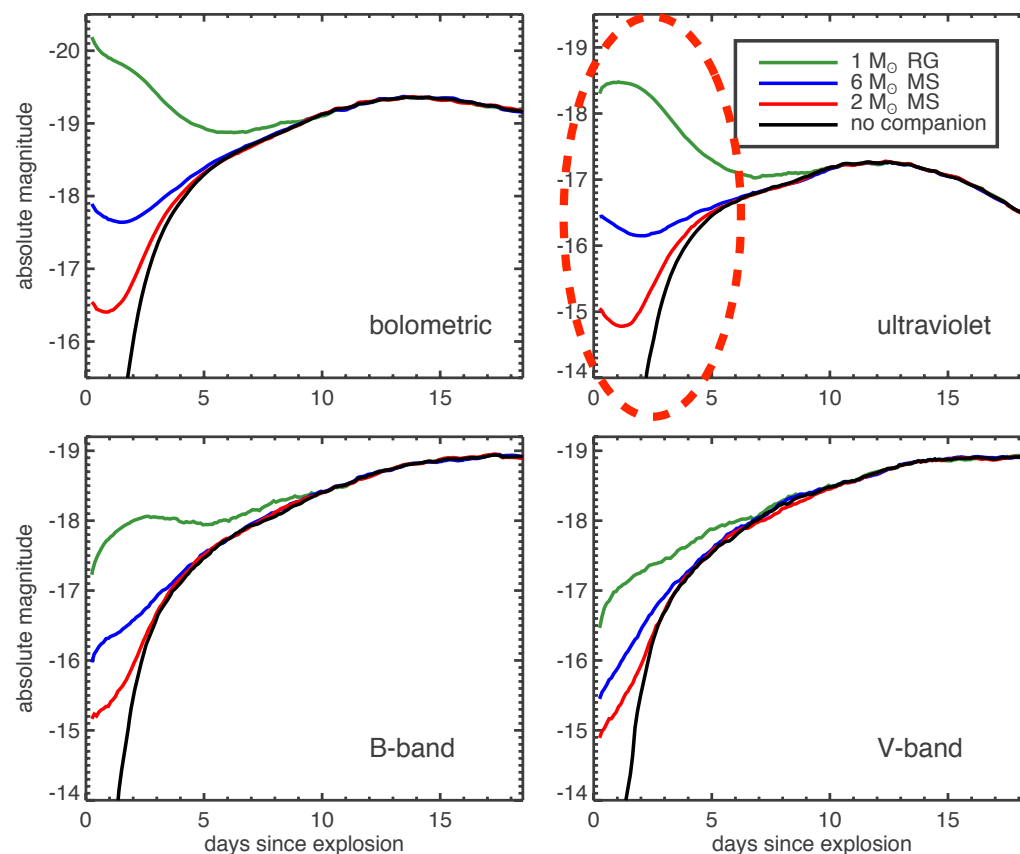
伴星との衝突に伴う熱放射

X-ray ~ UV/optical: 爆発数日後に超過が予想 (Kasen 2010)

See also Kutsuna & Shigeyama 2015



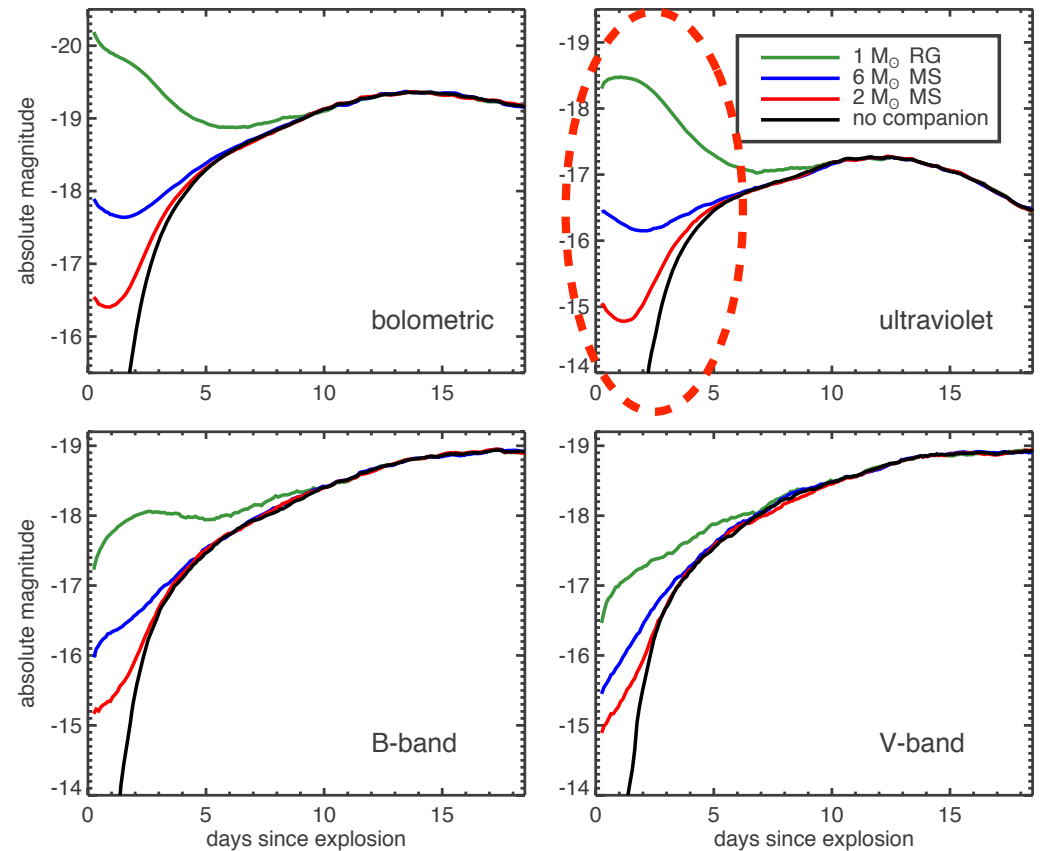
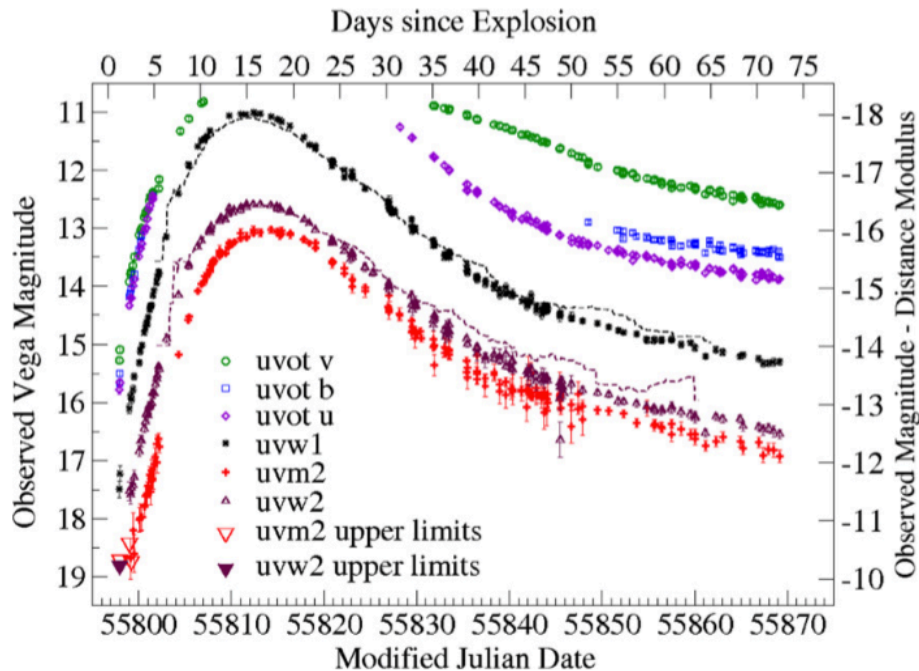
Kasen 2010



伴星との衝突に伴う熱放射

X-ray ~ UV/optical: 爆発数日後に超過が予想 (Kasen 2010)

See also Kutsuna & Shigeyama 2015



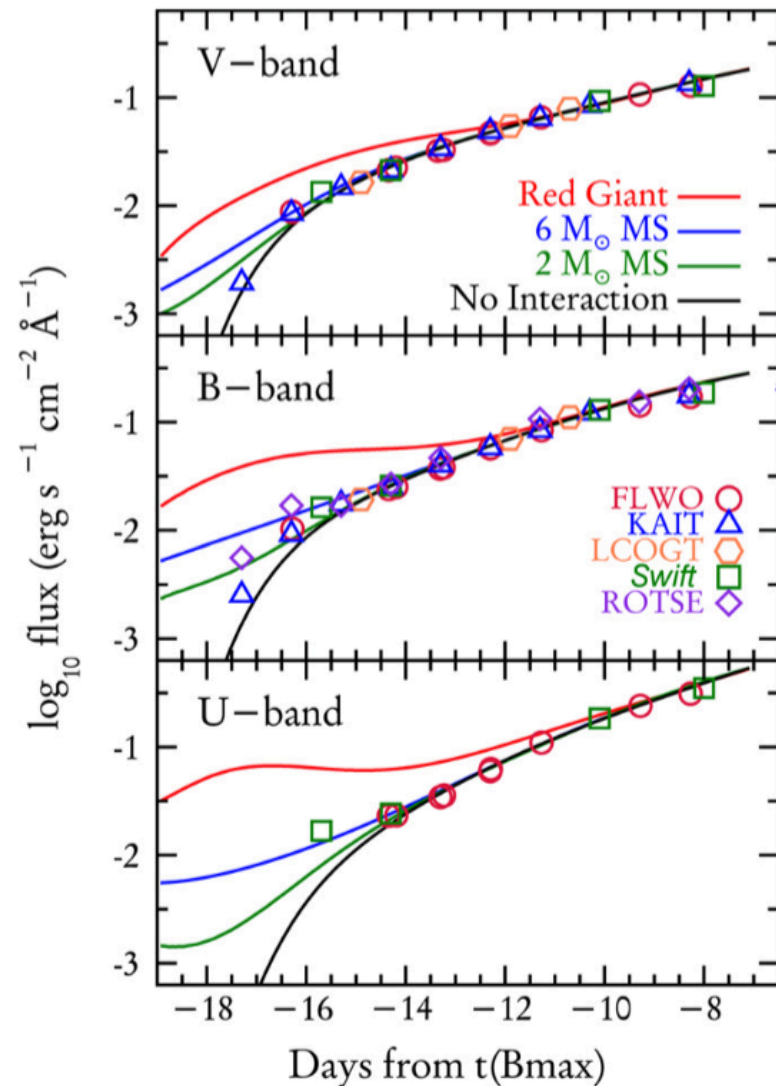
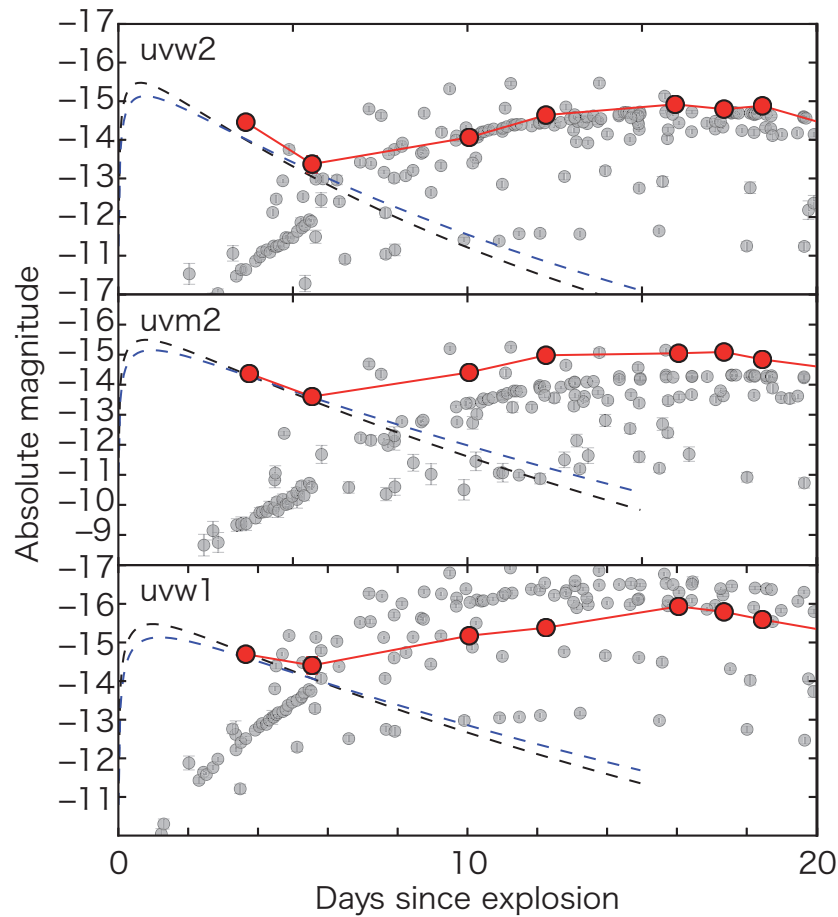
**SN 2011fe: >1M_⊙の MSを
> 95%棄却 (Swift衛星)**

Blown 2012

伴星との衝突に伴う熱放射

iiPTF14atg
(Cao+2015)

SN 2012cg
(Marion+2016)



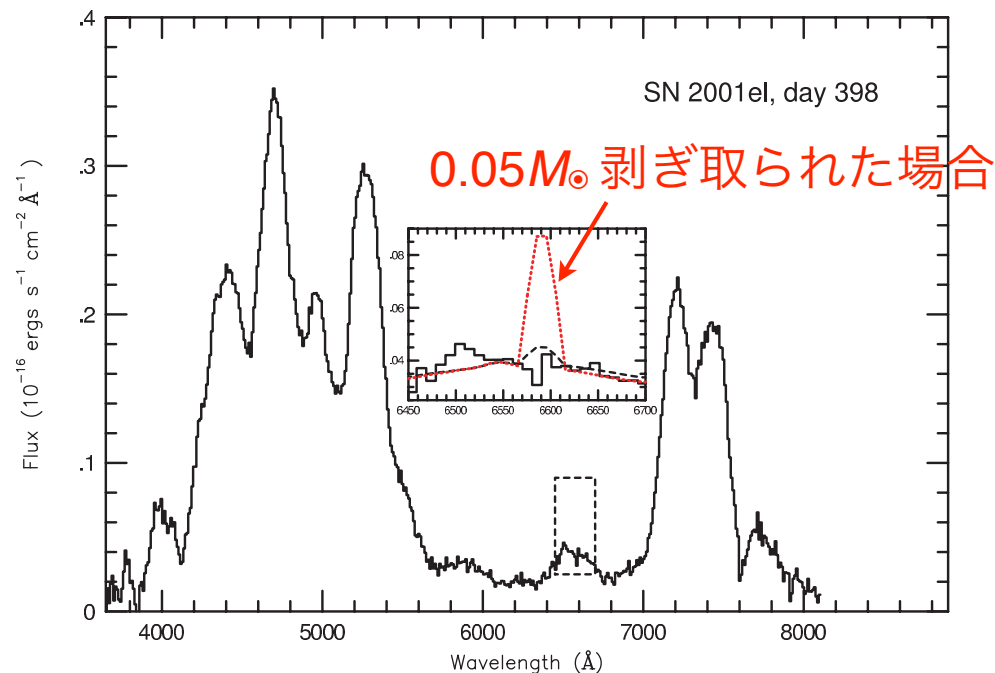
UV超過の発見!

衝突時に剥ぎ取られる伴星外層

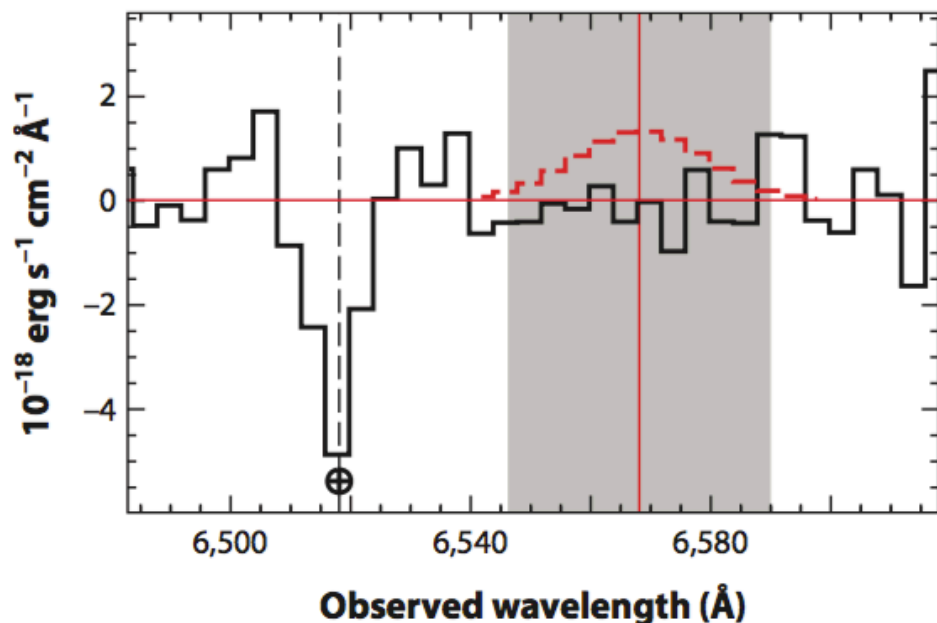
水素 $\sim 0.1 M_{\odot}$ 程度を剥ぎ取り

→ ^{56}Co 崩壊 γ 線により励起

→ nebular phaseに H α 線
(e.g, Mattila+2005)



SN 2011fe (Shappee+13)



SN 2011fe:

$< 0.001 M_{\odot}$ (Shappee+2013)

$< 10^{-4} M_{\odot}$ (Botyanszki+2017)

SN 2014J:

$< 0.005 M_{\odot}$ (Lundqvist+2015)

主星爆発後の伴星探査

LMC SNR 0509-67.5

HSTにより残存伴星に上限

$$M_V < +8.4, L_V < 0.04L_{\odot V}$$

→ 全SDシナリオを棄却

(Schaefer+2012, Litke+2017)

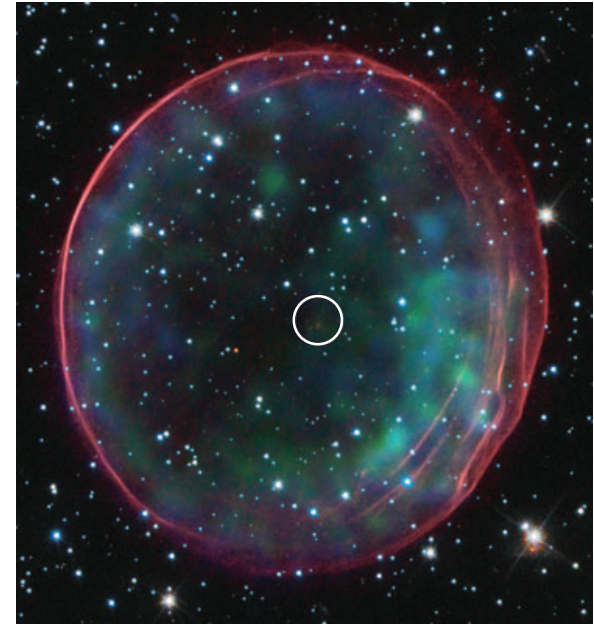


Table 1 | Candidate progenitor classes

Candidate class	P_{orb} (d)	$v_{\text{ex-comp}}$ (km s^{-1})	Surviving companion	M_V (mag)	V range in LMC (mag)
Double-degenerate	NA	NA	None	NA	NA
Recurrent nova	0.6–520	50–350	Red giant or subgiant	–2.5 to +3.5	16–22
Symbiotic star	245–5,700	50–250	Red giant	–2.5 to +0.5	16–19
Supersoft source	0.14–4.0	170–390	Subgiant or $>1.16 M_{\odot}$ MS	+0.5 to +4.2	19–22.7
Helium star donor	0.04–160	50–350	Red giant or subgiant core	–0.5 to +2.0	18–20.5
Spin-up/spin-down	245–5,700	50–250	Red giant or subgiant core	–0.5 to +2.0	18–20.5

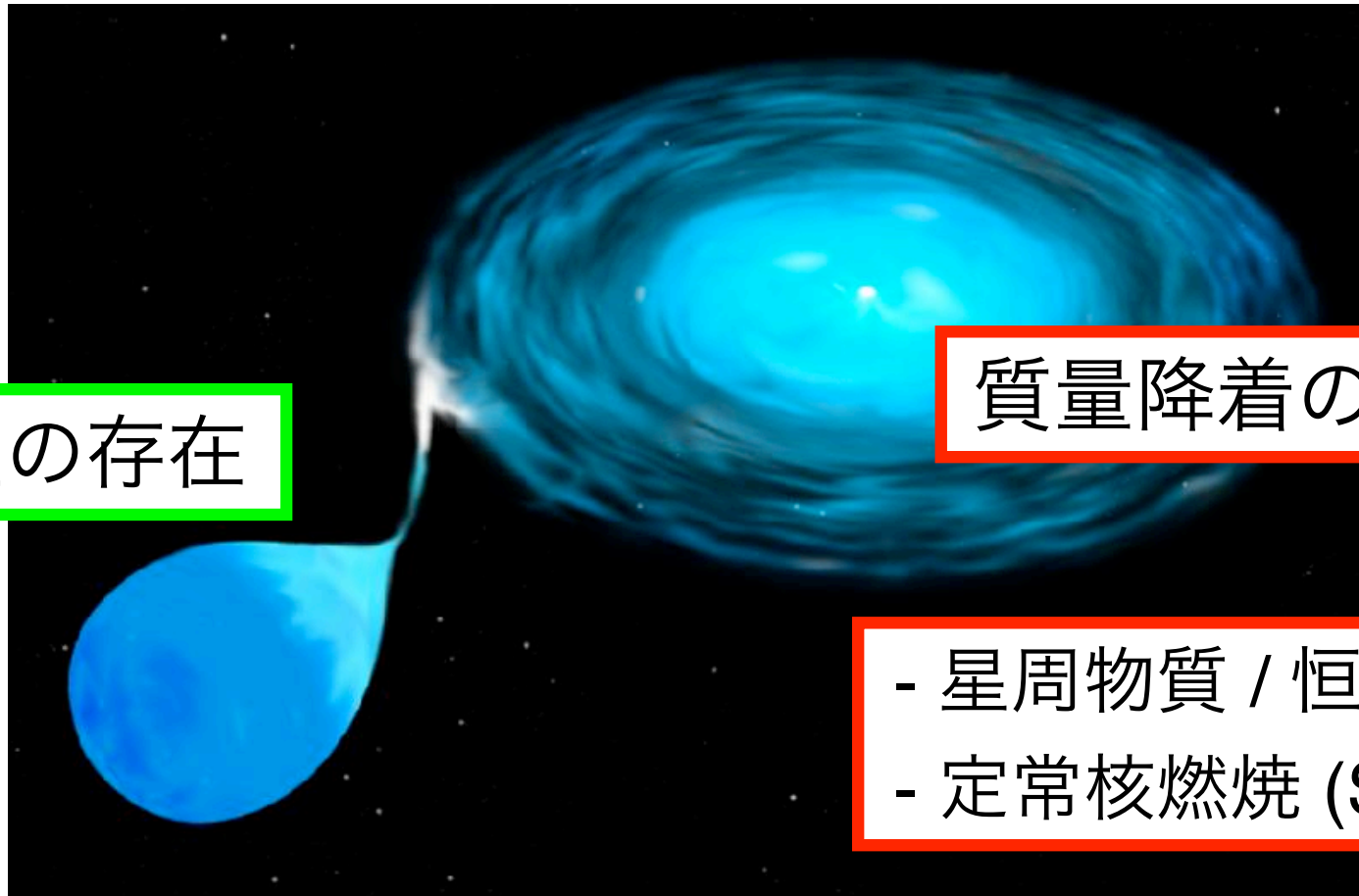
同様の観測 → 赤色巨星ドナーのみ棄却

SN1006 (Gonzalez Hernandez+2012)

SNR 0519-67.5 (Edwards+2012)

ああ四面楚歌

SDの痕跡が見つからない



伴星の存在

質量降着の名残り

- 星周物質 / 恒星風
- 定常核燃焼 (SSS)

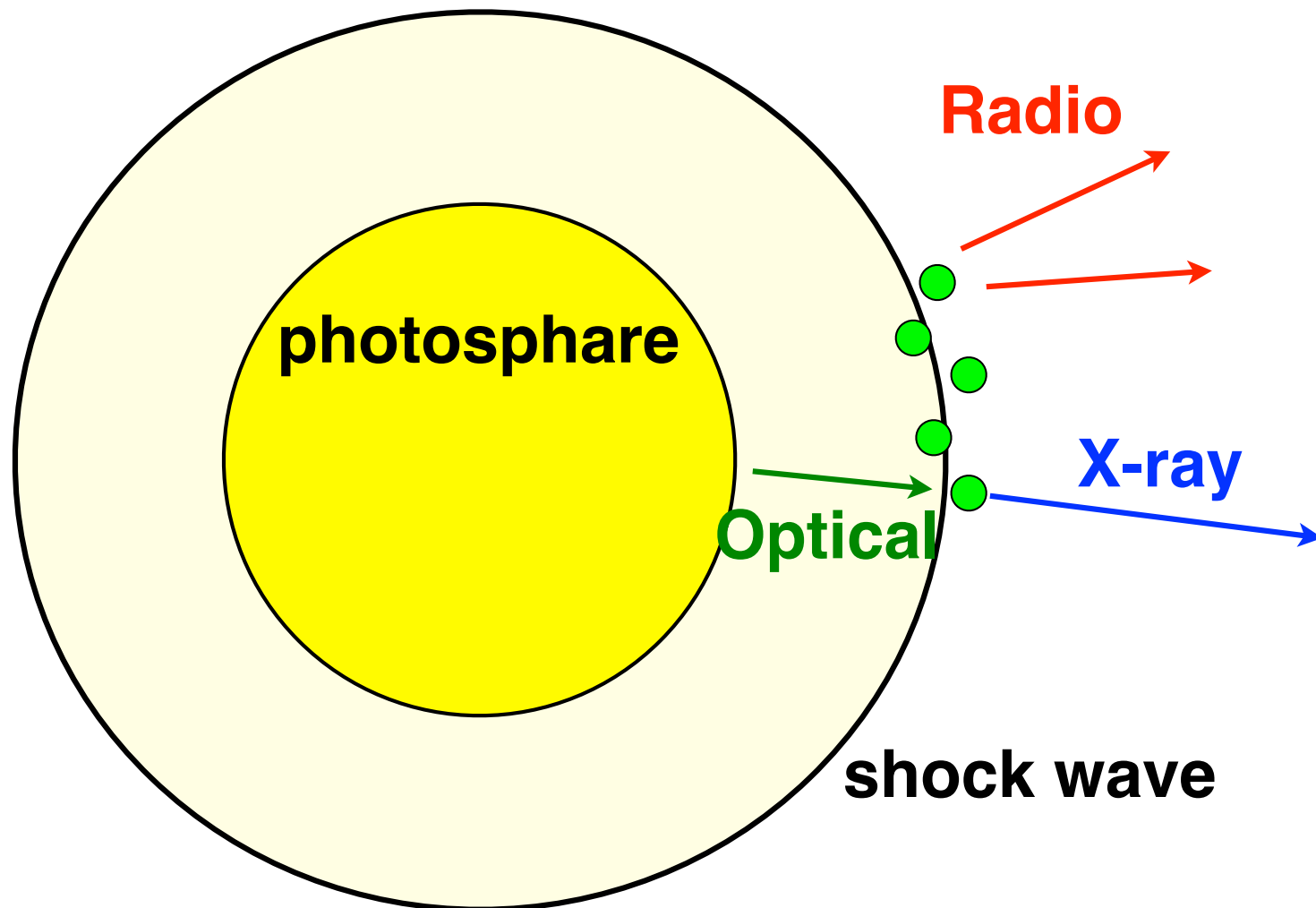
安定燃焼: $\sim 10^{-7} M_{\odot} \text{ yr}^{-1}$ (e.g., Nomoto+2007)

超過した降着物質は星風で放出 (Hachisu+1996)

星周物質

イジェクタとCSMの衝突 → 衝撃波

→ 電波（非熱的電子） + X線（可視光光子とのIC）



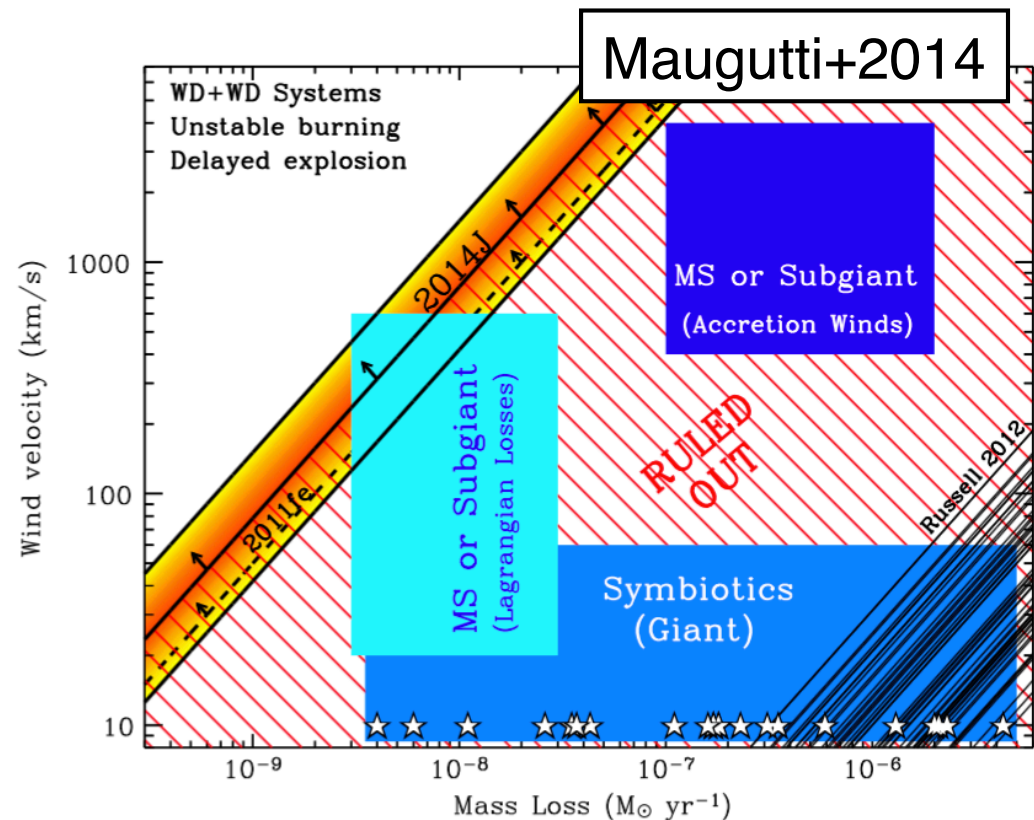
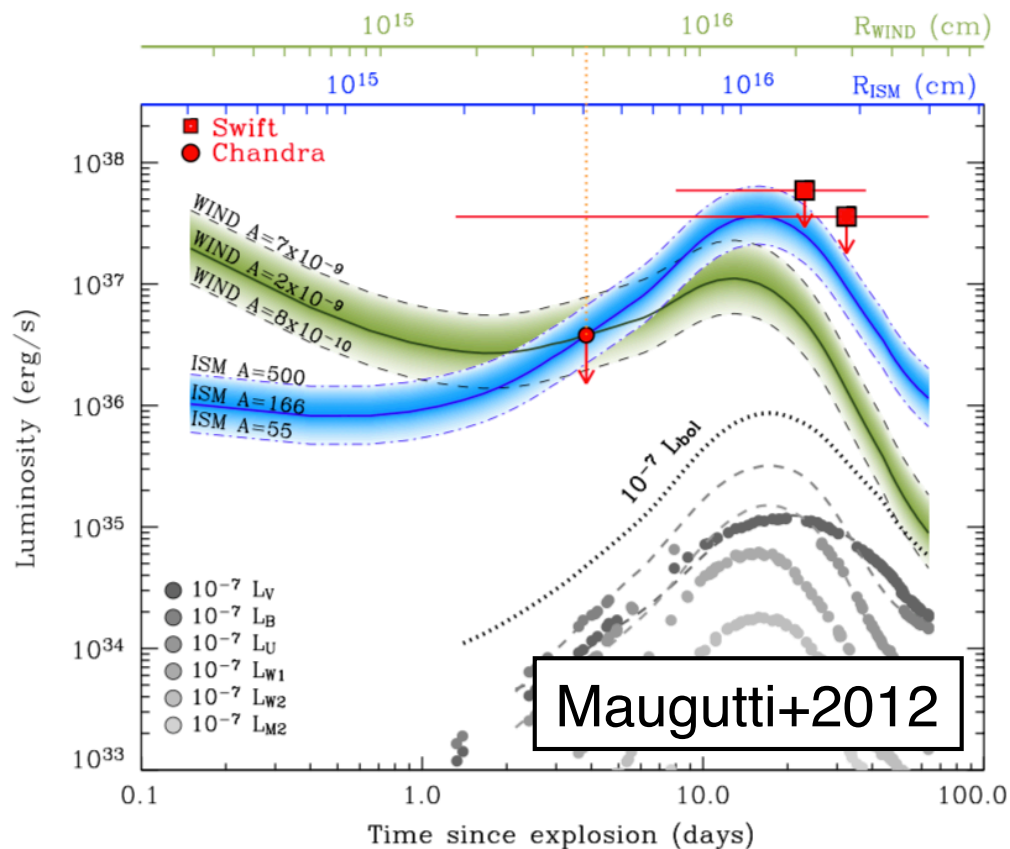
星周物質

イジェクタとCSMの衝突 → 衝撃波

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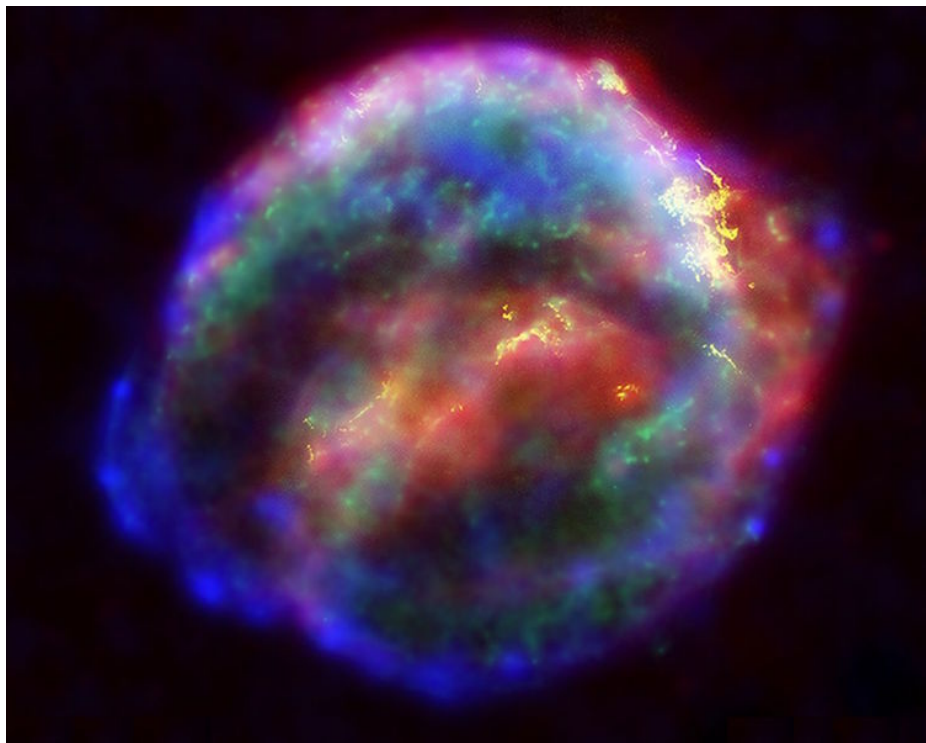
SN 2011fe, SN 2014J: 検出なし; $dM/dt \lesssim 10^{-9} M_{\odot} \text{ yr}^{-1}$

(Chomiuk+2012, Maugutti+2012,2014, Perez-Torres+2014)



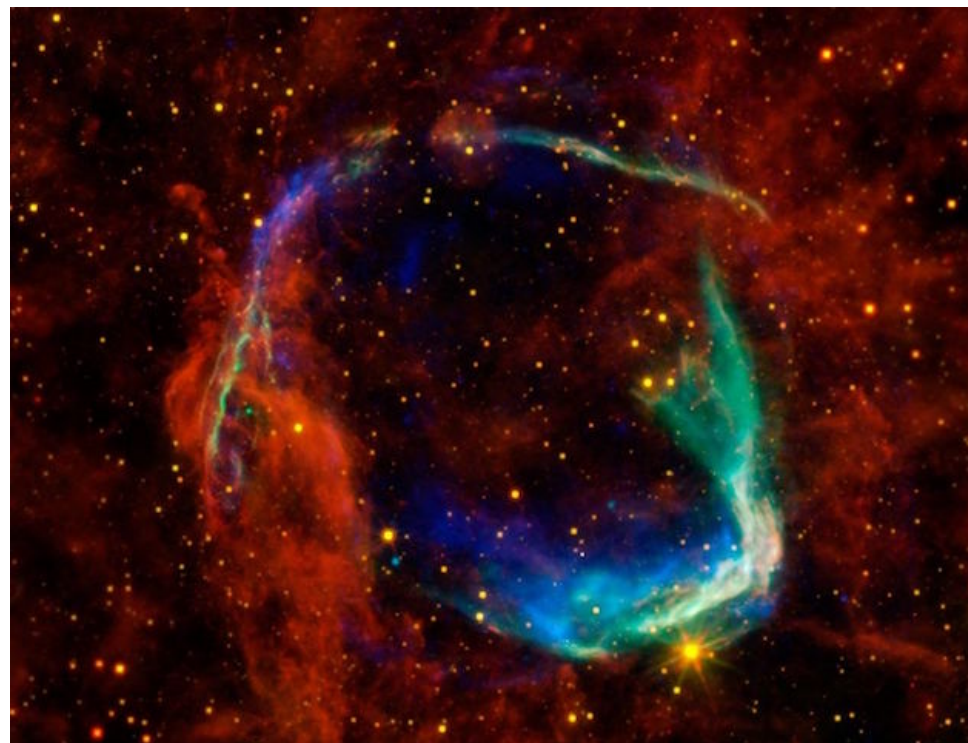
星周物質 (超新星残骸)

Kepler



CSM ~ 2 pc away
衝突は ~ 200 年後ぐらい?
(Katsuda+2015)

RCW86



“Hachisu wind” による
大規模な cavity
(Williams+2011)

Super-soft source (SSS)

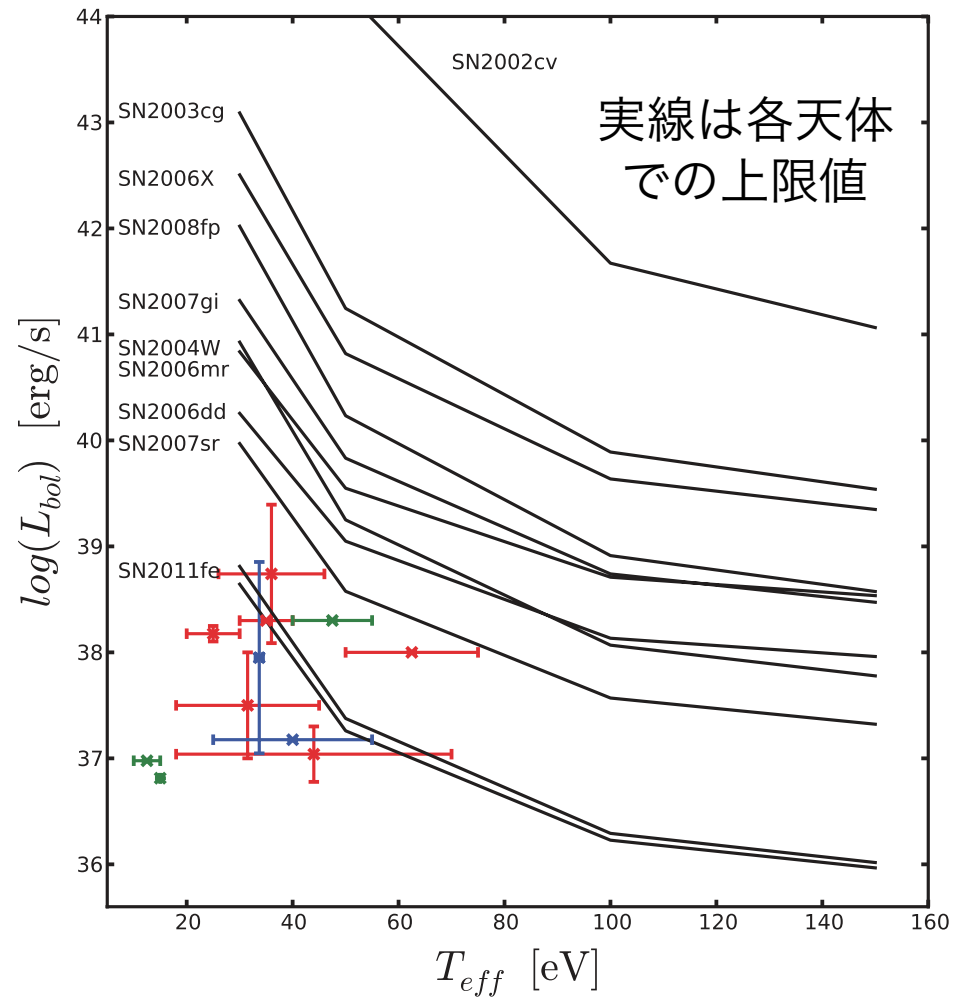
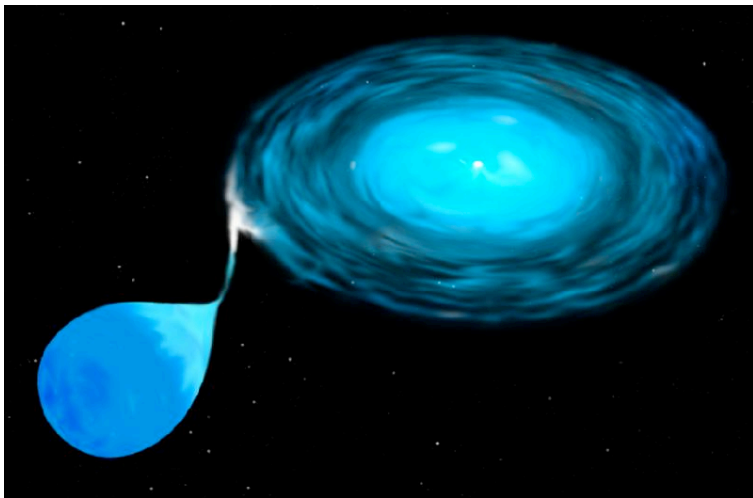
降着物質の定常核燃焼 → 軟X線放射 (e.g., Kato 2010)

$$T_{\text{BB}} \sim 10^{5-6} \text{ K}$$

$$L_{\text{bol}} \sim 10^{37-38} \text{ erg s}^{-1}$$

Chandraによる探査

→ 緩い上限のみ



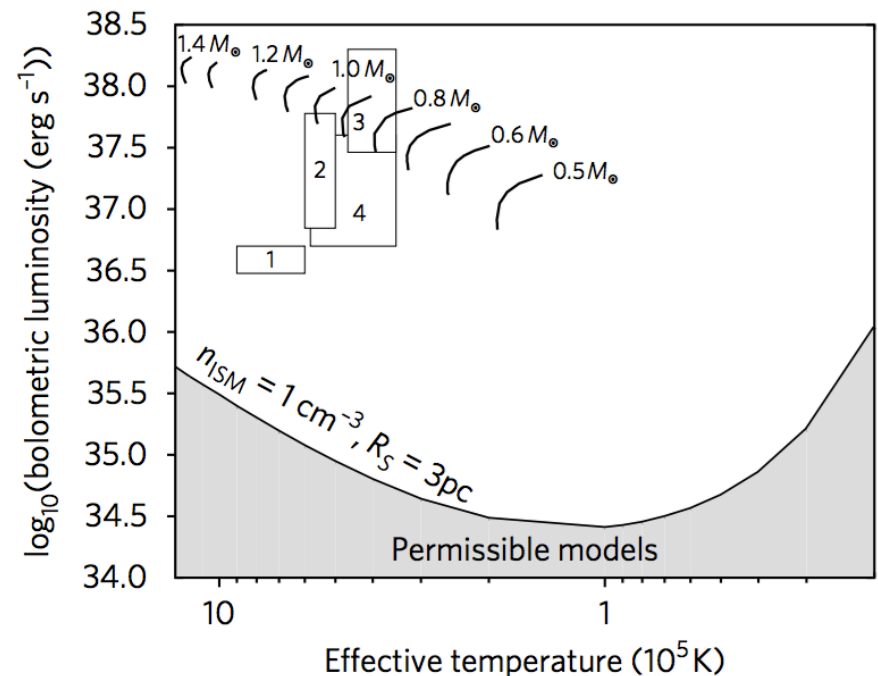
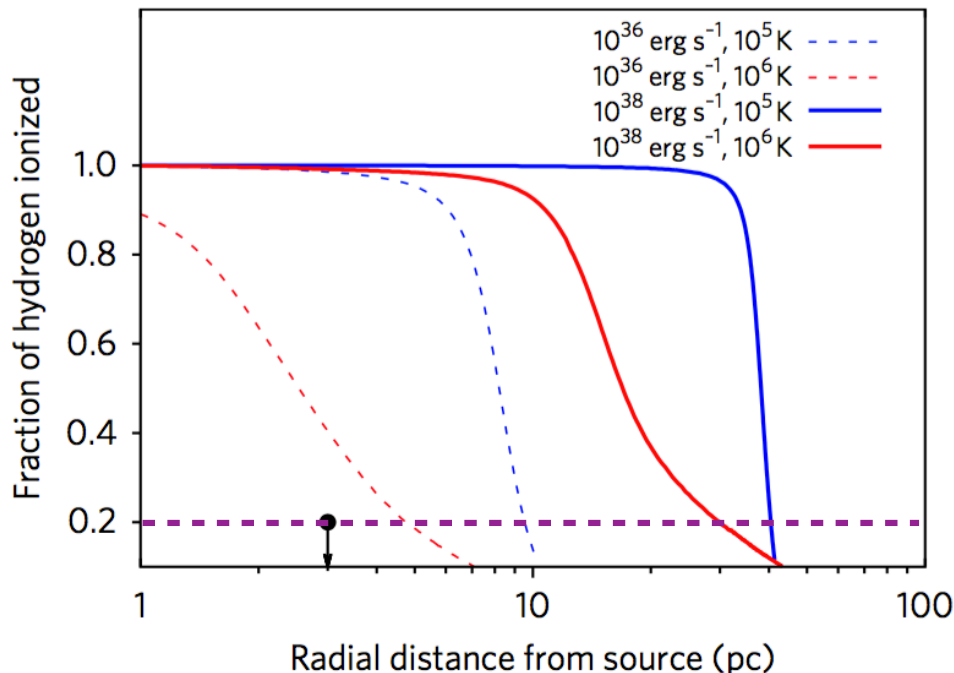
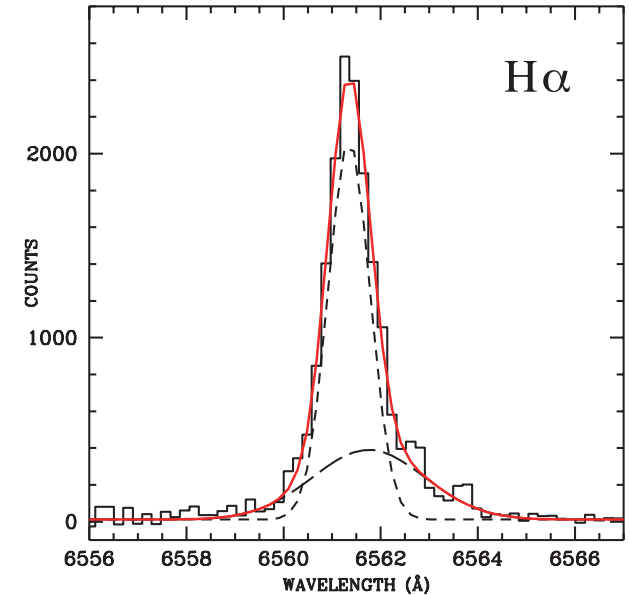
Nielsen+2012, 2013, 2014

SSSによるISMの電離

Ia型超新星残骸の衝撃波: 中性水素が普遍的に存在 (e.g., Ghavamian+2003)

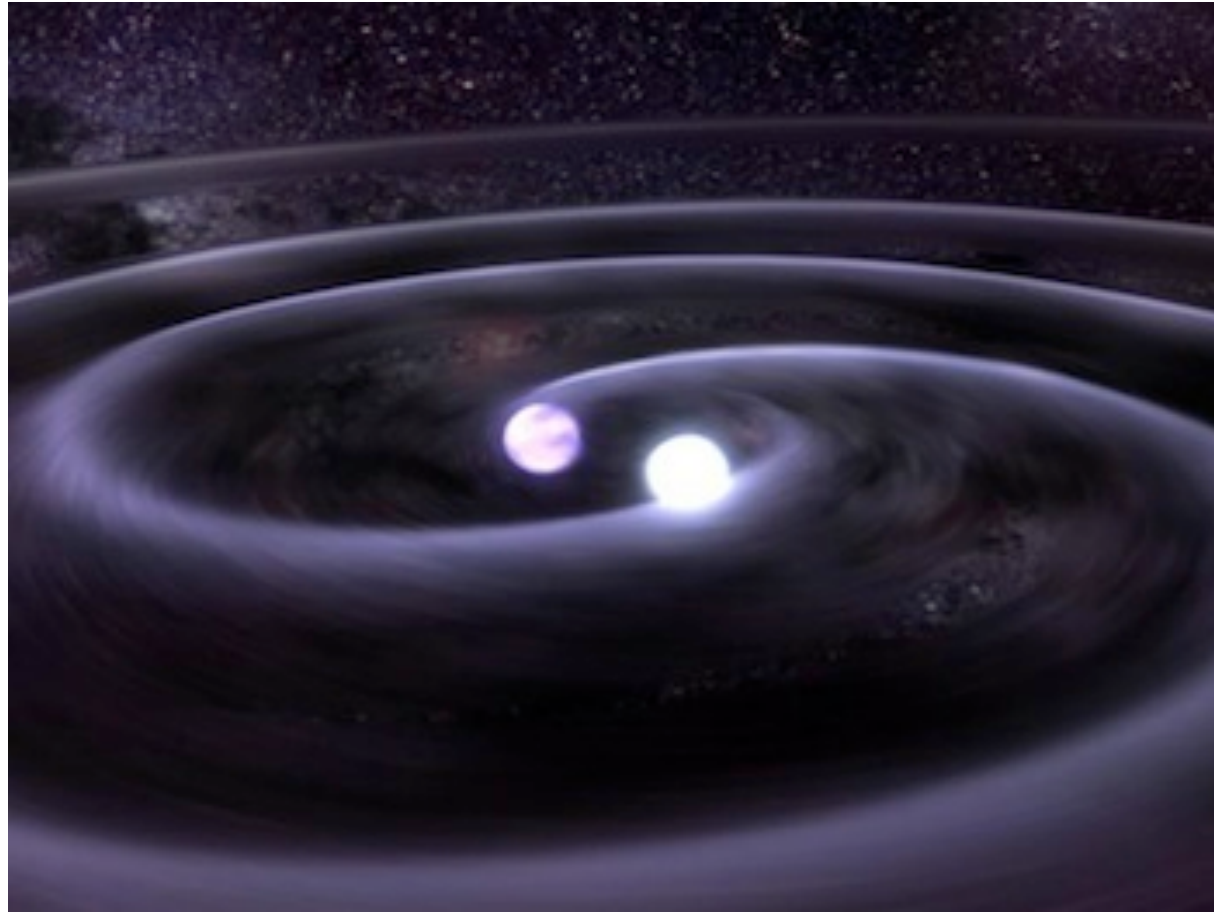
過去のSSSはISMを電離するはず
 $t_{\text{rec}} \sim 10^5/n \text{ yr} \rightarrow \text{SNR}$ で観測可能

Tycho: 電離度 < 20% (Woods+2017)



そこで Double Degenerate (DD)

伴星不要・定常降着不要

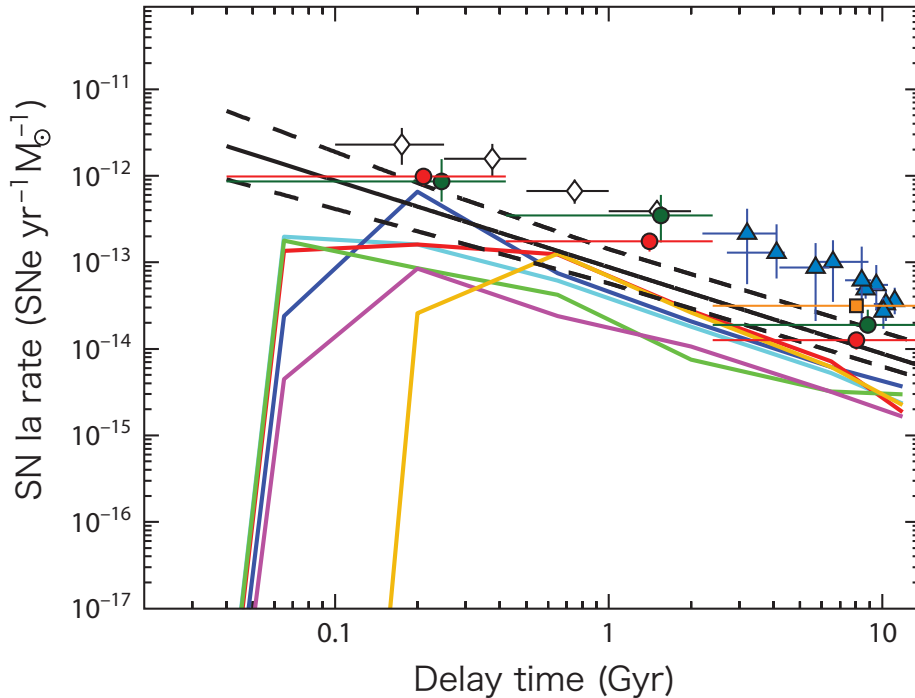


「反SD」の多くが upper limit の議論

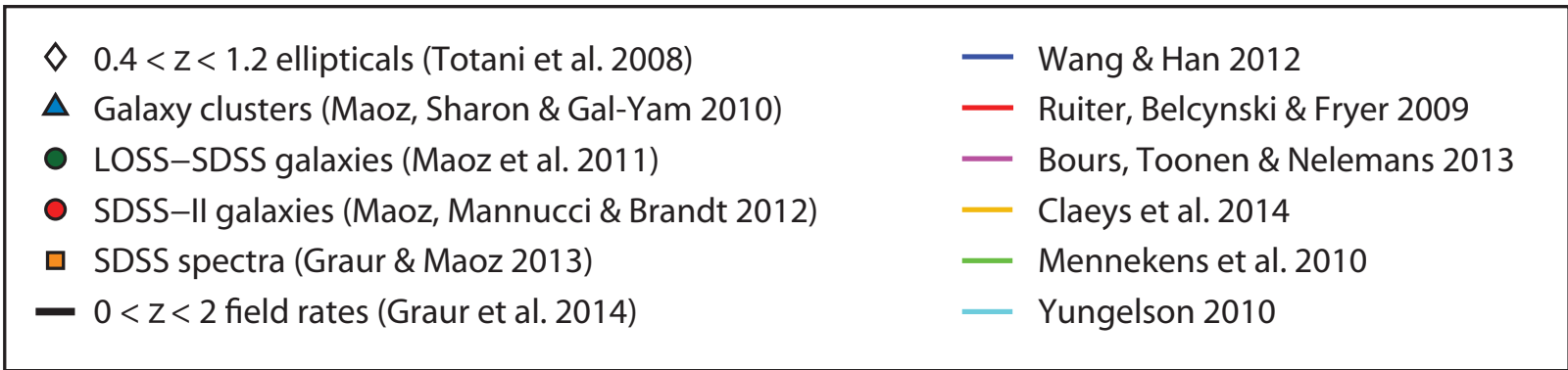
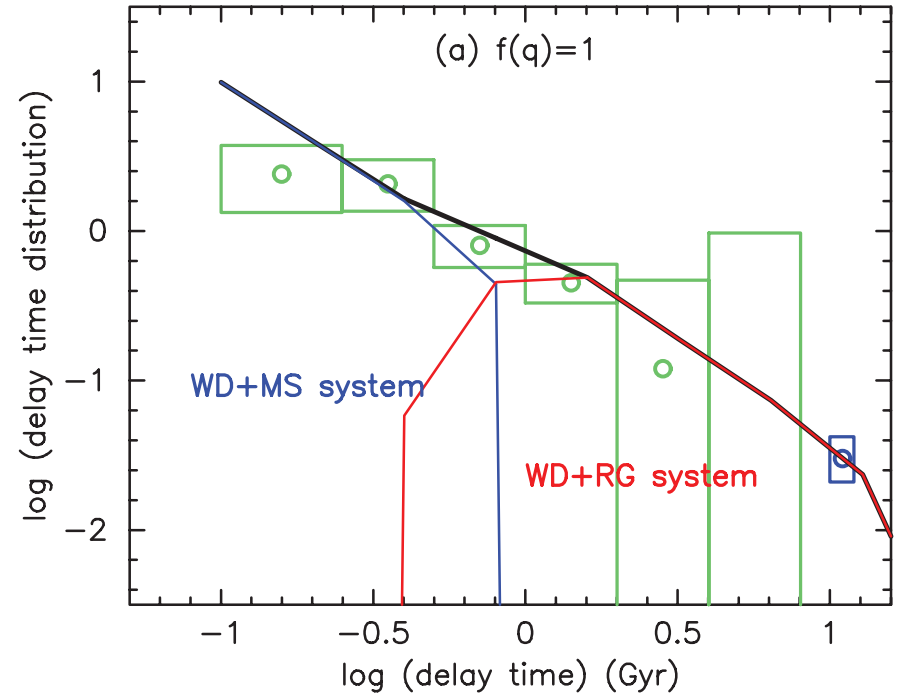
Absence of evidence is not evidence for absence

Delay Time Distribution (DTD)

DD



Hachisu, Kato & Nomoto 2008

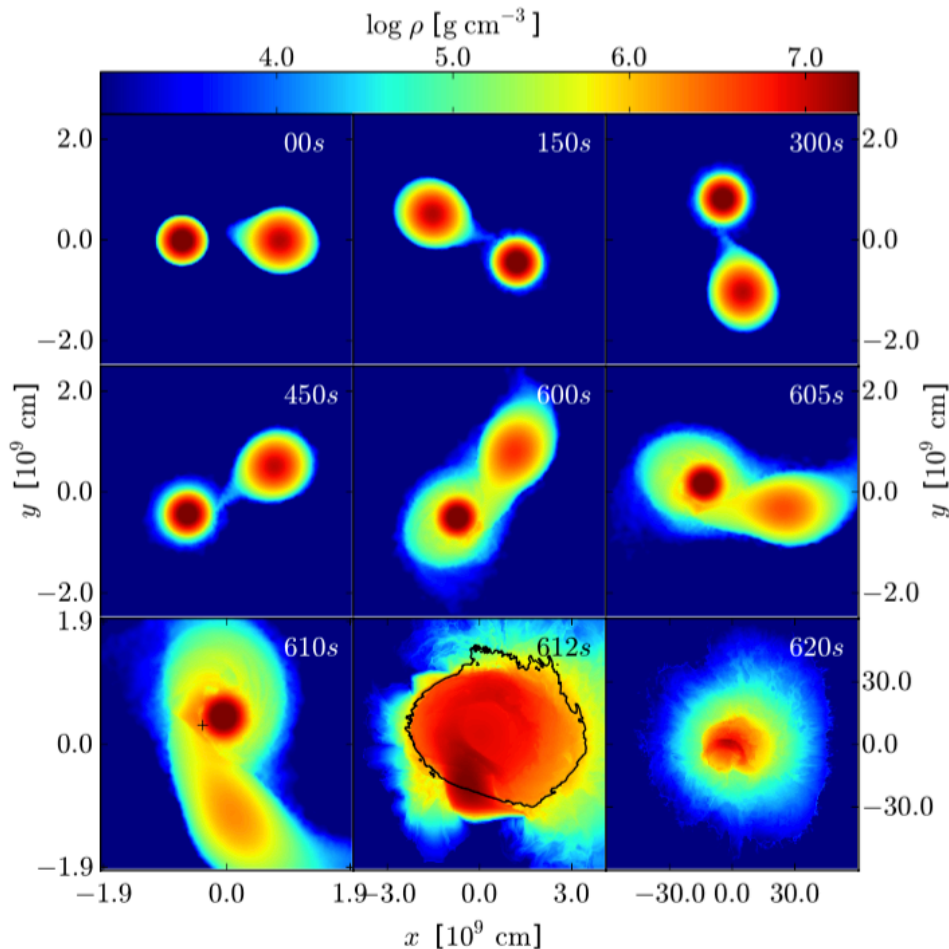


昔のDD・今のDD

当初は「いかに M_{Ch} に近づくか」が問題の本質だった

→ 主星への“速い” ($\sim 10^{-5} M_{\odot}/\text{yr}$) 降着

→ ONeMg WDを経てNSに崩壊 (e.g., Saio+1985)



最近の理論は“violent merger”

$M_1 \approx 1 M_{\odot} \gtrsim M_2$, $t \sim 100 \text{ s}$ の

“**sub- M_{Ch} model**”.

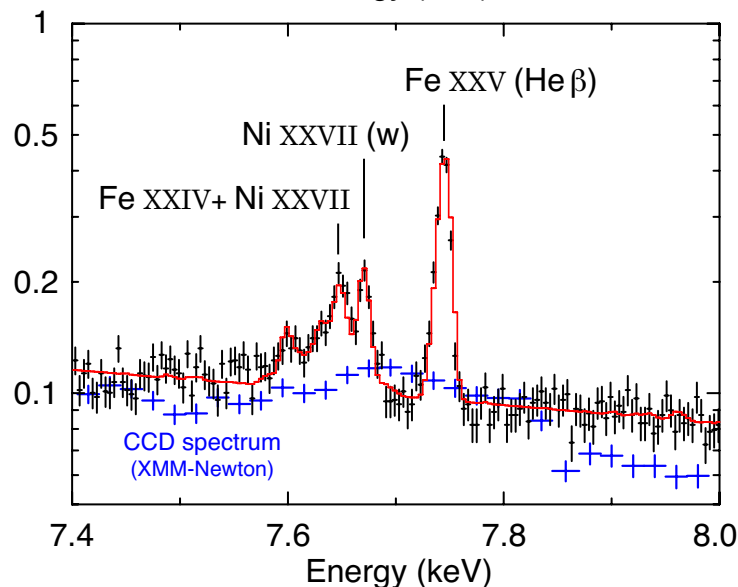
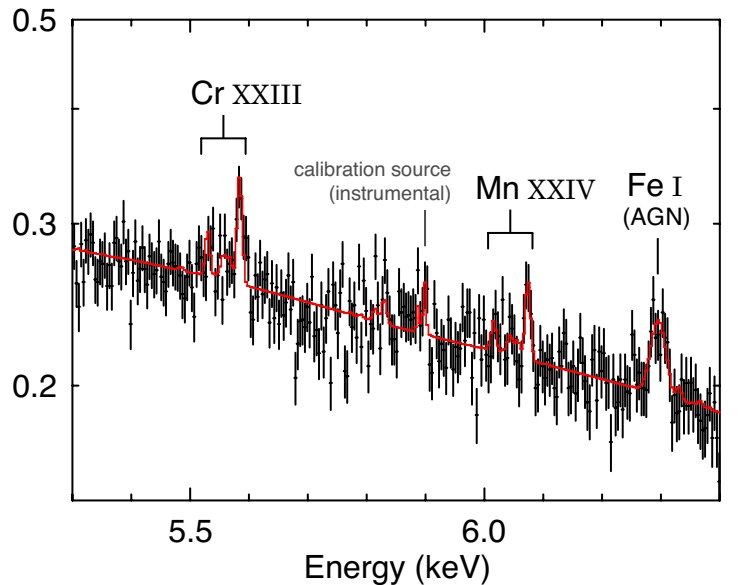
(e.g., Pakmor+2010, 2012)

主星の質量が物事を決める.

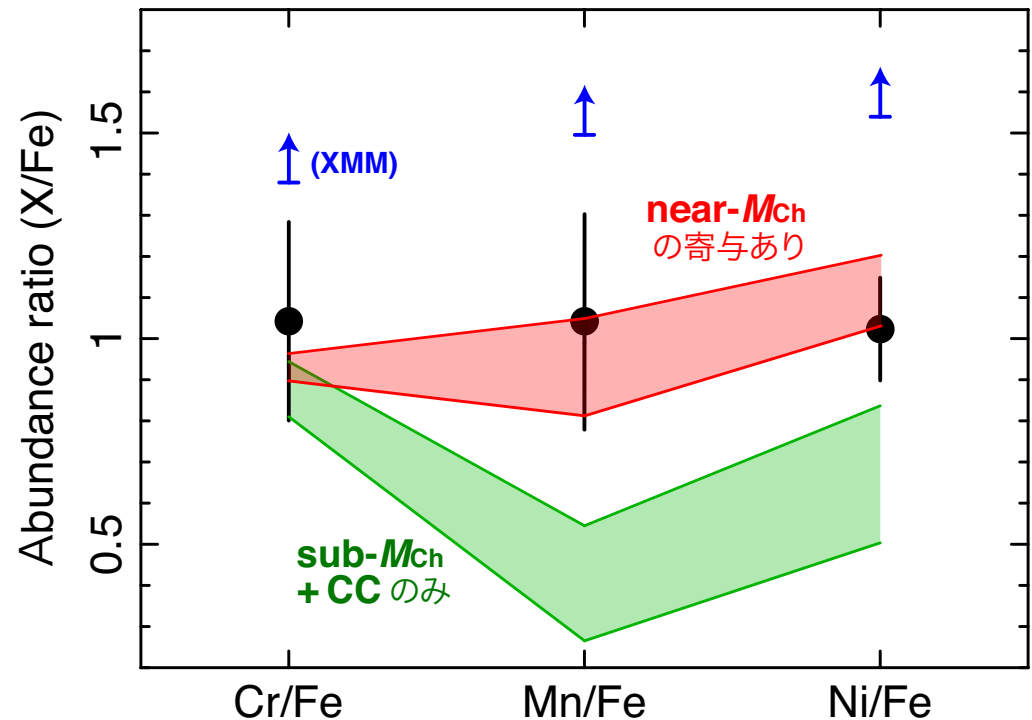
← $1.1 M_{\odot} + 0.9 M_{\odot}$ の merger
(Pakmor+2012)

(私見ですが) DDシナリオ最大の弱点

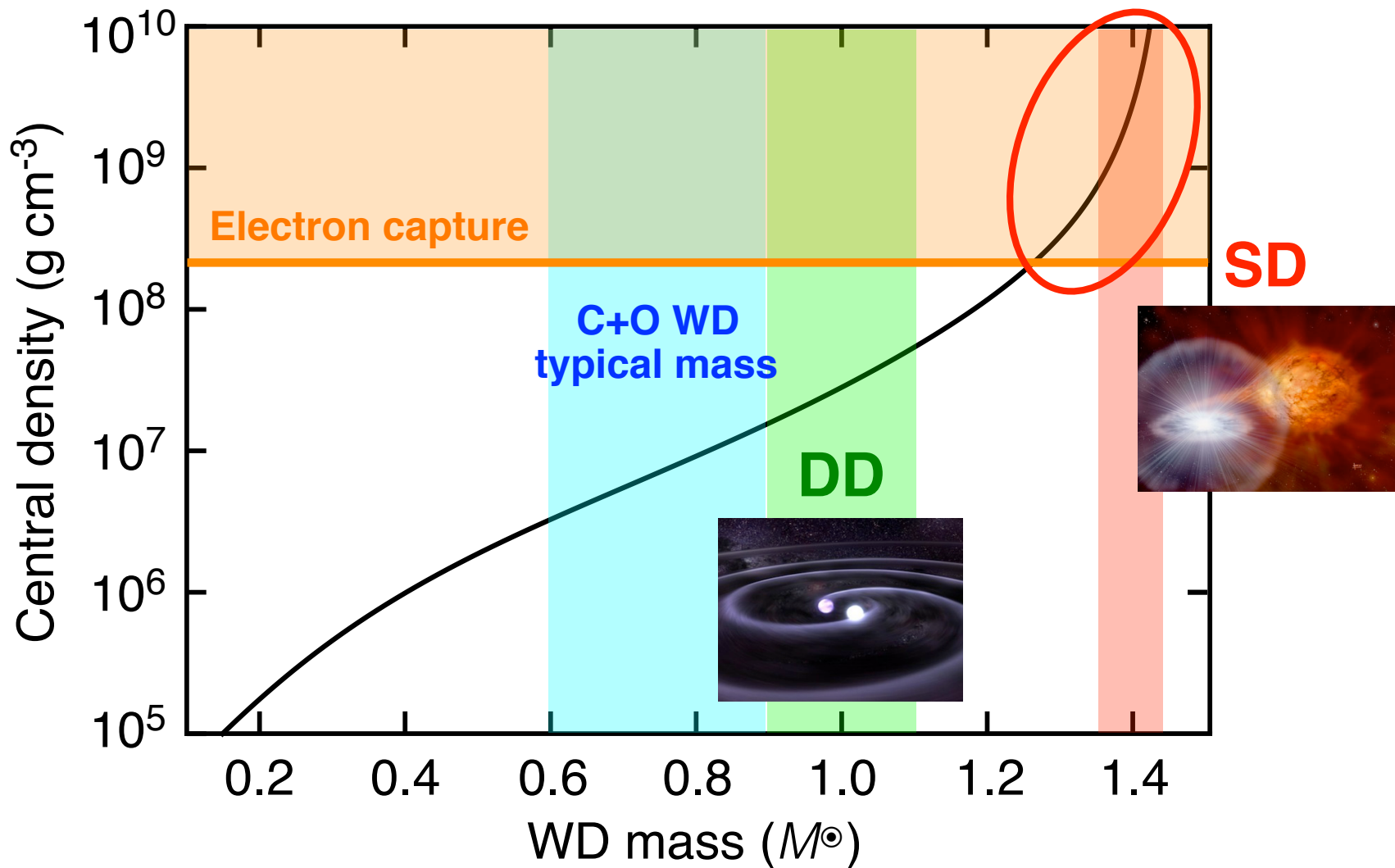
鉄族元素組成を説明できない



ひとみ衛星の数少ない成果
銀河団の鉄族元素精密測定
→ 太陽組成に完全一致
(Hitomi Collaboration 2017)



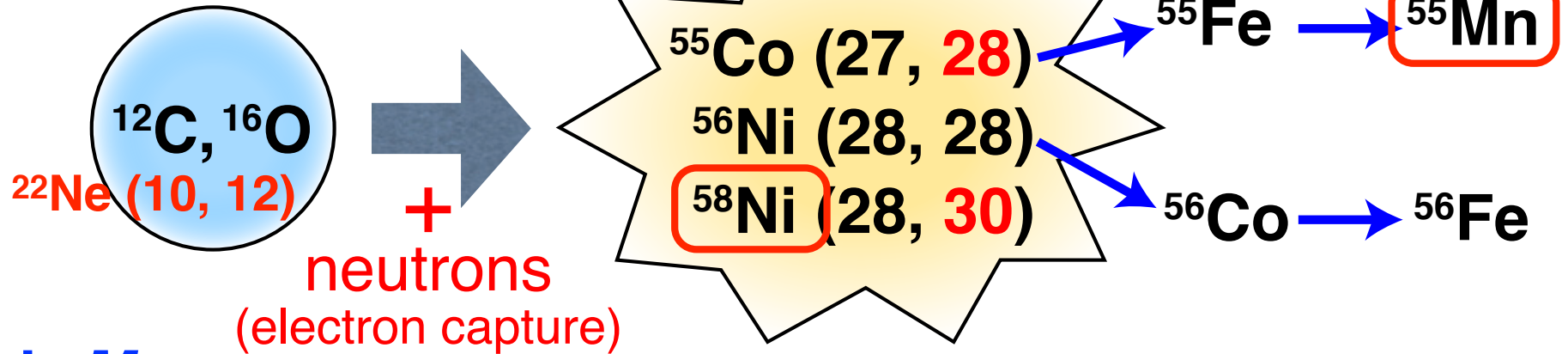
鍵は白色矮星の中心密度



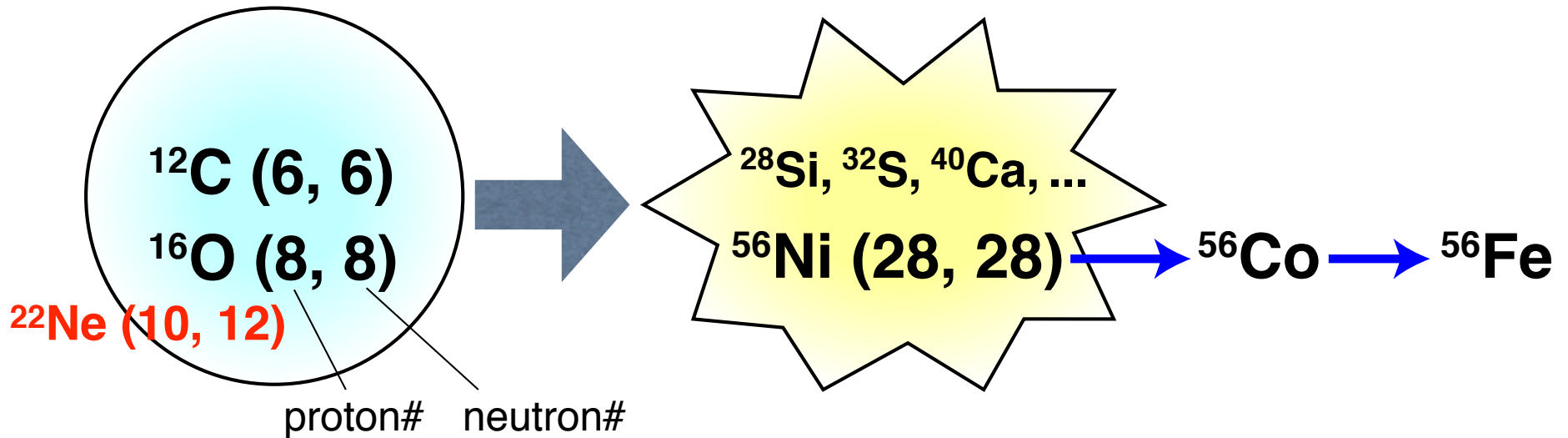
電子捕獲： $p + e^- \rightarrow n + \nu_e$ ($\sim M_{\text{Ch}}$ のときだけ起こる)

鉄族元素の合成

near- M_{Ch}

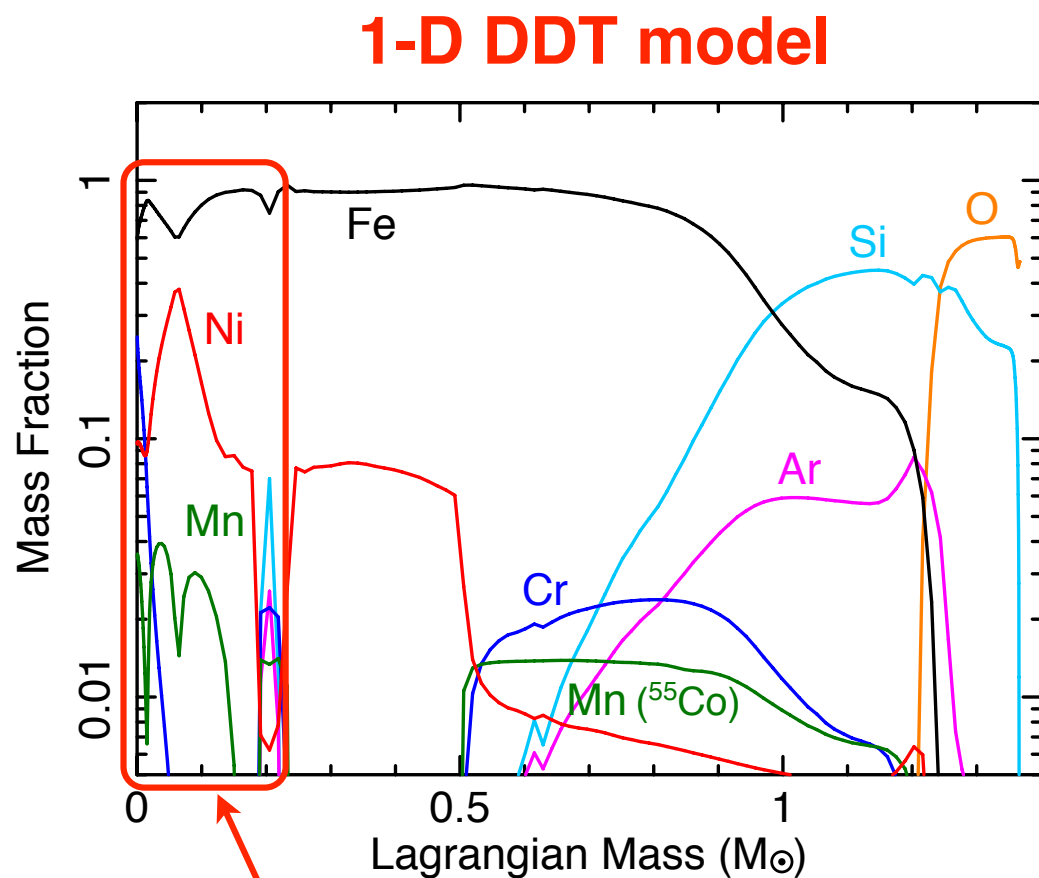
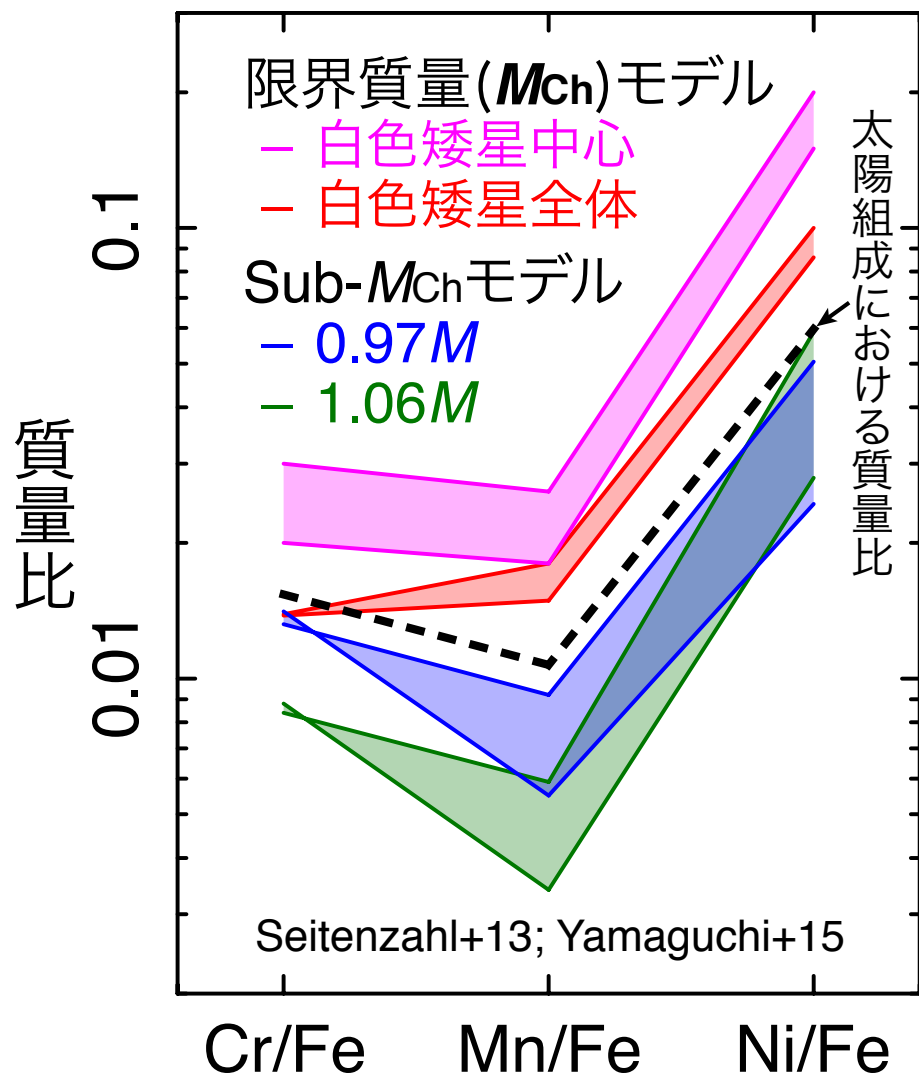


sub- M_{Ch}



Ni, Mn の多い超新星を見つけたい！

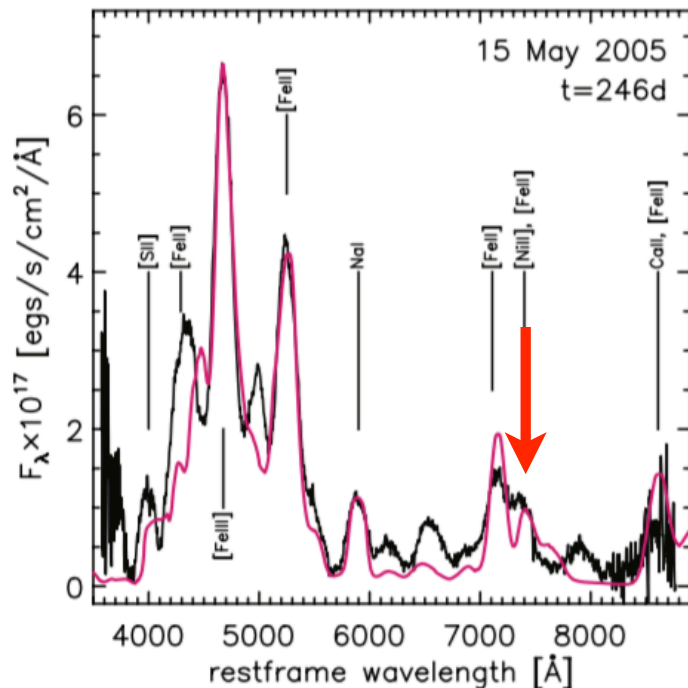
理論計算の一例



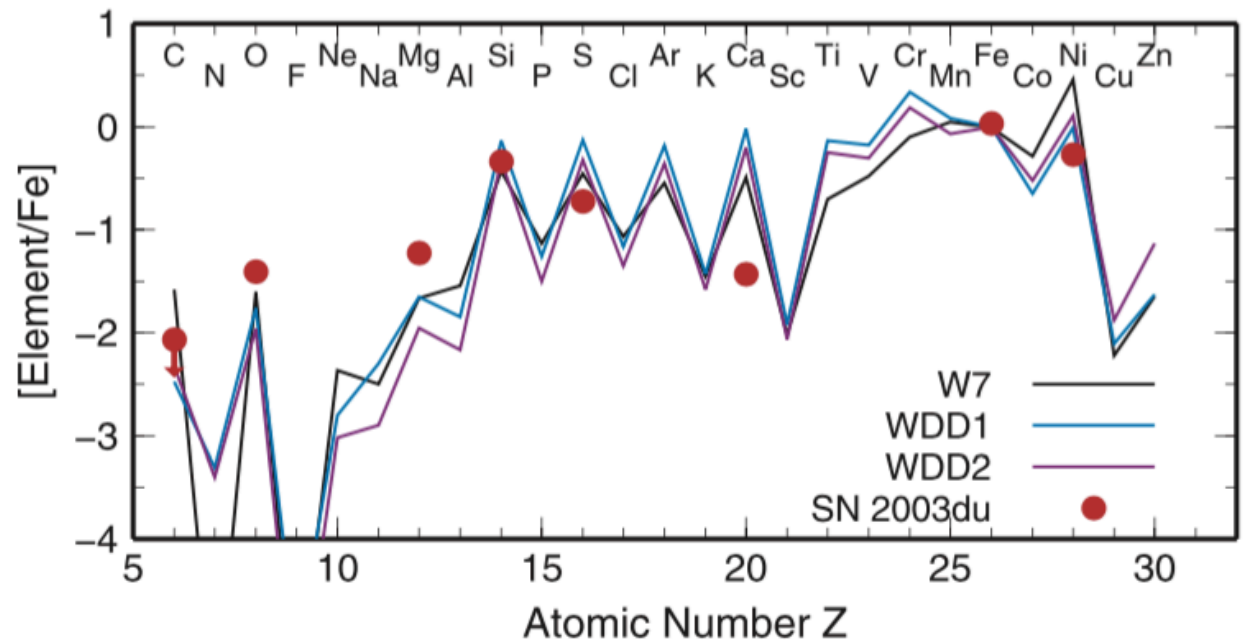
電子捕獲の寄与
(領域の大きさはモデルによる)

^{58}Ni の直接探査 (nebula phase)

SN 2004eo
(Mazzali+2008)



SN 2003du (Tanaka+2011)

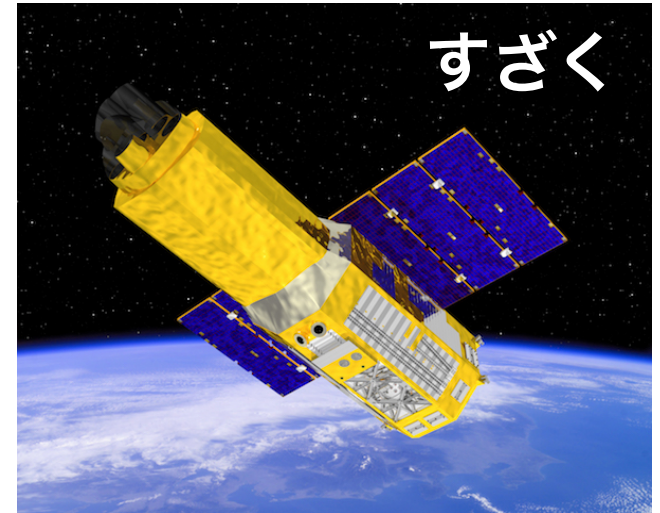
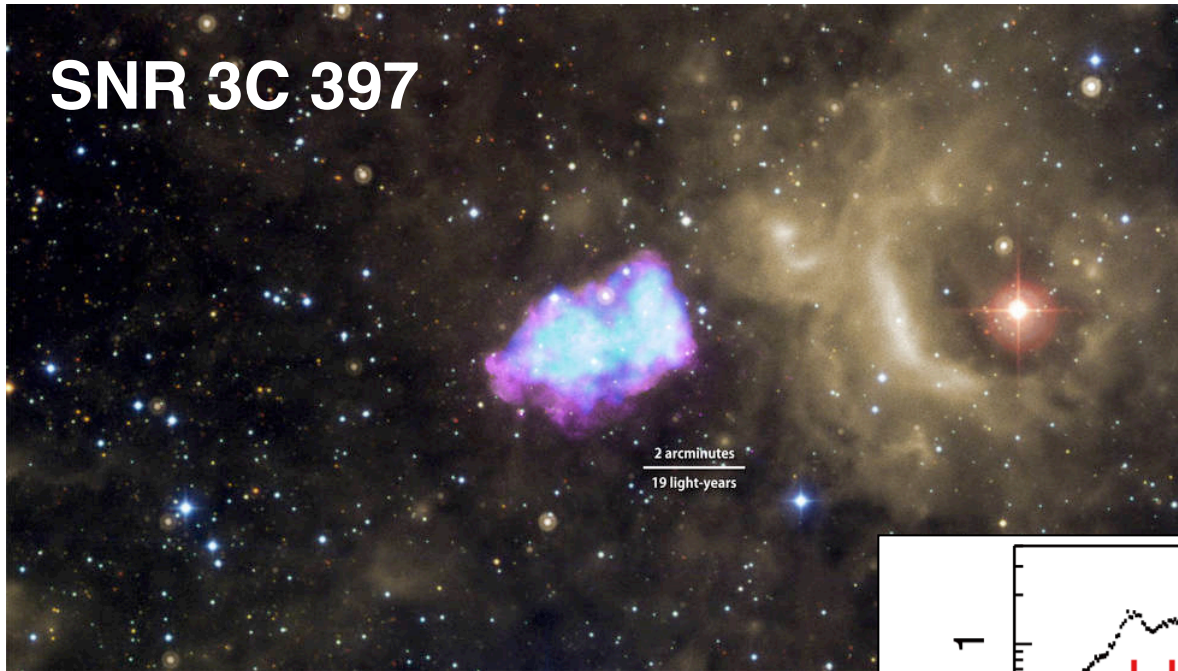


See also Maeda+2010 for systematic observations

正確な質量決定は難しい

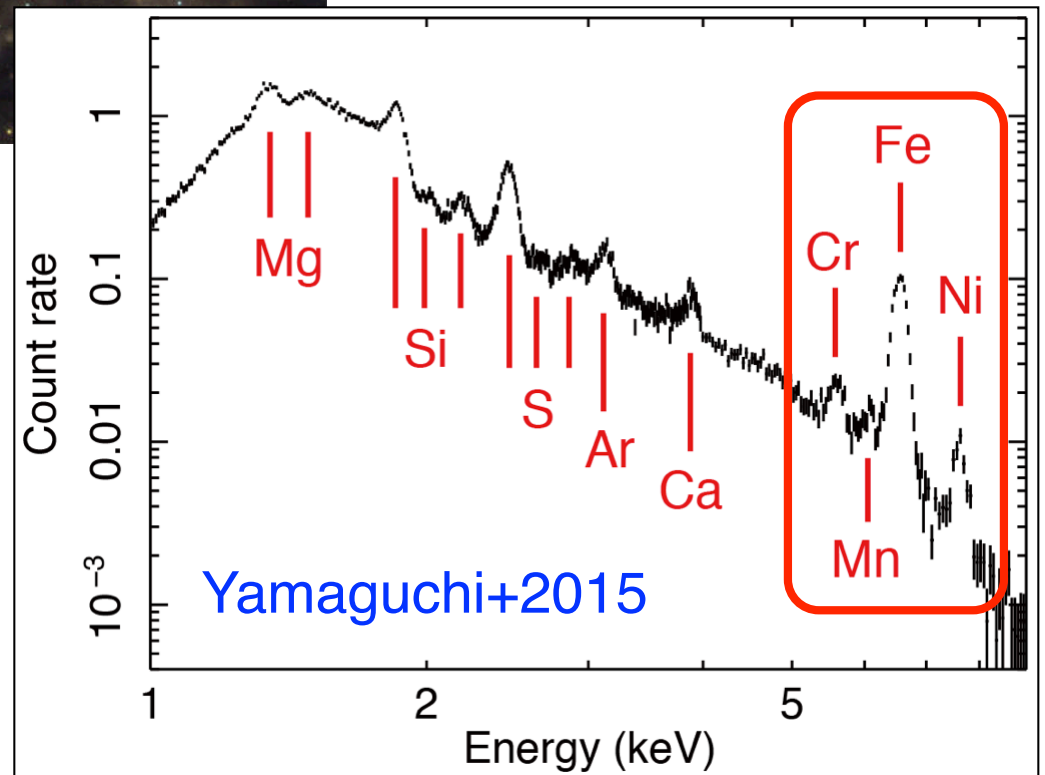
Mn は SN の観測で検出できない

超新星残骸



すざく: 多数のSNRから
鉄族元素輝線を検出

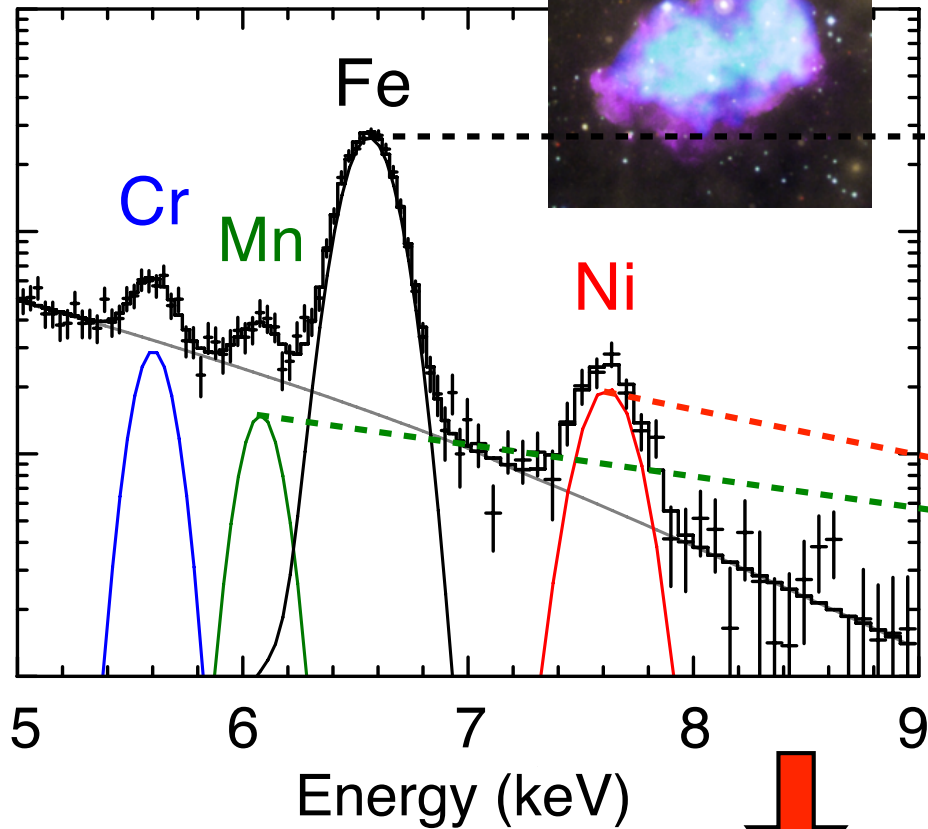
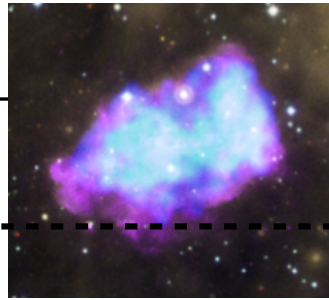
比較的精度のよい
質量比測定が可能



3C 397: 異常に強い Mn, Ni 輝線

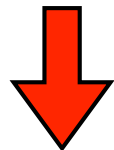
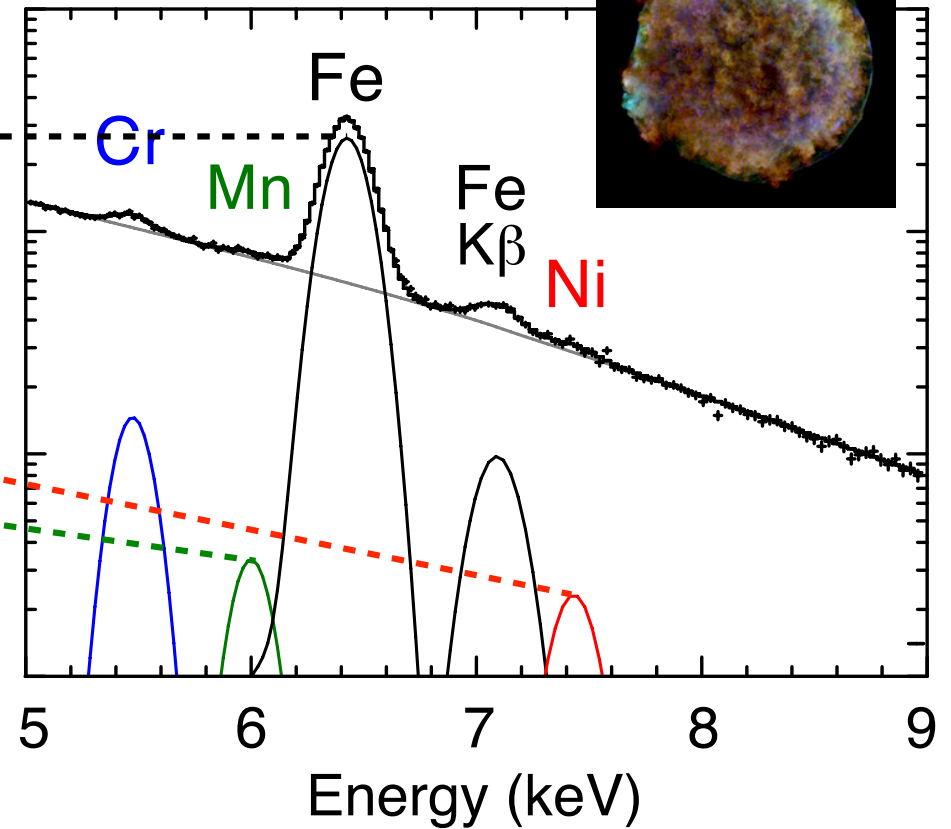
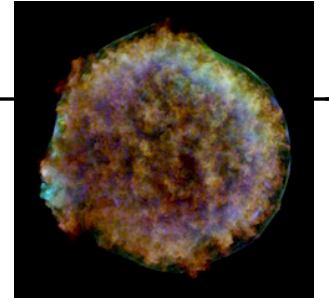
3C 397

Yamaguchi+15



Tycho

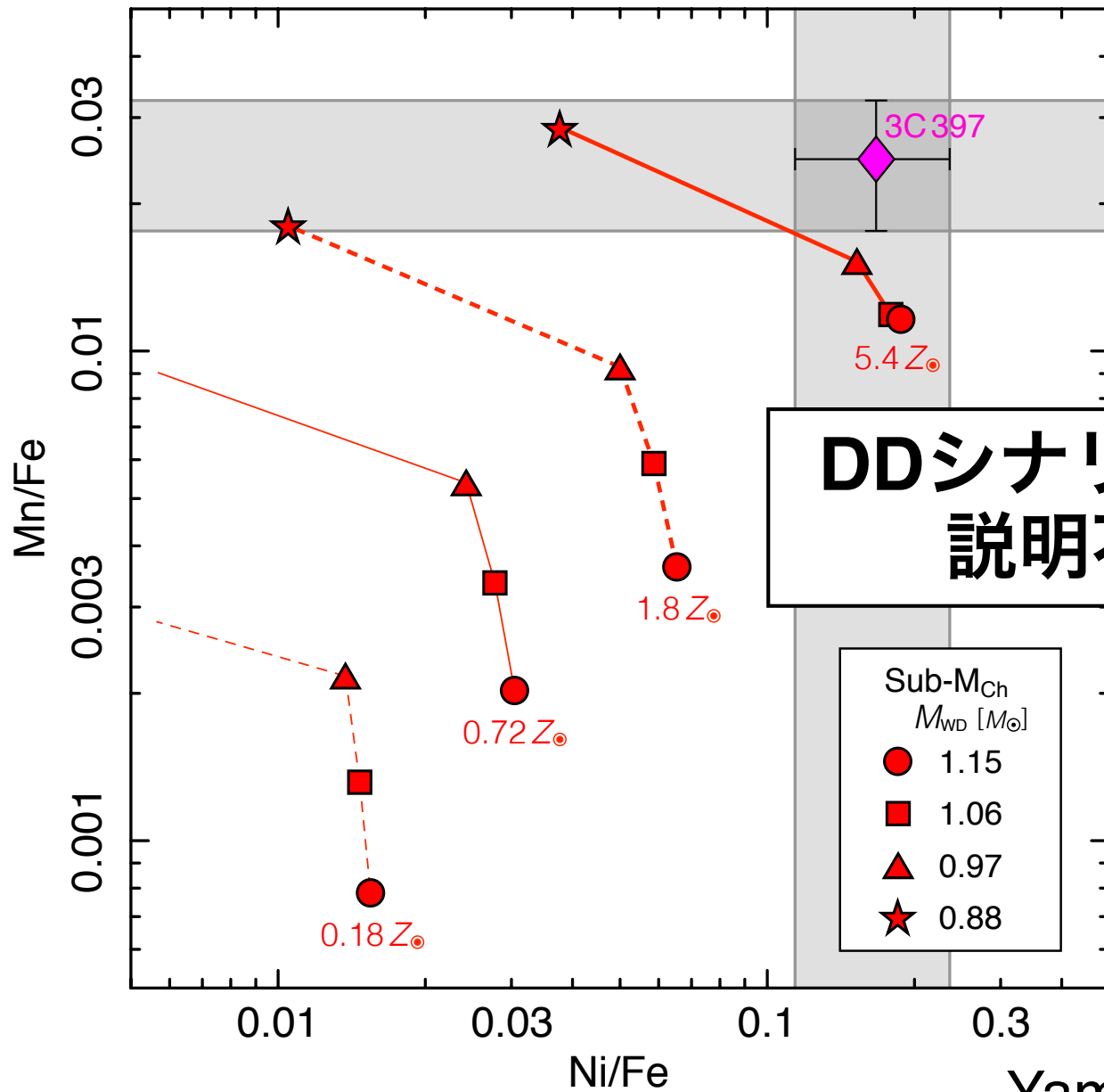
Yamaguchi+14;+17



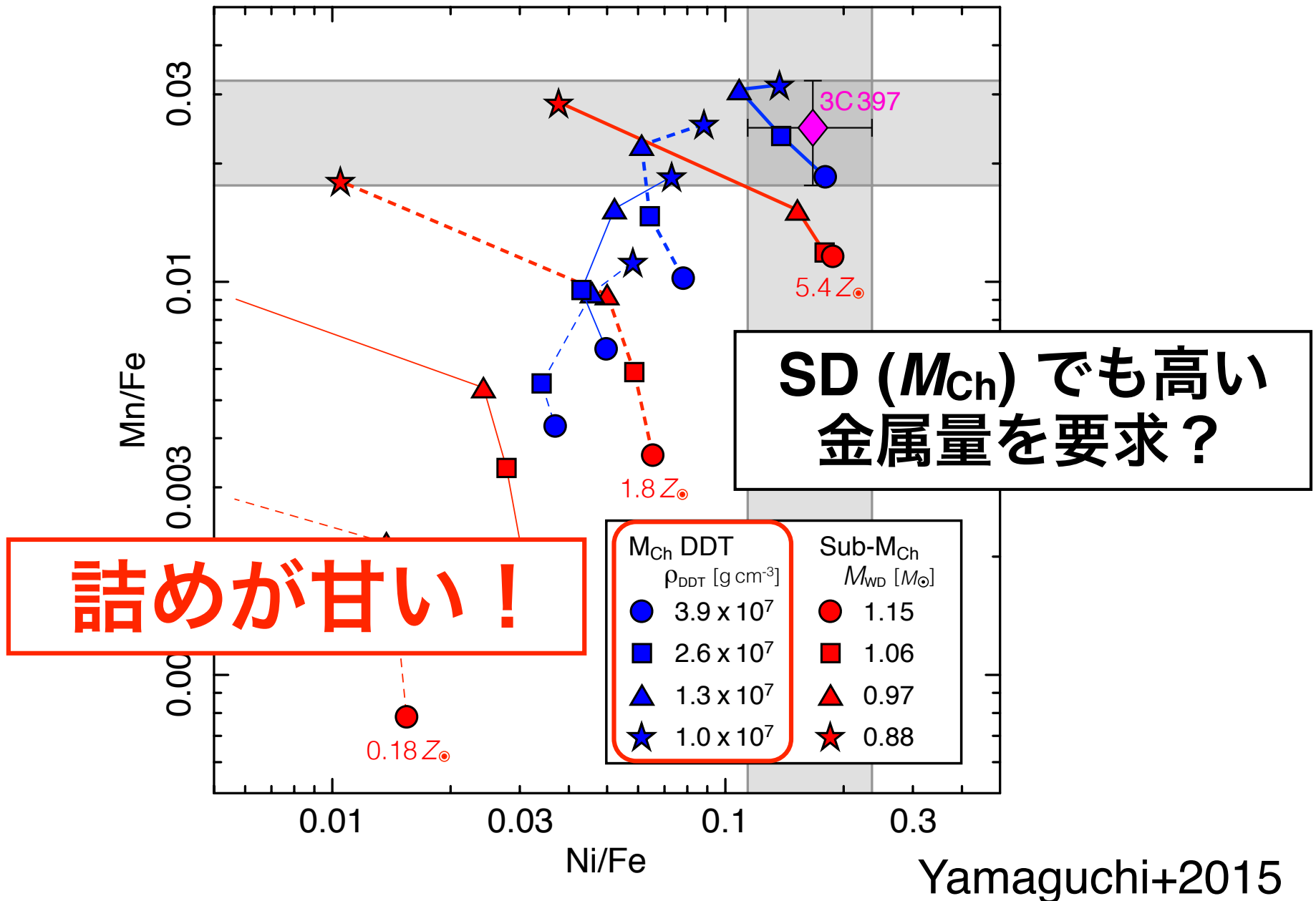
Ni/Fe \approx 0.17 (0.12–0.24)

Mn/Fe \approx 0.025 (0.018–0.033)

SN Ia 元素合成モデルとの比較

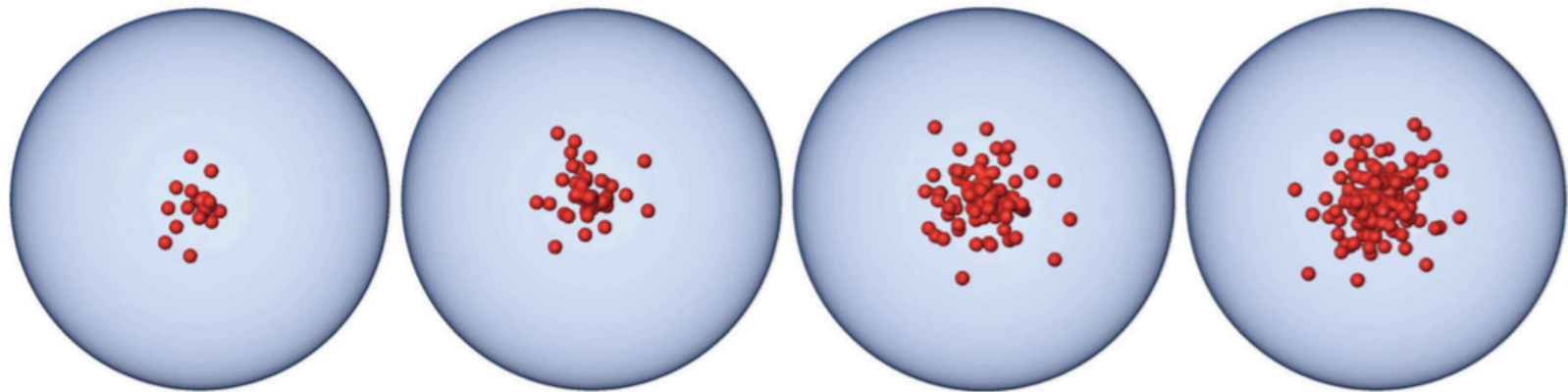


SN Ia 元素合成モデルとの比較



M_{Ch} 爆発モデルは自由度大

- 爆轟波に切り替わる条件 \rightarrow ^{56}Ni 生成量
- 親星の金属量 \rightarrow 爆発前の ^{22}Ne 混入率
- C/O比
- **爆発時の質量 & 中心密度**
 実際は厳密に M_{Ch} まで達するわけではない
- 燃烧開始点の数や位置 (e.g., off-center ignition)



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- 爆轟波に切り替わる条件 \rightarrow ^{56}Ni 生成量
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- C/O比
- **爆発時の質量 & 中心密度**

実際は厳密に M_{Ch} まで達するわけではない

伝統的に $\rho_c = 2 \times 10^9 \text{ g cm}^{-3}$ が

採用されるケースが多く (理由は後述)

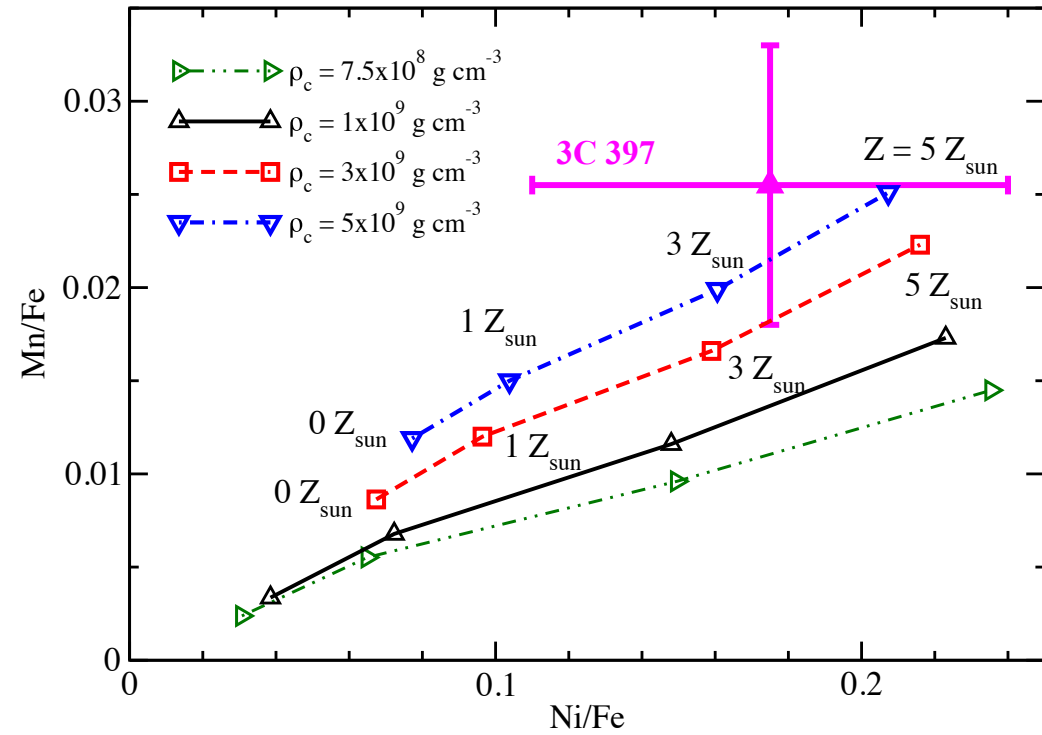
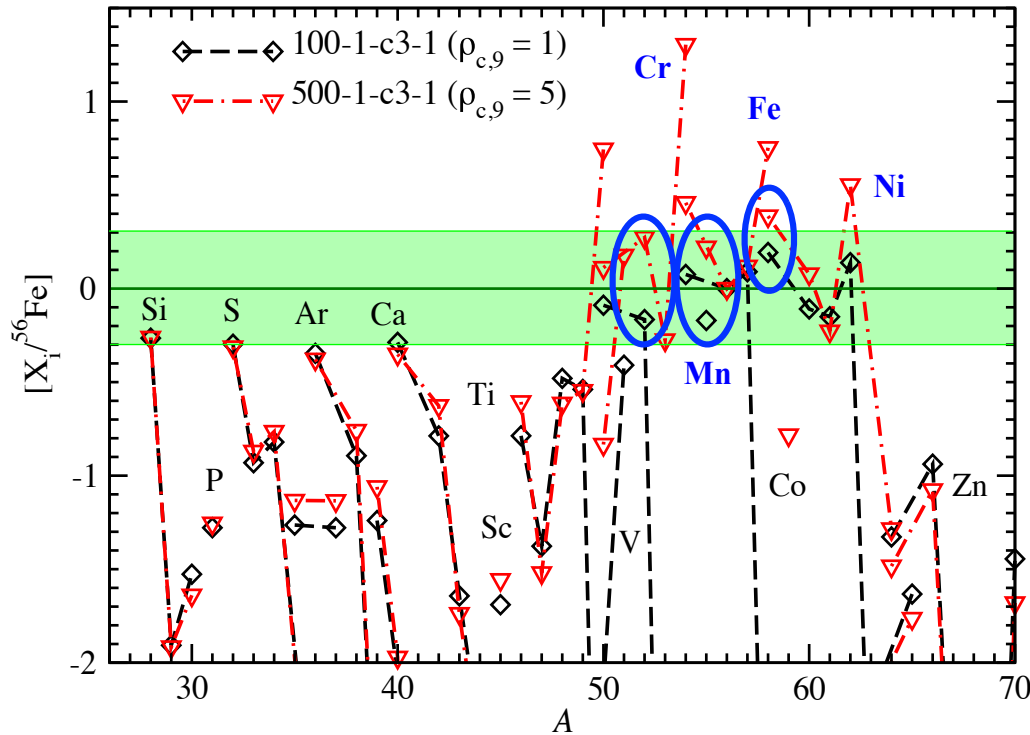
先述の研究でもそれに倣った.

高密度ほど電子捕獲が起こりやすいのだから

その効果ぐらい調べるべきだった...

親星中心密度の効果

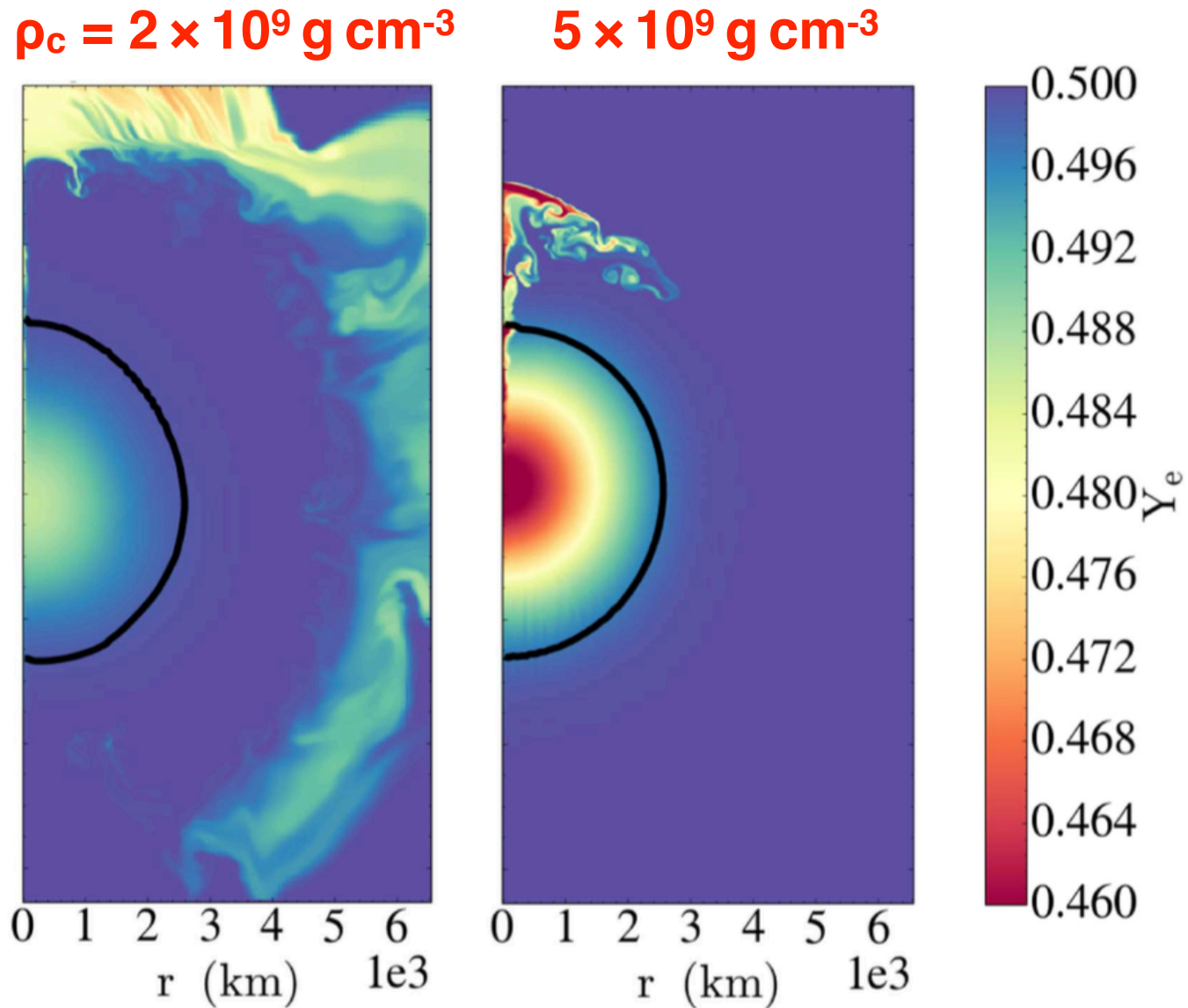
Leung & Nomoto 2017



$\rho_c = 5 \times 10^9 \text{ g cm}^{-3}$ にすると
 ^{52}Cr , ^{55}Mn , ^{58}Ni の Fe比が
 軒並み増加

そこそこの金属量でOK.

親星中心密度の効果

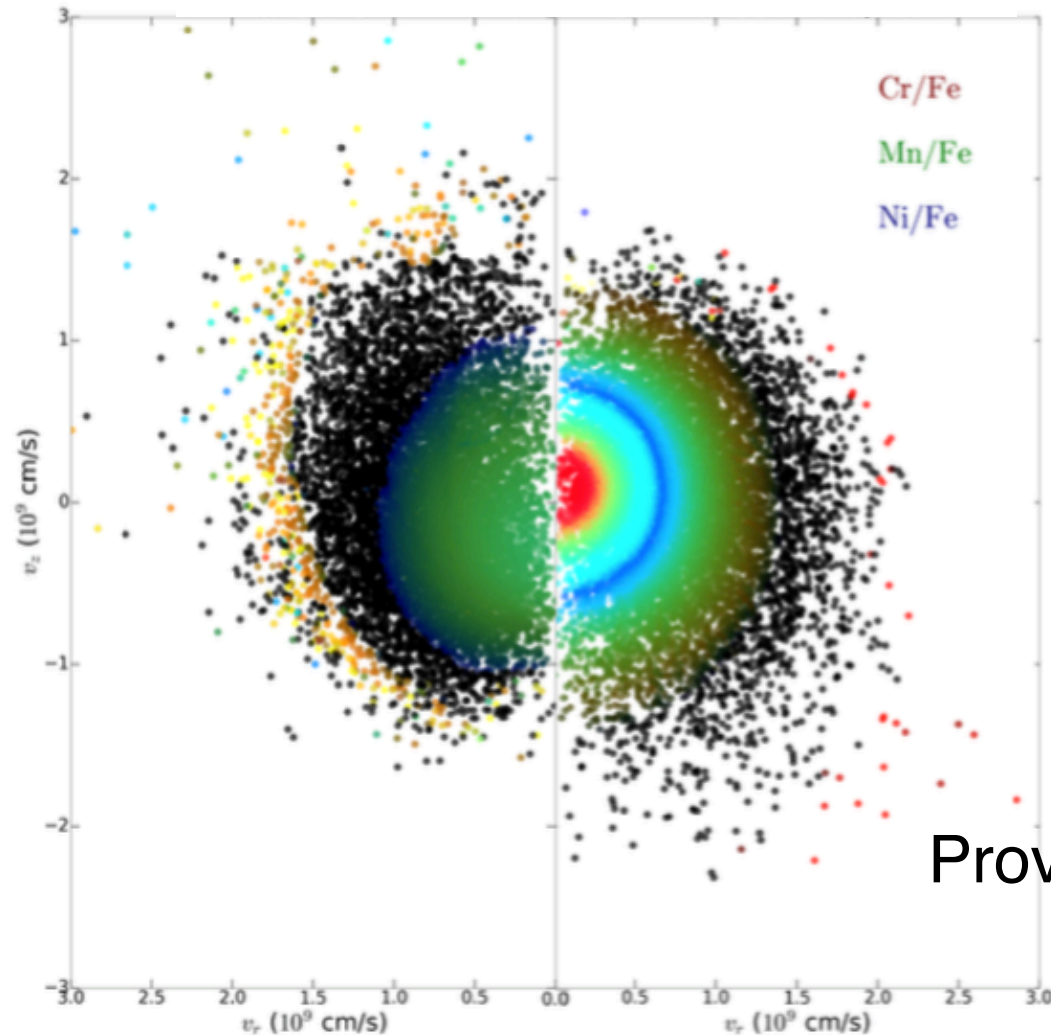


Dave+2016 (U.Mass group)

親星中心密度の効果

$\rho_c = 2 \times 10^9 \text{ g cm}^{-3}$

$5 \times 10^9 \text{ g cm}^{-3}$

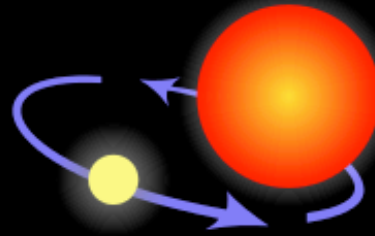


M_{Ch} SN Ia は従来の理解より高密度で爆発？

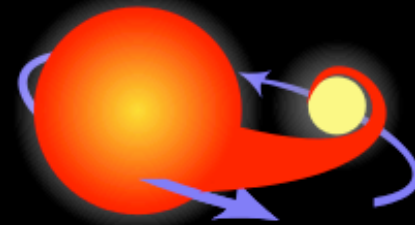
SDシナリオの進化経路



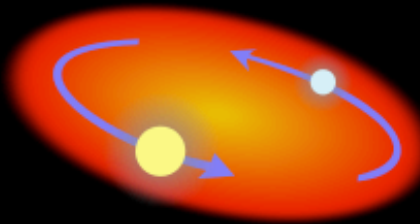
Two normal stars are in a binary pair.



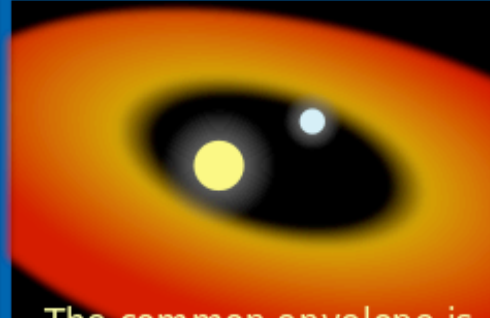
The more massive star becomes a giant...



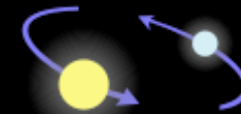
...which spills gas onto the secondary star, causing it to expand and become engulfed.



The secondary, lighter star and the core of the giant star spiral toward within a common envelope.



The common envelope is ejected, while the separation between the core and the secondary star decreases.



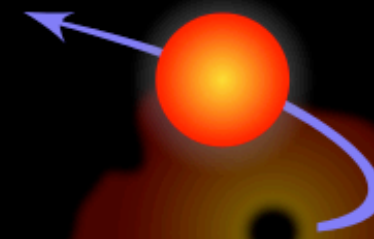
The remaining core of the giant collapses and becomes a white dwarf.



The aging companion star starts swelling, spilling gas onto the white dwarf.



The white dwarf's mass increases until it reaches a critical mass and explodes...

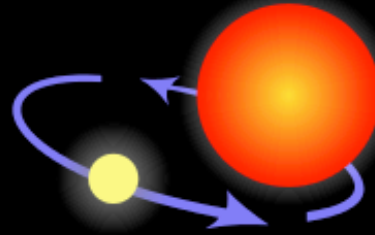


...causing the companion star to be ejected away.

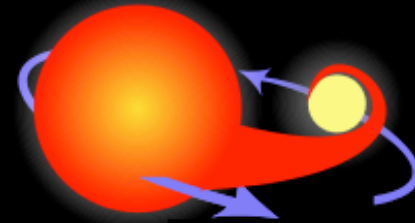
SDシナリオの進化経路



Two normal stars are in a binary pair.

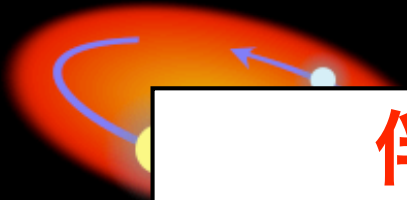


The more massive star becomes a giant...



...which the secondary expand and

白色矮星の
初期質量

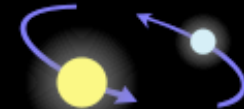


The second
and the
star spin
a com

伴星の質量

→ 降着開始までの時間

→ 白色矮星のcooling



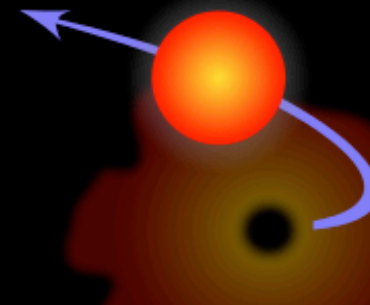
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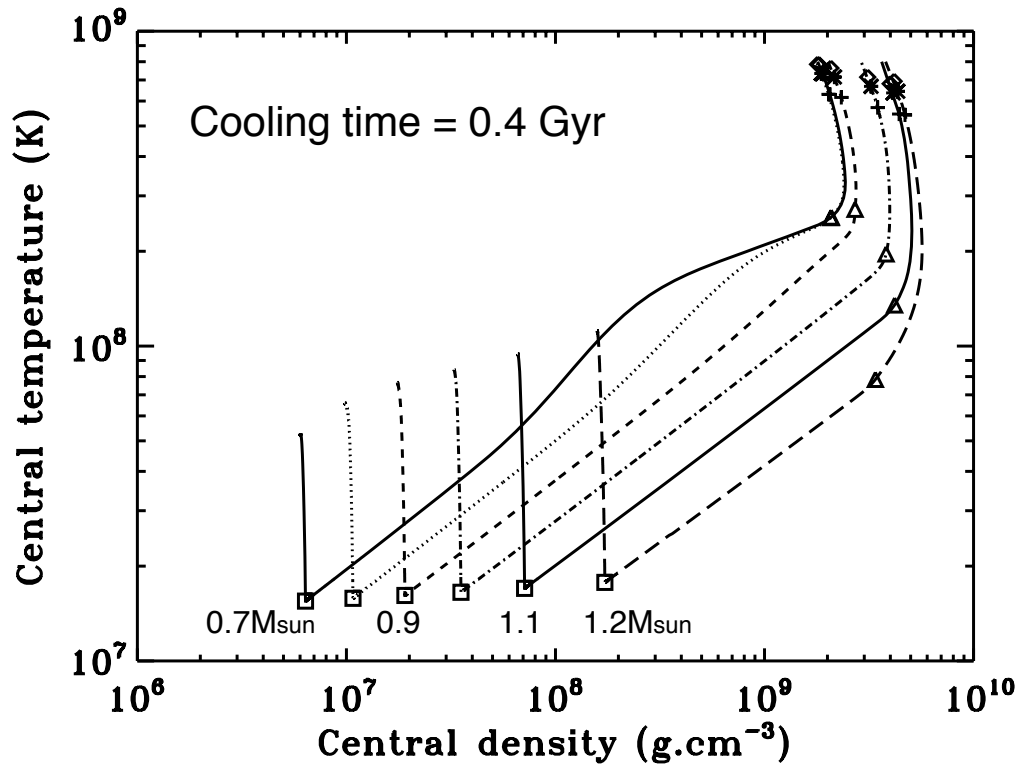


...causing the companion
star to be ejected away.

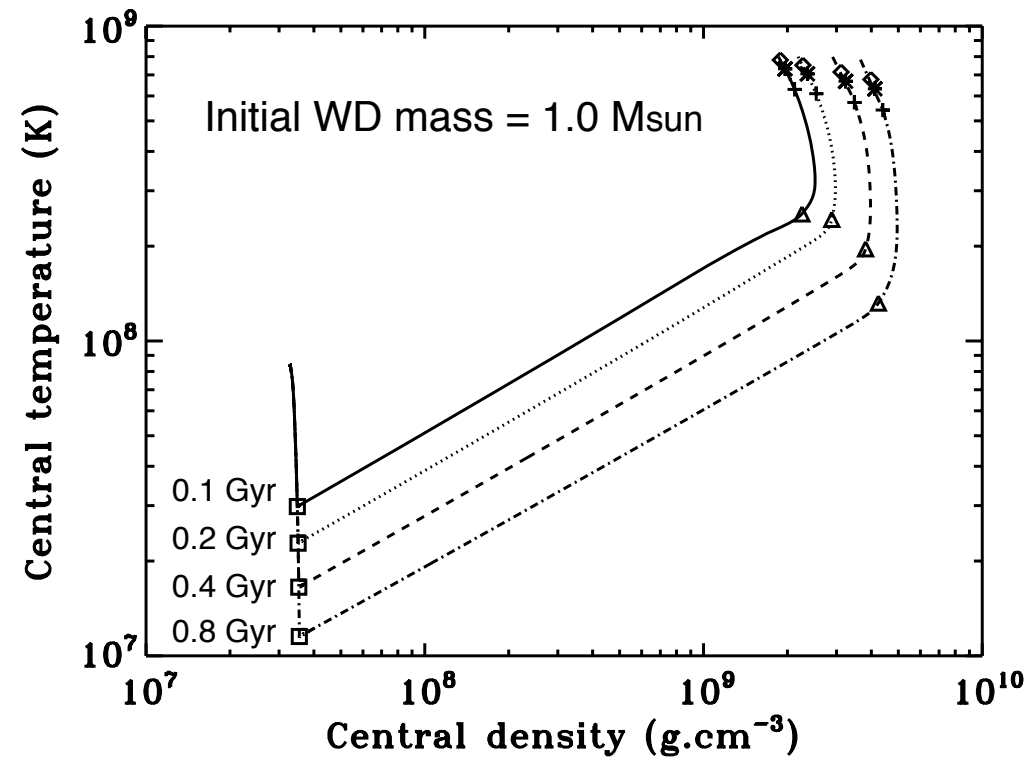
親星の内部構造に与える影響

Lesaffre+2006

Initial WD mass effect

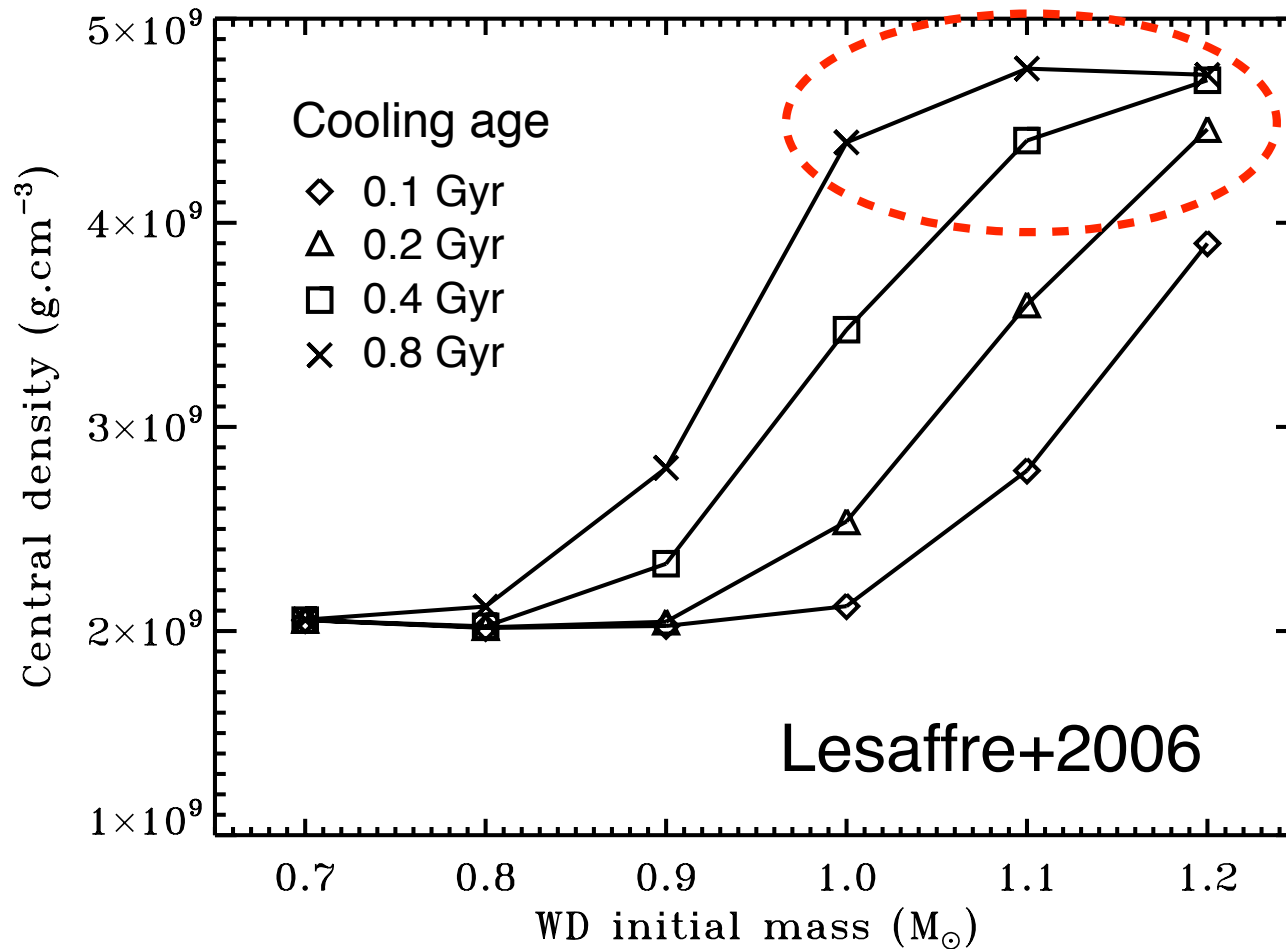


Age (cooling time) effect



爆発時の中心密度は
初期の内部状態に引きつられる

親星の内部構造に与える影響



3C 397 の親星 = (i) 重い主星 + (ii) 軽い伴星

超新星残骸の観測で連星進化にも制限！

考察と提言

$\rho_c = 2 \times 10^9 \text{ g cm}^{-3}$ が定着した経緯：

M_{Ch} SNe Ia だけで鉄族元素の太陽組成を説明するため (Nomoto+1997, Woosley+1997)

→ SNe Ia はもっとバラエティーに富んでいる.

DD (Mn, Niを作らない) の寄与があるなら,
「high- ρ な SD」と DD の組み合わせでもOK.

– これまでの“前提”を改めて疑ってみる.

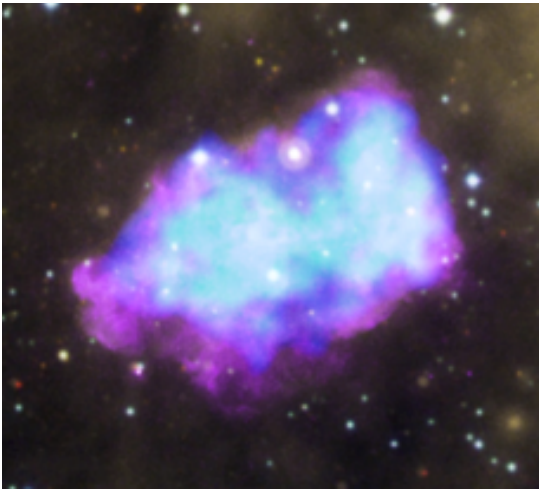
– 「星の進化」から出発した爆発モデルの追求.

まとめ

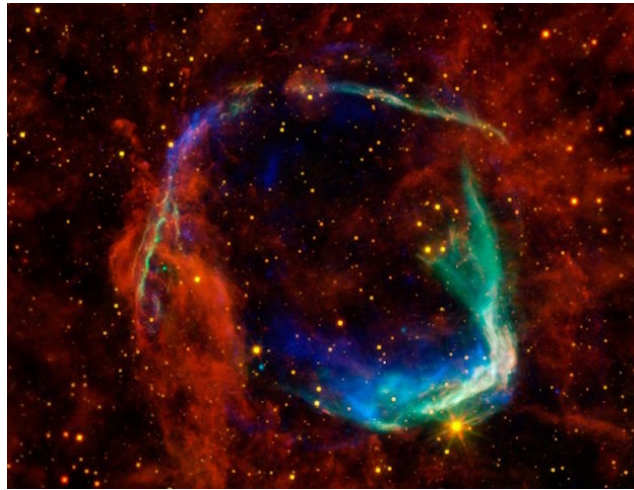
SD vs DD 仁義なき戦いの行方

- SDに不利な観測事実が多いのは確か
- 一方でSDを支持する観測も存在
- 両方正解でいいんじゃないでしょうか
 - 仲良くしましょう
 - 多様性を受け入れる
 - 一様性に立脚した前提の見直し (e.g., 爆発密度)
- 観測されるsubclassと両シナリオのリンクが大切
 - 宇宙論への貢献 (非標準光源の除外)

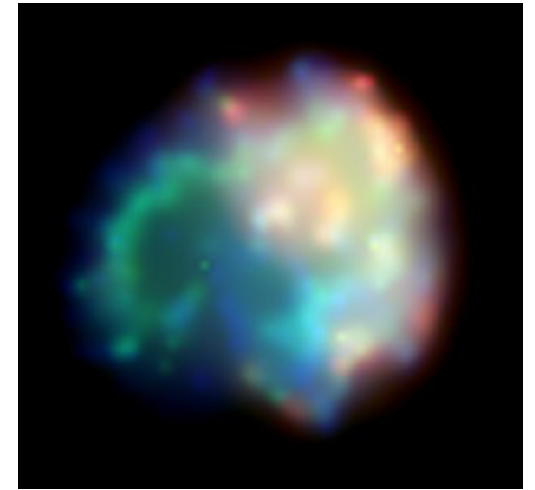
SD family



3C 397

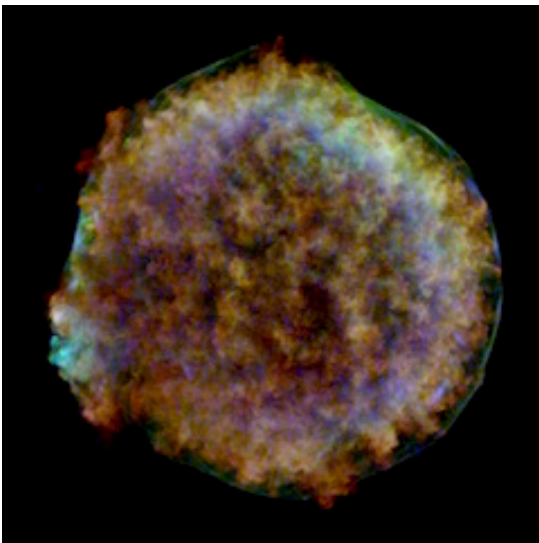


RCW 86

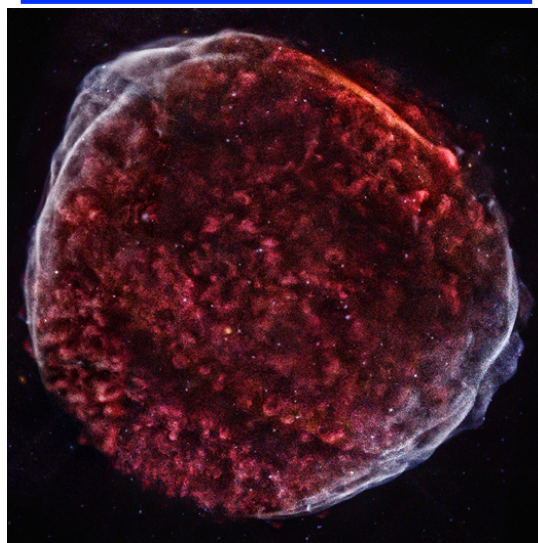


N103B

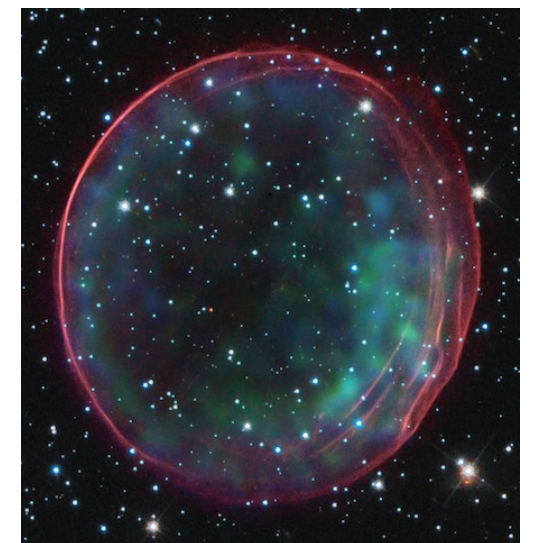
DD family



Tycho



SN 1006

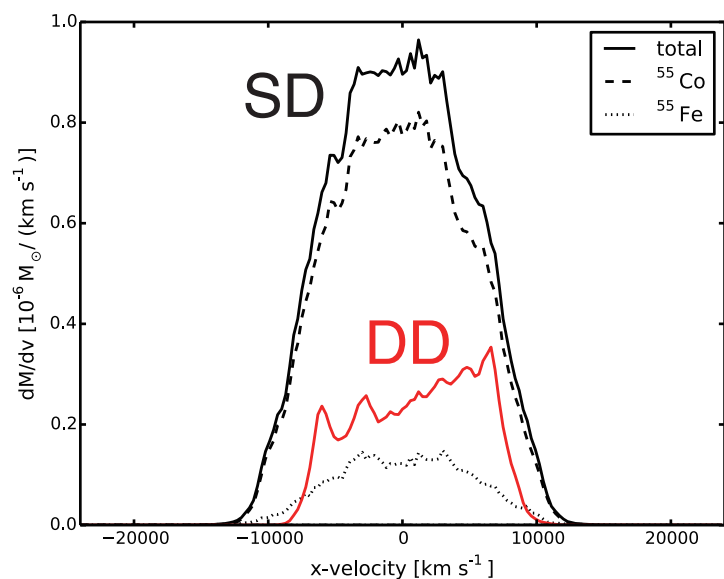


0509-67.5

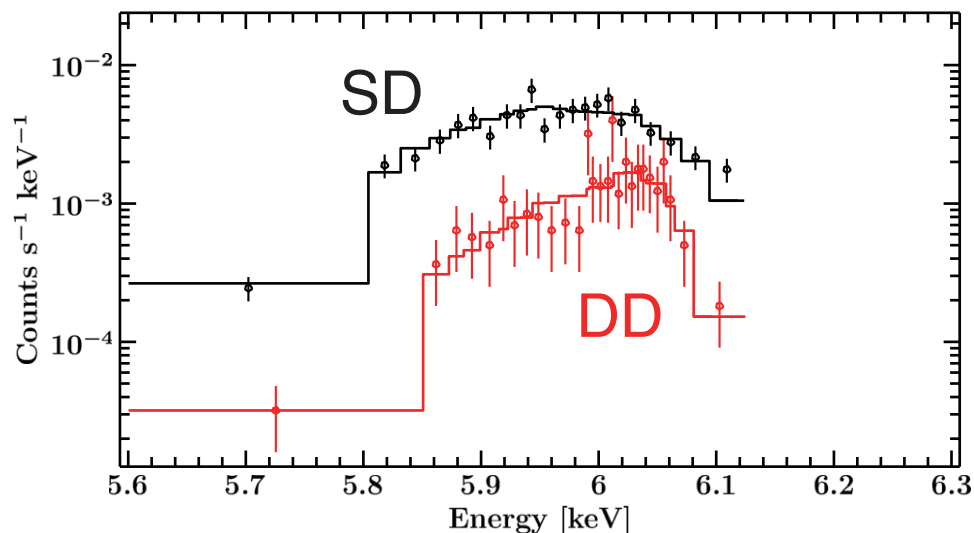
とは言え、決着をつけたい

将来の観測への期待

- ^{55}Fe (^{55}Co) 崩壊後の Mn Ka



Athena/X-IFU simulation



Seitenzahl+2015

- 重力波: LISA ... また次の機会に!