

# 星の進化と超新星爆発：現状と課題

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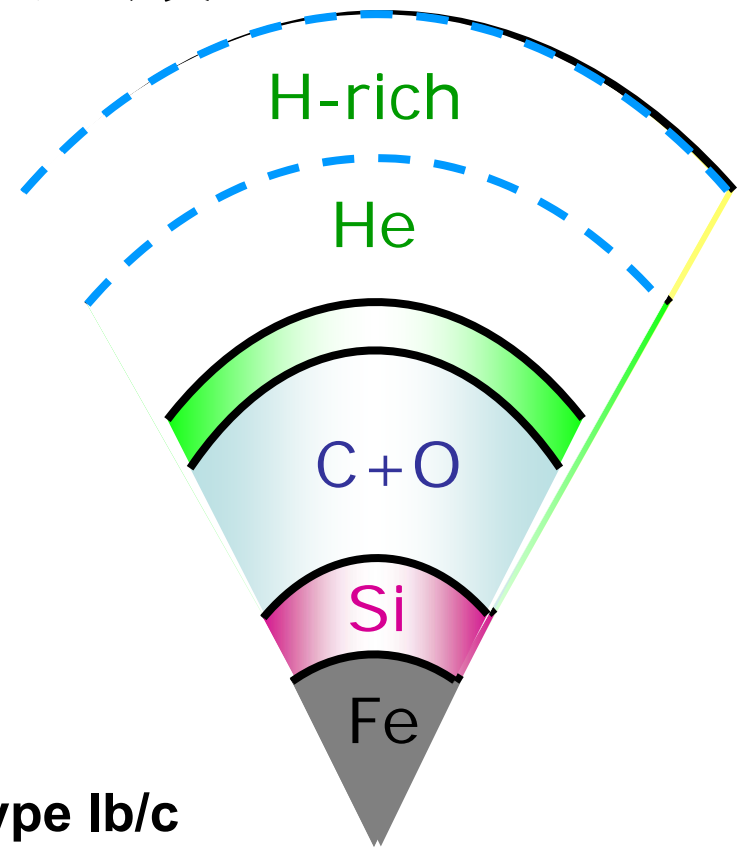
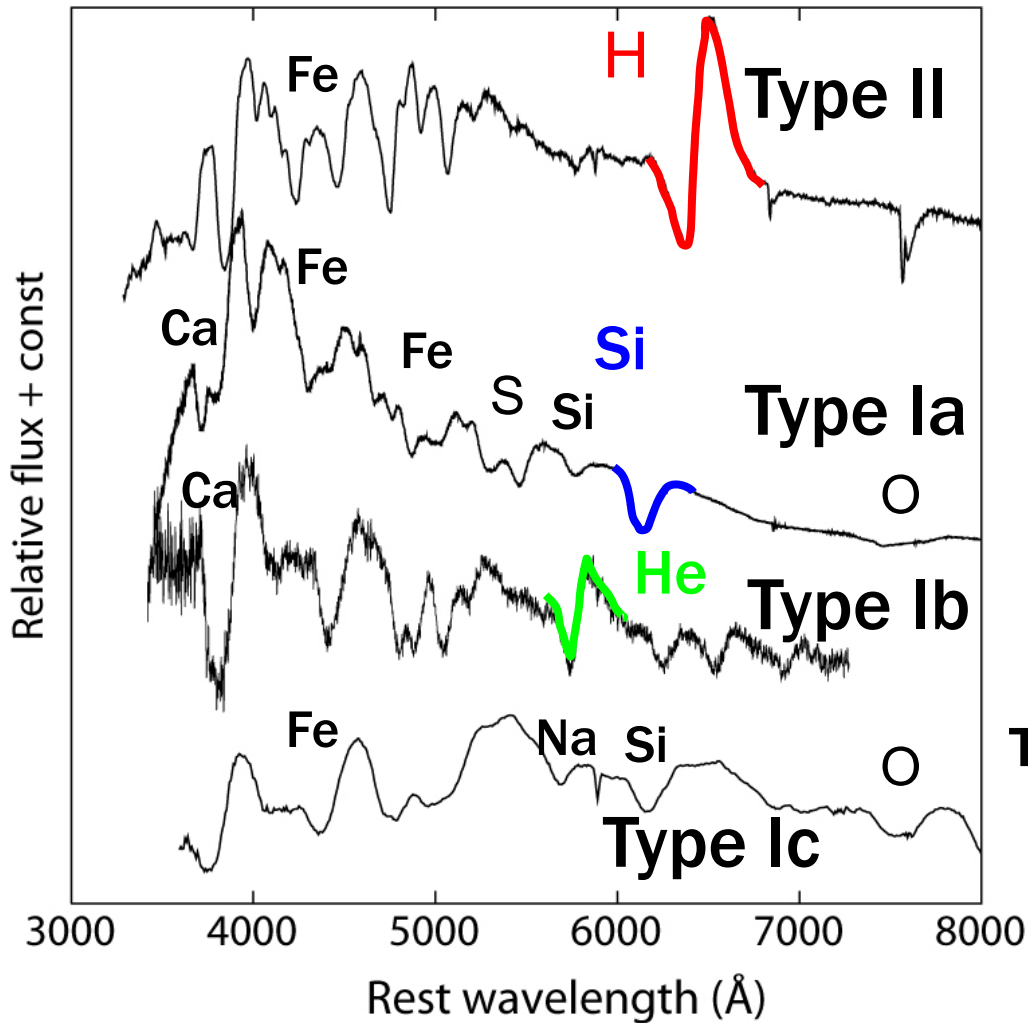


# Working Hypothesis on Pop III Stars

- $M_{\text{ms}} \sim 20 - 100M_{\odot}$ .  
→ Core-Collapse Supernovae.
- $M_{\text{ms}} \sim 100 - 300M_{\odot}$ .  
→ Pair-Instability Supernovae.
- $M_{\text{ms}} \sim 300 - 1000M_{\odot}$ .  
→ Core-Collapse Supernovae.

**A possibility of low mass stars (須田さん講演)。**

# 超新星タイプ分類

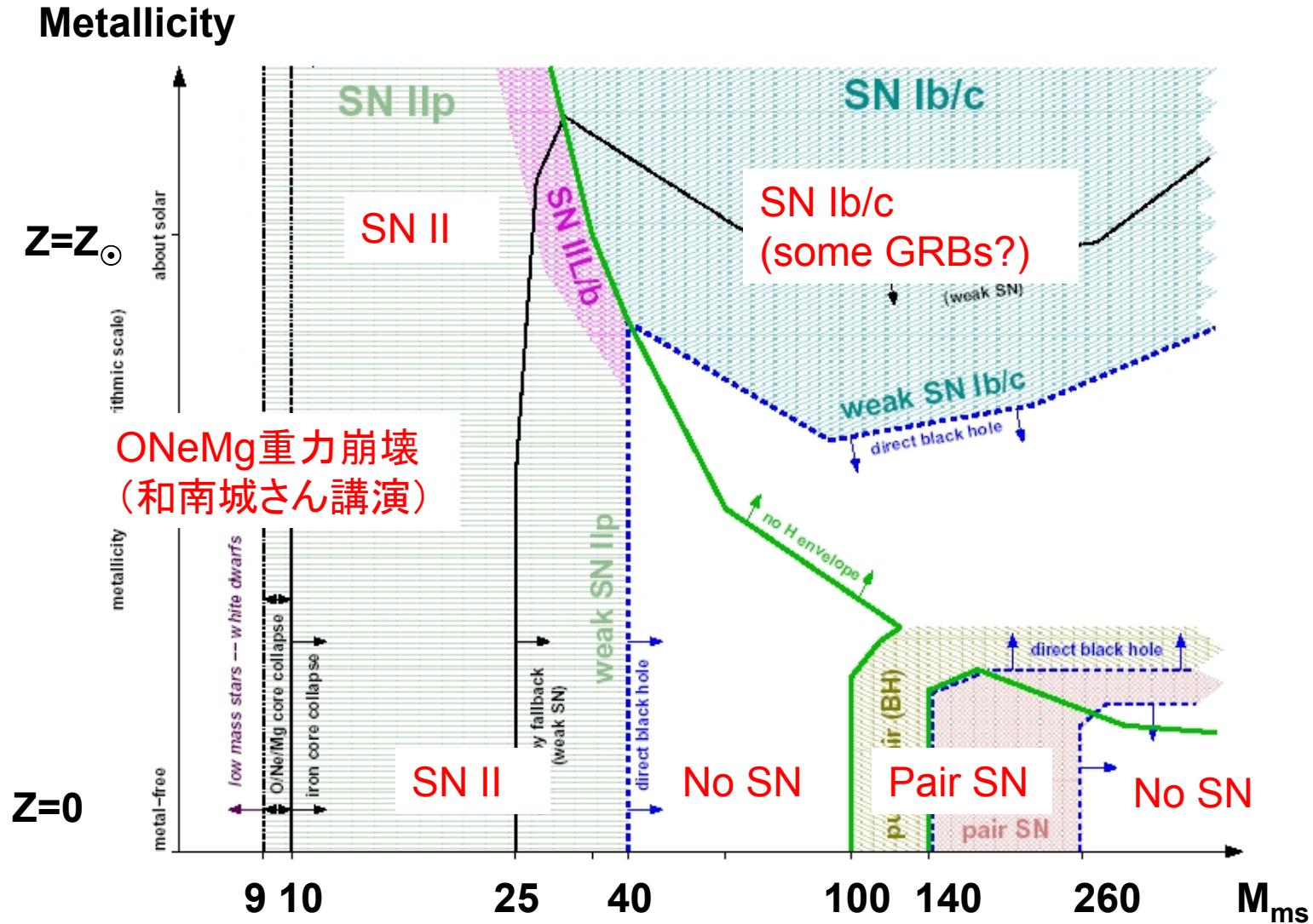


Type Ib/c

Massive ( $> \sim 30 M_{\odot}$ ) + metal  
 => Wind

Less massive or low metal  
 => Close binary

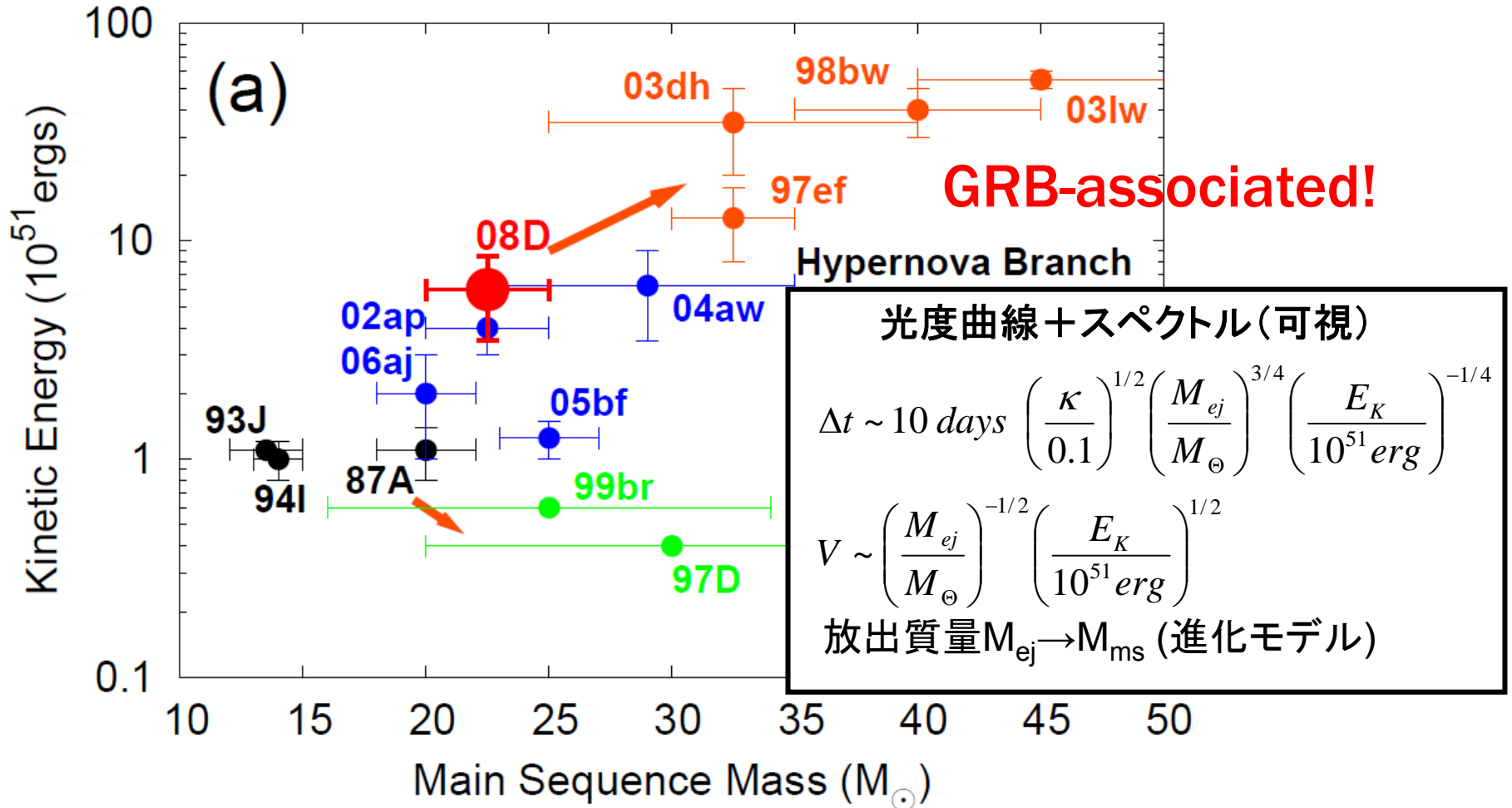
# End products of single stars (w/o rotation)



Heger & Woosley 2002 (similar results by other researchers, e.g., Umeda-san)

# $M_{\text{ms}}$ vs $E_K$ (Kinetic Energy)

**NOTE: biased sample!**



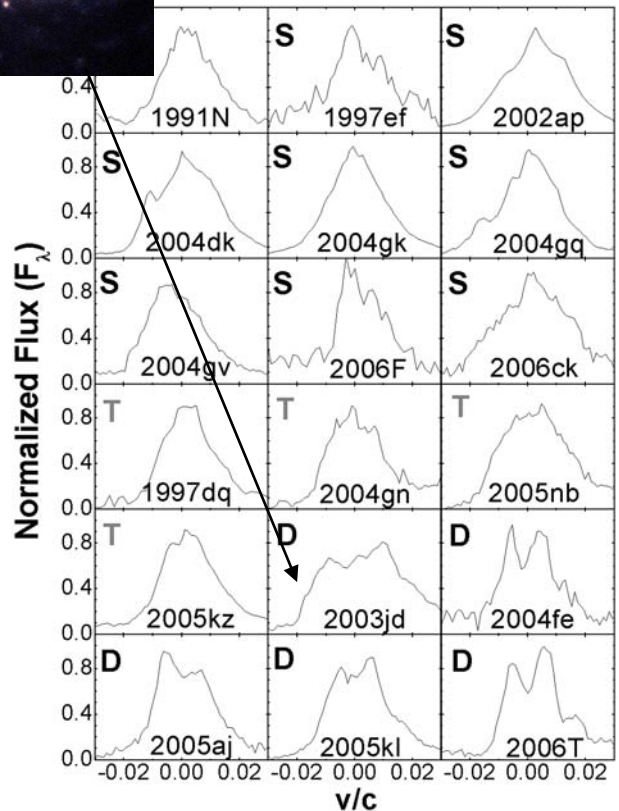
# Explosion Geometry of CC-SNe

- Core-collapse (CC) SNe are NOT spherical in general.

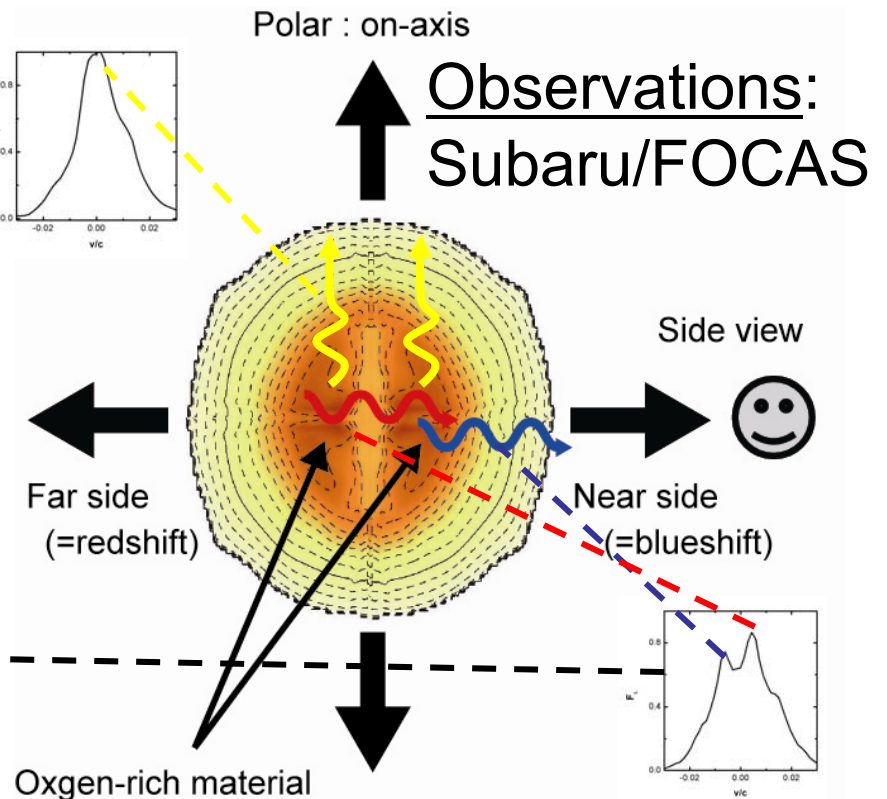
KM, Kawabata+, 2008, Science, 319, 1220



Spectra @ 1 year for 18 SNe



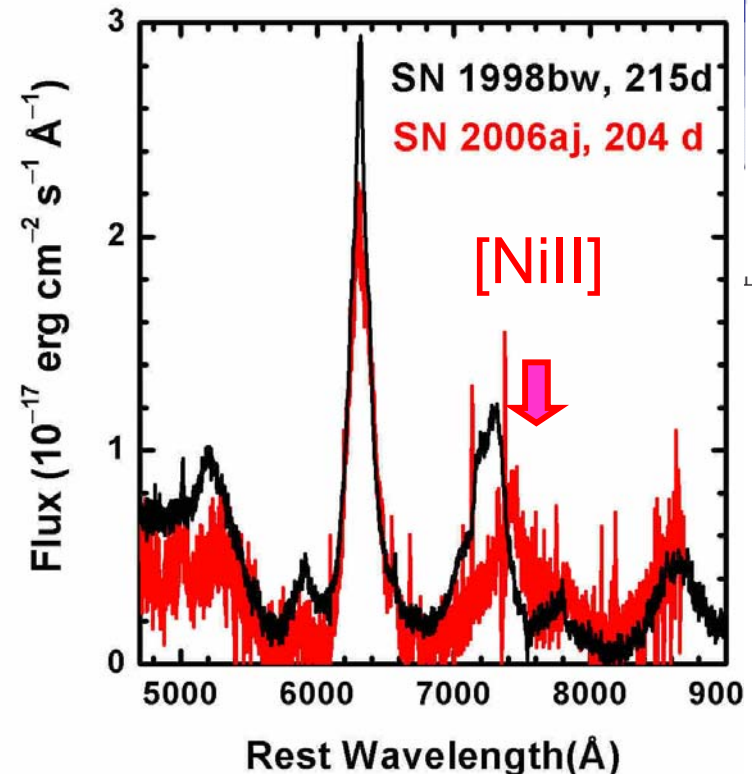
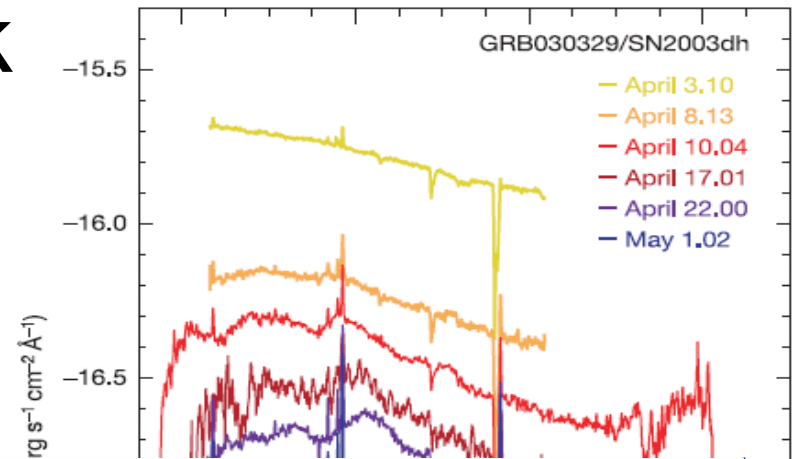
爆発理論とのつきあわせ。



# SN $\leftrightarrow$ GRB/XRF Link

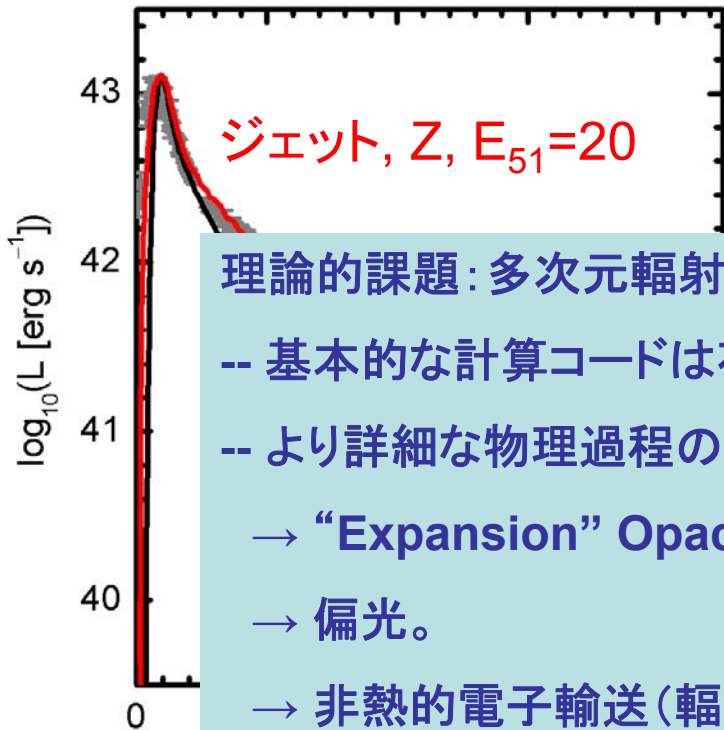
“ガンマ線バースト”

- To date 4 examples.
  - Nearby weak (peculiar) GRB/XRF.
- 3 SNe with a GRB.
  - “hypernova” (large Vel.).
  - $E_{51} > 10$ ,  $M_{\text{ms}} \sim 40M_{\odot}$ .
- 1 SN with a XRF.
  - $E_{51} \sim 2$ ,  $M_{\text{ms}} \sim 25M_{\odot}$ .
  - NS formation, not a BH?
    - N-rich  $^{58}\text{Ni}$  detected.  
KM+ 2006, ApJ, 658, L5



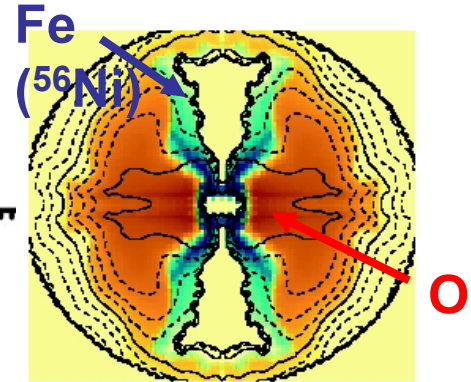
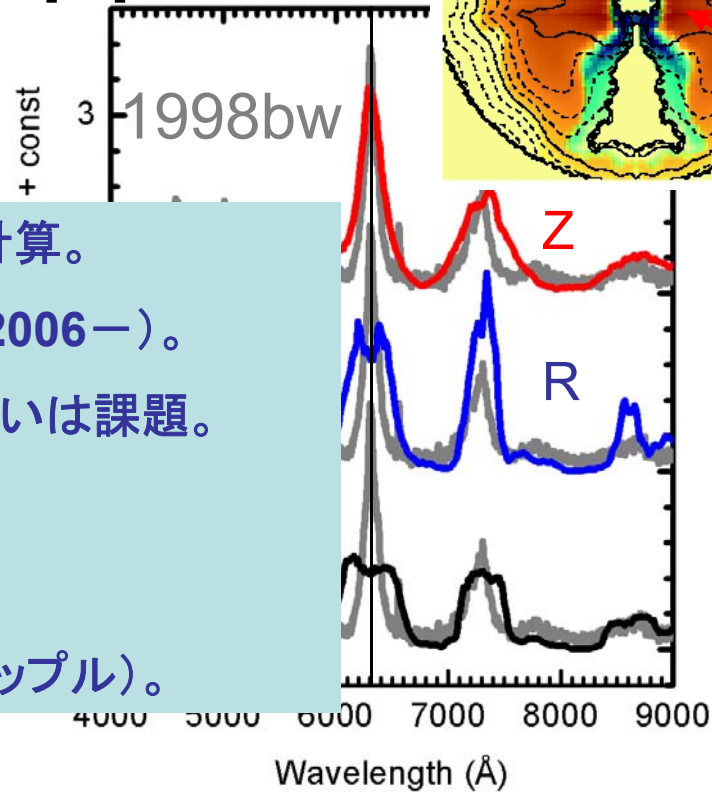
# GRB-SNe: Highly Jet-like explosion?

KM 2006, ApJ, 644, 385; KM+ 2006, ApJ, 640, 854;  
 KM+ 2006, ApJ, 645, 1331; Tanaka, KM+ 2007, ApJ, 668, L19



理論的課題: 多次元輻射輸送計算。  
 -- 基本的な計算コードは存在(2006-)。  
 -- より詳細な物理過程の取り扱いが課題。  
 → “Expansion” Opacity。  
 → 偏光。  
 → 非熱的電子輸送(輻射とカップル)。

[O I] 6300, 6363



$$V(\text{weeks}) \sim M_{ej}^{-1/2} E_K^{1/2}$$

視線方向に沿った“Isotropic” E

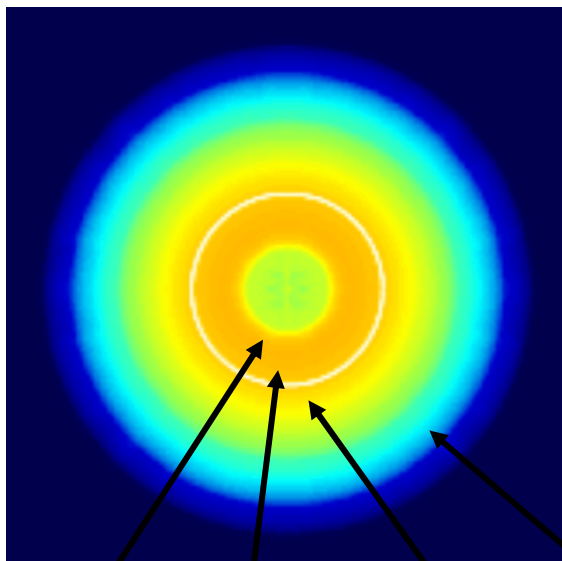
$$L(\text{year}) \propto M(^{56}\text{Ni}) \tau_\gamma \propto M_{ej}^2 / E_K \quad \text{全膨張物質での”instinsic” E}$$

# 一般のIbcに比べより“jet的”(KM+, 2008, Sci.)

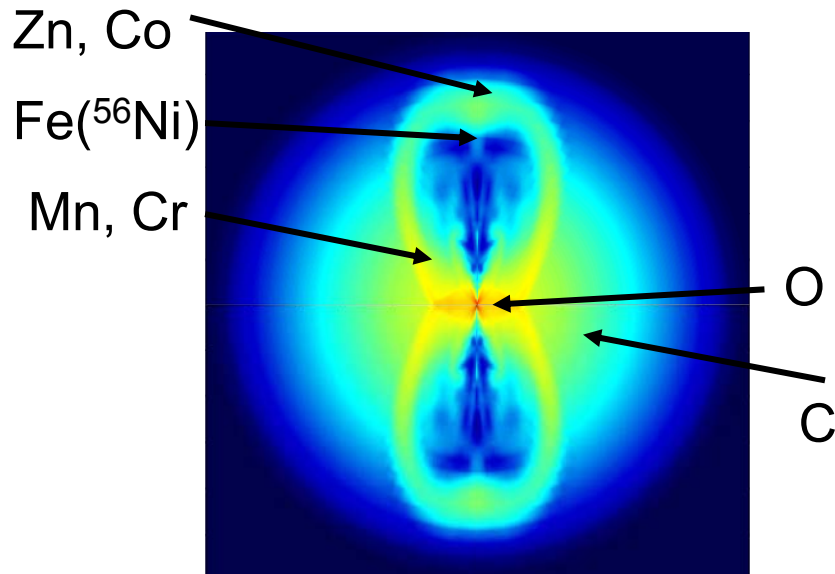


# Nucleosynthesis in “jet” CC-SNe

球対称



ジェットの



内側 Zn, Co, Ti → Fe(Ni) → Mn, Cr → O, C

$$T_{shock} \sim 24 E_{52}^{1/4} r^{-3/4}$$

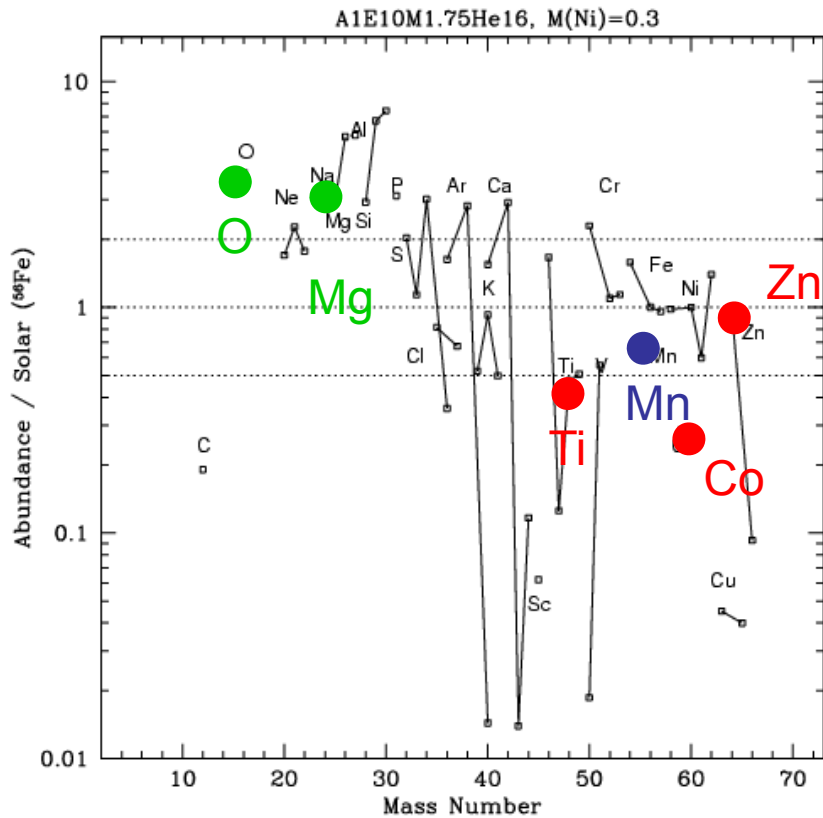
$$V \propto \sqrt{E/M}$$

E(isotropic) 大 → Tshock 大 & V 大

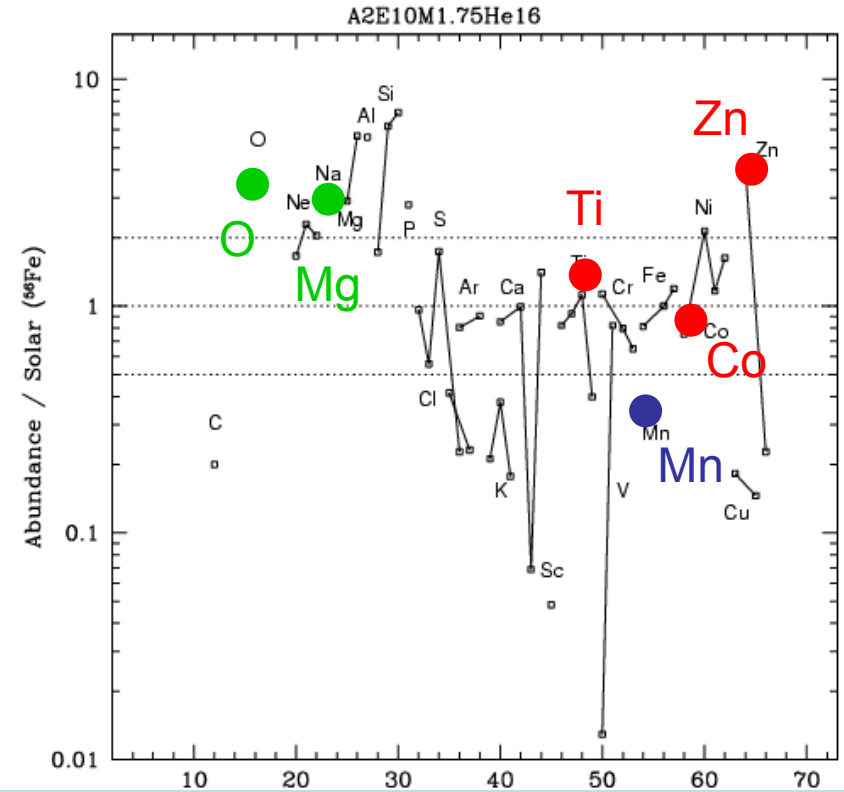
重い元素ほどより放出されやすい

KM+ 2002, ApJ, 565, 405; KM & Nomoto, 2003, ApJ, 598, 1163;  
 長滝さんの一連の仕事; 富永さんの仕事 “Tracer” Particle Method

# 球対称



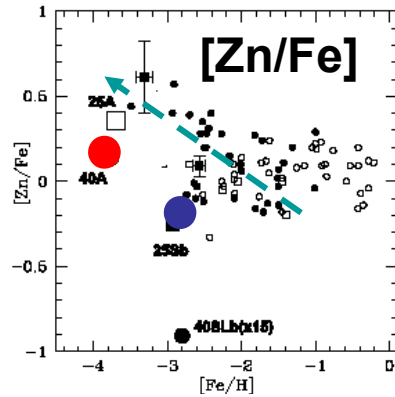
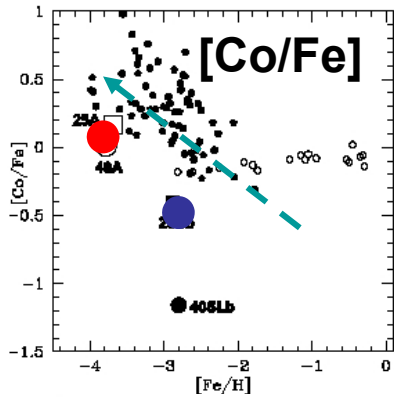
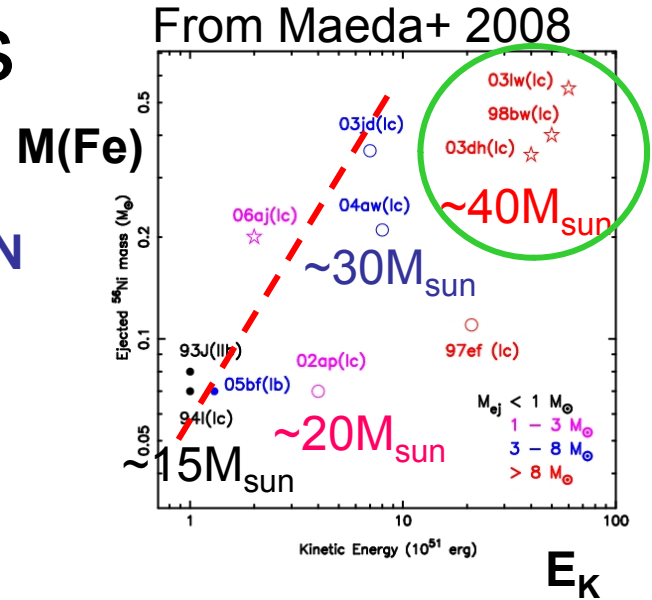
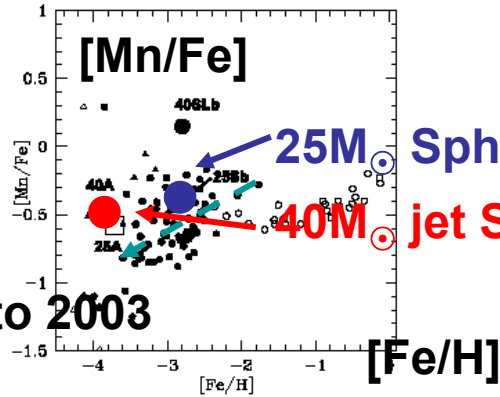
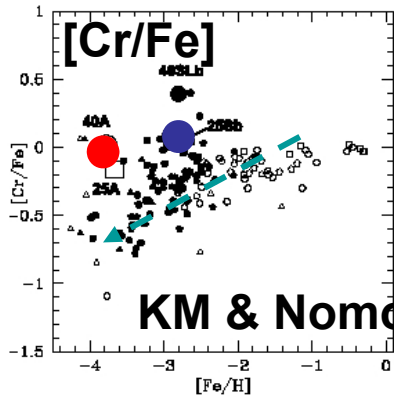
# ジェットの



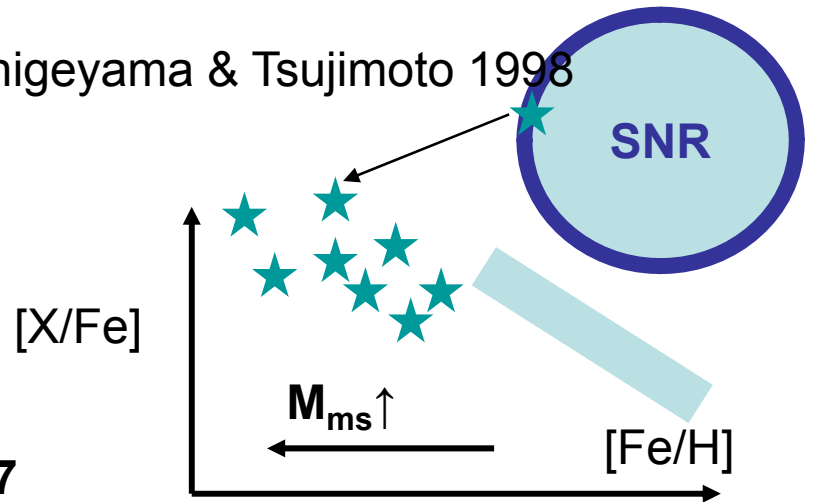
流体とカップルした元素合成計算が必要。  
爆発から衝撃波伝播までつなげた理論計算。

- (Zn,Co,Ti)/Fe↑, (Mn,Cr)/Fe↓
    - 銀河初期化学進化: 金属欠乏星、炭素過剰星
    - KM & Nomoto 2003; Tominaga, KM+ 2007, ApJ, 657, L77
- # 1次元の”Mixing & Fallback model”と同様の効果  
(Umeda & Nomoto 2002 Nat.; Iwamoto+ 2005 Sci.)

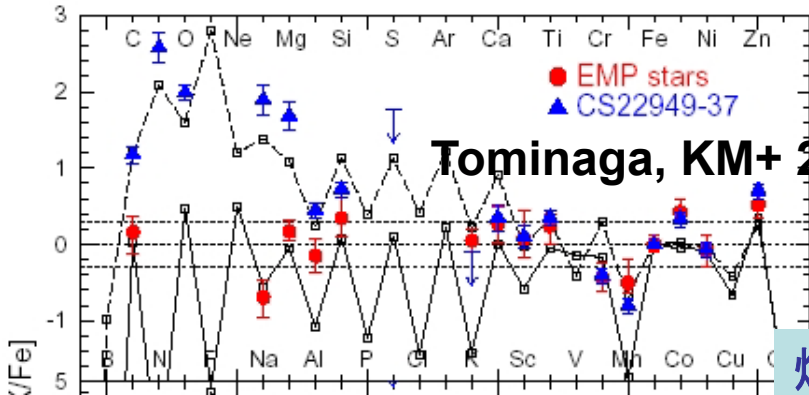
# Metal Poor Stars



Shigeyama & Tsujimoto 1998



$$[Fe/H] \propto \log\left(\frac{M(Fe) / M_{sun}}{E / 10^{51} \text{ erg}}\right) + const$$



**Tominaga, KM+ 2007**

**爆発モデル(元素分布) + 星形成シミュレーション**

# Metallicity Effect?

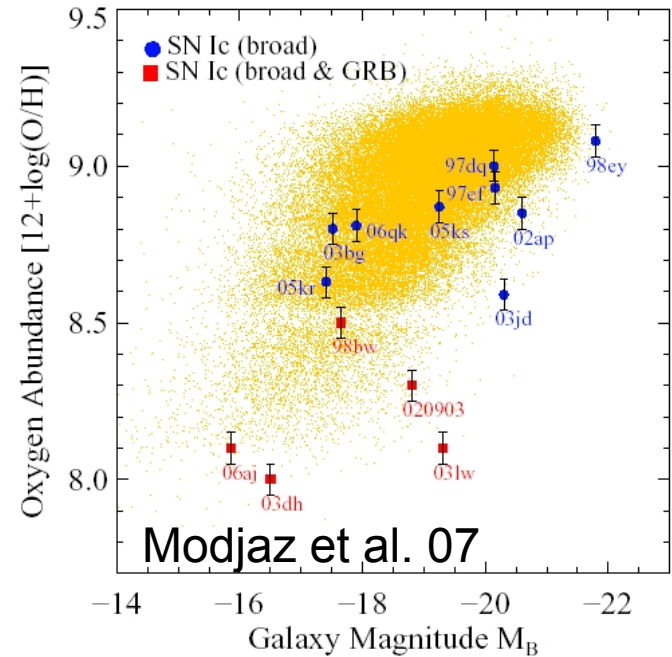
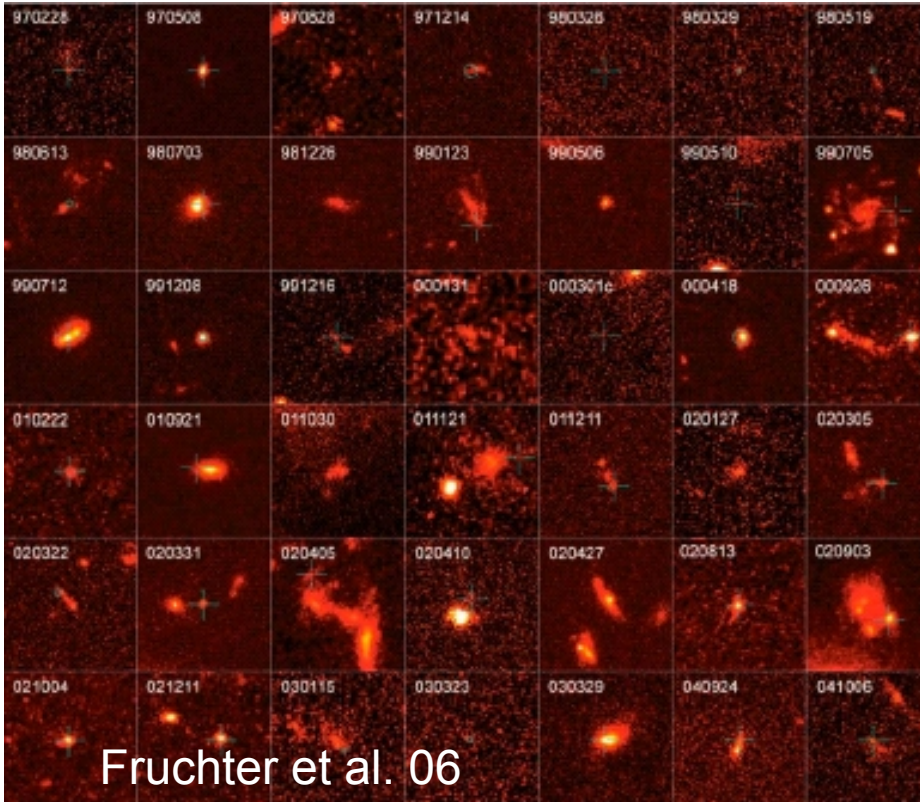


FIG. 5.— Host galaxy luminosity ( $M_B$ ) and host galaxy metallicity (in terms of oxygen abundance) of nearby broad-lined SN Ic (“SN Ic (broad)”; blue circles: this study) and broad-lined SN Ic connected with GRBs (“SN (broad & GRB)”; red squares: Stanek et al. 2007; Kewley et al. 2007). The oxygen abundances are in the Kewley & Dopita (2002) scale and represent the abundance at the SN position. Labels represent the SN names while one (“020903”) refers to its associated GRB. Yellow points are values for local star-forming galaxies in SDSS (Tremonti et al. 2004) and illustrate the empirical luminosity-metallicity ( $L-Z$ ) relationship for galaxies. Host environments of GRBs are less luminous and less metal-rich than host environments of broad-lined SN Ic where no GRB was observed. See text for details.

GRB hosts = Small & Faint

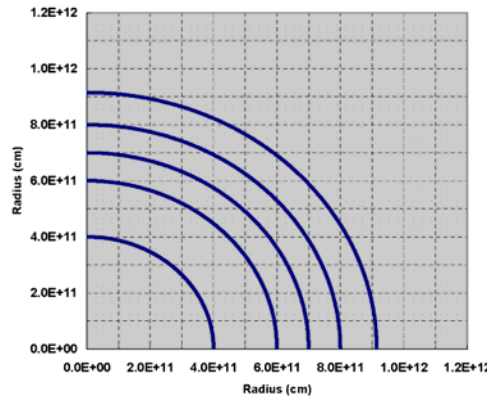
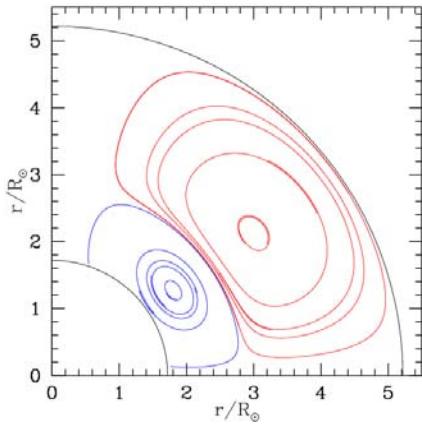
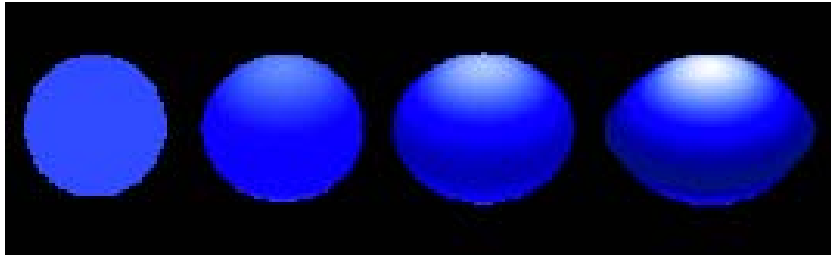
GRB hosts = Metal Poor

- 初代星が $\sim 20 - 100 M_{\odot}$ なら、GRBとして観測されるかも。

# Stellar Rotation and Metallicity?

By courtesy of M. Limongi

Increasing rotation  $\longrightarrow$

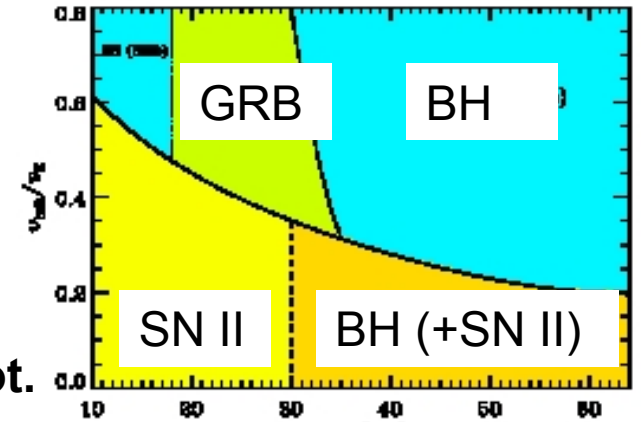


Yoon+ 2006

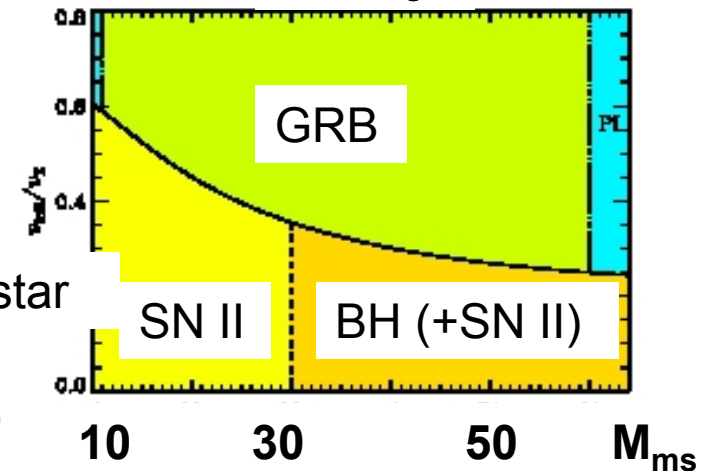
$0.1 Z_{\odot}$

Rapid rot.

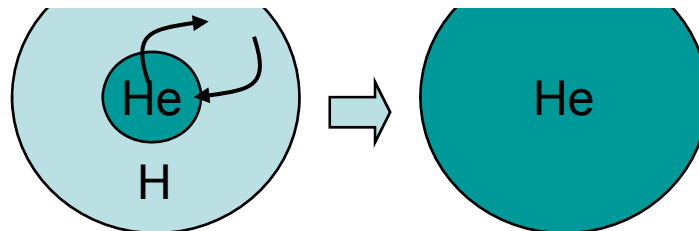
No rot.



$10^{-3} Z_{\odot}$



Single star GRB progenitor model: rapid rot. C+O star



回転の効果; 1次元から先へ。

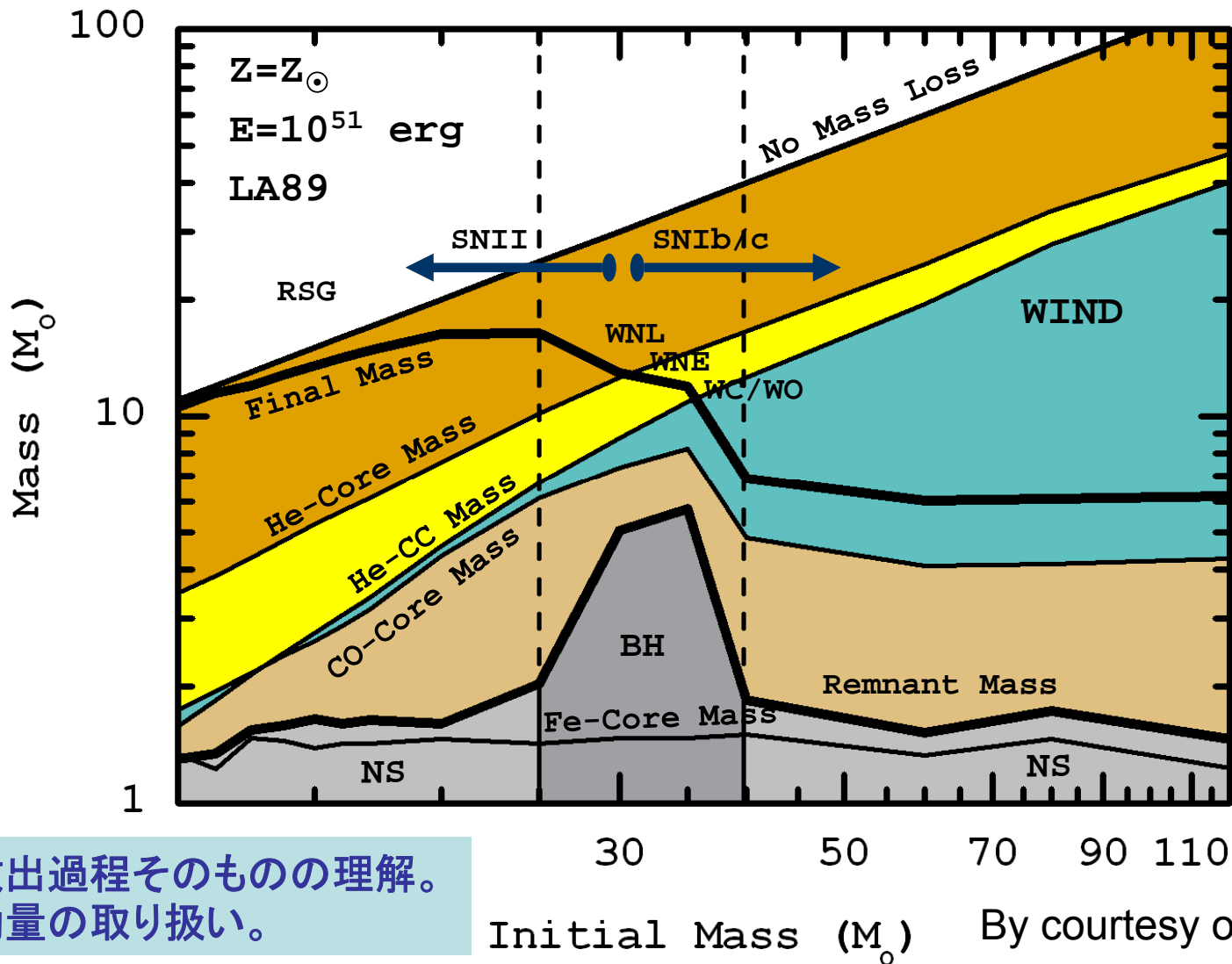
# Mass loss

Nugis & Lamers (2000) (NL00)

$$M_{dot} = 10^{-11} (L/L_{\odot})^{1.29} Y^{1.7} Z^{0.5} M_{\odot} / \text{yr}$$

Langer (1989) (LA89)

$$M_{dot} = 10^{-7} (M/M_{\odot})^{2.5} M_{\odot} / \text{yr}$$



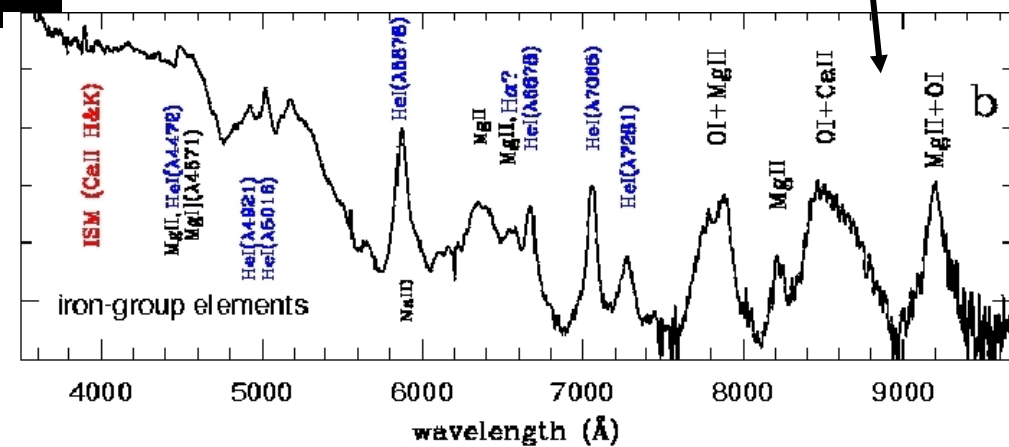
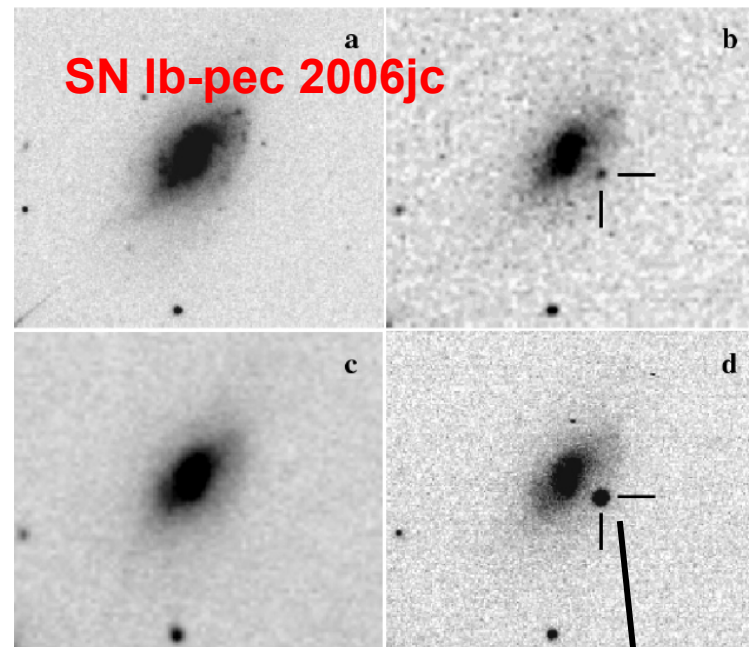
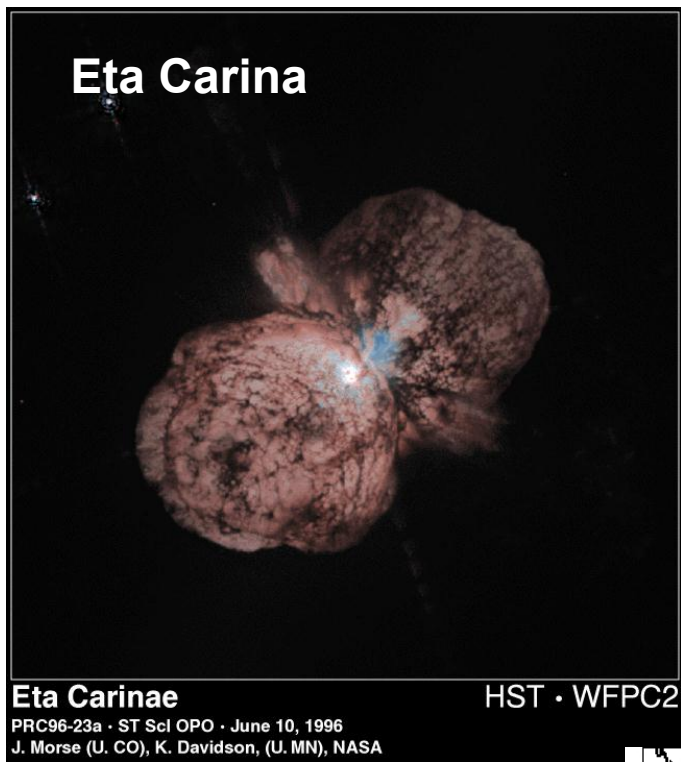
質量放出過程そのものの理解。  
角運動量の取り扱い。

By courtesy of M. Limongi

# Dynamical Mass Loss...

Pastorello+ 2007, Nat.

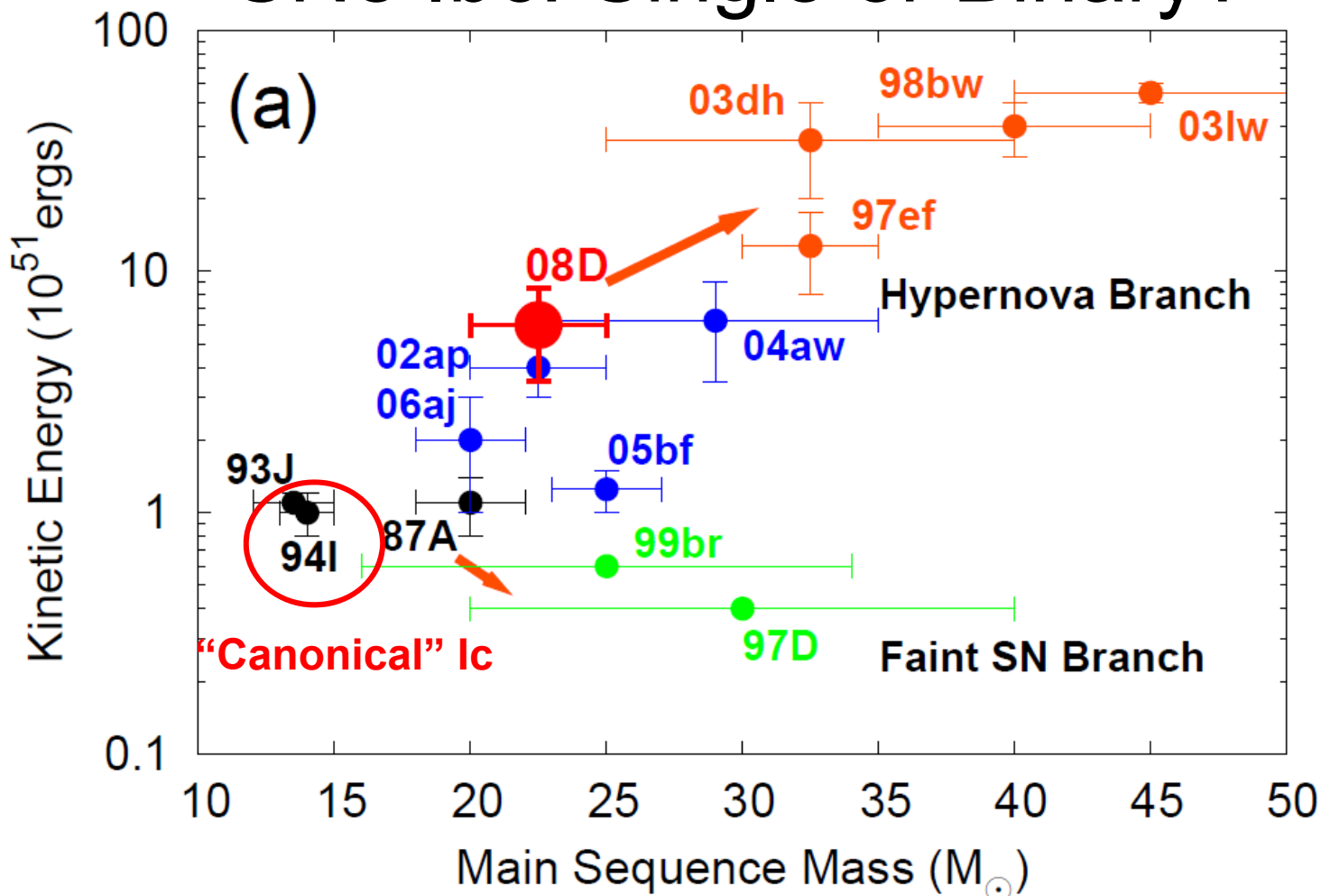
Tominaga+ 2008 他



Line-driven以外の質量放出の理解と進化理論での取り扱い。

超新星周りの星周物質の構造  
 ⇔ 質量放出の歴史。  
 放射流体力学計算。

# SNe Ibc: Single or Binary?



連星進化: 簡単なモデルから先へ。  
最近の”single star”進化の研究結果。  
→ Coenvelope evolution などは、シミュレーションでないと明らかには出来ないだろう。



# Summary

- ここ数年の超新星観測データの急激な増大⇔現在の理論の様々な限界。
  - 進化: 質量放出、回転、連星。
  - 爆発と元素合成: 非対称性。超新星+ガンマ線バーストの理解。流体+詳細な核反応ネットワーク。
  - 放射輸送: 多次元計算。輻射流体。
- 第一世代星。
  - 様々な可能性:  $M_{ms} \sim 20 - 100 M_{\odot}$ ?  $> 300 M_{\odot}$ ?
  - 観測で検出できる理論予測が今後の課題。
    - 元素合成+星形成+放射。