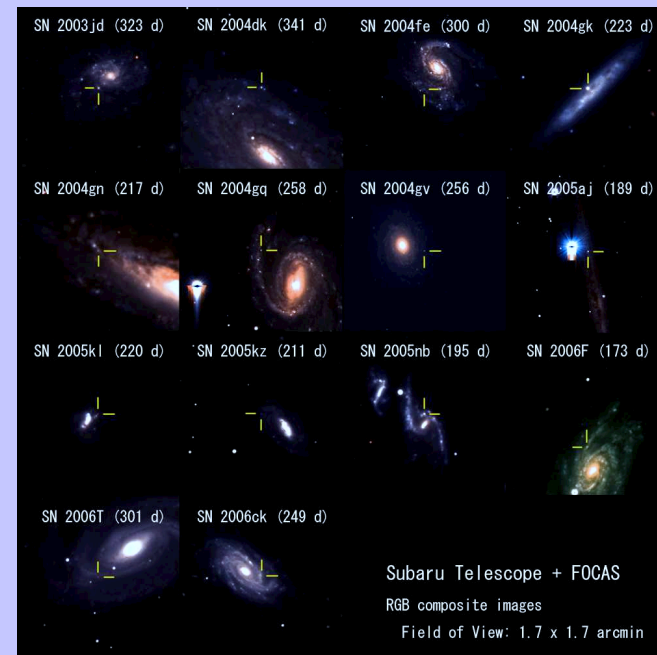
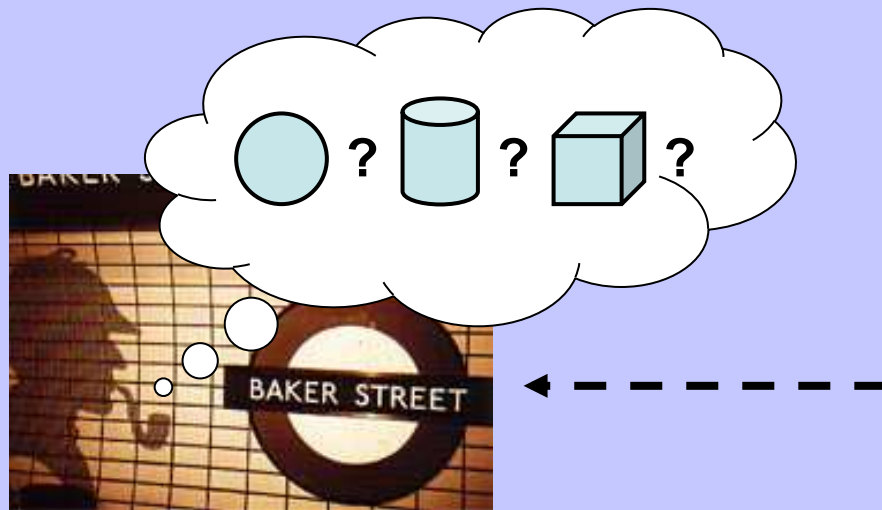


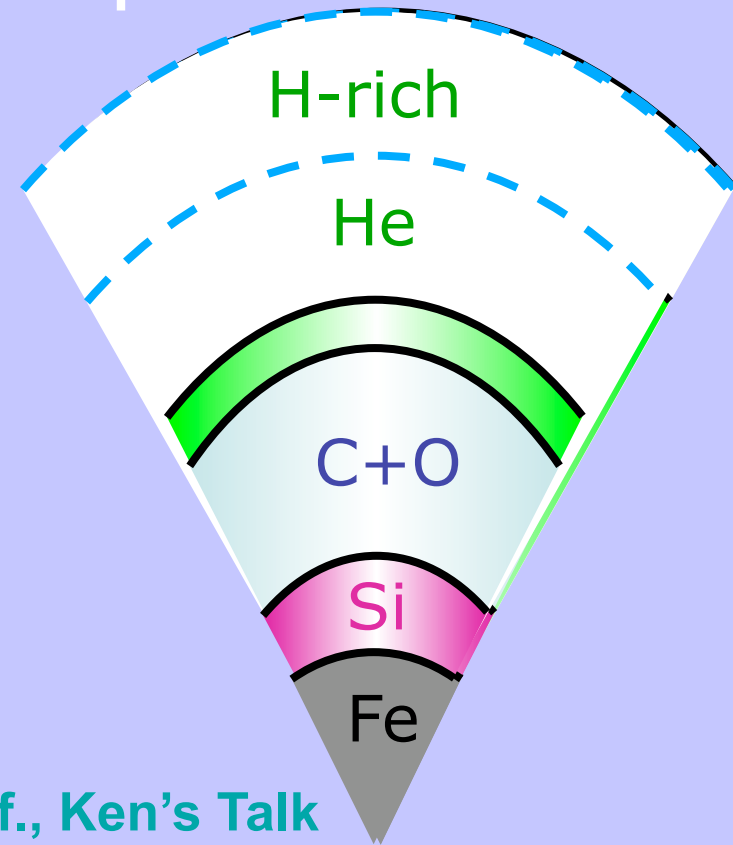
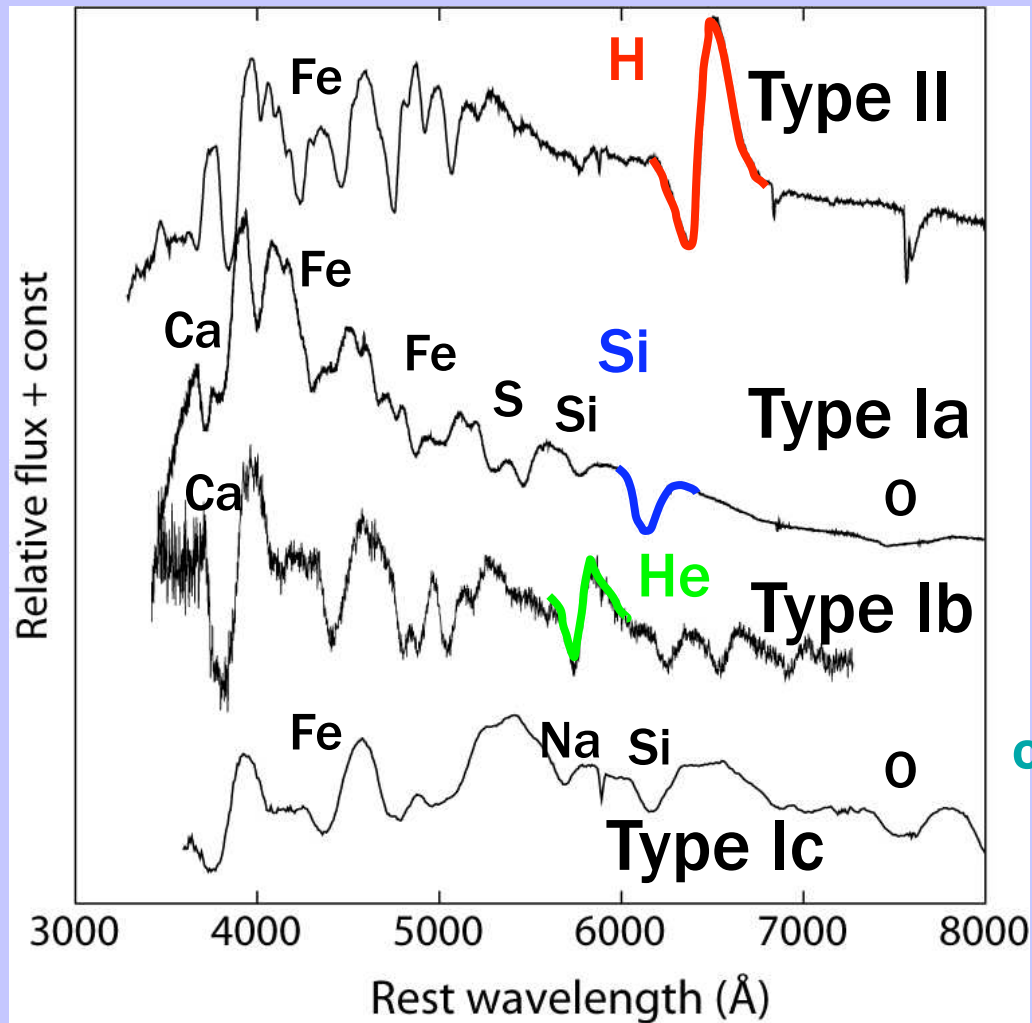
# Asymmetry and Other Hints for the Supernova Explosion Mechanism



Keiichi Maeda (IPMU)

IPMU Focus Week, 2008.11.17-21

# Stripped-envelope supernovae



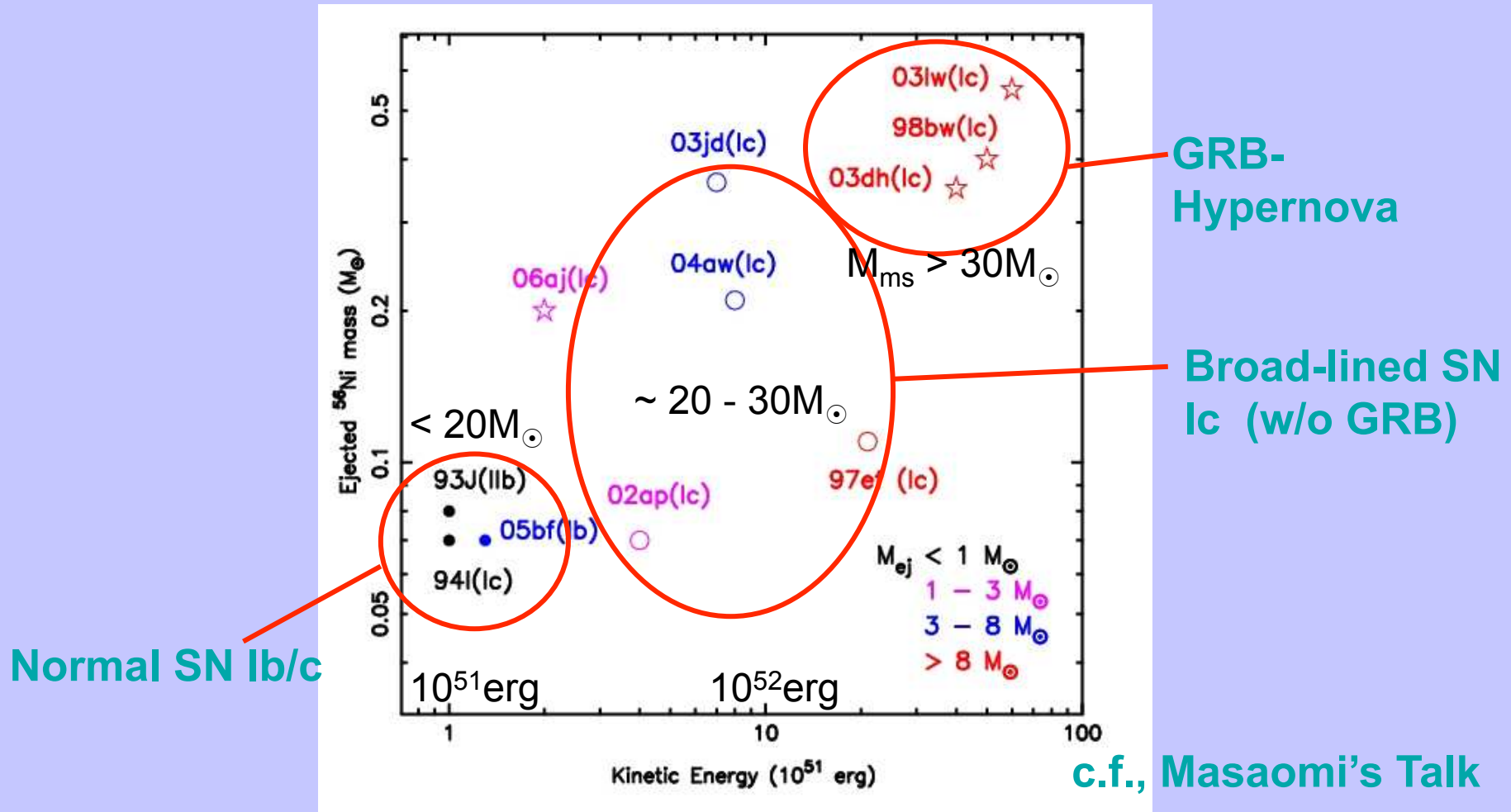
c.f., Ken's Talk

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

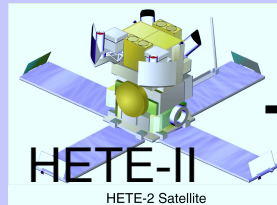
Less massive or low metal  
=> Close binary

# General picture: supernova properties

Fig. 1 of Maeda et al. 2008, Science, 319, 1220



Most massive stars:  $M_{\text{ms}} > \sim 30M_{\odot}$



GRB030329



Hjorth et al. 2003

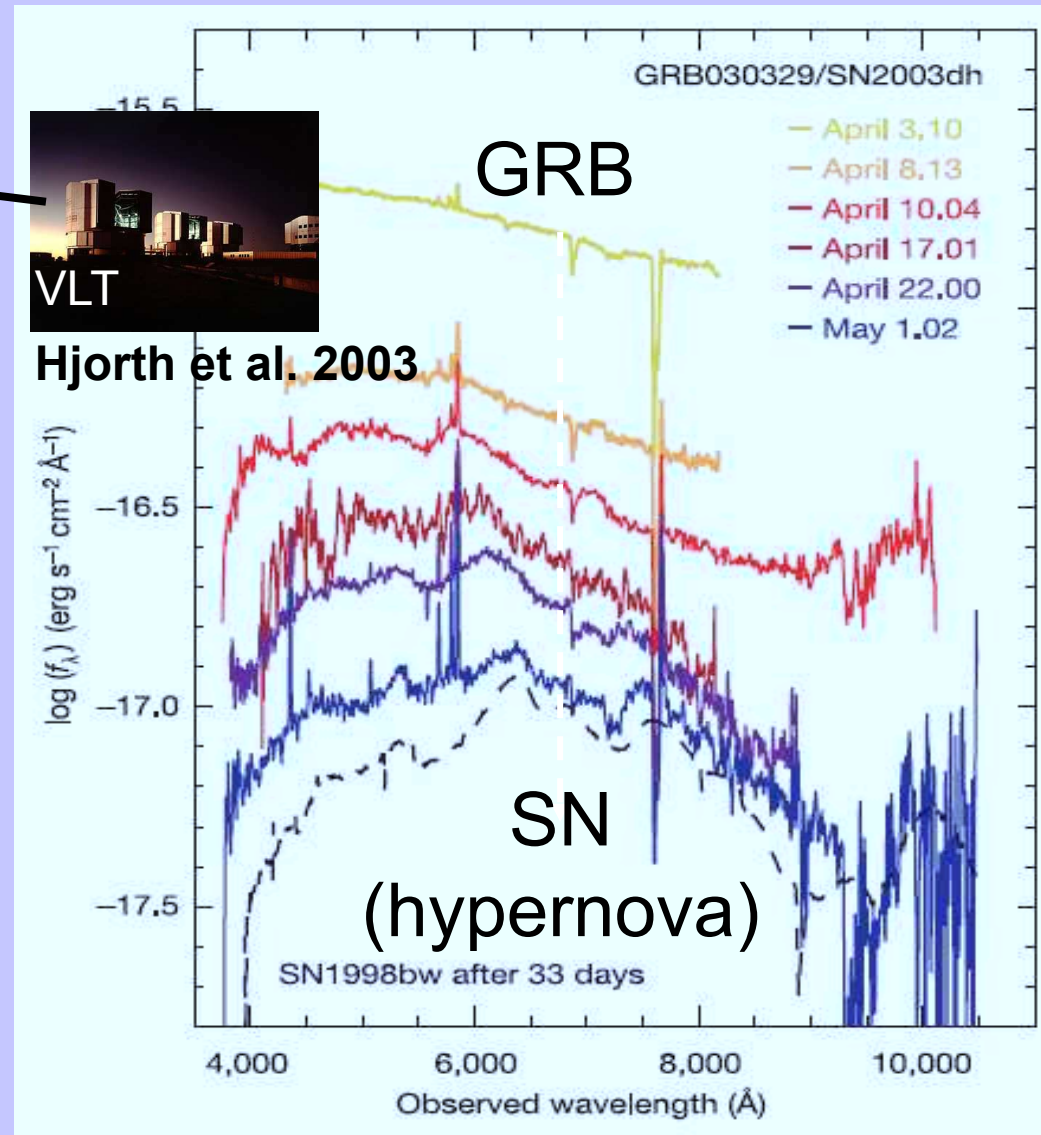


Kawabata et al.  
2003

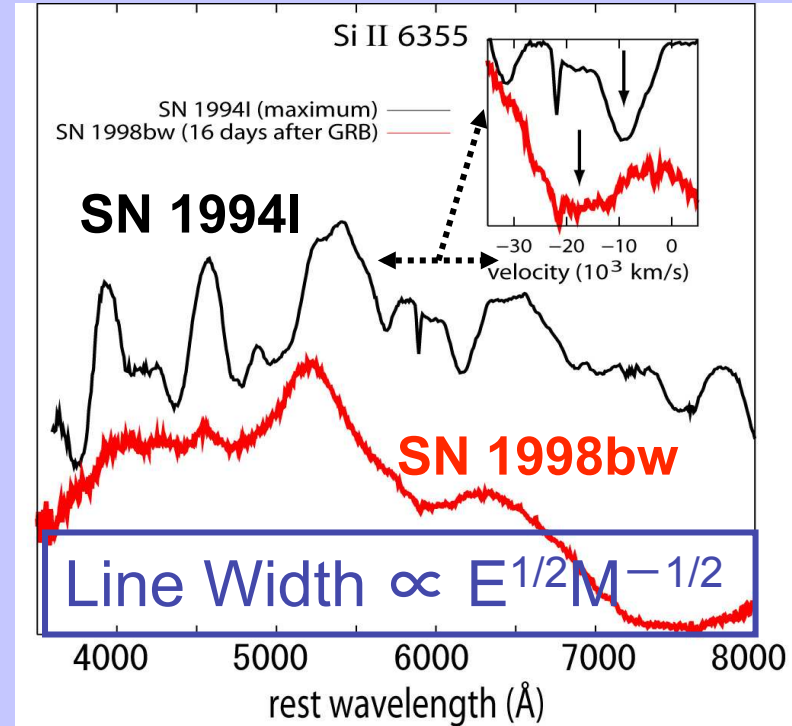
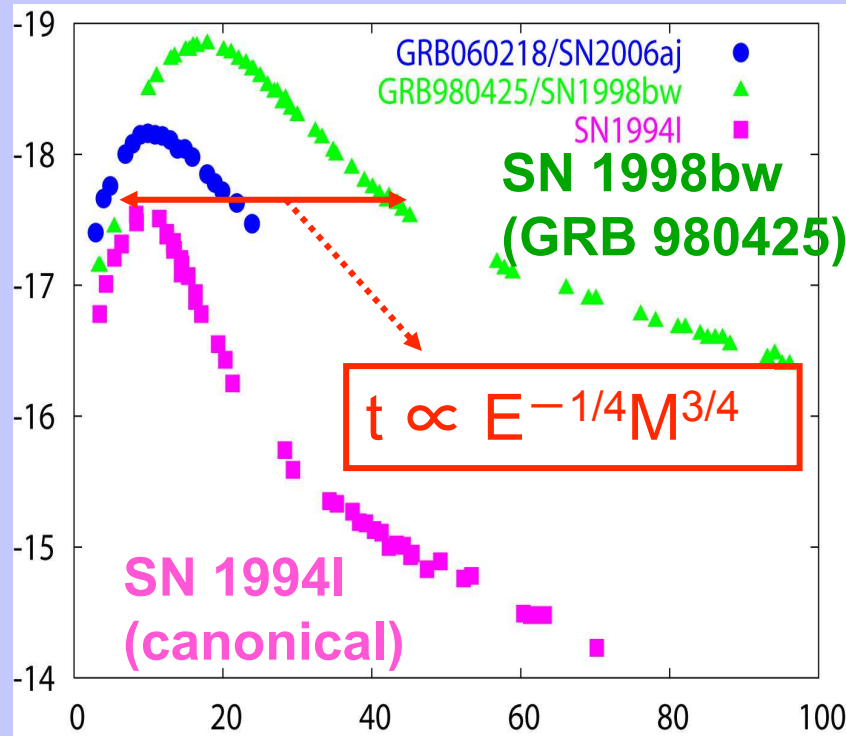


Stanek et al. 2003

A class of GRBs are associated with SNe.



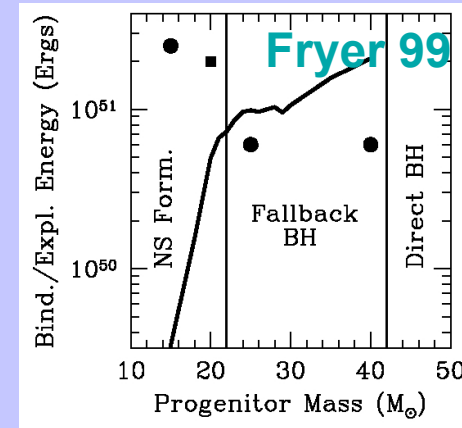
# GRBs, Hypernovae, ... and Black holes?



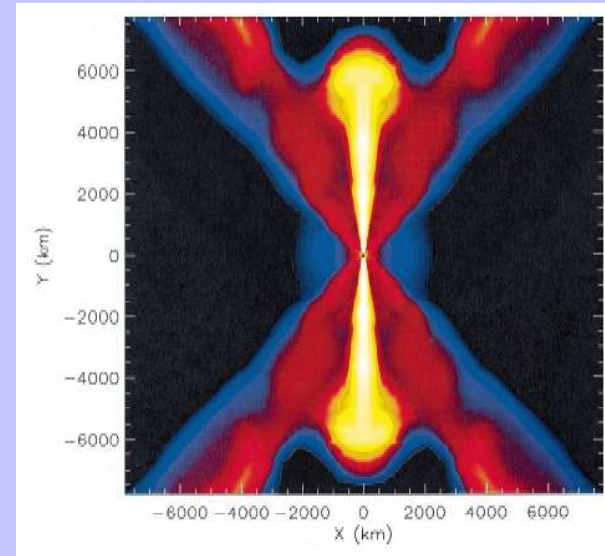
Prototypical GRB-SN 1998bw:

$$\left\{ \begin{array}{l} E_K \sim 5 \times 10^{52} \text{ erg} \rightarrow \text{''Hypernova''} \\ M_{\text{ej}} \sim M_{\text{C+O}} - M_{\text{rem}} \sim 10 M_{\odot} \end{array} \right.$$

$$\rightarrow M_{\text{ms}} \sim 40 M_{\odot} \rightarrow \text{''Black Hole?''}$$



# Jet-like, collimated explosion?



MacFadyen & Woosley 1999

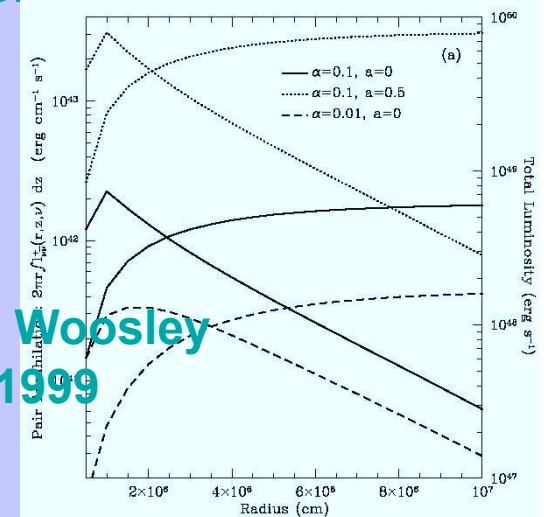
- **Black Hole + Accretion Disk?**

- $E \sim \epsilon M c^2 \sim 10^{52} \text{ erg } (\epsilon/0.01)(M/M_{\odot})$

- Jet-like Explosion?

e.g., “Collapser model”, Woosley 1993

$\nu + \bar{\nu}$  as the energy source. ← not that efficient?

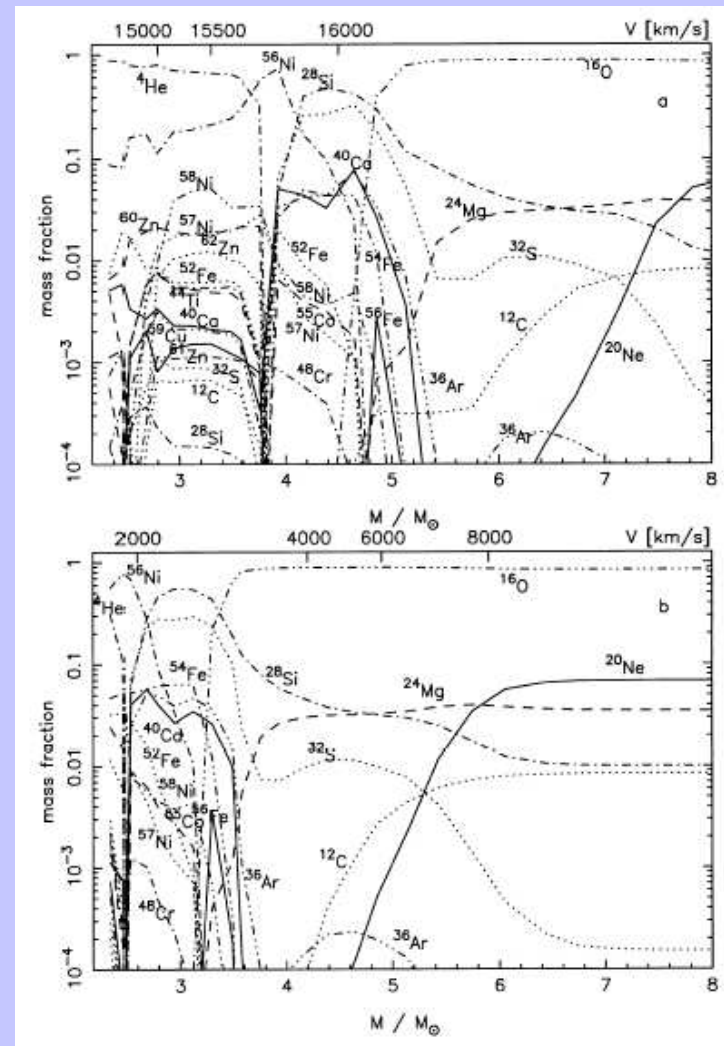
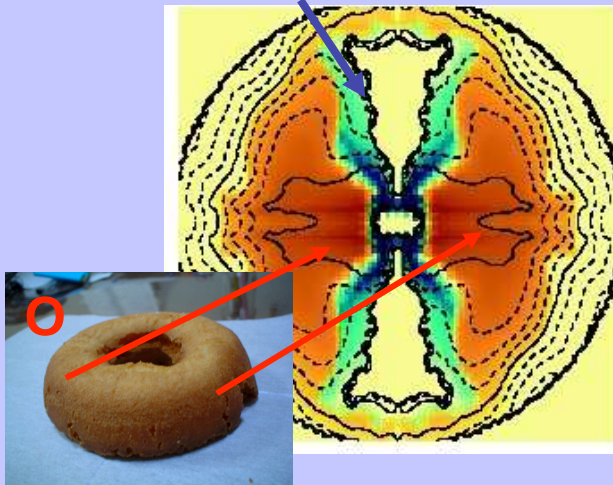


Popham Woosley & Fryer 1999

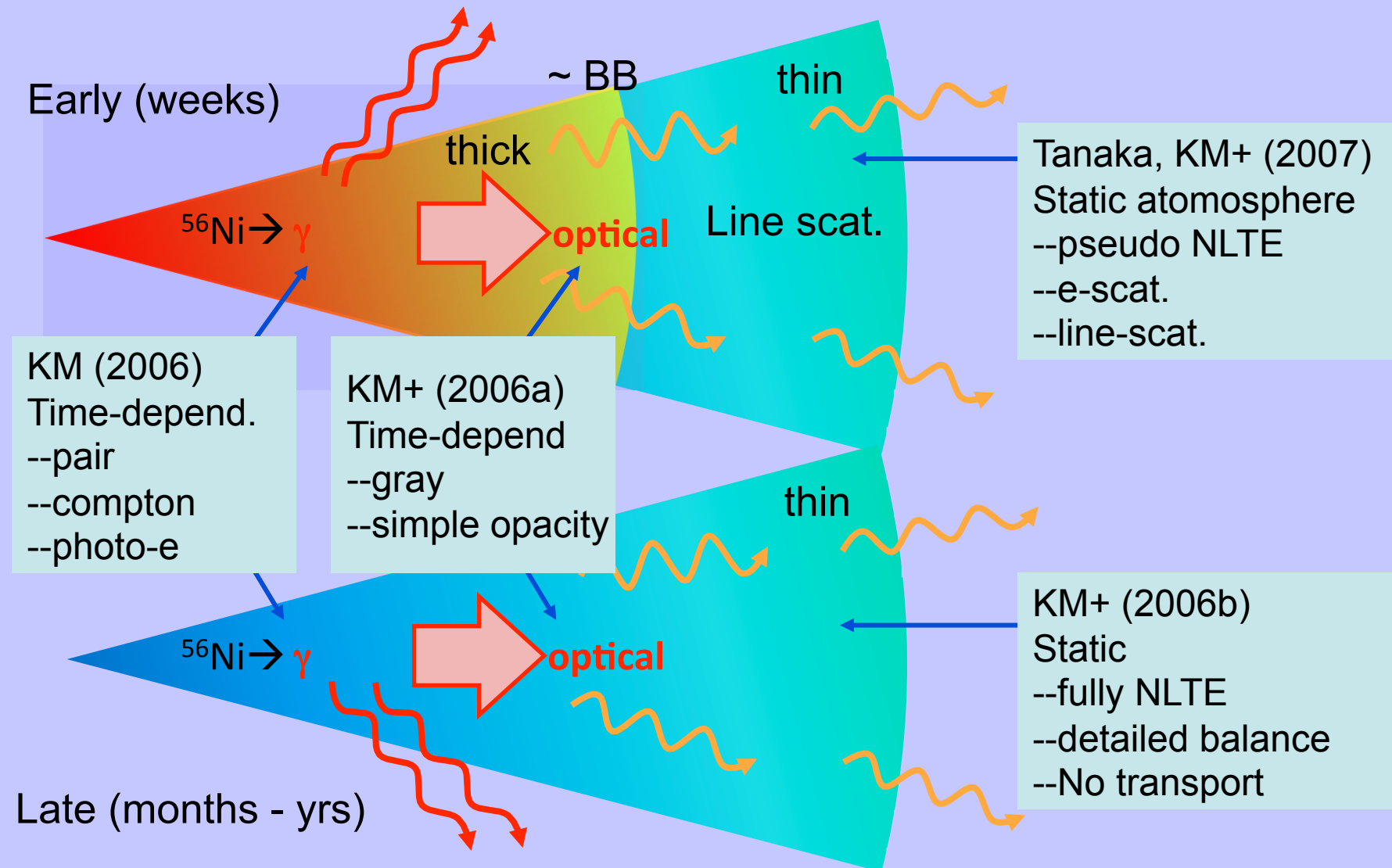
# Nucleosynthesis in aspherical explosions

- Multi-D Hydro + Nucleosynthesis: Maeda et al. 2002,  
ApJ, 565, 405
  - by S. Nagataki.
  - by myself and Nozomu.
  - by Chris and Aimee.

Fe ( $^{56}\text{Ni}$ )

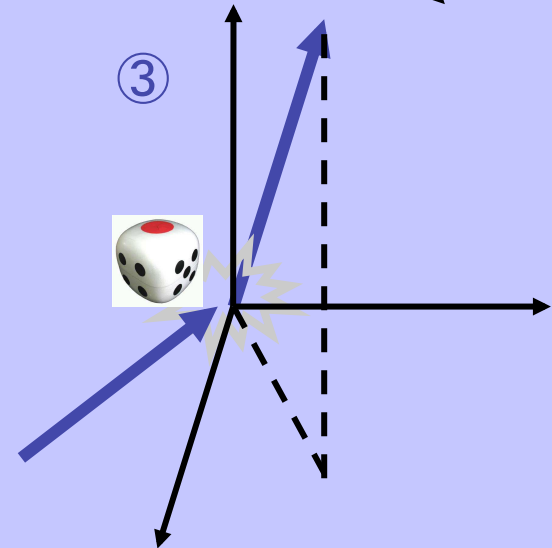
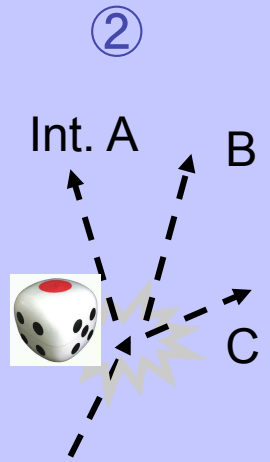
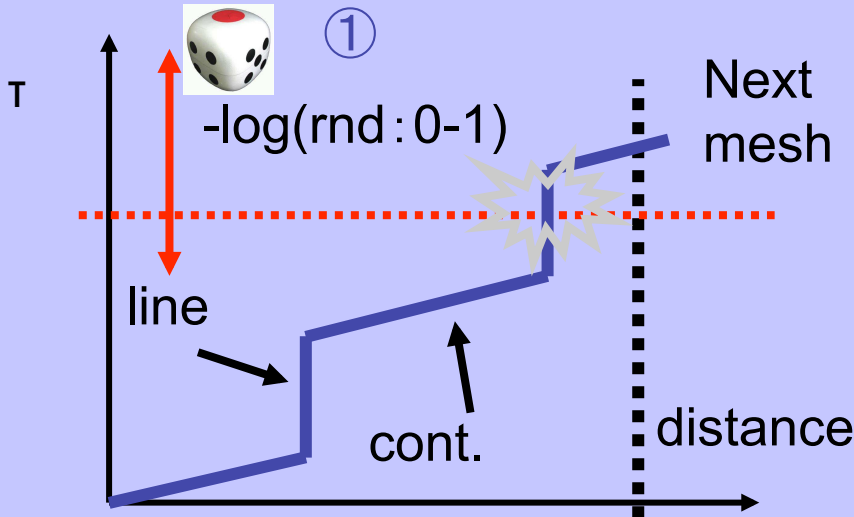
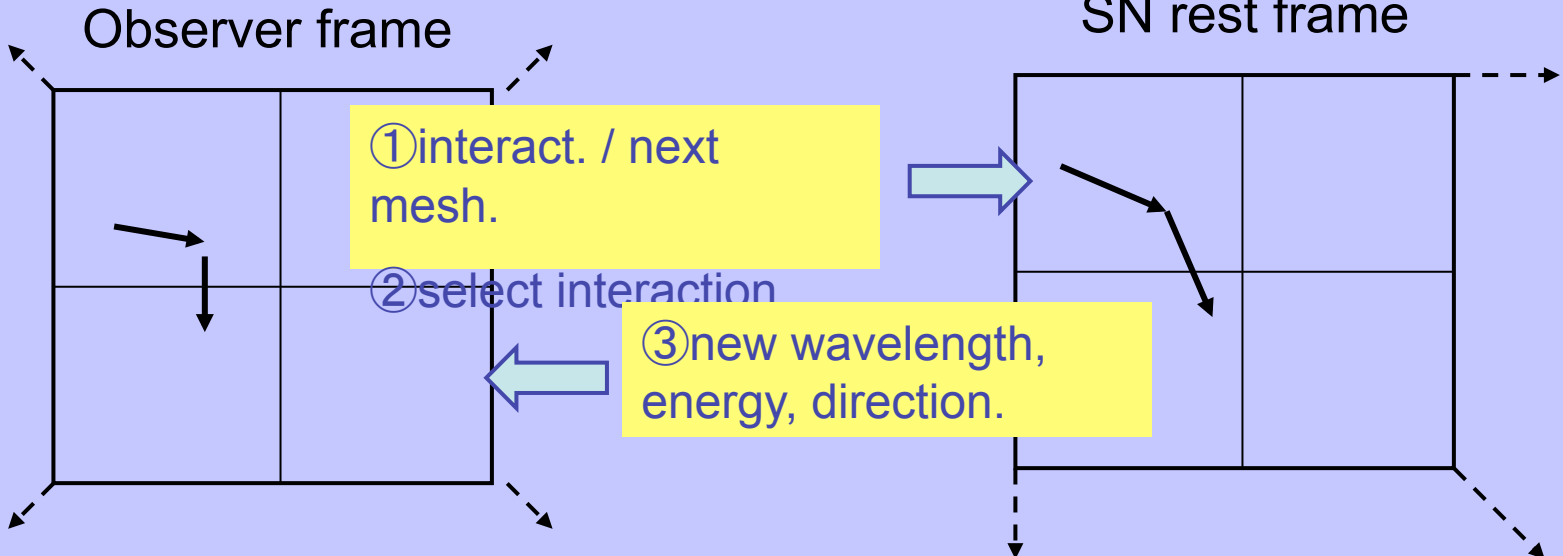


# 待... SupernovA MUlti-dimensional RAdiation transfer

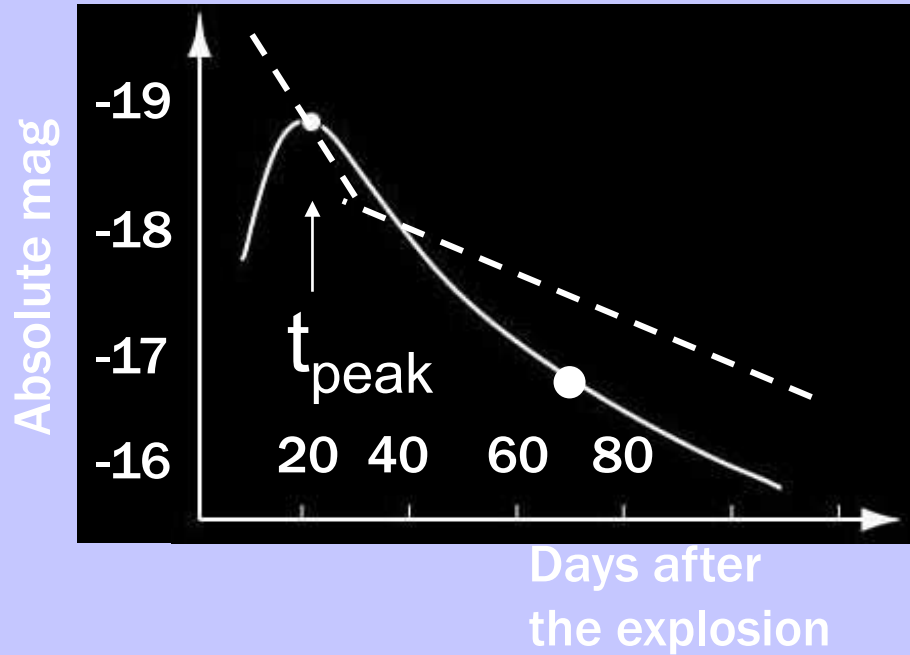




# Monte-Carlo Transfer



# $^{56}\text{Ni}/\text{Co}/\text{Fe}$ Heating



$$L_{\gamma} = M(^{56}\text{Ni})[S_{\text{Ni}} \exp(-t/8.8d) + S_{\text{Co}} \exp(-t/113d)]$$

$$t_{\text{peak}} \propto M^{3/4} E^{-1/4}$$

$$L_{\text{peak}} \approx L_{\gamma}(t_{\text{peak}})$$

$$L_{\text{late}} \approx L_{\gamma}(t) \tau_{\gamma}$$

$$\tau_{\gamma} \propto M^2 E^{-1} t^{-2}$$

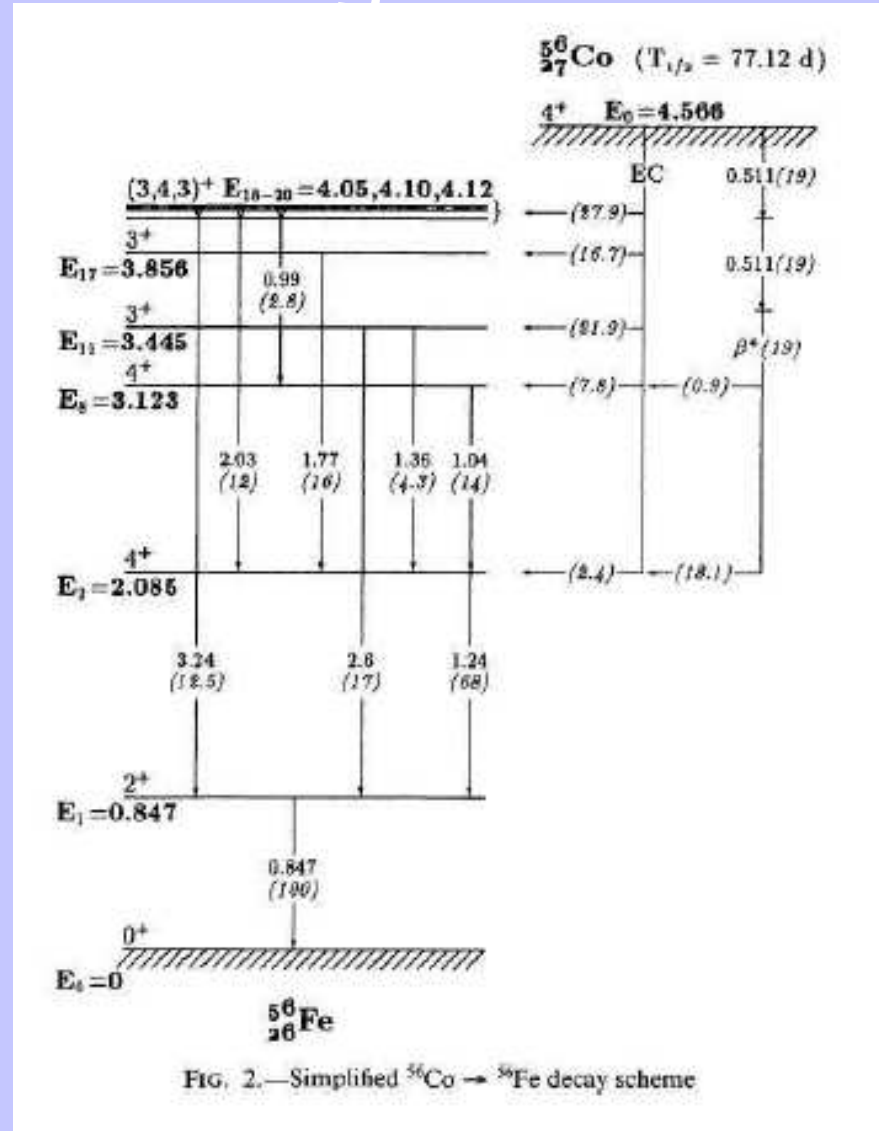
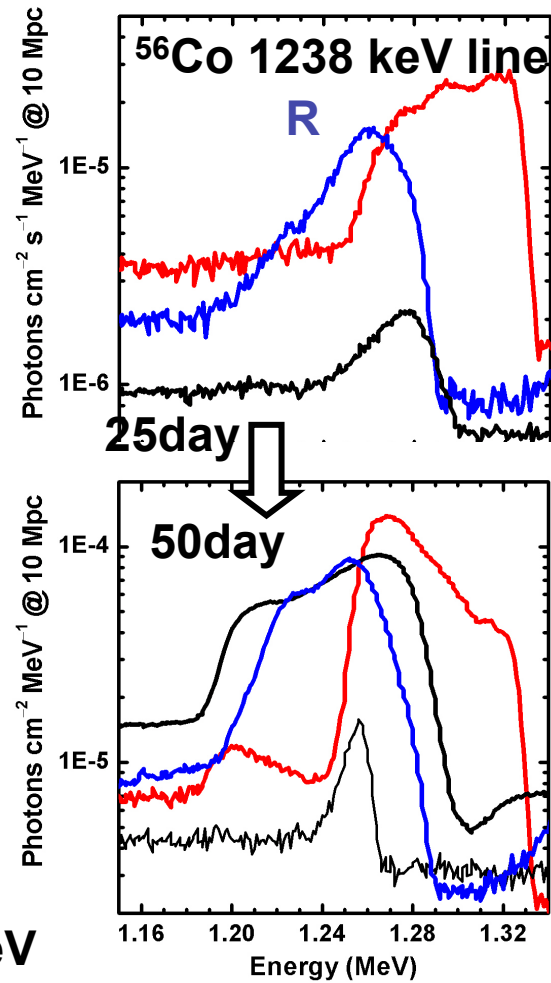
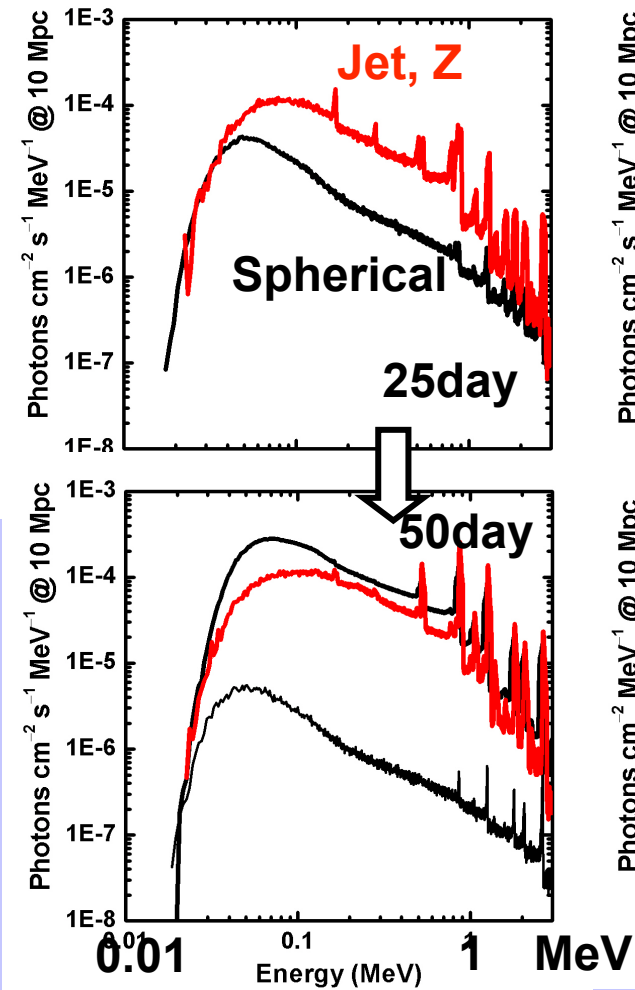


FIG. 2.—Simplified  $^{56}\text{Co} \rightarrow ^{56}\text{Fe}$  decay scheme

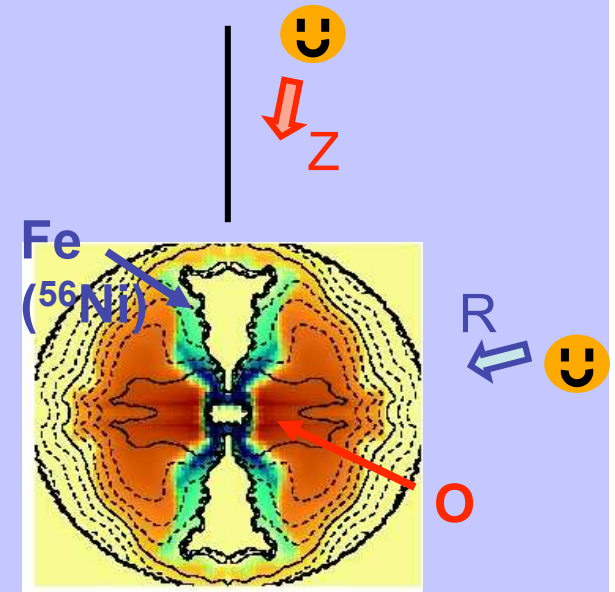
# X, $\gamma$ -rays from radioactive $^{56}\text{Ni}/\text{Co}$

INTEGRAL, 10ksec  $\sim$  a few 100 kpc...



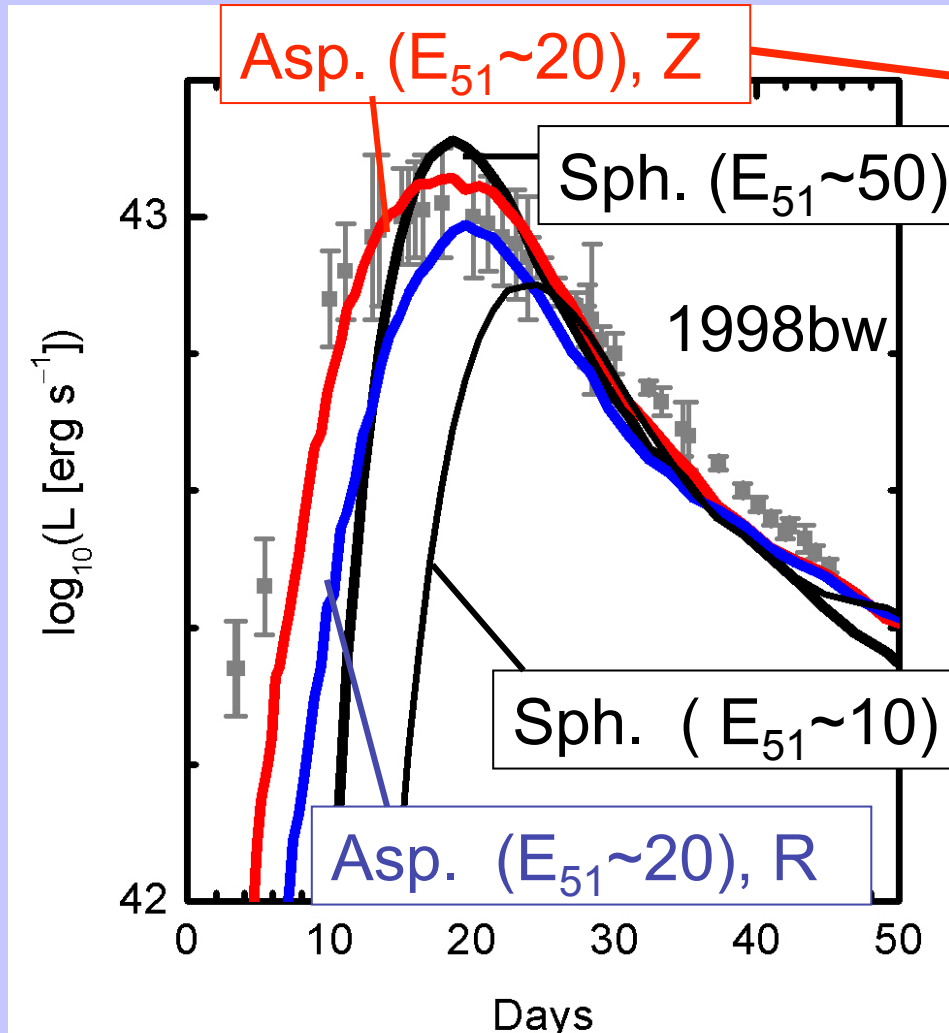
Maeda, ApJ, 2006, 644, 385

c.f., Aimee & Chris's work



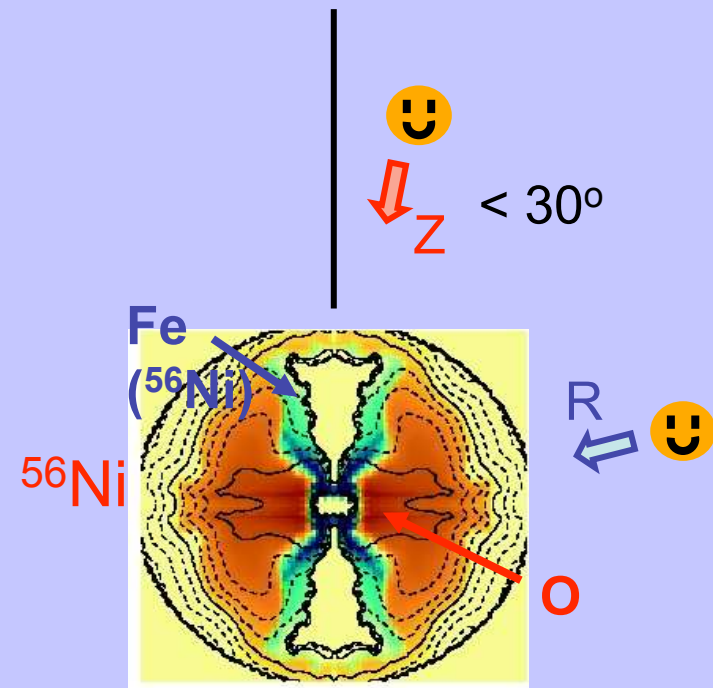
# SN 1998bw (GRB 980425) – Early LC

\*  $E_{51} = E/10^{51}$  ergs ( $\sim 1$  for a normal SN)



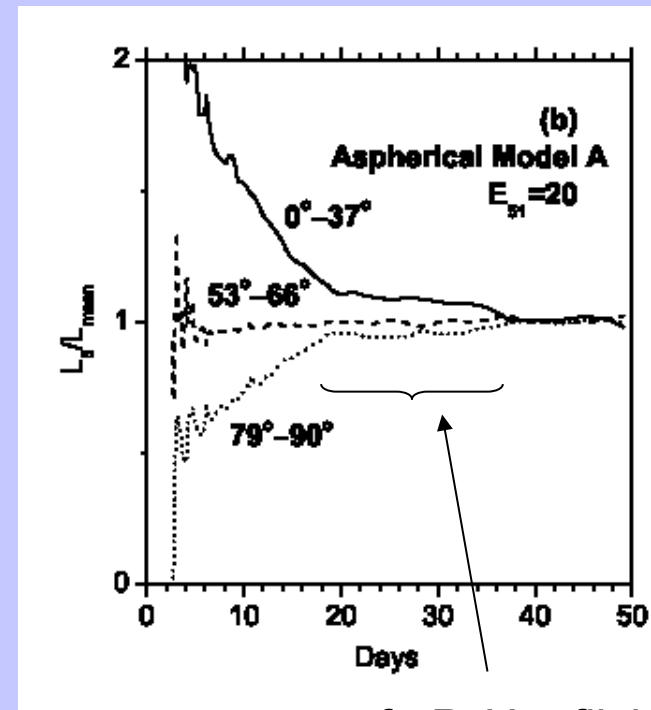
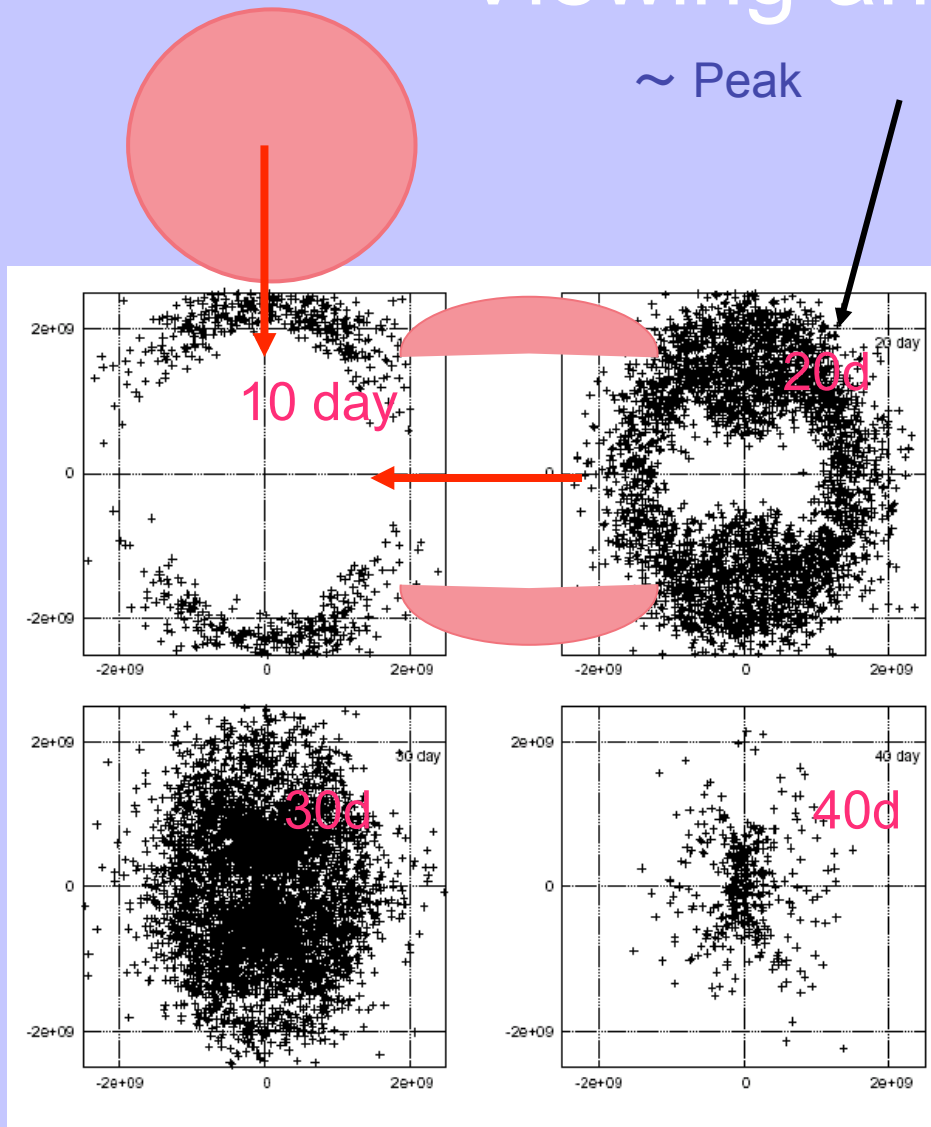
Consistent with obs.

c.f., P. Hoeflich's work



# Viewing angle effects

$$L_{\theta}/L_{\text{mean}}$$



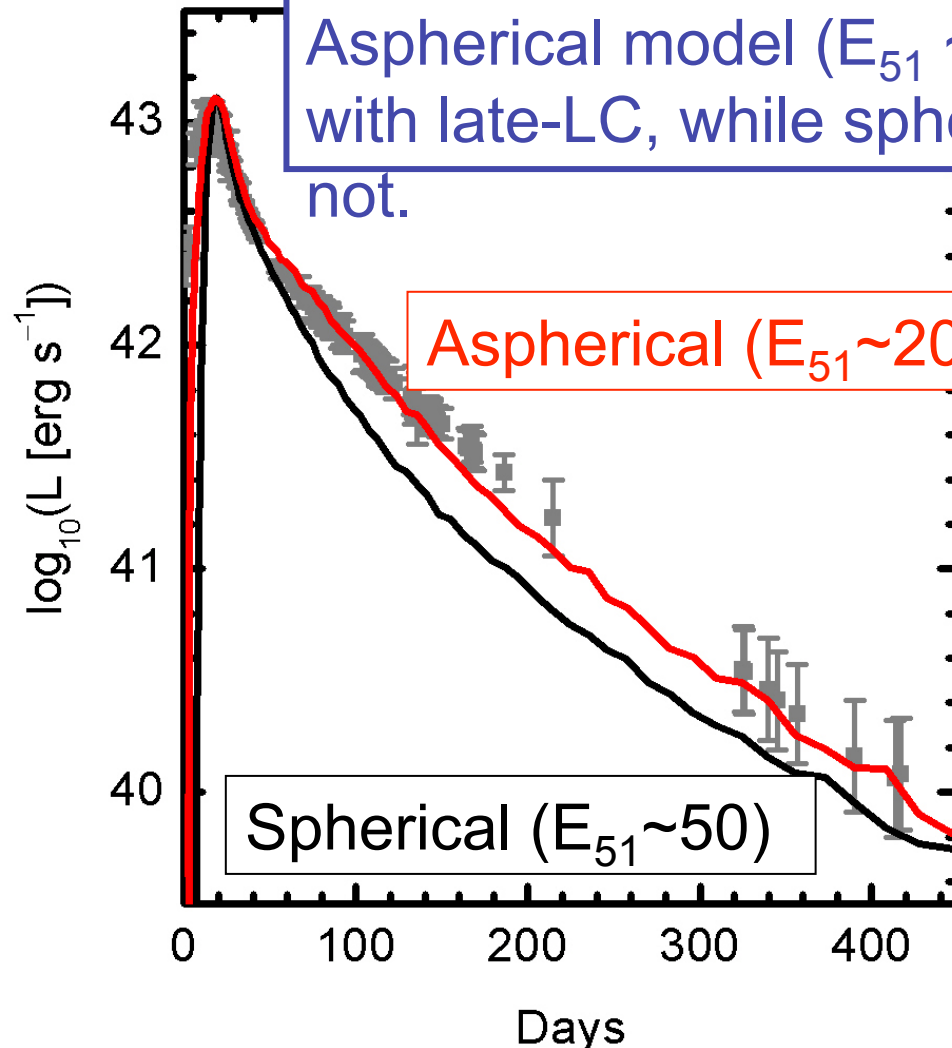
c.f., P. Hoeflich's work

Only strong before the peak,  
anyway within the factor of a few.

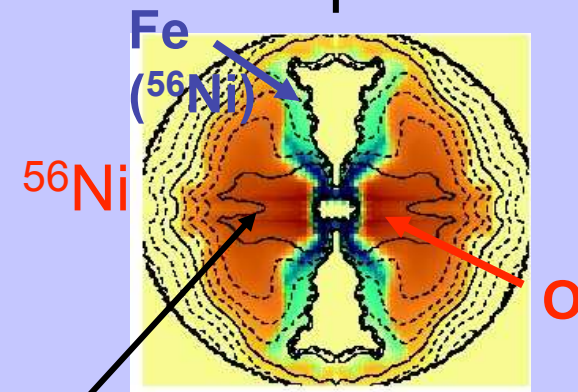
# Late-LC

Maeda et al. 2006b

Both consistent with early-LC.  
Aspherical model ( $E_{51} \sim 20$ ) is consistent with late-LC, while spherical model does not.



< 30°



Dense region trapping  $\gamma$  efficiently.

- $\tau_{\gamma} = CM^2/E$   
– Small E (“intrinsic”).

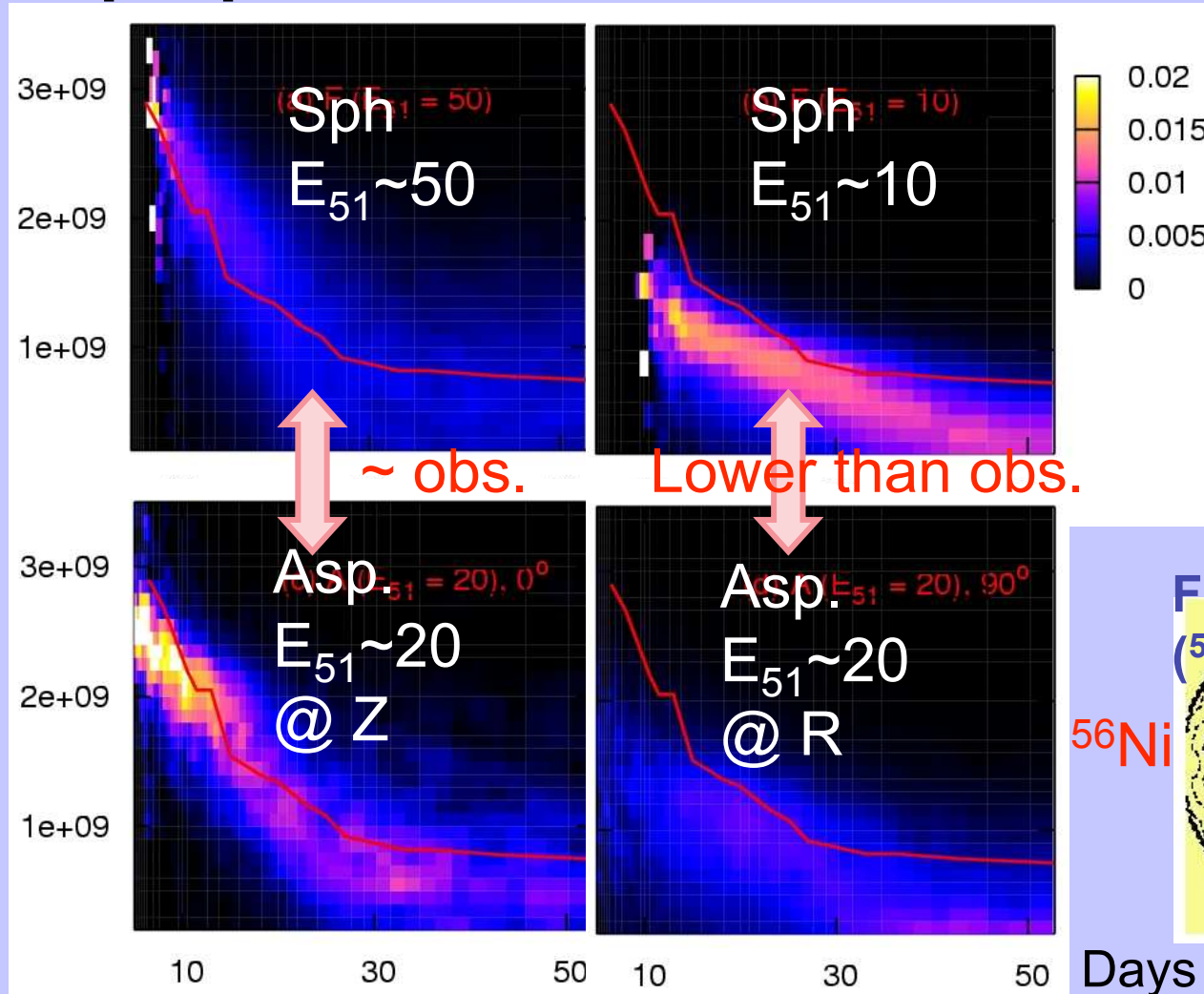
# Early-Spectra

c.f., Masaomi's work for more details.

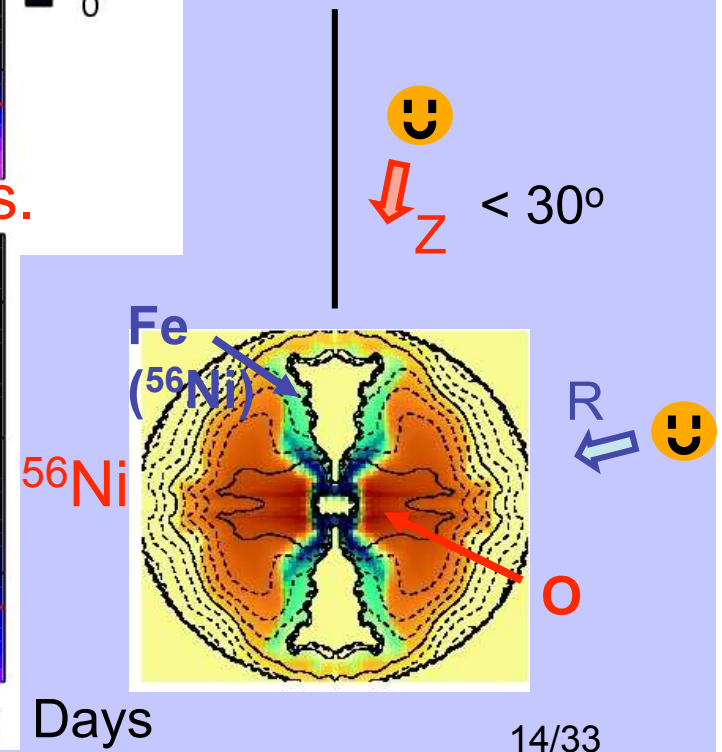
$$V \sim (E_{\text{isotropic}}/M)^{1/2}$$

Phot. V [cm/s]

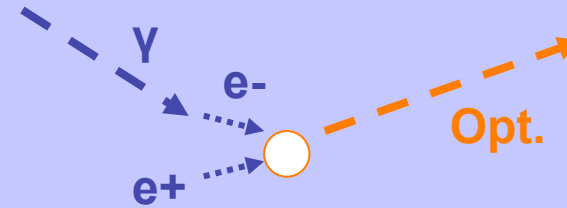
Maeda et al. 2006b



Color: model  
red: obs (Si vel.)



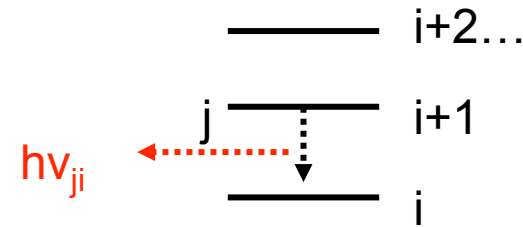
# Late-Time Spectra



Ionization

$$\sum_j N_j \Gamma_j = N_e N^+ \sum_j \alpha_j$$

Non-thermal e<sup>-</sup> impact ionization rate.



Excitation

$$\sum_i (N_e C_{ji} + \tilde{A}_{ji} + \chi_{ji}) N_j + \Gamma_j N_j = \sum_i N_i (N_e C_{ij} + \tilde{A}_{ij} + \chi_{ij}) + N_e N^+ \alpha_j$$

Non-thermal e<sup>-</sup> impact excitation rate

Energy balance

$$L_{ji} = A_{ji} h\nu_{ji} N_j$$

$$\sum_{j,i} L_{ji} = \Gamma^{thermal}$$

Non-thermal e<sup>-</sup> heating rate

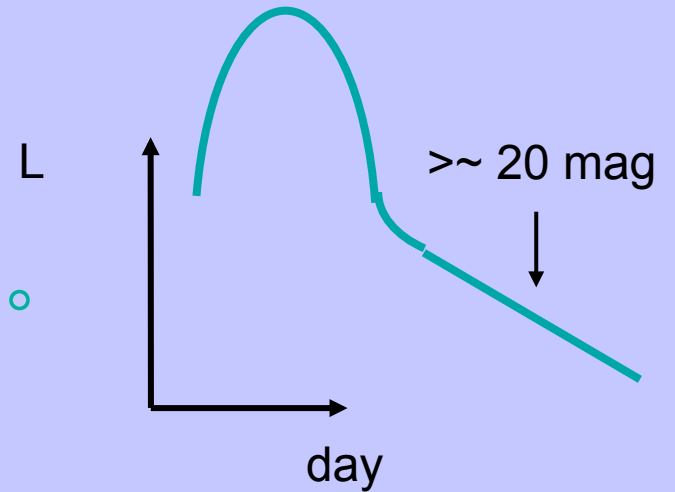
Non-thermal electrons  
 { →ionization  
 →excitation  
 →heating } ⇒ Enters into rate equations.

\* In some situations, UV photons are also important for ionization/excitation (i.e., photoionization and stimulated emission omitted above).

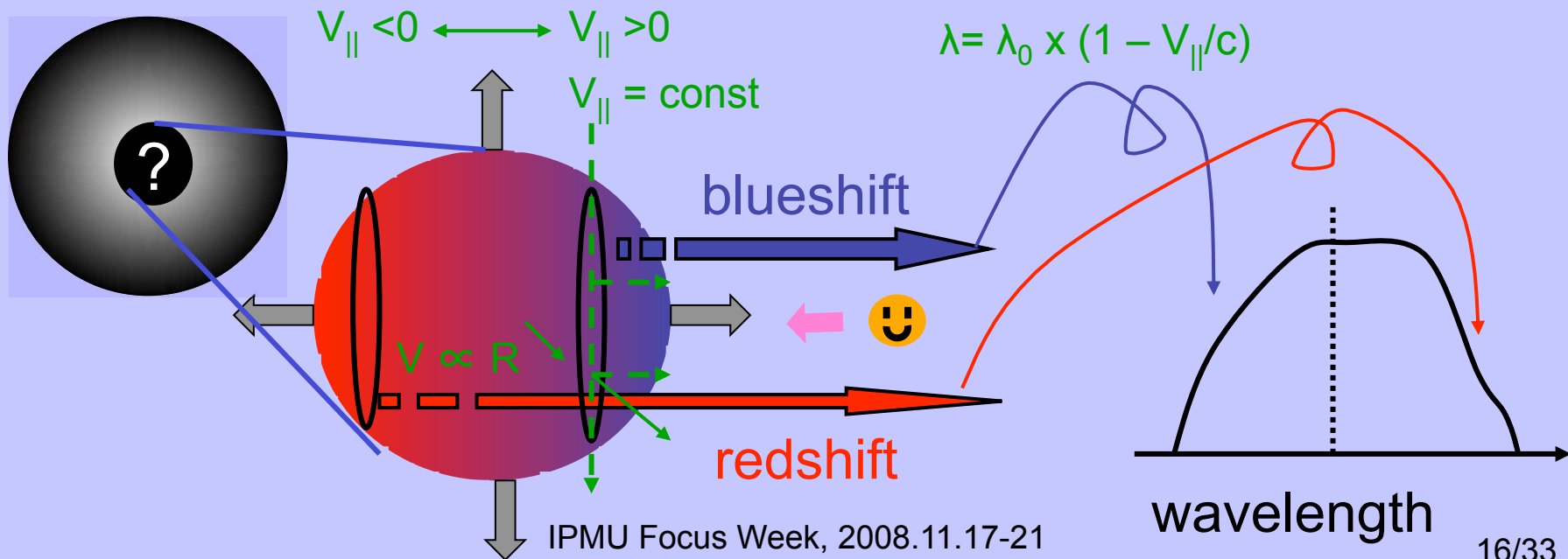


# Late-phase Spectra

- ~ 200days: optically thin ( $\rho \propto t^{-3}$ ).
  - Looking into the center!
- Line profiles  $\rightarrow$  distribution.
  - [OI] = distribution of neutral O.
  - Emission from Near/Far side = Blue/Red-shifted.



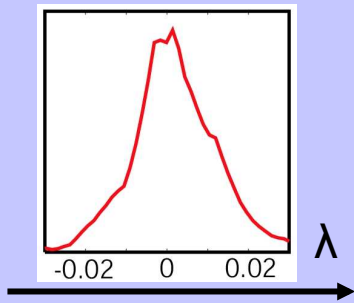
faint  $\rightarrow$  need 8m telescope



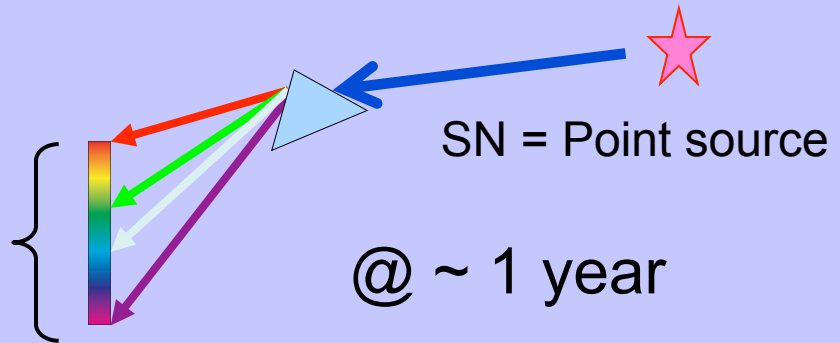
# “Geometry” $\Leftrightarrow$ Line profile

Maeda+, 06, ApJ, 645, 1331; Maeda+, 06, ApJ, 640, 854

“Single-peak”



Geometry

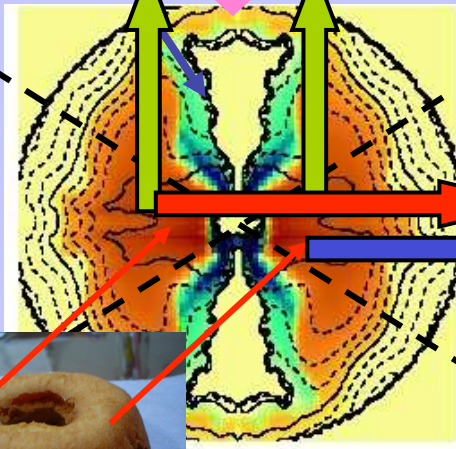


[O I] 6300

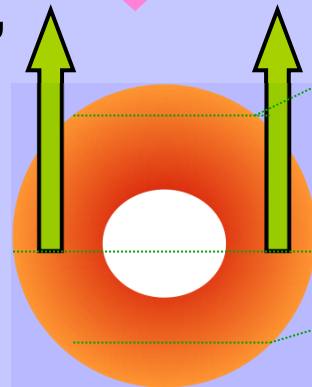
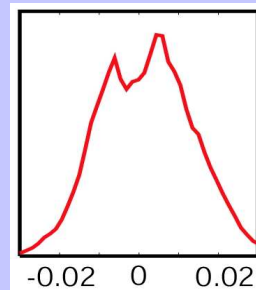


“Single-peak”

Fe (<sup>56</sup>Ni)



“Double-peak”



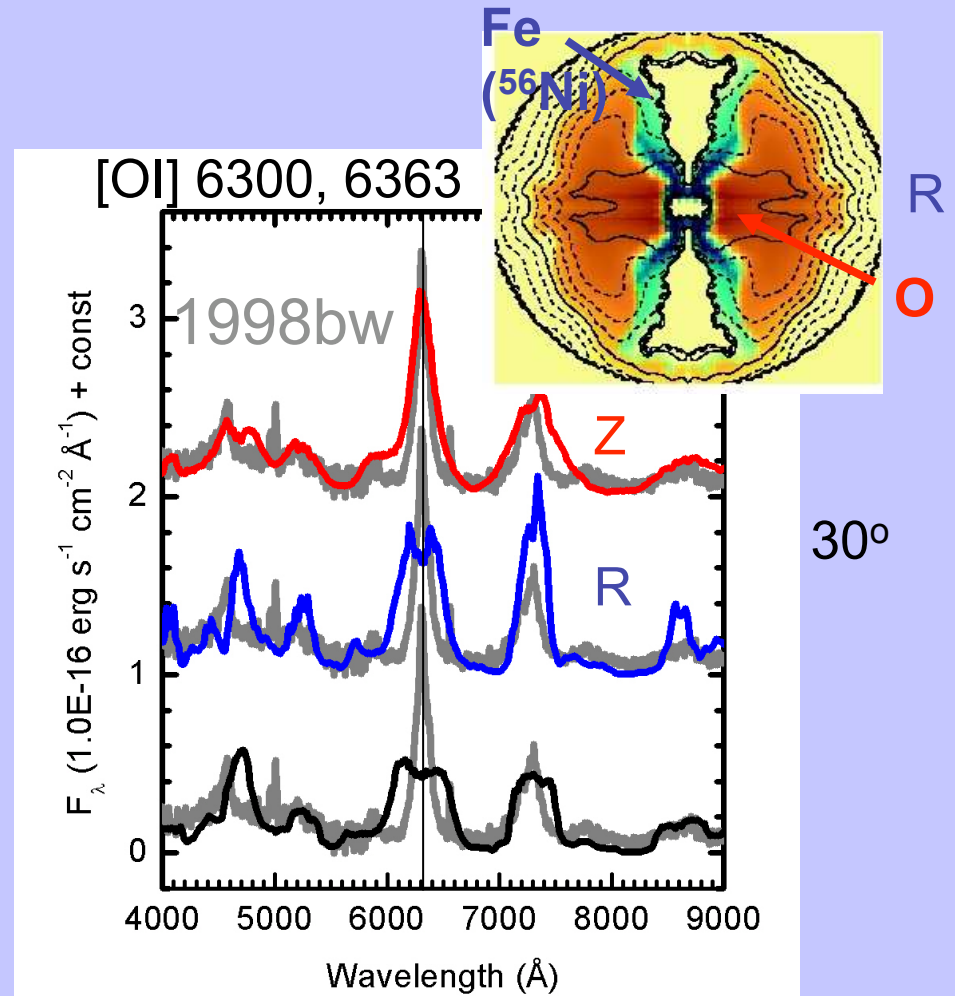
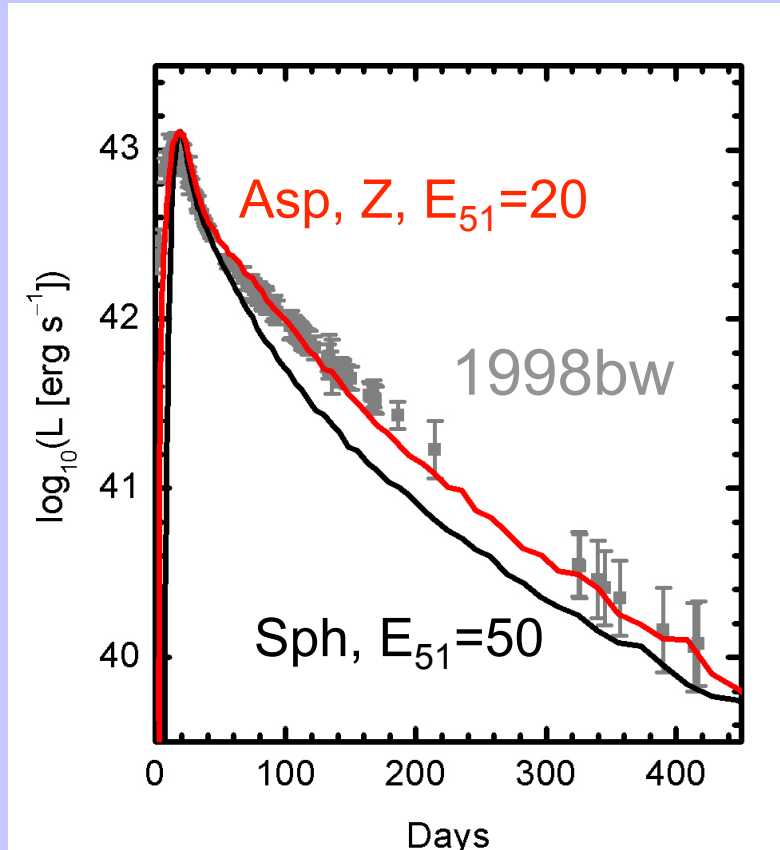
“Single-peak”



Doppler shift

IPMU Focus Week, 2008.11.17-21

# SN 1998bw@1 year



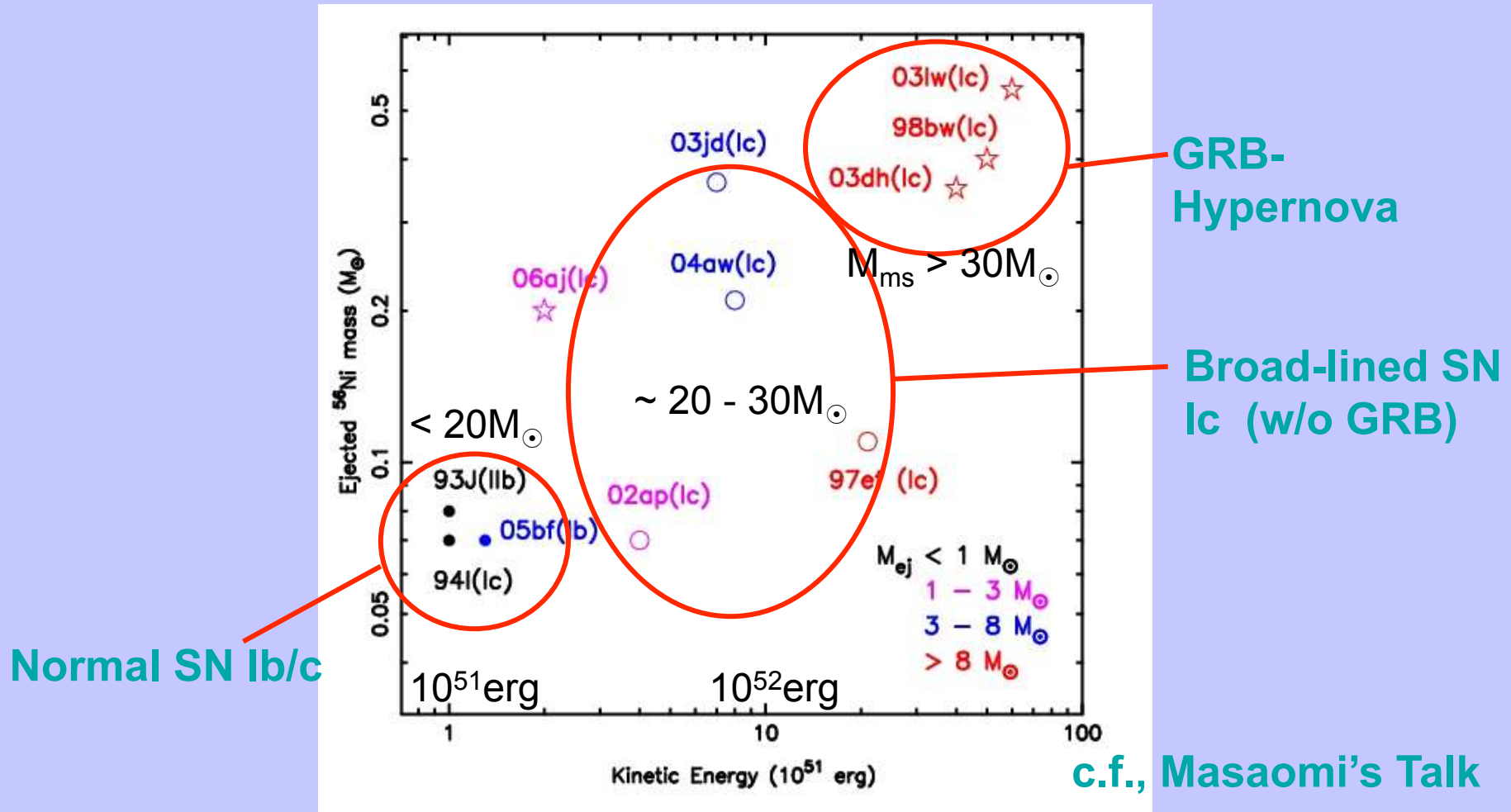
Maeda, et al. 06, ApJ, 645, 1331

Maeda et al. 06, ApJ, 640, 854

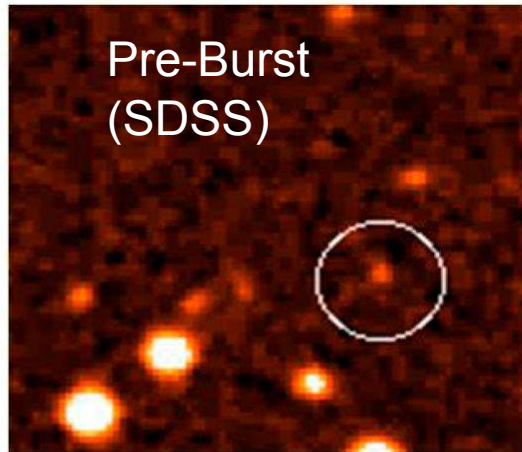
- **Aspherical ( $E_{51}=20$ ) viewed at Z, not by spherical models.**  
A bit small “intrinsic” E is important, as it’s optically thin.

# General picture: supernova properties

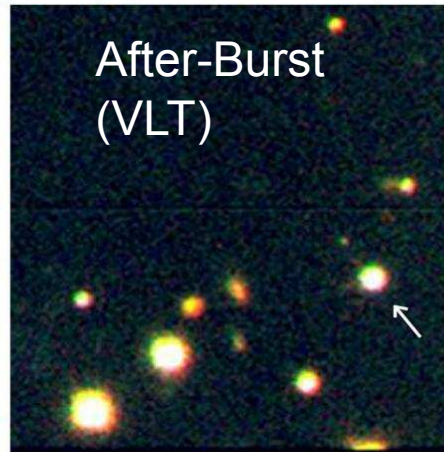
Fig. 1 of Maeda et al. 2008, Science, 319, 1220



# Massive stars: $M_{\text{ms}} \sim 20 - 30M_{\odot}$



Credit: DSS2

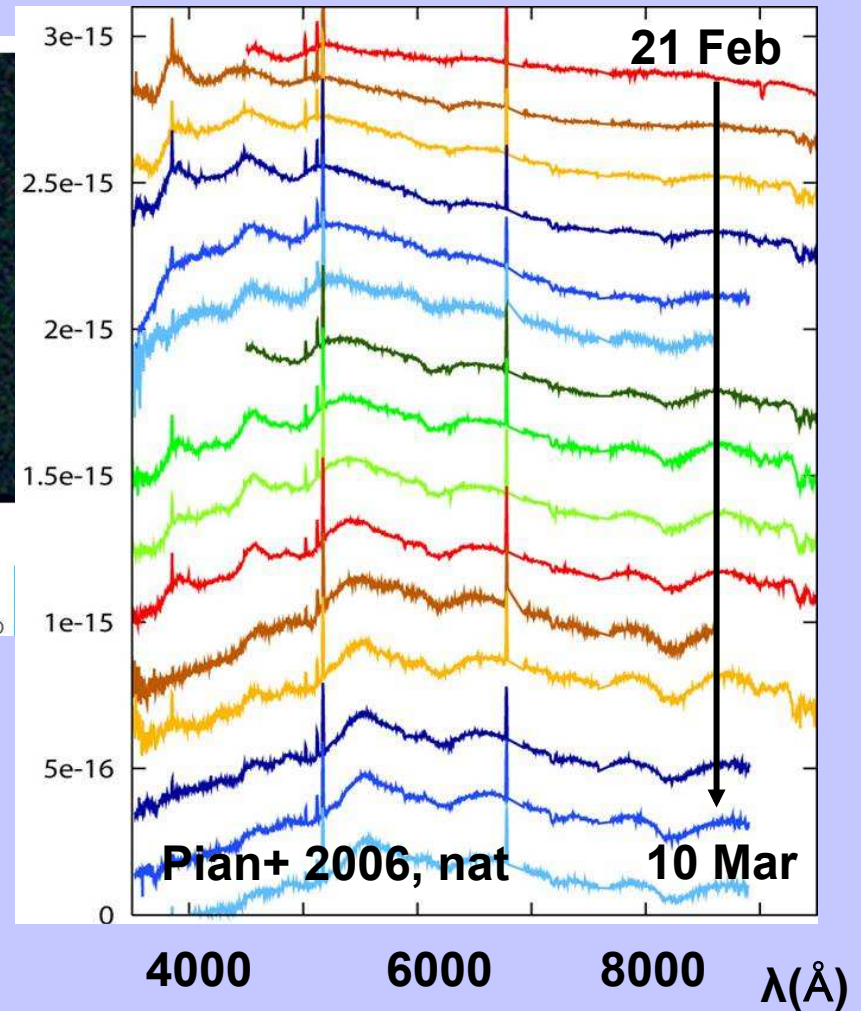


A New Kind of Stellar Explosion  
(FORS/VLT)

© ESO

XRF = a low E subclass of  
Gamma-Ray Bursts

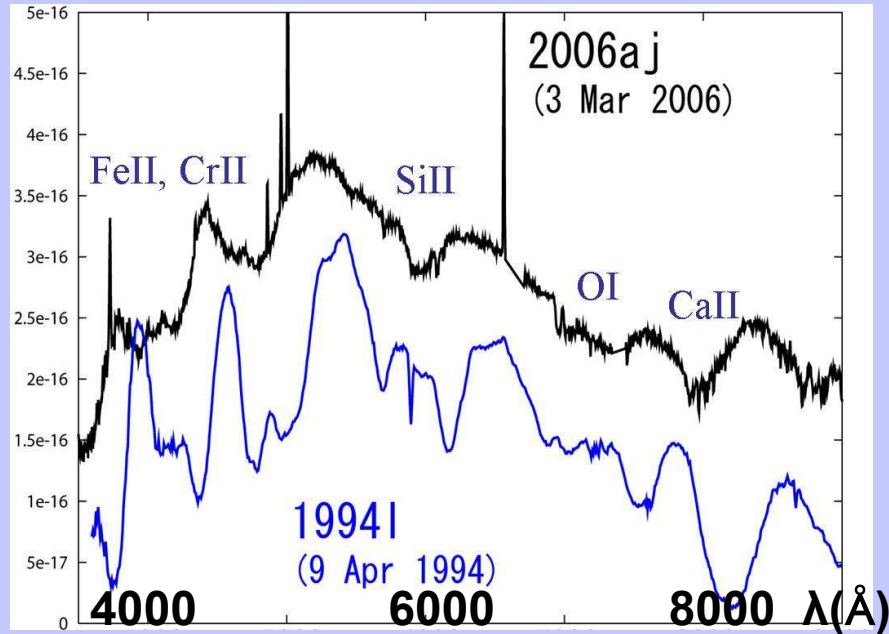
The first discovery of an SN  
associated with an X-Ray Flash!



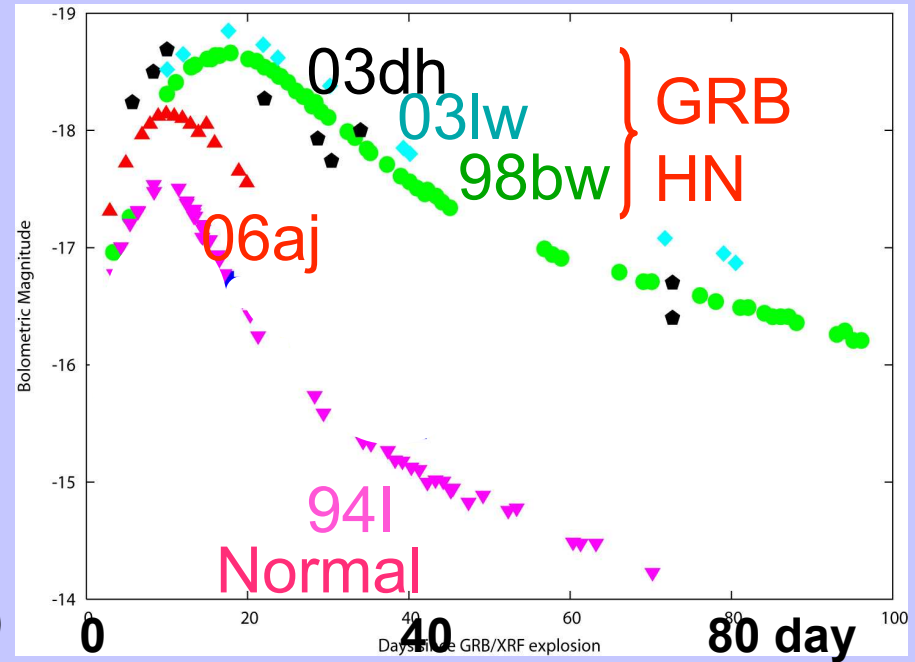
Pian+, 06, Nature

Mazzali+, 06, Nature

## Spectra @ ~ 2 weeks



## Light Curve @ 1st month



	1994I	2006aj	1998bw
High-E event	none	XRF	GRB
$M_{ej}/M_{\odot}$	~1	~2	~10
$M_{ms}$	10-15	20-25	35-45
$E_{51}$ ( $10^{51}$ erg)	1	2	20
$M(^{56}\text{Ni})$	0.07	0.3	0.4

Broader

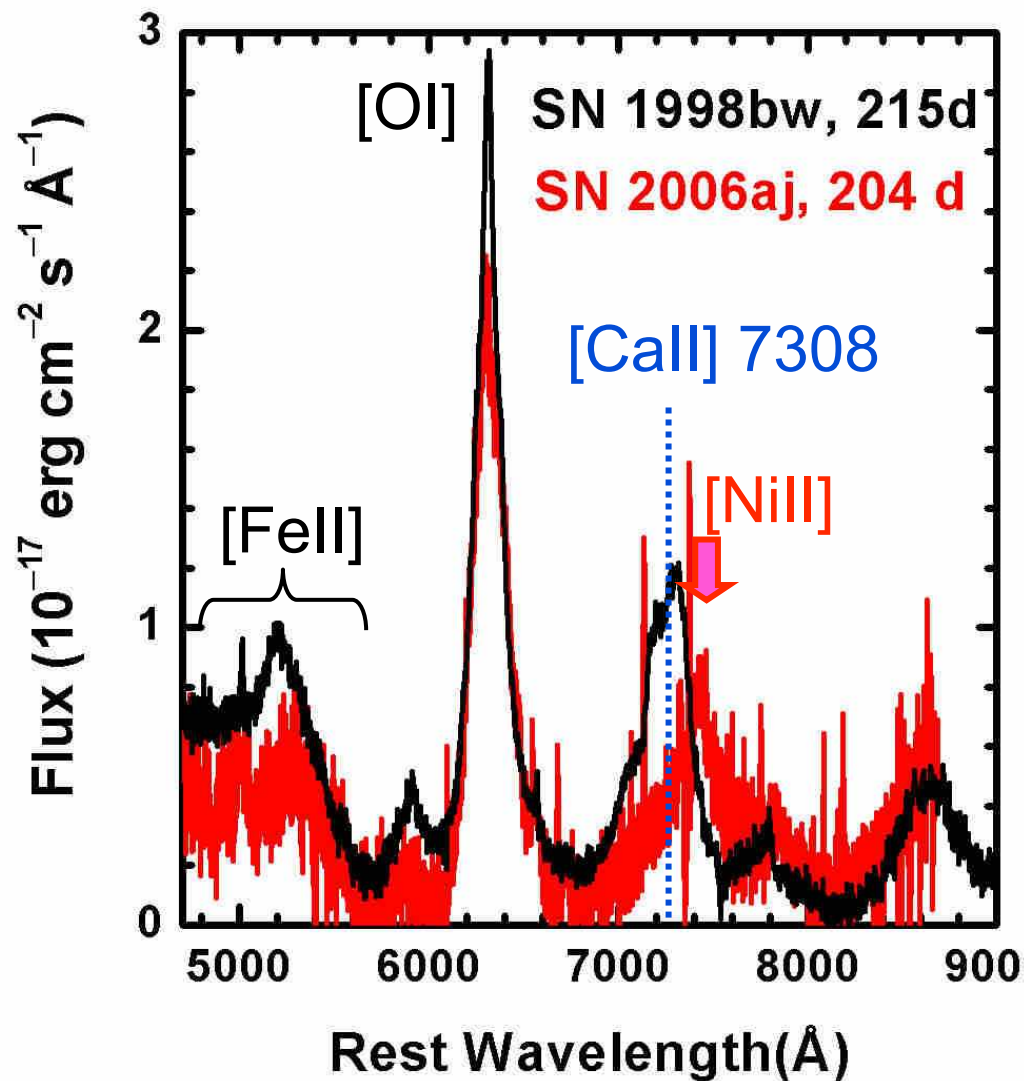
Line width

LC width

Iwamoto et al. 98

Mazzali et al. 06

Maeda et al. 06



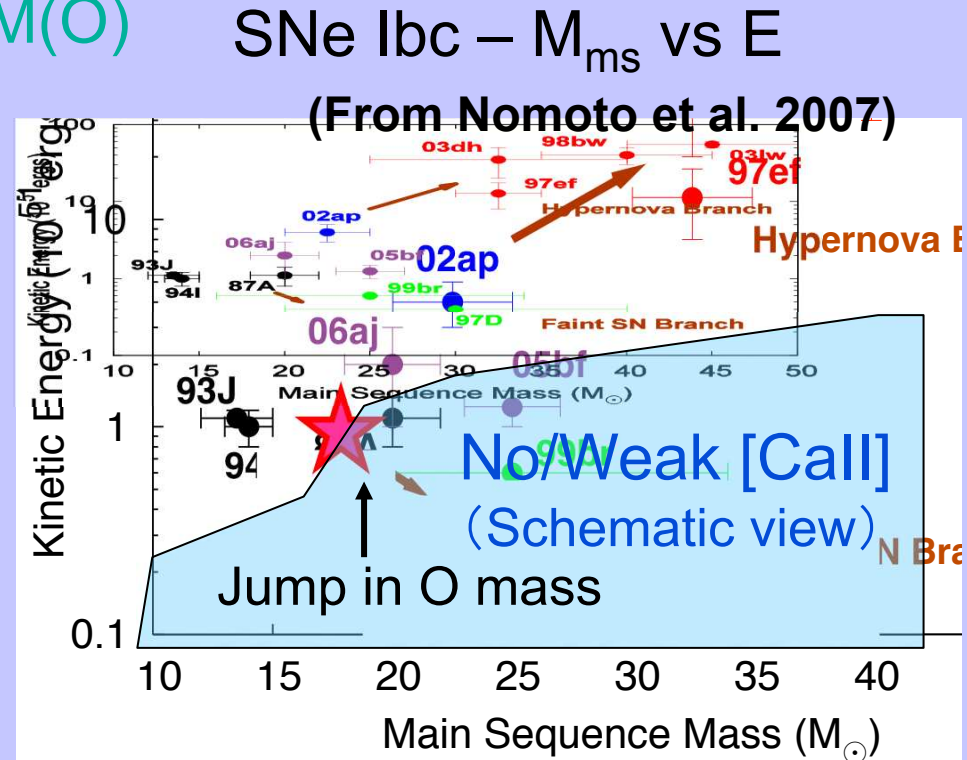
Maeda+, 2007, ApJ, 658, L5

$M(^{58}\text{Ni}) \sim 0.05 M_{\odot}$   
 Neutron-rich  
 $\Rightarrow$  NS formation(?)

The XRF was produced by a strong activity of the NS? (e.g., Magnetar?)

# [CaII]/[OI] as a possible diagnostics

- Other SNe Ibc show strong [CaII], comparable to [OI].
- $L(\text{CaII})/L(\text{OI}) \propto M(\text{Si-rich})/M(\text{O})$   
 $\Rightarrow$  larger for larger  $E/M_{\text{ms}}$



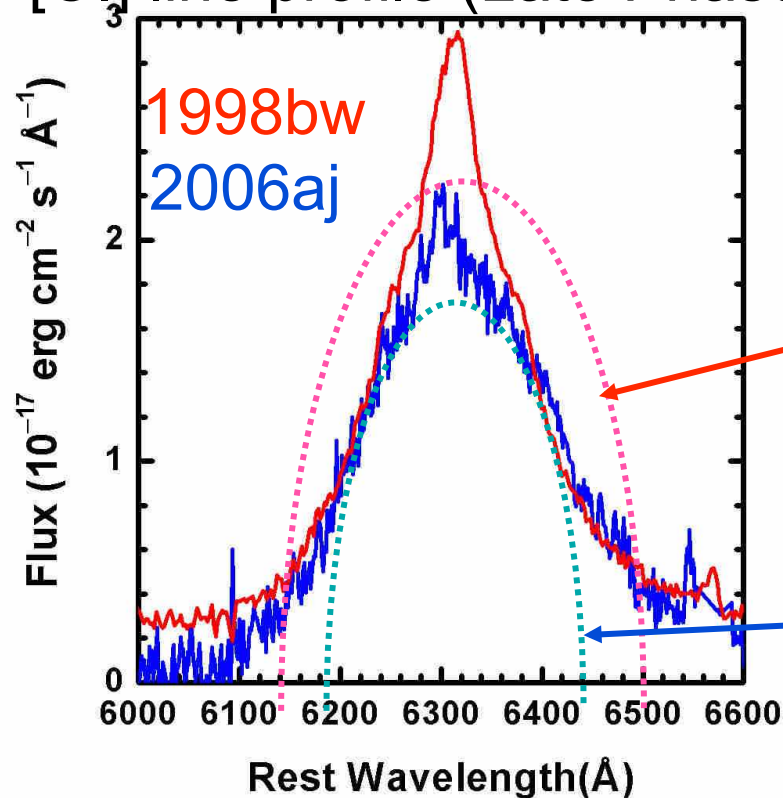
- Majority of SNe Ibc ( $E \sim 10^{51}$  erg) are likely from  $M_{\text{ms}} < 20_{\text{ms}}$ .  
 $\Rightarrow$  Most of them come from binary path?



# Geometry of XRF-SN 2006aj

[O I] line profile (Late Phase)

Spherical models (Early)



Line width  
 $V \sim (E/M)^{1/2}$

1998bw

$E/M \sim 5$

2006aj

$E/M \sim 1$

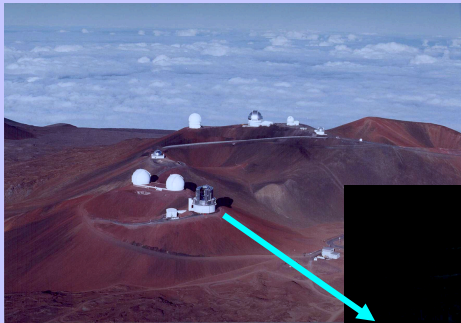
E in  $10^{51}$  erg,  
M in  $M_{\odot}$

- 98bw: [O I] profile inconsistent with the spherical model.
- 06aj : overall, consistent.
  - Excessive emission @ the innermost part
  - possibly, just mildly asymmetric.

# Massive stars, in general : $M_{ms} < \sim 30M_{\odot}$

Collaborators; **Kawabata (Hiroshima), Tanaka, Nomoto (U. Tokyo), Hattori (NAOJ/Subaru) et al.**

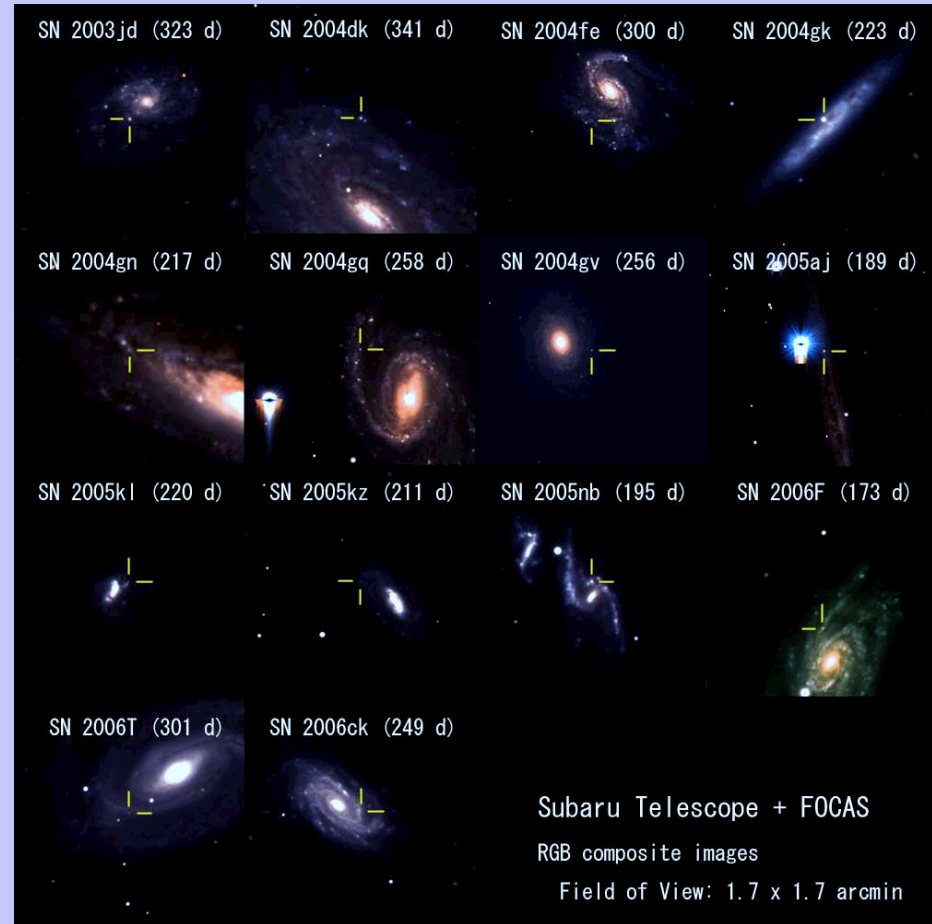
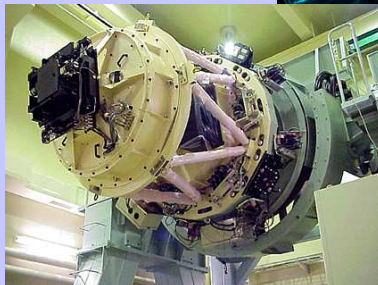
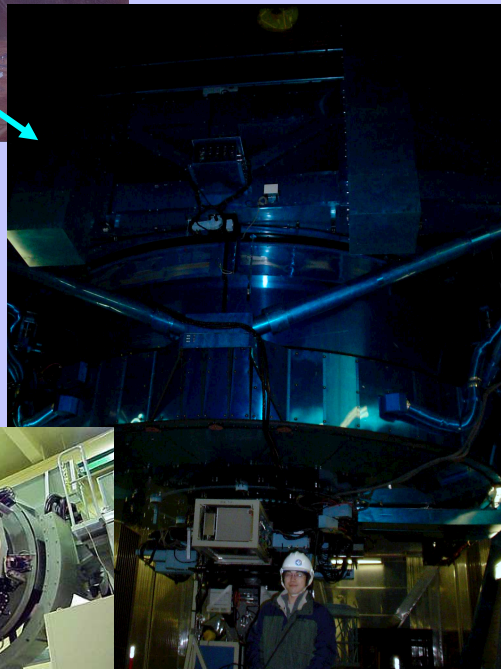
- 15 SNe @ >200days (~ 20 – 23mag).



Hawaii, Mauna Kea @ 4,200m

Subaru, 8 m

FOCAS





Archaeologists have found that ancient people were eating meat, as evidenced in 2005. Scientists do study the modern, industrialized world. However, for the majority of us, what we handle and every structure we excavate is an ancient piece of history. Much is hardly recognizable after the natural ravages of the centuries. Some of it probably much even when it was new, but still, we regularly find objects and structures of daily life. They come in all sizes, from minuscule beads to ancient field systems covering miles of them and works of art in their own right. Of course, I want to understand the

### SCIENTIFIC METHOD

Do certain supernovae explode only aspherically?

The universe would contain only hydrogen, helium, and a few other light elements, which is not for supernovae. These stellar explosions create the elements that make up the planets and life. For nearly 30 years, astronomers have investigated the explosion mechanism in supernovae. Their two most prominent theories both require that the explosions be asymmetrical, but until now nobody had observed the shape of supernovae asymmetries. Recently, a team led by University of Tokyo astronomer KOICHI MAEDA examined the geometry of a certain class of supernovae and found that they are, indeed, all aspherical.

Because supernovae are distant objects, it is impossible to measure their geometries directly. Instead, to determine the shapes of the explosions, Maeda and his colleagues observed the color of the emitted light. When a moving object emits light, its speed and direction affect how an observer will perceive the light's color. If the source is approaching, wavelength is shorter, and the light is blue-shifted—the faster the source is traveling, the closer to blue it appears. If the source is receding, the light is red-shifted. When a star explodes, matter on one side hurries toward us, and matter on the opposite side flies away. If there is more blue-shifted light than red-shifted, or vice versa, we know the explosion is aspherical.

In order to determine which way the color of the light had shifted, the researchers needed a point of reference. When different elements are ionized, they emit characteristic frequencies of light. Some of the elements in supernovae emit light that is 100 times as bright as oxygen, which emits a strong, simple orange light with a

Aim = Spectroscopy → Geometry!

$v < c$   
 $v_0 < c$   
 $f(x) \sim (R/c)^2$   
 Spectroscopy      Geometry

Strategy ① Use Doppler shift

- ✓ [Mg I] - theoretically good, but not for obs...
- ✓ [O I] - too much blend...
- • [O II] - good!

{ low optical depth  
no line blending  
ok for obs.

② Measuring Bias

$T_e \sim \left(\frac{M}{M_\odot}\right)^2 \left(\frac{E}{10^{51} \text{erg}}\right)^{-1} \left(\frac{T}{70 \text{ day}}\right)^{-2}$        $M \lesssim 3 M_\odot \Rightarrow T_e \lesssim 1$       ④  $T \gtrsim 200$  day

•  $T_{[O II]} \sim 0.01 \left(\frac{M}{M_\odot}\right) \left(\frac{T}{200 \text{ day}}\right)^{-2}$

Observing Strategy Feb - Jun 2008  
 SN 2006cs      Feb - Jun 2008

$1s_0$	4.24 eV
$1s_1$	2.0 eV
$1s_2$	0.15 eV
$1s_3$	0.02 eV
$1s_4$	

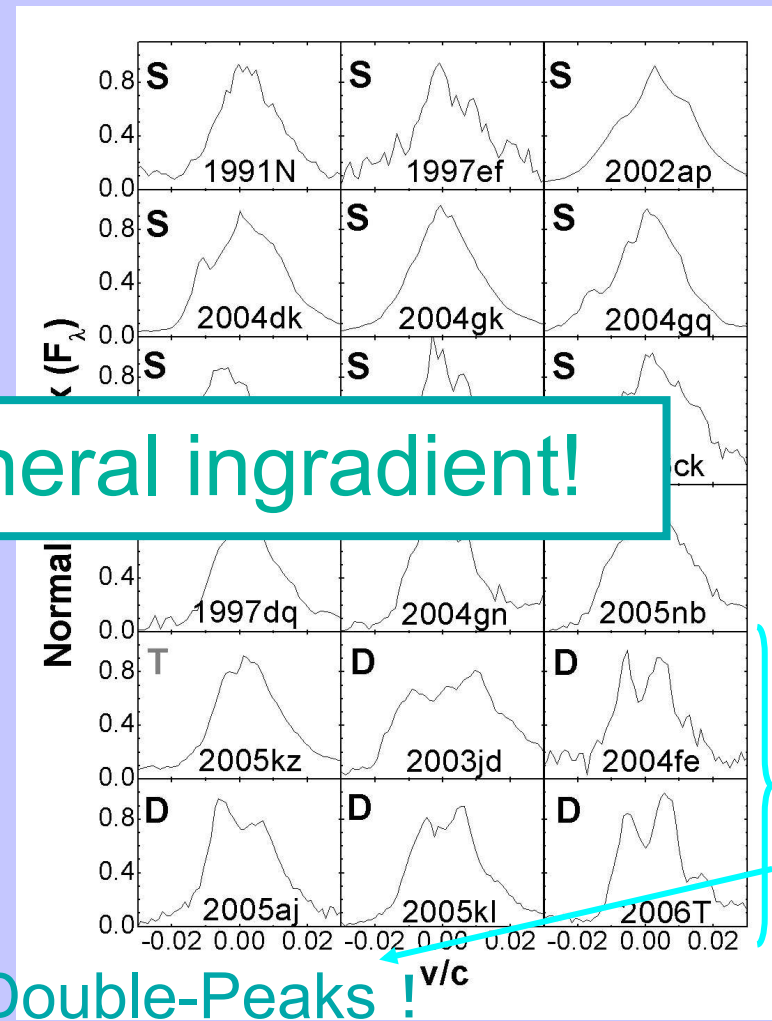
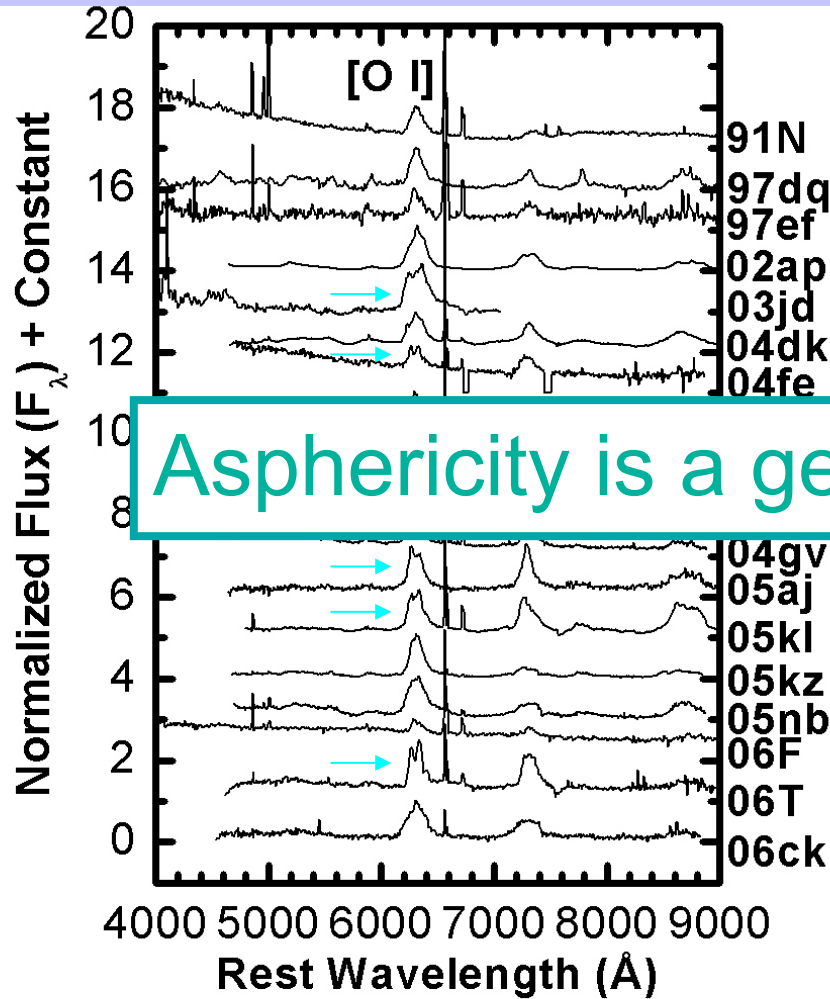
g others. In the spectrum of scientific disciplines, combination of BIOLOGY\* and NEUROSCIENCE\*.

However, the detailed explosion mechanism is still an open question.

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# Late-time spectra by Subaru/VLT

Maeda, Kawabata+, 08, Science, 319, 1220



Asphericity is a general ingradient!

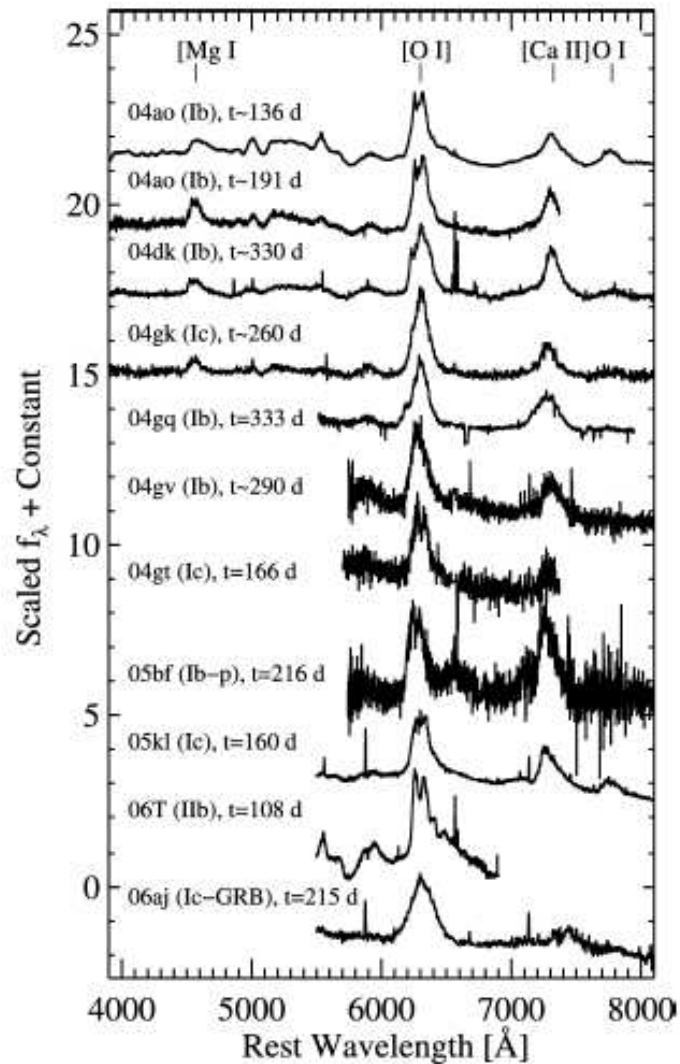
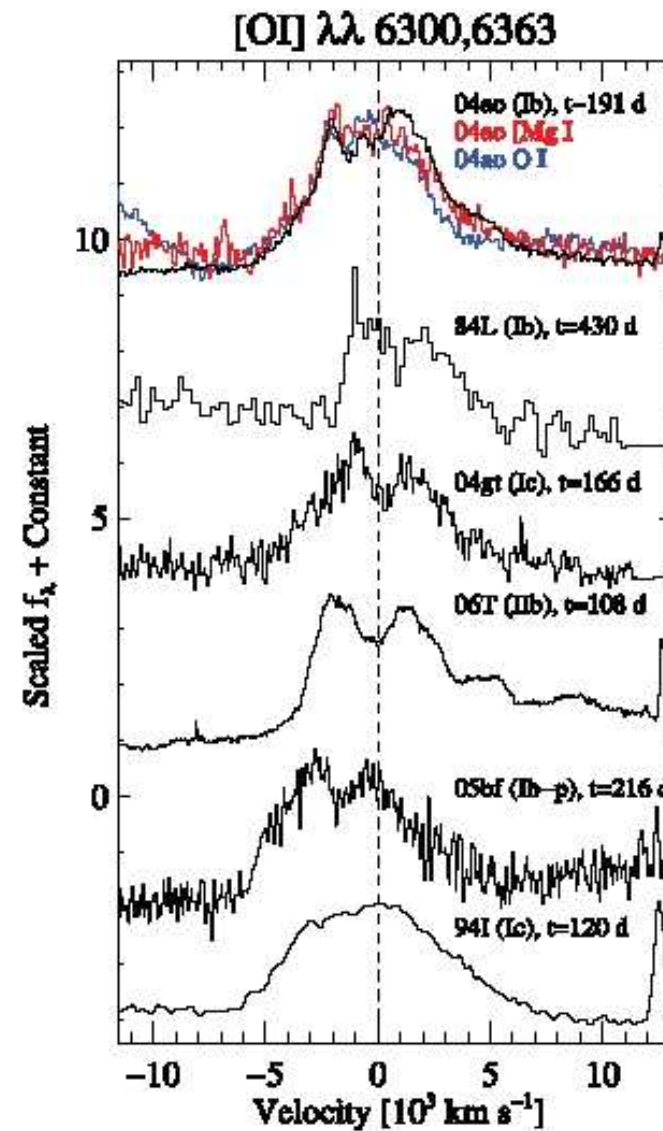
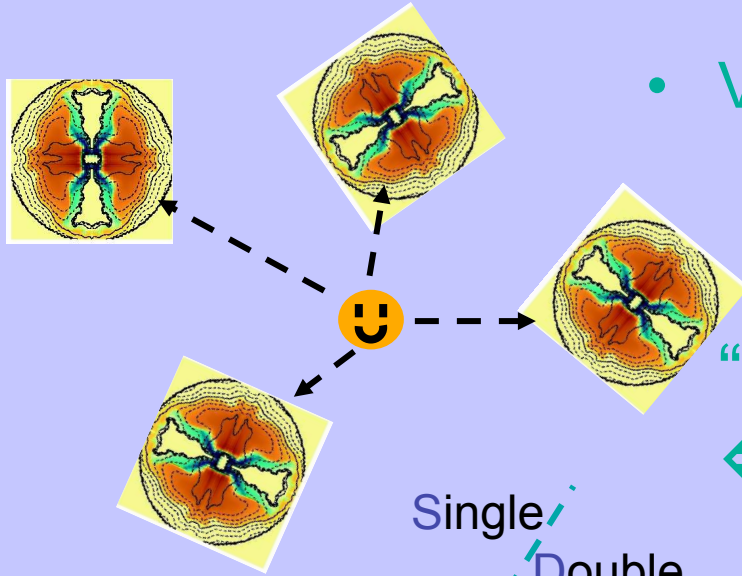


FIG. 1.—Selection of nebular spectra of SNe IIb, SNe Ib, and SNe Ic in their respective rest frames. SN name, type, and phase of spectrum (with respect to maximum light, except for GRB 060218/SN 2006aj which is referenced to



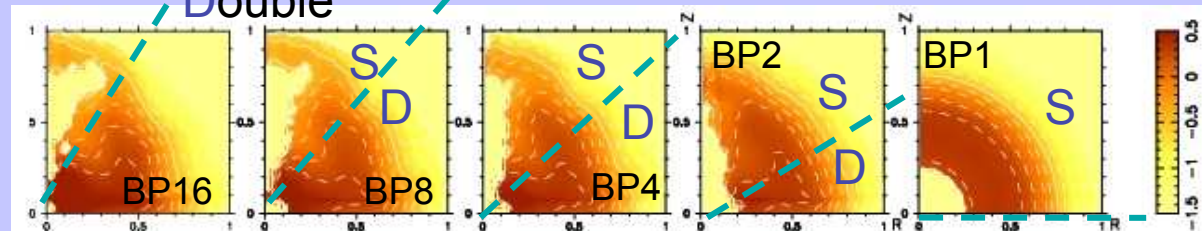
# How much “asphericity”?



- Viewing angle... Random.
  - Omitting GRB and XRFs.



“Average” Geometry  
 $\Leftrightarrow (\text{double})/(\text{single} + \text{double})$



Expected  $D/(S+D)$

0.64

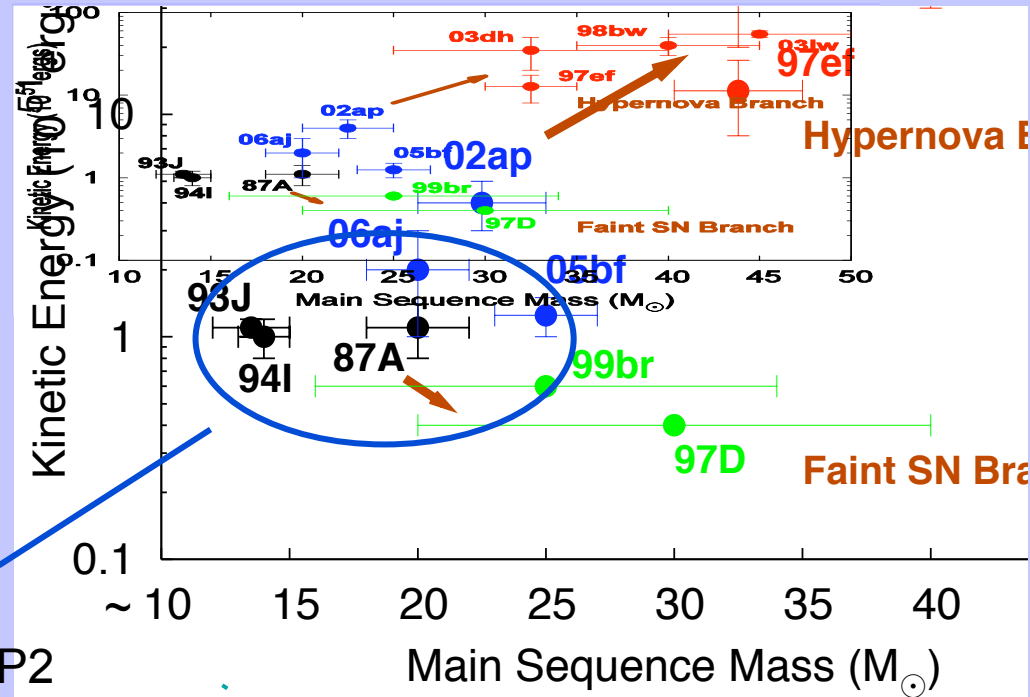
0.34

0.0

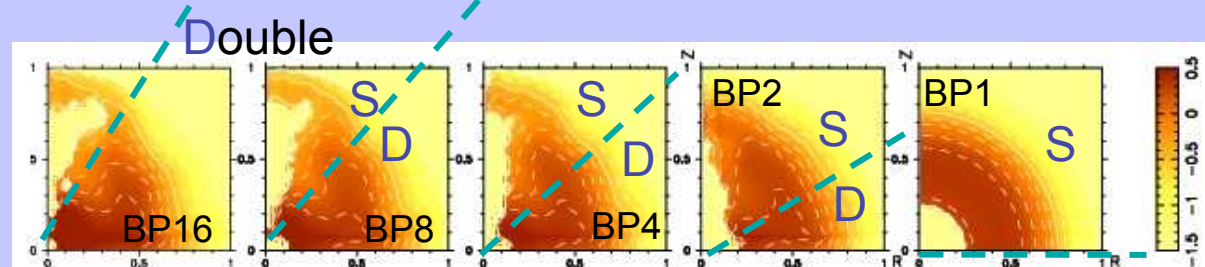
Observed  $D/(S+D) = 0.3 \sim 0.5$

$D/(S+D)$  depends only on BP (degree of asphericity)!

# Progenitor mass vs. asphericity



$D/(S+D)$   
0.3 – 0.5  $\rightarrow$  BP2



Expected  $D/(S+D)$

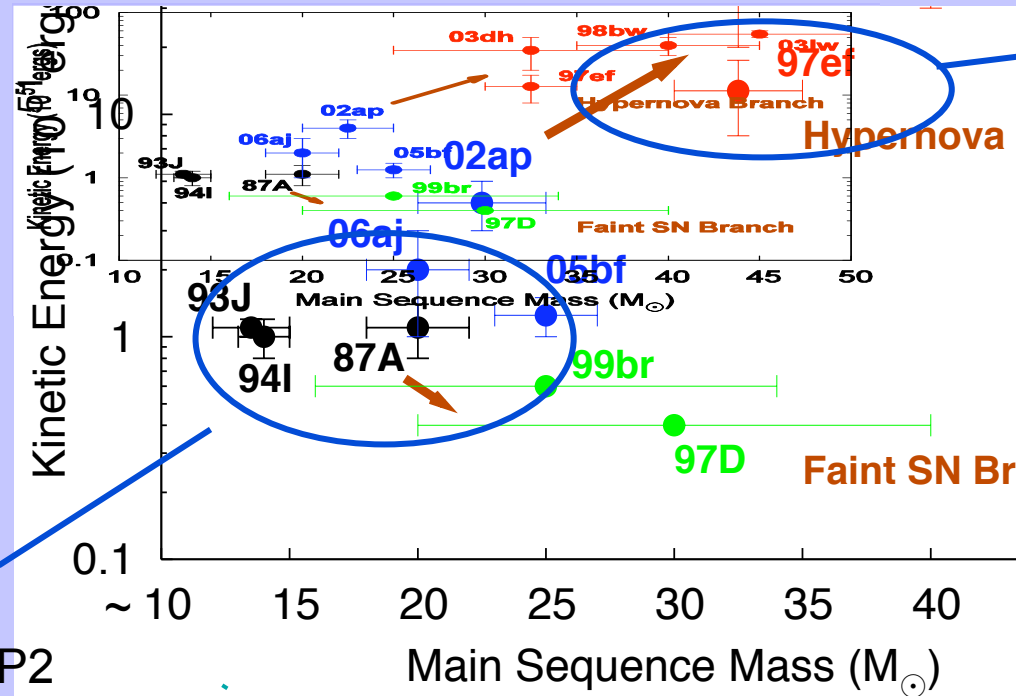
0.64

0.34

0.0

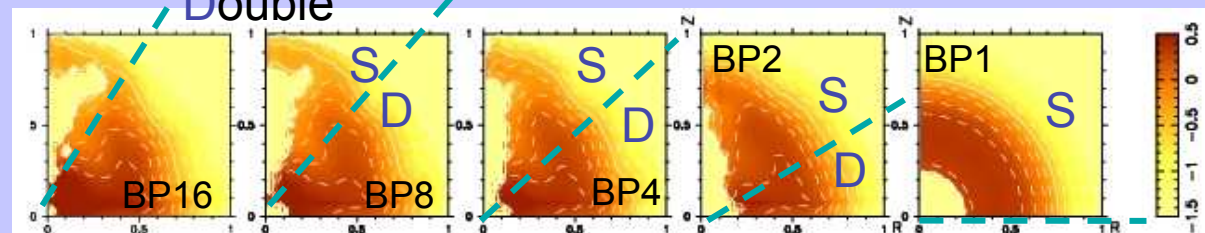
SNe Ib/c.  $< 30 - 40 M_{\odot}$

# Progenitor mass vs. asphericity



GRB-Hypernova  
(SN1998bw → BP8)

$D/(S+D)$   
0.3 – 0.5 → BP2



Expected  $D/(S+D)$

0.64

0.34

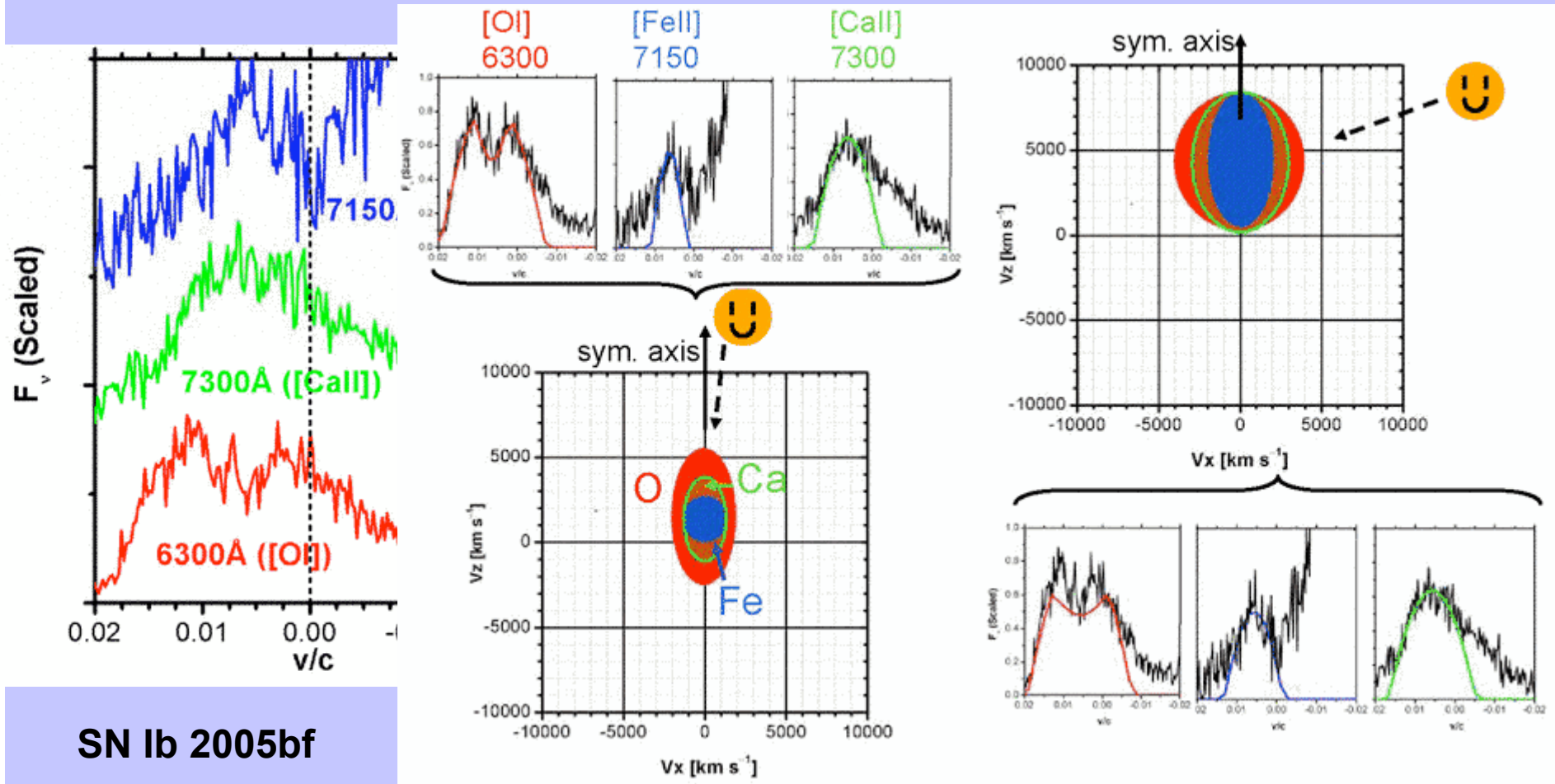
0.0

GRB-Hypernova

SNe Ib/c. < 30 – 40  $M_{\odot}$



It is probably not the end of story...



SN Ib 2005bf

Uni-pole...? e.g., SASI, c.f., Chris & Aimee for nucleosynthesis

# Conclusion

- **Mass vs. SN properties.**
  - $\sim 40M_{\odot}$  : GRB-SNe.
    - Black hole?
  - $20 - 40M_{\odot}$  : Variety. XRF-SNe.
    - Neutron star? ...Detection of  $^{58}\text{Ni}$  at late phases.
- **Asphericity.**
  - SNe are not spherical in general.
  - GRB-SN 1998bw explained well by the highly jet explosion, viewed on axis.
  - Different for  $>40M_{\odot}$  and below?
    - Difference in the explosion mechanism(s)? Does SASI fit into this context?