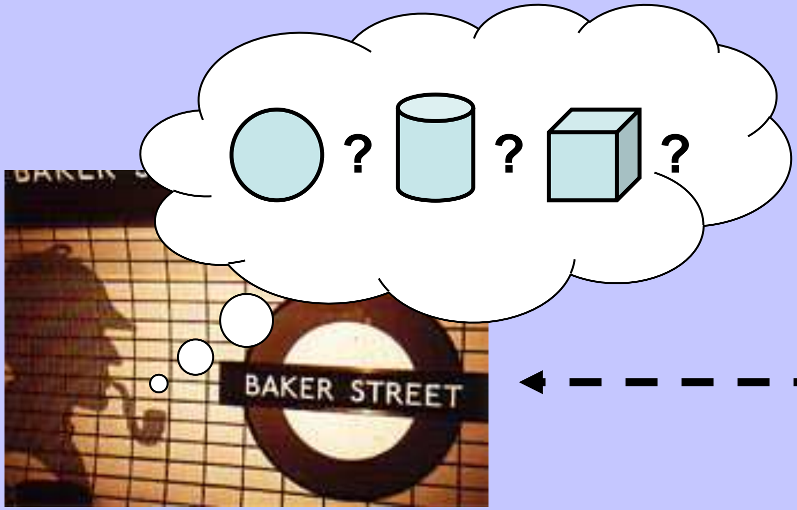
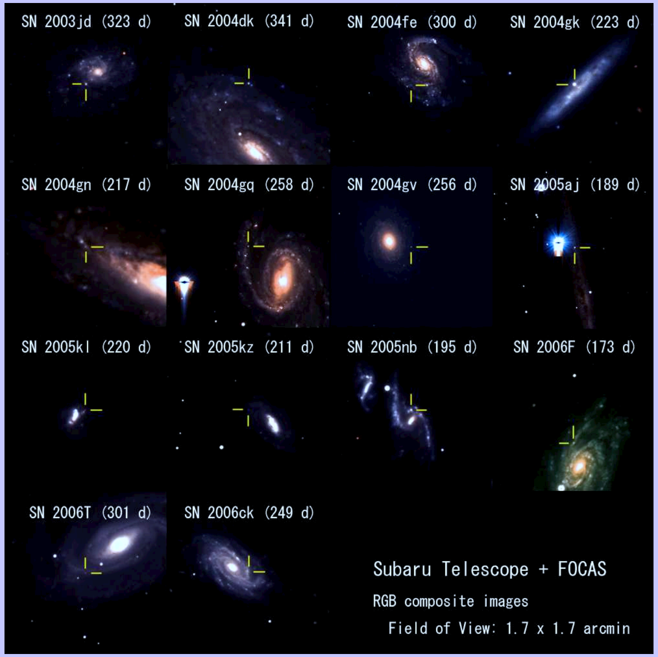
Asymmetry and Other Hints for the Supernova Explosion Mechanism

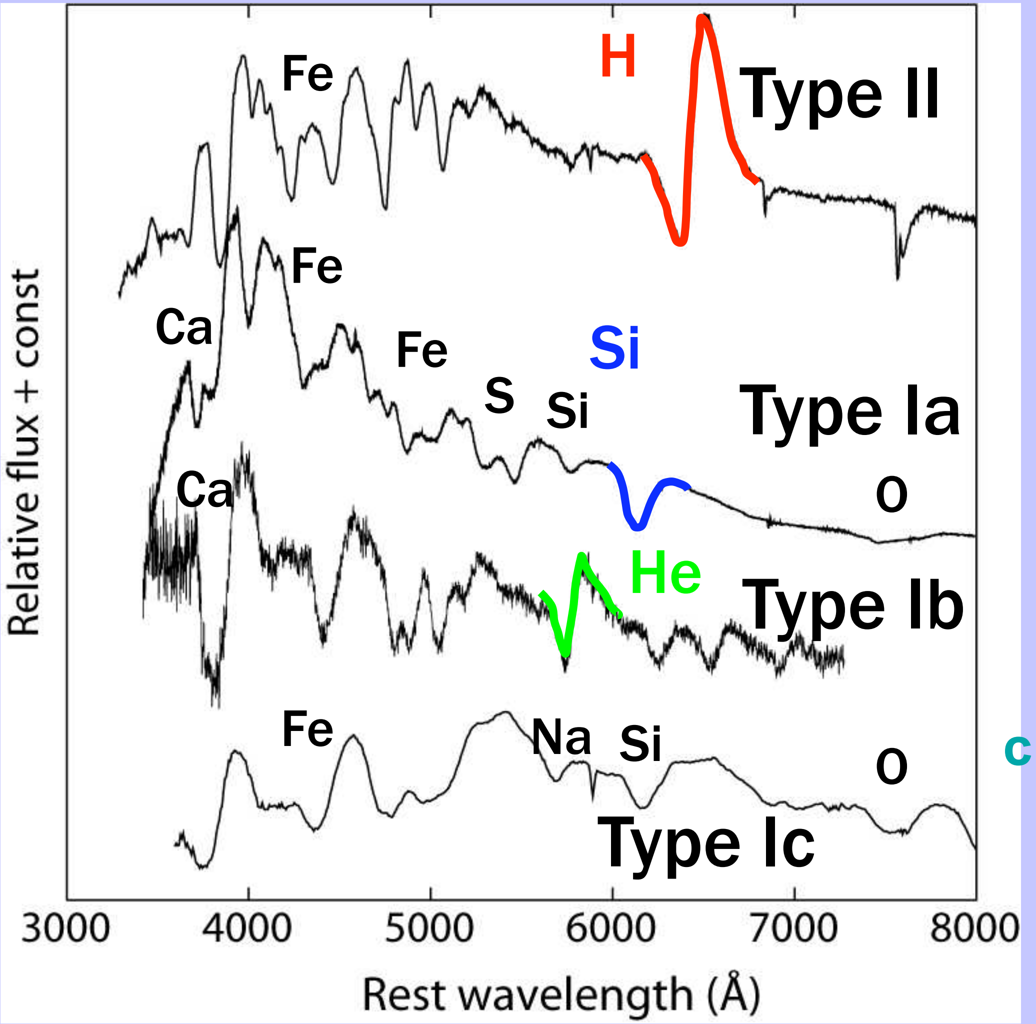


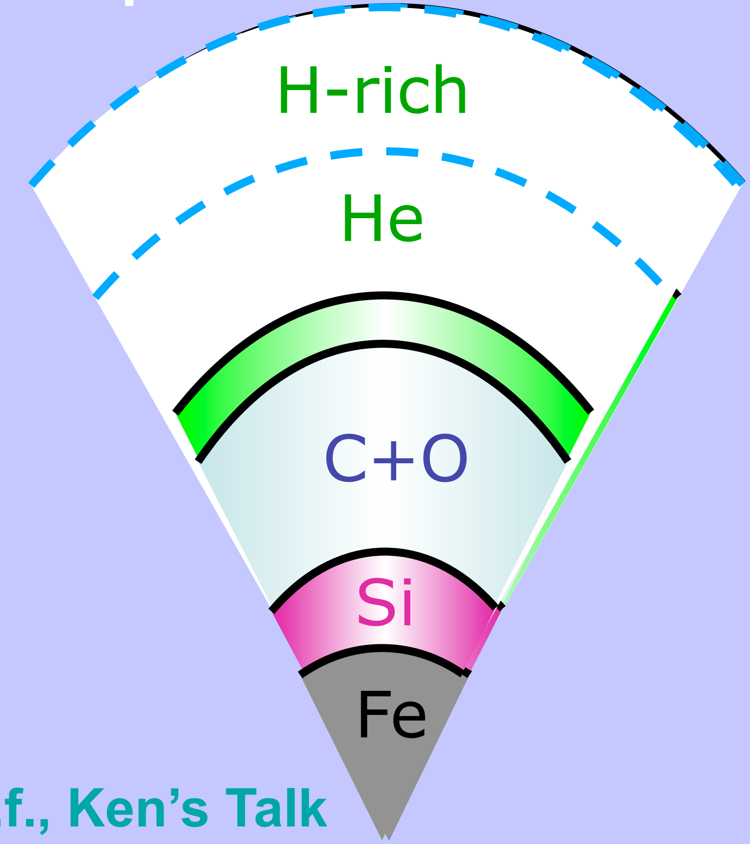


Keiichi Maeda (IPMU)

IPMU Focus Week, 2008.11.17-21

Stripped-envelope supernovae





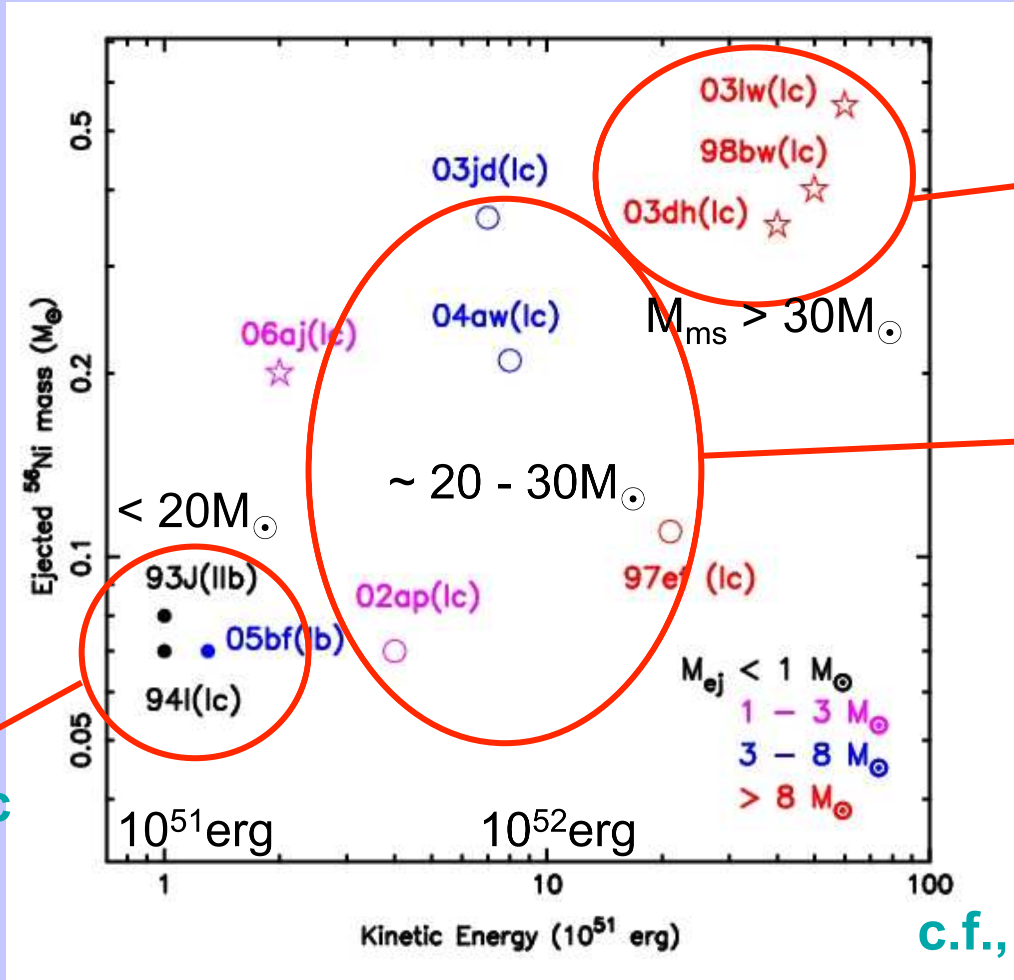
c.f., Ken's Talk

Massive (>~30M$_\odot$) + metal
=> Wind

Less massive or low metal
=> Close binary

General picture: supernova properties

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



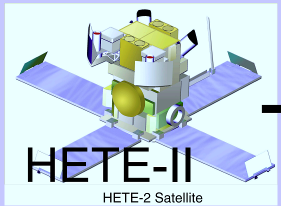
GRB-Hypernova

Broad-lined SN Ic (w/o GRB)

Normal SN Ib/c

c.f., Masaomi's Talk

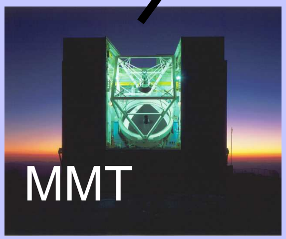
Most massive stars: $M_{ms} > \sim 30M_{\odot}$



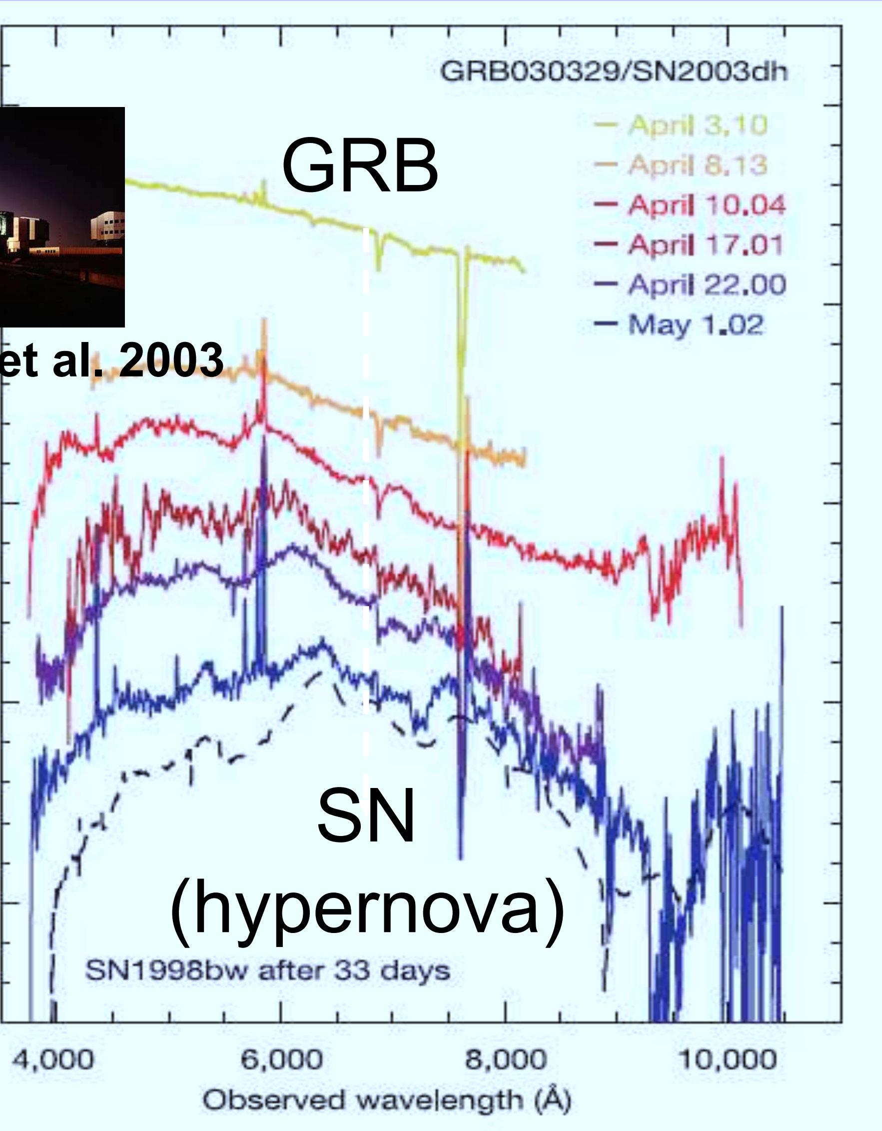
GRB030329

Hjorth et al. 2003

Kawabata et al. 2003

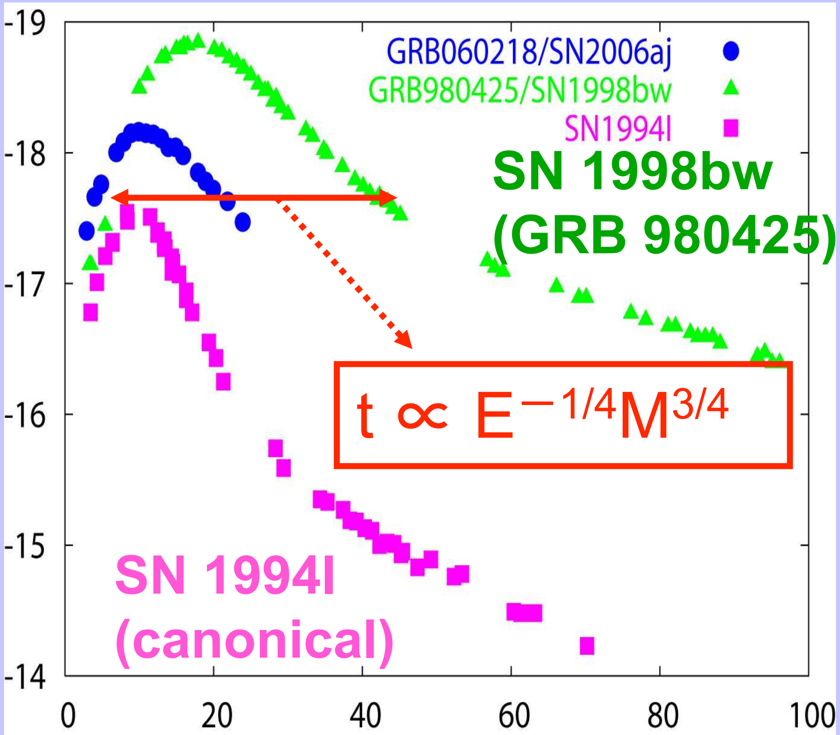


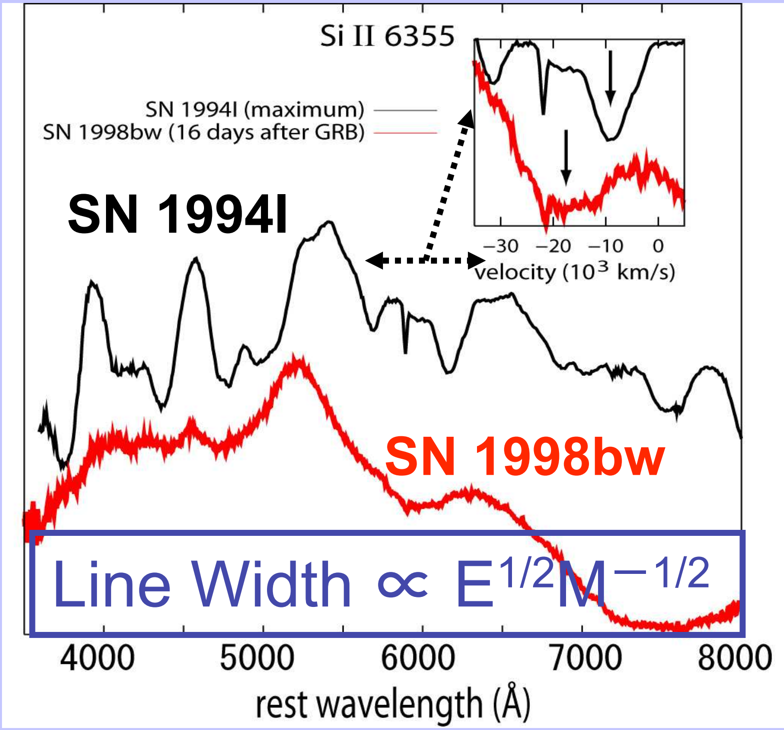
Stanek et al. 2003



A class of GRBs are associated with SNe.

GRBs, Hypernovae, … and Black holes?



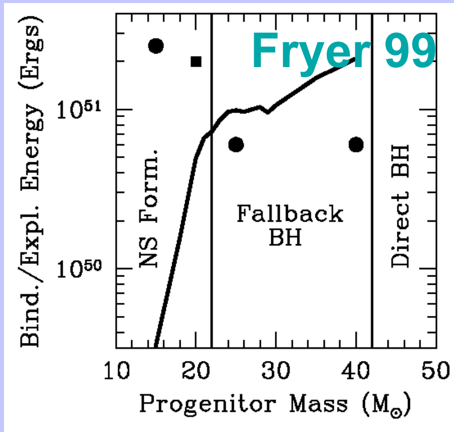


Prototypical GRB-SN 1998bw:

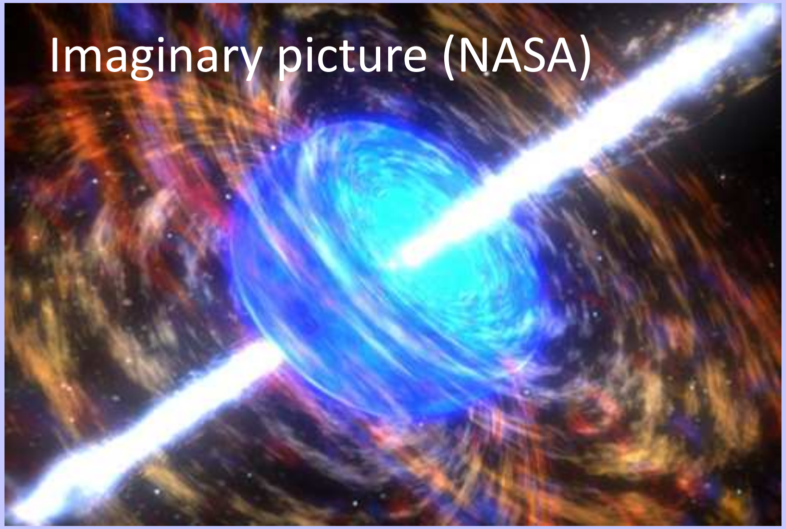
E_K ~ 5 x 10^{52} erg→"Hypernova"

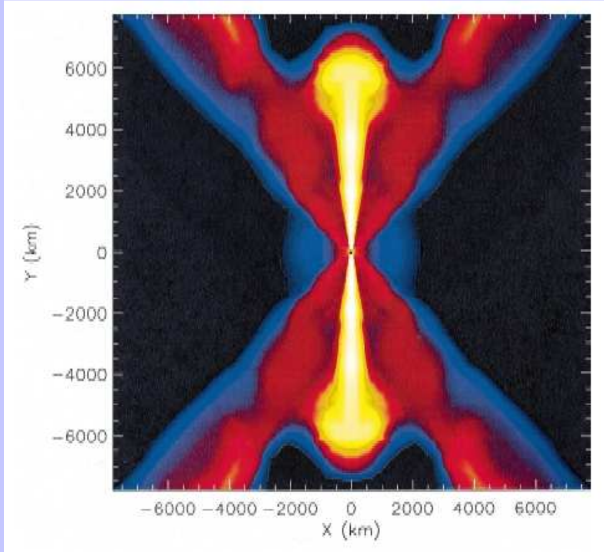
M_{ej} ~ M_{C+O} - M_{rem} ~ $10M_\odot$

→M_{ms} ~ $40M_\odot$→"Black Hole?"

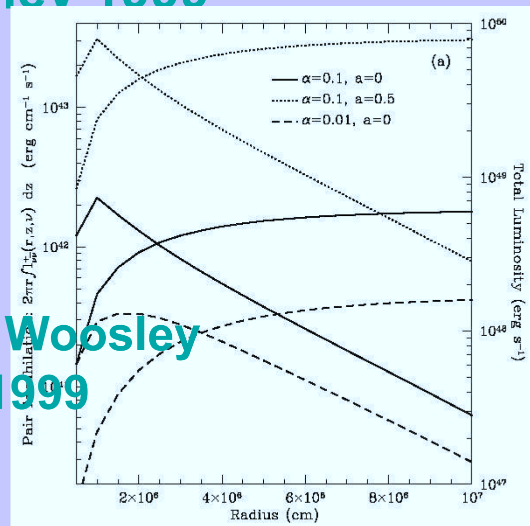


Jet-like, collimated explosion?





MacFadyen & Woosley 1999



- Black Hole + Accretion Disk?
  - E ~ εM c^2 ~ 10^{52} erg (ε/0.01)(M/$M_\odot$)
  - Jet-like Explosion?

Popham Woosley & Fryer 1999

e.g., "Collapser model", Woosley 1993

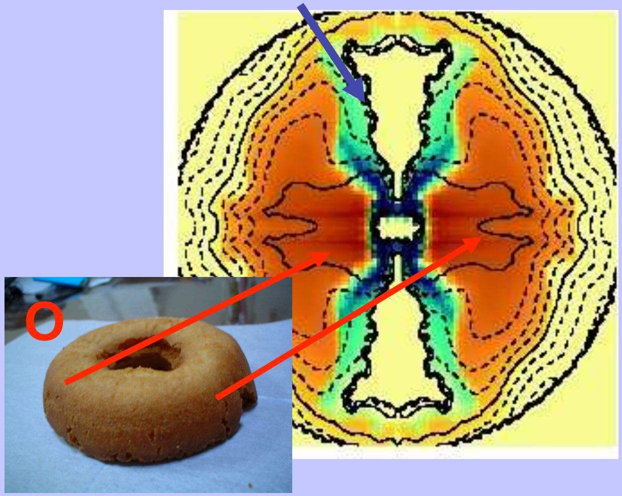
ν+$\bar{\nu}$ as the energy source. ← not that efficient?

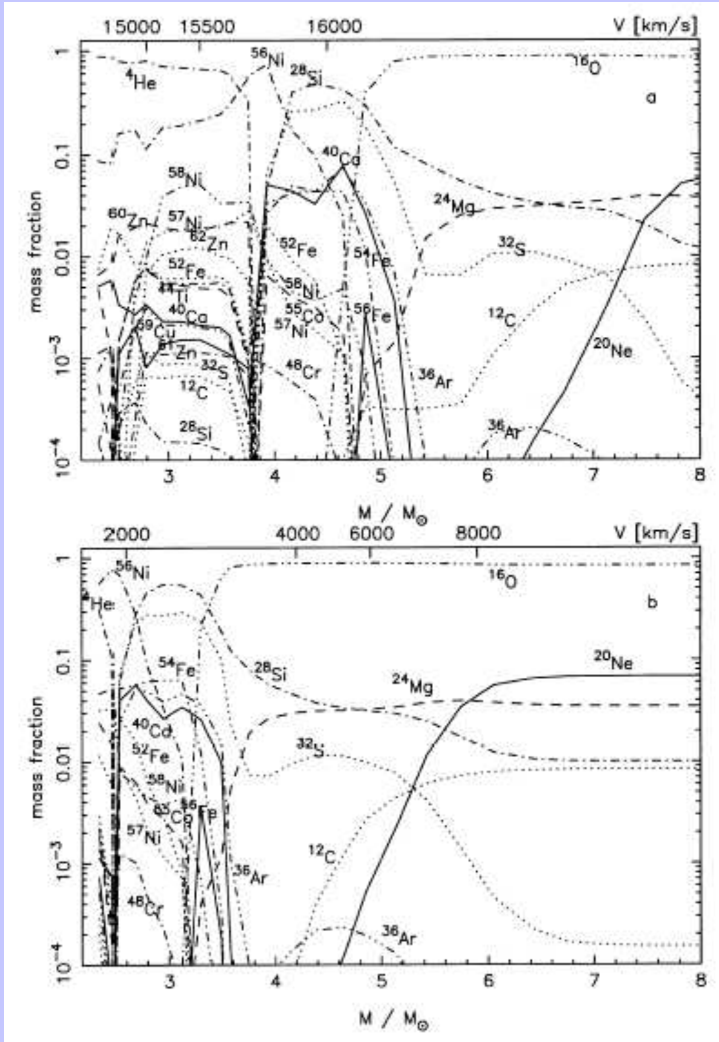
Nucleosynthesis in aspherical explosions

- Multi-D Hydro + Nulcleosynthesis:
  - by S. Nagataki.
  - by myself and Nozomu.
  - by Chris and Aimee.

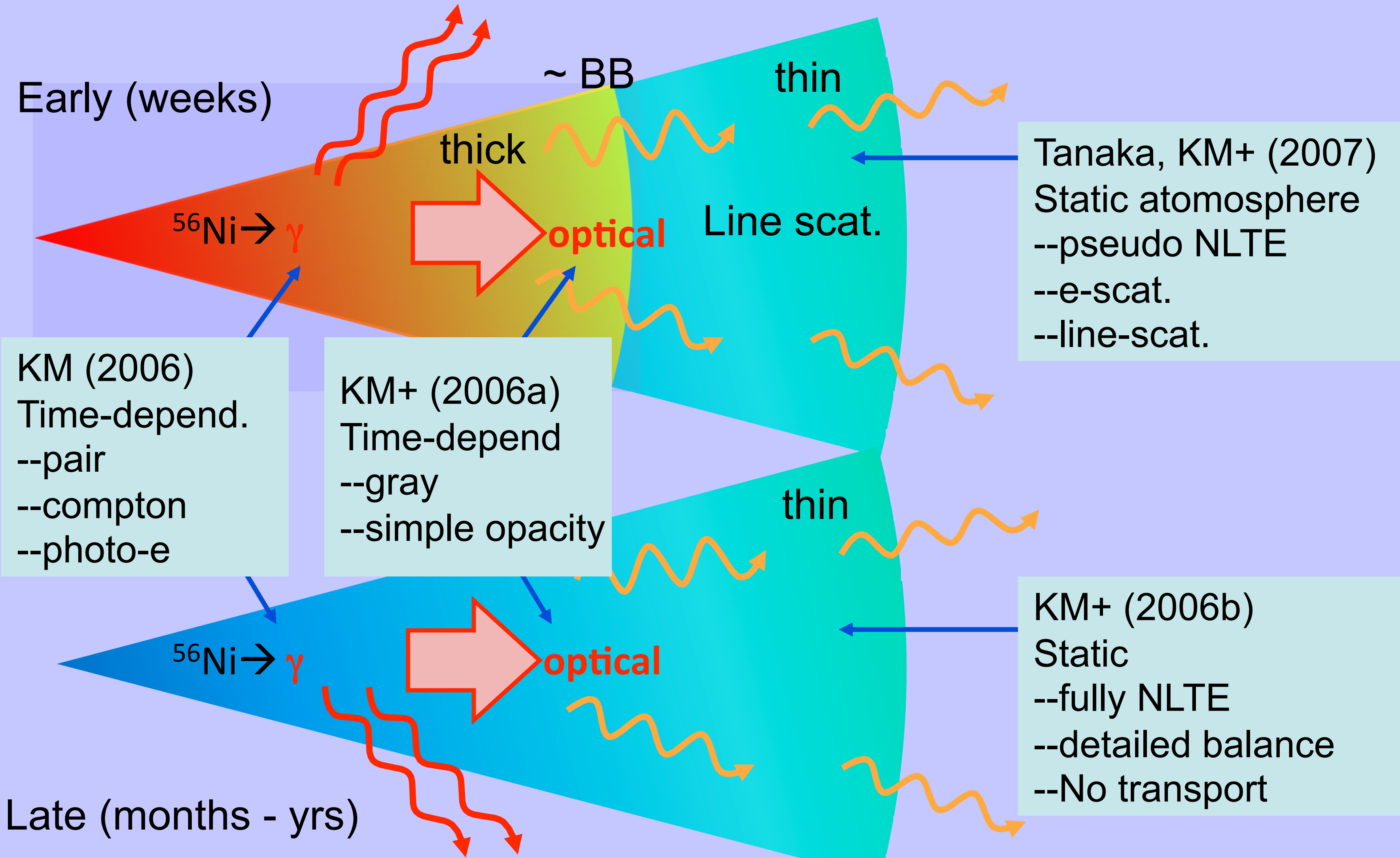
Maeda et al. 2002, ApJ, 565, 405

Fe (^{56}Ni)

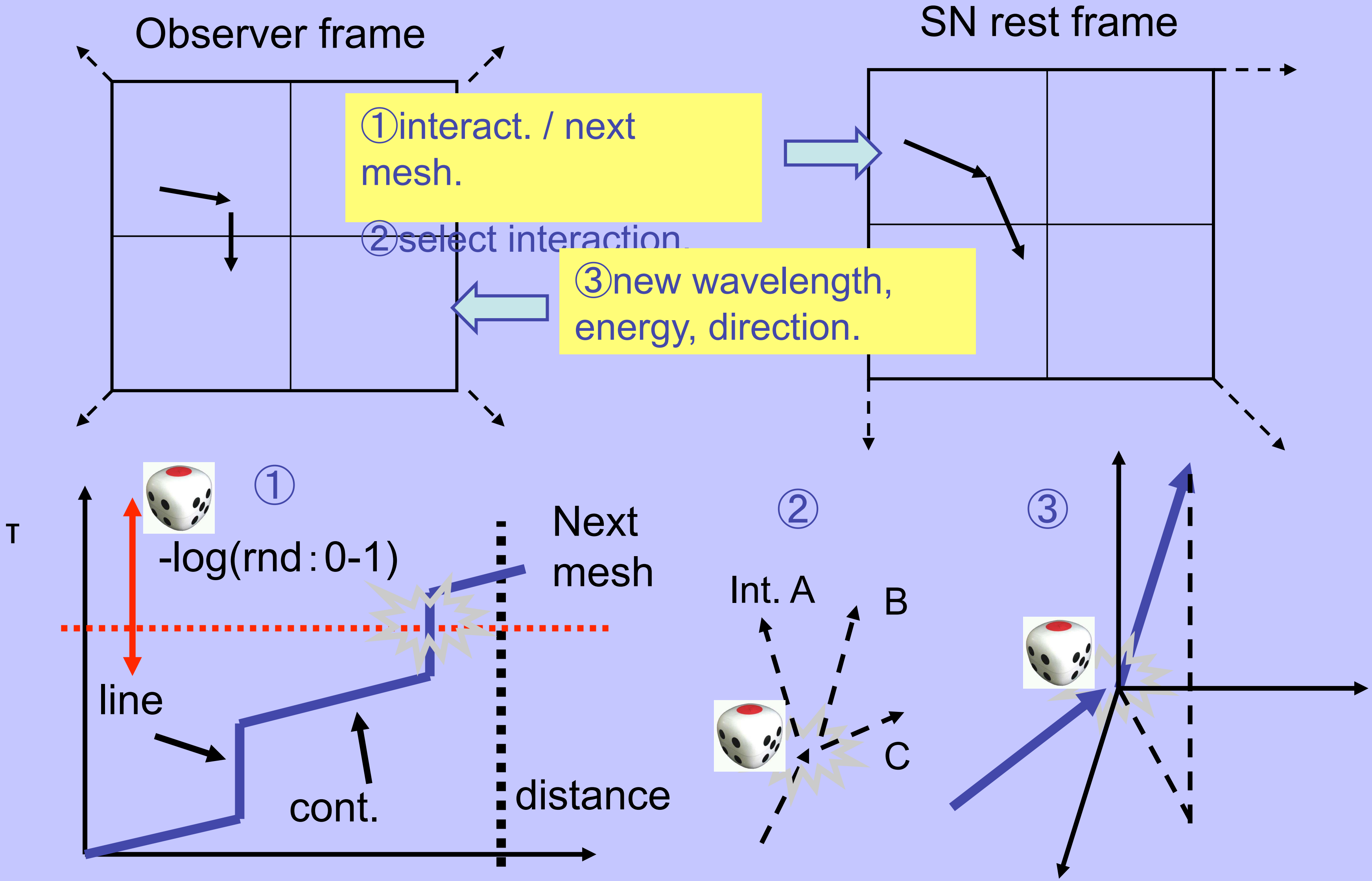




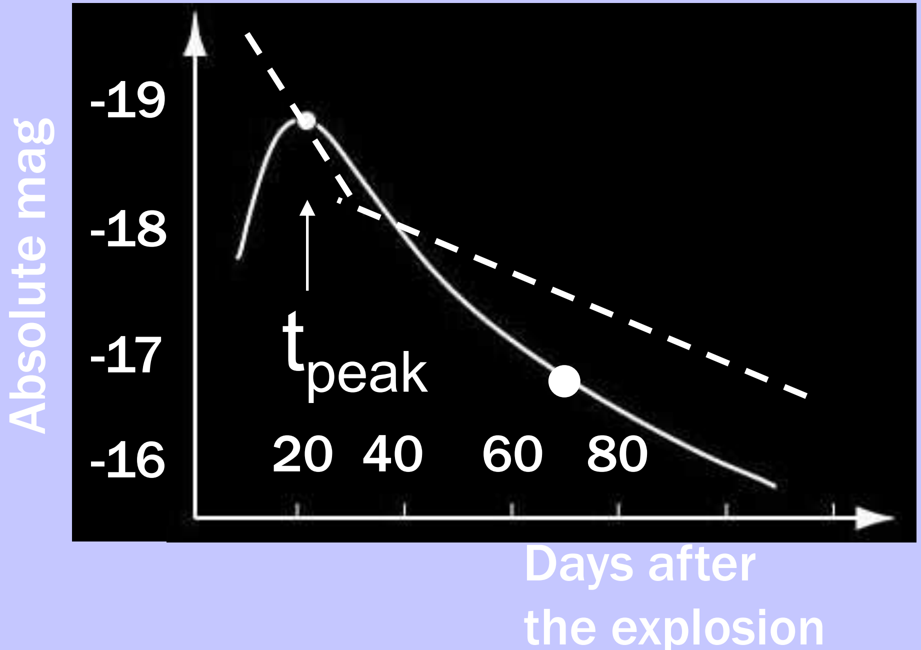
侍… SupernovA MUlti-dimensional RAdIation transfer



Monte-Carlo Transfer



^{56}Ni/Co/Fe Heating



$$L_\gamma = M(^{56}Ni)[S_{Ni}\exp(-t/8.8d)$$
$$+S_{Co}\exp(-t/113d)]$$
$$t_{peak} \propto M^{3/4}E^{-1/4}$$
$$L_{peak} \approx L_\gamma(t_{peak})$$
$$L_{late} \approx L_\gamma(t)\tau_\gamma$$
$$\tau_\gamma \propto M^2E^{-1}t^{-2}$$

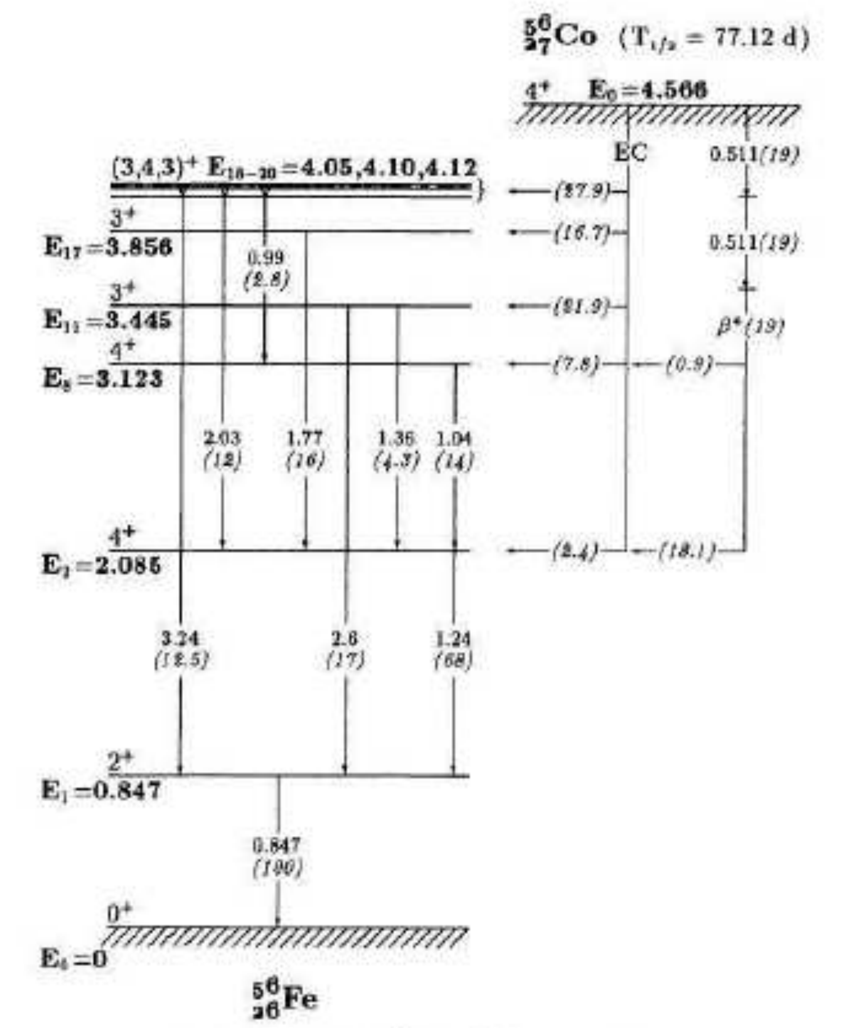
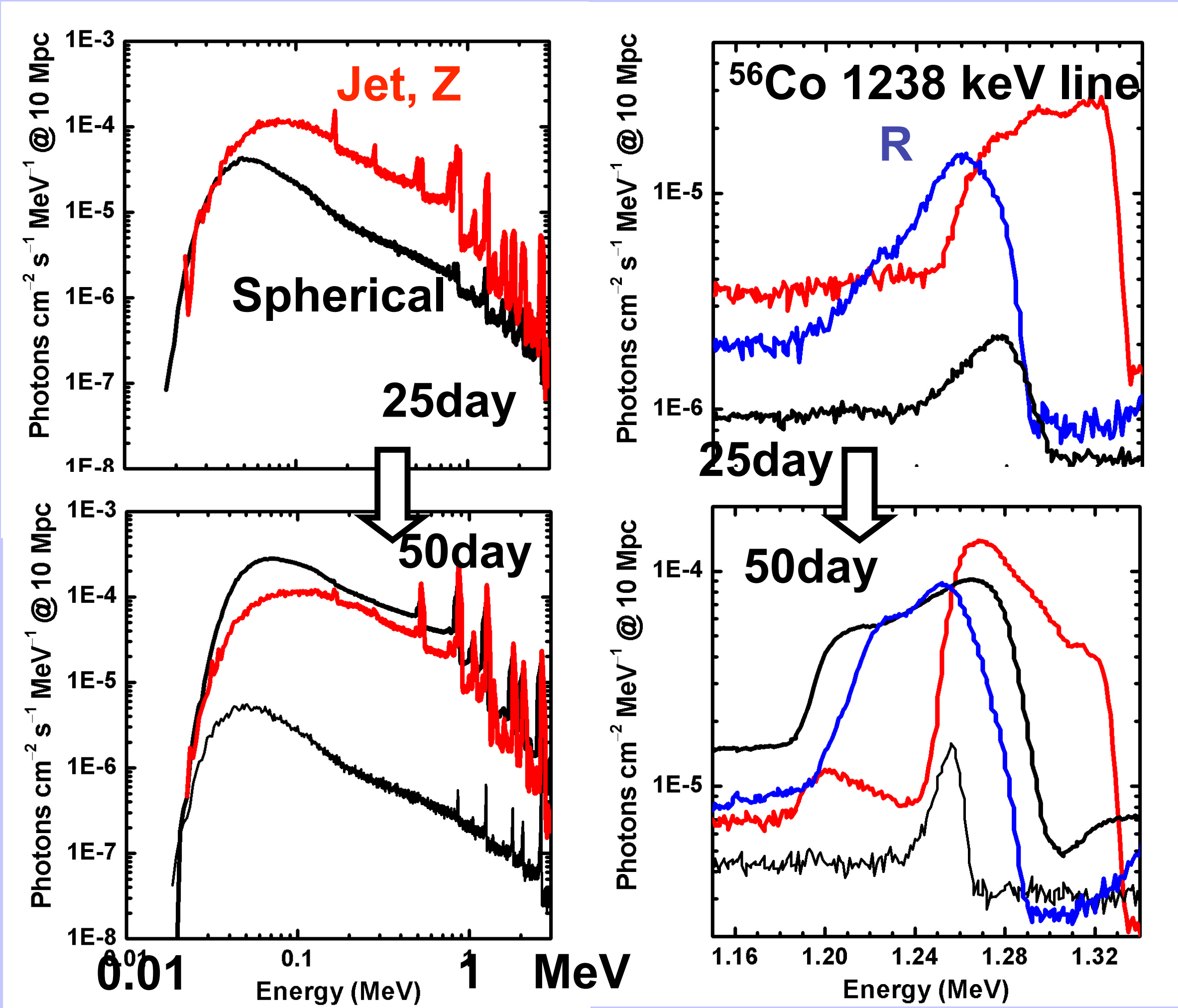


FIG. 2.—Simplified ^{56}Co → ^{56}Fe decay scheme

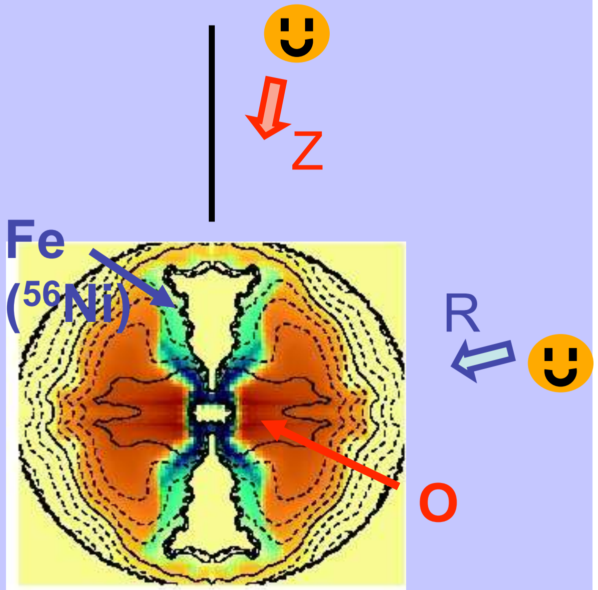
X, γ-rays from radioactive ^{56}Ni/Co

INTEGRAL, 10ksec ～ a few 100 kpc…



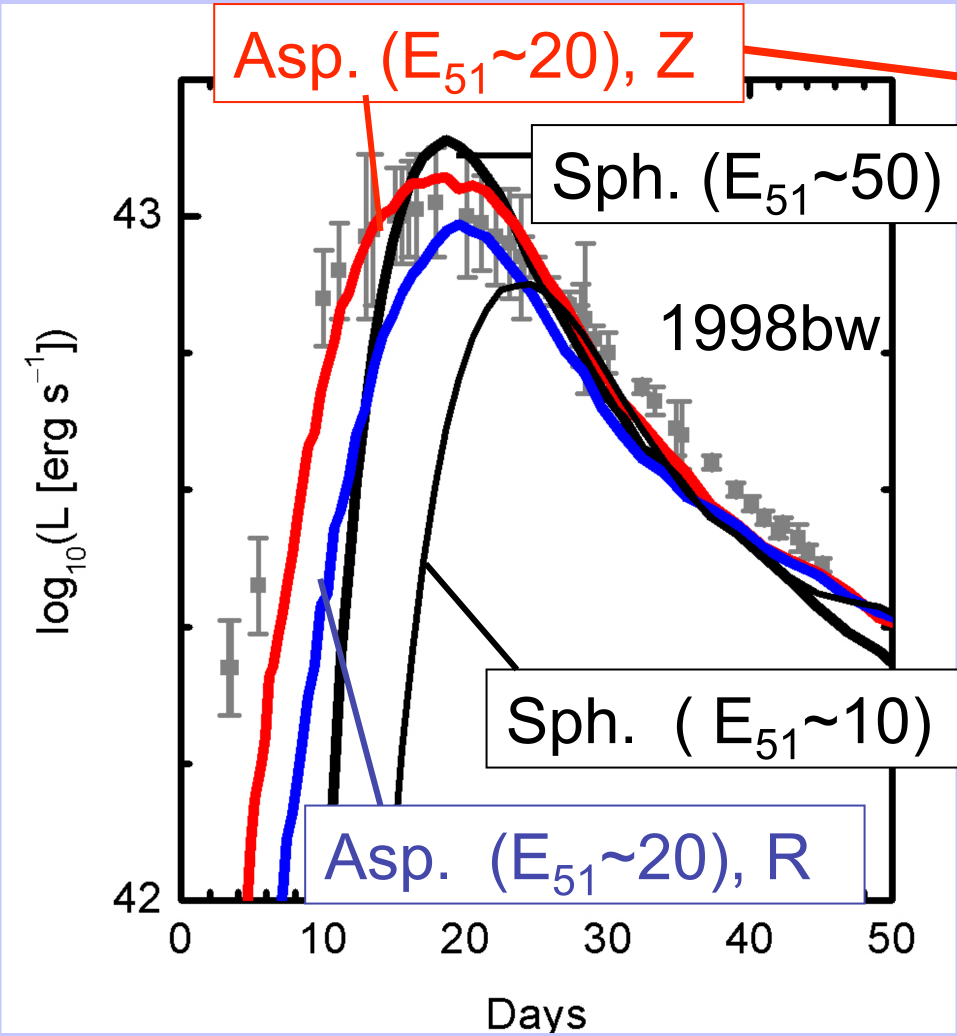
Maeda, ApJ, 2006, 644, 385

c.f., Aimee & Chris's work



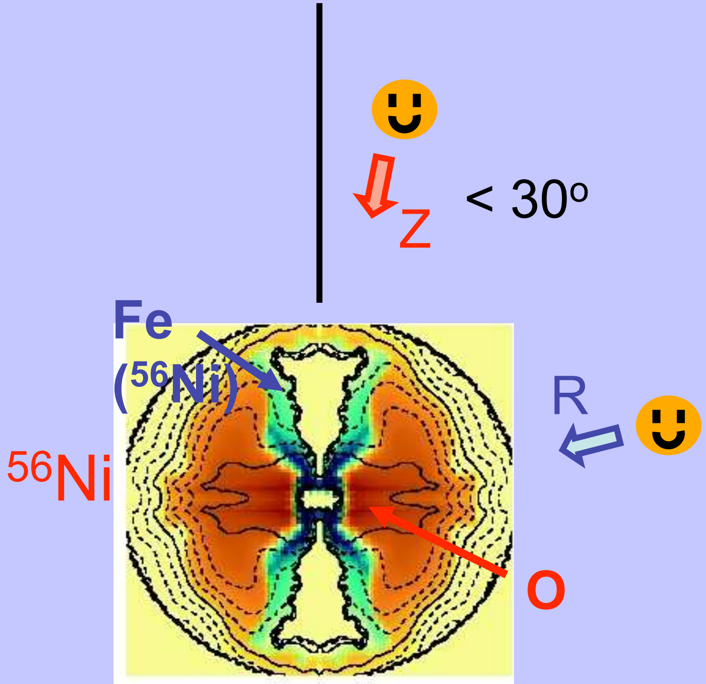
SN 1998bw (GRB 980425) – Early LC

∗ E_{51}=E/10^{51}ergs (~1 for a normal SN)



Consistent with obs.

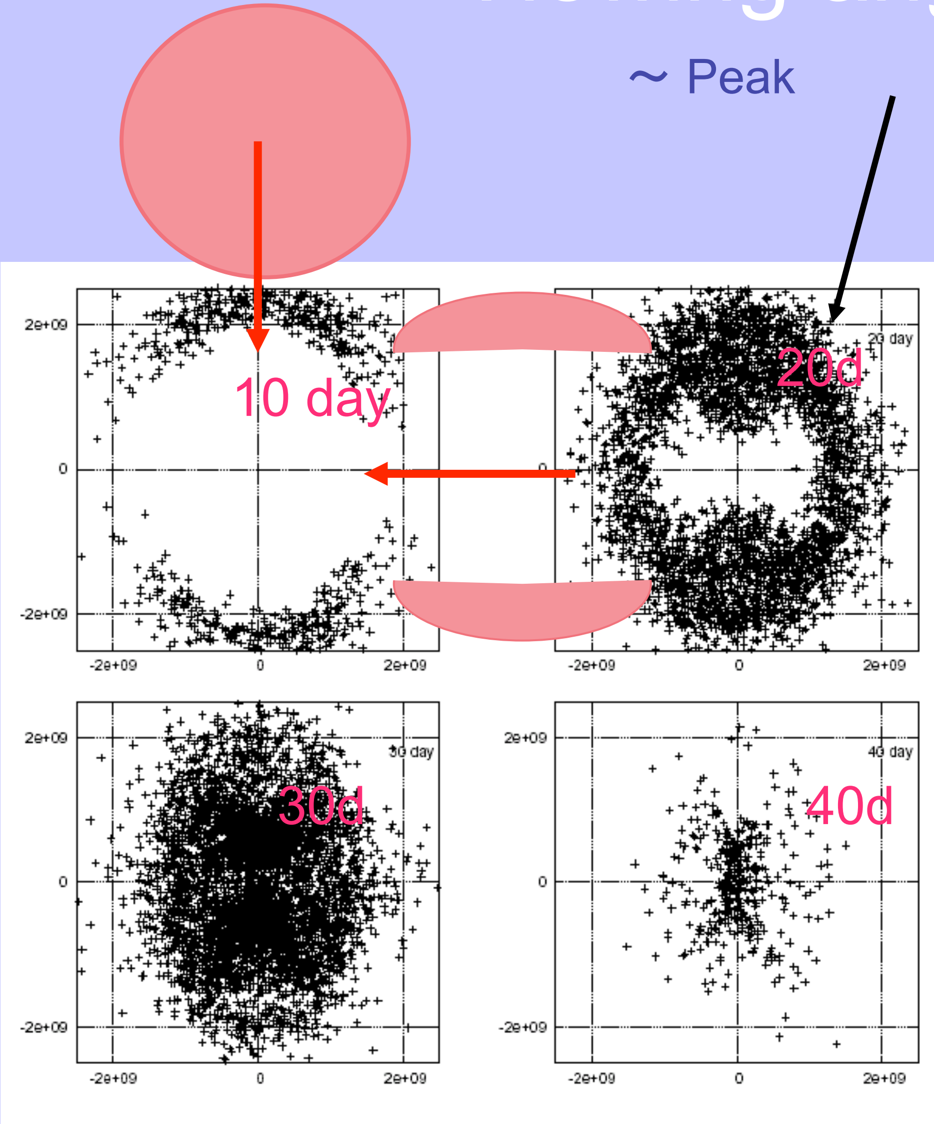
c.f., P. Hoeflich's work

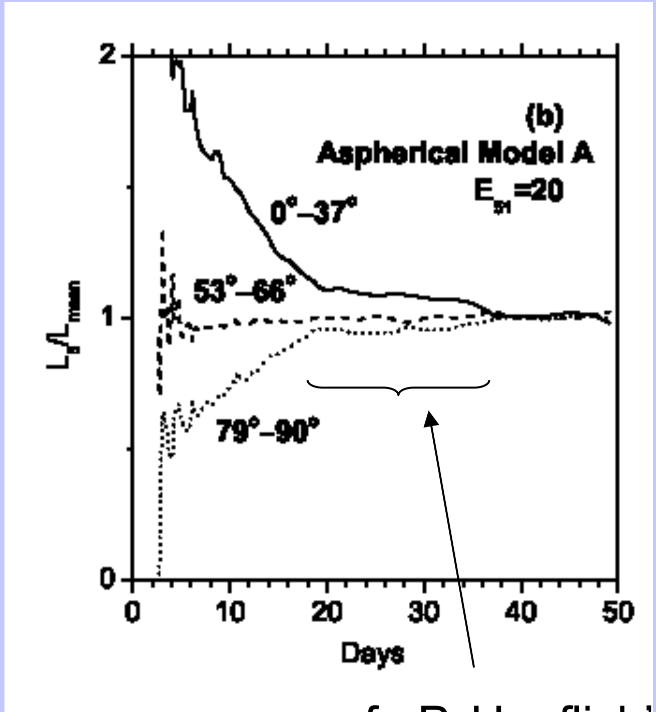


Viewing angle effects

L_θ/L_{mean}

~ Peak





c.f., P. Hoeflich's work

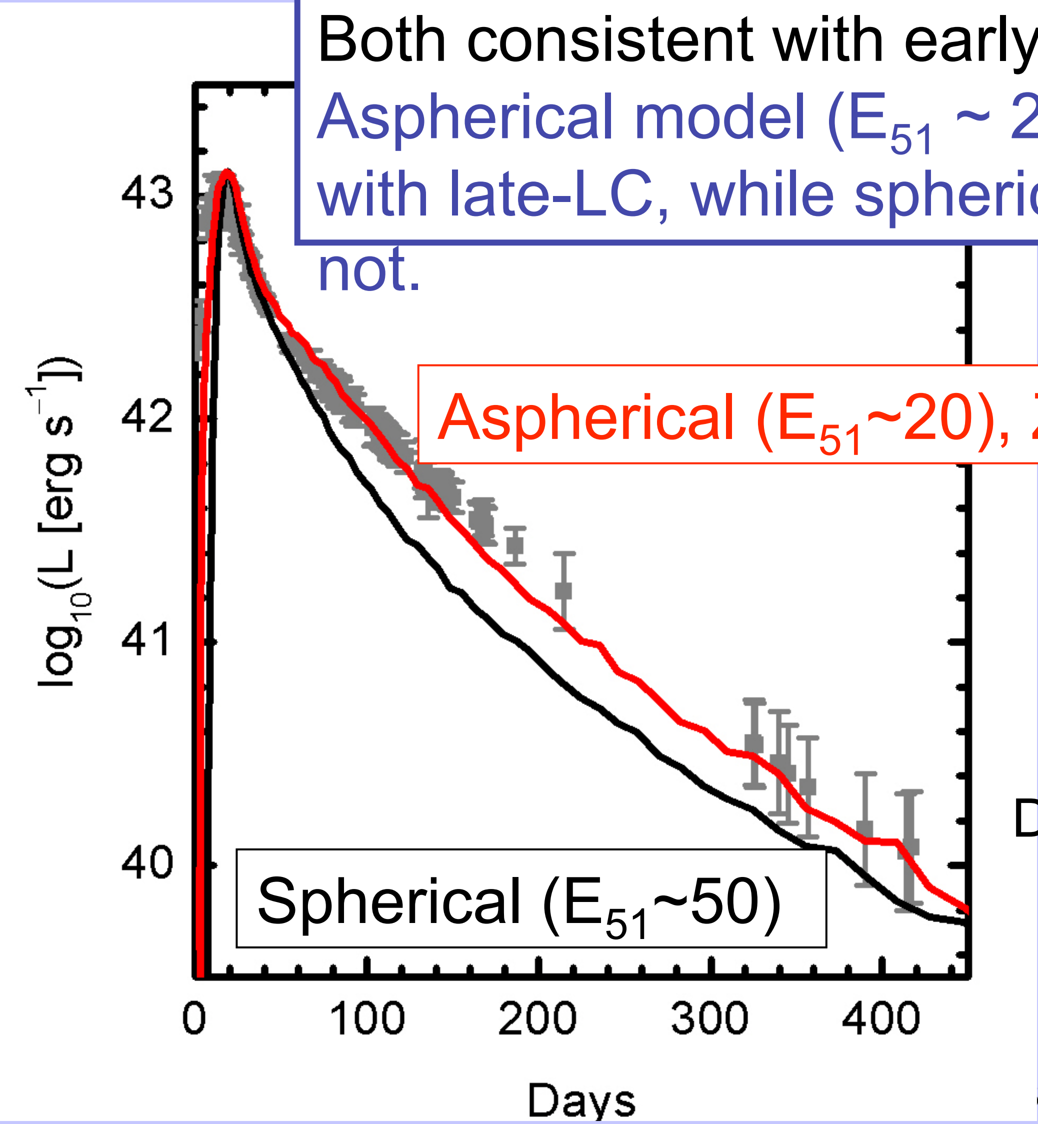
Only strong before the peak,

anyway within the factor of a few.

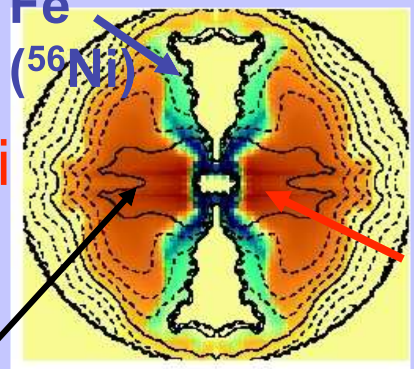
Late-LC

Maeda et al. 2006b

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



< 30^o



Dense region trapping γ efficiently.

- $\tau_\gamma = CM^2/E$
  – Small E ("intrinsic").

Early-Spectra

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

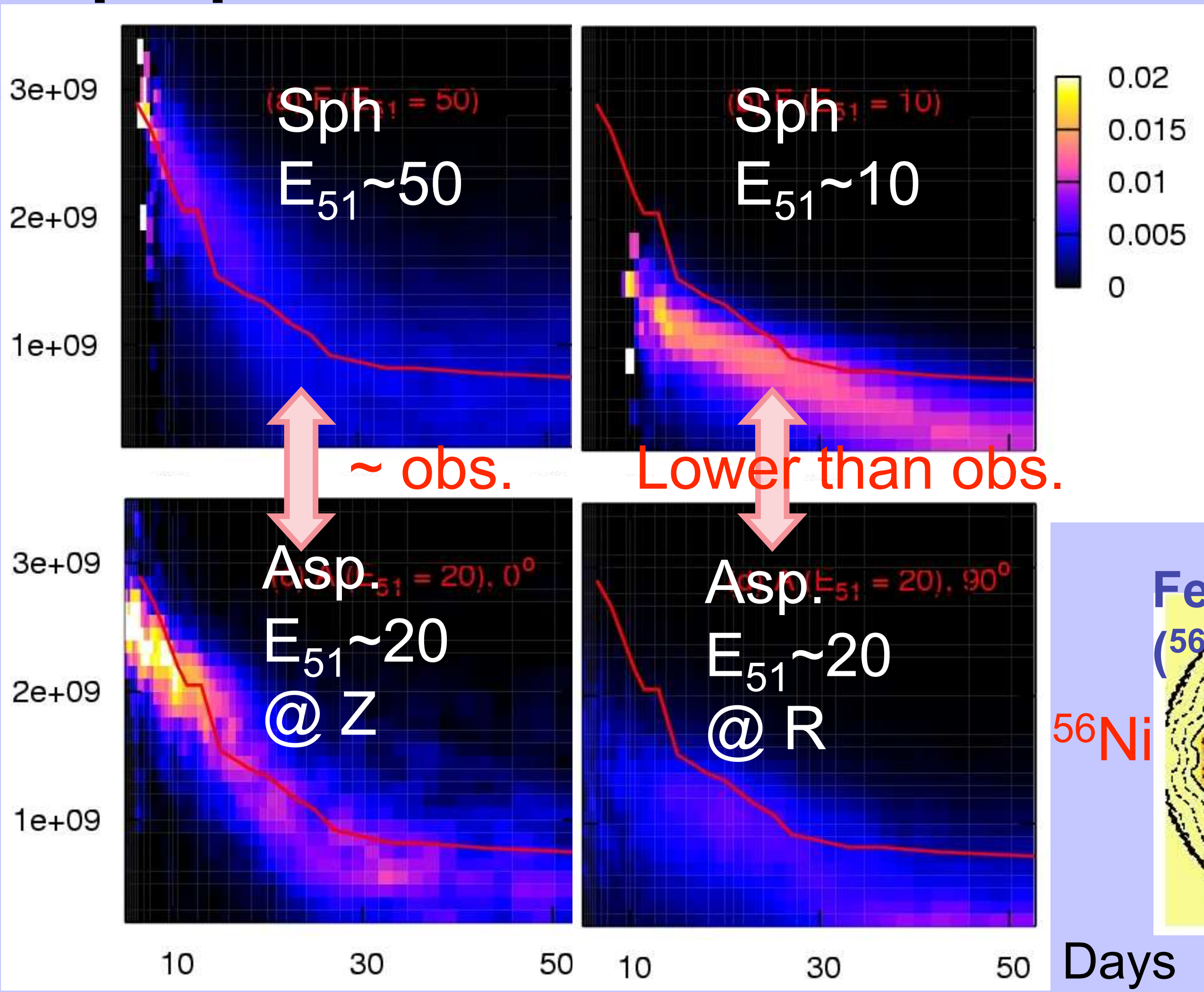
$V \sim (E_{isotropic}/M)^{1/2}$

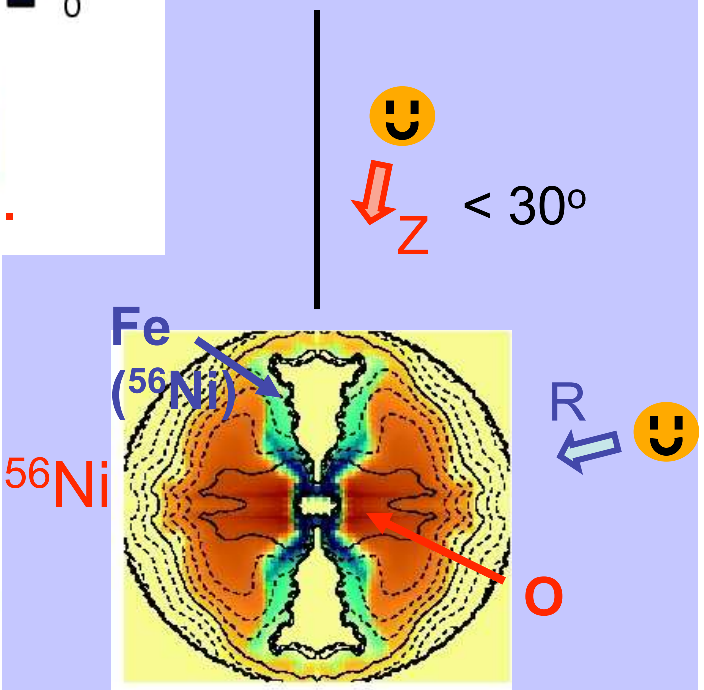
Phot. V [cm/s]

Maeda et al. 2006b

Color: model

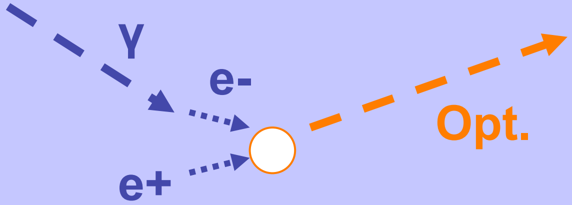
red: obs (Si vel.)





Days

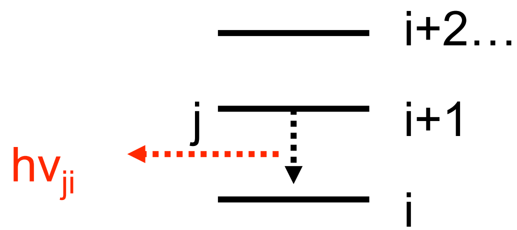
Late-Time Spectra



Ionization

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

↑ Non-thermal e⁻ 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⁻ impact excitation rate

Energy balance

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

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

↑ Non-thermal e⁻ heating rate

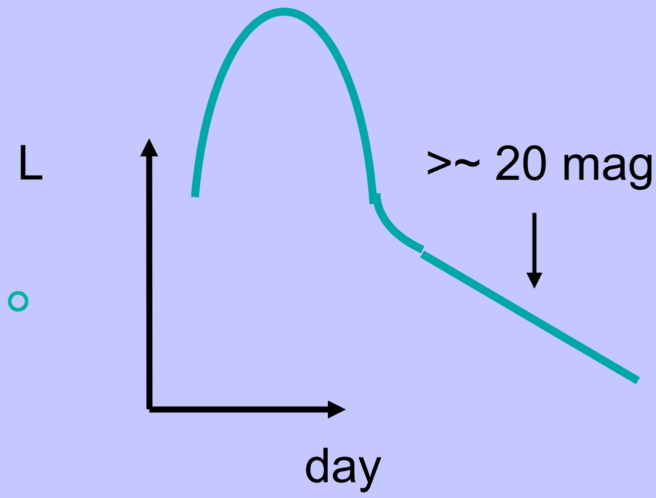
Non-thermal electrons

- →ionization
- →excitation
- →heating

⇒Enters into rate equations.

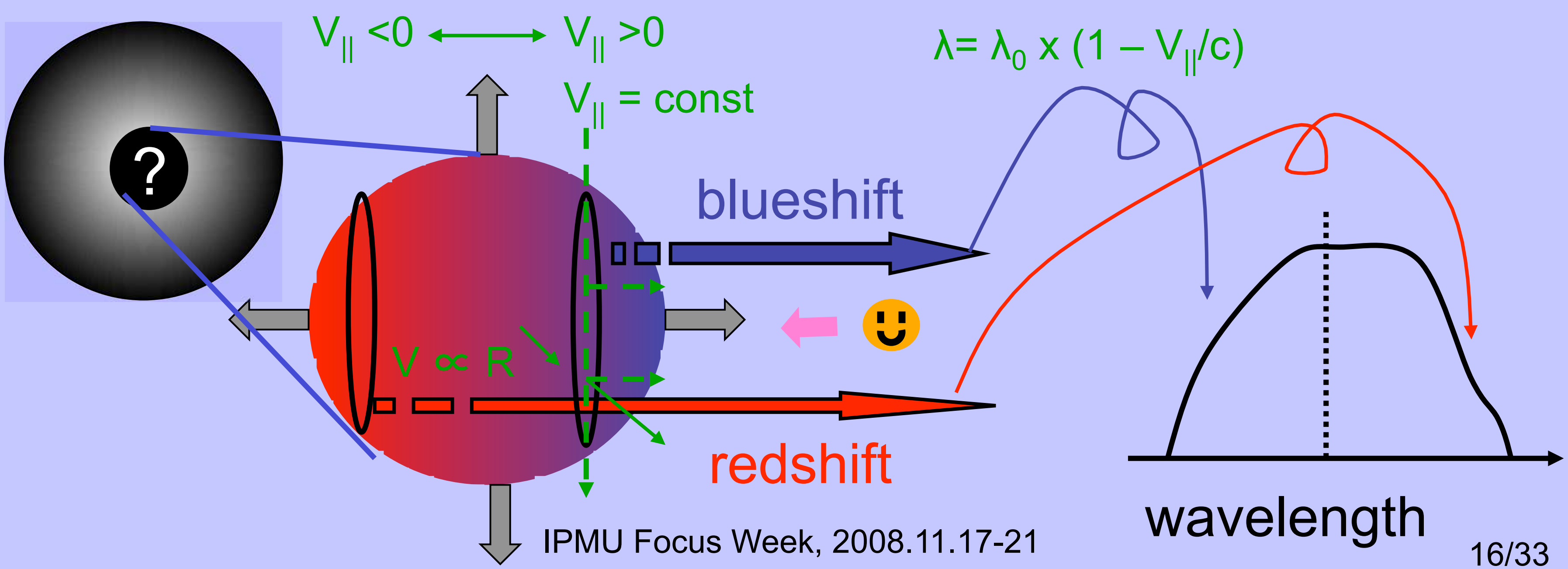
∗ In some situations, UV photons are also important for ionization/excitation (i.e., photoionization and stimulated emission omitted above).

Late-phase Spectra



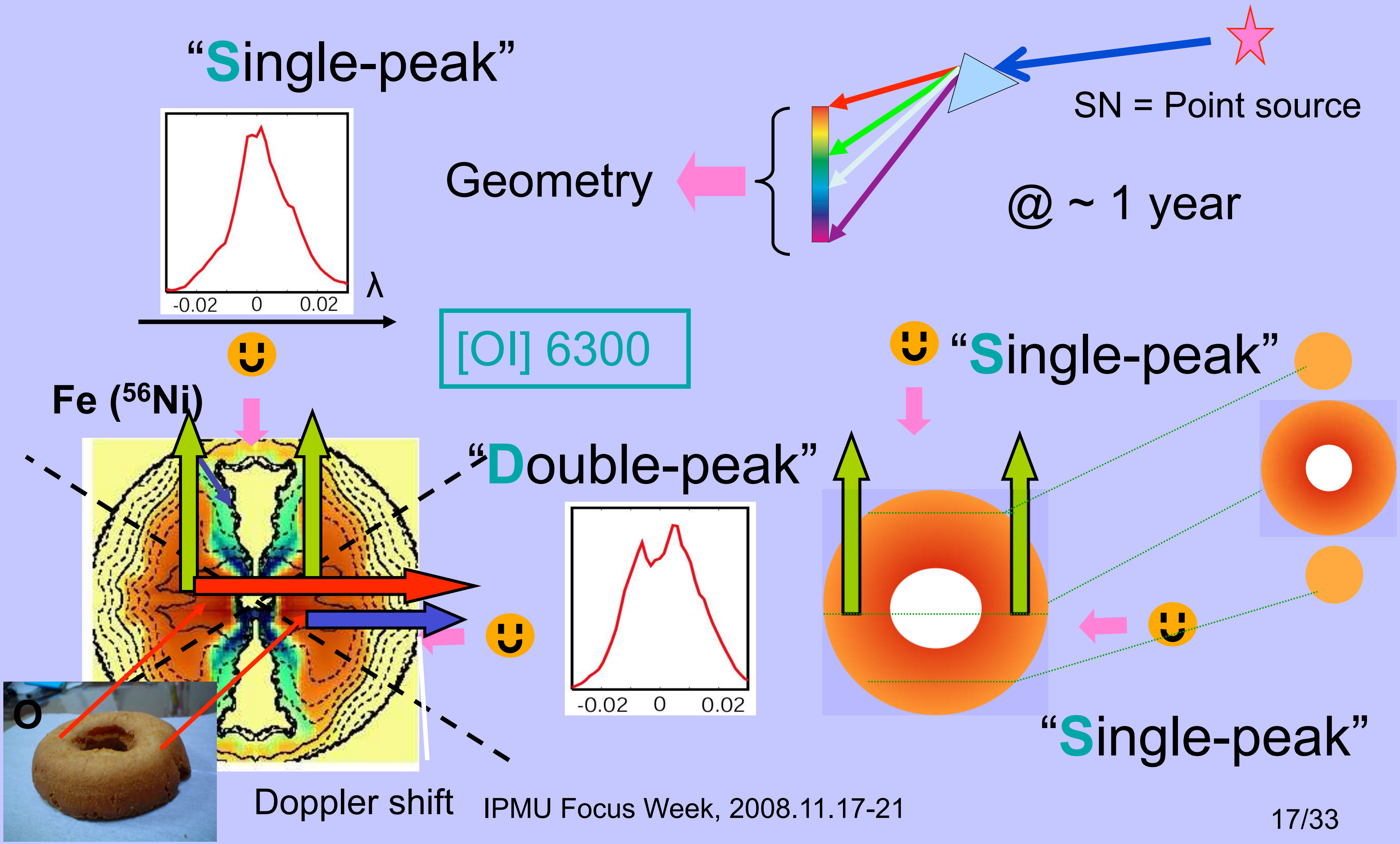
- ~ 200days: optically thin ($\rho \propto t^{-3}$)。
  - Looking into the center!
- Line profiles→distribution.
  - [OI]= distribution of neutral O.
  - Emission from Near/Far side = Blue/Red-shifted.

faint→need 8m telescope

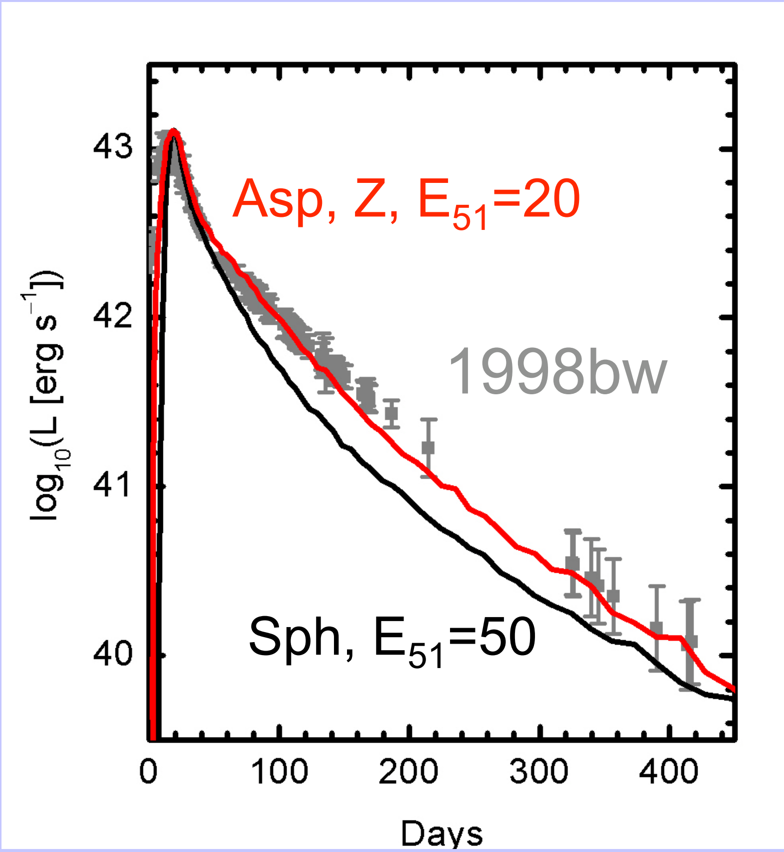


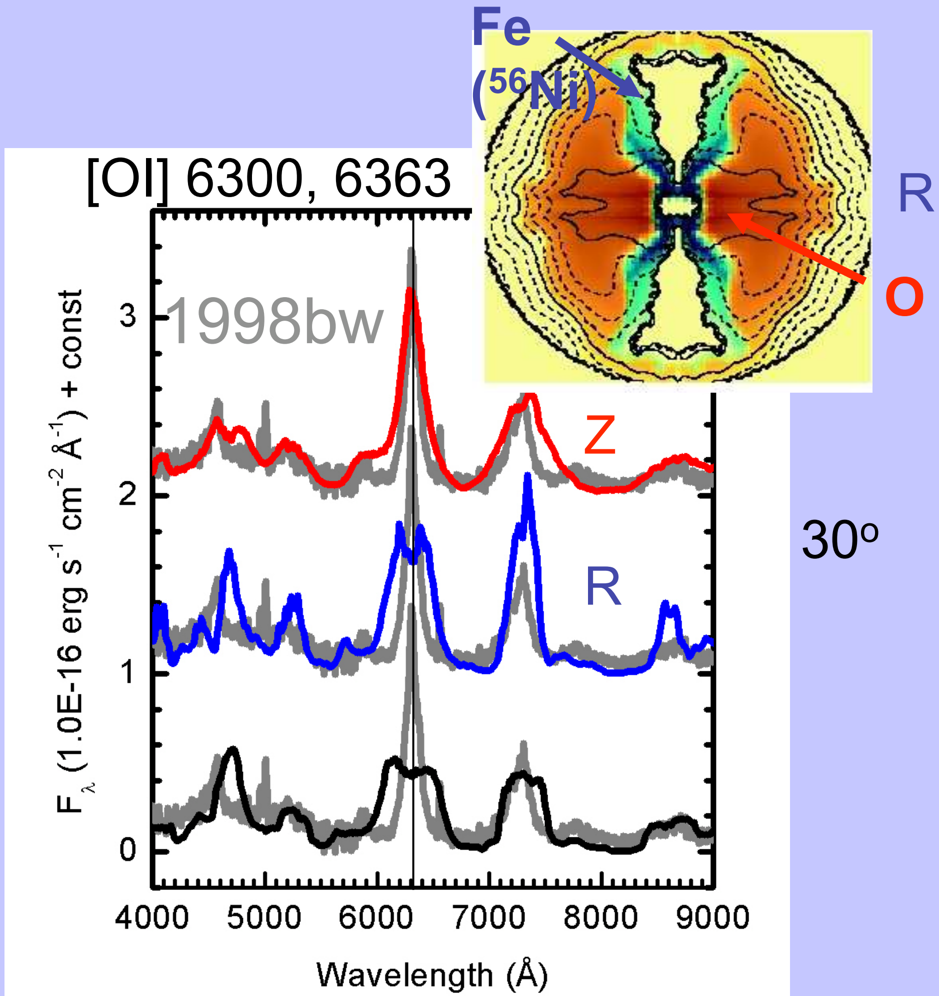
"Geometry" ⇔ Line profile

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



SN 1998bw@1 year





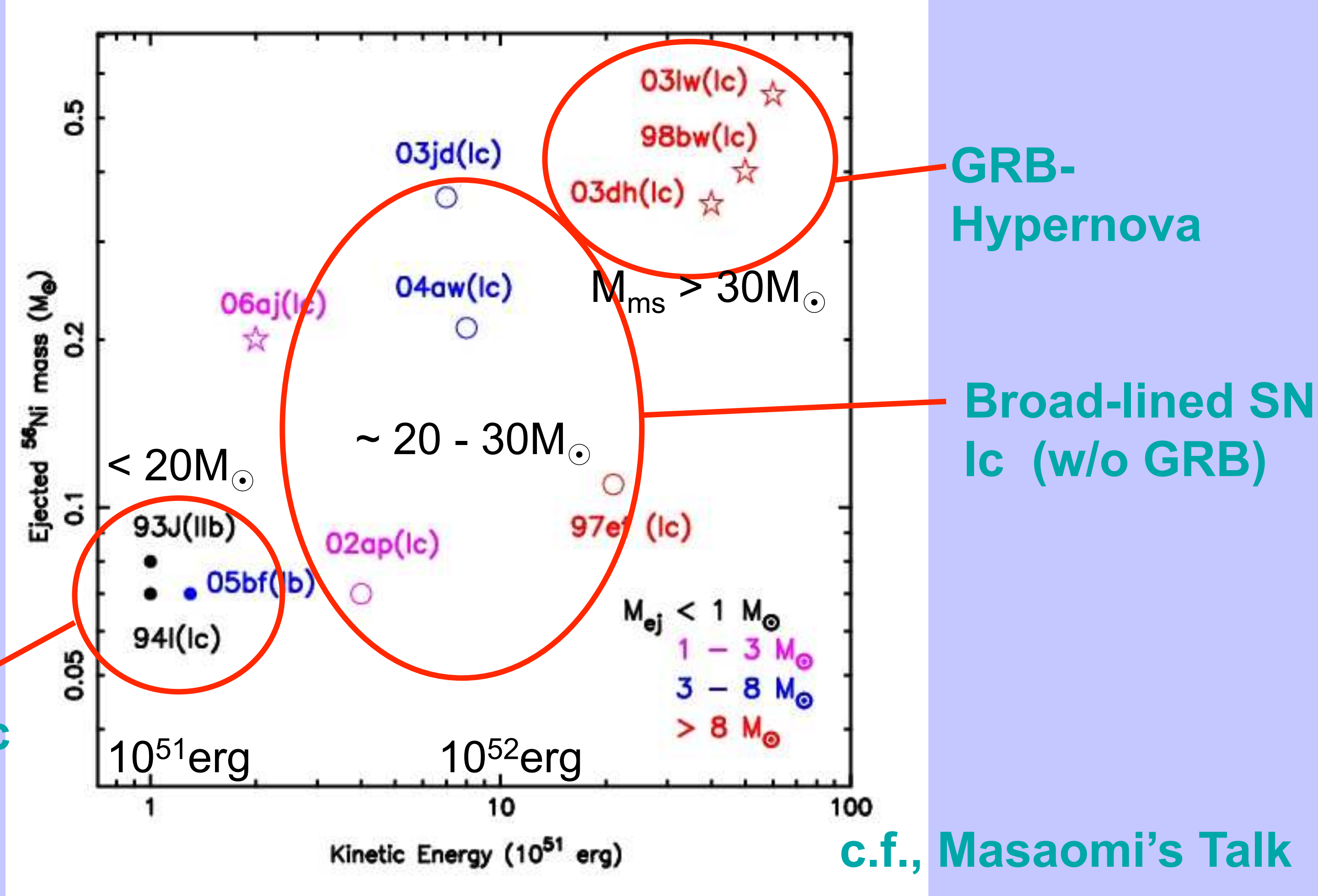
Maeda, et al. 06, ApJ, 645, 1331 **Maeda et al. 06, ApJ, 640, 854**

- Aspherical (E_{51}=20) viewed at Z, not by spherical models.

A bit small "intrinsic" E is important, as it's optically thin.

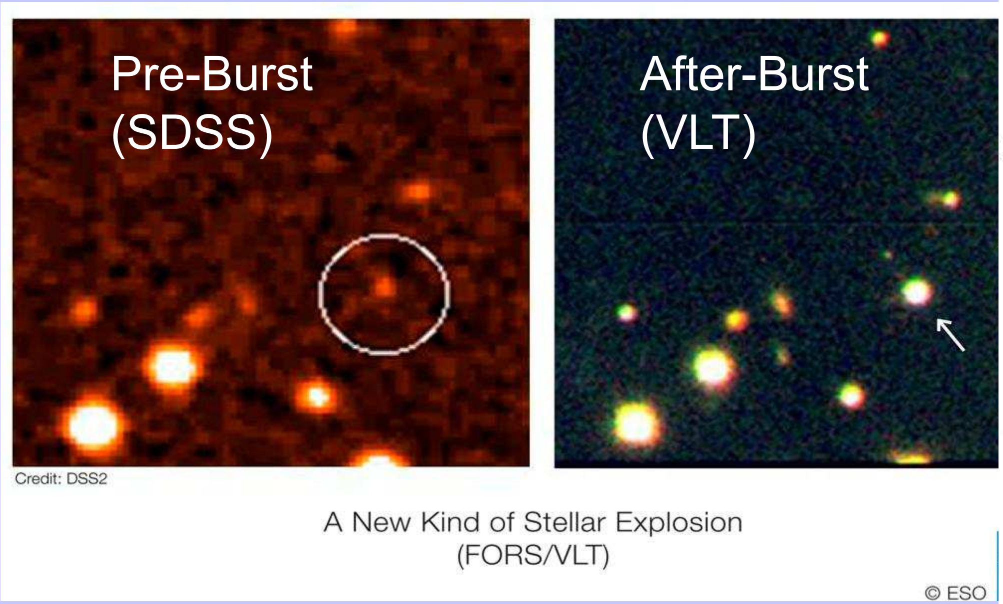
General picture: supernova properties

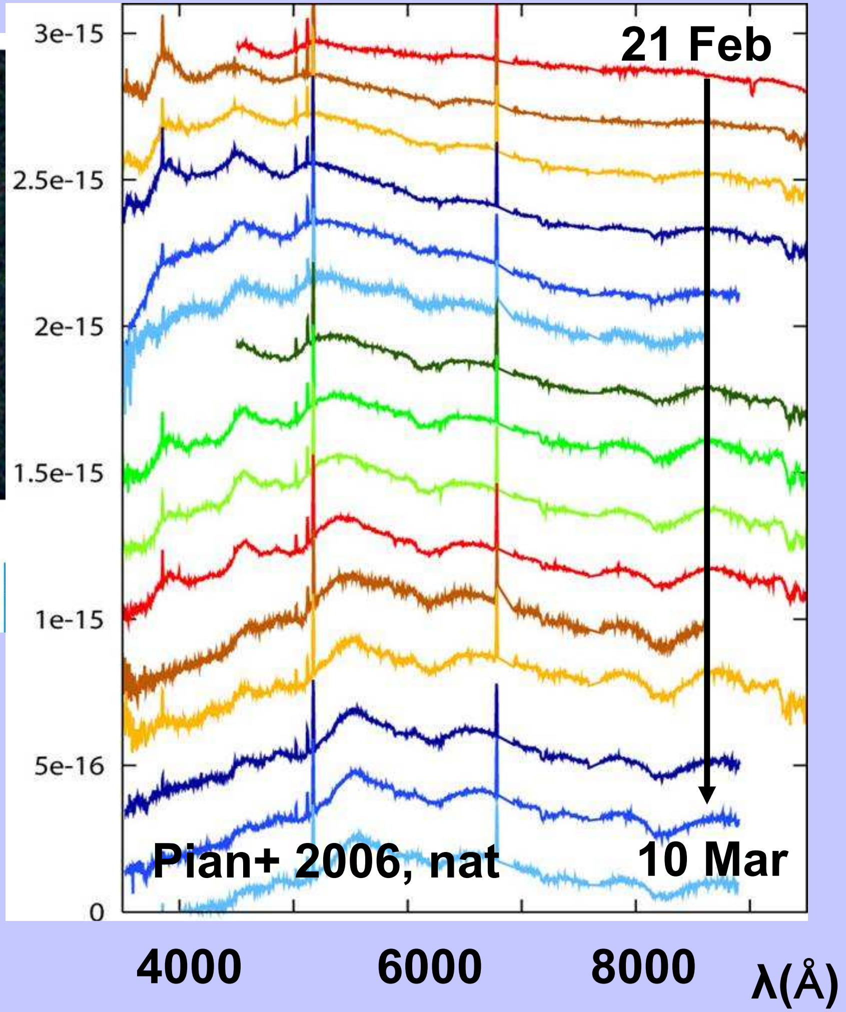
Fig. 1 of Maeda et al. 2008, Science, 319, 1220



c.f., Masaomi's Talk

Massive stars: M_{ms} ~ 20 - 30$M_\odot$





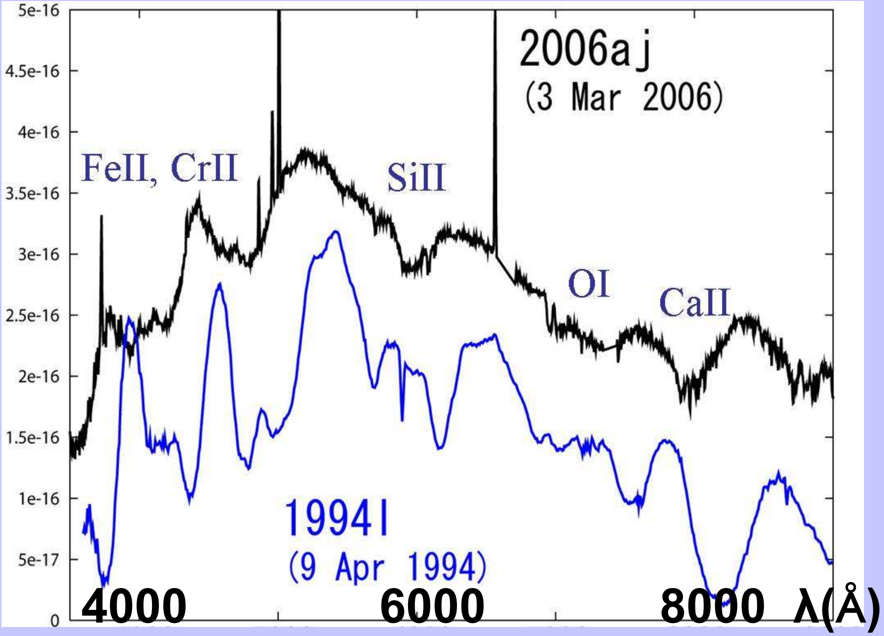
XRF = a low E subclass of Gamma-Ray Bursts

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

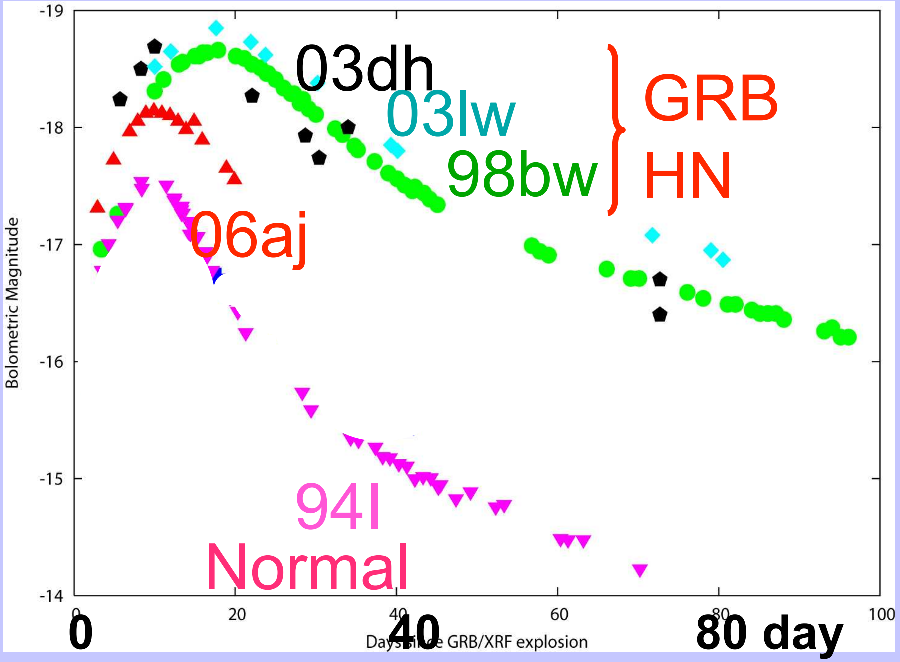
Pian+, 06, Nature

Mazzali+, 06, Nature

Spectra @ ~ 2 weeks



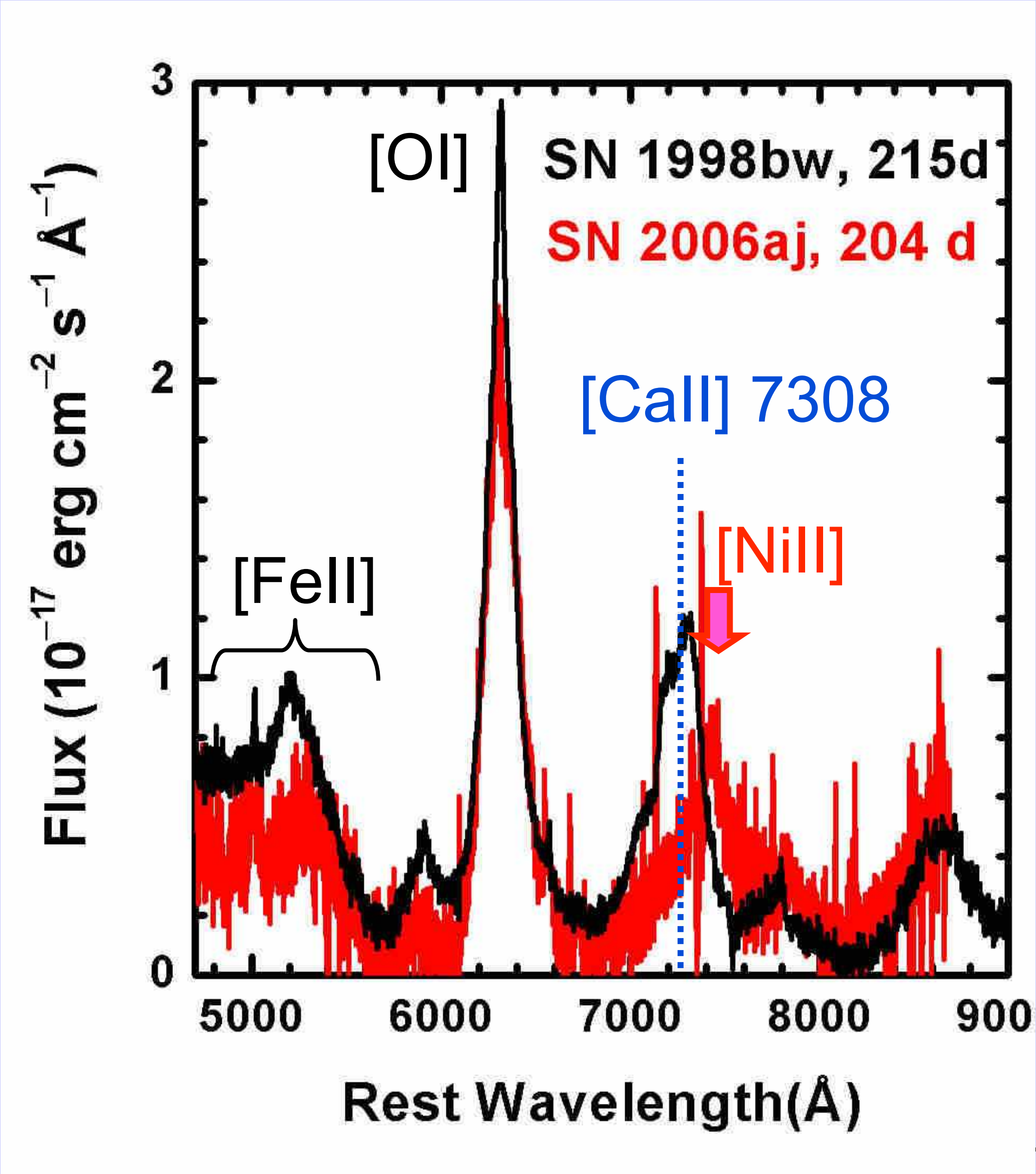
Light Curve @ 1st month



	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}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}Ni)~0.05M$_{\odot}$
Neutron-rich
⇒NS formation(?)

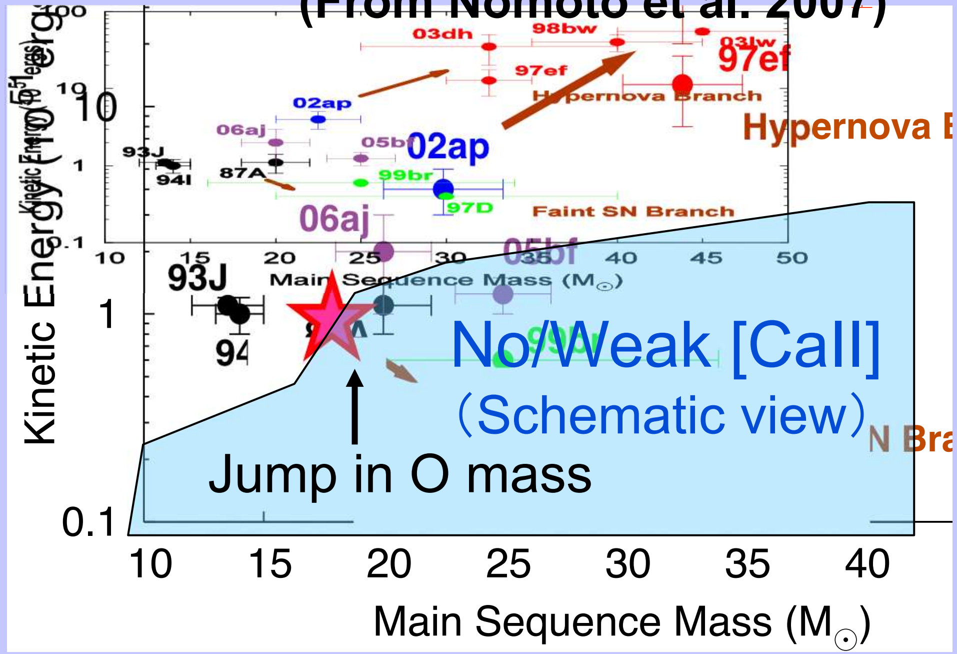
The XRF was produced by a strong activity of the NS? (e.g., Magnetar?)

[CaII]/[OI] as a possible diagonostics

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

SNe Ibc – M_{ms} vs E

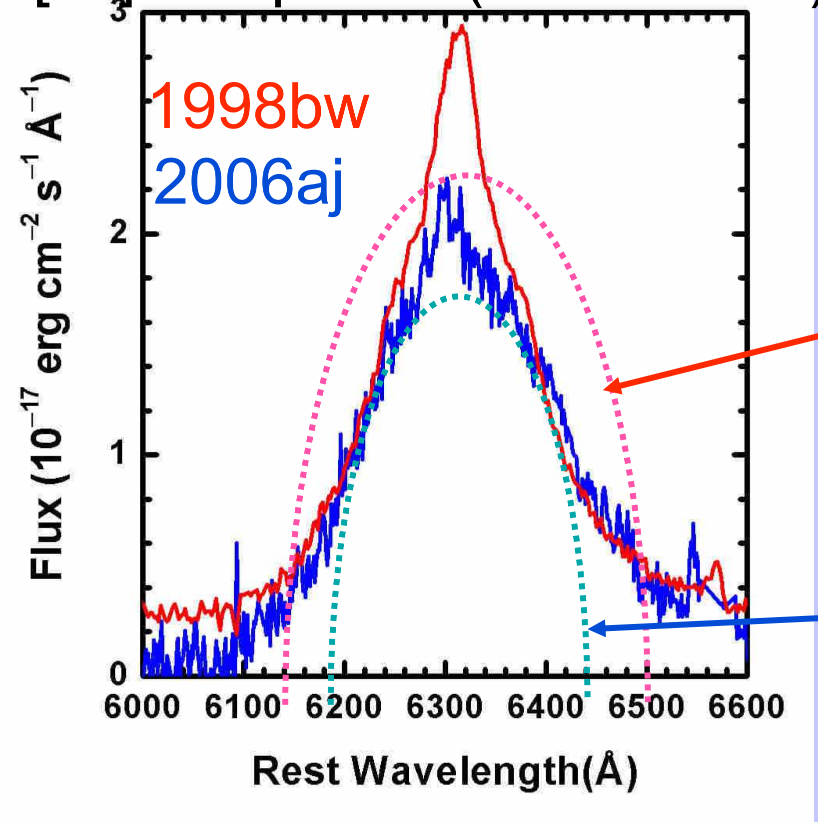
(From Nomoto et al. 2007)



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

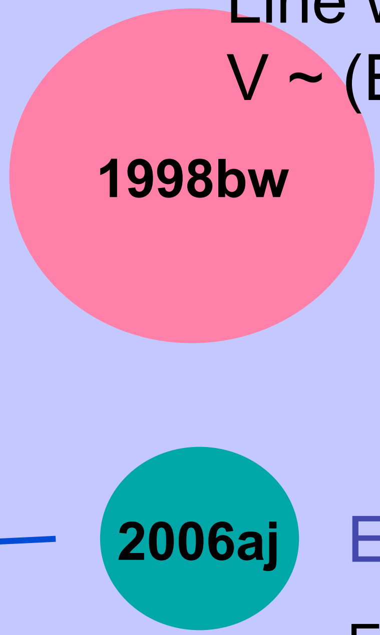
Geometry of XRF-SN 2006aj

[OI] line profile (Late Phase)



Spherical models (Early)

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



E/M ~ 5

E/M ~ 1

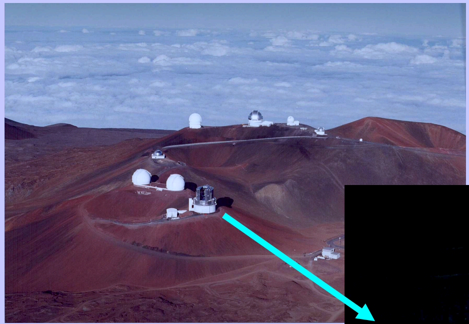
E in 10^{51}erg,
M in $M_{\odot}$

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

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

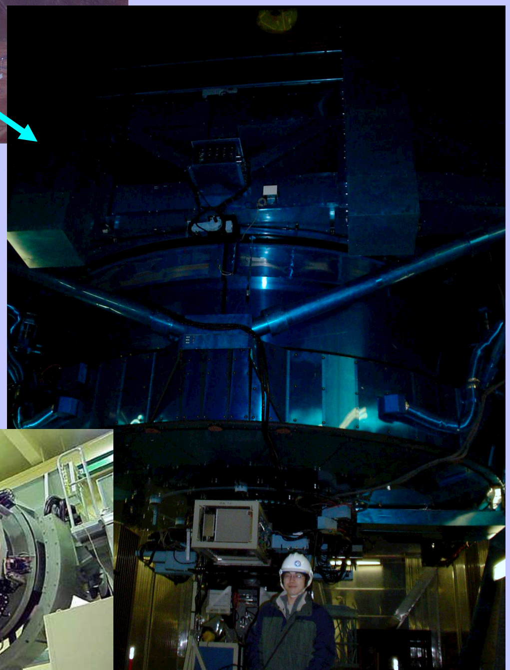
Collaborators; **Kawabata（Hiroshima）, Tanaka, Nomoto（U. Tokyo）, Hattori (NAOJ/Subaru)et al.**

- 15 SNe @>200days (~ 20 – 23mag).

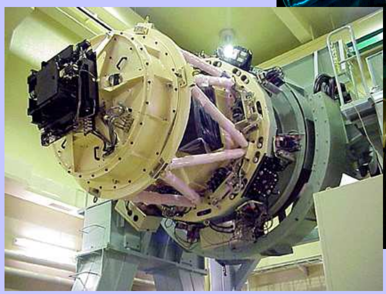


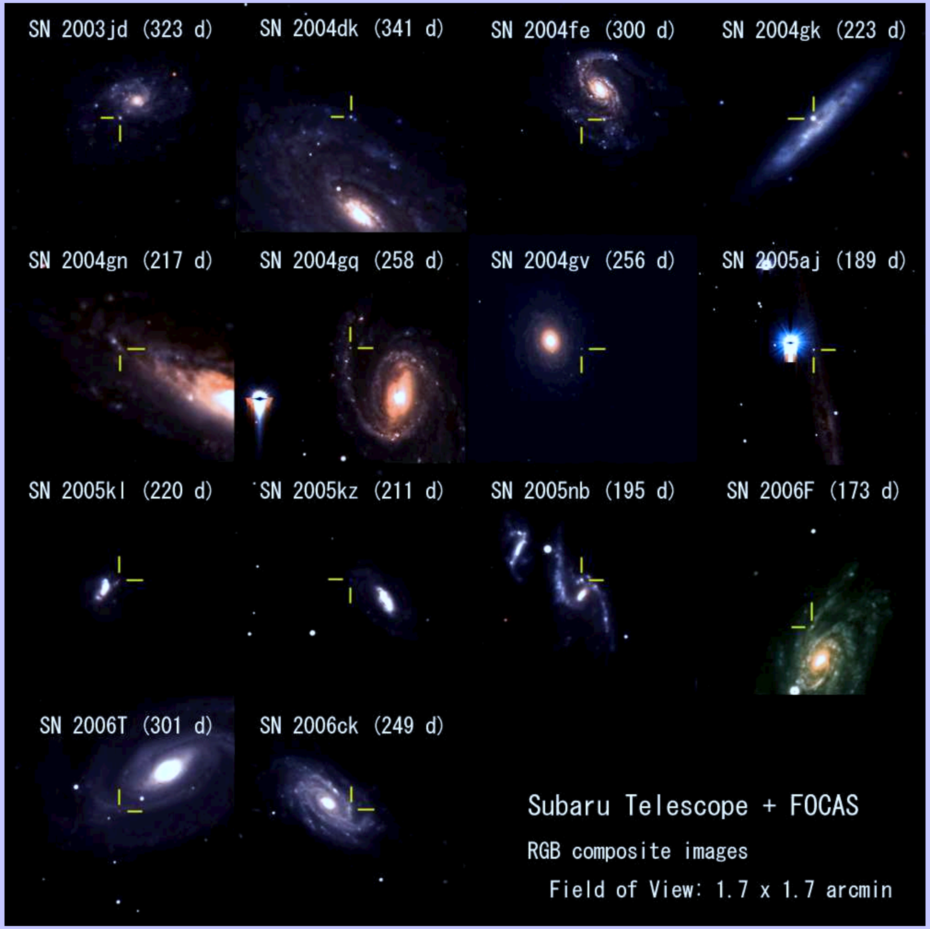
Hawaii, Mauna Kea @ 4,200m

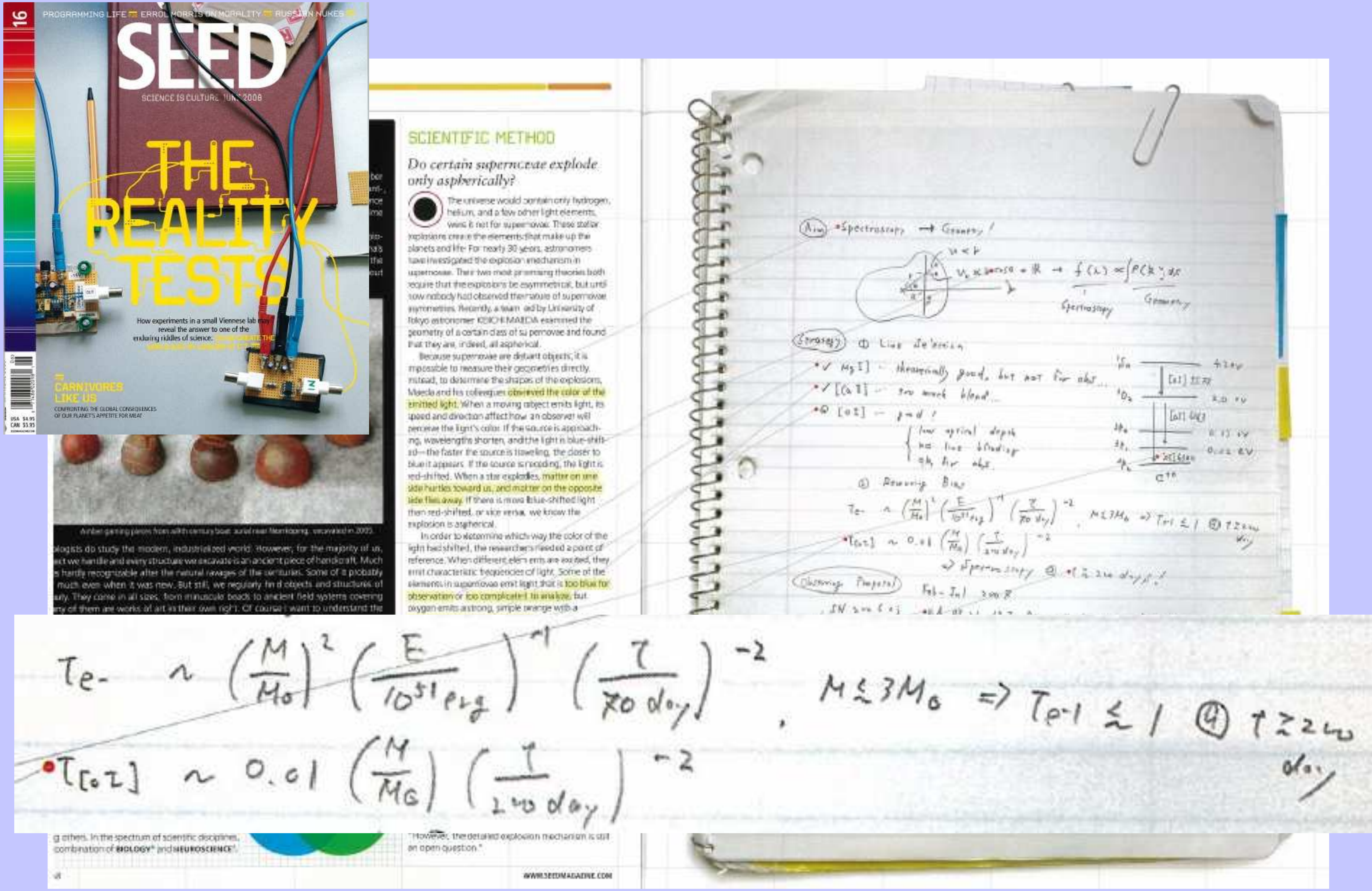
Subaru, 8 m



FOCAS

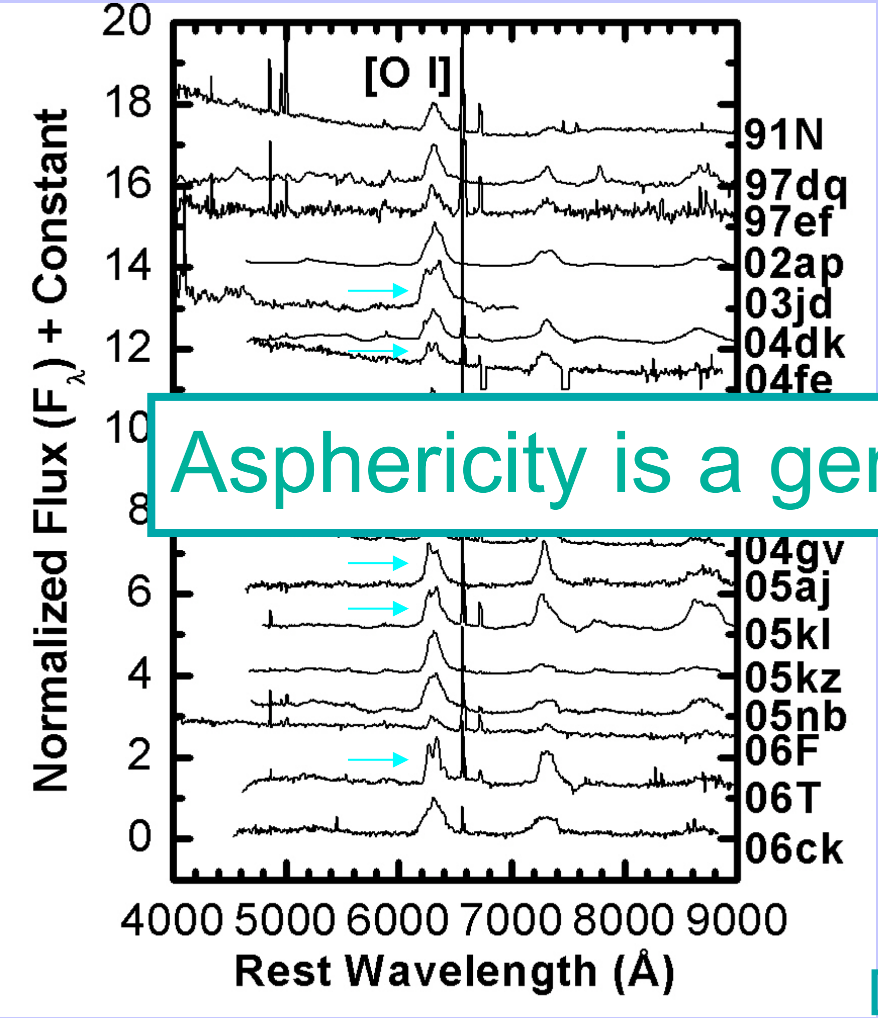


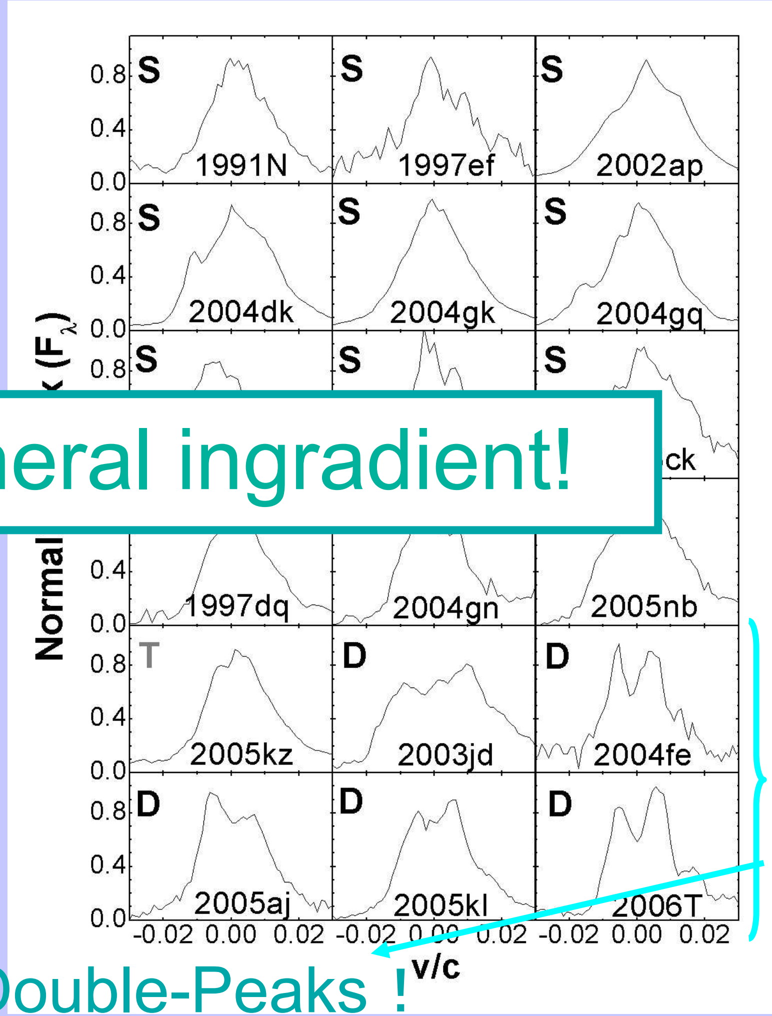



16
PROGRAMMING LIFE
SEED
SCIENCE IS CULTURE
THE REALITY TESTS
CARNIVORES LIKE US
SCIENTIFIC METHOD
Do certain supernovae explode only aspherically?
Aim
Spectroscopy → Geometry !
Strategy
Observing Proposal
Te- ~ (M/Mo)^2 (E/10^51 erg)^-1 (T/70 day)^-2 , M ≲ 3Mo ⇒ Te-1 ≲ 1 @ t ≳ 200 day
T[OI] ~ 0.01 (M/Mo) (T/200 day)^-2

Late-time spectra by Subaru/VLT

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





Asphericity is a general ingradient!

Double-Peaks !

Modjaz+, 08

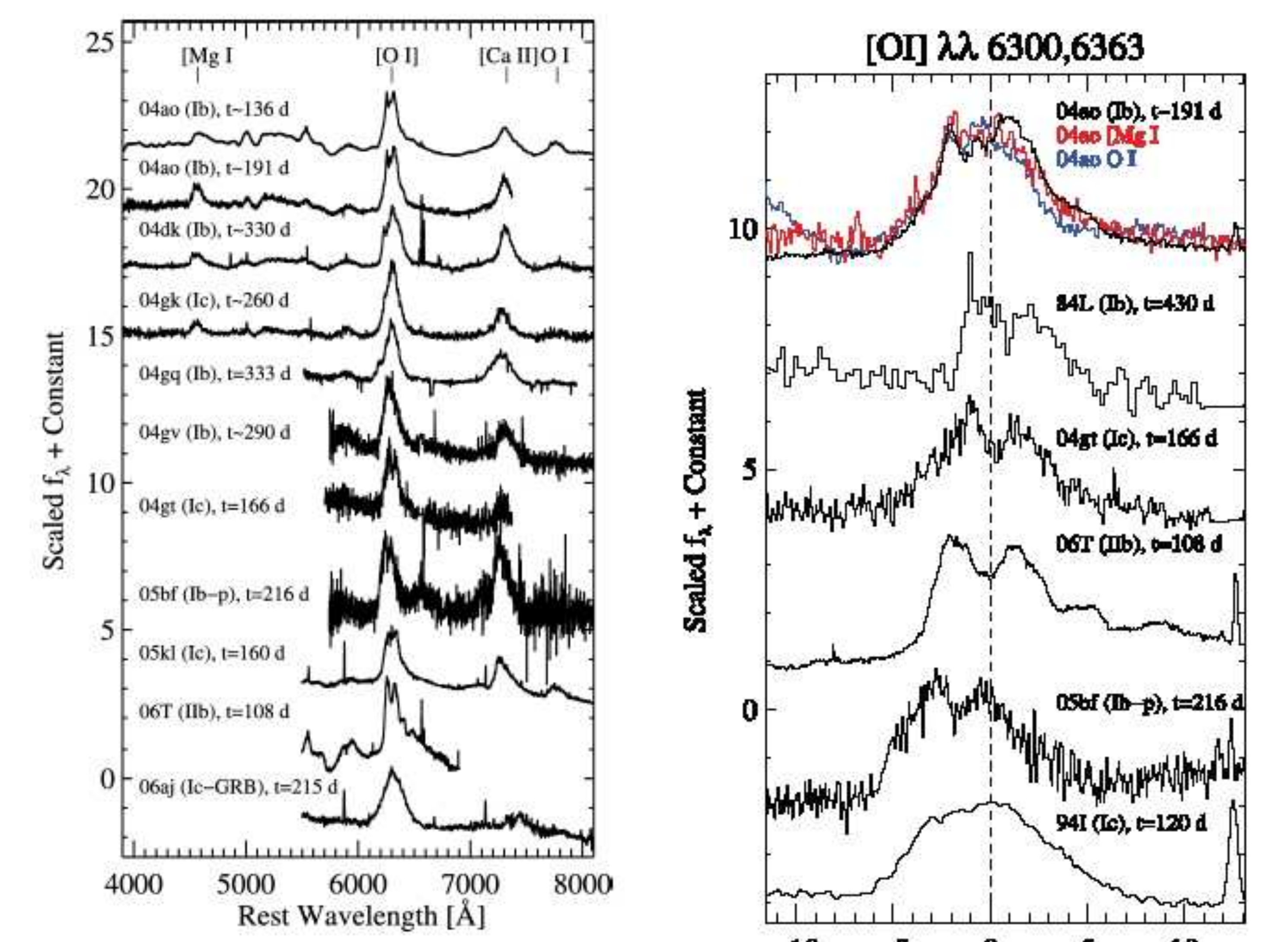
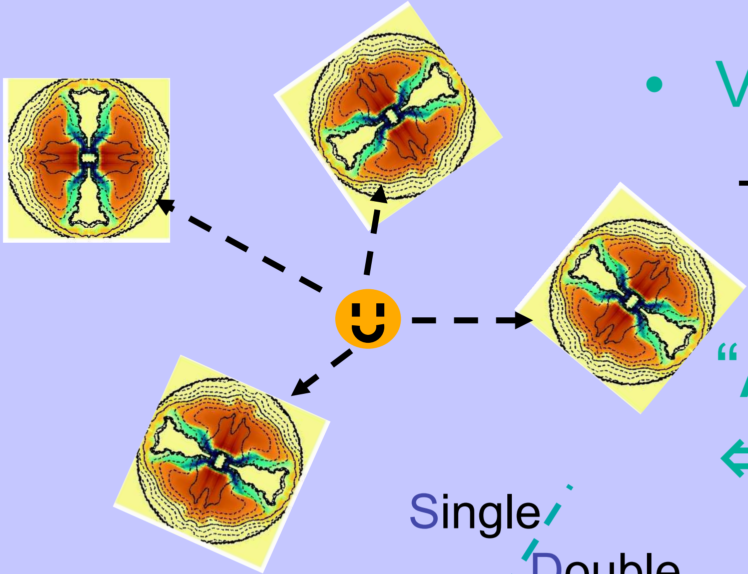


FIG. 1.—Selection of nebular spectra of SNe IIb, SNe Ib, and SNe Ic in their respective rest frames. SN name, type, and phase of spectrum (with respect to maximum light, except for GRB 060218/SN 2006aj which is referenced to

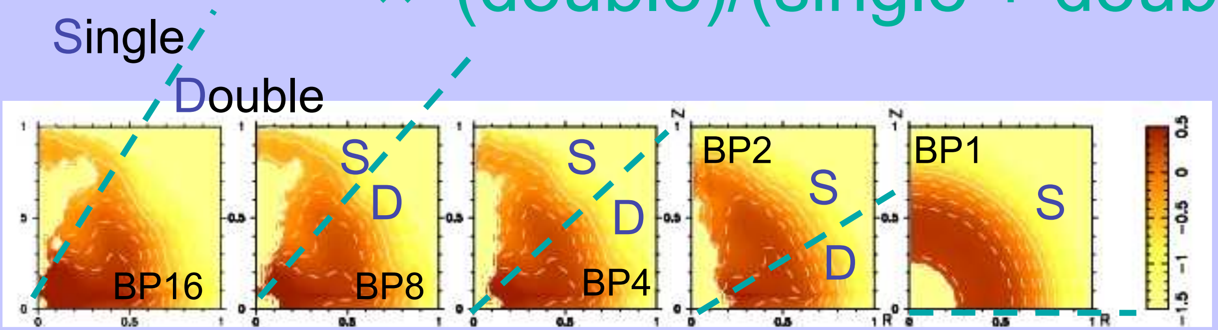
How much "asphericity"?



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

"Average" Geometry

⇔ (double)/(single + double)

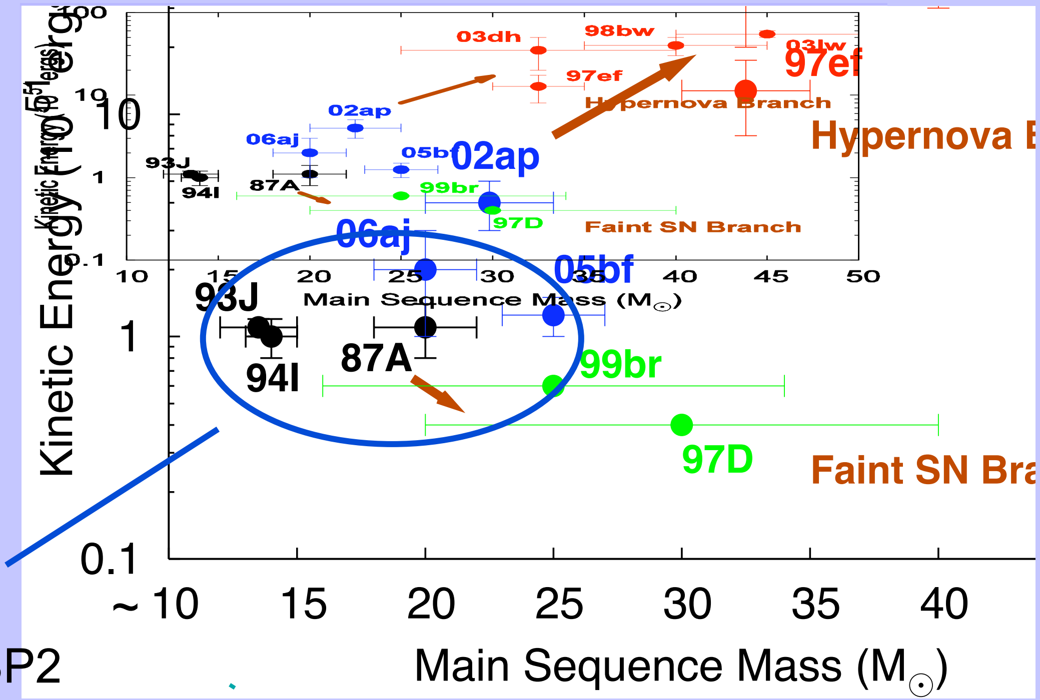


Expected D/(S+D) 0.64 0.34 0.0

Observed D/(S+D) = 0.3 ~ 0.5

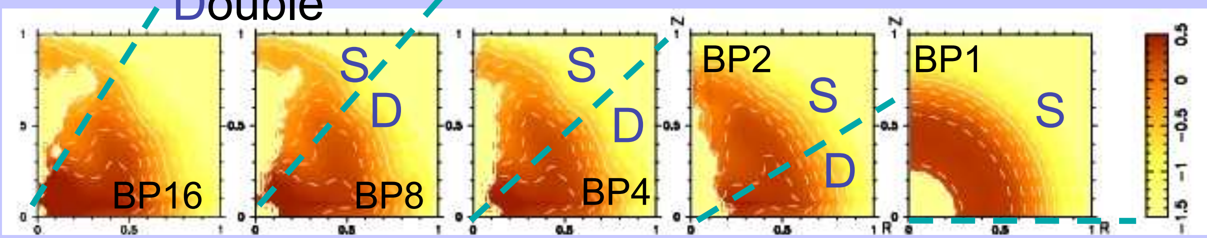
D/(S+D) depends only on BP (degree of asphericity)!

Progenitor mass vs. asphericity



D/(S+D)
0.3 – 0.5 →BP2

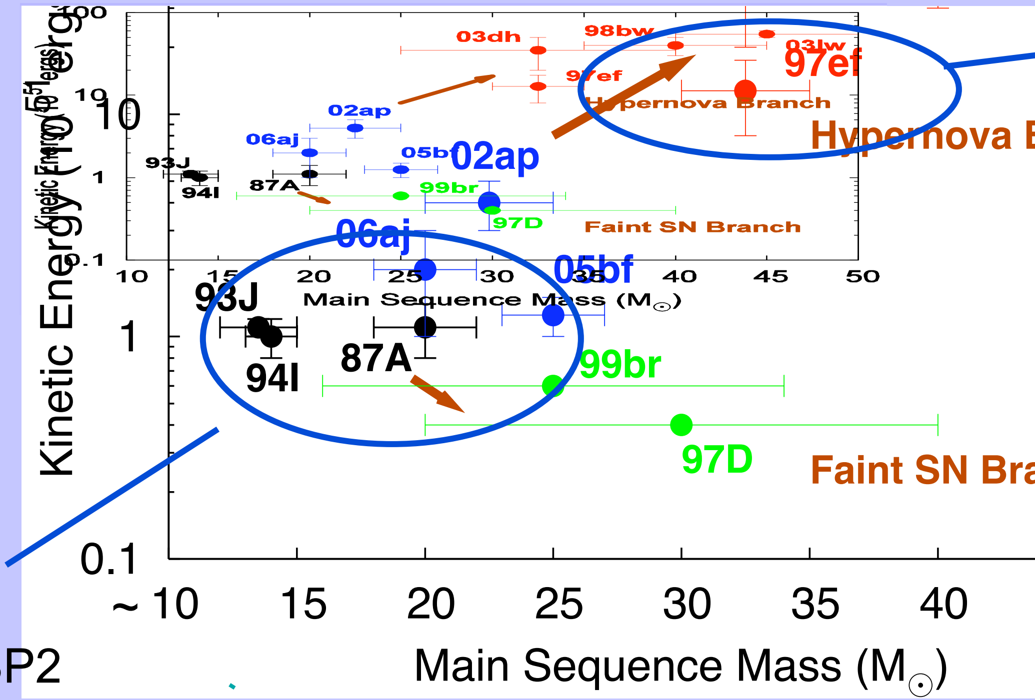
Double



Expected D/(S+D) 0.64 0.34 0.0

SNe Ib/c. < 30 – 40 $M_\odot$

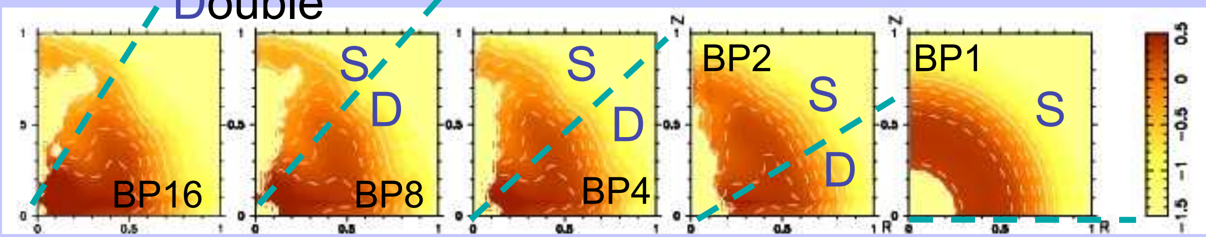
Progenitor mass vs. asphericity



GRB-Hypernova
(SN1998bw→BP8)

D/(S+D)
0.3 – 0.5 →BP2

Double

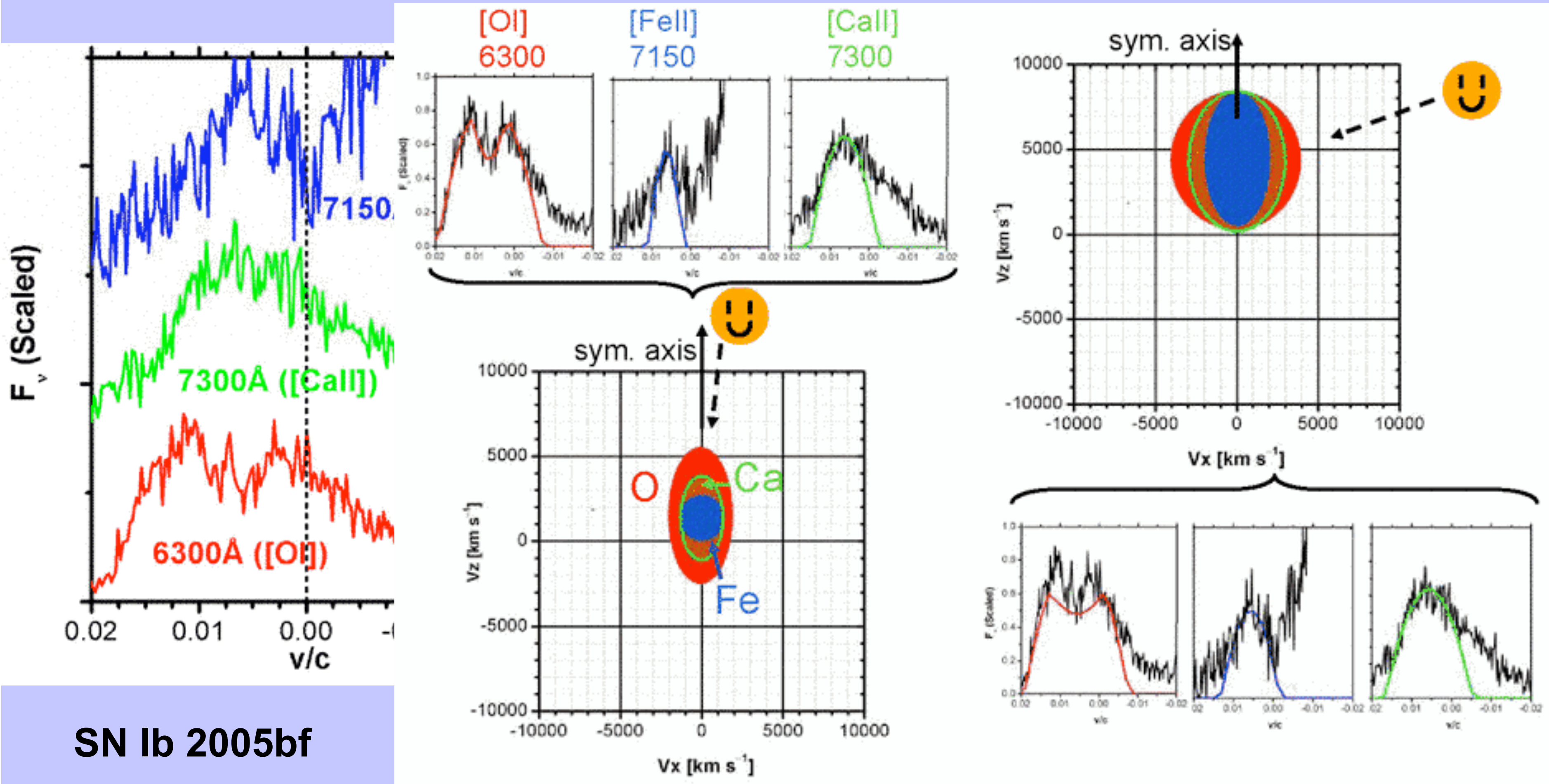


Expected D/(S+D) 0.64 0.34 0.0

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.
  - ~ $40M_{\odot}$: GRB-SNe.
    - Black hole?
  - 20 – $40M_{\odot}$: Variety. XRF-SNe.
    - Neutron star? …Detection of ^{58}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?