Extracting physical information from SN data: Type Ib/c and Superluminous SNe

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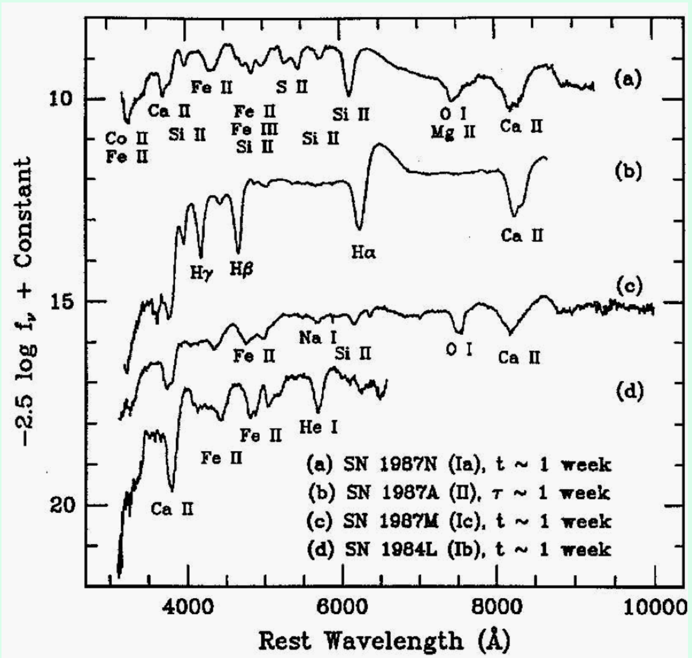

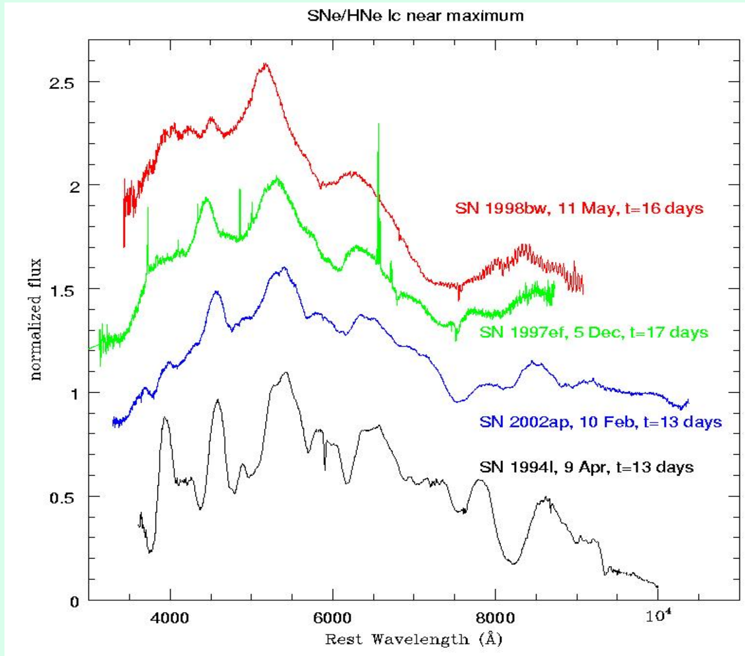

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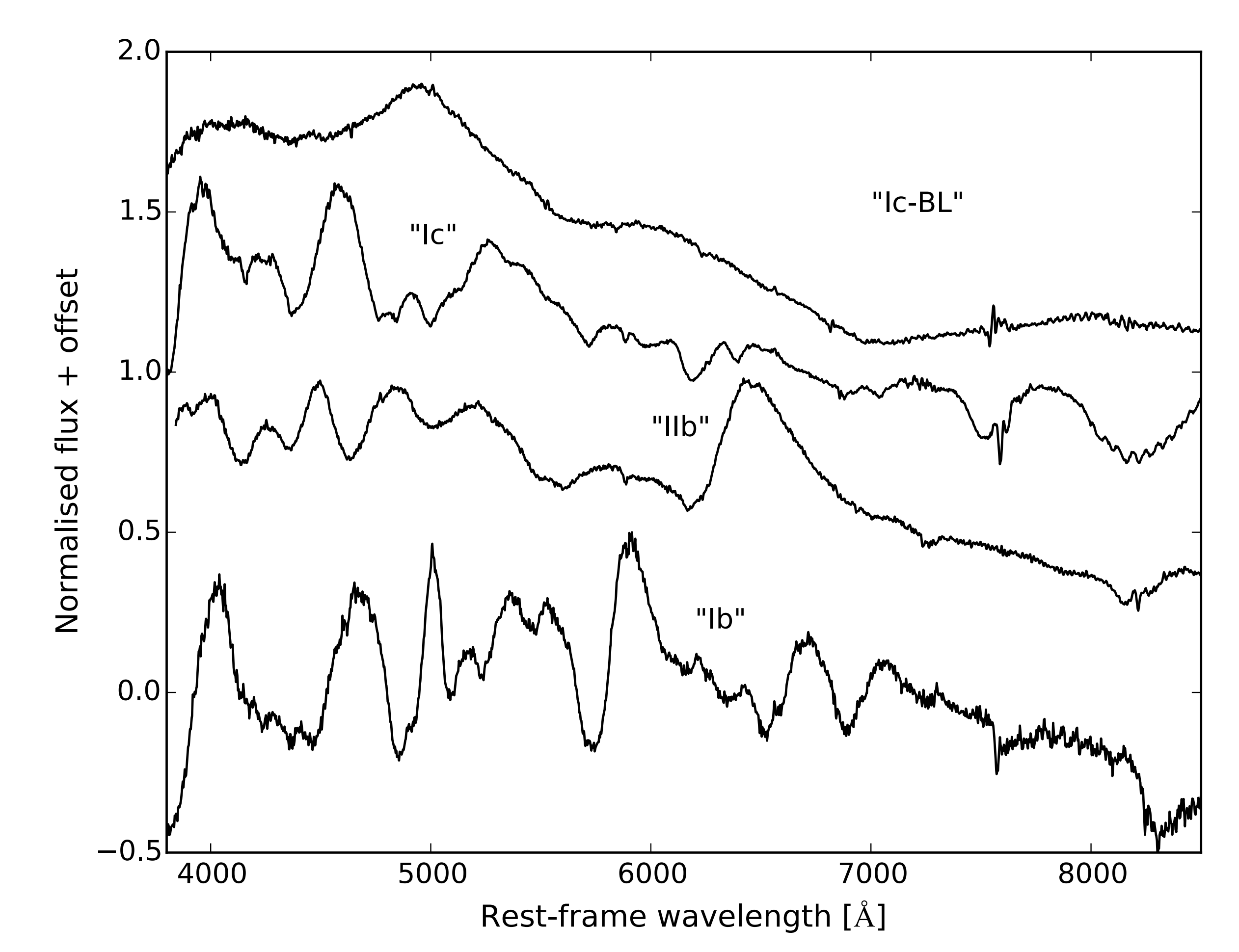
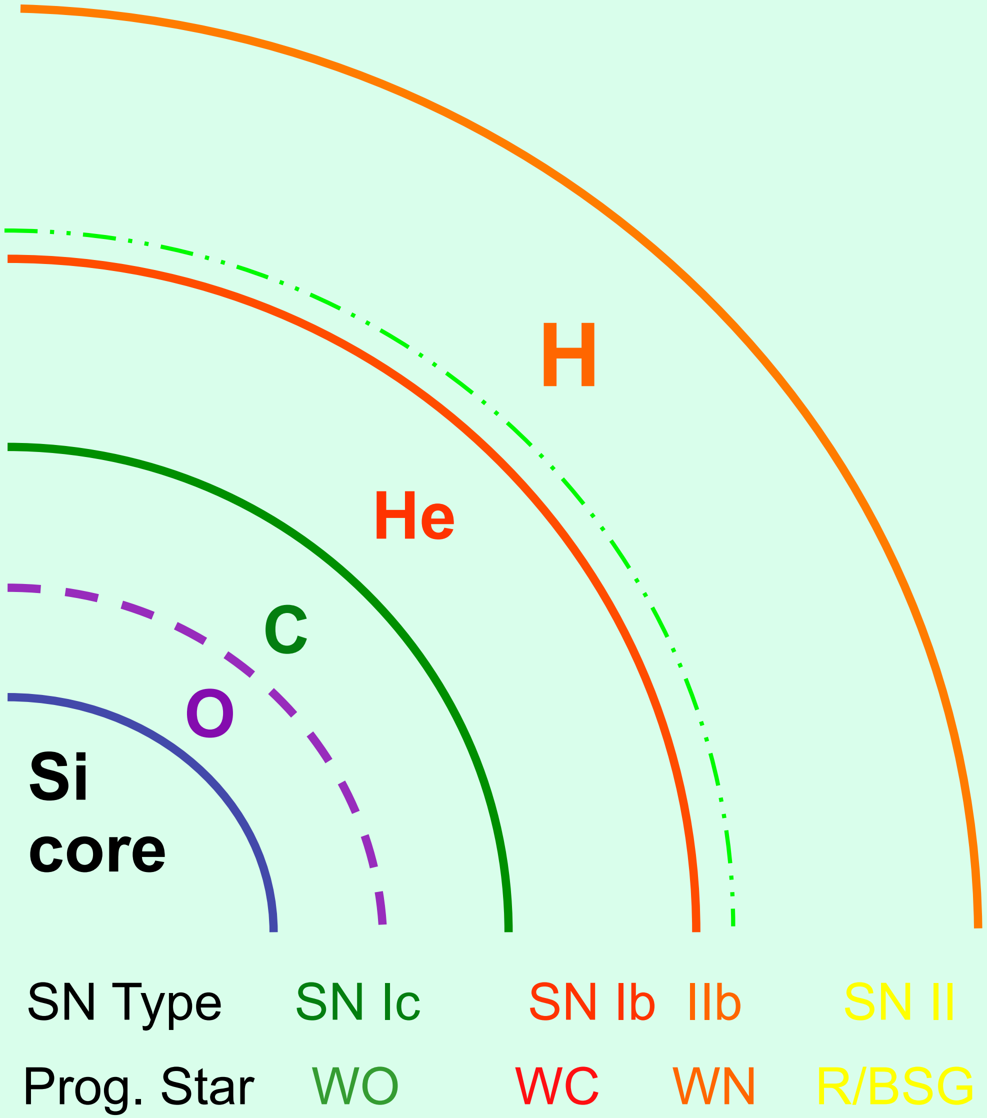
Stripped-envelope SN classification

SNe Ib/IIb: amount of He/H **SNe Ic: width of lines**



Core-Collapse SNe

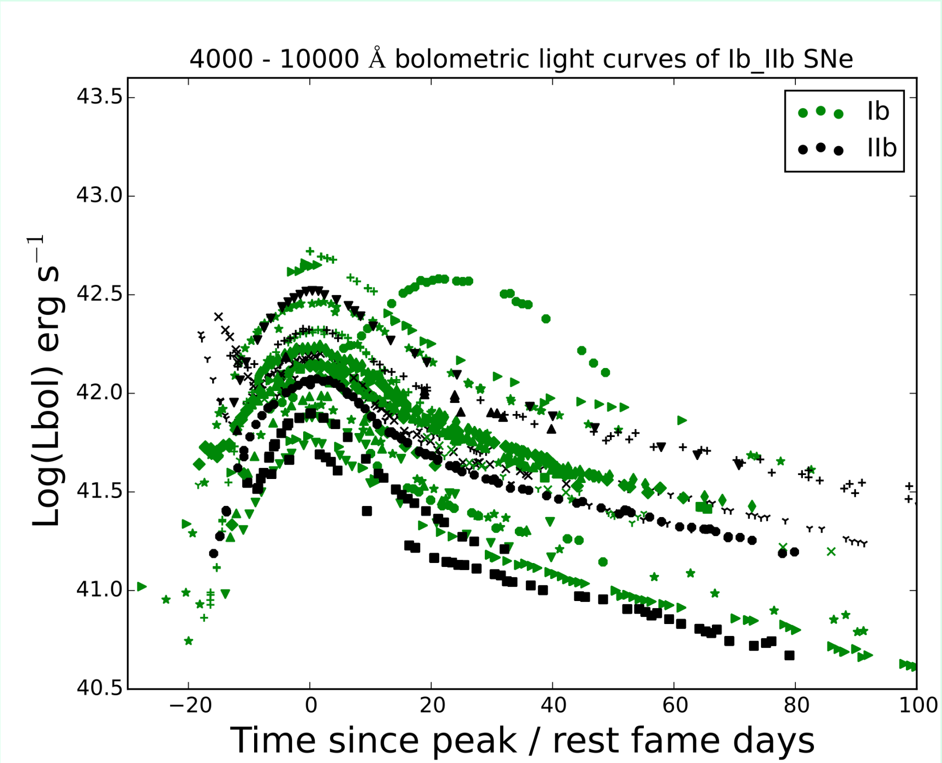
Massive Star (>8$M_\odot$)



- Si burning → NSE
  → ^{56}Ni (~0.1-1$M_\odot$)
- Core collapse
- Compact object
  (NS/BH)
- ν emission
- KE deposited
- envelope ejection

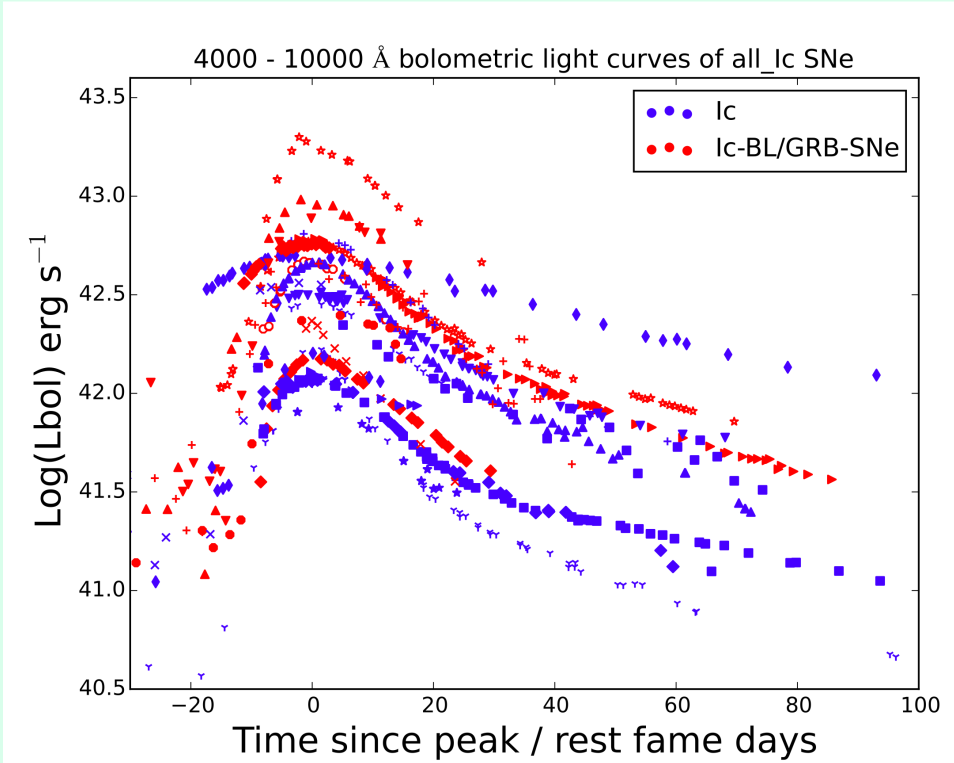
Different LC distributions

SNe Ib/IIb: more homogeneous



On average less luminous

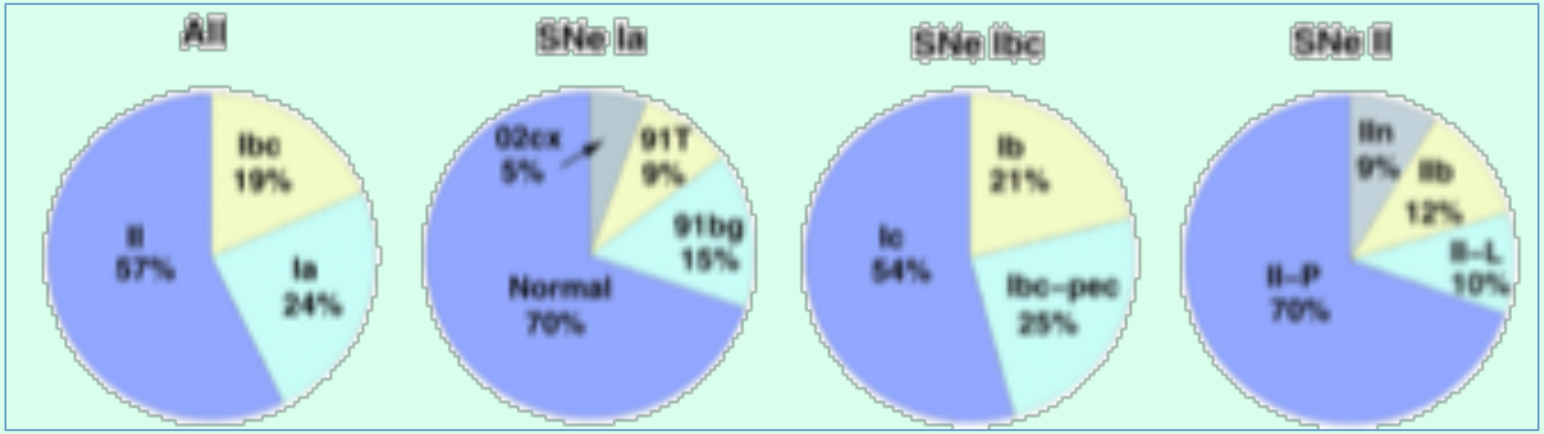
SNe Ic: wider range of Lum



On average more luminous

84 SNe, Prentice et al. 2016

Distribution by subtype

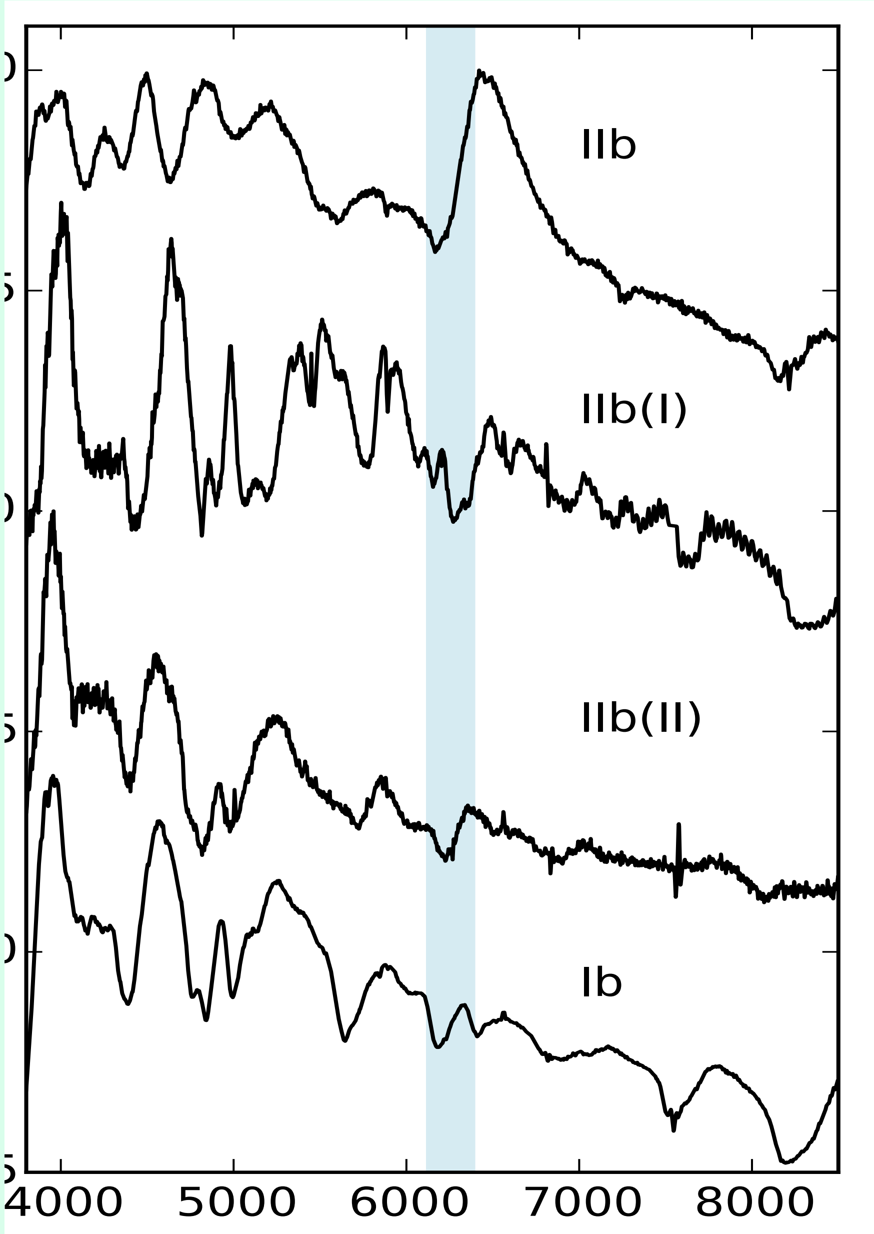


- SN Lum fn, Li et al. 2011
- SE-SNe NOT dominated by H/He rich SNe: numbers of He-rich and He-poor actually similar
  - IIb: 7% of all, 9% of CC-SNe, 27% of all SE-SNe
  - Ib: 4% 5% 15%
  - Ic: 15% 20% 58%

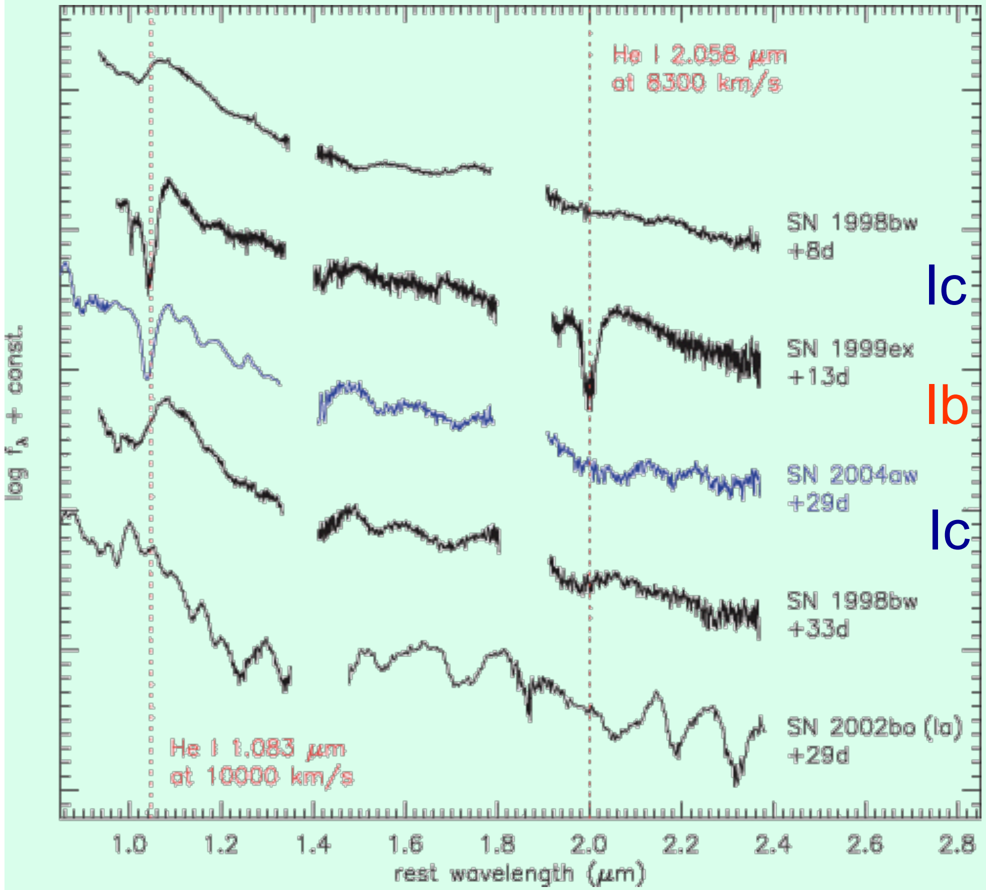
SNe IIb – Ib are a continuum

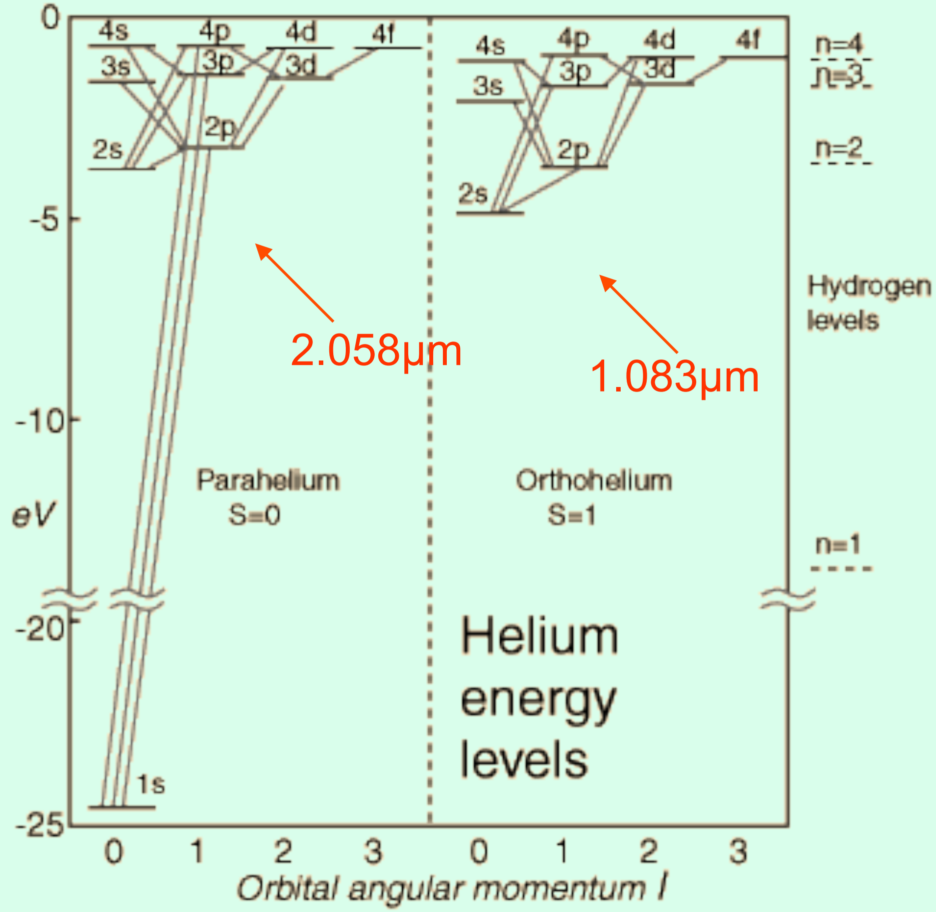
- different strength of Balmer lines: range of H shell masses, although capped at a few 0.1 $M_\odot$ to preserve Type I light curve
- Many SNe classified as Ib show weak or intermediate strength Balmer lines (in part. Hα)

(Prentice & PM 2017)



SNe Ic show no Helium



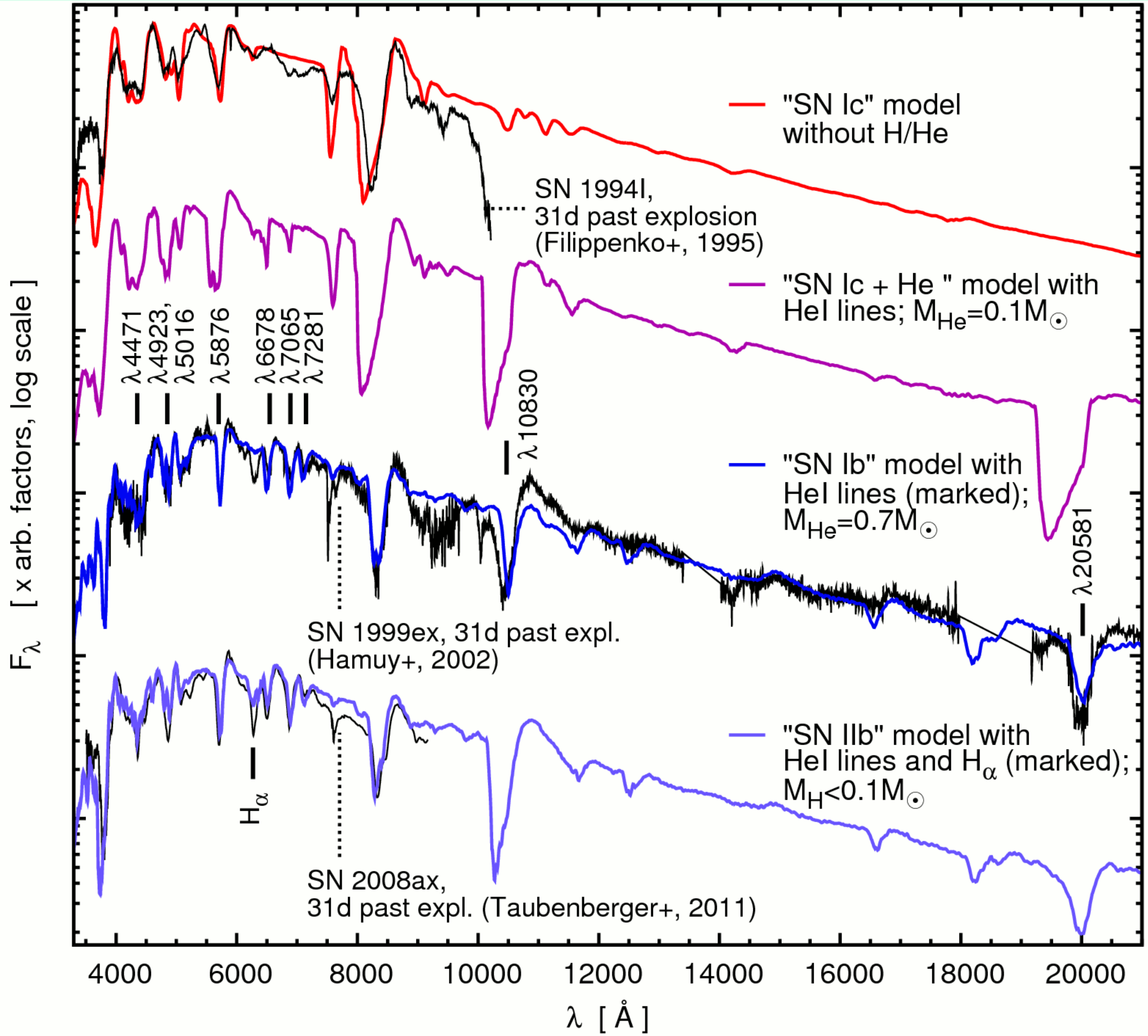


Taubenberger et al. 2006

Strongest HeI lines in IR. 1μ can cause confusion, 2μ line unique

It takes little H/He to make a SN IIb/Ib

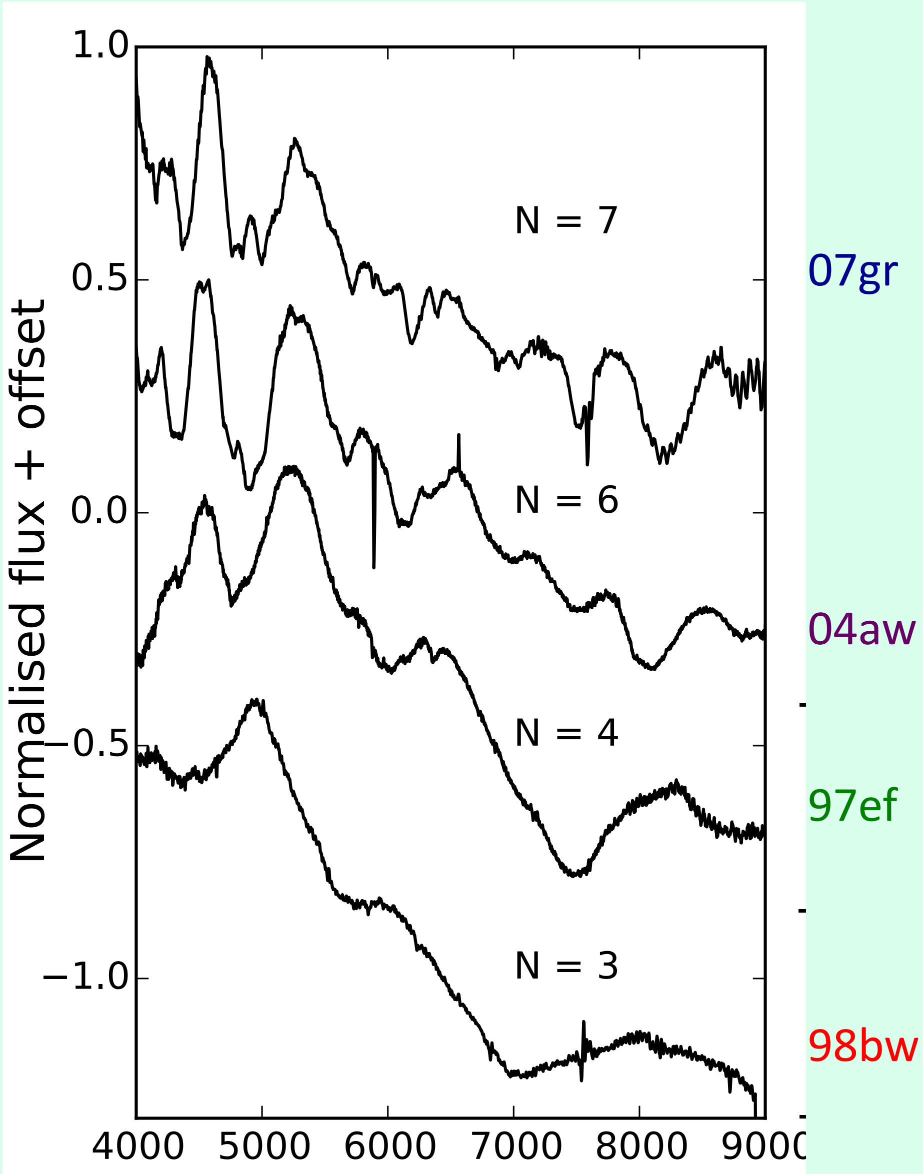
- HeI requires non-thermal processes
- SNe Ib: $M(He) >\sim 0.1\ M_\odot$
- SNe IIb: $M(H) \sim 0.02 M_\odot$
- Different spectral subclasses are sharply separated



(Hachinger et al. 2012)

SNe Ic: meaning of broad lines

- Broad lines indicate sufficient line opacity at high velocity
- indicative of Kinetic Energy
- As lines get broader (larger velocity span) they blend more
- Broader-lined SNe have fewer lines
- Number of lines is a more accurate and quantitative criterion for spectral classification than "broad-line"
- Vel increasing as N_{lin} decreases indicates that Ek ~ $(Mej)^n$



Useful to verify classification

Presence of H in Ib quite common

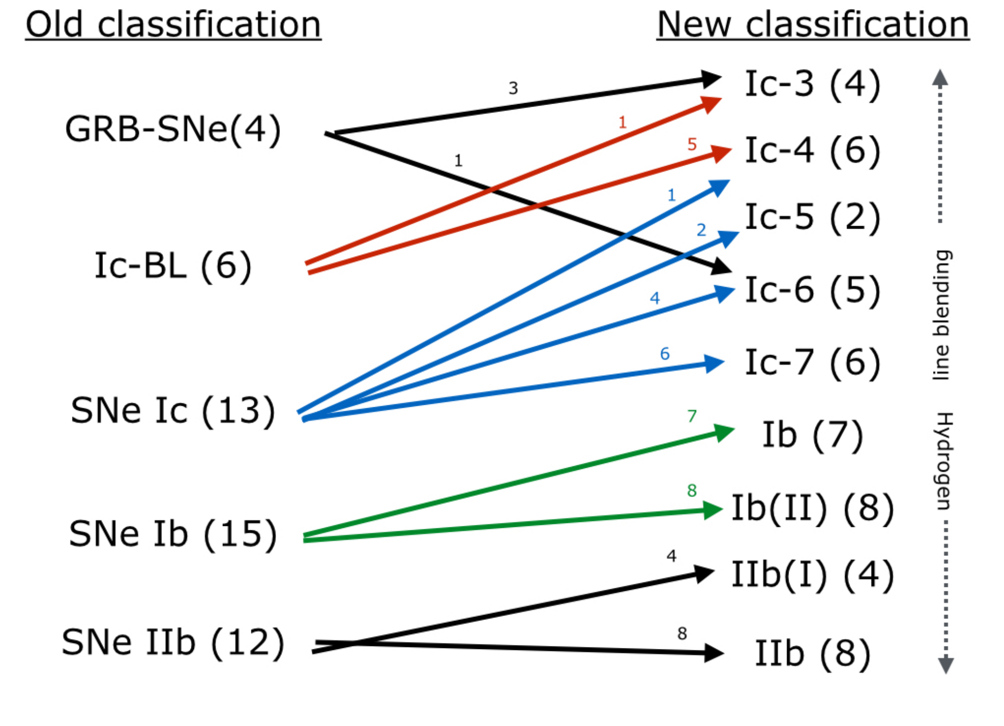
- Many SNe classified as Ib show weak or intermediate strength Balmer lines (in part. Hα)
- More SNe with H
- SN IIb—IIb(I)—Ib(II)—Ib

  by decreasing H line strength

  50 of 82 SNe, Prentice & PM 2017

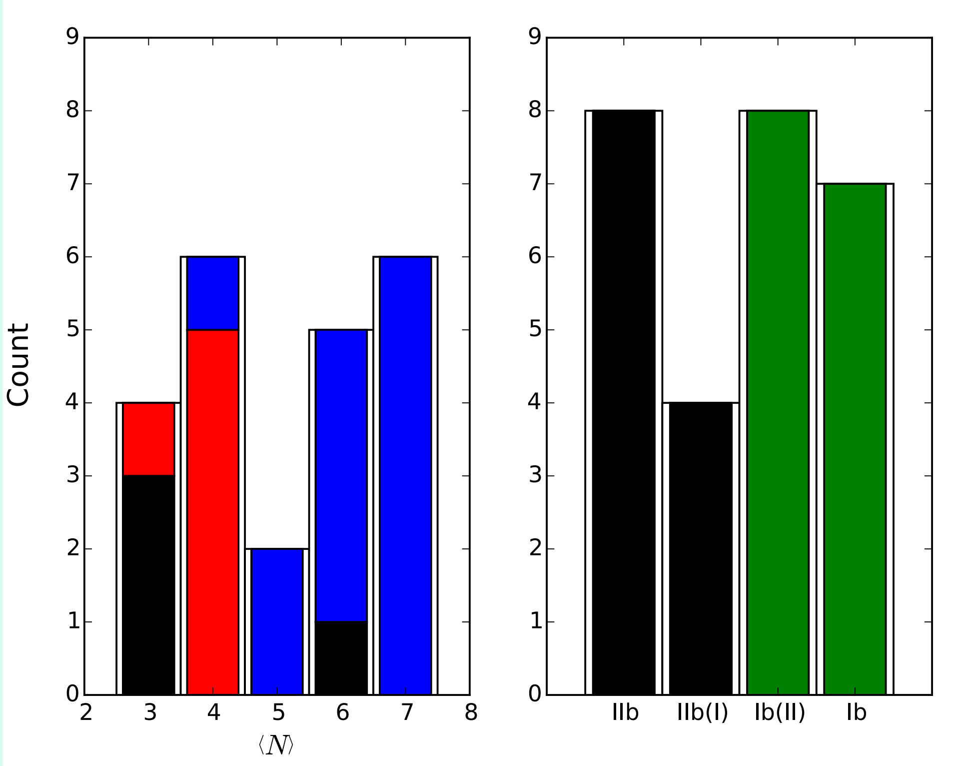
No trace of He in Ic

- SNe Ic can be ordered by line width/number



Updated distribution by subtype

- Relative numbers close to Li et al.'s rates
- Considering weak Hα lines, n(IIb) >> n(Ib)
- Difficult to strip all H, as would be expected in single star evolution
- n(Ic)~n(IIb+Ib): are all SNe Ic the product of close binary interaction?

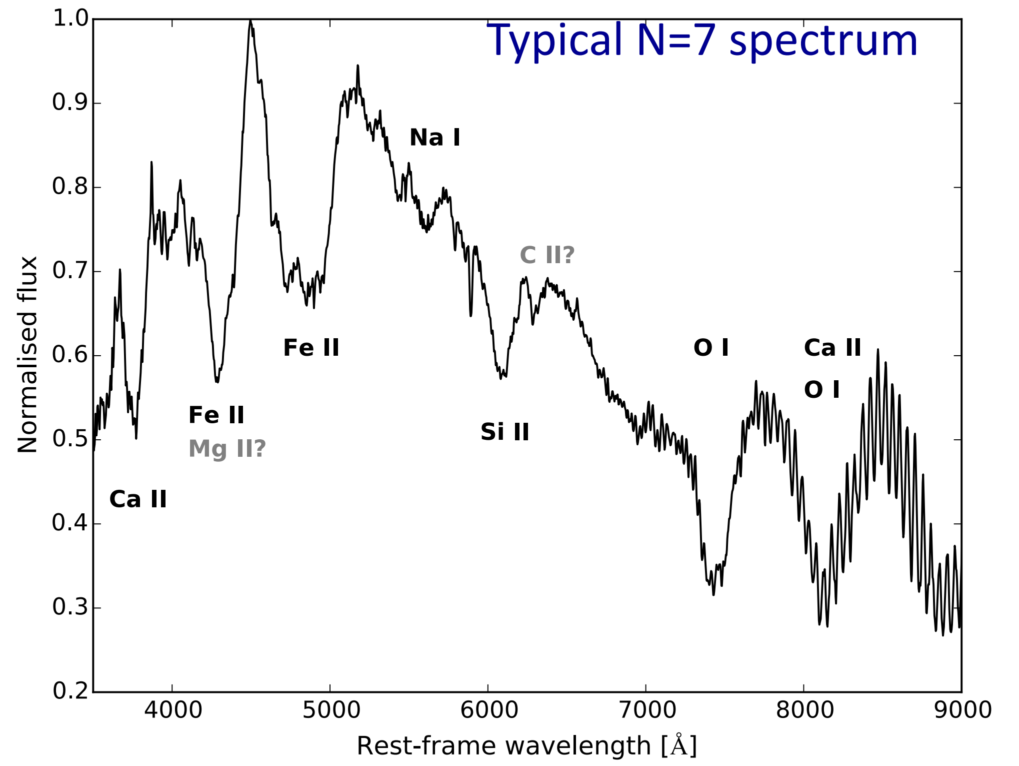


SN Ic	IIb	Ib
46%	40%	14%

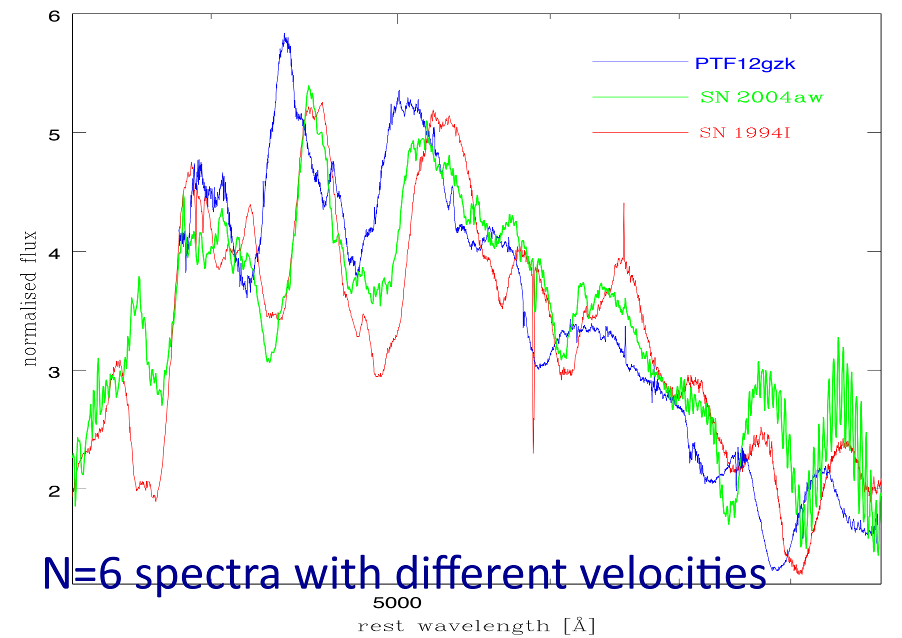
50 SNe, Prentice & PM 2017

Line blending and number of features

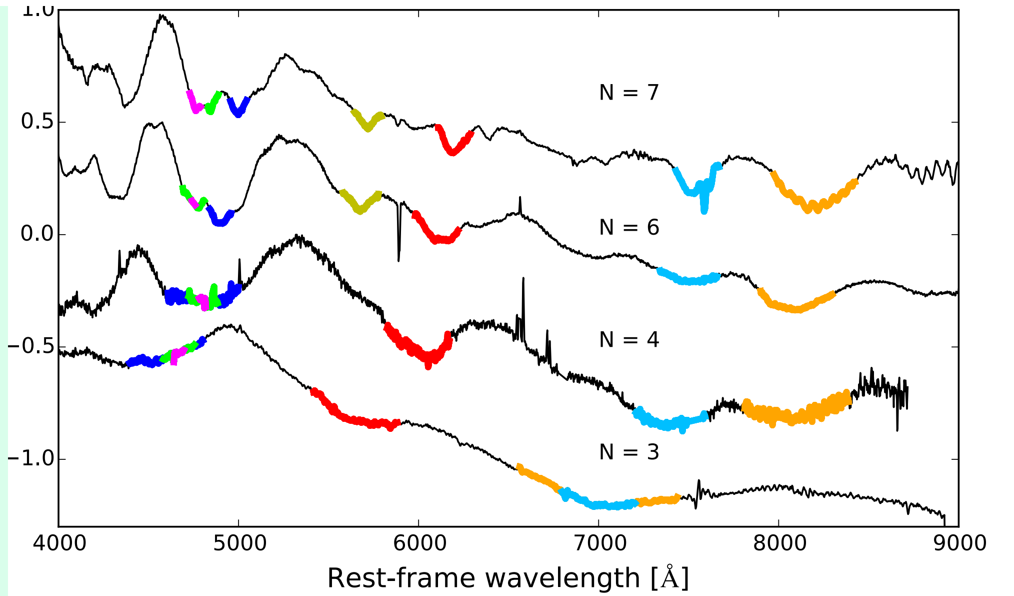
- As velocity increases, features blend:
  - Fewer features
  - Higher E/M
- As velocity increases, features just shift
  - Larger M
  - Constant E/M



Typical N=7 spectrum

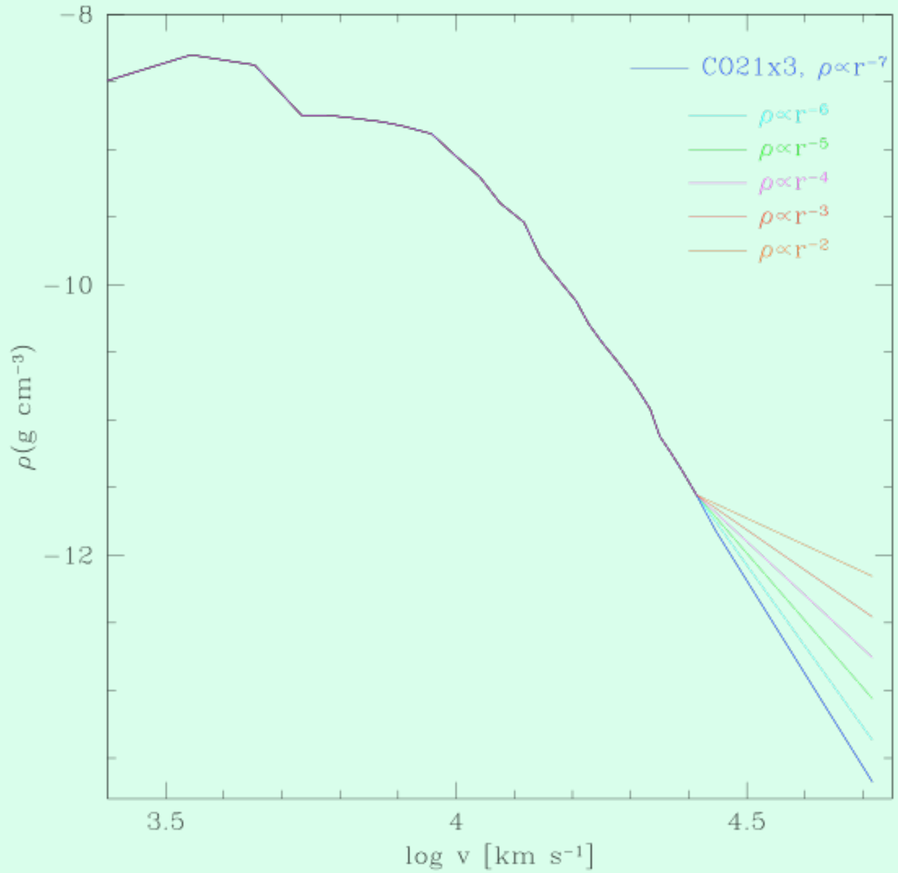


N=6 spectra with different velocities



Density profile as cause of broad lines

- What matters for a broad-lines spectrum is the range of velocities at which absorption is active
- This is more a function of the density slope in the outer layers than mass



PM+ 2017

Explosion Parameters

$$M_{ej}, M(^{56}Ni), KE$$

Light Curve

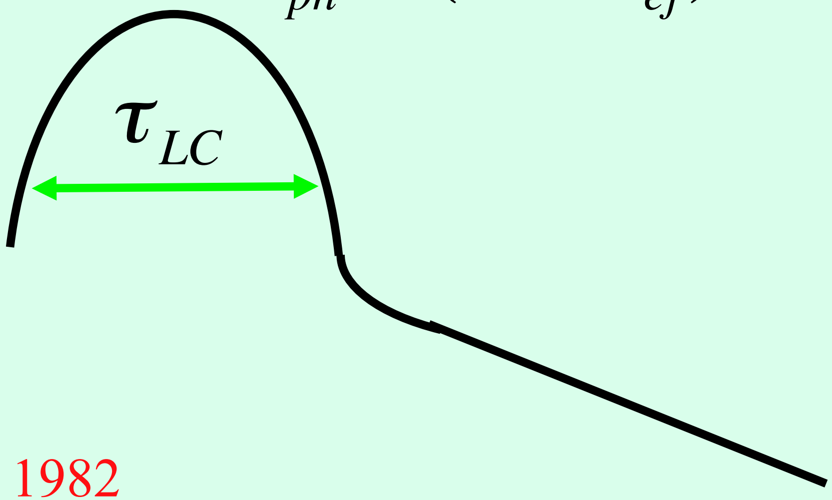
$$\tau_{LC} \sim (\tau_{dyn} \cdot \tau_{diff})^{1/2}$$

$$\sim \left(\frac{R}{V} \; \frac{\kappa M_{ej}}{R c} \right)^{1/2}$$

$$\tau_{LC} \propto \frac{\kappa^{1/2} M_{ej}^{3/4}}{E^{1/4}}$$

Spectra

$$v_{ph} \propto (E / M_{ej})^{1/2}$$



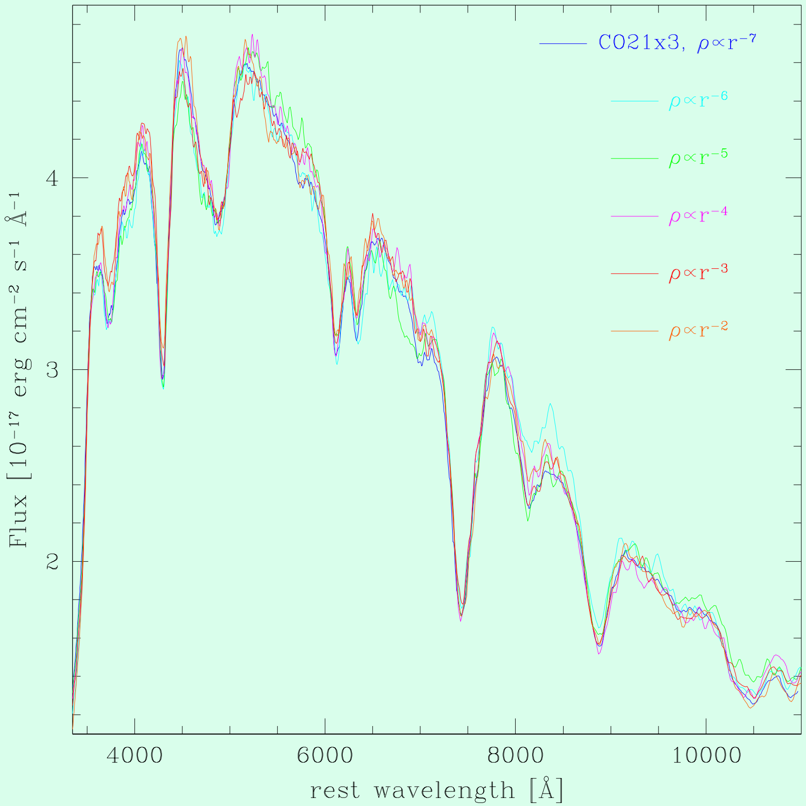
Arnett 1982

Use of line width

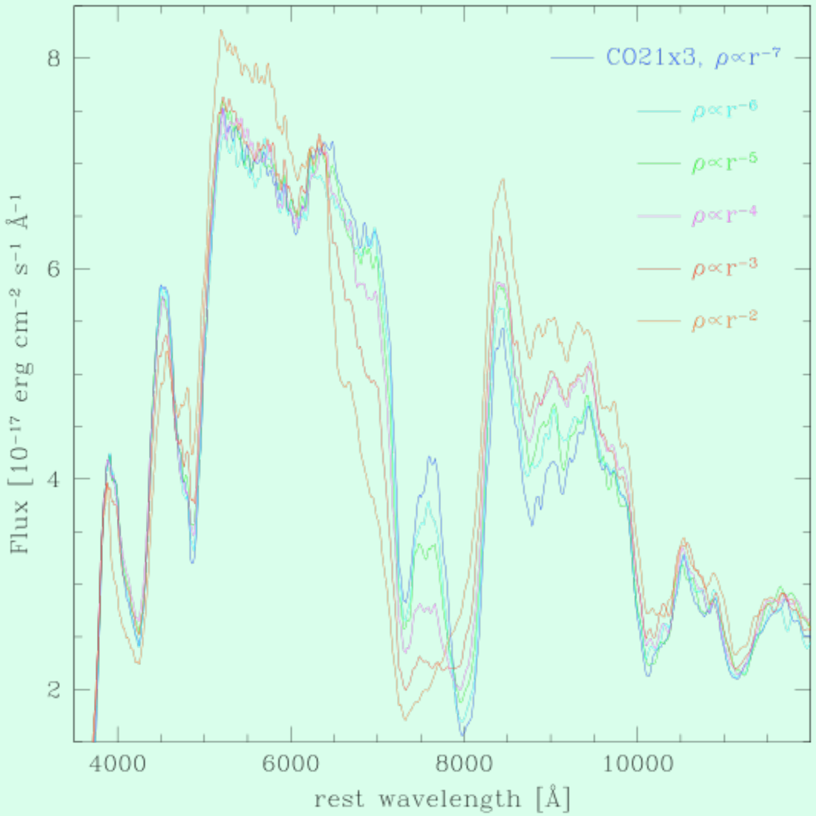
- Single velocity measurement often used combined with LC shape to obtain Mass AND Ek:
  this is VERY RISKY (euphemism)
  - Velocity is time-dependent: what epoch do you choose?
  - Maximum does not always happen at the same epoch
  - Blending depends on velocity (line id uncertain)
  - Highest velocities may carry most Ek if they contain sufficient mass
  - Width and breadth may not always correlate: distribution of mass with velocity may not be constant

Lack of early data can be fatal for Ek estimate

day 15 (~ Max)



day 7 (often not observed)



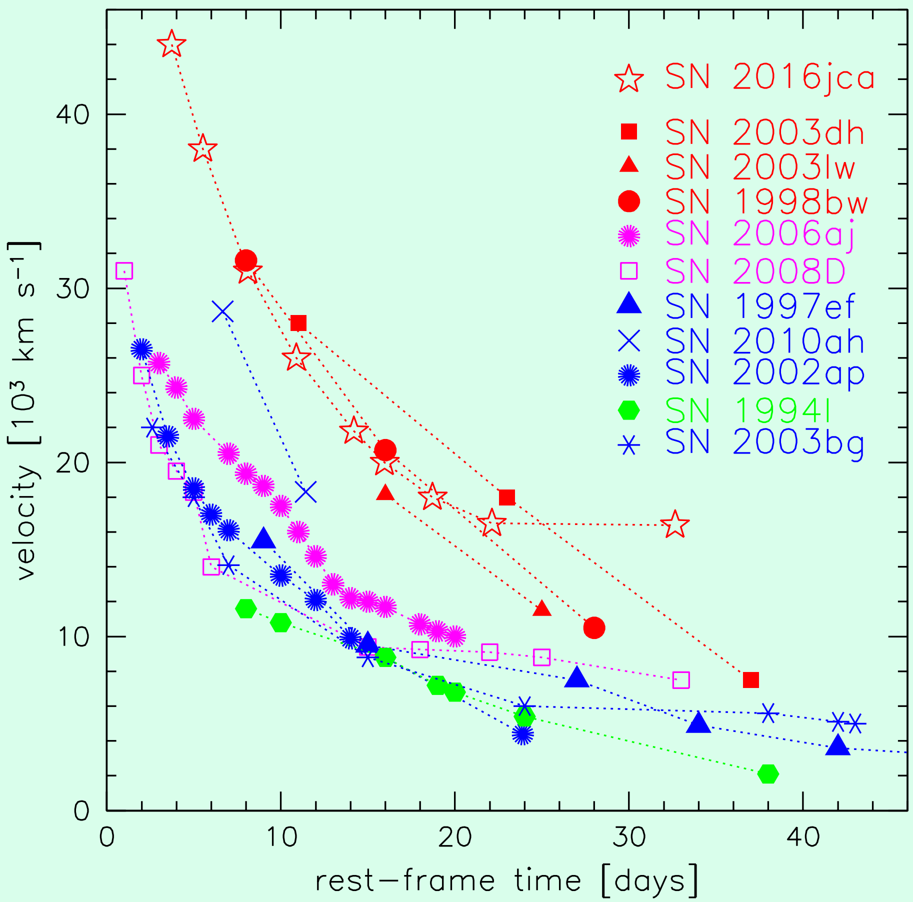
Range of outer density slope from n=-7 to n=-2 leads to range of Ek spanning factor ~ 2

GRB/SNe may have very high velocities

SN2016jca/GRB161219B:
One of the best observed GRB/SNe

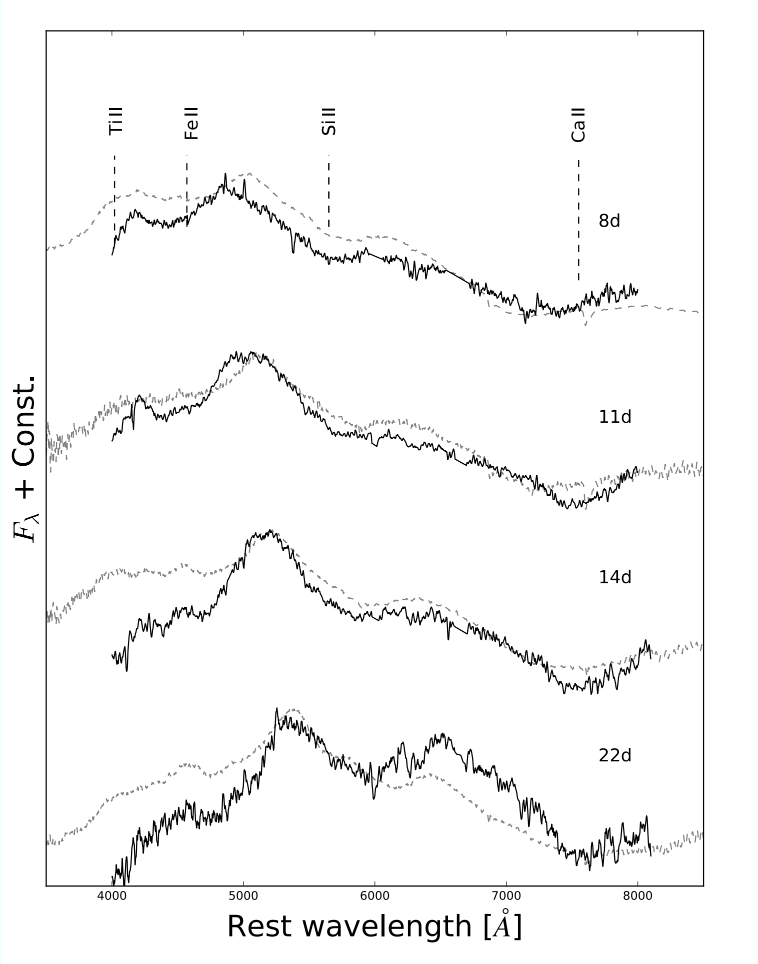
- Early data show highest velocities ever recorded
- Ek estimate higher than other GRB/SNe because outermost layers better probed
- Mej ≅ 8 M⊙
- Ek ≅ 5 10^{52} erg
- M(^{56}Ni) ≅ 0.4 M⊙

Ashall et al 2017

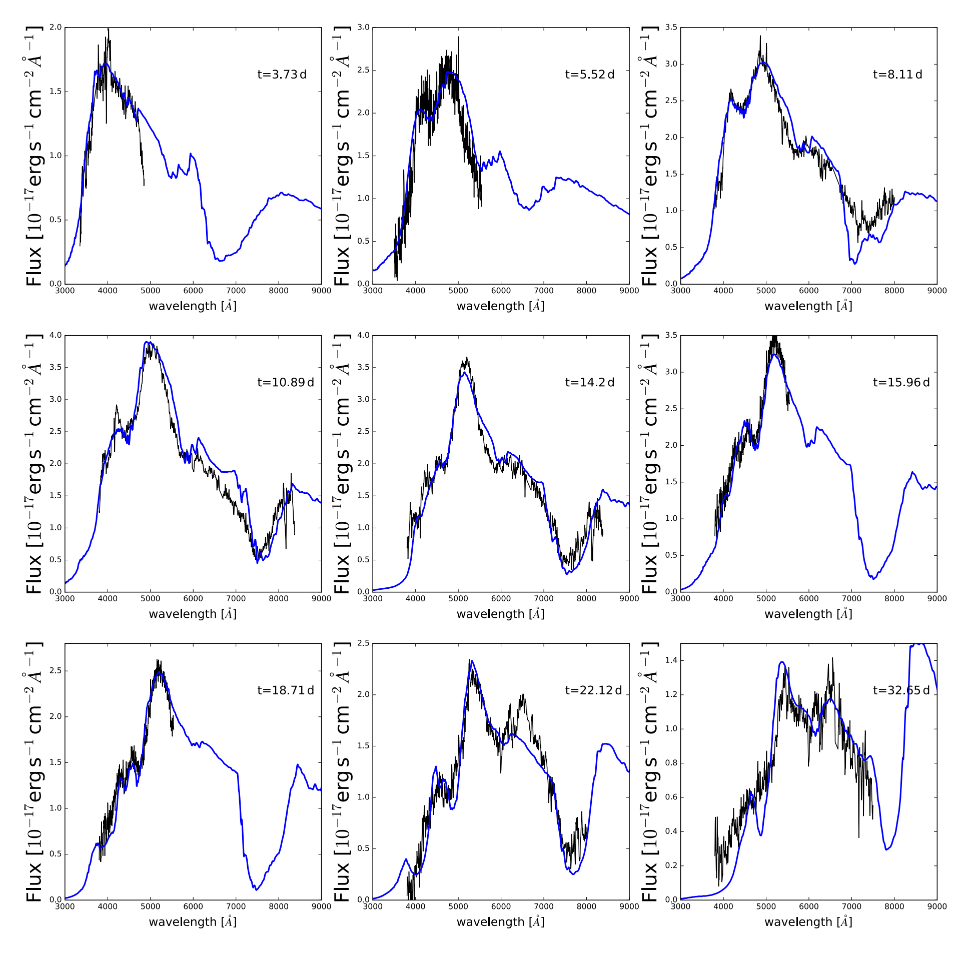


SN2016caj/GRB161219B

Higher velocities than 1998bw, UV suppressed: more Ni

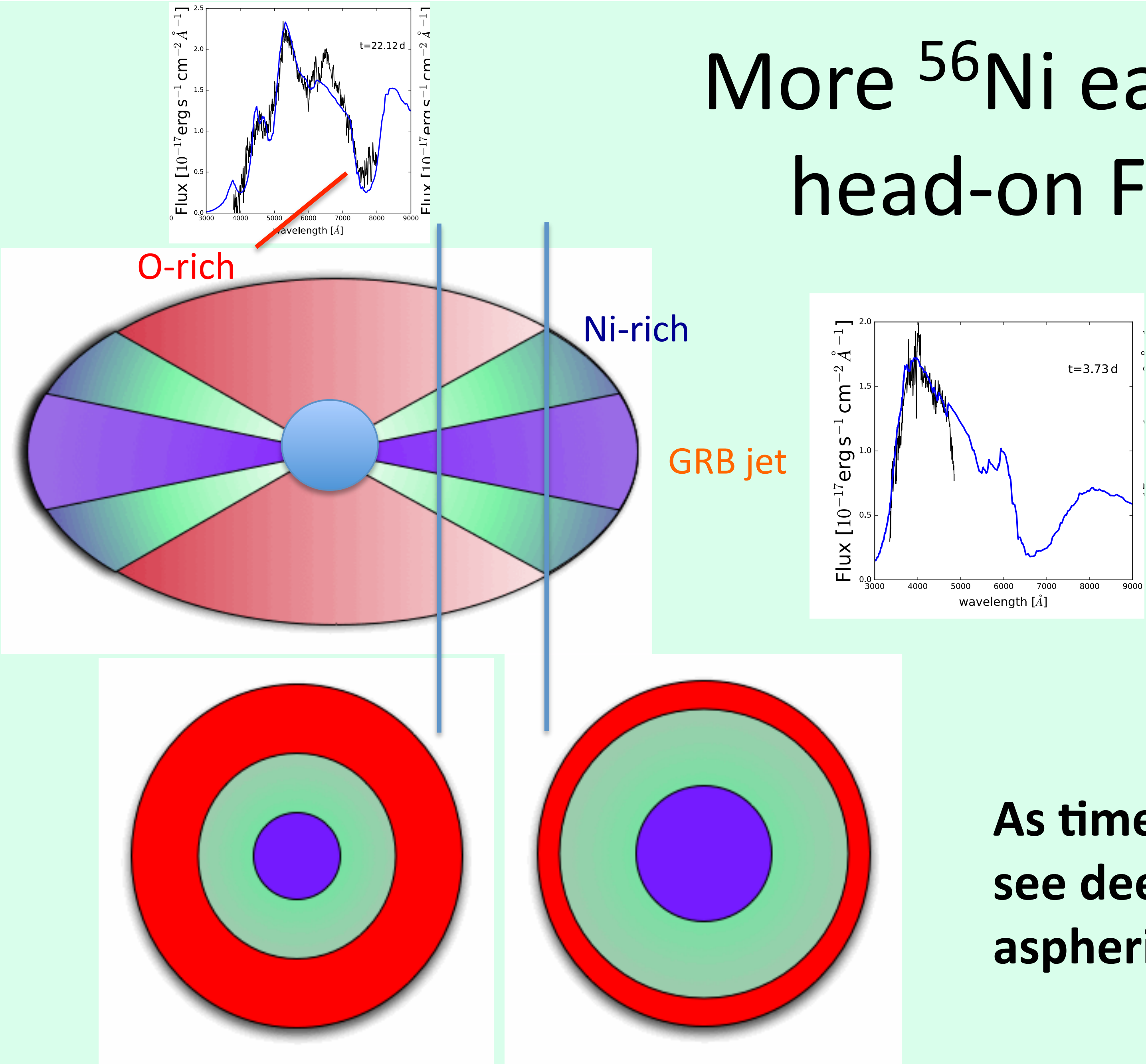


Early data allow better models: increasing O ab. at low velocities, indicative of aspherical props.



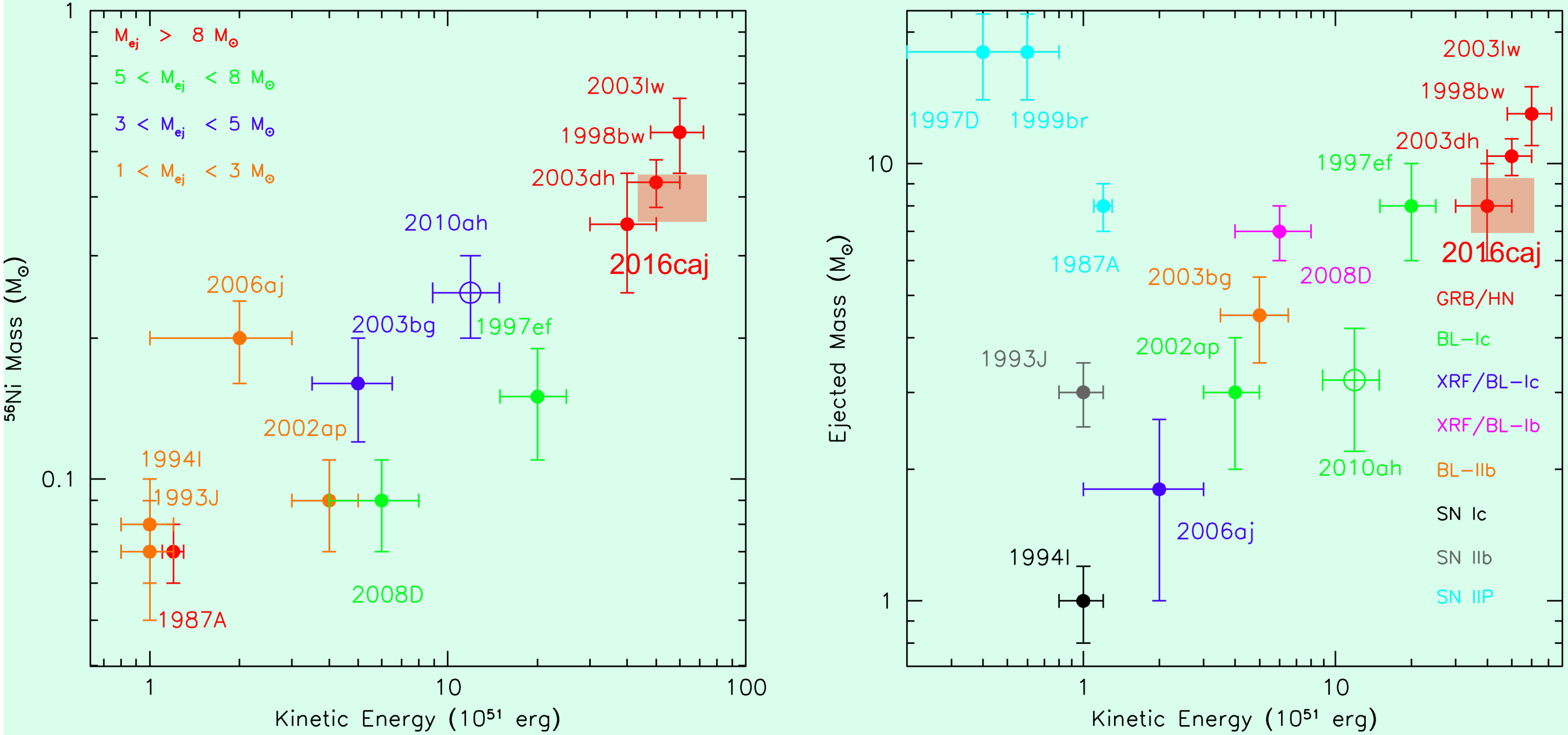
Ashall et al. 2017

More ^{56}Ni early on: head-on Fe jet



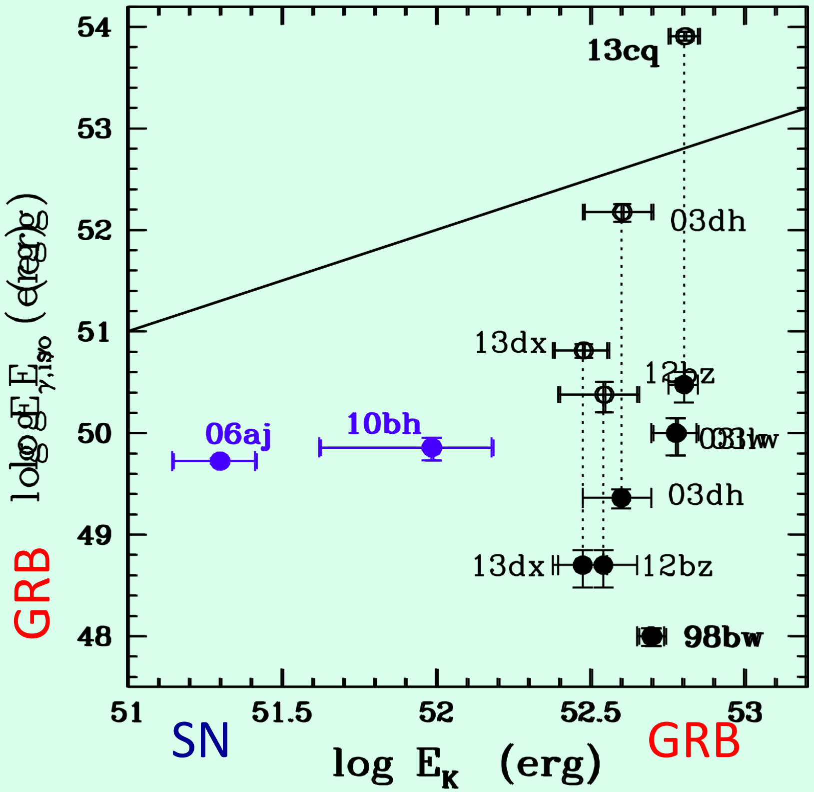
As time passes, see deeper into aspherical ejecta

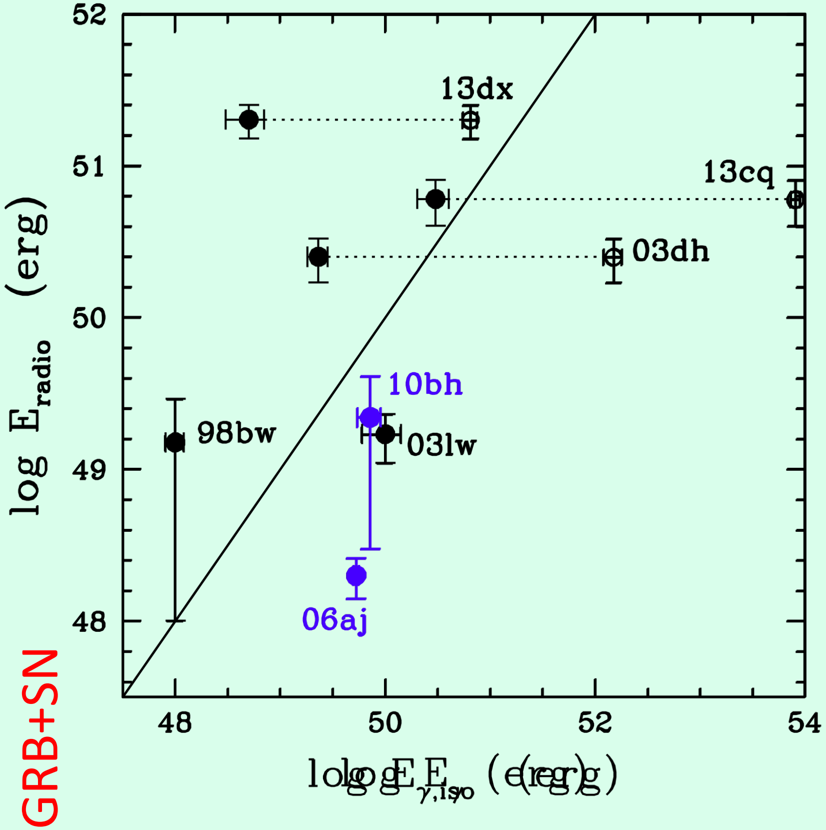
Modelling results



SN2016caj was (again) similar to all other GRB/SNe

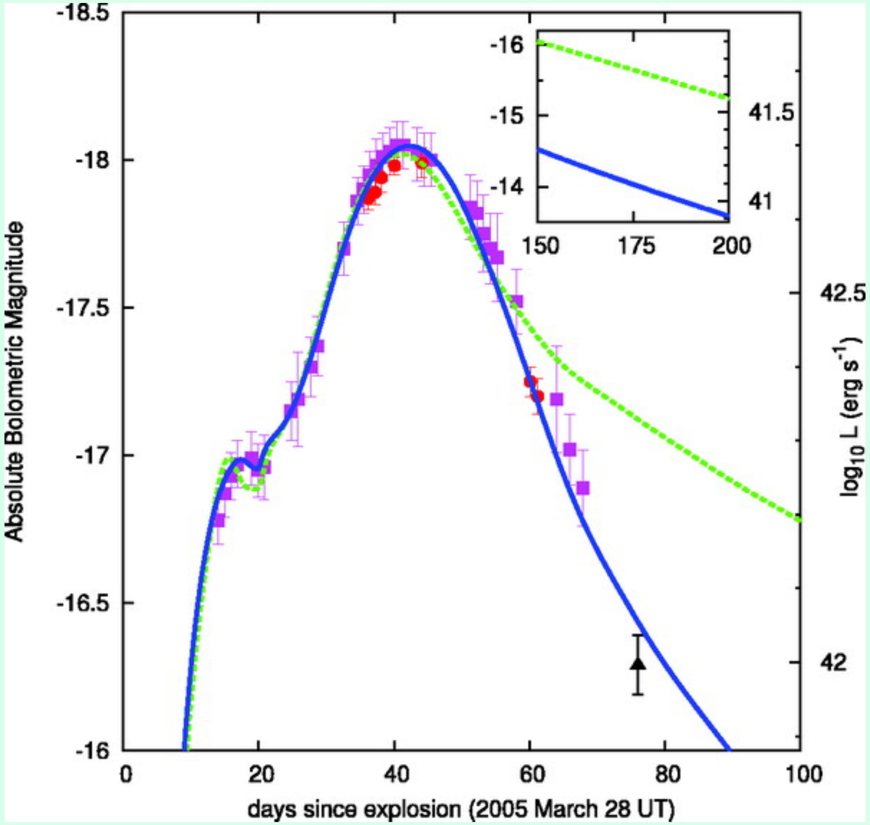
What is the "driving force"?
Compare energies of GRBs and SNe

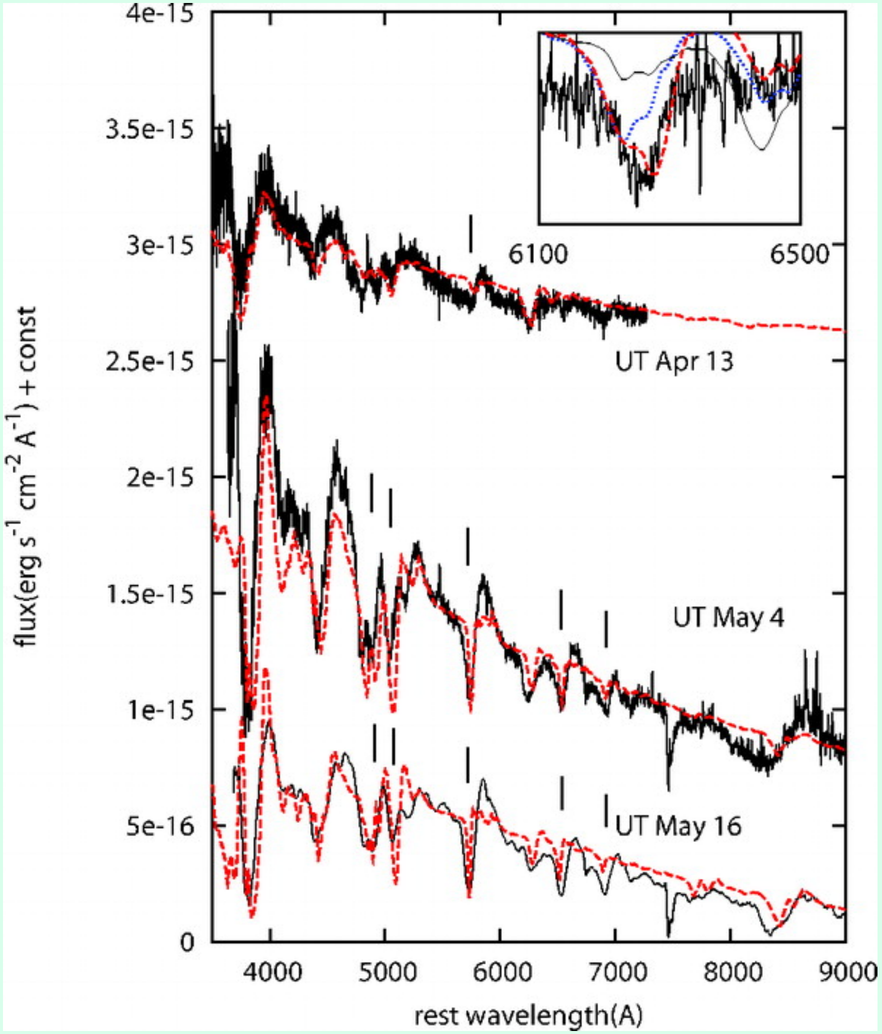




SN Ek always dominates, and it is close to maximum magnetar energy (PM+2014)

A Magnetar in SN Ib 2005bf?

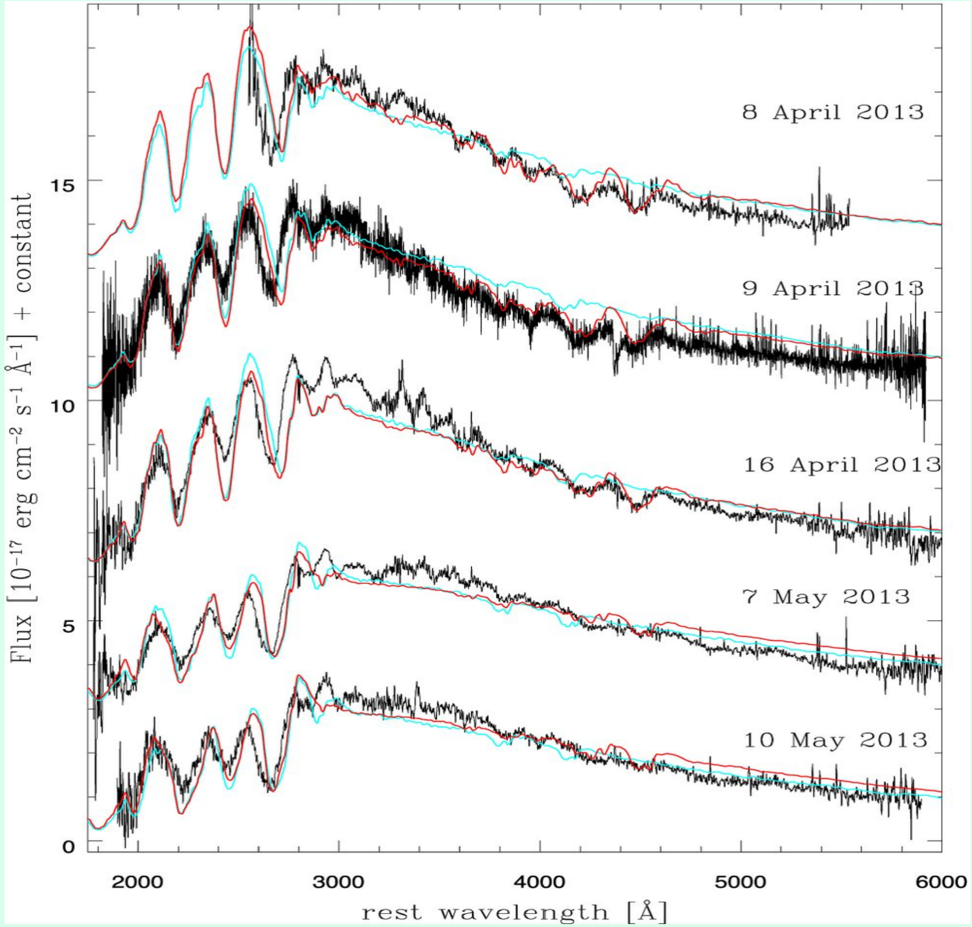


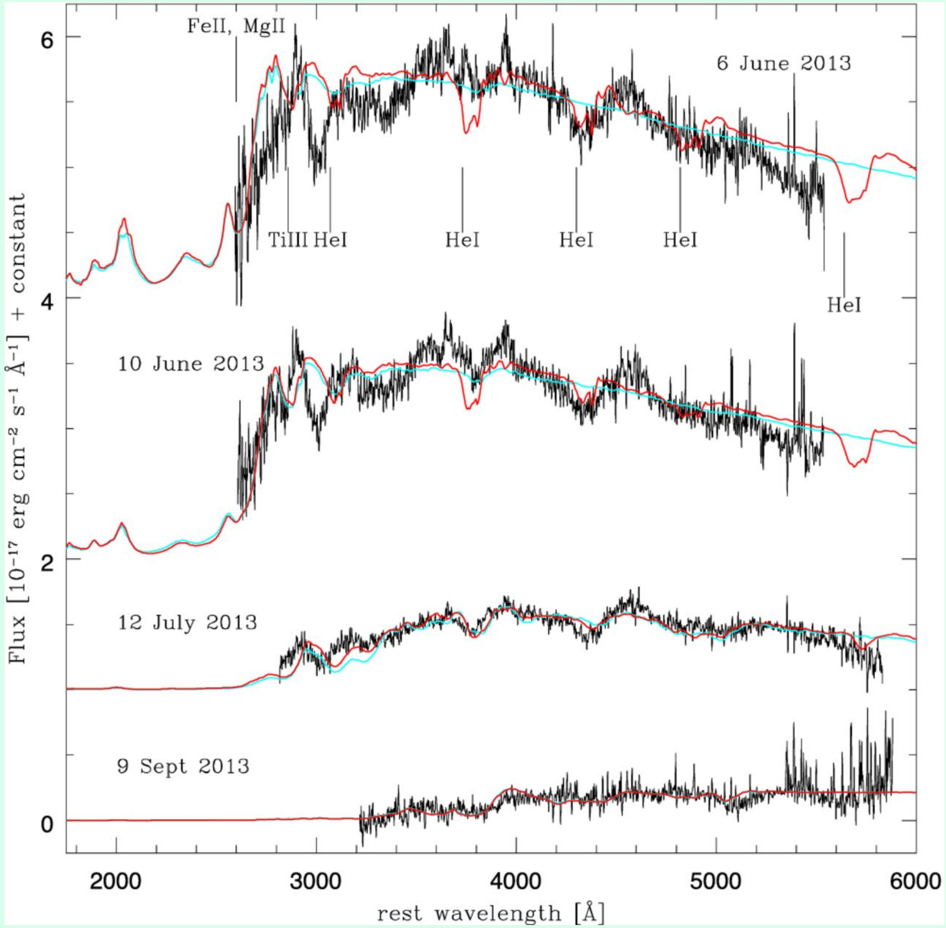


SN 2005bf (Tominaga et al. 2007)
showed a bright, late 2nd LC peak

Magnetar activity may have been responsible for the rebrightening
(Maeda et al. 2007)

Non-thermal spectra of SLSNe-I





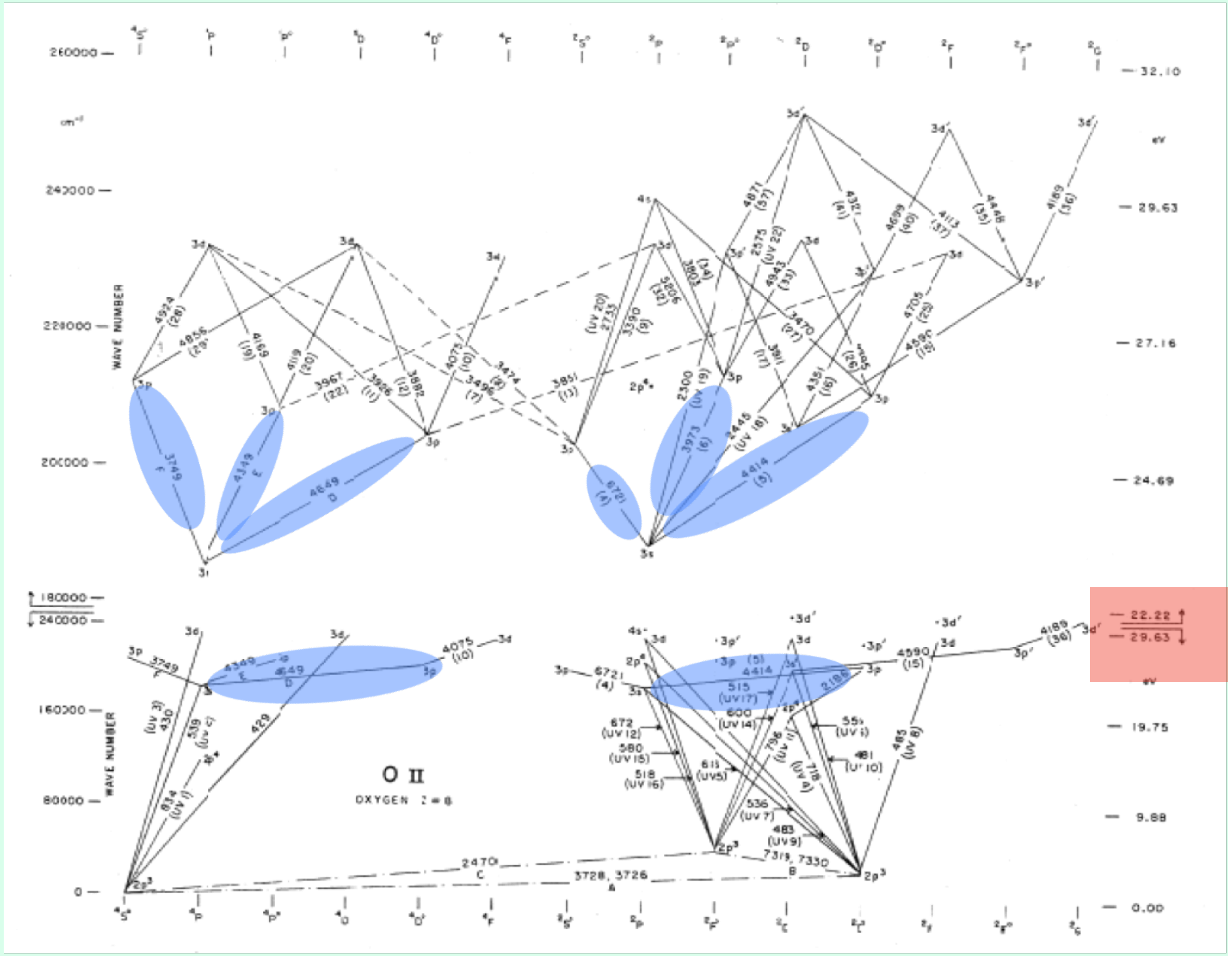
"peculiar" OII lines are result of non-thermal excitation/ionization at high Temp

HeI lines appear via same process only later, when Temp is "right" (lower)

The OII ion

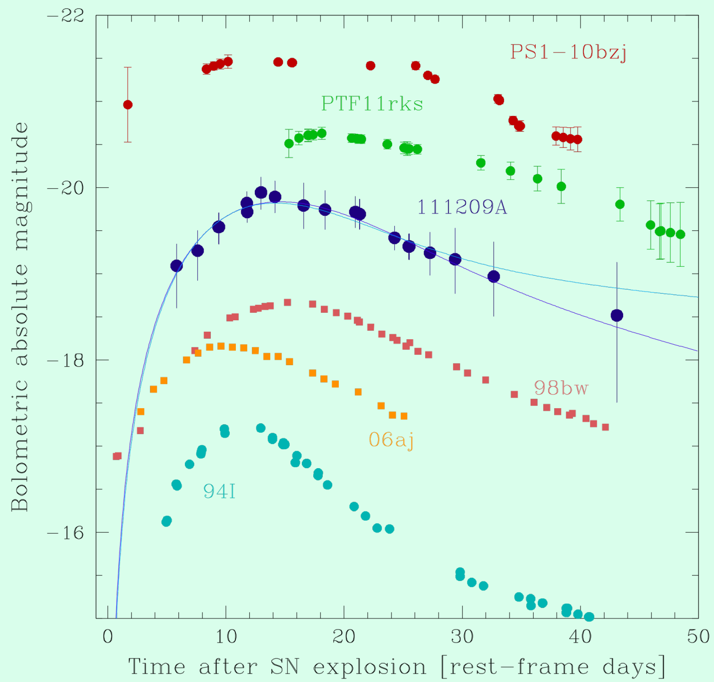
Optical OII lines come from lower levels with higher excitation energy than HeI (>22eV).

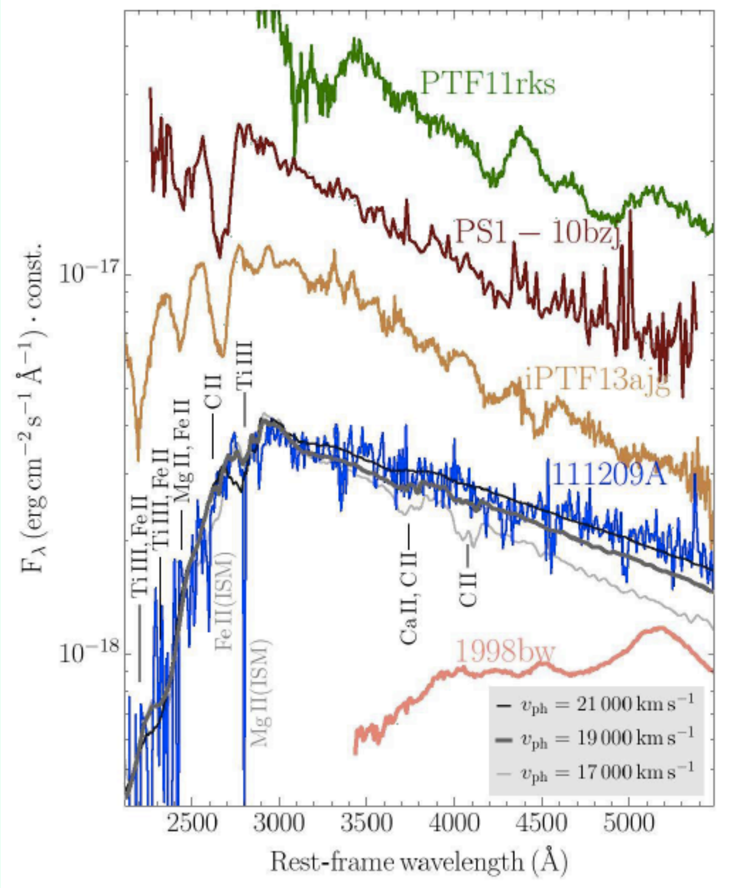
Not thermally excited



SLSNe and ULGRBs?

- Ultra-long (>10^4 s) GRB111209 showed a SN bump (SN2011kl)
- SN LC intermediate in Lum between GRB/SNe and SLSNe
- Blue spectrum, consistent with high Ek SLSN





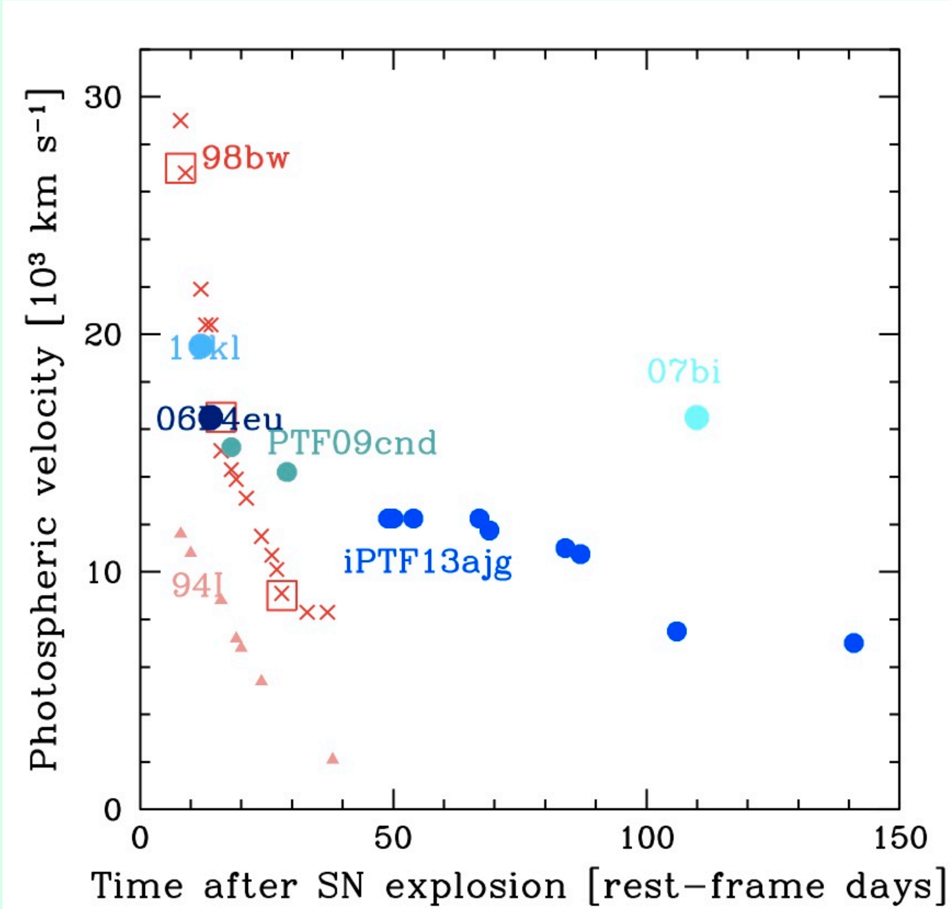
Consistent with Magnetar powering

Are all luminous SNe magnetars?

Greiner et al 2015, Nature

Velocity evolution: SNe Ic v. SLSNe

- Both SLSNe and HNe have high velocities,
- but in SLSNe high vel is sustained over a much longer time
- ULGRB/SLSN has higher vel than other SLSNe
- Slow decline of vel in SLSNe suggestive of Magnetar powering in SLSNe



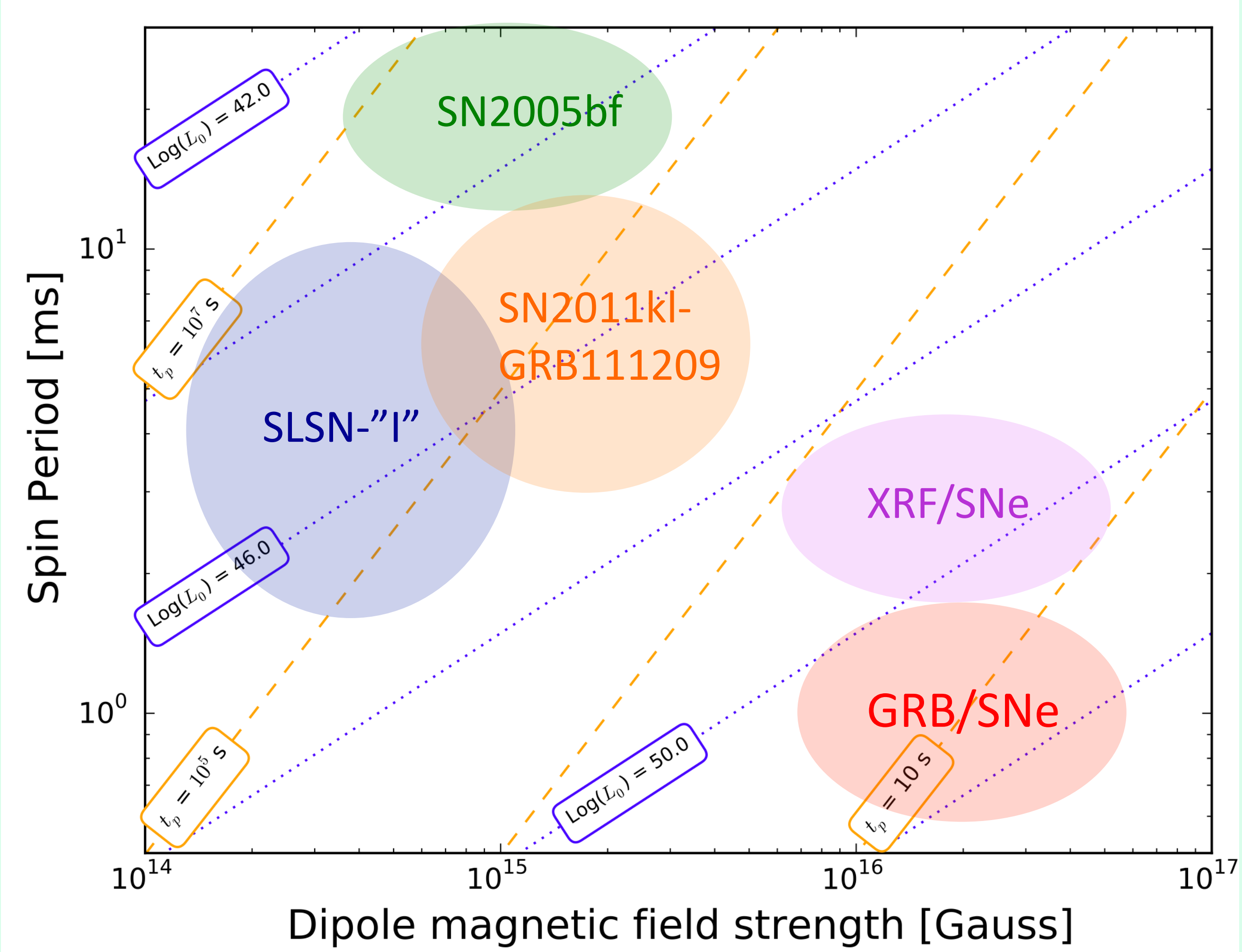
Comparing properties

	M_{ej} ($M_\odot$)	Ek (10^{51}erg)	Ek/Mej		M_{ej} ($M_\odot$)	Ek (10^{51}erg)
SNe Ic-7,6,5	1-4	1-4	~1	SLSNe-"I"	5-40	5-40
SNe Ic/BL	4-8	4-20	1-2			
GRB/HNe	8-12	20-50	3-5	ULGRB/SN	2-3	5-8

- ULGRB/SNe can have He and H (like SNe Ib/c, IIb)
- Highly excited OII (and He I) lines due to non-thermal excitation
- These are all cores of massive stars (binaries?)
- GRB/SNe, ULGRB/SNe have the highest Ek, Ek/Mej
- ULGRB/SNe NOT at massive end of range
- GRB/SNe driven by ^{56}Ni, ULGRB/SNe probably not.
- Magnetar powering likely in both GRB/HNe and ULGRB/SNe

Magnetar parameters?

- GRB, XRF require rapid energy injection, large E/M
- SLSNe powered by interaction: late injection



After Metzger+ 2015

The Grand Scheme

- Collapse of very massive (~35-50 $M_\odot$), stripped stars makes aspherical GRB-HN (GRB can be very different, HN much less).
  Driver could be Collapsar or Magnetar.
  Constancy of Ek suggests Magnetar.
- Collapse of less massive star (~ 20 $M_\odot$) to NS can cause a less energetic, less aspherical SN and an XRF (also via Magnetar?).
- Presence of too much He prevents GRB, still allows XRF (fast/aspherical breakout)