The Most Asymmetric SNe

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Asymmetry matters

- Stars may have companions, and they all rotate
- Core-collapse produces rapidly rotating neutron stars or black holes
- Stars have magnetic fields
- Explosions are subject to various hydrodynamic instabilities
- and more …

How can asymmetry be measured?

- Direct imaging - SN 1987A, CAS A
- Spectroscopy - SN 1987A, SN 1993J, and some hypernovae
- Spectropolarimetry - Over 30 SNe …

How does spectropolarimetry work?

Electron scattering and line scattering

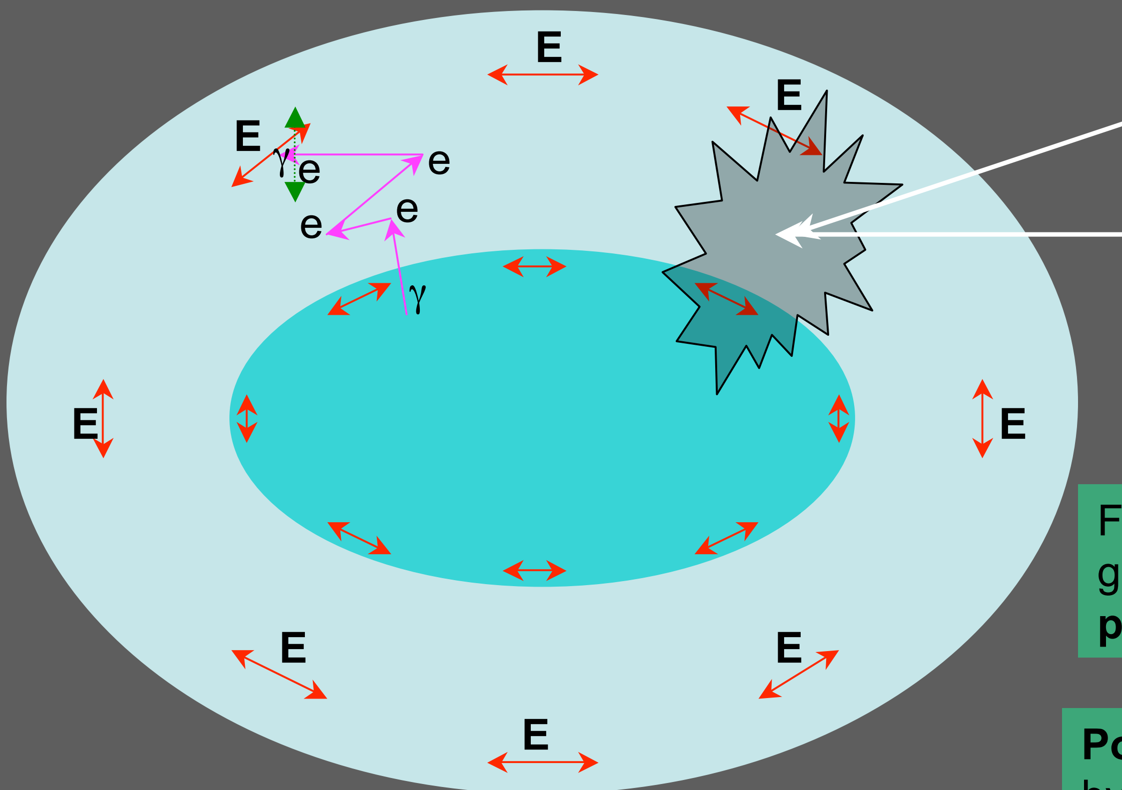
+

Aspherical explosions

(bipolar, unipolar, clumpy explosions)

Random walk in the debris

Photospheric Origin of Polarization

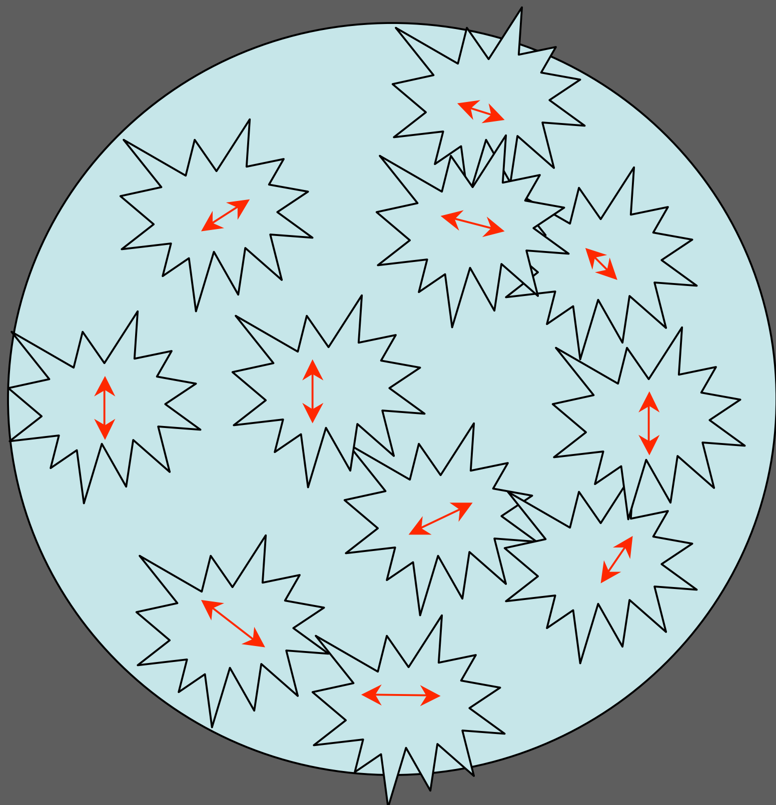


f ——> $f\text{-}f_i$
p*f* ——> **p***f***-p**$_i f_i$

Continuum or line opacity

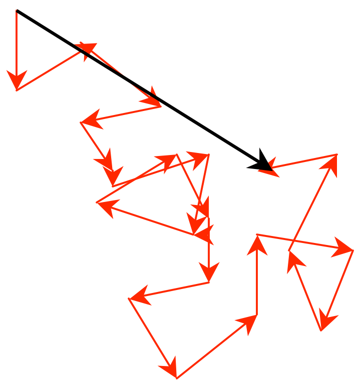
For spherically symmetric geometry, the integrated **polarized flux** equals zero

Polarized flux is generated by electron scattering



Random Walk

$$\mathbf{P}f = N^{1/2}\mathbf{p_0}f_i$$



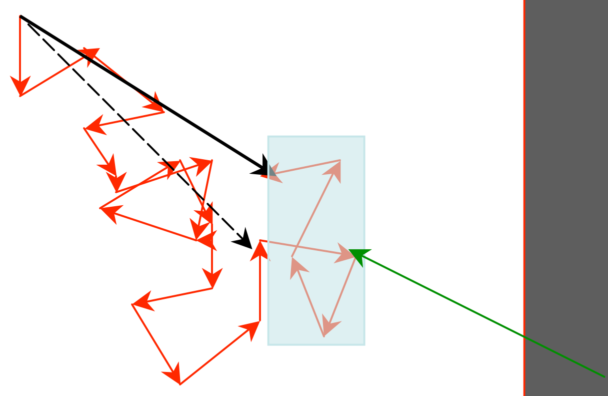
$$P = \frac{\Sigma\, p_i f_i}{1-\Sigma f_i} \sim \frac{f_i N^{1/2}}{1-f} p_0 = \frac{f N^{-1/2}}{1-f}\, p_0$$

where p_0 is the polarization of an individual clump if only that clump is observed. Typically $p_0 \approx 3\text{-}10\%$.

f - total area covering factor of clumps (≤ 1)
f_i - area covering factor by a typical clump ($\sim f/N$)
N - total number of clumps ($=f/f_i$)
$p_i f_i$ - polarized flux due to individual clump ($\sim 3f_i\%$)
$P \approx f\, N^{\sim 1/2} 3\%/(1-f) \sim 0.5\%$, $N \sim 36$ for $f \sim 0.5$, $f_i \sim f/N = 0.014$
d_c- diameter of a typical clump ~ 2,400 km/sec

Random Walk

$$Pf = N^{1/2} p_0 f_i$$

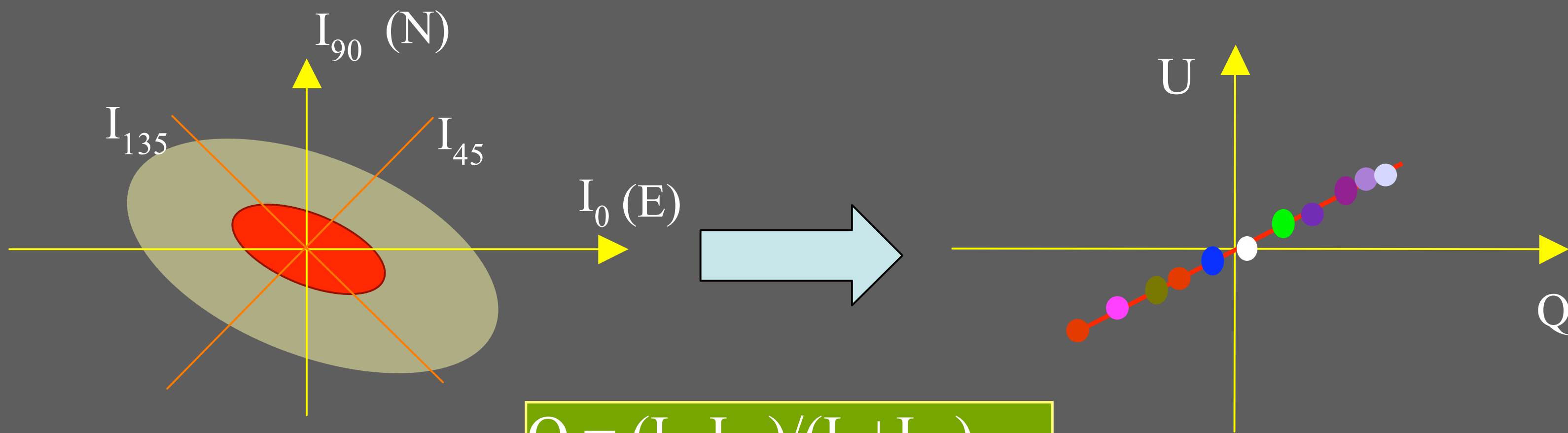


1) When **N is sufficiently large** P is a stable vector that does not show large random fluctuations with time.

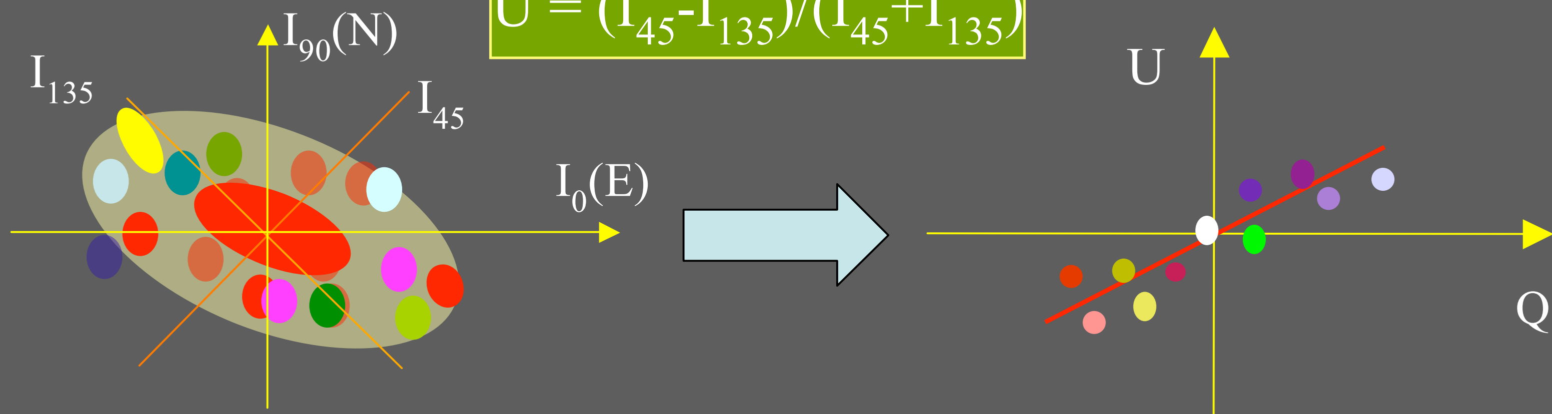
2) When **N is small**, P is still a stable quantity as such clumps will shield the photosphere at all epochs

These vectors/clumps moved outside the surface of the photosphere at a later epoch.

The Concept of Dominant Axis

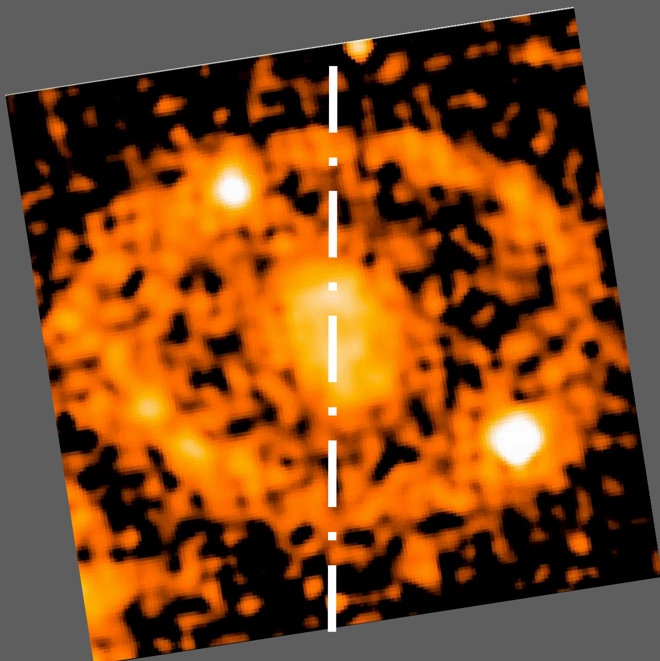


$Q = (I_0 - I_{90})/(I_0 + I_{90})$
$U = (I_{45} - I_{135})/(I_{45} + I_{135})$



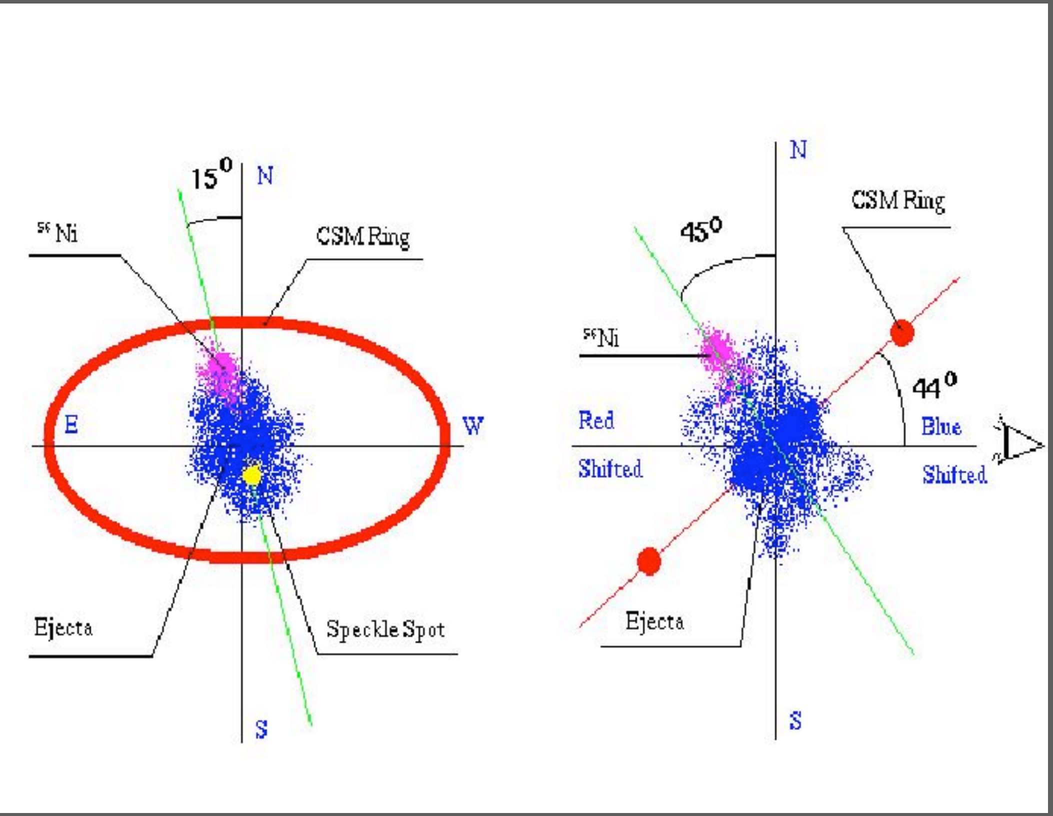
Wang et al. 2003

SN 1987A



SN 1987A is the only SN with spatially resolved ejecta structure

There is a constant symmetry axis from the center of the SN ejecta to the CSM matter that the SN lost more than 20,000 years before explosion

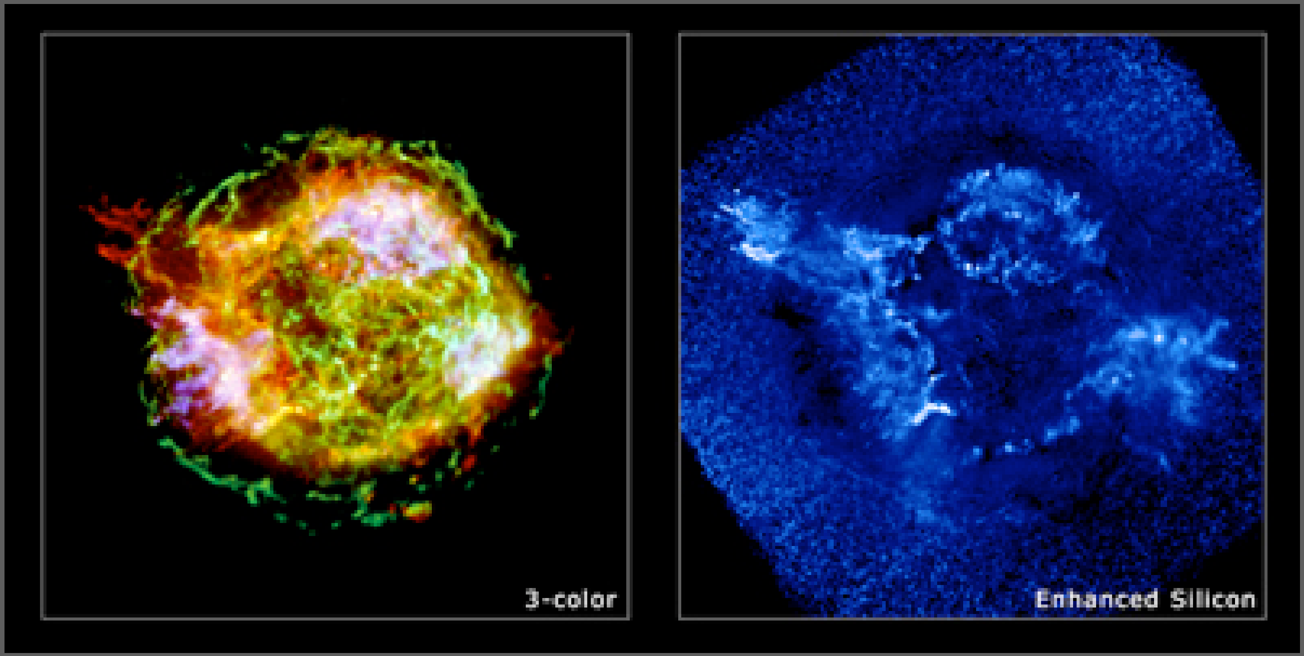


Rotation must have played an important role in making this SN explode

Wang et al. 2002

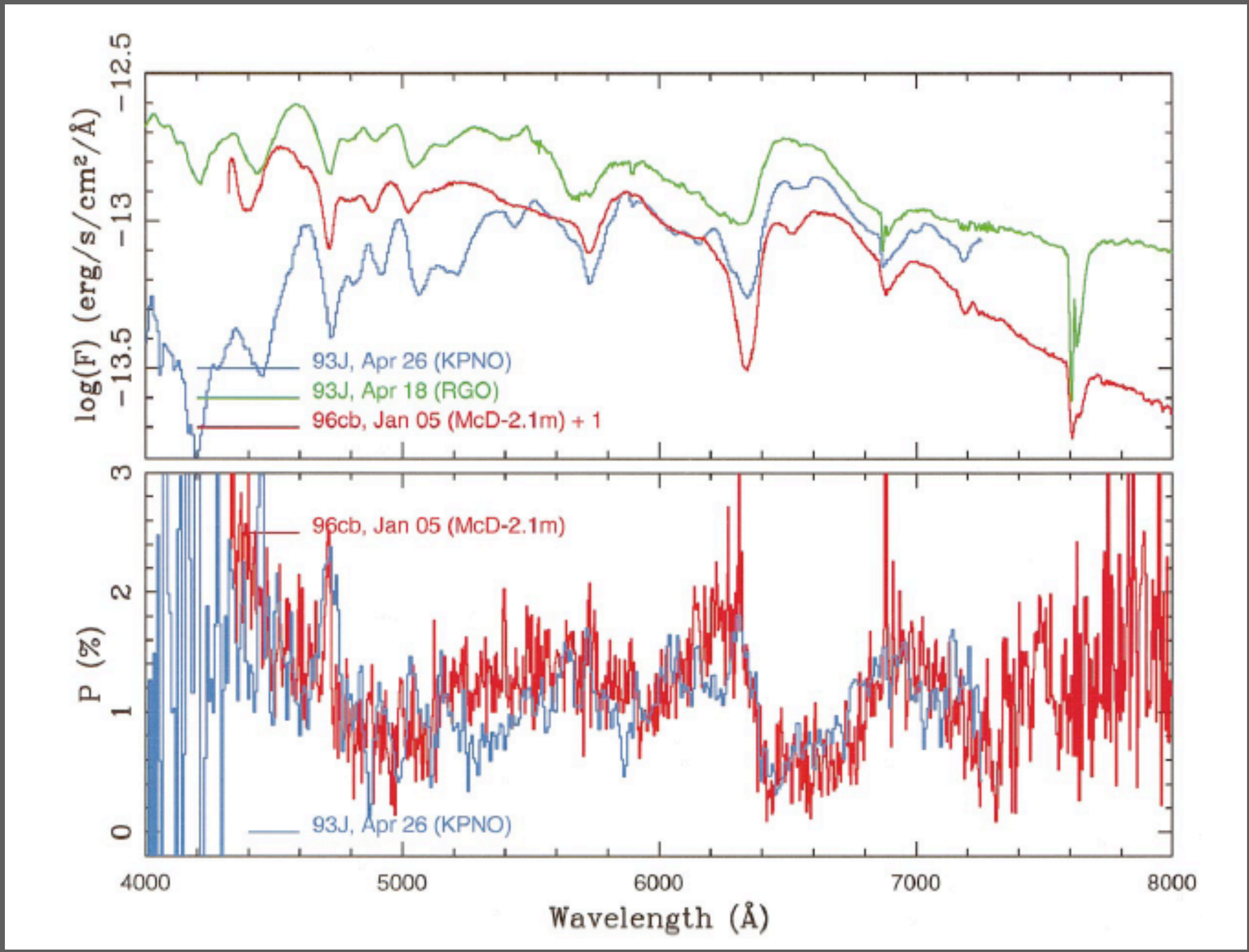
CAS A

Young SNR



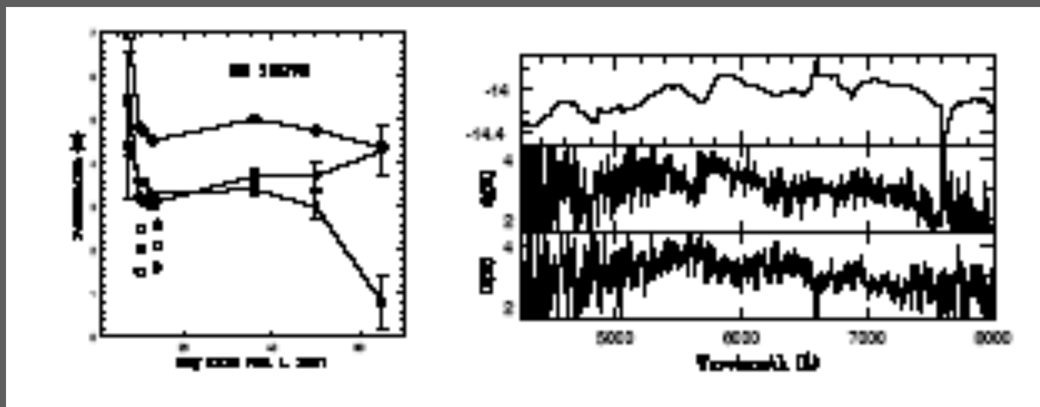
Core-Collapse SNe

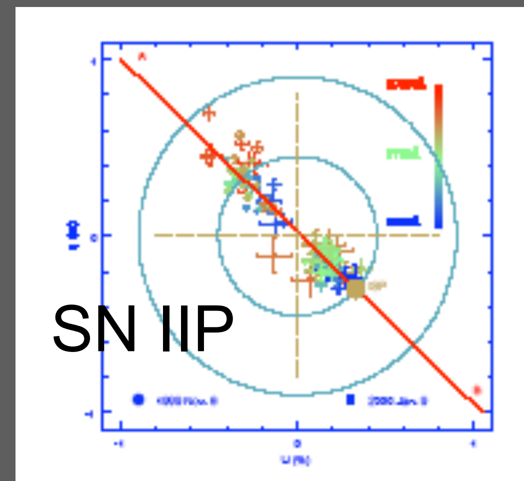
SN 1987A
SN 1993J
SN 1994Y
SN 1995H
SN 1996cb
SN 1997X
SN 1998S

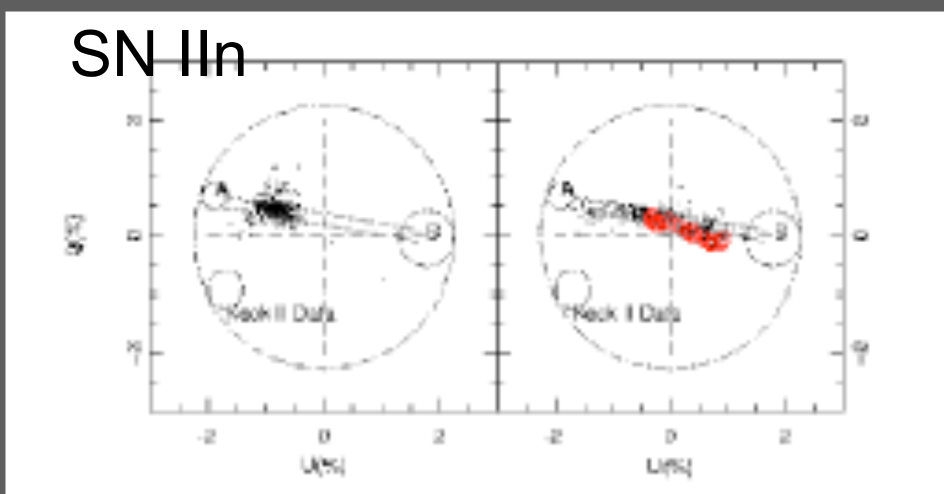


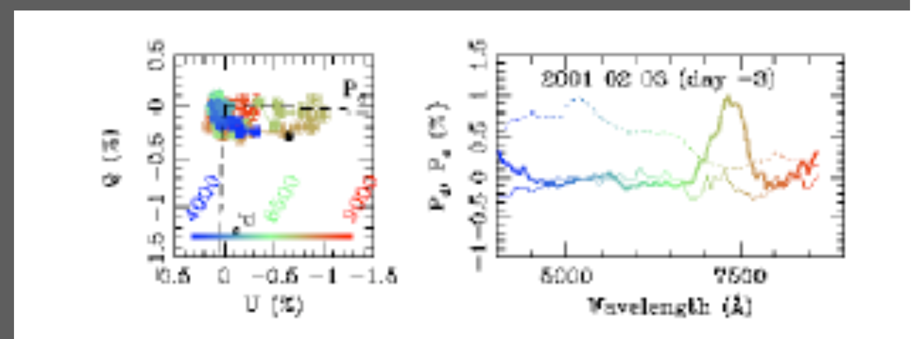
Wang, L. (2004), in *Cosmic explosions in three dimensions: asymmetry in supernovae and gamma-ray bursts*, edited by P. Hoeflich, P. Kumar, and J. C. Wheeler, P 27

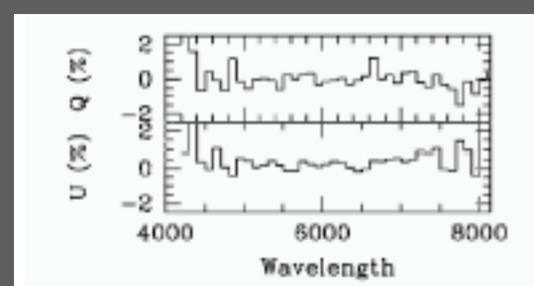
SN Ic



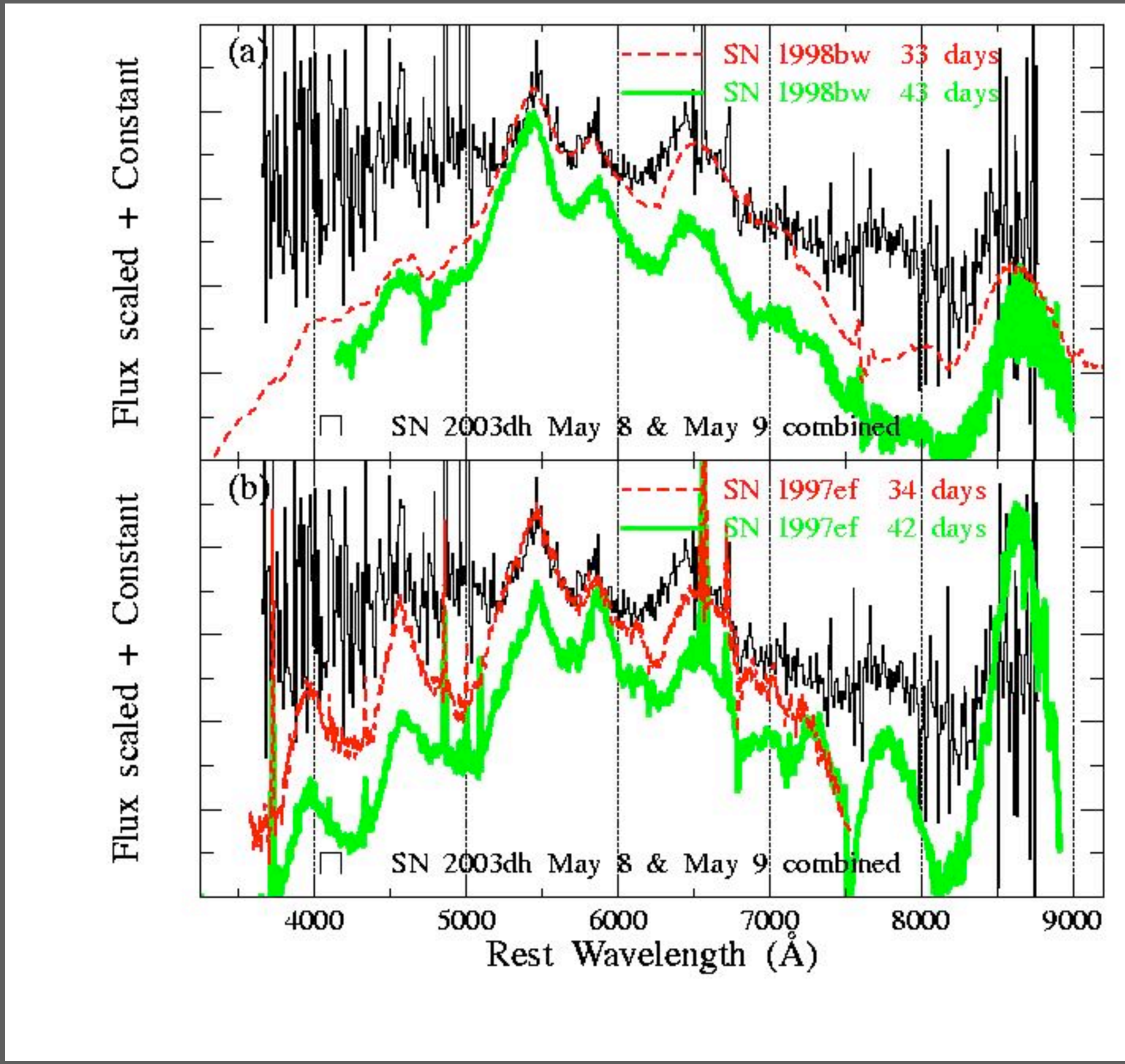








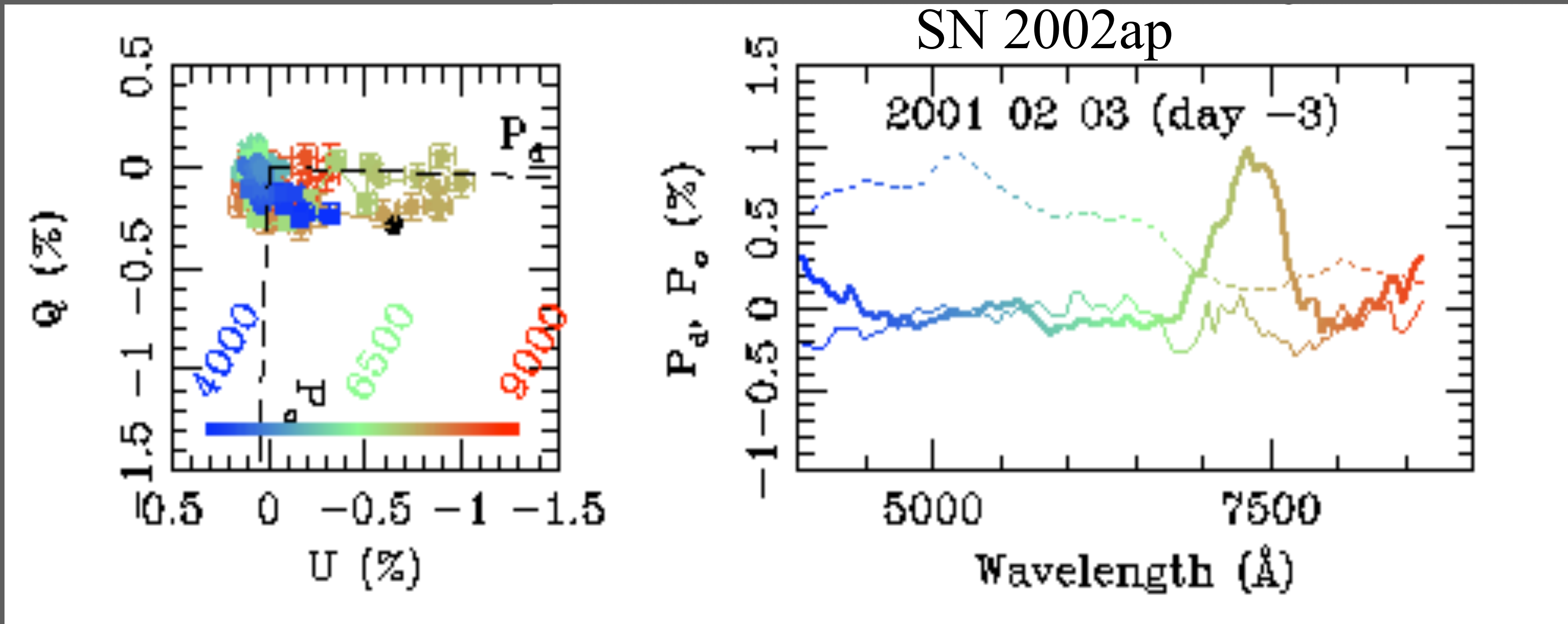
Hypernovae

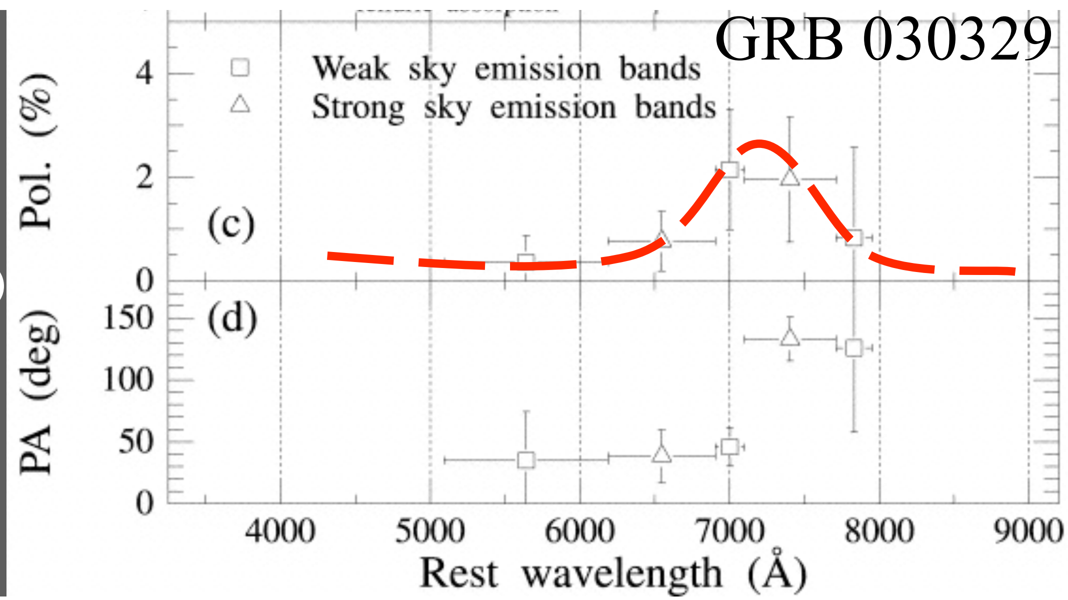


GRB 030329/
SN 2003dh

Redshift: 0.1685

(Kawabata, Deng,Wang, Mazzali, Nomoto, et al 2003)





- SN 1997ef
- SN 2002ap (Wang et al. 2003)
- SN 2003dh/GRB 030329
  (Kawabata, Deng,Wang, et al 2003)

Massive asymmetric
Oxygen shell

Type Ia SNe

Before SN 2001el:

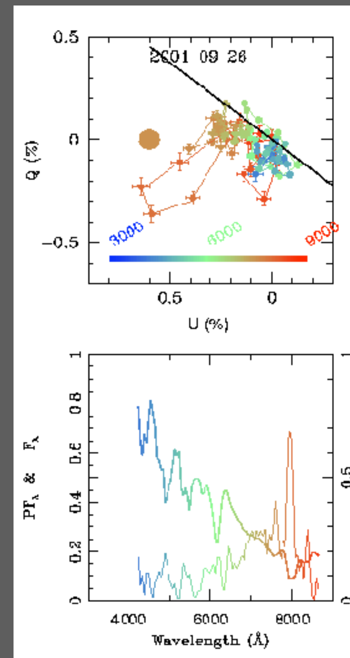
Supernovae are polarized

SN 1994D, SN 1994ae,
SN 1995D
(Broad band polarimetry)

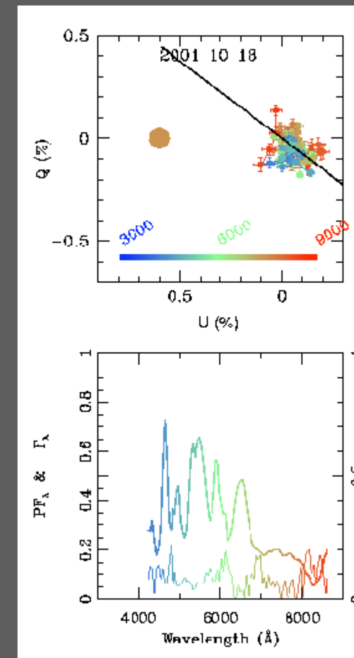
SN 1996X, SN 1997bp,
SN 1997br, SN 1999by
(Spectropolarimetry)

(Much ado about nothing)

Day -4



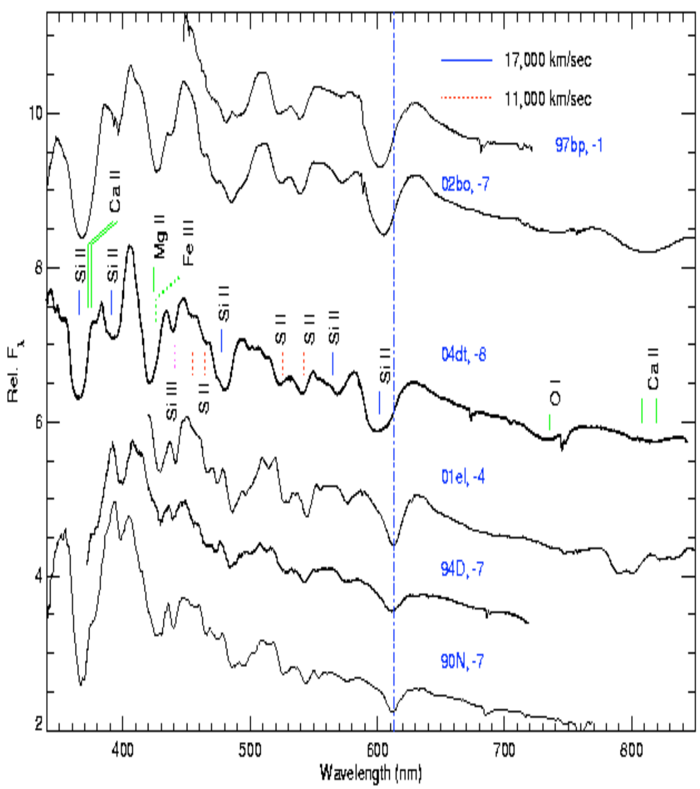
Day 19



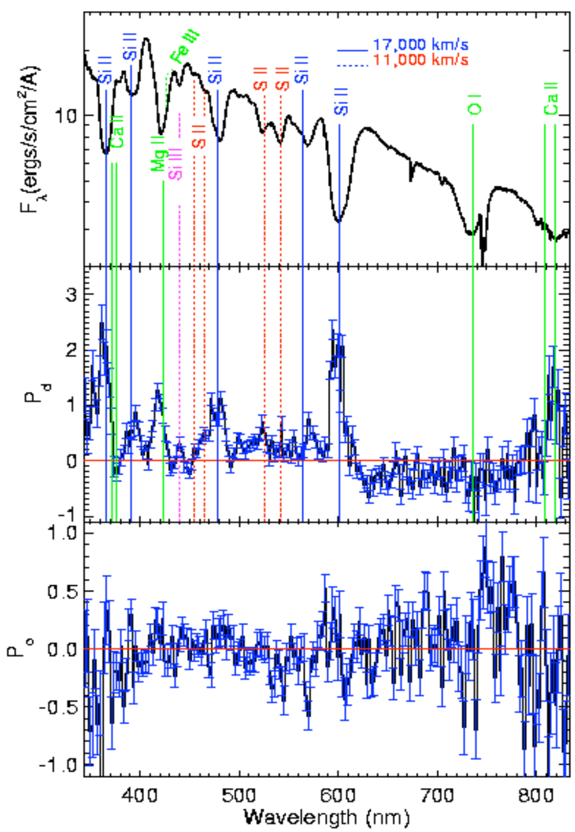
After 2001el:

- Multi-epoch data
- Detailed map of the geometric structures of SNe
- The CSM dust at the immediate neighborhood of SNe

SN 2004dt

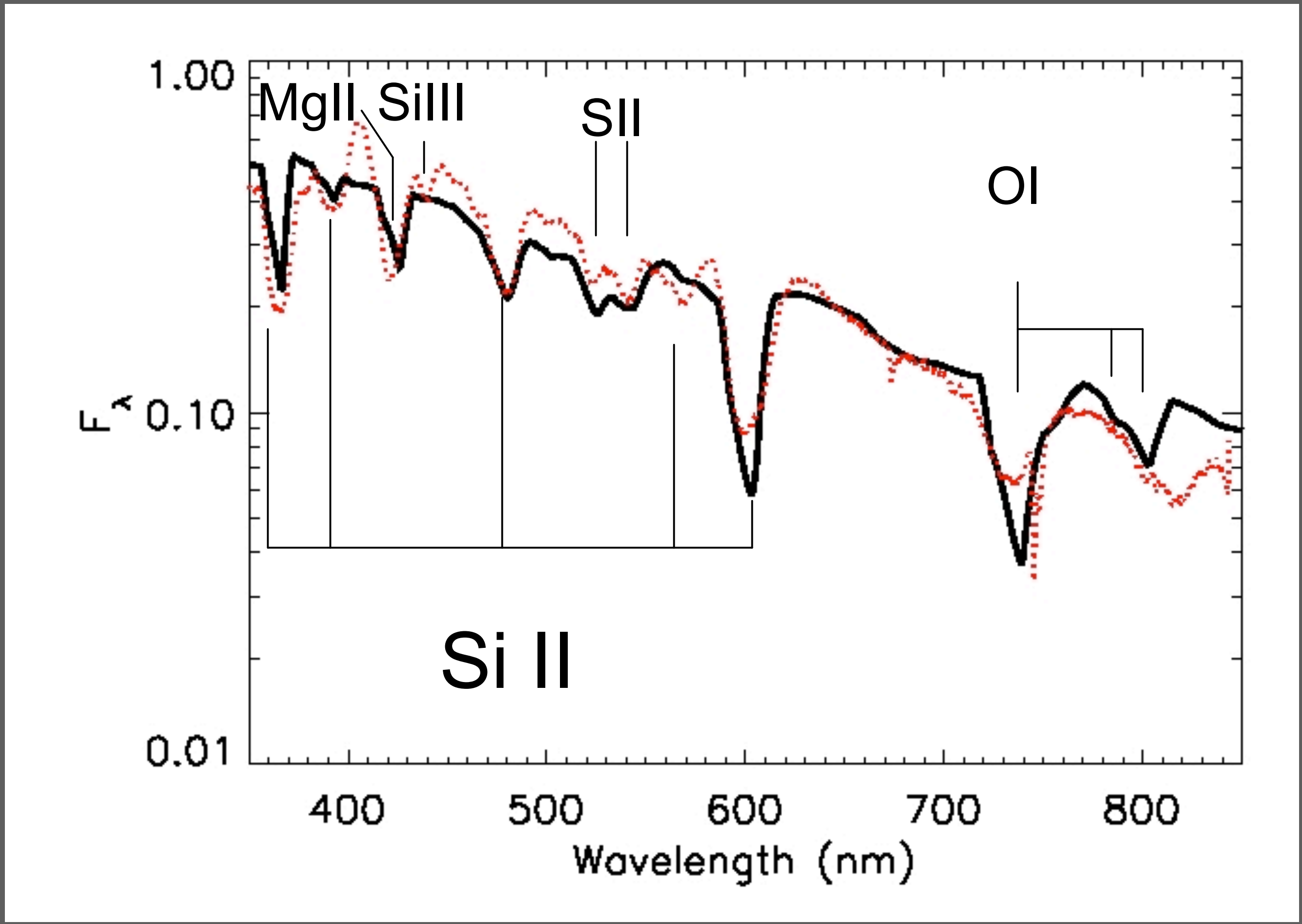


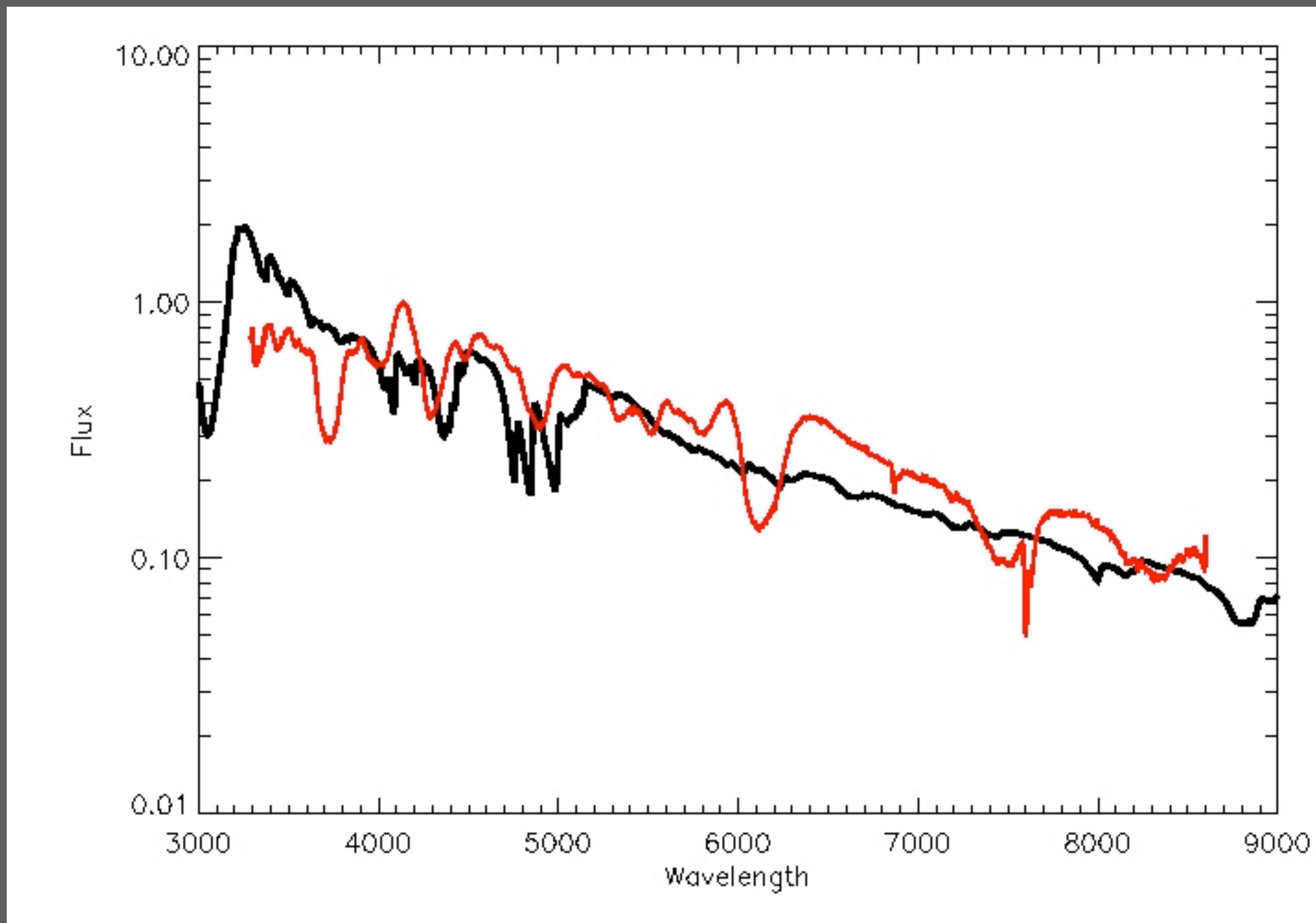
A high velocity SN



Distorted envelope

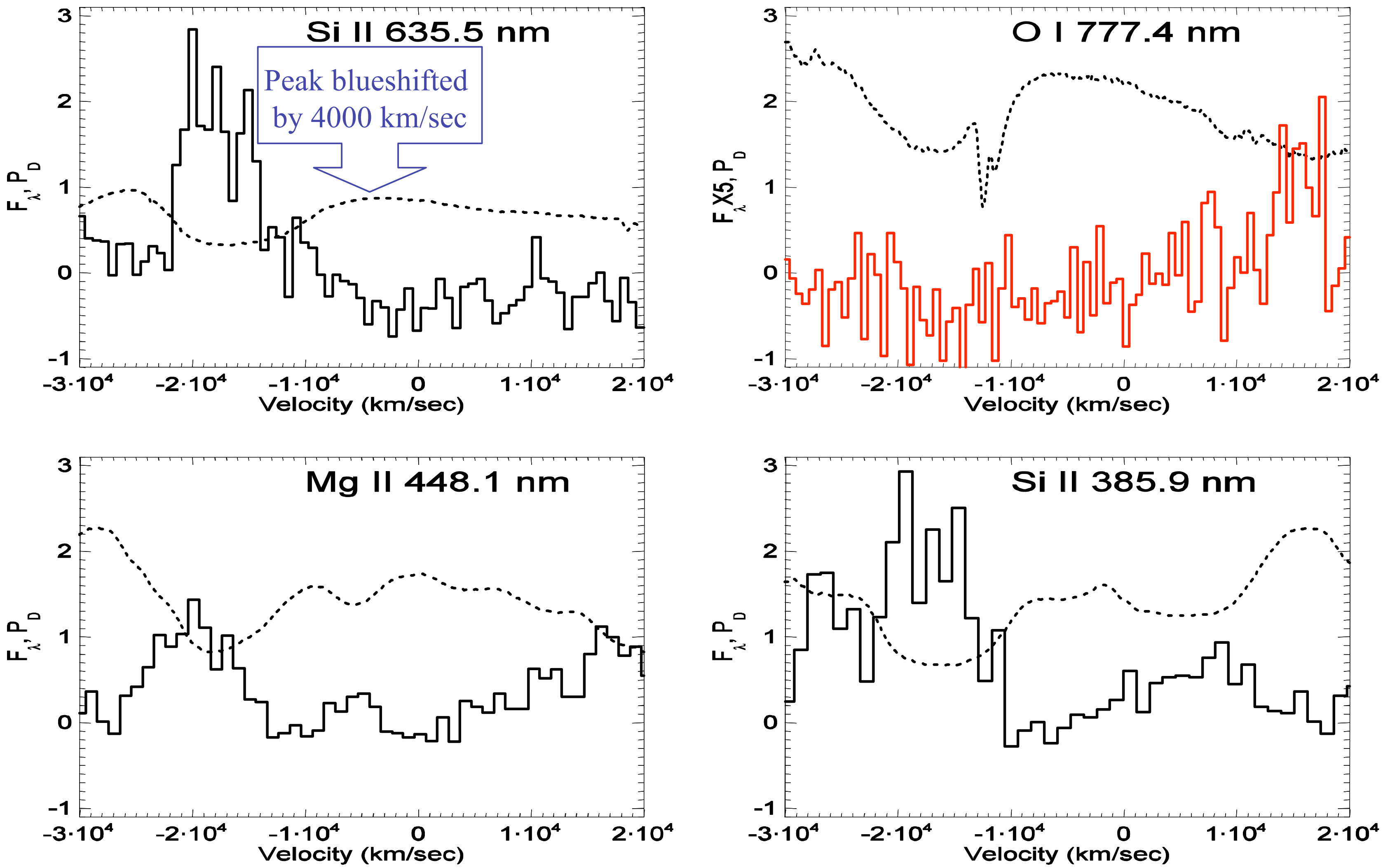
Synthesized spectrum with: Si II, S II, O I, and Mg II

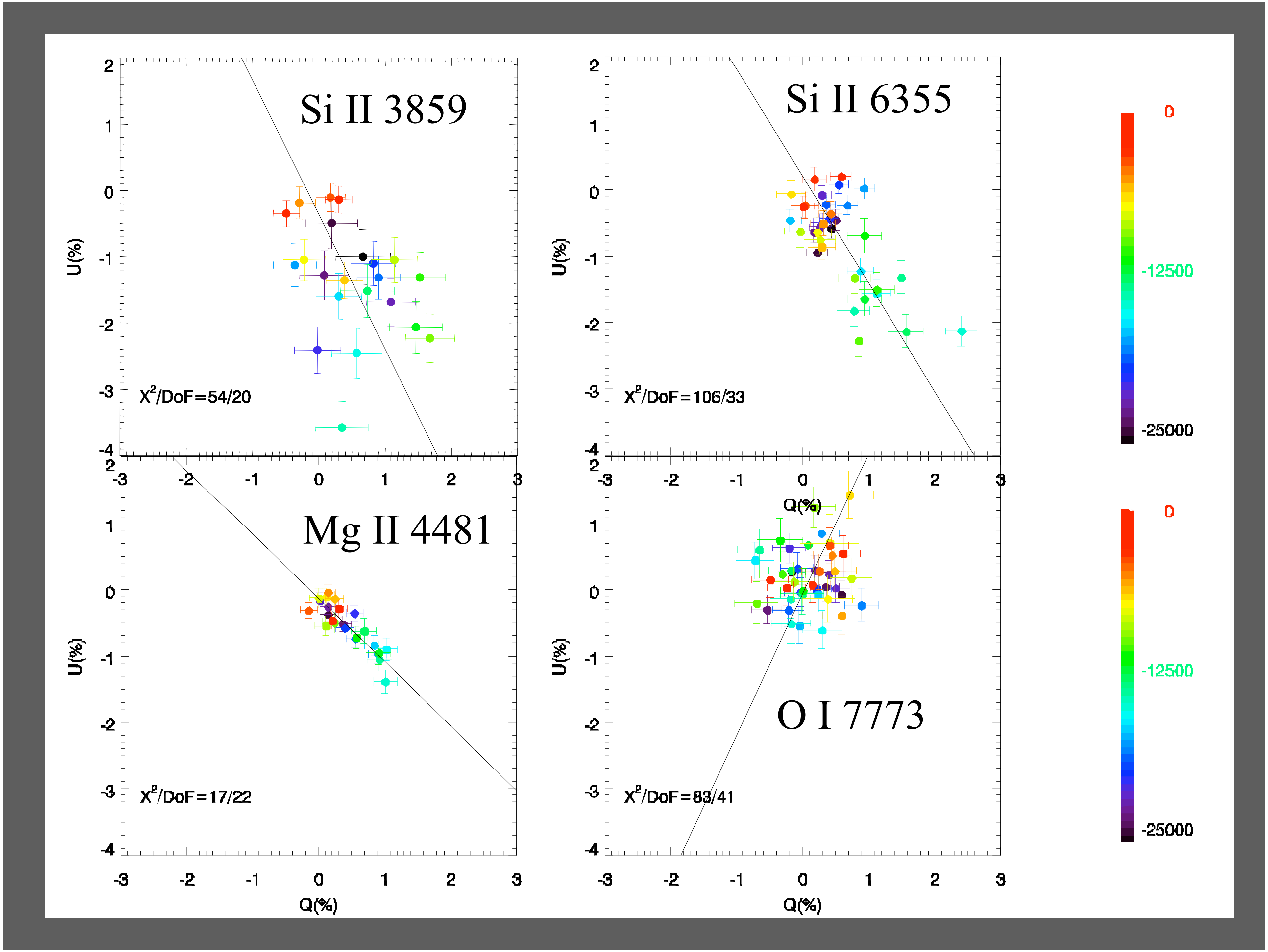



10.00
1.00
0.10
0.01
Flux
3000
4000
5000
6000
7000
8000
9000
Wavelength

No Fe II

Line/Polarization Profiles

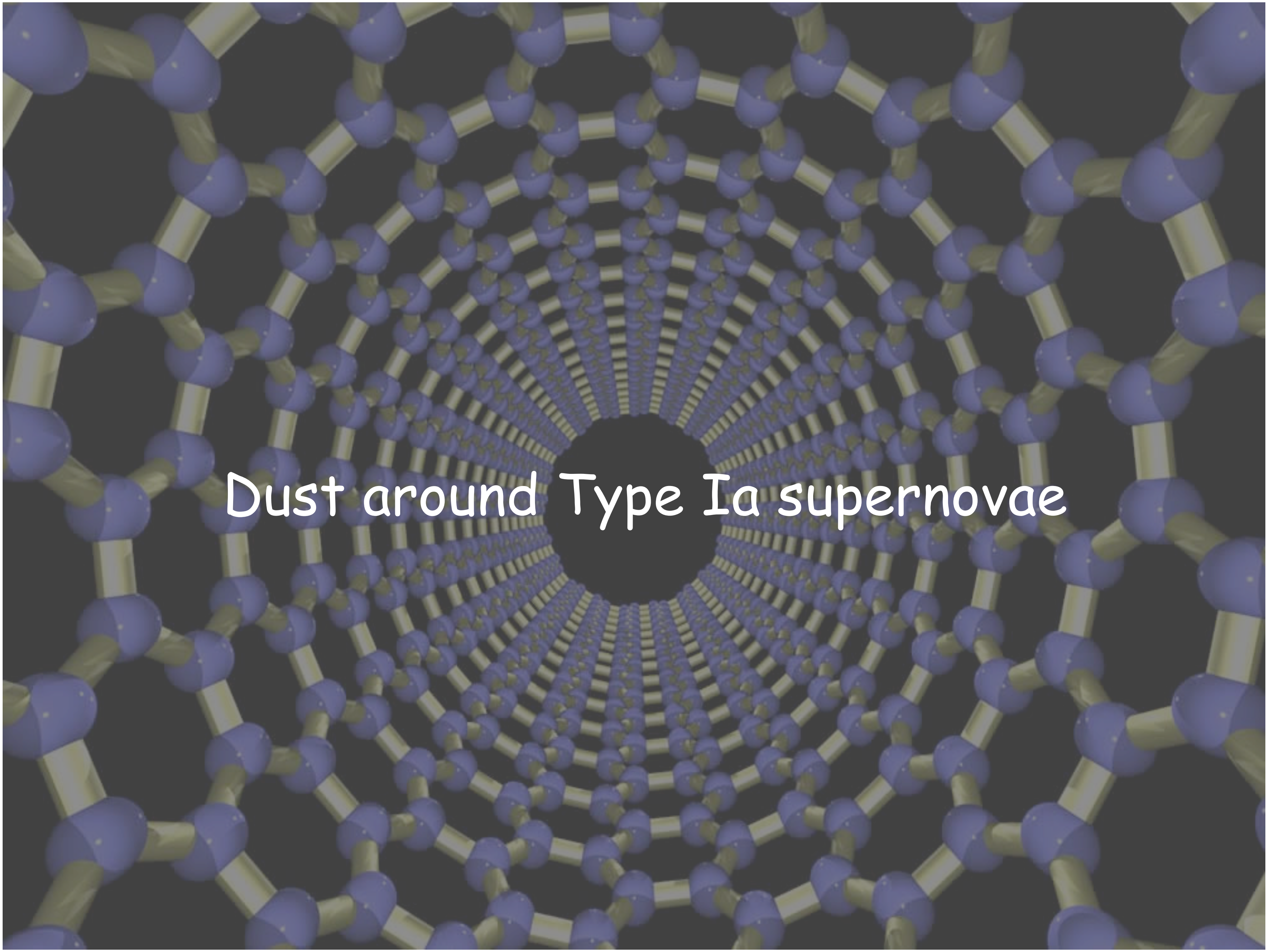




Si II 3859
χ²/DoF=54/20
Si II 6355
χ²/DoF=106/33
Mg II 4481
χ²/DoF=17/22
O I 7773
χ²/DoF=83/41
U(%)
Q(%)
0
-12500
-25000

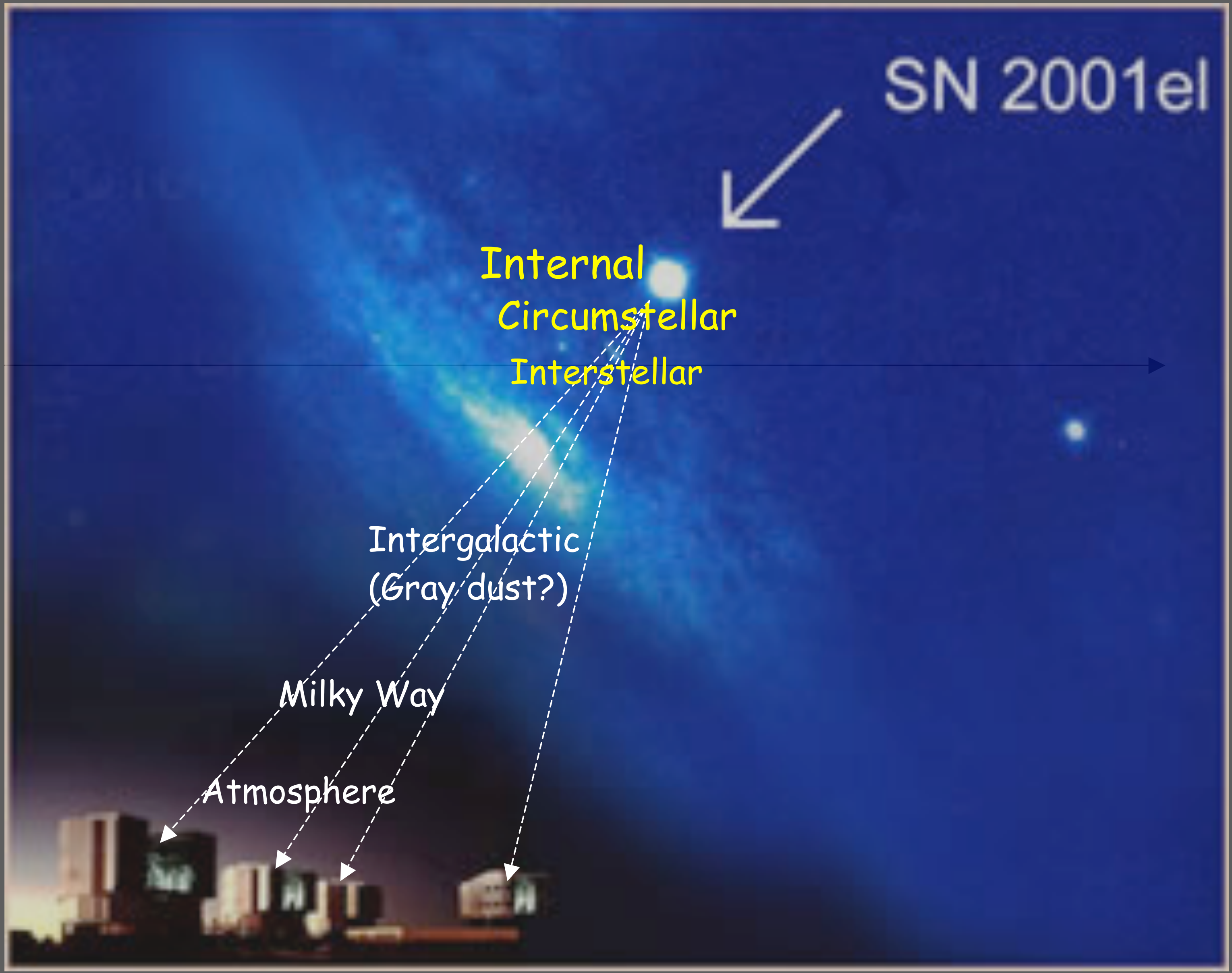
Summary of SN Ia Polarimetry

- Multi-epoch high quality data from pre-max to a month after max
- Higher degree of polarization at earlier phases
- The degree of polarization decreases significantly two weeks past optical maximum
- Large dispersions on the Q-U plane, which indicates that SN Ia ejecta are in general clumpy
- Unexplored: Dust scattering, magnetic fields



Dust around Type Ia supernovae

The Universe is dusty



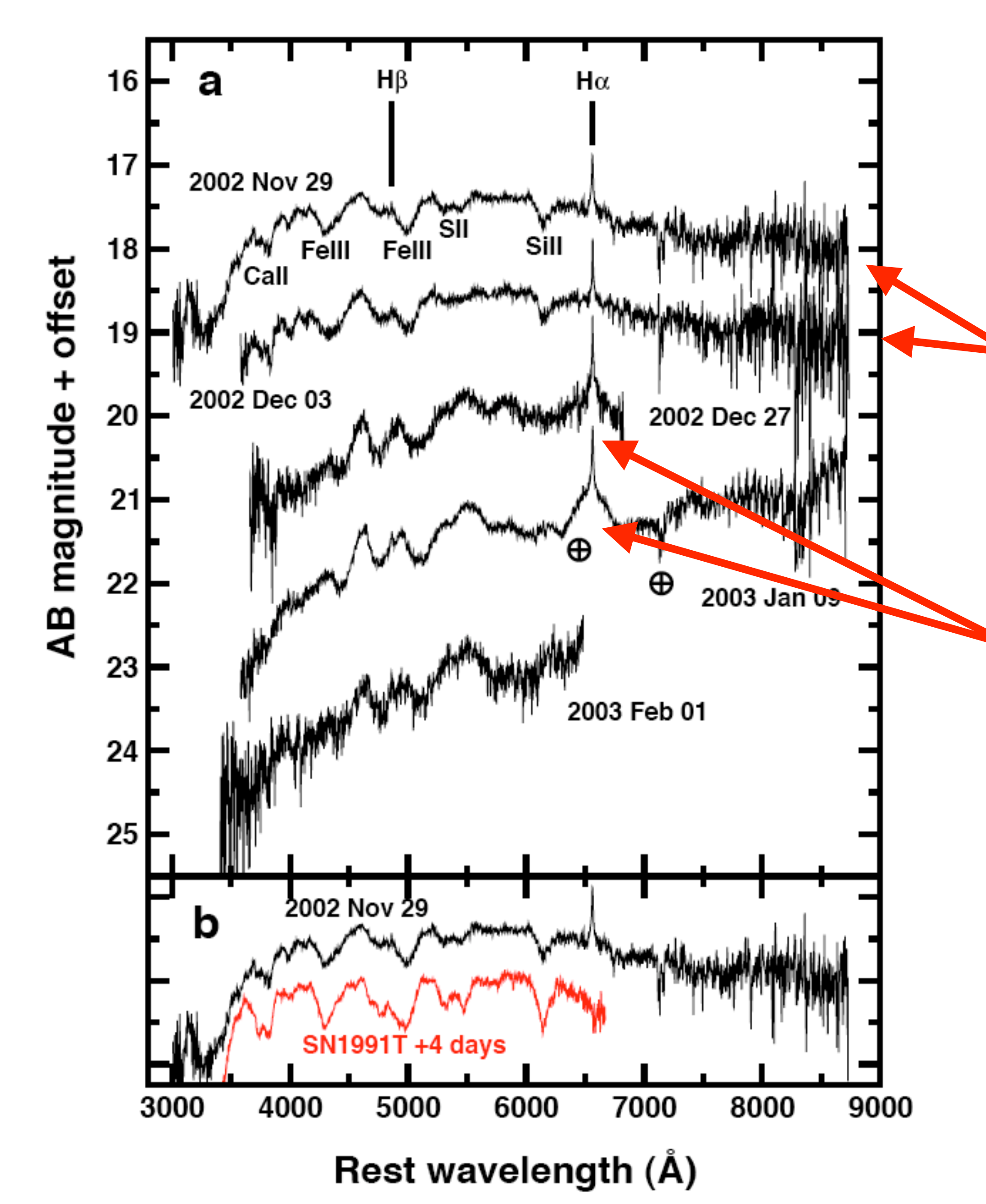
The circumstellar environment of SNIa

Observational constraints

- No radio detection of any SNIa
- No detection of narrow CSM lines expected from ejecta-circumstellar matter interactio (Implies mass loss rate < $10^{-5} M_{sun}$/year, Mattila et al. 2005)

Hamuy et al. (Nature, 426, 651, 2003)

SN 2002ic - a SN Ia with hydrogen



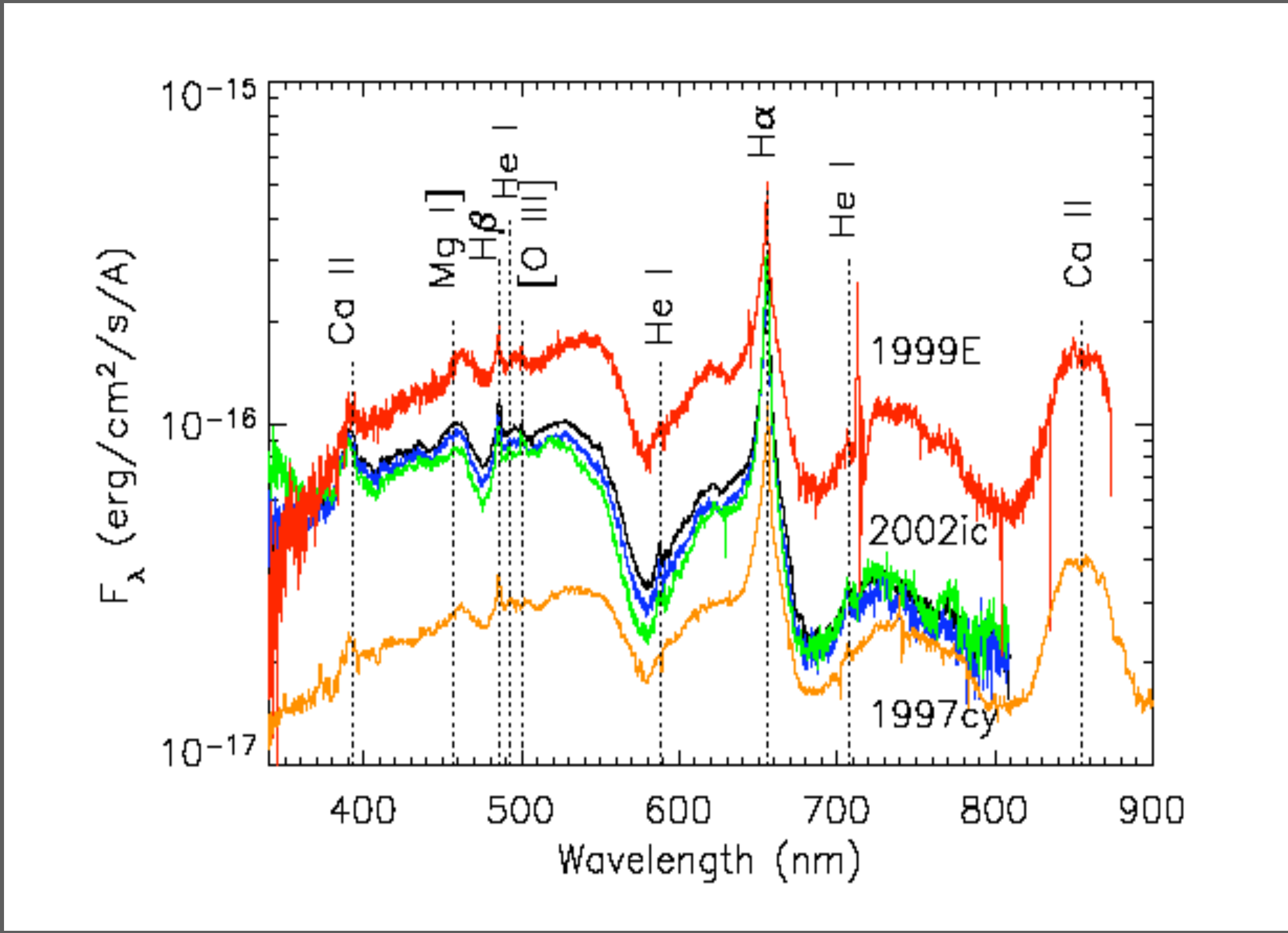
A Type Ia supernova at early time

A Type IIn supernova at Late phase

The H_{α} line is caused by the interaction of SN ejecta and the CSM

Wang, et al (ApJ, 604, L52, 2004)

Hydrogen in SN 2002ic

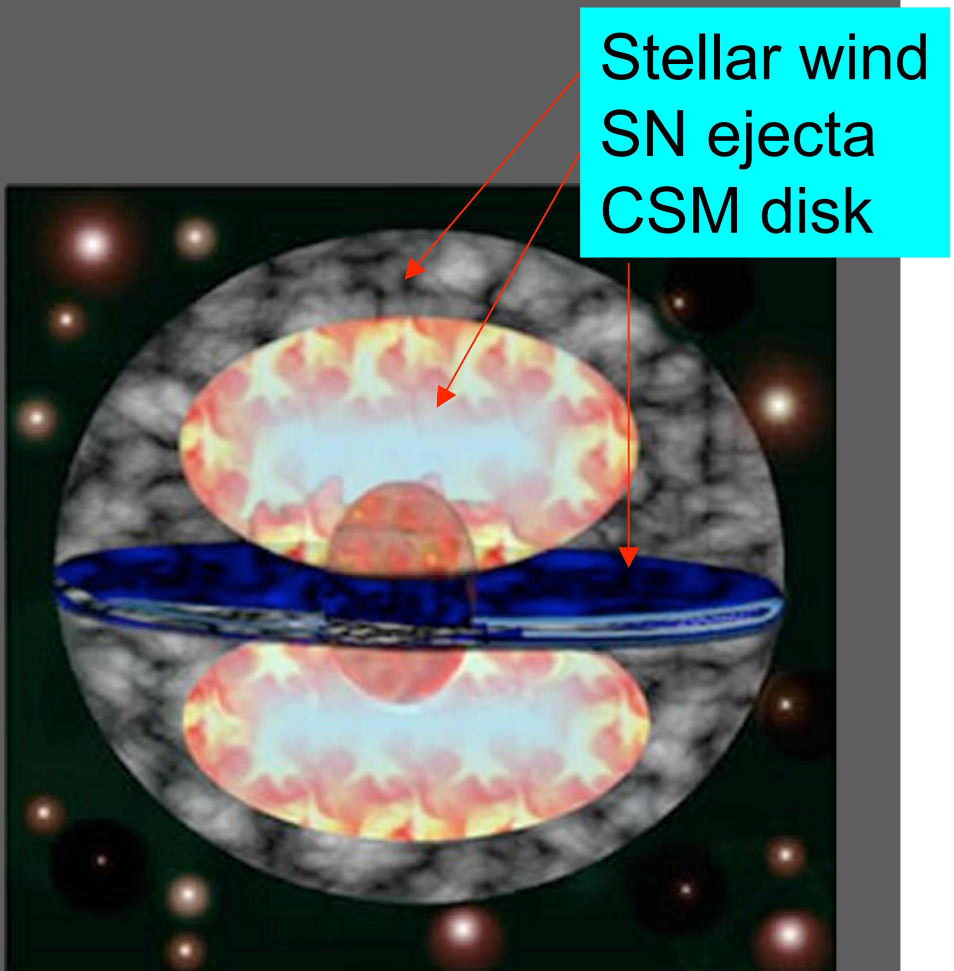


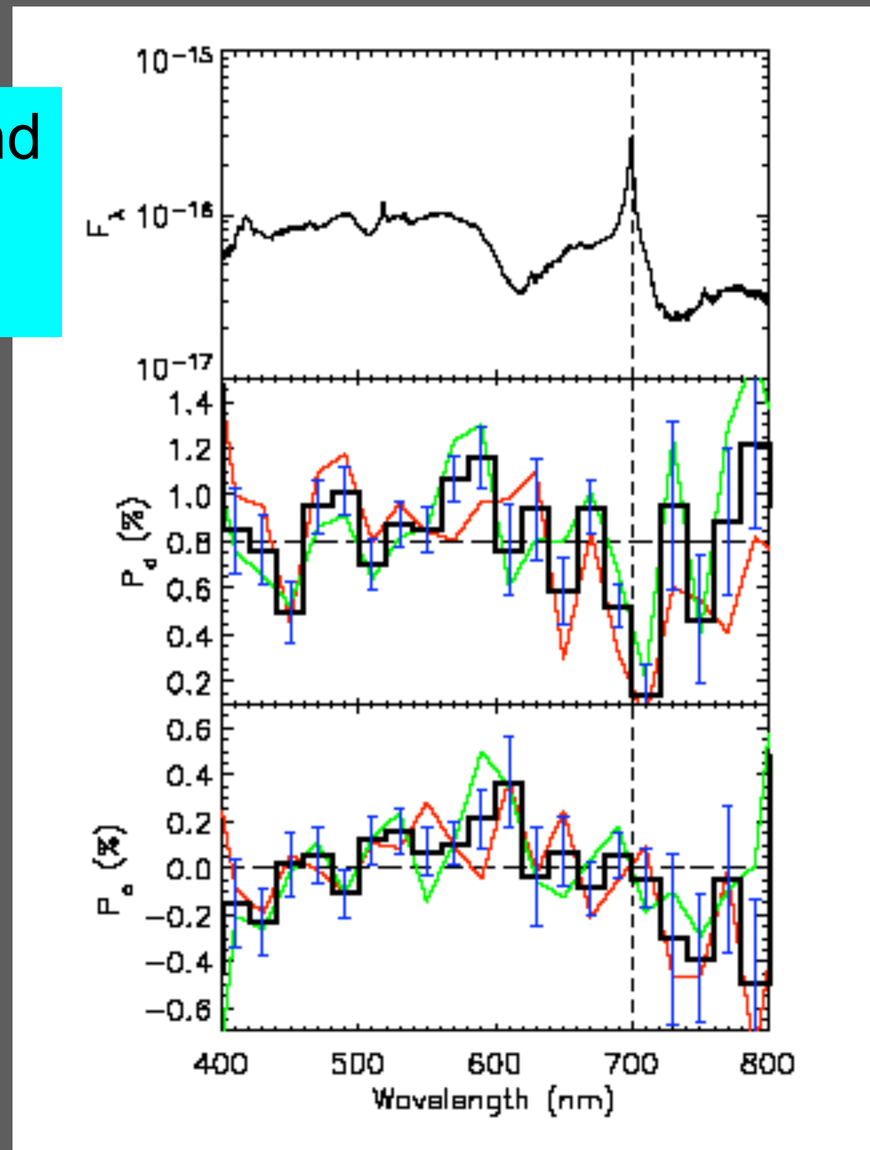
1. The mass of the H-rich envelope is around $6M_{sun}/(n_e/10^8 cm^3)$

2. Two or three other Sne are very similar to SN 2002ic

Wang, et al (ApJ, 604, L52, 2004)

An SN inside a post AGB wind



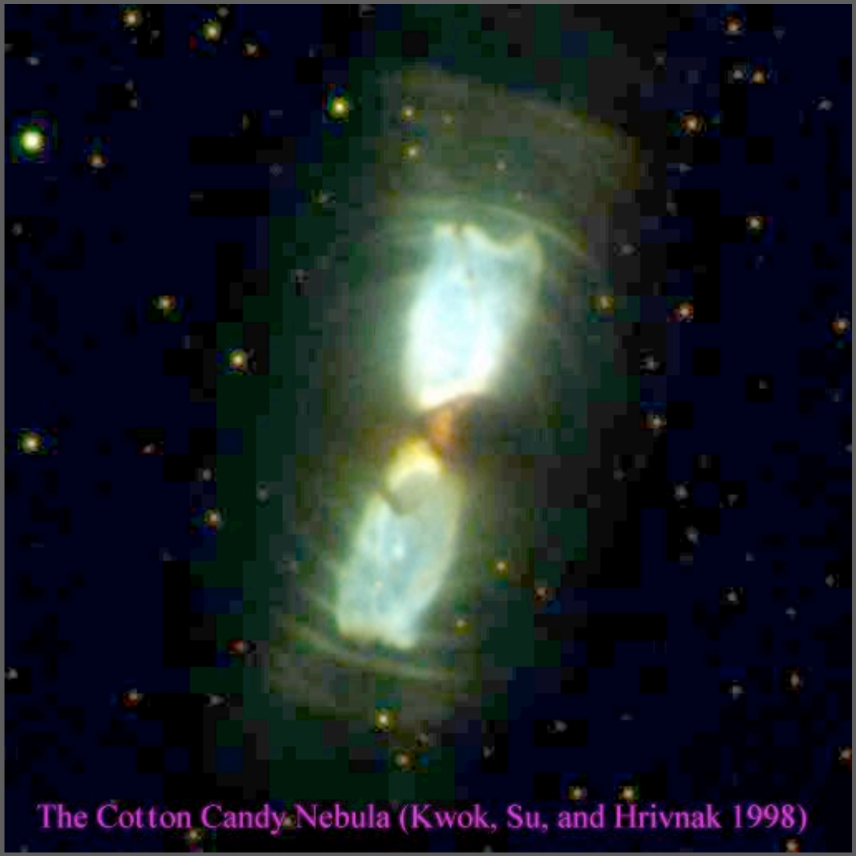


Spectropolarimetry shows
a disk-like structure

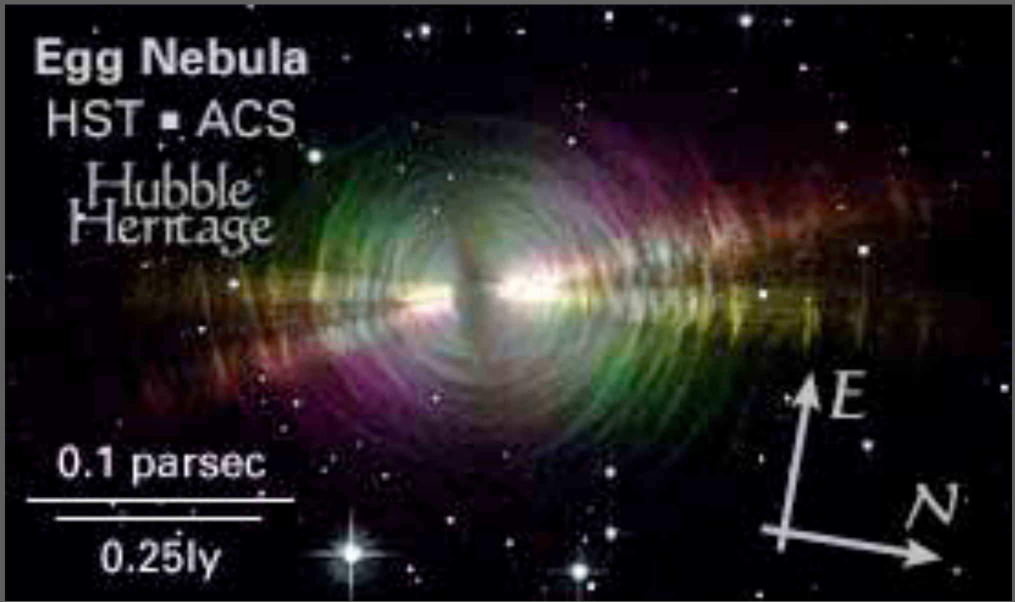
SN 2002ic

Mass loss rate prior to explosion approaches a few times of $10^{-3} M_{sun}$/year, but such a large mass lass rate is not uncommon in post-AGB stars!

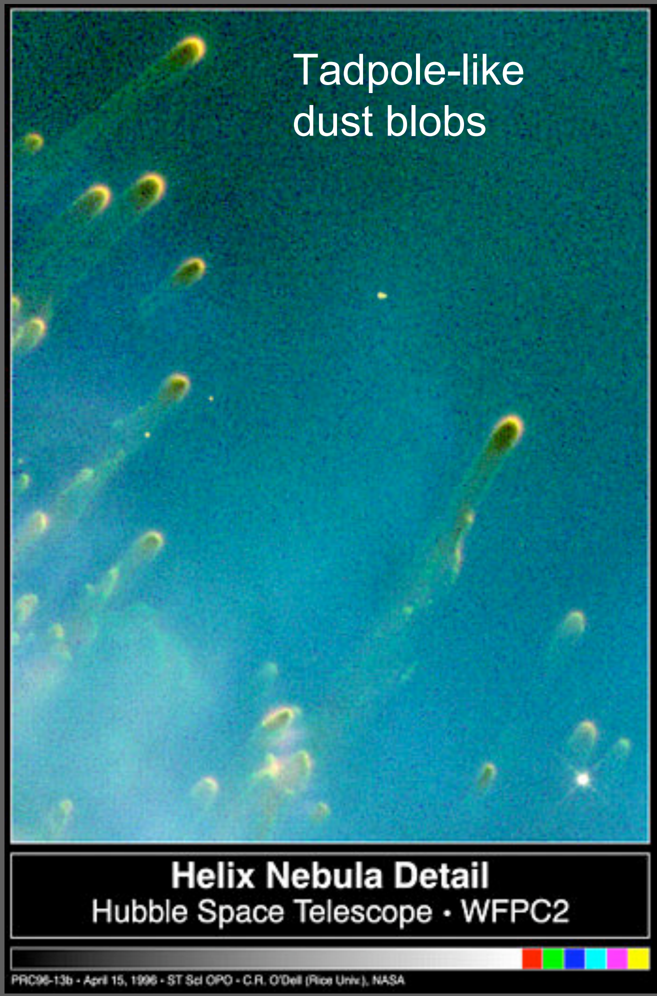
Proto planetary nebulae (PPNe)

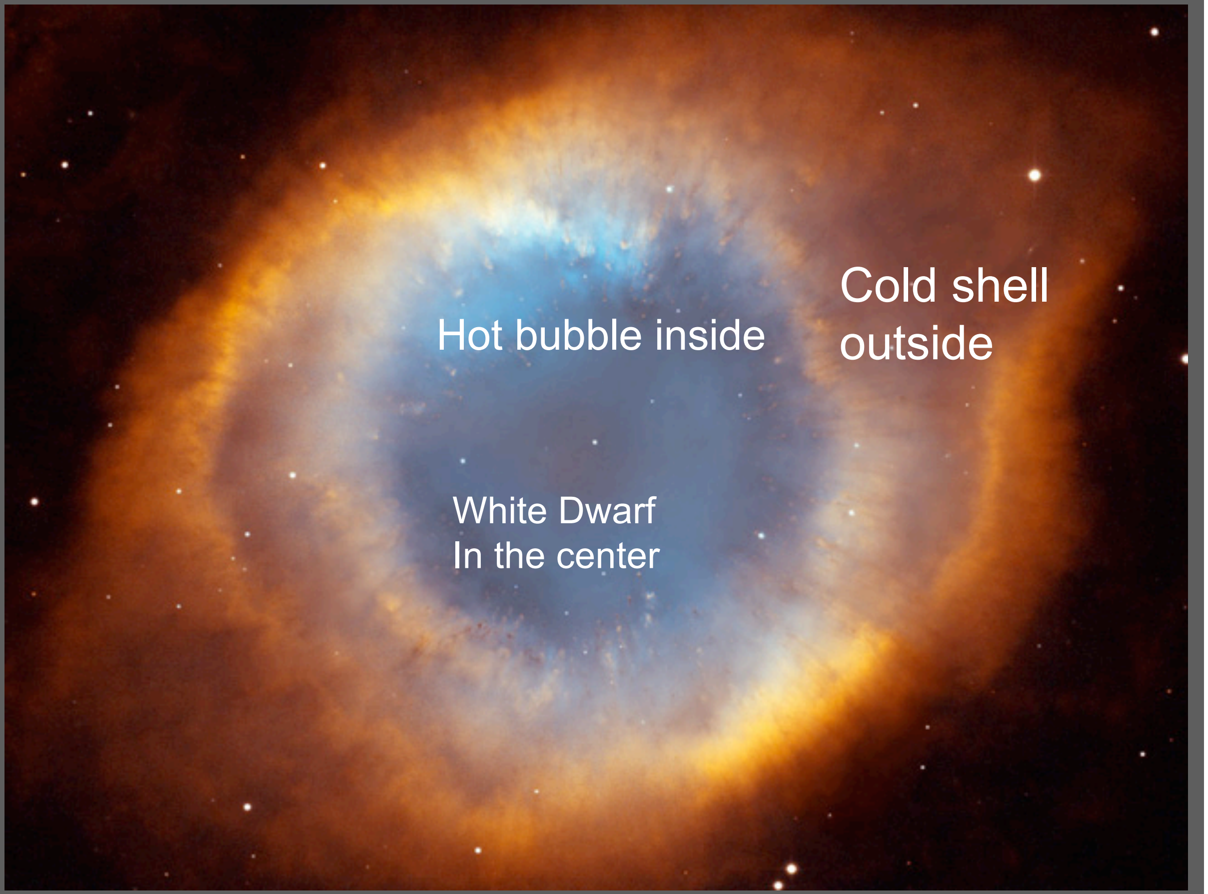


Proto planetary nebulae (PPNe)



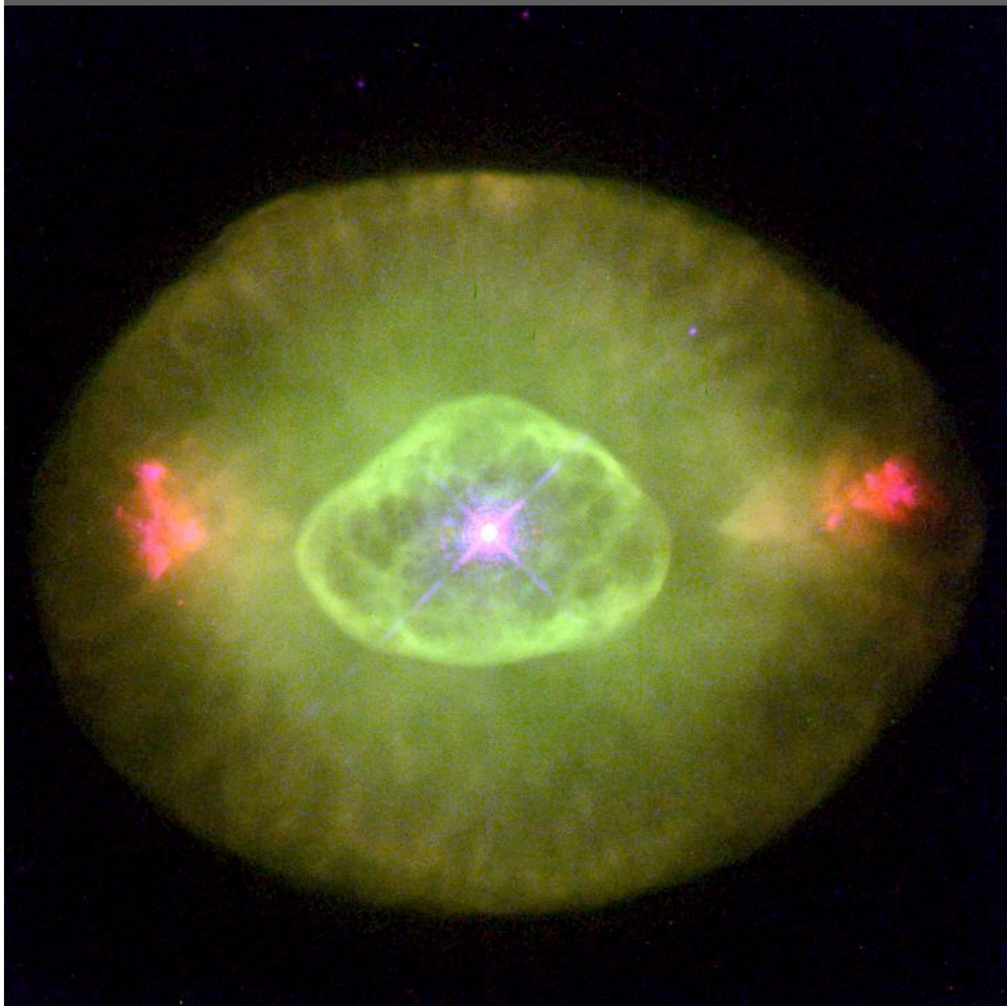
From post-AGB stars to planetary nebulae



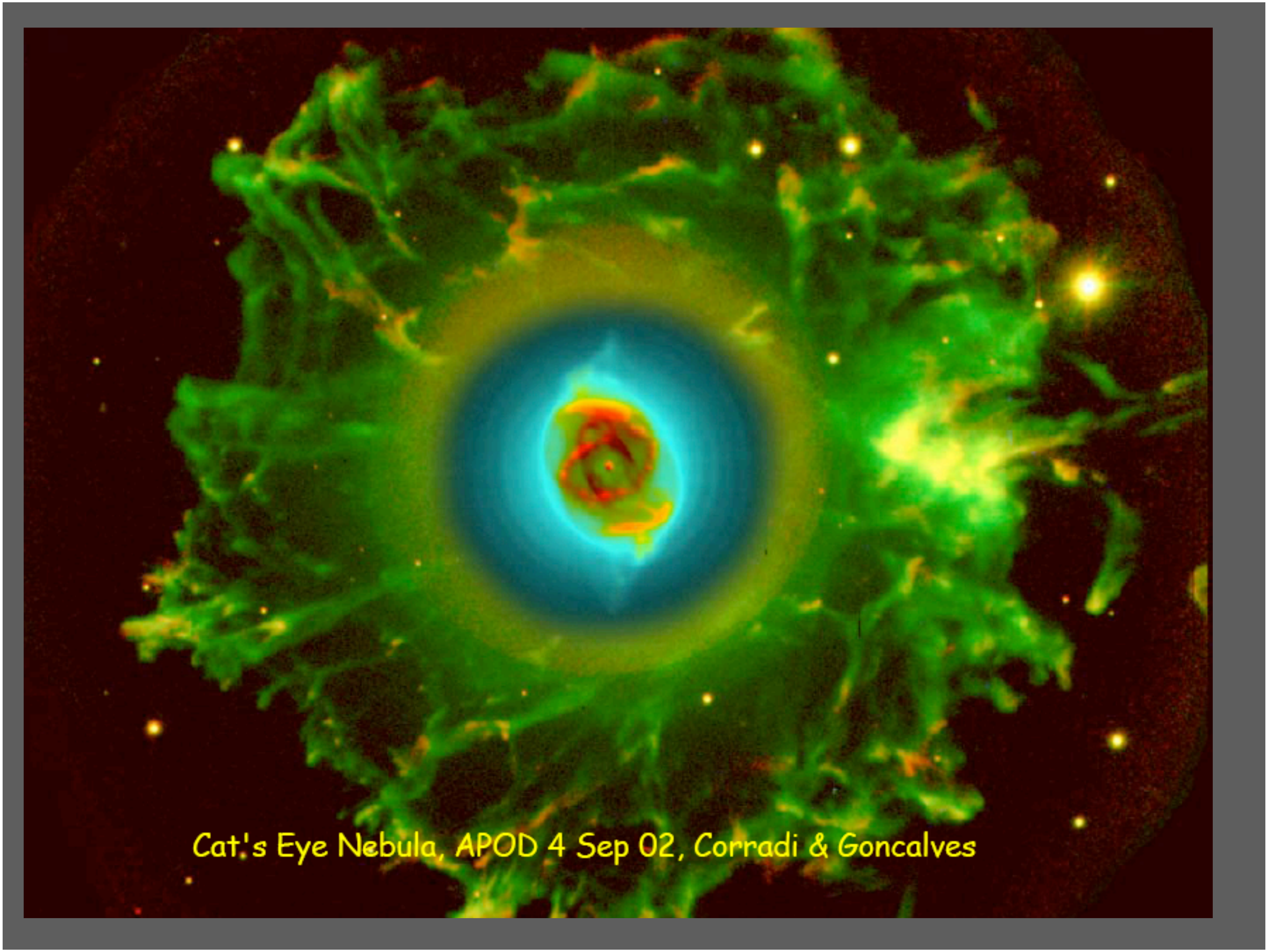


- The heads of the tadpoles are about 100 AU
- The trails of the tadpoles are about 1000 AU

- The photosphere of SNIa at optical max is about 150 AU




Planetary Nebula IC 418
Hubble Heritage


Cat's Eye Nebula, APOD 4 Sep 02, Corradi & Goncalves

The lifetime of PNe is a few 10,000 years

Eventually PNe expand to become part of the interstellar medium

Dust extinction to central stars of PNe

PN Name	E(B-V)	A_B	τ_B
IC 2165	0.40	1.64	1.51
Me 2-1	0.15	0.62	0.57
NGC 2440	0.15	0.62	0.57
NGC 7027	1.10	4.51	4.15

Wolff, Code, & Groth (AJ, 119, 302, 2000)

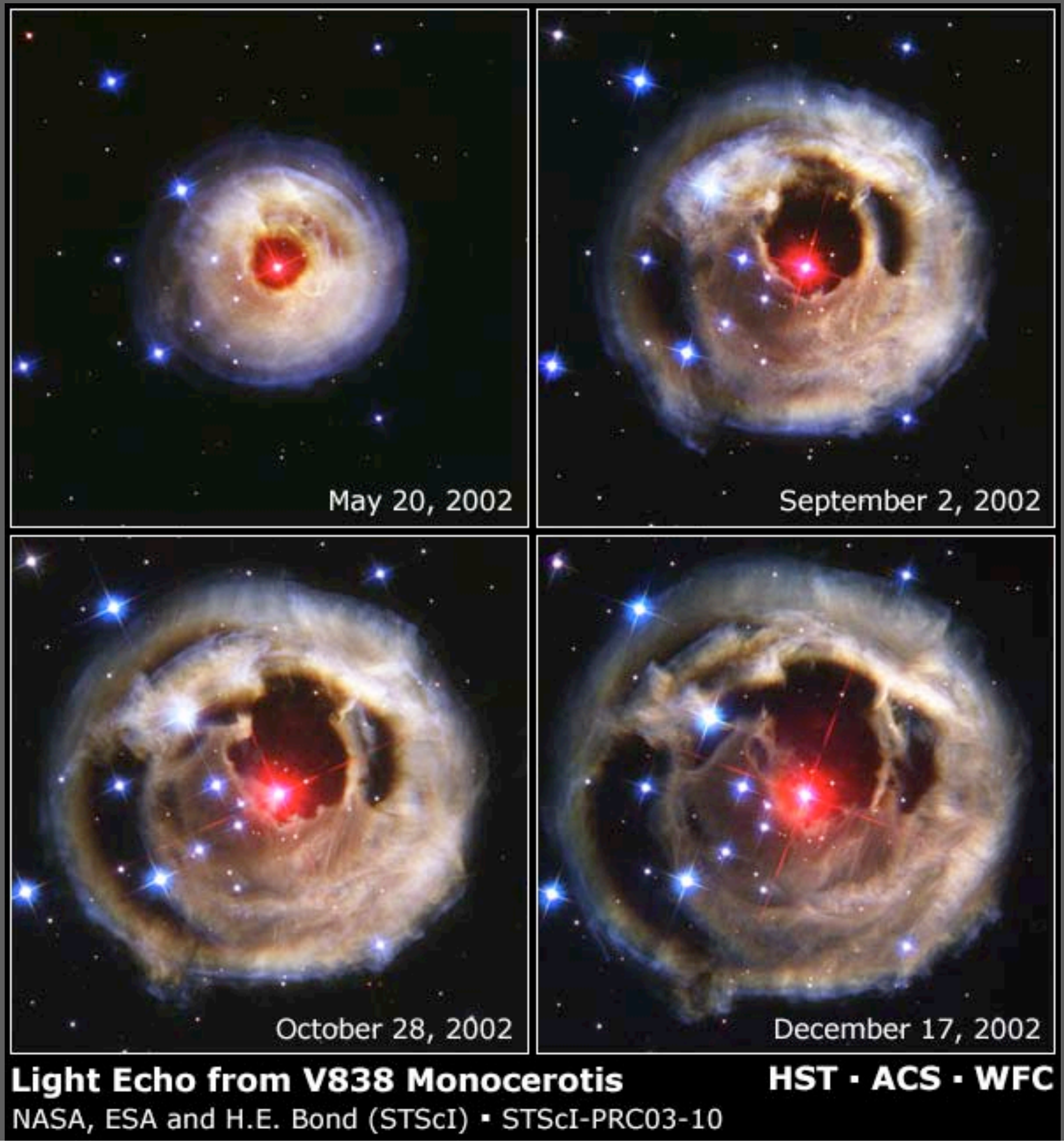
Assuming no new dust is created after PPN phase then

$$\tau = \tau_0 \left(\frac{t}{10{,}000\, years} \right)^{-2}.$$

Dust optical depth becomes τ_B~0.01 (corresponds to E(B-V) ~0.011) after 10 dynamical time scales.

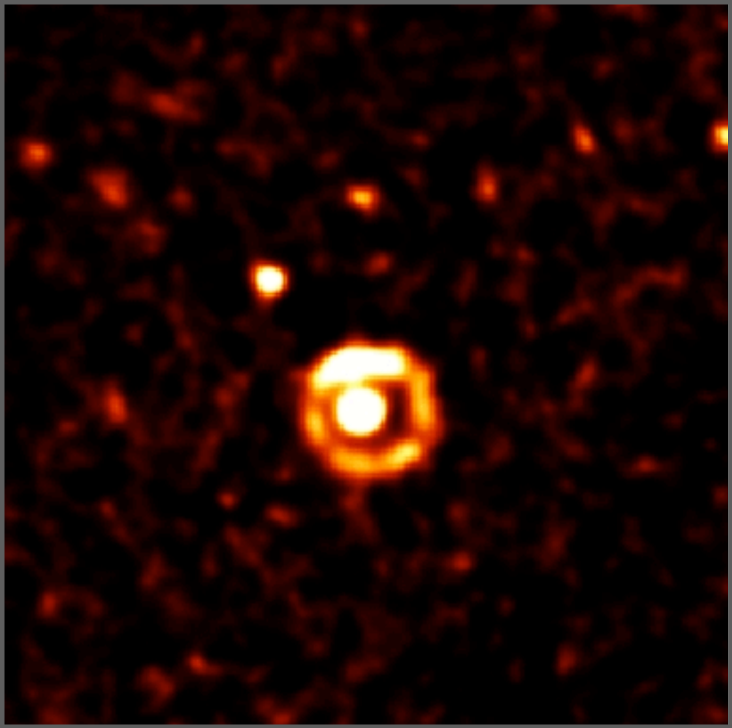
New dust particles may be created in the wind of the companion or the white dwarf. The total optical depth at post-PN phase can only be larger than the above estimate.

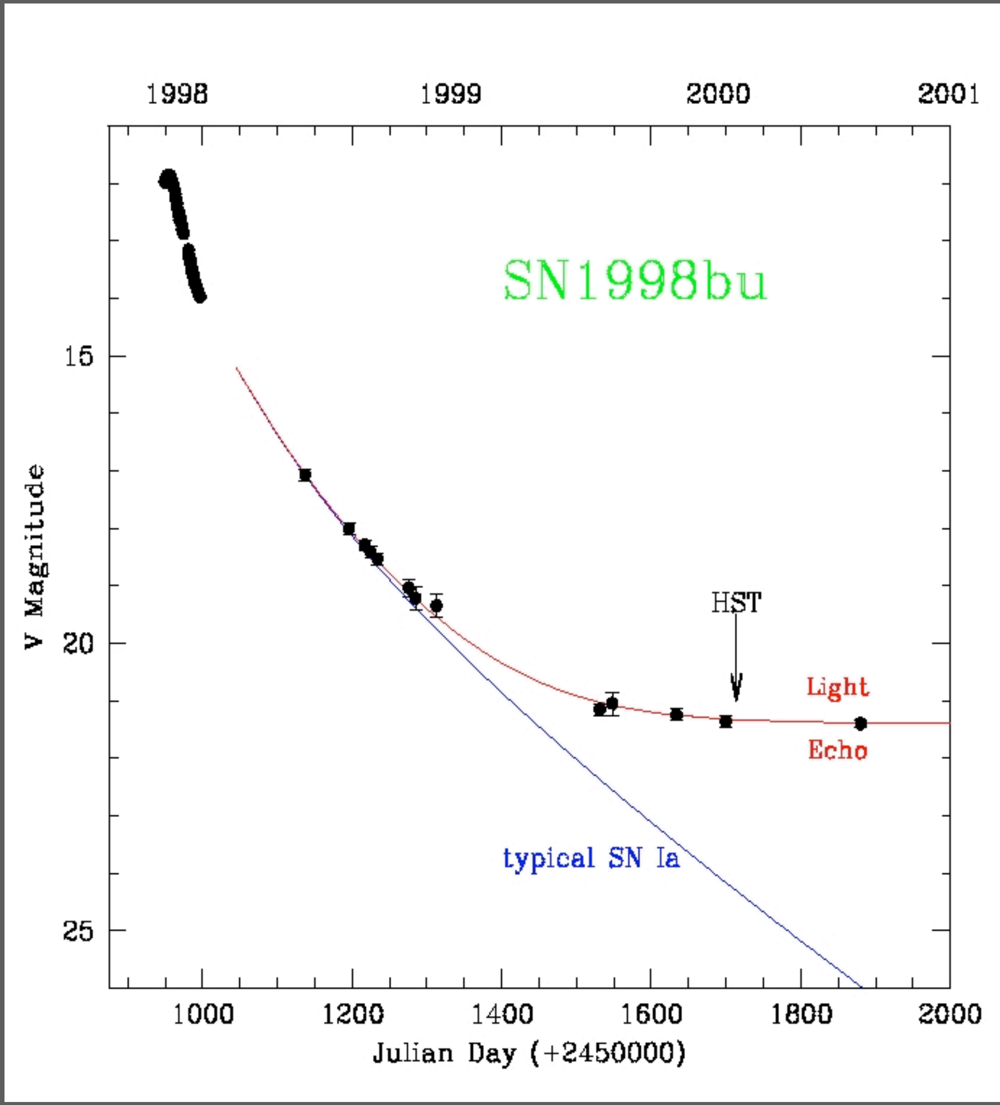
Light echo from V838 Monocerotis



The SINS collaboration

Light echoes





- ❑The inner echo is from dust at a distance < 10 pc from the SN.

- ❑The SN has a red color of B_{max}-V_{max}= 0.38, which indicates E(B-V) of around 0.4.

- ❑The outer echo is from dust at a distance ~ 120 pc from the SN.

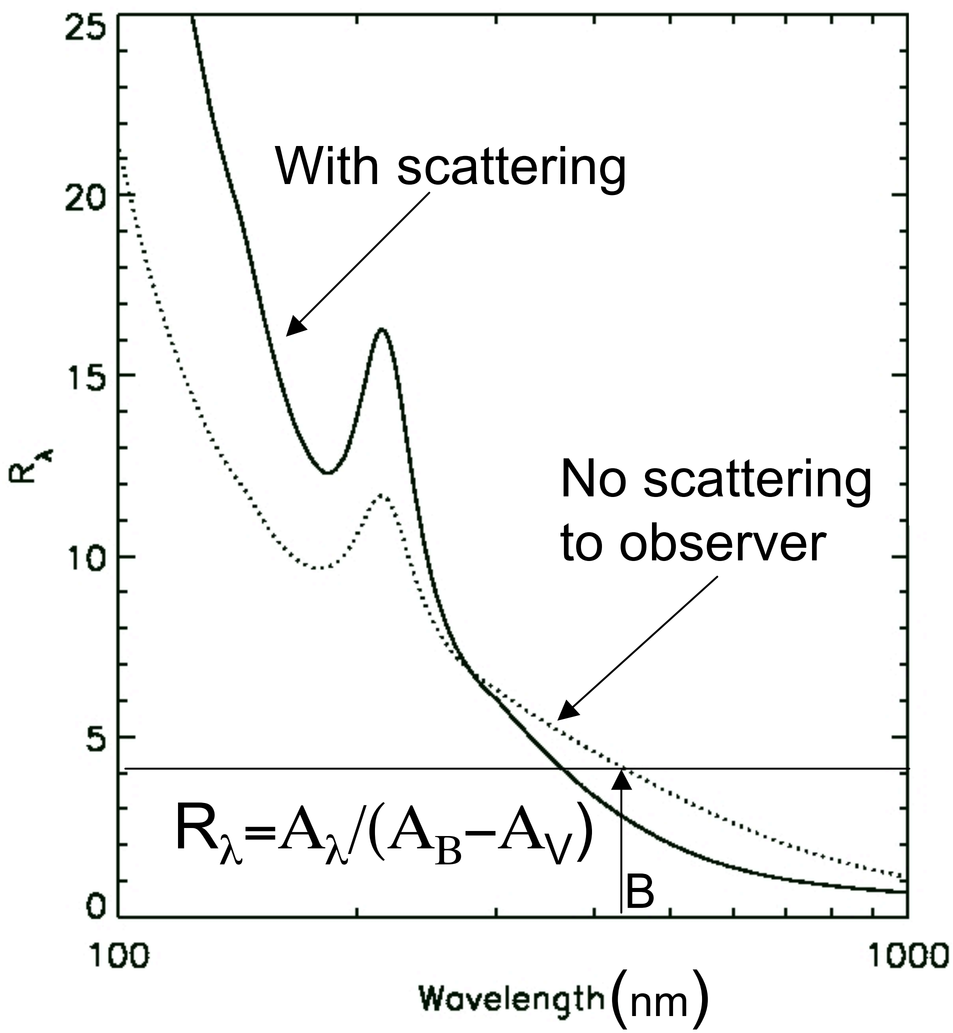
(Wang, 2005, ApJL, Dec. 2005).

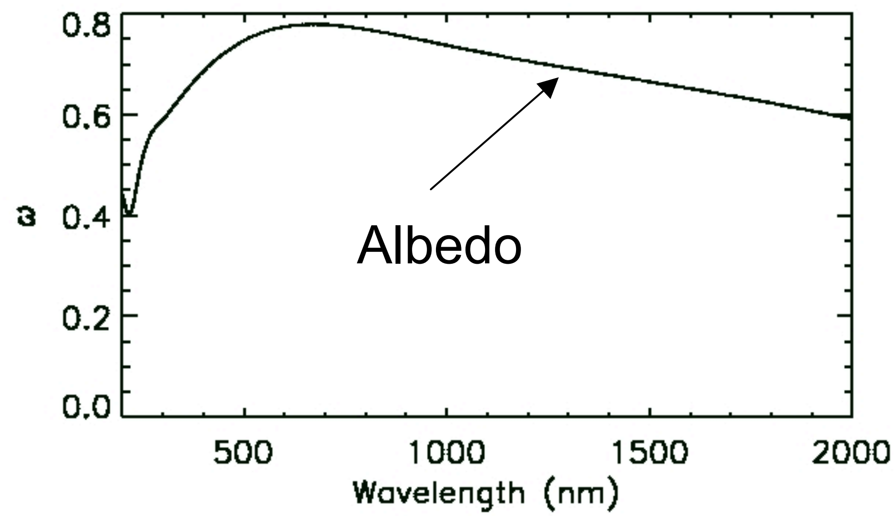
The CSM absorbs and scatters light from the central source.
The observable flux by a distant observer must be calculated by careful modeling of radiative transfer through the CSM dust.

Wang (ApJL, 2005)

The effective R_λ when scattering is included

Calculated assuming LMC dust



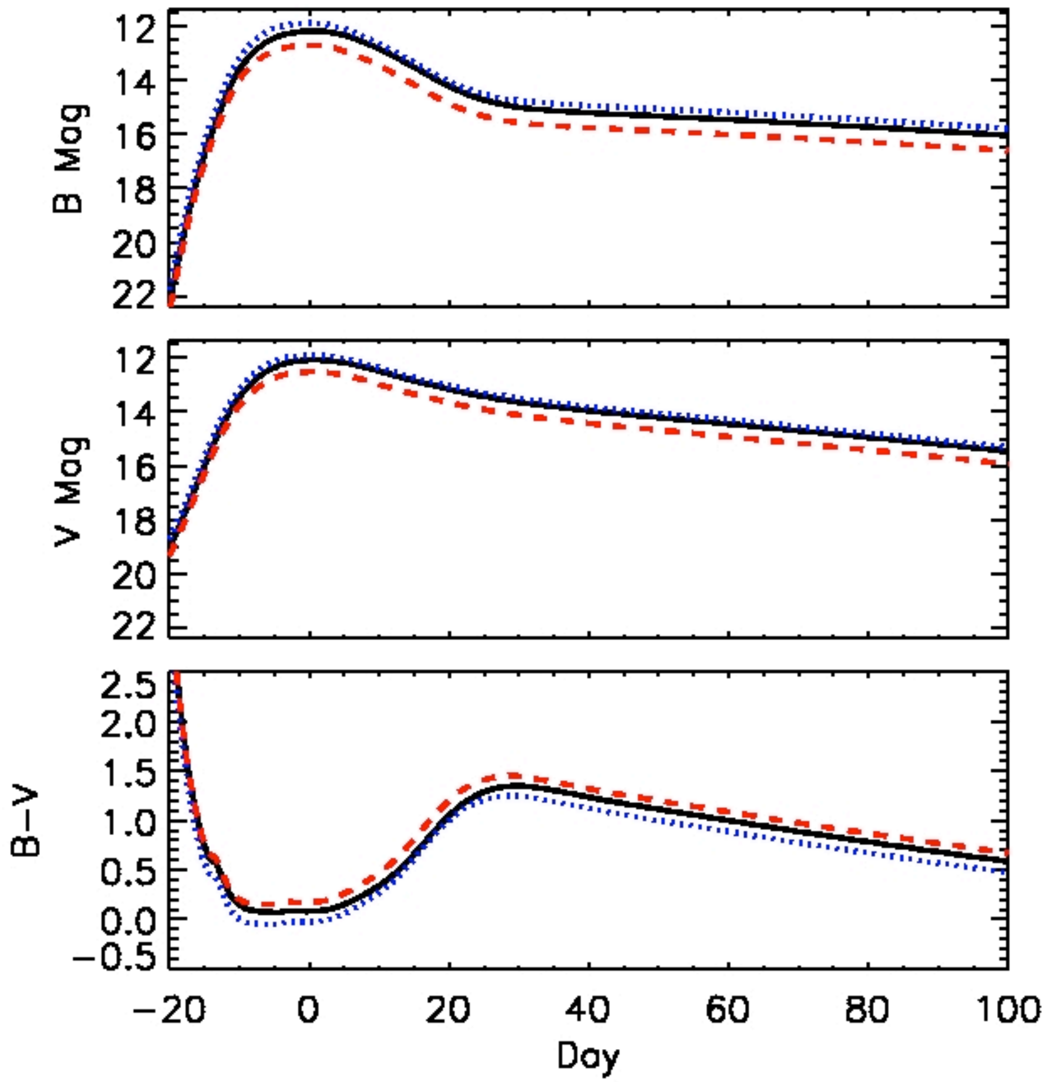


Weingartner & Draine (ApJ, 548, 296, 2001)

R_λ is significantly smaller than given by the standard interstellar extinction law in the optical, if all the scattered photons escape and can be observed.

Wang (ApJ, 2005)

The effect of CSM dust on the light curves

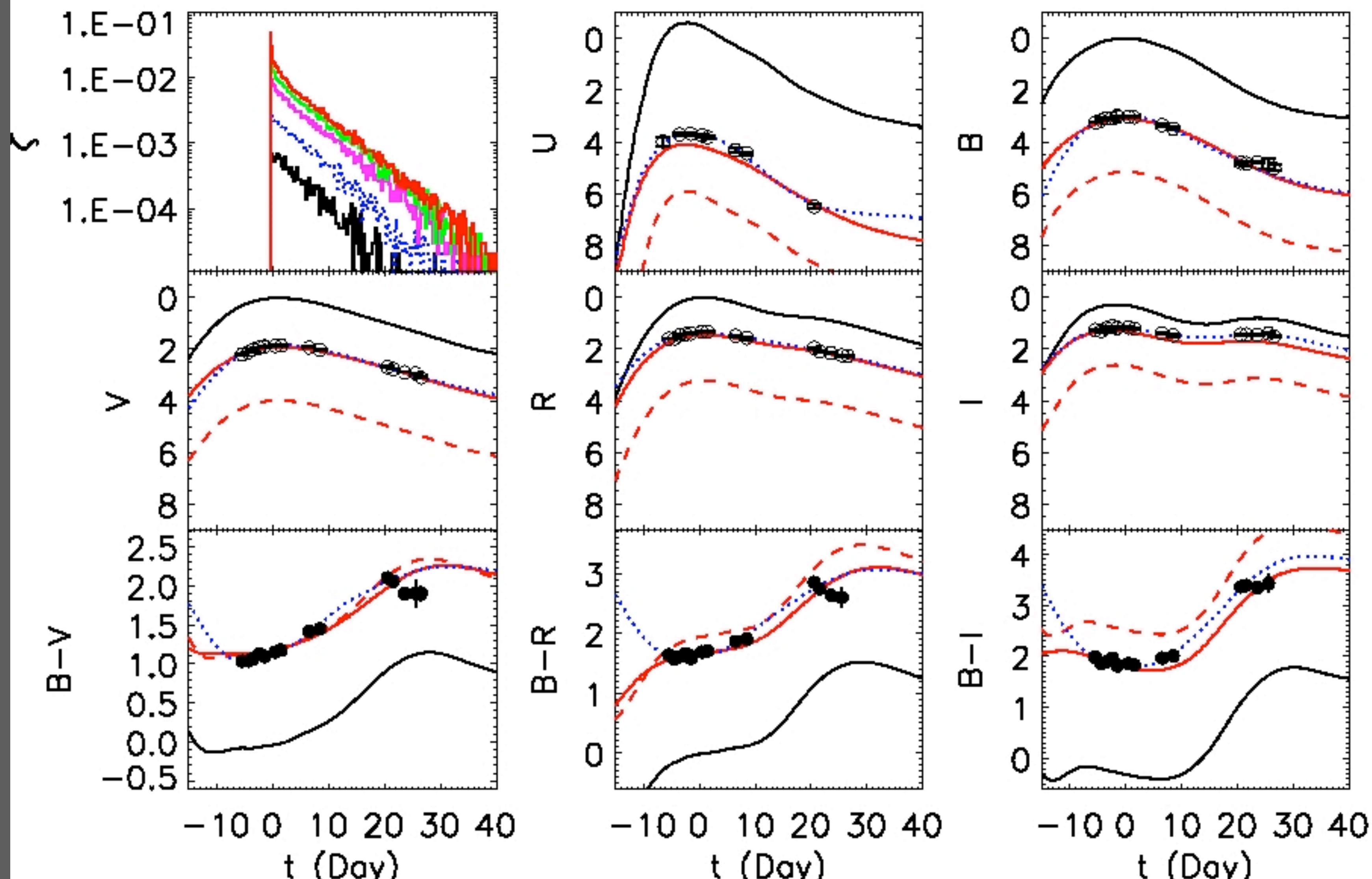


Absorption+ Scattering

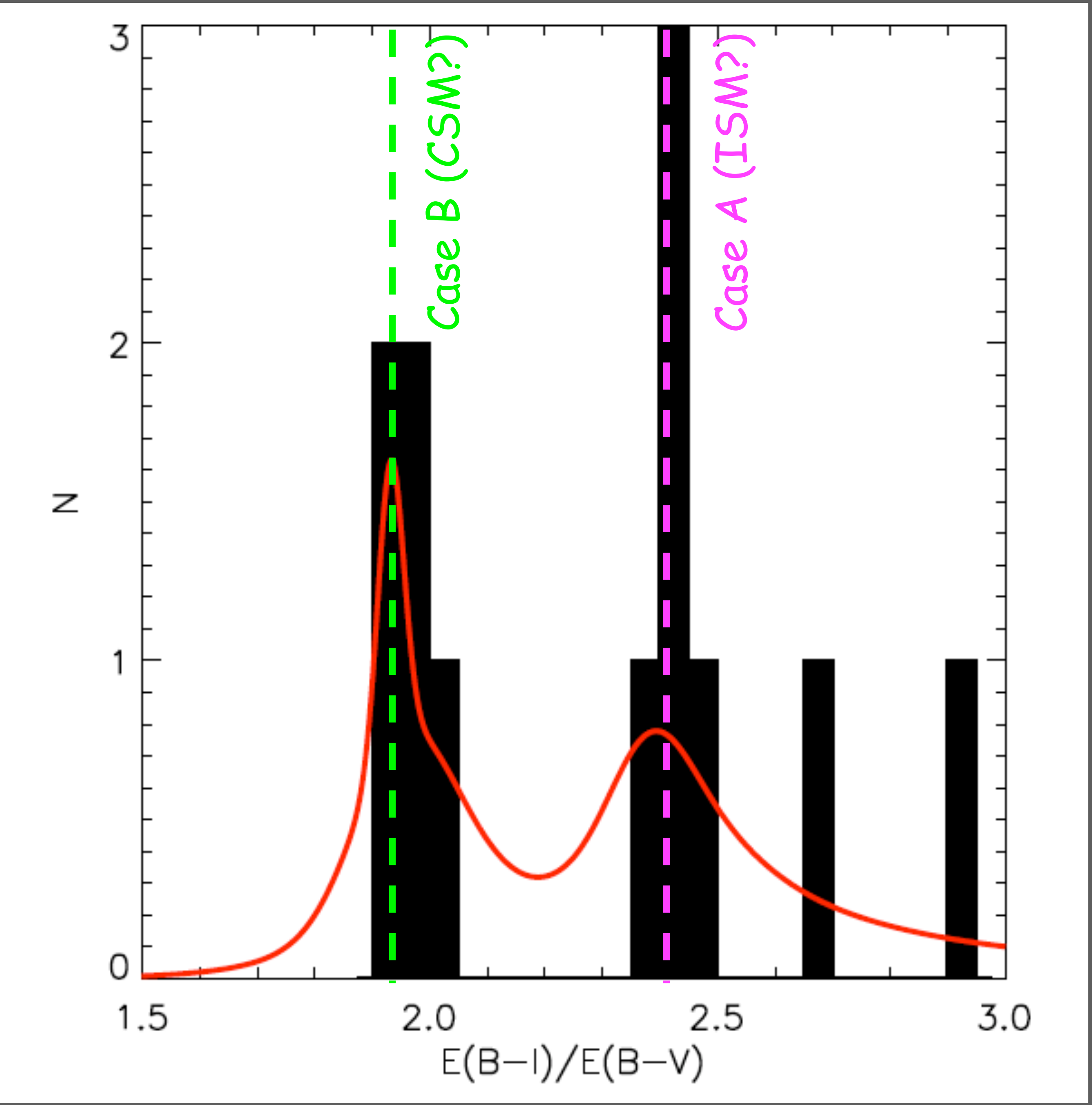
Absorption only

Unextincted

E(B-V) = 0.2 (τ_B=0.755 and τ_V=0.571)



1.E−01
1.E−02
1.E−03
1.E−04
ζ
U
B
V
R
I
B−V
B−R
B−I
t (Day)
t (Day)
t (Day)



The probability of the histogram are drawn from a random sample is 0.1%.

More than 50% of highly reddened SNIa are due to circumstellar dust.

Over 50% SNe Ia Are from young Stars

What are the progenitors of SNe Ia?

Merging white dwarfs?

Accreting white dwarfs?

Or,

Type I.5 SNe from post-AGB stars (Iben & Renzini, 1983)?

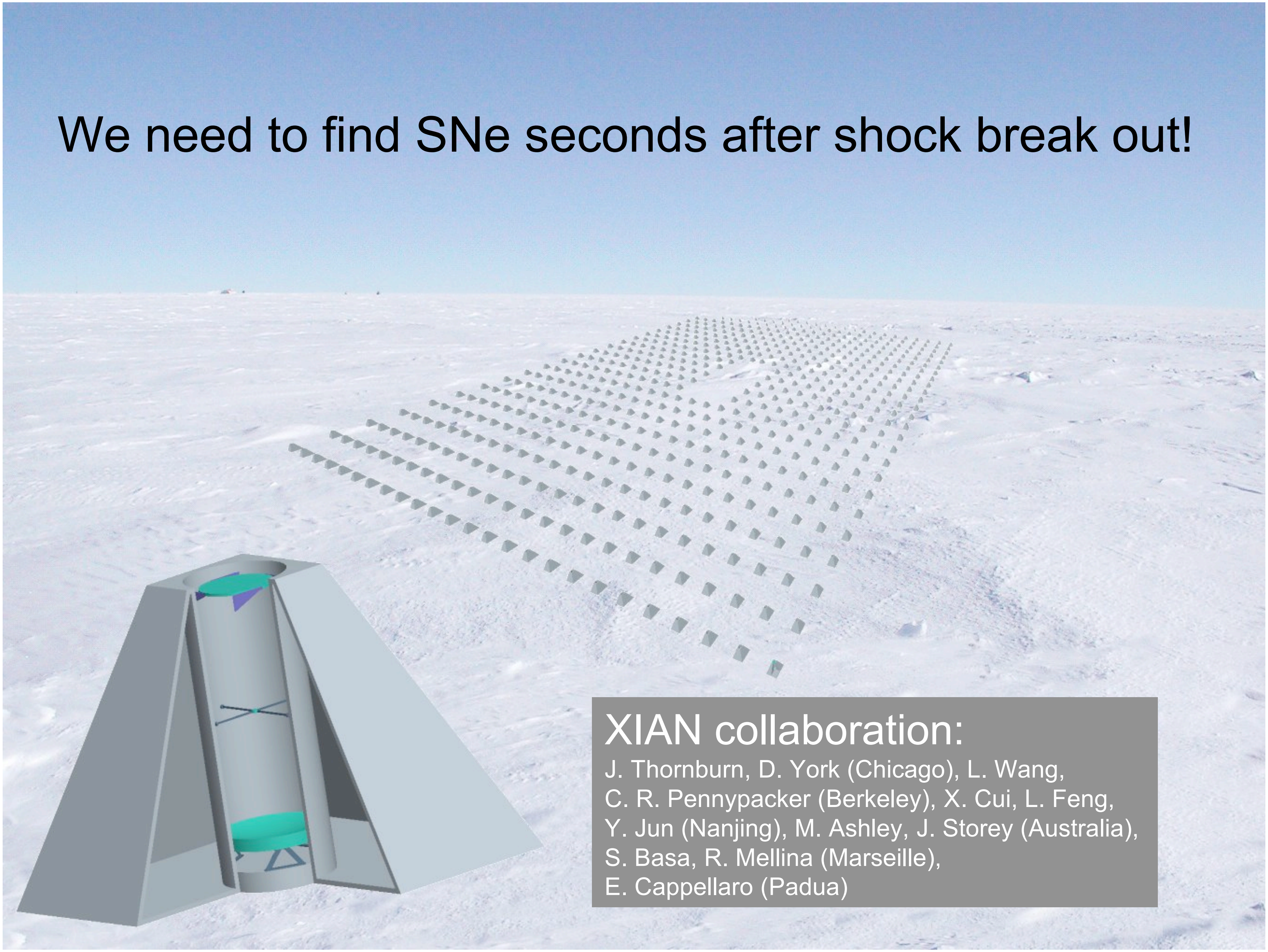
Final remarks on core-collapse SNe

Does every CC-SN harbor a jet?

This is the most fundamental question for the link between GRBs and SNe.

The observational consequences of a jet:

1. Neutrino burst
2. Gamma-ray burst (some time)
3. Highly asymmetric chemical structure


We need to find SNe seconds after shock break out!
XIAN collaboration:
J. Thornburn, D. York (Chicago), L. Wang,
C. R. Pennypacker (Berkeley), X. Cui, L. Feng,
Y. Jun (Nanjing), M. Ashley, J. Storey (Australia),
S. Basa, R. Mellina (Marseille),
E. Cappellaro (Padua)