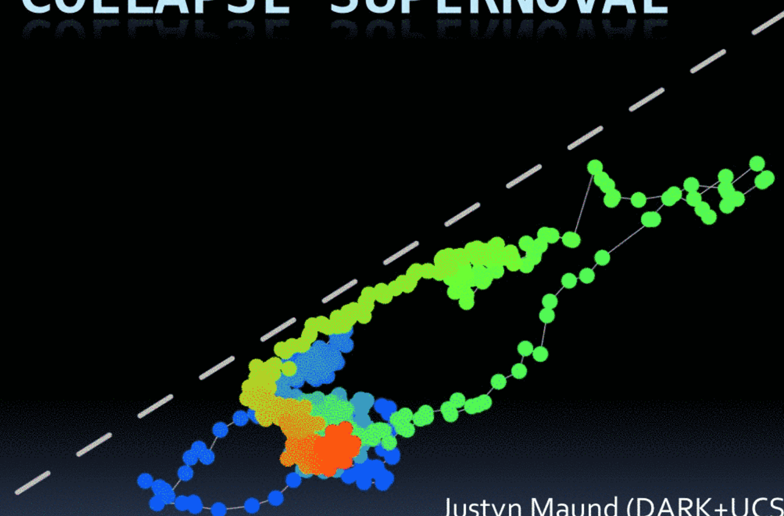
SPECTROPOLARIMETRY OF CORE-COLLAPSE SUPERNOVAE



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Wang & Wheeler, 2008, ARAA,46, 433
Stellar Death & Supernovae, KITP, 20th August 2009

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Asymmetries in CCSNe

Evidence for asymmetries in CCSNe:

- Shape of SN remnants (Cas A)
- Runaway stars (α Cam)
- Peculiar line profiles (esp. in late-time spectra)

The study of peculiar emission line profiles in nebular phase spectroscopy gives some (weak) information on the late-time geometry, but the geometry is projected onto the radial velocity direction

Study of linearly polarized light from Supernovae provides a measure of their shape in the plane of the sky

Spectropolarimetry provides unique information on geometry in the form of the two additional Stokes parameters (Q,U) which, along with the velocity information derived from the spectrum, provides 3D information on these events.

Extra parameters can lead to better constraints on explosion models

Technique can be used to study asymmetries at early optically thick times

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Polarization Parameters

$$S = \begin{pmatrix} I \\ \hat{Q} \\ \hat{U} \\ \hat{V} \end{pmatrix}$$

- I: Intensity
- $\hat{Q}$: Vertical – horizontal components
- $\hat{U}$: Diagonal components
- $\hat{V}$: Circular components

$\hat{Q}$ and $\hat{U}$: Linear Stokes parameters

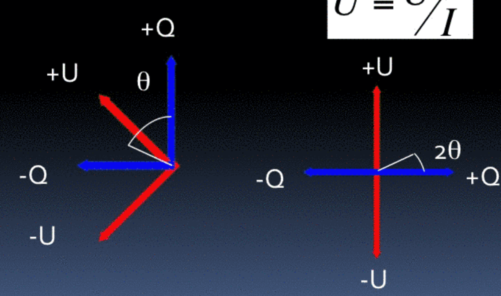
Normalized Stokes parameters

$$Q = \hat{Q}/I$$

$$U = \hat{U}/I$$

$$\hat{P} = \sqrt{\hat{Q}^2 + \hat{U}^2}; P = \frac{\sqrt{\hat{Q}^2 + \hat{U}^2}}{I}$$

$$\theta = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)$$



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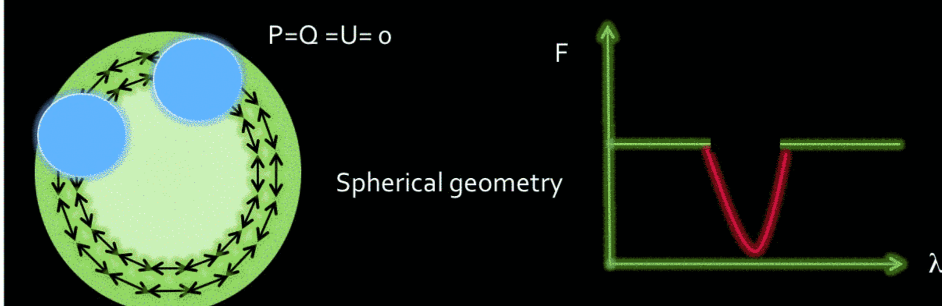
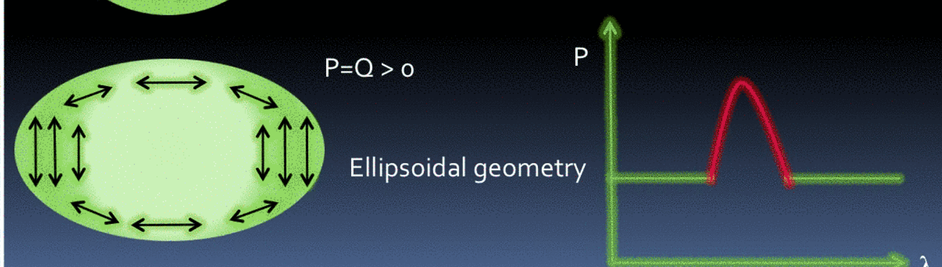
Continuum+Line polarization

Polarized component arises from the limbs of the photosphere by e- scattering (wavelength independent) . Line forming region casts shadows over photosphere (wavelength dependent).





Ellipsoidal geometry Axial ratio 0.5 => p=3.5%; Hoflich 1991

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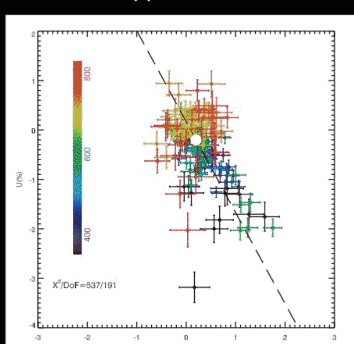
Type Ia vs. CCSNe

Type Ia	CCSNe
Low continuum polarization (<= 0.5%)	Low & high continuum polarization (<= 4% 97X)
Continuum polarization decreases with time	Continuum polarization increases with time
Data generally conform to a dominant axis (single axis of symmetry)	Data show dominant axes, large loops

CCSNe show a wider range of polarization properties – generally more polarized in lines and continuum implying significant asymmetries , increasing at depths closer to the explosion mechanism

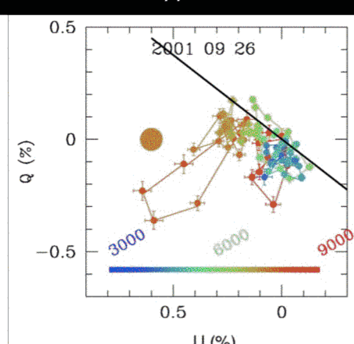
Type Ia vs. CCSNe

Type Ia



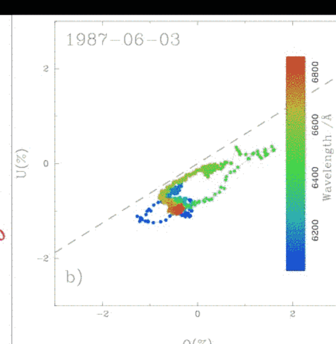
(SN 2004dt – Wang et al., 2006)
Dominant Axis
Single Global Axial symmetry

Type Ia

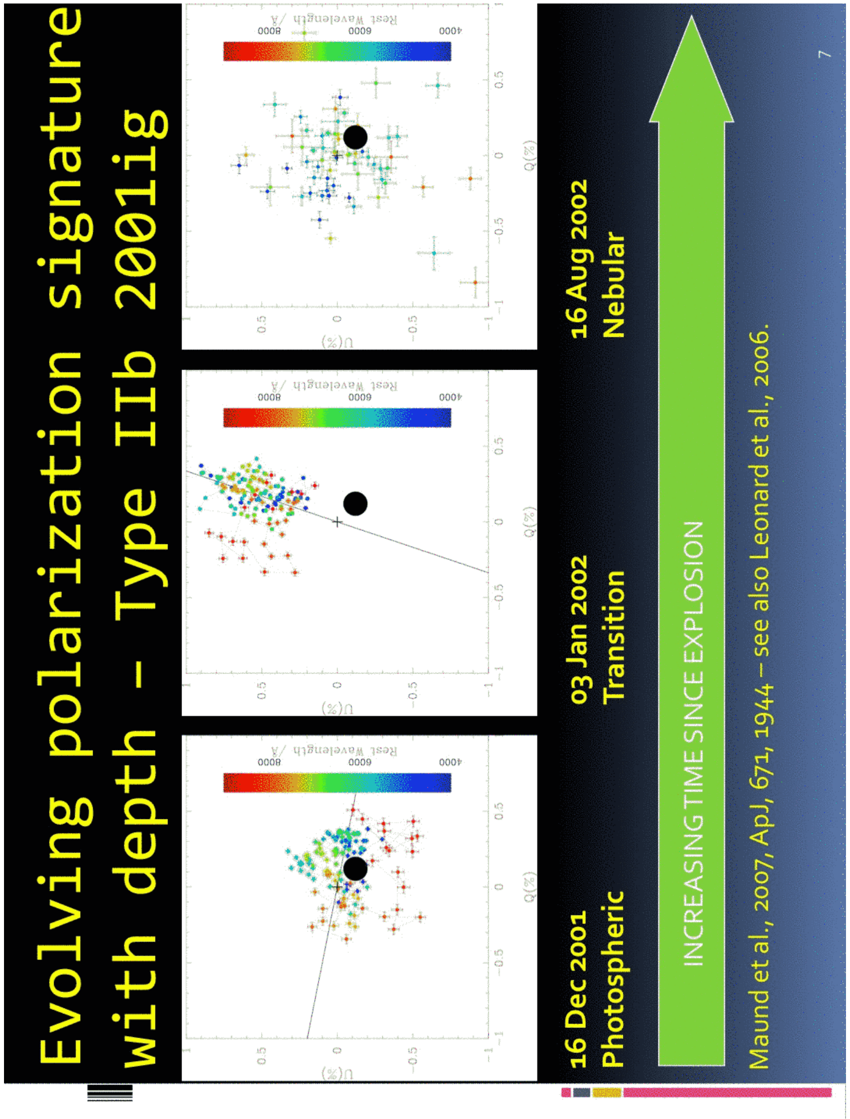


(SN 2001el – Wang et al., 2003)
Dominant Axis+loop

CCSNe



(SN 1987A – Cropper et al. 1988)
Loops


Evolving polarization signature with depth – Type IIb 2001ig
16 Dec 2001
Photospheric
03 Jan 2002
Transition
16 Aug 2002
Nebular
INCREASING TIME SINCE EXPLOSION
Maund et al., 2007, ApJ, 671, 1944 – see also Leonard et al., 2006.
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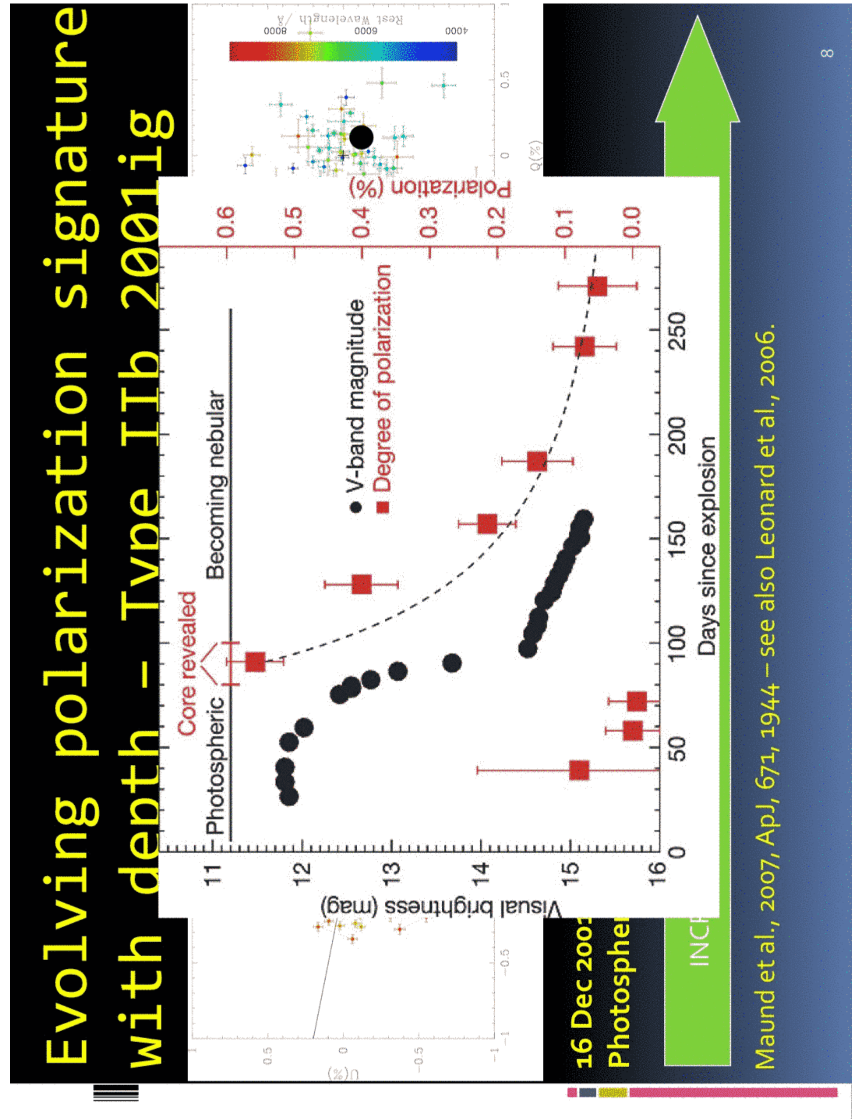
Evolving polarization signature with depth – Type IIb 2001ig
Photospheric
Core revealed
Becoming nebular
V-band magnitude
Degree of polarization
Visual brightness (mag)
Polarization (%)
Days since explosion
0
50
100
150
200
250
11
12
13
14
15
16
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Maund et al., 2007, ApJ, 671, 1944 – see also Leonard et al., 2006.
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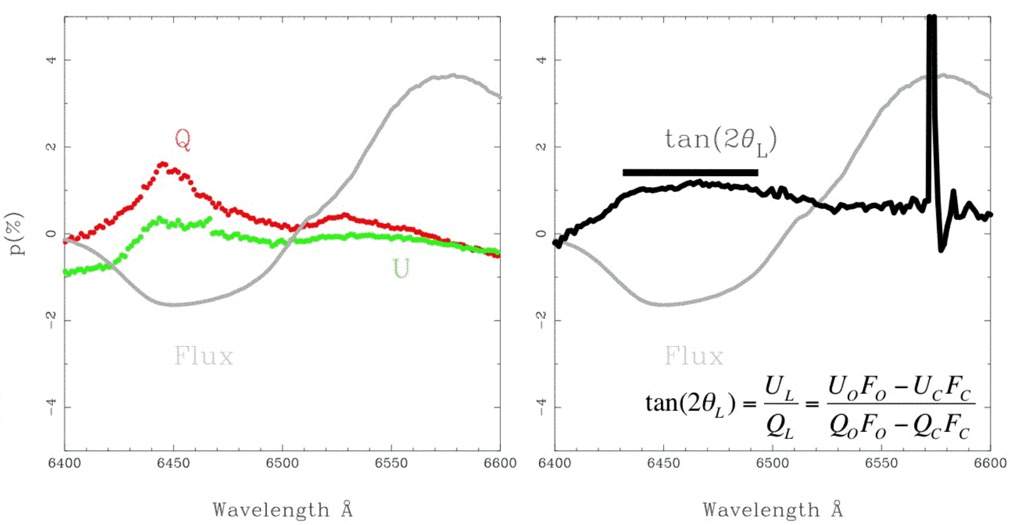
Continuous large scale structure in the line forming region

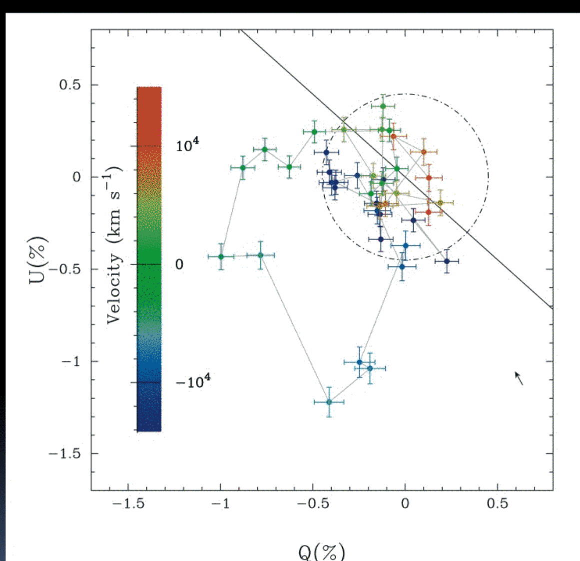


$$\tan(2\theta_L) = \frac{U_L}{Q_L} = \frac{U_O F_O - U_C F_C}{Q_O F_O - Q_C F_C}$$

$v_l \sim 1.5\ v_{phot}$ => continuous line forming region, not clumps (=>random θ_l)

SN 1987A, 06 March 1987, Cropper et al., 1988, MNRAS, 231, 695

Loop structures (SN 2005bf)



A peculiar Type Ib SN

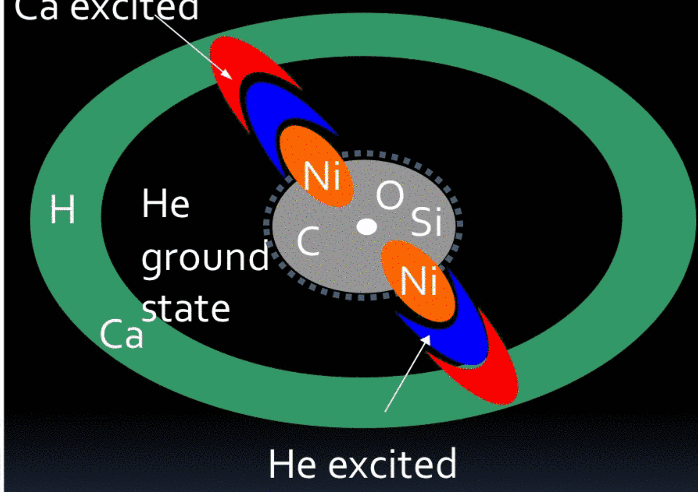
Started off as a Type Ic SN, He lines developed later on

Clear loop signature associated with He I λ5876

Axis of excited He is **tilted** w.r.t the photosphere

Q-U plane shows data colour-coded according to velocity across the P Cygni profile

Maund et al., 2007



Maund et al., 2007 proposed the action of a tilted jet (within the jet torus model)

The excitation axis for He I is tilted with respect to the main portion of the ejecta (photosphere)

Apparent offset of polarization angle between lines and continuum

Loop are common in the CCSNe spectra.

Maund et al., 2007b, MNRAS, 381, 201

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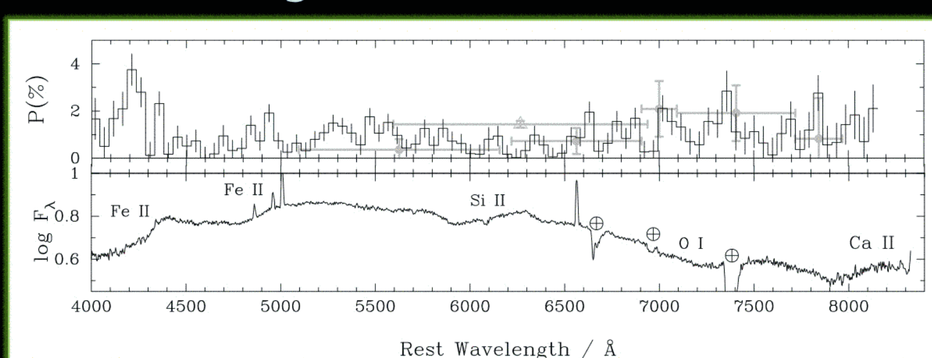
SN 2006aj



In the cases of SNe associated with GRBs we should know the orientation of the symmetry axis (if present): **parallel to the line of sight**

SN should appear symmetric about the line of sight – no polarization

Wavelength dependent polarization observed for SN 2006aj and 2003dh suggests asymmetric line forming regions about the line of sight

Maund et al. 2007; Kawabata et al., 2003

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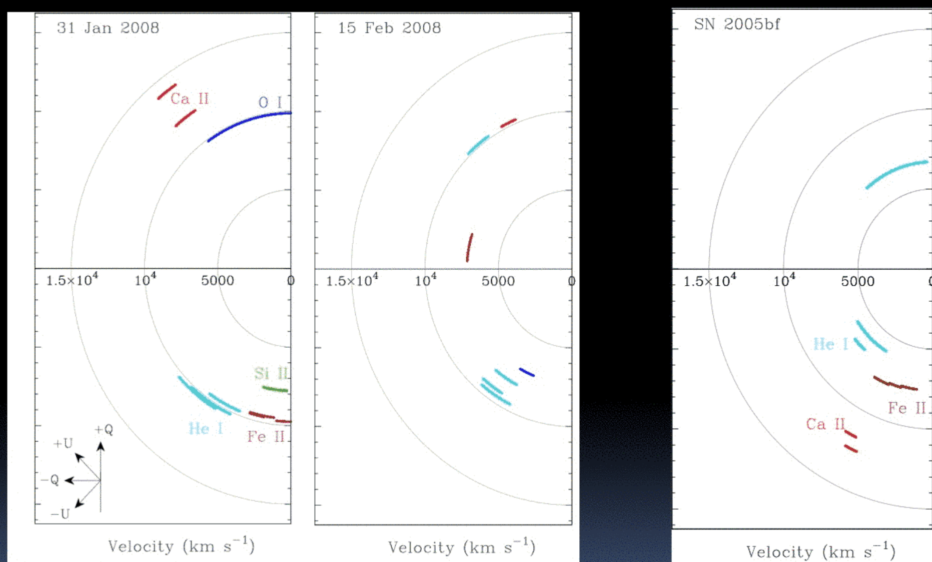
Chemically distinct structures in CCSNe

Polar plot showing velocities and polarization angle for lines in 2008D and 2005bf



SN2008D SN2005bf

Maund et al., 2009: astro-ph/0908.2841 13

Summary

- Still relatively few observations, so spotting patterns is still difficult – but Ca II is polarized in nearly all Type Ibc SNe
- Continuum polarization increases with time as more asymmetric interior layers are revealed (unlike Type Ia SNe)
- The line polarization signature is generally consistent with large scale asymmetries rather than clumping (SN 1987A)
- Ejecta are "chemically segregated", with Ca II being almost universally polarized with an offset from the polarization angle of other species – suggesting a separate formation scenario (in the progenitor or the explosion)
- Loops indicate complicated tilted excitation/structures with respect to the main body of the ejecta (2005bf, 2008D and 2006aj)
- Chemical discontinuities observed for photosphere transition from H to He layer (2004dj, 2001ig), but what about Type Ibc SNe?

Future: Comprehensive direct testing of explosion models against spectropolarimetric observations for a large number of objects.

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