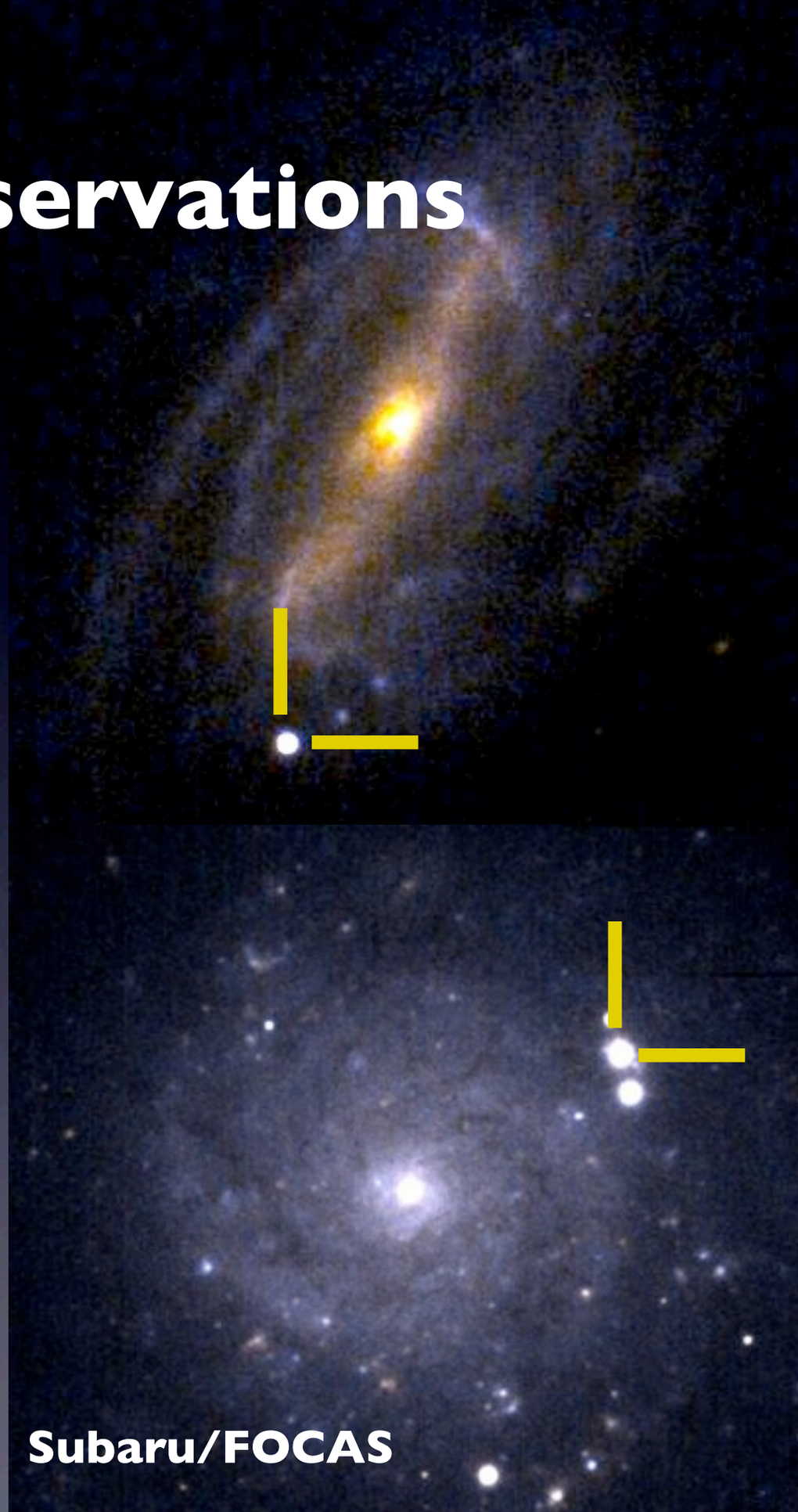
# Spectropolarimetric Observations of Supernovae

## - 超新星爆発の偏光分光観測 -

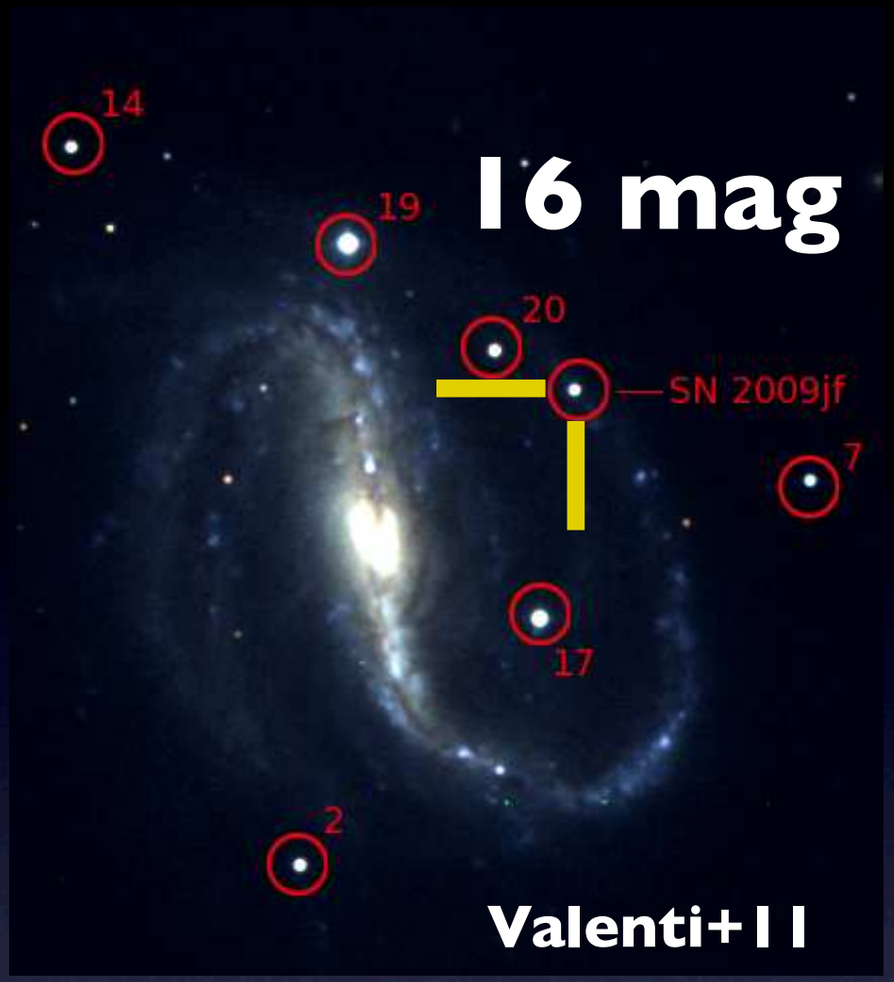

田中 雅臣
Masaomi Tanaka
(National Astronomical Observatory of Japan)


光赤外偏光天文学の軌跡と今後



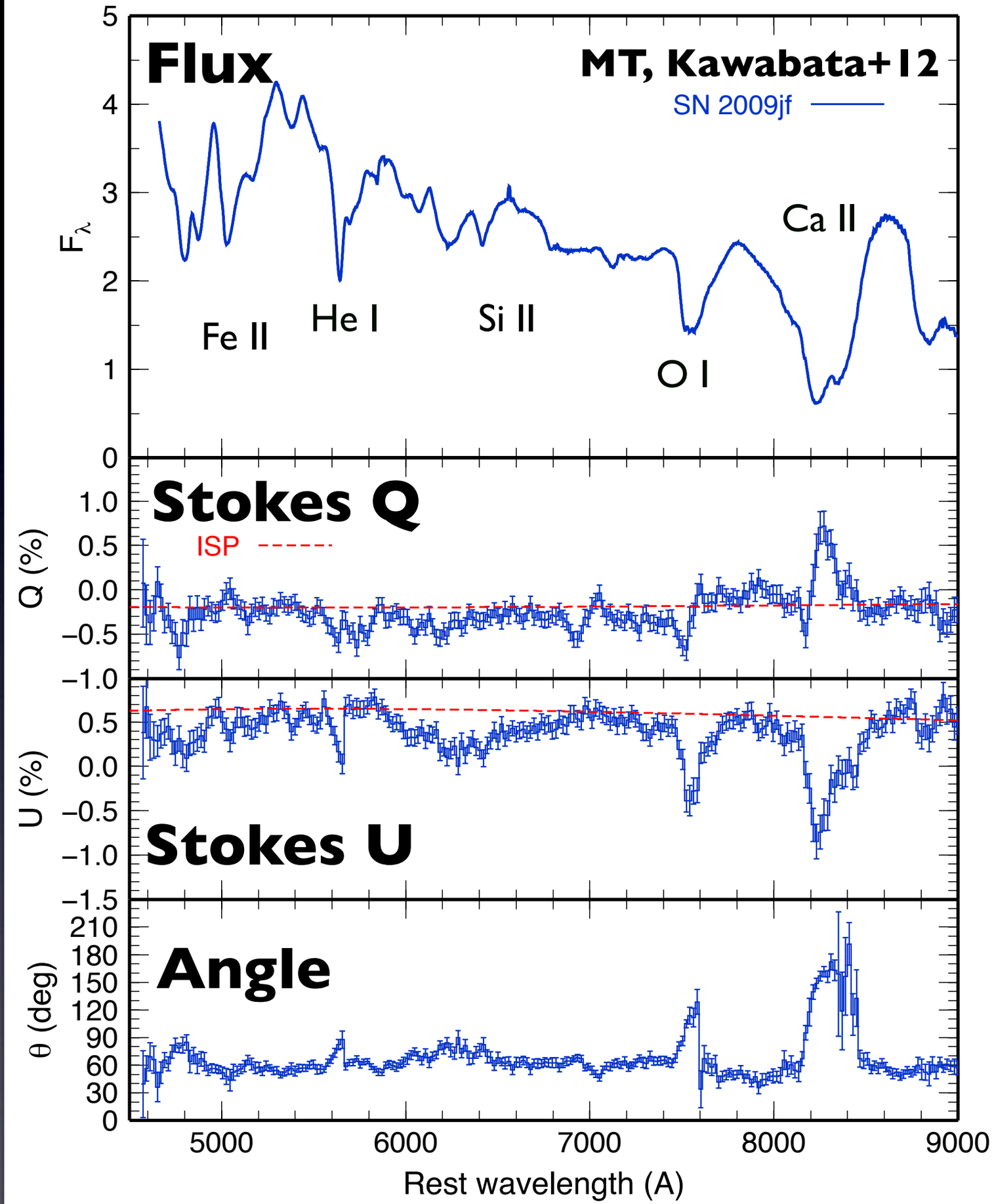
# Spectropolarimetric Observations of Supernovae

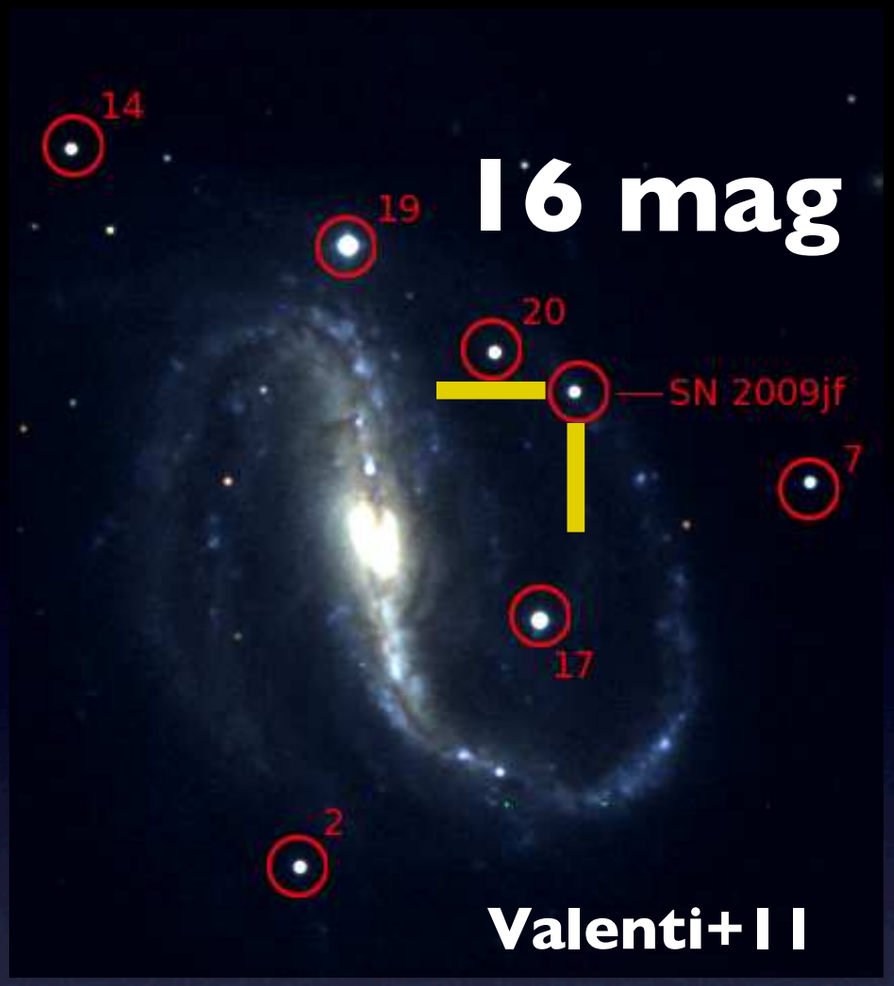
- **Why Spectropolarimetry**
- **Observing Strategy**
- **Results/Future**




**R ~ 600**
**(Δv~500 km/s)**

**ΔP ~ 0.05 %**



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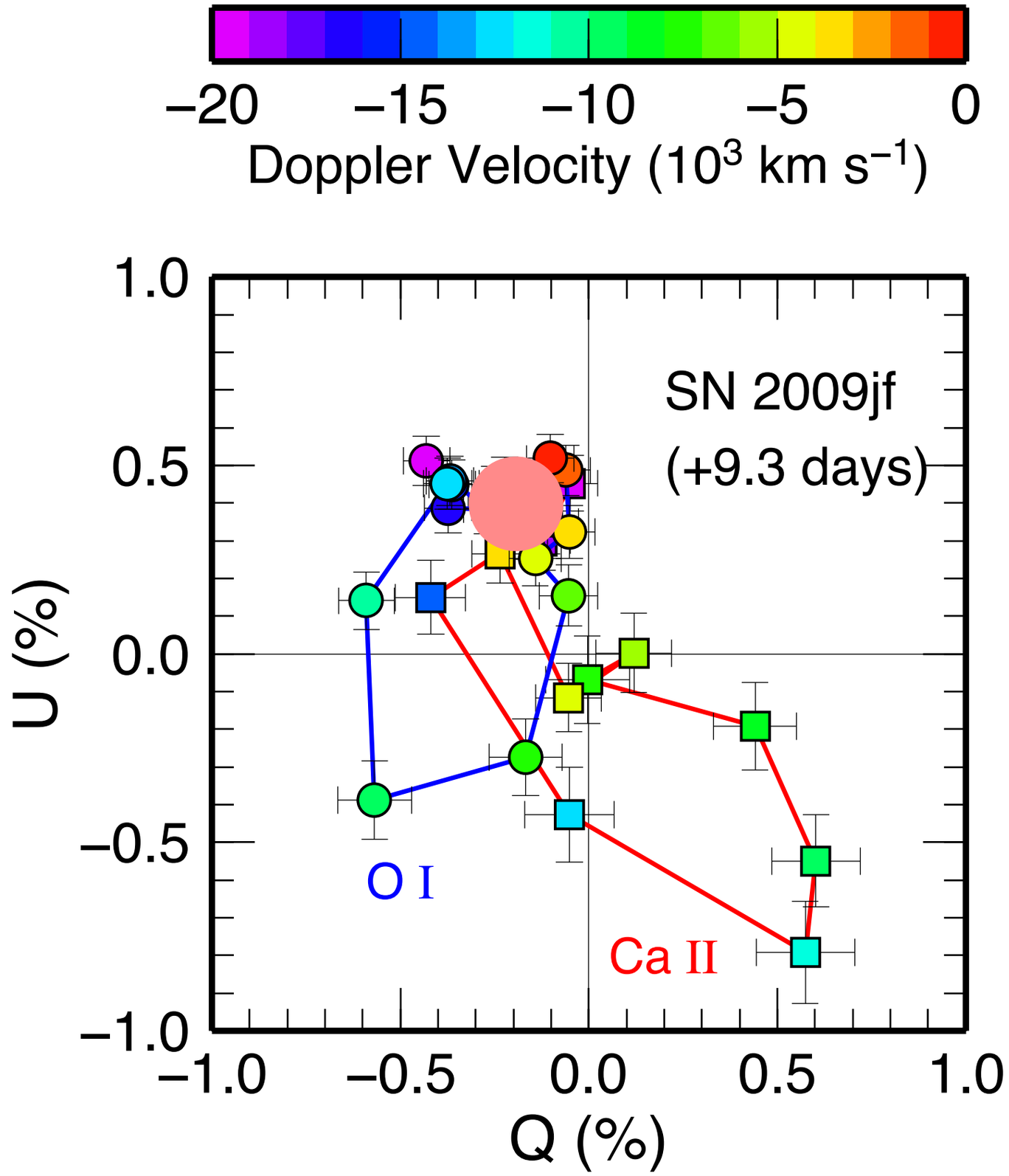
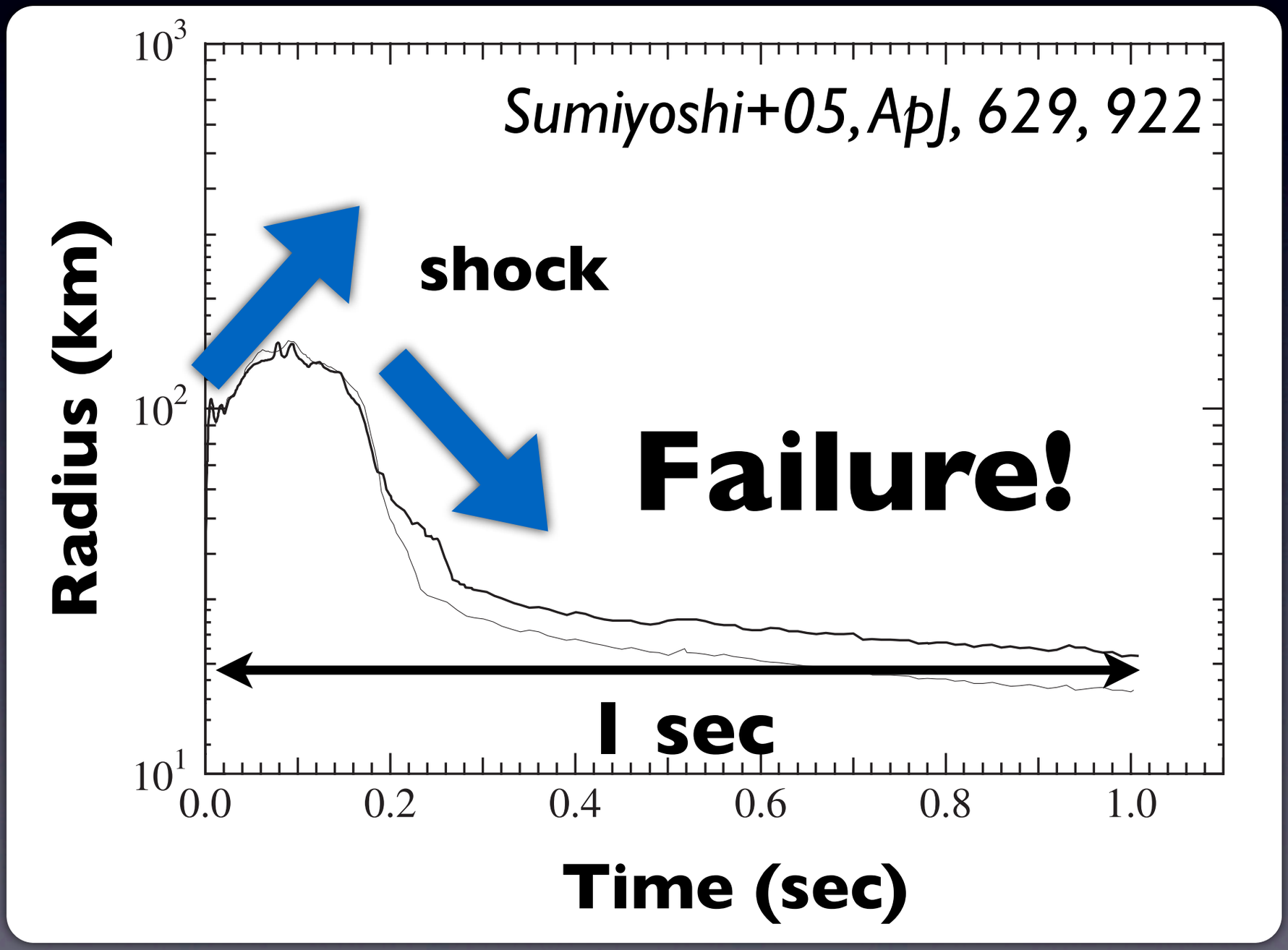


# Supernova

- **End point of stellar life**
- **Origin of elements**
  - Stellar nucleosynthesis
  - Explosive nucleosynthesis
- **Huge kinetic energy**
  - Injection to ISM
  - Cosmic ray acceleration
- **Gravitational wave source**
- **Neutrino source**
  - SN 1987A (in LMC)

# Long-standing problem

## After Fe core collapse



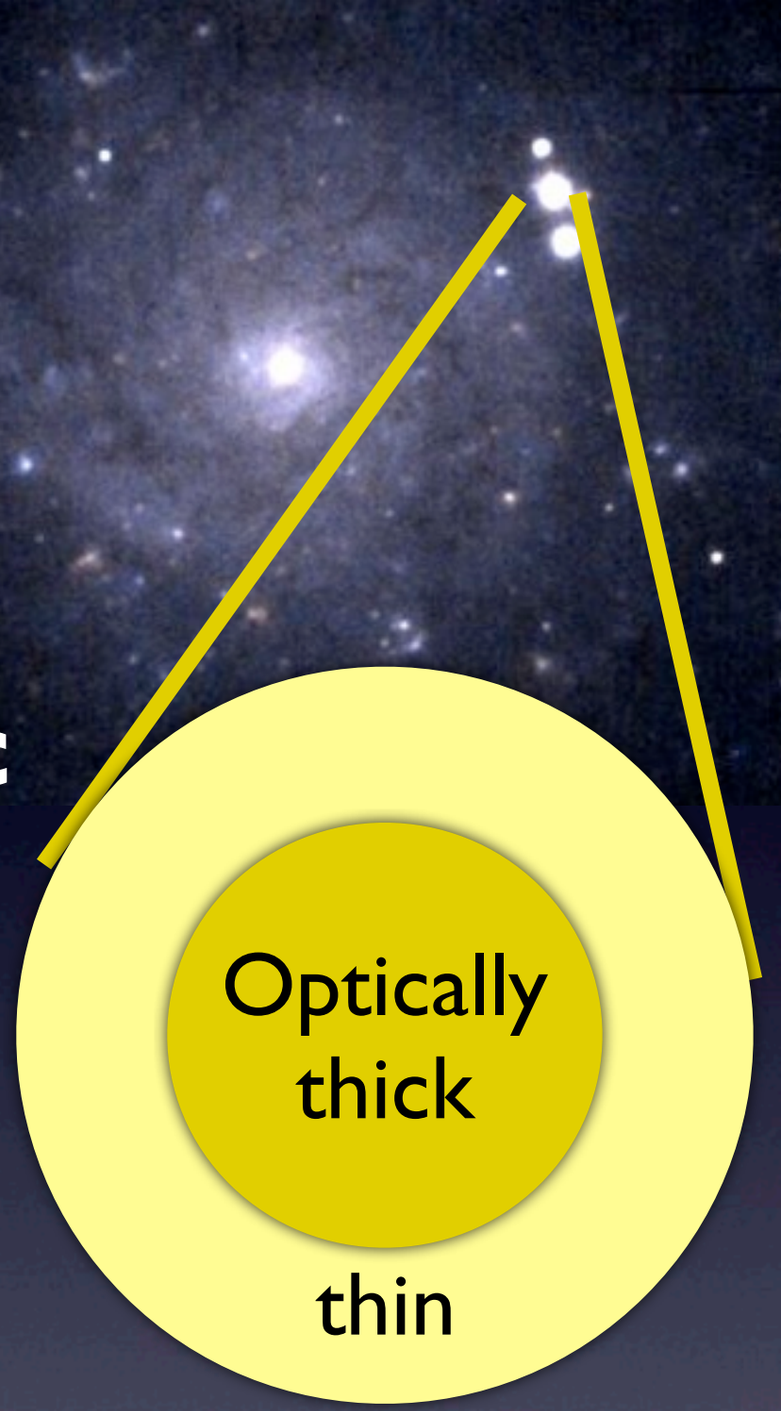
# Observations of supernovae

# Geometry of supernovae

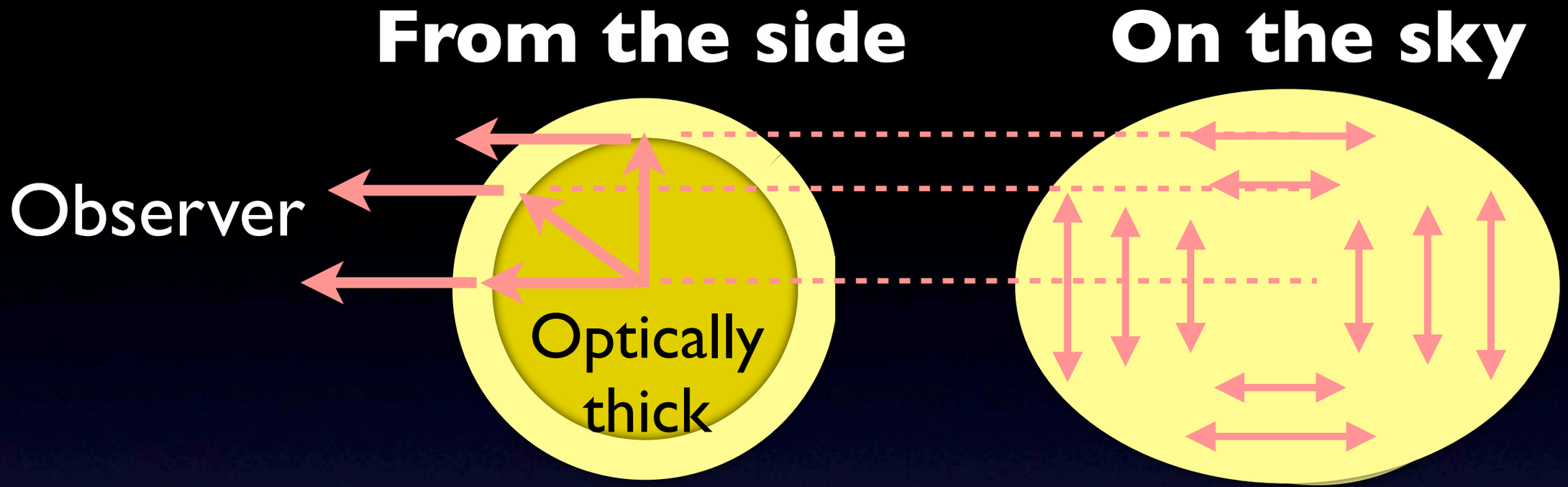
# Mechanism of the explosion

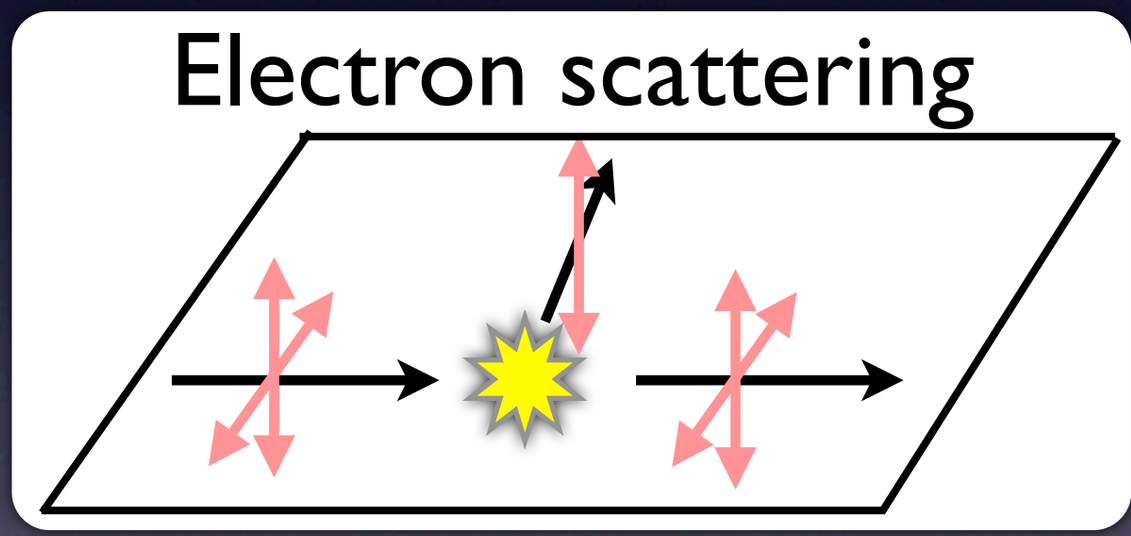
# Extragalactic Supernova @ 30 days

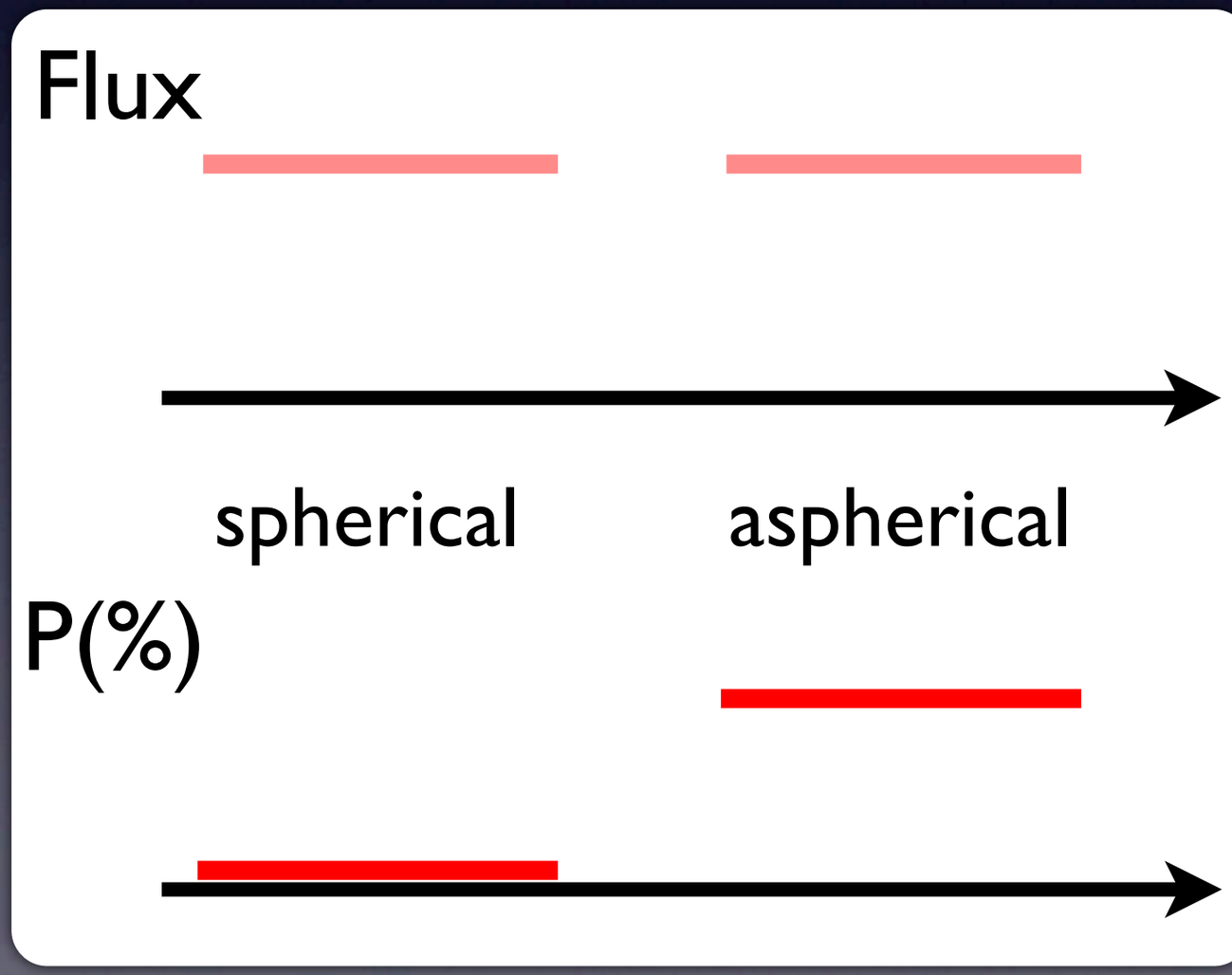
- **Velocity ~ 10,000 km/s**
- **Radius ~ 2 x $10^{15}$ cm ~ 0.001pc**
- **$\tau \sim n_e \sigma R \sim 10^2$ (t/10 days) $^{-2}$ optically thick**
- **Distance ~ 30 Mpc (~$10^{26}$cm)**
- **Angular size ~$10^{-6}$ arcsec point source**



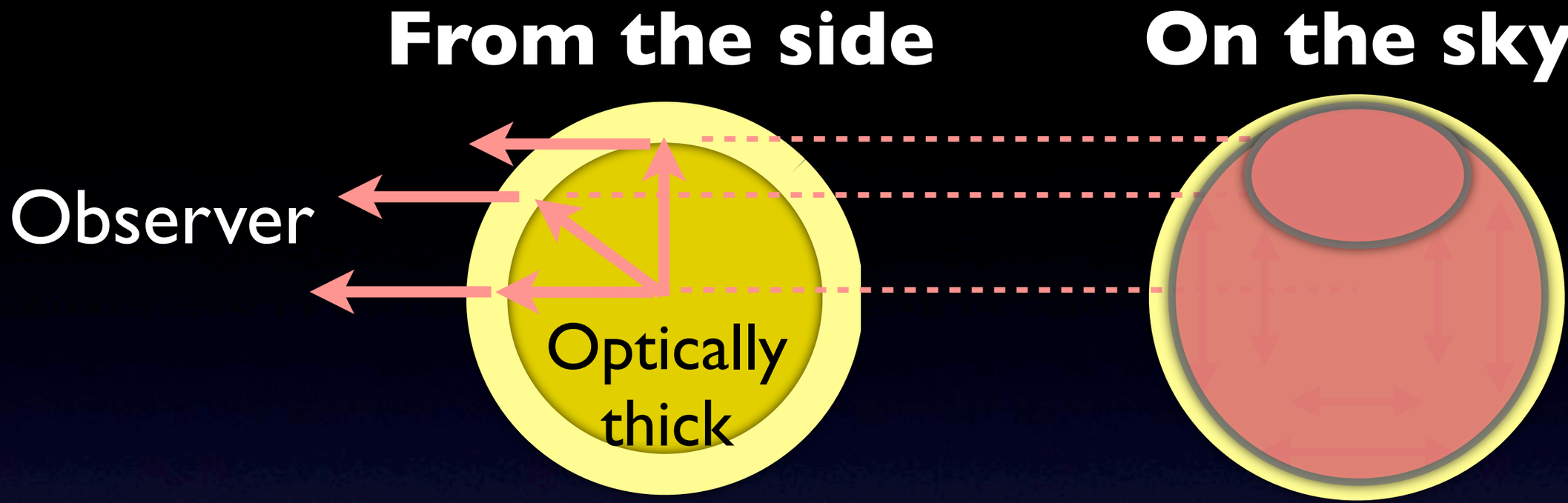

**Polarization**

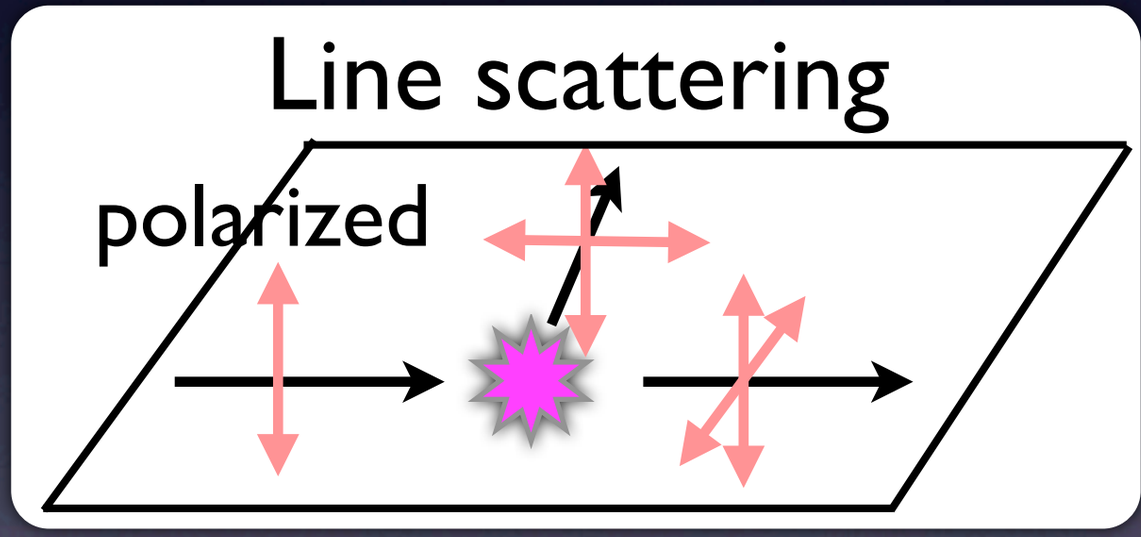


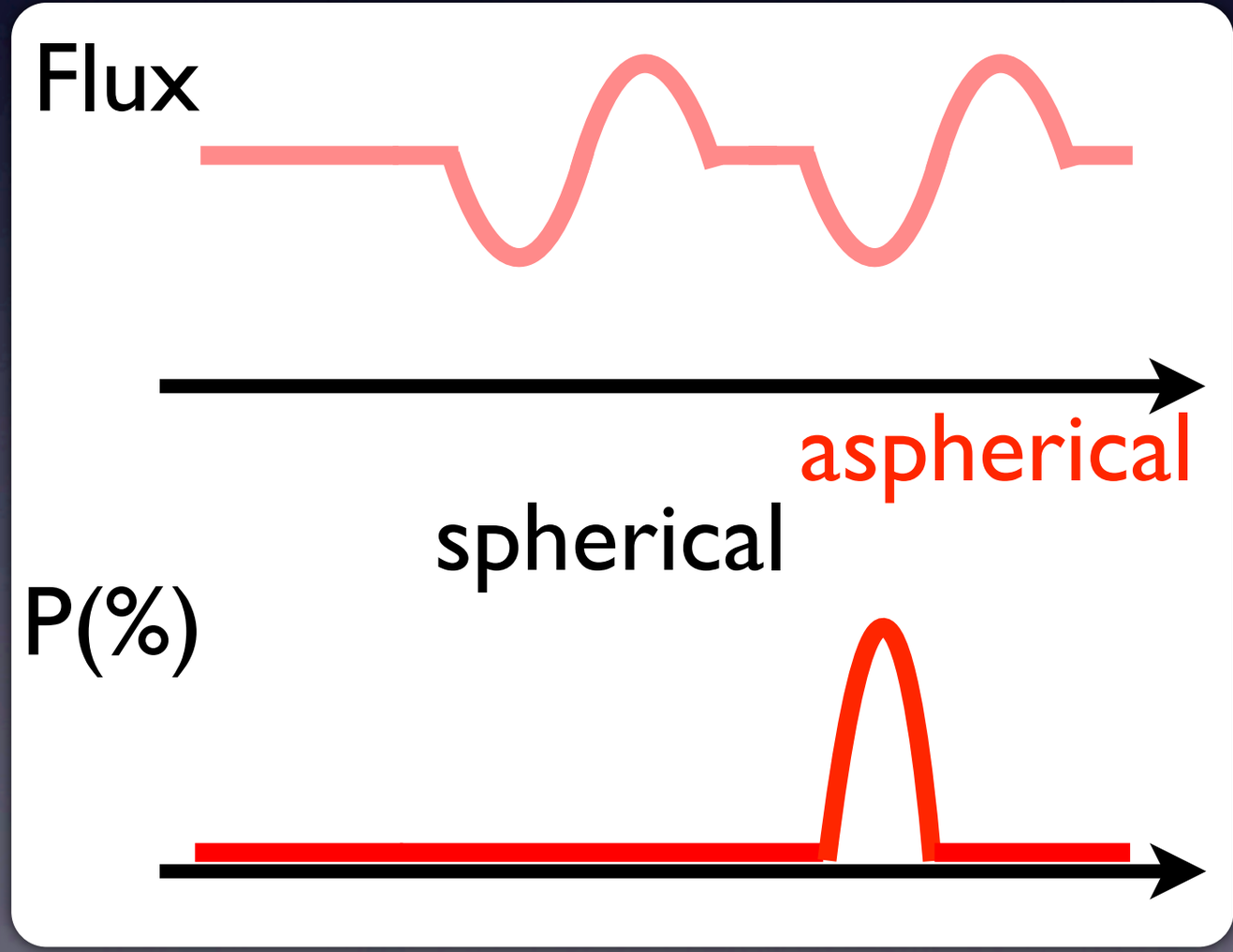

(Wang & Wheeler 08)



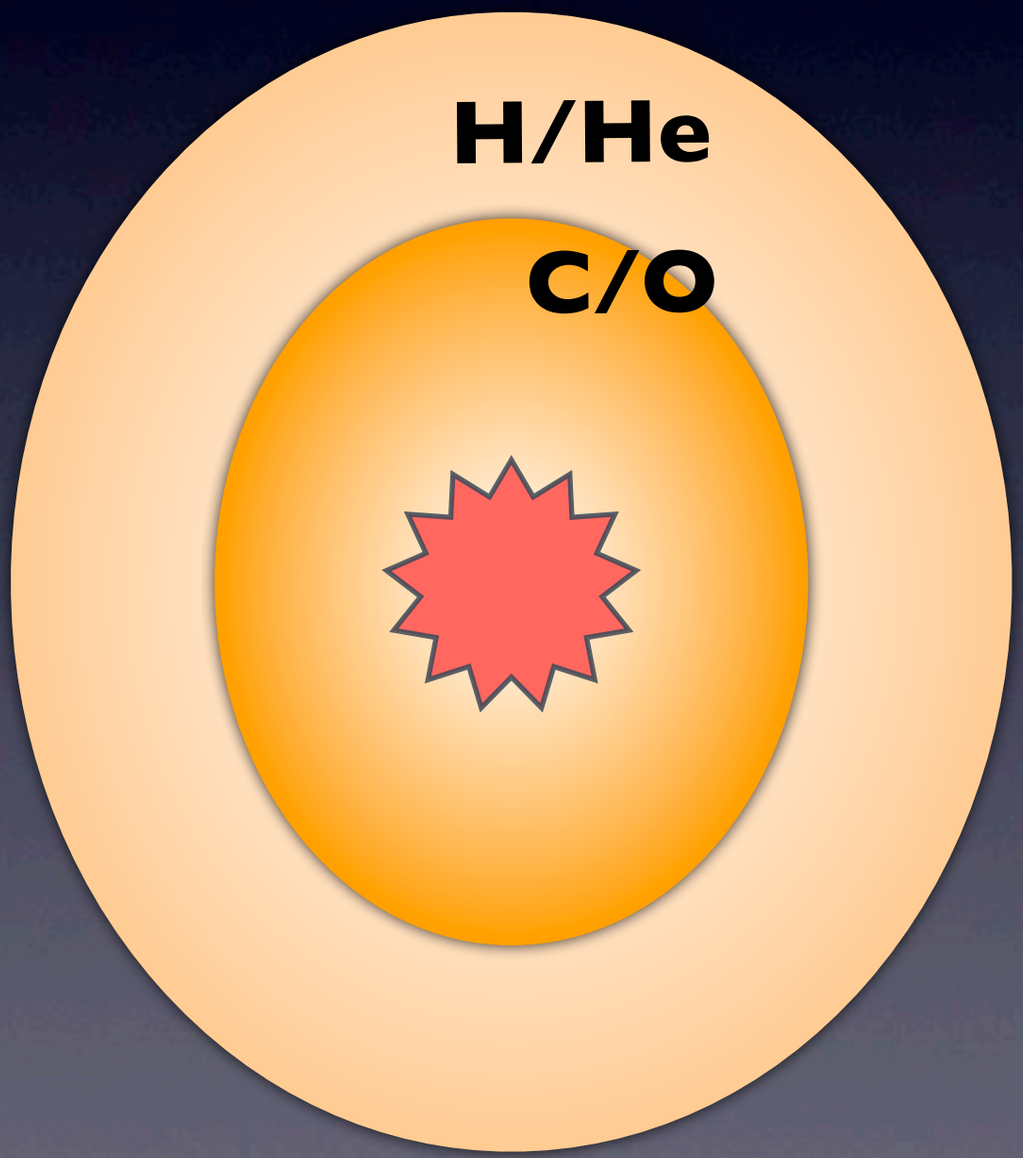

**“de-polarizer”**

(Wang & Wheeler 08)

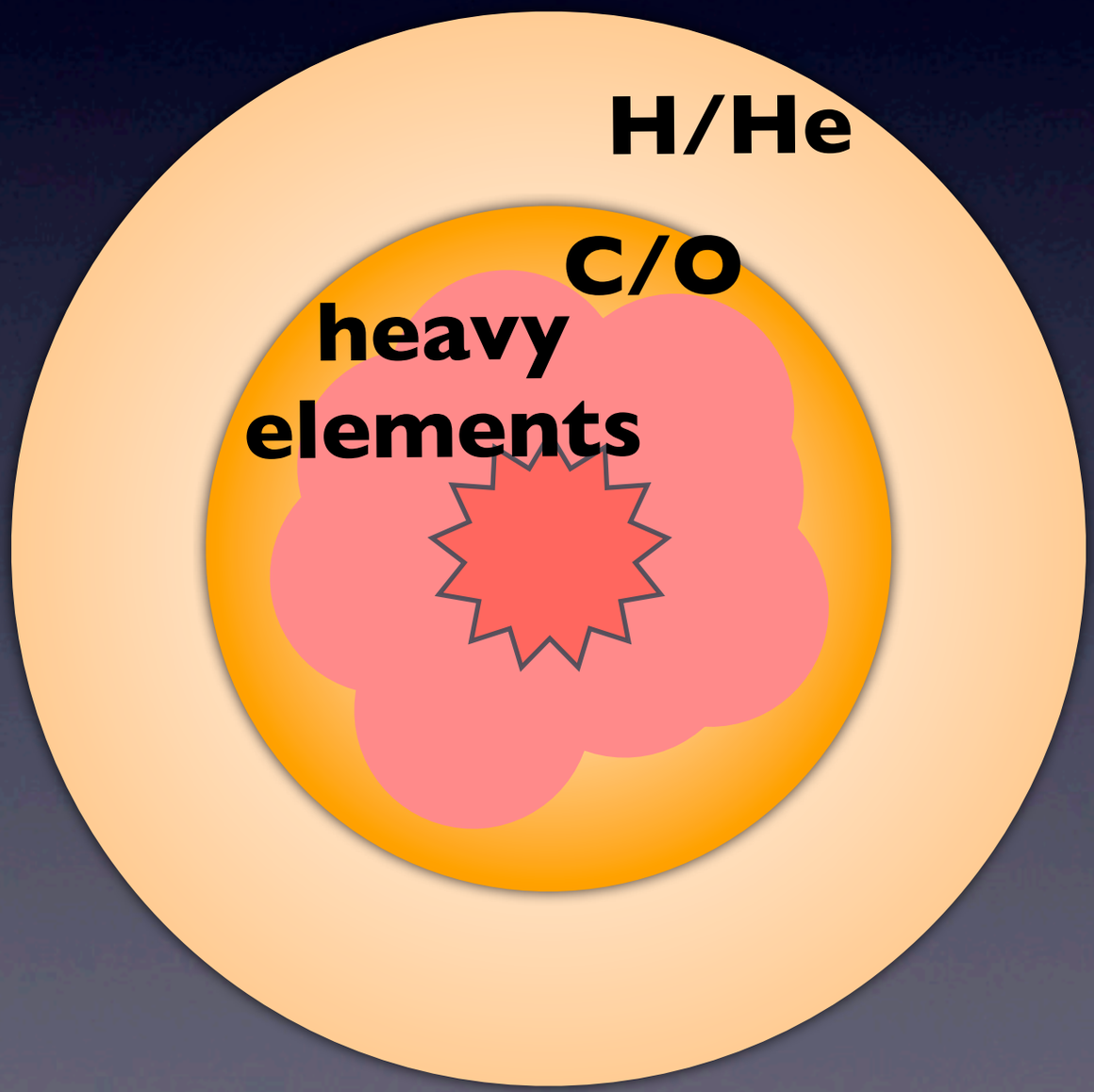


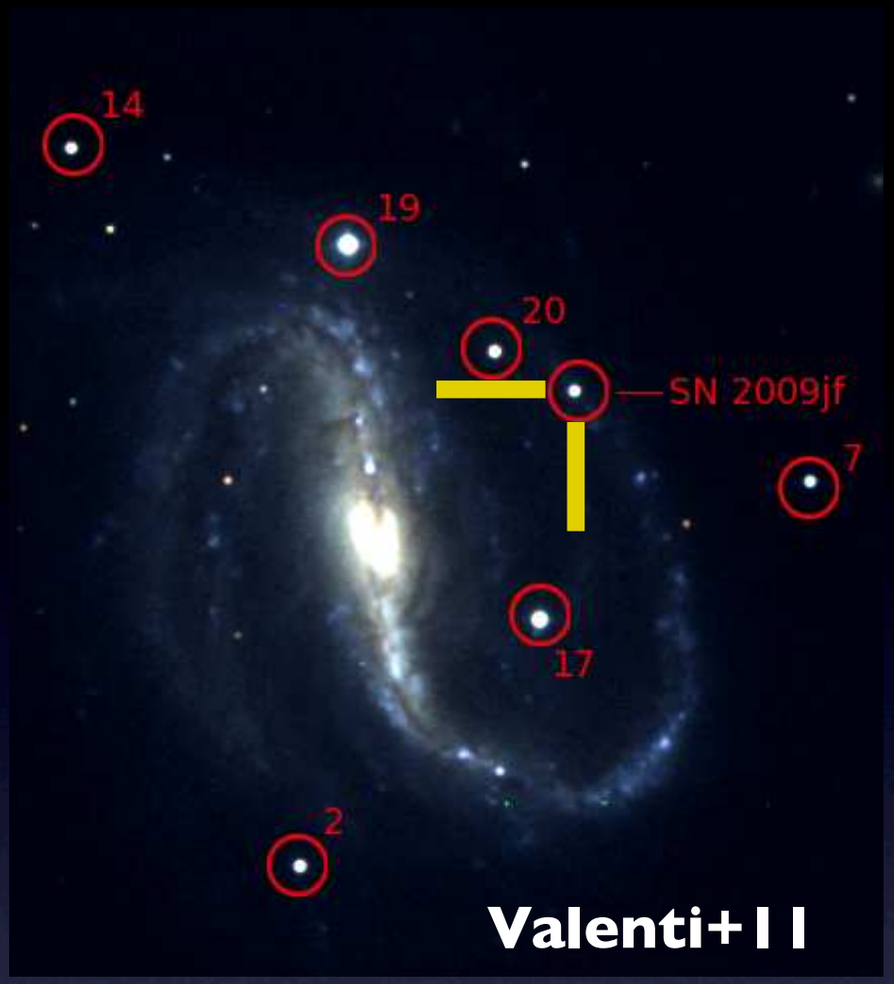
# Why spectropolarimetry

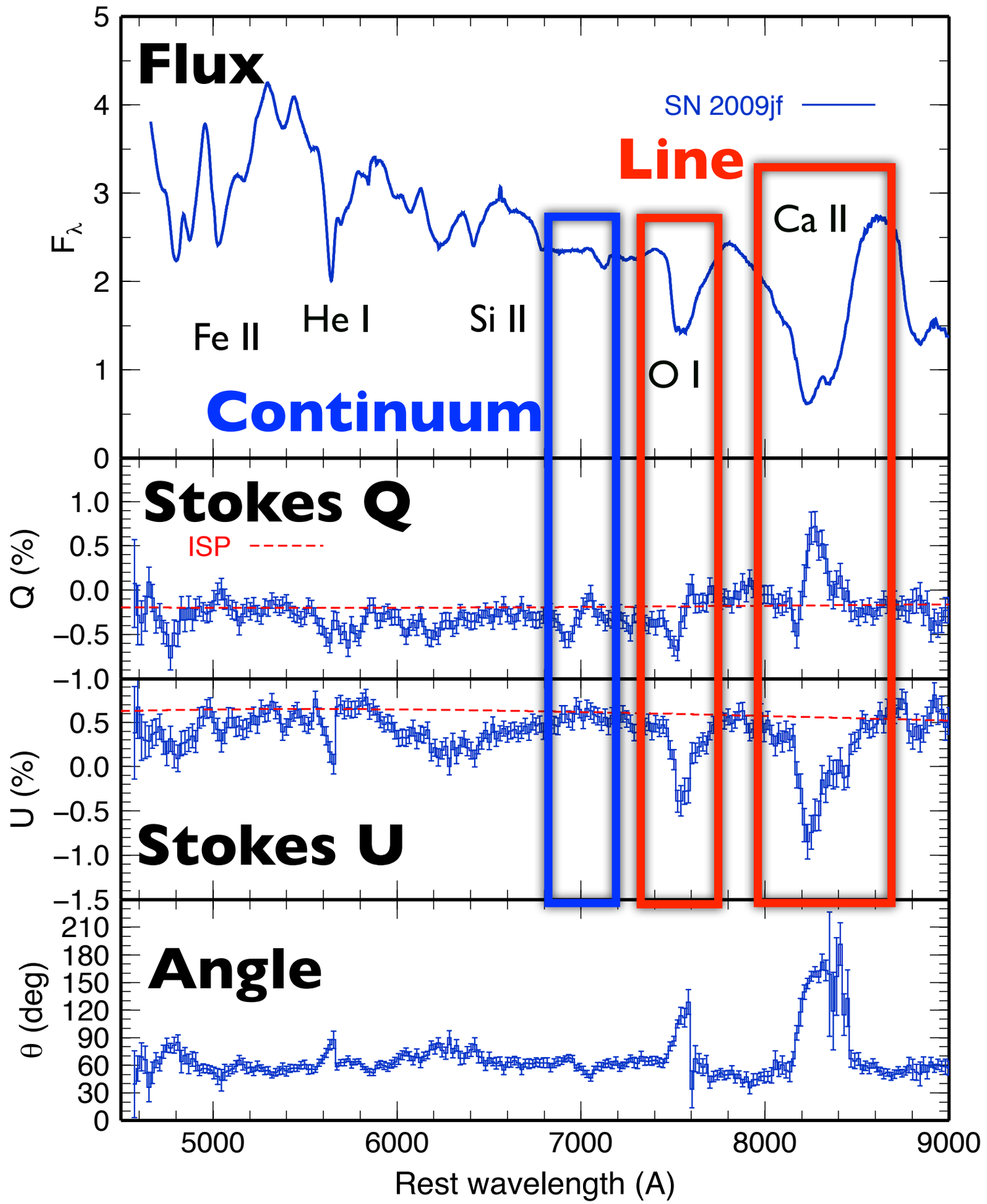
## Continuum polarization




## Line polarization




14
19
20
SN 2009jf
7
17
2
Valenti+11


Flux
SN 2009jf
Line
Ca II
O I
Fe II
He I
Si II
Continuum
$F_\lambda$
Stokes Q
ISP
Q (%)
Stokes U
U (%)
Angle
θ (deg)
Rest wavelength (A)

# Spectropolarimetric Observations of Supernovae

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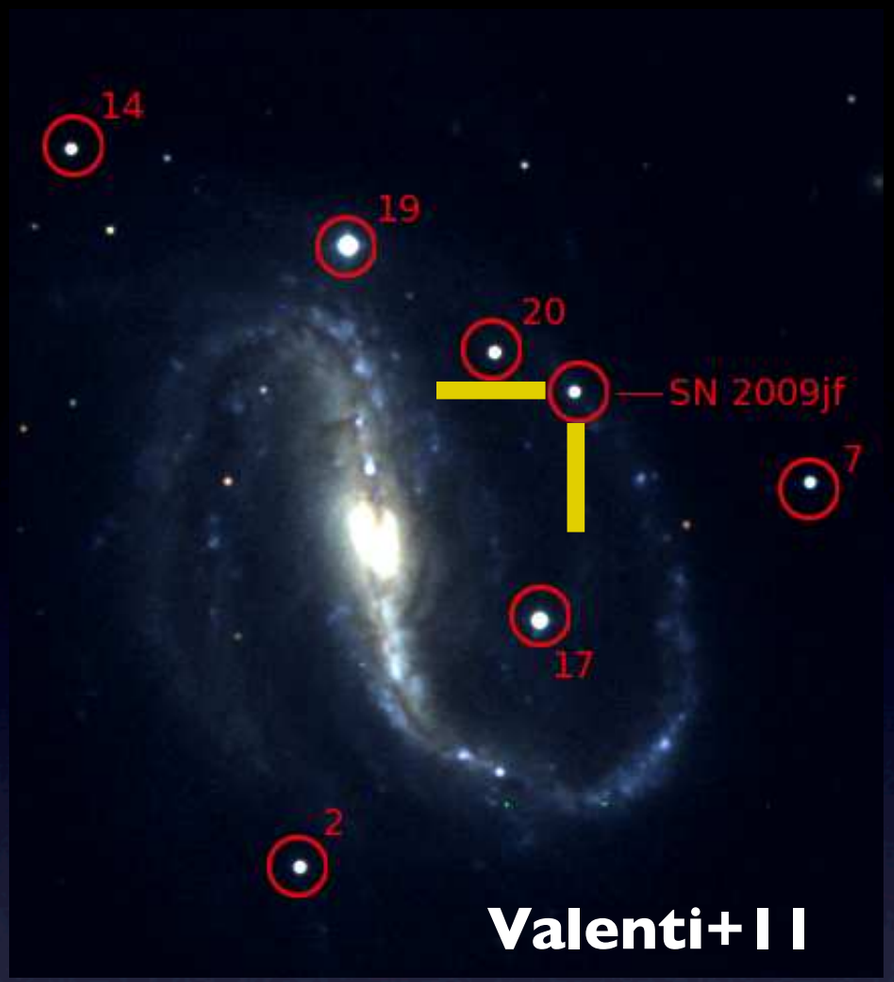
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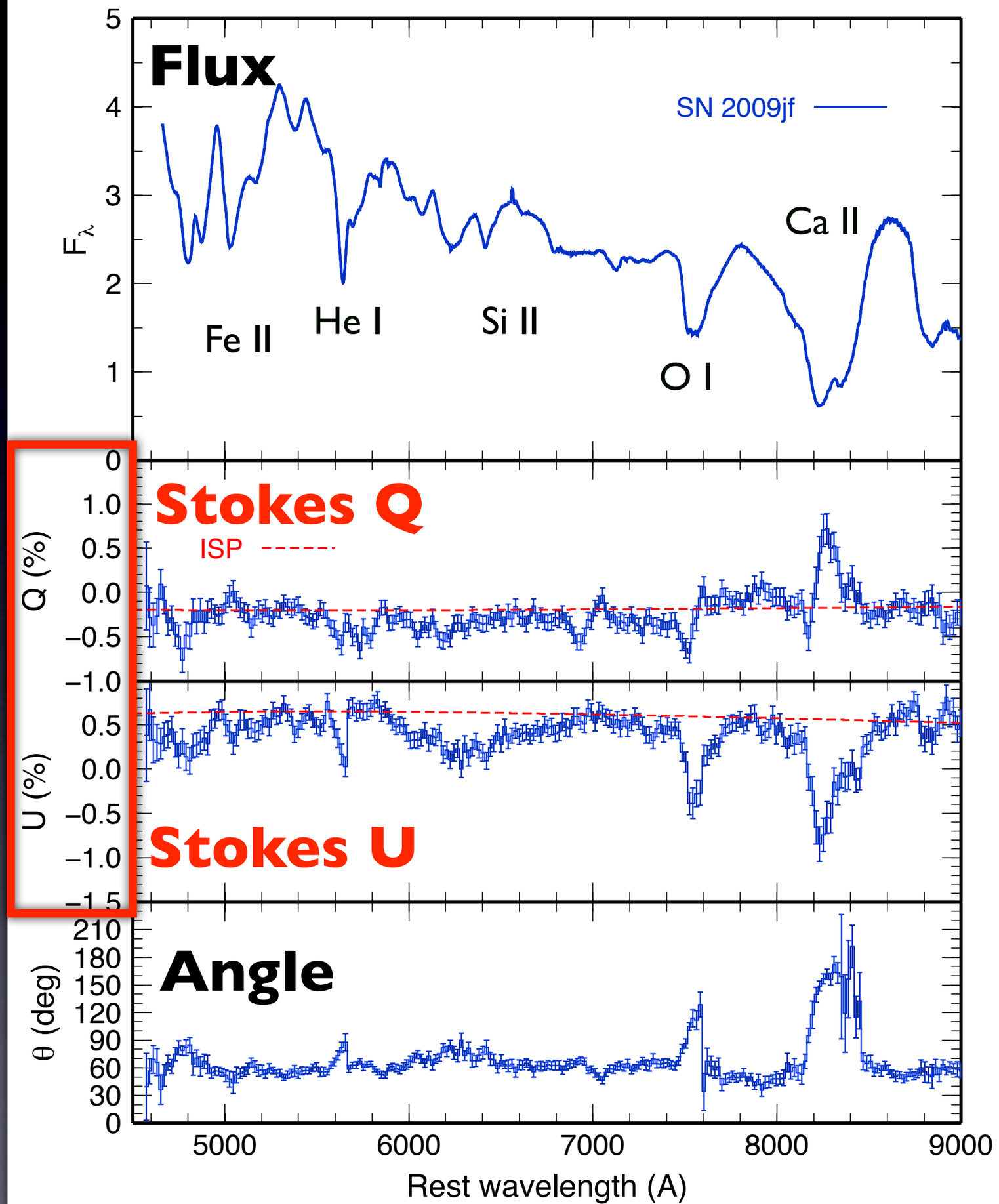

Flux
SN 2009jf
$F_\lambda$
Fe II
He I
Si II
O I
Ca II
Stokes Q
ISP
Q (%)
Stokes U
U (%)
Angle
θ (deg)
Rest wavelength (A)

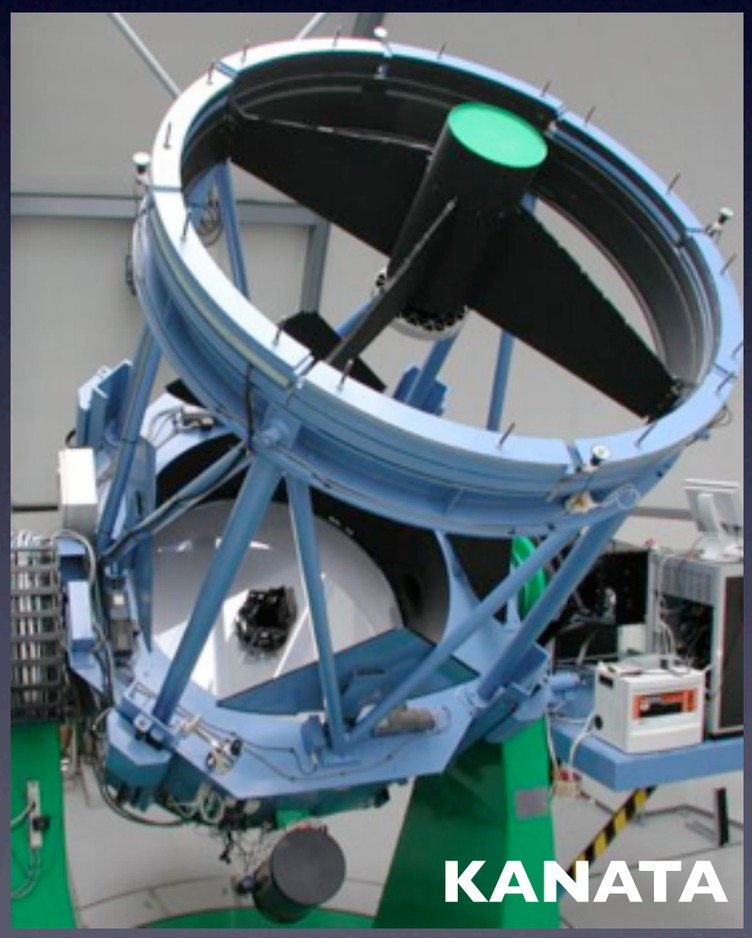
**Polarization ~ 1 %**
**Measurement error < 0.1 %**

**SN with ~16-18 mag**

## Imaging


**0.5-1 m**

## Spectroscopy




**1-4 m**

## Spectro-polarimetry

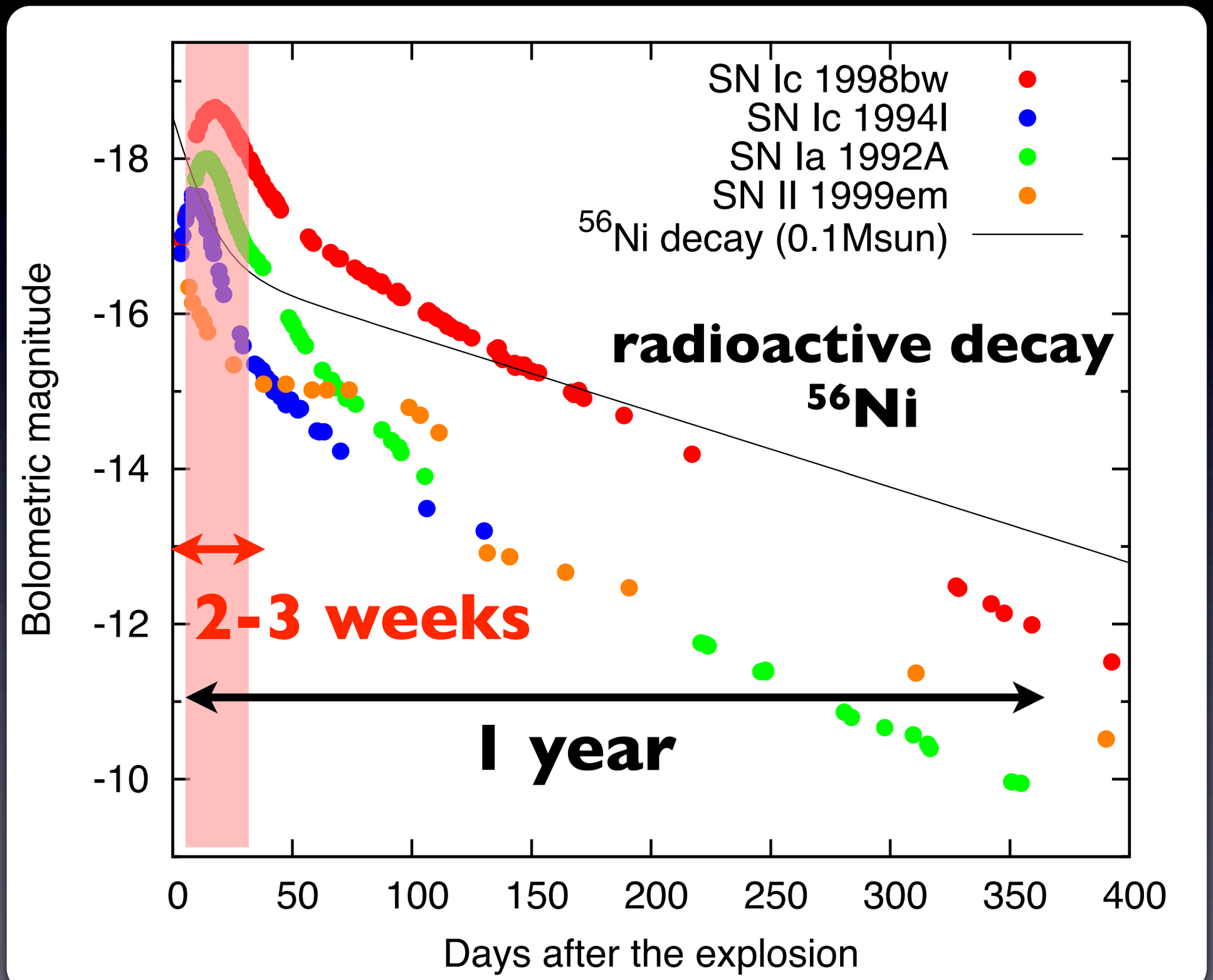

**8-10 m**

# Optical light curve

$10^9$ Lsun

$10^8$ Lsun

$10^7$ Lsun



# 8-10m級望遠鏡を、すぐ使う

## R~500, ΔP < 0.1% for 16-18 mag

# Brief history...

1987: SN 1987A (LMC, 50 kpc)

1993: SN 1993J (M81, 3.6 Mpc)

...

1990-2000: 8-10m telescopes

2002: SN 2002ap (M74, 10 Mpc)


THE ASTROPHYSICAL JOURNAL, 580:L39–L42, 2002 November 20

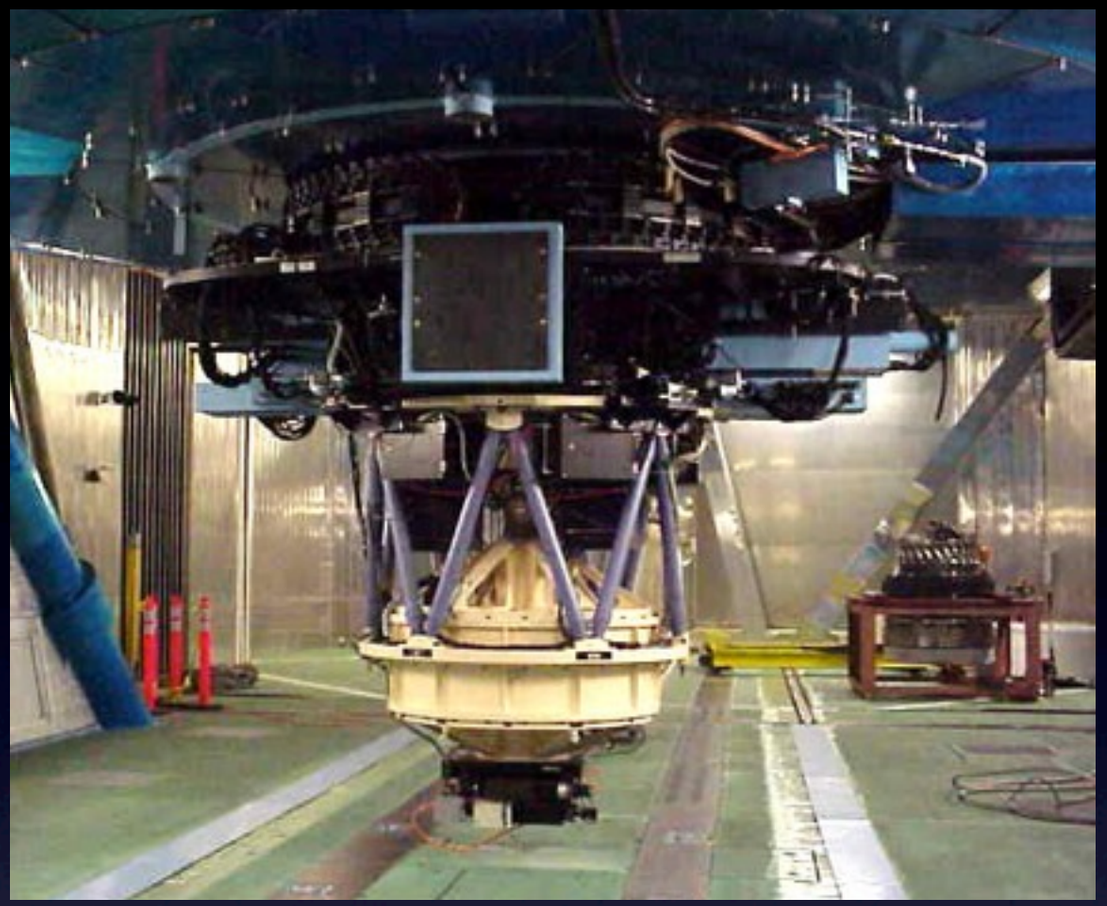

**Subaru/FOCAS**

OPTICAL SPECTROPOLARIMETRY OF SN 2002ap: A HIGH-VELOCITY ASYMMETRIC EXPLOSION[1]

K. S. KAWABATA,[2,3] D. J. JEFFERY,[4] M. IYE,[2,5] Y. OHYAMA,[6] G. KOSUGI,[6] N. KASHIKAWA,[2] N. EBIZUKA,[7] T. SASAKI,[6] K. SEKIGUCHI,[6] K. NOMOTO,[8,9] P. MAZZALI,[8,9,10] J. DENG,[8,9] K. MAEDA,[8] H. UMEDA,[8] K. AOKI,[6] Y. SAITO,[2] T. TAKATA,[6] M. YOSHIDA,[11] R. ASAI,[8] M. INATA,[11] K. OKITA,[11] K. OTA,[2,8] T. OZAWA,[12] Y. SHIMIZU,[11] H. TAGUCHI,[13] Y. YADOUMARU,[12] T. MISAWA,[2,8] F. NAKATA,[2,8] T. YAMADA,[2] I. TANAKA,[2] AND T. KODAMA[14]

*Received 2002 May 23; accepted 2002 October 15; published 2002 October 25*

# Subaru/FOCAS



**PASJ:** Publ. Astron. Soc. Japan **54**, 819–832, 2002 December 25


## FOCAS: The Faint Object Camera and Spectrograph for the Subaru Telescope

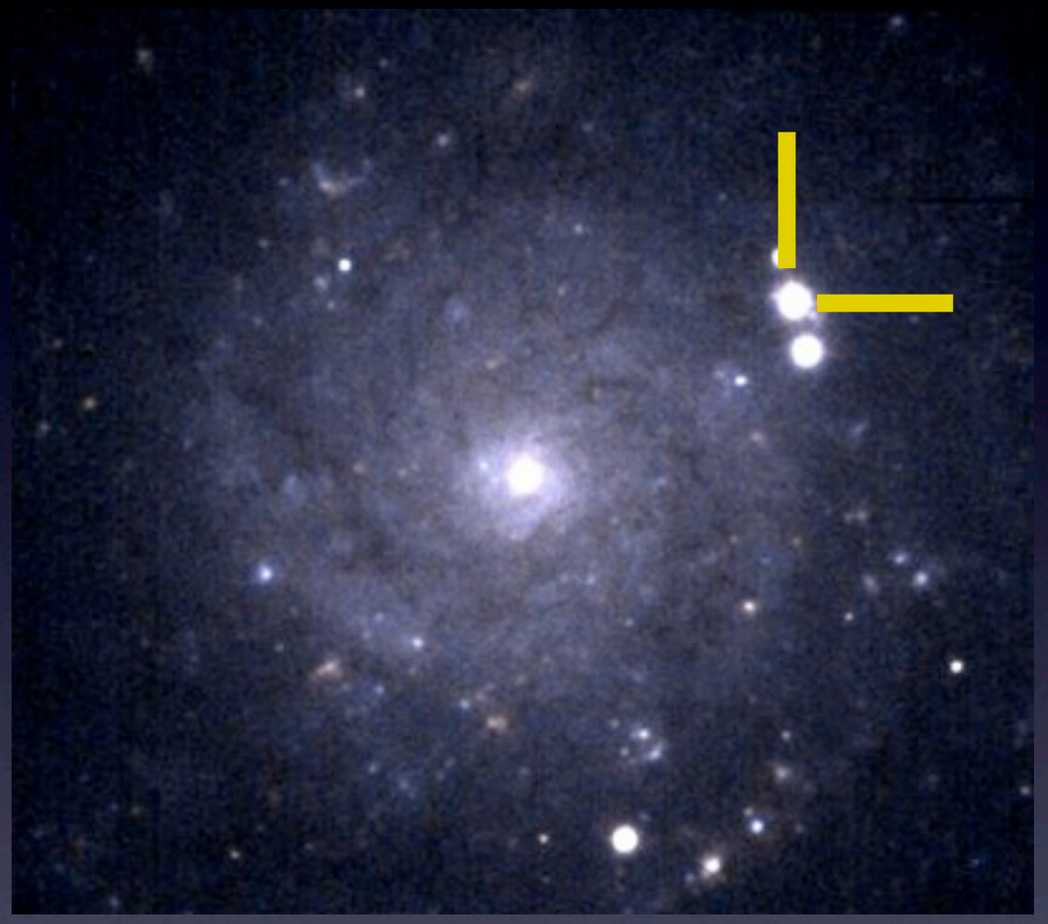
Nobunari KASHIKAWA,[1,2] Kentaro AOKI,[3] Ryo ASAI,[4] Noboru EBIZUKA,[5] Motoko INATA,[1]
Masanori IYE,[1,2] Koji S. KAWABATA,[1] George KOSUGI,[3] Youichi OHYAMA,[3] Kiichi OKITA,[1]
Tomohiko OZAWA,[6] Yoshihiko SAITO,[4] Toshiyuki SASAKI,[3] Kazuhiro SEKIGUCHI,[3]
Yasuhiro SHIMIZU,[7] Hiroko TAGUCHI,[8] Tadafumi TAKATA,[3]
Yasushi YADOUMARU,[6] and Michitoshi YOSHIDA[1,7]

# Kashikawa et al. 2002

# As of 2007

## No significant progress after 2002

## 2007: SN 2007gr (NGC 1058, 9 Mpc)



THE ASTROPHYSICAL JOURNAL, 689:1191–1198, 2008 December 20


**Subaru/FOCAS**

# OPTICAL SPECTROPOLARIMETRY AND ASPHERICITY OF THE TYPE Ic SN 2007gr[1]

MASAOMI TANAKA,[2] KOJI S. KAWABATA,[3] KEIICHI MAEDA,[4] TAKASHI HATTORI,[5] AND KEN'ICHI NOMOTO[2,4]

*Received 2008 June 9; accepted 2008 August 6*

# Spectropolarimetry of SNe with Subaru/FOCAS

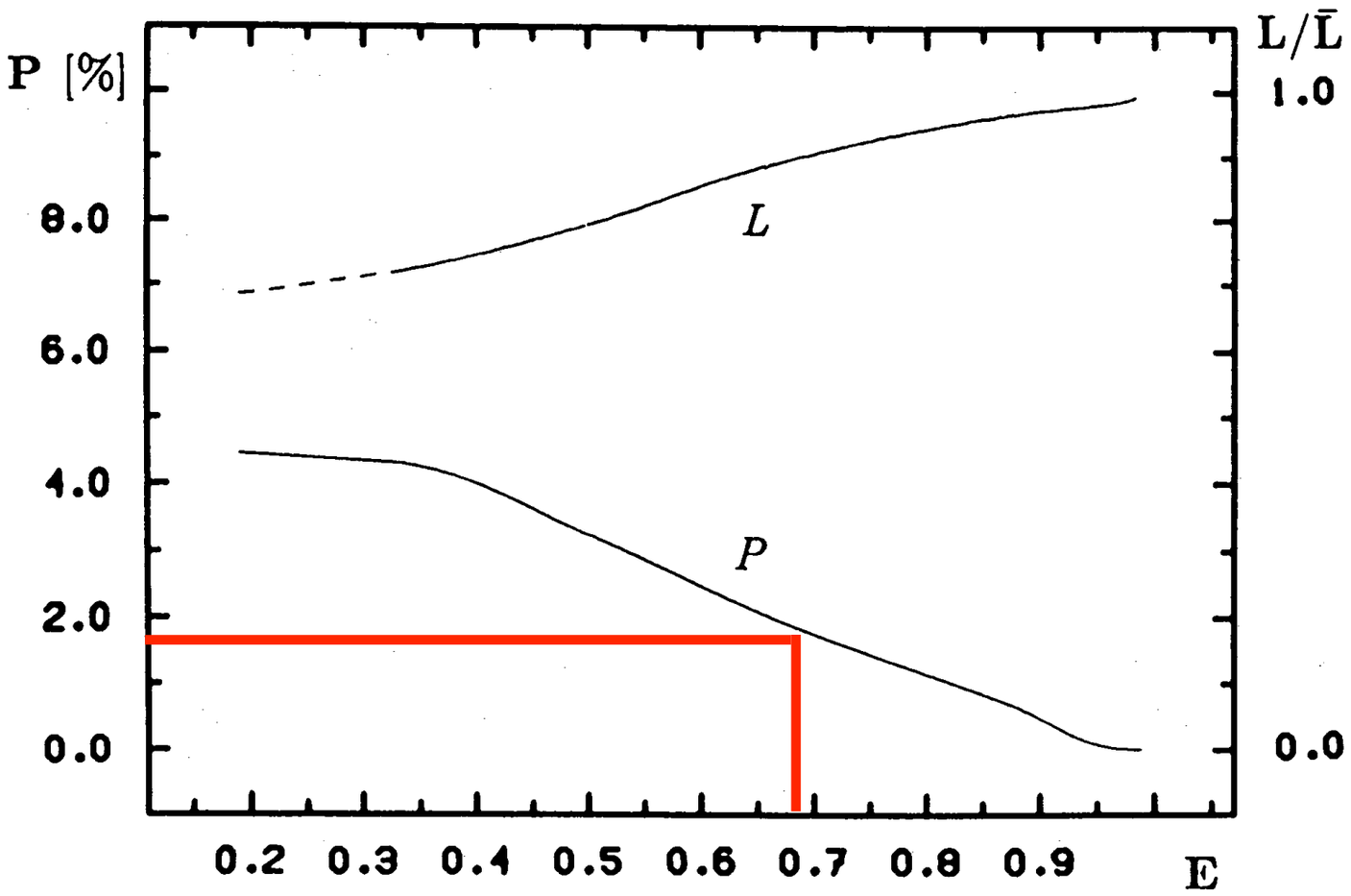
**PI: M. Tanaka**
**Co-I: K. S. Kawabata, T. Hattori.**
**E. Pian, K. Maeda, M. Yamanaka, K. Nomoto,**
**P. A. Mazzali, K. Aoki, T. Sasaki, and M. Iye**

| Object | Type | Date | Epoch | Mag | Quality | Ref. |
|---|---|---|---|---|---|---|
| SN 2005bf | Ib | 2005 May | +8 | 16 | Good | MT+09 |
| SN 2007gr | Ic | 2007 Sep | +21 | 14 | Good | MT+08 |
| SN 2009dc | Ia (sp-Ch) | 2009 Apr/Jul | +6/+90 | 15/17 | Good | MT+10 |
| SN 2009jf | Ib | 2009 Oct | +9.3 | 15 | Good | MT+12 |
| OT U2773 | LBV? | 2009 Oct | | 17 | ISP | ... |
| SN 2009kk | Ia | 2009 Oct | +2 | 15 | Good | ... |
| SN 2009mi | Ic | 2010 Jan | +26.5 | 16 | Good | MT+12 |
| SN 2010ah | Ic broad | 2010 Mar | ~30 (disc) | 19 | Not good | ... |
| SN 2010cn | Ic broad/IIb | 2010 May | 2 (disc) | 18 | Good | in prep. |

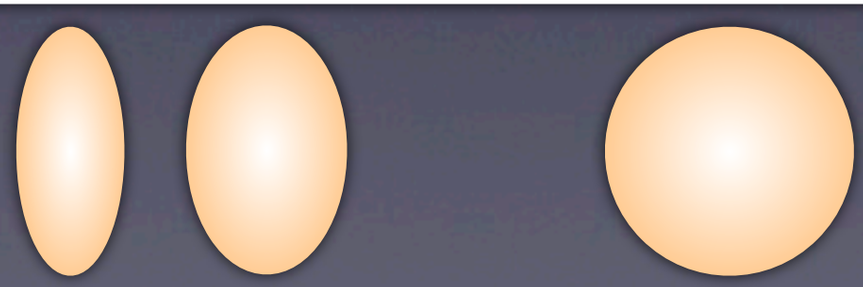
# Spectropolarimetric Observations of Supernovae

- Why Spectropolarimetry
- Observing Strategy
- Results/Future

# What do we expect?
## (Continuum polarization)



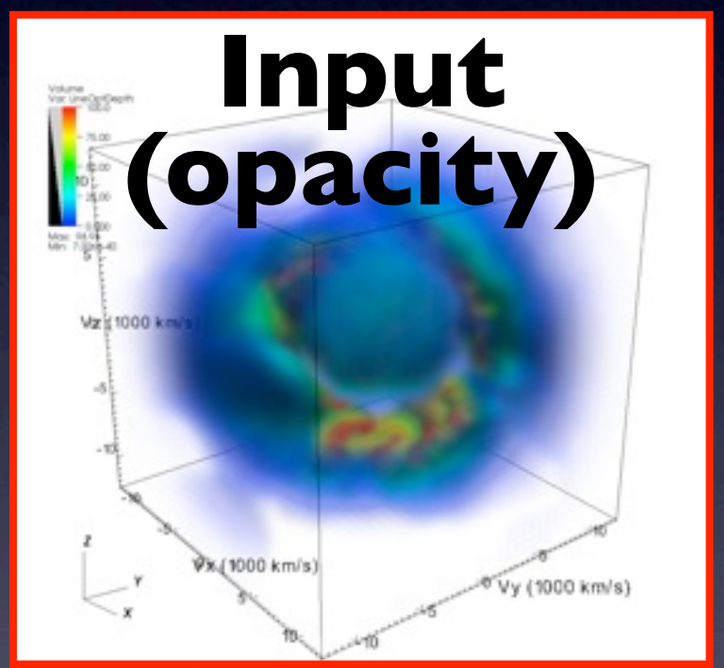

1:2 1:1.5 spherical

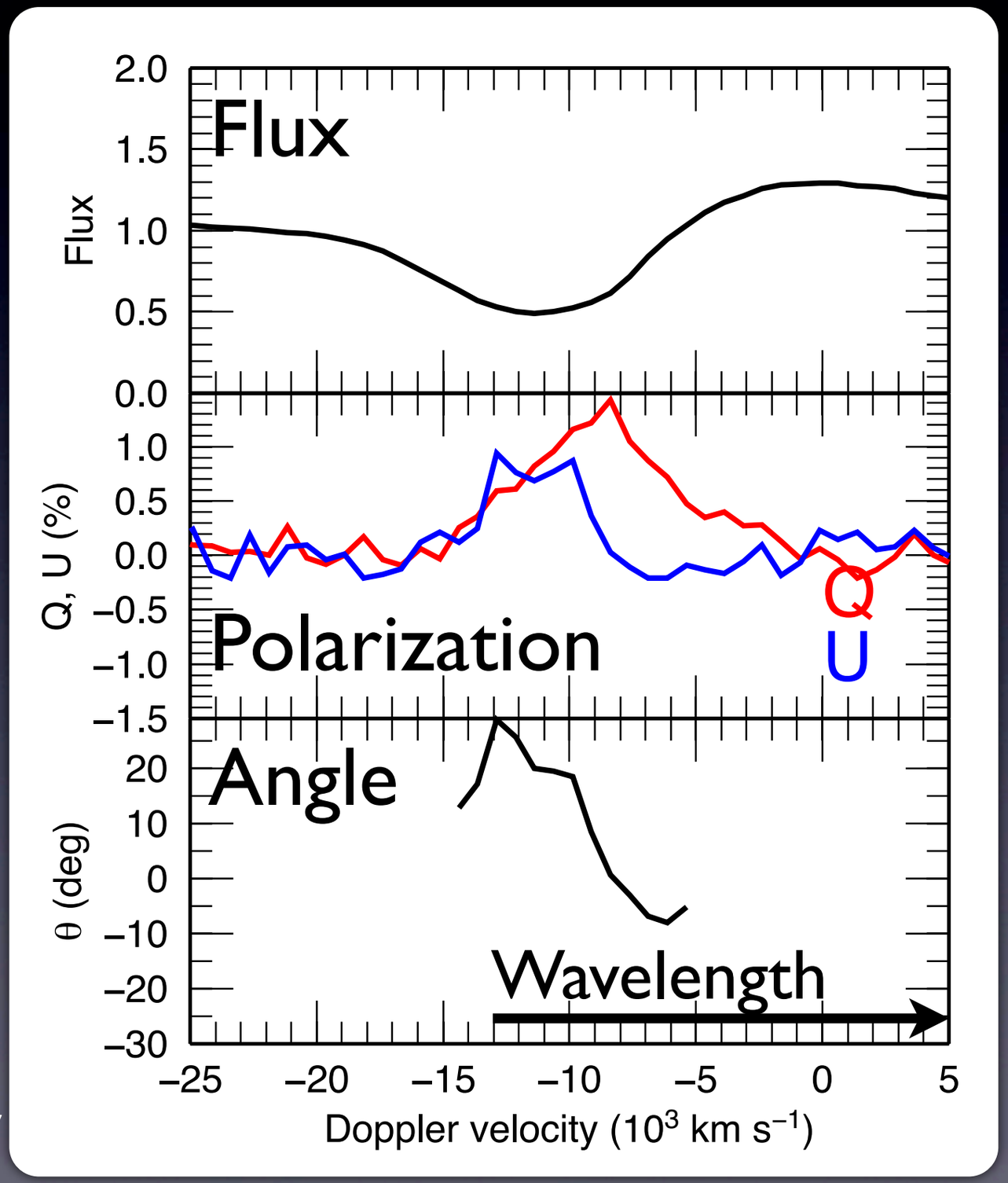


Hoeflich 91, A&A, 246, 481

# What do we expect?
## (Line polarization)

**3D Monte-Carlo radiative transfer with polarization**

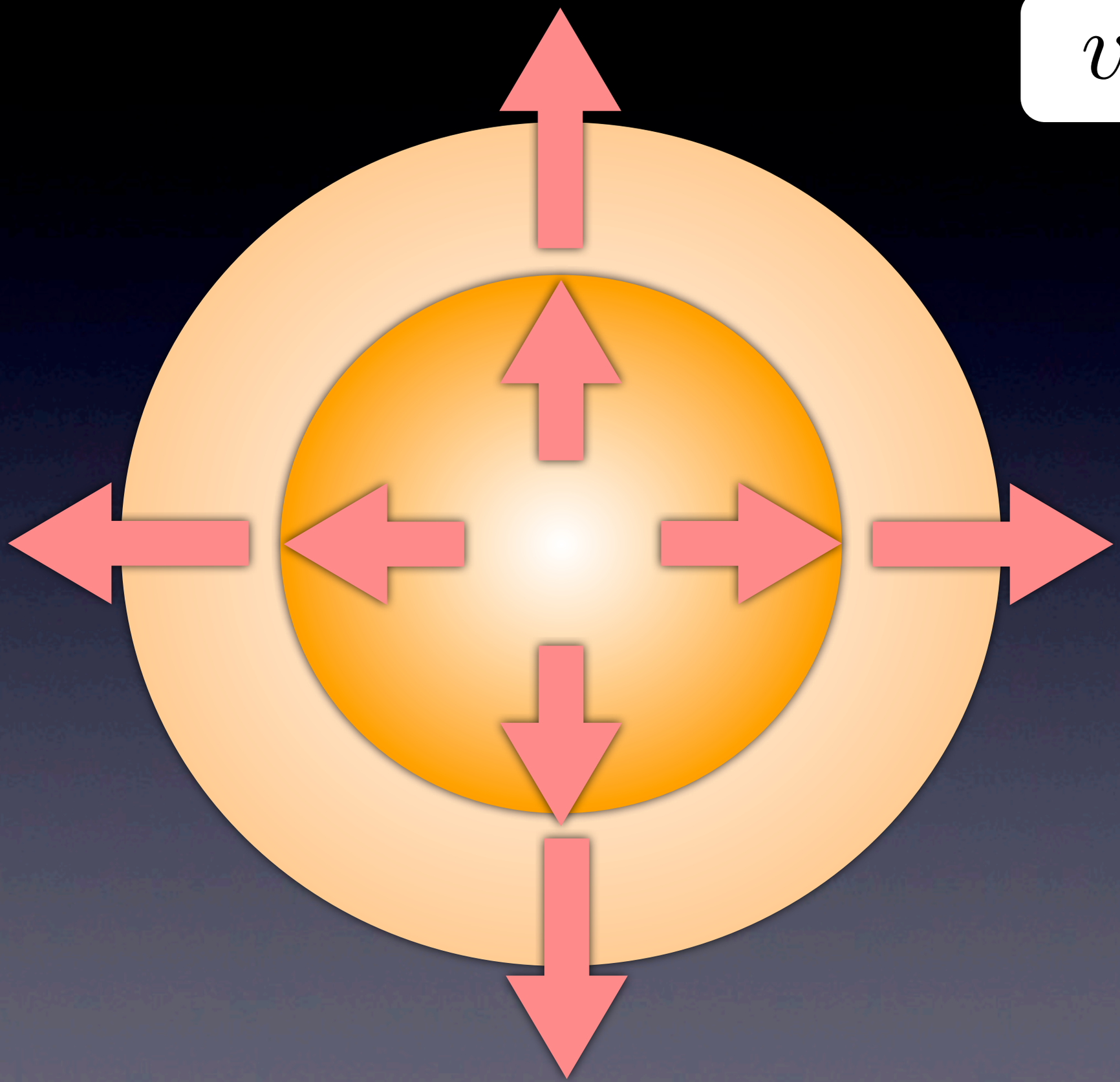



see also
Kasen+03, ApJ, 593, 788
Hole+10, ApJ, 720, 1500
Dessasrt & Hillier 11, MNRAS, 415, 3497

# Homologous expansion

$$v \propto r$$

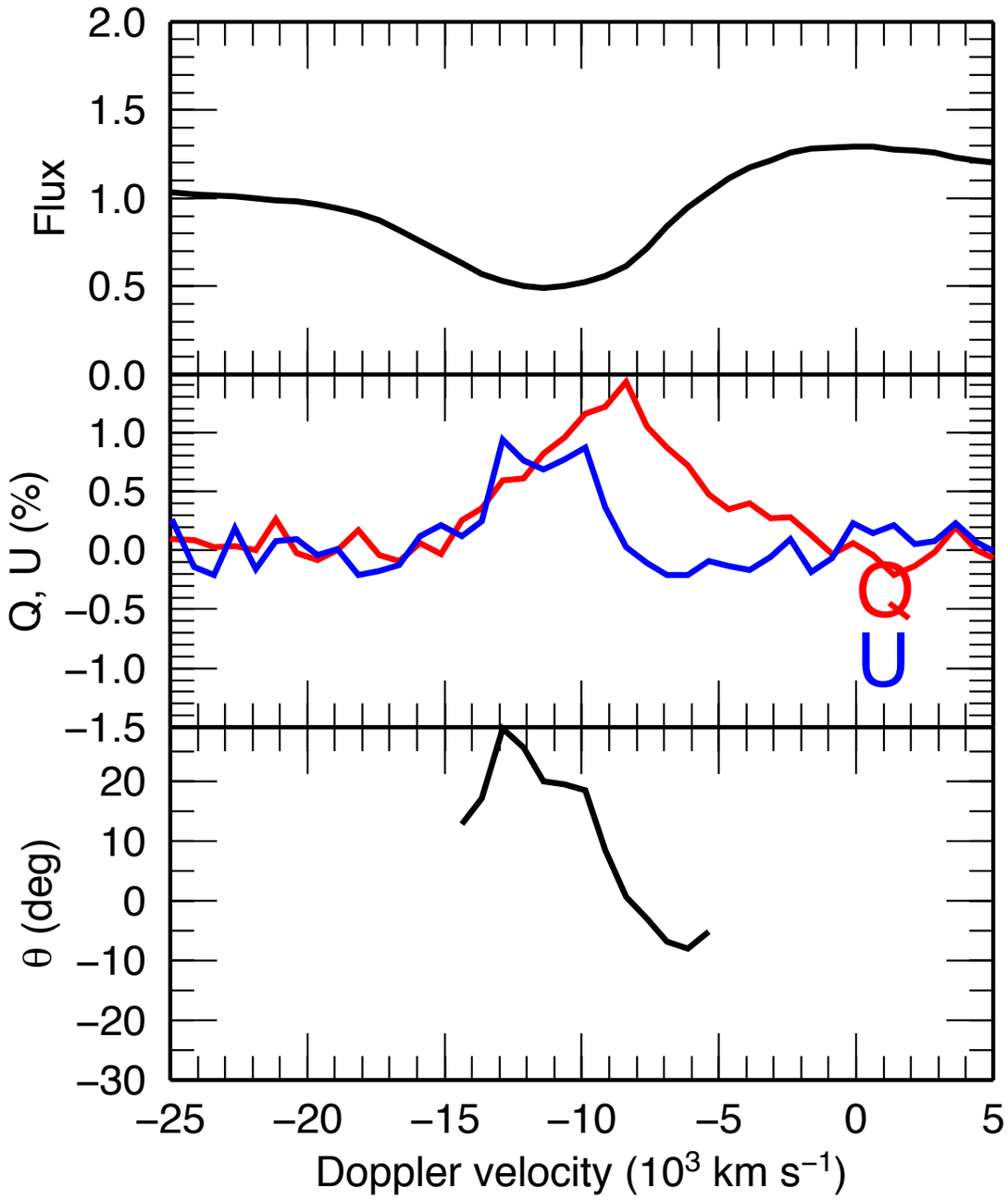


# Polarization in Q-U Plane

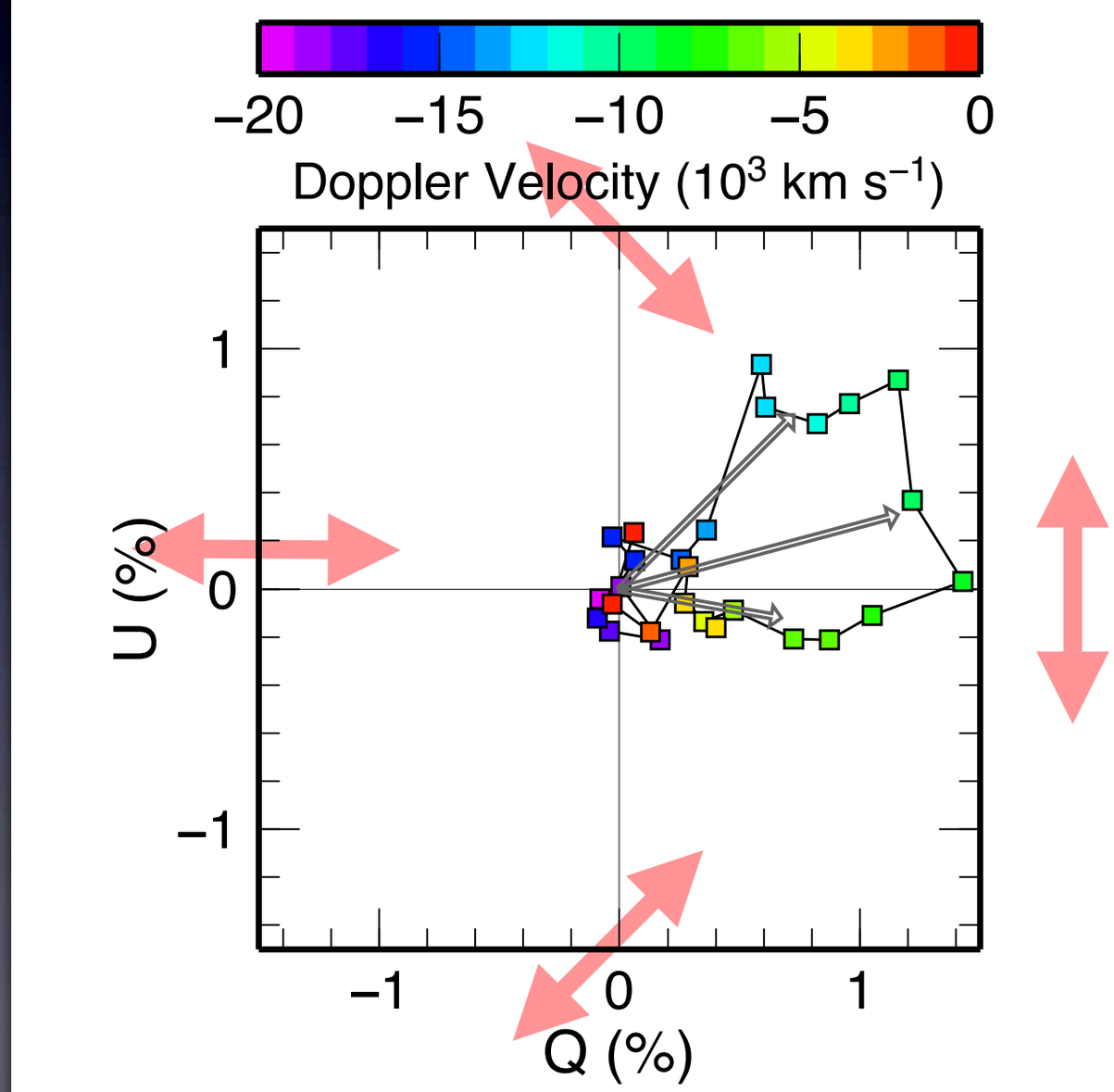
Q = ↕ -- ↔

U = ⤡ -- ⤢

## Polarization spectrum

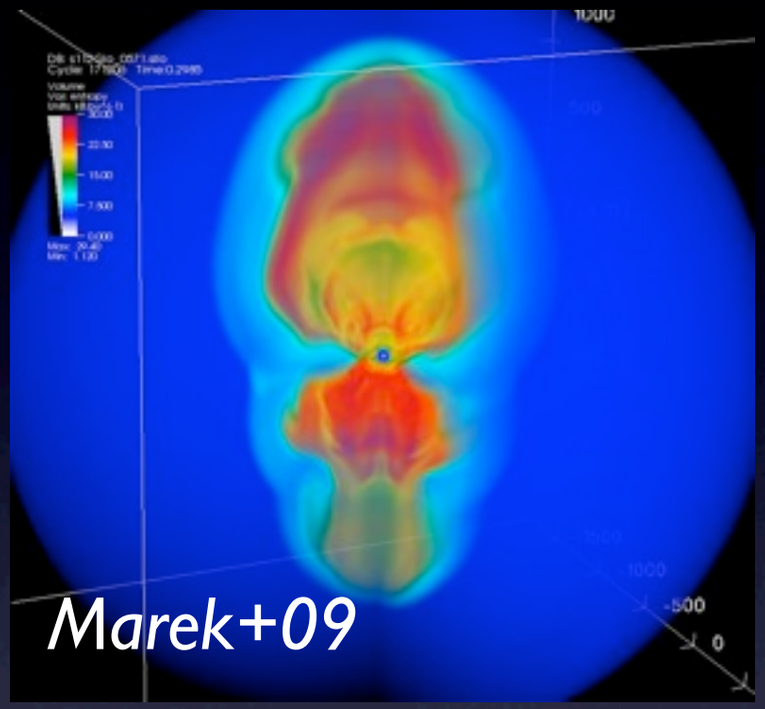


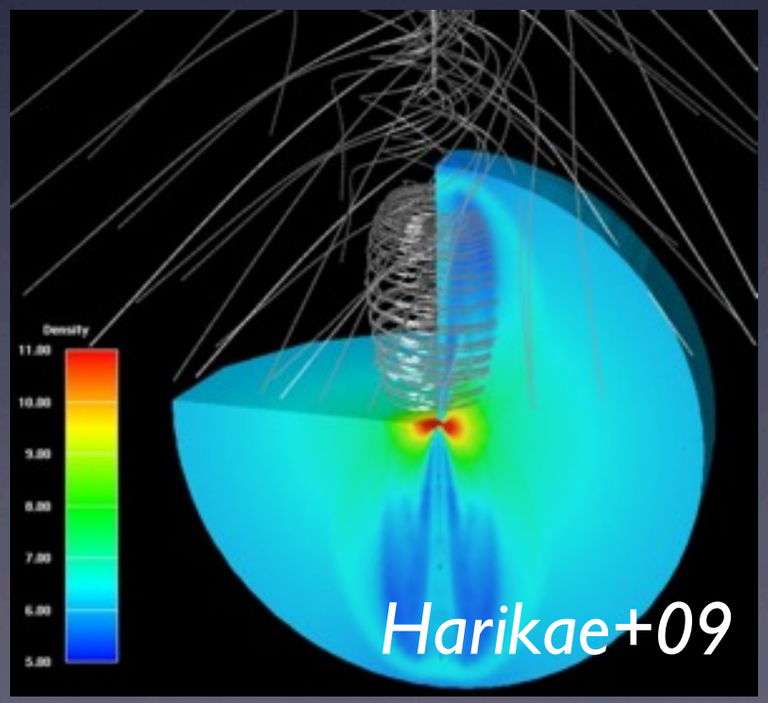

## Q-U plane



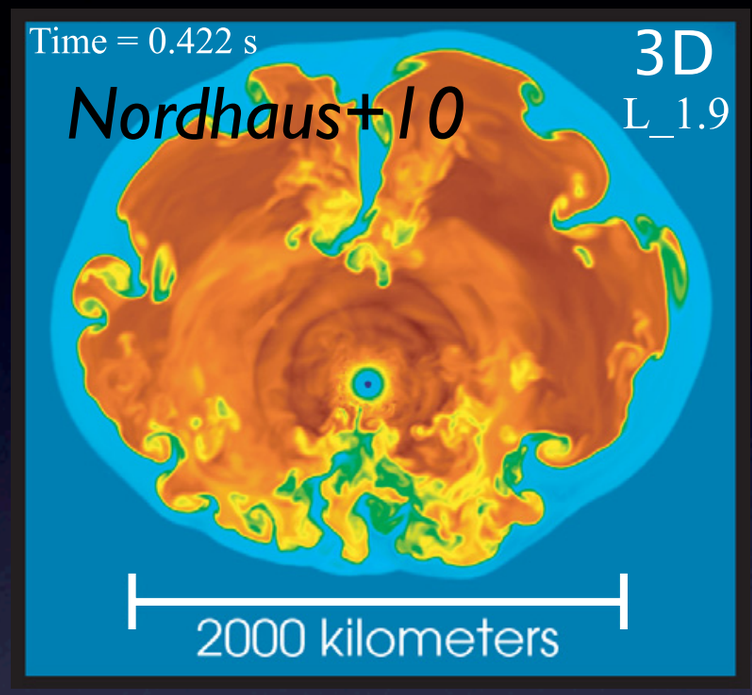
# Diagnostic of the Geometry?

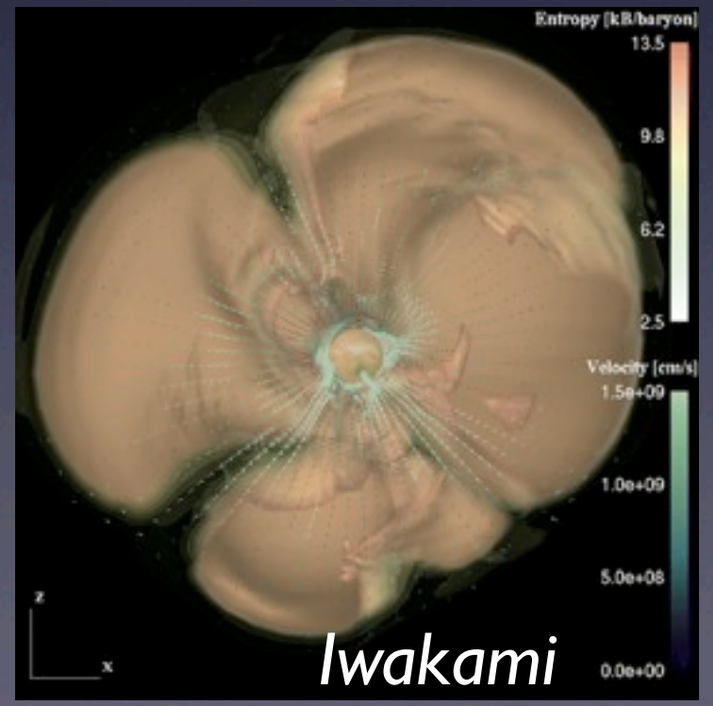
## *2D bipolar flow ?*



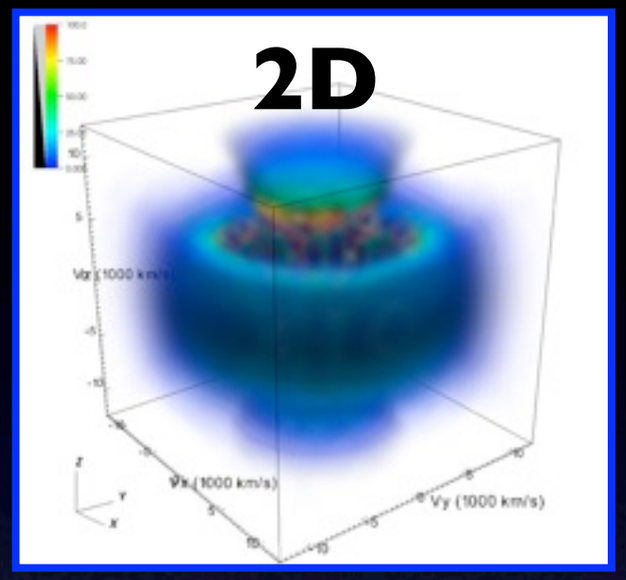



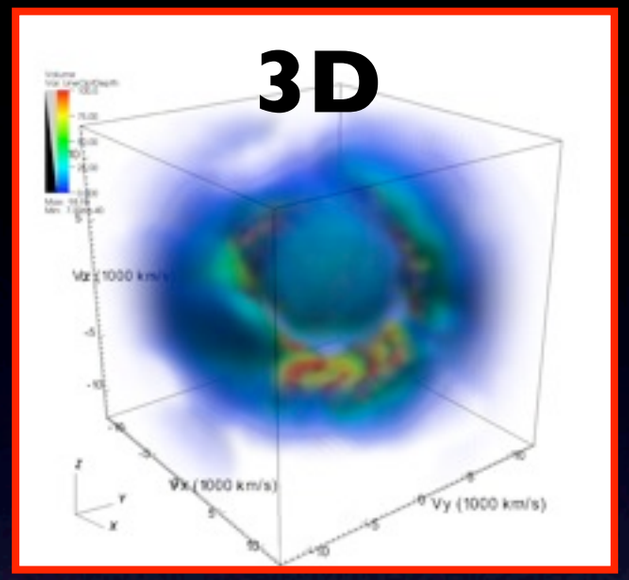

## *3D convection?*

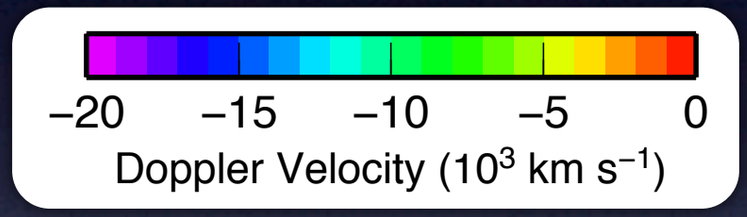


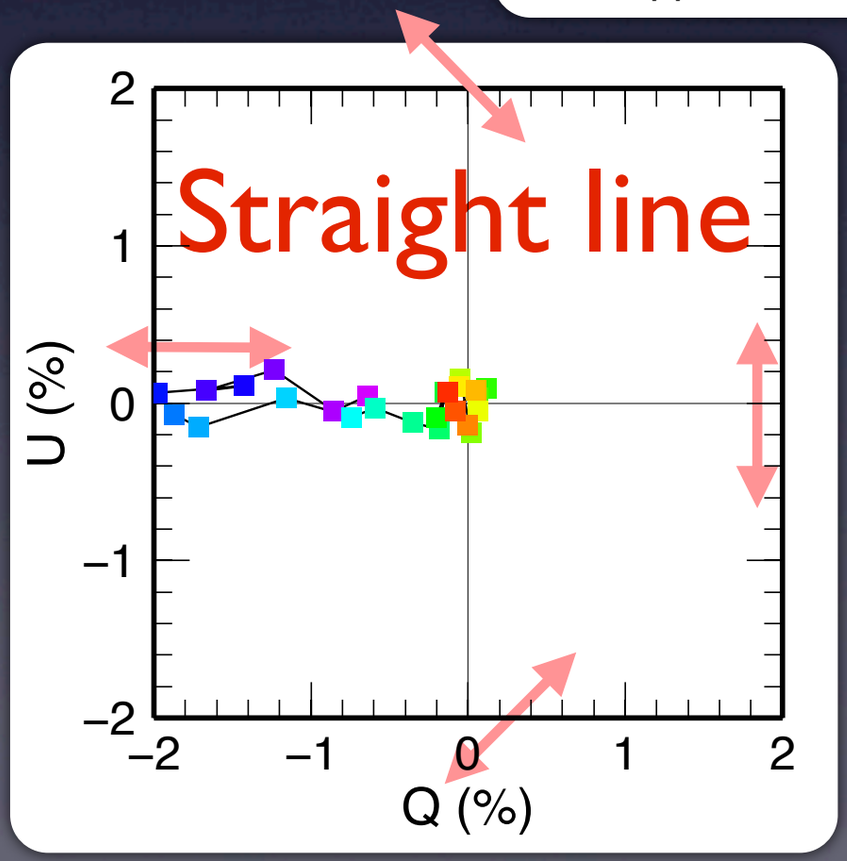



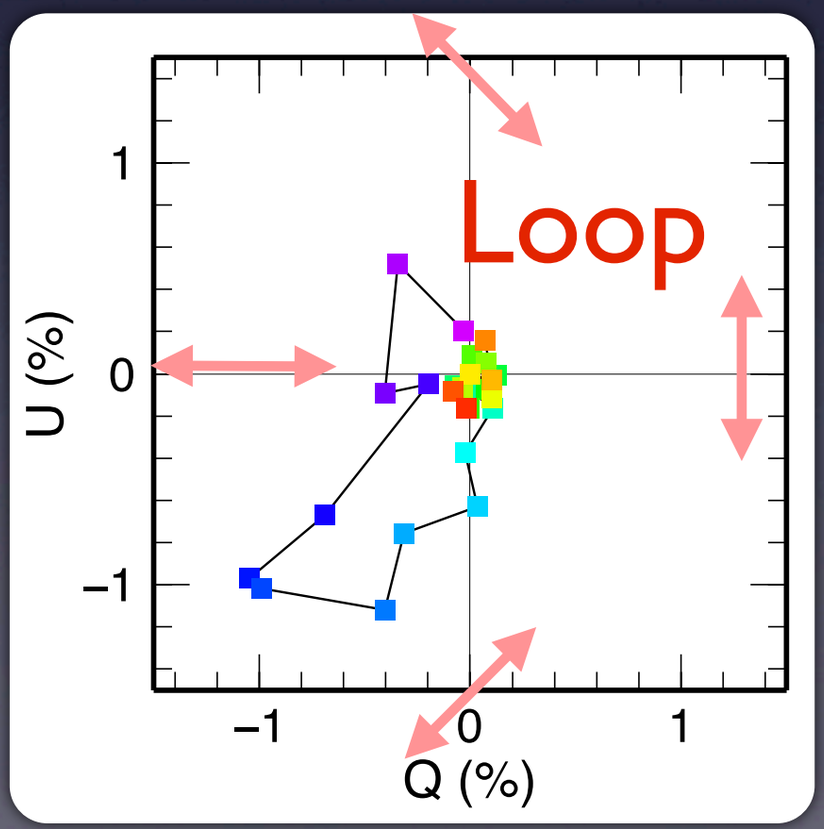
# Diagnostic of the Geometry?



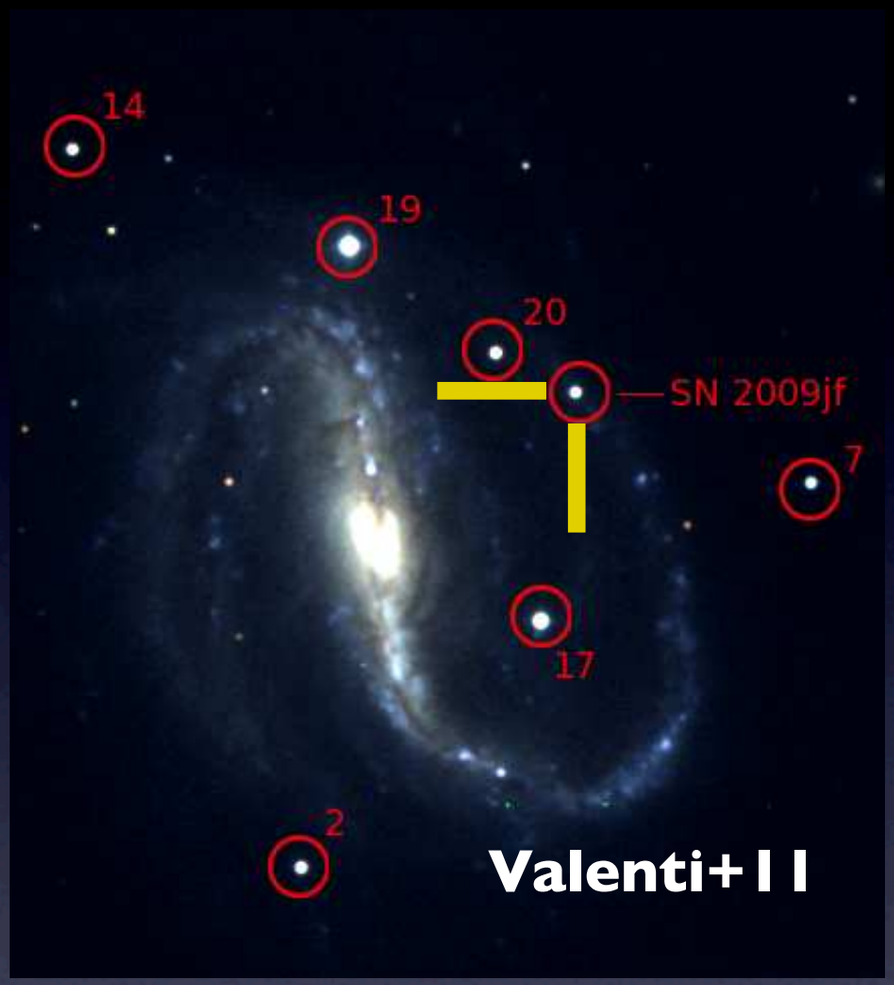



# Results

# SN 2009jf (Ib)


14
19
20
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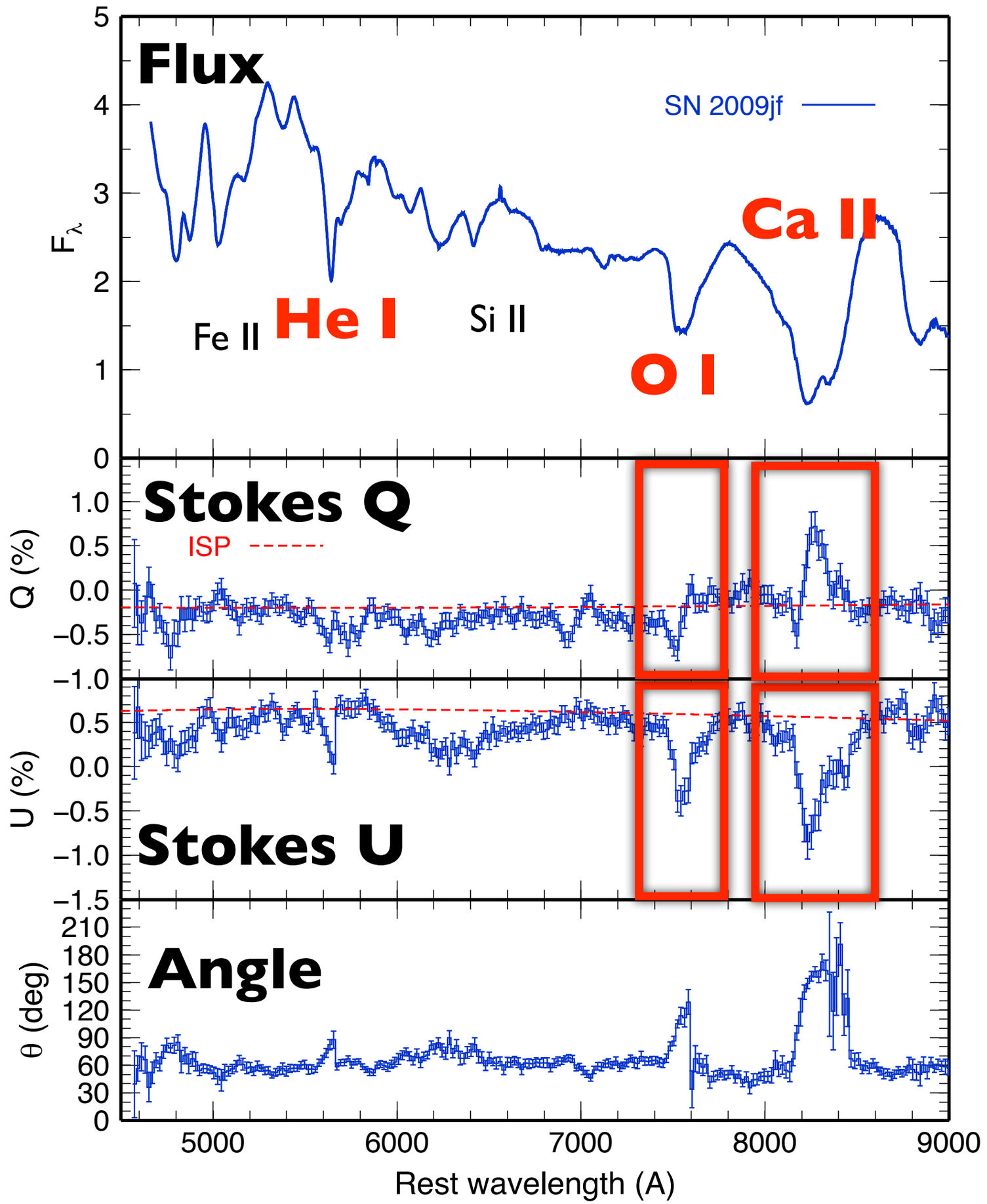
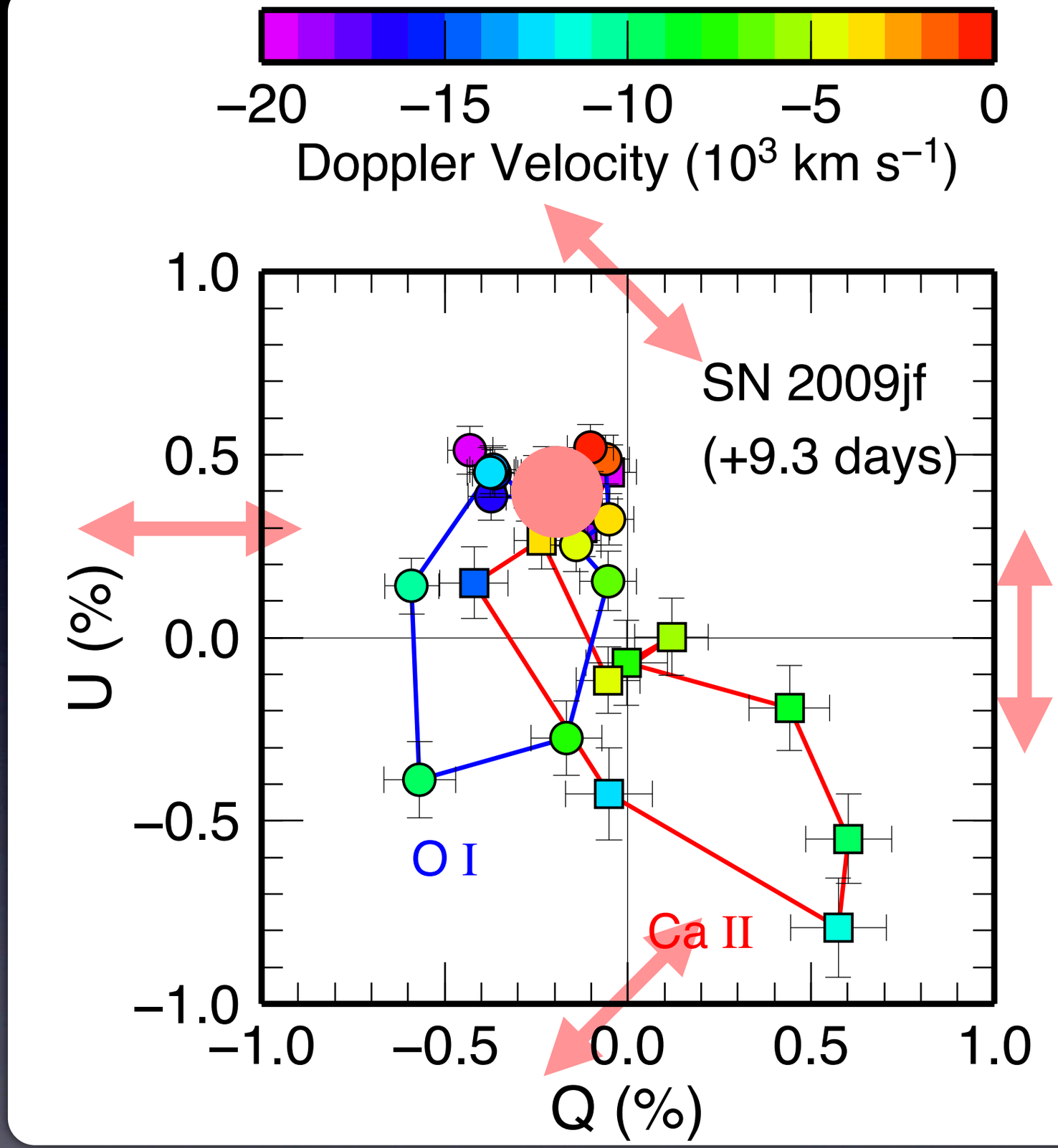
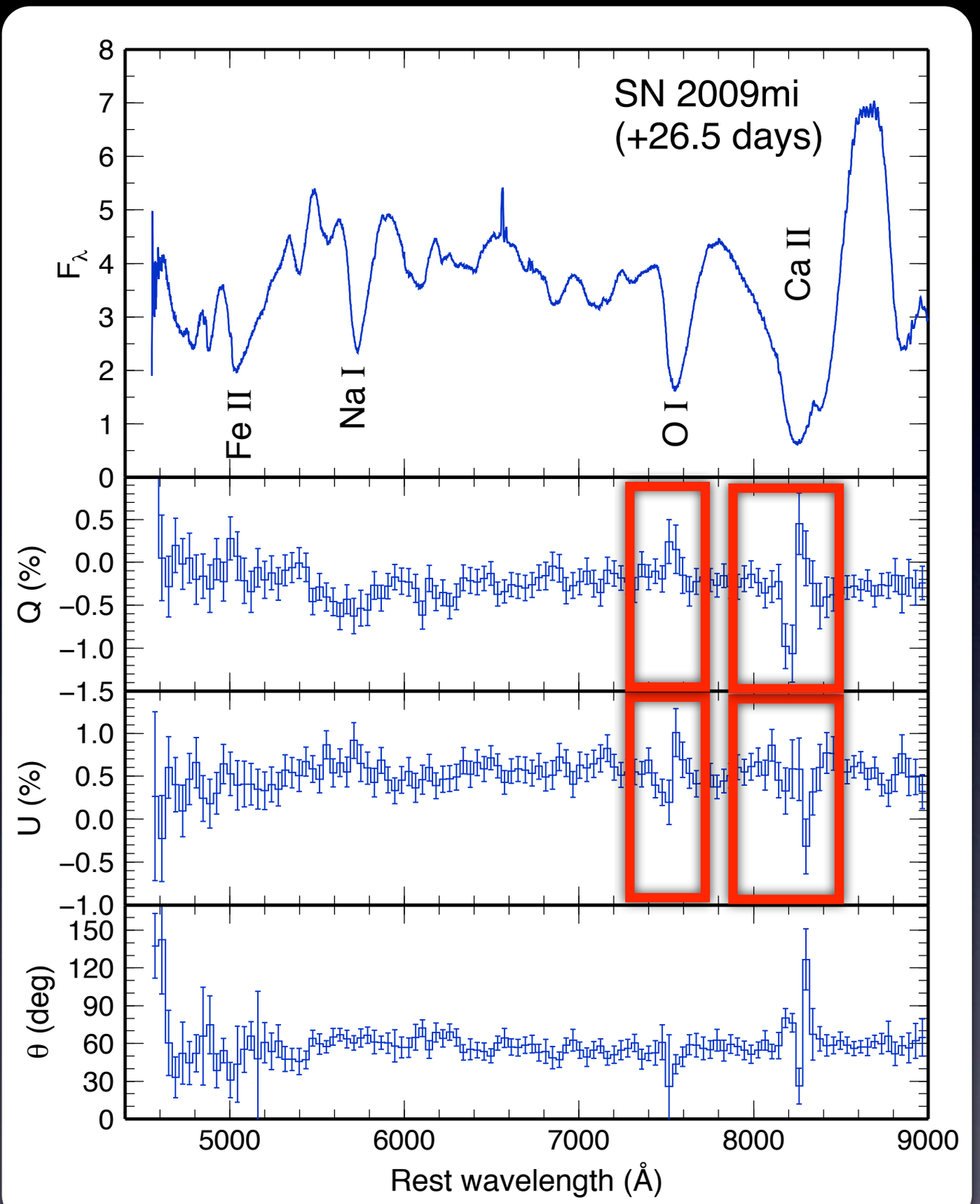

Flux
SN 2009jf
$F_\lambda$
Fe II
He I
Si II
Ca II
O I
Stokes Q
ISP
Q (%)
Stokes U
U (%)
Angle
θ (deg)
Rest wavelength (A)

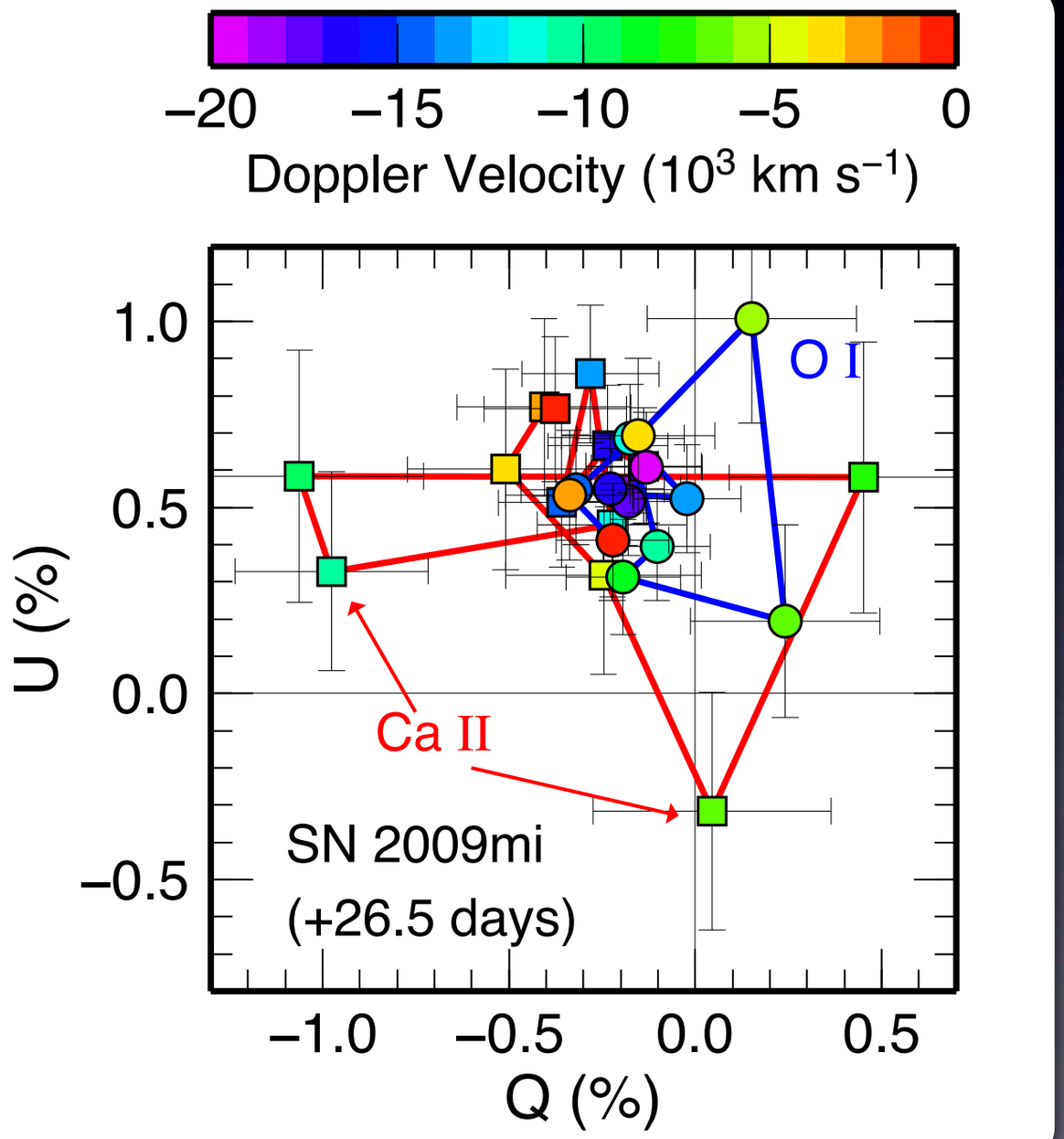



**Not axisymmetric**

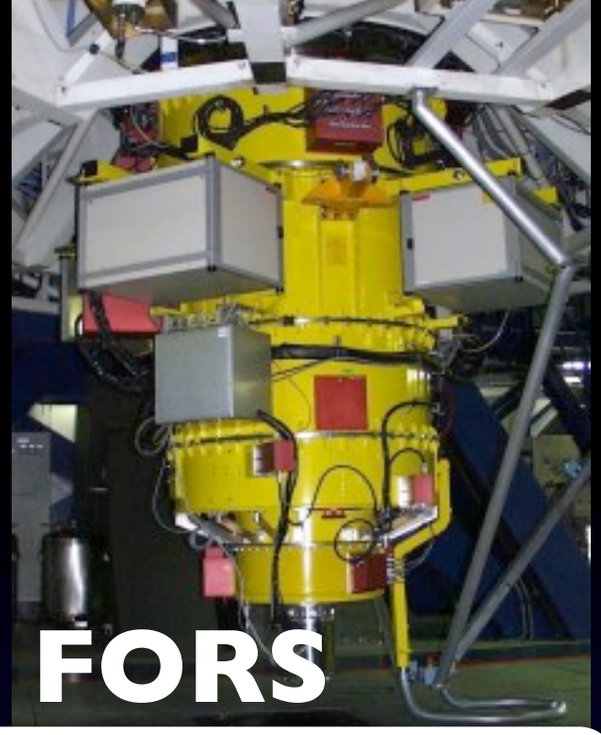
*(see also e.g., Kawabata+02, Wang+03, Maund+07)*

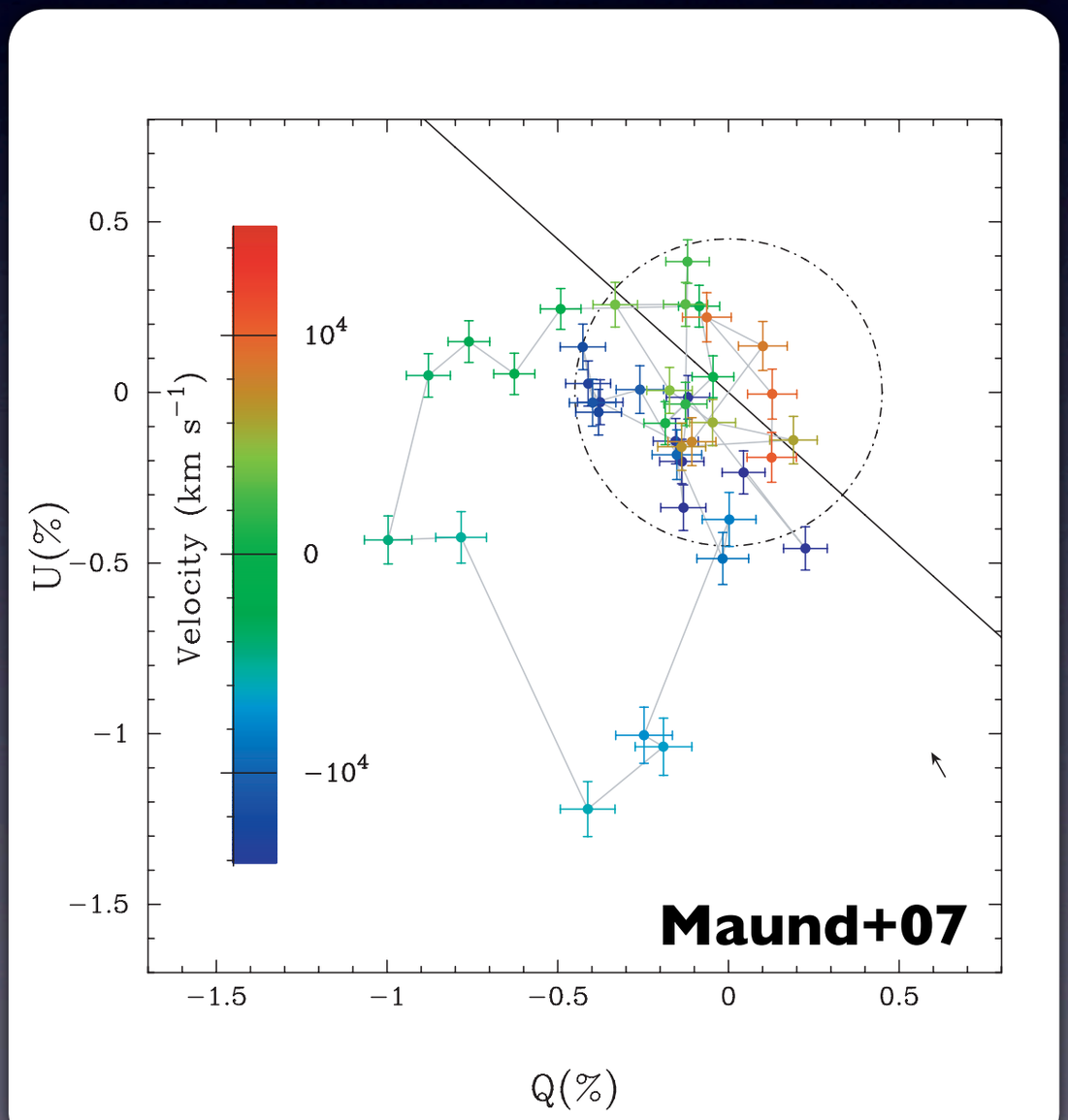
# SN 2009mi (Ic)

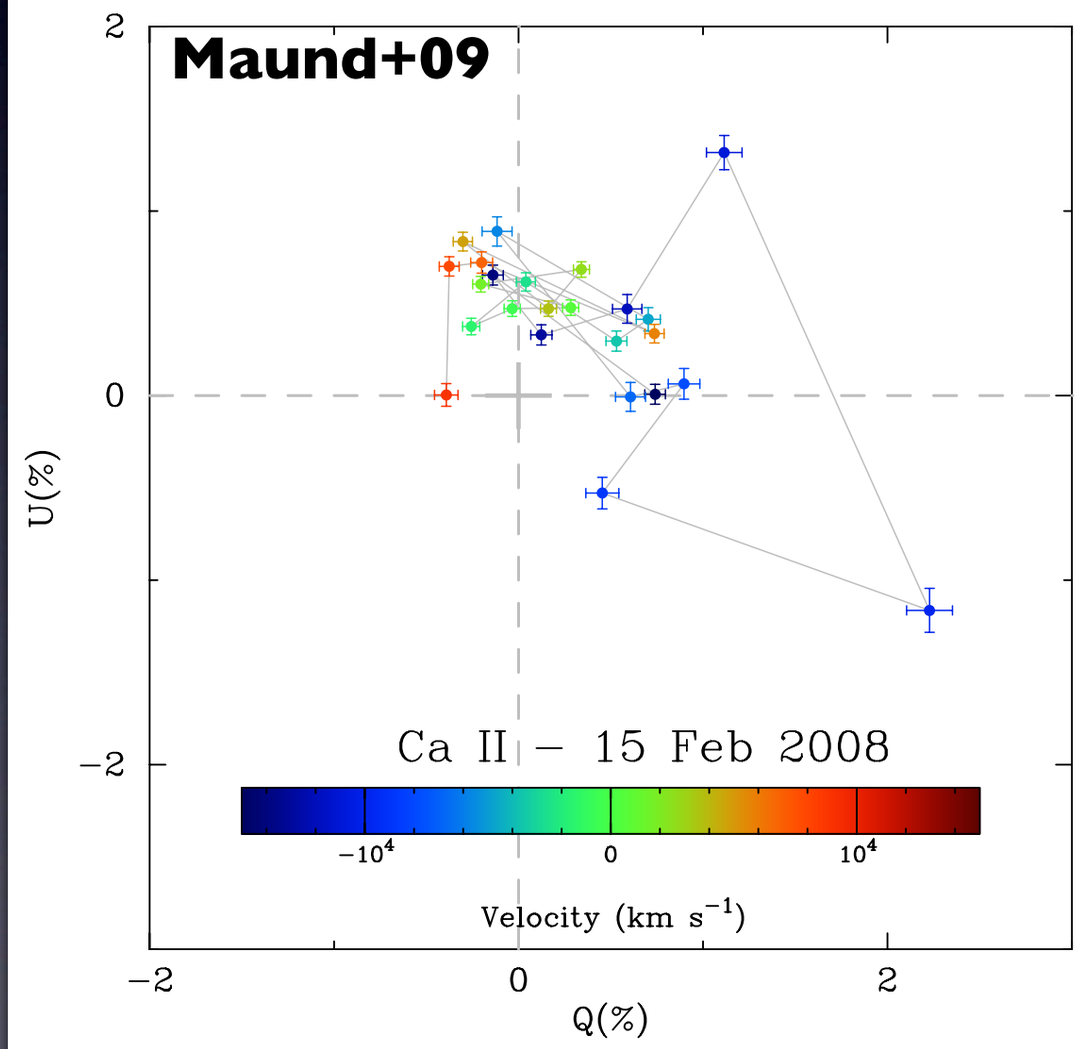

SN 2009mi
(+26.5 days)
Fe II
Na I
O I
Ca II
$F_\lambda$
Q (%)
U (%)
θ (deg)
Rest wavelength (Å)


Doppler Velocity ($10^3$ km $s^{-1}$)
O I
Ca II
SN 2009mi
(+26.5 days)
U (%)
Q (%)


VLT


FORS


Maund+07
U(%)
Q(%)
Velocity (km s$^{-1}$)
$10^4$
0
$-10^4$
0.5
0
−0.5
−1
−1.5

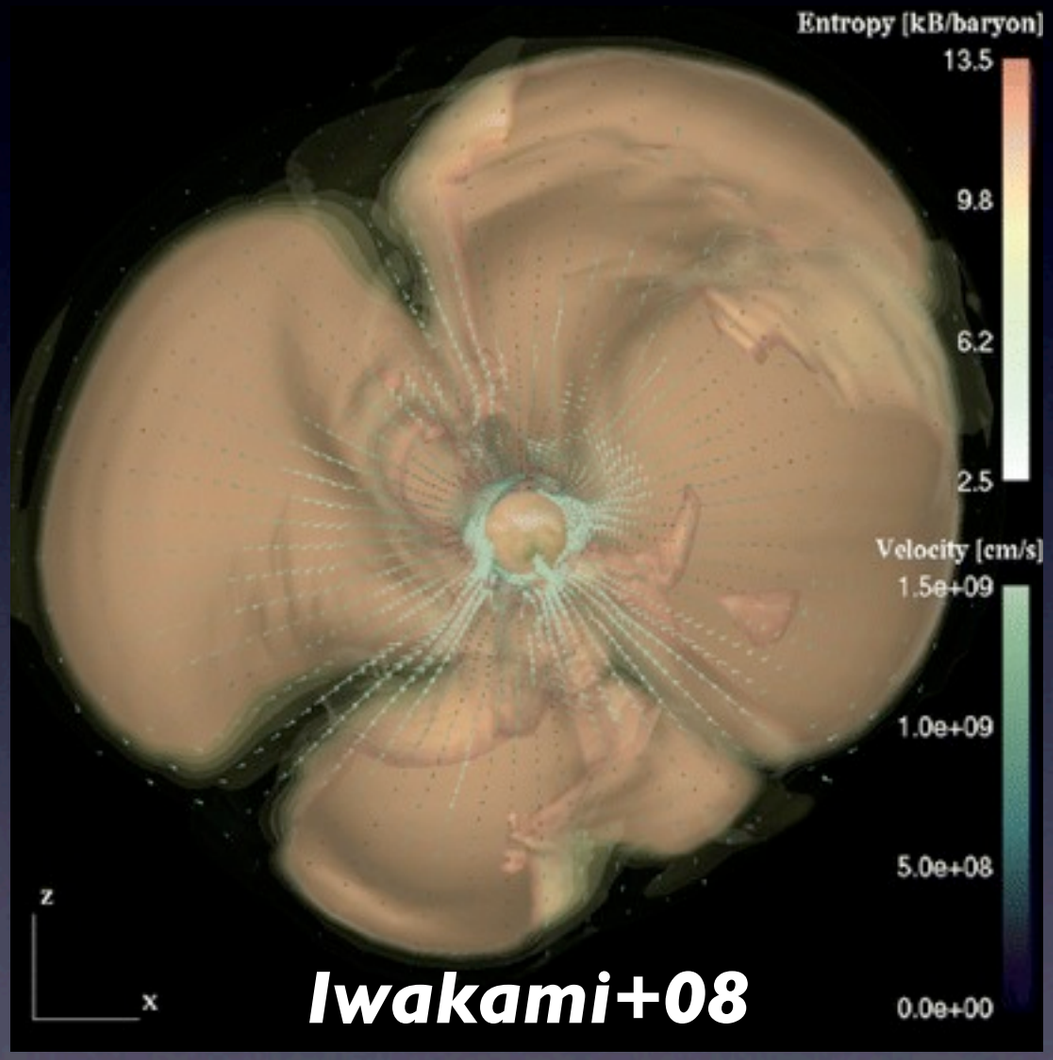

Maund+09
Ca II – 15 Feb 2008
U(%)
Q(%)
Velocity (km s$^{-1}$)
$-10^4$
0
$10^4$
2
0
−2

| Object | Type | 3D? | Ref. |
|---|---|---|---|
| SN 2002ap | Ic broad | YES | Kawabata+02, Leonard+02, Wang+03 |
| SN 2005bf | Ib | YES | Maund+07, MT+09 |
| SN 2007gr | Ic | No | MT+08 |
| SN 2008D | Ib | YES | Maund+09 |
| SN 2009jf | Ib | YES | MT+12 |
| SN 2009mi | Ic | YES | MT+12 |

***Non-axisymmetry is common***

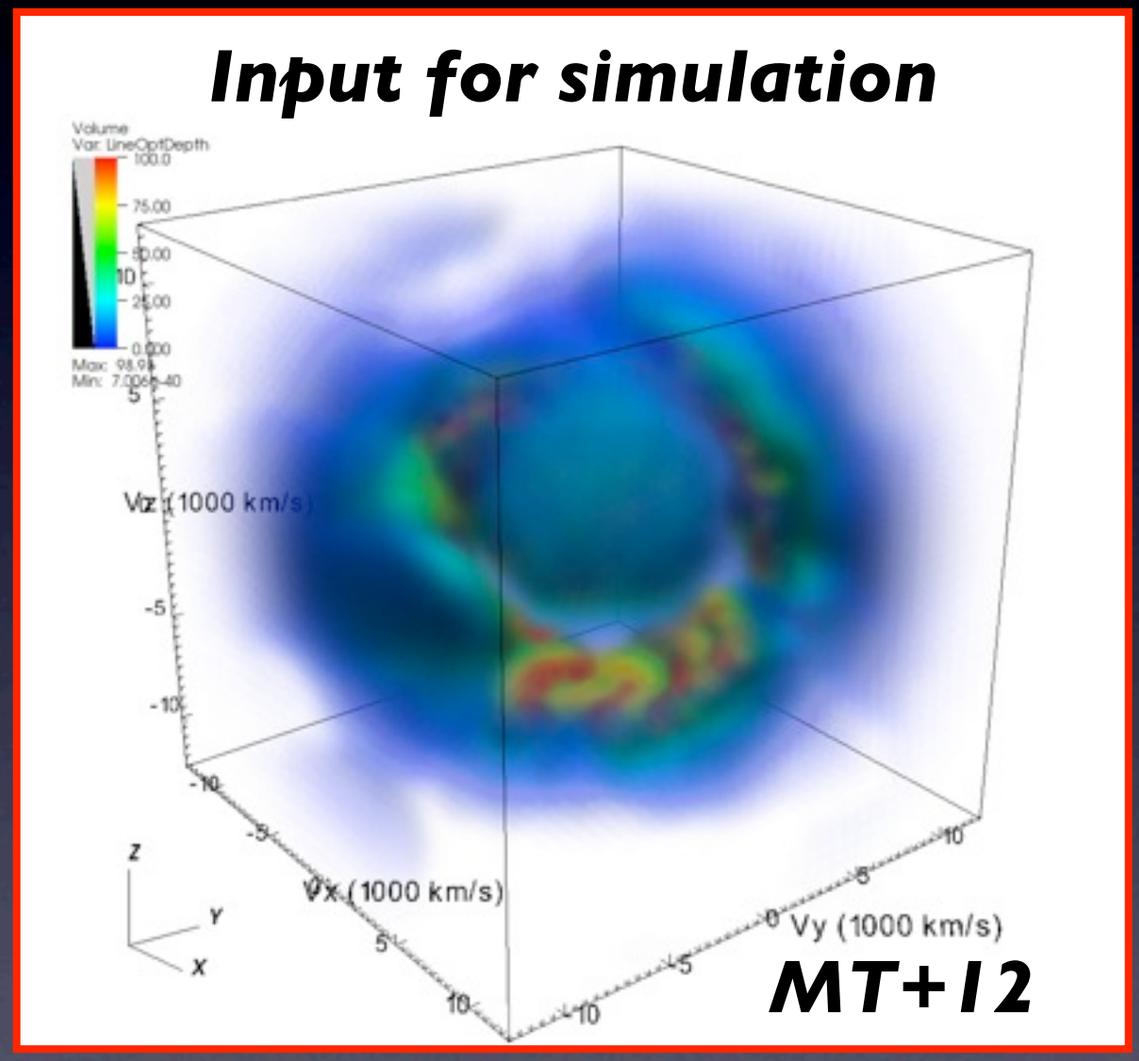
**(MT+2012, ApJ, 754, 63)**

# Hydrodynamic simulations



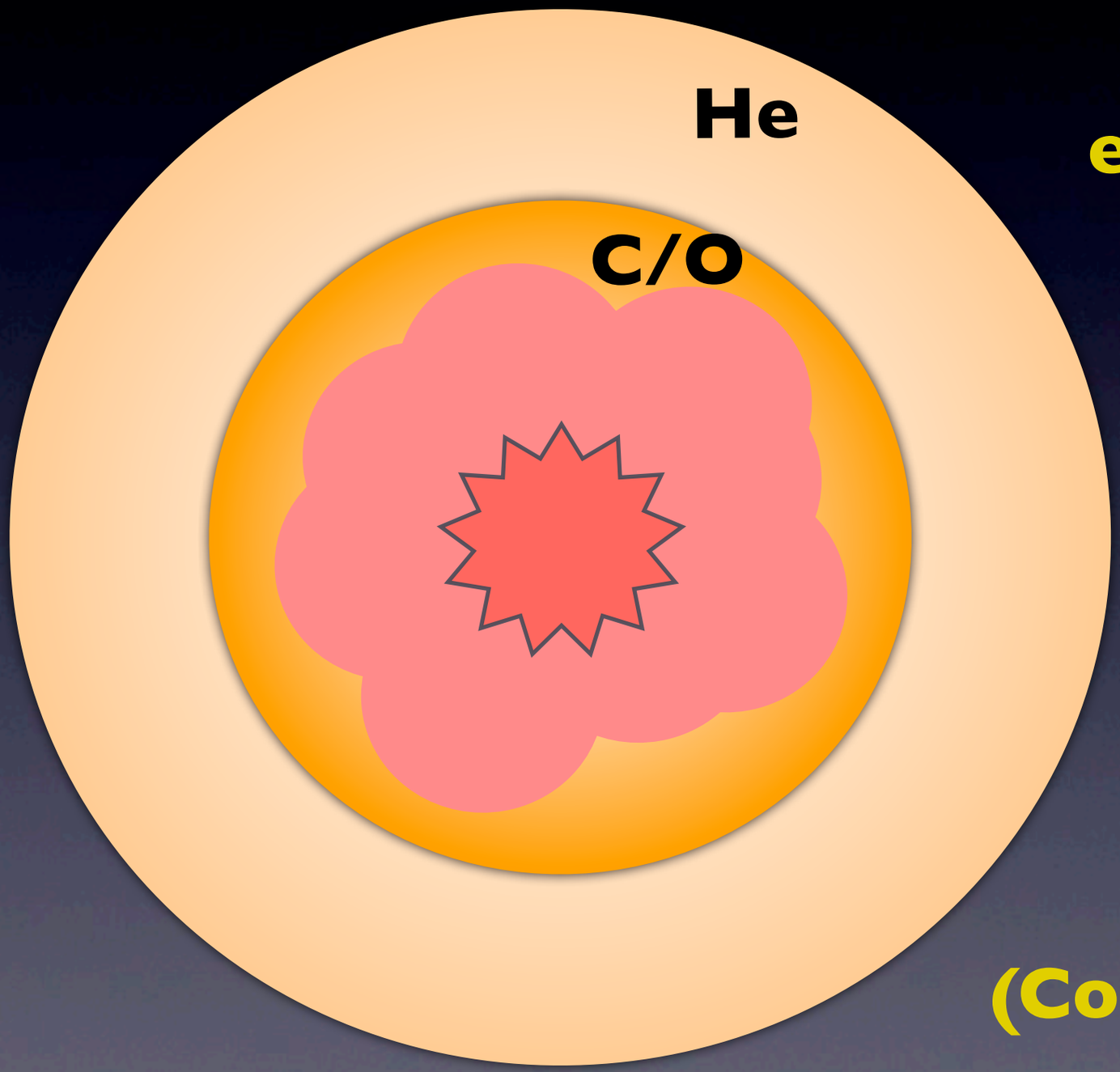

t ~ sec
r ~ $10^8$ cm

# Observations




t ~ day - year
r > $10^{14}$ cm

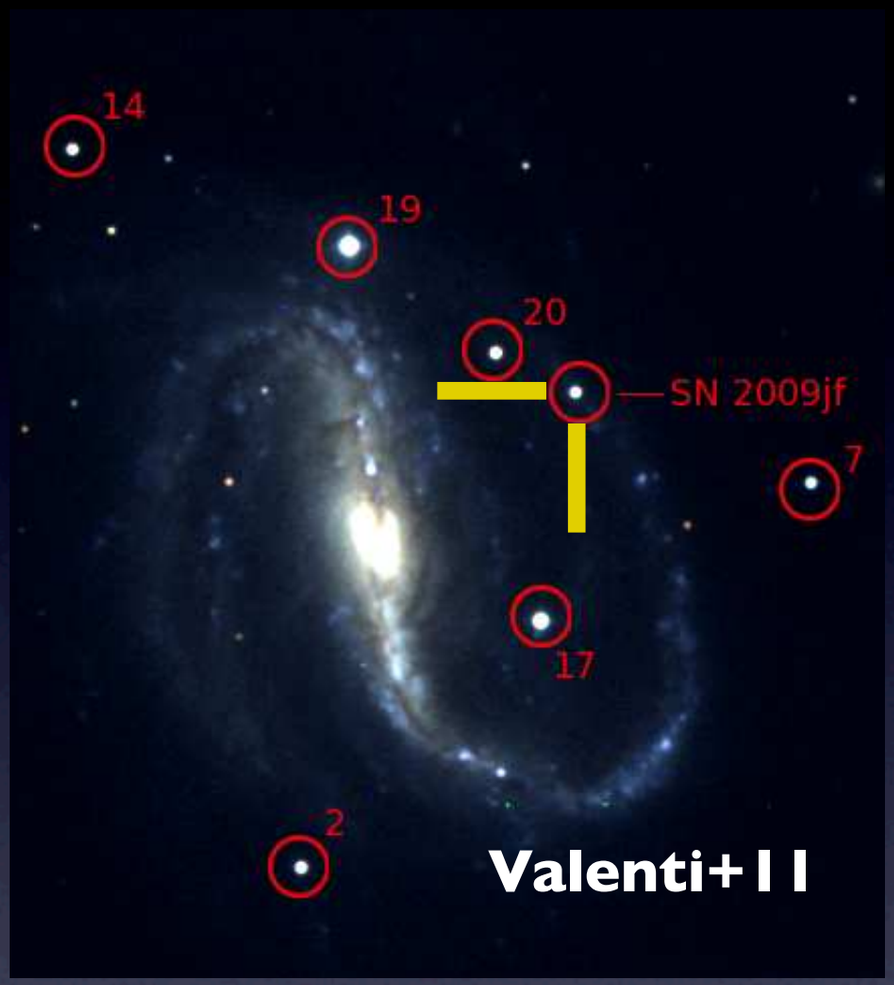
# Geometry of supernovae

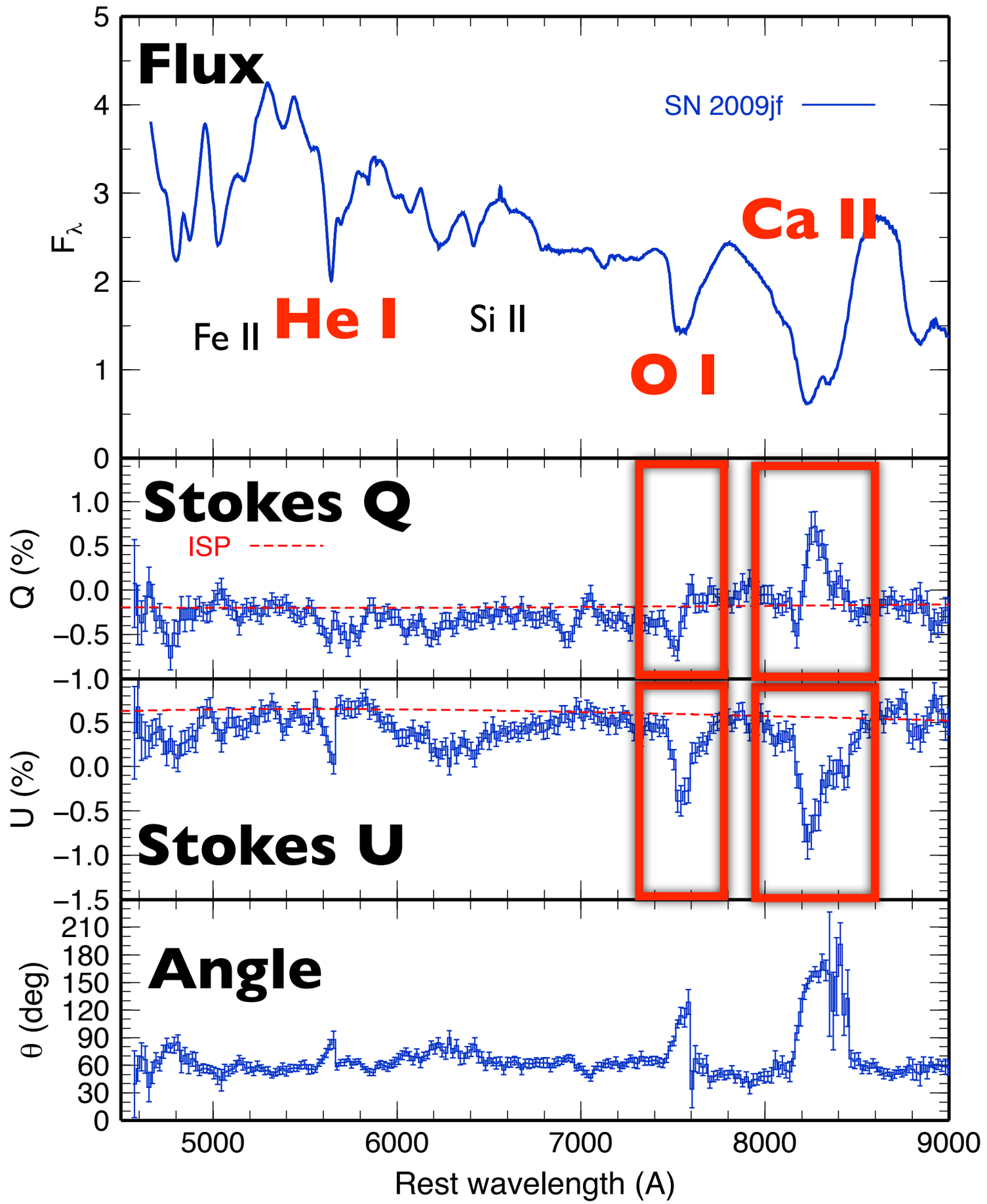



**Non-axisymmetric element distribution**

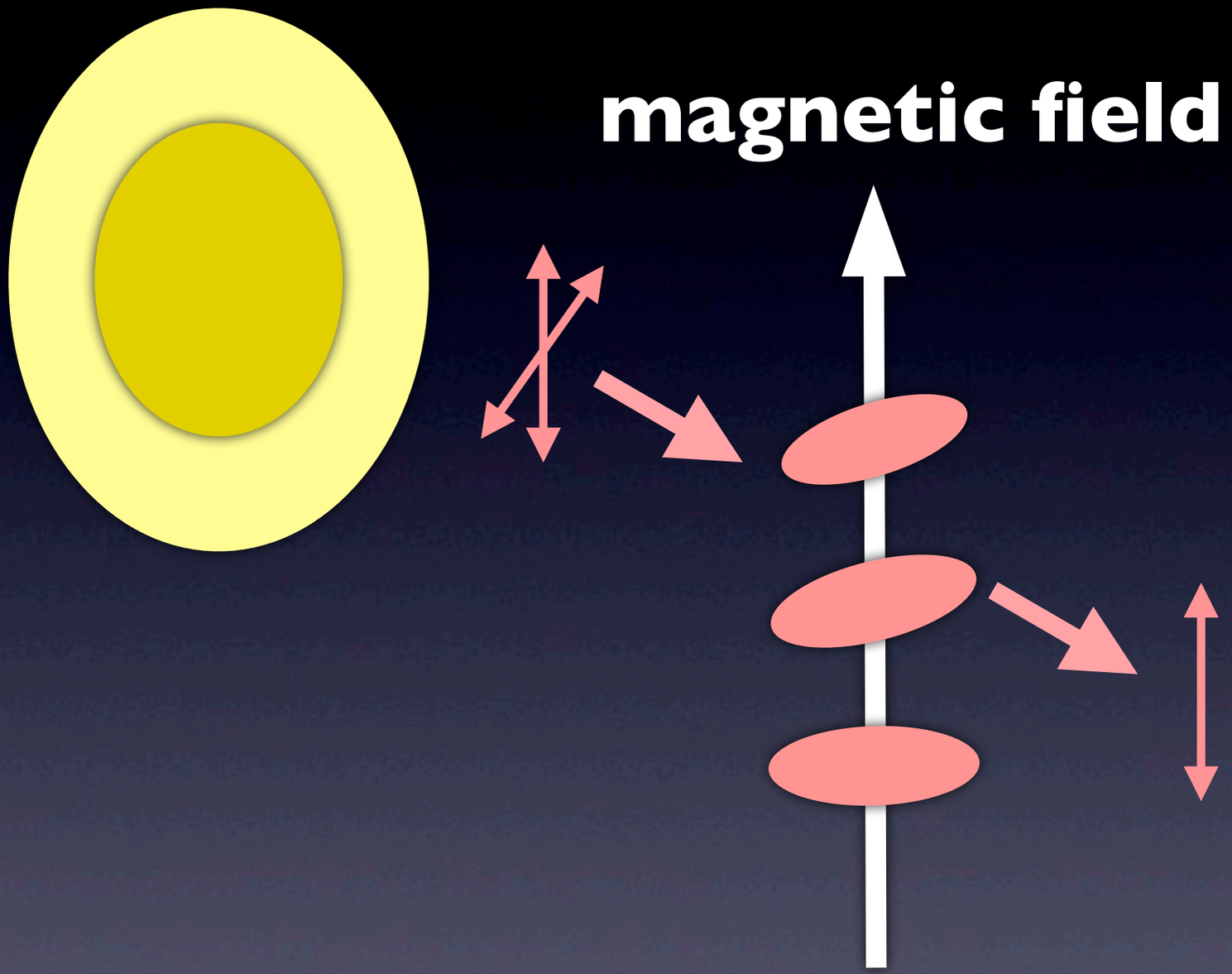
**Overall shape?**
**(Continuum polarization!)**

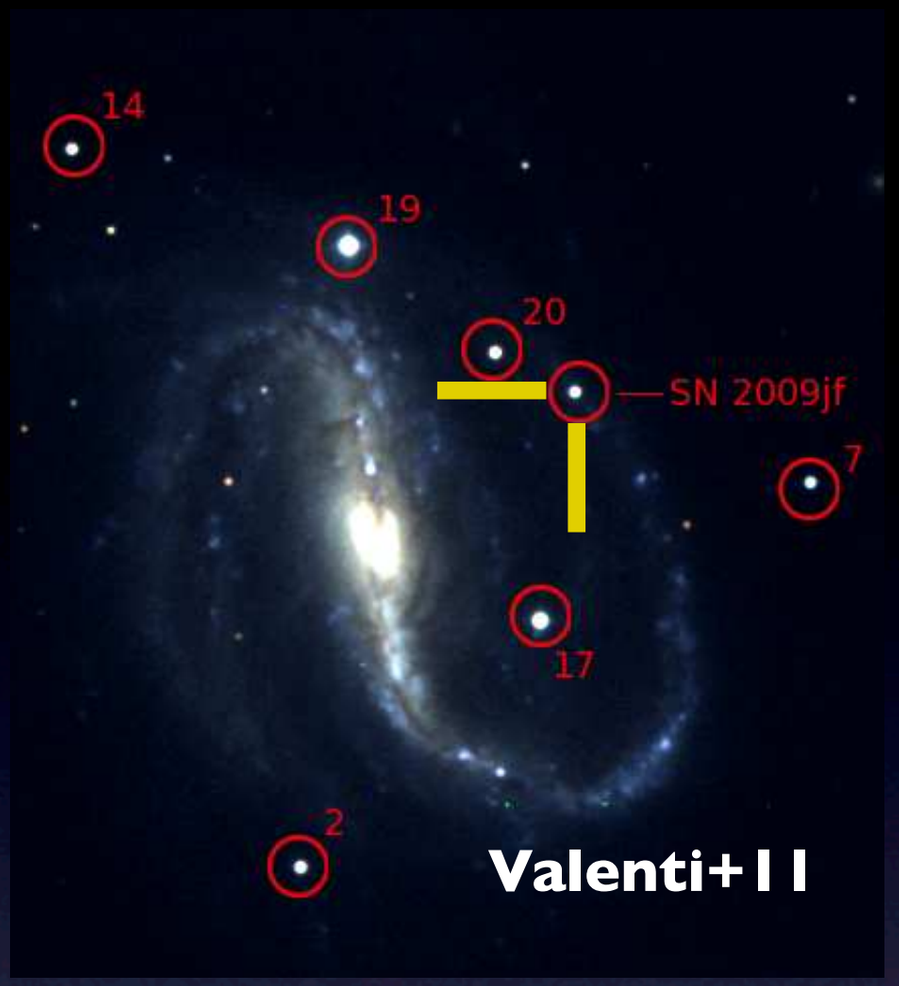
# SN 2009jf (Ib)


14
19
20
SN 2009jf
7
17
2
Valenti+11


Flux
SN 2009jf
$F_\lambda$
Fe II
He I
Si II
Ca II
O I
Stokes Q
ISP
Q (%)
Stokes U
U (%)
Angle
θ (deg)
Rest wavelength (A)

# Interstellar Polarization
## (especially in the host galaxy)



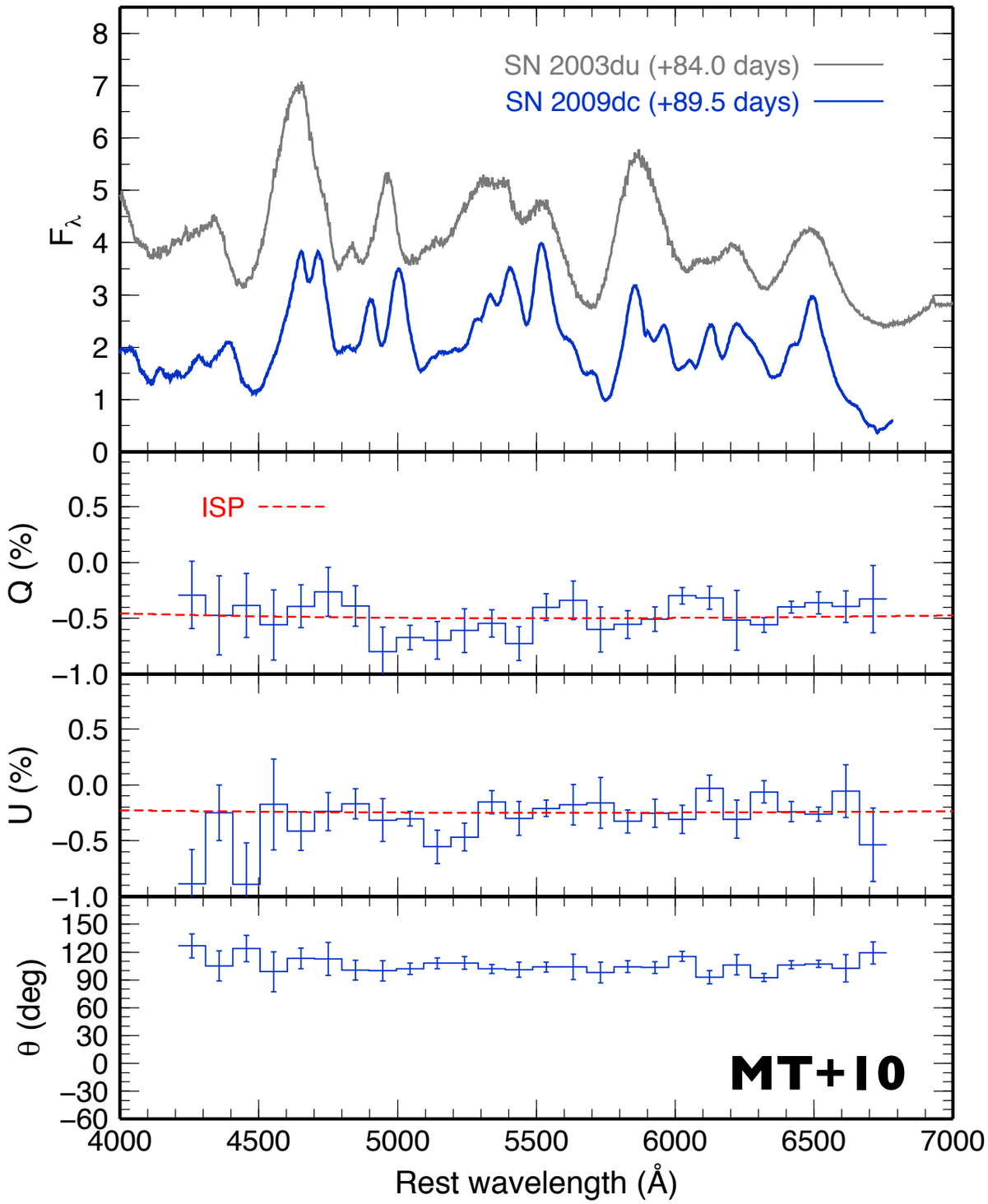




**ISP < 9 % x E(B-V)**
**Serkowski+75**

**SN + ISP**
**at 30 days**

**ISP**
**at ~100 days**

# ISP derived from “Unpolarized SN”



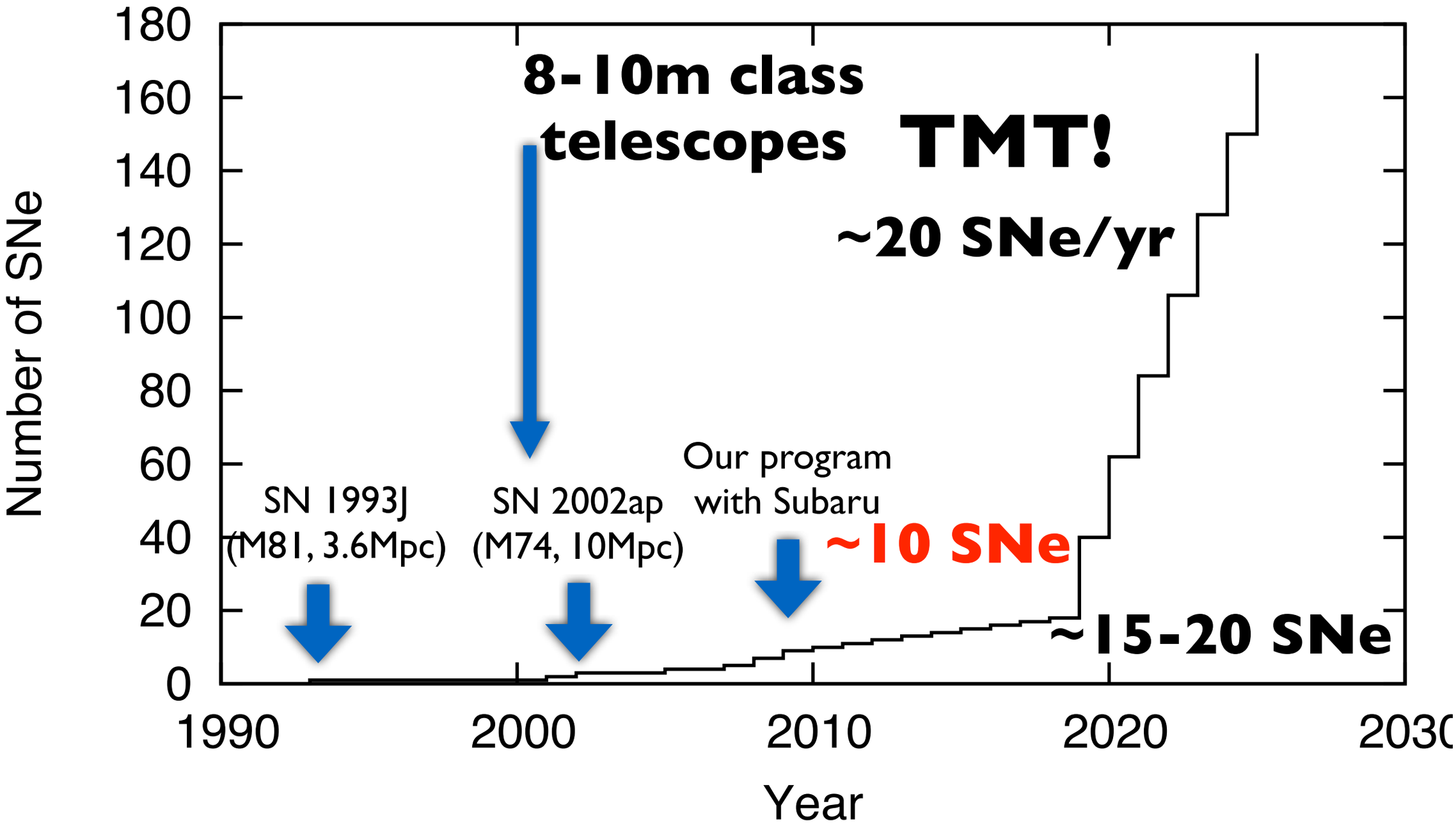

- **Polarization fitted by Serkowski’s law**

$$P(\lambda) \;=\; P_{\max} \exp\left[-K\, \ln^2\left(\lambda_{\max}/\lambda\right)\right]$$

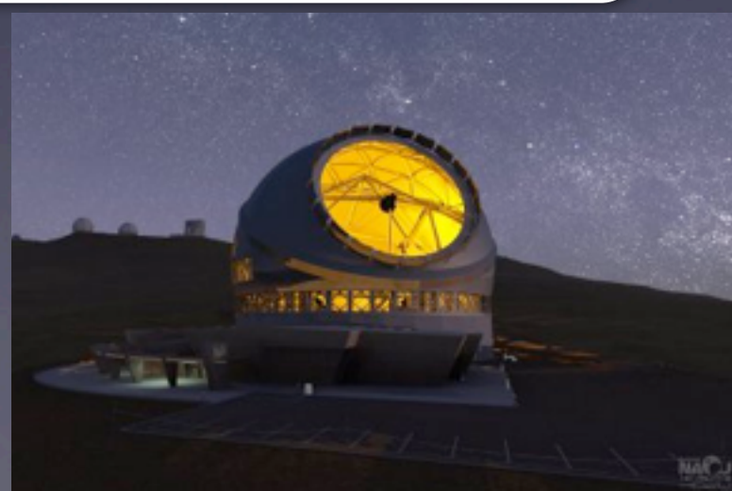
**19 mag**

# できたこと と できなかったこと

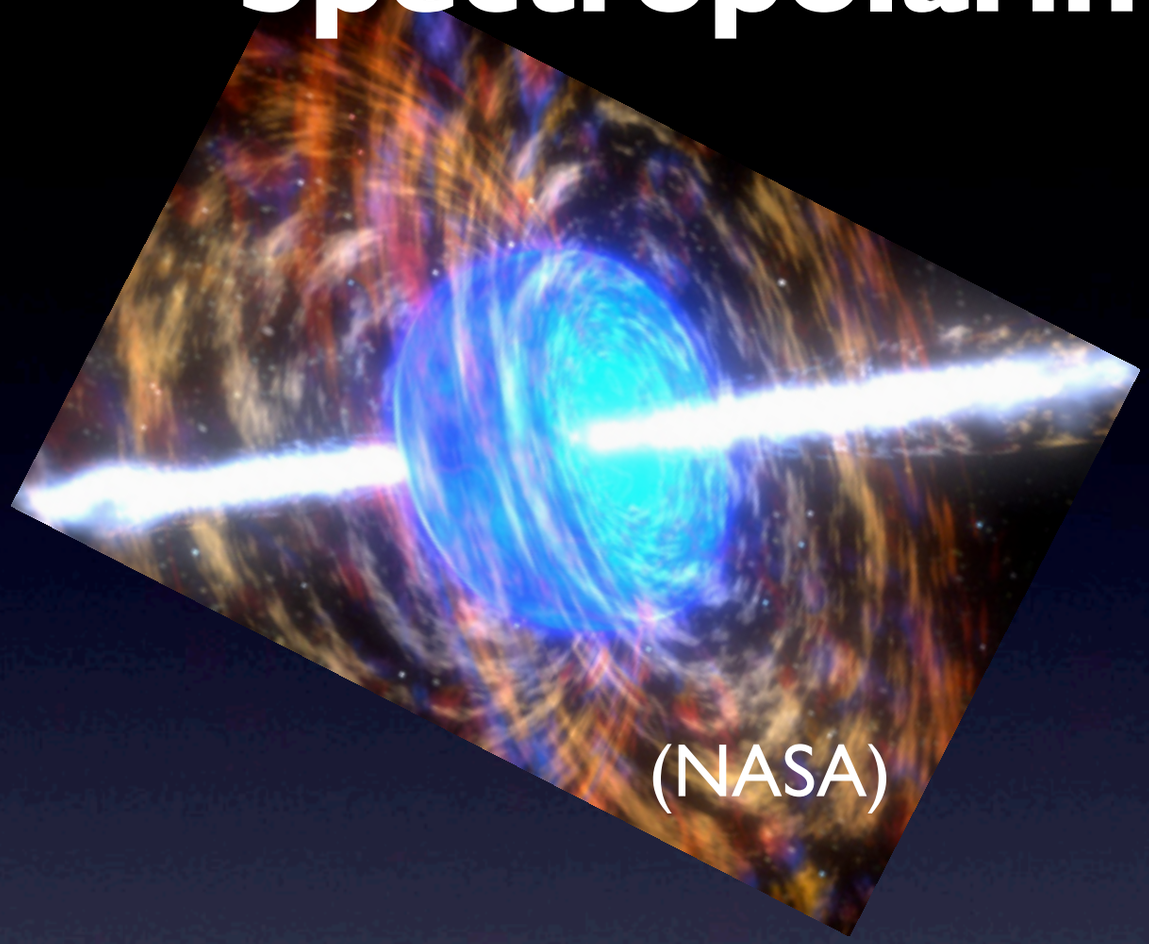
- できたこと
  - ライン偏光
    半径依存性がある＋元素依存性がある
- できなかったこと
  - 連続光偏光　「片手落ち」
  - 統計的性質　全６天体のみ
  - ガンマ線バースト　暗過ぎ



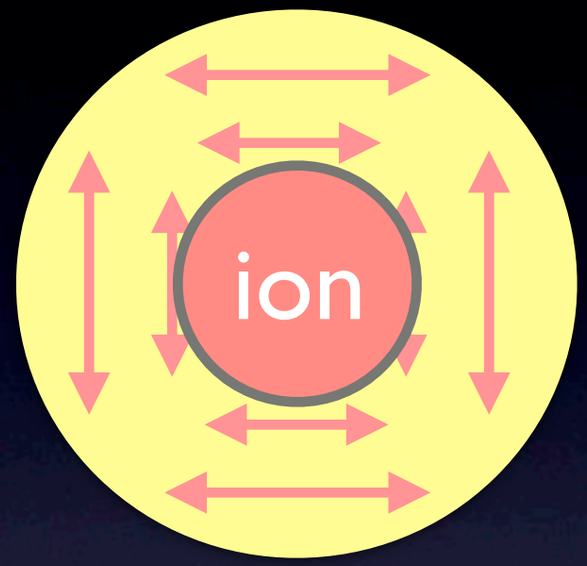

# ナスミス焦点での高精度偏光分光



# Spectropolarimetry of GRB-SNe




## On the sky




## Zero polarization

- **SN 2003dh/GRB 030329 @ z=0.17**
  **R~20.8 (Kawabata et al. 2003)**

**If line polarization is detected,**

- **Non-axisymmetry of GRB-SNe**
- **Non on-axis line of sight**

# Spectropolarimetry of supernovae

- **Geometry/Mechanism of SN explosion**
  - **Subaru/FOCAS spectropolarimetry**
    **R~500, ΔP < 0.1% for 16-18 mag**
- **Results**
  - **Change in polarization angle**
    **associated with absorption line**
    **=> Non-axisymmetry of SN explosion**
  - **Continuum polarization is still missing**
- **Future**