



# Transient Polarimetry in the era of Time-Domain Astronomy

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**银河系及近邻星系多波段全色时域研究研讨会**  
**Lijiang, Yunnan, 2024-08-05**

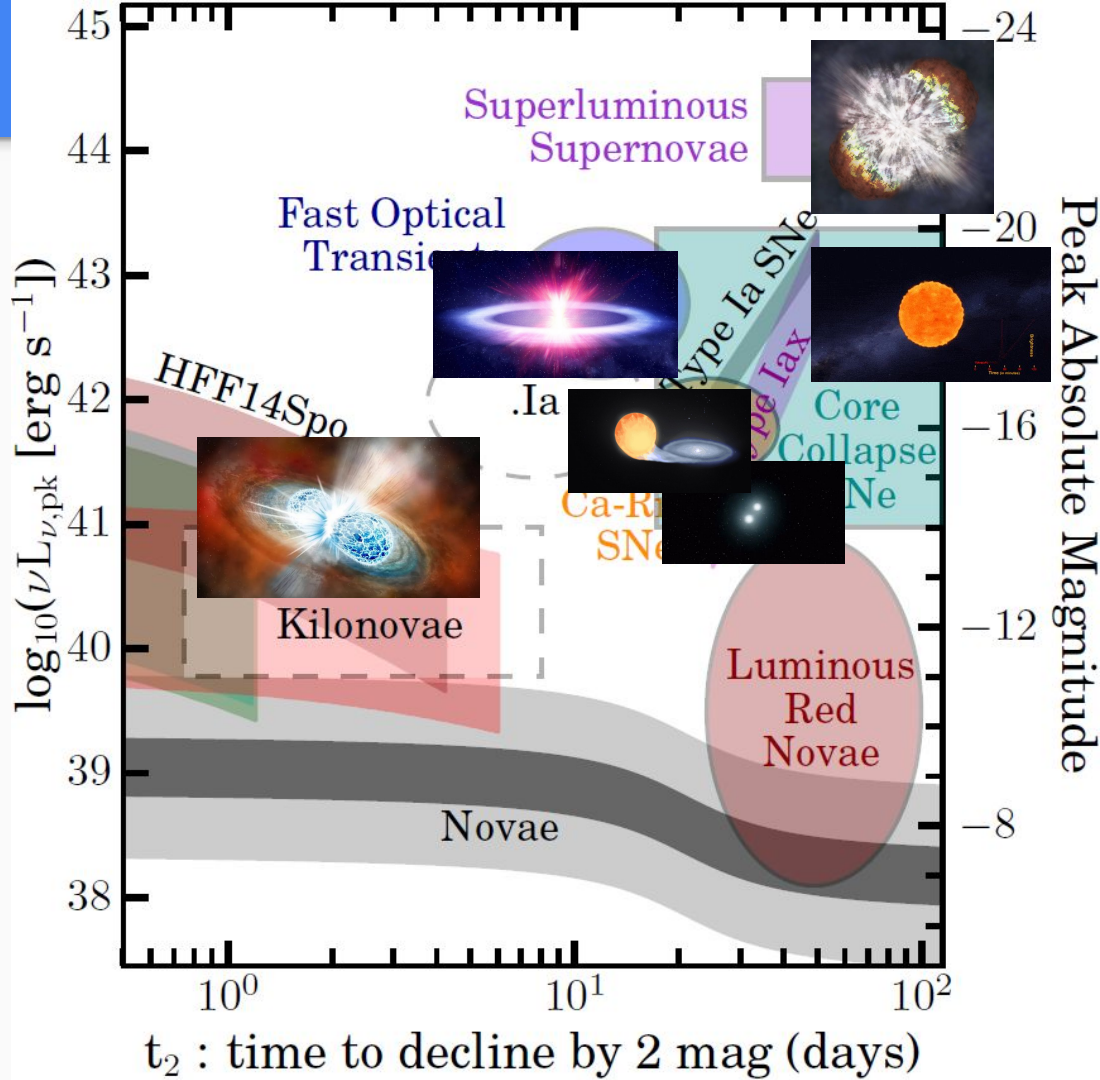
# Summary

**Q: Transient Shape?**

**A: Diverse;  
mostly aspherical**

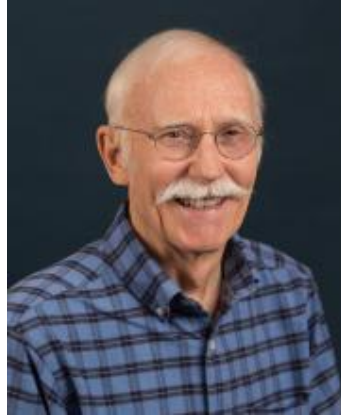
**Q: More Opportunities?**

**A: Binary, (Exo)Planets,  
Accretion, Dust & B-field,  
AGN, Kilonova, Galaxy...**



## The team:

**Lifan Wang (Texas A&M)**



Dietrich Baade (ESO)

Mattia Bulla (U of Ferrara)

Aleksandar Cikota (NOIRLab)

Peter Hoeflich (Florida State)

Justyn Maund (RHUL)

Ferdinando Patat (ESO)

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## UC Berkeley:

**Alexei V. Filippenko**

Thomas G. Brink

Sergiy Vasylyev

Kishore Patra

Weikang Zheng



## Weizmann & ZTF:

**Avishay Gal-Yam**

Ofer Yaron

Steve Schulze

Erez Zimmerman

Ido Irani

Rachel Bruch



Spectropolarimetry of Supernovae

Wang & Wheeler 2008ARA&A..46..433W

## **Part I:**

**Why transient geometry?**

**How do we know?**

**What have we learned?**

## **Part II:**

**More opportunities for Mephisto**

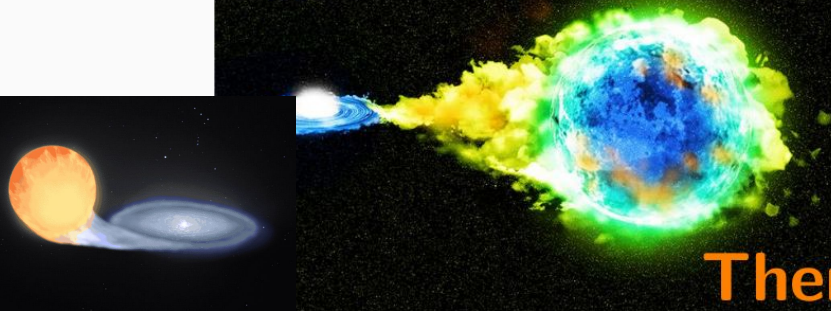
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+

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# The shape of cosmic explosions

Type Ia: Single Degenerate



Kavli/IPMU

Double Degenerate



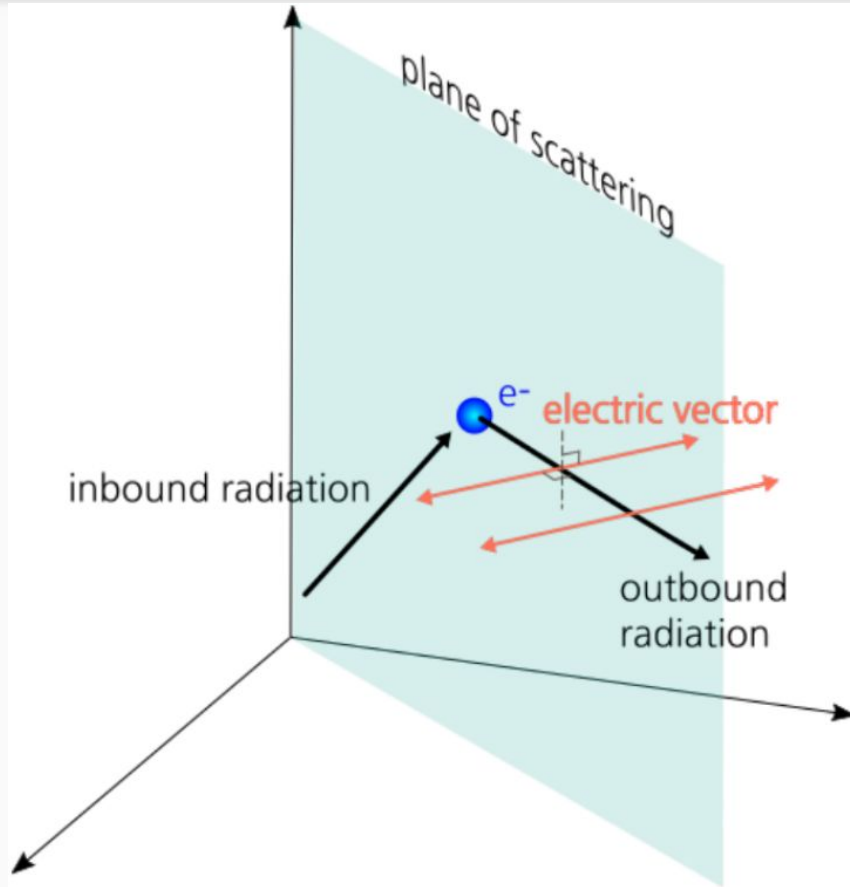
NASA/CXC/A.Hobart

Thermonuclear

Core-Collapse



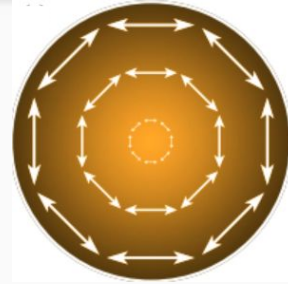
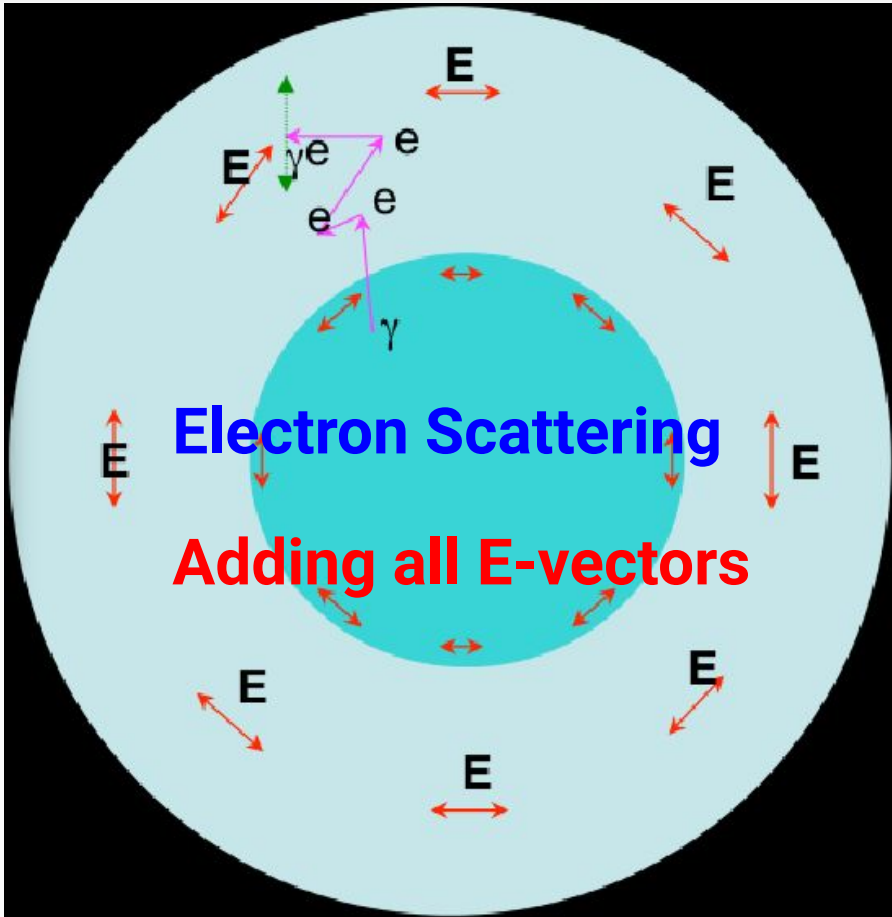
# How polarimetry measures the geometry?



**Basic principle:  
Electron (Thomson)  
Scattering**

**Electric vector  
⊥  
the plane of scattering**

# How Polarimetry measures the geometry?

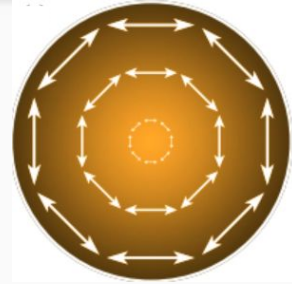
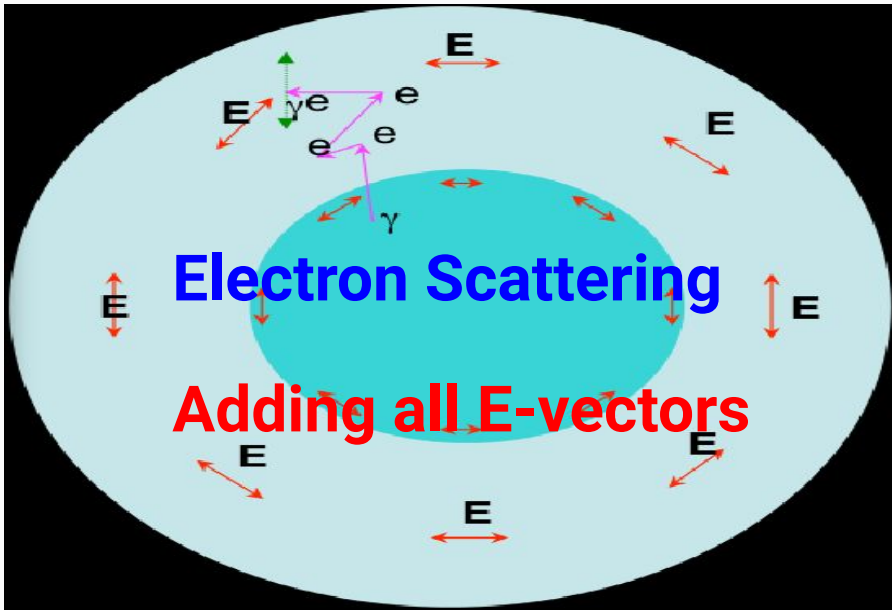


**Spherical:  $p = 0$**

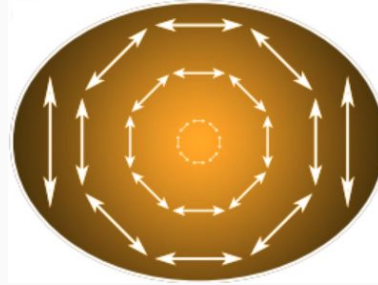
**The last scattering:**

**how the photon will be polarized;**

# How Polarimetry measures the geometry?



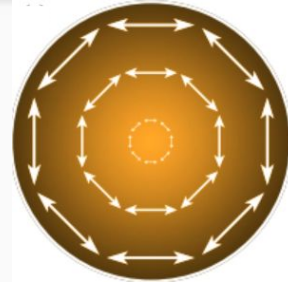
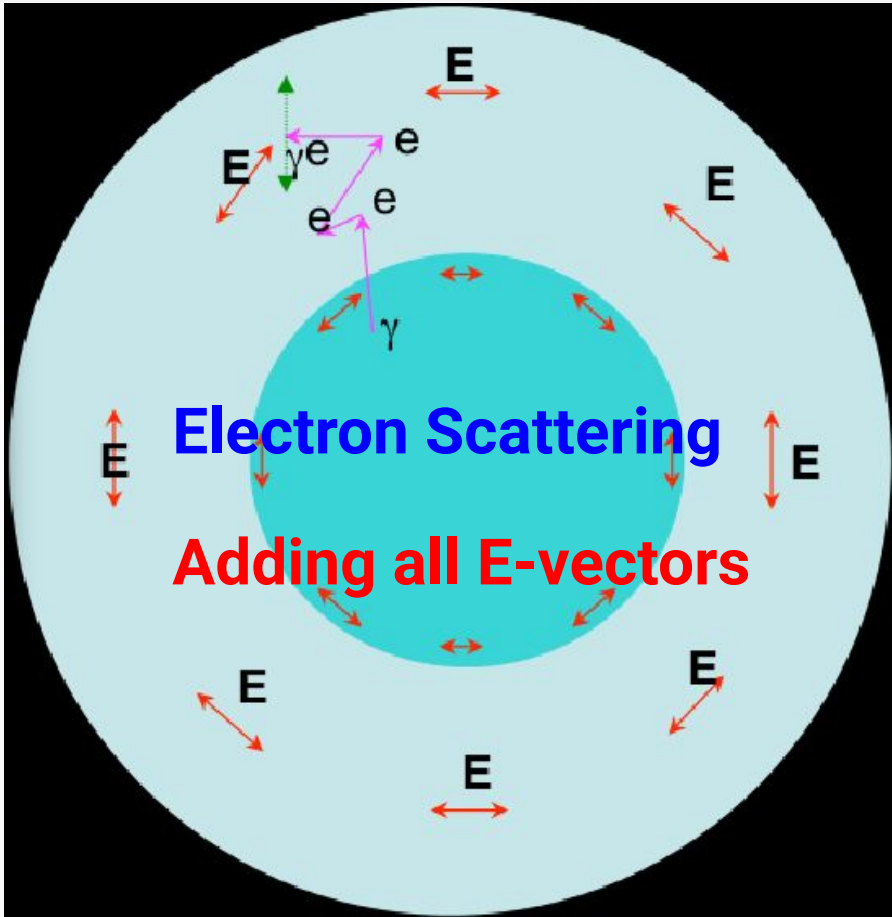
Spherical:  $p = 0$



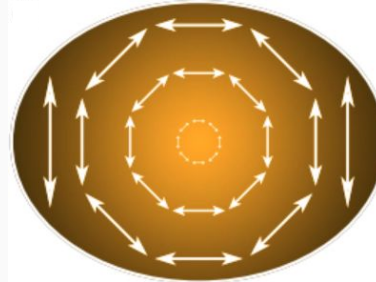
Aspherical:  $p \neq 0$



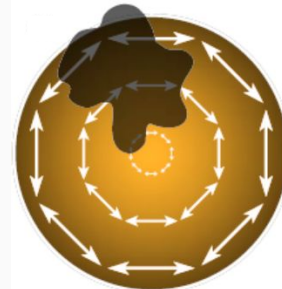
# How Polarimetry measures the geometry?



Spherical:  $p = 0$

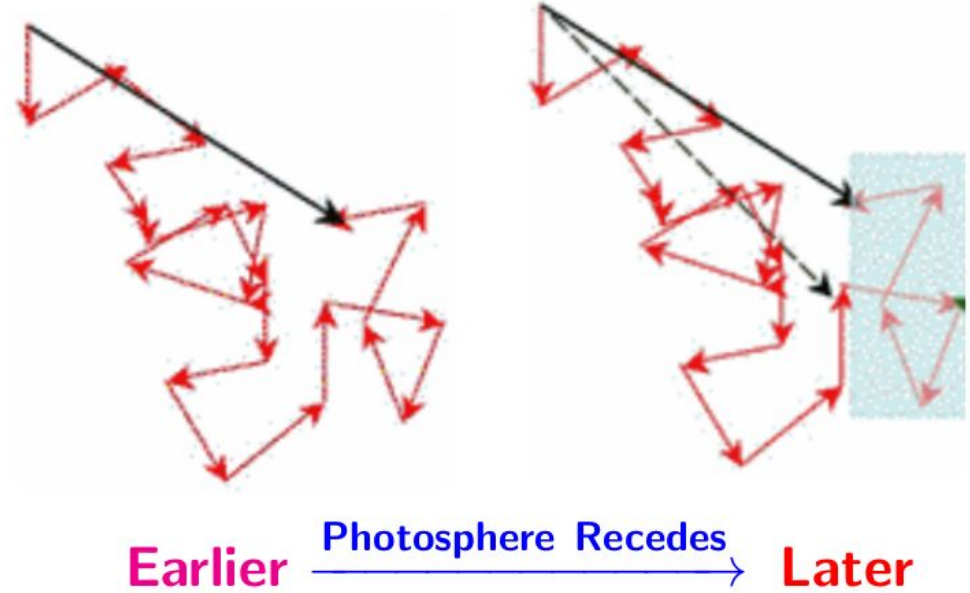
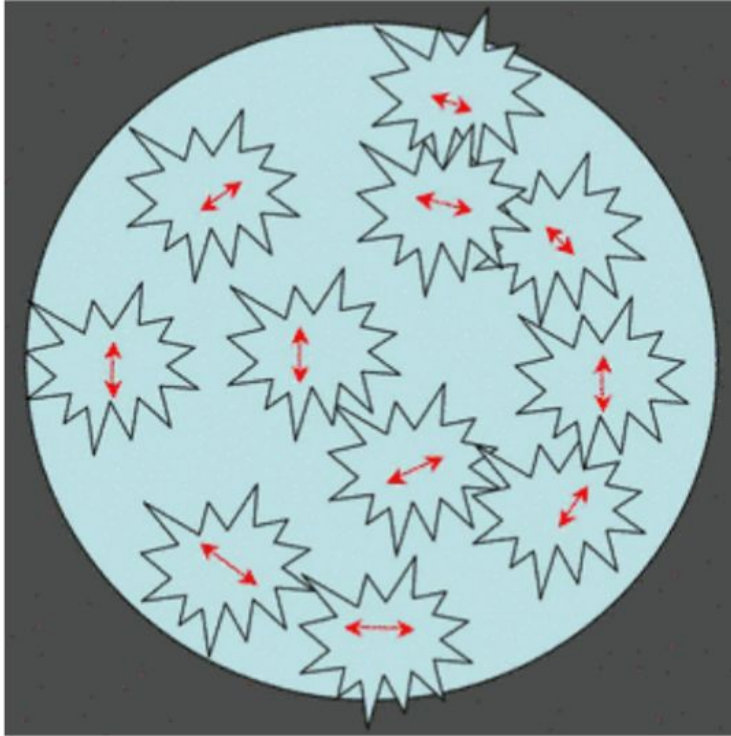


Aspherical:  $p \neq 0$



**Aspherical  
(elements):  
Spectral line  $p \neq 0$**

# How Polarimetry measures the geometry?

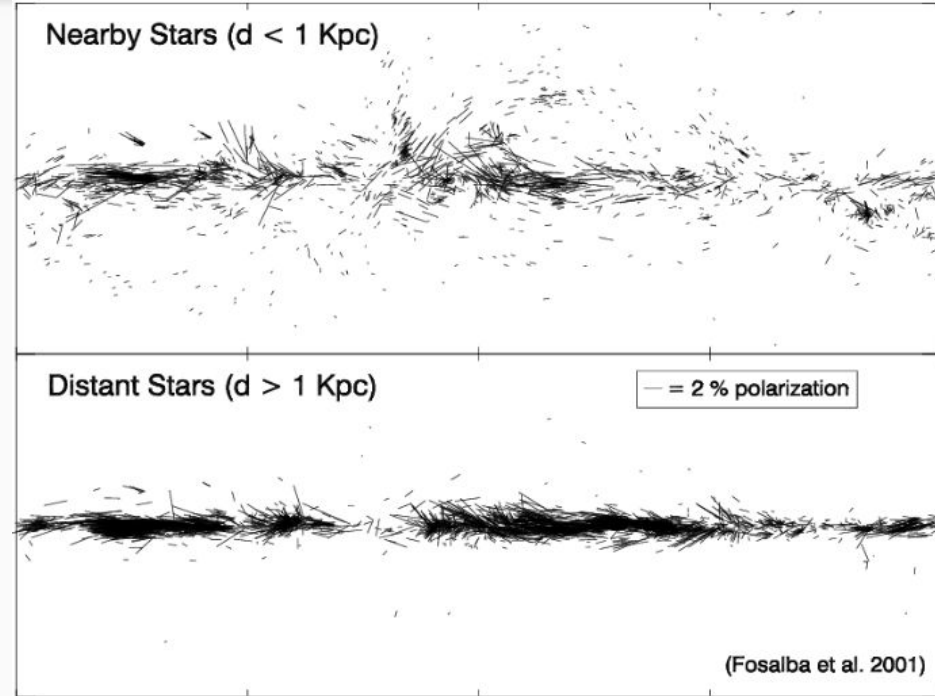
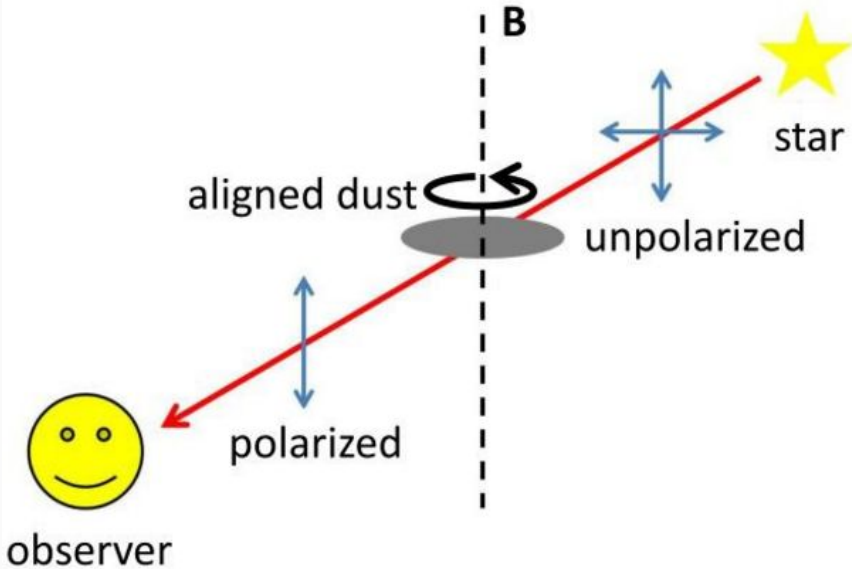


**Polarization may change over time: seeing different layers**

**Ejecta Expand  $\rightarrow$  Density Drops  $\rightarrow$  More Transparent  $\rightarrow$  Inner Seen**

# Tracing the B-field with aligned dust grains

interstellar polarization



**Large & Small-Scale B-field, Galaxy & Star-forming regions**

**Grain Size Distribution**

# Polarimeters

## Big Mirrors:

**FORS2 @ 8.2-m VLT UT1 (Chile)**

**LRISp @ 10-m Keck (US HI)**

**GPI-2.0 @ 8.1-m Gemini-N (Imaging, upcoming, US HI)**

**RSS @ 7.9–9.2-m SALT (South Africa)**

**PEPSI @ LBT (Double 8.4-m, R~100,000, US AZ);**

**SPOL (optical) and MMTPOL (Near IR) @ 6.5-m MMT, US AZ**

**WIRC+Pol @ 5-m Palomar 200 Inch (Near-IR, R~100, US CA)**

**ISIS (Spec) & LIRIS (Imaging) @ 4.2-m WHT, Spain**

...

## Small Mirrors:

**Kast (Spec only) @ 3-m Shane, US CA**

**ACS/WFC @ 2.4-m HST**



**Himaraya Chandra Telescope @ 2.0-m HCT, India**

**RINGO→MOPTOP (Imaging only) @ 2-m LT, Spain**

**HOWPoL @ 1.5-m Kanata Telescope, JP**

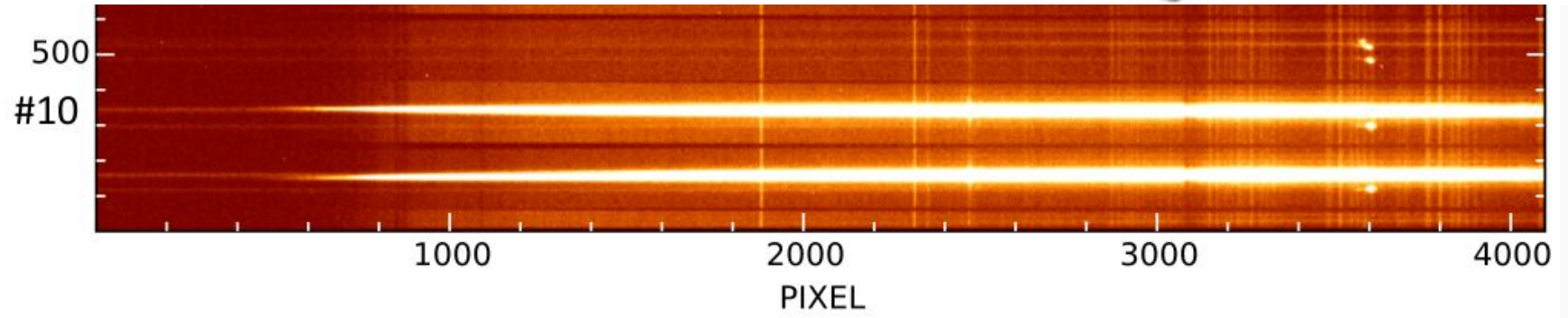
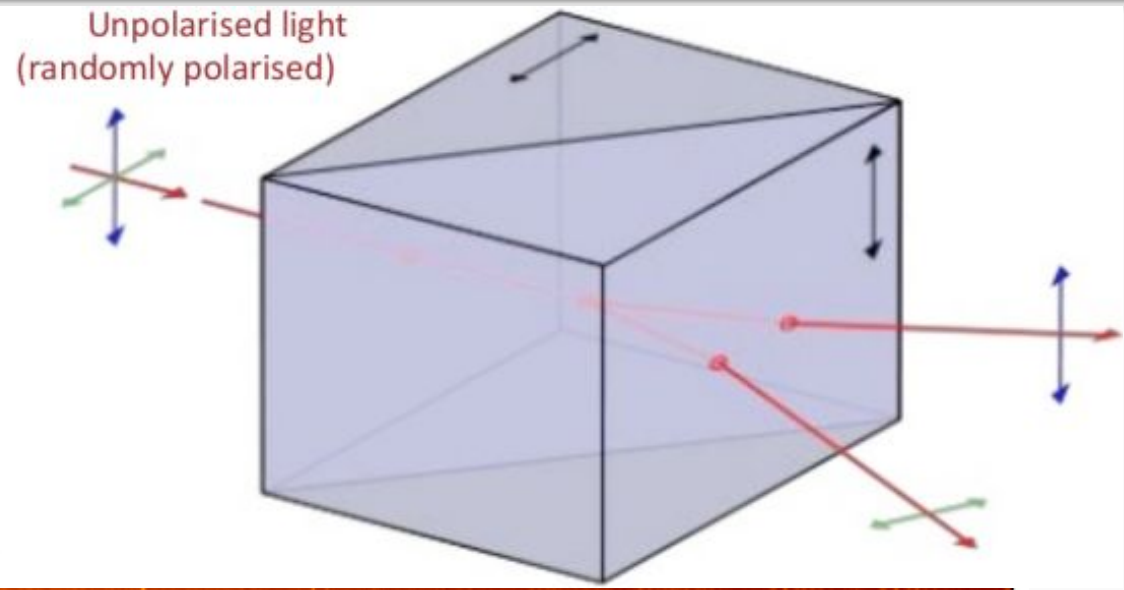
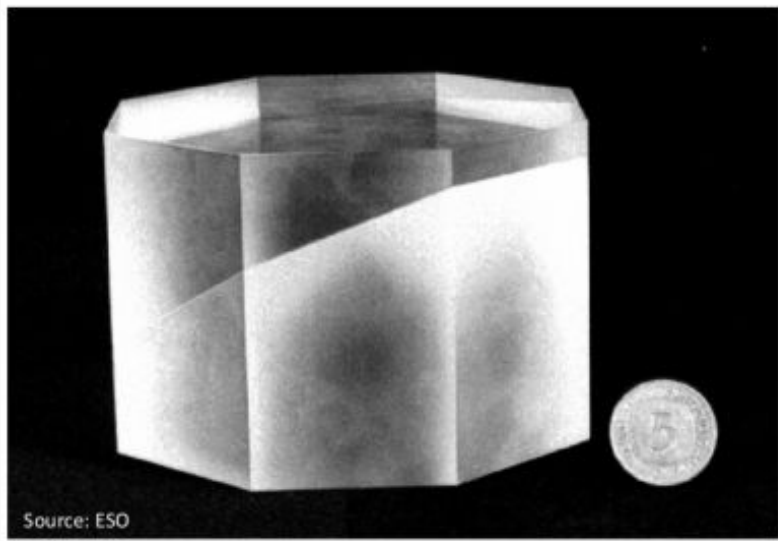
**Good Ref for**

**Mephisto Pol**

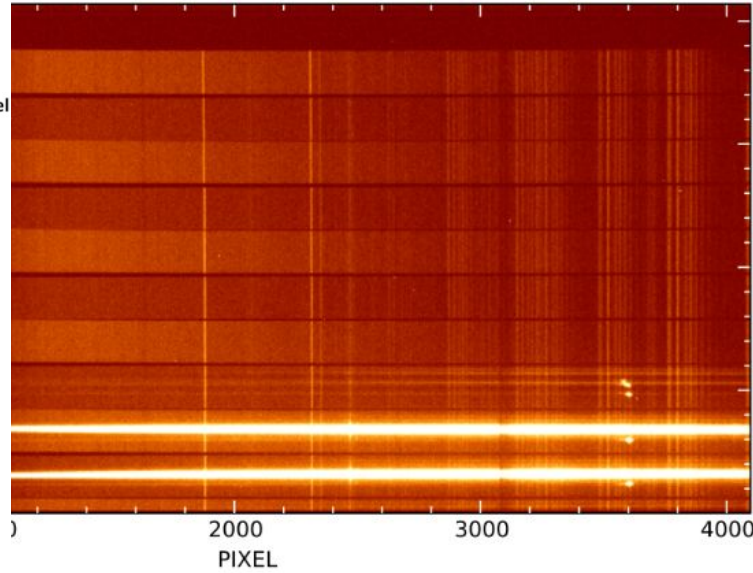
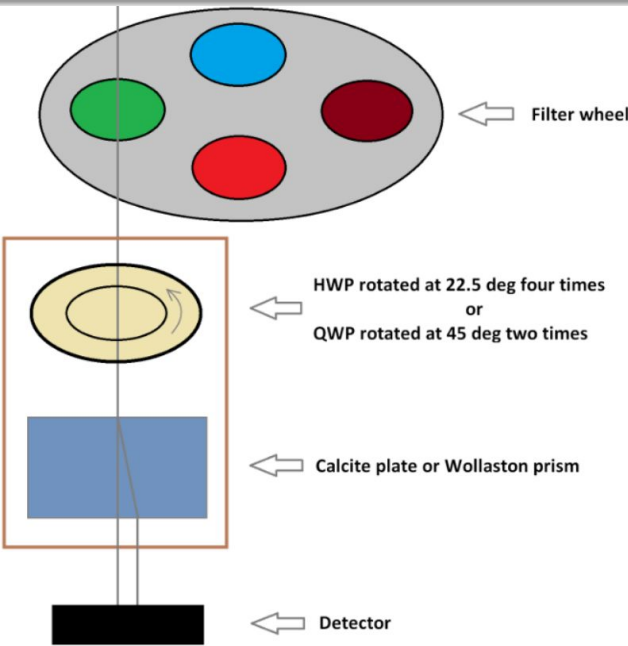
**Multi-color Polarized**

**Followup + Survey**

# Polarization - Wollaston Prism



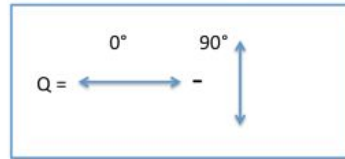
# Polarization - Wollaston Prism



FORS2:  
halfwave retarder plate (angles  
of 0, 22.5, 45, and 67.5 deg)  
+ Wollaston prism

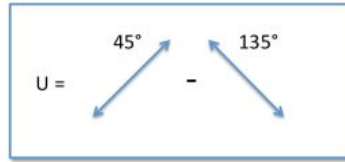
$$F(\theta_i) = \frac{f^o(\theta_i) - f^e(\theta_i)}{f^o(\theta_i) + f^e(\theta_i)}$$

$$Q = \frac{2}{N} \sum_{i=0}^{N-1} F(\theta_i) \cos(4\theta_i)$$



**Degree:**  $P = \sqrt{Q^2 + U^2}$

$$U = \frac{2}{N} \sum_{i=0}^{N-1} F(\theta_i) \sin(4\theta_i)$$



**Position Angle:**  $\theta = \frac{1}{2} \tan^{-1} \left( \frac{U}{Q} \right)$

# Polarization - 3 polarizers

## HST ACS/WFC Imaging Polarimeter

$$I = \frac{2}{3} [r(\text{POL}0) + r(\text{POL}60) + r(\text{POL}120)],$$

$$Q = \frac{2}{3} [2r(\text{POL}0) - r(\text{POL}60) - r(\text{POL}120)],$$

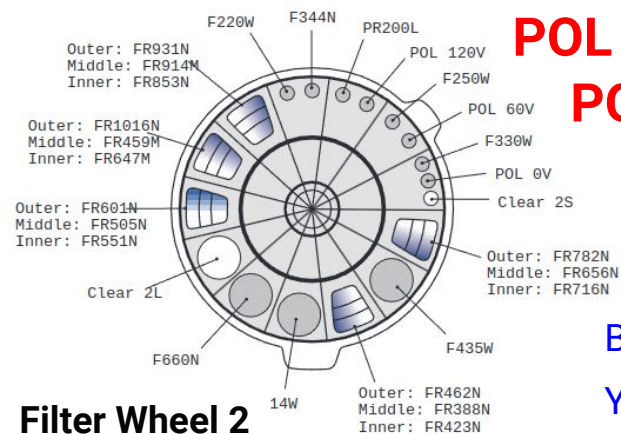
$$U = \frac{2}{\sqrt{3}} [r(\text{POL}60) - r(\text{POL}120)],$$

WFC/HRC 1

**POL 120V**

**POL 60V**

**POL 0V**

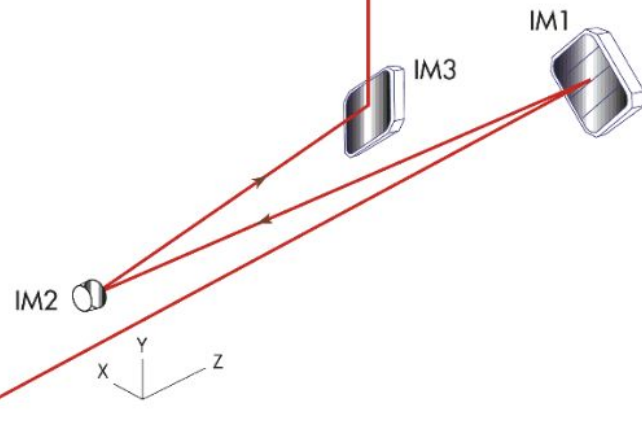


Filter Wheel 2

Brown, Yang, Wang+ (2016)

Yang, Wang+ (2018)

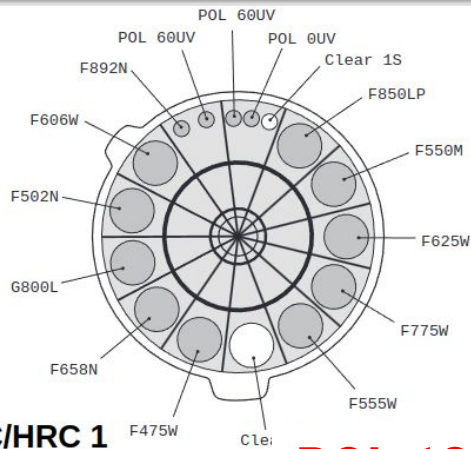
From OTA



WFC detector

WFC/HRC filter wheels

# Polarization - 3 polarizers

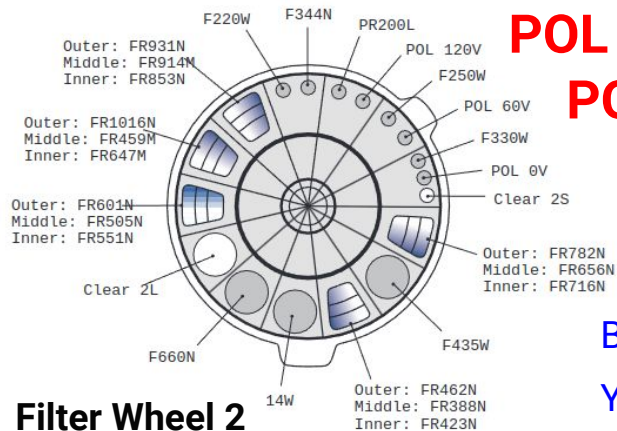


WFC/HRC 1

**POL 120V**

**POL 60V**

**POL 0V**



Filter Wheel 2

**Mephisto:**  
**3 polarizers (easier)**

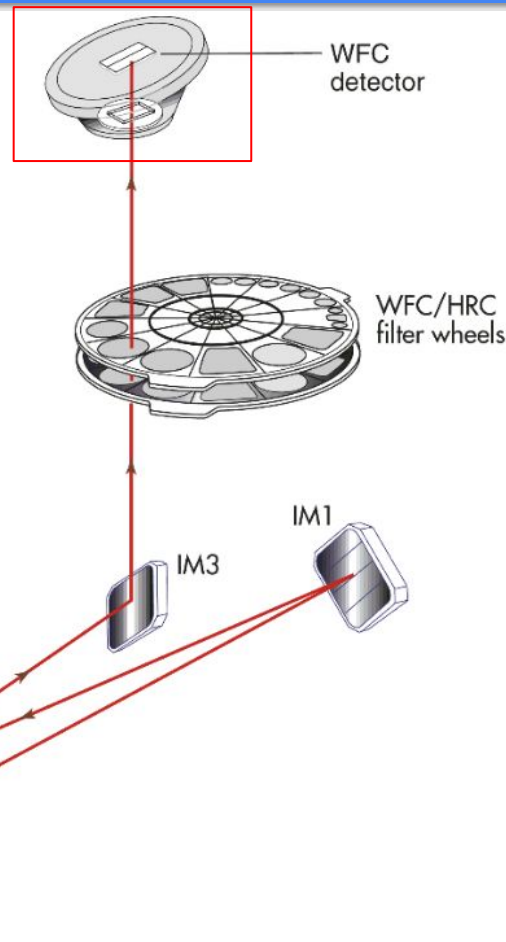
**Challenges:**  
**Instrumental Pol**  
**(beam split,**  
**off Cassegrain)**

**Calibration:**  
**Non-trivial, feasible**

Brown, Yang, Wang+ (2016)

Yang, Wang+ (2018)

From OTA





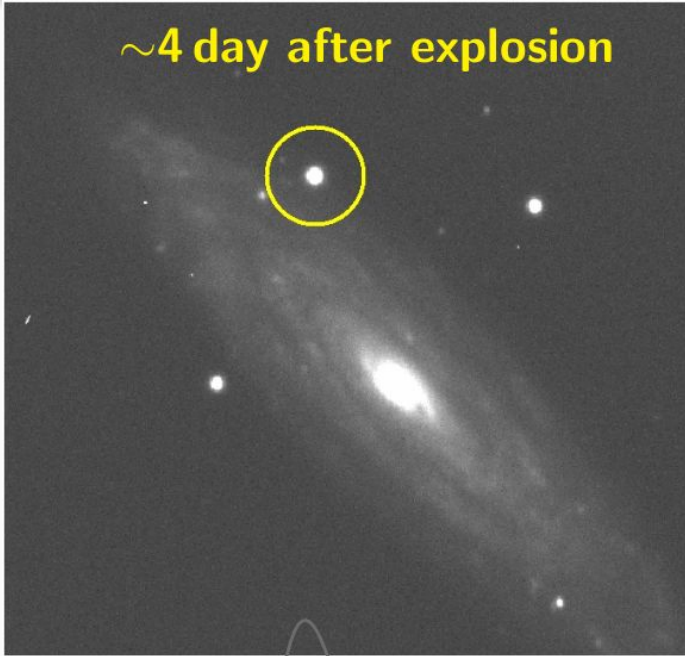
**Part I:**  
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**What have we learned?**

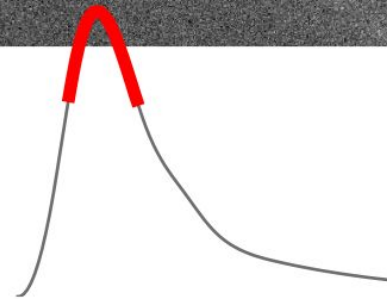
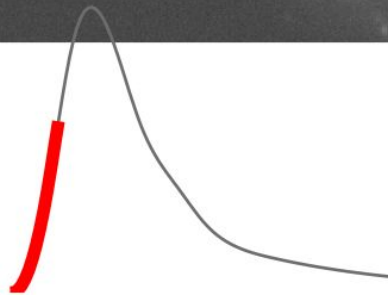
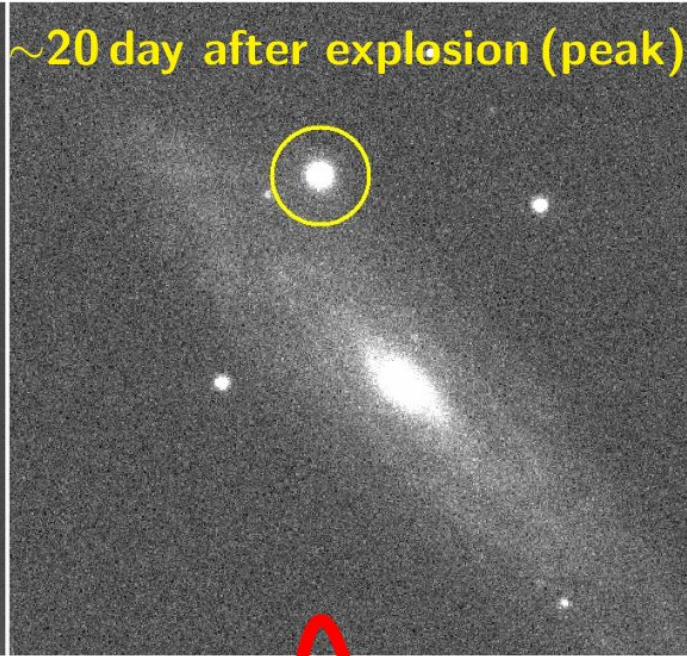
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# Thermonuclear supernovae

~4 day after explosion



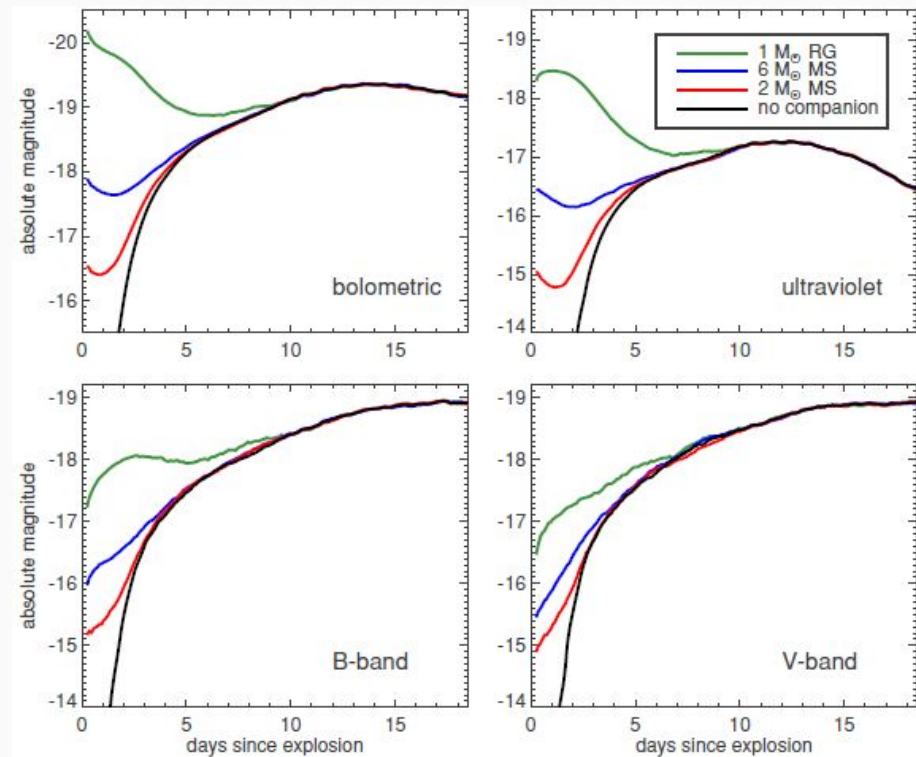
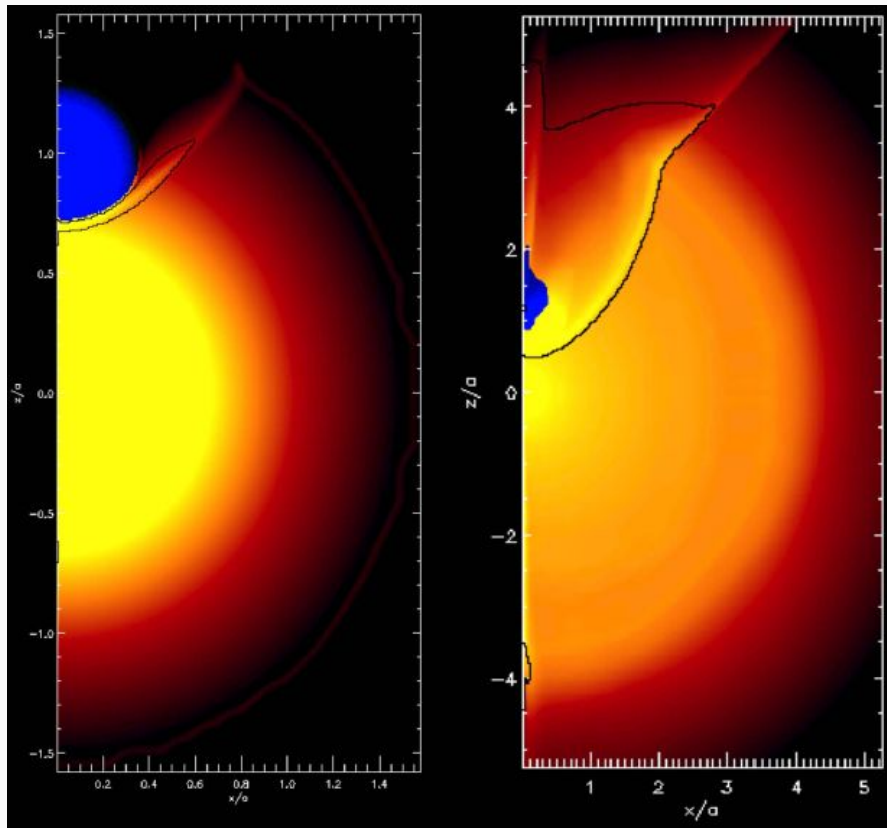
~20 day after explosion (peak)



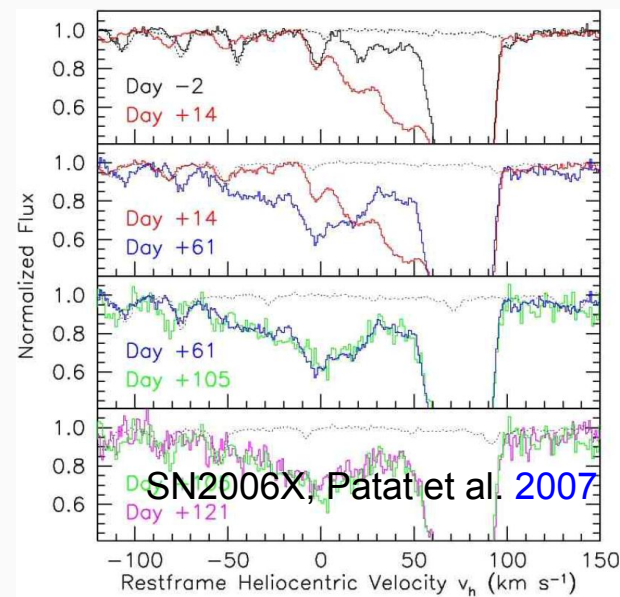
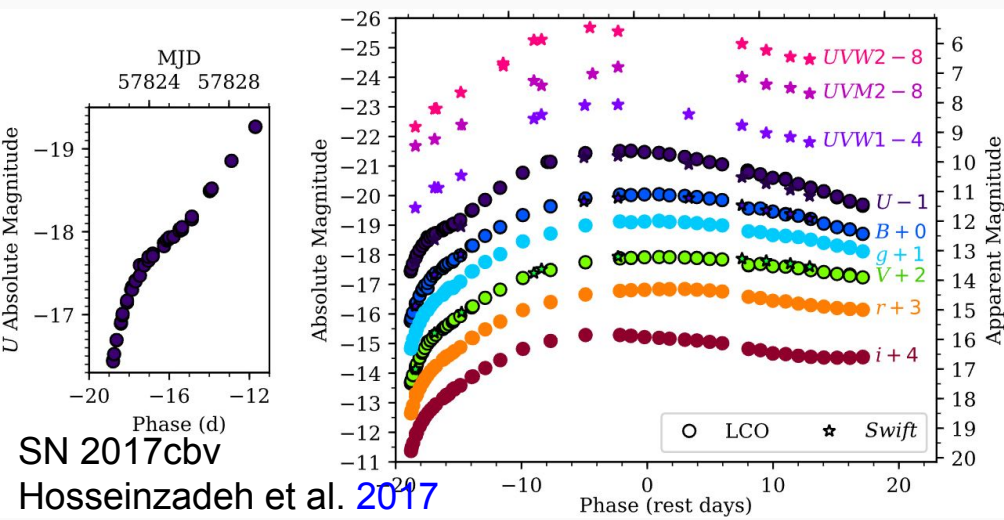
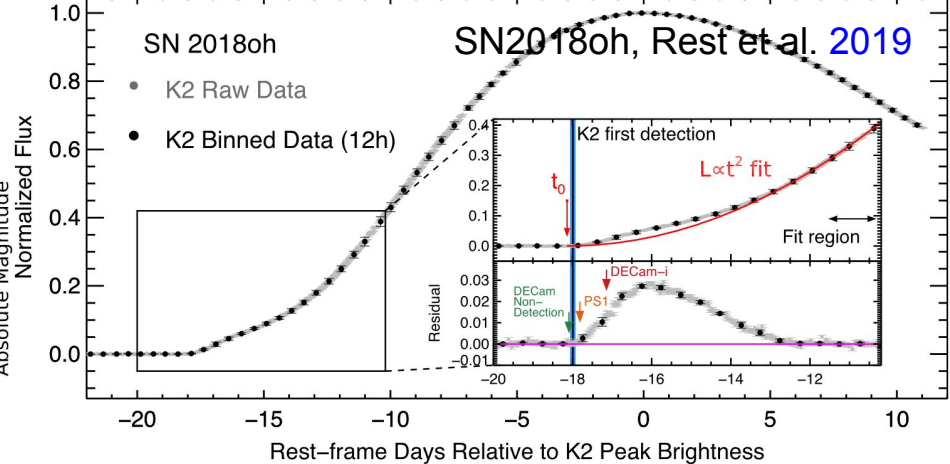
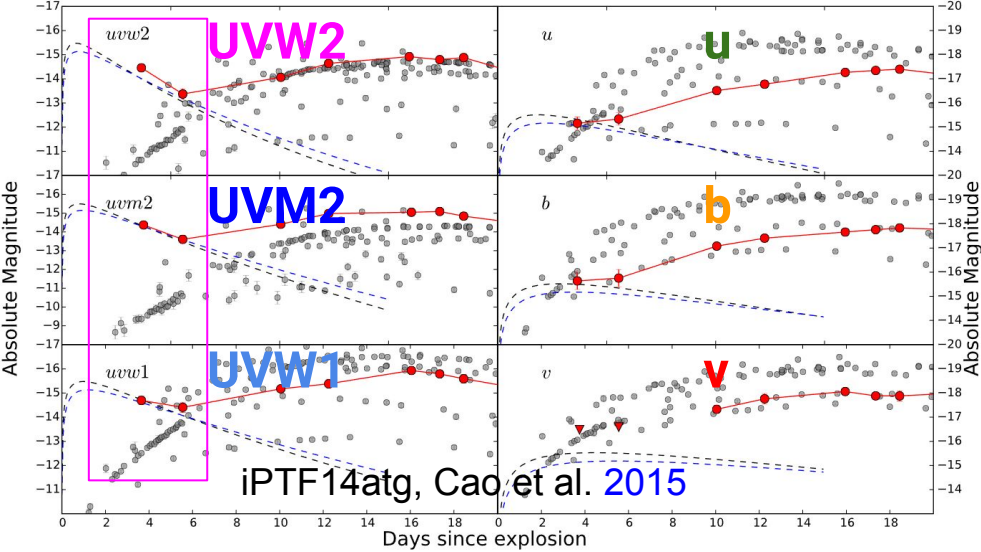
# Thermonuclear supernovae (Early Phase)

Ejecta-companion / CSM interaction:

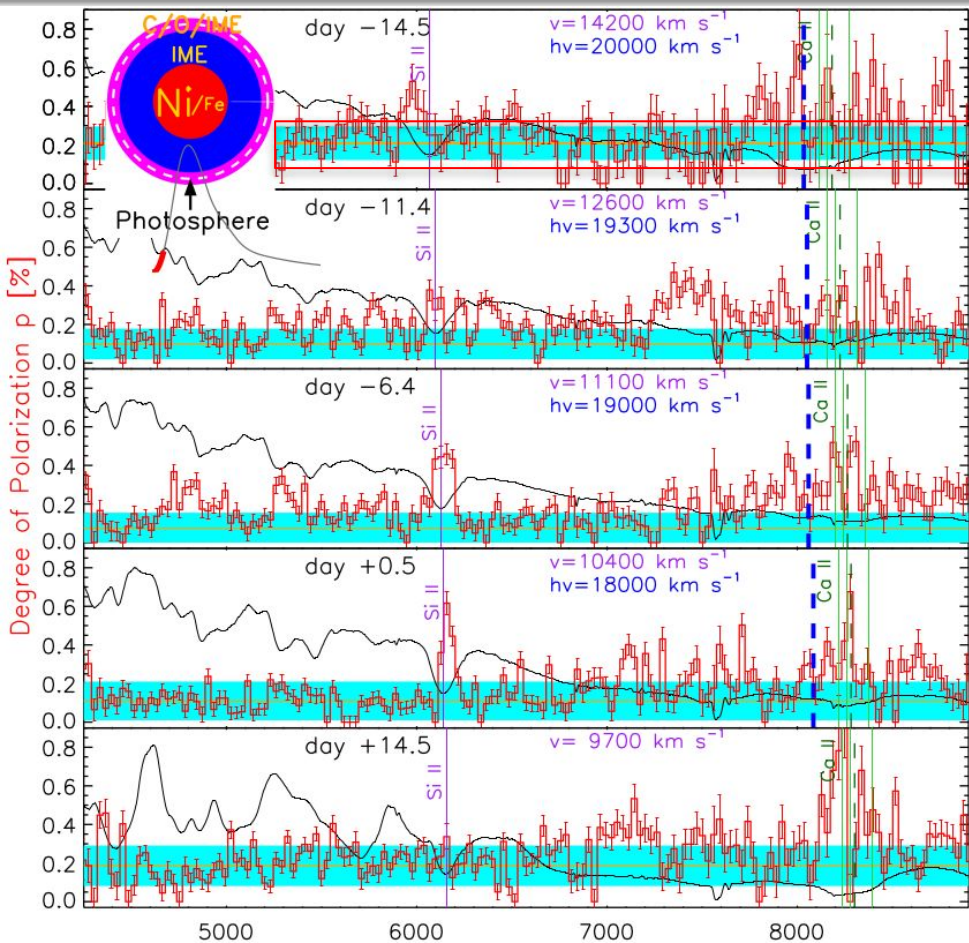
Short-lived: early data.



Kasen et al. 2010



# Thermonuclear supernovae (Early Phase)



$p^{\text{Cont}} = 0.21\% \pm 0.09\%$   
 @ Epoch 1, day -14.5

$p^{\text{Cont}} = 0.10\% \pm 0.08\%$   
 @ Epoch 2, day -11.4

$p^{\text{Cont}} = 0.08\% \pm 0.08\%$   
 @ Epoch 3, day -6.4

$p^{\text{Cont}} = 0.11\% \pm 0.10\%$   
 @ Epoch 4, day +0.5

$p^{\text{Cont}} = 0.19\% \pm 0.11\%$   
 @ Epoch 5, day +14.5

## Early Cont $p\%$

First ~3 days:  
 Aspherical Outer layer

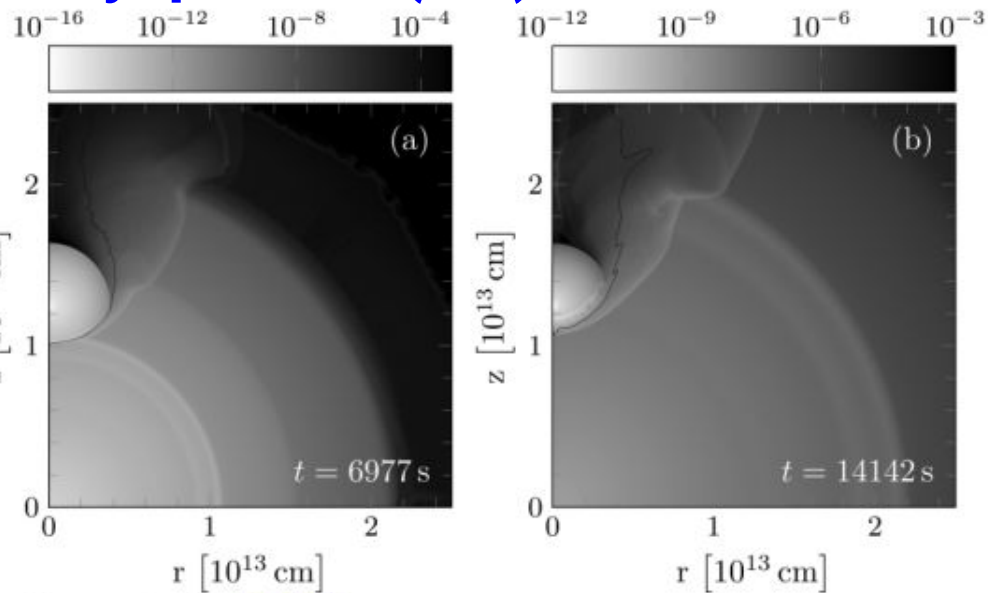
$\sim 1E-3 M_{\text{WD}}$

Inner:  
 Spherical

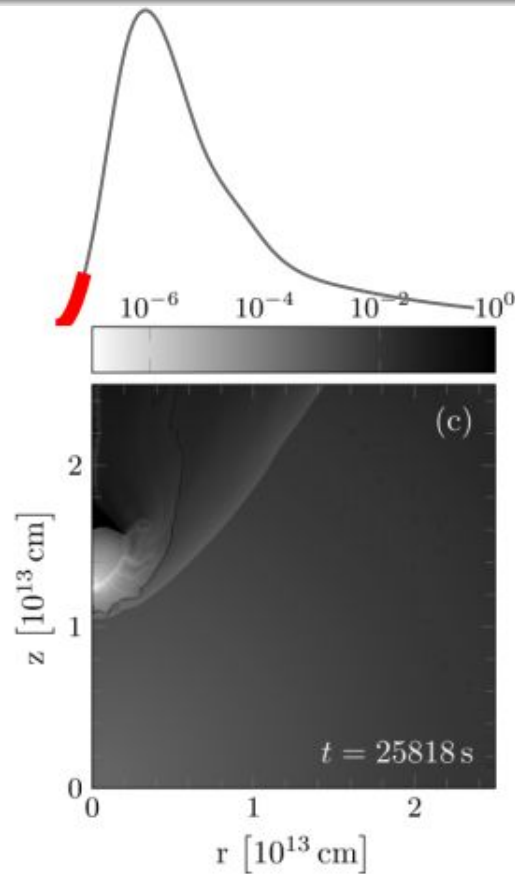
# Thermonuclear supernovae (Early = outer layers)

A thin, aspherical outer layer:  
Ejecta-Companion/Disk interaction;

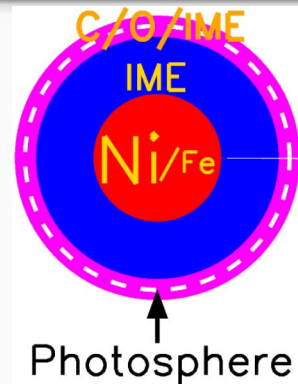
Early:  $p \sim 0.2\%$  ( $\neq 0$ ),  $a/b \sim 1.2-1.4$



Boehner et al. (2017)



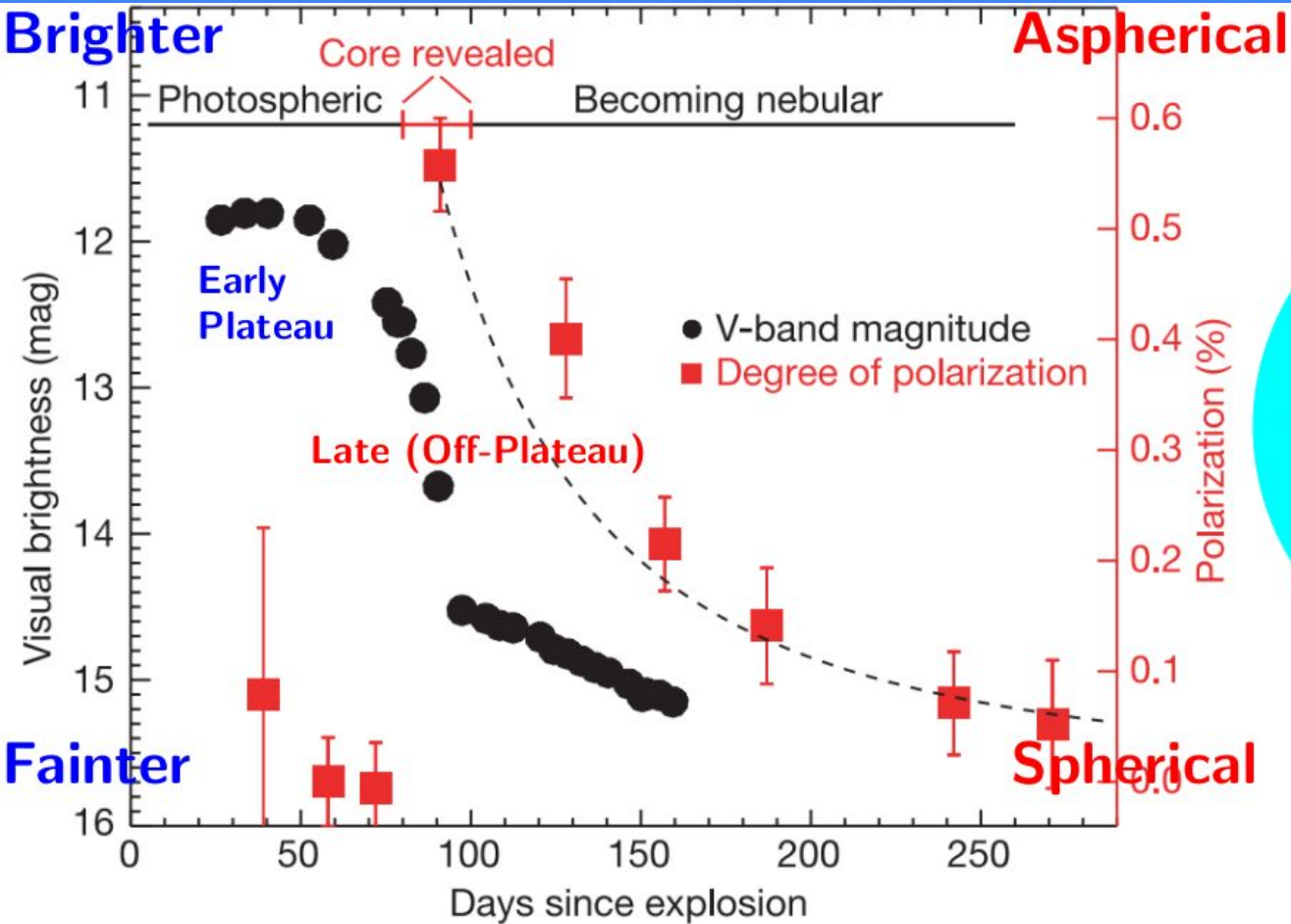
Yang & Hoeflich+ 2020, Hoeflich & Yang+ 2023



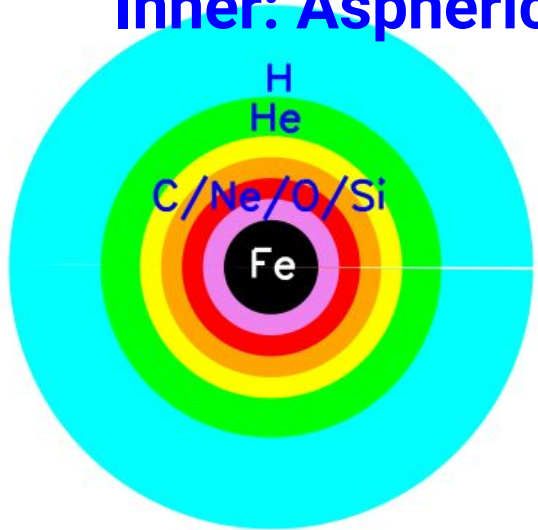
Mephisto:

Young Ia

# Type II/IIP SNe



**Outer: Spherical**  
**Inner: Aspherical**

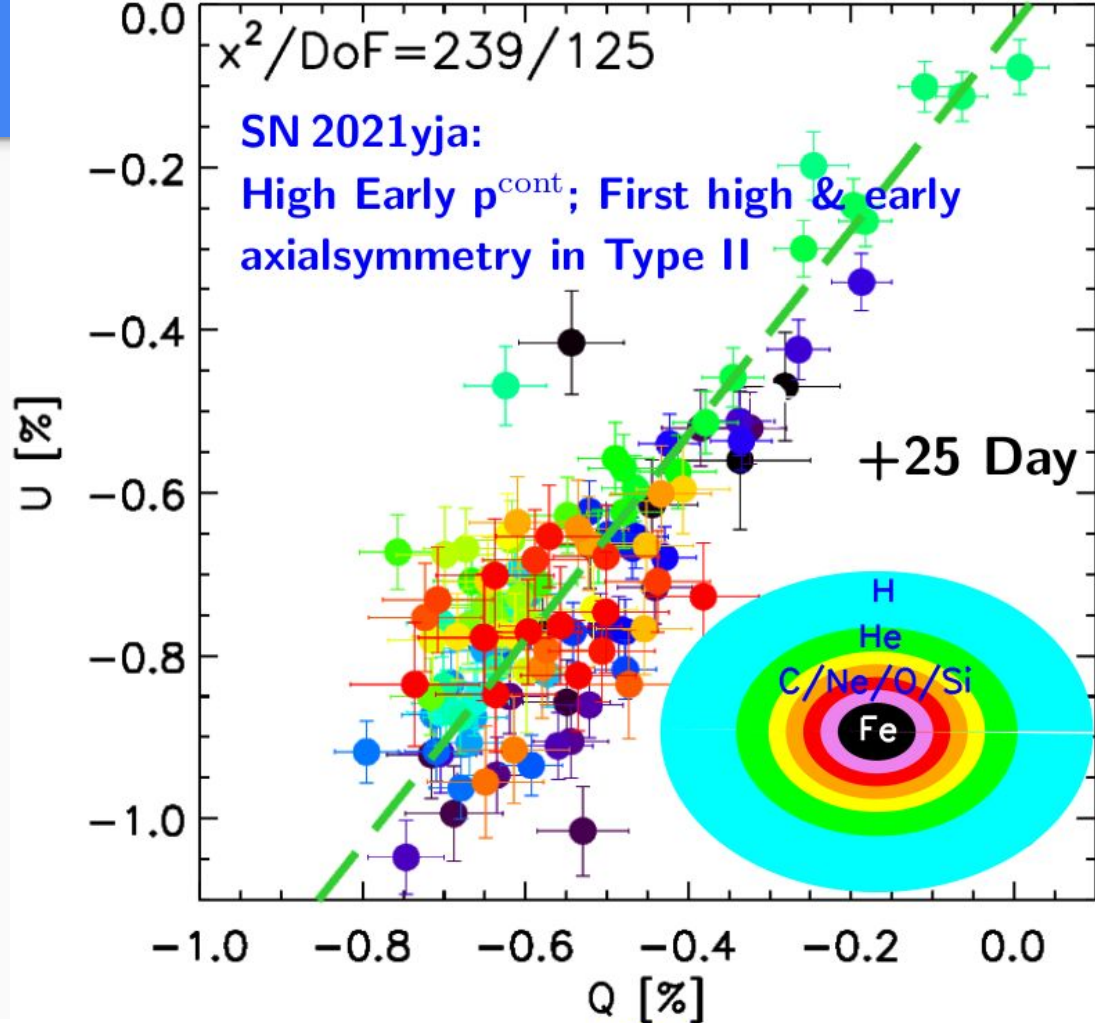


# Type II/IIP SNe

Outer: Aspherical

Bi-polar explosion?

Binary?





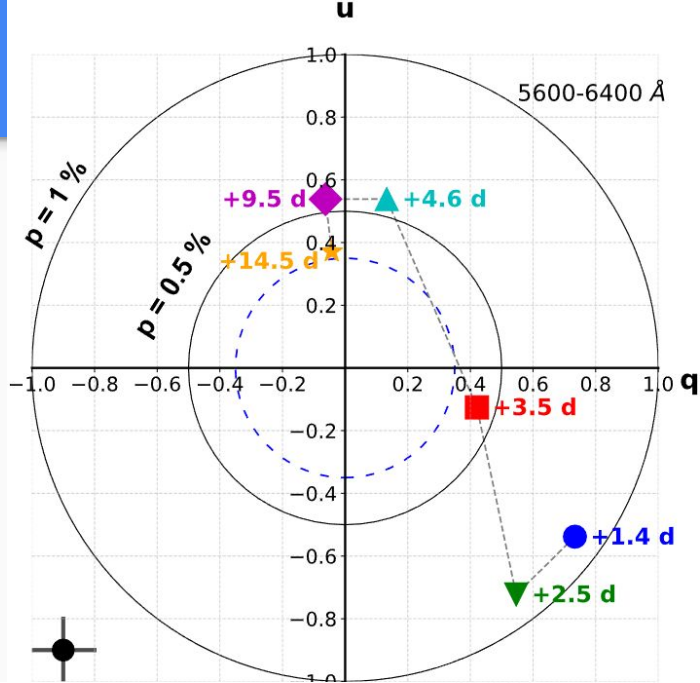
# Type II/IIP SNe

– Intense mass loss (disk) before death;

SN 2023ixf, from day +1.4

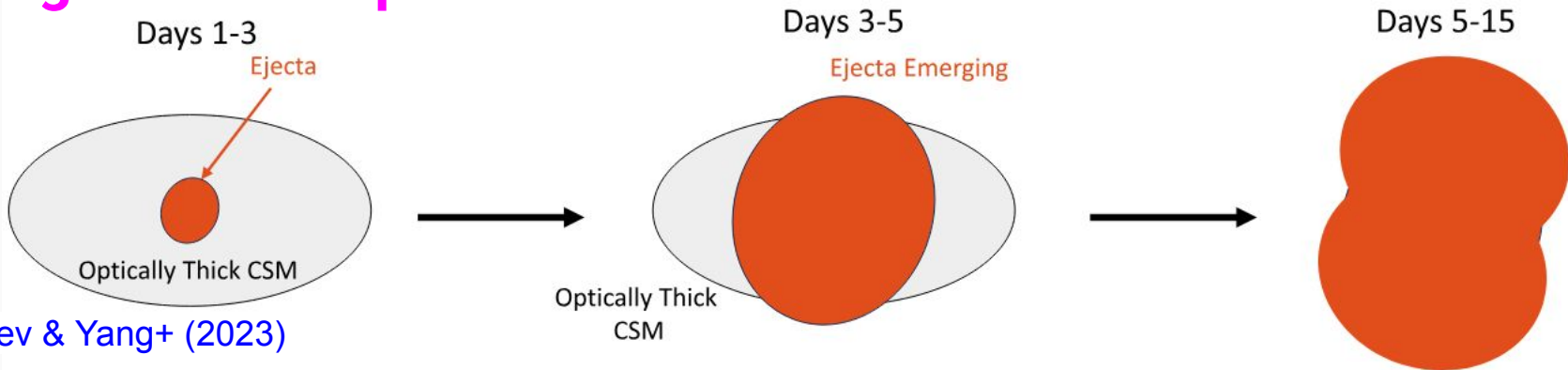
Degree:  $P = \sqrt{Q^2 + U^2}$

Position Angle:  $\theta = \frac{1}{2} \tan^{-1} \left( \frac{U}{Q} \right)$

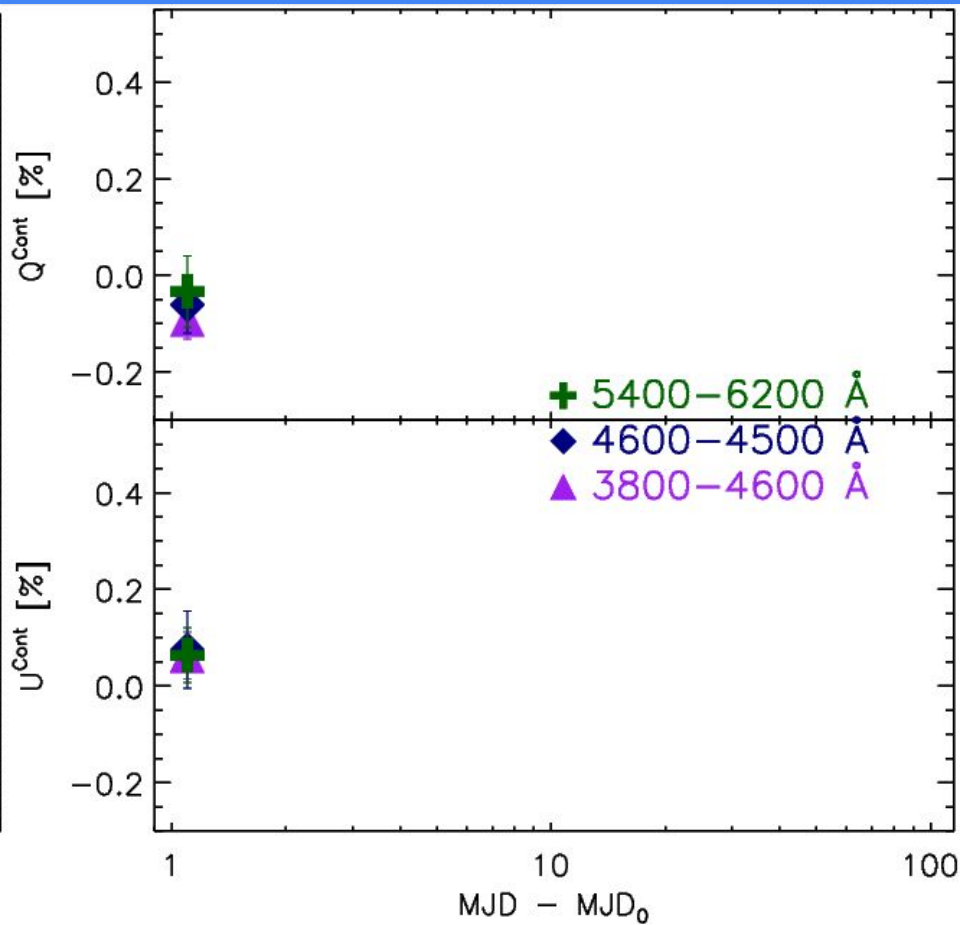
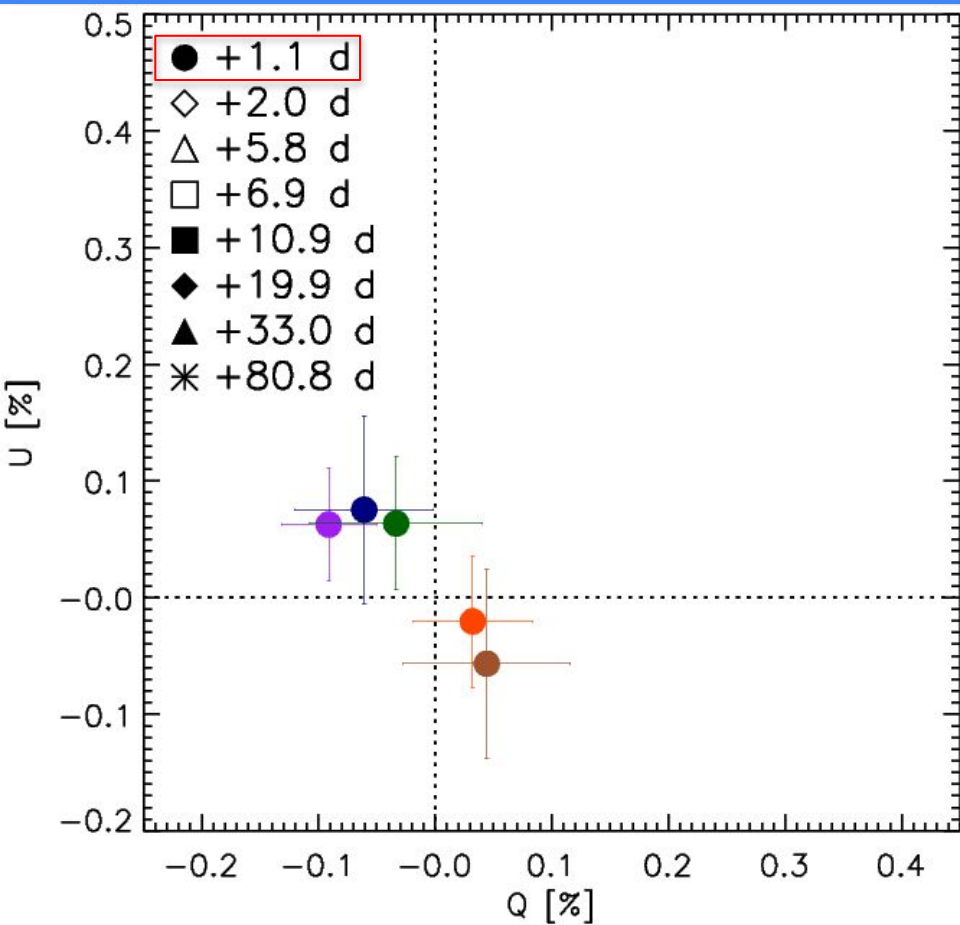


Mephisto:

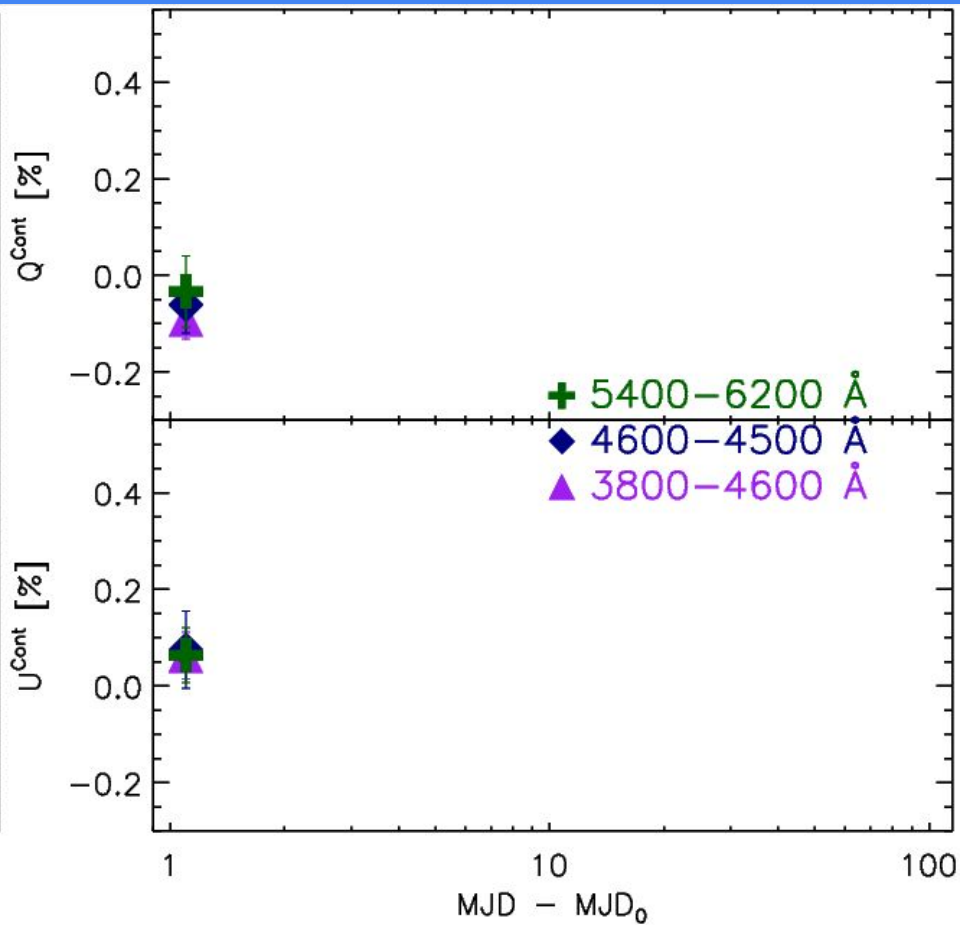
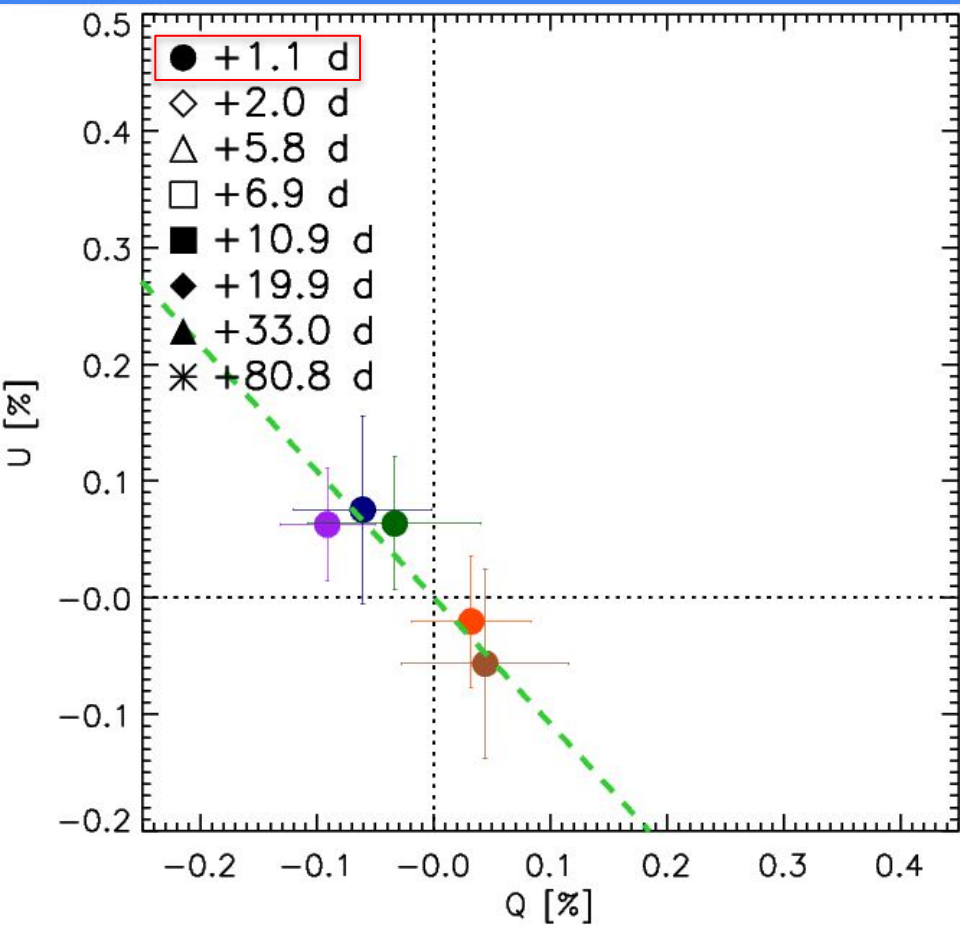
Young Core-Collapse



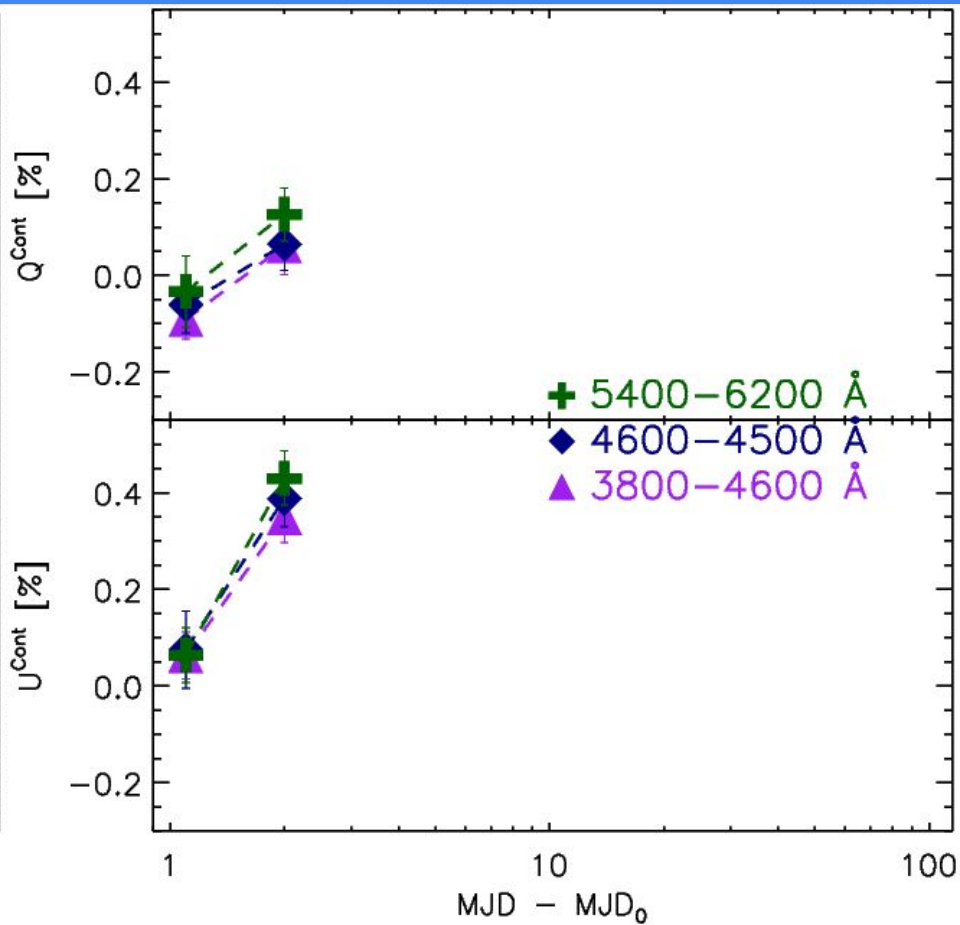
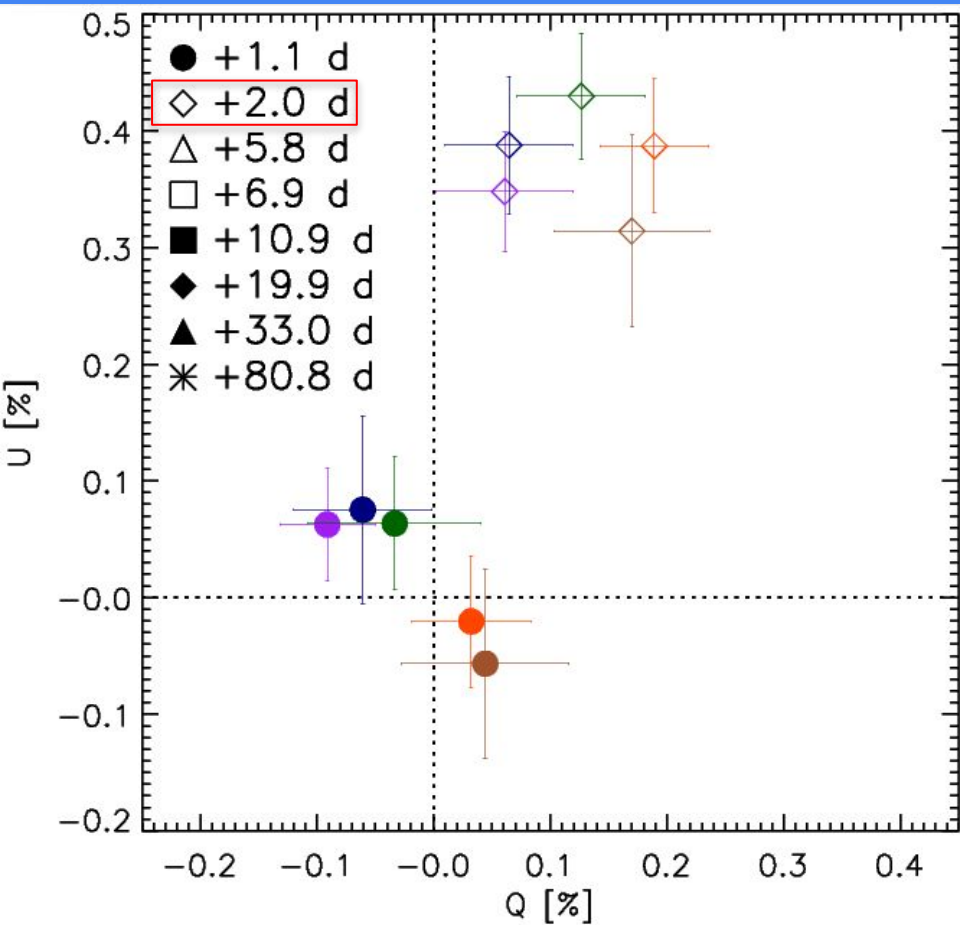
# SN2024ggi (VLT specpol)



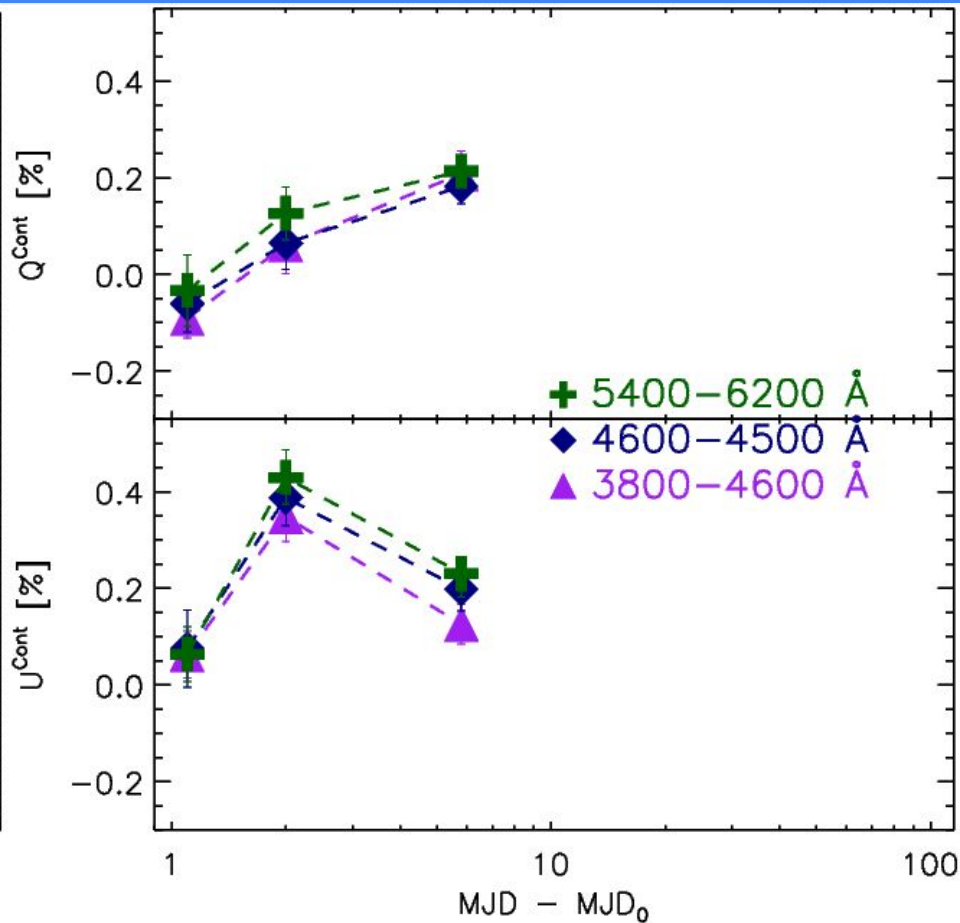
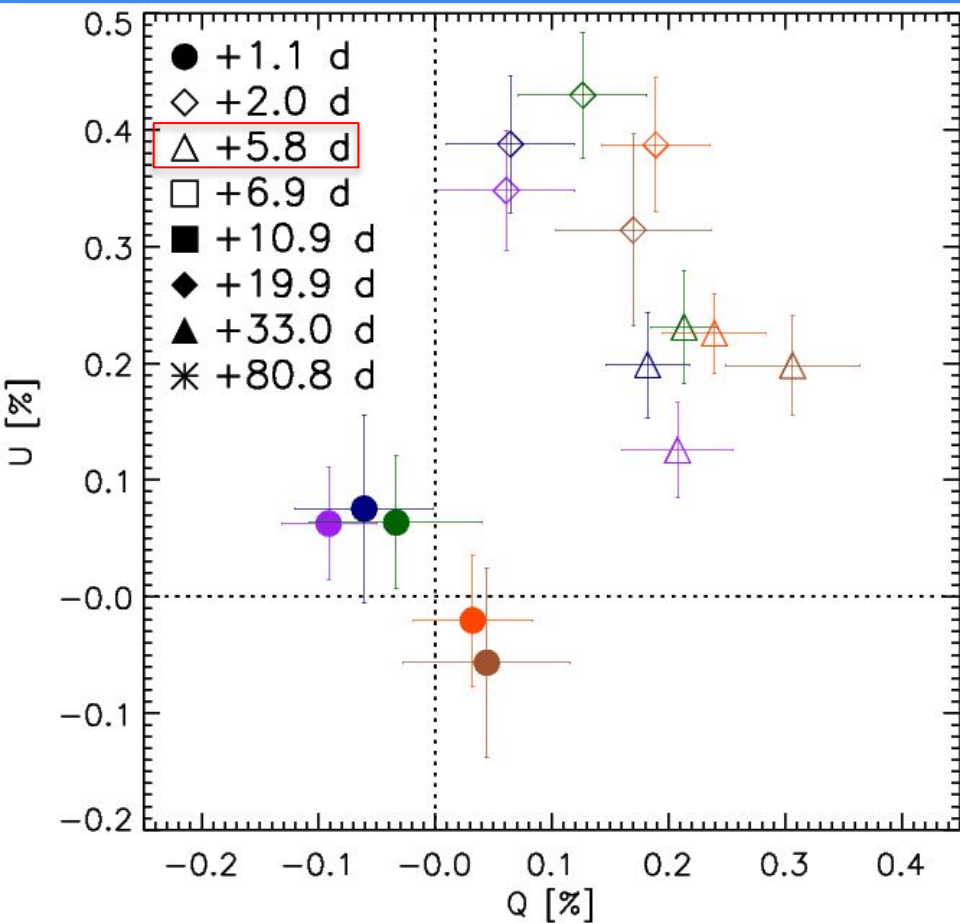
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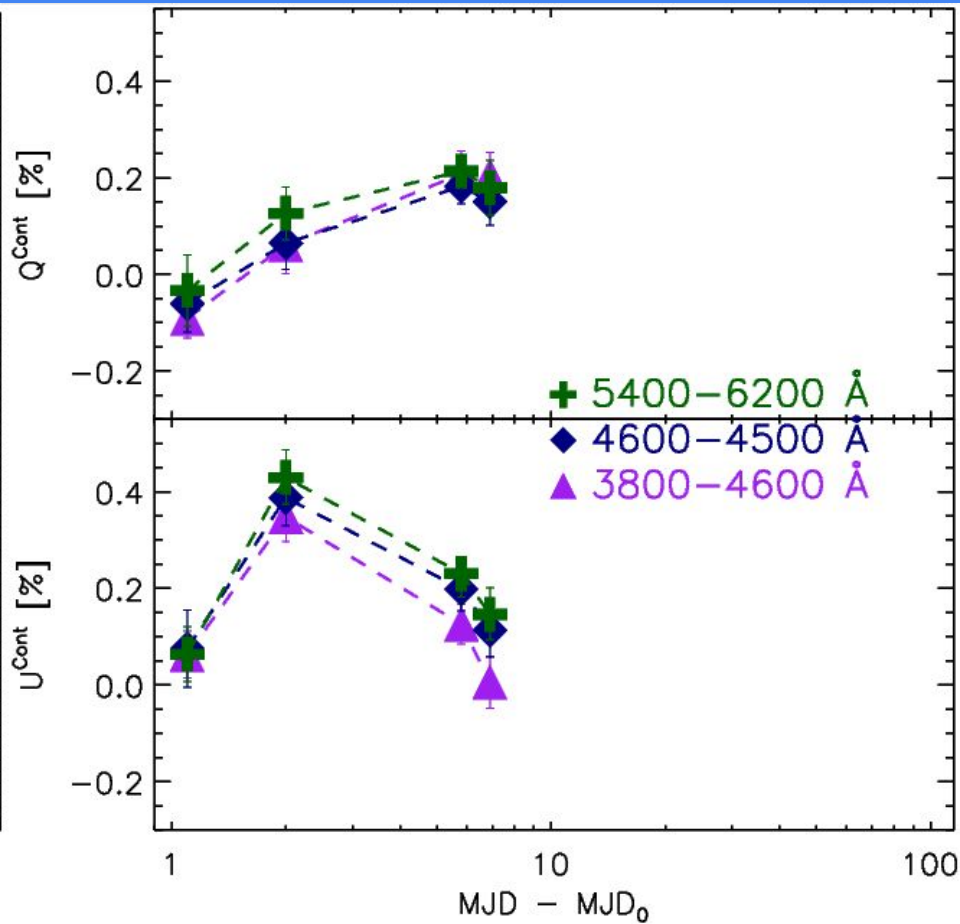
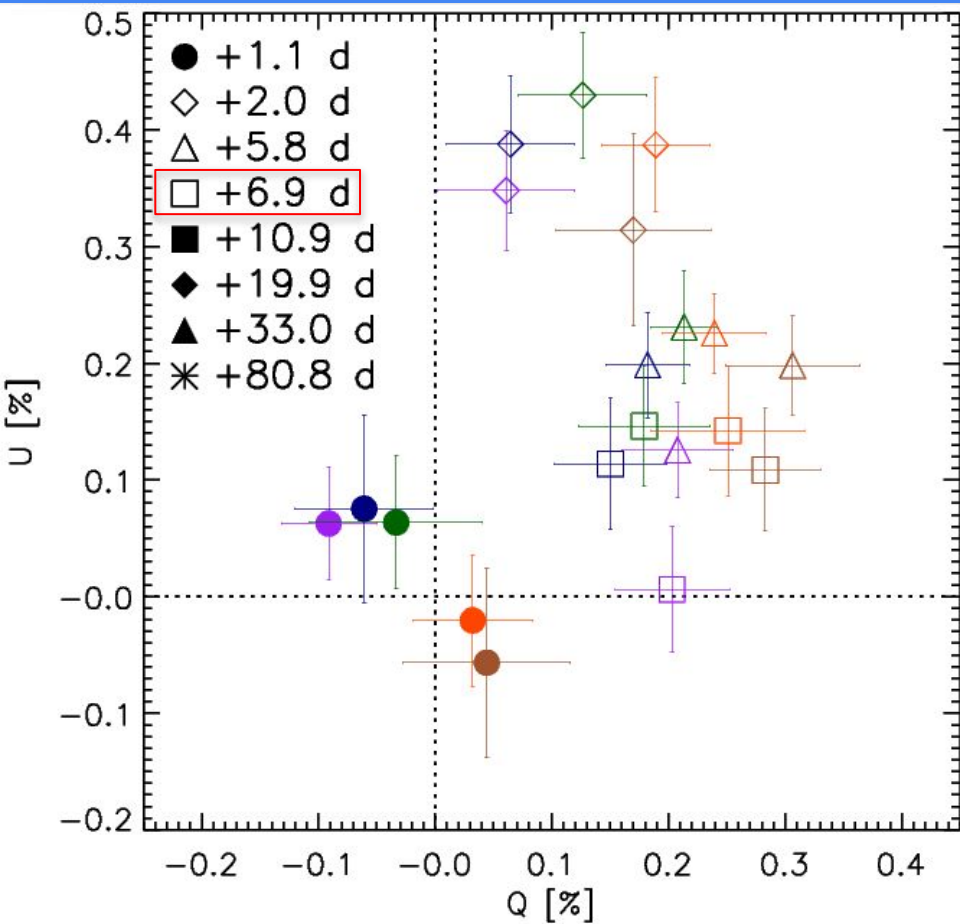
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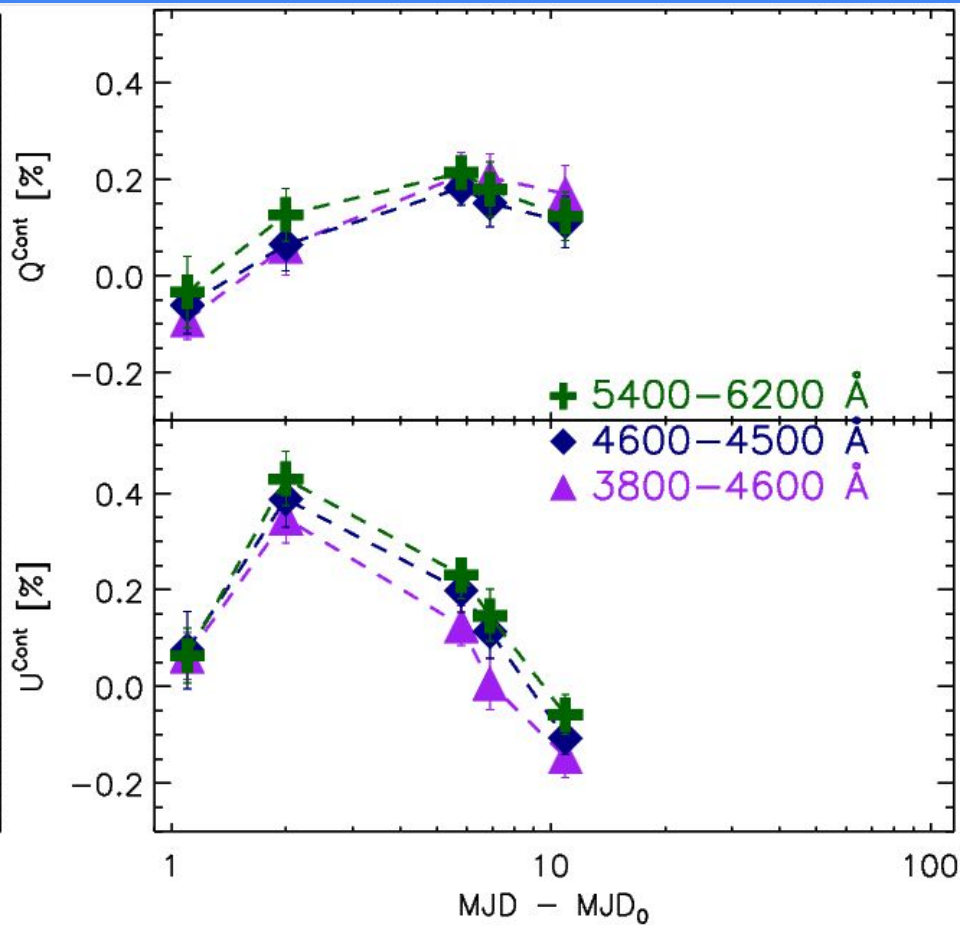
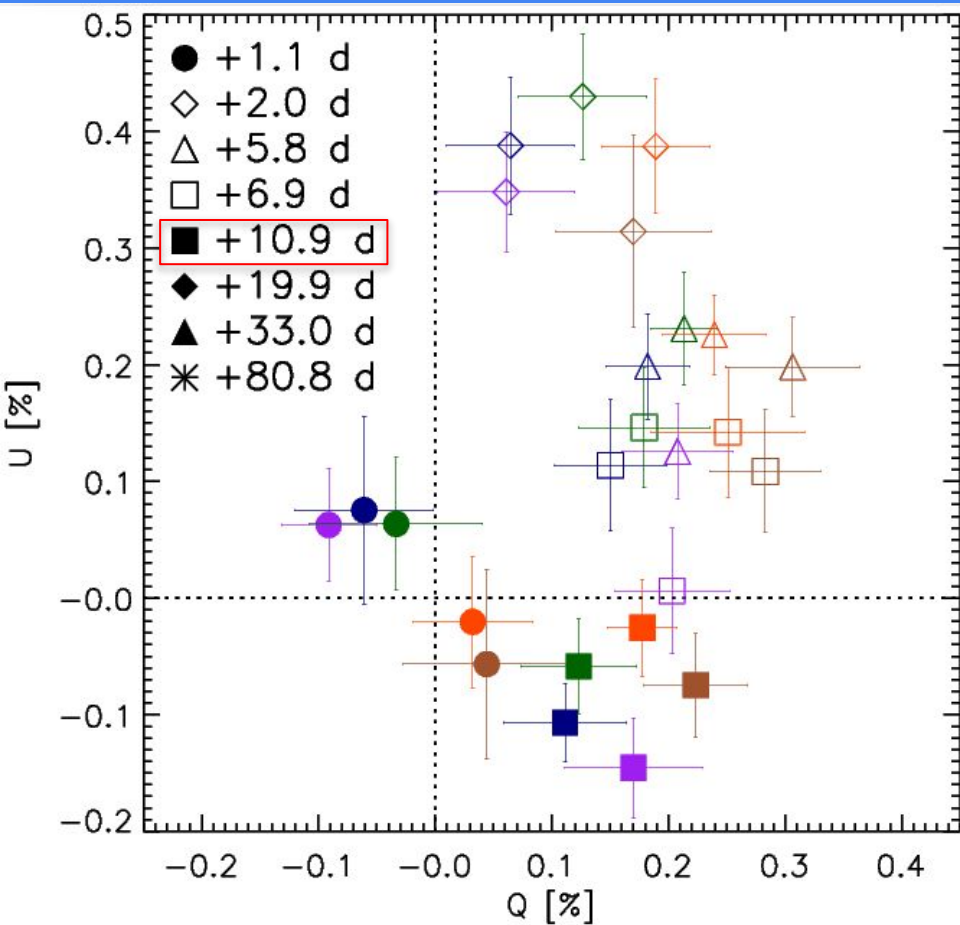
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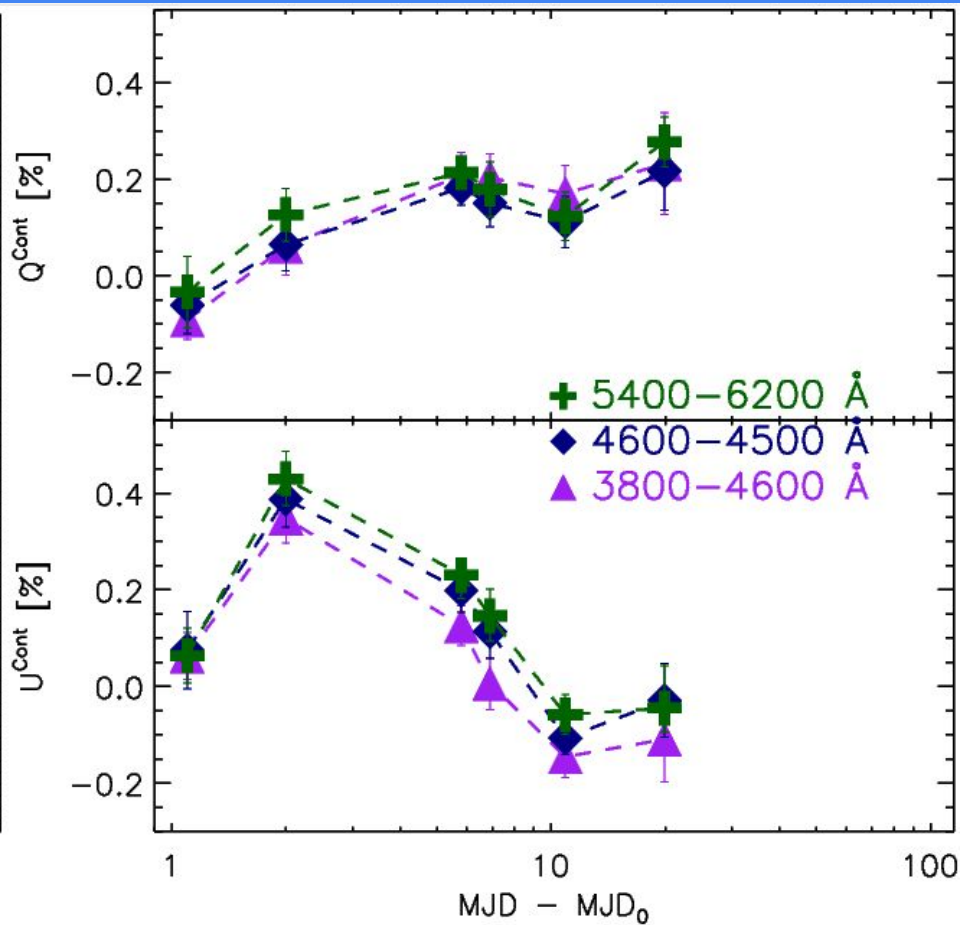
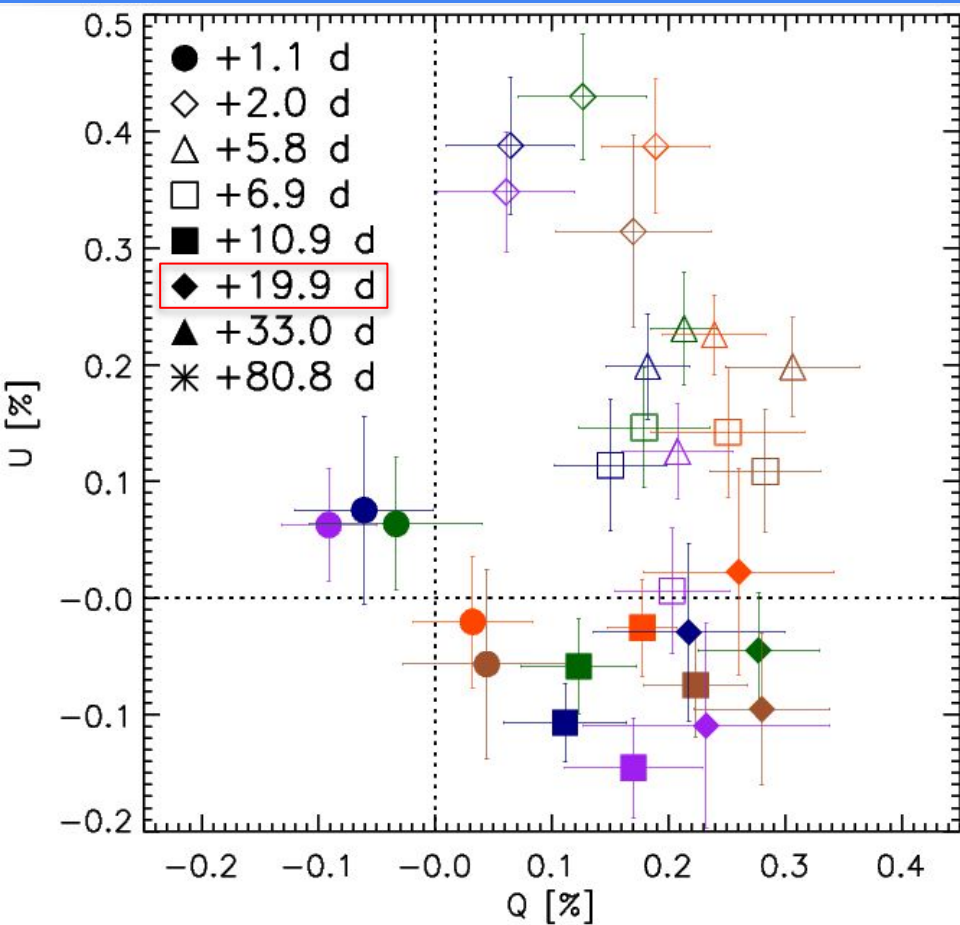
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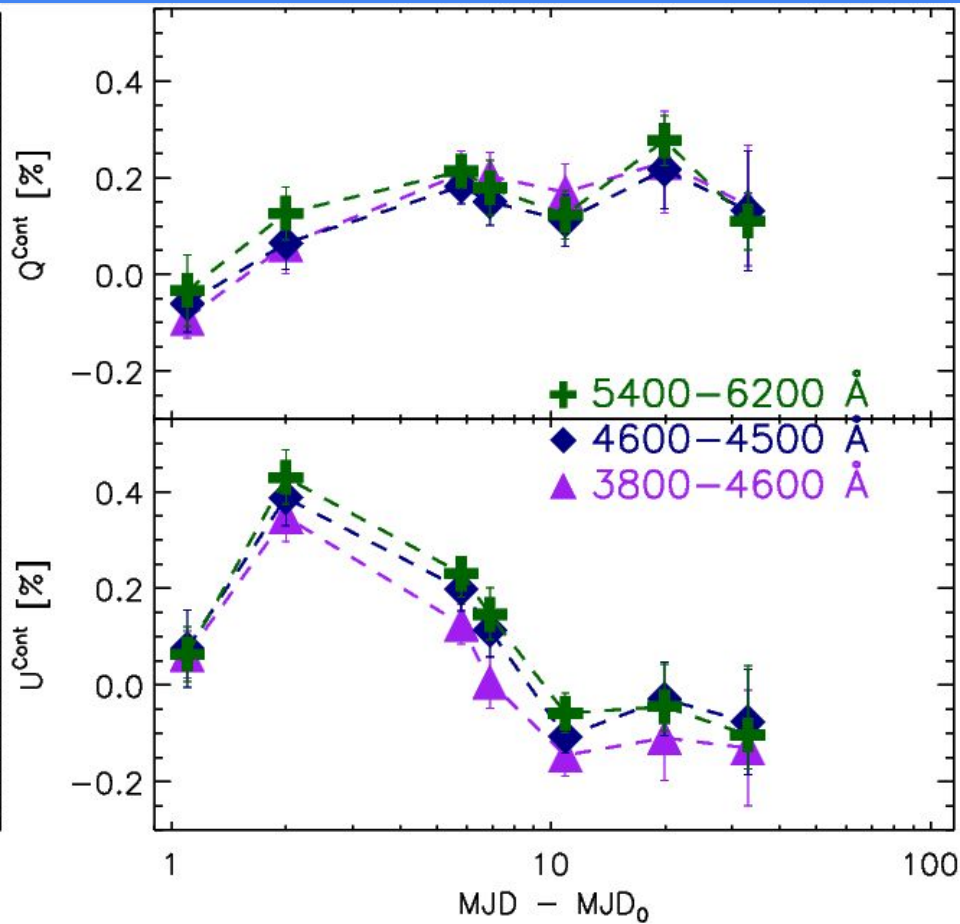
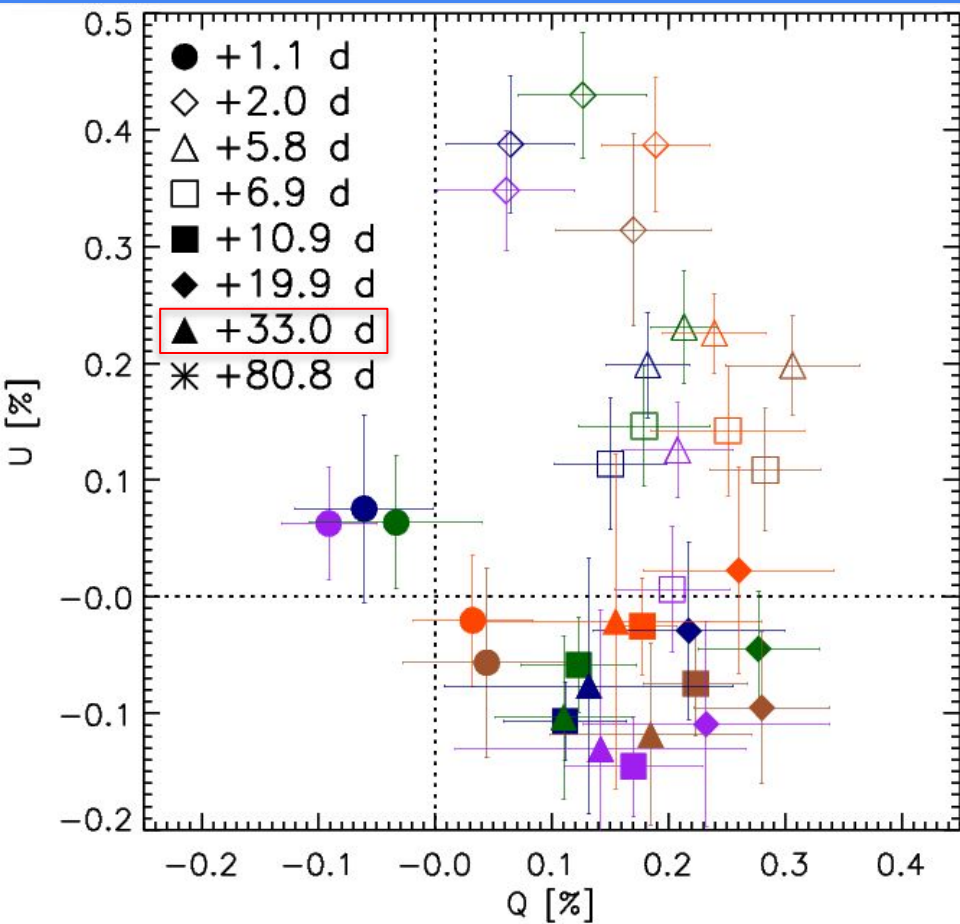


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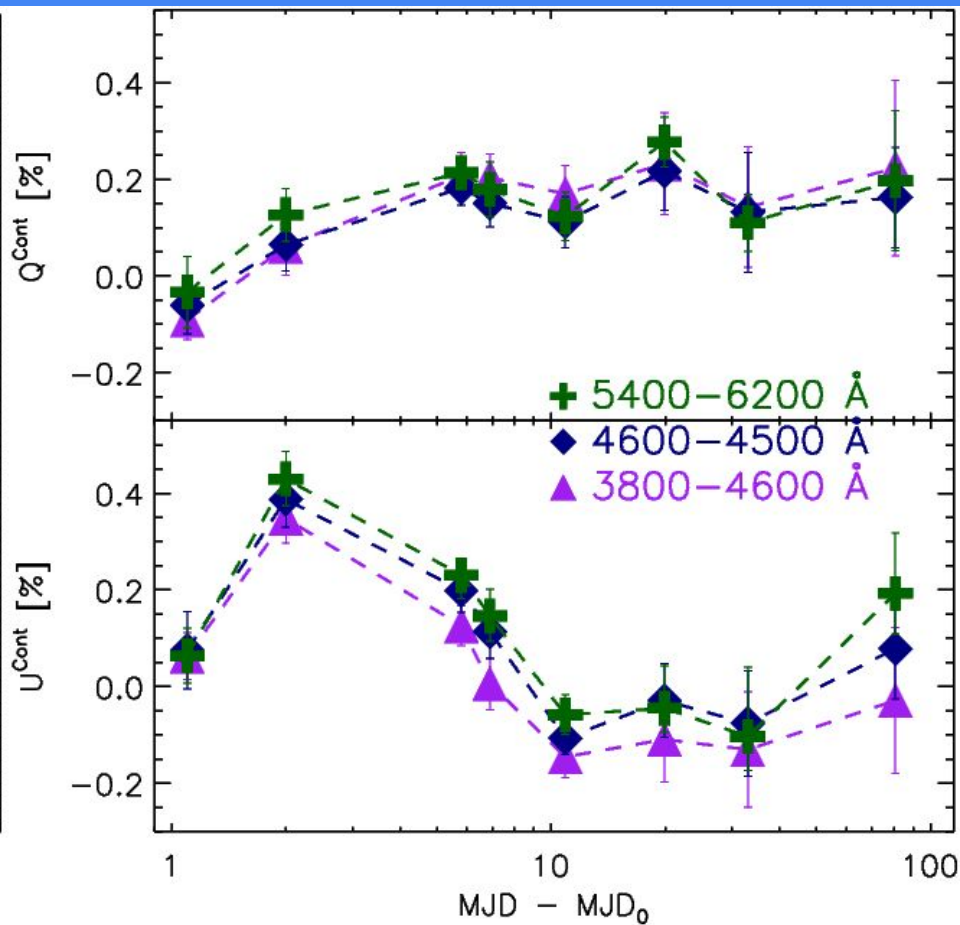
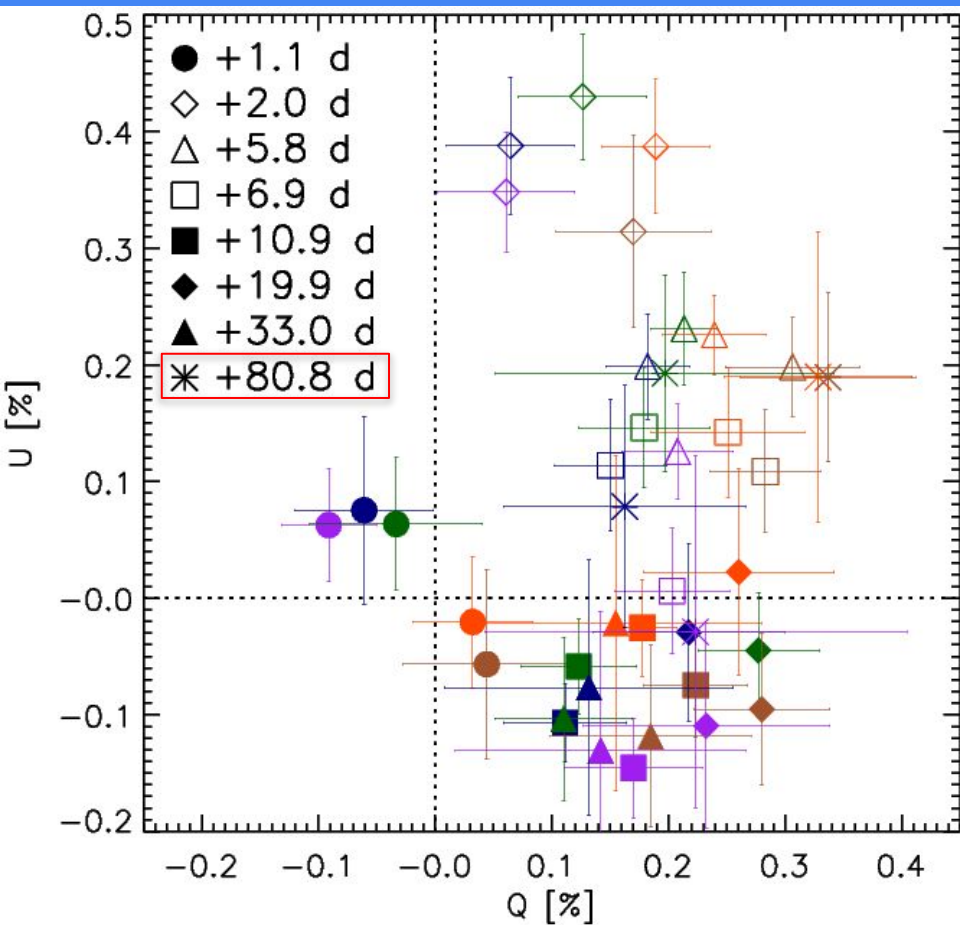




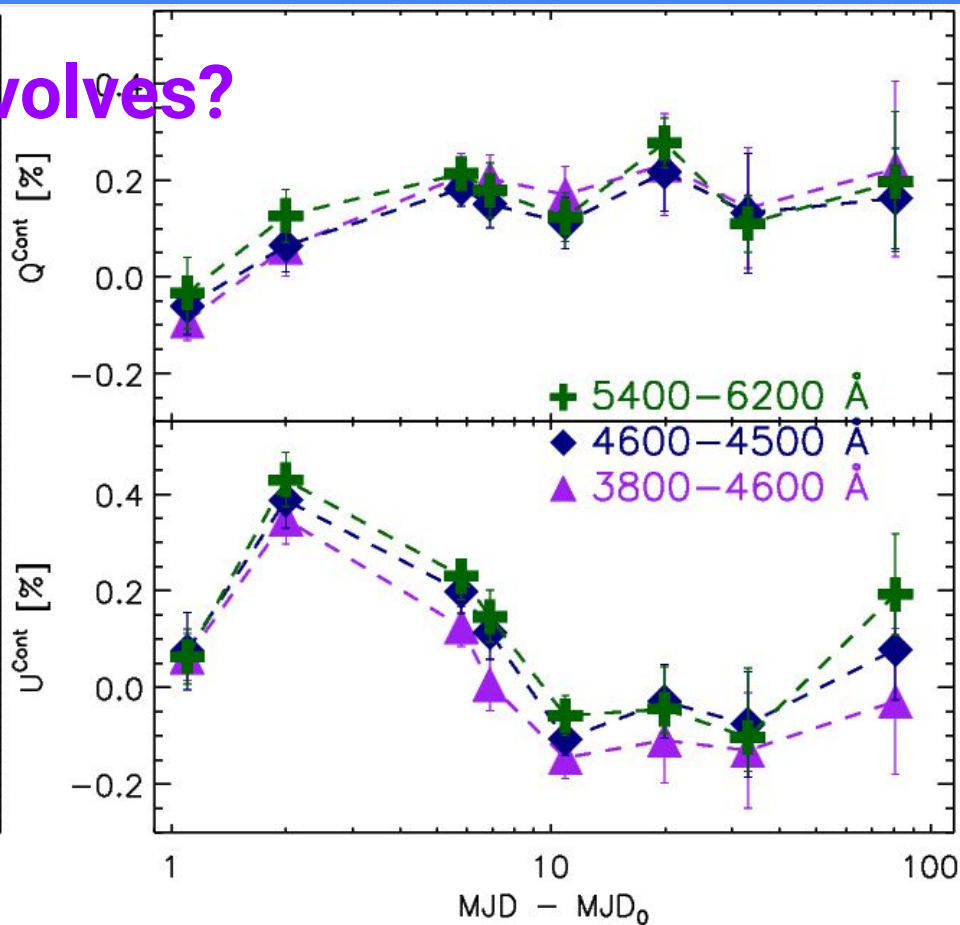
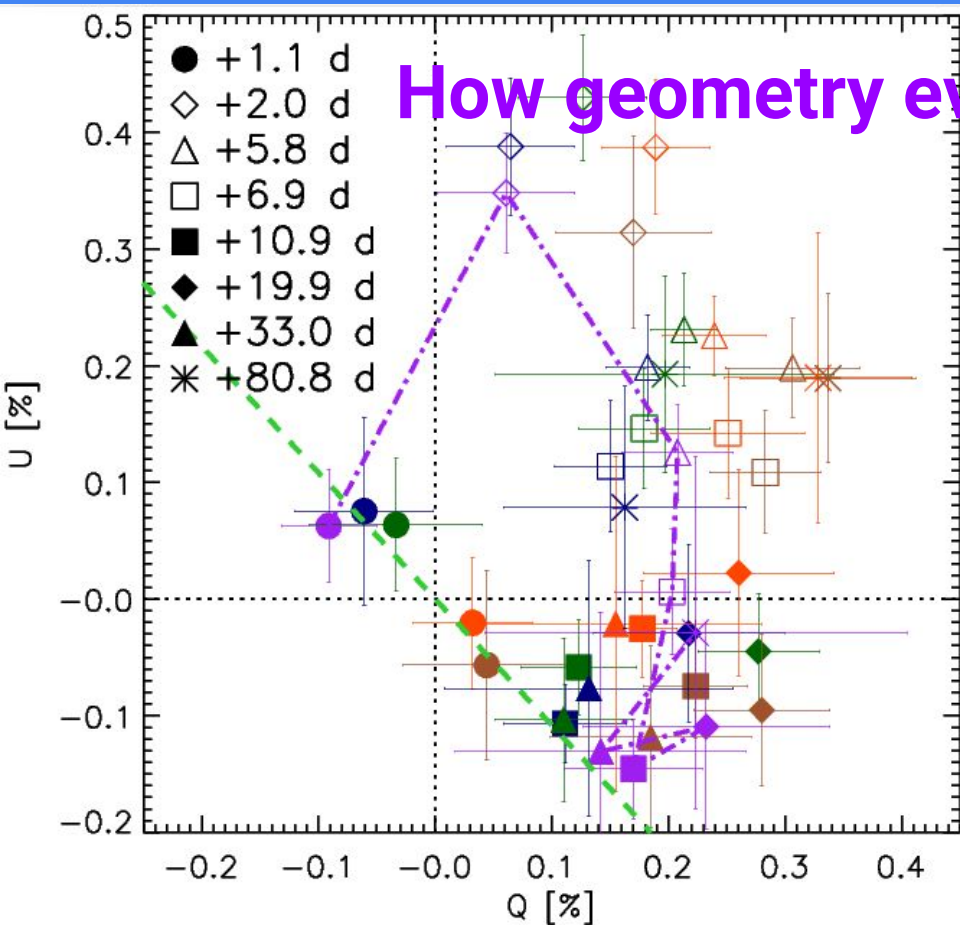
# SN2024ggi (VLT specpol)



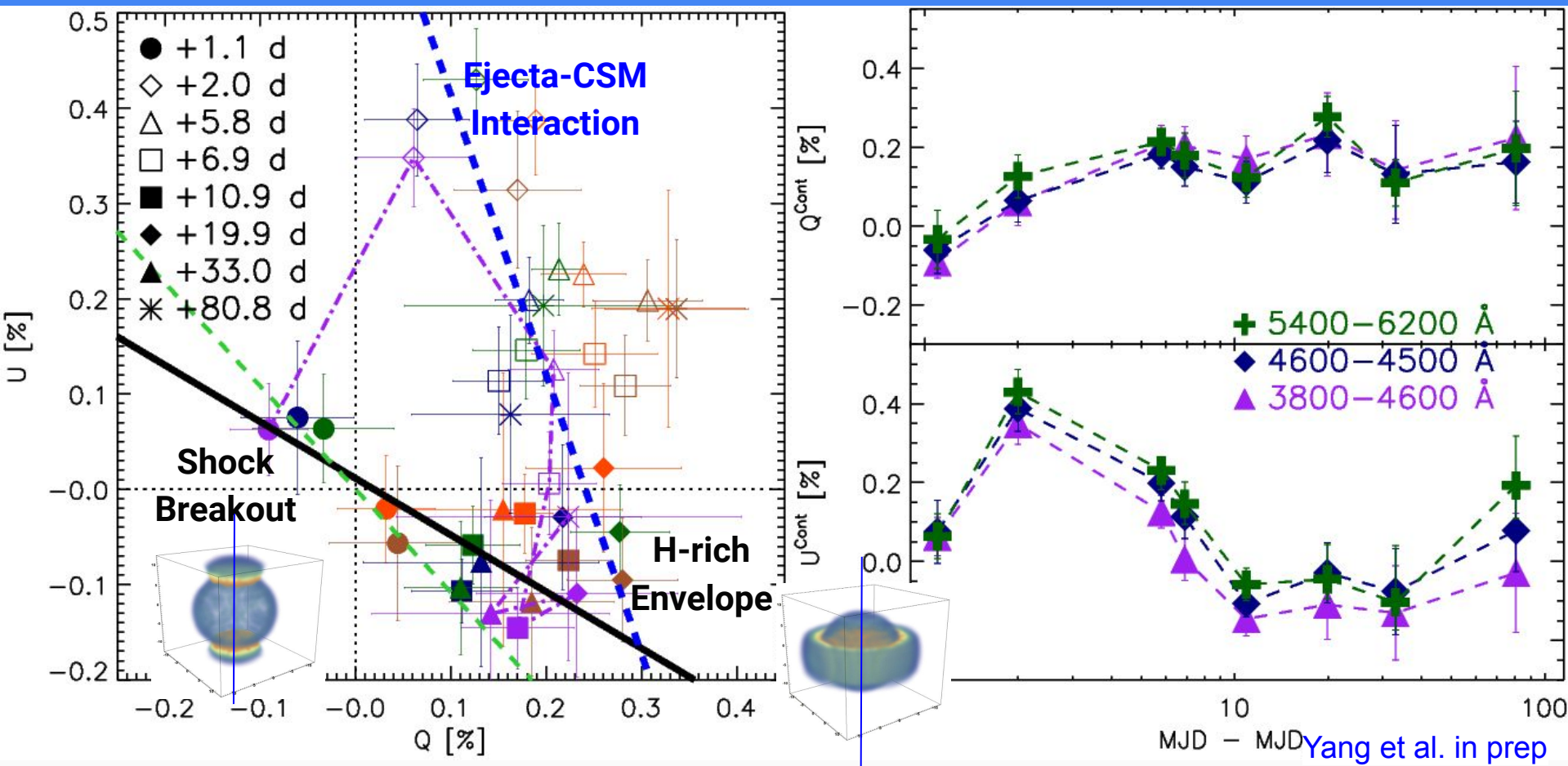
# SN2024ggi (VLT specpol)



# SN2024ggi (VLT specpol)



# SN2024ggi (VLT specpol)



# SN2024ggi (VLT specpol)

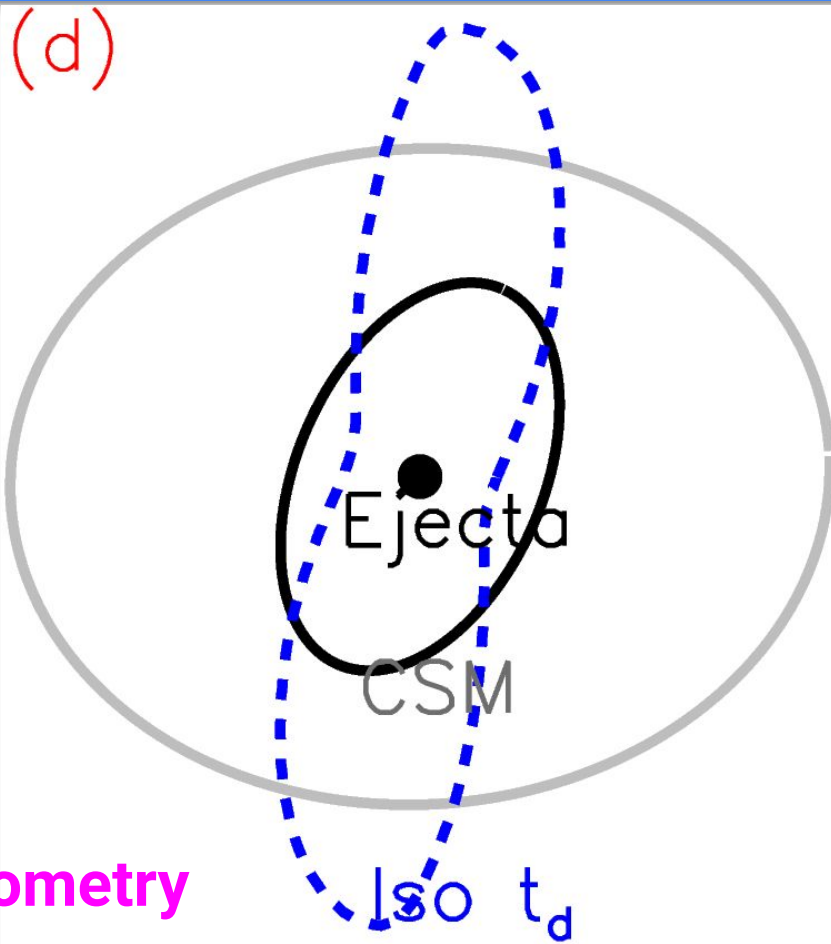
~day 1  
SN2024ggi

Shock Breakout  
Geometry

Well-structured  
Bipolar Explosion

Mephisto CCSNe:

Outer-to-Inner Geometry



**Aspherical  
Ejecta**

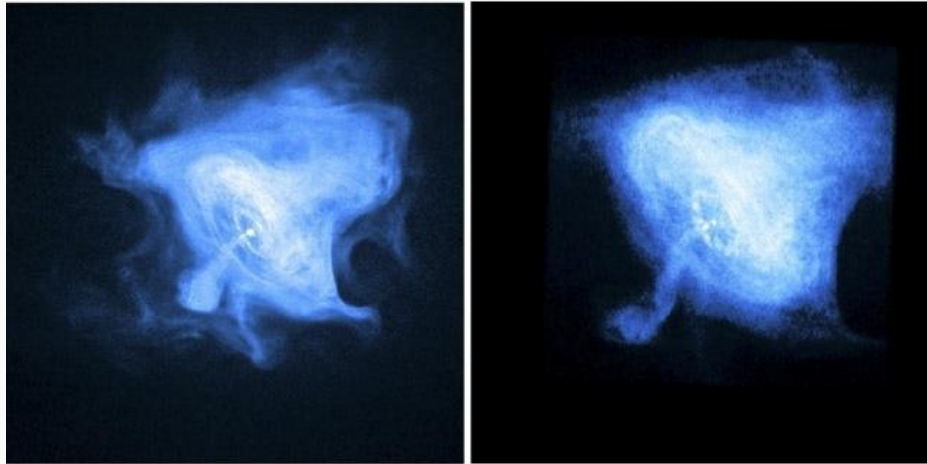
+

**Aspherical  
CSM:**

**Pol  $\neq 0$**

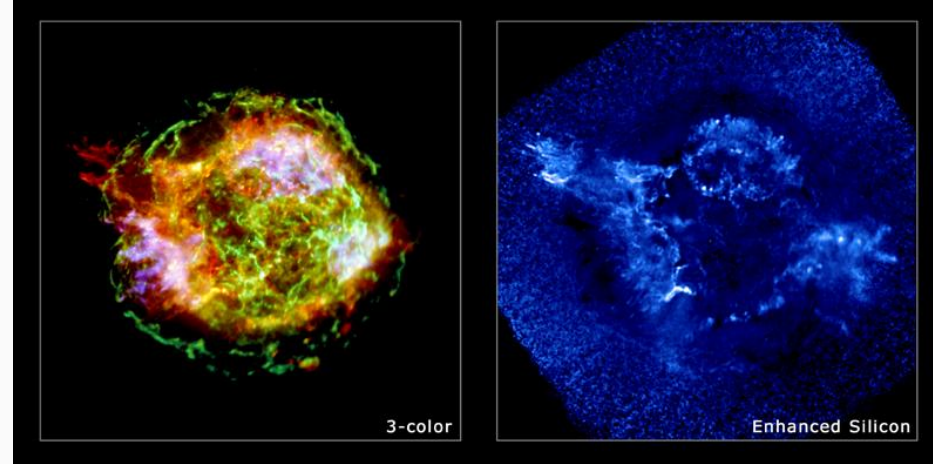
# Summary: SN2024ggi

## SN2024ggi: Highly structured, bipolar explosion (jet?) & disk-like CSM



Crab Nebula (Nov 2008 vs May 2011)

NASA / CXC / SAO



Jacco Vink

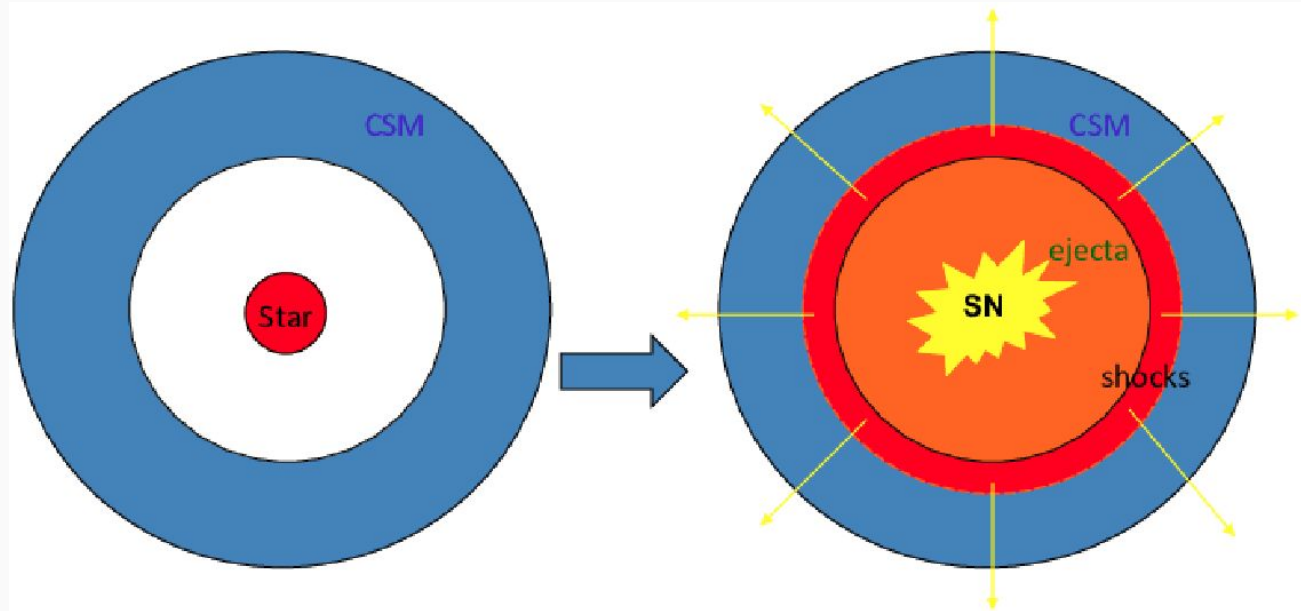
# Interacting Supernovae

Broad H/Alpha in  
Spectrum of SN 2005ip



Still shining after 17 years!

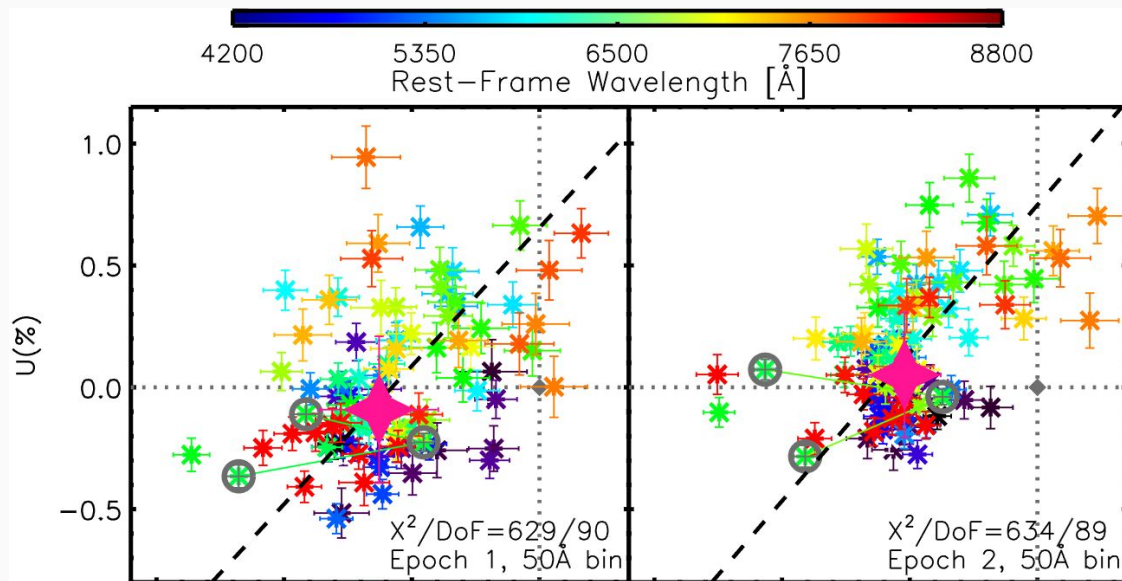
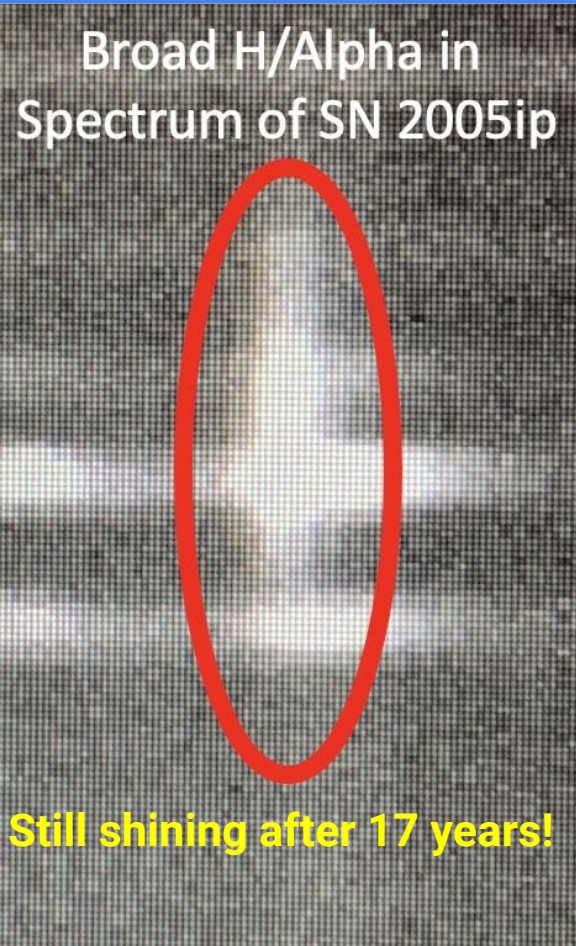
- Long-lived;
- dramatic mass loss;



# Interacting Supernovae

## Mephisto:

- Long-lived;
- SN2018evt: High p%: dramatic disk-like mass loss;
- Promising dust factories;



Yang, Baade, Wang+ (2023)



# Superluminous Supernovae

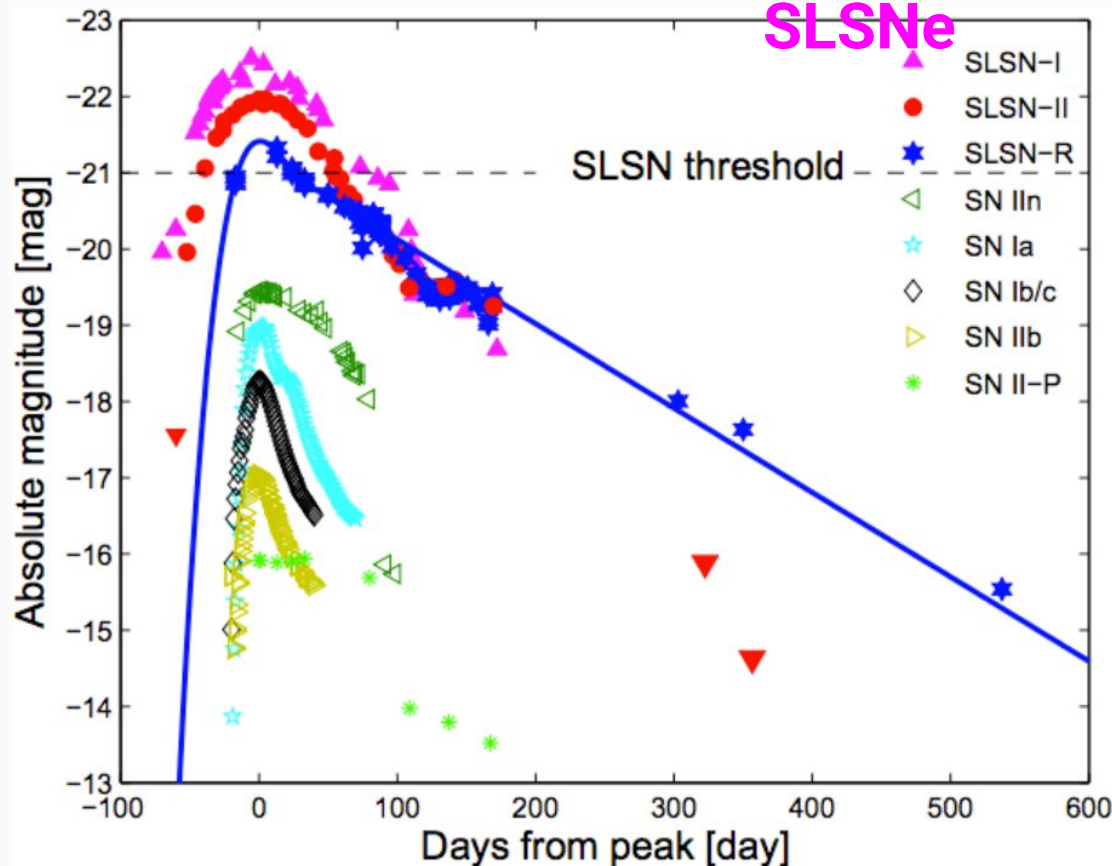
Mephisto:

- Superluminous supernovae (~10-100x brighter than others):

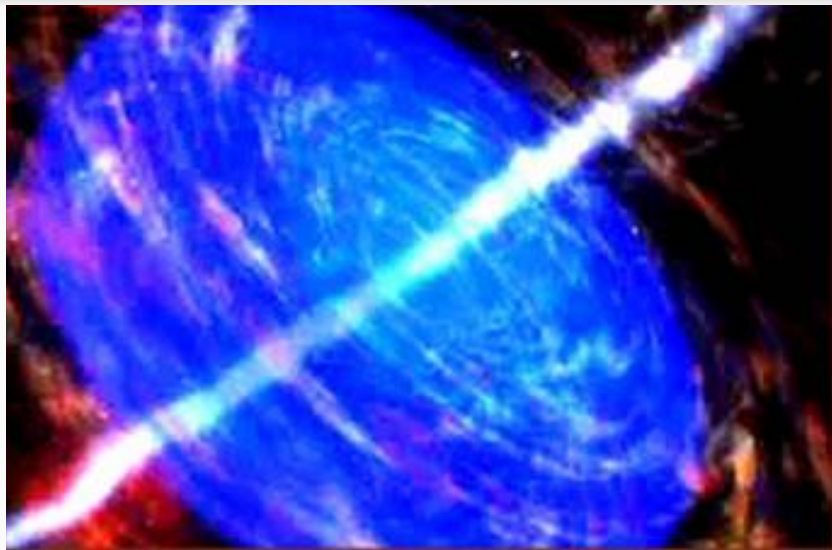
Highly spherical (p~0%):  
huge amount of energy!



Brown, Yang, Wang+ (2016)



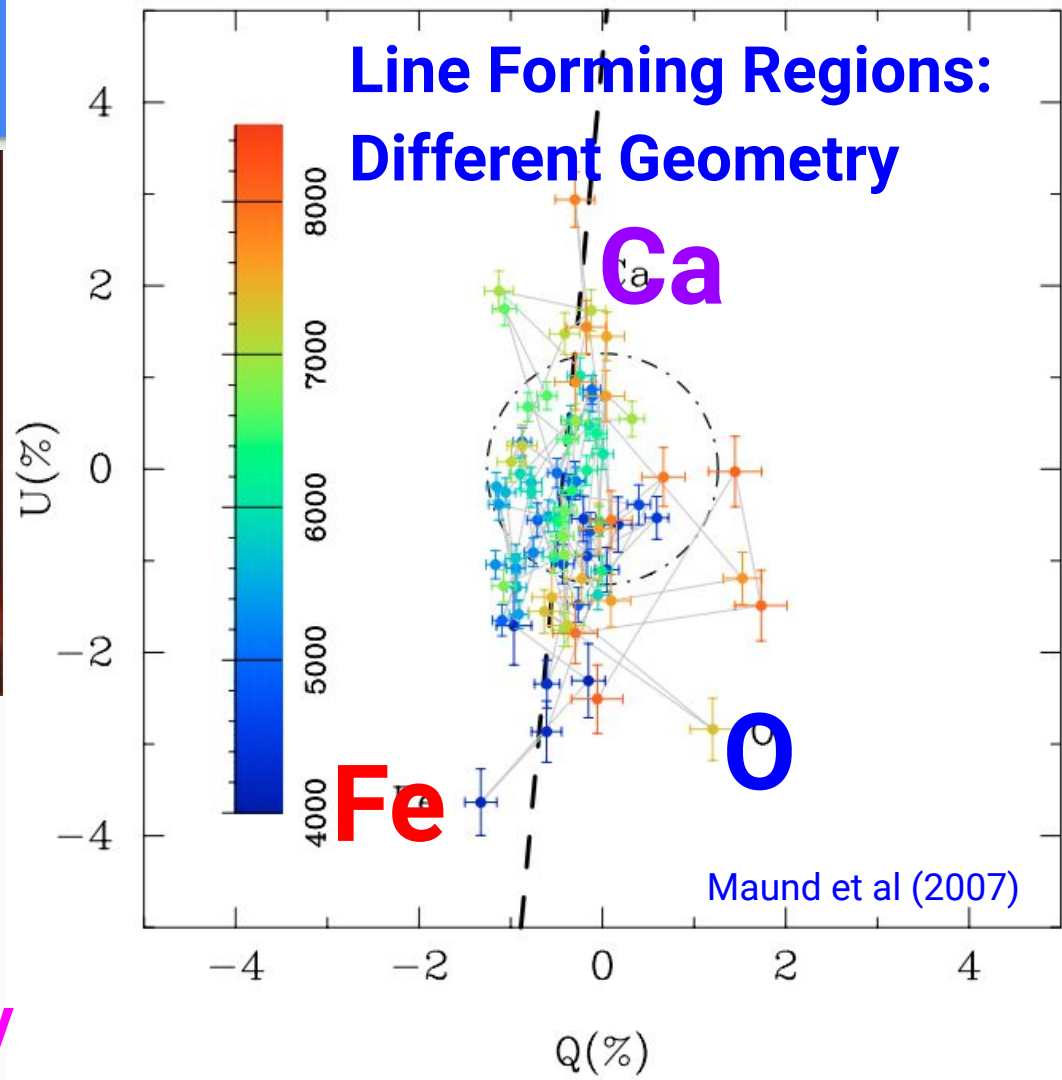
# GRB-Associated SNe



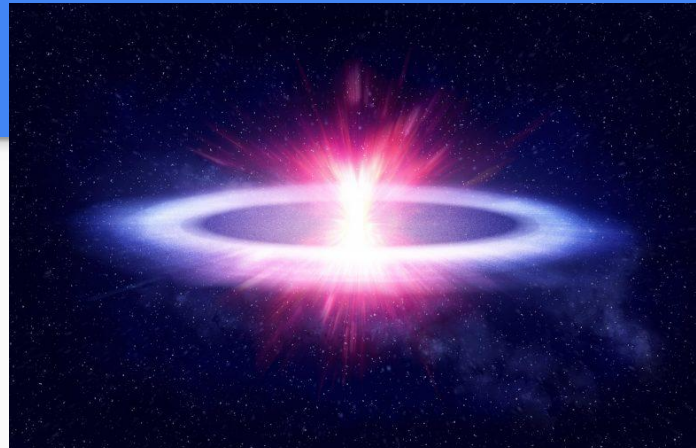
Symmetry axis: parallel to LOS:  
low p% .vs. high High p% observed:

Mephisto:

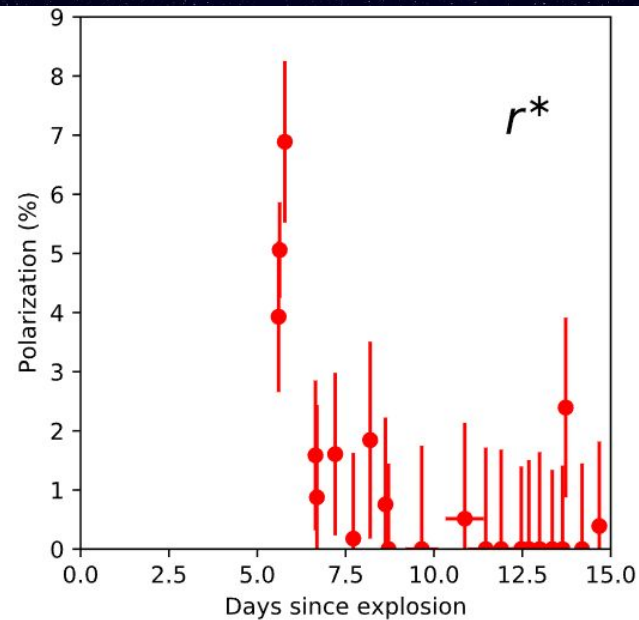
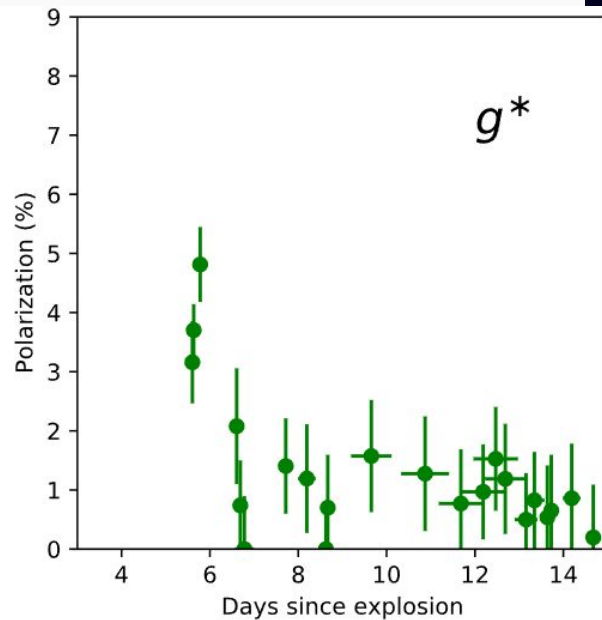
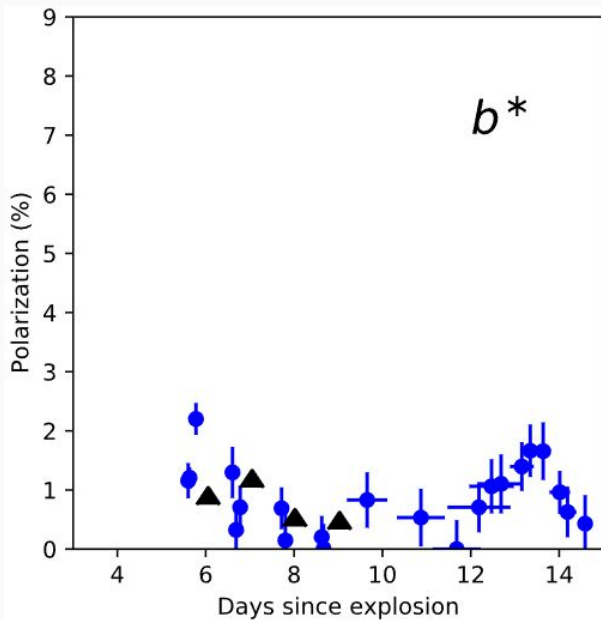
GRB-SNe, Ejecta Tomography



- Fast Blue Optical Transients (energetic):  
**A compact accretion disk**

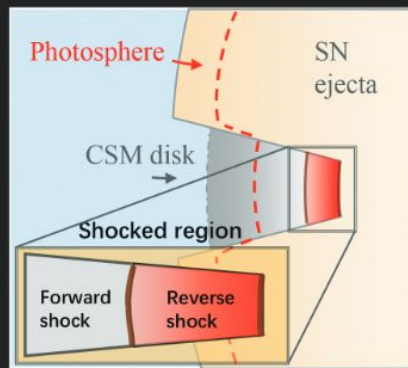
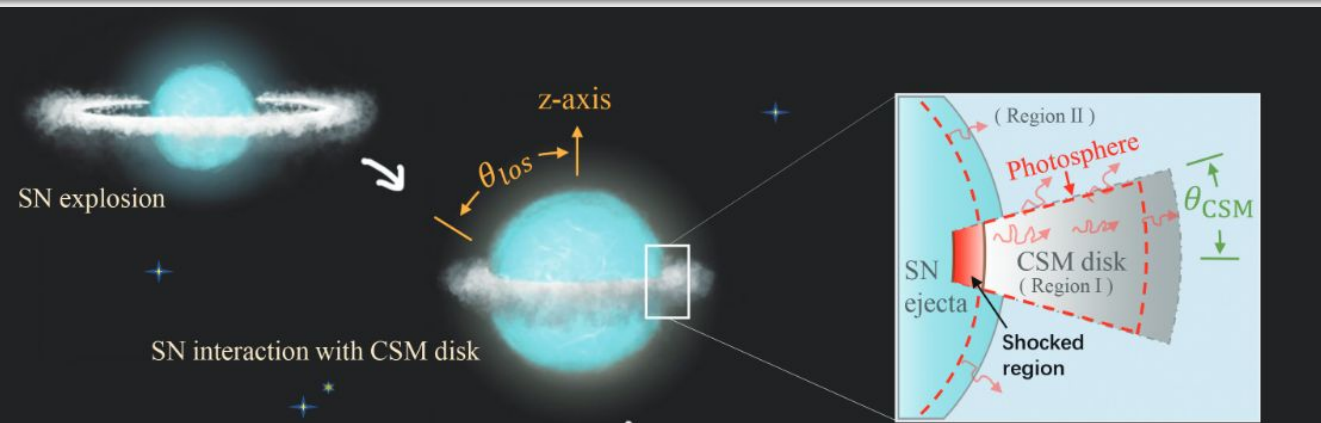


AT2018cow, Maund, Hoflich, Steele, Yang+ (2023)

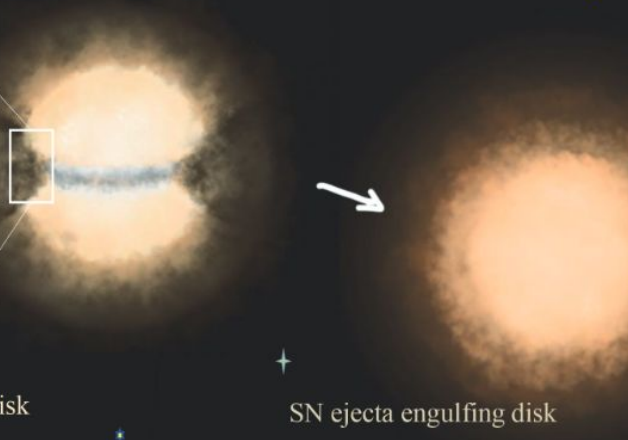


## Fast Transient (young)

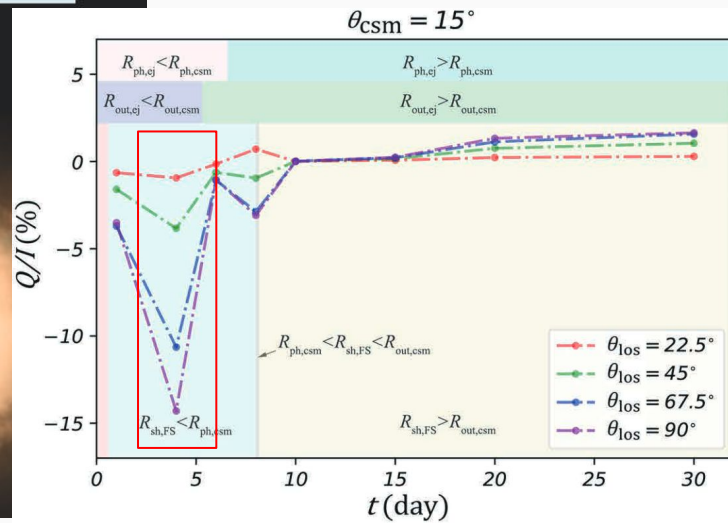
Wen, Gao & Yang+ (2024)



SN ejecta exceeding disk



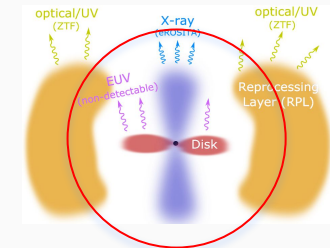
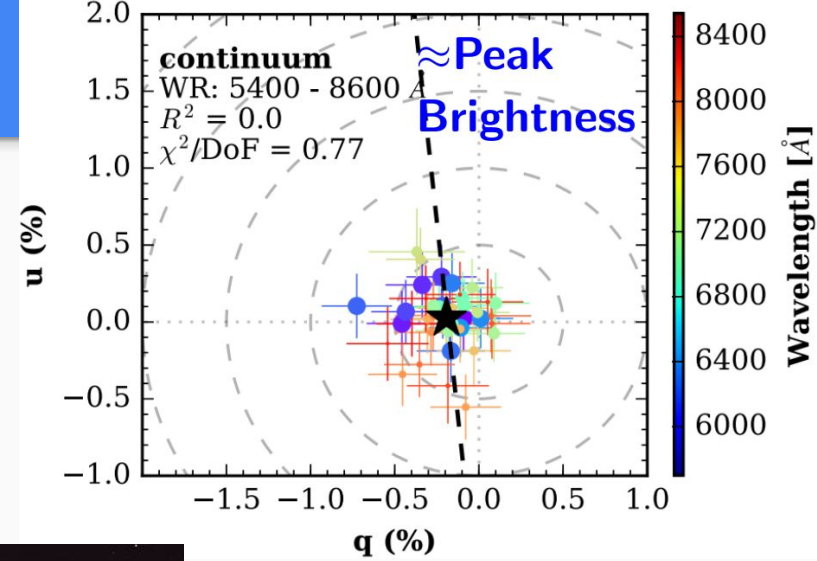
SN ejecta engulfing disk



# Tidal Disruption Events

- **Black Hole eating a star:**  
Accretion disk + reprocessing layer

Patra, Lu, Yang+ (2022)

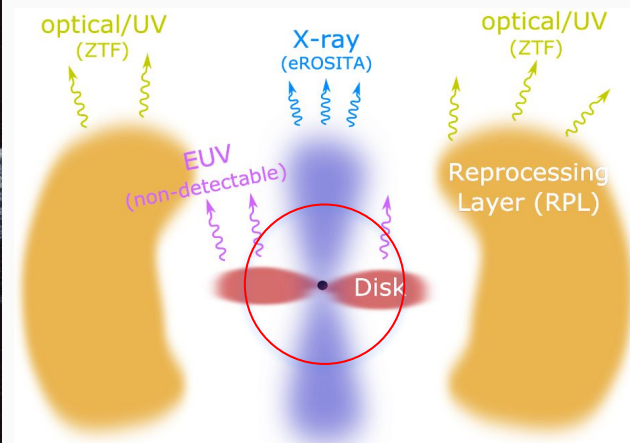
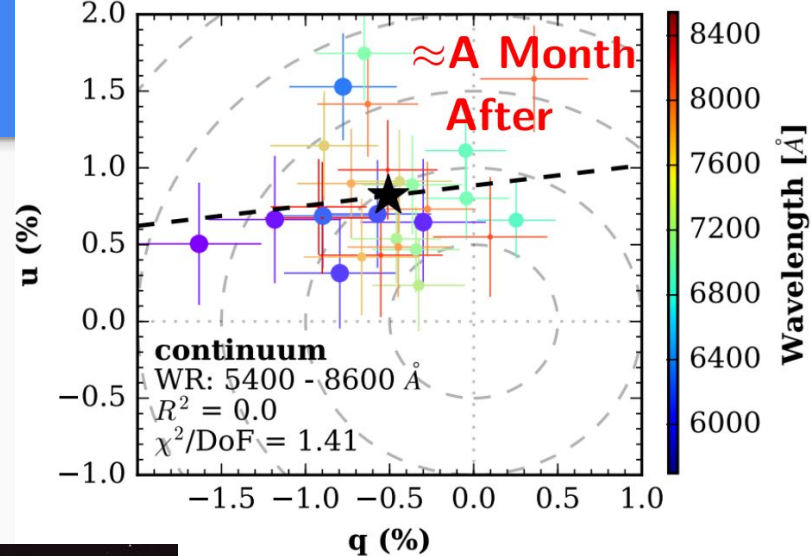


# Tidal Disruption Events

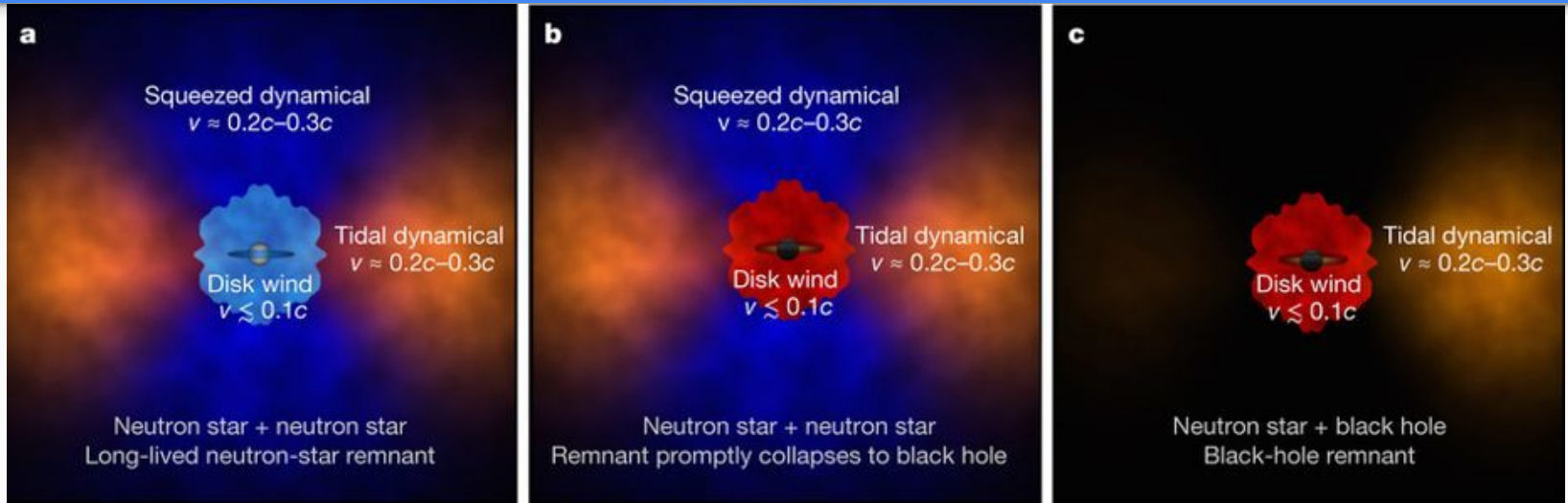
- **Black Hole eating a star:**  
Accretion disk + reprocessing layer

Patra, Lu, Yang+ (2022)

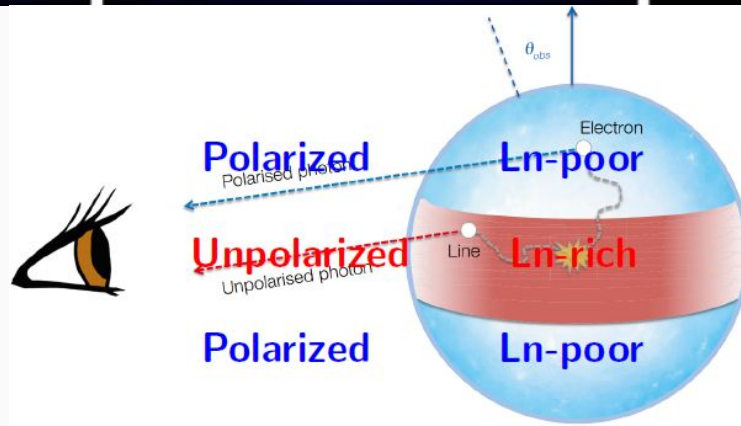
## Mephisto: TDE (early-to-late)



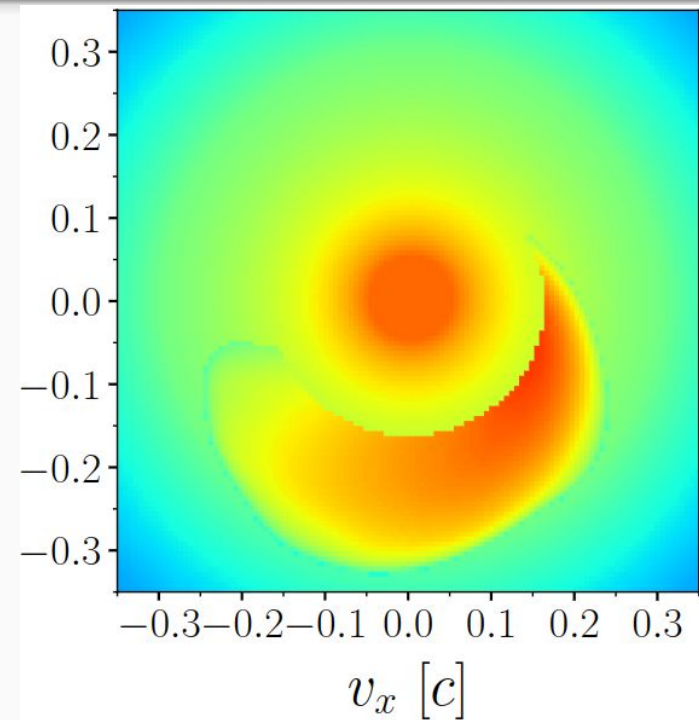
# Kilonova



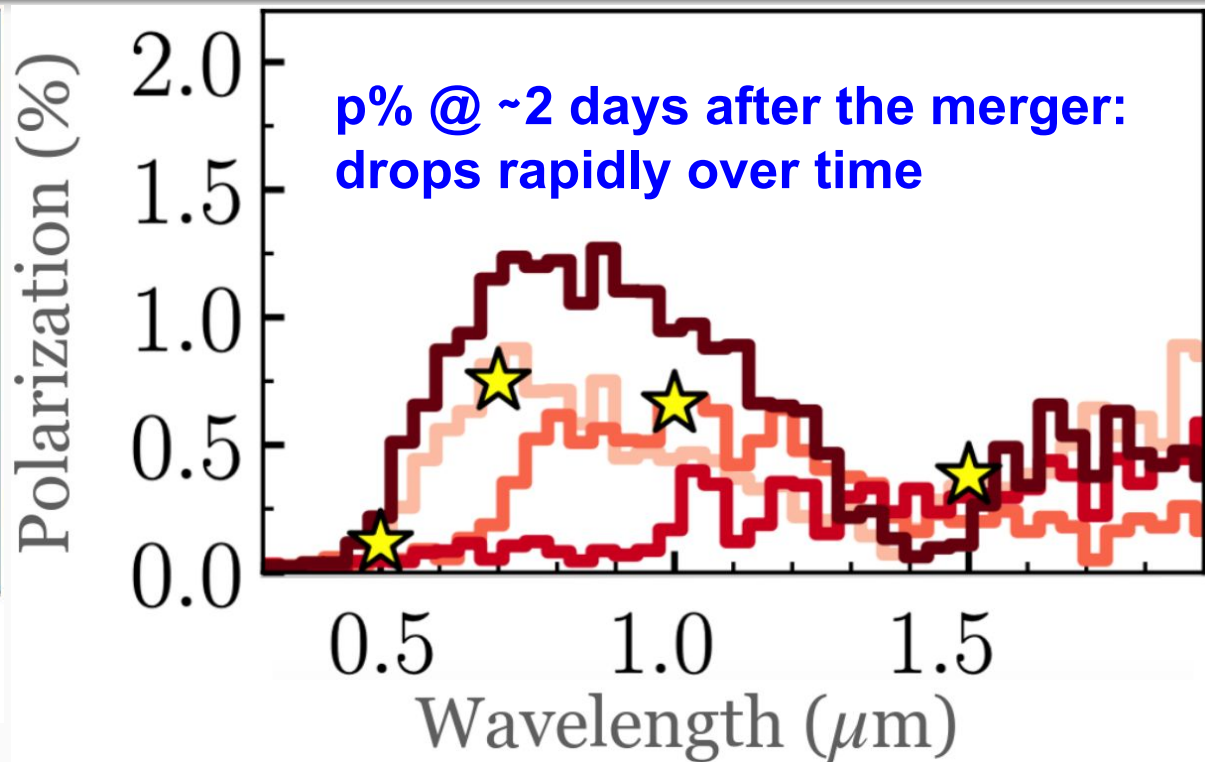
Kasen et al. 2017



# Kilonova



Bulla et al. 2021



**Mephisto: Kilonova (rapid followup)**



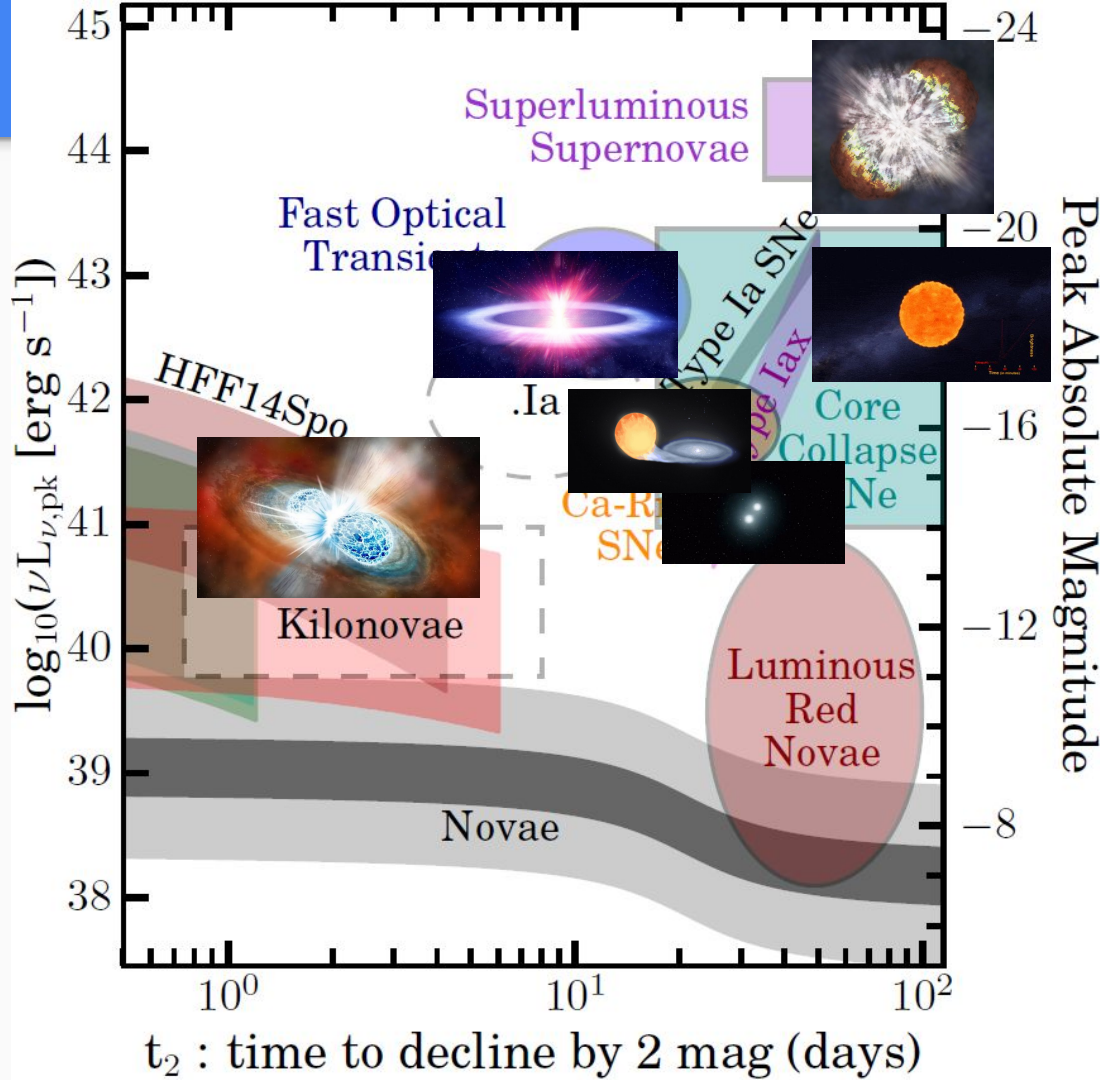
# Summary

Q: Transient Shape?

A: Diverse;  
mostly aspherical

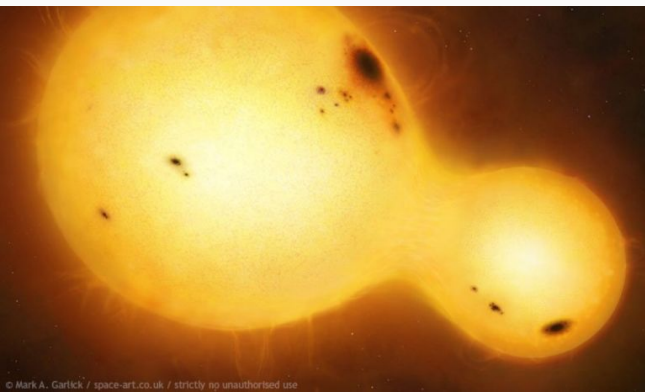
Q: More Opportunities?

A: Binary, (Exo)Planets,  
Accretion, Dust & B-field,  
AGN, Kilonova, Galaxy...



# Polarization of Binaries

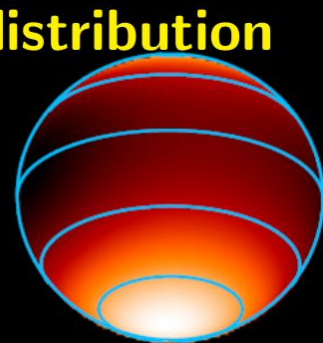
- Orbital inclination;
- Rotation (deformation);
- Detect the disk or wind (BH X-ray);
- Wind Profile & Mass-Loss Rate
- (WR Stars, colliding wind binaries);



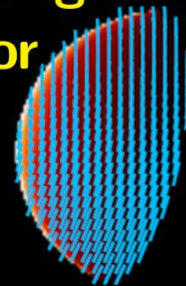
**Mephisto:  
Binaries**



**gravity distribution**

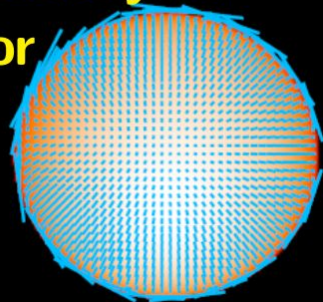
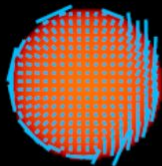


**reflected light &  
pol vector**



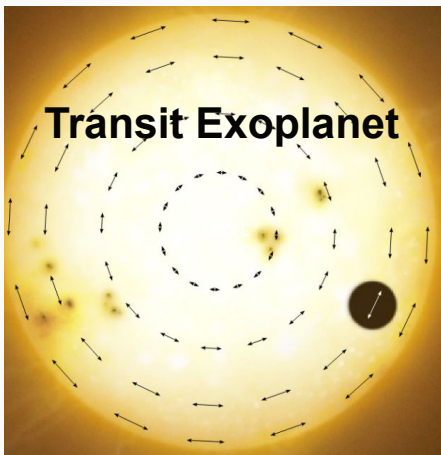
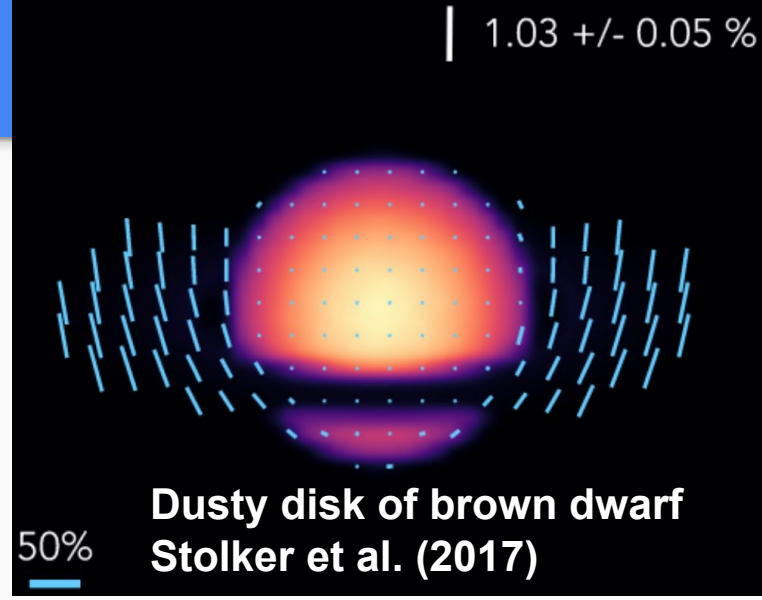
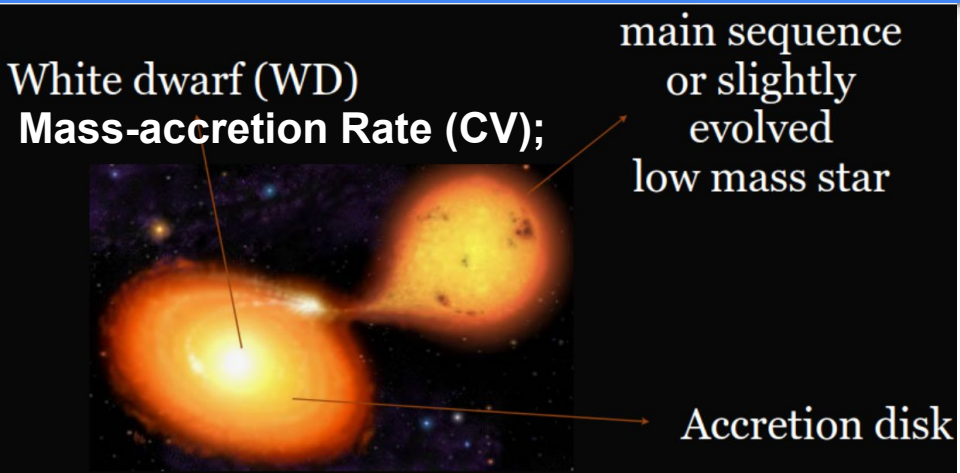
50 %

**Total intensity &  
pol vector**

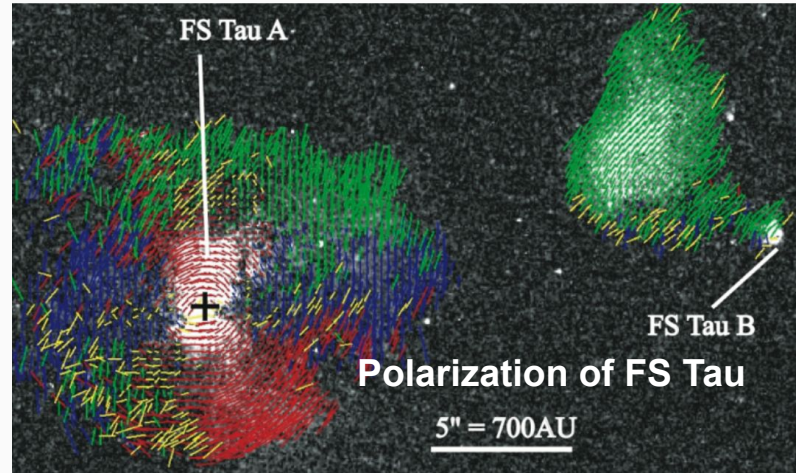


1000 ppm

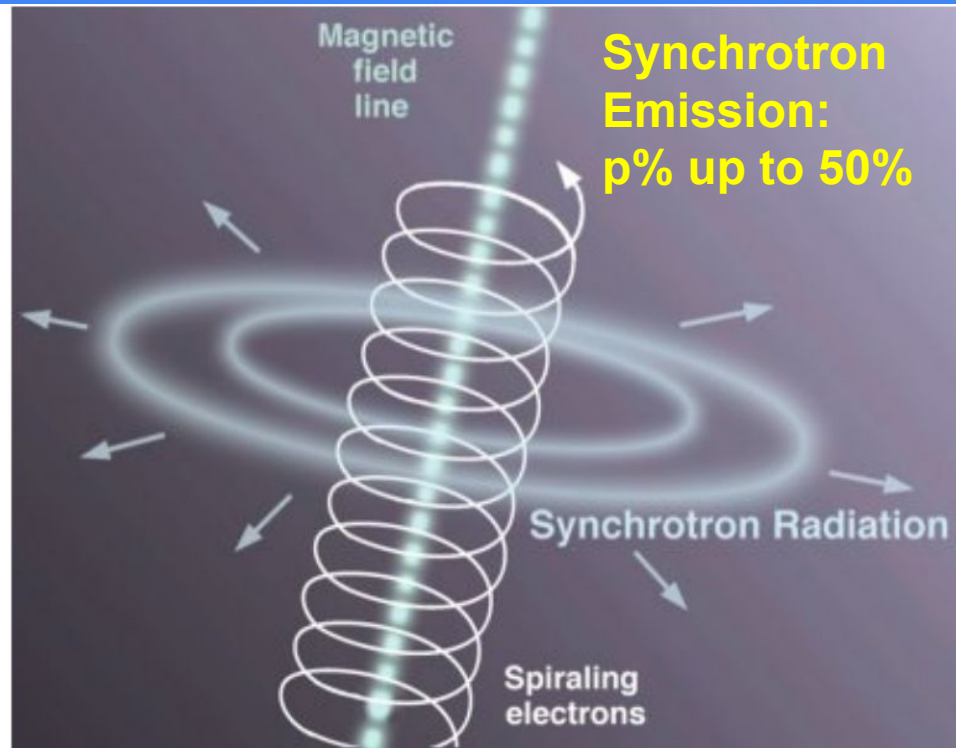
# Polarization of Accretions



Mephisto:  
Accretion  
Processes



# Polarization of AGN



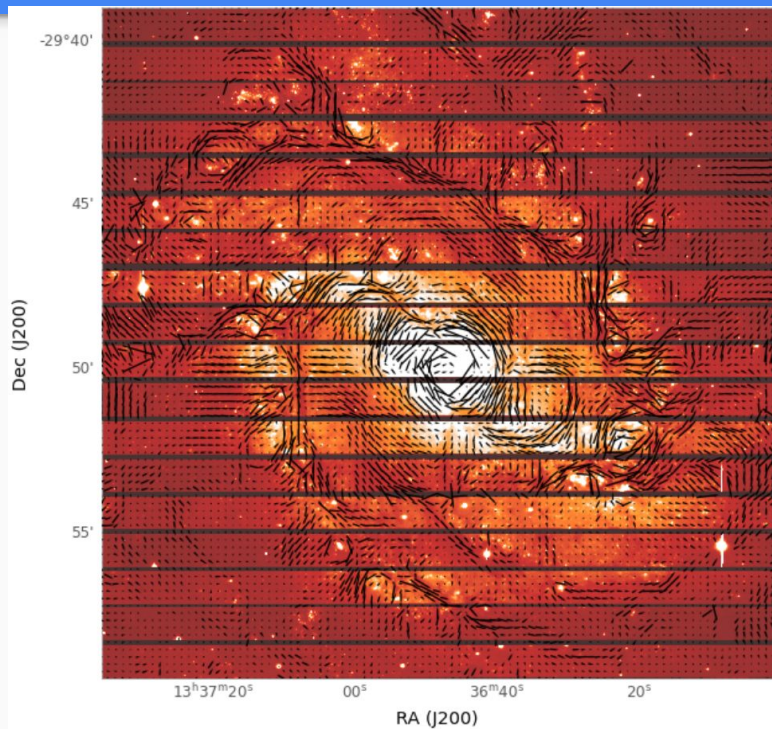
p% variability (min-to-yr): Blazar flares, B-field in jet evolution;

particle acceleration, jet dynamics, radiation processes...

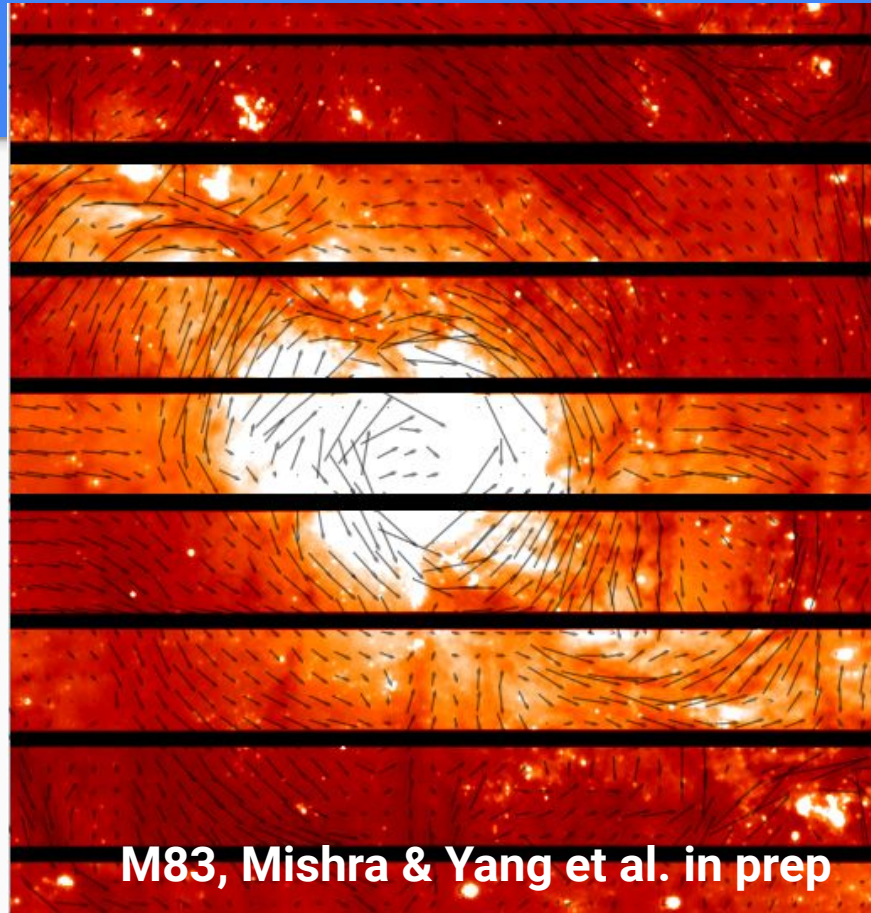
**Mephisto:**

**AGN & Blazars**

# Polarization of Galaxies



**B-field, grains, wavelength dependence;  
Young Stellar Objects & Star-Forming regions;  
Intragalactic regions;  
Galaxy mergers, etc**



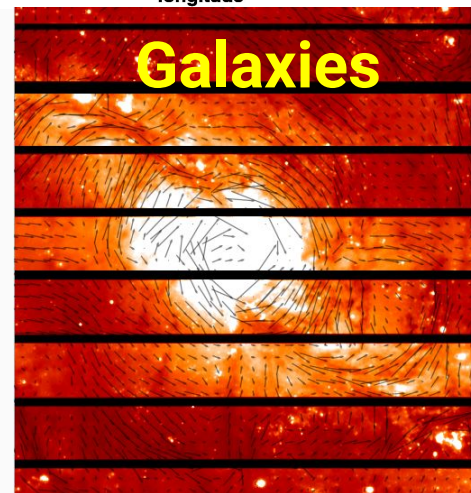
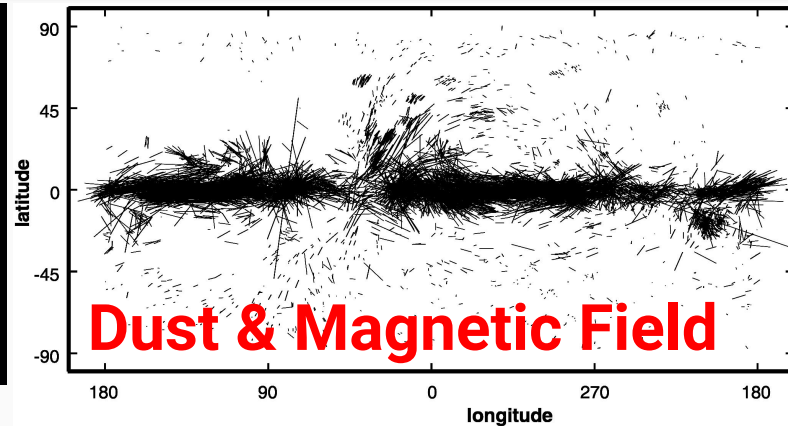
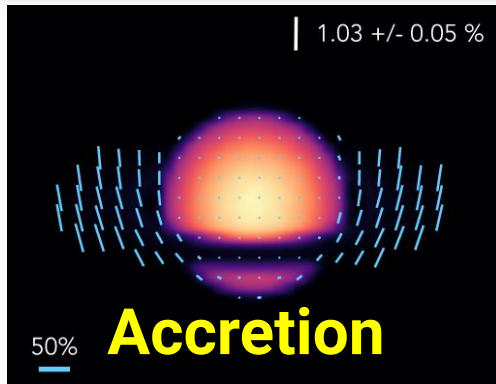
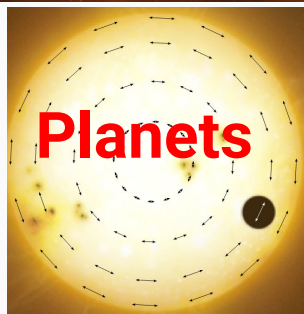
**M83, Mishra & Yang et al. in prep**

**Mephisto: p% map  
of Nearby Galaxies**

# Summary

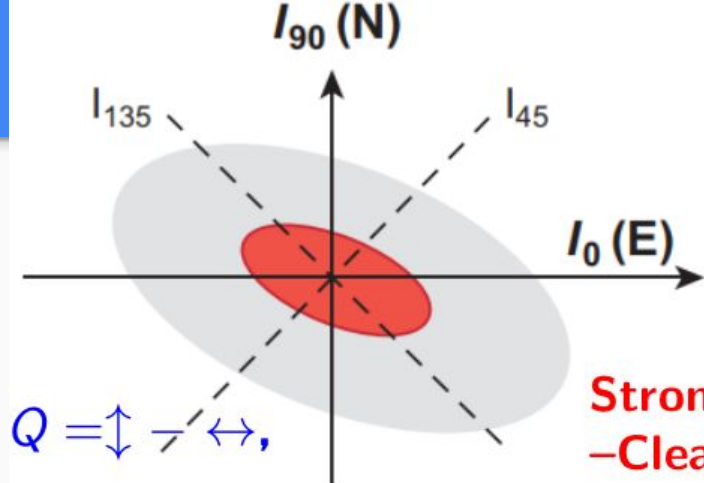
- **Mephisto**

- Polarimetry tech
- Polarized night Sky



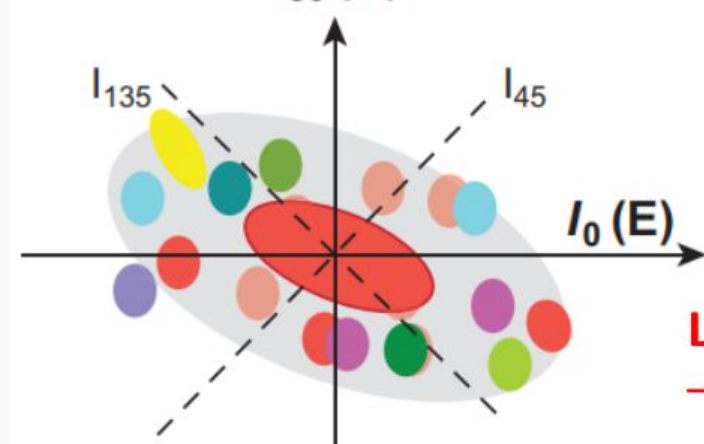
# References

- (1) Hoflich, Yang+ 2023, MNRAS 520, 560H;
- (2) Yang, Yan+ 2022, ApJ, 939, 18Y;
- (3) Patra, Yang+ 2022, MNRAS, 509, 4058P;
- (4) Yang, Hoflich+ 2020, ApJ, 902, 46Y;
- (5) Yang, Wang+ 2018, ApJ, 854, 55Y;
- (6) Yang, Wang+ 2018, ApJ, 852, 89Y;
- (7) Vasylyev, Yang+ 2023 ApJ, 955L, 37;
- (8) Vasylyev, Yang+ 2024 MNRAS, 527, 3106;
- (9) Maund, Yang+ 2021 MNRAS, 503, 312M;
- (10) Yang, Baade+2023 MNRAS, 519, 1618Y;
- (11) Wang, Hu, Wang, Yang+2024, Nature Astron, arXiv, 2310, 14874W;
- (12) Brown, Yang+ 2016, ApJ, 828, 3B; cite:39
- (13) Patra, Lu, Yang+ 2022, MNRAS, 515, 138P;
- (14) Maund, Hoflich, Steele, Yang+2023, MNRAS, 521, 3323



$$Q = \left\| \begin{matrix} \updownarrow \\ \leftrightarrow \end{matrix} \right\|,$$

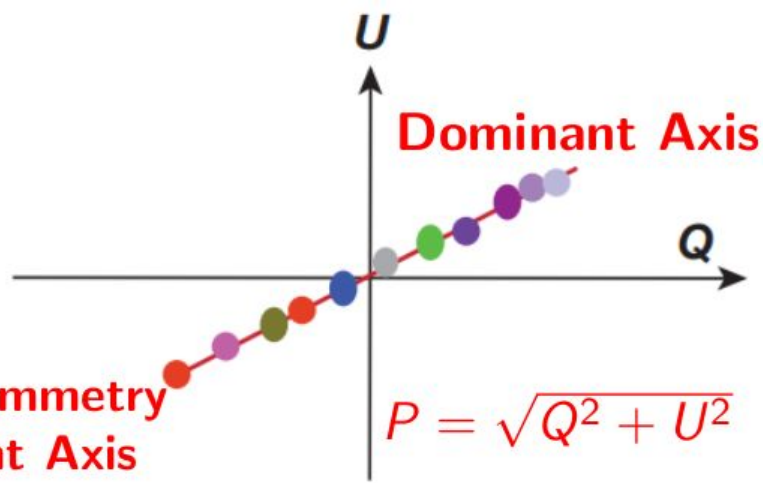
$$U = \left\| \begin{matrix} \nearrow \\ \nwarrow \end{matrix} \right\|$$



**Stronger Axial Symmetry**  
**-Clearer Dominant Axis**

Color: different wavelengths

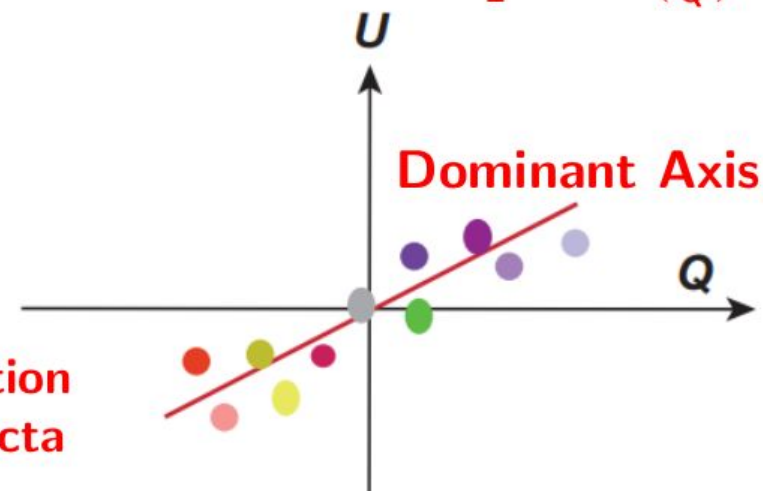
**Larger Deviation**  
**-Lumpier Ejecta**



**Dominant Axis**

$$P = \sqrt{Q^2 + U^2}$$

$$\theta = \frac{1}{2} \tan^{-1} \left( \frac{U}{Q} \right)$$



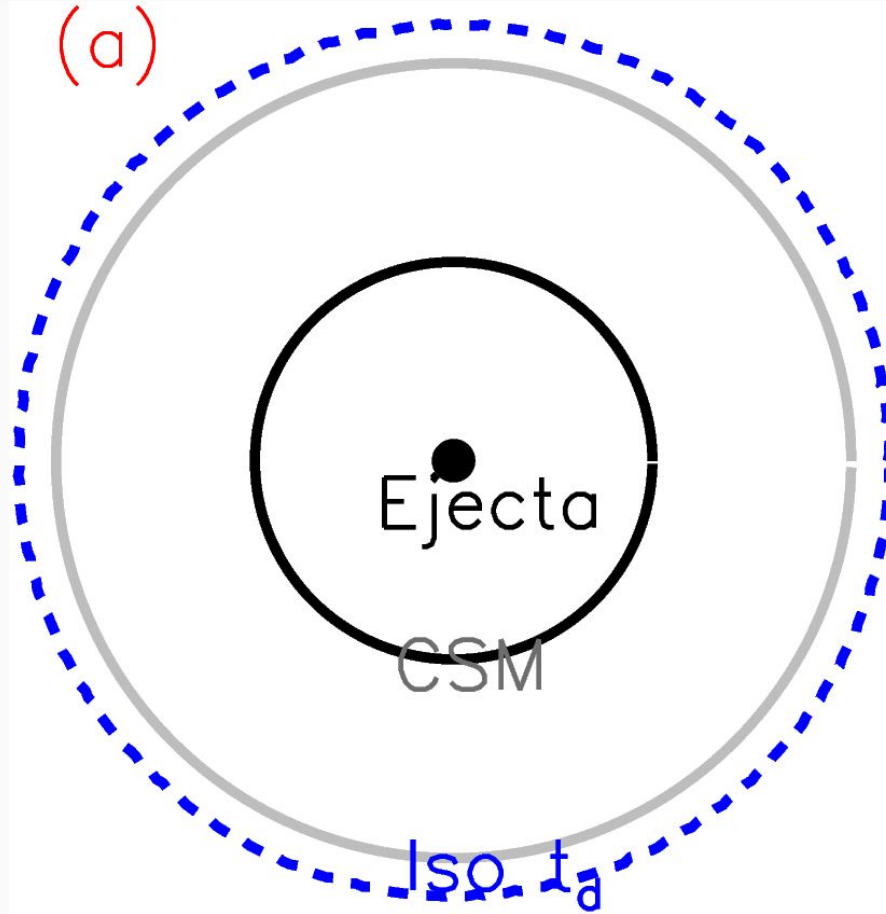
**Dominant Axis**





# SN2024ggi (VLT specpol)

**~day 1**

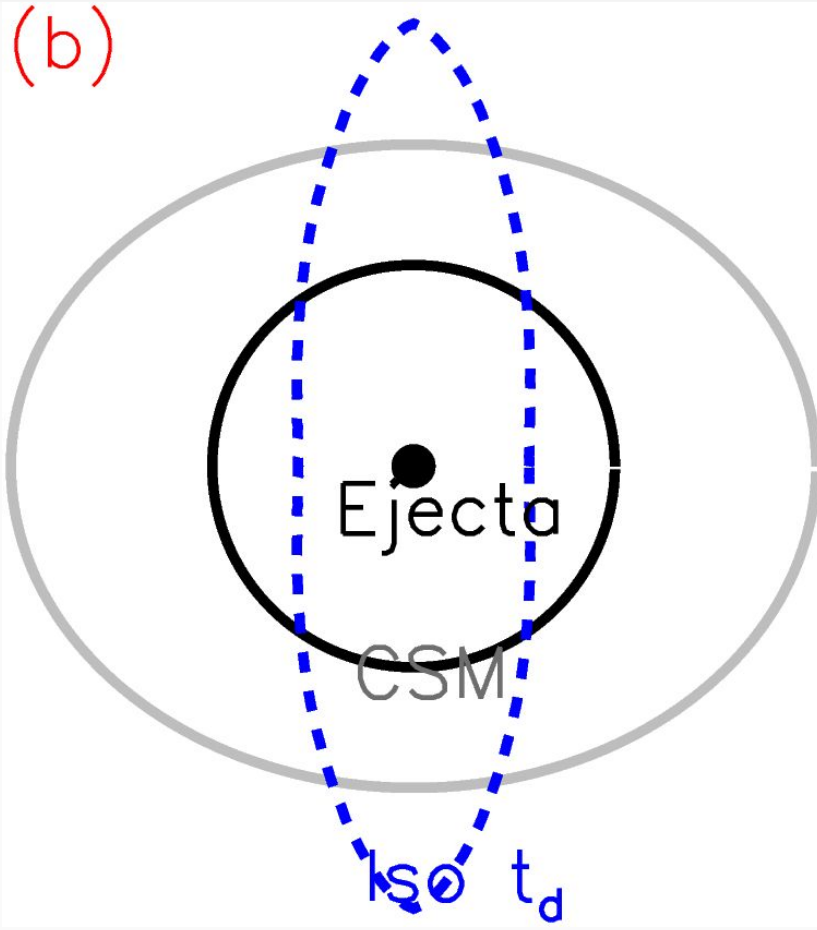


**Spherical  
Ejecta  
+  
Spherical  
CSM:**

**Pol = 0**

# SN2024ggi (VLT specpol)

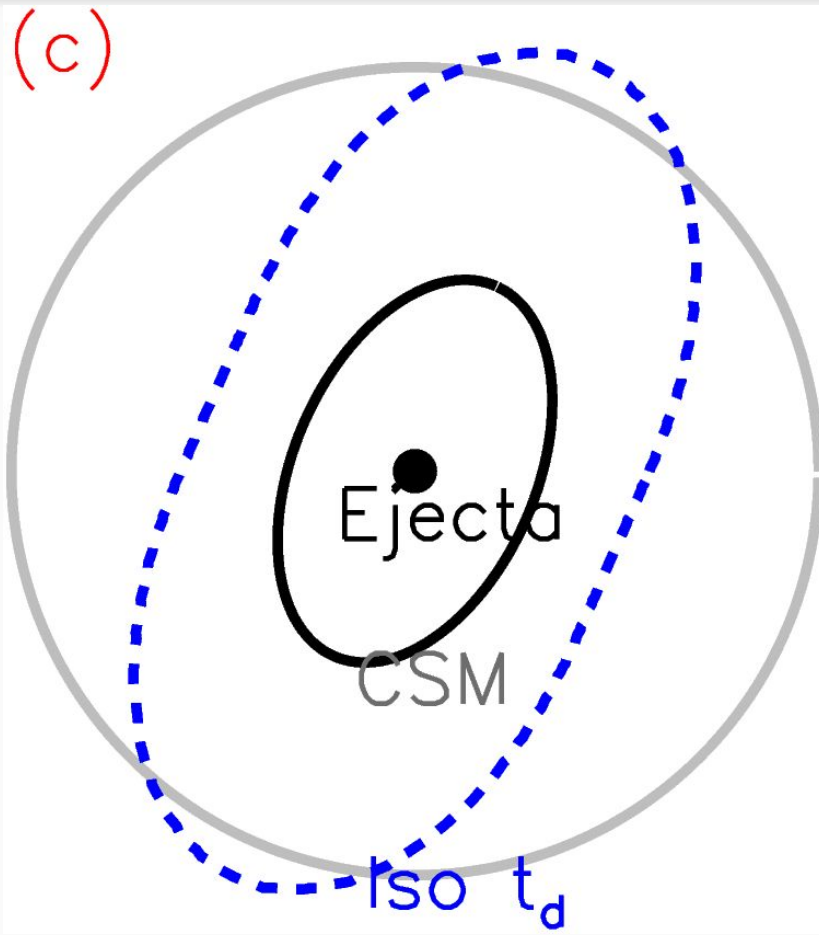
**~day 1**



**Spherical  
Ejecta  
+  
Aspherical  
CSM:**

**Pol  $\neq$  0**

~day 1



**Aspherical  
Ejecta**

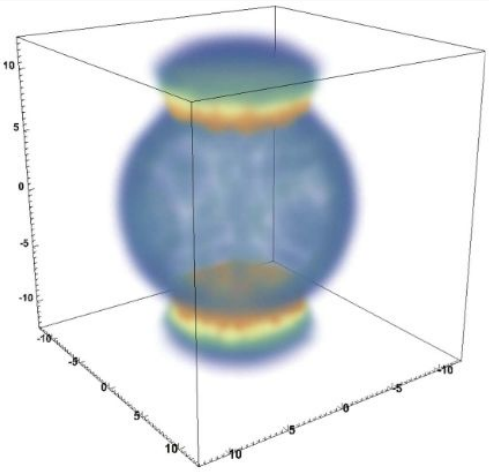
+

**Spherical  
CSM:**

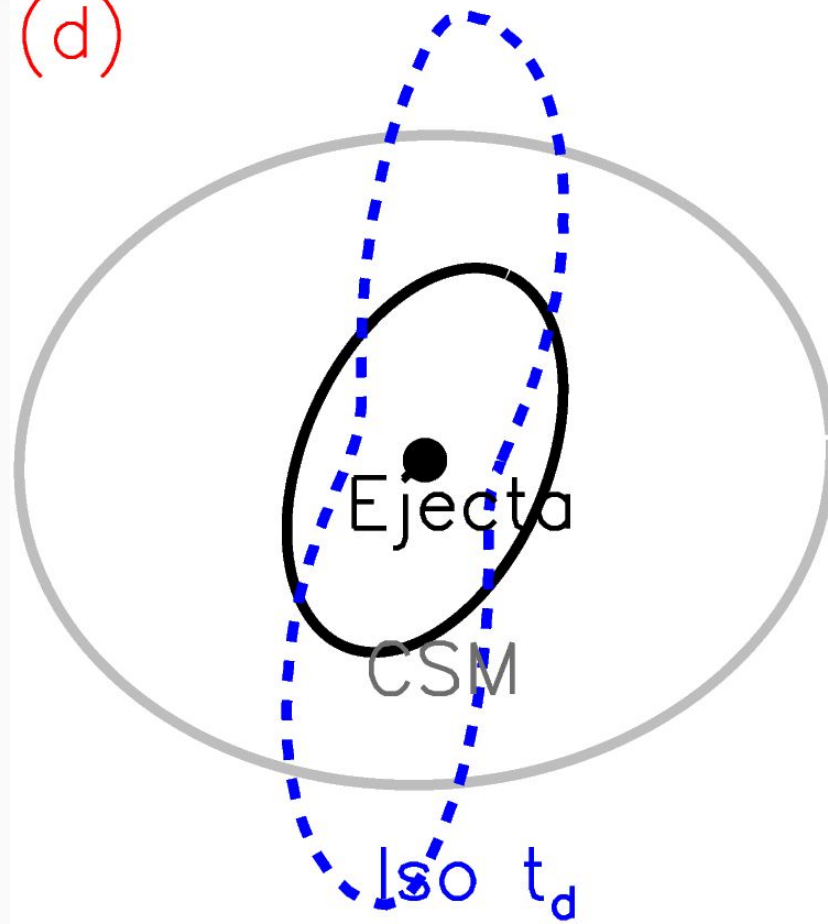
**Pol  $\neq 0$**

# SN2024ggi (VLT specpol)

**~day 1**  
**SN2024ggi**



(d)



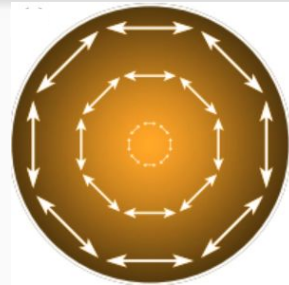
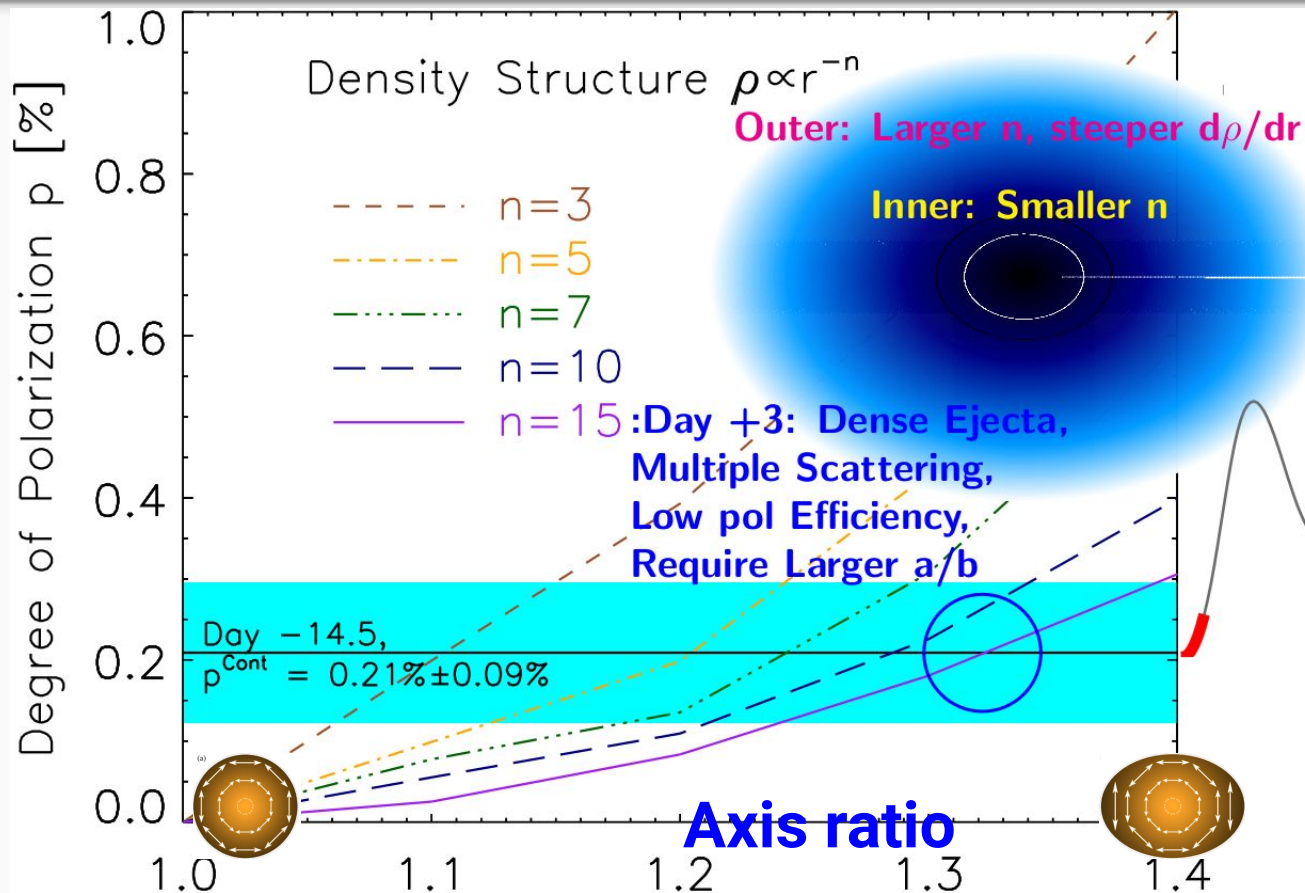
**Aspherical  
Ejecta**

**+**

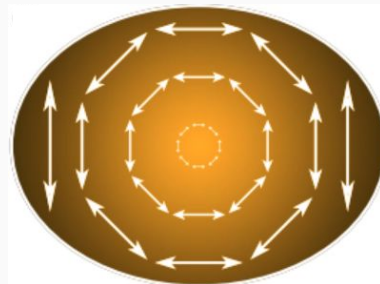
**Aspherical  
CSM:**

**Pol  $\neq$  0**

# Results: Thermonuclear supernovae (Early = outer layers)

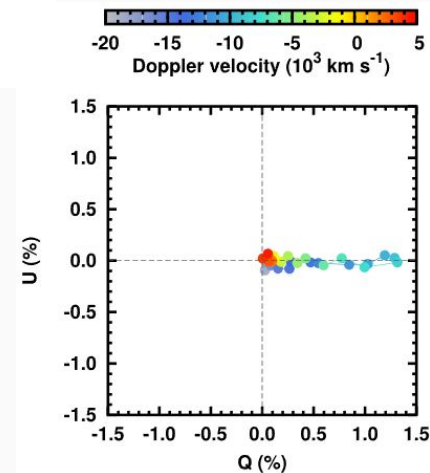
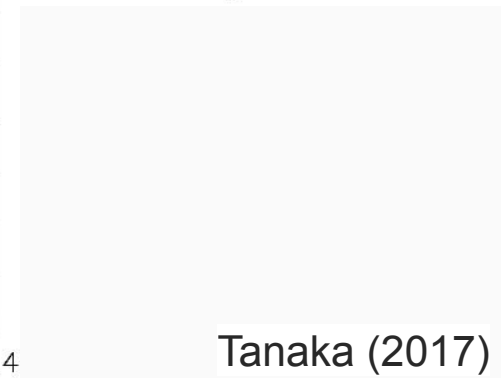
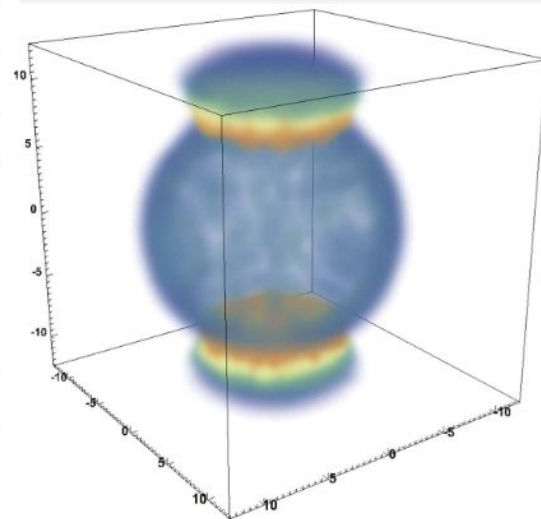
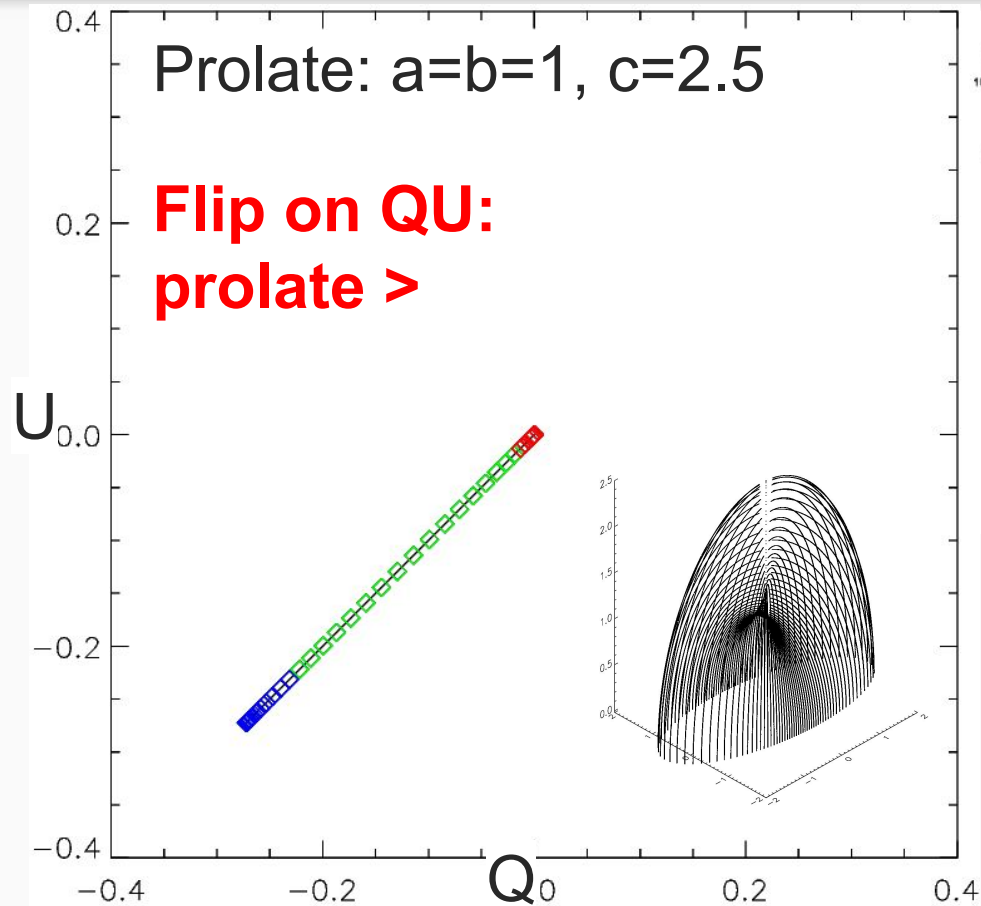


Spherical:  $p = 0$

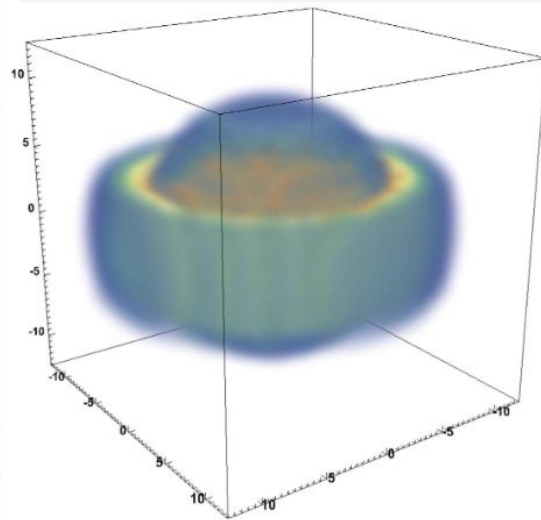
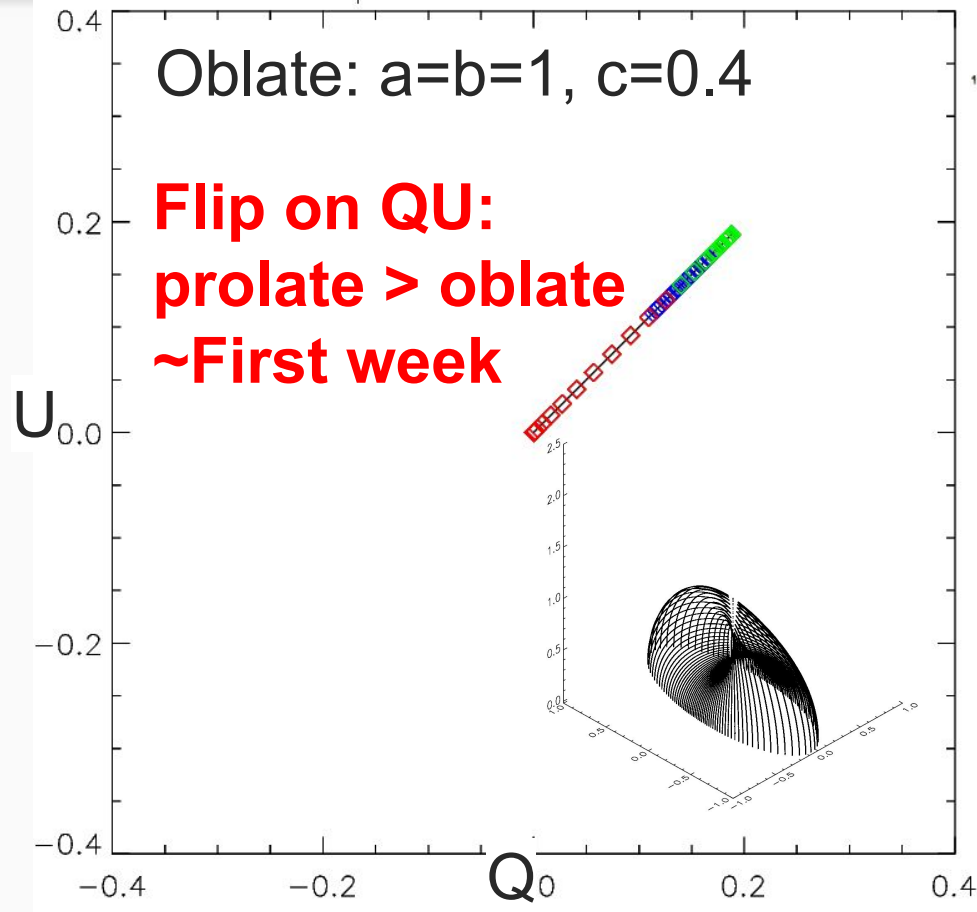


Aspherical:  $p \neq 0$

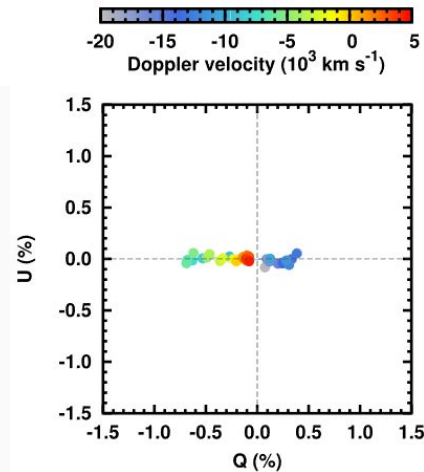
# What does a 'flip' mean?



# What does a 'flip' mean?

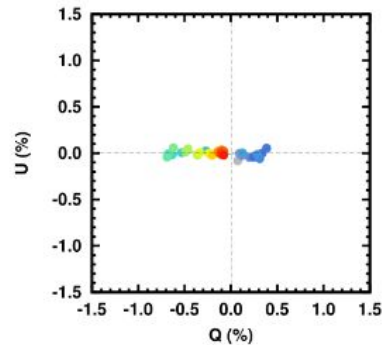
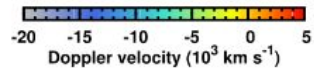
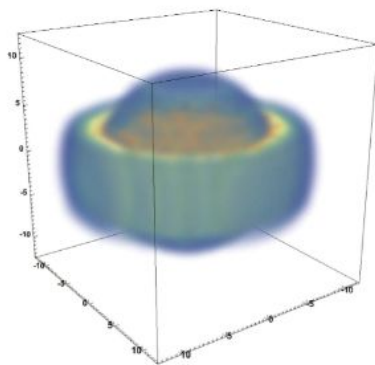
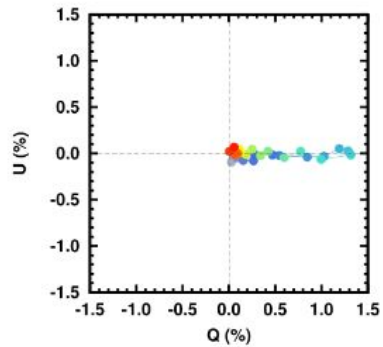
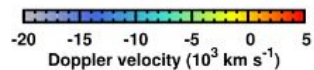
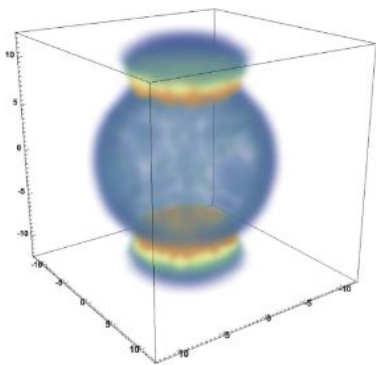


Tanaka (2017)

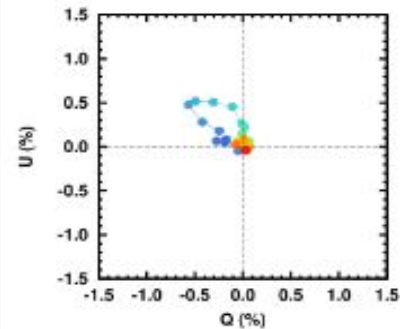
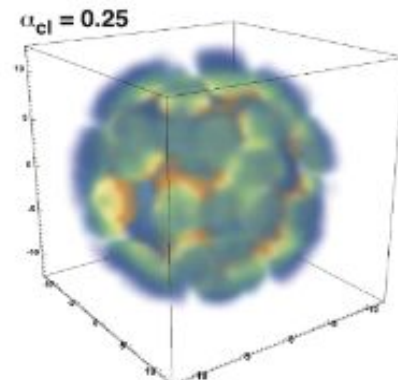
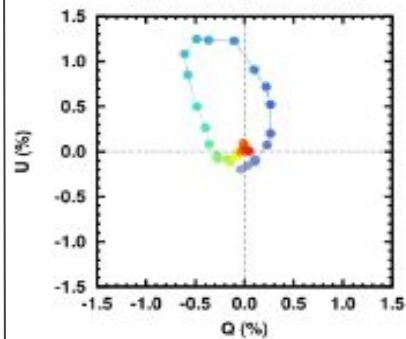
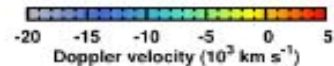
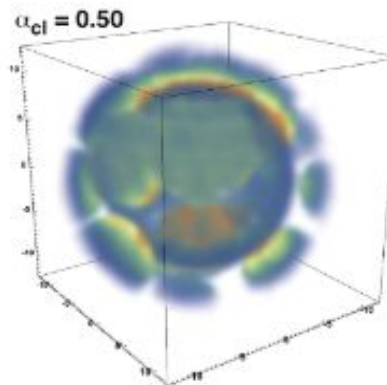




## Axisymmetric



## Asymmetric/Clumping



# Multi-Color Polarimetry

**Too far to resolve**

**Geometry: what are they, how they explode...**

