

# The Search for Light Echoes of Historic SNe in the Southern Hemisphere with DECam

Armin Rest  
(STScI)

Collaborators: Federica Bianco, Ryan Chornock, Alejandro Clocchiatti, Ryan Foley, **David James**, Tom Matheson, Gautham Narayan, Knut Olsen, **Sean Points**, Jose Luis Prieto, **Chris Smith**, Nathan Smith, Nick Suntzeff, Doug Welch, **Alfredo Zenteno**

# Why Light Echoes?

## Extragalactic SNe

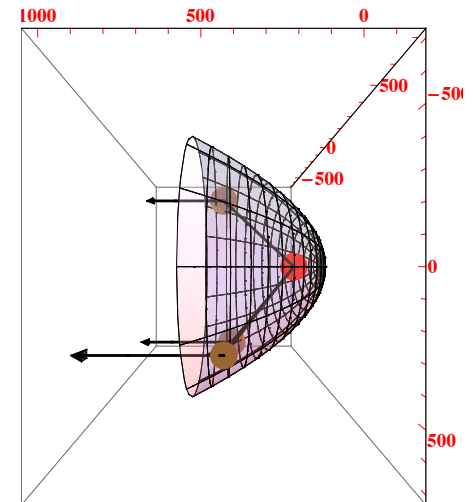
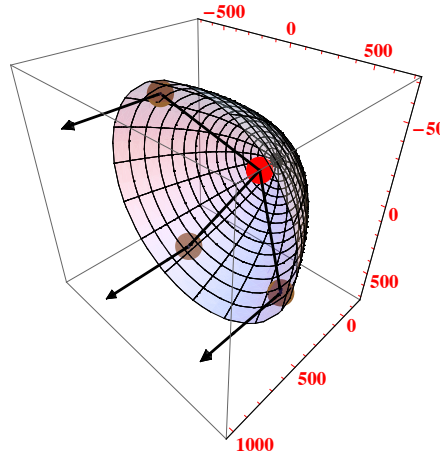
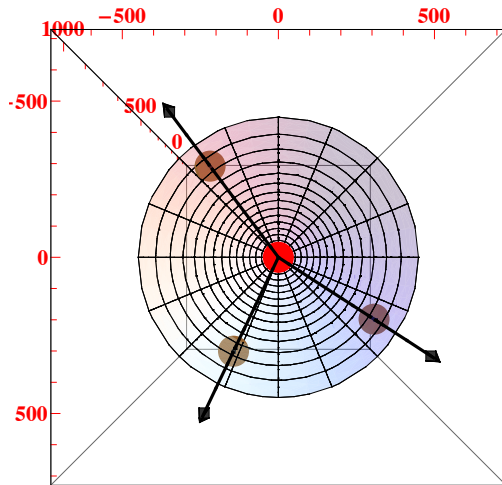
- Many surveys
- Spectra of 100s of SNe per year
- Populations, rates, properties
- Unresolved

## Light Echo Spectra

- Spectral classification of historic events
- 3D Spectroscopy
- Spectroscopic time series
- ~10 MWG SNe
- LMC, SMC, M31..

## Milky Way Galaxy

- 1 per 100 years
- Close!
- Environment
- Remnant
- Progenitor
- Composition
- **No spectra!**



# Outline

- Light Echo Primer
- Highlights of Light Echoes of Historic Events
- DECam Light Echo Search

## CTIO4m and KPNO4m: Light Echo Discovery Machines!

SN Name	RA	Dec	Date	Dist. (kpc)	Type	Search Radius (deg)	Search Area (deg <sup>2</sup> )	Discovery Telescope	Discovery Reference
<u>Cas A</u>	23:23	+58:48	1680	3.4	SN <u>IIb</u>	5	66	KPNO4m, LaSilla3.6m	Rest+08, Krause+08
<u>Tycho</u>	00:25	+64:09	1572	2.3	Normal SN <u>Ia</u>	10	287	KPNO4m	Rest+08
0509-67.5 (LMC)	05:11	-67:31	~1600	50	<u>Overlum.</u> SN <u>Ia</u>	1	3	CTIO4m	Rest+05
0519-69.0 (LMC)	05:19	-69:04	~1400	50	SN <u>Ia</u>	1	3	CTIO4m	Rest+05
N103B (LMC)	05:09	-68:42	~1000	50	SN <u>Ia</u>	1	3	CTIO4m	Rest+05
Eta Car	10:45	-59:41	~1840	2.4	Great Eruption	3	36	CTIO4m	Rest+12

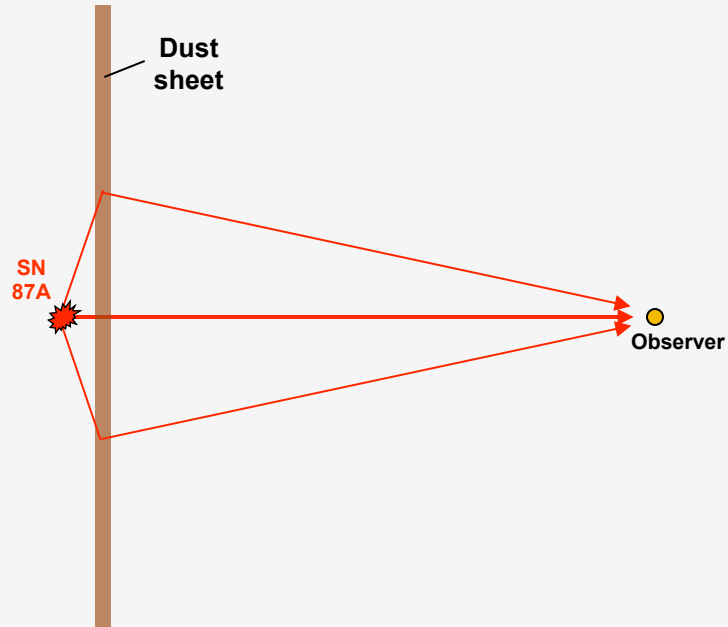


# The Light Echoes of SN 1987A (Suntzeff+88,Crotts+89)



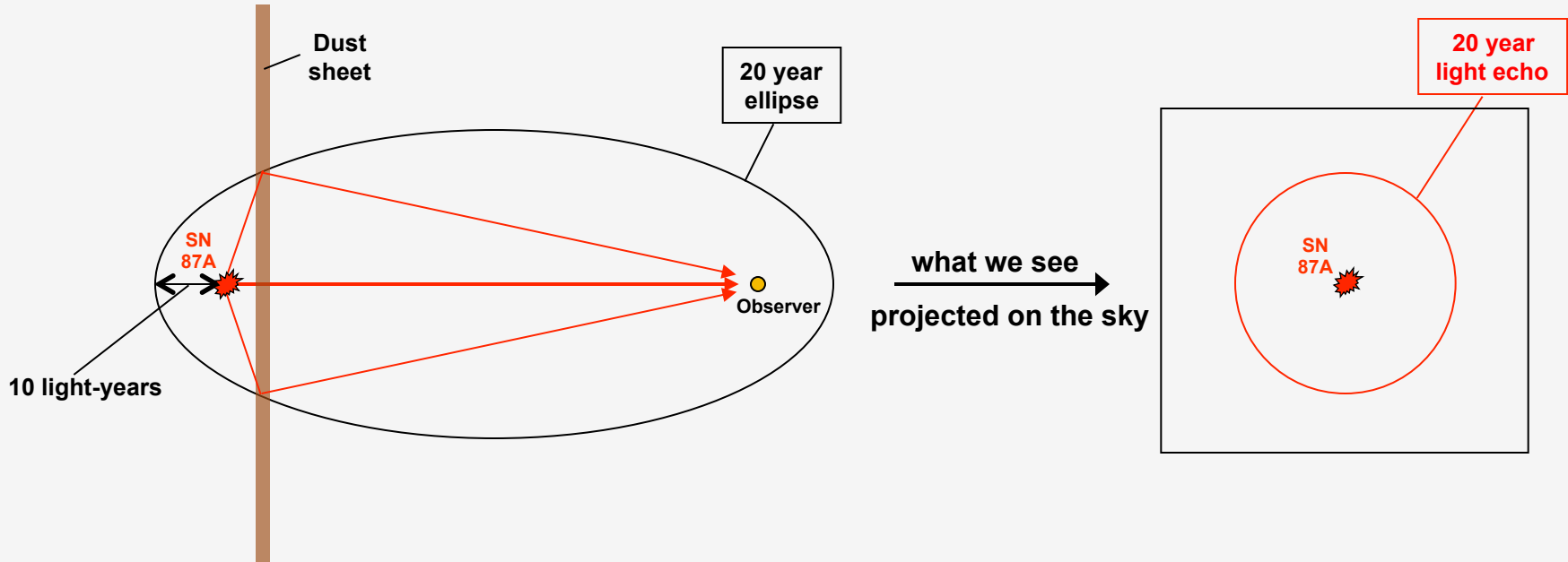


# Geometry of Light Echoes



# Geometry of Light Echoes

Ellipsoids trace out surfaces of constant arrival time

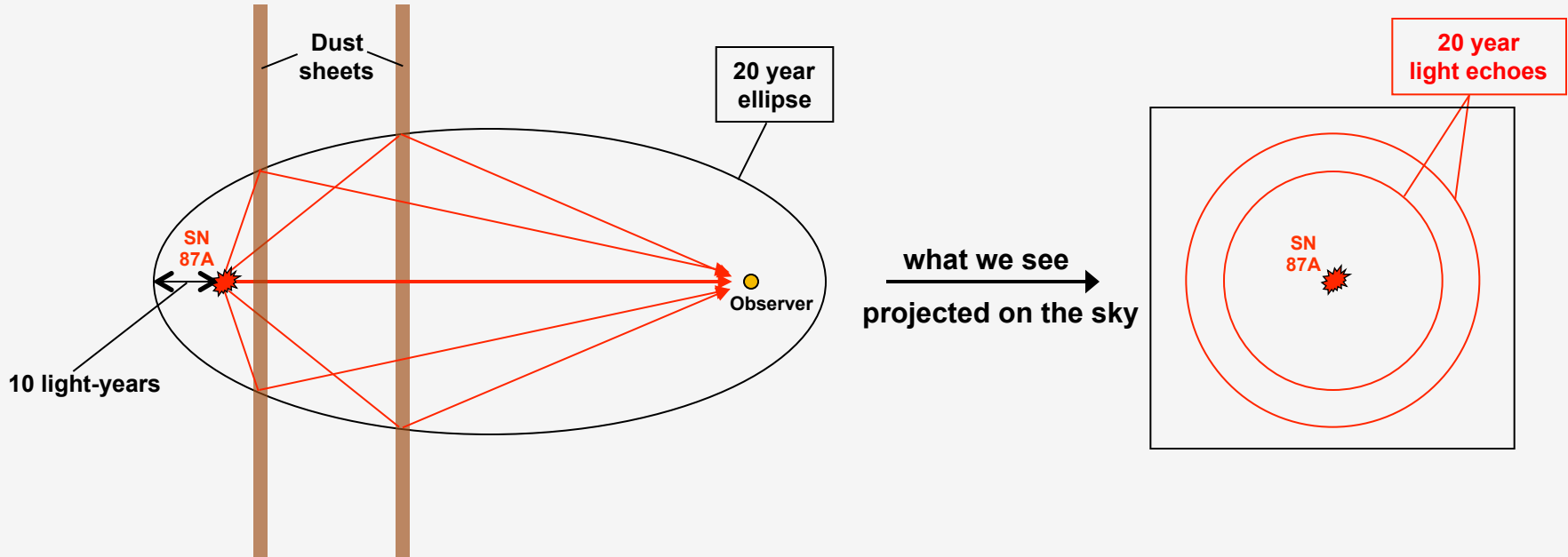


Extra path: 2 x 10 light years → Light echo after 20 years



# Geometry of Light Echoes

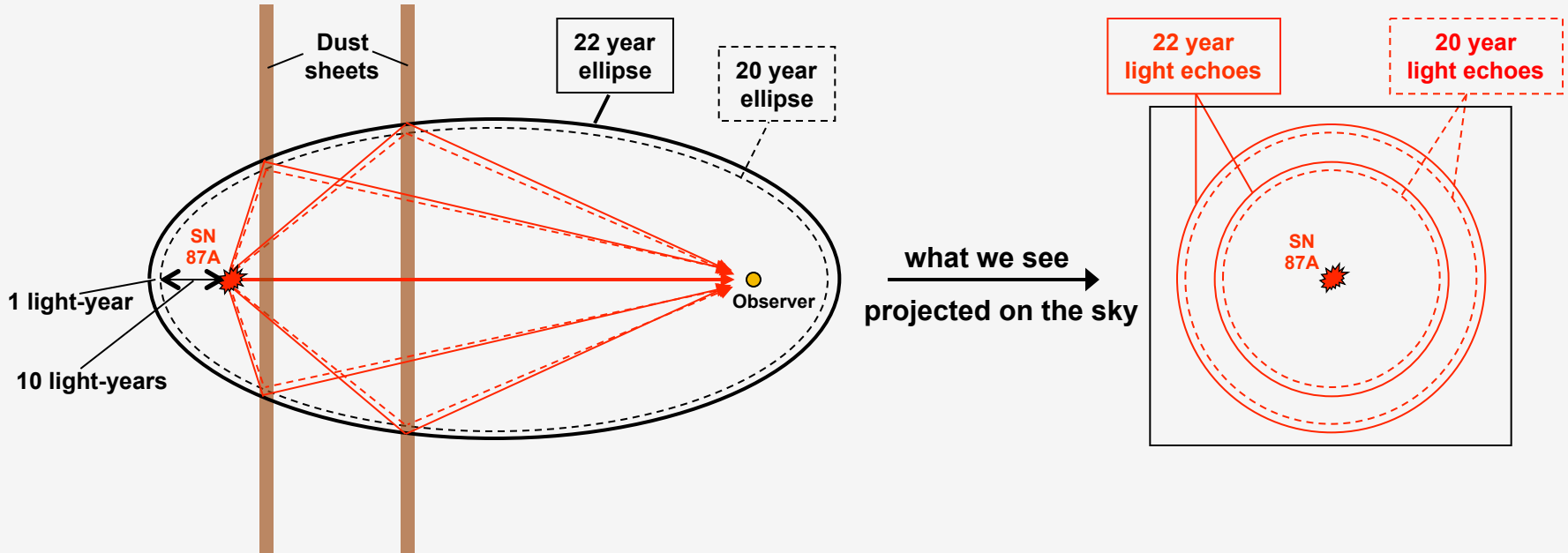
Ellipsoids trace out surfaces of constant arrival time



Extra path: 2 x 10 light years → Light echo after 20 years

# Geometry of Light Echoes

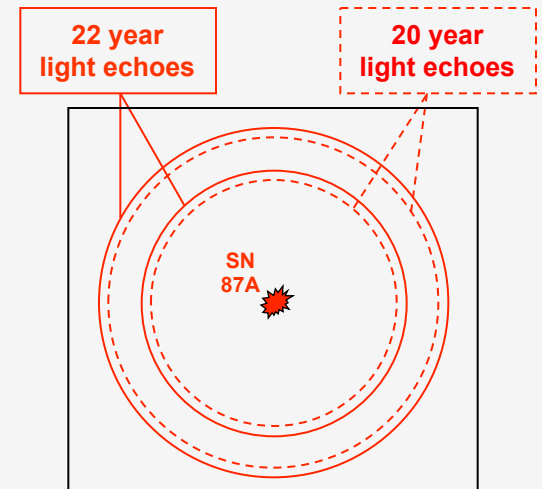
Ellipsoids trace out surfaces of constant arrival time



Extra path:  $2 \times 10$  light years  $\Rightarrow$  Light echo after 20 years  
Extra path:  $2 \times 11$  light years  $\Rightarrow$  Light echo after 22 years



# Geometry of Light Echoes



# Light Echoes from Ancient Supernovae in the Large Magellanic Cloud

- Three distinct light echo groups
- Apparent proper motion: between  $0.7c$  and  $1.8c$
- R magnitudes between 22.5 and 24.0

Rest et. al., 2005, Nature, 438, 1132

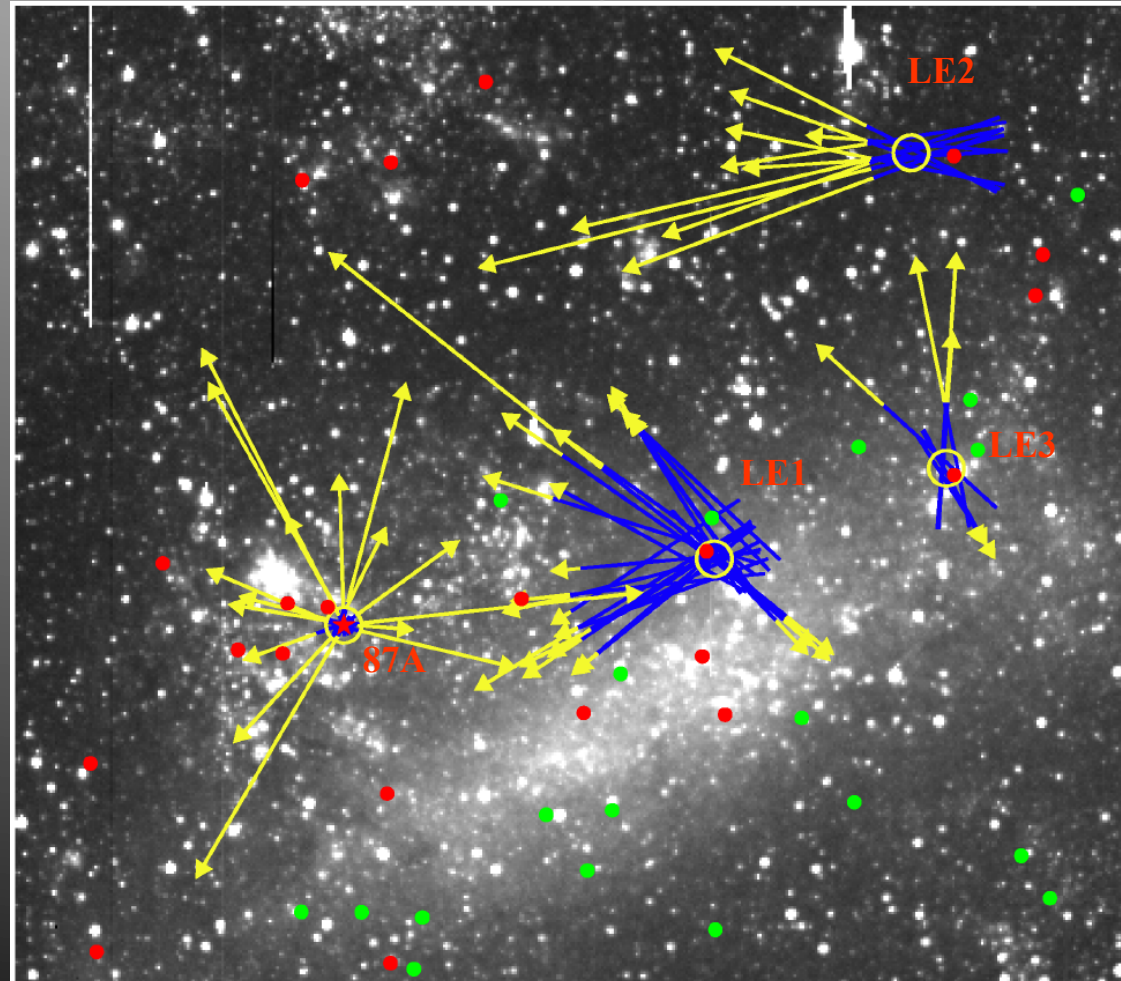


TABLE 1

THE SMALLEST SUPERNOVA REMNANTS  
IN THE LARGE MAGELLANIC CLOUD

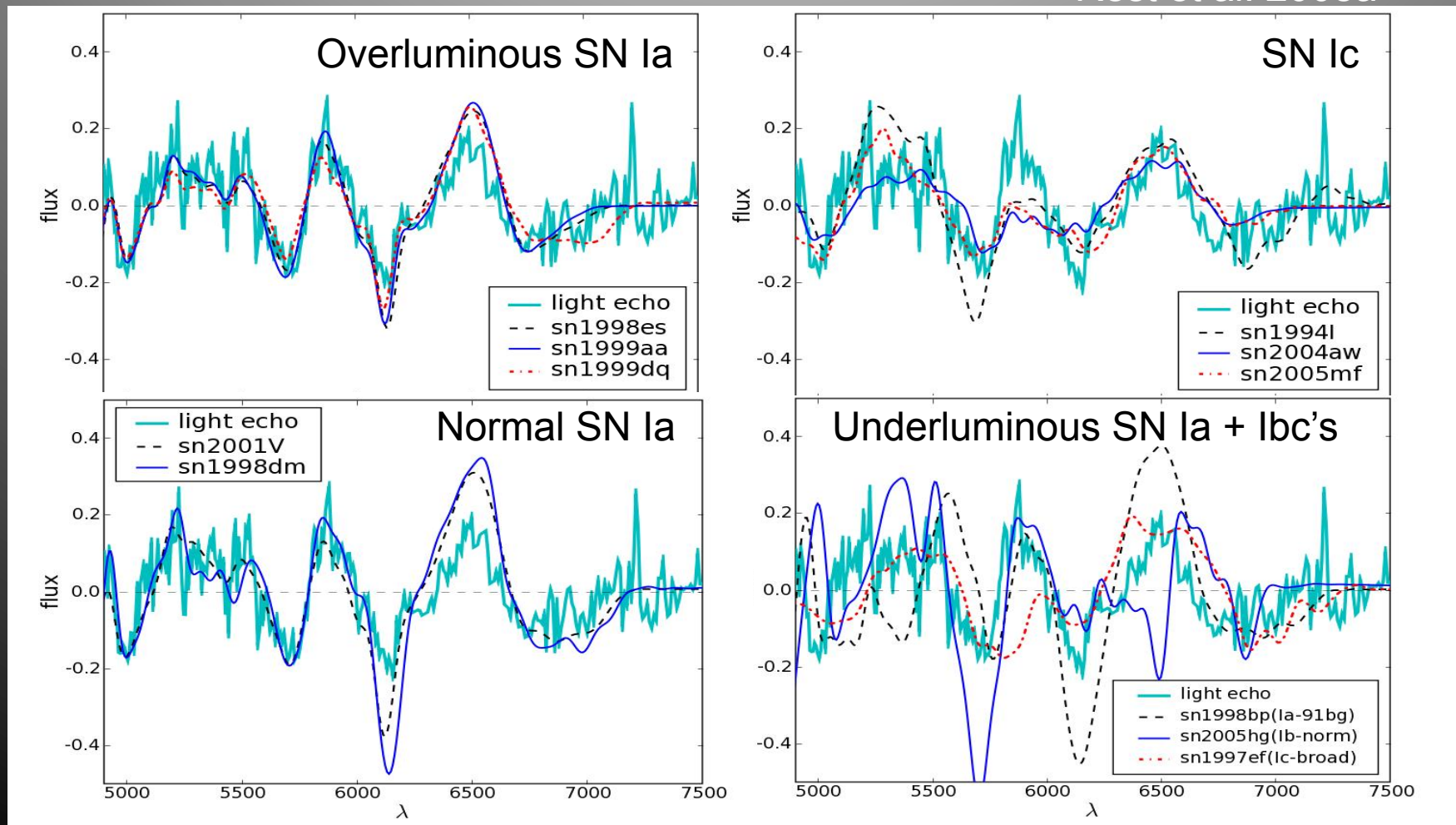
SNR Name	Age or Radius	SN Type
SN 1987A .....	8 yr	II
0540 – 69.3 .....	1.5 pc	II
N157B .....	1.8 pc	(II)?
N103B .....	3.0 pc	Ia LE3
0509 – 67.5 .....	3.3 pc	Ia LE2
0519 – 69.0 .....	3.6 pc	Ia LE1

Hughes et. al. (1995)



# Overluminous SNe Ia correlating best with LE spectra of SNR 0509-67.5!

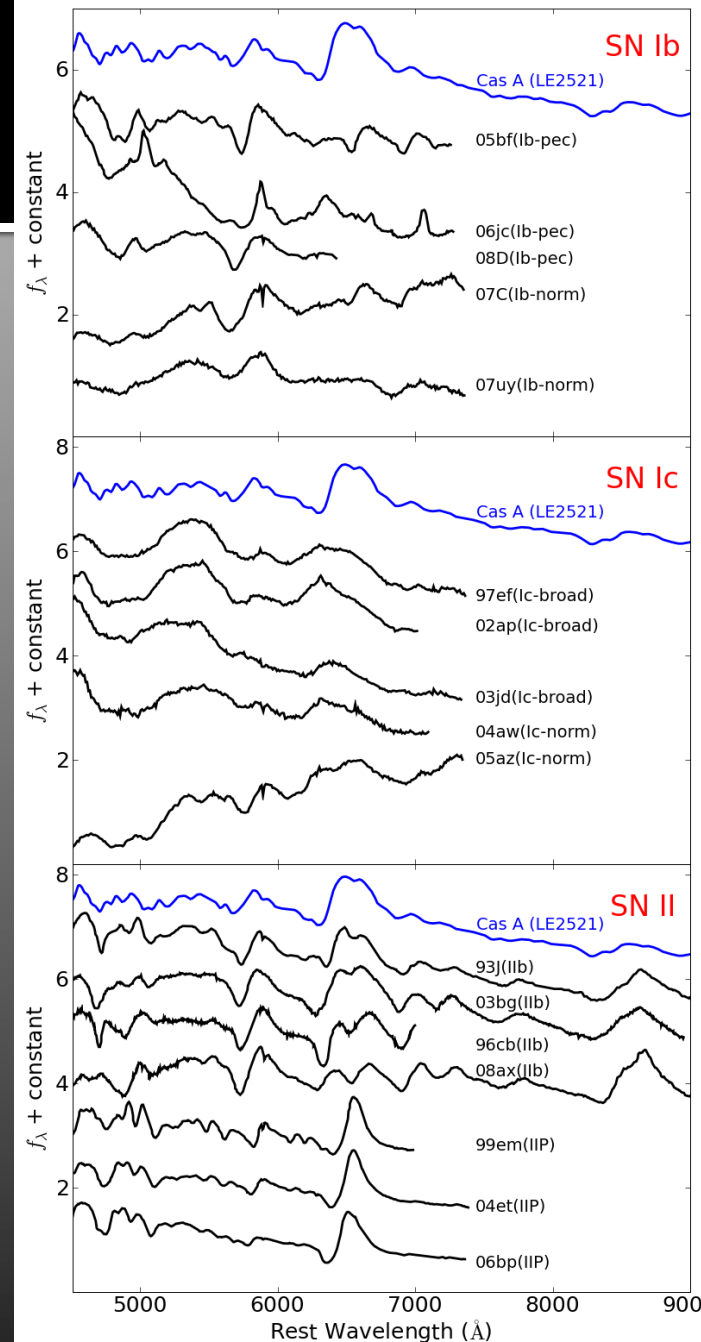
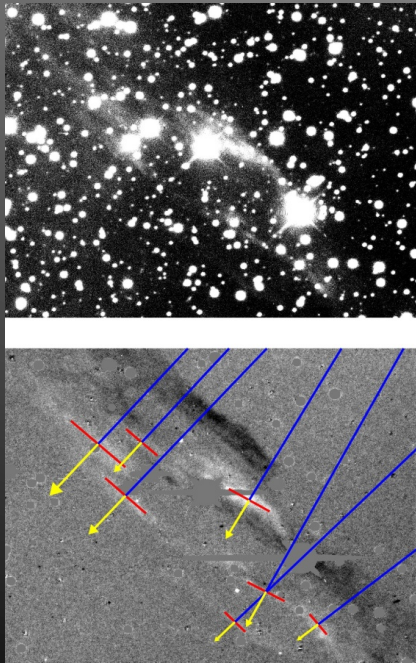
Rest et al. 2008a



# MWG SN light echoes

Rest et al. 2011a

- LMC light echoes inspired searches for historic MWG SN
- Cas A: SN IIb  
(Krause+08a, Rest+08b, 11a)





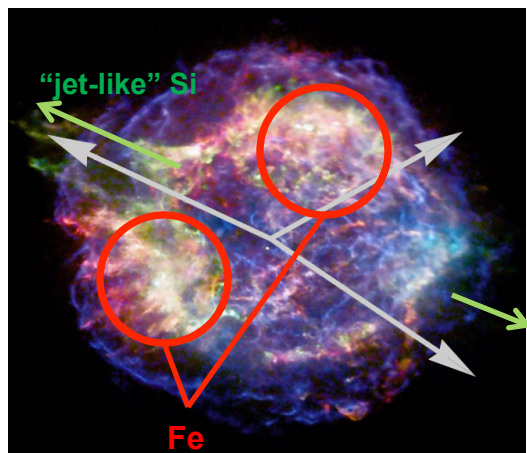
# Cas A SN

## 3D spectroscopy

Blue: 4.2-6.4

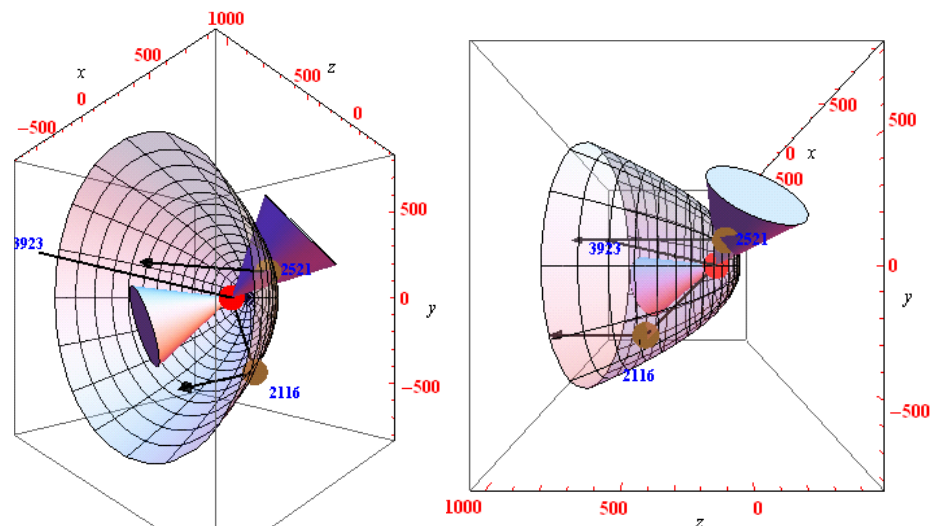
Red: Fe K

Green: Si

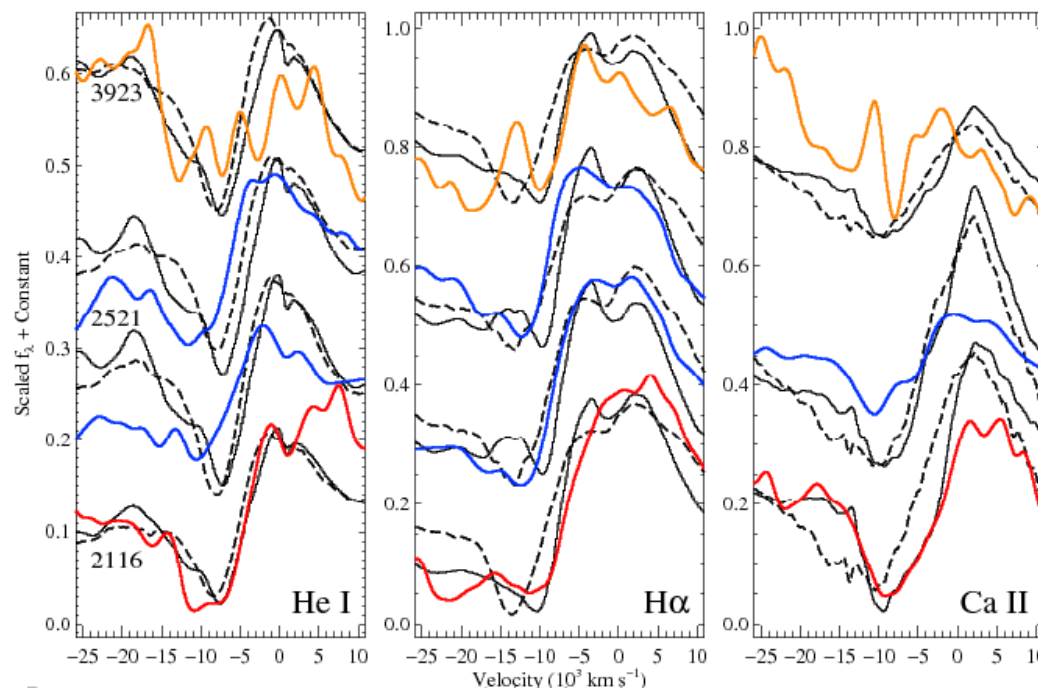


Willingale et al. 2002

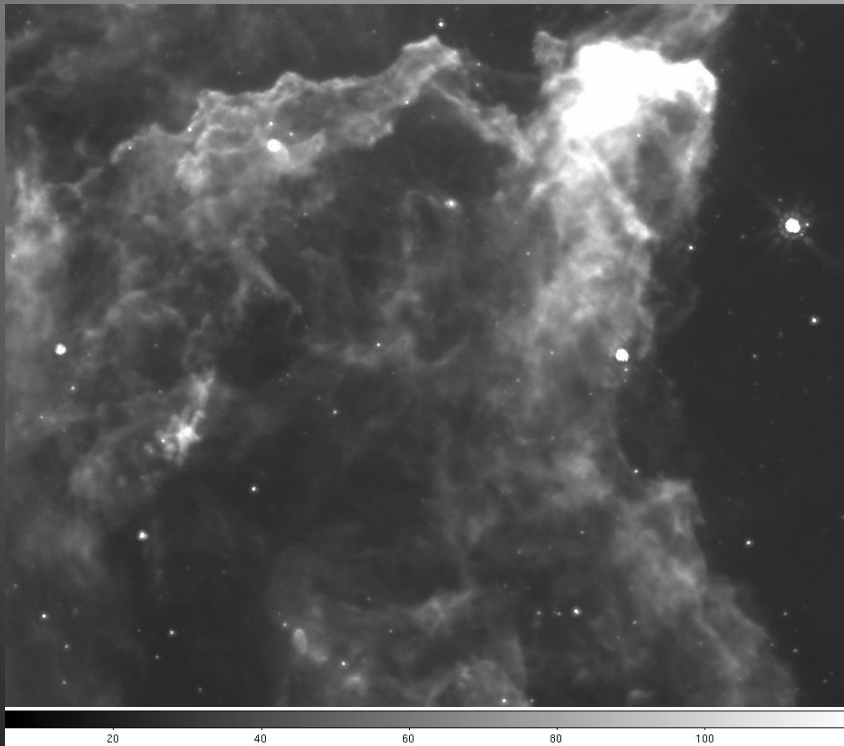
- Light echo 2521 (blue lines) H $\alpha$  and He I lines blueshifted by 4000 km/s compared to other directions (red and orange)
- Direction with blueshift: Fe-rich outflow



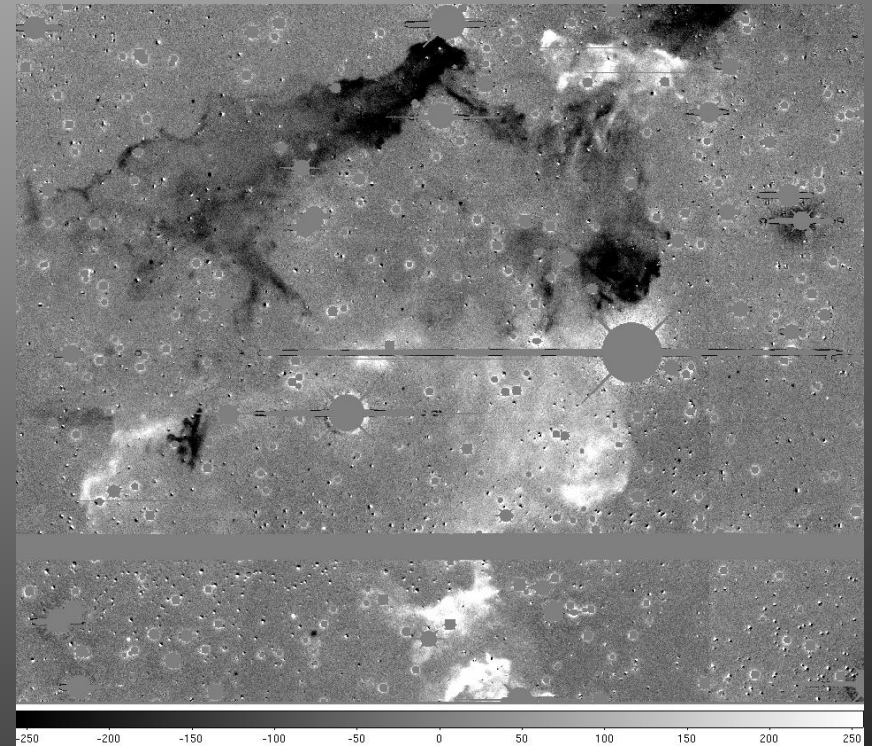
Rest+11a,11b



# Light Echoes of $\eta$ Car's Great Eruption



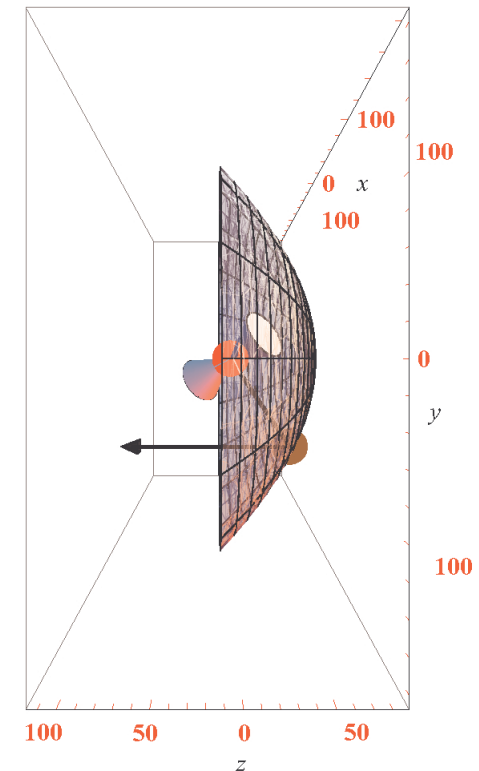
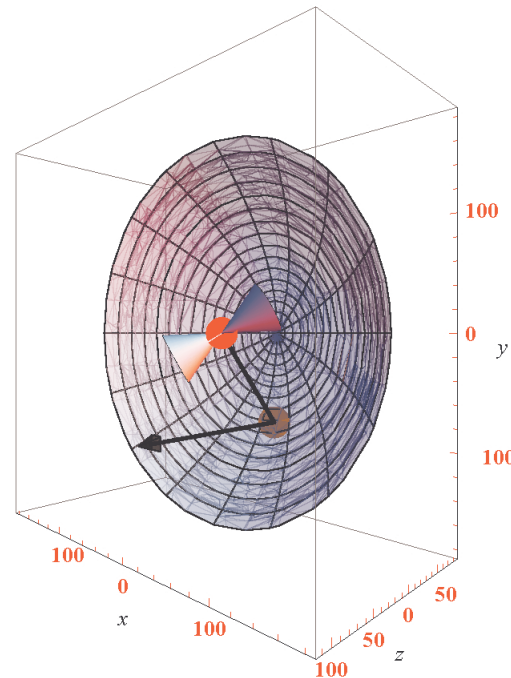
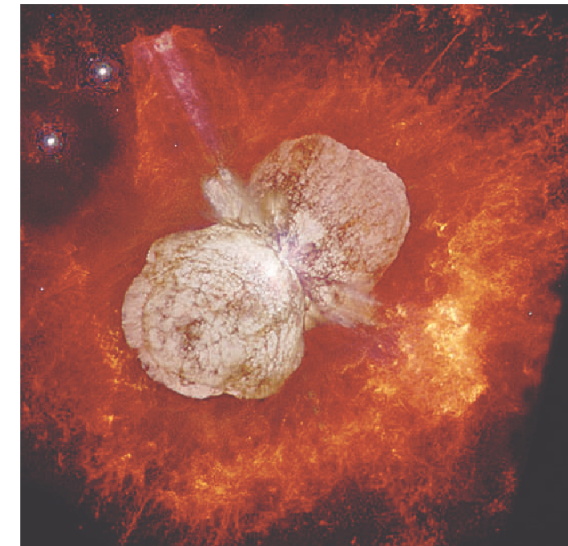
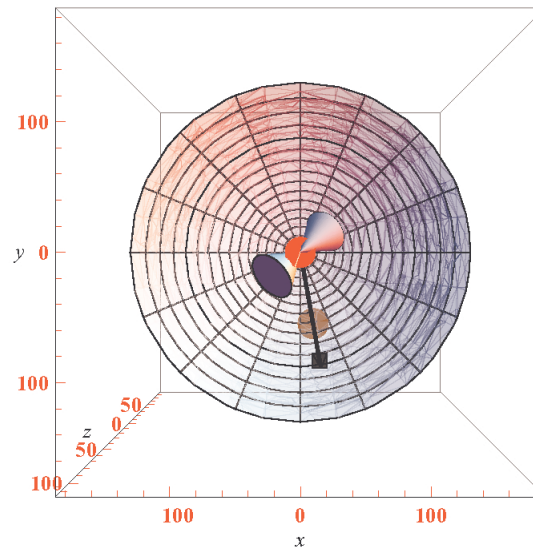
Spitzer Image (8 microns)



Difference Image (8x8 arcmin)  
black: light echo in 2003  
white: light echo in 2011

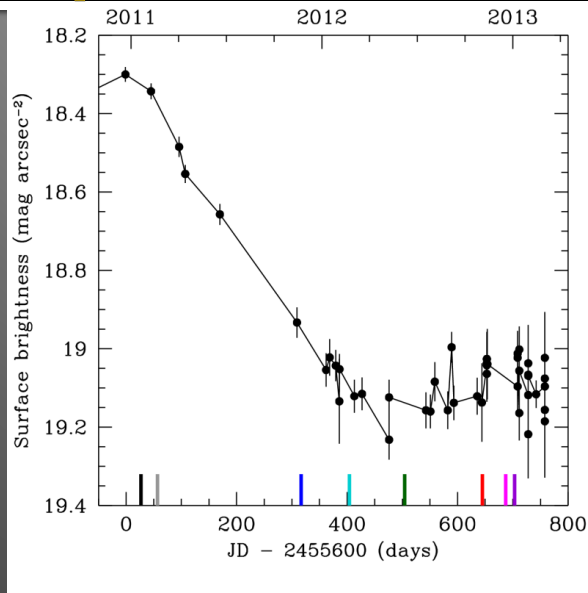
# $\eta$ Car's Light Echoes: 3D View

- Great Eruption from 1838-1858 (Mass loss  $\sim 20 M_{\text{solar}}$ )
- $\eta$  Car light echo roughly perpendicular to equator of Homunculus Nebula

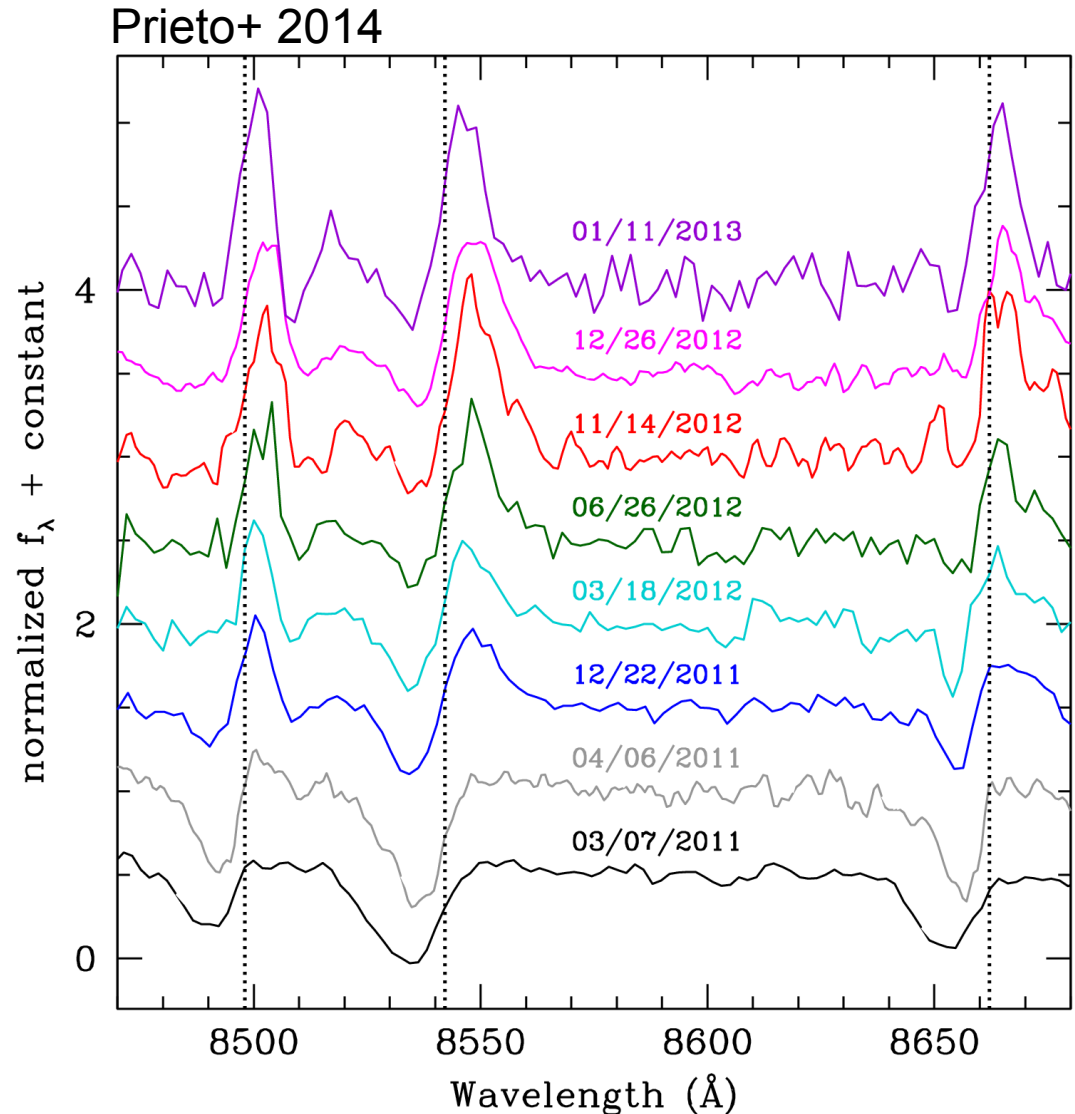




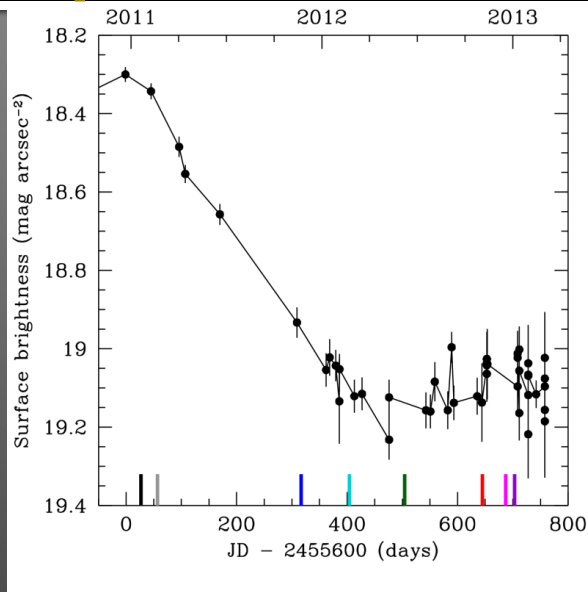
# Spectroscopic Evolution of $\eta$ Car's Great Eruption



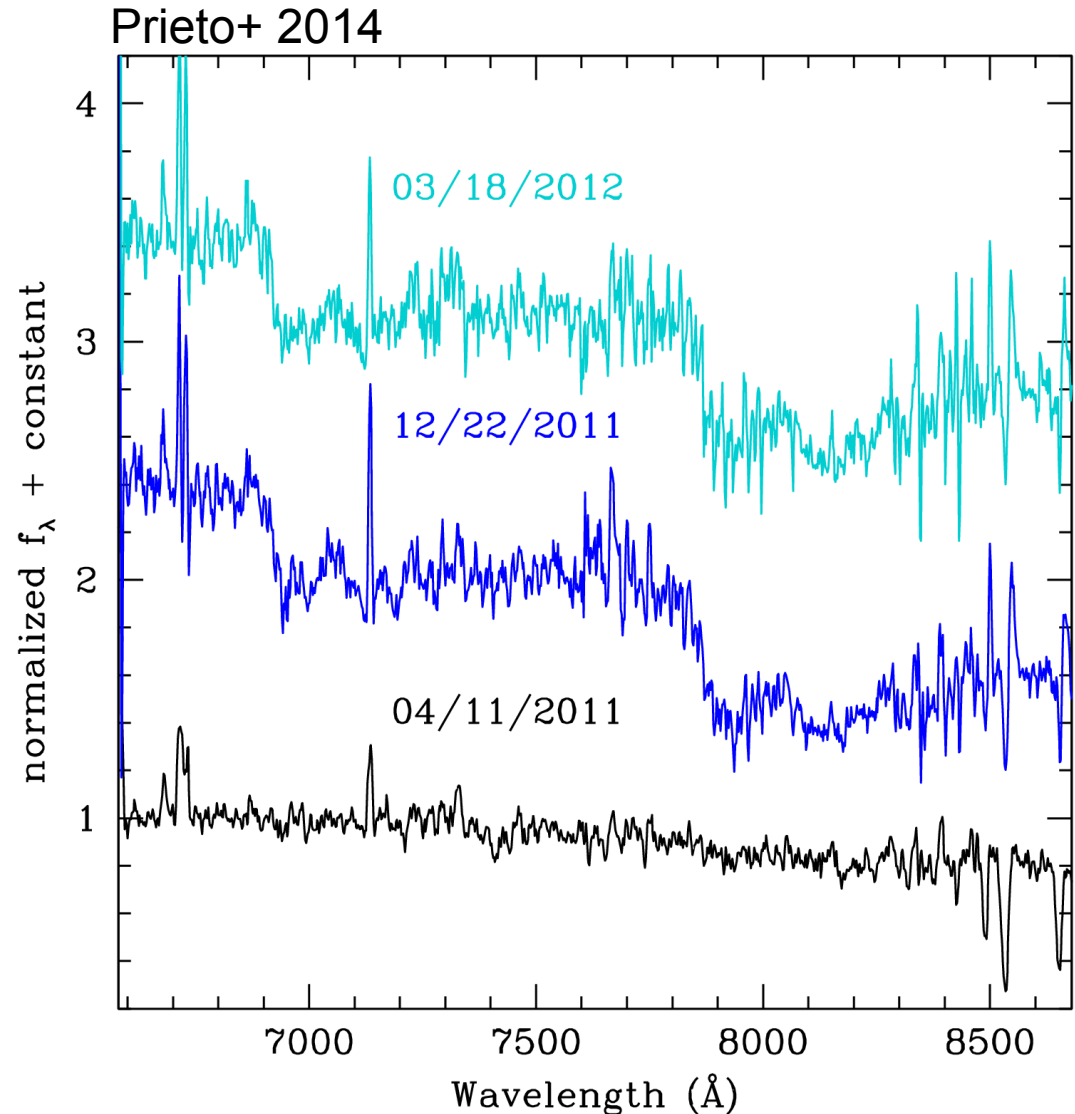
- Ca IR triplet: Absorption-only Spectrum at peak
- Transition to P-Cygni
- Emission-dominated at minimum



# Spectroscopic Evolution of $\eta$ Car's Great Eruption



- CN bands
- Develop during decline
- CN bands typically at  $T < \sim 5000\text{K}$
- N absorption found in UV (Gull+ 2006)



# DECam Light Echo Search

SN Name	RA	Dec	Date	Dist. (kpc)	Type	Search Radius (deg)	Search Area (deg <sup>2</sup> )	Discovery Telescope	Discovery Reference
<b>Cas A</b>	<b>23:23</b>	<b>+58:48</b>	<b>1680</b>	<b>3.4</b>	<b>SN IIb</b>	<b>5</b>	<b>66</b>	<b>KPNO4m, LaSilla3.6m</b>	<b>Rest+08, Krause+08</b>
<b>Tycho</b>	<b>00:25</b>	<b>+64:09</b>	<b>1572</b>	<b>2.3</b>	<b>Normal SN Ia</b>	<b>10</b>	<b>287</b>	<b>KPNO4m</b>	<b>Rest+08</b>
<b>0509-67.5 (LMC)</b>	<b>05:11</b>	<b>-67:31</b>	<b>~1600</b>	<b>50</b>	<b>Overlum. SN Ia</b>	<b>1</b>	<b>3</b>	<b>CTIO4m</b>	<b>Rest+05</b>
<b>0519-69.0 (LMC)</b>	<b>05:19</b>	<b>-69:04</b>	<b>~1400</b>	<b>50</b>	<b>SN Ia</b>	<b>1</b>	<b>3</b>	<b>CTIO4m</b>	<b>Rest+05</b>
<b>N103B (LMC)</b>	<b>05:09</b>	<b>-68:42</b>	<b>~1000</b>	<b>50</b>	<b>SN Ia</b>	<b>1</b>	<b>3</b>	<b>CTIO4m</b>	<b>Rest+05</b>
<b>Eta Car</b>	<b>10:45</b>	<b>-59:41</b>	<b>~1840</b>	<b>2.4</b>	<b>Great Eruption</b>	<b>3</b>	<b>36</b>	<b>CTIO4m</b>	<b>Rest+12</b>
SN 1181	02:05	+64:49	1181	2.6	?	17	2400		
P Cygni	20:17	+38:02	1600	1.6	Great Eruption	31	3000		
Crab Nebula	05:34	+22:01	1054	1.9	SN II?	31	3000		
W49B	19:11	+09:06	1000	8.0	Core-collapse	6	113		
Kepler	17:30	-21:29	1604	2.9	Peculiar SN Ia?	7	140		
SN 1006	15:02	-42:06	1006	2.2	SN Ia	27	2300		
RCW 86	14:43	-62:28	0185	2.8	SN Ia/II?	43	6000		

# The Search for SN Light Echoes...

- Previous searches:
  - CTIO/KPNO4m Mosaic: 0.3 deg<sup>2</sup> FOV
  - LEs of Cas A, Tycho, Eta Car, LMC SNR
- Now:
  - DECam: 3 deg<sup>2</sup> FOV, 300 sec VR exposures
  - Fast readout
  - 10-15 times more efficient!
  - Possible to cover large search areas



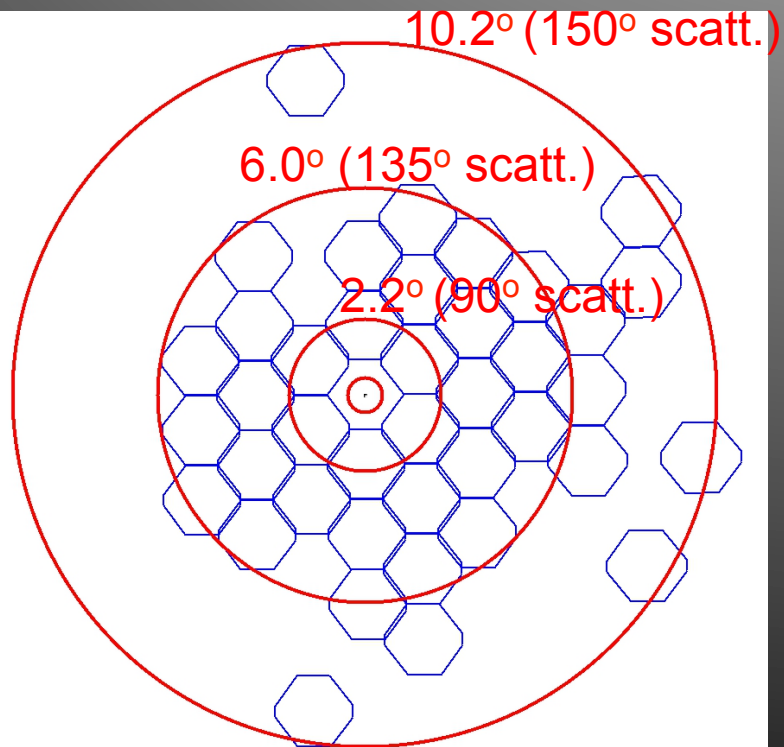
# The Search for SN Light Echoes with DECam

- 2500 deg<sup>2</sup> covered in last two years
- Reduction with photpipe (ESSENCE, PS1 MDF transient pipeline,...)
  - Standard reduction
  - Difference imaging (hotpants)
- Challenges:
  - Visual inspection not possible anymore.
  - Faint surface brightness objects with no center difficult to detect automatically
  - Image artifacts (stray light)

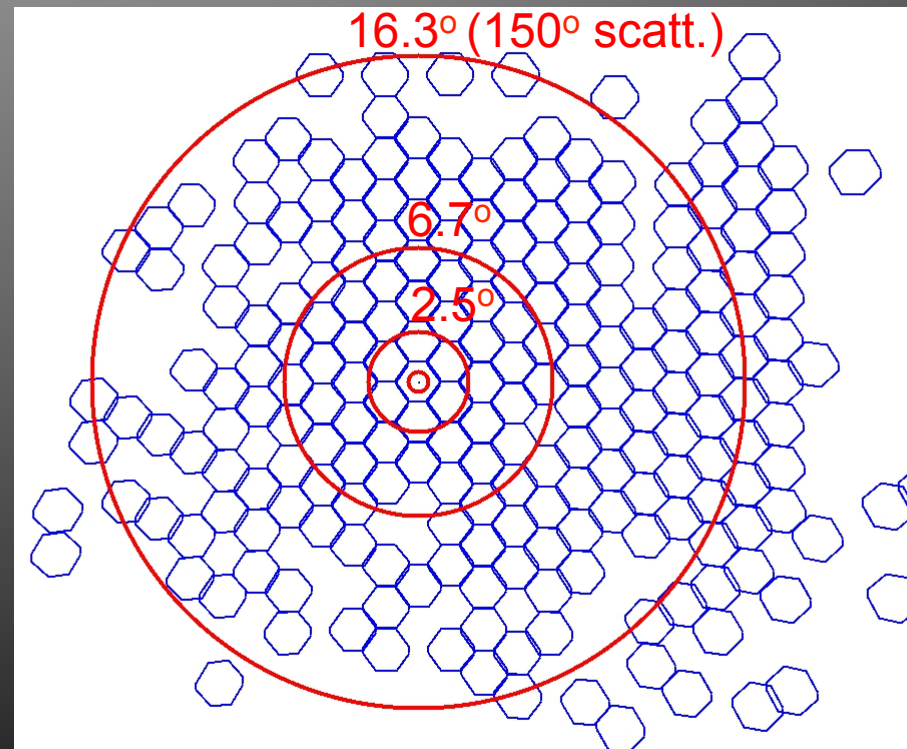
# DECam Light Echo Search

- **Blue**: observed DECam fields
- Sweet spot: 90-135 deg scattering angle

W49B



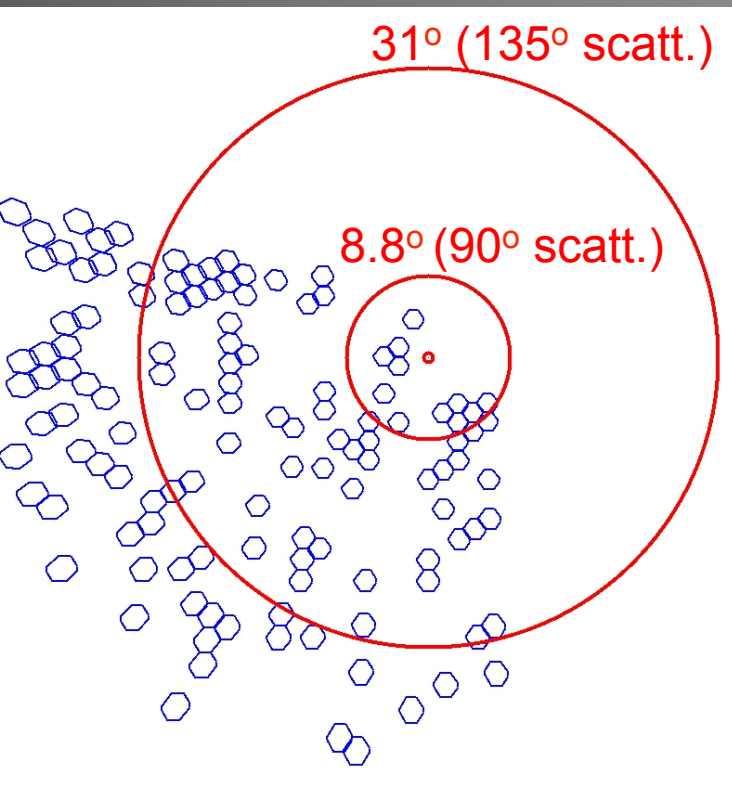
Kepler



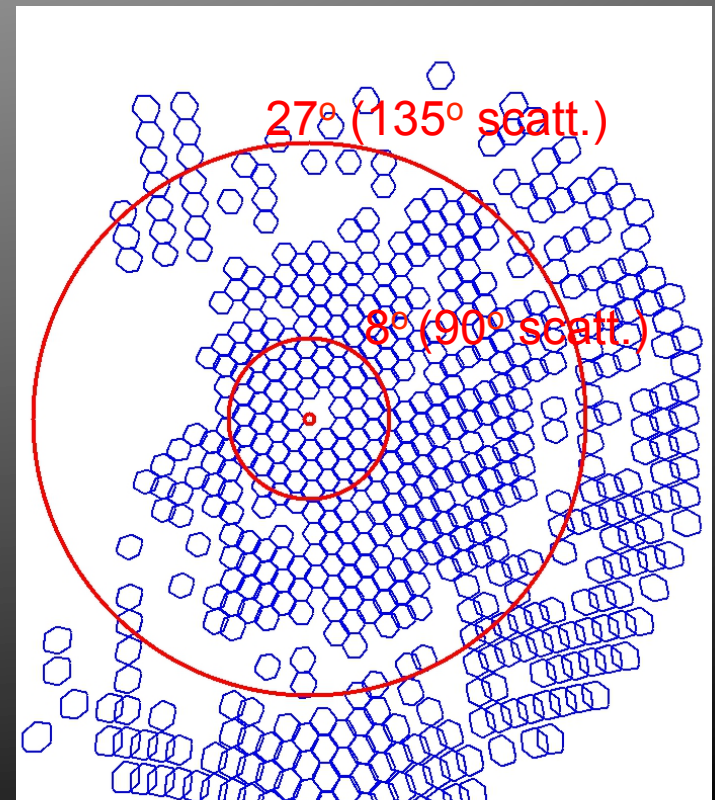
# DECam Light Echo Search

- **Blue**: observed DECcam fields
- Sweet spot: 90-135 deg scattering angle

Crab



SN 1006



# Summary

- DECam Light Echo survey:  
10-15 times more efficient!
- 2500 deg<sup>2</sup> covered in last two years
- Reductions ongoing (photpipe)
- Challenge: Automatic detection of faint light echoes

SN Name	RA	Dec	Date	Dist. (kpc)	Type	Search Radius (deg)	Search Area (deg <sup>2</sup> )	Discovery Telescope	Discovery Reference
Cas A	23:23	+58:48	1680	3.4	SN IIb	5	66	KPNO4m, LaSilla3.6m	Rest+08, Krause+08
Tycho	00:25	+64:09	1572	2.3	Normal SN Ia	10	287	KPNO4m	Rest+08
0509-67.5 (LMC)	05:11	-67:31	~1600	50	Overlum. SN Ia	1	3	CTIO4m	Rest+05
0519-69.0 (LMC)	05:19	-69:04	~1400	50	SN Ia	1	3	CTIO4m	Rest+05
N103B (LMC)	05:09	-68:42	~1000	50	SN Ia	1	3	CTIO4m	Rest+05
Eta Car	10:45	-59:41	~1840	2.4	Great Eruption	3	36	CTIO4m	Rest+12
SN 1181	02:05	+64:49	1181	2.6	?	17	2400		
P Cygni	20:17	+38:02	1600	1.6	Great Eruption	31	3000		
Crab Nebula	05:34	+22:01	1054	1.9	SN II?	31	3000		
W49B	19:11	+09:06	1000	8.0	Core-collapse	6	113		
Kepler	17:30	-21:29	1604	2.9	Peculiar SN Ia?	7	140		
SN 1006	15:02	-42:06	1006	2.2	SN Ia	27	2300		
RCW 86	14:43	-62:28	0185	2.8	SN Ia/II?	43	6000		