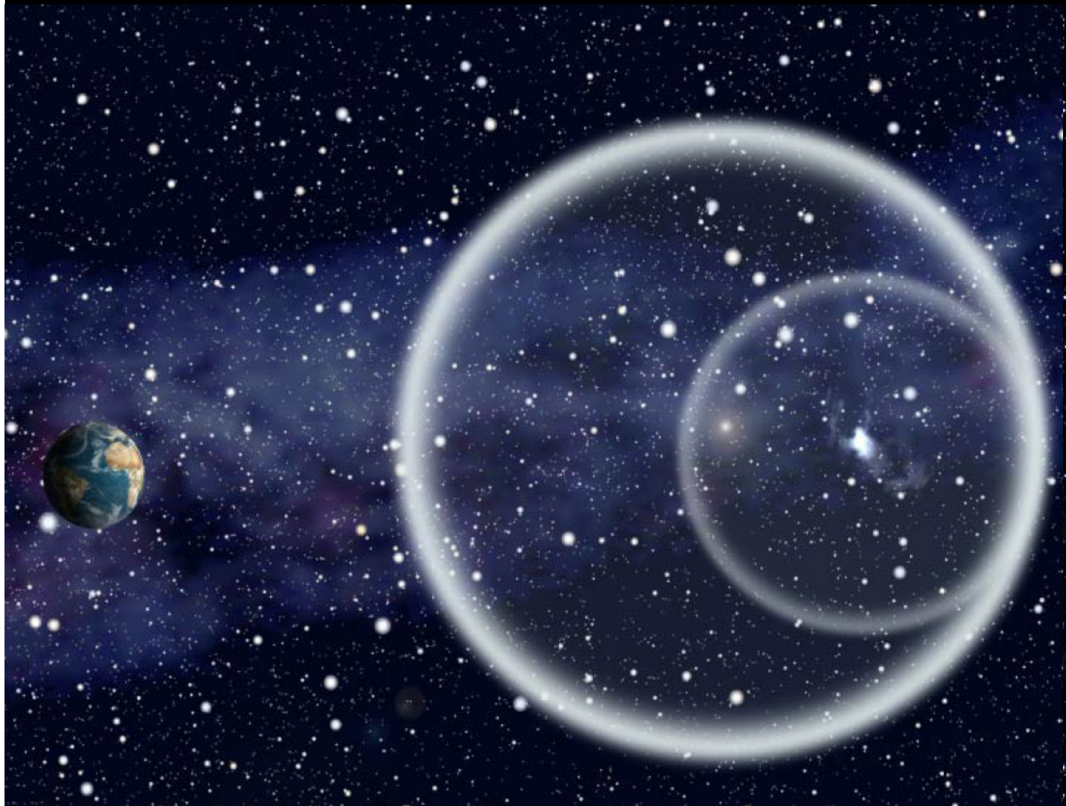
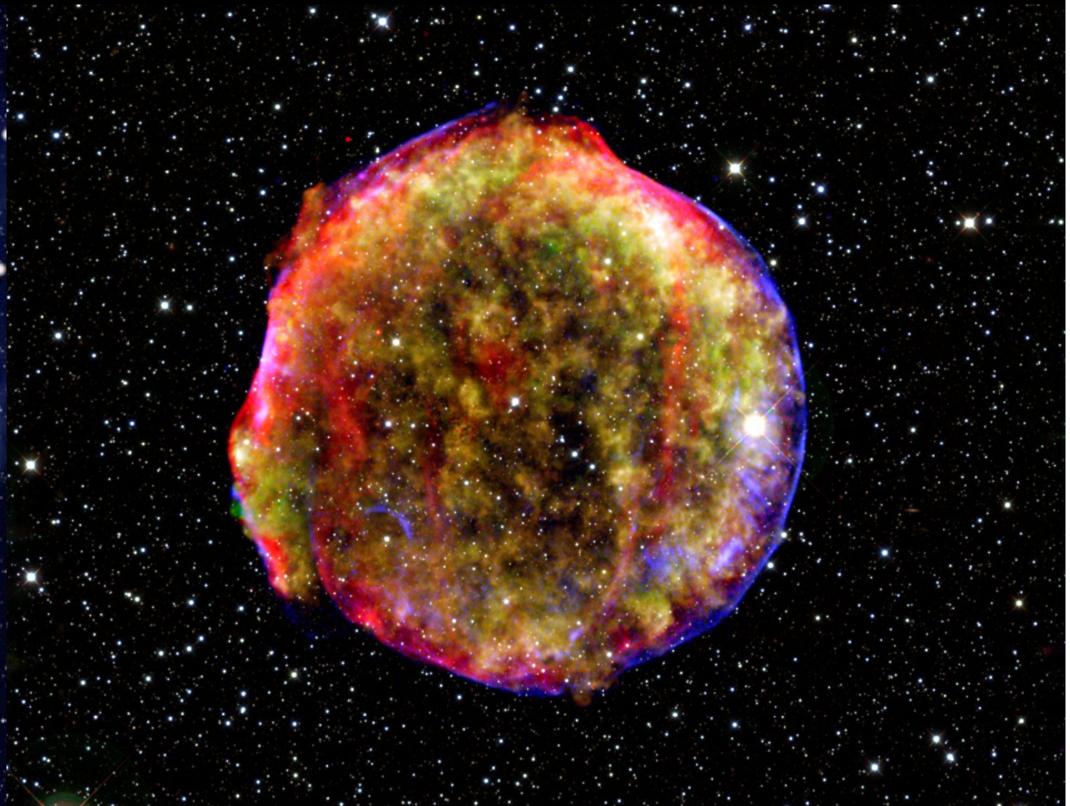
Light-echo spectroscopy of historical supernovae





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- Stephan Birkmann (ESA)
- Ken´ichi Nomoto, Masaomi Tanaka (U. Tokyo)
- Tomo Usuda, Takashi Hattori (Subaru Telescope, HI)
- George Rieke, Karl Misselt (U. of Arizona)
- Miwa Goto (MPIA Heidelberg)

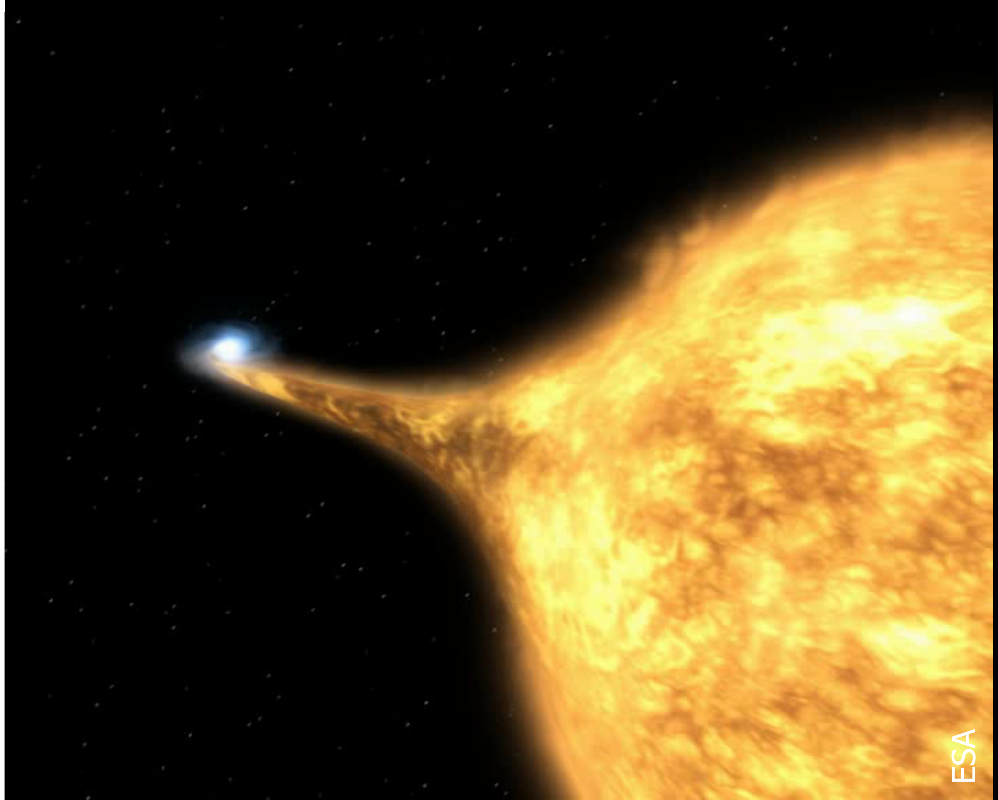
The next galactic supernova ?

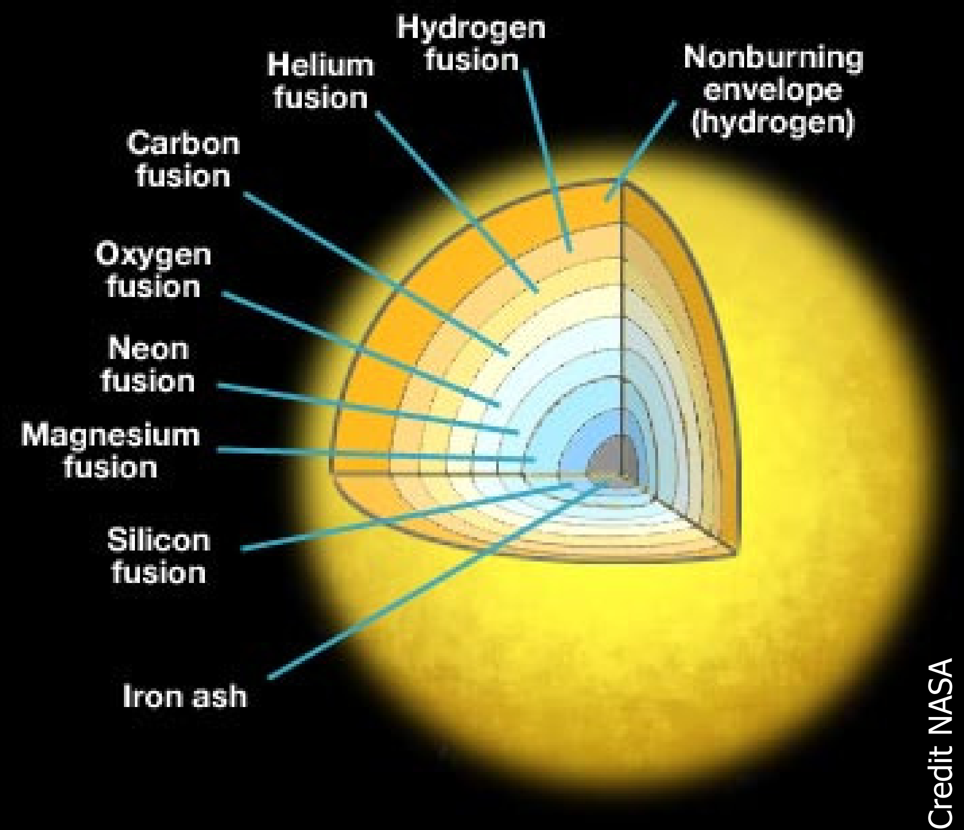
SNe: Our ancestors were fascinated as well

Supernova 1054 observed by the Anasazi

SN1054 today - The Crab nebula

Supernova explosions





Thermonuclear explosion of carbon-oxygen white dwarf (M > 1.4 $M_{\odot}$)

Core collapse of high-mass star (M > 8 $M_{\odot}$)

Spectroscopic type: Ia (Si, no H)

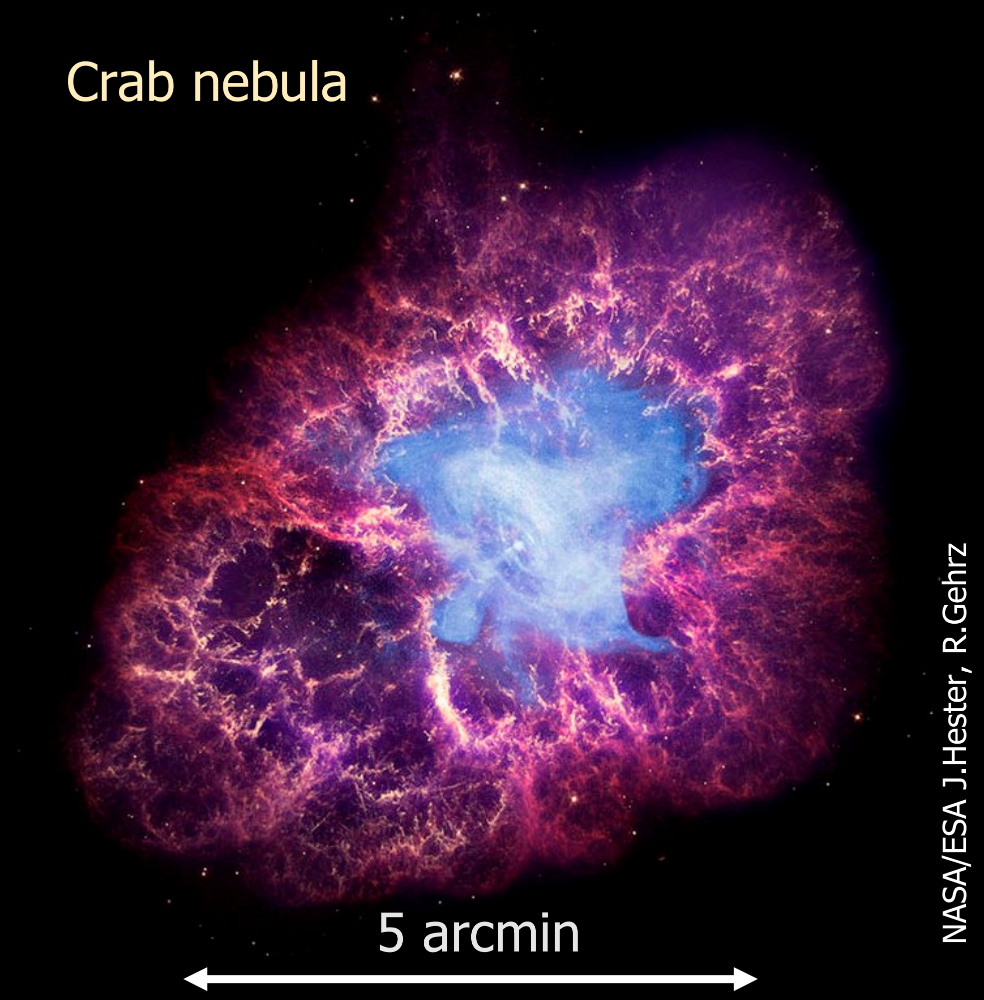
Ib, Ic (no H and Si) II, IIb (H)

Energy release ~ $10^{51} - 10^{53}$ erg
Optical luminosity due to Ni-56 decay into Co-56 and Fe-56

The importance of SNe: Probing extreme physics and more

- Nucleosynthesis of heavy elements
- Matter under extreme conditions (GRBs, neutron stars, black holes, magnetars,…)
- Cosmic lighthouses and standard candles -> dark energy
- Acceleration of cosmic rays
- Dust formation (in the early universe)
- ISM energetics / dynamics (triggering star formation)
- Potential tracers of the very first stars in the universe

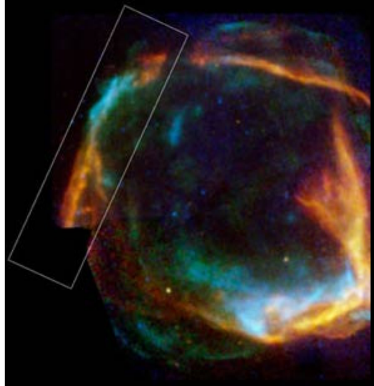
Observational dichotomy to test the explosion mechanism



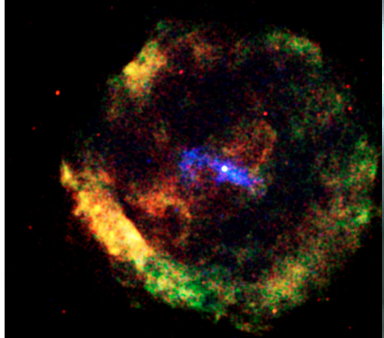
extragalactic SNe
d ~ 100 Mpc

galactic remnant
d =2 kpc

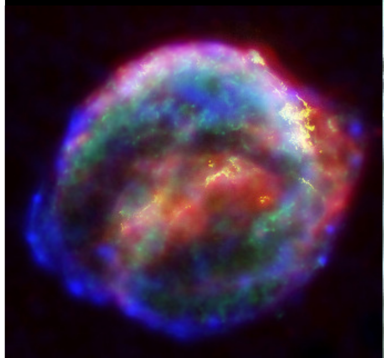
Historic Galactic Supernovae



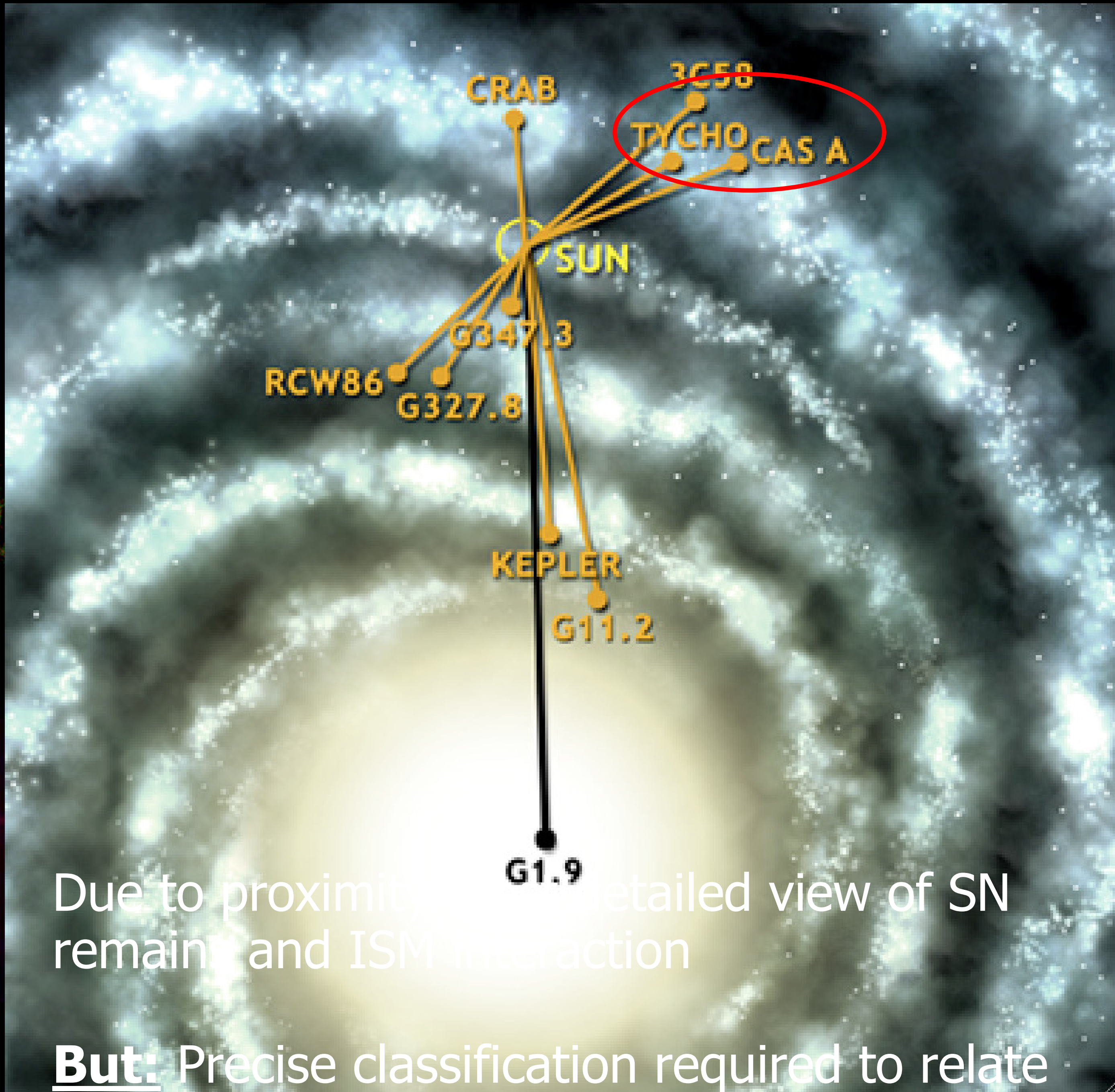
RCW86



G11.2

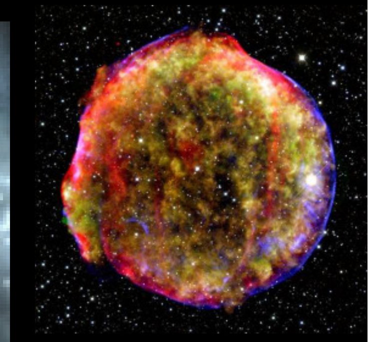


Kepler



Due to proximity: detailed view of SN remnants and ISM interaction

But: Precise classification required to relate SNRs to the diverse SN population



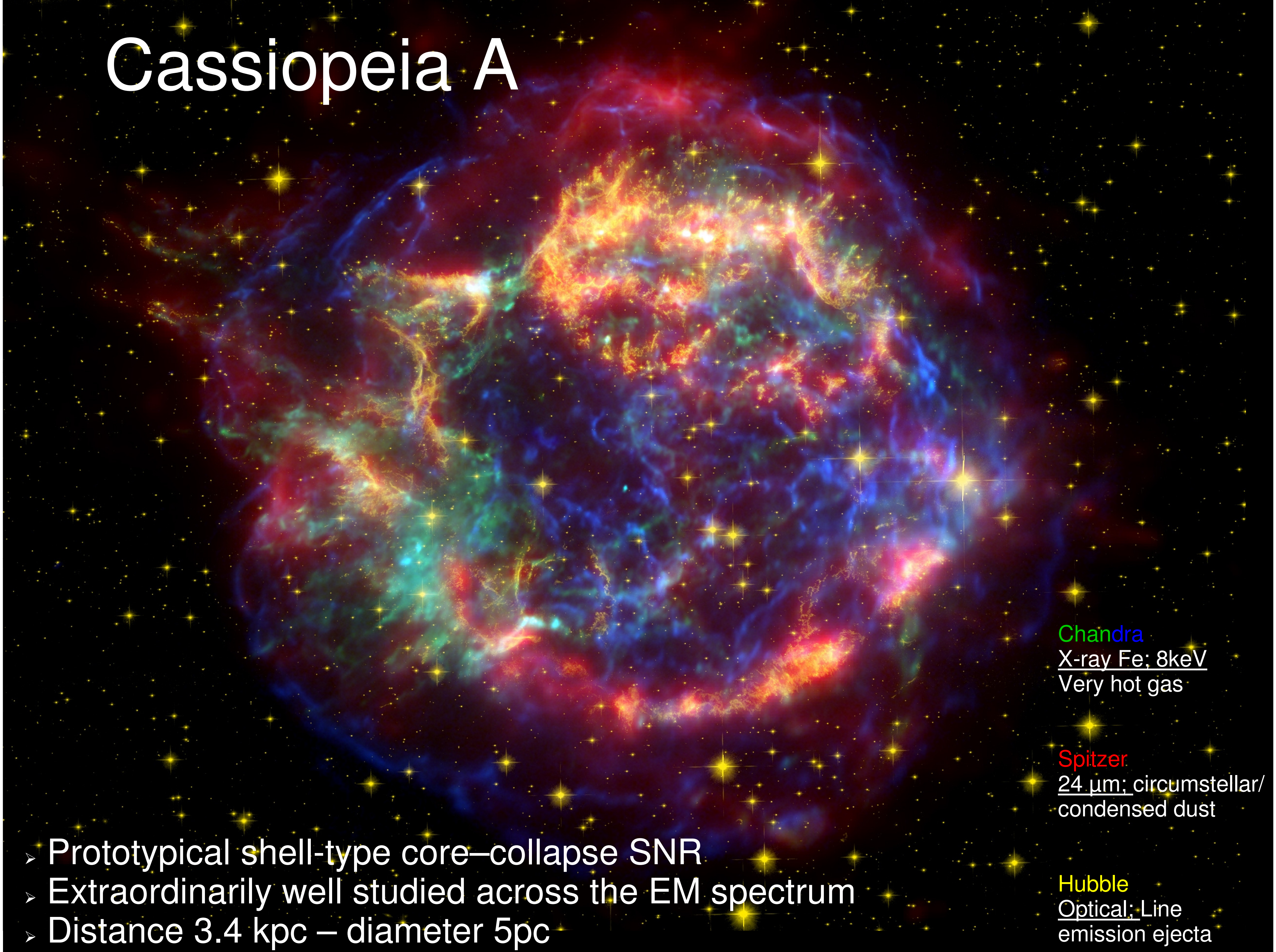
Tycho

Crab

Cas A

G1.9

Cassiopeia A



- Prototypical shell-type core–collapse SNR
- Extraordinarily well studied across the EM spectrum
- Distance 3.4 kpc – diameter 5pc

Proposed Cas A SN types and progenitors

Important observational constraints:

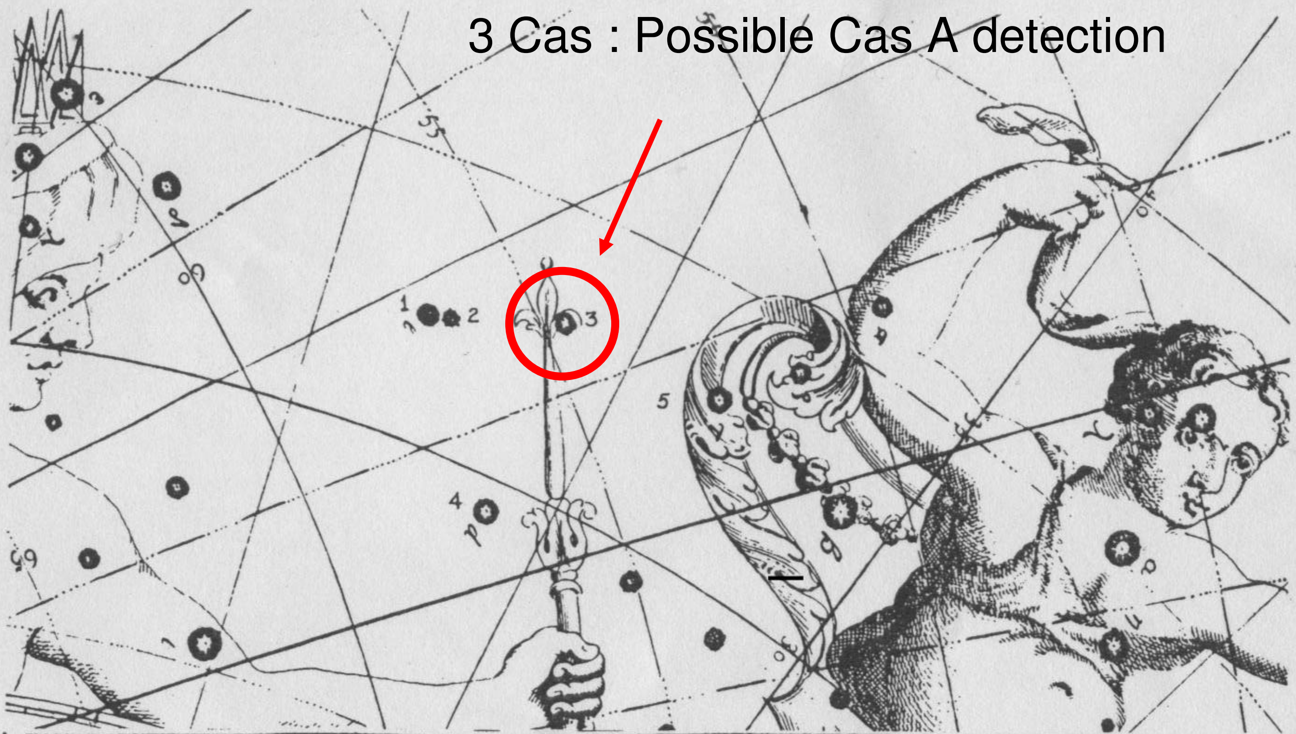
- Fast moving N-rich, H-poor knots, CNO-ashes at surface
- Ejecta mass ~ 2 – 4 $M_\odot$
- Compact object mass ~ 2 $M_\odot$ (neutron star)
- ^{44}Ti mass 1.6 10^{-4} $M_\odot$; Fe mass > 0.06 $M_\odot$
- Hydrodynamical stage of remnant – stellar wind density -> RSG
- Assymetric explosion

Most quoted progenitor: Wolf-Rayet Star e.g. Fesen ApJ 133, 161 (2001)
(Initial) mass range 15-60 $M_\odot$
Type Ib / Ic explosion (GRB?)

Some hydrogen in a few fast moving knots (>9,000 km/s)
-> type II / IIb spectrum
Fesen & Becker ApJ 371, 621 (1991); Oishi & Chevalier ApJ 593, L23 (2003)

Taking into account all contraints, recent analysis favours 15-25 $M_\odot$ star in binary system Young et al. ApJ 640, 891 (2006)

Did Flamsteed witness the outburst ?



In Conſtellatione CASSIOPEÆ.

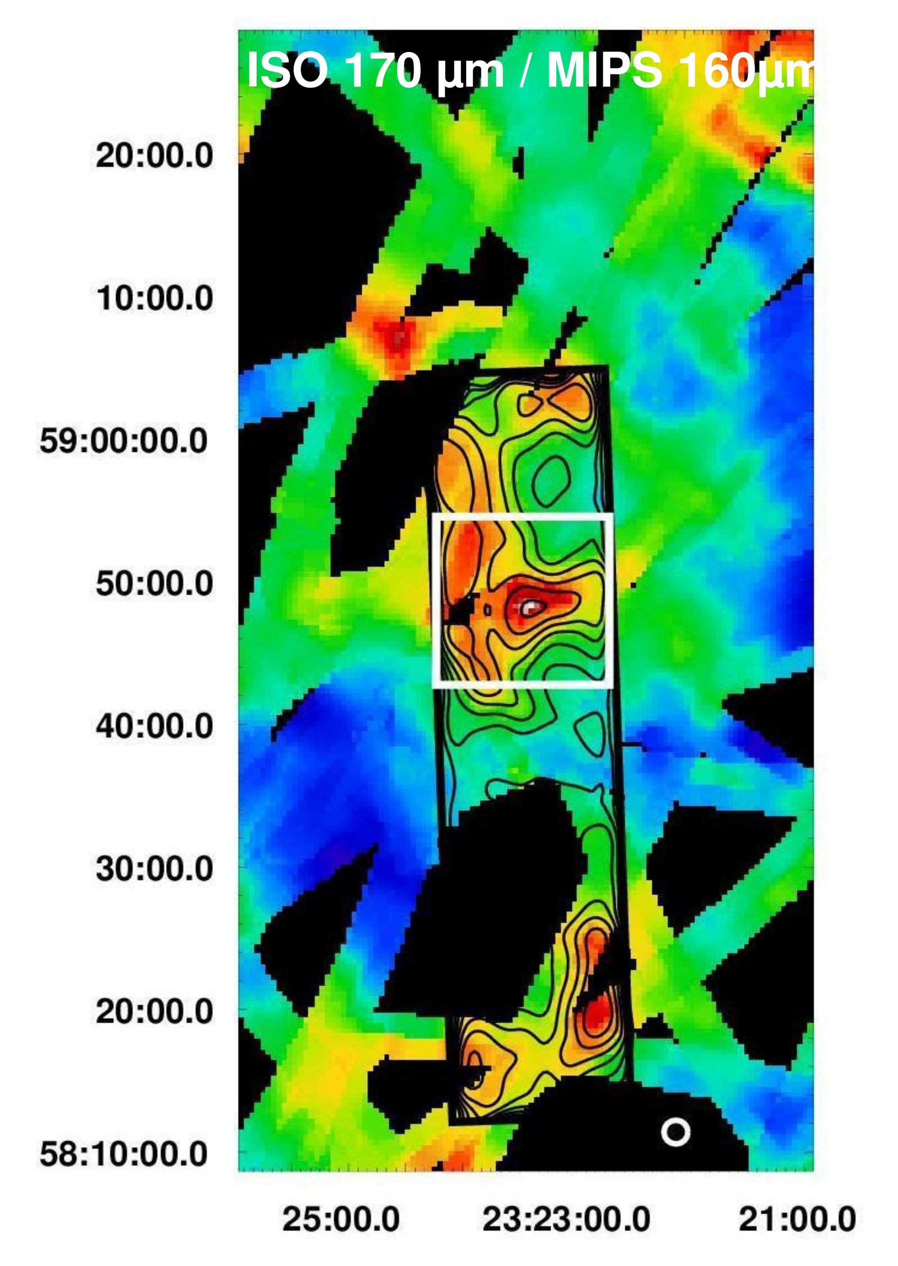
ORDO Ptol.	ORDO Tych.	STELLARUM Denominatio.	Bayer. Cha.	Aſcenſio Recta. ° ′ ″	Diſtantia à Polo B. ° ′ ″	Longitudo. s ° ′ ″	Latitudo. ° ′ ″	Varia. Aſc.R. ′ ″	Varia. D. à P. ′ ″	Magnitud.
		Quæ eſt	e	343 25 0	32 14 20	♈ 21 6 45	56 46 0 B.	44 4	22 48	6
				344 7 30	32 20 0	21 29 16	56 26 10	44 32	22 55	7
				347 37 0	33 1 30	23 5 5	54 38 32	46 57	22 20	6
			d	347 49 30	29 24 30	27 42 49	57 10 12	45 53	23 17	5
	14		τ	353 1 30	33 3 30	26 46 31	52 39 50	50 21	23 40	5

FIG. 1. The positions of the first five Cassiopeia stars, as given in Flamsteed's 1725 catalogue and as depicted in his atlas of 1729.[5] The Flamsteed numbers on the star map have been added.

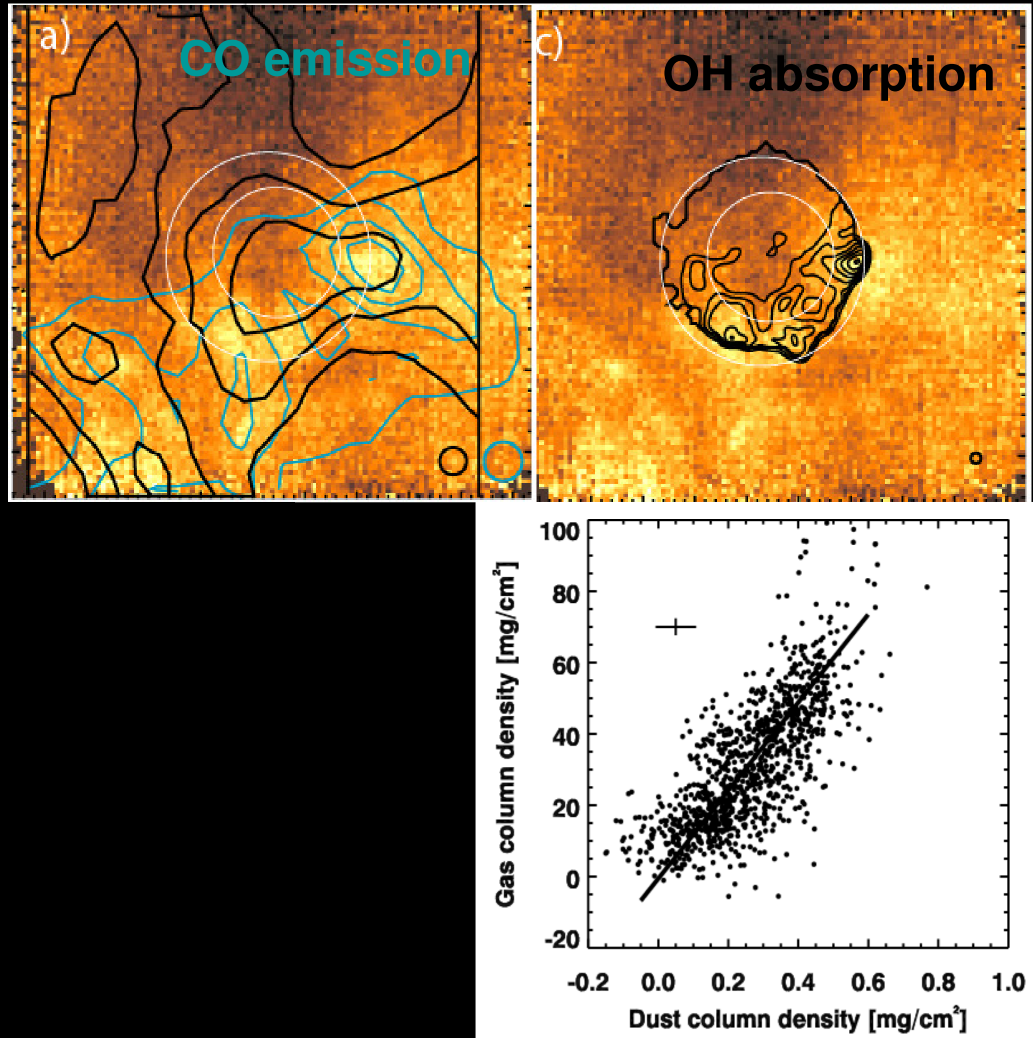
John Flamsteed (1646-1719)
Astronomer Royal

Hughes Nature 285, 132 (1980).

Why was SN1680 optically so faint ?



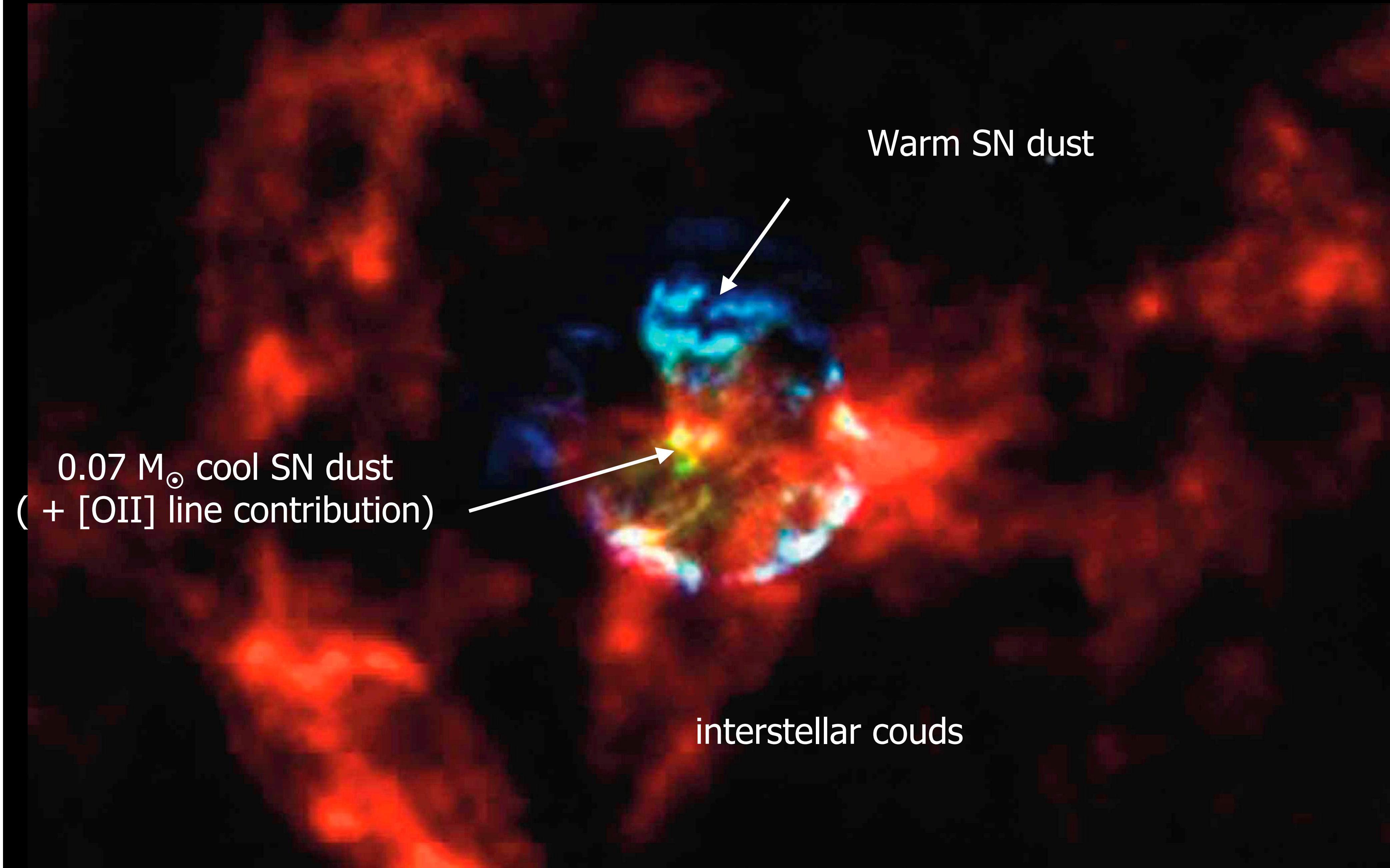
Dust emission



Severe fore-/background confusion by interstellar clouds in the direction of Cas A (Av > 6-8 mag)

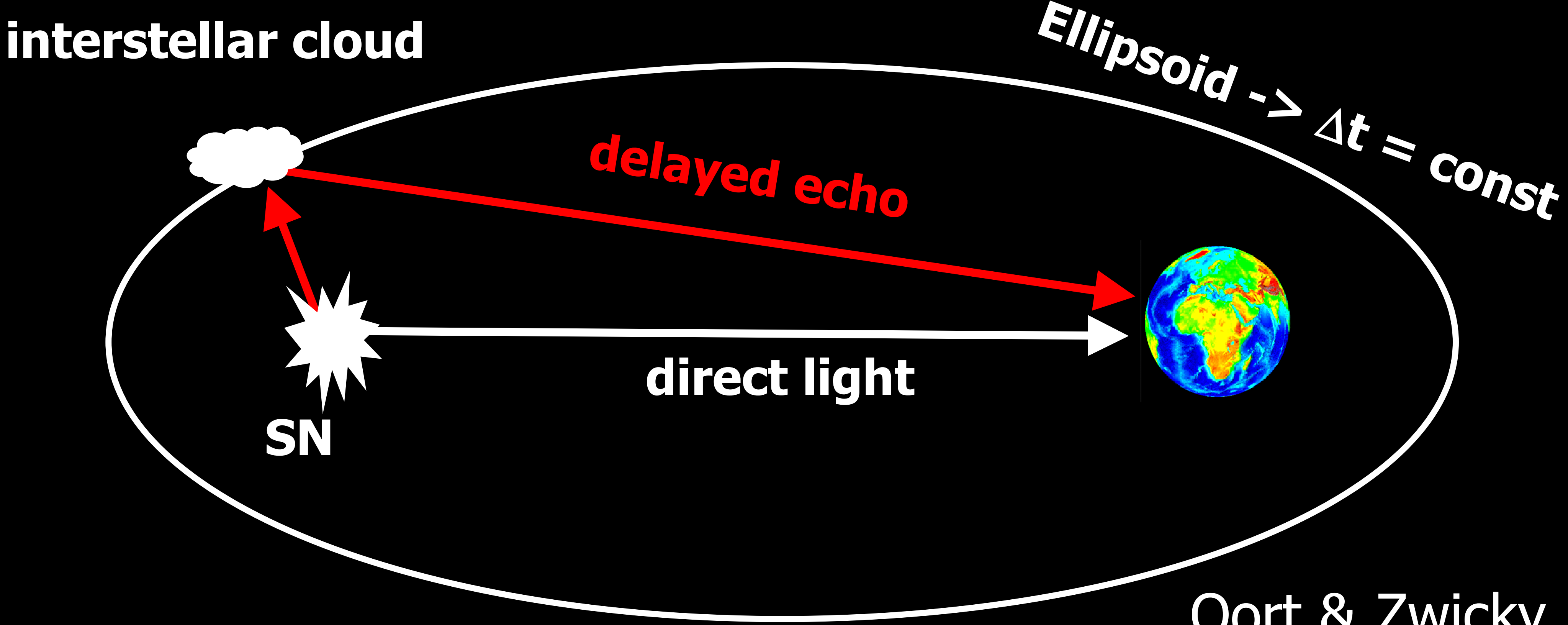
Krause et al. Nature 432, 596 (2004)

Herschel imaging of Cas A



Barlow, Krause, Swinyard et al., A&A 518, 138 (2010)

Time travel with light echos - Connecting SNe with their remnants



Oort & Zwicky

Zwicky Rev. Mod. Phys. 12, 66 (1940)

(Unsuccessful) search for galactic SN light echoes using Palomar by van den Bergh PASP 77, 269 (1965); van den Bergh PASP 78, 74 (1966)

Light echo principle

Discovery of infrared echoes near Cas A

24μm time series (2003-2008)

Krause et al. Science 308, 1604 (2005)

Light-echo observations from Königstuhl: The ″nebulae″ around Nova Persei 1901

- Max Wolf, Astronische Nachrichten 1901

Die Nebel um Nova (3.1901) Persei.

Die erste brauchbare Photographie dieser merkwürdigen Nebel wurde, wie A. N. 3736 mitgetheilt, hier am 23. August mit dem Bruce-Teleskop erhalten. Eine ausgezeichnete Photographie derselben hat dann Ritchey vom Yerkes Observatory am 20. September mit einem grossen Reflector hergestellt und im Astrophys. Journal, 1901 October, mitgetheilt.

Eine Vergleichung der beiden Bilder zeigt auf den ersten Blick, dass in der Nebelmasse in der kurzen Zwischenzeit von nicht ganz einem Monat grosse Veränderungen vor sich gegangen sind. Ueberall erscheinen die Hauptknoten und Linien mehr oder weniger verändert und verschoben. Die Entdeckung dieser Veränderungen wurde zuerst — nach telegraphischer Mittheilung — von Herrn Perrine auf dem Lick Observatory gemacht, der den Nebel mit dem Crossley-Reflector ebenfalls aufgenommen hat.

Inzwischen ist hier am 17. November wieder eine vorzügliche Aufnahme der Nebel mit dem Bruce-Teleskop gelungen. Sie zeigt abermals grosse Veränderungen im Nebel gegen die Aufnahme von Ritchey vom 20. September.

Leider verhindert das schlechte Wetter weitere Aufnahmen, deshalb theile ich die obigen Messungen vorläufig mit.

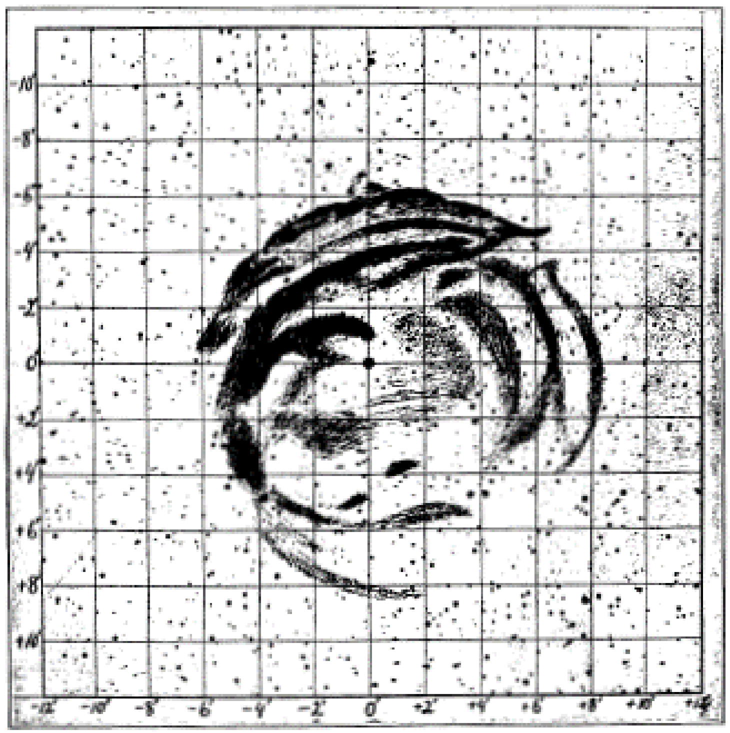
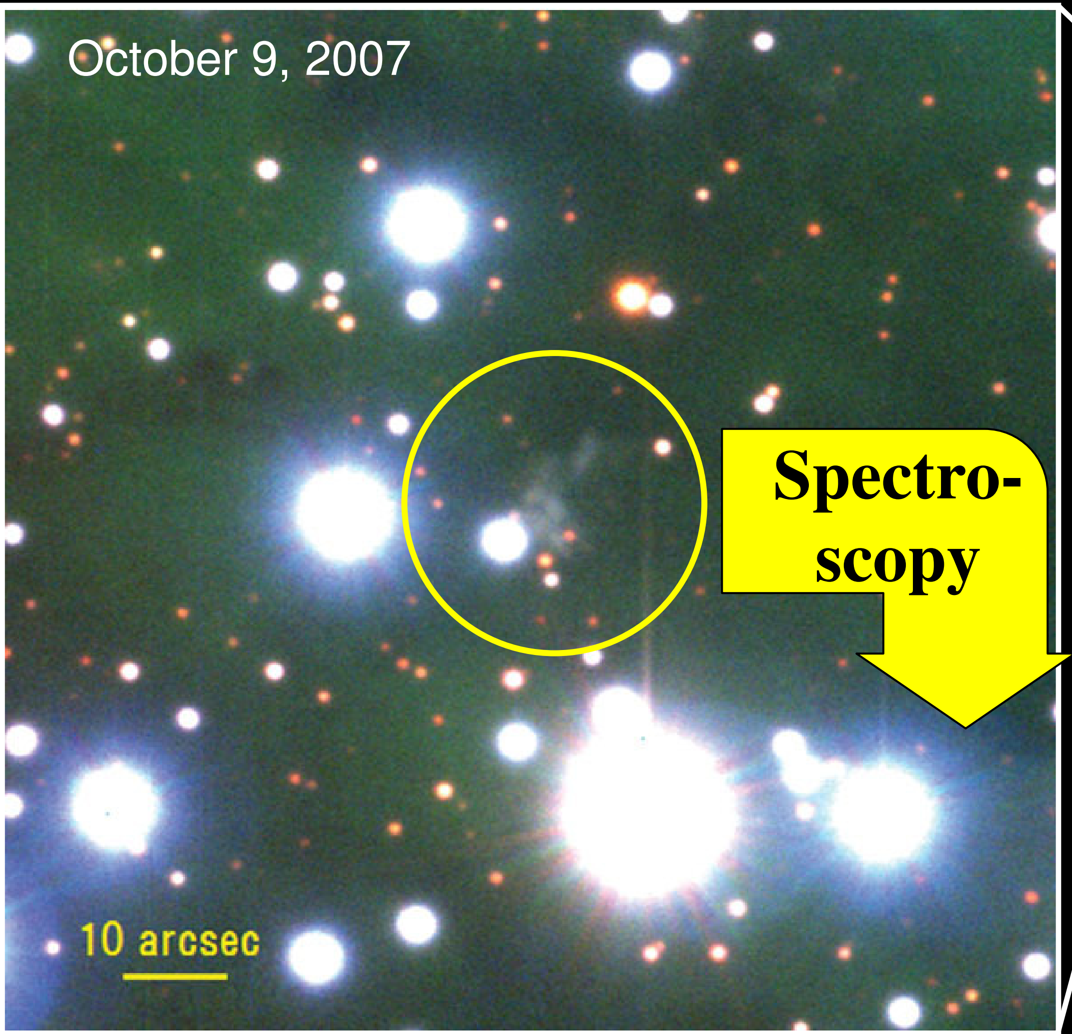
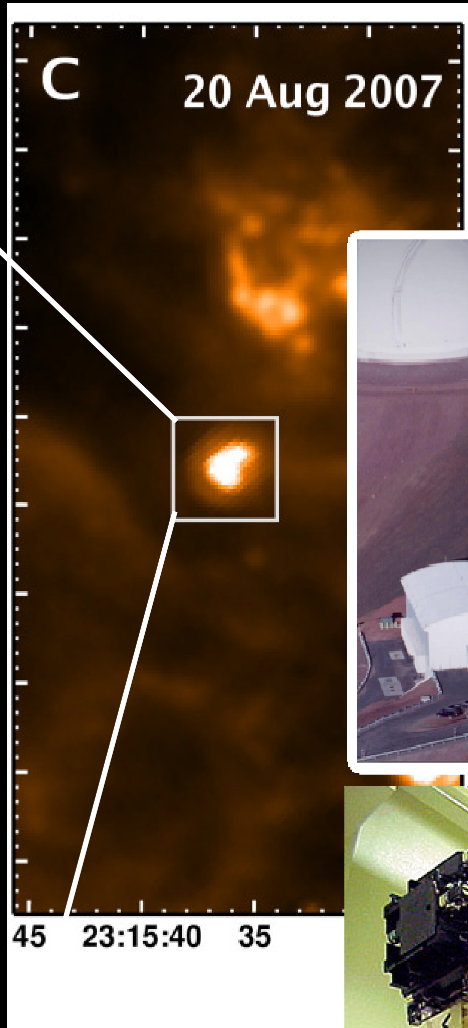


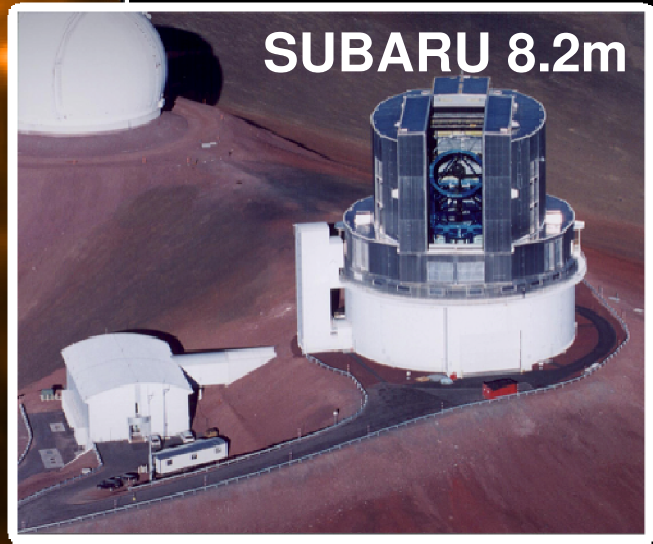
FIG. 2.—DIAGRAM FROM ORIGINAL NEGATIVE.
NEBULOSITY AROUND *NOVA PERSEI*, Sept. 20, 1901.
By G. W. RITCHEY, Yerkes Observatory.

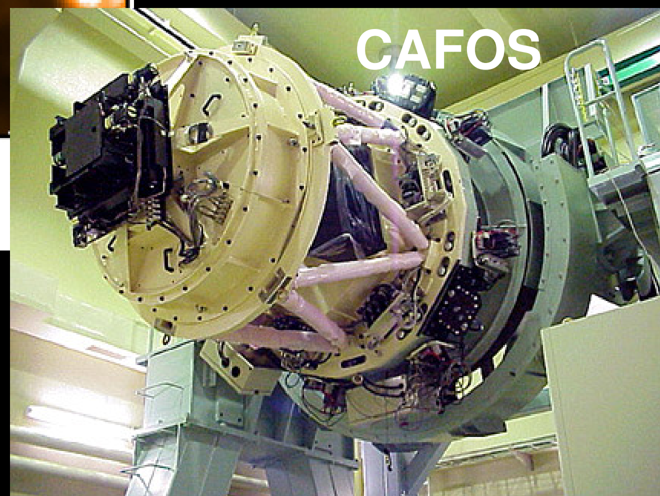
Light-echo nature concluded by Kapteyn (1902)

Finding a scattered light echo



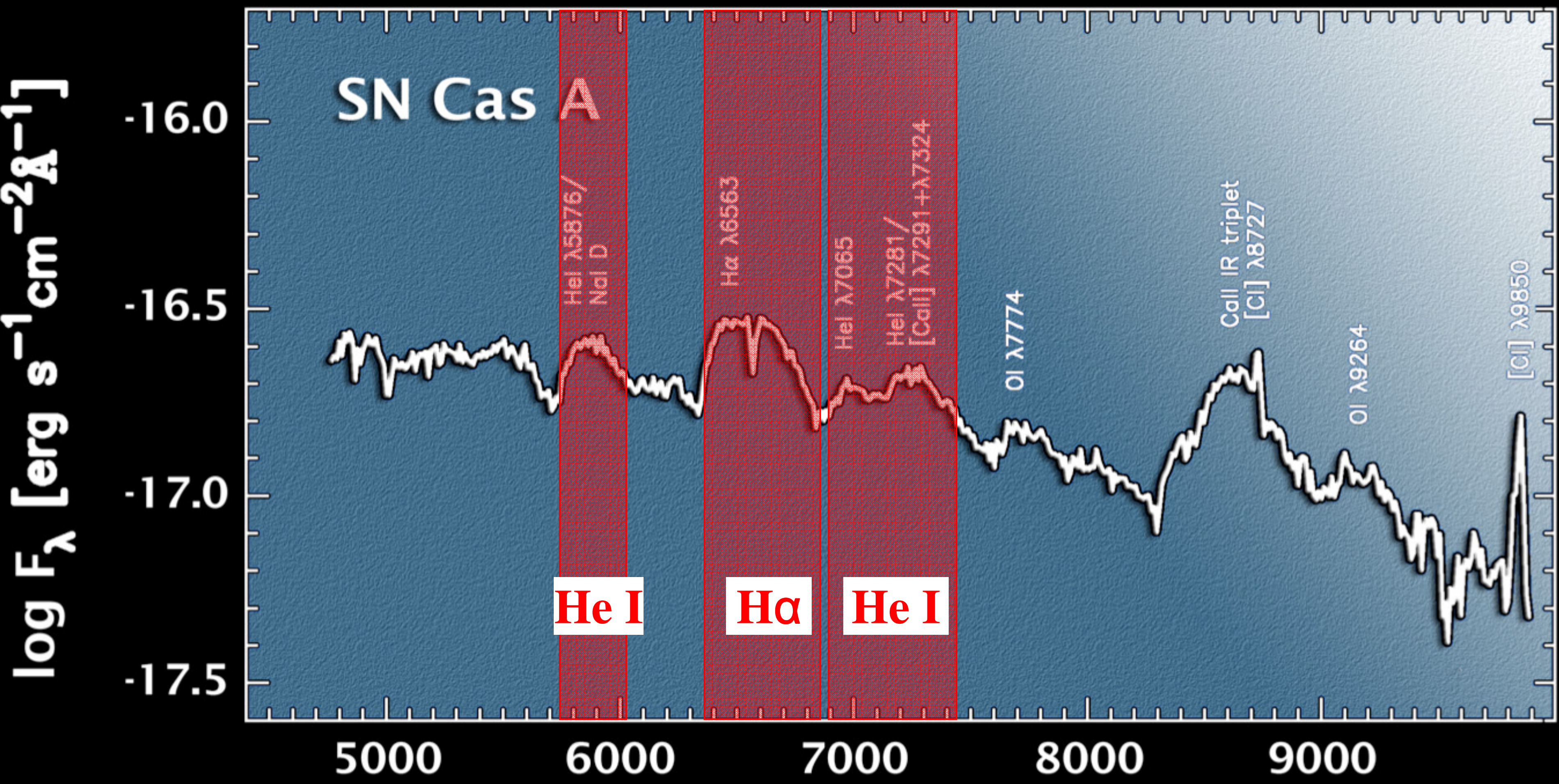






Echo surface brightness R = 23.4 mag / arcsec^2

Results: Spectroscopy



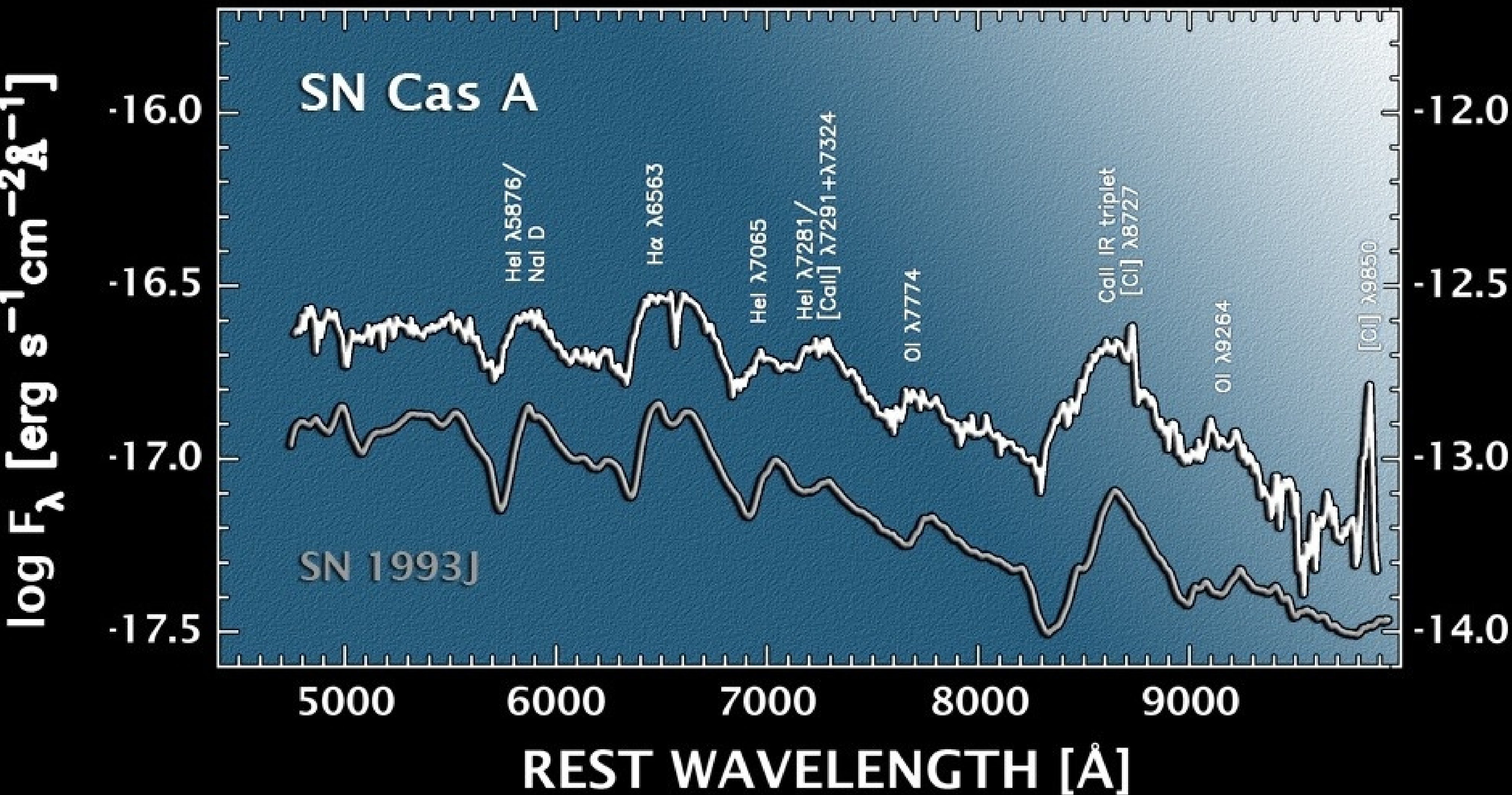
.5 h

First spectrum of a Galactic Supernova: 327 years after its light originally arrived at Earth

- **Typ**
  - **E**
  - **S**

(2008)

Comparison with the proto-typical type IIb SN 1993J



The Nature of SN1993J

Rare type with spectral transition from type II to Ib
Swartz et al. Nature 365, 232 (1993)

Explanation: Hydrogen rich envelope transfered to binary companion -> collapse of helium core
Nomoto et al. Nature 364, 507 (1993); Woosley et al. Ap*J* 429, 300 (1994)

→ Established physical connection of SNe II and Ibc

Parameters for SN1993J
- (Initial) stellar mass 13-20 $M_\odot$
- M(H) ~ 0.1-0.5 $M_\odot$
- He core ~ 3-6 $M_\odot$
- $M(^{56}Ni)$ ~ 0.08 $M_\odot$ → M_v ~ -17.5 mag
- $M(^{44}Ti)$ ~ 0.7 – 1.7 10^{-4} $M_\odot$

Fast moving N-rich, H-poor knots
Ejecta mass ~ 2 – 4 $M_\odot$
Compact object ~ 2 $M_\odot$ (neutron star)

^{44}Ti mass 1.6 10-4 $M_\odot$ M(Fe) > 0.06 $M_\odot$
Hydrodynamical stage of remnant – stellar wind density -> RSG
Assymetric explosion
CNO-ashes

Progenitor was a red supergiant Aldering et al. AJ 107, 662 (1994)

Binary companion recently detected Maund et al. Nature 427, 129 (2004)

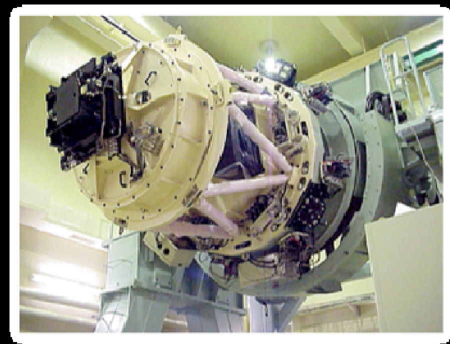
➡ Such a progenitor is also compatible with Cas A

More Cas A echo observations

SUBARU

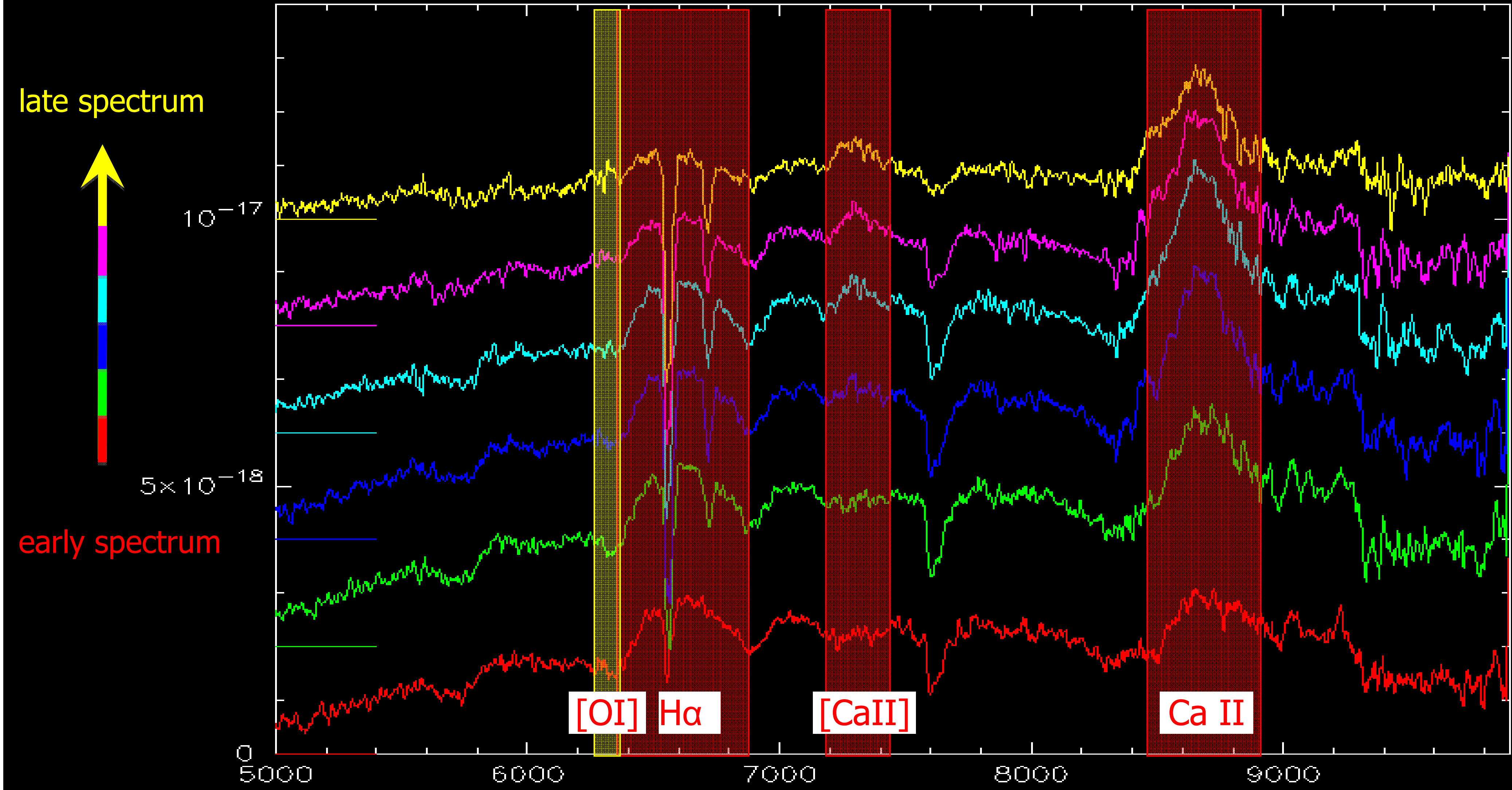
+

FOCAS



Color composite:
B-band
R-band
I-band

Cas A SN: spectral evolution over time



➡ Strength of hydrogen emission decreasing -
Ca triplet, nebular lines increasing

Usuda et al. (in prep.)

The supernova of the year 1572

Stella Nova
(Tycho Brahe 1573)

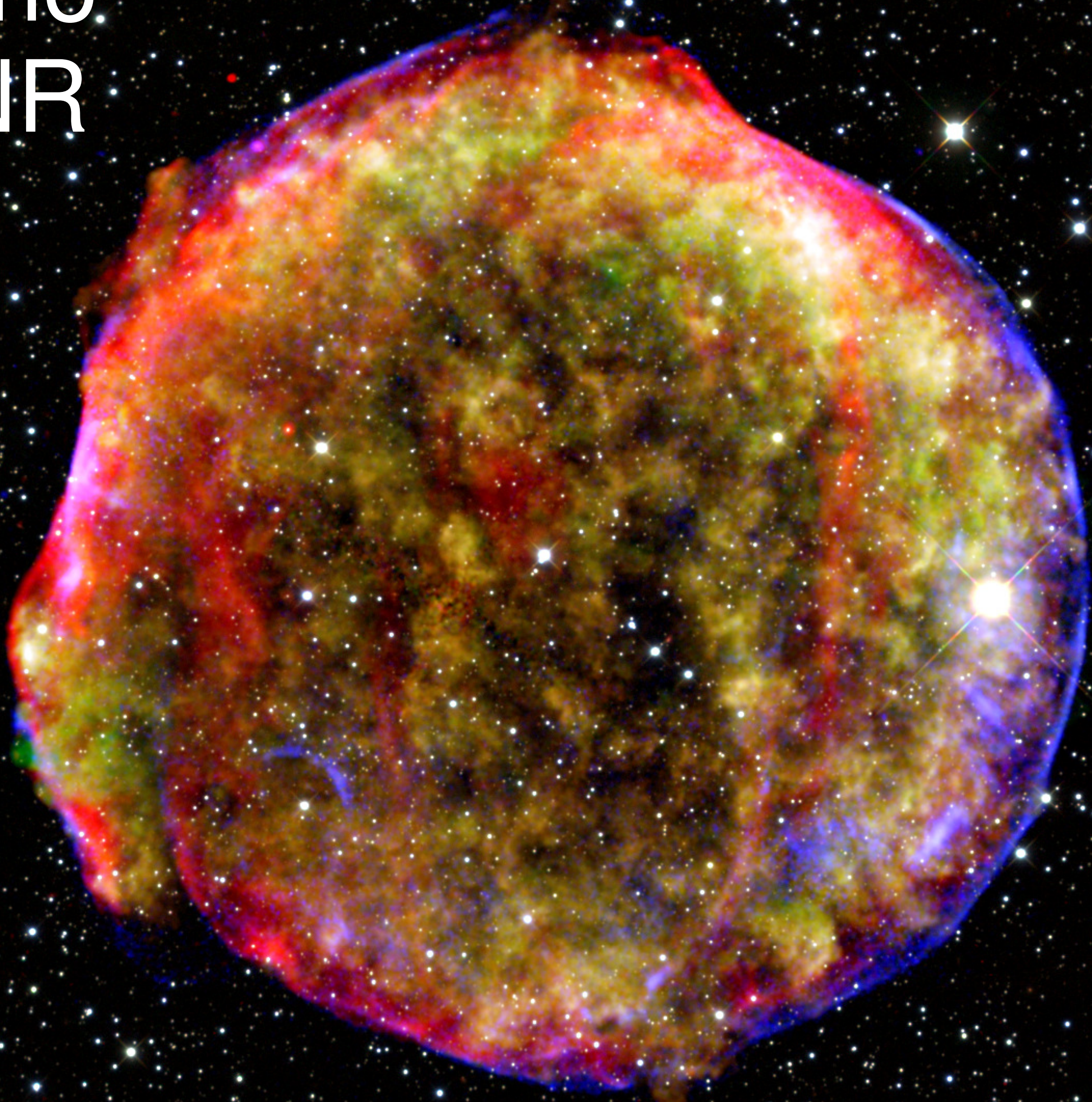
Milestone for a new view of the cosmos – together with Galileo and Kepler in 1609

Tycho Brahe: No parallax ⟶ more distant than the moon

Contradiction to Aristotle –
Heavens not immutable and eternal

„Astronomie Populaire"
Camille Flammarion, 1884

Tycho SNR



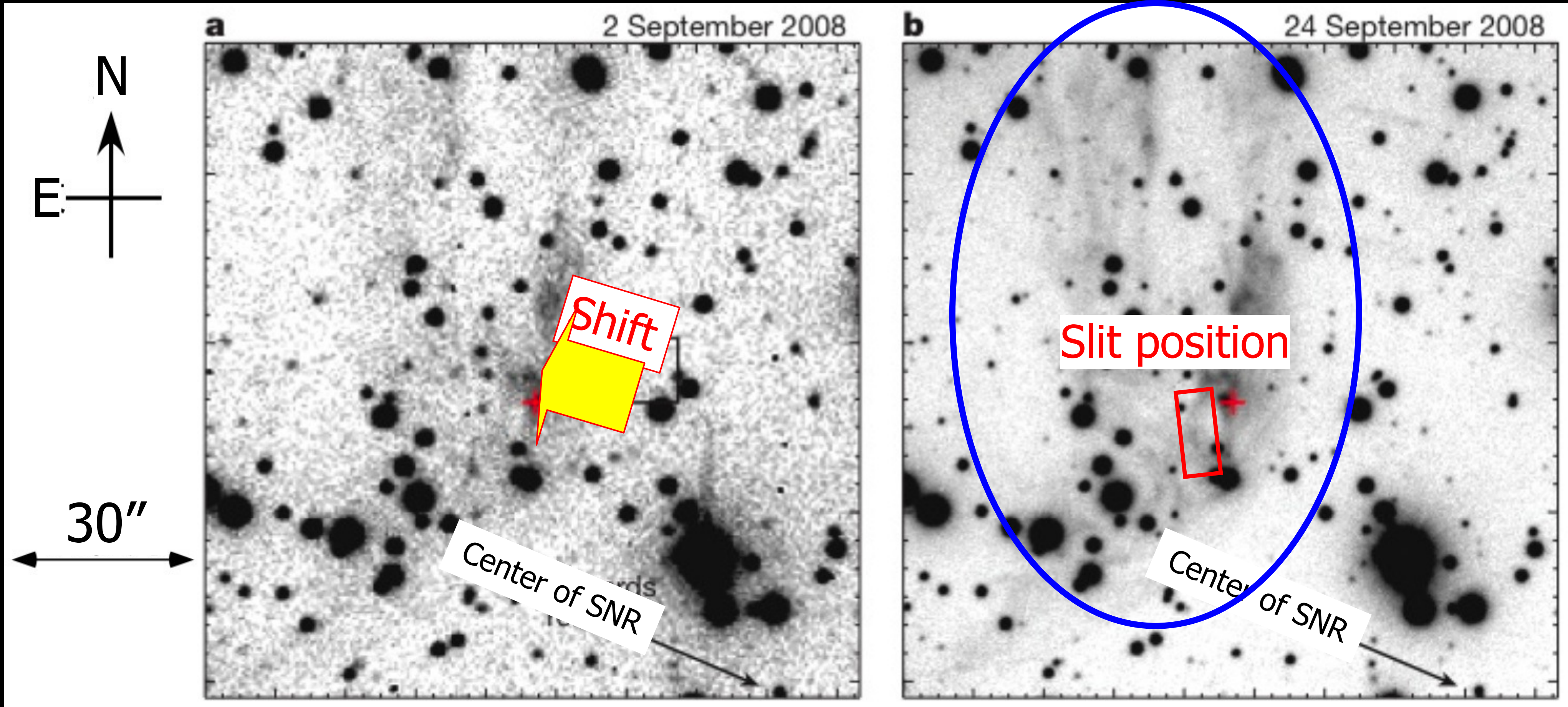
Chandra
X-ray Fe;Si;8keV
Hot gas

Spitzer
24 µm; circumstellar/
synthesized dust

Calar Alto 3.5m
JHK_s
fore-/background stars

- Balmer dominated optical spectra
- Historic light curve ⇒ type Ia
- Ejecta morphology and composition
- Binary companion Ruiz-Lapuente et al. Nature 431, 1069 (2004)
- Subclass uncertain (subluminous – slightly overluminous)

Results: Imaging



a: Calar Alto 2.2m
b: Subaru + FOCAS

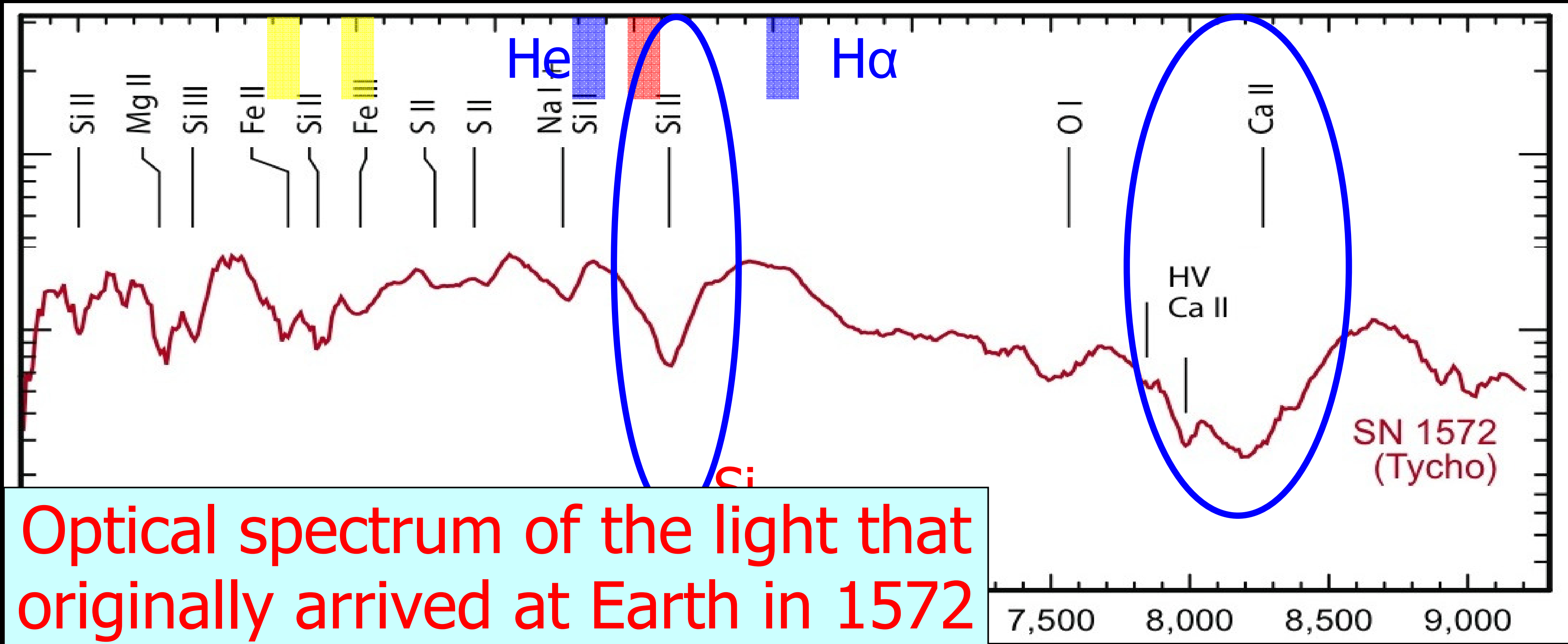
Back box: Previous light echo position in 2006

Red+ mark: Brightest position (R=23.5 mag)

→ Slit position (2.8″x2.0″) for spectroscopy by FOCAS

→ Subtraction of sky & nebulosity lines

Results: Spectroscopy



Optical spectrum of the light that originally arrived at Earth in 1572

- Exp time=2.5 hours (Red) + 1.5 hours (Blue)
- Av=2.4 mag

- Typical SN spectral features
  - Broad line width (9,000~12,000 km/s)
  - No H & He lines
  - Strong absorption lines of Si and Fe

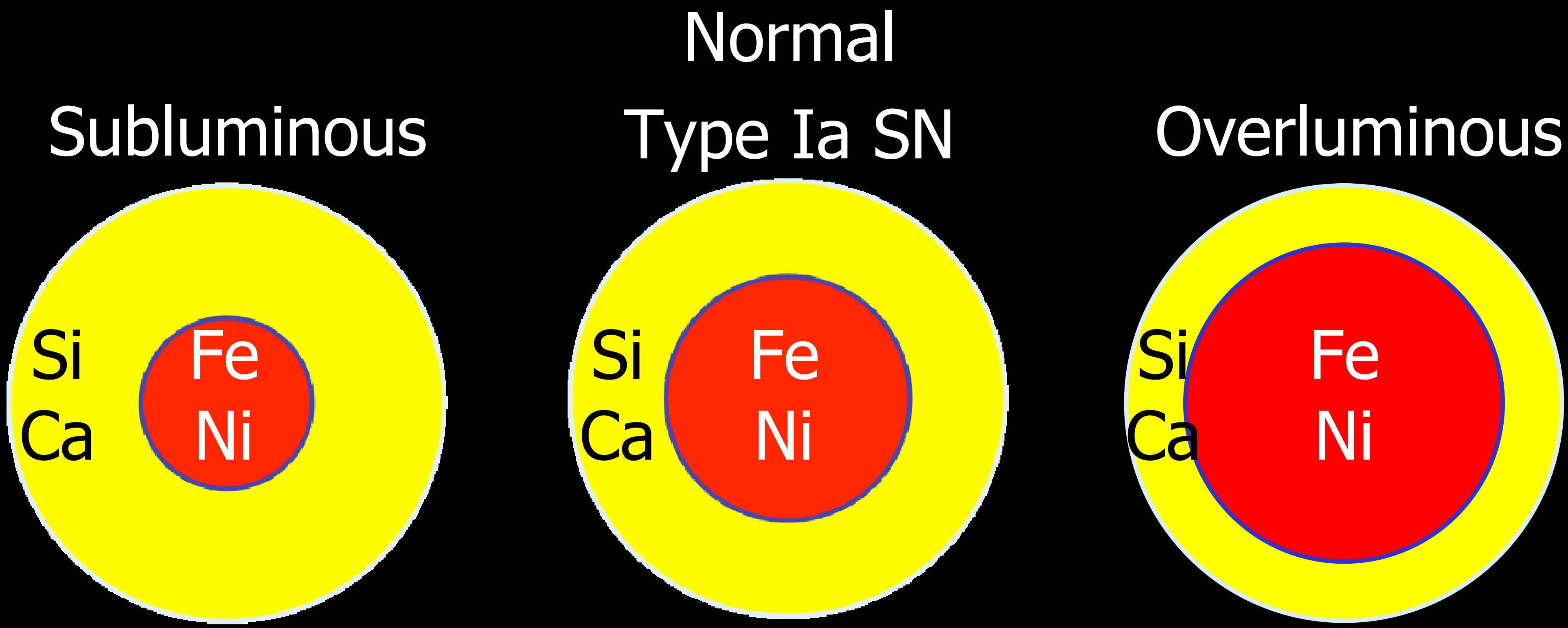
Krause et al. Nature 456, 617 (2008)

Various type Ia Supernova

Type Ia SN = Cosmological distance indicator

→ Discovery of the accelerated expansion of Universe

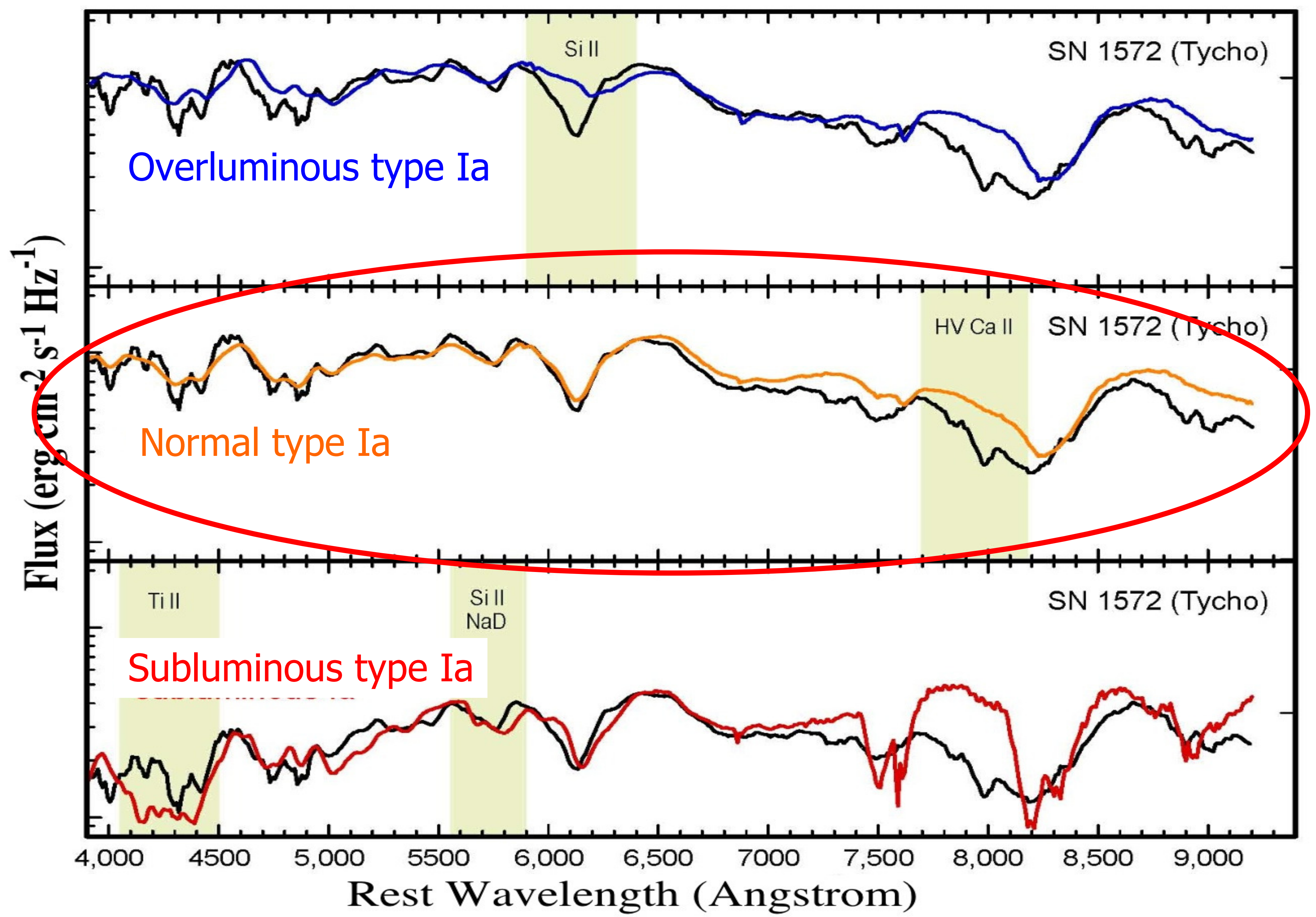
Luminosity is NOT uniform!



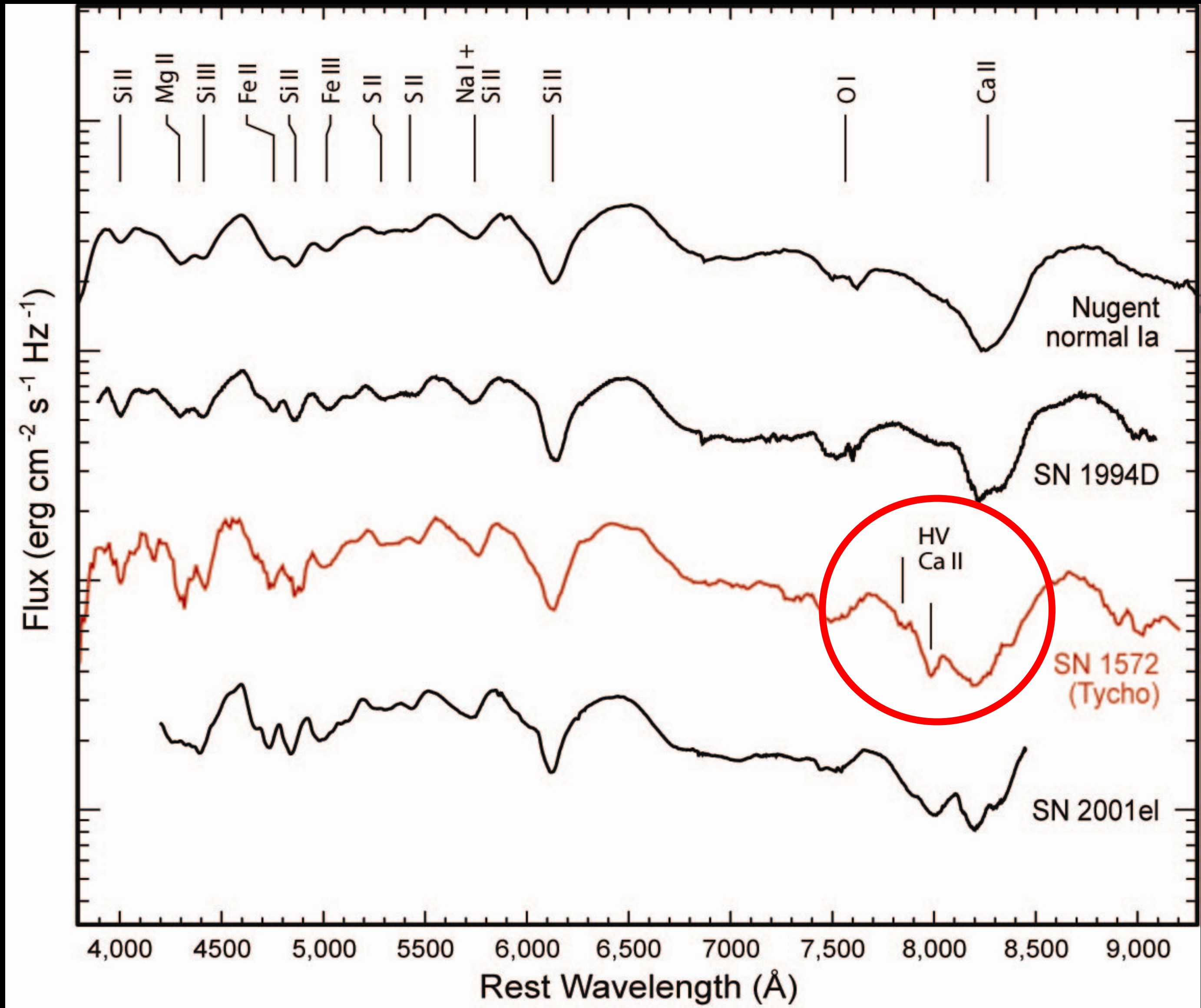
Reason why its variety of luminosity?

→ Accurate cosmological distance indicator?

Results: Spectroscopy



High-velocity Ca II absorption in SN 1572



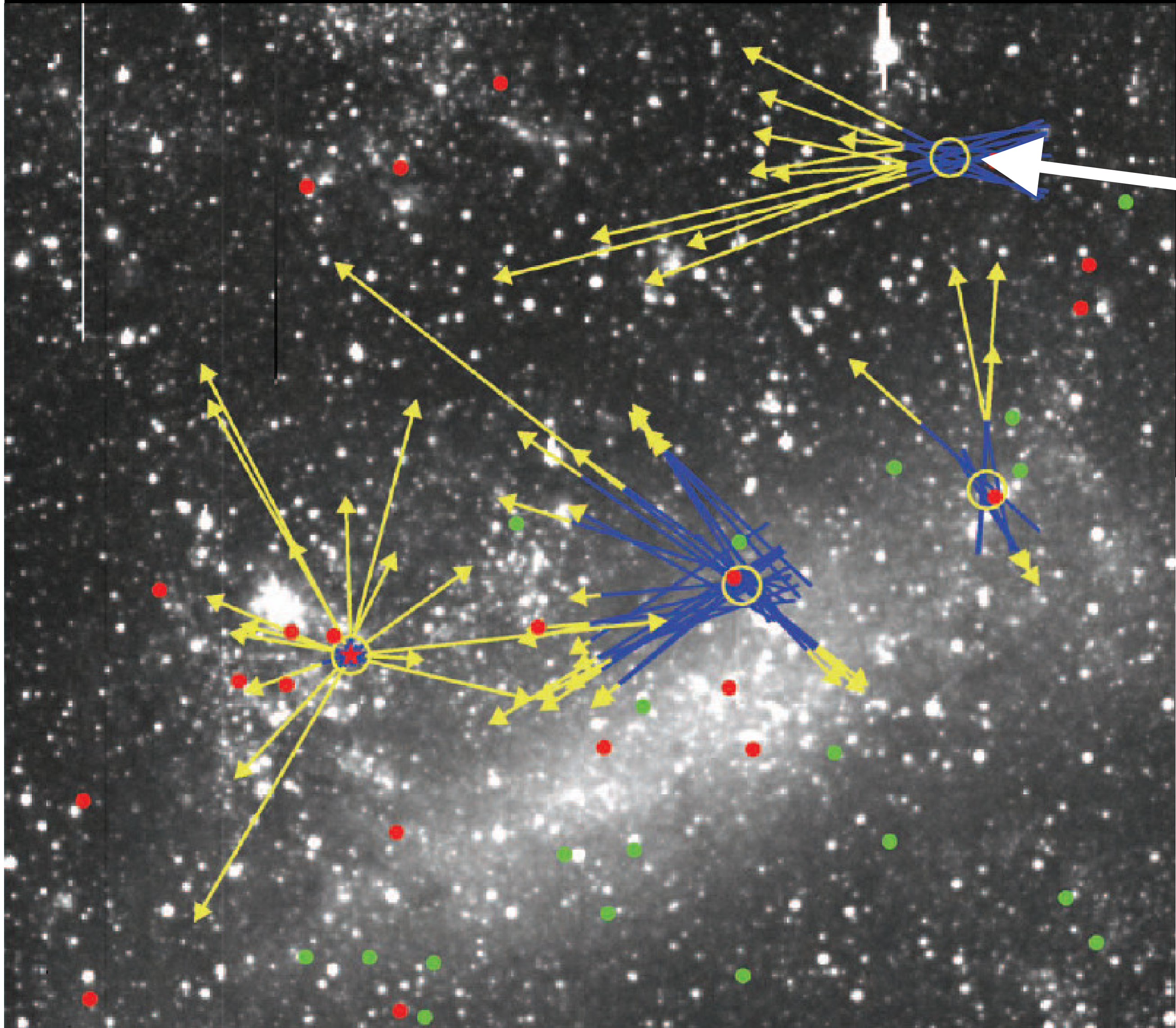
Photospheric Si II
12,000 km/s

HV Ca II
22,000 - 30,000 km/s

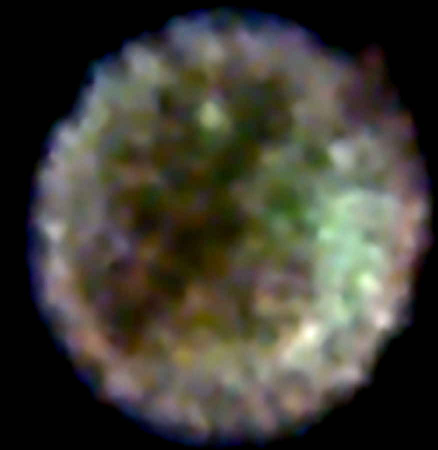
- Strength similar to SN 2001el
- Spectropolarimetry suggests asphericity in the case of SN 2001el

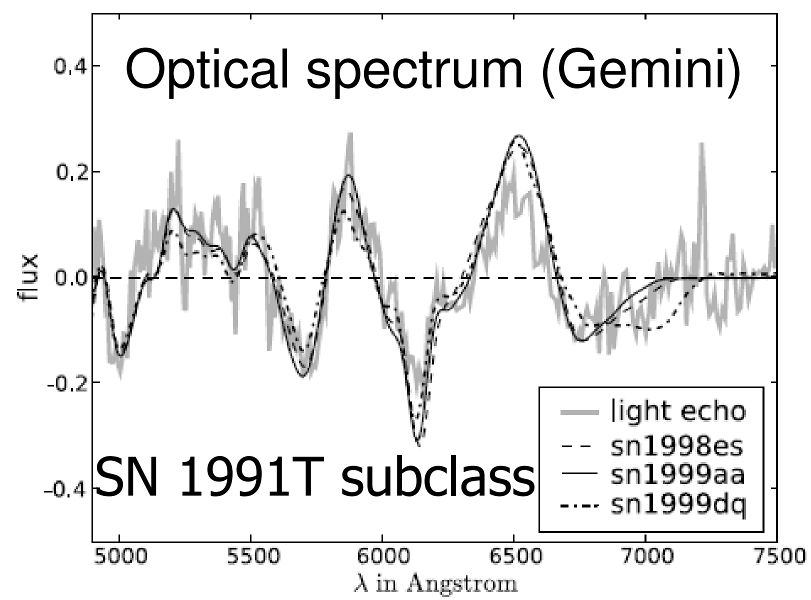
Wang et al. 2003, ApJ 591, 1110; Kasen et al. 2003, ApJ 593, 788

Light echoes in the LMC from SuperMACHO



Type Ia SNR 0509-675

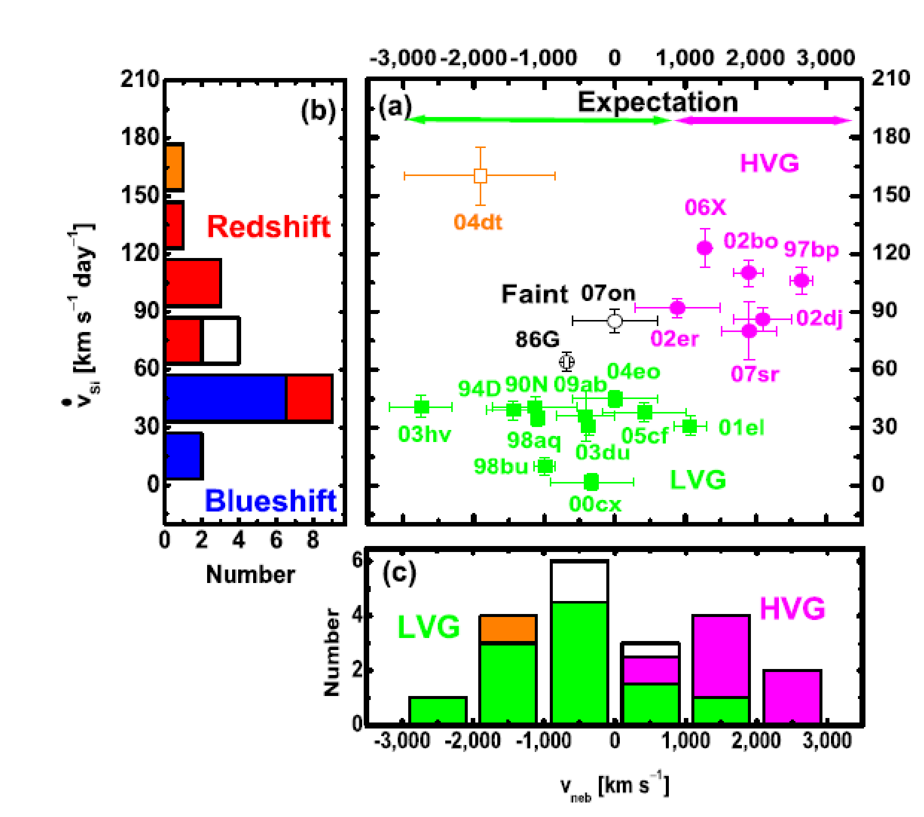


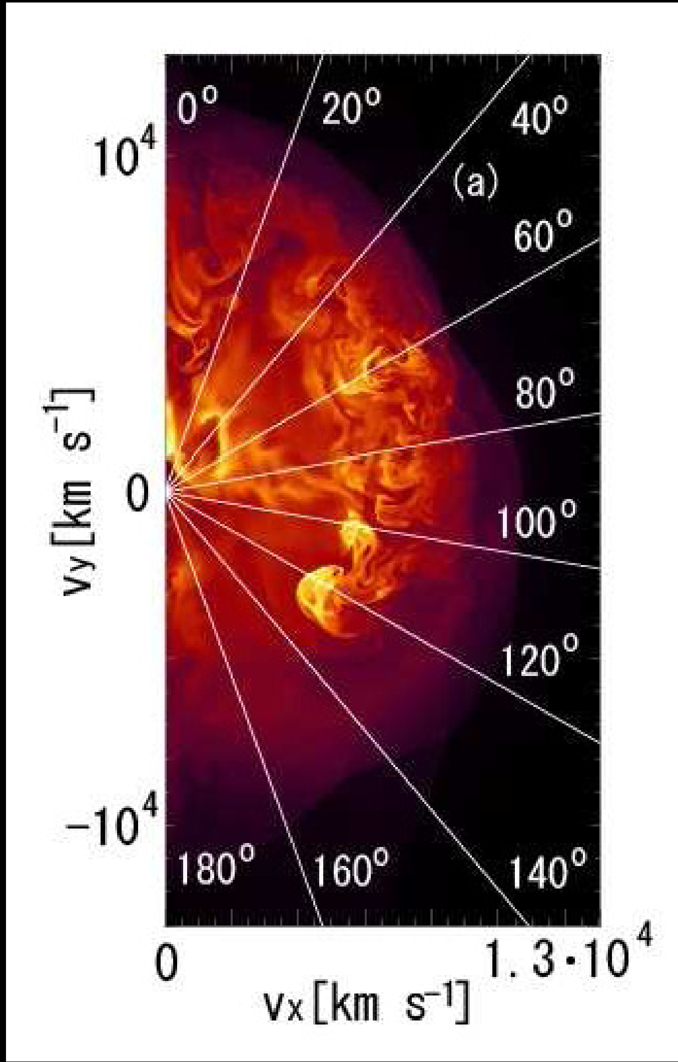


Rest et al. Nature 438, 1132 (2005)

Rest et al. ApJ 680, 1137 (2008)

Spectral diversity of type Ia SNe

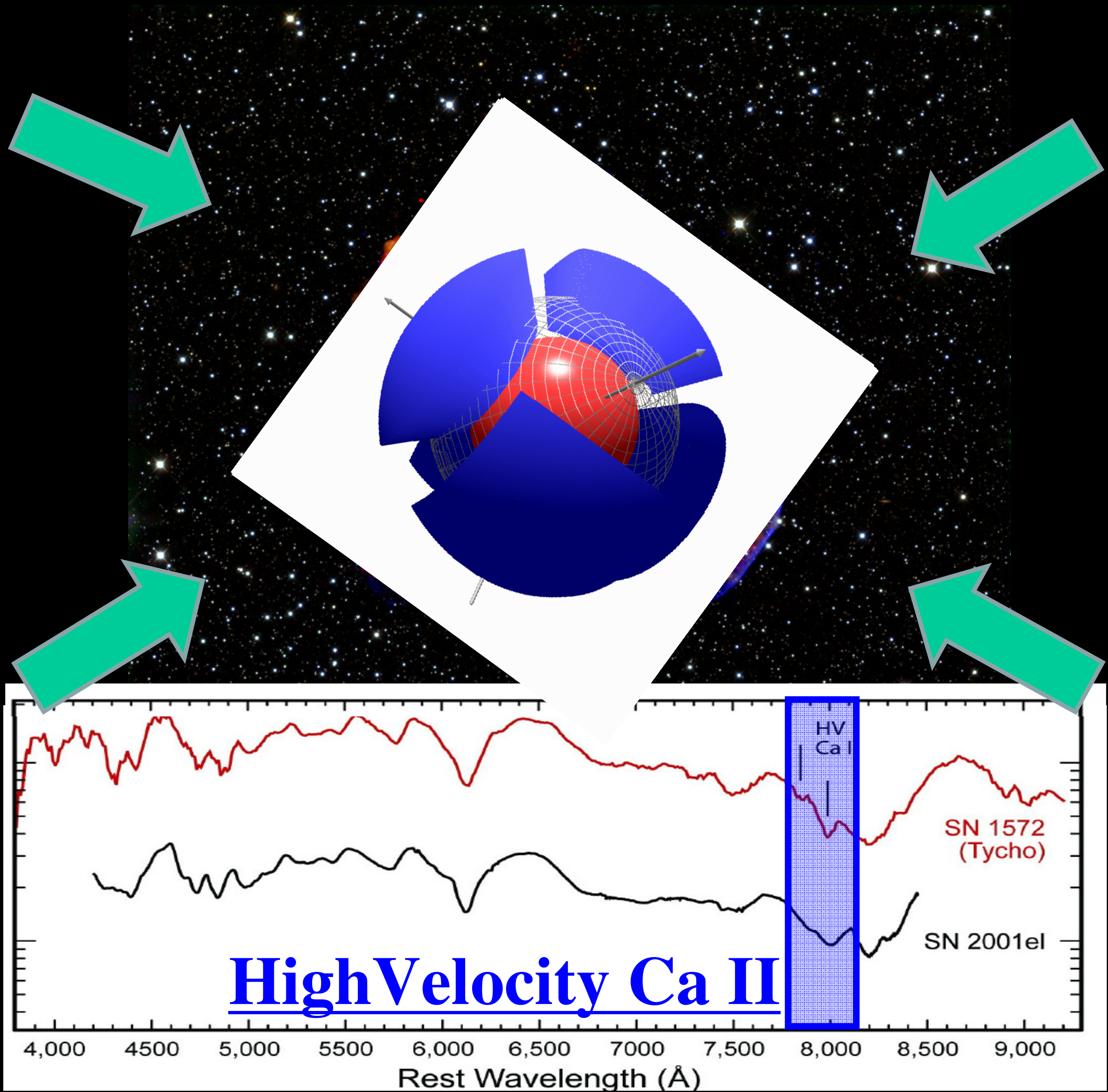




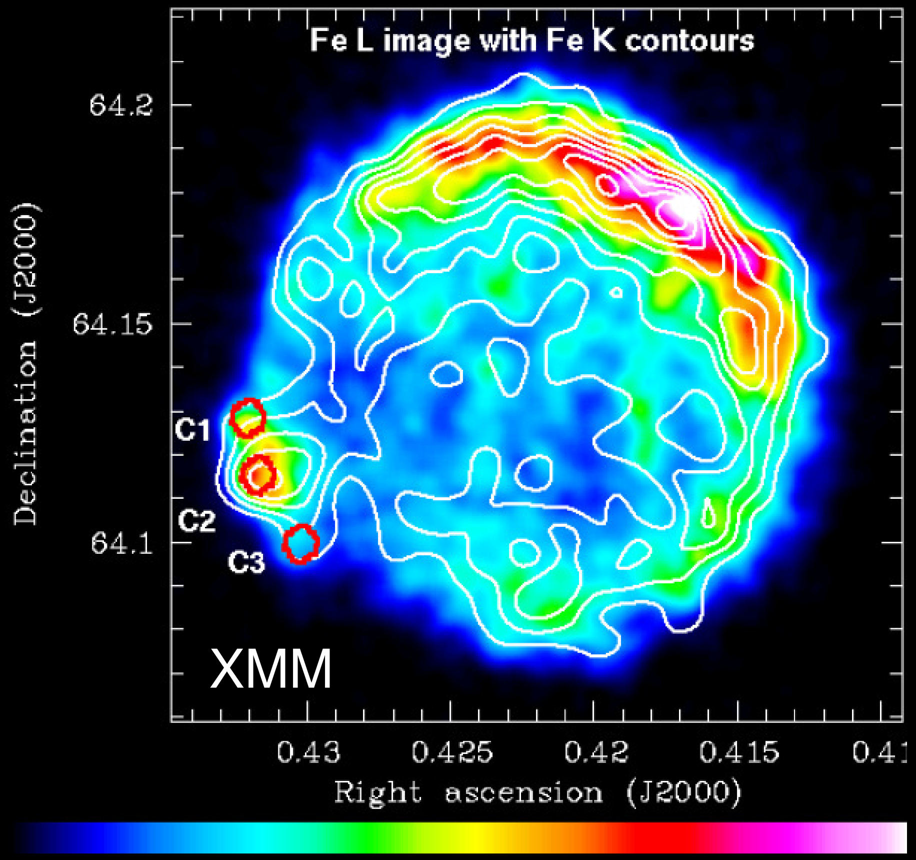
An asymmetric explosion has been invoked as the origin of spectral evolution diversity in type Ia SNe

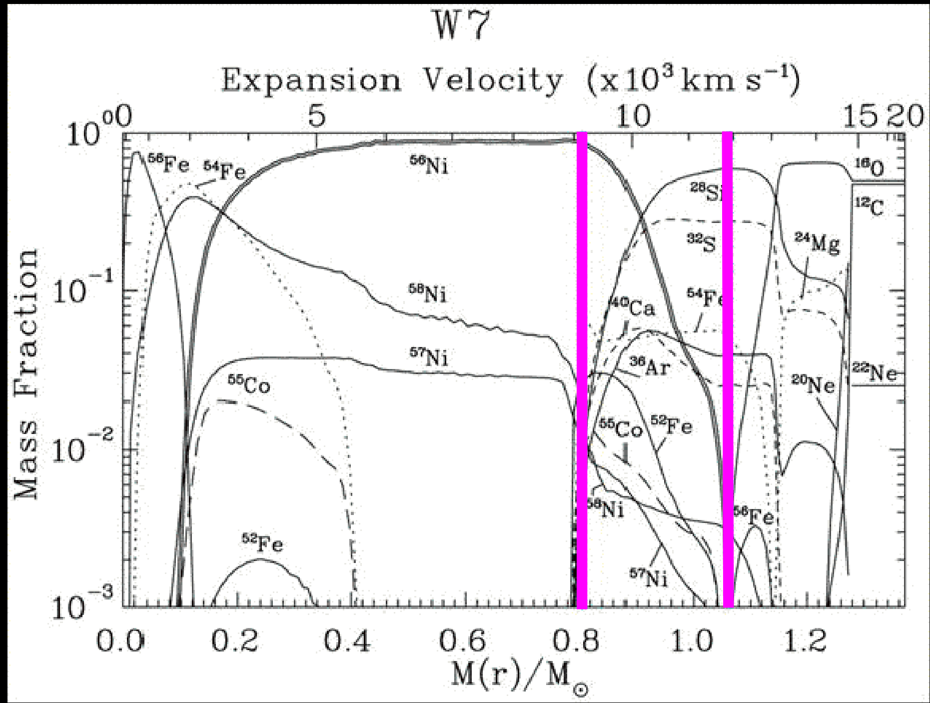
Maeda et al. Nature 466, 82 (2010)

Spatially resolved spectroscopy



Asymmetries in the Tycho remnant





Si/Fe abundances change in Fe knots
C1: [Si/Fe] ~ 10
C2: [Si/Fe] ~ 3
C3: [Si/Fe] ~ 30

Decourchelle et al. 2001, A&A 365, 218

Similar abundances between Si+S and Fe rich zones

Connection to HV Ca II emission ?

Ca X-ray emission deviates most in DDT models by Badenes et al. 2006, ApJ 645, 1373

Conclusion and outlook

- Light echoes from historic SNe can be still observed and analyzed after several centuries

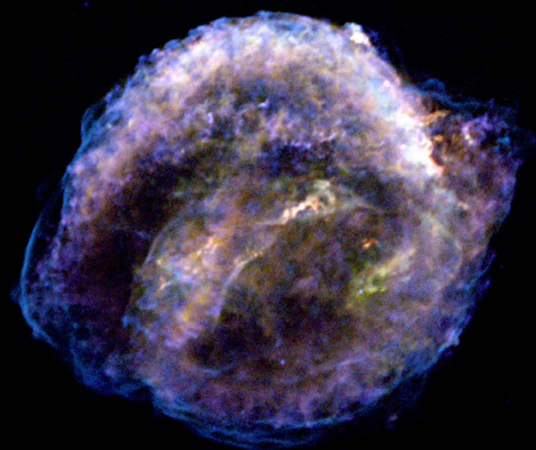
- They can yield precise spectroscopic classifications of the underlying explosions - as demonstrated for Tycho's SN1572, Cas A and SNR 0509-675 – and link the wealth of knowledge on their remnants with the original outbursts

  - 3-dimensional echo spectroscopy

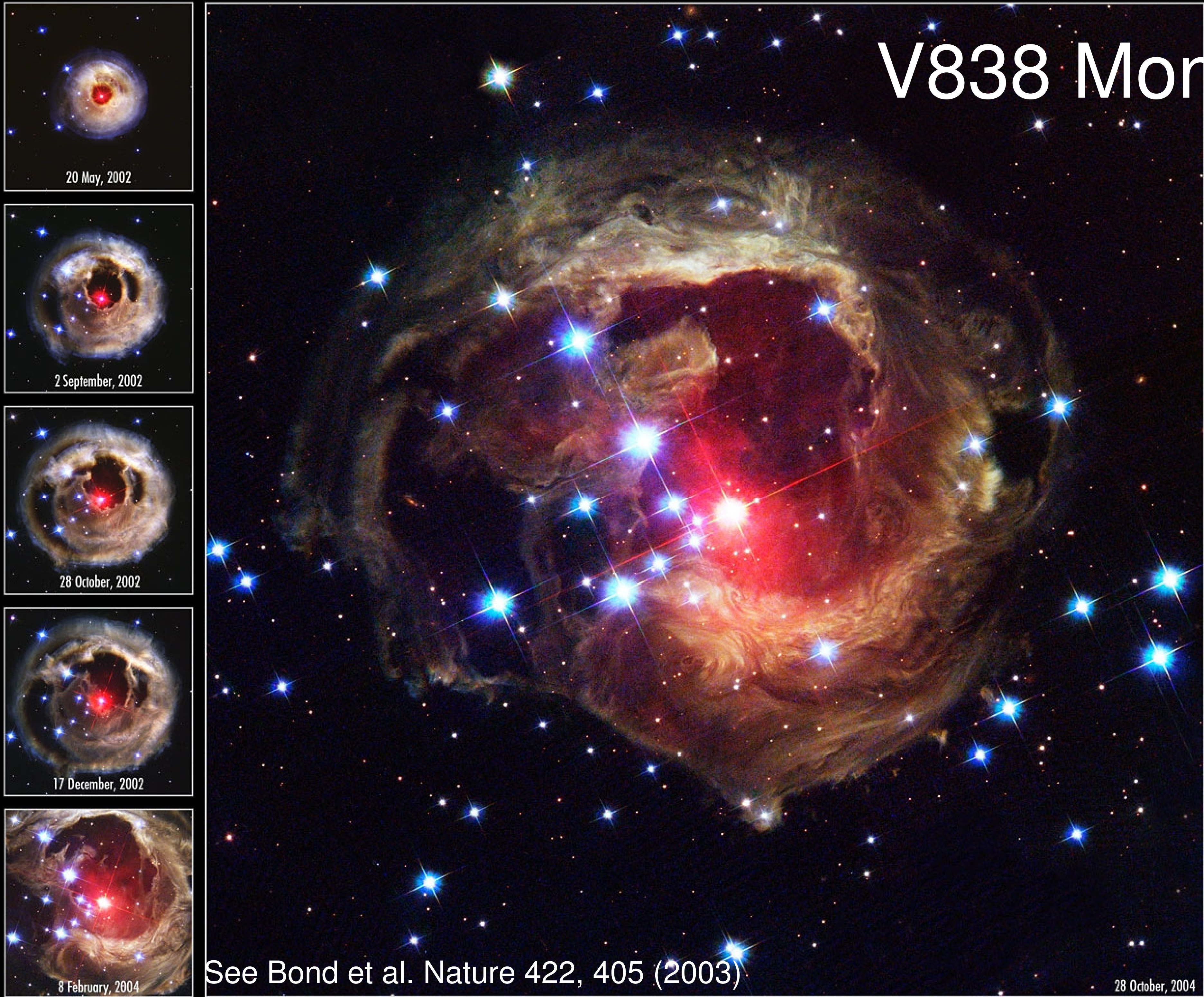
    Light echoes at different lines of sight relative to the remnant provide a true 3-dimensional spectroscopic view of the explosion

  - Kepler

    Nitrogen-rich (CSM?) material and morphology indicates unusual Ia scenario – Spectral classification urgently required

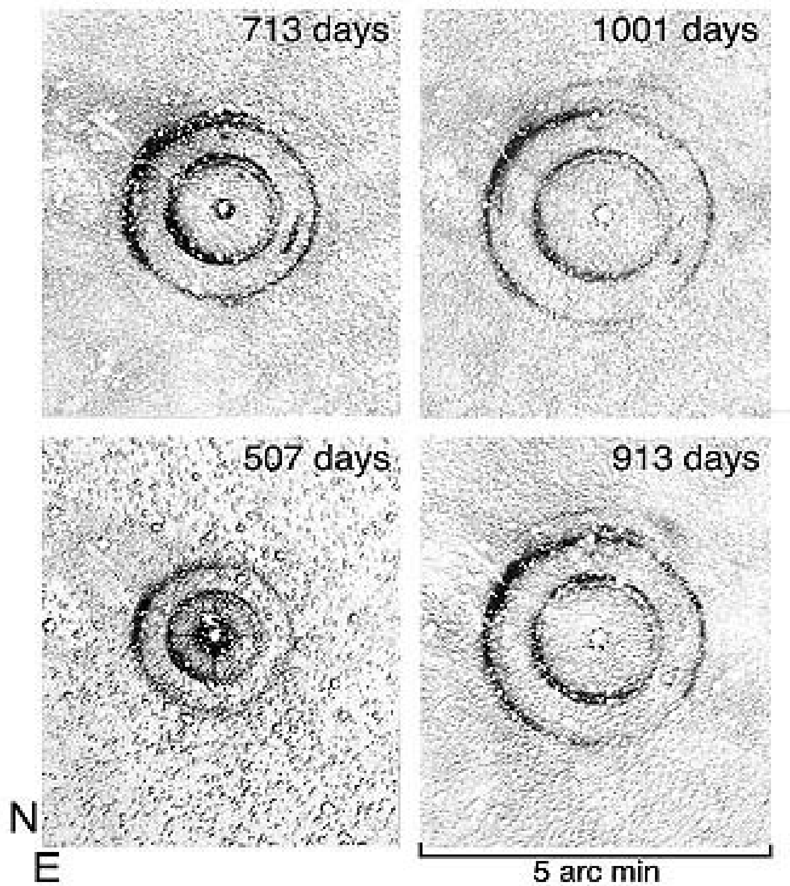


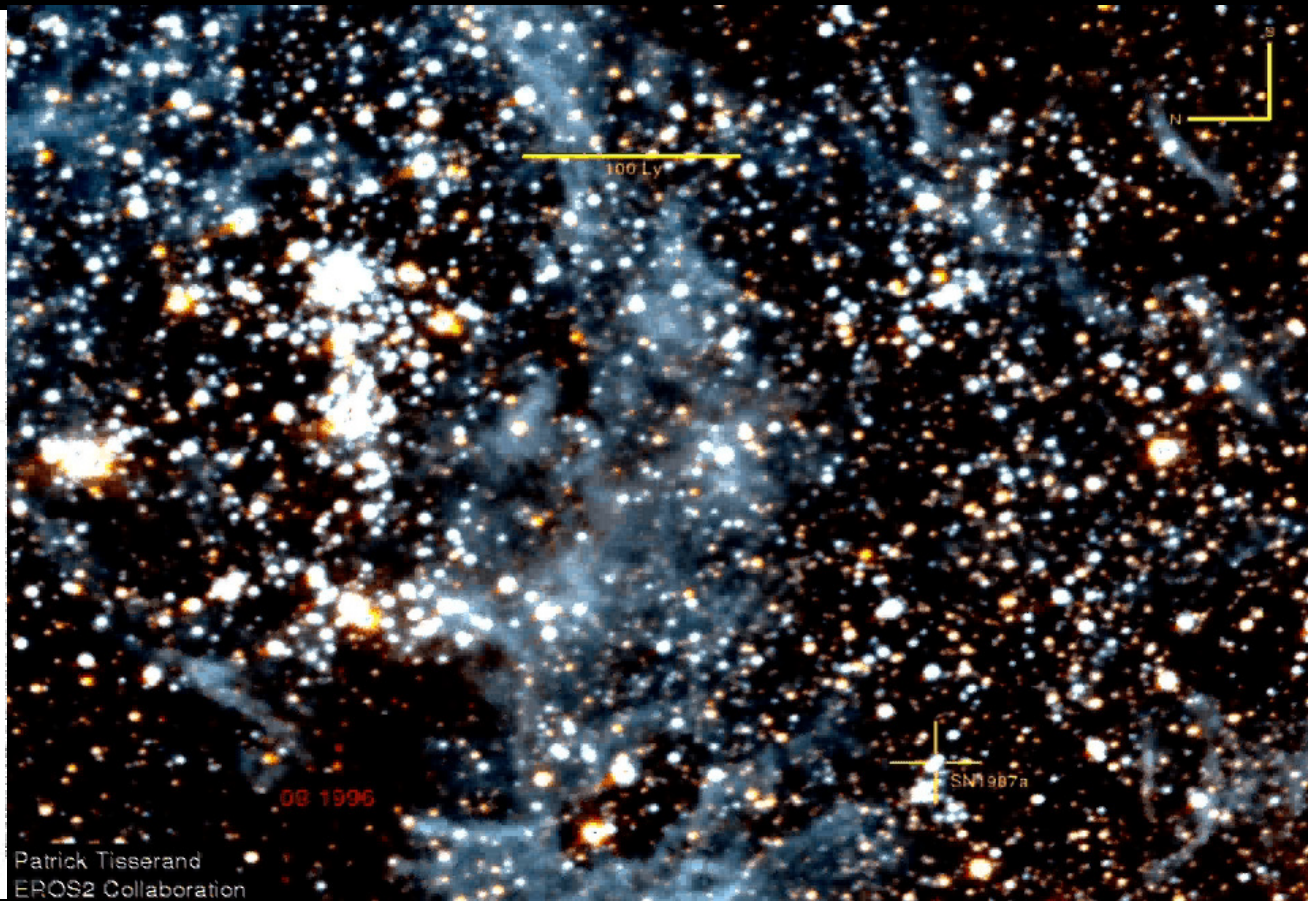
V838 Mon



See Bond et al. Nature 422, 405 (2003)

SN 1987A light echos





Crotts (1988)
Chevalier & Emmering (1988)
Suntzeff et al. (1988)