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# Cassiopeia A: Supernova Remnant for a Case Study of Core-Collapse Supernova Explosion

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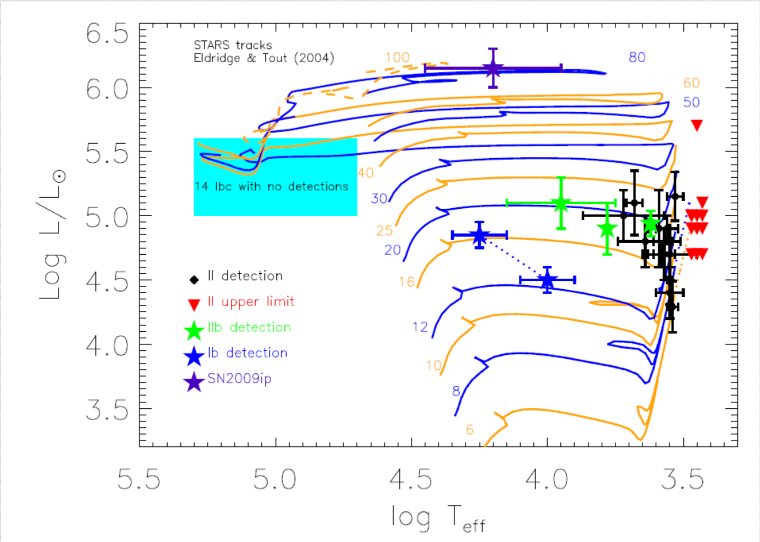
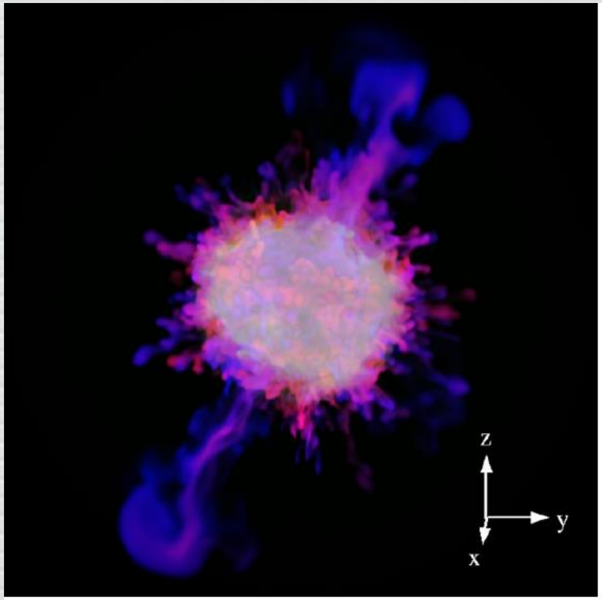
# Core-Collapse Supernova (CCSN)

- **SN = SN Ia + CCSN (or SN II)**
  - SN Ia: thermonuclear explosion of white dwarfs
  - CCSN: explosion of massive ($M \geq 8\ M_{\odot}$) stars
    - CCSN: SN Ia = 76:24 (Li+ 2011)
    - Types: IIP, IIL, Ib, Ic + IIb, IIn, Ibc-pec
- **Two big questions**
  - What are the progenitors of different SN types?
  - How do they explode?



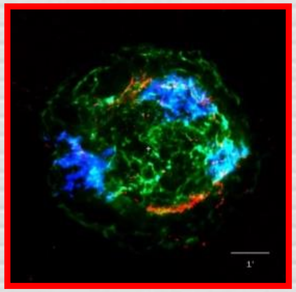
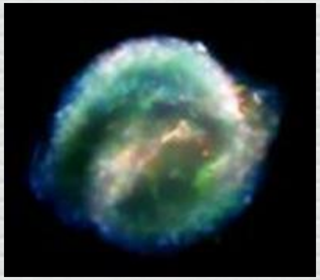
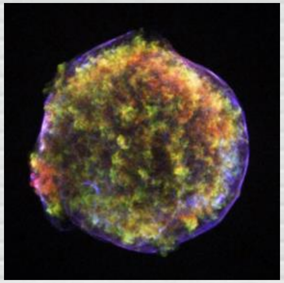
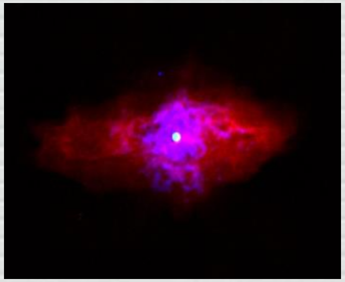

Progenitors of SN II (Smart 2015)

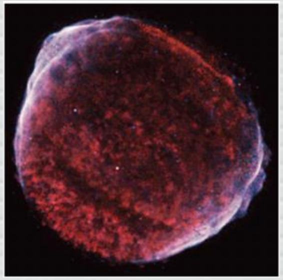


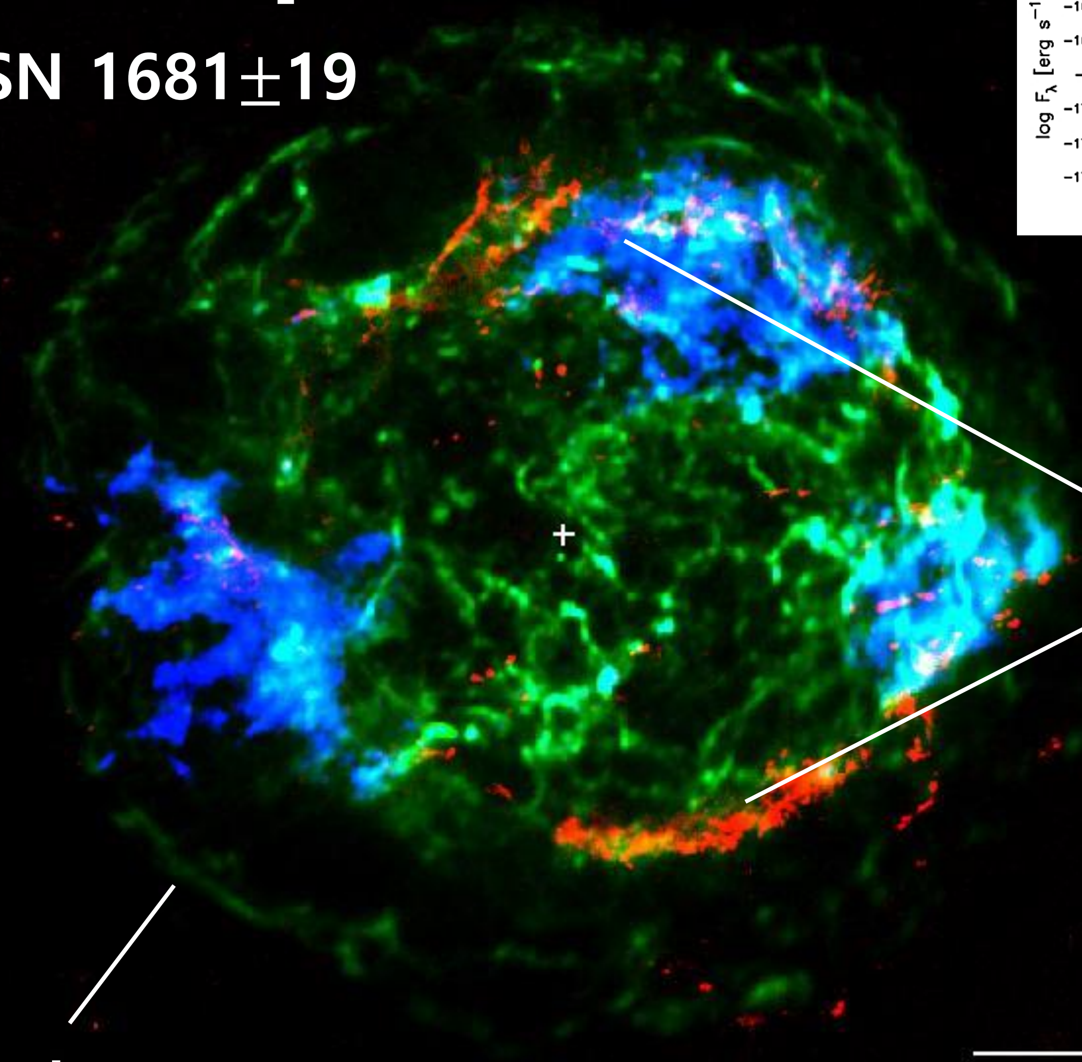

Blue=$^{56}$Ni, Red=O, Green=C at 9000 s after the explosion of 15.5 $M_{\odot}$ star (Hammer+ 2010)

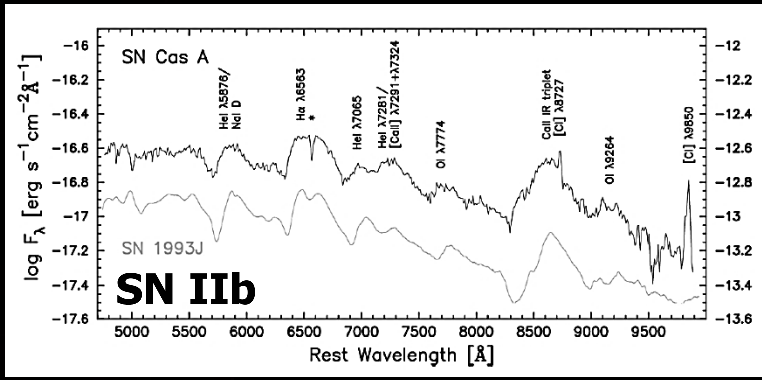
# Historical SN after AD 1000

| SN date | SNR name | distance (kpc) | SN Type |
|---|---|---|---|
| AD 1680? | Cas A | 3.4 | IIb |
| AD 1604 | Kepler | 2.9 | Ia |
| AD 1572 | Tycho | 2.3 | Ia |
| AD 1181 | 3C58 | 3.2 | II |
| AD 1054 | Crab | 1.9 | II |
| AD 1006 | SN1006 | 2.2 | Ia |



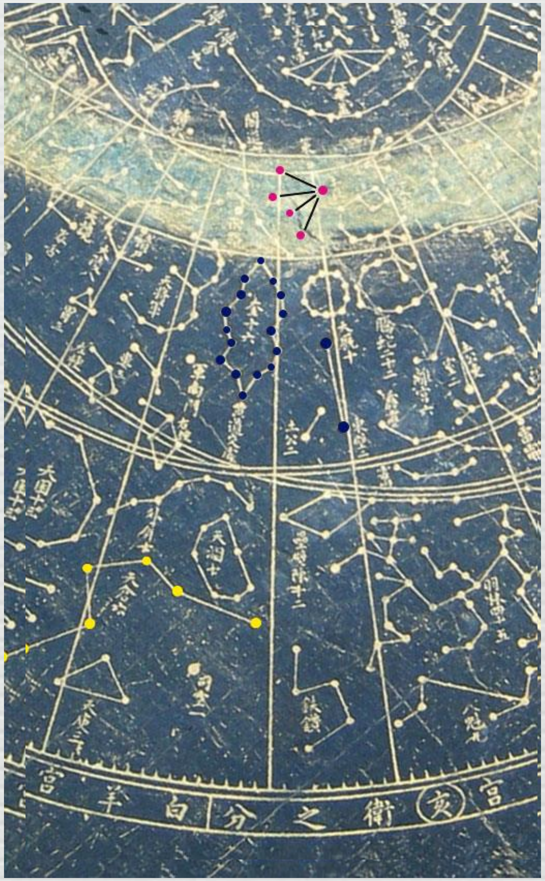



(R) Palomar [Fe II] 1.644 μm (G) Chandra 4.2-6.4 keV continuum (B) Chandra 6.52-6.94 keV

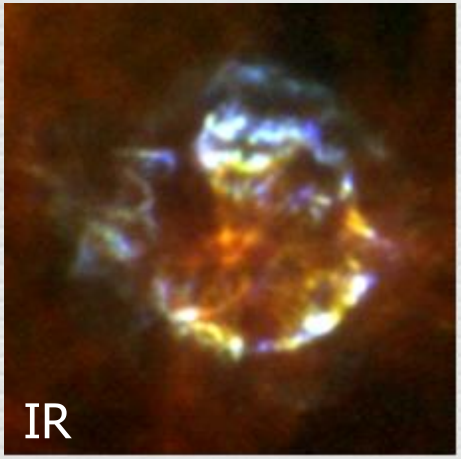
# Cas A: Missing Historical Records

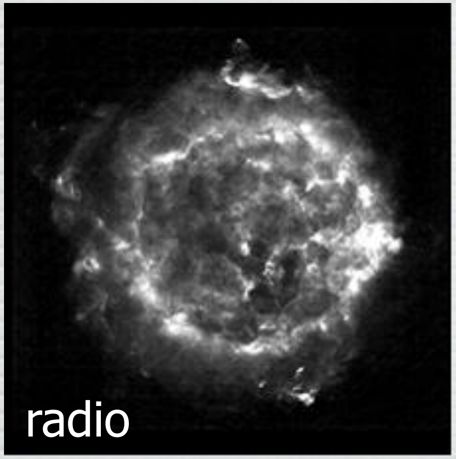
- **Two proposed historical records**
  - John Flamsteed's 3 Cas (Ashworth 1980)
    - 6th mag star observed on August 26, 1680; ~10′ from Cas A (cf) usual error 1′-2′
    - Misidentification of AR Cas + *SAO 35386* (Stephenson and Green 2002 and others)
  - 1592 Korean guest star (Brosche 1967; Chu 1968)
    - "a guest star appeared at the first star in the west of *Wangyang*" (December 4, 1592; 宣祖實錄)
- **Large extinction?**
  - $A_{V,\,ISM}$=6±2 mag → $m_{V,\,SN}$ = 1.1±2.9 mag
    - d=3.4 kpc, $M_V$ = -17.6±0.9 mag
  - Extra extinction?
    - Mass loss from progenitor (Hartmann et al. 1997)
    - Korean guest star = Supernova `imposter'? (Park et al. 2016)

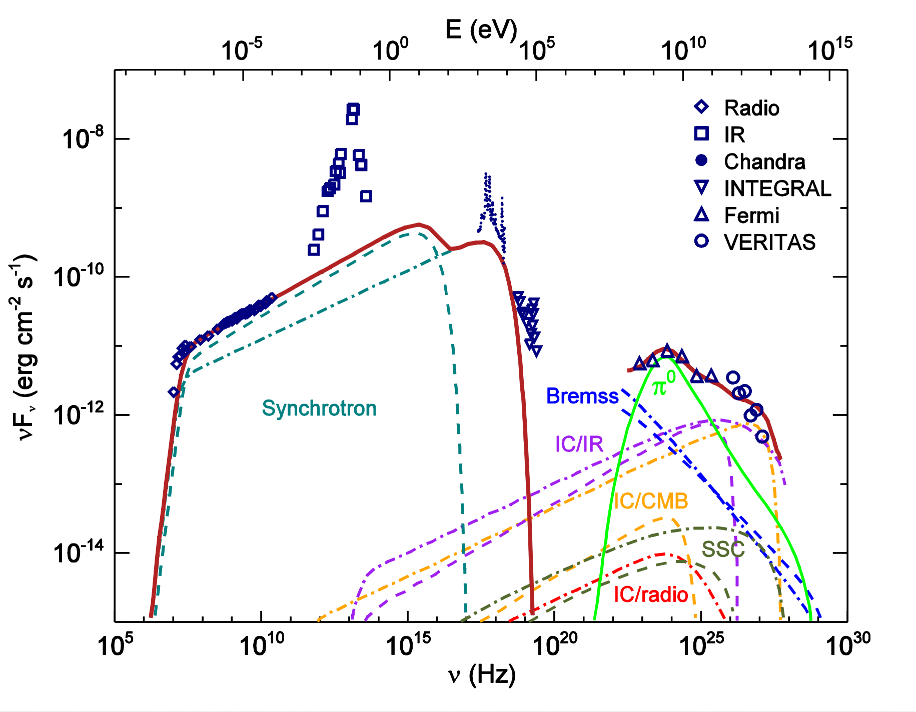


A part of *Cheonsang Yulcha Bunyajido* 天象列次分野之圖, the old Korean constellation map of *Joseon* dynasty. The right most star of *Wangyang* (王良, pink dots) is β Cas (Park et al. 2016).

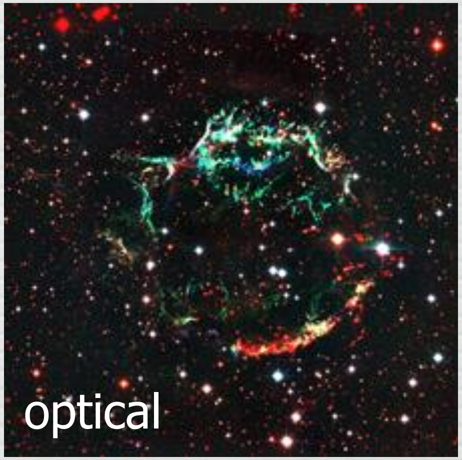
# Cas A in Multi-wavelength

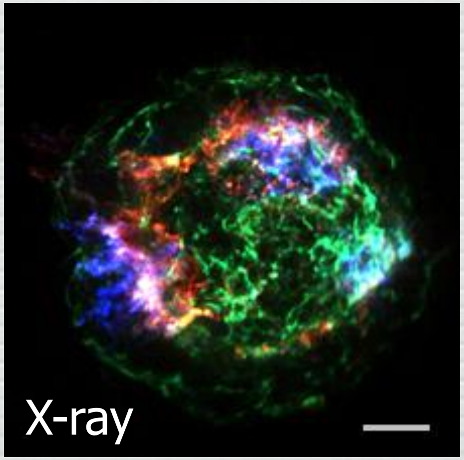


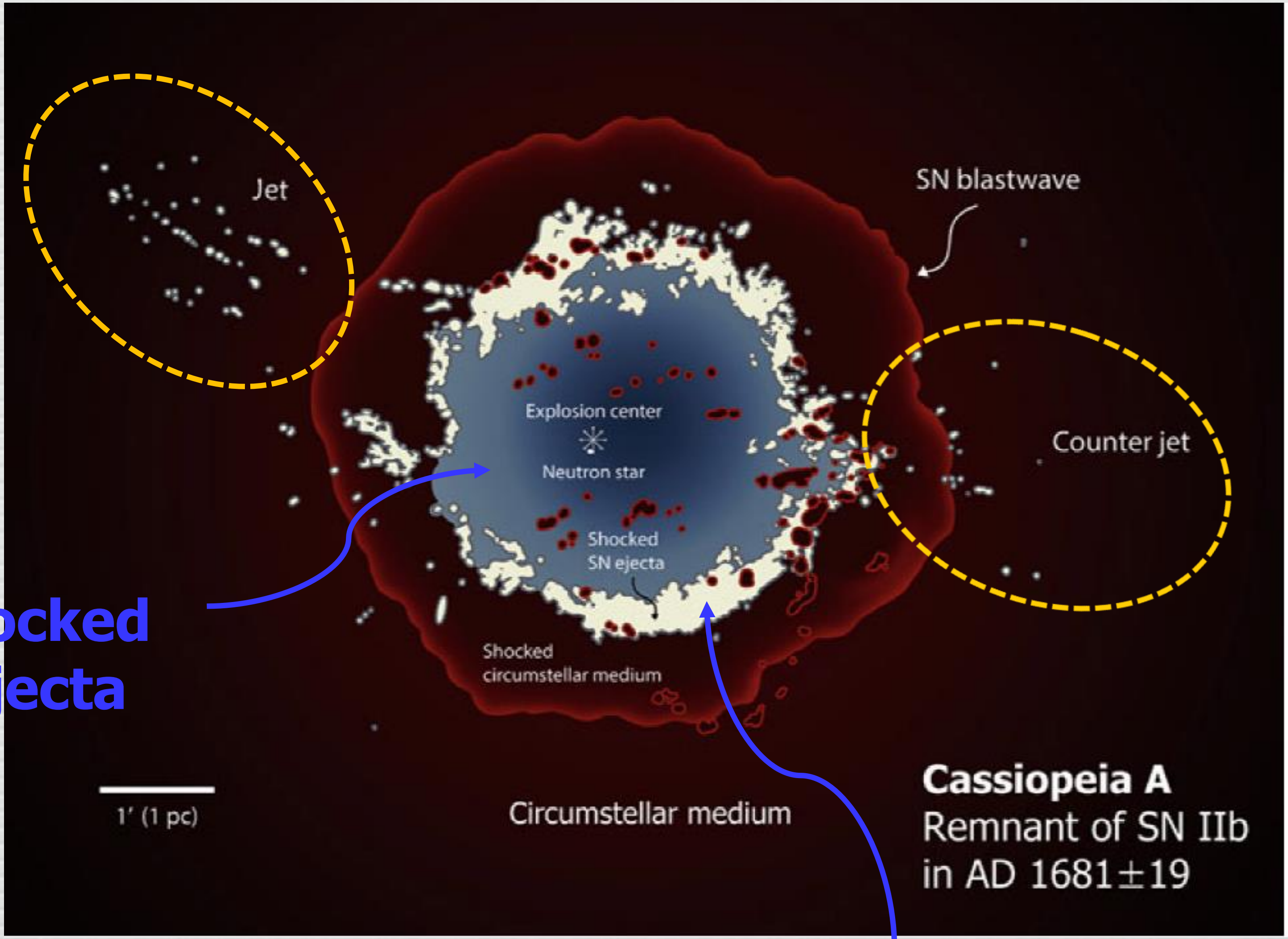




Broadband spectral energy distribution of Cas A. Lines represent two-zone model of Araya & Cui (2010). (Koo and Park 2017 in Handbook of SNe)



# Schematic Picture of Cas A




**Unshocked SN ejecta**

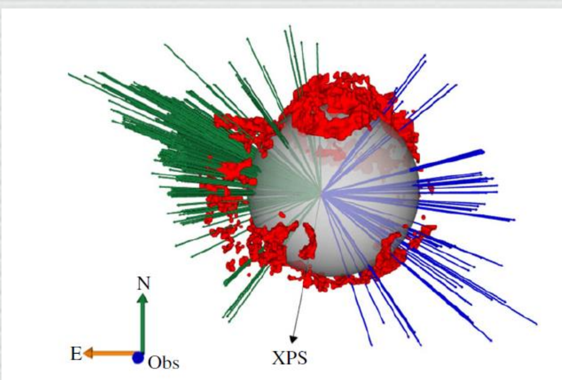
(Koo & Park 2017 in Handbook of SNe)

**main ejecta ring**

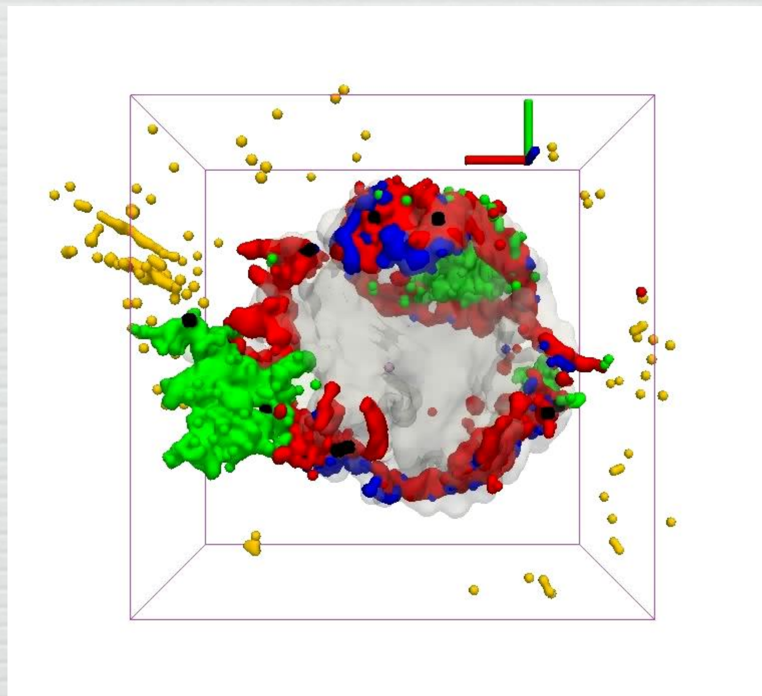
# 3-D structure of dense SN ejecta

- **Main ejecta shell:** Tilted thick torus + circular ring-like structures
- **Jet-counter-jet:** $\theta_{half}$~40°, E~1×10$^{50}$ ergs (≪ $E_{exp}$~3×10$^{51}$ ergs)

## Where is Fe?




Vector representation of Jets(G) and counter-jets (B). R=optical ejecta (Milisavljevic and Fesen 2013; Fesen 2016)



[Ar II]
High [Ne II]/[Ar II]
[Si II]

Si XIII (X-ray)
Fe-K (X-ray)

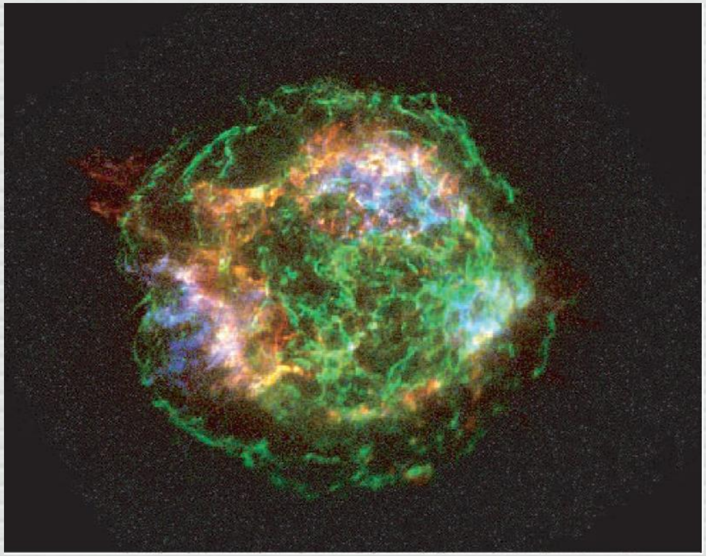
Outer optical knots

DeLaney+(2010)

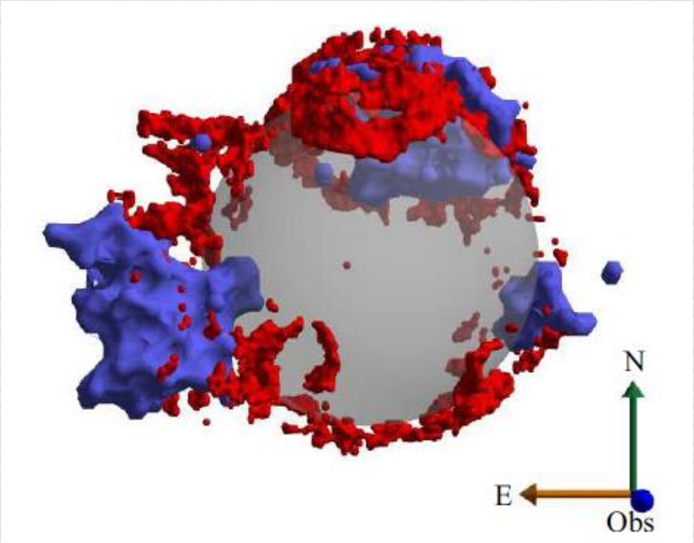
# Diffuse X-ray emitting Fe ejecta

- **Fe-rich ejecta detected by Chandra**
  - Three large concentrations, extend beyond the main ejecta ring and bounded by optically emitting ejecta
  - M(Fe)=0.09-0.13 $M_{\odot}$ (Hwang & Laming 2012)

**Is this all Fe ejecta?**



Chandra image; Red=Si, Blue=Fe, Green=continuum (Hwang et al. 2004; Hwang and Laming 2012)

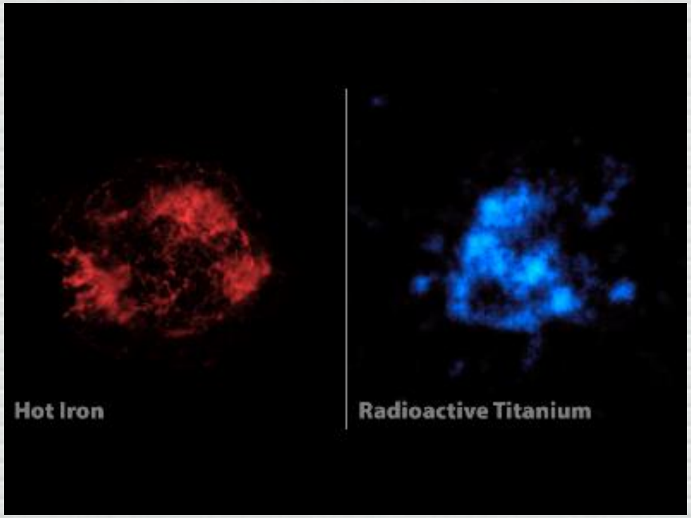


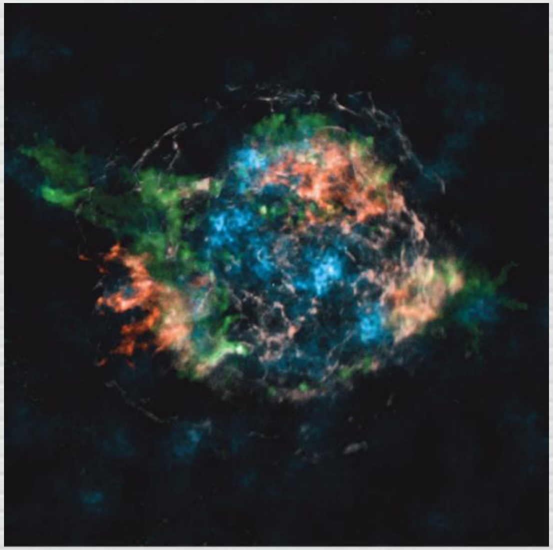

Blue = X-ray emitting Fe-rich ejecta, Red=O/S-rich optically emitting ejecta (Milisavljevic and Fesen 2013)

# $^{44}$Ti Ejecta

- **$^{44}$Ti = good tracer of $^{56}$Ni**
  - $^{44}$Ti → $^{44}$Sc → $^{44}$Ca (58.9 yr); 67.86, 78.36, 1,157 keV lines
- $^{44}$Ti distribution mapped by NuSTAR
  - Not much correlation with the X-ray emitting Fe ejecta; mostly unshocked SN ejecta in the interior?

What's the relation between the $^{44}$Ti ejecta and the Fe ejecta?

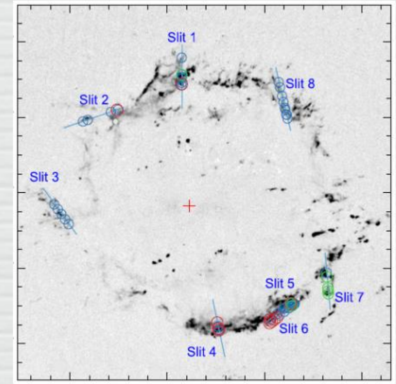


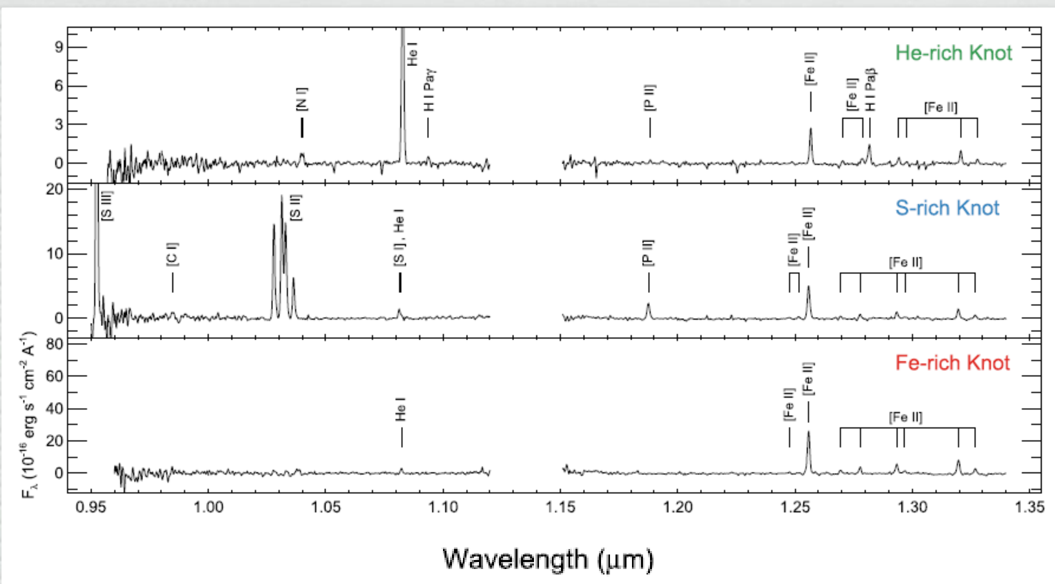
B=$^{44}$Ti, R=X-ray emitting Fe, G=X-ray emitting Si (Grefenstette+ 2014, 2017)

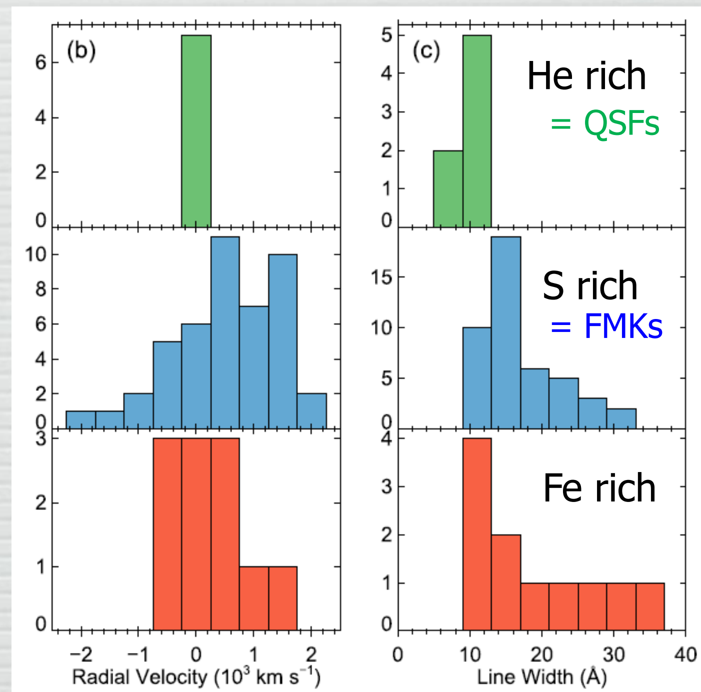
# NIR Spectroscopic Study of Cas A

- **Three types of `knots'**
  - **He-rich knots** = dense CSM (QSFs)
  - **S-rich knots** = dense O-burning SN ejecta (FMKs)
  - **Fe-rich knots** = dense `pure' Fe ejecta



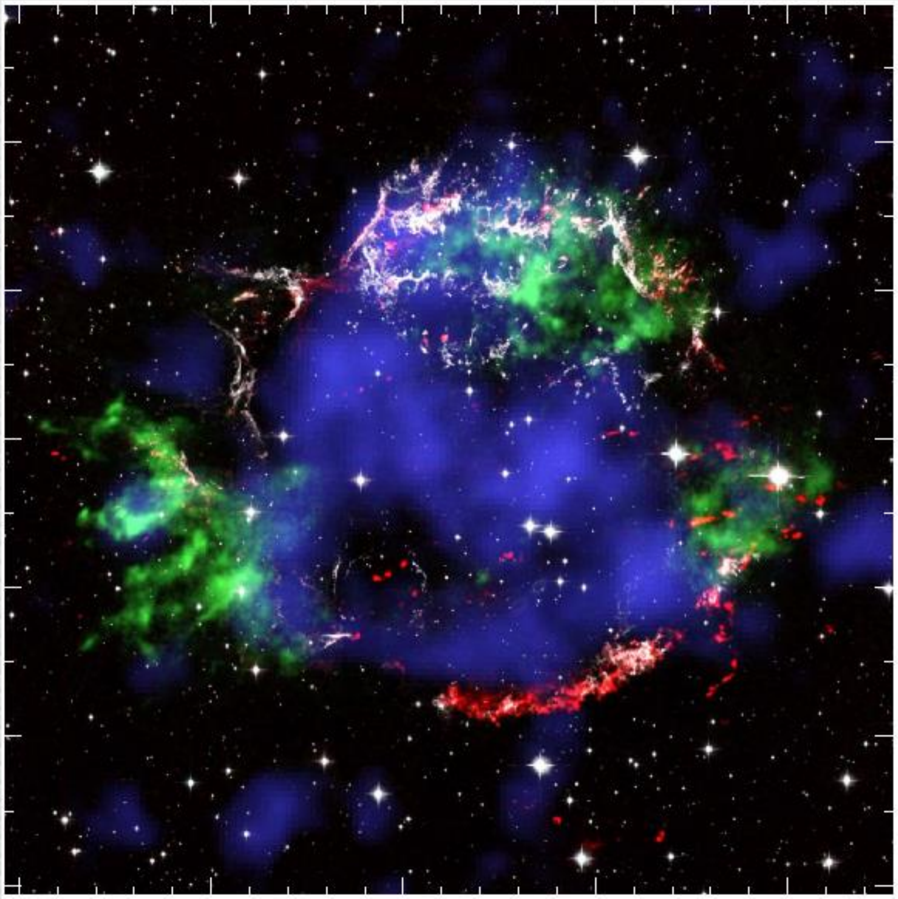

[Fe II] 1.644 μm image



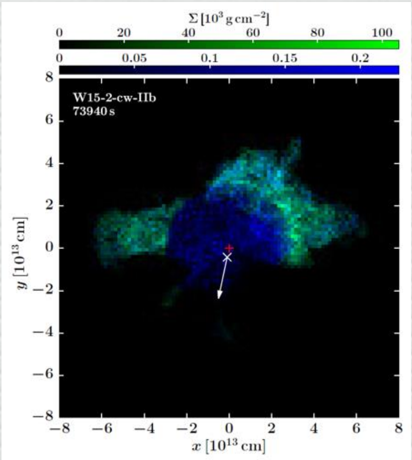

Koo et al. (2013), Lee, Y.-H. et al. (2017)

# Dense Fe Ejecta and $^{44}$Ti



R = [Fe II] 1.644 μm, G = Chandra Fe K-shell,
B = NuSTAR hard X-ray $^{44}$Ti,
W = HST ACS/WFC F850LP ([S III], [S II])

- **[Fe II]-rich ejecta**: mainly in the SW shell where diffuse X-ray Fe ejecta is missing
  → Dense Fe ejecta associated with $^{44}$Ti?




Neutrino-driven explosion model; B = $^{44}$Ti,
G=$^{56}$Ni (Wongwathanarat et al. 2016)

# Summary

- Cas A is the youngest (~340 yr) CCSN remnant of confirmed SN type (SN IIb) in the Milky Way, and as such it provides a unique opportunity to see the fine details of the SN explosion.
- In debt to recent thorough observational studies, we now have a good understanding of the 3-dimensional structure of SN ejecta. The various anisotropic structures of SN ejecta indicate that the explosion was highly asymmetric and turbulent.
- A new form of Fe-rich ejecta has been discovered in NIR band, and its distribution seems to match the existing X-ray-emitting Fe and $^{44}Ti$ observations. Further studies are needed to understand the relation among these different forms of Fe ejecta, and its implication for the SN explosion.