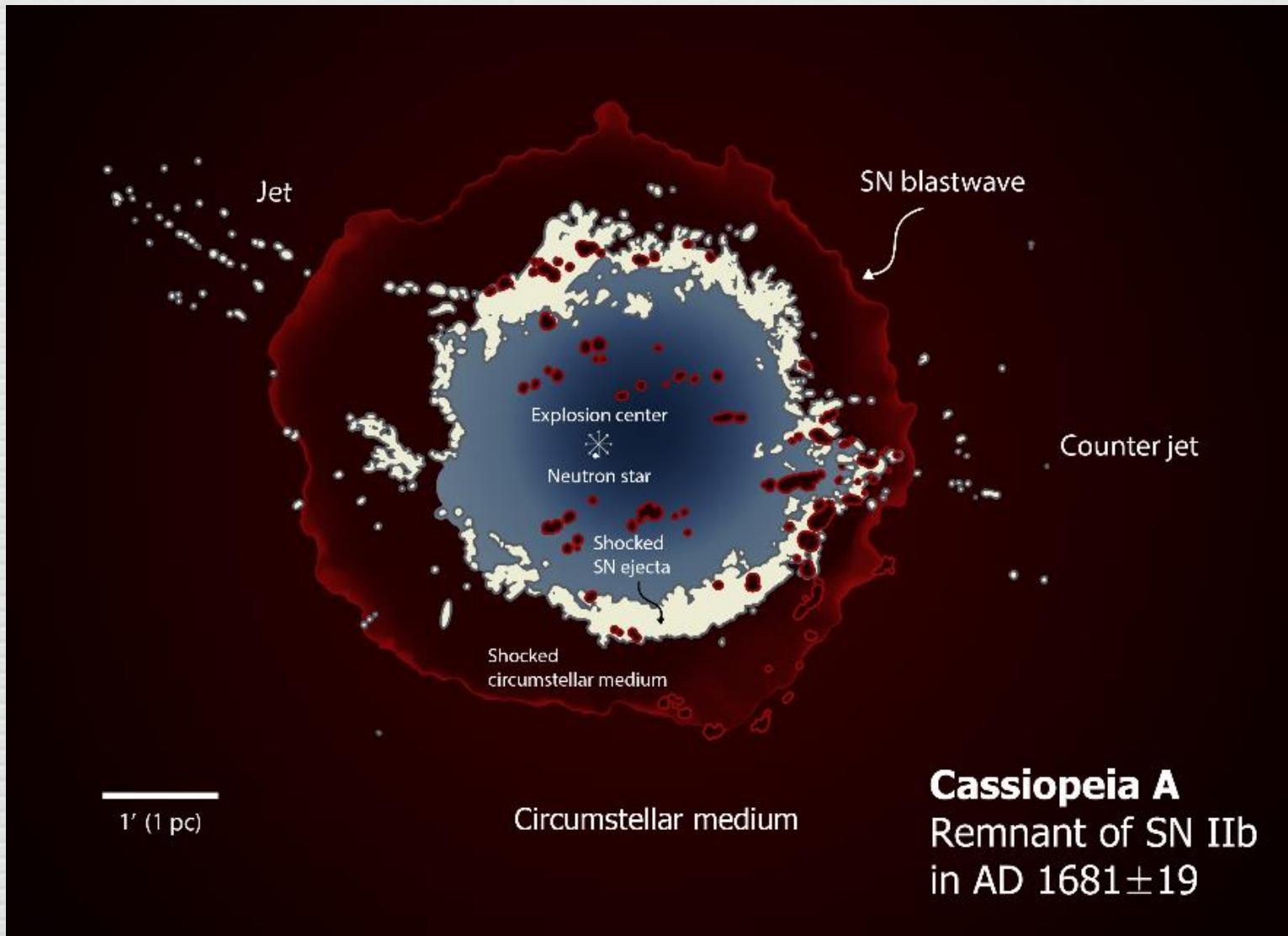


2019. 6. 7. SNR2019

Dense Circumstellar Knots in Cassiopeia A

Bon-Chul Koo

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Raymond (CfA), Hee-Young Oh (KASI), Jae-Joon Lee (KASI),
Sung-Chul Yoon (SNU), Dae-Sik Moon (Univ. of Toronto)**



<http://astro.snu.ac.kr/~koo/casa.html>

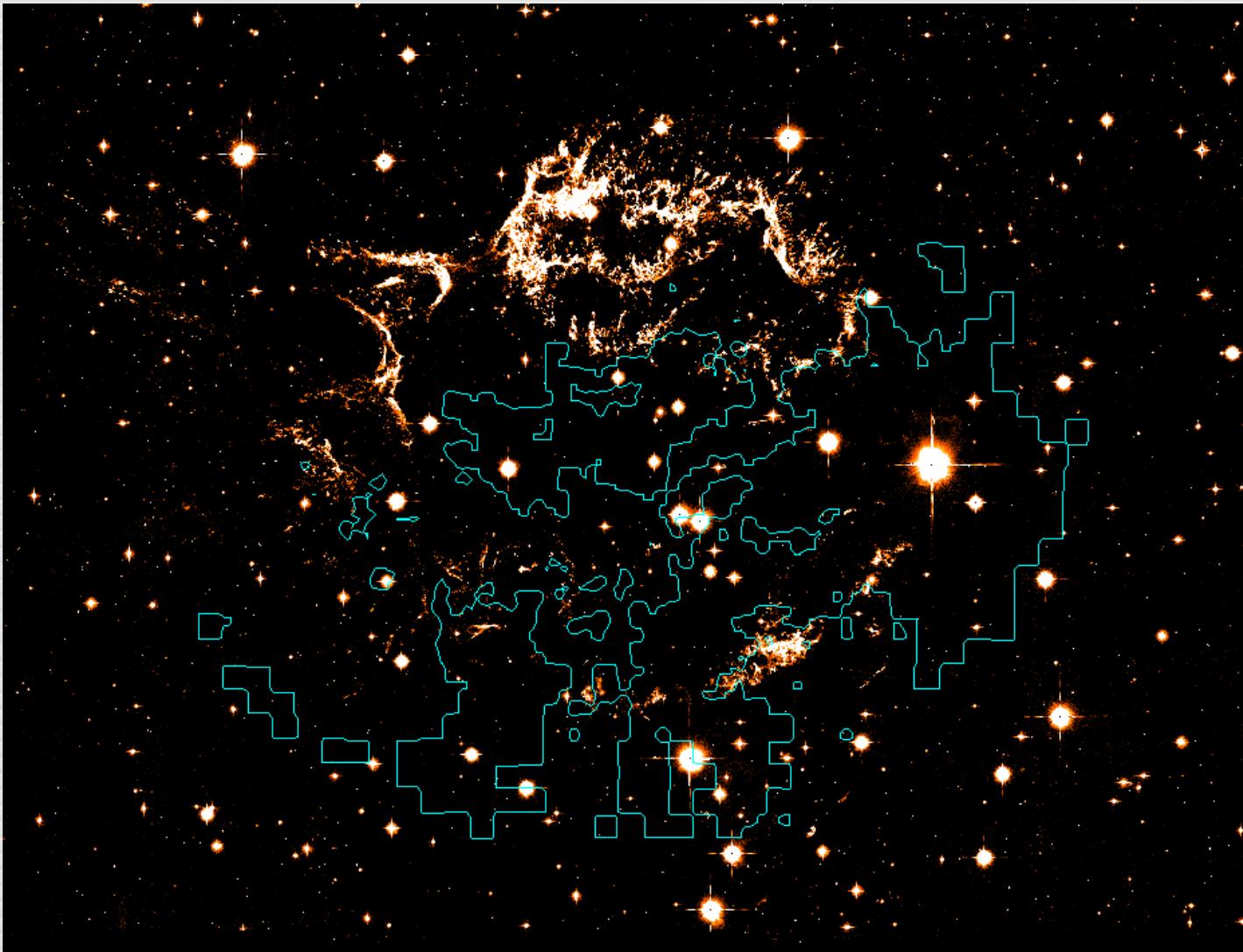
Outline of Talk

I. Deep [Fe II]+[Si I] 1.64 μ m Image

- Background
- UWIFE survey

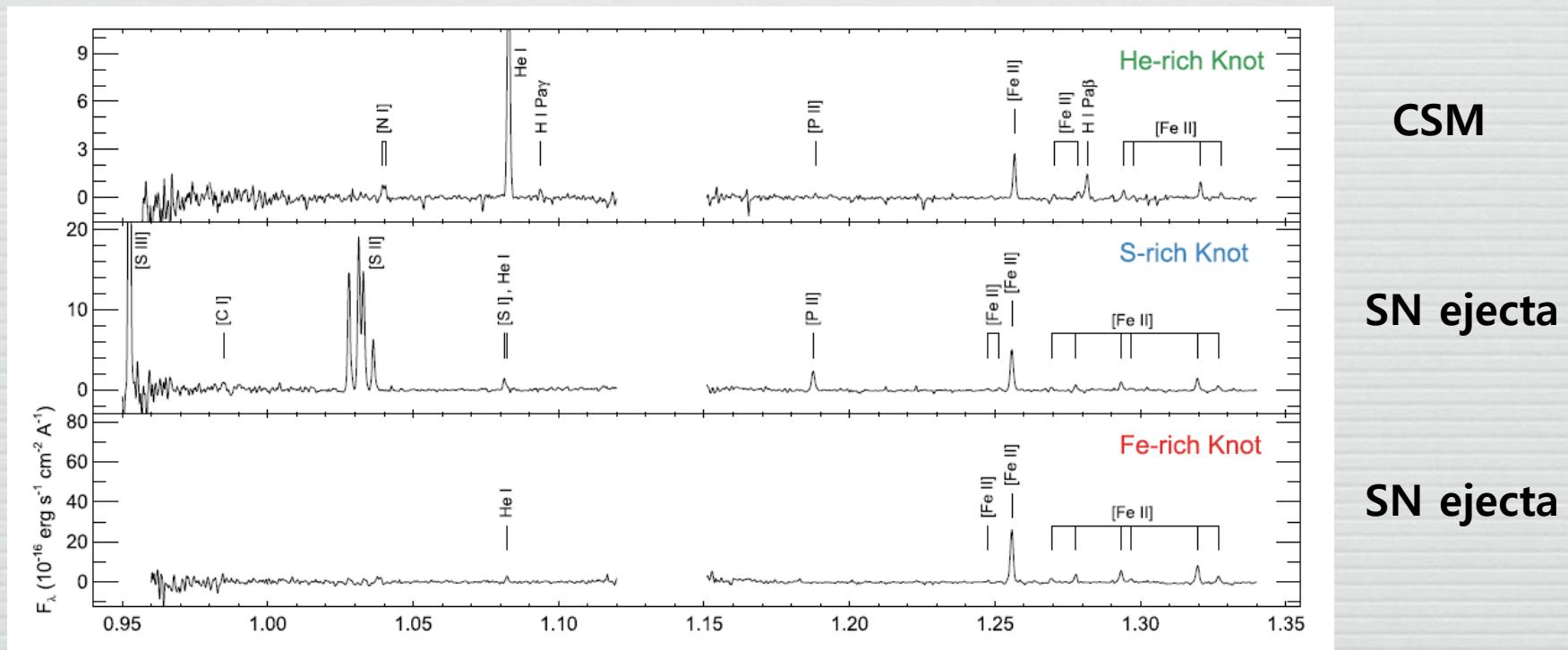
II. Dense Circumstellar Knots

- QSFs in the deep 1.64 μ m image
- High-resolution spectroscopic results



**HST ACS F625W image of Cas A with $A_V \sim 10$ mag
contour from X-ray study (Hwang and Laming 2012)**

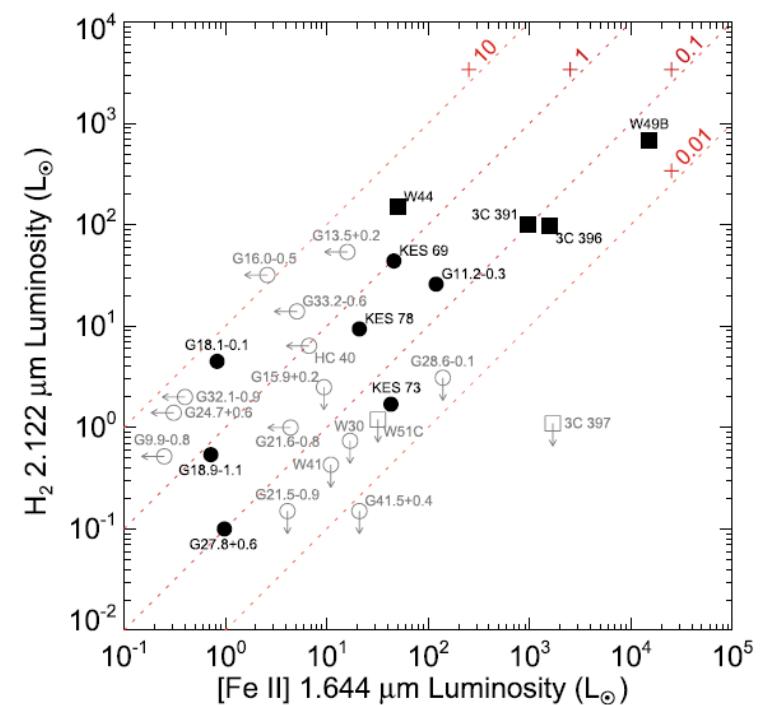
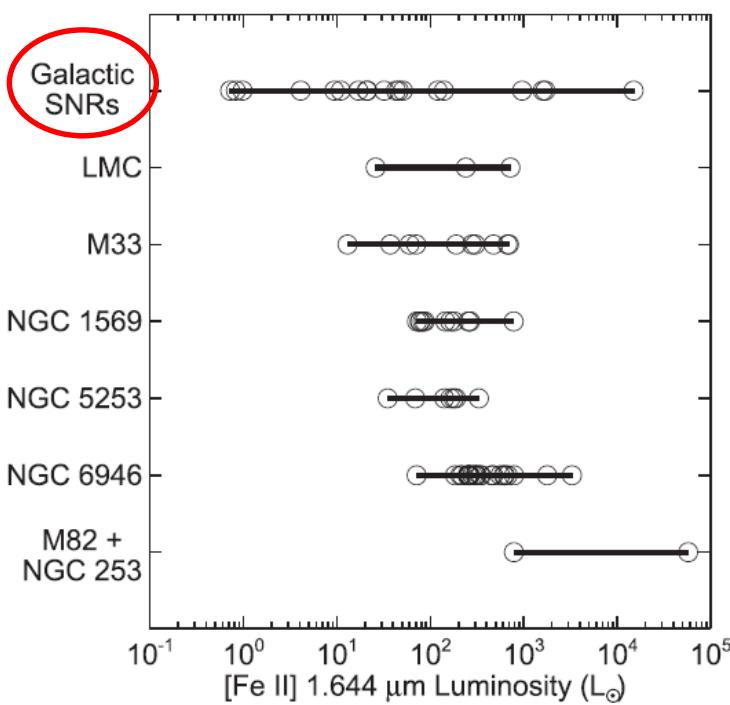
- Obtain an ‘extinction-free’ image of shocked dense gas in Cas A
- [Fe II] 1.64 μm line = shock tracer
 - [Fe II] 1.64 μm filter at UKIRT 3.8 m telescope



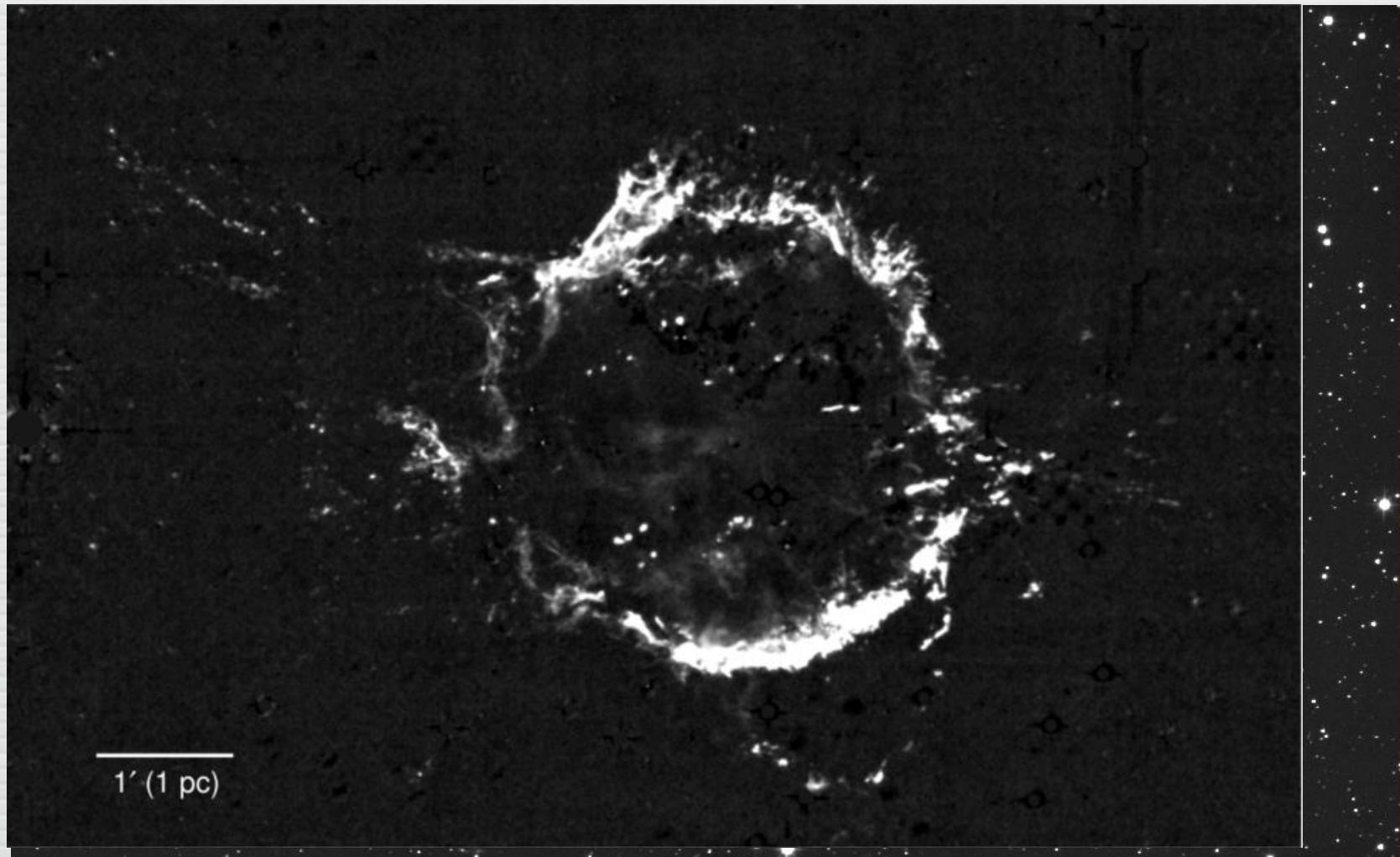
Sample 1-D spectra of Cas A knots (Lee, Y.-H.+ 2017)

UWIFE Survey

- **UKIRT Widefield Infrared survey for Fe⁺** (Lee, J.-J.+ 2014)
 - $\ell = 7^\circ$ to 62° , $|b| \leq 1.5^\circ$
- **Cas A: $L([Fe\ II]) = 12\ L_\odot$**



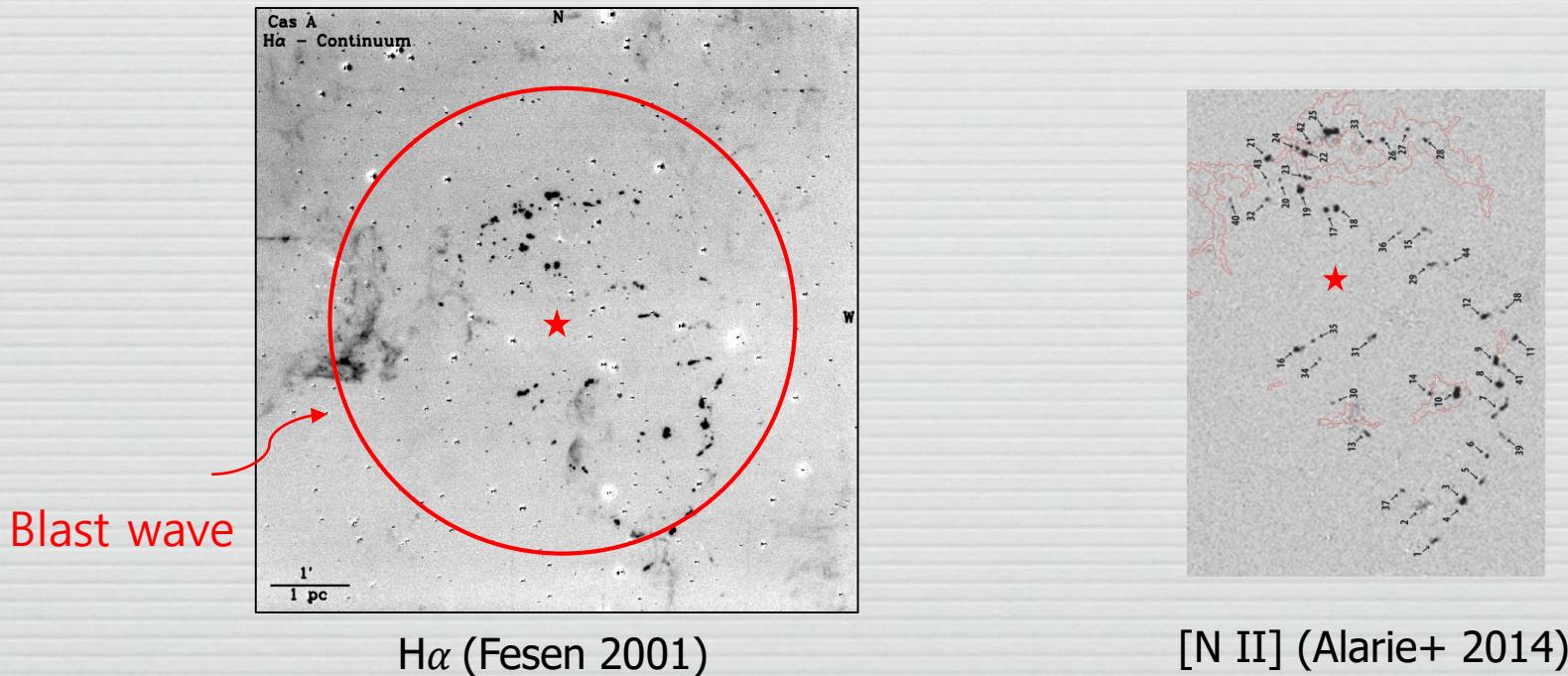
[Fe II] 1.64 μm luminosity of **19(79) Galactic SNRs** in $\ell = 7^\circ$ to 62°
 (Lee, Y.-H.+ 2019)



Deep [Fe II]+ [Si I] 1.64 μm image obtained by 10-hr exposure using UKIRT 3.8 m telescope in 2013 September (seeing $\sim 0.7''$ or 0.012 pc; Koo et al. 2018)
($\Delta v_{\text{FWHM}} \sim \pm 2600 \text{ km/s}$)

Dense CSM of Cas A

- Two types of “Knots” (Minkowski 1959)
 - Fast-moving ejecta knots
 - QSFs (Quasi-Stationary Floculli): CNO processed CSM
 - $|v| \leq 500 \text{ km/s}$, He and N-enriched
 - vdB (1971), Peimbert and vdB (1971), Chevalier and Kirshner (1978), vdB and Kemper (1985), Lawrence+ (1995), Hurford & Fesen (1996), Gerardy & Fesen (2001), Alarie+ (2014), Lee, Y.-H.+ (2017)



- **Origin of QSFs**

- (1) Fragments of RSG shell swept up by fast wind**

- Chevalier and Liang (1989), Reed (1995), Garcia-segura+ (1996)

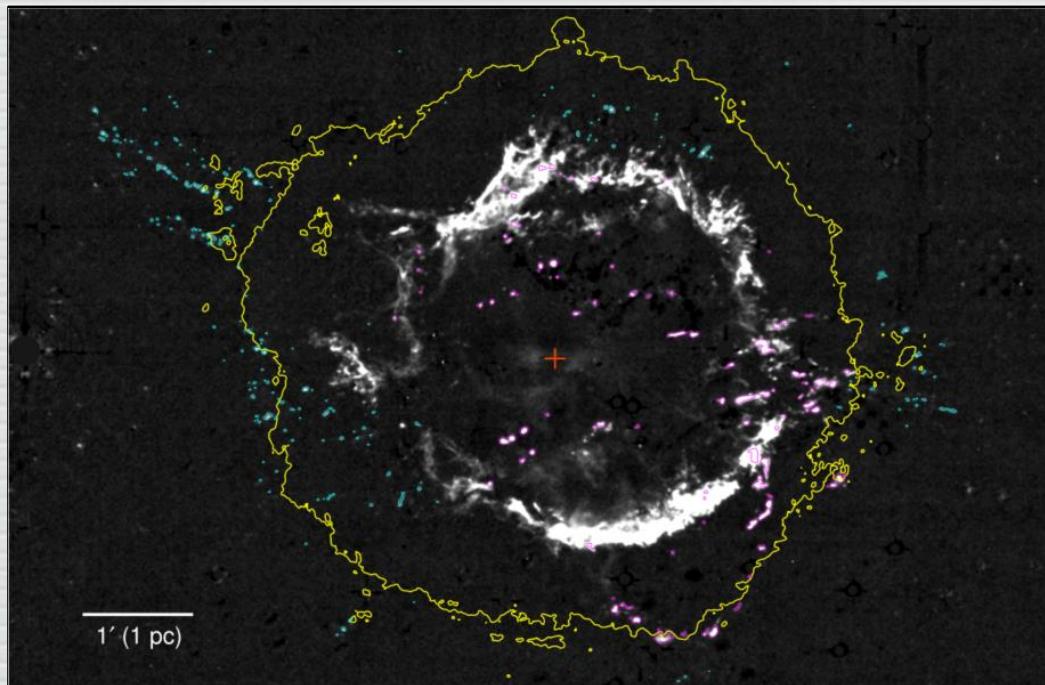
- (2) Dense clumps embedded in RSG wind**

- Chevalier and Oishi (2003), Laming & Hwang (2003), Lee, J.-J. (2014); Schure et al. (2008), van Veelen et al. (2009), Hwang and Laming (2009)
 - QSFs are not restricted to a shell
 - Expansion velocity is small for them to be (1)
 - Cas A is interacting with smooth RSG wind

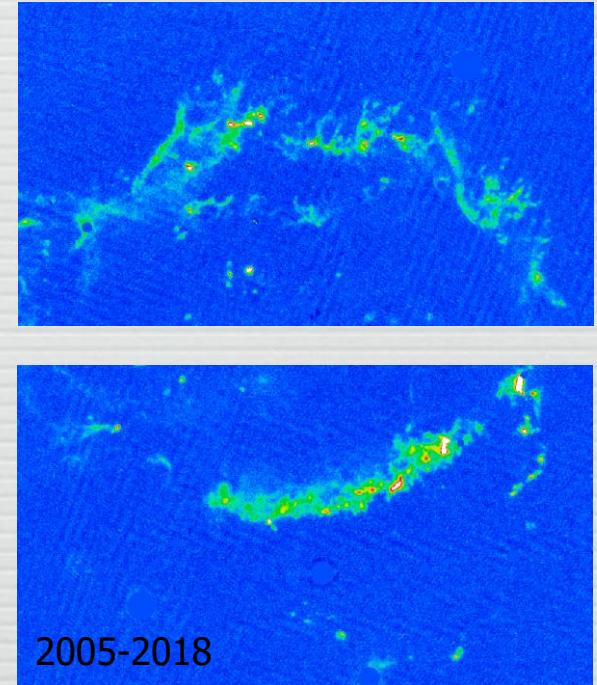
- **N overabundance?**

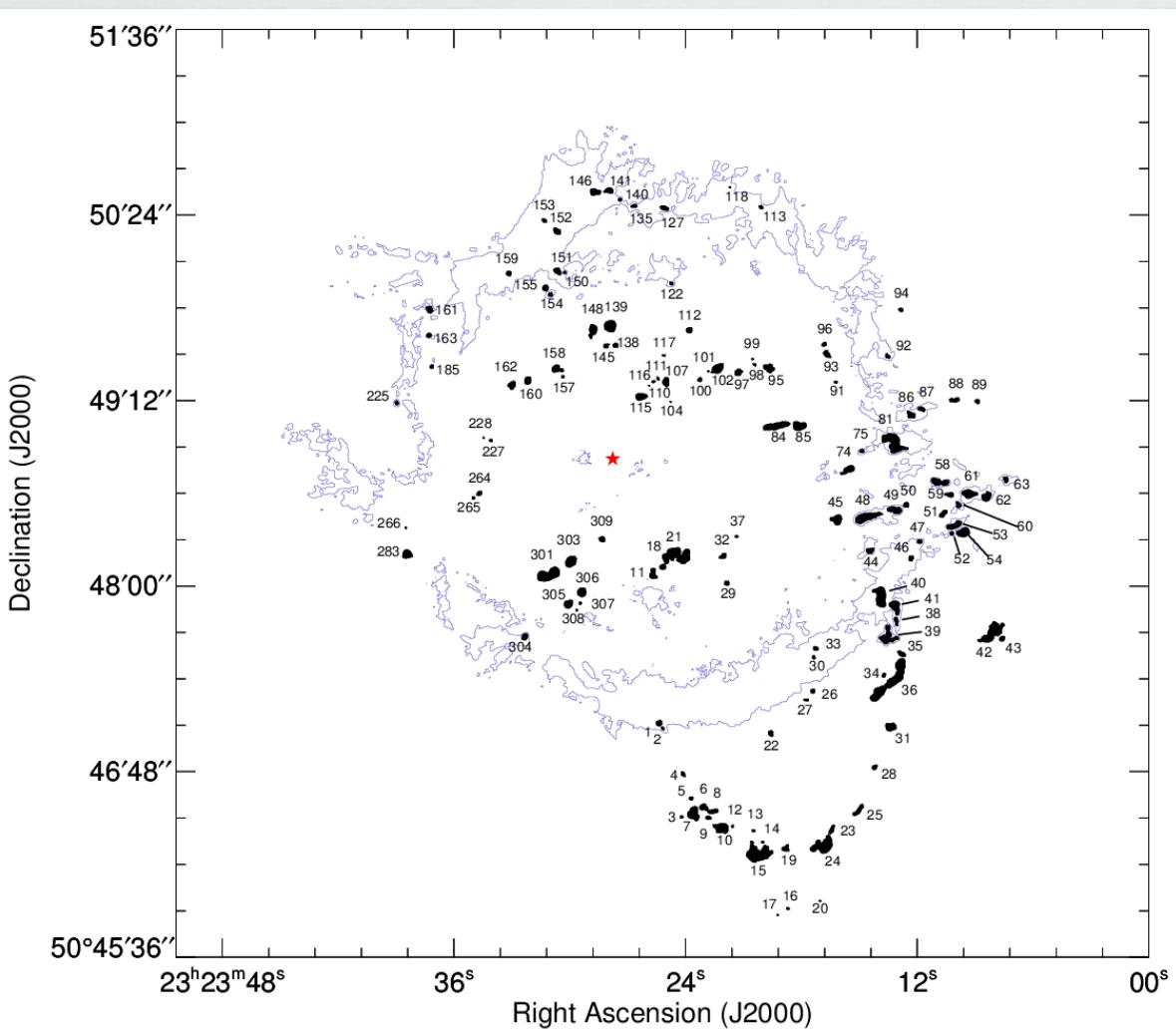
QSFs in the Deep [Fe II] Image

- **Identification of 309 Knots (=130 QSFs + 179 FMKs)**
 - 5σ above background
 - proper motion in 2008 and 2013 [Fe II] images
 - Counterparts in HST F098M and HST F850LP images
 - (cf) **~40 QSFs in $\text{H}\alpha + [\text{NII}]$** (vdB and Kemper 1985; Alarie 2014)

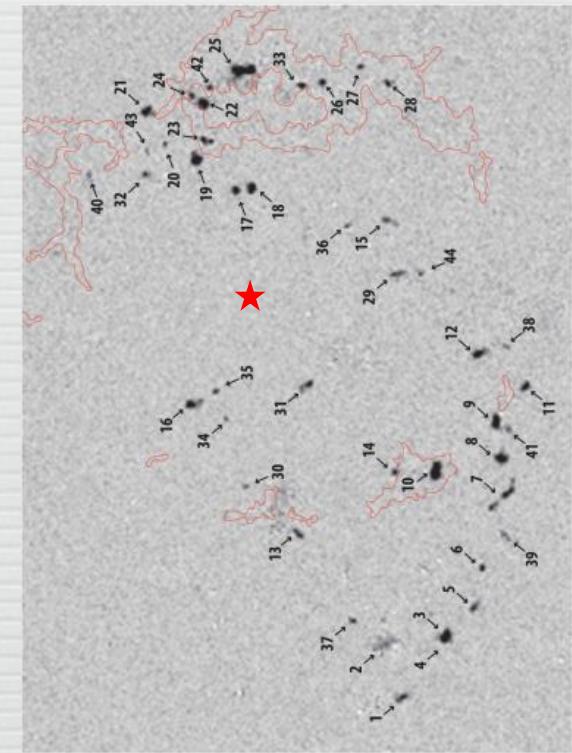


G= FMKs, Magenta contour = QSFs





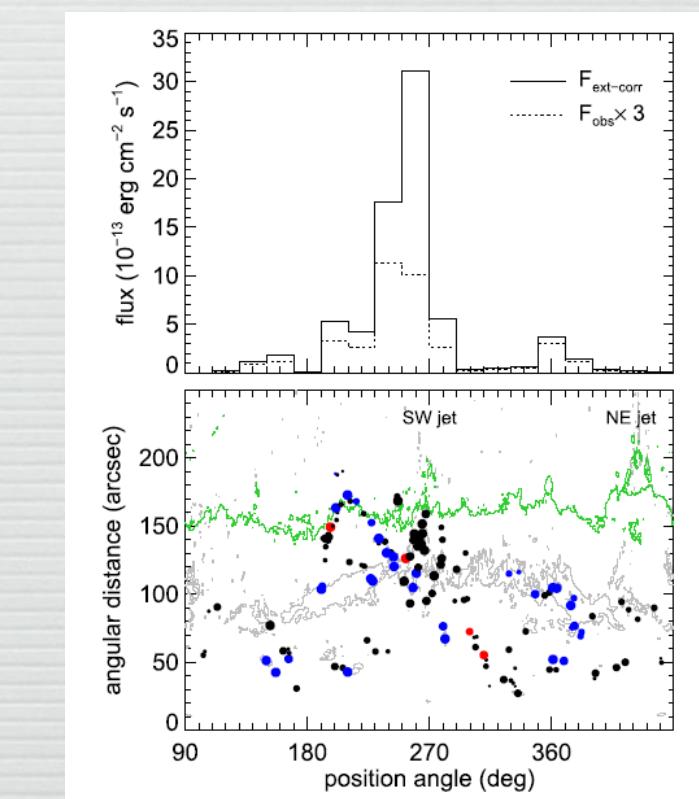
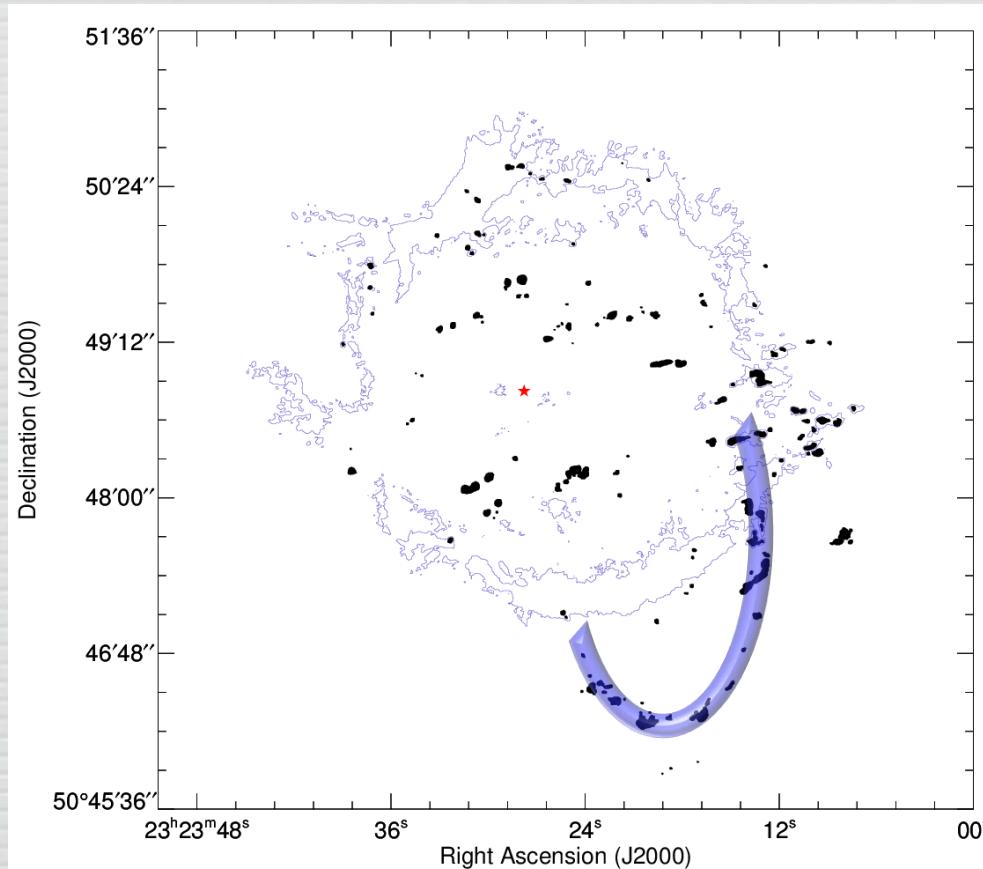
2013 [Fe II] (Koo+ 2018)



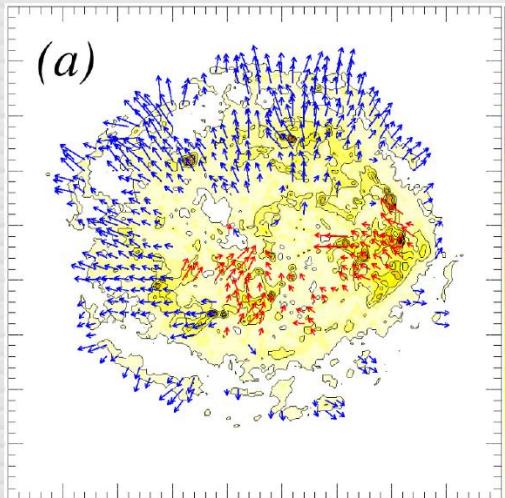
**2011 [N II]
(Alarie+ 2014)**

QSF Spatial distribution

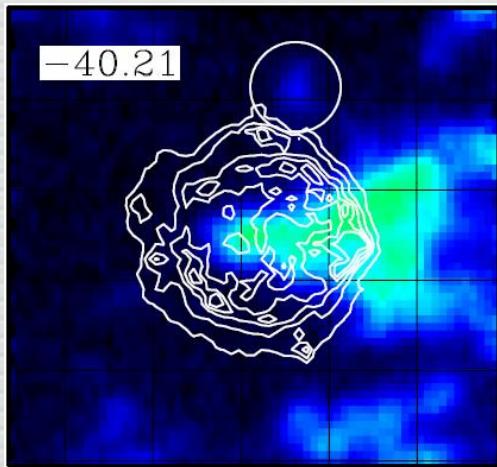
- Highly asymmetric with prominent features
 - 60% in P.A.=240° – 280°
 - Southwestern QSF arc (Lawrence+ 1995)



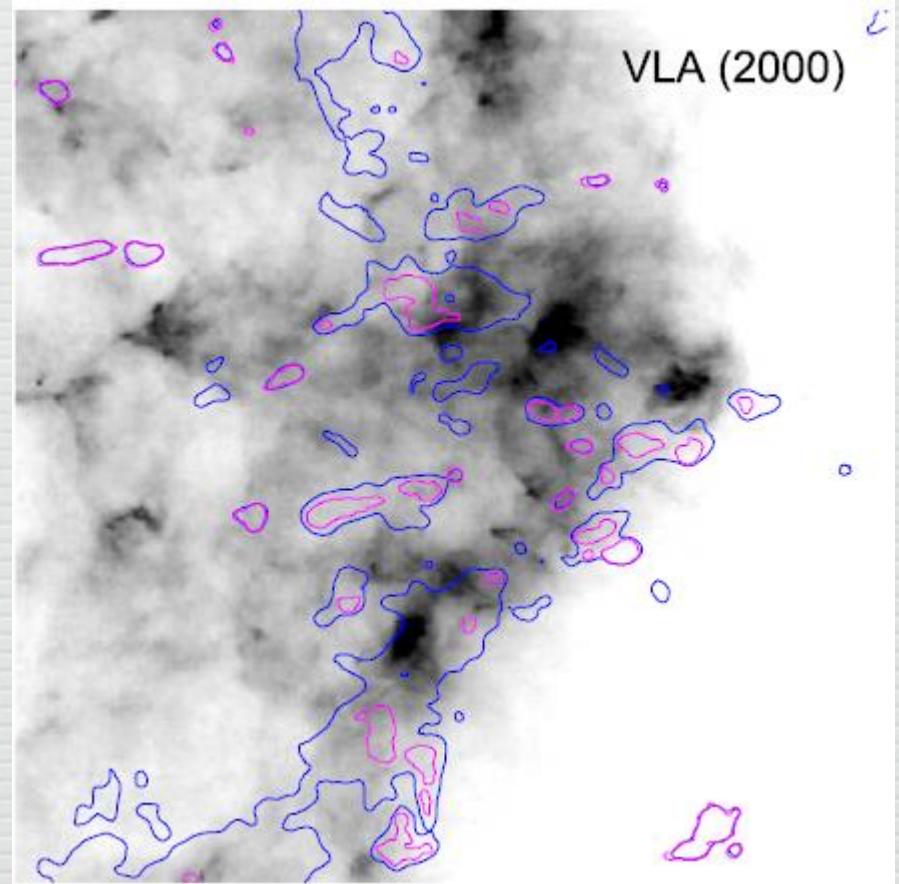
Western area



Shock proper motion (Sato 2018)



CO (Kilpatrick+ 2014; see also the poster by Ping Zhou)



Blue = [Fe II] intensity, Magenta = QSFs

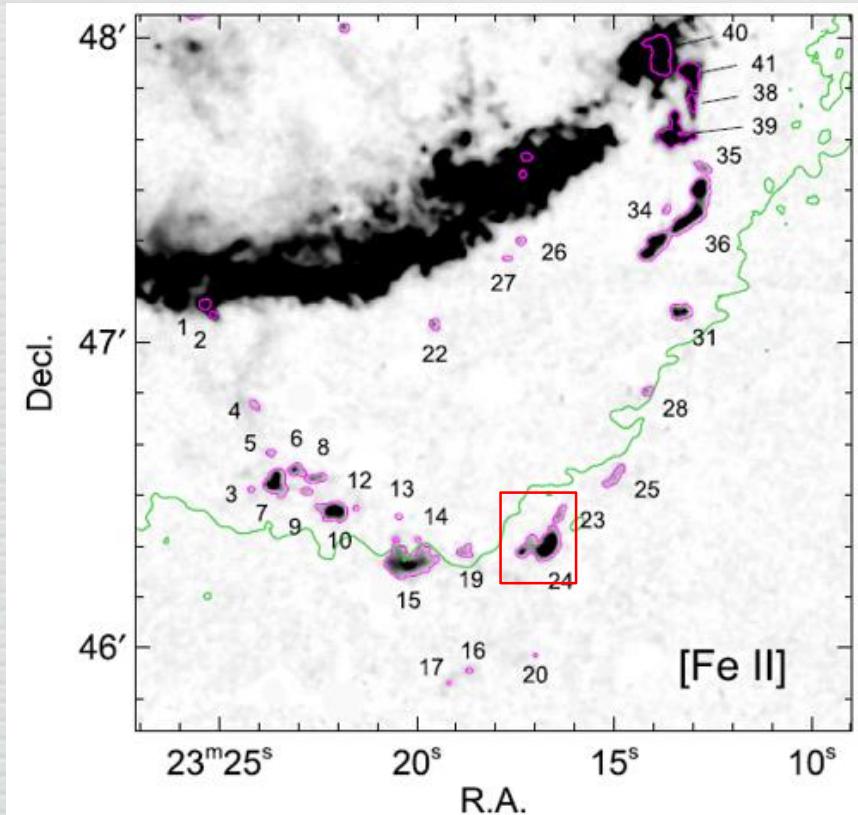
QSF Mass and Lifetime

- **Total Mass**
 - $M(\text{Fe}) \sim 7.9 \times 10^{-6} M_{\odot}$ → $M_{\text{QSF}}(\text{H+He}) \sim 0.23 M_{\odot} \sim 4\% \text{ of } M_{\text{SW}}$
(cf) $M_{\text{SW}} \sim 6 M_{\odot}$ (Lee, J.-J.+ 2014)
 - **Lifetime**
 - Most QSFs in 1951 are seen in our 2013 image → $\tau \geq 60 \text{ yr}$
-
- **Lab for cloud-shock interaction**
 - **Mass-loss history of Cas A**

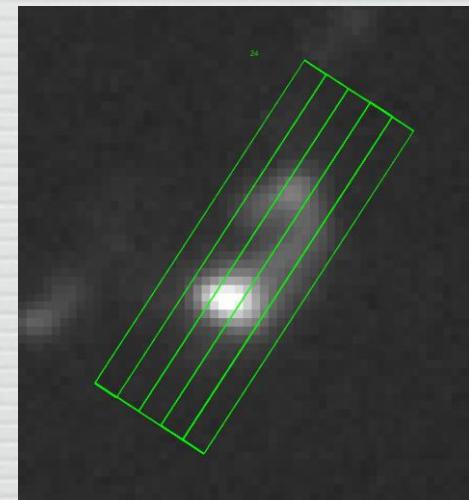
High-resolution Spectroscopy of QSFs

- **IGRINS Observations of Knot 24**

- **IGRINS**: High-resolution($R \sim 45000$) H&K spectrometer
- Harlan J. Smith telescope at McDonald Obs. + **DCT at Lowell Obs.**



QSF Knot 24



since 1951

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Page

Summary

- A deep [Fe II]+[Si I] 1.64 um image
 - shocked SN ejecta + shocked CSM in [Fe II] emission
 - unshocked SN ejecta in [Si I] emission
- 130 QSF knots
 - highly anisotropic spatial distribution
 - dense, clumpy CSM in west
 - $M(\text{QSFs})=0.23 M_{\odot} \sim 4\% \text{ of the RSG wind}$
- NIR spectroscopic observations of QSFs.
 - radiative precursor in QSF 24
 - Cas A progenitor $v_{\text{LSR}} \sim -50 \text{ km/s}$
 - Fe is not heavily depleted
 - BSG progenitor