Harvard-Smithsonian
Center for Astrophysics

Explosion and Circumstellar Asymmetries Revealed in the Cas A Supernova Remnant

Dan Patnaude (SAO)

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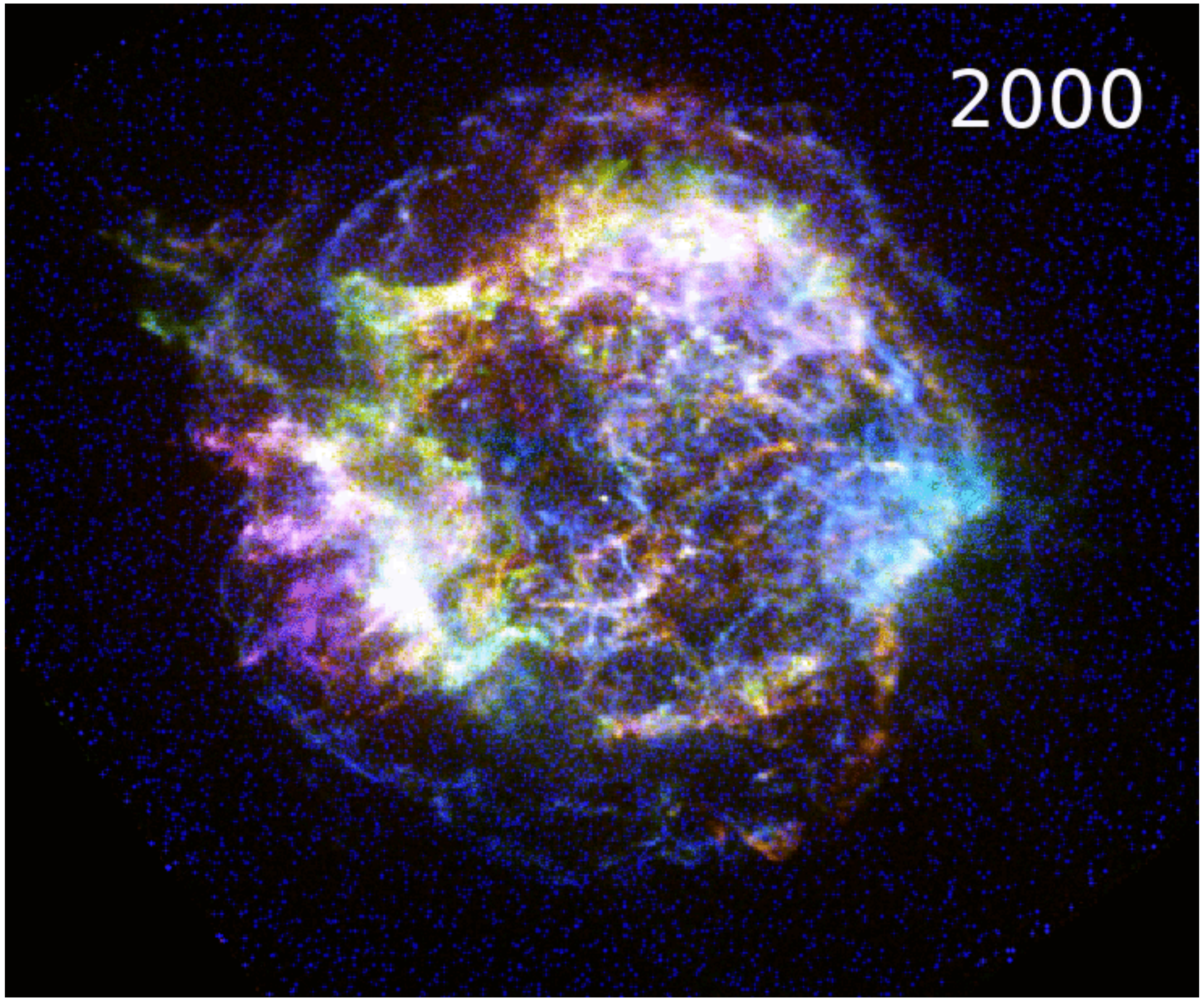
A Monitoring Program of Cas A

Only nearby SNR to show yearly variations in thermal and nonthermal emission, and also evidence for a young and evolving neutron star



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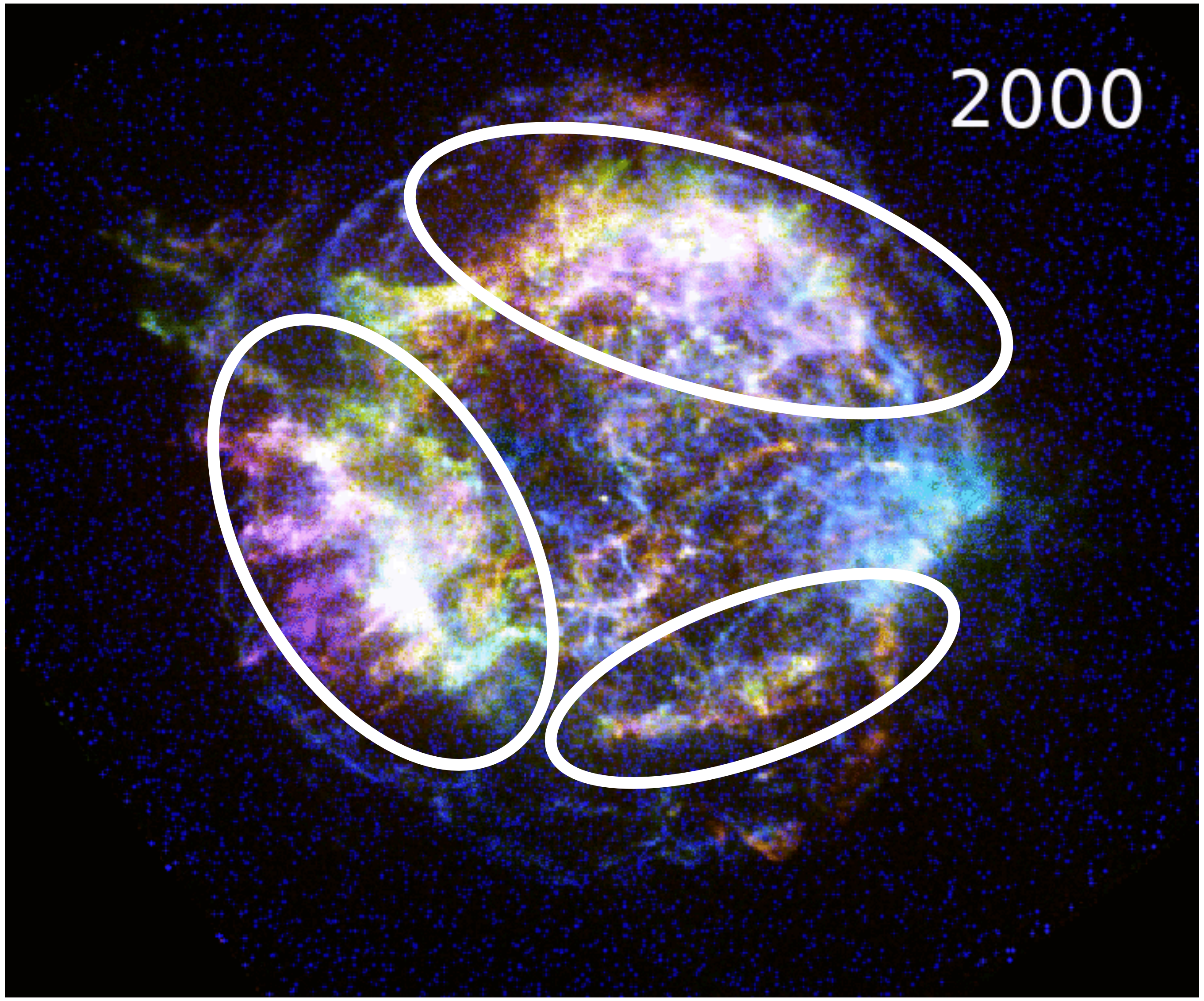
- changes in neutron star emission test models for solid state astrophysics



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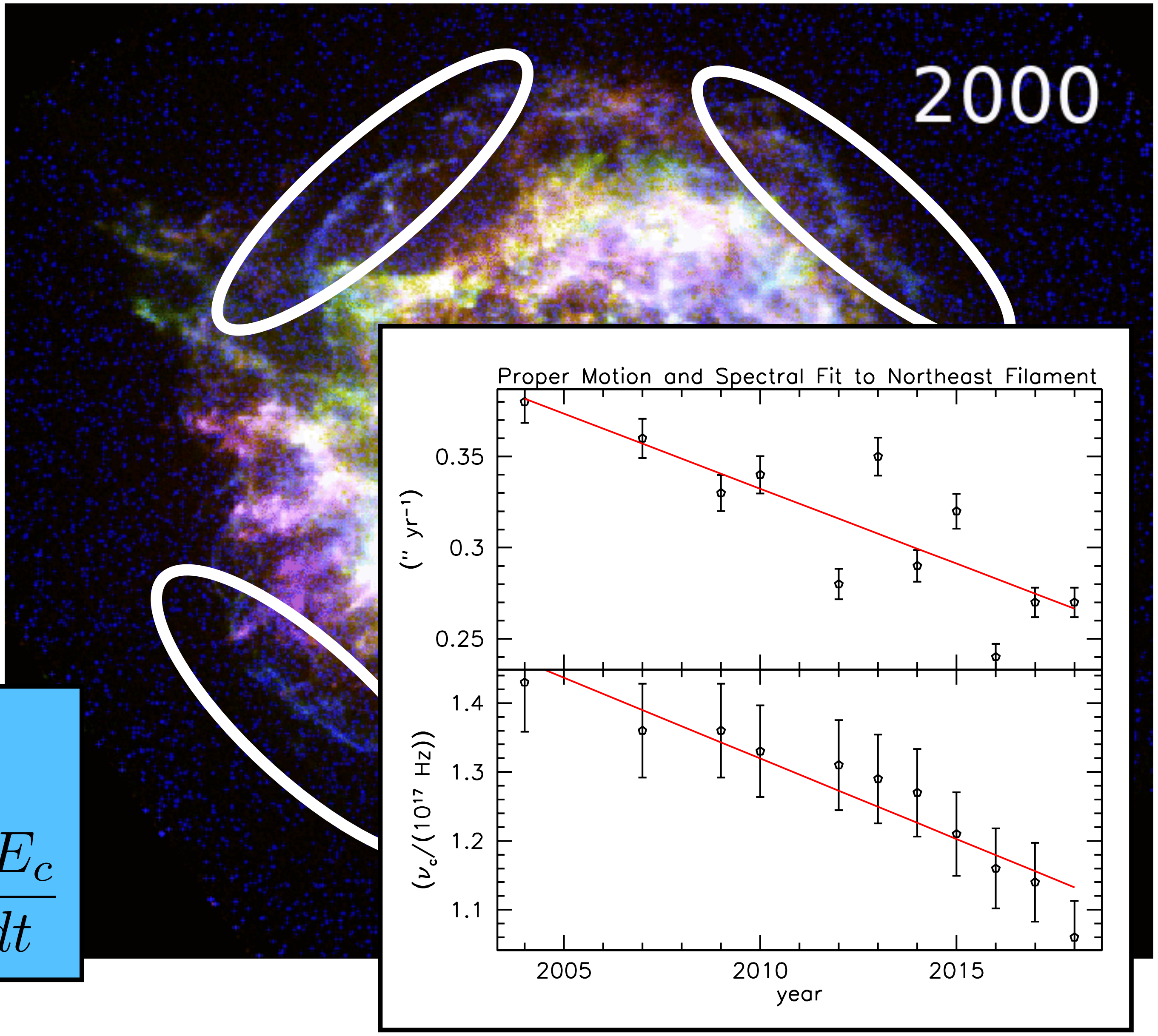
$$\frac{dV_s}{dt} \lesssim -100\,\mathrm{km\ s^{-1}\ yr^{-1}}$$

$$\frac{dV_s}{dt} = 3.5 \times 10^6 \left(\frac{V_s}{\mathrm{km\,s^{-1}}}\right)^{-1} \eta \frac{dE_c}{dt}$$



Castro et al. in prep.

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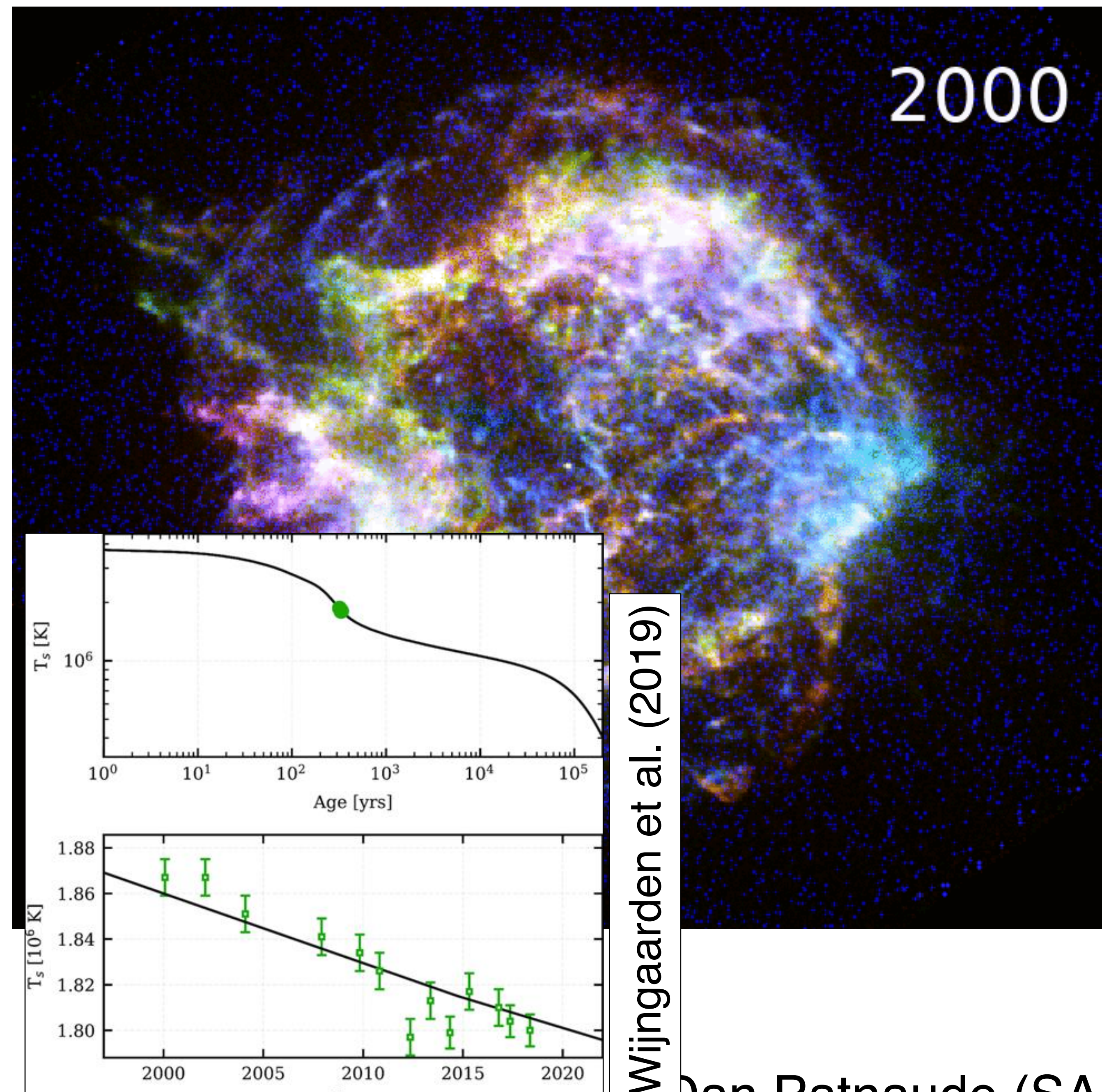

Wijngaarden et al. (2019)

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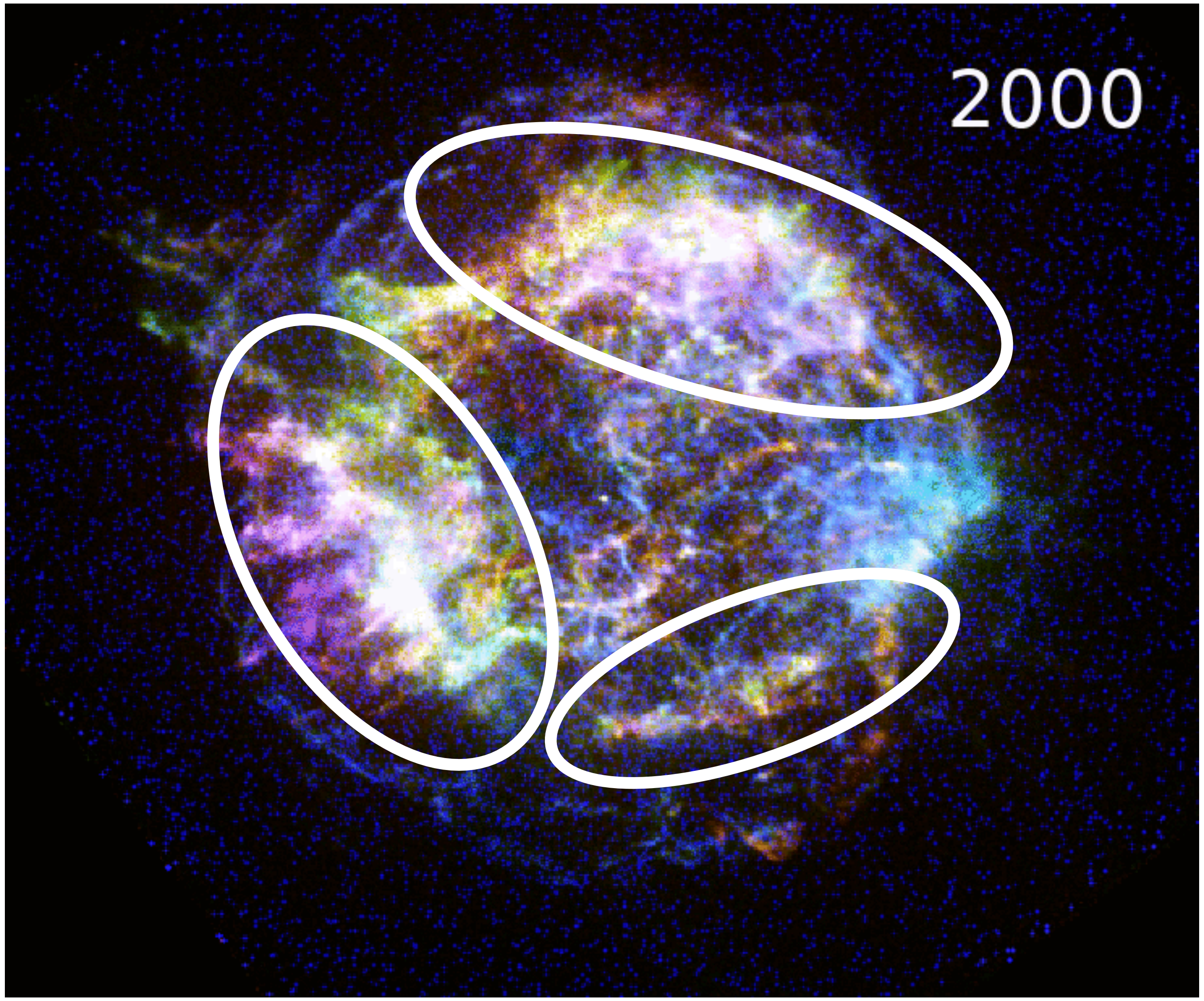
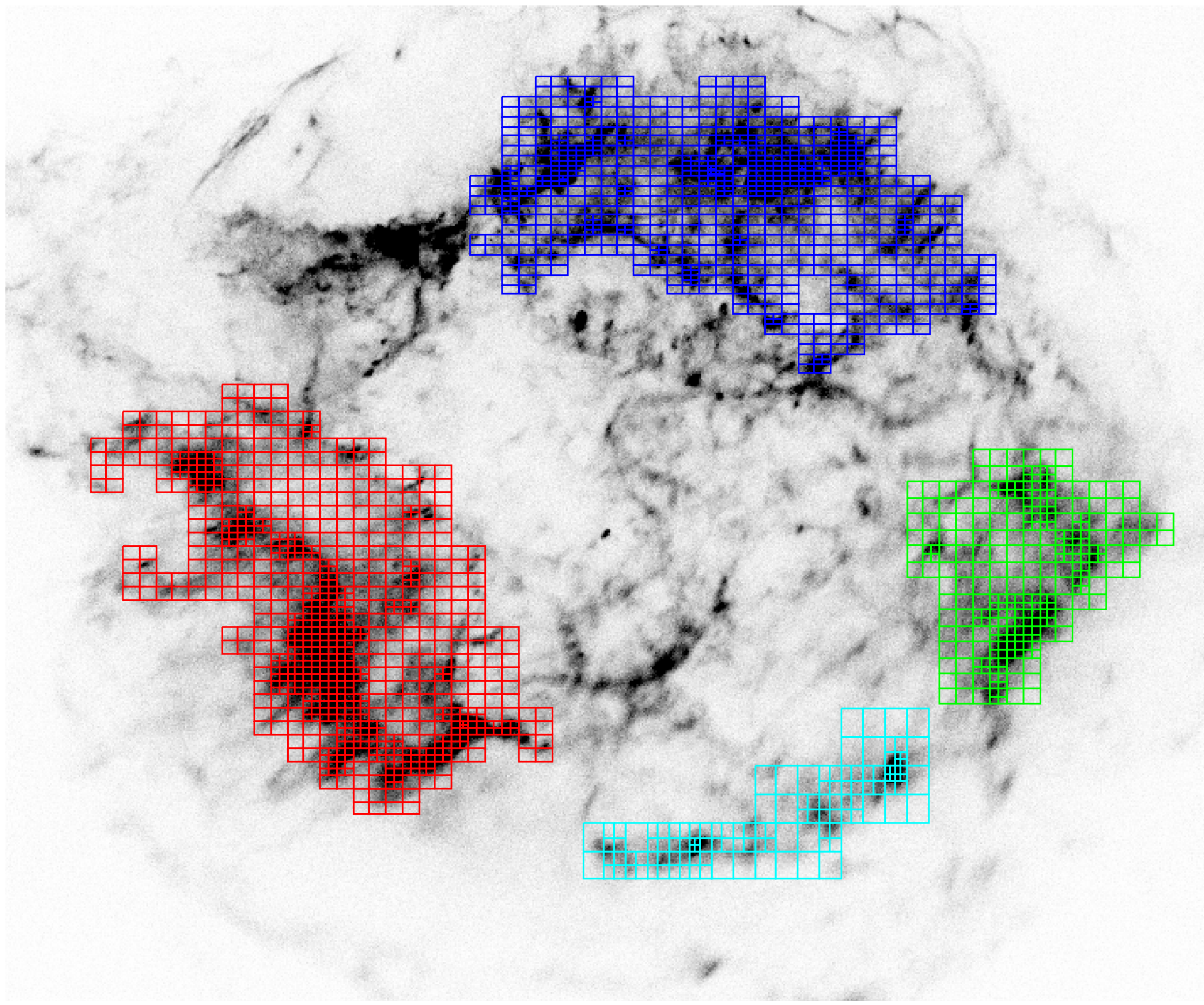


For each epoch from 2000 - 2018:

- pixels are selected using a Weighted Voroni Tesselation with S/N > 80 (> 1000 counts/region)
- due to the bulk expansion of Cas A, the region locations and number of regions are epoch dependent
- spectral parameters in any region are a convolution of the emission from that region and contributions from adjacent pixels
- use WVT mask to inform fitting parameters



Broadband X-ray image of Cas A with WVT selected regions overlaid

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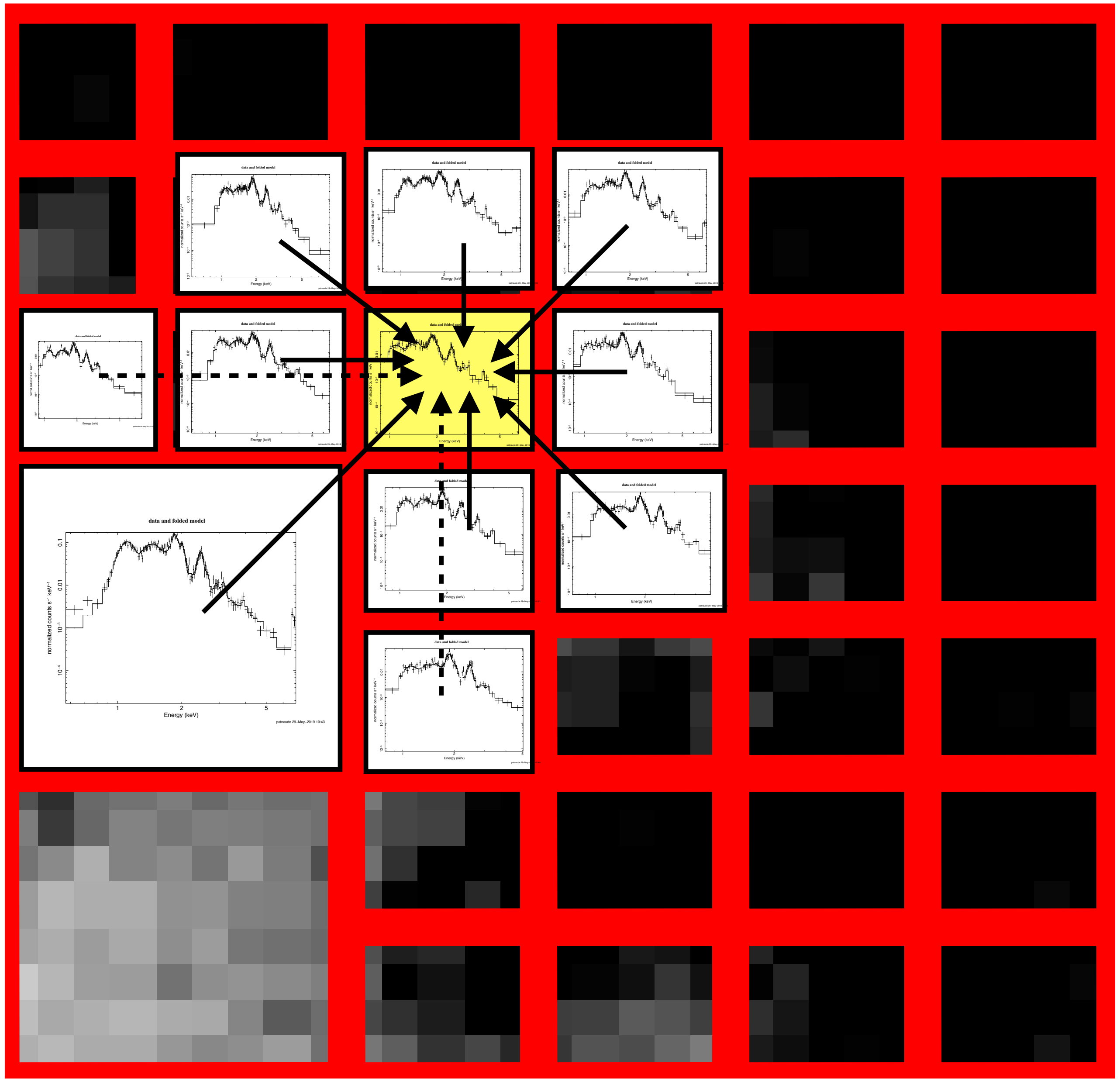
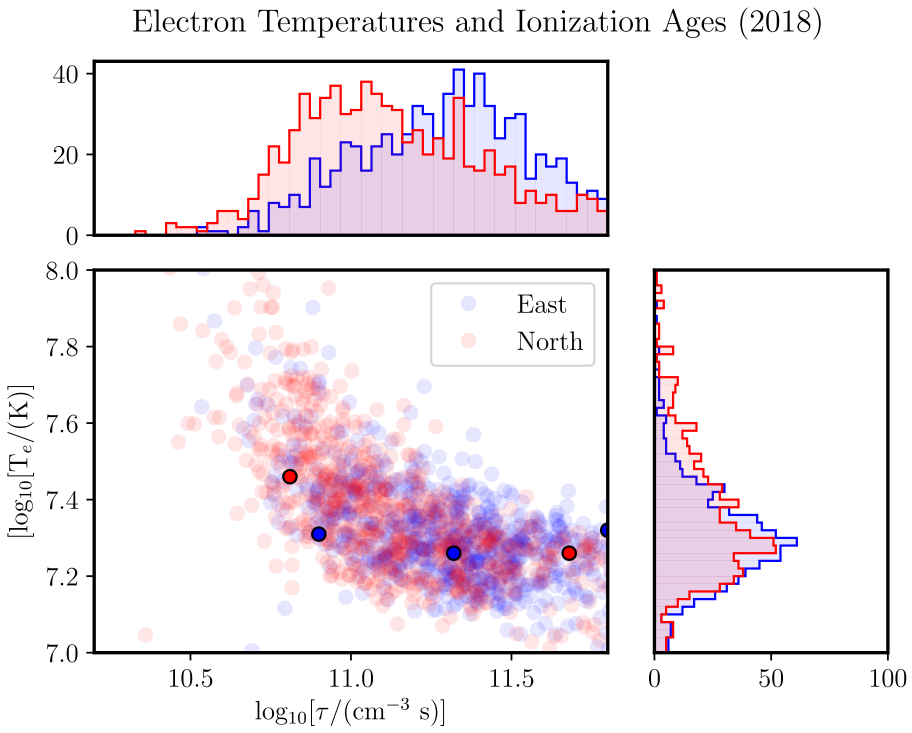
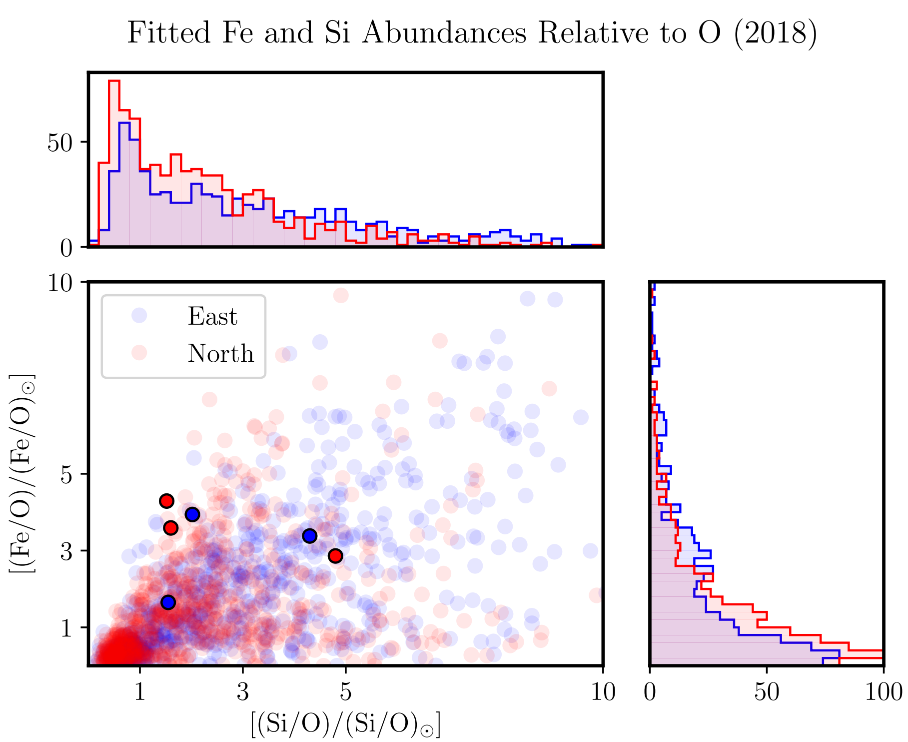
$$p_i = \frac{\sum_{i \neq j} \left(p_j w_{ij} \sigma_j^{-2} \right)}{\sum_{i \neq j} \left(w_{ij} \sigma_j^{-2} \right)}$$

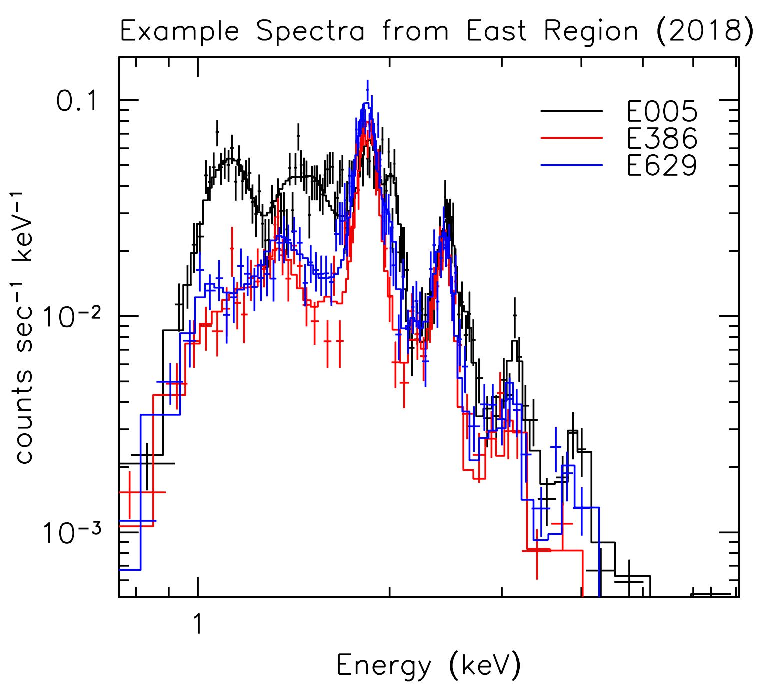


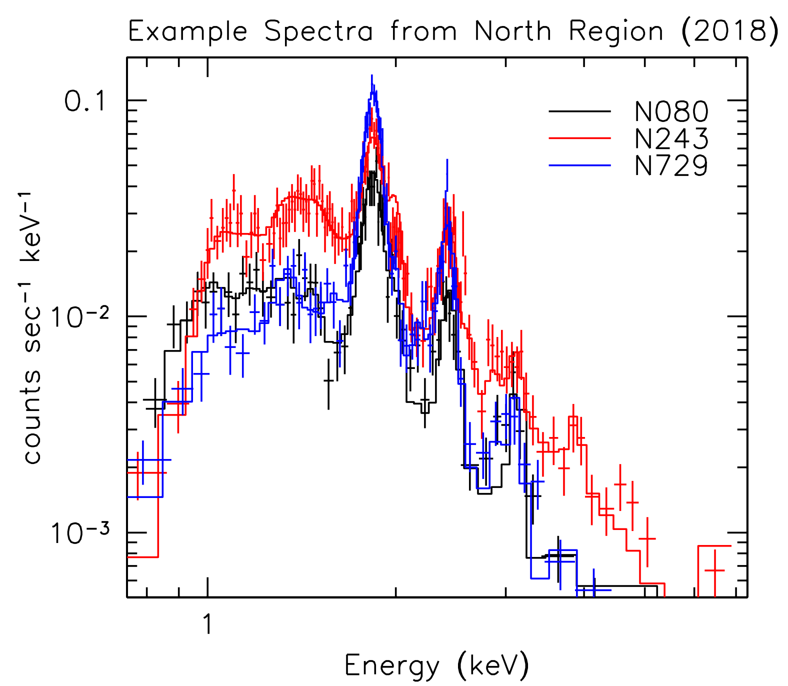
Schematic representation of how adjecent regions contribute to the initial spectral parameter estimates for the region in yellow



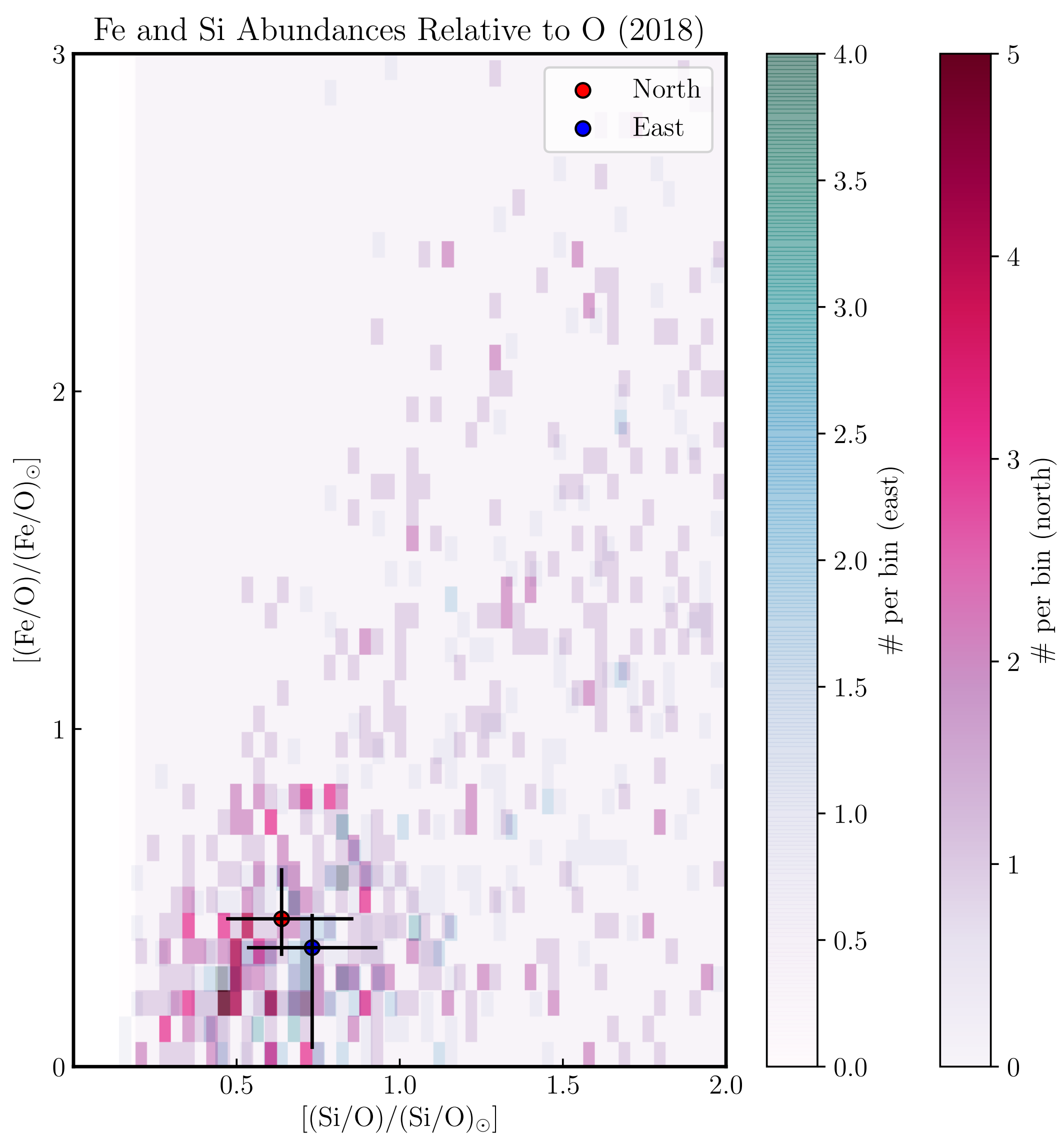
- Fits to each region produce a distribution of temperatures, ionization states, and chemical compositions
- Comparisons of the distribution of fit parameters from different cardinal directions highlight asymmetry in the SNR







Quantitative Differences Between Regions



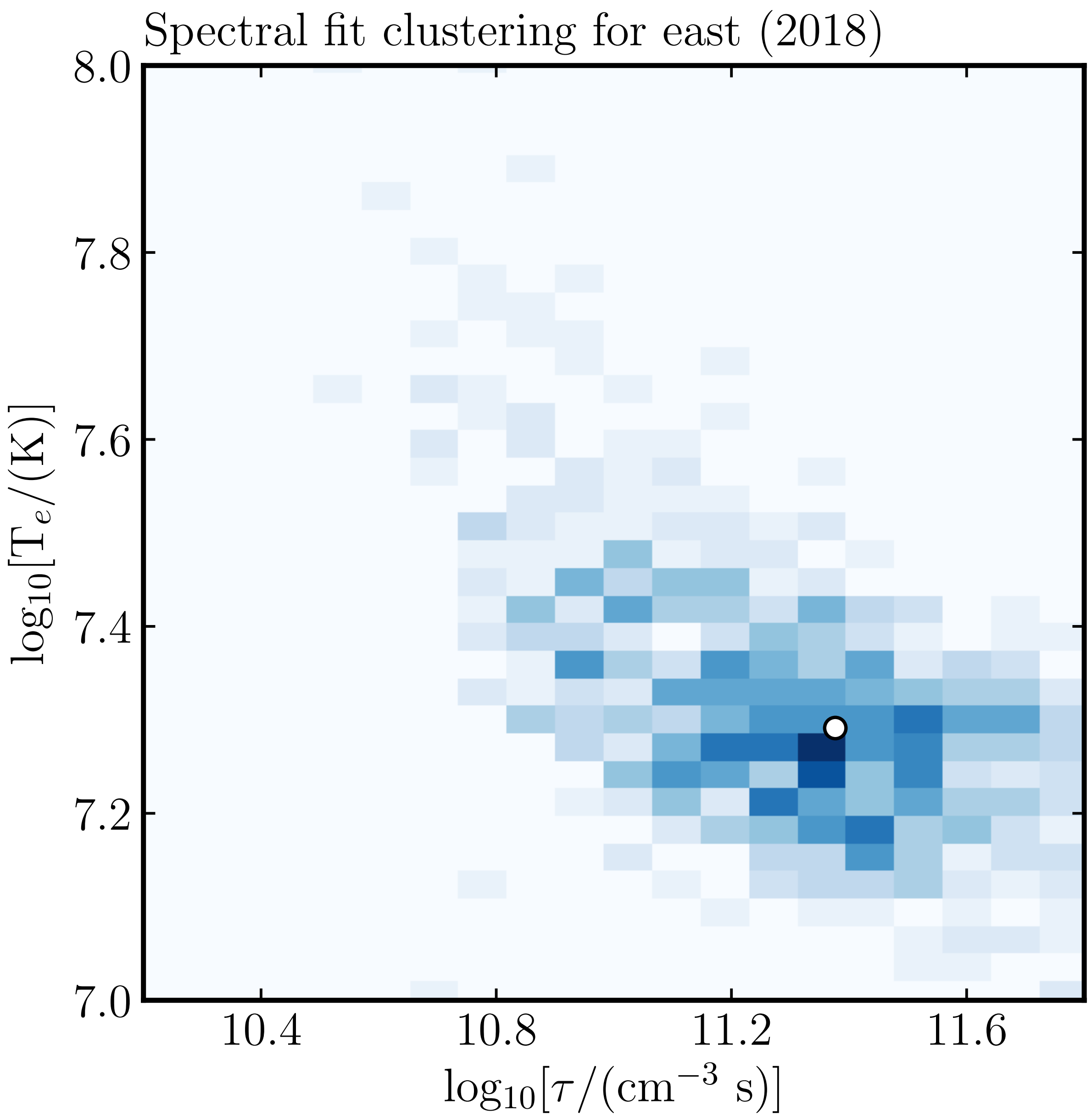
- In each region, abundances are fit relative to oxygen
- Fe/Si is generally higher in east than in north (~ 0.5)
- Results are broadly consistent with Laming & Hwang (2003) and $15M_{sun}$ progenitor models

Beyond larger scatter in 2018 dataset, no gross differences are seen in the abundances between 2000 and 2018

Quantitative Differences Between Regions

	T_e (keV)	$n_e t$ (10^{11} s cm^{-3})
2000	2.1	1.5
2018	1.7	2.4

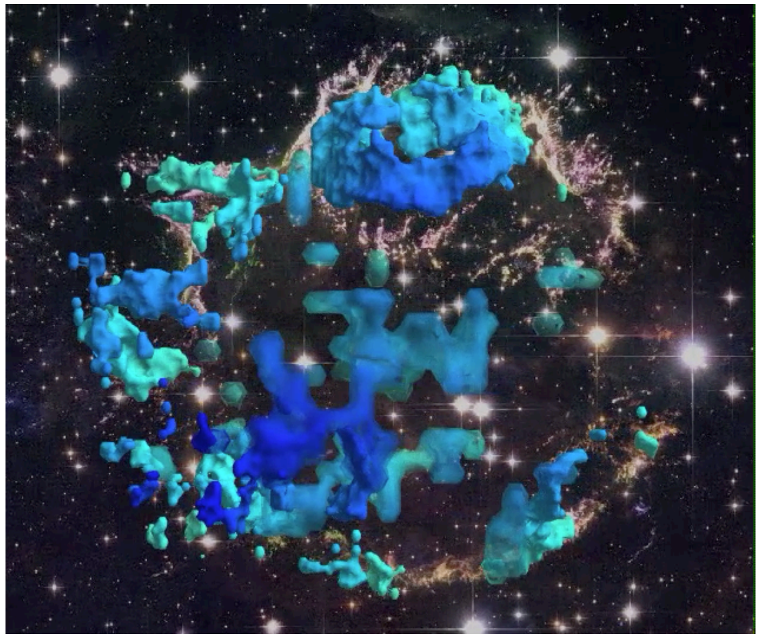
- "k-means" test computes cluster averages from 2D distribution
- outliers can drag mean away from "best fit (by eye)"
- underlying kernel is dependent upon the explosion, composition, and circumstellar properties
- differences between epochs also reflect underlying adiabatic expansion of the SNR (Sato et al. 2017)



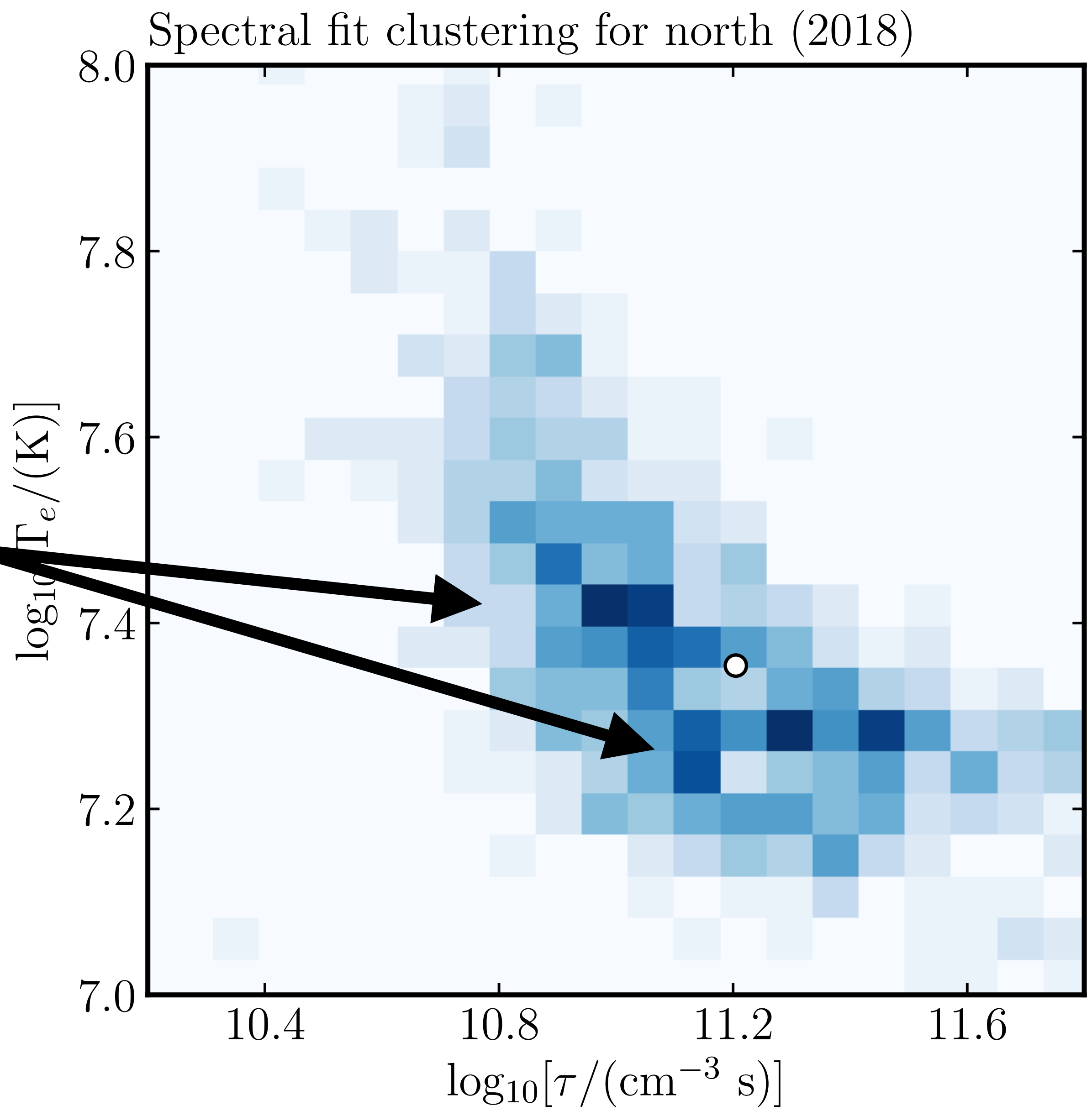
Quantitative Differences Between Regions

	T_e (keV)	$n_e t$ (10^{11} s cm^{-3})
2000	2.9	1.1
2018	1.9	1.6

- North region probably consists of more than one cluster



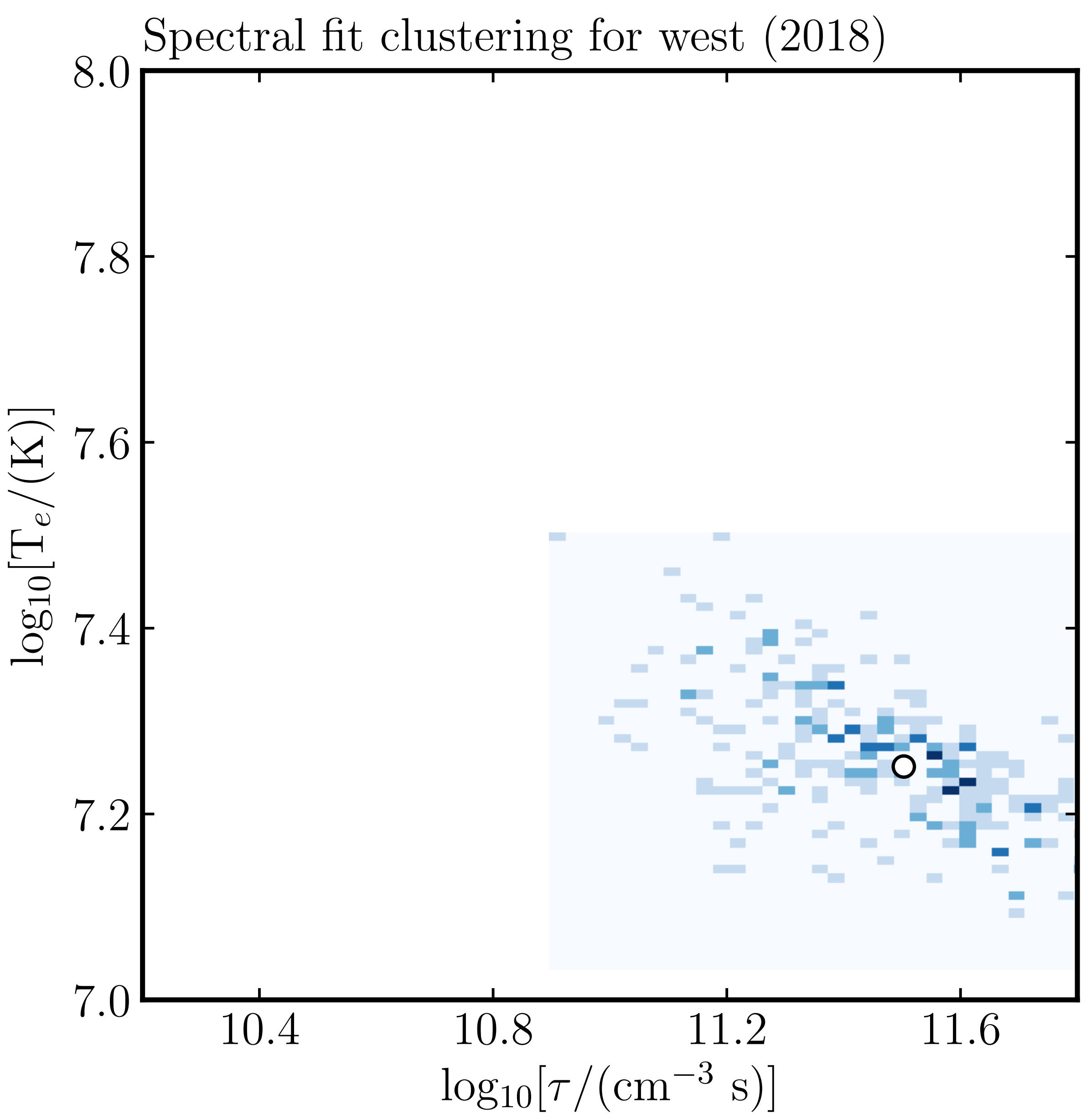
Milisavljevic & Fesen (2015)



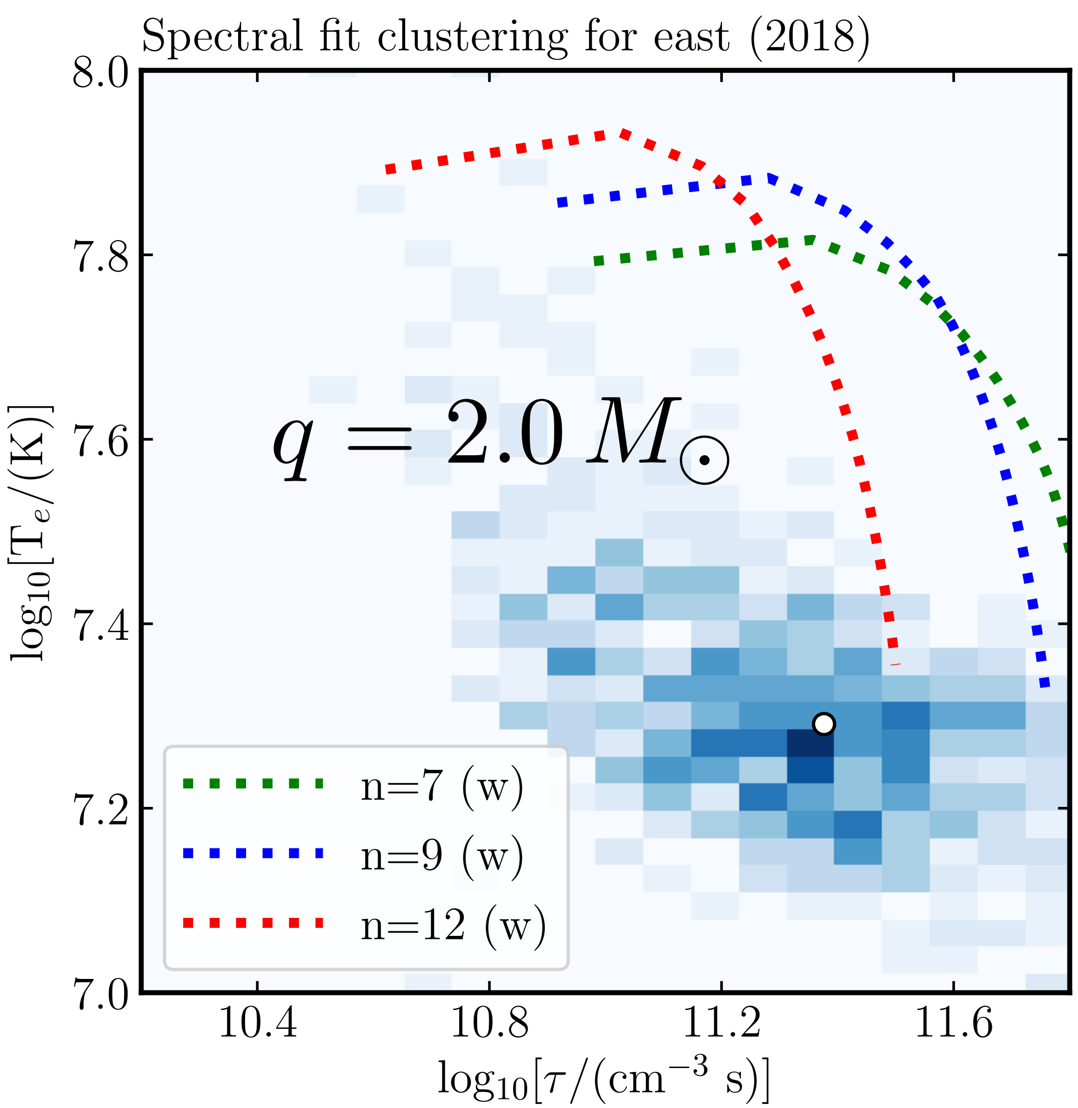
Quantitative Differences Between Regions

	T_e (keV)	$n_e t$ (10^{11} s cm^{-3})
2000	1.5	4.2
2018	1.5	3.2

- West region shows highest ionization ages
- In all, results are broadly consistent with results from Hwang and Laming
- changes in T_e and $n_e t$ can be compared against 3D models



Comparisons to 1D Hydro Models



Model Cas A evolution to compare against the observed properties of the ejecta

$$\rho_{\rm CSM} = \frac{\dot{M}}{4\pi v_{\rm w} r^2}$$

v_w = 15 km s^{-1}

M_{dot} = 2×10^{-5} M_{sun} yr^{-1}

$$\rho_{\rm ej} \propto v^{-n}$$

$$\rm M_{ej} \approx 3\,M_\odot$$

$$\rm E_{SN} = 1.5 \times 10^{51}\ erg$$

Use chemical composition from a model for SN 1993J, mapped onto a self-similar ejecta profile

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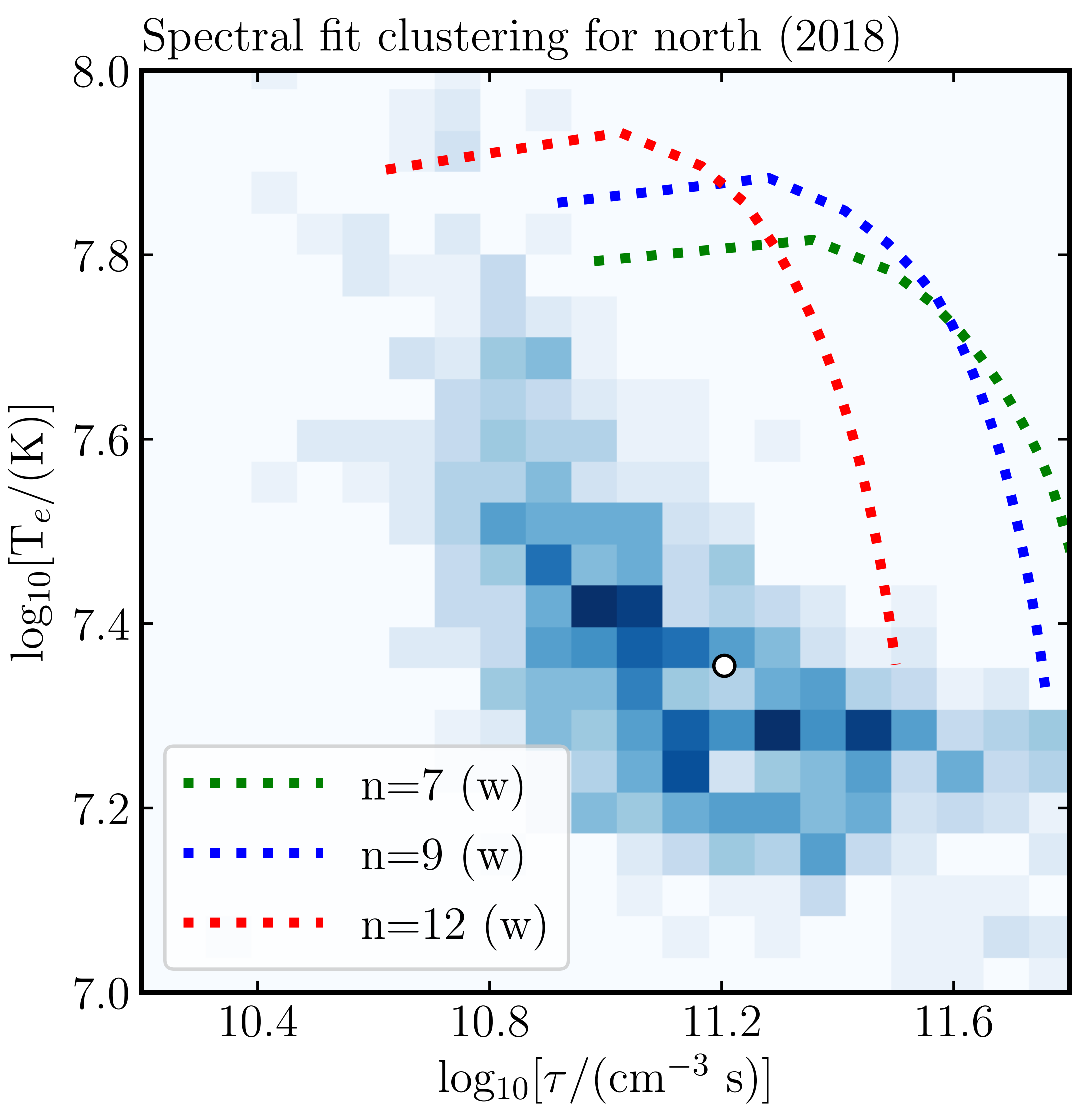

Model Cas A evolution to compare against the observed properties of the ejecta

$\dot{M}$ … $v_w = 15\ km\ s^{-1}$

ρ_C … yr^{-1}

Ionization state and temperature of the ejecta are inconsistent with pure r^{-2} winds

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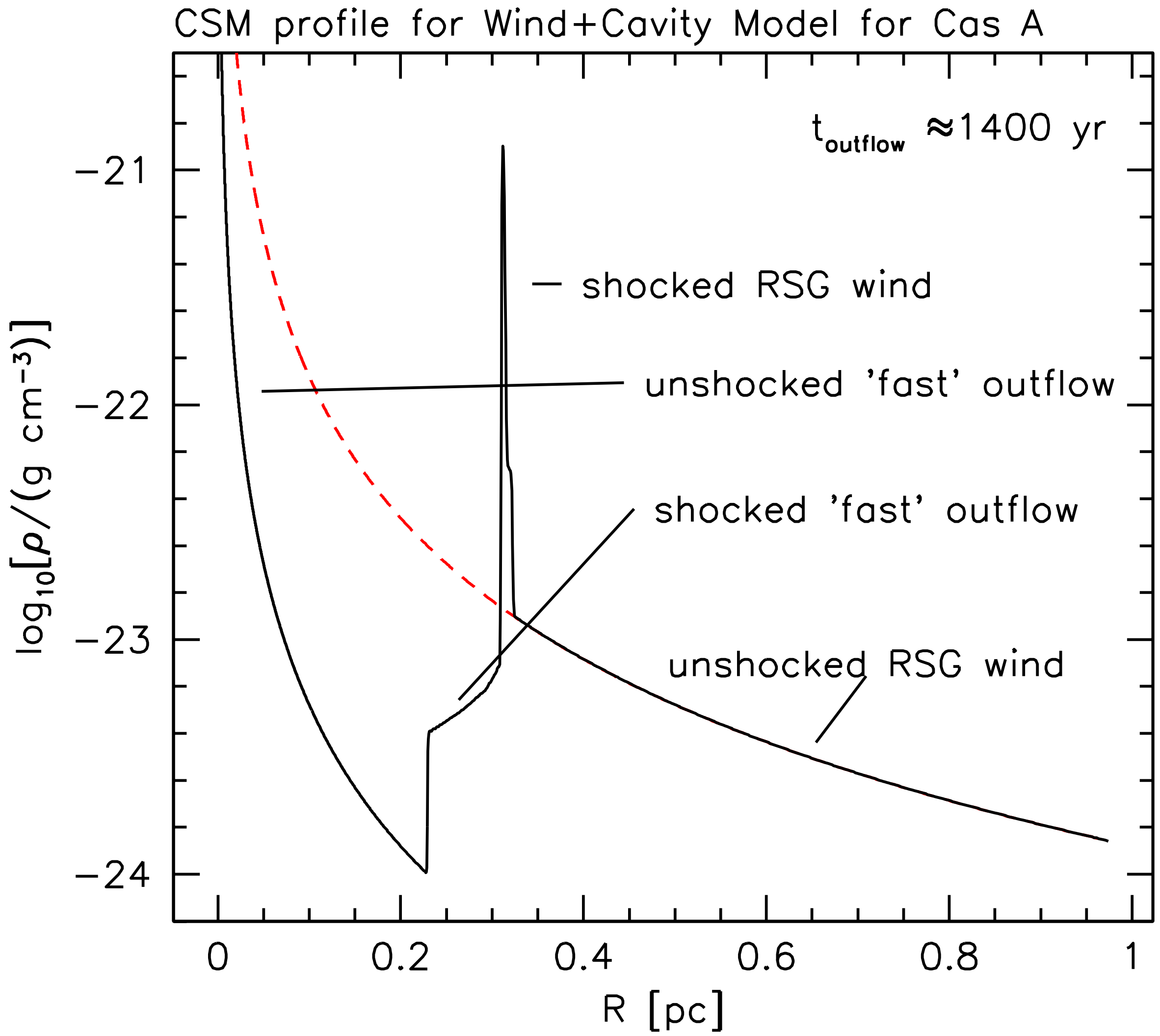

Possible CSM for Cas A progenitor

Model Cas A evolution to compare against the observed properties of the ejecta

$$\rho_{\rm CSM} = \frac{\dot{M}}{4\pi v_{\rm w} r^2}$$

- v_w = 15 km s^{-1} (r > 0.2 pc)
- **v_w = 10^3 km s^{-1} (r < 0.2 pc)**
- M_{dot} = 2×10^{-5} M_{sun} yr^{-1}

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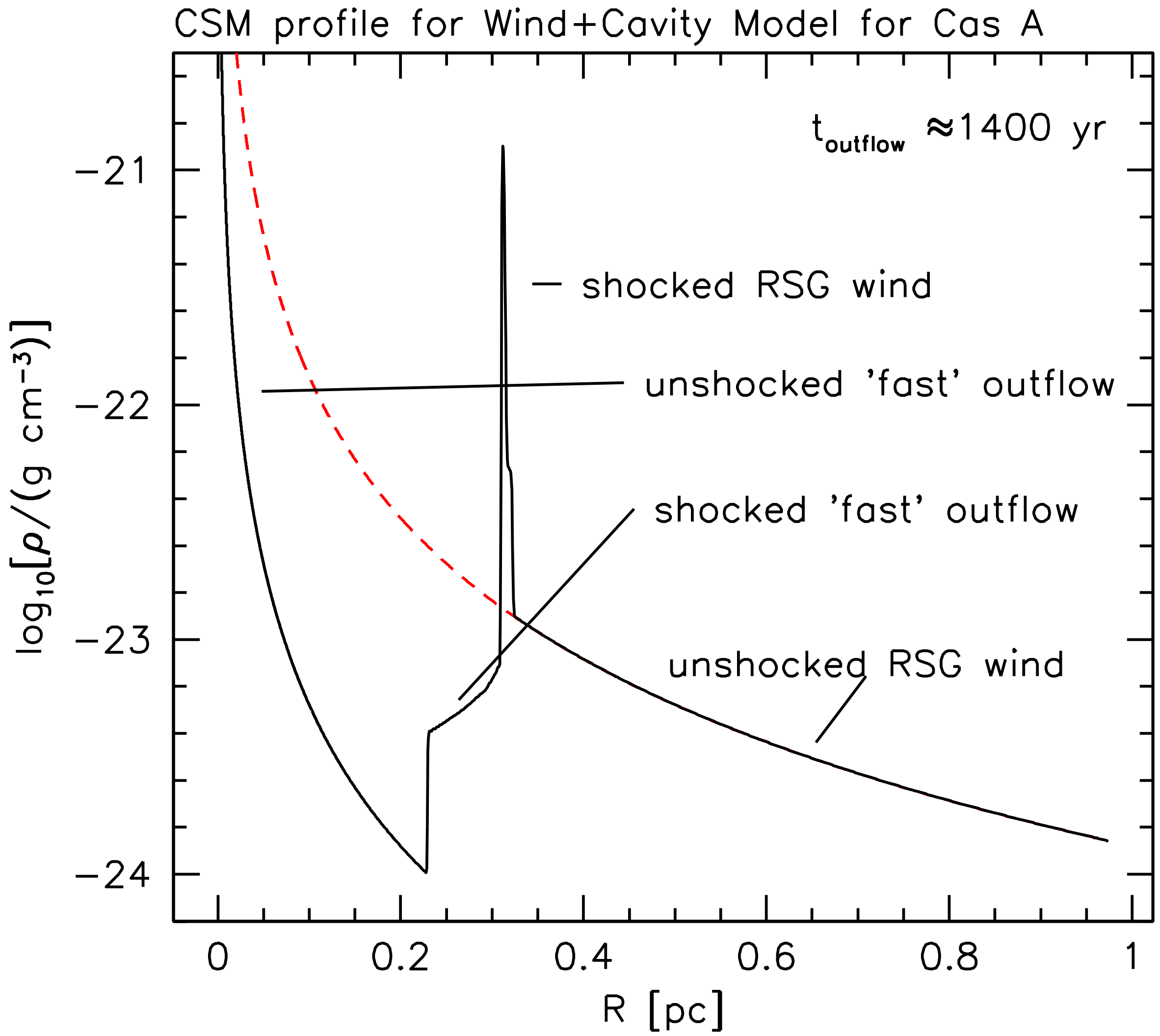

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n_{ej}	τ (10^{11} cm^{-3} s)	T$_e$ (10^7 K)	R$_{FS}$ pc	τ (10^{11} cm^{-3} s)	T$_e$ (10^7 K)	R$_{FS}$ pc
	Isotropic Wind[a]			Wind–Cavity[b]		
7	7.14	2.02	2.36	2.22	1.99	2.58
9	5.73	2.14	2.35	1.67	2.07	2.56
12	3.16	2.27	2.34	3.12	2.02	2.55

CSM models which include a small cavity produce larger SNR at 340 years, and generally lower ionization ages in the shocked ejecta

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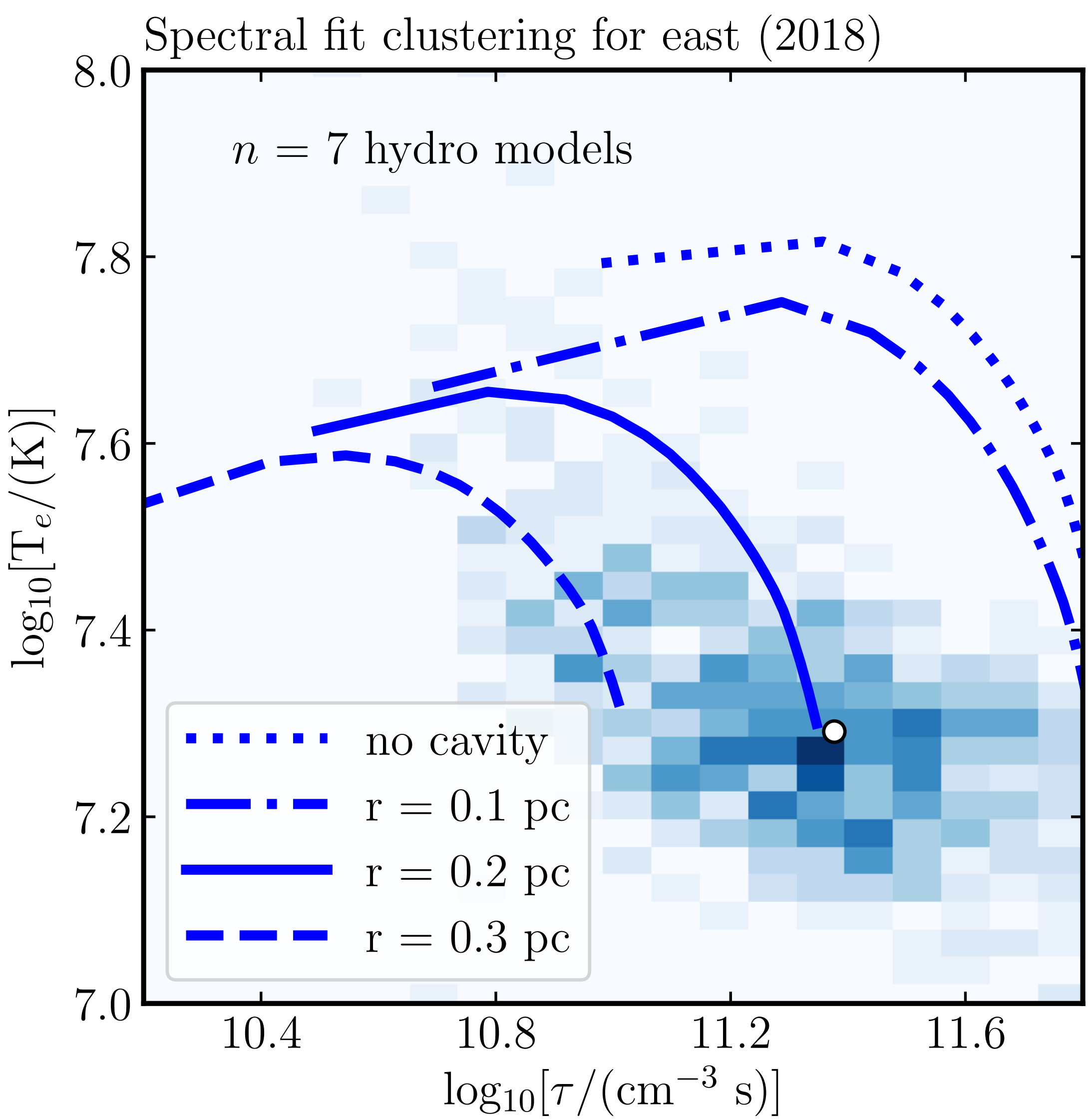

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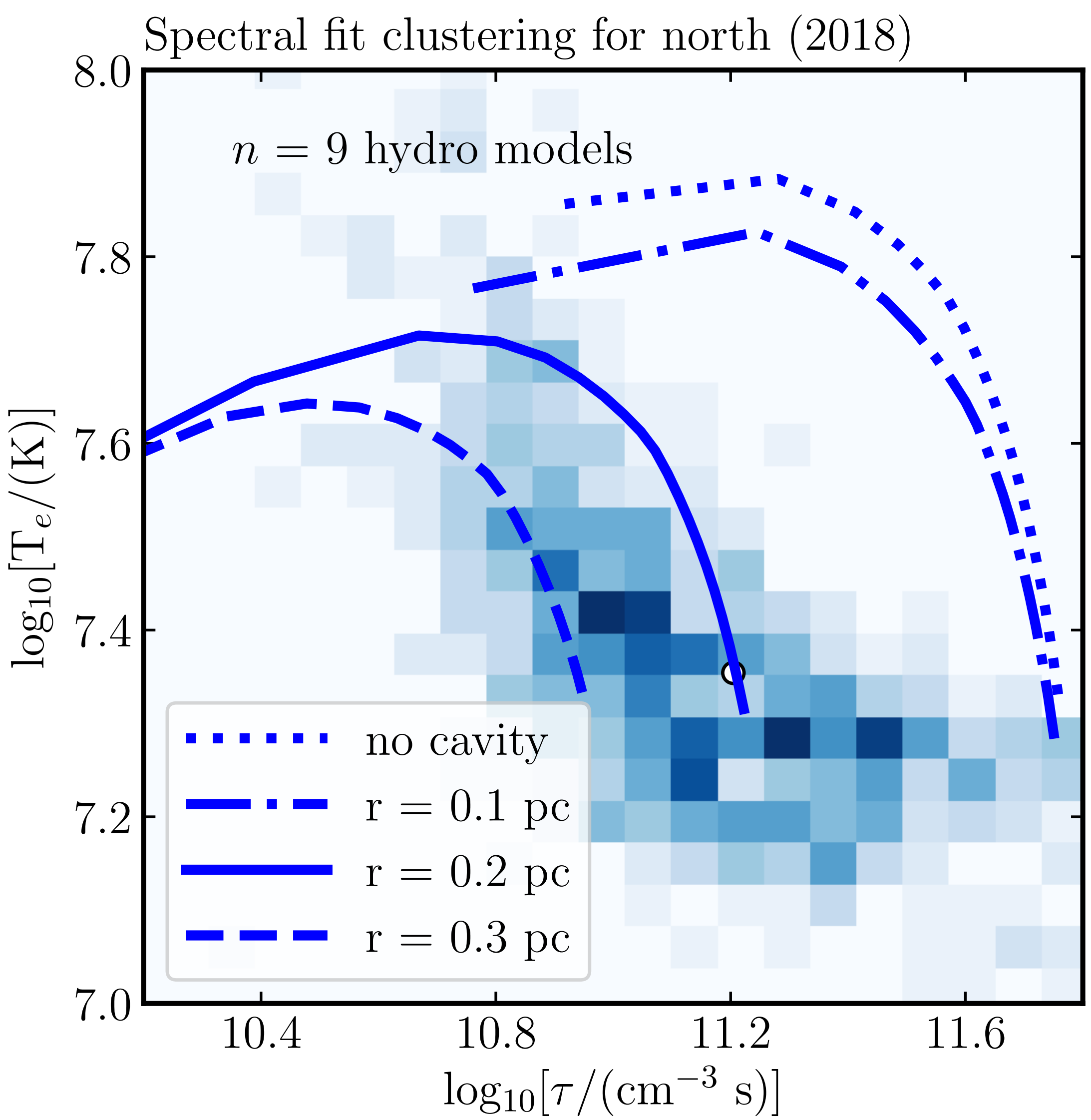

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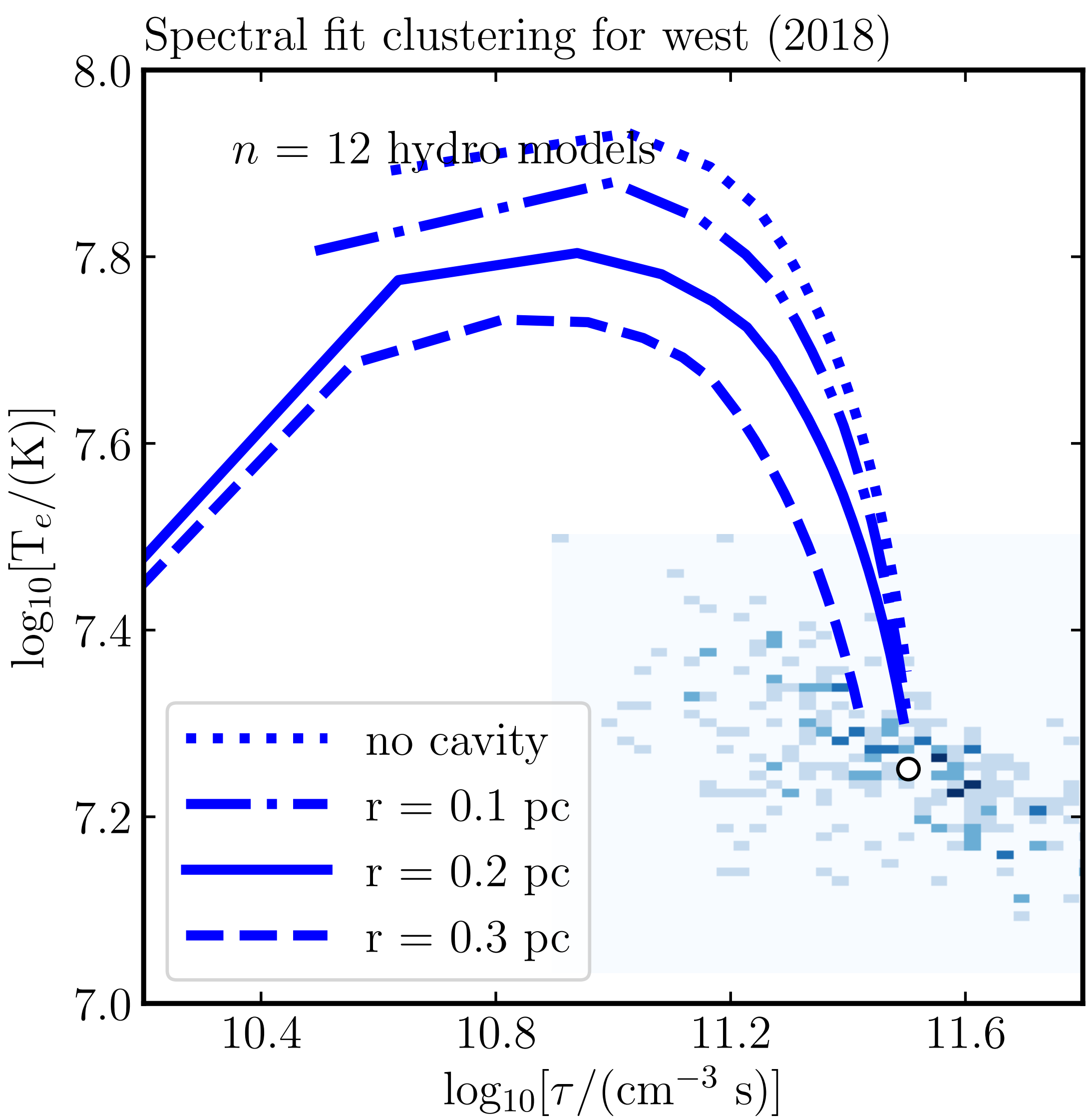

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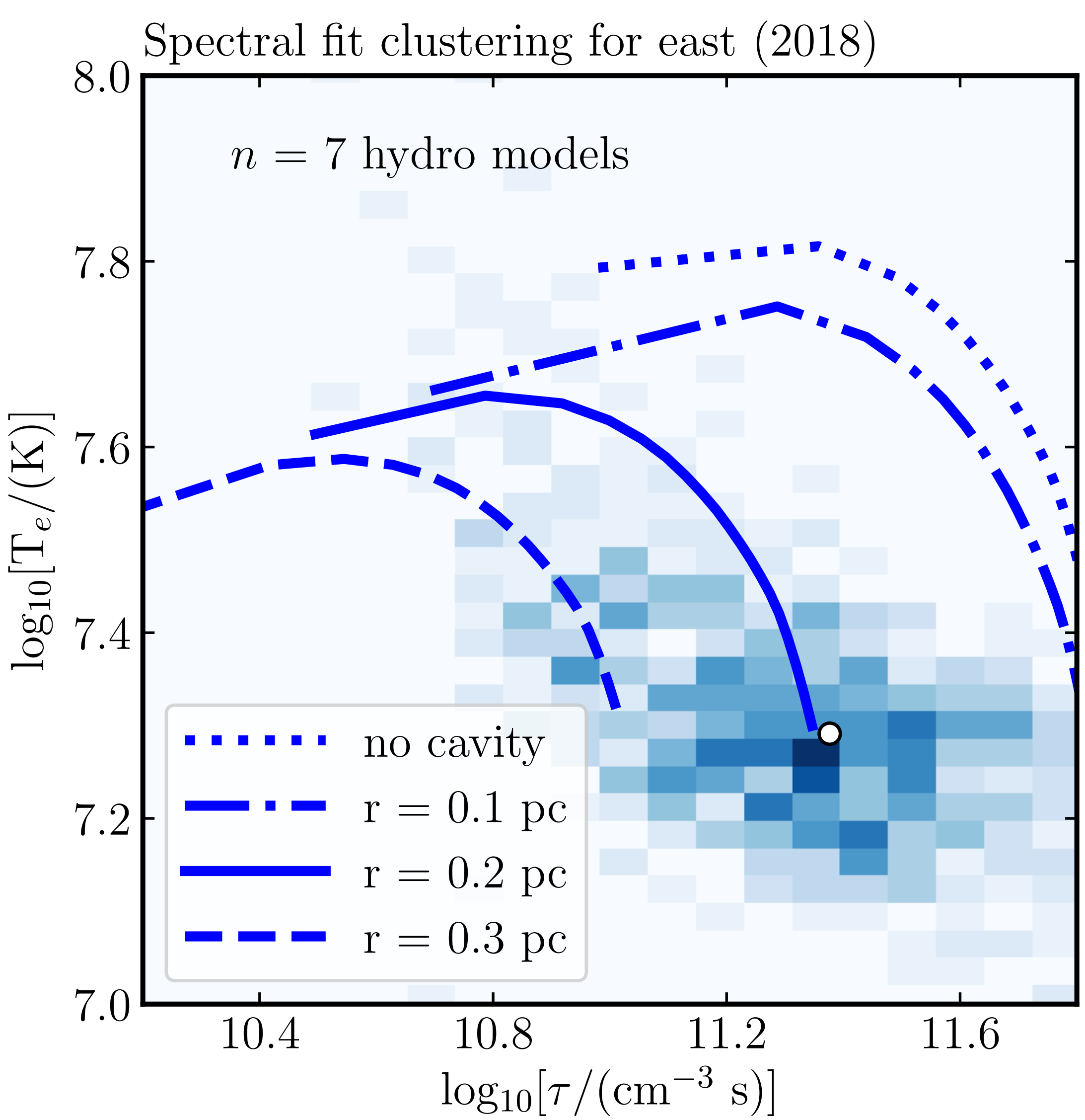

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CSM ...
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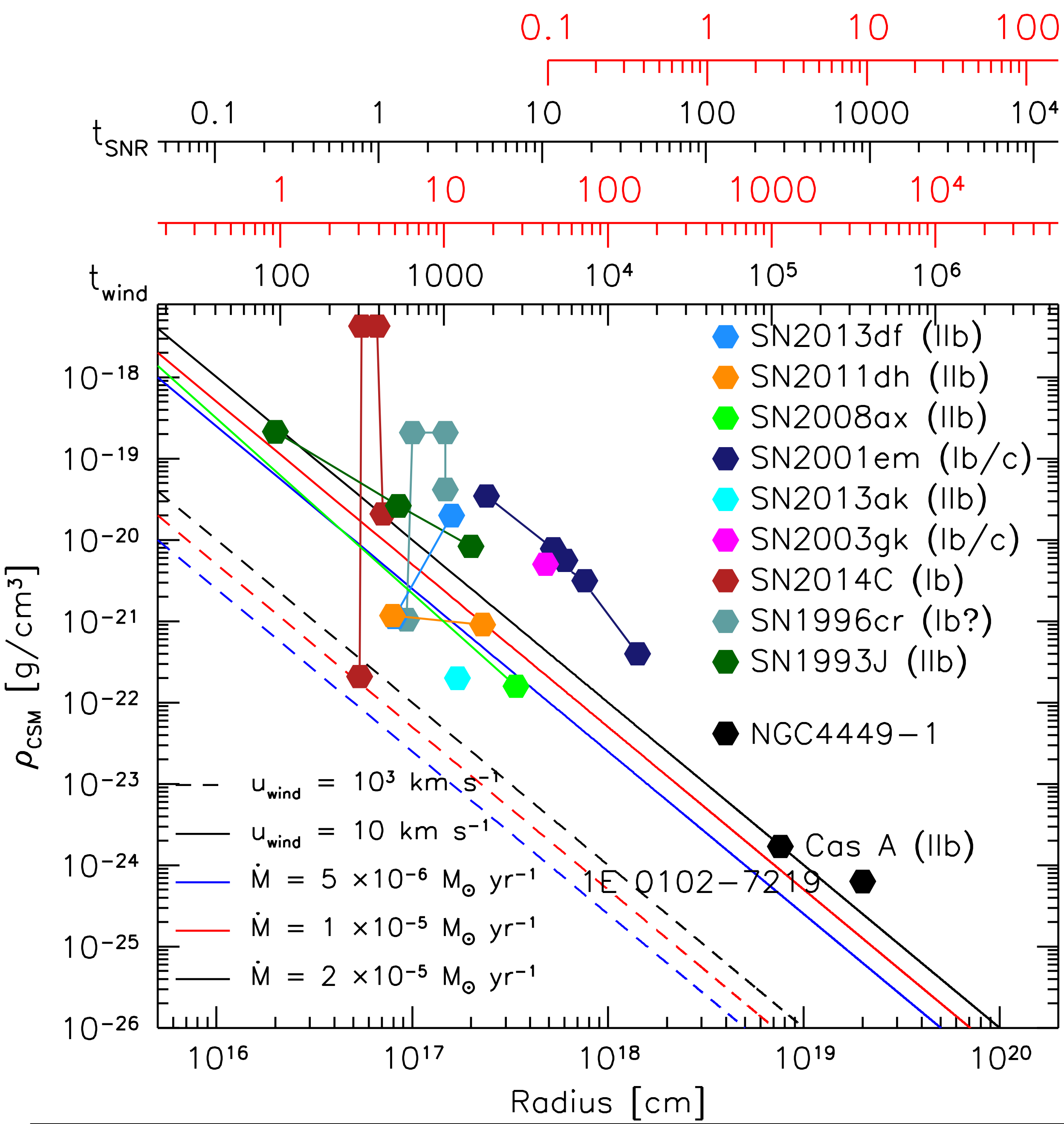
Origin of the cavity could be from:
i: binary interaction
ii: enhanced, late stage mass loss



$v_{wind} = 10^3$ km s^{-1}

$v_{wind} = 10$ km s^{-1}

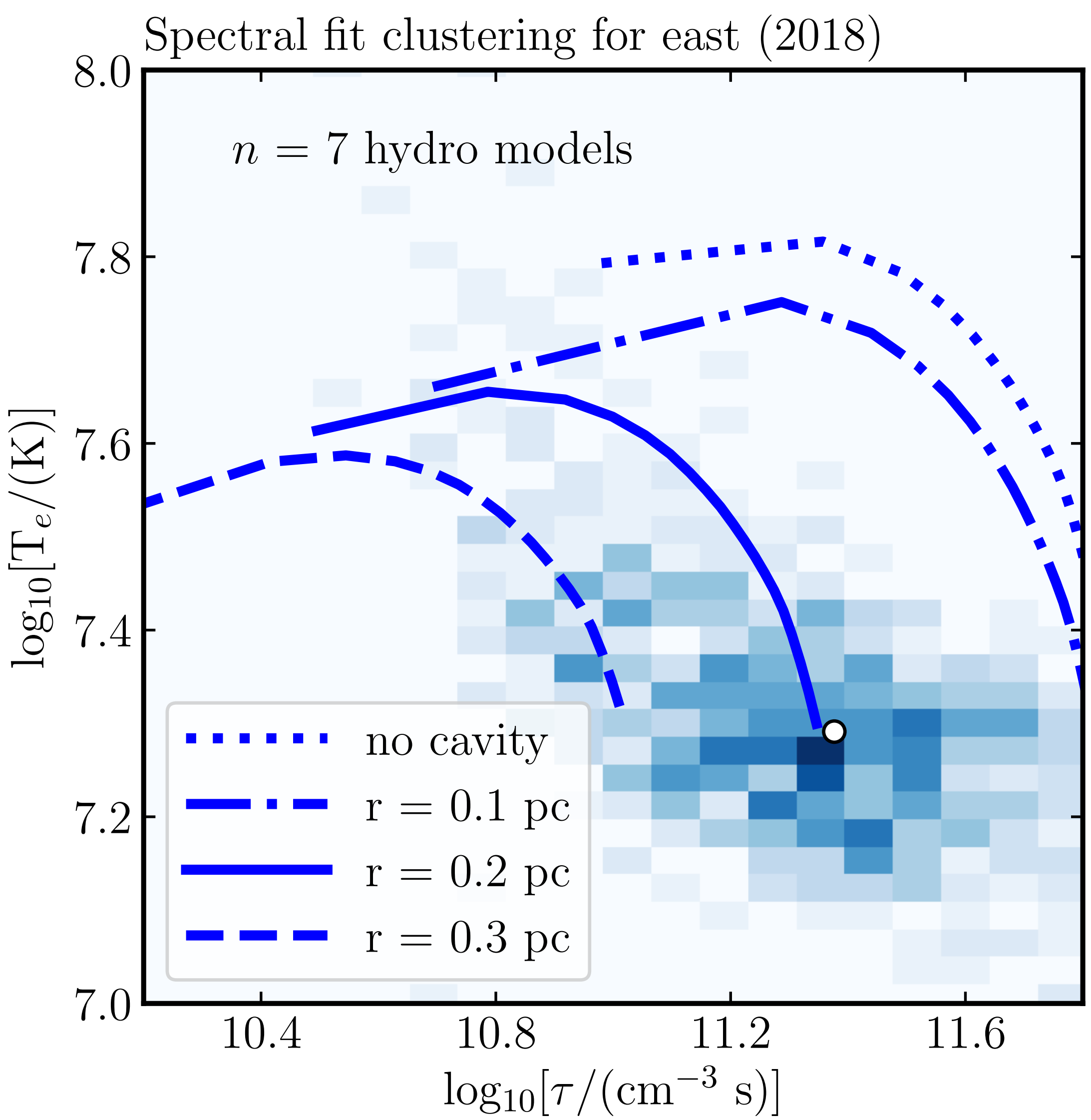
CSM properties for several Ib/c and IIb SNe and SNR

- cavities around IIb and Ib/c SNe appear to be common
- an increase in X-ray emission signals the interaction between the shock and denser circumstellar material

$$L_X = \left(\frac{4}{\pi \bar{m}^2}\right)\left(\frac{\dot{M}}{v_w}\right)\frac{\Lambda(T)}{R_s}$$

data from: Dwarkadas & Gruszko (2012); Margutti et al. (2017); Kundu et al. (2019); Patnaude et al. (2019, in prep); Milisavljevic & Fesen (2008); Lee et al. (2014); Xi et al. (2019)

Comparisons to 1D Hydro Models



1D models also inform us on large scale azimuthal asymmetries in the ejecta

- In broad terms, different cardinal directions favor different ejecta power law indices

$$E_{\mathrm{SN}} \propto M_{\mathrm{ej}}^{5/7} \frac{(n-3)^{5/3}}{n^{2/3}(n-5)}$$

- When ejecta mass and ejecta core density are held constant, lower values of “n” correspond to higher explosion energies

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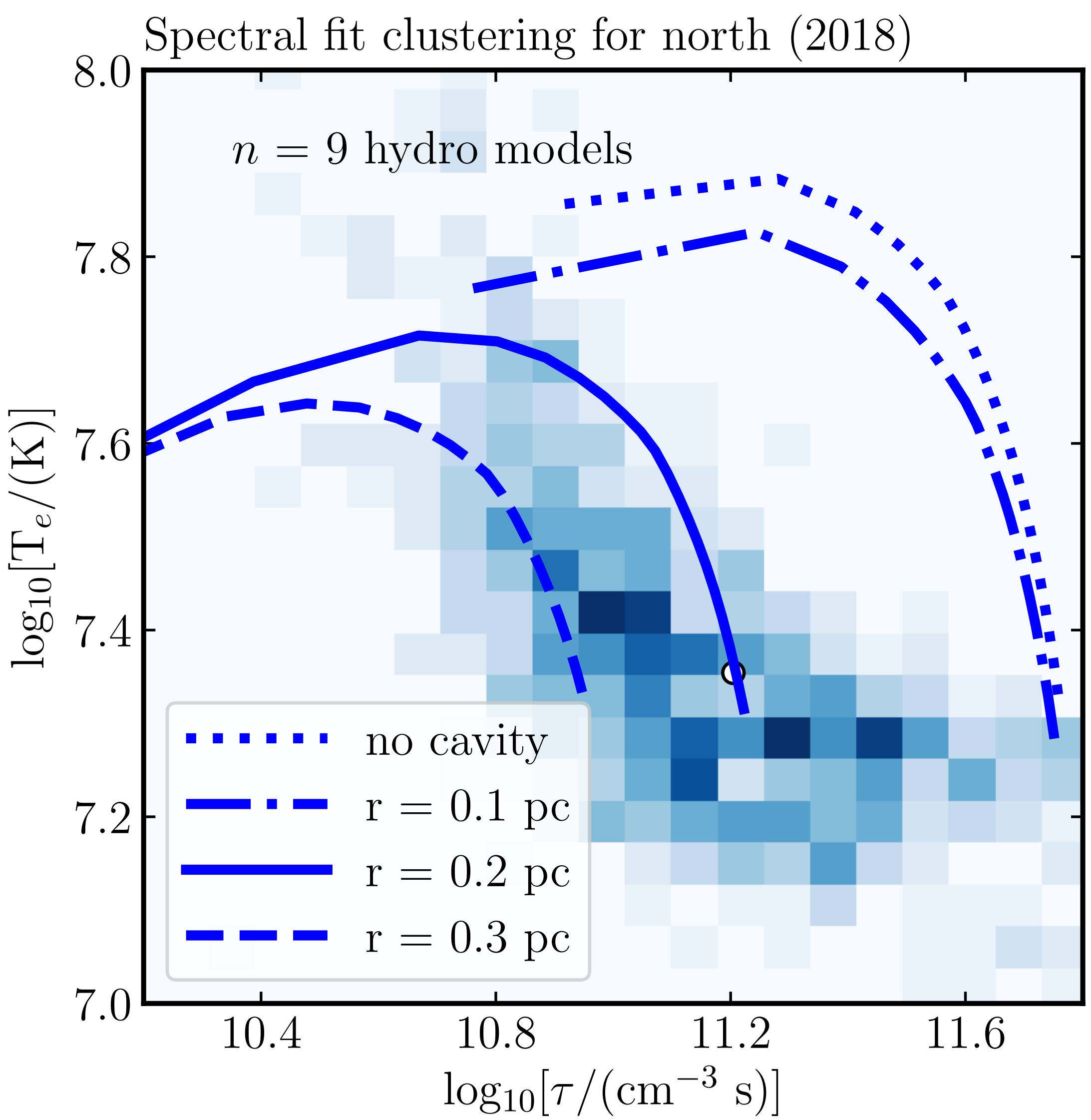

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Azimuthal differences in Spectral Fits

- Spectral fits in the east regions point to lower ejecta densities
  - observed lower densities suggest ^{56}Ni heating of ejecta plume
  - radioactive heating can alter ejecta structure and force a different time evolution of the density

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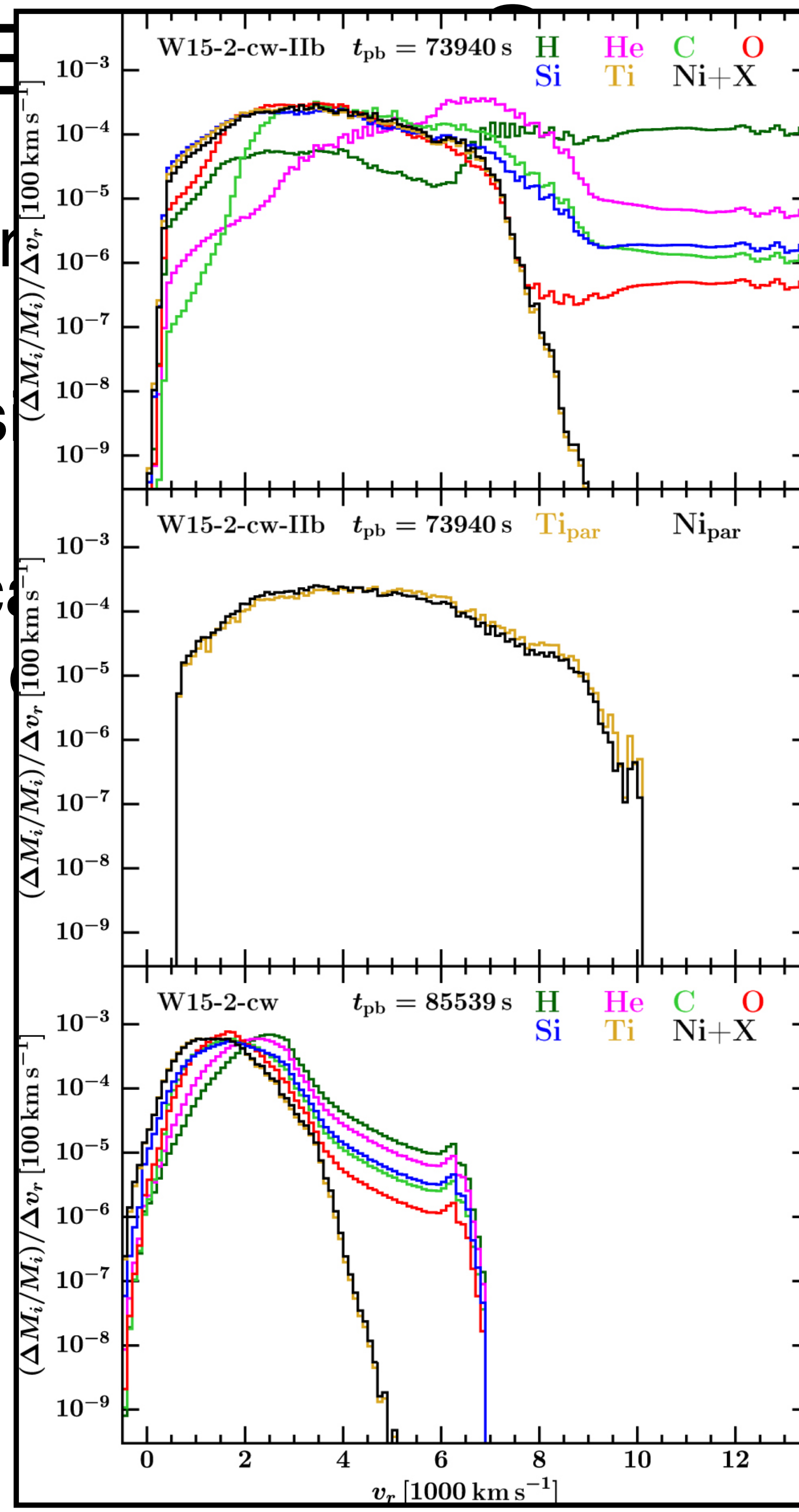

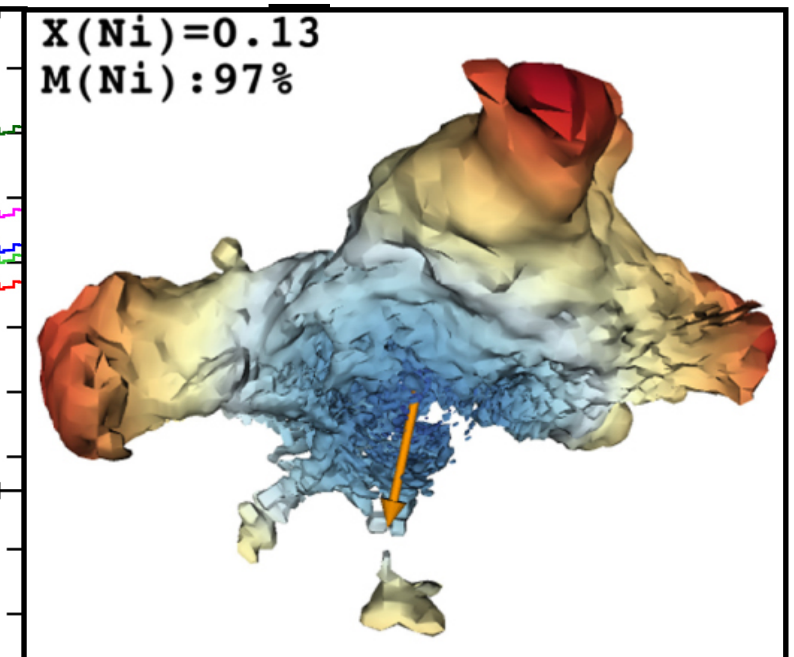

Wongwathanaratt et al. (2017)

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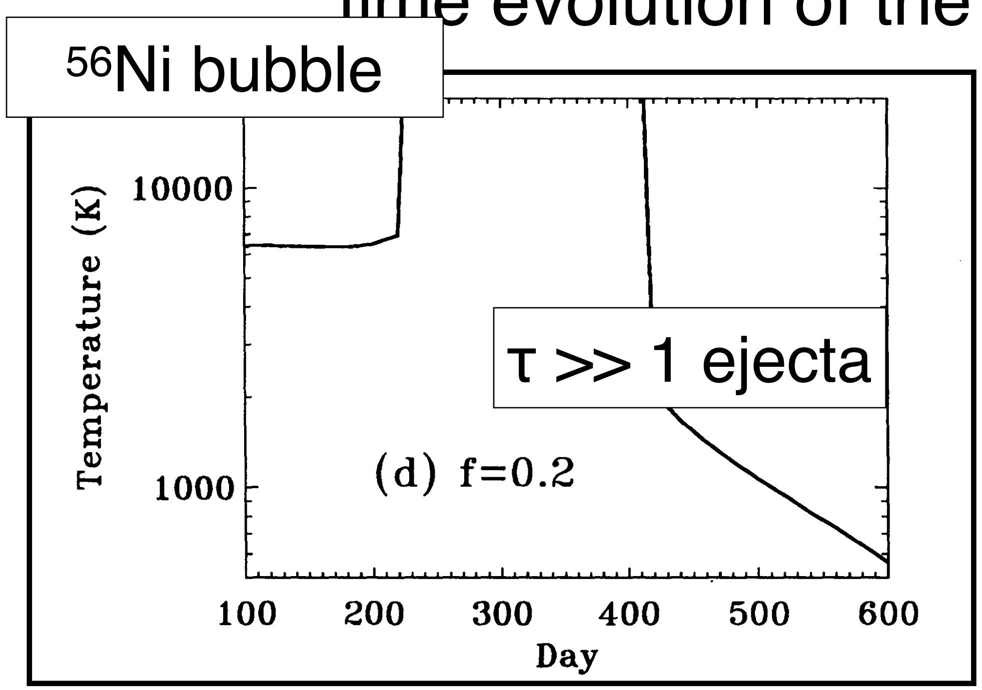
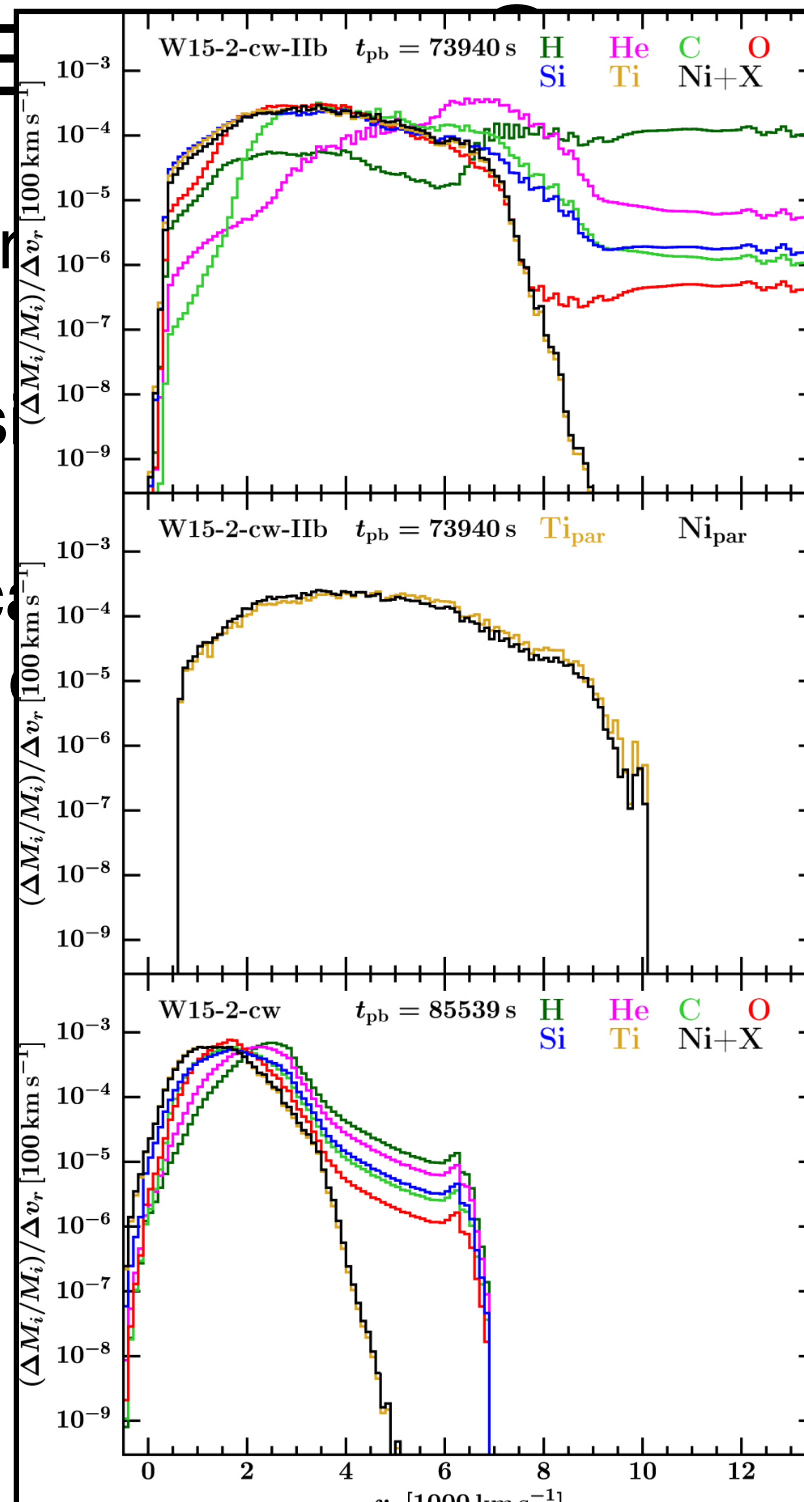
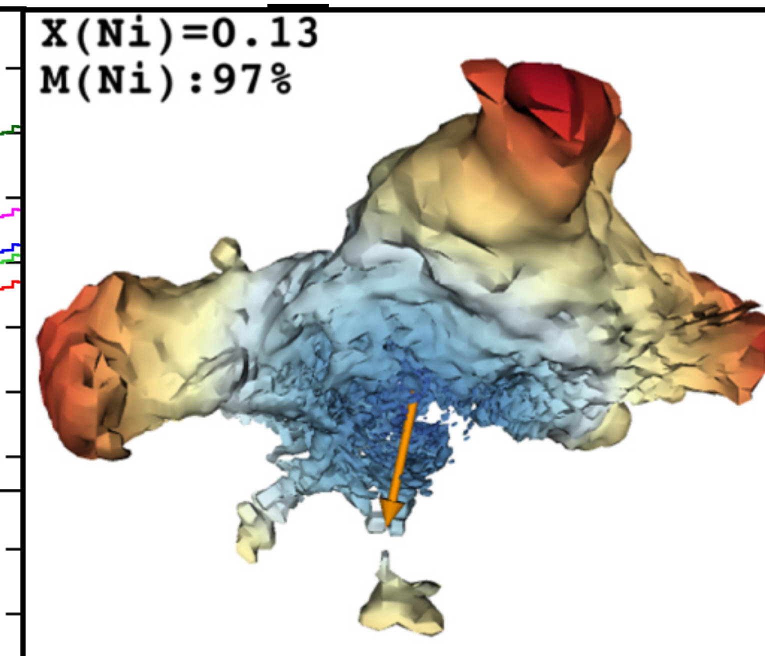


Li, McCray, and Sunyaev (1993)





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- west region shows highest ionization — Fraschetti et al. (2018) argued that this is due to interaction with a nearby molecular cloud

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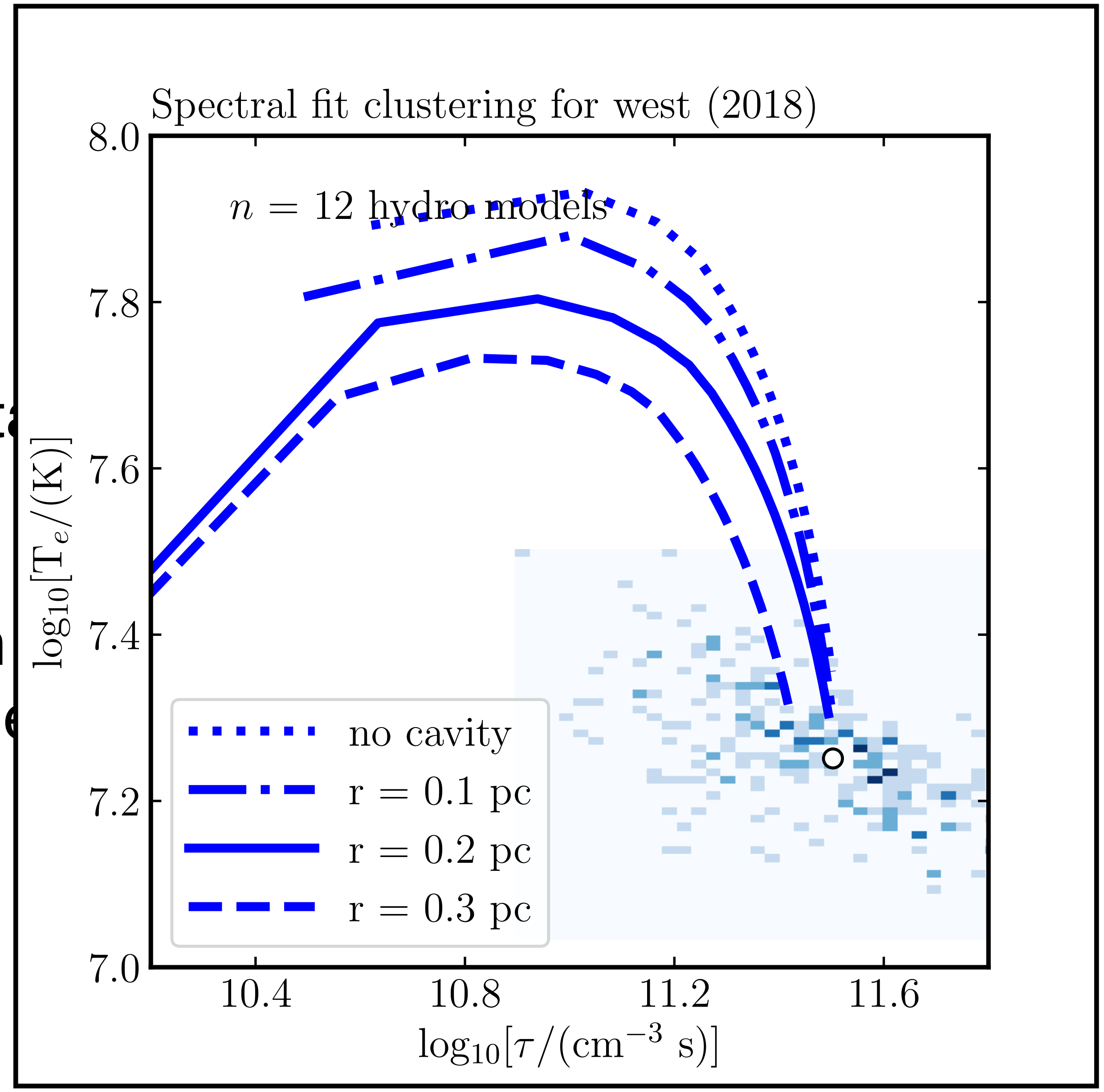

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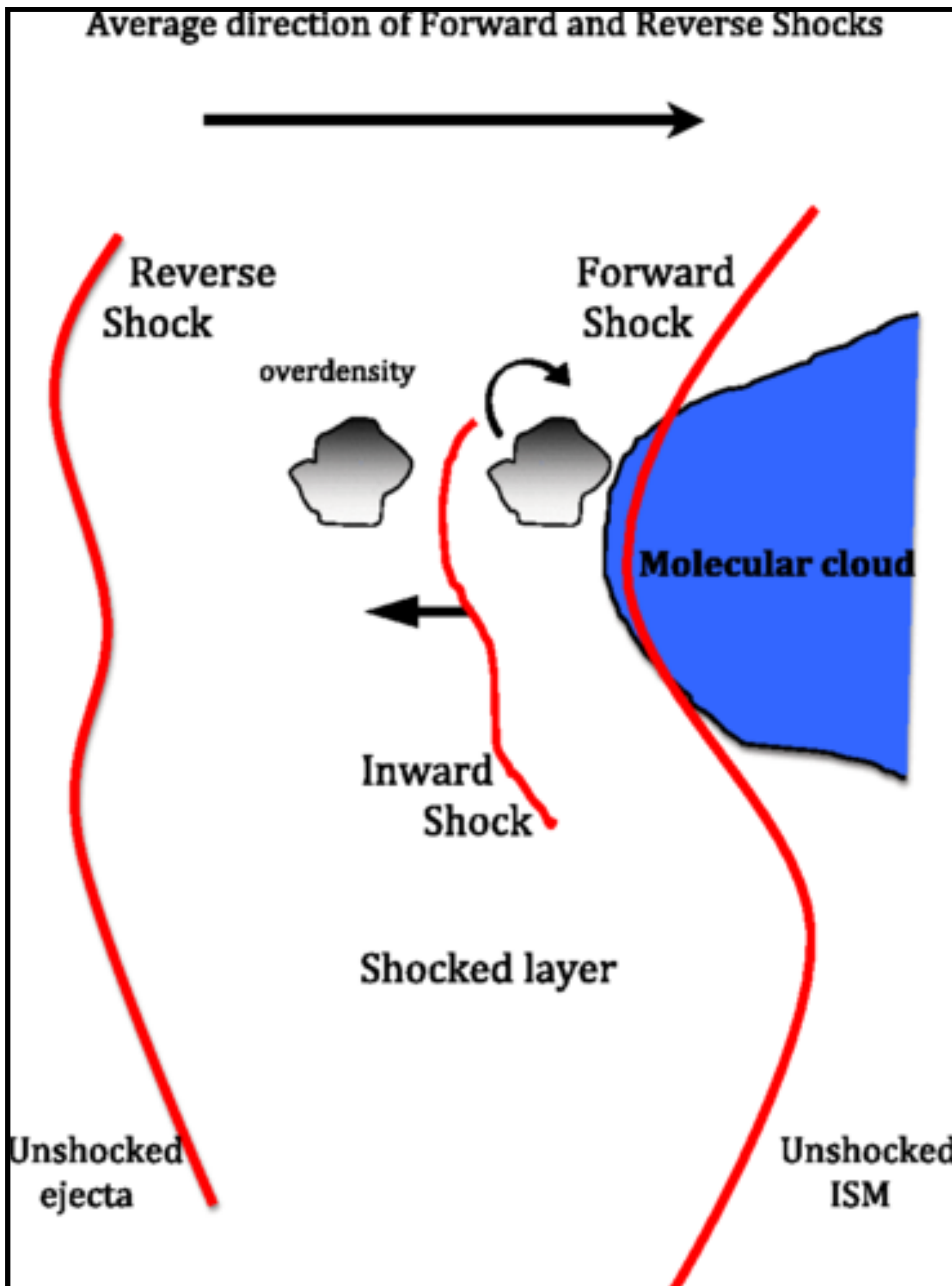

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  - Zhou et al. (2017) showed that cloud is not coincident with Cas A
  - optical/NIR observations suggest a larger concentration of CSM in that direction (QSFs; Koo et al. 2017) which would lead to multiple reflected shocks in the ejecta, raising the ionization age

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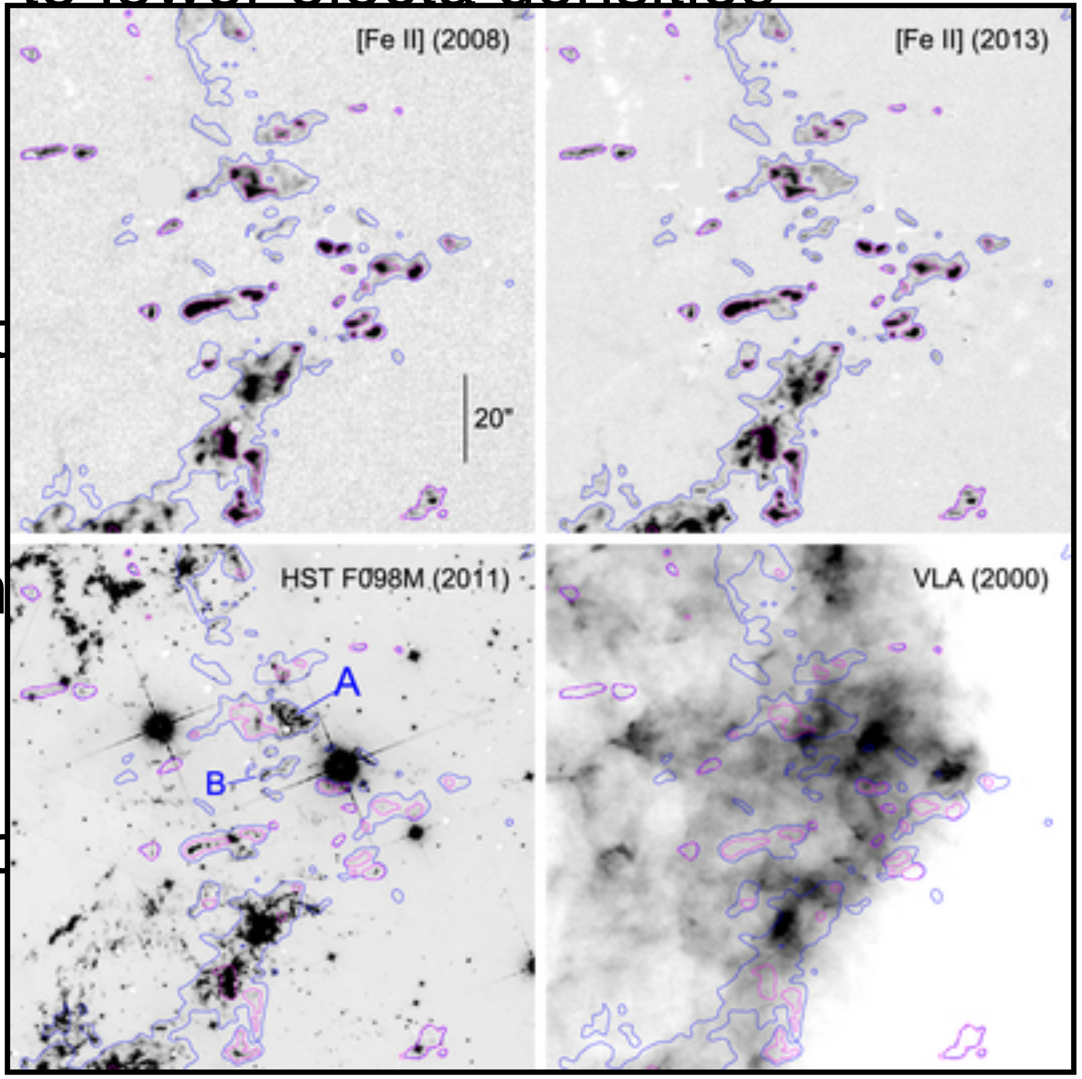

Conclusions

- X-ray observations of thermal emission from SNR inform us on the properties of both the circumstellar environment and explosion

    - Cas A shows azimuthal variations in the bulk spectral properties of the ejecta — can be explained by ^{56}Ni heating of ejecta in the east and (possibly) the north

    - Spectral features (ionization age, line centroids) suggest a late stage enhanced mass loss event in Cas A, possibly due to a short YSG phase or binary interaction

WHAT COULD BE DONE IN THE NEXT 20 YRS?

- Uncover any unshocked iron — reconcile with models for explosive nucleosynthesis, mixing, etc.,
- Measure the blastwave deceleration — combined with measurements of synchrotron emission changes, provides a direct measurement of the CR diffusion parameter
- Determine the nature of the nonthermal emission located in the main shell — is it from the reverse shock or forward shock seen in projection?
- Settle the question of the cooling CCO — is it real or a detector artifact?