Supernova Remnants: An Odyssey in Space after Stellar Death, Chania, Greece, June 8, 2016

A *Chandra* Study of G299.2-2.9:
The Remnant of an Asymmetric Type Ia Explosion?

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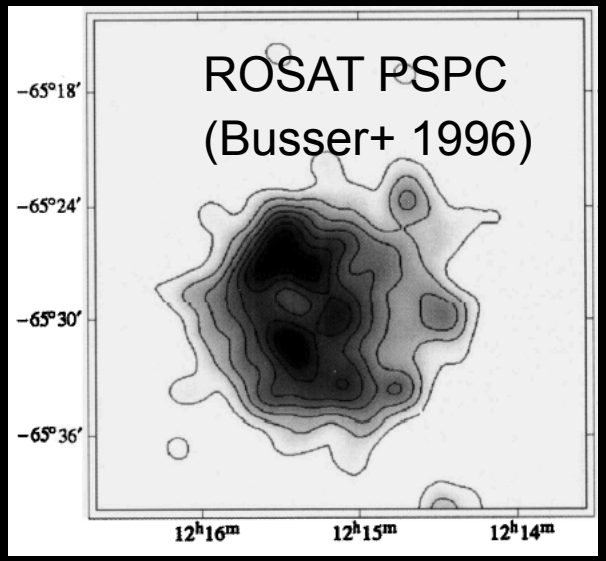
Introduction

X-ray-discovered: d ~ 500 pc, τ < 10^3 yr (RASS, Busser et al. 1995)

(Faint shell in radio/IR: e.g., ~0.5 Jy at 1 GHz [Green 2014])

Thermal composite/partial shell: *ROSAT*, *Einstein*, *ASCA*
(Busser et al. 1996, Slane et al. 1996,
Bai & Wang 2000)



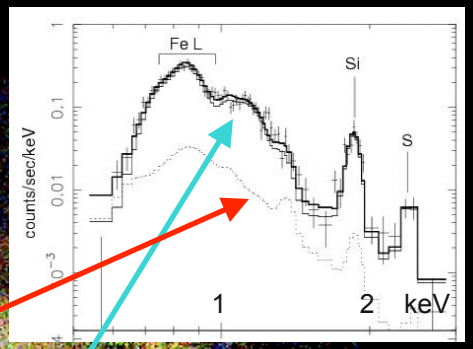
τ_{Sed} ~ 6-9000 yr for d ~ 5-6 kpc
(Busser et al. 1996, Slane et al. 1996,
Bai & Wang 2000)

Radio Σ-D relation: d > 15 kpc
(Slane et al. 1996)

Low E_0 ~ 1-3 × 10^{50} erg at d ~ 5 kpc
(Busser et al. 1996, Slane et al. 1996, Bai & Wang 2000)

Initial *Chandra* Observation

30 ks *Chandra*
ACIS-S3
(SP et al. 2007)



Red: 0.4-0.9 keV
Green: 0.9-1.4 keV
Blue: 1.4-3.0 keV

Multiple shells: sub-solar
→ Non-uniform medium

Central metal-rich ejecta:
Fe-, Si-, S-rich
No O, Ne
No compact remnant
→ Type Ia SNR

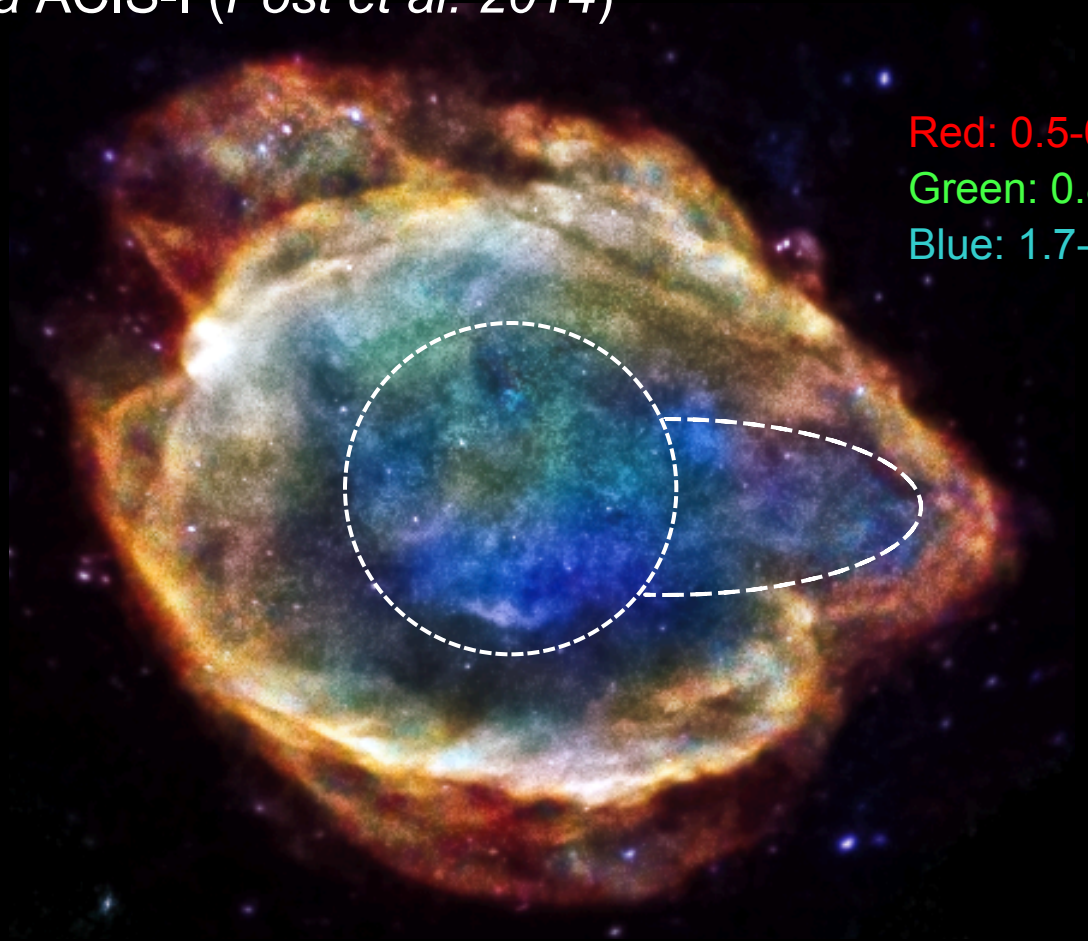
τ_{Sed} ~ 4500 yr for d ~ 5 kpc

E_0 ~ 1.5 × 10^{50} erg at d ~ 5 kpc
(~10^{51} erg at d ~ 10 kpc)

→ Sub-energetic Type Ia SN (unless $d \gtrsim 10$ kpc) in a non-uniform medium?

Deep *Chandra* Observation

640 ks *Chandra* ACIS-I (*Post et al. 2014*)

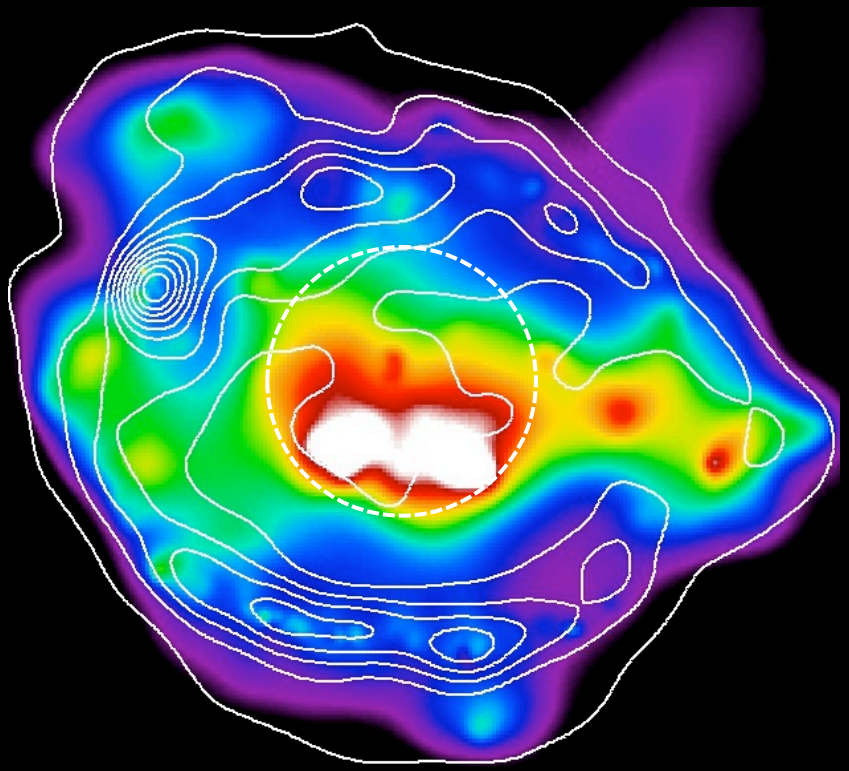


Complete coverage with ~20× deeper exposure

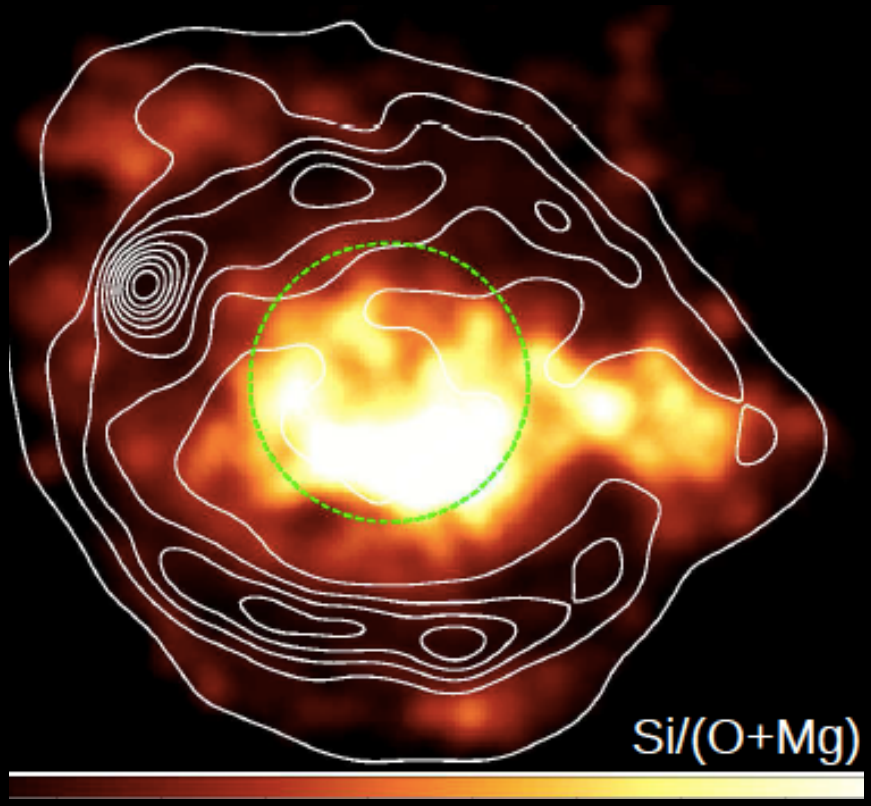
→ Central ejecta extends to west?

Si & Fe line maps

Post et al. 2014



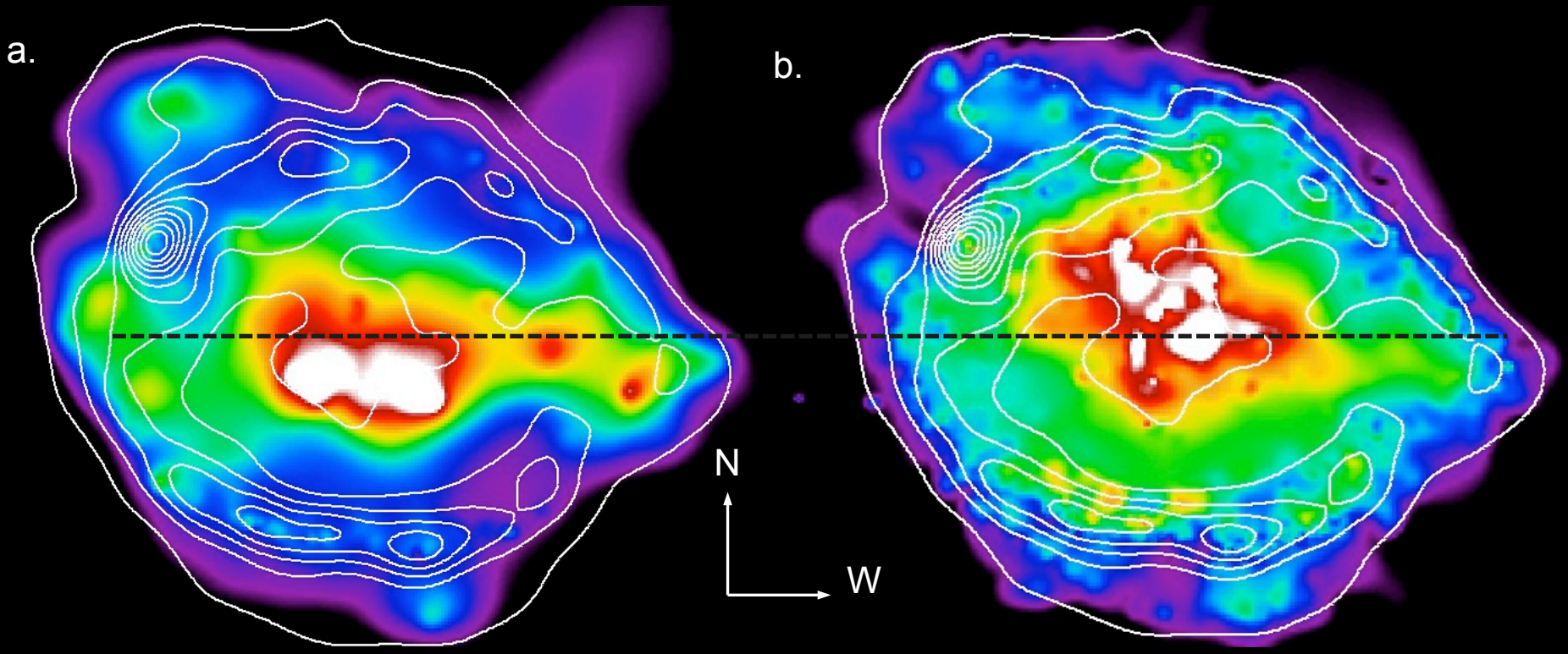
Si line EW



Si / (O + Mg)

Si & Fe line maps

Post et al. 2014



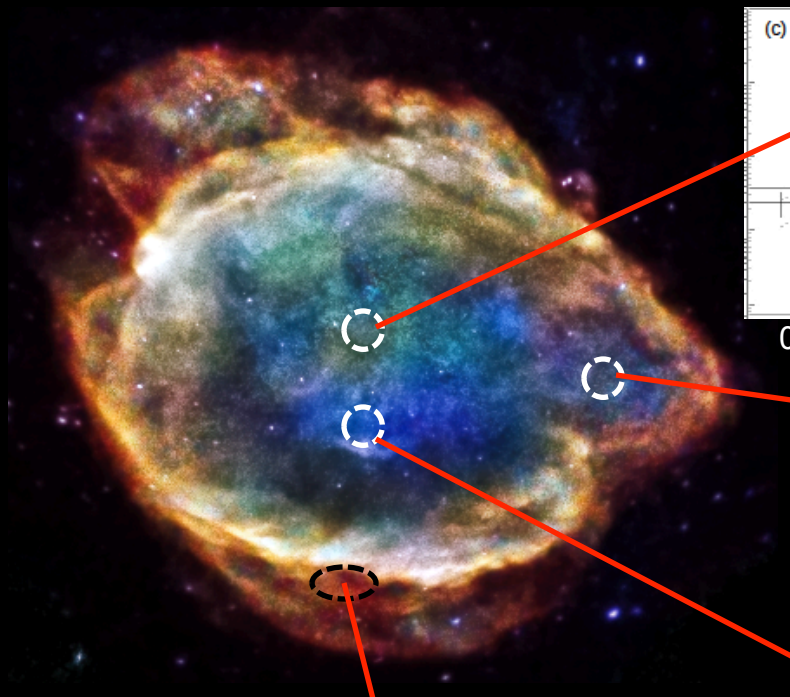
Si line EW

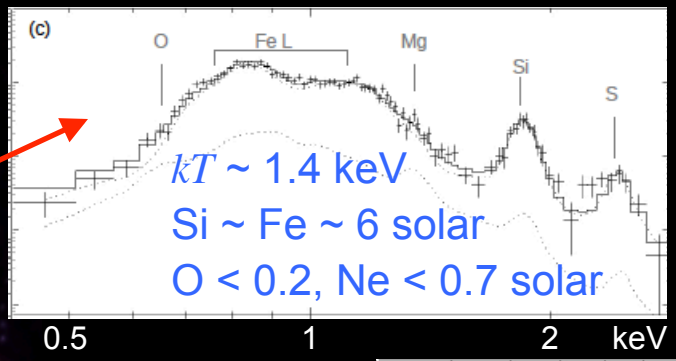
Fe line EW

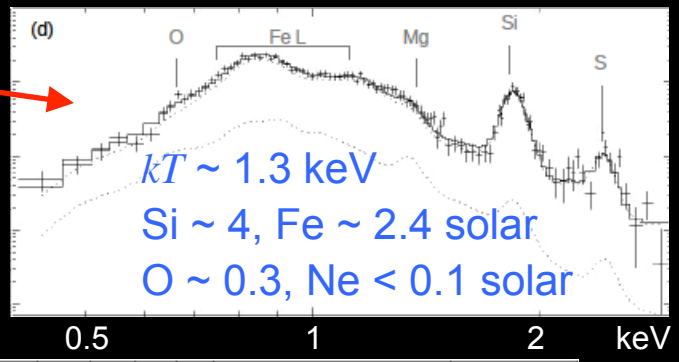
Asymmetric structure of enhanced Si and Fe (L) line emission

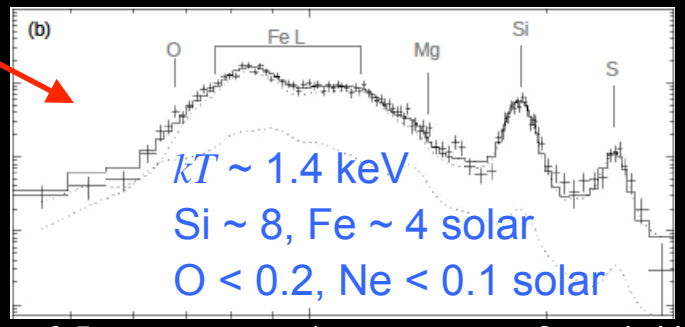
Characteristic Spectra

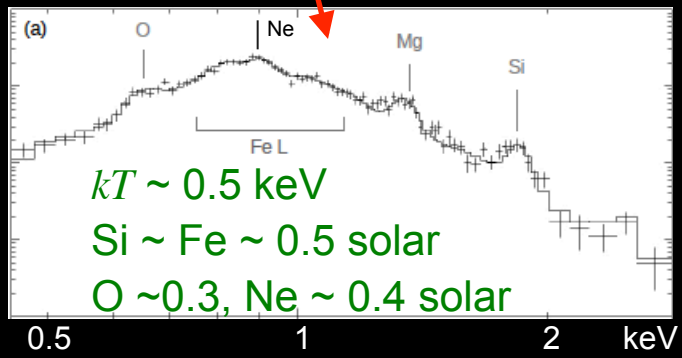
Post et al. 2014





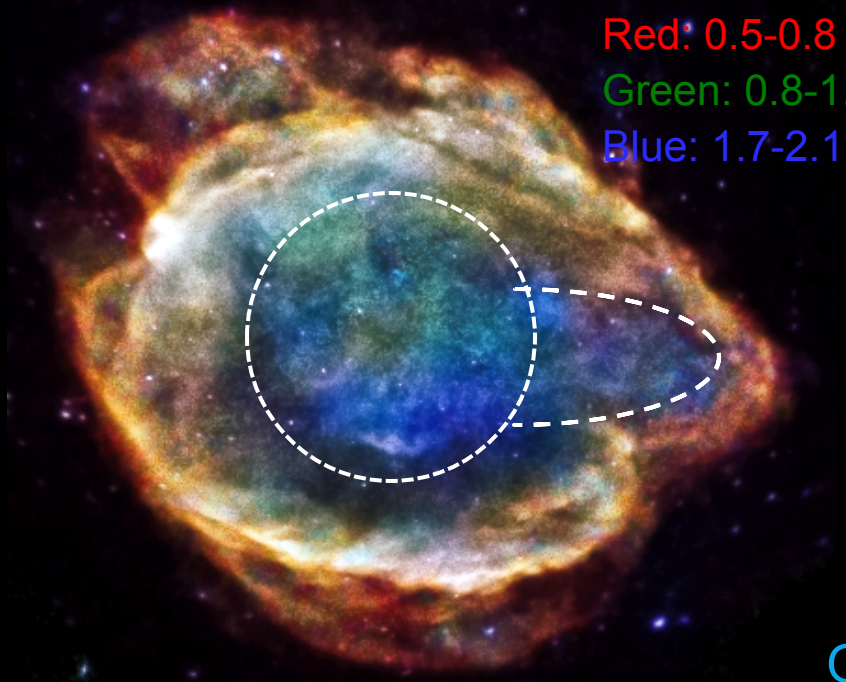






Ejecta Distribution

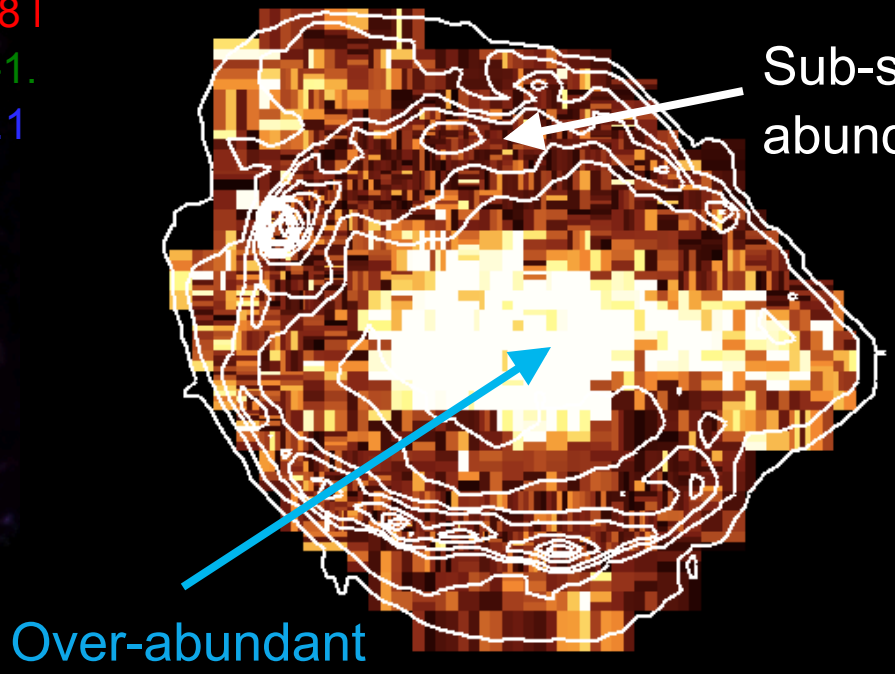
640 ks *Chandra* (***Post et al. 2014***)



Complete coverage with a ~20× deeper exposure

→ Central ejecta extends to west

χ^2_ν map (***Post et al. 2016, in prep***)

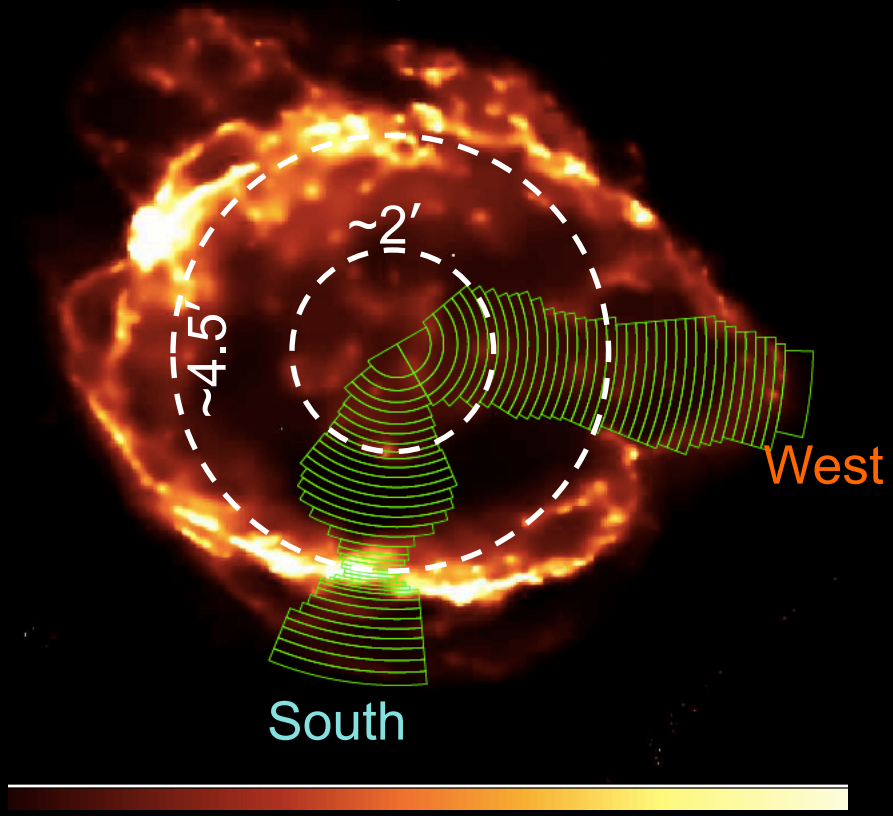


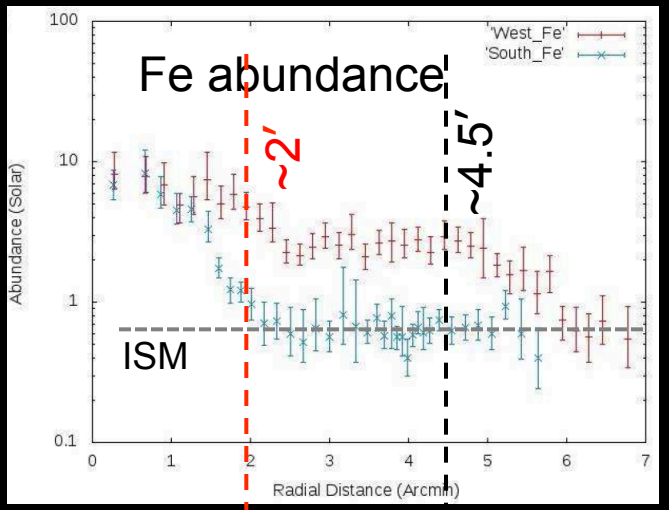
~1600 sub-regions with >1500 cts each. NEI-shock model fits with abundances fixed at shell values.

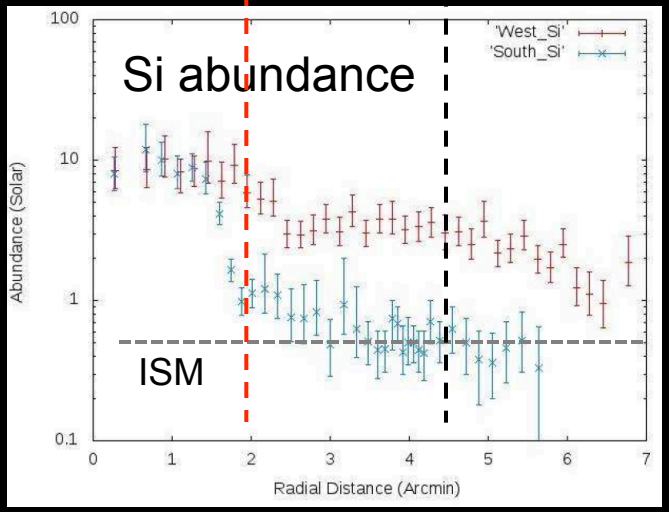
Ejecta Distribution

Detailed spatially-resolved spectral analysis

Post et al. 2016, in prep



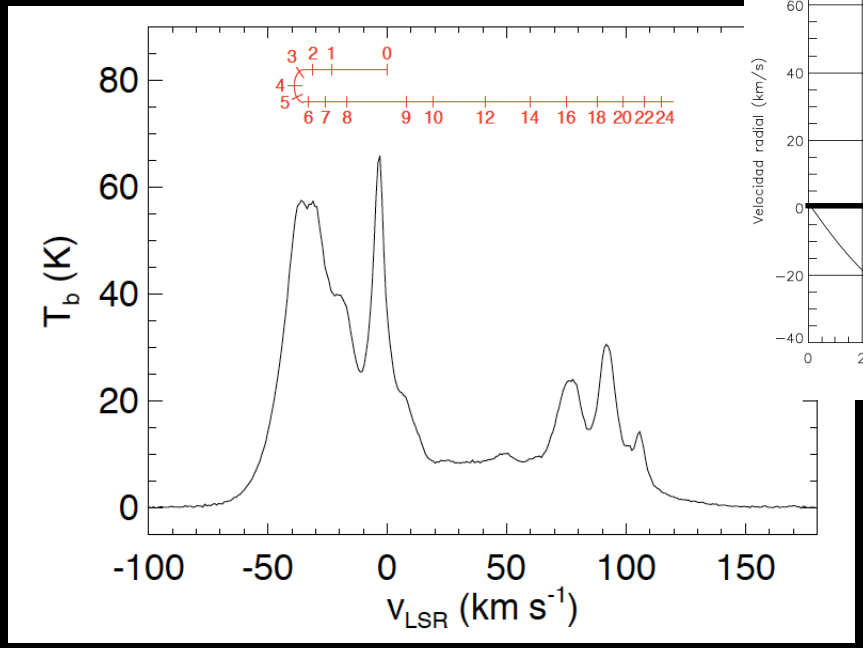


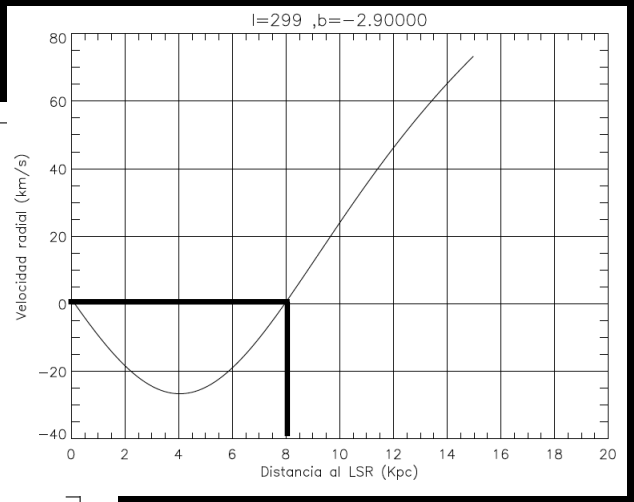


Constraint on Distance

Post et al. 2016, in prep

Parkes 21 cm survey
(Staveley-Smith et al. 1996)





HI fluxes toward G299.2-2.9
(l, b ~ 299°, -3°) & kinematic distances

HI flux (N_{HI} ~ 4.7 × 10^{21} cm^{-2} for $v \leq 0$ km s^{-1}) & X-ray column (N_H ~ 3.2 × 10^{21} cm^{-2}) place a conservative distance limit of $d < 8$ kpc for G299.2-2.9.

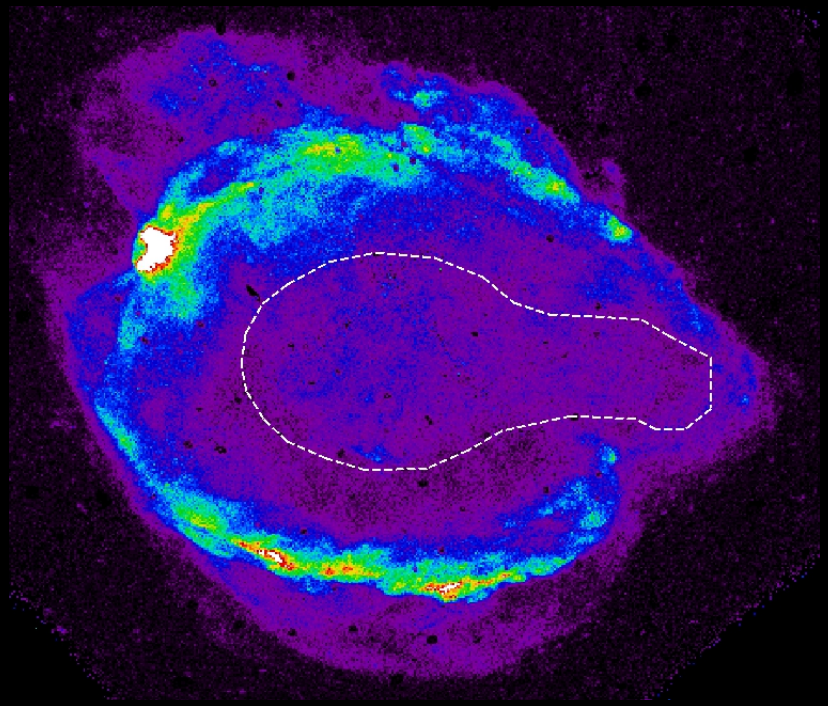
→ "d ~ 5 kpc"

($d \not> 10$ kpc)

Ejecta Mass

Post et al. 2016, in prep

Contact discontinuity map



For d = 5 kpc

Fe mass: ~0.2 $M_\odot$

E_0 ~ 2 - 4 × 10^{50} erg

$\tau_{\rm Sed}$ ~ 3800 – 4400 yr

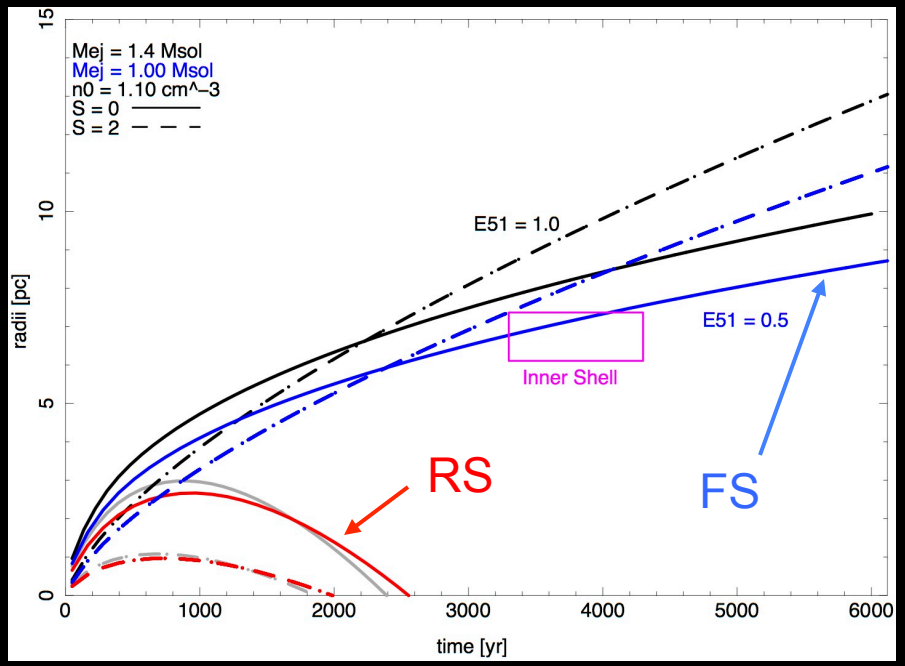
Total ejecta mass for FS/CD ratio of ~2.1 (inner) and ~2.6 (outer) (Wang & Chevalier 2001, Hughes et al. 2003): $M_{\rm ej}$ ~ 0.3 - 1 $M_\odot$

Dynamics & Energetics

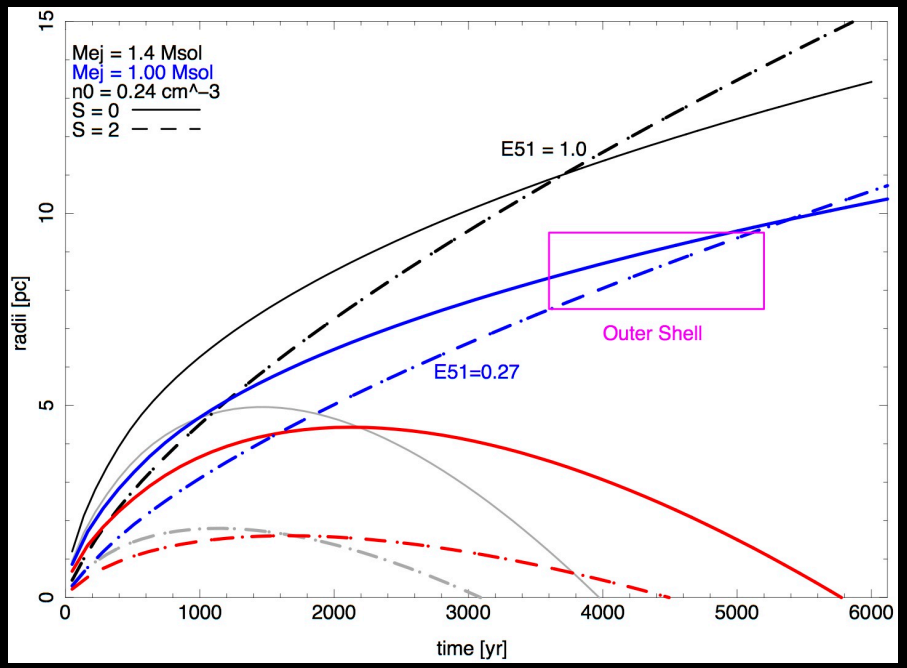
Post et al. 2016, in prep

1-D model calculations for SNR dynamics (Truelove & McKee 1999) compared with G299.2-2.9

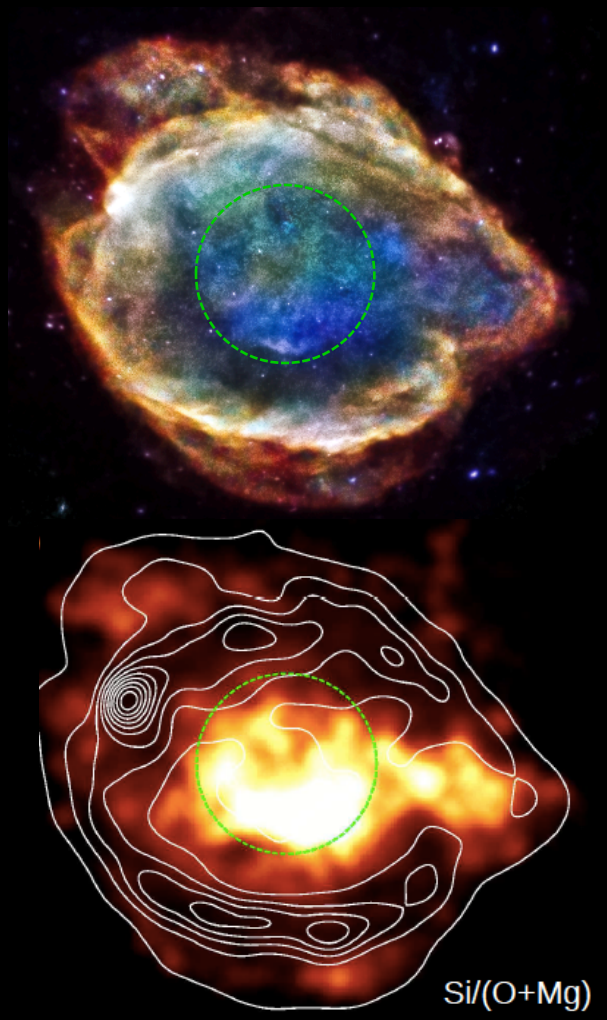
For inner shell



For outer shell



Origin of Asymmetric Ejecta?



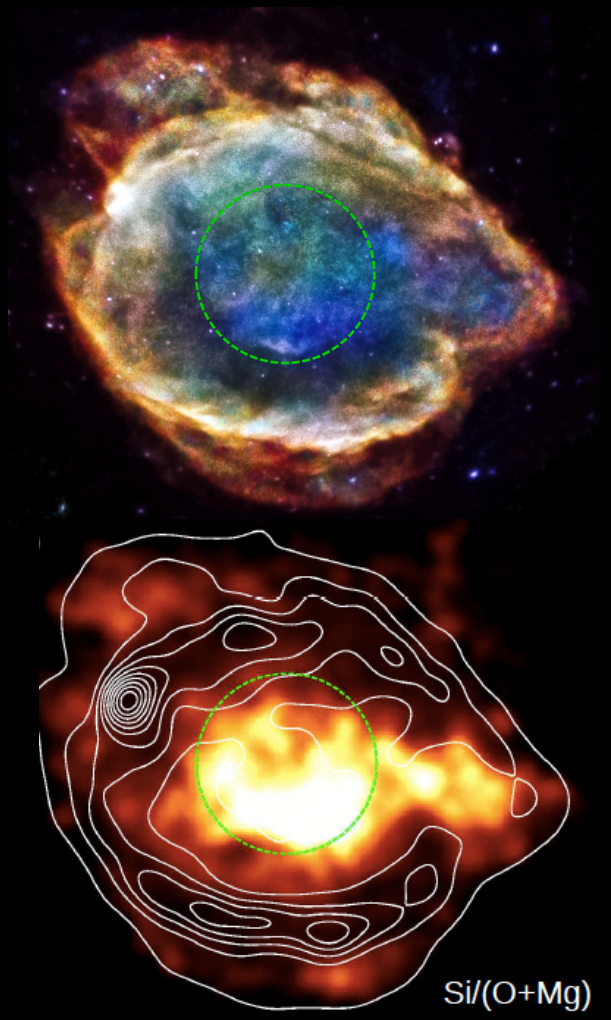
Post et al. 2014

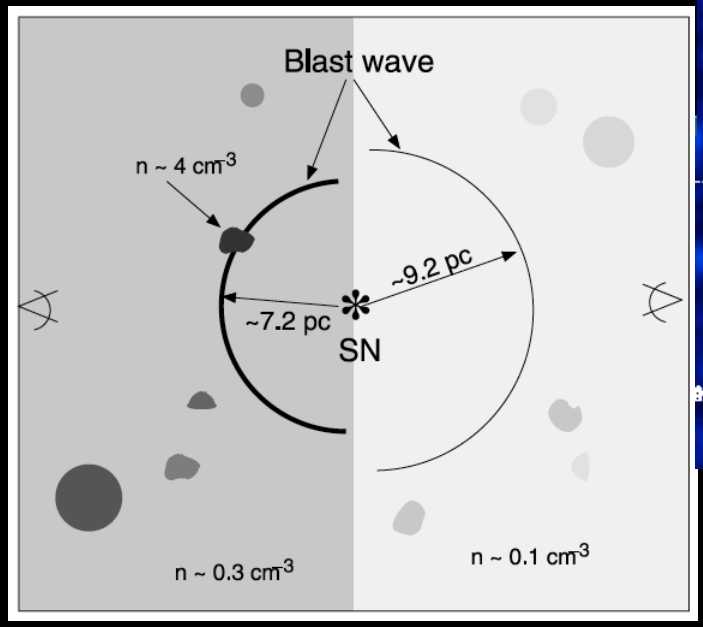
→ Asymmetric Type Ia explosion?

Multiple off-center ignitions, double-detonation (e.g., *Maeda et al. 2010, Fink et al. 2010*)

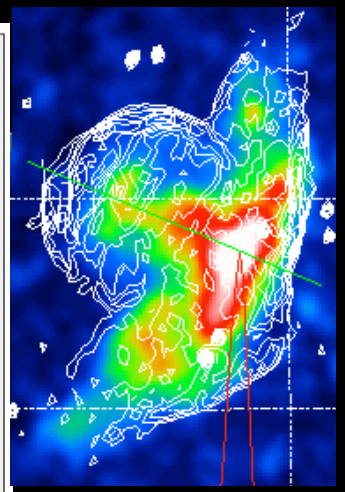
Can such an explosion produce *"one-sided"* ejecta outflows (that would sustain for ~4000 yr after the explosion)?

Origin of Asymmetric Ejecta?





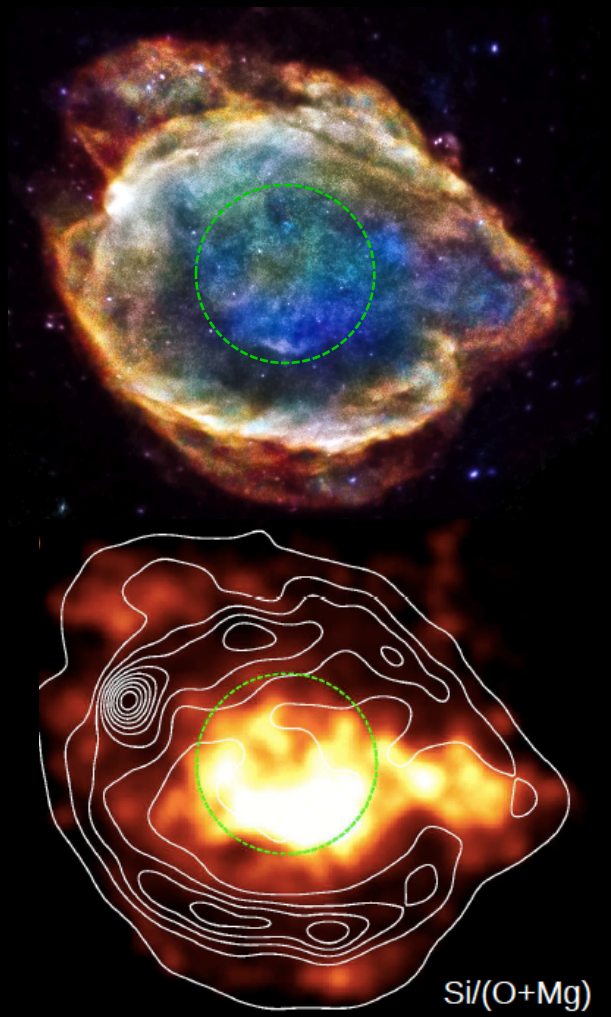
SP et al. 2007

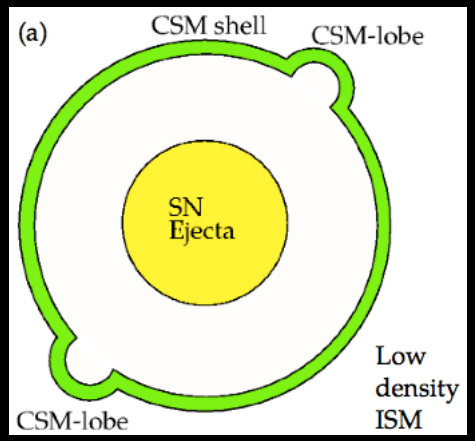


VRO 42.05.01 (Burrows & Guo 1994)

→ Ejecta expansion through non-uniform medium along the line of sight ?

Origin of Asymmetric Ejecta?





→ Ejecta expansion altered by modified CSM?

PN-like bi-polar outflows from the companion star (*Tsebrenko & Soker 2013*) ?

G299.2-2.9: Summary

Type Ia SNR with non-symmetric ejecta and environment:

→ Asymmetric explosion and/or surrounding?

Ejecta mass and energetics: $M_{\rm Fe} \sim 0.2\ M_\odot$, $M_{\rm ej} \lesssim 1\ M_\odot$
$E_0 \sim 3 \times 10^{50}$ erg

→ Sub-energetic (low-L , e.g., sub-$M_{\rm Ch}$) Type Ia SN?

→ Cosmic-ray effect ?

→ True geometry of reverse-shocked ejecta ?
(*Hitomi* could've helped..)