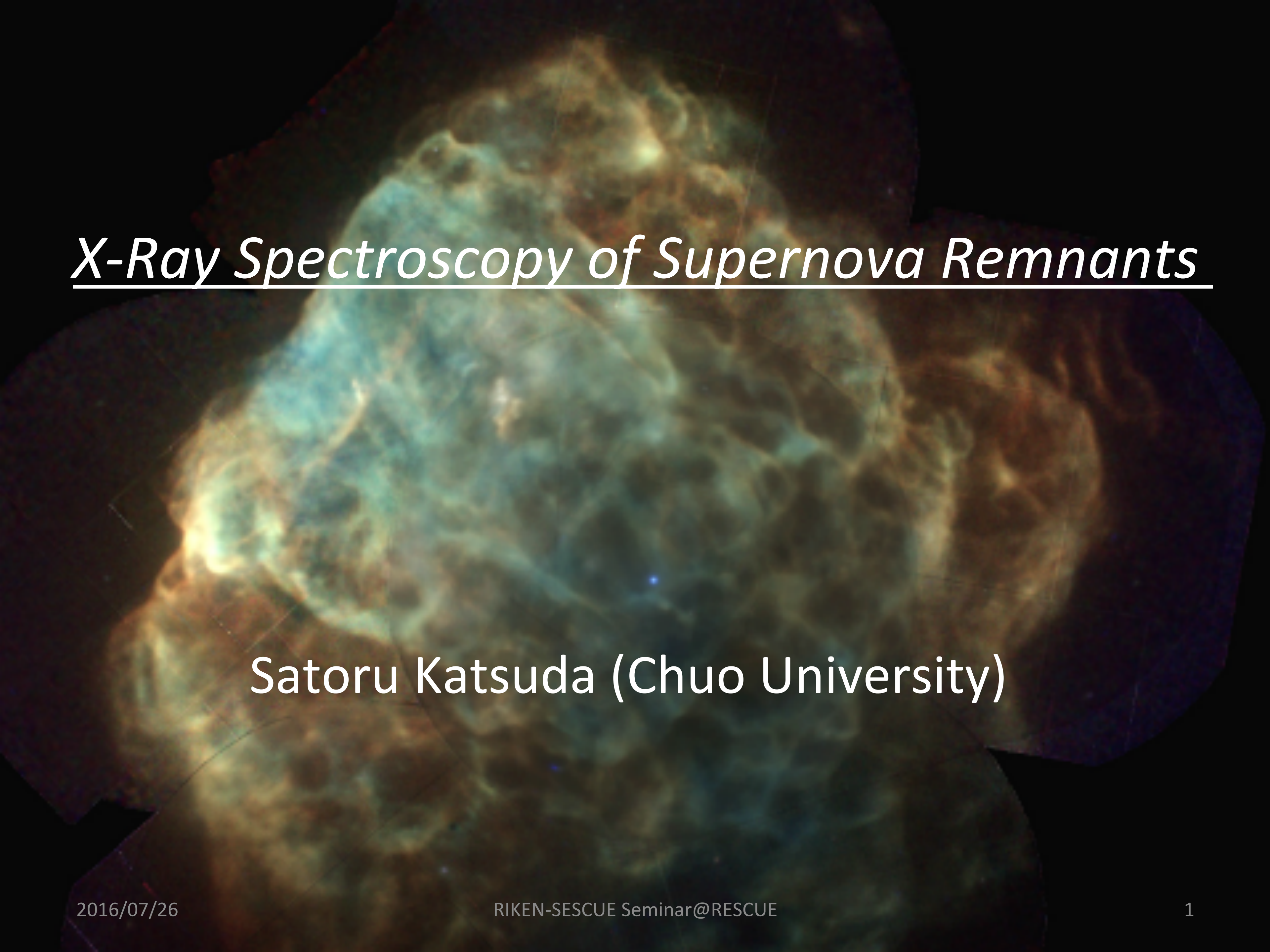
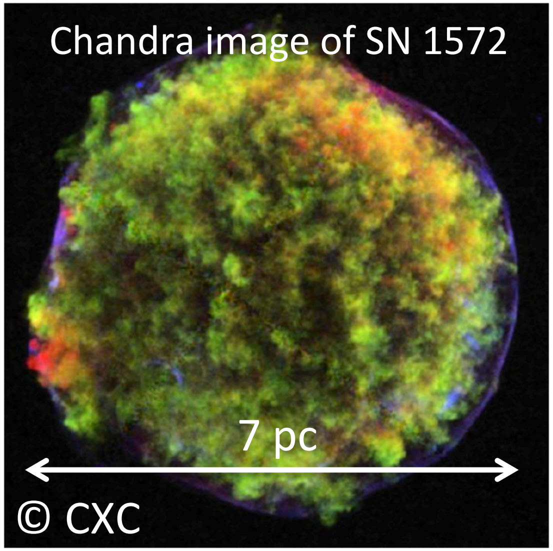
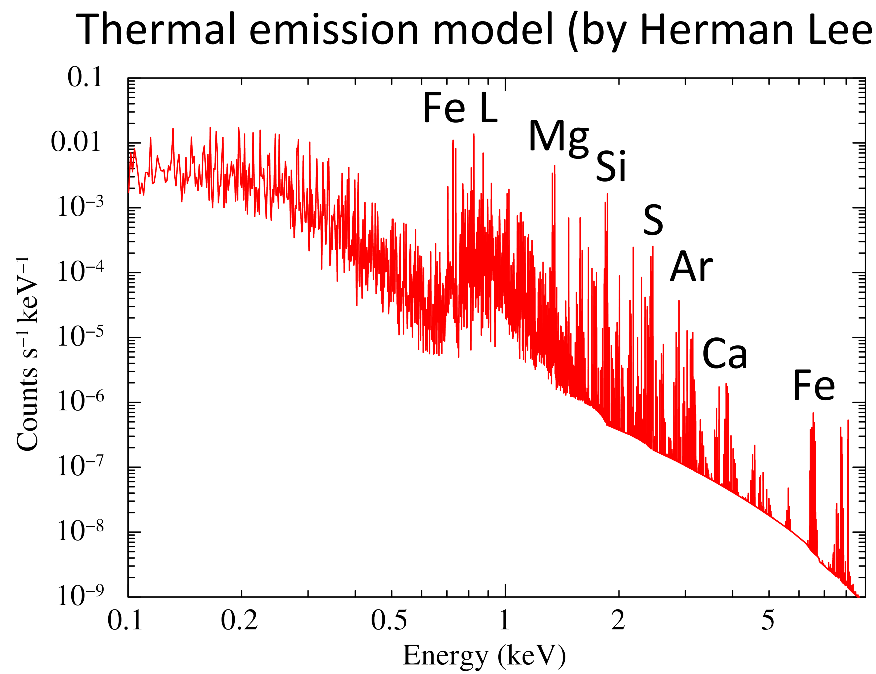


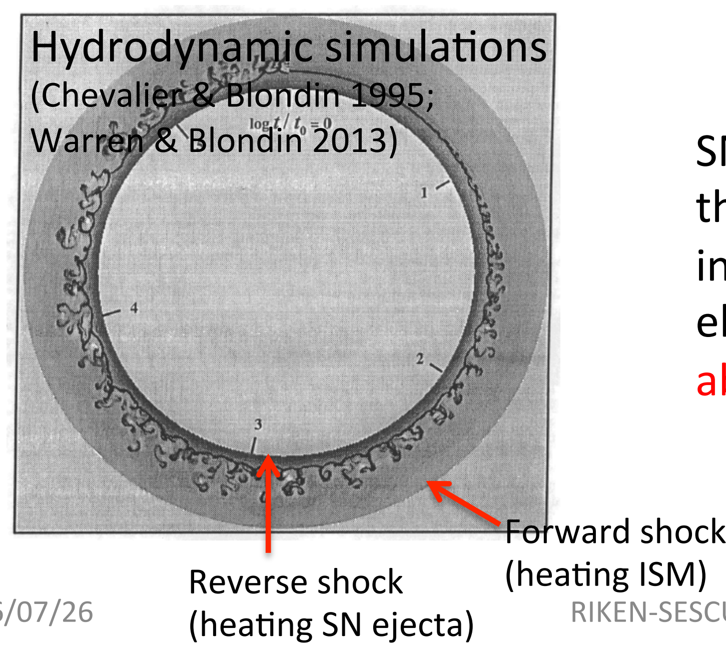
X-Ray Spectroscopy of Supernova Remnants

Satoru Katsuda (Chuo University)

SuperNova Remnant (SNR)





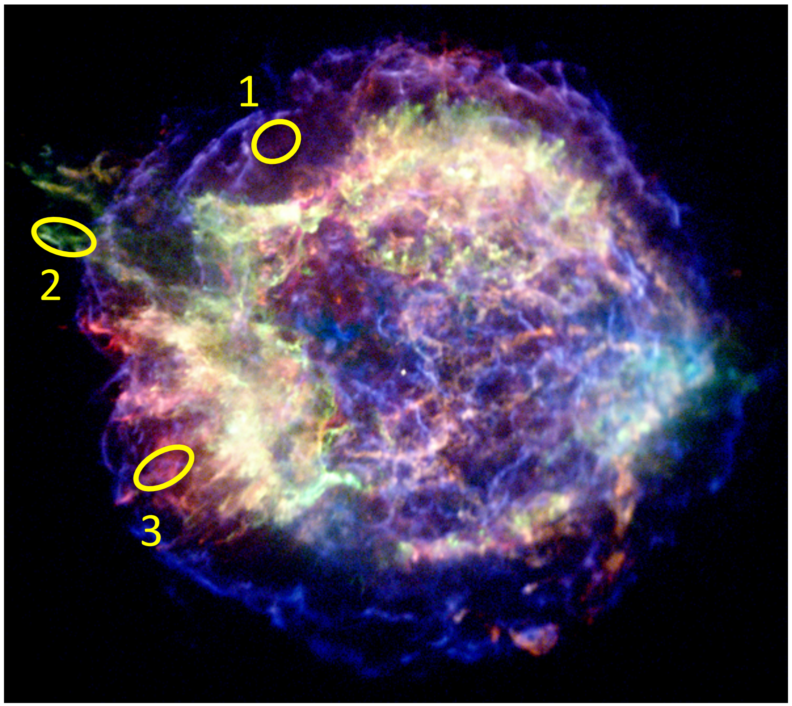


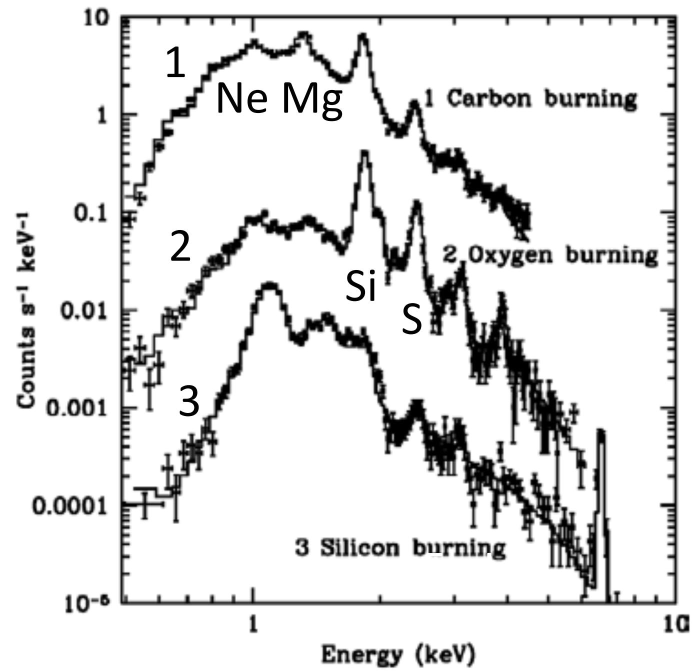
SNRs are usually extremely hot (~10^7 K), so that they can efficiently emit X-rays. The X-ray emission includes a number of lines from almost all elements, allowing us to measure elemental abundances as well as elemental distribution.

X-ray observations of SNRs can directly test SN nucleosynthetic/explosion models.

Imaging Spectroscopy with X-Ray CCDs

X-ray CCDs allowed for detailed spatially-resolved spectroscopy.



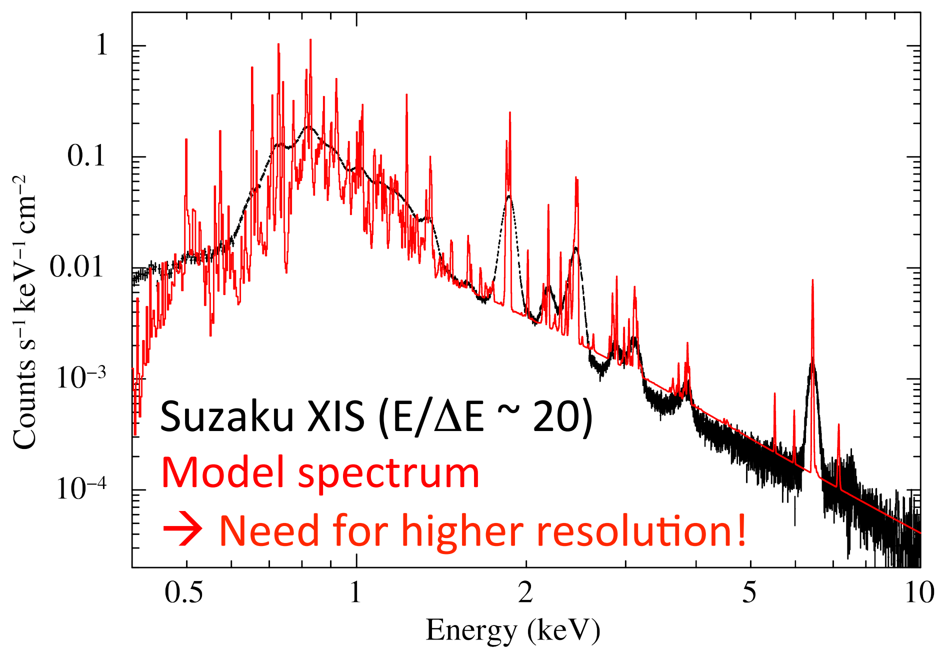


Vink (2004)

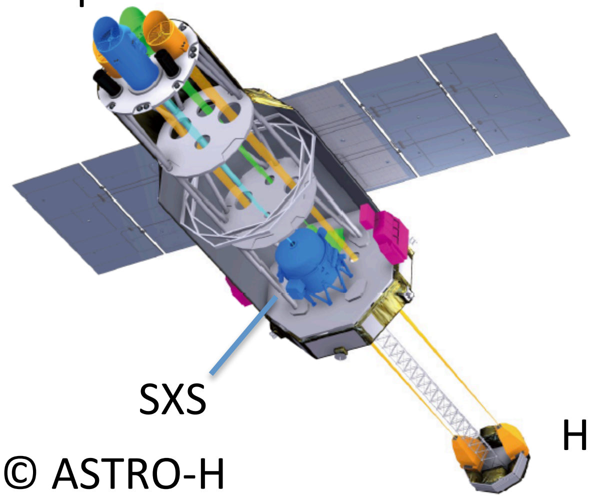
- □ The jets are rich in Si (Not Fe!).
- □ There seems to be inversion of Si and Fe in the SE.

Need for High-Res. X-Ray Spectroscopy (E/ΔE>100)

- Ejecta dynamics
  - Reconstruction of 3D ejecta structures
    - → Explosion asymmetries & NS kicks
- Collisionless shock physics
  - T_i-T_e equilibration
  - Cosmic-ray acceleration
- Plasma diagnostics
  - Thermodynamic parameters
  - New radiative processes
- Composition measurements
  - Odd-Z/neutron-rich elements



High-Resolution Spectroscopy with Hitomi



© ASTRO-H

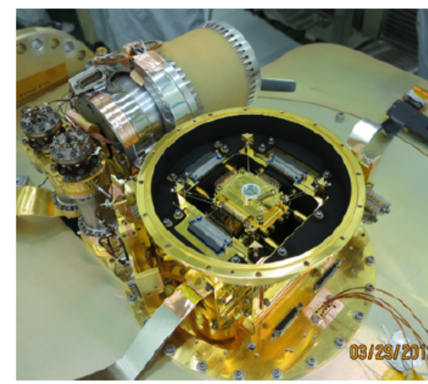

Astronomy Picture of the Day (2016-02-18) © F.S. Porter

□「ASTRO-H」→「Hitomi」:

- The 6th Japanese X-ray astronomy satellite
- Successfully launched on 2/17
- Lost its ground contact on 3/26

□ X-ray micro-calorimeter (SXS):

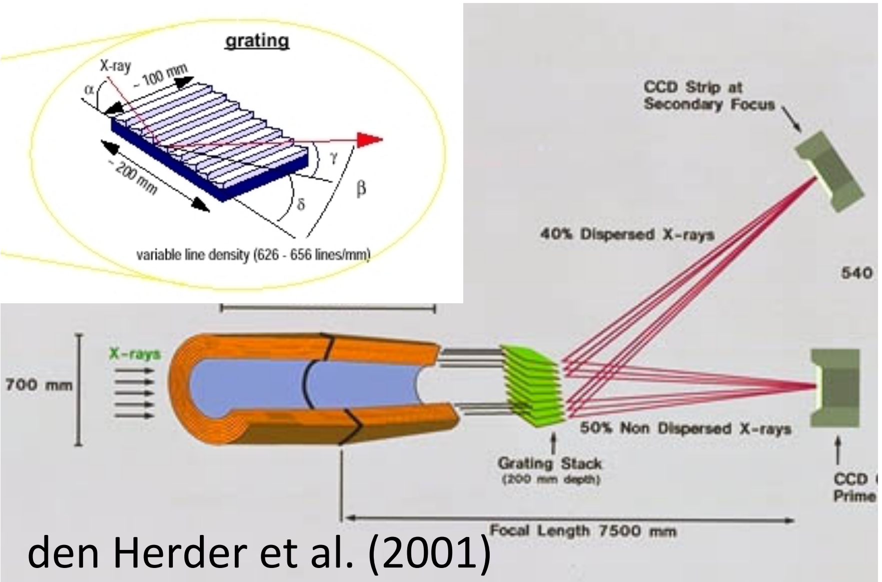
- E/ΔE: ~200@1keV (Non-dispersive!)
- Spatial resolution: 1’
- FoV: 3’x3’ (6x6 array)
- Dynamic range: 0.2-10 keV



SXS detector assembly

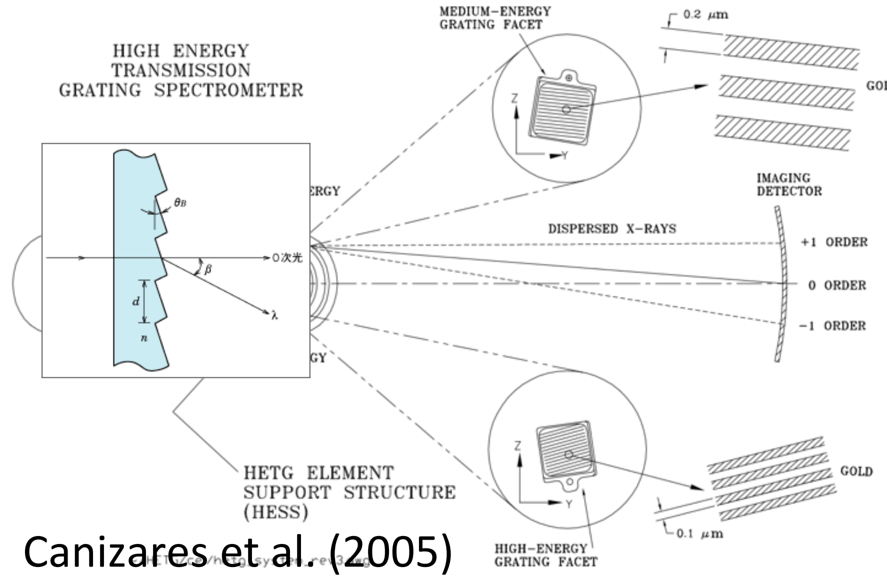
Gratings onboard XMM-Newton & Chandra

XMM-Newton (RGS)



den Herder et al. (2001)

Chandra (H/LETG)



Canizares et al. (2005)

Reflection grating

Slitless → Degradation in λ resolution:

$\Delta\lambda \sim 0.13 * \Delta ext(arcmin)$ Å

Δext_{min}(spatial resolution): 0.25'

($E/\Delta E \sim 200$ @1keV; cf. $E/\Delta E \sim 20$ for CCD)

Strong for relatively large sources (a few arcmin size is OK)

Transmission grating

Slitless → Degradation in λ resolution:

$\Delta\lambda \sim 0.67 * \Delta ext(arcmin)$ Å

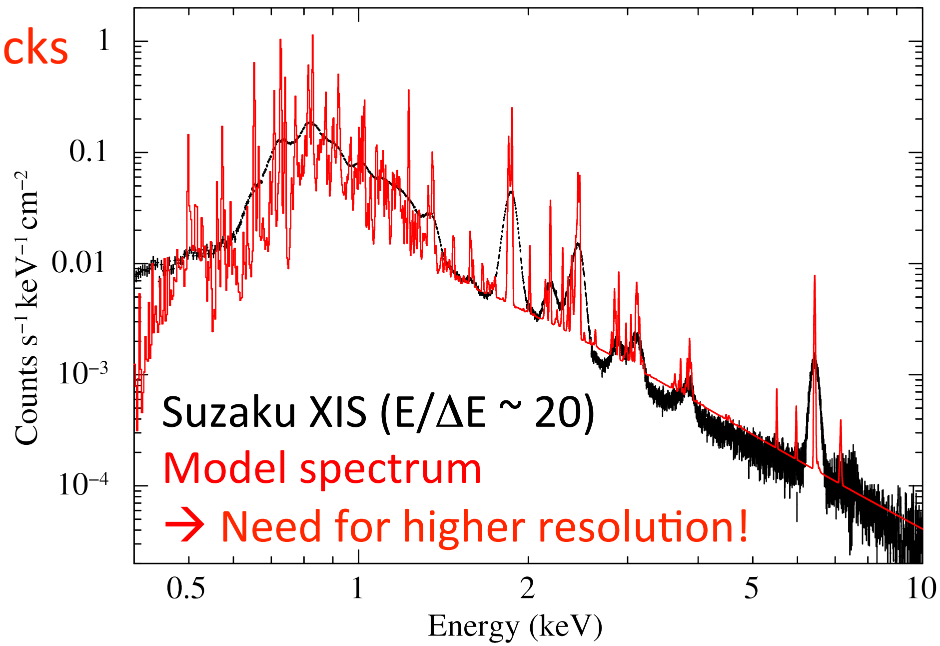
Δext_{min} (spatial resolution): 0.01'

Strong for small(")-scale features

complementary

High-Res. X-Ray Spectroscopy (E/ΔE>100)

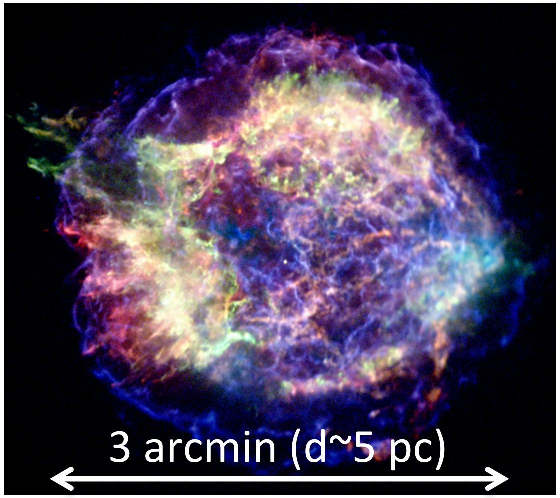
– Ejecta dynamics
  - 3D ejecta structures
    → Explosion asymmetries & NS kicks
– Collisionless shock physics
  - T_i-T_e equilibration
  - Cosmic-ray acceleration
– Plasma diagnostics
  - Thermodynamic parameters
  - New radiative processes
– Composition measurements
  - Odd-Z/neutron-rich elements



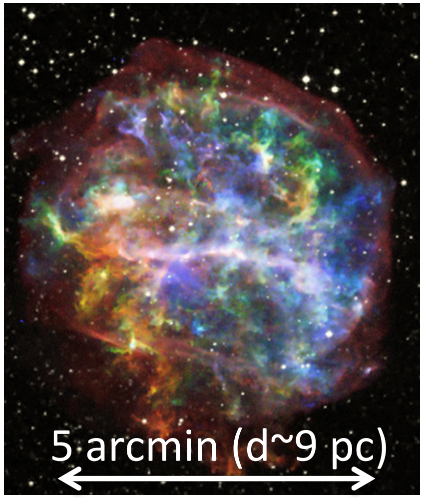
Good Targets to Reveal Ejecta Dynamics

- Galactic (so-called) Oxygen-rich SNRs

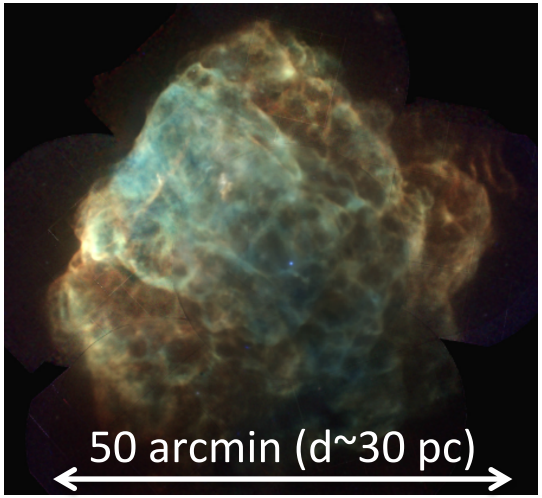
Cassiopeia A (~340 yr old)



G292.0+1.8 (~3000 yr old)



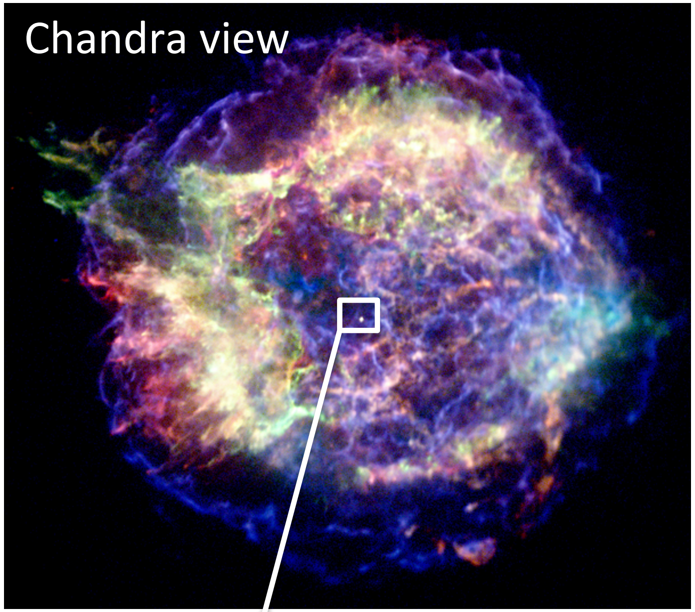
Puppis A (~4500 yr old)



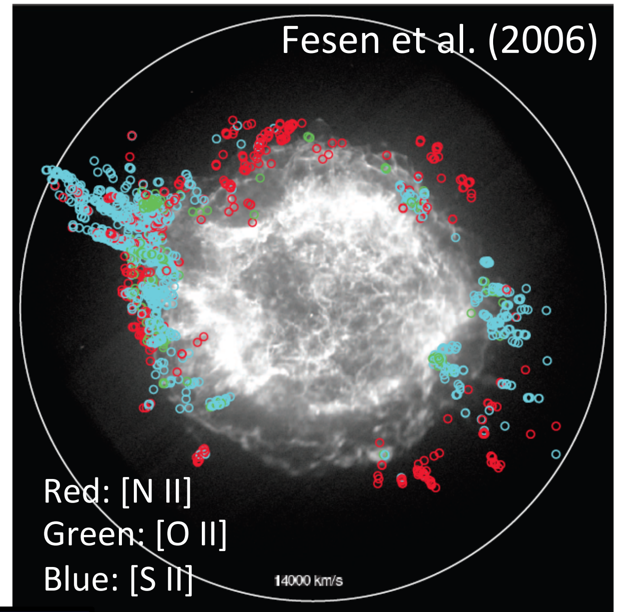
Very small-scale (″-scale) knots are suitable for the Chandra HETG.

Small-scale (′-scale) knots are suitable for the XMM-Newton RGS.

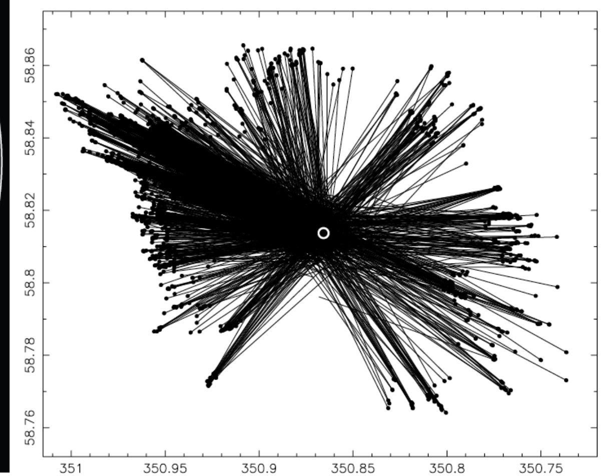
Cassiopeia A: NS Kick?



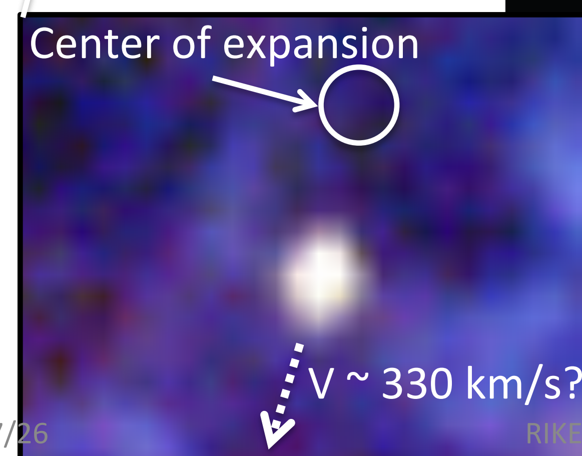
□ Optical fast-moving knots



Proper motion of the knots



□ Neutron star

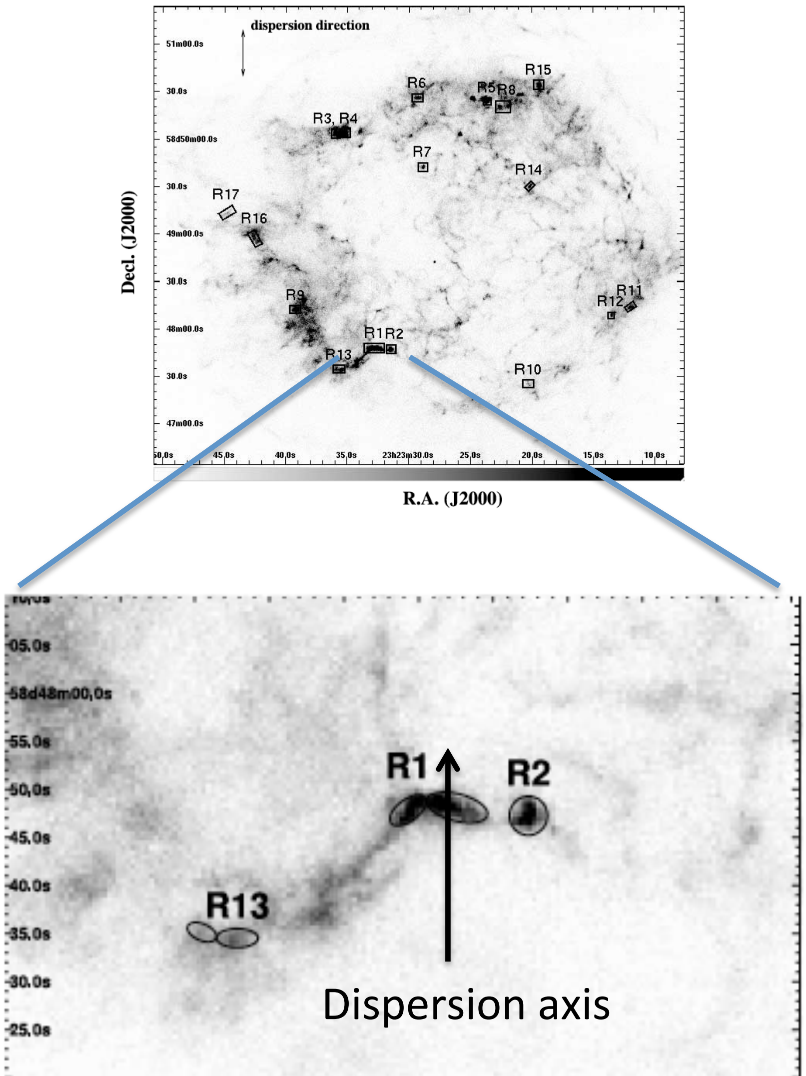


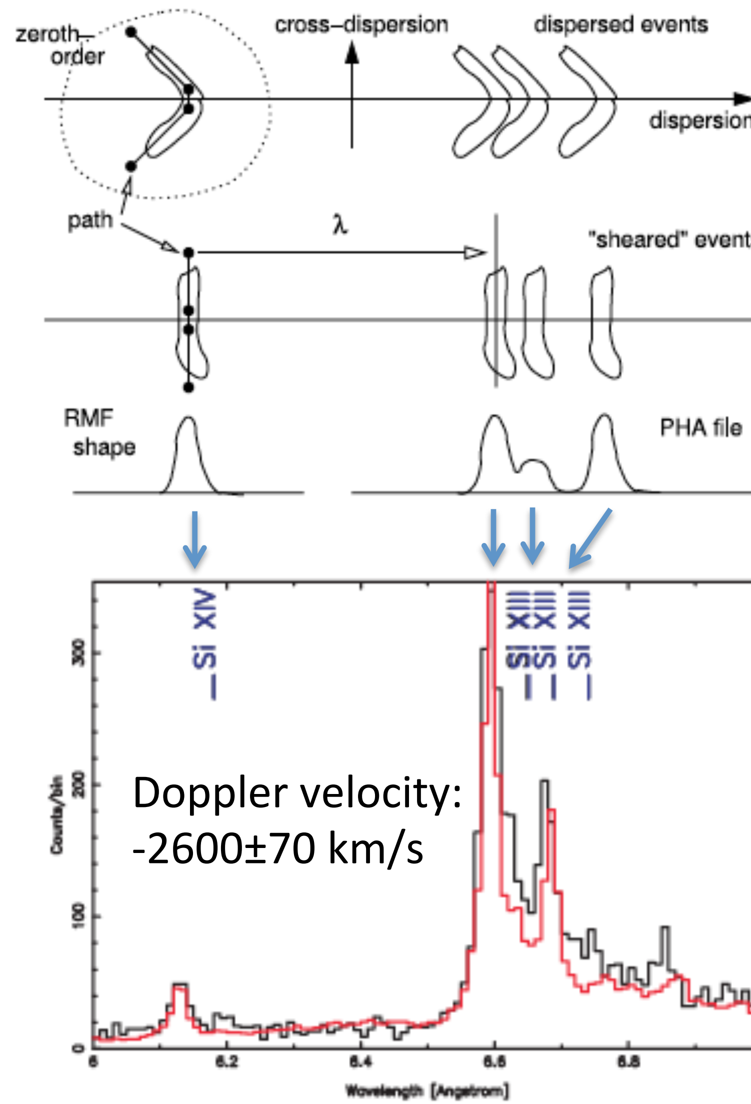
(proper motion not yet measured)

The NS is displaced from the expansion center, suggesting a kick.

Spectroscopy with the Chandra HETG

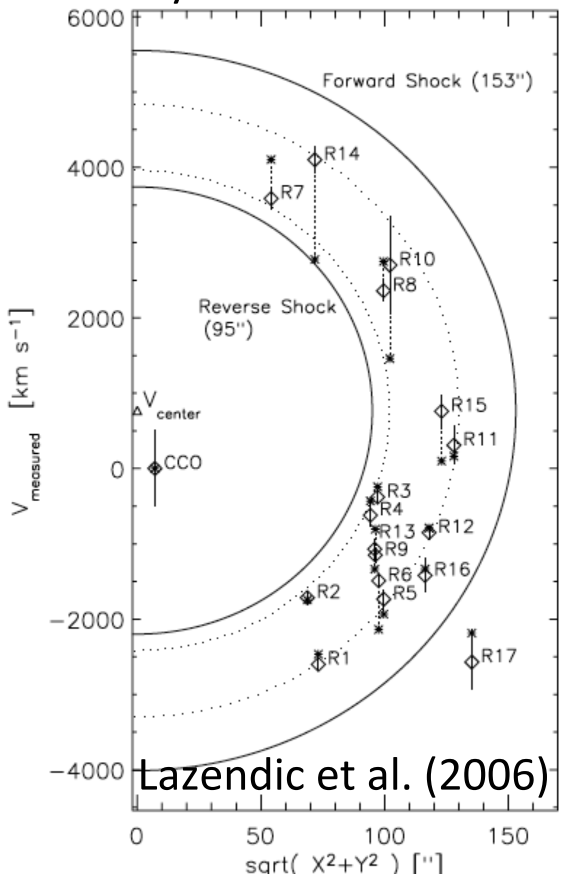
Lazendic et al. (2006)





Doppler Velocities → 3D Structure

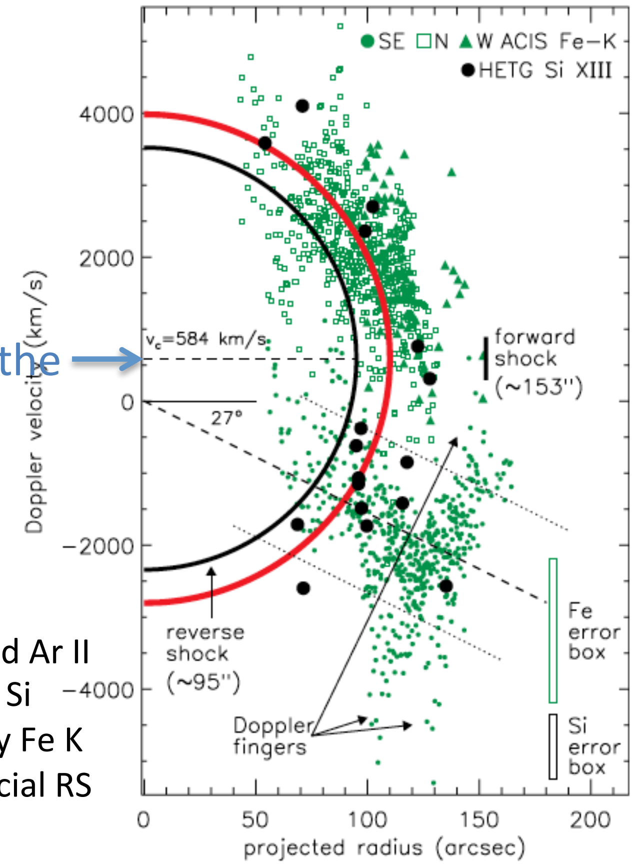
Line of sight locations of 21 knots measured by Si K lines



Line of sight

DeLaney et al. (2010) added Fe (X-ray) as well as Ar data (infrared).

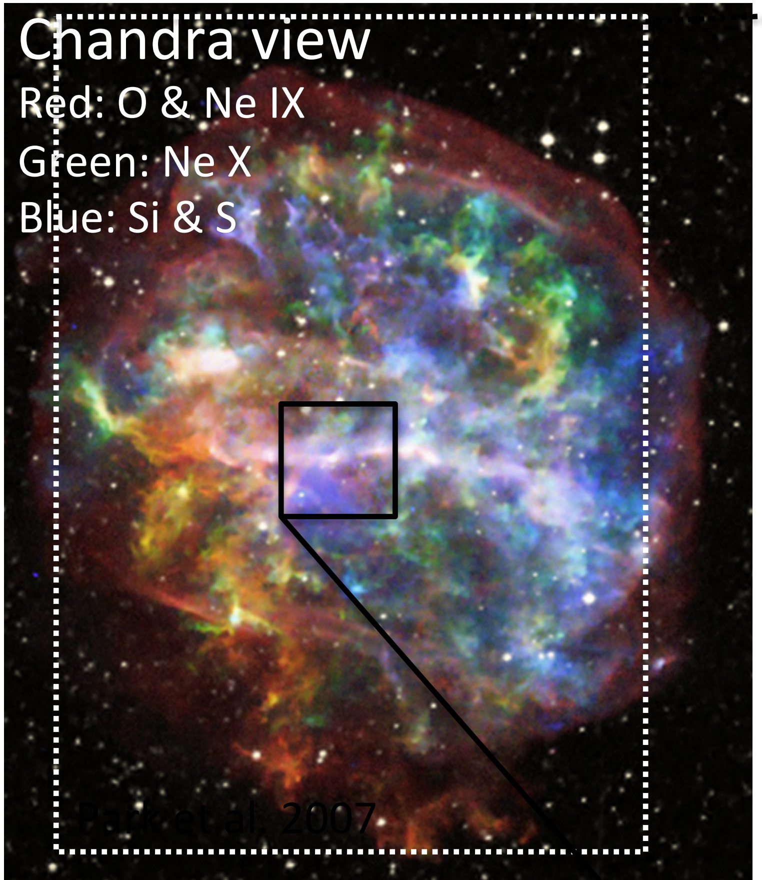
The center of the fitted sphere.



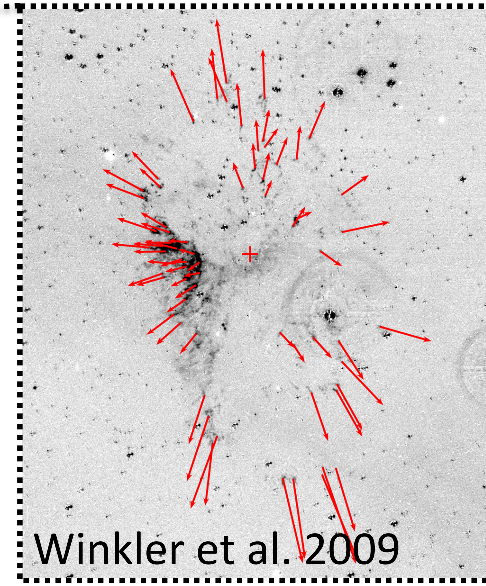
Red: Infrared Ar II
Black: X-ray Si
Green: X-ray Fe K
Peach: Fiducial RS

→ V_{center} = +589 km/s
(CCO's velocity is unknown)

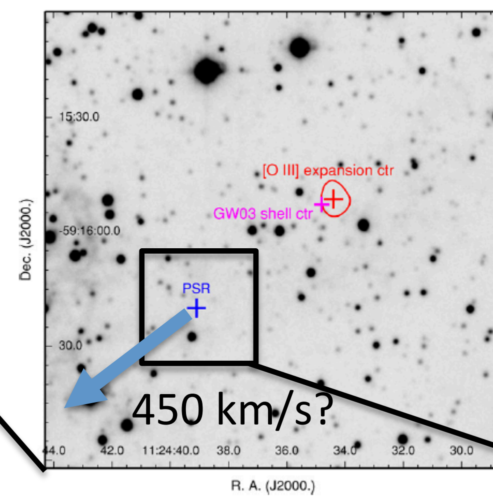
G292.0+1.8



□ Fast-moving knots in optical



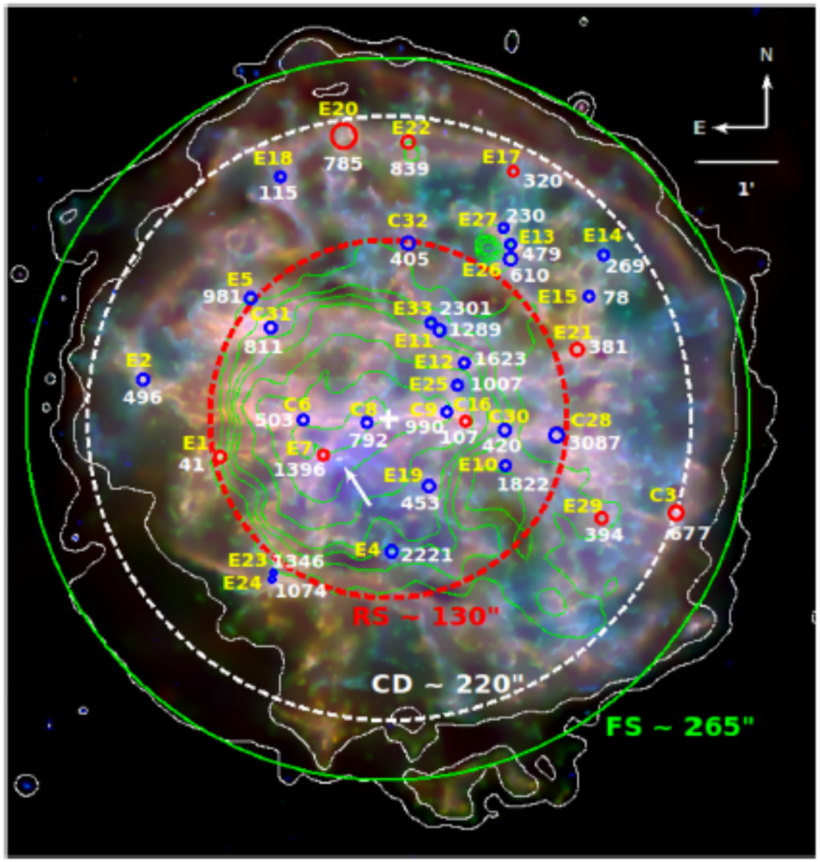
□ NS displacement

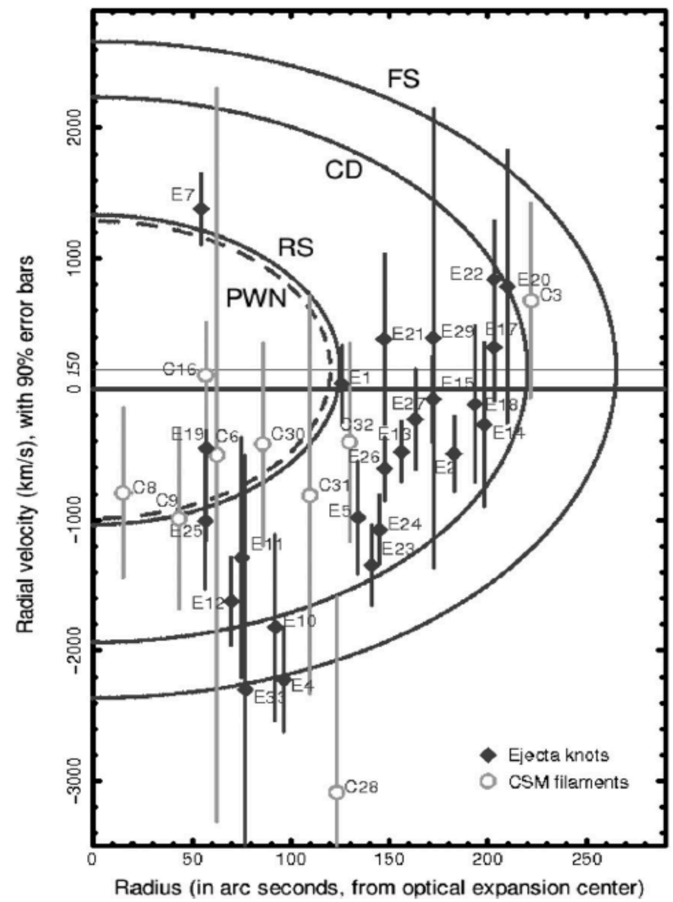


Neutron star & its wind nebula

High-Res. X-Ray Spectroscopy with HETG

Bhalerao et al. (2015)

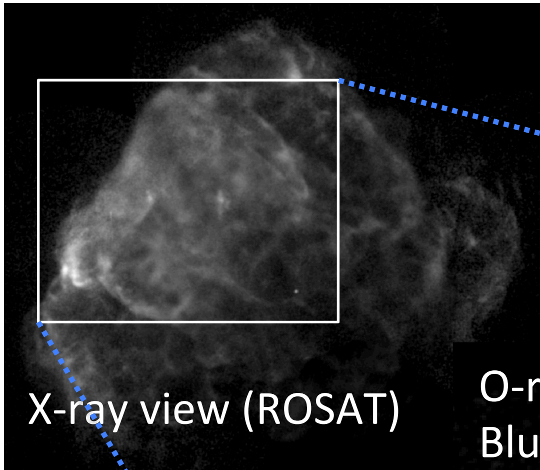




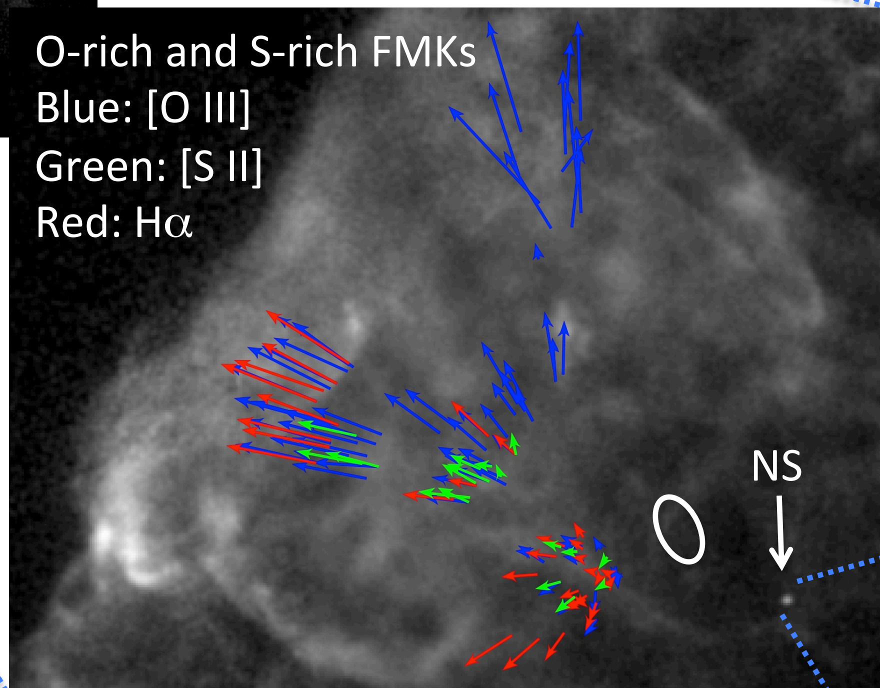
□ The ejecta are biased to the near side. → Asymmetric explosion?

□ The ejecta distribution suggests R_{RS}/R_{FS} ~ 0.5.

Puppis A:
Recoil between Ejecta and NS

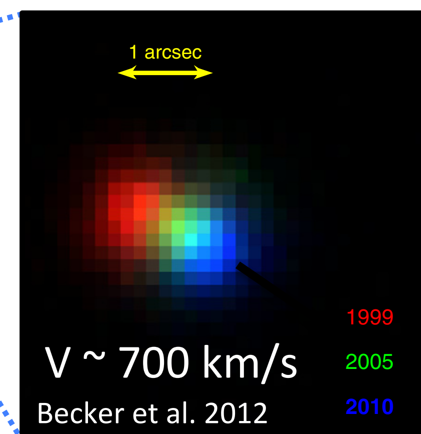


Proper motions of fast-moving ejecta knots



Winkler & Kirshner 1985; Garber et al. 2010

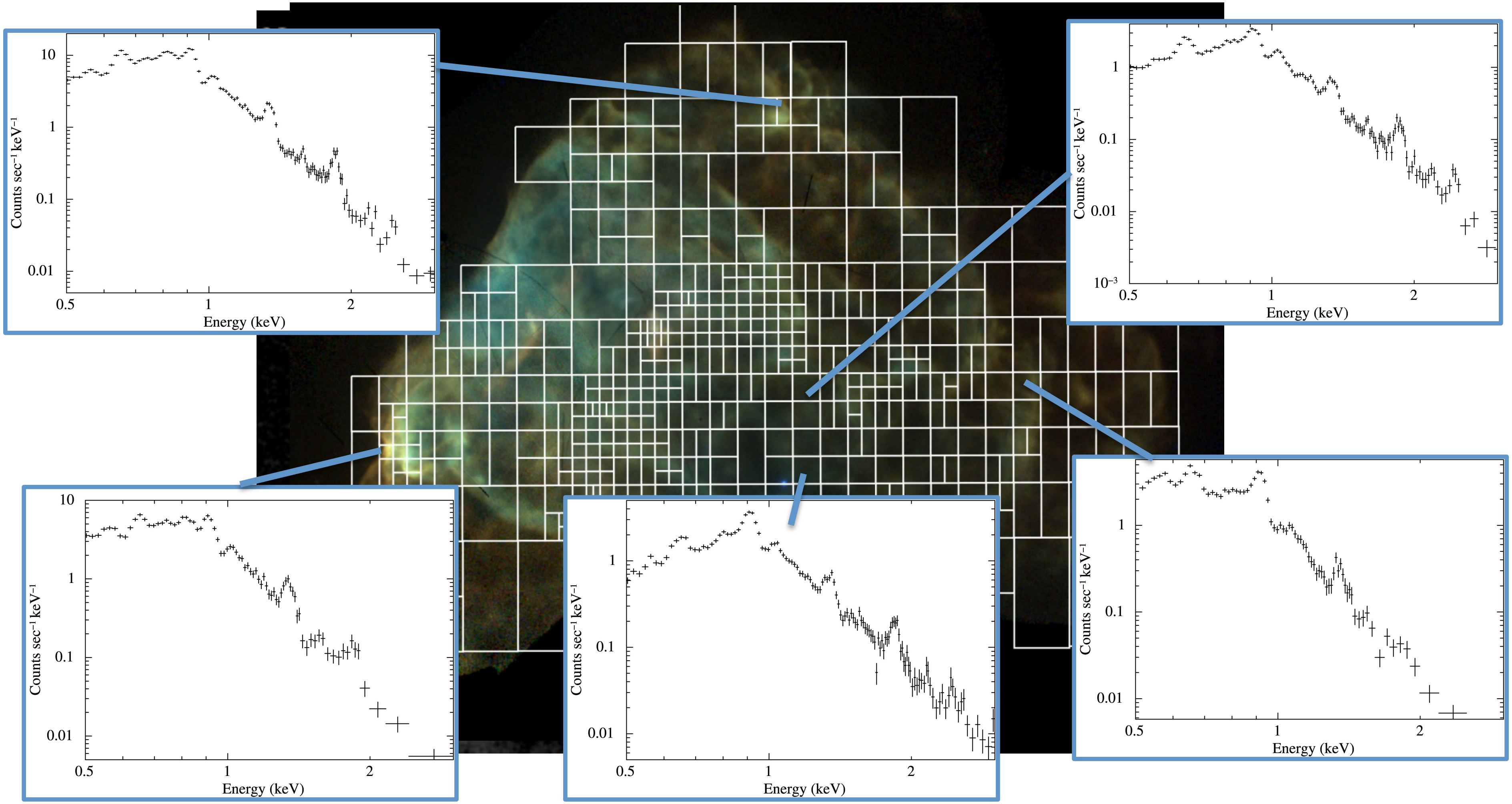
Fast-moving NS



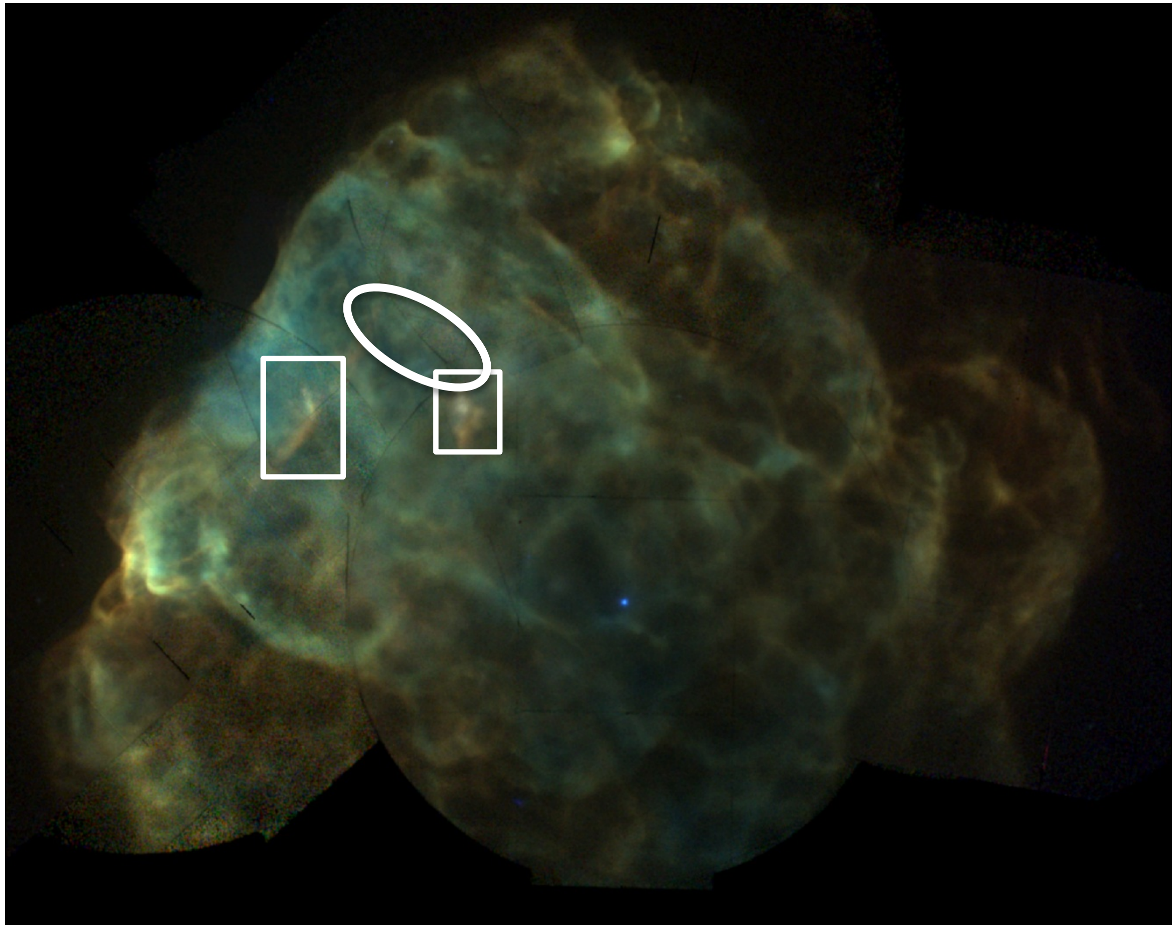
- □ One-sided O-rich fast-moving knots
- □ A recoiling (fast-moving) neutron star

Searching for Ejecta with X-Ray CCDs

SK 2008 PhD thesis

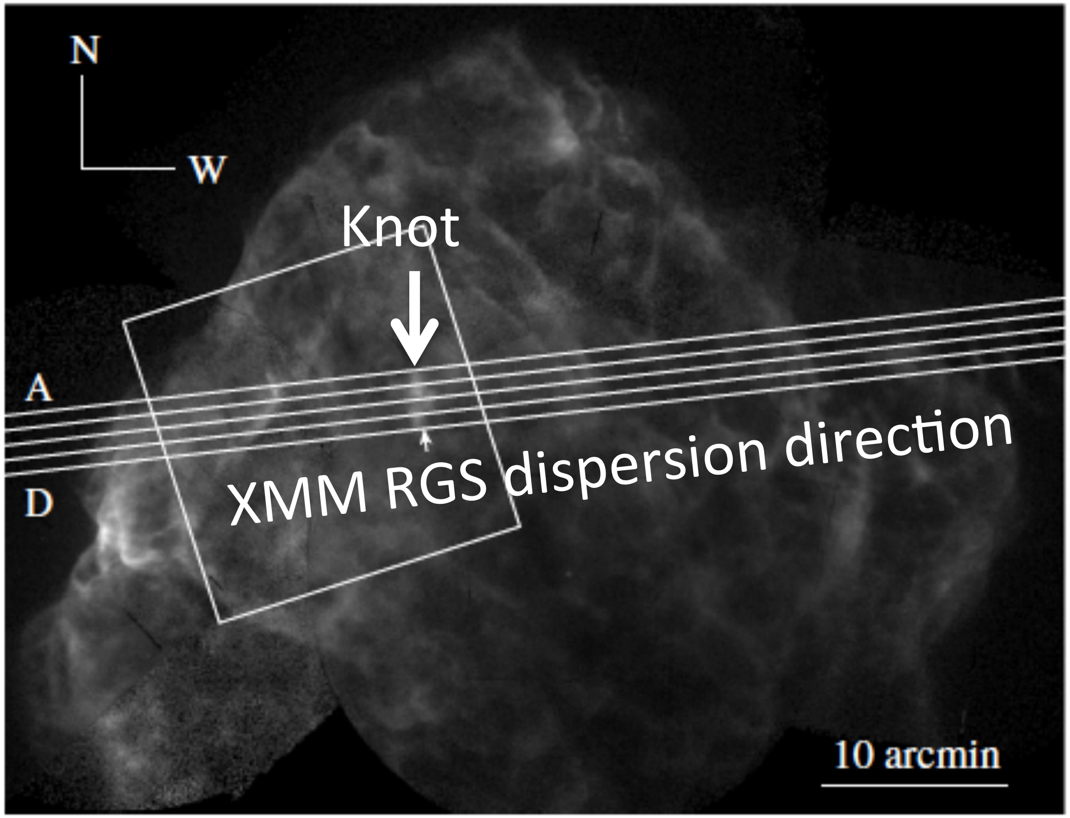


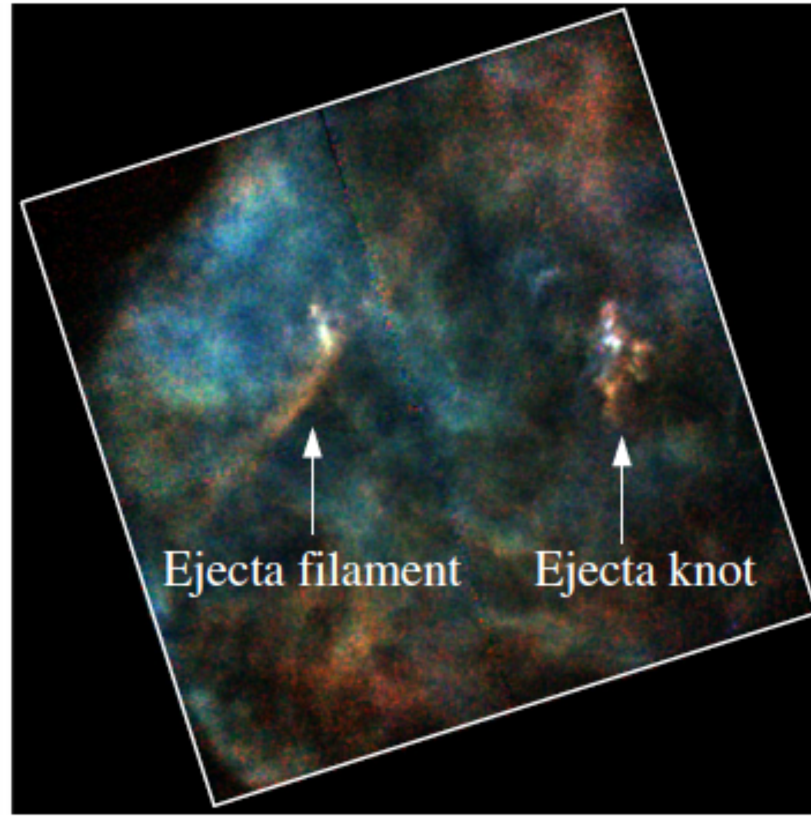
Discovery of X-Ray Emitting Ejecta



Mostly ISM. But, we do find ejecta which are concentrated in the NE. → Asymmetric explosion

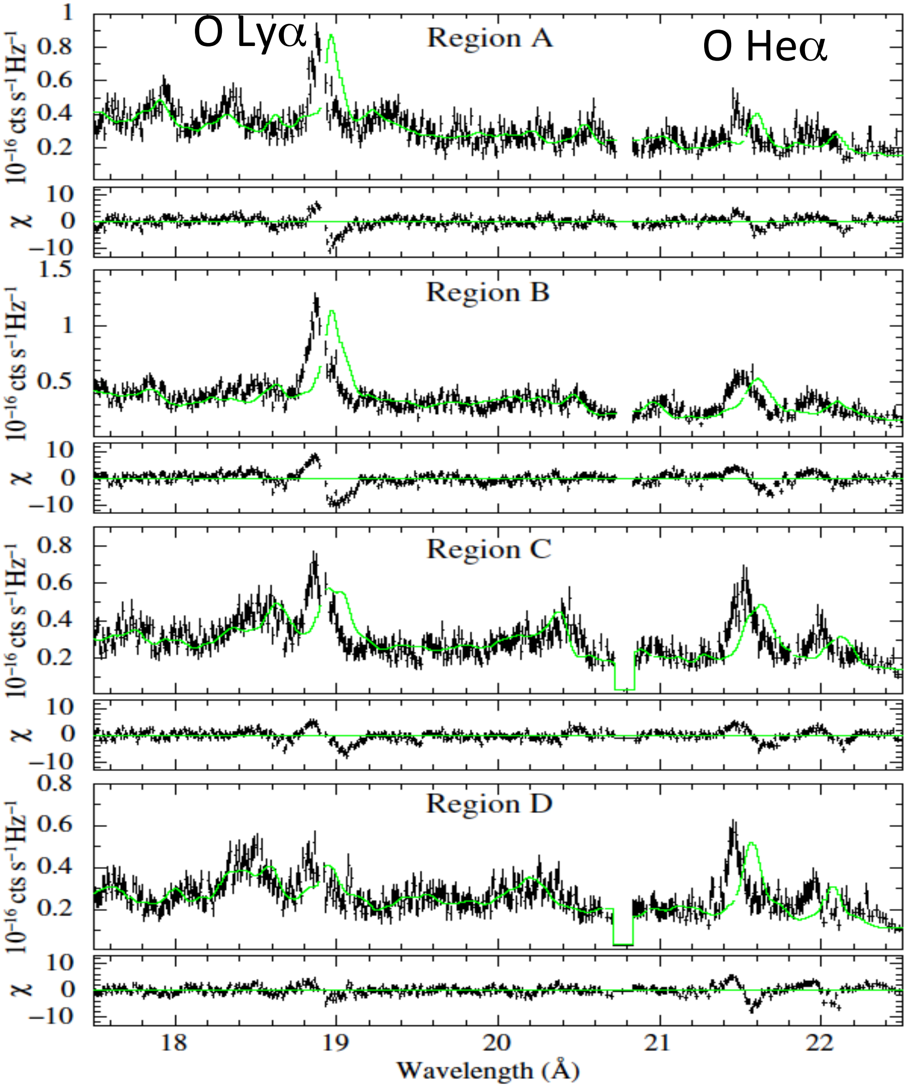
RGS Observation of the Ejecta





Observation date：2012-10-20
Exposure time：21 ks

RGS Spectra



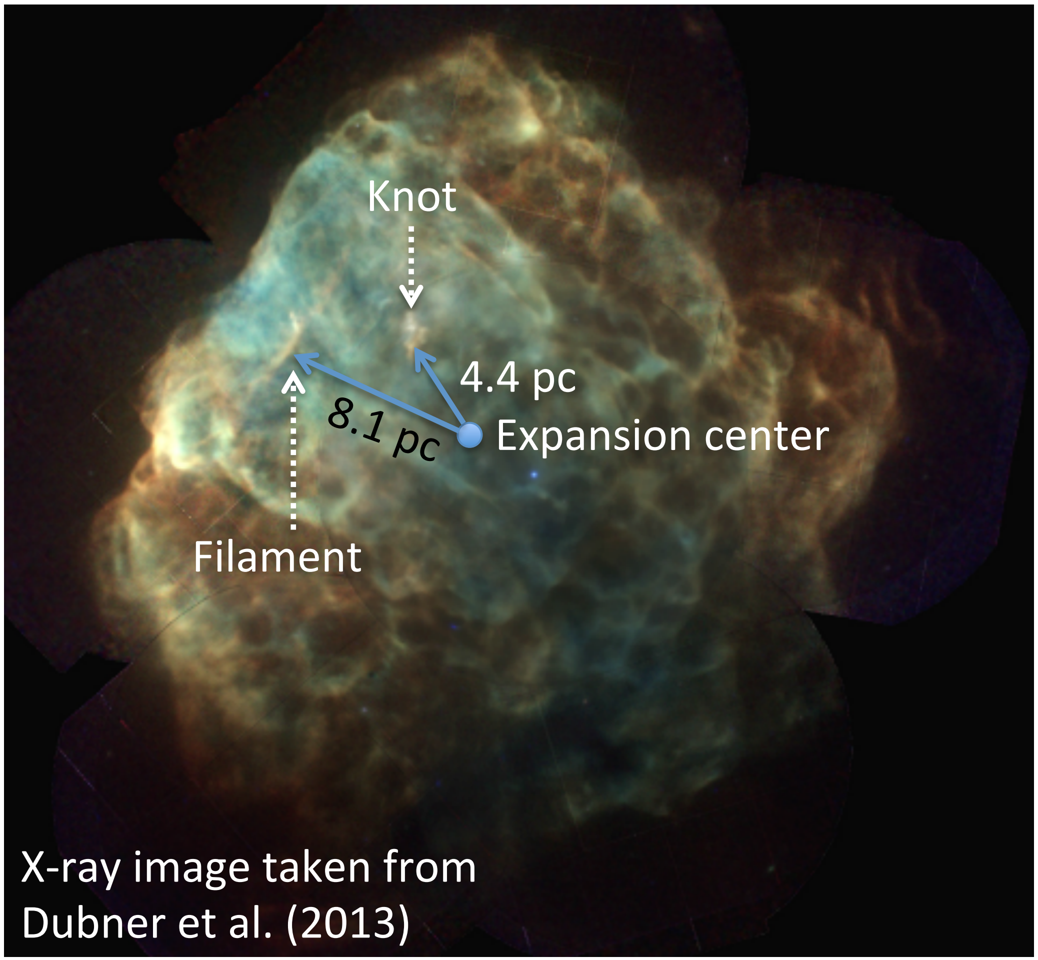
Doppler velocities:

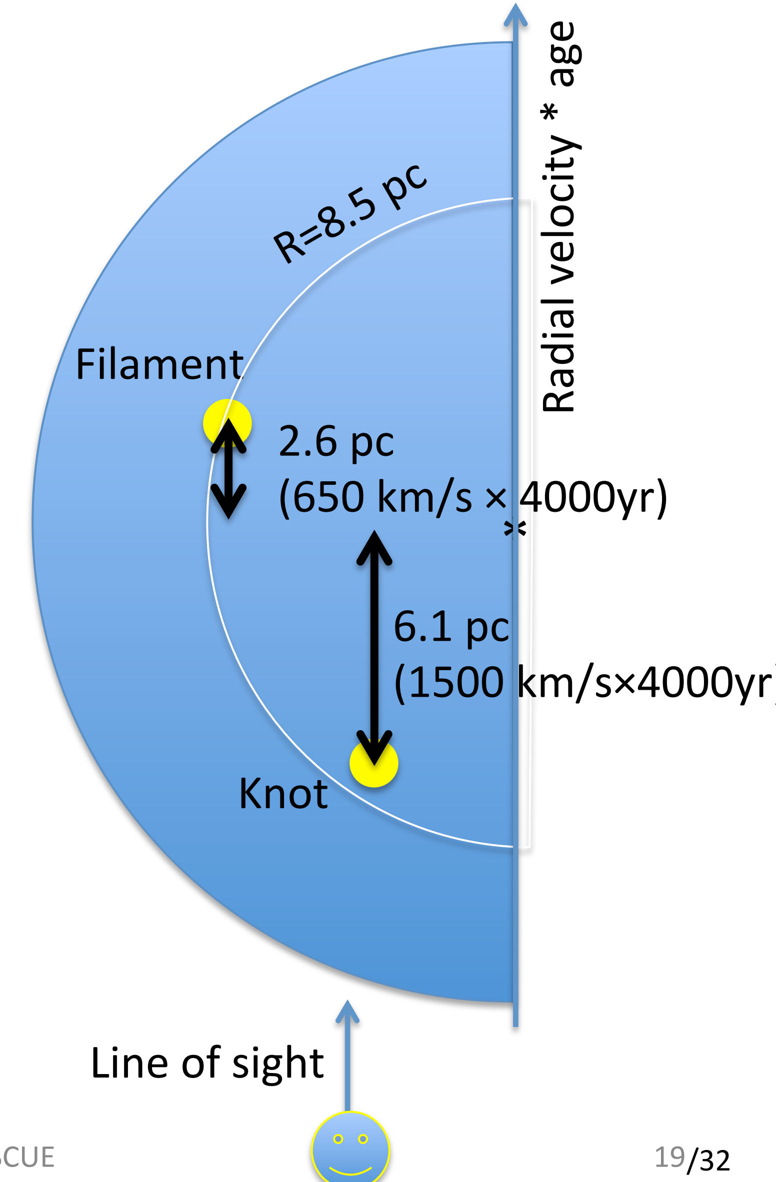
	Knot	Filament
Reg A	-1290±60 km/s	690±90 km/s
Reg B	-1440±60 km/s	570±90 km/s
Reg C	-1590±60 km/s	660±90 km/s
Reg D	-1560±60 km/s	720±90 km/s

Doppler shifts
Knot: -1500 ± 200 km/s
Filament: +650 ± 130 km/s

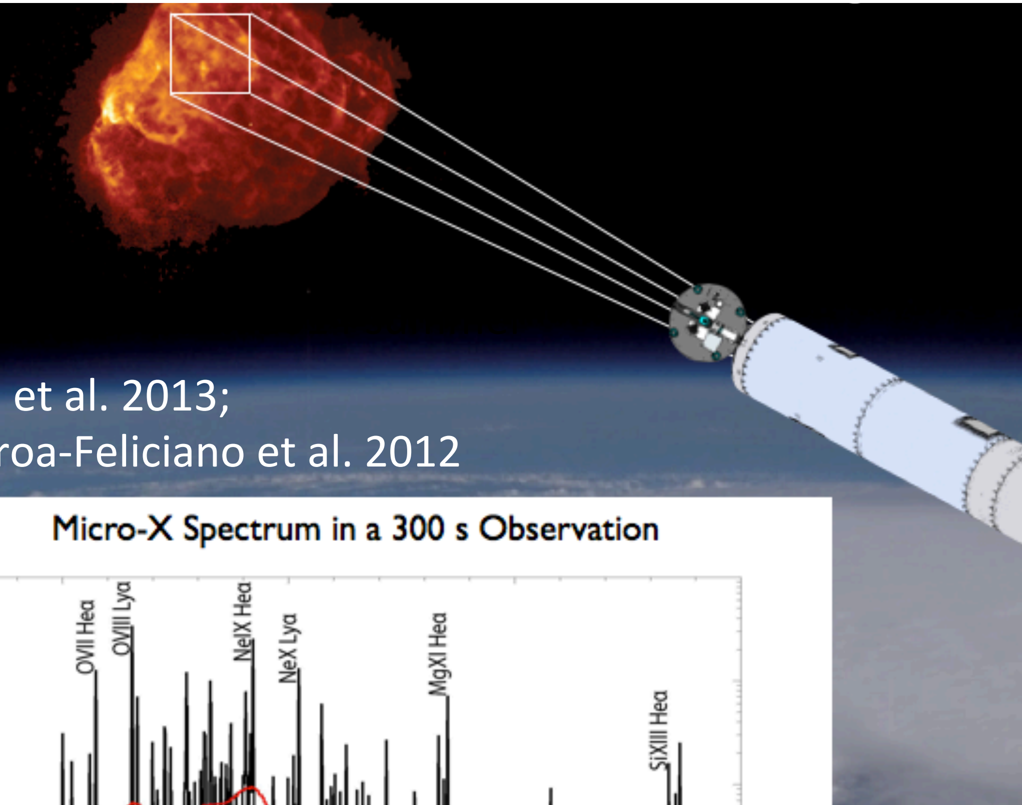
SK et al. (2013)

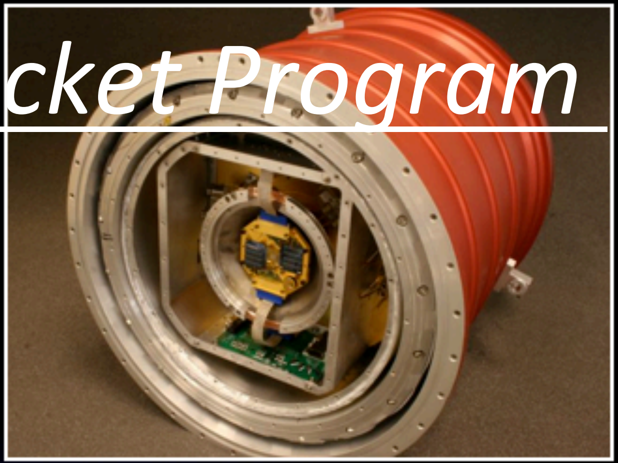
Line-of-Sight Location of the SN Debris



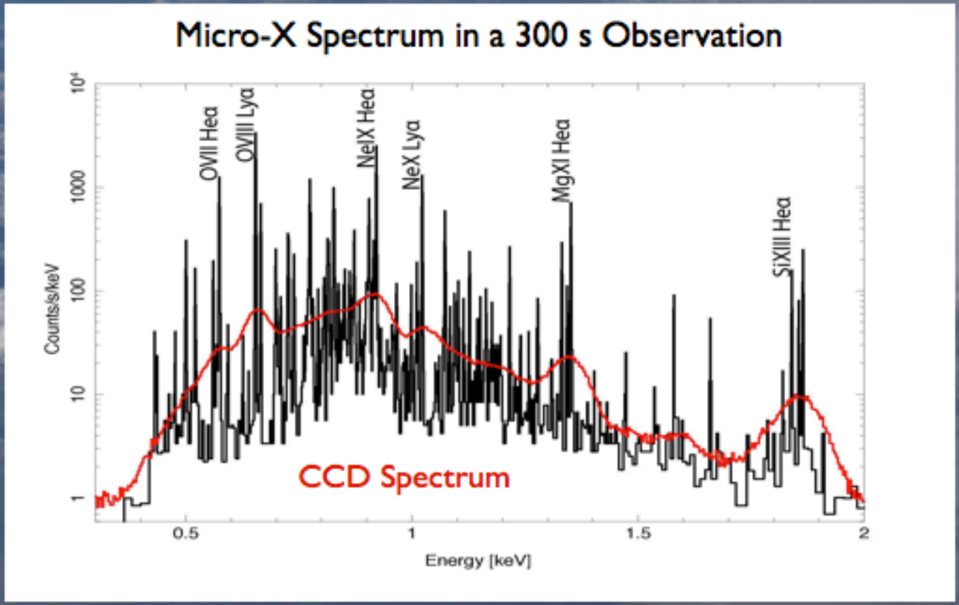


The Micro-X Sounding Rocket Program





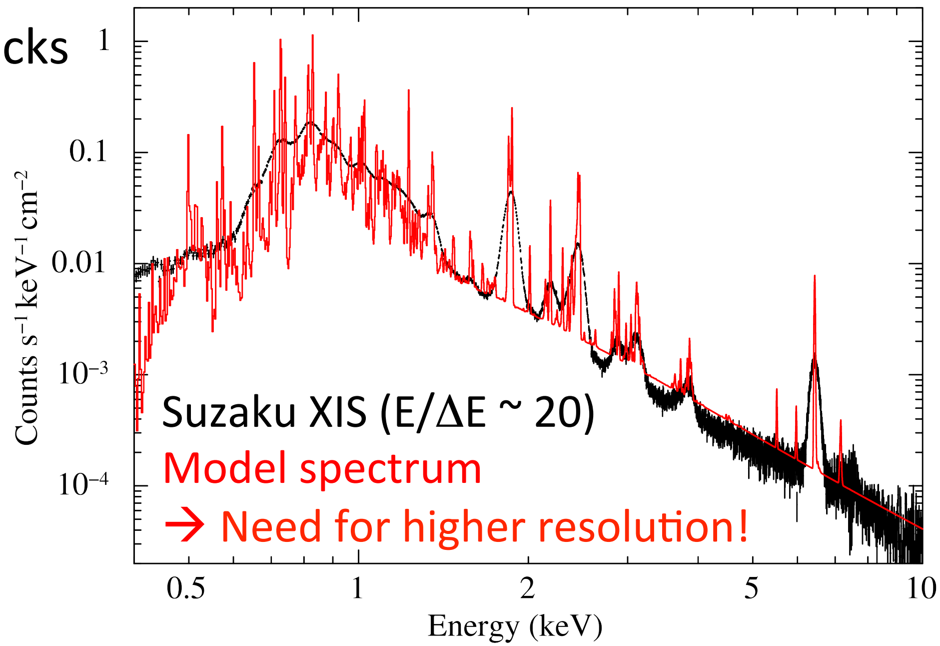
Heine et al. 2013;
Figueroa-Feliciano et al. 2012



Just launched on July 6th in 2016!

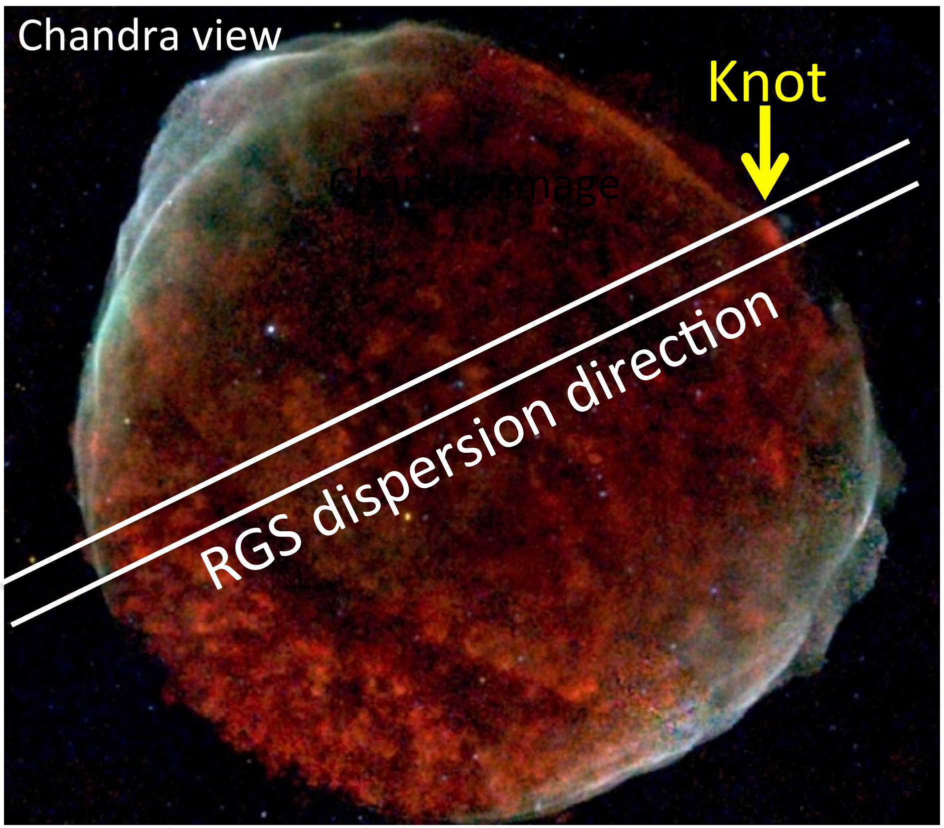
High-Res. X-Ray Spectroscopy (E/ΔE>100)

– Ejecta dynamics
  - 3D ejecta structures
    → Explosion asymmetries & NS kicks
– Collisionless shock physics
  - T_i-T_e equilibration
  - Cosmic-ray acceleration
– Plasma diagnostics
  - Thermodynamic parameters
  - Radiative processes
– Composition measurements
  - Odd-Z/neutron-rich elements

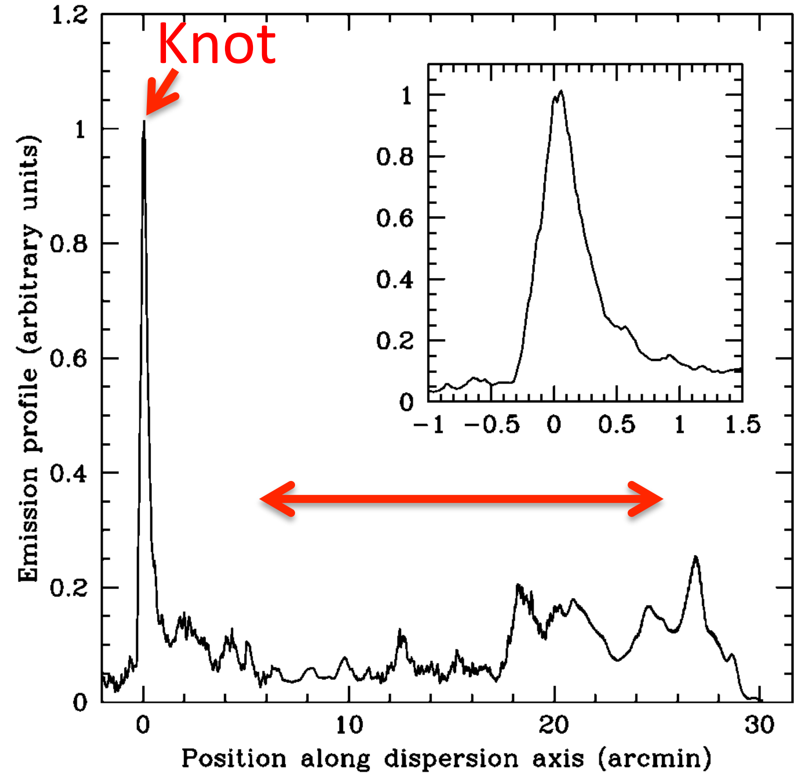


RGS Spectroscopy of SN 1006 NW Knot

Vink et al. (2003)



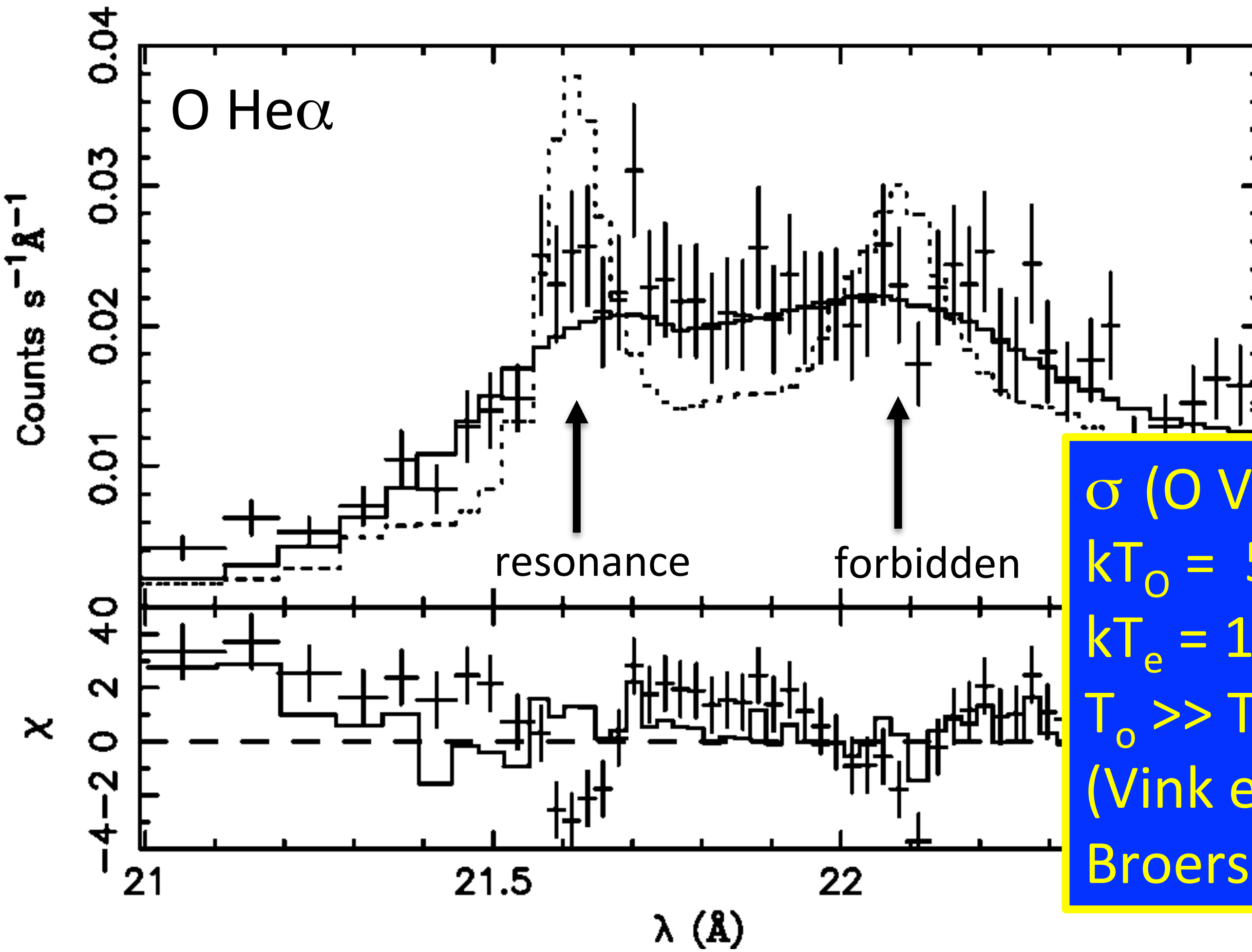
Emission profile



Knot's size ~ 0.4' (FWHM)

→ RGS spectral resolution for O VII ~ 3 eV

Temperature Nonequilibration: $T_{O\,VII} >> T_e$!



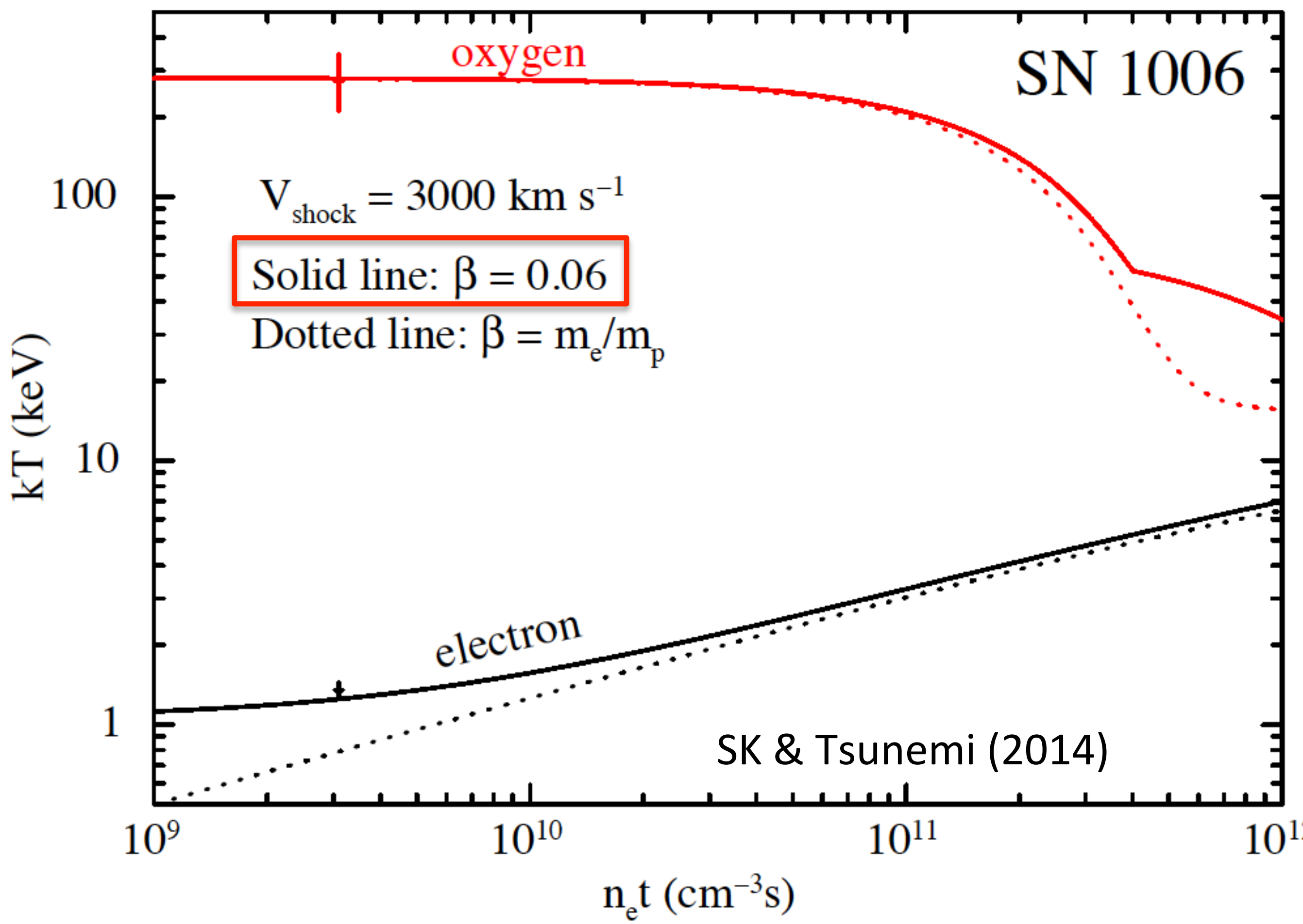
σ (O VII) = 3.4 ± 0.5 eV
kT_O = 530 ± 150 keV
kT_e = 1.5 keV
$T_o >> T_e$!
(Vink et al. 2003; see also Broersen et al. 2013)

Dotted line: emission model w/o broadening
Solid line: emission model w/ thermal broadening

$$\sigma = E_0\sqrt{kT/mc^2}$$

Coulomb Equilibration (+ Collisionless Heating)

$$\frac{dT_i}{dt} = \frac{T_j - T_i}{t_{\rm eq(i,j)}},\ t_{\rm eq(i,j)} = 5.87\frac{A_i A_j}{n_j Z_i^2 Z_j^2 \ln(\Lambda)}\left(\frac{T_i}{A_i} + \frac{T_j}{A_j}\right)^{\frac{3}{2}}$$



High-Res. X-Ray Spectroscopy (E/ΔE>100)

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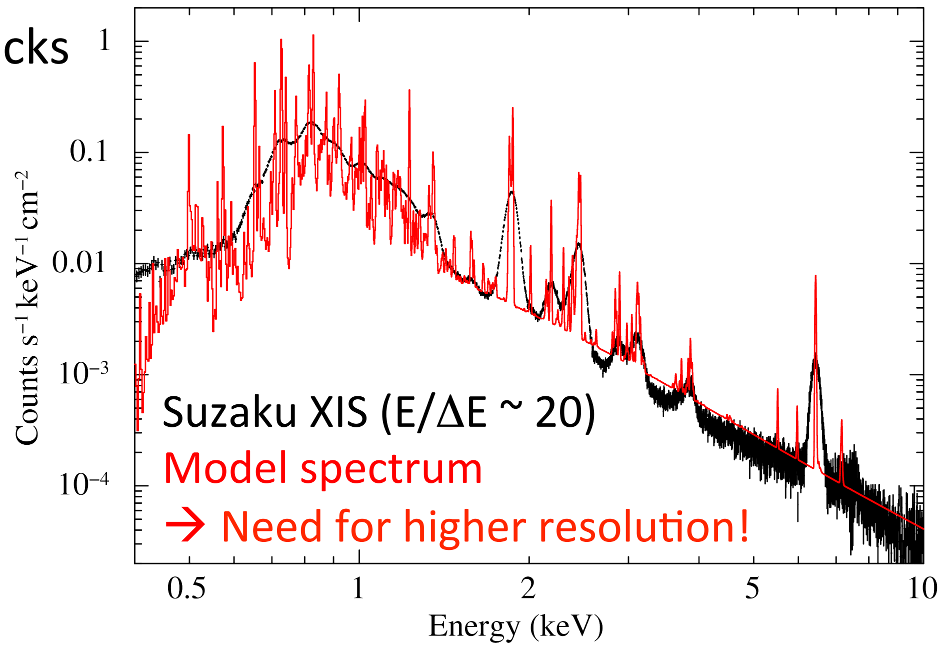
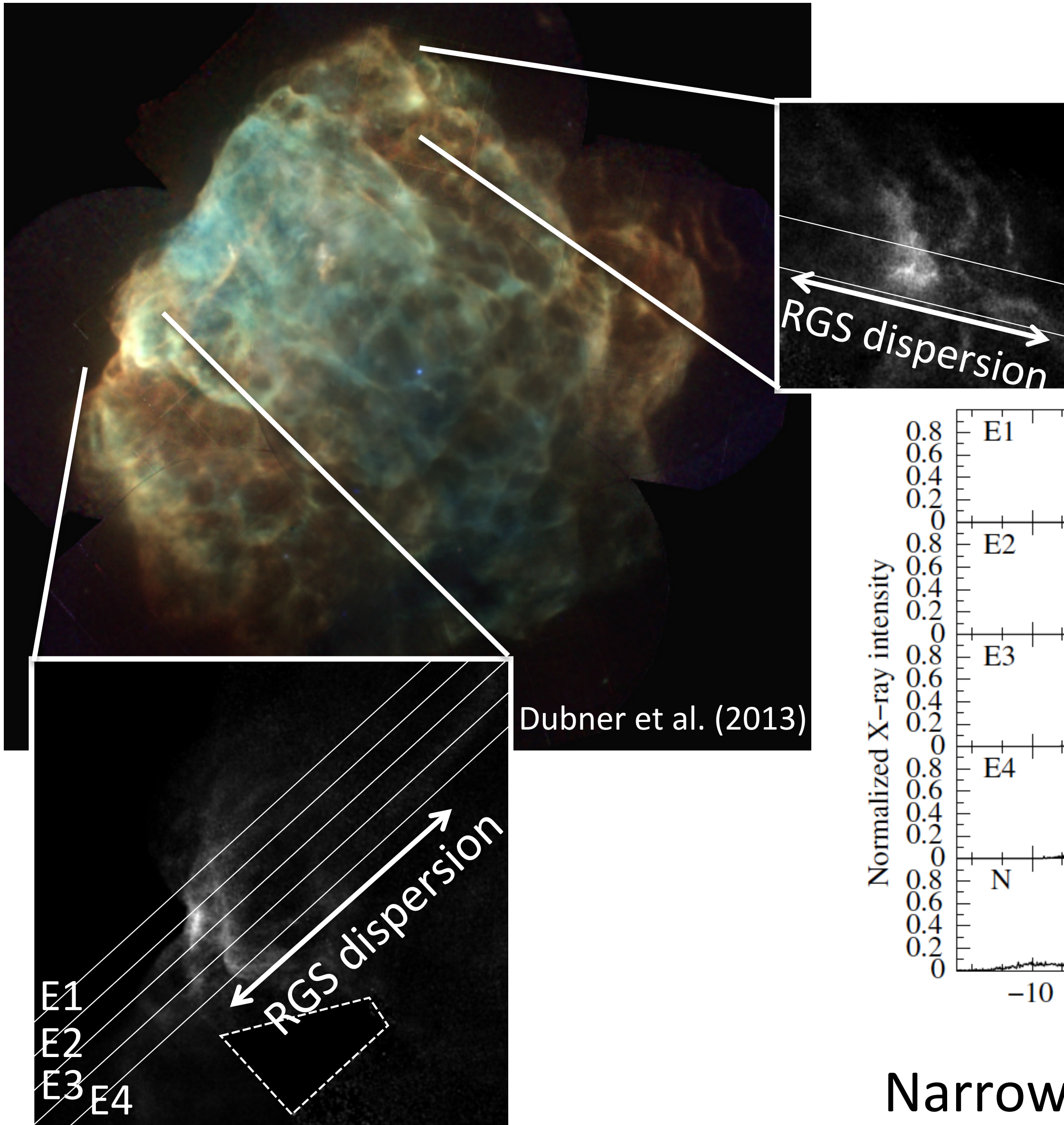
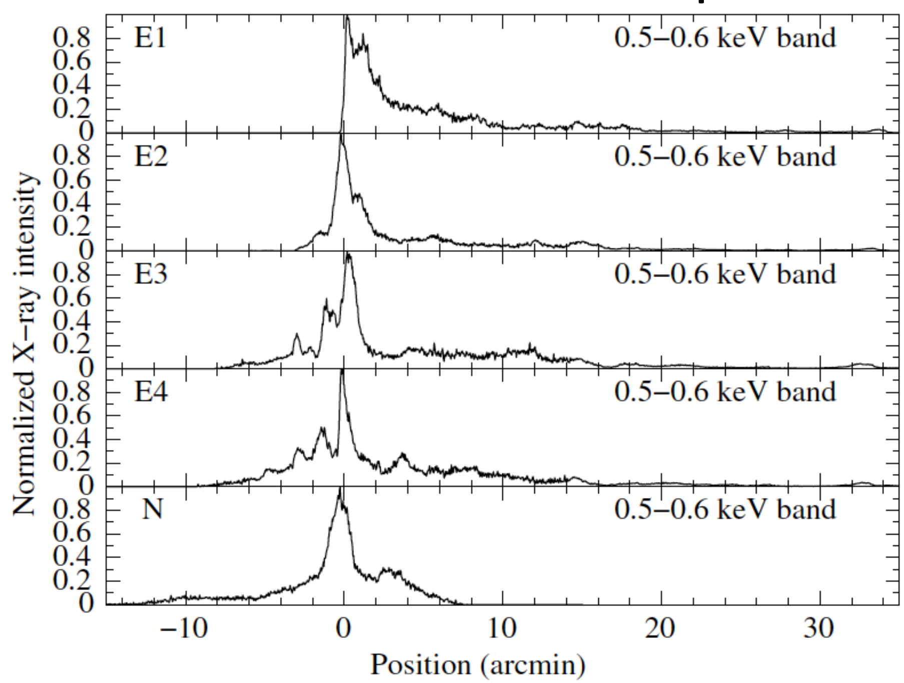


RGS Observations of ISM-Dominated Regions in The Puppis A SNR



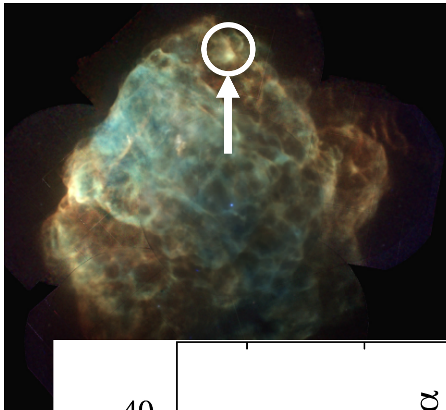
SK+2012

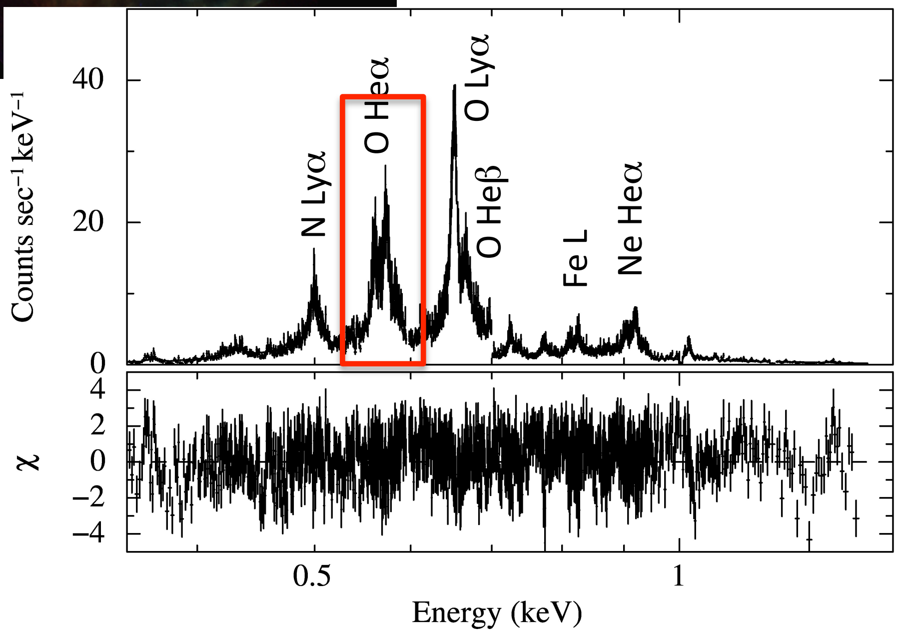
Emission profiles



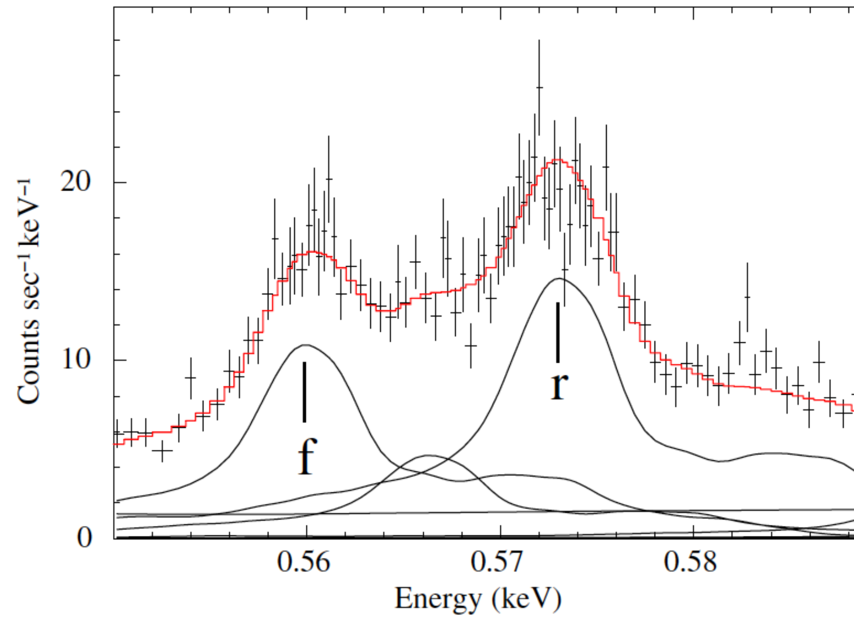
Narrow & bright → Good for RGS

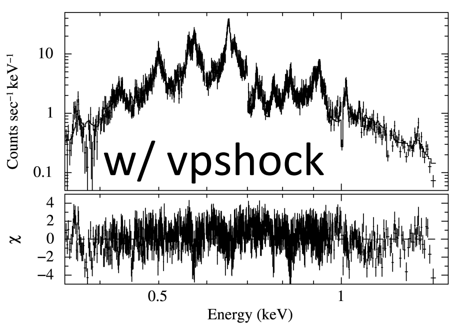
The Northern Knot



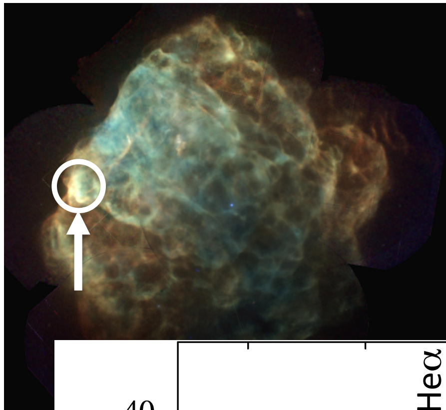


Forbidden and resonance are clearly resolved!



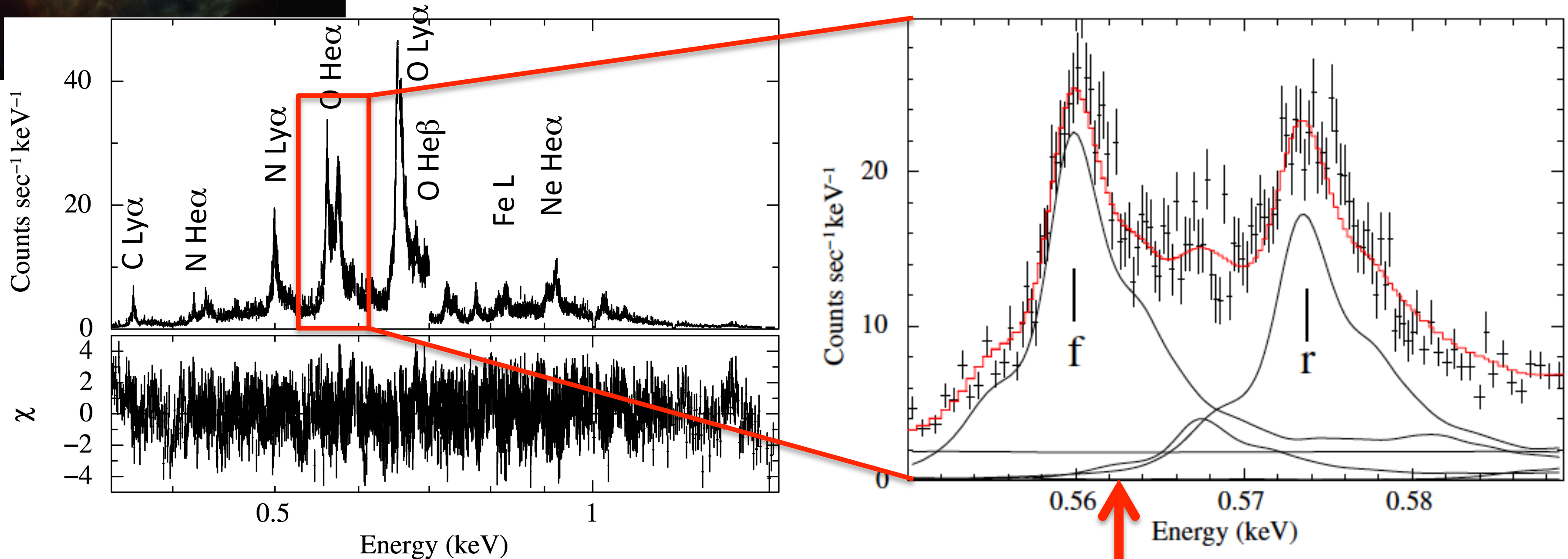


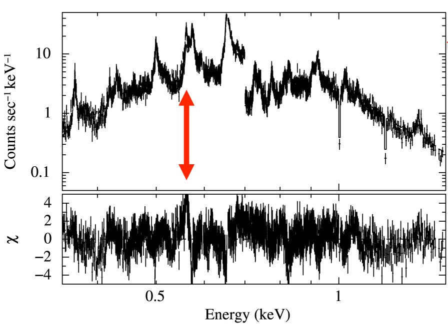
Thermal emission model reasonably reproduces the data.



Surprise from the Eastern Knot

Forbidden > Resonance!





Thermal emission model can not reproduce the f/r ratio.

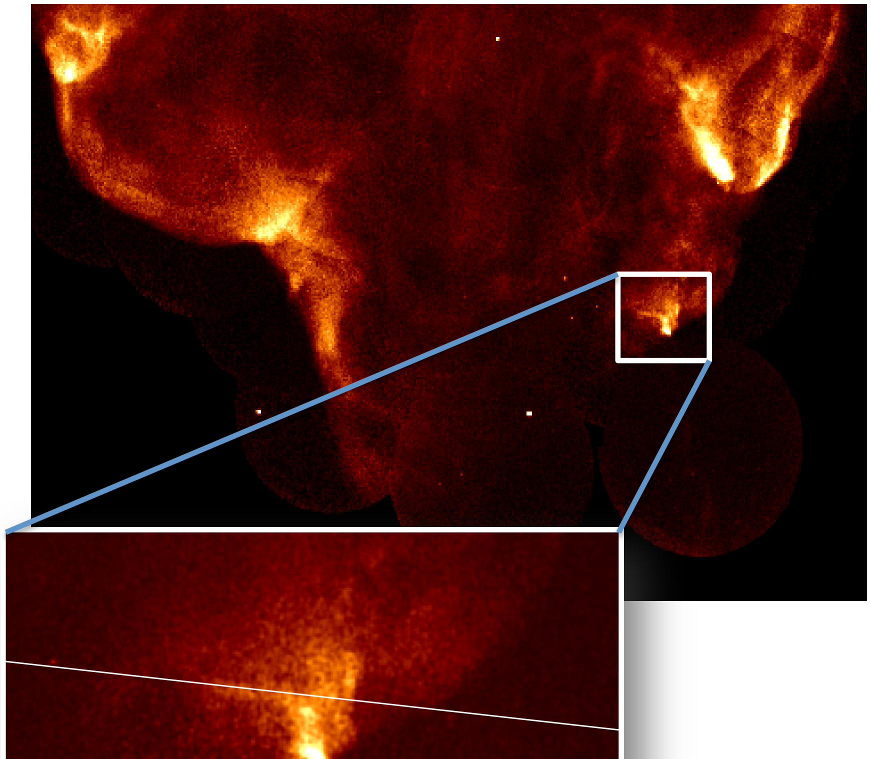
Possibilities to explain the data:

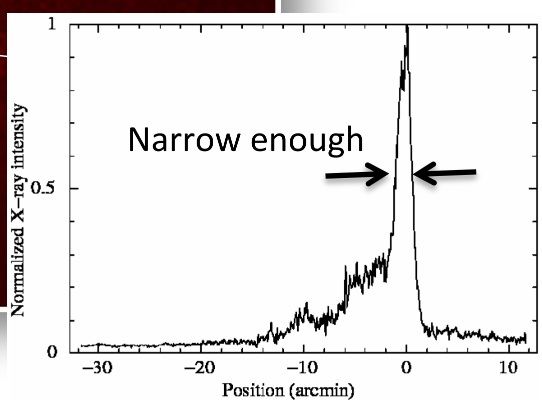
- resonance line scattering
- recombination
- charge exchange

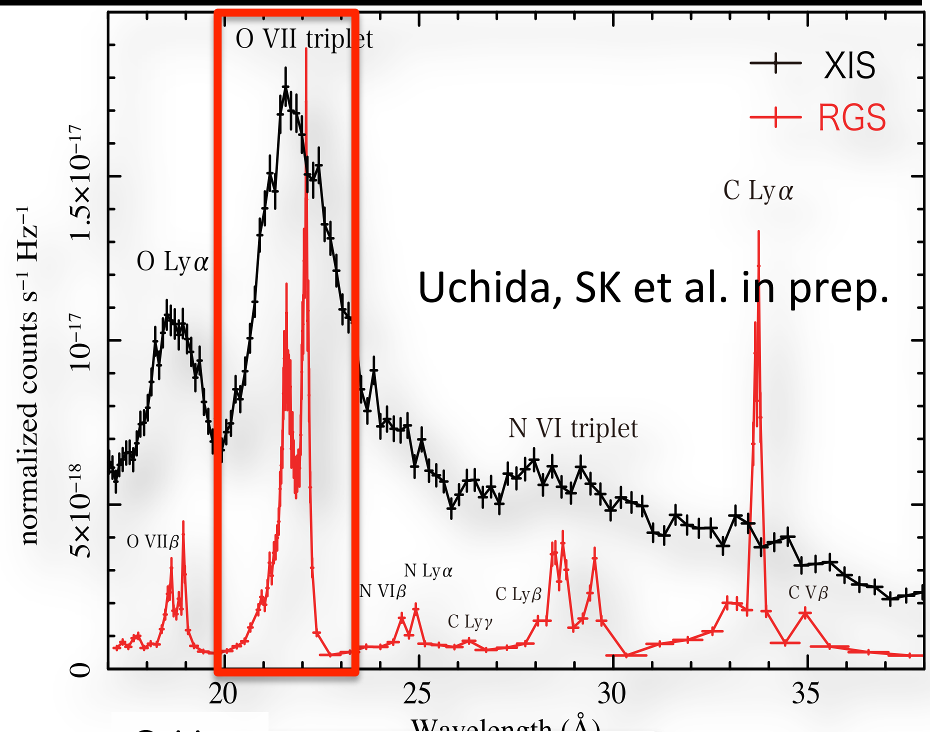
Our proposal

SK et al. (2012)

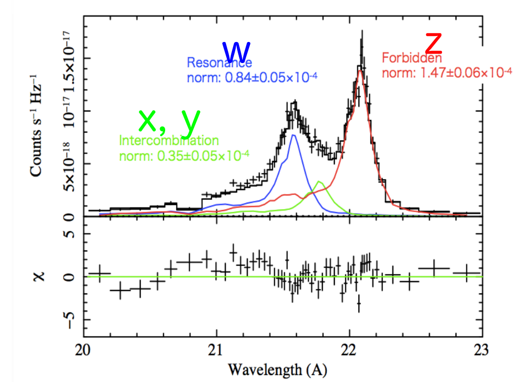
Another Example: The Cygnus Loop







O Heα

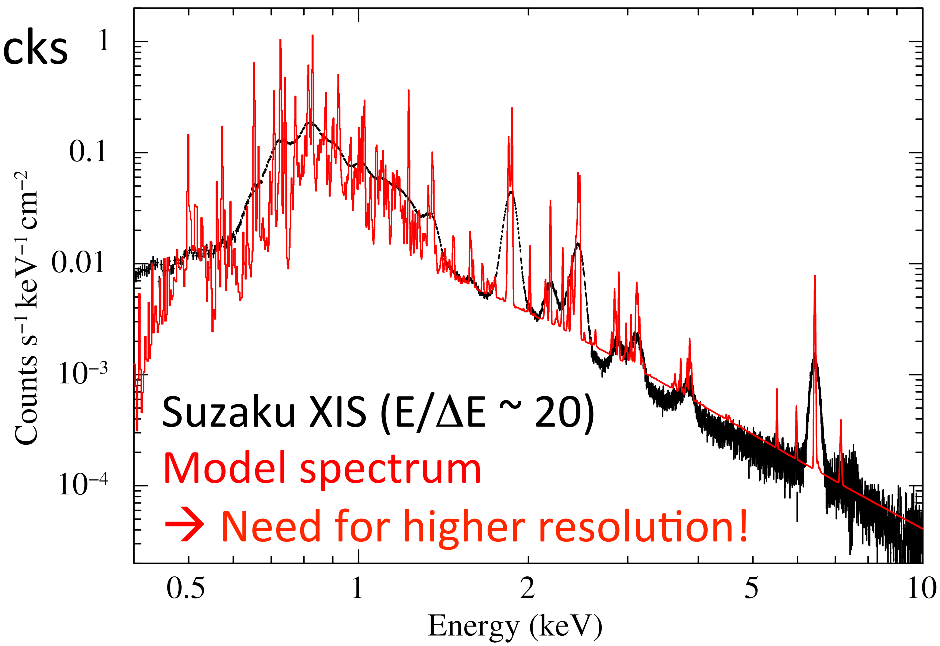


f/r (=z/w): ~ 1.8

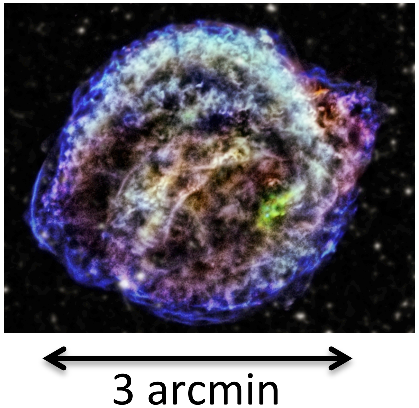
Again, forbidden is stronger than resonance!

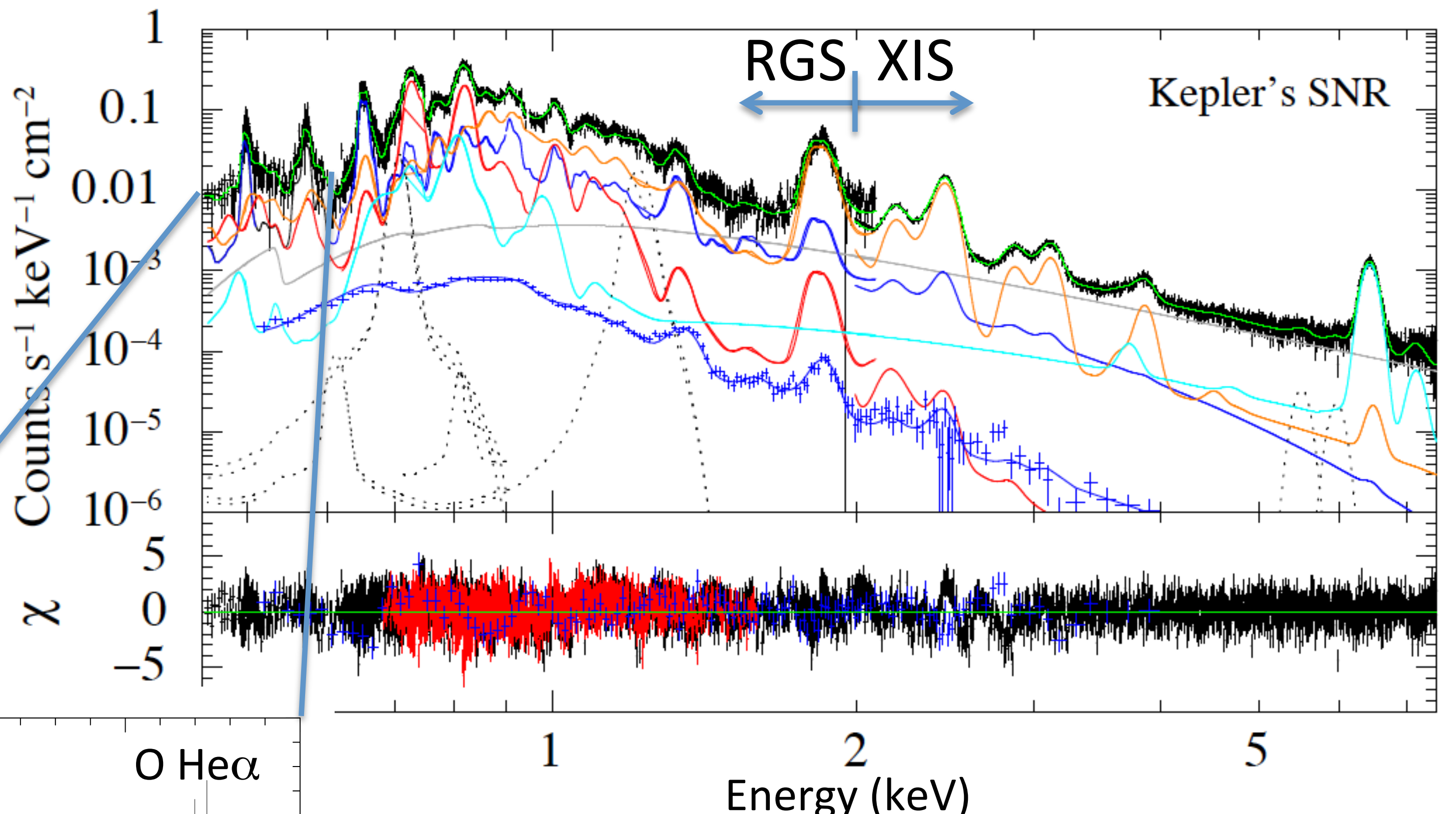
High-Res. X-Ray Spectroscopy (E/ΔE>100)

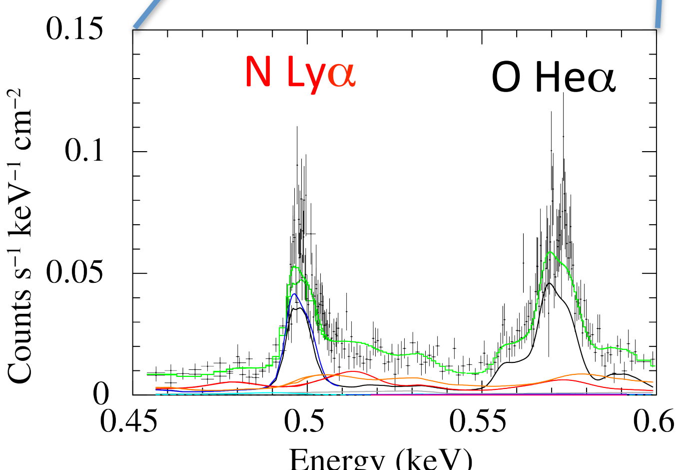
– Ejecta dynamics
  - 3D ejecta structures
    → Explosion asymmetries & NS kicks
– Collisionless shock physics
  - T_i-T_e equilibration
  - Cosmic-ray acceleration
– Plasma diagnostics
  - Thermodynamic parameters
  - New radiative processes
– Composition measurements
  - Odd-Z/neutron-rich elements



The Circumstellar Medium in Kepler's SNR







The N abundance: ~4 $Z_\odot$ → CNO-processed CSM

The CSM mass: ~1 $M_\odot$

Mass-loss rate: ~ 1.5e-5 $M_\odot$/yr

(SK, Mori, Maeda, Tanaka et al. 2015)

Summary

- X-ray observations of supernova remnants provide us with important opportunities to test SN nucleosynthetic/explosion models.
- High-resolution X-ray spectroscopy has long been an anticipated discovery space especially for diffuse sources such as SNRs and galaxy clusters.
- The cutting-edge research has been explored by grating spectrometers onboard XMM-Newton and Chandra.
- We do hope Hitomi-2 mission, but it's also important to continue grating spectroscopy.