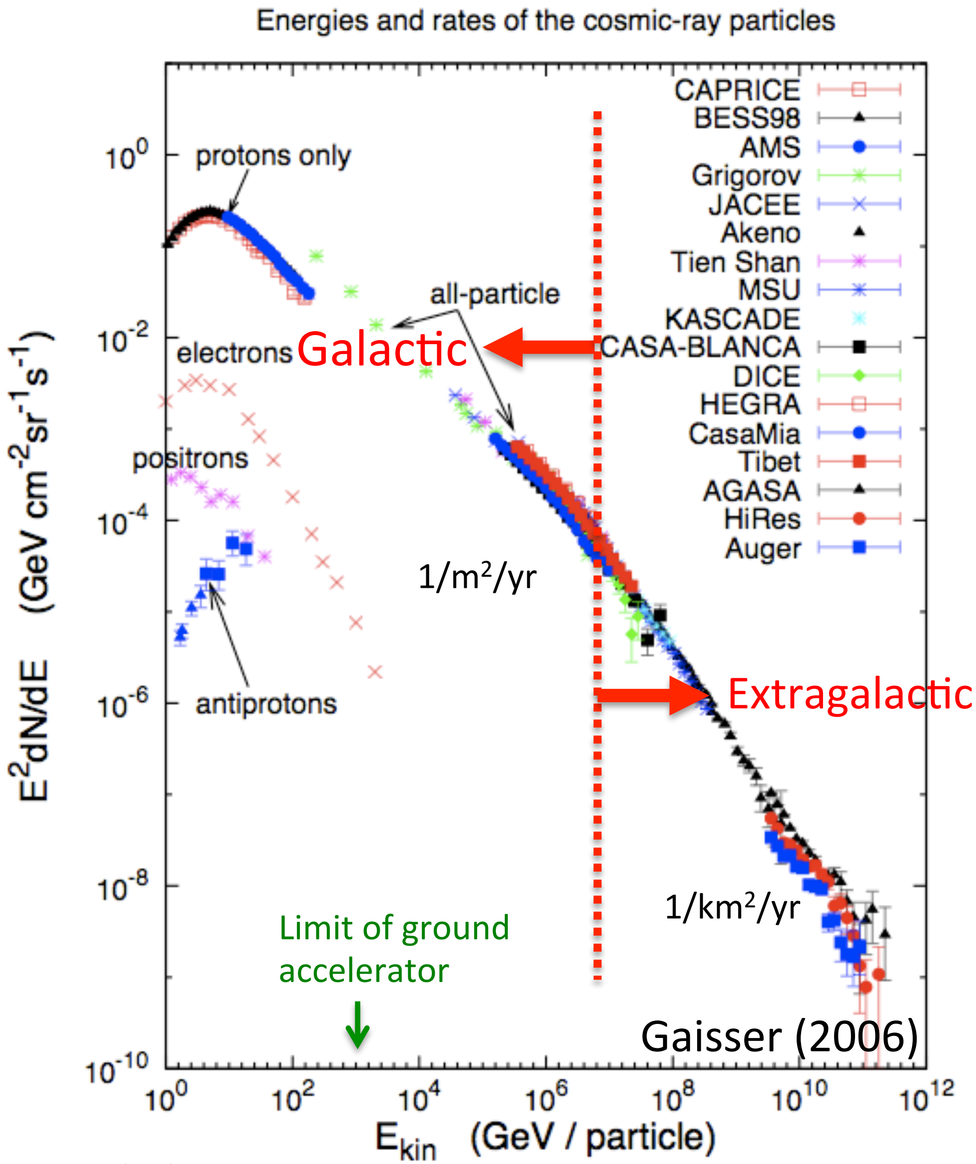
X-Ray Measurements of Cosmic-Ray Acceleration Efficiencies in Supernova Remnants

Satoru Katsuda (Saitama University)

Cosmic Rays (CRs)



Cosmic rays were discovered by a balloon experiment led by V. Hess in 1912.

A long-standing question connected to astrophysics: Where are CRs accelerated?

Supernova Remnants: Promising Origin of Galactic CRs

1) Energy per unit time to maintain Galactic CRs:

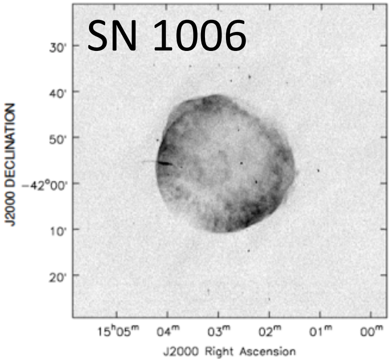
$$L_{GCR} = 10^{40\text{-}41}\ \mathrm{erg/s} = U_{GCR} \sim 10^{55}\ \mathrm{erg} / \tau \sim 10^{7}\ \mathrm{yr}$$

2) Energy per unit time given by supernova explosions:

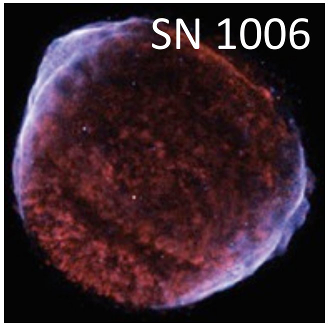
$$L_{SN} = 10^{42}\ \mathrm{erg/s} = E_{SN} \sim 10^{51}\ \mathrm{erg} * R_{SN} \sim 1/30\ \mathrm{yr}^{-1}$$

→ The energy budget can be balanced, if 10% of SN explosion energy goes into CR acceleration: $L_{GCR}/L_{SN} \sim 0.1$ (e.g., Baade & Zwicky 1934).

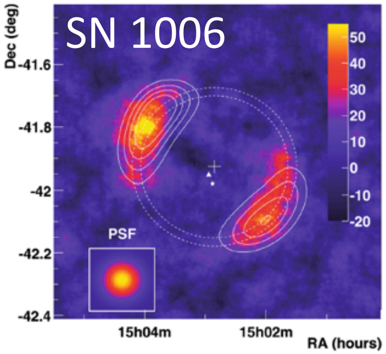
Mounting evidence for SNRs being CR accelerators



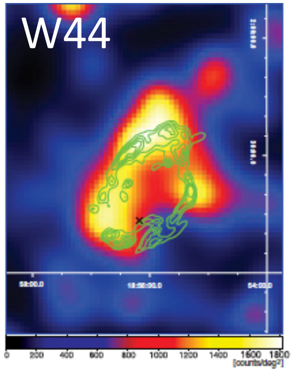
Radio synchrotron
→ Electrons up to GeV



X-ray synchrotron
→ Electrons up to 100 TeV



VHE gamma-rays
→ Electrons up to 10 TeV



GeV gamma-rays
→ Protons up to GeV

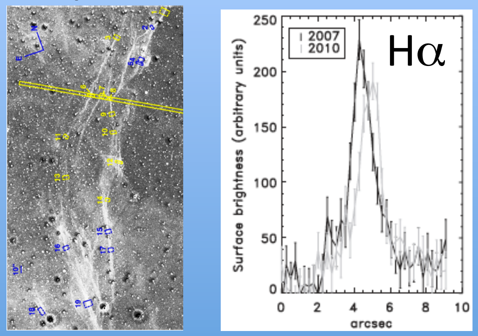
How to Estimate CR Acceleration Efficiencies at SNR Shocks

Shock energy = Thermal energy + Nonthermal (CR) energy

3/16 mV_s^2

3/2 kT

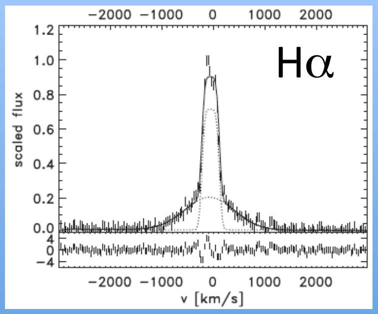
Proper motion of a shock



Helder et al. (2013)

V_s = 1200 km/s

Thermal Doppler broadening



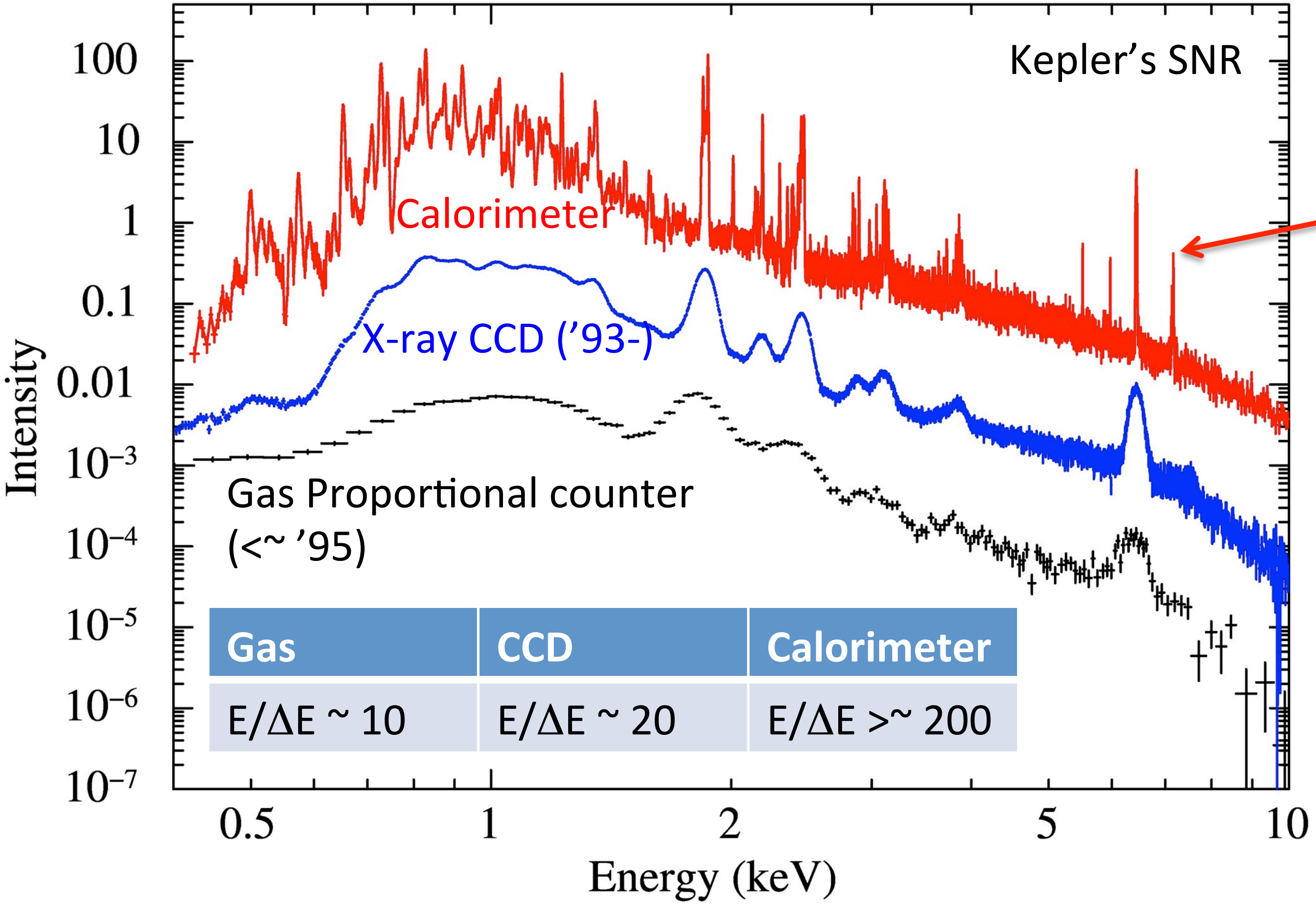
Helder et al. (2009)

kT_p = 2.3 keV

CR acceleration efficiency < 30% for the NE RCW 86

Measurements of CR acceleration efficiencies have been still scarce.

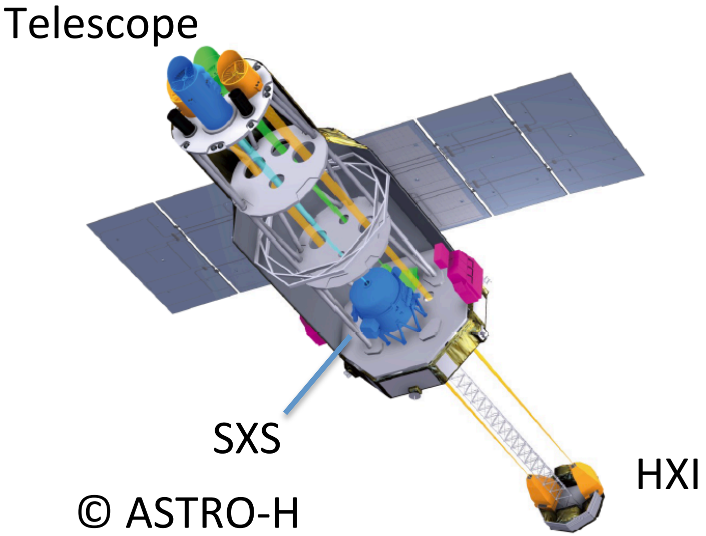
High-Resolution X-Ray Spectroscopy: A New Clue to CR Acceleration Efficiencies



Gas	CCD	Calorimeter
E/ΔE ~ 10	E/ΔE ~ 20	E/ΔE >~ 200

This allows us to measure ion temperatures!!

The Hitomi Satellite



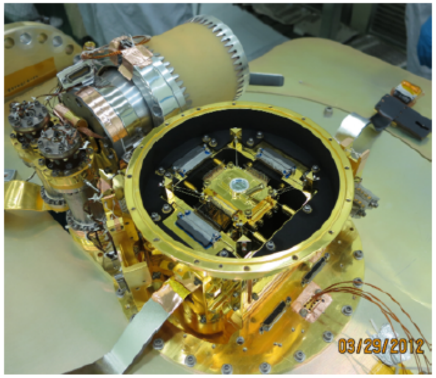
Astronomy Picture of the Day
(2016-02-18) © F.S. Porter

□ Hitomi:

- The 6th Japanese X-ray astronomy satellite
- Successfully launched on 2016/2/17
- Lost its ground contact on 2016/3/26

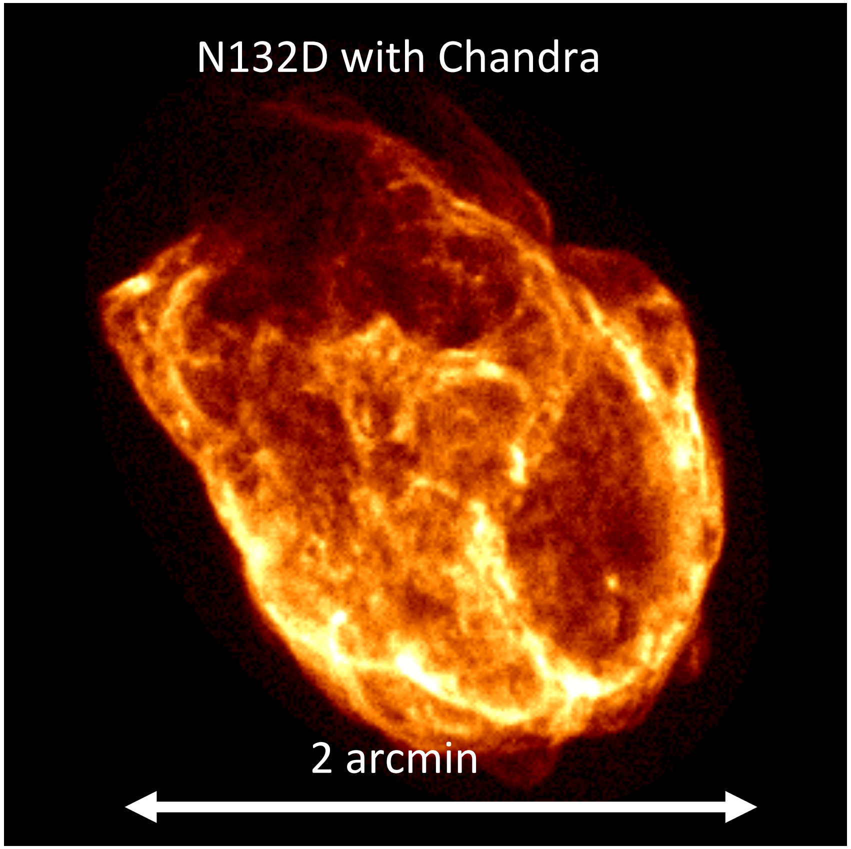
□ X-ray micro-calorimeter (SXS):

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



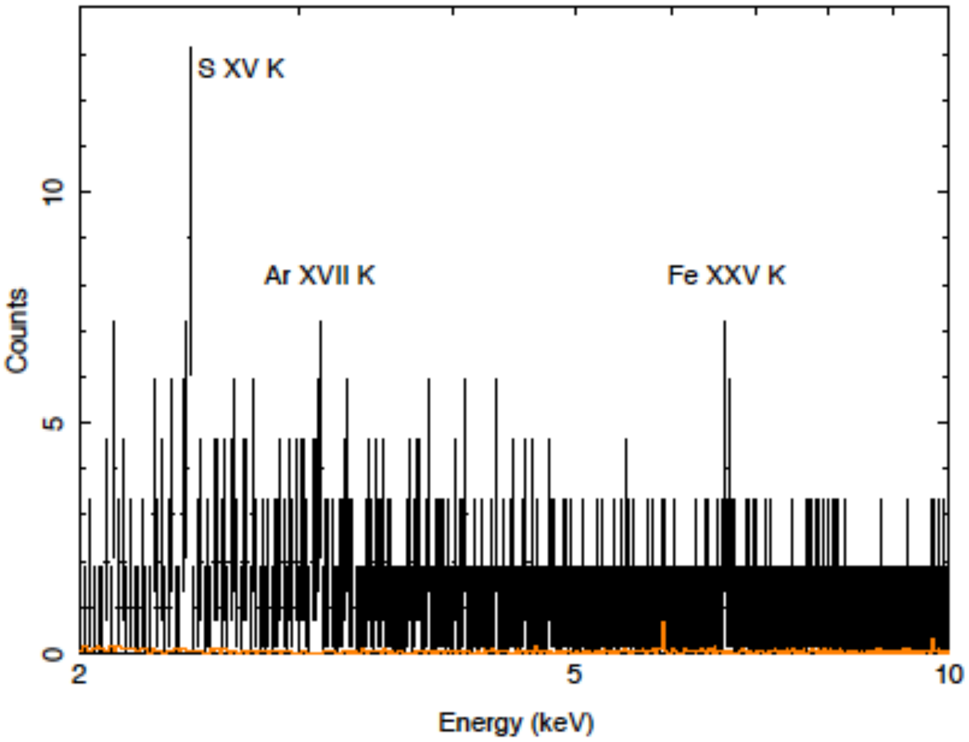
SXS detector assembly

Hitomi Observation of N132D



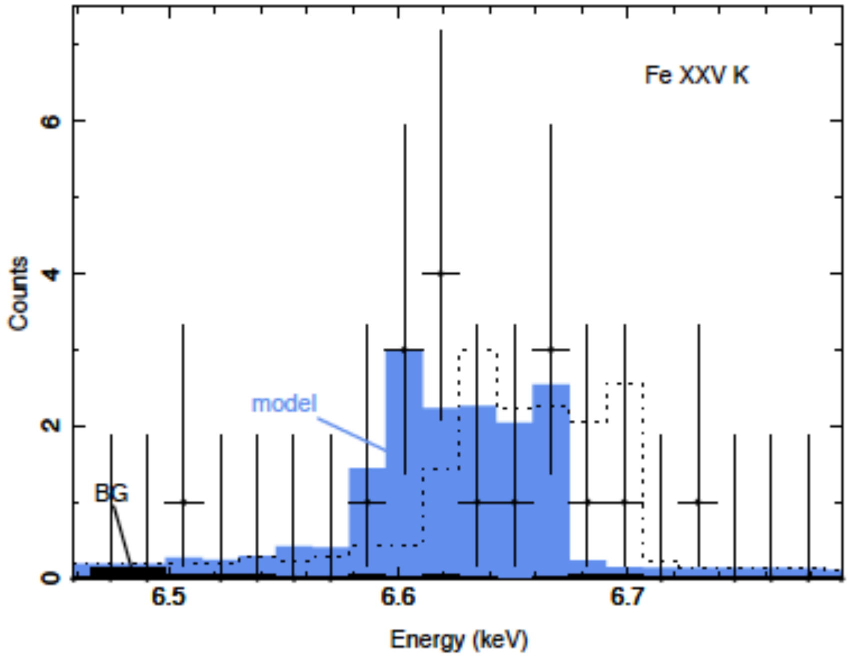
- Very bright in radio, optical, X-ray, and gamma-rays
- Core-collapse, ~2500 yr old

SXS spectrum with an exposure time of only 1 hr due to attitude control failure

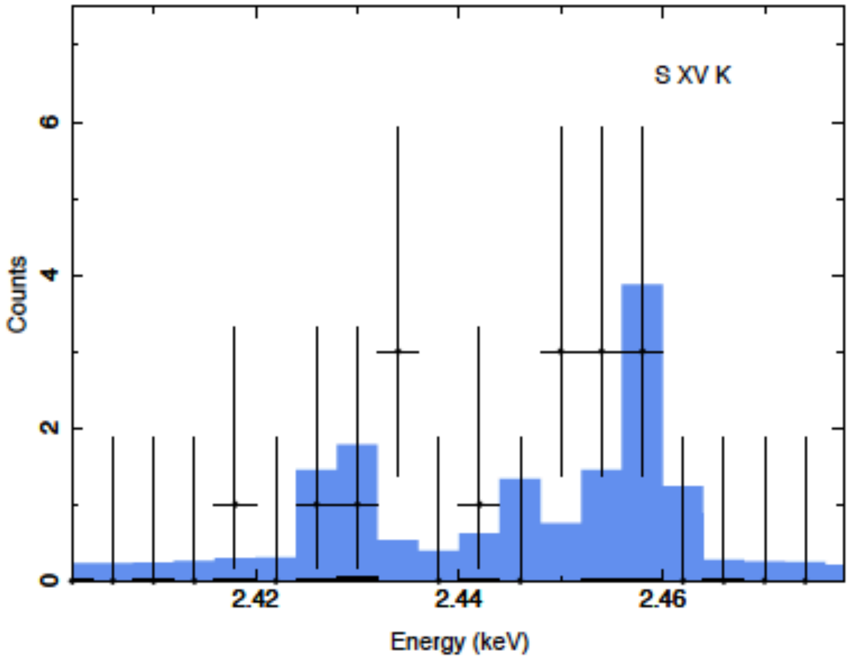


Hitomi Collaboration (2018)
accepted by PASJ on 2017-12-06

S Heα & Fe Heα with the SXS



Fe K (17 counts)



S K (16 counts)

Doppler velocity wrt. LMC:
800 (50--1500) km/s
→ Asymmetric ejecta

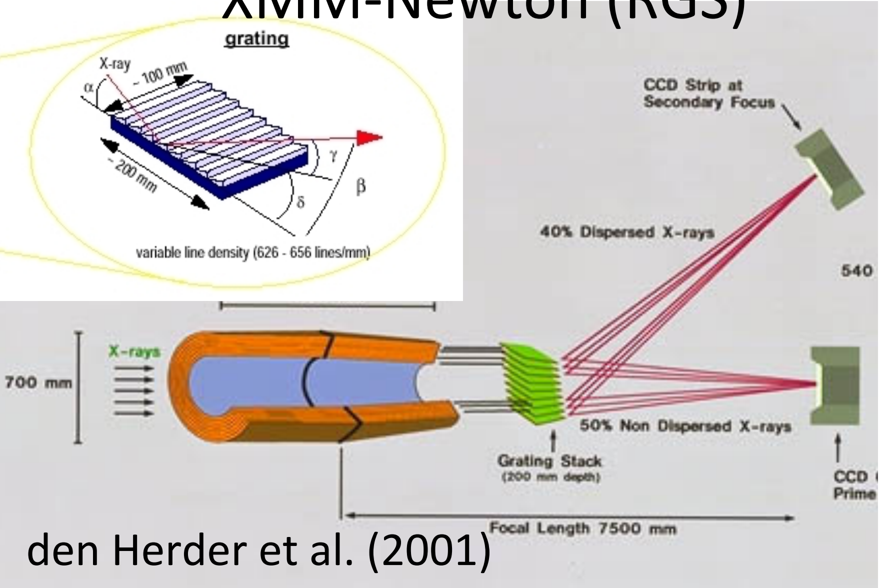
Doppler velocity wrt. LMC:
-65 (-450--435) km/s
→ Swept-up ISM

$\sigma_{\text{Fe-K}}$ ~ 11 eV → kT_{Fe} ~ 150 keV

$\sigma_{\text{S-K}}$ ~ 4 eV → kT_{s} ~ 90 keV

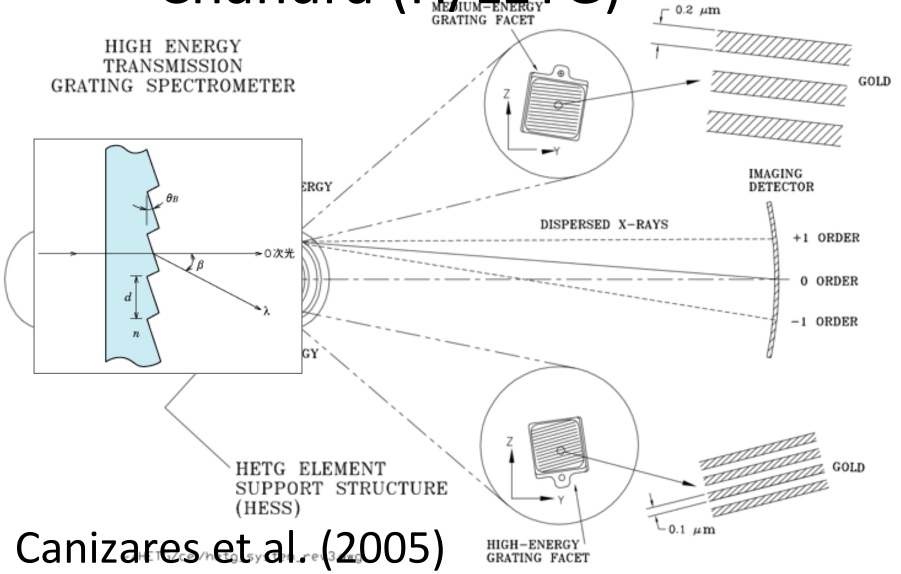
Challenges with Gratings on XMM/Chandra

XMM-Newton (RGS)



den Herder et al. (2001)

Chandra (H/LETG)



Canizares et al. (2005)

Reflection grating

Slitless → Degradation in λ resolution:

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

$\Delta\text{ext}_{\text{min}}$(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:

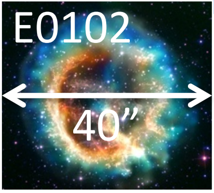
$\Delta\lambda \sim 0.67 * \Delta\text{ext(arcmin)}$ Å

$\Delta\text{ext}_{\text{min}}$ (spatial resolution): 0.01'

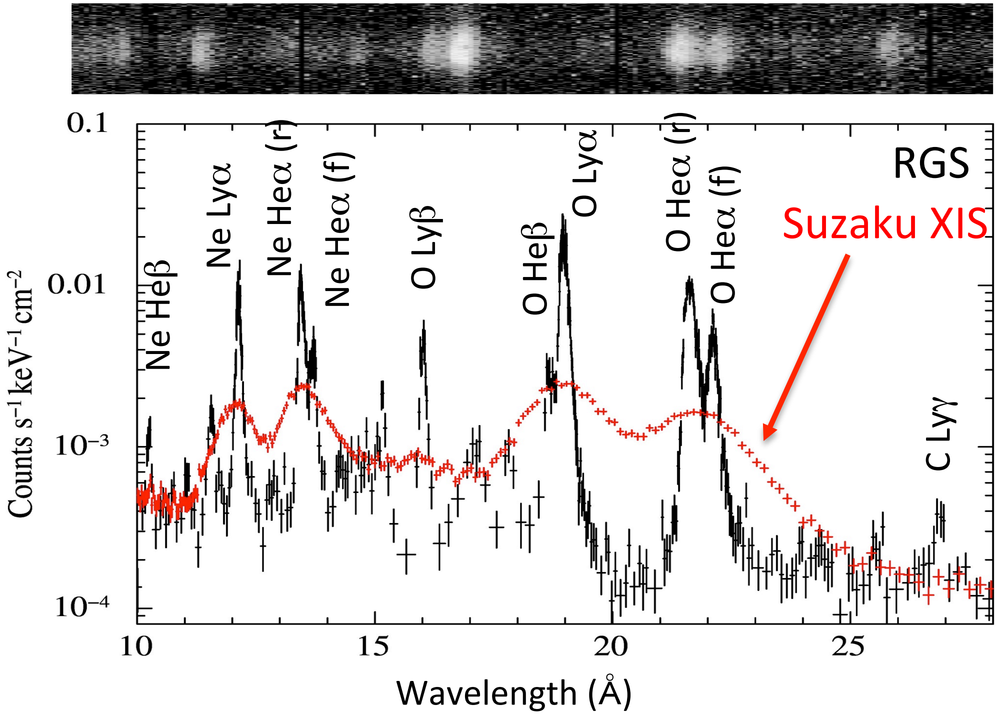
Strong for small(")-scale features

complementary

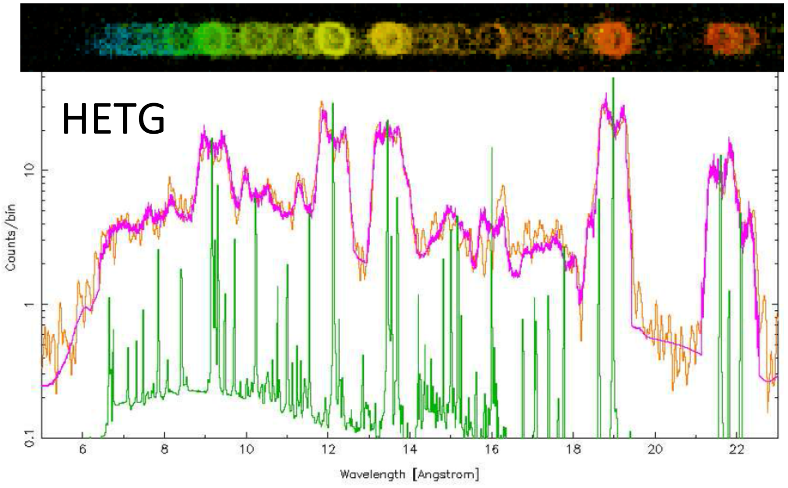
Example Spectra of the RGS and HETG



XMM-Newton RGS (Rasmussen et al. 2001)



Chandra HETG (Flanagan et al. 2004)

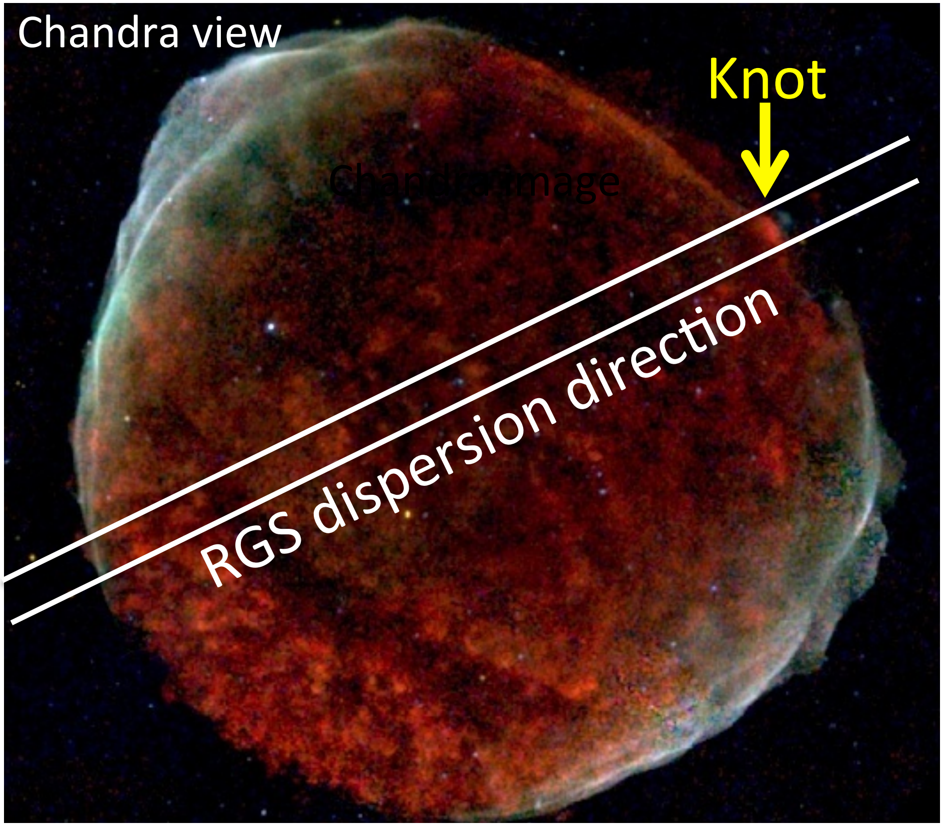


- N132D (Behar et al. 2001)
- B0540-69.3 (van der Heyden+2001)
- N103B (van der Heyden et al. 2001)
- DEML71 (van der Heyden et al. 2003)
- 0509-67.5 (Kosenko et al. 2008)
- 0519-69.5 (Kosenko et al. 2010)
- 0506 (Broersen et al. 2011)

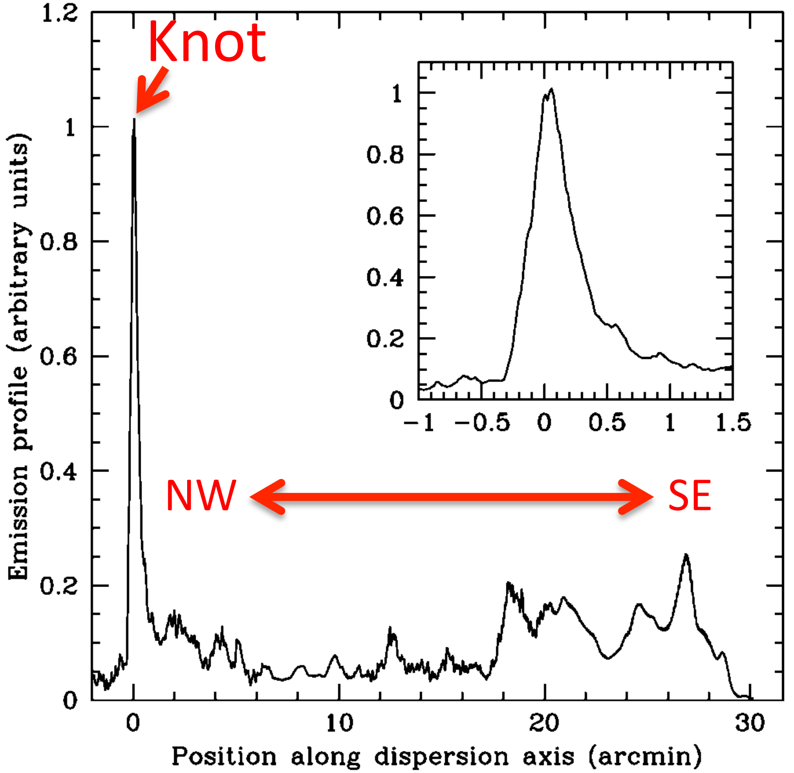
However, the RGS spectra are spatially integrated over the entire SNR, and therefore the interpretations are complicated.
→ Bright hot spots in Galactic SNRs should be good sites for RGS spectroscopy.

A Knot in NW SN 1006

Vink et al. (2003)



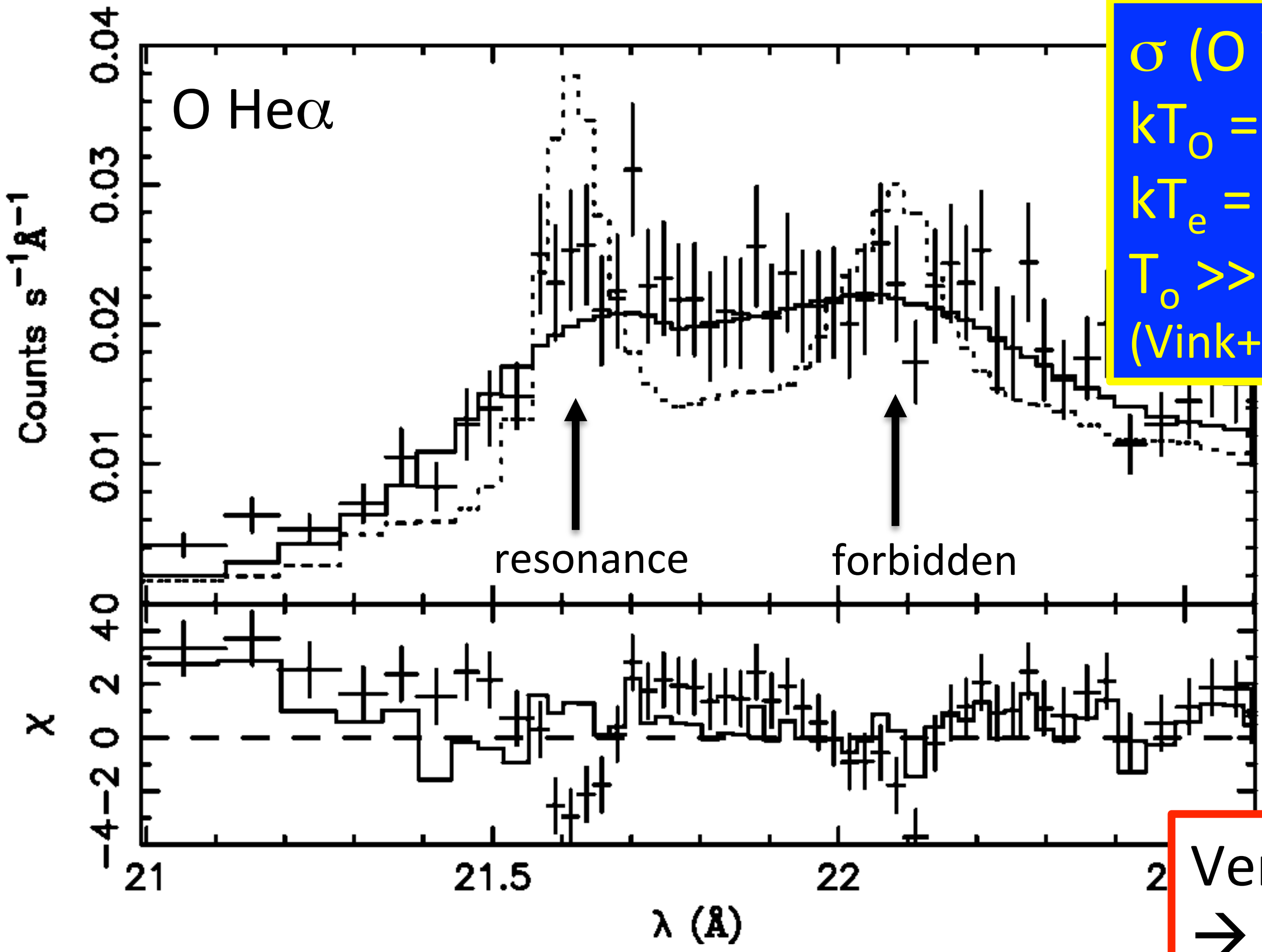
Emission profile



Knot’s size ~ 0.4’ (FWHM)

→ RGS spectral resolution for O VII ~ 3 eV

Temperature Nonequilibration: $T_{\mathrm{O\ VII}} \gg T_e$!



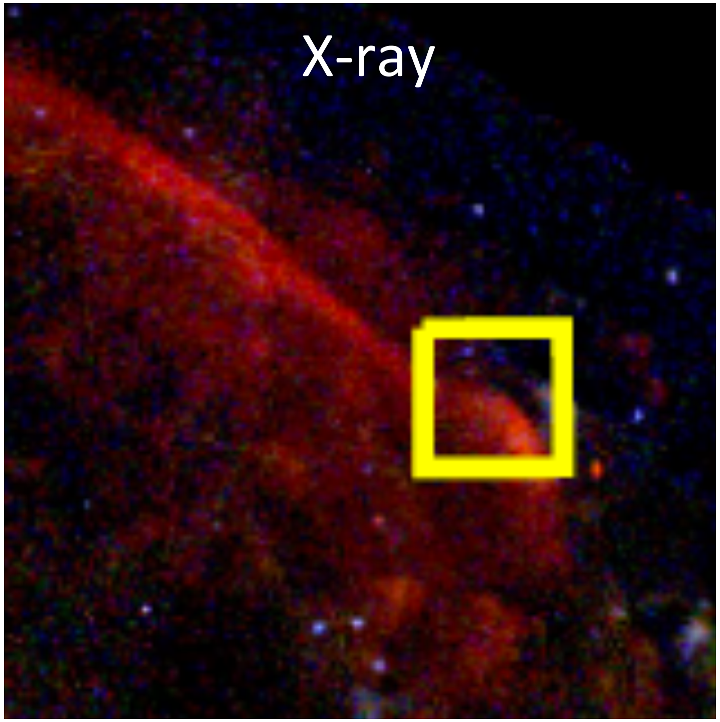
σ (O VII) = 2.4 ± 0.3 eV
kT_O = 275 ± 70 keV
kT_e = 1.5 keV
$T_o \gg T_e$!
(Vink+2003; Broersen+2013)

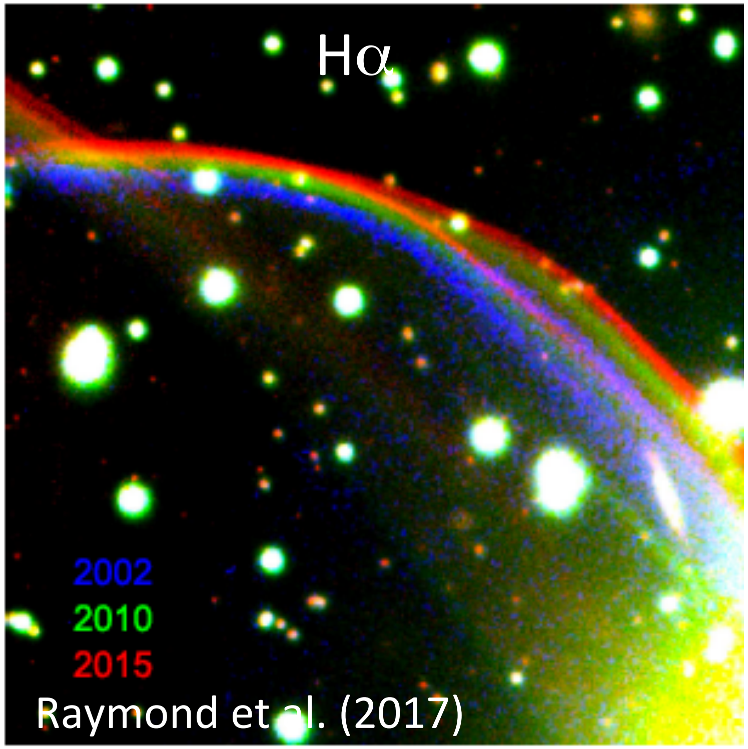
$$\sigma = E_0\sqrt{kT/mc^2}$$

Very broad O K lines → Large amount of thermal energy

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

Shock Speed Measurements





Raymond et al. (2017)

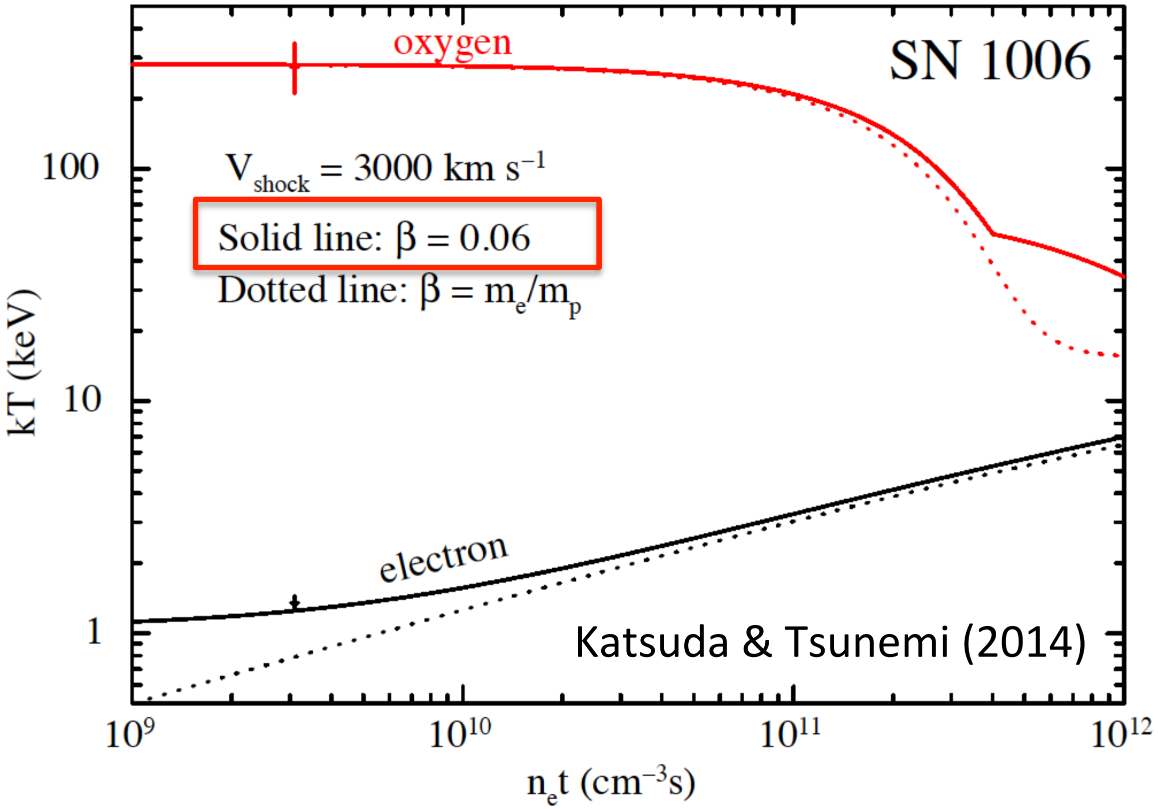
Proper motion measurement gives:
V_{shock} = 3000 km/s at a distance of 1.85 kpc

(Raymond et al. 2017 see also Winkler et al. 2003; SK et al. 2013)

→ Expected $kT_O = 280 (V_{shock} / 3000 \text{ km s}^{-1})^2$ keV (@maximum), which agrees with the RGS measurement (→ No energy for CRs).

Considering Coulomb Equilibration

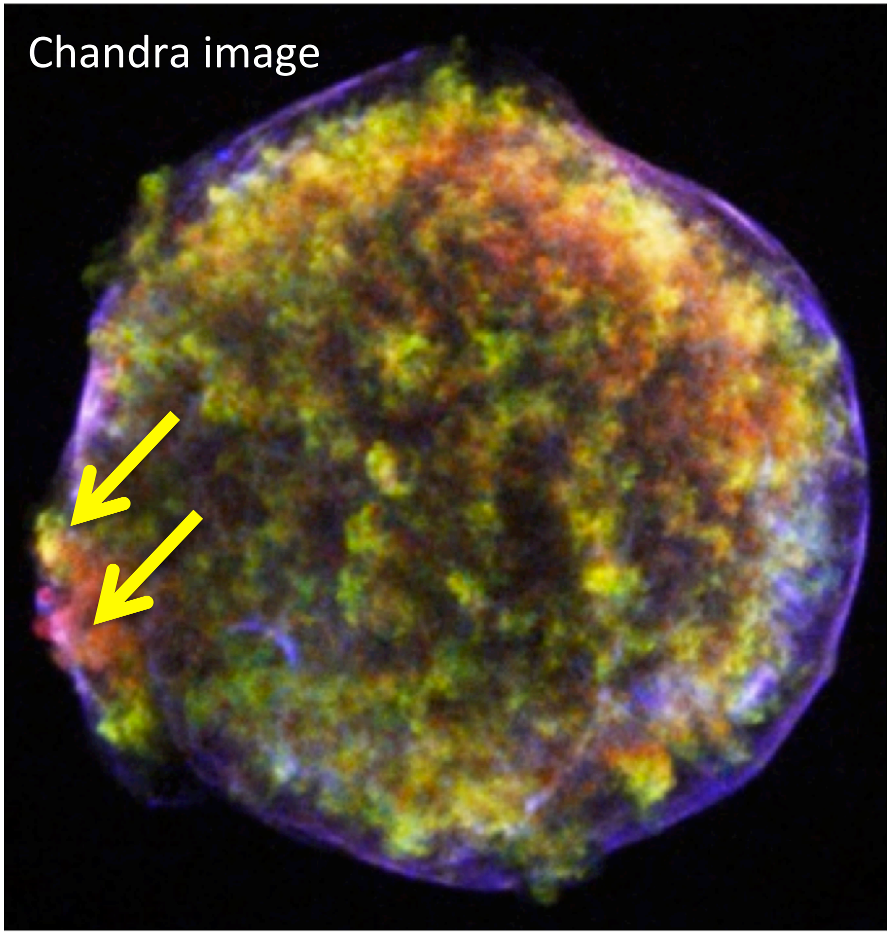
$$\frac{dT_i}{dt} = \frac{T_j - T_i}{t_{\mathrm{eq(i,j)}}},\ t_{\mathrm{eq(i,j)}} = 5.87 \frac{A_i A_j}{n_j Z_i^2 Z_j^2 \ln(\Lambda)} \left(\frac{T_i}{A_i} + \frac{T_j}{A_j} \right)^{\frac{3}{2}}$$



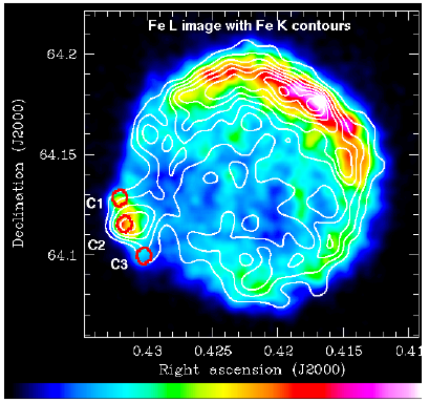
No energy is left for the CR acceleration.

However, this may not be true if the plasma was heated by a reverse shock.

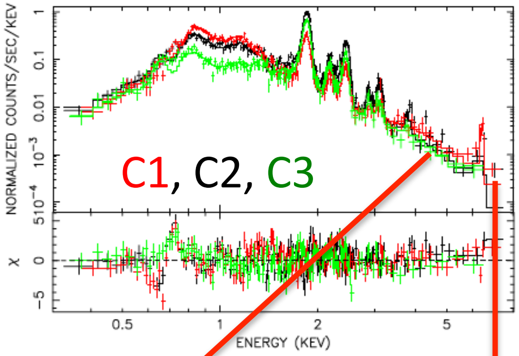
Ejecta Knots in SE Tycho's SNR



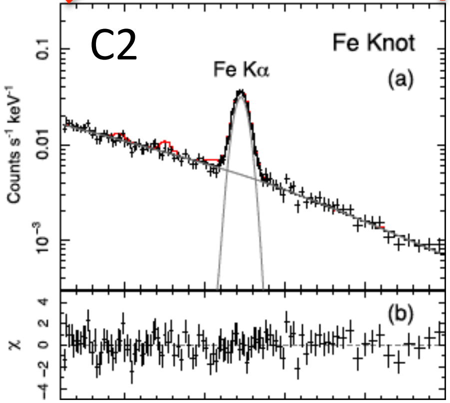
Decourchelle et al. (2001)



XMM-Newton



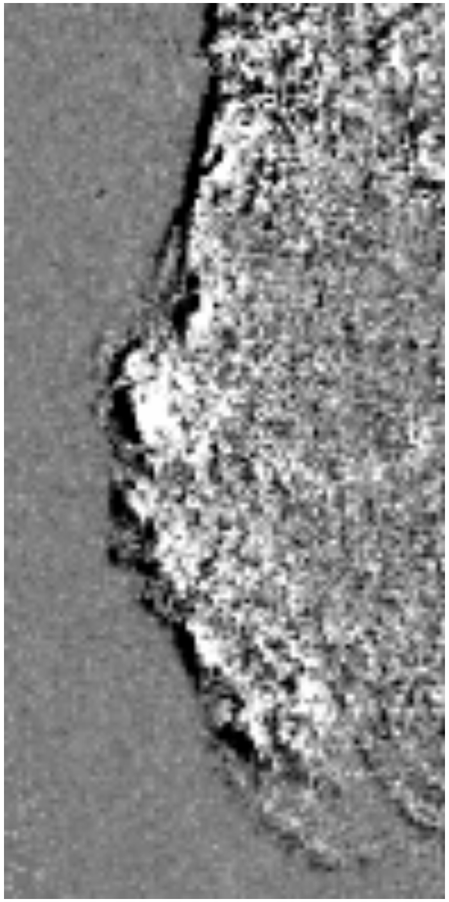
Suzaku



No Cr Mn lines (Yamaguchi et al. 2017)

Shock Speed Measurement

Chandra's difference image (2000 - 2007)

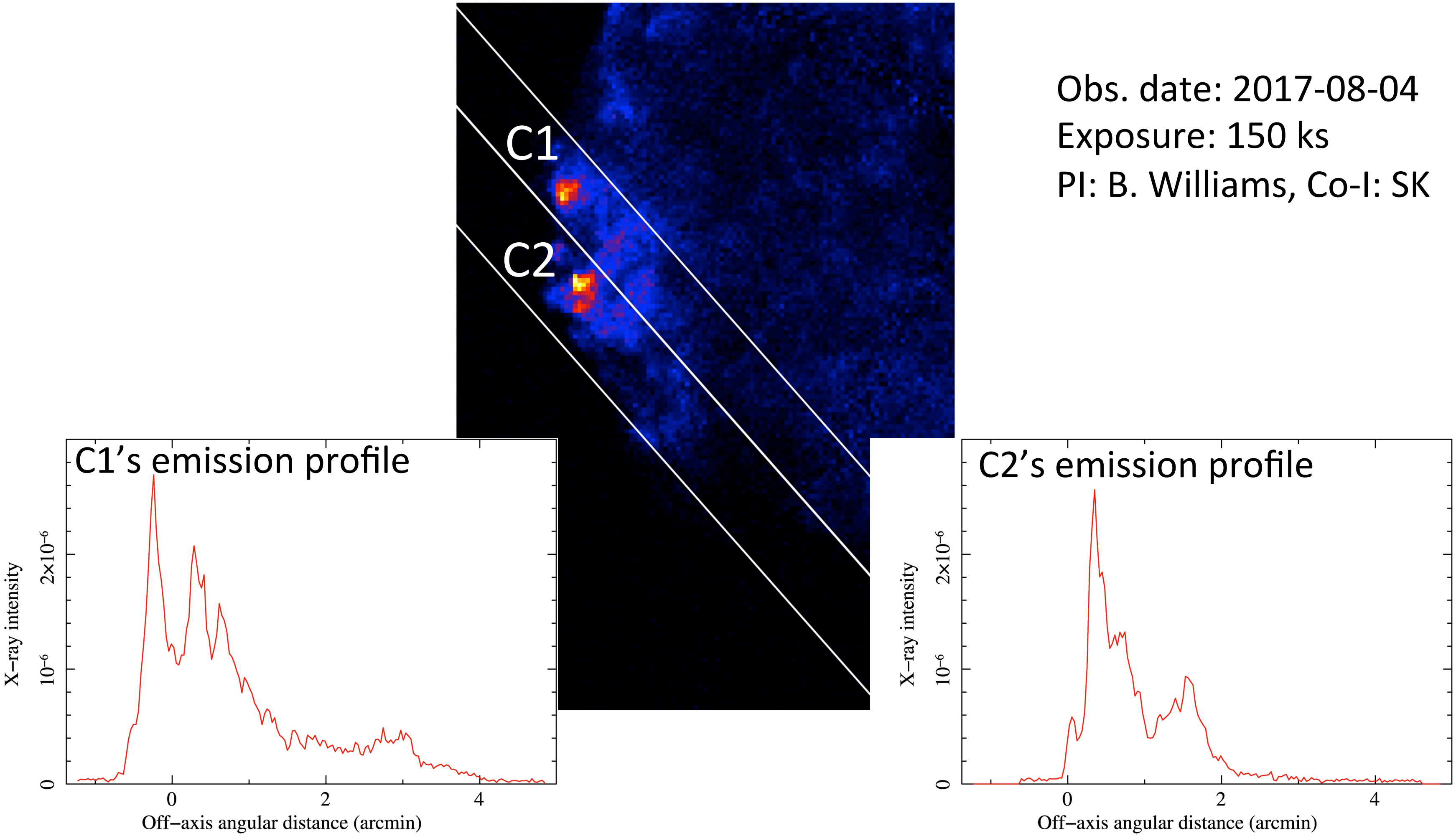


Proper motion measurements:
V_{shock} = 4300 km/s at d = 3 kpc
(SK et al. 2010)

→ Expected ion temperatures:

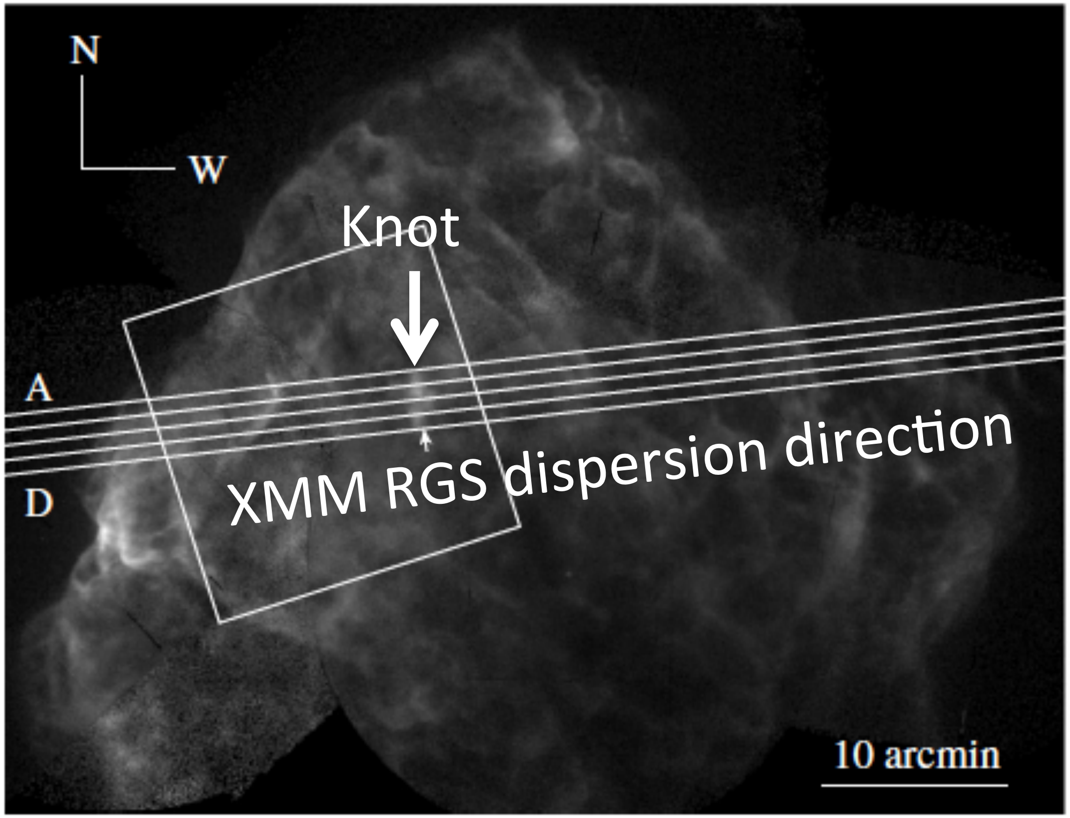
$kT_{Oxygen} = 580\ (V_{shock}\ /\ 4300\ \mathrm{km\ s^{-1}})^2$ keV
$(\sigma_{O\ Ly\alpha} = 4.1$ eV)
$kT_{Fe} = 2.0\ (V_{shock}\ /\ 4300\ \mathrm{km\ s^{-1}})^2$ MeV
$(\sigma_{FeL} = 5.2$ eV)

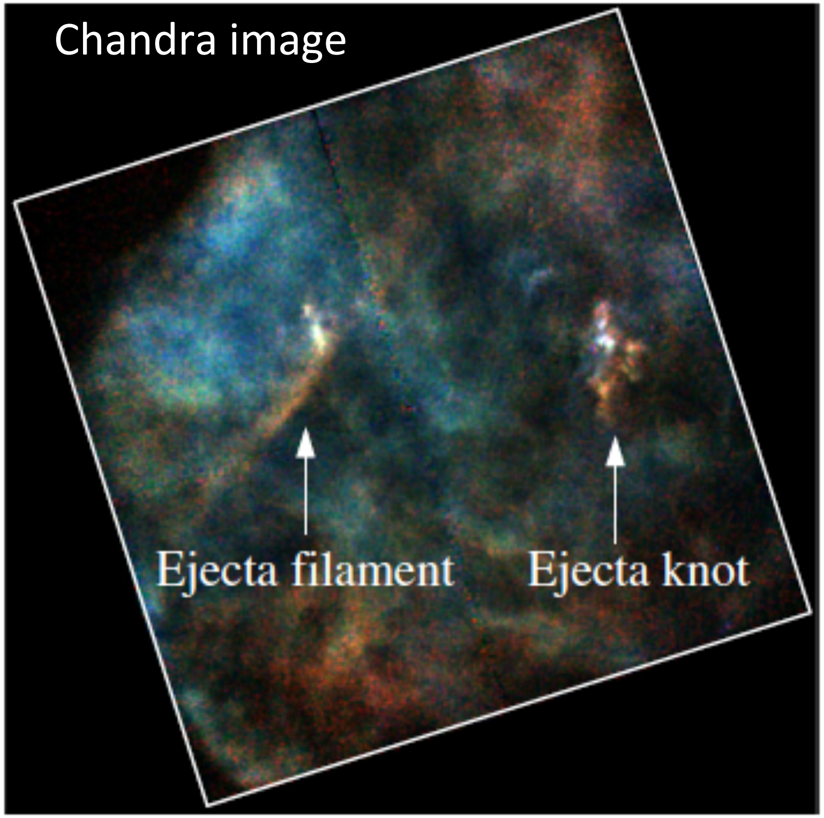
RGS Observation in 2017



Obs. date: 2017-08-04
Exposure: 150 ks
PI: B. Williams, Co-I: SK

Ejecta Knots in Puppis A

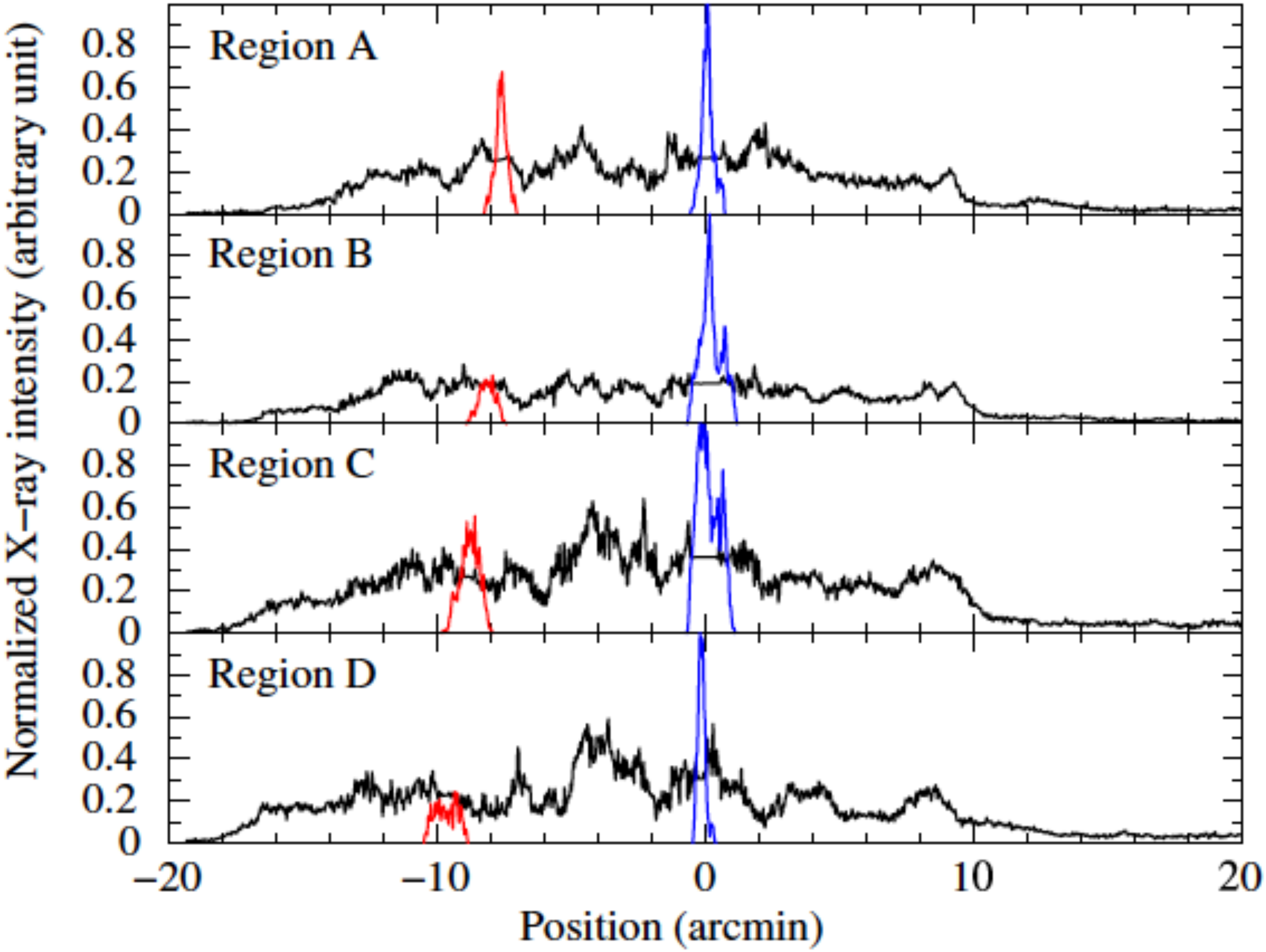




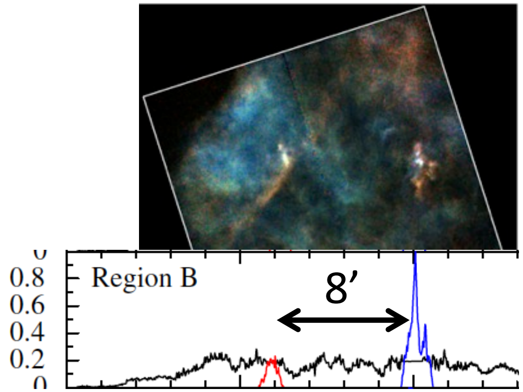
Observation date : 2012-10-20
Exposure time : 21 ks

ONeMg-rich ejecta features
(Winkler et al. 1985; SK et al. 2008; 2010)

Emission Profiles (RGS Response)

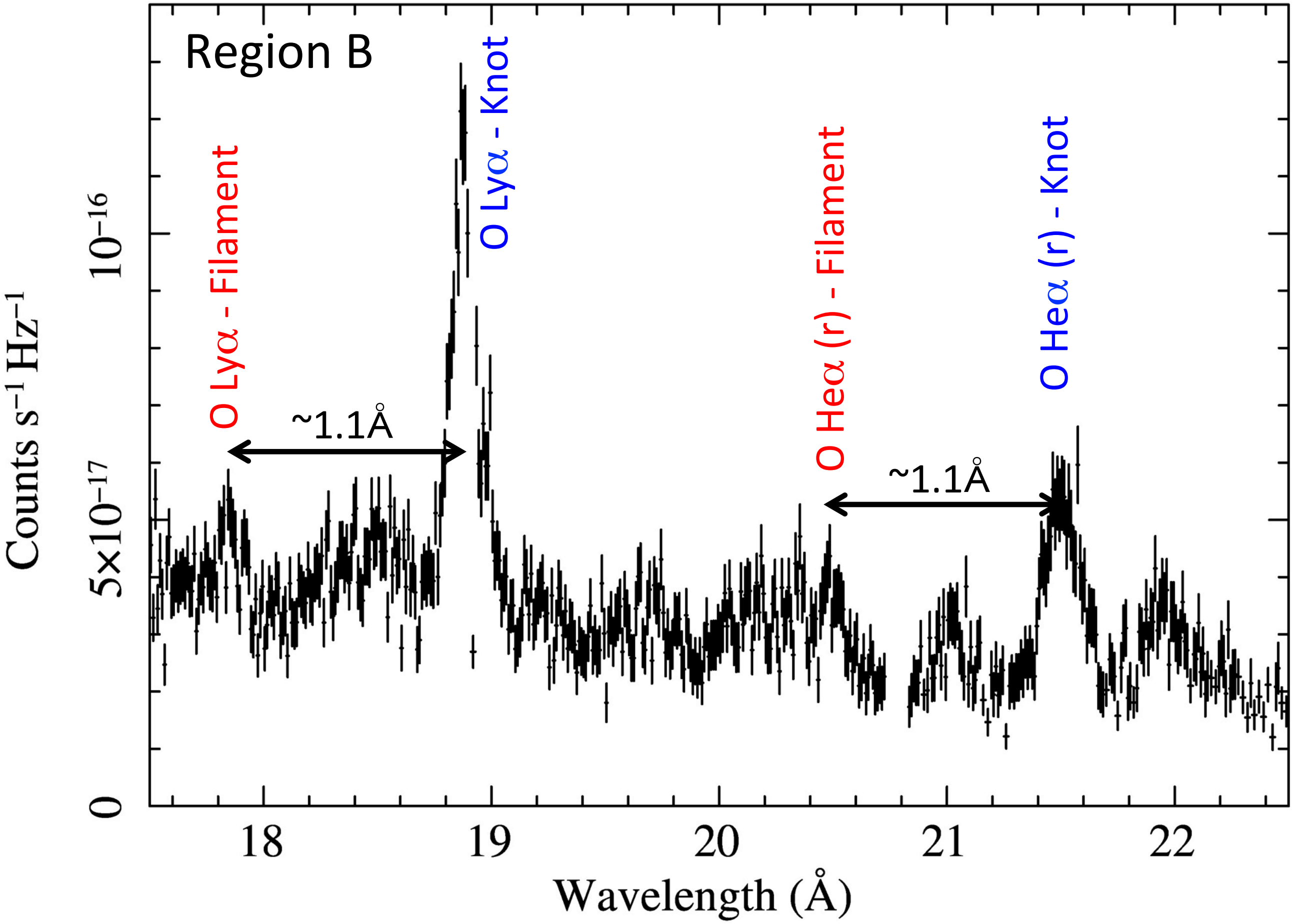


RGS Spectrum



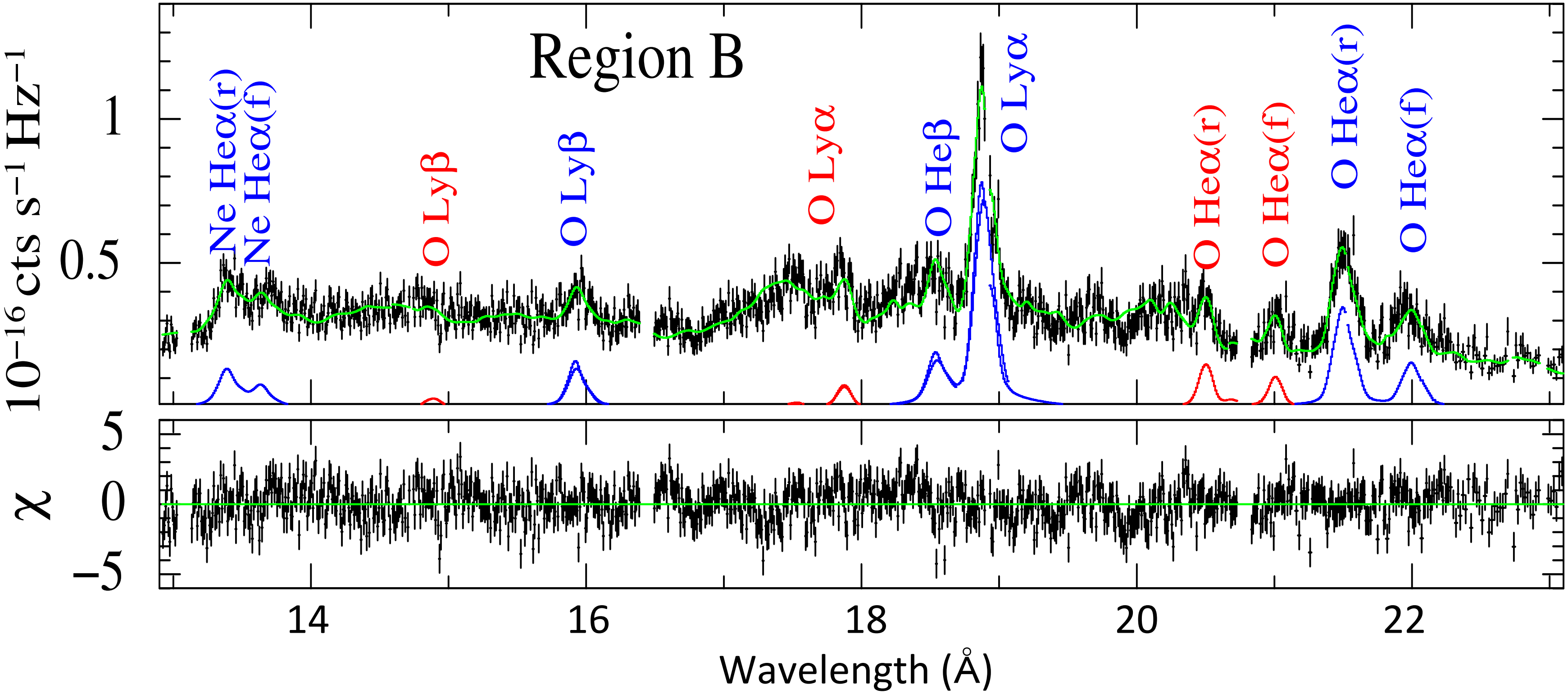
Spatial displacement
<-> Wavelength shift
8 arcmin → 1.1 Å
(Δλ ~ θ × 0.138/m Å)

Lines from the knot and filament are detected!



Spectral Modeling

Blue=Knot Red=Filament Green=Total (incl. local BG)



	Knot	Filament
Doppler velocity	1500 ± 200 km/s	-650 ± 130 km/s
Line width (σ)	< 0.9 eV (→kT$_O$ < 30 keV)	

Shock Speed Estimate

Estimate of a forward shock speed

▪Line-of-sight velocity: 1500 km/s

▪Proper motion: ~0.12 ”/yr (Winkler et al. 1988) → 1260 km/s

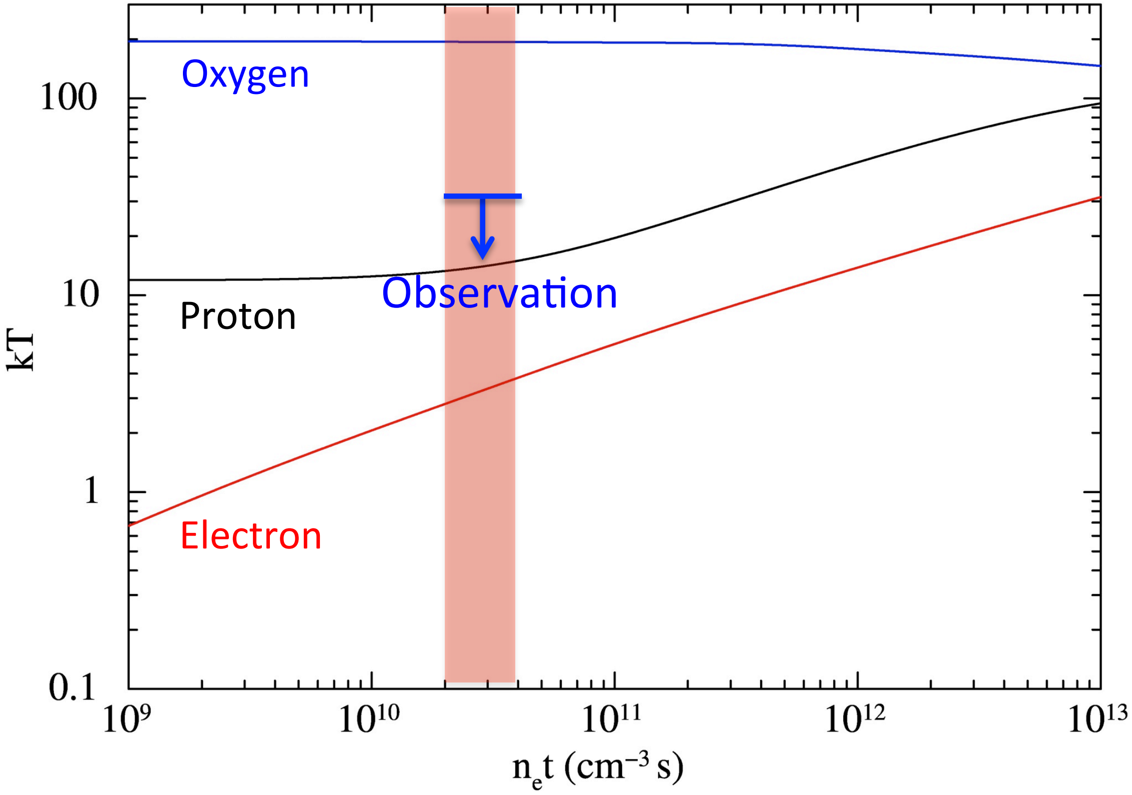
→ Gas motion: $V_{\text{shocked gas}} = \text{sqrt}(1500^2+1260^2) = 2000$ km/s

→ Forward shock speed: $V_{\text{shock}} = 4/3\ V_{\text{gas}} \sim 2500$ km/s

$kT_O = 195\ (V_{sh}/2500\ \text{km/s})^2$ keV (@maximum, $n_e t = 0$),
which is much higher than the upper limit of $kT_o < 30$ keV
→ Extremely high CR acceleration efficiency ?!

Coulomb Equilibration

Temperature evolution after shock heating for V_{shock} = 2500 km/s



The kT_o measured is significantly lower than the value expected at V_{shock} = 2500 km/s, even if we take into account the Coulomb equilibration.

→ An extremely high CR acceleration efficiency (> 85%)?!

However, this may not be true if the plasma was heated by a reverse shock.

X-Ray Astronomy Recovery Mission

Telescope

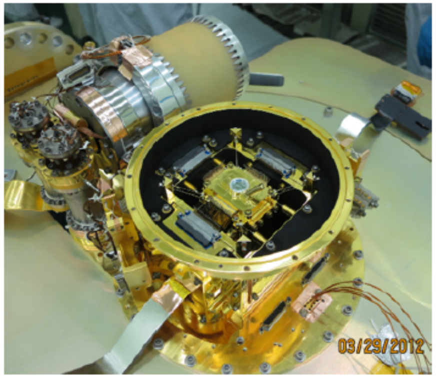
© ASTRO-H

□ XARM:

- The 7th Japanese X-ray astronomy satellite
- To be launched in 2021
- Carries X-ray calorimeter & X-ray CCD

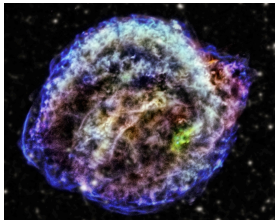
□ X-ray micro-calorimeter (SXS):

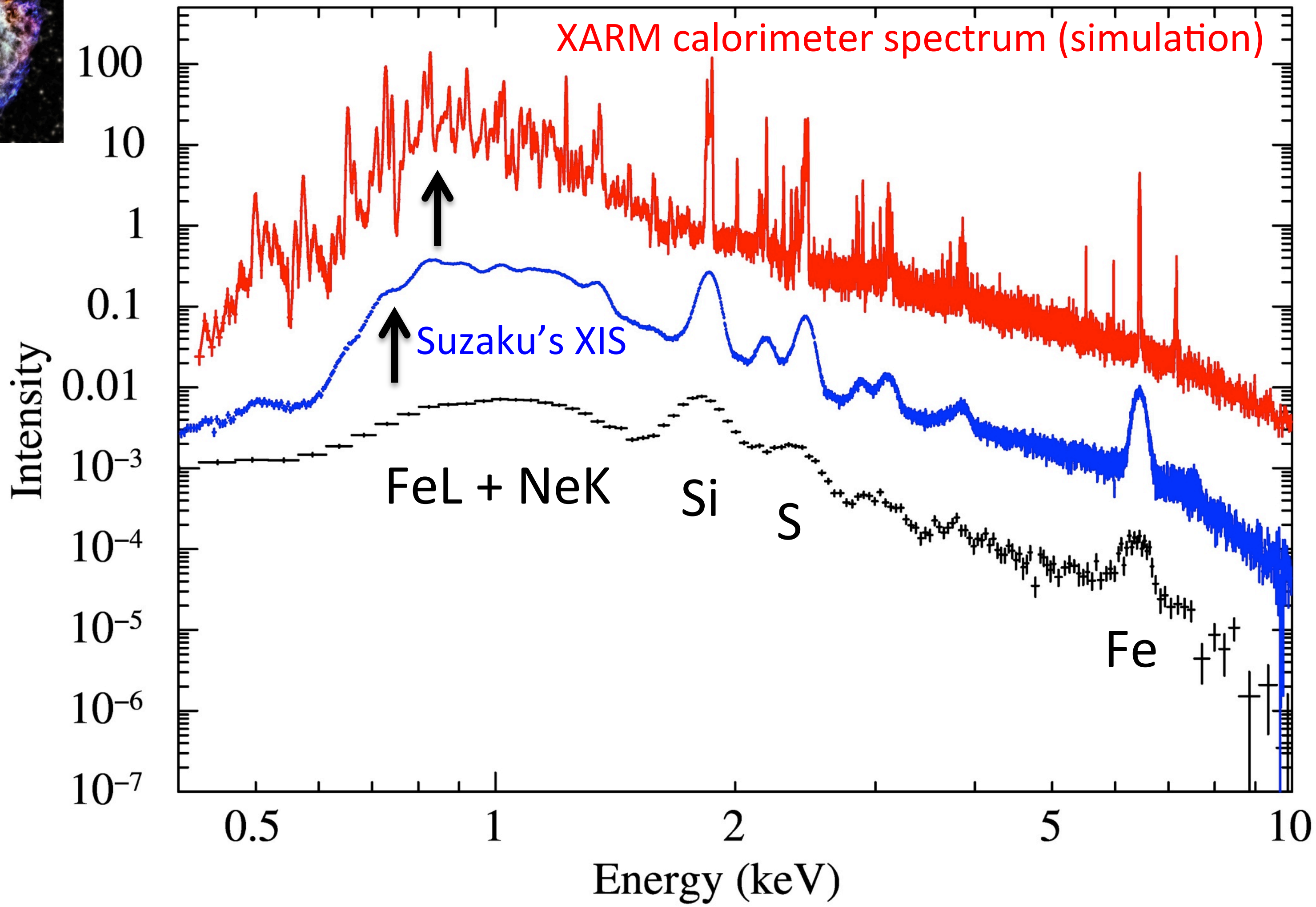
- E/ΔE: ~200@1keV
  (Non-dispersive!)
- Spatial resolution: 1’
- FoV: 3’x3’ (6x6 array)
- Dynamic range:
  0.5-25 keV



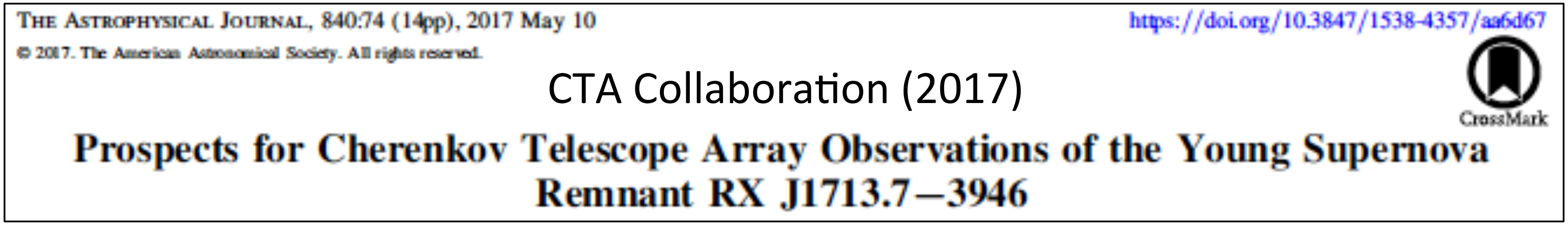
SXS detector assembly

Spectral Simulation with XARM





A Little Thought about Synergy with CTA

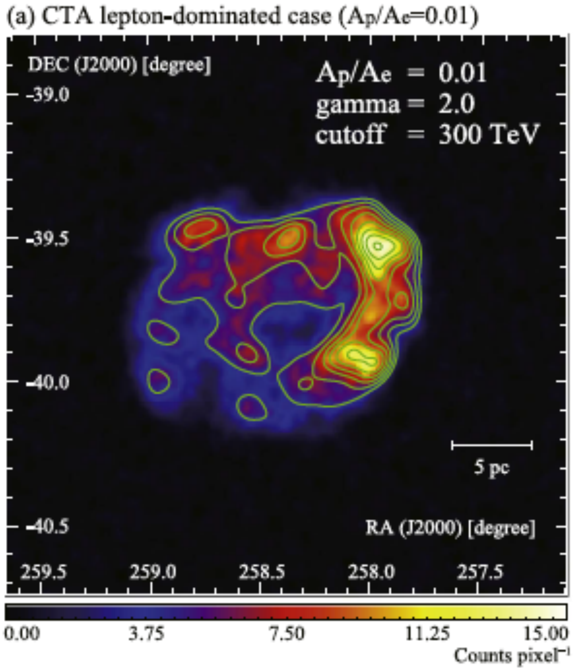


The Astrophysical Journal, 840:74 (14pp), 2017 May 10 https://doi.org/10.3847/1538-4357/aa6d67

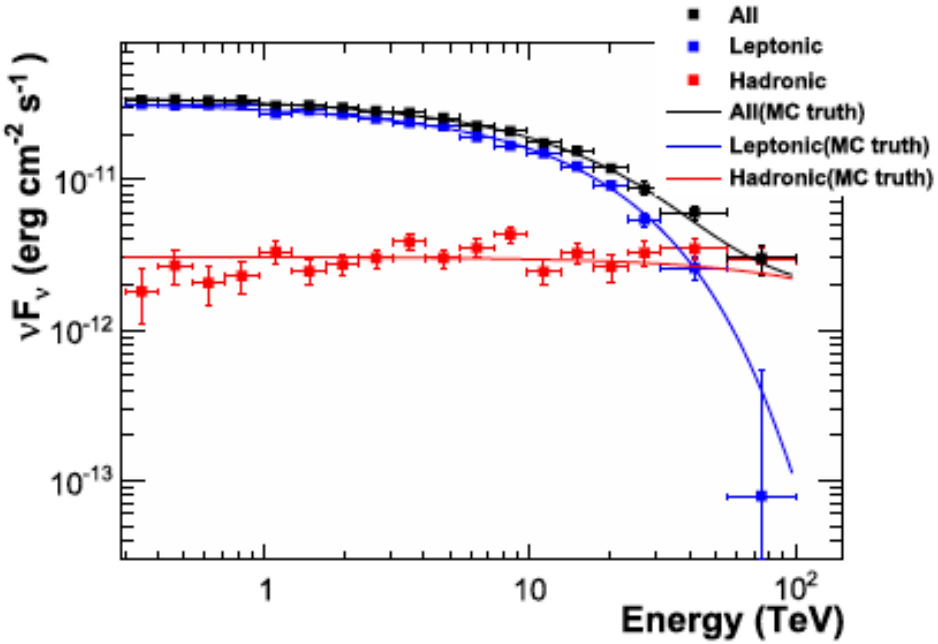
CTA Collaboration (2017)

Prospects for Cherenkov Telescope Array Observations of the Young Supernova Remnant RX J1713.7−3946

- CTA will reveal leptonic/hadronic contribution in SNRs, as well as its spatial distribution.



(a) CTA lepton-dominated case (Ap/Ae=0.01)

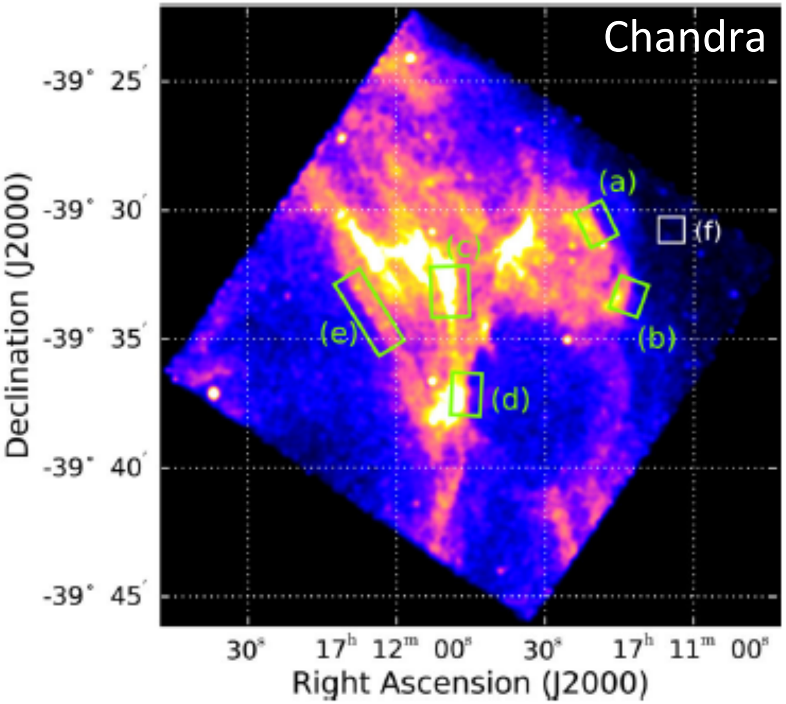


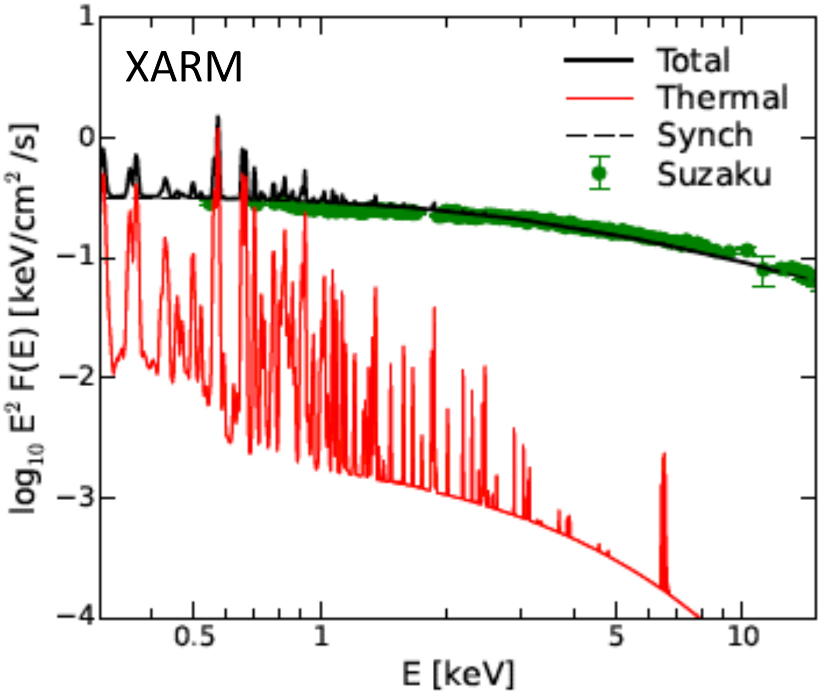
X-Ray Measurements

Spatial variation of TeV gamma-rays

Spatial variation of proper motions

Spatial variation of CR acceleration efficiency





Tsuji & Uchiyama (2016)
Acero, SK, Ballet, & Petre (2017)

ASTRO-H white paper

Summary

- SNRs are the best candidates for Galactic cosmic rays. However, the CR acceleration efficiency at SNR shocks has been rarely measured.
- High-resolution X-ray spectroscopy is a hope to measure CR acceleration efficiencies.
- Current measurements with gratings onboard XMM revealed CR acceleration efficiencies (including upper limits) in a few SNRs.
- X-ray astronomy recovery mission (XARM) will greatly enhance this field.