A spatially resolved study of hard X-ray emission in Kepler's SNR:

Indications of different regimes of particle acceleration

Sapienza et al. (2022) publ. ApJ

Vincenzo Sapienza

INAF - Osservatorio Astronomico di Palermo

Department of Physics and Chemistry “Emilio Segré” - University of Palermo

Collaborators:

M. Miceli, A. Bamba, S. Katsuda, Y. Terada, T. Nagayoshi, F. Bocchino, S. Orlando, G. Peres

Synchrotron emission in SNR

Synchrotron emission is a powerful tool to study:

- The distribution the accelerated electrons
- The mechanism that limits their **maximum energy**

We chose to study the non-thermal emission of the young **Kepler's SNR:**

- Young SNRs have high shock velocities → Excellent accelerators of particles
- Strong synchrotron emitter
- First detection of **HARD NON-THERMAL** X-ray emission but no spatial resolution

Sapienza et al. (2022) publ. ApJ

Hard non-thermal X-rays of Kepler’s SNR

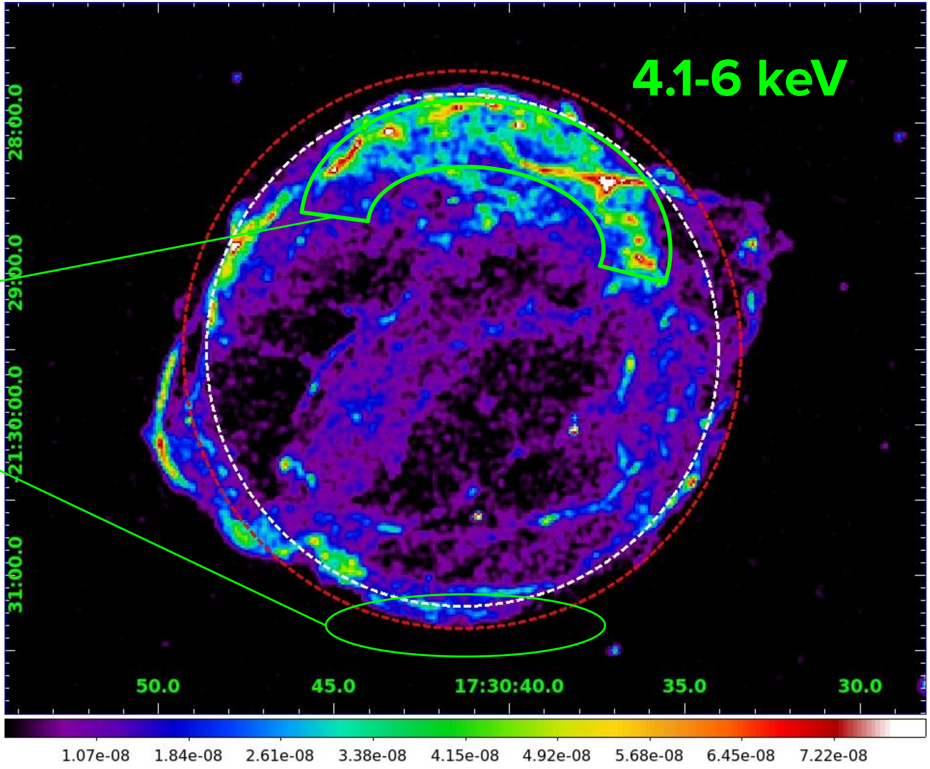
Distance (pc)	Age (yrs)	Physical origin
∼5000	418	type Ia SN

Shock interacting with dense circumstellar medium
$v_{sh} \sim 2000$ km/s

Shock expanding in subtle homogeneous medium
$v_{sh} \sim 5000\text{-}6000$ km/s

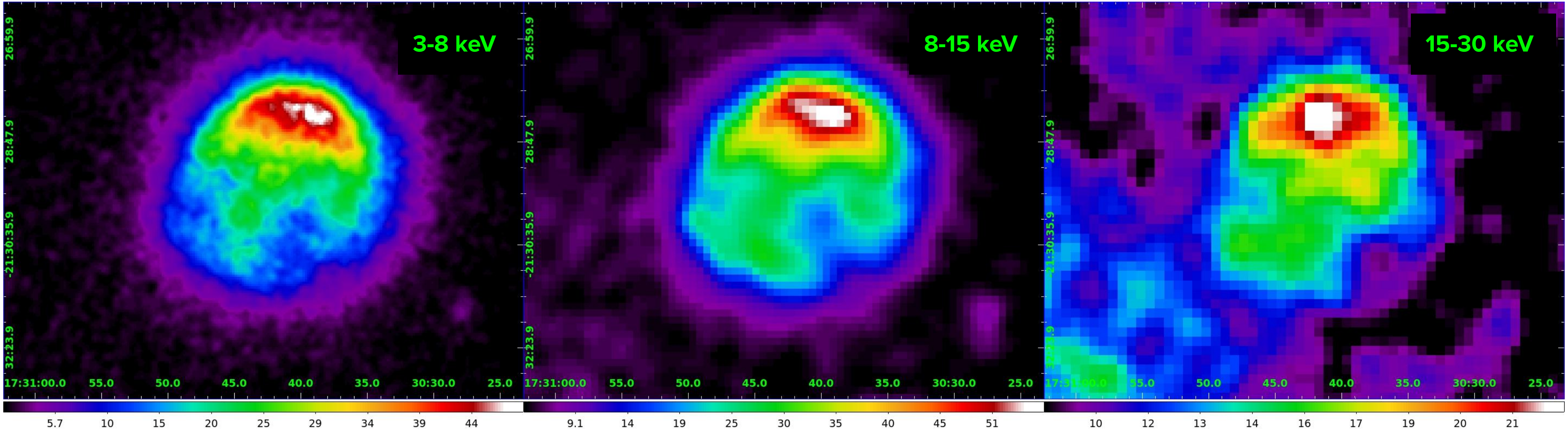
Spatially resolved spectral analysis

Non-thermal radiation from Kepler’s SNR



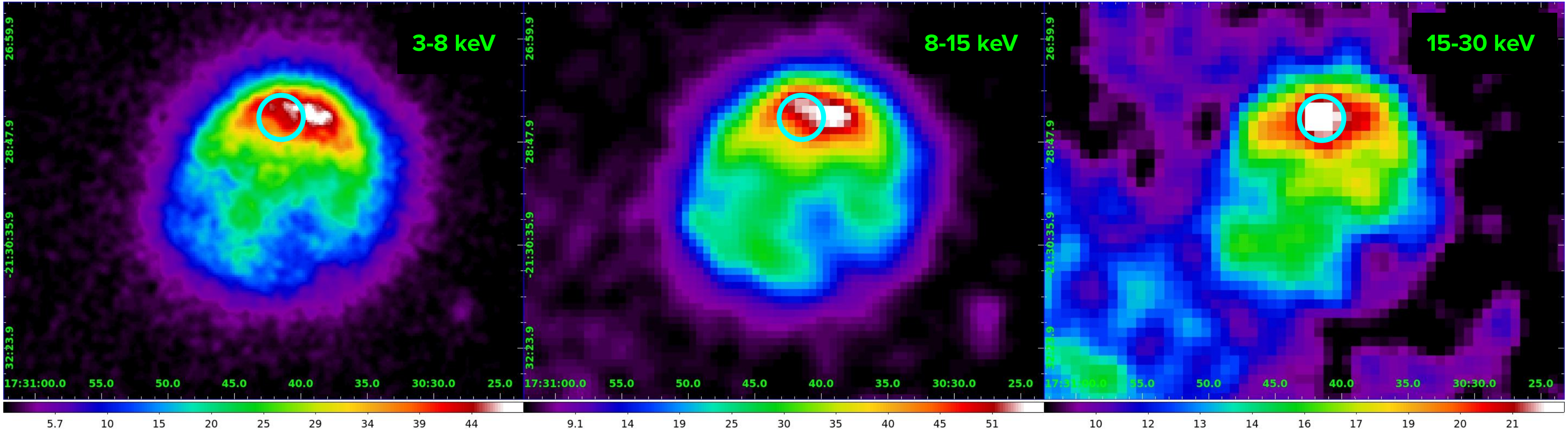
***Chandra** flux image*

First Hard X-rays Images of Kepler’s SNR



Sapienza et al. Subm. to ApJ: ***NuSTAR*** *counts images in 3-8 keV, 8-15 keV and 15-30 keV from left to right*

First Hard X-rays Images of Kepler’s SNR



Sapienza et al. Subm. to ApJ: ***NuSTAR*** *counts images in 3-8 keV, 8-15 keV and 15-30 keV from left to right*

Loss limited model

Loss-limited spectrum model is (Zirakashvili & Aharonian 2007):

$$\frac{dN_X}{d\varepsilon} \propto \left(\frac{\varepsilon}{\varepsilon_0}\right)^{-2}\left[1 + 0.38\left(\frac{\varepsilon}{\varepsilon_0}\right)^{1/2}\right]^{11/4} \exp\left[-\left(\frac{\varepsilon}{\varepsilon_0}\right)^{1/2}\right]$$

cutoff photon energy

$\tau_{sync} \sim$ 60 yrs (B=100 μG E=20 TeV)

$$\tau_{sync} \approx 12.5\left(\frac{E}{100\mathrm{TeV}}\right)^{-1}\left(\frac{B}{100\mu\mathrm{G}}\right)^{-2} \quad \mathrm{yrs}$$

$\tau_{sync} < \tau_{age}$

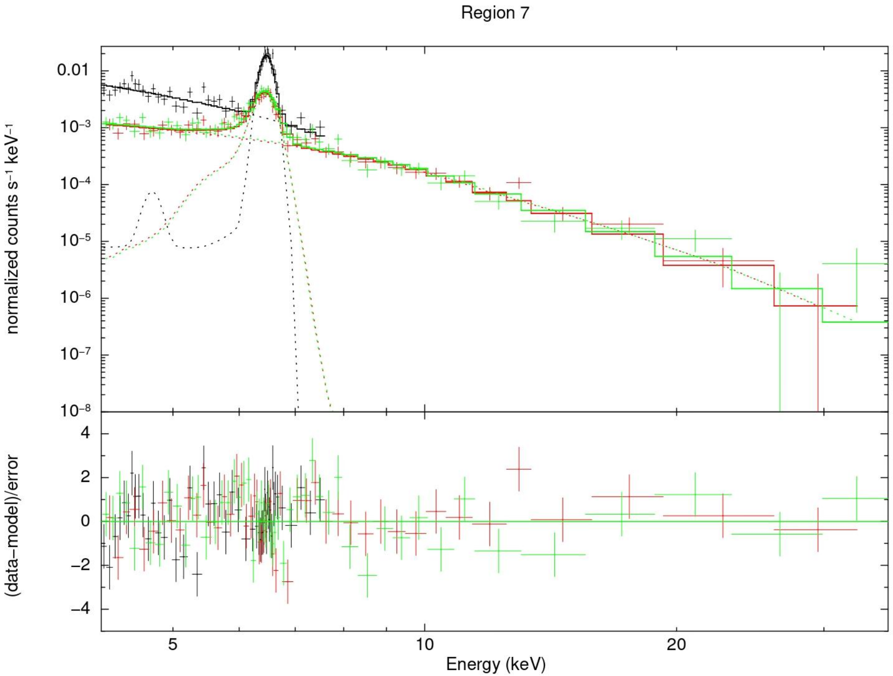
Relation between ε_0 and shock velocity

$$\varepsilon_0 = \frac{1.6}{\eta}\left(\frac{v_{sh}}{4000\ \mathrm{km\ s^{-1}}}\right)^2 \quad \mathrm{keV}$$

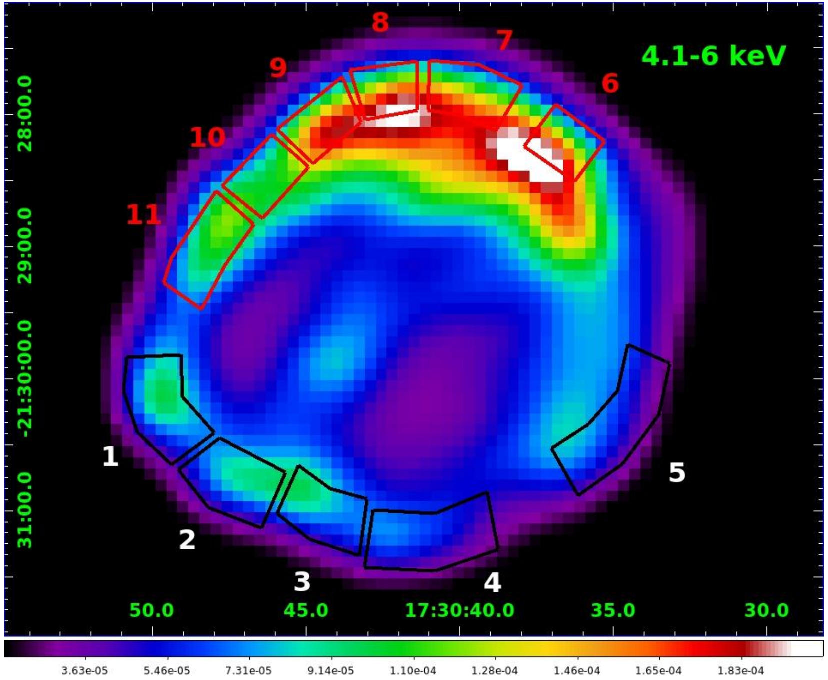
η related to the magnetic turbulences

Bohm limit: η=1

Spatially resolved spectral analysis

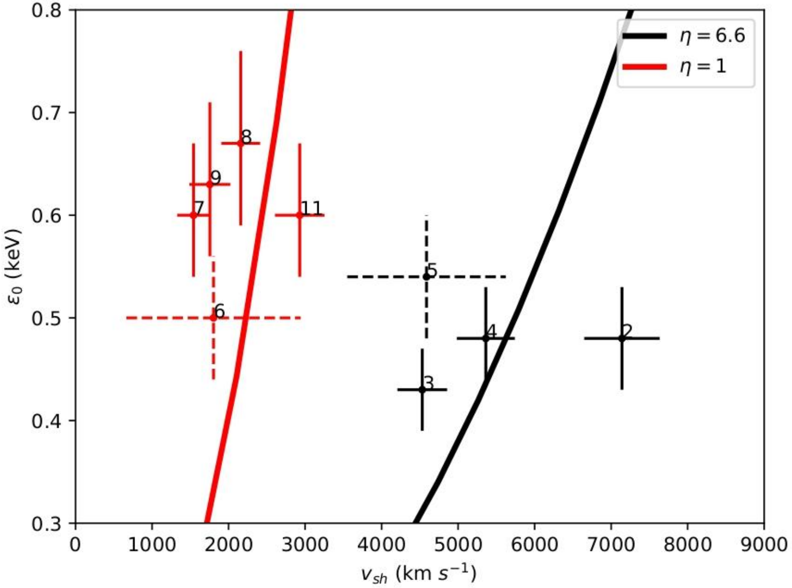


Sapienza et al. (2022): pn (black) FPMA (red) and FPMB (green) spectra of region 7 with best fit model and residuals in 4.1-30 keV band



Sapienza et al. (2022): XMM-Newton MOS count-rate map of Kepler's SNR in 4.1-6 keV band

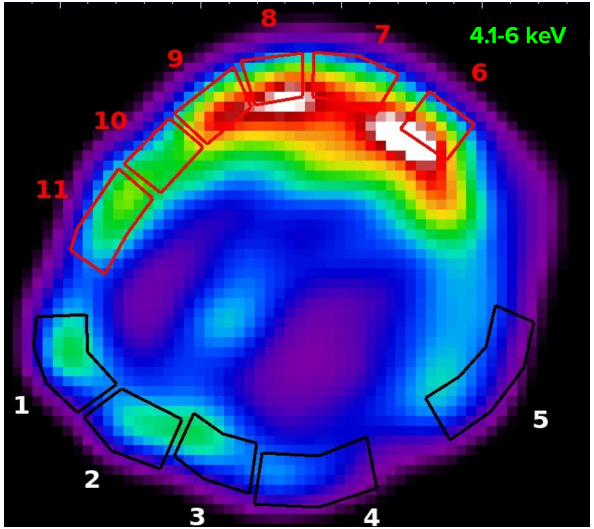
Two different regimes of acceleration



Sapienza et al. (2022):

ε_0 vs. Coffin et al. (2022, Solid crosses) and Katsuda et al. (2008, dashed crosses) v_{sh}

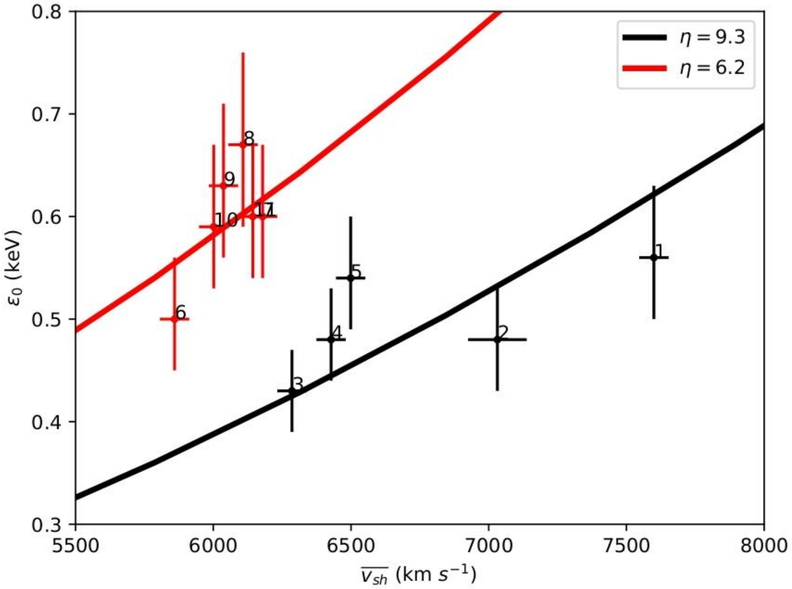
$$\varepsilon_0 = \frac{1.6}{\eta}\left(\frac{v_{sh}}{4000\ \mathrm{km\ s^{-1}}}\right)^2 \quad \mathrm{keV}$$



Sapienza et al. (2022): XMM-Newton MOS count-rate map of Kepler's SNR in 4.1-6 keV band

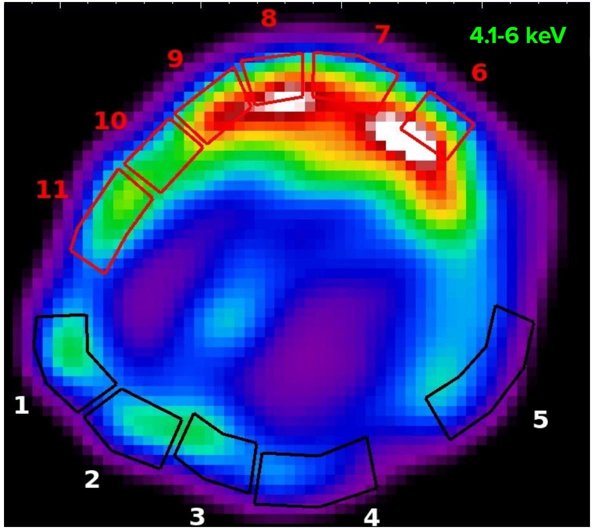
V_{sh} (Km/s)	ε_0(keV)	η	t_{acc}(yrs)
1800	0.64	1	$300*(B_{100})^{-3/2}$

Two different regimes of acceleration



Sapienza et al. (2022):

ε_0 vs. average velocity using Sato & Hughes (2017) center



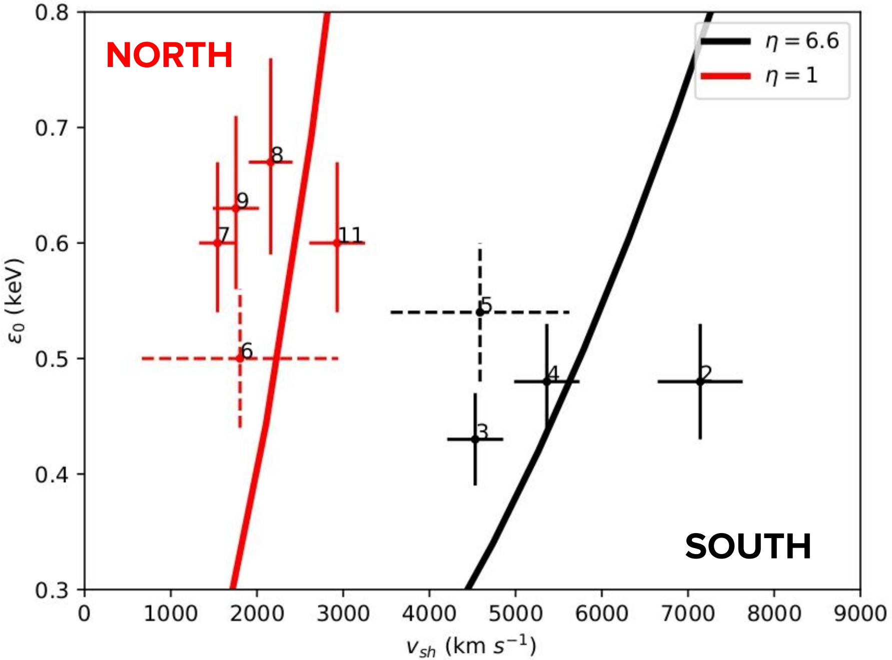
Sapienza et al. (2022): XMM-Newton MOS count-rate map of Kepler's SNR in 4.1-6 keV band

$$\varepsilon_0 = \frac{1.6}{\eta}\left(\frac{v_{sh}}{4000\ \mathrm{km\ s^{-1}}}\right)^2 \quad \mathrm{keV}$$

Bohm limit: η=1
Best acceleration efficiency

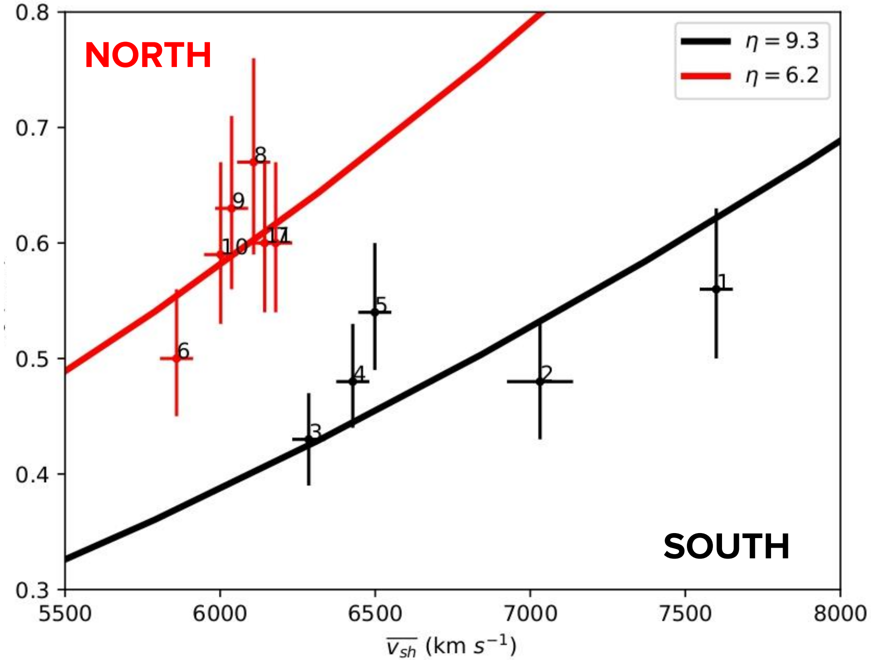
Sapienza et al. (2022) publ. ApJ

Two different regimes of acceleration



Sapienza et al.(2022):

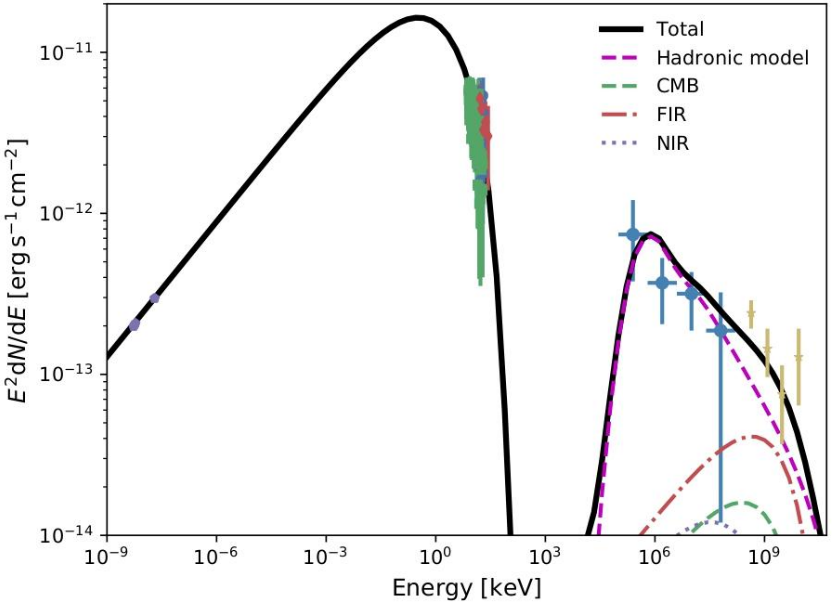
ε_0 vs. Coffin et al. (2022, Solid crosses)/Katsuda et al. (2008, dashed crosses) v_{sh}



Sapienza et al. (2022):

ε_0 vs. average velocity using Sato & Hughes (2017) center

Spectral Energy Distribution



Sapienza et al. in prep: Radio: DeLaney et al. (2002). X-ray: Sapienza et al. in prep, Nagayoshi et al. (2021). γ-ray: Acero et al. (2022), Prokhorov et al. (2021).

Recent detection of γ-rays from Kepler's SNR

X-ray data from this project

One-zone Lepto-hadronic model:

- Synchrotron for X-rays and Radio
- Inverse Compton and Pion decay for γ-rays

α	E_{cut} (TeV)	B (μG)	n (cm^{-3})	W_p (erg)
2.44	16	100	20	4.2×10^{48}

Sapienza et al. (2022):

First data analysis on NuSTAR data from Kepler's SNR

Brighter non-thermal emission in the north than in the south

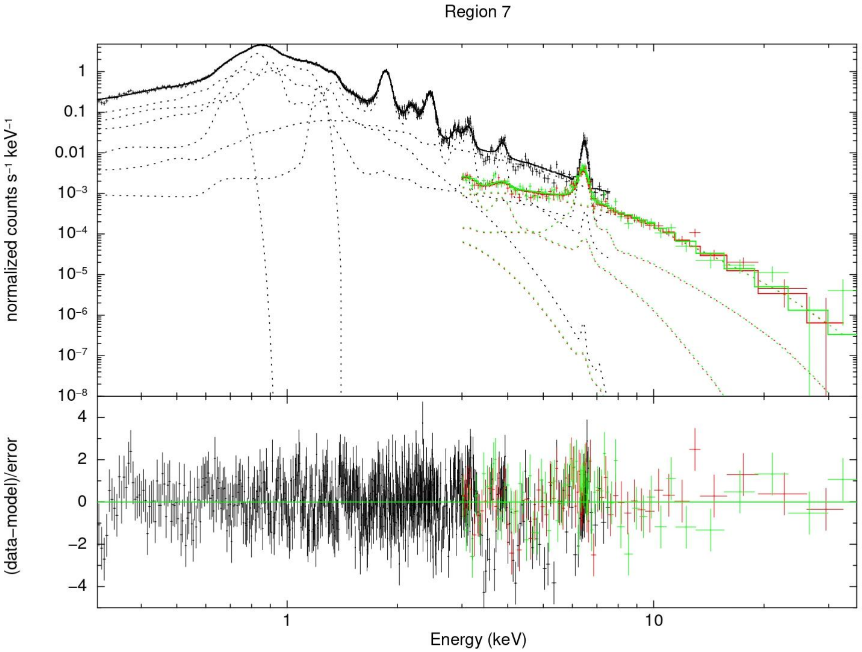
Spatially resolved spectral analysis with a loss limited model

Electrons in northern regions are accelerated closer to Bohm limit

Turbulences generated in Shock/CSM interaction enhance acceleration efficiency

SED: Indication of hadronic acceleration in Kepler's SNR

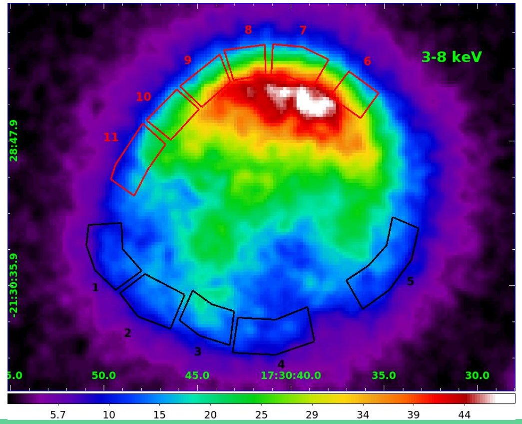
Broadband spectra as crosscheck



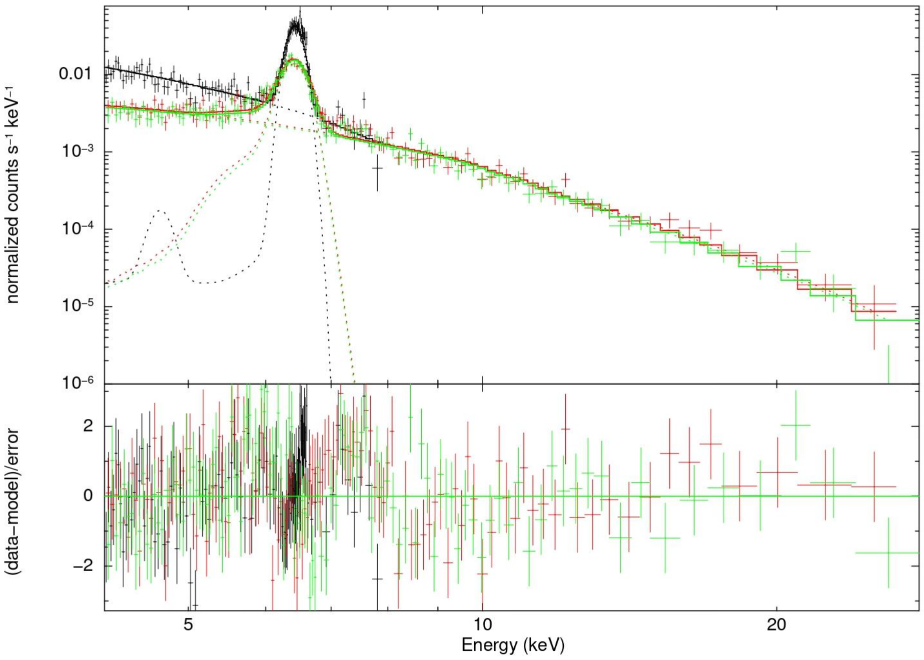
Sapienza et al. Subm. to ApJ: pn (black) FPMA (red) and FPMB (green) spectra of region 7 with best fit model and residuals in 0.3-30 keV band

Model with three thermal components and loss limited model

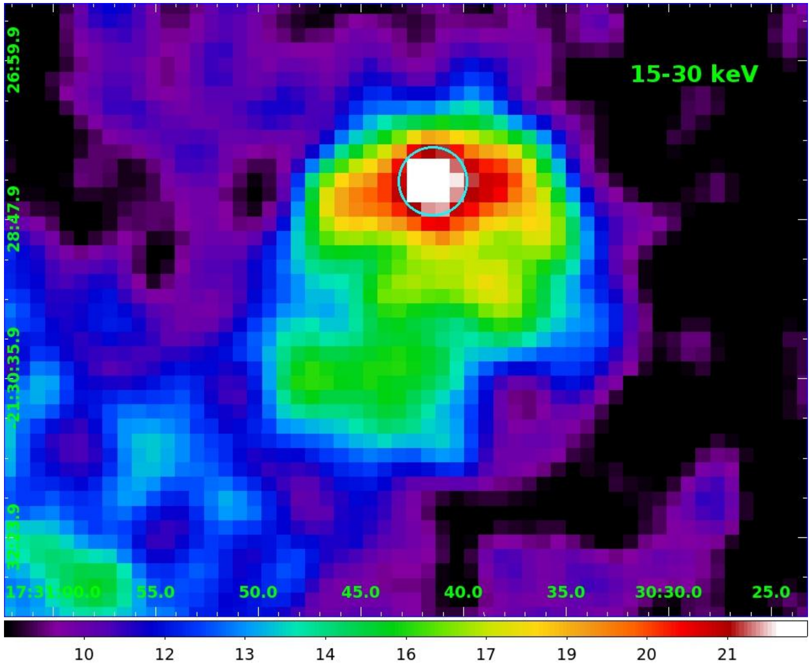
$1 < \chi^2/\text{d.o.f.}\ (400\text{-}700) < 1.4$



Hard Knot spectrum

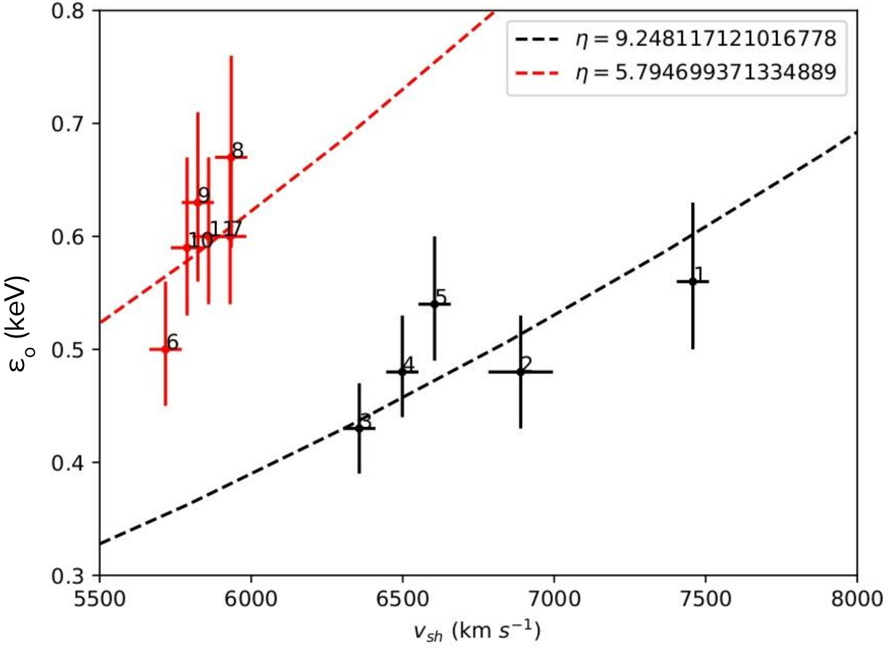


Sapienza et al. Subm. to ApJ: pn (black) FPMA (red) and FPMB (green) spectra of hard knot region with best fit model and residuals in 4.1-30 keV band

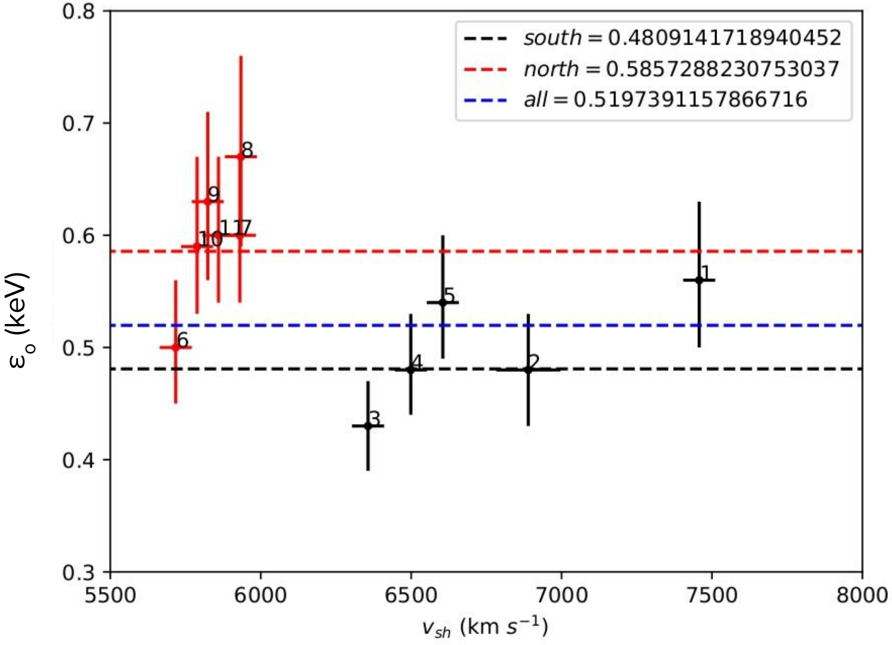


Sapienza et al. Subm. to ApJ: NuSTAR counts map of Kepler's SNR in 15-30 keV band

Quadratic vs. constant



null hypothesis probability~95%



null hypothesis probability ~15%