ANTON PANNEKOEK INSTITUUT

SHARP

ISTITUTO NAZIONALE DI ASTROFISICA INAF

Evidence for a Pulsar Wind Nebula in SN1987A

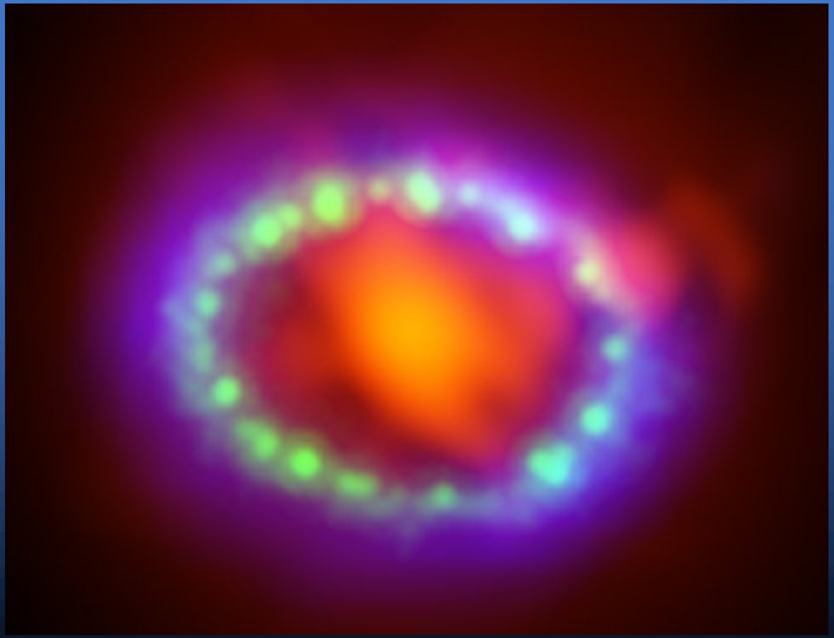
Emanuele Greco

M. Miceli, S. Orlando, B. Olmi, J. Vink, L. Sun, S. Nagataki, A. Dohi, V. Sapienza, M. Ono, G. Peres

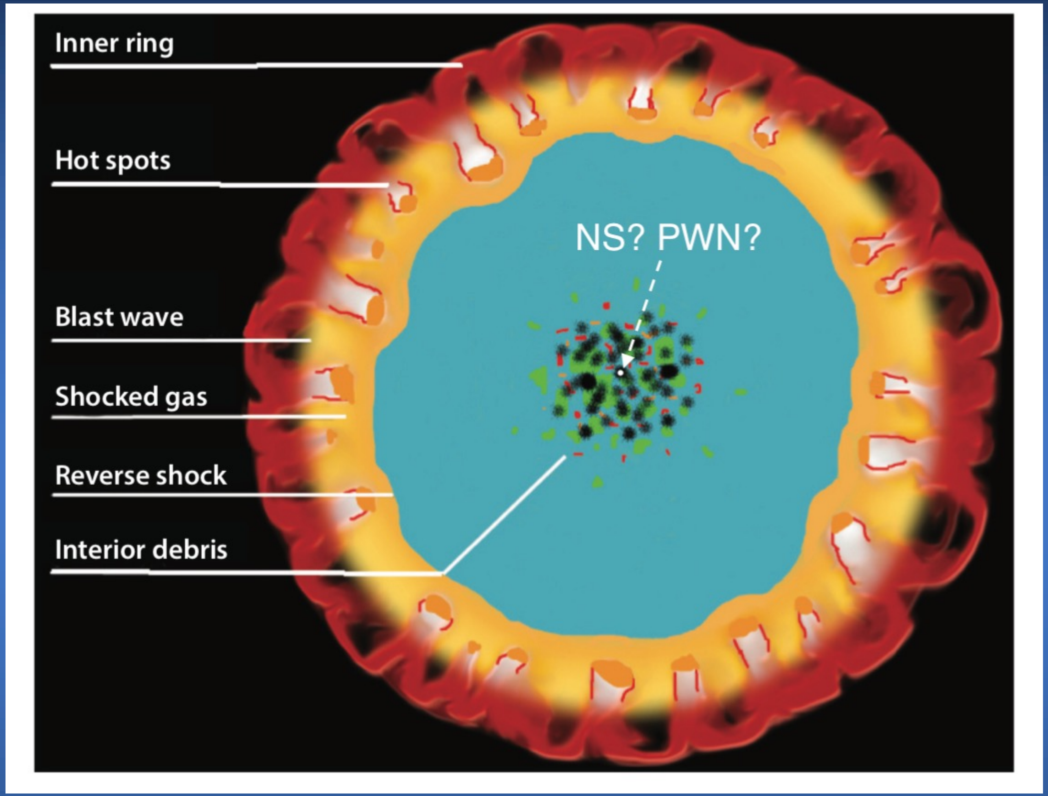
Greco et al. 2021, ApJL
Greco et al. 2022, ApJ

SN 1987A...

- Most recent naked-eye visible supernova at 51.4 kpc
- Unique laboratory to study the link between progenitor-supernova-remnant
- Embedded in an HII region and interacting with a dense ring-like structure
- Reverse shock has not reached inner ejecta yet



Red: ALMA (radio)
Green: Hubble (optical)
Blue: Chandra (X-ray)



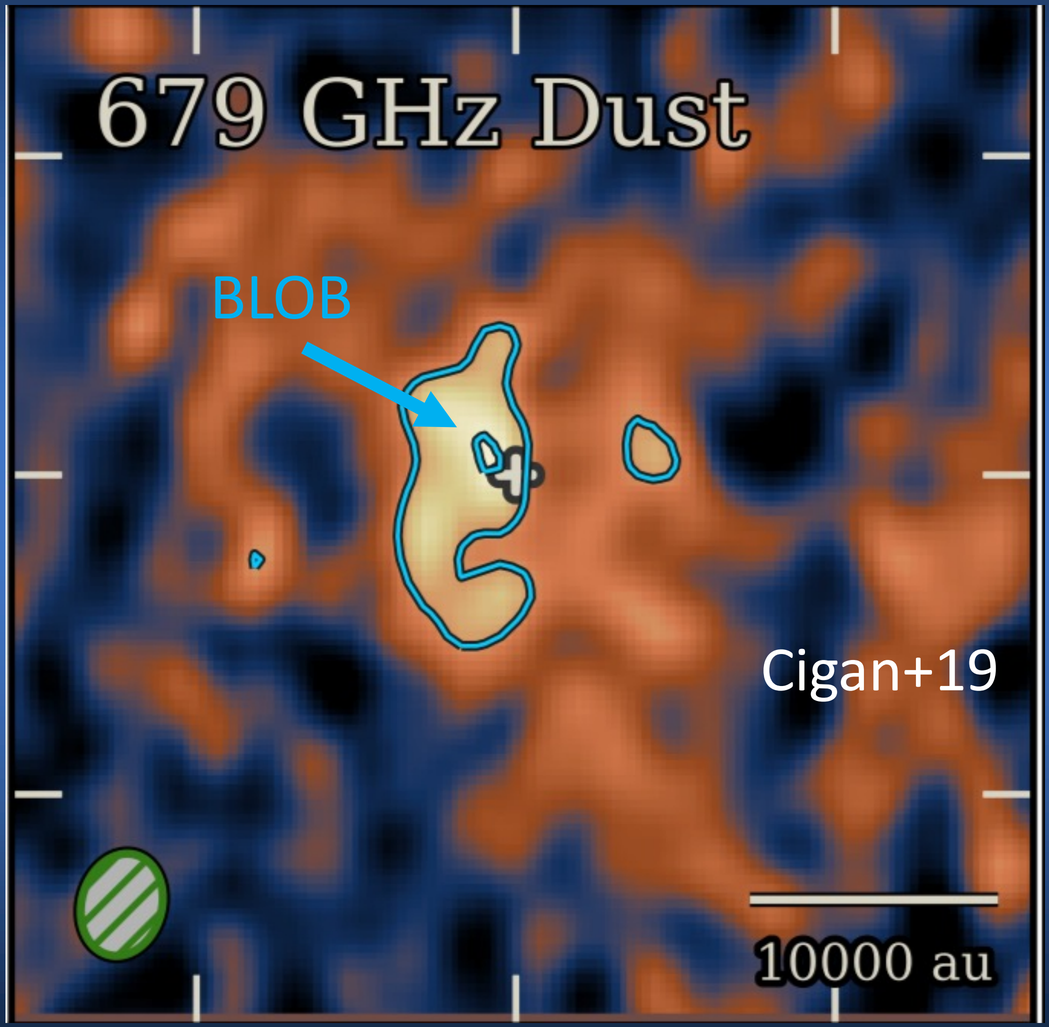
Schematic representation of SN 1987A (McCray & Fransson 2016)

...and its elusive compact object

- Detected neutrino emitted during SN 1987A... (Bionta+, 1987)
- ... but no proofs of NS! Why?
- Only hint about its existence is a *blob* in ALMA data (Cigan+19)
- Absorption of cold ejecta hides radiation stemming from the putative compact object

X-ray band: less efficient absorption but we need to estimate it → MHD model

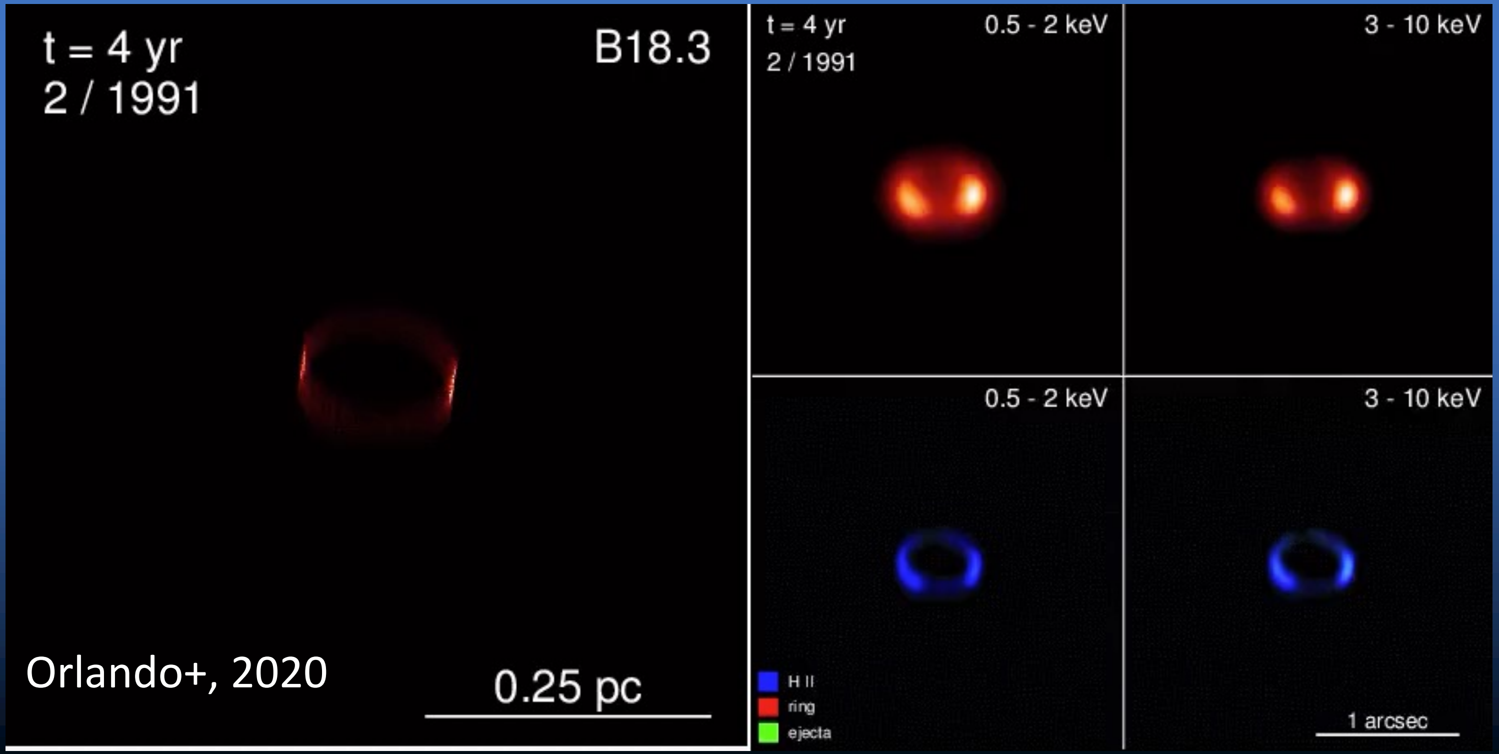
We can include absorption effect in the X-ray spectral analysis



State-of-the-art MHD modeling of SN1987A

- MHD model (Orlando+, 2020) reproduces observables of the progenitor star, SN and SNR
- Self-consistently describes the dynamical evolution of the system and the multi-wavelength emission
- Provides a grid with all the info necessary to estimate ejecta absorption
- $n_{H_{ejecta}} > 10^{23}\ \mathrm{cm}^{-2}$

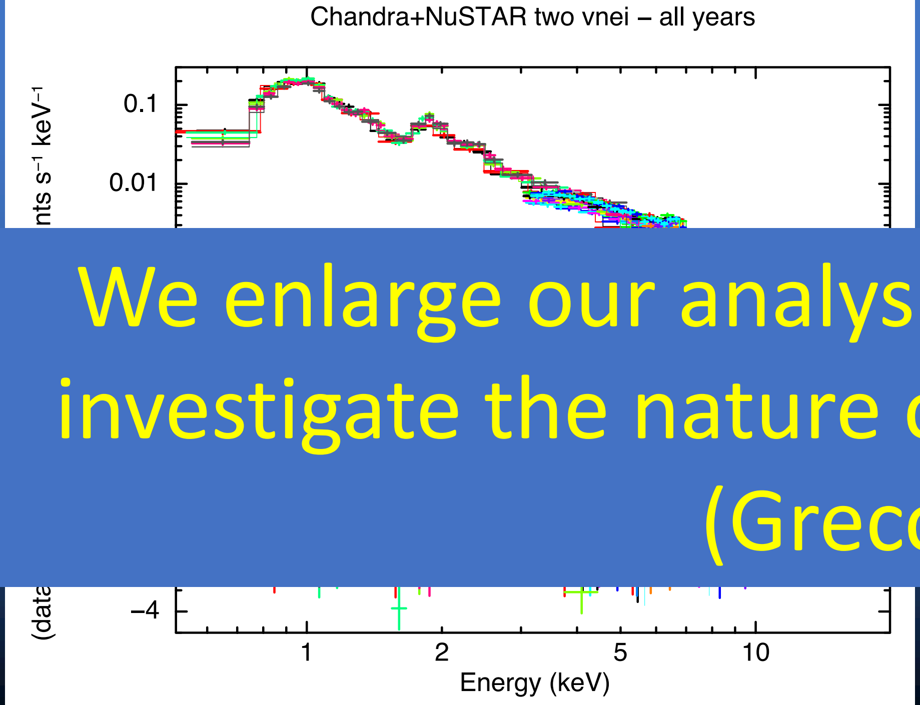
$(n_{H_{Gal}} = 2.35 \times 10^{21}\ \mathrm{cm}^{-2})$

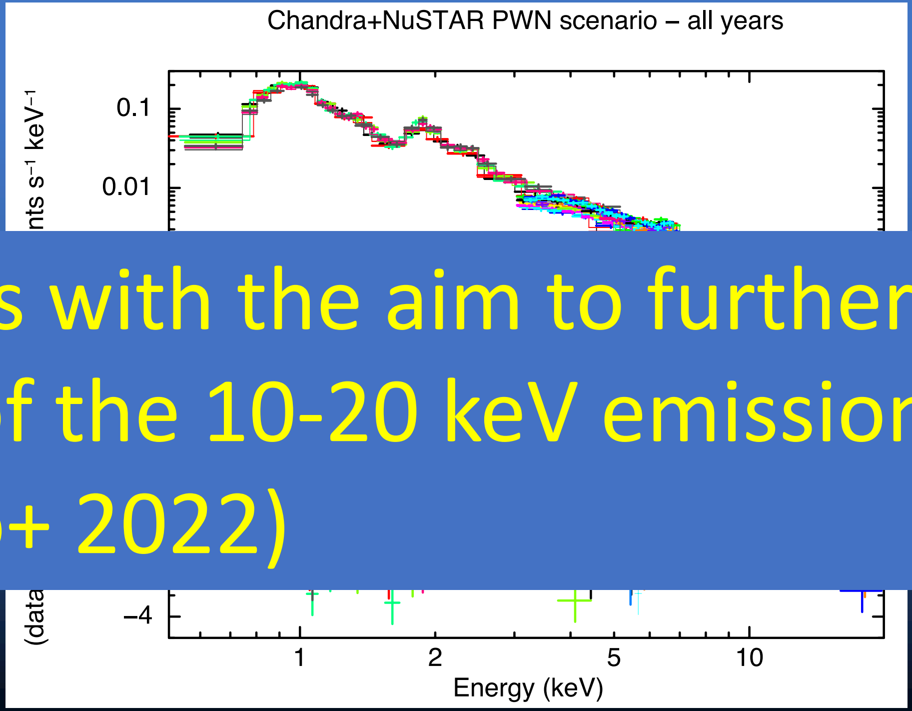


Indication of a PWN in SN1987A (Greco+, 2021)

- Simultaneous analysis of Chandra and NuSTAR data in 2012-2014 reveals non-thermal emission in the 10-20 keV band
- Most likely explanation is emission from an heavily absorbed PWN
- Diffusive schock acceleration is unlikely, but cannot be ruled out

Thermal only scenari





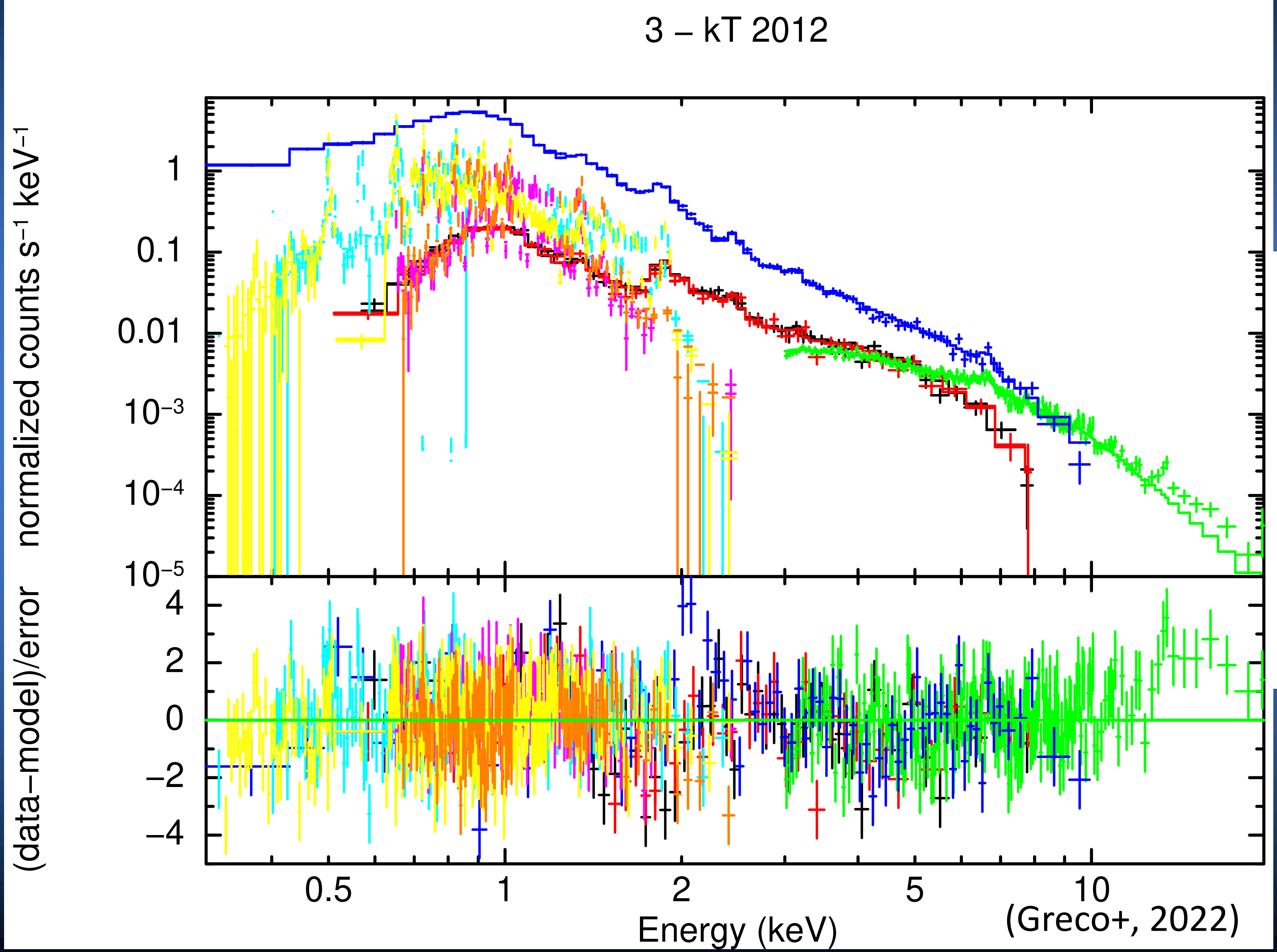
Thermal + PWN ario

We enlarge our analysis with the aim to further investigate the nature of the 10-20 keV emission (Greco+ 2022)

Chandra+RGS+PN+NuSTAR analysis

- We add XMM-Newton/PN,RGS → higher statistics and spectral resolution → better constraints on the thermal emission
- We include also 2020 data → larger time lapse to follow the time evolution of the emission
- Soft X-ray emission can be described with 2-kT model (as Greco+, 2021)
- Third thermal component not significant for Chandra
- Third thermal component improves the fits of PN-RGS data (Sun+, 2021; Alp+, 2021)

Chandra+RGS+PN+NuSTAR analysis: 3 kT

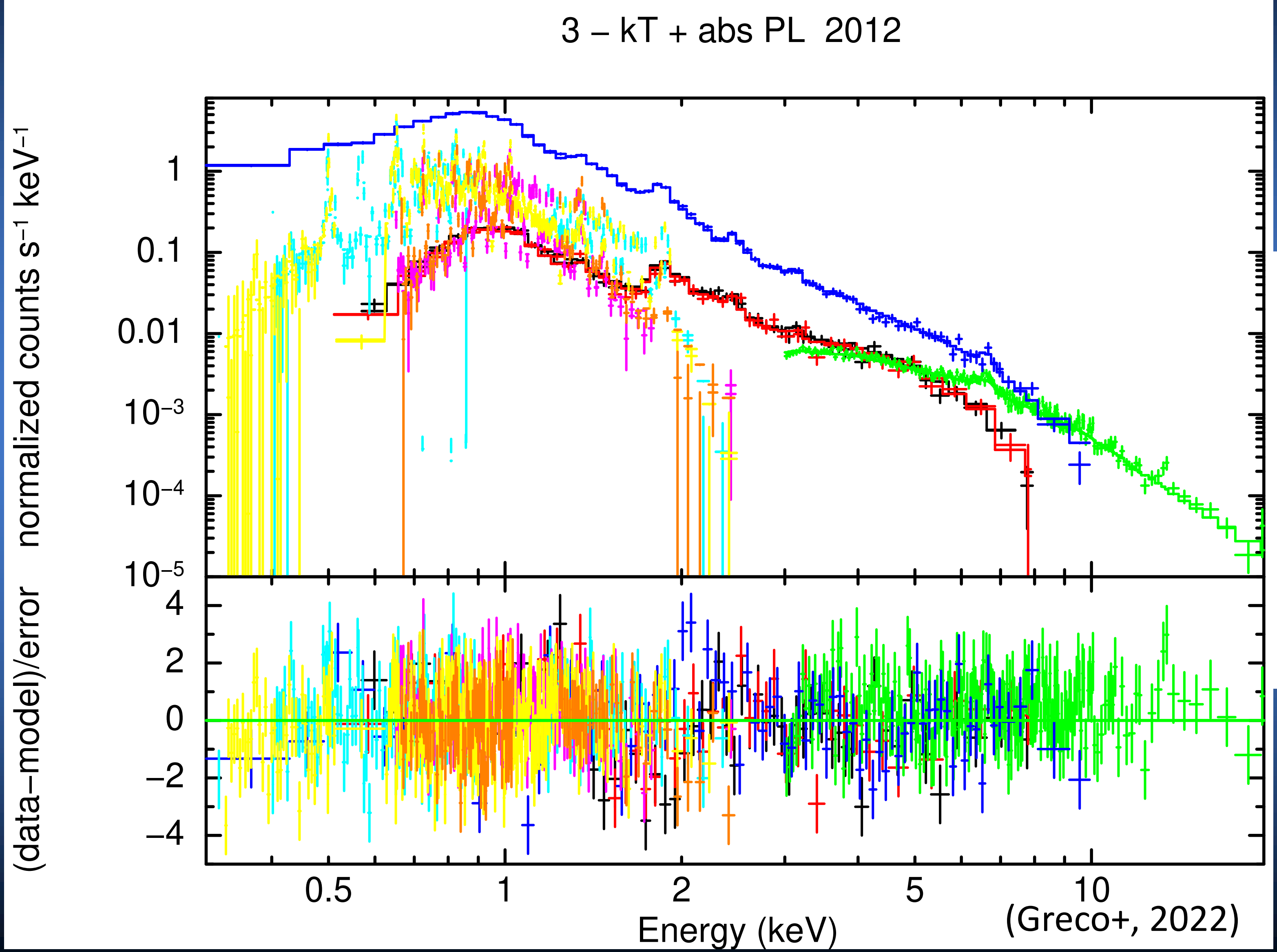


$\chi^2\ (d.o.f.) = 2754\ (2139)$

Detector legend

Chandra
XMM-Newton/PN
XMM/RGS1O1
XMM/RGS1O2
XMM/RGS2O1
XMM/RGS2O2
NuSTAR

Chandra+RGS+PN+NuSTAR analysis: 3 kT+PL



$\chi^2\,(d.o.f.) = 2680\,(2137)$

$\Delta\chi^2 = -74$ $\Gamma = 2.8$

Detector legend

Chandra

XMM-Newton/PN

XMM/RGS1O1

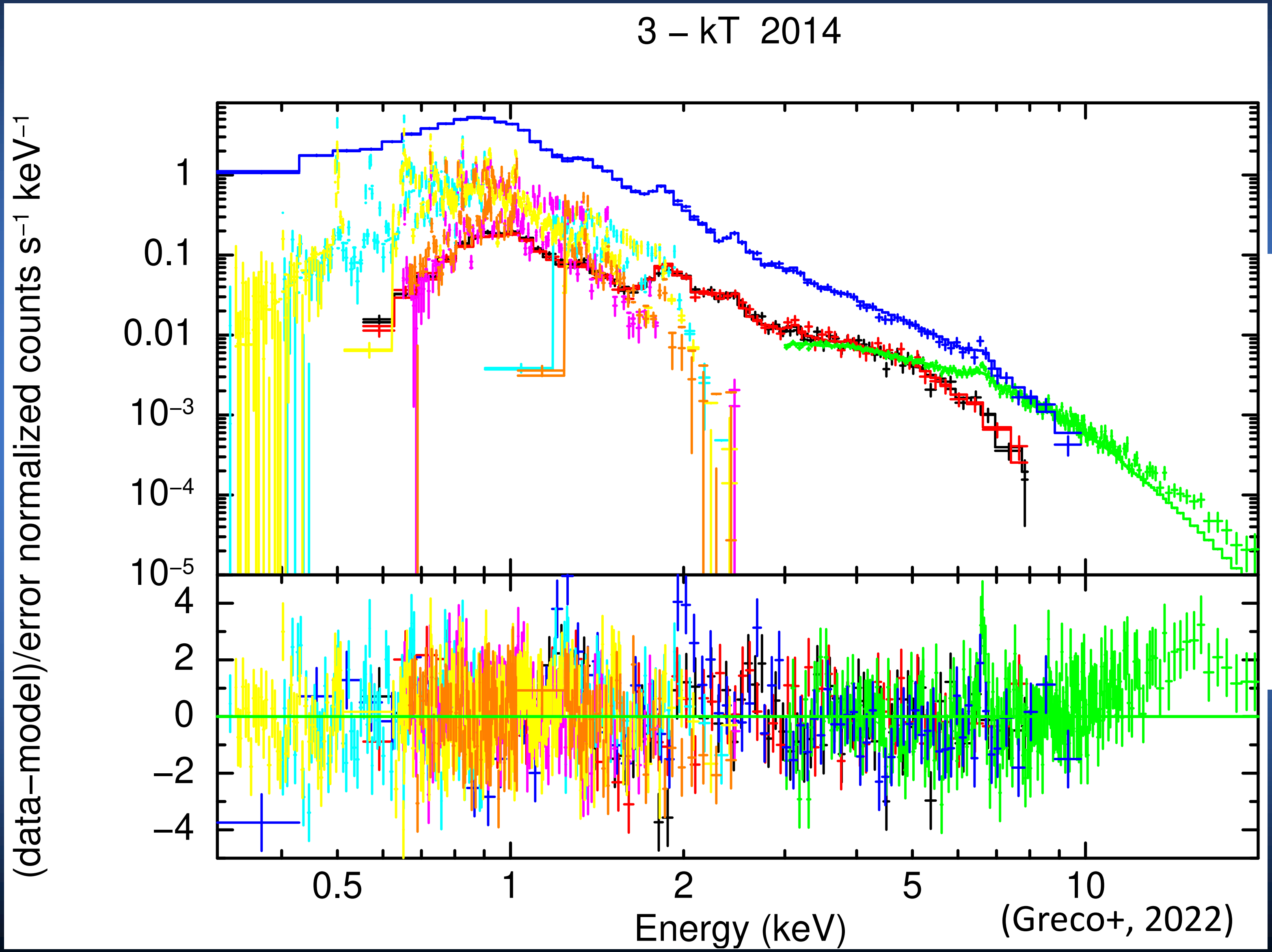
XMM/RGS1O2

XMM/RGS2O1

XMM/RGS2O2

NuSTAR

Chandra+RGS+PN+NuSTAR analysis: 3 kT

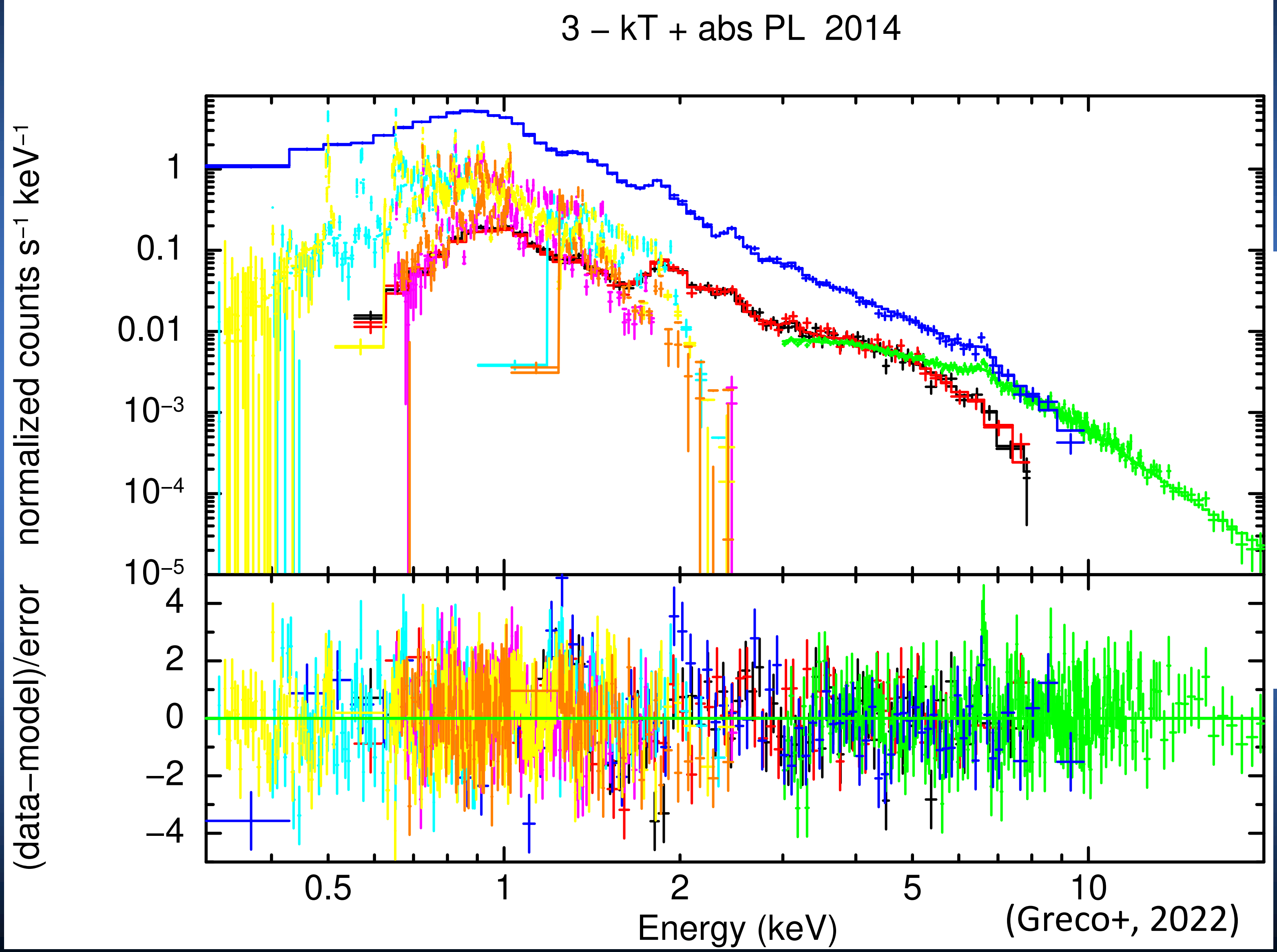


$$\chi^2\ (d.o.f.) = 2912\ (2199)$$

Detector legend

- Chandra
- XMM-Newton/PN
- XMM/RGS1O1
- XMM/RGS1O2
- XMM/RGS2O1
- XMM/RGS2O2
- NuSTAR

Chandra+RGS+PN+NuSTAR analysis: 3 kT+PL

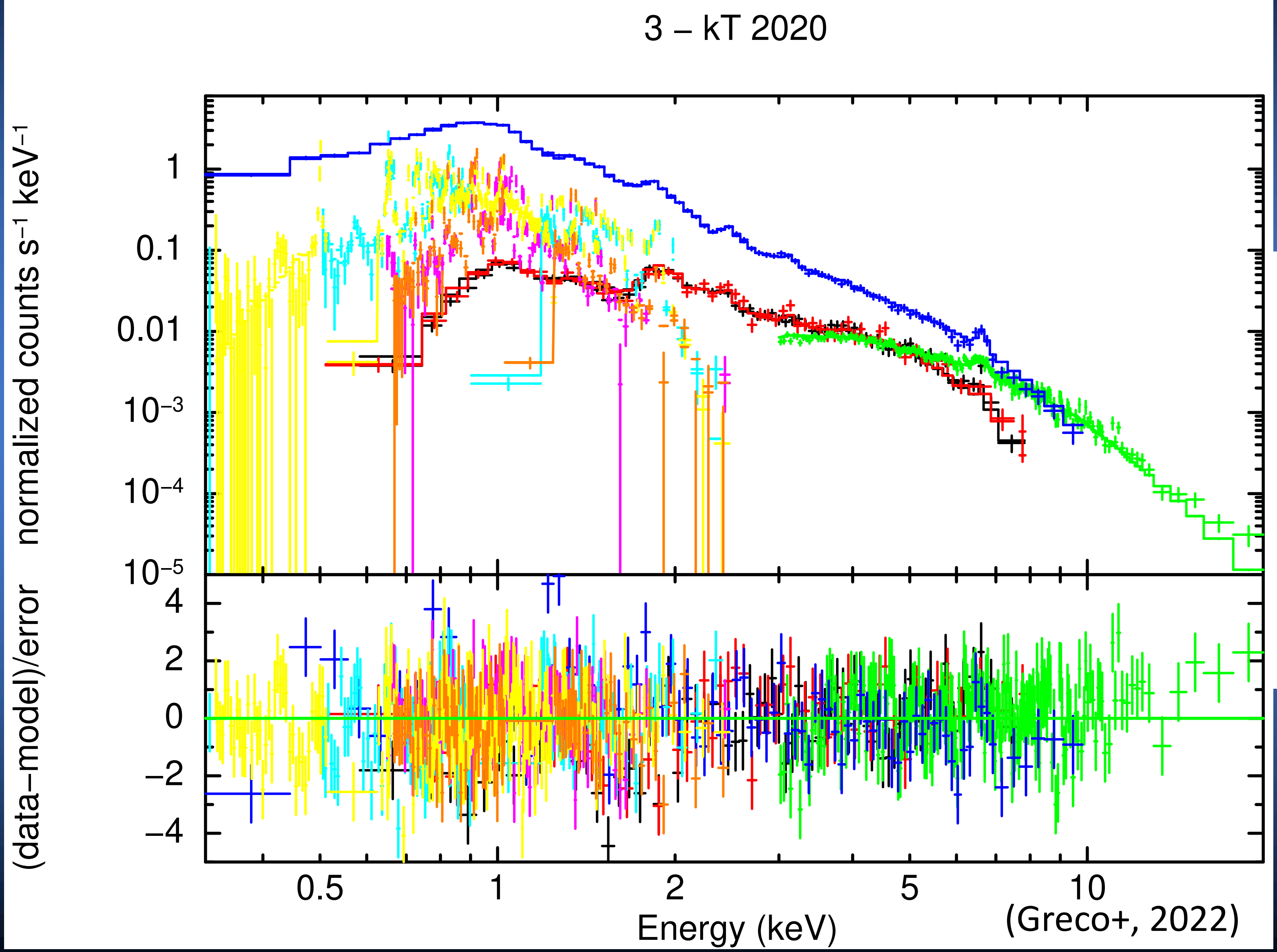


$\chi^2\,(d.o.f.) = 2814\,(2197)$

$\Delta\chi^2 = -98$ $\quad\Gamma = 2.8$

Detector legend
Chandra
XMM-Newton/PN
XMM/RGS1O1
XMM/RGS1O2
XMM/RGS2O1
XMM/RGS2O2
NuSTAR

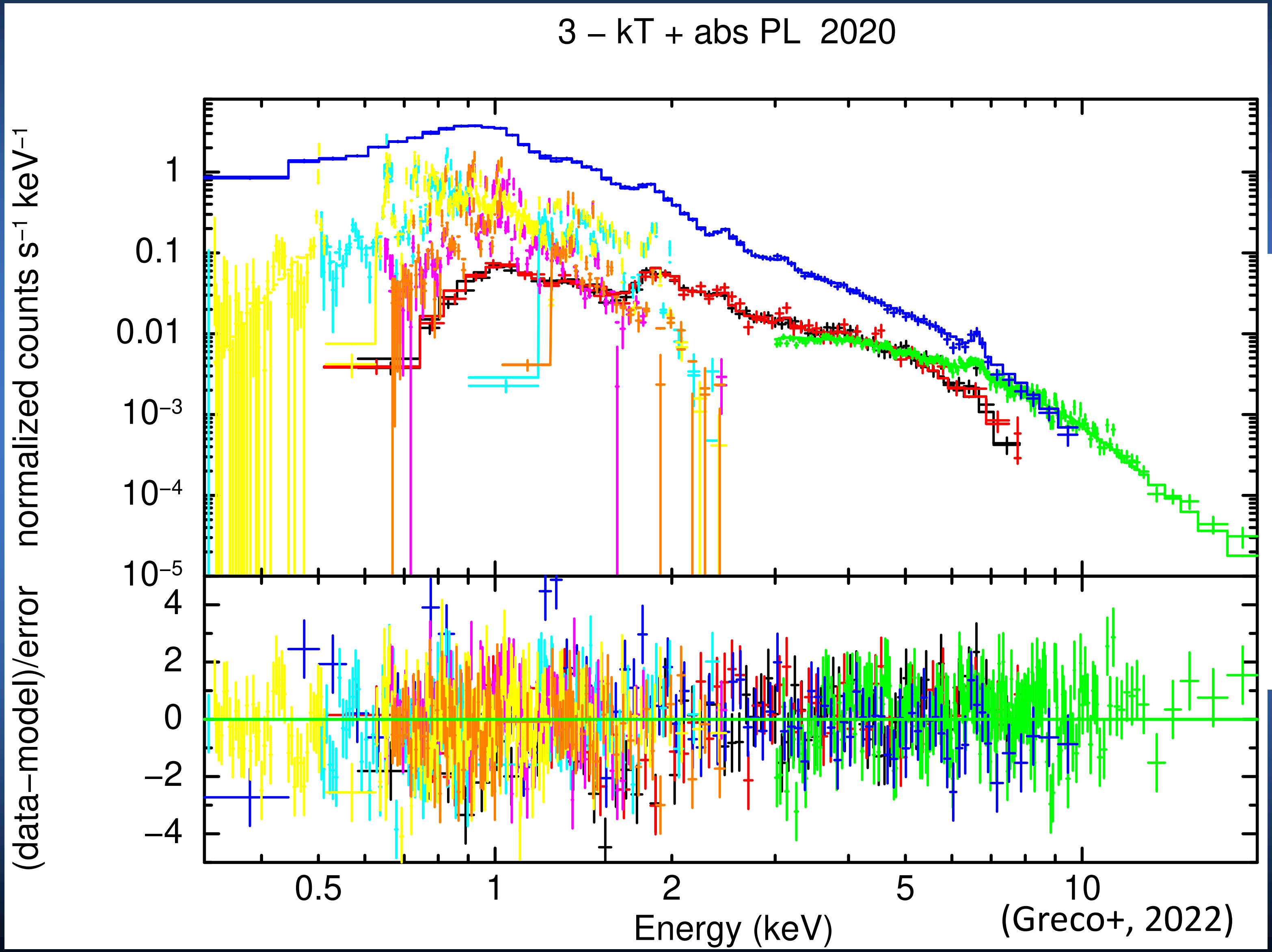
Chandra+RGS+PN+NuSTAR analysis: 3 kT



$\chi^2\,(d.o.f.) = 2382\;(1897)$

Detector legend
Chandra
XMM-Newton/PN
XMM/RGS1O1
XMM/RGS1O2
XMM/RGS2O1
XMM/RGS2O2
NuSTAR

Chandra+RGS+PN+NuSTAR analysis: 3 kT+PL



$\chi^2\ (d.o.f.) = 2377\ (1895)$

$\Delta\chi^2 = -5$

$\Gamma = 2.8$

Detector legend

- Chandra
- XMM-Newton/PN
- XMM/RGS1O1
- XMM/RGS1O2
- XMM/RGS2O1
- XMM/RGS2O2
- NuSTAR

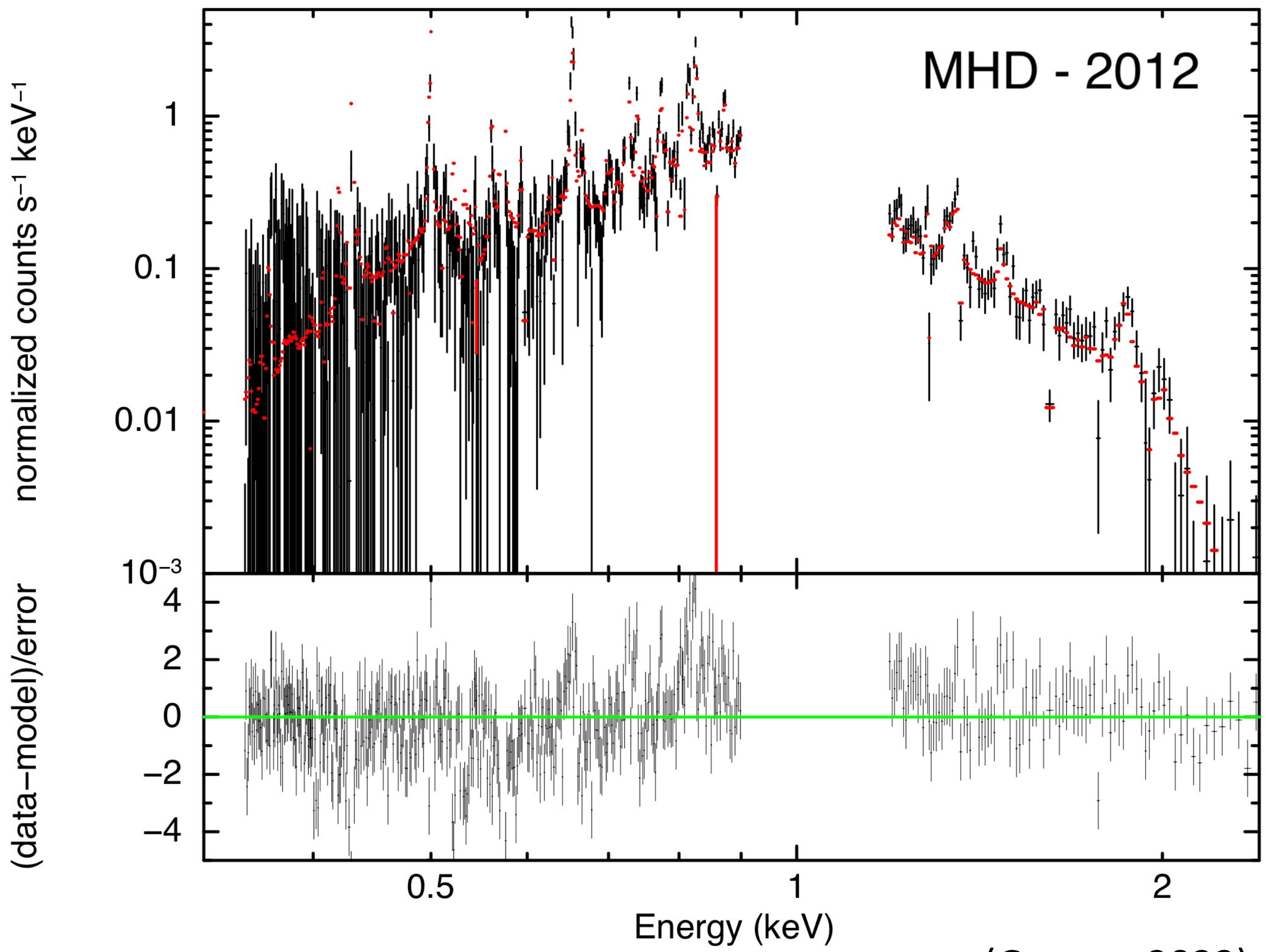
A step beyond the standard spectral fit

The standard phenomological analysis of the enlarged data sample confirm the results from Greco+, 2021

Self-consistent synthesis from the MHD model by Orlando+

- We also include doppler and thermal broadening effects
- *Physical interpretation* of all available X-ray data thanks to the MHD model
- Epochs: 2012-2014-2020

MHD model over RGS data: 2012



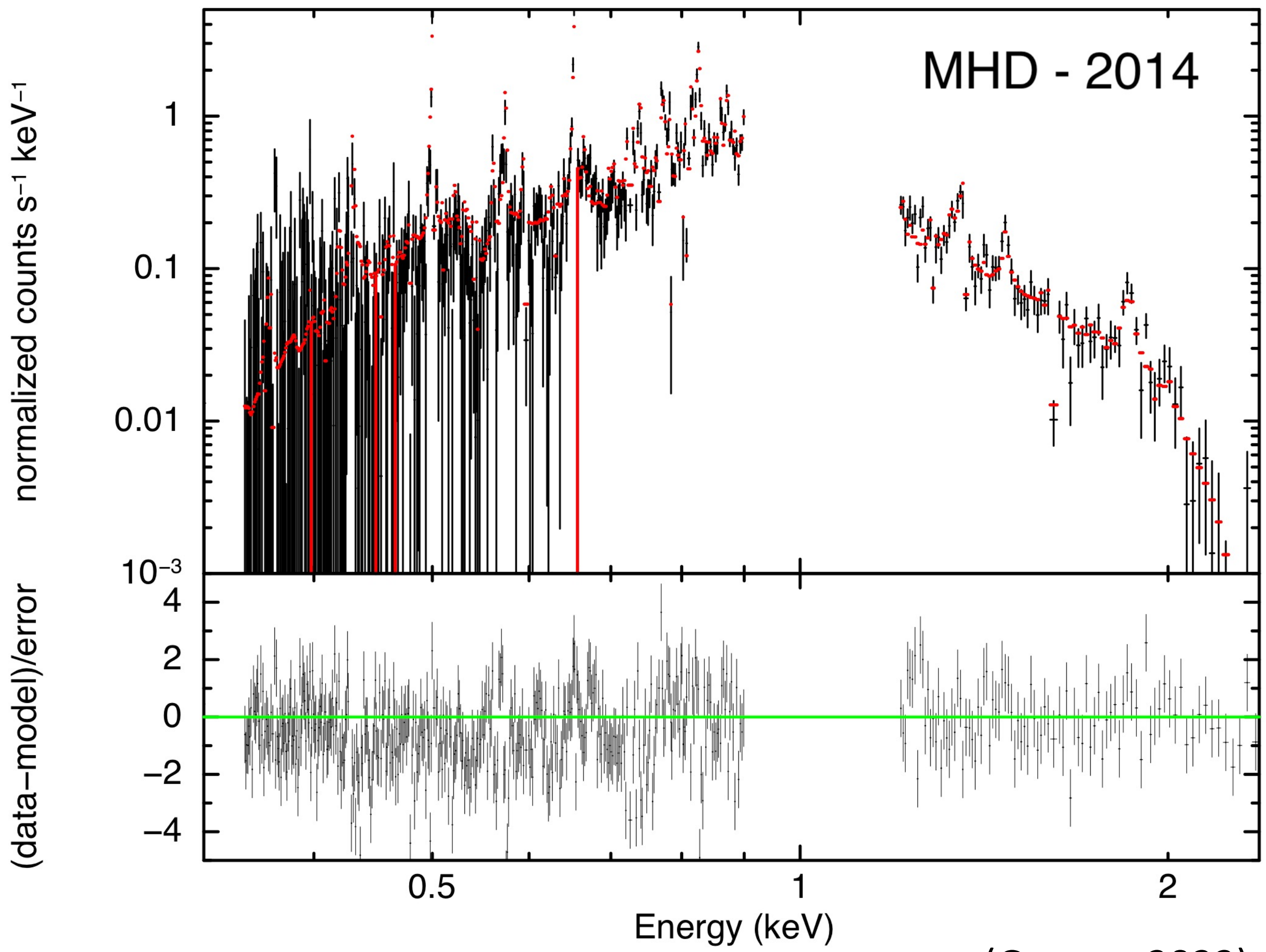
(Greco+, 2022)

No fitting performed

$\chi^2_{RGS} = 893$ (457 dof)

Continuum and line emission are well reproduced

MHD model over RGS data: 2014



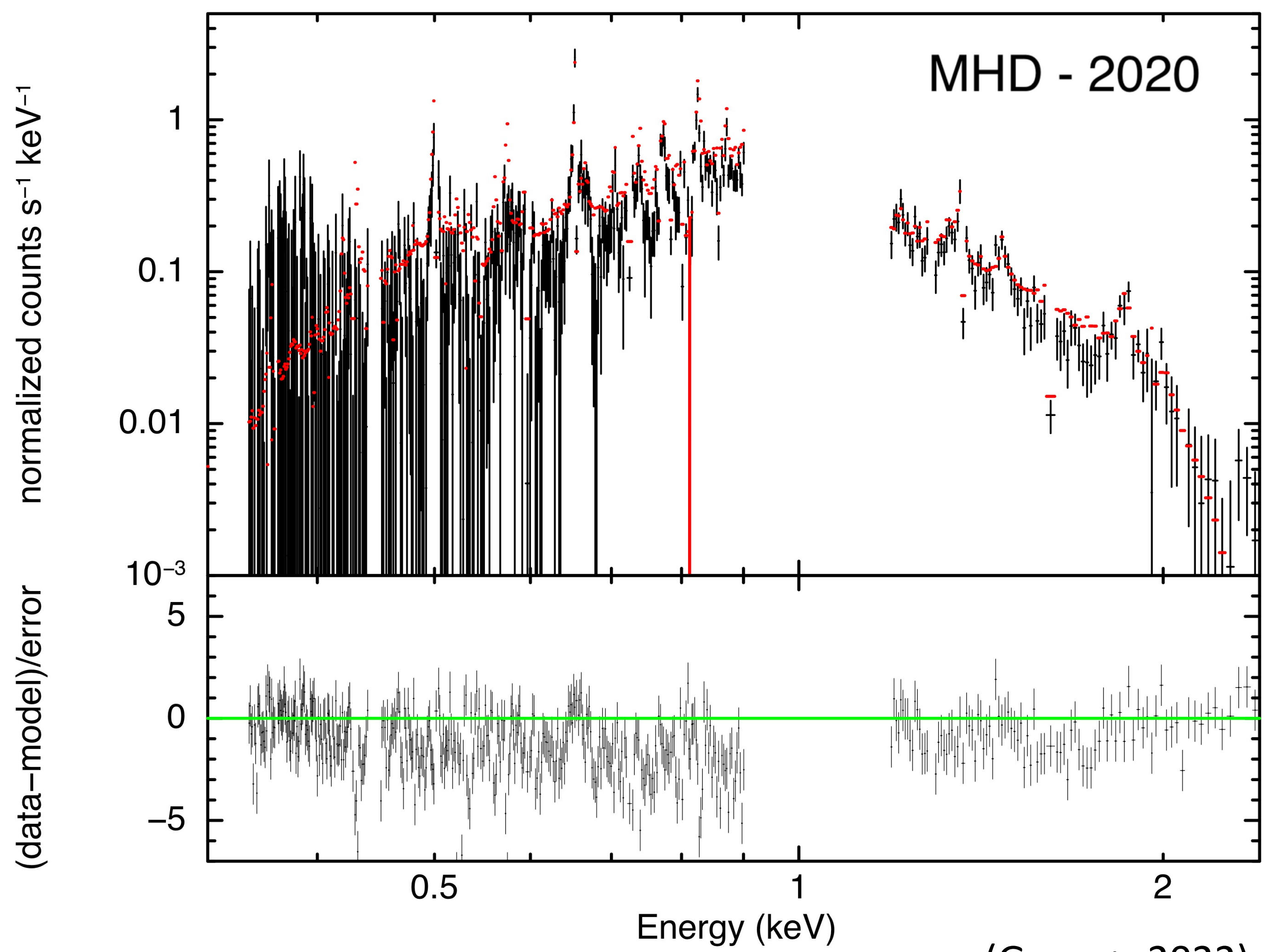
(Greco+, 2022)

No fitting performed

$\chi^2_{RGS} = 959$ (456 dof)

Continuum and line emission are well reproduced

MHD model over RGS data: 2020



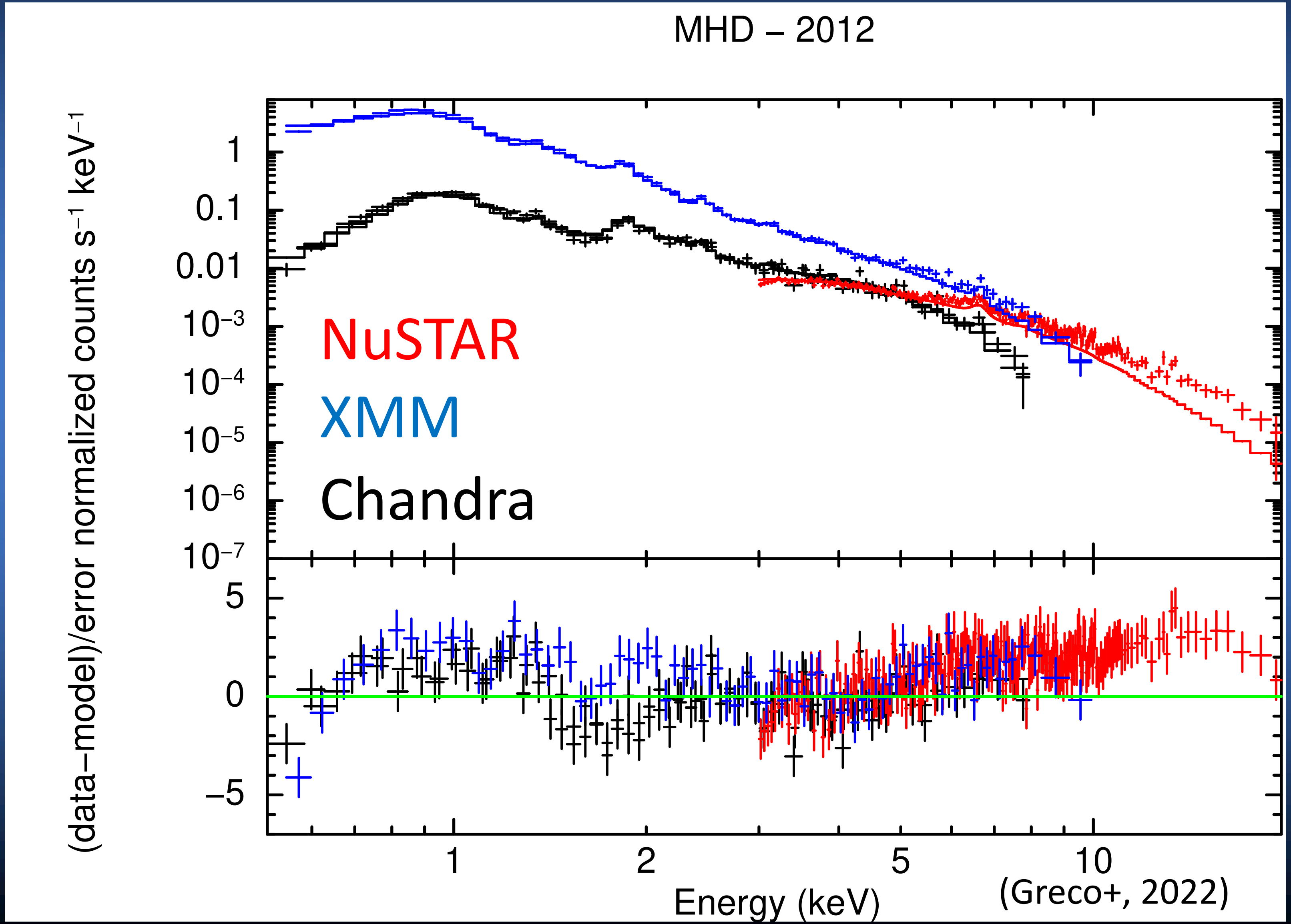
(Greco+, 2022)

No fitting performed

$\chi^2_{RGS} = 1677$ (434 dof)

Continuum and line emission are well reproduced

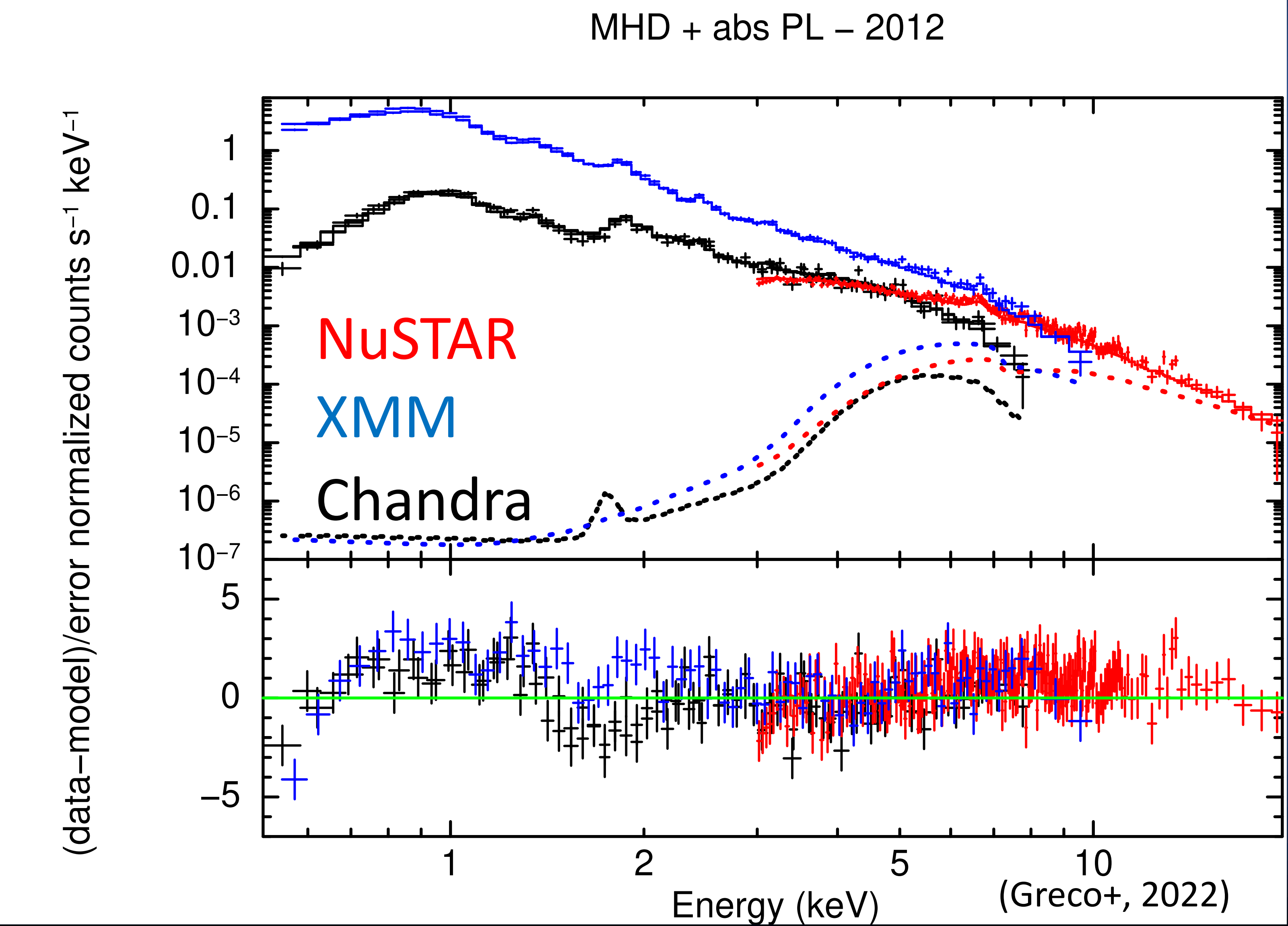
MHD model over actual spectra: 2012



$\chi^2_{NoPWN} = 1375$ (553 dof)

No fitting performed

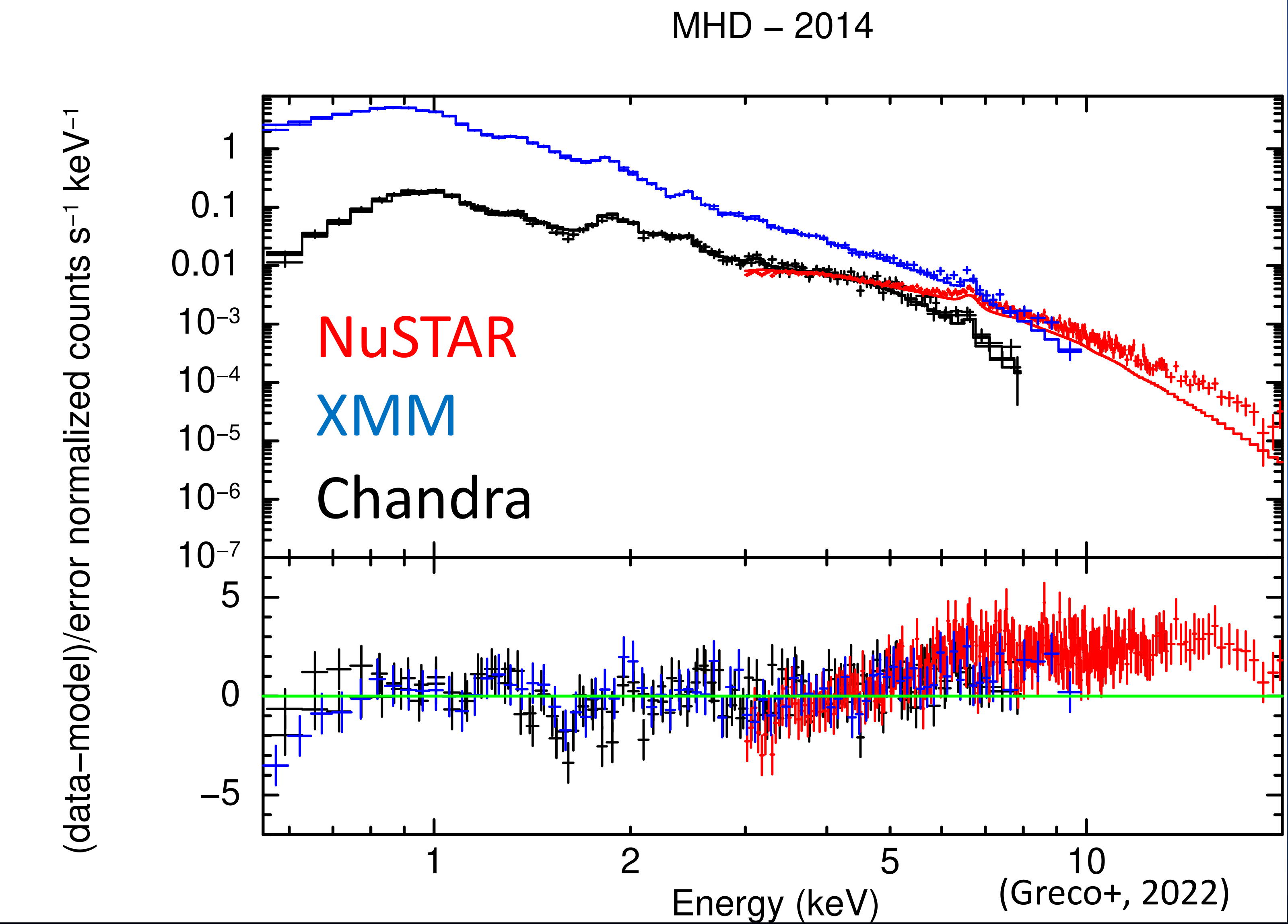
MHD+PWN model over actual spectra: 2012



$\chi^2_{PWN} = 864$ (551 dof)

No fitting performed

MHD model over actual spectra: 2014

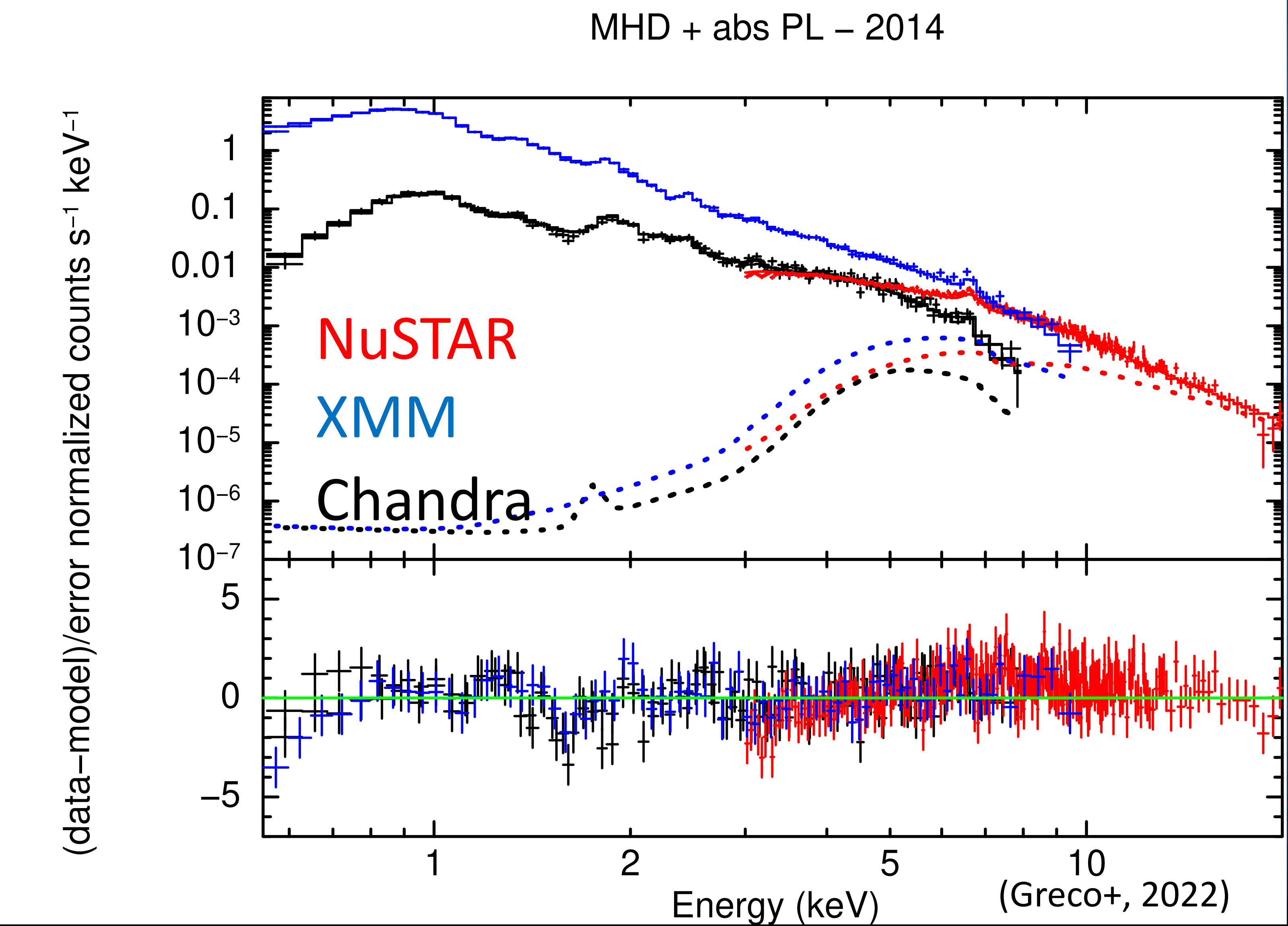


(Greco+, 2022)

$\chi^2_{NoPWN} = 1547$ (588 dof)

No fitting performed

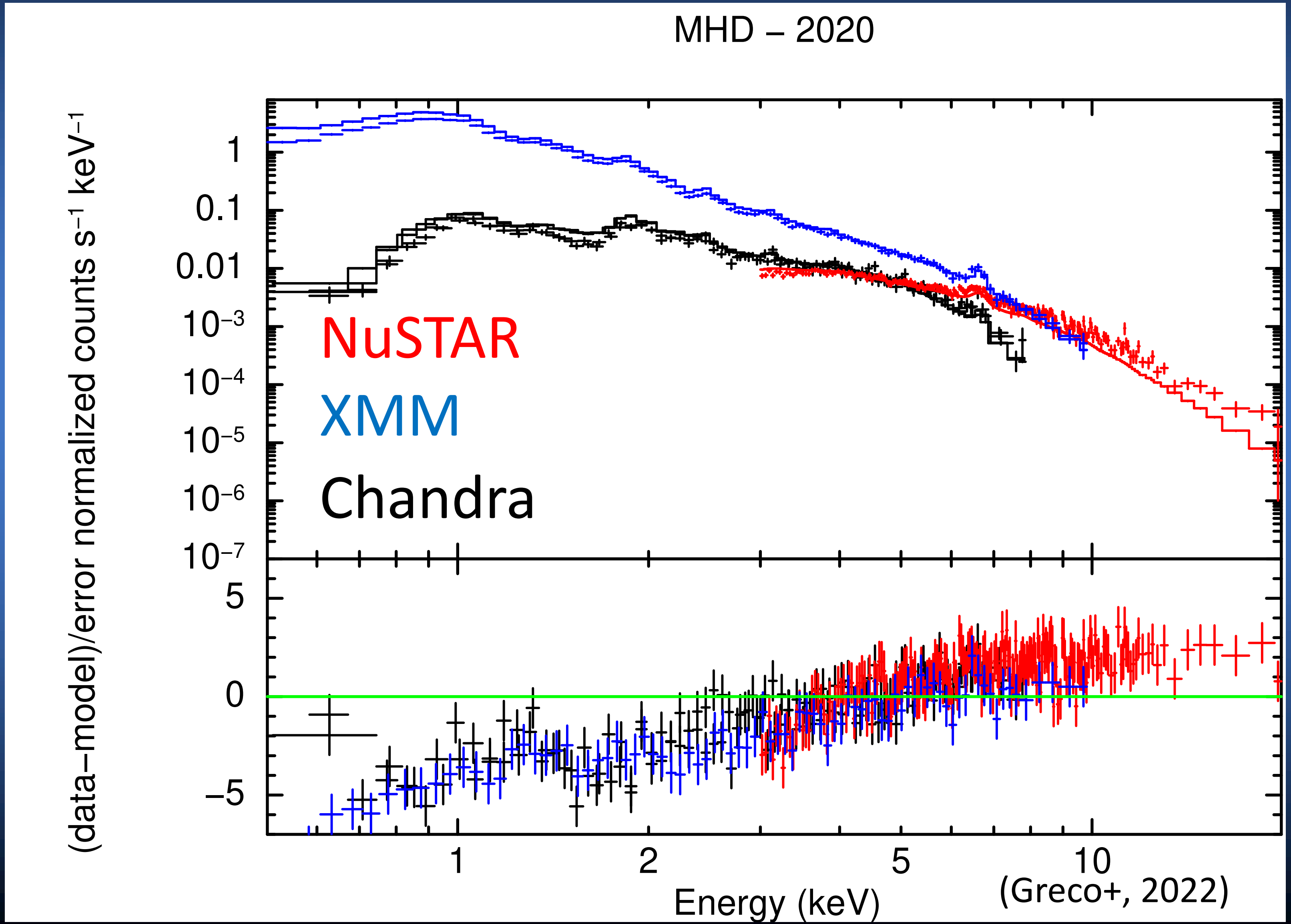
MHD+PWN model over actual spectra: 2014



$\chi^2_{PWN} = 694$ (586 dof)

No fitting performed

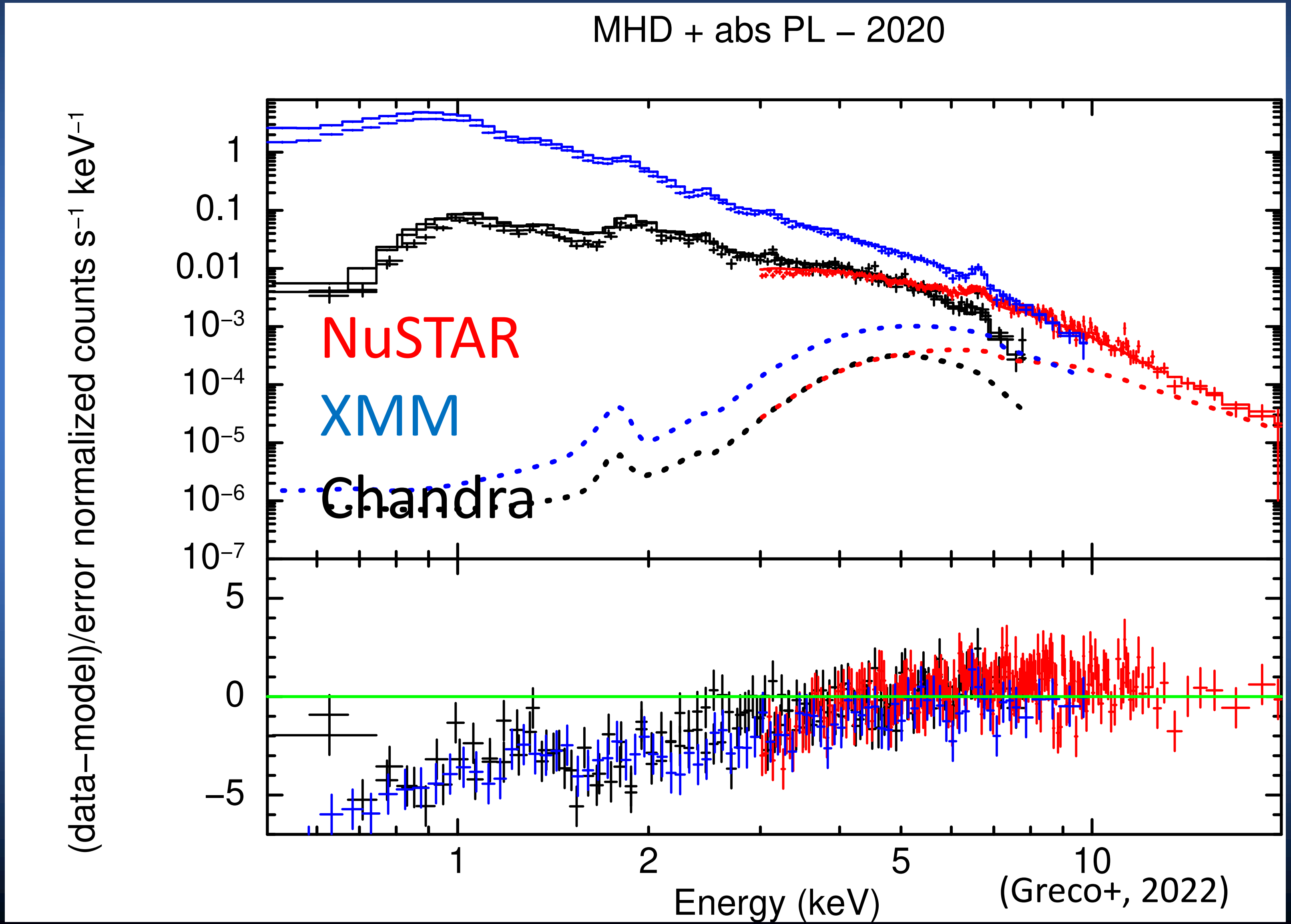
MHD model over actual spectra: 2020



$\chi^2_{NoPWN} = 1933$ (459 dof)

No fitting performed

MHD+PWN model over actual spectra: 2020



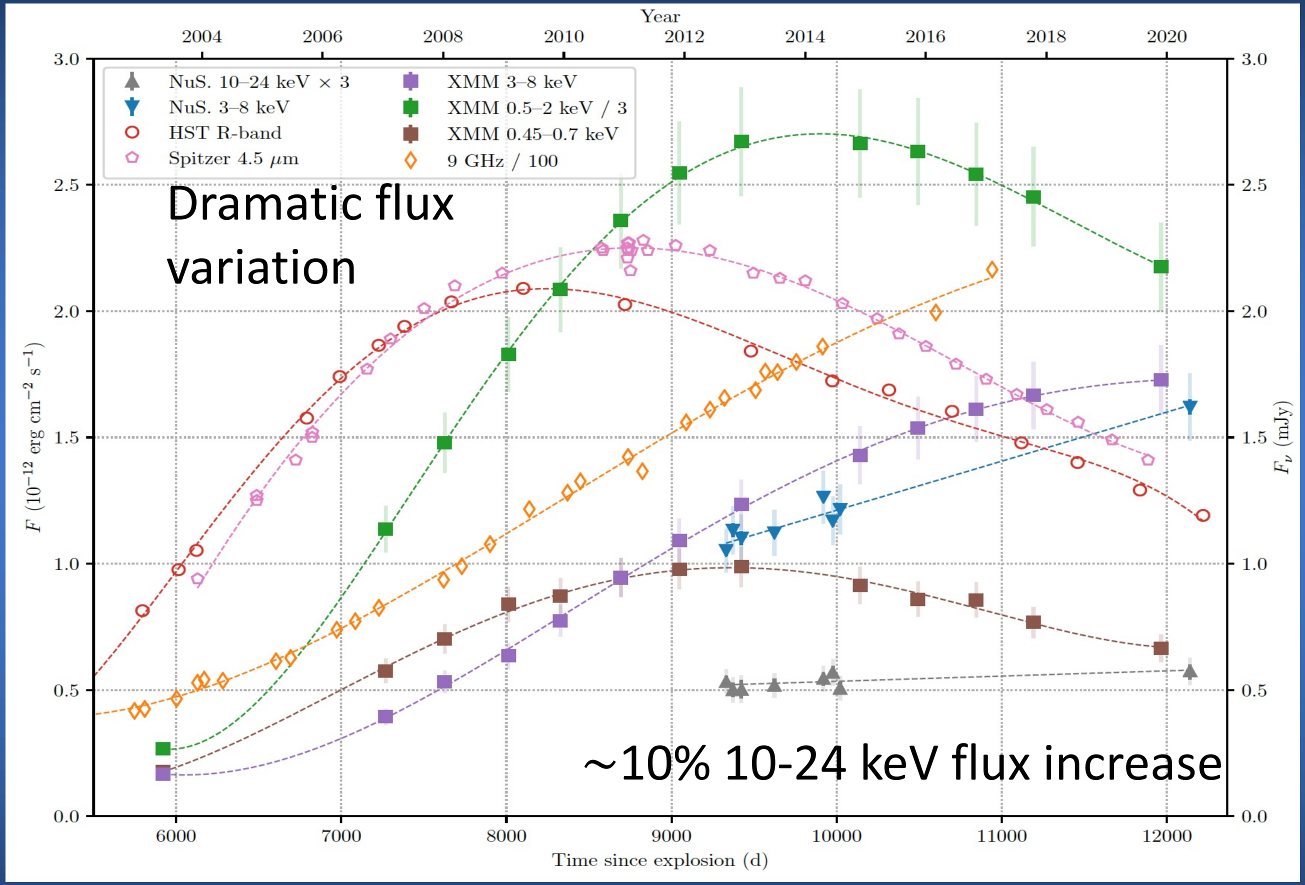
$\chi^2_{PWN} = 1643$ (457 dof)

No fitting performed

Challenging the DSA scenario

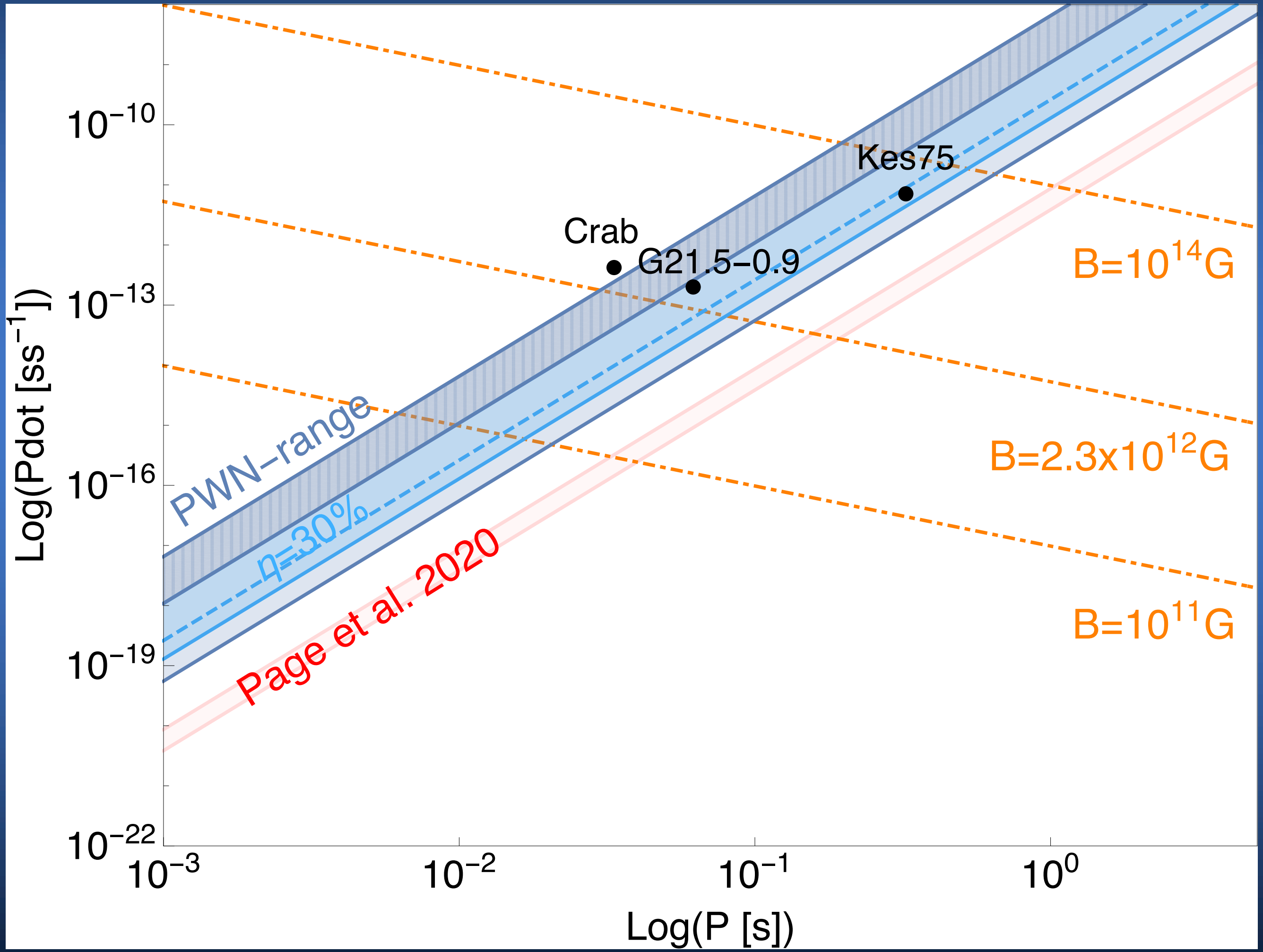
Alp+, 2021

- Flux of SN 1987A dramatically varies at all wavelengths
- 10-24 keV flux slightly increases → different origin: ejecta rarefaction and tail of thermal emission
- Standard fits favor PWN scenario over DSA ($\Delta\chi^2 \sim 20$)



These considerations point against DSA scenario

PWN 1987A in the $P\dot{P}$ diagram



We can constrain P and $\dot{P}$ from the measured parameters by building a toy-model of the PWN spectrum

$$\dot{E} = 4\pi^2 I \dot{P} / P^3$$

For an average magnetic field of $B \sim 2.3 \times 10^{12}$ G → P = [30,100] ms

The bolometric PWN luminosity inferred from the SED is compatible with upper limits in other bands (Alp+, 2018)

Summary

- Thermal-only scenario fails in describing data points between 10 and 20 keV
- An additional absorbed power-law best fits all the X-ray data
- The whole picture coherently point against DSA scenario
- This $\sim$10% increase is ascribable to the hottest plasma component and expansion of the cold ejecta
- MHD modeling corroborates the PWN scenario
- The properties of the PWN are perfectly compatible with known young sources, with multi-wavelength upper limits and with the ALMA detection