Synthetic X-ray Spectra from 3D MHD Simulations: the case of SN 1987A

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Bridging the Gap between models and Observations

3D MHD Models show the internal physics of SNR

MHD model of SN1987A. Credit: S. Orlando (INAF-OAPa)

BUT

OBSERVATIONS HAVE:

- Instrumental Response
- Projection Effects
- Line-of-Sight Integration

We developed an in-house tool to synthesize spectra from MHD model and compare it with observations

See: Miceli et al. (2019), Ustamujic et al. (2021), Greco et al. (2022), Sapienza et al. (2024), Orlando et al. (2025)

Synthesis procedure

In each cell we calculate kT, $n_e t$, n_e

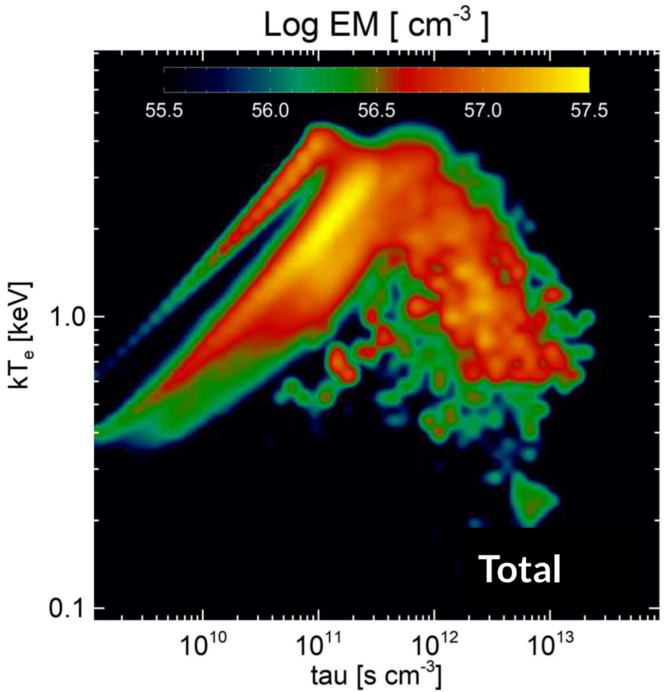
Input to a *vnei* model absorbed by a *tbabs*

Folded through the response matrix

We can take in account for:

- Discriminate CSM from Ejecta
- Bulk motion Doppler broadening
- Thermal Broadening

Summed cell by cell



An example of distribution of the emission measure as a function of the temperature *kT* and the ionization parameter $n_e t$ (τ)

SN 1987A

Distance (kpc)	Age (yrs)	Physical origin
51.4	38	core collapse SN

Evolving in a complex circumstellar medium:

- Dense and clumpy Equatorial Ring
- Diffuse hourglass-like H II region

CSM dominated the X-ray emission in the past

BUT

Fast outermost ejecta started to be shocked

Fe-rich blob have reached RS (Larsson+2023)

SN1987A (NIRCam Image), Image credit: ESA/Webb

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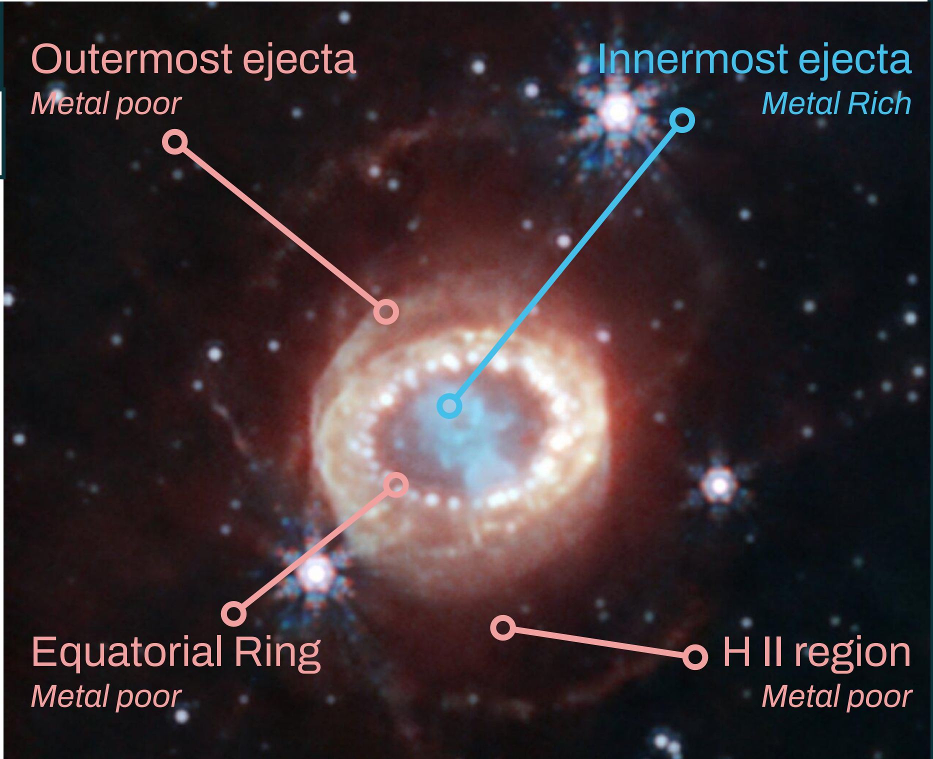


SN1987A (NIRCam Image), Image credit: ESA/Webb

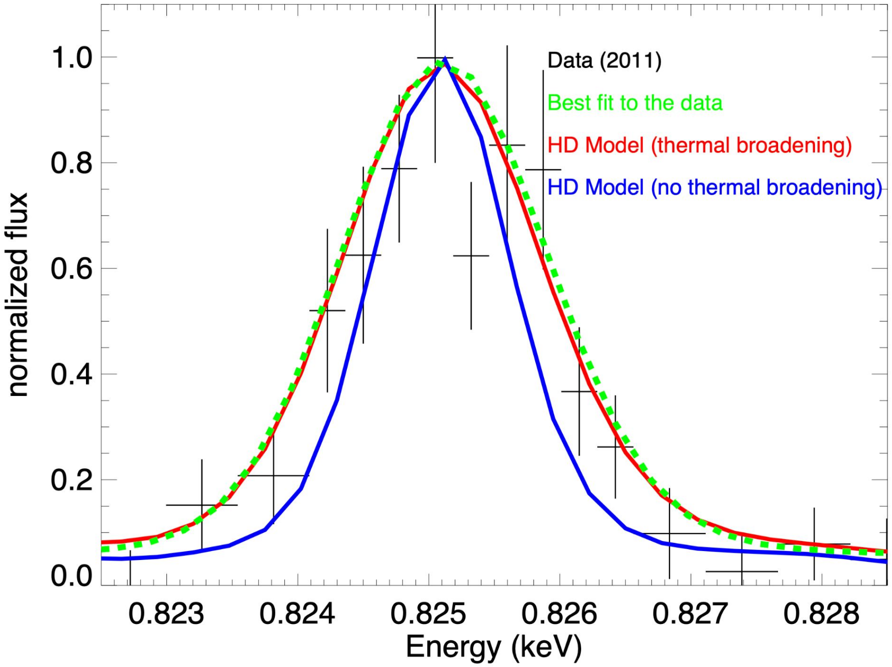
The hybrid approach: data and models

Adopting a similar approach of Miceli et al. (2019): Data+model to derive post-shock ion temperature

XRISM observed SN 1987A in the PV phase

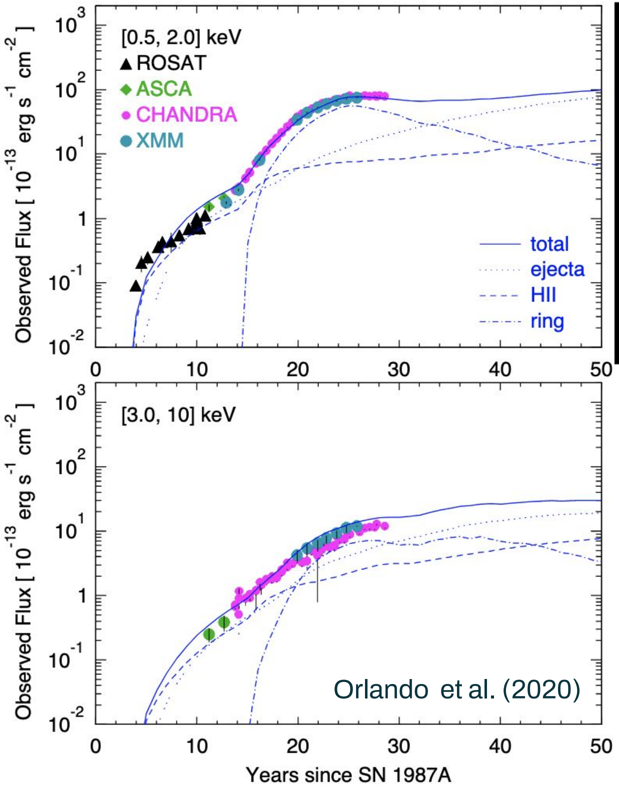
AIM:

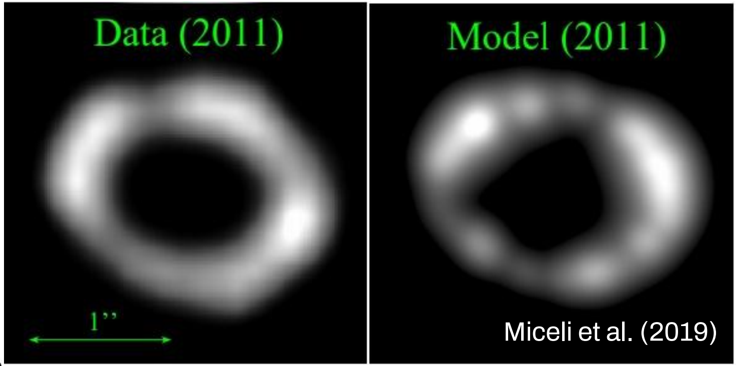
- **Synthesize the spectrum of SN1987A**
- **Synthetic spectrum vs. real data**
- **Find new diagnostics to trace ejecta**

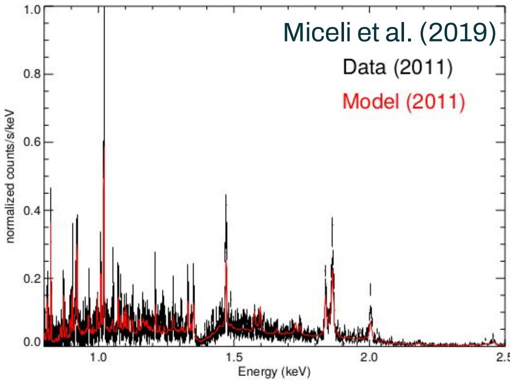


Miceli et al. (2019): Chandra data and models derived from the HD simulation of the Fe XVII emission line

Model (Orlando et al. 2020) **vs. Data**







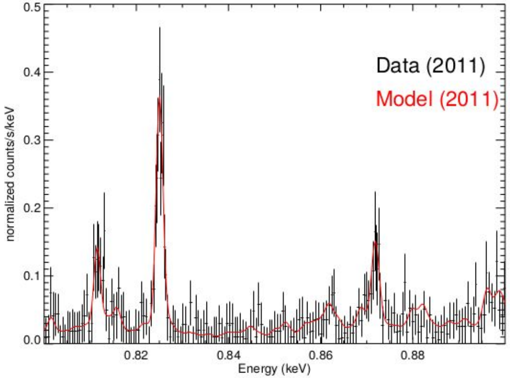
From the SN explosion (Ono et al. 2020) to the SNR

Reproduces size and morphology

Able to describe X-ray observables

Accurate description of:

- X-ray evolution
- X-ray emitting Plasma
- Plasma ionization state



Synthetic Spectrum

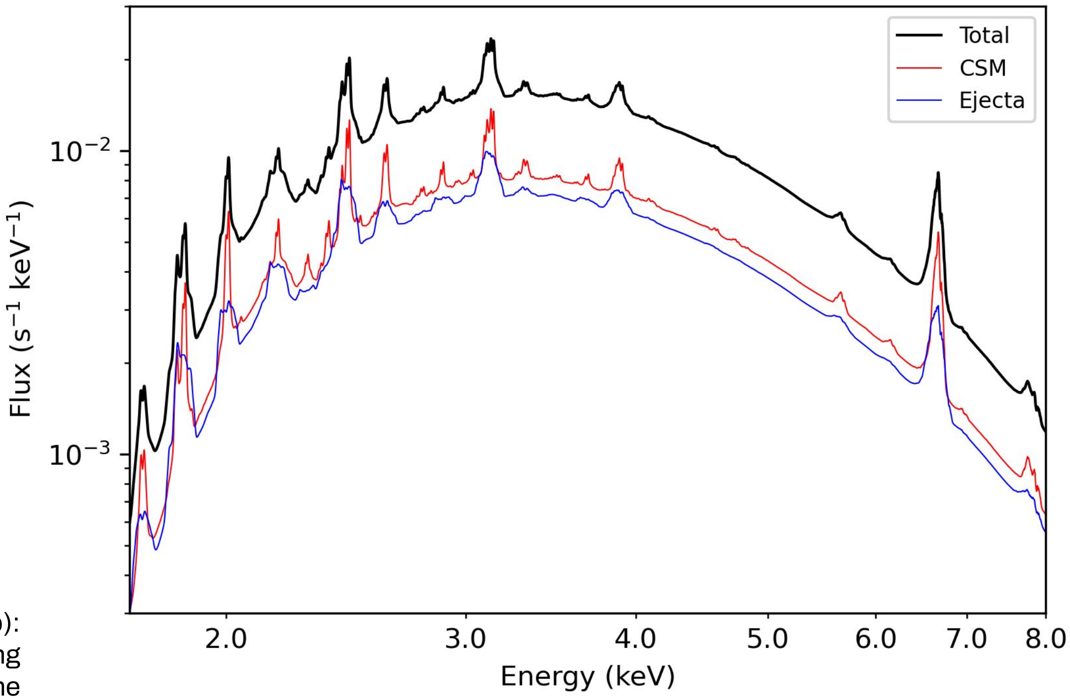
We applied the effect of Bulk Motion Doppler Broadening

This effect largely broadens the emissior lines

complex profile and line blending

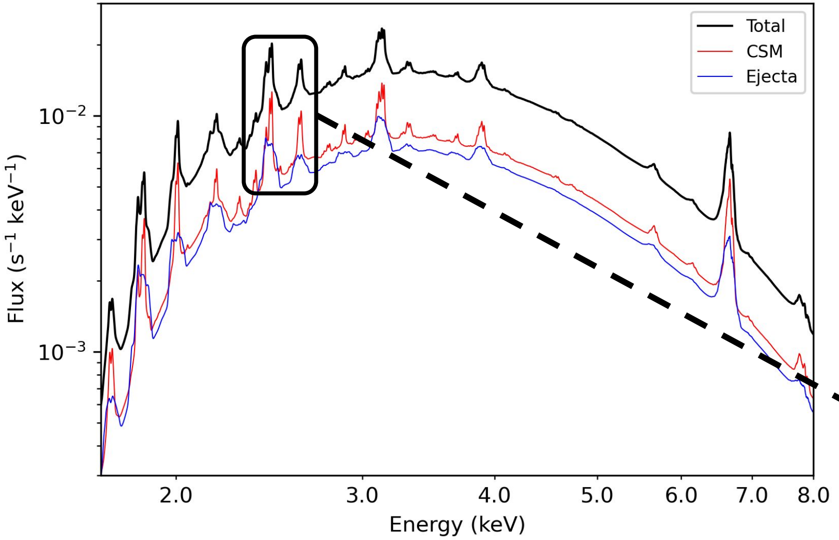
Ejecta emission comparable to CSM

Major contribution to the broadening comes from the ejecta

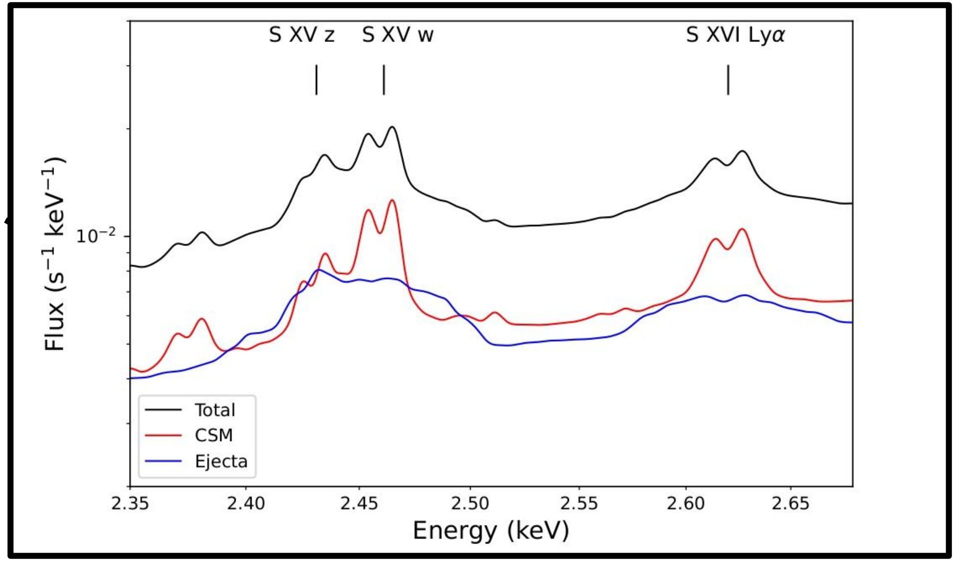


Sapienza et al. (2024b):
SN 1987A synthetic spectrum with Bulk motion broadening (black), with ejecta (blue) and CSM (red) contribution to the emission

Synthetic Spectrum



- Broad wing (Ejecta) + peaked center (CSM)
- Major contribution coming from ejecta
- Ejecta contributes more to the He-like species



Sapienza et al. (2024b):
(Top) SN 1987A synthetic spectrum with Bulk motion broadening (black), with ejecta (blue) and CSM (red) contribution to the emission. *(Left)* Zoom in the Sulfur XV and XVI Lines

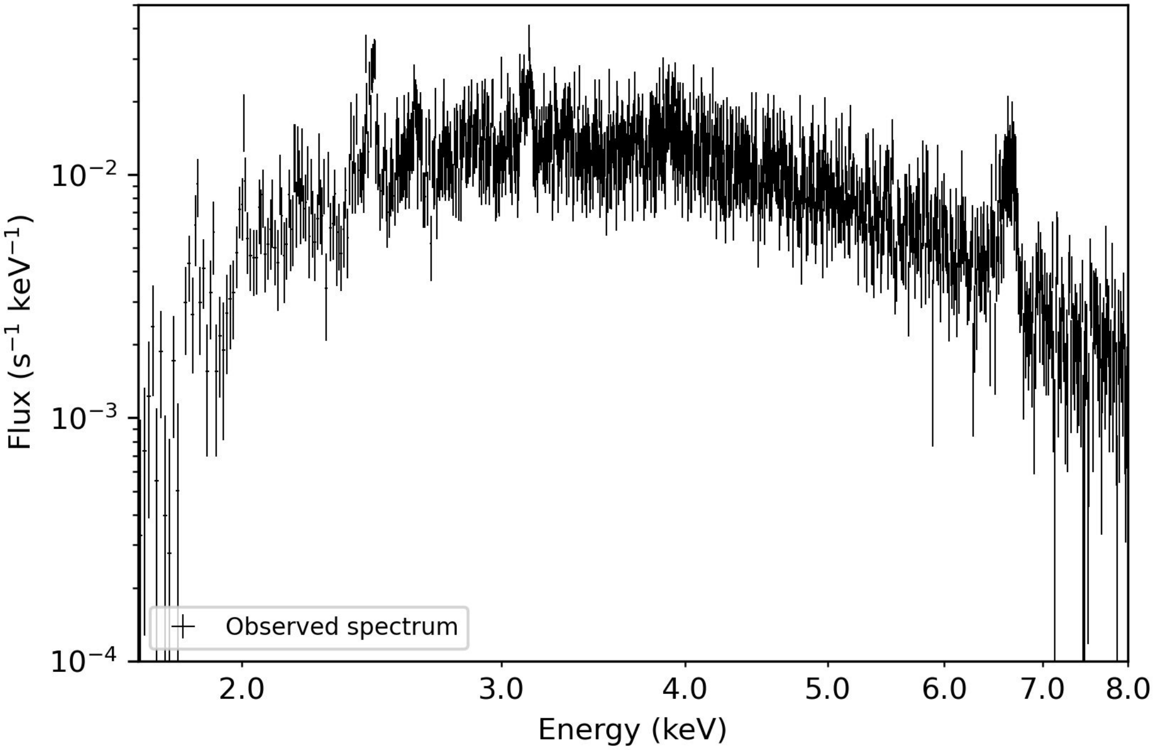
XRISM - Resolve PV observation

Performance Verification data

Collected from June 17 2024 to June 22 2024

Clean T_{exp}= 290 ks

Data analysis presented in XRISM Collaboration (2025)



XRISM Collaboration (2025):
The background-subtracted Resolve spectrum

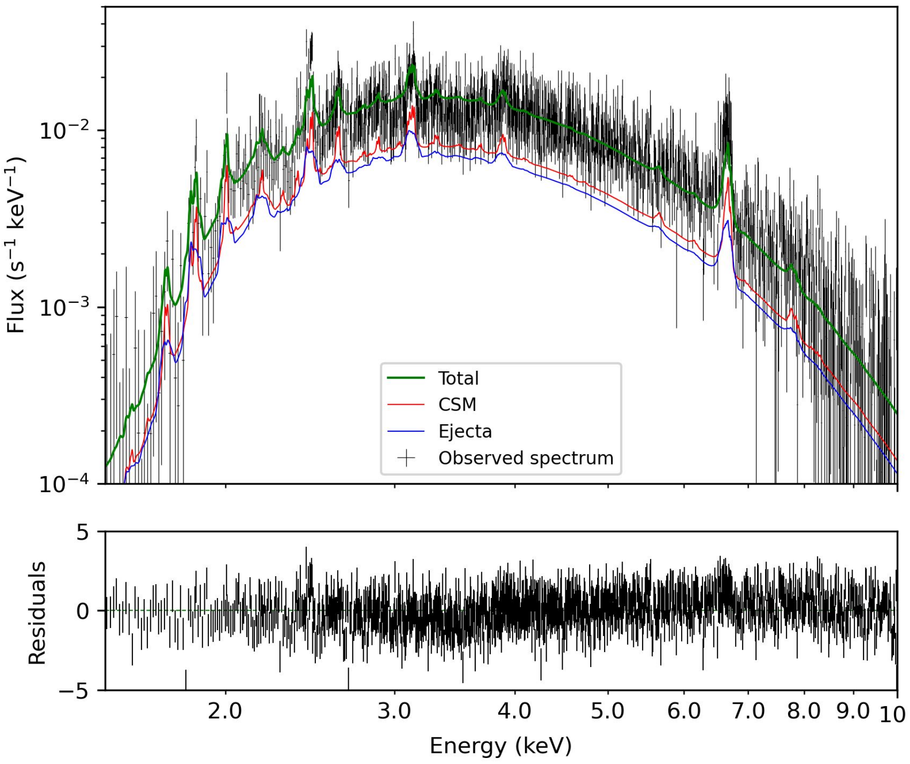
Data vs. Model

Data and model match incredibly well with **NO FITTING** procedure needed, however:

Some small residual can be spotted

Measured velocities not compatible with the CSM velocities, therefore:

First clear X-ray evidence of emission from shocked ejecta in SN 1987A



XRISM Collaboration (2025): The background-subtracted Resolve spectrum with the synthetic spectral model (green) with ejecta (blue) and CSM (red) contribution for the year 2024

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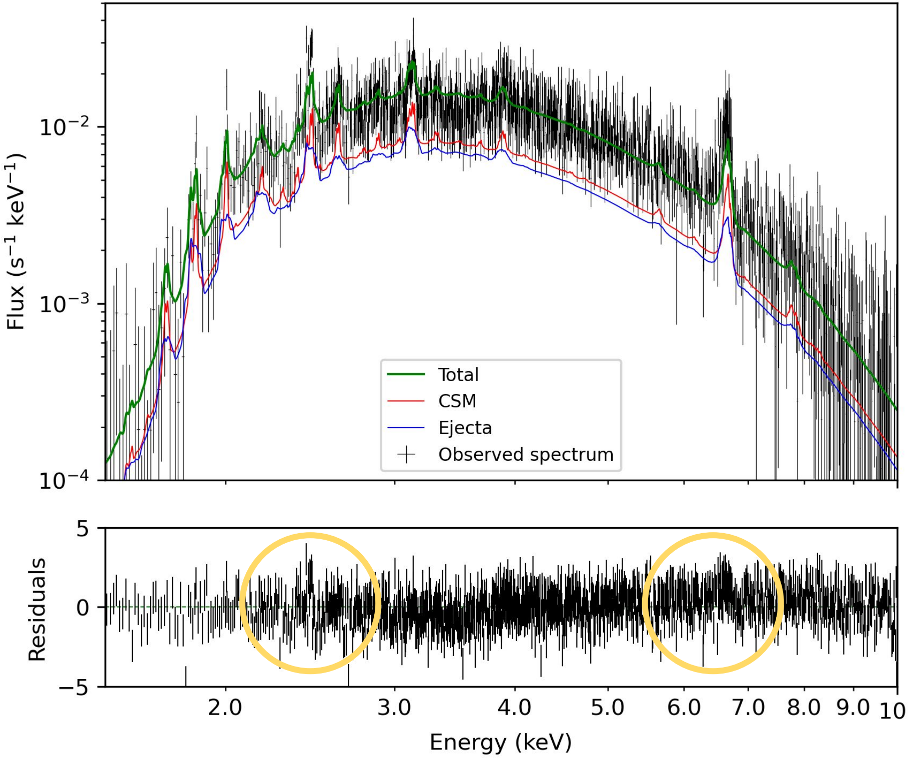
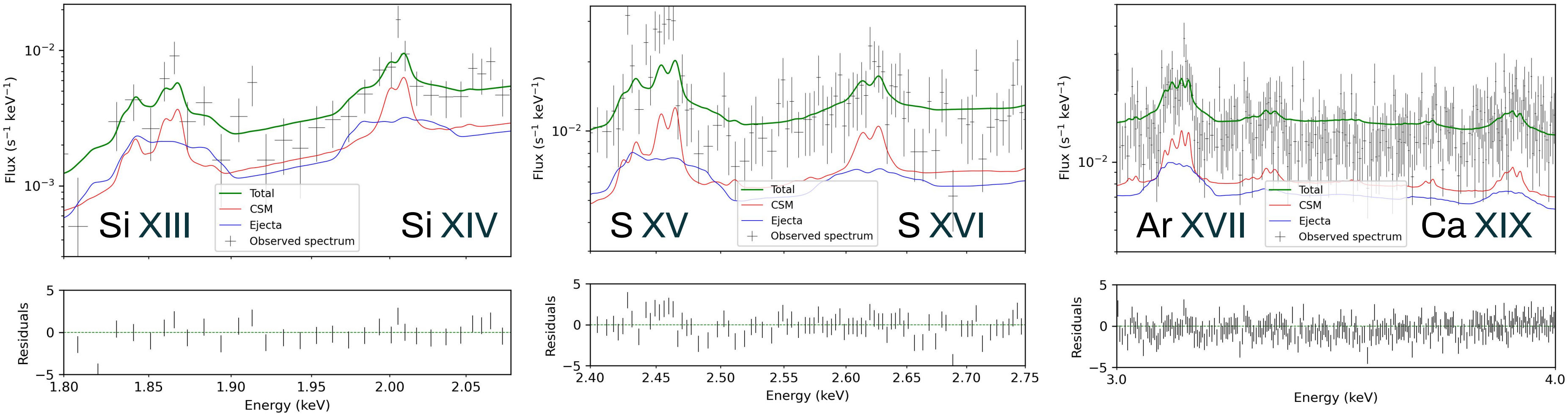


XRISM Collaboration (2025): The background-subtracted Resolve spectrum with the synthetic spectral model (green) with ejecta (blue) and CSM (red) contribution for the year 2024

Lines close-up



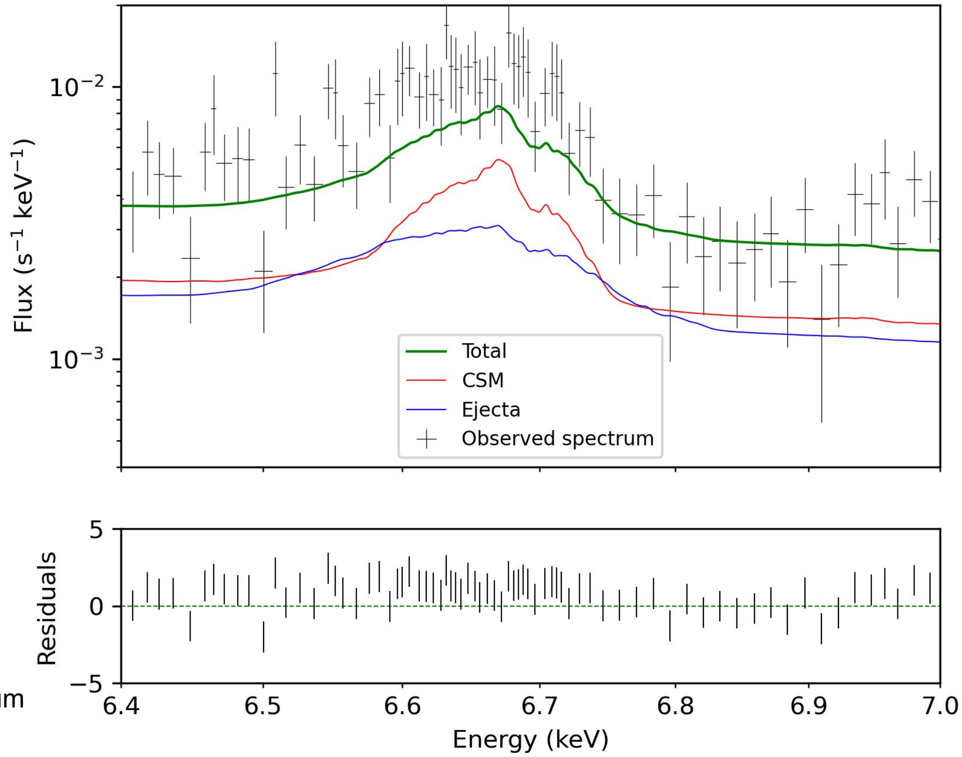
XRISM Collaboration (2025): The background-subtracted Resolve spectrum with the synthetic spectral model (green) with ejecta (blue) and CSM (red) contribution for the year 2024. Close-up around Si XIII, Si XIV, S XV, S XVI, Ar XVII, and Ca XIX lines

Fe XXV line

The model under-reproduces both the line flux and its redshifted wing, indicative of:

- a larger contribution from the Fe-rich plasma than the model
- a larger velocity of the Fe-rich material

The differences are enhanced in the low-energy wing of the line.



XRISM Collaboration (2025): The background-subtracted Resolve spectrum with the synthetic spectral model (green) with ejecta (blue) and CSM (red) contribution for the year 2024. Close-up around Fe XXV.

Fe XXV line

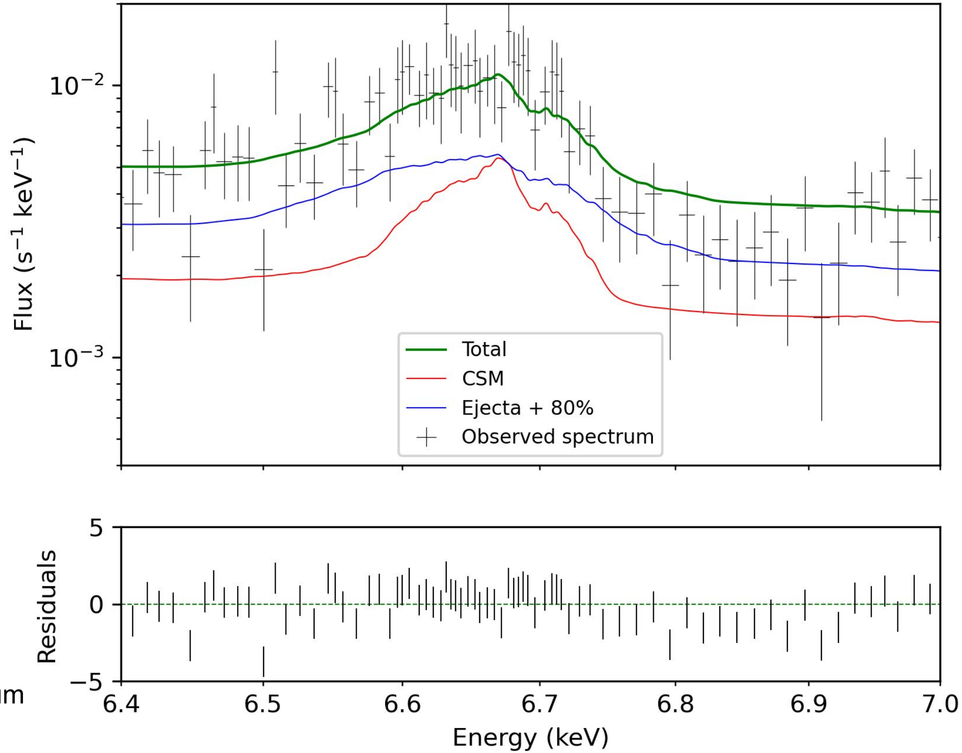
Red-shifted Fe-rich ejecta in Larsson+2023

Adding by hand contribution from ejecta component we can reproduce well the line profile

This suggests the presence of more shocked Fe-rich ejecta (as in Larsson+2023)

New MHD Orlando+2025 with Ni Bubble effect:

- More expanded Fe-rich ejecta
- but still need 30% increase in velocity



XRISM Collaboration (2025): The background-subtracted Resolve spectrum with the synthetic spectral model (green) with ejecta (blue) and CSM (red) contribution for the year 2024. Close-up around Fe XXV

Conclusions

A tool to synthesize spectra from MHD to directly compare them with observations

My case study was SN 1987A: Orlando et al. (2020) vs. XRISM PV data

XRISM Resolve PV data confirm the presence of shocked ejecta in SN 1987A

Synthetic spectrum match observations remarkably well

Fast Ejecta now contribute significantly to the X-ray emission with broad line profiles

Fe XXV underpredicted → likely more Fe-rich plasma and higher velocities

Backup Slides

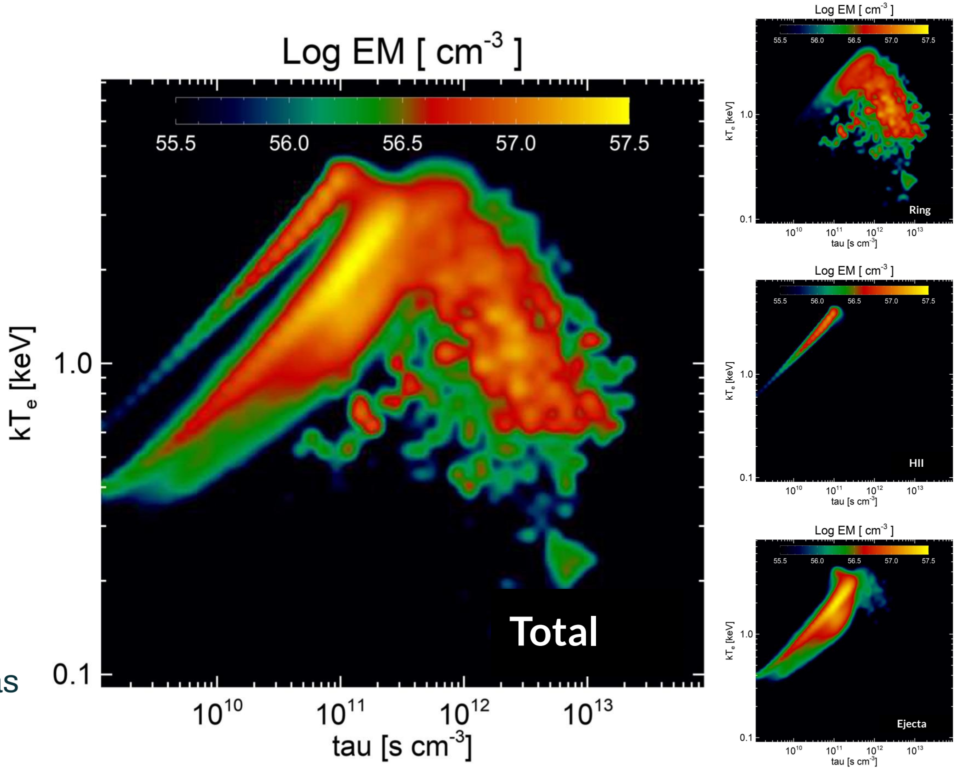
Contribution to X-ray emission

Contribution from the ejecta increased

Comparable to the EM of the ring

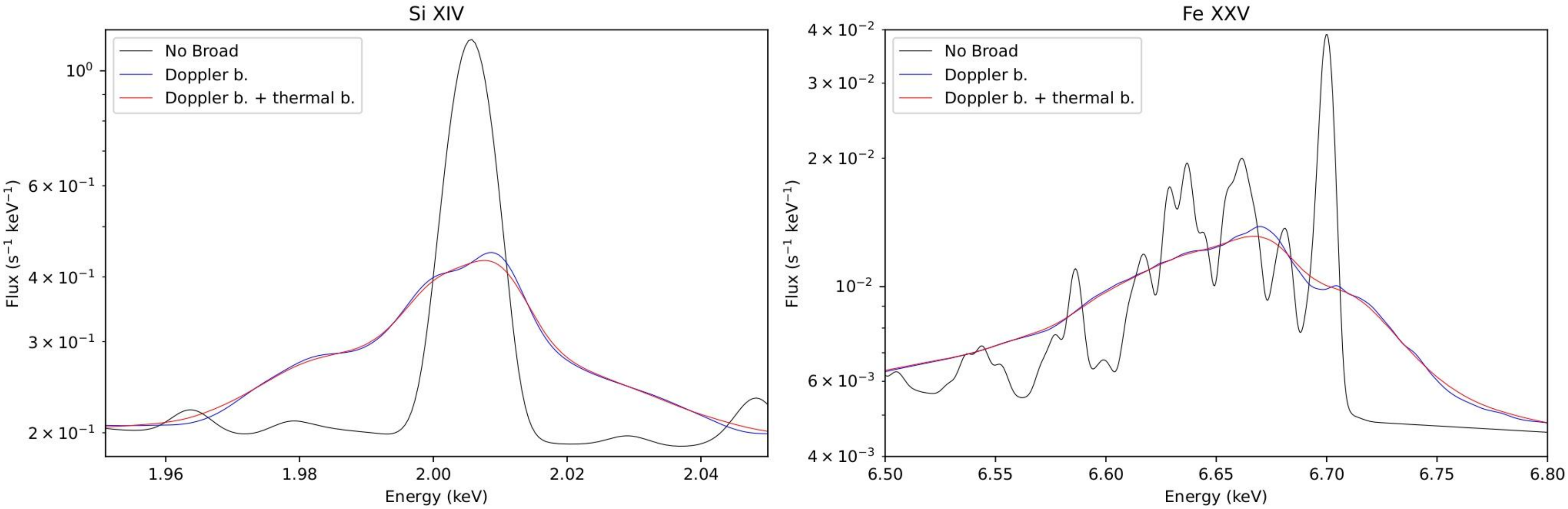
CSM emission dominated by the ring

The ring has on average higher $n_e t$



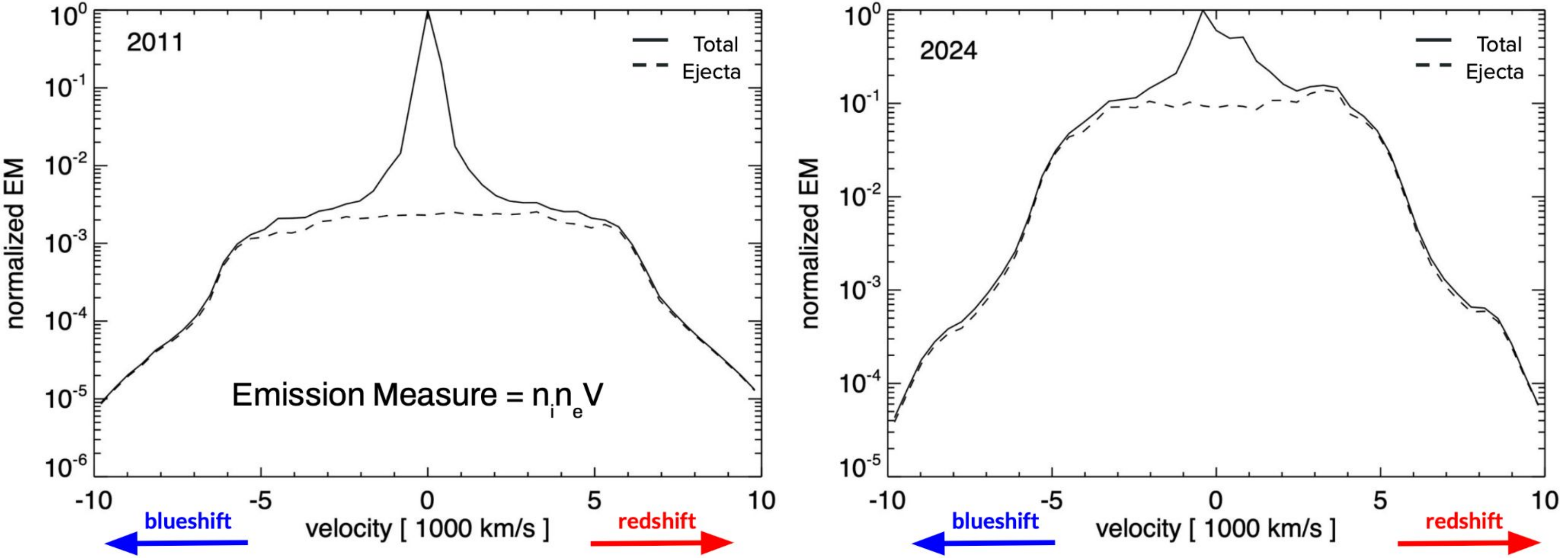
Sapienza et al. (2024): Distribution of the emission measure as a function of the temperature *kT* and the ionization parameter $n_e t$ (τ) for the year 2024

Adding the thermal broadening



Sapienza et al. (2024): Comparison between the spectral models with No broadening (black), Bulk motion (Blue) and bulk motion plus thermal (red), for the Si XIV and Fe XXV lines.

Fast Evolving Situation



Sapienza et al. (2024a): Normalized Emission Measure (EM) distribution as a function of the velocity along the line of sight for the 2011 (left panel) and 2024 (right panel).