Synthetic Observations with pyXSIM and SOXS for XRISM

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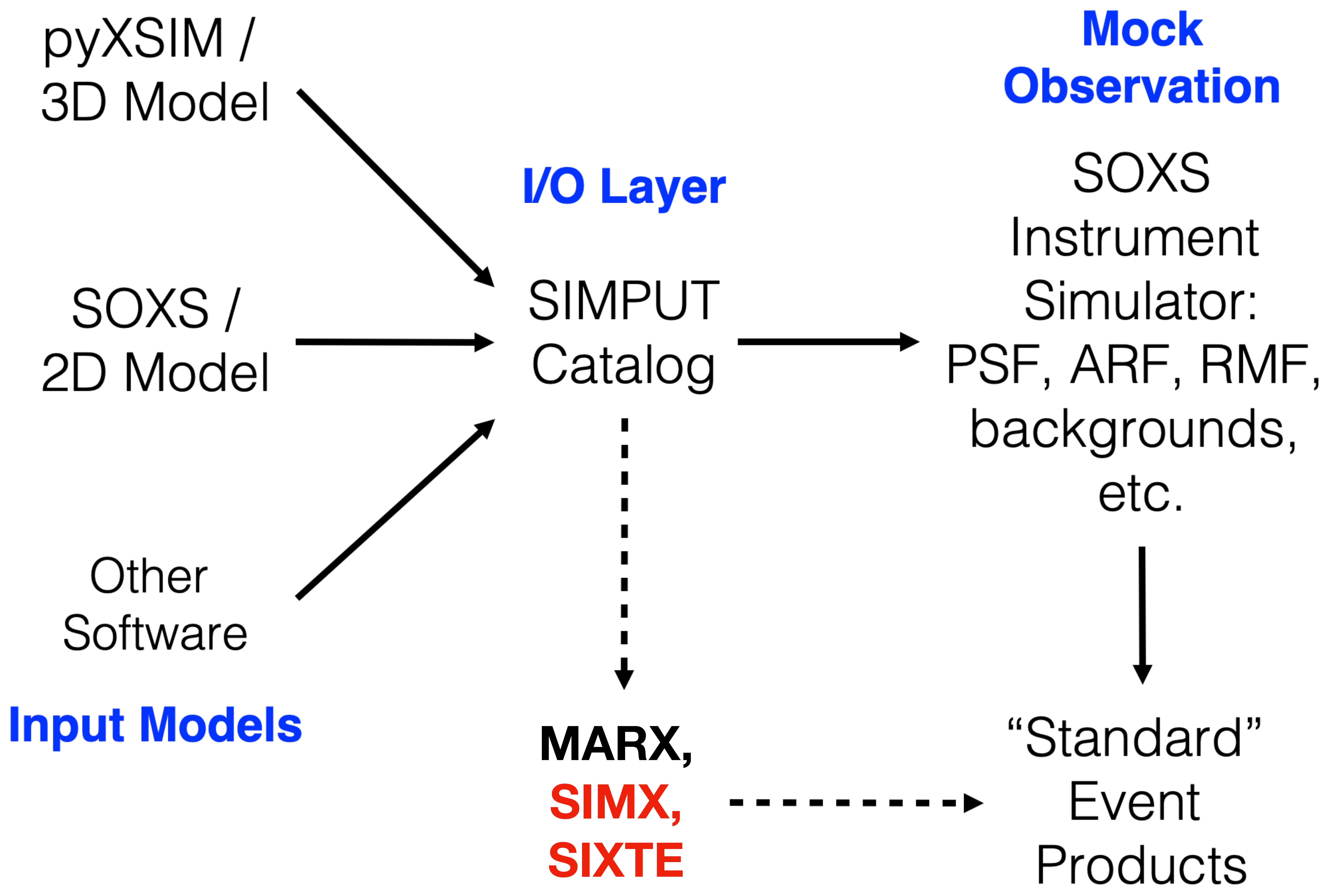
Two Python Packages

- SOXS: http://hea-www.cfa.harvard.edu/soxs
  - Simple spectral models and 2D spatial models → SIMPUT
  - Instrument simulation (supports XRISM similar to SIMX, not as good as SIXTE, HEASIM)
- pyXSIM: http://hea-www.cfa.harvard.edu/~jzuhone/pyxsim
  - Simulated X-ray emission from 3D sources → SIMPUT
  - Most of the spectral machinery is outsourced to SOXS, then used in pyXSIM
- Both open-source, Python-based, hosted on GitHub
- pip and conda-installable

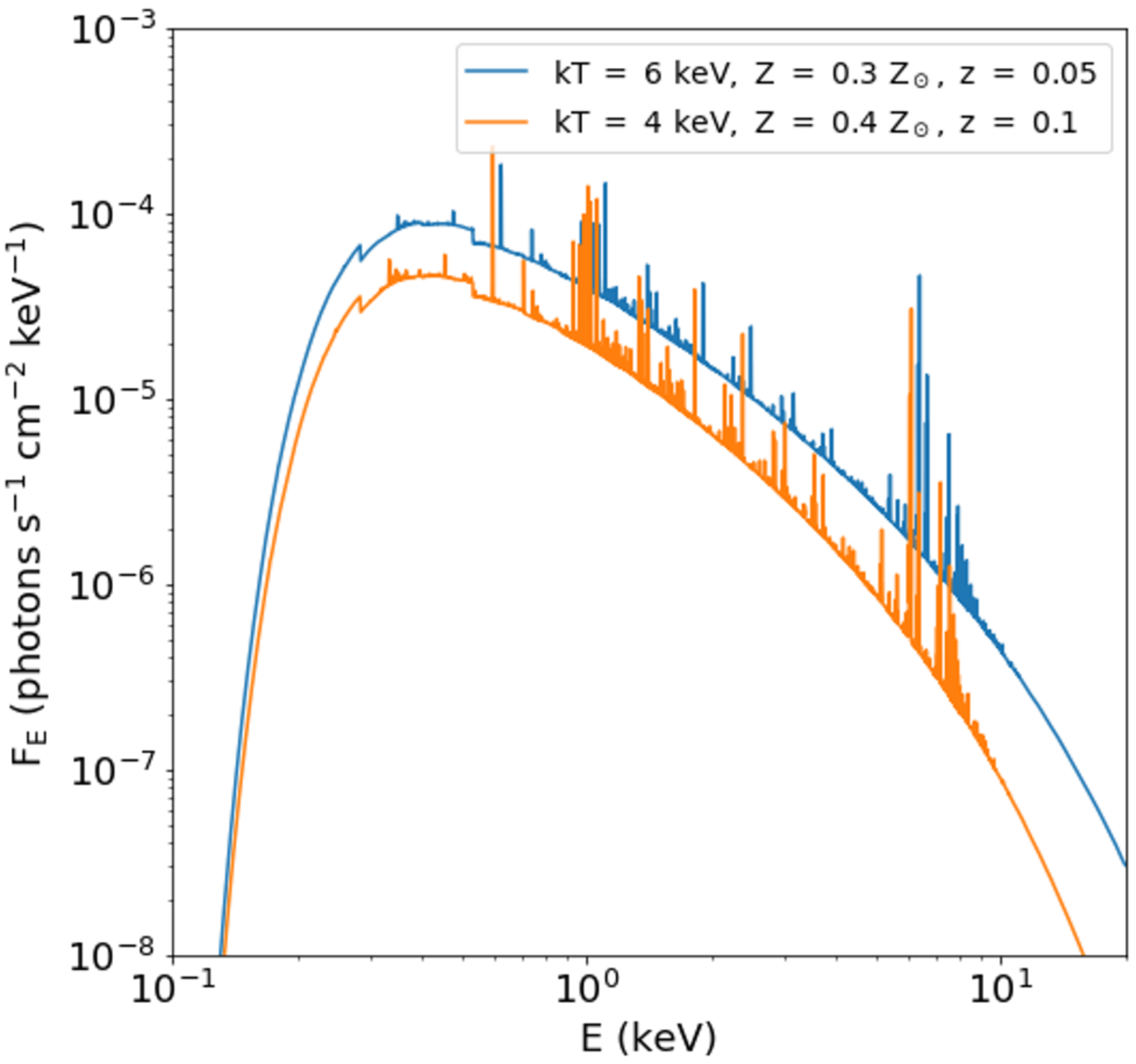
SOXS Overview



https://hea-www.cfa.harvard.edu/soxs/

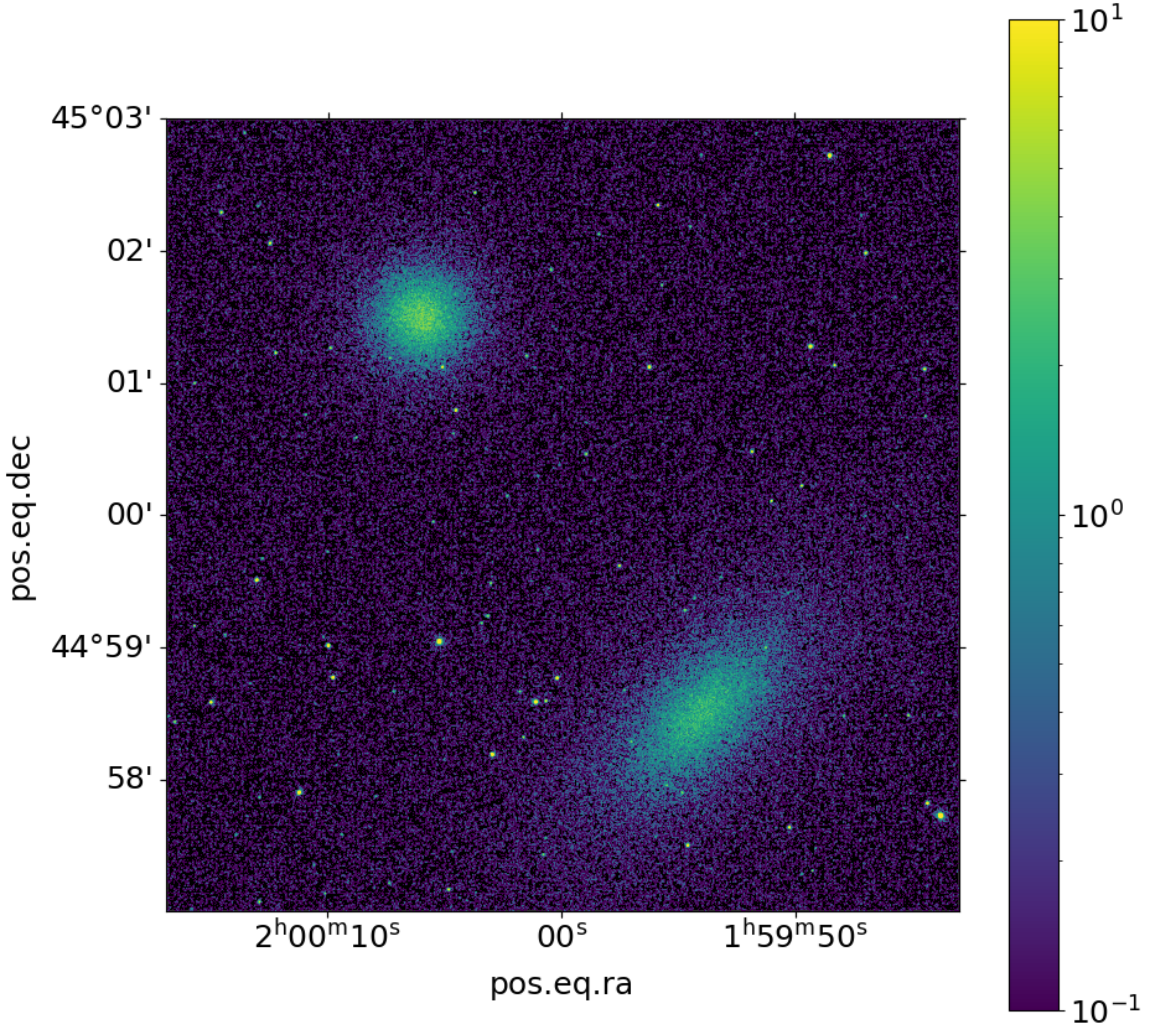
Spectral Models

- Spectral models:
    - Thermal (APEC CIE/NEI, SPEX CIE, Cloudy CIE/PIE)
    - Power-law
    - From an XSPEC model or script
    - From a file
- Operations:
    - Arithmetic with spectra (add spectra, multiply by a constant, etc.)
    - Foreground absorption (wabs, tbabs)
    - Add emission and absorption lines by hand
- Can also do spectral-only simulations with instruments (basically a Python version of XSPEC's fakeit)



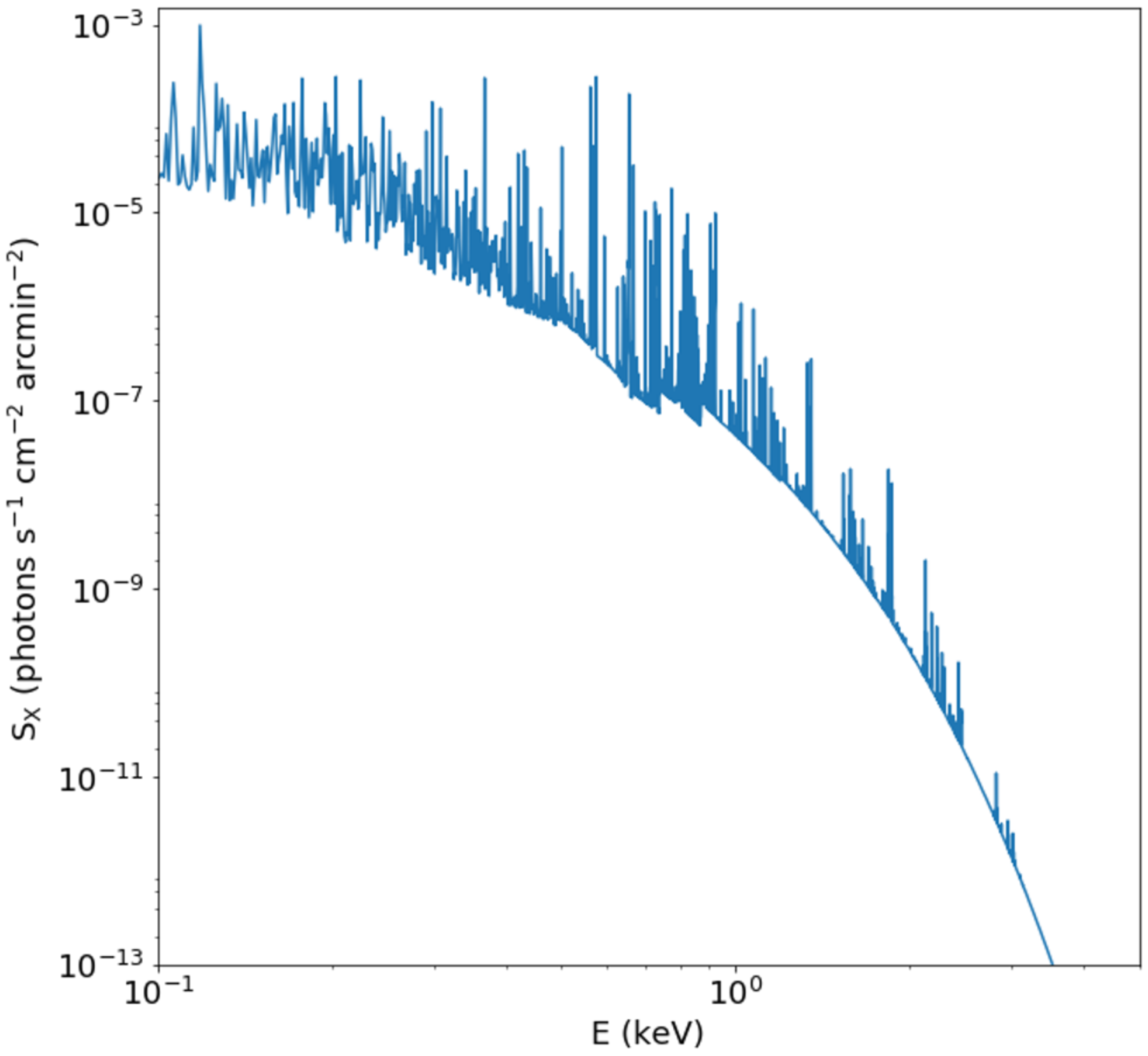
2D Spatial Models

- These models generate images and photon coordinates for SIMPUT catalogs
  - Point sources
  - β-models
  - Annuli and disks
  - Generic models from Python functions, files, arrays

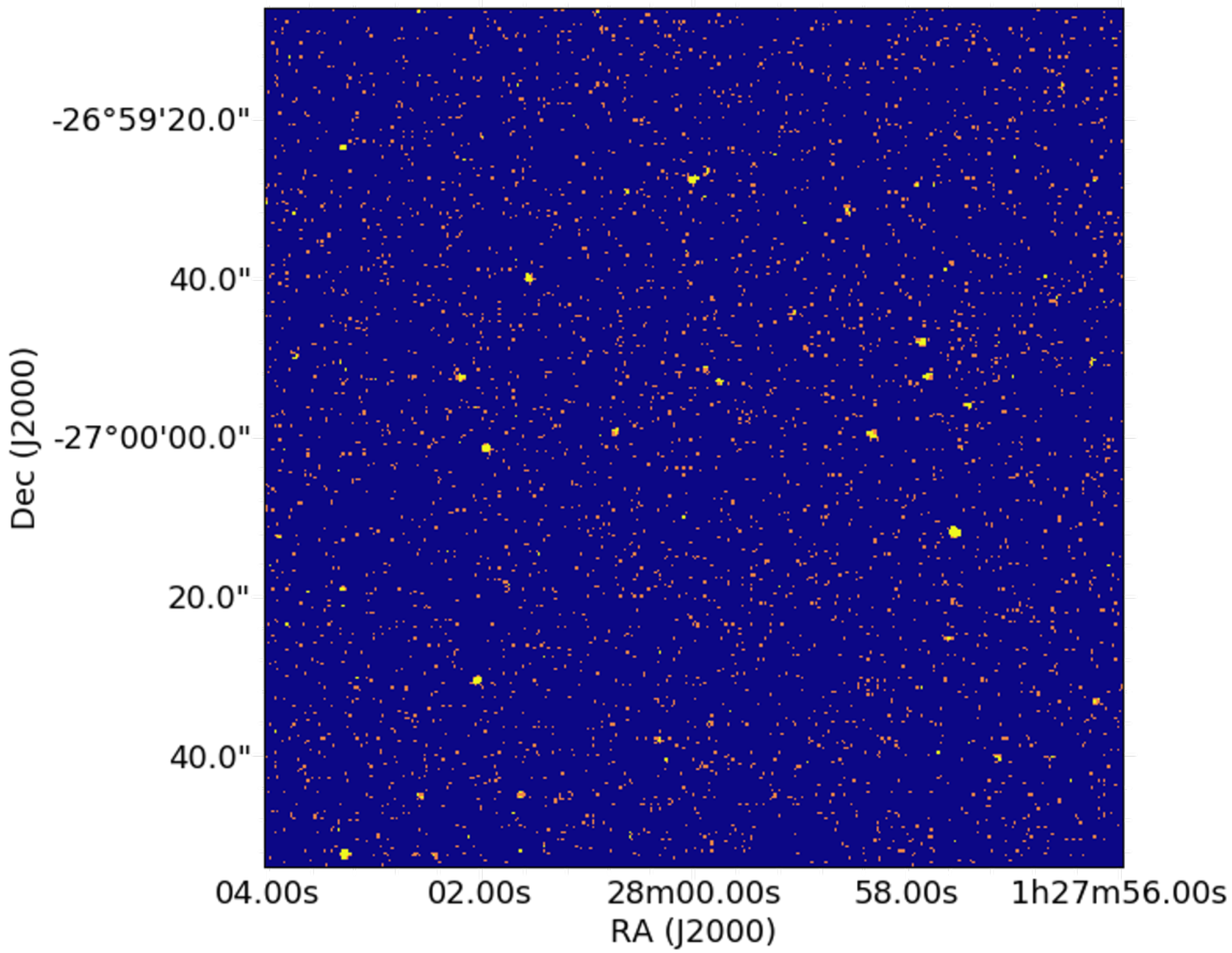


Backgrounds/Foregrounds

Milky Way Foreground



Cosmic X-ray Background



These can be exported to SIMPUT files if you want to use them with SIXTE/SIMX

SOXS XRISM Models are Pretty Simple

- All instruments based on HEASARC-hosted Cycle 1 files (so GV closed)
- Resolve
  - Square FOV, 3’ on a side
  - Three RMF options assuming high-res, mid-res, low-res events
  - Three ARF options assuming no filter, Be filter, ND filter
  - PSF based on image
  - NXB from model
- Xtend
  - 4-CCD FoV
  - Single RMF and ARF
  - PSF based on image
  - NXB from model
- If you want to use SOXS/pyXSIM models but want more accurate instrument models, use SIXTE!

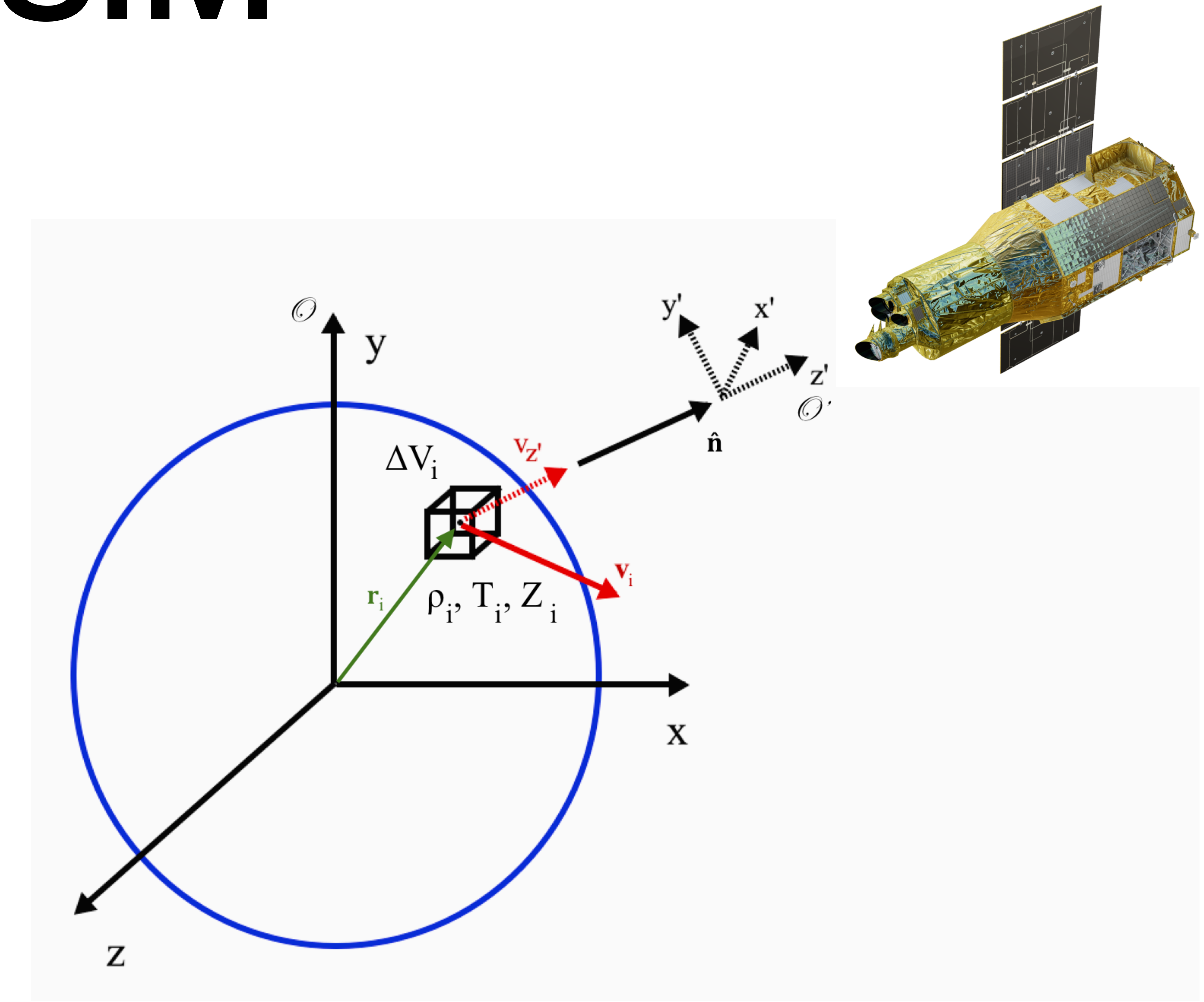
pyXSIM

- Built on top of the yt package so that many different simulation dataset types can be used (FLASH, Enzo, Gadget, Arepo, RAMSES, etc.)

- Take material properties of source from 3D model, construct X-ray emission field, generate simulated X-ray photons

- Project photons to sky, Doppler and cosmologically shift their energies, apply galactic foreground absorption

- Save the pre-detected "events" to disk

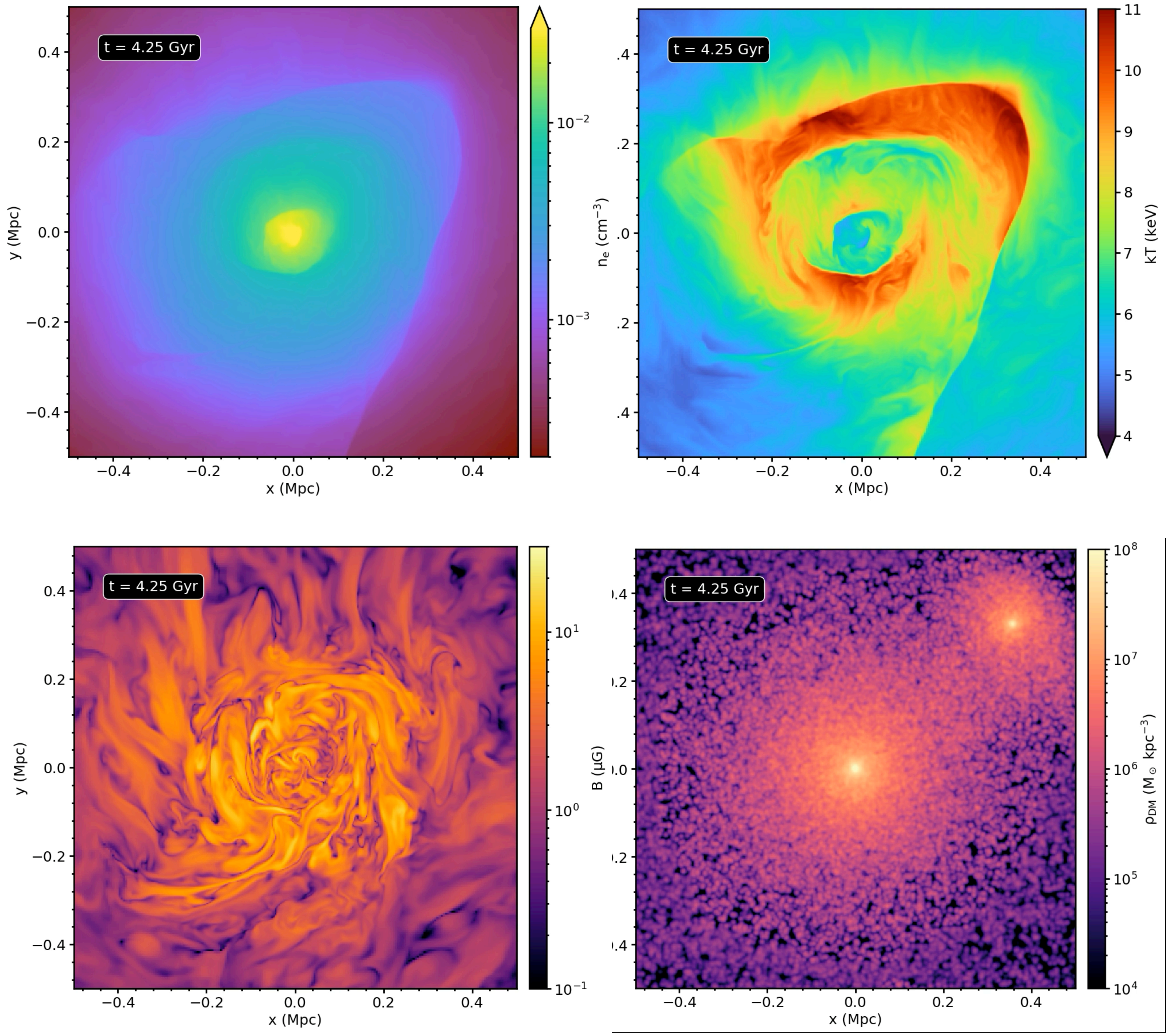


https://hea-www.cfa.harvard.edu/~jzuhone/pyxsim/

Source Models in pyXSIM

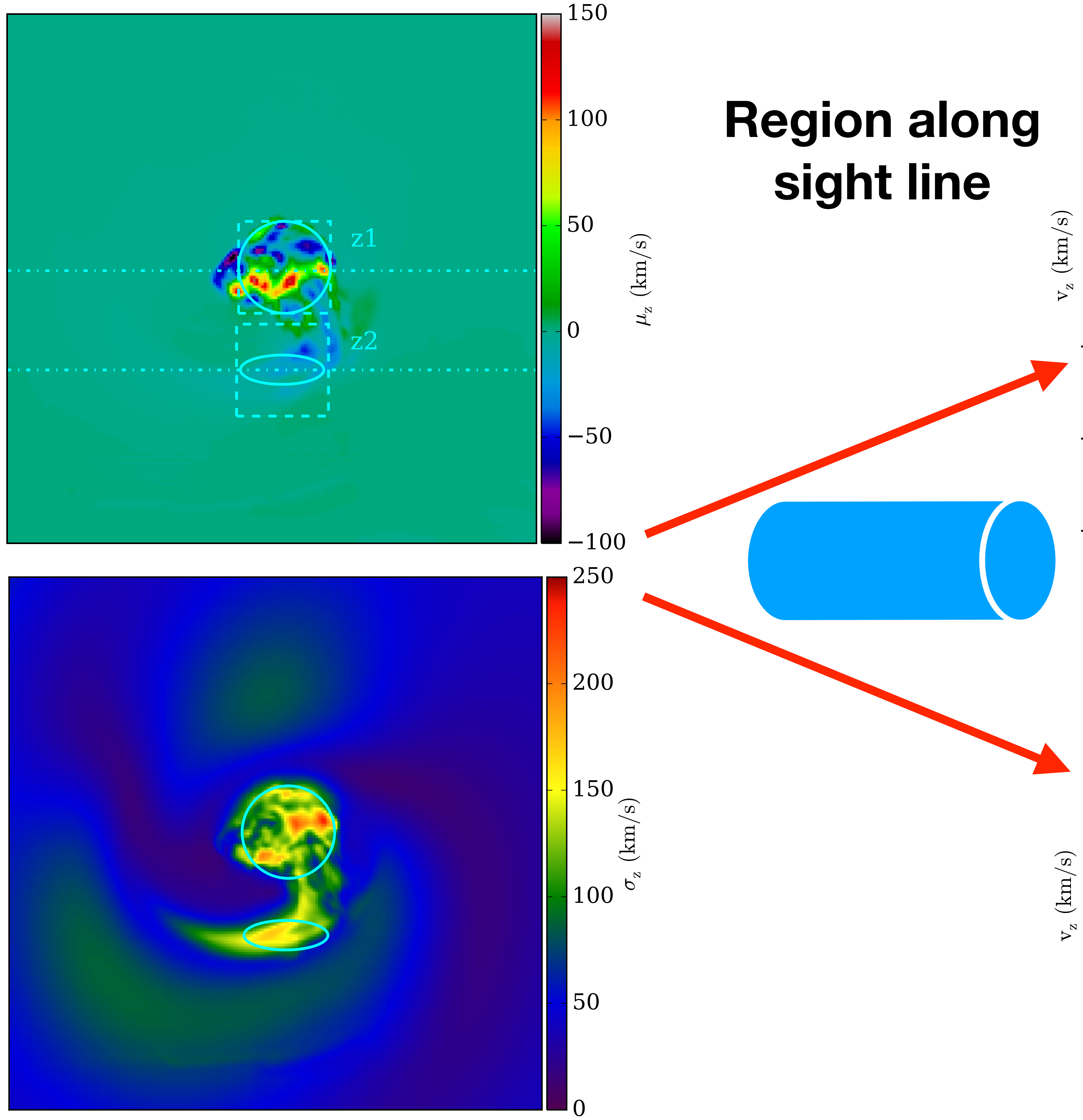
- Thermal Sources (hot plasma of many kinds)
  - APEC (CIE/NEI)
  - SPEX (CIE only currently)
  - Cloudy-based photoionization model (with optional resonant scattering off the CXB)
  - Cloudy-based CIE model
- Power-law Sources (emission from BHs, XRBs, etc.)
- Emission Line Sources (…)
- Everything is currently under the assumption of an optically thin plasma, but we can try something else if you would like!

Galaxy Cluster Gas Motions



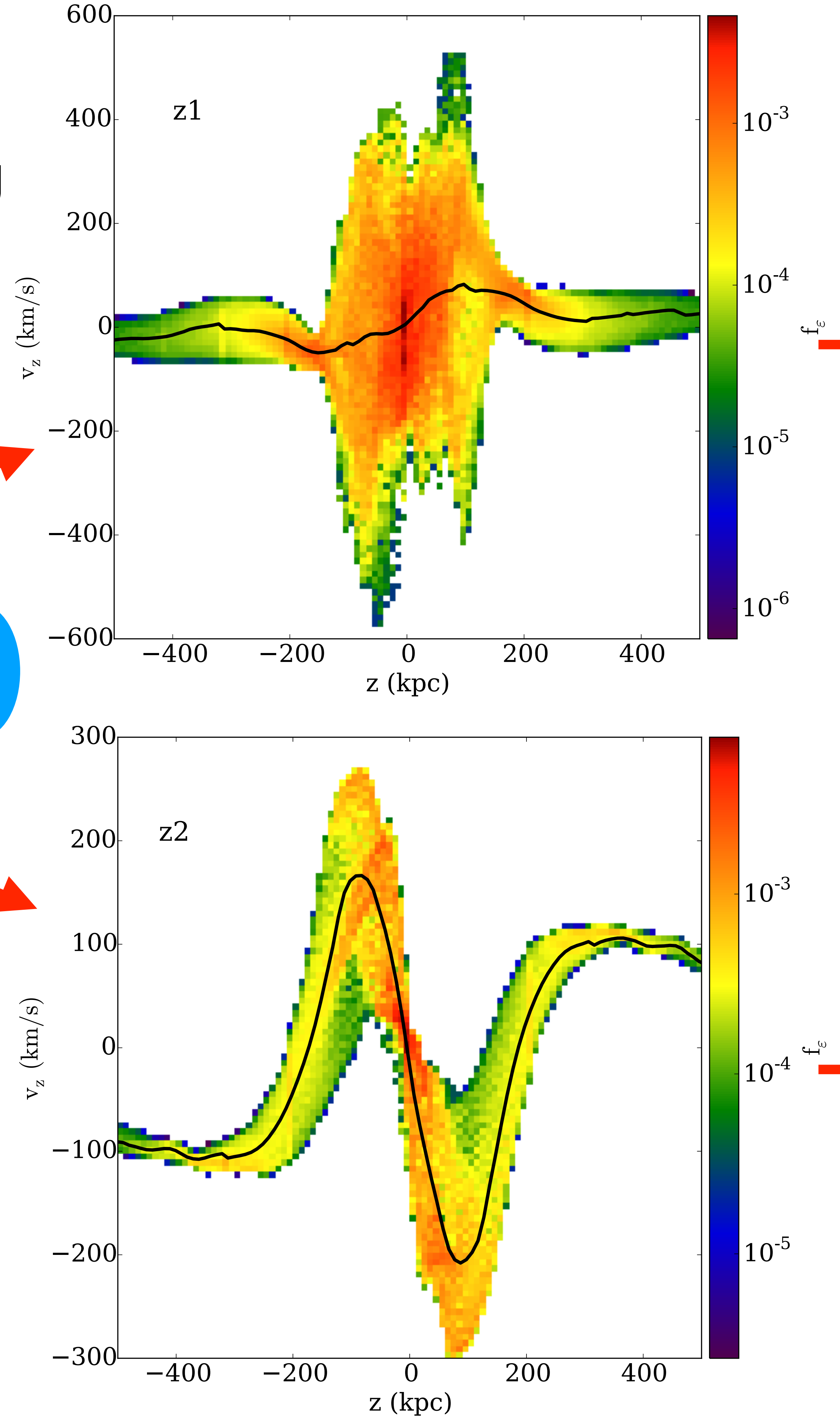
Velocity Fields are Complicated!

Velocity Moment Maps

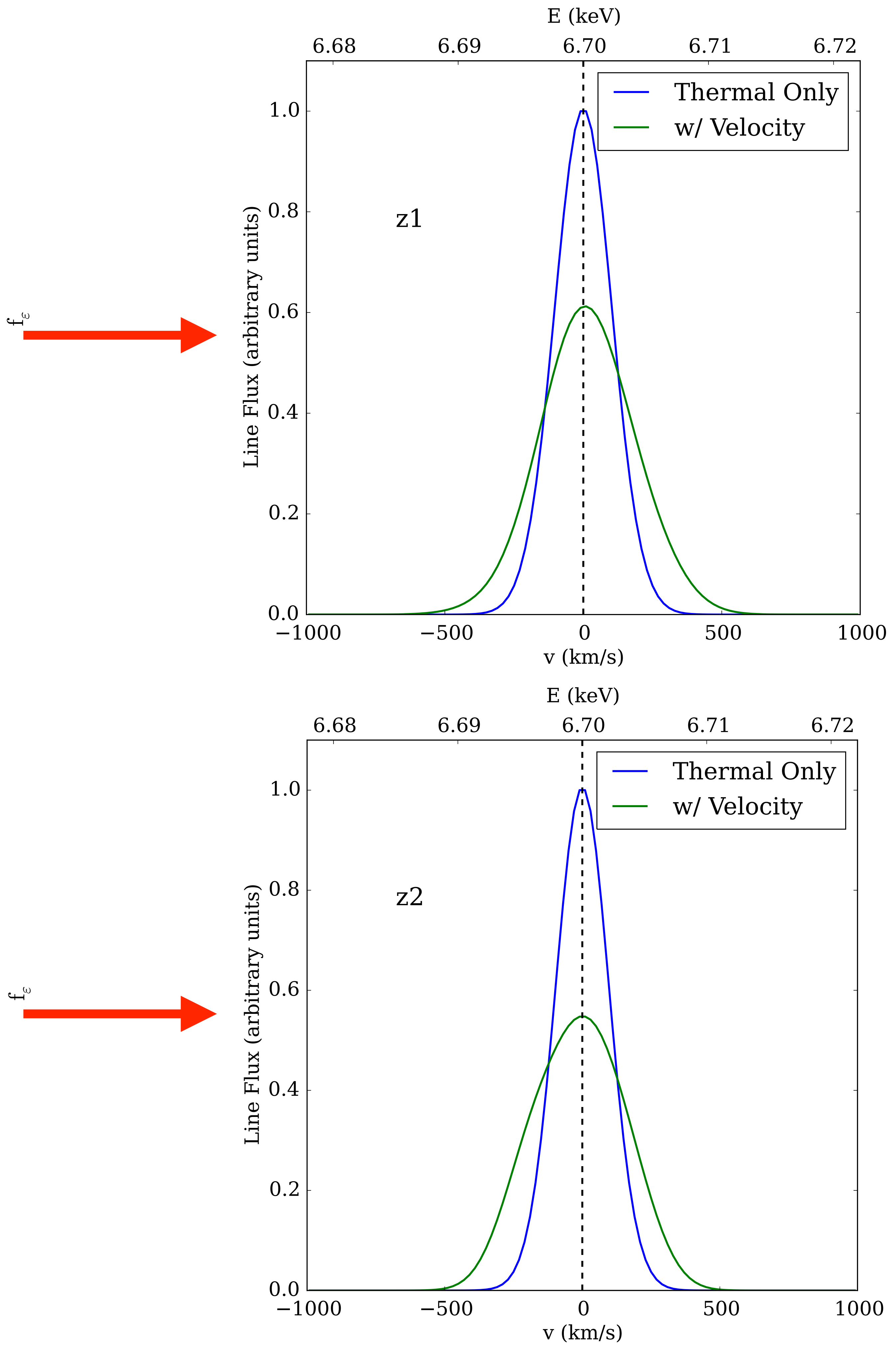


Region along sight line

Phase plot of velocity vs. LOS position

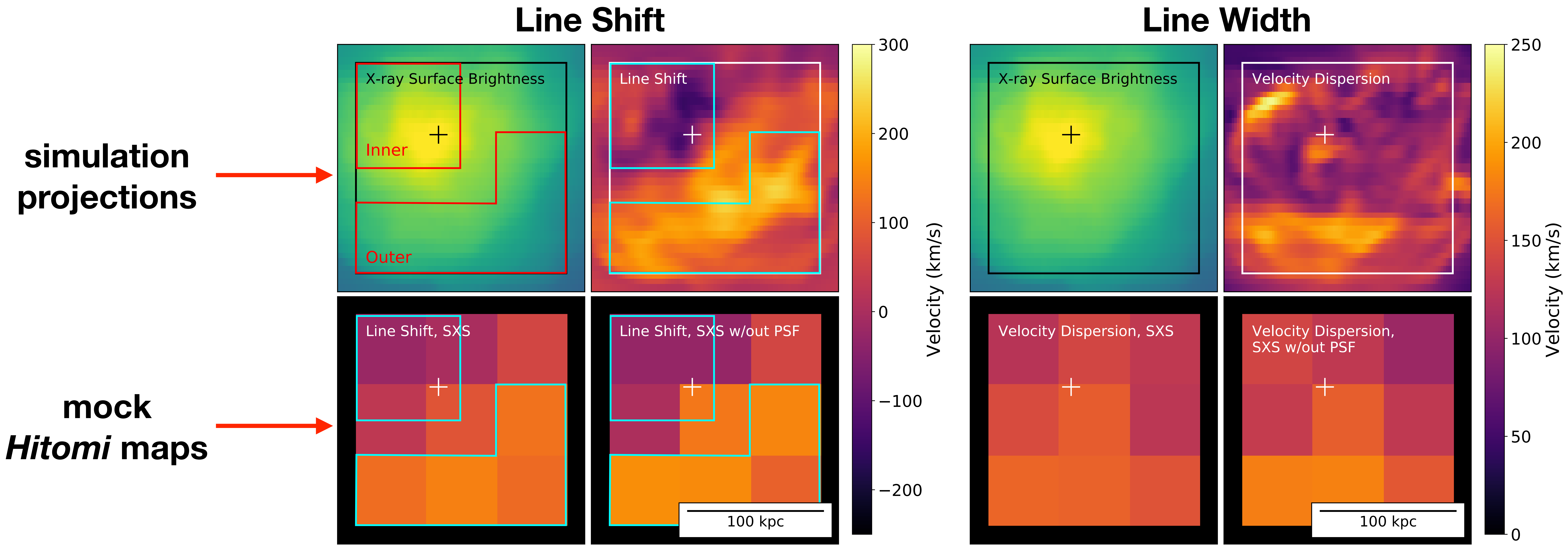


"Toy" Broadened Emission Line



ZuHone et al. 2016

Hitomi Mocks from Cluster Simulations

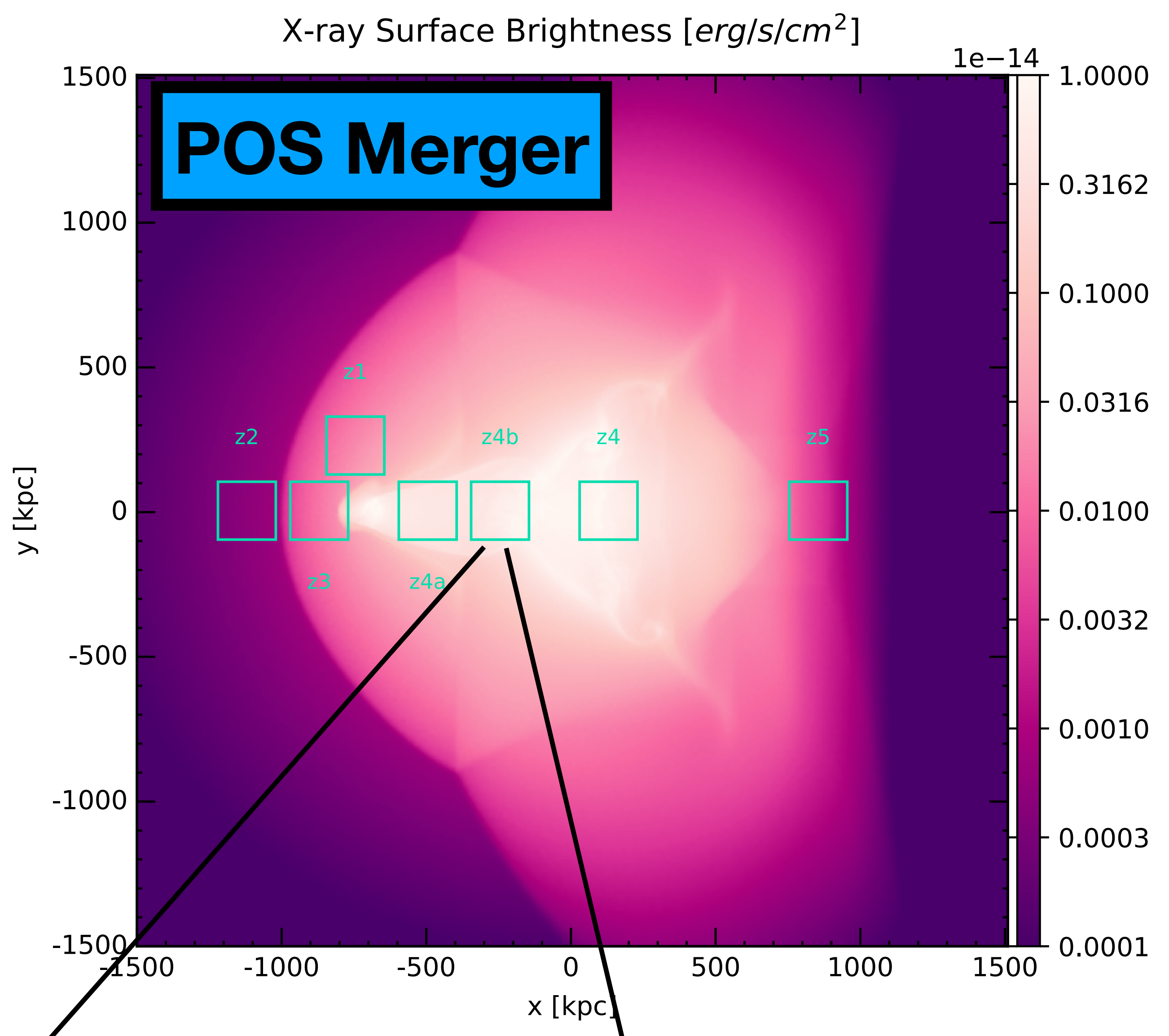


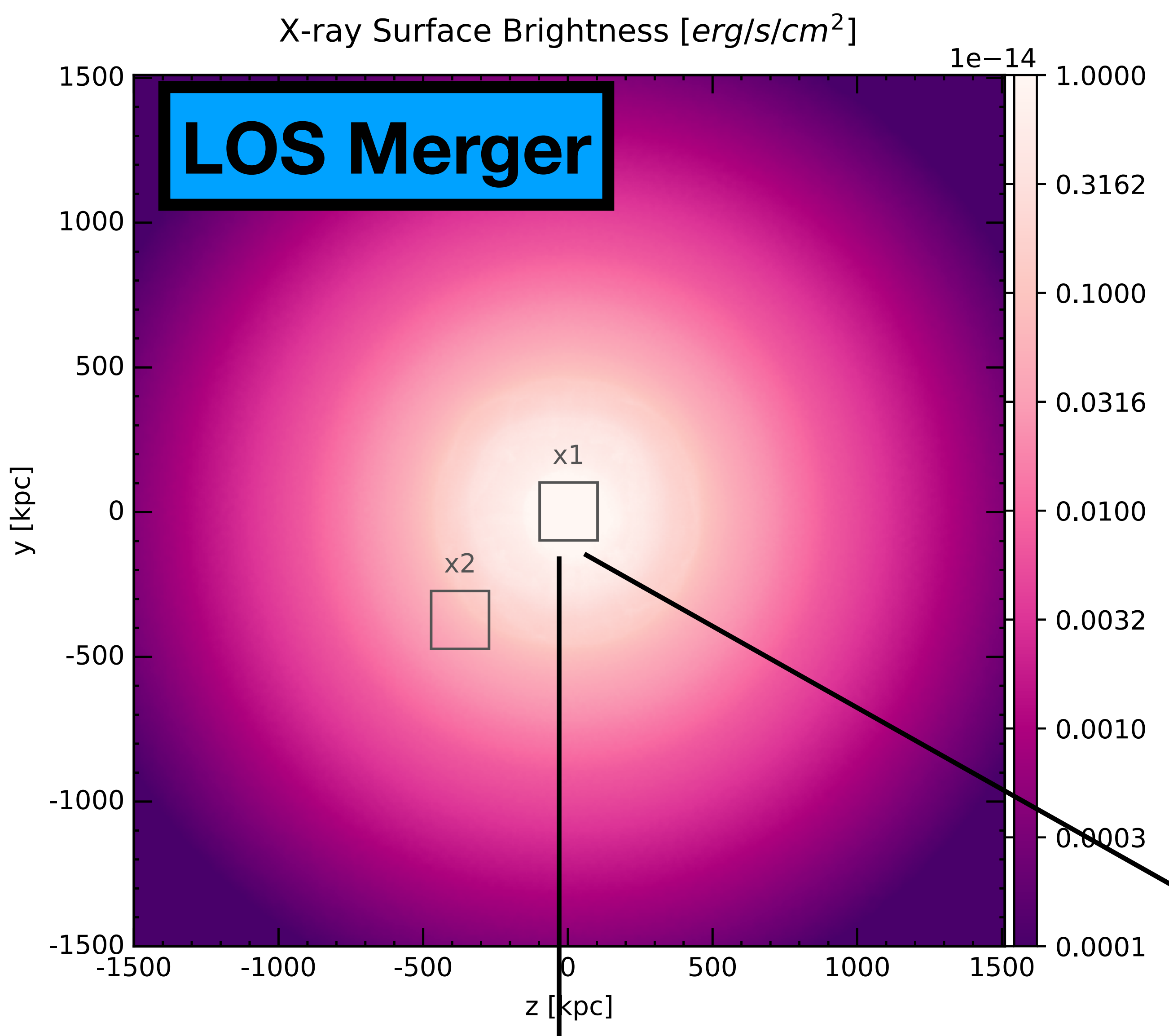
ZuHone et al. 2018

Mock XRISM Observations of a Major Cluster Merger in AREPO

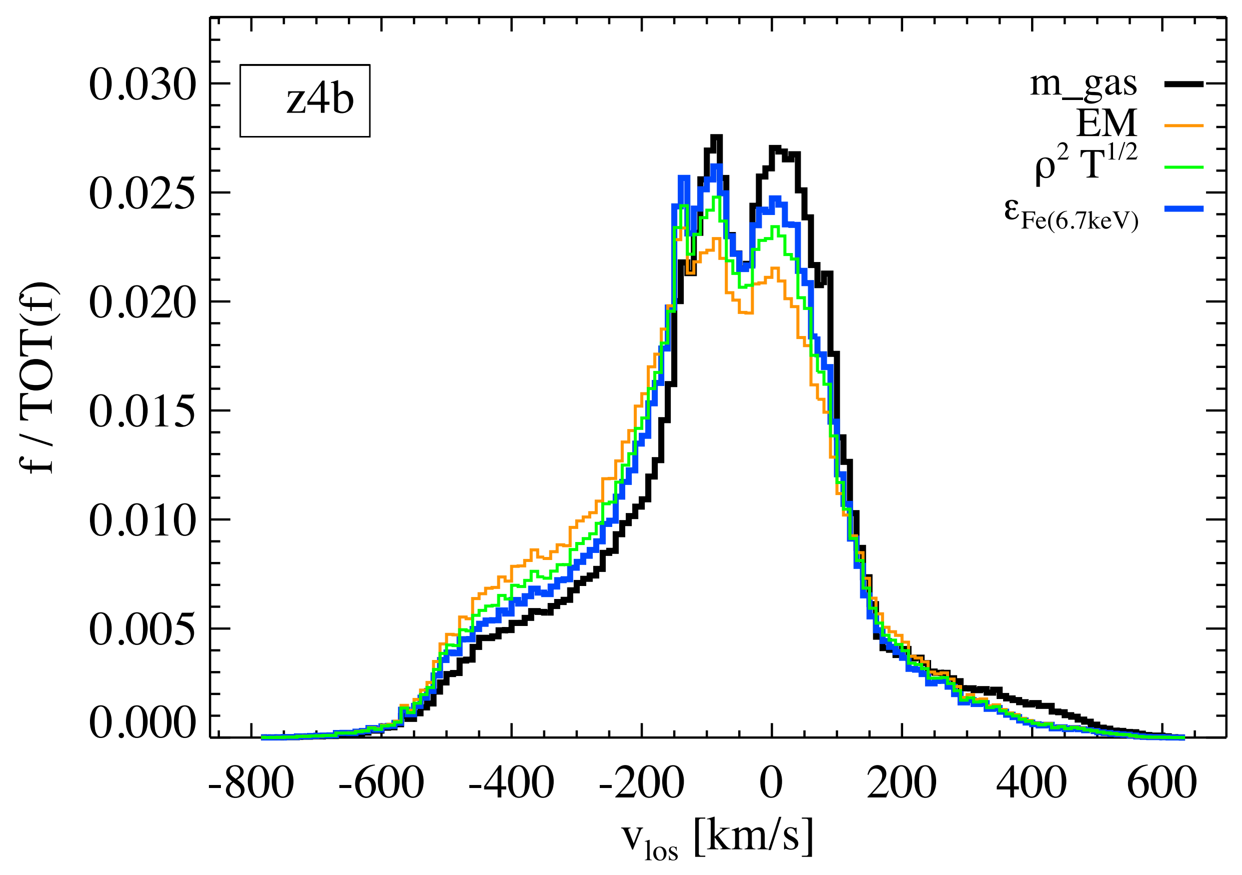
- Major mergers can show some interesting velocity distributions along different sight lines

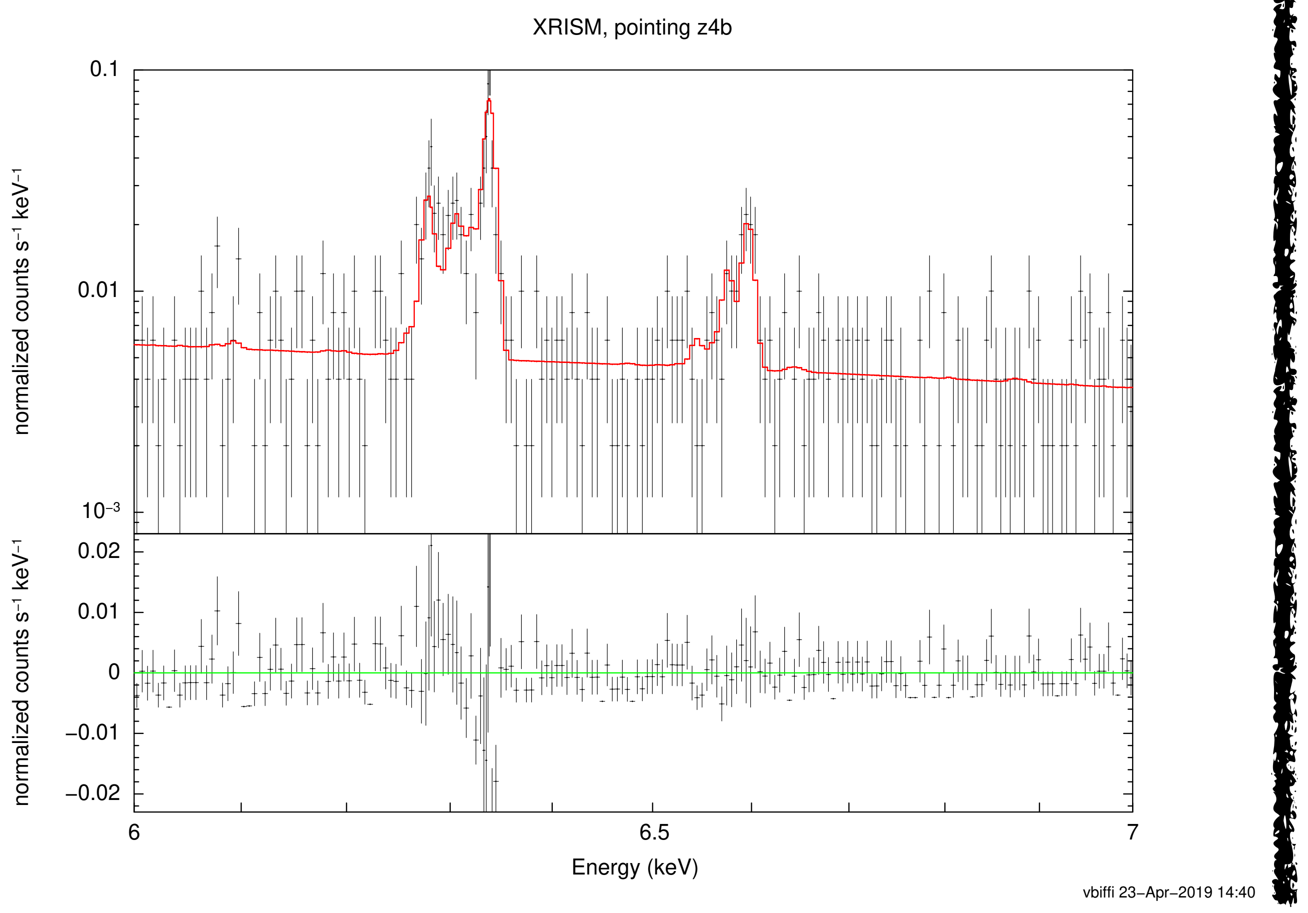
- Mock XRISM/Resolve observations and mock Athena/XIFU observations

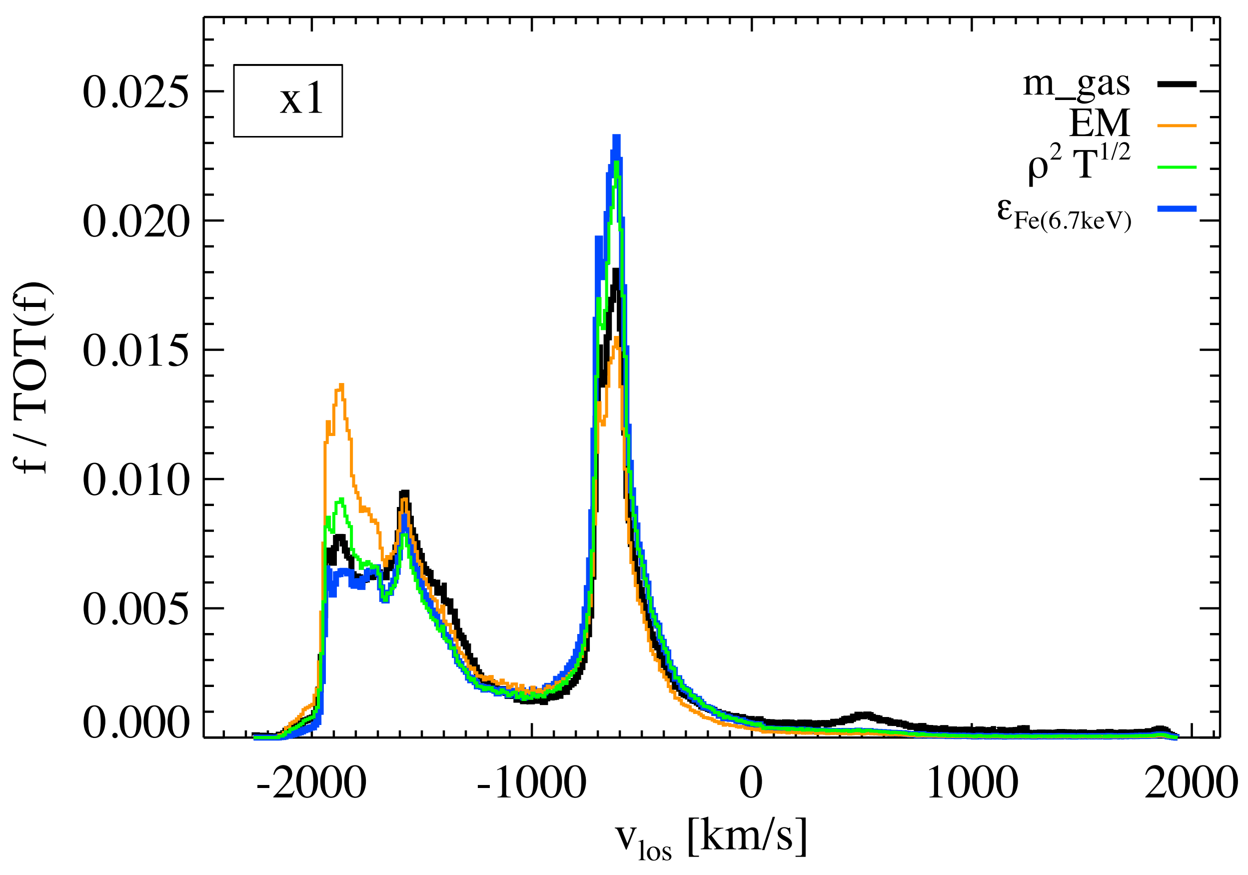


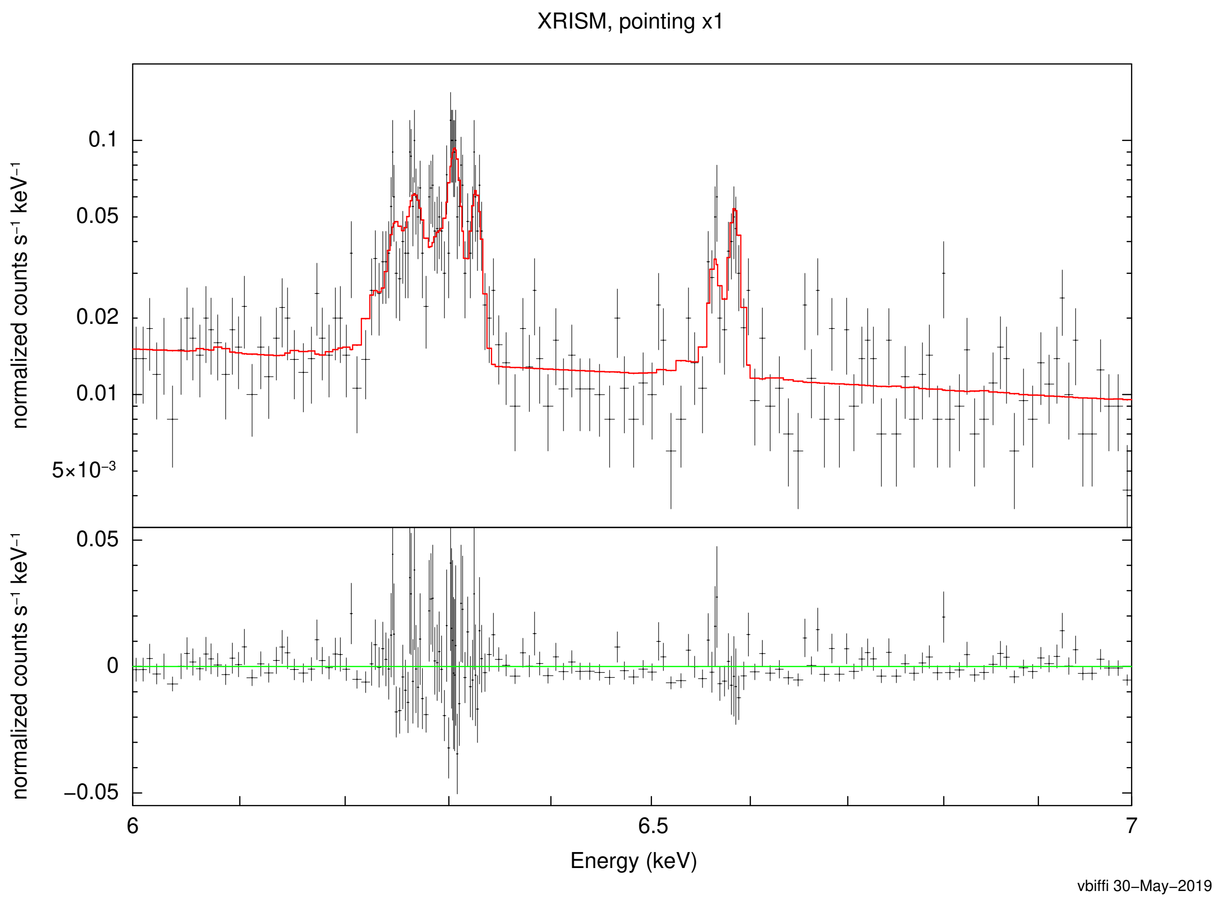


Biffi et al. (2022)

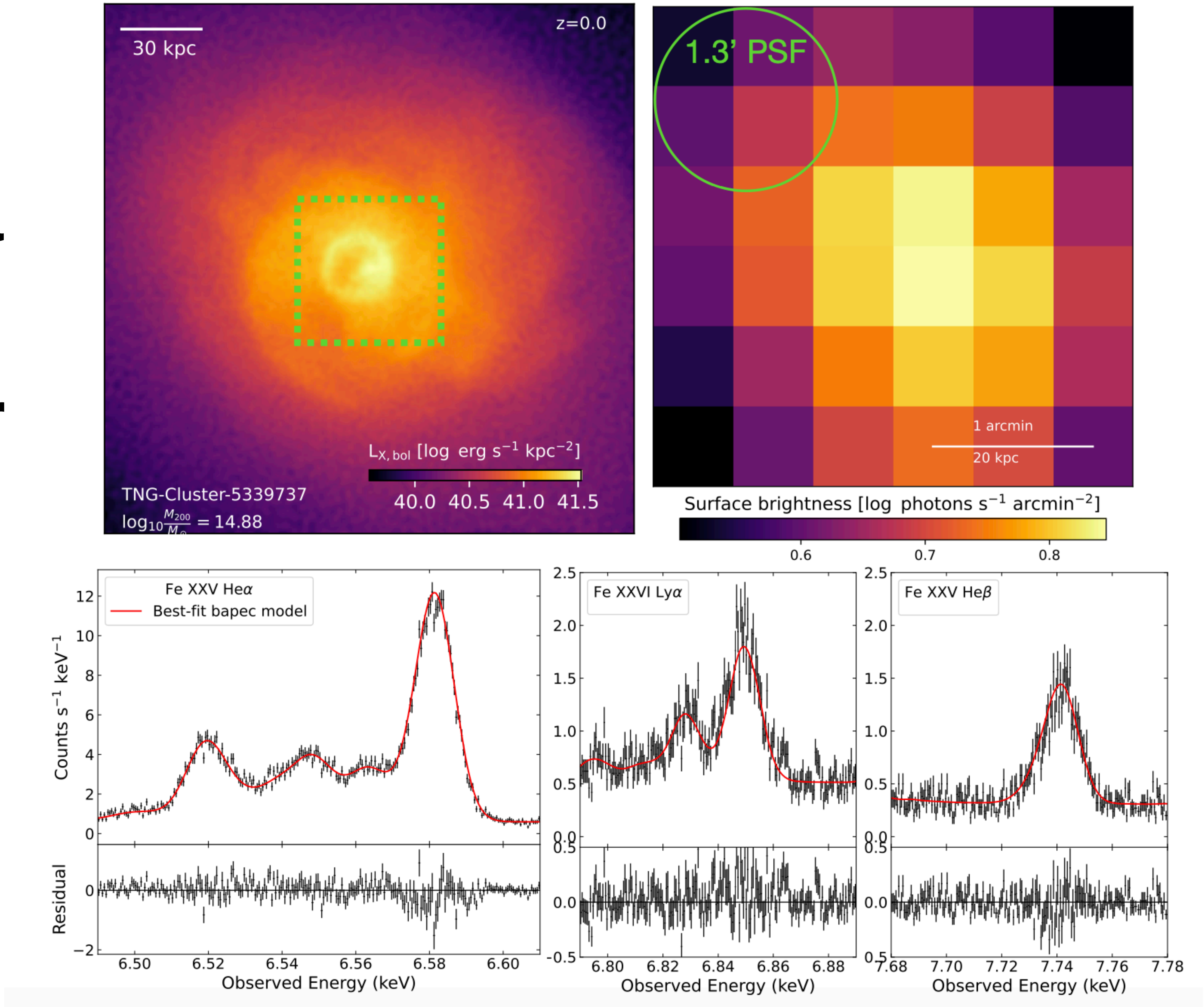






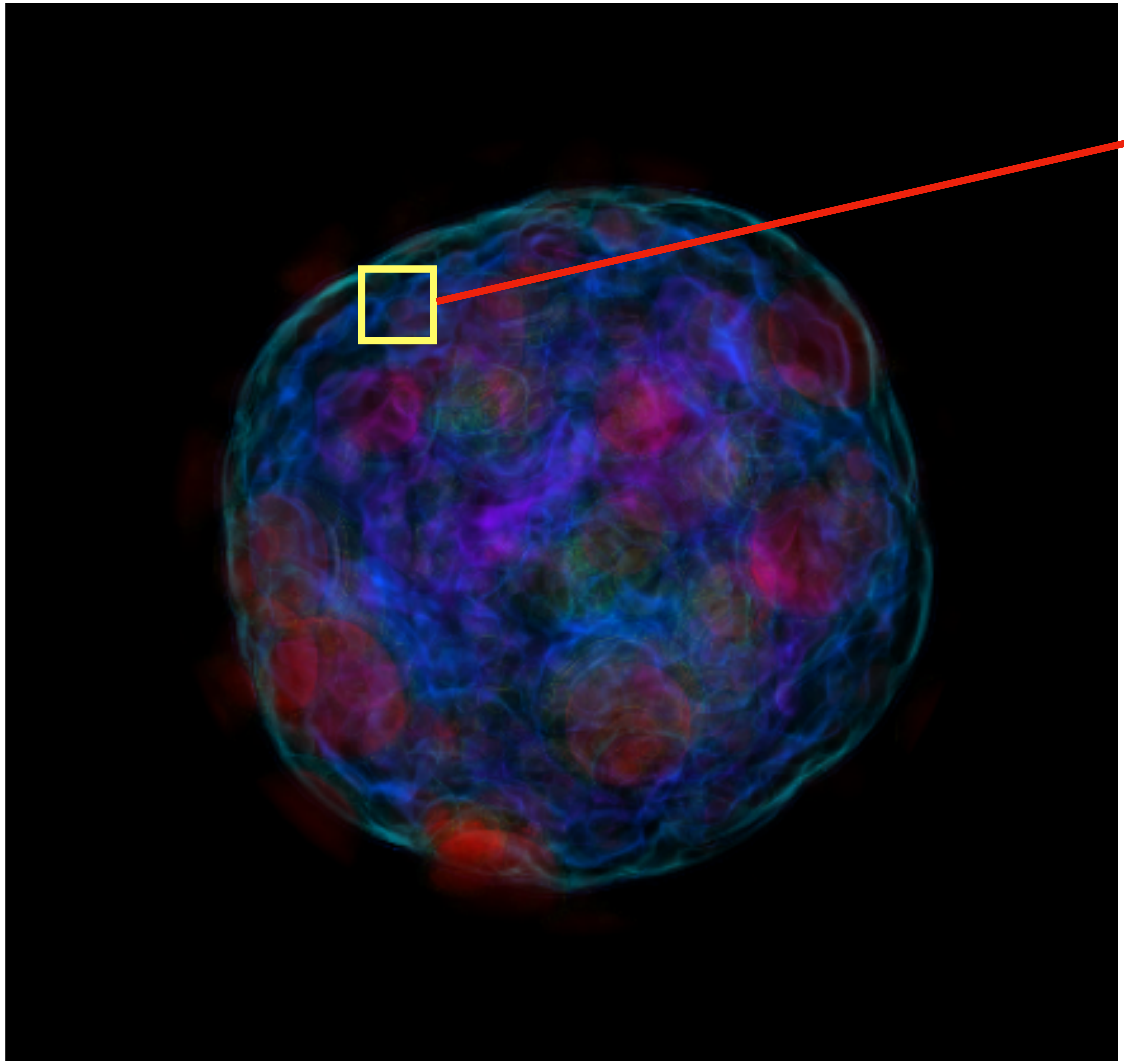


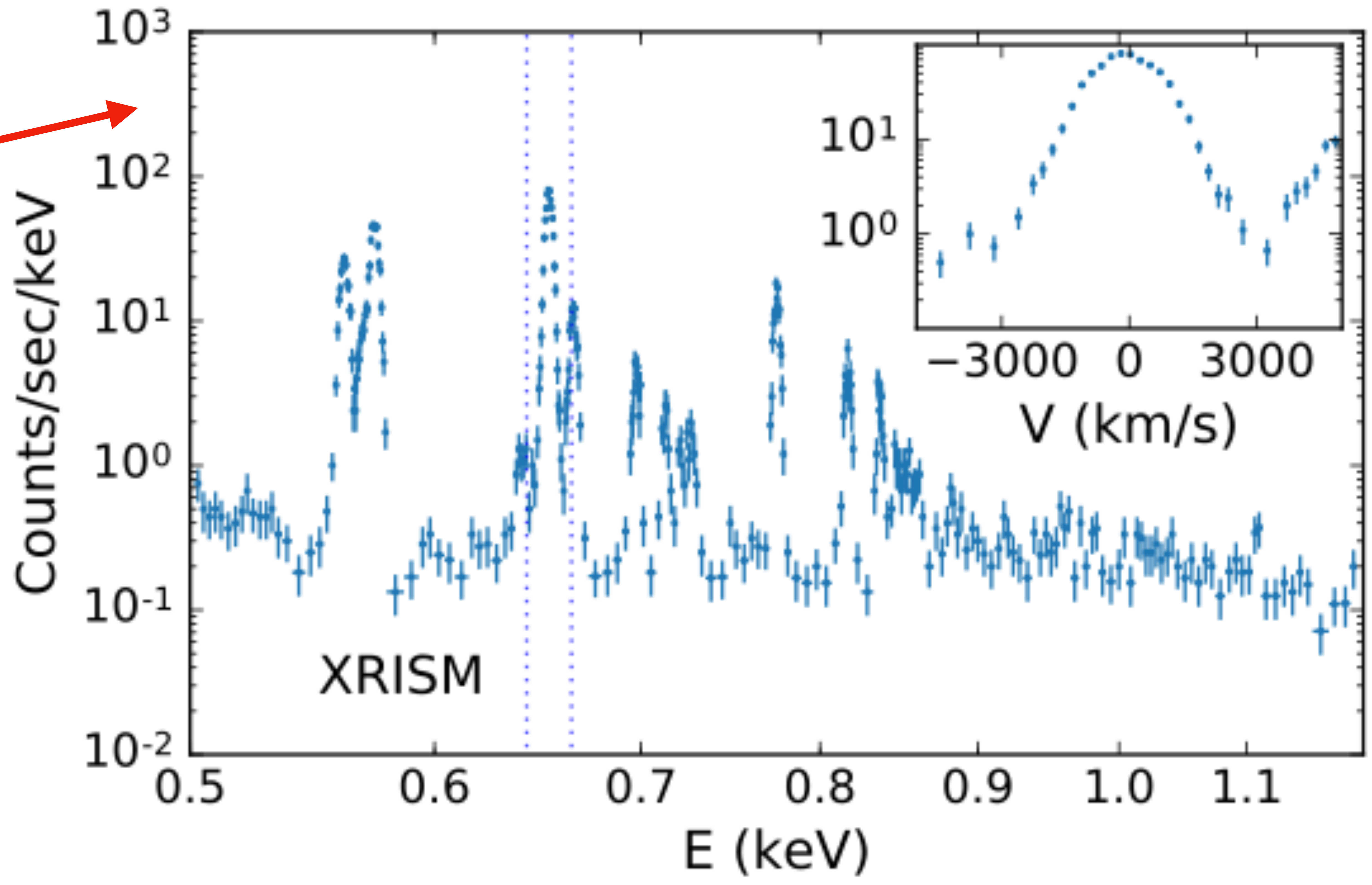
Mock XRISM Observations of a galaxy cluster from TNG-Cluster



Truong et al. (2024)

NEI Spectra from SNR





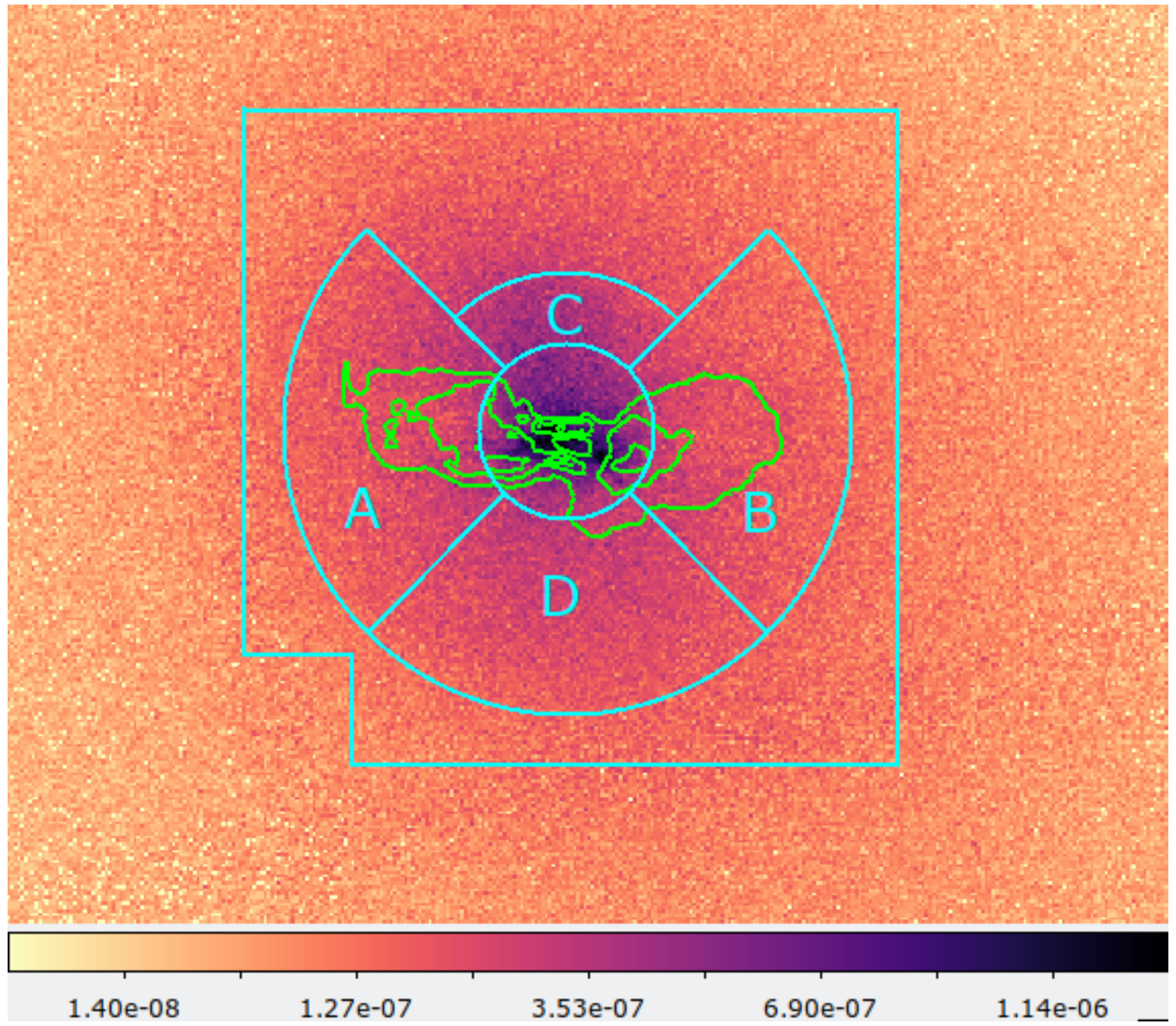
Zhang et al. (2019)

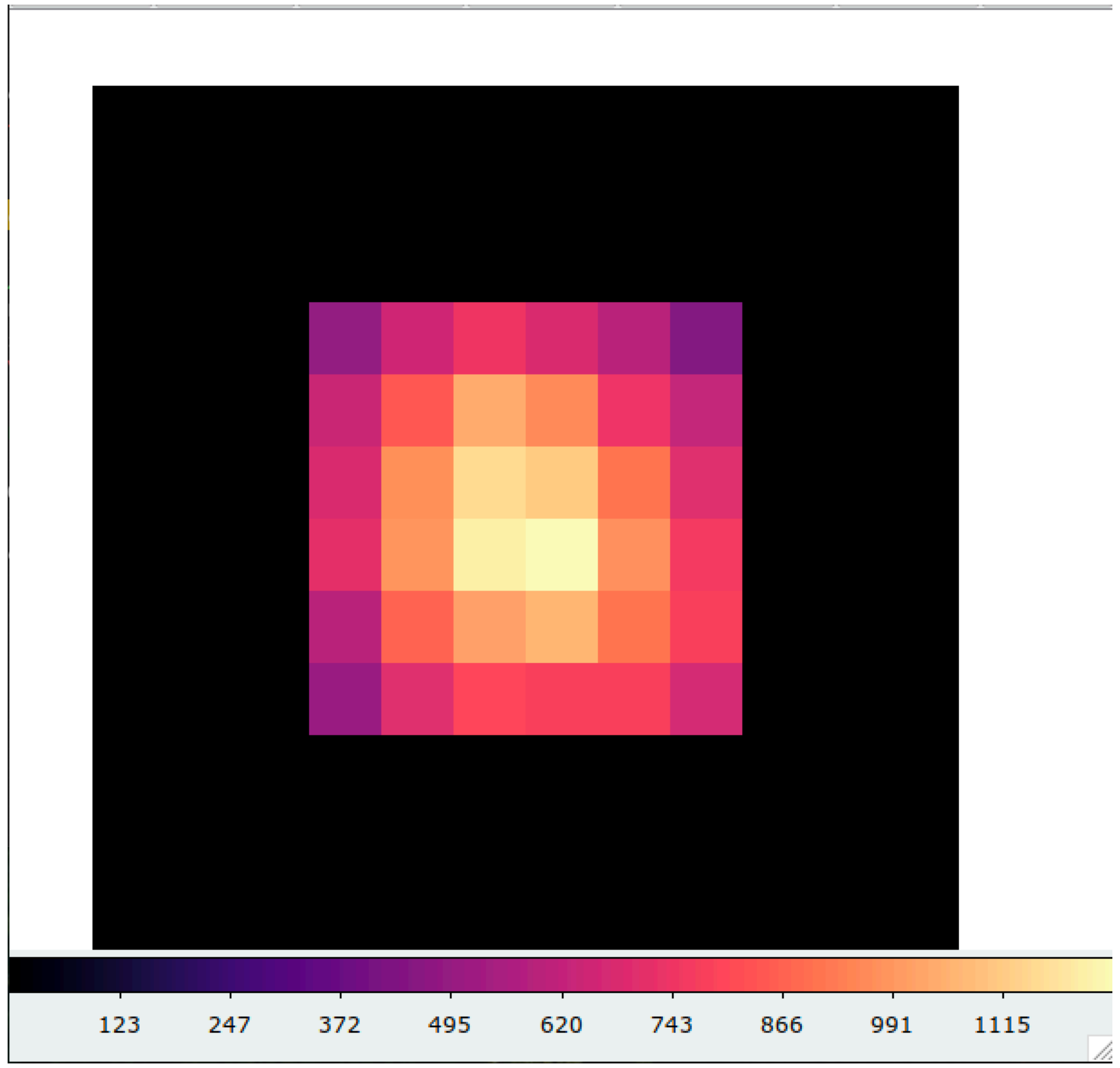
What's Coming Next?

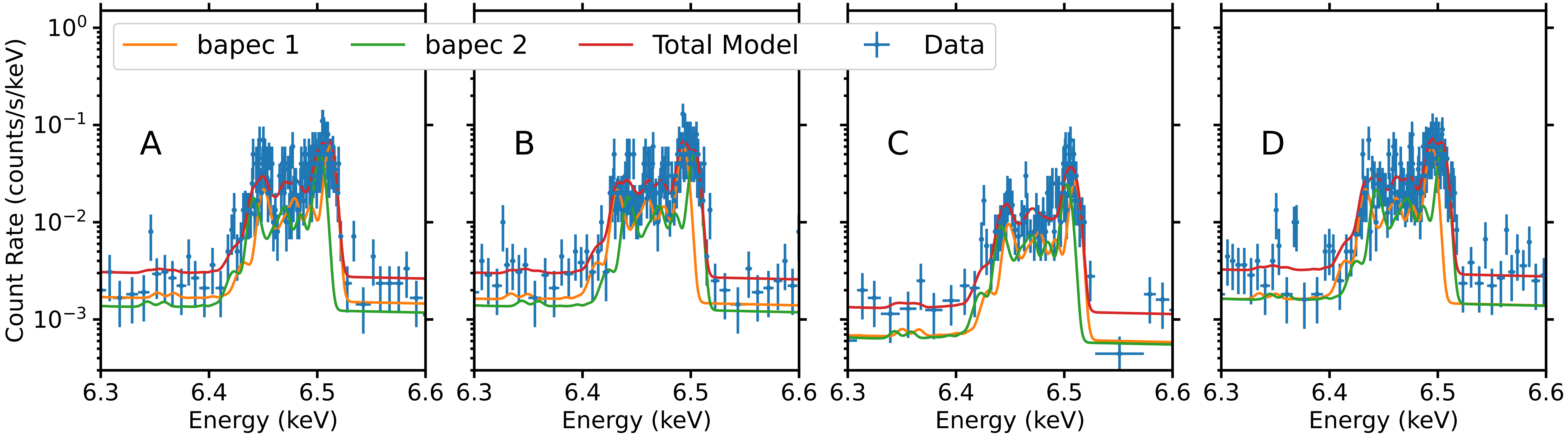
- SOXS 5.0.0 (hopefully out soon…)
  - Create SIMPUT catalogs from multiple 2D maps (flux+kT+abund+velocity)
  - Charge exchange spectra using AtomDB/ACX2
  - "Spectral cubes" from event files, e.g. RA/Dec/Energy cubes
- pyXSIM 5.0.0 (hopefully out soon…)
  - Charge exchange spectra using AtomDB/ACX2 (from 3D sources)
  - Simple modeling of "internal" absorption from neutral gas

Use it in Proposals!

- Used *Chandra* data to create maps for *XRISM* observation
- Created custom velocity map to make predictions for galaxy cluster







Things I Would Love to Add But Need Someone to Push Me to Do It (or Better Yet, Help)

- XSTAR models
- More SPEX models
- Physically-motivated AGN models
- Breaking optically thin assumption wherever feasible
- Time dependence in models / light curves
- X-ray binary simulations from cosmological simulations