

From Simulations to Observations: the Necessity of End-to-End Simulations for Linking Science Objectives to Mission Requirements

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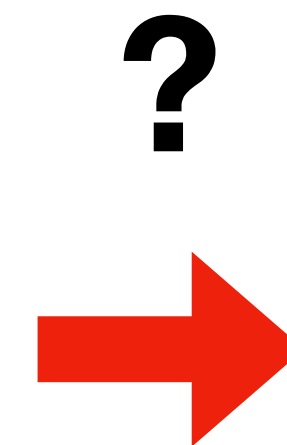
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ASTROPHYSICS

HARVARD & SMITHSONIAN

Tracing Science to Capabilities

Goal	Objective	Measurement Requirements	
		Physical Parameter	Observable
How does AGN feedback work in galaxy clusters?	Is dissipation of turbulence sufficient to balance cooling?	Velocity dispersion measurements in inner 60 kpc	Width of emission lines
	What is the contribution from shock heating?	Ion temperature jumps in the inner 60 kpc	Emission line ratios

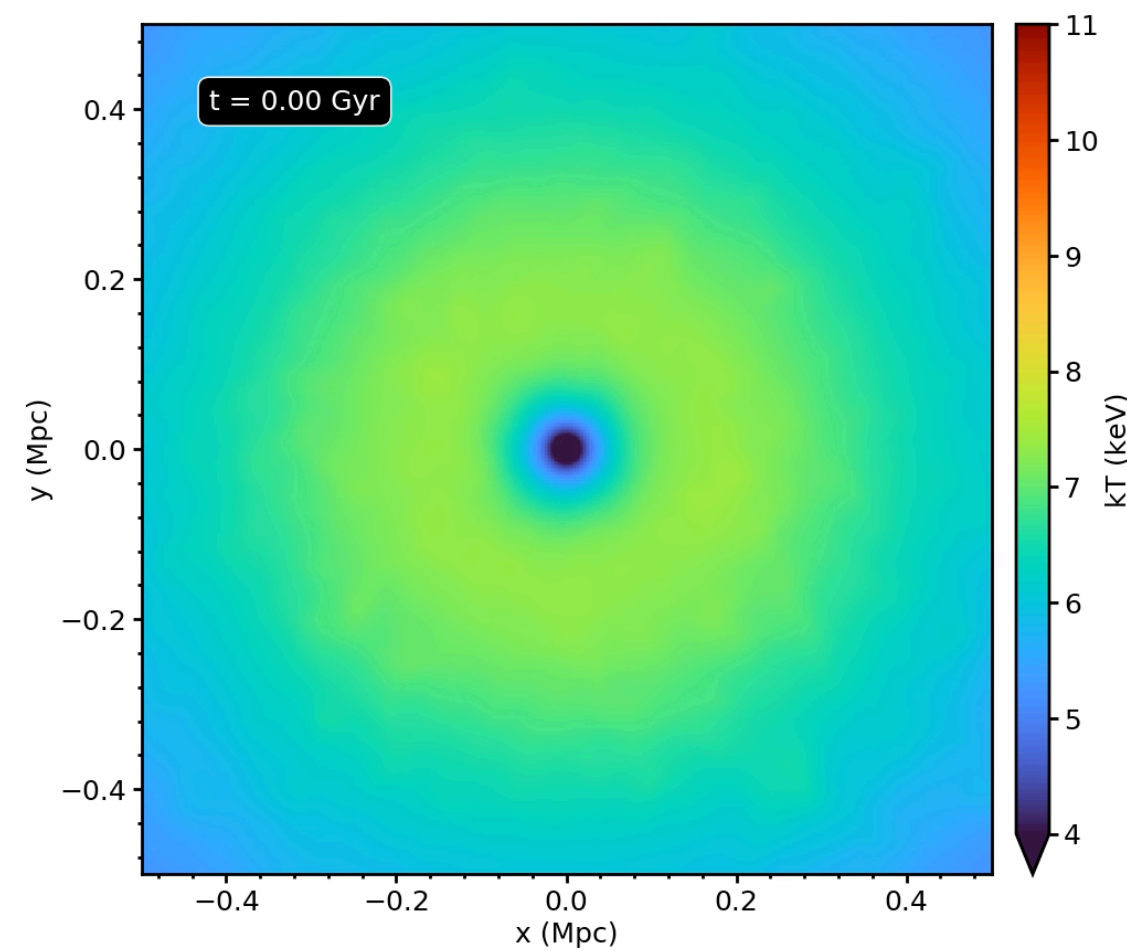


Telescope/Instrument Requirements			
Energy Resolution	Effective Area @ 1 keV	FoV	PSF FWHM
2 eV	1000 cm ²	20'	12"
3 eV	1000 cm ²	20'	10"

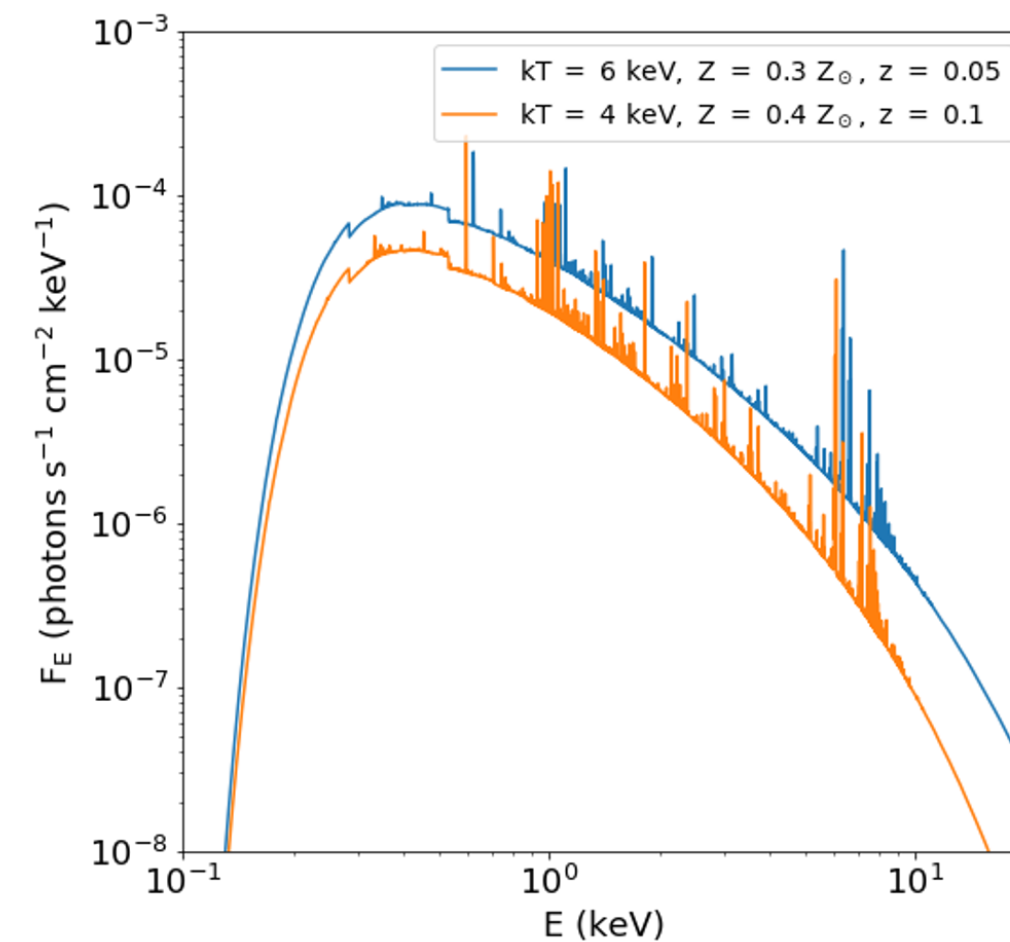
Minding the Gap

- How does the gap between the science and the required instrument capabilities get bridged?
- Often, we take the numbers in the rightmost science column, put them into a simple model, convolve them with some simple model of the instrument—and often this is enough (if you know X-rays, an example is doing an XSPEC simulation)
- But sometimes this is not enough—it often ignores, marginalizes over, or over-simplifies several things:
 - Projection effects
 - Multiphase or multistate sources
 - Backgrounds and foregrounds
 - Various instrumental effects

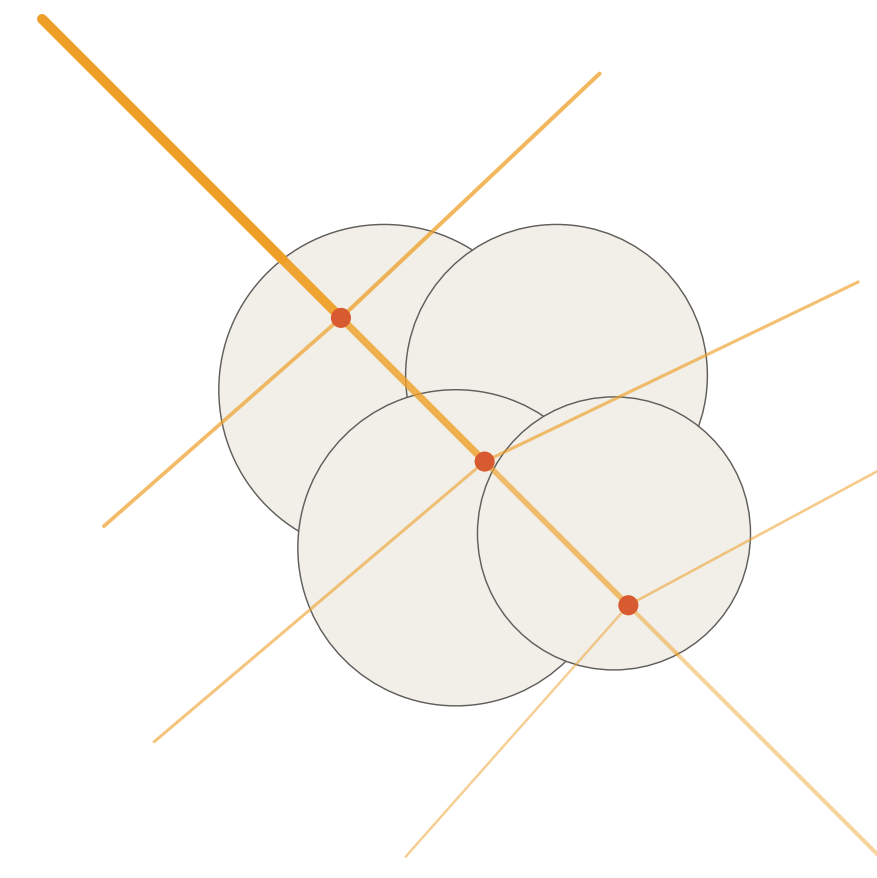
The "End-to-End" Perspective



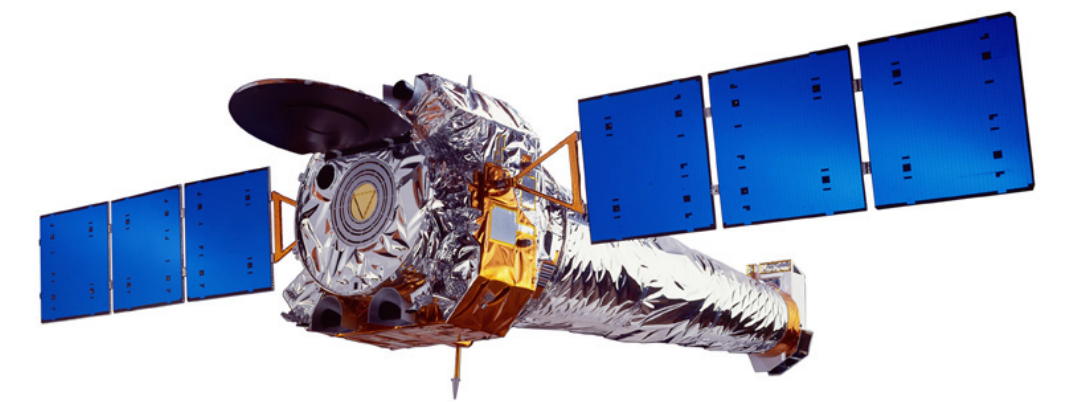
3D simulations: e.g. hydrodynamics, N-body—spatial, material, and kinematic properties of the source



Emission and absorption models: how do we get from physical properties of the source to photons?



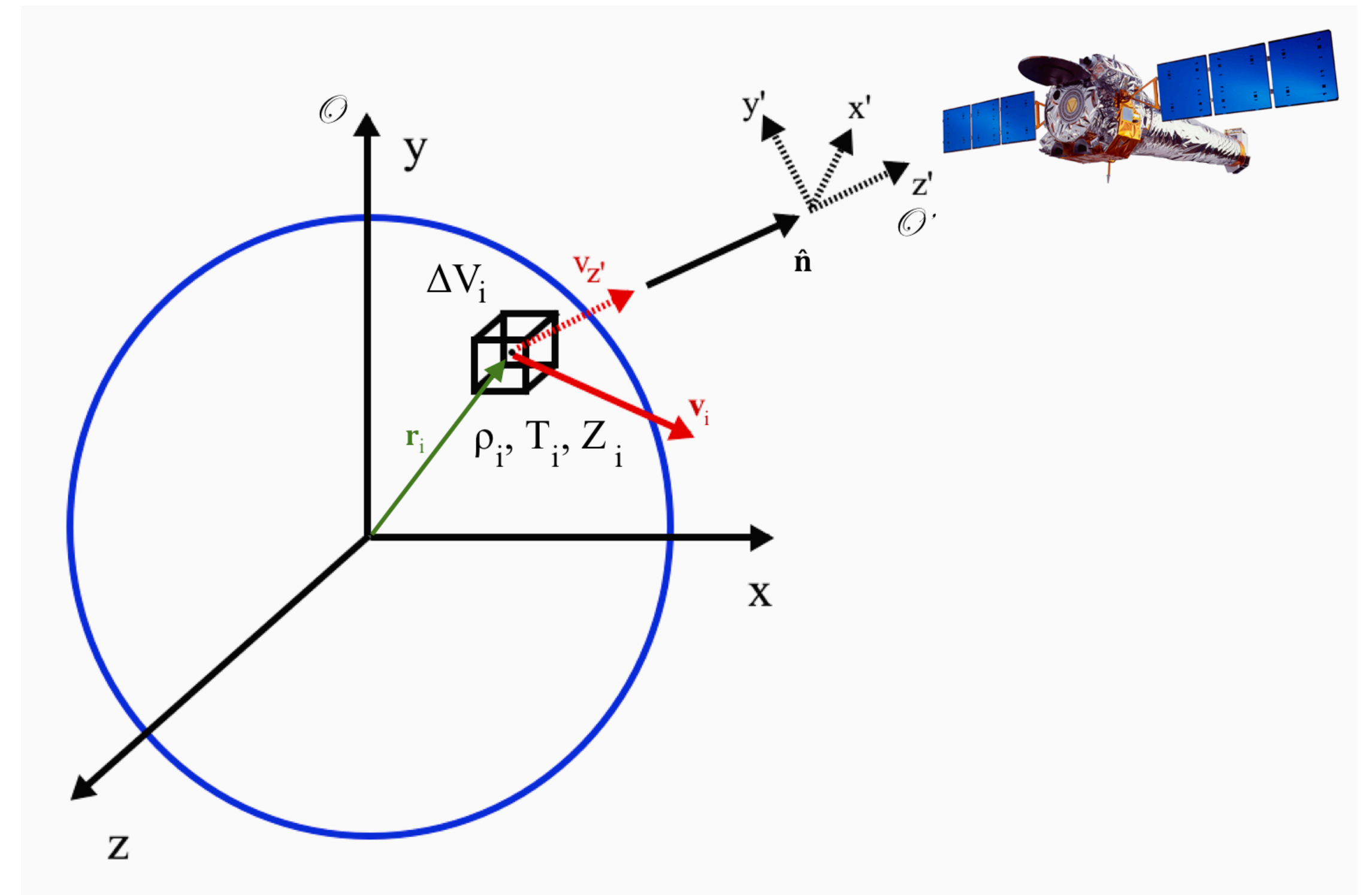
Radiative transfer: how do photons get from the source to the telescope?



The instrument: how does the instrument process the data that the observer sees?

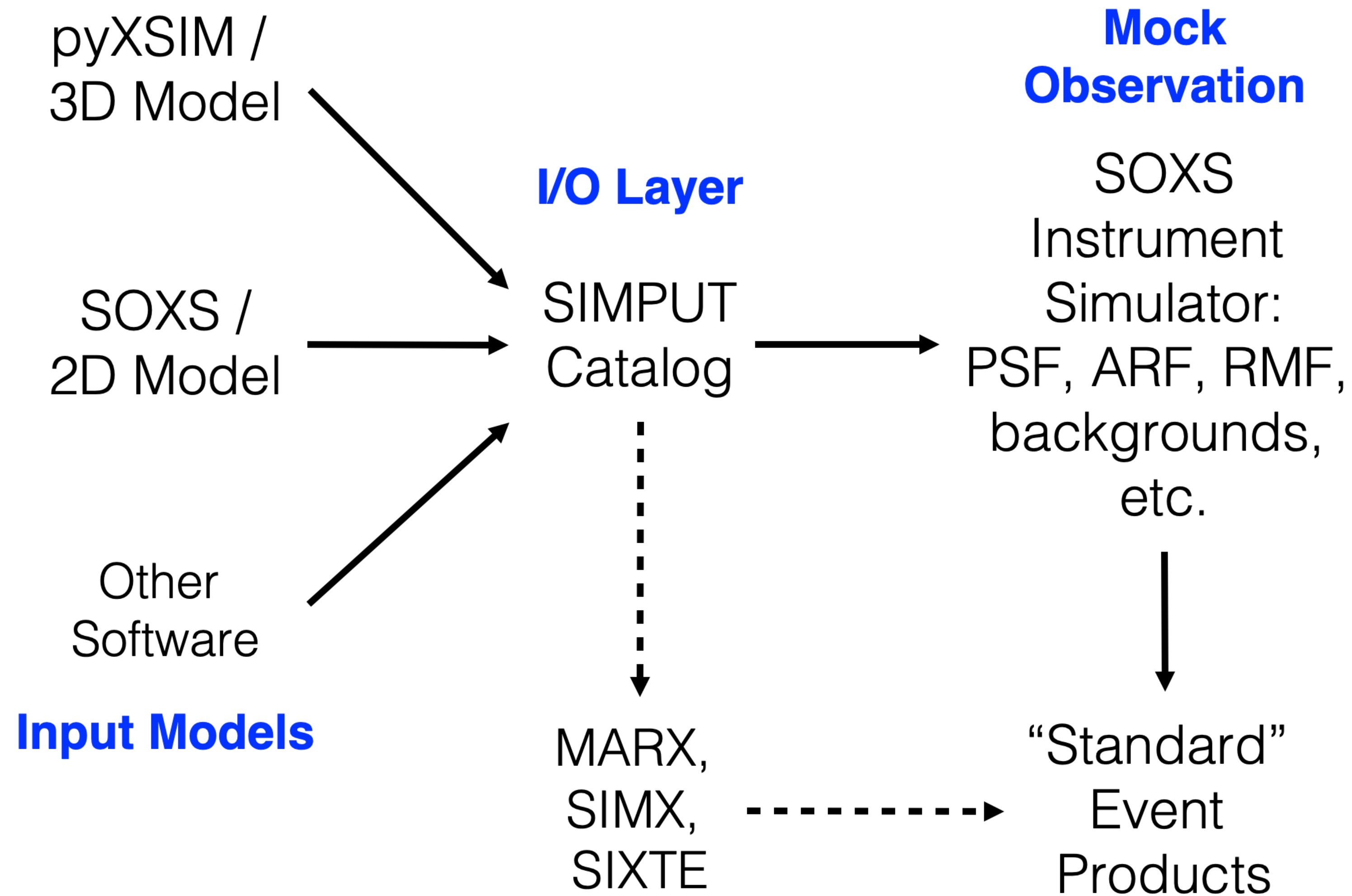
pyXSIM

- Many different simulation dataset types can be used as inputs
- Take material properties of source from 3D model, construct X-ray emission field, generate simulated X-ray photons—save to disk
- Project photons to sky, Doppler and cosmologically shift their energies, apply galactic foreground absorption
- Save the pre-detected "events" to disk



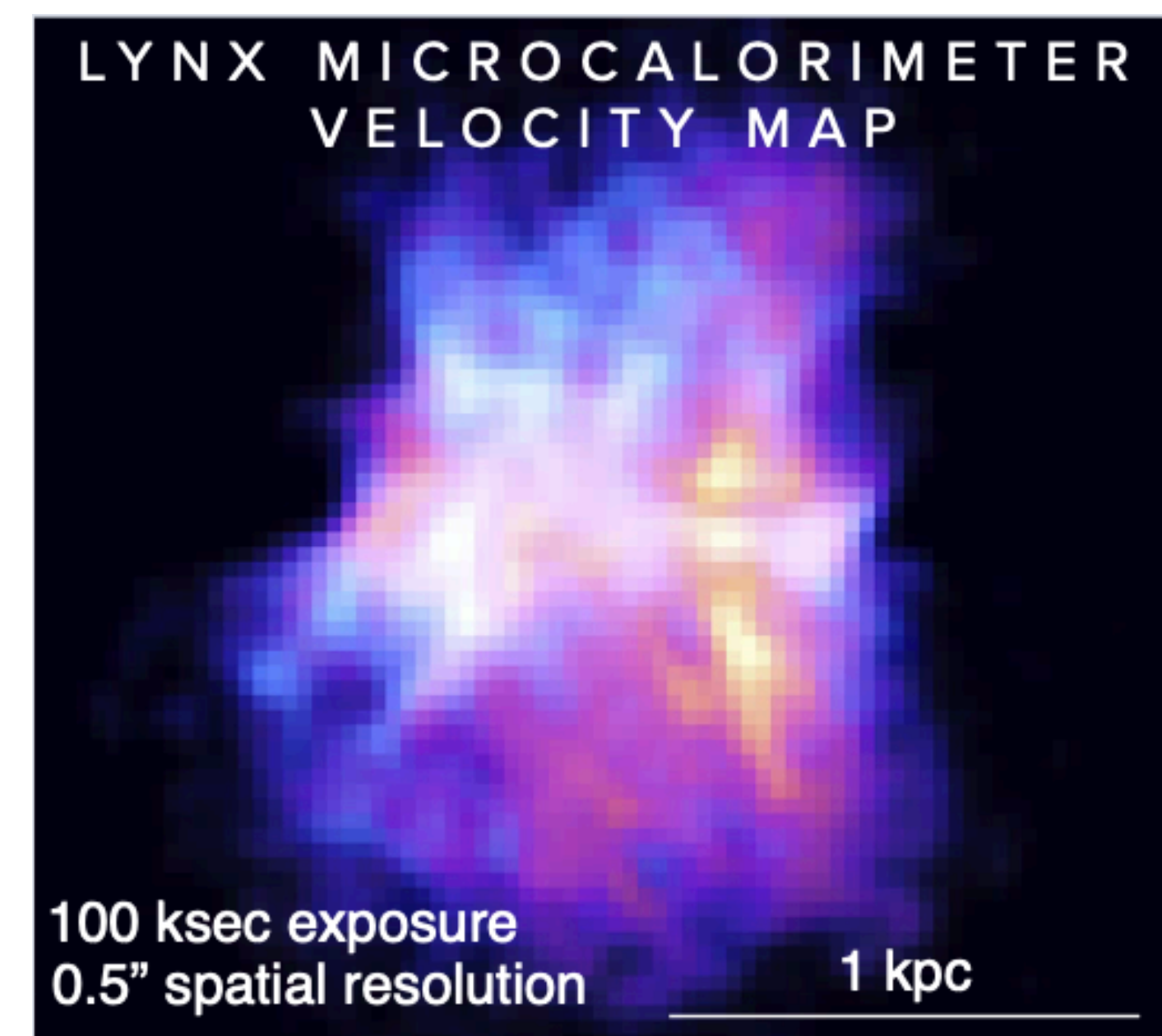
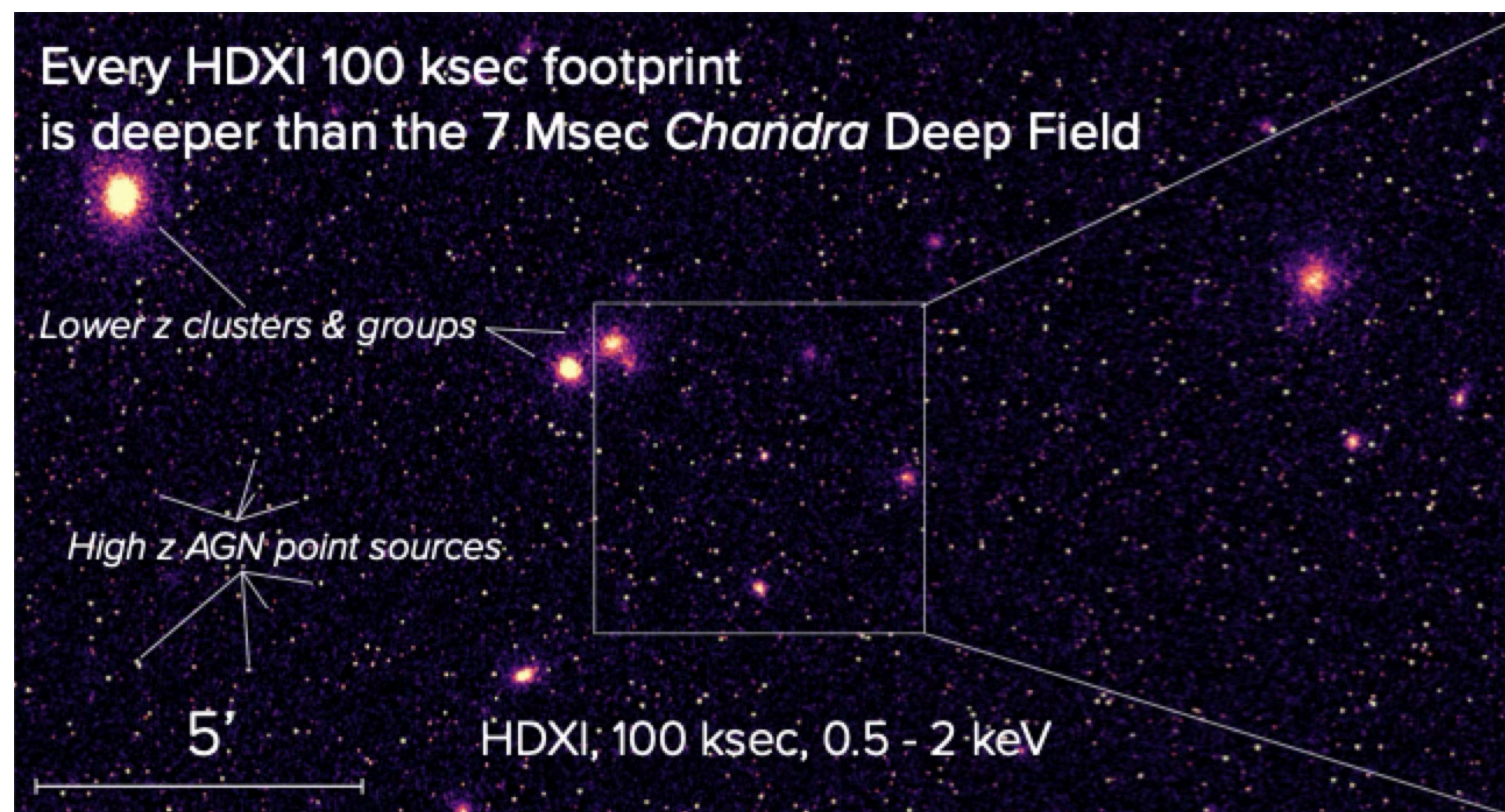
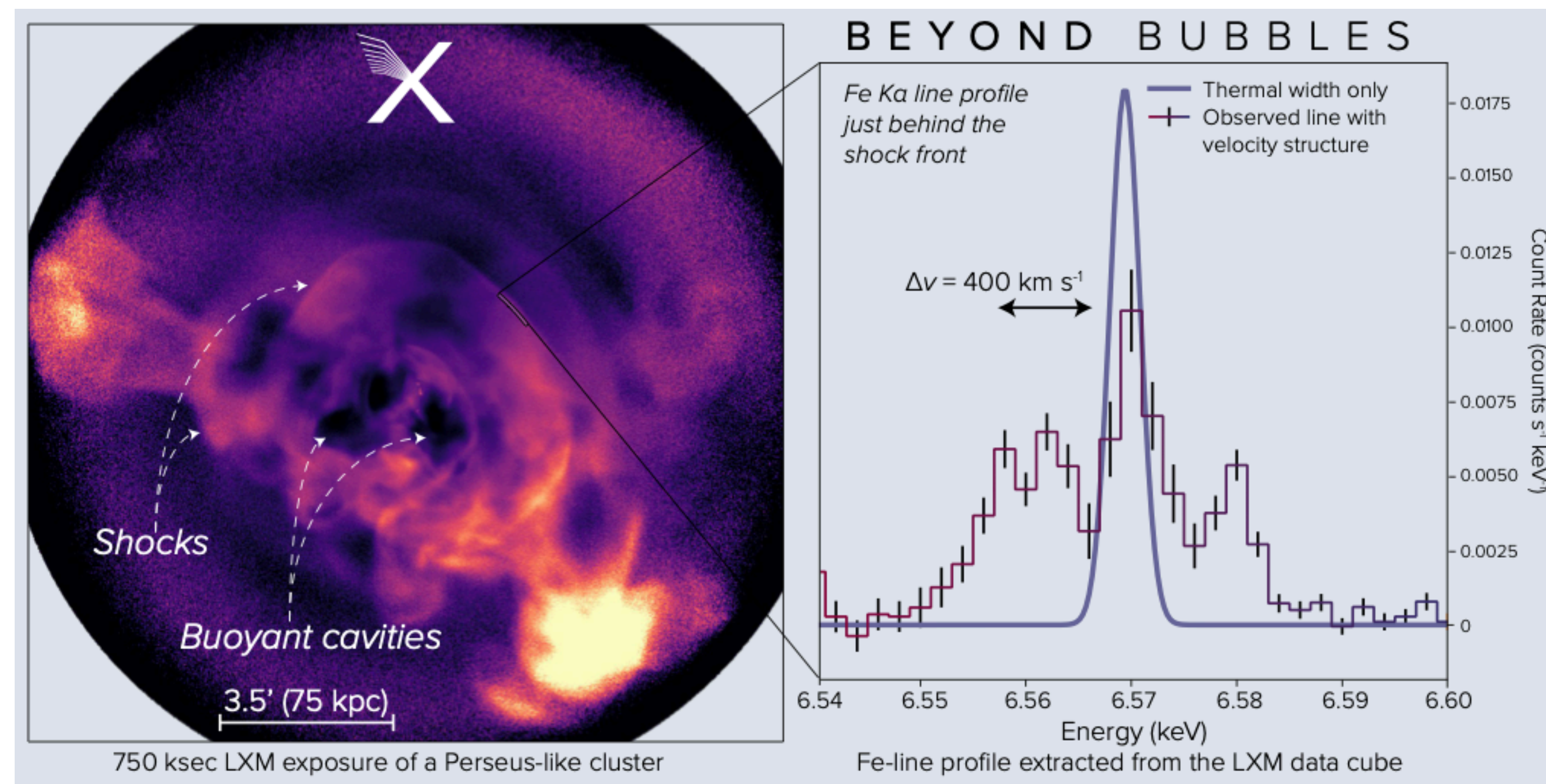
<https://hea-www.cfa.harvard.edu/~jzuhone/pyxsim/>

SOXS Overview



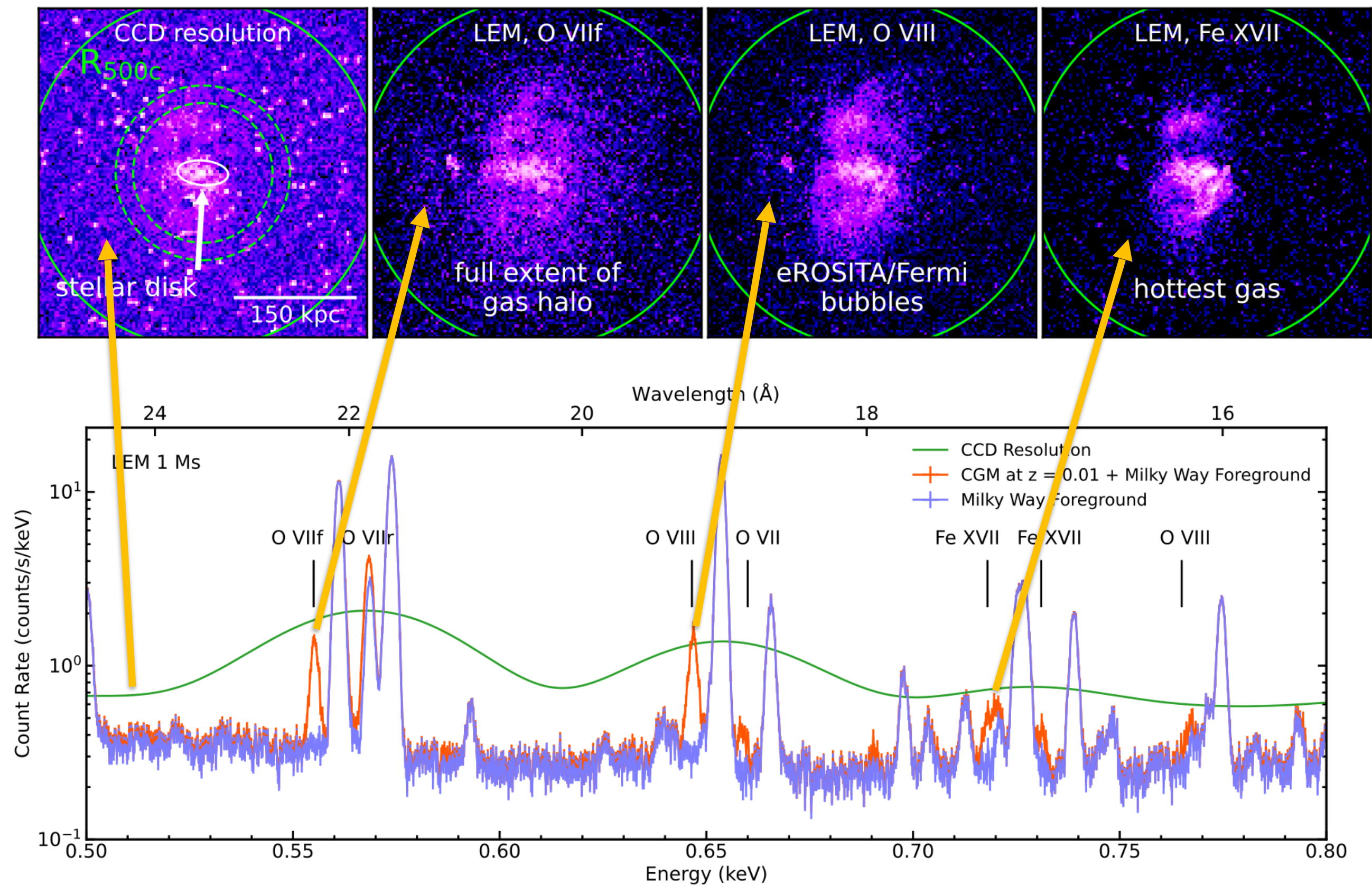
<https://hea-www.cfa.harvard.edu/soxs/>

Lynx

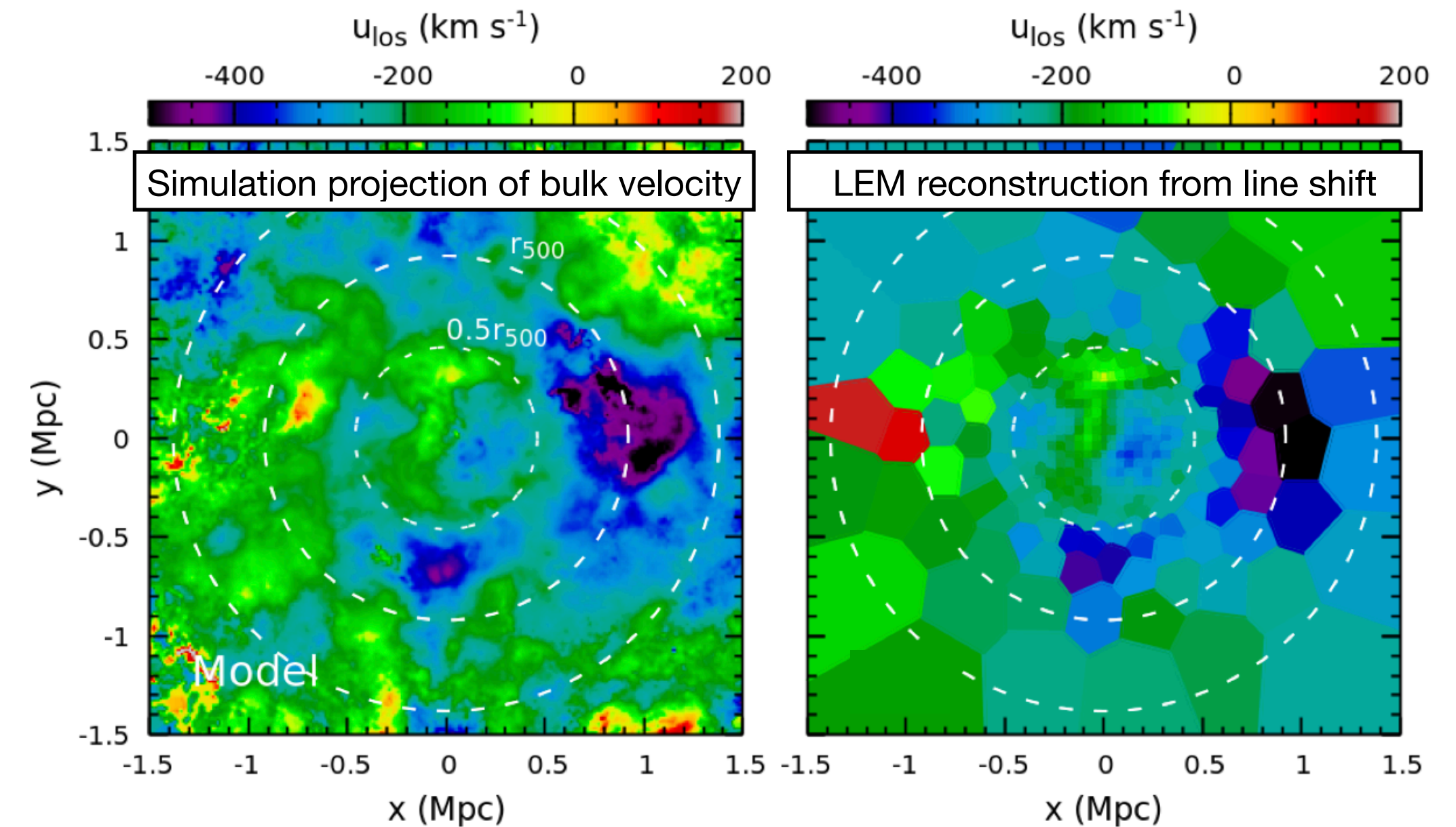


LEM and ExCEED

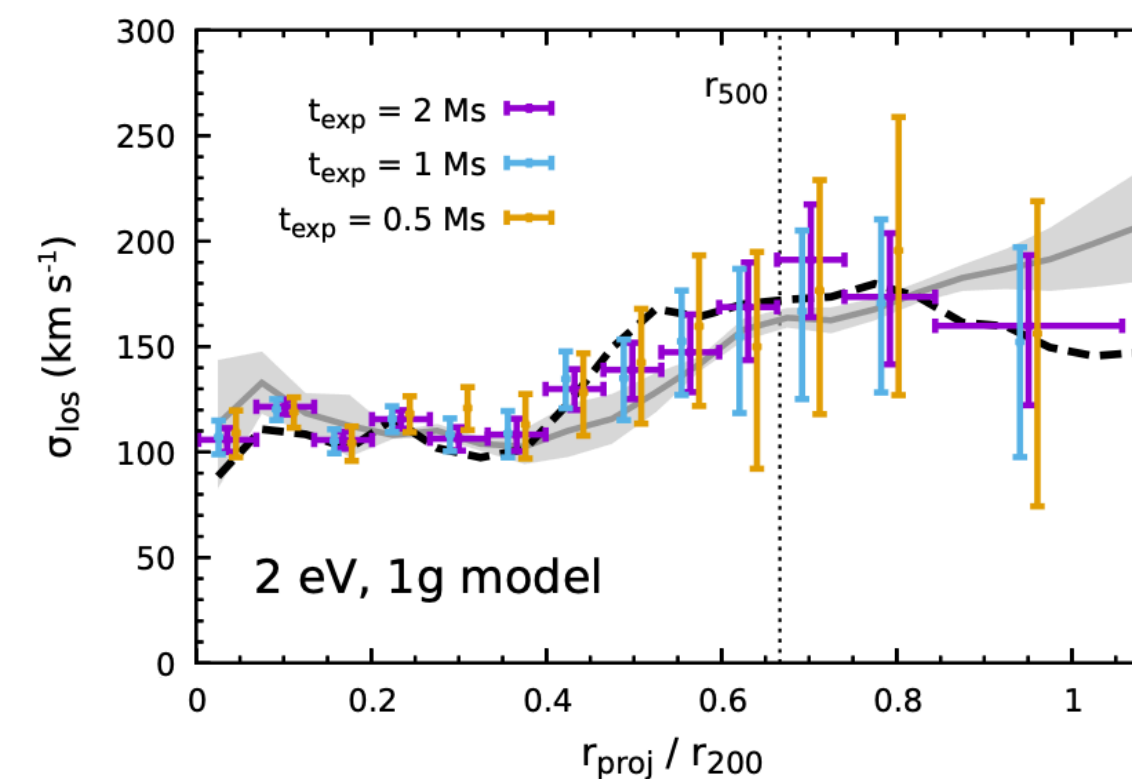
Circumgalactic Medium



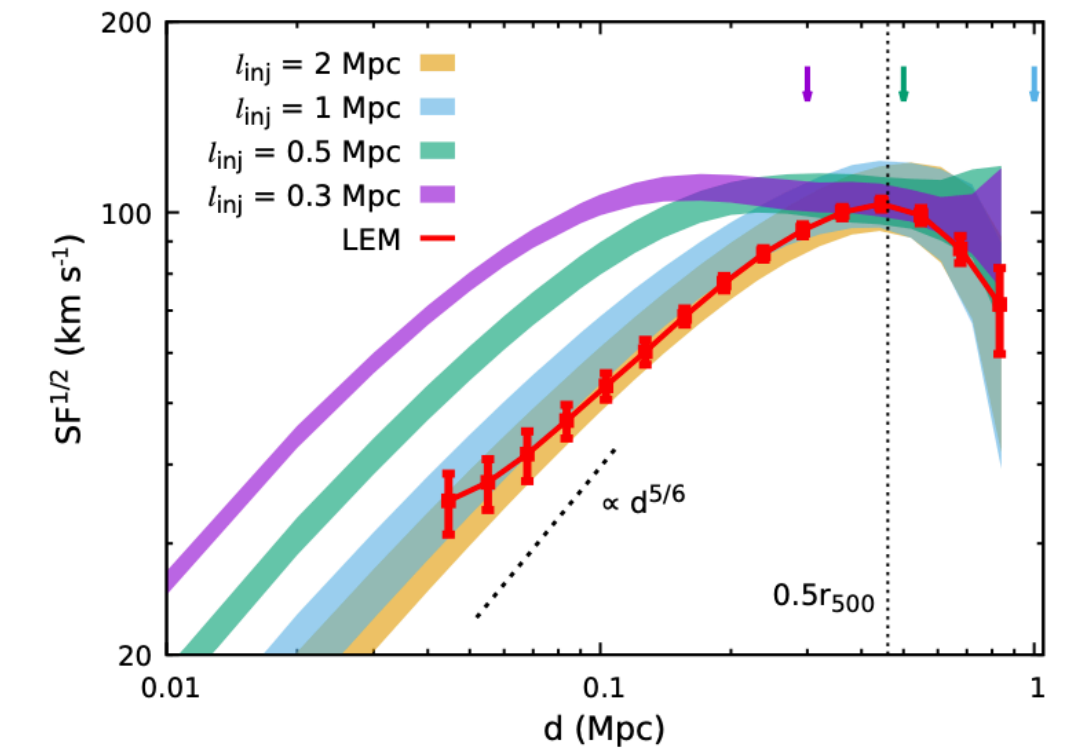
Galaxy Cluster Outskirts



Radial profile of velocity dispersion



Bulk velocity structure function



Zhang et al. (2024)

Design Choices and Tradeoffs

- Some simplifications will always need to be made. Such as:
 - Lookup tables for complex emission spectra models, instead of reconstructing the spectrum for every cell in the simulation (though this could lead to interpolation errors)
 - Using image-based models for the PSF instead of a raytrace
 - Radiative transfer is typically greatly simplified in our models, since most of the sources are optically thin or we can treat absorbers as "screens"

Demo

[2]:

SOXS Image Cube Simulations

Mission and Instrument Options

Choose a mission: Lynx

Choose an instrument: LXM main array (3.0 eV)

Choose a PSF: Chandra-like on-axis

Field of View (arcmin): 5.0

Plate Scale (arcsec): 1.0

Background Options

☒ Foreground

☒ Cosmic X-ray Background

☒ Particle Background

Particle Background Scale: 1

Random seed for CXB point sources: 0

Observation Options

Choose a source: CGM

Exposure time (ks): 1000

Observe!

SOXS Output