High-Resolution X-ray Spectroscopy of Galaxy Clusters, Groups, and Massive Galaxies

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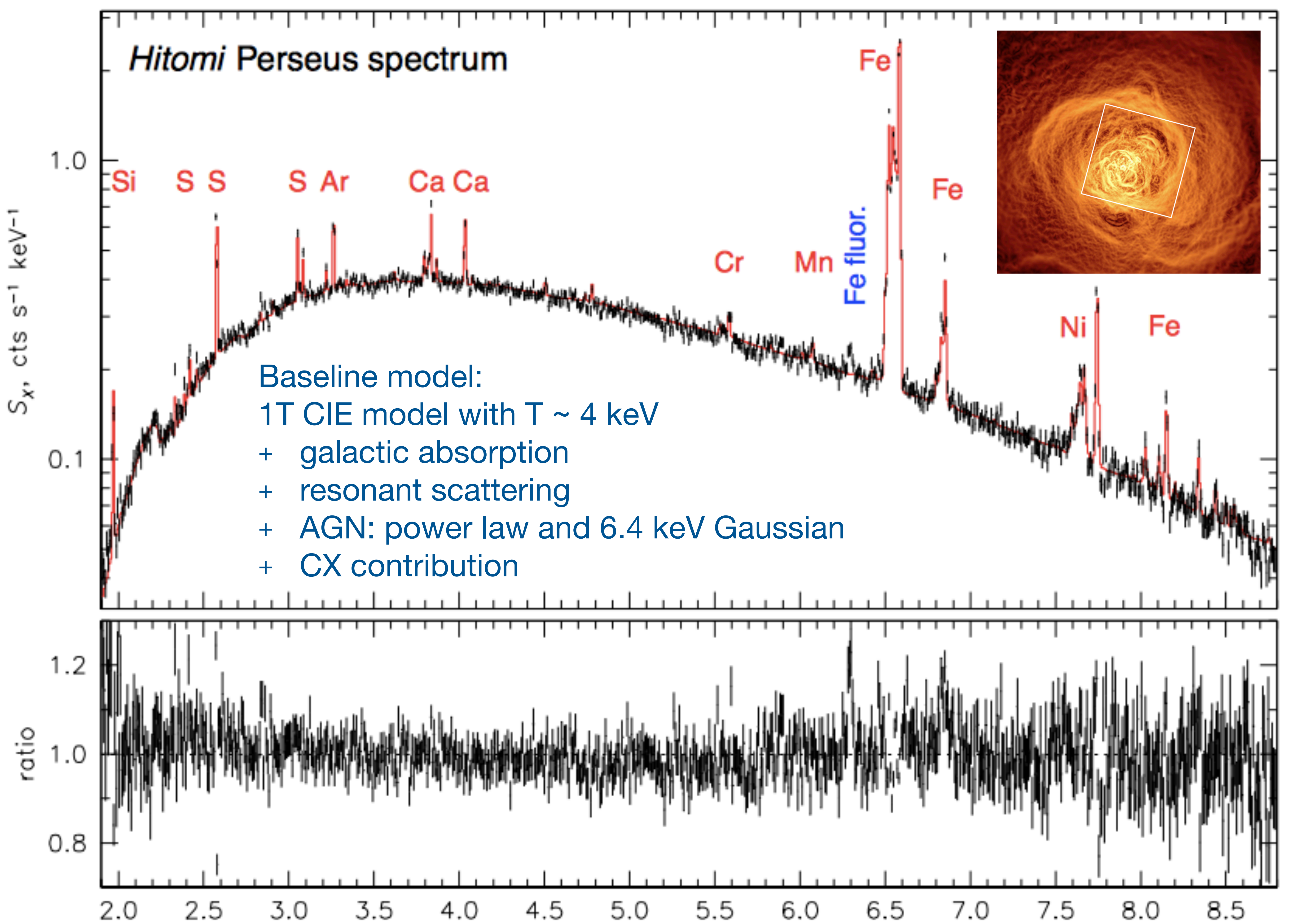
University of Chicago

High Resolution X-ray Spectroscopy · Chandra Workshop
Cambridge · MA · 2 August 2023

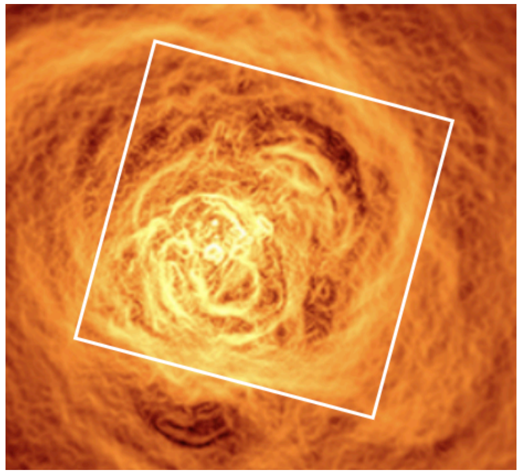
Bright Future in 23 Days

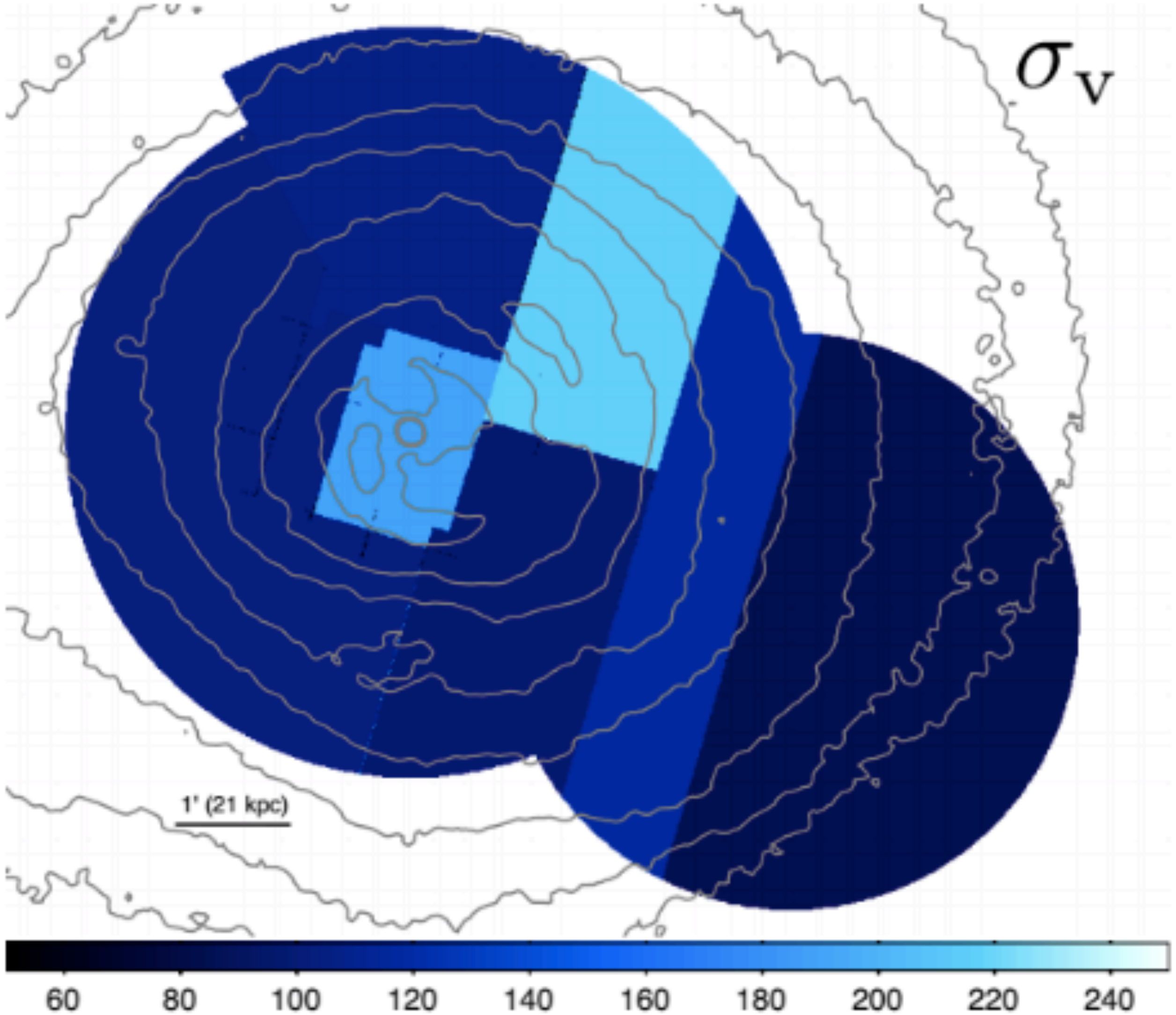
Launch: August 26th at 9:34 am (Japan)

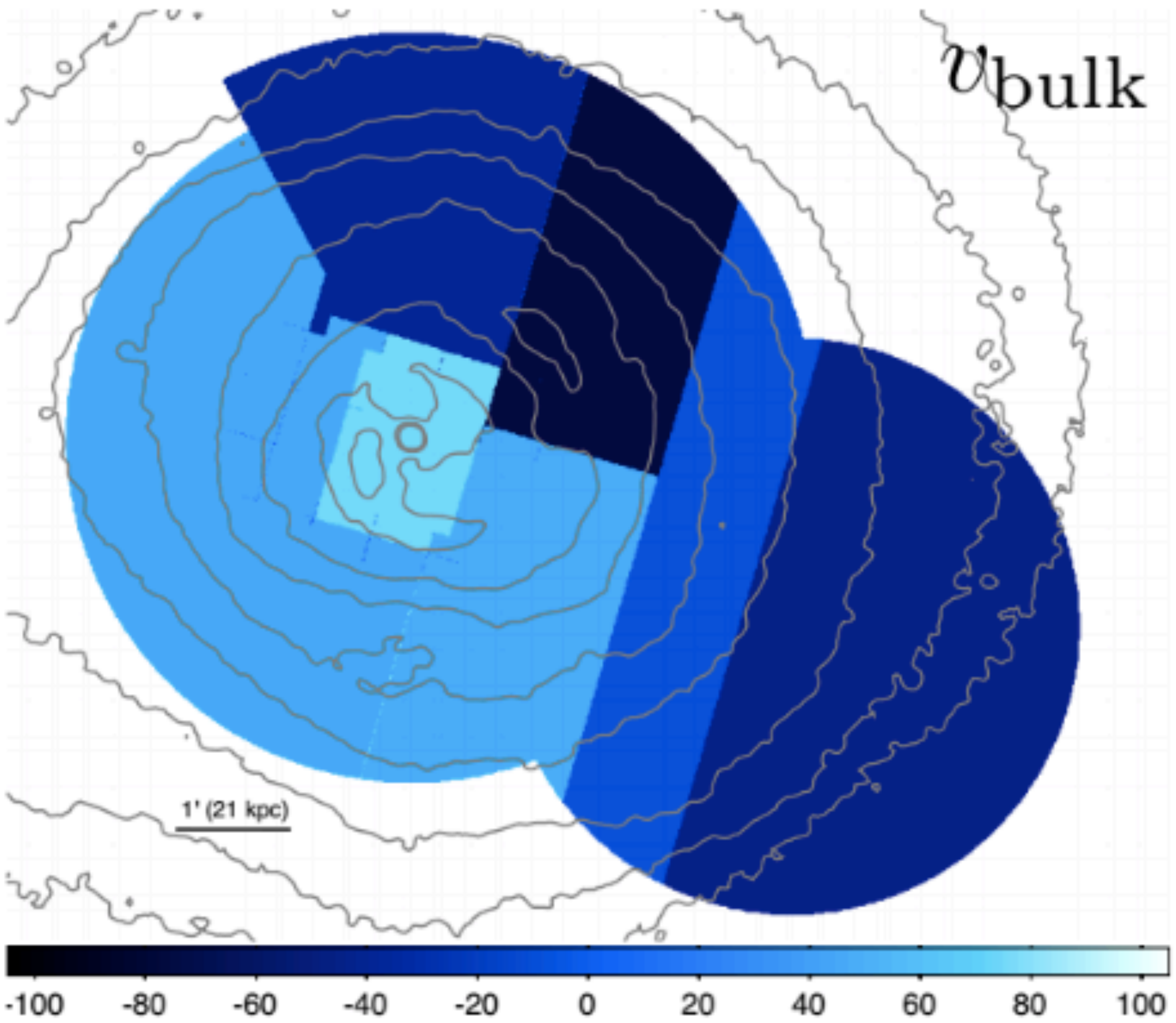


Hitomi collaboration (atomic paper) 2017

Hitomi Results on Perseus: Velocities





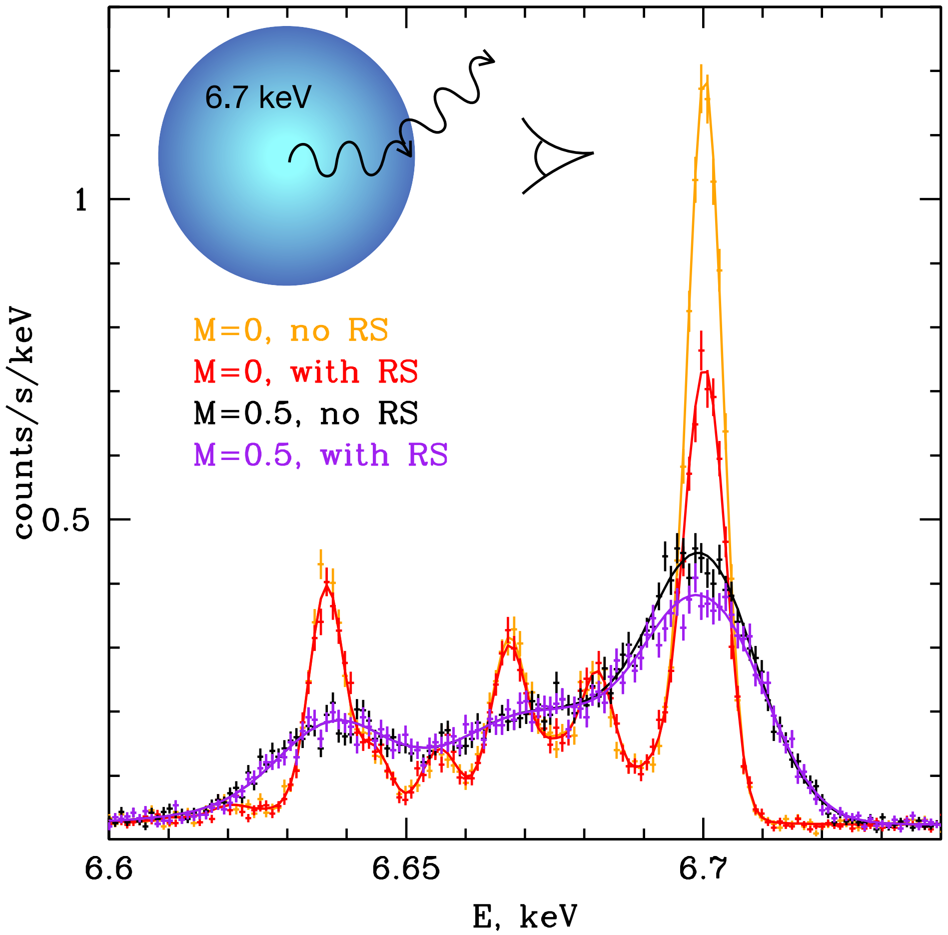


- no deviations from Gaussianity
- injection scale < a few 100 kpc

- M ~ 0.3 - 0.45
- P_{turb}/P_{therm} = 5-11 %

Hitomi collaboration (gas dynamics) 17

Hitomi Results on Perseus: Resonant Scattering



Gilfanov et al. 87, .., Zhuravleva et al. 13

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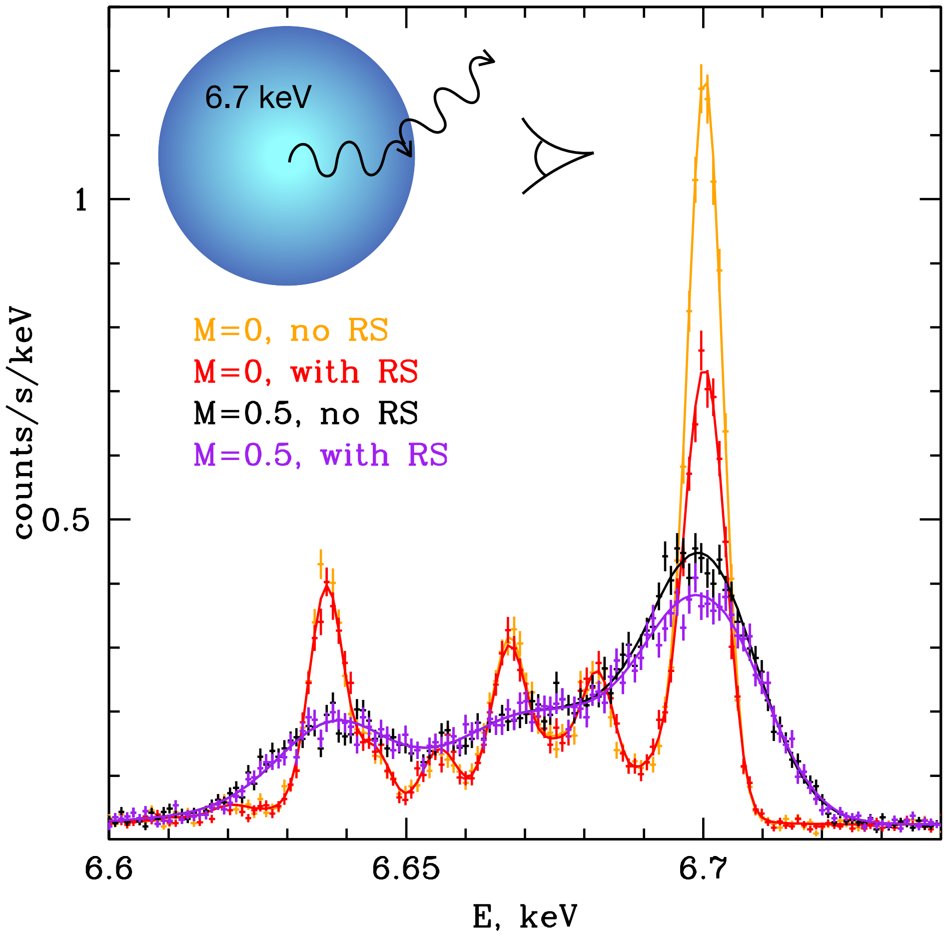

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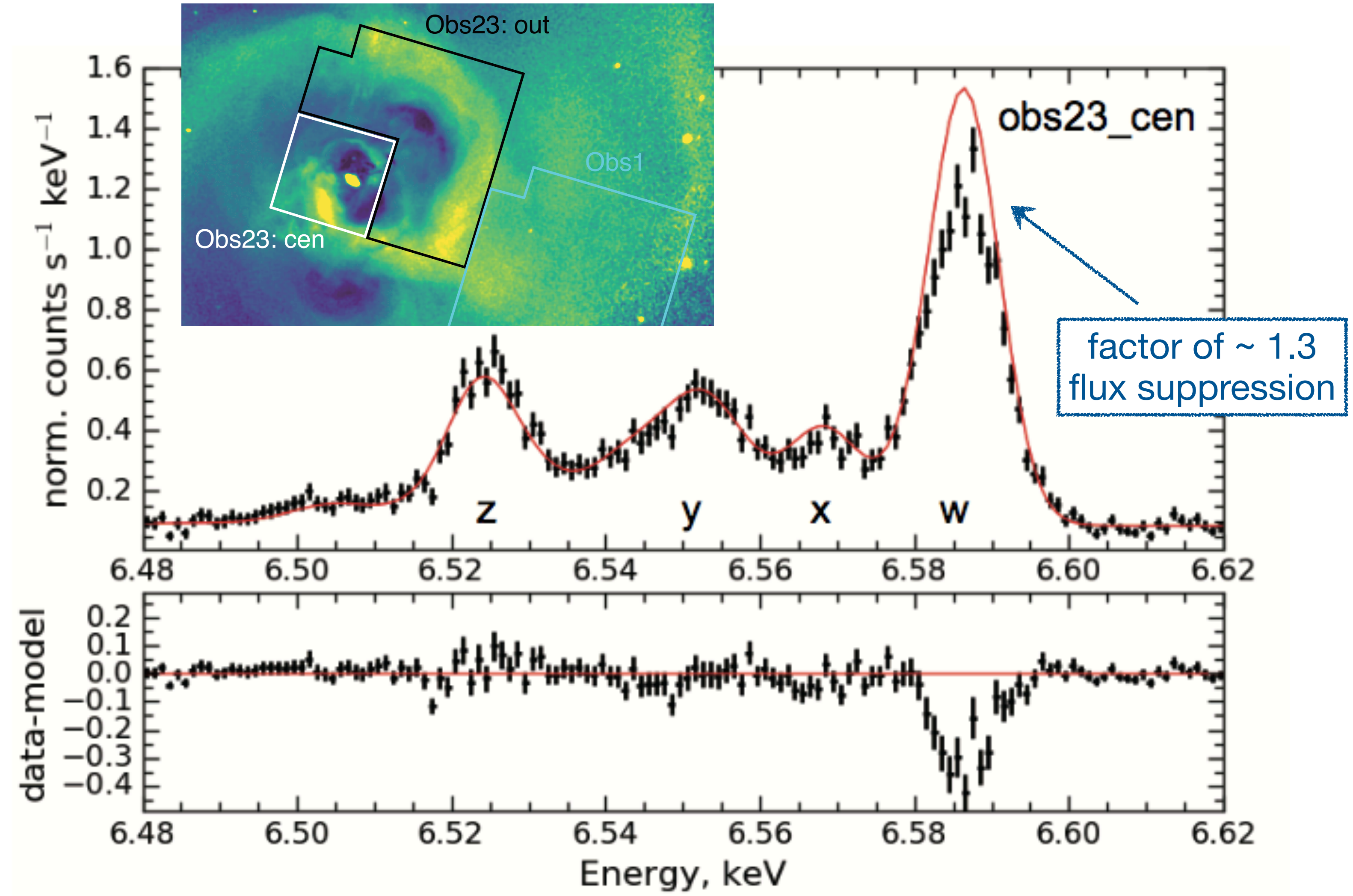

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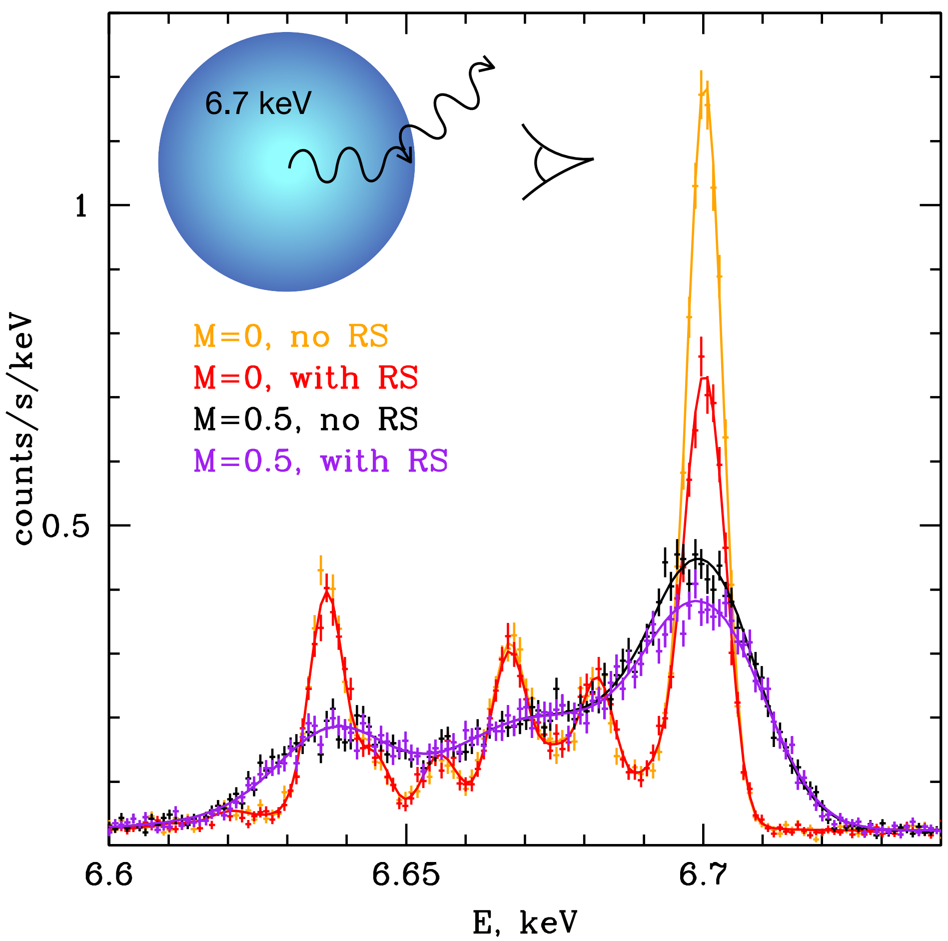
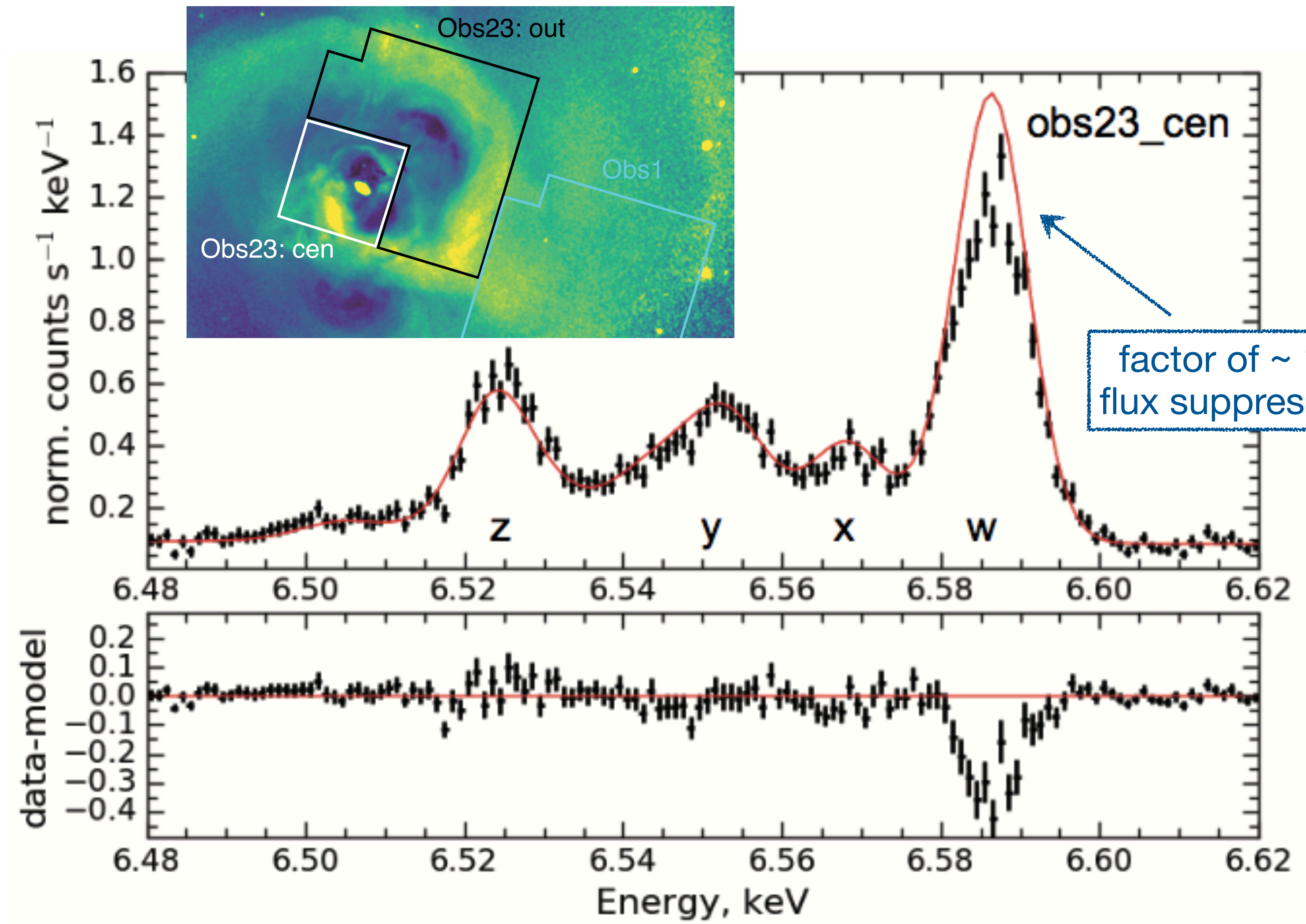
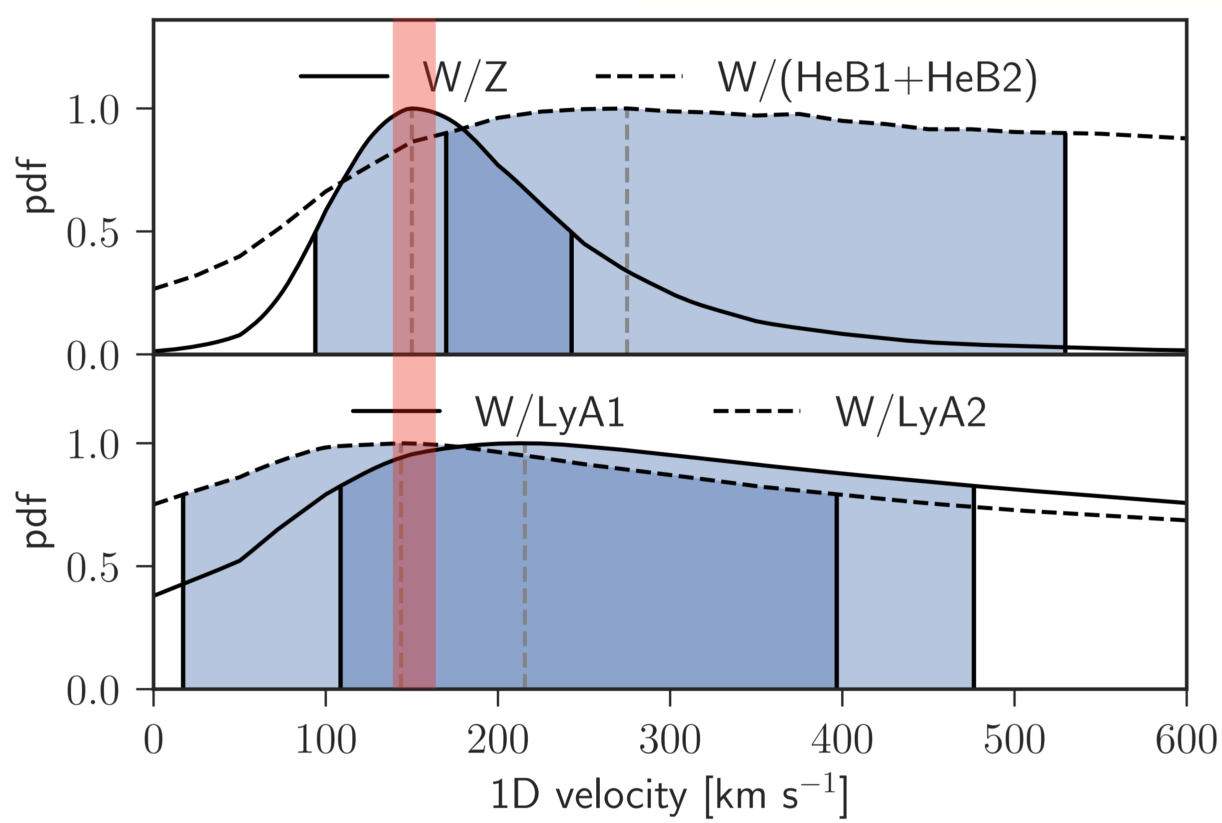


Gilfanov et al. 87, .., Zhuravleva et al. 13



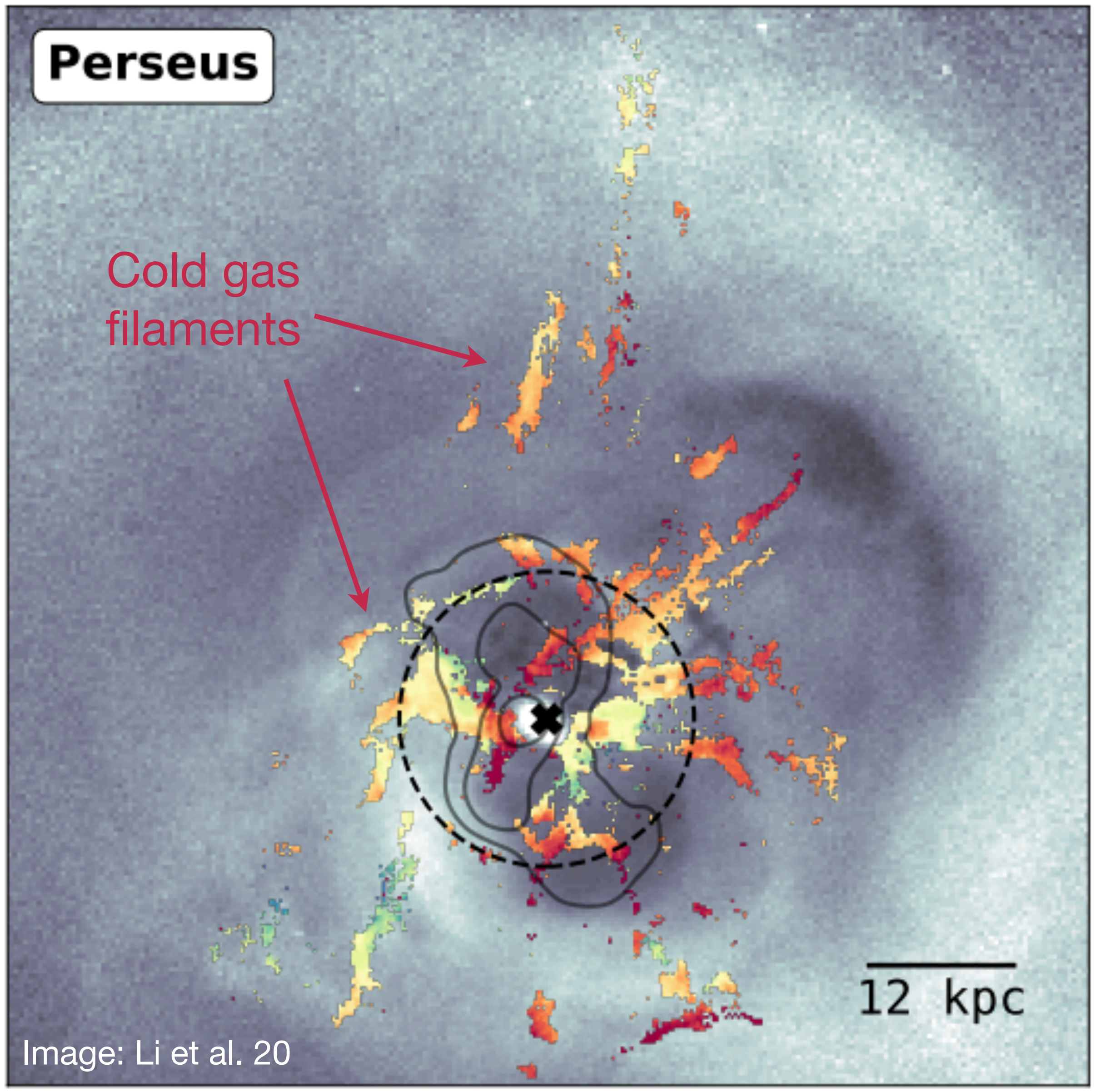


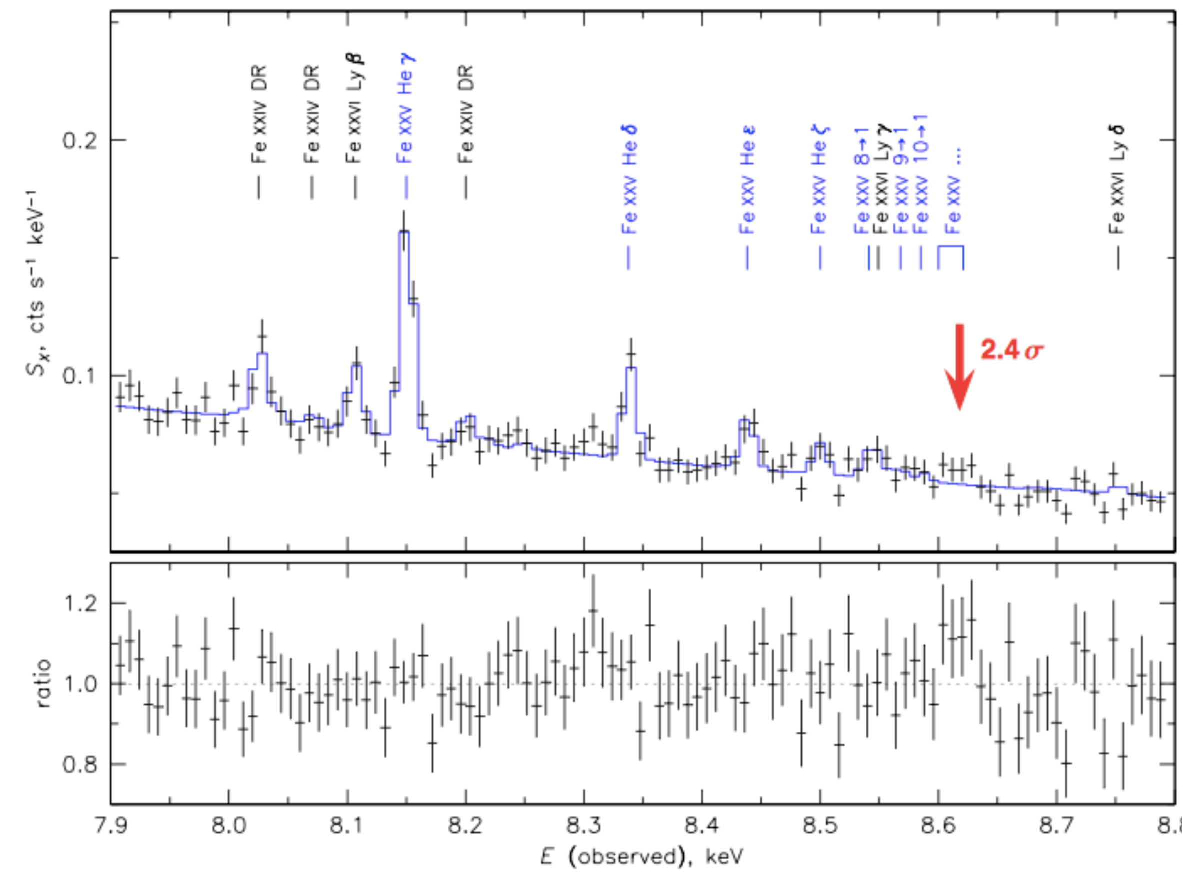
RS W/Z: 150^{+80}_{-56} km/s

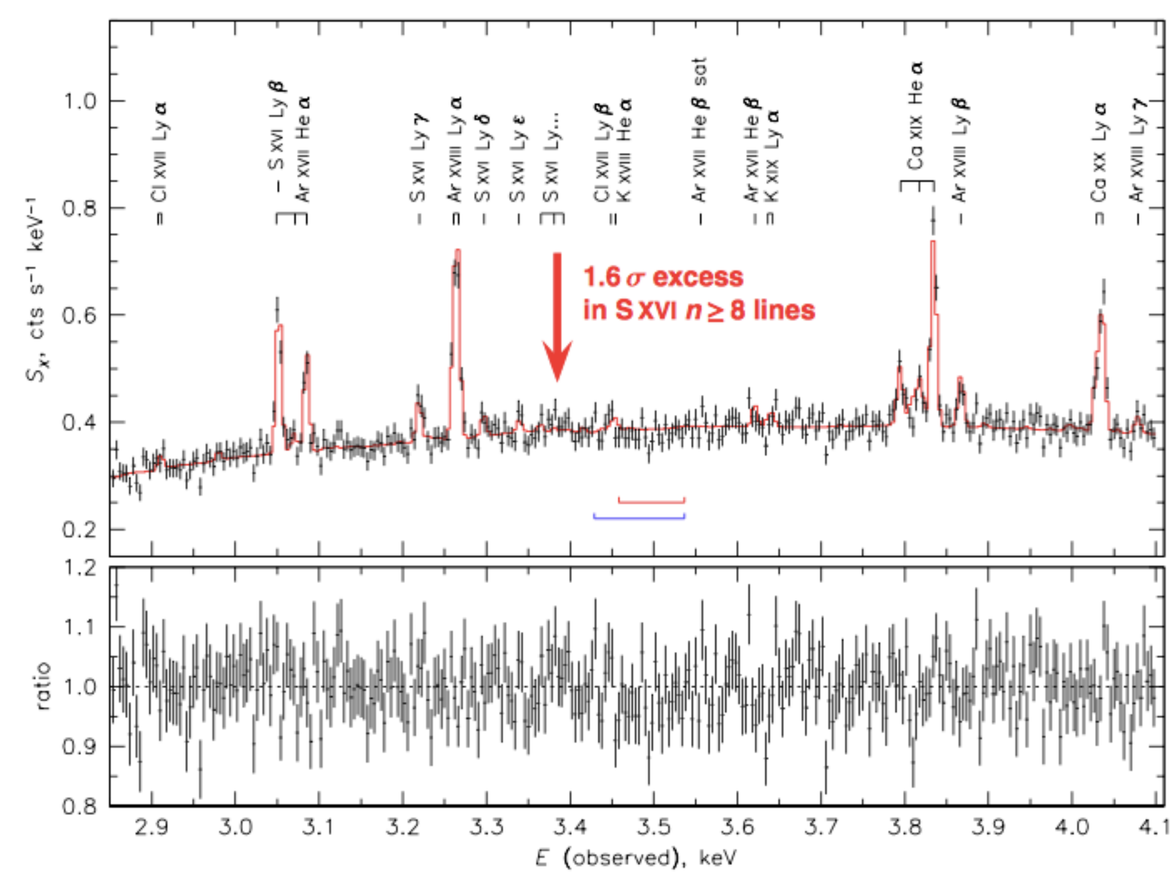
DB σ : 155 ± 7 km/s

Hitomi collaboration (resonant scattering) 17

Hitomi Results on Perseus: Charge Exchange?



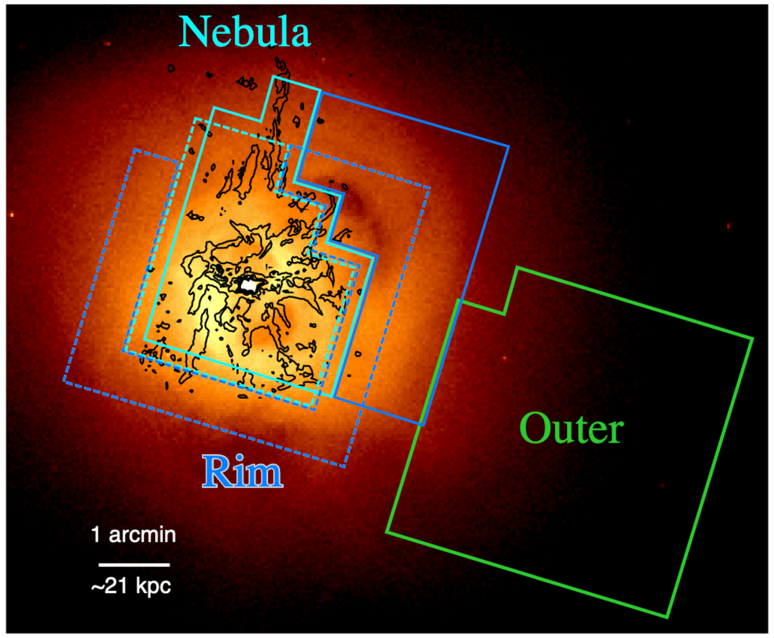




Anomalously high flux in high-n transitions?

Hitomi collaboration 16

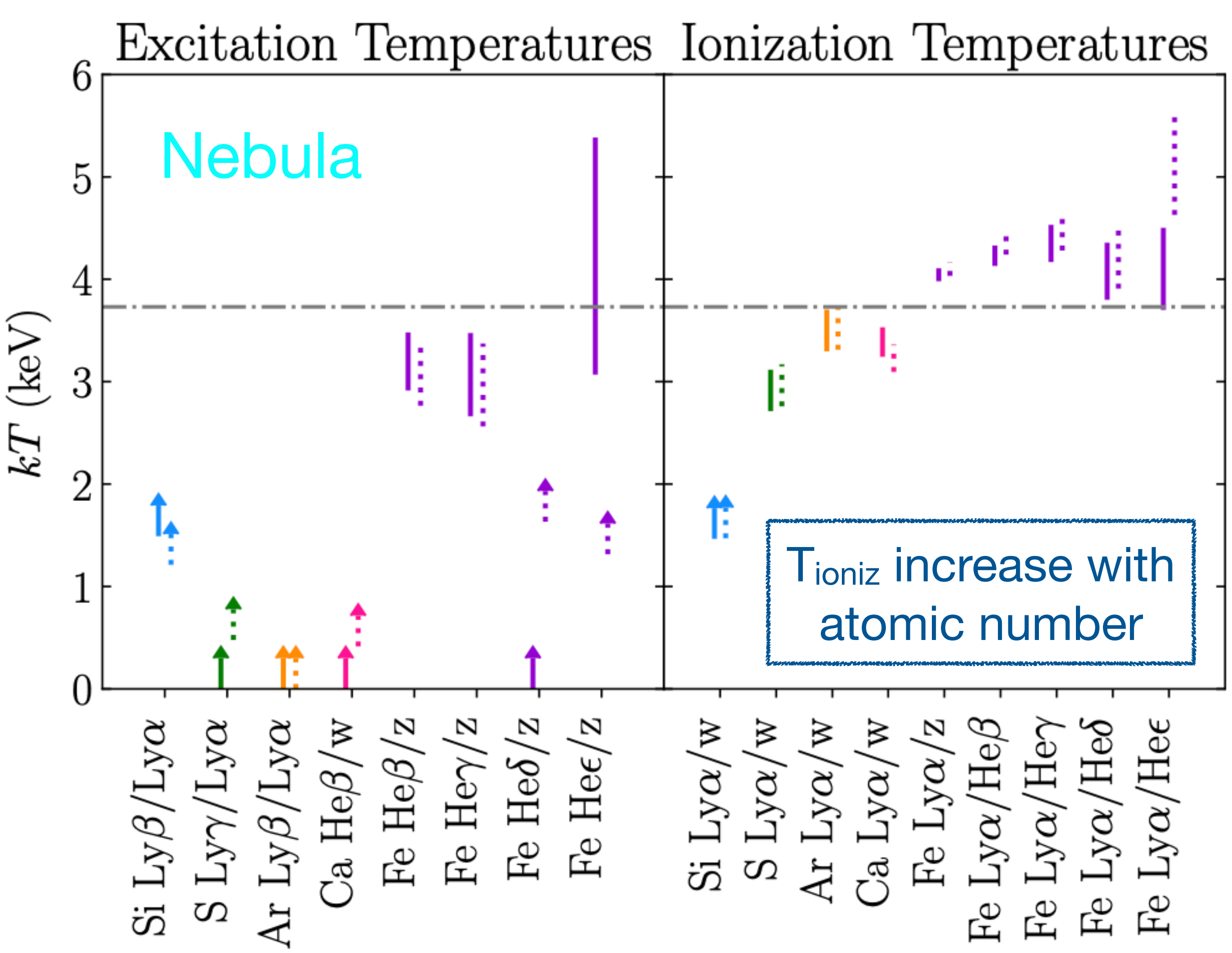
Hitomi Results on Perseus: Plasma Temperature Diagnostic



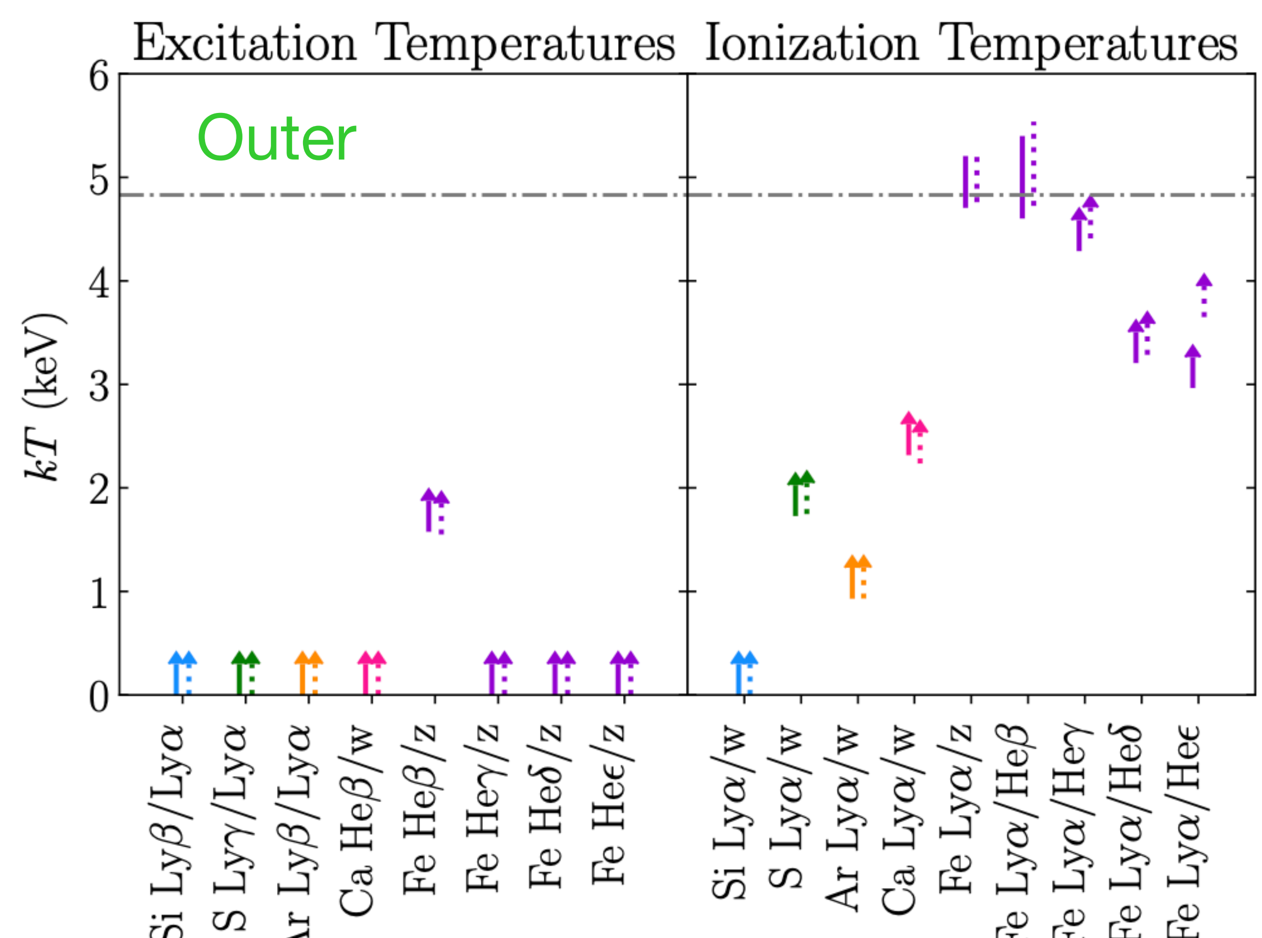
Excitation T (reflects kinetic T of free electrons): ratio of lines from the same ion (Lyα/Lyβ)

Ionization T (represents ion fraction): ratio of lines from different ionization states (Heα /Lyα)

Single-T optically-thin CIE plasma: $T_{excit} = T_{ioniz} = T_{contin}$



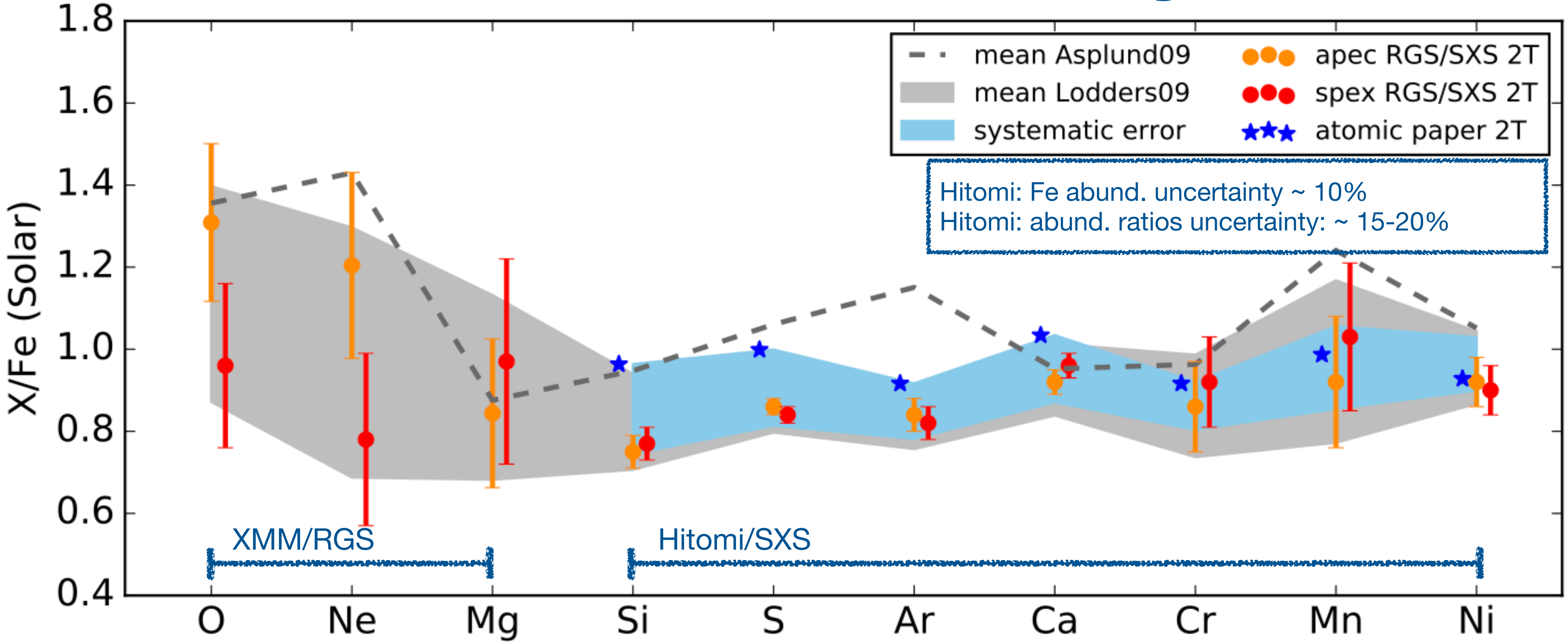
Mix of two T: 3 and 5 keV



Consistent with a single T

Hitomi collaboration (temperature structure paper) 2017

Hitomi Results on Perseus: Chemical Enrichment History



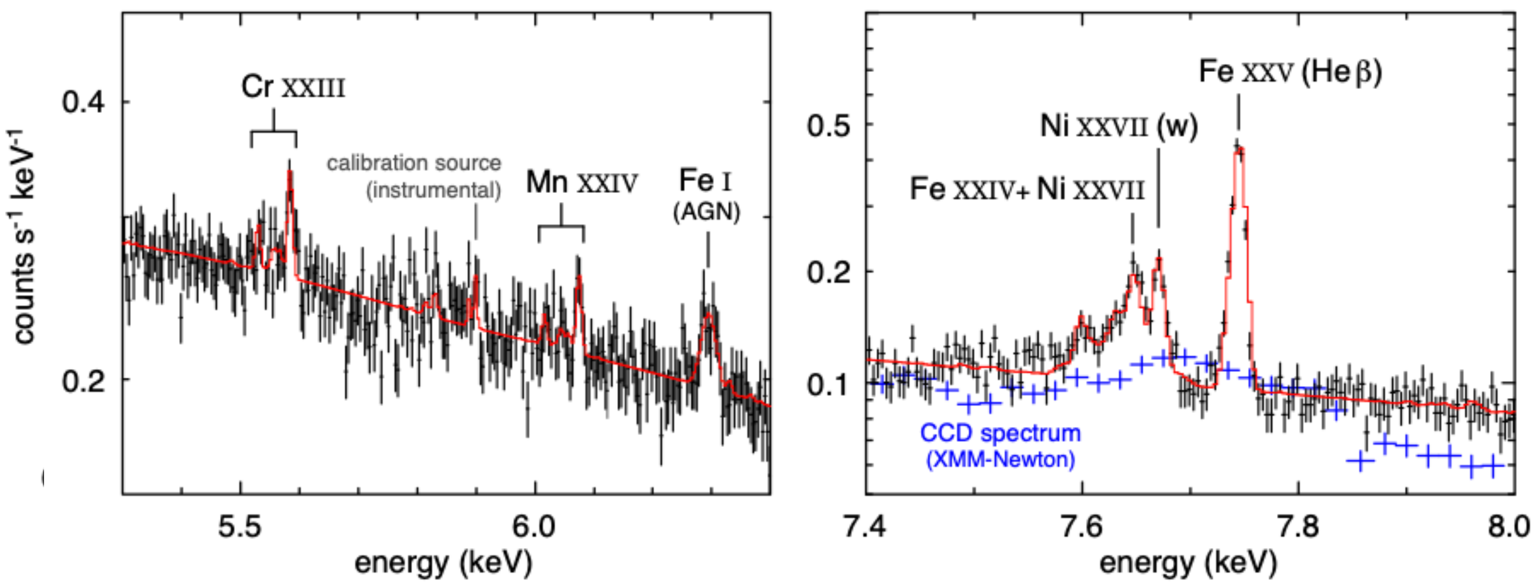
- CCD spectra results are biased on average by 15-40%
- Abundance ratios are consistent with those in protosolar nebula, low-mass early type galaxies, and in typical Milky Way stars (with near-solar absolute metallicity)

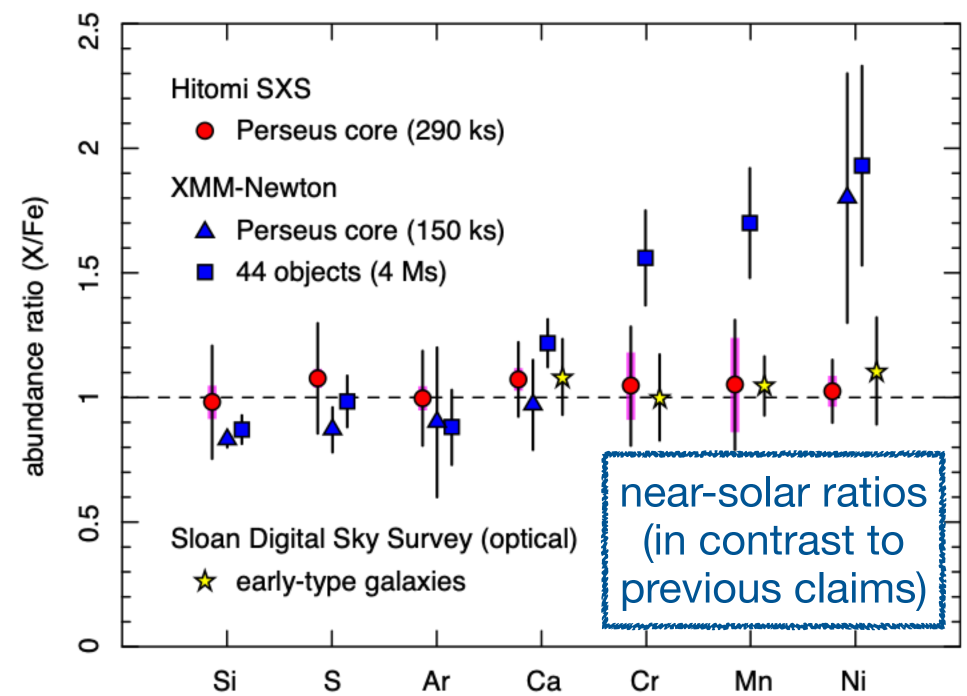
How well current SN yield calculations reproduce the observed abundance pattern in ICM?

- A simple model (enrichment in Perseus and protosolar nebula are identical) is a good description
- Challenges to reproduce with linear combinations of existing SN nucleosynthesis calculations, particularly of intermediate α-elements
- Including neutrino physics in the SNcc yield calculations may improve the agreement

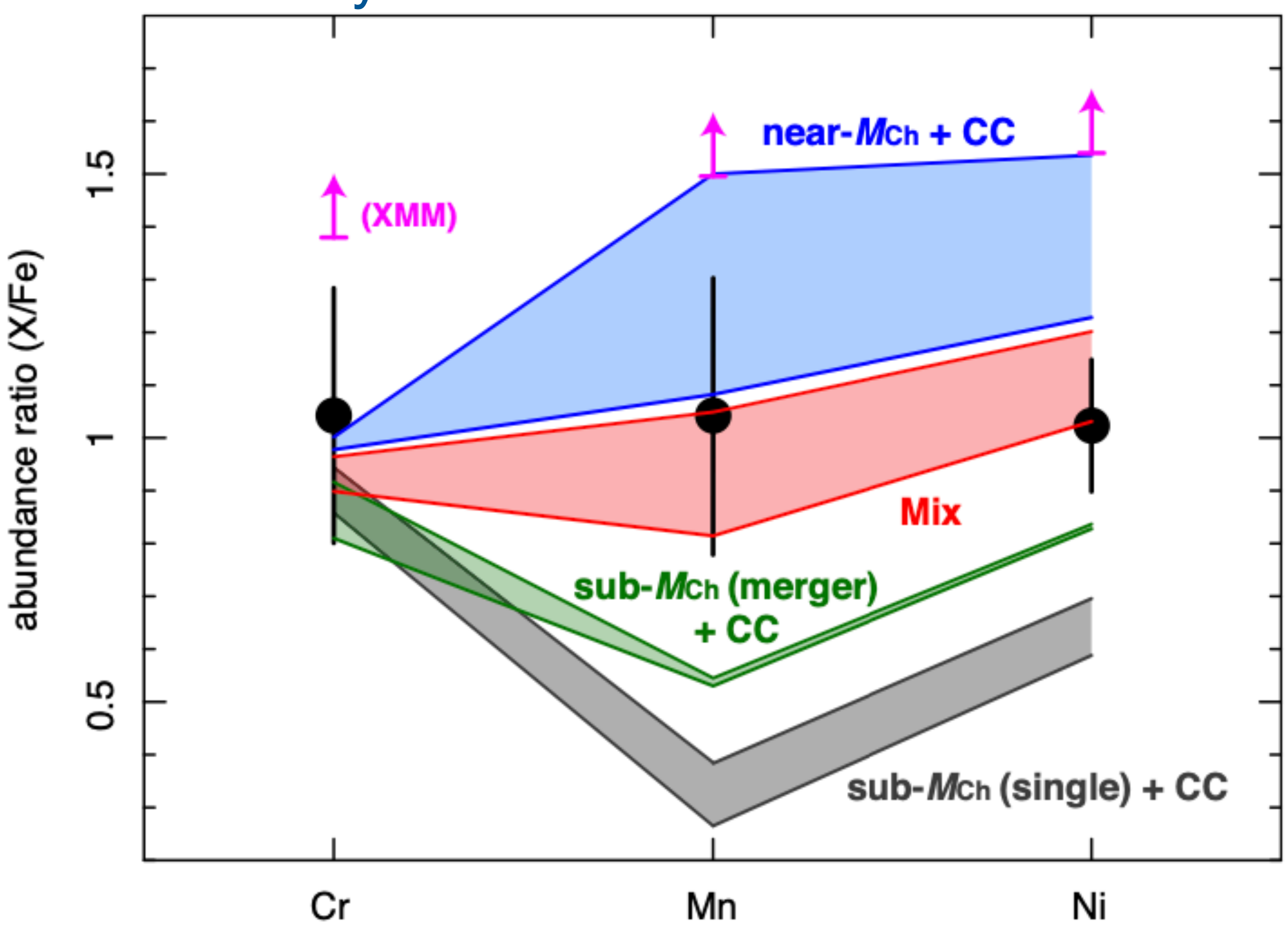
Simionescu et al. 2018

Hitomi Results on Perseus: SNIa Progenitors





Nucleosynthesis models and observations



Abundances of Fe-peak elements (Cr, Mn, Fe, Ni) trace how the progenitors of typical SNIa evolve and explode

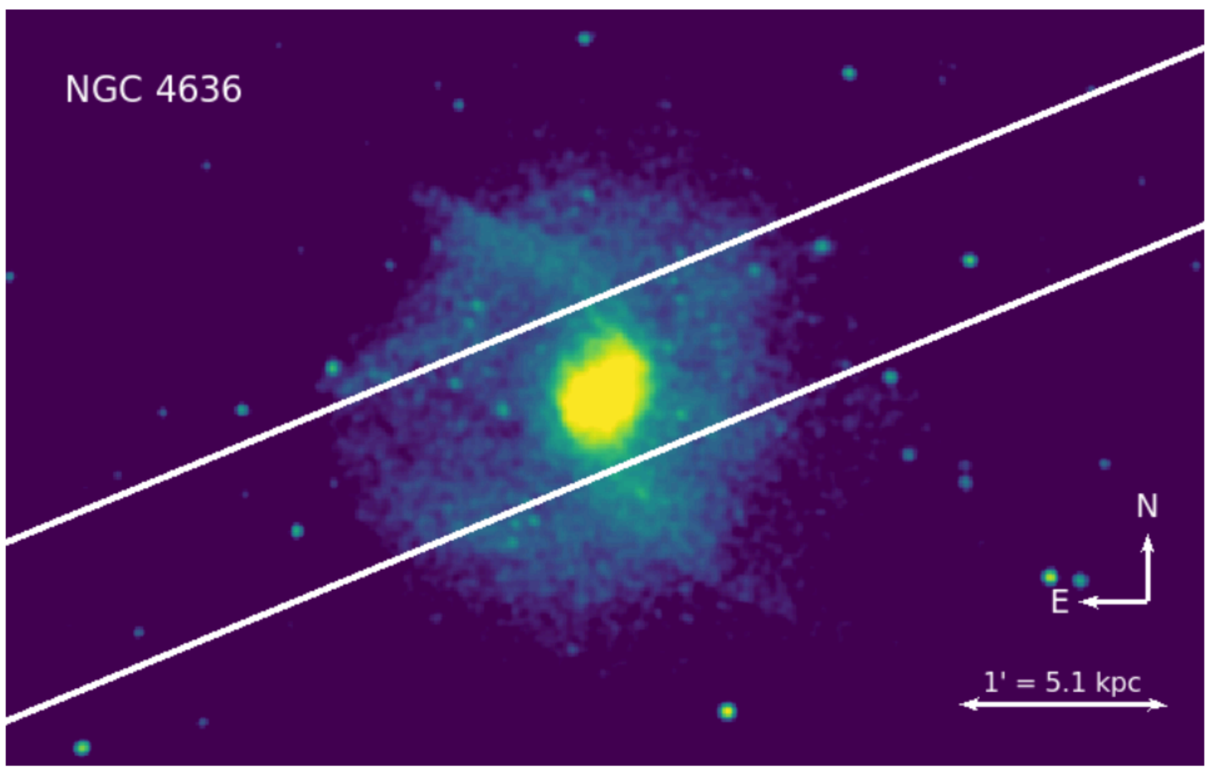
The Fe-peak abundances can be explained with a combination of near- and sub-M_{Ch} SNIa systems

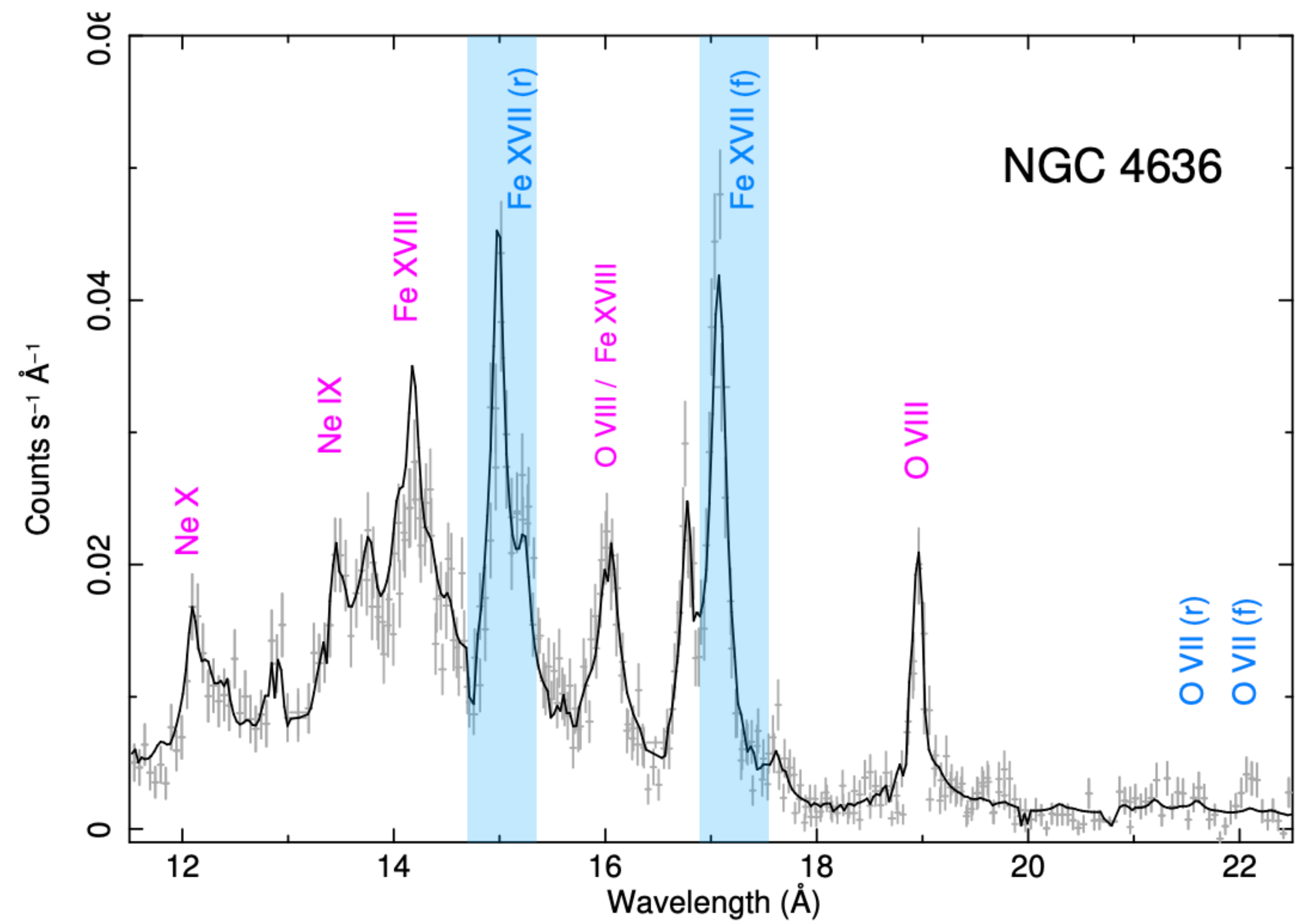
Hitomi collaboration (iron-peak elements abundances, Nature) 2017

XMM-Newton RGS Results (selected)

CHEERS sample: X-ray bright galaxy groups, clusters and elliptical galaxies (include OVIII 19 Å line detection)

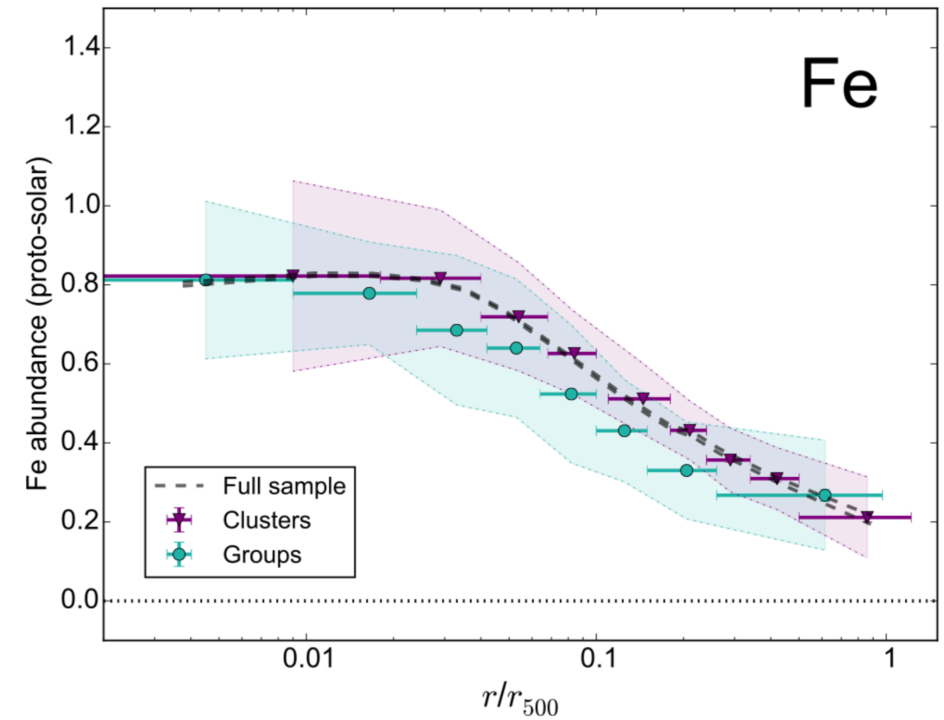
de Plaa & Mernier 2016





XMM-Newton RGS Results (selected)

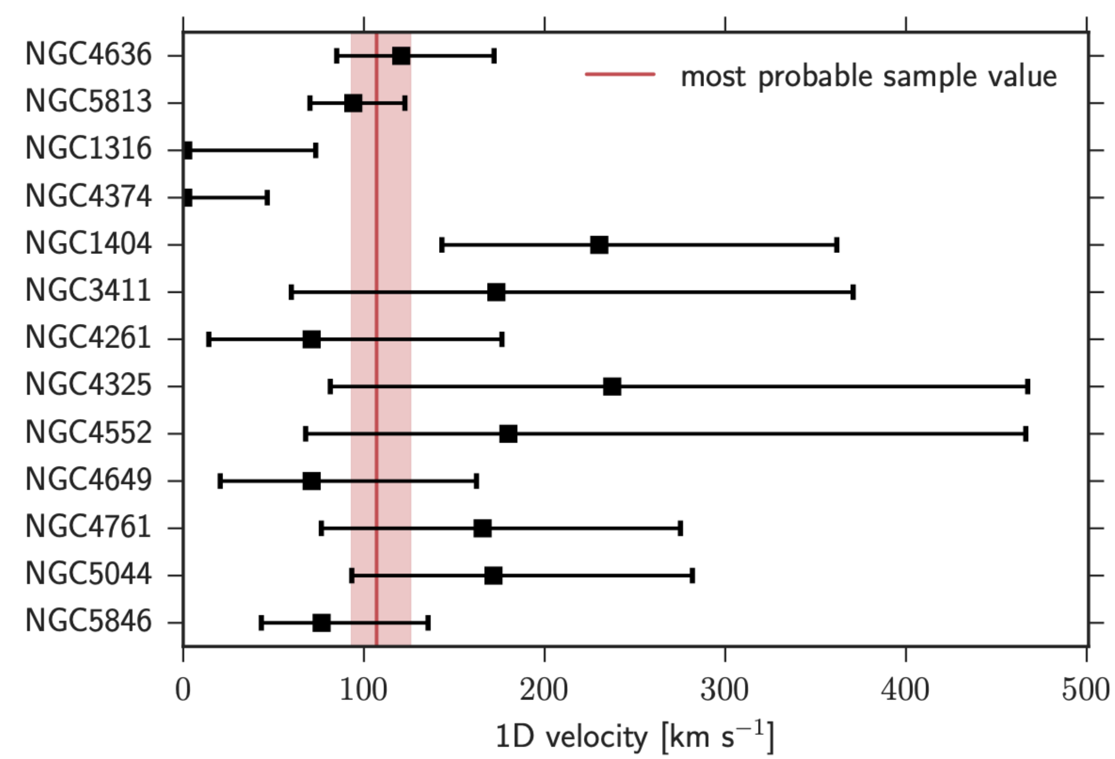
- accurate abundance measurements of O and Fe: no dependence on T —> ICM enrichment independent of M and enrichment likely took place before the ICM was formed
  de Plaa et al. 2017



- Average radial O, Mg, Si, S, Ar, Ca, Fe and Ni abundance profiles
  Mernier et al. 2017

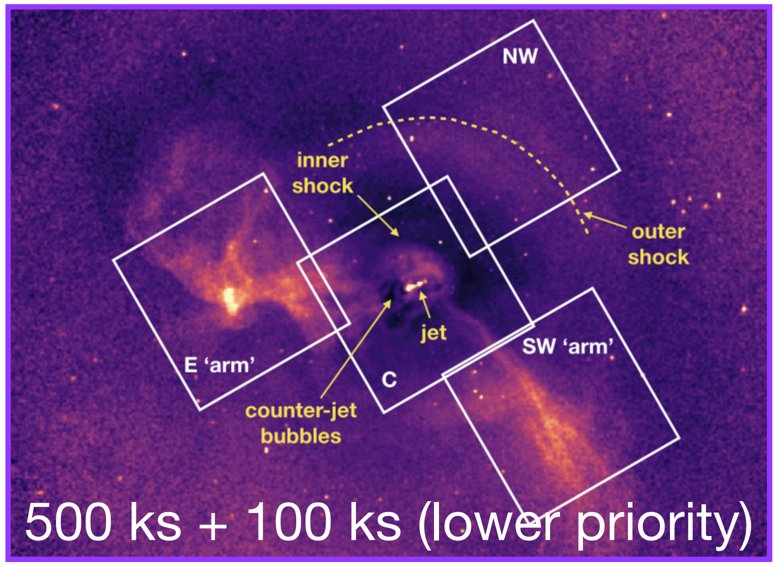
- Doppler broadening velocity constraints: ~1/2 of sample - < 500 km/s, several sources - upper limits > 1000 km/s
  Pinto et al. 2015

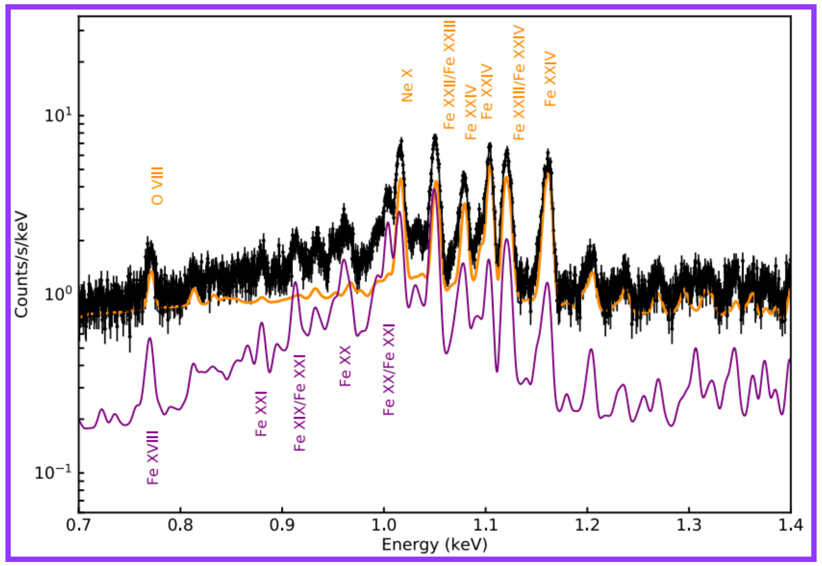
- Combined DB and RS velocity measurements
  Ogorzalek et al. 2017



See talk by Brian Williams

XRISM Diffuse Extragalactic PV Science





M87/Virgo cluster

- Spatially and spectrally resolve AGN feedback physics
- Kinematics of uplifted gas
- Turbulence in the BH vicinity, pre- and post-shock
- Mixing of metals and gas phases
- Metallicity: stat. uncert. 5-7 %

on behalf of XRISM collaboration

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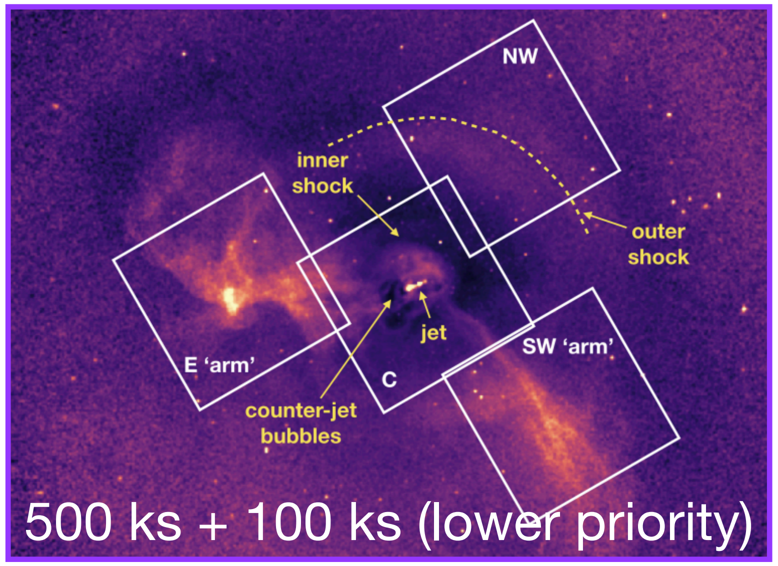

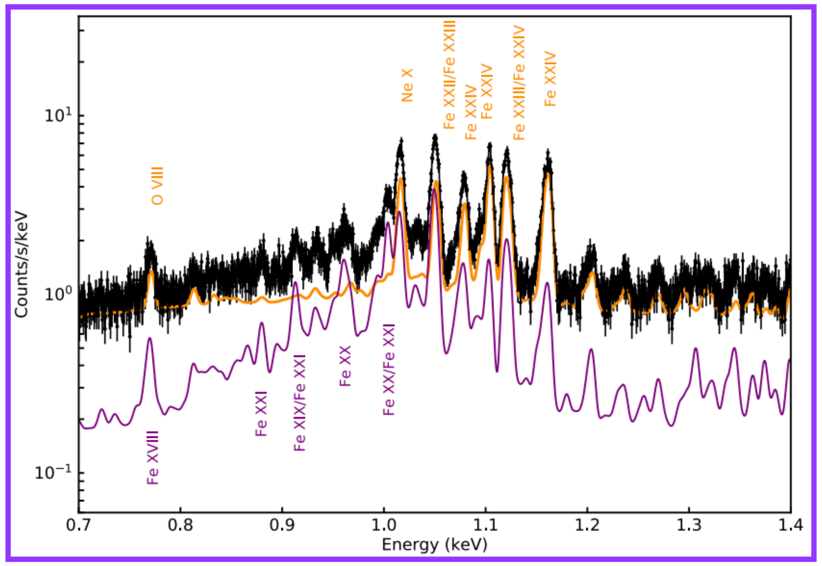

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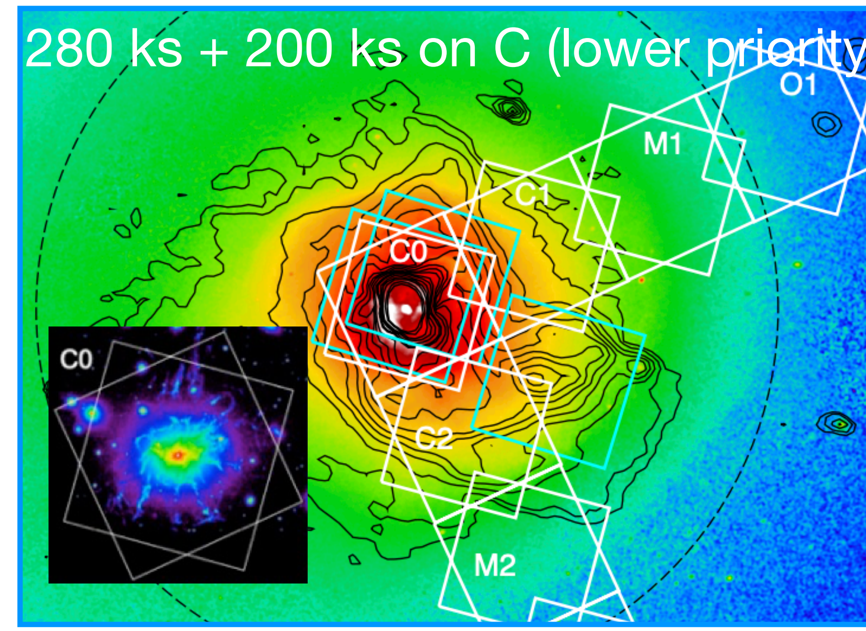
Perseus cluster

- Turbulence driven by feedback vs. mergers
- Turbulence from shear motions behind cold fronts
- Scales of motions, power spectra
- Turbulence in the uplifted by bubbles gas
- Particle acceleration by turbulence
- Radial metallicity profile, tight constraints on enrichment mechanisms
- Detection of rare element (Na, Al)
- Search for new physics (CX, RS)



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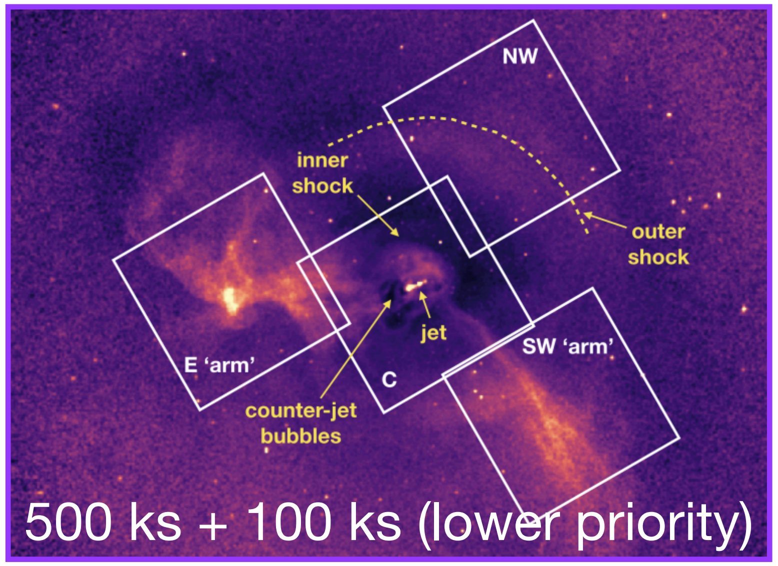

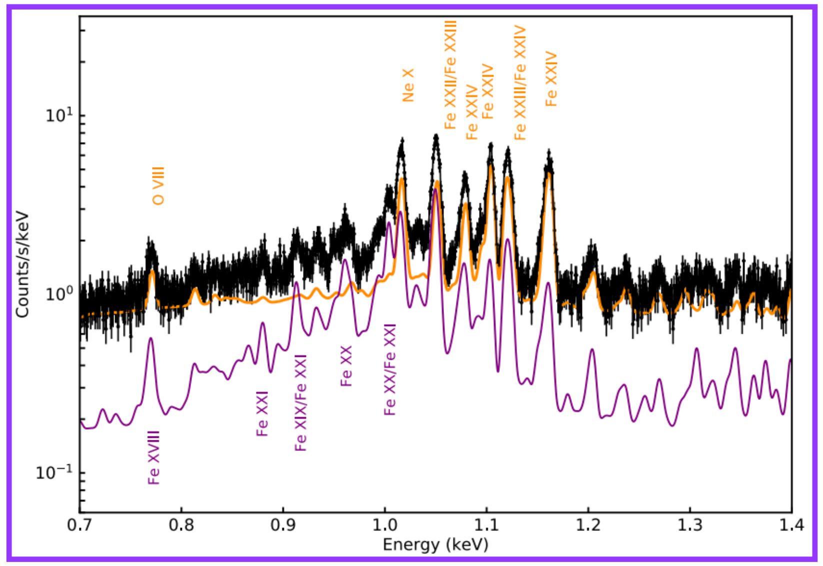

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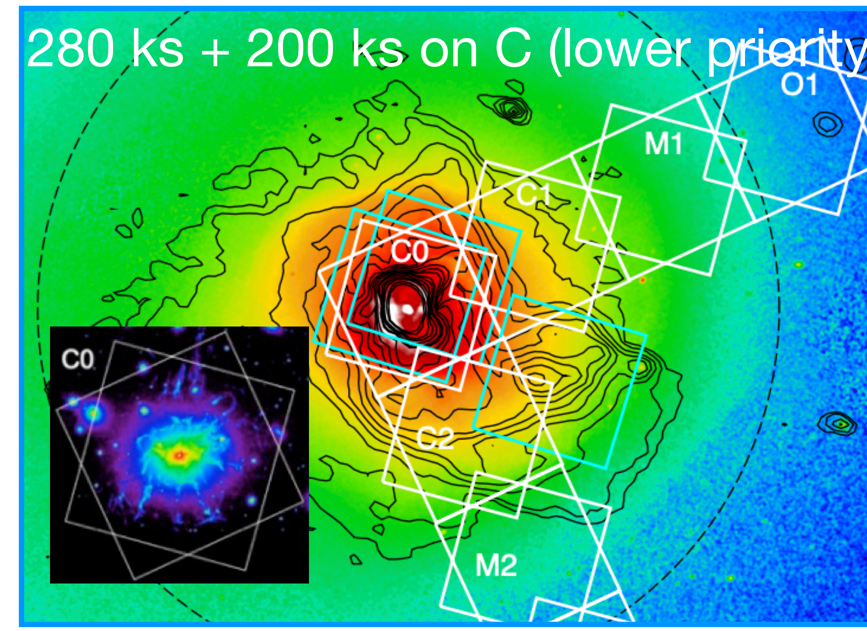
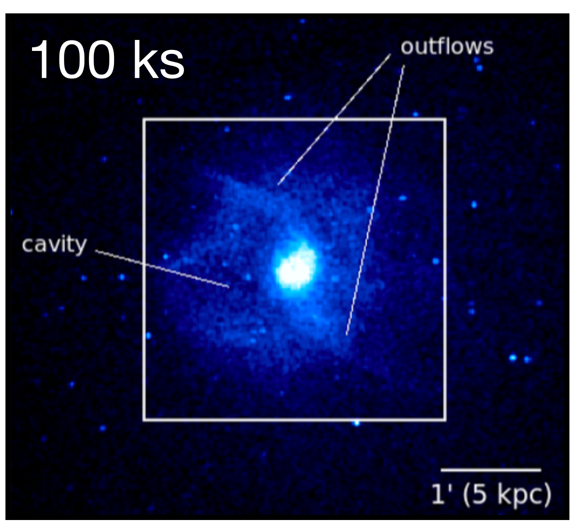




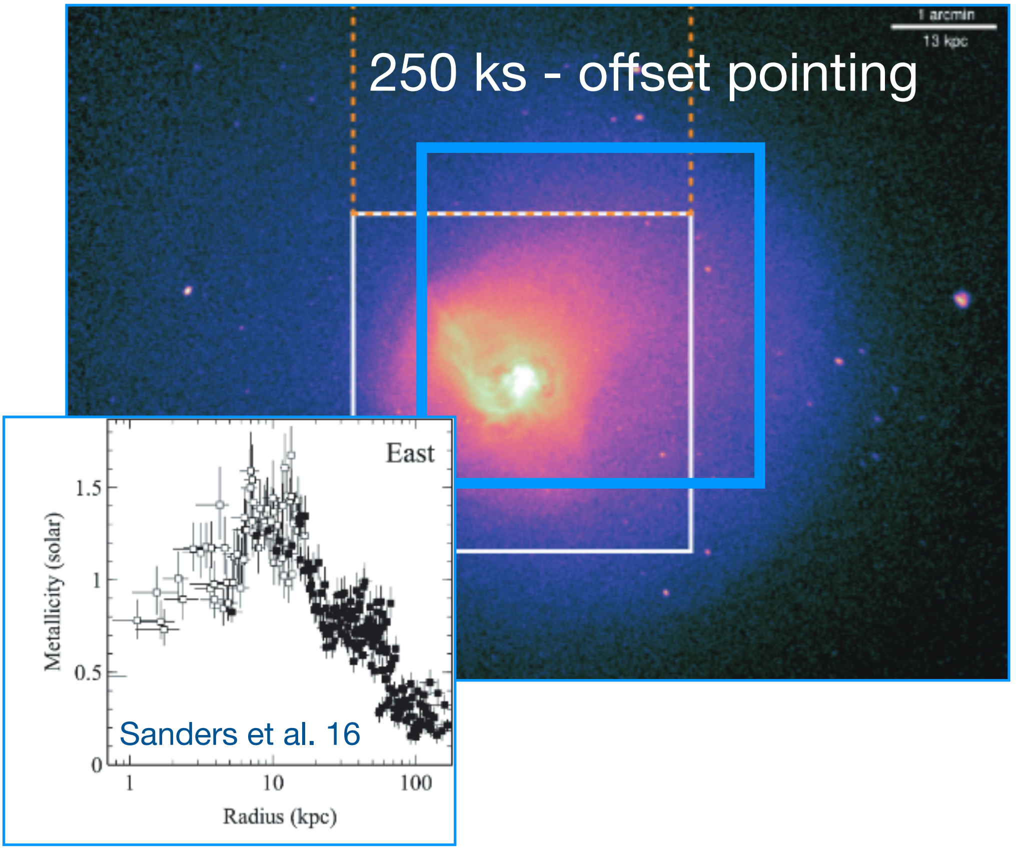
NGC4636

- Turbulence driven by AGN feedback in low-mass halos
- Chemical enrichment studies
- Resonant scattering
- Atomic physics in sub-keV plasma

Physics of AGN feedback as a function of halo mass

on behalf of XRISM collaboration

XRISM Diffuse Extragalactic PV Science

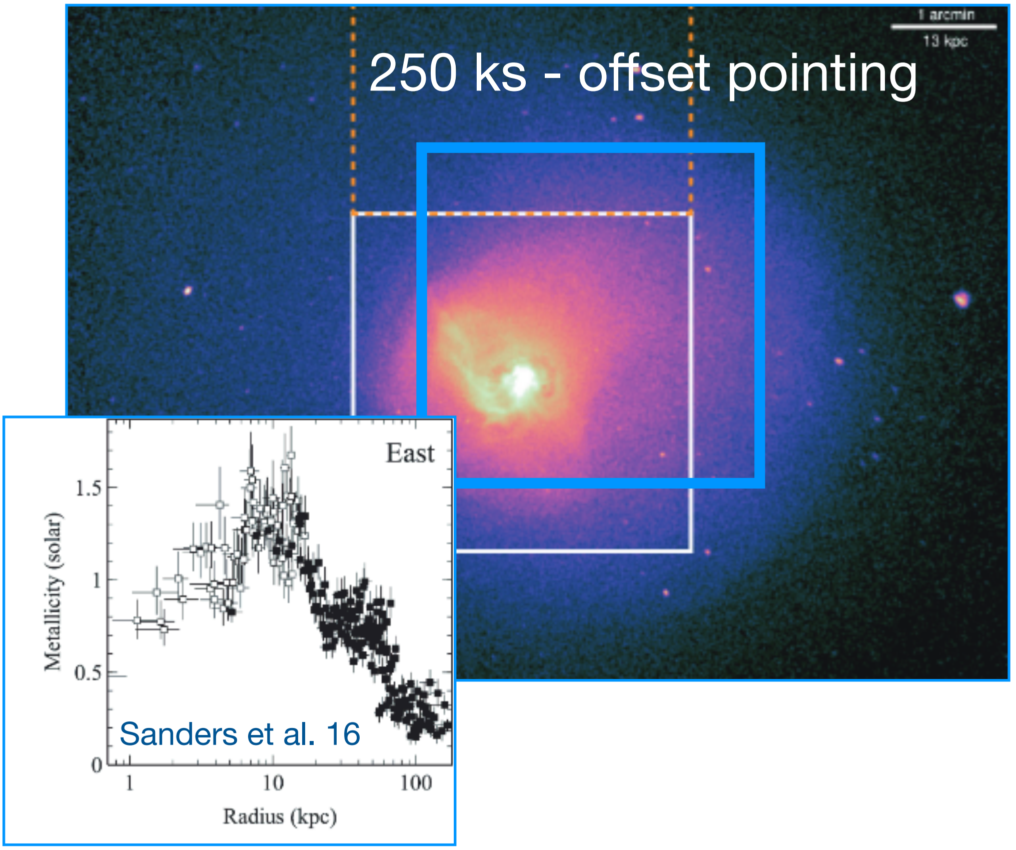


Centaurus cluster

- Depletion of metals: Fe (form the dust) vs. Ar and Ne (noble gas)
- Multi-T vs. metallicity, probe metallicity peak
- Turbulence driven by feedback when AGN is relatively quiet
- Velocities of gas motions driven by sloshing

on behalf of XRISM collaboration

XRISM Diffuse Extragalactic PV Science



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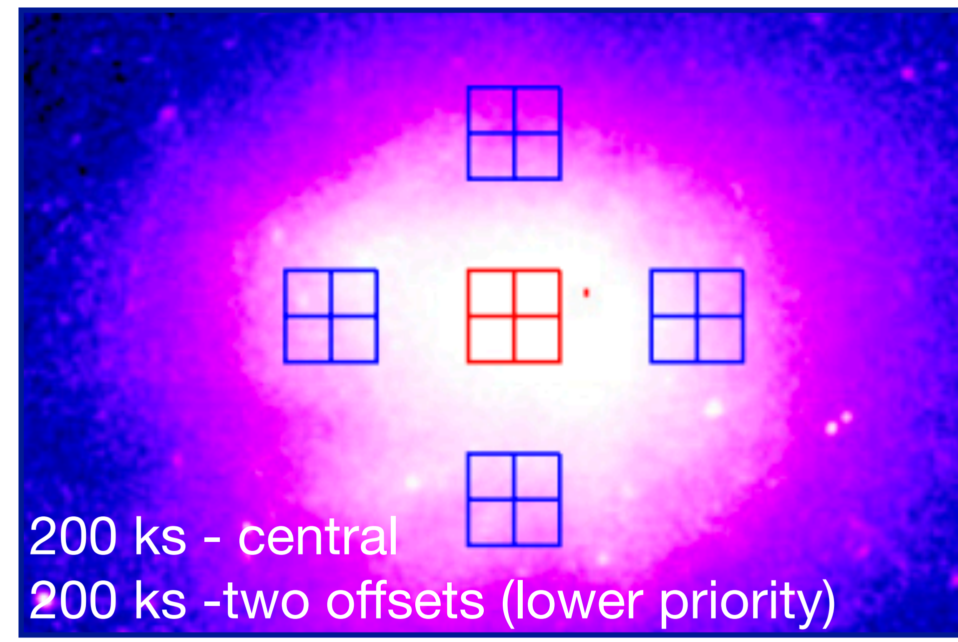
Coma cluster

- Turbulence and bulk motions driven by mergers
- Probing textbook example of turbulence in the ICM
- Structure function of turbulence



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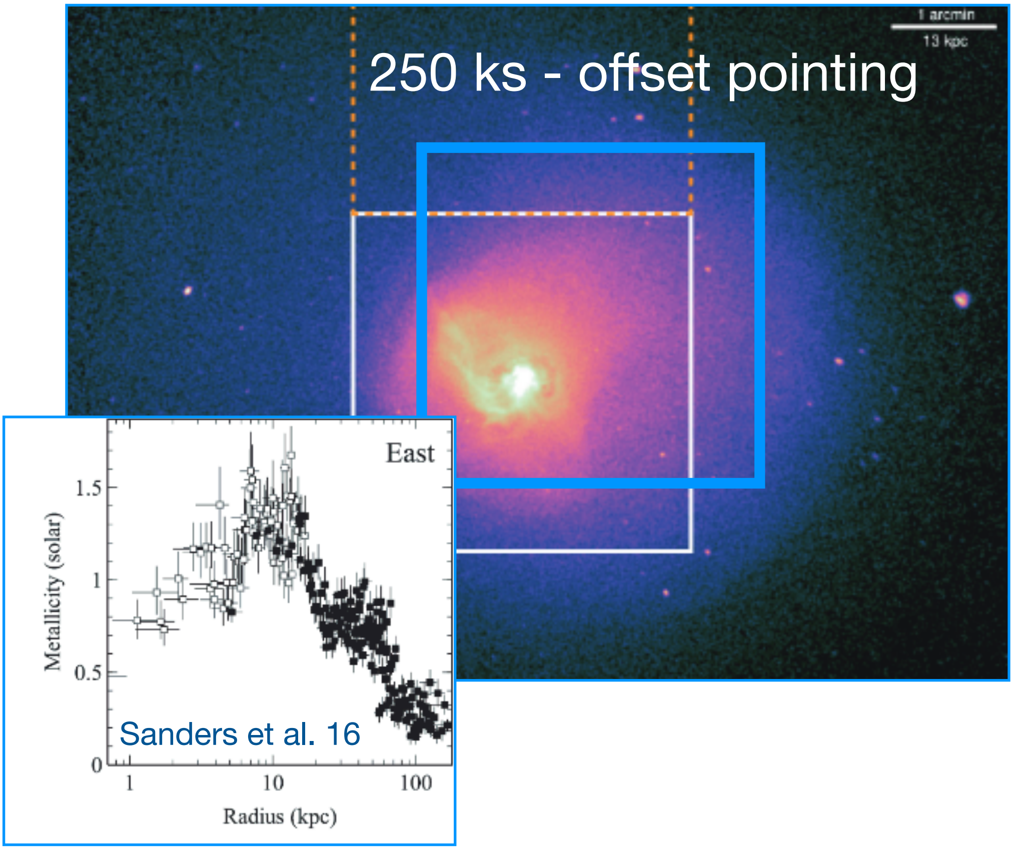

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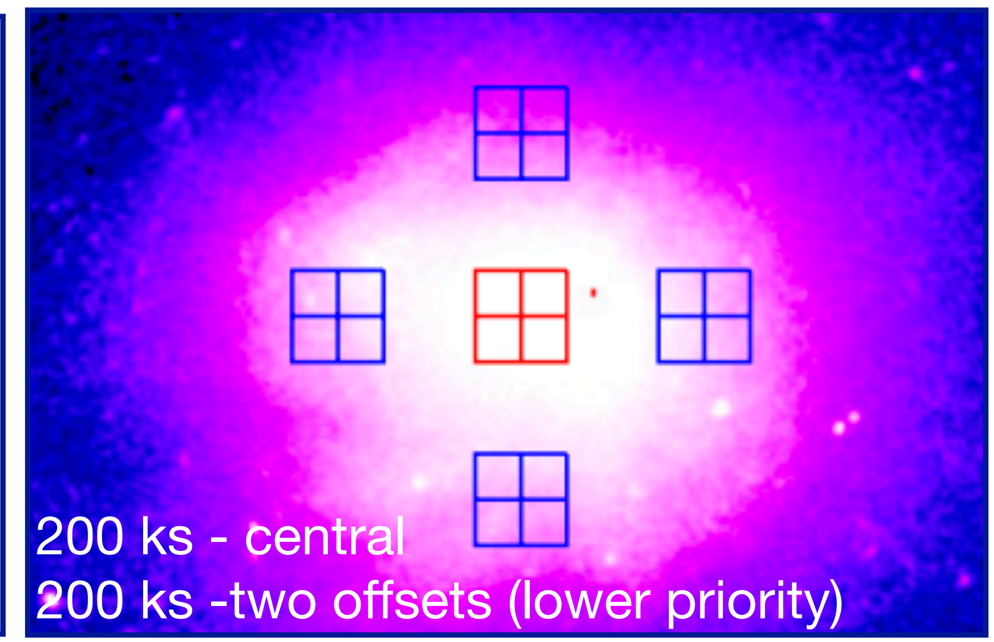
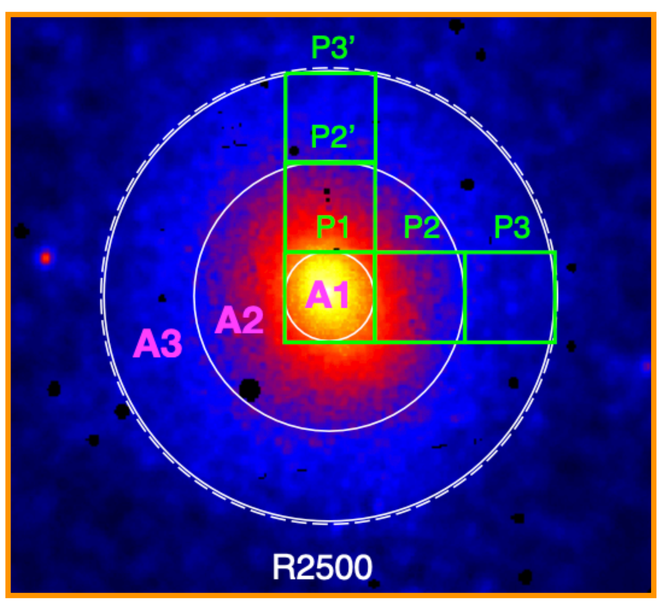




320 ks + 300 ks (lower priority)

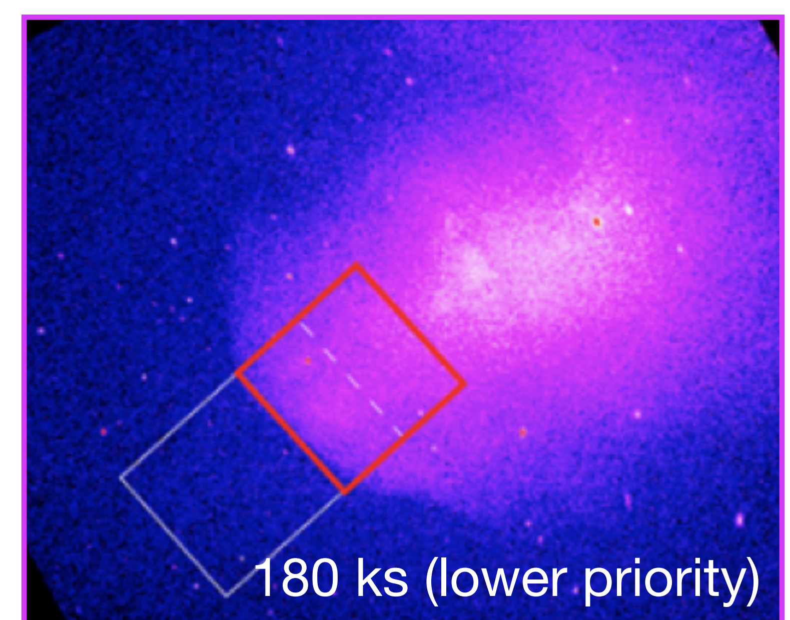
Abell 2029

- Gas dynamics in outers (~r_{2500})
- Non-thermal pressure, mass bias for cluster cosmology

see talk by Eric Miller

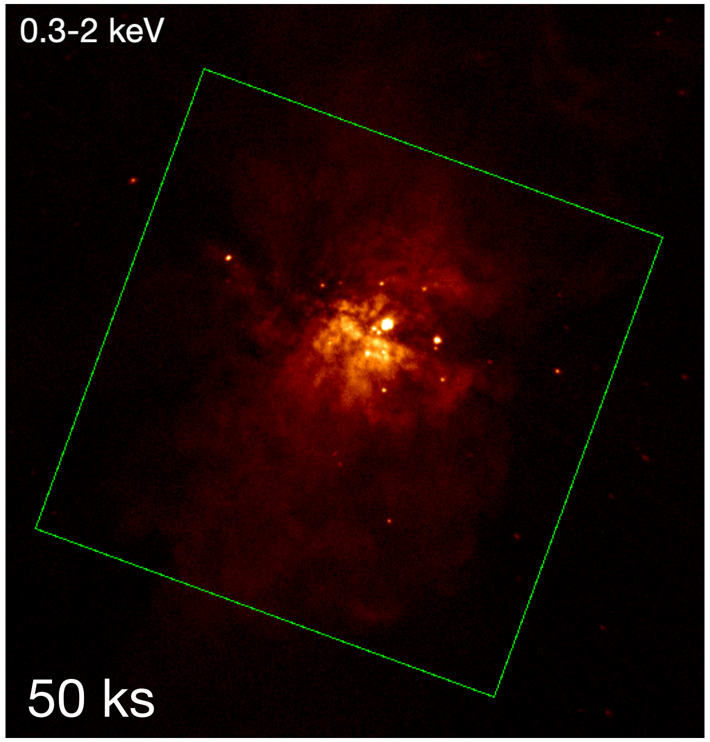
Abell 3667 (lower priority)

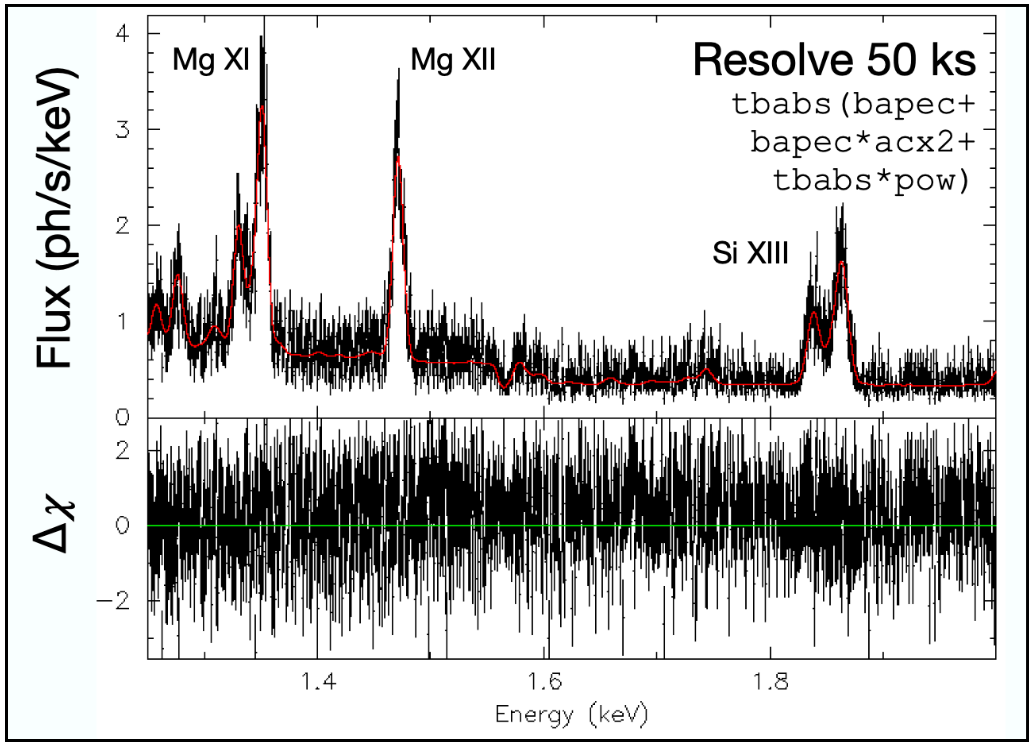
- Reveal the merger geometry (sloshing or stripping)
- Directly constrain gas viscosity



on behalf of XRISM collaboration

XRISM Diffuse Extragalactic PV Science



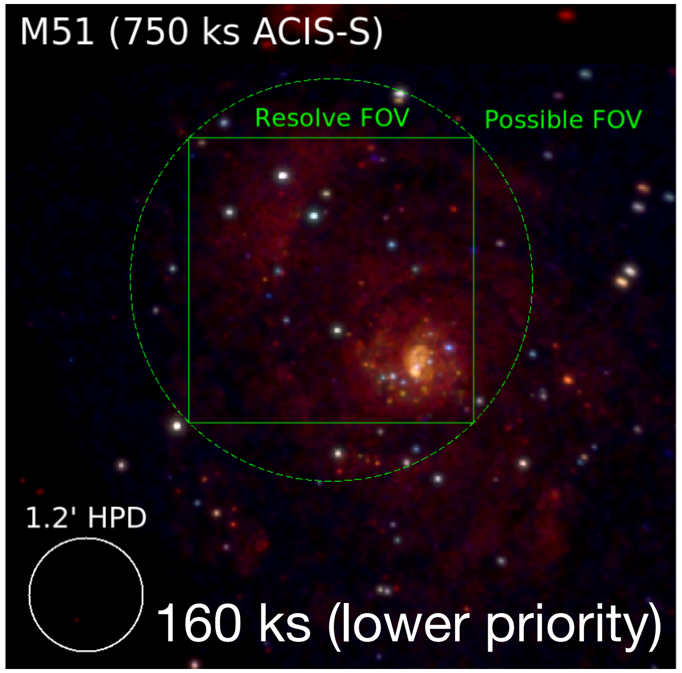


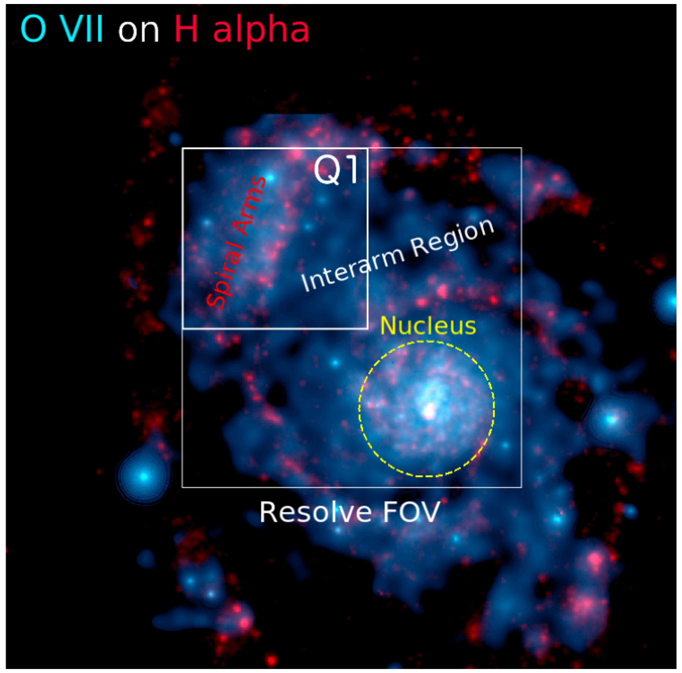
M82: probe stellar feedback via galactic winds

- Velocities of outflows (different phases): does the wind speed exceed the escape velocity?
- What drives winds? Confirm that hot gas pressure is the primary wind driver.
- Charge exchange + determine the relationship between hot, warm, and cool wind gas
- Chemical composition

M51

- Measure emission measure distribution in the nucleus and spiral arms
- Search for NEI plasma, its distribution
- Chemical composition
- Charge exchange





on behalf of XRISM collaboration

High-Resolution X-ray Spectroscopy of Galaxy Clusters, Groups, and Massive Galaxies

Today: Hitomi spectrum + RGS (compact, bright regions)

In 23 days: XRISM (mostly bright cores/regions)

More distant future?

Line Emission Mapper (LEM)

LINE EMISSION MAPPER

A mission concept for the NASA 2023 Astrophysics Probes AO

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

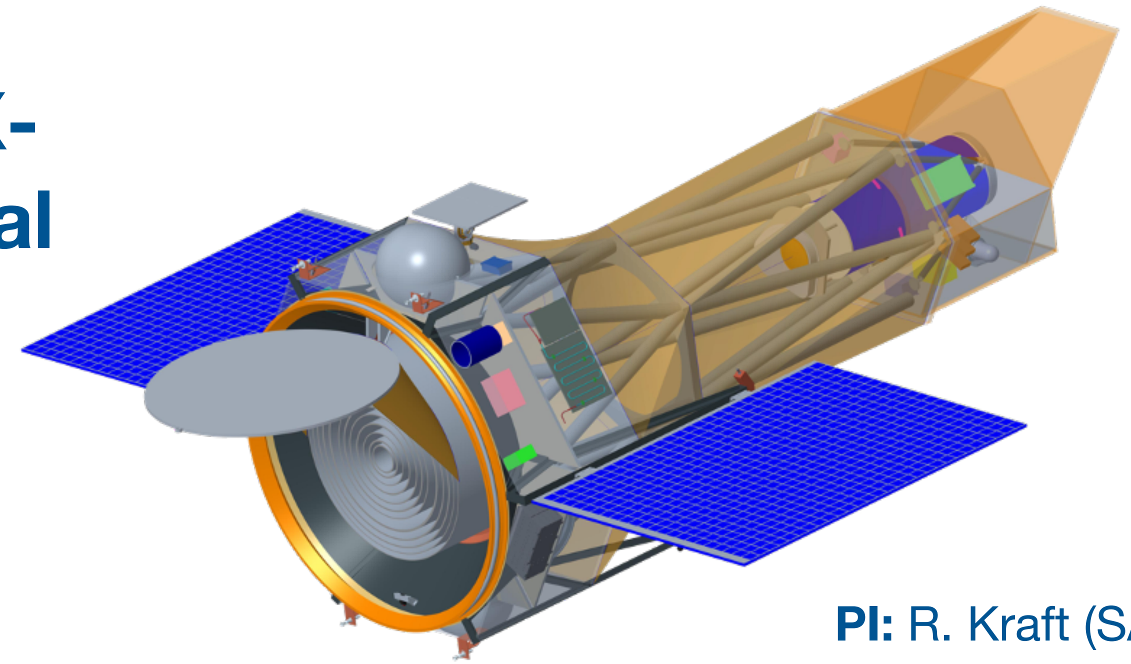
NASA Goddard

THE UNIVERSITY OF CHICAGO

LOCKHEED MARTIN

Designed to study faint, extended X-ray sources with calorimeter spectral resolution in 0.2-2 keV band

- 30’x30’ FOV with 15” pixels
- 1-2 eV spectral resolution



PI: R. Kraft (SAO)
Deputy PI: C. Kilbourne (NASA GSFC)

		LEM	XRISM Resolve	Athena XIFU*	HUBS
Energy band, keV		0.2–2	0.4–12	0.2–12	0.2–2
Effective area, cm^2	0.5 keV	1600	50	6000	500
	6 keV	0	300	2000	0
Field of view		30′	3′	5′	60′
Grasp, 10^4 cm^2 arcmin^2	0.5 keV	140	0.05	12	180
Angular resolution		15″	75″	5″	60″
Spectral resolution		0.9 eV (central 8′), 2 eV (rest of FOV)	7 eV	2.5 eV	2 eV
Detector size, pixels (equiv. square)		118×118	6×6	50×50	60×60

on behalf of LEM collaboration

see talk by Ralph Kraft

LINE EMISSION MAPPER

Line Emission Mapper (LEM)

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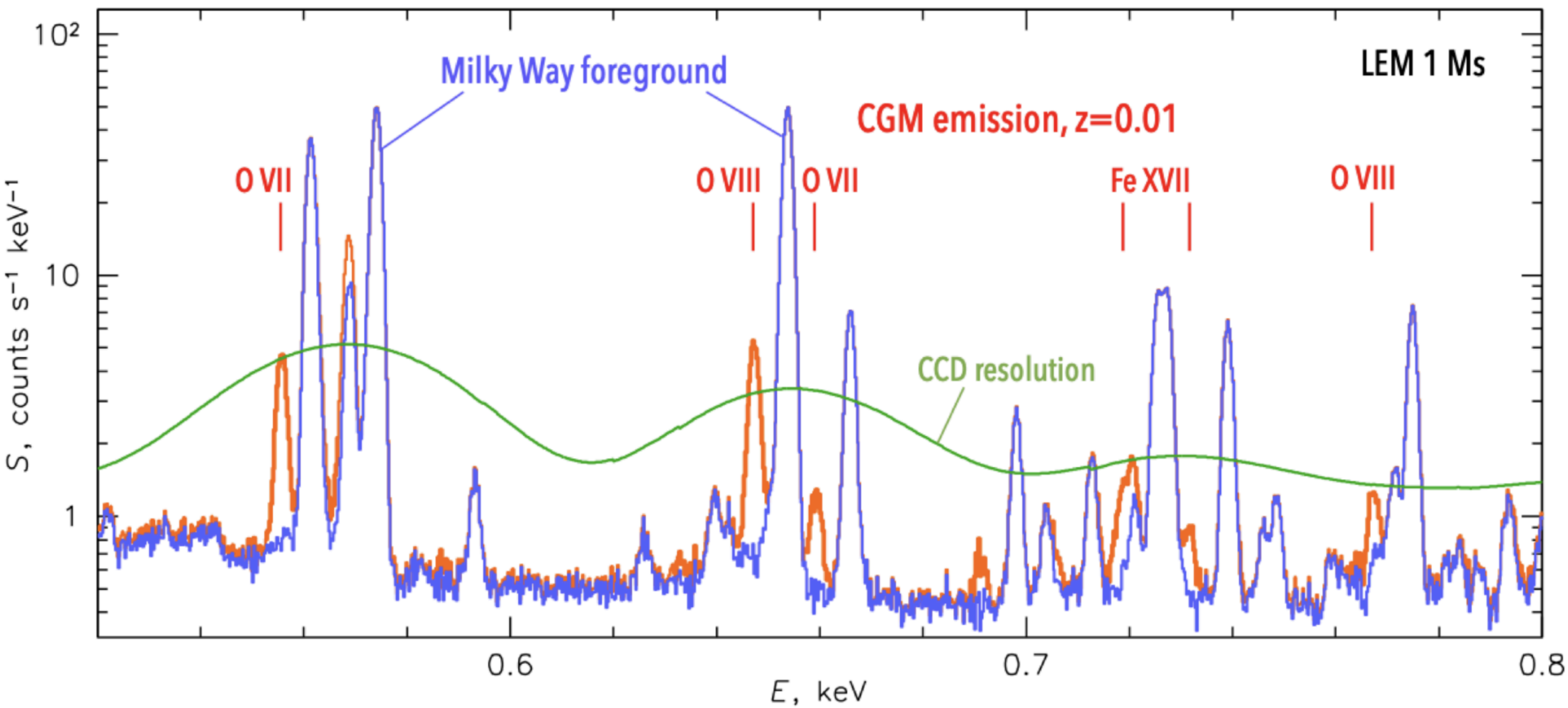
NASA Goddard

THE UNIVERSITY OF CHICAGO

LOCKHEED MARTIN



LEM will map the CGM and IGM in emission (Astro2020 Decadal discovery area)

on behalf of LEM collaboration

LEM White Paper: Kraft et al. 2022

Line Emission Mapper (LEM)

Mapping the CGM in Emission

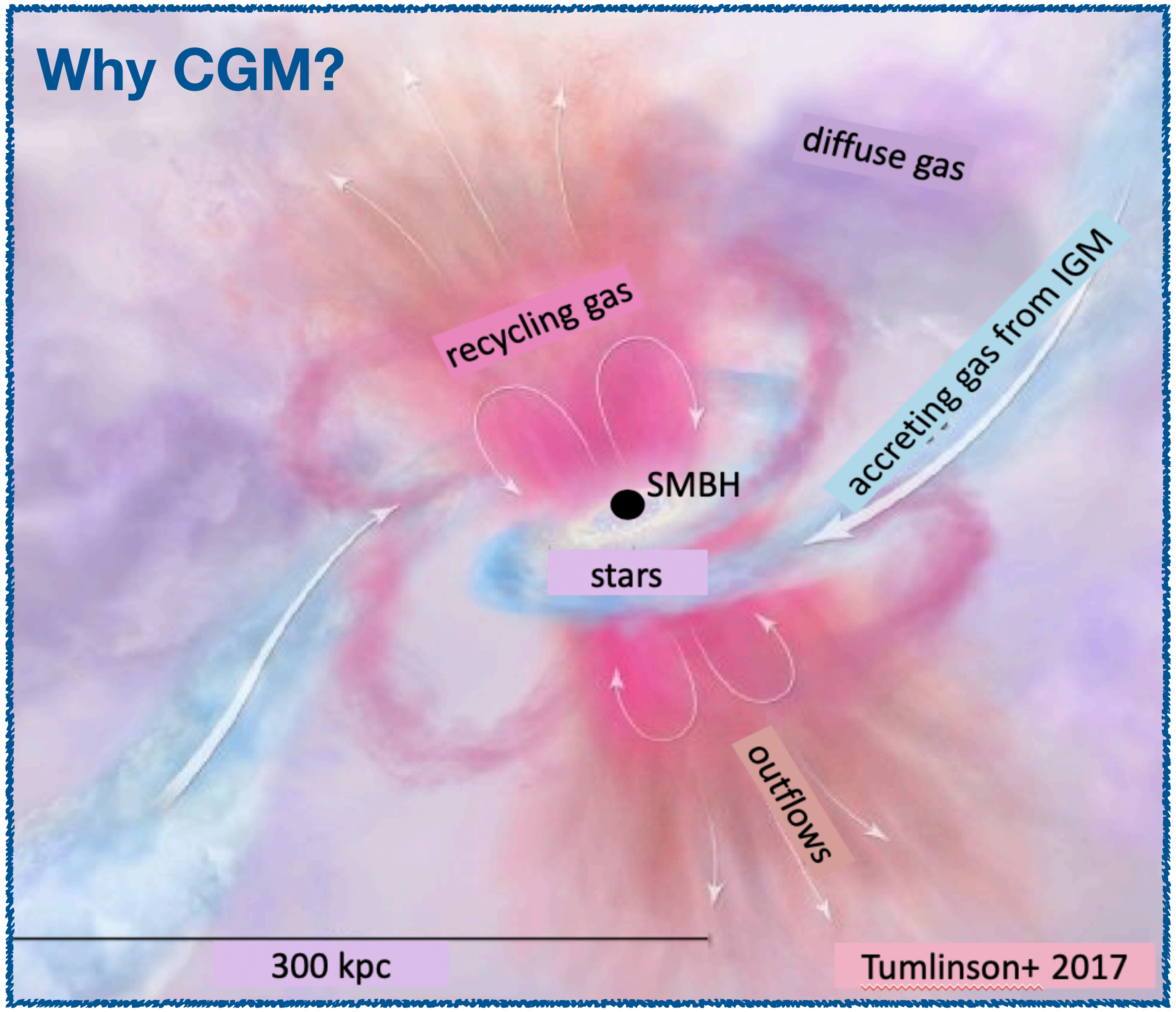
LINE EMISSION MAPPER

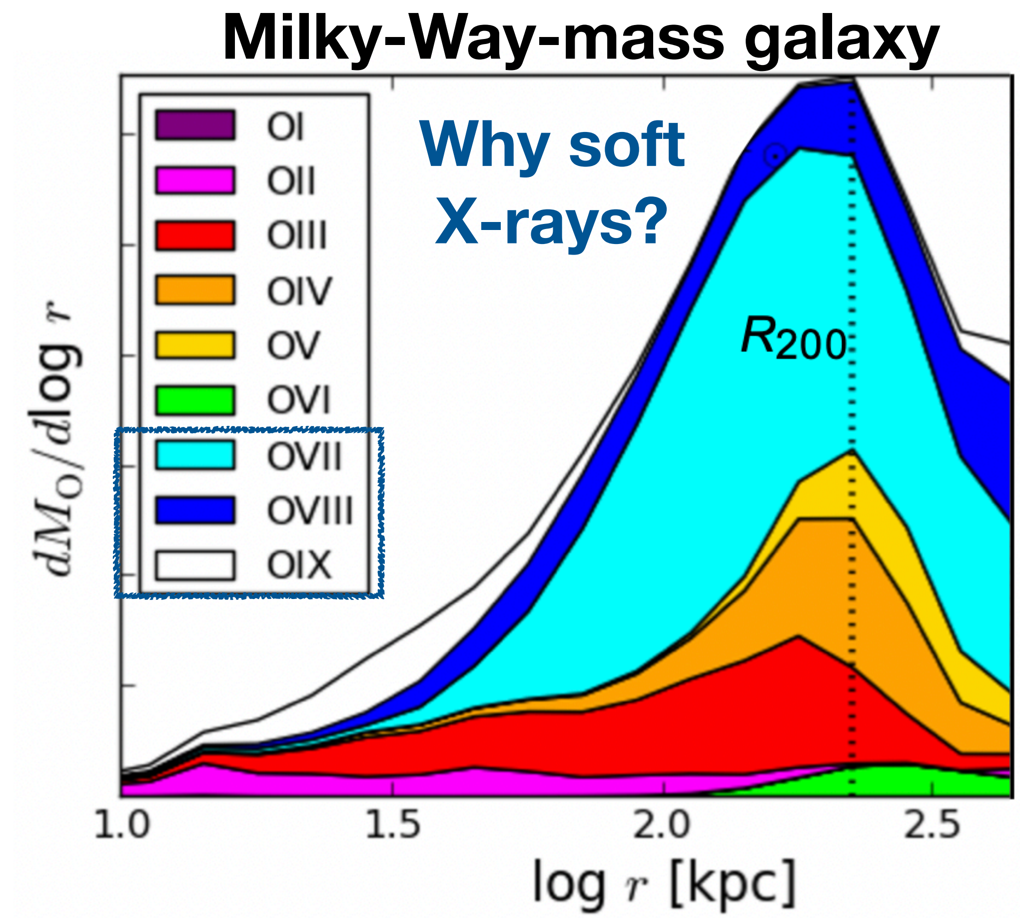
CENTER FOR ASTROPHYSICS | HARVARD & SMITHSONIAN

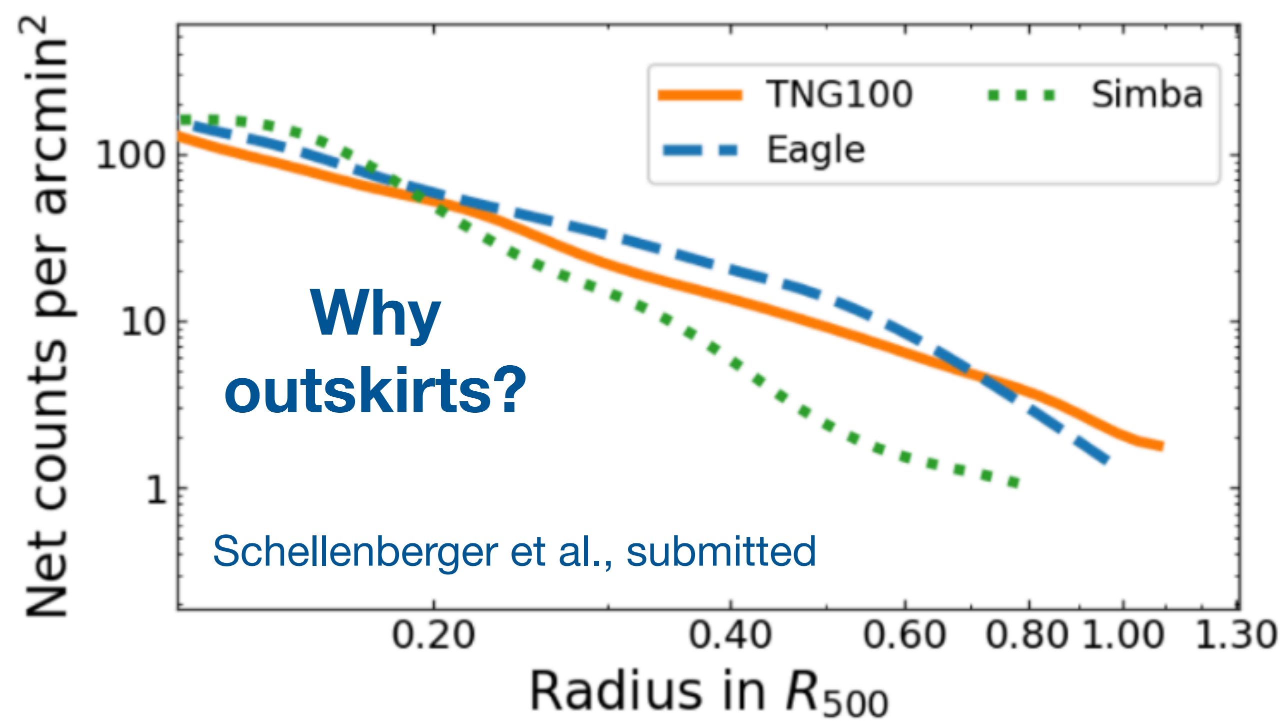
NASA Goddard

THE UNIVERSITY OF CHICAGO

LOCKHEED MARTIN





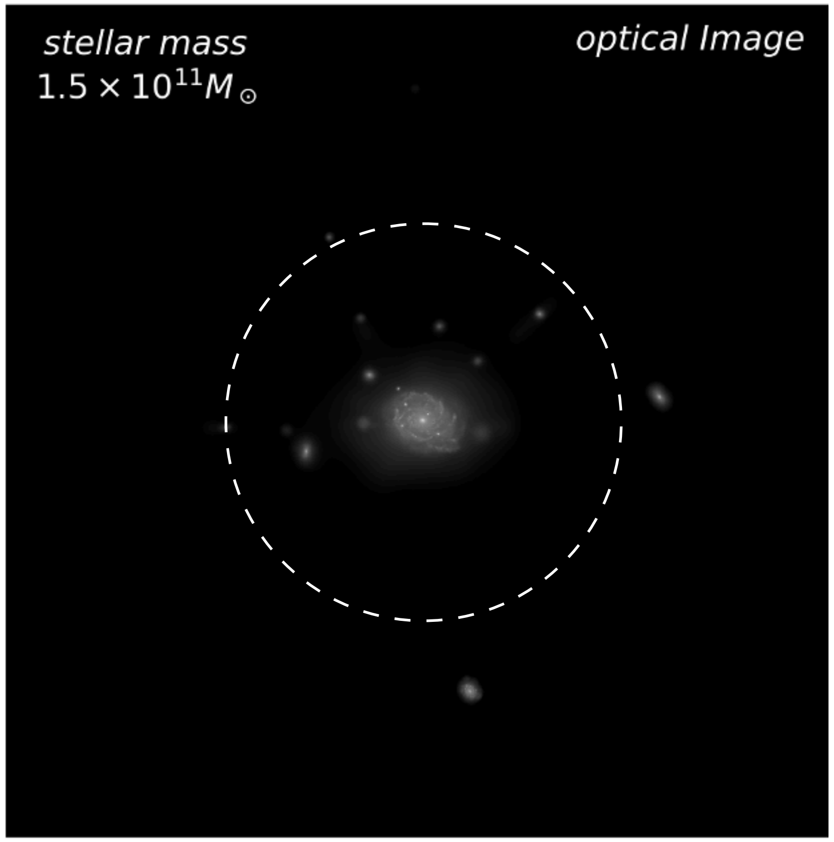


on behalf of LEM collaboration

Line Emission Mapper (LEM)

Mapping the CGM in Emission

Milky Way-type galaxy at z=0.035 from TNG



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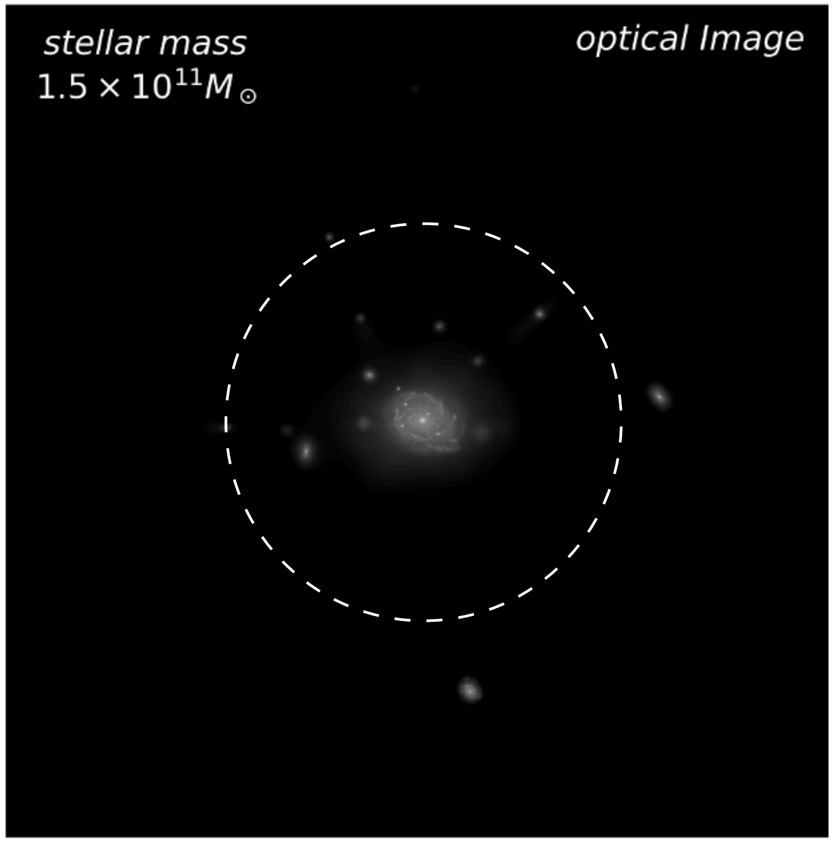
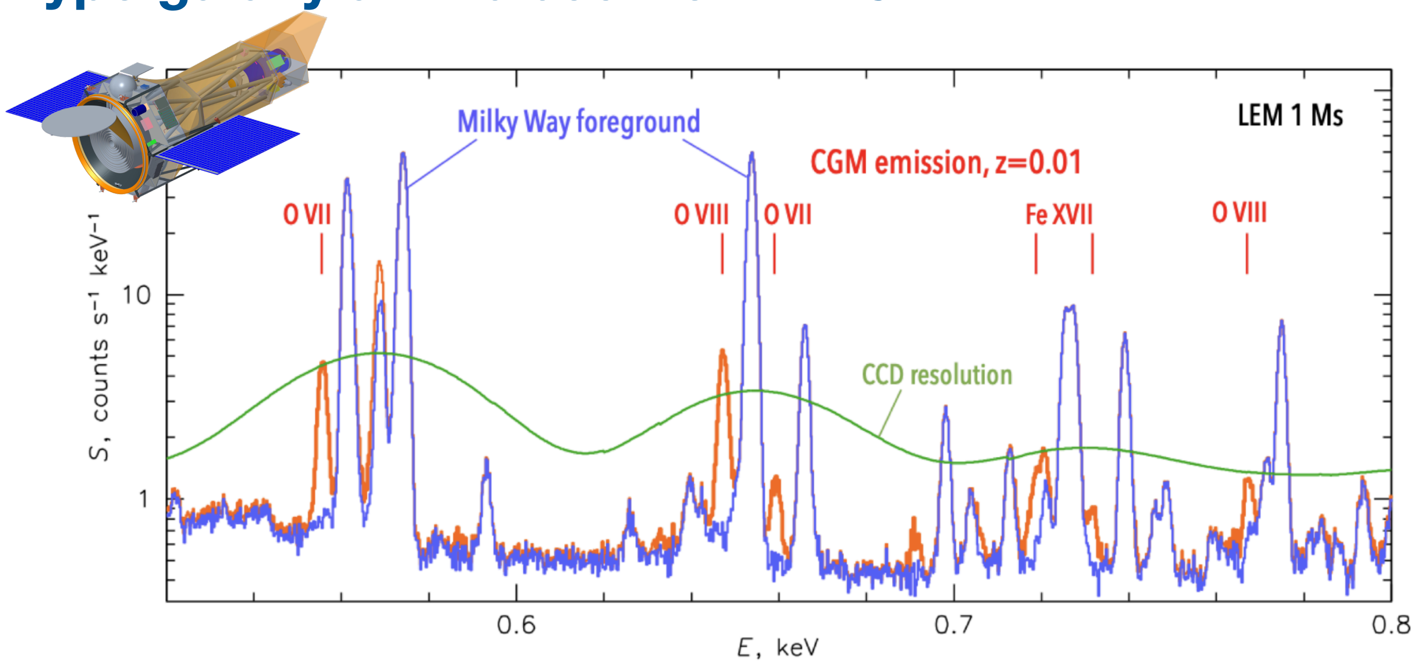
Milky Way-type galaxy at z=0.035 from TNG





on behalf of LEM collaboration

Line Emission Mapper (LEM)

Mapping the CGM in Emission

LINE EMISSION MAPPER

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

NASA Goddard

THE UNIVERSITY OF CHICAGO

LOCKHEED MARTIN

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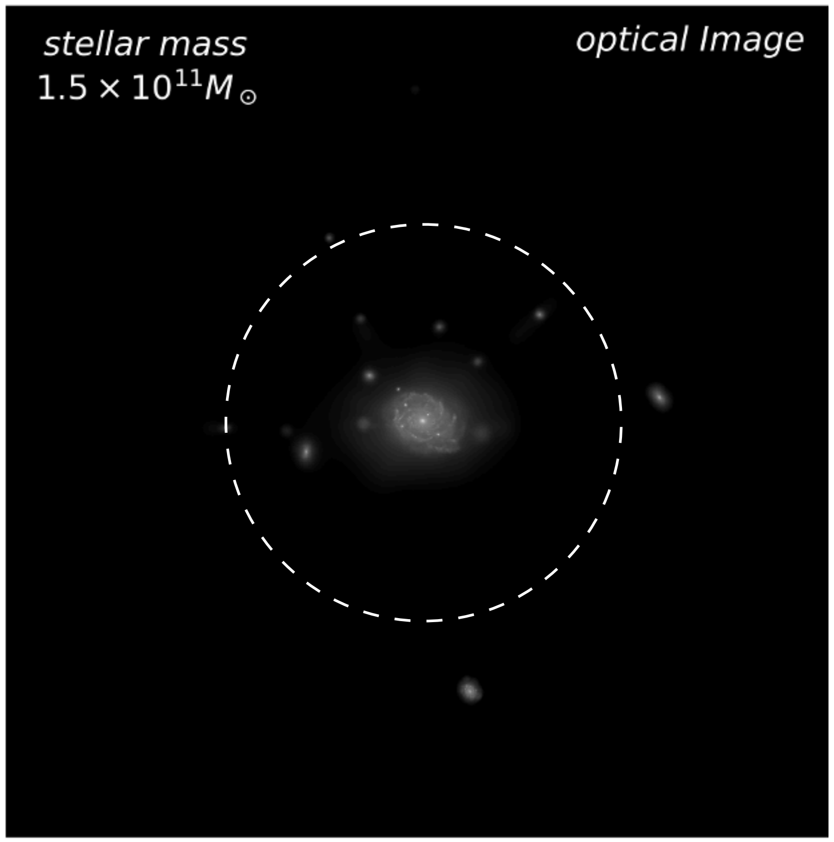

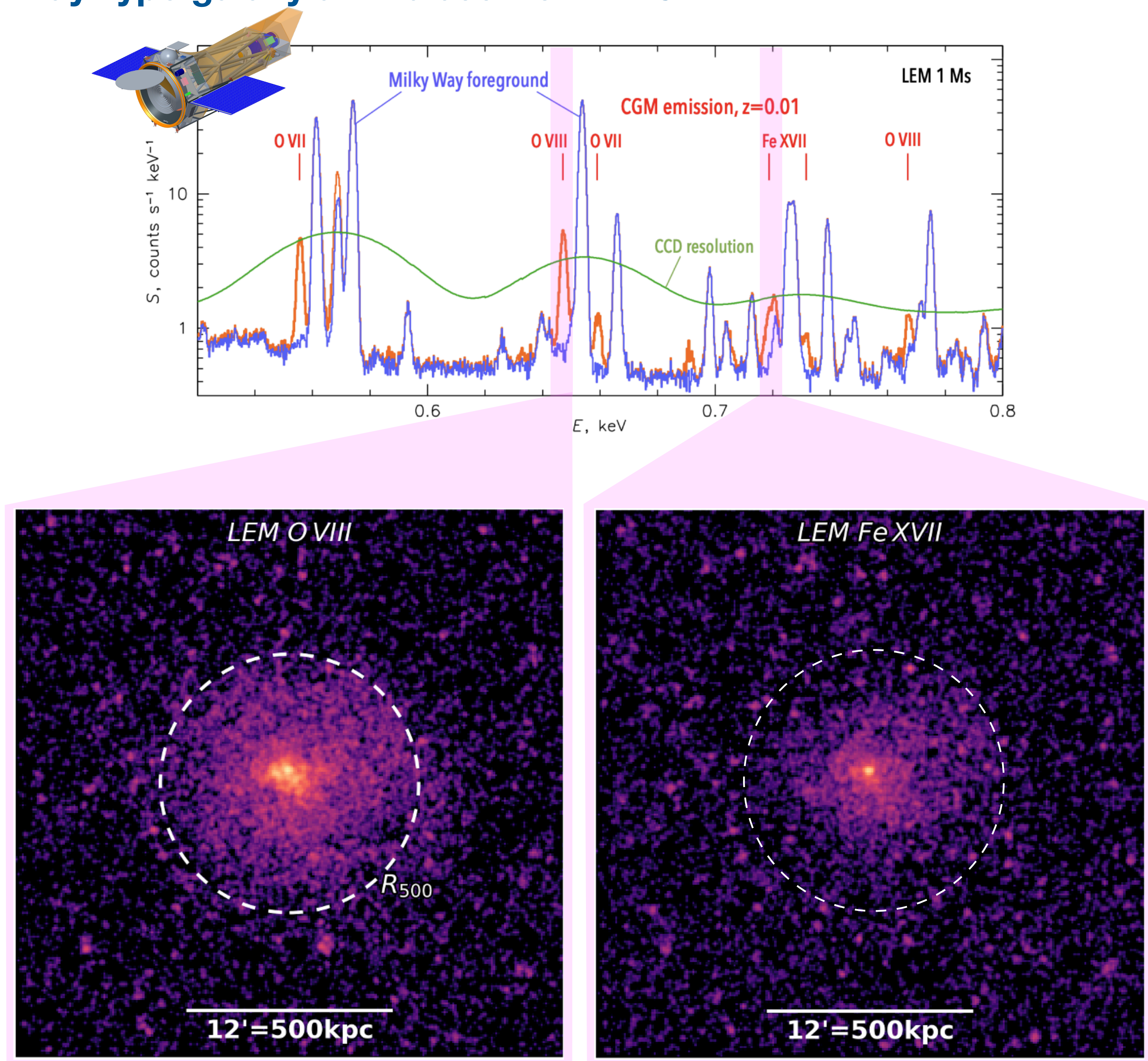

Schellenberger et al., submitted
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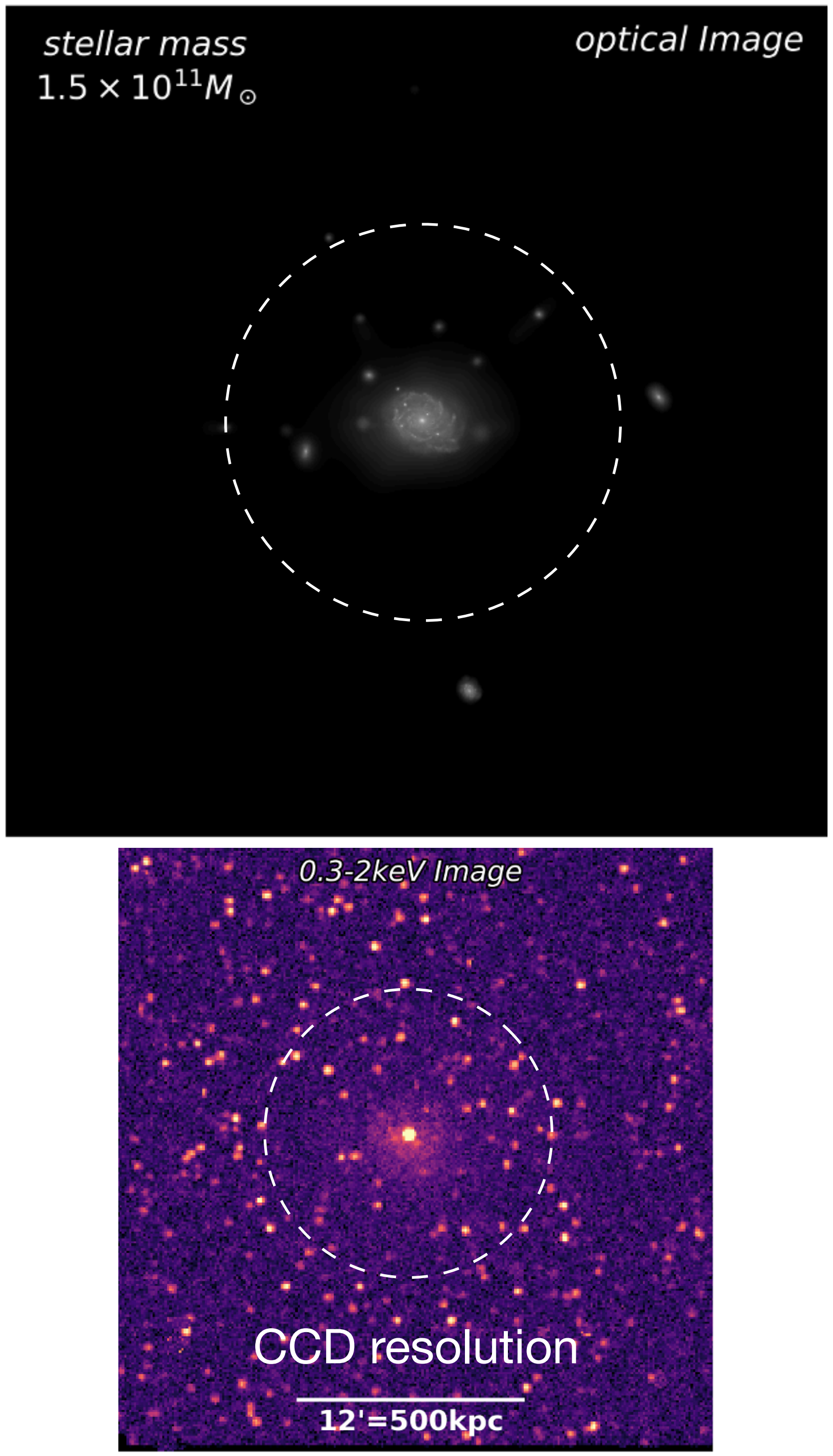

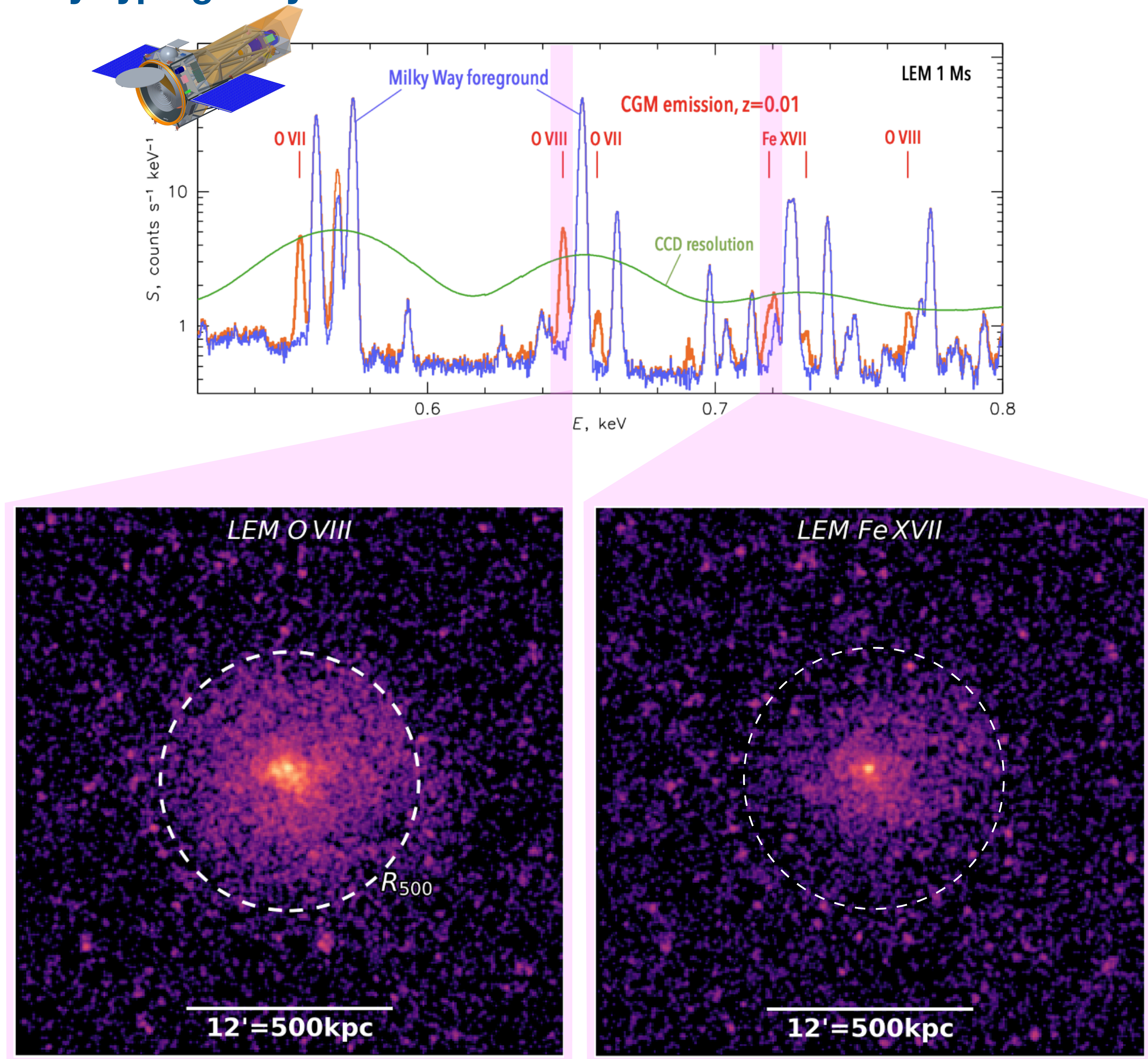

Schellenberger et al., submitted on behalf of LEM collaboration

The main goal:
Determine how CGM regulate galaxy evolution

- Are galaxies around the Milky Way mass scale surrounded by extended hot, volume-filling gas halos (CGM)? Has feedback ejected some of this gas from galactic potential wells?

- What drives galactic *outflows* that suppress star formation?
    - Mode of feedback: thermal or kinetic?
    - Is kinetic feedback impulsive (e.g., SMBH, producing Fermi bubbles) or continuous (SN wind - no bubbles)?

- How do *inflows* feed the ongoing star formation in Milky Way-type galaxies?

And many more …

See talk by John ZuHone

on behalf of LEM collaboration

LEM
LINE EMISSION MAPPER

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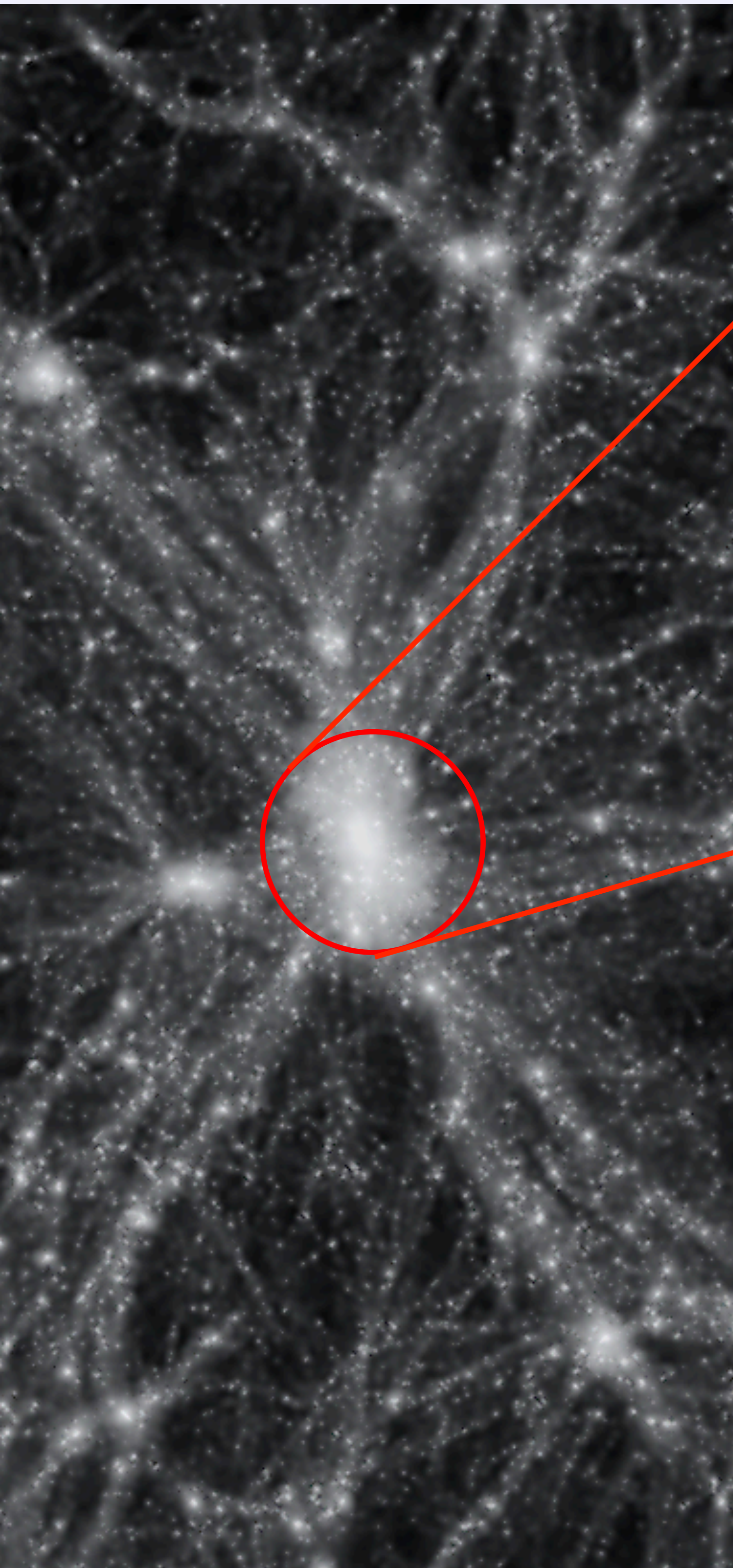
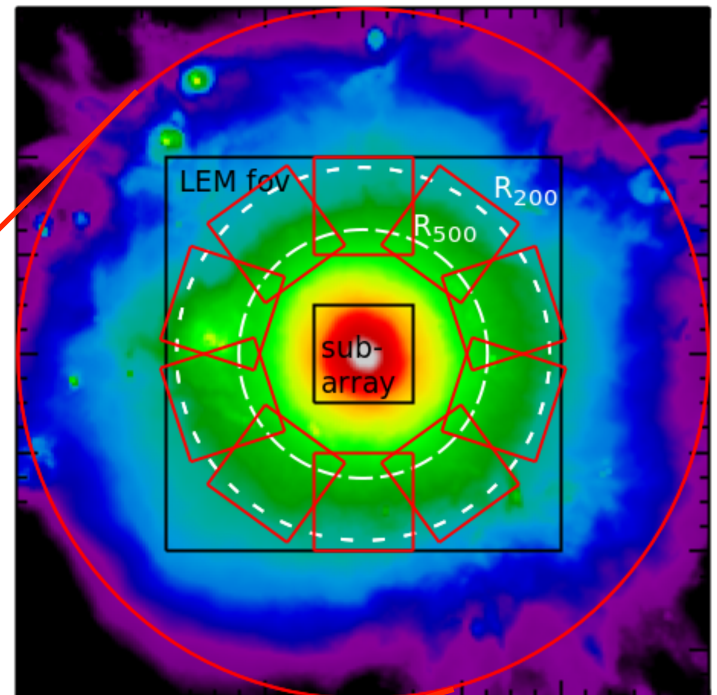
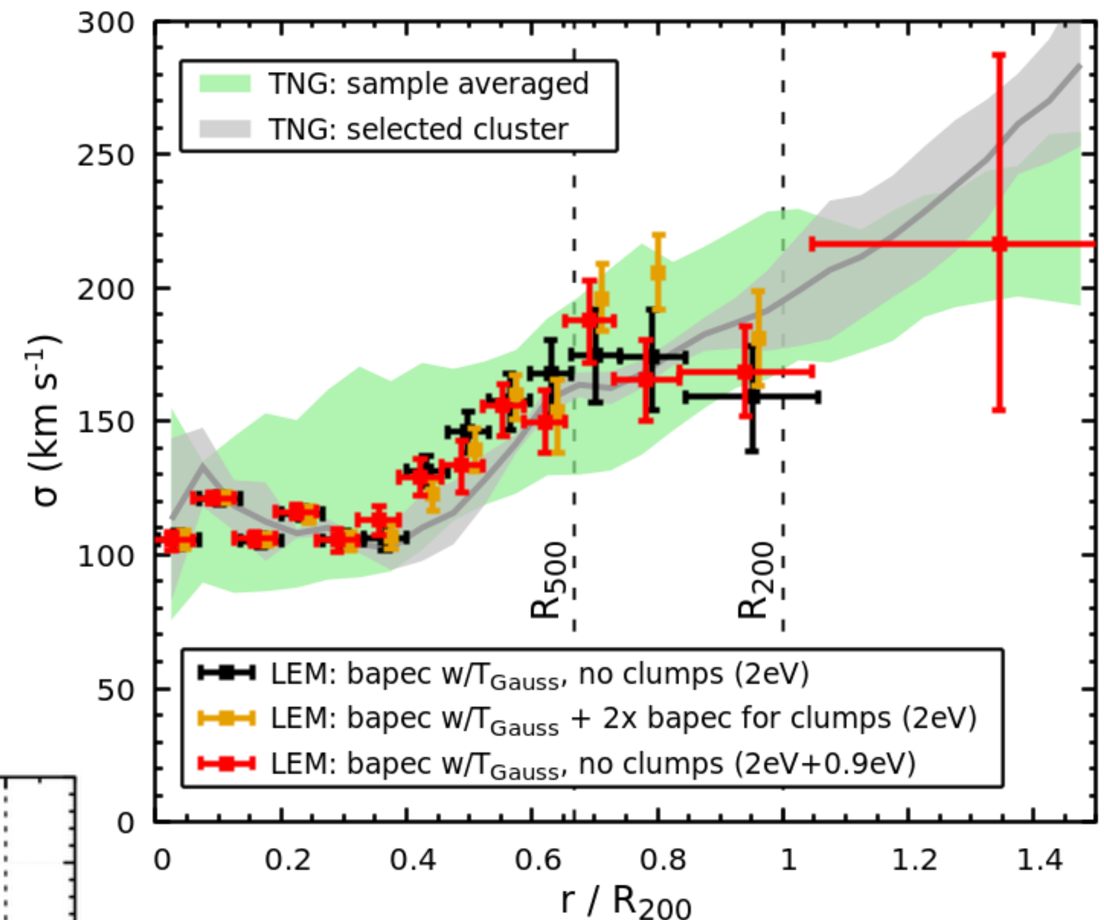
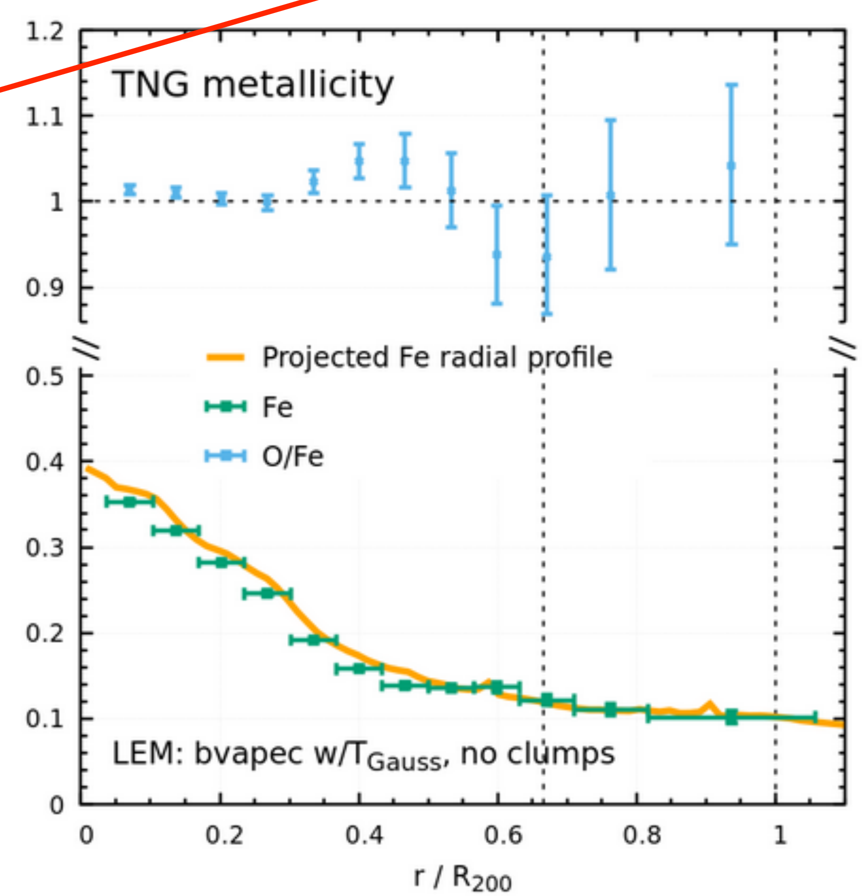








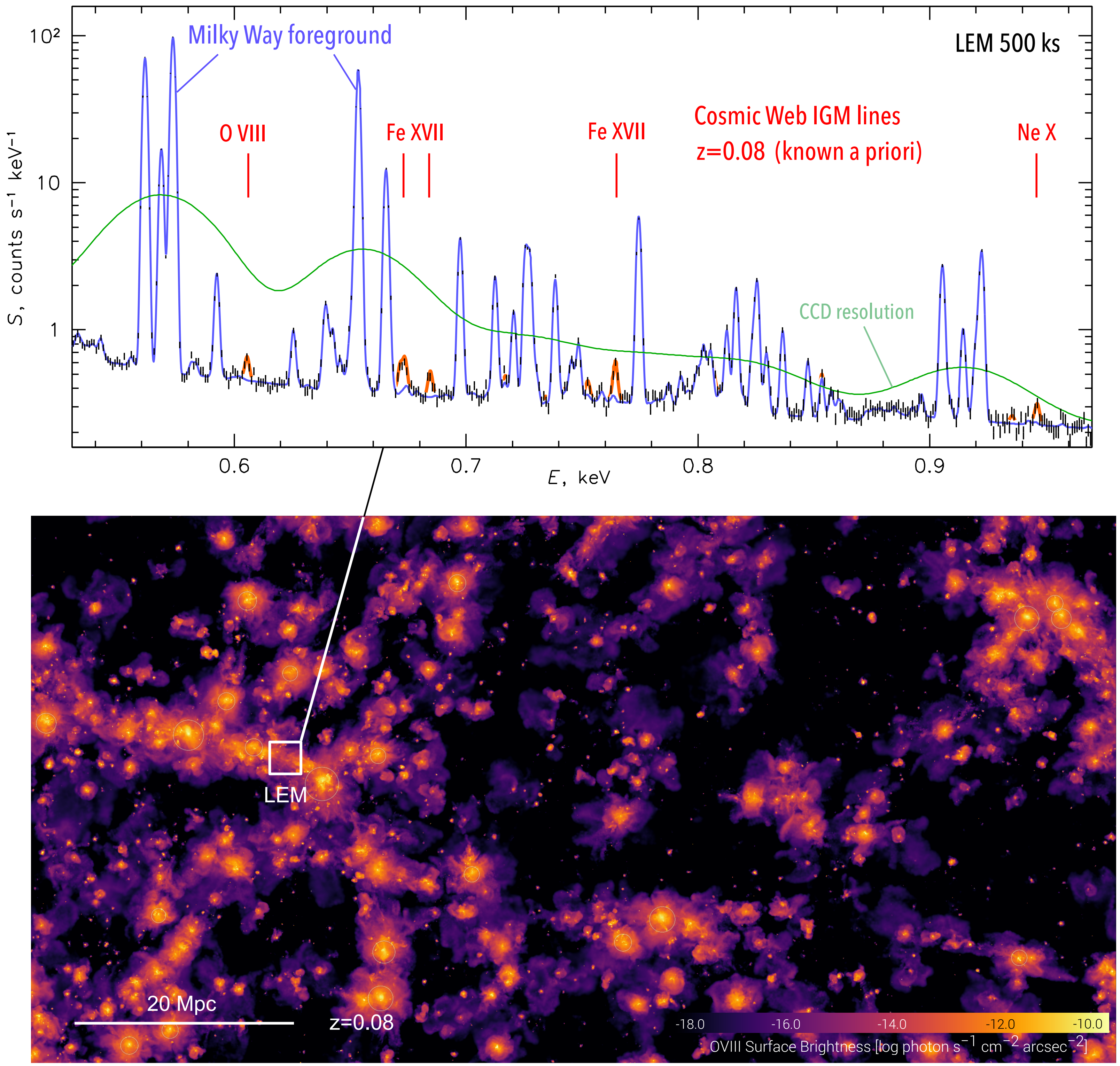
- When and how was IGM enriched?
- What types of stars and SN have produced the bulk of metals?
- How the flow of matter along the Cosmic Web filaments virializes and thermalizes in clusters?

on behalf of LEM collaboration

Zhang et al., in prep.

Line Emission Mapper (LEM)

Mapping the IGM in Emission



Have galaxies been proficient chemical polluters of the Cosmic Web?

Or have the feedback products been kept inside the galactic halos?

LEM will probe a depository of metals ejected from galaxies over their lifetime

on behalf of LEM collaboration

Credit: M. Markevitch

Summary

The future of high-resolution X-ray spectroscopy of galaxy clusters, groups, and galaxies is bright!

- RGS and Hitomi showed the wealth of physics hidden in high-resolution spectra of galaxy clusters, groups, and massive galaxies: first measurements of velocities, accurate abundance measurements, robust resonant scattering detection, multi-T diagnostics, possible charge exchange, SNIa progenitors and many more!

- XRISM diffuse extragalactic PV program: physics of AGN feedback from clusters to massive galaxies, a few per cent level abundance measurements, origin of abundance peaks/dips, detection of rare elements, resonant scattering, charge exchange, non-thermal pressure support, gas microphysics, turbulence power spectra, physics of winds in starburst galaxies, hot gas in spiral galaxies and more.

- Possible exciting (more) distant future: LEM detection of low surface brightness emission from cluster outskirts, cosmic filaments and hot halos around galaxies down to MW mass. Expanding our collected knowledge on scales of galaxies and beyond virialized regions.