Line Emission Mapper (LEM) – Probing the Physics of Cosmic Ecosystems

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A mission concept for the NASA 2023 Astrophysics Probes AO

Presentation to the X-ray Science Interest Group

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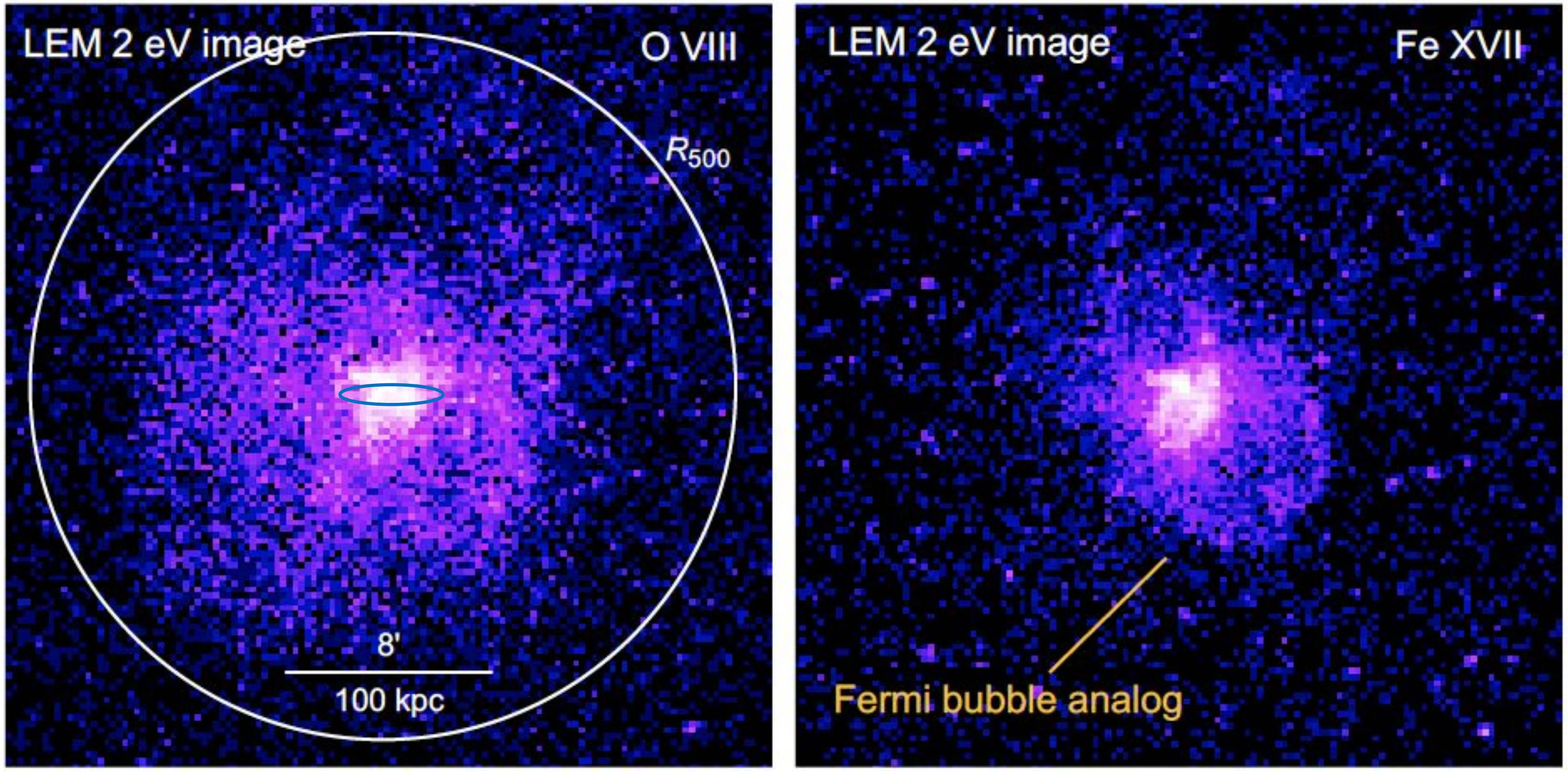
LEM Probe mission concept – Cosmic Ecosystems

- Conceived to study large-scale, low surface brightness diffuse X-ray emission in the 0.2–2 keV band
- Large FOV (30'x30') Si meta-shell X-ray optic – 40x larger FOV than ATHENA XIFU, 10” angular resolution HPD (XMM-like imaging)
- X-ray microcalorimeter – 15” pixels, 2 eV spectral resolution, 1 eV in central 8' array
- Designed as a mapping instrument – primary science will be achieved via a program of directed observations of galaxies, clusters, and Galactic structures plus an all-sky survey for detailed study of Milky Way halo and diffuse structures
- L1 orbit – optimized for long continuous observations of targets
    - >90% observing efficiency to maximize science return
- **Opens enormous discovery space for Guest Observations in all areas of X-ray astrophysics**

LEM Science: The Power of Wide-Field, Large Area, High Spectral Resolution X-ray Imaging Spectroscopy



LEM simulated images of a Milky-Way-mass galaxy at z = 0.01 in 3 eV wide bins centered on the OVIII and FeXVII CGM emission lines. Panels are 30’ with 15” pixels (LEM FOV and pixelation), 1 Ms. Blue ellipse: the size of the optical disk, seen edge-on. The bright Milky Way foreground is almost completely resolved away, taking advantage of the galaxy’s redshift.

LEM Science Drivers – Summary

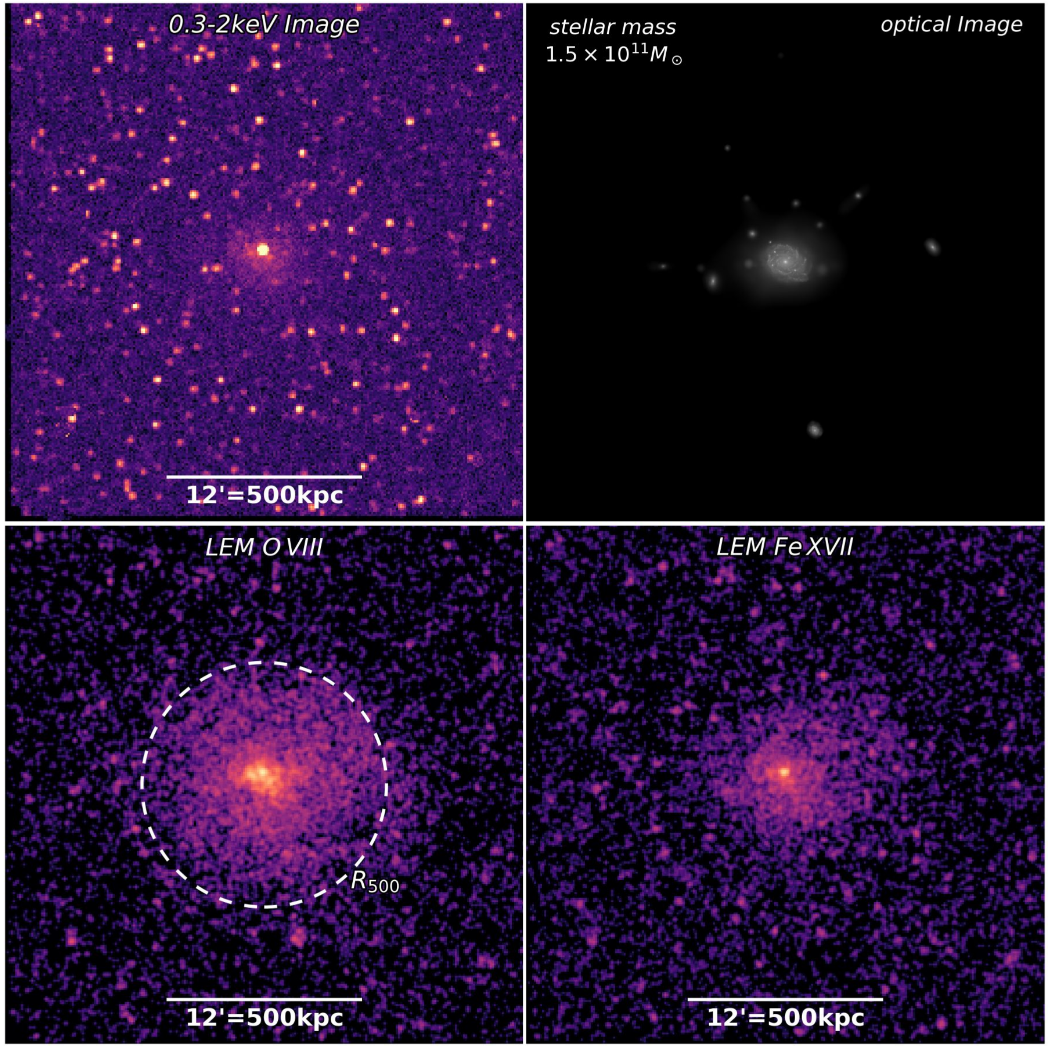
Primary LEM science theme – *Cosmic Ecosystems* – transforming our understanding of formation of cosmic structure over 6 orders of magnitude in length scale (pc to Mpc). LEM is optimized to address key science questions in Astro2020

- ***Map*** galactic gas halos over a range of masses – gas temperature, density, elemental abundance, and velocity - "key missing link" in our understanding of galaxy formation (enabled by **grasp and high spectral resolution**)
  - including halo of our own Milky Way in unmatched detail via shallow all-sky survey – feasible because of **large grasp**
- ***Map*** metals in IGM to probe cosmological history of galactic feedback
- ***Map*** star-forming regions, SNRs of all ages, Fermi bubbles, Galactic Center chimneys, giant molecular clouds, Local Hot Bubble – **survey the *Cosmic Ecosystem* that is our Milky Way**
- **None of LEM key science can be done with wavelength dispersive spectroscopy or CCD/CMOS imaging**

LEM Science: Unveiling the Invisible Galaxy Halos

- LEM is an X-ray IFU that will ***map*** CGM halos (cannot be done with wavelength dispersive spectroscopy)
- Its high spectral resolution will separate faint CGM signal from the Milky Way foreground
- Its grasp (area × FOV) will let us map a sample of nearby galaxies across a range of masses/types

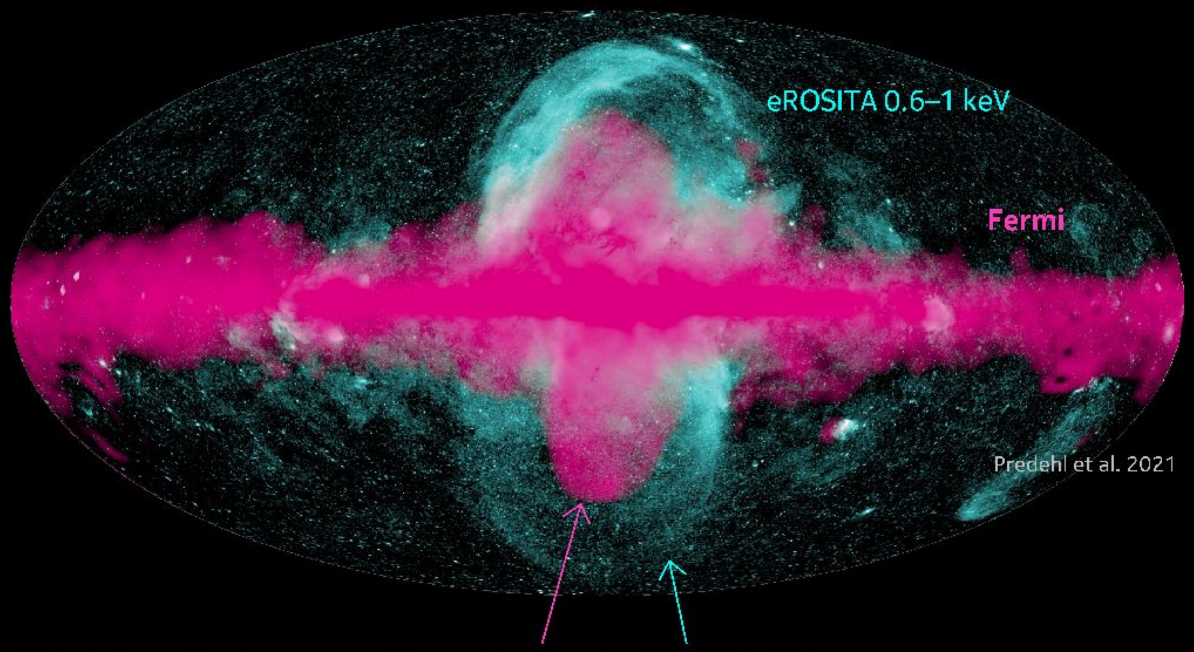
- Complex structure of CGM X-ray line emission – diagnostics of gas conditions, feedback mechanisms
- We will measure density, temperature, entropy, velocity, and elemental abundance of the gas in the haloes of a representative sample of galaxies.
- ***LEM measurements will complete the picture of galaxy evolution***



Simulated 1 Ms LEM observation of a Milky Way-type galaxy at z=0.01 from TNG50.

LEM Science – Shallow All-Sky Survey

Our location inside the Milky Way gives us a unique viewpoint on **black hole feedback in galaxies.** Fermi bubbles are blown by the supermassive black hole at the center of our Galaxy. LEM will see how our black hole shapes the Milky Way gas halo in unprecedented detail.



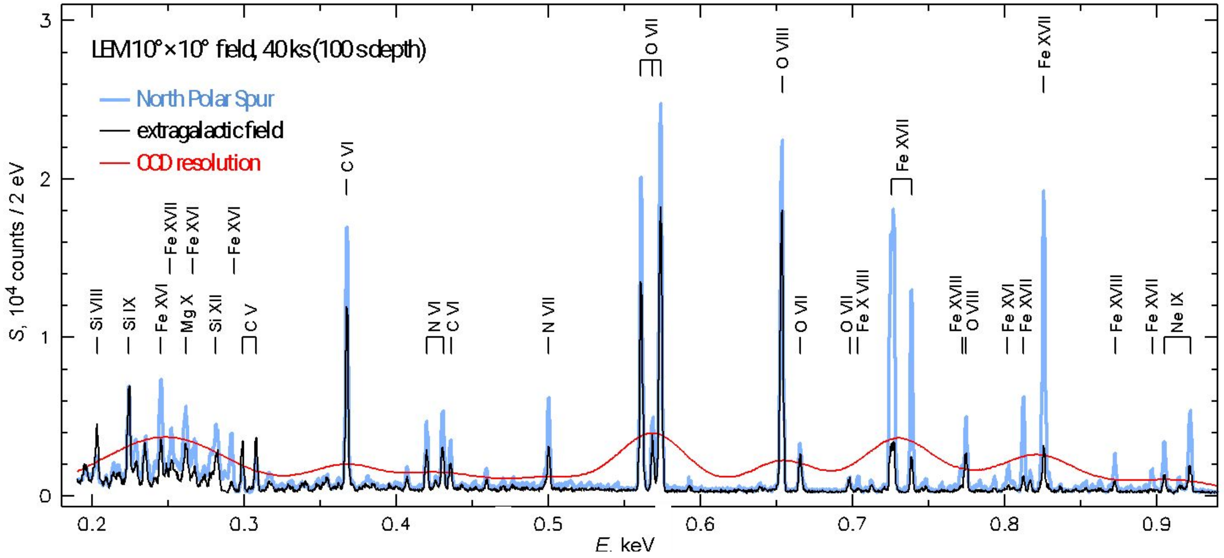
Predehl et al. 2021

LEM shallow all-sky survey will map Fermi and eROSITA bubbles

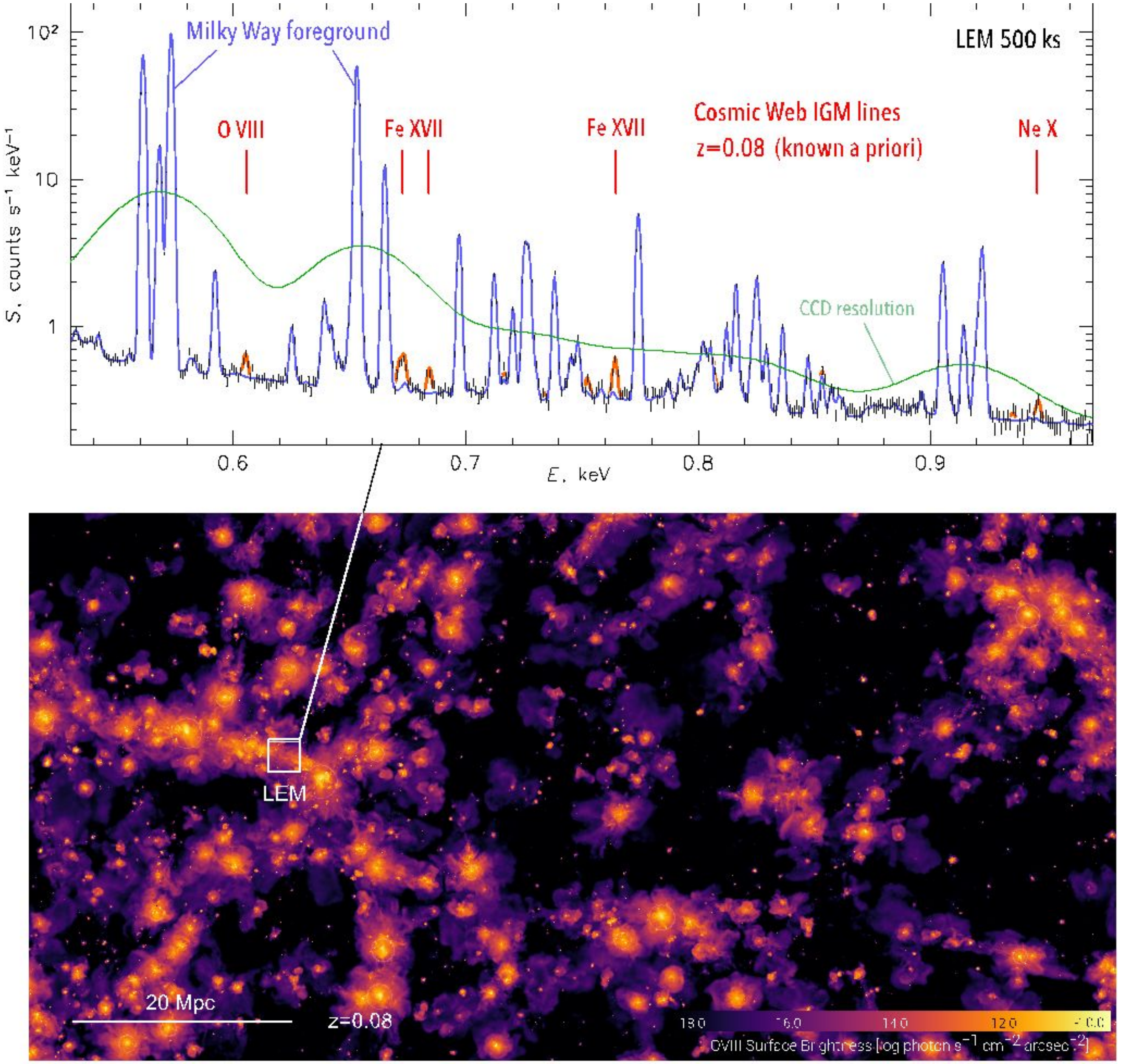
- Map **velocities** of gas displaced and uplifted by Fermi bubbles (using Doppler effect)
- detect **nonthermal emission** from Fermi bubbles (by resolving line-dominated diffuse foreground), giving the total energy of the explosion that created them

Probing galactic gas flows from inside the Milky Way

- ☐ LEM science program will include a shallow all-sky survey to probe Milky Way CGM
- ☐ At 100s depth, half-sky coverage (omitting the disk) takes 8 Ms or 3 months of observing time. **LEM's large grasp makes it possible**



LEM Science: Probing Cosmic Web



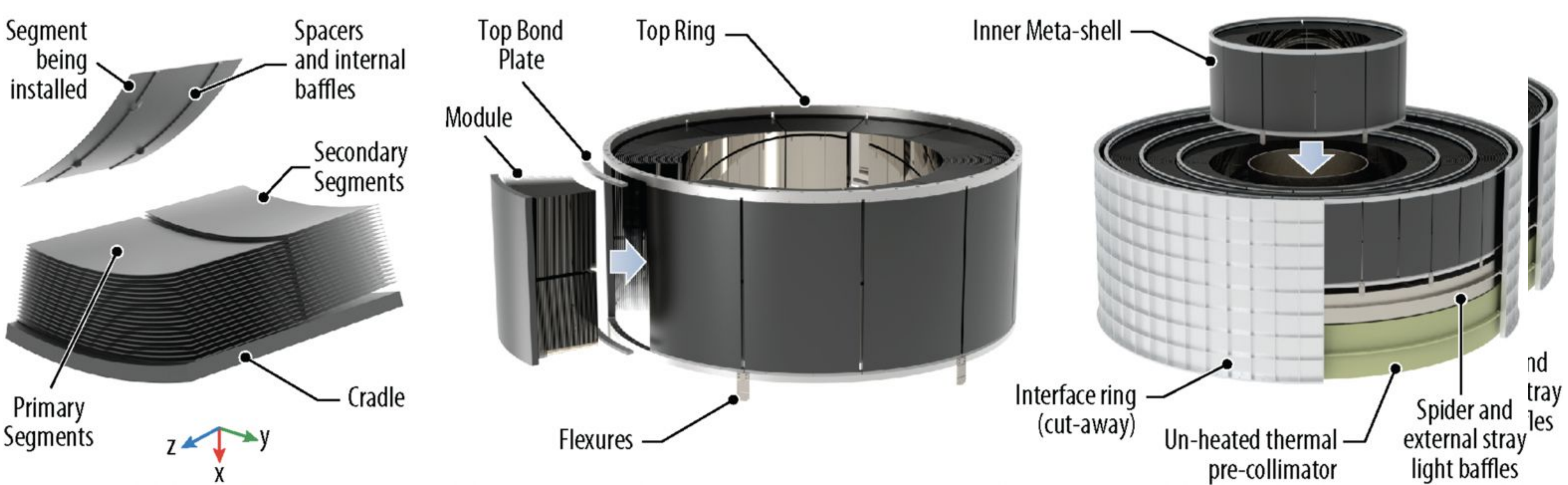
Intergalactic Medium (IGM) between galaxies and clusters is the ultimate **repository of metals ejected from galaxies over their lifetime**

- ❑ LEM will detect metals in IGM, probe cumulative effect of galactic feedback
  - ❑ **high spectral resolution is required**

- ❑ LEM will resolve Milky Way foreground to detect faint signal from IGM
- ❑ LEM's large grasp is required for collecting enough photons from very faint IGM lines
- ❑ While IGM *presence* on random sightlines can be detected via absorption-line studies, mapping requires wide-field X-ray IFU

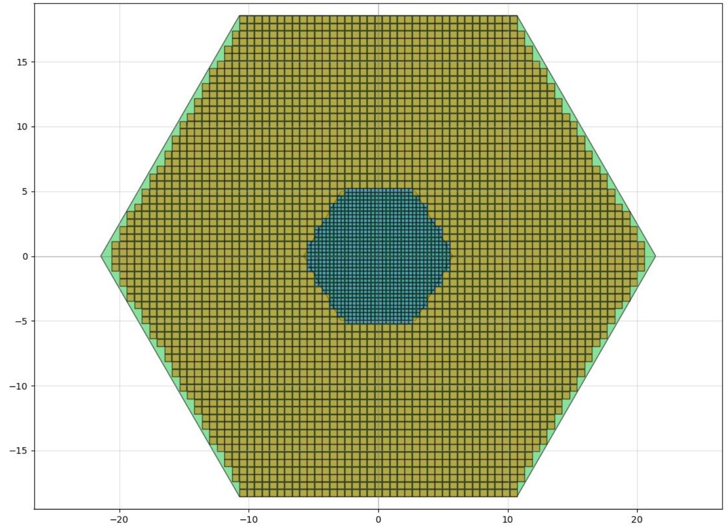
LEM Technical Capabilities – the X-ray Optic

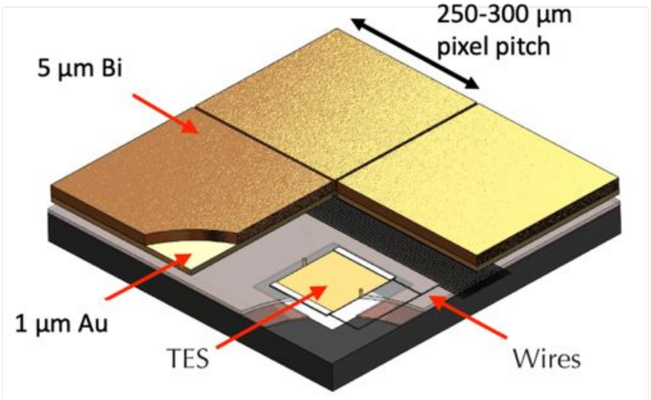
- **GSFC developed – decades of investment**
- Pt-coated Si thin-shell grazing-incidence mirror, d = 1.5m, f = 4m
- Require 10" HPD angular resolution
  - 2.7" HPD already demonstrated at 4.5 keV in the lab (Mar 2021) for single module
  - A 15” detector pixel contains 90% of the PSF
- Synergy with mirror development for STAR-X, AXIS, and HEX-P
  - **TRL 5 demonstration required as part of StarX phase A – the LEM optic is effectively undergoing a TRL 5 demonstration as well**



LEM Technical Capabilities – the microcalorimeter focal plane array

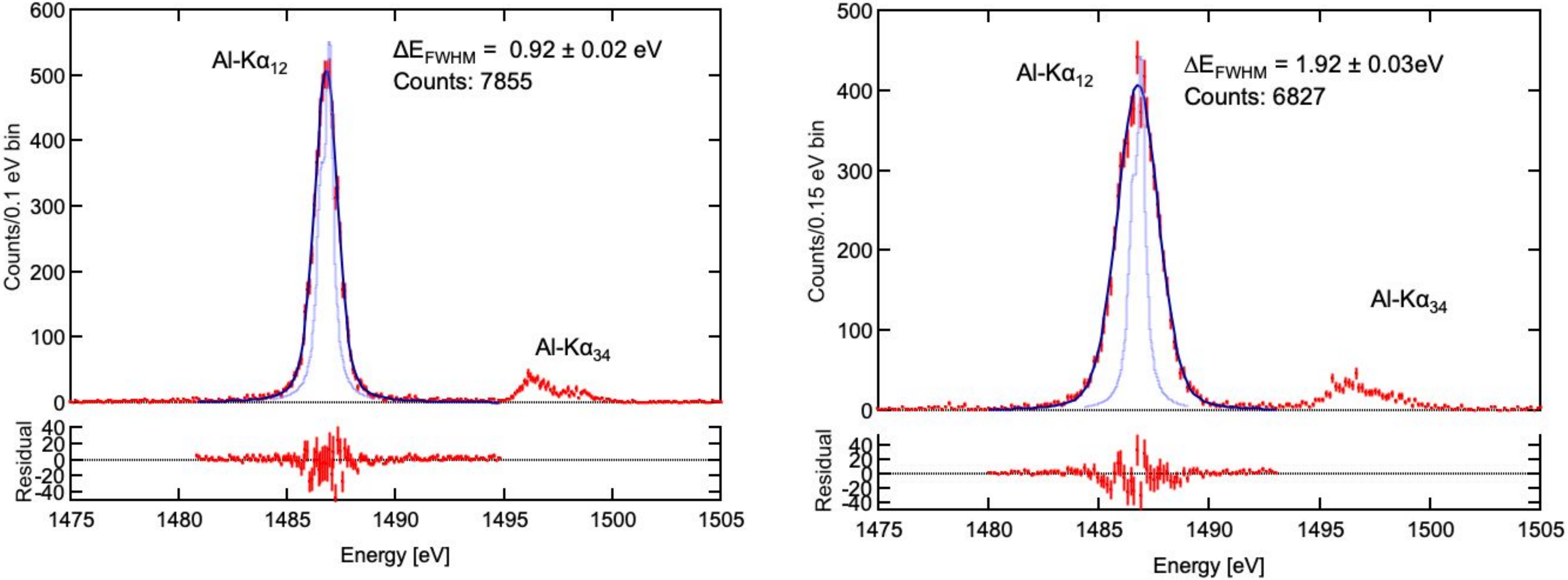
- Lockheed Martin dewar and cryocoolers
- **GSFC detectors, focal-plane assembly, sub-50-mK cooler, aperture filters**
- Detectors based on Transition-Edge Sensor (TES) detectors being developed for Athena/X-IFU
  - Same basic sensor design, but lower T_c and absorber composition optimized for <2 keV
  - 15” (0.29 mm) pitch
  - 8’ x 8’ square central sub-array with 1 pixel/TES, **0.9 eV resolution**
- outer array filling out to hexagonal perimeter – area equivalent to 30’ x 30’ square
  - Hydras (4 pixels/TES) to provide more FOV/channel with same angular resolution – **2.0 eV resolution**





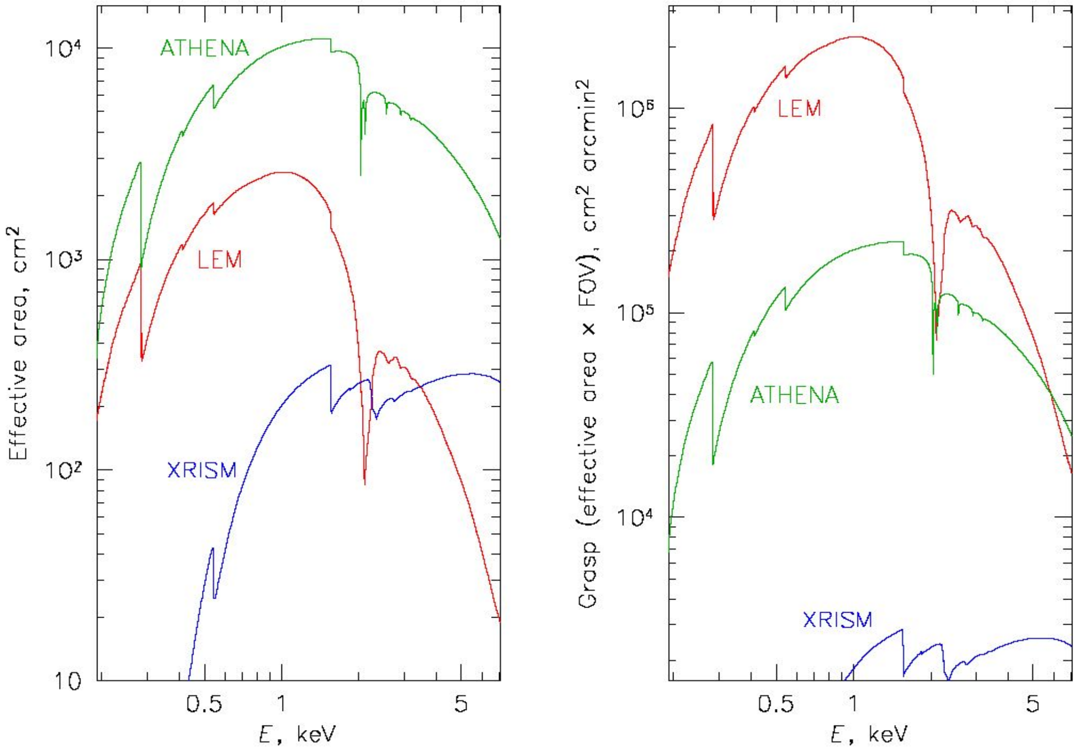
LEM absorbers will be 0.64 µm Au

LEM microcalorimeter focal plane array – recent results



Laboratory measurements of energy resolution of LEM TES pixels – 0.92 eV (left) and 1.92 eV (right) demonstrated for single pixels and hydras, respectively

LEM Technical Capabilities



Comparison of LEM, Athena XIFU (pre-reformulation) and XRISM Resolve effective area and grasp

		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

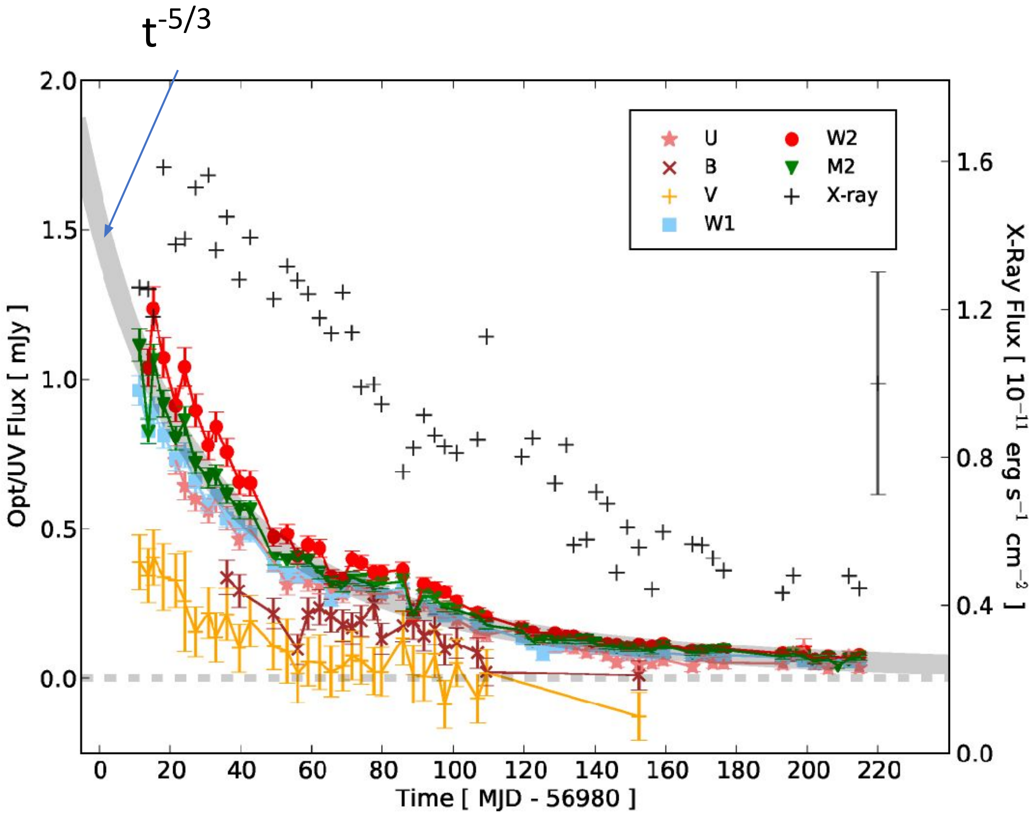
Key parameter comparison of LEM, XRISM Resolve, Athena XIFU (pre-reformulation), and the notional Chinese HUBS mission

LEM Guest Observer Science

- Cooling, AGN feedback in galaxy clusters
- Protoclusters
- High-z AGN
  - every LEM deep field will have 3-4 AGN at $z > 2.5$ - Fe Kα line
  - disk reflection
  - heavily obscured AGN
- Galaxy-scale AGN outflows
- Variable black hole winds
- Hot ISM in nearby galaxy disks
  - Separate ISM and XRBs in $z < 2$ galaxies
- Jellyfish galaxy tails mixing with ICM
- Abundances in SNRs
- Light echo on giant molecular clouds in GC
- Time Domain and MMA science
- Shocks at radio relics in galaxy clusters
- H II region/superbubble evolution
- Planetary Nebulae
- Flare frequency distribution in exoplanet host stars
- Proto-stellar accretion rate variability
- Interstellar dust in emission and absorption
- Charge Exchange in Jovian magnetosphere
- Shallow All-Sky Survey
  - Emission mechanisms in LHB
  - Find all old, faded SNRs
  - Nonthermal emission in Fermi bubbles

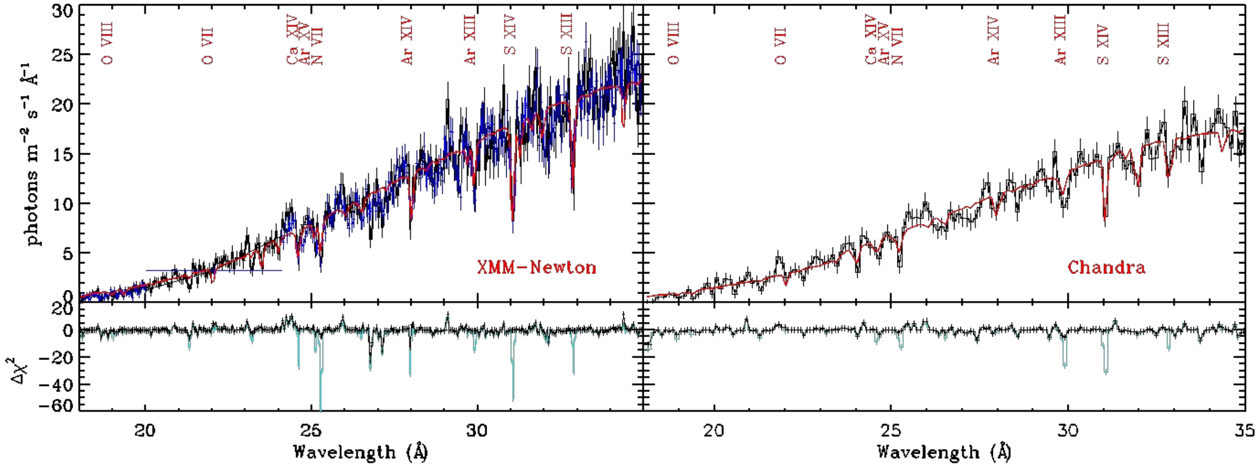
- **Unexpected discoveries!**

LEM Time Domain Science – TDEs



Example: ASASSN14li

(one of the brightest and best-studied TDEs)



Multi-wavelength light curve (left) and deep (500 ks) Chandra/HETG and XMM/RGS exposures of ASASSN14li

Figures from Miller et al. 2015

- Hundreds of TDEs per year will be detected by ground-based methods, many expected to be X-ray bright for months to years
- Follow-up of these and other nuclear transients can probe powerful winds

Final Thoughts about LEM

- ❑ Will deliver ***paradigm-changing*** science in the area of 'Formation of Structure' in a Probe package
- ❑ Will provide the X-ray astrophysics community with a powerful new tool that will transform all areas of high energy astrophysics
- ❑ Will fit comfortably into the $1B PIMMC with healthy margins in both cost and schedule
- ❑ LEM Science Workshop at the CfA – Feb 28th to Mar 3rd – all are welcome to sit in on the discussions
  lweb.cfa.harvard.edu/lem/workshops/2023/

Backup

LEM Science: How do Galaxies form?

Main players:

- Dark Matter halo
- Stars
- Central supermassive black hole (SMBH)
- Circumgalactic Medium (CGM), Intergalactic Medium (IGM)

Feedback between stars, SMBH, CGM / IGM over cosmic time shapes the local Universe

Virtually no data on bulk of CGM or IGM

- CGM dominated by X-ray emitting ion species – best studied in soft X-rays
- CGM extends far beyond optical size of galaxy
- X-ray emission drowned out by bright Milky Way foreground – impossible to study at CCD spectral resolution

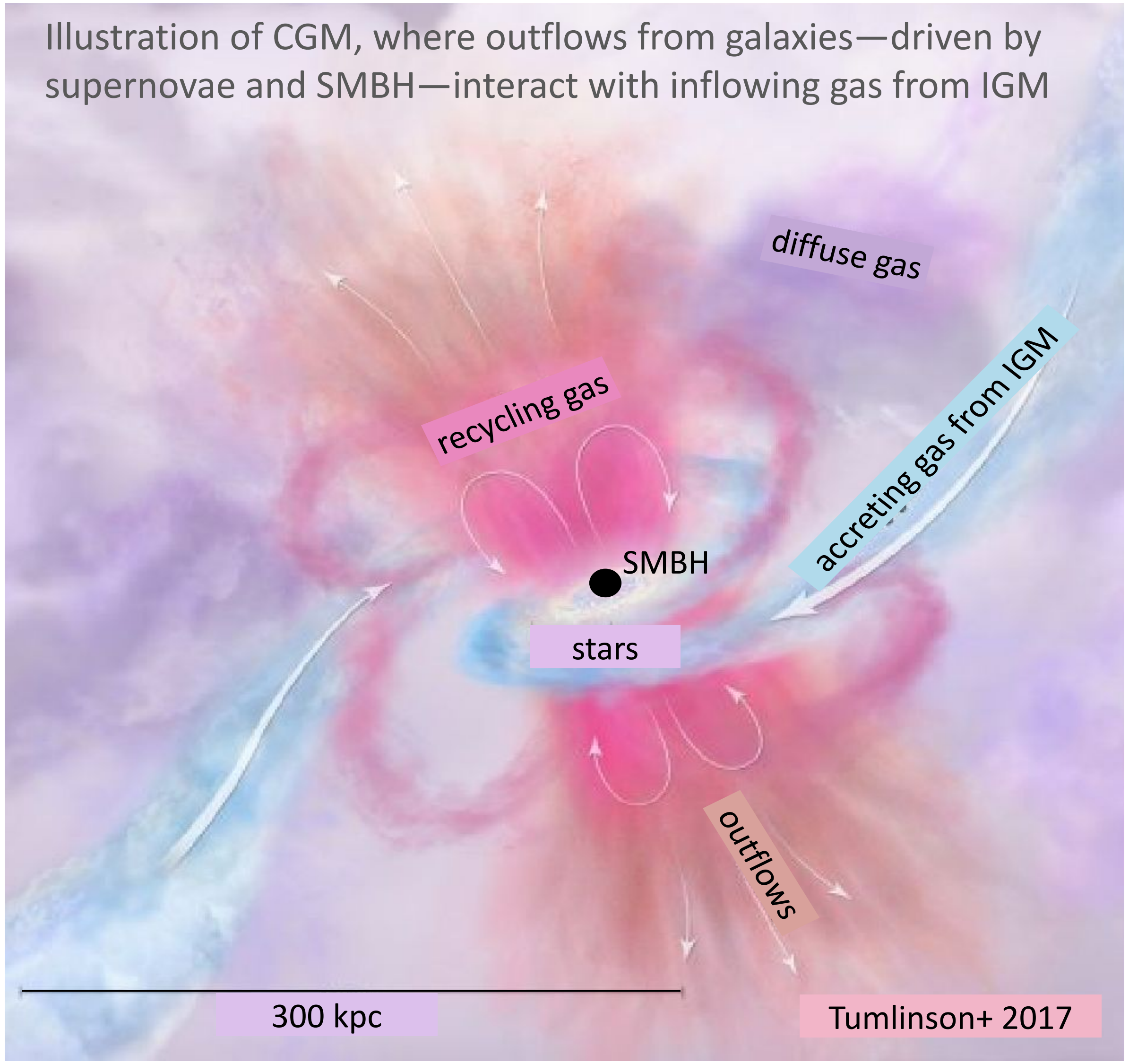
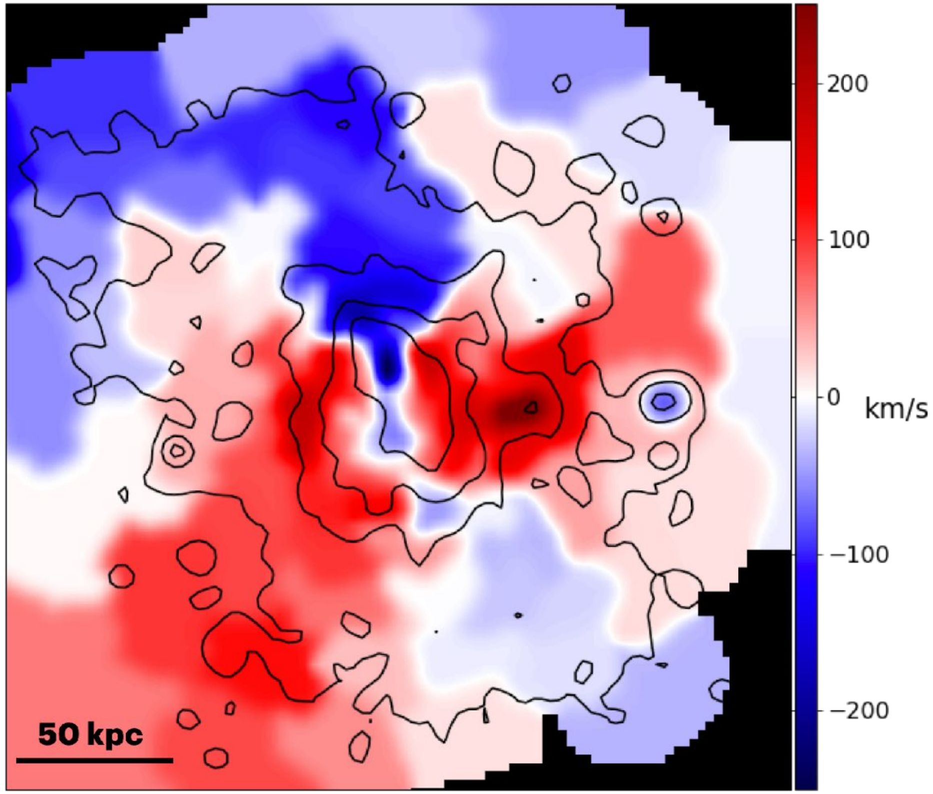


Illustration of CGM, where outflows from galaxies—driven by supernovae and SMBH—interact with inflowing gas from IGM

Tumlinson+ 2017

Mapping the Velocities of Galaxy Halos

LEM Velocity map of a $M_\star = 1.5 \times 10^{11}\ M_\odot$ galaxy

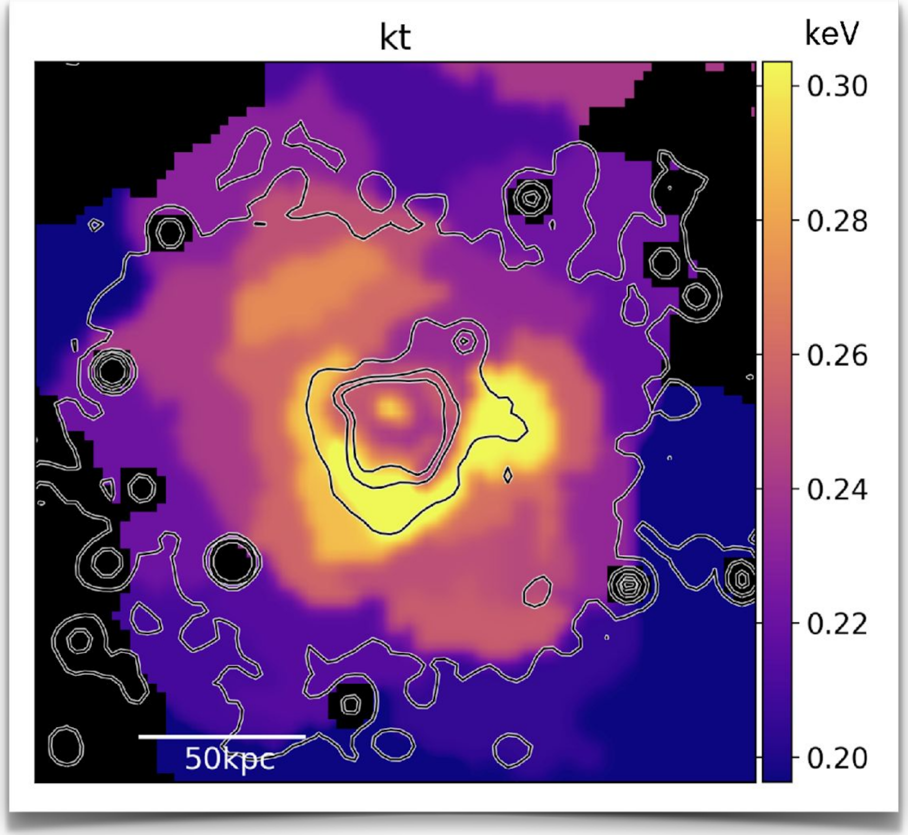


Schellenberger et al, in prep.

- LEM will measure the velocity of gas flows with 30-50 km/s
- Tracing SN and BH driven outflows and even rotation
- Velocity structure can be traced in the inner 40-80 kpc (r = 3-6 arcmin)
- Temperature and abundance maps (O/Fe, C/Fe) maps can also be derived
- **High resolution (0.9 eV) subarray provides precise velocities**

Mapping the Temperatures of Galaxy Halos

LEM temperature map of a $M_\star = 1.2 \times 10^{11}\ M_\odot$ galaxy

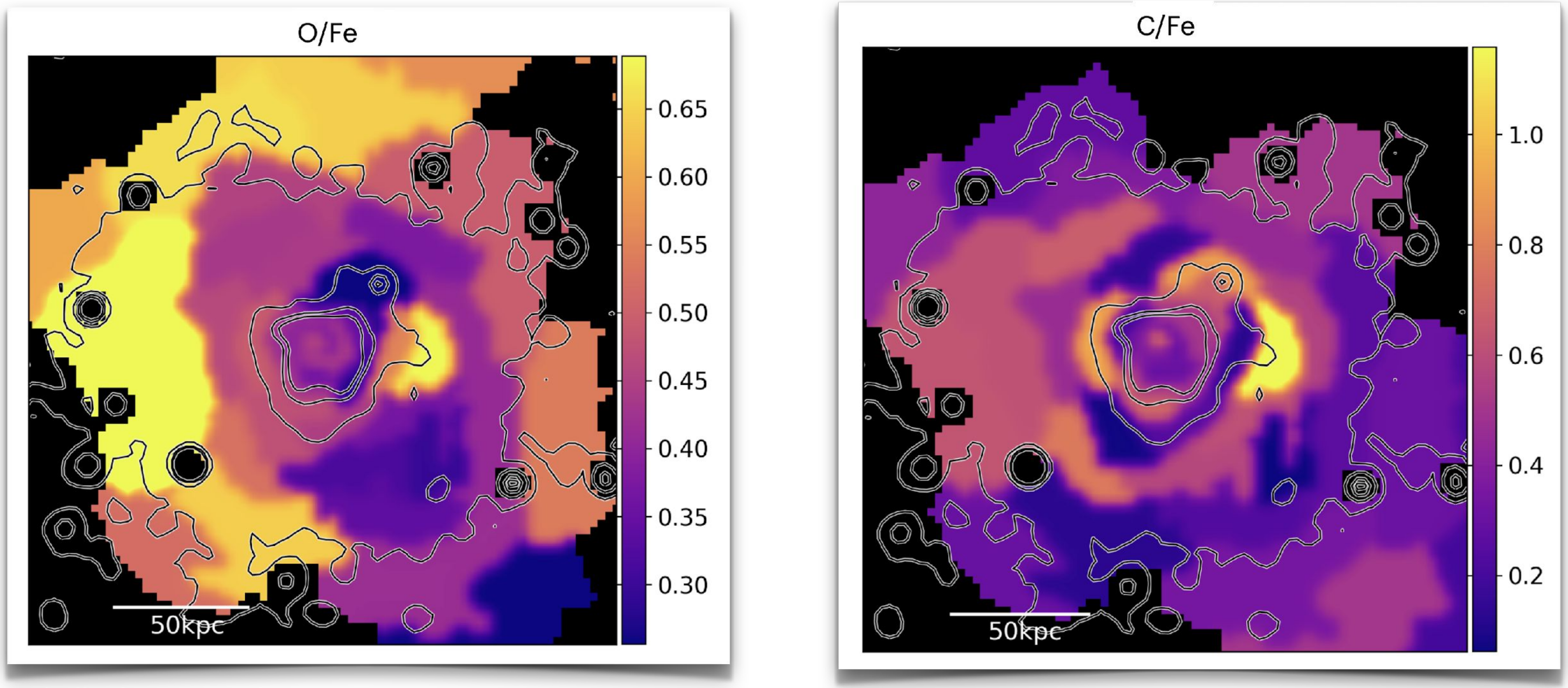


Schellenberger et al, in prep.

- LEM will measure gas temperatures with 0.05-0.1 K
- Detailed temperature structure of MW-type (and more massive) galaxies can be accurately mapped
- Temperature structure can be traced in the inner 50-150 kpc
- **High resolution (0.9 eV) subarray provides accurate temperatures** — map was generated using 2 eV simulation

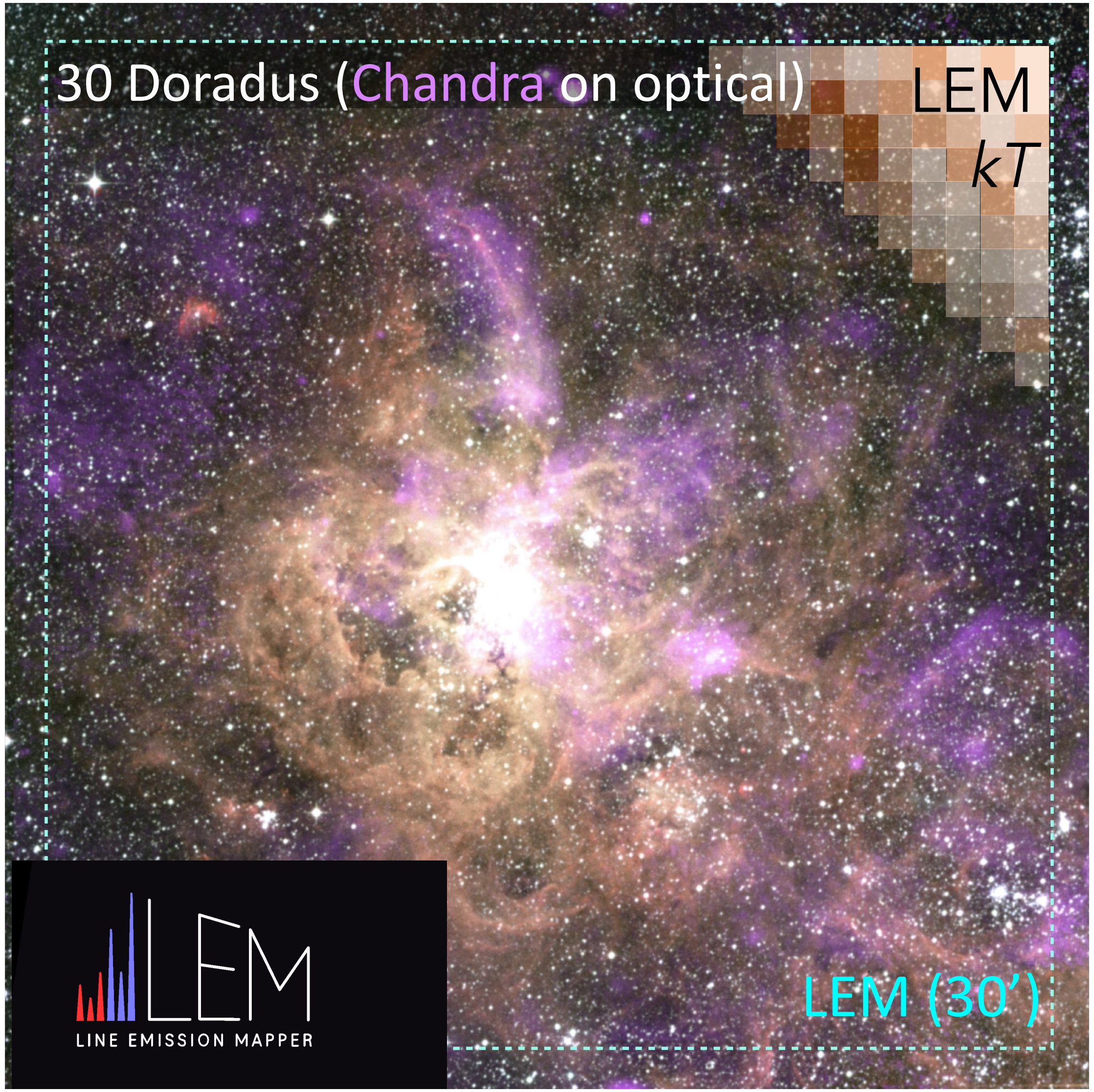
Mapping the Metallicity of Galaxy Halos

LEM O/Fe and C/Fe map of a $M_\star = 1.2 \times 10^{11}\ M_\odot$ galaxy



Schellenberger et al, in prep.

LEM Science: Star Forming Regions, Stellar Feedback



How do massive star clusters impact their surroundings?

1. How do bubbles grow?
2. How do bubbles break out?
3. How do winds form?

Key quantities: kT, P, Δv

Need to *map* thermodynamic properties across bubbles

Spatial variation diagnoses growth, breakout

Bubbles have d ~ 100 pc (2" at 10 Mpc)

Local Group bubbles span 0.1-20 deg

CCD energy resolution is *inadequate*

XMM and Chandra cannot distinguish many CIE models from those including NEI or CX

Metallicity and density are degenerate

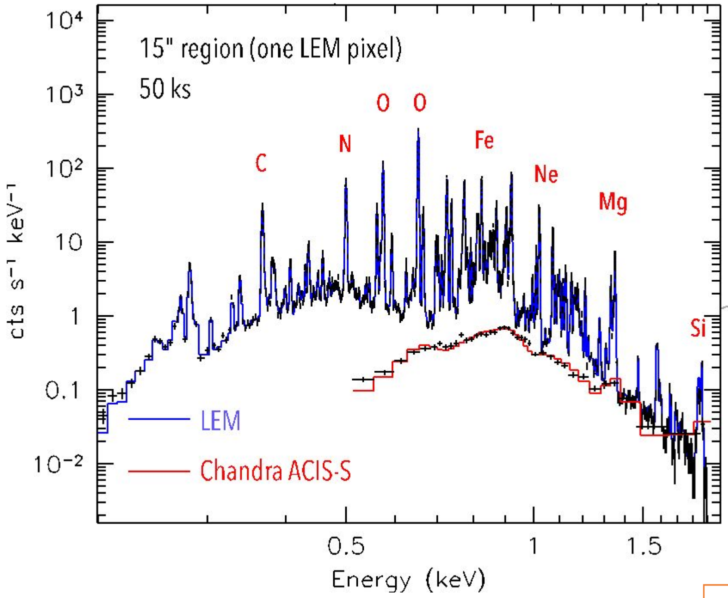
These combine for up to 10x uncertainty in n*KT!

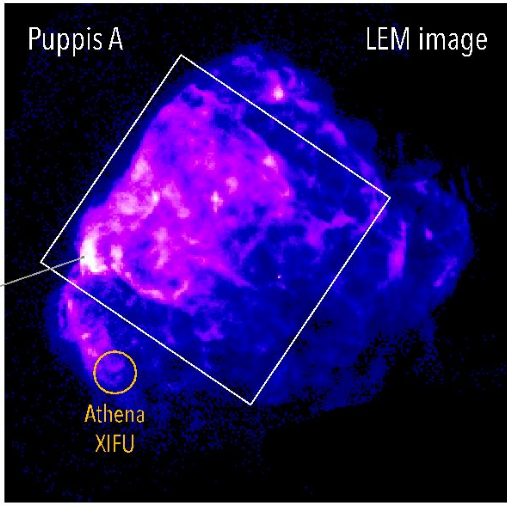
Notional LEM program

Map 20 MW/LMC/SMC/M31/M33 bubbles on 1-10 pc scales to measure n, kT, P, Z, τ_{NEI}, CX fraction, nonthermal energy density, velocities

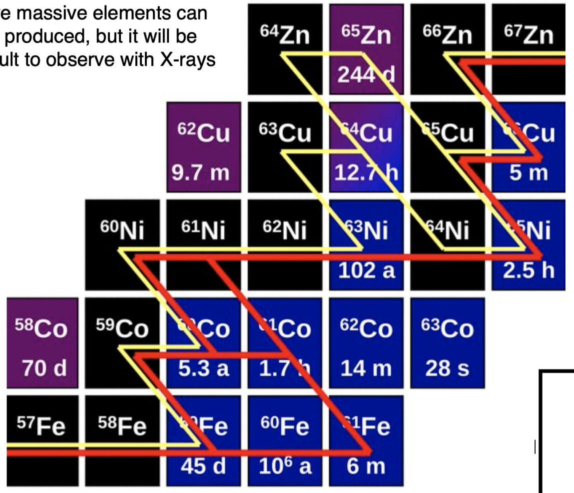
LEM Science: Supernova Remnants

- Supernovae chemically enrich their environments and can drive future generations of star formation
- LEM will:
  - Directly measure the line of sight velocity of the ejecta in young ejecta dominated SNRs such as Cas A and Tycho, allowing for a 3D kinematic reconstruction of the explosion for the entire SNR
  - Measure the abundances of weak s-process nucleosynthesis in O-rich SNRs – a direct probe of the progenitor metallicity – measure Ni/Fe, Co/Fe/Cu/Fe, Zn/Fe from L-shell emission in the LEM band
  - Measure O/F ratio in O-rich SNRs – probes neutrino asymmetries during the explosion – Puppis A, G292.0+1.8 and 1E 0102-7219 are good candidates as the temperature of the ejecta is low enough that low-Z elements are not fully ionized
- LEM science has a strong need for updated atomic data and accurate nucleosynthetic yields





More massive elements can be produced, but it will be difficult to observe with X-rays



- The seed of the weak s-process is ^{56}Fe, which depends on Z/Z_{sun}
- Elements produced by weak s-process are increased during RSG phase of stellar evolution

The main neutron source is

$$^{22}\mathrm{Ne}(\alpha, \mathrm{n})^{25}\mathrm{Mg}$$

during He-burning