Measuring Inflows, Outflows, and Rotation in the Hot Circumgalactic Medium of Nearby Simulated Disc Galaxies with High-Resolution X-ray Spectroscopy

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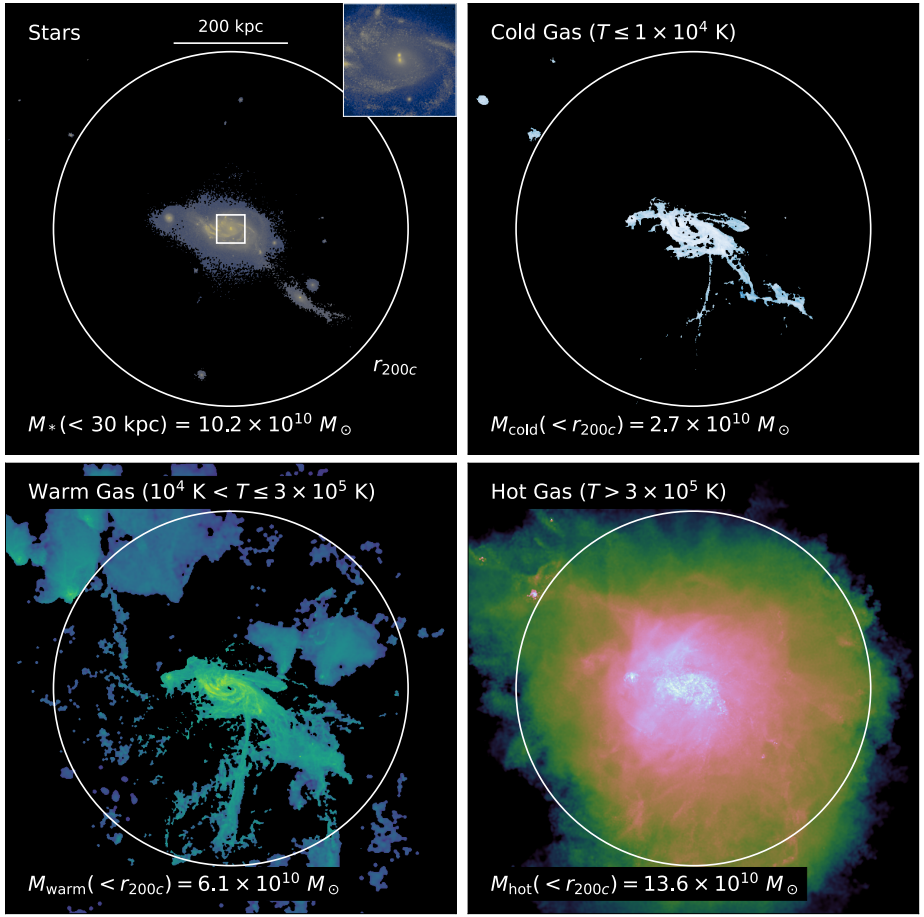
with Gerrit Schellenberger, Anna Ogorzalek, Ben Oppenheimer, Jonathan Stern, Ákos Bogdán, Nhut Truong, and many others…

The Circumgalactic Medium

- The circumgalactic medium (CGM) is the multiphase gas medium filling the halos of galaxies
- The CGM is the repository of gas falling into the halo from the intergalactic medium and expelled from the galaxy via feedback from AGN and stars
- For galaxies with Milky Way mass and above, the dominant phase of the CGM is hot and emits in X-rays



Velocities in the Hot CGM

- Outflows
  - Feedback from AGNs, supernovae, starbursts
- Inflows
  - Cosmological accretion
  - “hot” or “cold” mode?
- Rotation
  - How much angular momentum does the hot CGM have?
- Turbulence

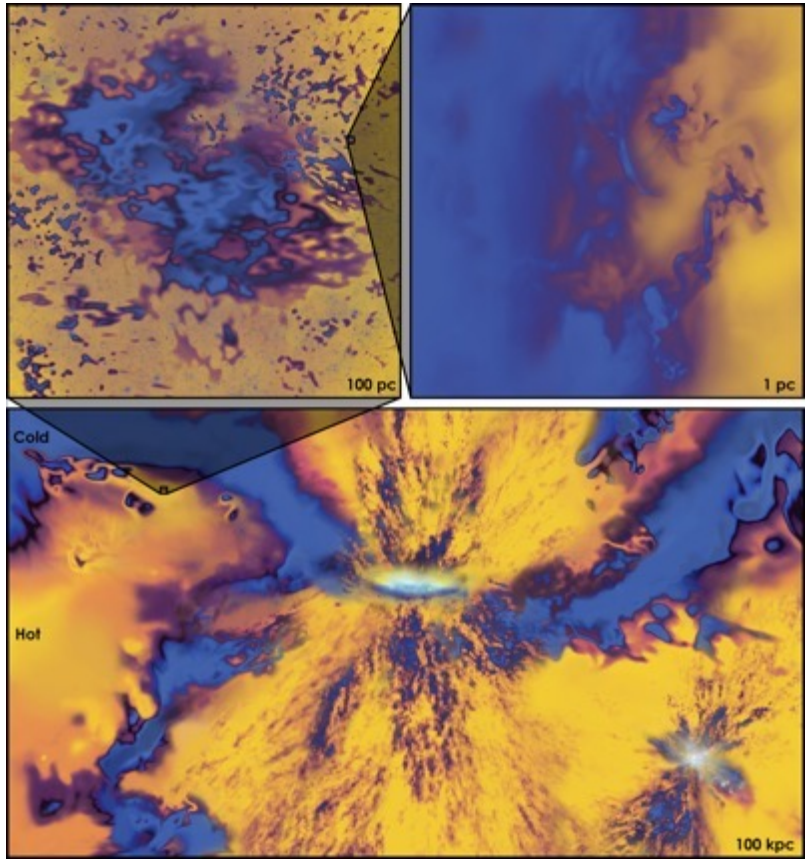
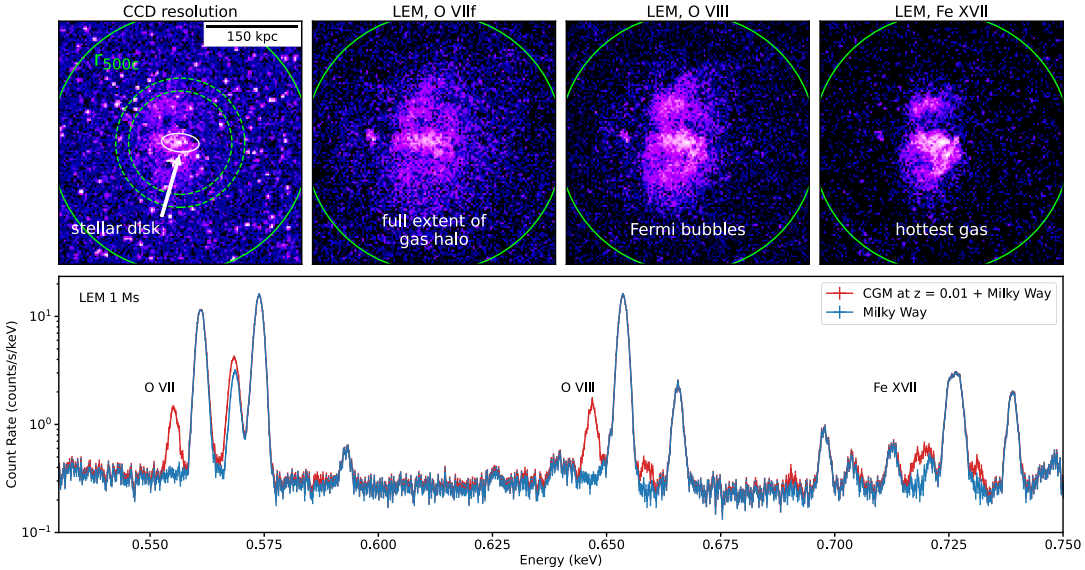


Figure credit: Aaron M. Geller, from Faucher-Giguère & Oh (2023)

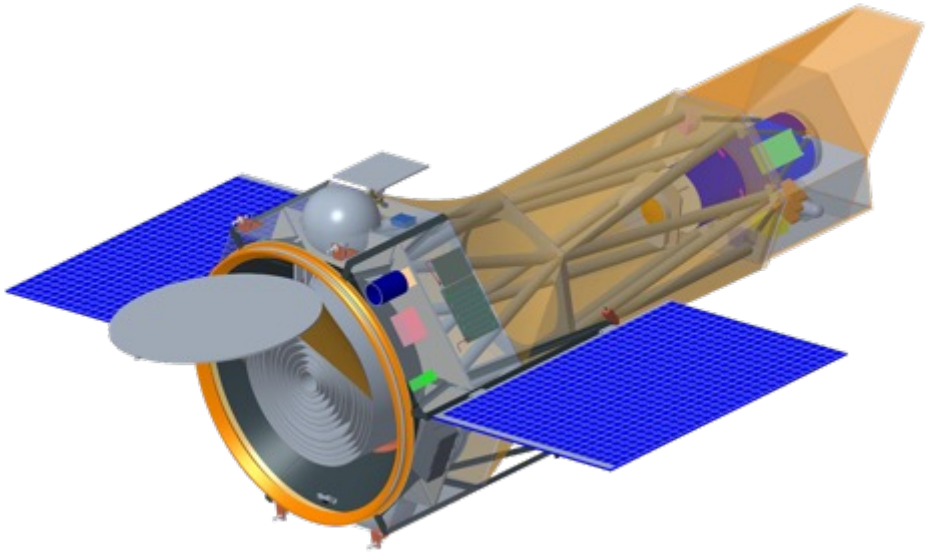
High Spectral Resolution is Necessary!

- Can’t measure velocities or even see the hot CGM (except the innermost parts in massive nearby galaxies) at all without it
- The MW hot CGM emits at the same atomic transitions (O VII, O VIII, Fe XVII, etc.) and is much brighter
- High spectral resolution allows one to distinguish the emission lines between source and foreground if the source is cosmologically redshifted
- Different lines reveal different phases, kinematics



LEM Observatory Design

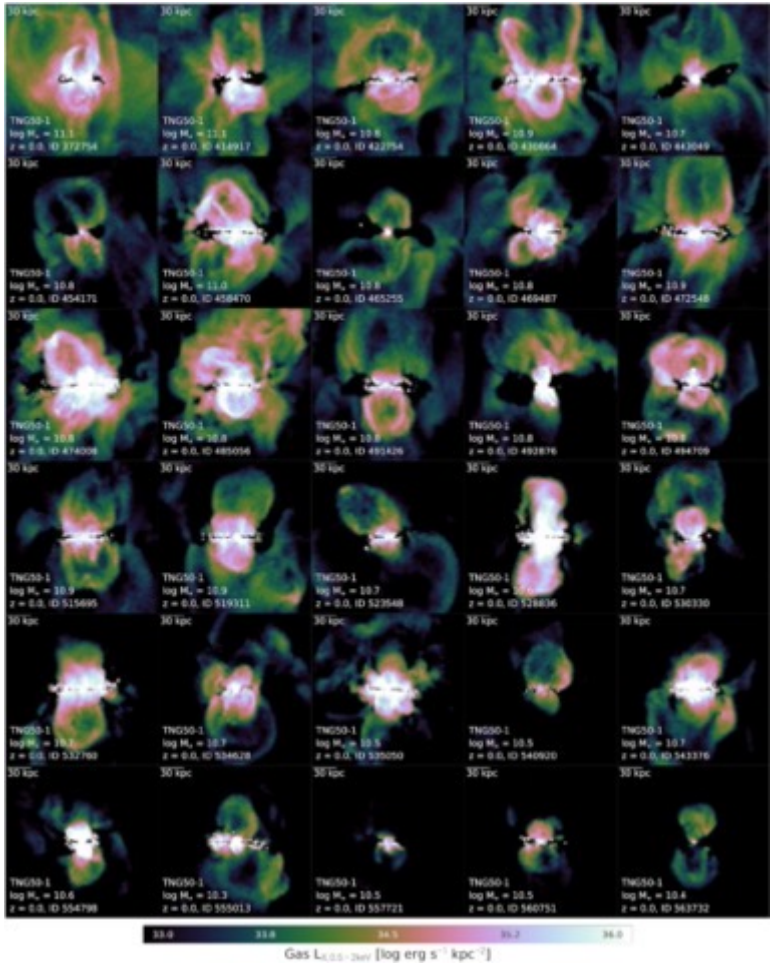
- The Line Emission Mapper (LEM) is an X-ray integral field unit (IFU) microcalorimeter
- Effective area ~4-6x Chandra/ACIS (launch) at 1 keV
- PSF of ~10”
- Field of view of 30’, main outer array with ~2 eV spectral resolution
- Inner array of 7’ with ~1 eV spectral resolution



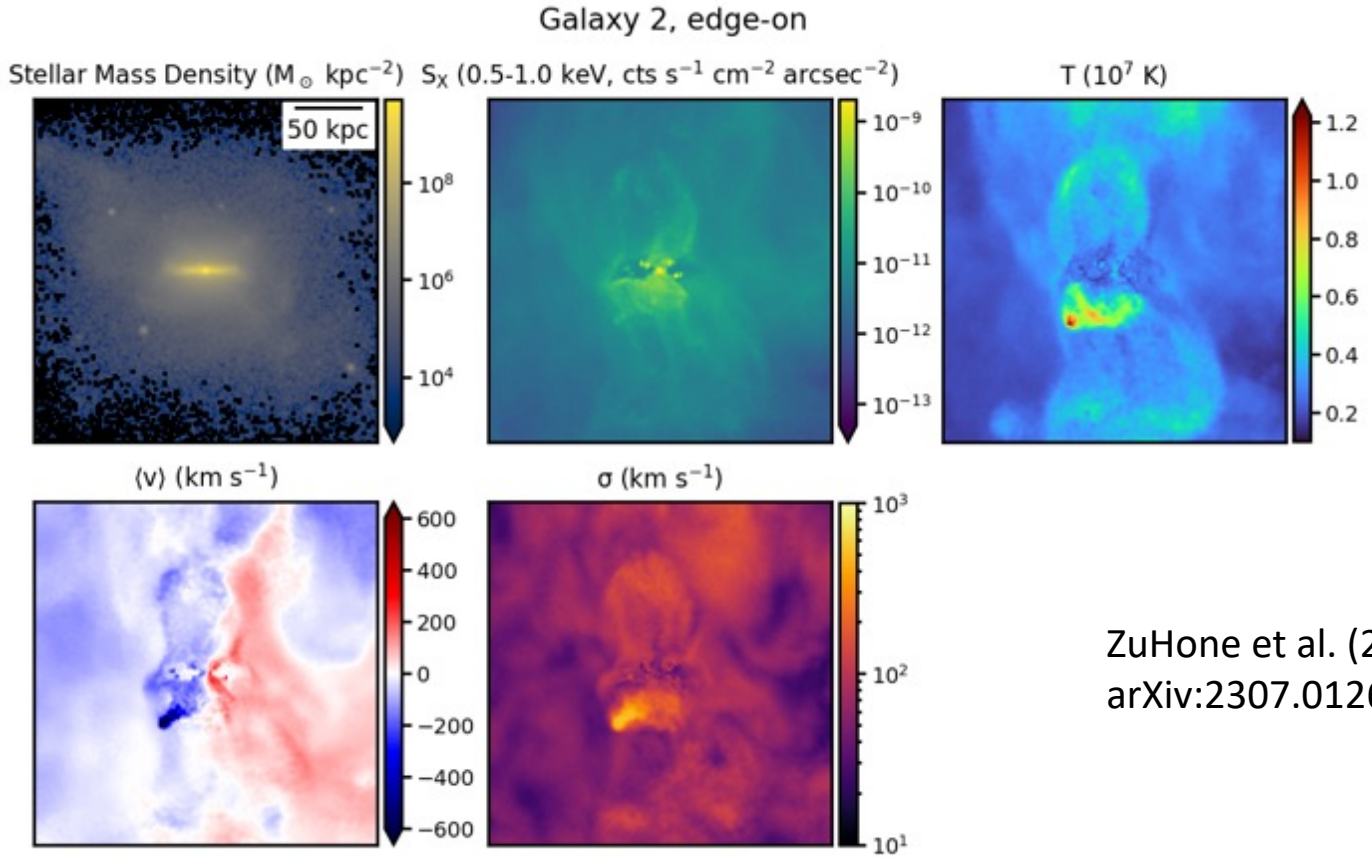
TNG50 Disk Galaxies Sample

- Used 6 galaxies from the Illustris TNG50-1 simulation, part of the MW/M31-like sample in Pillepich et al. 2021
- These galaxies all exhibit cavities like the Fermi/eROSITA bubbles seen in our own galaxy
- Used the pyXSIM code to simulate the X-ray emission from the galaxies, and the SOXS code to pass the emission through an instrument model for LEM

ZuHone et al. (2023), arXiv:2307.01269



Maps: Edge-On



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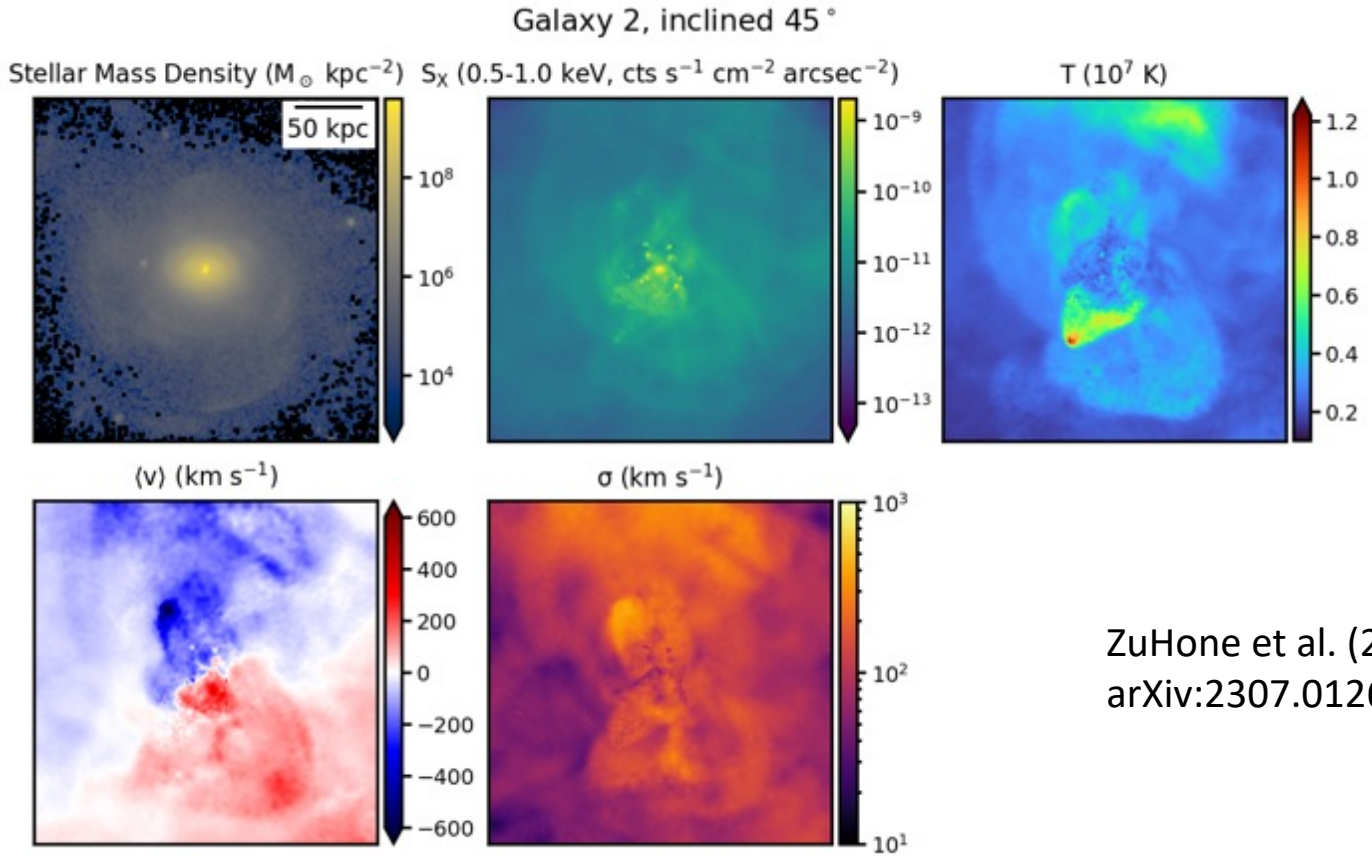
Maps: Inclined 45°



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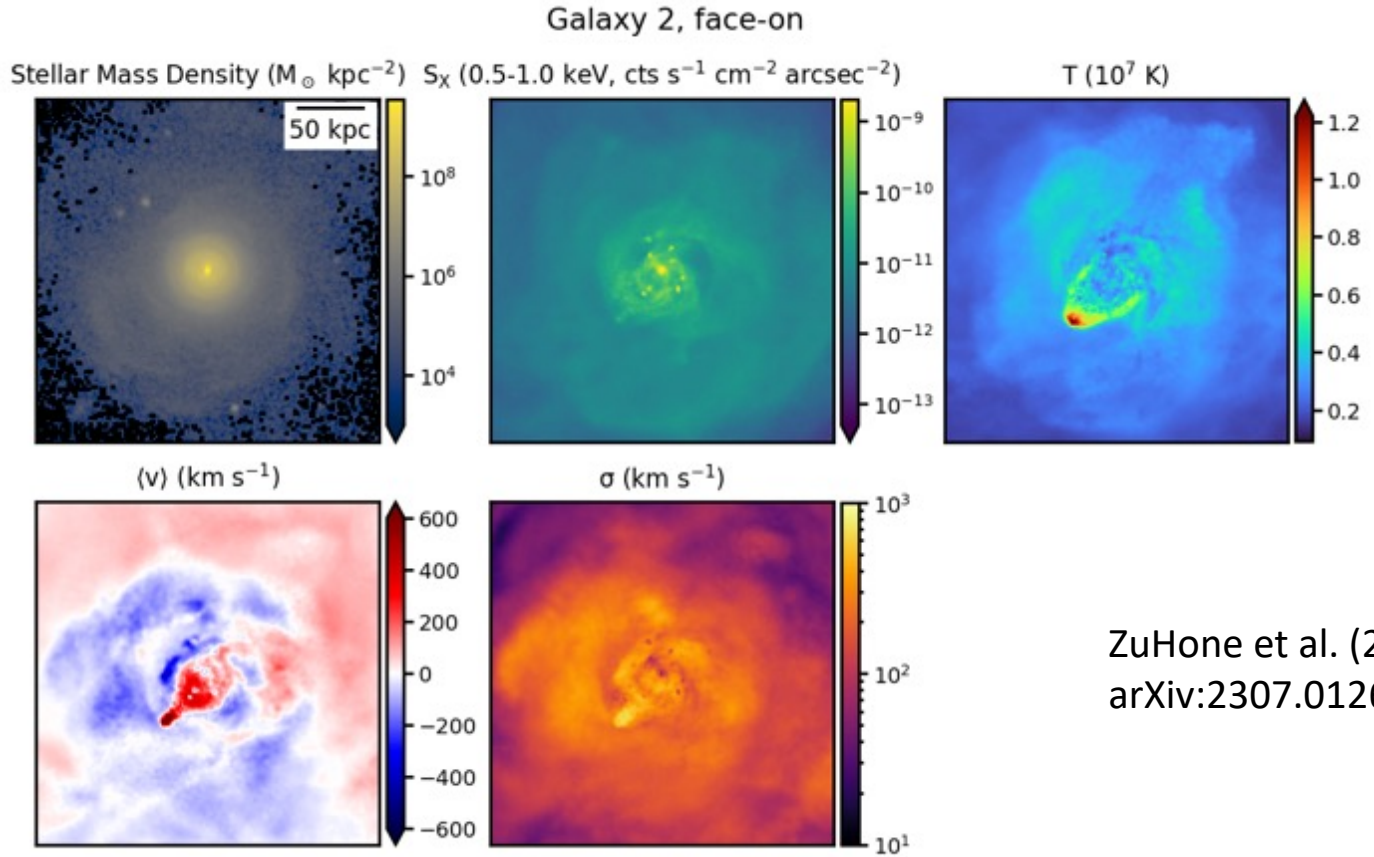
Maps: Face-On



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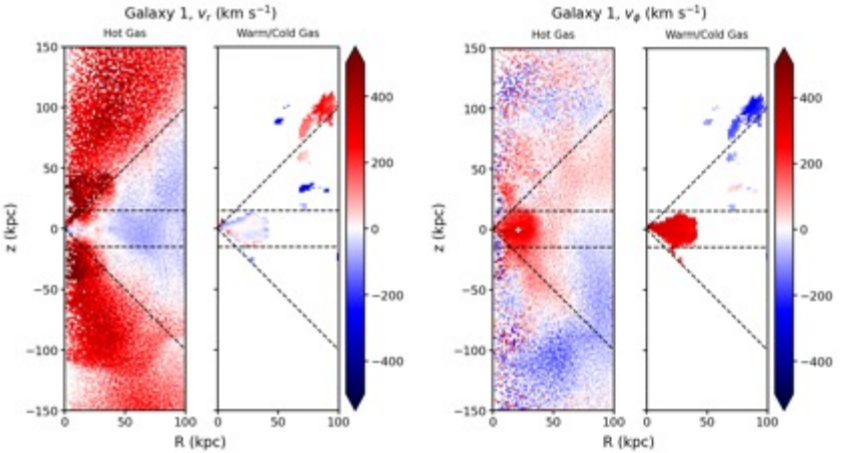
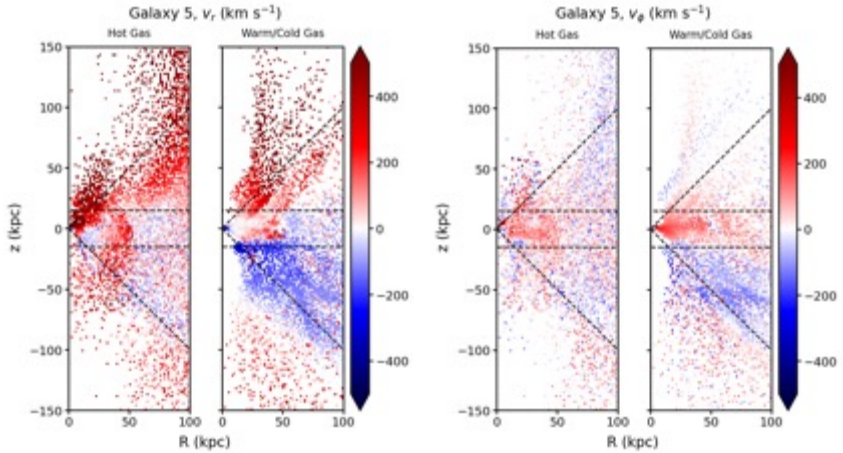
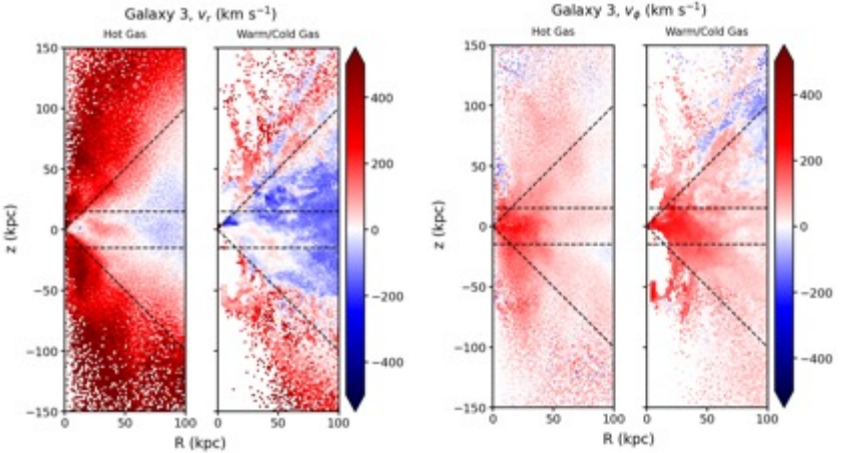
Inflows, Outflows, and Rotation

- There is a natural cylindrical geometry aligned with the disk
- In most of these galaxies, there is a simple velocity structure of fast outflows near the vertical axis, slow inflows near the plane, and rotation in the inner ~50 kpc
- Other galaxies—more complicated

ZuHone et al. (2023), arXiv:2307.01269

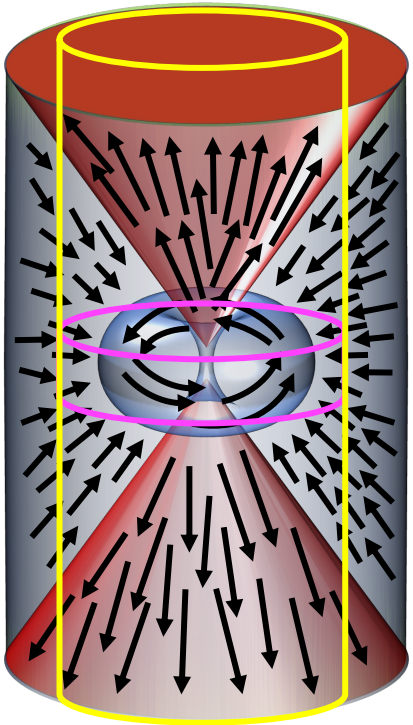




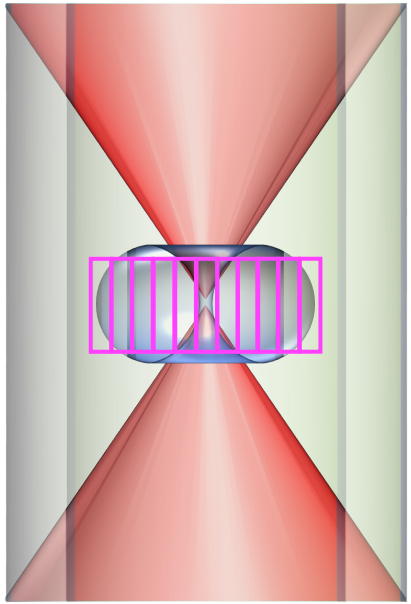


A Schematic View

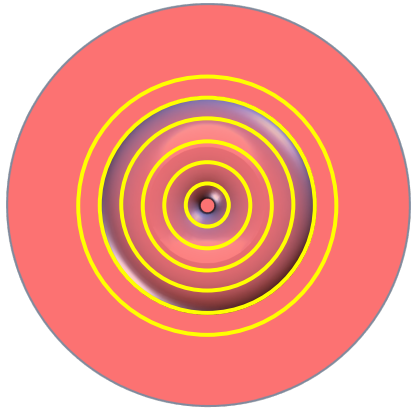
Inflows
Outflows
Rotation



Edge-On



Face-On



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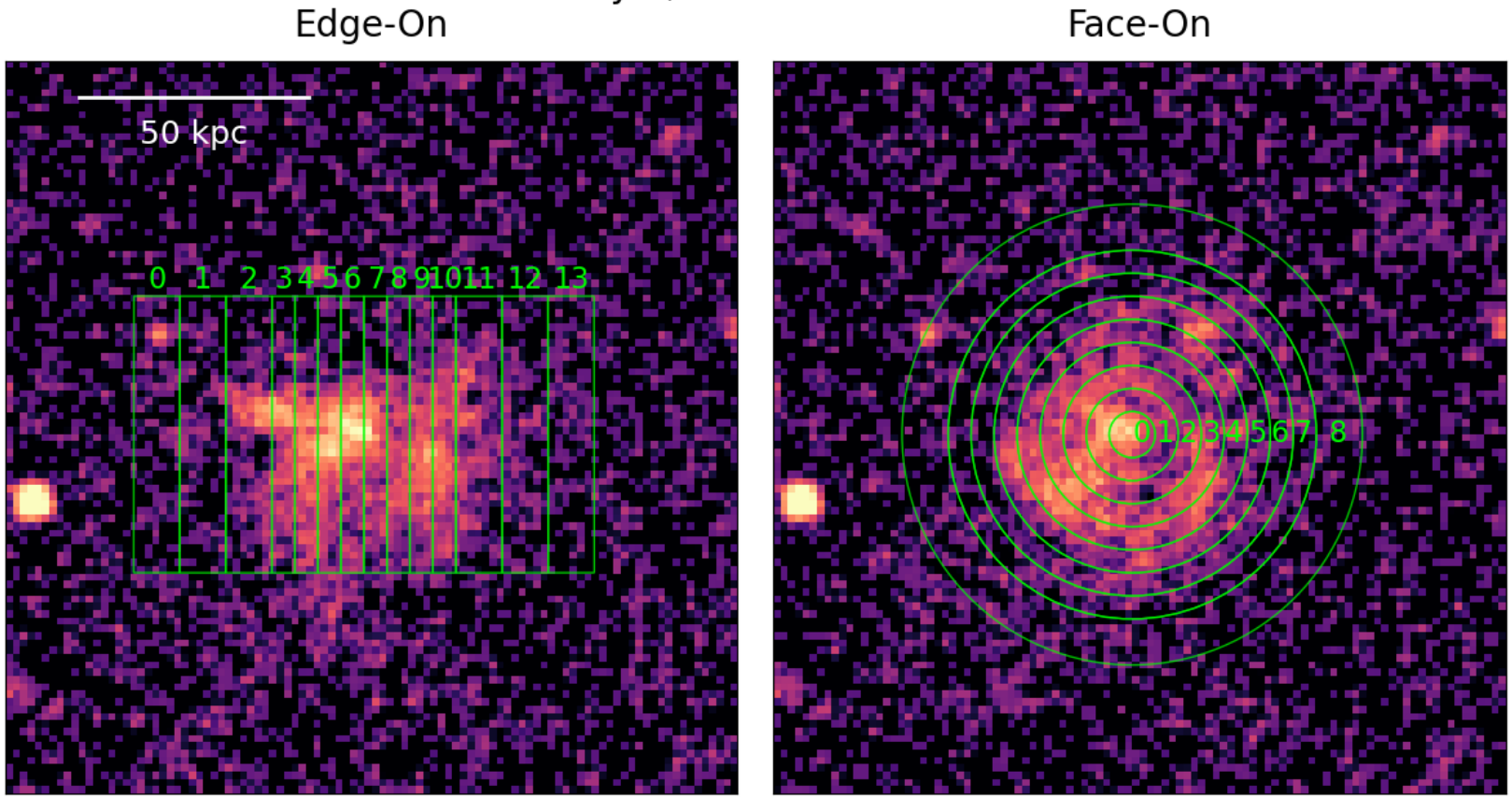
Mock Event Files

Galaxy 1, O VIII Emission



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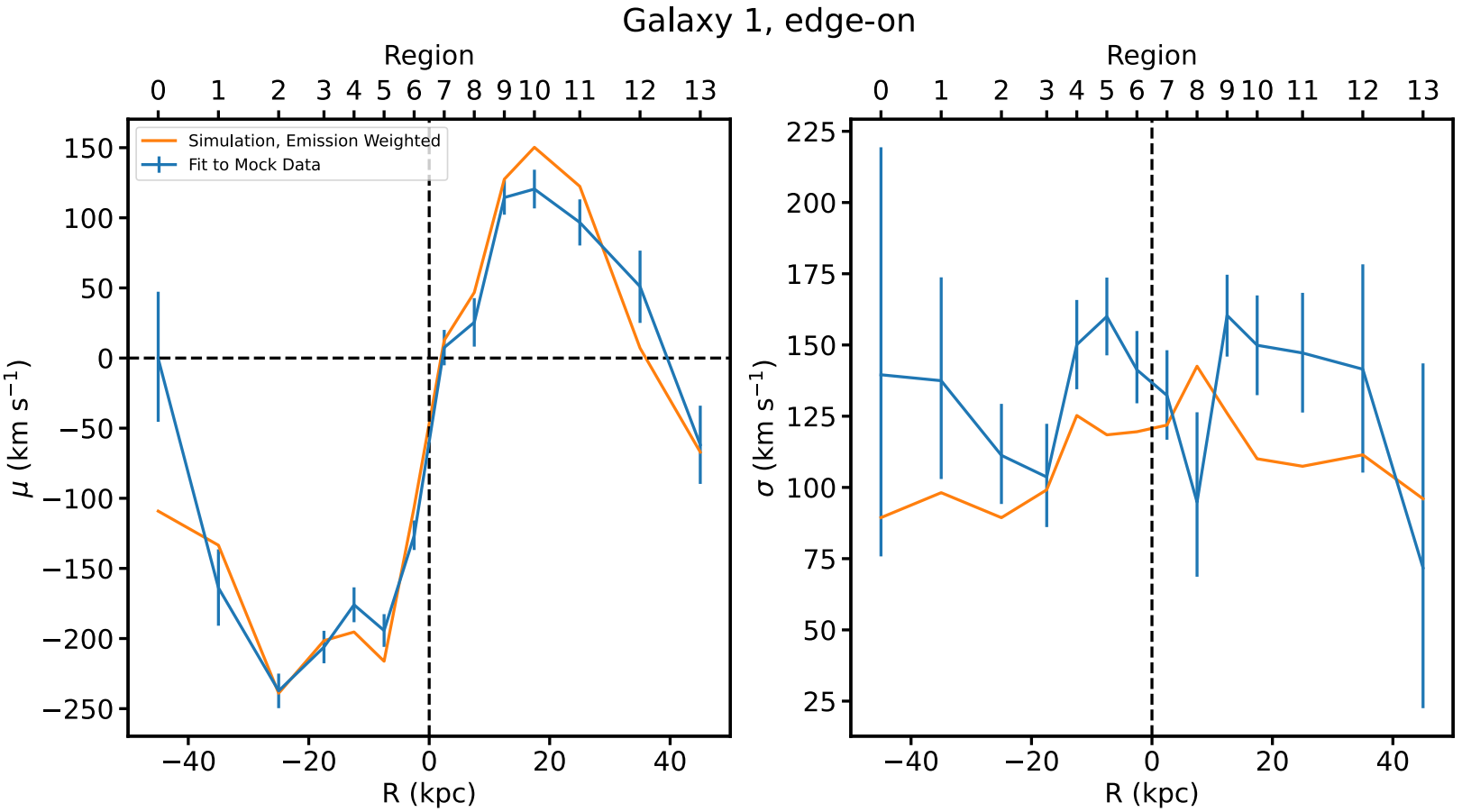
Edge-On–Rotation Curve!



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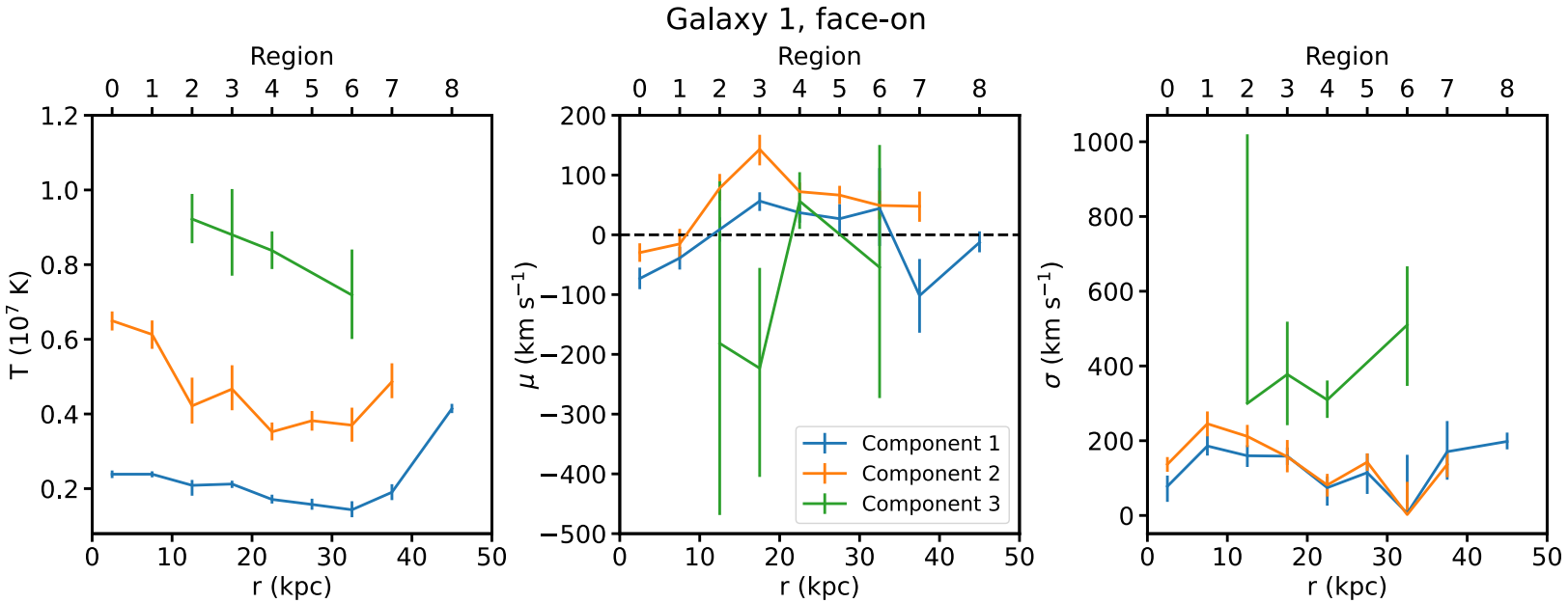
Face-On—A Bit More Complicated…



- Face-on, we are looking down into the outflows, seeing the winds coming and going, as well as intervening cooler gas
- This requires a fit with multiple thermal emission models, with different temperatures, line shifts, line widths
- Hotter gas has larger velocity dispersion (as expected)

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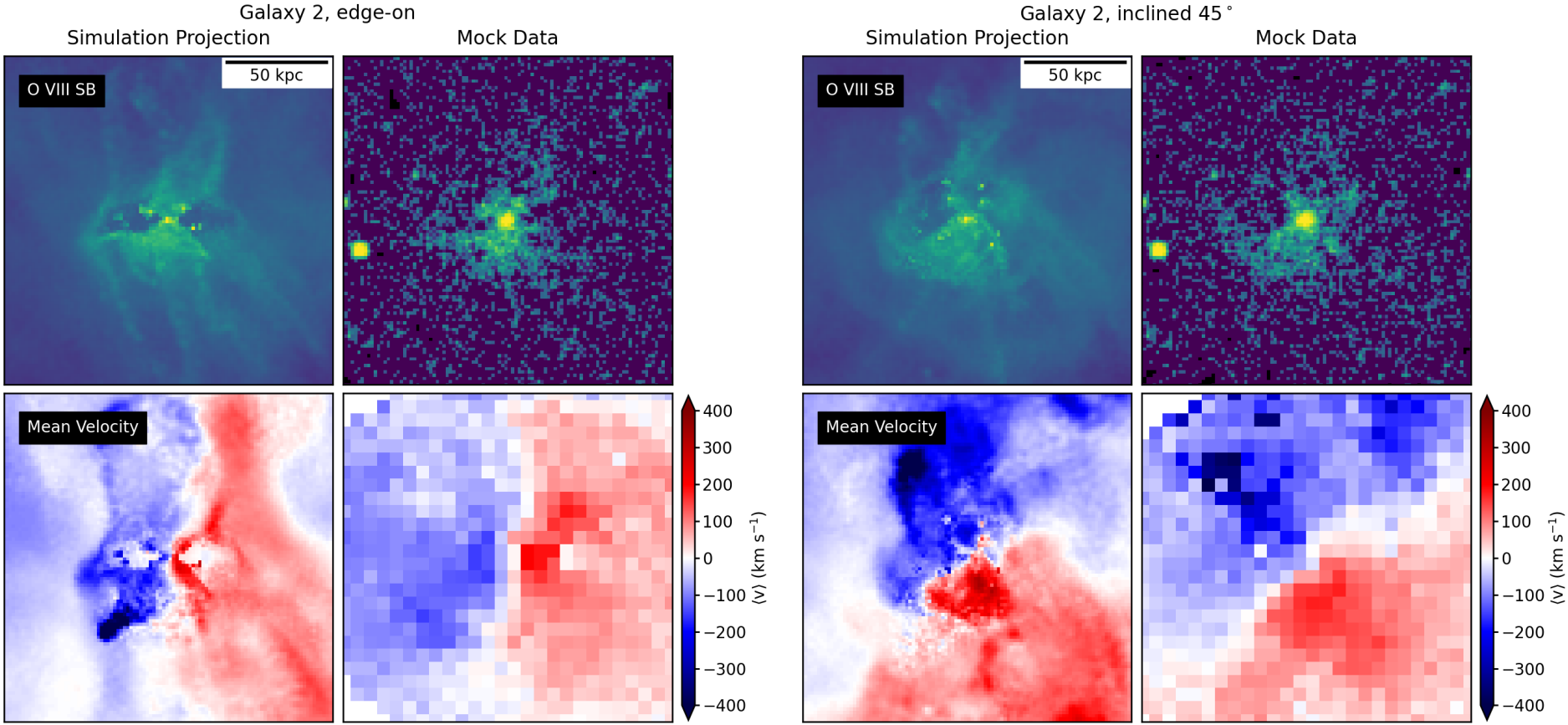
Velocity Maps–Edge-On vs. Inclined



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Summary

- Disk galaxies with mass of the Milky Way and above will be surrounded by a hot, X-ray emitting circumgalactic medium
- Many such galaxies in the TNG50 simulation exhibit a structure where slowly inflowing gas at large radii transitions into rotation near the galactic disk, with AGN-driven fast outflows on either side of the disk
- This velocity structure can be observed by the wide-field microcalorimeter aboard the Line Emission Mapper probe
- Observing these galaxies edge-on reveals the rotation curve
- Observing these galaxies face-on peers through complex multi-phase flows that will require careful modeling
- Observing at inclined angles produces interesting combinations of rotation and outflows in velocity maps

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