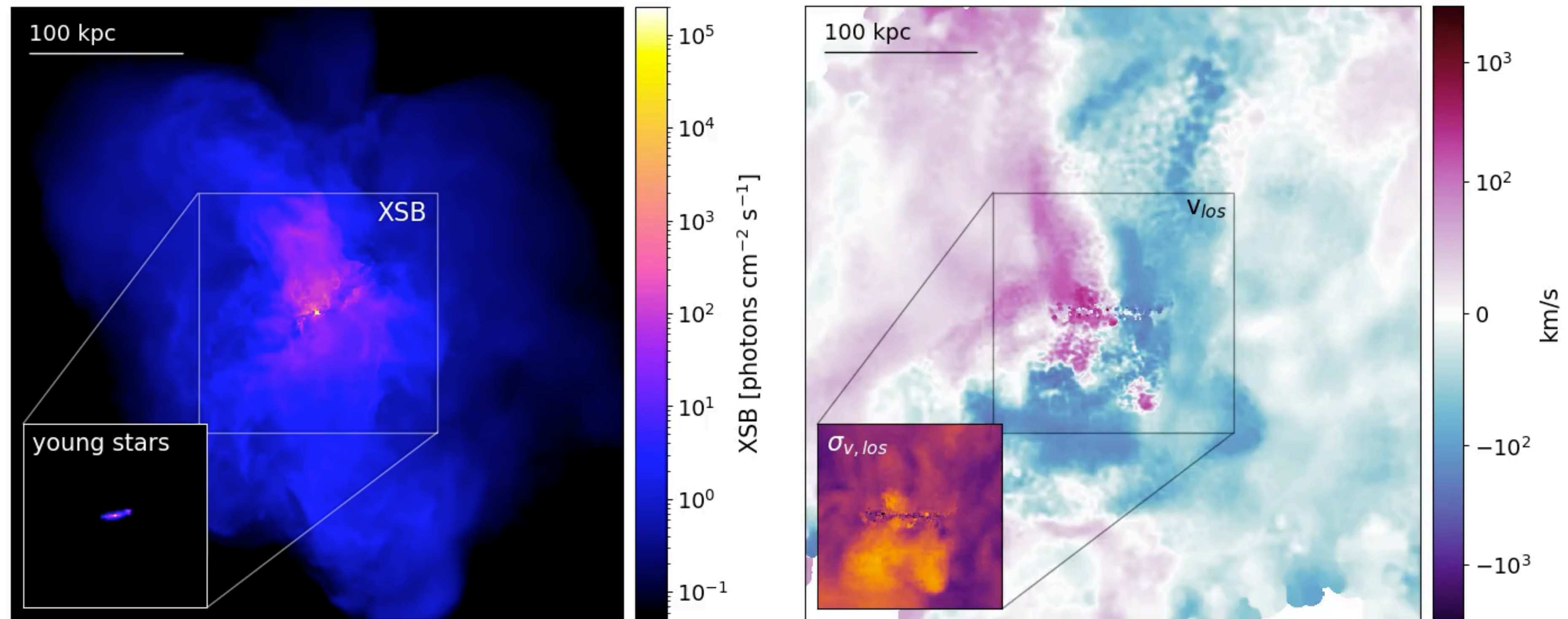


Elucidating the Nature of Feedback Mechanisms in Galaxies via Emission-Line Studies of the Warm and Hot Circumgalactic Medium



John ZuHone with Emily Silich, Cameron Hummels,
Gerrit Schellenberger, Anna Ogorzałek,
Elena Bellomi, Ben Oppenheimer,
and many others...

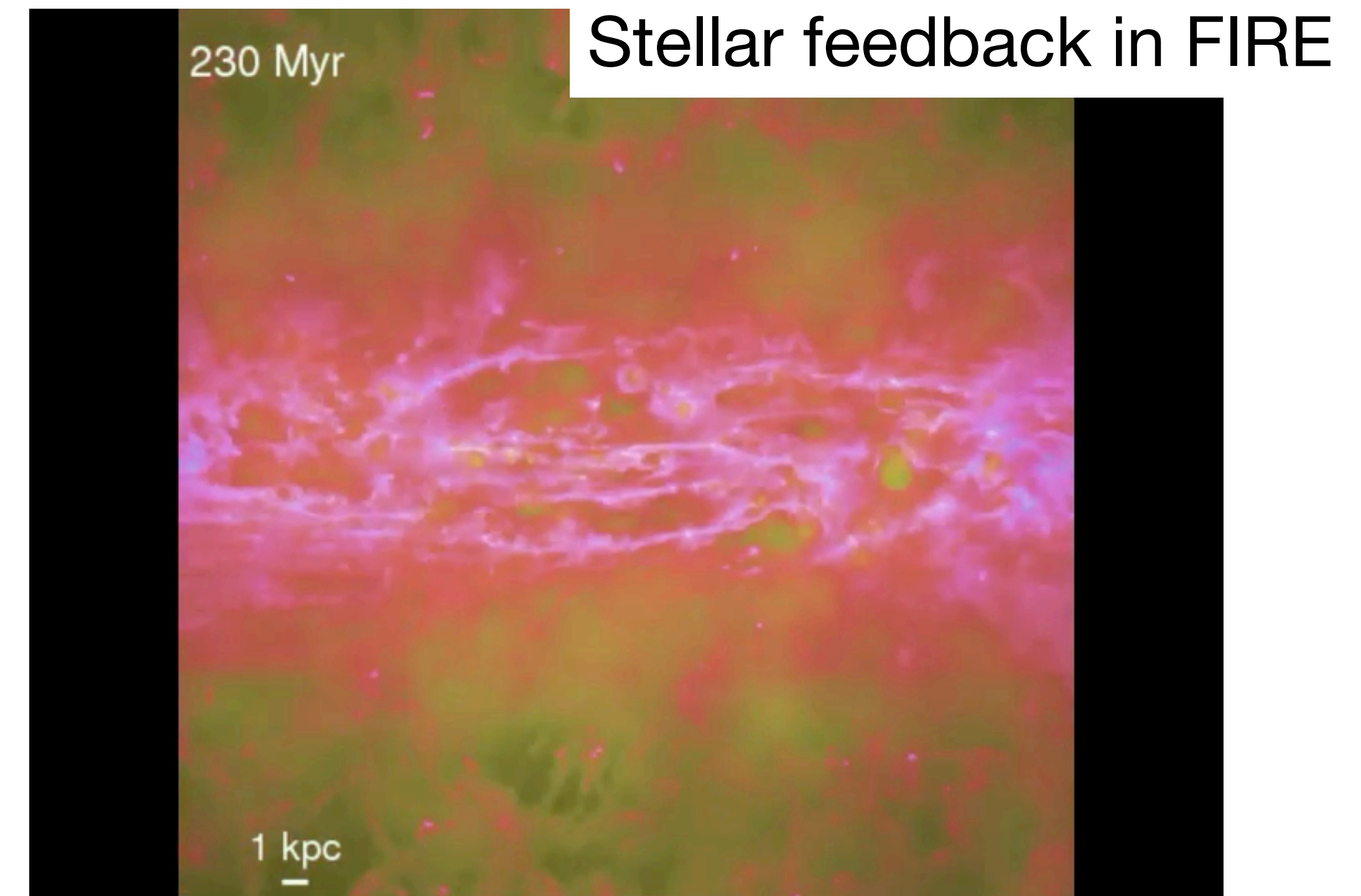
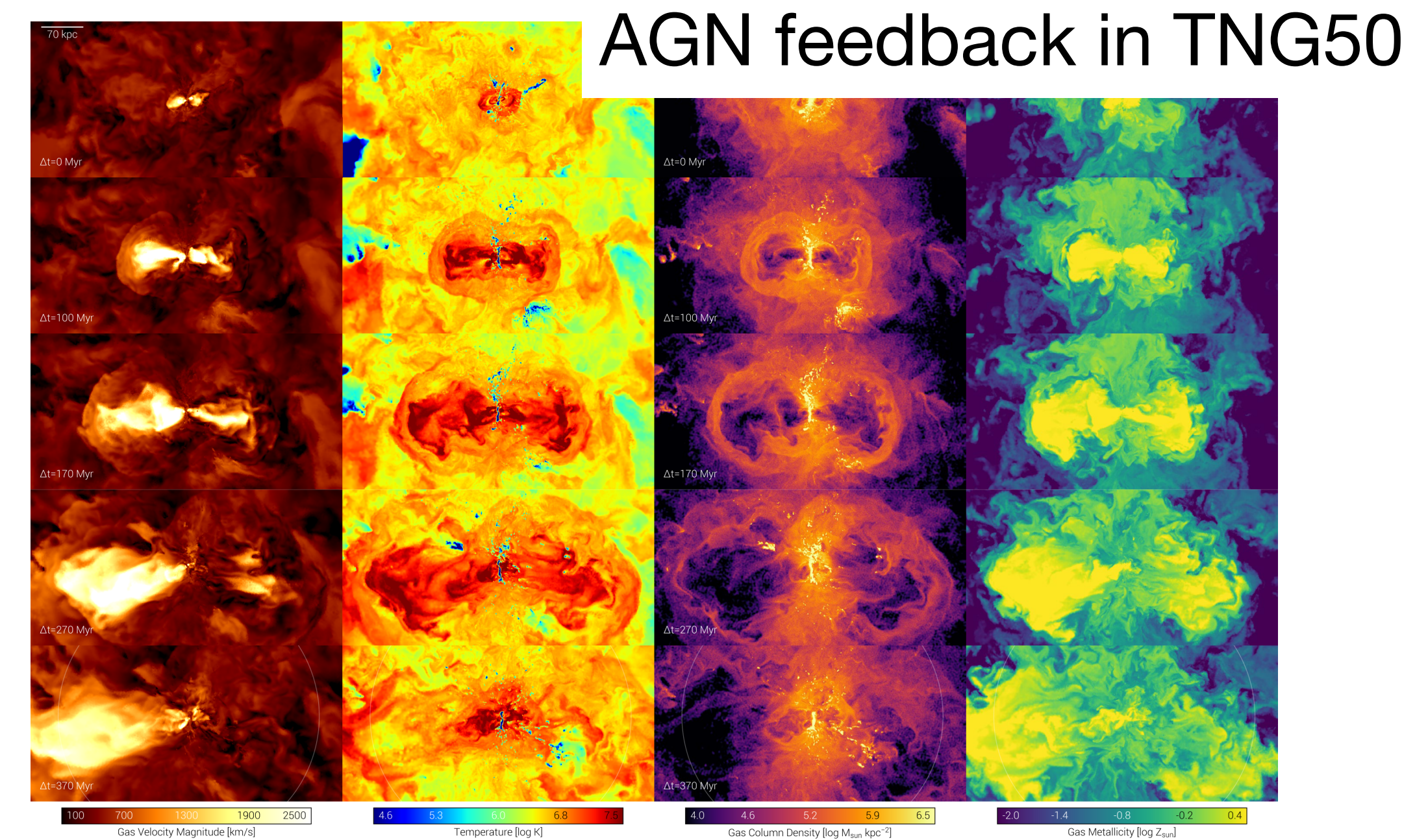
CENTER FOR

ASTROPHYSICS

HARVARD & SMITHSONIAN

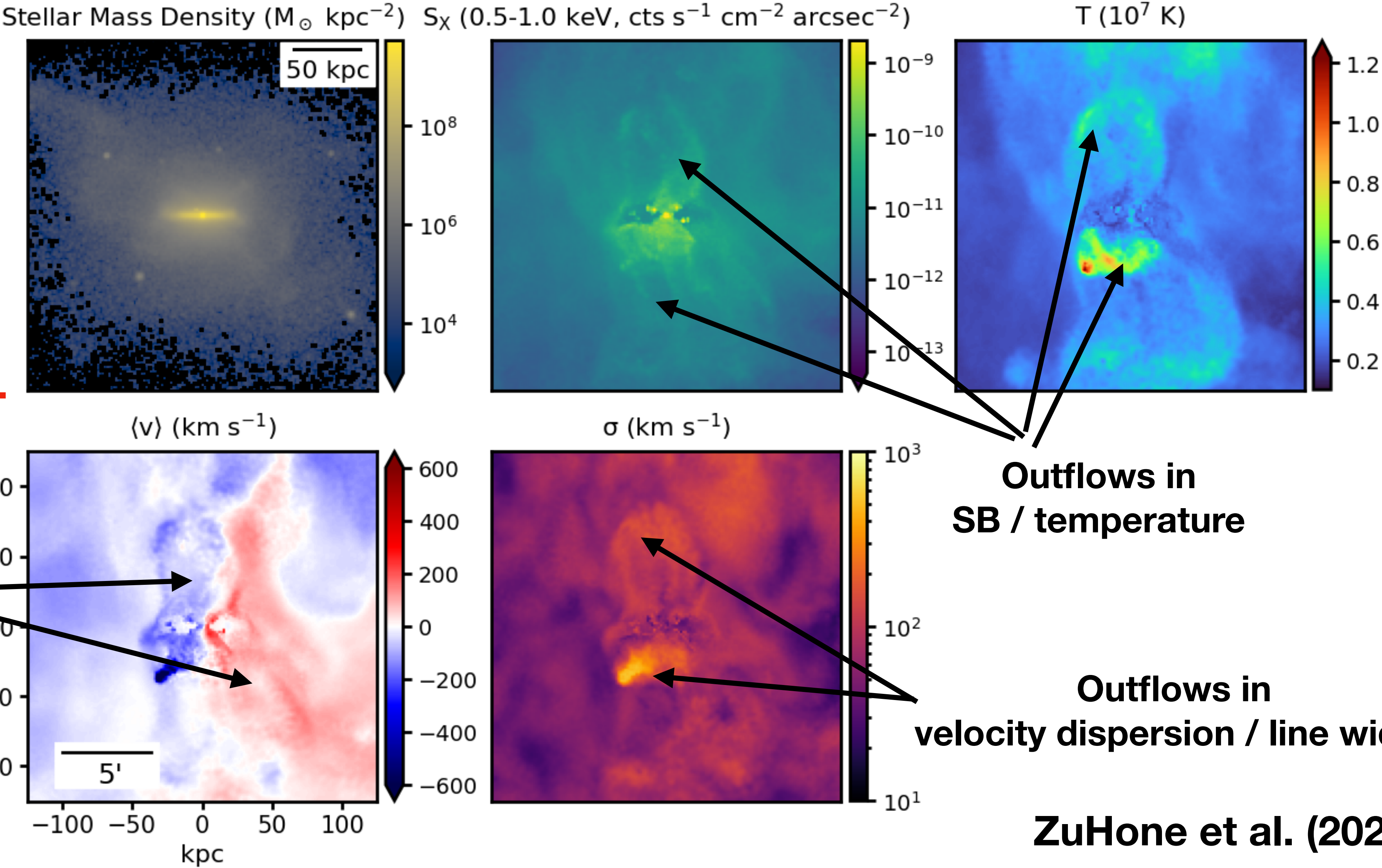
Galactic-Scale Feedback and the Circumgalactic Medium

- To reproduce observations, simulations of galaxy formation require feedback to prevent excess star formation
- We know the most likely sources of this feedback: stars, supernova explosions, black holes
- Many things are unknown about how the feedback works, thus simulations usually make entirely different choices: thermal vs. kinetic feedback, cosmic rays, magnetic fields, bipolar outflows, stars vs. AGN
- If the simulations are all tuned to match certain observables (e.g., galaxy luminosity function, etc.), what observables would help to distinguish the models?
- One under-explored place is the circumgalactic medium, specifically the warm (UV) and hot (X-ray) phases

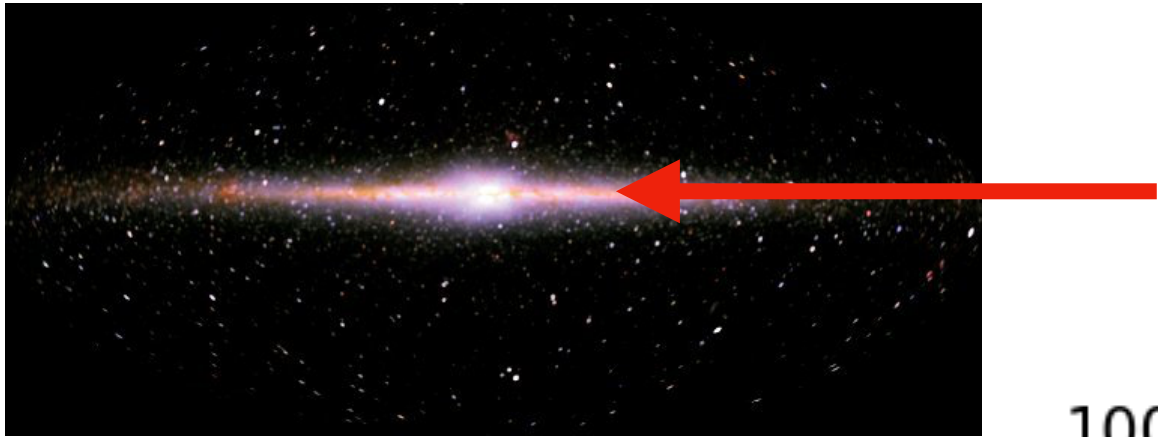


A ~MW-mass galaxy from TNG50: Edge-On

Galaxy 2, edge-on



Cloudy-based modeling of X-ray emitting CGM: photo- and collisional ionization in projected maps



Rotation curve produces a dipole in bulk velocity/line shift

Outflows in SB / temperature

Outflows in velocity dispersion / line width

ZuHone et al. (2024)

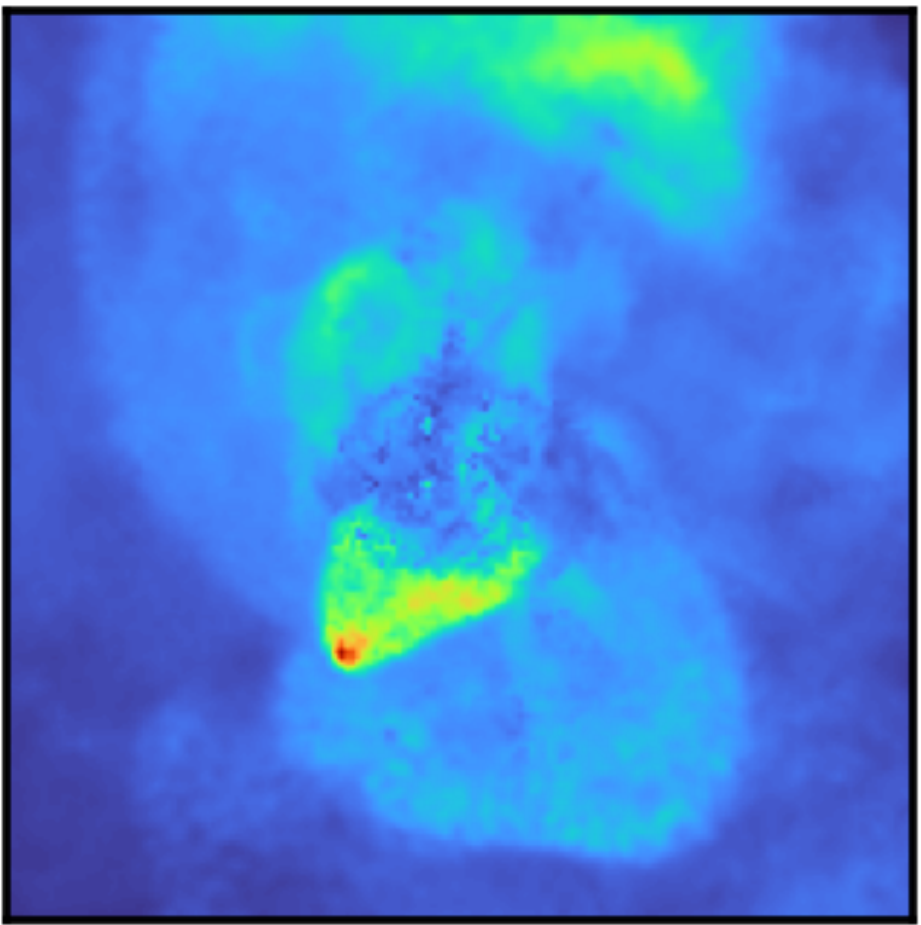
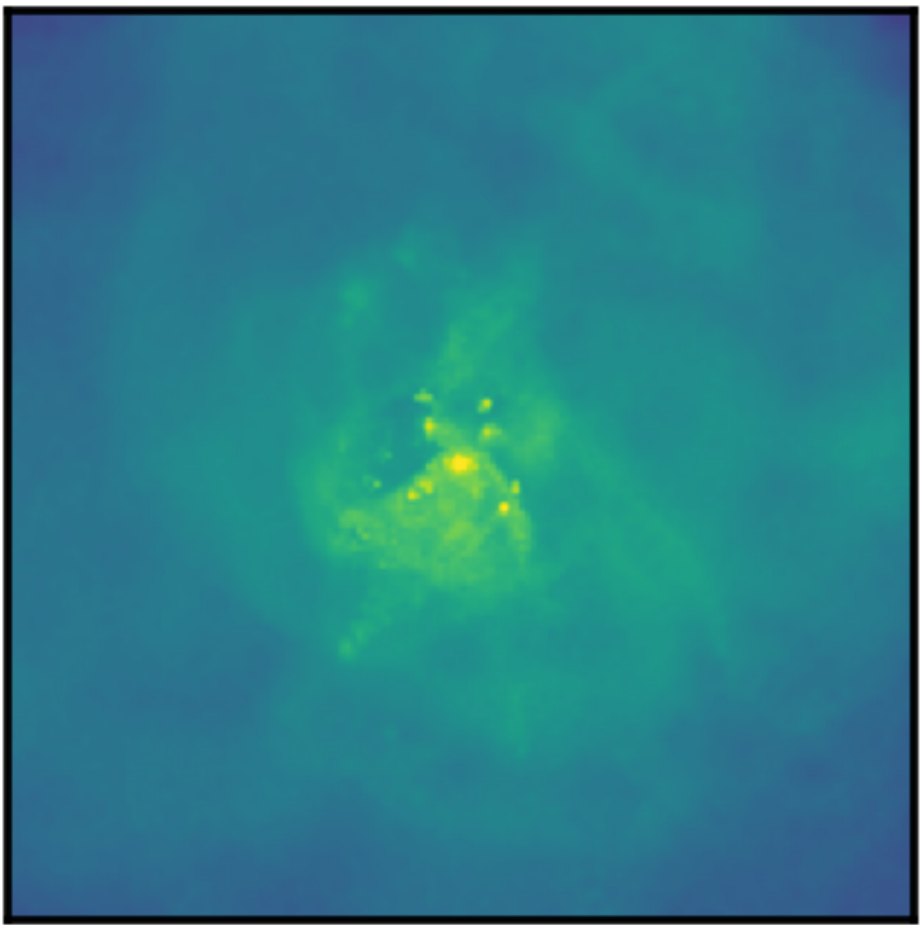
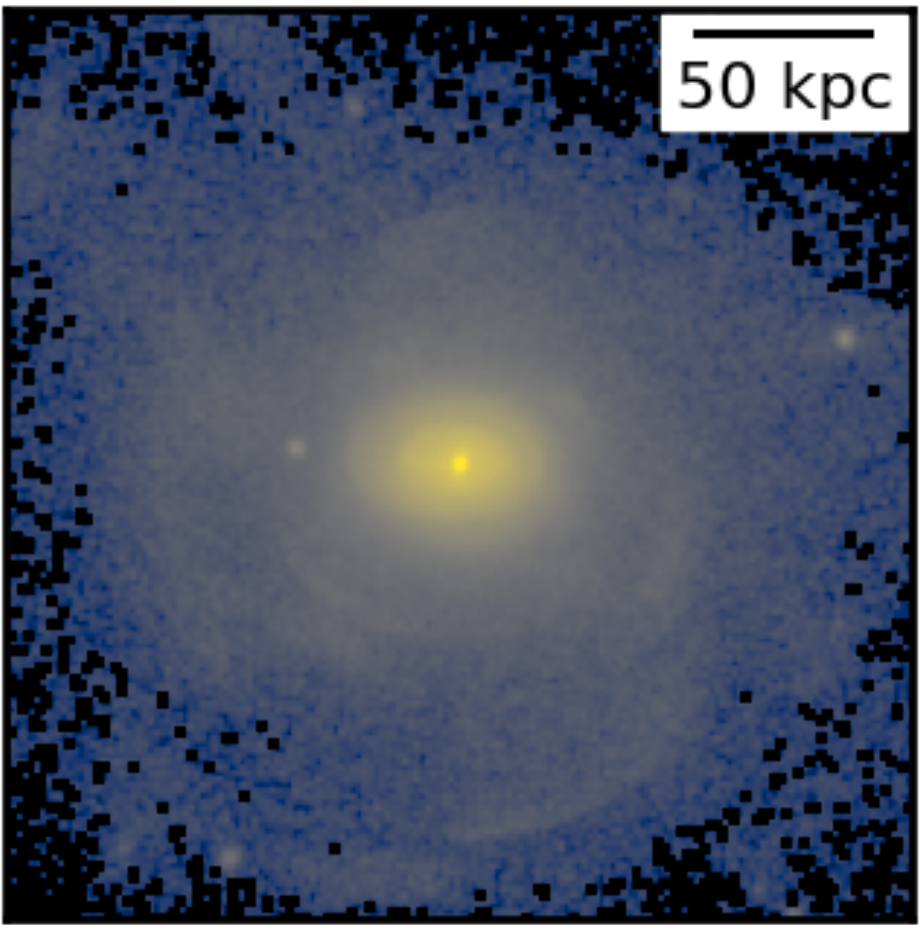
A ~MW-mass galaxy from TNG50: "Mid-On"

Galaxy 2, inclined 45°

Stellar Mass Density ($M_{\odot} \text{ kpc}^{-2}$)

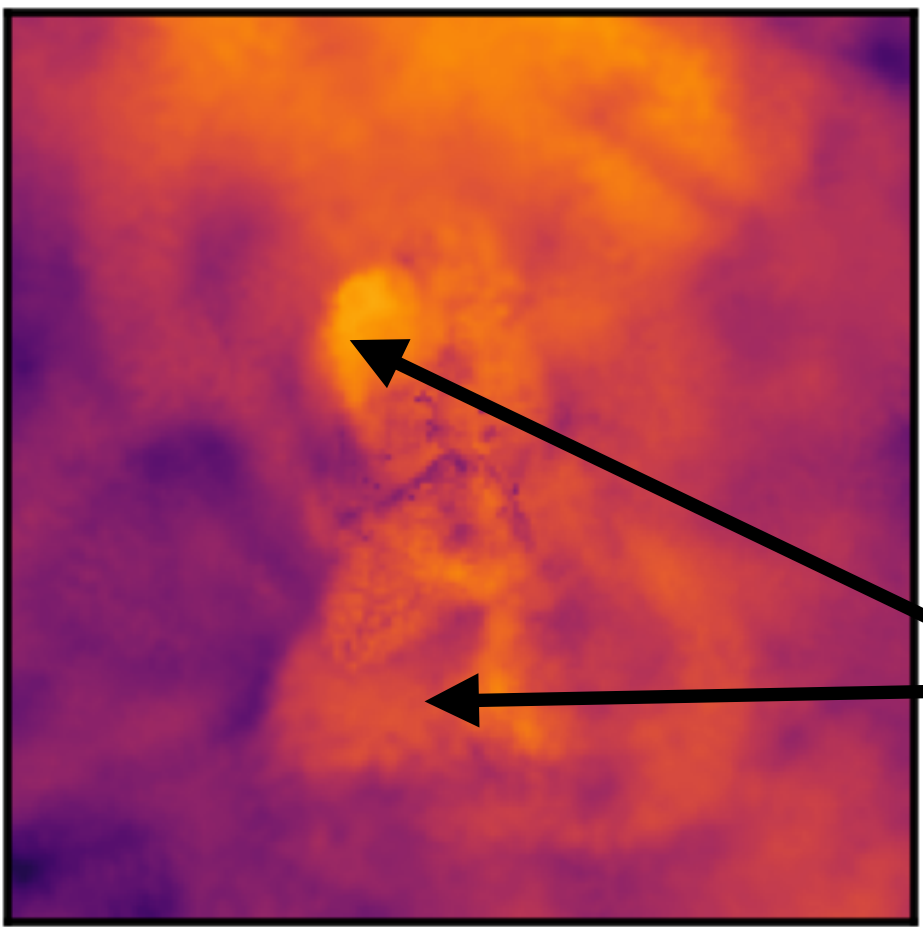
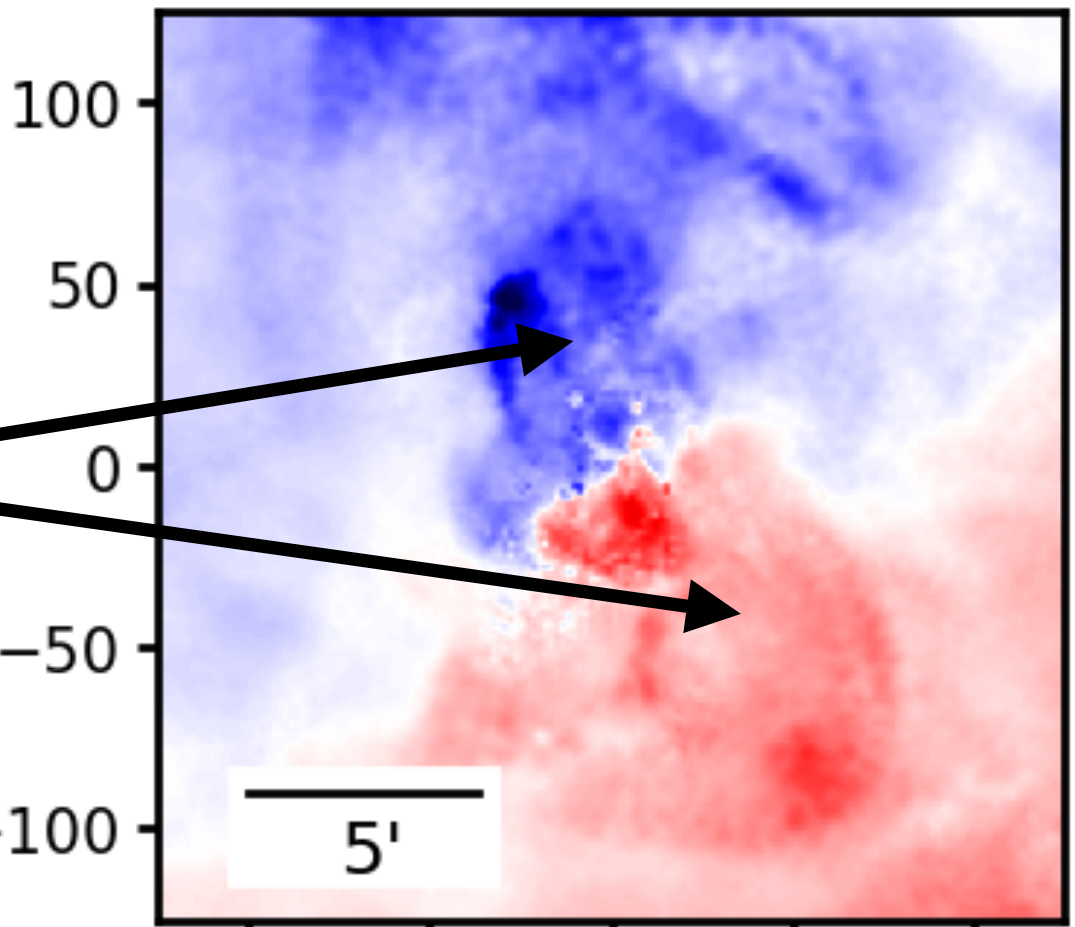
S_X (0.5-1.0 keV, $\text{cts s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$)

T (10^7 K)



$\langle v \rangle$ (km s^{-1})

σ (km s^{-1})



Cloudy-based modeling of X-ray emitting CGM: photo- and collisional ionization in projected maps



Rotation curve and outflows in bulk velocity/line shift tilt the velocity dipole

$\langle v \rangle$

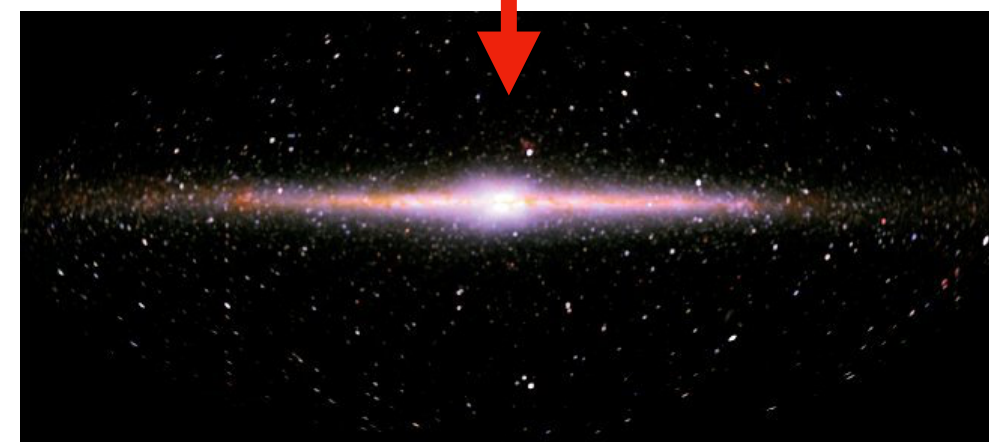
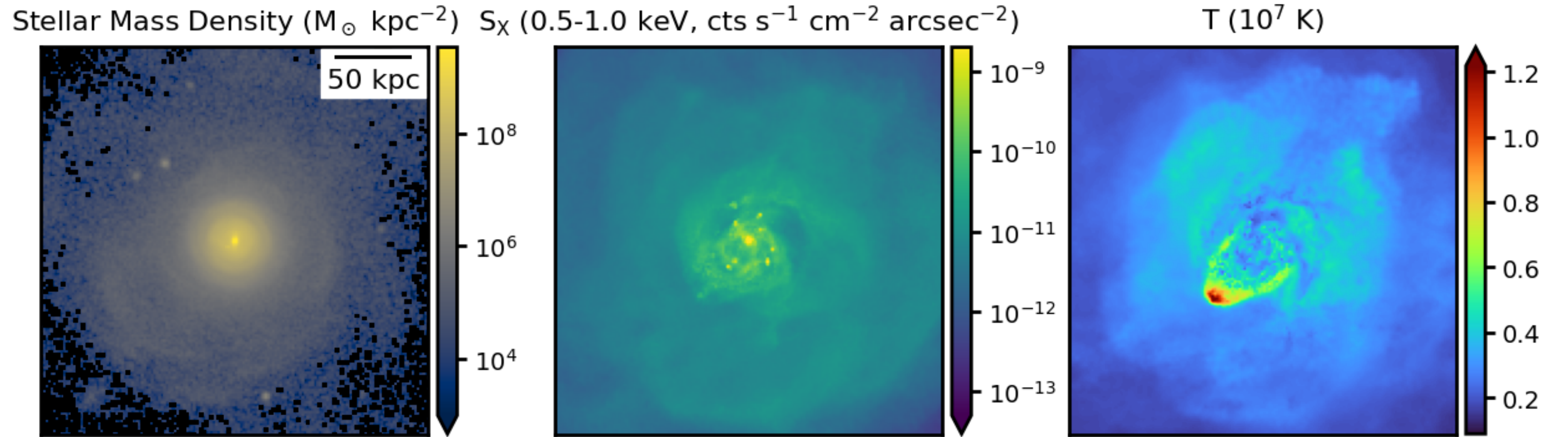
σ

Outflows in velocity dispersion / line width

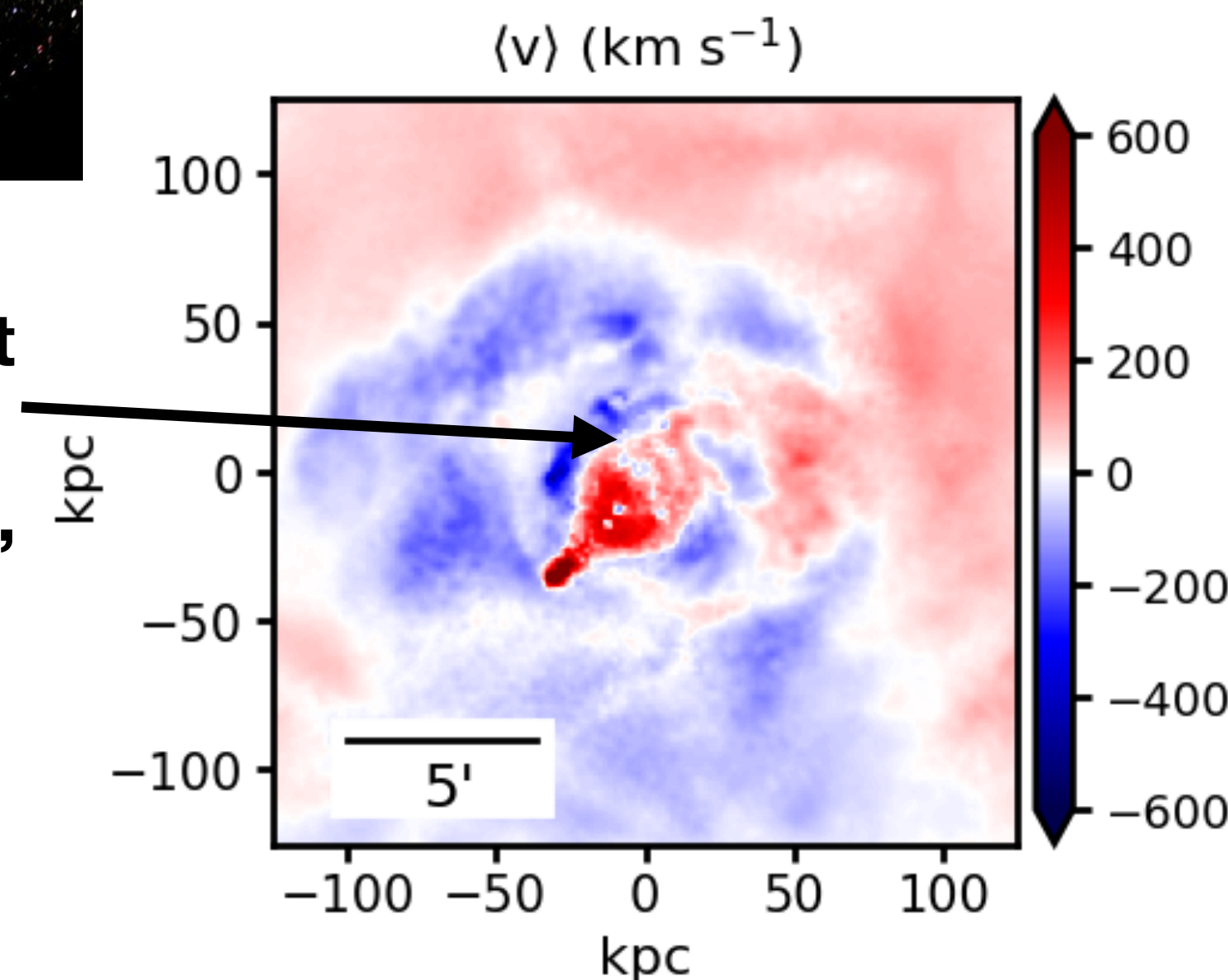
ZuHone et al. (2024)

A $\sim$ MW-mass galaxy from TNG50: Face-On

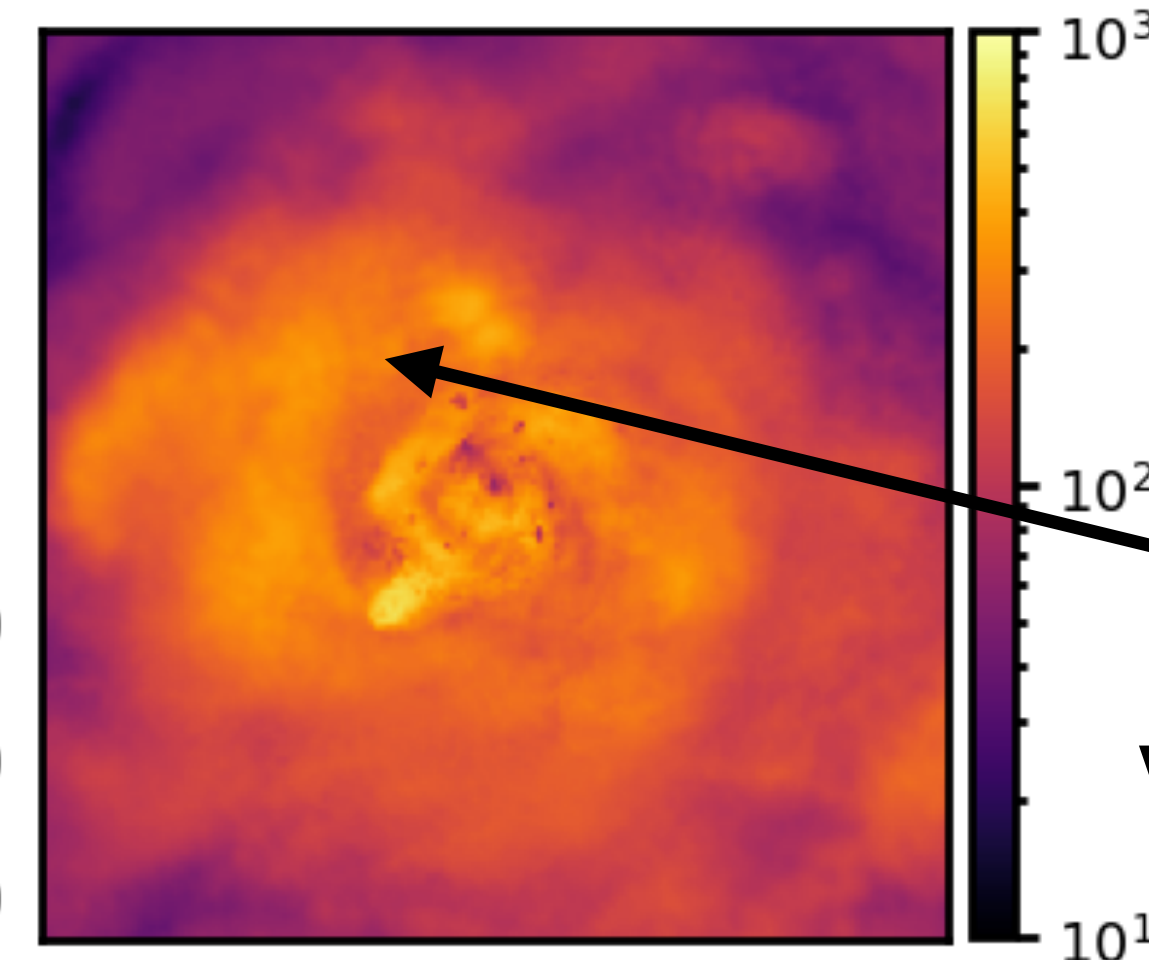
Galaxy 2, face-on



0th-order component
of bi-directional
outflows cancels out,
leaving a turbulent-
looking structure



σ (km s^{-1})



Cloudy-based modeling of
X-ray emitting CGM: photo-
and collisional ionization in
projected maps

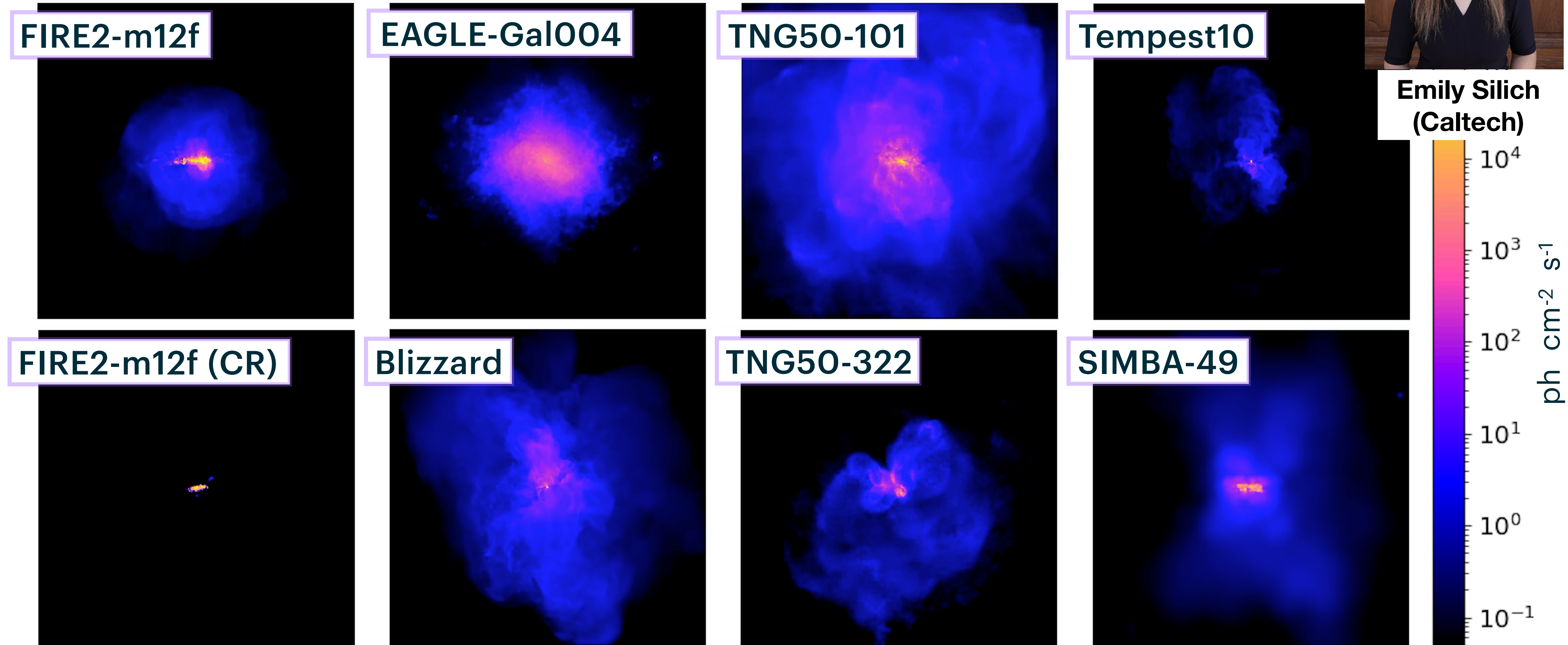
Outflows in
velocity dispersion / line width

ZuHone et al. (2024)

X-ray Surface Brightness

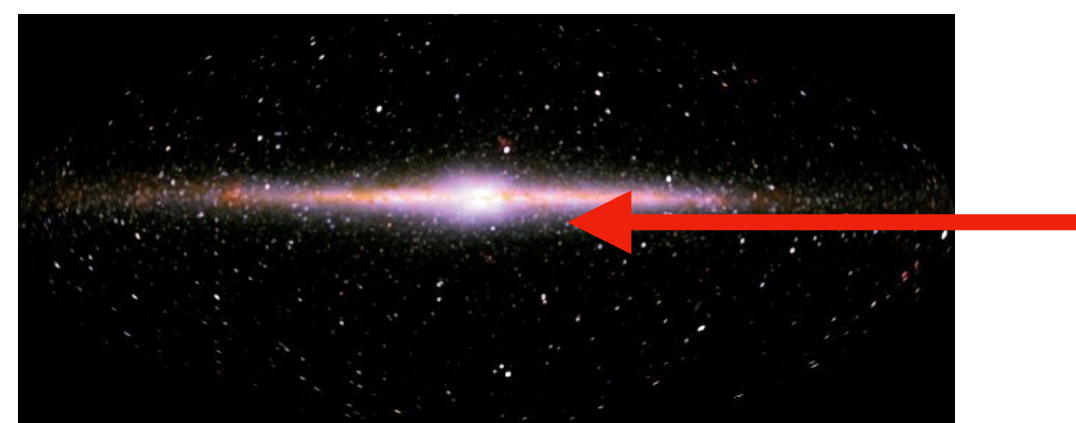


Emily Silich
(Caltech)

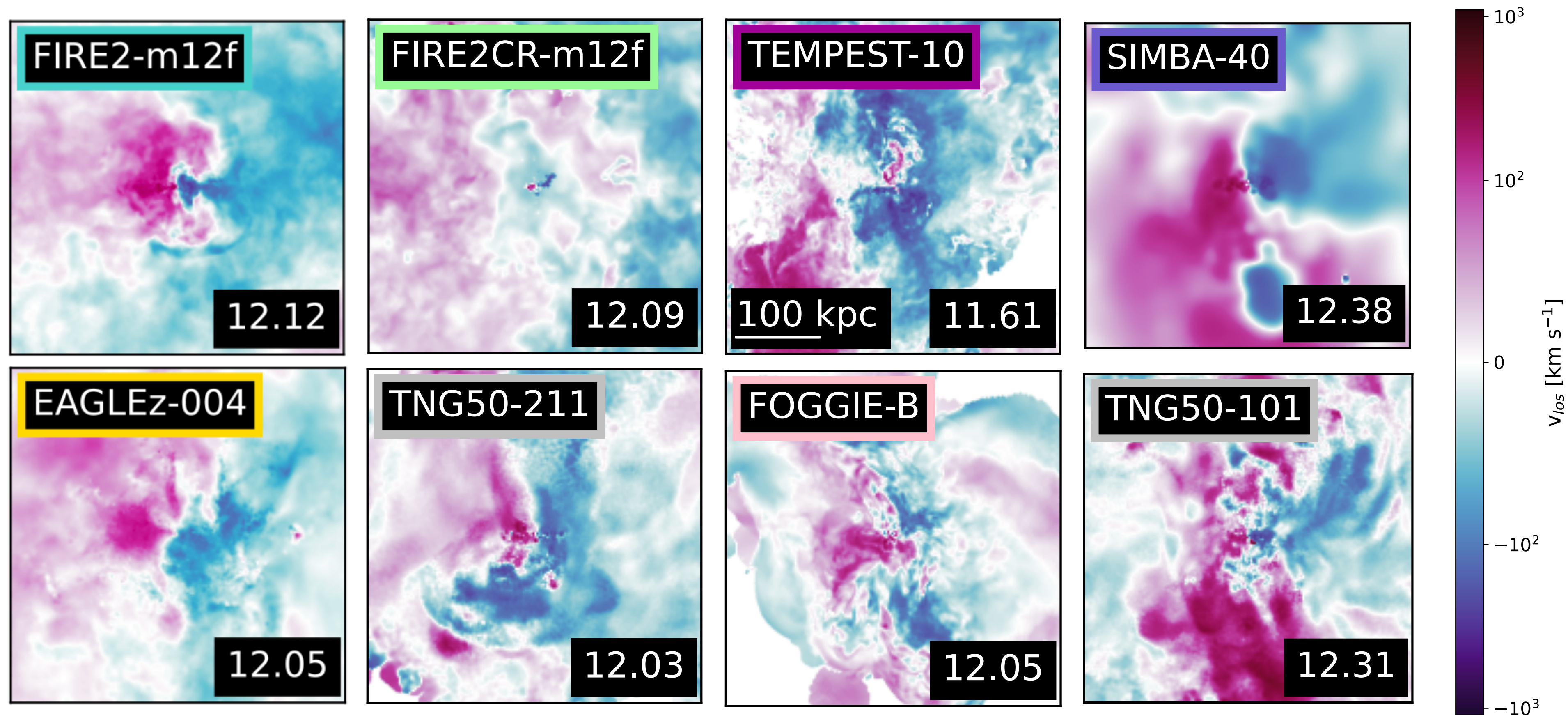


Silich et al. (2025)

Bulk Velocity: Edge-On

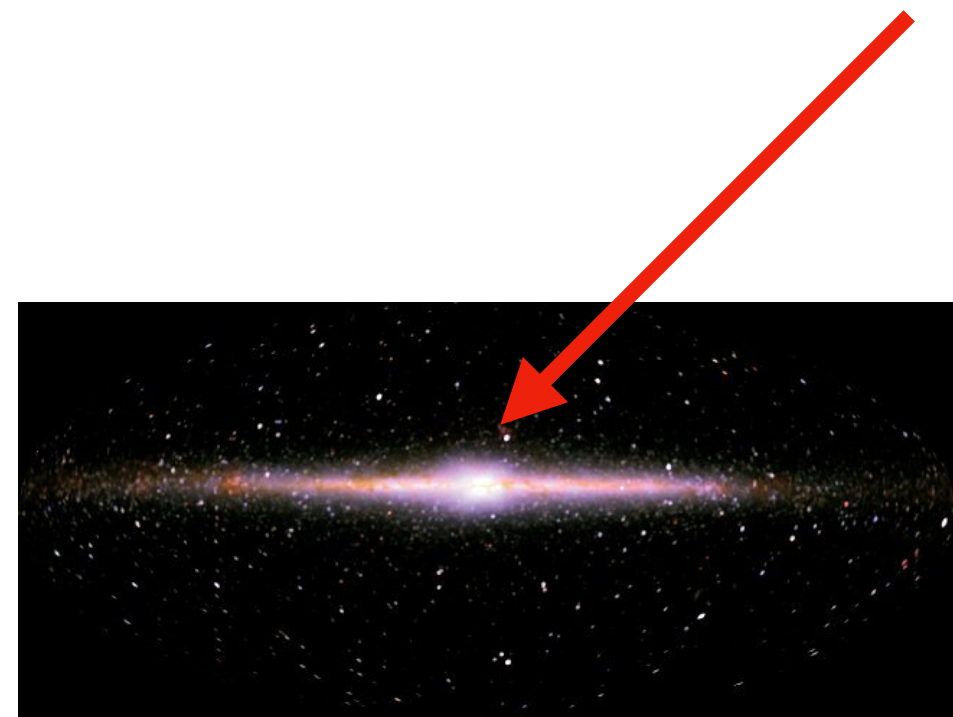


All models look very similar edge-on (modulo differences in resolution), with rotation curves

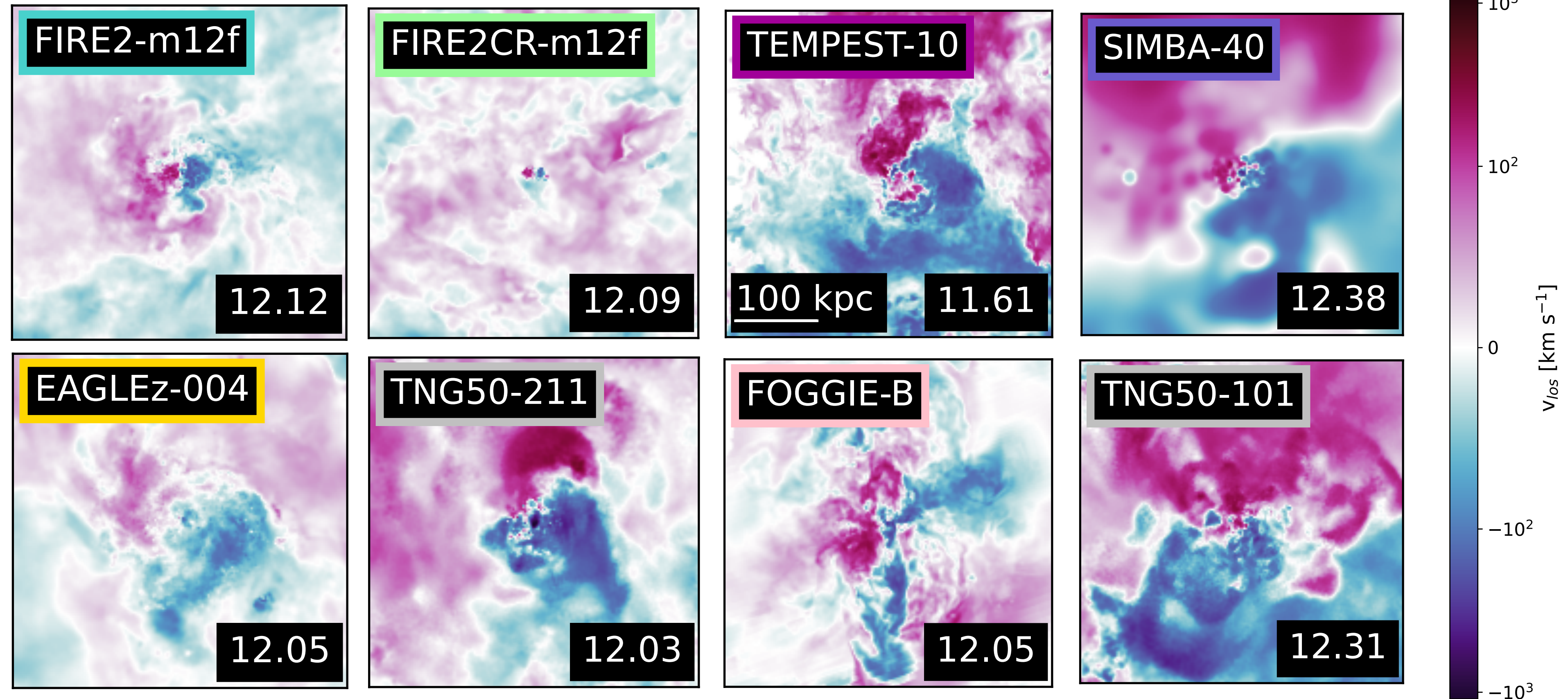


Silich et al. (2025)

Bulk Velocity: "Mid-On"

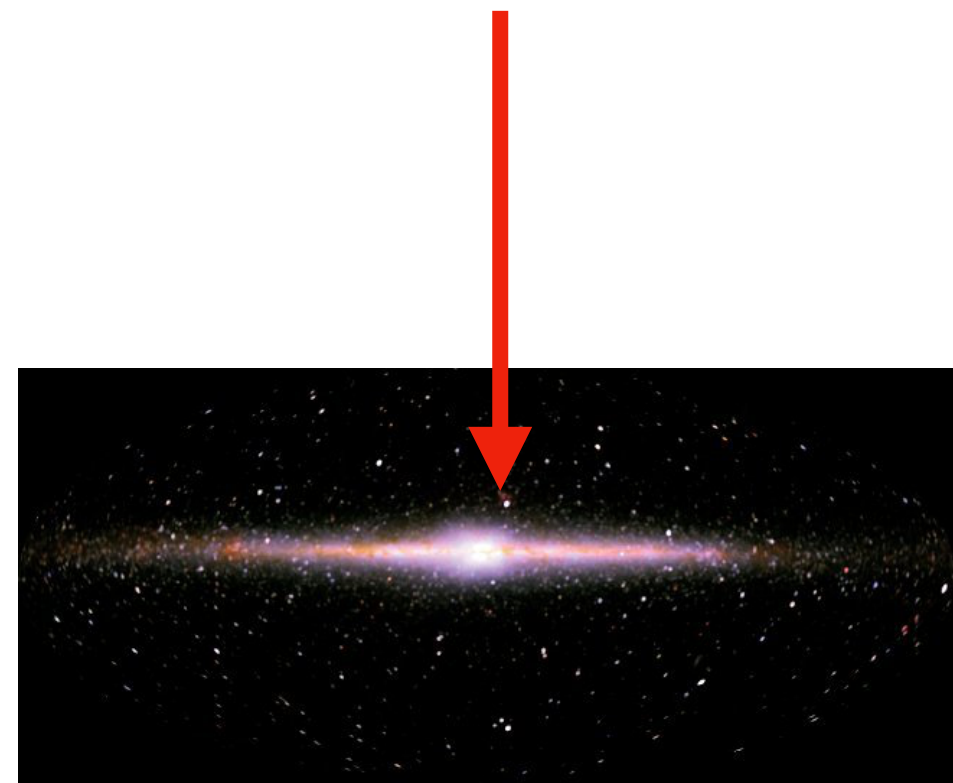


Models with bi-directional outflows show a tilt in the velocity map dipole, others do not

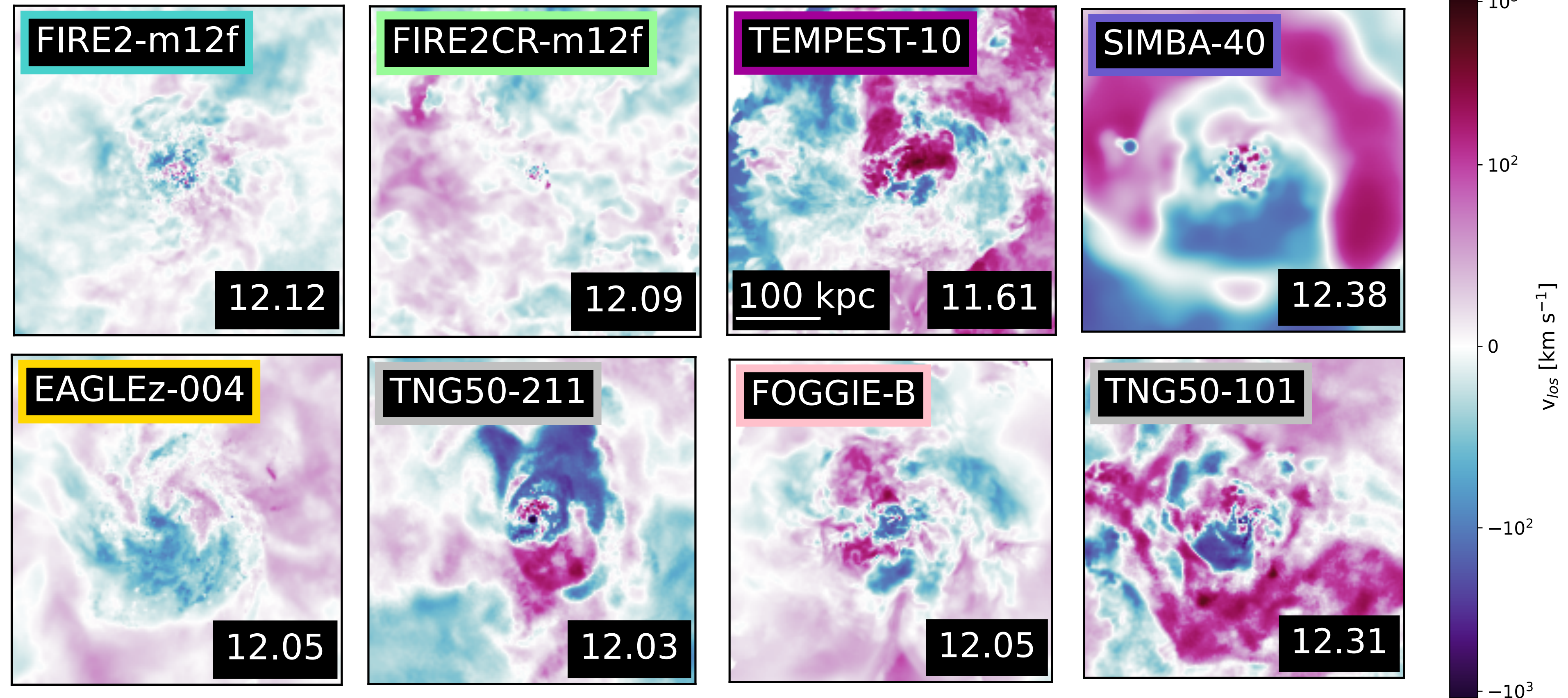


Silich et al. (2025)

Bulk Velocity: Face-On



The typical speeds of the bulk motions reveal the presence or absence of a bi-directional outflow

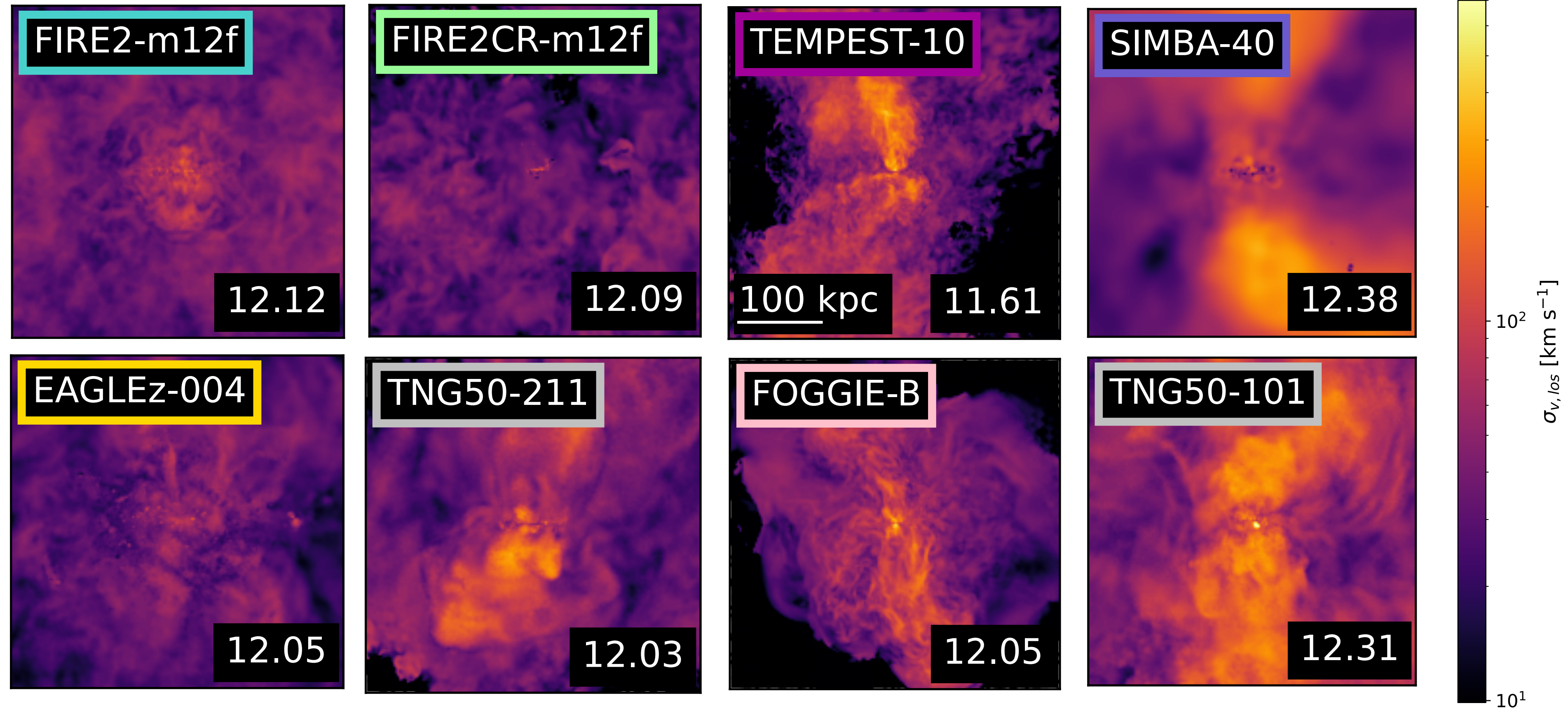


Silich et al. (2025)

Velocity Dispersion: Edge-On

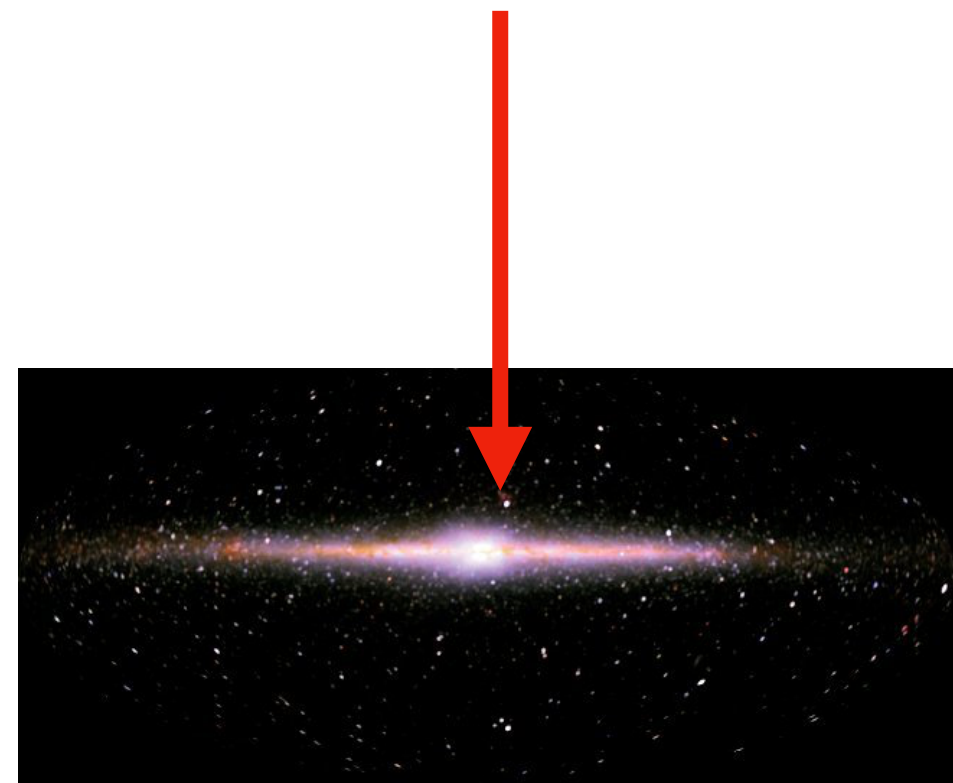


Dispersions in
several 100s of km/s
in sims with
outflows—much
lower without them

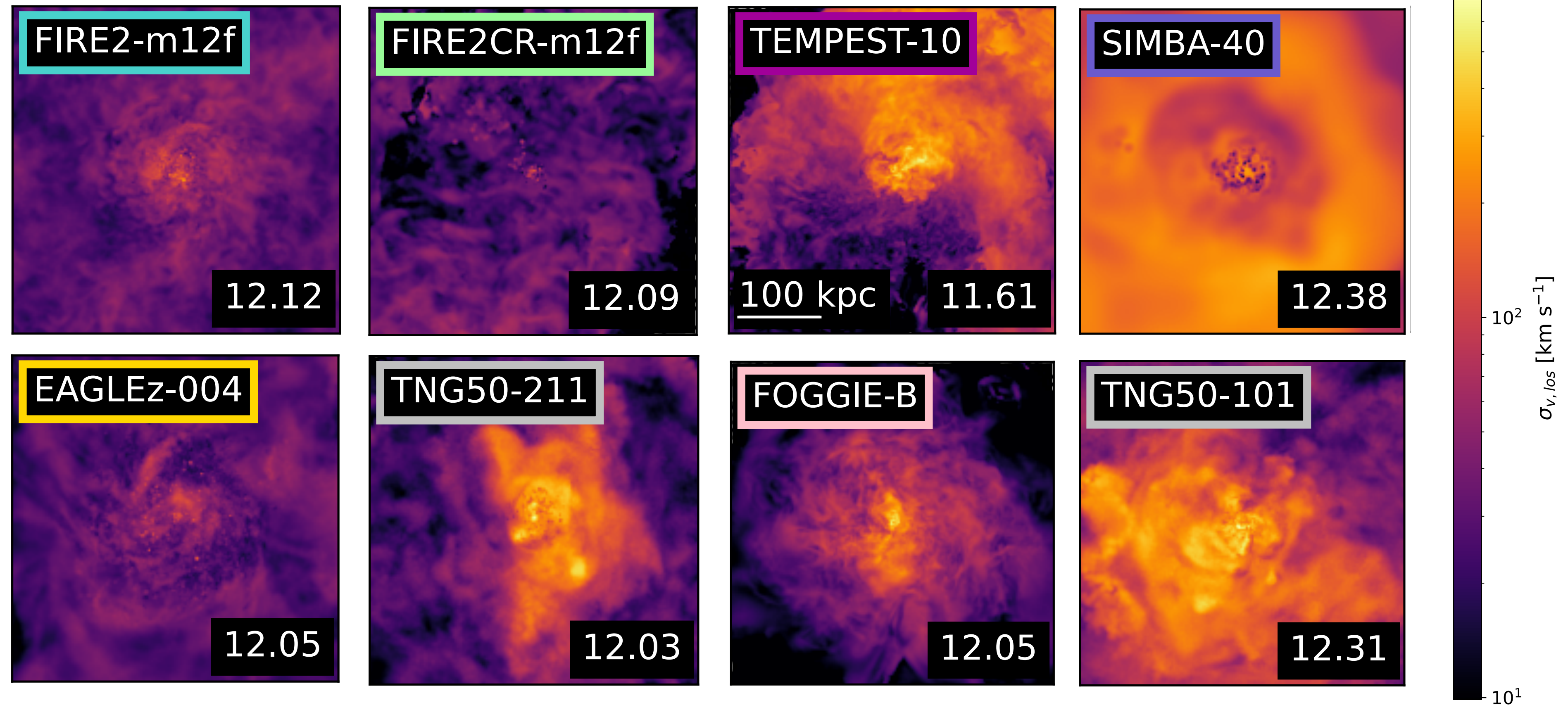


Silich et al. (2025)

Velocity Dispersion: Face-On

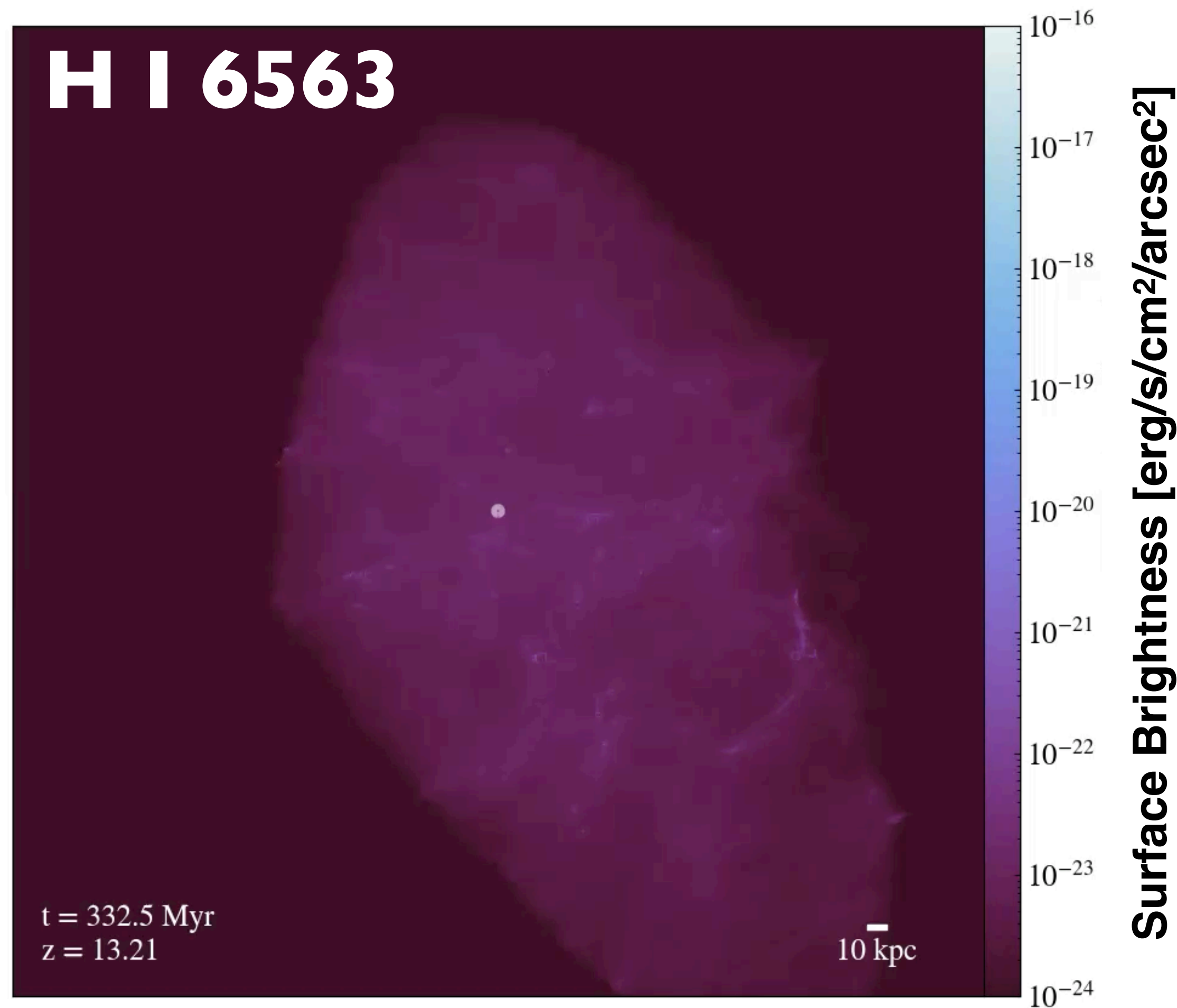


Looking straight into
the outflows—very
large velocity
dispersions, almost
1000 km/s

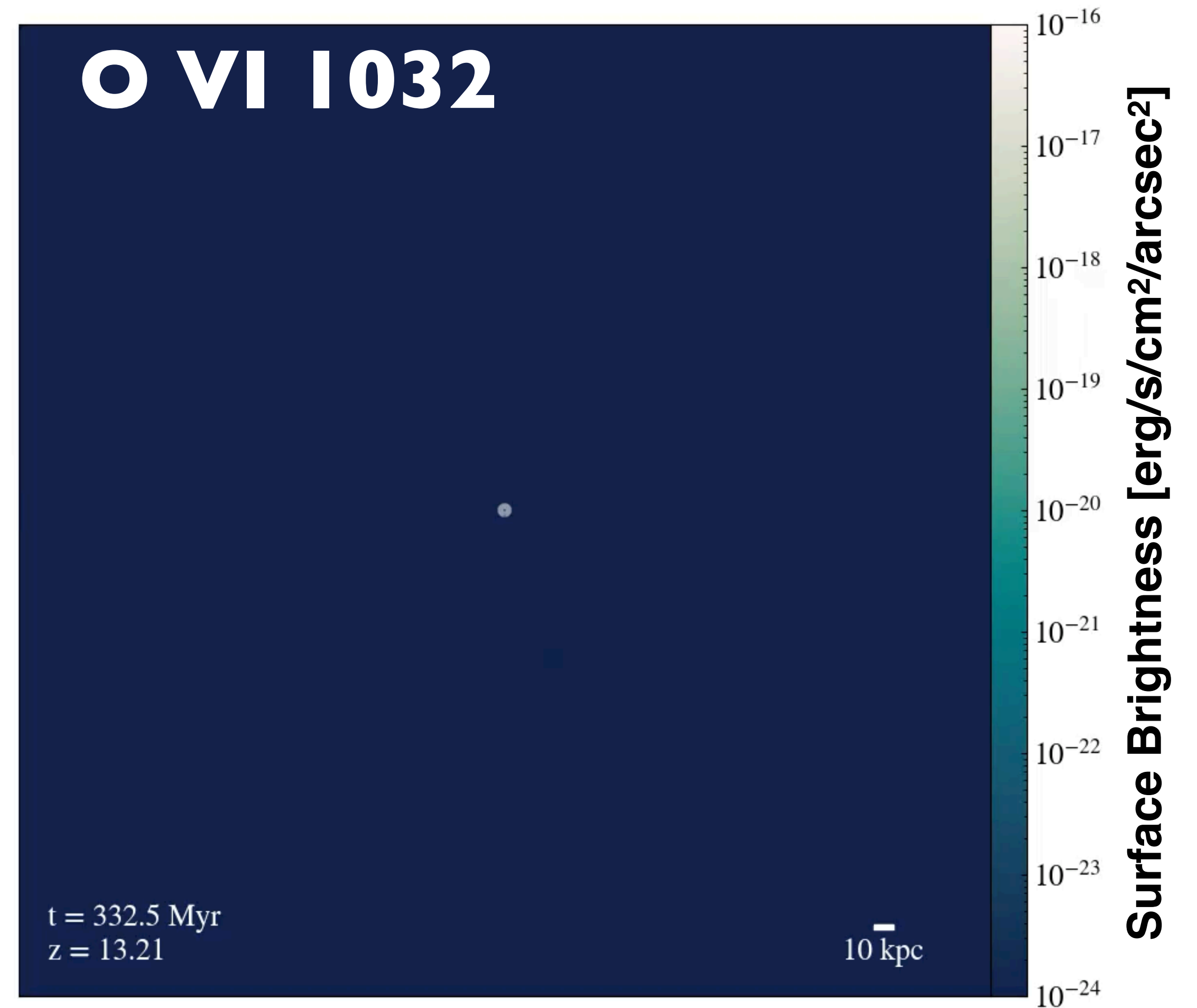


Silich et al. (2025)

Models of UV Emission Lines



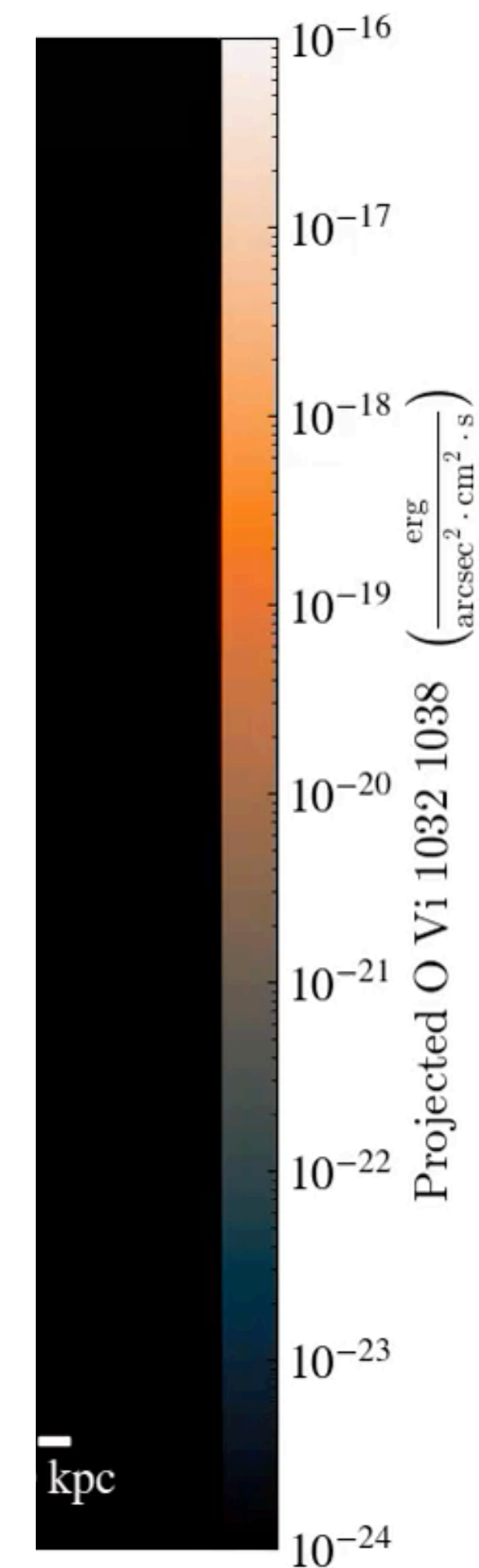
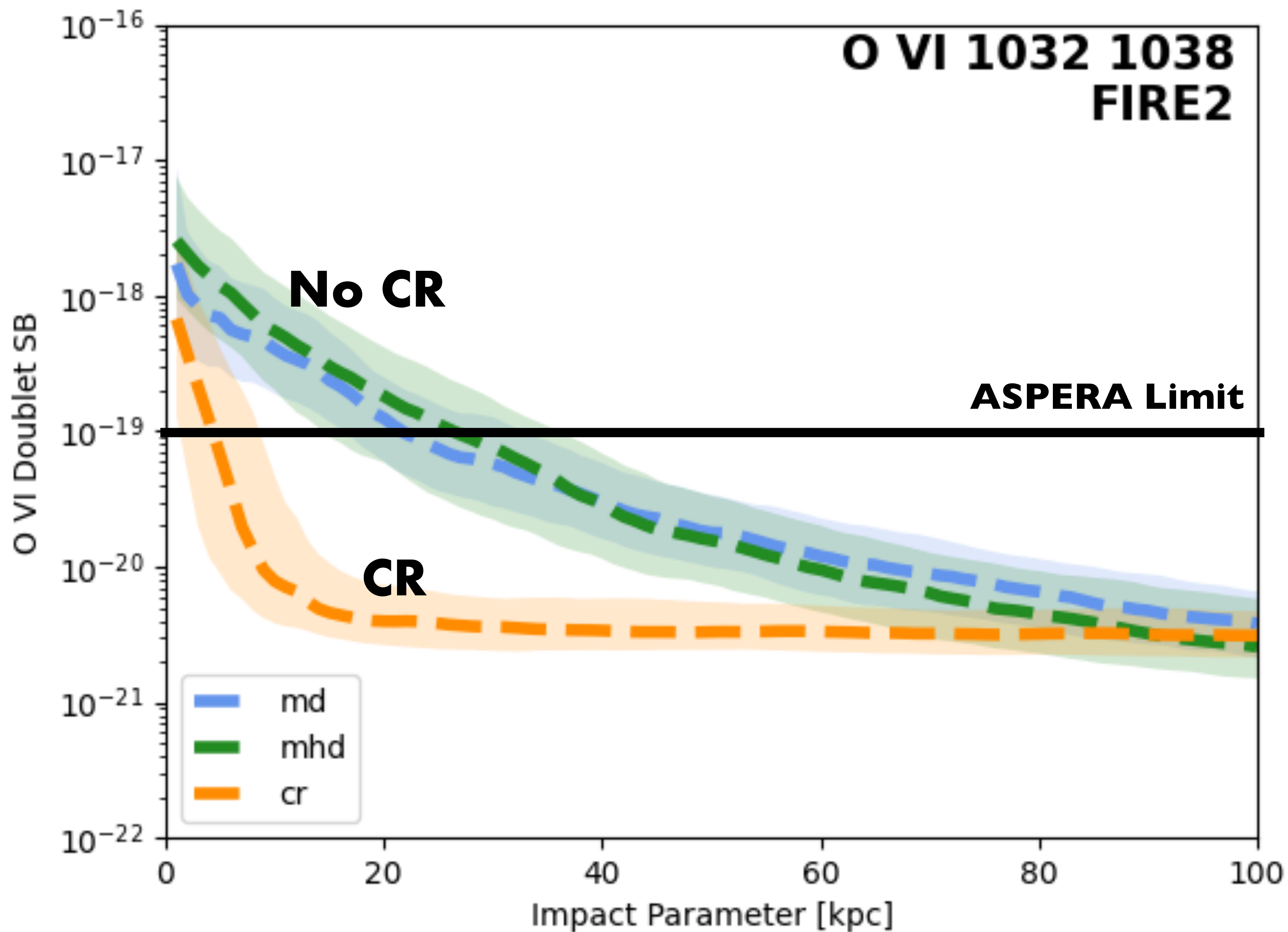
FIRE m12i halo
Milky Way analog



Cameron Hummels+
in prep

Th

ack



Cameron Hummels+
in prep

How do we observe this?

- The diffuse warm/hot CGM in extragalactic systems is faint—and typically drowned out by the MW foreground—but may be detected in individual emission lines
- These same lines will provide thermodynamic, chemical, and kinematic information
- Thus, one needs imaging spectroscopy:
 - In the UV: Aspera, HWO
 - and in the soft X-ray: NewAthena/XIFU, Lynx, LEM, ExcEED
 - or why not both at once? Ardua
- See talks by Vargas, Chung, Kilbourne, Kraft

