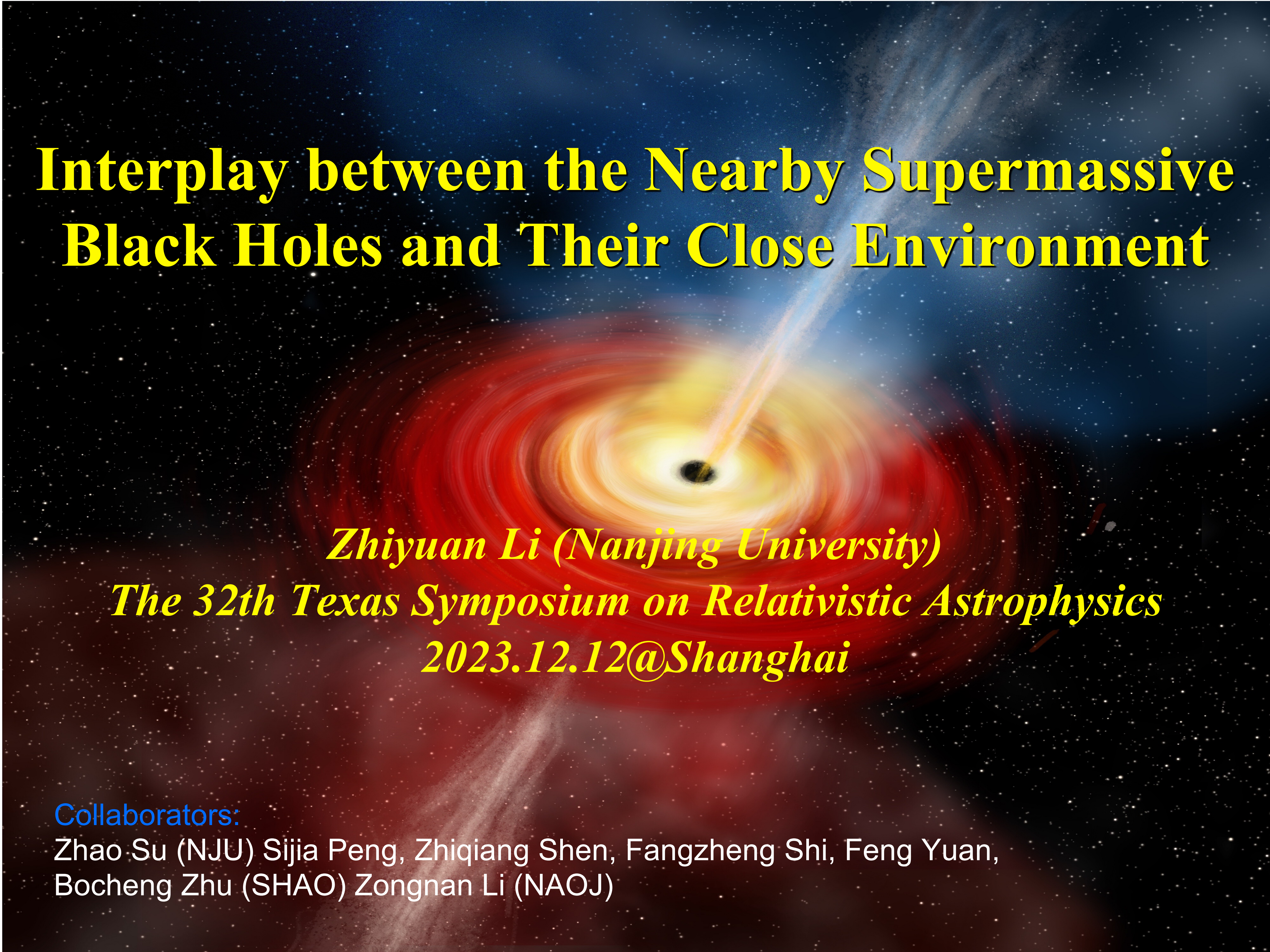


Interplay between the Nearby Supermassive Black Holes and Their Close Environment

Zhiyuan Li (Nanjing University)

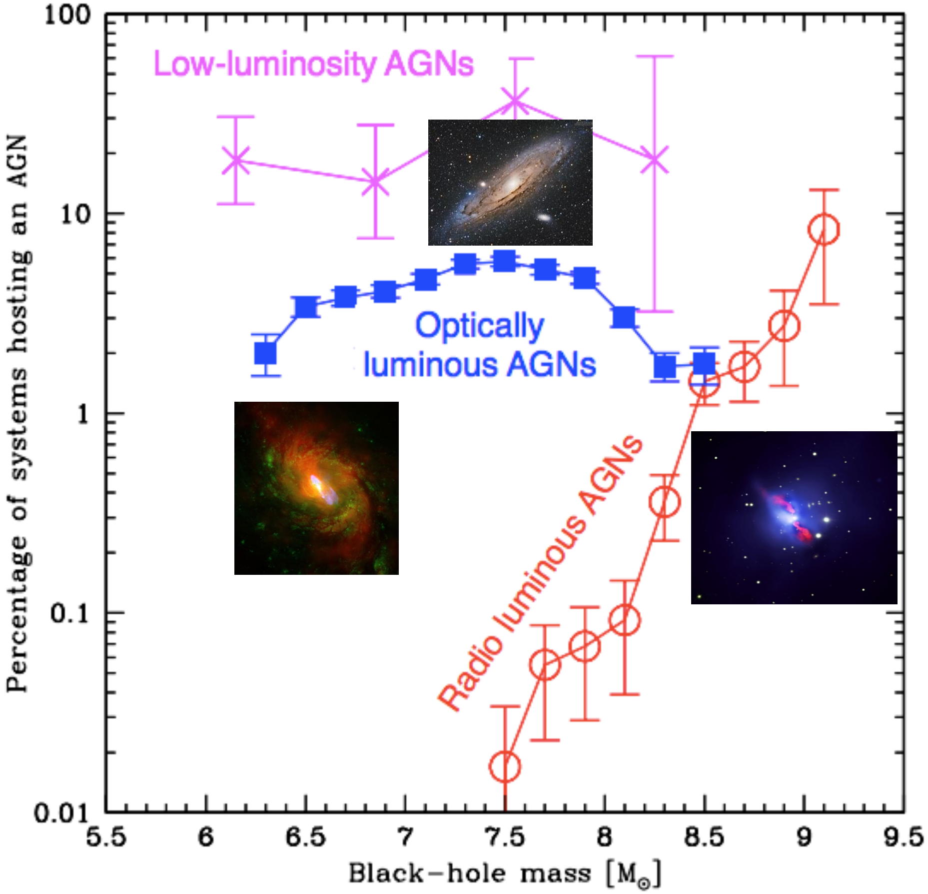
The 32th Texas Symposium on Relativistic Astrophysics

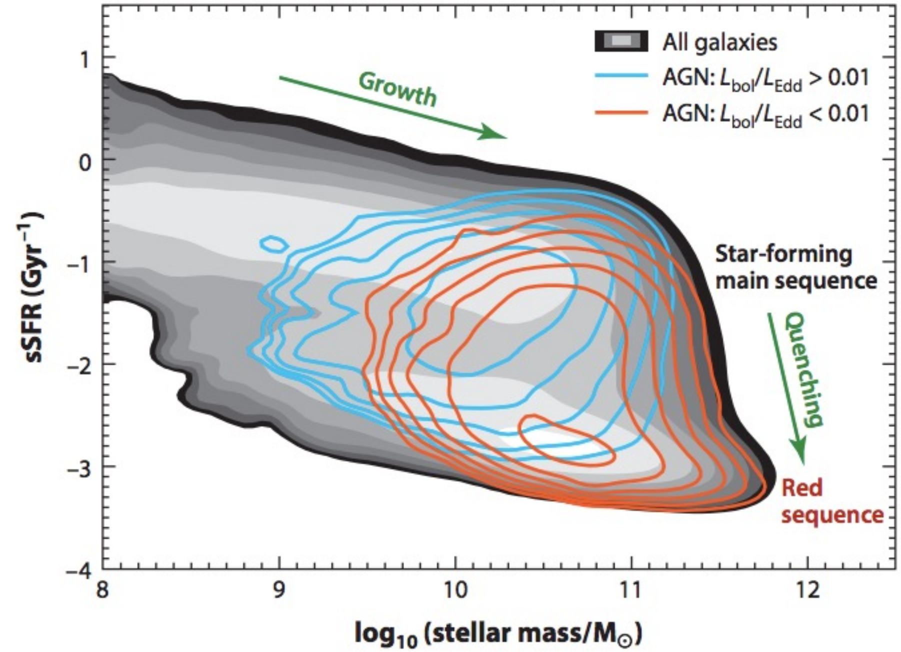
2023.12.12@Shanghai

Collaborators:
Zhao Su (NJU) Sijia Peng, Zhiqiang Shen, Fangzheng Shi, Feng Yuan,
Bocheng Zhu (SHAO) Zongnan Li (NAOJ)

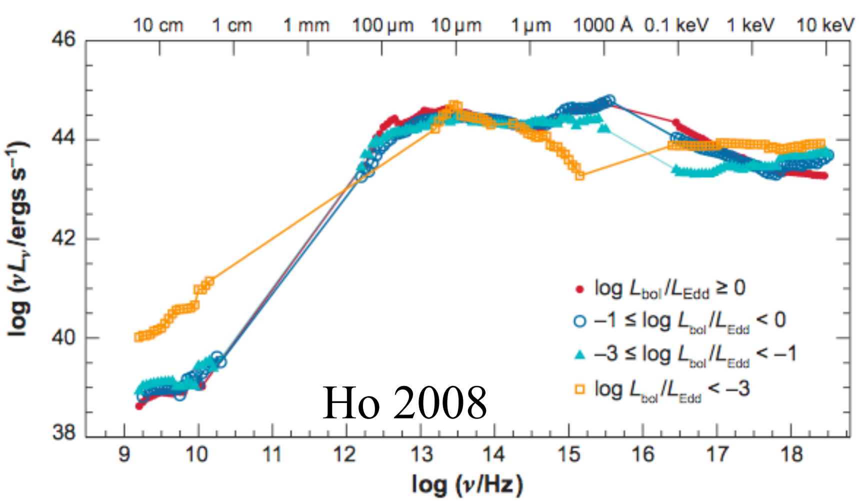
Outline

- Background
- New observational evidence for LLAGN (wind) feedback
- Hydrodynamic simulations of wind-fed MBHs (M31* as a testbed)
- Summary and Prospect



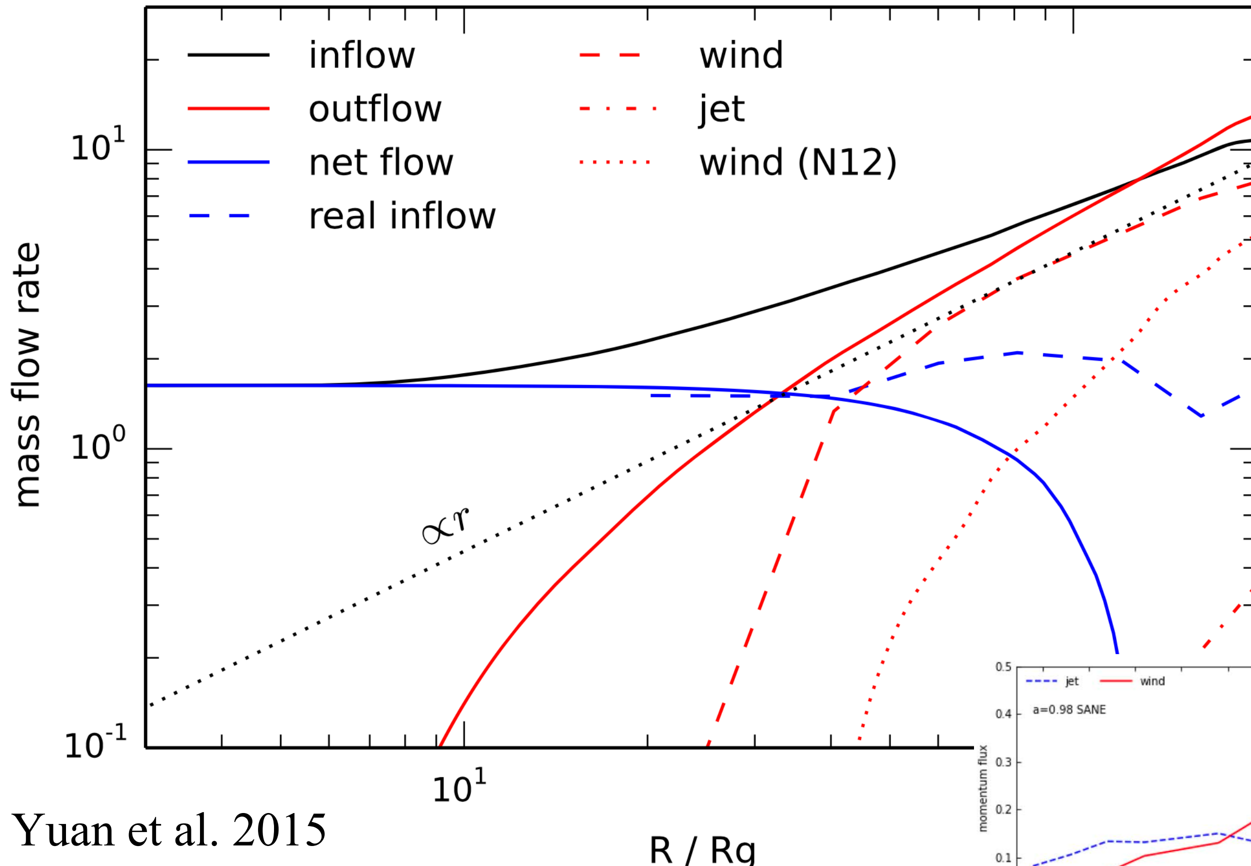


Alexander & Hickox 2012

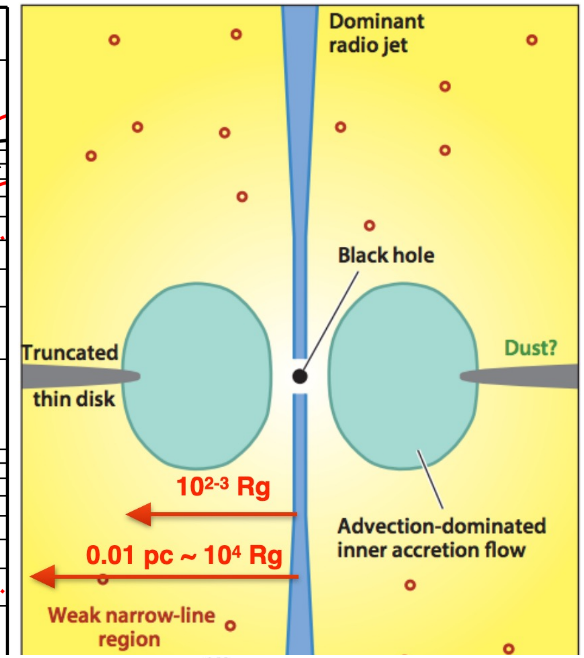


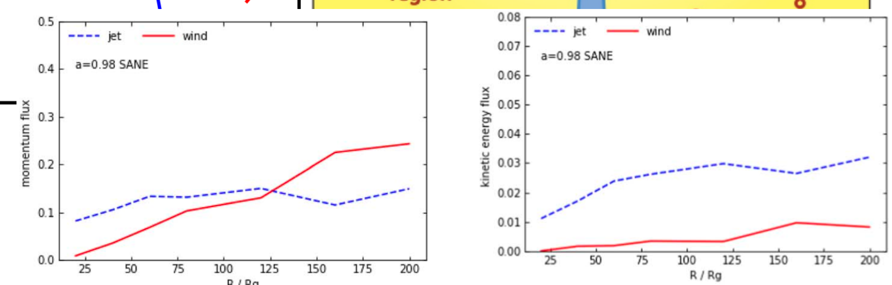
Some still unclear mechanism (other than AGN jets and SNe) required to suppress SF and SMBH accretion

Wind from a weakly accreting BH

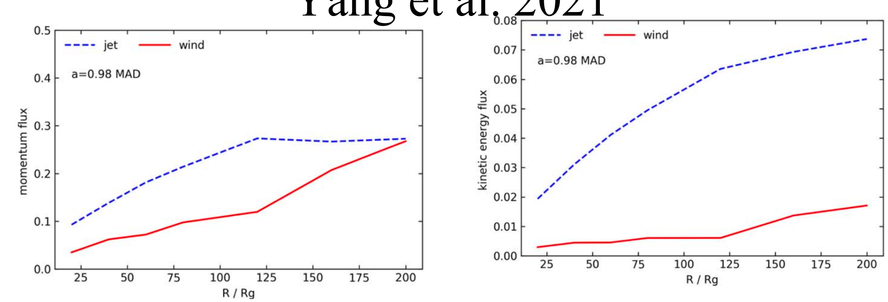


Yuan et al. 2015

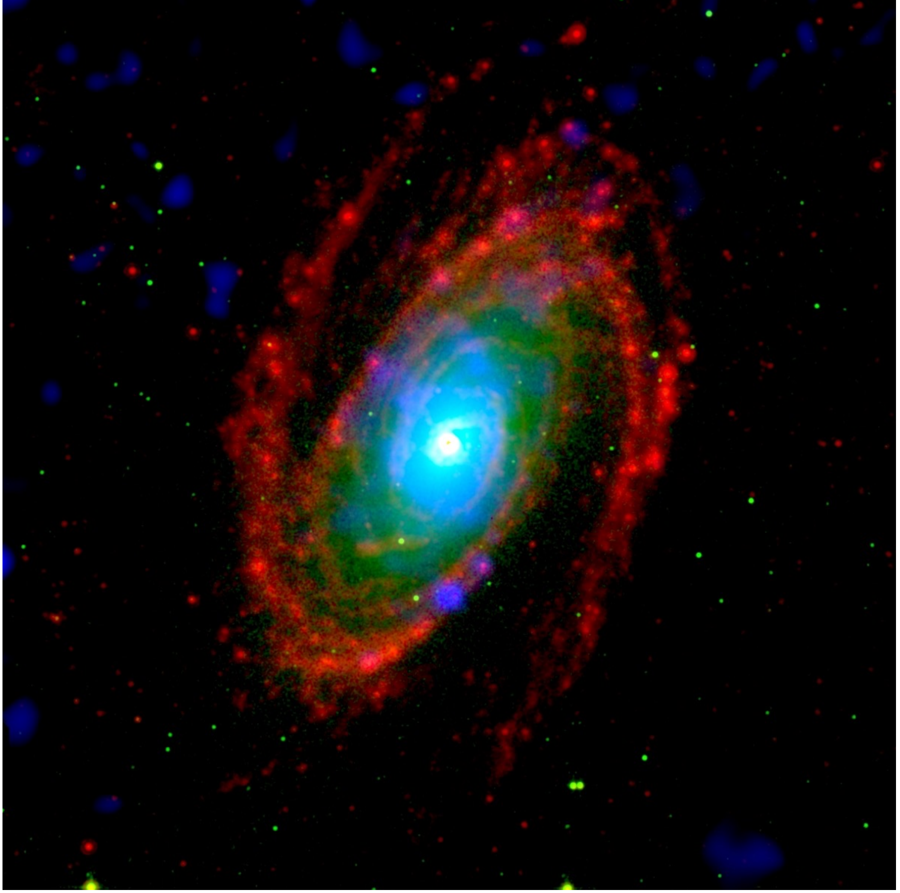




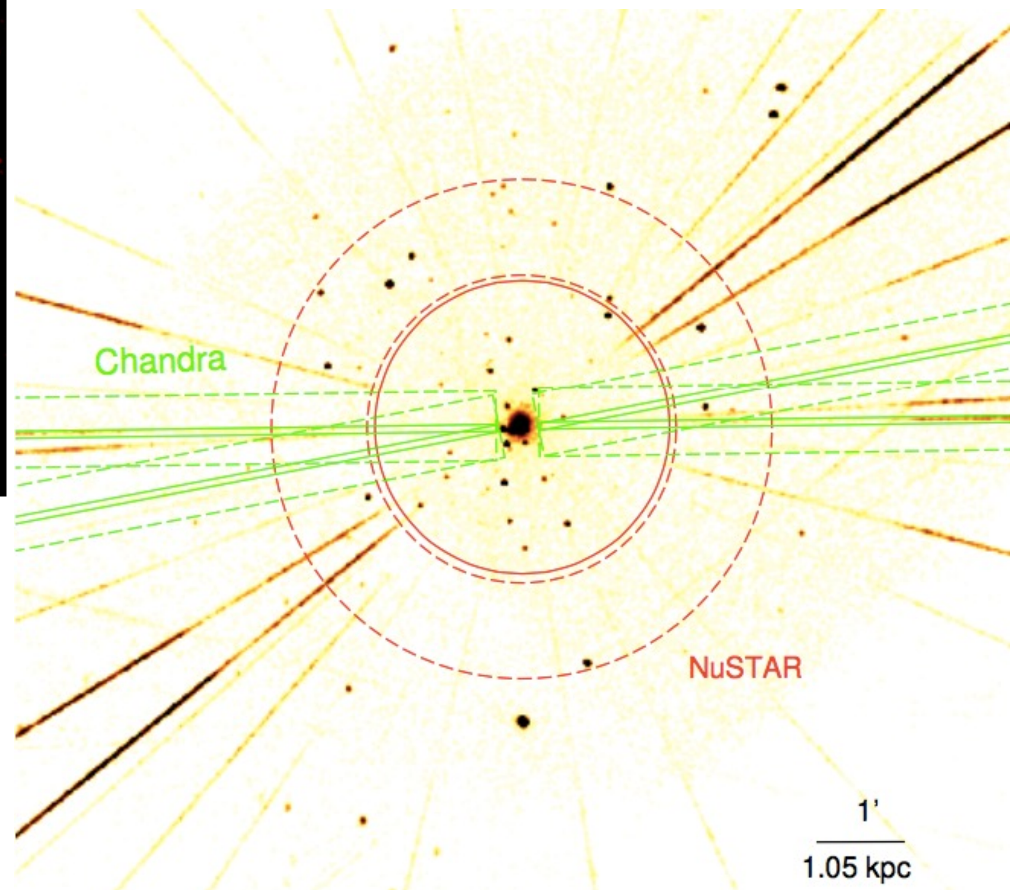
Yang et al, 2021



Direct evidence for the HAF-wind is still scarce!



Deep Chandra/HETG observations of M81* promise to detect a hot wind on scales $\lesssim 10^7$ Rg (40 pc)



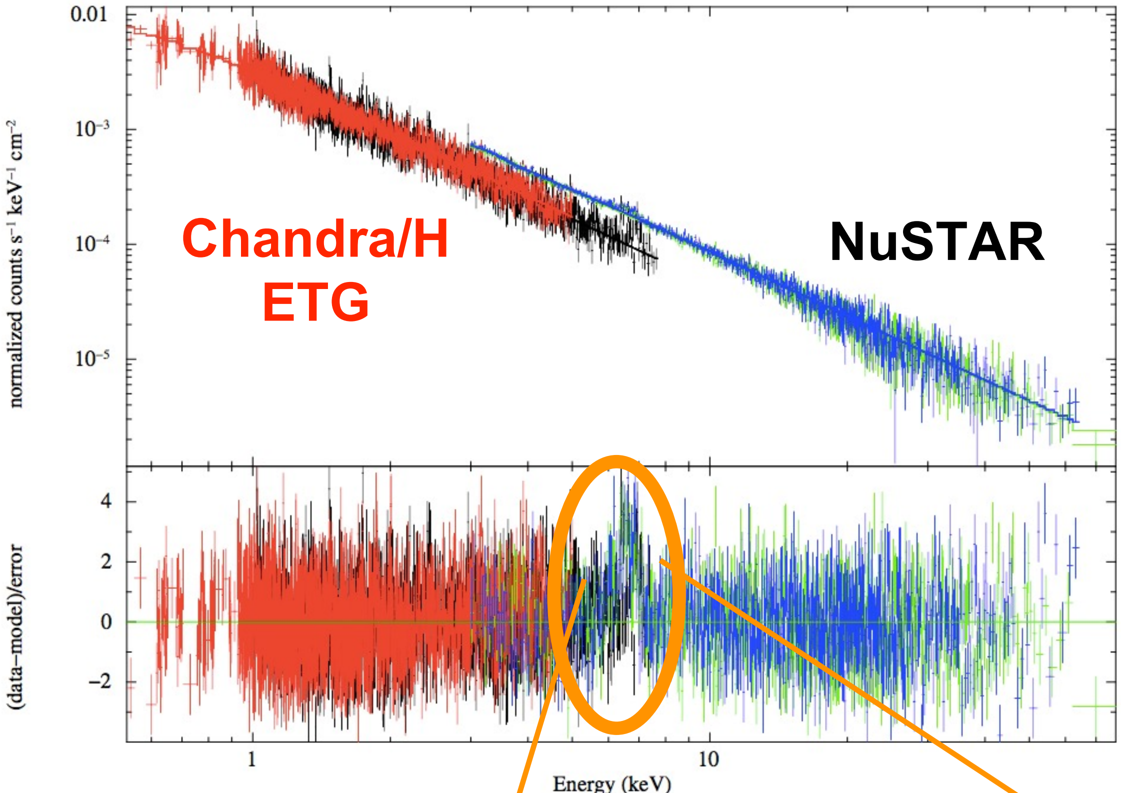
M81*: the nearest prototype LLAGN

$M_{BH} \sim 7 \times 10^7\ M_\odot$ $L_{bol}/L_{Edd} \sim 3 \times 10^{-5}$

One-sided radio jet

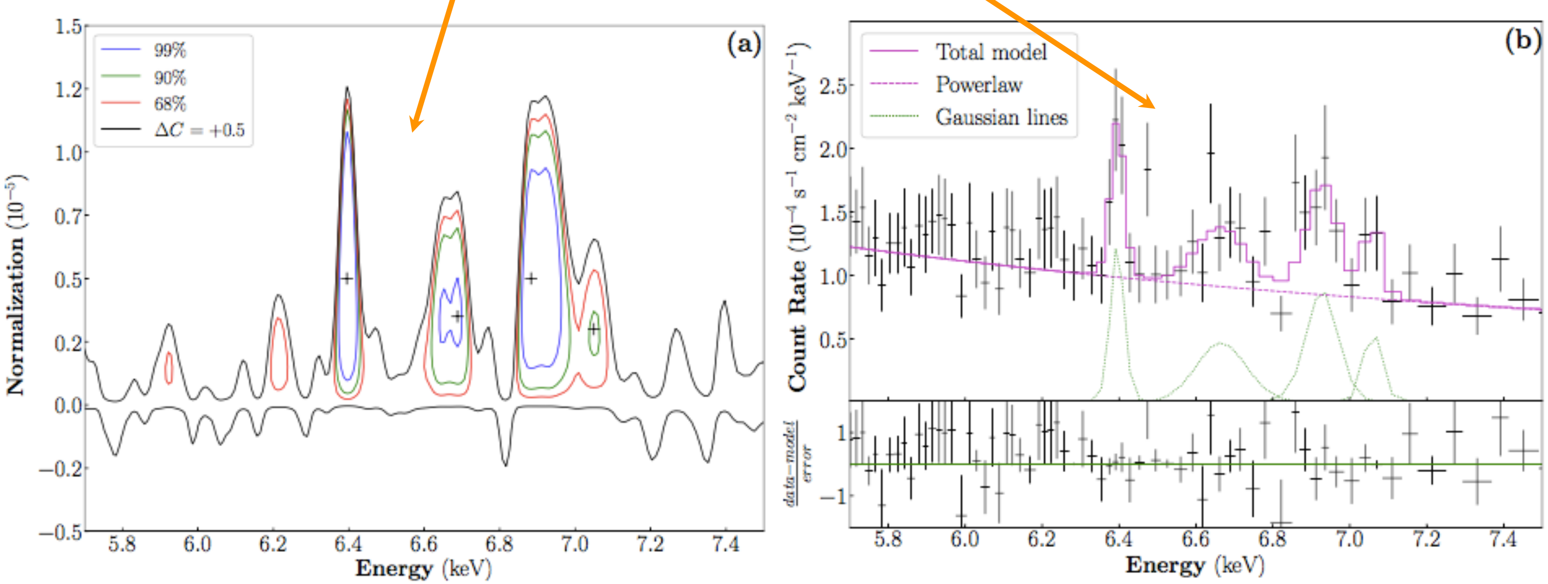
Truncated disk ($R_{tr} \gtrsim 3000\ r_g$)

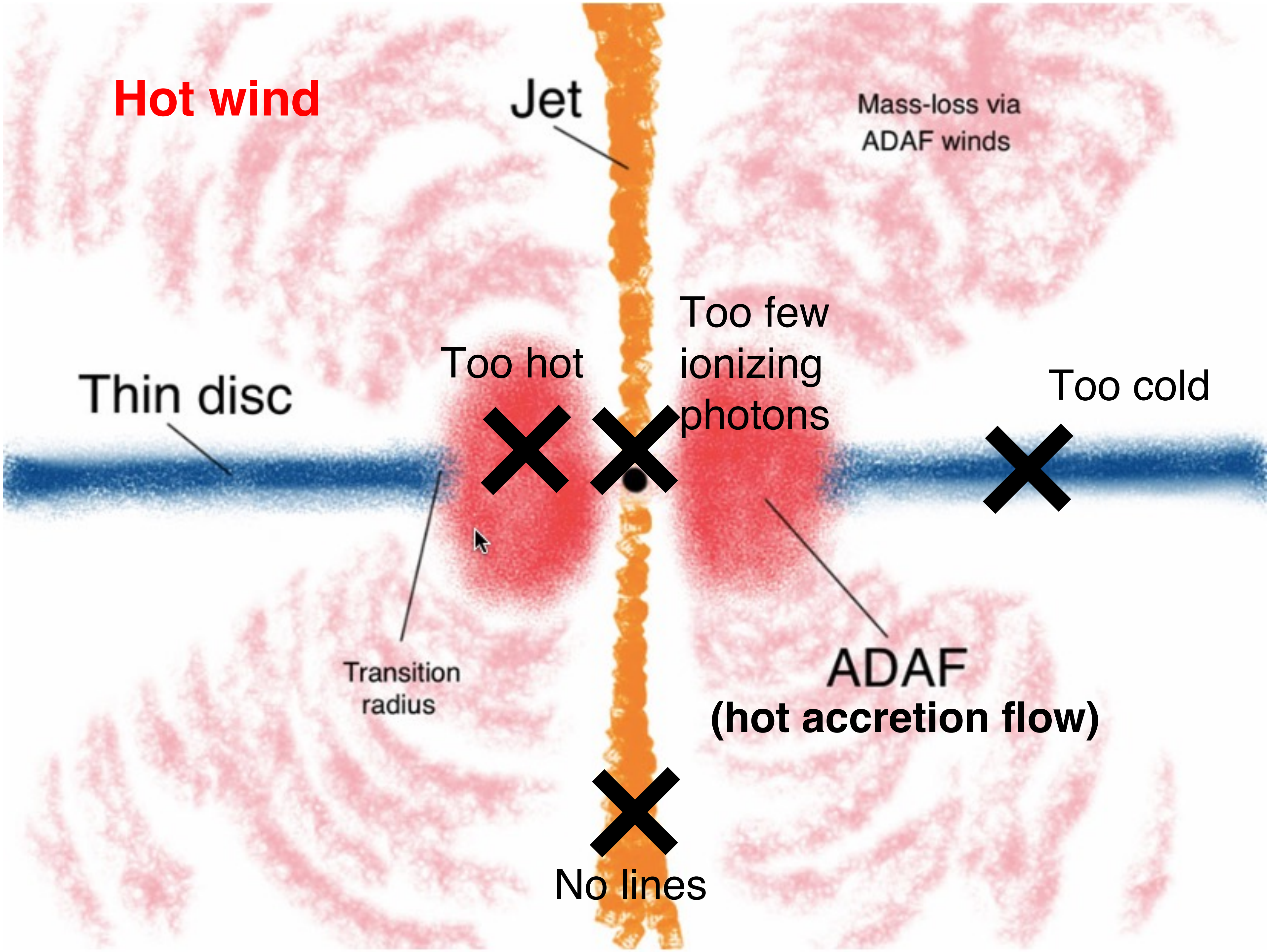
No nuclear star formation

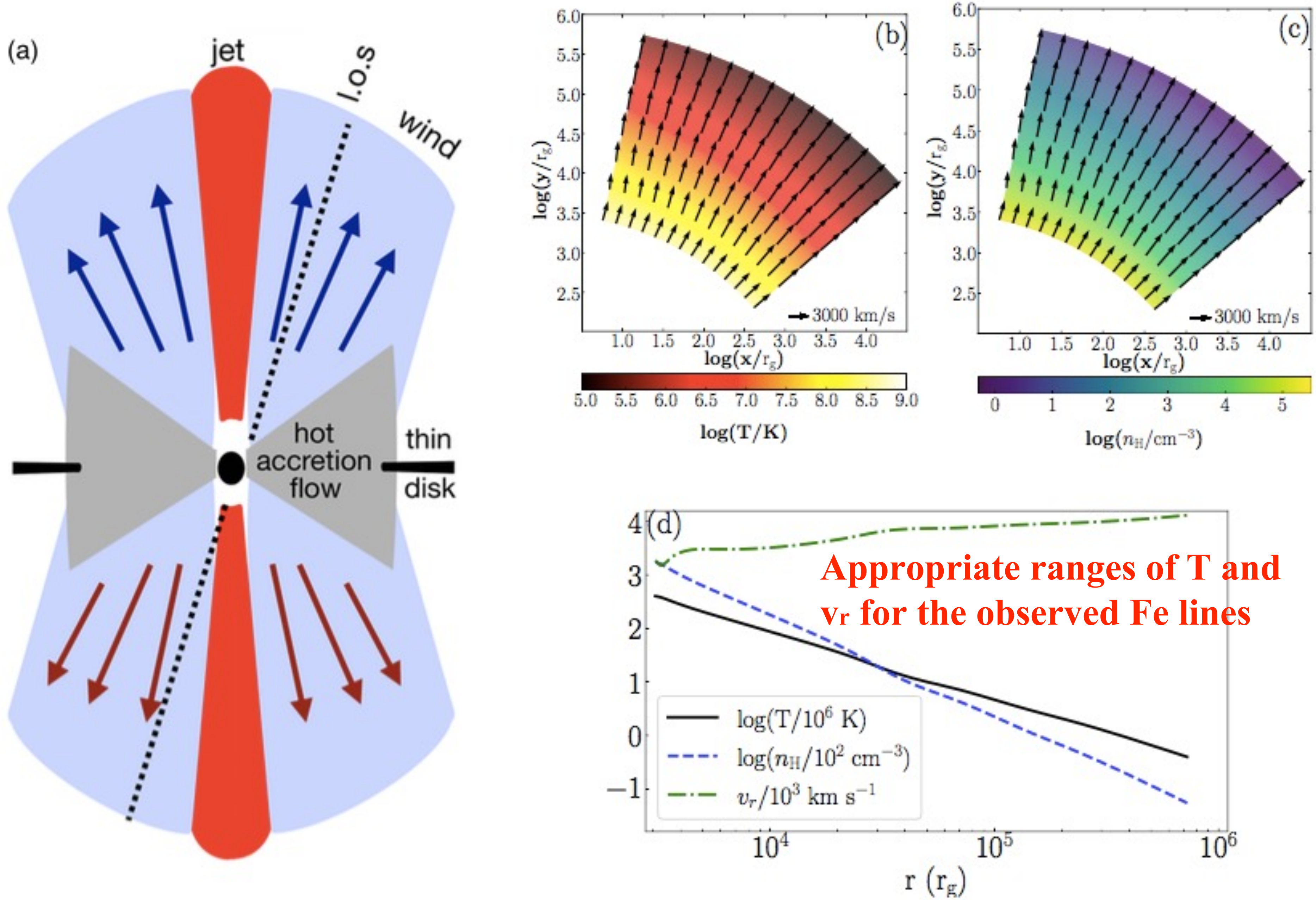


- **Emission lines at 6.90/7.05 keV: a pair of redshifted/blueshifted Fe XXVI Lyα (rest-frame 6.97 keV)**
- **Doppler shift ~2700 km/s!**
- **Fe XXVI-to-Fe XXV ratio implies T ~ 1.3x10^{8} K!**

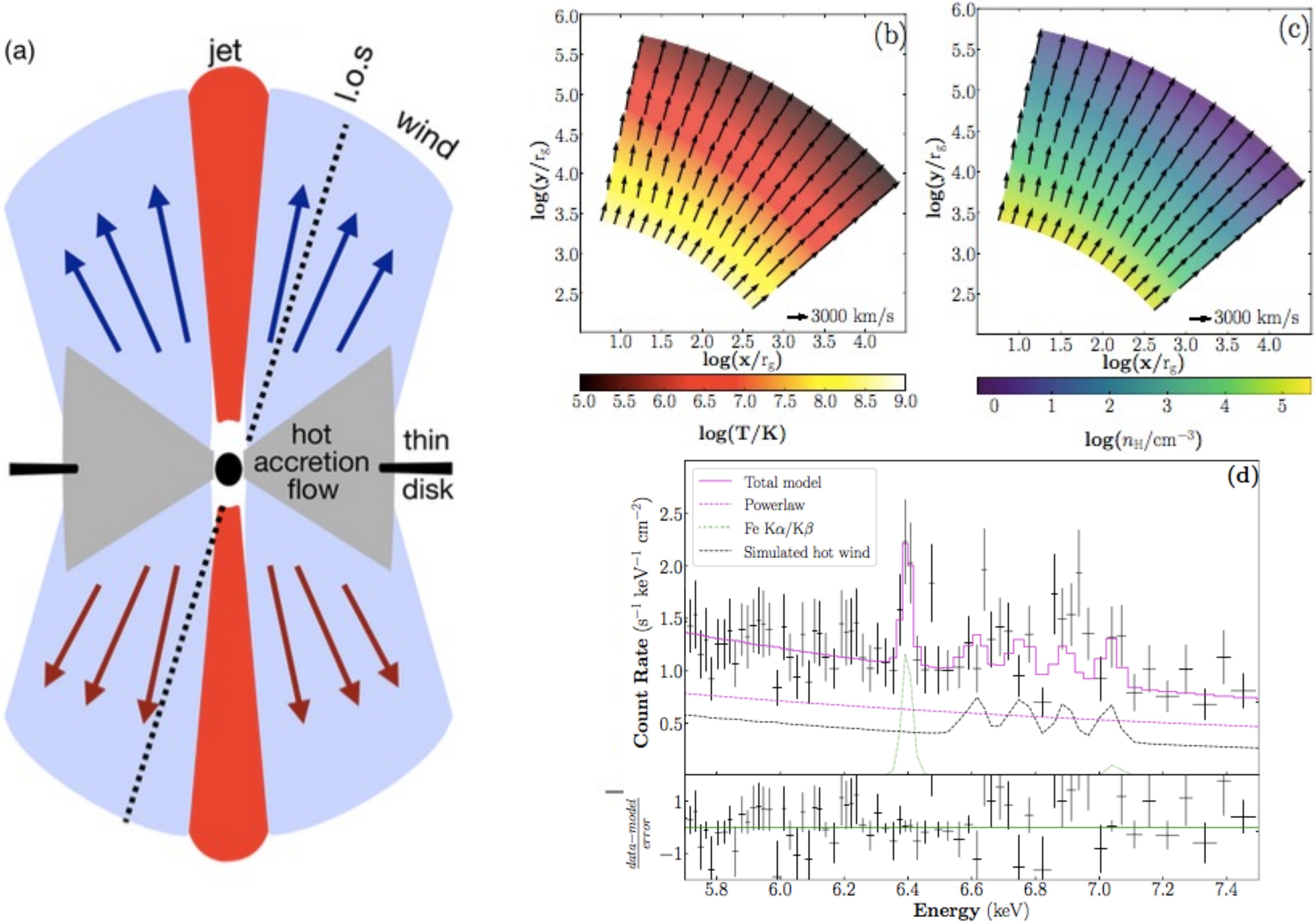
Shi et al. 2021



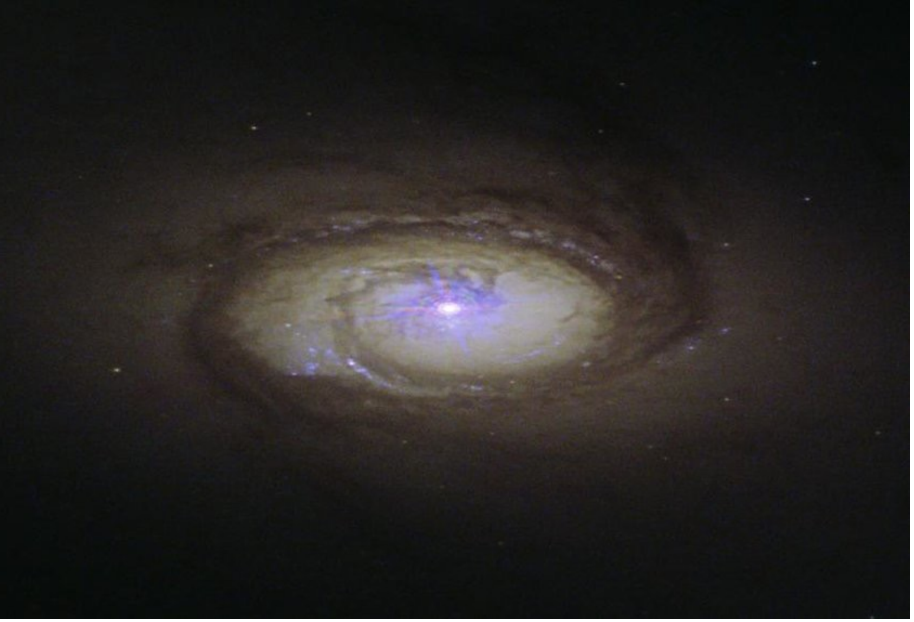

Hot wind
Jet
Mass-loss via
ADAF winds
Too few
ionizing
photons
Too hot
Thin disc
Too cold
Transition
radius
ADAF
(hot accretion flow)
No lines



MHD simulations of a hot wind from the HAF, tailored to M81* conditions



The synthetic wind X-ray spectrum well matches the observed spectrum



Are there more M81*-like hot winds?

examine local LLAGNs with existing Chandra/HETG data

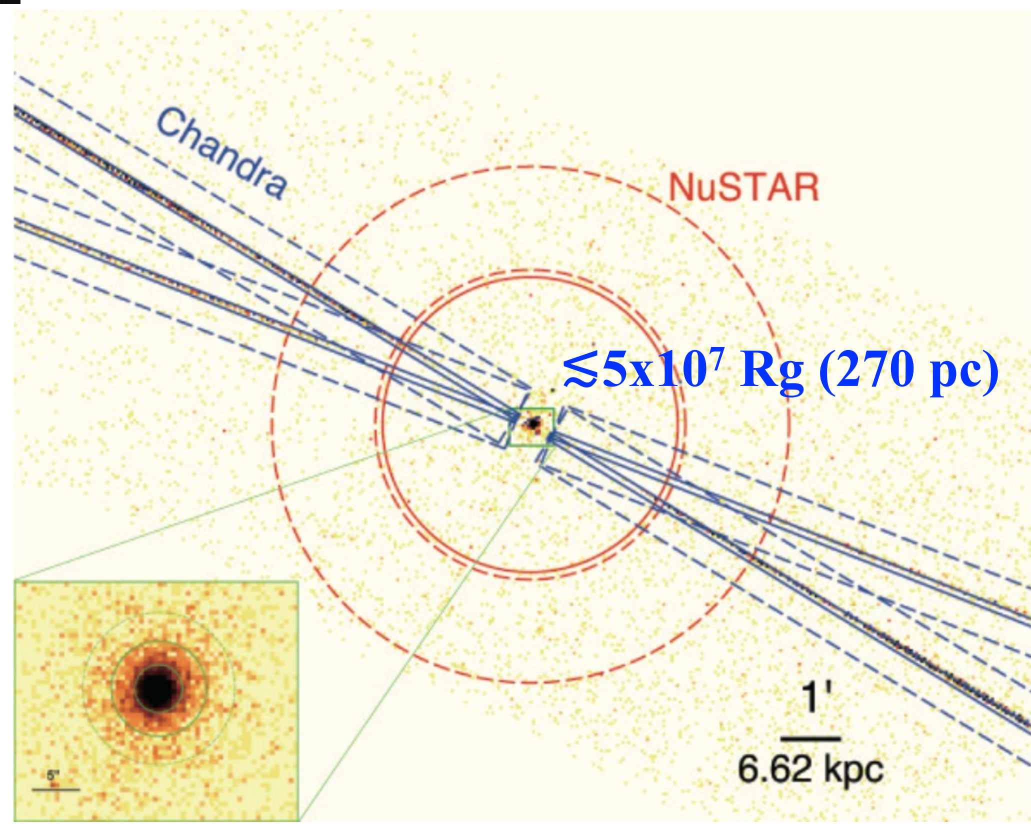
The LLAGN in NGC7213 (Sa)

$M_{BH} \sim 10^8\ M_\odot$ $L_{bol}/L_{Edd} \sim 10^{-3}$

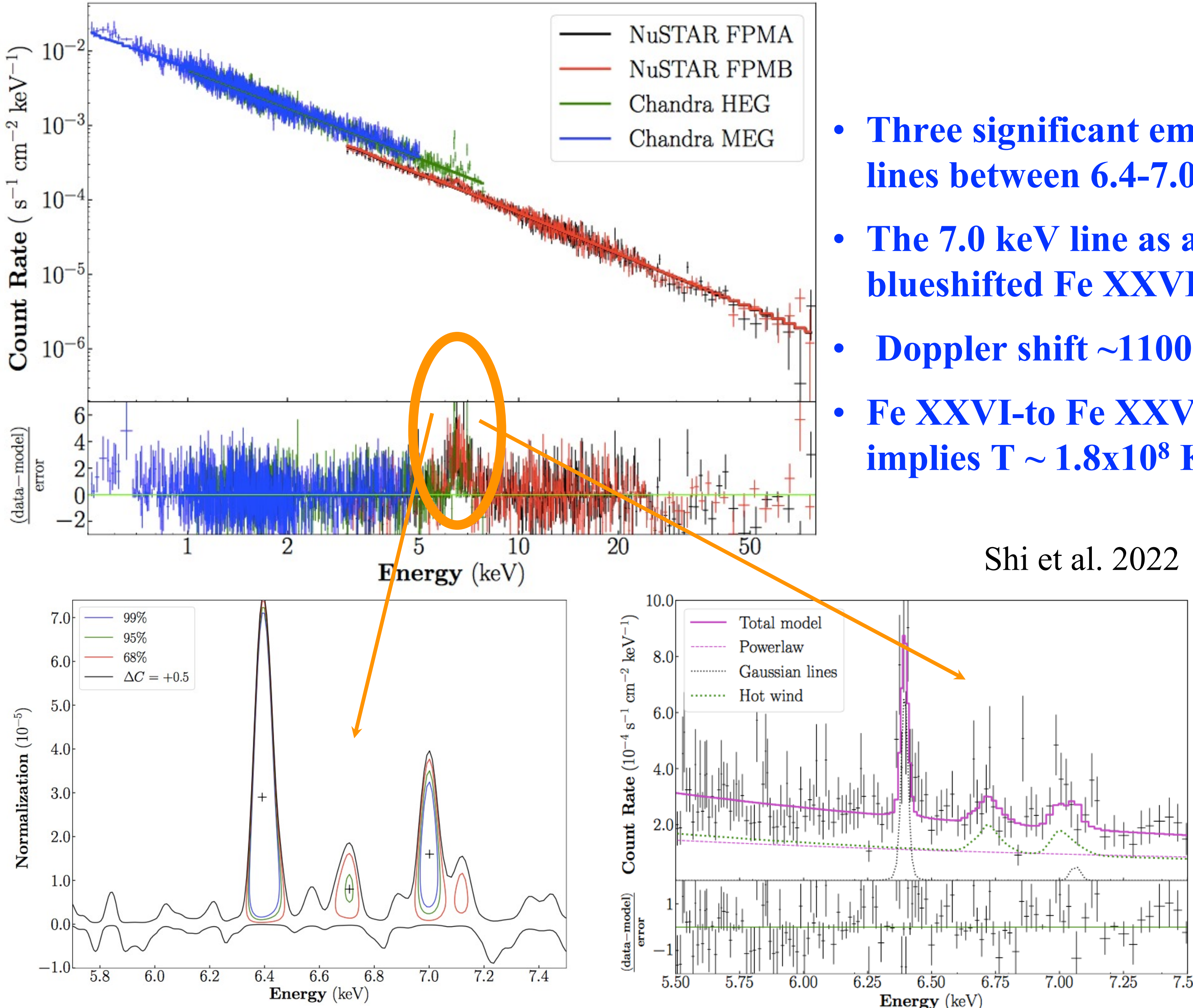
Compact radio core

Truncated disk ($R_{tr} \gtrsim 1000\ r_g$)

No nuclear star formation

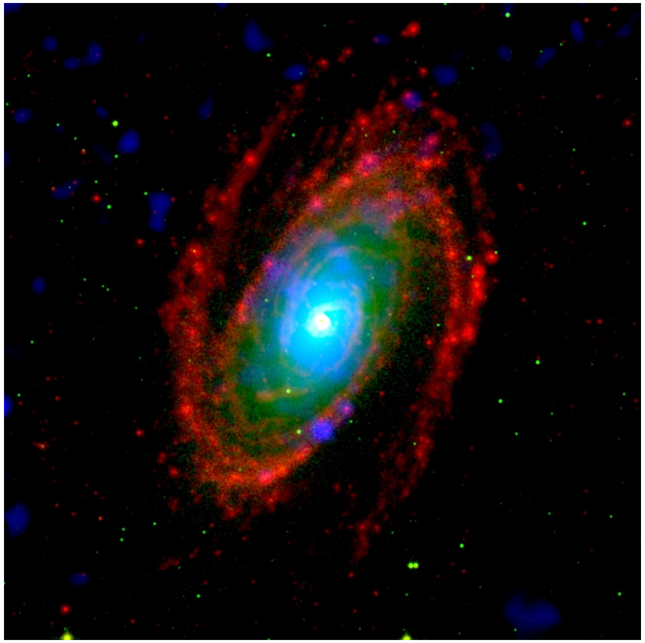


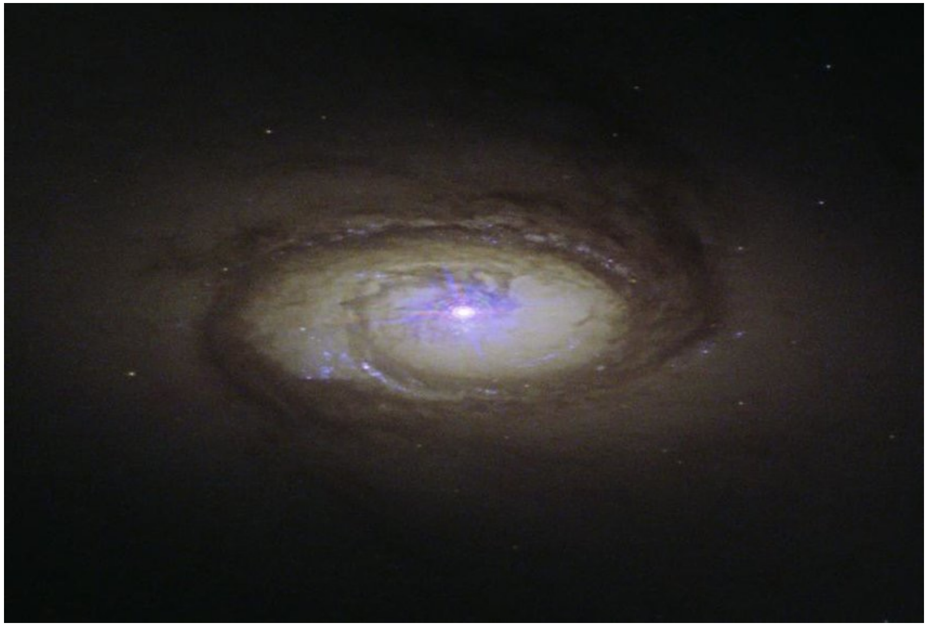
$\lesssim 5 \times 10^7$ Rg (270 pc)



- **Three significant emission lines between 6.4-7.0 keV**
- **The 7.0 keV line as a blueshifted Fe XXVI Lyα**
- **Doppler shift ~1100 km/s**
- **Fe XXVI-to Fe XXV ratio implies T ~ 1.8x10^8 K**

Shi et al. 2022

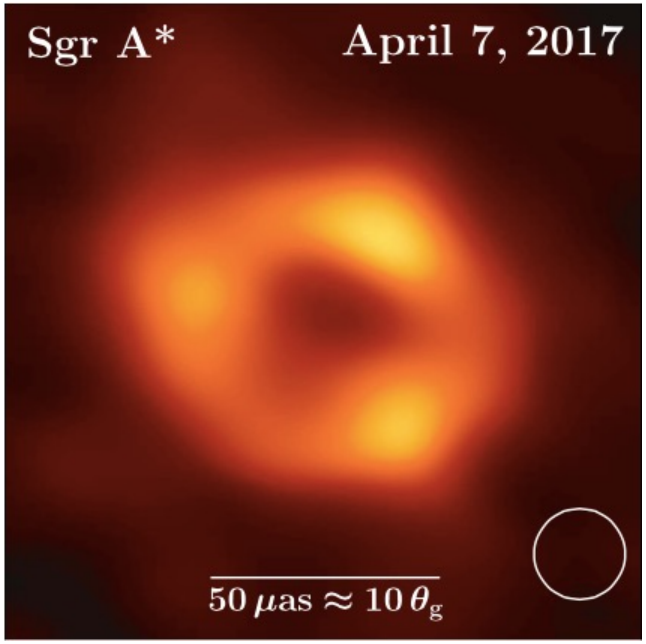


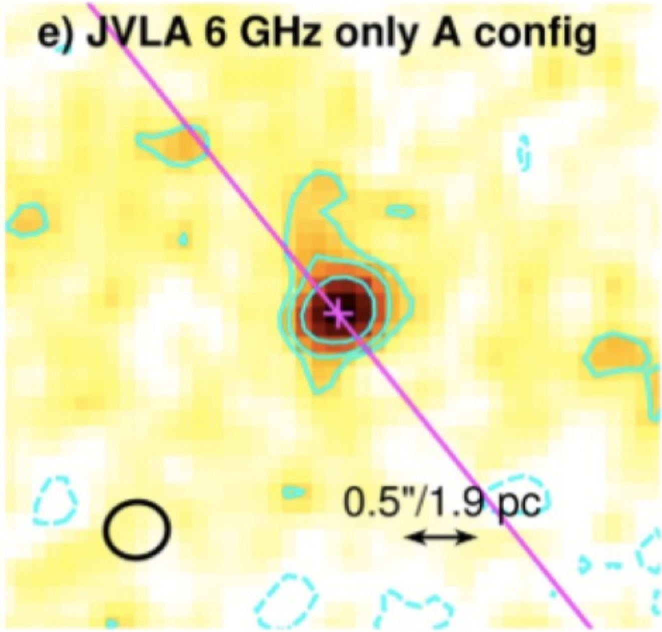


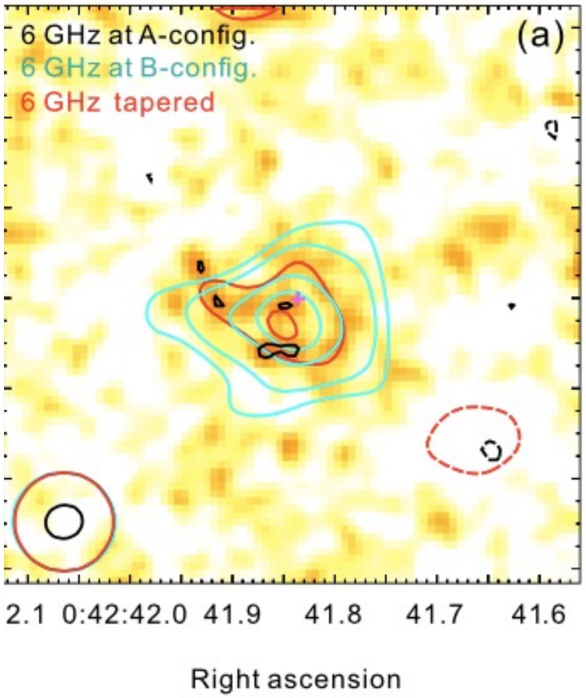
	M81*	N7213
M_{BH}	7×10^{7} M$\odot$	$\sim10^{8}$ M$\odot$
L_{bol}/L_{Edd}	3×10^{-5}	$\sim10^{-3}$
$\dot{M}_{w}$ ($\sim \dot{M}_{in}$)	2×10^{-3} M$\odot$/yr	8×10^{-2} M$\odot$/yr
$\dot{E}_{w}$ ($\sim$15% $\dot{E}_{ph}$)	2×10^{40} erg/s	3×10^{42} erg/s
$\dot{S}_{w}$ ($\sim$5x $\dot{S}_{ph}$)	6×10^{31} g cm/s	4×10^{33} g cm/s

A third LLAGN (NGC4579, $M_{BH}\sim10^{8}$ M$\odot$, $L_{bol}/L_{Edd}\sim10^{-4}$) awarded Chandra/HETG time (PI: F. Shi)

The three nearest SMBHs/LLAGNs







Sgr A*
core-dominated
no jet?

ZL et al. 2013
Zhu, ZL et al. 2019

M31*
pc-scale core
resolved at >500 Rg
HAF wind?

Yang, ZL. et al. 2017
Peng, ZL et al. 2023

M32*
already resolved
at pc-scale
HAF wind?

Yang, ZL. et al. 2015
Peng, ZL et al. 2020

Some outstanding questions

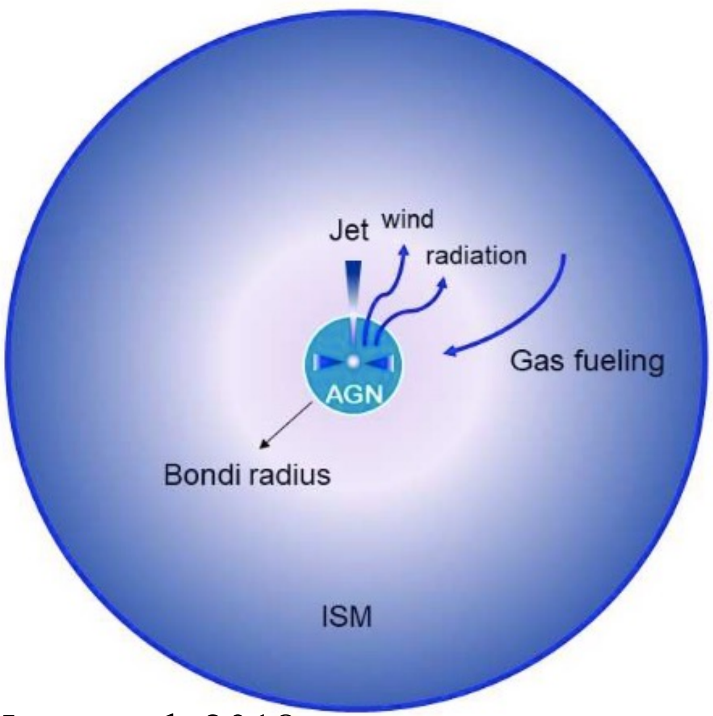
- Is the HAF-wind an efficient mode of feedback?
  - Need observational evidence from ~10 Rg to >> R_{Bondi}
  - Challenge: multi-phase and multi-scale
- How special is Sgr A*?
  - Jet or no jet? Wind feedback?
  - Need to look at other quiescent SMBHs
- What controls accretion from circumnuclear scale （～100 pc) to horizon scale (~ 1 AU) ?
  - ISM accretion vs. stellar wind accretion

Bondi Accretion

- Spherical symmetric, non-viscous and steady fluid

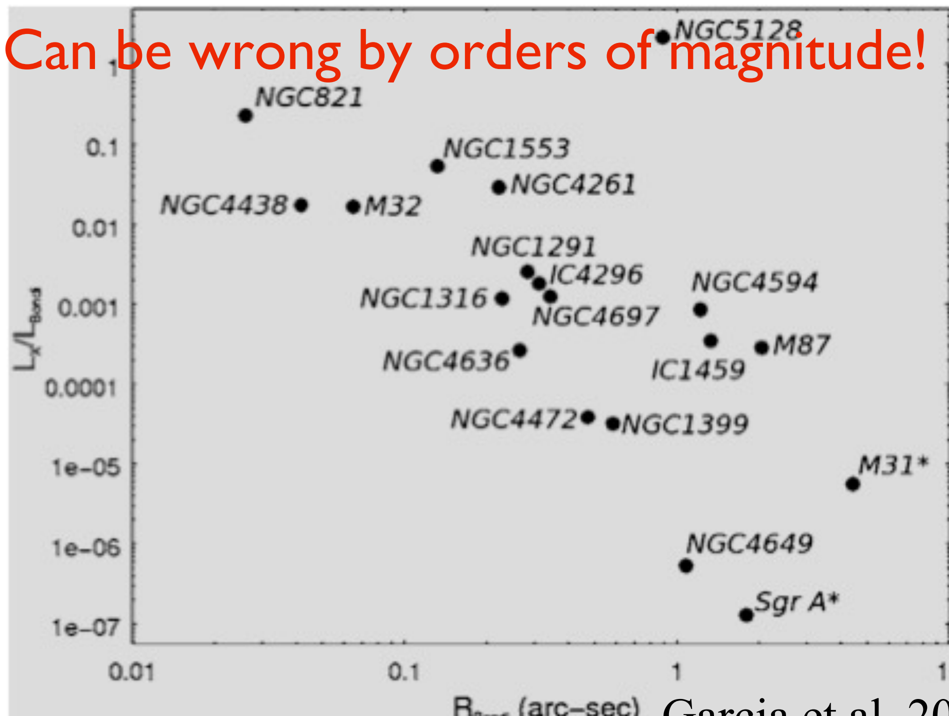
$$\dot{M} = \frac{4\pi\rho G^2 M^2}{c_s^3} = 3.2\mathrm{x}10^{-4}\,(M/10^8\,M_\odot)^2(n/1\ \mathrm{cm}^{-3})(T/10^7\,\mathrm{K})^{-1.5}\,M_\odot/\mathrm{yr}$$

$$L_{\mathrm{Bondi}} = 1.8\mathrm{x}10^{42}\,(\eta/0.1)(M/10^8\,M_\odot)^2(n/1\ \mathrm{cm}^{-3})(T/10^7\,\mathrm{K})^{-1.5}\ \mathrm{erg/s}$$

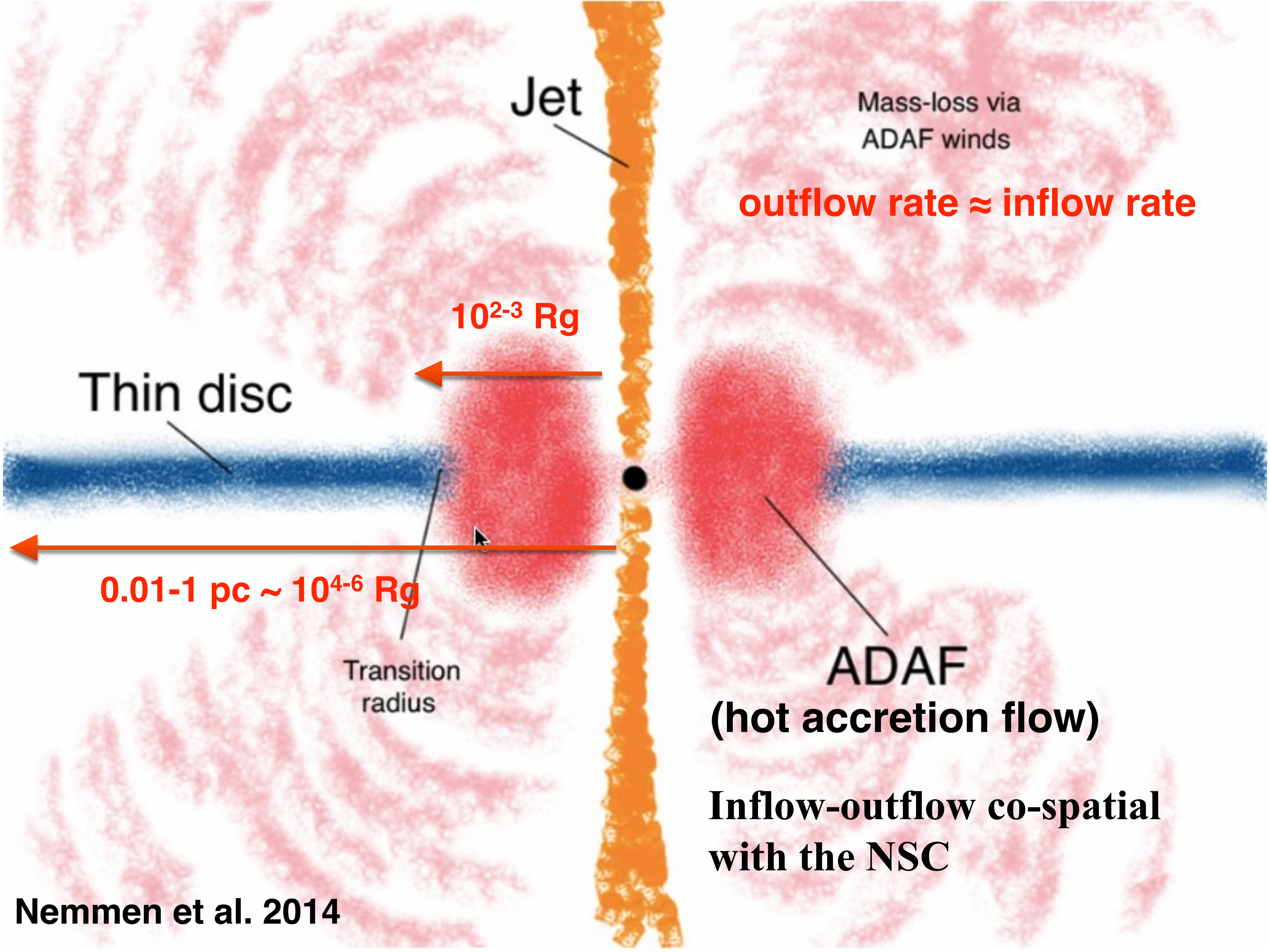


Yuan et al. 2018

Can be wrong by orders of magnitude!

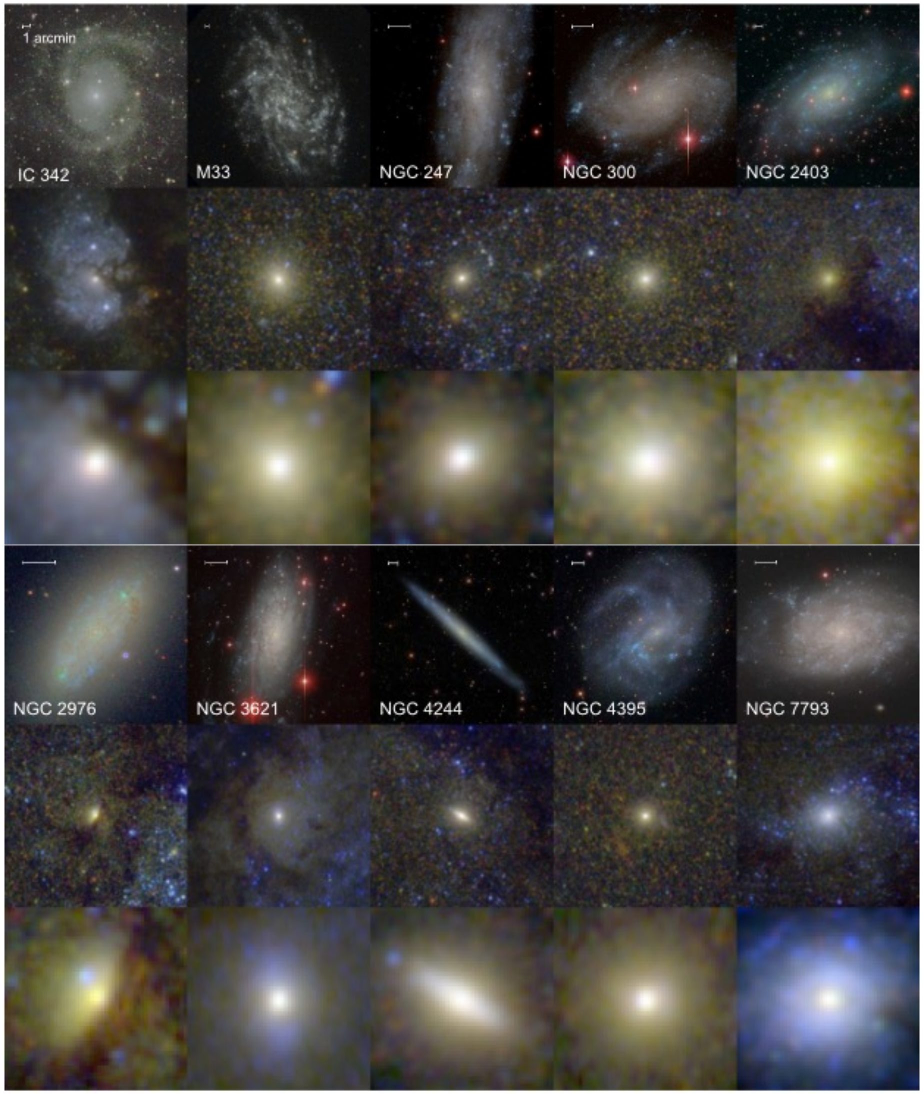


Garcia et al. 2010

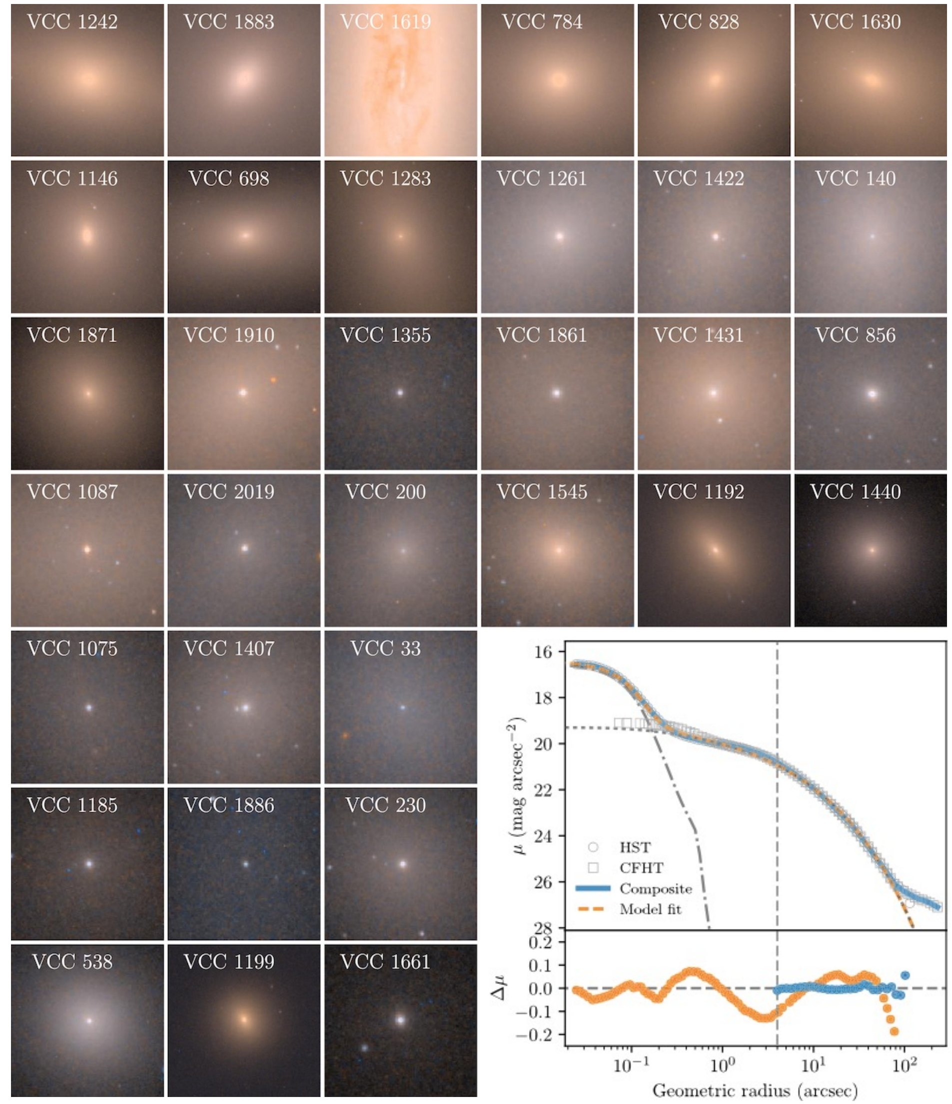


Jet
Mass-loss via
ADAF winds
outflow rate ≈ inflow rate
10^2-3 Rg
Thin disc
0.01-1 pc ~ 10^4-6 Rg
Transition
radius
ADAF
(hot accretion flow)
Inflow-outflow co-spatial
with the NSC
Nemmen et al. 2014

Nuclear Star Clusters



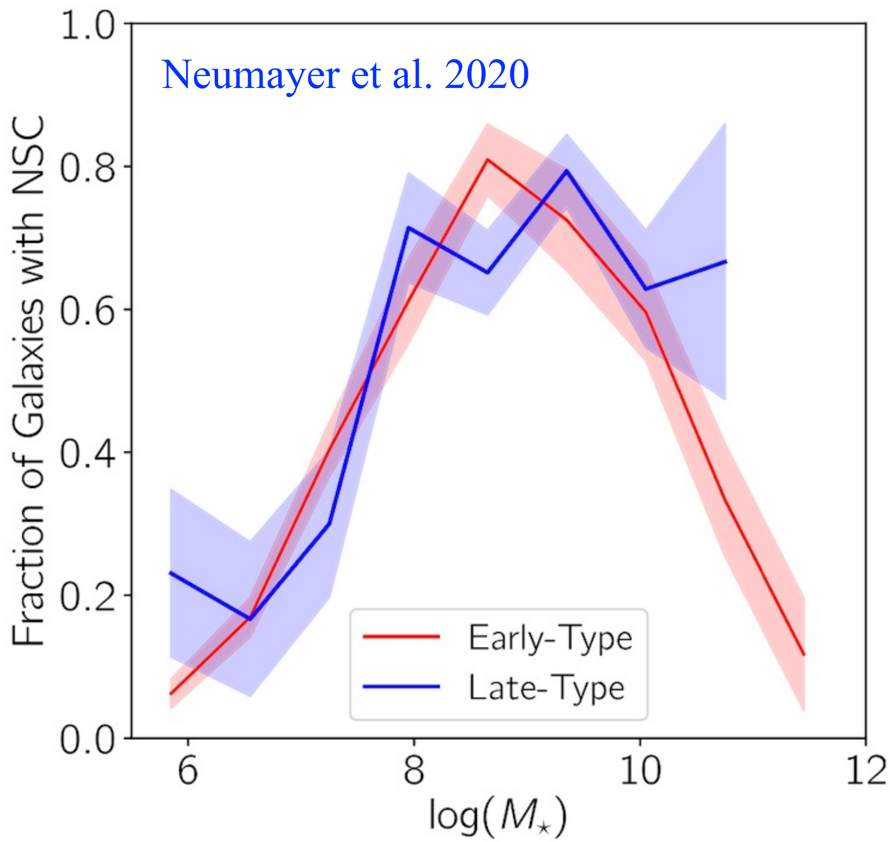
Carson et al. 2015

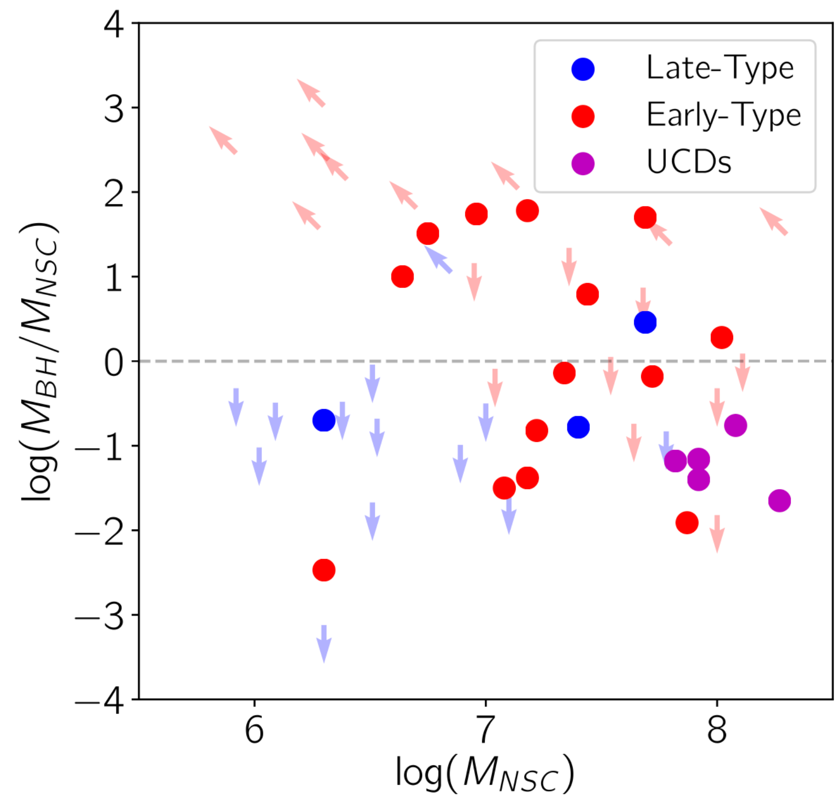


Spengler et al. 2017

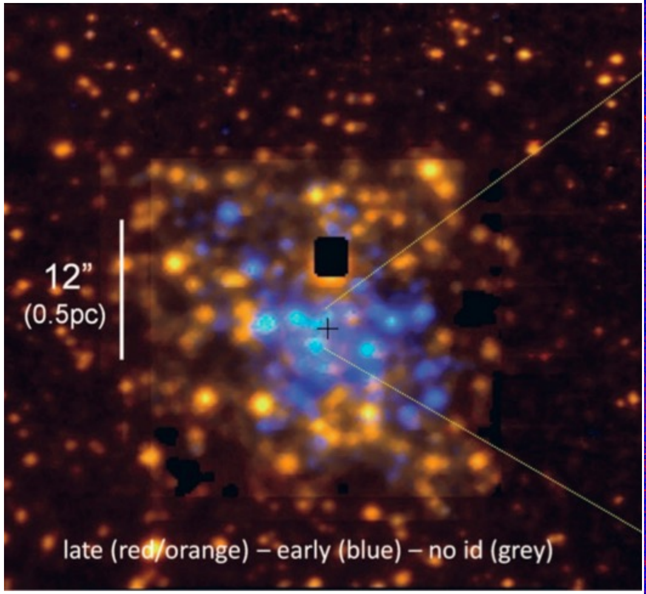
Need sub-arcsec resolu.
even for local galaxies

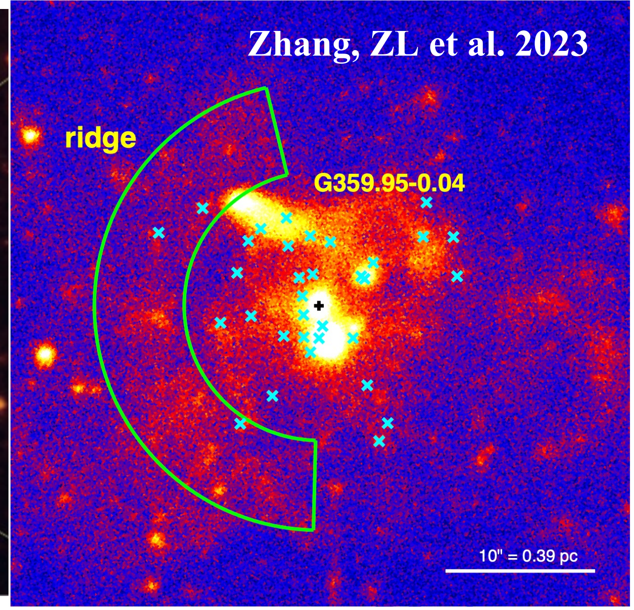
NSCs are prevalent





- Exist in almost all types of galaxies
- Likely progenitor of, and co-evolve with, a central SMBH
- But so far not included in cosmological/idealized simulations

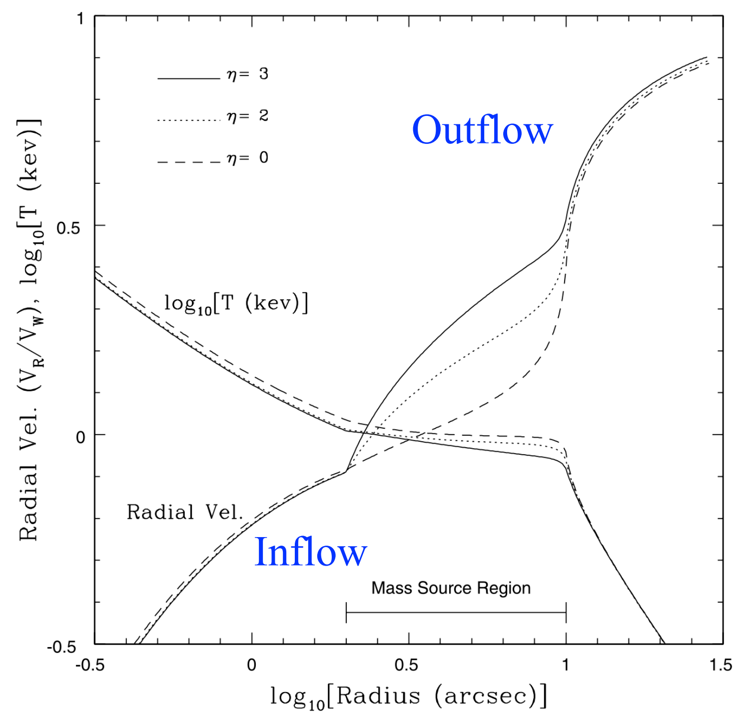




- ~30 Wolf-Rayet stars blow strong winds, producing a hot gas network
- Sgr A* fed by the hot gas

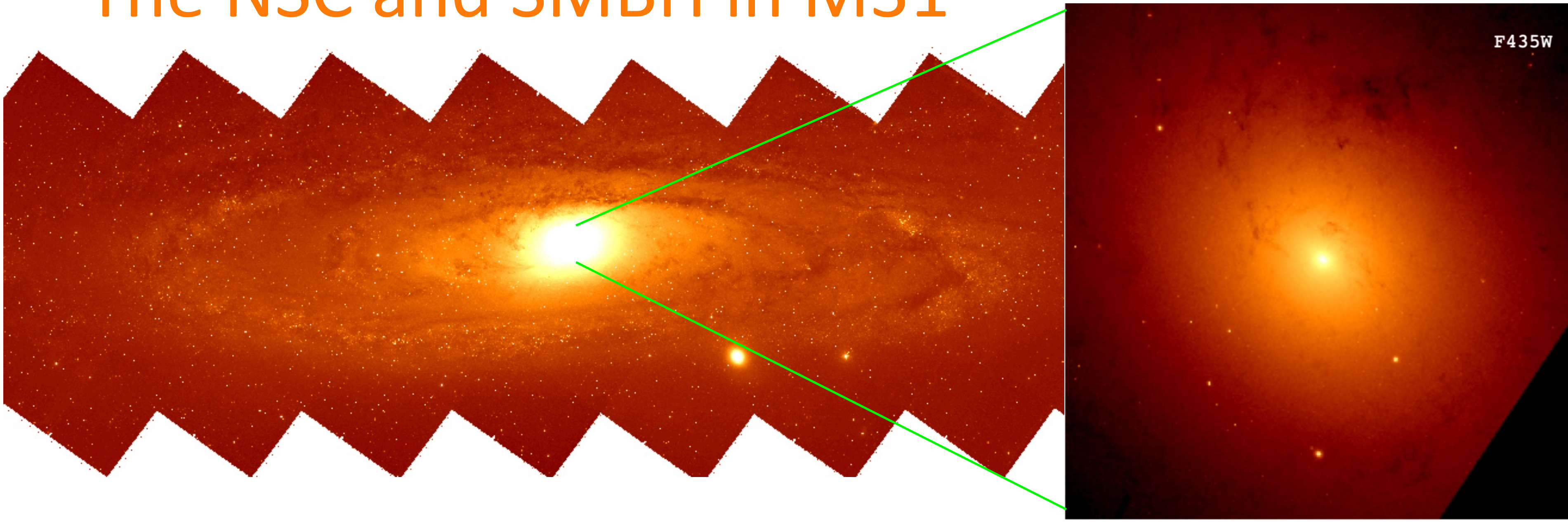
$$R_B = 2GM/c_s^2 = 0.15\,(M/4\mathrm{x}10^6\,M_\odot)(T/10^7\,K)^{-1}\ \mathrm{pc}$$

NSCs as a persistent fuel ?

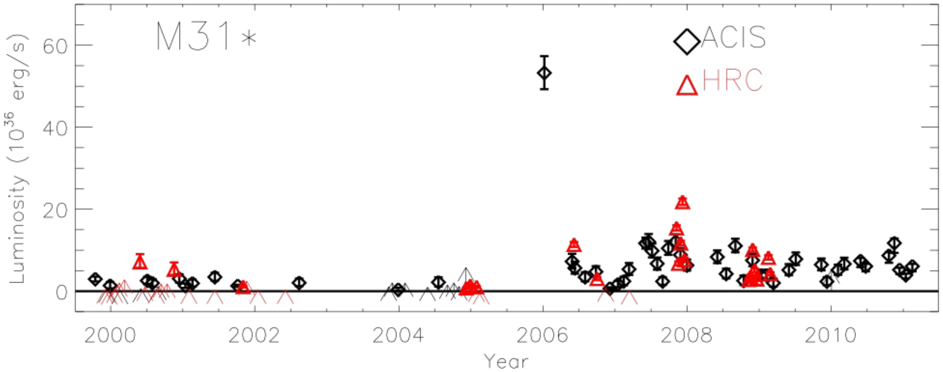


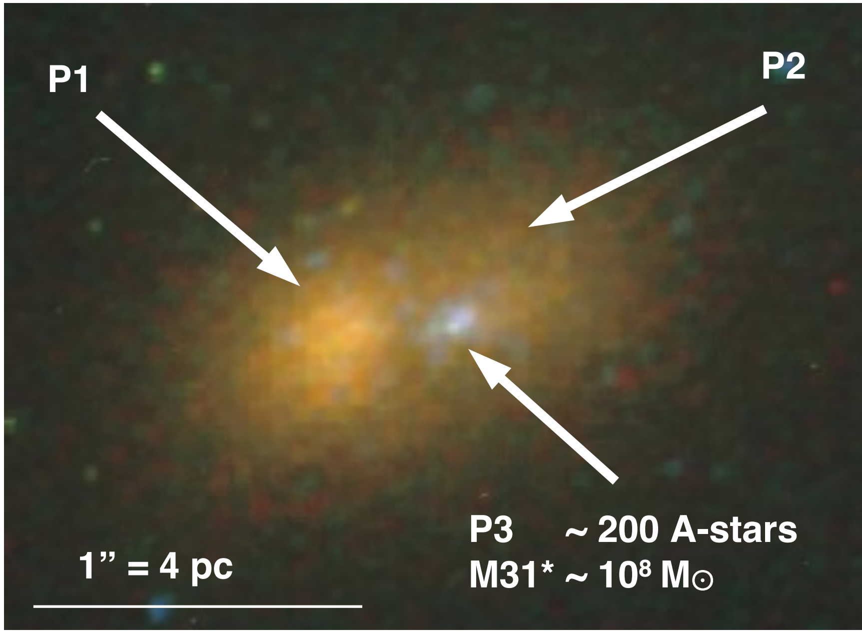
Quataert 2004

The NSC and SMBH in M31



- An eccentric old stellar disk of ~10^7 $M_\odot$, plus a small group of 100-Myr-old A-stars (P3)
- A ~10^8 $M_\odot$ SMBH in P3
- Low but variable X-ray luminosity





Key questions:

- Whether and how is M31* (and quiescent SMBHs in general) fed by the NSC stellar winds?
- Is star formation in the M31 NSC self-regulated?

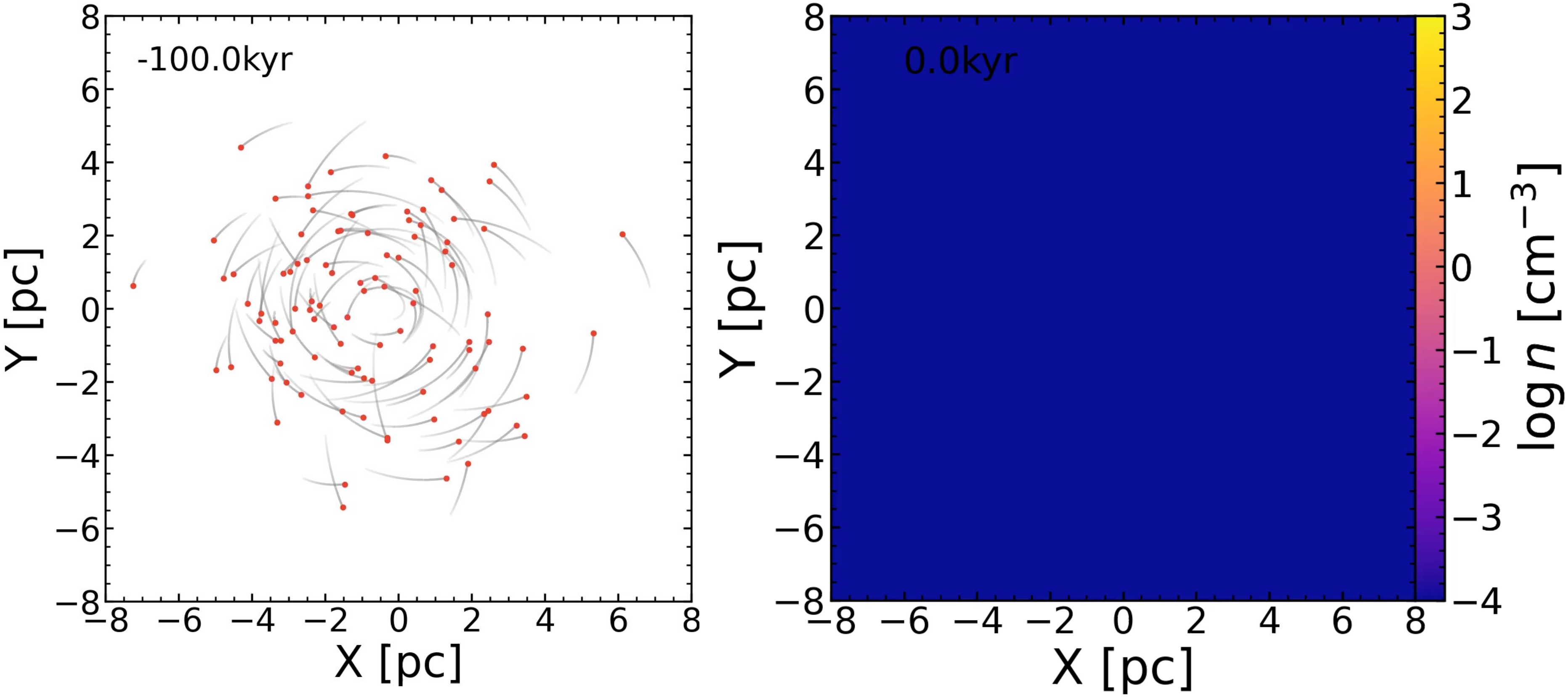
Hydrodynamic simulation

Su, ZNL & ZYL in prep.

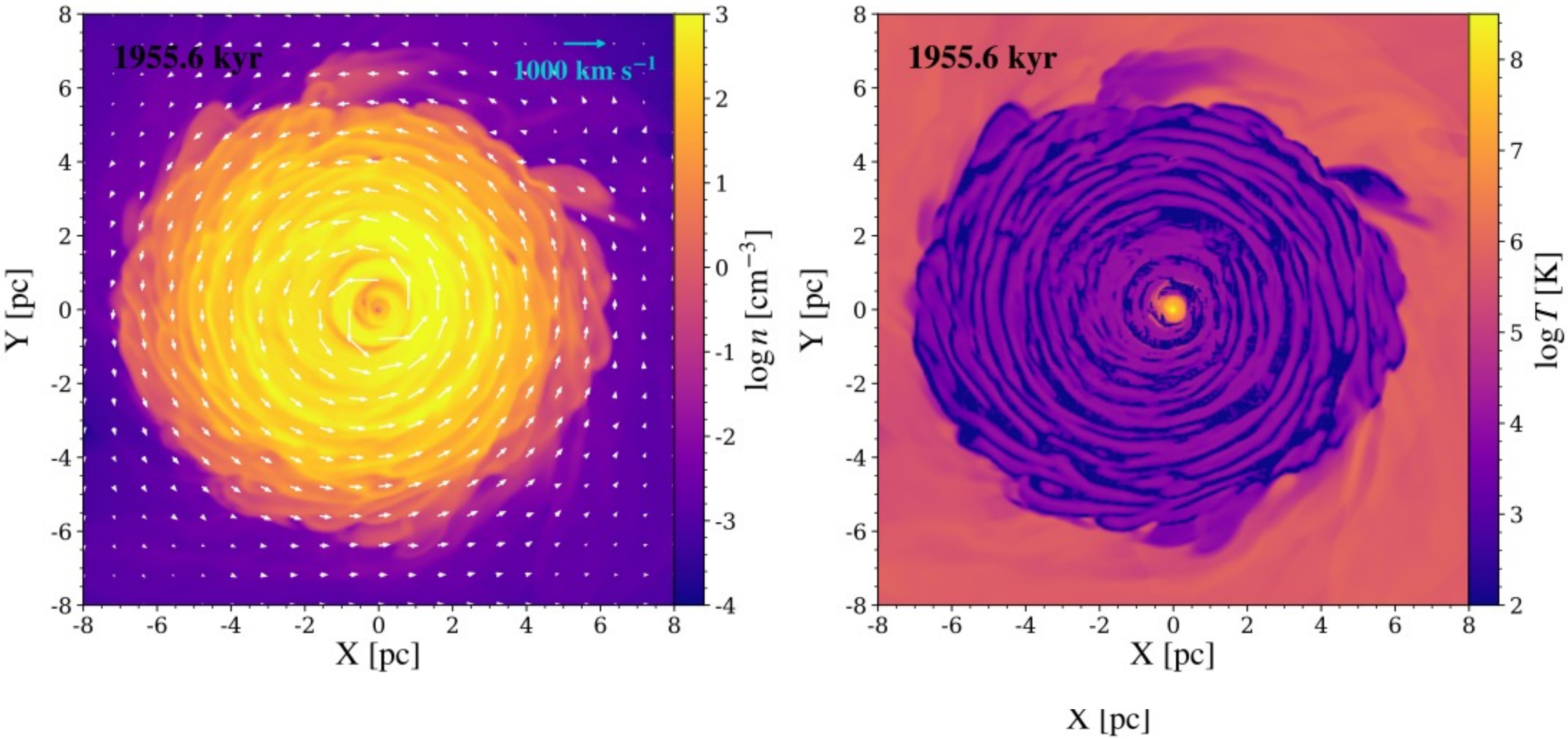
- PLUTO code
- A static potential defined by a central M_{BH} ($10^8\ M_\odot$) with/without an eccentric stellar disk ($2\times10^7\ M_\odot$)
- Resolution ~ 0.04 pc (~10^4 Rg); Box size = 16*16*8 pc
- Isotropic wind from 100 AGB stars following Keplerian orbits
  - $\dot{M}_w = 4\times10^{-7}\ M_\odot$/yr, V_w=10 km/s, T_w=3000 K
- Radiative cooling included for solar-abundance gas; floor T ~ 10 K
- Without/with an isotropic inflow ($1.6\times10^{-5}\ M_\odot$/yr, 40% of wind loss rate)

Advantage: no parameter fine-tuning

- Isotropic wind from 100 AGB stars following Keplerian orbits
  - $\dot{M}_w = 4 \times 10^{-7}\ M_\odot$/yr, V_w=10 km/s, T_w=3000 K

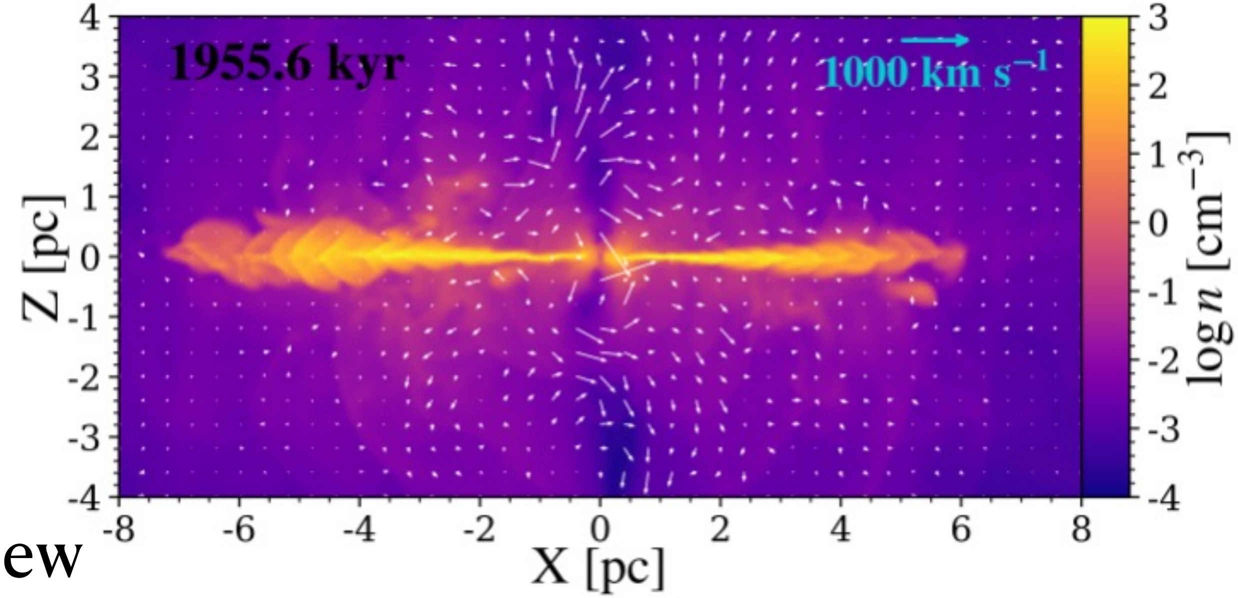


Simulation 1: SMBH only potential, no inflow

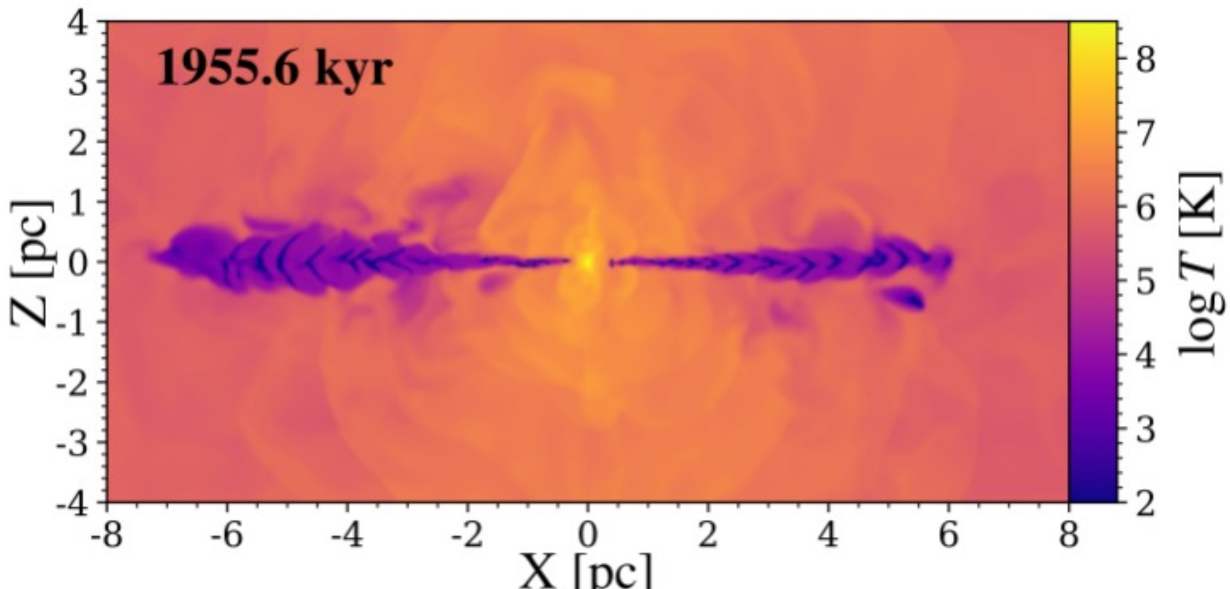


Face-on view: density & temperature distribution

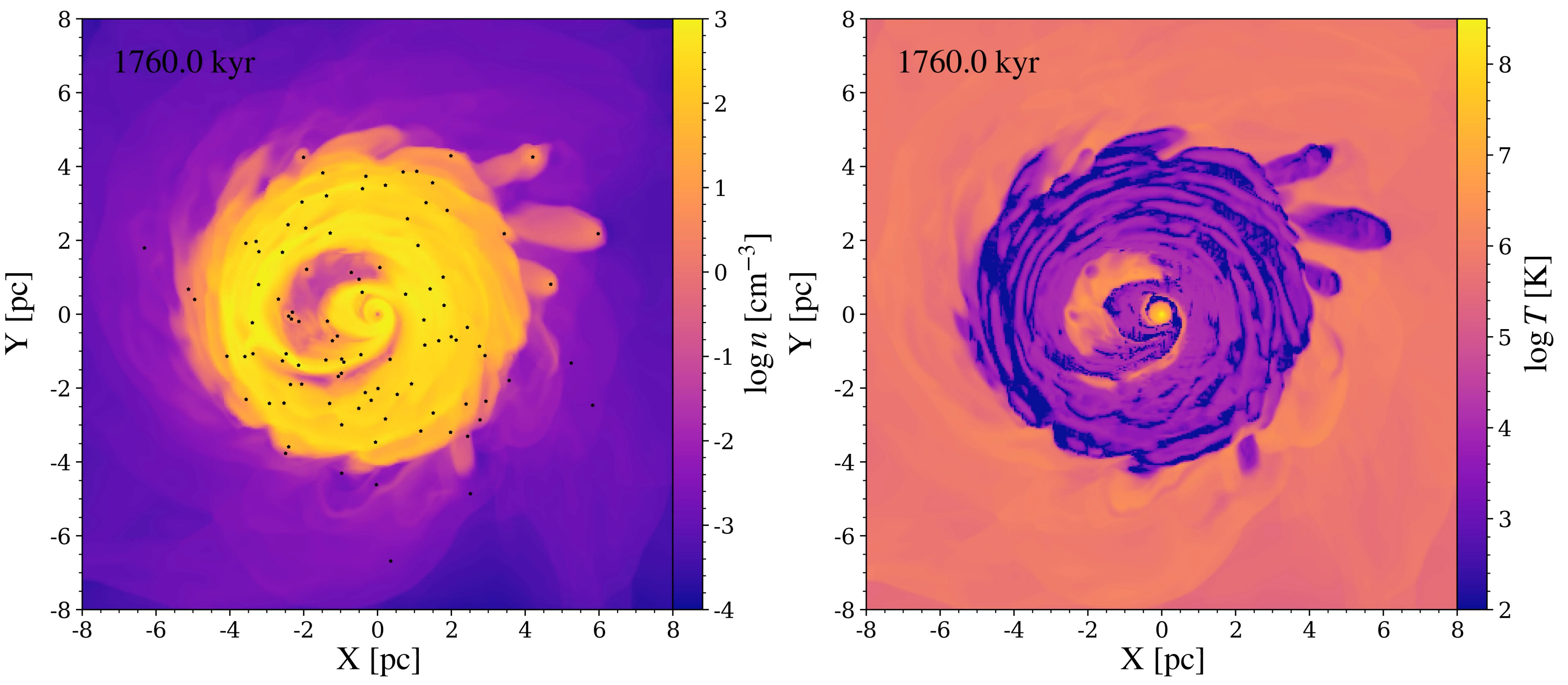
Simulation 1: SMBH only potential, no inflow



Edge-on view

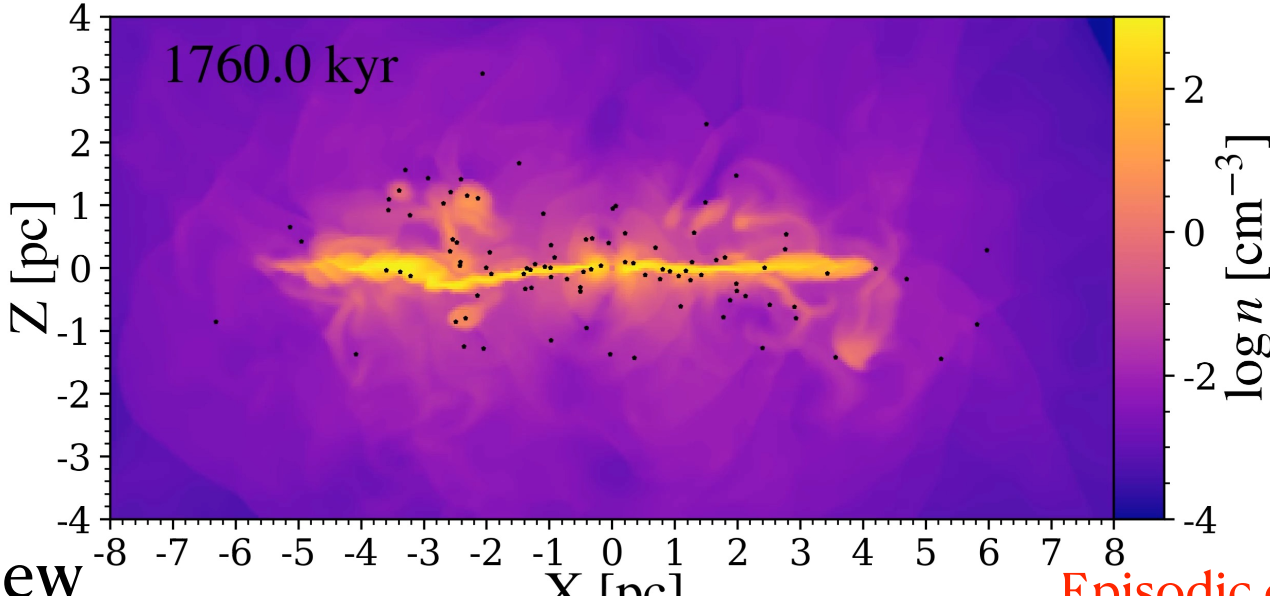


Simulation 2: SMBH+NSC potential, no inflow



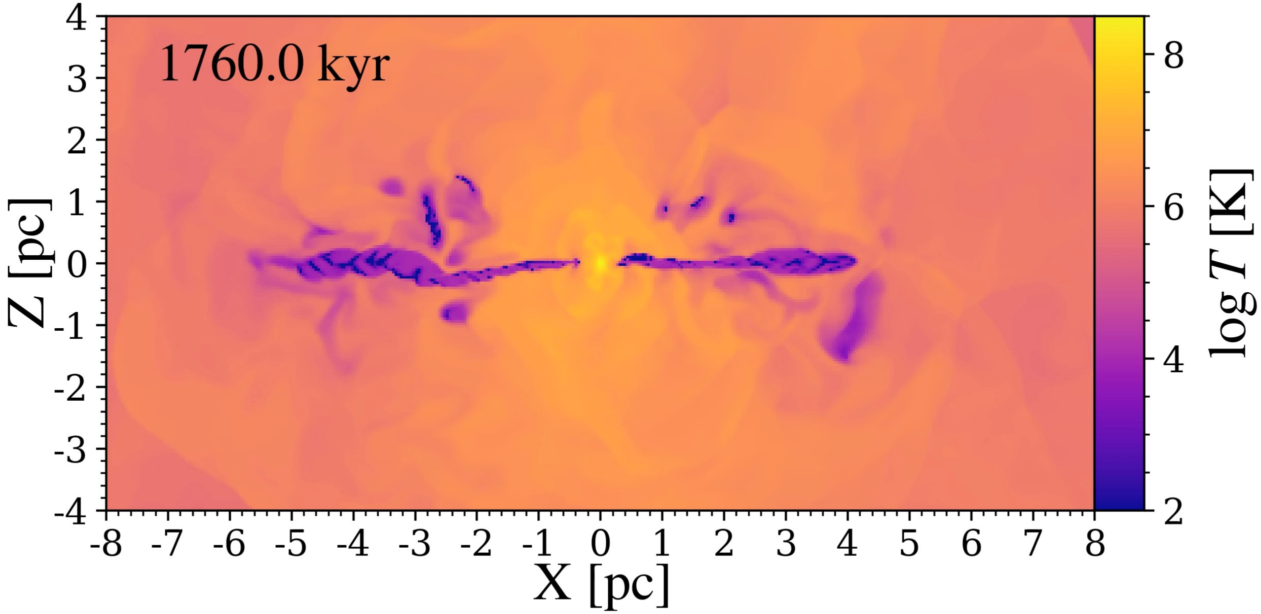
Face-on view density & temperature distribution
from 1.76Myr to 1.86Myr, frame time step 1 kyr

Simulation 2: SMBH+NSC potential, no inflow

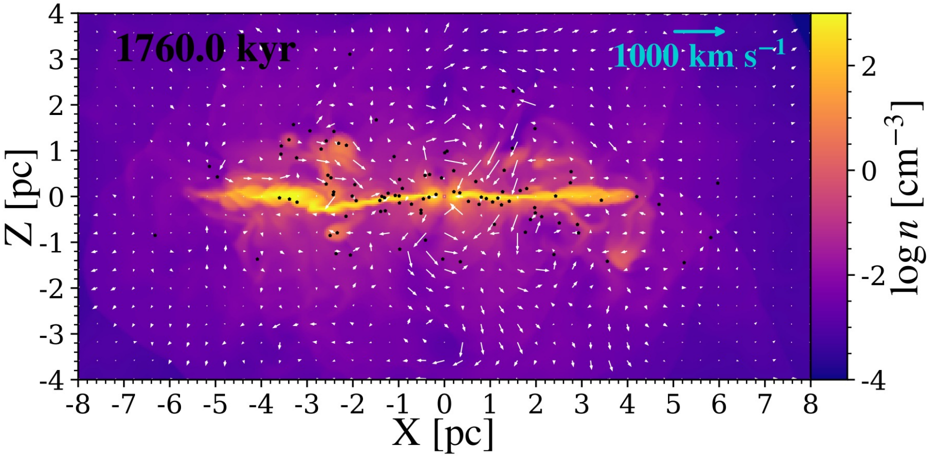


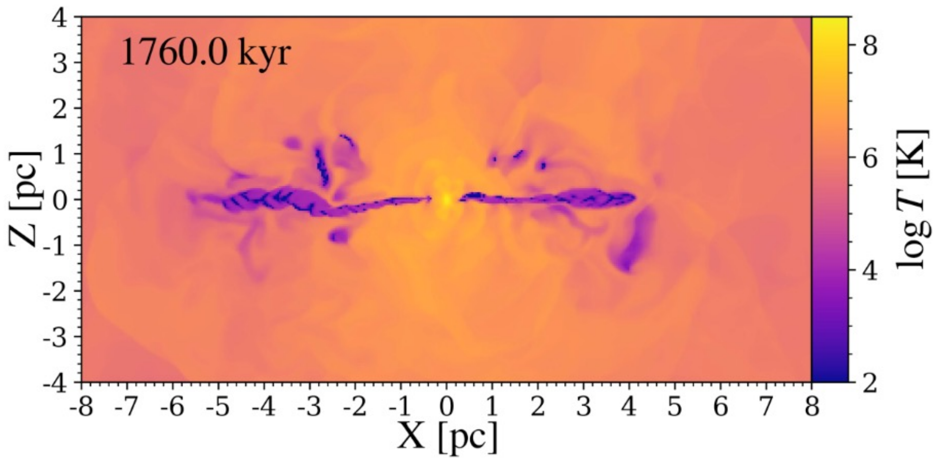
Edge-on view

Episodic outflow ?!

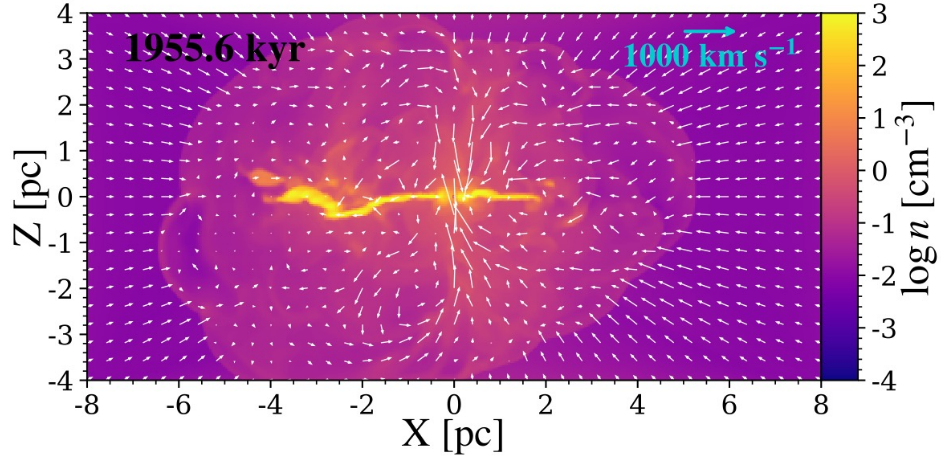


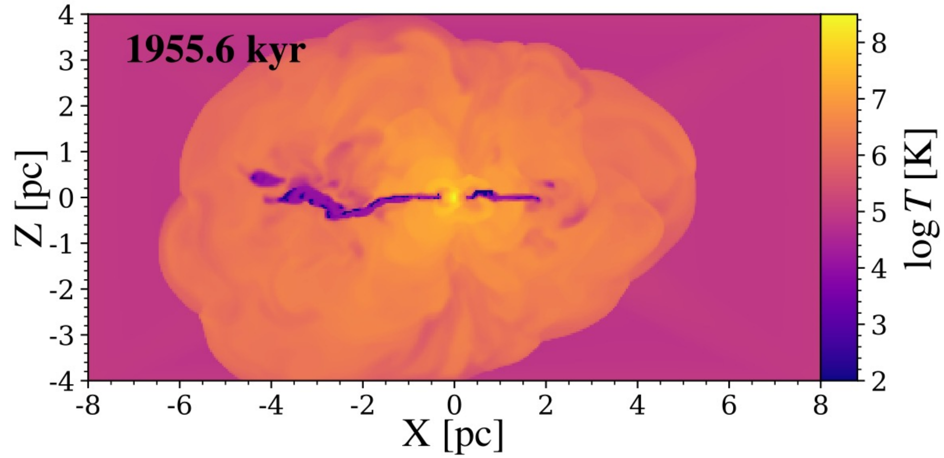
Sim.2 No inflow

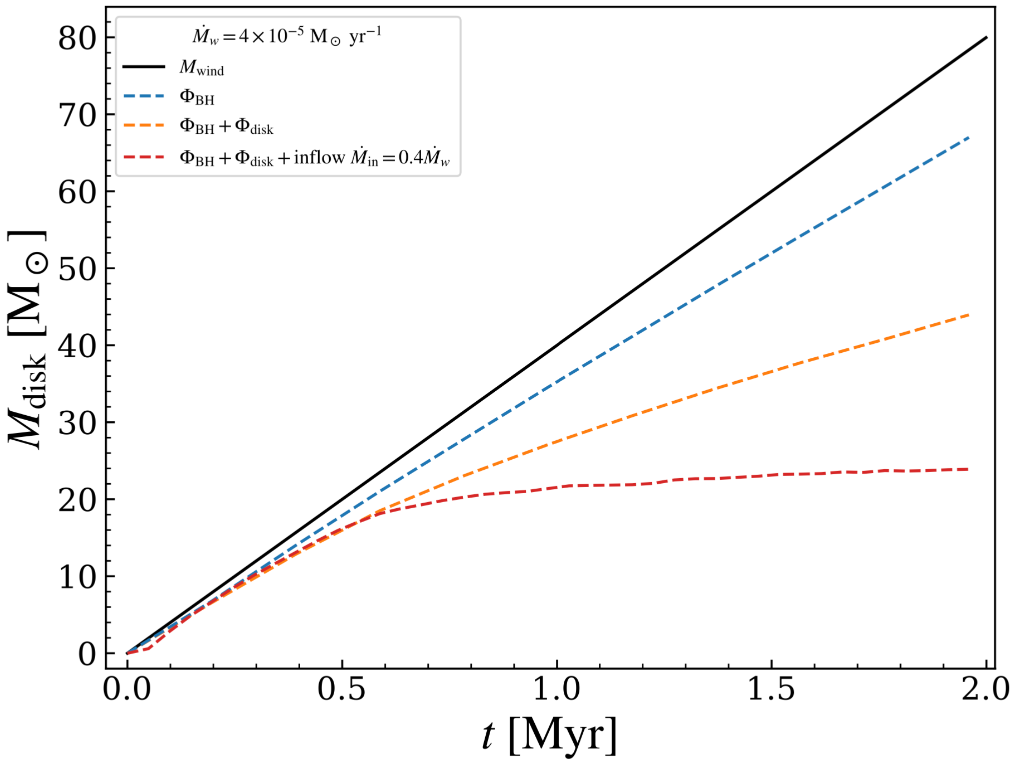




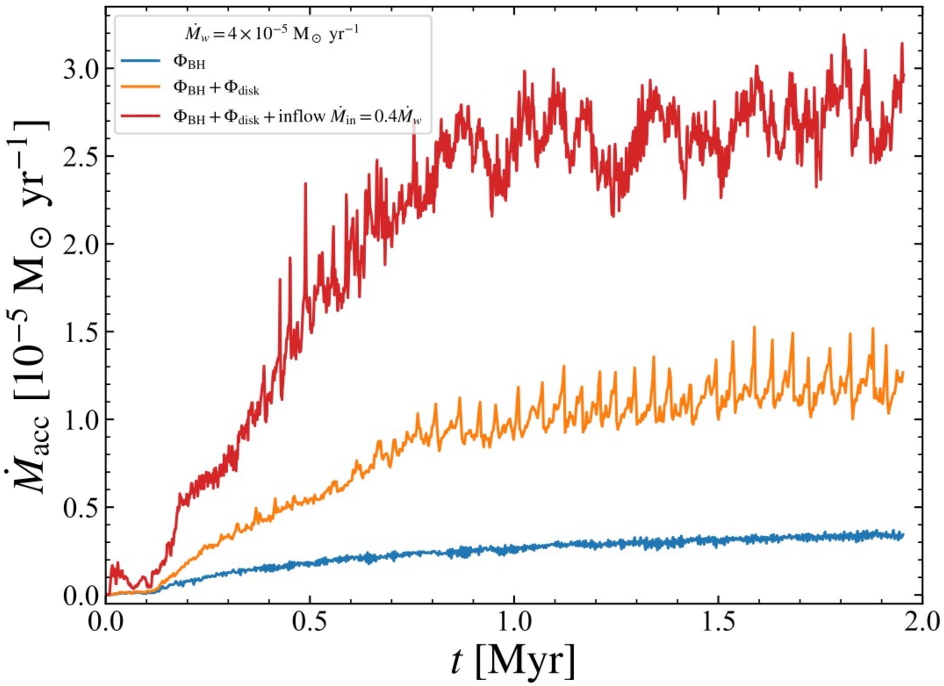
Sim.3 With inflow

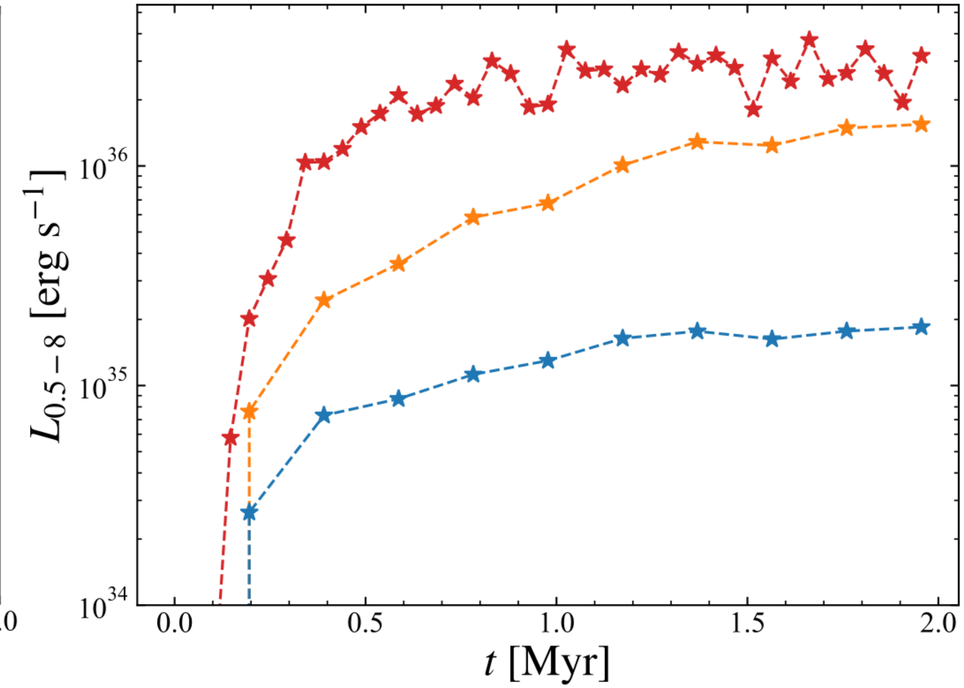




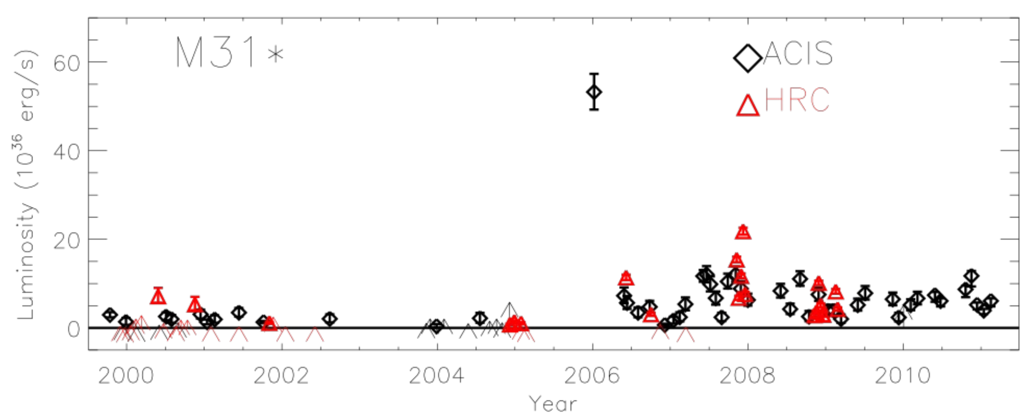


- Consistent with current upper limit (~40 M⊙) by NOEMA and ALMA
- It takes ~300 Myr to accumulate the required gas mass (~10^4 M⊙) to account for the putative mini-starburst of P3
- But M31* is unlikely to remain quiescent during this period
- For instance, a TDE occurs every 10^4-10^5 yr, energetically sufficient to unbound ~10^5 M⊙ gas within the NSC
- Need gas inflow to form new stars

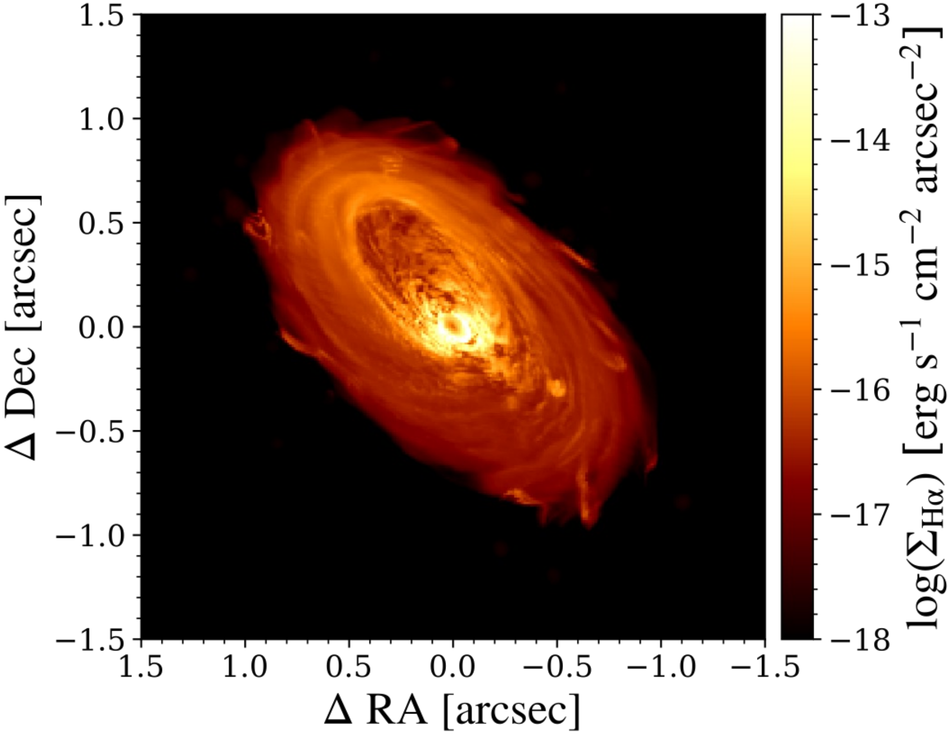




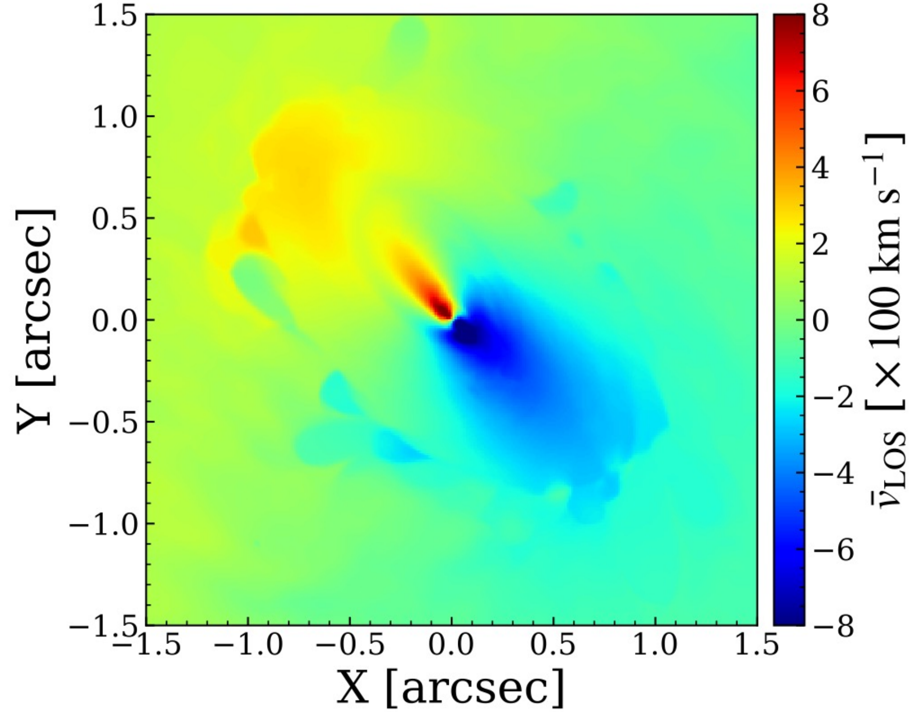
- X-ray luminosity (and possible variability) well reproduced



Synthetic Hα surface brightness

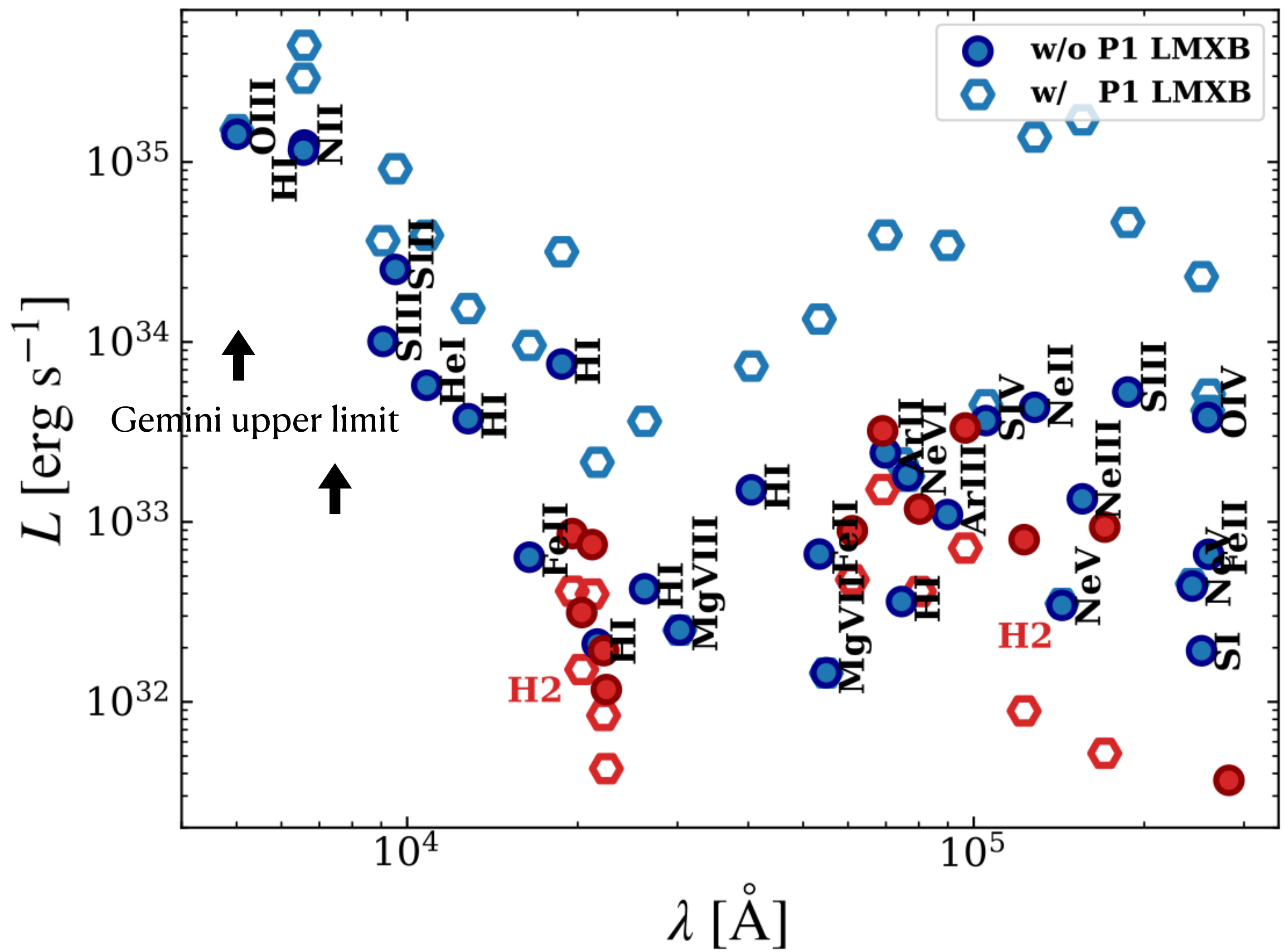


Hα line-of-sight velocity



- **Post-processing of photoionization by 200 A-stars**
- $L_{\mathrm{H}\alpha} \approx 10^{35} \mathrm{ergs}^{-1}, \mathrm{v}_{\mathrm{LOS}} \lesssim 800 \mathrm{kms}^{-1}$
- **Free-free emission @ 6 GHz is only ~1 μJy (compared to ~30 μJy observed)**

Emission line prediction



- **Can be probed byHST/JWST/CSST-IFS**

Some caveats, some prospects

- Treated as an isolated system (except for an *ad hoc* inflow)
- TDEs or SNe Ia may disrupt the gas disk on shorter timescales
- AGB/RGB stars may not exist in the NSC, due to tidal stripping or collision

- Explore the parameter space (BH mass, stellar mass, shape, inflow, etc.)
- The effect of magnetic field on inflow/outflow dynamics
- The effect of TDE or SN
- A self-consistent treatment of wind/jet

Summary & Prospect

- AGN feeding and feedback are essential to the SMBH-host coevolution, but details remain largely unclear
- The nearest SMBHs and their immediate environments are of unique importance in understanding the physics of accretion and feedback
- We find strong evidence for an energetic hot wind from M81* and NGC7213, based on high-velocity, highly-ionized Fe lines
- We find evidence for pc-scale radio synchrotron outflow (wind and/or jet) from M31* and M32*
- Stellar winds may dictate the fueling of the most dormant SMBHs
- Observational diagnostics of the feeding and feedback of weakly accreting SMBHs beyond Bondi radius are needed: XRISM/HUBS/Athena and SKA/ngVLA