

AGN Feedback: From Nuclear Outflows to Galactic Winds

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Cen A; ESO/WFI (optical), MPIfR/ESO/
APEX/A. Weiss (submm, orange), NASA/
CXC/CfA/R. Kraft et al. (X-ray, blue)

Big AGN Feedback Questions

- How much/what part of galaxy evolution is caused by AGN feedback?
 - Trigger or quench/suppress star formation?
 - (Compare to SF-driven winds)
- How does black hole accretion translate into feedback?
 - Including different kinds of feedback: radio mode, quasar mode

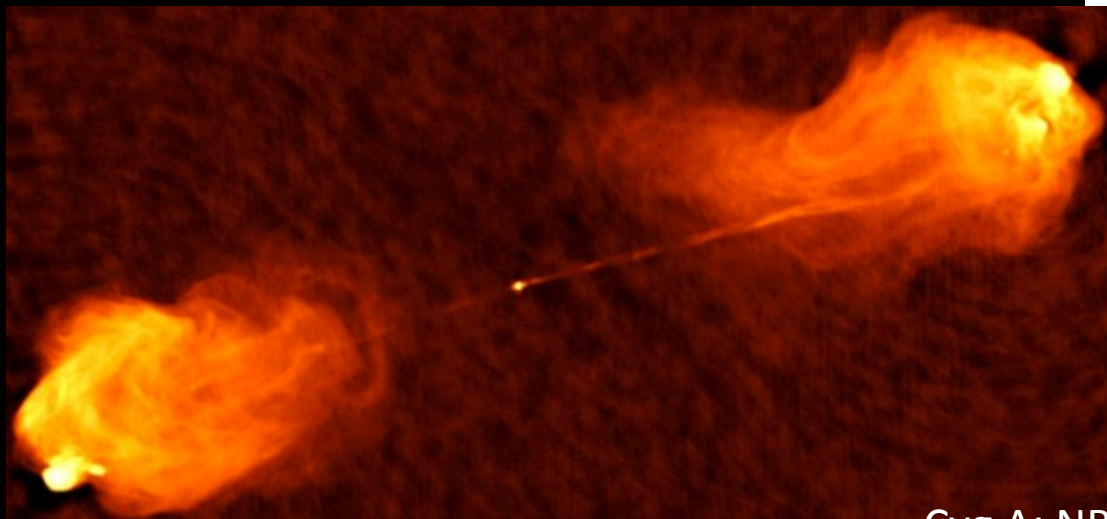
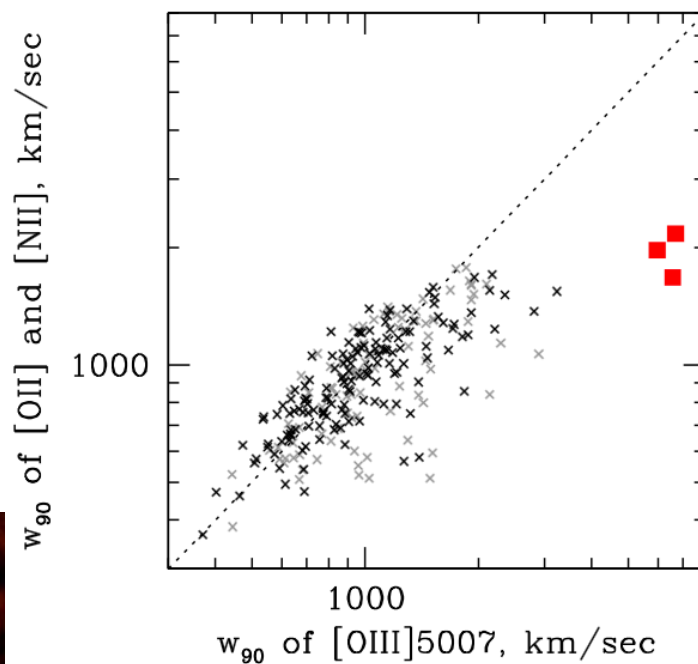
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We know AGN feedback is ‘a thing’

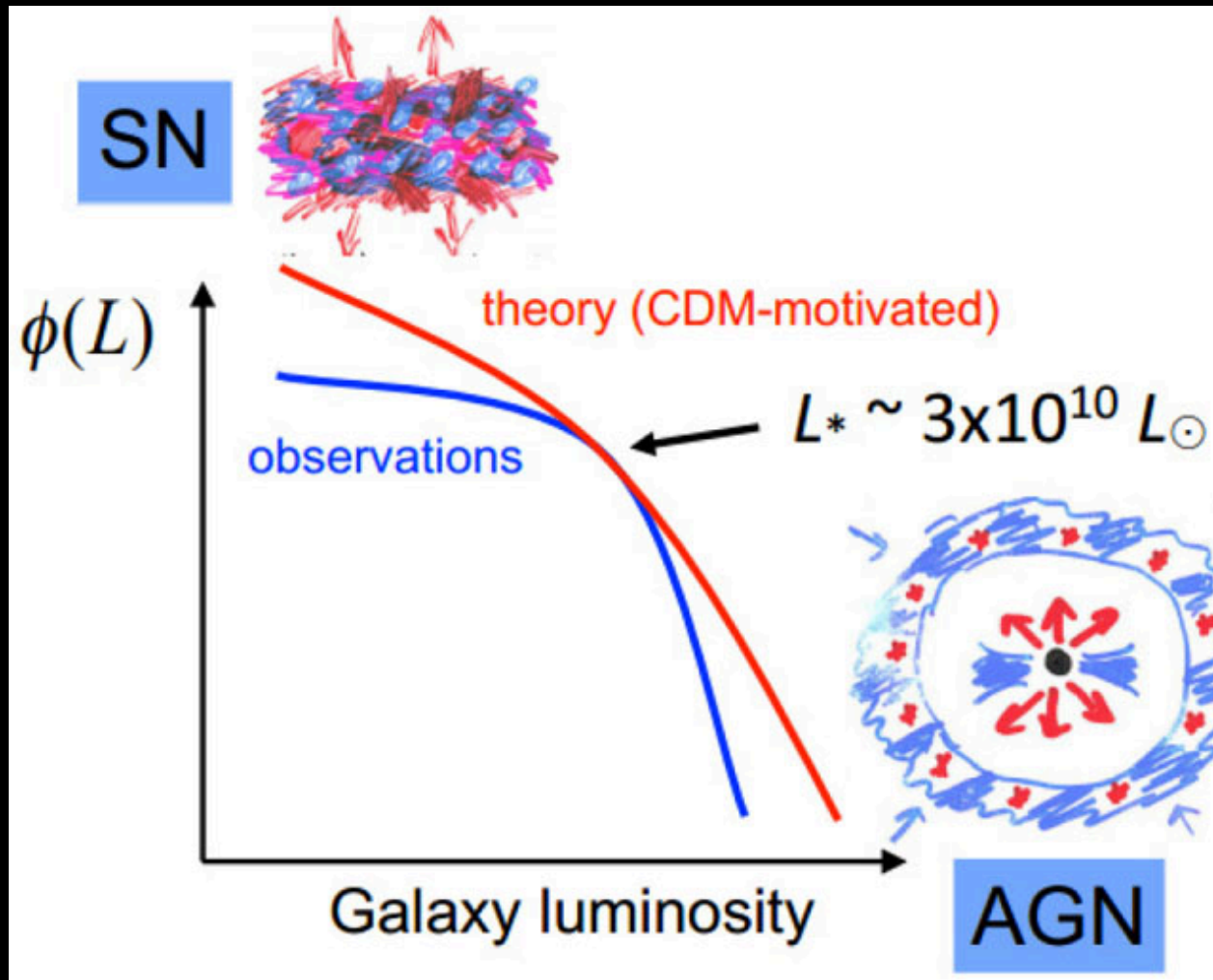
- Gas seen at enormous velocities, too energetic for SF
- Striking radio jets stretching >100 kpc

Zakamska+16, see also Husemann+15



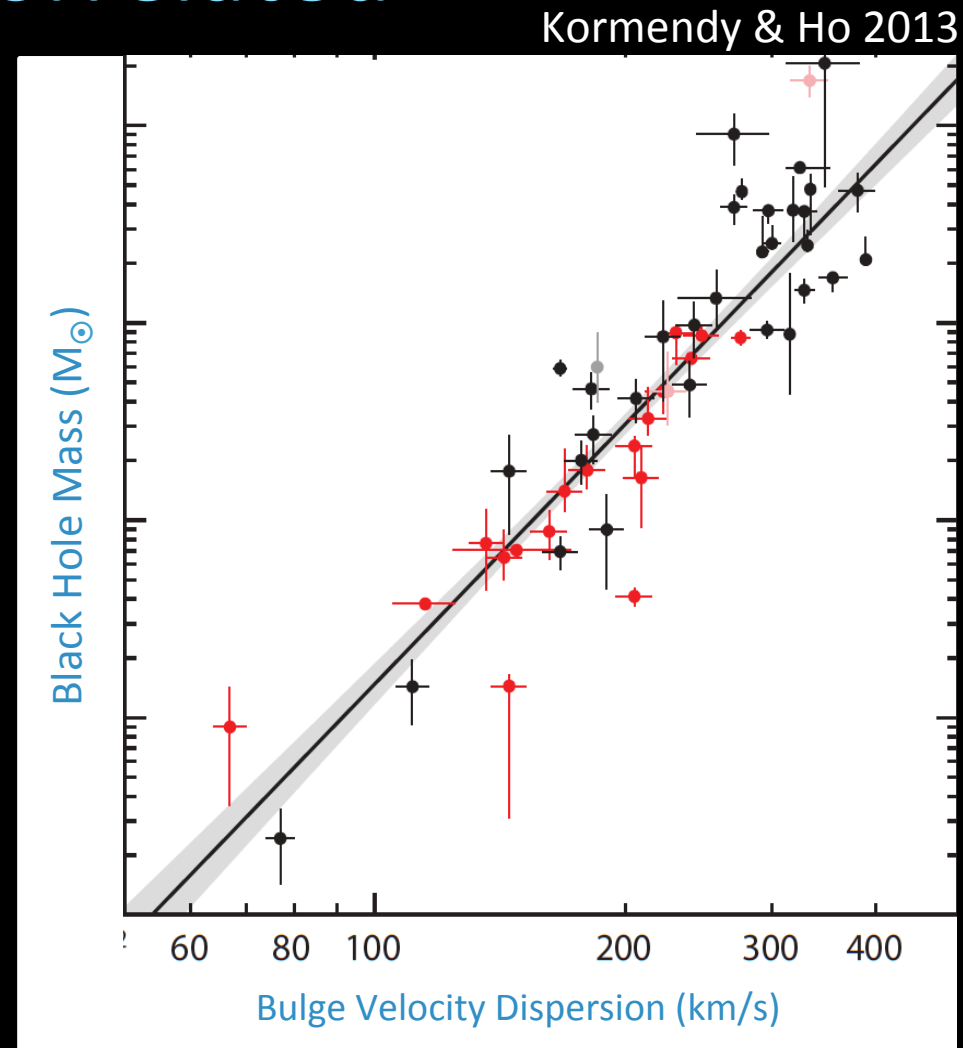
Cyg A: NRAO/AUI

AGN feedback is required to suppress high end of galaxy luminosity function

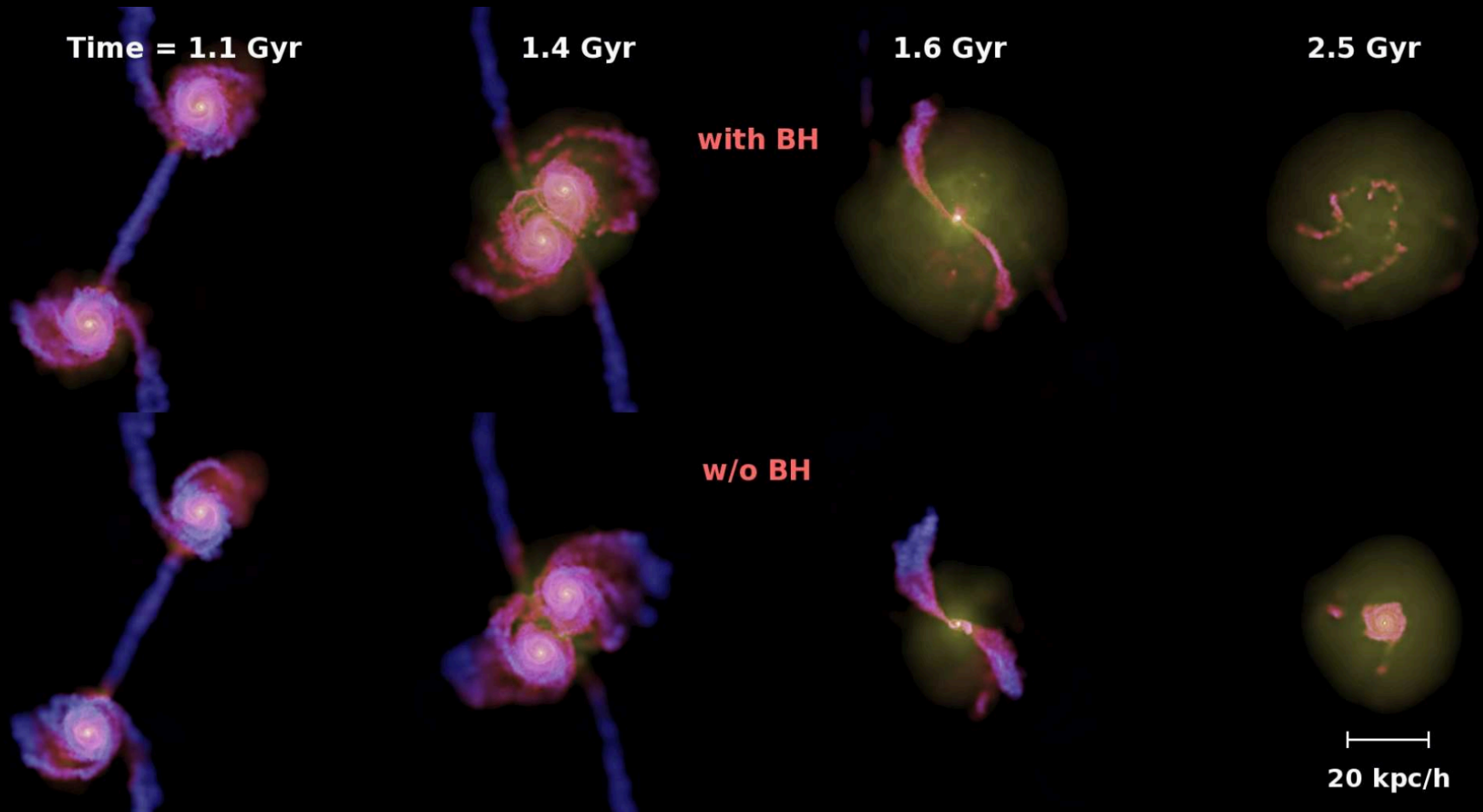


BH mass and host galaxy properties tightly correlated

- BH scaling relations suggest a tight relationship between galaxy growth and black hole growth
 - One regulates the other, or perhaps both are fueled by the same events



Initial simulations with AGN feedback easily quench quickly during post-merger quasar-mode feedback

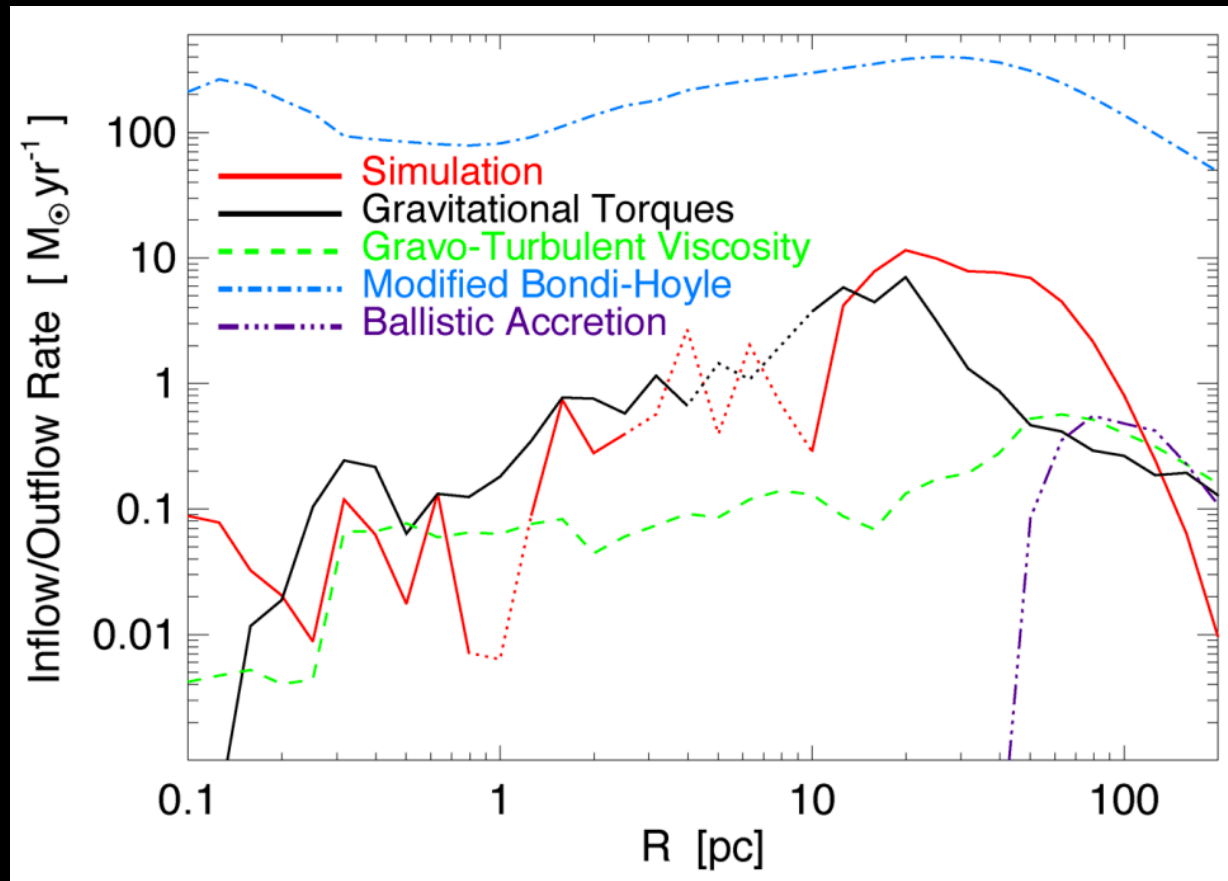


What are the important components of an AGN feedback model?

- Black hole accretion rate

The common Bondi-Hoyle accretion rate applies to gas with no angular momentum.

Different prescriptions differ by many orders of magnitude.



Hopkins, PF et al. 2016, MNRAS, 458, 816

See also Power+10,11ab, Hobbs+12

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 - Collimation, heating vs. breakout, coupling to ISM
 - Energy-conserving vs. momentum-conserving

These are the ideas we need to test and constrain observationally!

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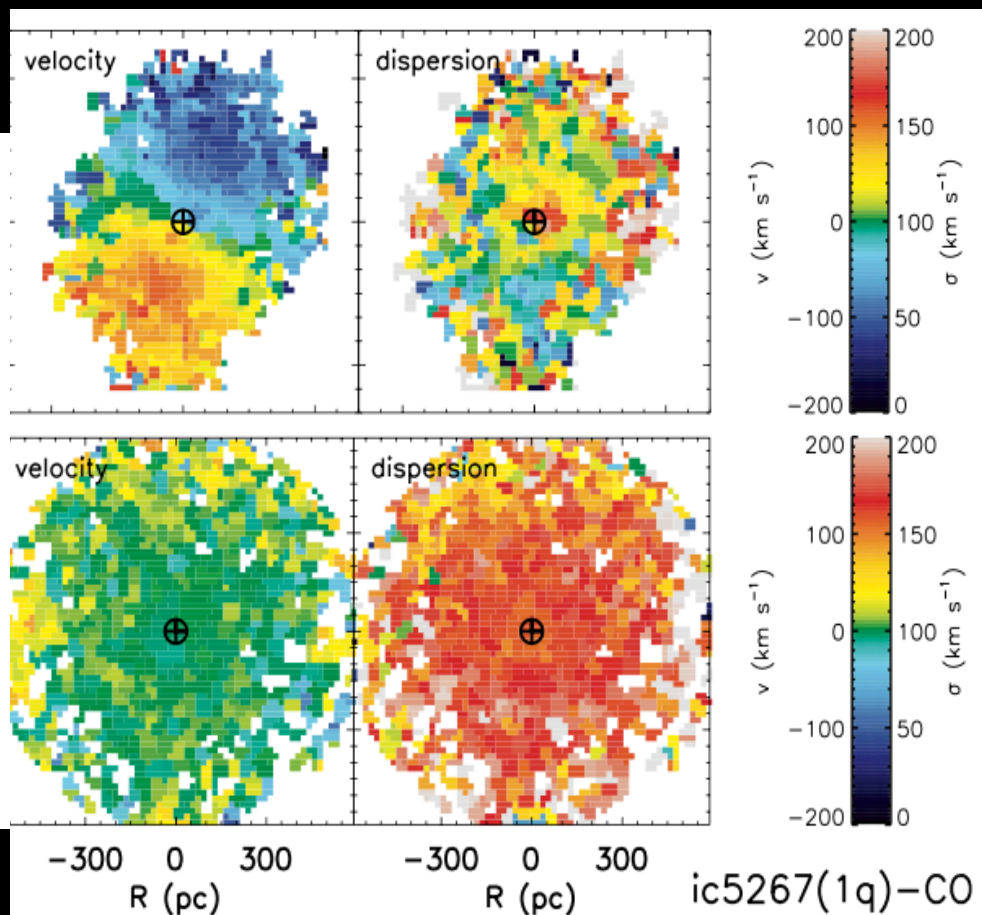
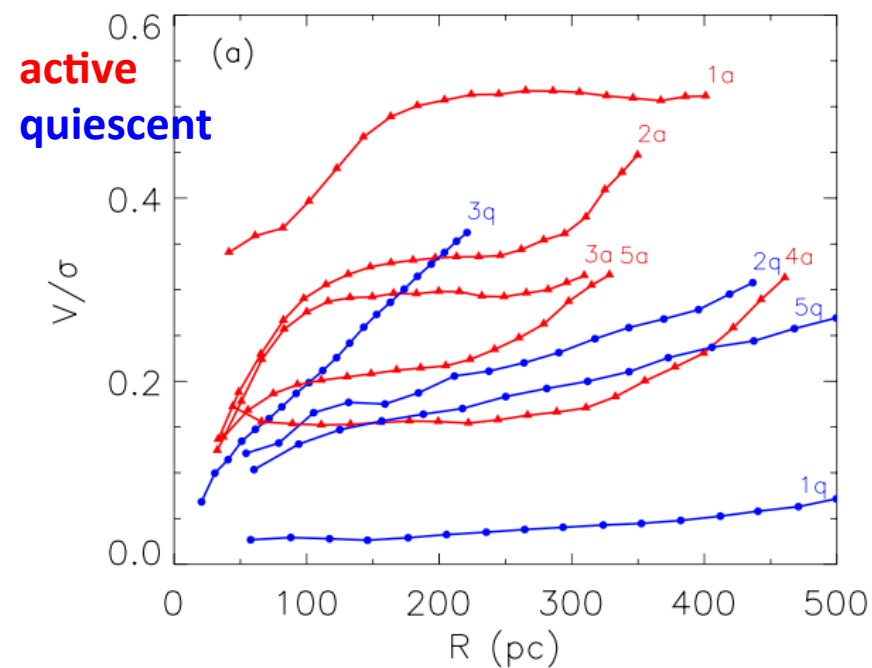
- Mass inflow
 - What are conditions like near an accreting black hole?
 - When and how quickly do black holes grow?
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Nuclear disks funnel gas to AGN

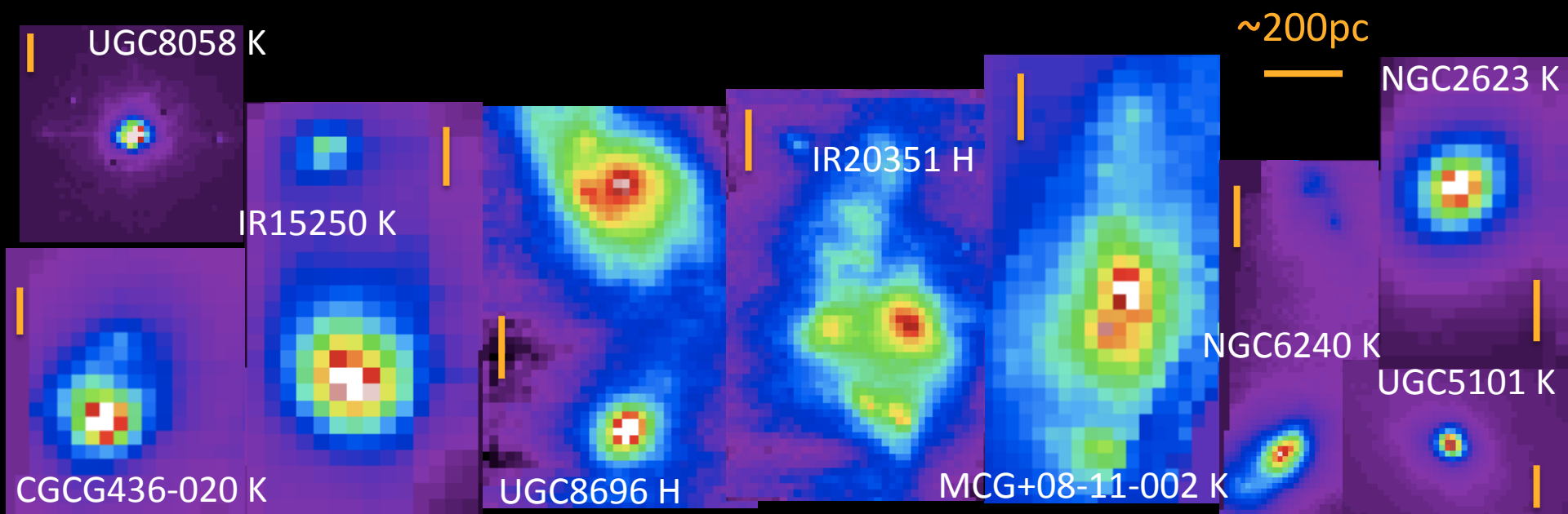
- Matched samples of Seyferts and quiescent galaxies show that Seyferts have higher v/σ in the central 250+ pc



See AMM+11,14, 15b, U+13 – and U's talk from yesterday

The GOALS/OSIRIS program

- High spatial resolution IFU spectroscopy of central kpc at 0.035 and 0.1 "/pixel scales
- Probing nuclei of gas-rich mergers (local U/LIRGs) (Armus+09)

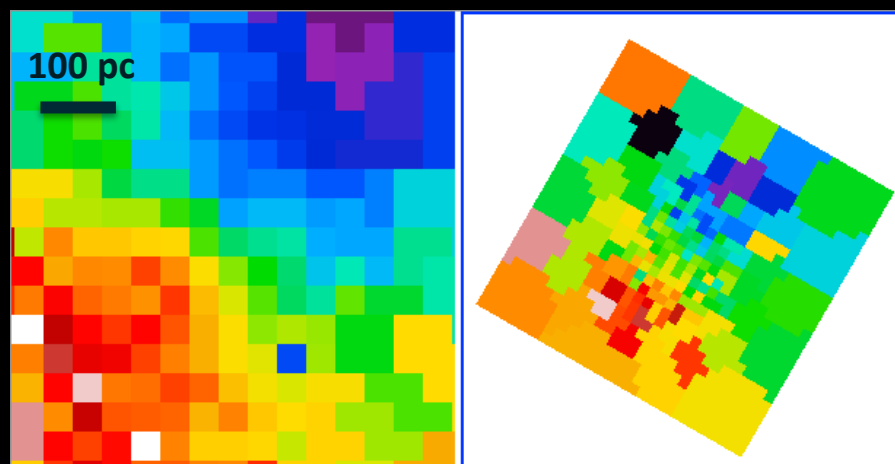


Nuclear disks in nearly every U/LIRG

NGC2623 H₂ velocity, stellar velocity

MCG+08-11-002

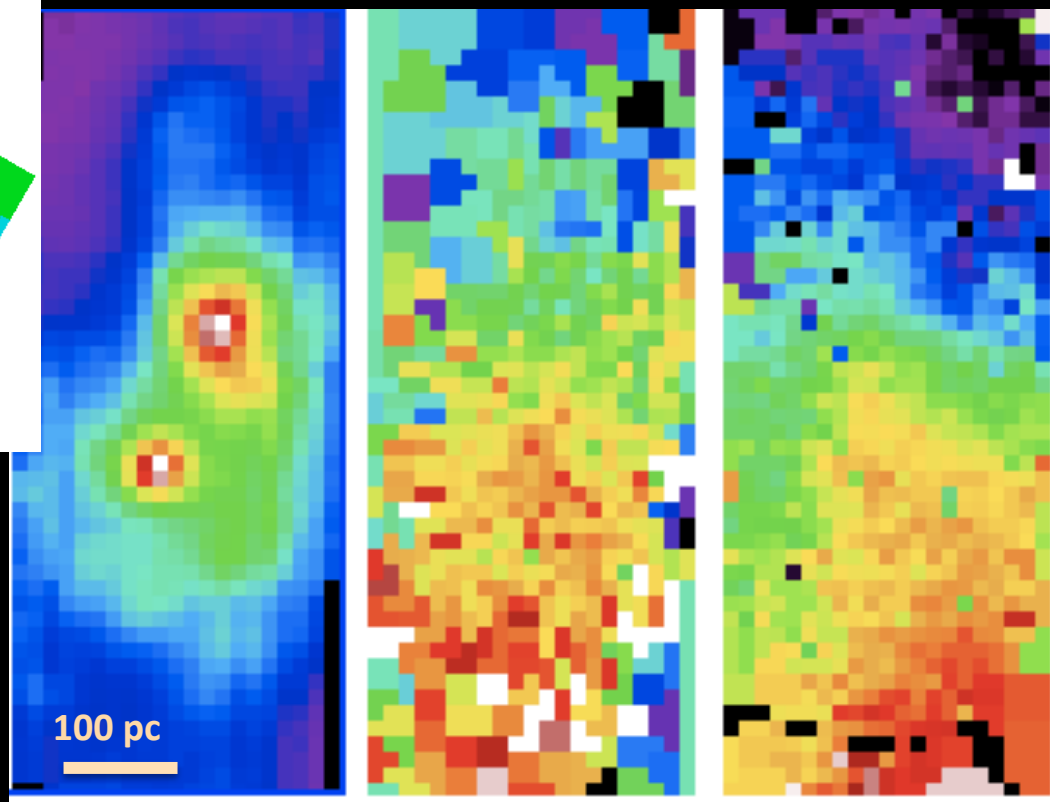
continuum flux, stellar velocity, Brγ velocity



Velocity colorbar = [-400,-100] km/s

Gas and stars both
show similar rotation

CO index: stars are
young, formed during
merger



Velocity colorbar = [-150,250] km/s

Compare to disks in e.g. Mayer+07,08, Chapon+13,
and the FIRE simulations by Hopkins et al.

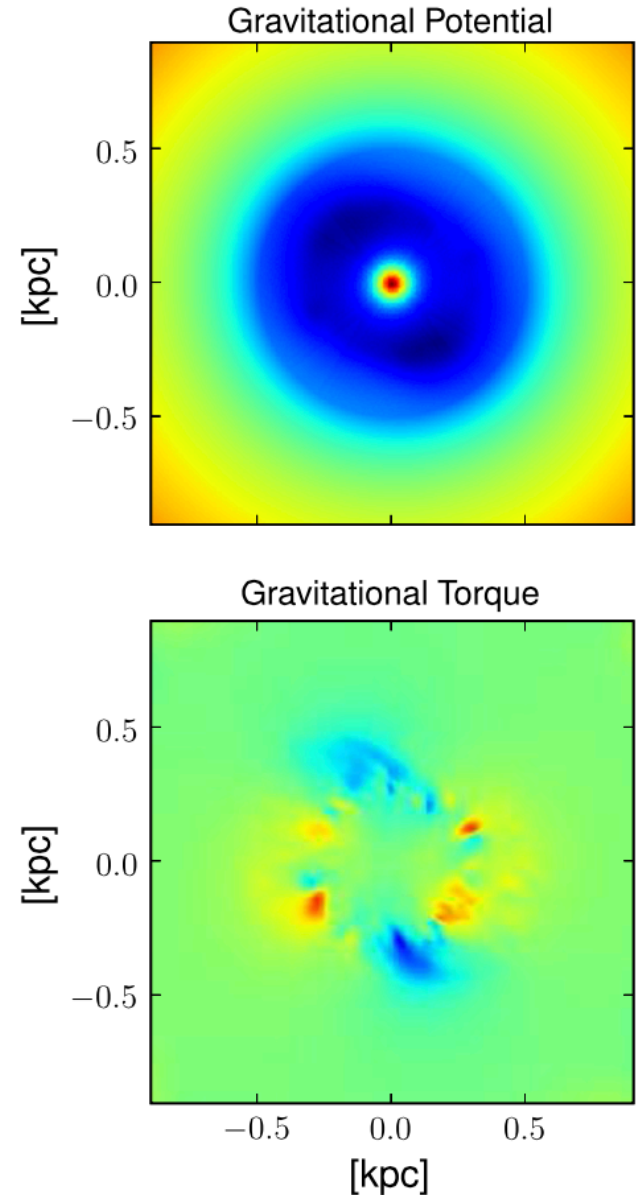
Multiphase structure of nuclear disks

- Hot ionized gas – Br γ
- Warm molecular gas - H₂ (1-0)S(1) 2.12 μm
- Young stars – CO absorption bandheads
- Cold molecular gas - CO
 - Ueda+14, Smajić+15, NUGA team (García-Burillo, Combes++)

Combining multiphase observations for individual galaxies can give density/temperature profiles for comparison with simulations

NUGA – directly estimating inflow

- Use IR images to map stellar potential $\rightarrow$ gravitational torques
- Measure molecular gas kinematics relative to potential to demonstrate loss of angular momentum down to 100-500 pc
- Viscous torques or other mechanisms required to funnel gas all the way to core
- And/or fueling finished by the time we see AGN activity



+/- quadrants implies gain/loss of angular momentum ($m=2$ modes);
Haan+09

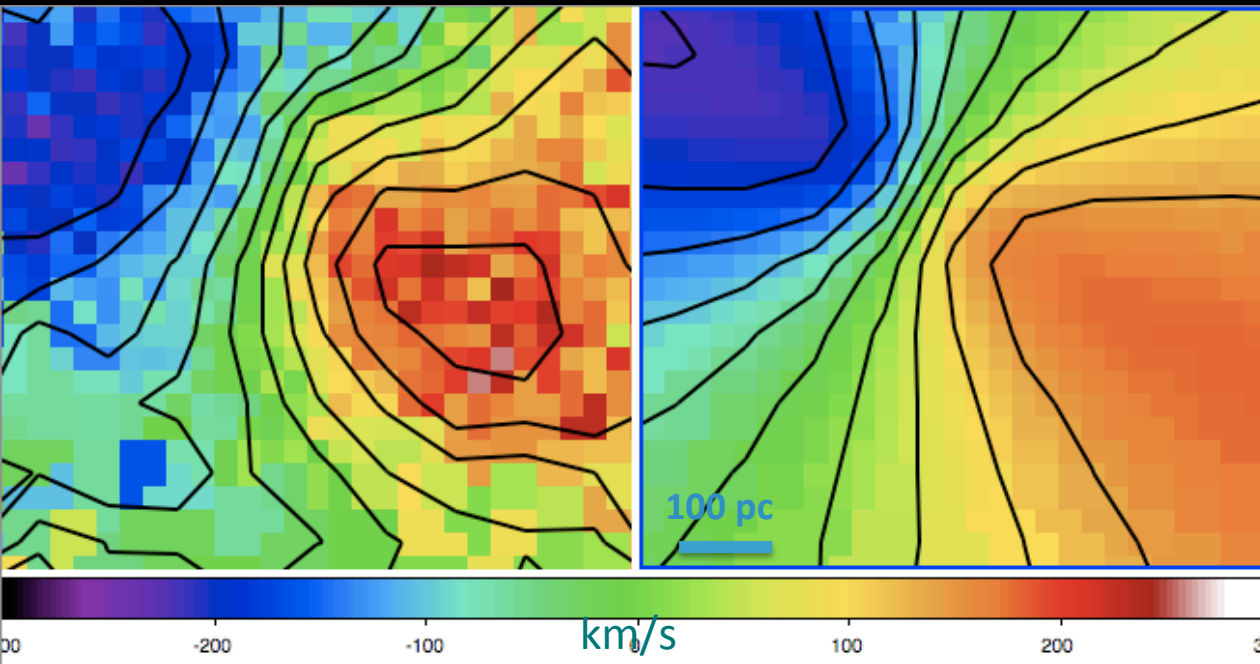
Tracing BH mass growth in mergers

- The GOALS/OSIRIS dataset resolves inside BH sphere of influence -> measure dynamical black hole masses
- Assume pre-merger, galaxies lie on BH scaling relations

Mrk 273's N black hole: gas disks

Observed velocity map

Model velocity map



Matches maser BH mass measurement! $1.4 \pm 0.2 * 10^9 M_{\odot}$ (Klöckner & Baan 2004)

Model:

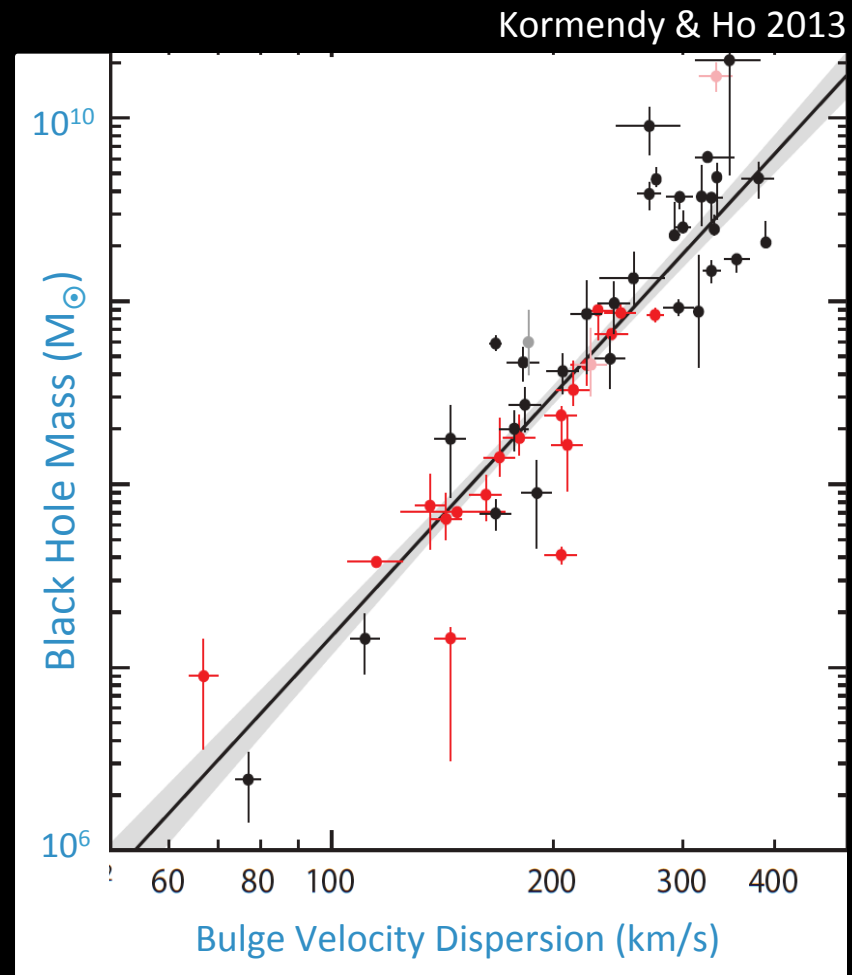
$$v = \sqrt{\frac{GM_{encl}(r)}{r}}$$

$$M_{encl}(r) = M_{BH} + \rho_0 r^{\gamma}$$

$$M_{BH} = 1.1 \pm .1 * 10^9 M_{\odot}$$

Now that we have a technique to measure black hole masses, we can determine where these major gas-rich mergers fall on black hole scaling relations

This will tell us about BH growth and host galaxy coevolution



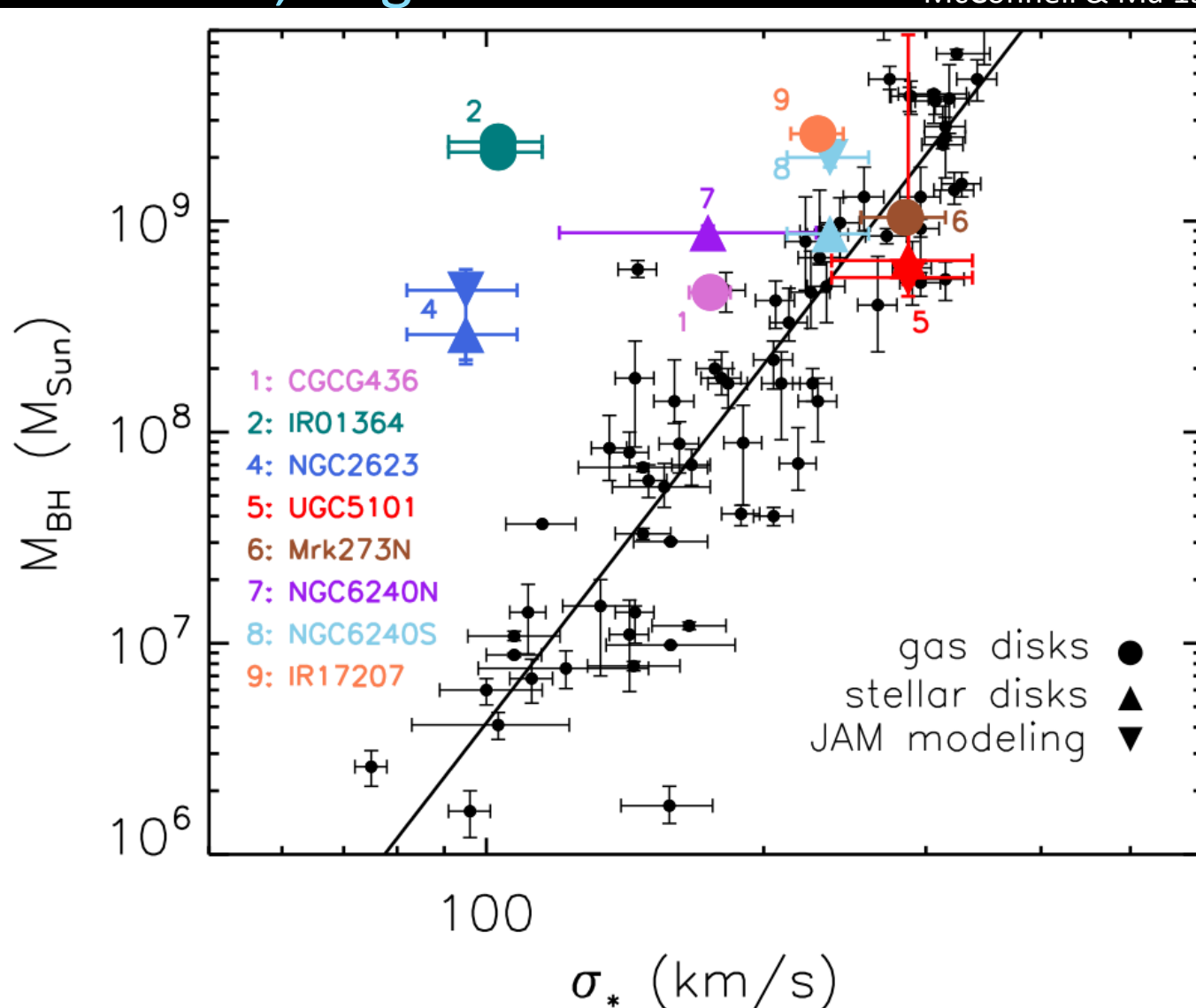
$M_{\text{BH}}-\sigma_{*,\text{bulge}}$ Relation

Data & fit from
McConnell & Ma 13

σ is the most difficult galactic parameter to measure in mergers

Currently pulled from literature but systematic approach best

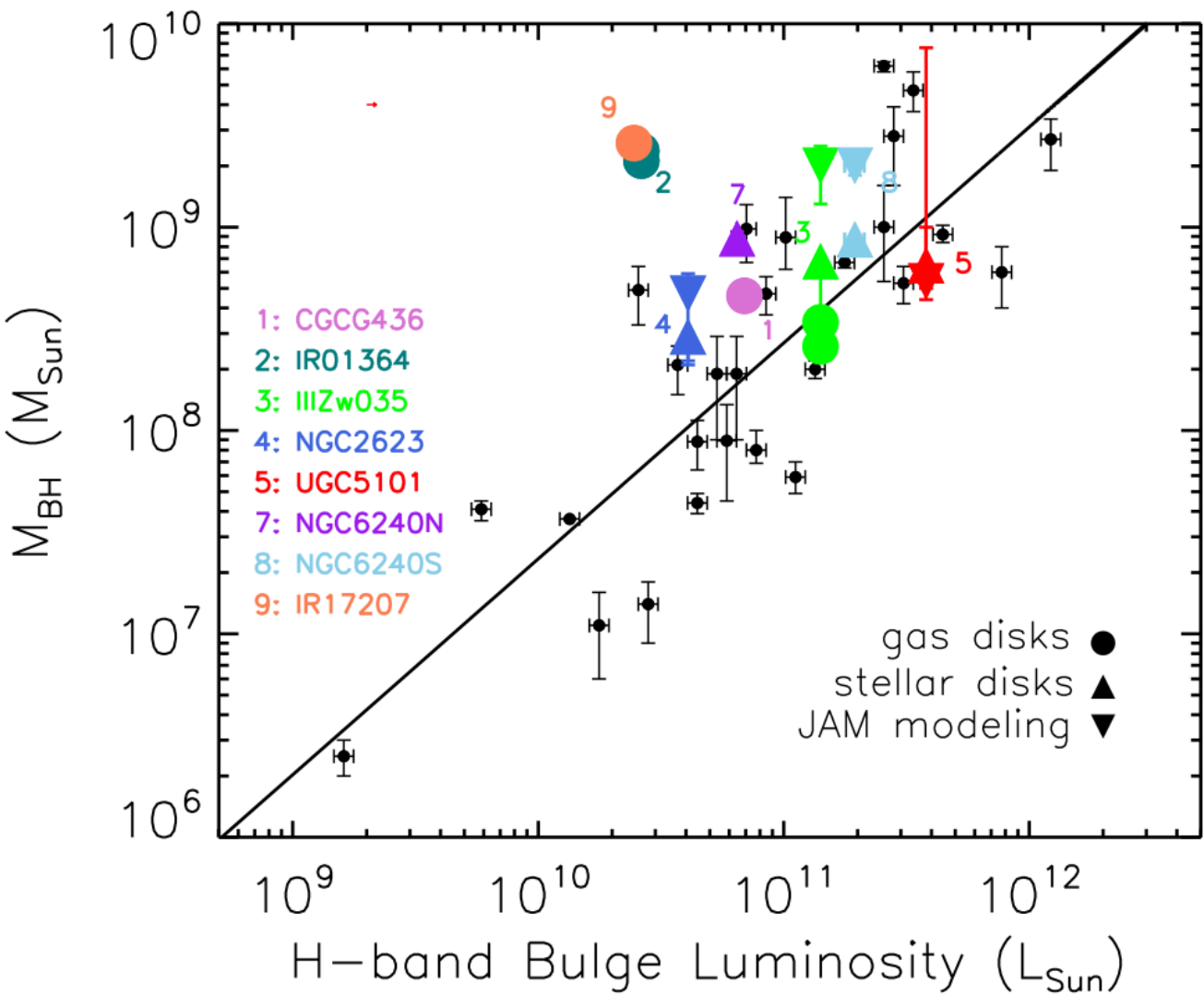
But see also Stickley +12,14; Bellovary+14



$M_{\text{BH}}\text{-}L_{\text{bulge}}$ Relation

Data from
Marconi & Hunt 03,
McConnell & Ma 13

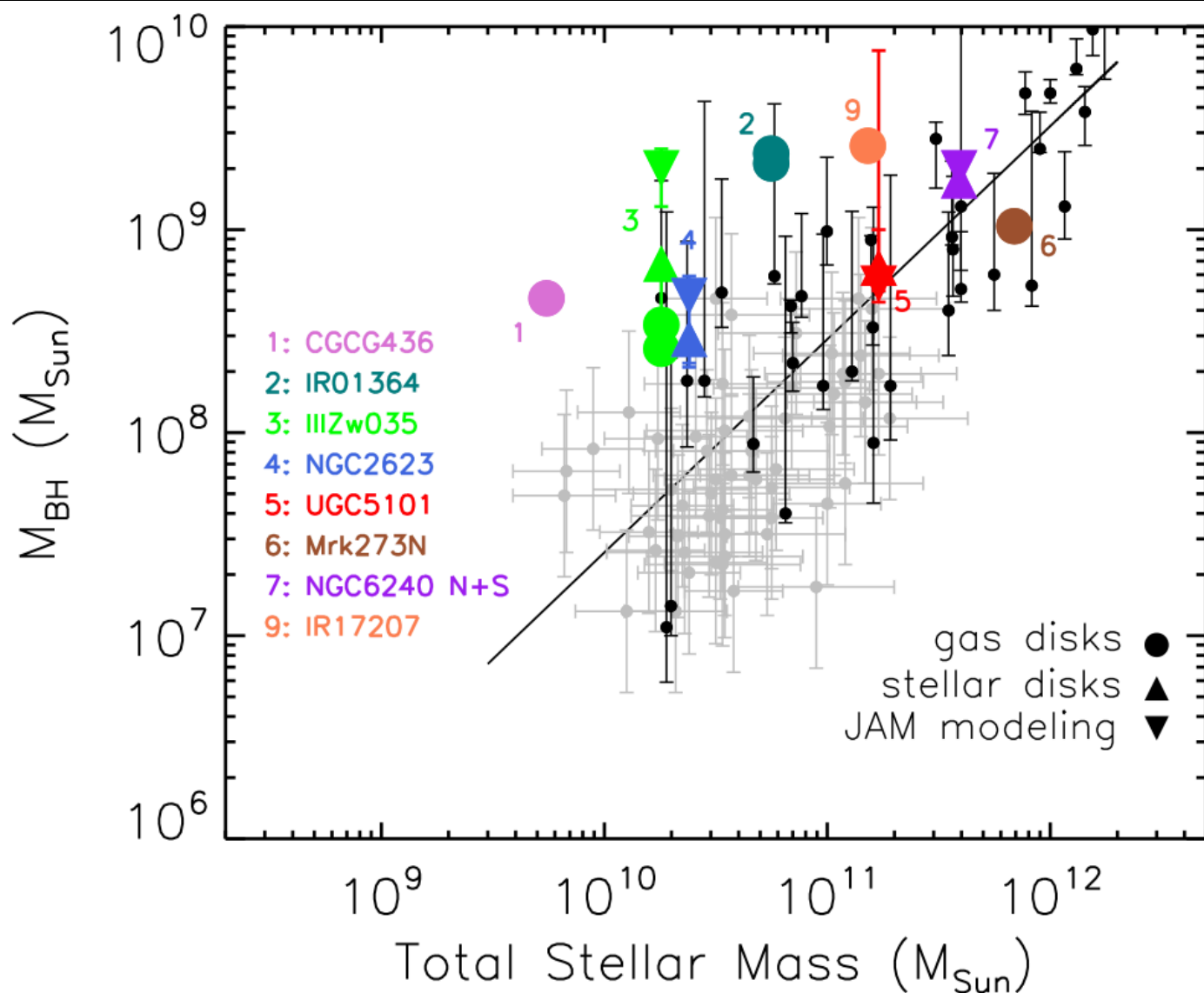
Bulge
luminosities
systematically
measured from
GALFIT & GOALS
NICMOS images
by Haan+11



$M_{\text{BH}}-M_*$ Relation

Data from Bennert+11 & Cisternas
+11; data+fit from McConnell &
Ma 13

Total stellar
masses
measured by U
+12 using multi-
band SED fitting



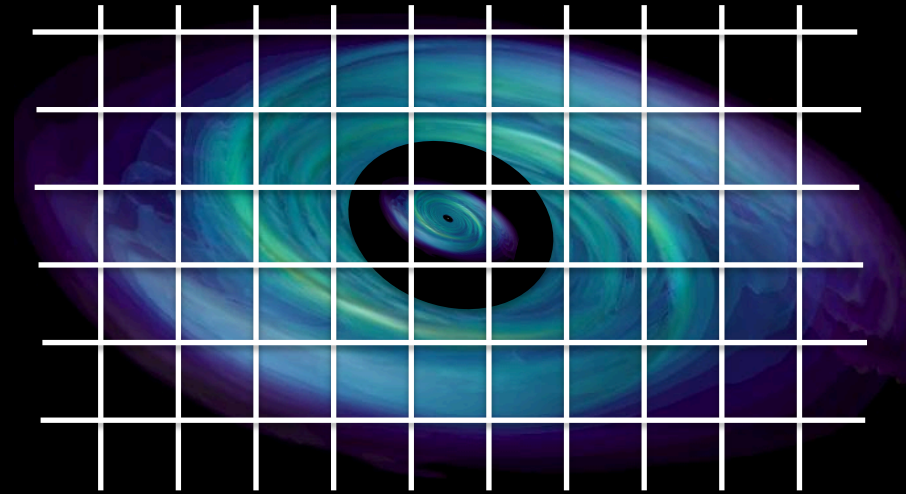
Why would black hole growth start early when AGN activity is linked to end stages of mergers?

We measure $M(r < 25 \text{ pc})$

- Could be that mass piles up in or outside accretion disk; viscous accretion timescale may delay feedback (e.g. King08; Power, Nayakshin & King 11, Hopkins+15)
- And/or, extra mass might be the material later entrained in massive molecular outflows (e.g. Rupke & Veilleux 11, Sturm+11, Spoon+13, Veilleux+13)

ALMA observations could confirm this – Scoville's Arp220 very suggestive!

Image Credit: M. Owen & J. Blondin



These are the ideas we need to test and constrain observationally!

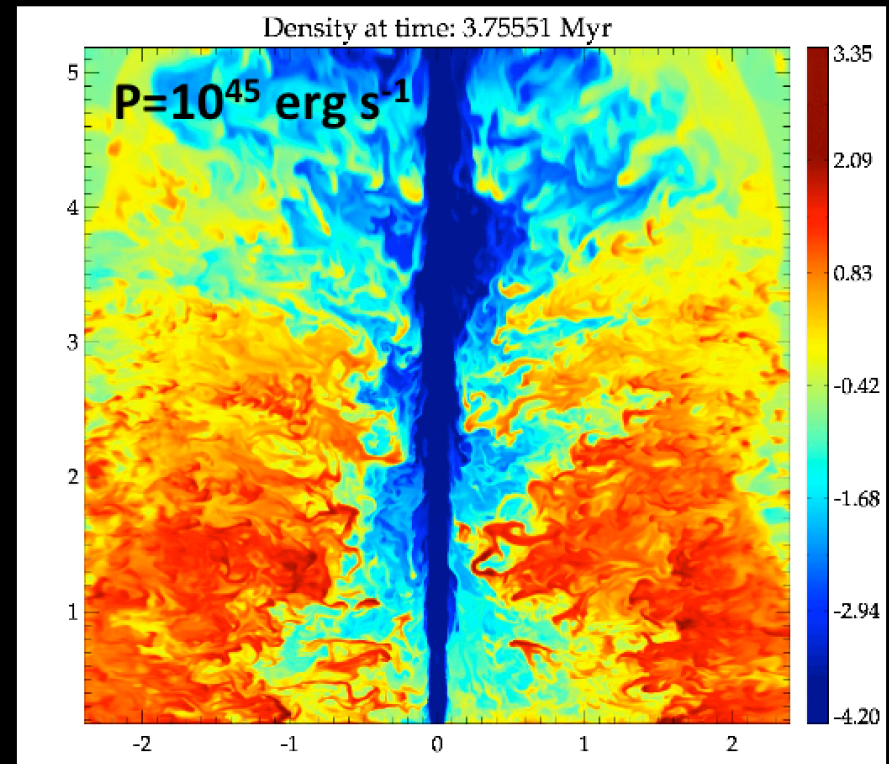
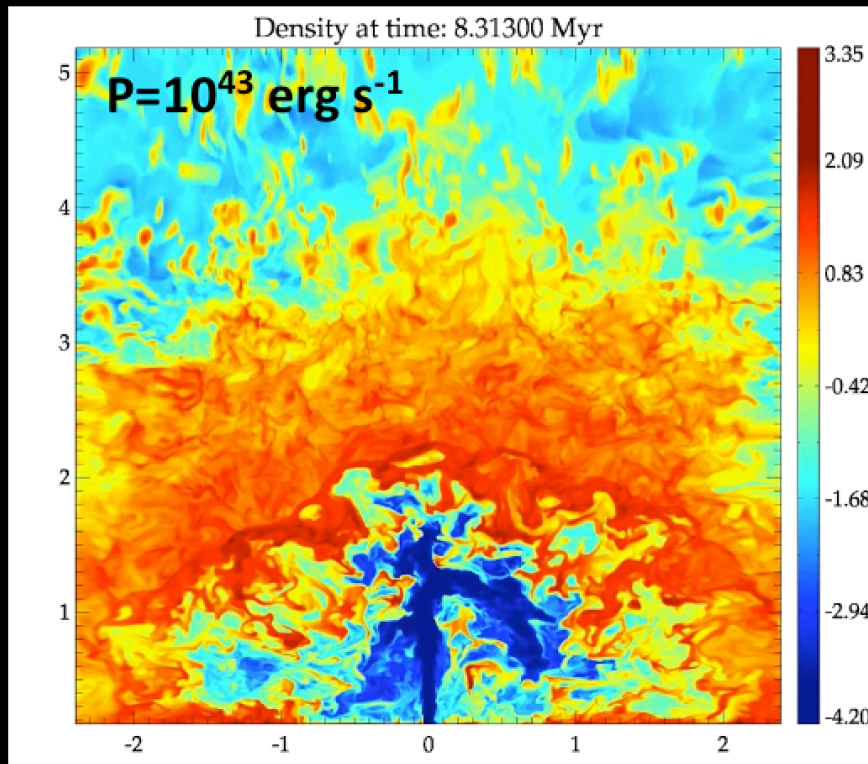
- Mass inflow
 - What are conditions like near an accreting black hole?
Disky: not Bondi-Hoyle accretion!
 - When and how quickly do black holes grow?
Likely some delay between mass inflow and AGN activity

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 - How collimated are AGN-driven outflows?
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Lower power jets disrupt more of ISM because they are stalled; higher power jets break through (Mukherjee+16)

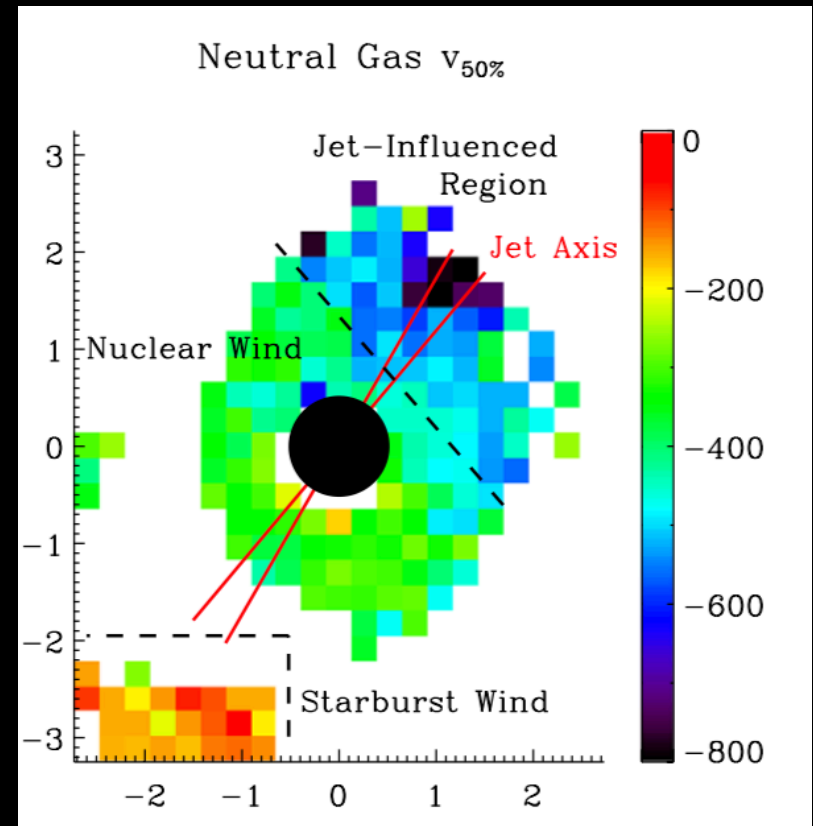
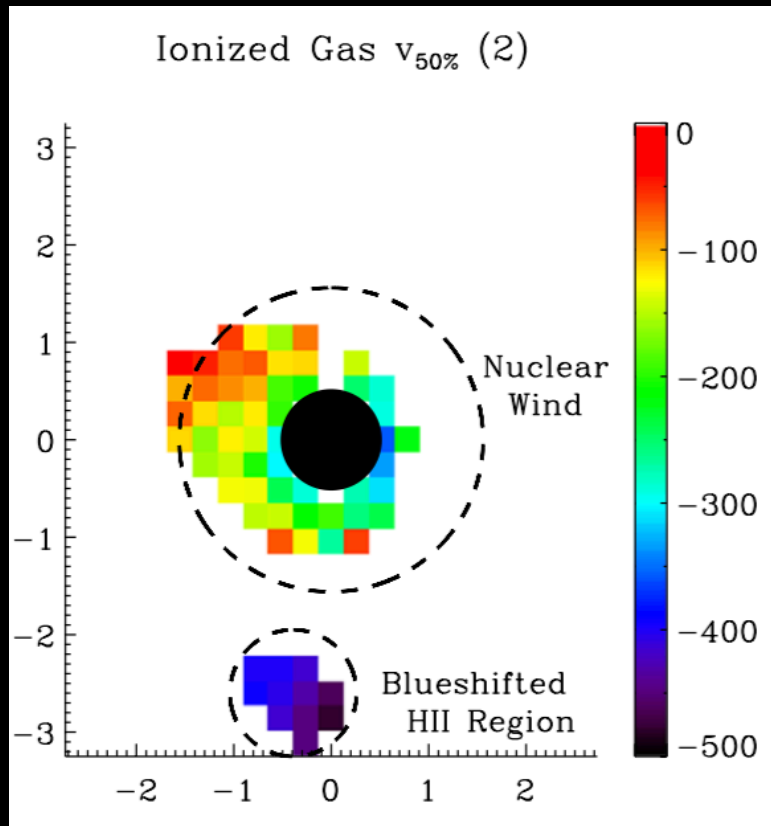
- This is why radio mode = maintenance mode



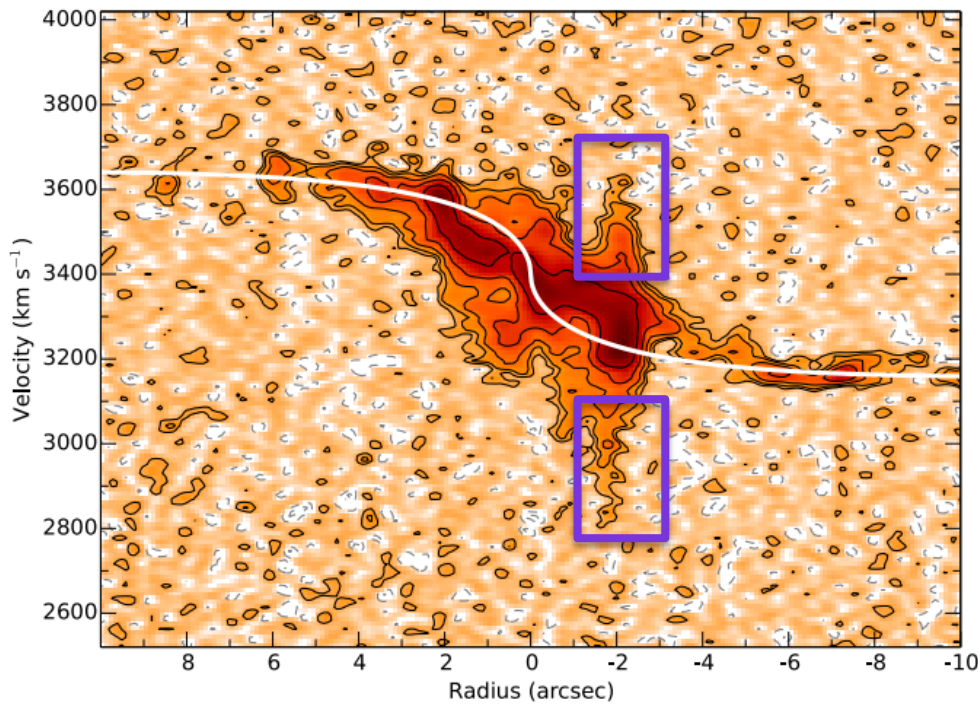
Look for AGN-driven outflows in local galaxies with IFS

- CARS – Close AGN Reference Survey
 - Tanya Urrutia's talk today
- KONA – Keck OSIRIS Nearby AGN Survey
 - Francisco Müller-Sánchez' talk today
- GOALS/OSIRIS – Vivian U's talk yesterday
- AGNIFS – Storchi-Bergmann, Riffel ++
- S7 – Siding Spring Southern Seyfert Spectroscopic Snapshot Survey – Dopita ++
- Also work by Martin++, McElroy++, Rupke +Veilleux and others

IFS provides spatially resolved mapping of outflows

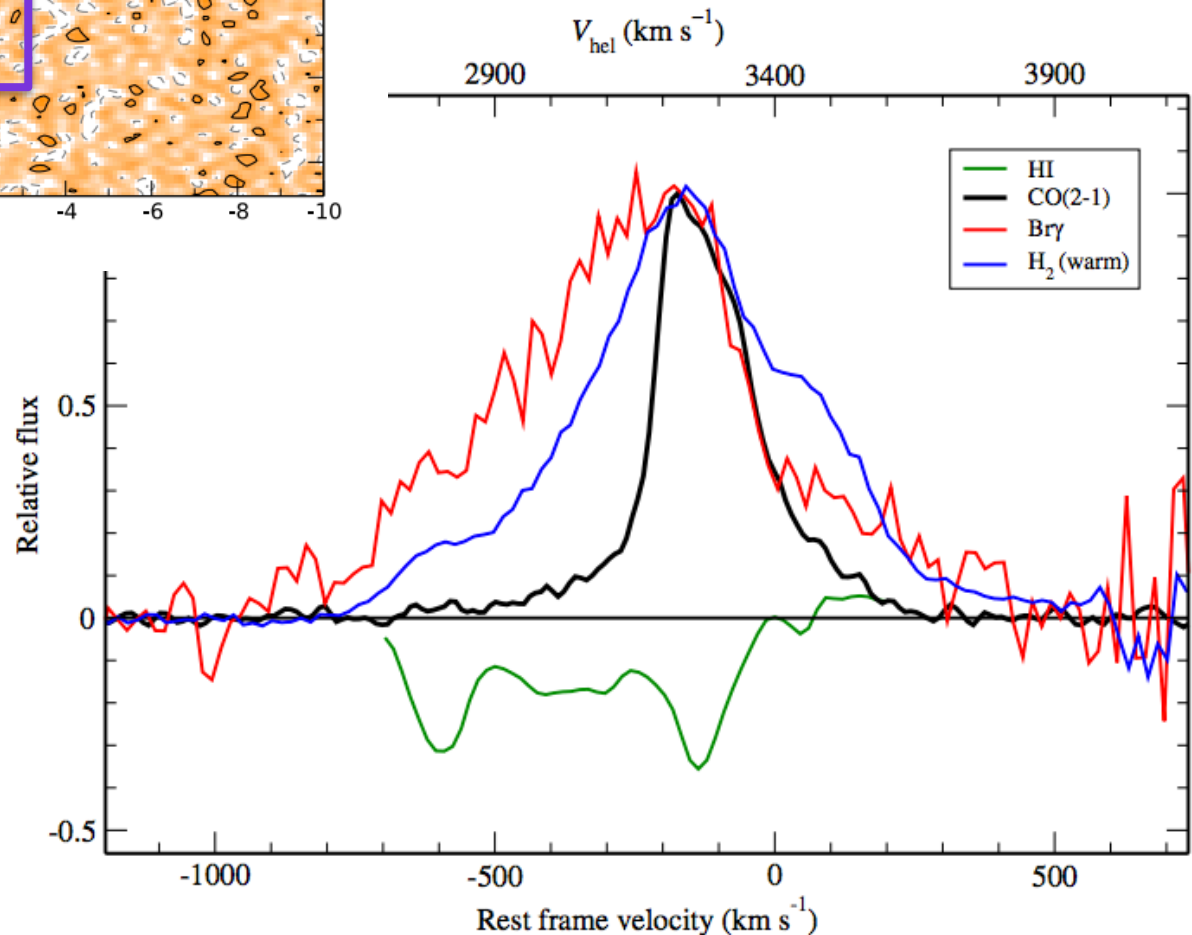


Mrk231 has AGN-driven wind traced by ionized and neutral gas. Rupke & Veilleux 2011



IC5063 demonstrates
the multiphase nature
of outflows. Morganti+15

ALMA is
bringing high
res cold
molecular gas
to the table



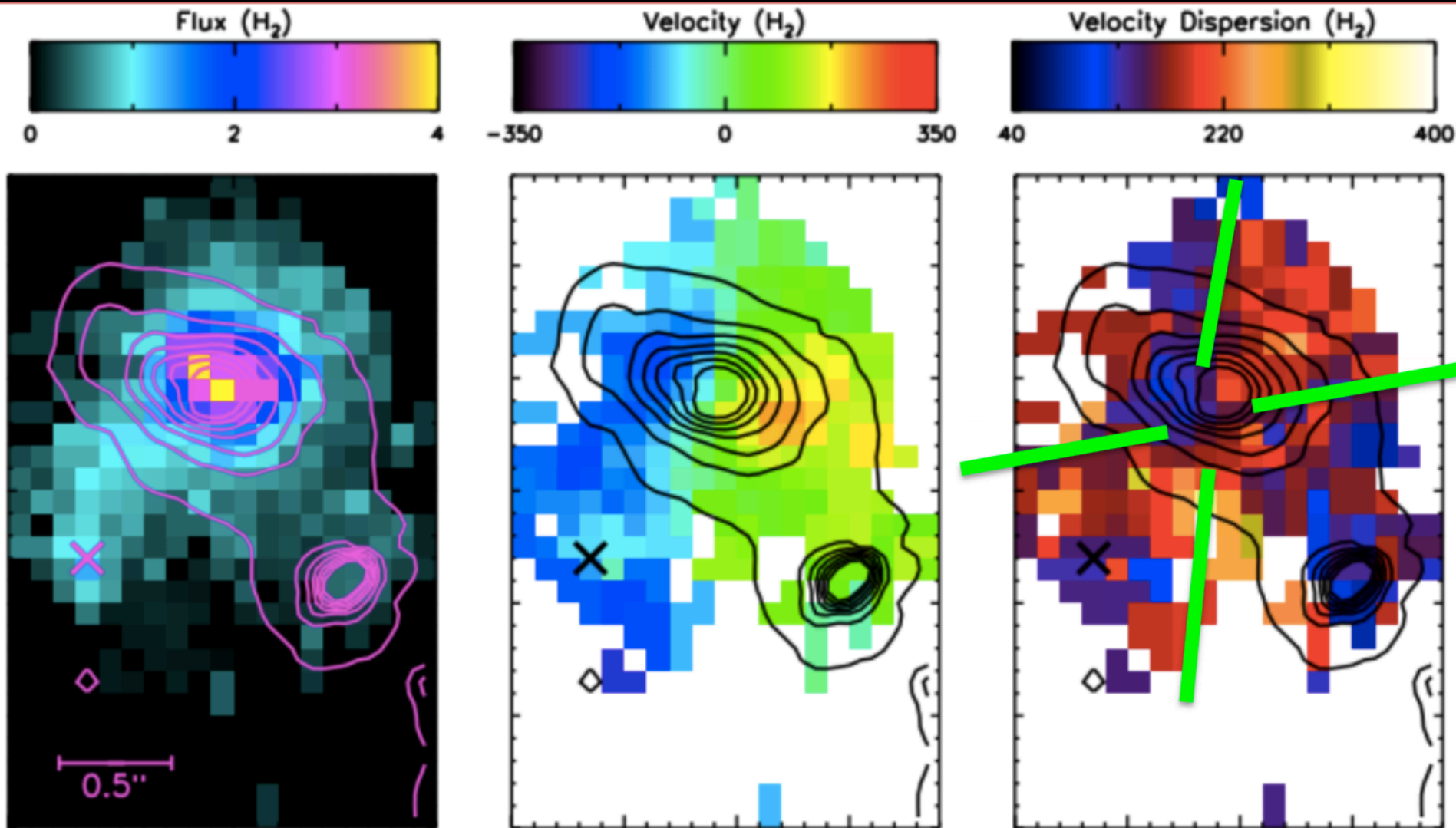
Multiphase Nature of Outflows

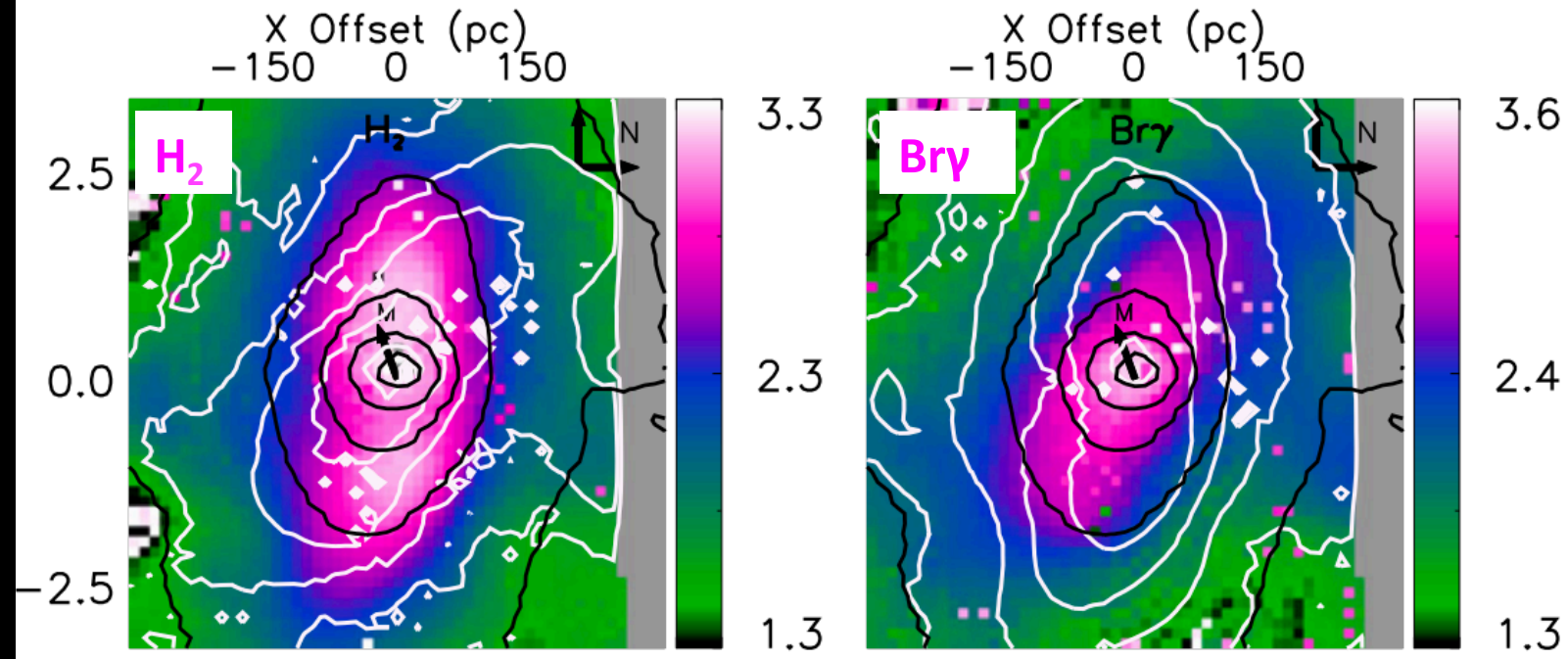
The AGN pumps energy into a multiphase medium. Does it:

- Sweep up/avoid multiphase gas without evaporating the molecular clumps? e.g. Zubovas & King 2014
- Heat/destroy molecular gas, then produce shock fronts that make new dense regions where gas can cool back into molecular state? e.g. Scannapieco & Brüggen 2015, Brüggen & Scannapieco 2016

We need high resolution multiphase maps!

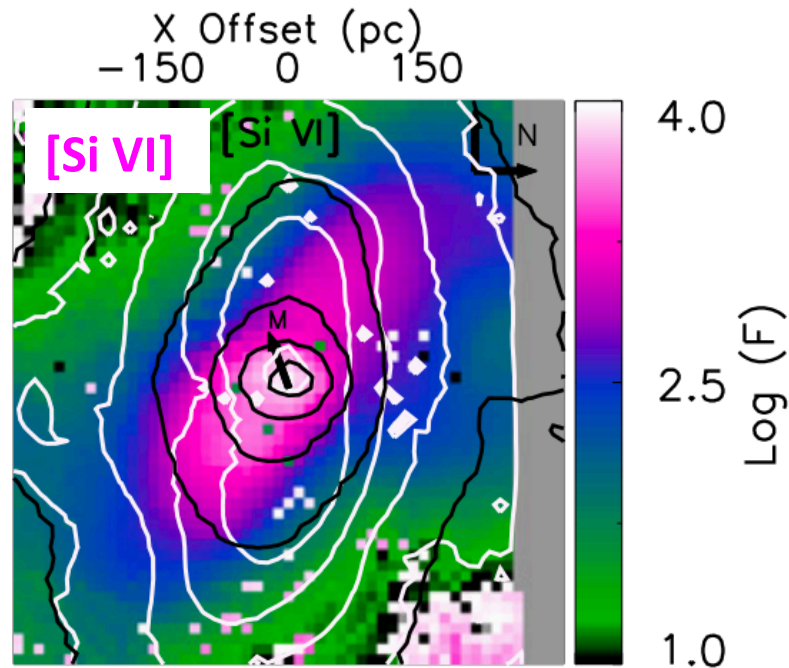
In U/LIRGs, we see narrow warm H_2 tracing outflows,
with well-behaved disk $\text{Br}\gamma$. U, AMM+13 and in prep





Line flux maps of
NGC4388 AGN/
megamaser disk
galaxy. Black
contours:
continuum.

From Greene+14



Other AGN show
the opposite: H_2
with regular/
inflow
kinematics and
outflows in
ionized gas.

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These all seem **variable** in small samples –
but more data are coming; we'll need to
look at the problem from all angles!

Take-Home Messages

New high-spatial resolution multiphase spatial +kinematic datasets are telling us:

- Bondi-Hoyle accretion is not okay any more
- It might take a long time for mass to move from $\sim 20\text{pc}$ down to the accretion disk
- Outflows are multiphase; structure can vary
- It's time to start figuring out what's driving the variation!